ASTROPARTICLES

ESIPAP - 2017

François Montanet

Plan of the course

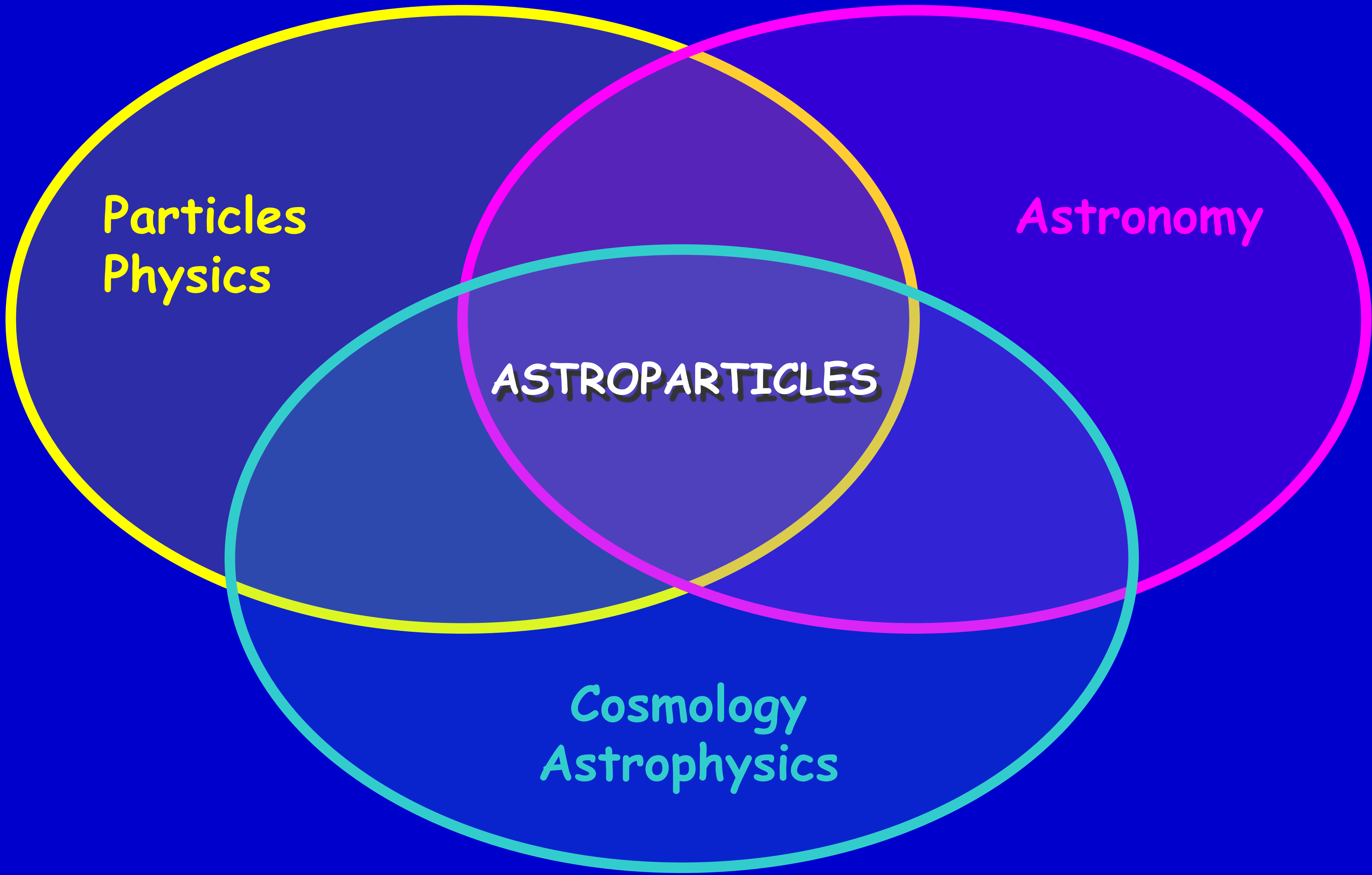
- Introduction
- Nature and properties of Astroparticles
- Propagation medium, IGM, ISM and atmosphere
- Astrophysical Sources
  - Astrophysical shocks
  - Fermi acceleration
  - Standard Model for the production of galactic CR, SNR
  - Gamma-ray sources, pulsars
  - AGN and other extragalactic sources
  - Neutrinos sources
- Cosmological Sources
  - Cosmological implications
  - Dark Matter as a source of CR
  - "top-down" type of sources at UHE
- Propagation
  - CR propagation in the Galaxy: The Leaky box model
  - VHE γ-rays propagation
  - UHECR propagation
  - Air Showers Development
- Observables & Observations
  - Primary CR detection (on top of atmosphere)
  - Gamma-ray (EM) induced showers detection => my lecture on Cherenkov det.
  - Hadronic Showers Models and Detection
  - UHECR detection => my lecture on Cherenkov det
- Dark matter search (very briefly on this, covered by J.Macias)
- Neutrino Physics with astroparticules (briefly on this, overlaps with other lecturers & detection discussed in my lecture on Cherenkov det)
- Gravitational waves (not covered, very specific)

Why studying Astroparticles

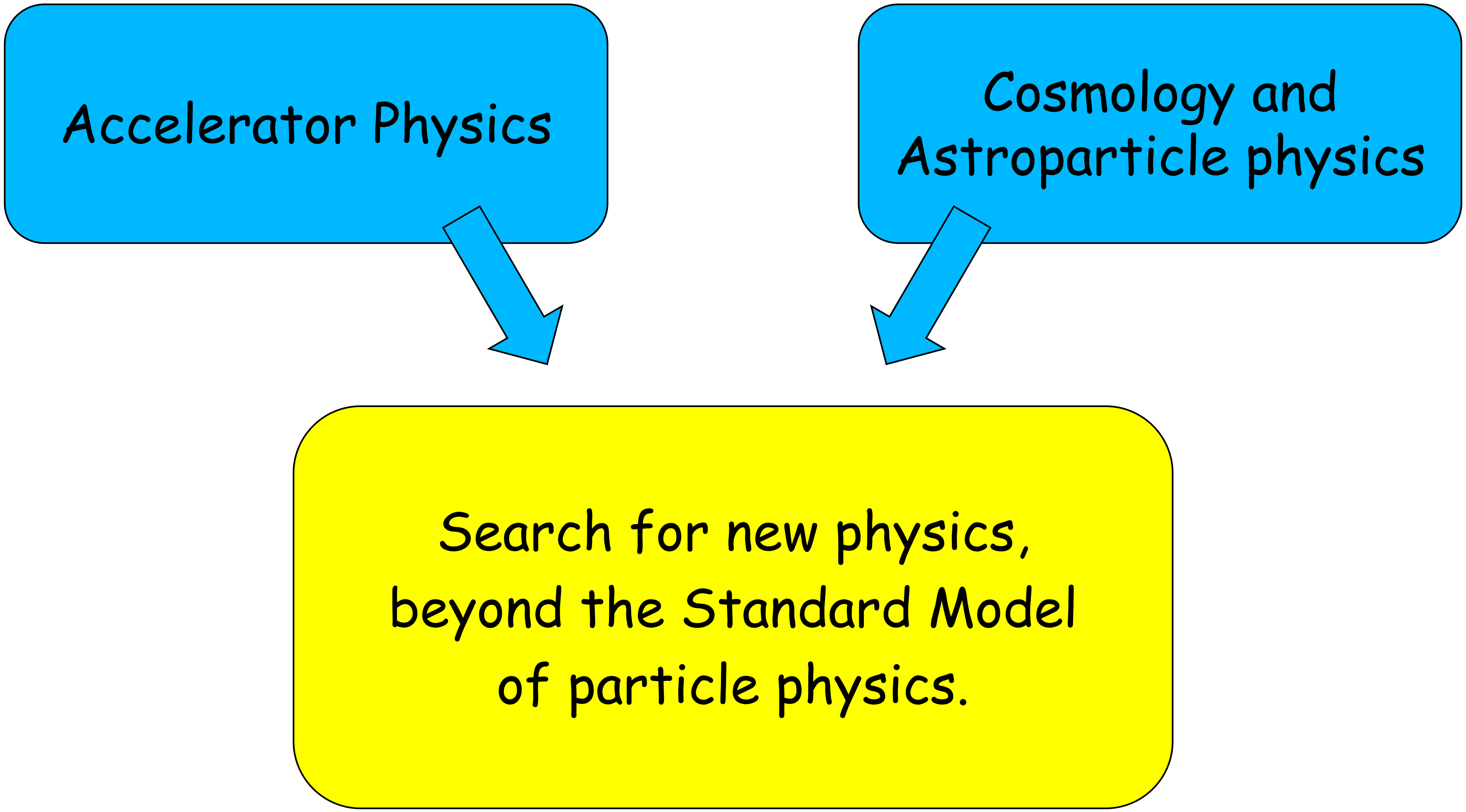
Open questions

Understand our Universe at extreme scales

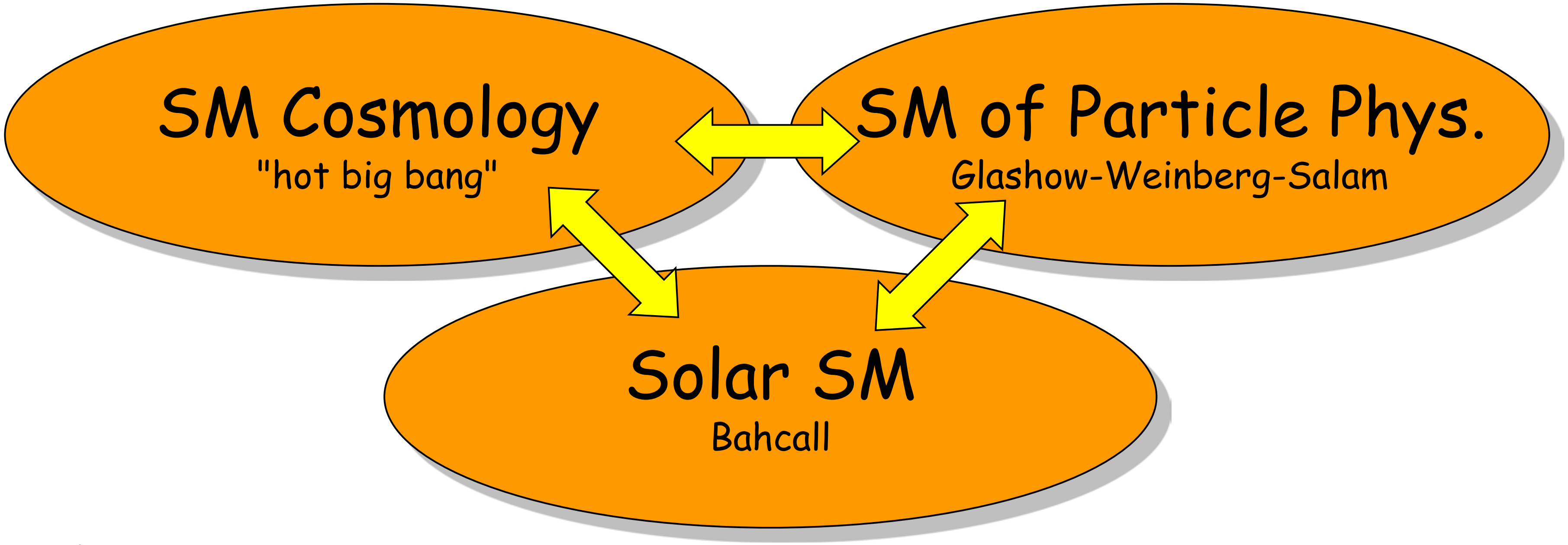
- The Higgs boson or the origin of mass
- Nature and mass of Neutrinos
- Fundamental symmetries: CP , supersymmetry
- New dimensions in physical space ?
- What is our Universe made of ?
- Sources and propagation of cosmic rays ?
- New Physics at E >> E(LHC) ?


Particles
Physics
Astronomy
ASTROPARTICLES
Cosmology
Astrophysics

Astroparticles & HEP



Matching "standard models"



Examples of happy breeding...

Nucleosynthesis $\Rightarrow N_\nu$

$\Omega h^2, LSS... \Rightarrow \sum m_\nu < ...$

... as well as some disputes...

BigBang ↔ Dark Matter, Dark Energy, Inflation, Matter Anti-Matter Asymmetry ↔ GWS

GWS ↔ Solar ν deficit, Atmospheric ν anomalies ↔ Solar SM

Direct searches

↓

new particles production-observations

(Tevatron, LHC)

Indirect searches

$FCNC$, CP

$FV \rightarrow \mu \rightarrow e\gamma$

d_n^e

B physics

New Physics

This decade's grail:
solve the puzzle of
electroweak symmetry
breaking

Progress in Theory

Supergravity

→ Superstrings, M-Theory

Cosmology

Measure the parameters
of the Univers
and their evolution

Astroparticle Physics

Neutrino Physics

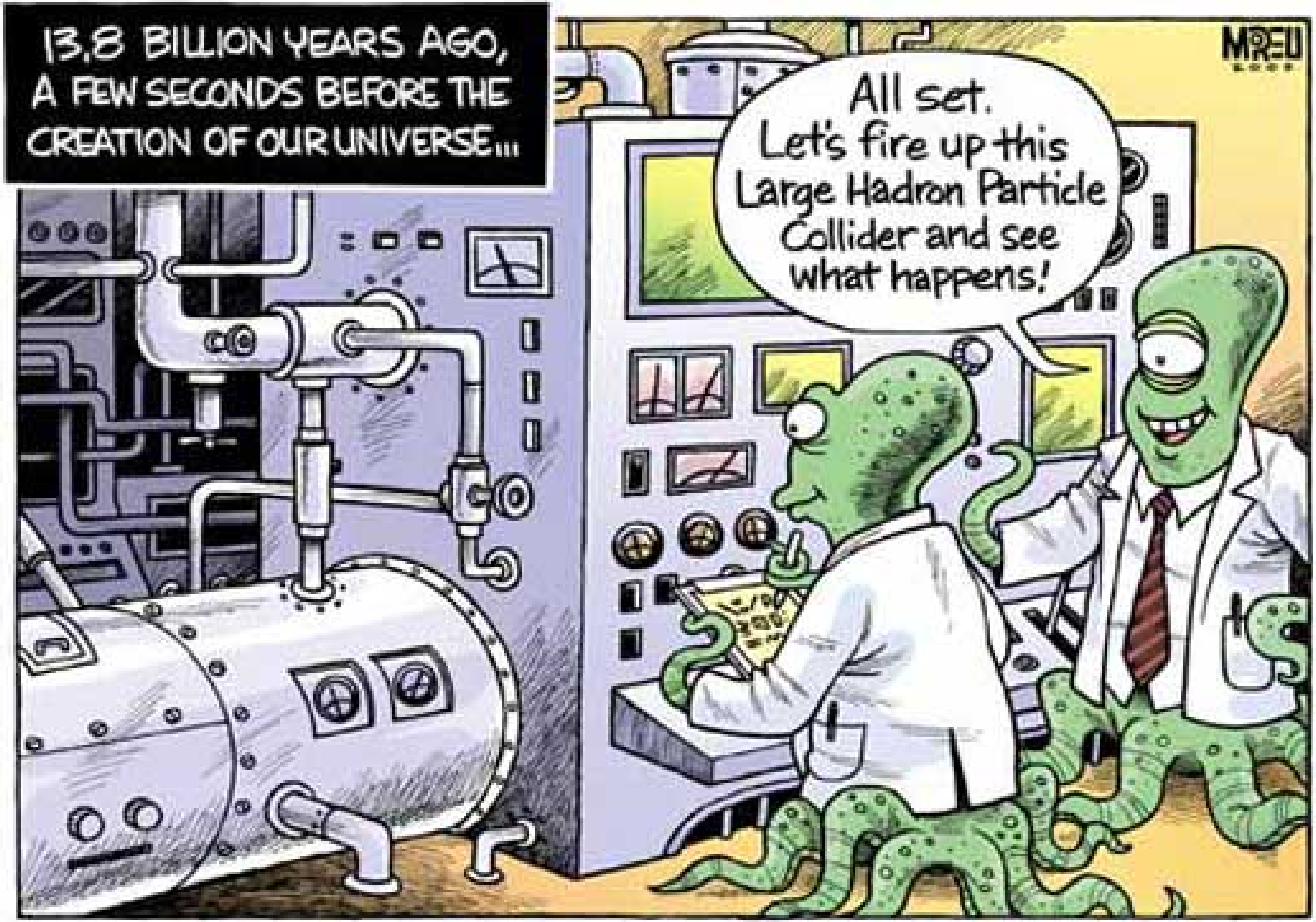
Cosmic Rays

γ Astronomy

Gravitationnal Waves

↓

New Physics probes


13.8 BILLION YEARS AGO, A FEW SECONDS BEFORE THE CREATION OF OUR UNIVERSE...
All set. Let's fire up this Large Hadron Particle Collider and see what happens!
MREU

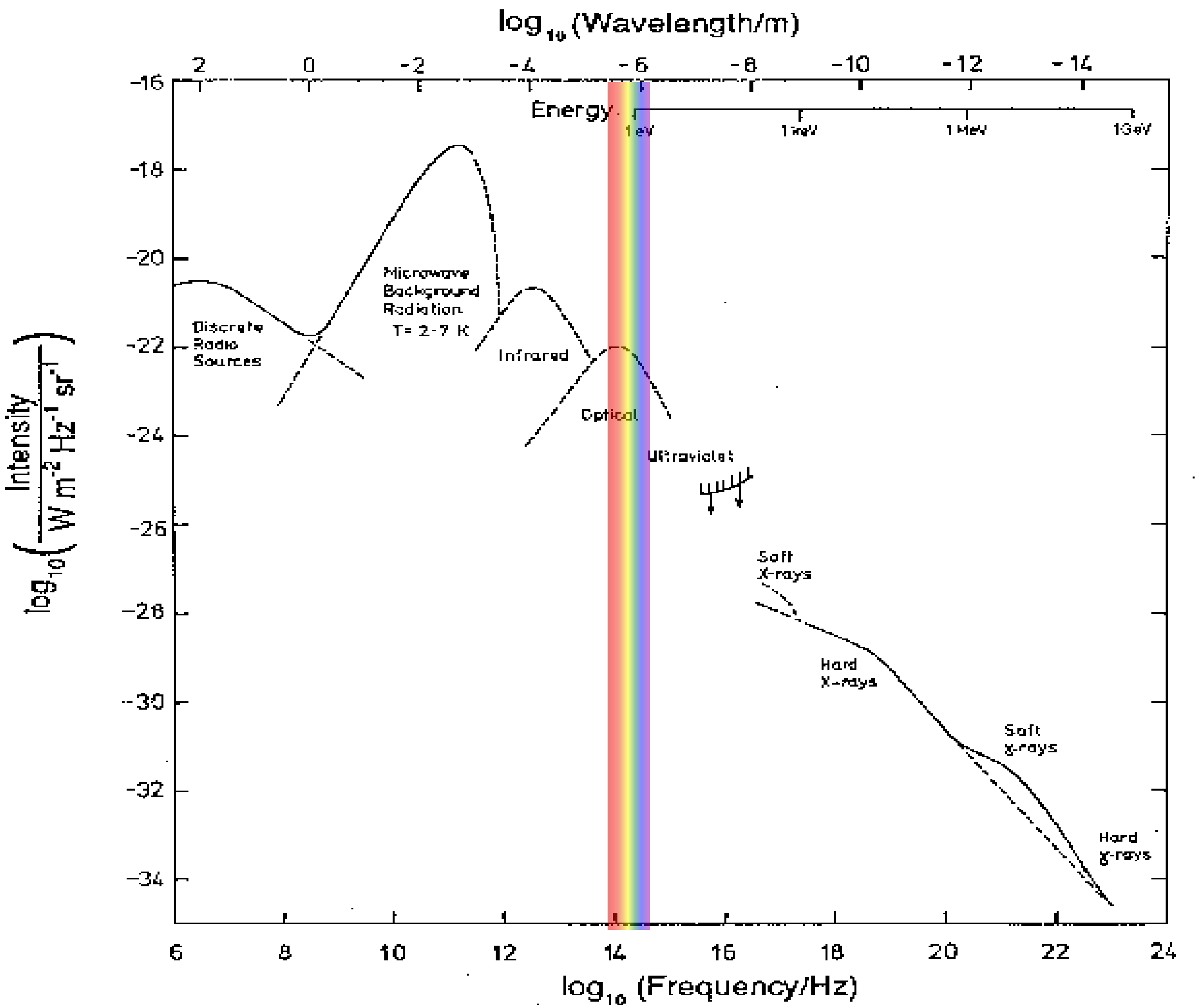
What are "Astroparticles"

What we know... roughly.

Let there be light !

All what we know in astrophycics is thanks to the light !

- A multi-wavelength sky

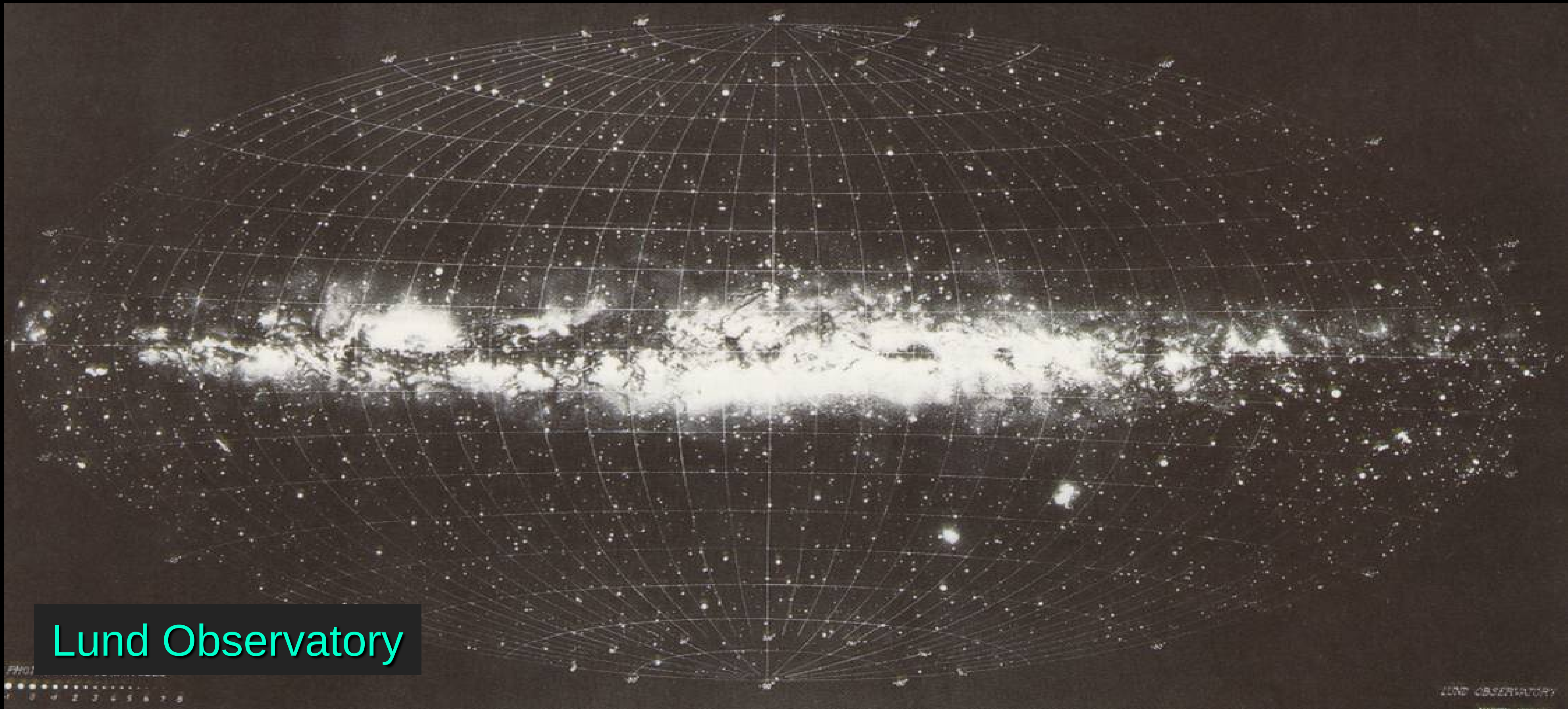


Our Galaxy

The optical Milky Way

Our Galaxy

The optical Milky Way

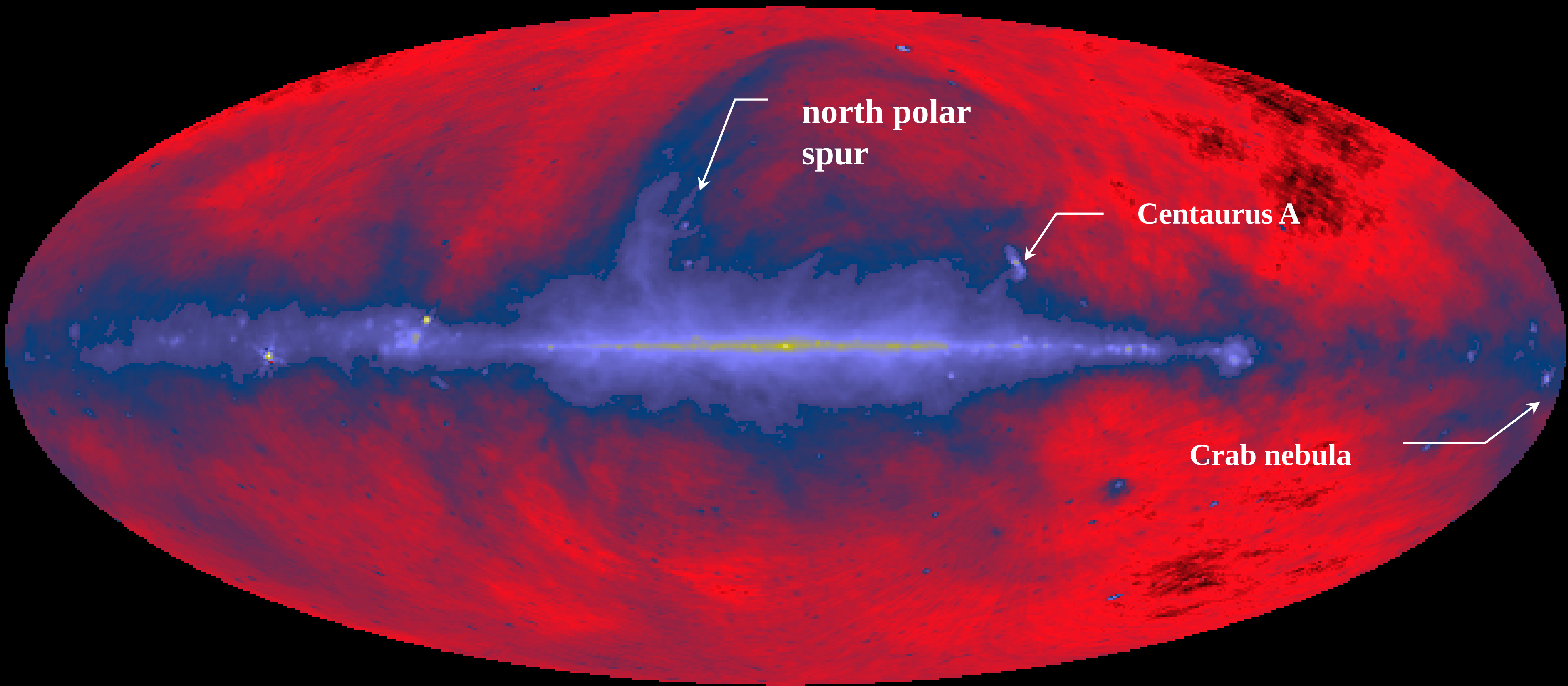


Lund Observatory

Our Galaxy

The Milky Way : Radio at 73cm

408 MHz / 73.5 cm / 1.6 10^{-6} eV)

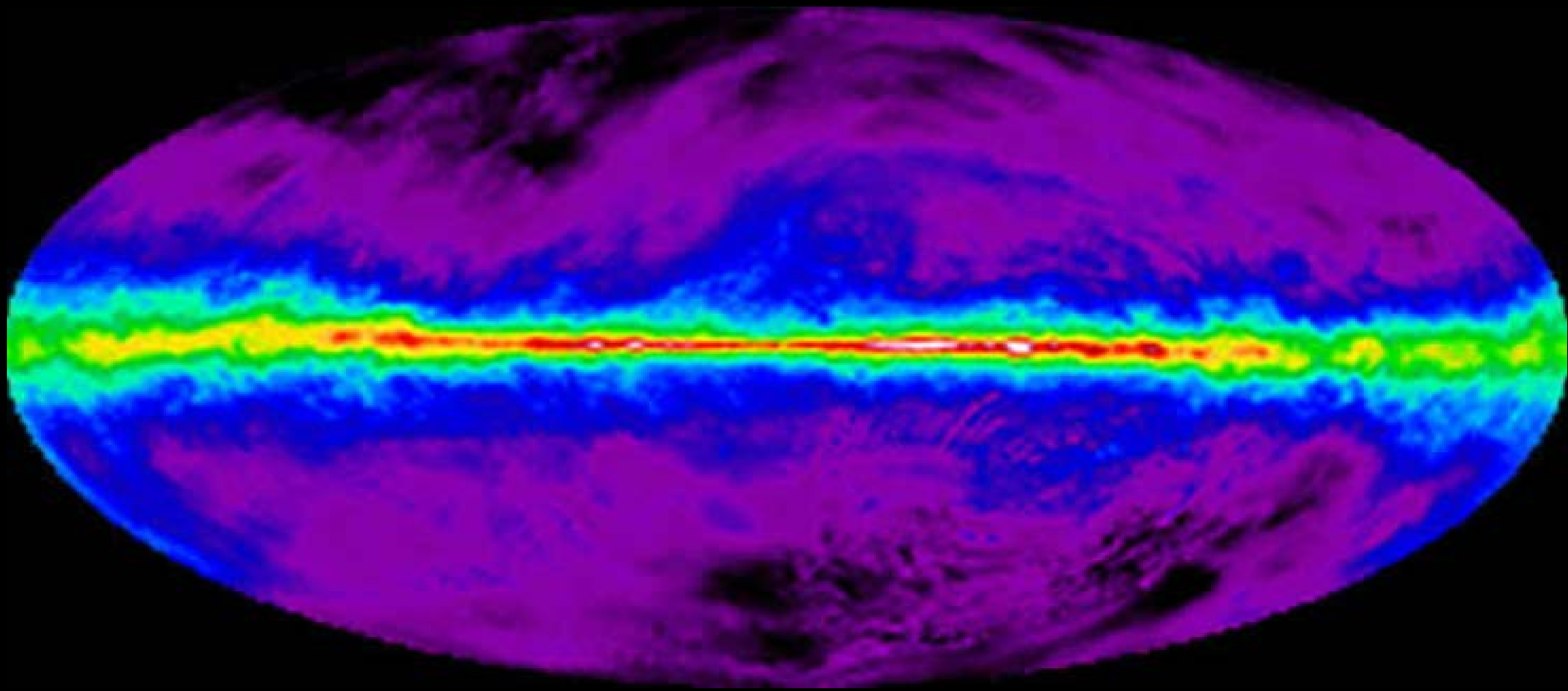


Essentially from the movement of ultra relativistic electrons probably issue from supernovae remnants in the galactic magnetic field.

Our Galaxy

The Milky Way : Radio at 21 cm

(~1.42 GHz / 21.1 cm / 5.9 10^{-6} eV)

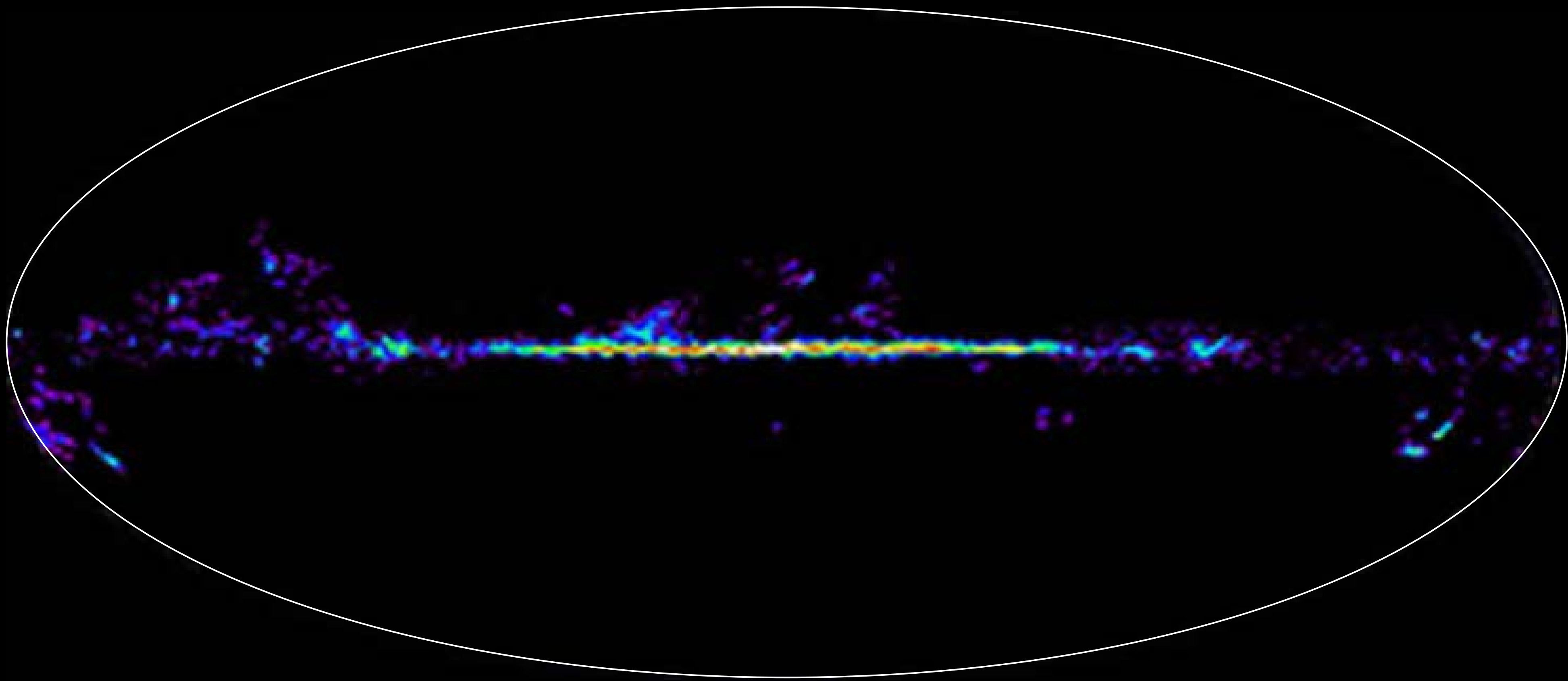


Hyperfine transition of hydrogen. Structures are due to the column density of atomic hydrogen clouds along the line of sight.

Our Galaxy

The Milky Way : Radio at 2,6mm

Millimetric waves (115 GHz / 2.6 mm / 4.7 10^{-4} eV)

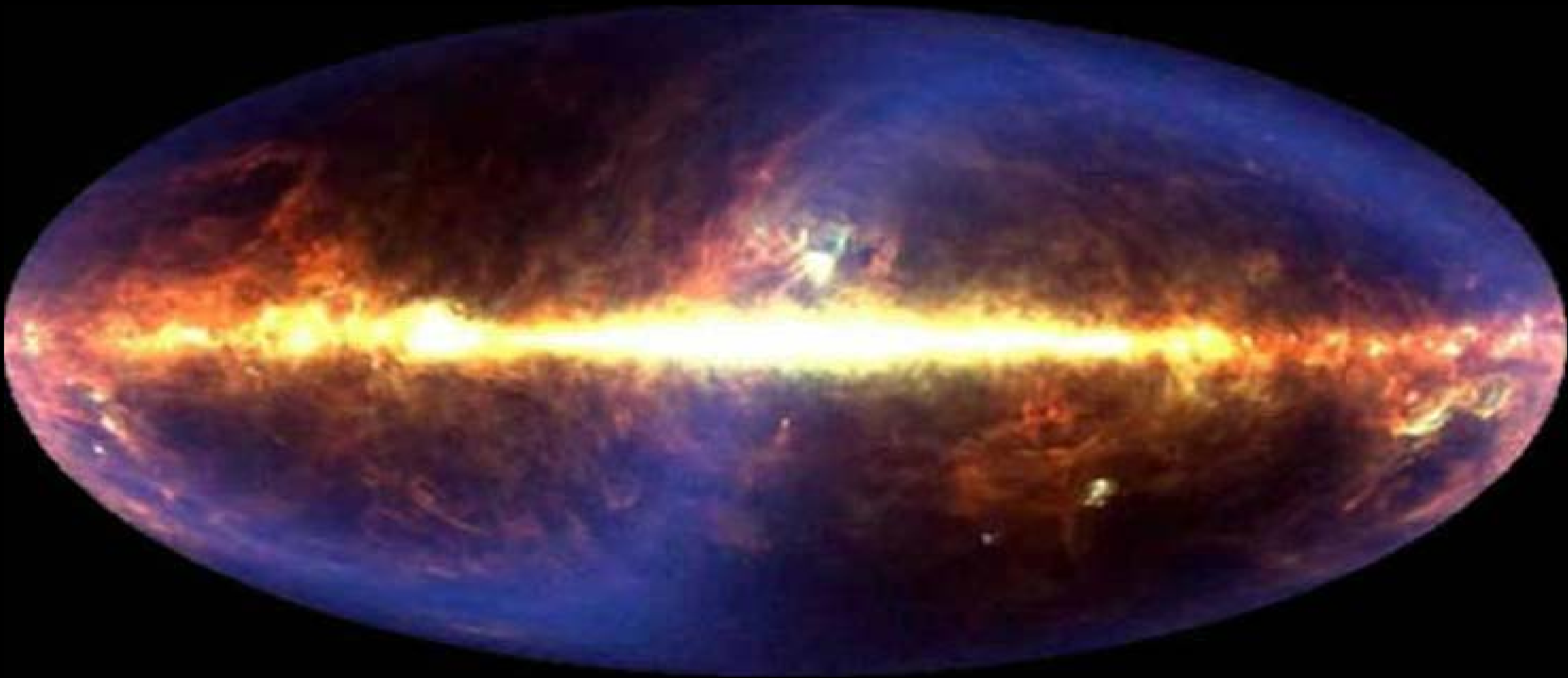


Rotation mode ray of carbon monoxide. One assumes that CO abundance is proportional to that of cold molecular hydrogen (directly undetectable).

Our Galaxy

Infra red

Infrared (3 10^3 to 25 10^3 GHz / 100 to 12 μm / 0.01 to 0.1 eV)

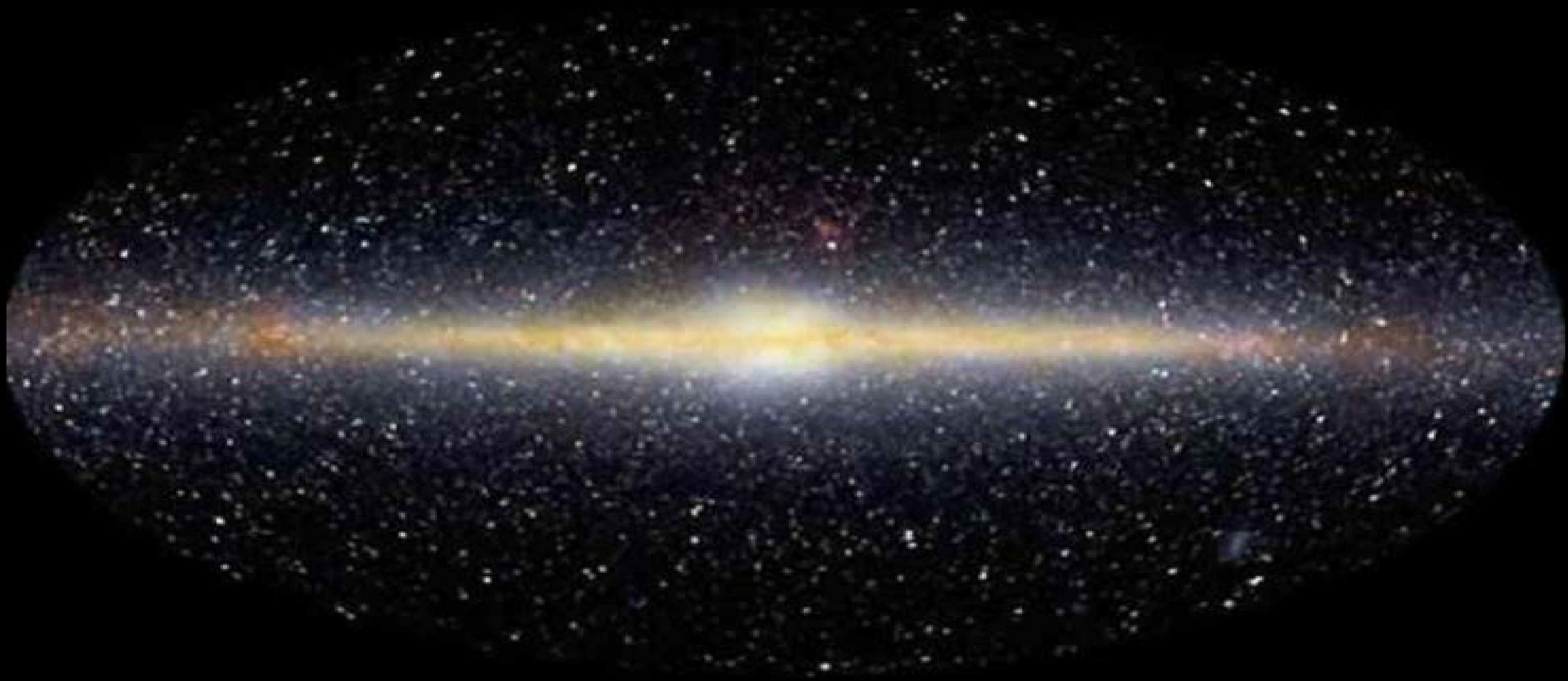


Thermal emission, due to interstellar dust heated by starlight.

Our Galaxy

It structure is clearly visible in IR (COBE satellite).

Near Infrared (86 10^3 à 240 10^3 GHz / 1.25 à 3.5 μm / 0.35 à 1 eV).



Giant stars emission in the disk and in the bulb

Our Galaxy

Optical

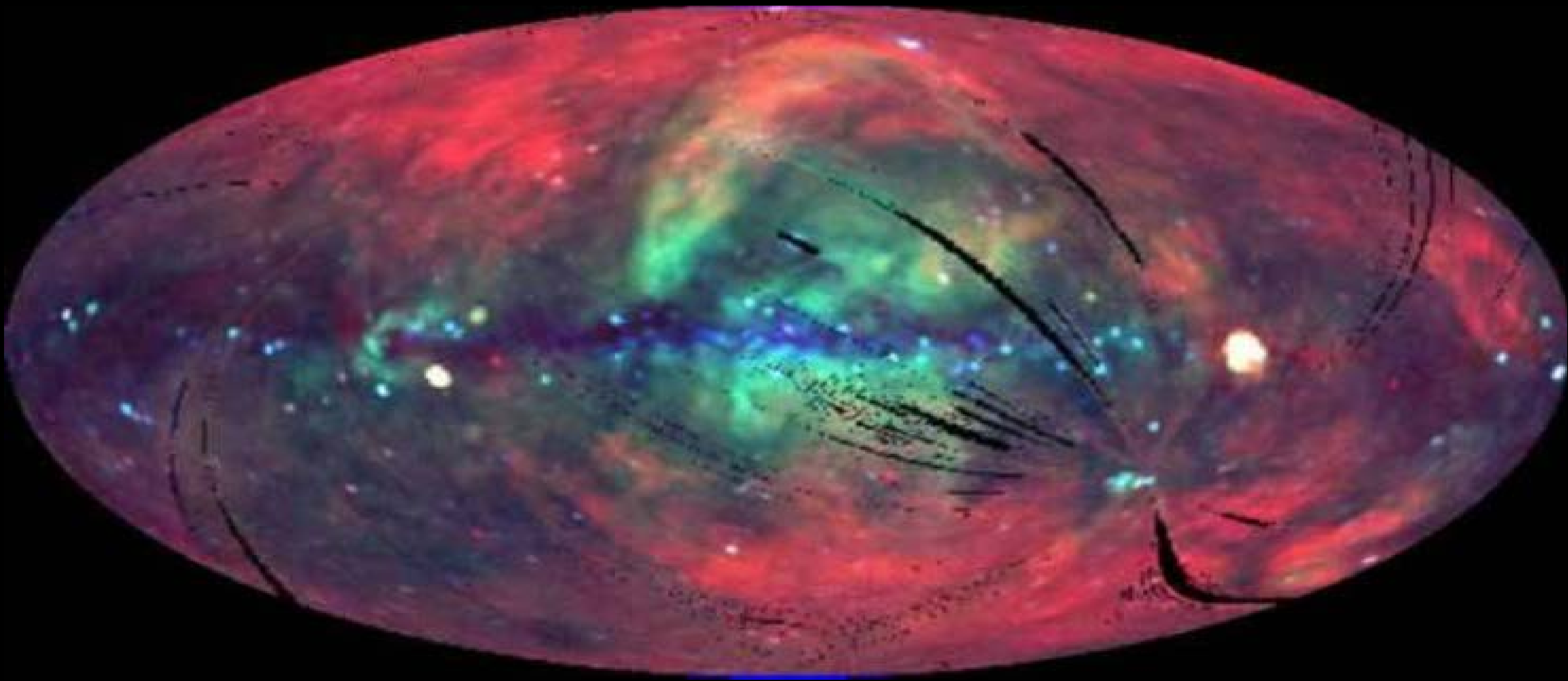
Visible (460 10^3 GHz / 0.65 μm / 2 eV – red)

Visible light is absorbed by interstellar dust clouds.
Only stars close enough to the solar system (few parsec) are seen.

Our Galaxy

X-rays

X -rays (60.10^6 to 360.10^6 GHz / 5 to 8.3 nm / 0.25 to 1.5 keV).

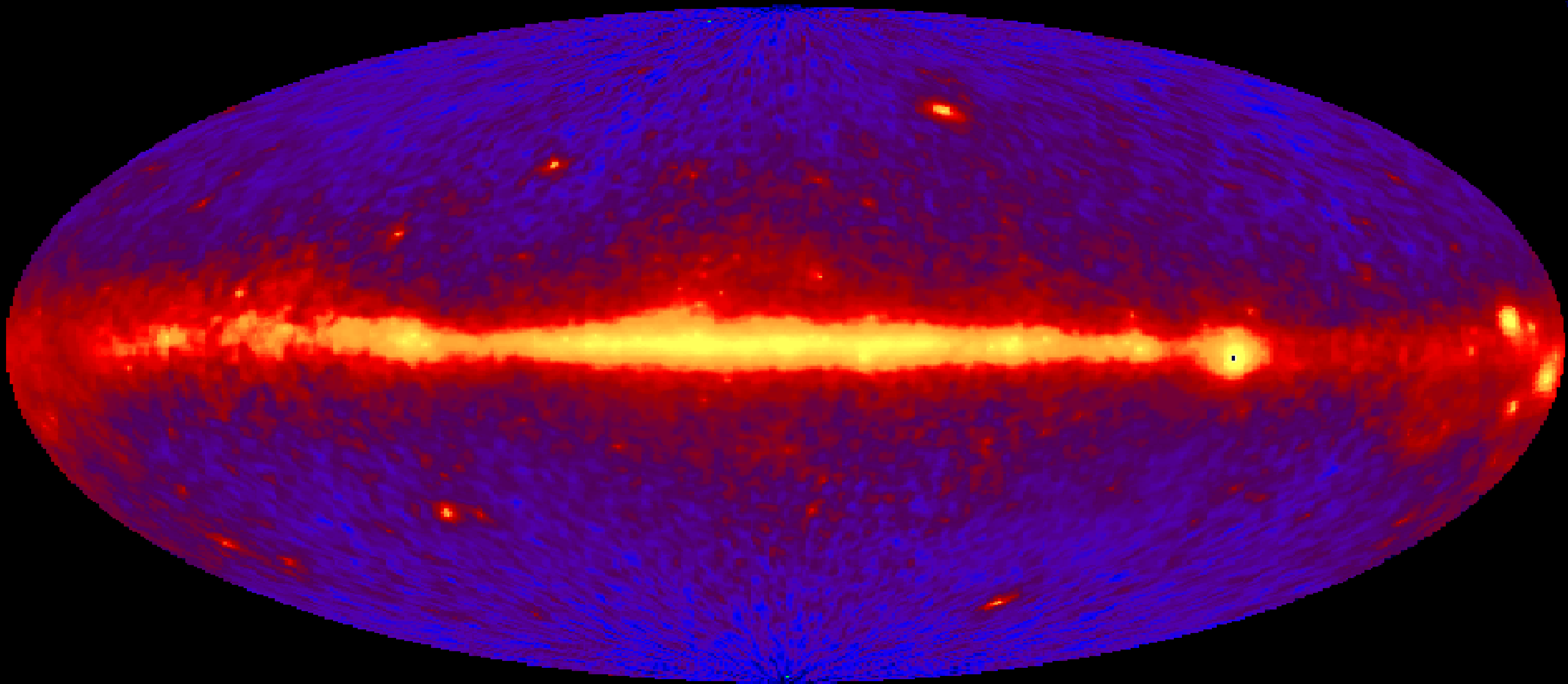


Diffuse X-ray emission from overheated and shocked gas.

Our Galaxy

Gamma-rays

Gamma-rays (> 2.4 10^{13} GHz / < 12.5 fm / >100 MeV).



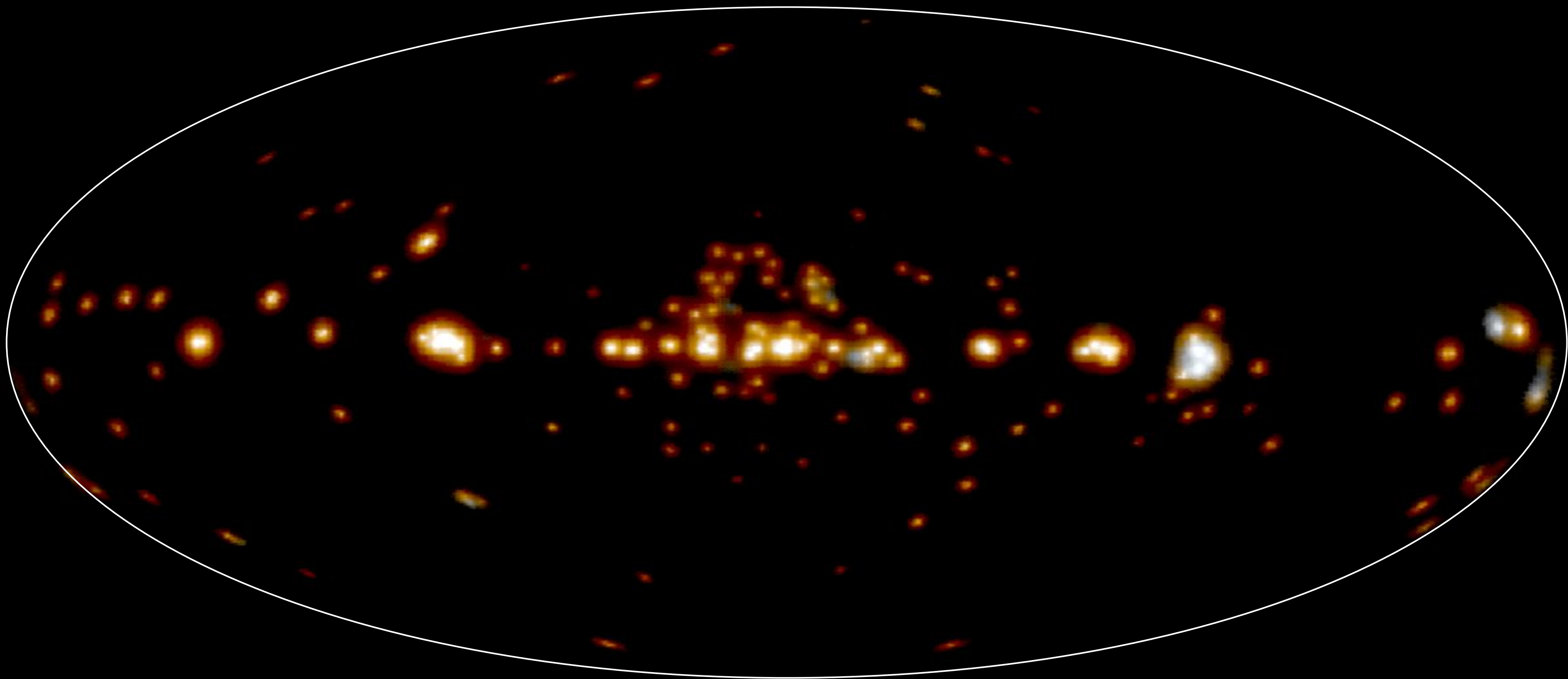
Photons (gammas) from the decay of neutral pions produced in the interaction of CR with interstellar matter, from the Bremsstrahlung of CR and from the inverse Compton of relativistic electrons with ambient photons.

Our Galaxy

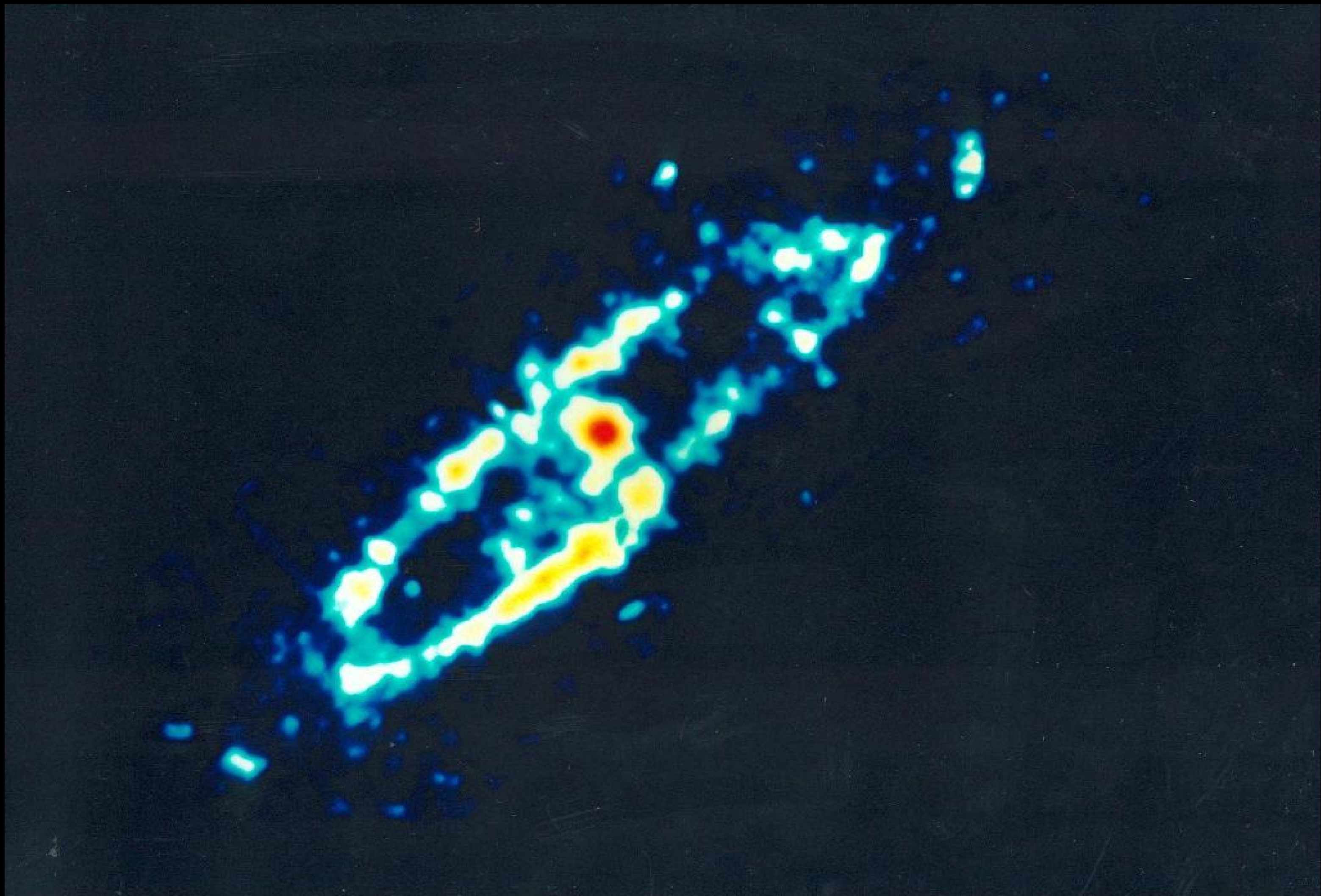
HE gamma-rays (>100MeV EGRET satellite)

Resolved point-like sources:

Binary systems, pulsars, SN remnants...



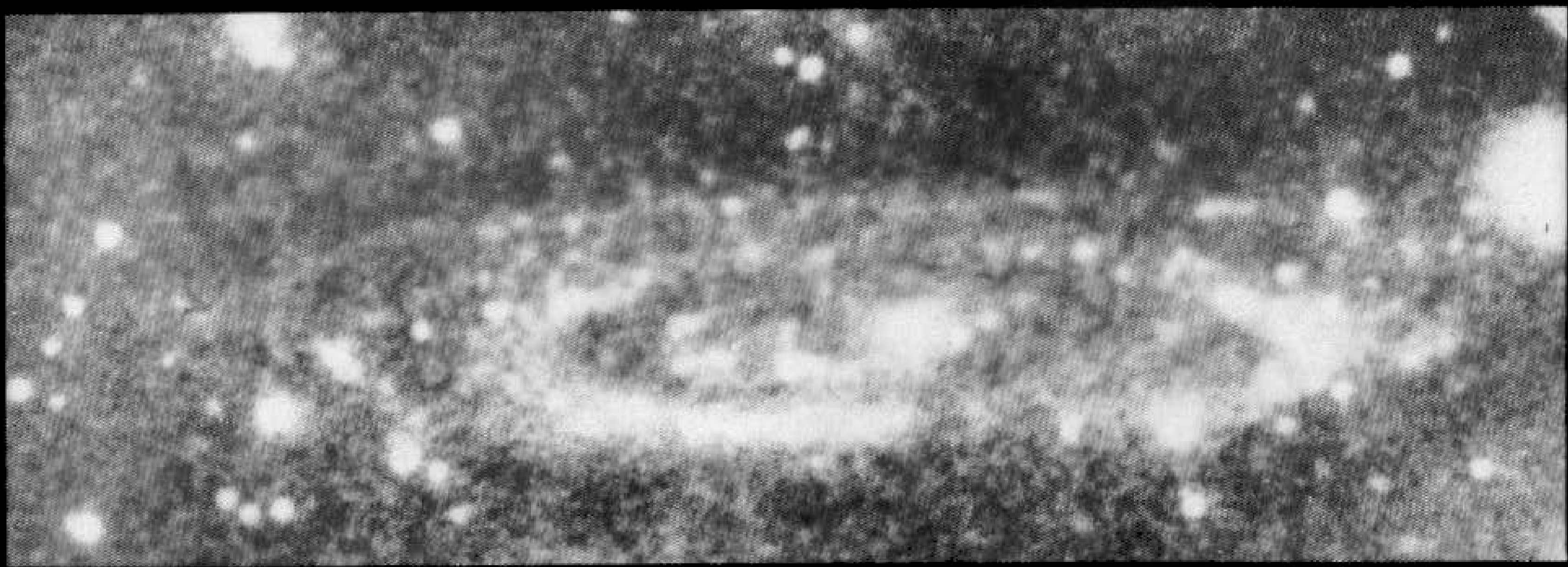
Andromeda (M31): IR



Star forming regions in spiral arms

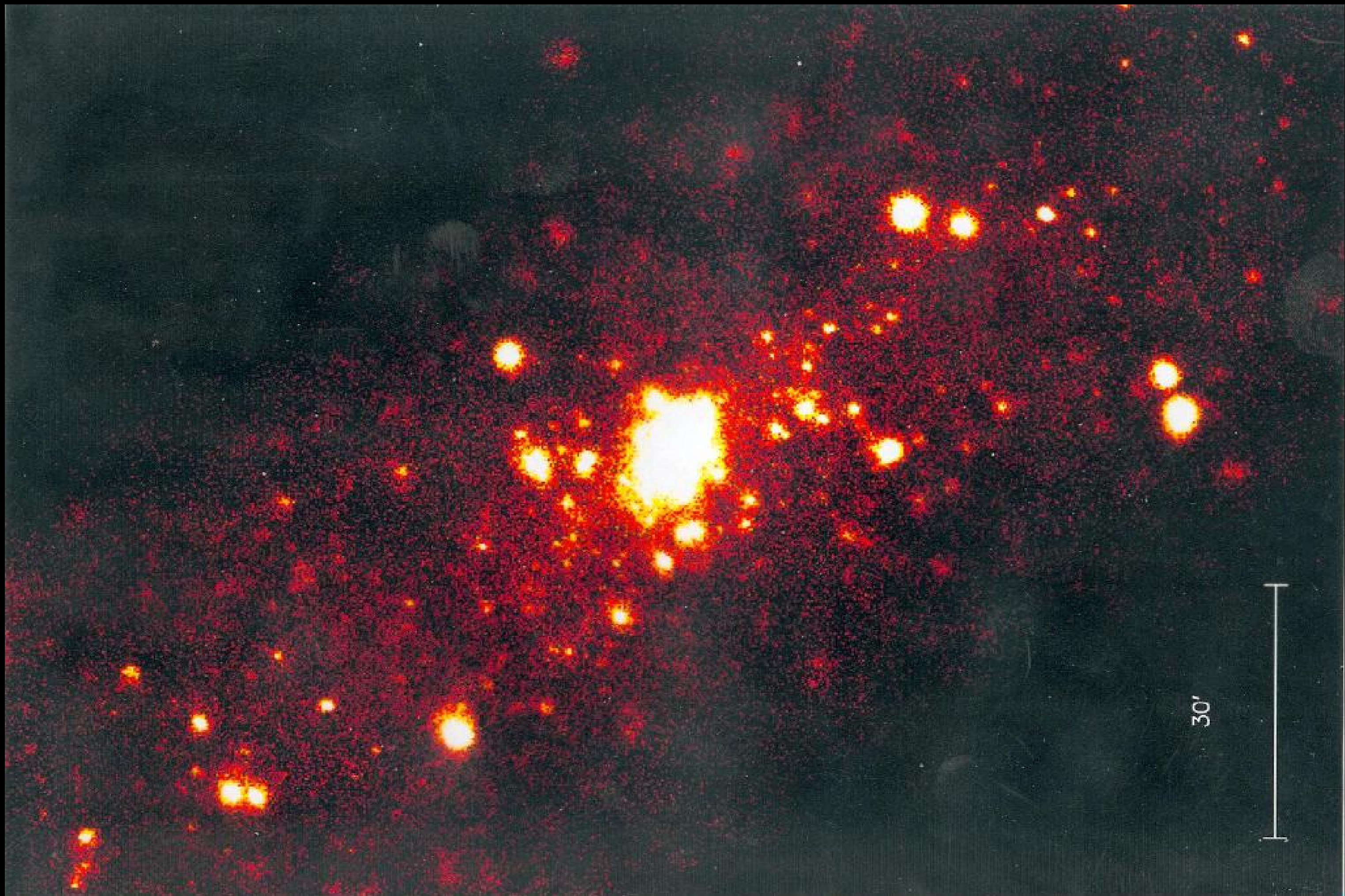
Andromeda (M31): UV

This photograph of the galaxy M31 reveals the prominence at ultraviolet wavelengths (2000 Å) of young stars in the spiral arms over the older population in the central bulge. (B. Milliard/ Laboratoire d'Astronomie Spatiale).



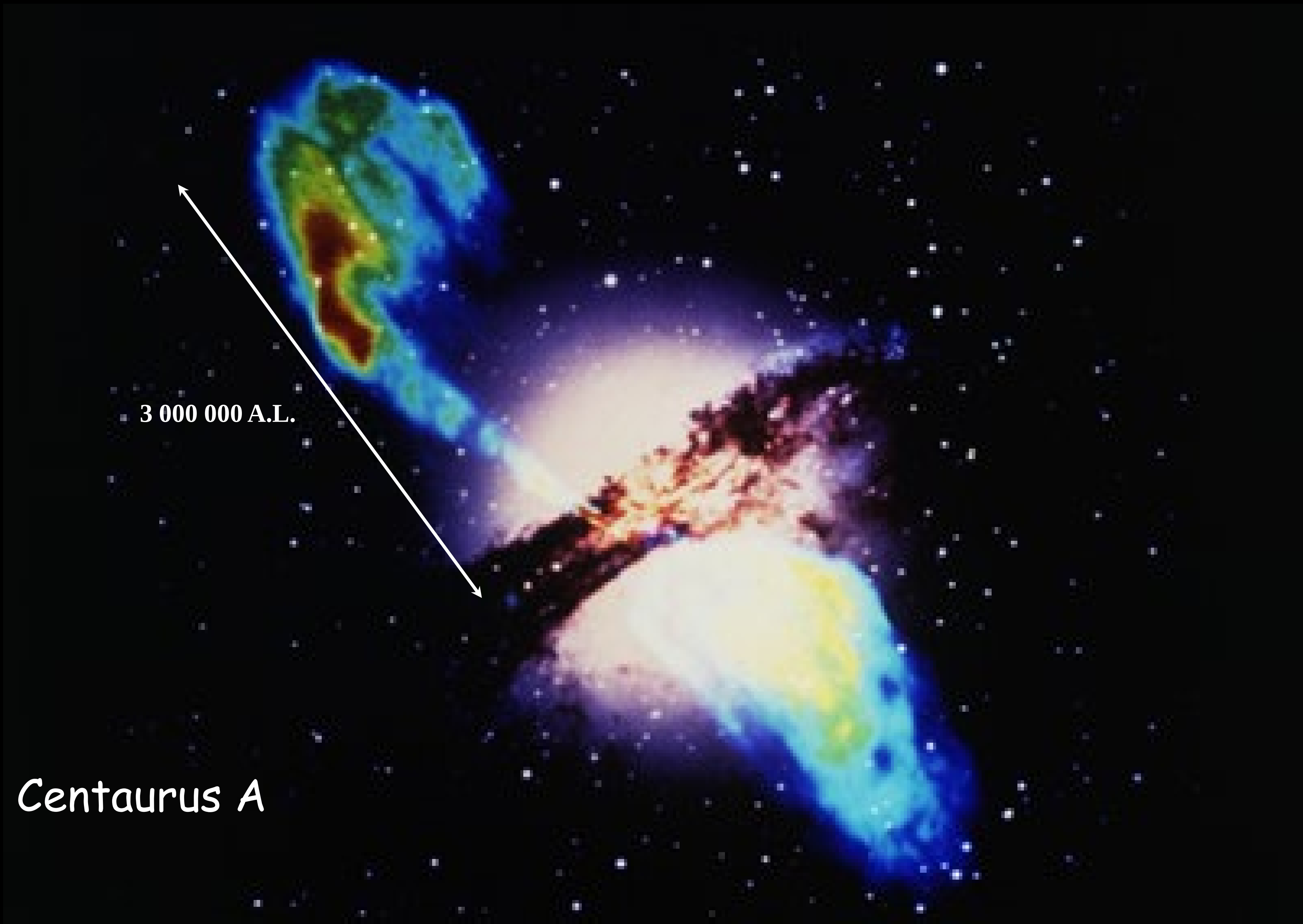
Young, hot stars in spiral arms

Andromeda (M31): Xray



Xray binaries, supernova remnants, hot gas

Radio Galaxy



Let there be light !

All what we know in astrophycics is thanks to the light !

- Temperatures, stars masses, galaxies, magnetic fields, chemical composition, age of stars and structures…
- Nuclear reactions, galactic and extragalactic hydrodynamics, MHD, explosions, nucleosynthesis, past, future… EVERYTHING !

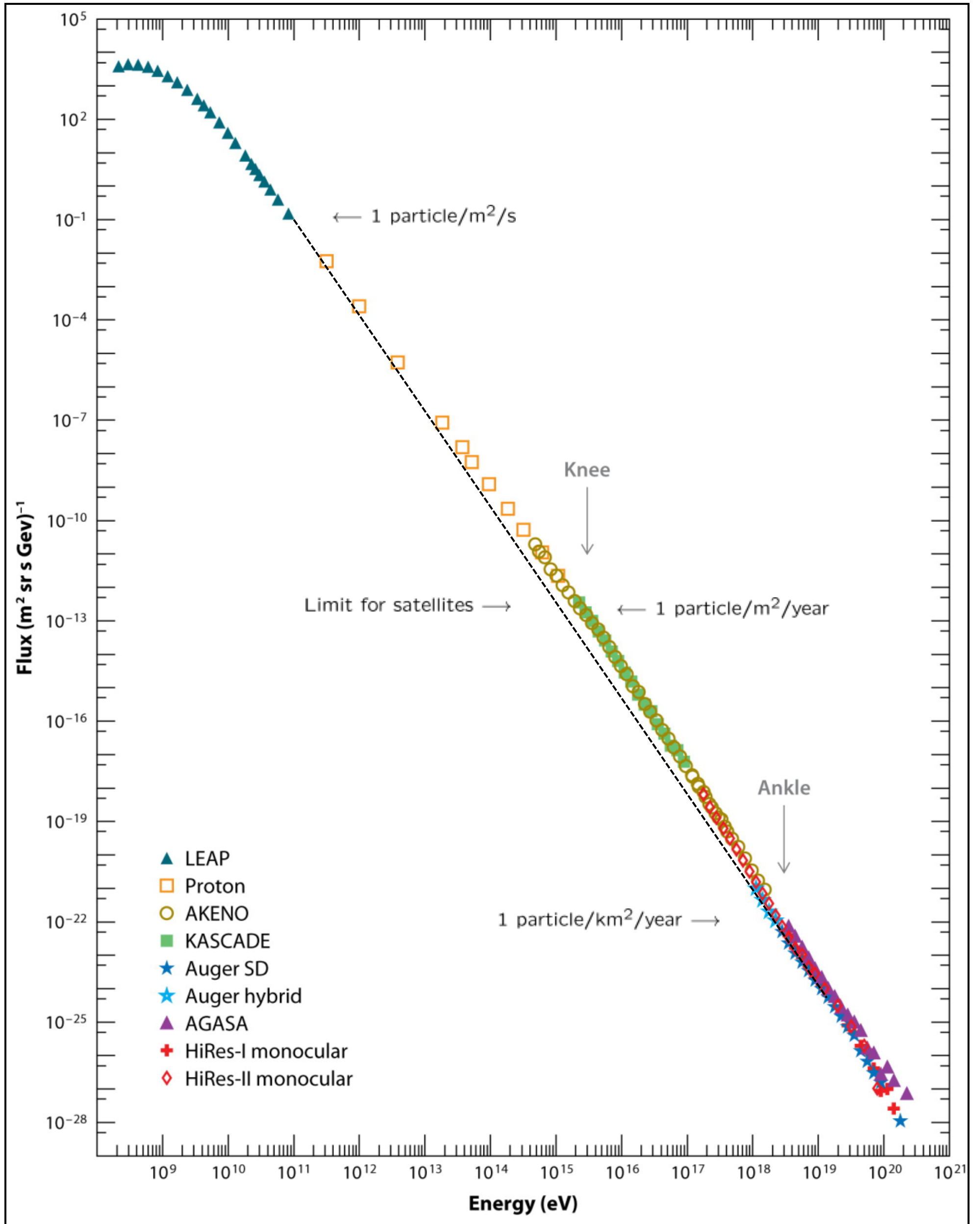
- Well, almost everything…
  - ∃ non-luminous messengers : cosmic rays (charged) and neutrinos
  - Rare but precious : ~ **4 CR/cm²/s**
    ~**30 µg/s** on entire earth (**1kg** per year !)

- CR astronomy is impossible…
  - Directions randomized by magnetic fields
  - What we would know if it was the same for photons !

…but not astrophysics !

- Energy spectra and chemical composition tells us a lot…

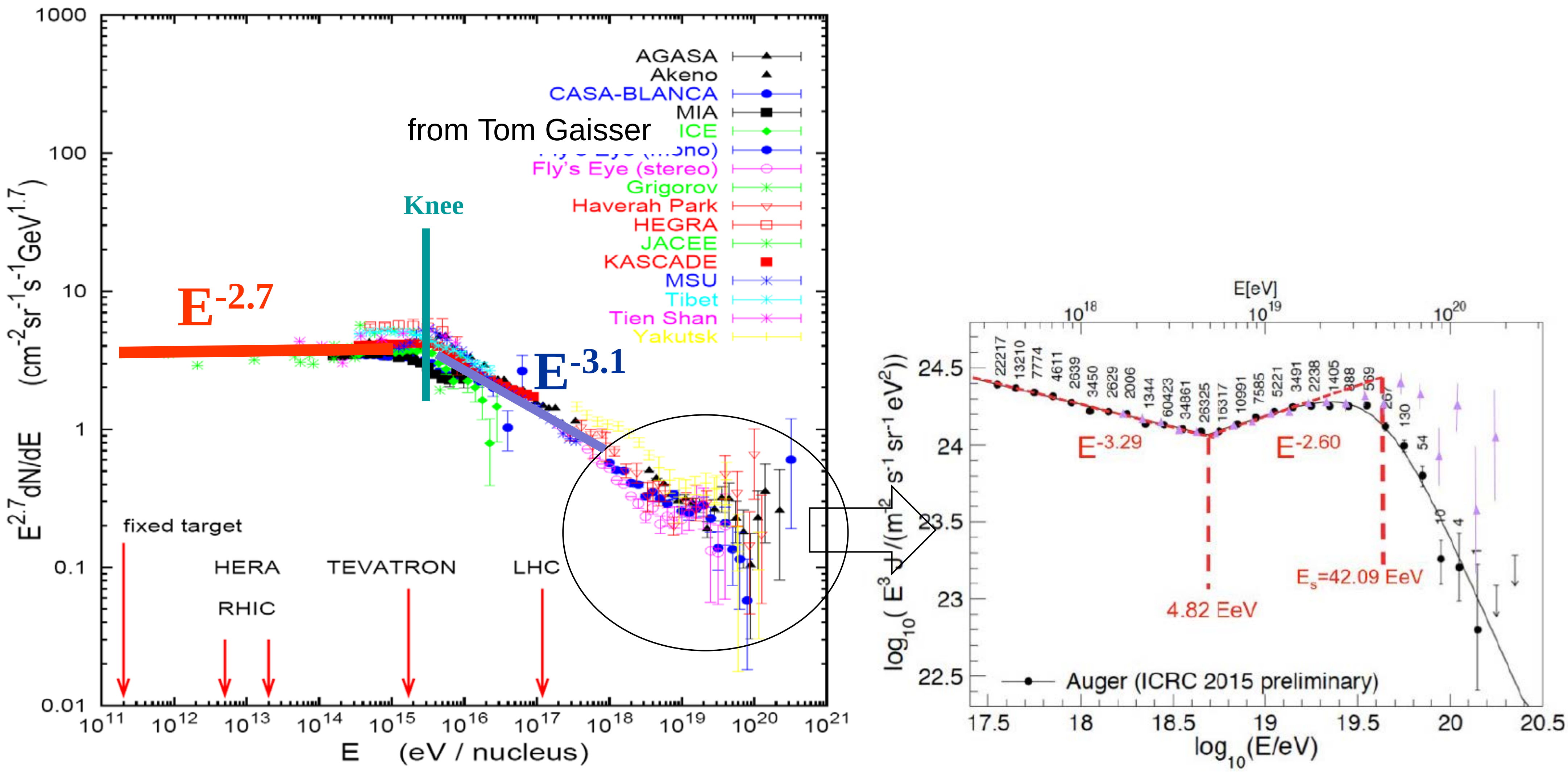
The "all particles" spectrum



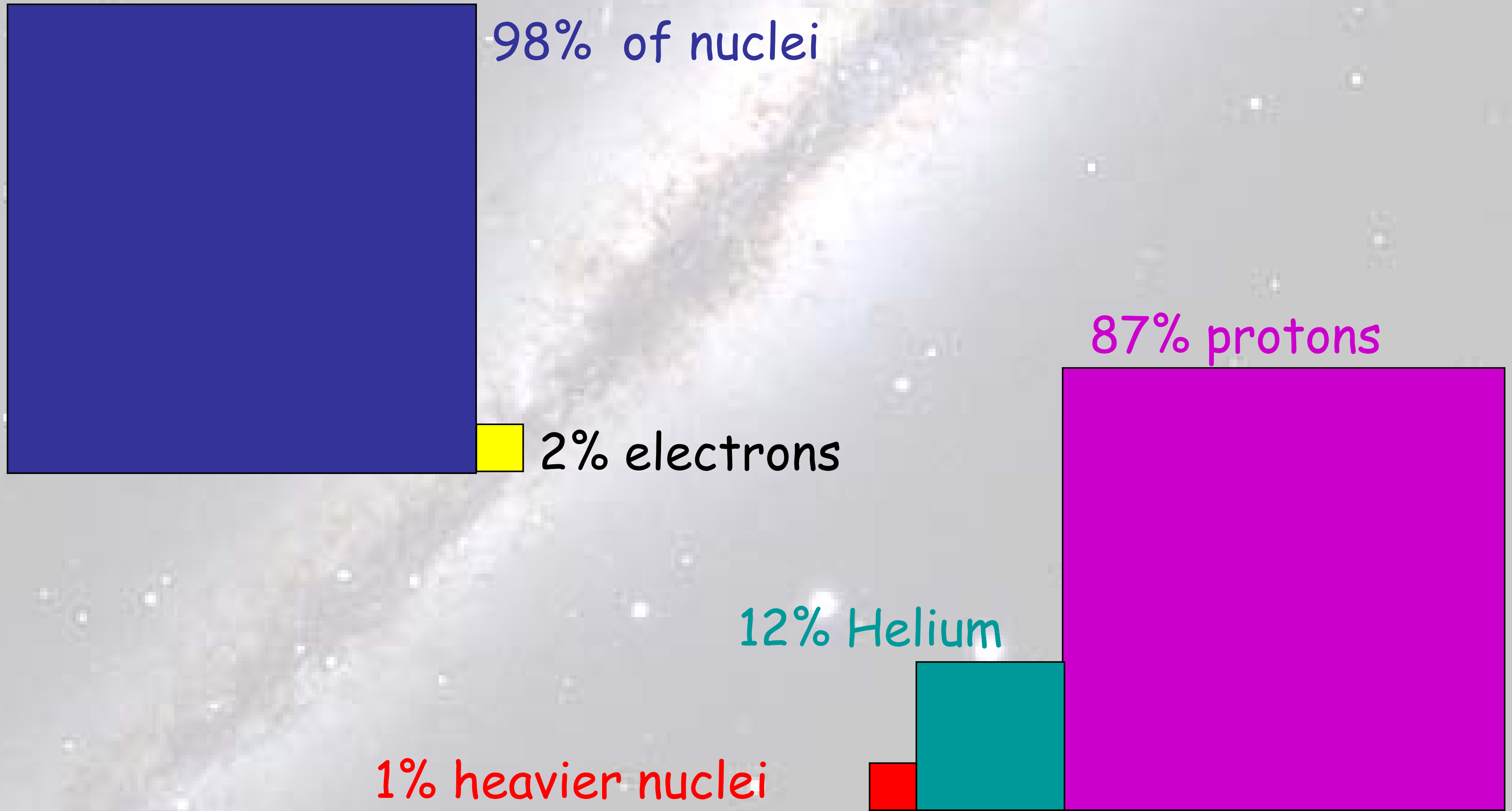
Beatty JJ, Westerhoff S. 2009.
Annu. Rev. Nucl. Part. Sci. 59:319–45

- Regular spectrum over 12 decades in energy, and 32 decades in flux !!!
- Small break near 3×10^{15}eV: the "knee"
- An other one near 10^{18}eV: the "ankle"
- Spectrum badly known at the two extremities
  - Geomagnetic "shield" + Solar modulation
  - Extreme rareness…

CR Spectrum above 1 TeV

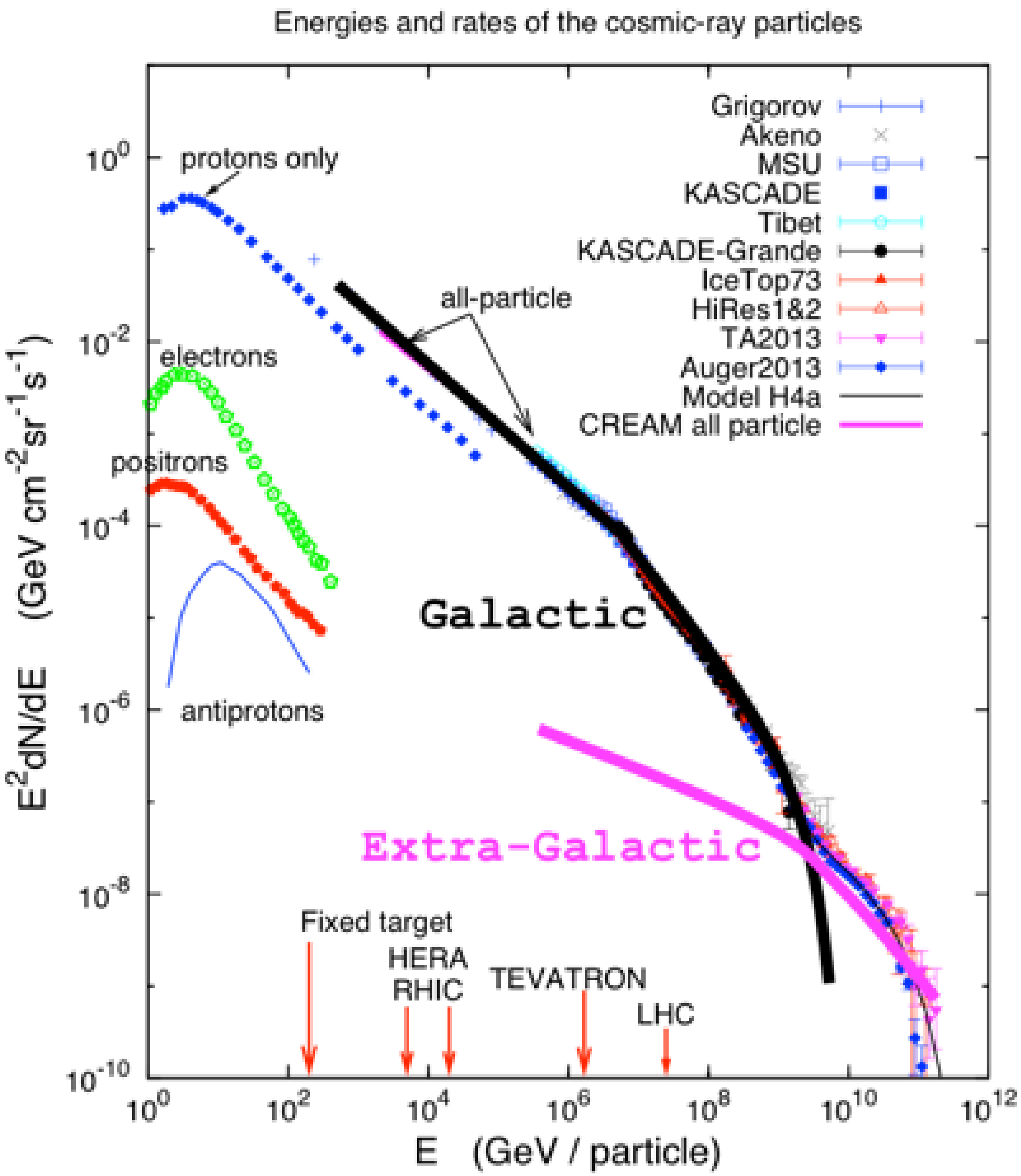


Charge cosmic rays composition

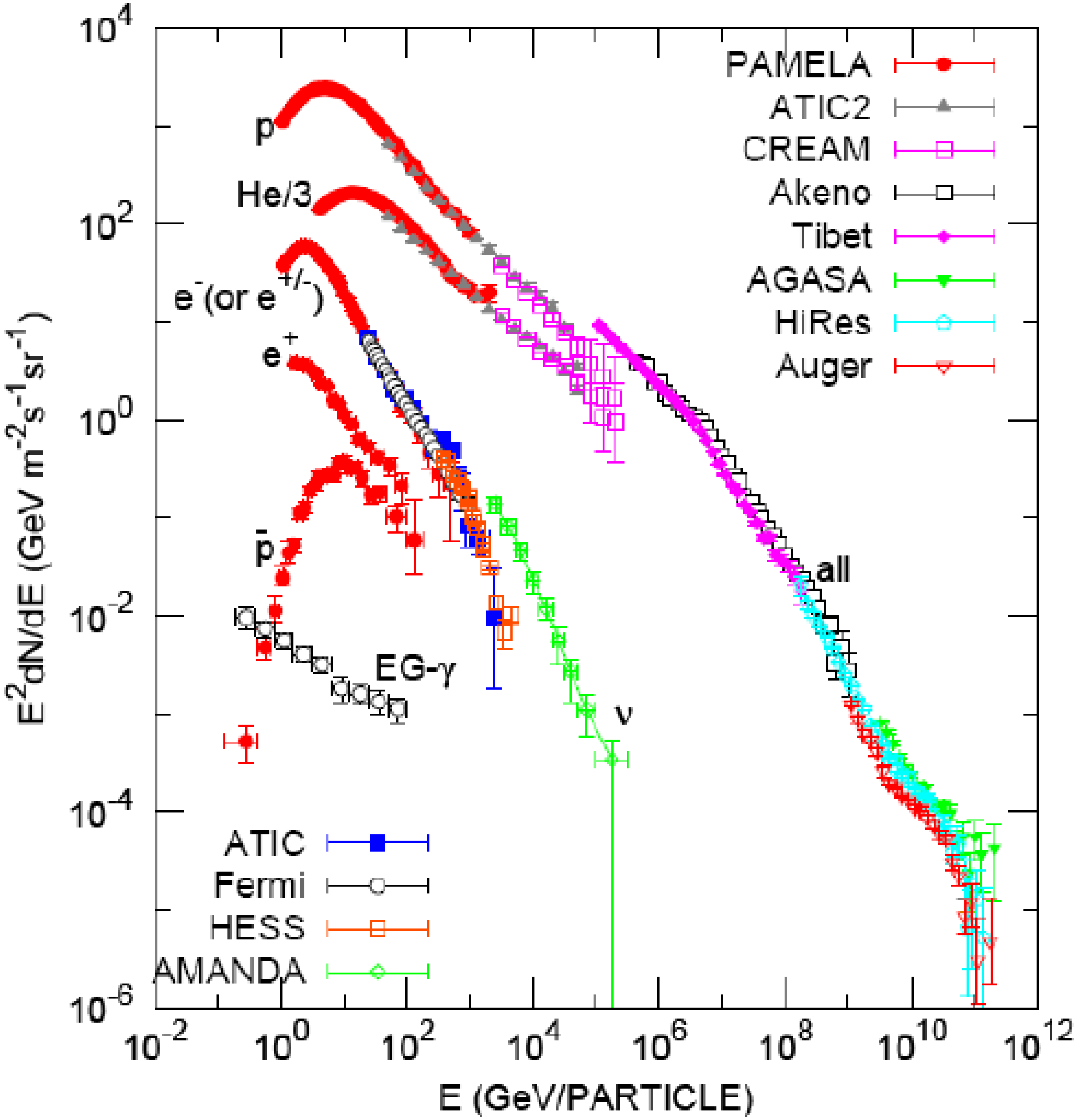


Flux : 4 RC/cm²/s ⇒ 1 kg/year << 40 000 ton/year (meteorites)

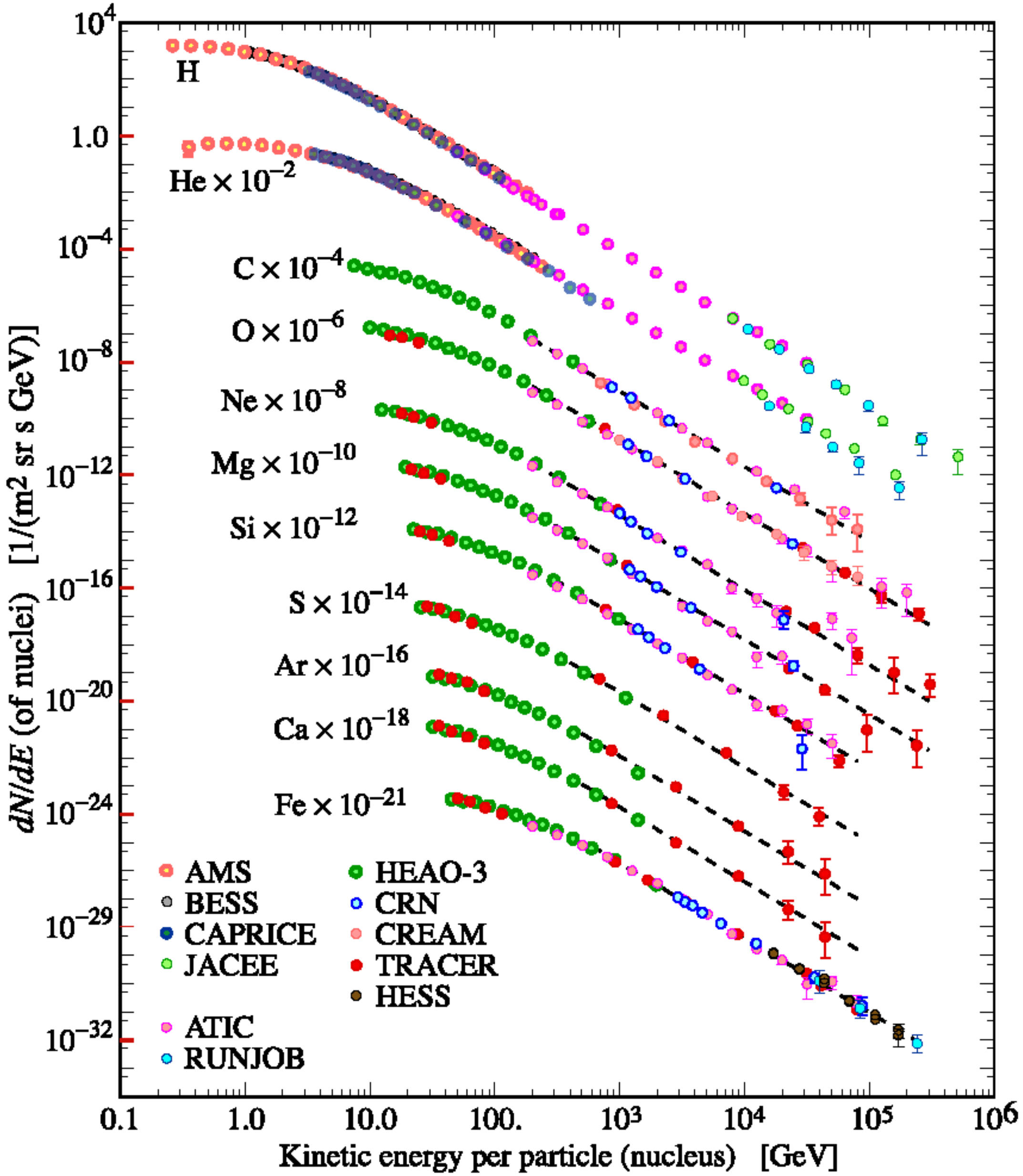
Identified spectra



Identified spectra

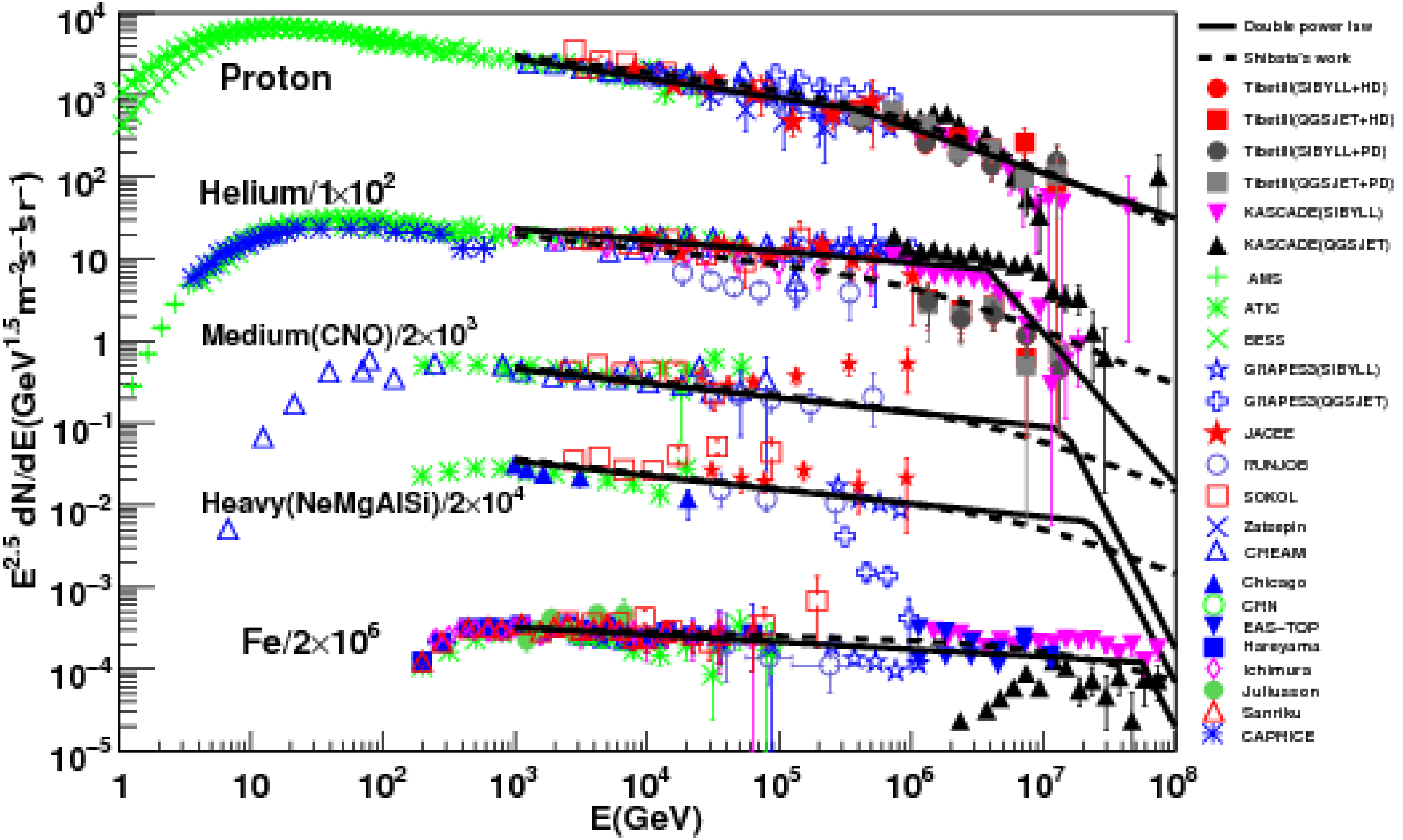


Identified spectra



Parallel power-laws up to 10^{14} eV/nucleon : impressively quasi-universal spectral indices.

Z dependent cutoff at the knee ?



Overview of CR data on composition

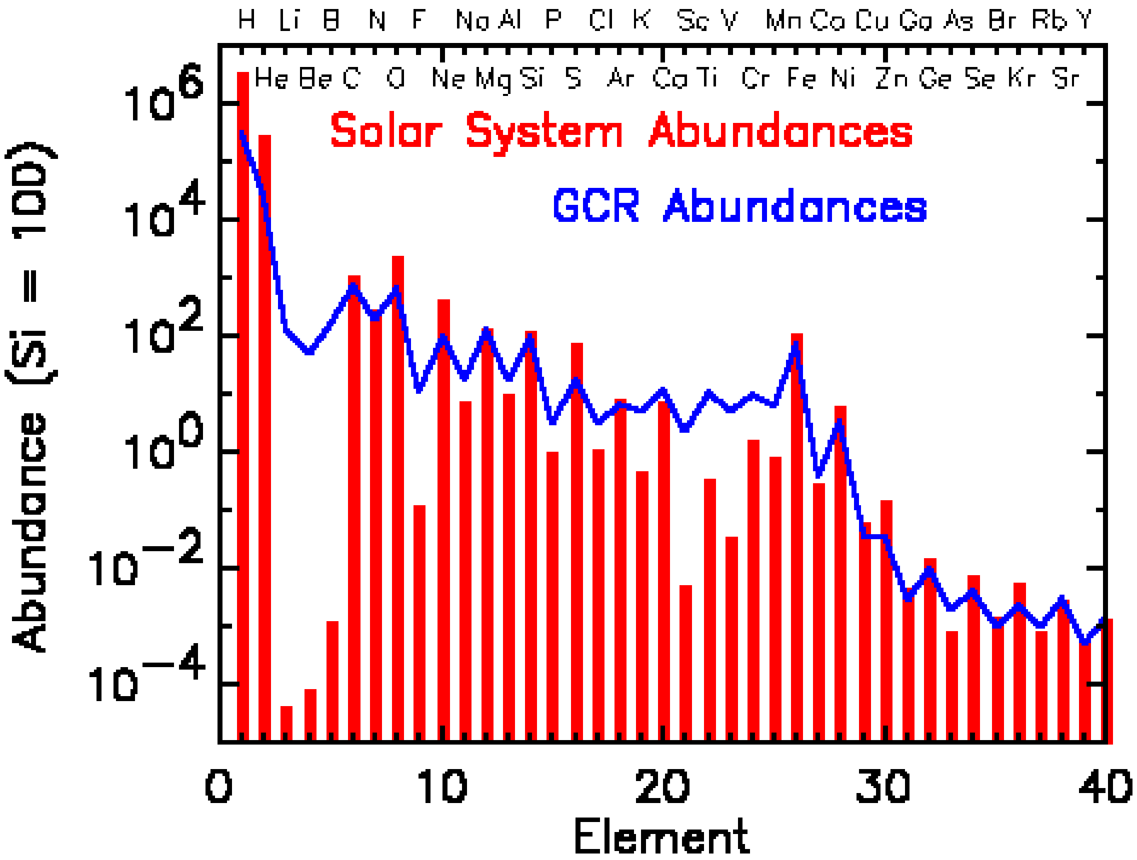
- **Chemical composition**
  - Nuclei = 98% (H = 87%, He = 12%, "metals" = 1%)
  - Electrons = 2%
  - More or less standard compositon (i.e. solar system) except for fewer H and He, presence of secondary nuclei, and a few "anomalies"...

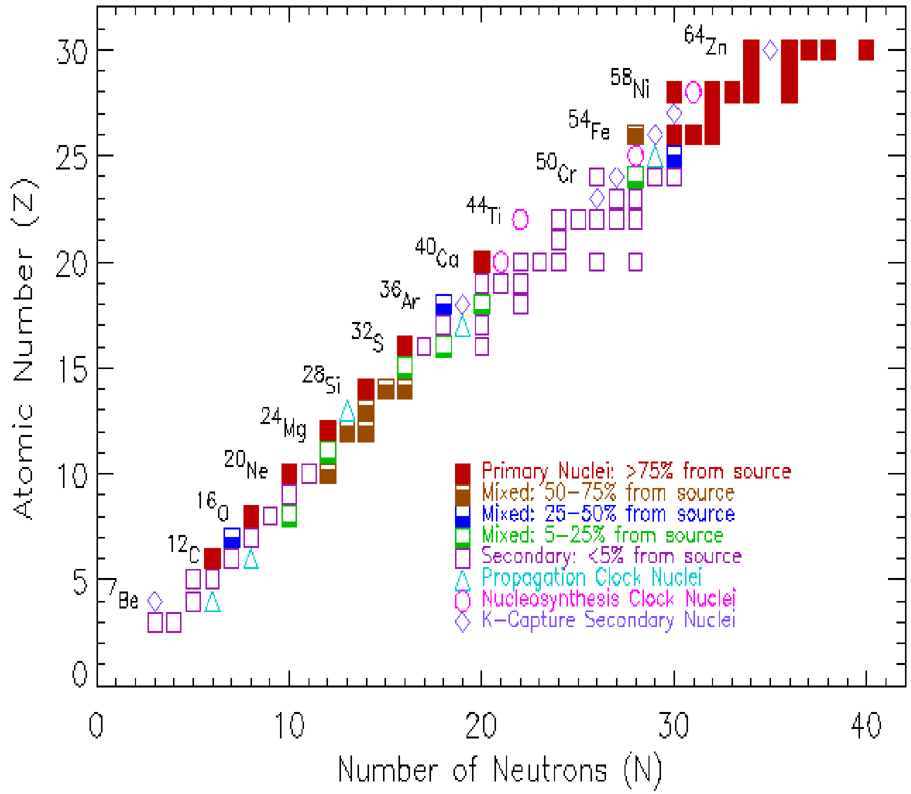
- **Secondary atoms**
  - Li, Be, B : spallation of C, N, O (+ nuclei below the Fe peak)
  - Nuclear thicknesses traversed by CR : $X_{CR} = 6$ to 10 g/cm^2

- **Isotopic anomalies**
  - $^{22}Ne \rightarrow$ link with massive stars

- **Cosmic clocks**
  - $^{10}Be \rightarrow ^{10}B$, $\tau \approx 4 \times 10^6$ years (as well as ^{26}Al, ^{36}Cl, ^{53}Mn, ^{54}Mn, ^{59}Ni)
  - $\tau_{RC} \approx 2 \times 10^7$ years
  - $\frac{X_{RC}}{c\tau_{RC}} \approx 0.2$part/cm^3 $\Rightarrow$ CR halo extention ($\approx$ 3-7 kpc)

Nature of cosmic rays

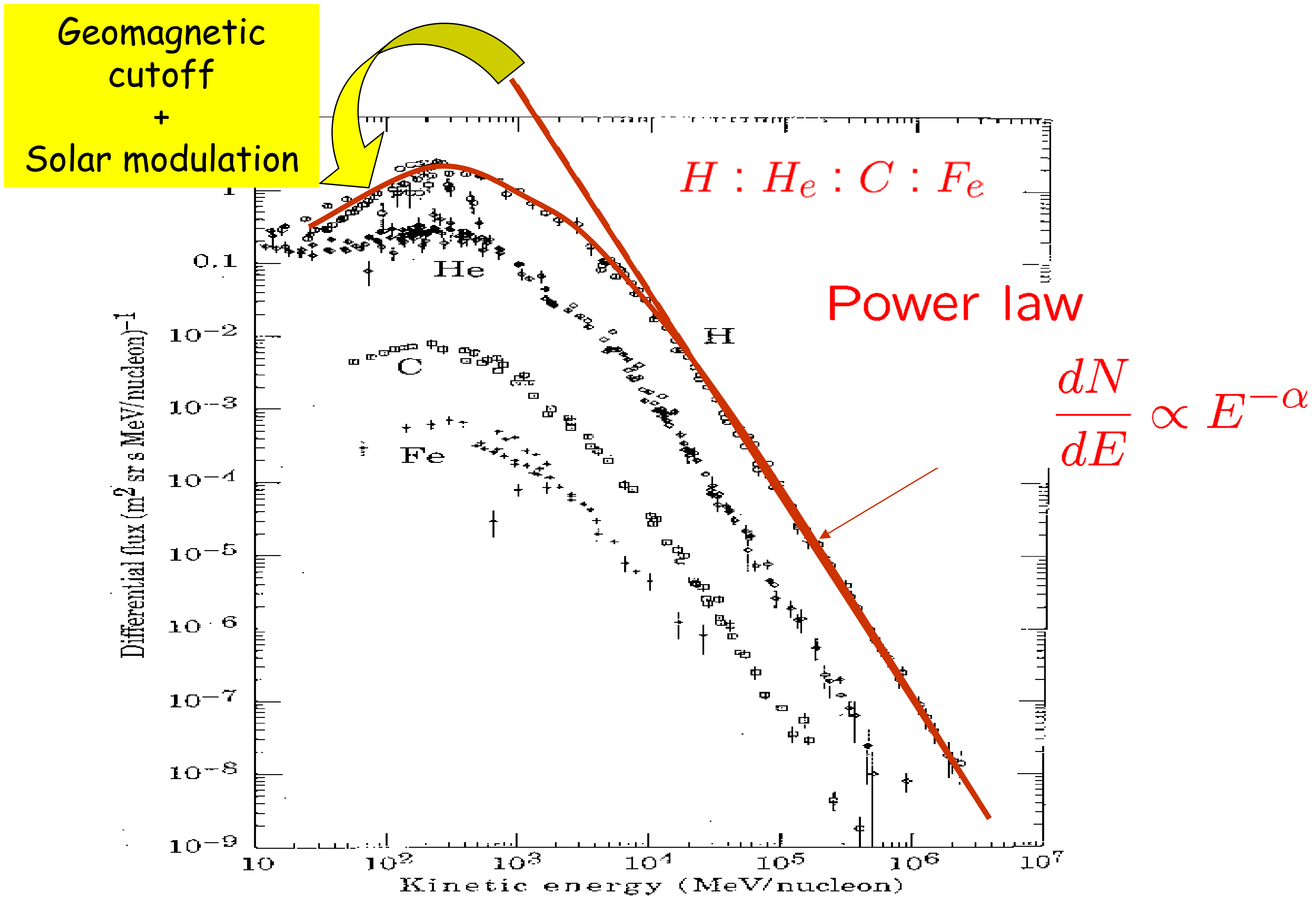




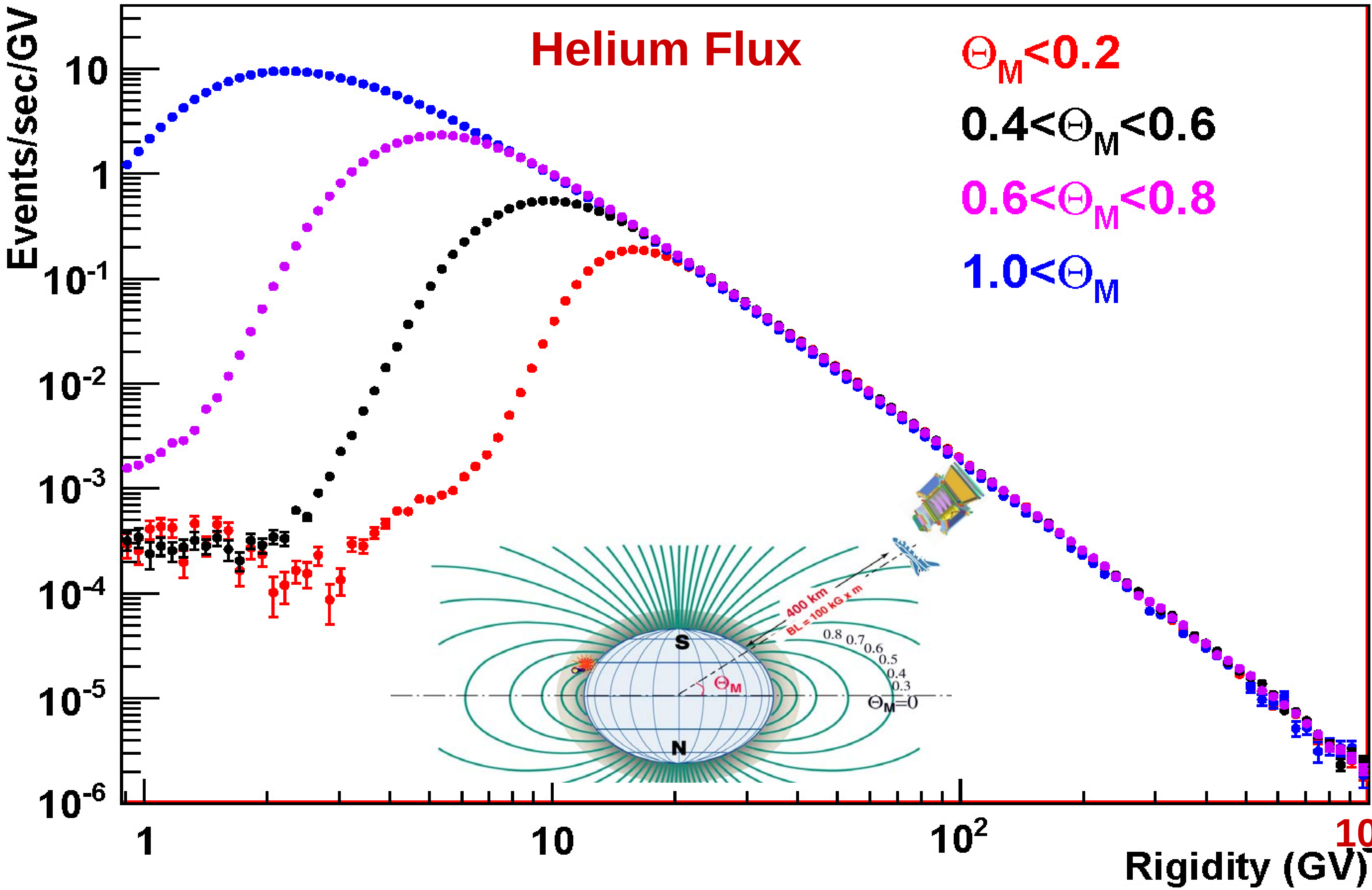
Abundances different in CR and local measurements
(Li Be B and Sub-Fe)

CR undergo spallations and produce secondary CR

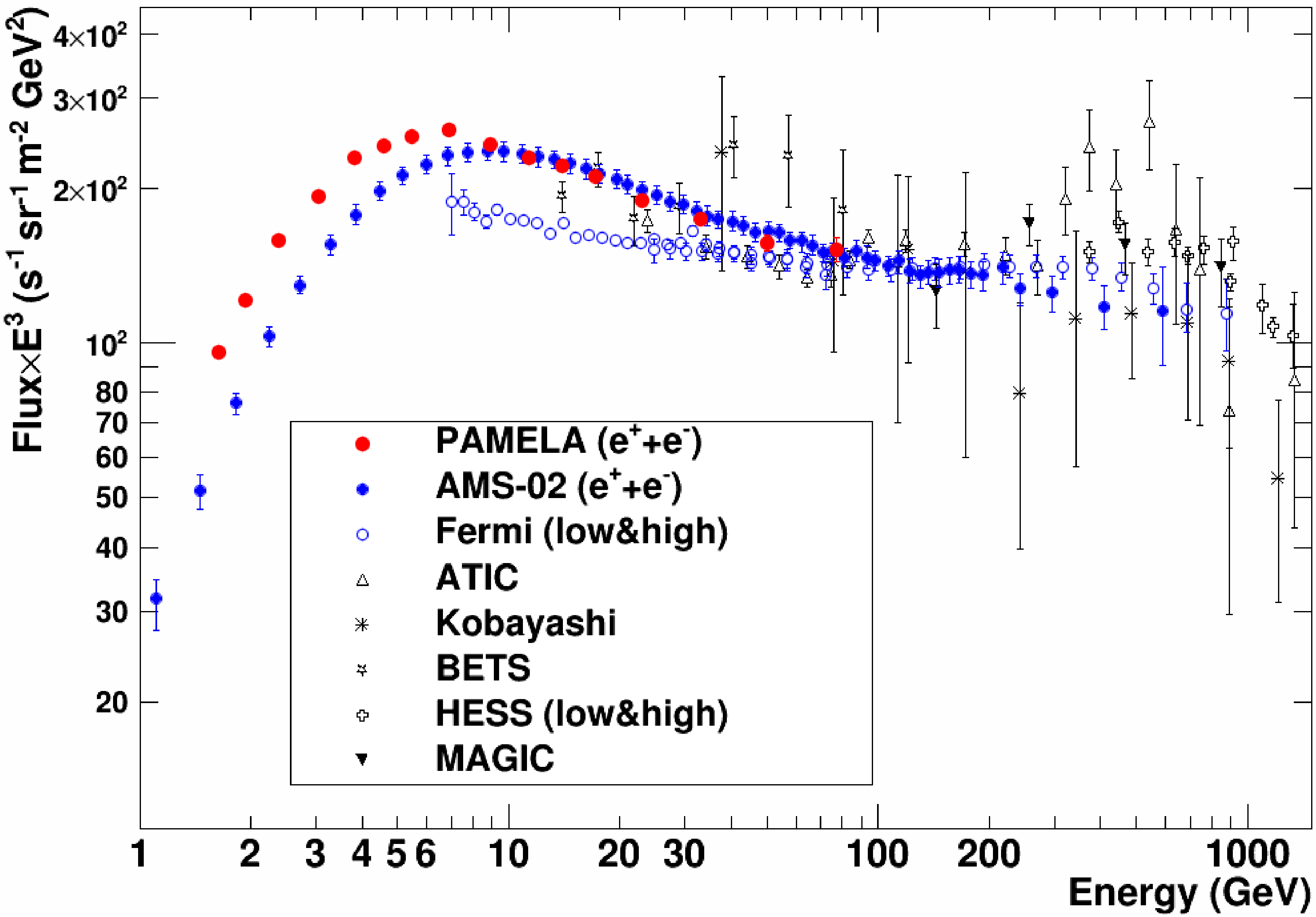
Nature of primary cosmic rays



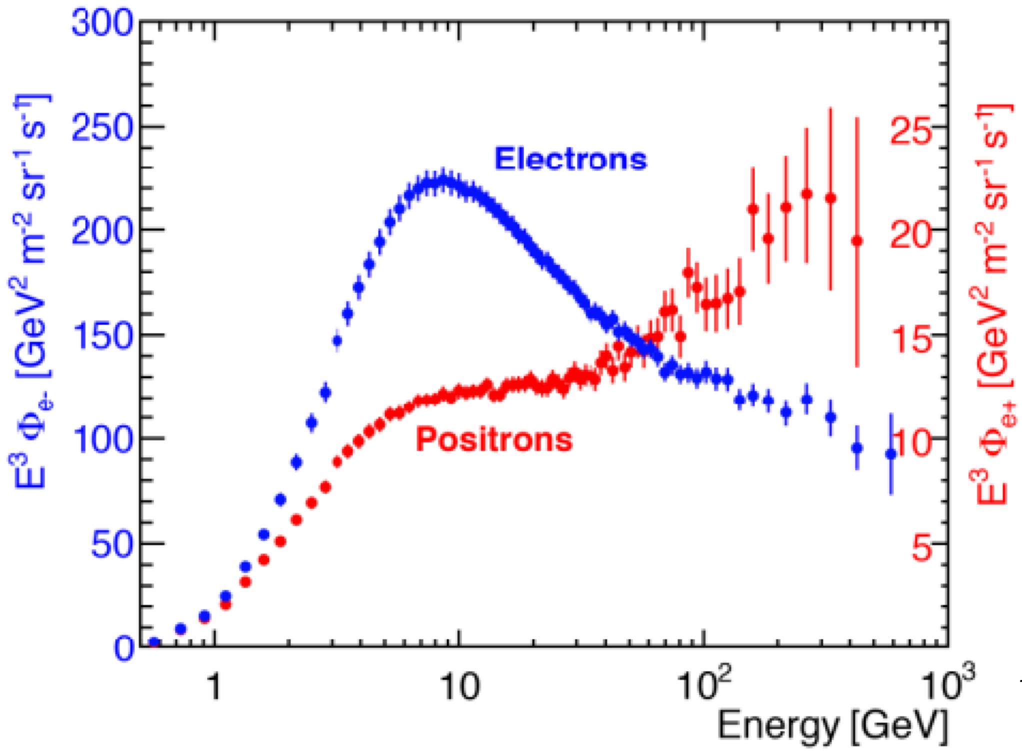
Data from AMS on ISS

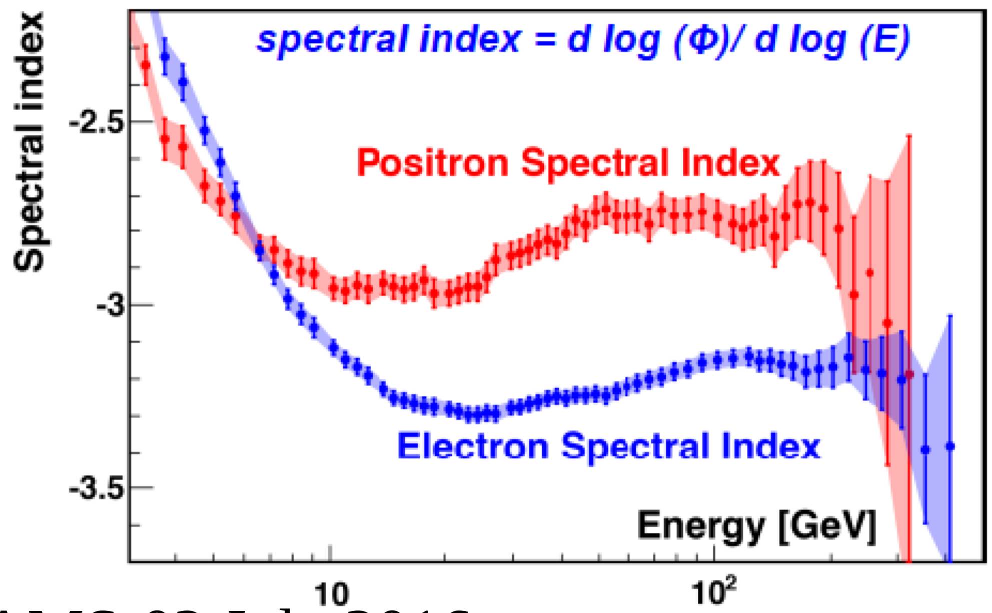


Electron and positron primary flux



Electron and positron primary flux





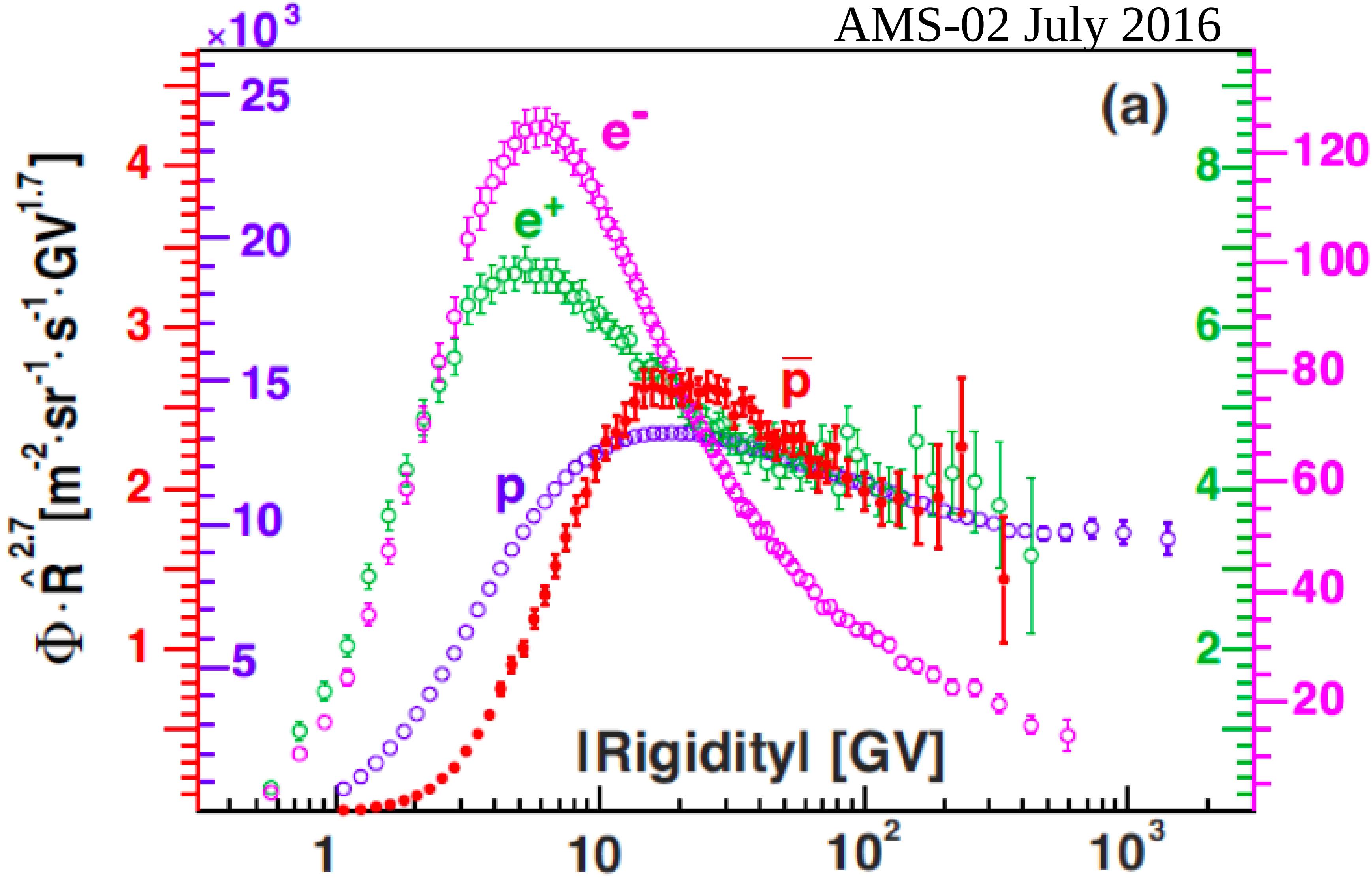
AMS-02 July 2016

Observations:

1. The electron flux and the positron flux are different in their magnitude and energy dependence.
2. Both spectra cannot be described by single power laws.
3. The spectral indices of electrons and positrons are different.
4. Both change their behavior at ~30GeV.
5. The rise in the positron fraction from 20 GeV is due to an excess of positrons, not the loss of electrons (the positron flux is harder).

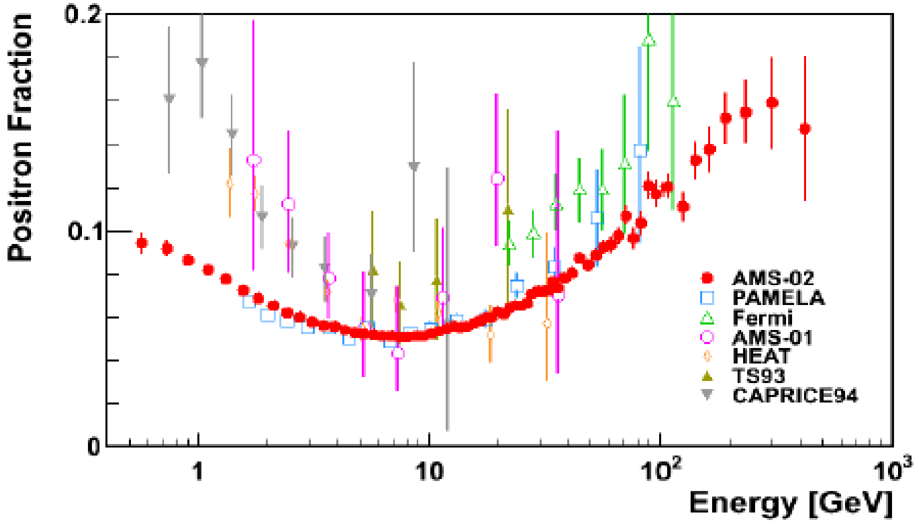
Fluxes of e^+, e^-, p and anti-p

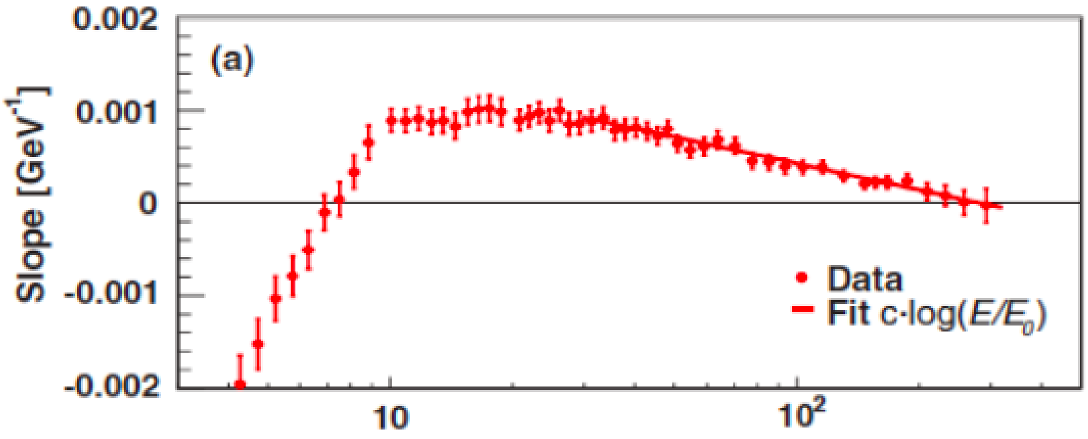
AMS-02 July 2016

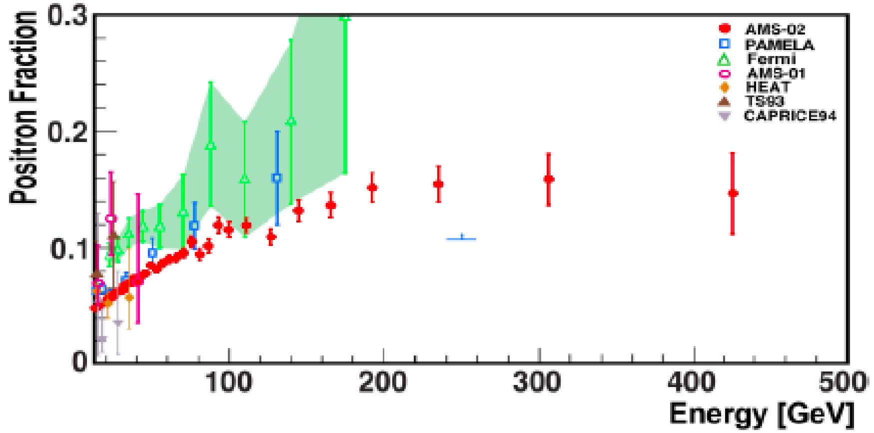


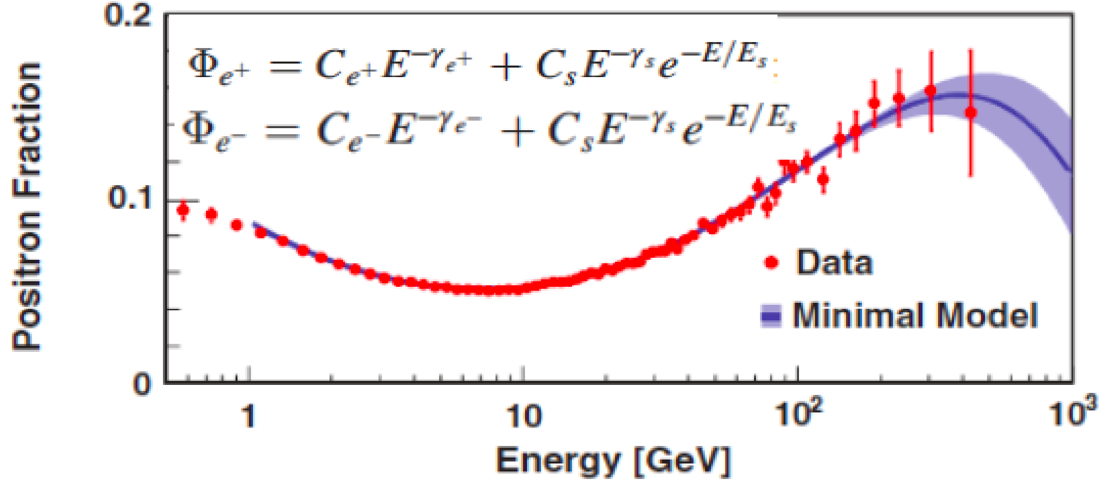
AMS-02: positron fraction

- ✓ No sharp structures
- ✓ Steady increase of the positron content up to ≈ 275 GeV
- ✓ Well described by an empirical model with a common source term for e^+/e^-

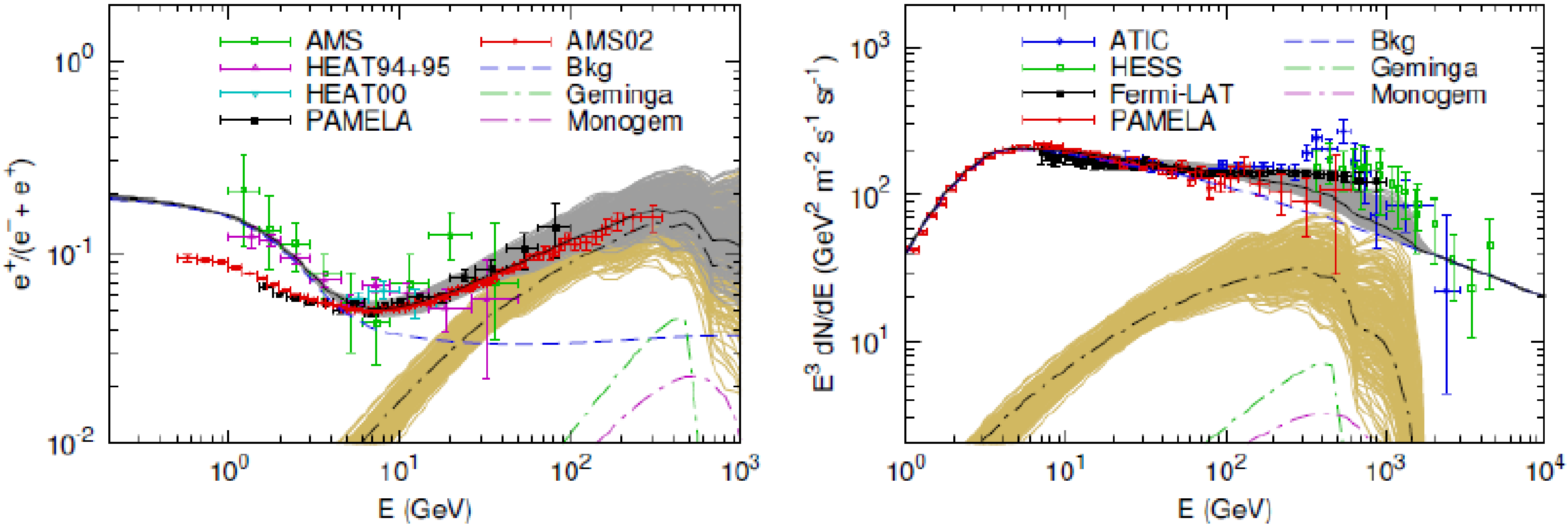








Antimatter search (Dark Matter ?)



… or rather a boring "local" pulsar spoiling physicists dreams !

Gamma rays

- Gamma-rays observed → TeV
- Spectrum ± understood up to MeV.
- Above, the diffuse spectrum and that of sources are very "hard", in $1/E^2$ revealing acceleration processes.

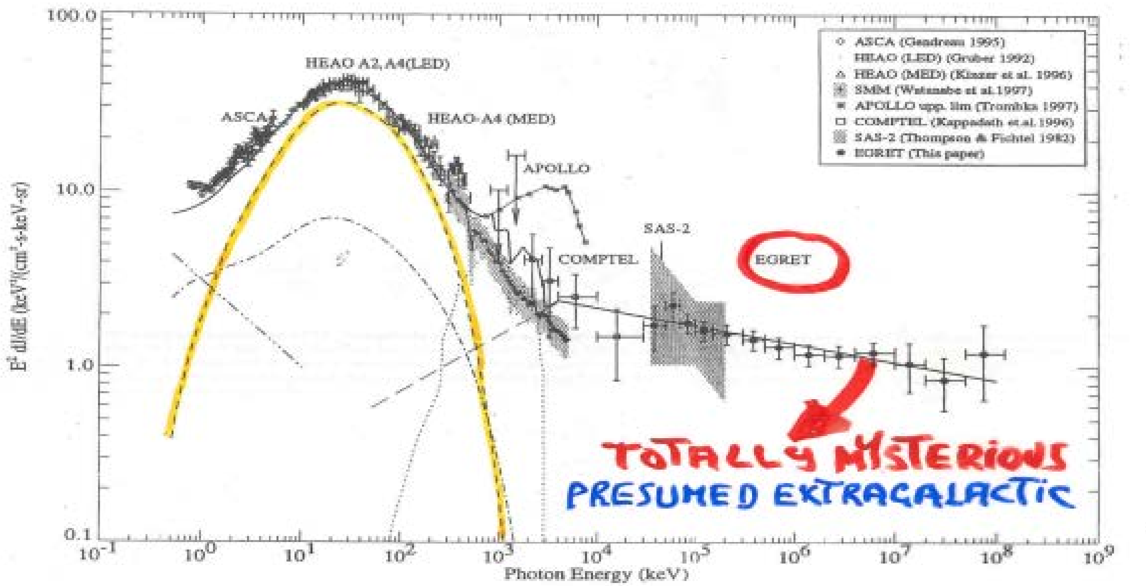
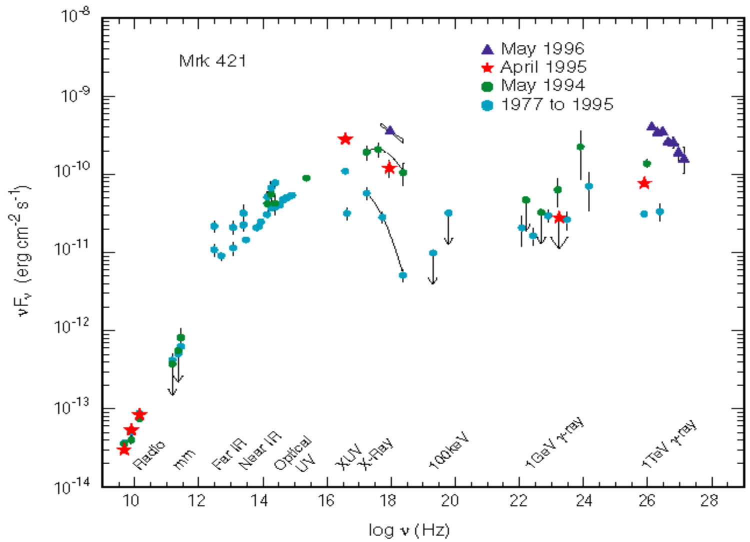


FIG. 10.—Multiwavelength spectrum of the extragalactic gamma-ray spectrum from X-rays to high-energy gamma rays. The estimated contribution from Seyfert I (*dot-dashed line*), and Seyfert II (*dashed*) are from the model of Zdziarski (1996); steep-spectrum quasar contribution (*triple-dot-dashed line*) is taken from Chen, Fabian, & Gendreau (1997); Type Ia supernovae (*dotted line*) is from The et al. (1993). The blazar contribution below 4 MeV (*long-dashed line*) is derived assuming the average blazar spectrum breaks around 4 MeV (McNaron-Brown et al. 1995) to a power law with an index of ∼ −1.7. The thick solid line indicates the sum of all the components.



Why all this non thermal equilibrium radiation?

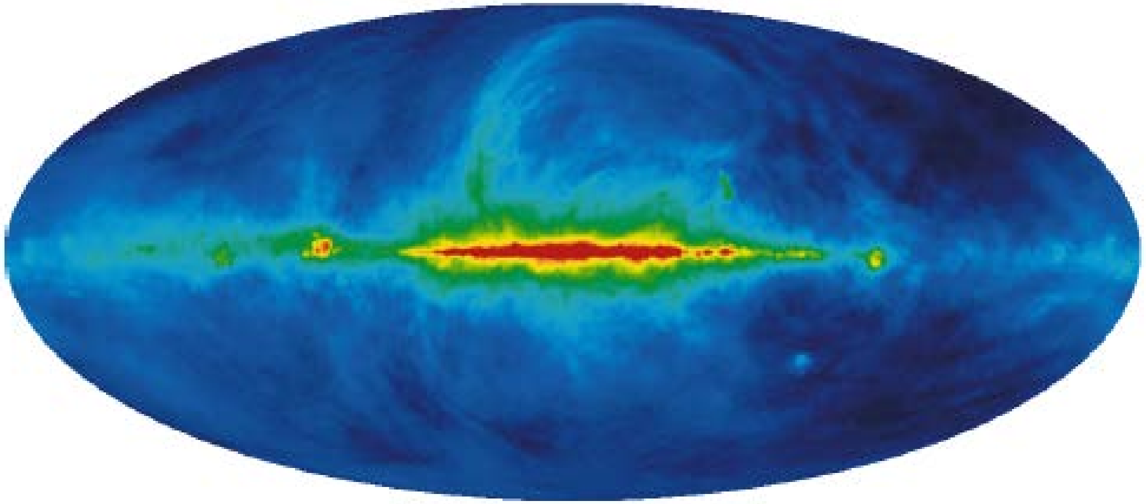
Gamma, diffuse emission

Emission due to:

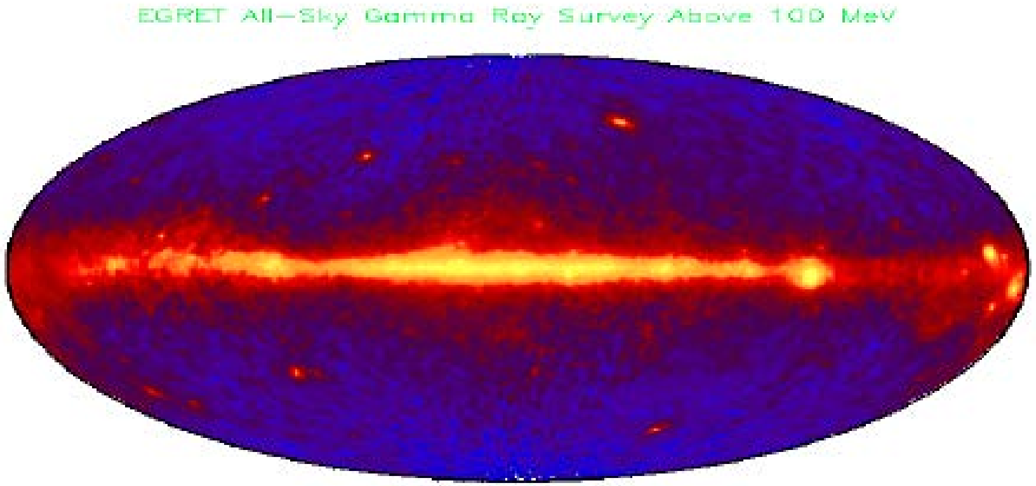
- the interactions of cosmic electrons with:
  - the magnetic fields (synchrotron radiation dominates the radio emission of the Galaxy up to a few GHz)
  - interstellar Matter (ISM); bremsstrahlung important bellow 100 MeV
  - Interstellar photon: Inverse Compton above GeV
- the decay of π^0 produced when CR interact with protons and nuclei
  - $\pi^0 \rightarrow \gamma\gamma$ above 100 MeV
  - Concomitant emission of ν in the decay of $\pi^{\pm}$

Gamma, diffuse emission

408 MHz



100 MeV



Galactic or Extragalactic CR ?

F.Montanet Astroparticle physics ESIPAP 2017

Definite answer from EGRET, already in 1993 !

Hypothesis: if CR are extra or metagalactic, the density of CR should be identical in our Galaxy and in its satellites

- Radio observations radio give the mass of gas M_H in the SMC
- M_H implies a measurable flux for SMC of: $2.5 \times 10^{-7} cm^{-2}.s^{-1}$

$$F_\gamma \propto M_H N_{CR} R_q$$

- EGRET gaves an upper limit (at 95%CL): $< 0.5 \times 10^{-7} cm^{-2}.s^{-1}$
- The CR density is 5 times smaller within SMC

Cosmic rays are indeed mostly produced by the Milky-Way!

The general problematic

- Thermal speeds → RCUHE (few 10^{20} eV)

Produce them

- From top to bottom (decay…)
- From bottom to top (acceleration)

Preserve them

- Energy losses (Synch., IC, π, pairs…)
- Destruction (photo-dissociation…)
- Escape probabilities

Propagate them

- Propagation in ISM and IGM (mag fields: deflection, confinement…)
- Re-acceleration

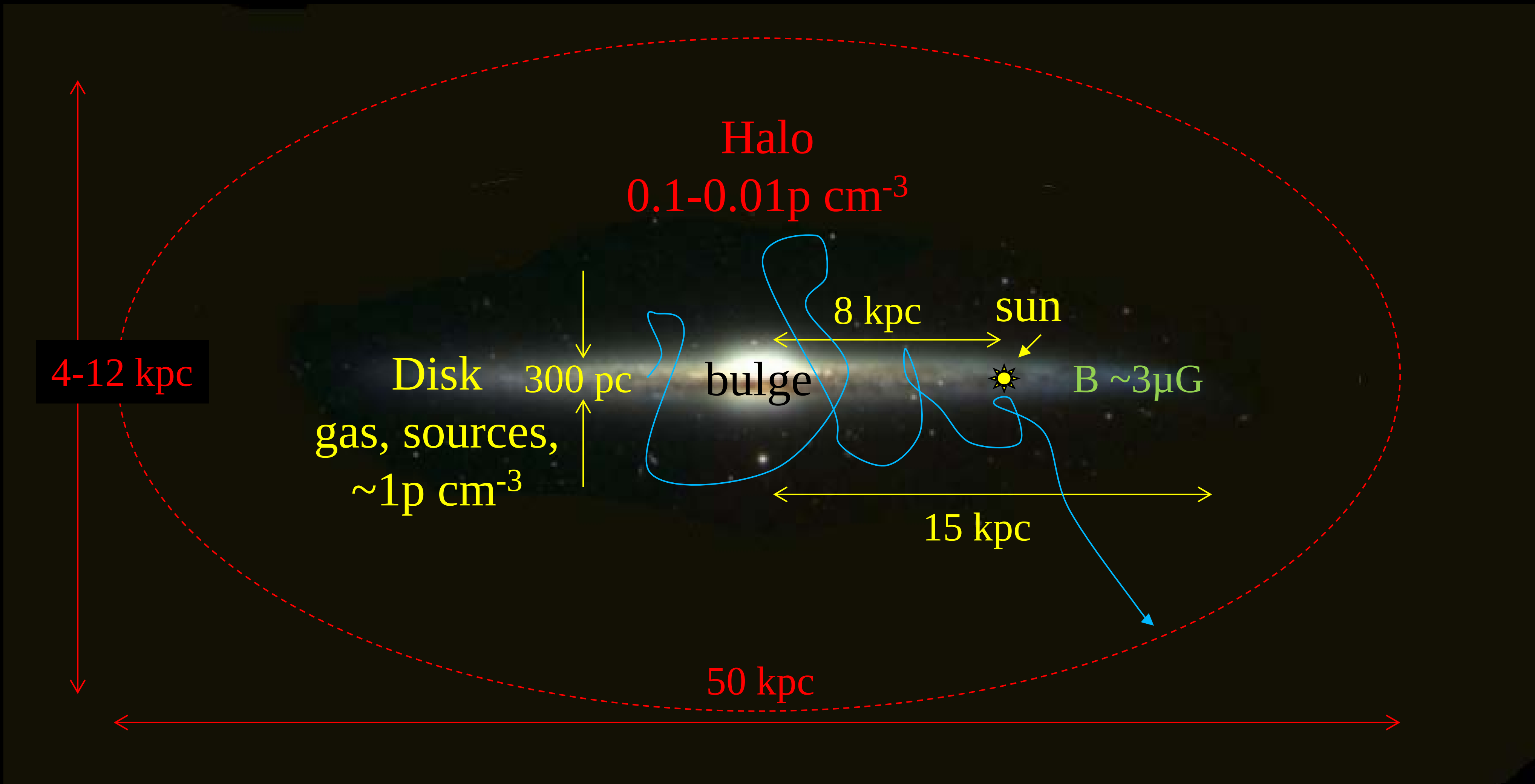
Detect them

- Balloons, satellites…
- Air showers…
  - Cherenkov telescopes
  - Surface & Fluorescence Detectors

Propagation medium, IGM, ISM and atmosphere

Dimensions of the Milky Way

1 pc ≈ 3 l.y. ≈ 3 × 10^{16} m

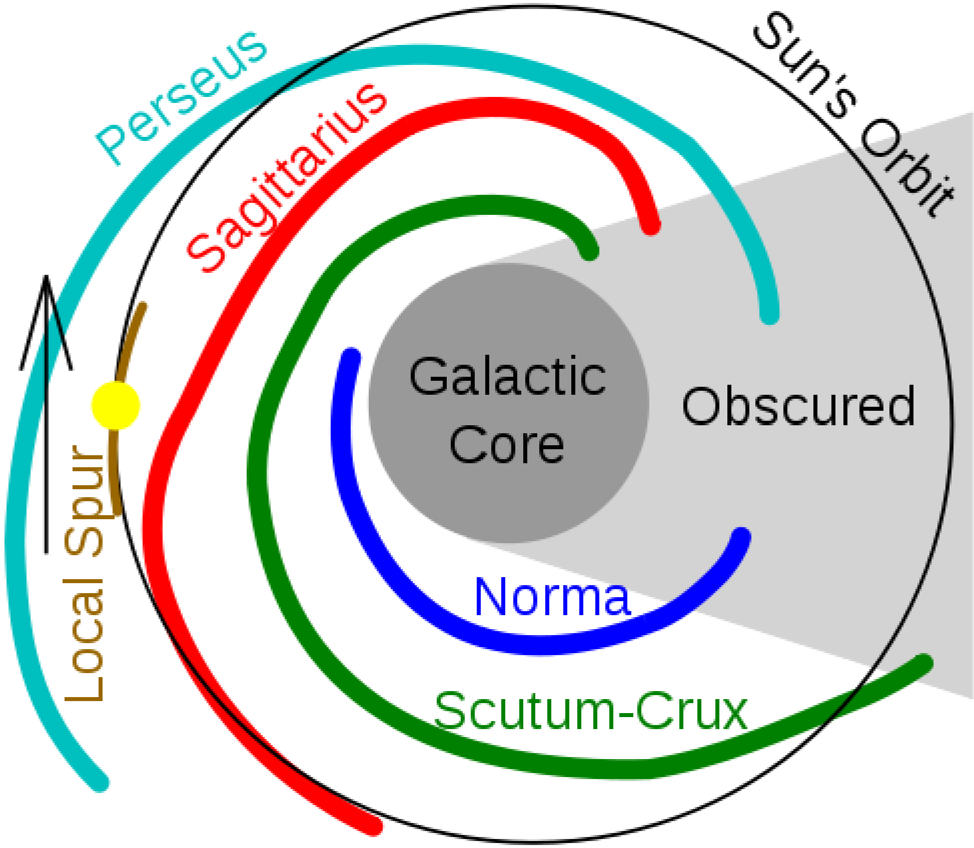


Milky Way, a spiral galaxy

Milky Way, a spiral galaxy

Local spur and neighboring arms $\Rightarrow$ local matter and B field inhomogeneity.

Mean "regular" B field $\sim 3\mu G$ roughly parallel to spiral arms, more intense in between arms.

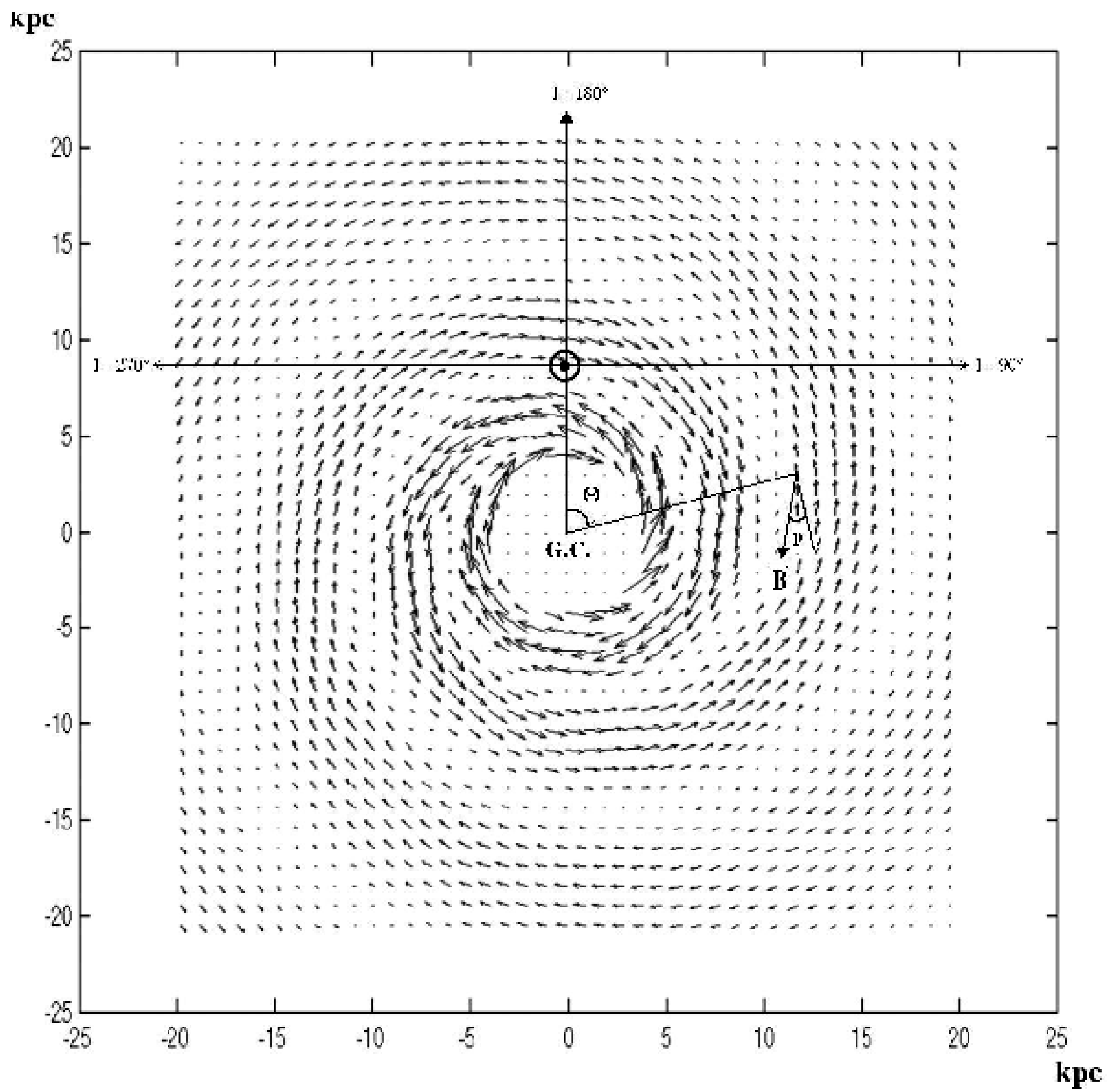


Milky Way, a spiral galaxy

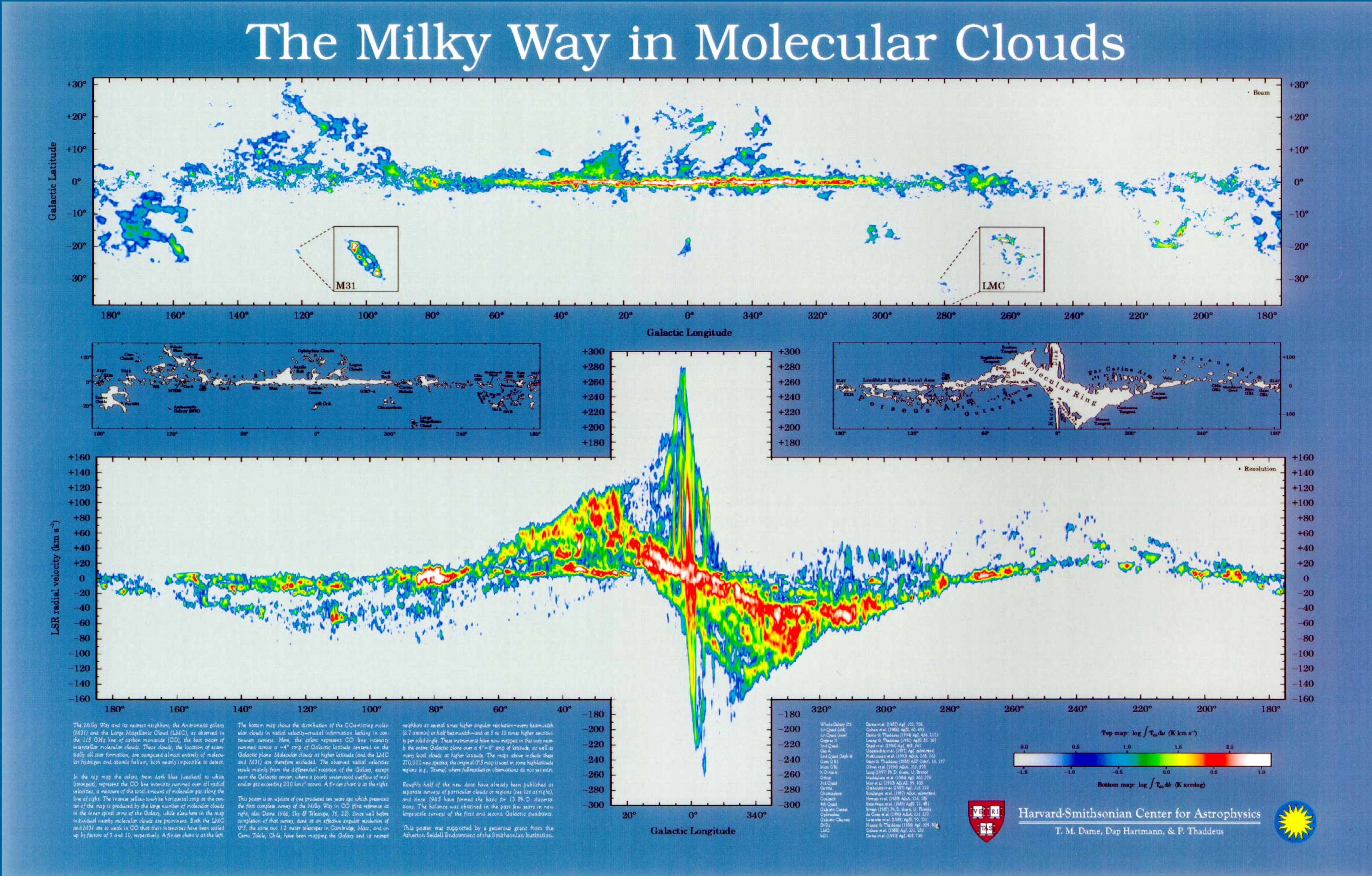
Local spur and neighboring arms
$\Rightarrow$ local matter and
B field inhomogeneity.

Mean "regular" B field
$\sim 3\mu G$ roughly parallel
to spiral arms, more intense in
between arms.

Measured from Faraday rotation of the polarized emission and dispersion measurements on pulses from radio pulsars.

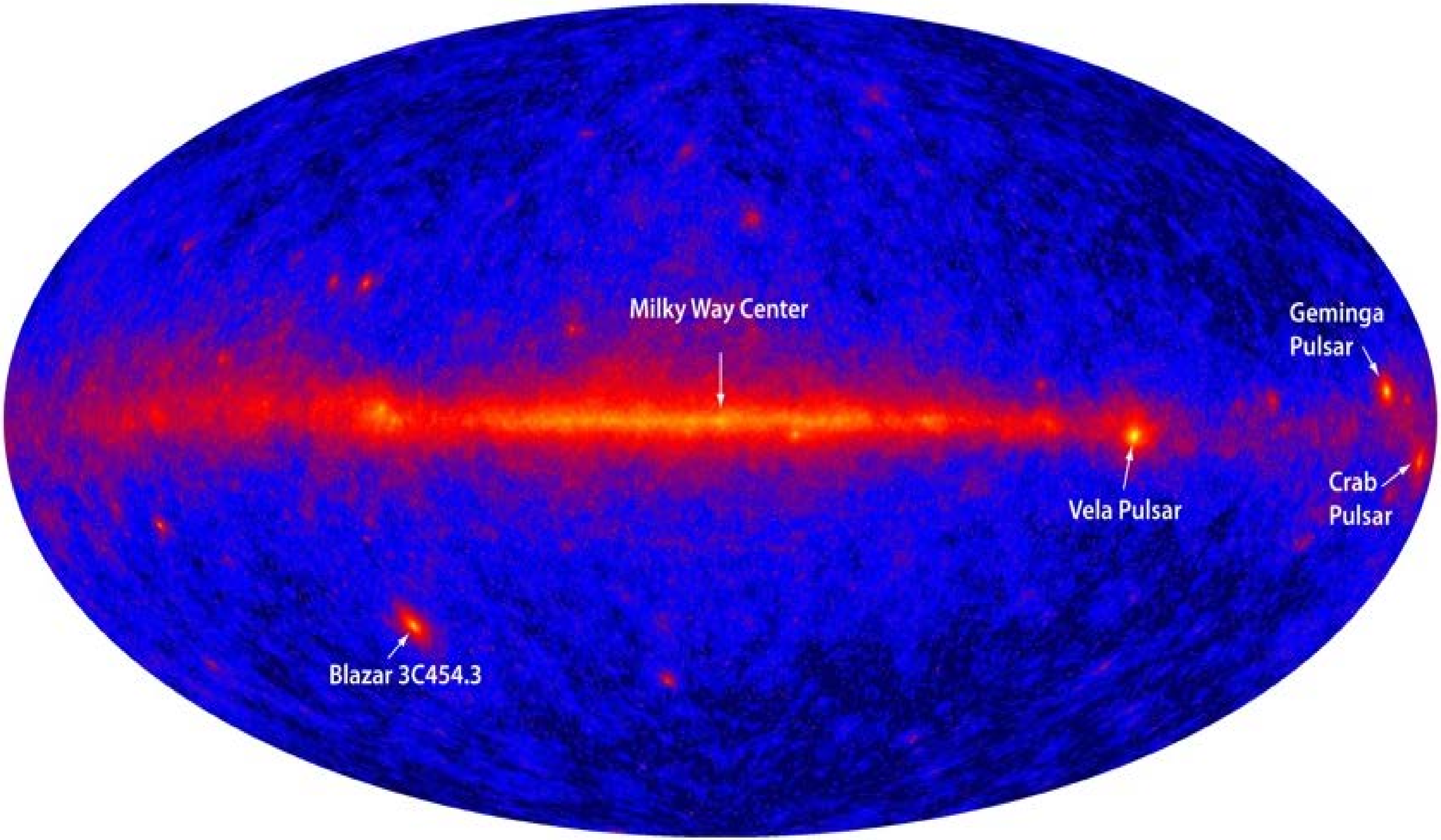


A thick target…

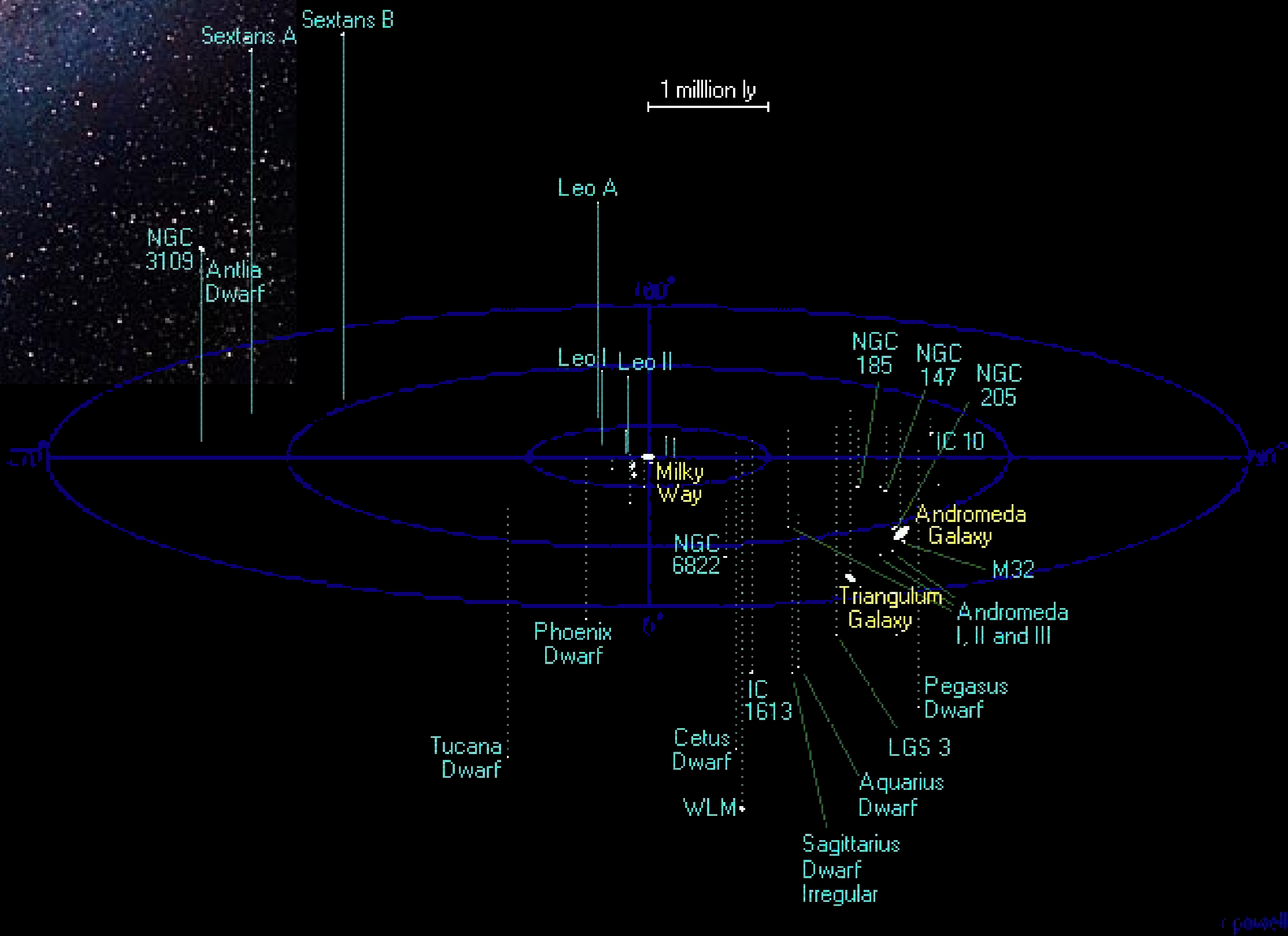


A thick target

- Diffuse gamma-ray emission from galactic CR interaction with matter (mostly molecular H clouds).



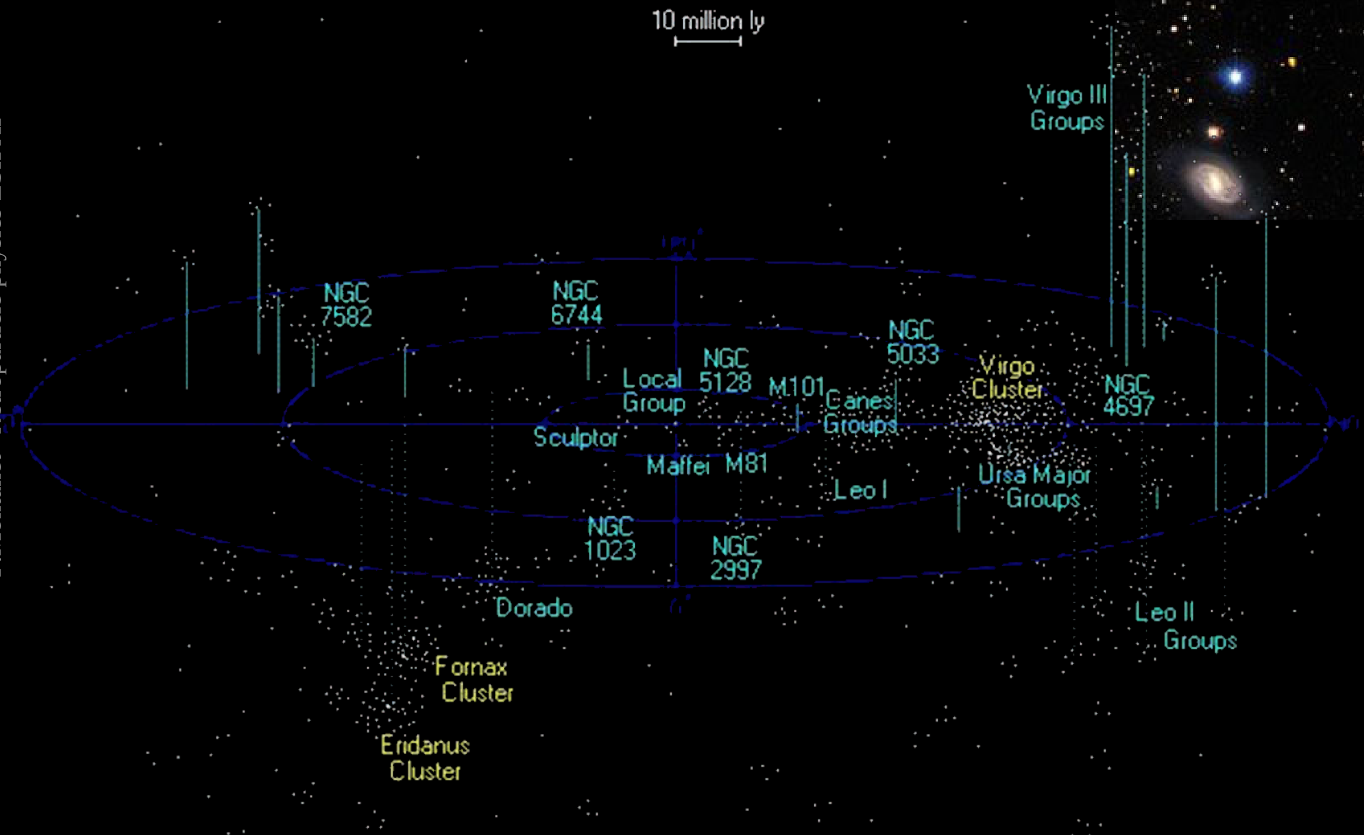
The nearby islands…



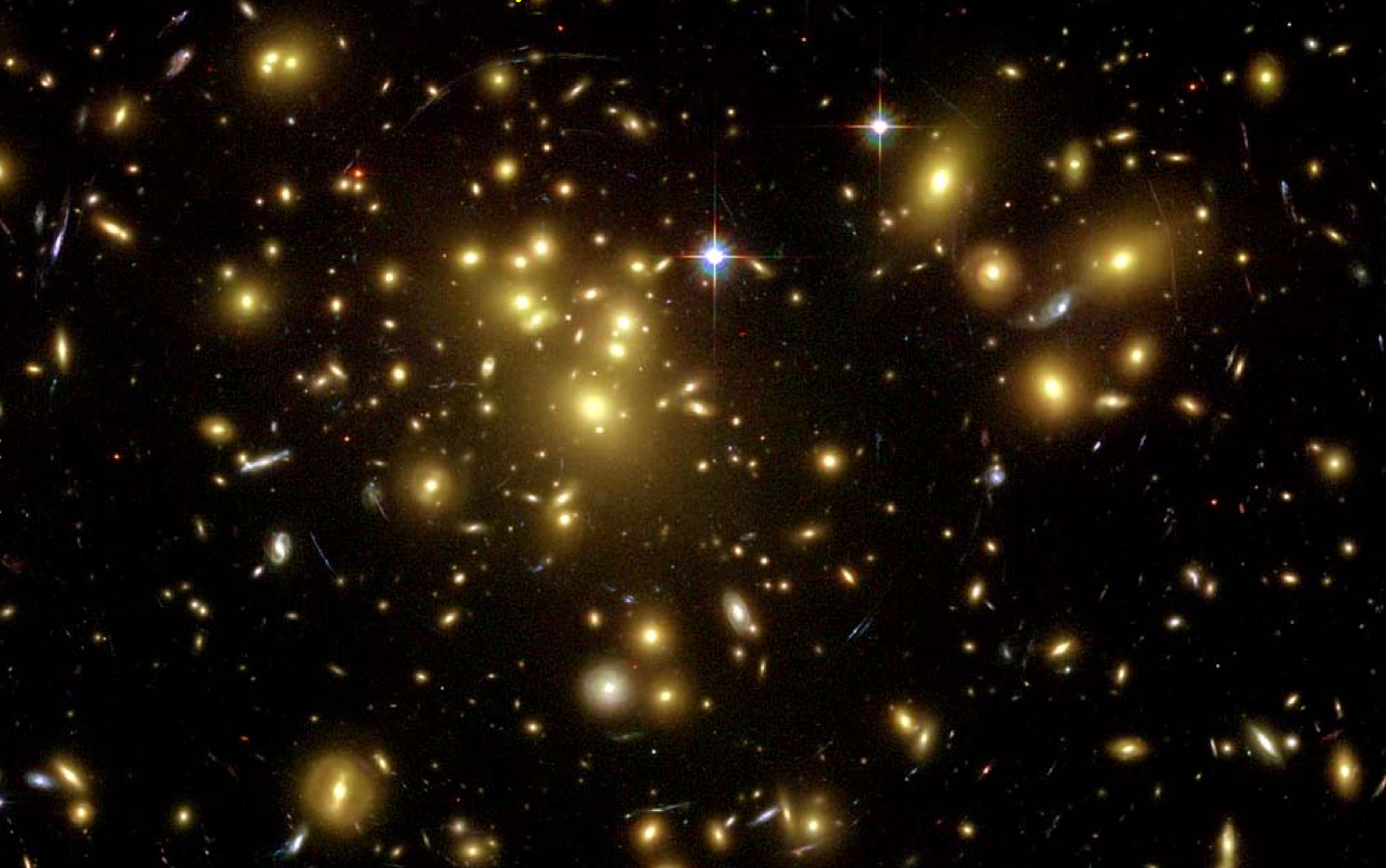
Andromeda (M31)
A twin of our Milky Way slightly larger and (only) distant by 780kpc.
Many small (dwarf) galaxies are orbiting around these twins.

The local group and the Virgo cluster

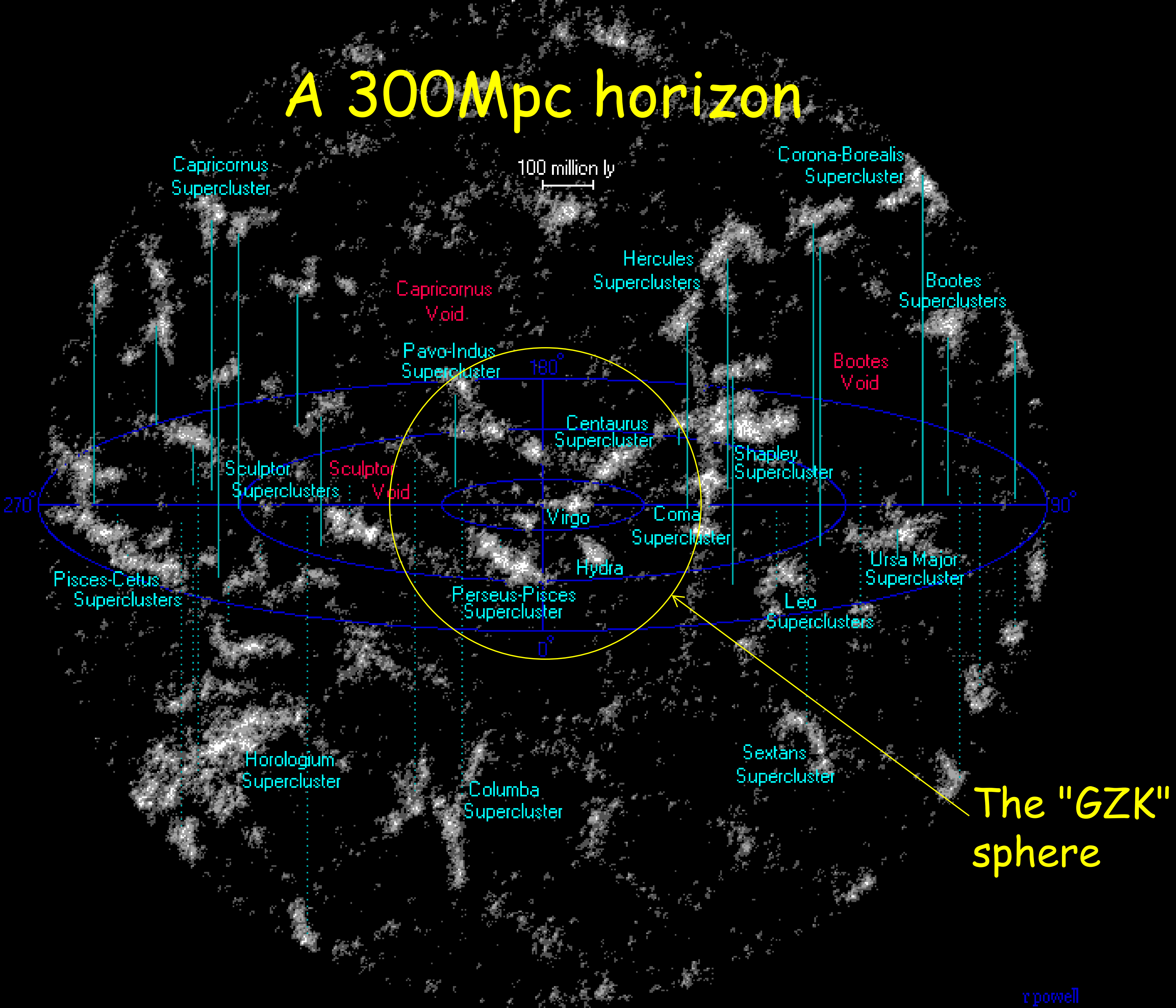
Our local group is at the periphery of the large Virgo supercluster (~2000 galaxies) at ~20Mpc



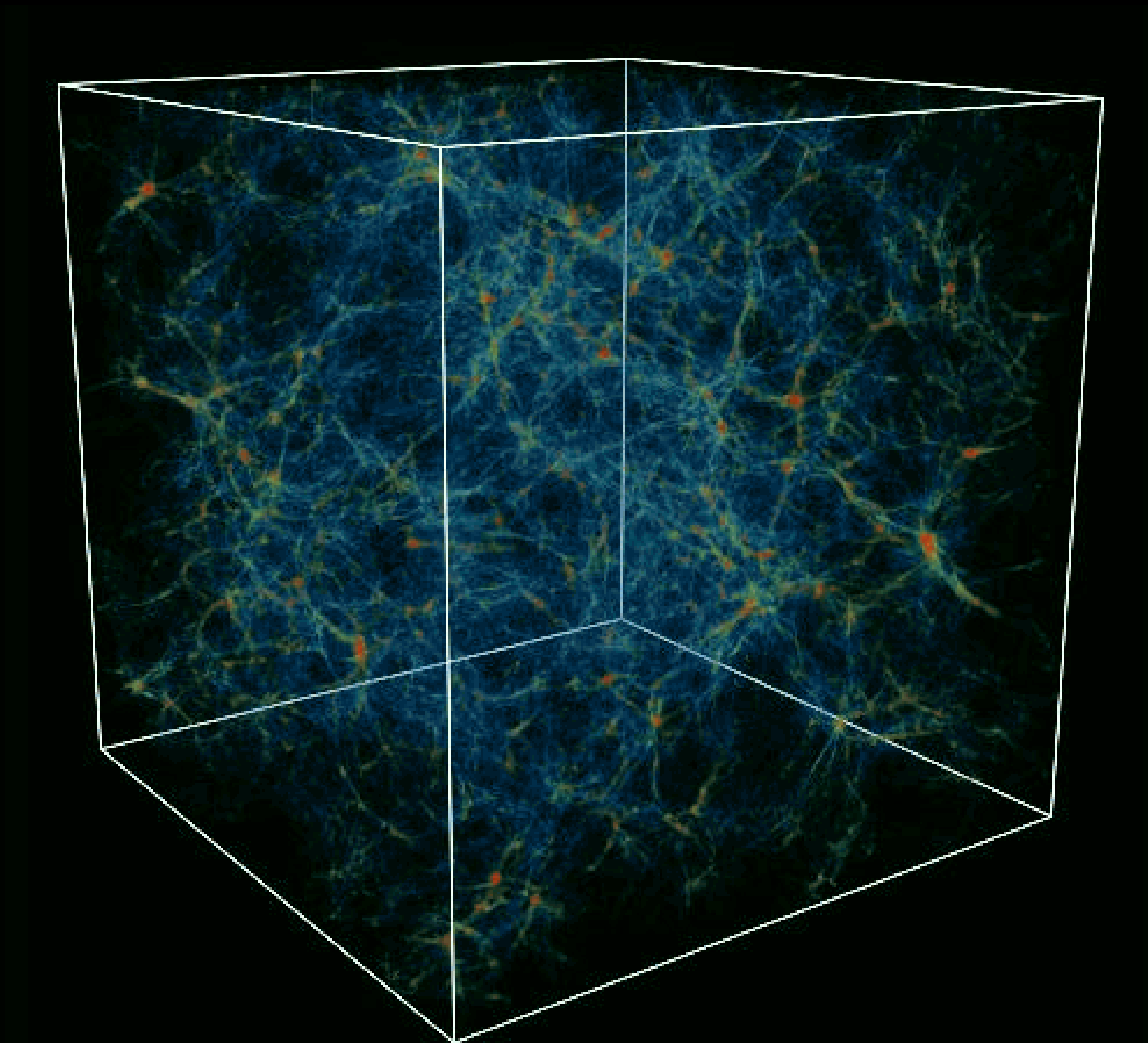
Another super cluster: Abel 1689

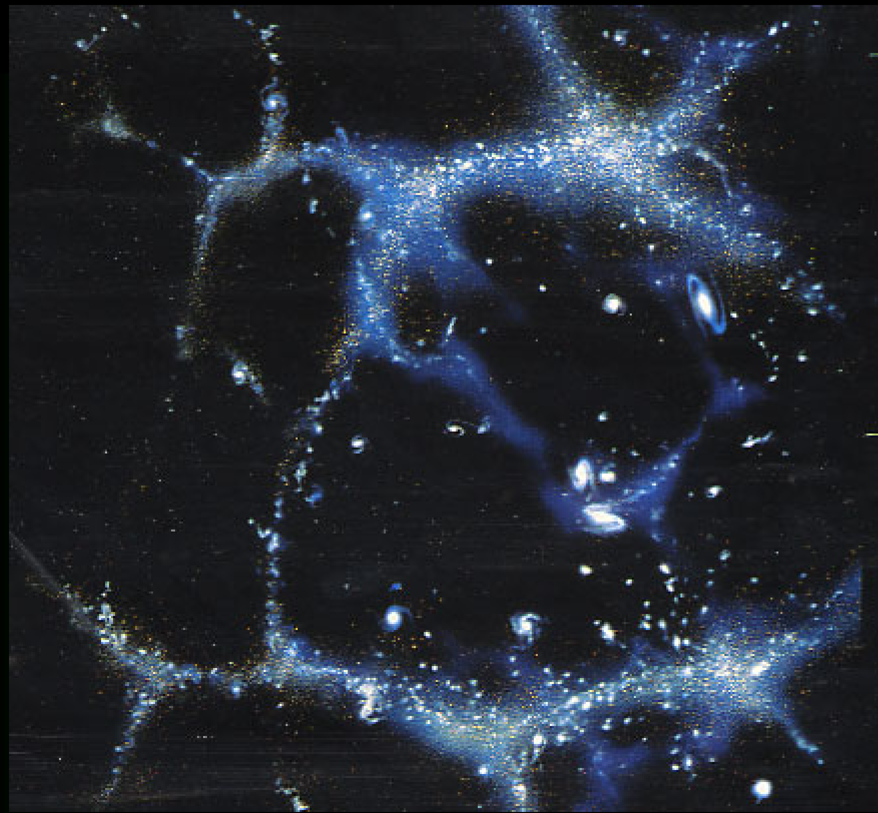


A 300Mpc horizon



Large scale filamentary structures

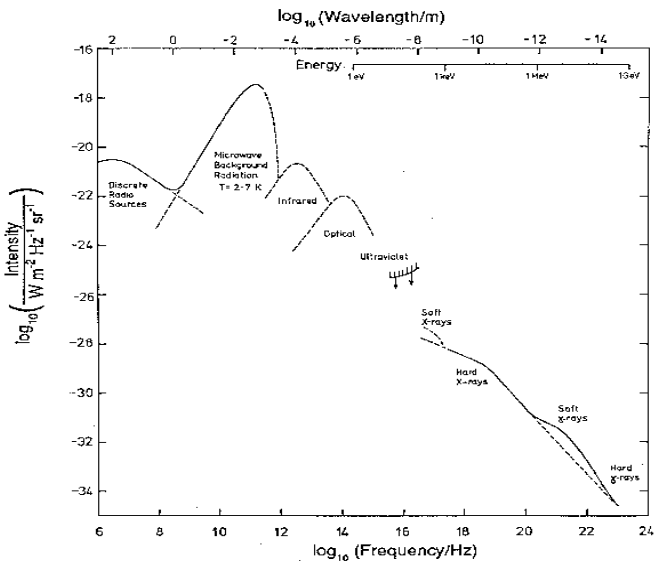




Vacuum is not emptiness !

- Inter Galactic Medium (vacuum) contains:
  - Magnetic fields (regular + random) are highly speculative and range from $2{\cdot}10^{-6}$ nT (20pG) to 10^{-4} nT (1nG).
  - Very little matter (p, He, and a few electrons): $\leq$ 1 proton / m^3
  - Electromagnetic radiations:
    - 413 CMB photons per cm^3
    - Also IR, radio photons…
  - Neutrinos:
    - Mostly CνB neutrinos (decoupled when universe was only 2" old!)
    - Today 1.95K i.e. 1.7×10^{-3} eV
    - 336 ν (all species) per cm^3

+ Many mysterious dark matter WIMPs …



The earth atmosphere

An evident characteristic of the atmospheric medium is that of being inhomogeneous.

- Its density, decreases by 6 orders of magnitude from ground to 100km, and another 6 orders for the range 100km to 300km.

- However, up to ~100km the composition is nearly constant: 78.47% N, 21.05% O, 0.47% Ar and 0.03% other elements.

- It follows a quasi exponential profile ("quasi" because T is not quite constant!)

The earth atmosphere

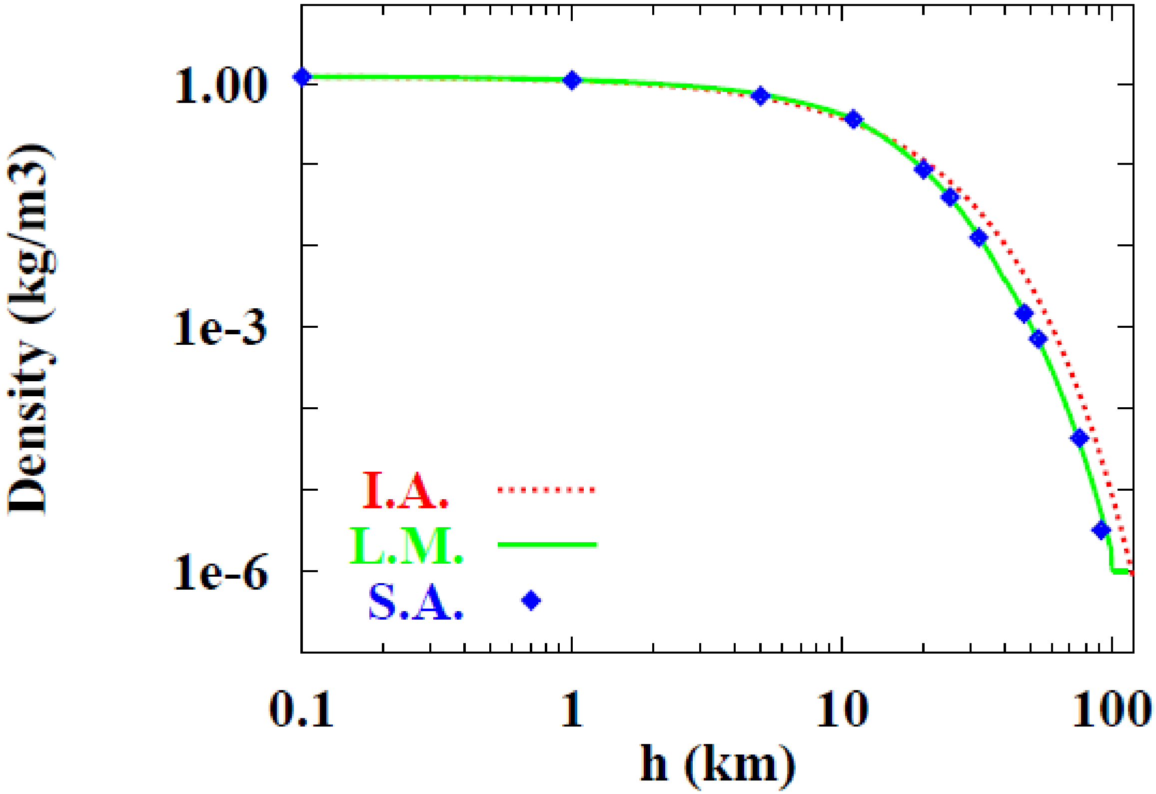


Figure 2.3. Density of the air as a function of the vertical altitude. The dots represent the US standard atmosphere data [14], while the full green line corresponds to Linsley's model [16] and the dashed red one to the isothermal atmosphere
$\rho(h) = \rho_0\, e^{-gMh/RT}$ *with*
$\rho_0 = 1.225\ \mathrm{kg/m^3}$,
$M = 28.966$ *and* $T = 288\ K$.

$$\rho(h) = \rho_0 e^{-gMh/RT}$$

$$\text{Scale height } gM/RT \approx 9km$$

The earth atmosphere

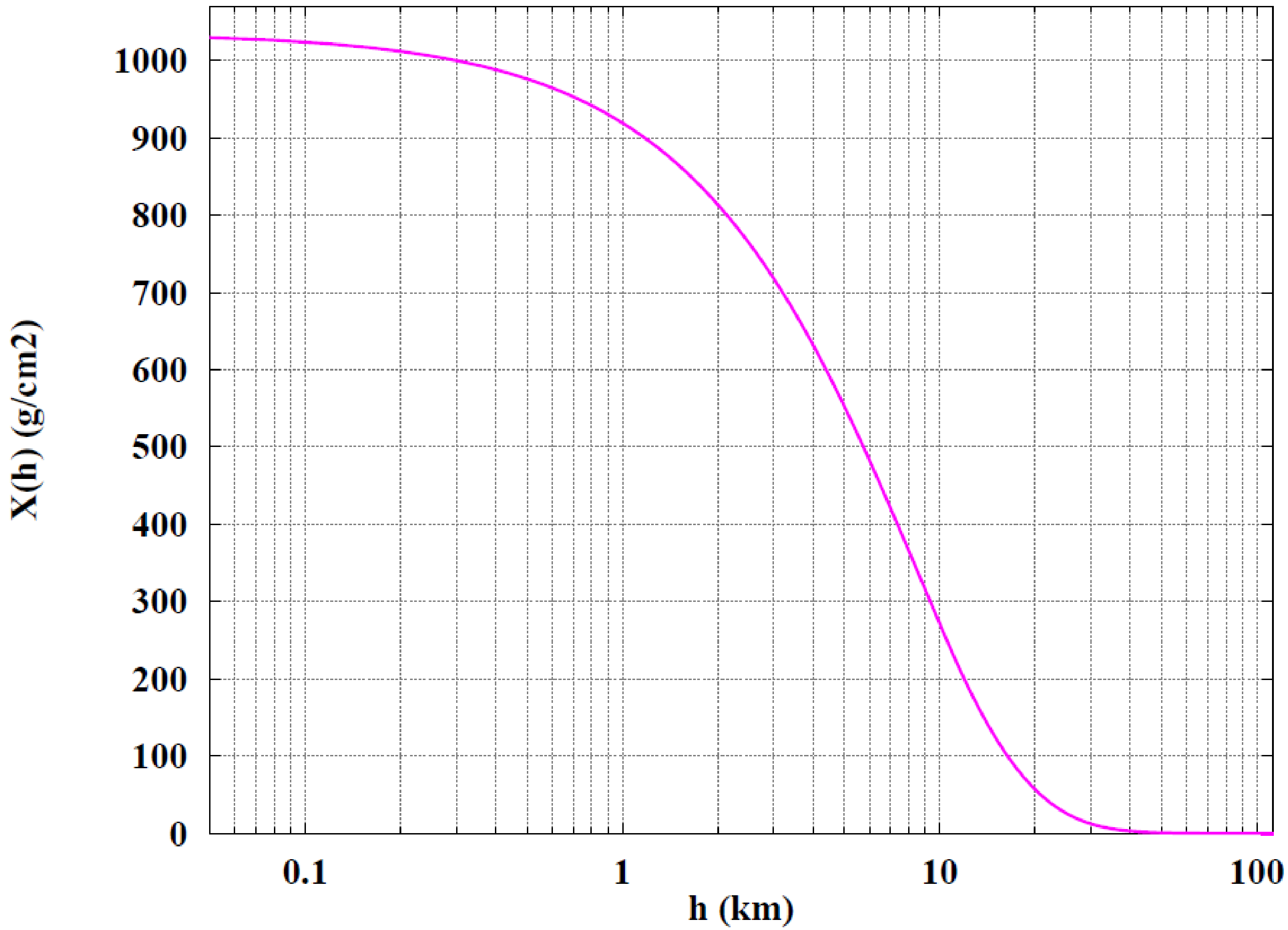


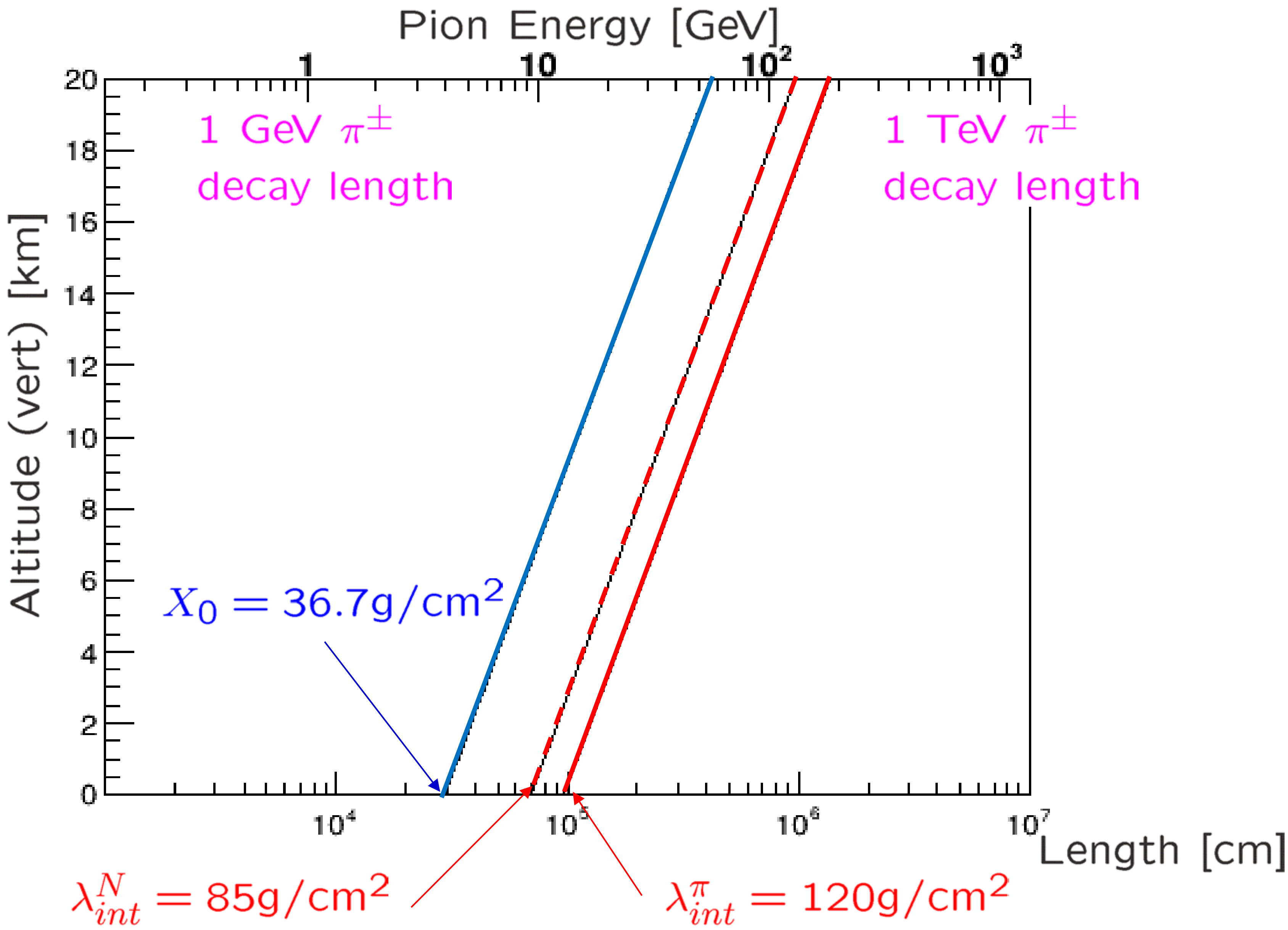
Figure 2.4. *Vertical atmospheric depth, X_v, versus vertical altitude over sea level, h, accordingly with Linsley's model [16].*

The earth atmosphere

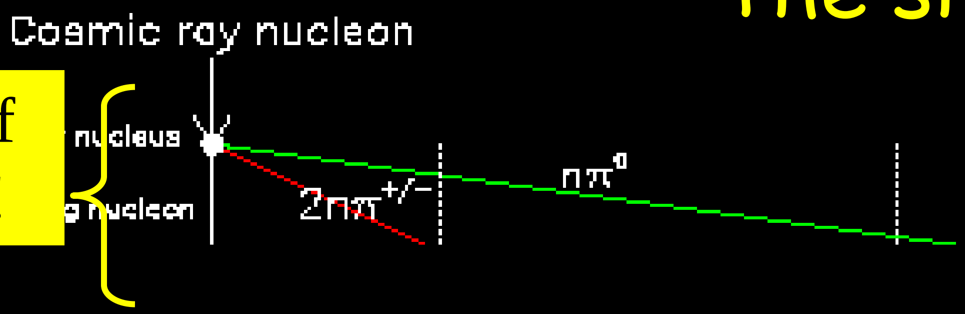
In terms of particle/radiation interaction with matter, the atmosphere is:

- A total of ≈ 1000 g/cm^2 at sea level.
- So 1 atm ≈ 12 interaction lengths ($\lambda_N \approx 85$ g/cm^2).
- A vertical proton first interacts at $h \approx 15$ km
- One radiation length (at 1 atm) is $X_0 = 36.6$ g/cm^2 ≈ 300 m.
- One Moliere radius (at 1 atm) is $\rho_M \approx 78$ m.
- The Lorentz factor for a muon produced at $h = 10$ km to reach ground before decaying is $\Gamma > 15$ (i.e. $E > 1.6$ GeV).
- The critical energy (EM) is $Ec = 84.2$ MeV.

Interaction and radiation lengths in atmosphere



The shower development



Physics well out of reach of colliders !

At each step energy is shared by more numerous particles

"Hadronic" shower

$\lambda_{interaction} < \beta\gamma c\tau_{decay}$

"Electro-Magnetic" shower

$\lambda_{radiation} < \lambda_{ionisation}$

Maximum of developpement

Critical Energy E_c

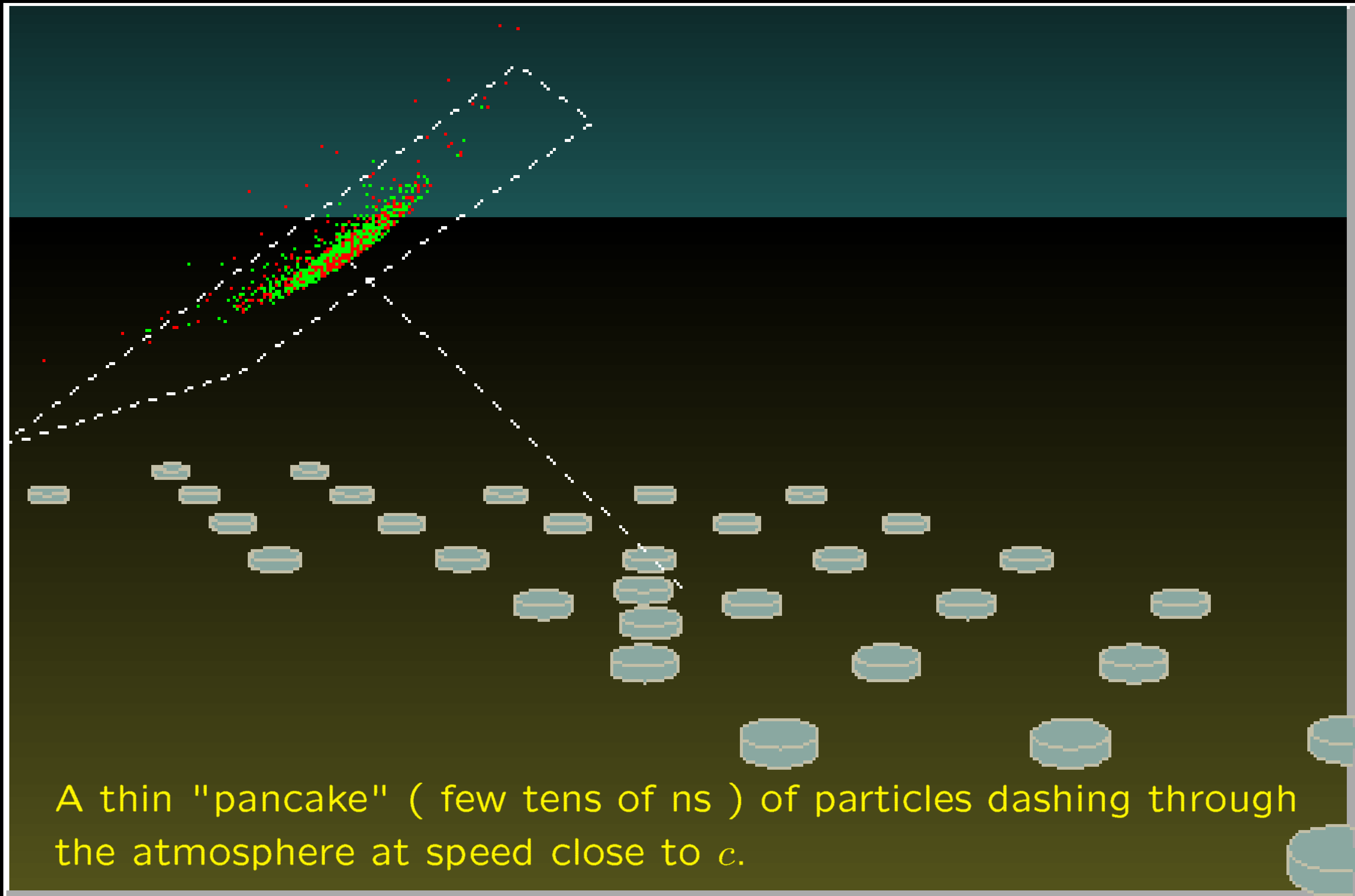
No more multiplication, decrease by decay and energy loss

$\lambda_{interaction} > \beta\gamma c\tau_{decay}$

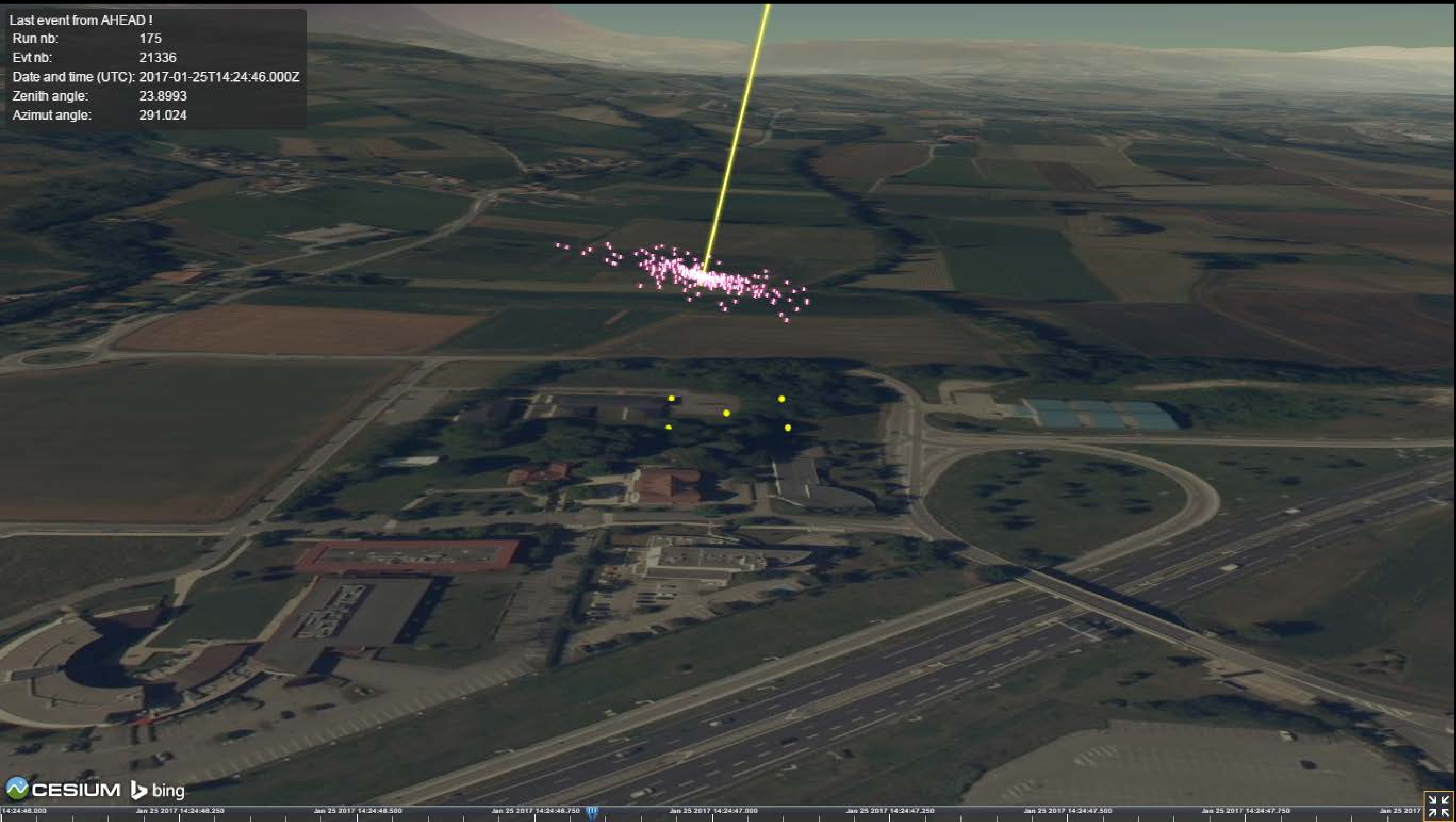
$\lambda_{radiation} > \lambda_{ionisation}$

At ground, essentially $\mu^{\pm}$ γ $e^{\pm}$

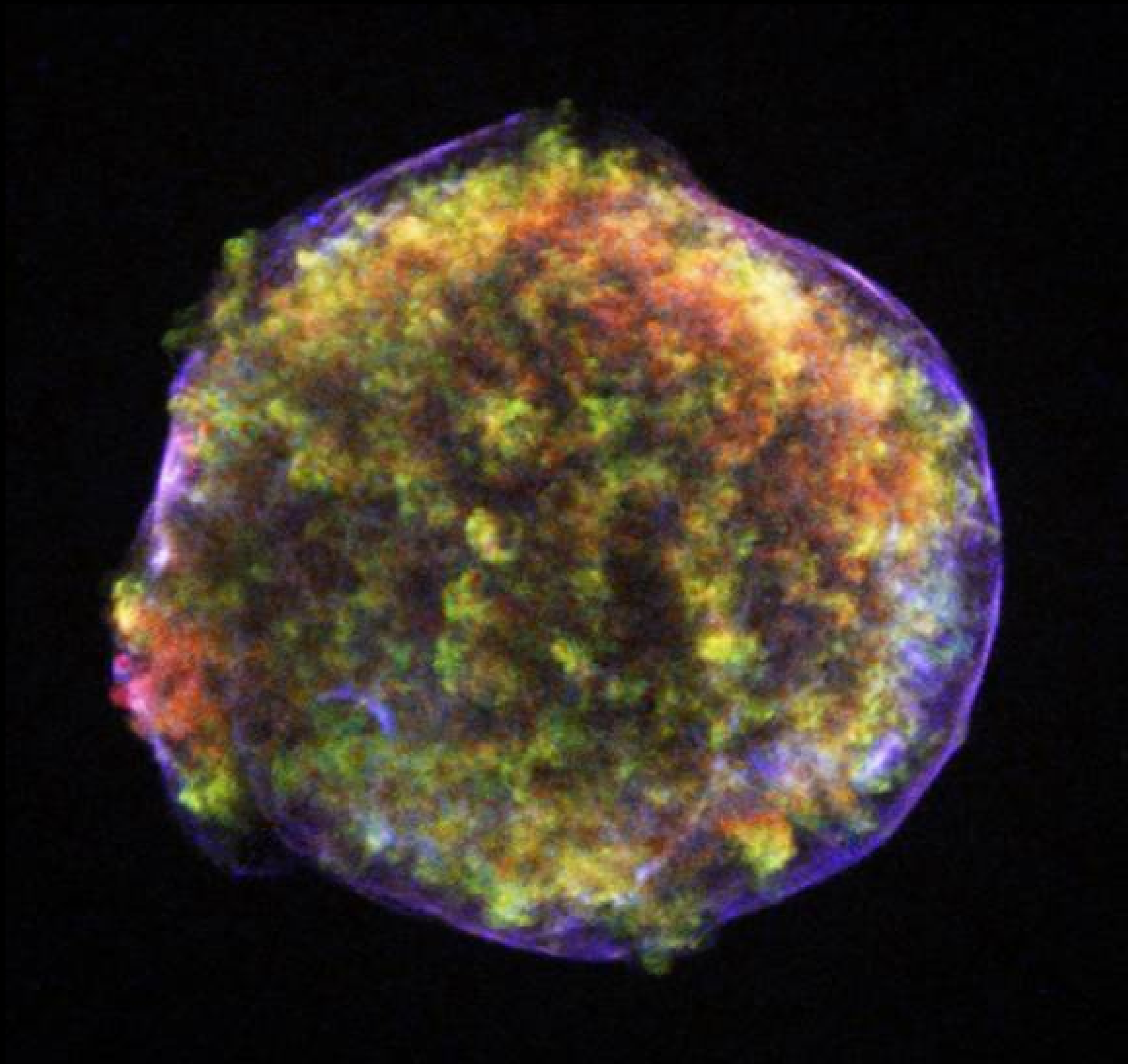
Time structure



AHEAD


Last event from AHEAD !
Run nb: 175
Evt nb: 21336
Date and time (UTC): 2017-01-25T14:24:46.000Z
Zenith angle: 23.8993
Azimut angle: 291.024
CESIUM
bing

Astrophysical Sources
Cosmic Accelerators

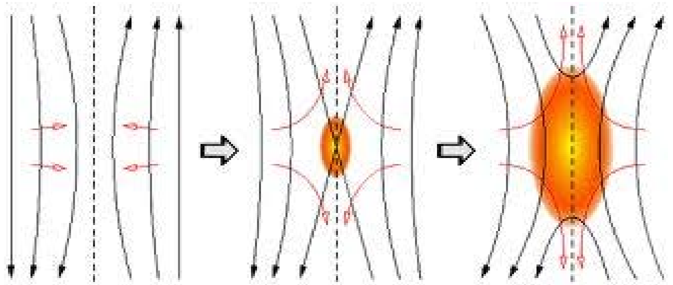


General ideas on acceleration

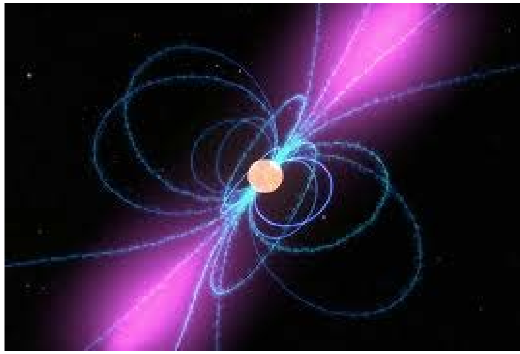
- Take the necessary energy somewhere…
  - Kinetic energy:
    - Translation: shock waves, moving clouds…
      → Fermi acceleration
    - Rotation : pulsars, black holes, neutron stars
  - Gravitational energy
    - via accretion (→ jets…): accretion disks (divers)
  - Electromagnetic (EM)
    - From turbulence, from compression, or from rotating magnets…
- In fine, charged particles interact
  with EM fields: $f = q\,(E + v \times B)$
- Remember:
  Astrophysical shocks are collision-less.

→ Energy transfert through EM fields !

E and B fields in Universe



- * In ISM as on earth, $< E > \approx 0$
  - ISM is neutral or conducting
- * Transient electic fields:
  - Magnetic re-connections (e.g. solar flares...)
  - EM waves



- * Producing E fields in EM "engines"
  - Astrophysical dynamos, induction machines
- * Magnetic fields :
  - $\varepsilon_B \approx 1eV/cm^3 \approx \varepsilon_{optique} \approx \varepsilon_{CMB} \approx \varepsilon_{CR}$!!!
  - Astrophysical plasmas :
    ISM, stars, accretion disks, IGM, jets, etc...

Magnetic field production

- Large scale movements of ionized media
  → generating magnetic fields, magnetized clouds...
- Turbulence in interstellar medium
  → Magnetic turbulence, inhomogeneous B fields, plasma waves...
- Hydro and MHD instabilities
  - e.g. Rayleigh-Taylor in supernova remnants
- "Streaming" instabilities
  - CR generates waves in a magneto-active plasma
  → creating the conditions for their own diffusion

Magnetic field production

In many cases, **equipartition** can be reached

- for ex: behind a shock wave :
  thermal energy ~ kinetic energy ~ magnetic energy

⇒ Energy exchange between macroscopic structures and individual particles

⇒ individual particles may reach very high energies!

Magnetic fields and acceleration !

- **How is it possible at all?**
  magnetic fields don't work ! $(\vec{F} \perp \vec{B})$

- Well, variable $\vec{B}(t)$ fields do ! (example: *Betatron*)
  $$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

- In a different reference frame,
  a pure $\vec{B}$ field is feeled as a $\vec{E}$ field...
  $\vec{E}' = \vec{v} \times \vec{B}$ (for $v \ll c$)

- In principle, one can always identified an effective $\vec{E}$ field that works, but the description in terms of $\vec{B}$ fields is often simpler (and more physical !)

$\rightarrow$ Acceleration by "change of reference frame"

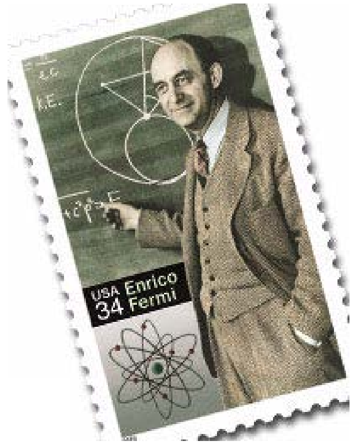
Where to accelerate

- At creation :
  - For example: e^- extracted from the surface of a neutron star by an intense E field.

- Within the source neighborhood :
  - For example: Fermi acceleration in plasma shocks in a SNR.

- During transport:
  - "reacceleration" by shock waves and excitation of Alfven waves during diffusive transport in the Galaxy.

Principle of Fermi acceleration



The Ingredients :

- **A magnetic field** $\vec{B}$
  $=$ with a regular component $\vec{B}_0$
  $+$ and irregular component $\delta\vec{B}$
- **A plasma** i.e. a good electrical conductor :
  $\vec{E} + \vec{u} \times \vec{B} = 0$ and $|E| \approx 0$
  $\Rightarrow$ the magnetic field is "frozen" and moves with the plasma (Alfven).
- **A CR population** coupled to the medium via the magnetic field $\vec{B}$. They scatter on the field irregularities. This diffusion processes are **collisionless** i.e. they conserve the particle energy. The MHD or Alfven waves act as massive scattering centers (recoilless).

Fermi 1949 :

- first hypothesis of converging movements of MHD perturbations
  $\Rightarrow$ "first order" acceleration, but where ?
- second more realistic hypothesis at that time: random mouvement of interstellar gas clouds (observed) or MHD perturpations
  $\Rightarrow$ "second order acceleration.

Power laws and stochastic processes

- The power laws observed in differential energy spectra follow naturally from cyclic acceleration mechanisms with constant energy gain and constant escape probabilities:

  - Initial energy: E_0
  - Energy gain at each cycle: $\Delta E = \varepsilon E$
  - Particle energy after n iterations: $E_n = E_0(1+\varepsilon)^n$
  - Escape probability from the acceleration zone: P_{esc}
  - Probability to remain in the acceleration zone: $(1 - P_{esc})^n$

Power laws and stochastic processes

- Particle energy after n iterations: $E_n = E_0(1+\varepsilon)^n$
- Probability to remain in the acceleration zone: $(1-P_{esc})^n$

Number of iterations to reach an energy E:

$$n = \frac{\ln(E/E_0)}{\ln(1+\varepsilon)}$$

Proportion of particles accelerated up to an energy equal or greater than E :

$$N(\geq E) = N_0 \sum_{m=n}^{\infty} (1-P_{esc})^m = N_0 \frac{(1-P_{esc})^n}{P_{esc}}$$

thus :

$$\frac{\ln(P_{esc}N/N_0)}{\ln(1-P_{esc})} = n = \frac{\ln(E/E_0)}{\ln(1+\varepsilon)}$$

eliminating n:

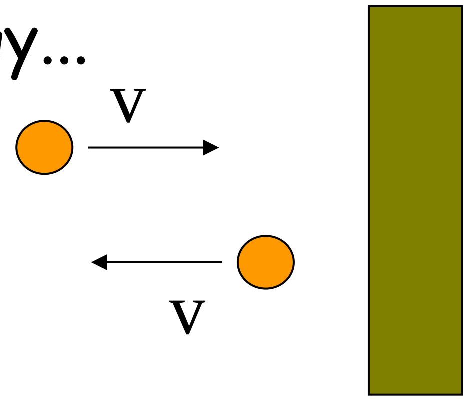
$$N(\geq E) \propto \left(\frac{E}{E_0}\right)^{-\gamma}$$

with $\gamma = \dfrac{-\ln(1-P_{esc})}{\ln(1+\varepsilon)} \approx \dfrac{P_{esc}}{\varepsilon} = \dfrac{1}{\varepsilon}\dfrac{T_{cycle}}{T_{esc}}$

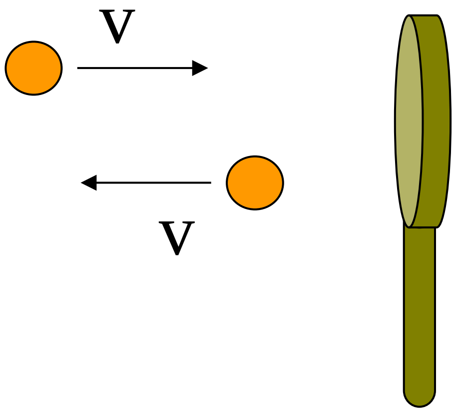
→ Power laws are natural !

A small analogy…

- A tennis ball bouncing on a wall
  - neither gain nor loss of energy…



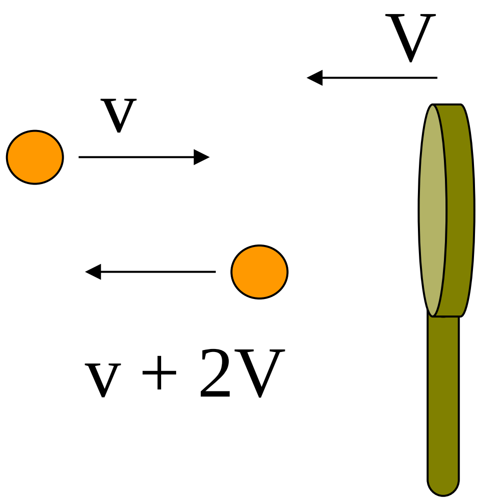
bounce = speed unchanged



Same thing with
a motionless racquet…

Then how does one accelerate a tennis ball ?!

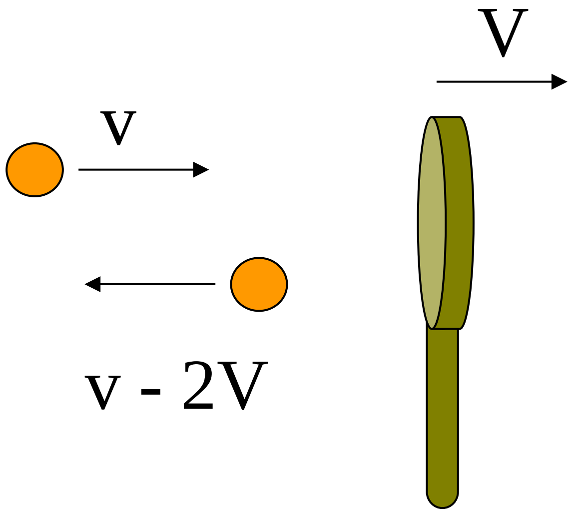
- Moving racquet
  - Neither gain nor loss of energy… in the racquet reference frame !



Speed unchanged with respect to the <u>racquet</u>

→ acceleration through a change of reference frame

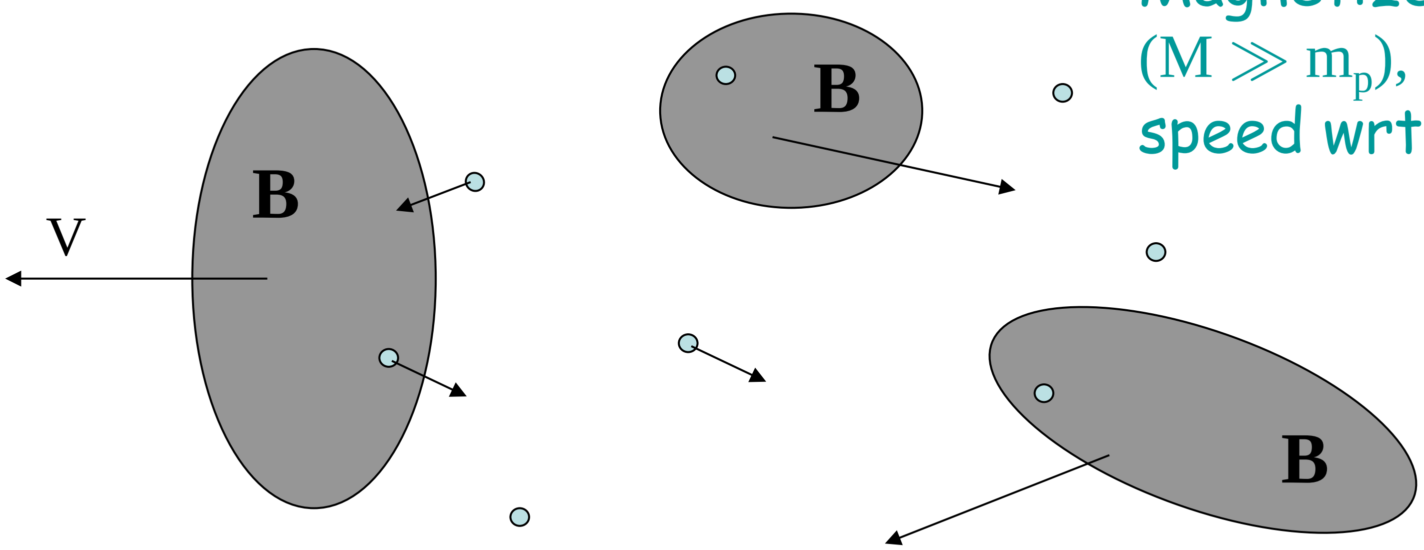
- A drop shot:



Particle deceleration !

Fermi Acceleration

- Ball → charged particle
- Racquet → "magnetic mirrors"



Magnetized clouds ($M \gg m_p$), with a typical speed wrt ISM ~10km/s

- Magnetic inhomogeneities or plasma waves also work…

The essence of stochastic Fermi acceleration

1. When a particle bounces on an **incoming** magnetic mirror, in a **head-on** collision, it **gains** energy.

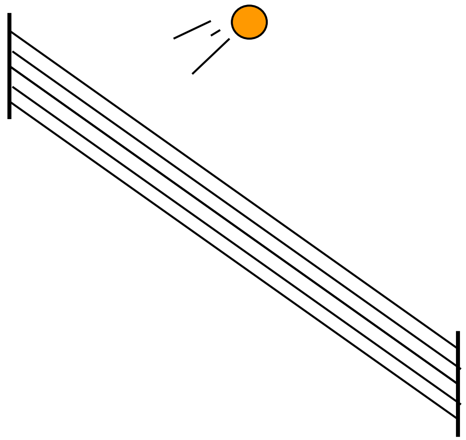
2. When a particle bounces on a **receding** magnetic mirror that it catches back, it **loses** energy.

3. Head-on collisions are **more frequent** than receding collisions.

⇒ Net energy gain in average (stochastic process)

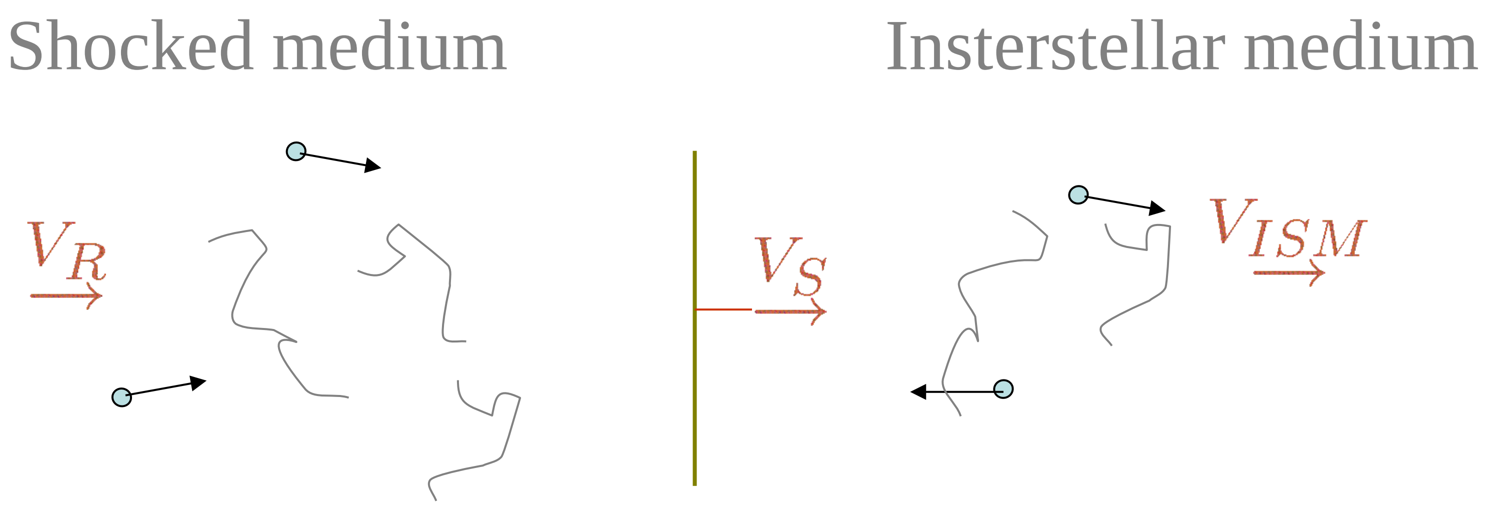
Add a second player...

- Converging flows...



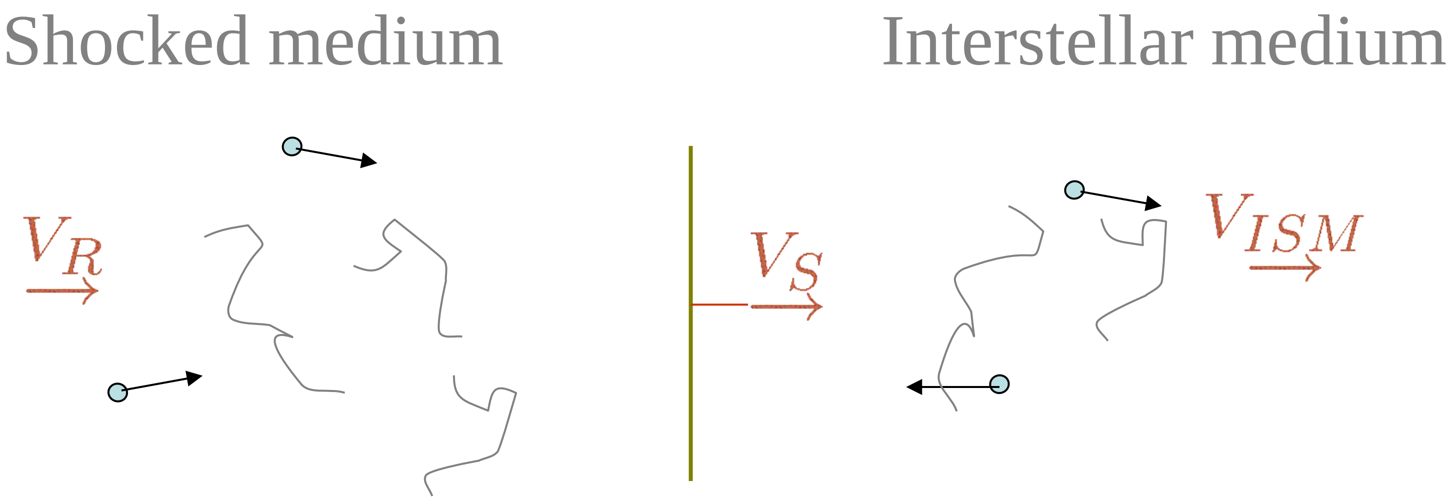
Shocks hydrodynamics

- Shock waves (e.g. supernova explosion) : expending plasma flow with a speed V_R much larger than the sound speed in the interstellar medium (ISM).



Shocks hydrodynamics

- Shock wave:



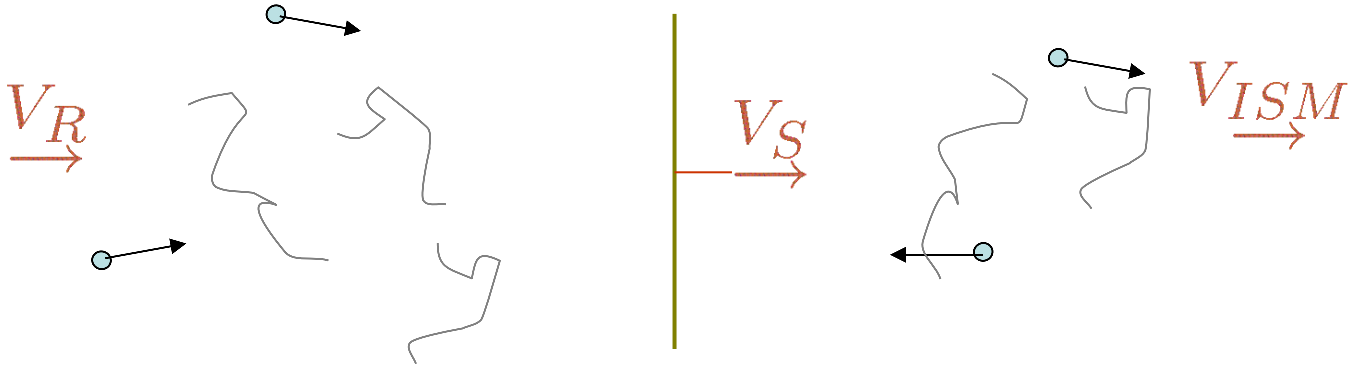
- The shock moves at a speed V_S which depends on V_R and the specific heat of both media.

- For an ionized ISM: $V_S \approx \frac{4}{3} V_R$

Shocks hydrodynamics

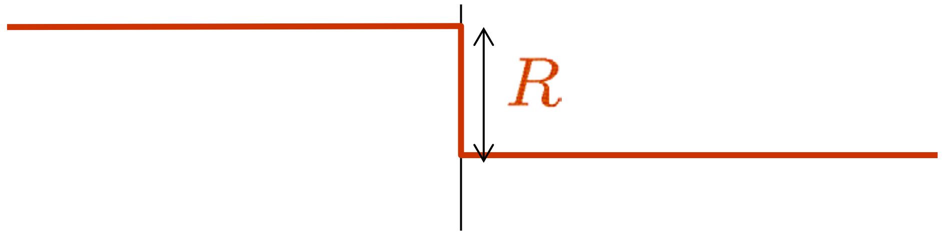
- Onde de choc :

Shocked medium Interstellar medium



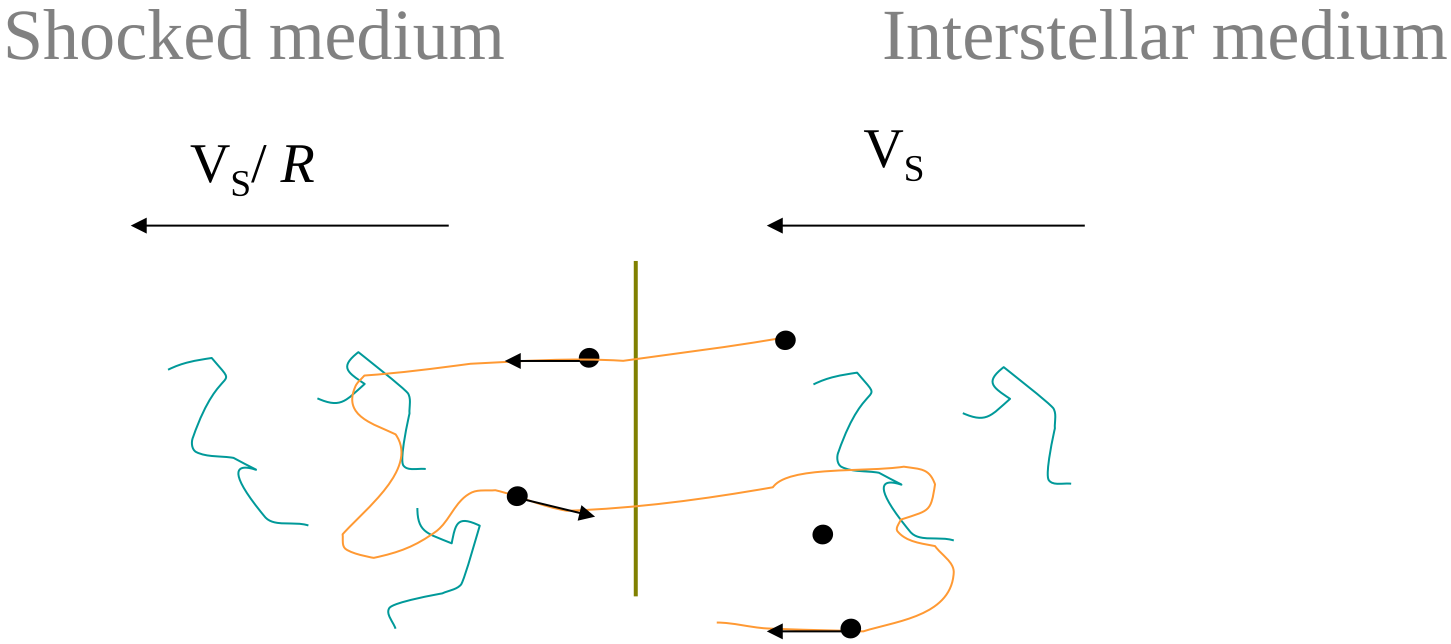
- The shock intensity is characterized by the compression factor:

$$R = \frac{V_S/V_R}{V_S/V_R - 1} \approx 4$$



Shocks hydrodynamics

In the shock frame

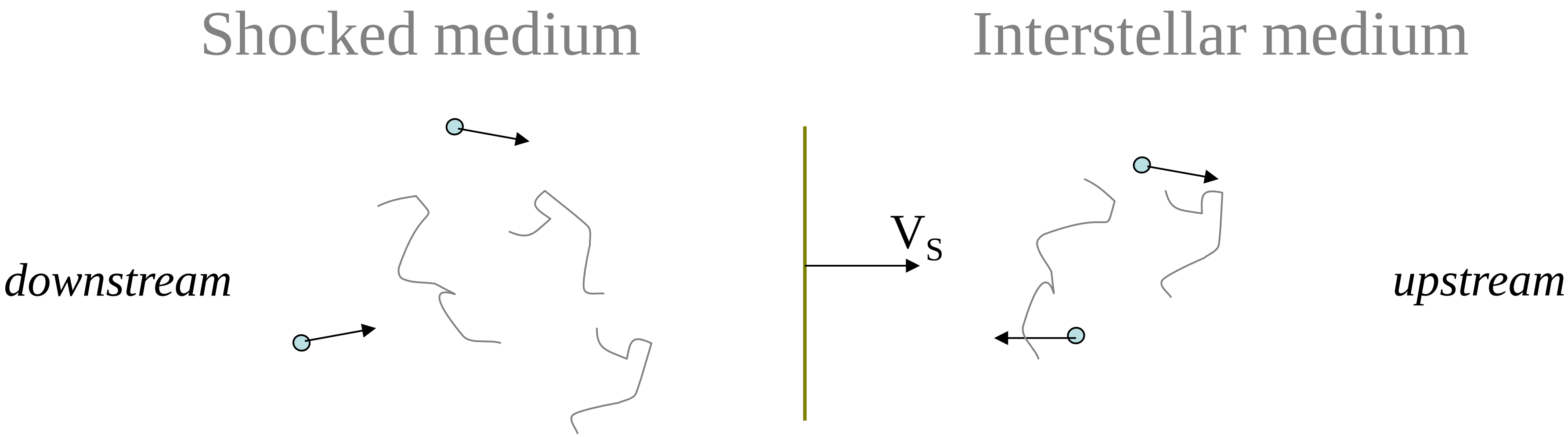


- In the shock frame, the upstream (non-shocked) medium flows toward the shock at a speed V_S and the downstream (shocked) medium flows away with a speed reduced by the compression factor (mass flow conservation) :

$$V_S/V_d = R \approx 4$$

Shock wave diffusive acceleration

- Shock wave (e.g. supernova explosion)

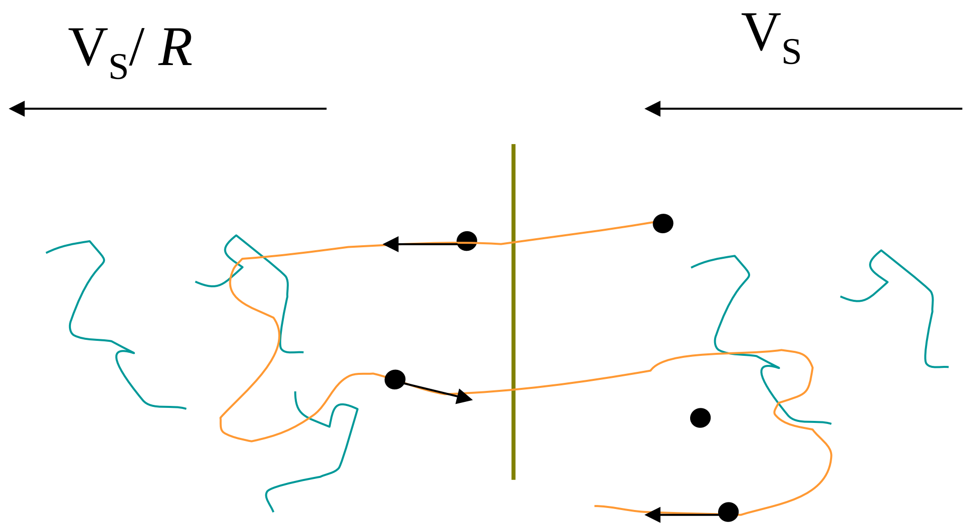


- Magnetic wave generation:
  - **Downstream** : by the shock (compression, turbulence, hydro and MHD instabilities, shear, etc.)
  - **Upstream** : by the accelareted cosmic rays themselves !

→ 'isotropization' of the distribution
(in the local frame)

A win-win process !

Shocked medium Interstellar medium



In the shock frame

- At each shock crossing, one way or the other, the particle hits a "magnetic wall" with a relative speed:

$$V = (1 - 1/R)V_S$$

$\rightarrow$ only head-on collisions…

Summary on acceleration

- Acceleration from interaction with fields
  - **E** field: e.g. induced by spinning magnets such as neutron stars (pulsars) or black holes…
  - **B** field: inhomogeneous moving fields
  - MHD waves
- Acceleration by reference frame transformation
  - Fermi stochastic acceleration (2nd order)
  - Diffusive shock acceleration diffusive (1st order)
- Power law are natural
  - Fermi type process ($\Delta E \propto E, P_{ech}$)
  - Universal power law for non relativistic shocks ($N(E) \propto E^{-2}$)
- Cosmic rays up to the knee
  - CR power = power of SNe, $E_{max} \approx 10^{14}$ eV hardly 10^{15} eV

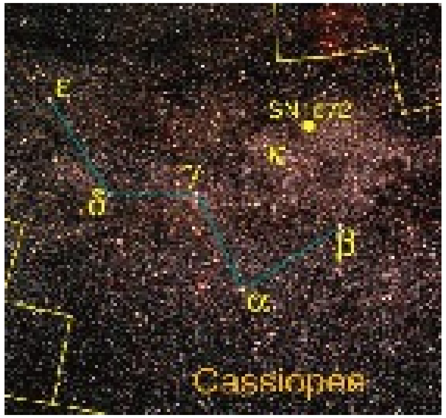
The CR standard model

- Analytic calculations, simulations and observations show that diffusive shock acceleration works !

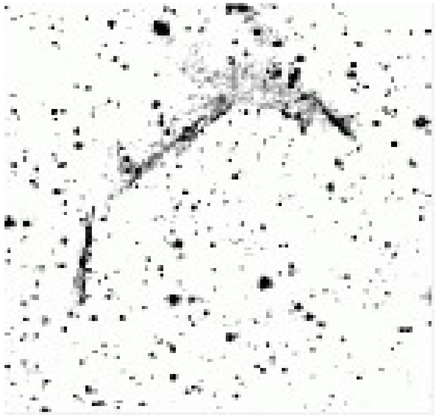
- Supernovae and GCRs
  - Estimated efficiency of shock acceleration :... $10-50\%$
  - Power required to sustain CR energy density: ..... $\varepsilon_{CR} \times V_{conf}/\tau_{conf}$ $\sim 10^{41}\mathrm{erg/s}$!
  - Power injected by SN power in the Galaxy: ....$10^{42}\mathrm{erg/s}$!

→ Enough power for Galactic CR

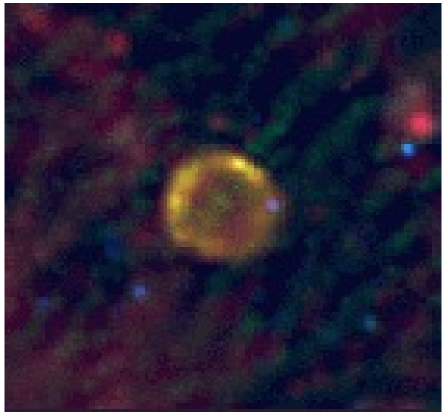
Tycho, 11 November 1572...



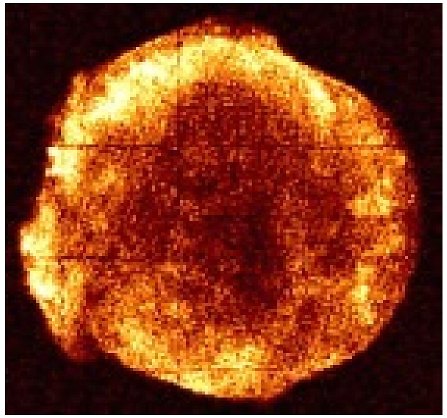
position



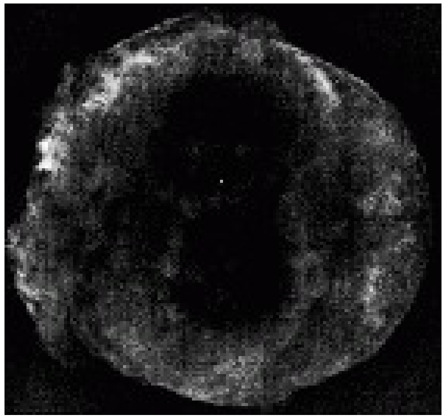
visible



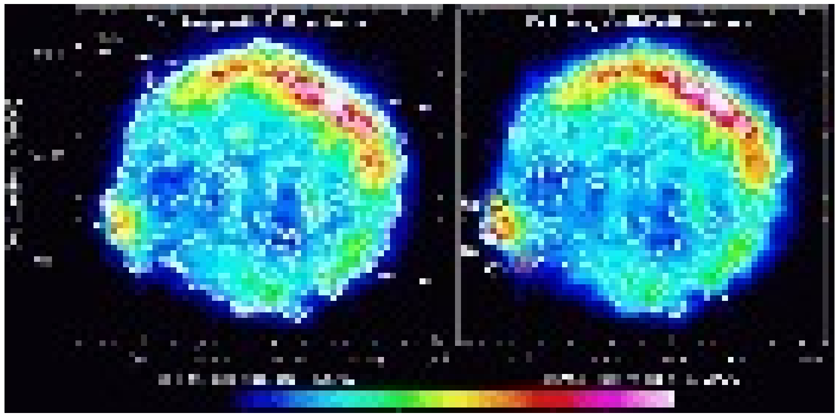
IRAS



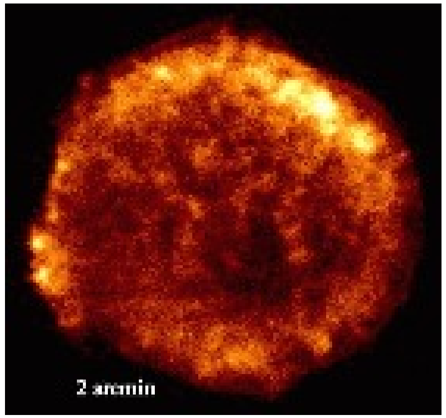
Km (VLA)



6 cm (VLA)



Si K (XMM) Fe K



X (ROSAT)

The CR standard model

- Proposed acceleration site, isolated SNR
  - Supernovæ : ejection of many solar masses of nuclear matter at supersonic speeds (~ 10 000 km/s) following massive star explosion.
  - Formation of a quasi spherical expending shock wave that wipes out the interstellar medium (ionized beforehand by the progenitor's radiation).
  - Total kinetic energy injected by the explosion: 10^{51} erg (= 10^{44} J).
  - Roughly 3 SNe per century witin our Galaxy, which corresponds to an averaged power of 10^{42} erg/s (10^{35}W)
  - SNR are observed at all wavelength.
  - SNe explosion is essential to the Galaxy chemical content: heavy elements enrichment.

The CR standard model

- Shock waves in isolated SNe (SNR)
  - Source composition source ~ interstellar medium + modifications (ionizability, volatility, Z/A effects, ^{22}Ne...)
  - Source spectrum: E^{-2} power law
  - Maximal energy reached: $E_{max} \sim 10^{15}$ eV
- Energetics :
  - Measured flux / speed = CR density
  - CR density × mean energy = energy density
  - Energy density × confinement volume = total energy
  - Total energy / confinement time = necessary injected power
  - $P_{CR} \sim 1.5 \times 10^{41}$ erg/s
- Required efficiency ~ 10-30%...

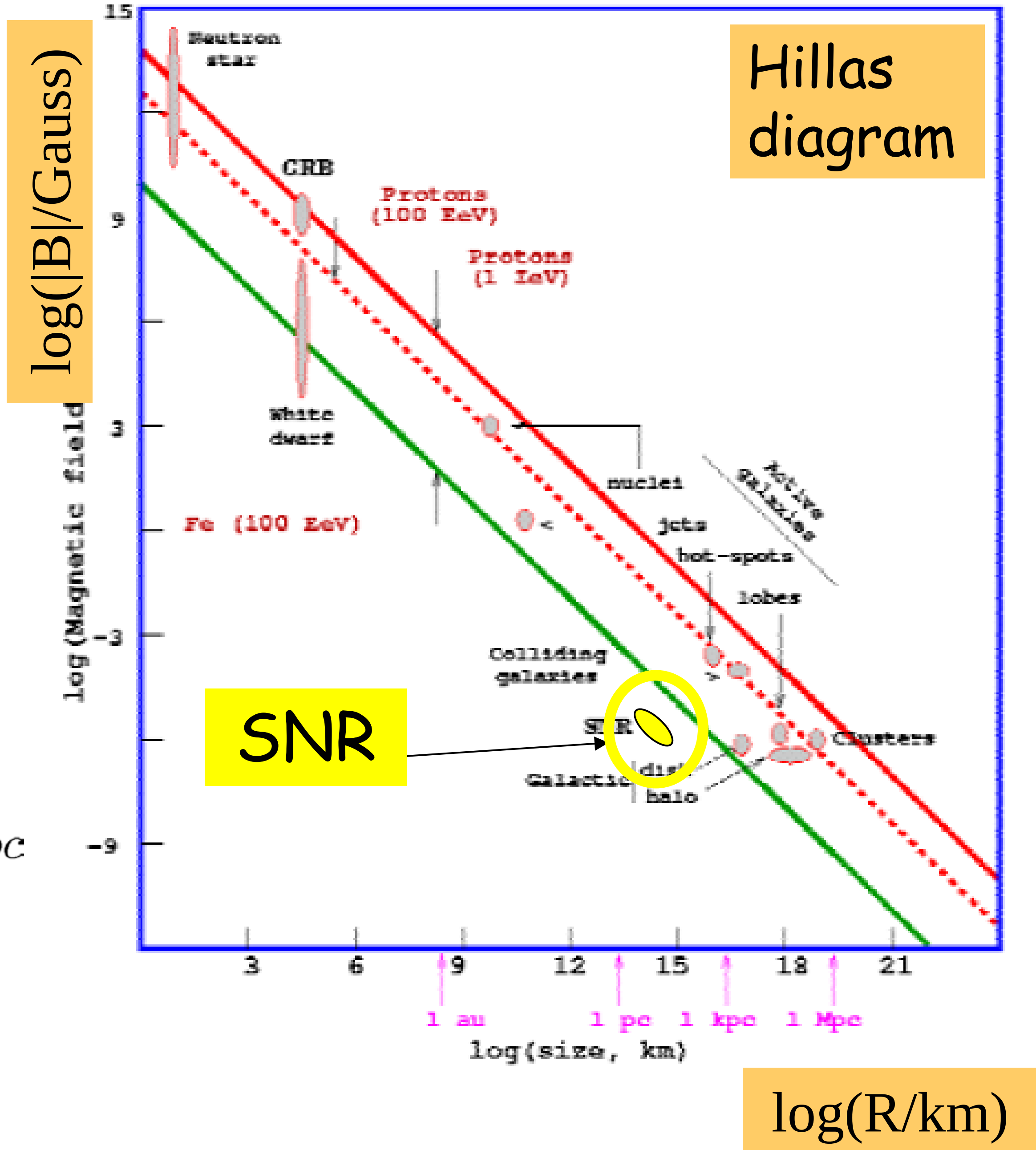
Finite size

Finite size of confinement magnetic field

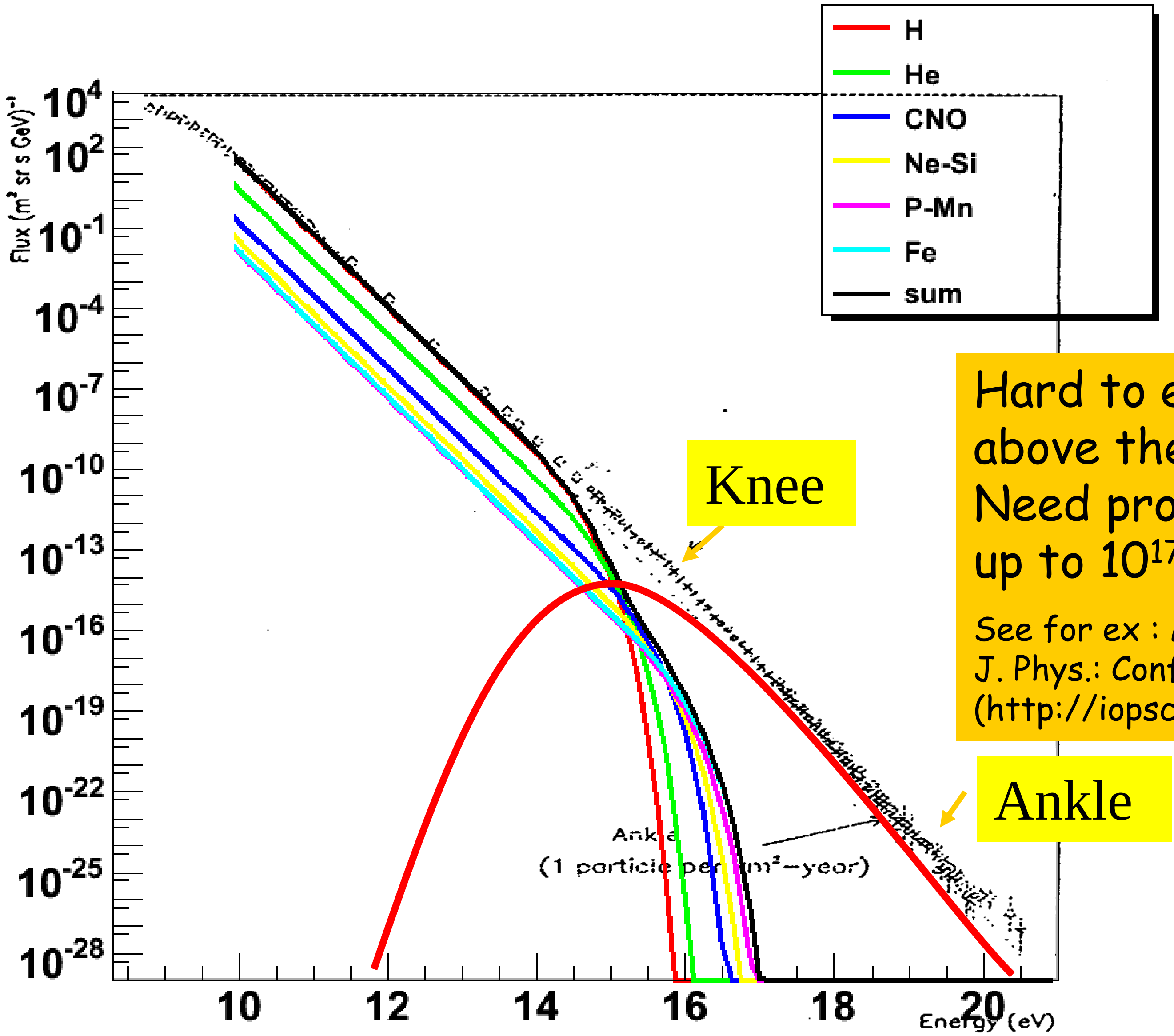
⇕

Larmor radius

$$r_g \leq R$$
$$\Leftrightarrow \quad \frac{p}{ZeB} \leq R$$
$$\Leftrightarrow \quad E \leq Ze \times B \times R$$
$$\Leftrightarrow \quad E \leq (10^{17} eV) Z B_{\mu G} R_{pc}$$



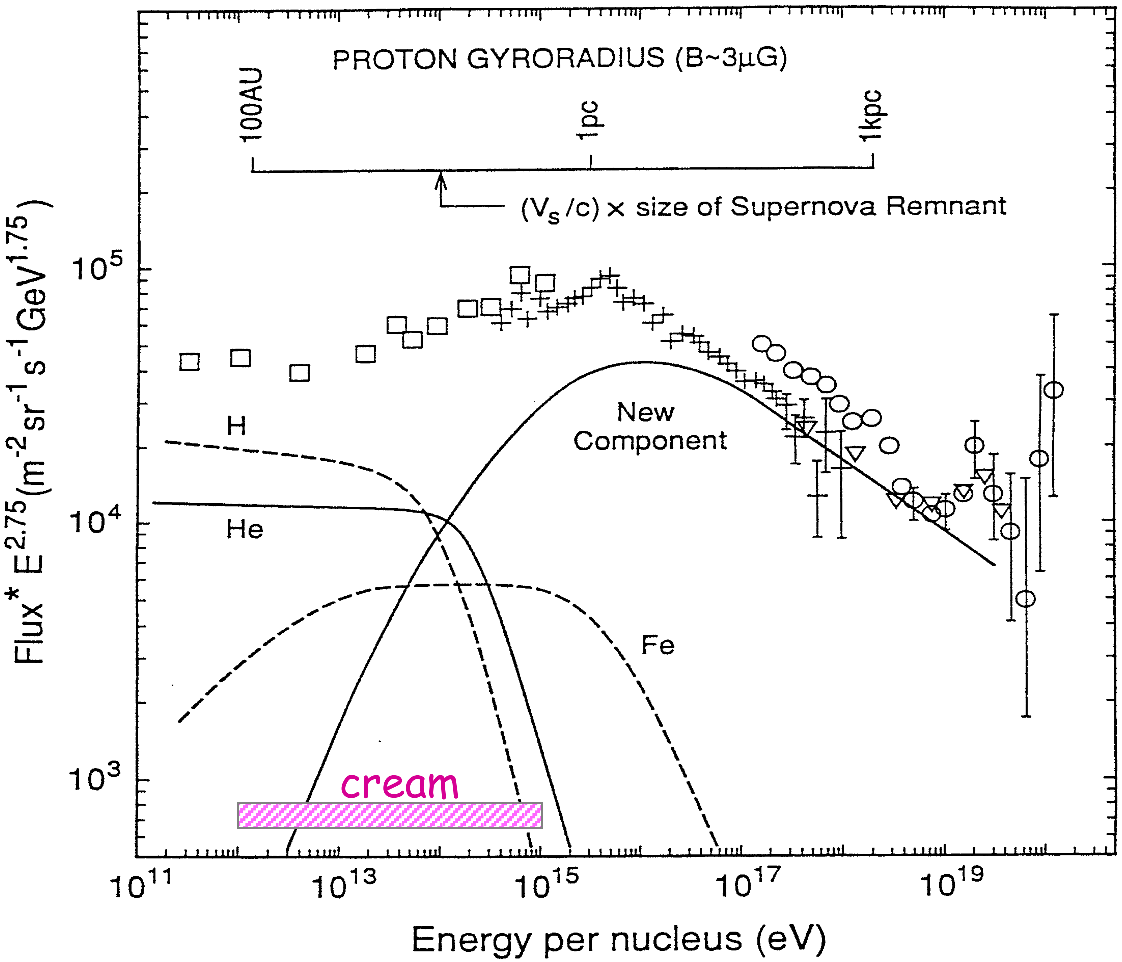
CR SM with Emax ∝ Z



Hard to explain a single power law above the knee.
Need probably another component up to 10^{17}eV or more.

See for ex : M. Hillas
J. Phys.: Conf. Ser. 47 (2006) 168
(http://iopscience.iop.org/1742 6596/47/1/021)

The knee



- Is the knee simply the consequence of an energy cut-off of accelerators (SNR) or is it due to :
  - a propagation effect ?
  - different CR sources ?
  - a physics threshold at ~E_{LHC} ?

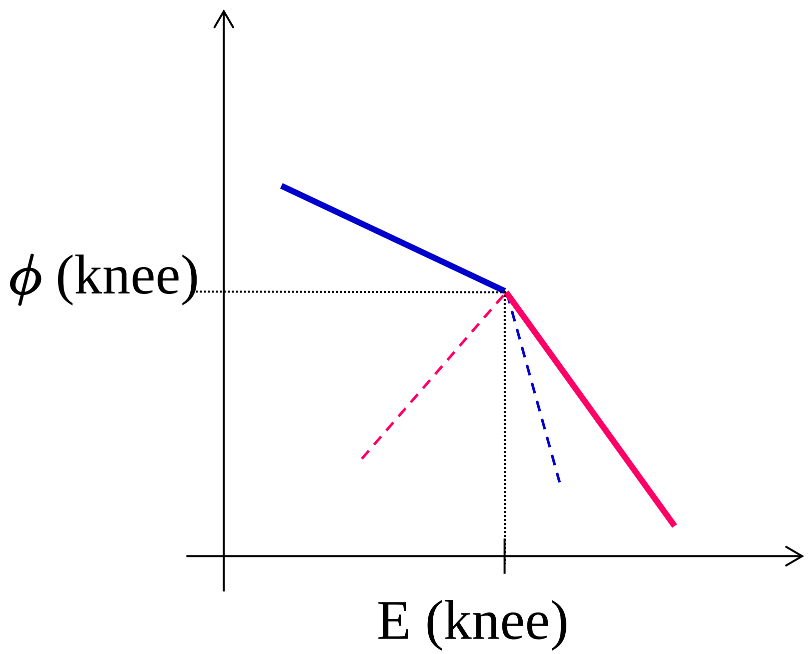
⇨ The CR SM implies a change in composition at the knee energy.

SNR energy limit : $E_{max} \sim Z \cdot 10^{15}$ eV

Data:
- Proton4 sat
- Akeno
- Yakutsk
- Haverah Pk

Explaining the knee is tough !

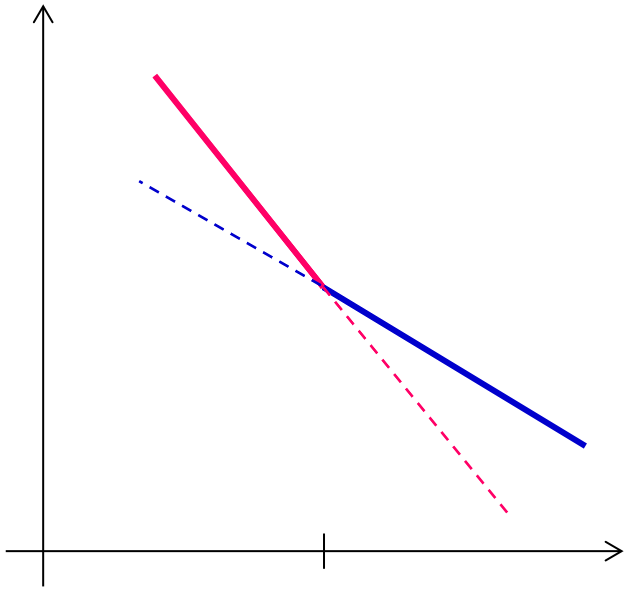
- Need two components matching precisely both energy and flux right at the knee !



→ quite an unnatural coincidence but why not ?

Explaining the ankle is much easier...

- Two components with two different slopes...



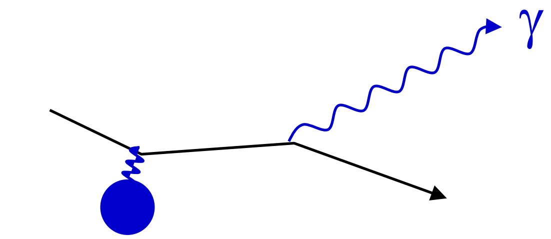
- For example, galactic → extragalactic...

DIFFUSE GAMMA-RAY SOURCE

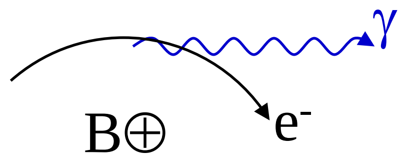
VHE gamma-rays sources

γ-rays production processes:

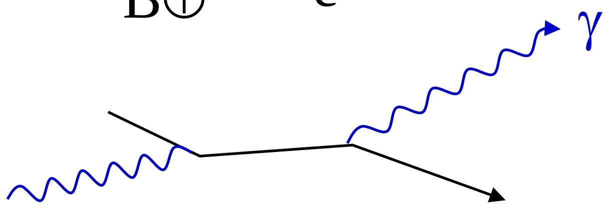
- Electro-Magnetic processes :
  - Bremsstrahlung



  - Synchrotron radiation



  - Inverse Compton



- Hadronics processes:

$$(p, N) + (N\gamma) \rightarrow \pi_0 + \ldots$$
$$\hookrightarrow \gamma\gamma$$

Hadronic production of gamma-rays

Source function [TK Gaisser]

$$q_k(E_k, r) = \int \frac{d\sigma_{i\to k}(E_k, E_i)}{dE_k} \left(\frac{c\rho(r)}{m}\right) \left(\frac{4\pi}{c}\phi(E_i)\right) dE_i$$

Fluxes on earth (neutrals)

$$\phi_{k=\gamma} = \frac{dN_k}{dAdE_kd\Omega} = \int \frac{q_k(E_k, r)}{4\pi r^2} d^3r = \int_0^{r_{max}} \frac{q_k(E_k, r)}{4\pi} dr d\Omega$$

Scale invariance : $E_\gamma / E_i = Z$ (Z indep. of E)
(for $E_k \gg m_i/2 = m_\pi/2 \approx 70 MeV$)
(system mass scale).

$\Rightarrow \phi_k \propto \phi_i$

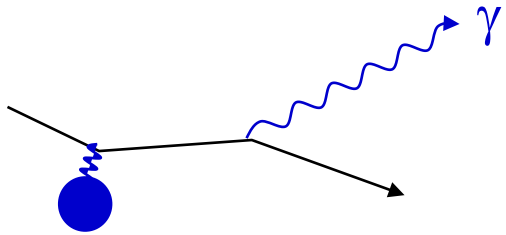
Parent spectral density power law $\phi_i \propto E_i^{-\alpha}$
[Gaisser,Halsen,Berezinsky,Stanev]

$$\phi_\gamma = 4\pi\rho \left[\frac{\sigma_{inel}}{m_N}\right] \left[\frac{2Z_{N\to\pi^0\to\gamma}}{\alpha}\right] \phi_{CR}(E)$$

$$\frac{\phi_\gamma}{\phi_{CR}} \approx 6\times 10^{-4} \times \left(\frac{\rho R}{[g.cm^{-2}]}\right) \quad \rho R = \text{target colonm density}$$

Bremsstrahlung

$$\frac{d\sigma_{e\to\gamma}(E_\gamma, E_e)}{dE_\gamma} = \frac{1}{E_e}\frac{\phi(z)}{N_A X_0}$$



where $\phi(z)$ is a function of $z = E_\gamma / E_e$

For energies $> 70 MeV/c^2$, there is a scaling relation between the γ energy and that of the parent electron. (the only mass scale in the problem is the electron mass, much lower than 70 MeV).

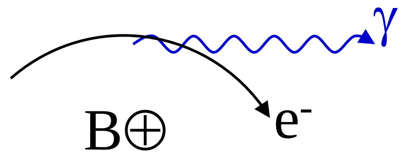
$\Rightarrow$ the differential spectrum of the progenitor electrons ($\phi_e(E_e) \propto E^{-\alpha}$) is transmitted to the γ differential spectrum:

$$\phi_\gamma(E_\gamma) \propto E_\gamma^{-\alpha}$$

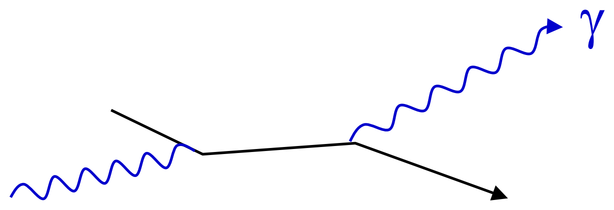
For $dN/dE_e = a_e E_e^{-\alpha}$ and $\alpha = 2.7$
$q_{br} \approx 1.2 \times 10^{-25} a_e n E_\gamma^{-2.7}$ photons GeV^{-1} s^{-1} cm^{-3}

VHE Gamma sources

- Productions of γ > 10 MeV
  - Synchrotron radiation negligible.



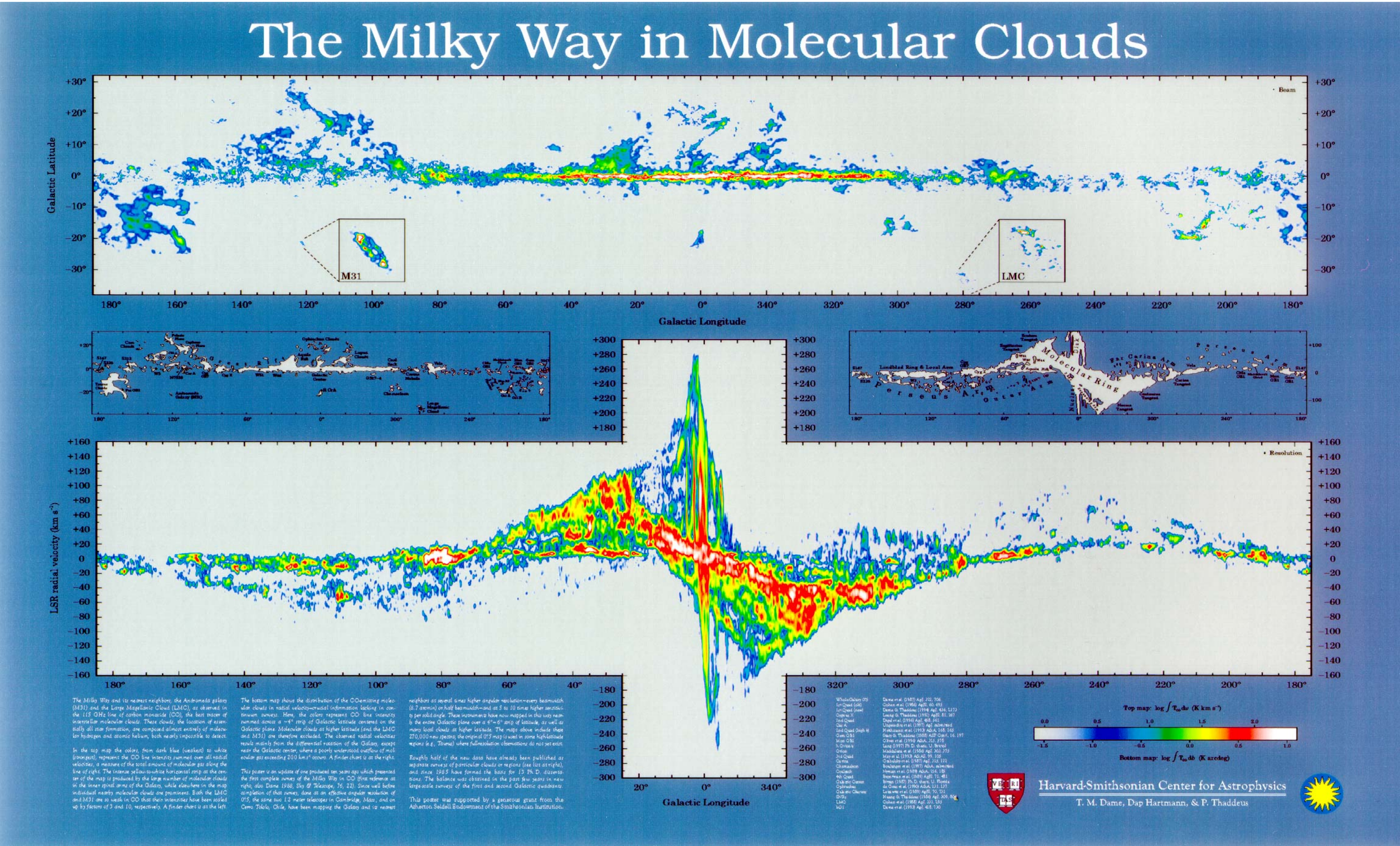
  - Inverse Compton



For $\phi_e \propto E^{-\alpha}$
the IC spectrum is much flatter
$\propto E^{-(\alpha+1)/2}$

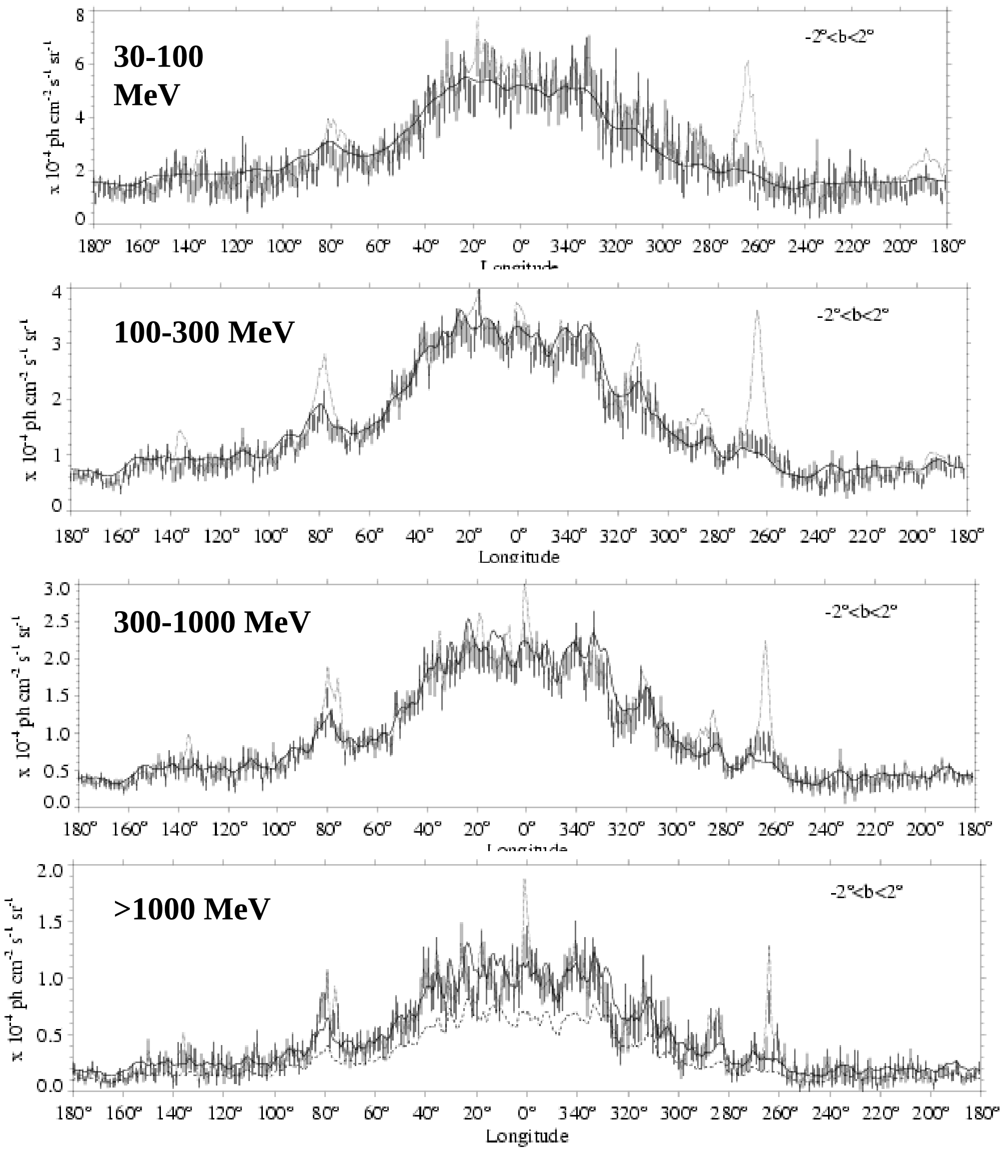
but $N_e \ll N_p$ and the electron spectrum drops $\searrow$ above a few GeV (synchrotron radiotion energy losses)

The target…


The Milky Way in Molecular Clouds
Galactic Latitude
Galactic Longitude
M31
LMC
Beam
Resolution
LSR radial velocity (km s⁻¹)
Harvard-Smithsonian Center for Astrophysics
T. M. Dame, Dap Hartmann, & P. Thaddeus

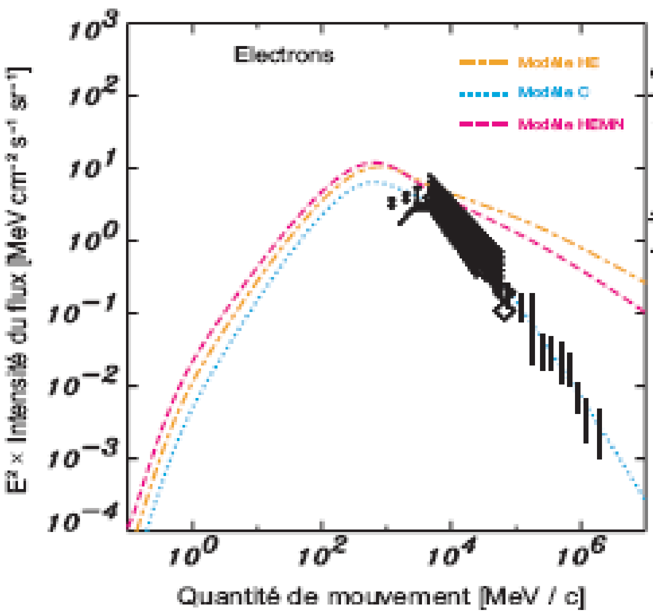
Tracking back the CR flux elsewhere in the Galaxy

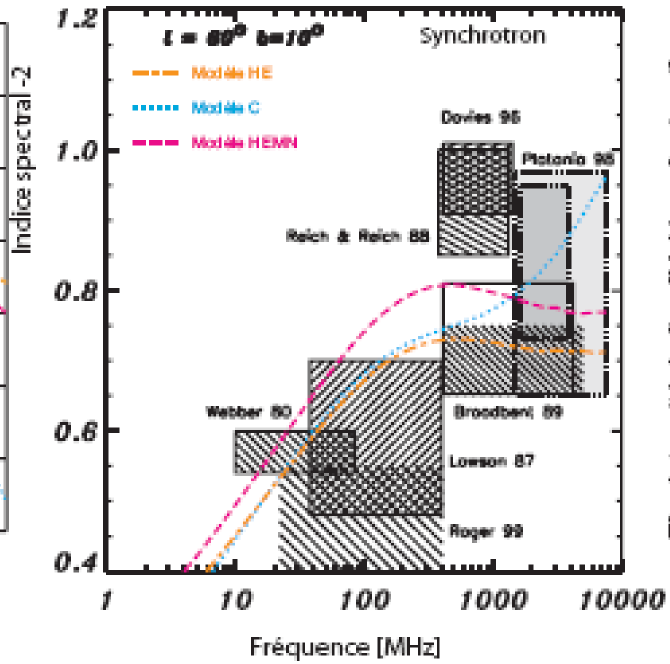
- Knowing the target column density from radio 21cm measurements and fitting the diffuse γ flux, one can map the density, spectrum and composition of CR elsewhere in the galaxy.
  - S.D.Hunter et al, ApJ 481 (1997) 205
  - M.Pohl and J.A.Esposito ApJ, 507 (1998) 327
  - S.LeBohec et al, astro-ph/0003265
  - Strong, A.W., Moskalenko, I.V., ApJ 509:213-228, 1998

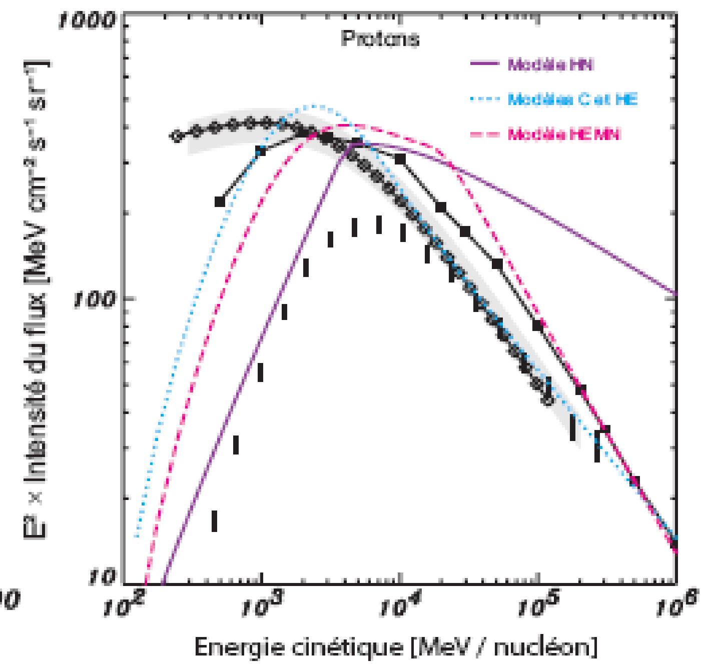


Tracking back the CR flux elsewhere in the Galaxy

- Other constrains
  - Protons local spectrum and flux (altered <10GeV solar magnetic field)
  - Electrons local spectrum and flux (influenced by the local bubble of matter under-density)
  - Radio measurements of the synchrotron emission

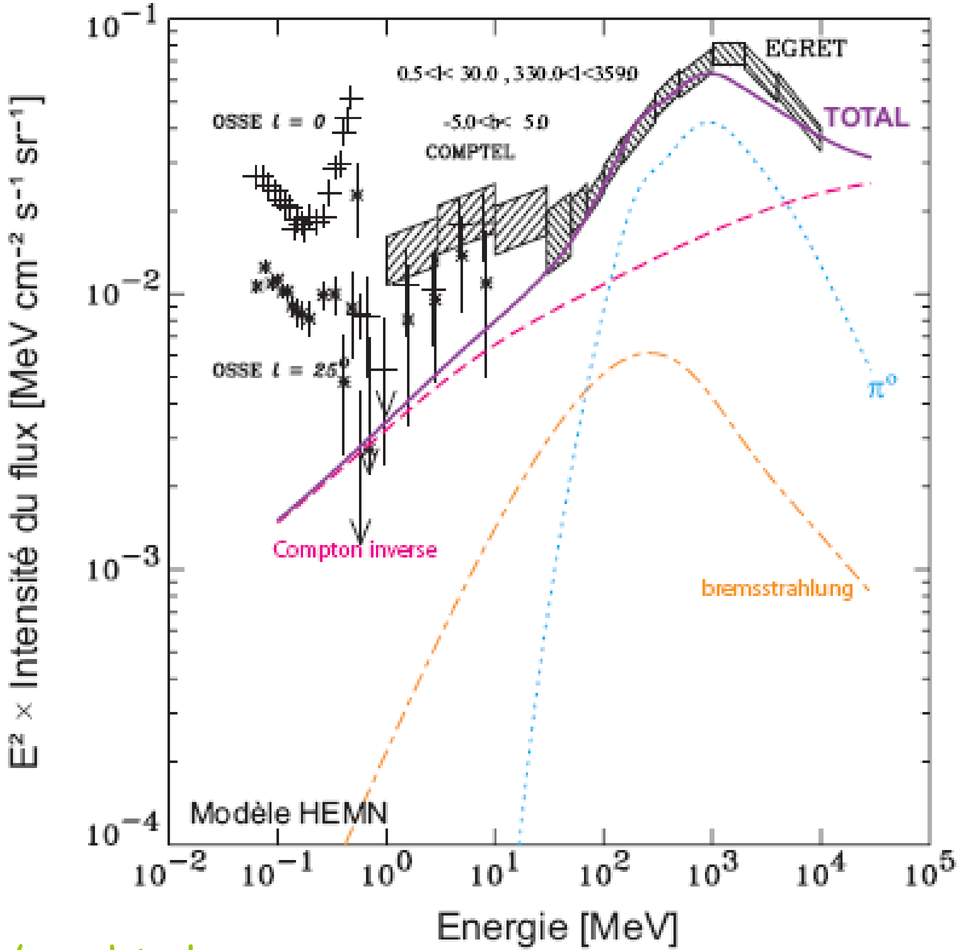






Tracking back the CR flux elsewhere in the Galaxy

- Refined predictions based on detailed simulations (magnetic model of the galaxy, CR diffusion equation, matter density maps…):
  for ex: GALPROP program

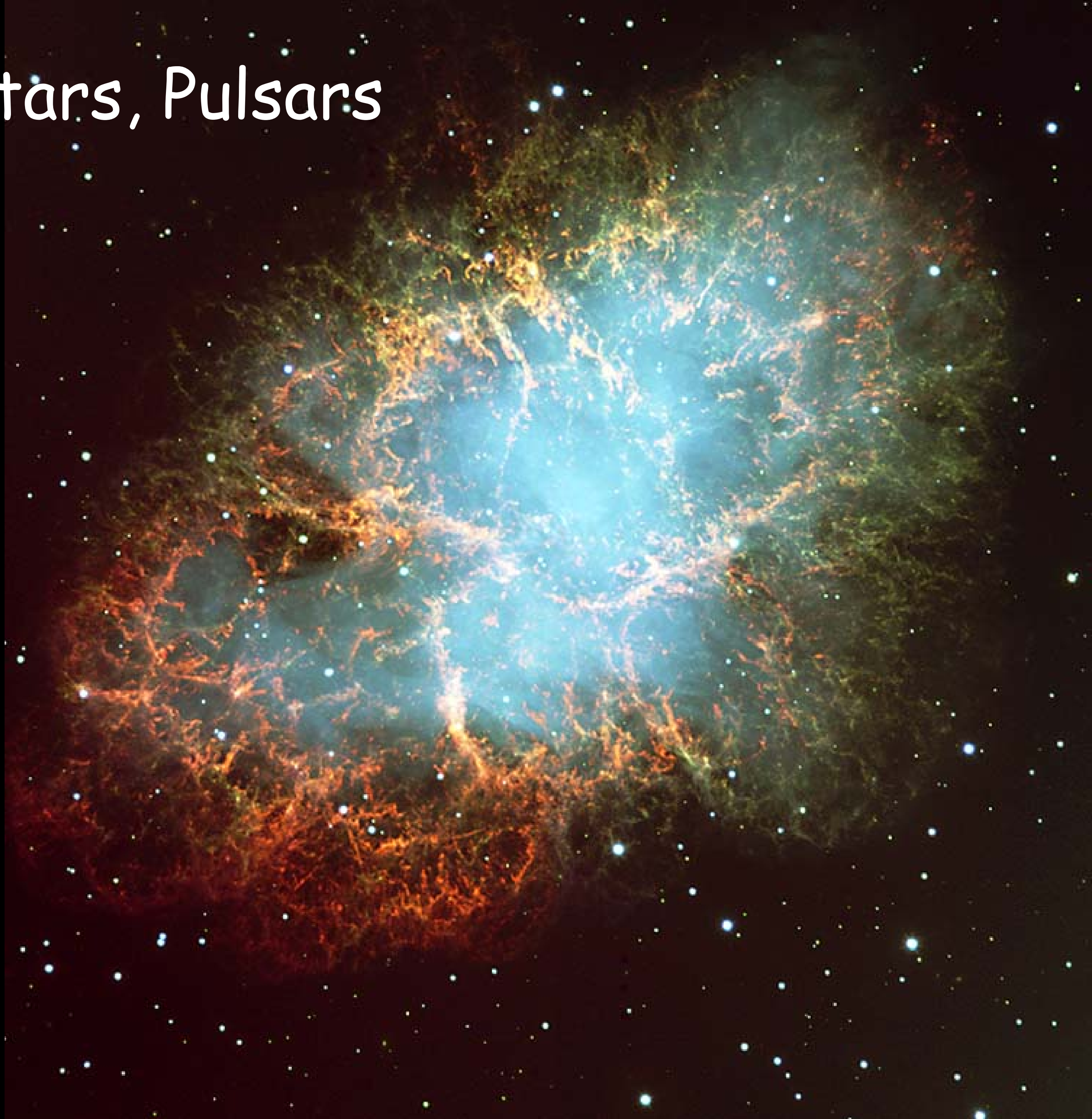


http://www.gamma.mpe-garching.mpg.de/~aws/aws.html

COMPACT OBJECT ENVIRONMENT : NEUTRON STARS AND PULSARS BLACK HOLES

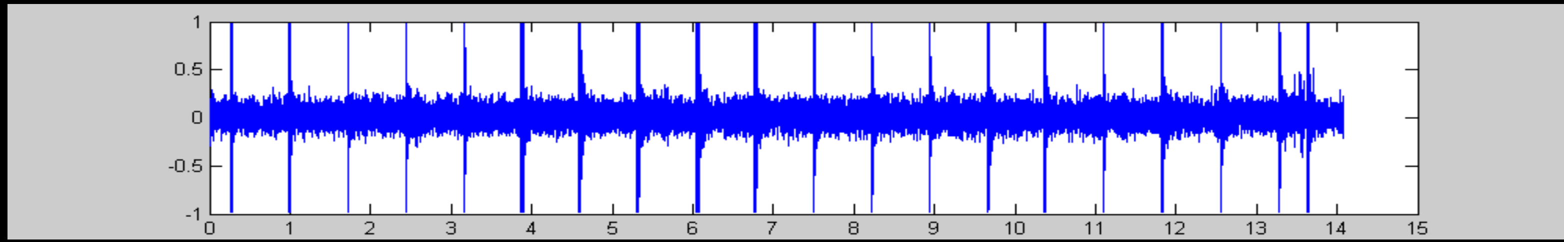
Neutron stars, Pulsars

Journey into the Crab nebula.

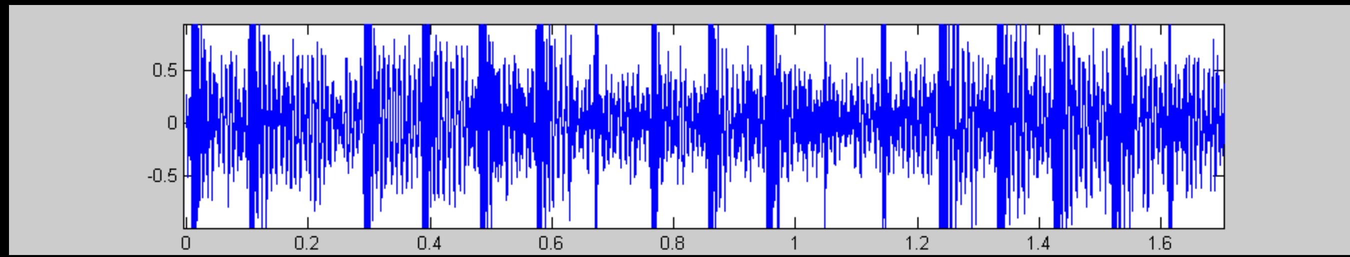


Here is radio pulsar…

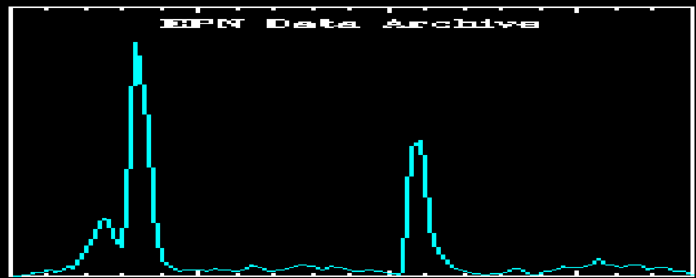
PSR0329+54
~1,40 Hz



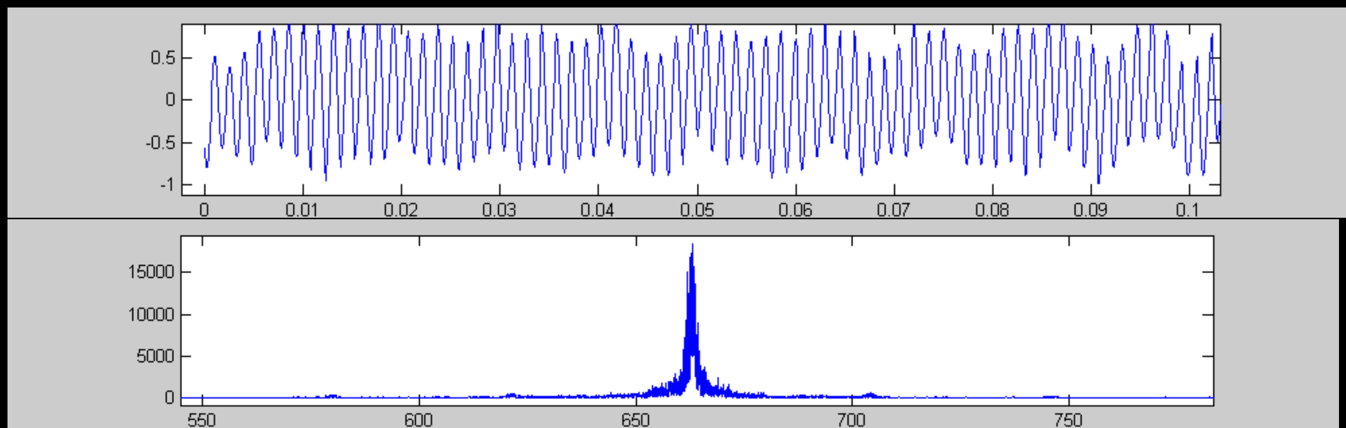
Vela
PSR0833-45
~11Hz



Crabe
PSR0531+21
~30 Hz



PSR1937+21
~641 Hz



Neutron stars

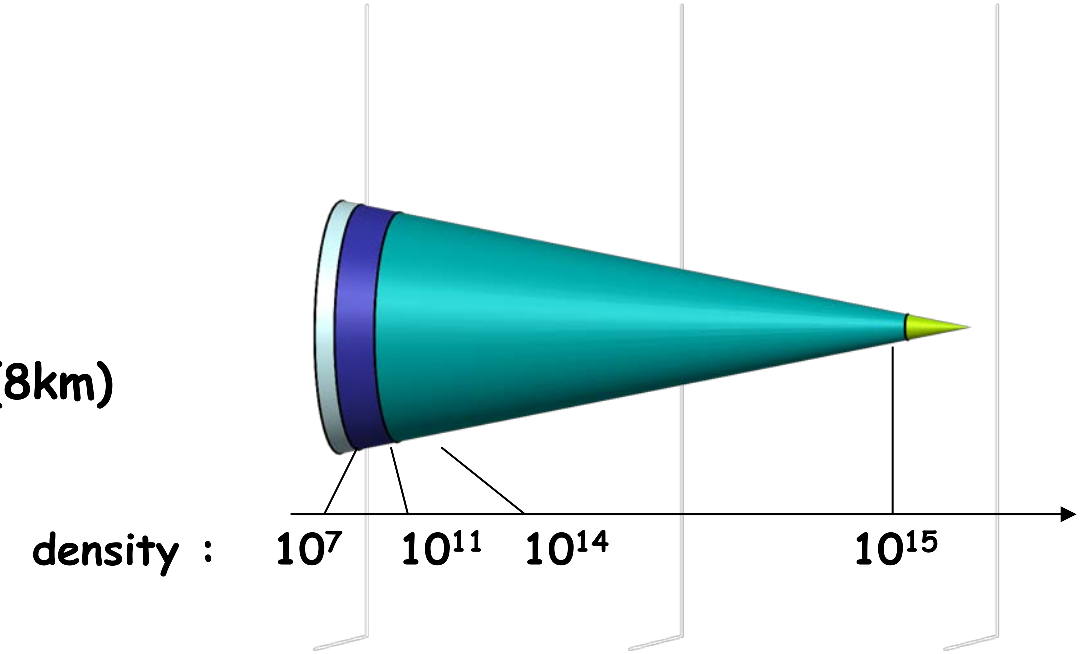
- Ultra compact objects:
  - Density ~ nuclear matter ($10^{13} \times$ water !)
  - sphere ~ 10 km radius
  - gravitation at surface ~ $5\times10^{10} \times$ gravitation on earth
- Density and structure varies with :

Iron core (0,3km)

Neutrons and Nuclei (0,6km)

Neutrons forming an superfluid ocean (8km)

Unknown (1km)



Magnetic field of a neutron star

- Most celestial bodies bear a magnetic field (i.e. the sun: 10^{-3}Tesla)
- A the surface of a neutron star, it is $\approx$ 10 million Tesla
- This value is intrinsically linked to the rapid rotation (conservation of rotation kinetic energy and magnetic energy $\rightarrow$ concentration)
- A kind of giant COSMIC DYNAMO : rotation of $\vec{B} \Rightarrow \vec{E} \Rightarrow 10^{18}V$!!
- The electric force at the surface is $\gg$ gravitationnal force !
  $\rightarrow$ charged particles are expelled and accelerated
  $\Rightarrow 10^{38}\ e^-$ per second radiating synchrotron light.
- The strong anisotropy of the radiation is badly understood but probably due to the intense $\vec{E}$ and $\vec{B}$ fields near the "polar caps".

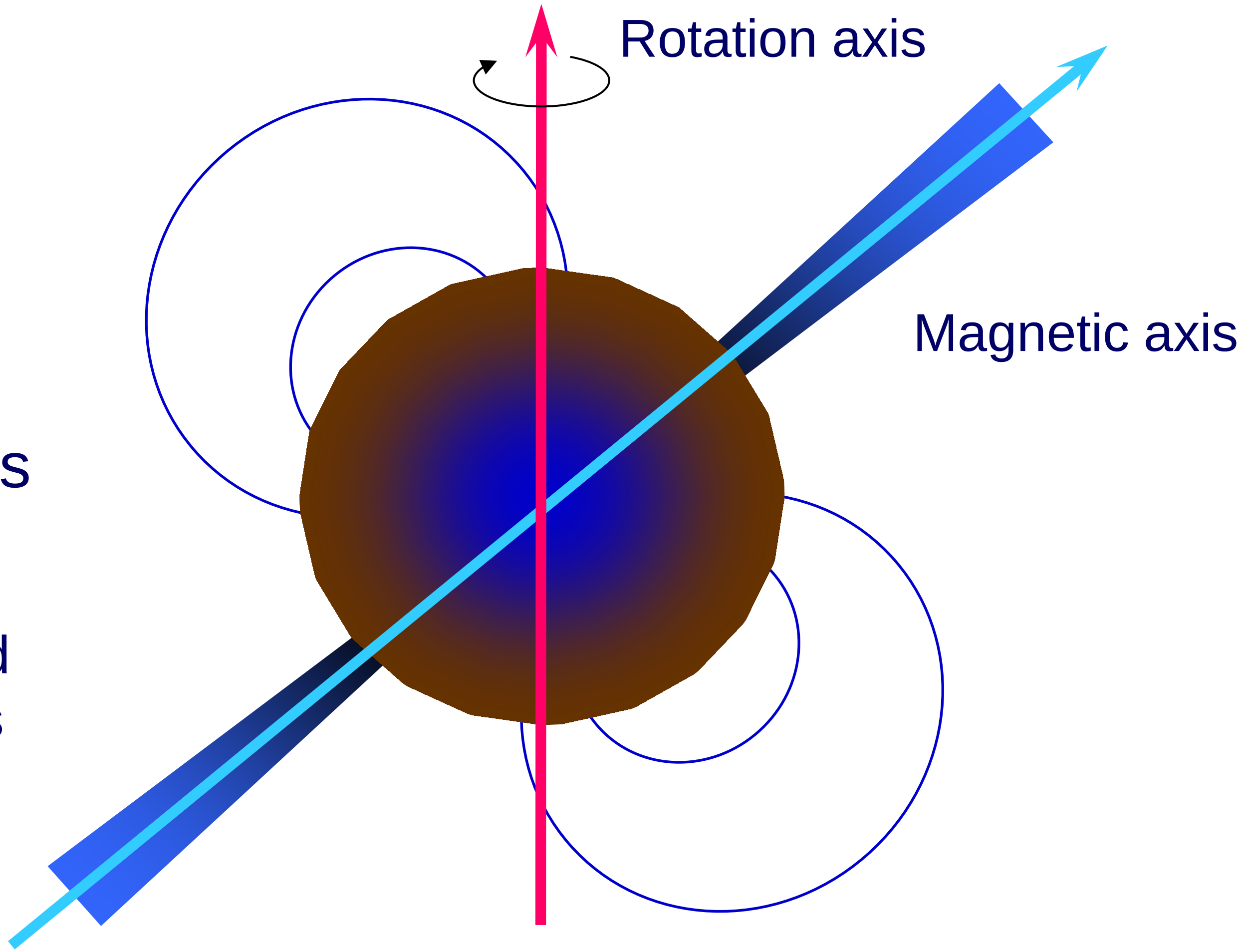
Unipolar Induction

- **Neutron star :**
  a rotating magnet with a magnetosphere

Neutron star

Mass = 1.4 $M_\odot$
Radius = 10 km
Rotation period = 1 s

Radio beam emitted
along magnetic axis

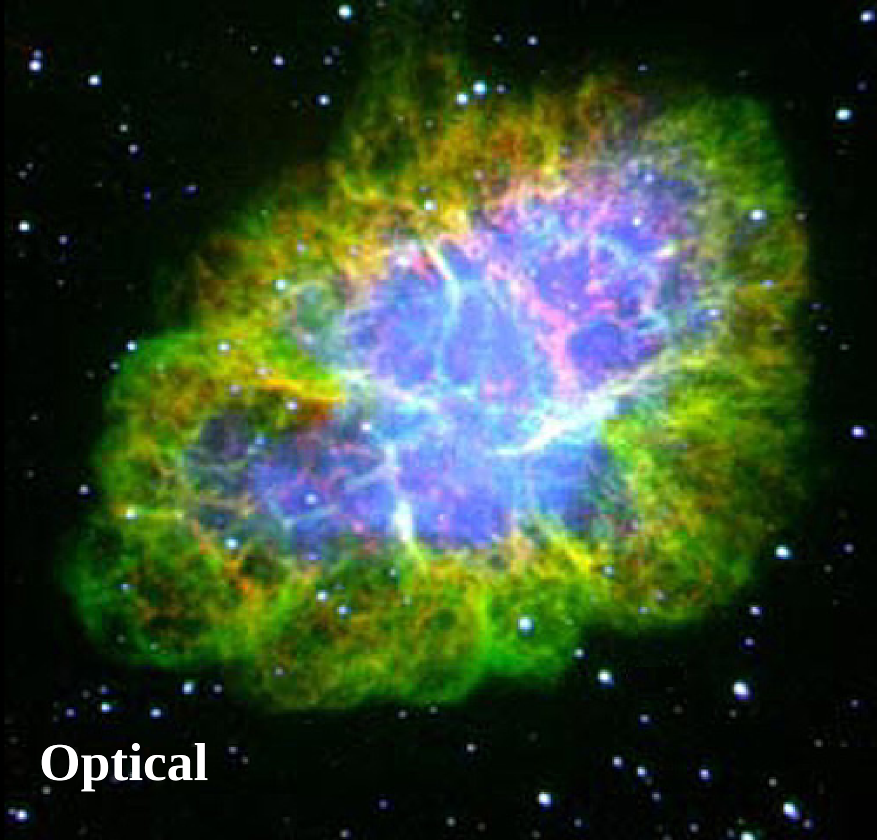


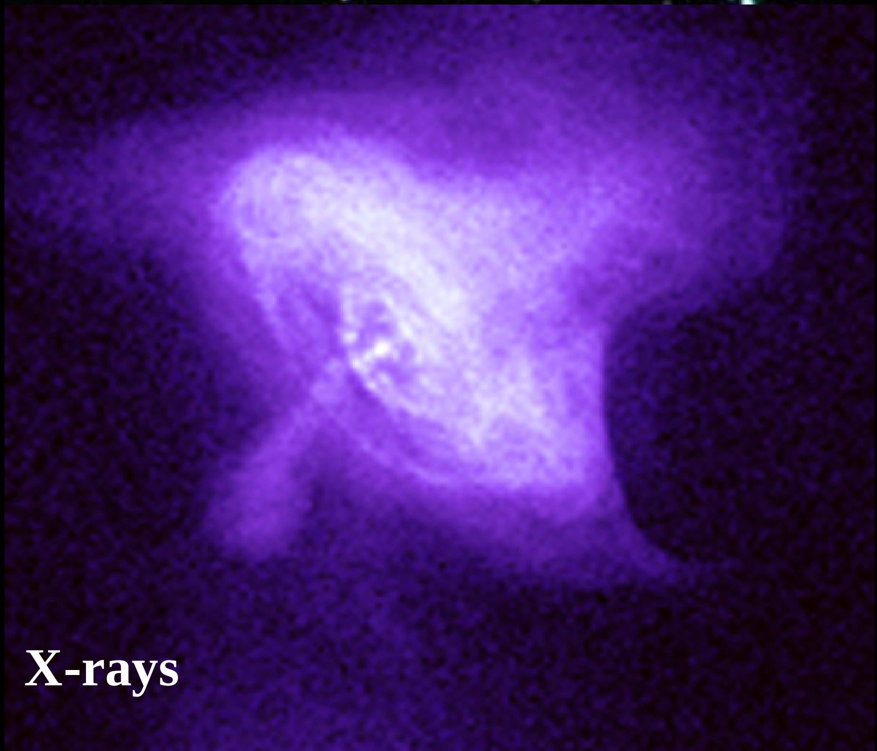
Unipolar induction

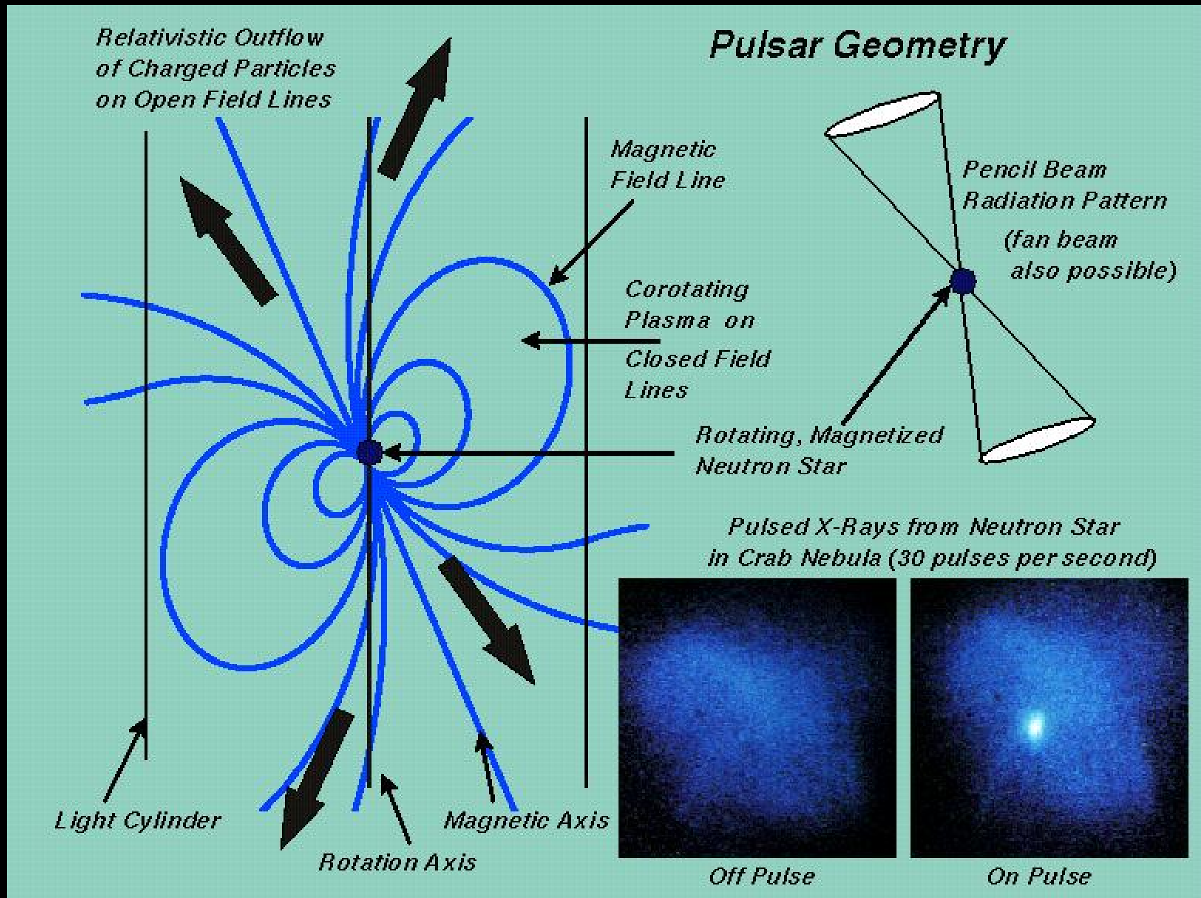
- **Neutron star** :
  a rotating magnet with a magnetosphere

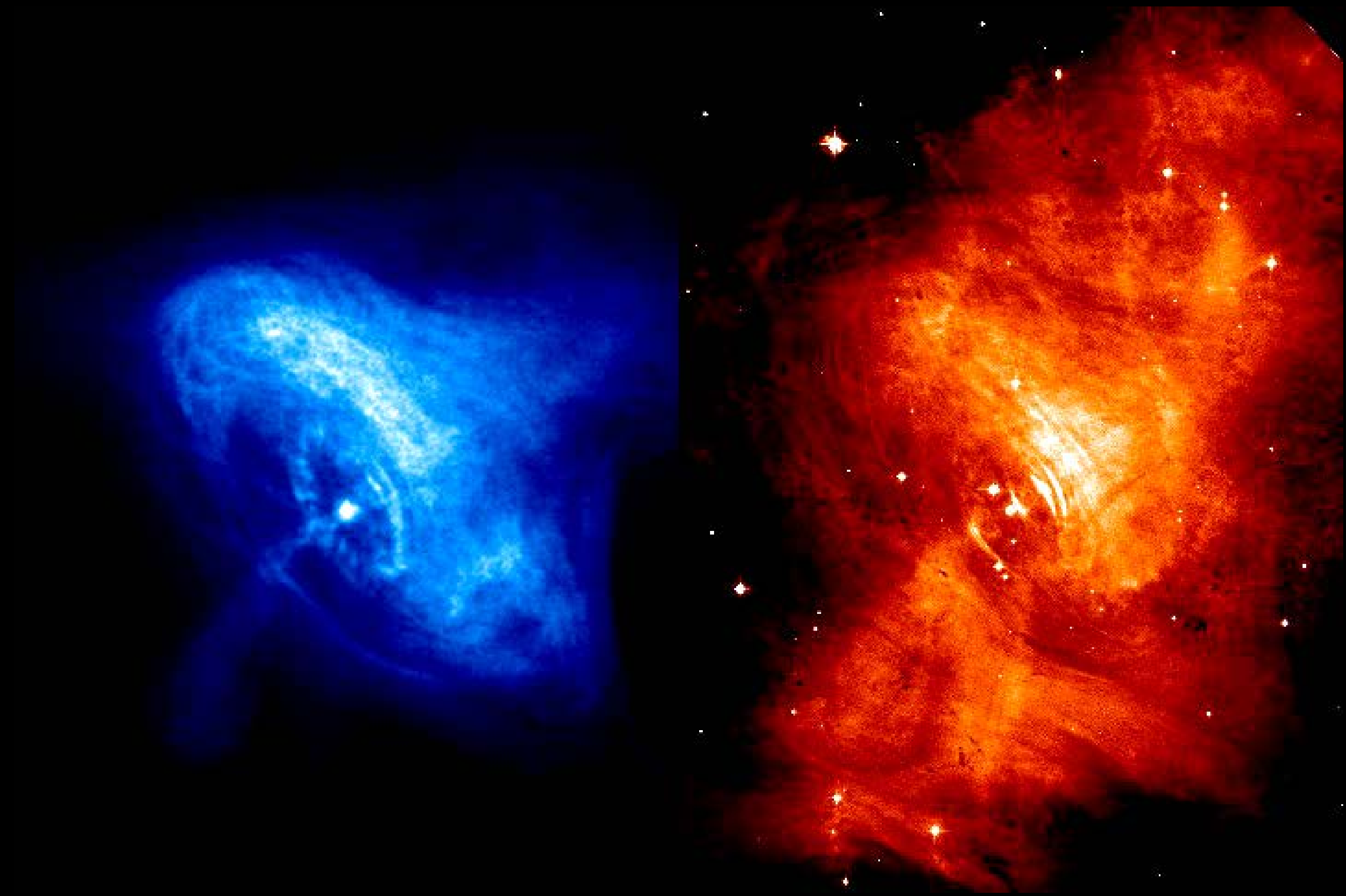
$$\rho_0 = \vec{\nabla}. \left(\frac{\left(\vec{\Omega} \times \vec{r}\right) \times \vec{B}}{4\pi c} \right) = \frac{\vec{\Omega}.\vec{B}}{2\pi c \left(1 - \left|\vec{\Omega} \times \vec{r}/c\right|^2\right)}$$

$$\Delta V \approx \frac{\Omega^2 B_s R^3}{c^2} = 3 \times 10^{16}\ \Omega_2^2\ B_{13}\ R_6^3\ \text{Volts}$$


Optical

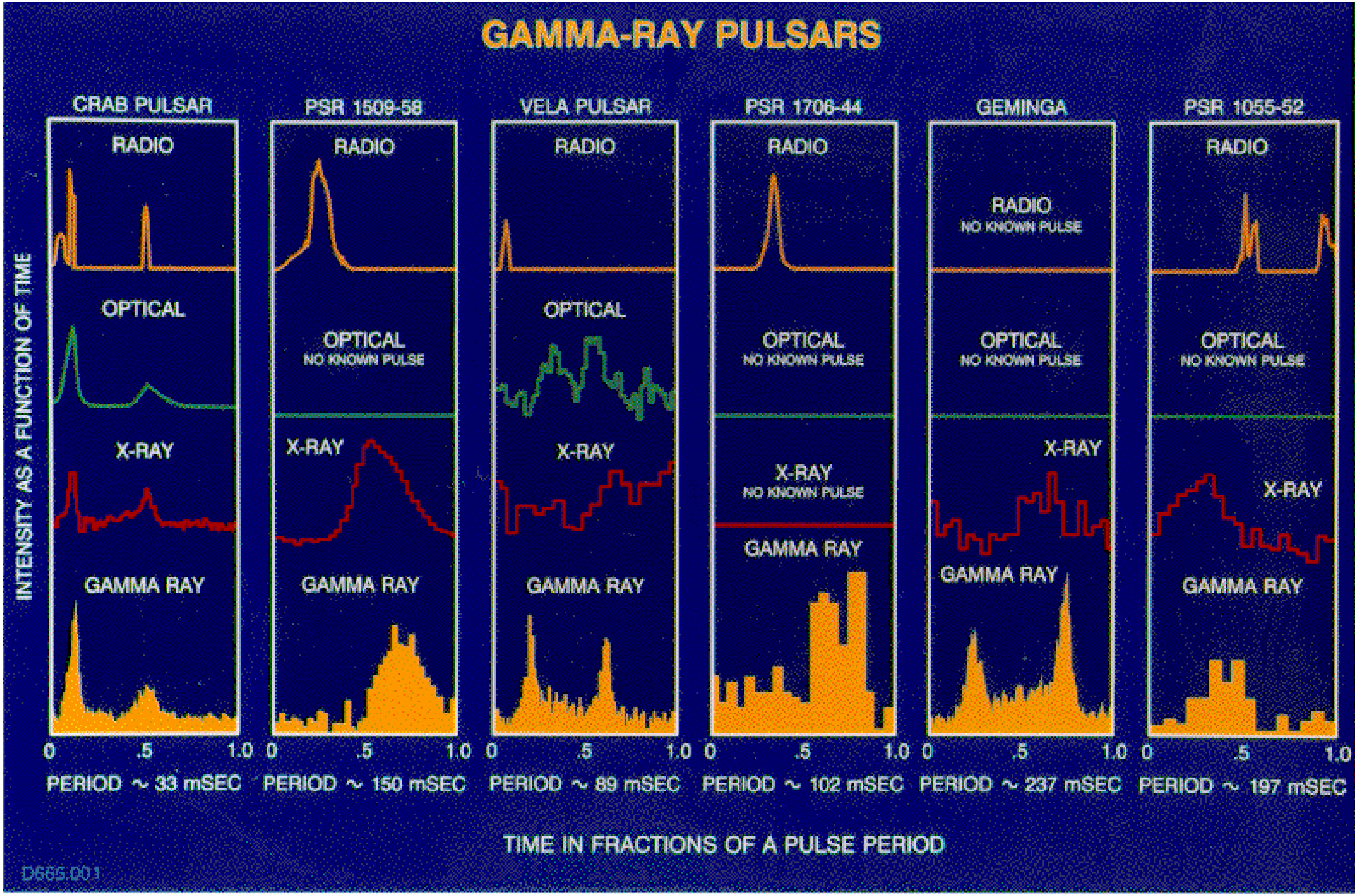

X-rays


Pulsar Geometry
Relativistic Outflow of Charged Particles on Open Field Lines
Magnetic Field Line
Pencil Beam Radiation Pattern
(fan beam also possible)
Corotating Plasma on Closed Field Lines
Rotating, Magnetized Neutron Star
Pulsed X-Rays from Neutron Star in Crab Nebula (30 pulses per second)
Light Cylinder
Rotation Axis
Magnetic Axis
Off Pulse
On Pulse



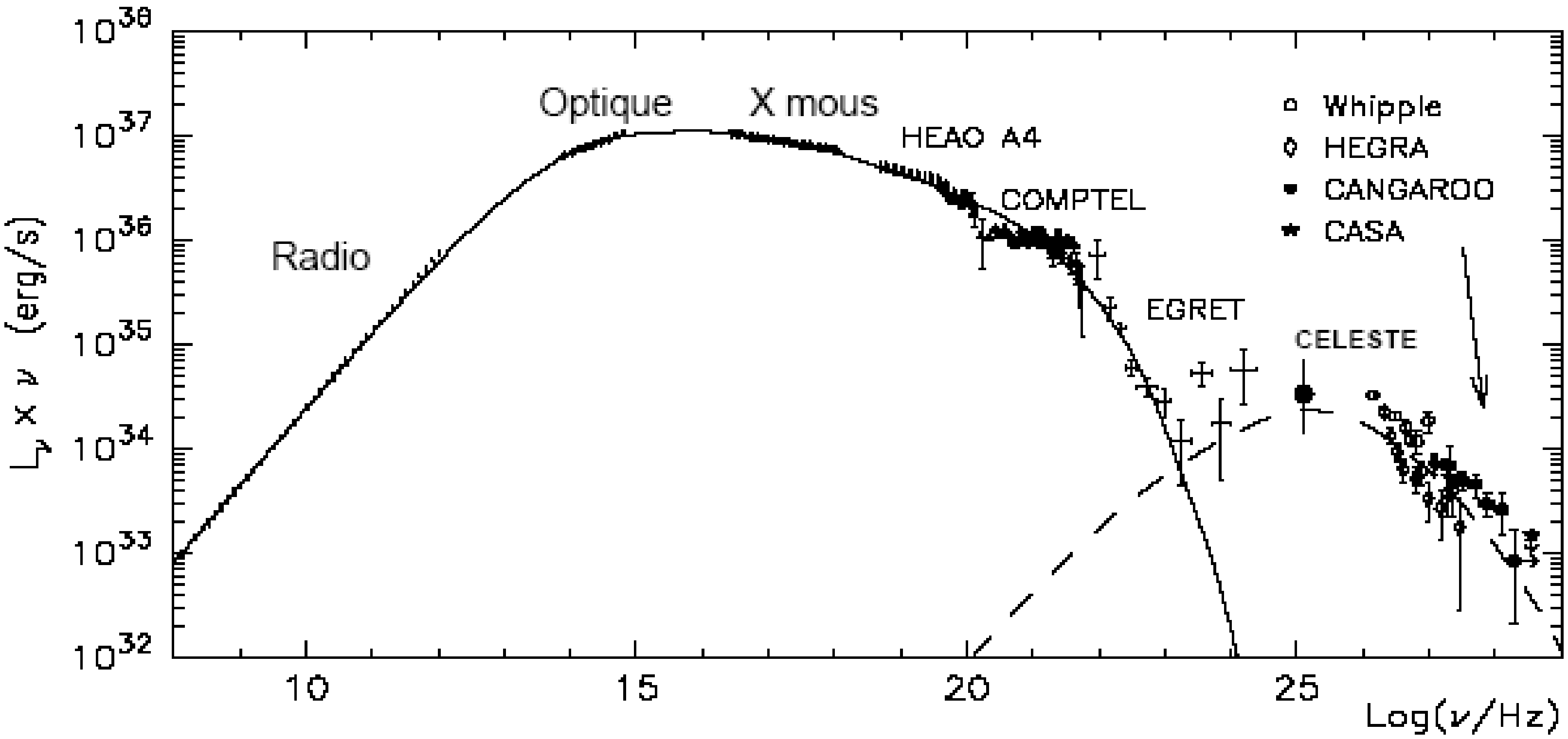
The Crab X-source, the central engine, X (Chandra) et optical (HST)

7 images from november 2000 to april 2001, showing the time and space coincidence between the shocks observed at the very center of the system (close to the pulsar) and the X-ray radiation produced by the accelerated VHE electrons


GAMMA-RAY PULSARS
CRAB PULSAR
PSR 1509-58
VELA PULSAR
PSR 1706-44
GEMINGA
PSR 1055-52
RADIO
RADIO NO KNOWN PULSE
OPTICAL
OPTICAL NO KNOWN PULSE
X-RAY
X-RAY NO KNOWN PULSE
GAMMA RAY
INTENSITY AS A FUNCTION OF TIME
0 .5 1.0
PERIOD ~ 33 mSEC
PERIOD ~ 150 mSEC
PERIOD ~ 89 mSEC
PERIOD ~ 102 mSEC
PERIOD ~ 237 mSEC
PERIOD ~ 197 mSEC
TIME IN FRACTIONS OF A PULSE PERIOD
D665.001

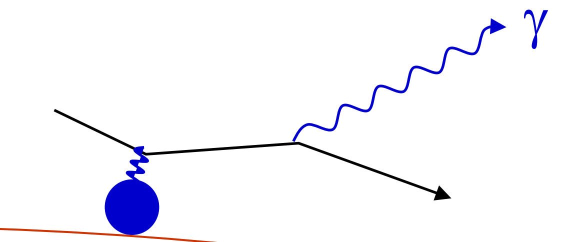
The Crab Nebula
a case study for VHE gamma-rays VHE

- Steady emission observed at all wavelengths.
- First point like γ source identified
- Intense flux: a "standard candle" for γ-ray observatories

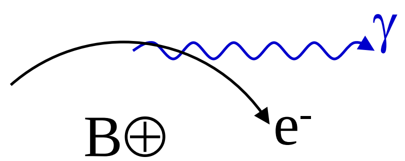


VHE photons sources

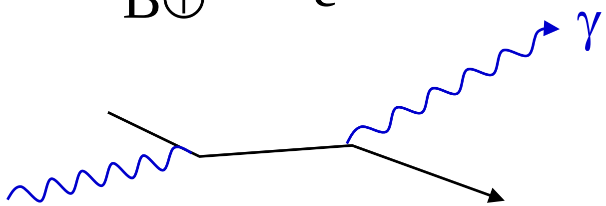
- γ-ray production:
  - Electro-magnetic processes :
    - Bremsstrahlung



    - Synchrotron radiation



    - Inverse Compton scattering



  - Hadronic processes :

$$(p, N) + (N\gamma) \rightarrow \pi_0 + \ldots$$
$$\hookrightarrow \gamma\gamma$$

The Crab Nebula
a case study for VHE gamma-rays VHE

- TeV emission is based on Inverse Compton scattering

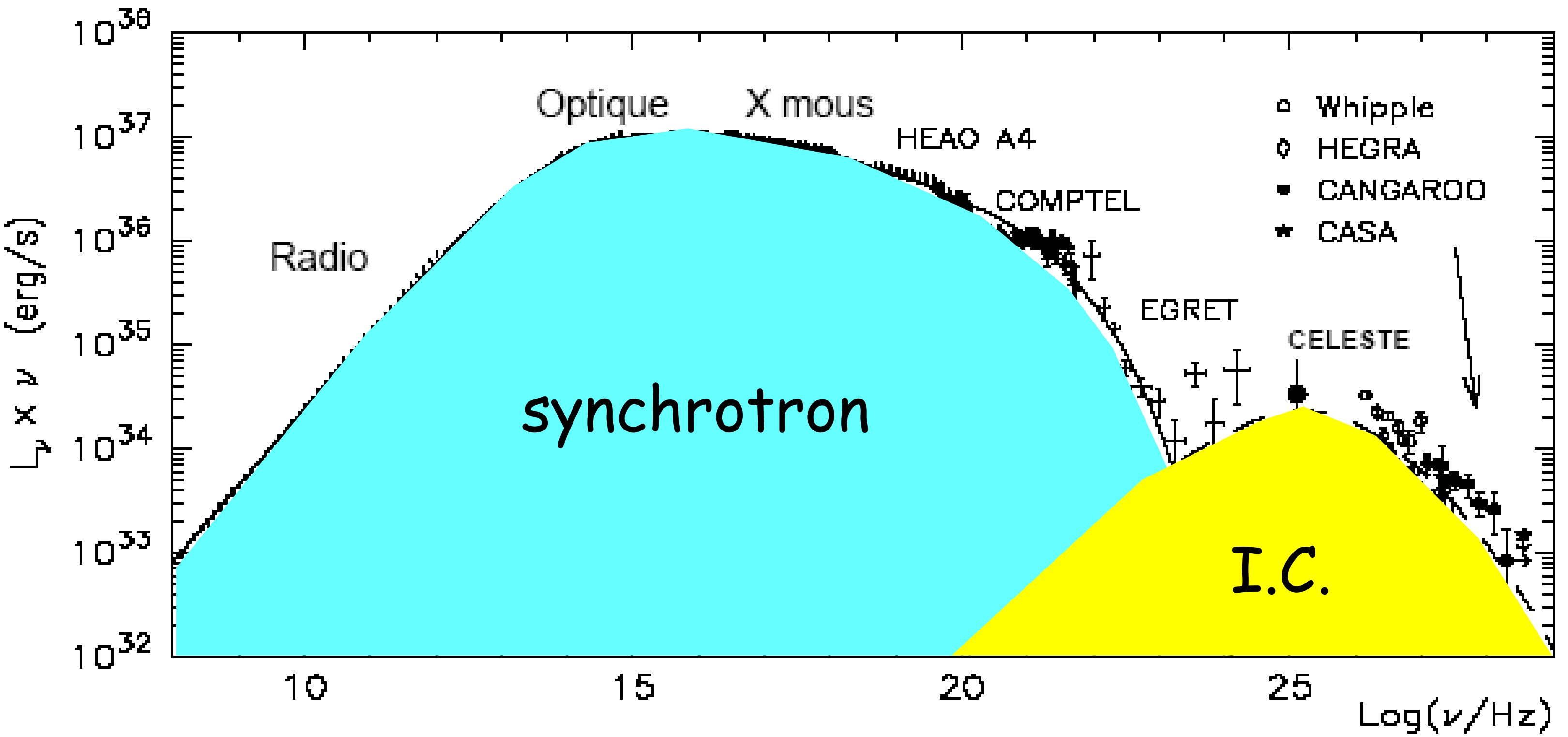
- The e^- producing synchrotron radiation can interact with these synchrotron photons.

- If $\lambda_{\text{target photon}} \ll \lambda_{\text{compton}} = \frac{h}{m_e c}$ it is possible to transfer most of the incident e^- energy to the photon.
  ex: A $10^{13} eV$ e^- can boost an I.R. photon I.R. into a VHE gamma-ray.

- These "Self Synchrotron Compton" models reproduce both GeV and TeV spectra.

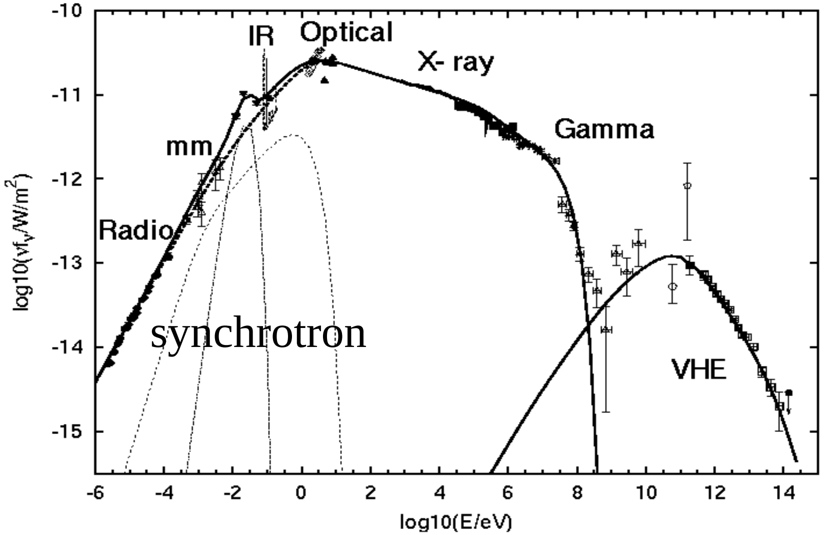
The Crab Nebula
a case study for VHE gamma-rays

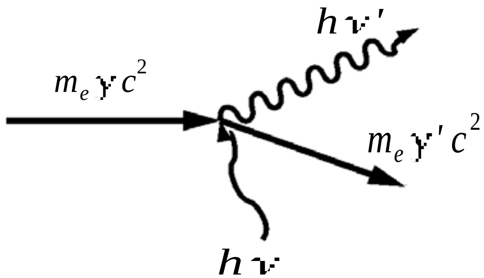
Model SSC : Synchroton Self Compton



PWN emission mechanisms: the Crab Nebula

- Assume leptonic model: synchrotron and Inverse Compton emission
- Relativistic electrons and positrons created and accelerated by the pulsar

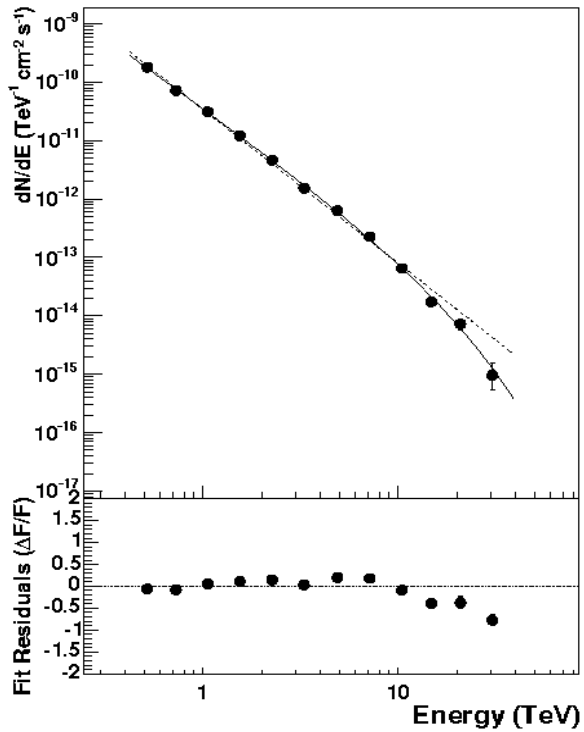




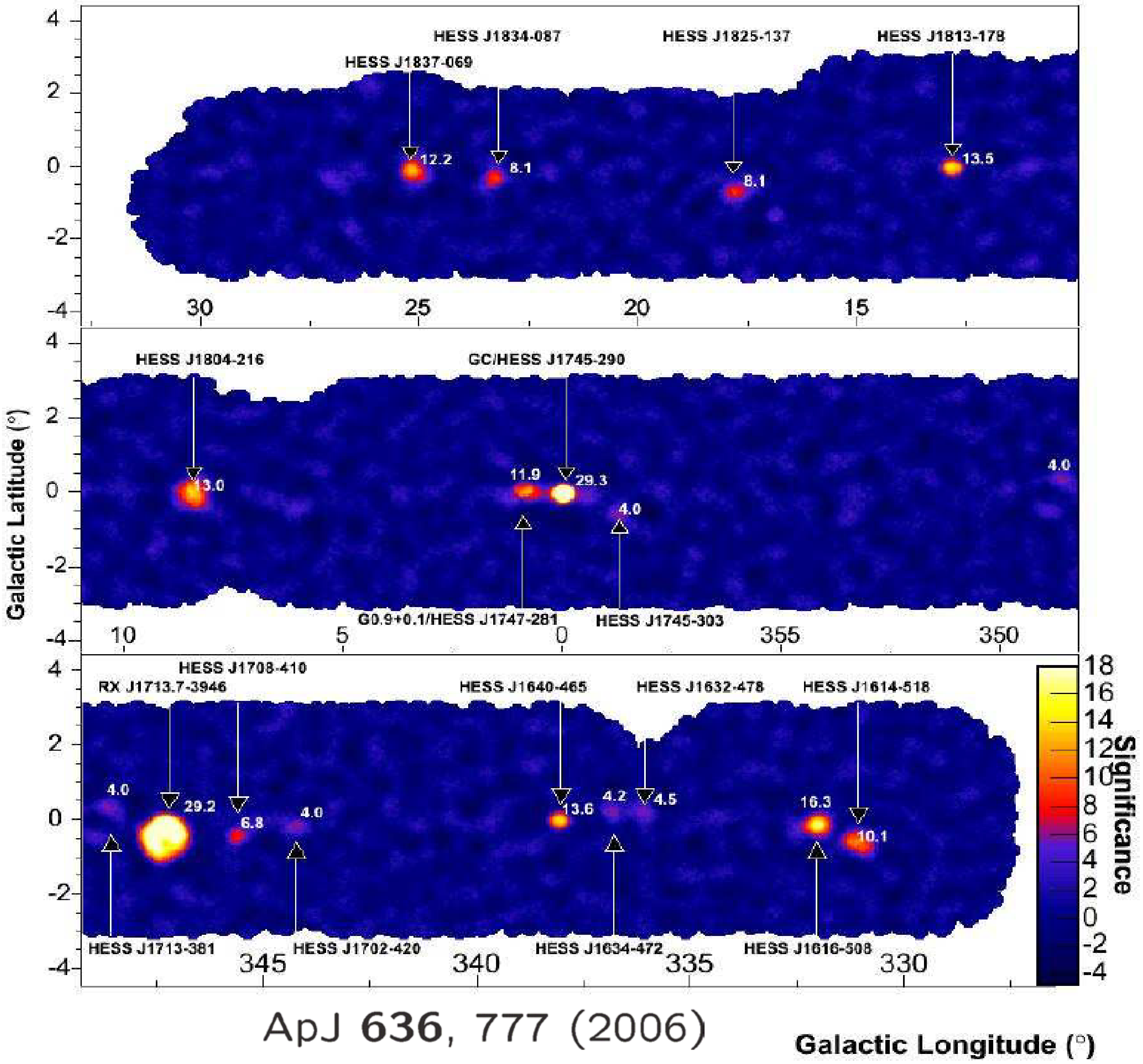
Target photons : CMB, interstellar IR, stellar photons, synchrotron (SSC)…

Radio, optical, X-rays

H.E.S.S. spectrum (*A&A* 2006 in press, astro-ph/0607333): Spectral curvature, Consistent with IC expectations



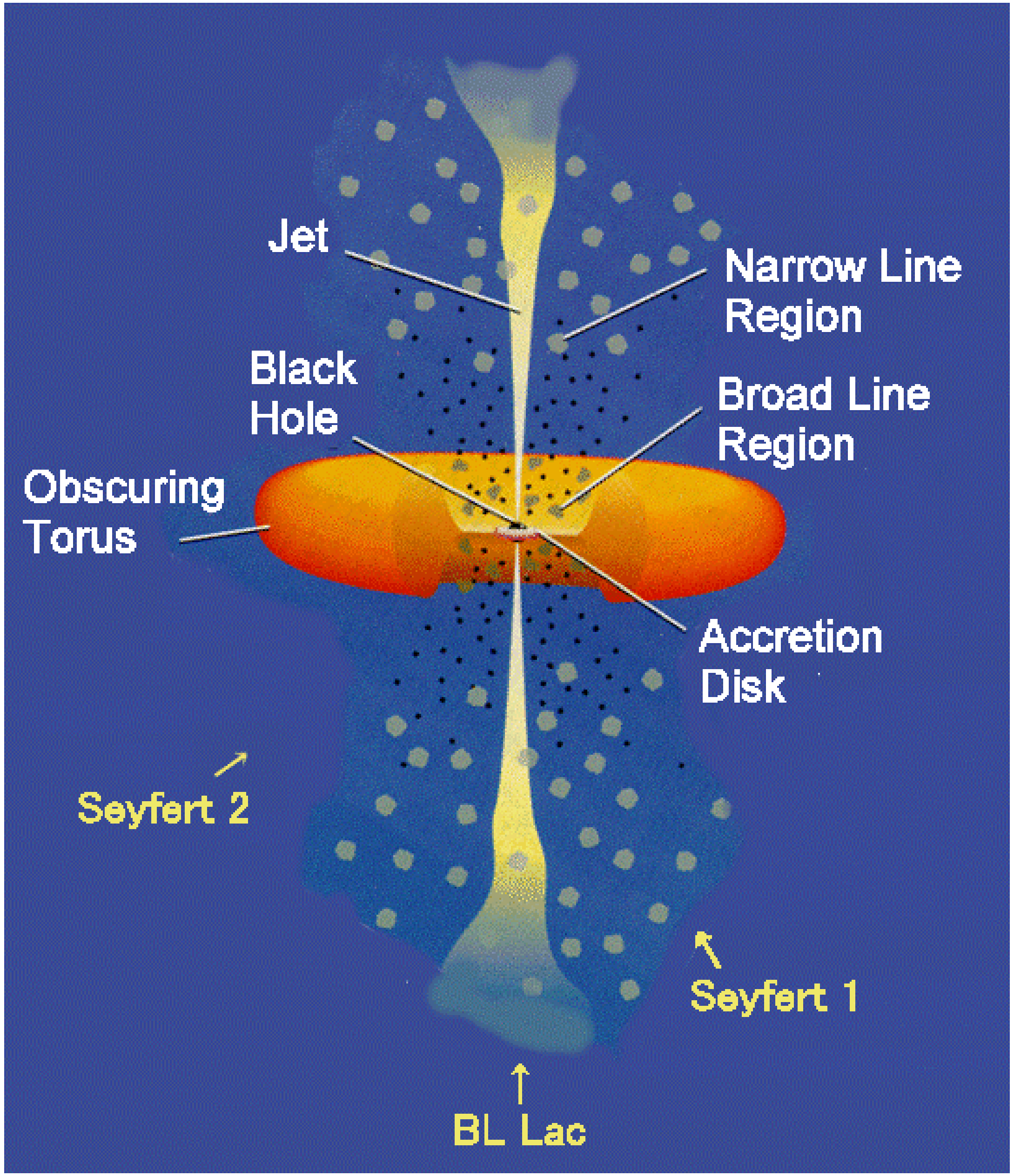
Many recently discovered sources in the Galactic plan by HESS, MAGIC and VERITAS large angle surveys



ApJ **636**, 777 (2006)

THE ENVIRONMENT OF SUPERMASSIVE BLACK HOLES: ACTIVE GALATIC NUCLEI

AGN: a unified scheme



Active Galactic Nuclei

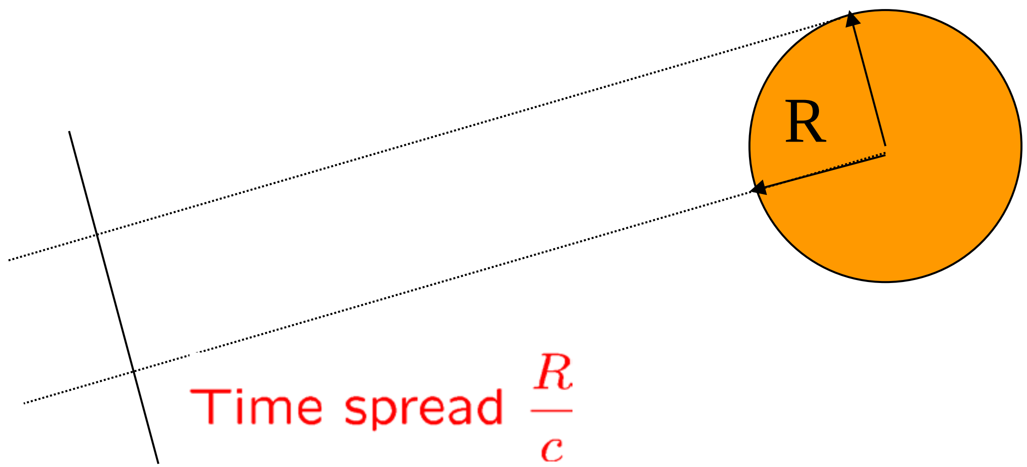
- Galaxies with an important activity of its nucleus
- Numerous classes of objects:
  - Radio-galaxies
  - Radio-quasars
  - BL Lac objects
  - Violently Variables objects (VVO)
  - Radio Quiet Quasars
  - Seyfert Galaxies of type 1
  - Seyfert Galaxies of type 2
  - Low Ionization Nuclear Emission-Line Regions (LINERs)
  - Nuclear HII Regions
  - "Star Burst" Galaxies
- Arbitrary categories et badly mal defined.

What is an AGN

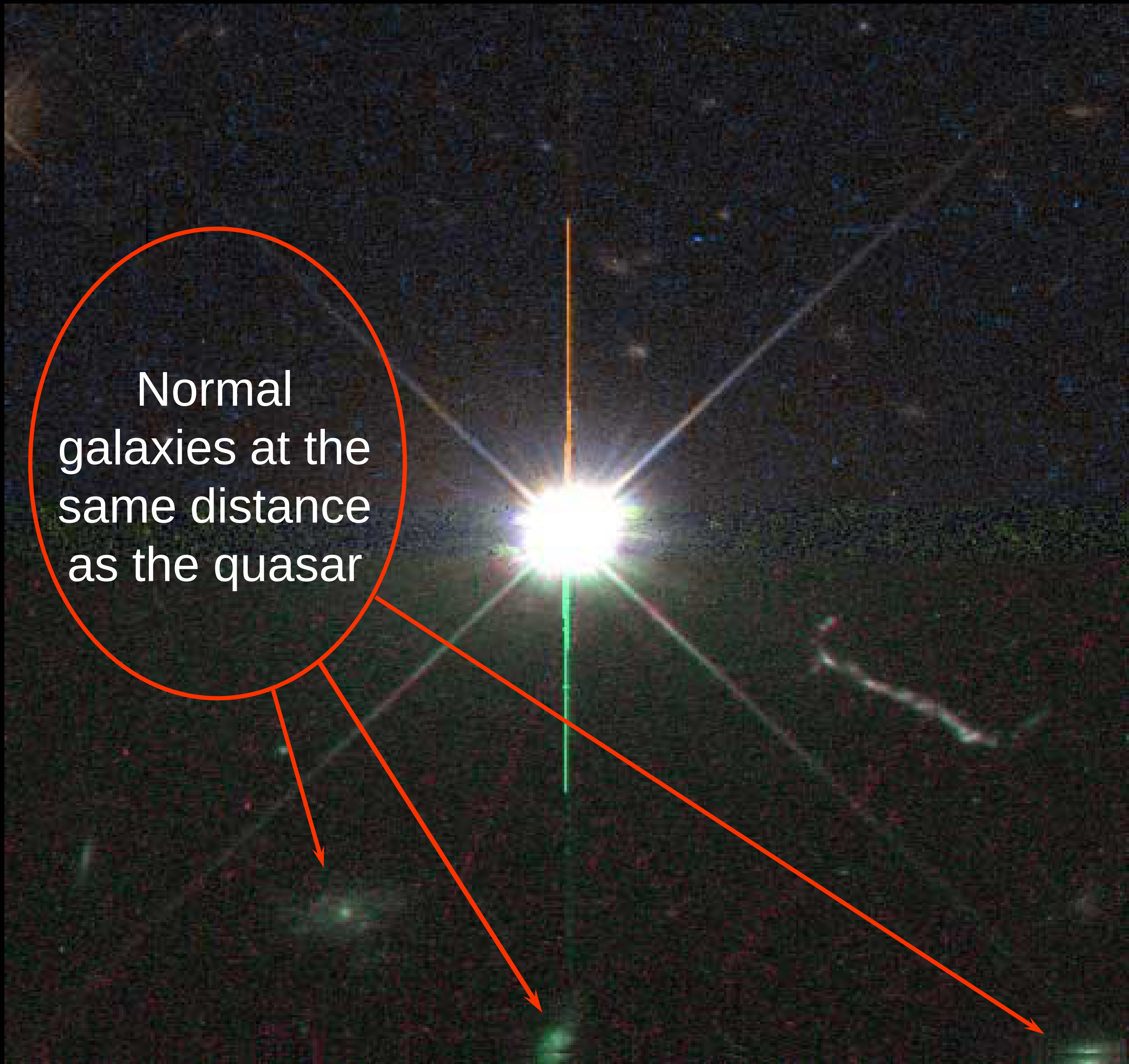
- Elementary AGN model:

  Discovered in the early 60ties when trying to identify the sources in the 3rd Cambridge Catalogue.

  - Superluminous objects
    - Spectral redshift → cosmological distances
    - For 3C273 → P ≈ 10^{40} Watts ≈ 10000 the Milky Way ≈ 1000 SN/year
  - Very small objects
    - Variability criteria → d ≈ solar system size !!



The Quasar 3C 273



In 1963, 3C 273, the first quasar, was discovered. They can be up to 1000 more luminous than the massive host galaxy. The emission originates in the active nucleus of the galaxy.

What is an AGN

- Elementary AGN model:

  Discovered in the early 60ties when trying to identify the sources in the 3rd Cambridge Catalogue.

  - Objects from the past
    - The most distance quasars observed ($z \approx 5$) are at distances of the order of the radius of the observable universe!
    - No such objects in our close environment $\rightarrow$ must be linked to a phase of the galaxy evolution.

What is an AGN

- Necessarily a gravitational engine

Thermonuclear falls short by a factor 10 to 100 !

Form of energy release	Efficiency of energy production (wrt mc^2)
• Chemical energy	10^{-9}
• Nuclear energy	10^{-2}
• Accretion of mass onto non-rotating black holes	6×10^{-2}
• Accretion onto maximally rotating Kerr black holes	0.42
• Rotational energy of maximally rotating Kerr black holes	0.29

What is an AGN

- Necessarily a gravitational engine

$$E_{tot} = 0 \Rightarrow E_{cin} = \frac{GmM}{R} \Rightarrow \text{R must be small}$$

Huge mass, small volume $\Rightarrow$ BLACK HOLE !!!

$$\text{With } R_S = \frac{2GM}{c^2} \Rightarrow E_{rad.max} \approx \frac{GM}{R_S}\frac{R_S}{R}m = \frac{1}{2}\frac{R_S}{R}mc^2$$

Accounting for relativistic corrections and ergosphere rotation
$\rightarrow$ conversion efficiency $m \rightarrow E$ few 10%

What is an AGN

- Necessarily a gravitational engine

One gets 10^{40} Watts with $15 M_\odot$/year.
Over 10^8 years (age measured from radio lobes) $\Rightarrow 10^9 M_\odot$
$\Rightarrow R_S \approx 10^{13} m$ compatible with variability.

More over, one is below Eddington luminosity
(radiation pressure = gravitational forces)

$$\left(L \approx \frac{4\pi c}{\sigma_T} G M m_H\right) \text{ from } \left(\frac{\sigma_T L}{4\pi R^2} = \frac{G M m_H}{R^2}\right)$$

$\Rightarrow$ PLAUSIBLE.

What is an AGN

- Accretion of matter:
  - In absence of angular momentum:
    $\vec{v}_\infty$ directed toward the BH: $\frac{GMm_H}{R} = kT$
    $\Rightarrow$ almost all is radiated in X or γ rays
    INCOMPATIBLE with MEASUREMENTS
  - With angular momentum:
    Intense radiation in the UV : OBSERVED

    $\Rightarrow$ Anisotropic Accretion
    in the shape of an ACCRETION DISK

What is an AGN

- **Jets:**

  Relativistic particles constituting the jets are accelerated when reflecting on the bondaries of a magnetic "tunnel" induced by the rotating plasmas near the BH.

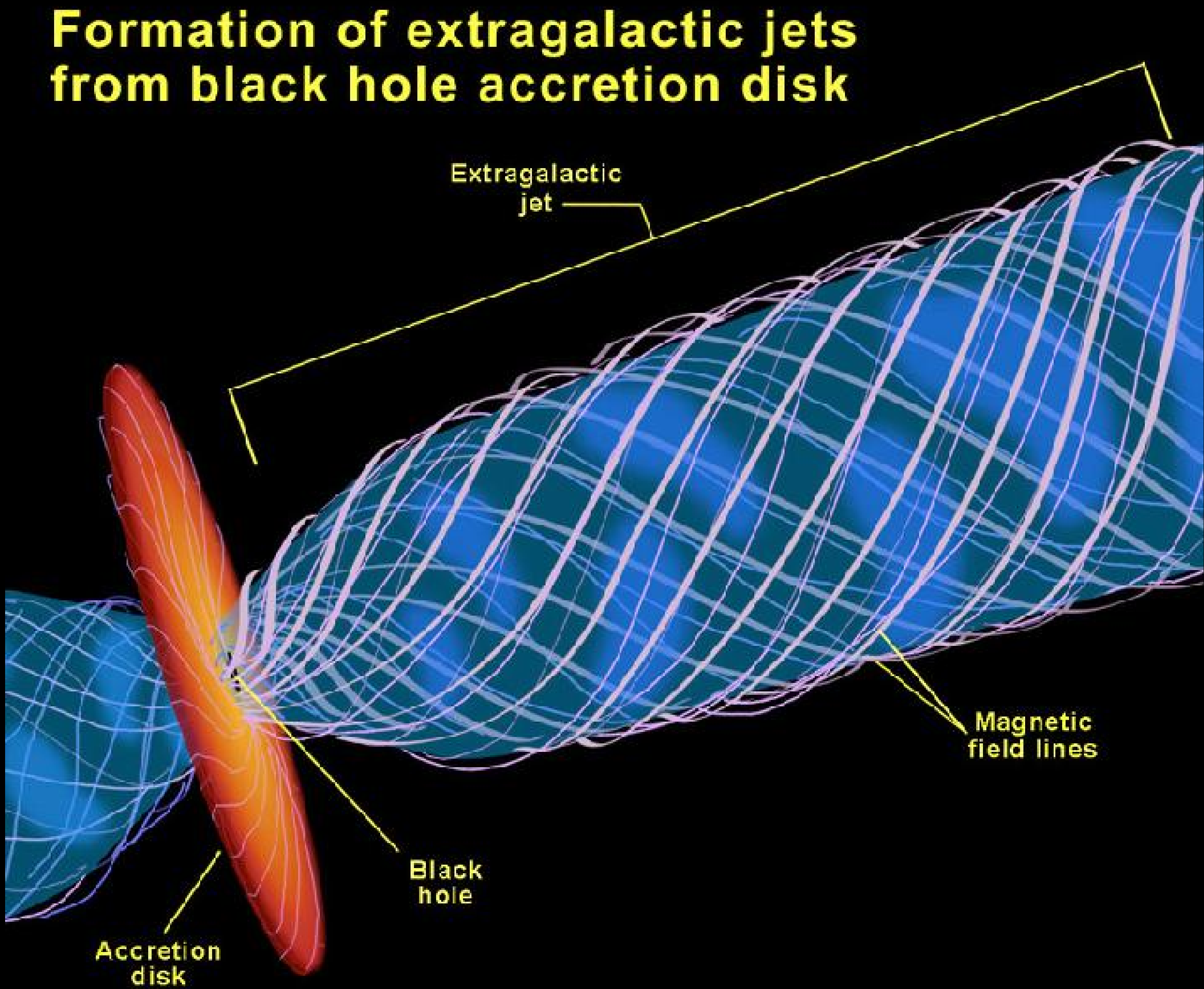
- **Hot spots**

Terminal shocks (jet-IGM): large size moderate field regions $\Rightarrow$ plausible place for UHECR production.

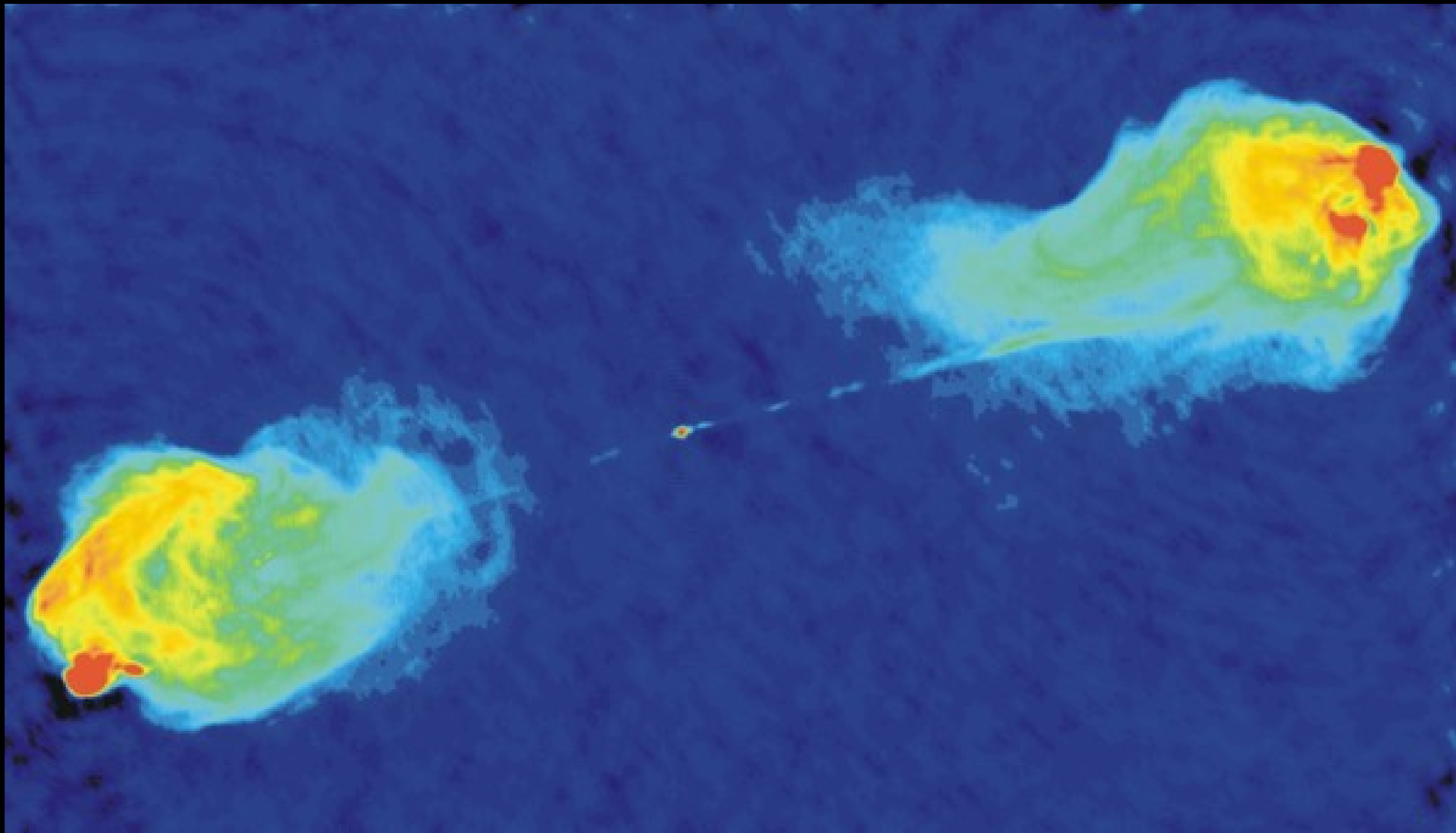
$\rightarrow$ explains many observed phenomena with both leptonic and hadronic models.

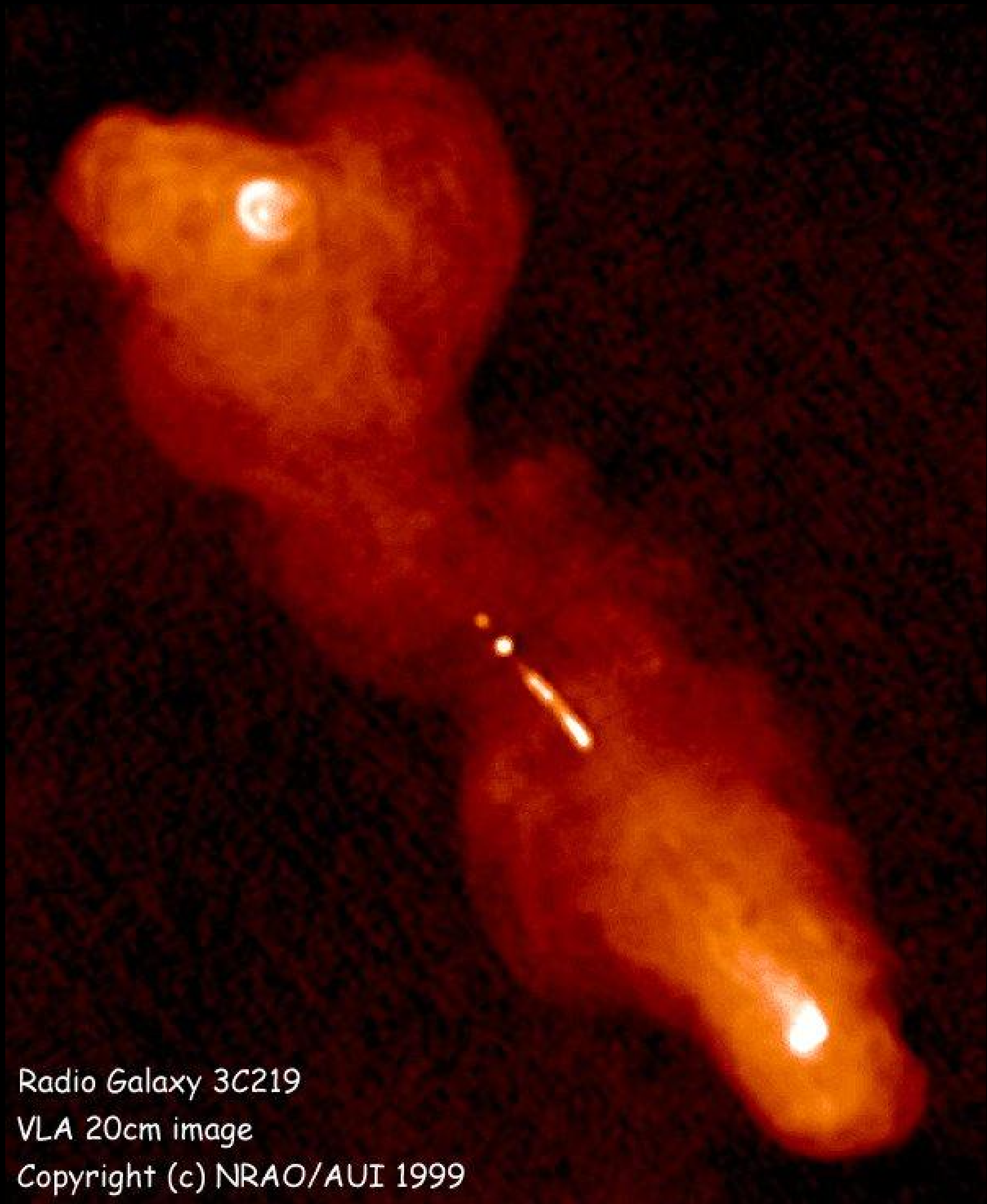
What is an AGN

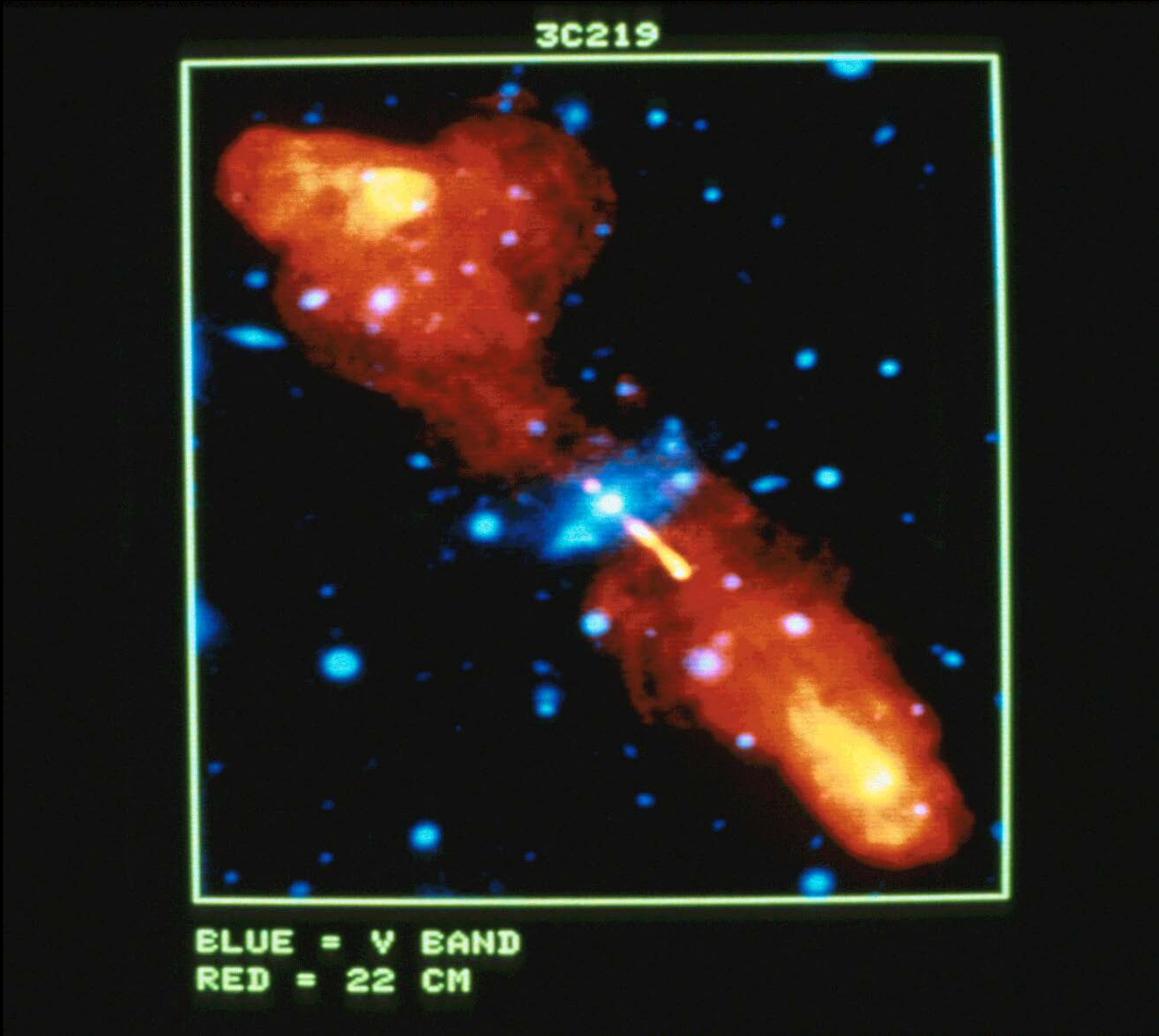
- Jets :

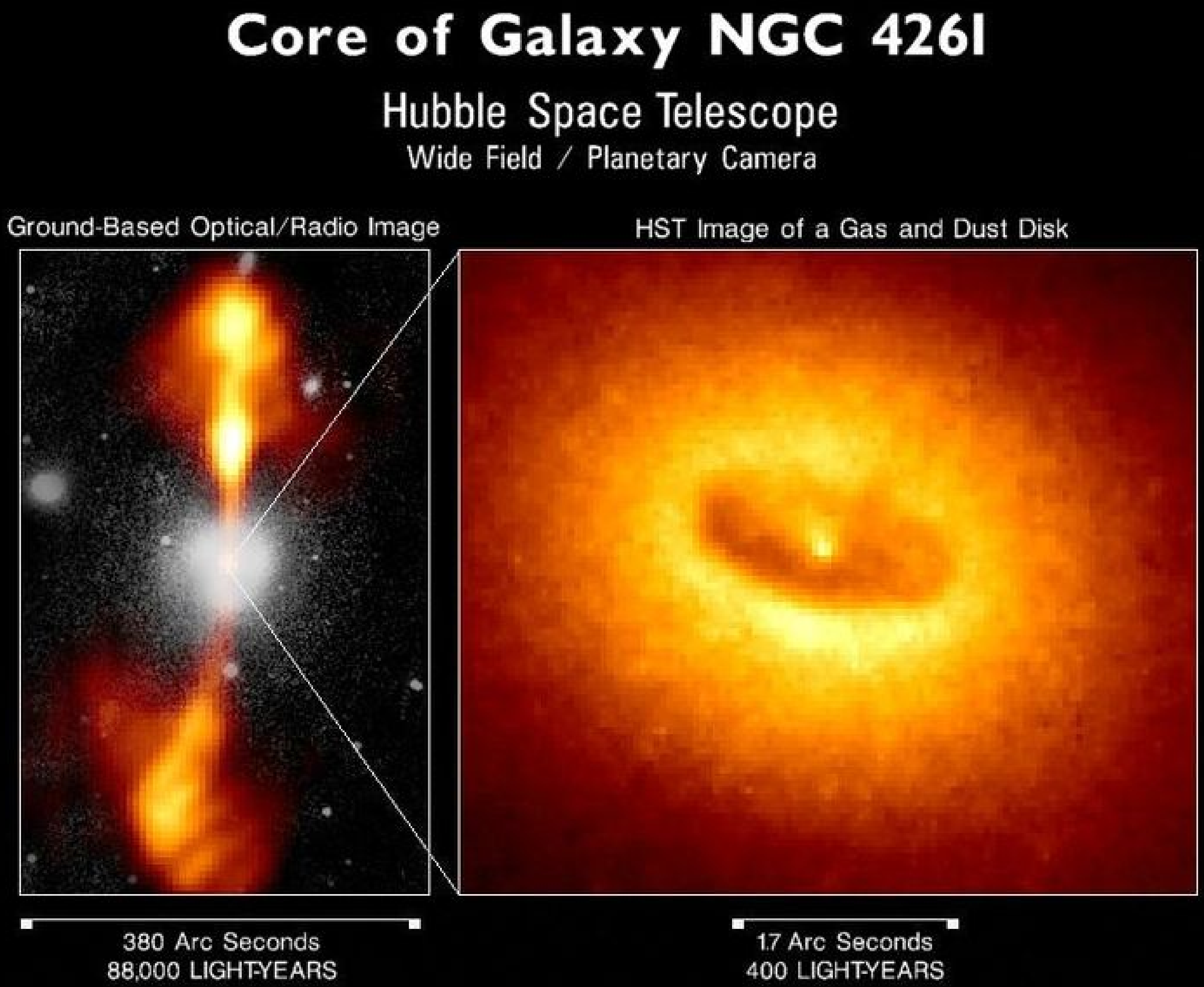


Cygnus A

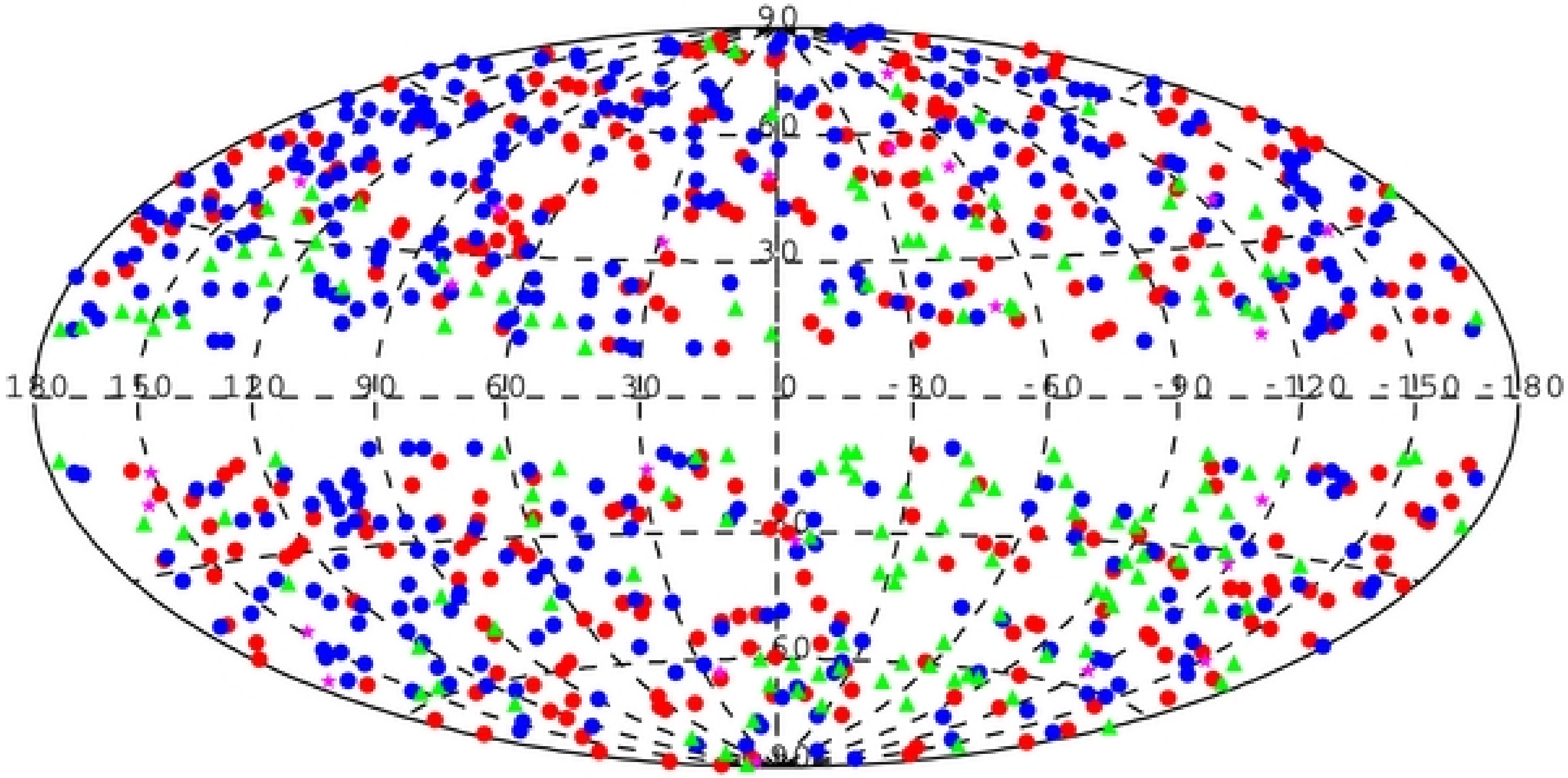



Radio Galaxy 3C219
VLA 20cm image
Copyright (c) NRAO/AUI 1999


3C219
BLUE = V BAND
RED = 22 CM


Core of Galaxy NGC 4261
Hubble Space Telescope
Wide Field / Planetary Camera
Ground-Based Optical/Radio Image
HST Image of a Gas and Dust Disk
380 Arc Seconds
88,000 LIGHT-YEARS
1.7 Arc Seconds
400 LIGHT-YEARS

FERMI 2nd LAC catalogue



886 AGN with a clear GeV gamma-ray signal, identified with comprising 395 BL Lacertae objects (BL Lac objects), 310 flat-spectrum radio quasars (FSRQs), 157 candidate blazars of unknown type (i.e., with broadband blazar characteristics but with no optical spectral measurement yet), 8 misaligned AGNs, 4 narrow-line Seyfert 1 (NLS1s), 10 AGNs of other types, and 2 starburst galaxies

EGRET

- AGN basic results :

  - The γ-ray energy flux is often dominent
  - A naive estimate $(4\pi d^2 L) \approx 10^{40}W/m^2 \rightarrow 10^{42}$W
  - $0,03 \leq z \leq 2,28$
  - $(30MeV - 30GeV)$ spectrum $\sim$ a power law: $\frac{dN}{dE} \propto e^{-\alpha}$ with $1,3 \leq \alpha \leq 3,0$
  - Many sources are strongly and rapidly variables on time scales $\sim$ 1 month.
  - Many known AGN are not detected in γ-rays.

AGN Variability

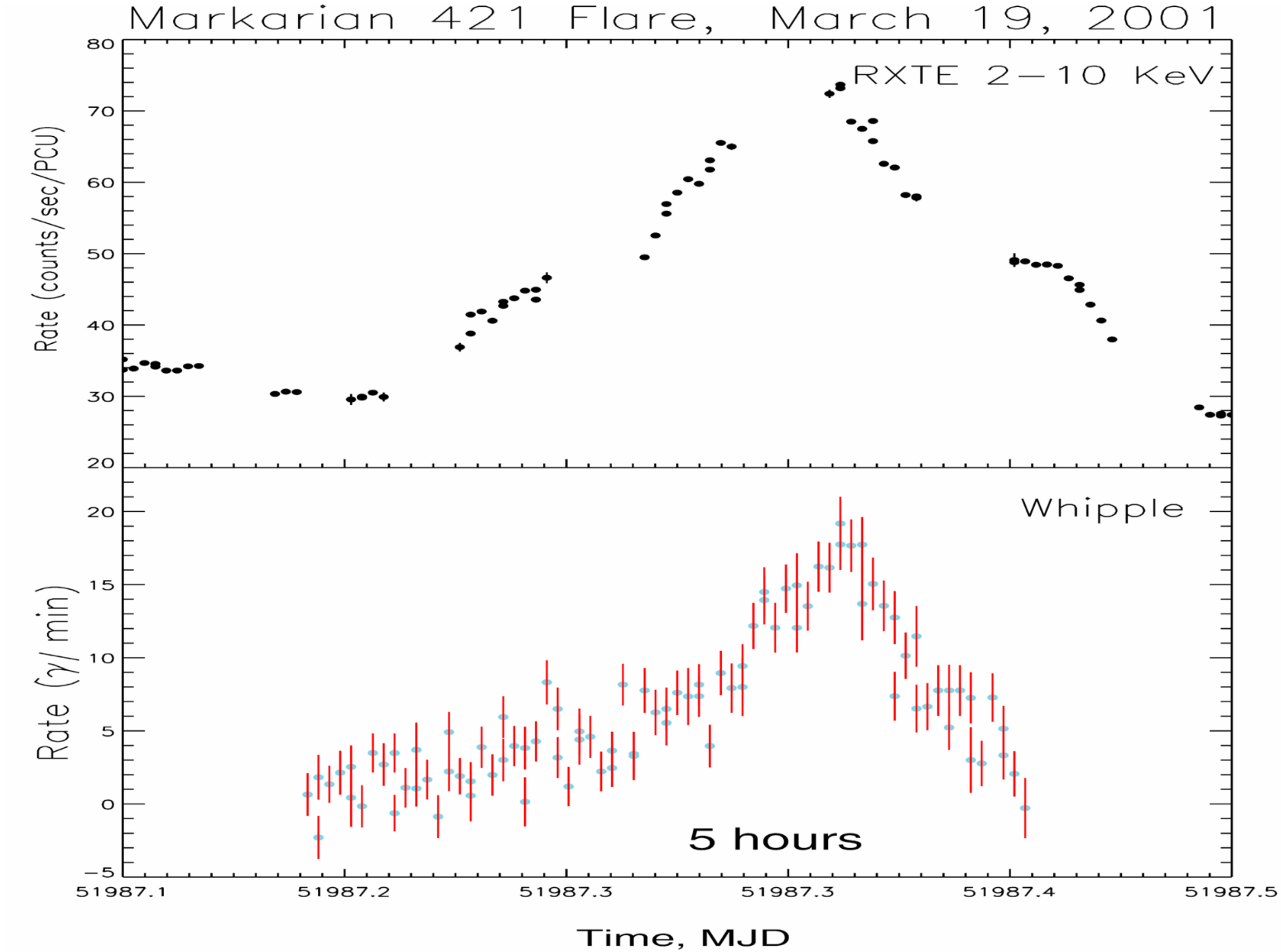
- Variability:
  - Most EGRET Blazars are variable on time scales ~days or months.

Source	T_{var} AGN (days)
0208-512	4
0235+164	<46
0528+134	0,65
1253-55	1,3
1406-076	2,4
1633+382	0,7
2251+158	2,2

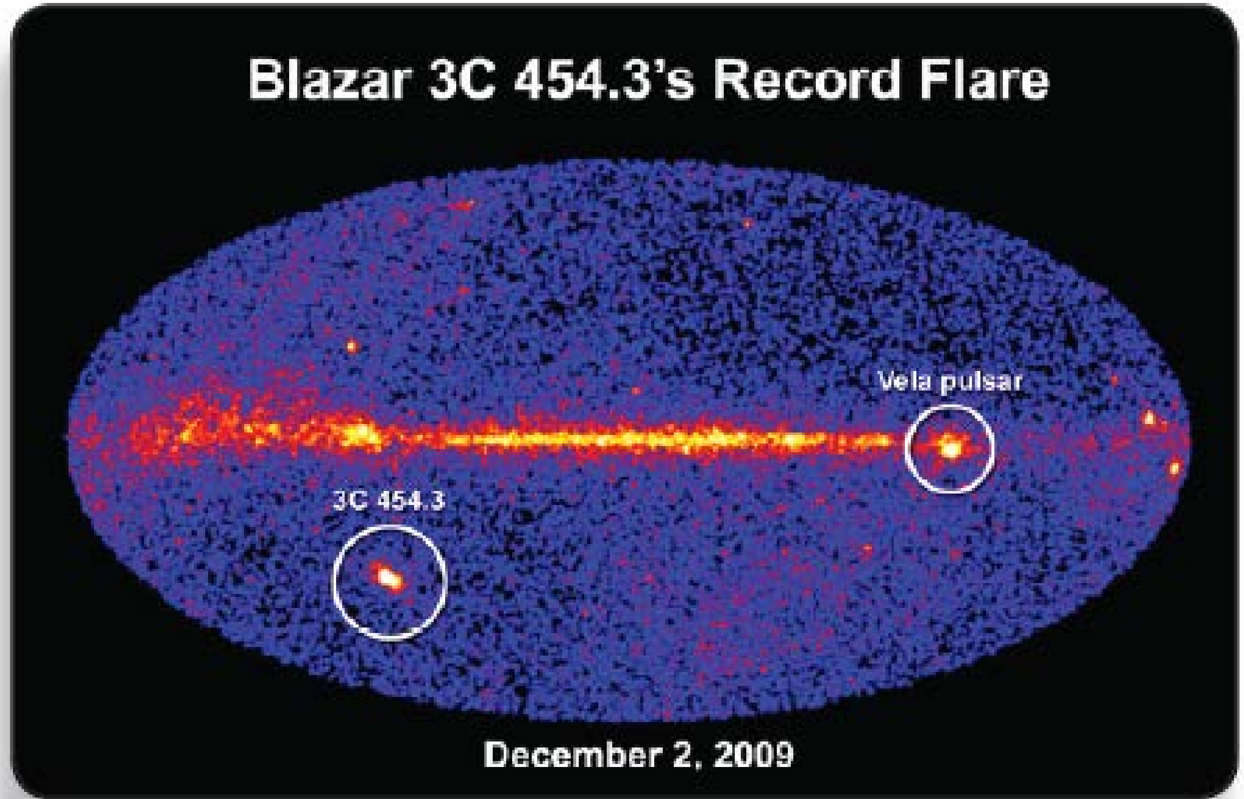
  - Short time scales are constraining the source size:

    1 day $\Rightarrow$ Scharzschild radius of a $10^{10}\,M_\odot$ black hole.

Time coincidence X and TeV γ

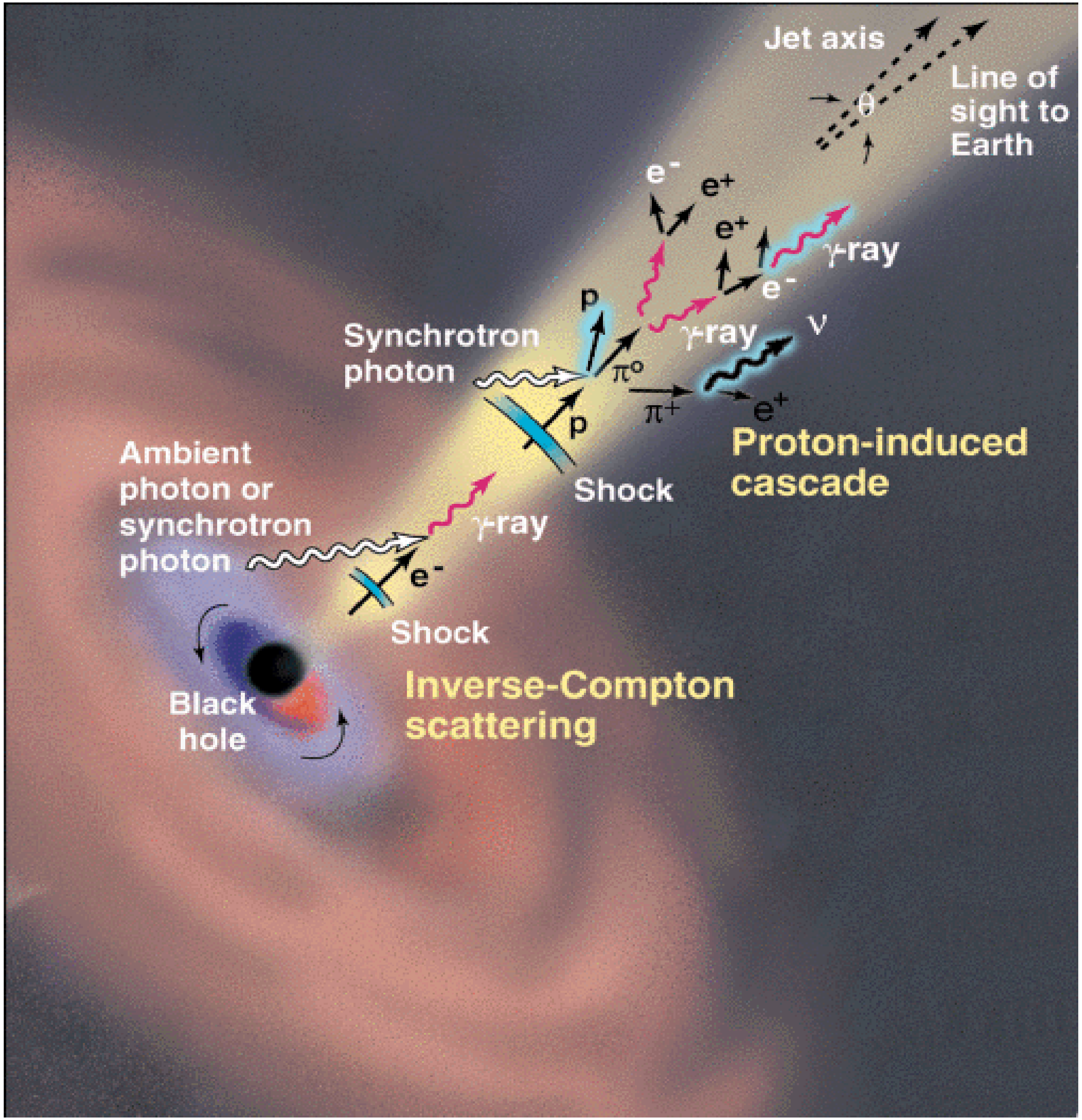


Flare de 3C454.3 : 2 x luminous than Vela although 10^6 x distant !



Unprecedented flares from the blazar 3C 454.3 in the constellation Pegasus now make it the brightest persistent gamma-ray source in the sky. That title usually goes to the Vela pulsar in our galaxy, which is millions of times closer (Credit: NASA/DOE/Fermi LAT Collaboration).

AGN Jet Emission Mechanisms



Cosmic Cannon:
Looking down the Barrel of the Cannon

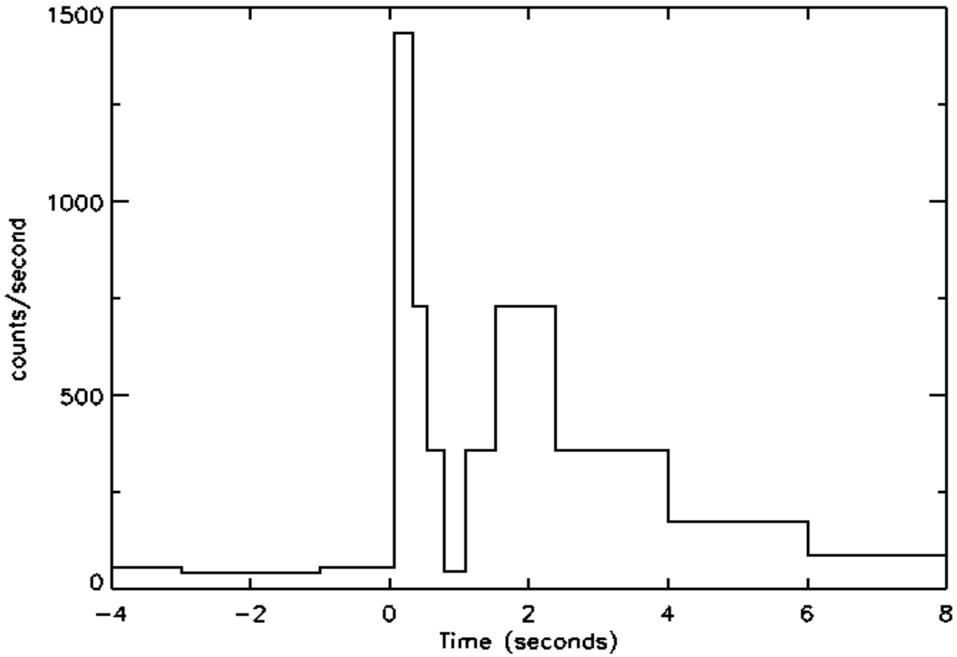
Electron Progenitors:
- Synchrotron Self Compton
- External Compton

Proton Progenitors:
- Proton Cascades
- Proton Synchrotron

(Buckley, Science, 1998)

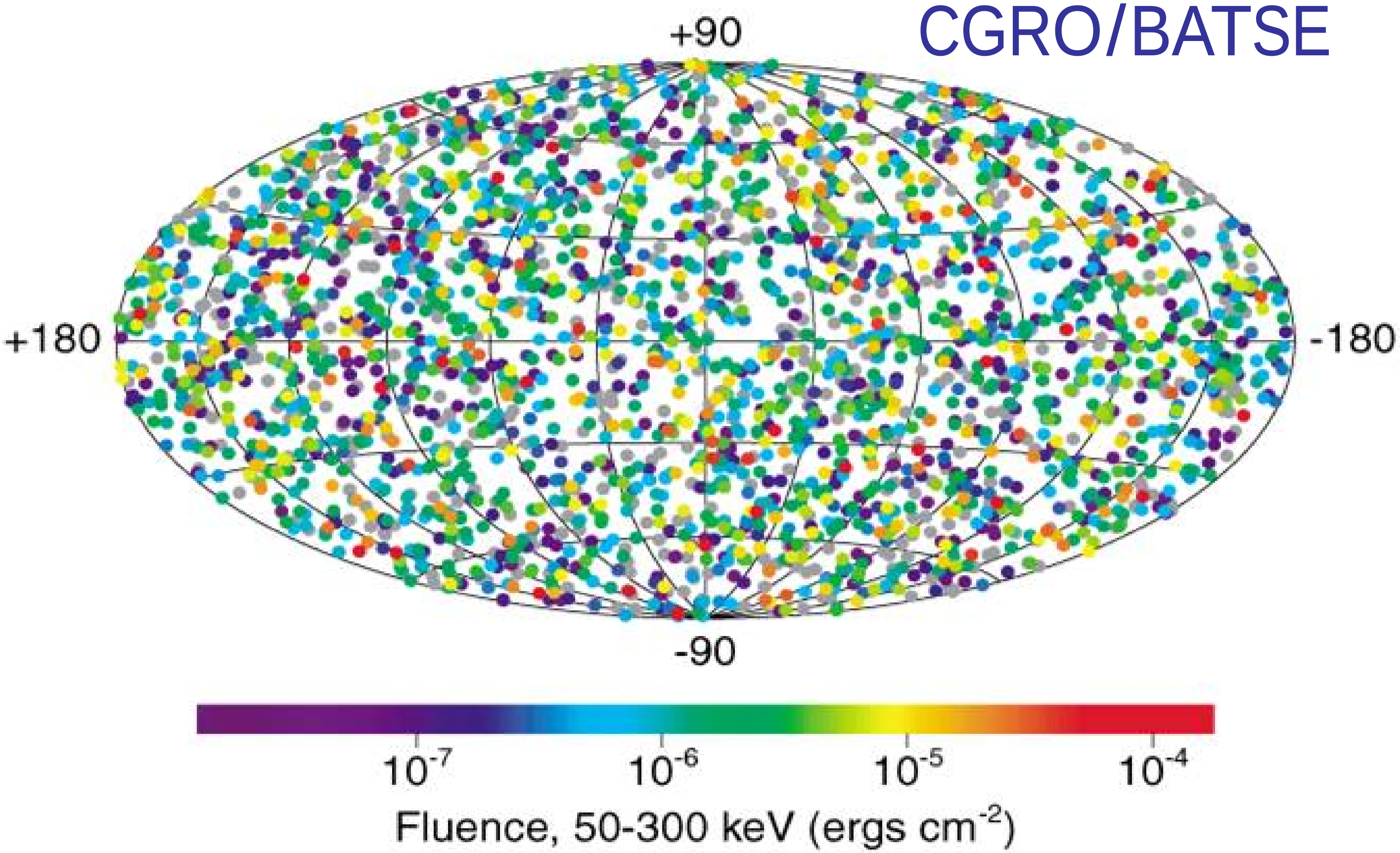
GAMMA RAY BURSTS

Vela Program (1969-1979)



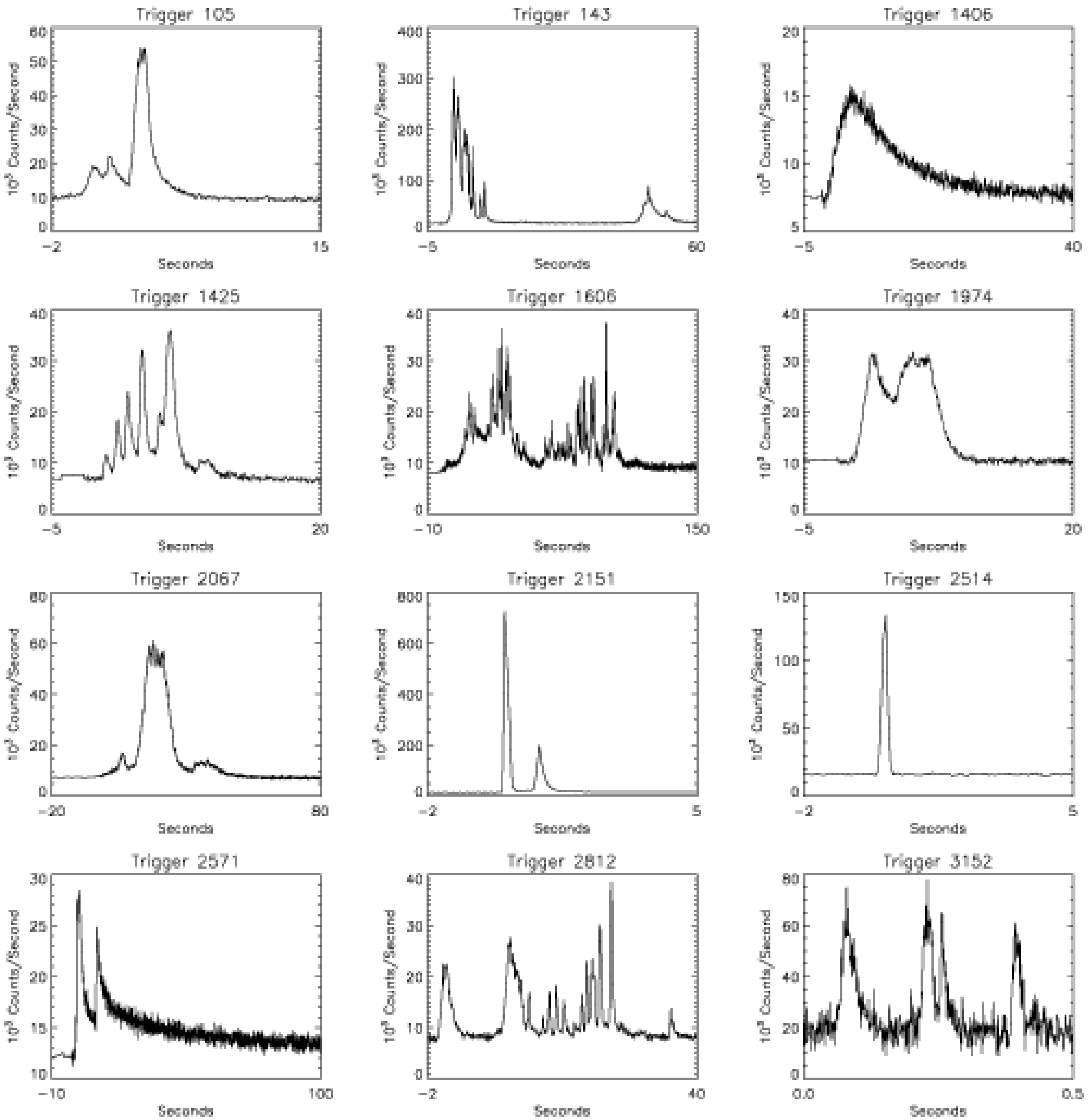
- Discovered in 1967 when spying thermonuclear bomb tests.
- A 30+ years old mystery unraveled in the 90ties !

Gamma-ray Burst Sky



~ Once a day, anywhere in the universe !

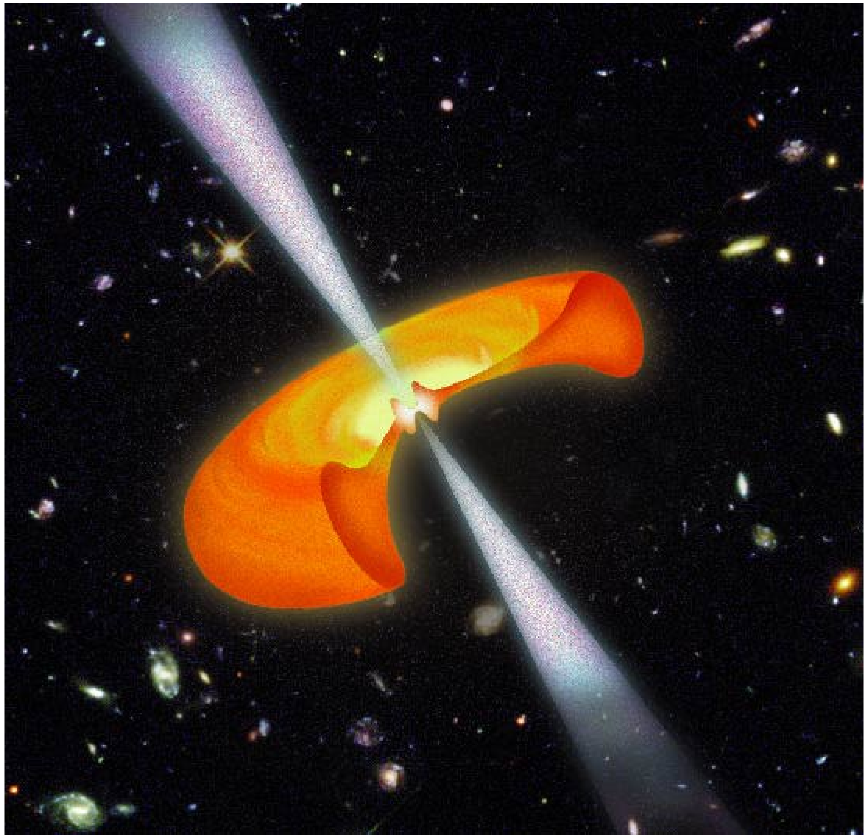
GRB



Trigger 105
Trigger 143
Trigger 1406
Trigger 1425
Trigger 1606
Trigger 1974
Trigger 2067
Trigger 2151
Trigger 2514
Trigger 2571
Trigger 2812
Trigger 3152
10^3 Counts/Second
Seconds

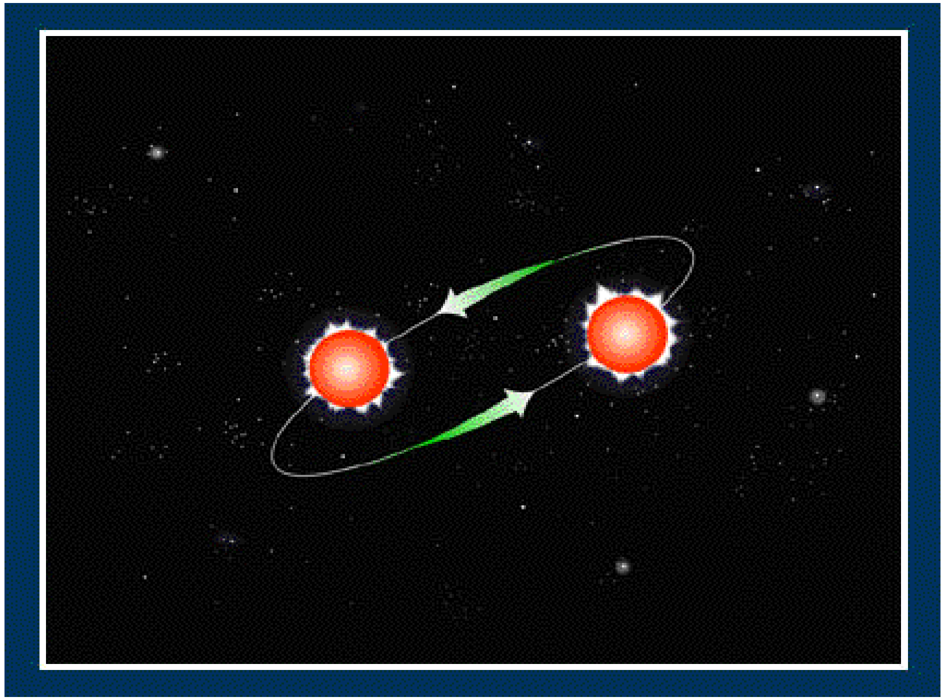
Hypernova

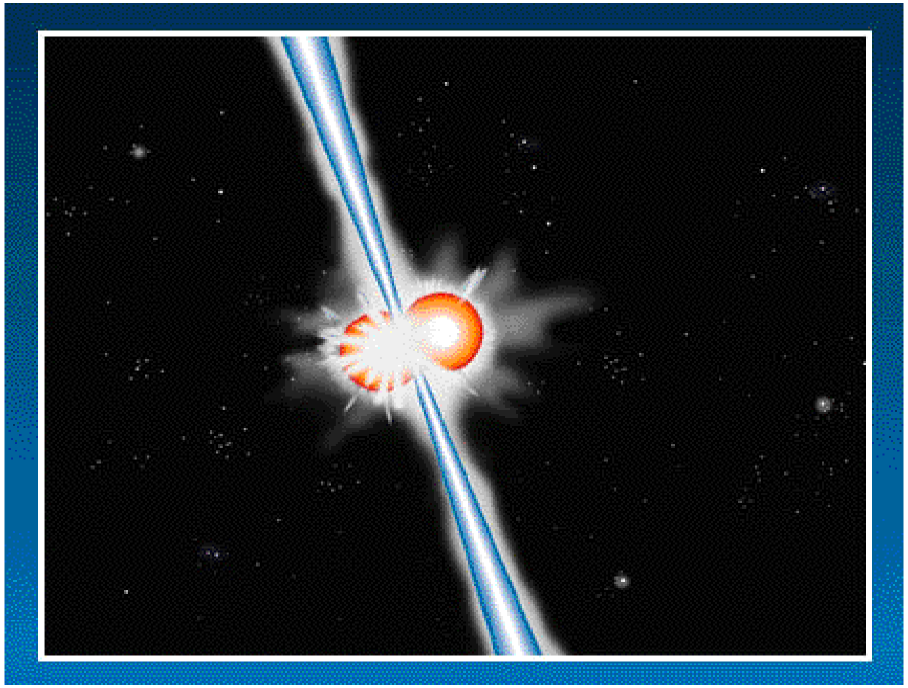
Death of a massive star ?



- A billion trillion times the power from the Sun

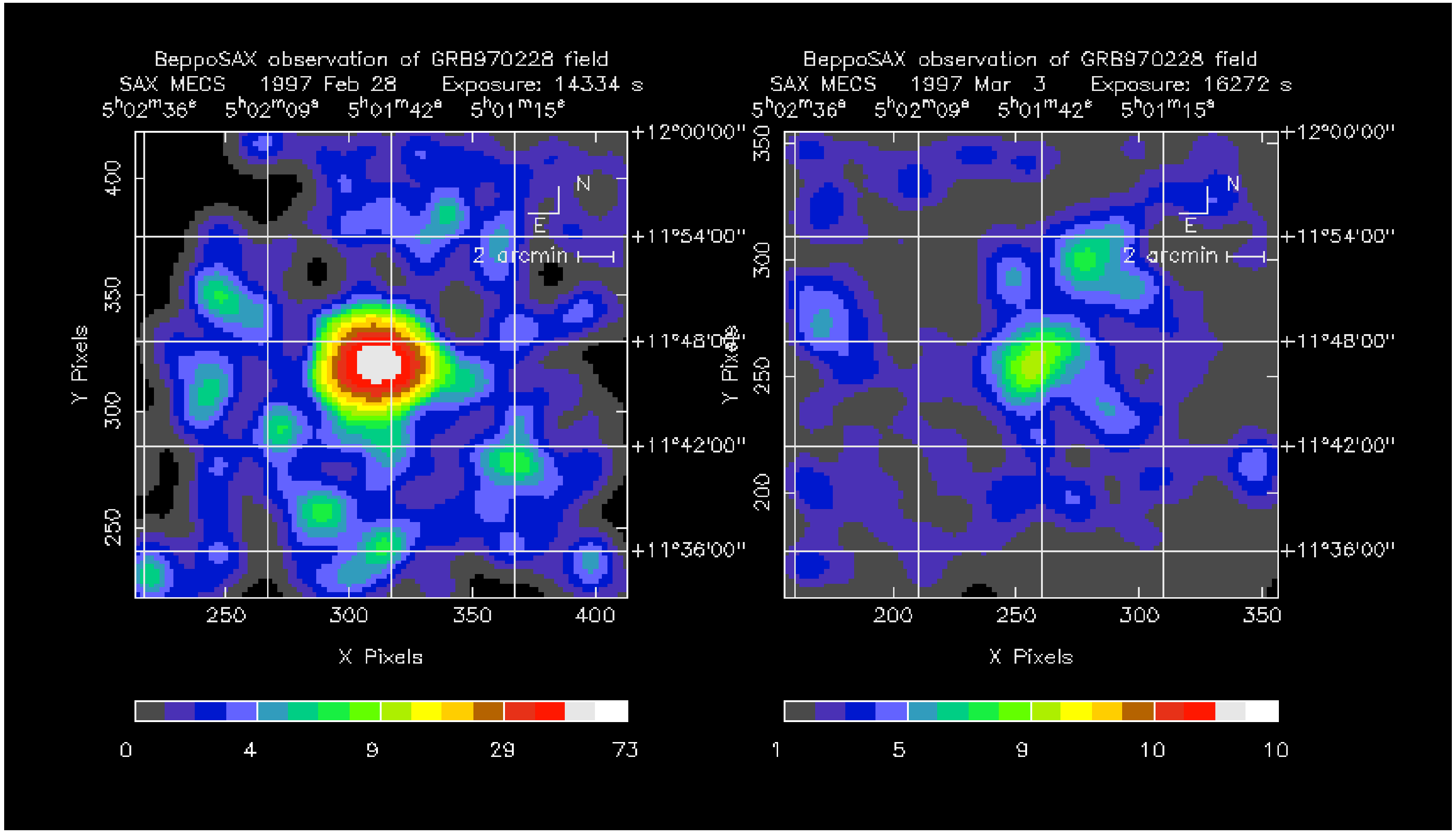
Catastrophic Mergers





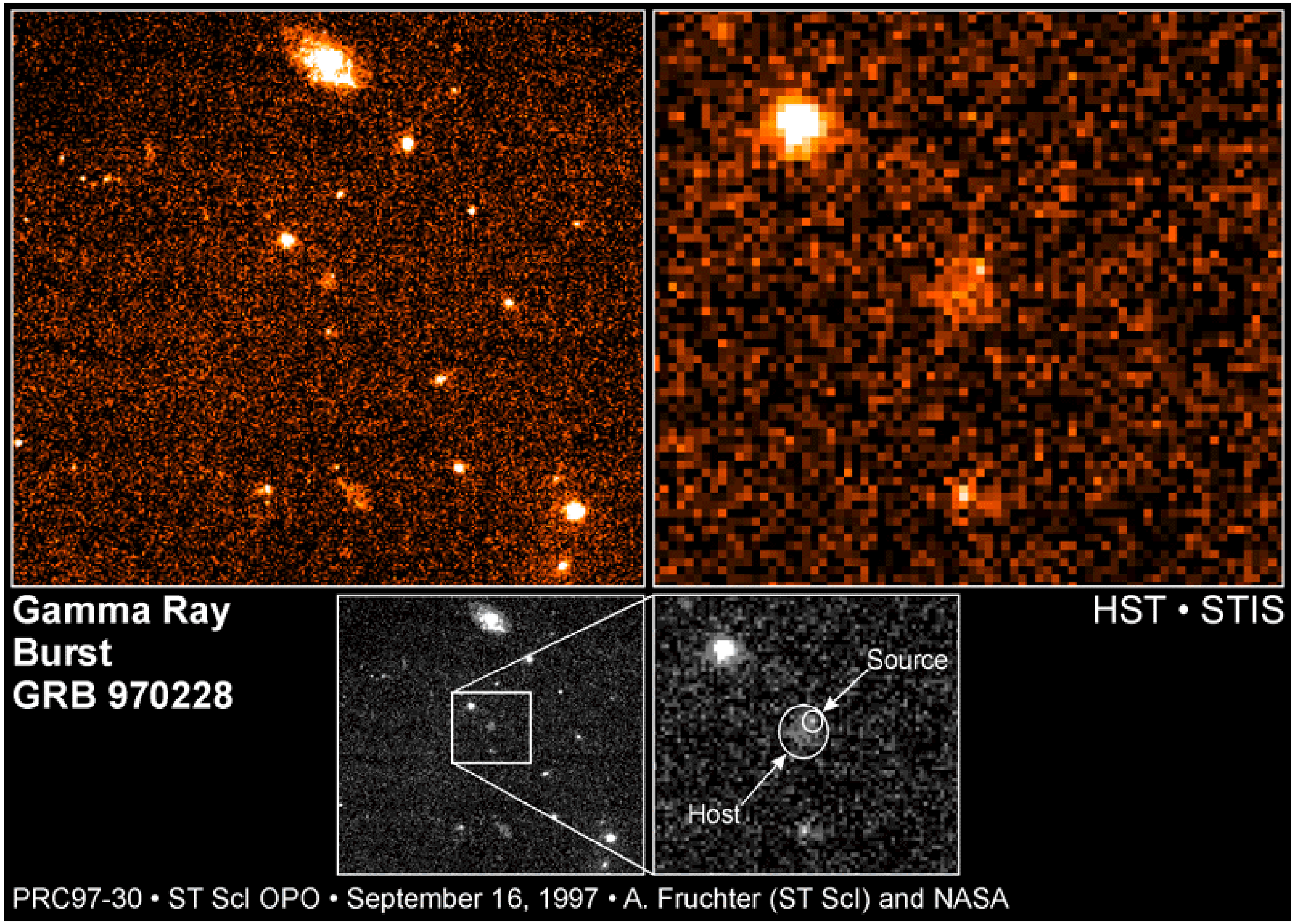
- Spiral death of 2 neutron stars or black holes

Afterglow



- Discovered in 1997 by BeppoSAX satellite

GRB optical afterglow



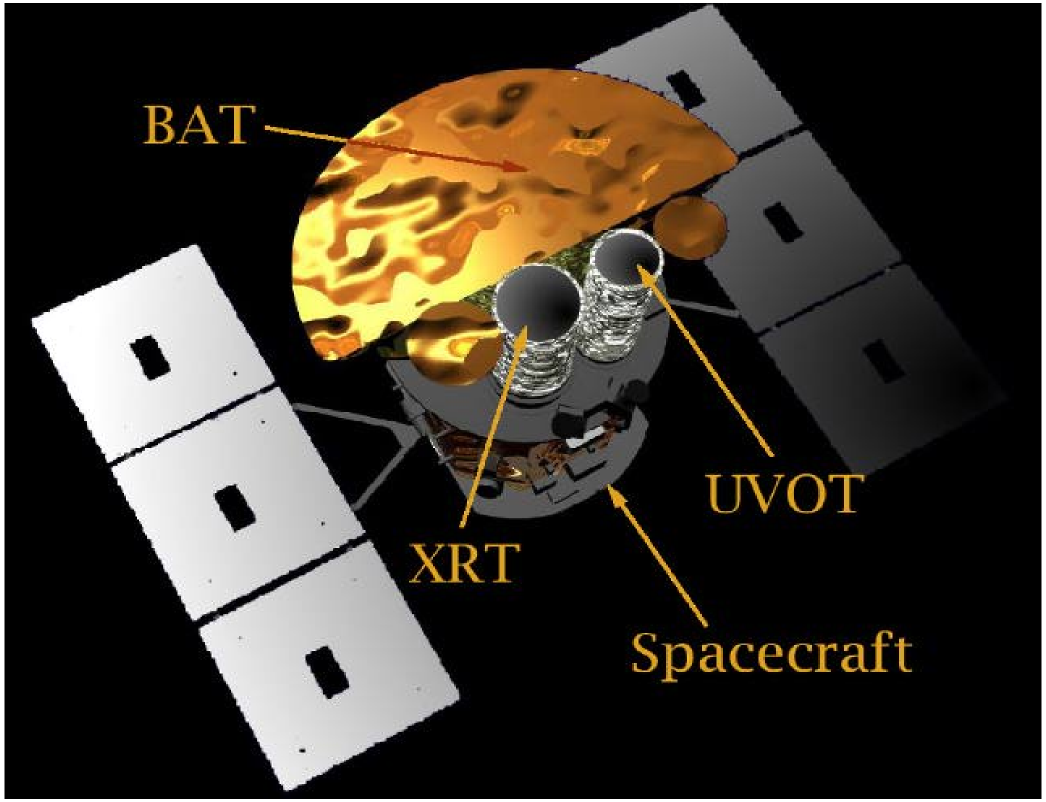
New Missions = Better Data

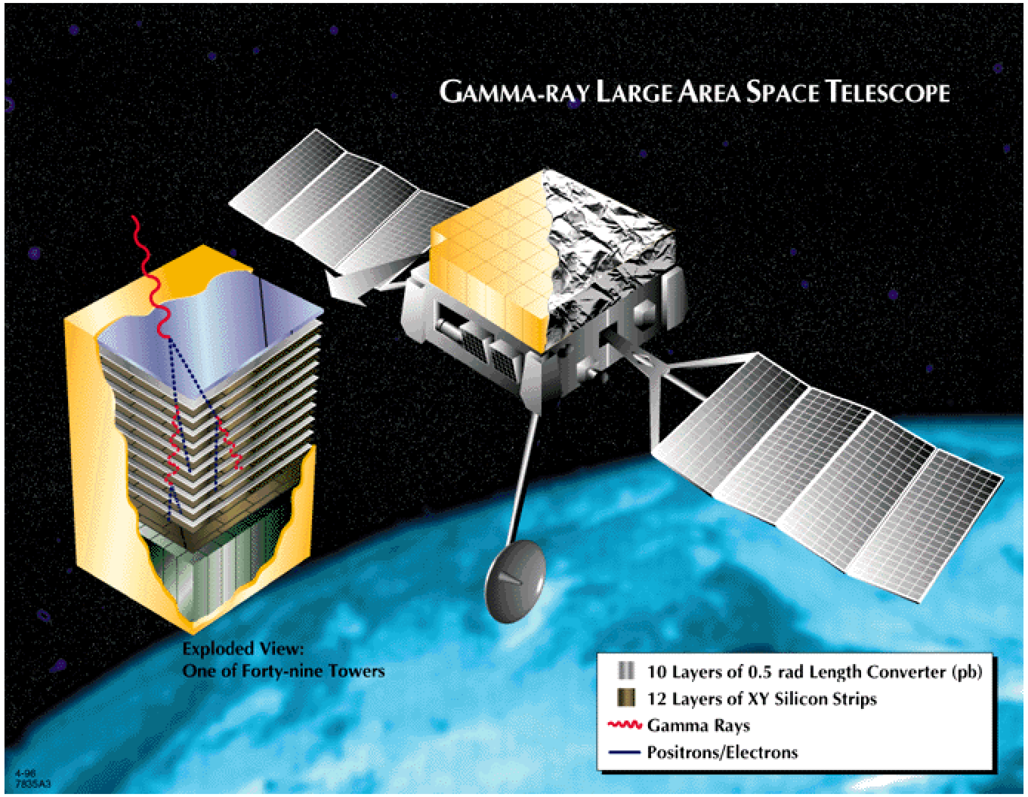
HETE II (launched 10/9/00)

INTEGRAL (launched 17/10/2002)

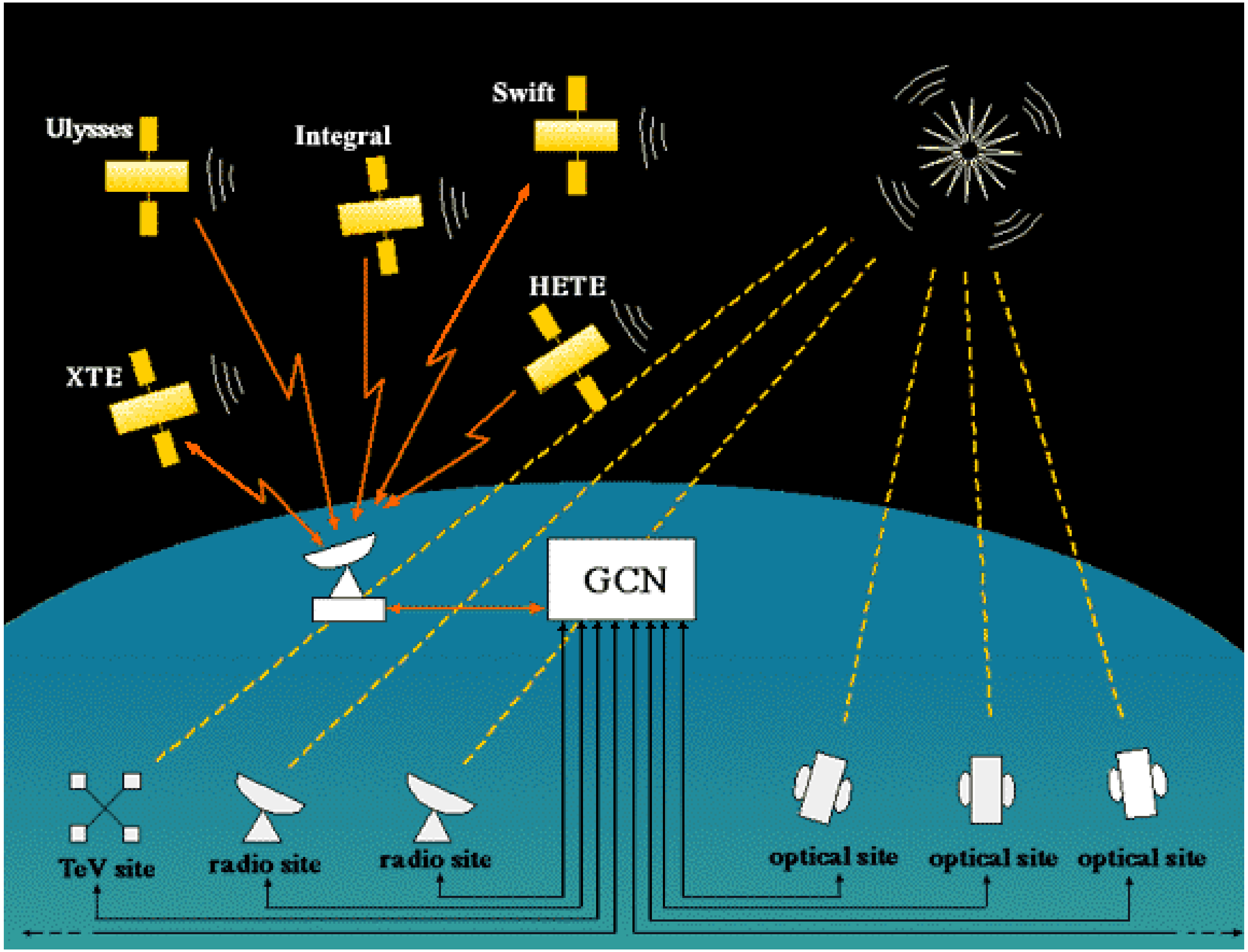
Swift (launched 20/11/2004)

FERMI (launched 16/5/2008)





The Gamma ray bursts Coordinates Network



GRB's

- Gamma-Ray Bursts : intense gamma-ray flux
  - 0.1 to 1 MeV, and up to 100 MeV
  - Emitted on a short time scale (~ 1 second !)
  - Observed ~once per day, with an isotropic distribution
  - Source at cosmological distances (most distant is z = 9.4 !!)

- γ-ray luminosity: ~ 10^{52} erg/s (10 $\times$ SNe !)

- Extreme variability in intensity and spectrum
  - Time scales from **10 ms** to **10 s**
  - Some very short **1 ms** variabilities $\rightarrow$ internal shocks

- Clear bimodality suggesting the existence of two separate populations:
  - a "short" population with an average duration of about 0.3 seconds
  - a "long" population with an average duration of about 30 seconds.

UHE SOURCES

General limits on models

Shock waves

- Acceleration site confinement: $r_g = E/ZeBc < L$
  - Depends in fact on $V_{shock} = \beta c$:

$$E_{max} \approx \beta \times Ze \times Bc \times L$$

Unipolar induction

- Accelerate in one step ($\mathbf{E}$ field, $f_{Lorentz} \approx V_{rot} \times B \times R$)
  → No confinement necessary

Top-Down Models

- No acceleration at all !
  - Decay products of exotic physics states, supermassive particles at E_{GUT}, Topological Defects…

Bottom-Up

ZeVatrons

Astrophysical Accelerators reaching ZeV

Acceleration = Fermi-like diffuse acceleration.

Frist challenge, E_{max} : Reach ≥ 10^{20} eV

(if 1 TeV is hard, guess for 10^9 TeV !!)

Second challenge, Propagation : B_{igm}

(determines the spectrum and the arrival direction)

Hillas criterion:

Magnetic confinement in the shock zone i.e.

1 R_{gyr} < accelerator size

Not many candidates survive!

Neutron stars (pulsars)

AGNs

Radio lobes

Clusters

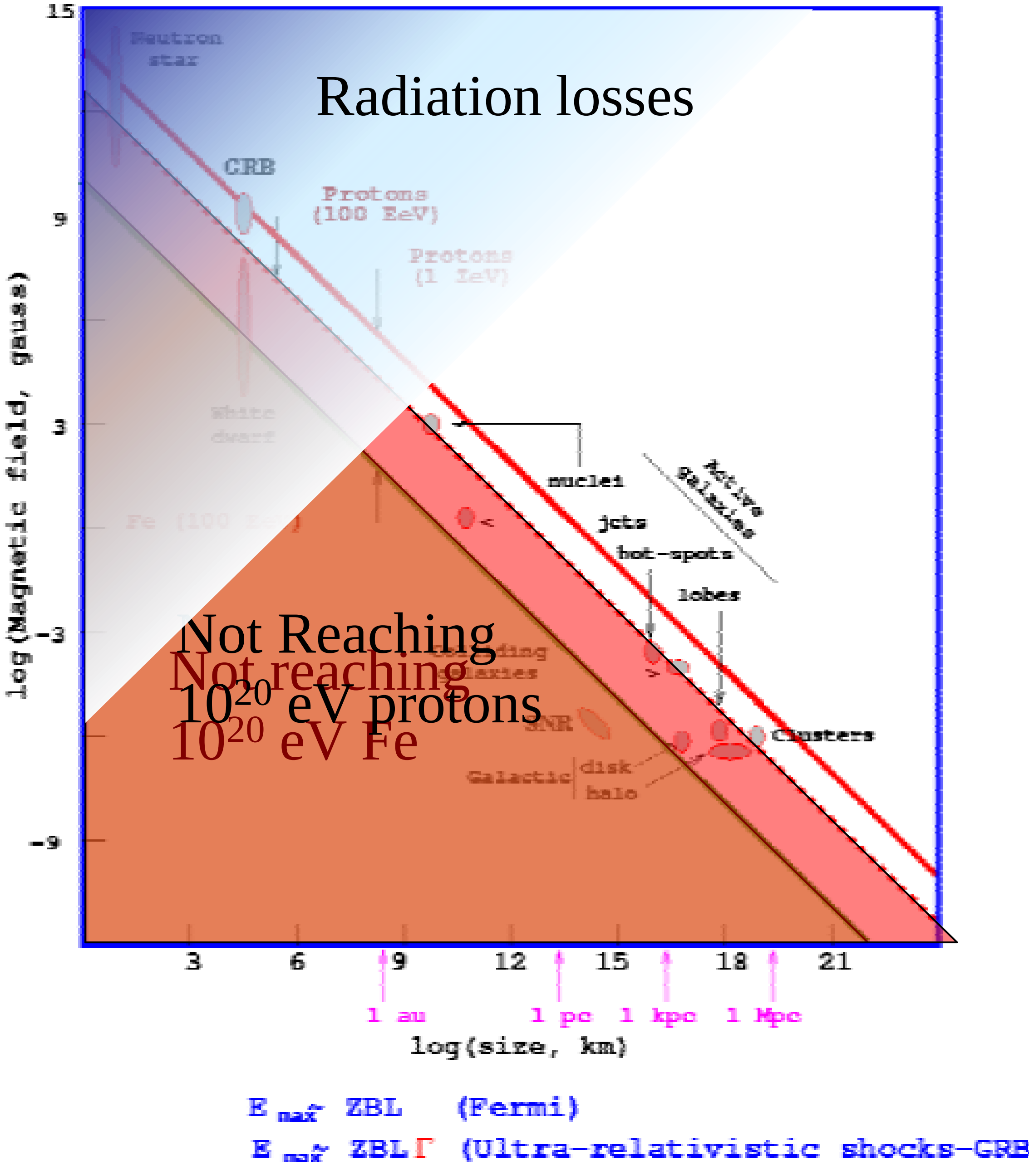
Colliding Galaxies/Clusters

Gamma Ray Bursts

Hillas diagram

Standard estimates for E_{max} :

- Confinement :
  $r_g = E/(ZeB) < R \Rightarrow E < ZeBR$
- Unipolar inductor (pulsar)
  $E < ZeBR(\Omega R/c) \approx \beta_s ZeBR$
- Diffusive acceleration
  by non relativistic shocks:
  $\tau_{acc} \approx 10\kappa/u_s^2 < R/u_s$ avec $\kappa > r_g c$
  $\Rightarrow E < \beta_s ZeBR$
- Diffusive acceleration
  by relativistic shocks:
  $E < \Gamma_s ZeBR$
- General Hillas condition:
  $E < 0.9\beta\Gamma ZeB_{Gauss}R_{pc}\ ZeV$



Relativistic shocks

- Acceleration $\propto \Gamma^2$ works fine for a couple of cycle
- After that it fails for mere kinematical reasons
- But this is still very efficient (>> standard shocks)
- Confinement is easier

A weak deflexion is enough : $\delta\theta \approx 1/\Gamma_s \Rightarrow r_g < R_s/\Gamma_s$

$\Rightarrow E_{max} \approx \Gamma_s \times$ larger

$\Rightarrow$ one can reach the limits induced by energy losses

BOTTOM -UP

Galactic pulsars

Extra-galactic radio galaxy lobes

Gamma Ray Bursts

Protons, Iron, Nuclei?

Spectral index

Explaining isotropy is not trivial

Angular coincidences to be confirmed…

Top-Down

Topological defects, superheavy relics with M ~ GUT scale that is ~10^{16}GeV

- Energy ≫ 10^{20} eV easy!
  (QCD fragmentation spectrum QCD with M~10^{24} eV!!)

- Explaining the flux is not trivial !!
  (natural density scale is ~ H_0^{-1})

- Composition of UHECR is the clue (photons + neutrinos) !!

Low energy gamma-rays constraint

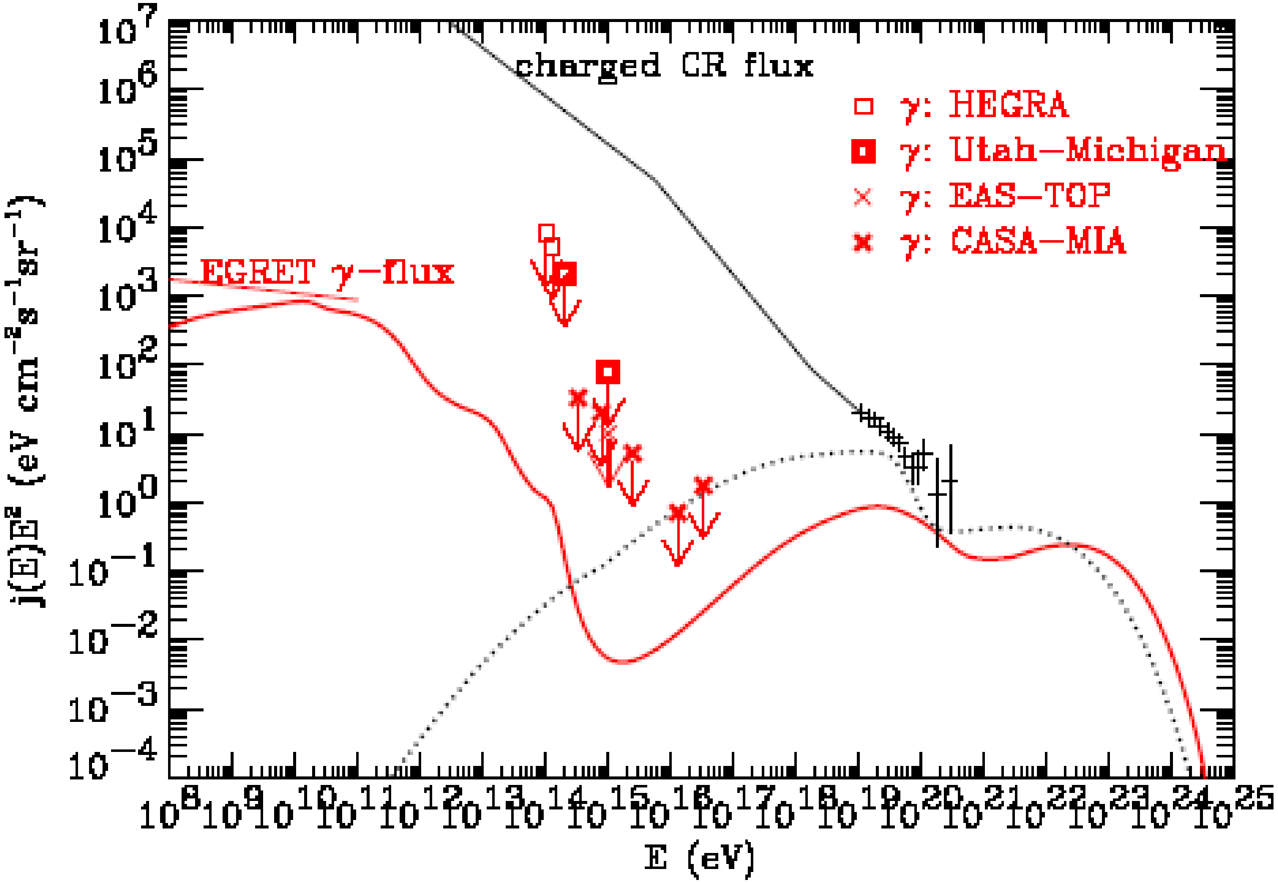


Figure 28: Predictions for the differential fluxes of $\gamma-$rays (solid line) and protons and neutrons (dotted line) in a TD model characterized by $p = 1$, $m_X = 10^{16}$ GeV, and the decay mode $X \rightarrow q + q$, assuming the supersymmetric modification of the fragmentation function, Eq. (57), with a fraction of about 10% nucleons. The calculation used the code described in Ref. [206] and assumed the strongest URB version shown in Fig. 10 and an EGMF $\ll 10^{-11}$ G. 1 sigma error bars are the combined data from the Haverah Park [3], the Fly's Eye [7], and the AGASA [8] experiments above 10^{19} eV. Also shown are piecewise power law fits to the observed charged CR flux (thick solid line) and the EGRET measurement of the diffuse $\gamma-$ray flux between 30 MeV and 100 GeV [185] (solid line on left margin). Points with arrows represent upper limits on the $\gamma-$ray flux from the HEGRA [257], the Utah-Michigan [510], the EAS-TOP [511], and the CASA-MIA [258] experiments, as indicated.

Top-Down Signatures

Composition:

Photons & Neutrinos fluxes $\gg$ Protons

The current (AUGER) limits on UHE neutrino and photon flux already kill most Top-Down models !!

Spectrum:

QCD-like fragmentation spectrum quite "hard"

Cosmography:

Halo distribution!! (SHRs & TDs locales)
or ~ Homogeneous

and even more exotic stuff…

Strongly interacting neutrinos

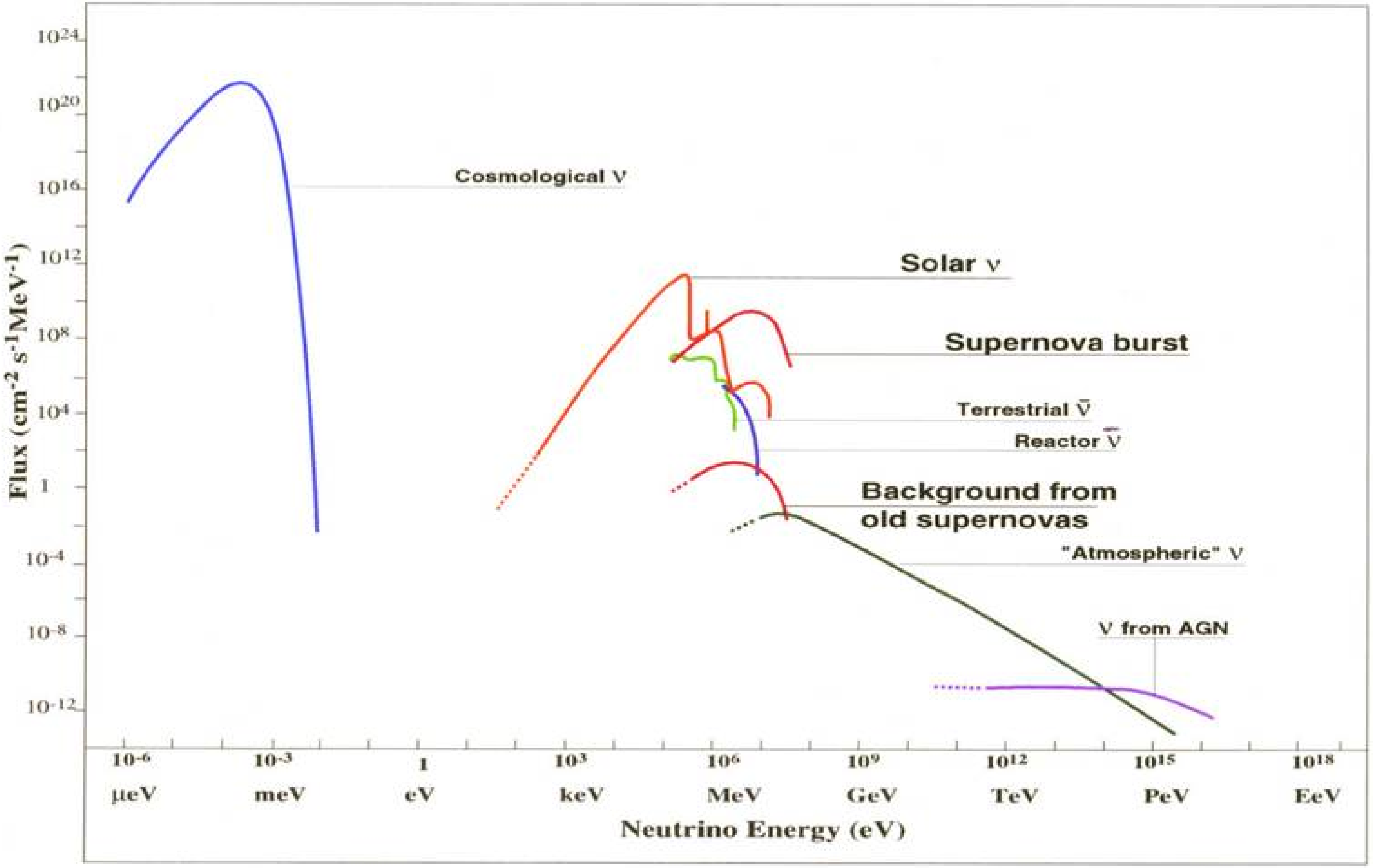
Lorentz Invariance Violation

Special Relativity Violation

etc…

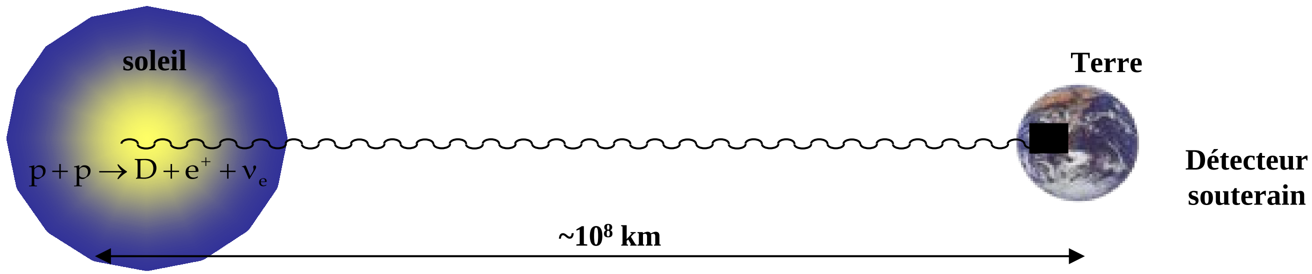
NEUTRINOS SOURCES

The overall neutrino spectrum

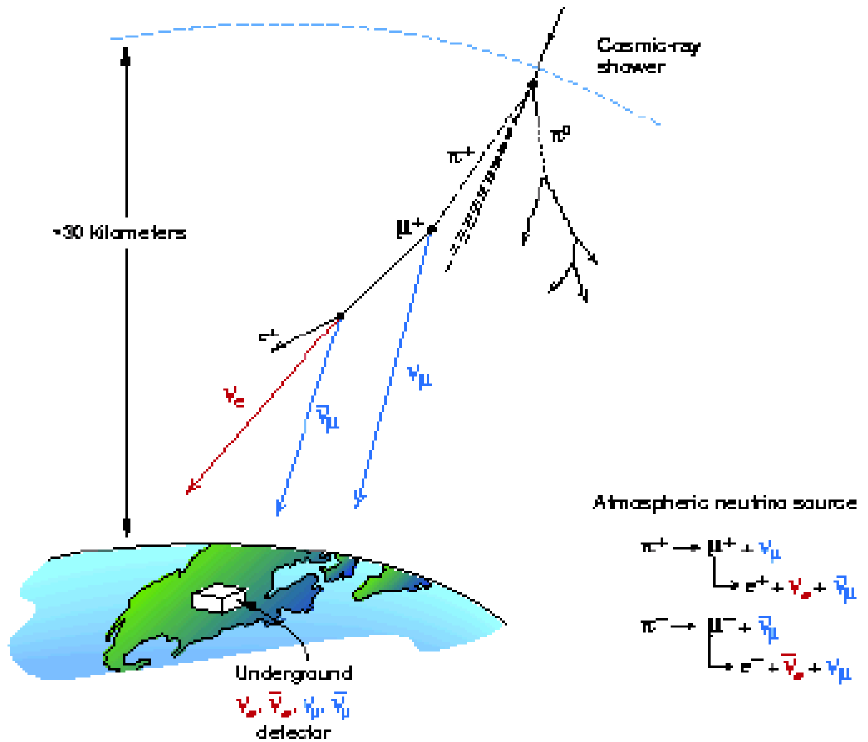


Natural Neutrinos Sources

Solar Neutrinos



Atmospheric Neutrinos



Also,
Super Novae (SN1987A),
Neutrinos de beam-dump cosmiques (AGN, GRB…),
Neutrinos cosmogéniques, Neutrinos reliques du BigBang…

Neutrino Production in the Sun

Light Element Fusion Reactions

$p + p \rightarrow {}^2H + e^+ + \nu_e$ (99.75%)

$p + e^- + p \rightarrow {}^2H + \nu_e$ (0.25%)

$\downarrow$

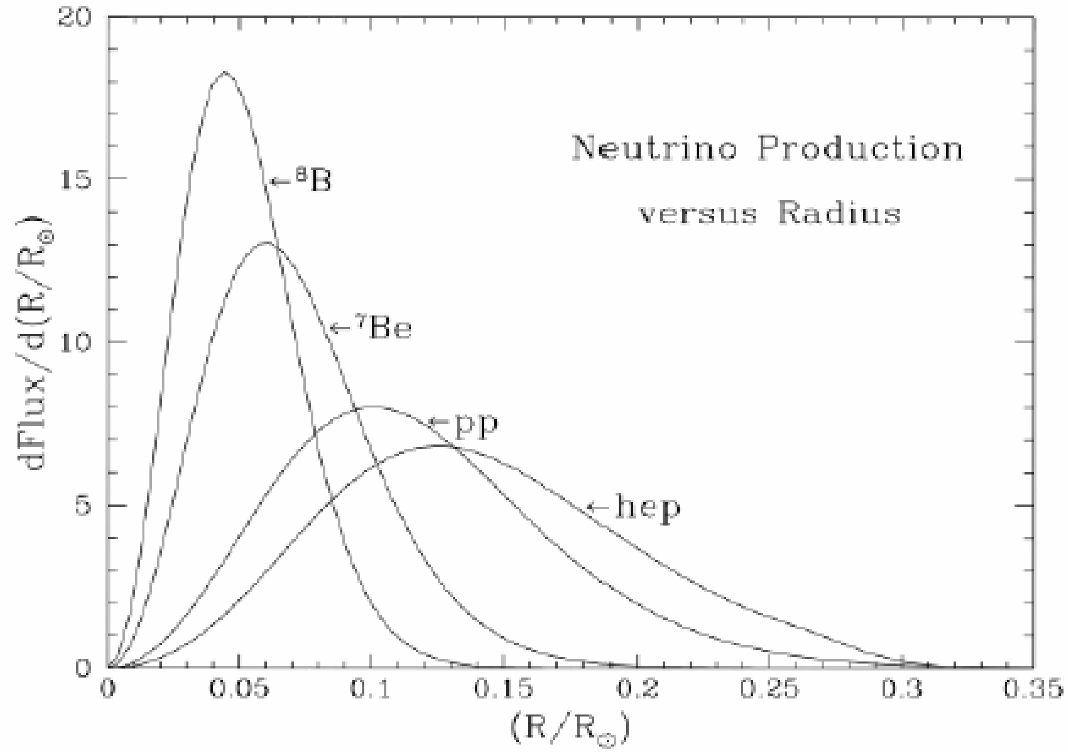
${}^2H + p \rightarrow {}^3He + \gamma$

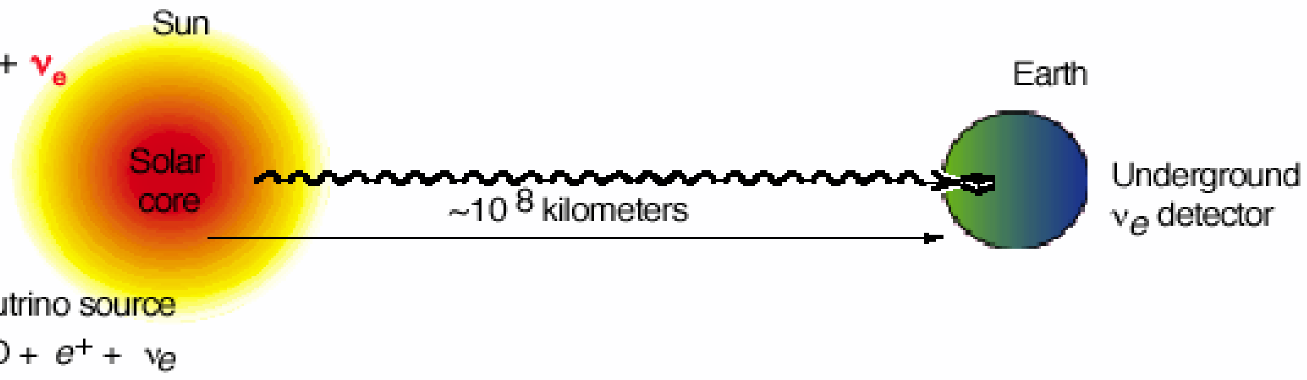
- 85%: ${}^3He + {}^3He \rightarrow {}^4He + 2p$
- ~15%: ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
- ~10^{-5}%: ${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$

From ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$:

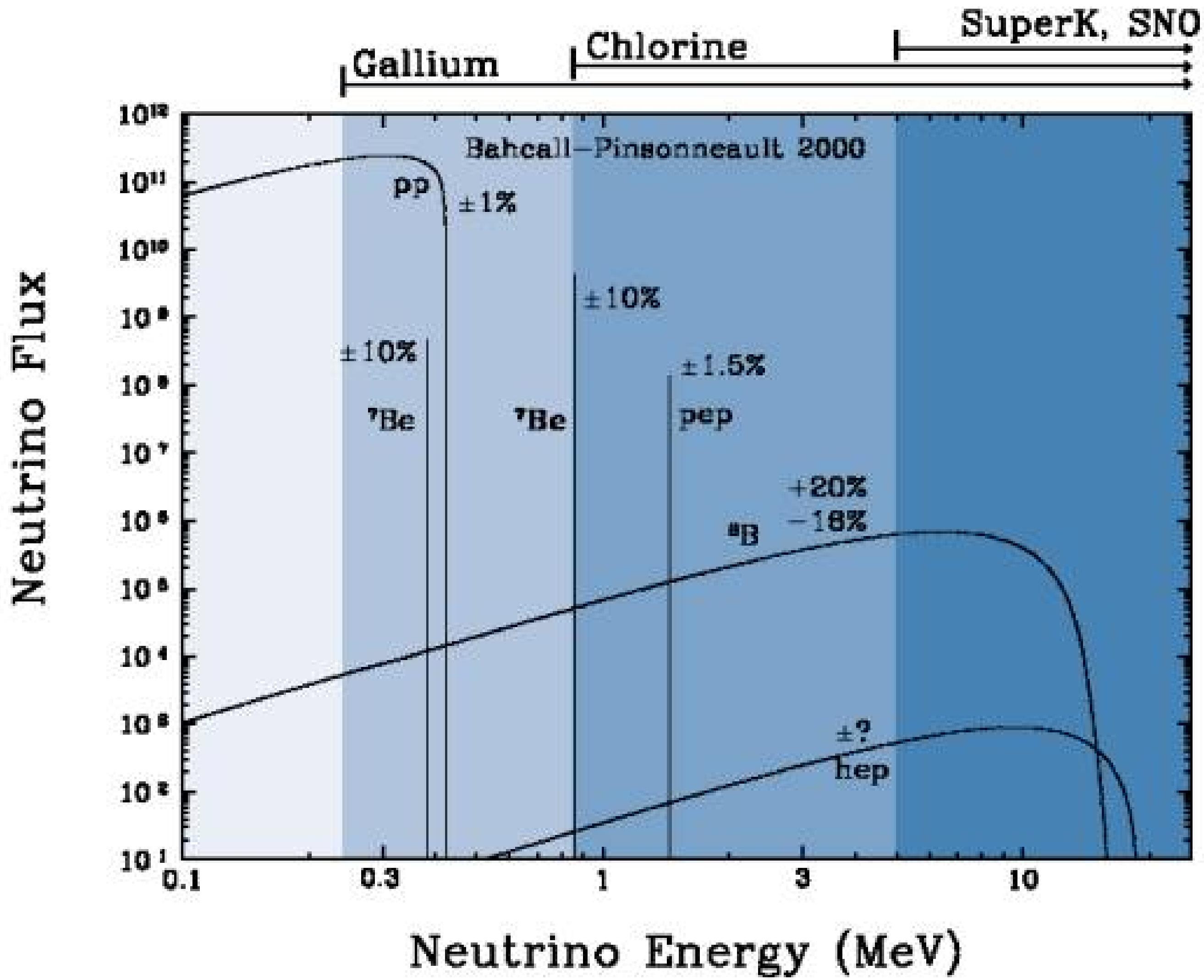
- 15.07%: ${}^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$ $\rightarrow$ ${}^7Li + p \rightarrow \alpha + \alpha$
- 0.02%: ${}^7Be + p \rightarrow {}^8B + \gamma$ $\rightarrow$ ${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

Neutrino Production Radius





Karsten Heeger, LBNL



Solar neutrino flux from p-p chain reactions based on the standard solar model (Bahcall and Pena-Garay, 2004) . Flux units are cm^{-2} sec^{-1} MeV^{-1} for continuum sources and cm^{-2} sec^{-1} for line sources.

SNe neutrinos

Normal stellar situation: the fusion thermal and radiation pressure compensate the gravitation pressure.

During the collapse, the gravitation binding energy ($\approx 3\times10^{53}$ erg) cannot escape in an other form than neutrino-antineutrino pairs.

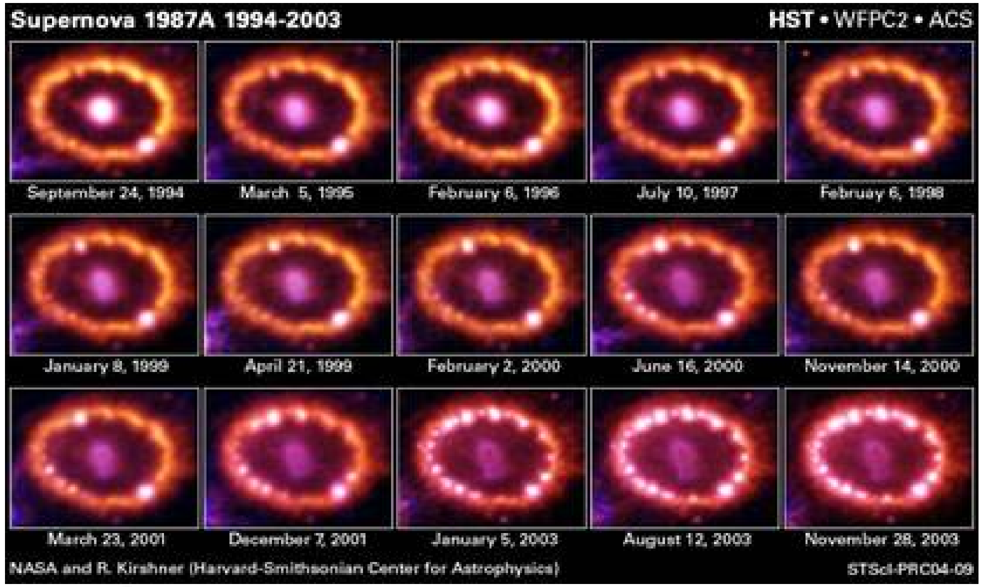
99% of the energy in the form of neutrinos
1% in the form of kinetic energy
0.01% of the energy in optical photons.

The neutron star is opaque to neutrinos. The diffusion and escape time is of the order of 1 second.

$$< E\nu_e > \approx 11 \text{ MeV}$$

$$< E\bar{\nu}_e > \approx 16 \text{ MeV}$$

SN1987a



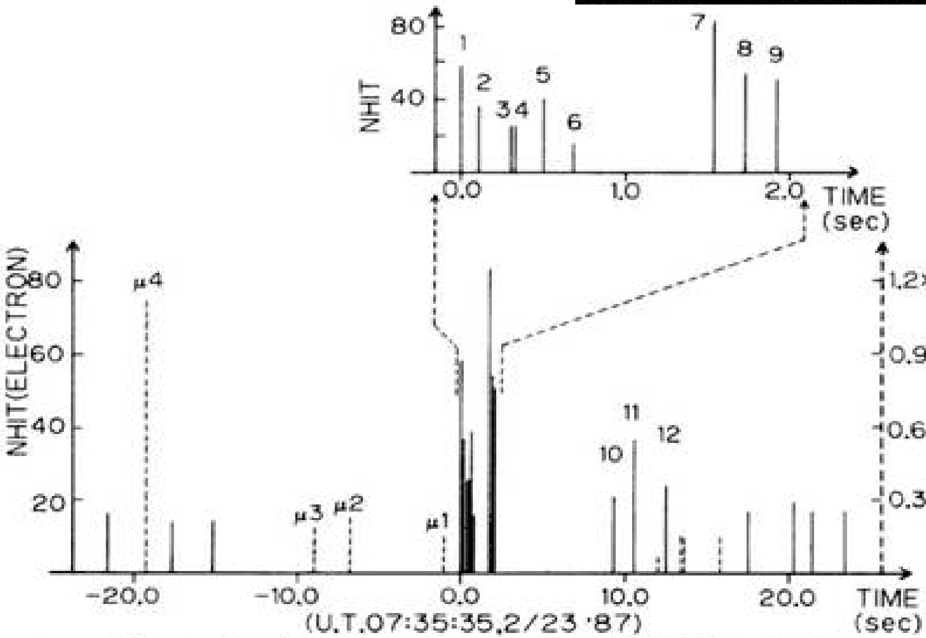
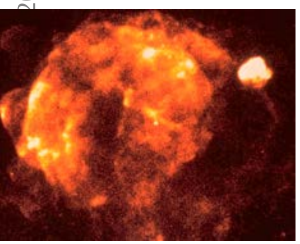


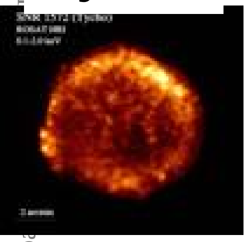
FIG. 2. The time sequence of events in a 45-sec interval centered on 07:35:35 UT, 23 February 1987. The vertical height of each line represents the relative energy of the event. Solid lines represent low-energy electron events in units of the number of hit PMT's, $N_{\rm hit}$ (left-hand scale). Dashed lines represent muon events in units of the number of photoelectrons (right-hand scale). Events $\mu 1-\mu 4$ are muon events which precede the electron burst at time zero. The upper right figure is the 0–2-sec time interval on an expanded scale.

SuperNovae Remnants

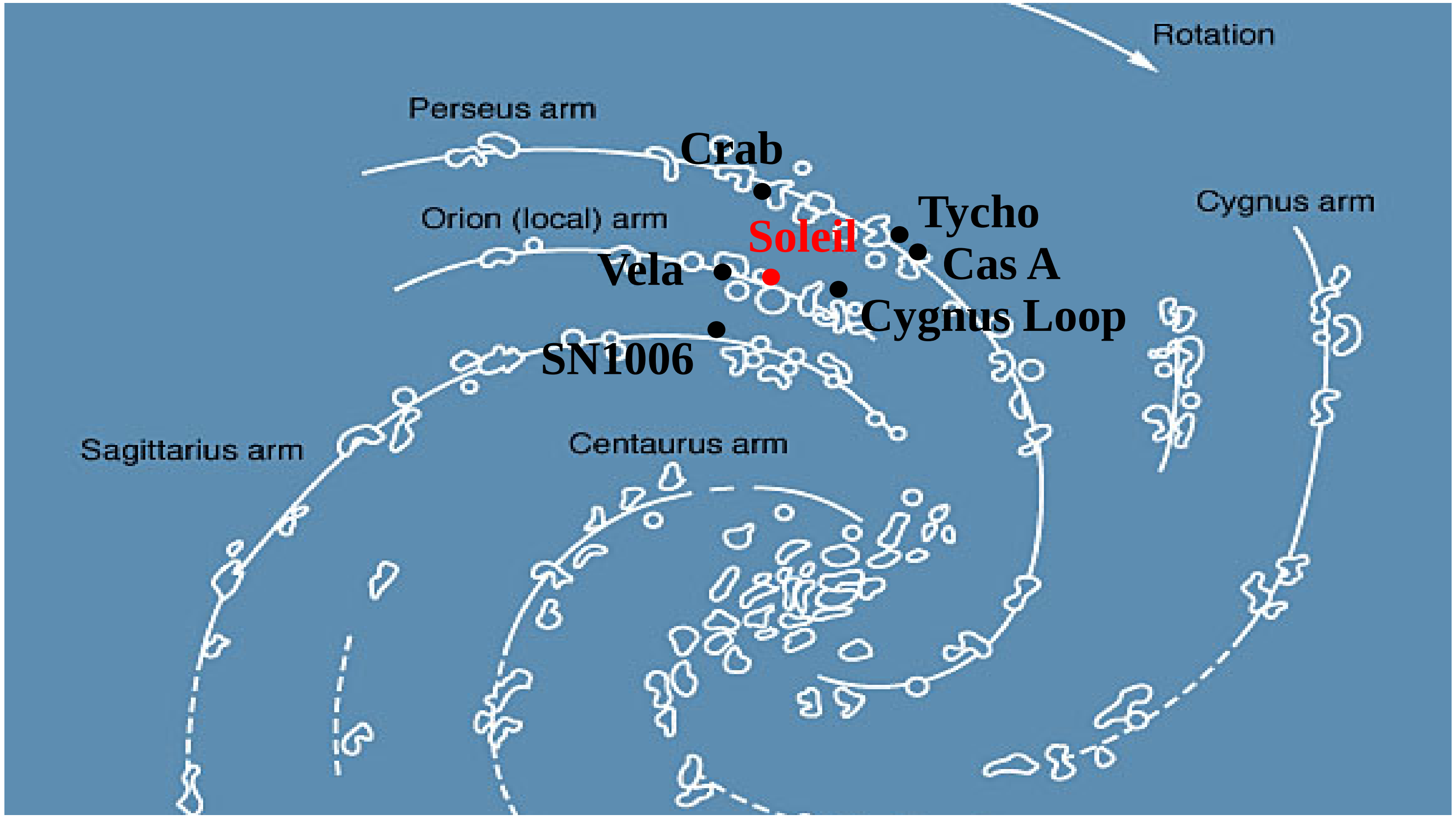
Vela

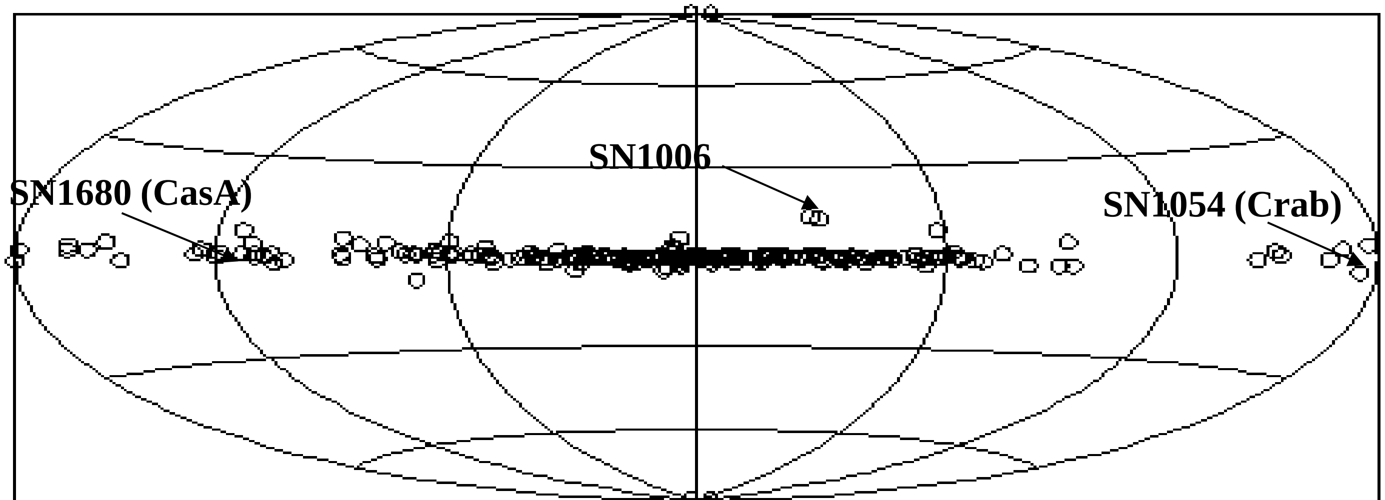


Tycho



Cygnus

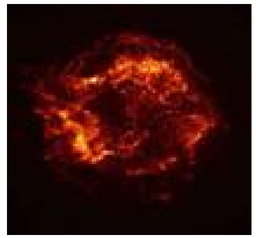




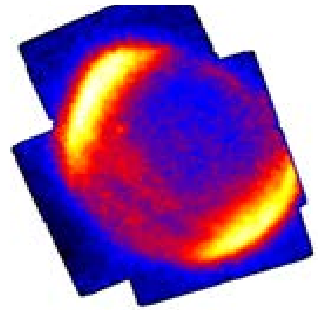
Crab

Kepler

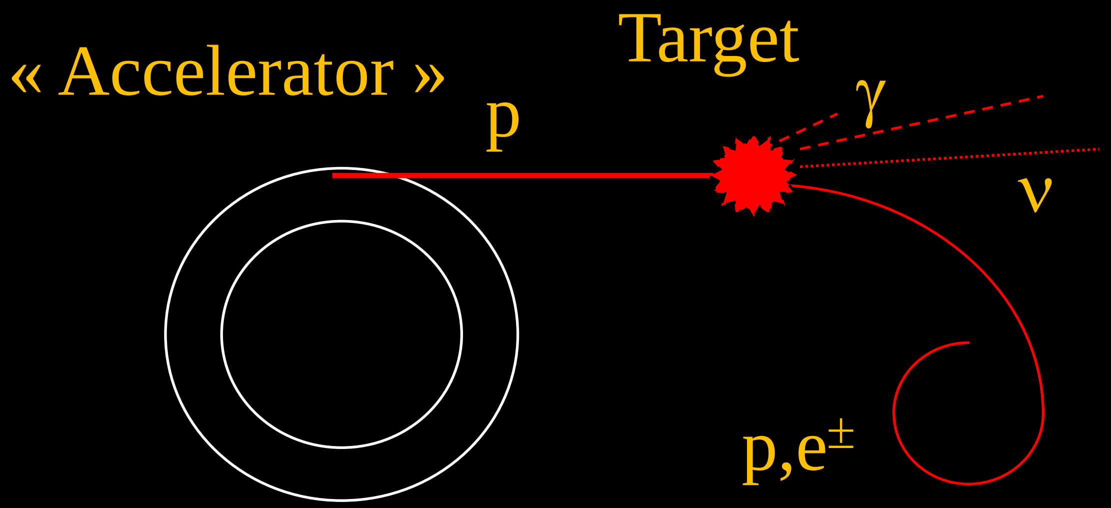
Cas A

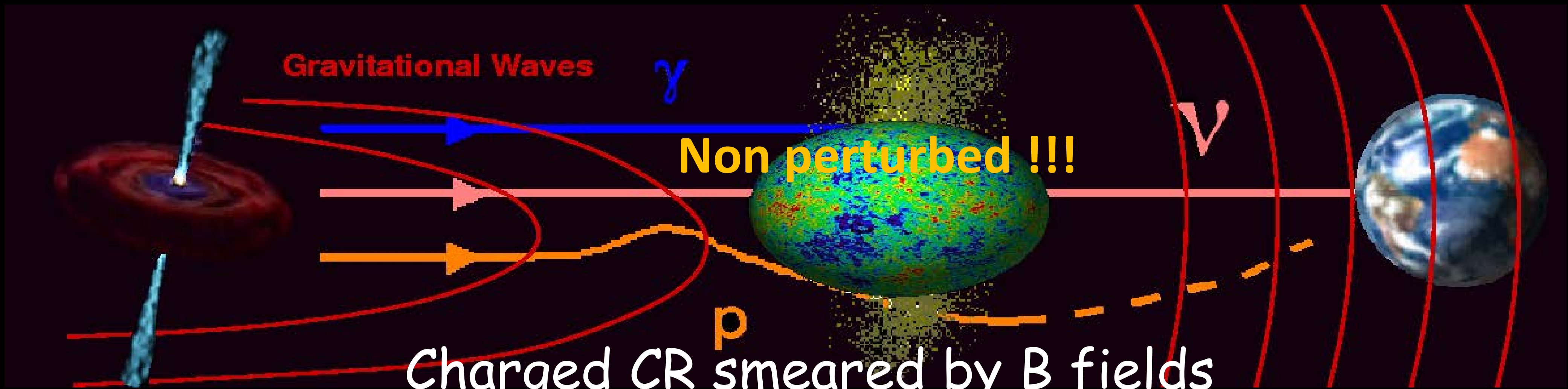


SN1006

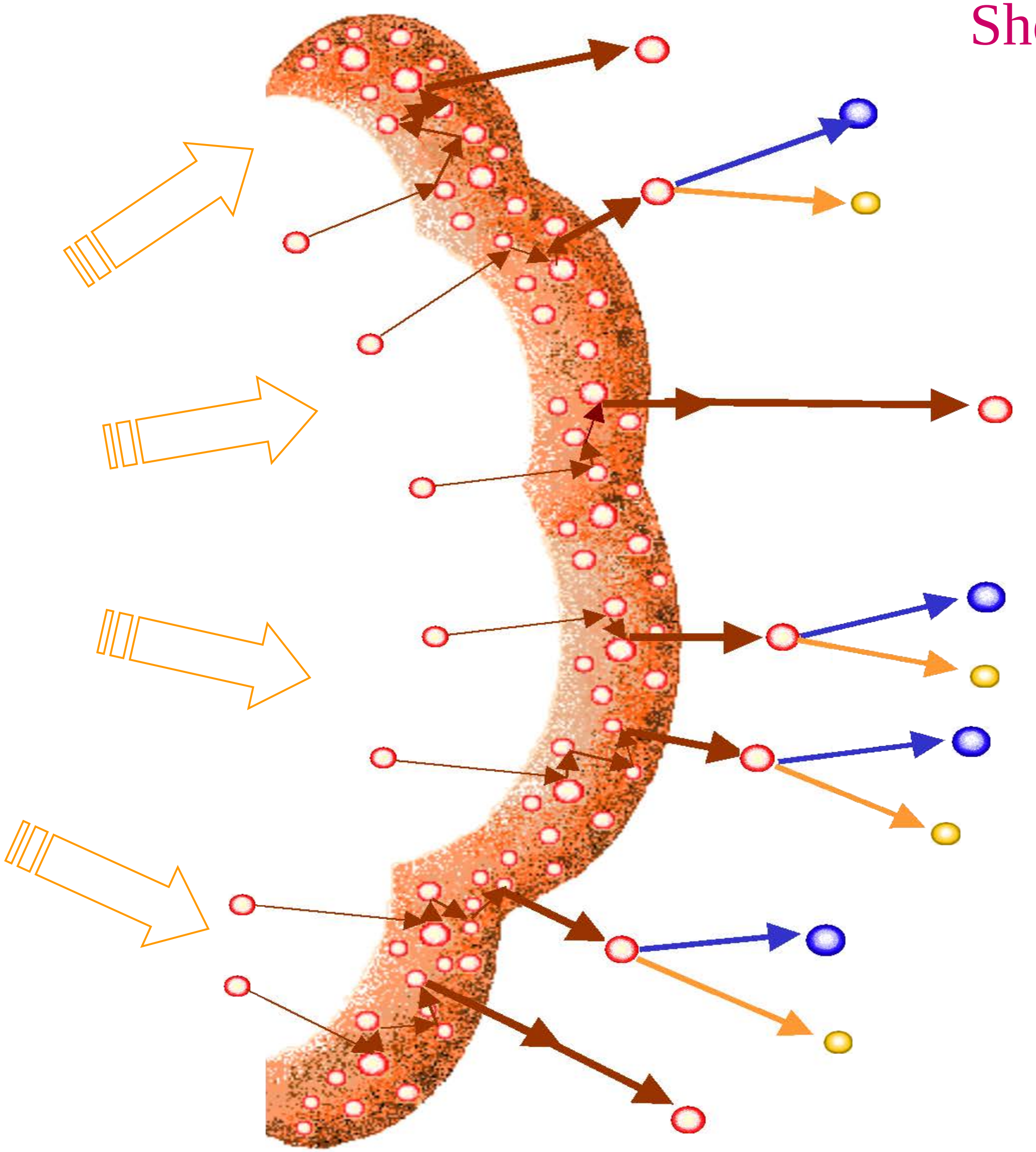


Cosmic Neutrino Beam





Fermi acceleration and UHE neutrino production



Shock wave proton of nuclei acceleration:

p/N interact with the ISM and produce pionic cascades

$$p/A + p/\gamma \rightarrow \pi^0 + \pi^{\pm} + \ldots$$

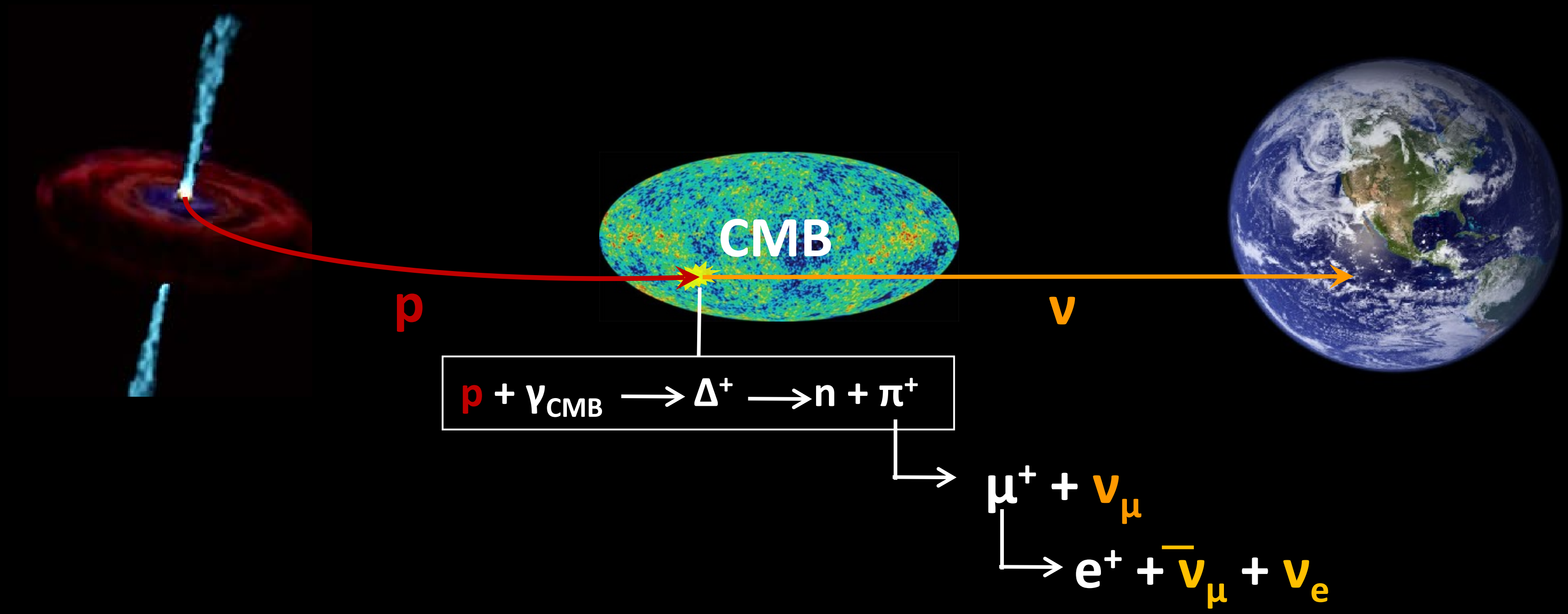
$\pi^0 \downarrow \gamma\gamma$

$\pi^{\pm} \downarrow \nu_\mu\ \mu$

$\mu \downarrow \nu_\mu\ \nu_e\ e$

"Cosmogenic" or "GZK" Neutrinos

- Produced by the propagation of UHECR in the IGM.
- Main assumptions:
  - UHECR are protons or nuclei (makes a big difference!)
  - The sources distribution is following a given redshift distribution
  - Spectra are known and flux are generic
  - The target density is well known (CMB photons)
- This flux can be predicted in a relatively robust manner.



Cosmogenic or "GZK" Neutrinos

Expected Fluxes

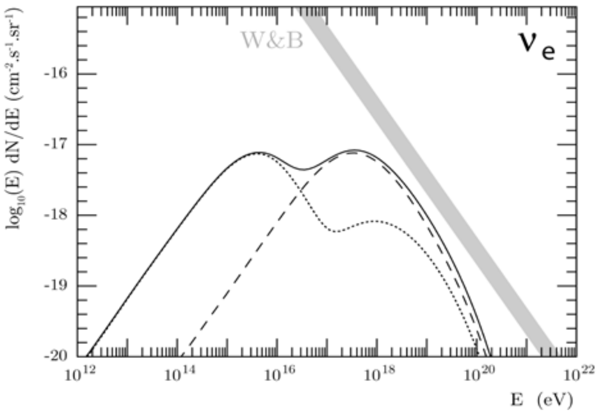
I - Sources	II – cosmic backgrounds	III – pγ Interaction
- Composition at the source - Spectral index + E_{max} - Source density + cosmological evol.	- Backgrounds (CMB, CIB…) - Photon spectrum evol vs z	- Cross Section - Differential cross-sections - Energy Distribution
Many uncertainties	CMB very well known. CIB and other bg less known	Very well known

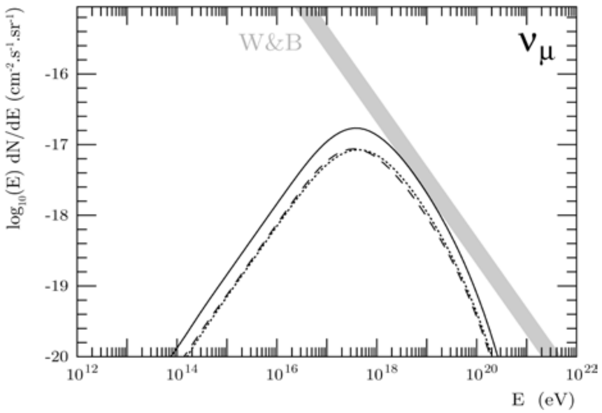
I + II + III ➔

$\nu_\mu:\nu_e:\nu_\tau$ = 2:1:0 (source)

oscillations ↓

1:1:1 (earth)

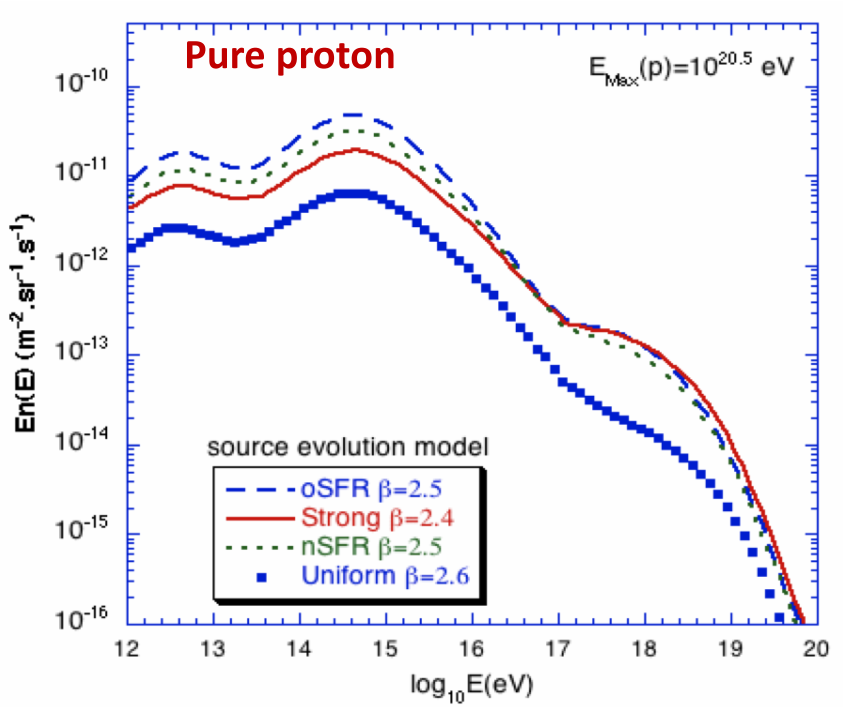


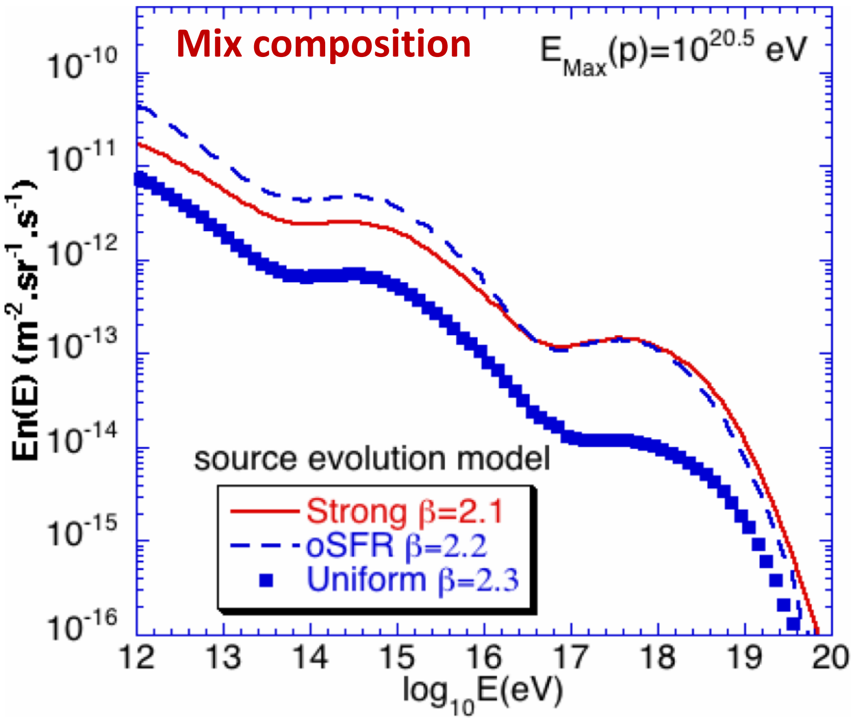


Flux of "GZK" neutrinos

Influence of

- Composition of UHECR,
- Sources distribution and evolution.



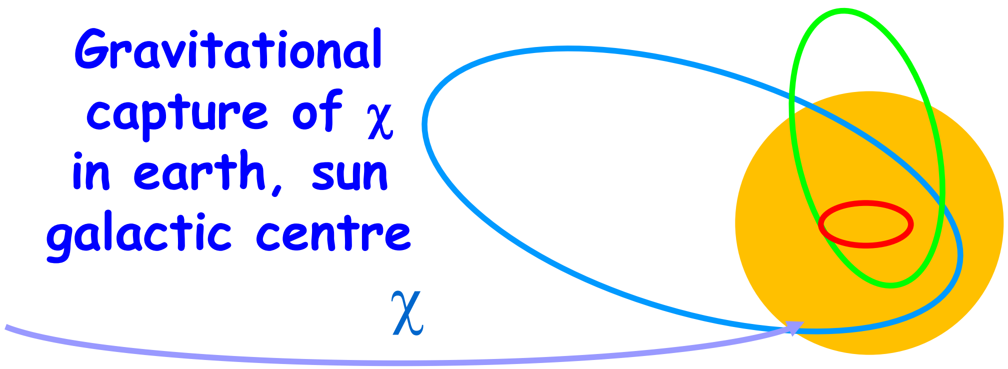


Dark Matter as a source of neutrinos

Annihilation in Halo, Earth, Sun or Galactic Centre

Signature	Experiment
Halo Positron, Antiproton Gamma rays $\chi\ \chi \rightarrow Z\gamma,\ \gamma\gamma$	BESS, CAPRICE, AMS, .. HESS, GLAST, MILAGRO,….
Earth, Sun, GC Neutrino $\chi\ \chi \rightarrow WW,\ ff$ $W, f \rightarrow \nu X$	SuperK, Baksan,IMB, MACRO AMANDA, ANTARES, Baikal, …

Gravitational capture of χ in earth, sun galactic centre



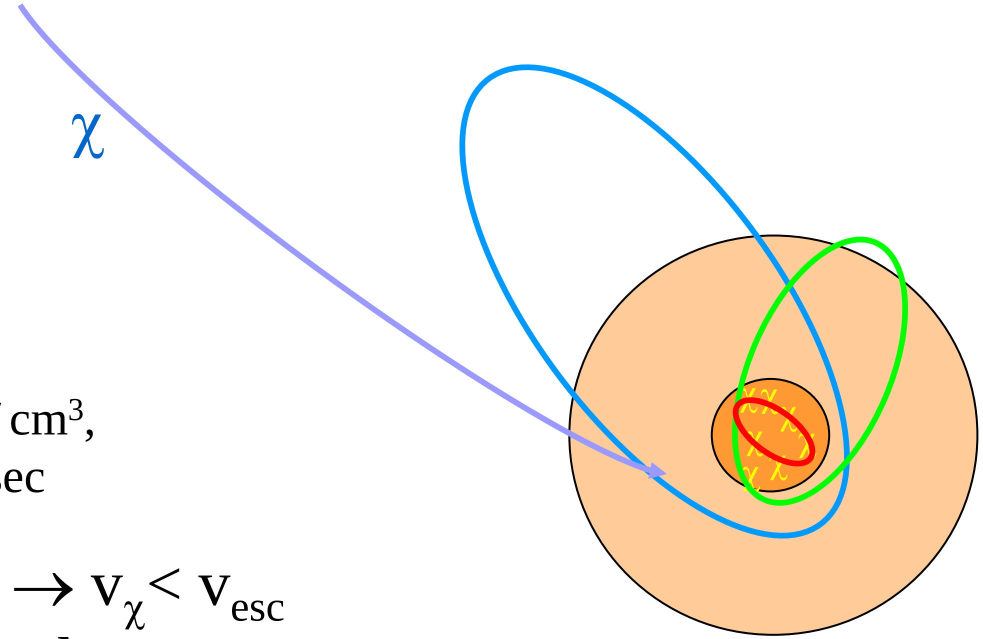
WIMP looses energy by elastic interaction

$\Rightarrow$ if $v < v_{escape}$, capture

capture + annihilation balance

$\Rightarrow$ constant density in core

Dark Matter as a source of neutrinos



DM halo

$\rho_\chi \sim 0.3$ Gev/ cm^3,
$v_\chi \sim 300$ km/sec

Collisions → $v_\chi < v_{esc}$
Gravitational capture
in the center
gravitational wells

$$\chi + \chi \rightarrow WW \quad bb \quad \ldots$$
$$\downarrow \qquad \downarrow$$
$$\mu\nu \qquad c\mu\nu$$
$$E_\nu \sim 0.3 - 0.5 \times m_\chi$$

⇒ Indirect search for Neutralinos by neutrino telescopes

Propagation

The general problematic

- Thermal speeds $\rightarrow$ RCUHE (few 10^{20} eV)

Produce them

- From top to bottom (decay…)
- From bottom to top (acceleration)

Preserve them

- Energy losses (Synch., IC, π, pairs…)
- Destruction (photo-dissociation…)
- Escape probabilities

Propagate them

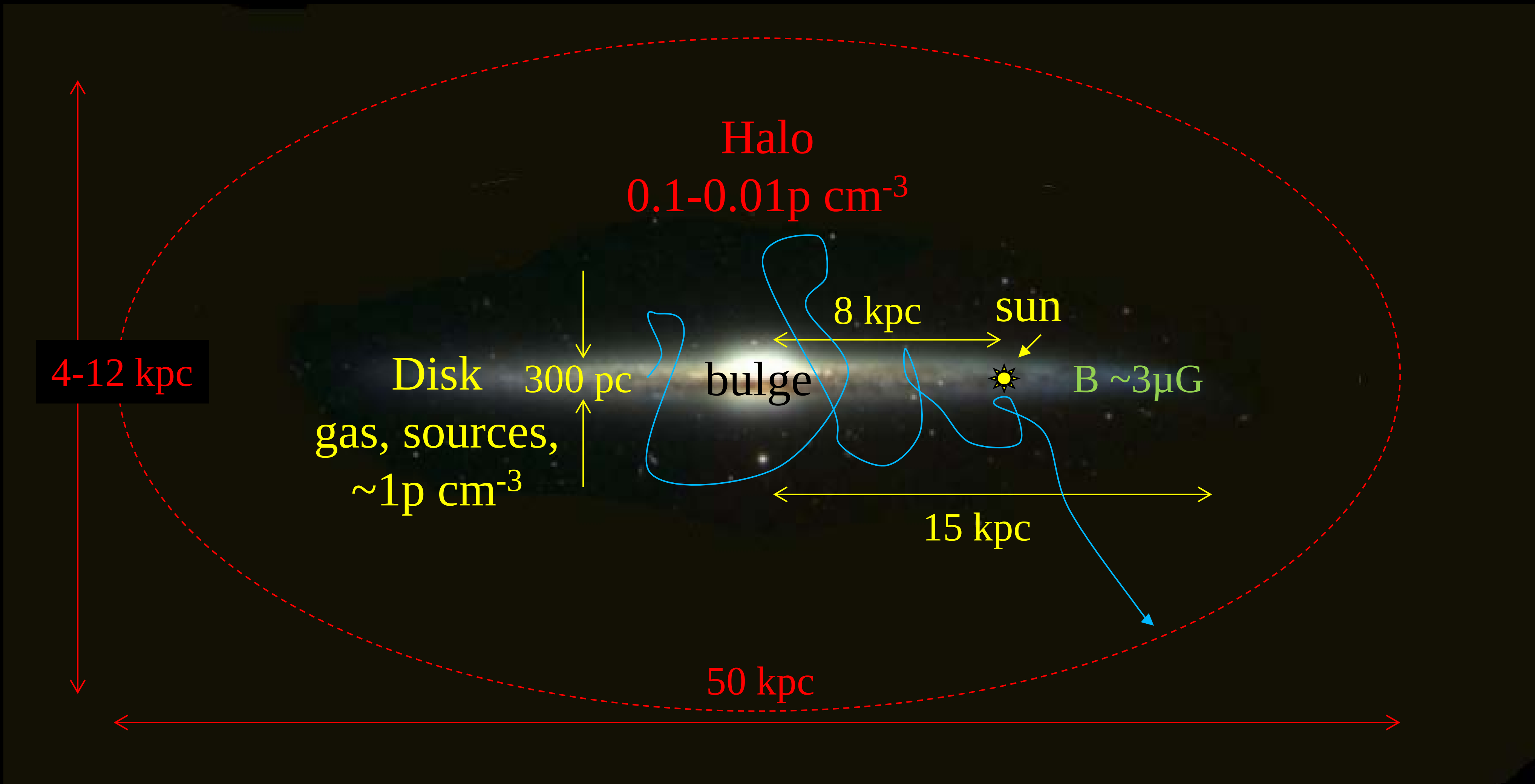
- Propagation in ISM and IGM (mag fields: deflection, confinement…)
- Re-acceleration

Detect them

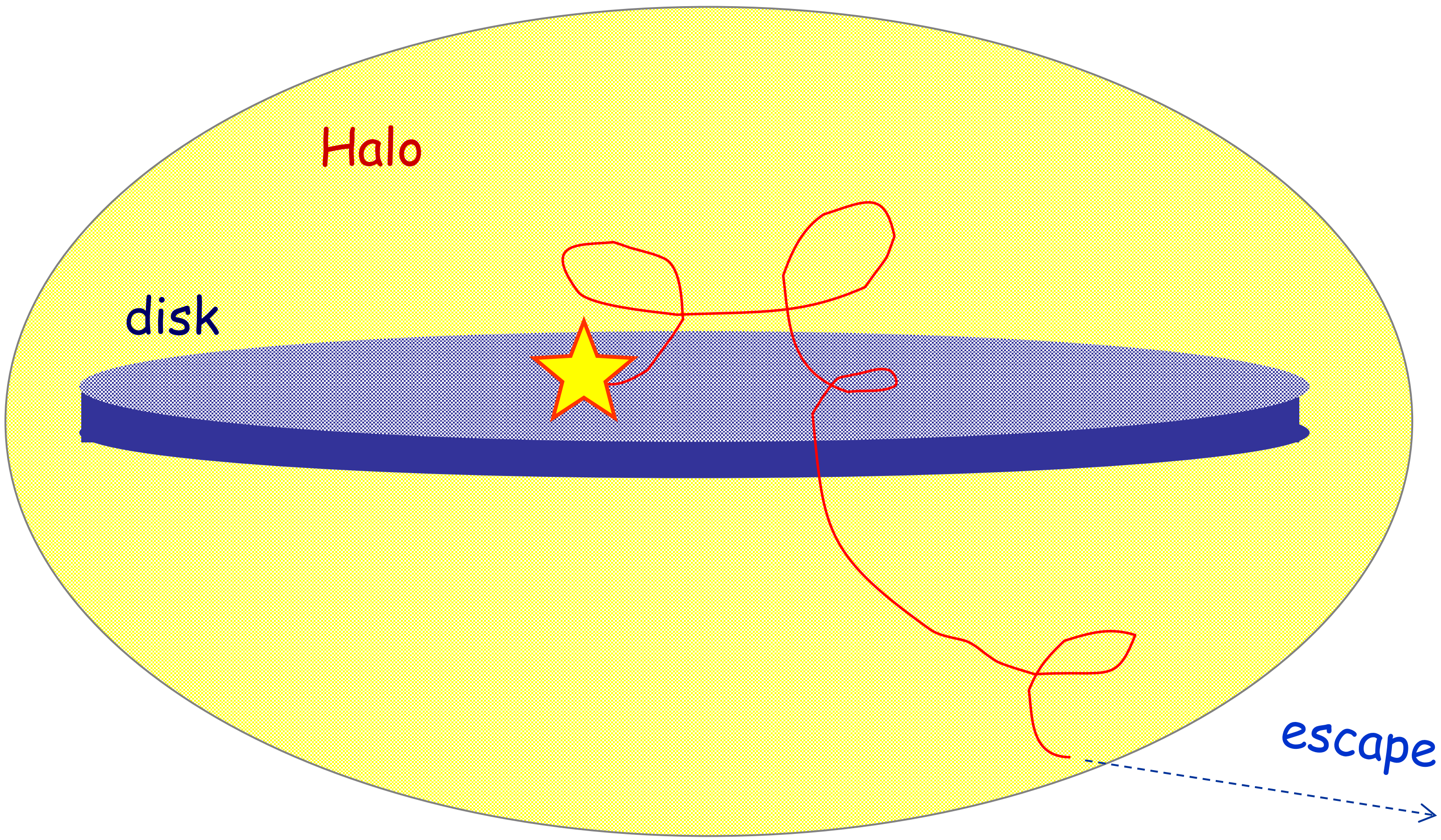
- Balloons, satellites…
- Air showers…
  - Cherenkov telescopes
  - Surface & Fluorescence Detectors

Dimensions of the Milky Way

$1\ pc \approx 3\ l.y. \approx 3 \times 10^{16}\ m$

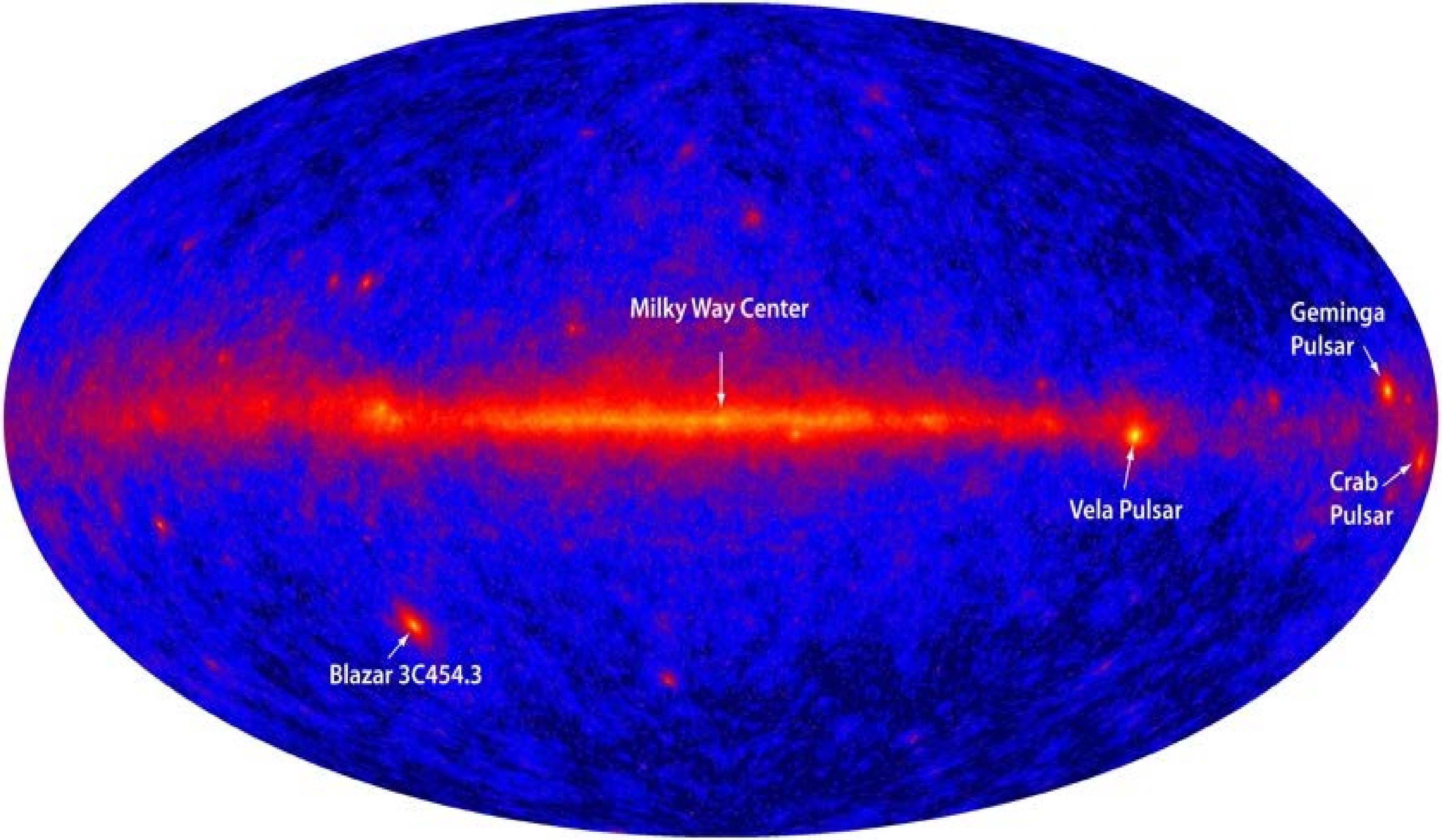


RC propagation in the Galaxy : the Leaky Box Model



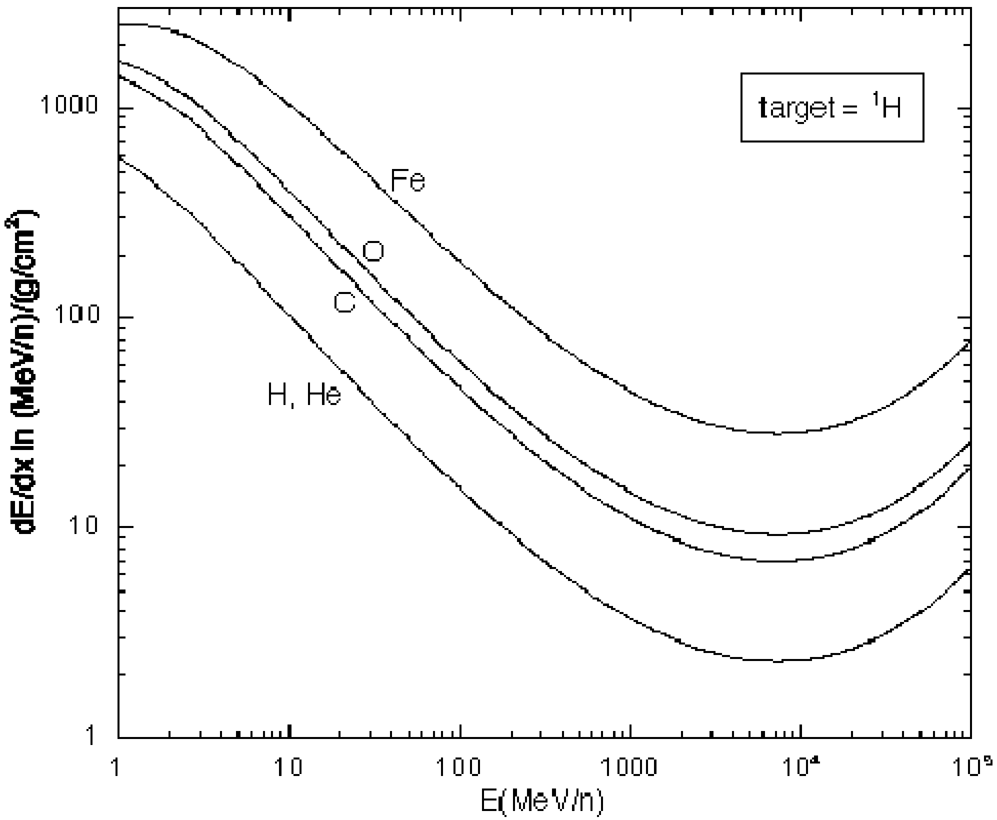
A thick target

- Diffuse gamma-ray emission from galactic CR interaction with matter (mostly molecular H clouds).

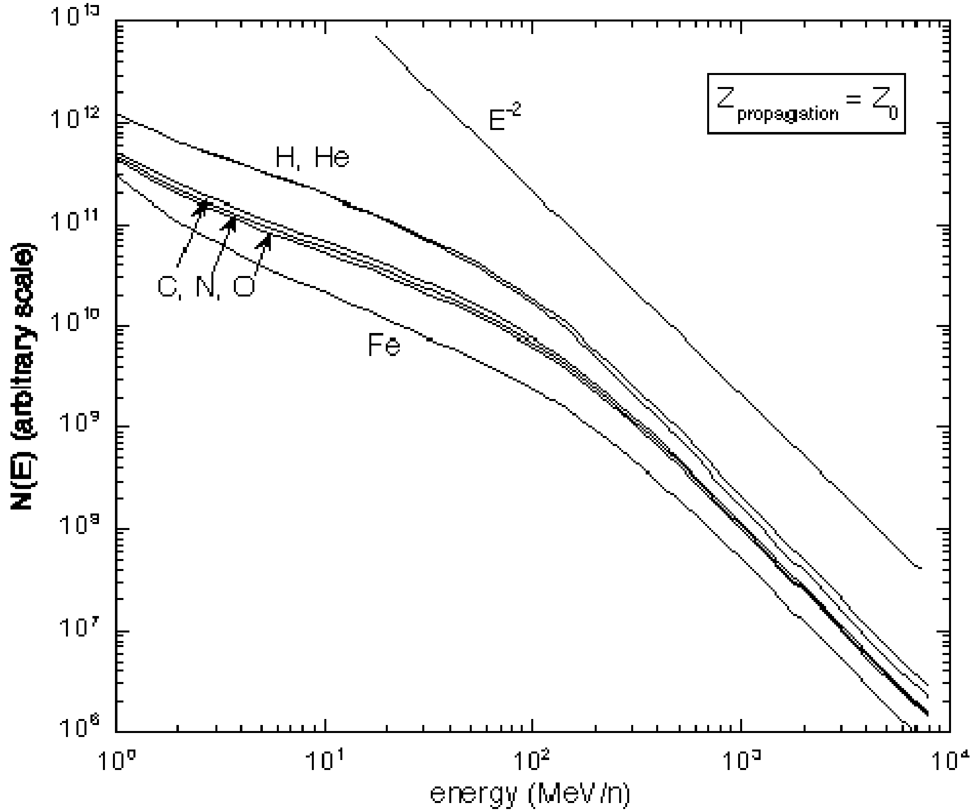


Cosmic rays transport

- Propagation in the interstellar medium



Energy loss: ionization, Coulombian interactions



Propagated spectra ionization losses only (thick target)

Grammage

- Column density or quantity of matter traversed by the CR from its production site to earth (in $kg \cdot m^{-2}$ or $g \cdot cm^{-2}$)
- Given the diffusion time known from cosmic clocks (see below) the measurement of grammage allows the understanding of the diffusion extension zone.
- The ratio secondary/primary allows estimating the grammage traversed:

$$\frac{dN_S}{dx} = -\frac{\sigma_P}{m} N_P$$

$$\text{donc} \quad N_S = N_P \exp -\frac{\sigma_P}{m} x$$

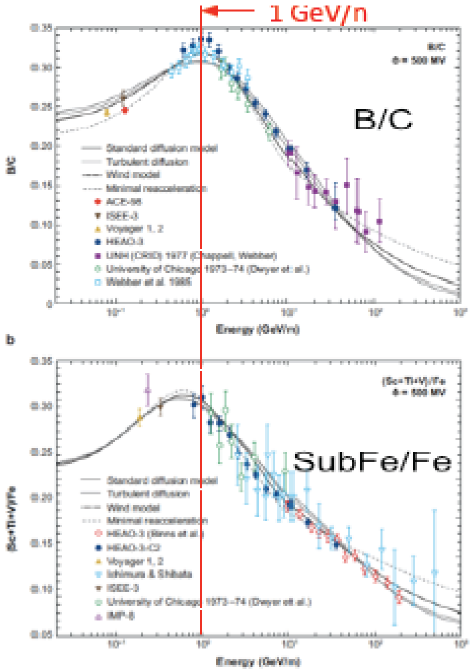
$$\text{et} \quad x = -\frac{m}{\sigma_P} \log(S/P)$$

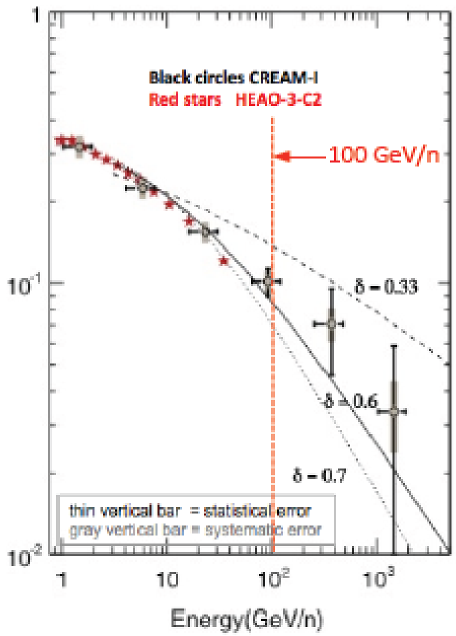
$$\text{B/C} \approx 35\% \Rightarrow x = -\frac{m}{\sigma_P} \log(B/C) \approx 60 kg.m^{-2}$$

$$\text{if} \quad Br(C + P \to B + X) \approx 100\%$$

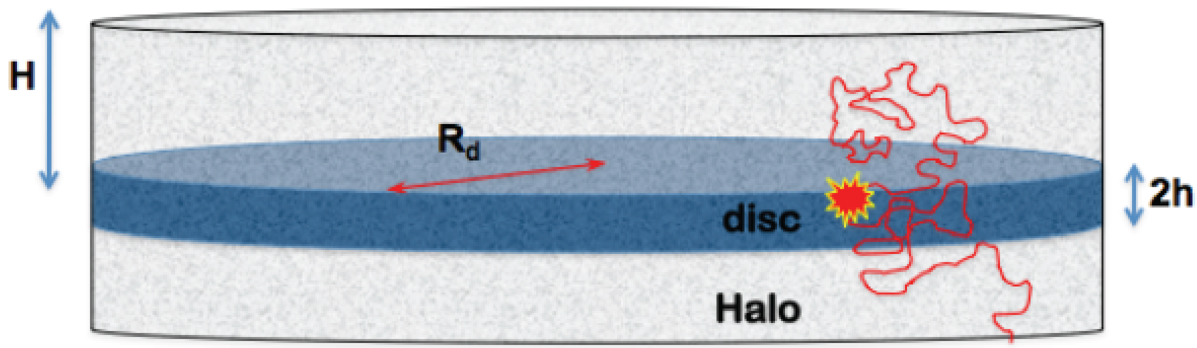
ECRS 2016 Torino, *P.S. Marrocchesi*

Secondary/Primary Nuclei Ratios





- Secondary/primary nuclei ratios decline for E > 1 GeV/n
- At high energy (E > 100 GeV/n) the S/P ratios measure the **rigidity R dependence of diffusion D(R)**
- Source spectra observed at Earth soften as a result of propagation in the Galaxy. In first approximation they factorize as $E^{-\delta}$



PRIMARY COSMIC RAY SPECTRUM AT EARTH

$$n_{CR}(E) = \frac{N(E)\,\mathcal{R}}{2\pi R_d^2}\frac{H}{D(E)} \equiv \frac{N(E)\,\mathcal{R}}{2H\pi R_d^2}\frac{H^2}{D(E)} \propto E^{-\gamma-\delta}$$

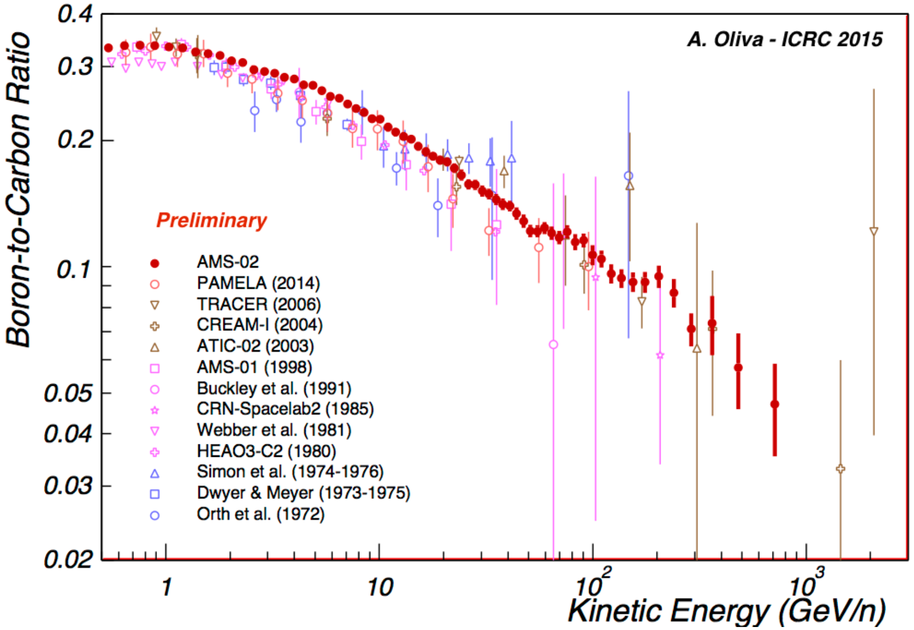
- **BUT** the diffusion coefficient might also depend on positon and have a **tensor** character (see next slide)

Secondary / Primary ratio

The grammage depend on the parent nucleus:

- (Li+Be+B) / (C+N+O) ⇒ mean grammage of 50 kg.m^{-2}
- (Sc+Ti+V)/Fe ⇒ mean grammage of 20 kg.m^{-2}

and Primary/Secondary ratio (thus grammage) depends on the energy as well:

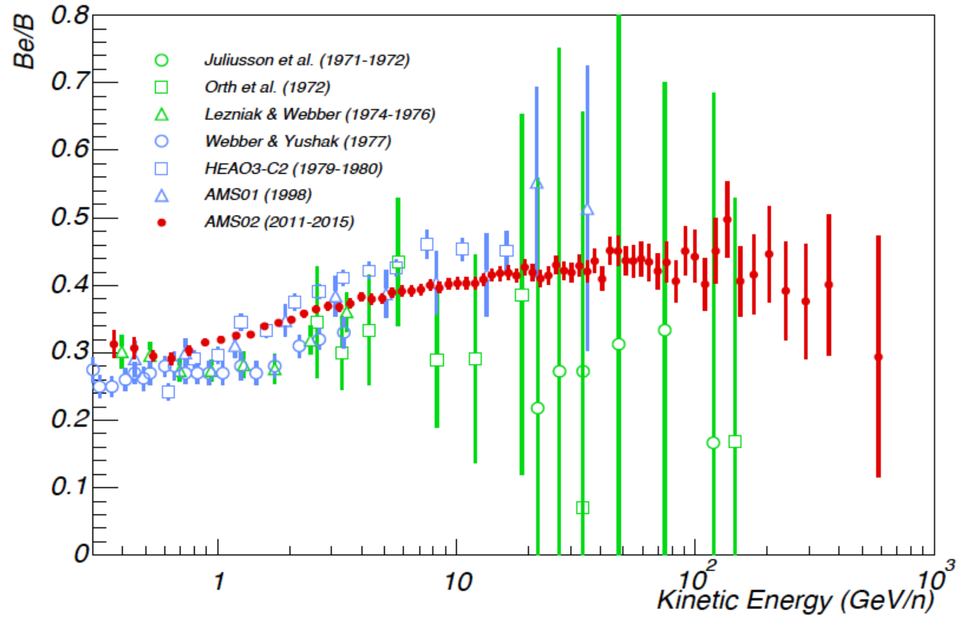


Beryllium-to-Boron Flux Ratio

C, N, O,..., Fe + ISM → Li, Be, B + X

B + ISM → Li, Be + X

^{10}Be → ^{10}B + e^{-} + ν_e



Secondary / Primary ratio

- A complete CR transport model
  - **The secondary to primary ratio can be expressed by:**

$$\frac{N_S}{\tau_{esc}} + \frac{N_S}{\tau_{spallation}} = \frac{N_P}{\tau_{P \to S}}$$

$$\Rightarrow \frac{N_S}{\tau_{esc}} + n\beta c \sigma_S N_S = n\beta c \sigma_{P \to S} N_P$$

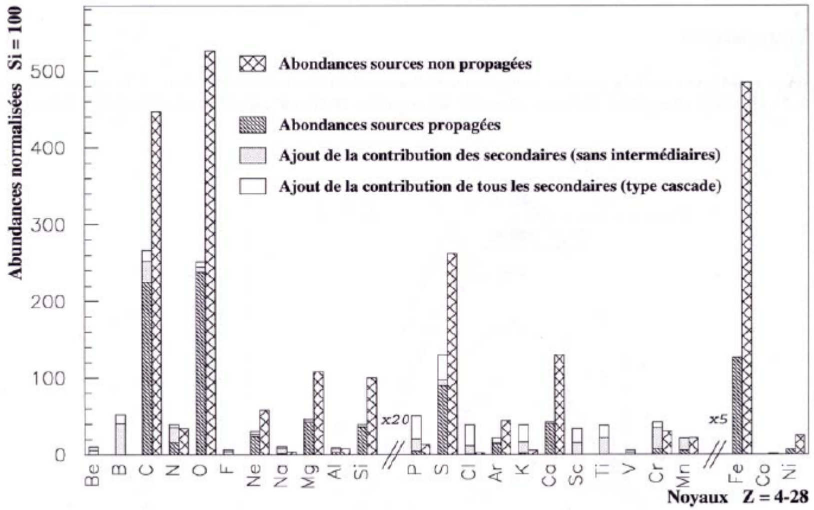
$$\frac{N_S}{N_P} = \frac{\sigma_{P \to S}}{\sigma_S + 1/\lambda_{esc}}$$

with $\lambda_{esc} = n\beta c \tau_{esc}$

Cosmic clocks

Unstable nuclei with lifetimes comparable to the escape time $T_{1/2} \approx \tau^{esc}$ can be used as cosmic clocks.
The ratio unstable/stable isotope helps desantangling density and escape time.

$$^{10}Be \rightarrow \tau = 2.17 Myr$$
$$^{26}Al \rightarrow \tau = 1.31 Myr$$
$$^{36}Cr \rightarrow \tau = 0.44 Myr$$



$$\frac{N_j}{\tau_{esc}} + \frac{N_j}{\tau_{rad}} + \frac{N_j}{\tau_{spallation}} = Q_j + \sum_{k>j} \frac{N_j}{\tau_{k \rightarrow j}}$$

Si $\tau_{rad} \ll \tau_e$ et $\tau_{rad} \ll \tau_{spallation}$:

Measure isotopic ratio

$$\frac{N_{rad}}{N_{stable}} = \frac{\tau_{rad}}{\tau_{esc}} + \frac{\tau_{rad}}{\tau_{spallation}}$$

Estimate escape time.

On gets $\tau_e \approx 20 Myr$

Cosmic clocks and halo size

- Radioactive decay:

$$\frac{N_j}{\tau_{esc}} + \frac{N_j}{\tau_{rad}} + \frac{N_j}{\tau_{spallation}} = Q_j + \sum_{k>j} \frac{N_j}{\tau_{k\to j}}$$

Measure isotopic ratios →

$$\frac{N_{rad}}{N_{stable}} = \frac{\tau_{rad}}{\tau_{esc}} + \frac{\tau_{rad}}{\tau_{spallation}}$$

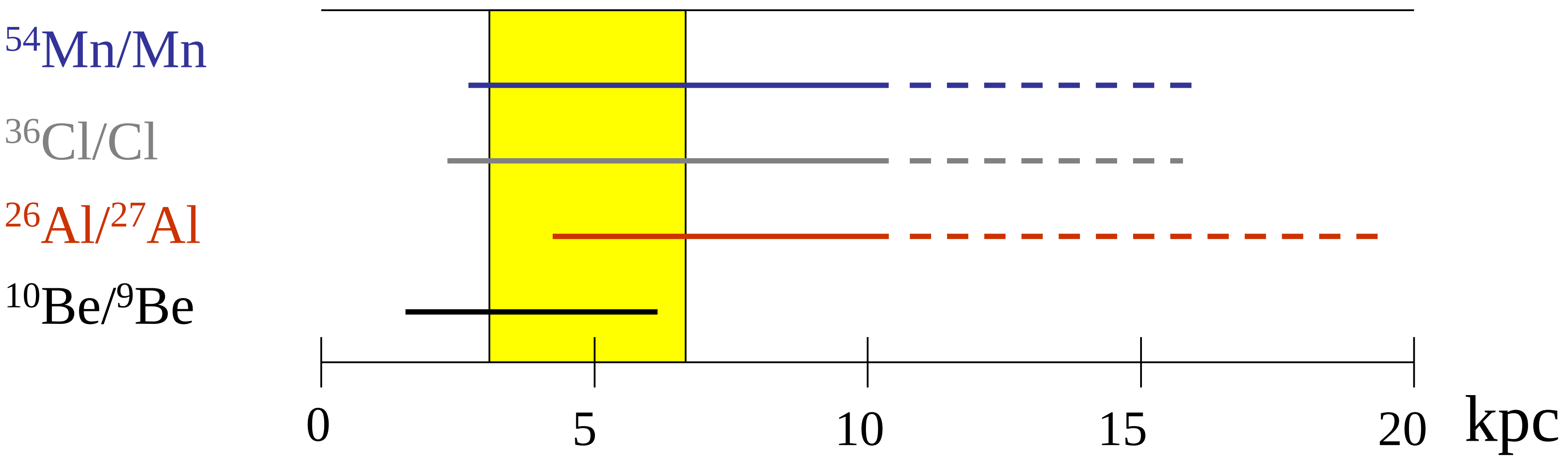
→ Estimate escape time

- $^{12}C + H \rightarrow {}^{9}Be$ (stable secondary nucleus)
  $^{12}C + H \rightarrow {}^{10}Be$ (unstable secondary nucleus: ~ 4×10^{8} years)
- The ratio ^{10}Be / ^{9}Be depends on secondaries **history** (and on cross sections).
  - Link between quantity of matter traversed and diffusion time.

Cosmic clocks and halo size

- $^{12}C + H \rightarrow\ ^{9}Be$ (stable secondary nucleus)
  $^{12}C + H \rightarrow\ ^{10}Be$ (unstable secondary nucleus: ~ 4×10^{8} years)
- The ratio $^{10}Be\ /\ ^{9}Be$ depends on secondaries **history** (and on cross sections).
  - Link between quantity of matter traversed and diffusion time.
- Diffusion parameters adjustments (excursion in the less dense galactic halo)

  $\Rightarrow$ determination of the CR confinement zone



Confinement and escape

- The average measured grammage is $x = 50 kg.m^{-2}$
- Associated lengths:

$$\begin{aligned} \lambda_{esc} &= x/\rho \approx 750 kpc, \\ \text{with} \quad \rho &= 1.4\, n_H\, m_p \approx 2.2 \times 10^{-21} kg.m^{-3} \end{aligned}$$

- $\lambda_{esc} \gg R = 20 kpc$ $\Rightarrow$ CR are confined
- $\lambda_{esc} \ll \lambda_{pp} = (n_H\, \sigma)^{-1} \approx 6 Mpc$ $\Rightarrow$ CR can escape
- Long lived radioactive secondaries (cosmic clocks) indicate $\tau_{esc} \approx 20 Myr$
- Average density scanned by CR:

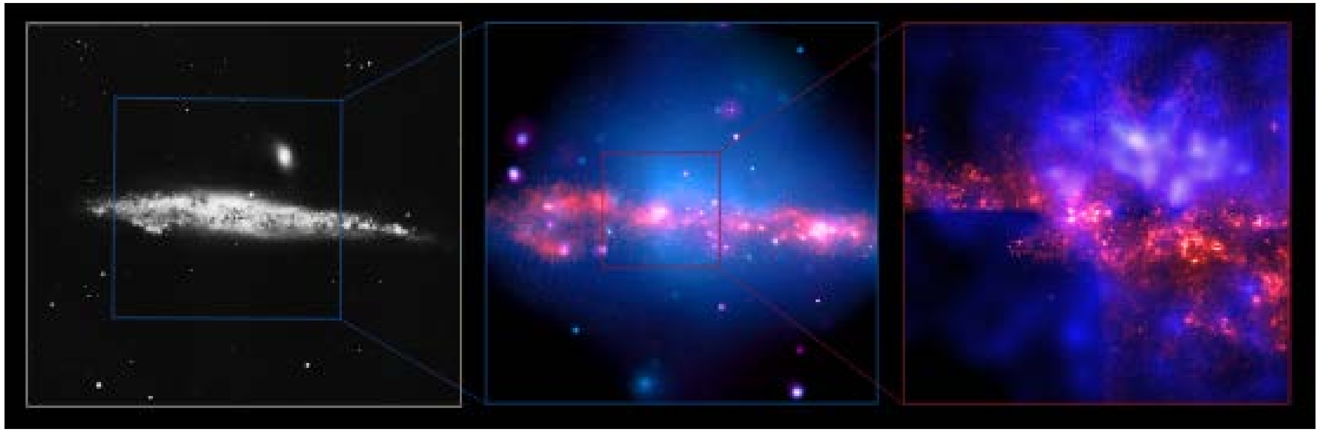
$$n_H = \lambda_{esc}/c\, \tau_{esc}\, m_p \approx 0.3 cm^{-3} < n_{disk} = 1 cm^{-3}$$

$\Rightarrow$ CR diffuse in a thinner region: the Halo

Disk & Halo

- CR can wander out of the disk in a magnetized halo of hot ionized matter

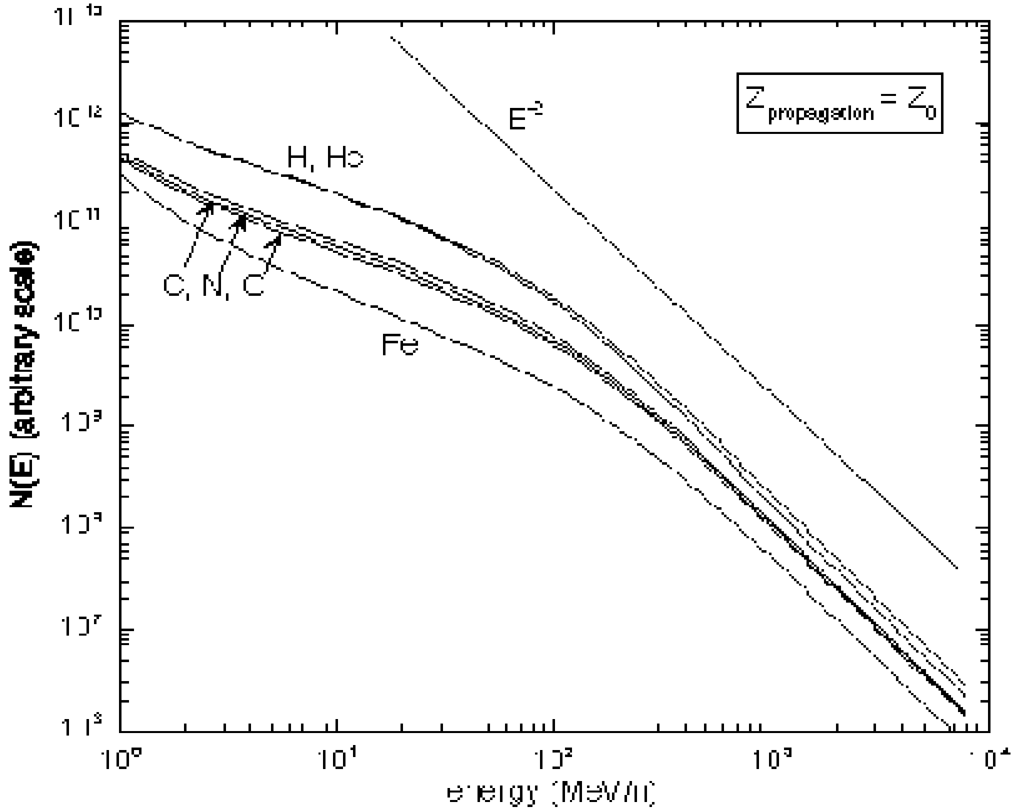
$$T = 10^6\ K \quad \text{et}\ n = 10^{-3} cm^{-3}$$



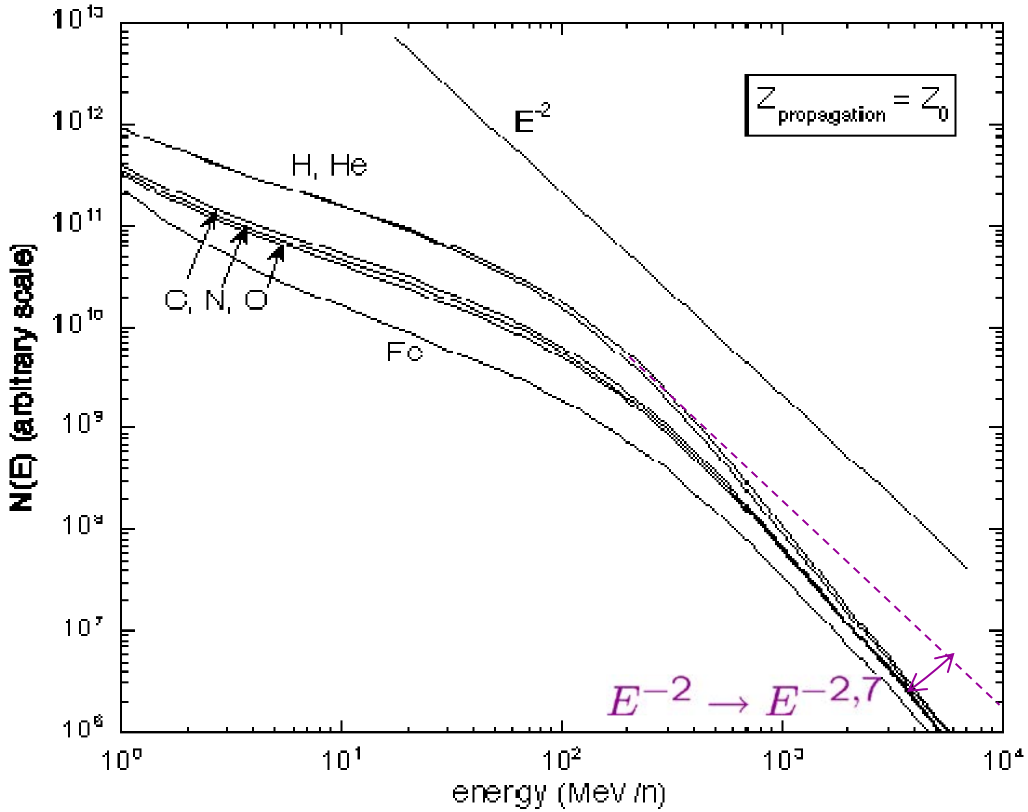
- NGC 4631 galaxy and its halo of hot ionized matter emitting X-rays as seen by Chandra

Slope of the propagated spectrum

- Escape out of the confinement zone
  - Confinement (escape probability) decrease with E



Without escape
(thick target)



$\tau_{conf} \propto E^{-0.7}$

$\rightarrow E^{-2.7}$ spectrum

CR confinement

- Escape depends on E
  - Diffusion on magnetic inhomogeneities
  - When $E \nearrow$, $r_g \nearrow$ thus interaction with inhomogeneities with larger wavelengths.

- $D(E)$ is an increasing function

$$D = \beta D_0 \left(\frac{\rho}{\rho_0}\right)^x$$ where ρ is the particle rigidity

$$\rightarrow \tau_{conf}(E) \propto E^{-x}$$

- Kolmogorov spectrum $\rightarrow \tau_{conf}(E) \propto E^{-1/3}$
  - $x - 2 = 1/3 < 0,7$ … clearly not enough but…
  - ISM perturbations ? Diffusion-convection, MHD ?

- Determination of $\tau_{conf}(E)$ a posteriori :

$$2,7 - 2 = 0,7 \text{ !!!}$$

Full transport equation

$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p)$$ sources (SNR, nuclear reactions…)

diffusion $$+ \vec{\nabla}.\left[D_{\chi\chi}\vec{\nabla}\psi - \vec{V}\psi\right]$$ convection

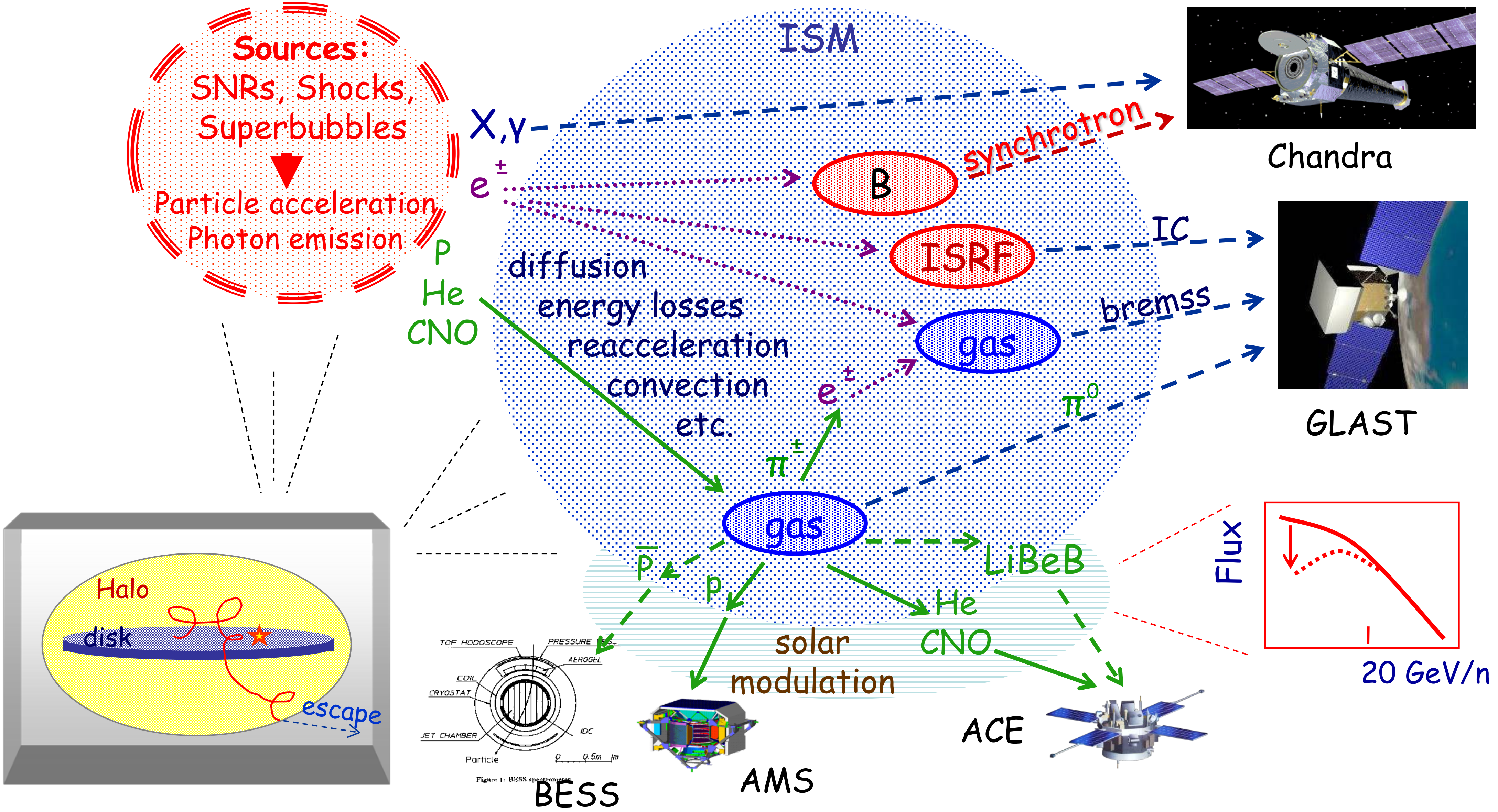
diffusive reacceleration $$+ \frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\left(\frac{\psi}{p^2}\right)\right]$$

E-loss $$- \frac{\partial}{\partial p}\left[\frac{dp}{dt}\psi - \frac{1}{3}p\vec{\nabla}.\vec{V}\psi\right]$$ convection

fragmentation $$- \frac{\psi}{\tau_f} - \frac{\psi}{\tau_d}$$ Radioactive decay

*ψ(**r**,p,t) – momentum density*

Propagation in the ISM et observational contrains



Summary for galactic CR

Everything works fairly well…

- Propagation in the ISM:
  - Complete theory with energy losses, diffusion, in flight nuclear reactions, CR escape, reacceleration, … impressive results.

(see for example GLAPROP model, A. Strong et I Moskalenko)

- Secondaries / Primaries
- Cosmic clock
- Anisotropies
- Theoretical expectations (~ Kolmogorov spectrum : $D(E) \propto E^{0.36}$)

…except naïve acceleration models!

- Observation + models require source spectra $\propto E^{-2.35}$ (high energy spectral shape and II^{aires}/I^{aires} ratio "best fit)
- "Softer" (steeper) than standard spectra for strong shocks f (E^{-2})

It is possible to find an agreement between diffusive propagation models and standard SNR models,

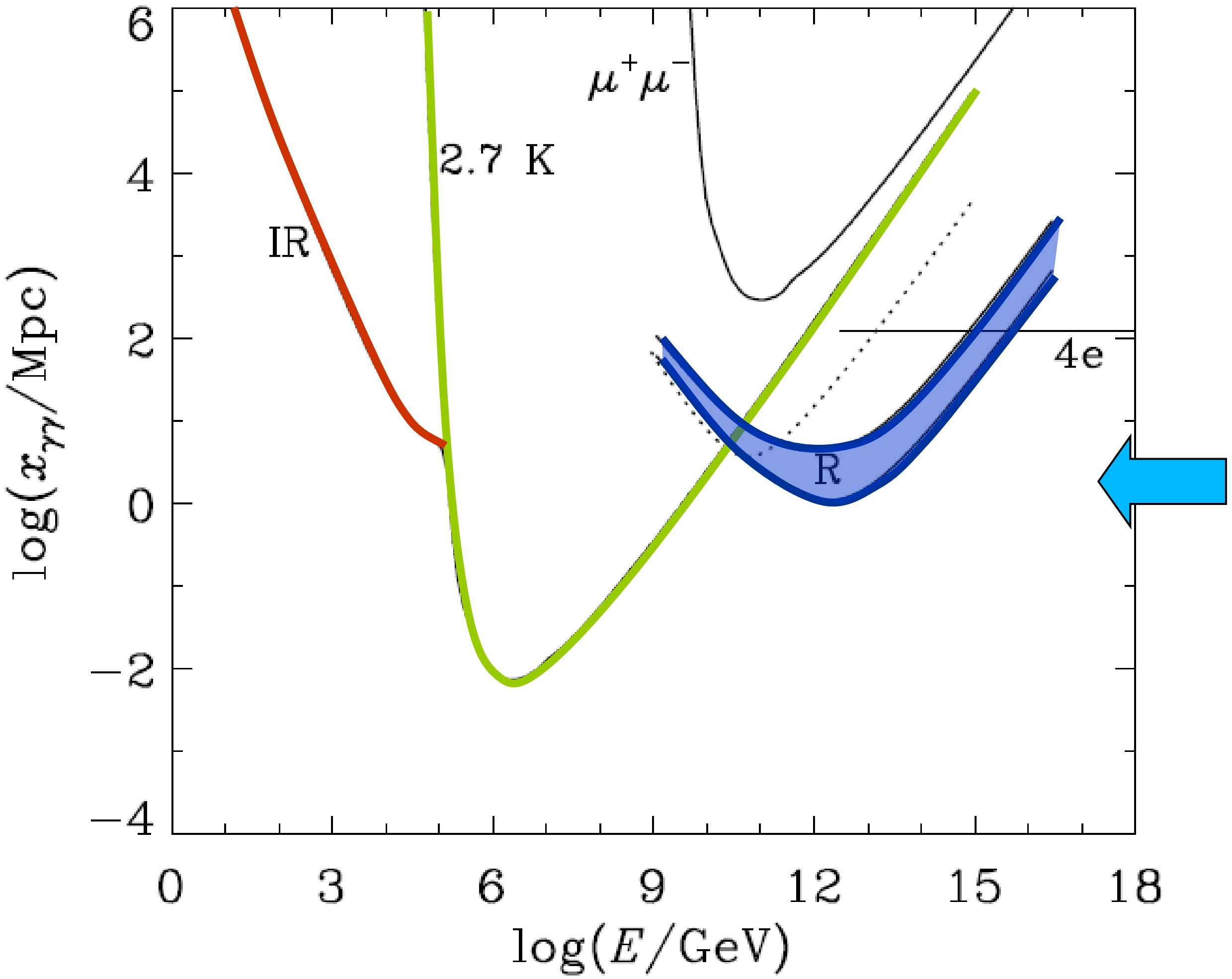
- Cut off energy, knee, non-linearities, γ-ray emission by SNR, source distribution…

Many parameters $\Rightarrow$ need many observational constrains.

GAMMA-RAY PROPAGATION

Photon attenuation at VHE
by intergalactic photon backgrounds

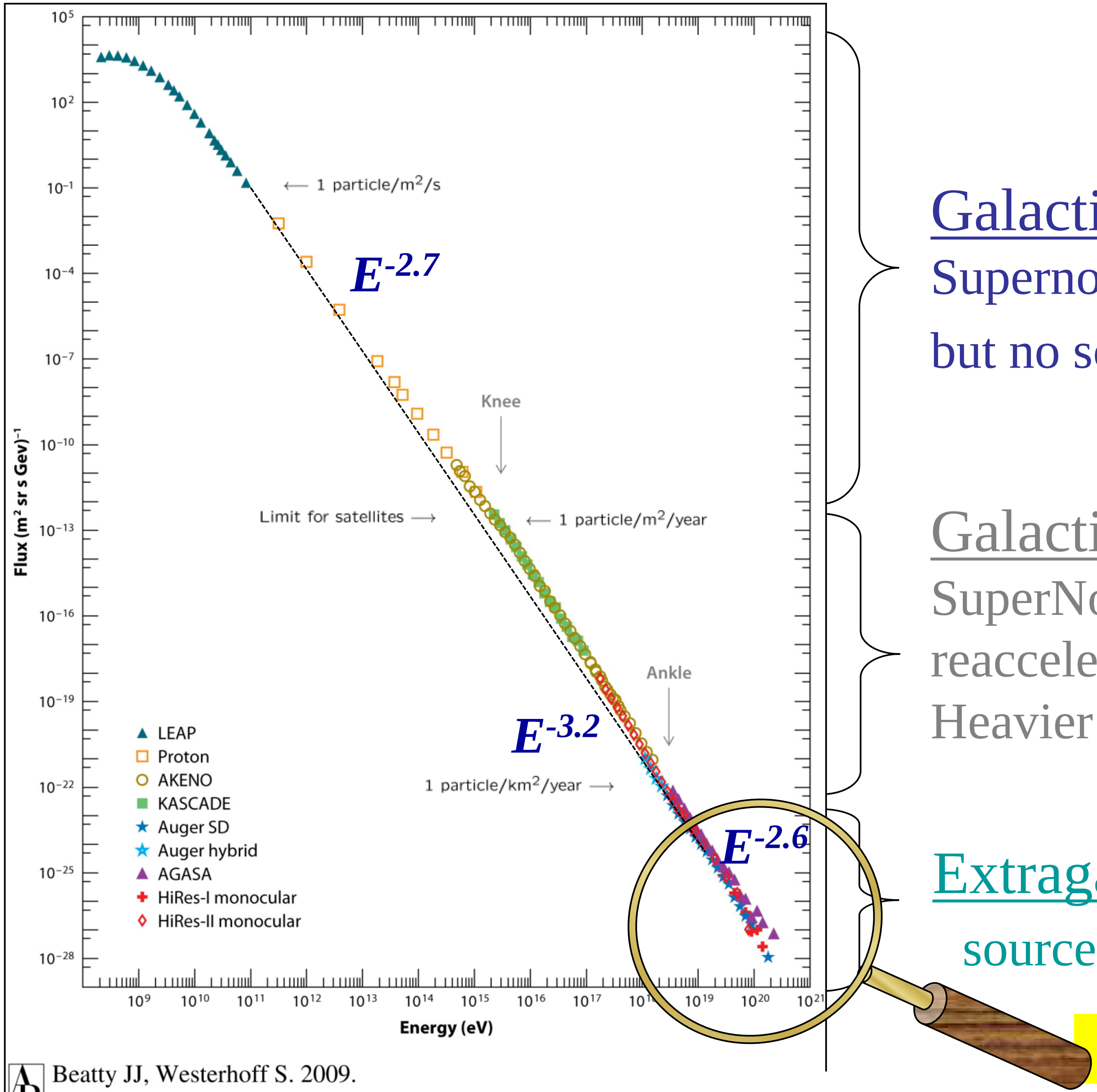
$$\gamma + \gamma_{BG} \rightarrow e^+ + e^-$$



Effective γ horizon:
100Mpc at 1TeV
1Mpc at 10 TeV
and above

UHECR PROPAGATION

The CR spectrum



Beatty JJ, Westerhoff S. 2009.
Annu. Rev. Nucl. Part. Sci. 59:319–45

Galactic CR :
Supernovae, MIS,
but no source pointing!

Galactic ?
SuperNovae? Superbubles?
reacceleration?
Heavier nuclei → protons ?

Extragalactic ?
source ? composition ?

UHECR, terra incognita

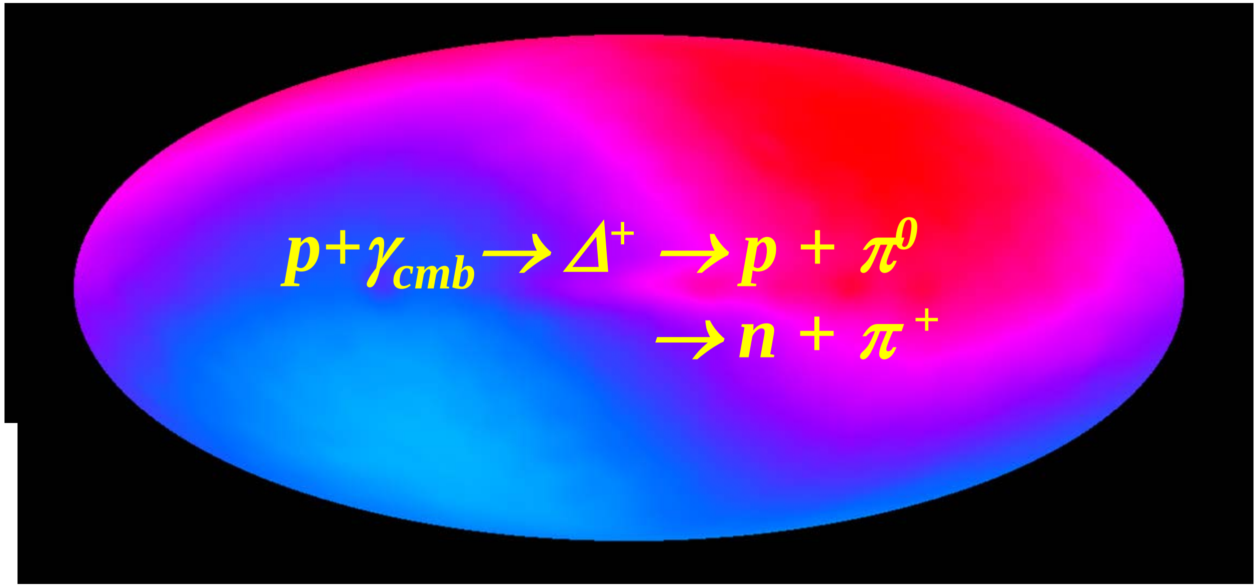
AUGER

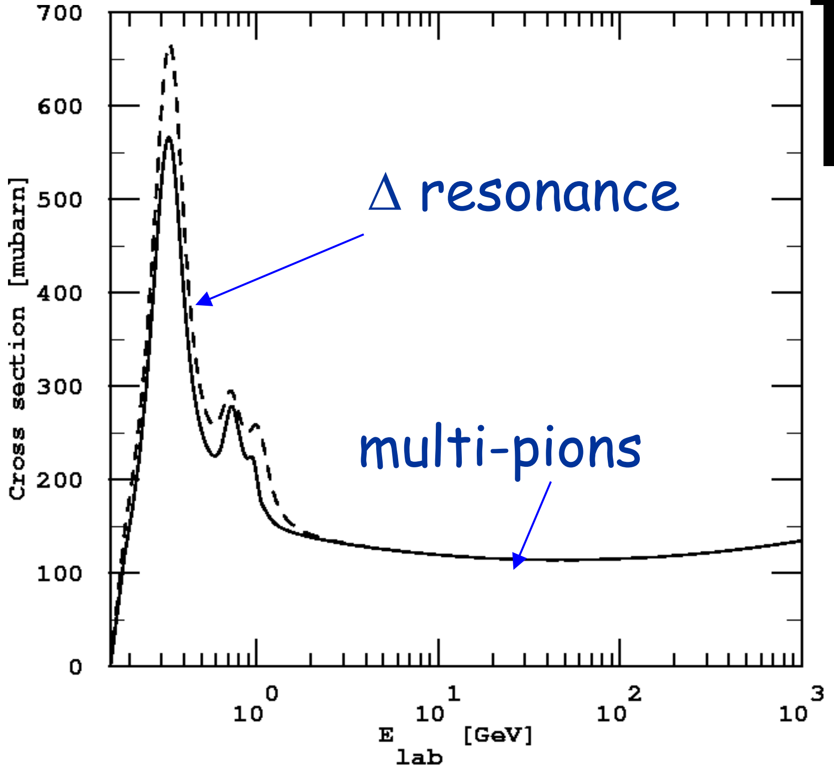
UHECR propagation

3 essential effects :

- Energy losses: modify the spectral shape
- Particle confinement
  (escape depending on energy)
- Spatial and angular diffusion
  due to magnetic fields.
  (regular or fluctuating, inhomogeneities, waves)

An extreme case of relativistic kinematics !!!



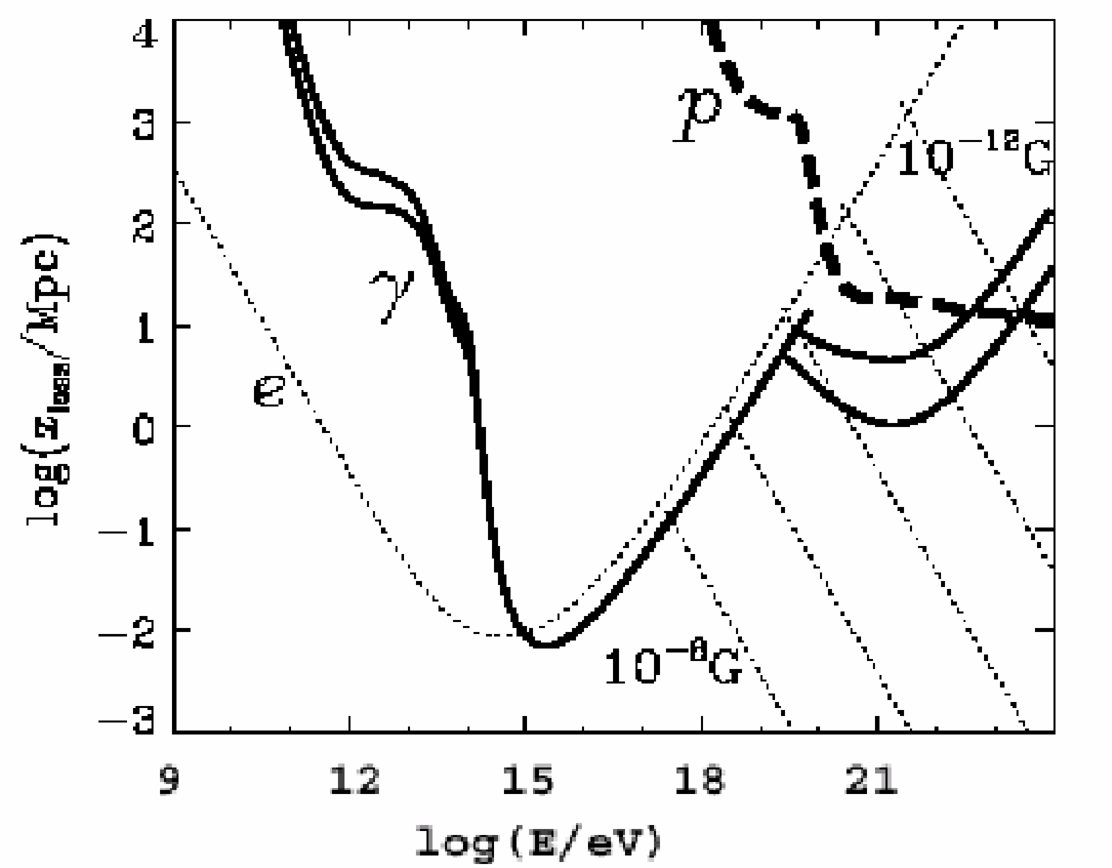


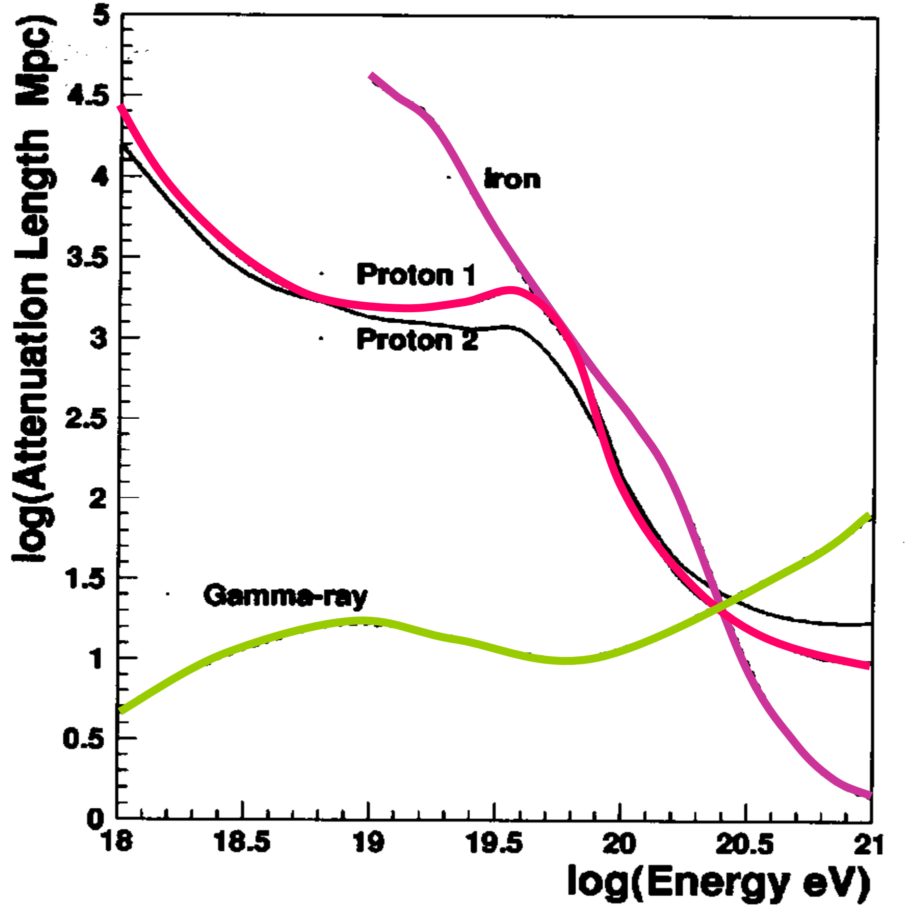
GZK "cutoff"

Greisen '66, Zatsepin & Kuzmin '66

Energy losses

- $p + \gamma_{2.7K} \rightarrow n + \pi^+; p + \pi^0; p + e^+ + e^-$
- $A + \gamma_{2.7K} \rightarrow (A-1) + N; (A-2) + 2N; A + e^+ + e^-$
- $\gamma + \gamma_{2.7K} \rightarrow e^+ + e^-$





Consequences on spectral shape

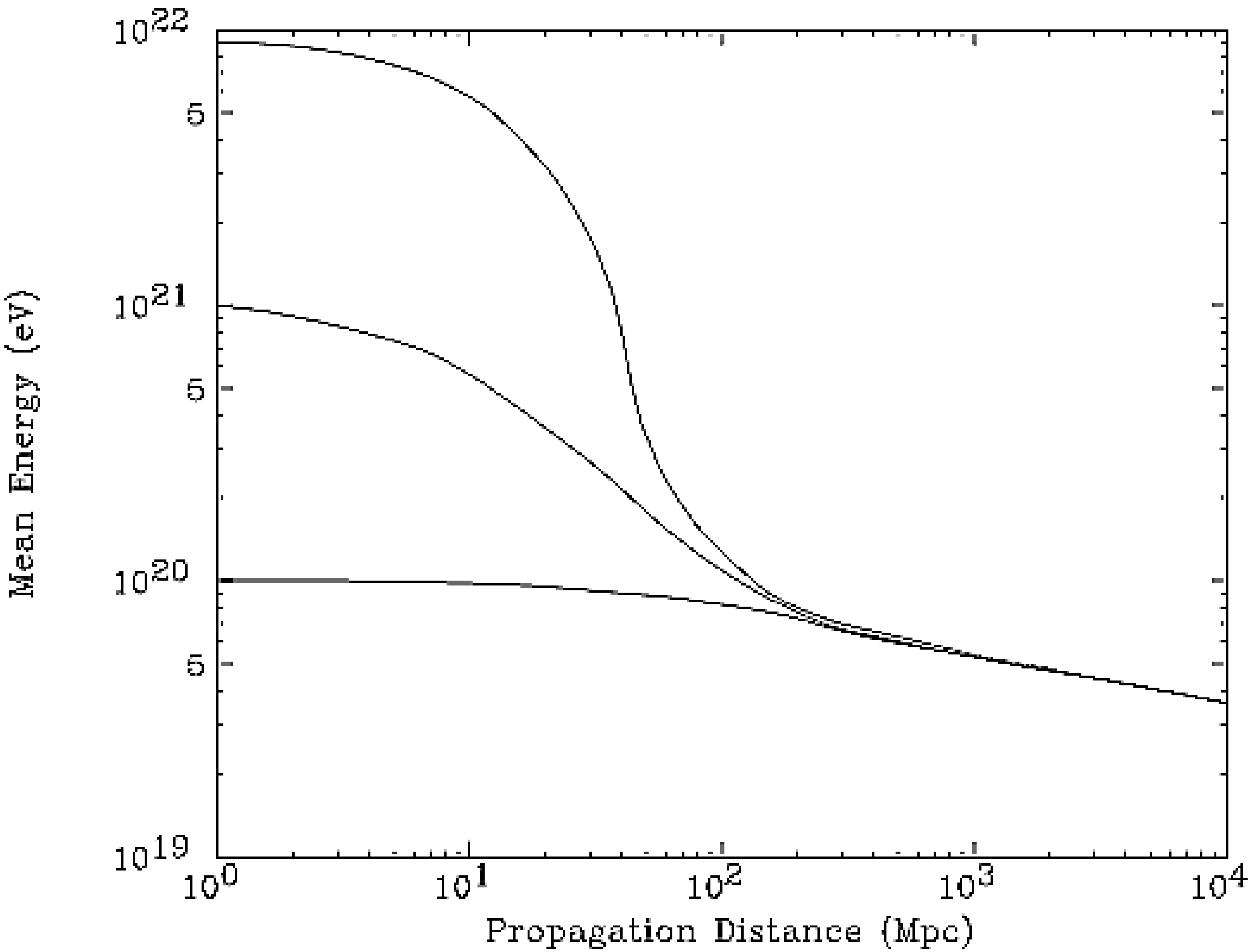
Protons:

Photo Pion production
CMB photons

$p+\gamma_{cmb} \rightarrow \Delta \rightarrow p/n+\pi$

Fe:
photo-dissociation
on IR bg and CMB

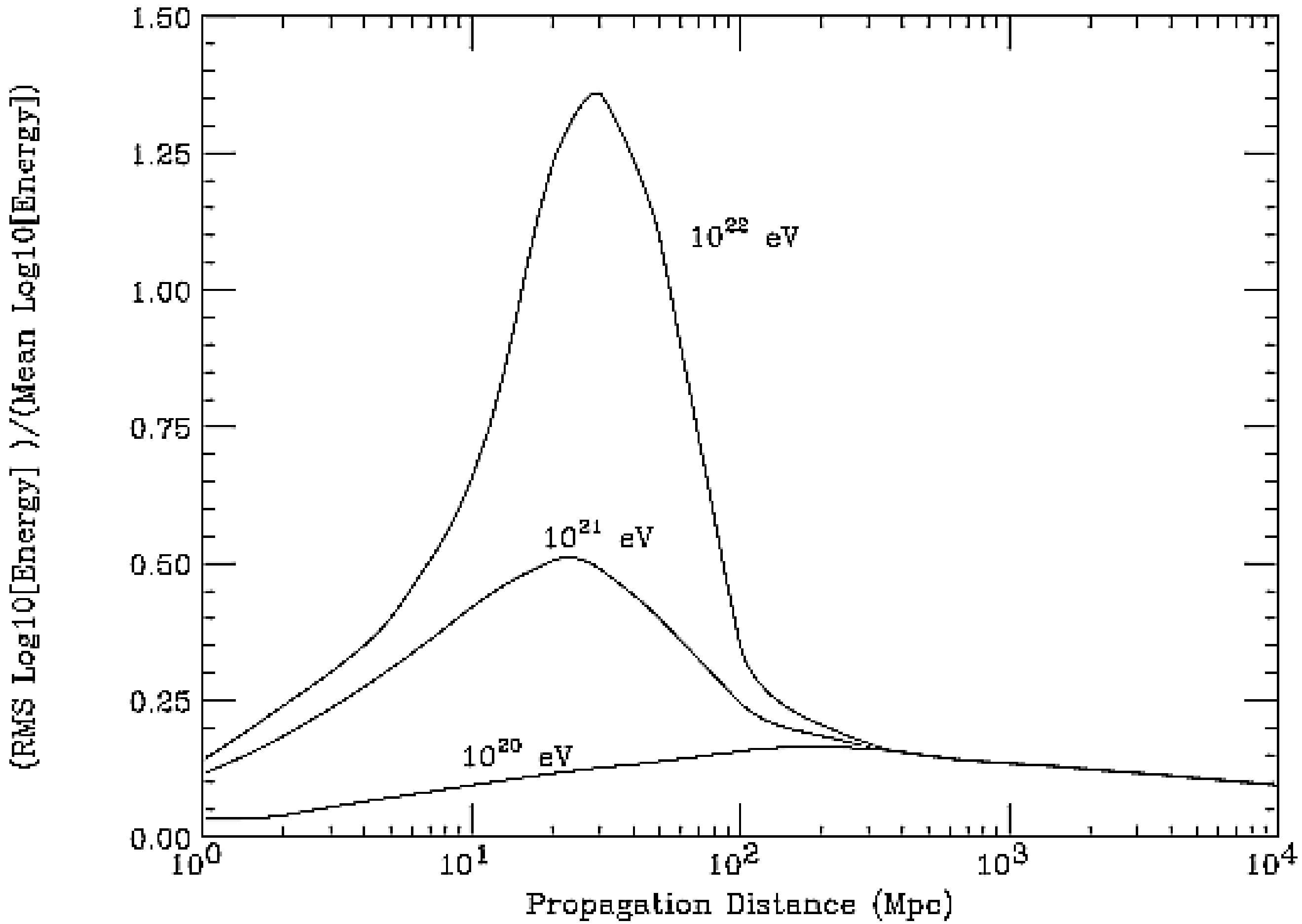
Photons: pairs e^+e^-
on radio bg



Protons energy vs. distance (J. Cronin)
Energy loss on CMB

UHE Extragalactic Particles

Fluctuation dues to multiple scattering



Protons energy vs. distance (J. Cronin)
Energy loss on CMB

UHE Extragalactic Particles

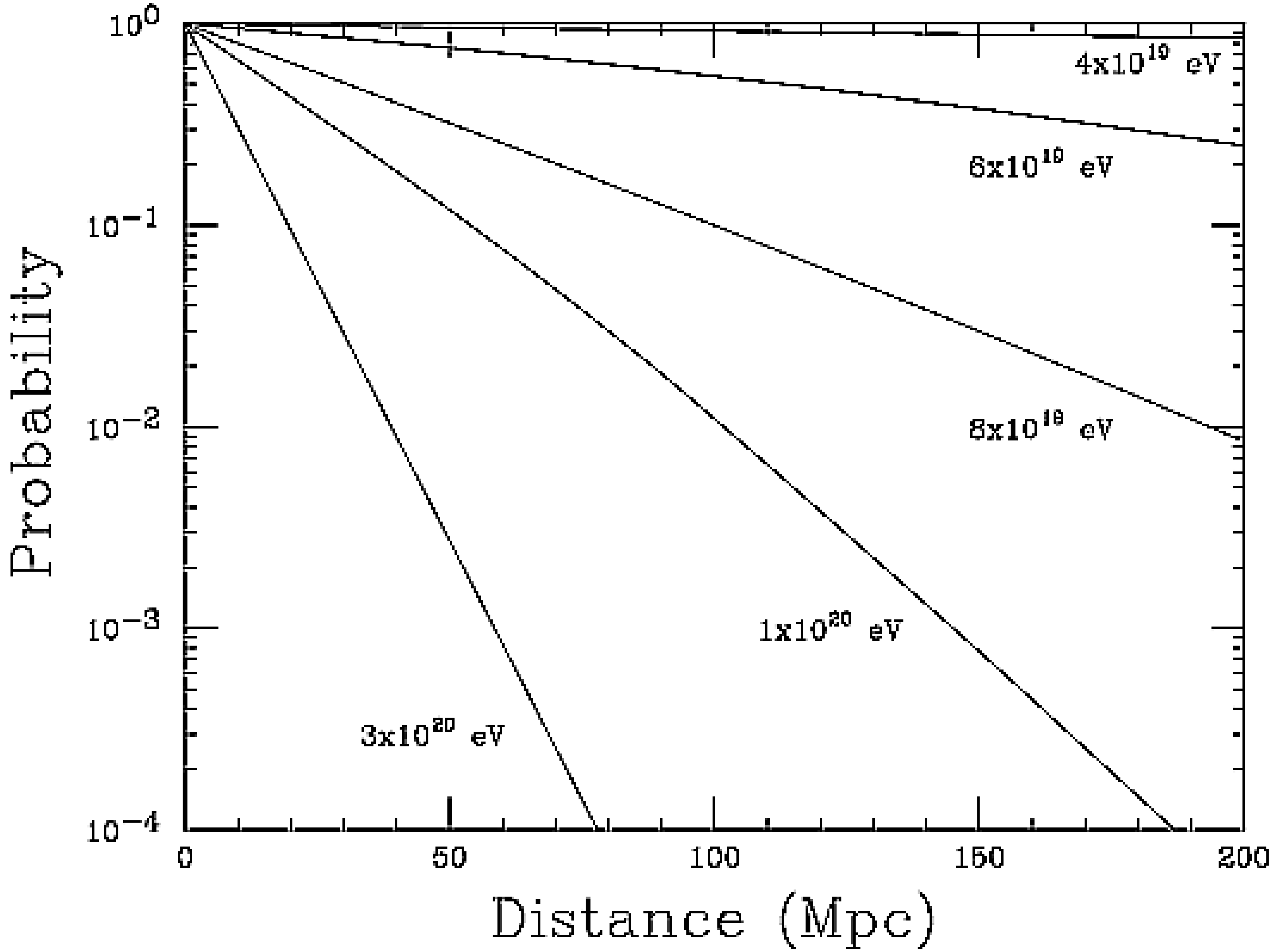
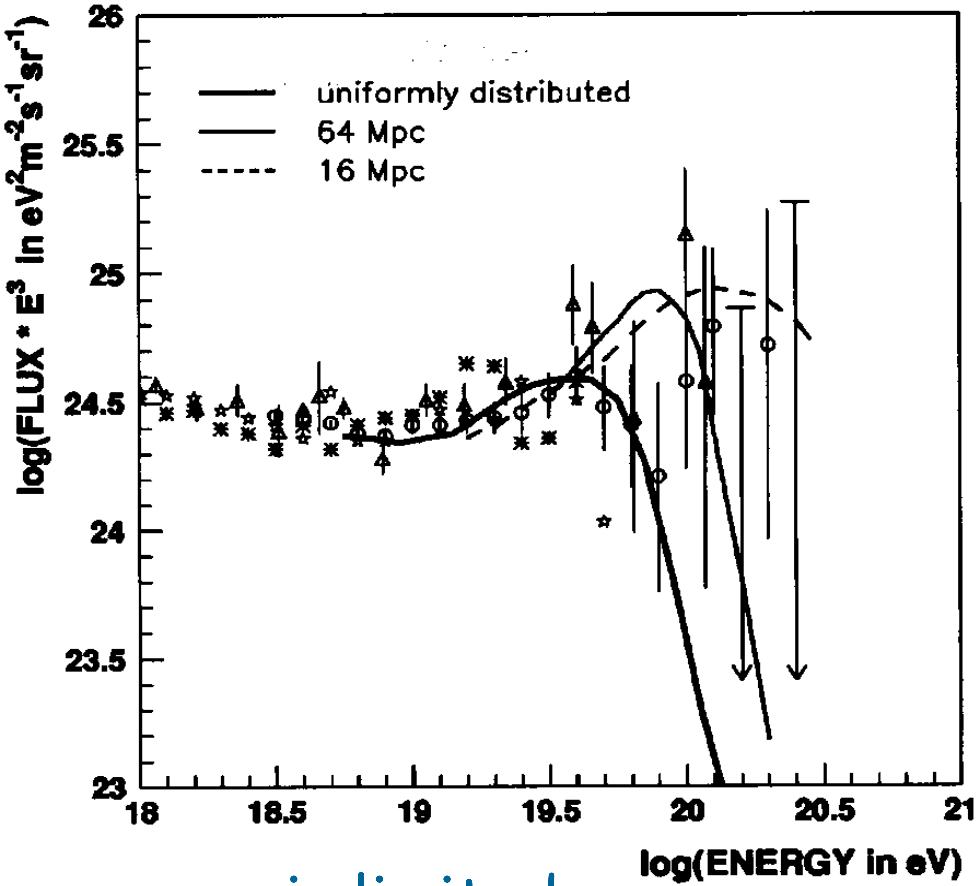


Figure 6: Probability that an observed event at a given energy has its source at a distance greater than the indicated distance. A source spectrum proportional to $E^{-2.5}$ is assumed. Figure provided Paul Sommers, University of Utah.

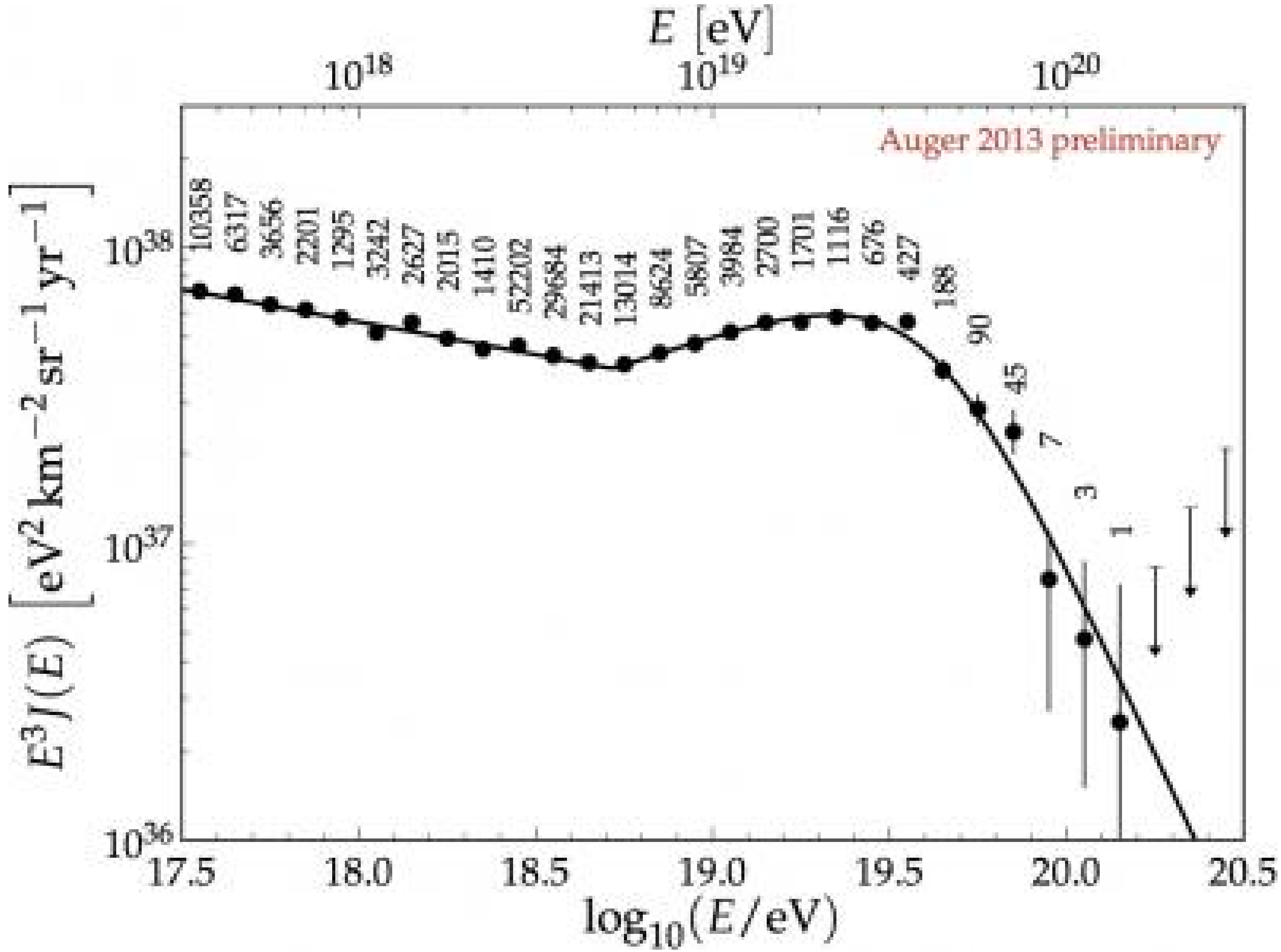
GZK suppression

- Greisen-Zatsepin-Kuz'min

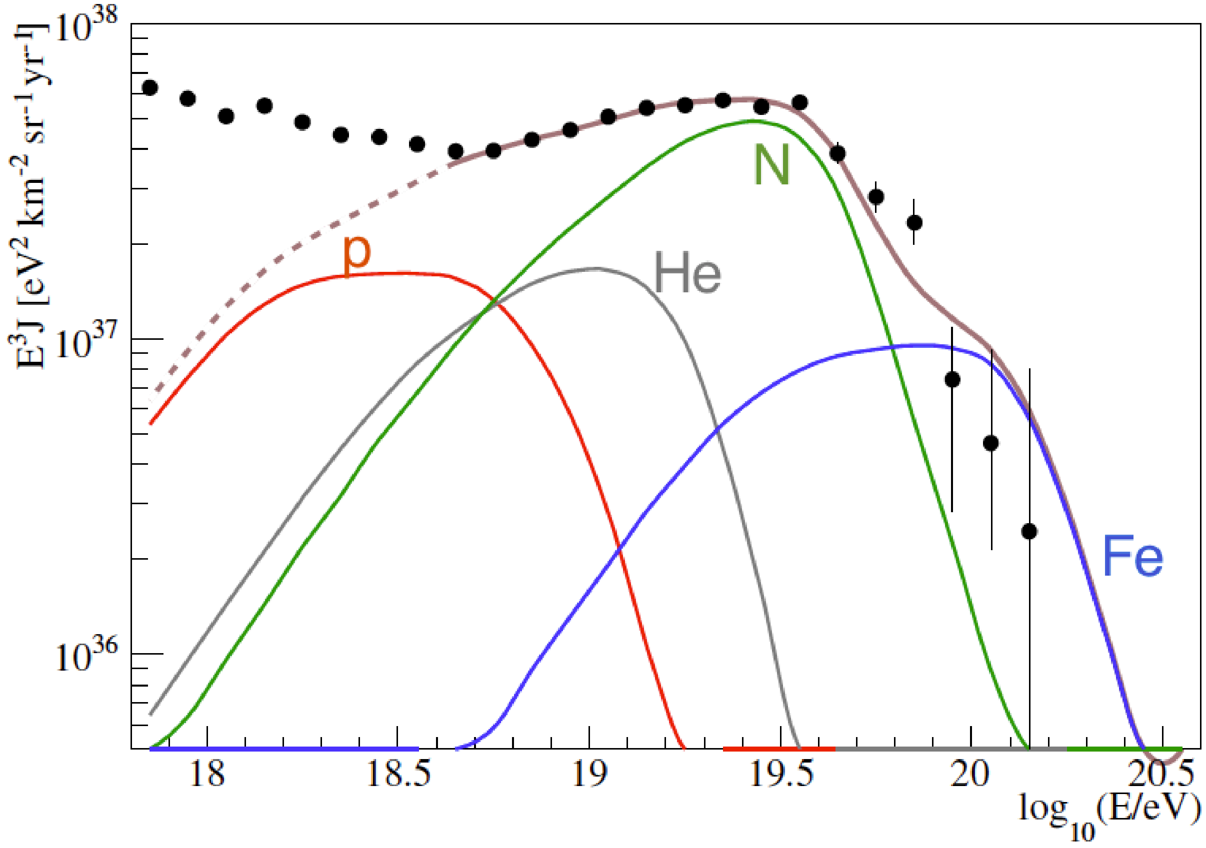


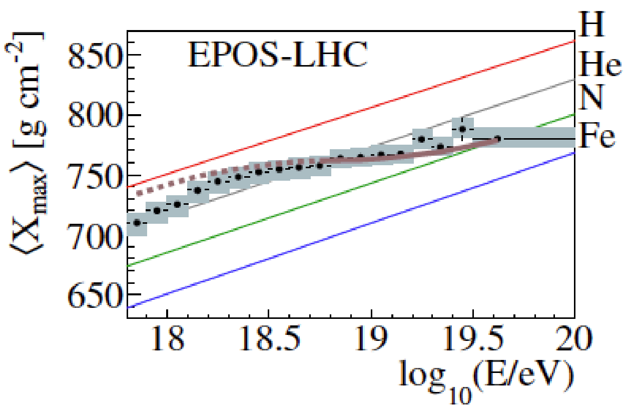
- Distance to the source is limited to 100 Mpc for 10^{20} eV protons, and 15 Mpc for 3×10^{20} !
- Actually even less if particles are deflected ($D_{effectif} > D_{linear}$)

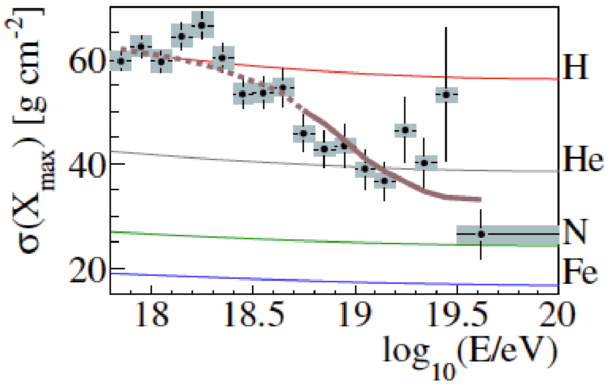
GZK like suppression (Auger)



Flux suppression (Auger)







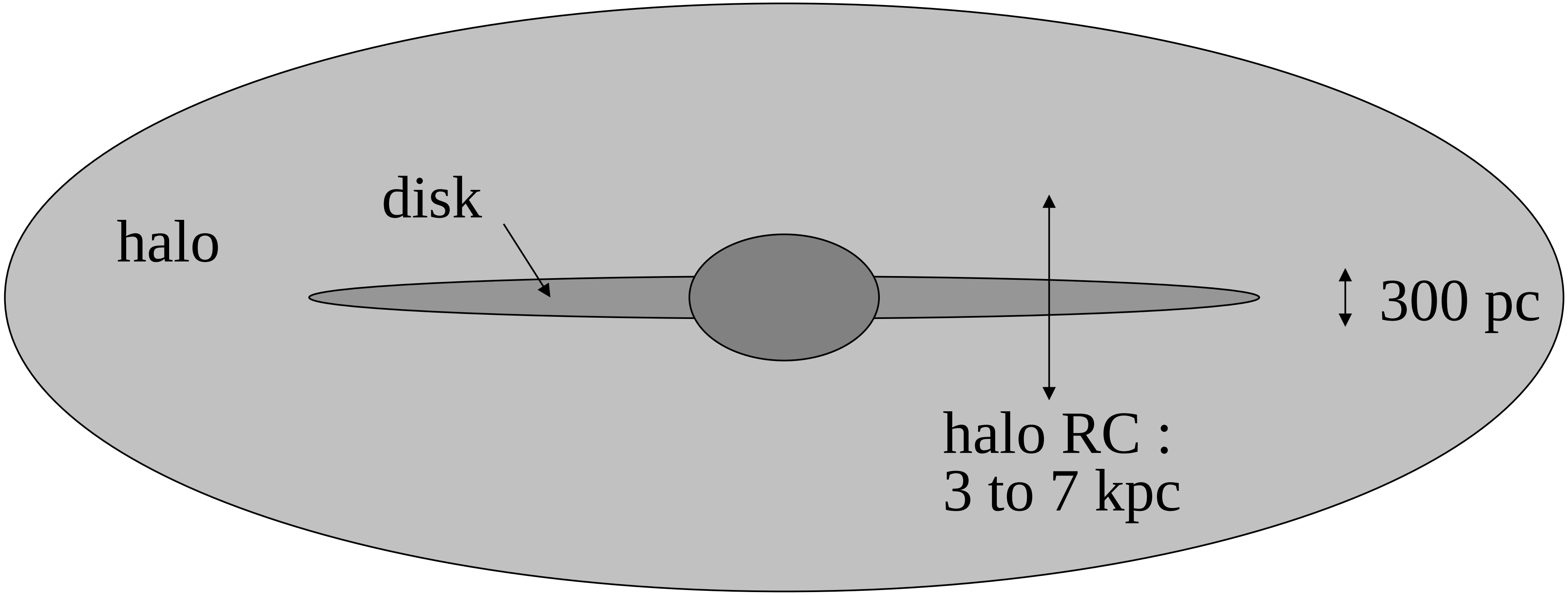
The spectrum is best fitted by a succession of cutoffs of the different groups of elements, with $R_{cut} = 10^{18.67 \pm 0.03} V$, thus pointing to the flux at Earth being partly limited by the maximum energy at the source. The best fit returns $\gamma = 0.94^{+0.09}_{-0.10}$, suggesting a very hard source spectrum, and an injection of mostly intermediate mass nuclei, with very few protons or iron nuclei.

It has to be noted that the fit also finds a second local minimum, with $\gamma = 2$ and a larger maximum rigidity, more in line with standard models of cosmic-ray acceleration. While the spectrum is fitted well in this case too, wider distributions of UHECR masses than observed in the data are in turn predicted at each energy, showing how crucial the measures of mass composition are to resolve the origin of the observed flux suppression.

MAGNETIC DEFLECTIONS

Galactic magnetic deflection

- 10^{18} eV proton in a B = 3 μG field ⇒ r_g ~ 370 pc

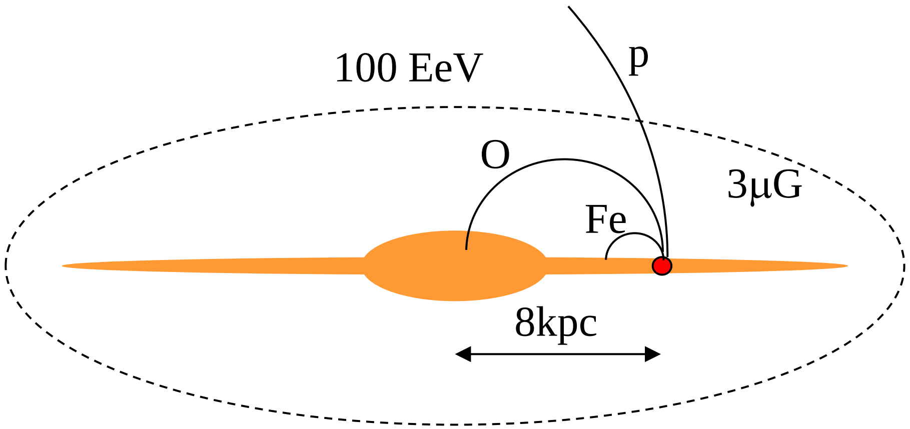


- 2×10^{19} eV proton in B = 3 μG ⇒ r_g ~ 7 kpc
- 5×10^{20} eV Fe in B = 3 μG ⇒ r_g ~ 7 kpc

Propagation the Galaxy

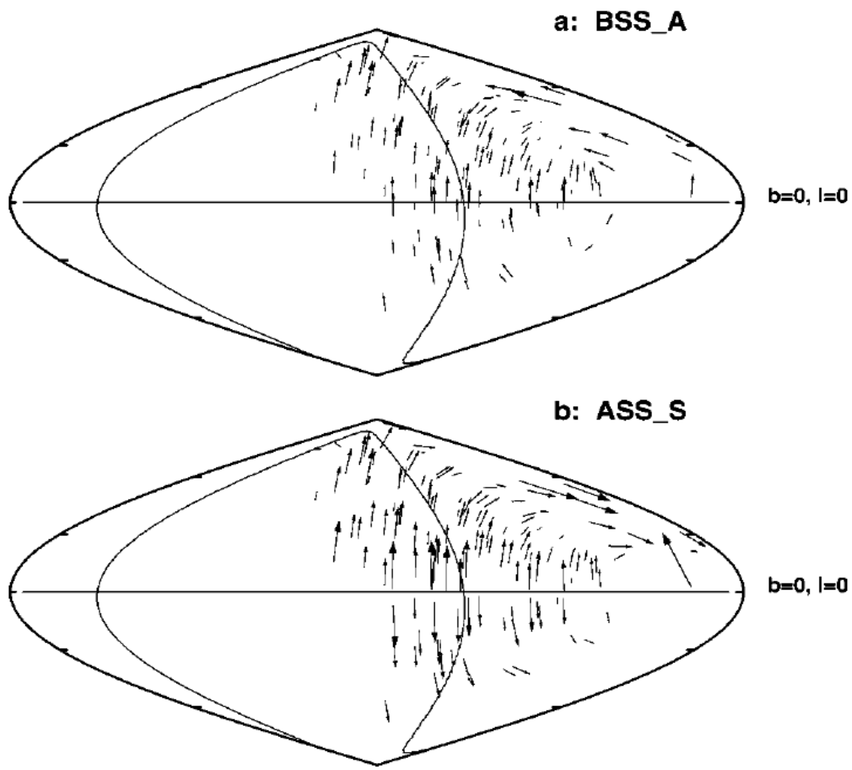
- Galactic magnetic field model

$$\left(\frac{R_{Larmor}}{kpc}\right)=\left(\frac{1}{Z}\right)\cdot\left(\frac{E}{1EeV}\right)\cdot\left(\frac{ZB}{\mu G}\right)$$



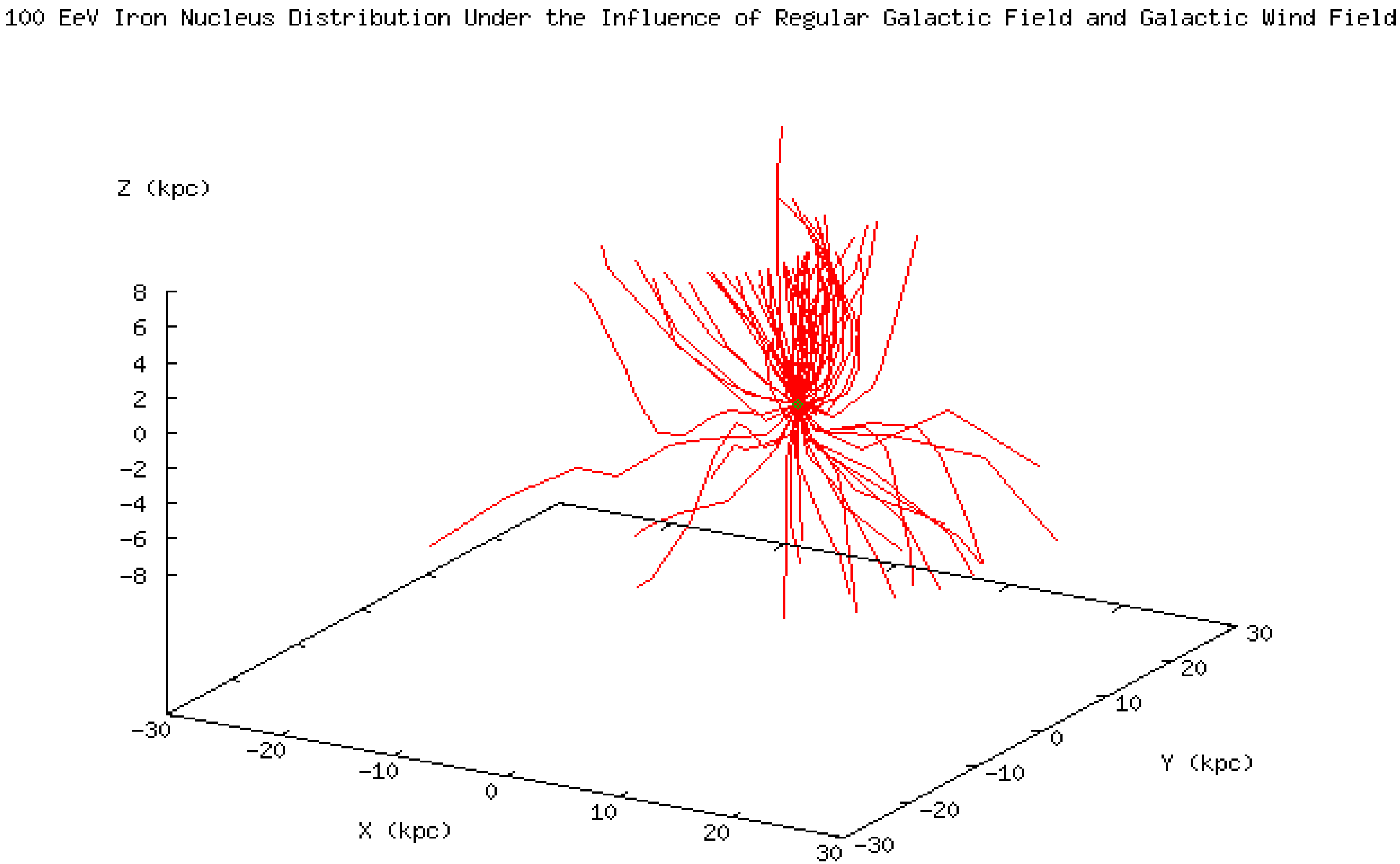
- Possible galactic confinement of 10^{20}eV nuclei

- 10^{18}eV neutrons decay length
  $\beta\gamma c\tau \approx$ 10kpc $\Rightarrow$ galactic distances



Tracking back direction of proton events >4 10^{19} out of the Galaxy, two different field hypothesis [Stanev97]

Pointing at UHECR sources?



O'Neil, Olinto, Blasi '01

Pointing at UHECR sources?

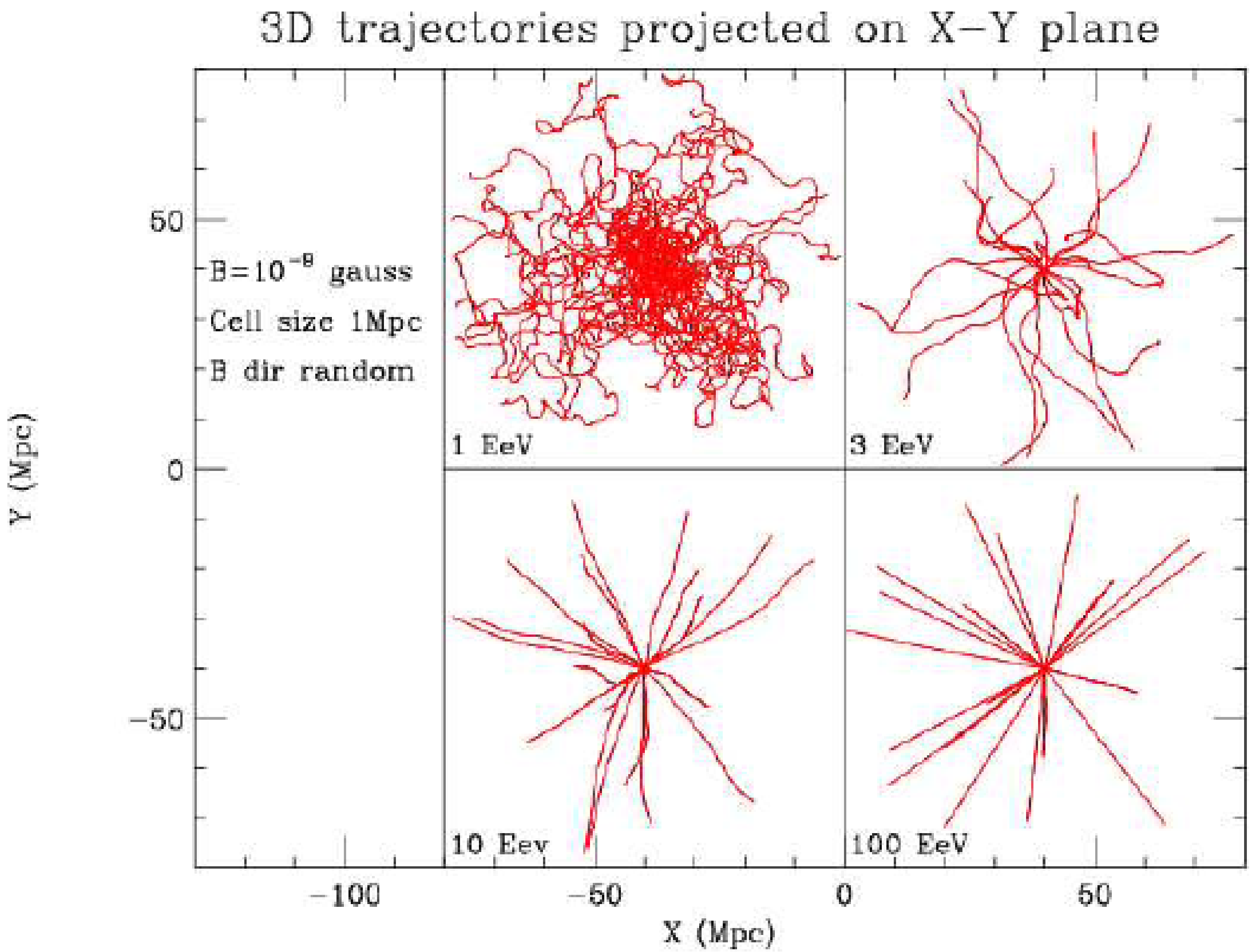
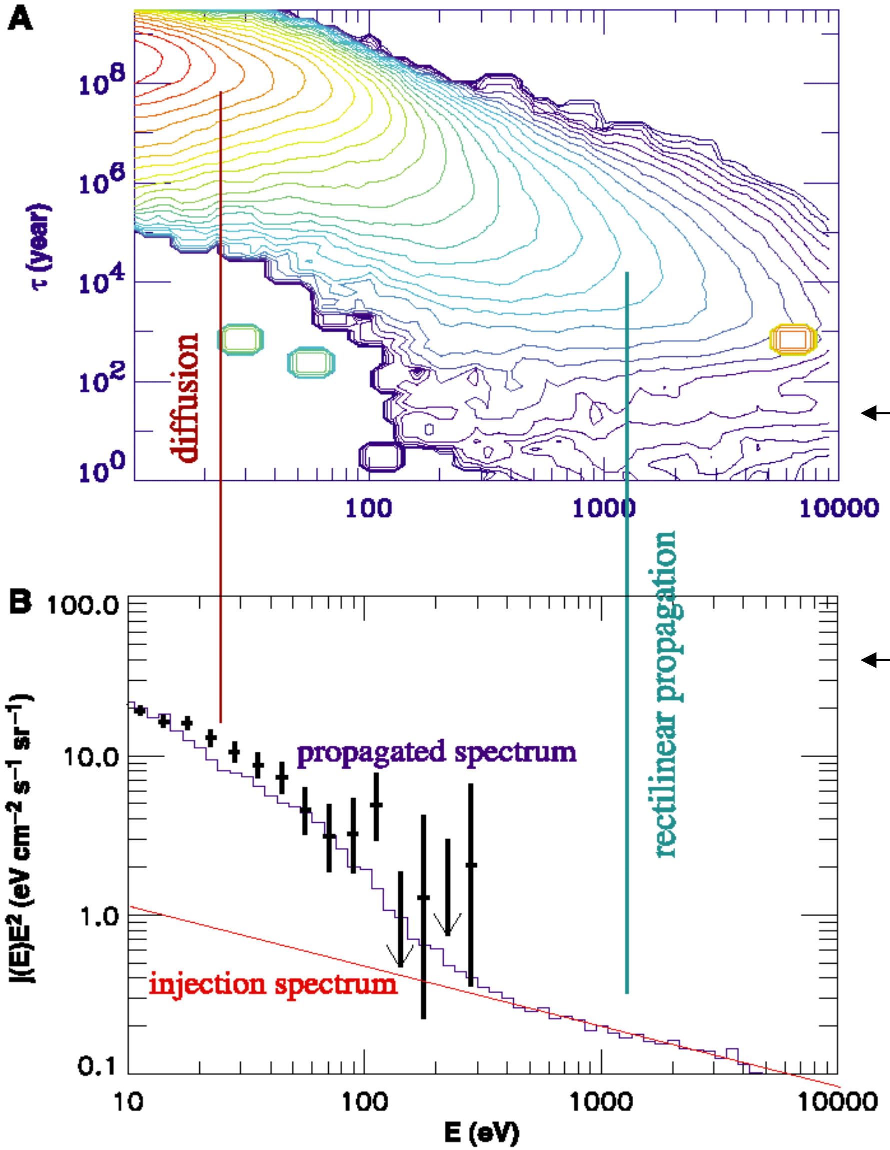


Figure 7: Projected view of 20 trajectories of proton primaries emanating from a point source for several energies. Trajectories are plotted until they reach a physical distance from the source of 40Mpc. See text for details.

Extra-galactic UHECR propagation



From diffusive regime to rectilinear propagation [Sigl]

Time-Energy correlation

Average spectrum

Depends on the strength and coherence length of EG magnetic fields

$$\theta(E) \approx 0.025^\circ \sqrt{\frac{d}{\lambda}} \left(\frac{\lambda}{10Mpc}\right)\left(\frac{B}{10^{-11}G}\right)\left(\frac{E}{10^{20}eV}\right)^{-1}$$

$$\tau(E) \approx 200\text{yr}\left(\frac{\text{d}}{100\text{Mpc}}\right)^2\left(\frac{\lambda}{10\text{Mpc}}\right)\left(\frac{\text{B}}{10^{-11}\text{G}}\right)^2\left(\frac{\text{E}}{10^{20}\text{eV}}\right)^{-2}$$

Mapping IG fields with UHECR?

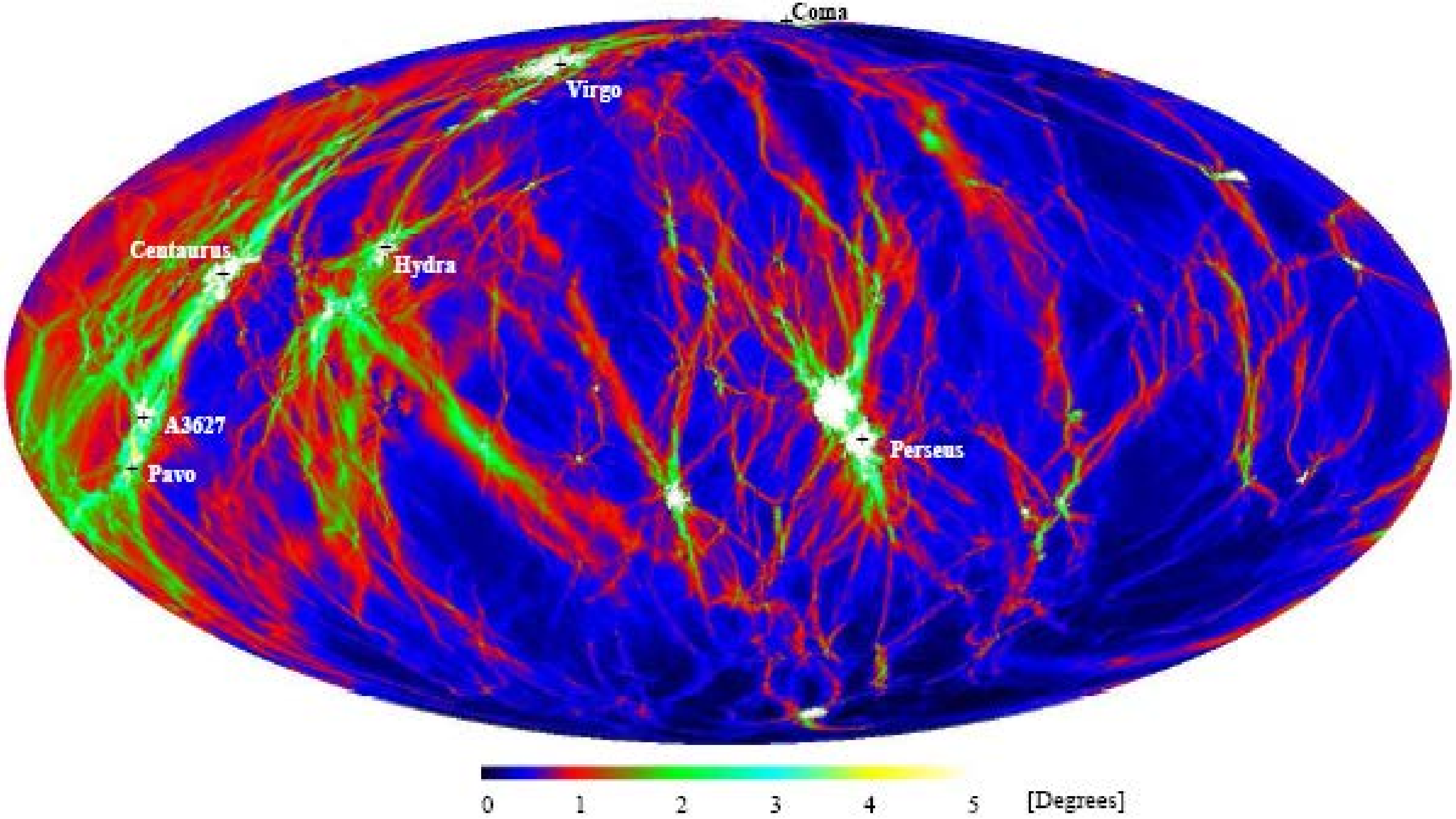


FIG. 1. Full sky map (area preserving projection) of deflection angles for UHECRs with energy 4×10^{19} eV using a linear color scale. All structure within a radius of 107 Mpc around the position of the Galaxy was used. The coordinate system is galactic, with the galactic anti-center in the middle of the map. Positions of identified clusters are marked using the locations of the corresponding halos in the simulation. Note that deflections internal to the Milky Way have not been included.

Diffusion in the Universe

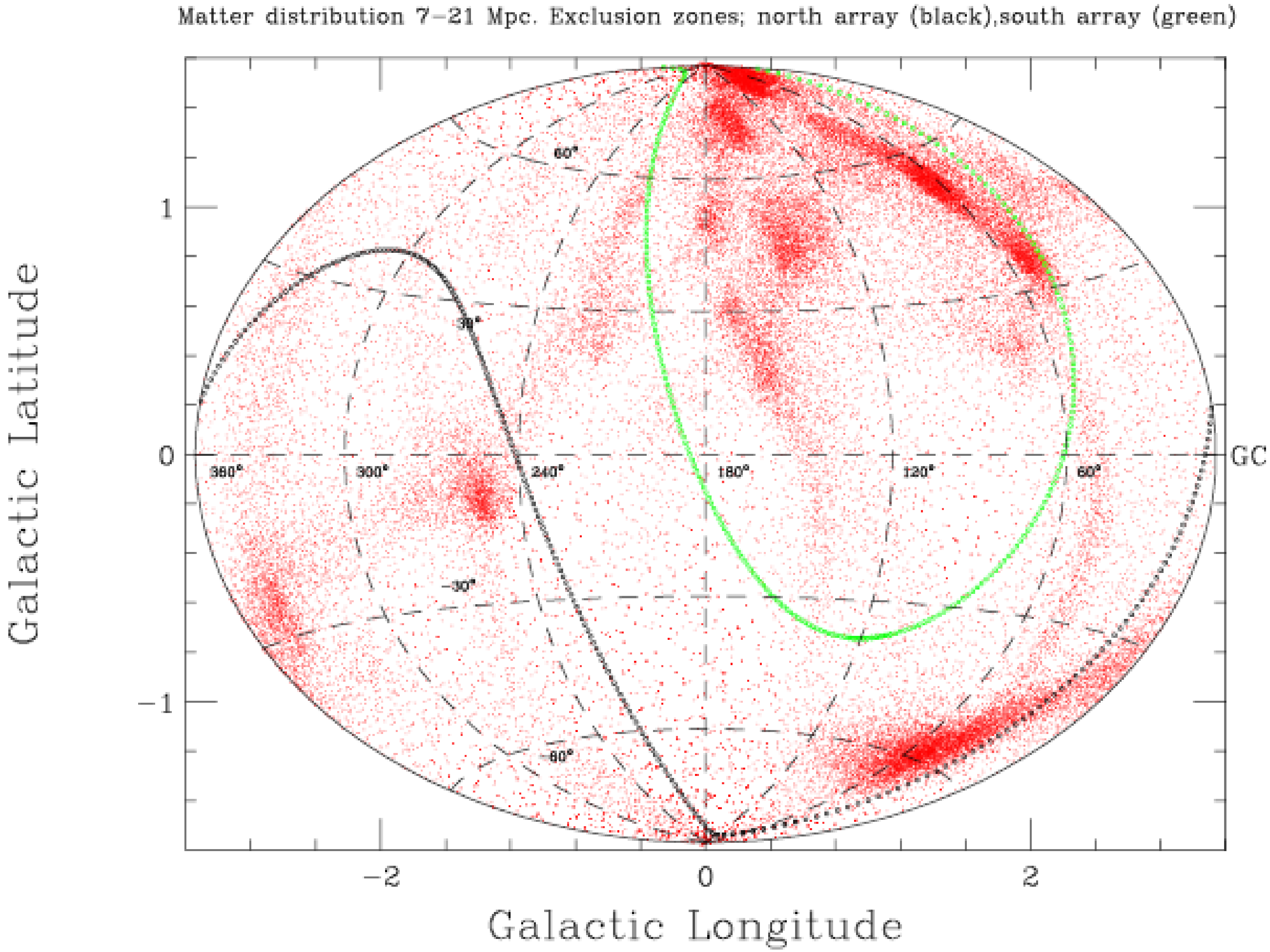
- If they are protons,
  arrival direction ≈ source direction
  $r_L \approx 100kpc \times Z \times (E/10^{20}eV) \times (B/10^{-6}G)^{-1}$
  $\delta\theta \sim \lambda_B/r_L$ deviation per field correlation length $\Rightarrow \Delta\theta \sim \sqrt{D\lambda_B}/r_L$
  → Proton astronomy !

- Correlations between arrival directions and sources:
  UHECR distribution is NOT ISOTROPIC!!! (AUGER 2007)
  - Confirmation of a GZK limited horizon
  - Few sources in the GZK sphere → anisotropy
  - Astrophysical origin is confirmed!

- Arrival time delay
  - $\Delta t \sim \Delta\theta^2 d/c \sim D^2\lambda_B/r_L^2 c$
  - If eruptive or transient sources (GRBs, TDs), the must overlap in time (otherwise E(t)!)
  - Multiplets of events from same direction observed but no significant ordering in E or deviation.

→ Correlation must be confirmed! (statistics...)

Matter distribution in the GZK sphere



Observables & Observations

Limited to 2 examples :

Direct CR measurement with AMS-02

UHECR measurement with Auger Observatory

PRIMARY RC DETECTION (ON TOP OF ATMOSPHERE)

How to characterize the primary particle?

- Mass m
- Electric charge Ze
- Velocity $v = \beta c$
- Lorentz Facteur $\gamma = E/mc^2$
- Momentum $p = mc\beta\gamma$
- Kinetic energy $T = mc^2(\gamma - 1)$

How to characterize the primary particle?

Detector	Observable	Link with the particule
Magnetic spectrometer	Rigidity & Sign of Z	pc/Ze
Time of flight	Velocity/c	β
Proportionnal counters Scintillators Ionisation chamber	Ionisation	$dE/dx = Z^2 f(\beta)$
Čerenkov effect	Č photons density	$dN/dx = Z^2 g(\beta)$
Transition radiation	Nomber of photons X	$N = Z^2 h(\gamma)$
Calorimeter	Deposited energie	$mc^2(\gamma - 1)$

Two important radiations for particle identification

Two effects of the polarization induced by charged particles in dielectric medium

Proportionnal to Z^2

- Čerenkov radiation : si $v > c/n$
  Sensitive to $\beta = v/c$

- Transition radiation : at the interface of $\neq$ dielectric media
  Sensitive to $\gamma = E/(mc^2)$

Two important radiations for particle identification

- Cherenkov radiation
- Transition radiation

} See my lecture week 3 of module 1 on this subject

Charge particles and cosmic antimatter

- First satellite based experiments on cosmic rays : HEAO-C,
  - Ariel-VI (1979) → relatively low energy (up to a few 10 GeV/nucleon)
- First satellite based magnetic spectrometer en satellite :
  - AMS-1 on the space shuttle « Discovery » (1998)
  - CRIS (onboard ACE at LagrangeL1 taking date for almost 18years!)
- Current generation of experiments:
  - PAMELA (since Juin 2006)
  - AMS-2 (since May 2011)
    on the International Space Station → data up to ~TeV

  and precise measurements of flux of cosmic antiparticles
- Next generation (just starting for some)
  - CALET
  - DAMPE
  - ISS-CREAM
  - …

AMS-2 On Board ISS

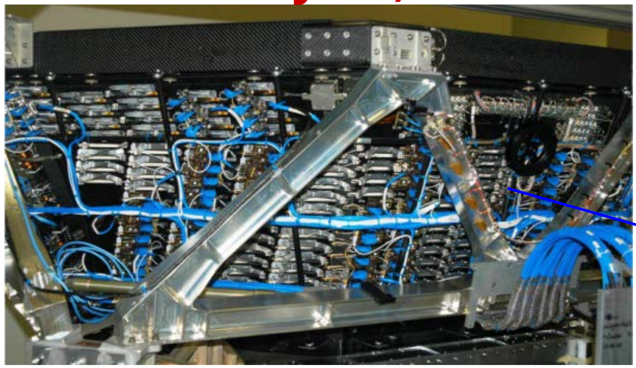
Mission Number: STS-134
Launch: **May 19, 2011**
Orbiter: Endeavour

Space spectrometers

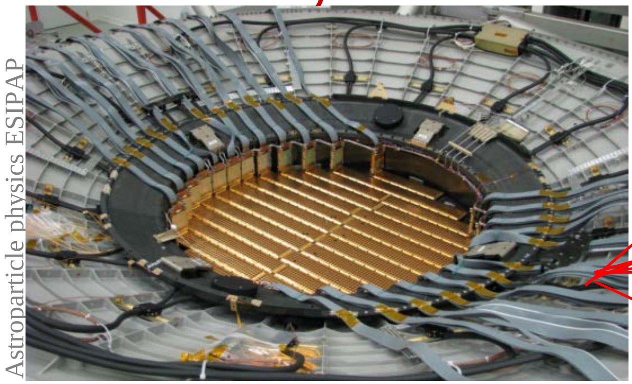
	AMS-1 (June 1998)	PAMELA (June 2006 - …)	AMS-2 (May 2011 - …)
Spectrometer Acceptance	$0.82\ m^2\ sr$	$20.5\ cm^2\ sr$	$0.82\ m^2\ sr$
Spectrometer	Permanent magnet Nd Fe B 0.15 T $BL^2 = 0{,}15\ T\ m^2$ 6 plans (Si)	Permanent magnet Nd Fe B 0.48 T $BL^2 = 0{,}10\ T\ m^2$ 6 plans (Si)	Permanent magnet Nd Fe B 0.15 T $BL^2 = 0{,}15\ T\ m^2$ 6 plans (Si)
Time of Flight	yes	yes	yes
Cherenkov	Aerogel (threshold)	-	Ring Imaging Ch.
Transition rad	-	yes	yes
Neutrons det.	-	^3He	-
Anticoincidence	-	yes	yes
Calorimeter	-	$16{,}3\ X_0$ W+22 plans (Si)	$16\ X_0$ Pb+fibers sc.

A precision, multipurpose spectrometer up to TeV

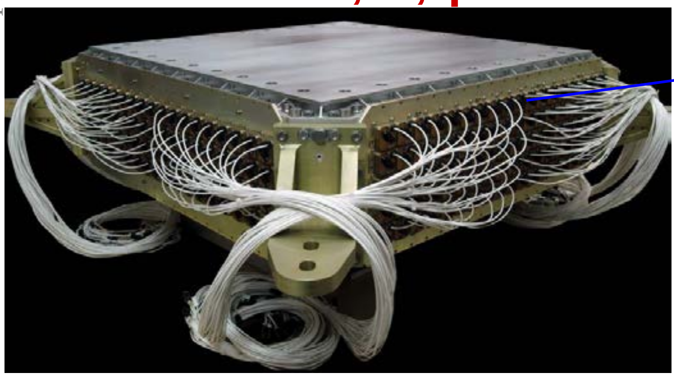
TRD
Identify e^+, e^-

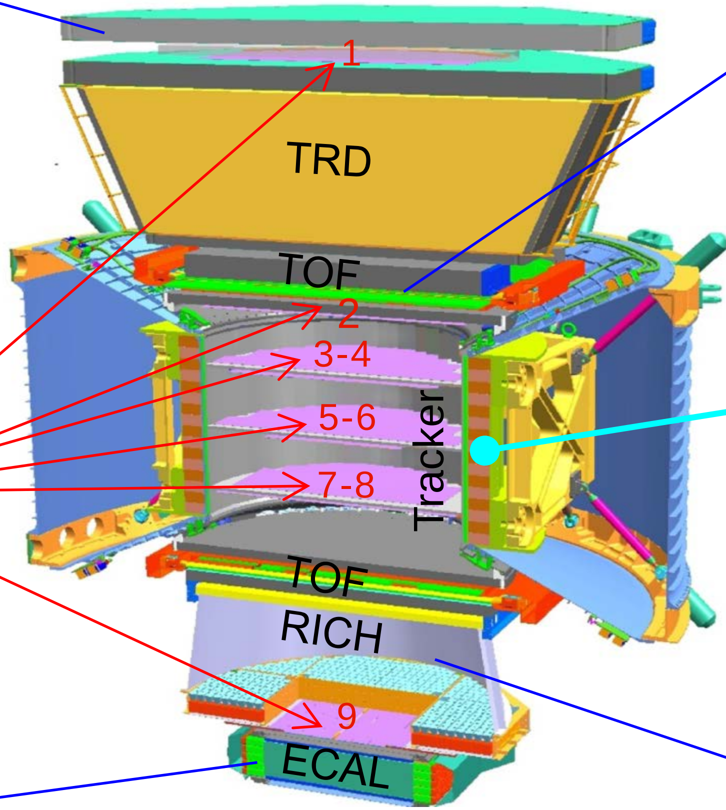


Silicon Tracker
Z, P



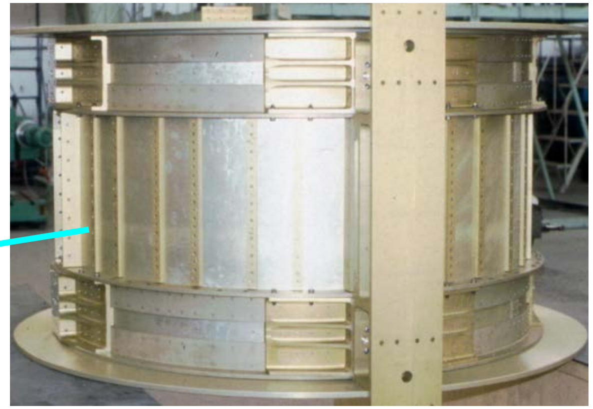
ECAL
E of e^+, e^-, γ



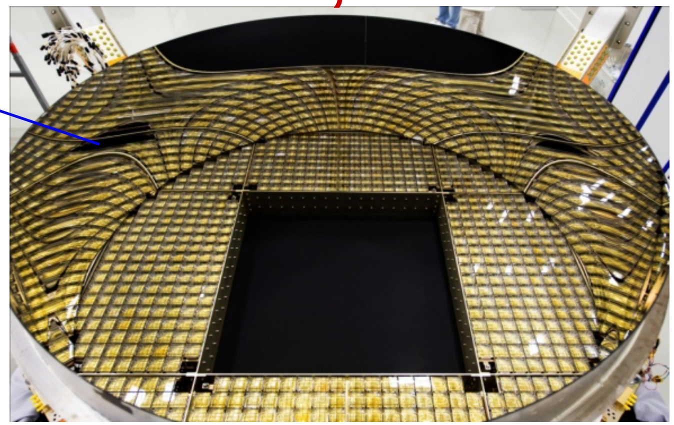


TOF
Z, E

Magnet
±Z



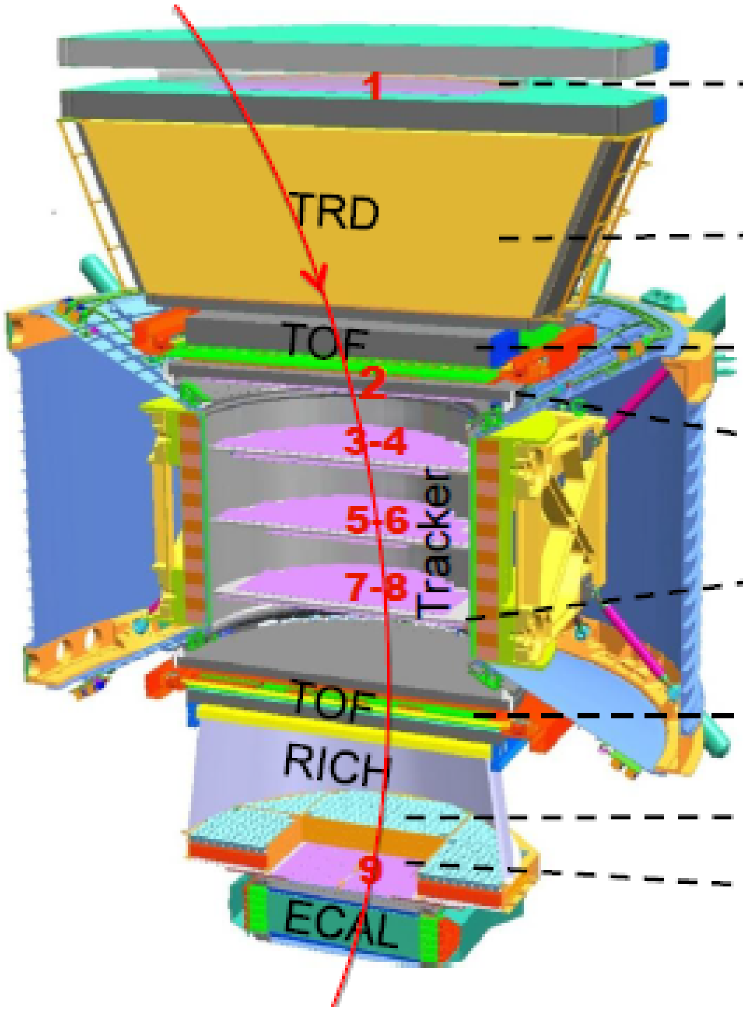
RICH
Z, E



***Z, P* are measured independently by the Tracker, RICH, TOF and ECAL**

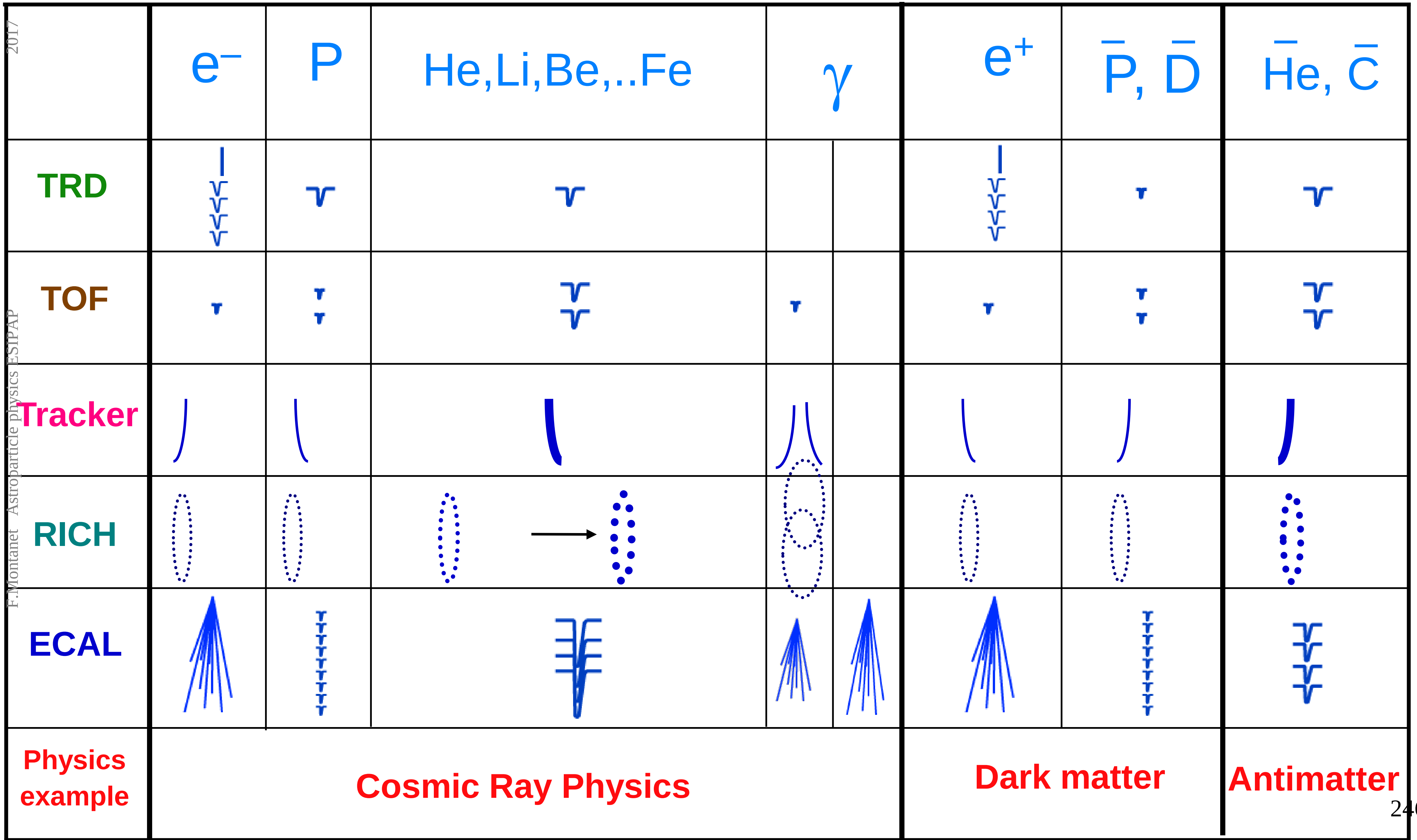
AMS charge identification

AMS: Multiple Independent Measurements of the Charge (|Z|)

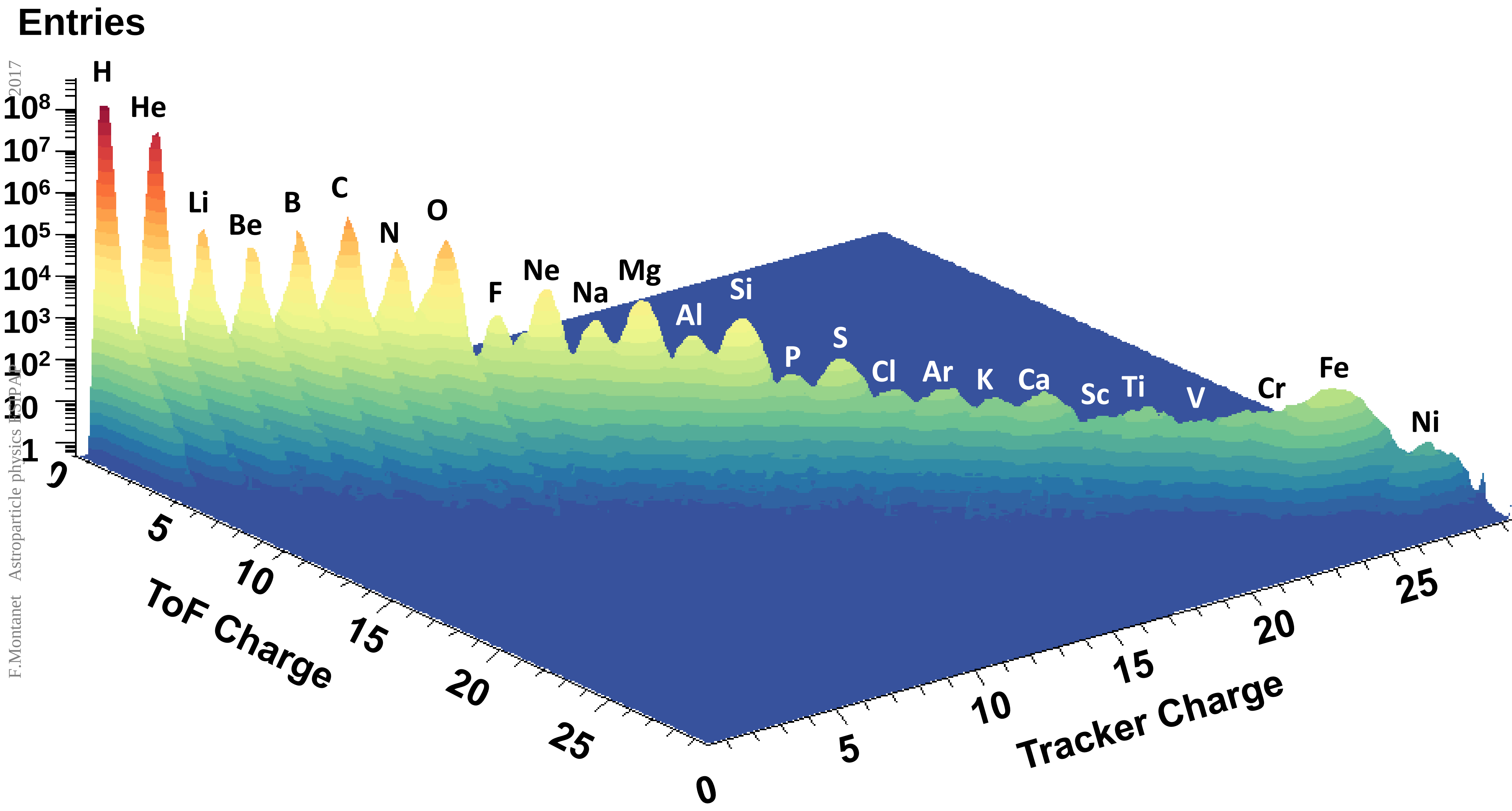


	Carbon (Z=6) ΔZ (cu)
1. Tracker Plane 1	0.30
2. TRD	0.33
3. Upper TOF (1 counter)	0.16
4. Tracker Planes 2-8	0.12
5. Lower TOF (1 counter)	0.16
6. RICH	0.32
7. Tracker Plane 9	0.30

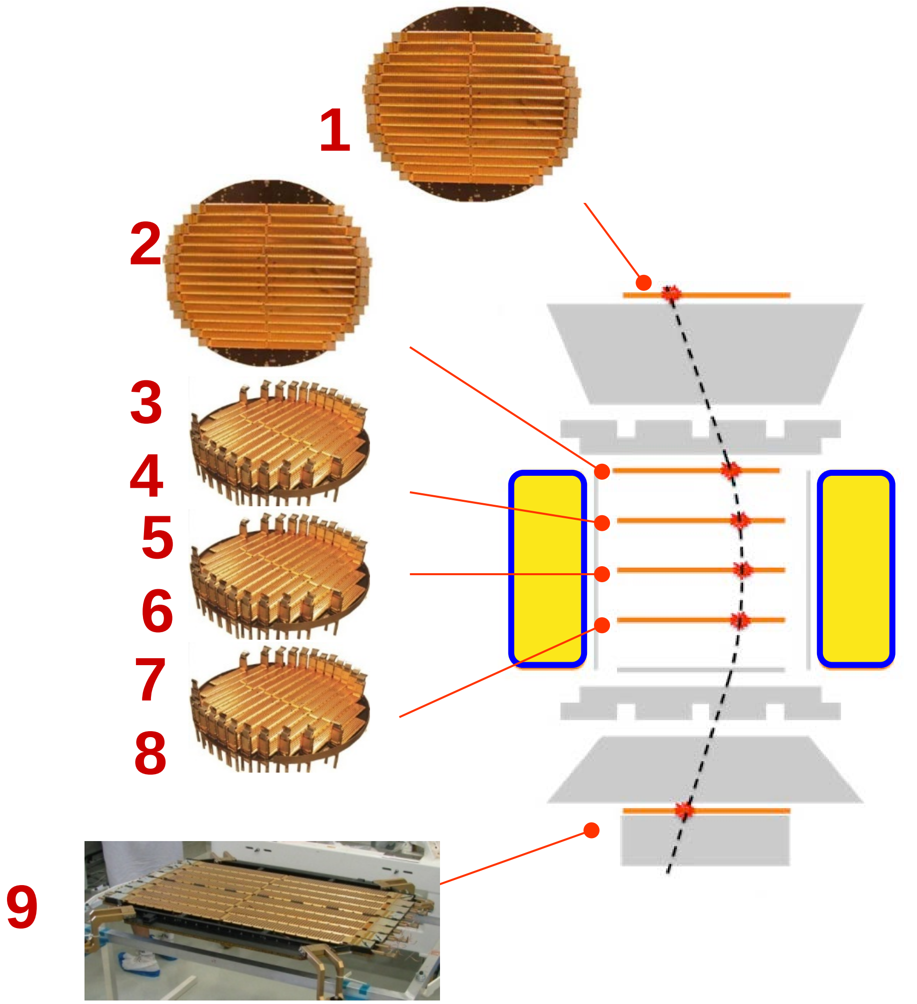
Full coverage of anti-matter & CR physics



AMS Nuclei Measurement on ISS



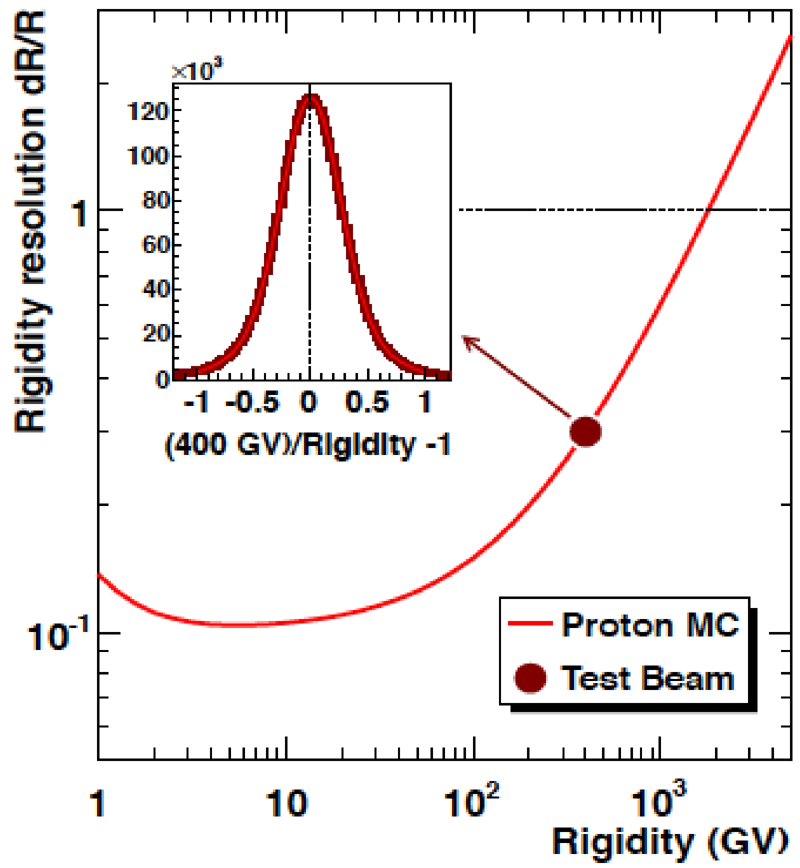
Silicon Tracker



Coordinate resolution 10 μm

→20–UV Lasers to monitor inner tracker alignment

→Cosmic rays to monitor outer tracker alignment

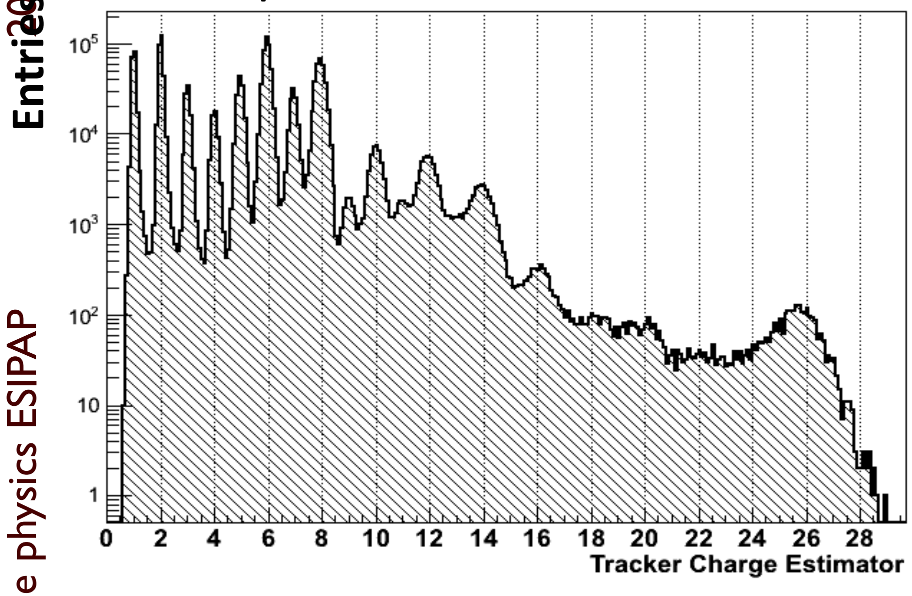


9 layers of double sided silicon microstrip detectors

192 ladders / 2598 sensors/ 200k readout channels

Silicon Tracker charge resolution

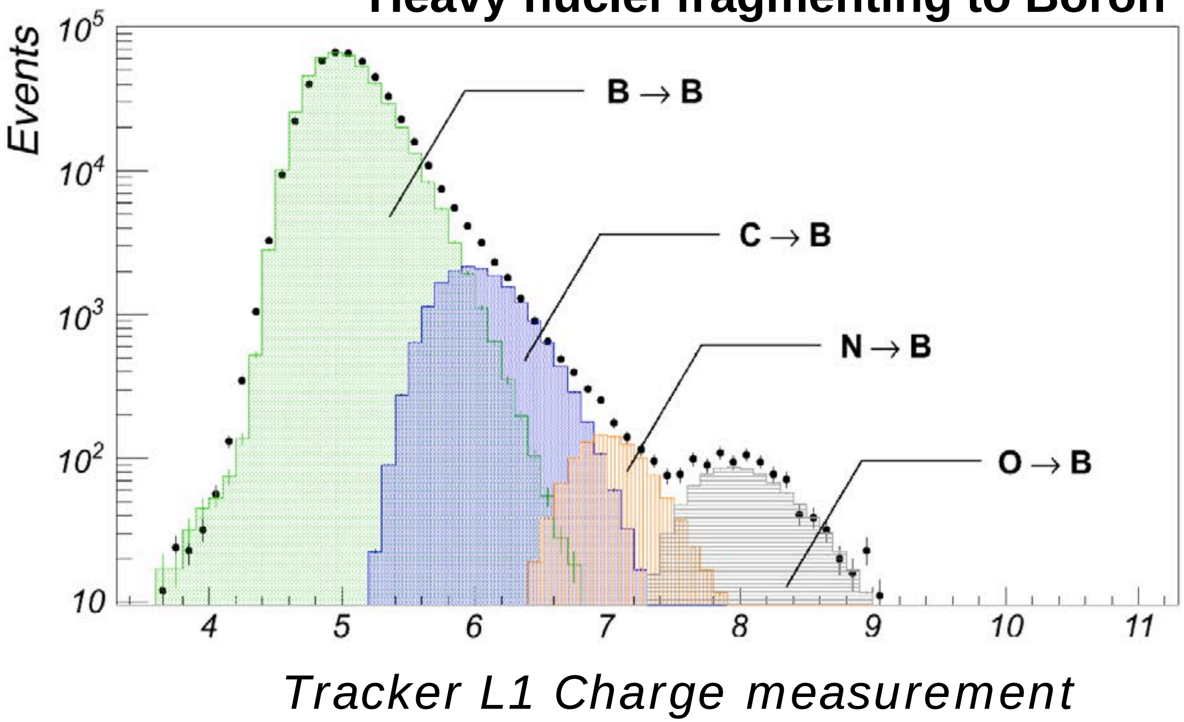
Abundances not corrected for detector efficiencies
H and He prescaled



Thanks to several energy deposits in silicon and the High Dynamic Range of the Front End electronics, the Silicon Tracker has a very accurate charge resolution

→ ~ 0.1 c.u.

Heavy nuclei fragmenting to Boron



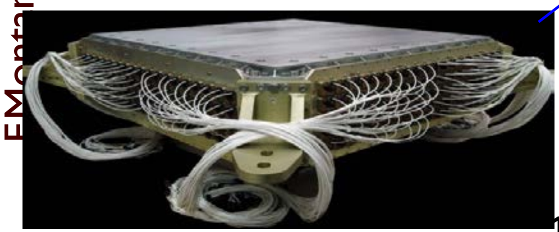
The first layer (L1), used as a standalone charge detector has a charge resolution (~ 0.3 c.u.) that allows the identification of the fragmentations, being at the top of the intrument (TOI)

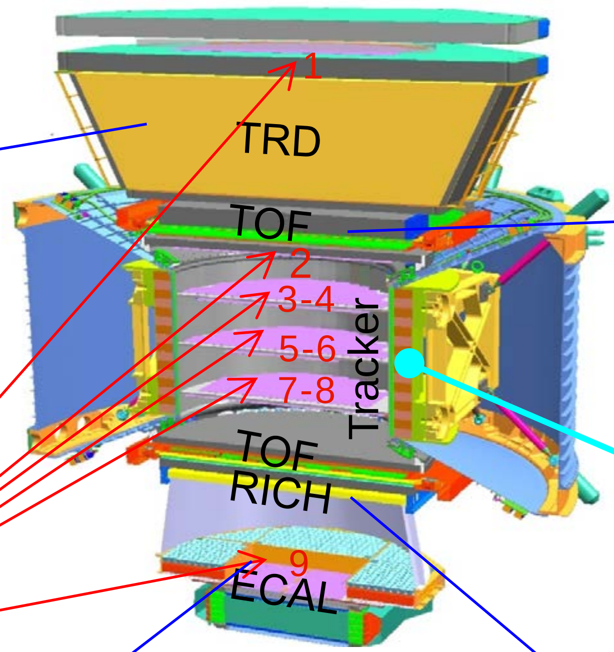
Flight electronics for thermal control

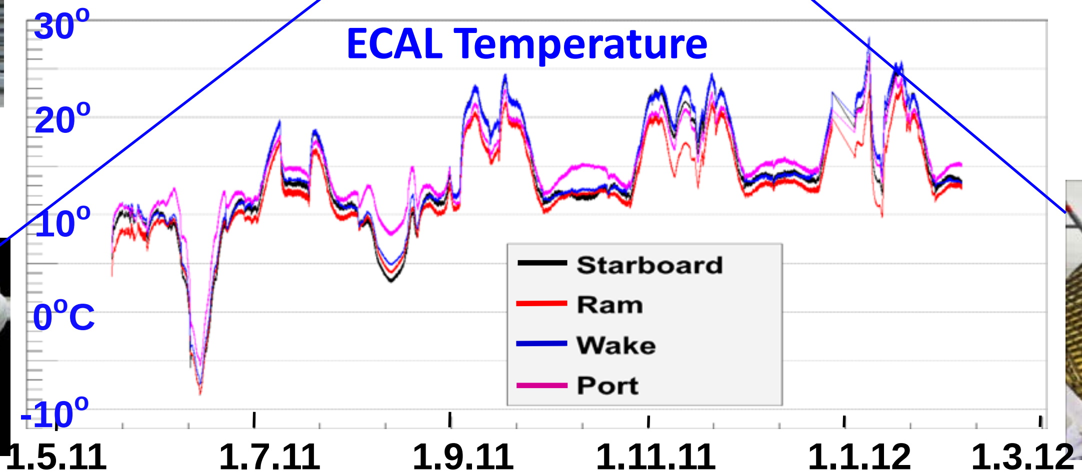
TRD
24 Heaters
8 Pressure Sensors
482 Temperature Sensors

Silicon Tracker
4 Pressure Sensors
32 Heaters
142 Temperature Sensors

ECAL
80 Temperature Sensors

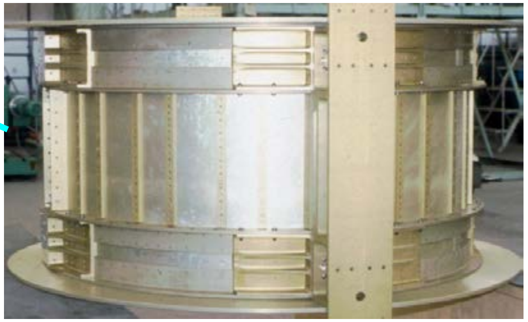




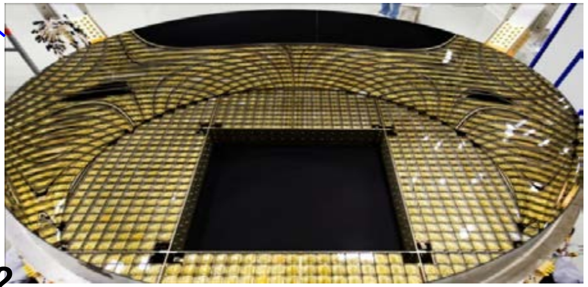


TOF & ACC
64 Temperature Sensors

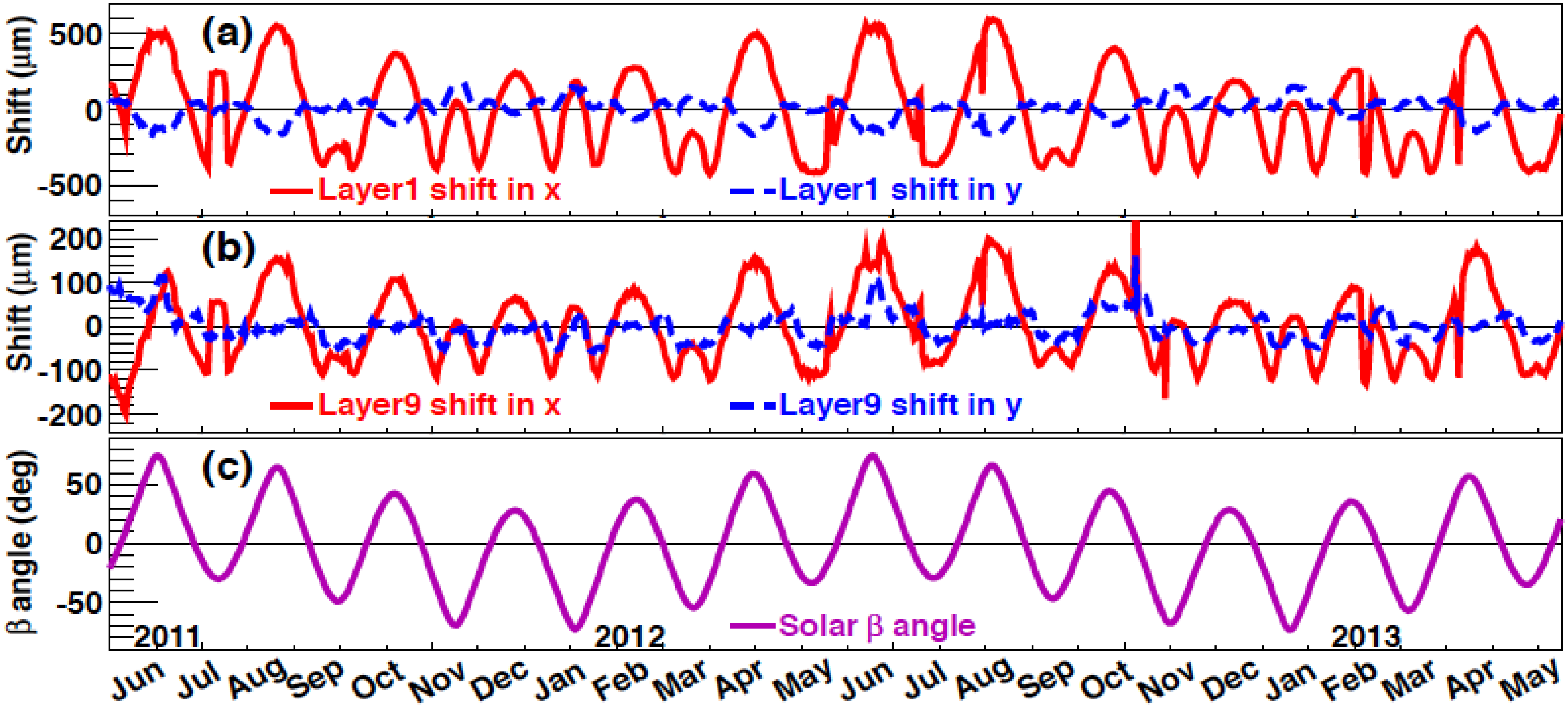
Magnet
68 Temperature Sensors



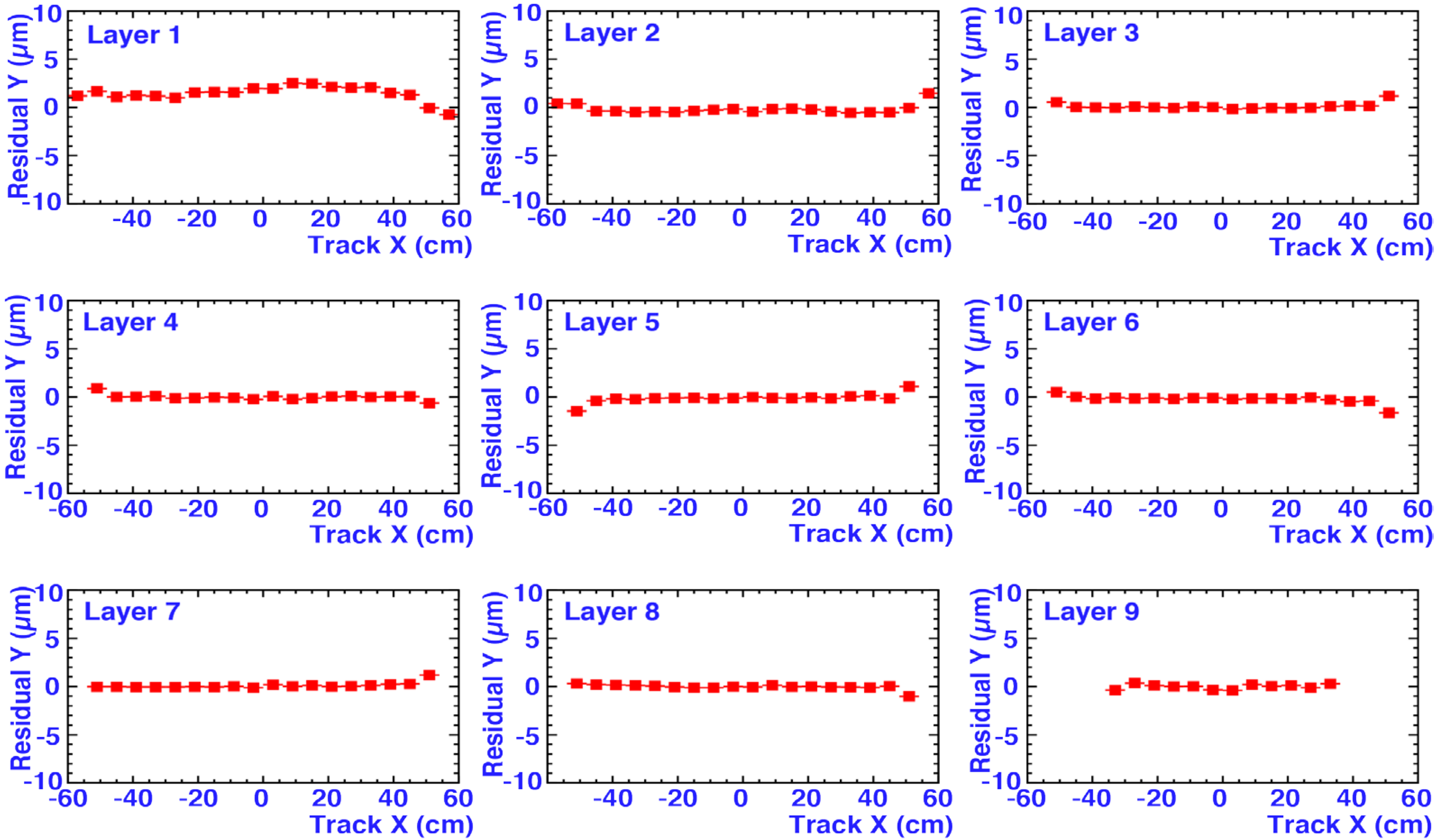
RICH
96 Temperature Sensors



Seasonal effects on Tracker

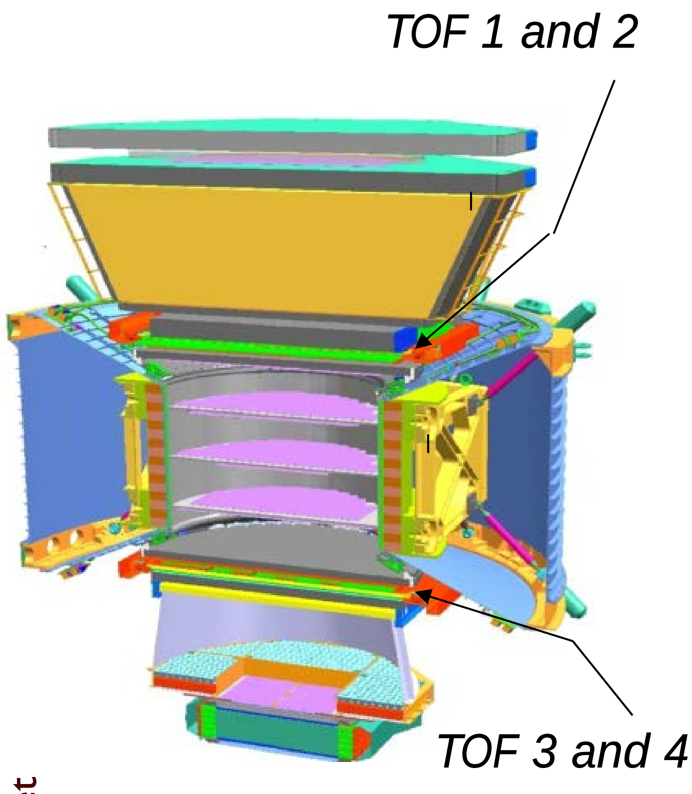


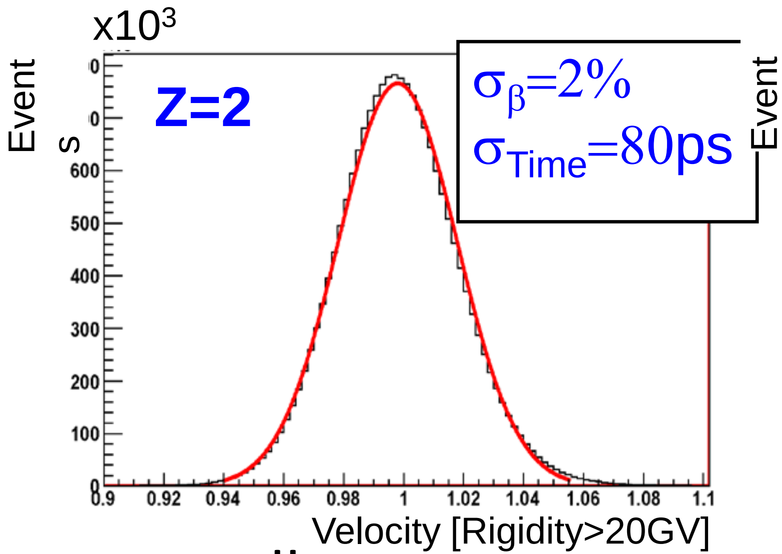
Tracker layers alignment accuracy

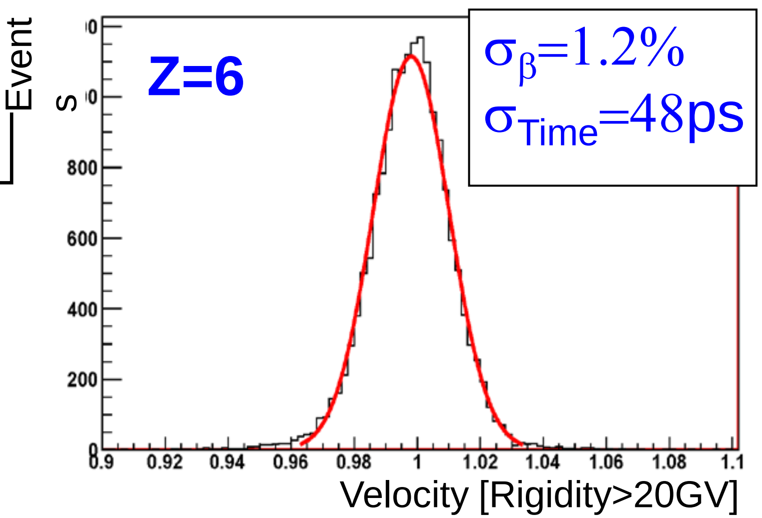


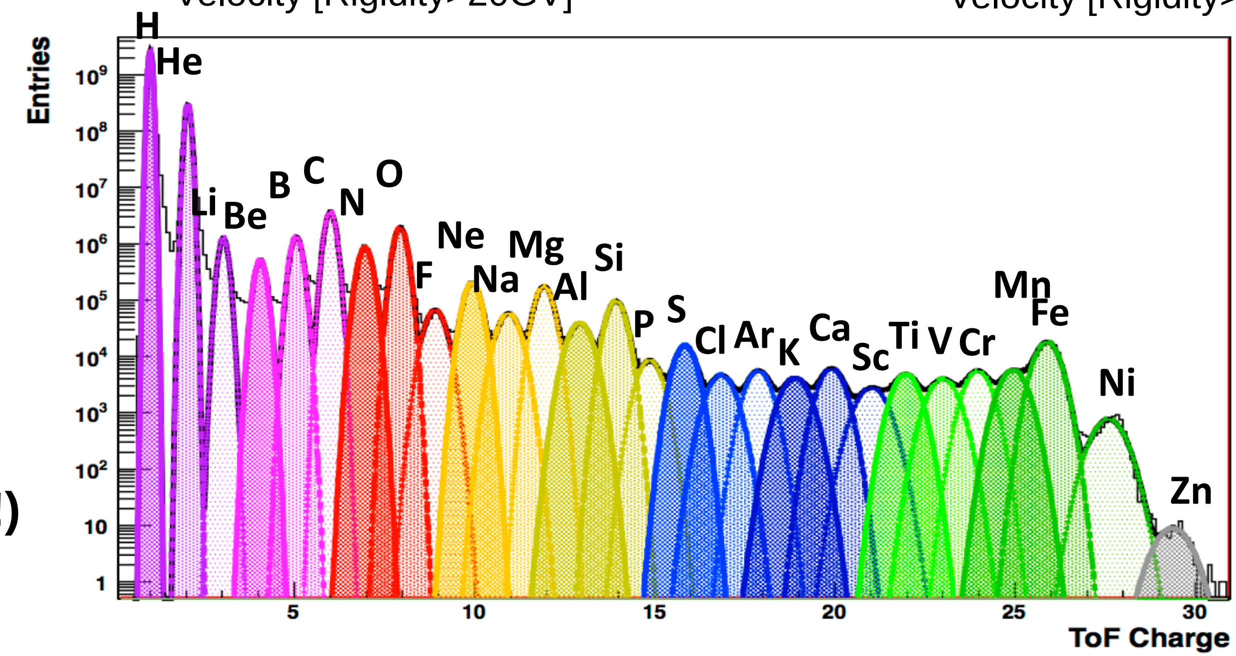
Time of Flight (TOF)

2017





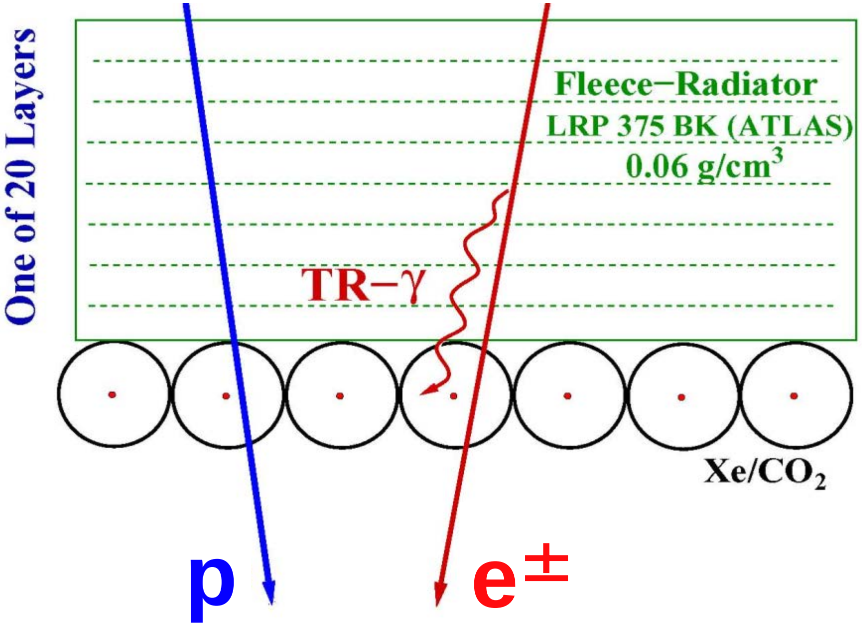


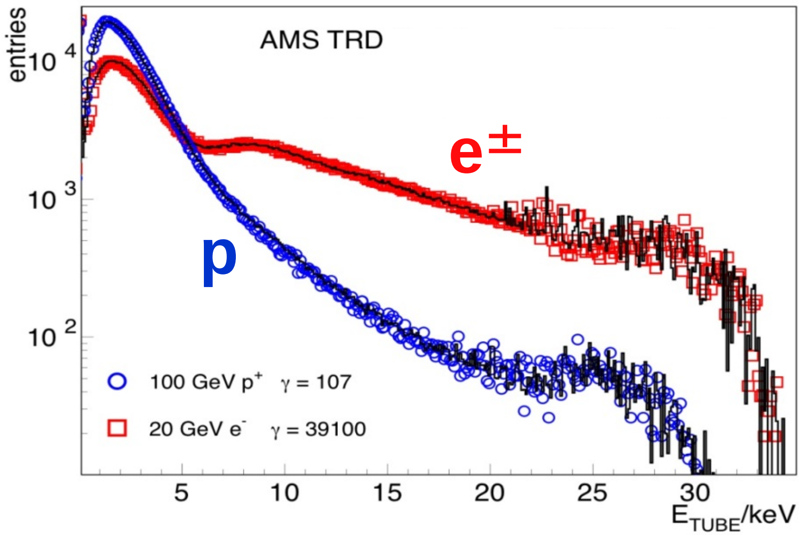


Up-going particles (fake anti-matter!) rejection up to 10^9

F.Montanet

Transition Radiation Detector (TRD)

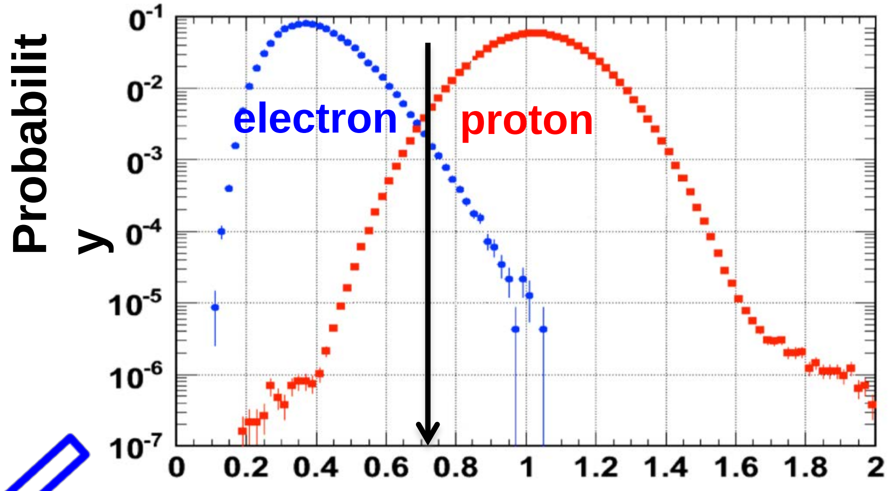




$$P_e = \sqrt[n]{\prod_i^n P_e^{(i)}(A)}$$

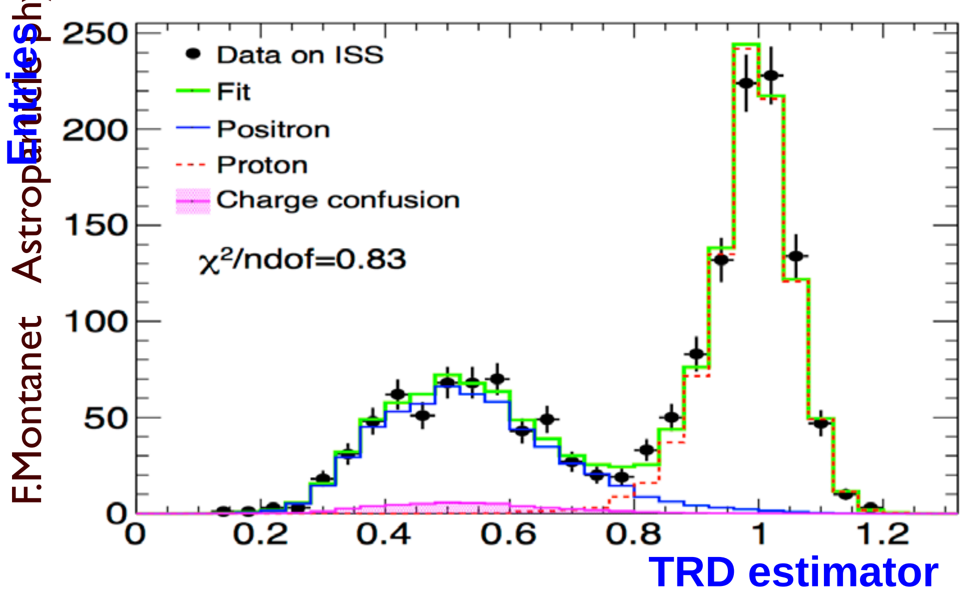
$$P_p = \sqrt[n]{\prod_i^n P_p^{(i)}(A)}$$

TRD e/p separation

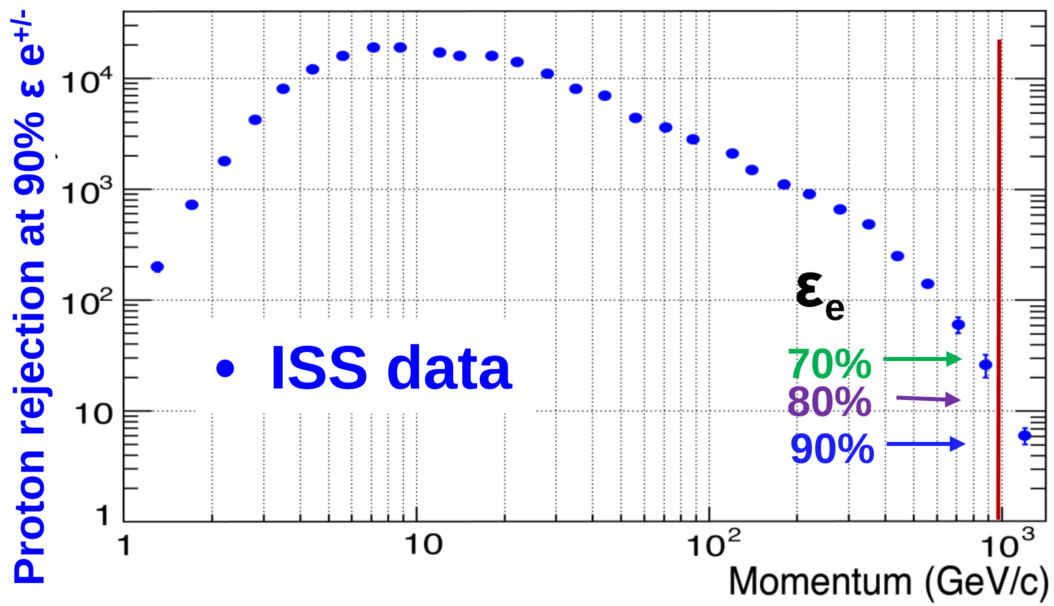


TRD estimator = $-\ln(P_e/(P_e+P_p))$

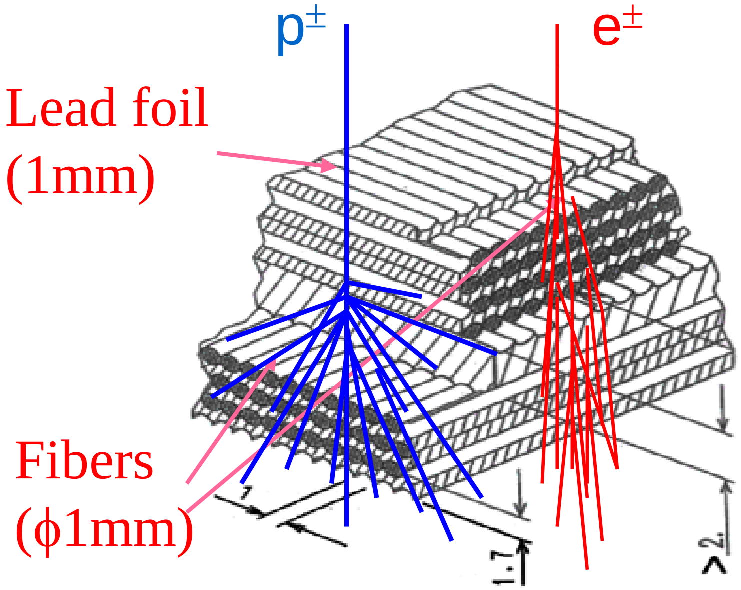
FIT



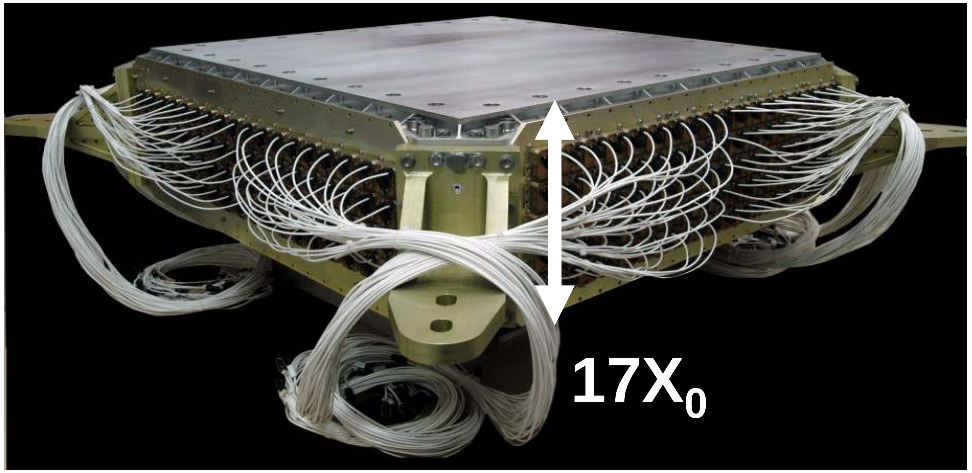
CUT



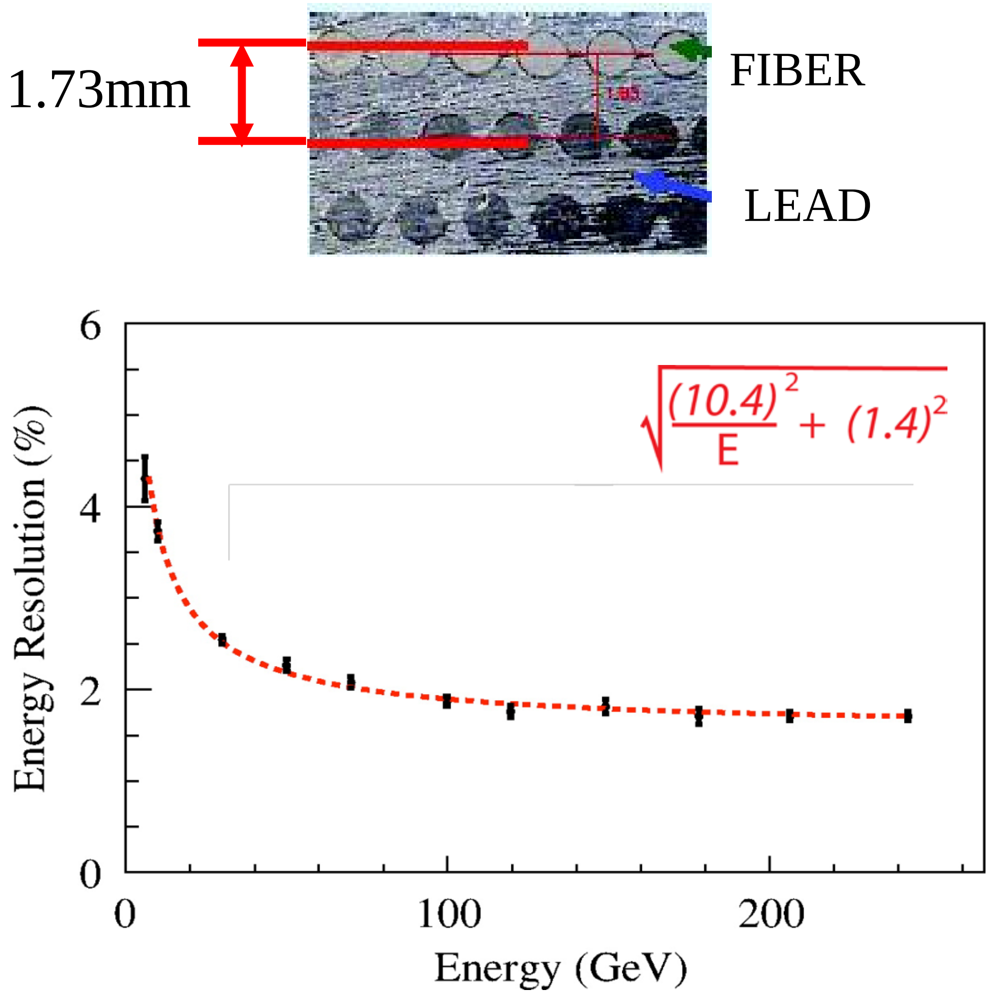
Electromagnetic Calorimeter (ECAL)



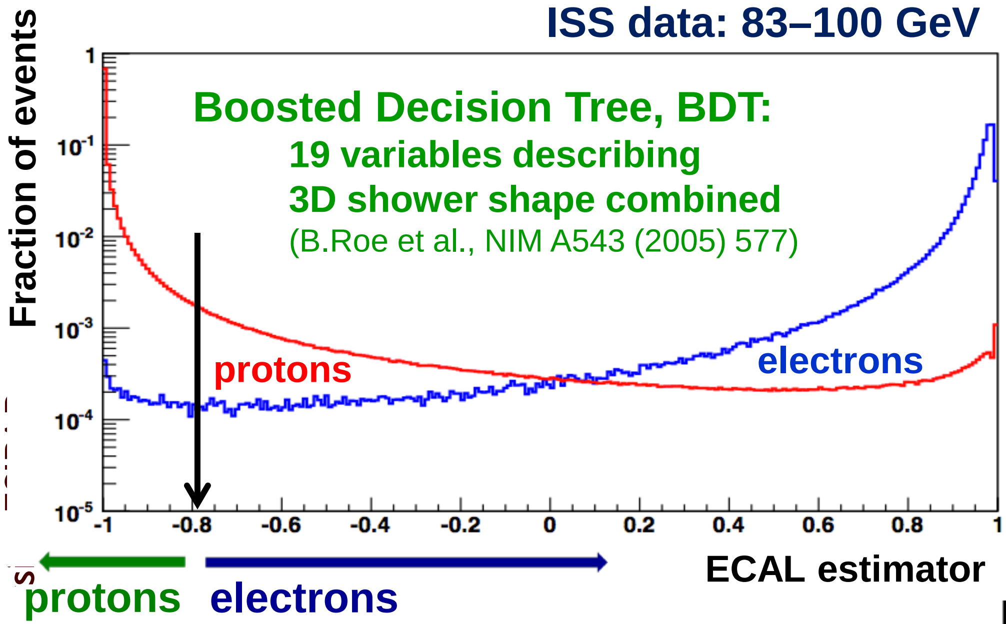
50,000 fibers, $\phi = 1$ mm
distributed uniformly Inside 600 kg of lead

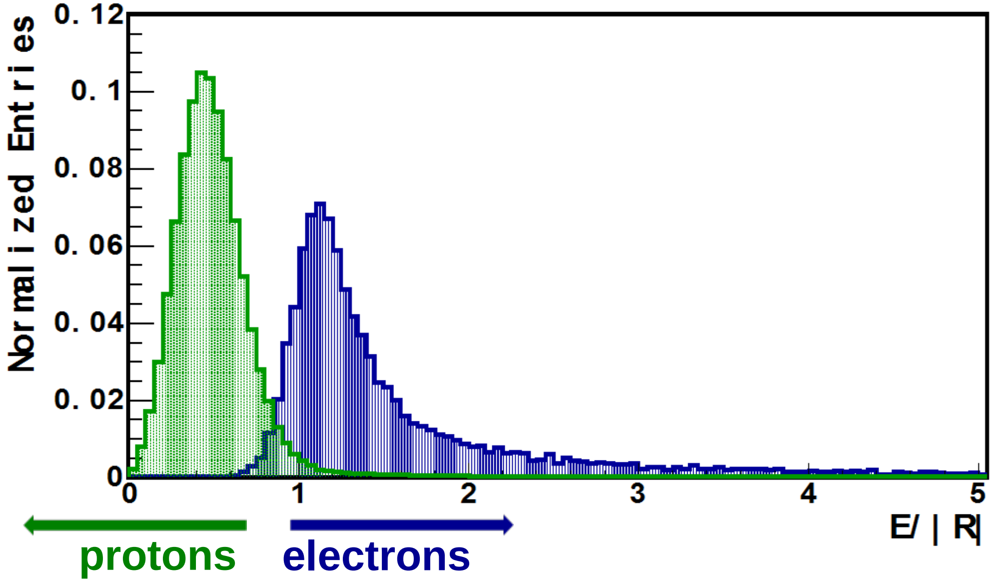


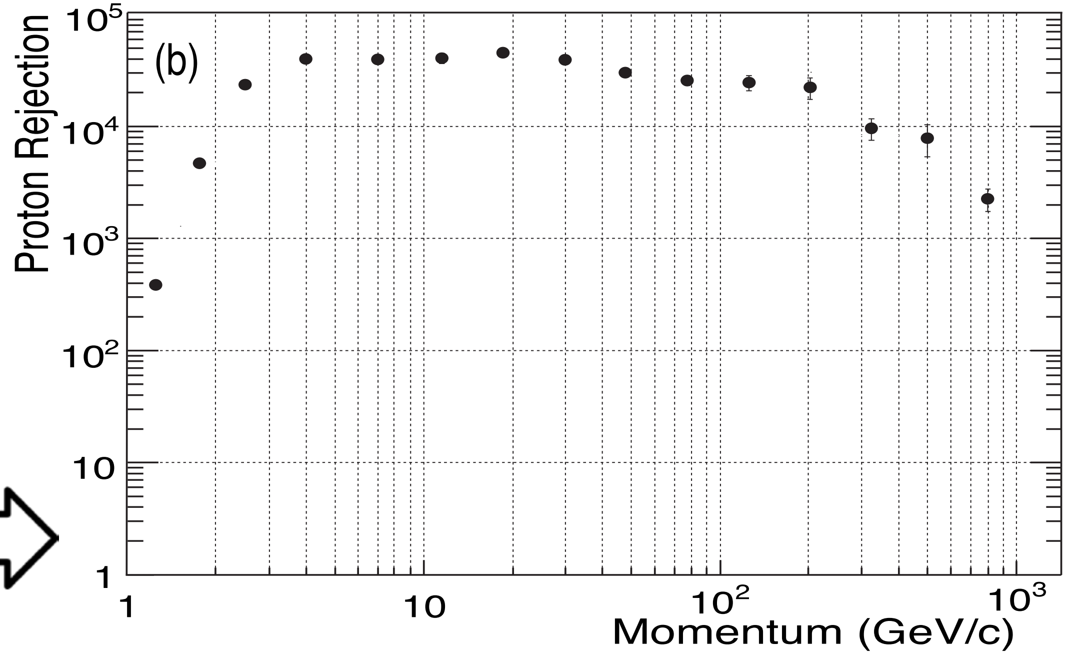
A precision, 3-D measurement of the directions and energies of gammas and electrons up to 1 TeV



ECAL e/p rejection



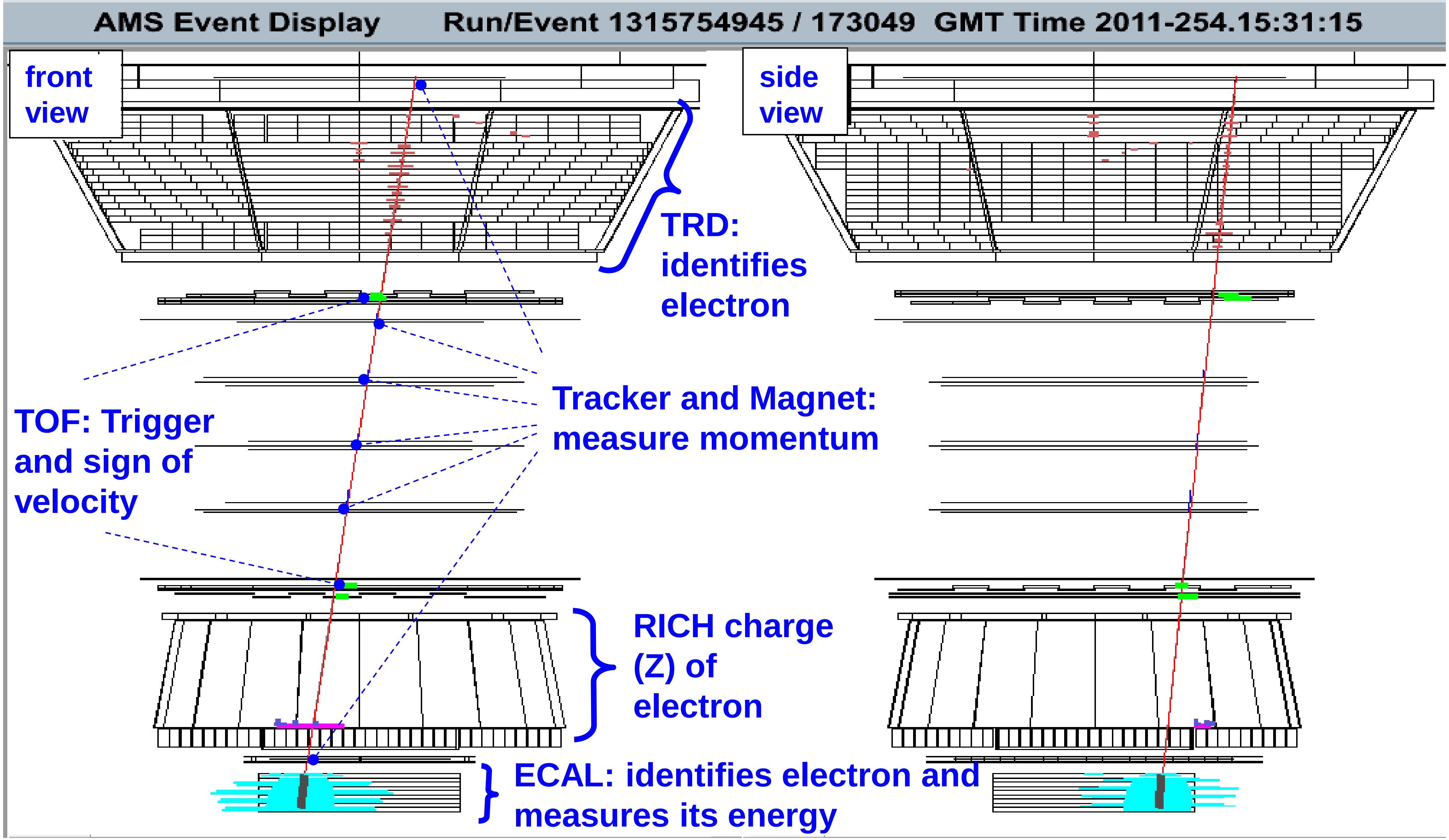




The Calorimeter thanks to its shower shape imaging capabilities can discriminate very sensibly eletromagnetic from hadronic showers

Combining the ECAL energy information with the Tracker Rigidity (E/R) the e/p rejection can be furtherly increased

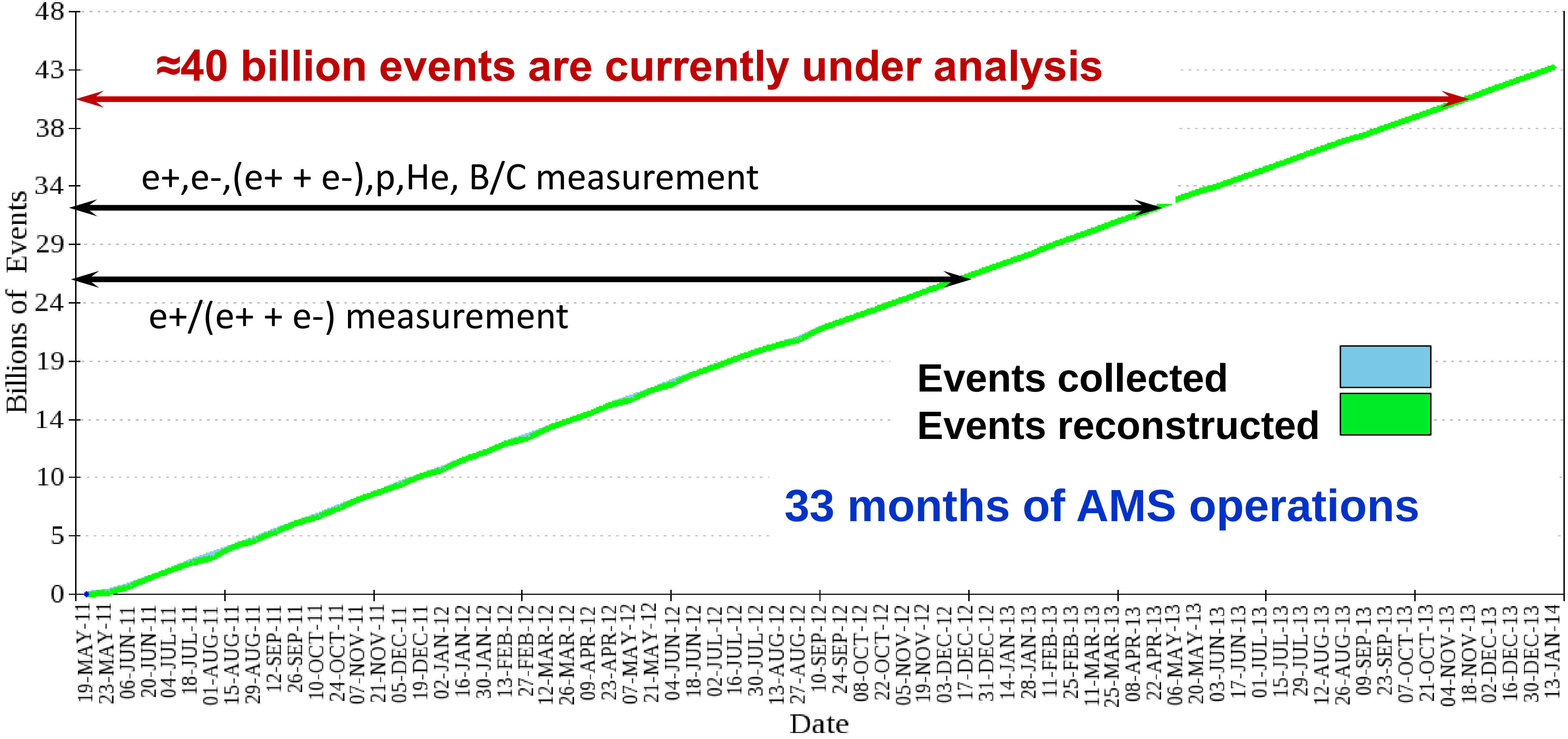
AMS data on ISS - 1.03 TeV electron



2017

High statistics

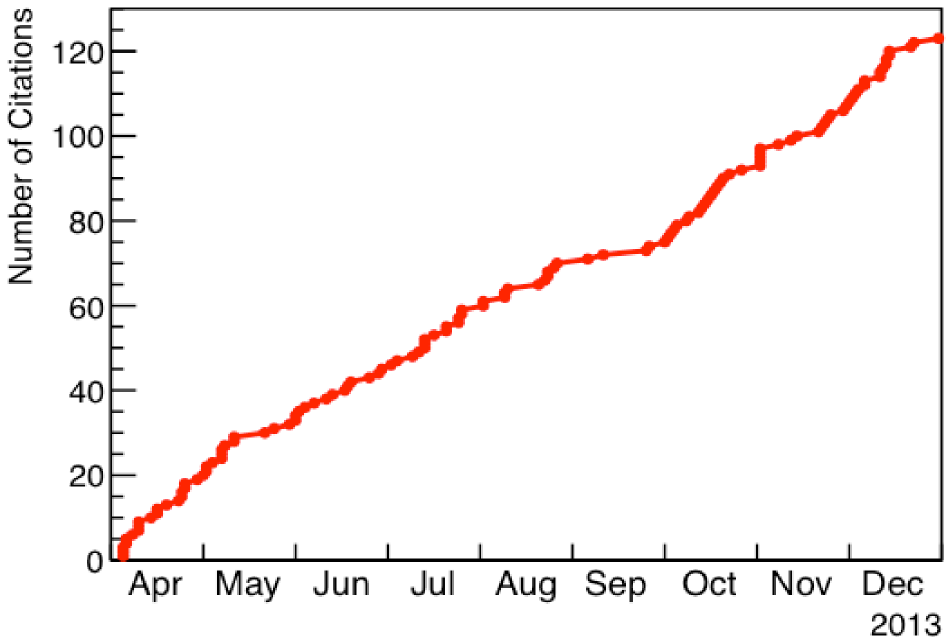
To date AMS collected ≈ 45 billion events

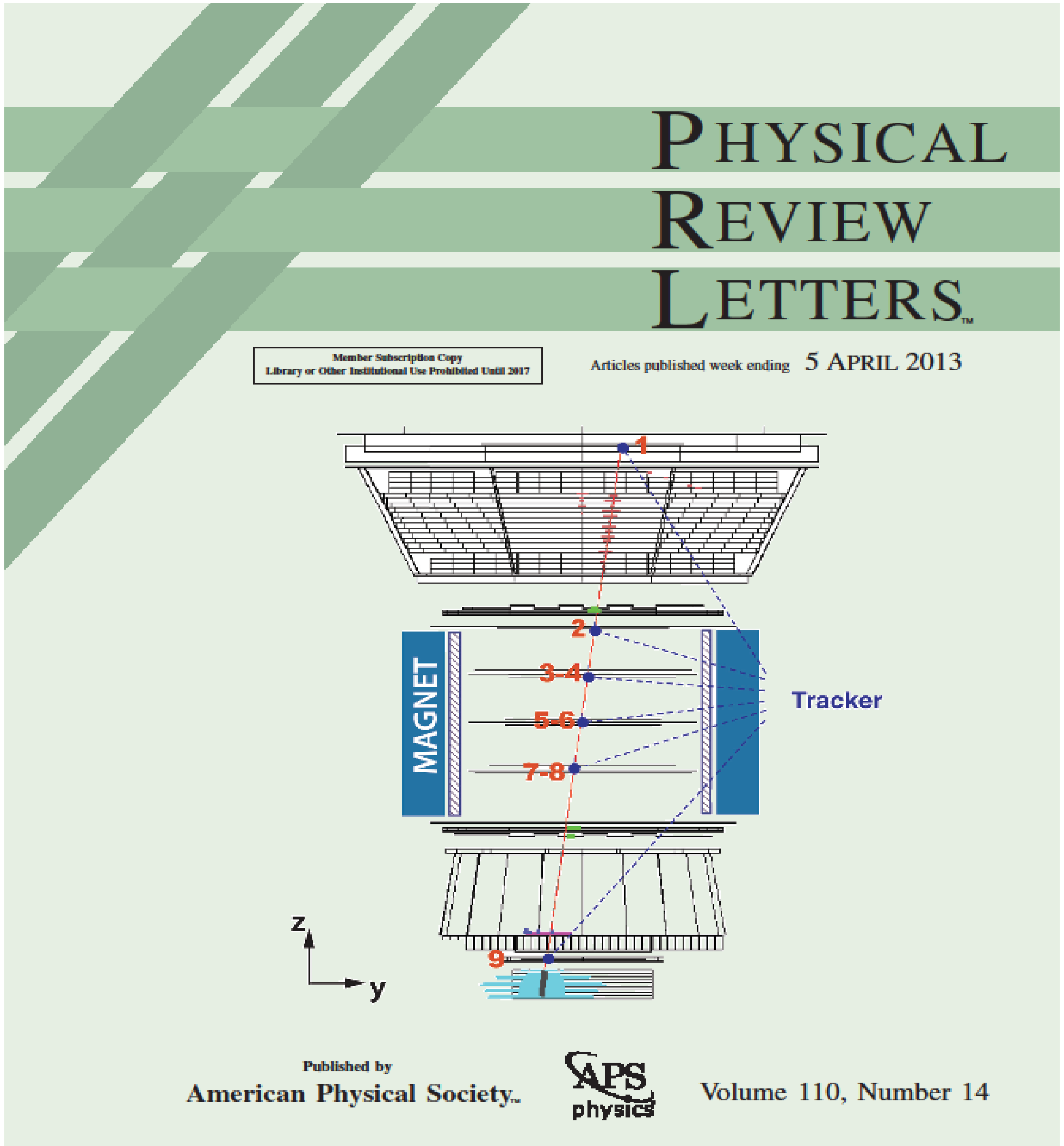


AMS-02 First Published Result

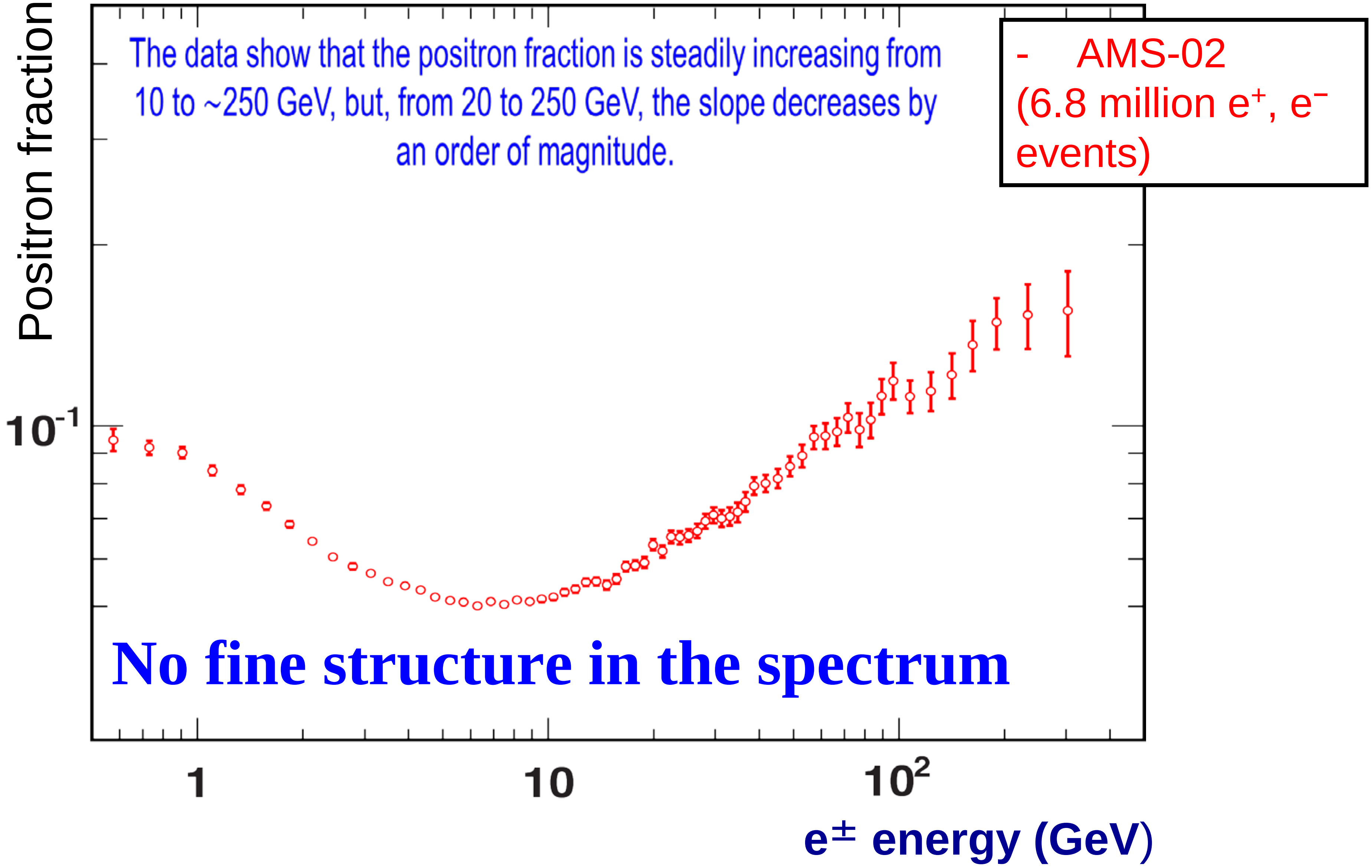
"First Result from the AMS on the ISS: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5-350 GeV"

Selected as a "Viewpoint" by APS

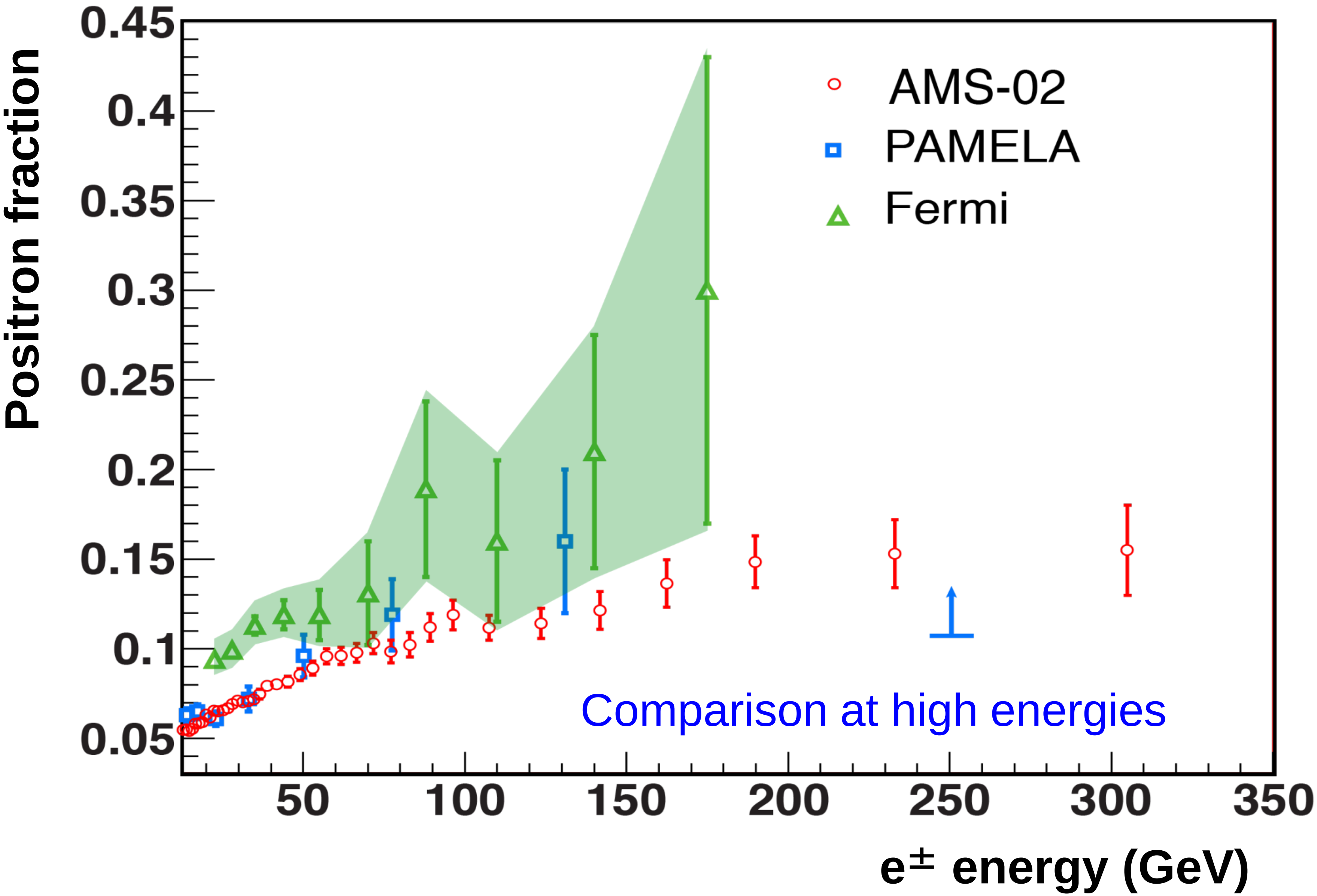




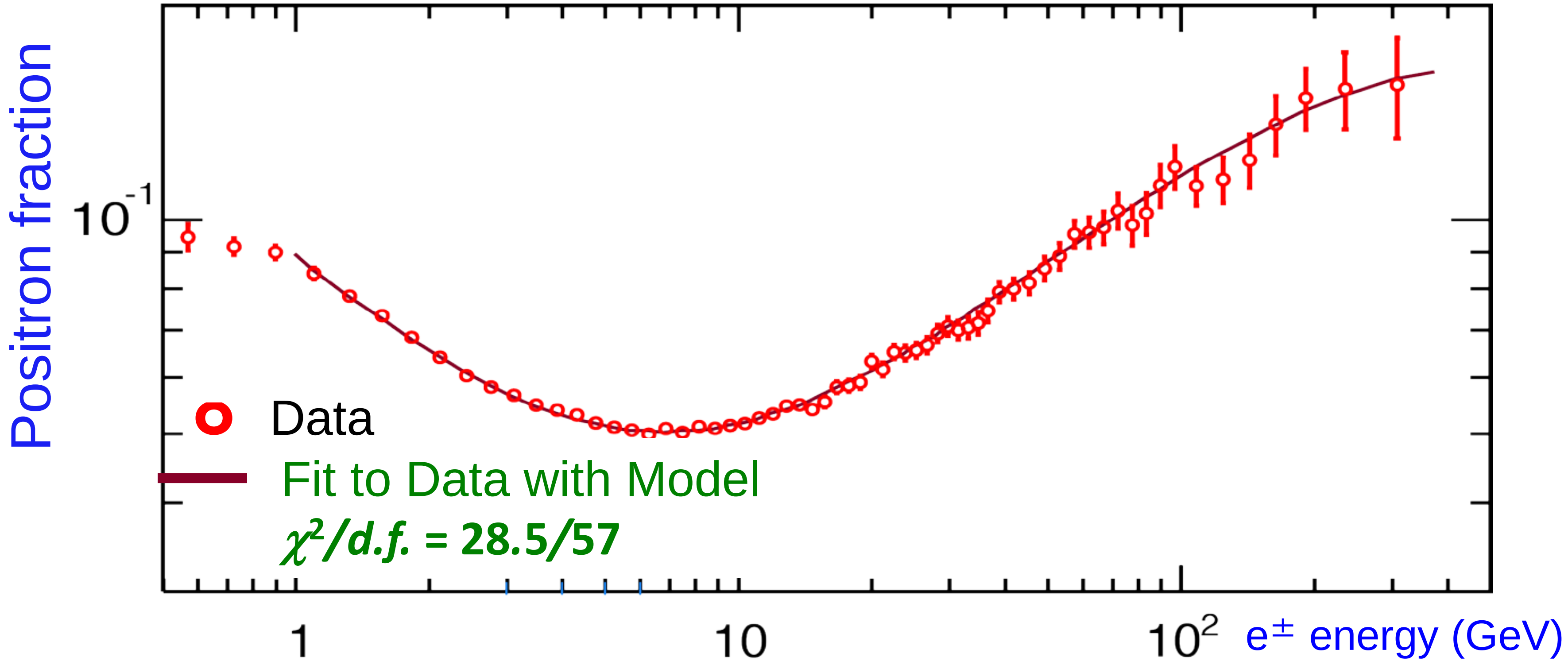
Positron fraction (0.5 - 350 GeV)



Positron fraction @ high energies



Minimal empirical model



Describe electron and positron fluxes as a sum of a **diffuse component** and a **common source** with a cutoff energy :

$$\Phi_{e^+} = C_{e^+} E^{-\gamma_{e^+}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

$$\Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

$\gamma_{e-} - \gamma_{e+} = -0.63 \pm 0.03$

$\gamma_{e-} - \gamma_{S} = 0.66 \pm 0.05$

$C_{e+}/C_{e-} = 0.091 \pm 0.001$

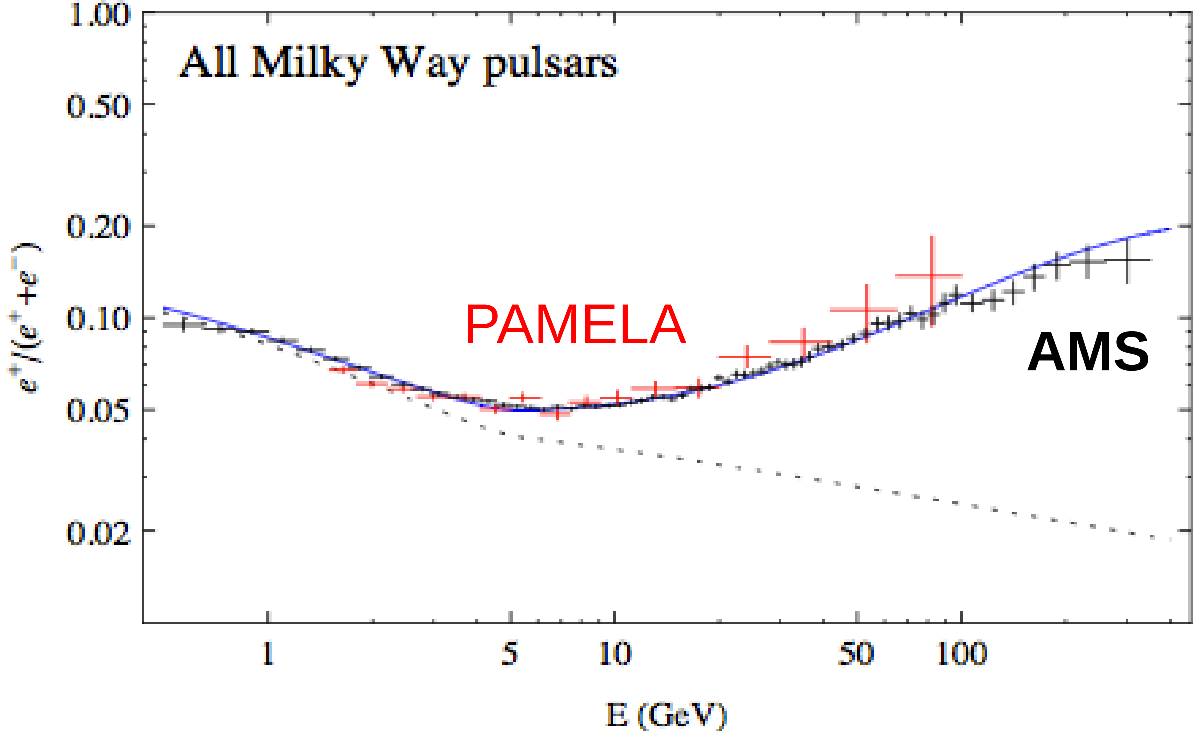
$C_S/C_{e-} = 0.0078 \pm 0.0012$

$1/E_s = 0.0013 \pm 0.0007$ GeV^{-1}, (760^{+1000} GeV

Origin of the excess

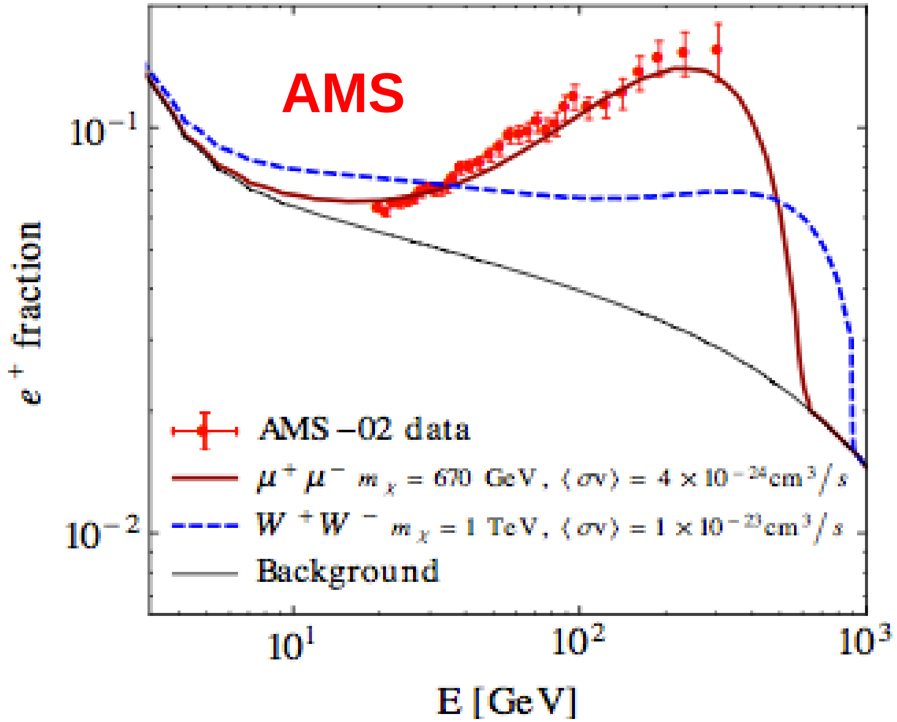
Astrophysical objects

Cholis arXiv: astro-ph/1304.1840



Dark Matter

Kopp hep-ph/1304.1184



Different energy behavior of the positron fraction:

- **Pulsars predictions:**
  - **slow fall at high energies**
  - **anisotropic positron flux**
- **Dark Matter prediction:**
  - **steeper fall at high energies**
  - **isotropic positron flux**

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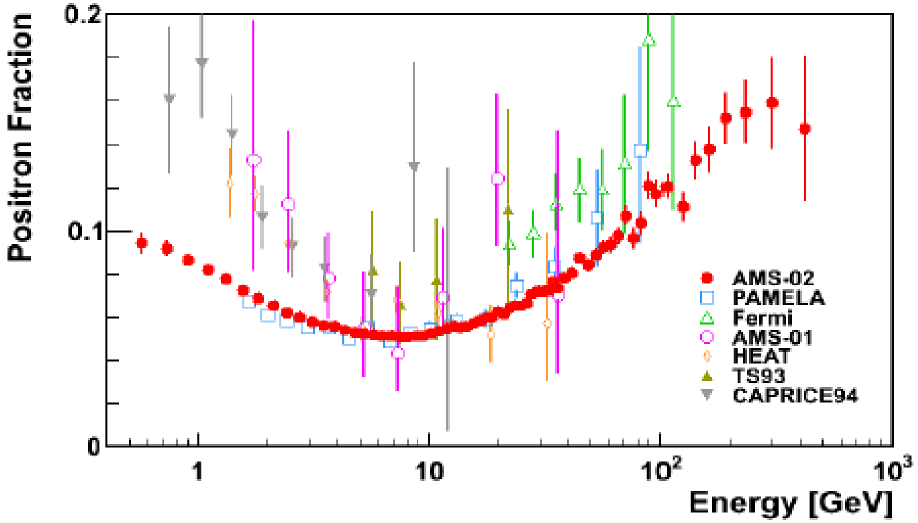
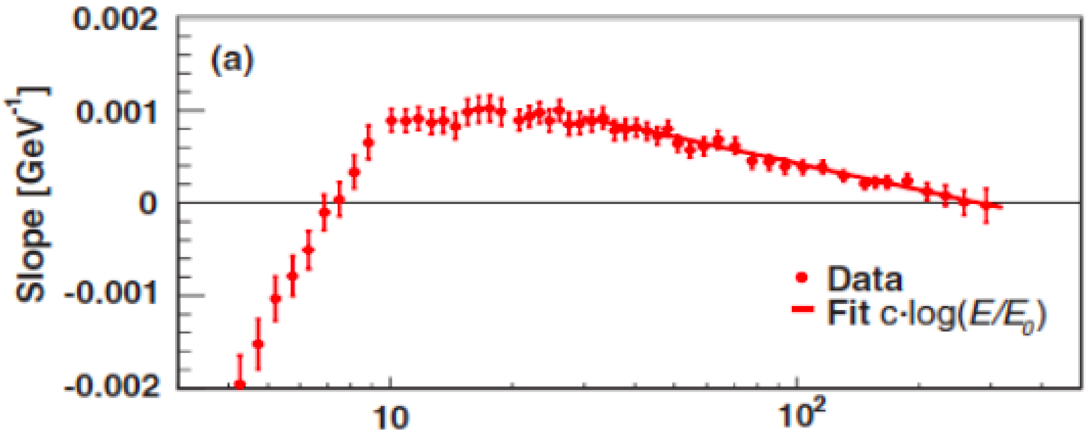
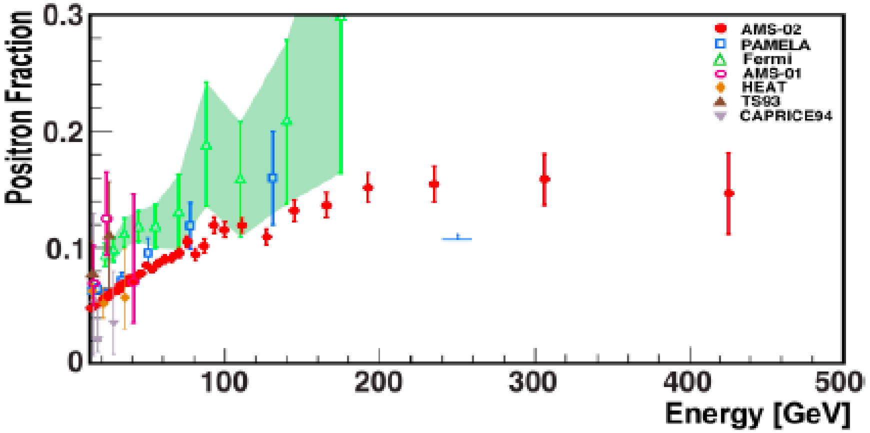
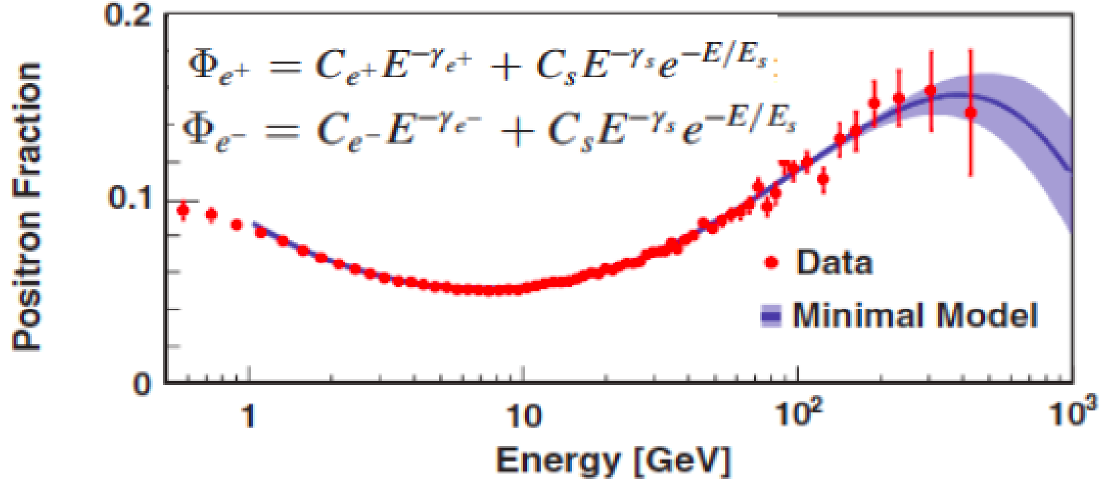
AMS-02: positron fraction

- ✓ No sharp structures
- ✓ Steady increase of the positron content up to ≈ 275 GeV
- ✓ Well described by an empirical model with a common source term for e^+/e^-









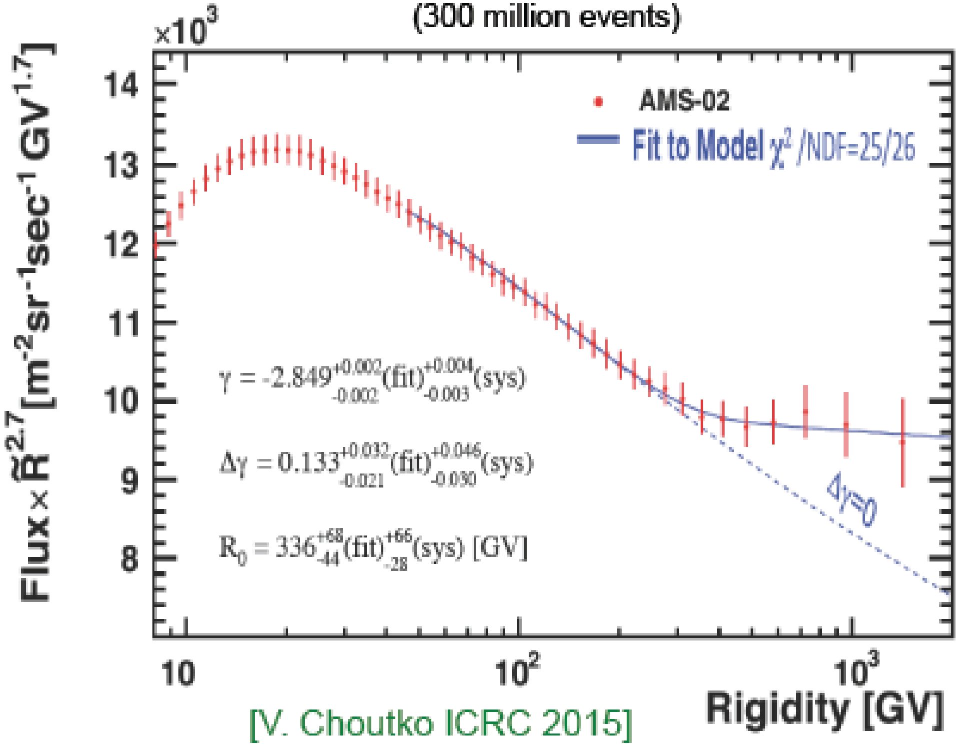
Proton and He fluxes

Proton and He fluxes measured by AMS-02

Two power laws with a characteristic transition rigidity R_0 and a smoothness parameter s are used by AMS-02 to fit the measured H and He spectra:

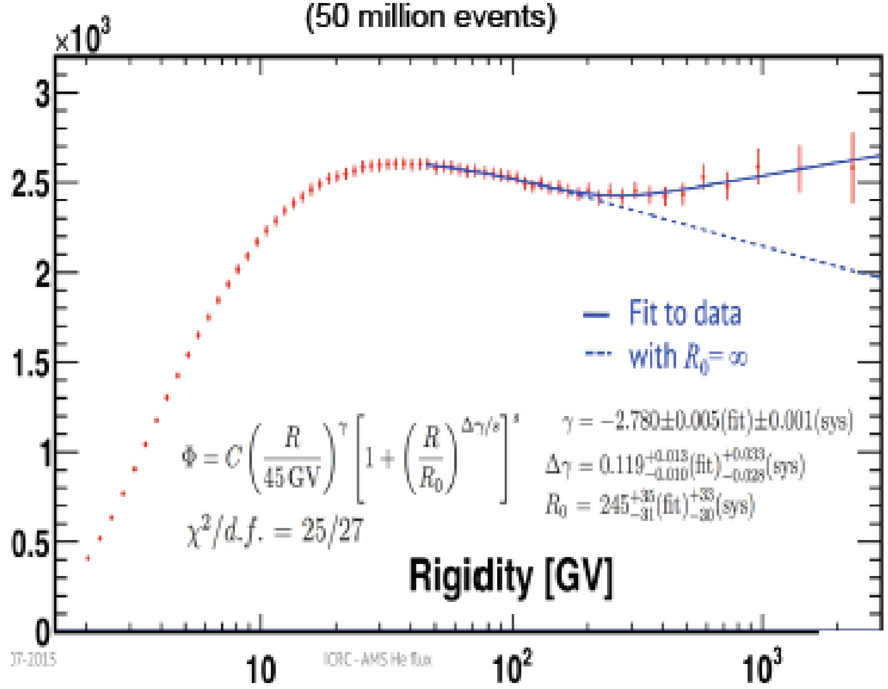
$$\Phi = C\left(\frac{R}{45GV}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/s}\right]^{s}$$

AMS proton flux
(300 million events)



[V. Choutko ICRC 2015]

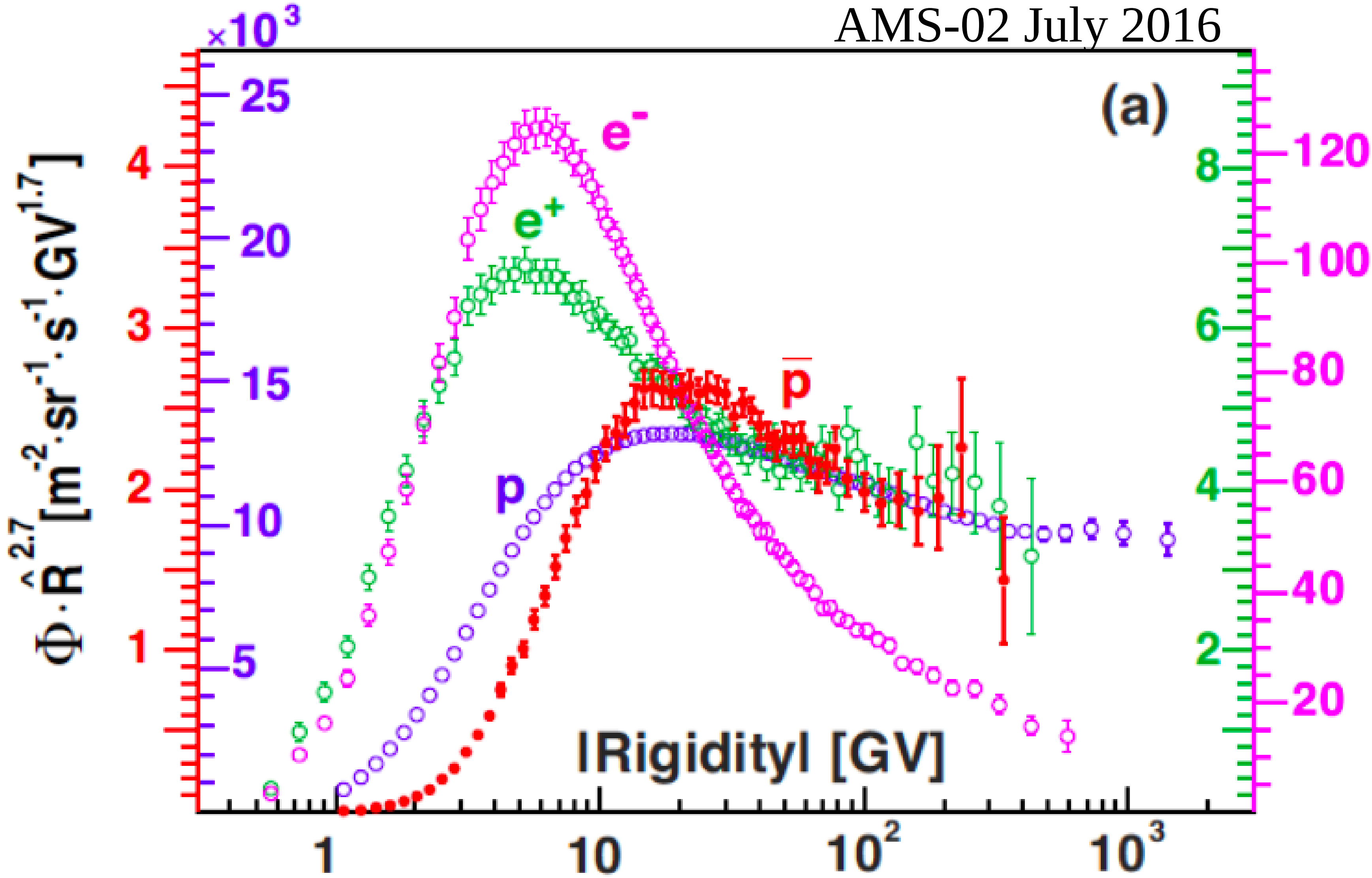
AMS He flux
(50 million events)



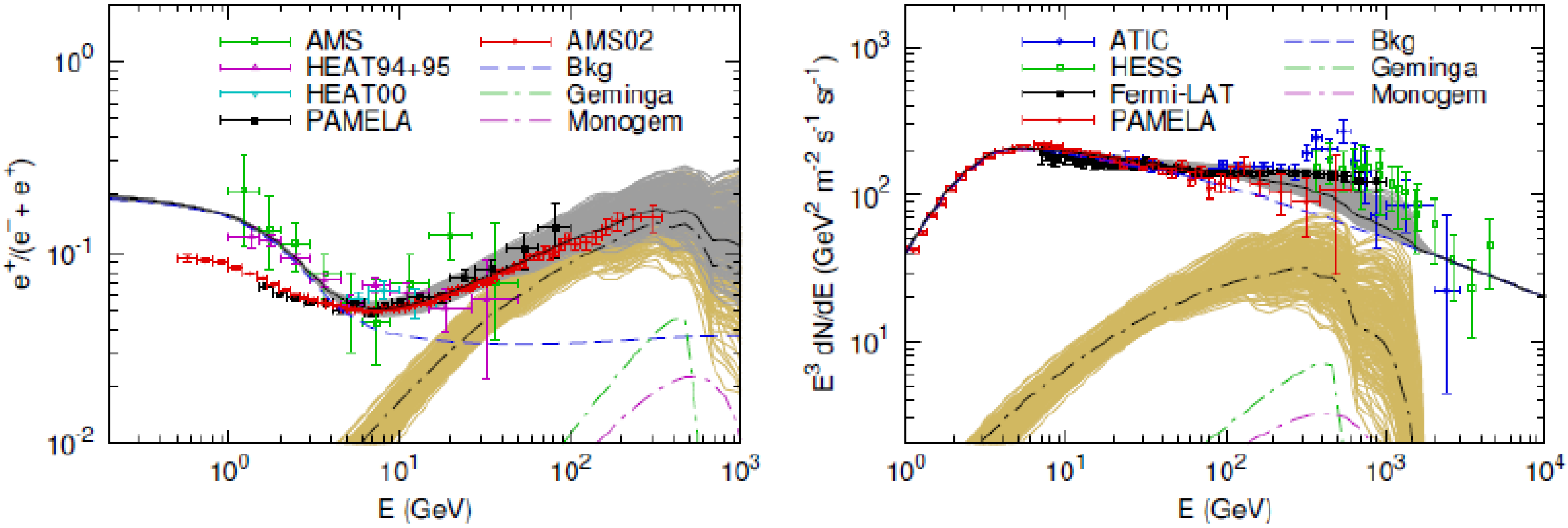
[S. Haino ICRC 2015]

Fluxes of e^+, e^-, p and anti-p

AMS-02 July 2016



Antimatter search (Dark Matter ?)



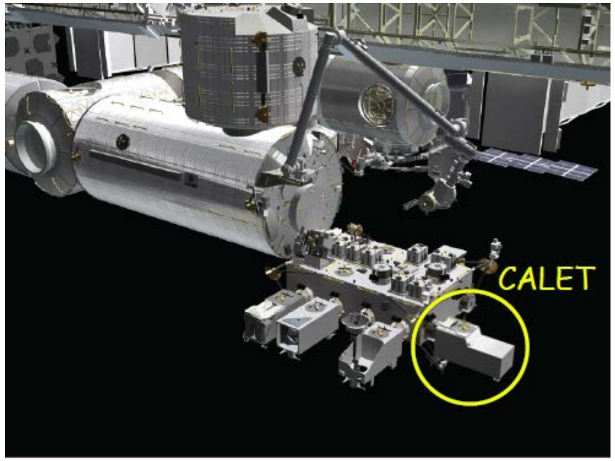
… or rather a boring "local" pulsar spoiling physicists dreams !

DM scenarios are conflicting with the anti-p/proton ratio that should show a huge excess and don't.

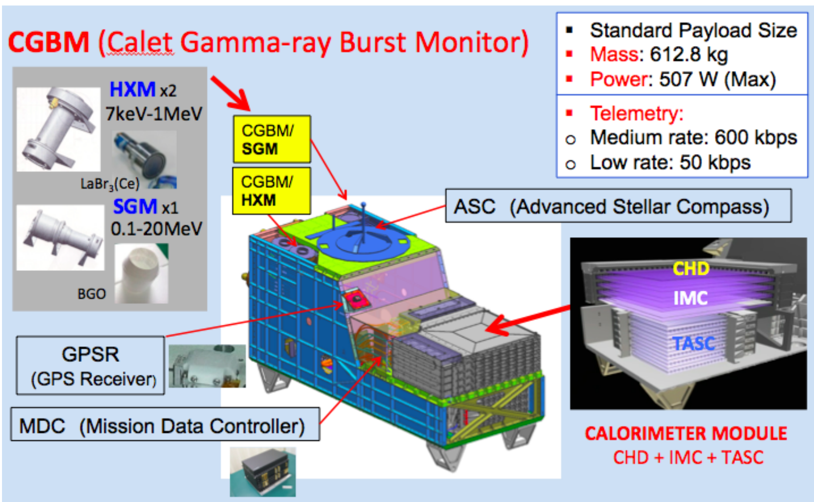
Charged particles (1 TeV → few 100 TeV)

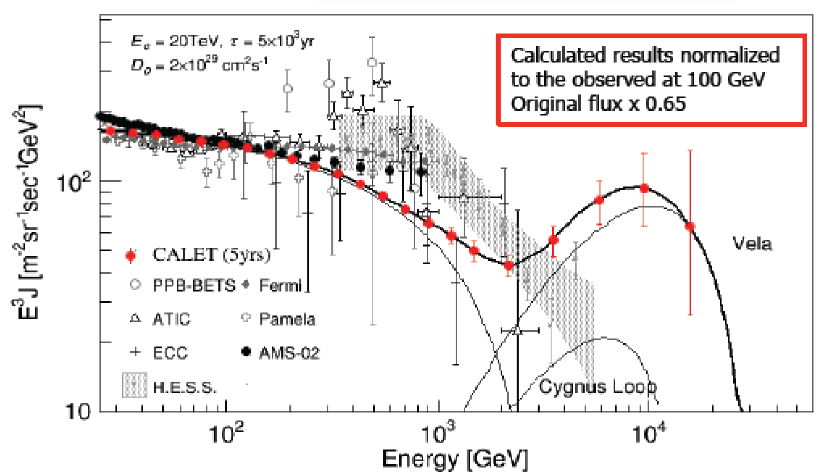
Calorimetric experiments

- Thick homogeneous high resolution calorimeters:
  ~ 30 X_0 , Δ E/E ~ 2%
- High granularity calo pre-sampler for e/p,A rejection: up to 10^5
- dE/dX charge assessment: up to Z=40



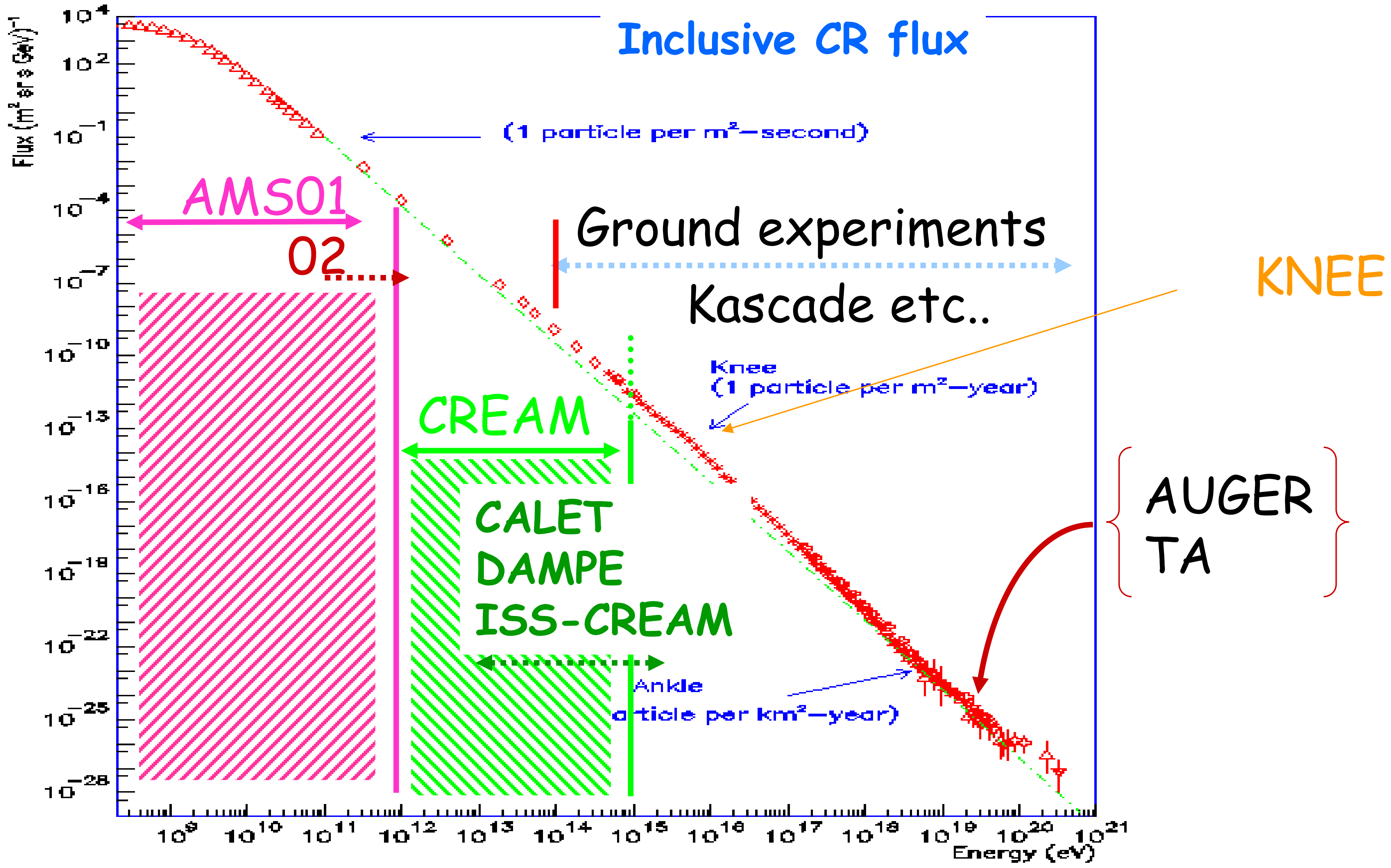
CALET aboard ISS since August 2015



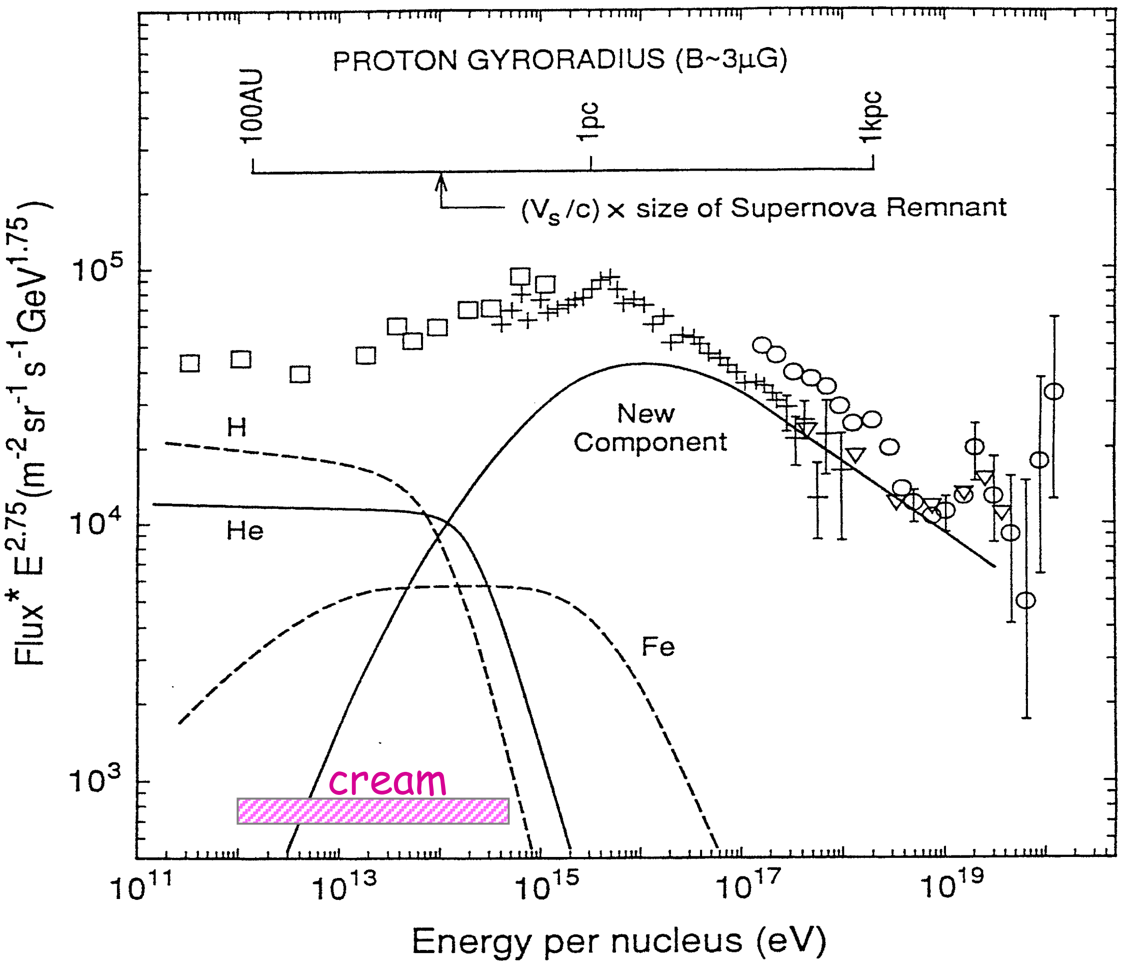


Identification of the unique signature from nearby SNRs, such as Vela in the electron spectrum by CALET

Reaching beyond the knee



The knee



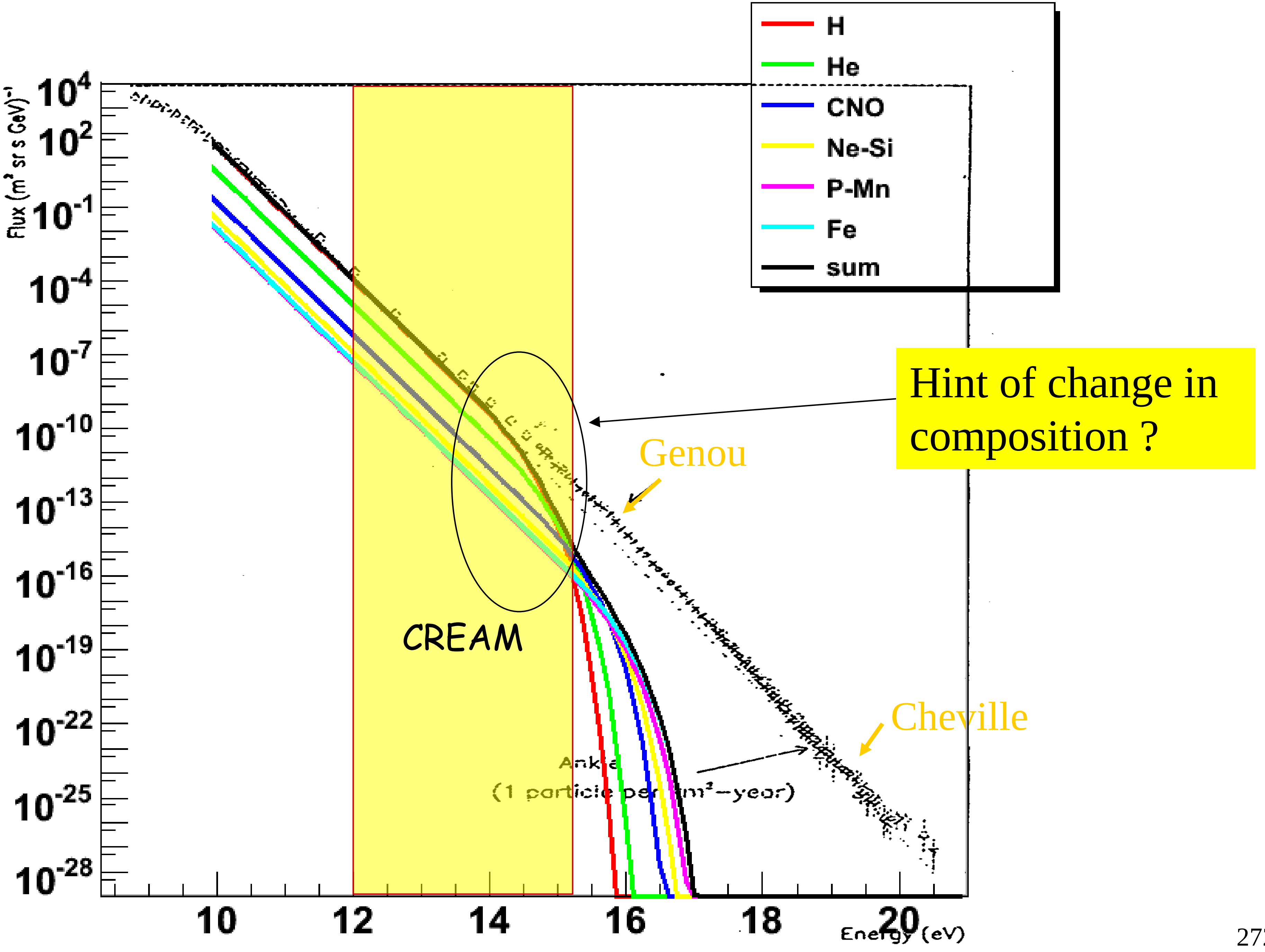
Is the knee due to:
- Acceleration mechanisms

or to changes :
- in propagation?
- in CR sources?
- in interaction properties (threshold) ?

⇨ A diffuse SNR shock acceleration with E_{max} implies a change in composition around ~10^{14} eV.

SNR energy limit: $E_{max} \sim Z \cdot 10^{14}$ eV

CR SM with Emax $\propto$ Z



AIR SHOWERS DEVELOPMENT MODELS

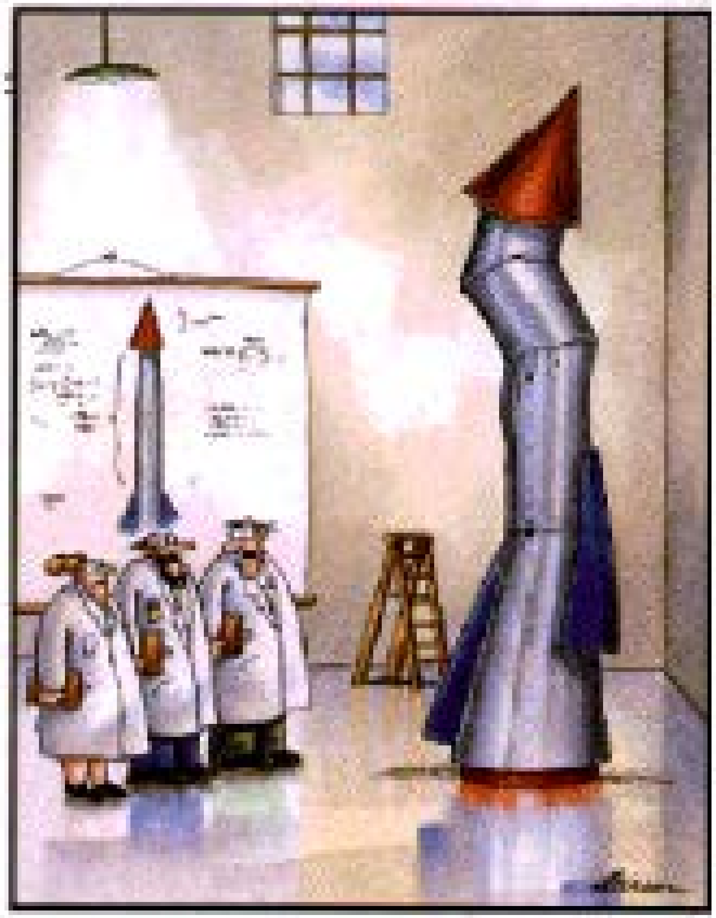
A peek above the knee !

To measure the inclusive spectrum at the knee, one needs a 10m^2 exposed during 10 years !

The realistic experimental limits are:

- For satellites ~ 1m^2 (sr) during ~few years
- For balloons, ~ 10m^2(sr) during n×30 days

→ E < 10^{15} eV



It's time we face reality my friends, we should keep to ground detectors !

Extensive Air Showers: the phenomenon and the observables

- The large shower of secondary particles induced by the interaction of a primary CR in the upper atmosphere can be detected on an extensive area → large effective surfaces to fight against low flux at E ≥ 1000 TeV

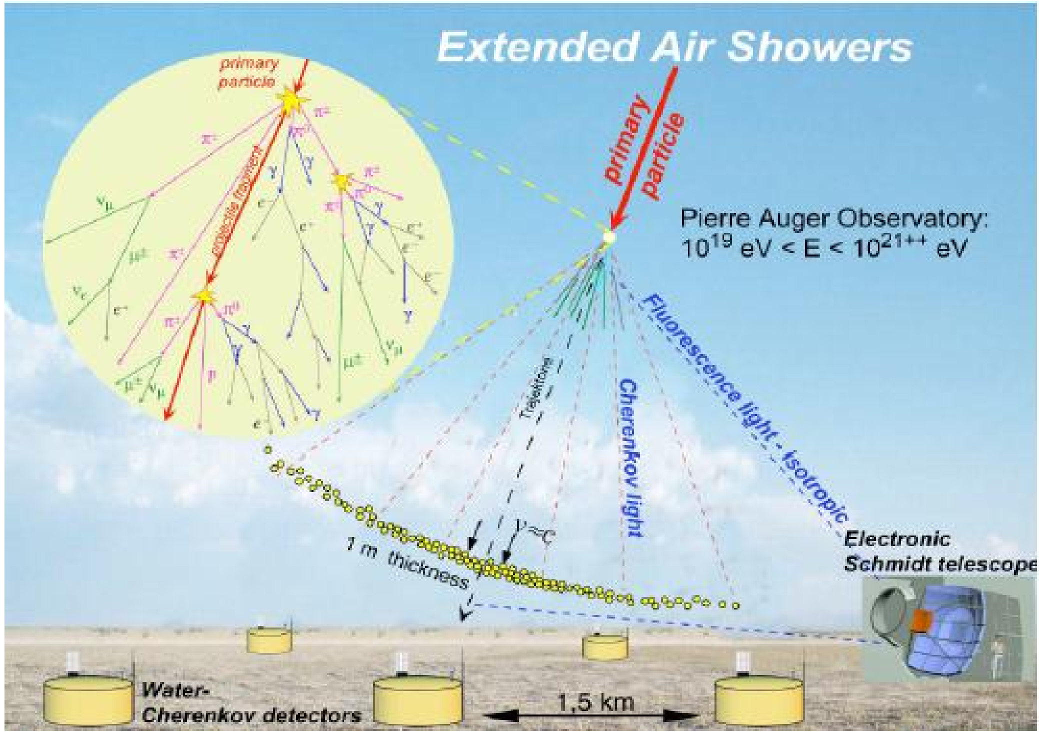
- Atmosphere used as an calorimeter (~1000 g cm^{-2} at sea level for a vertical shower)

- From the observables, one aims at measuring:
  - Incident direction;
  - Primary energy E_0 ;

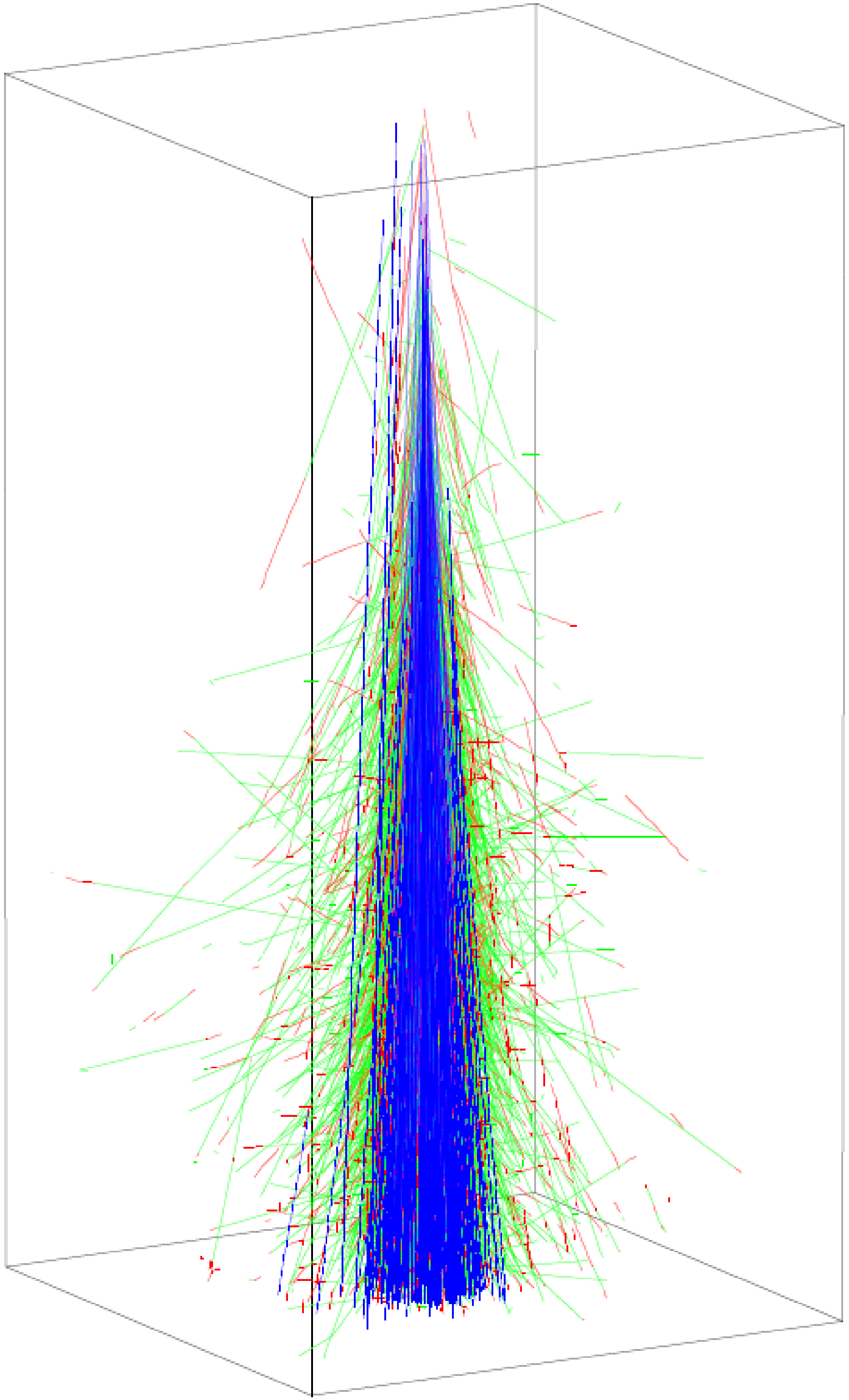
  and if possible, get access to the nature of the primary particle :
  - distinction γ-hadron ;
  - distinction light nuclei (p, He) - heavy nuclei(Fe)

p or nucleus + N or O nucleus → hadronic cascade

- Hadronic component: nuclear fragments, nucleons, mesons π, K, etc.
- Electromagnetic component: induced by $\pi^0 \to \gamma\gamma$ and other radiative decays
- Muonic component: induced by decays of $\pi^{\pm}$ and $K^{\pm}$
- Atmospheric Neutrinos issued from s $\pi^{\pm}$ $K^{\pm}$ and $\mu^{\pm}$ decays



Primary electrons and γ induce an electromagnetic shower consisting mainly of secondary electrons, positrons and γ (muon poor)



Shower development

« des giboulées d'électrons »

Rayons cosmiques
par Pierre Auger
1941 PUF

A 10^{19} eV shower

10^{11} particles
at sea level

Photons + electrons (99%),
muons (1%)

Ground observables

- Secondary particles reaching ground

  As a function of the primary energy and of the altitude:
  - Residual Hadrons (nuclear fragments): not numerous (>11 λ_{int}).
  - $e^{\pm}$: the more numerous at shower development maximum.
  - $\mu^{\pm}$: most reach ground and may penetrate deep underground.
  - γ secondaries : may be detected at ground level via e^+e^- pair conversion (e.g. Cherenkov effect in water).

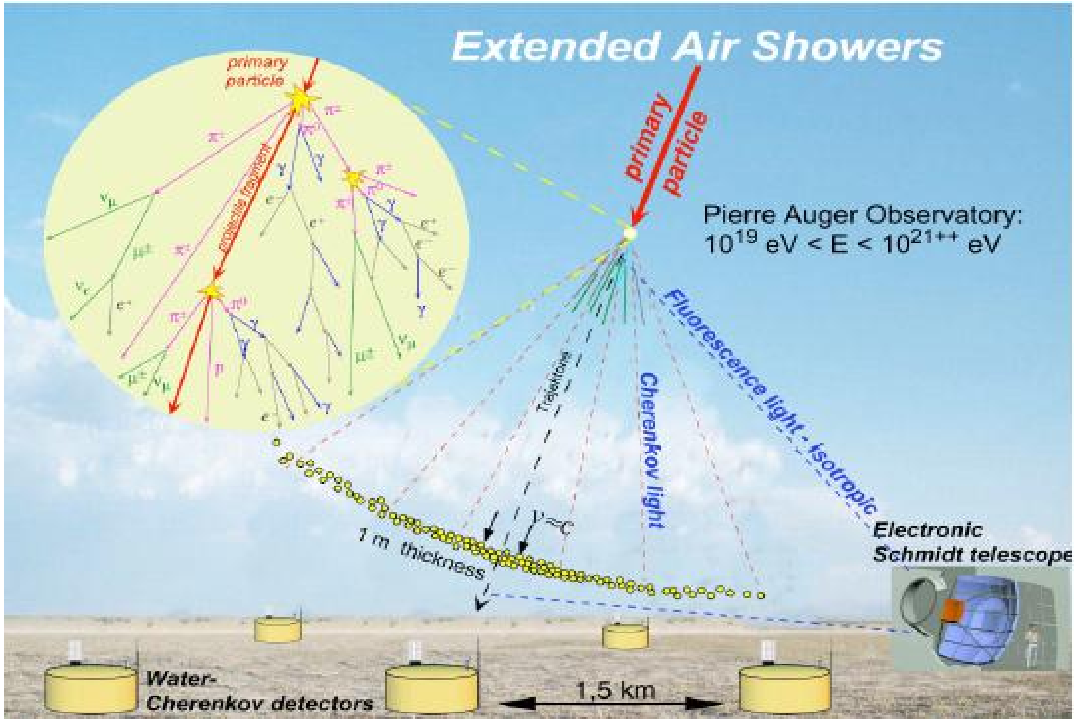
- Photons (visible, UV) emitted along the trajectories of charged particles (Cherenkov effect, N_2 fluorescence) during the shower development

  → Calorimetric 3D information !

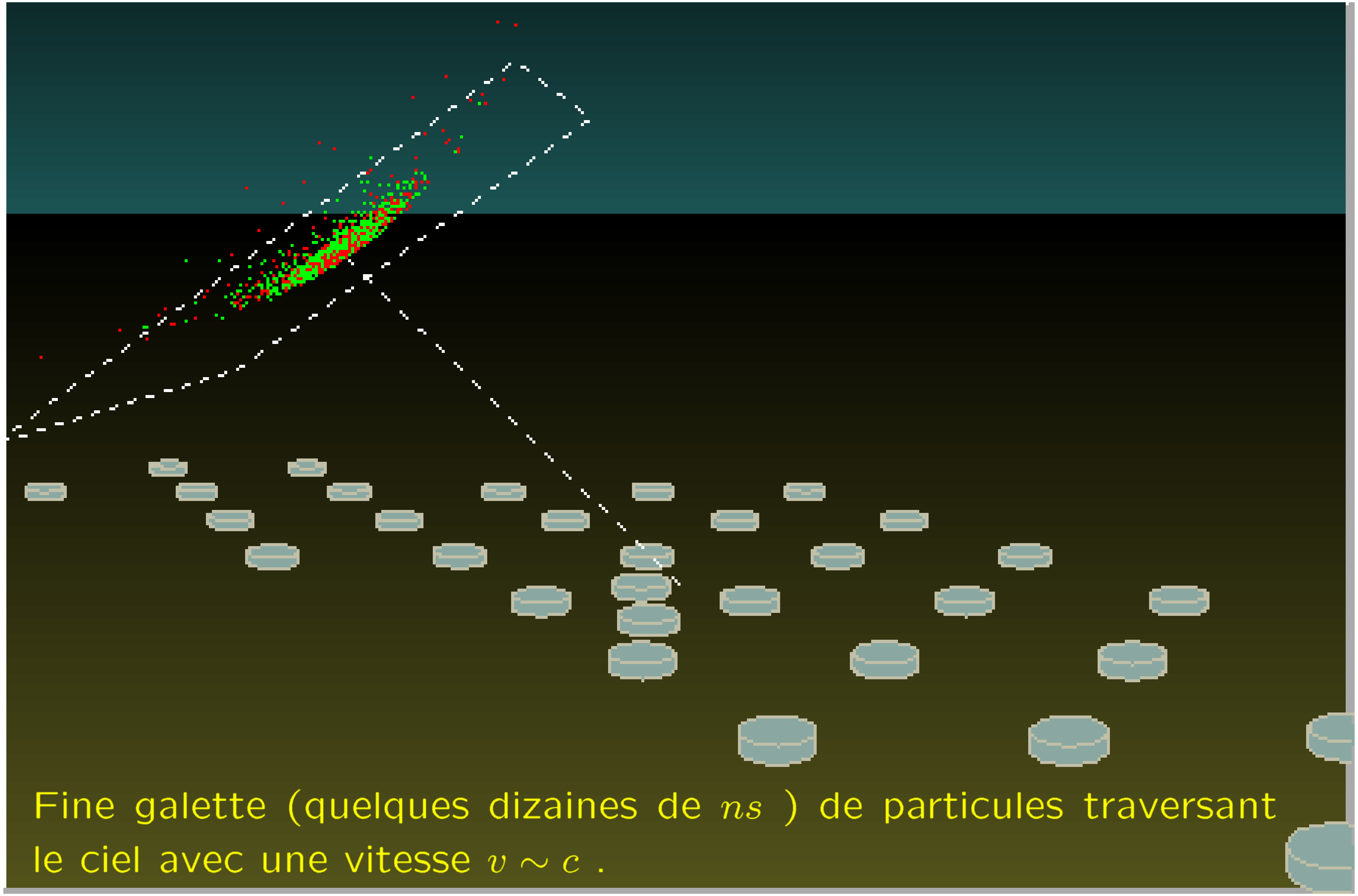
- Radio emission by the shower particles in the geomagnetic field or by the induced plasma.

Temporal aspects

- A light speed moving "pancake" of charged particles.
- This front is more or less curved depending on the shower development stage.
- The front thickness (~ 10 m) induce as signal time spread in each detector.
- The arrival time differences at ground on the sampling detectors → arrival direction (Δθ ≈ 1°).
- The Cherenkov light front (forward emission) is thinner (~m) than the charged particle front → well defined timing.



Time structure

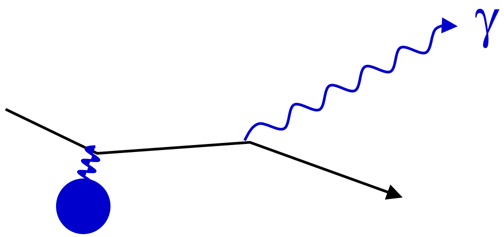


EM shower
Longitudinal development

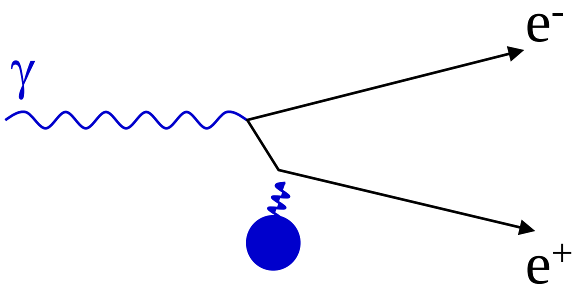
- Mean number of particles (e^+,e^- or γ) crossing a plan $\perp$ to the shower axis after a slant depth t (in units of X_0).
- As long as the ionization losses are small wrt radiation losses (bremsstrahlung and pair prod)
  the number of particle increase exponentially.
- When the mean energy per particle decreases below the critical energy
  ($E_c \approx$ 84,2 MeV in air), the number of particle decreases
  (shower extinction phase).
- At the transition between the two phases, (maximal development), the mean energy is equal to the critical energy.

Radiative processes (E > E_c)

Bremsstrahlung :



Pairs production :



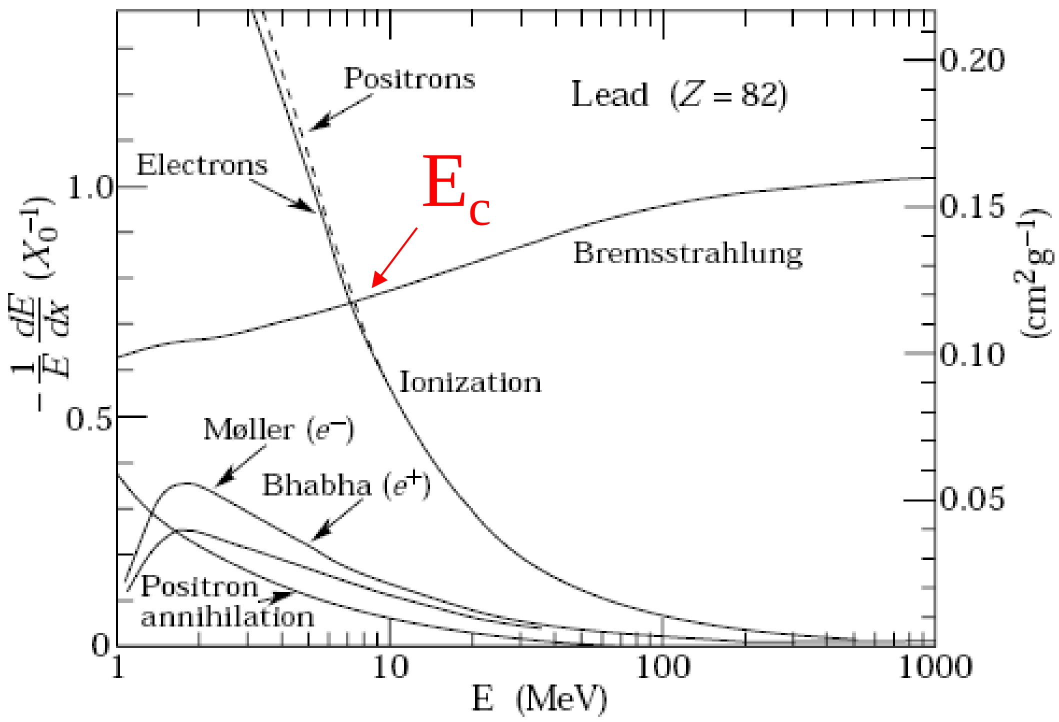
Radiation length X_0 :

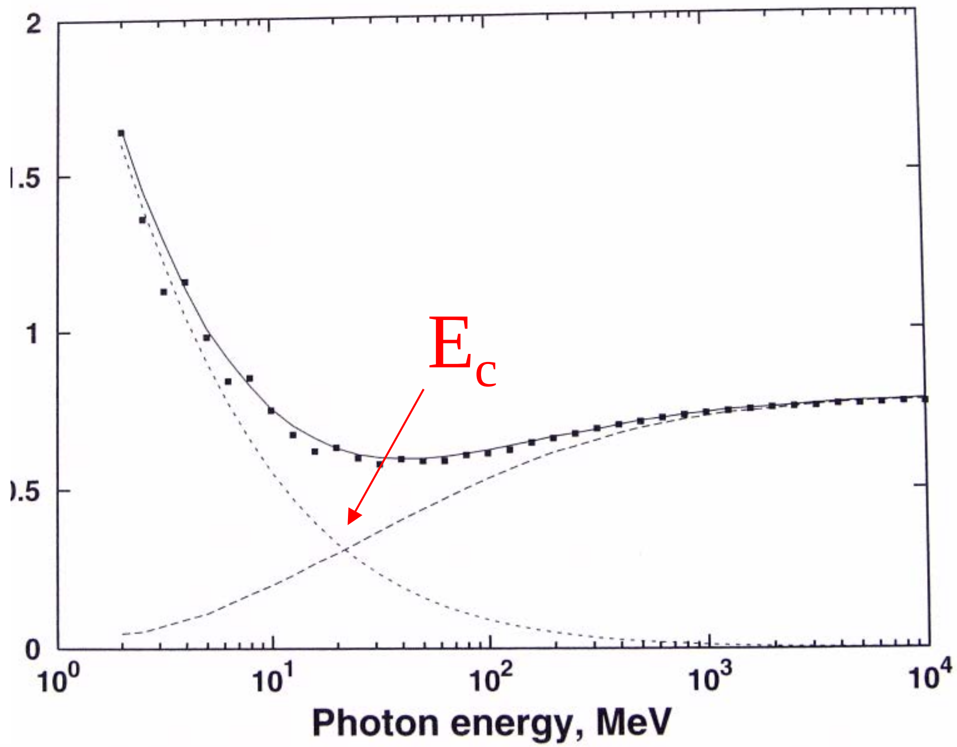
•energy loss $= 1/e$ due to bremsstrahlung

• 7/9 of the range of a γ due to pair production.

In air : $X_0 = 36.7\mathrm{g/cm}^2$

EM cascades (Rossi & Greisen)



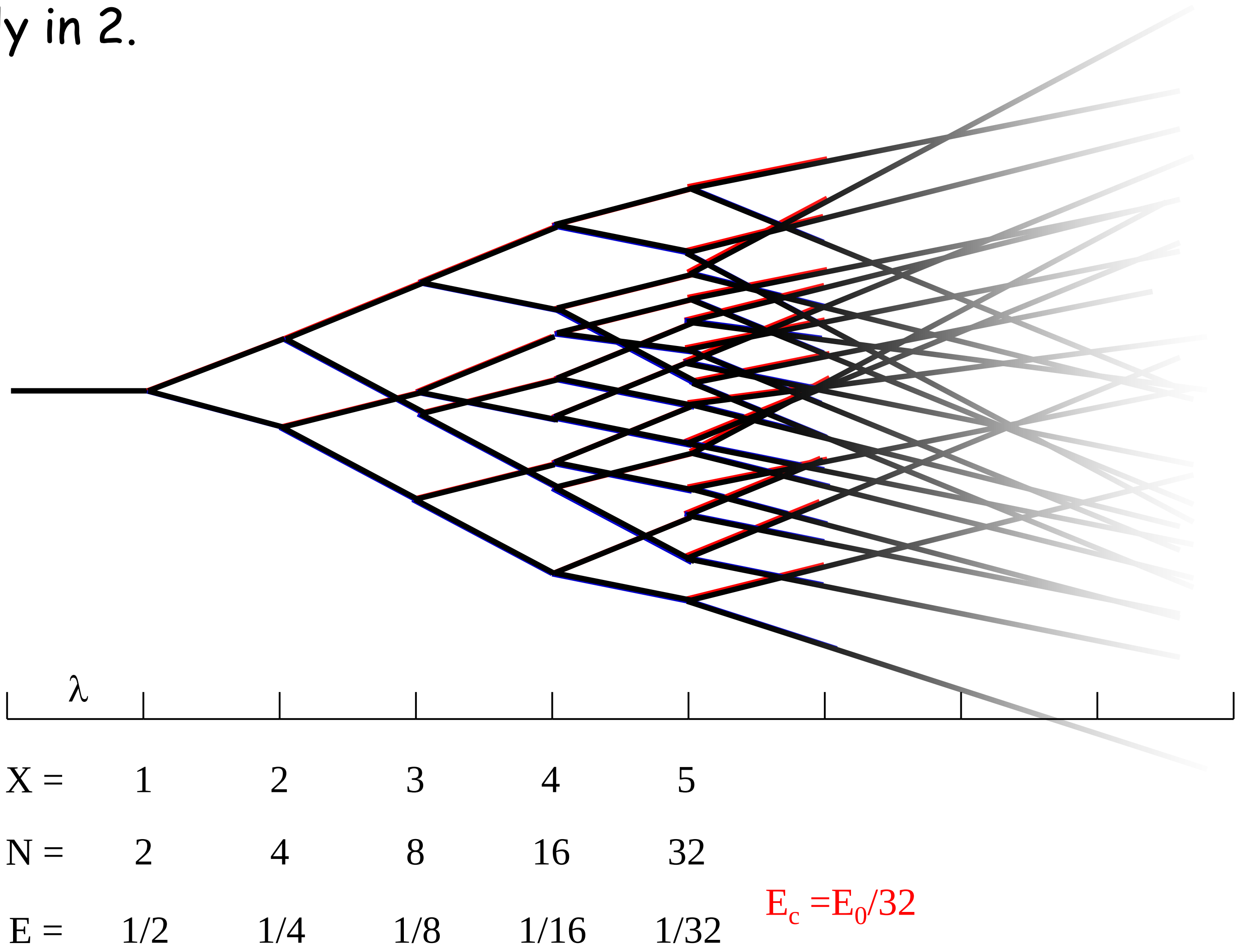


Critical energy: below this energy, ionization losses dominate.

Simplified development model (Heitler)

- Cascade consisting of only one type of particles having an interaction length λ.
- At each interaction, 2 particles of same type are emitted sharing the energy exactly in 2.

F.Montanet Astroparticle physics ESIPAP



Longitudinal development

- After t radiation length, there are 2^t particles with energy

$$E = E_0/2^t$$
$$\text{soit} : t \ln 2 = \ln(E_0/E)$$

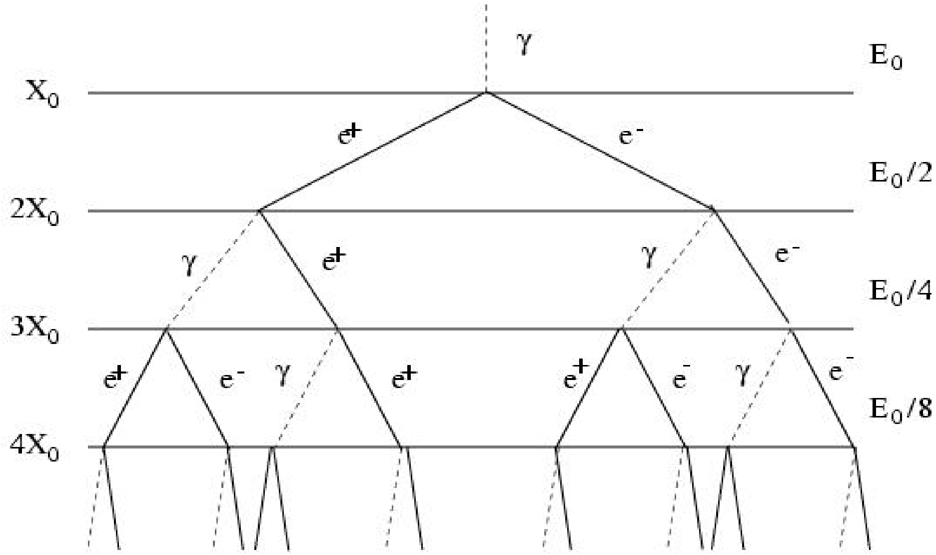
- The particles of energy E are produced at thickness:

$$t(E) \approx \ln(E_0/E)$$

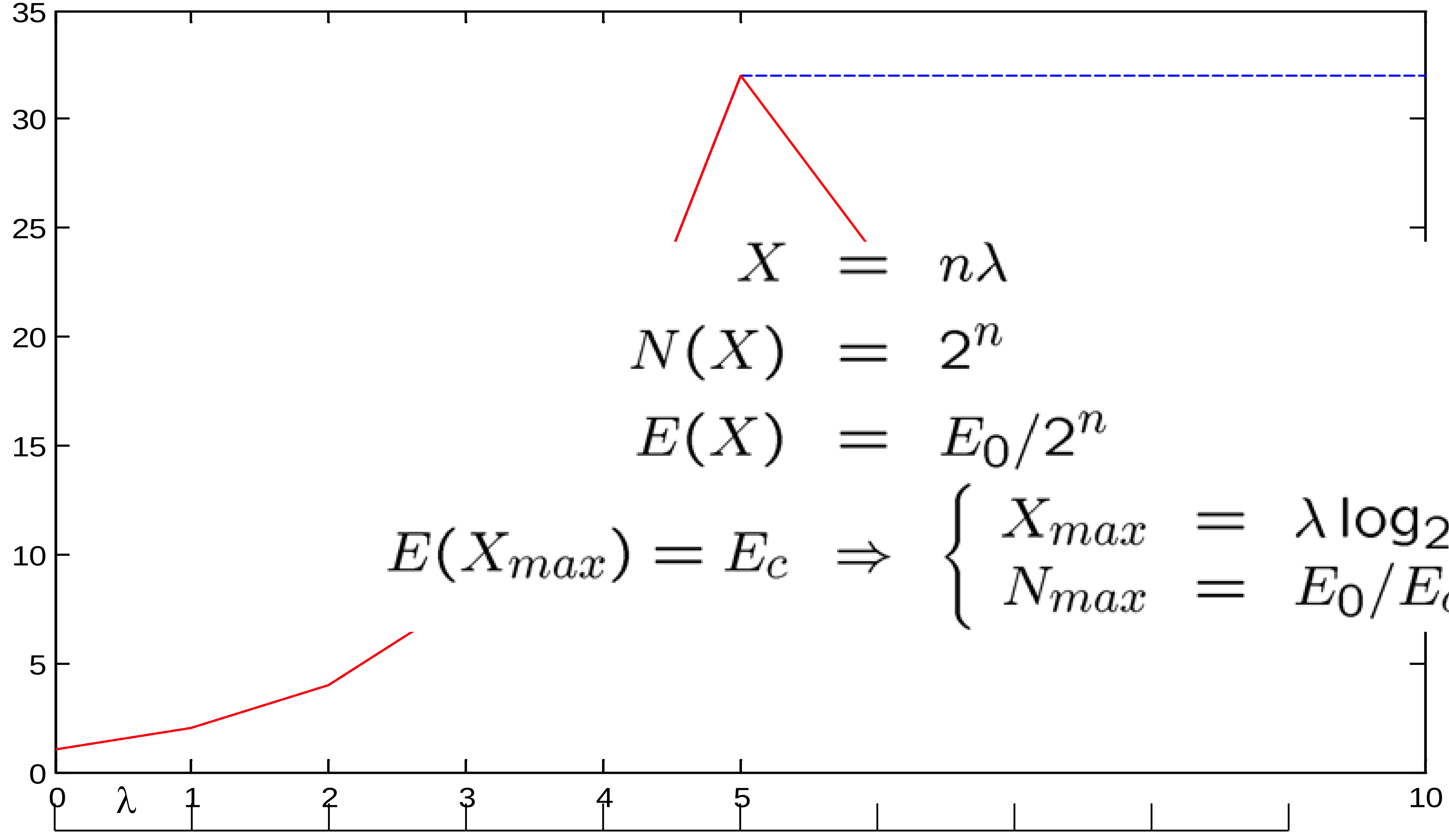
- The maximal development of the shower is reach for a thickness:

$$t_{max}(E_0) \approx ln(E_0/E_c)$$

- More realistic models agree with this rough estimate.



Simplified development model (Heitler)



$$X = n\lambda$$
$$N(X) = 2^n$$
$$E(X) = E_0/2^n$$
$$E(X_{max}) = E_c \Rightarrow \begin{cases} X_{max} = \lambda \log_2(E_0/E_c) \\ N_{max} = E_0/E_c \end{cases}$$

X =	1	2	3	4	5
N =	2	4	8	16	32
E =	1/2	1/4	1/8	1/16	1/32

$E_c = E_0/32$

Longitudinal development: Approximation "A" (B. Rossi, K. Greisen)

- Approximation "A" describes the shower development phase where only bremsstrahlung and pair creation are in action.
- From Bethe-Heitler theory, one obtains integral-differential linear and coupled equations leading to:
  - $\Pi(E,t)dE$ = average number of $e^{\pm}$ with energy $\in [E, E+dE]$, at tX_0 depth
  - $\Gamma(W,t)dW$ = average number of γ with energy $\in [W, W+dW]$, at tX_0 depth
- The simplifying factor is the absence of any energy scale.

Approximation A (cont)

- $\Pi(E,t)dE$ = average number of $e^{\pm}$ with energy $\in [E, E+dE]$, at tX_0 depth
- $\Gamma(W,t)dW$ = average number of γ with energy $\in [W, W+dW]$, at tX_0 depth

- Initial condition :
  - If the primary particle is a γ : $\Gamma(W,0) = \delta(E - E_0)$
  - If the primary particle is an $e^{\pm}$: $\Pi(E,0) = \delta(E - E_0)$

- Obvious special solutions:
  $\Gamma(W,t) = f(t)/W^{s+1}$ et $\Pi(E,t) = g(t)/E^{s+1}$
  (absence of energy scale)

... but they dont satify the initial conditions!

Approximation A (cont)

- The obvious solutions (power-law spectra, therefore scale invariant) correspond to an initial condition interesting in itself: an incident beam with a power law spectrum with an integral spectral index s.

- These special solutions form a base and a solution that fulfills the initial condition (photon or electron with an energy E_0) is obtained from a superposition of $1/E^{s+1}$ spectra (Mellin transformation, analogue to Fourier or Laplace transforms).

- Result : for a given value of t, the particle spectrum is very close to a power law $1/E^{s+1}$ with a value of s that varies with t and $y = \ln(E_0/E)$ following:

$$s = \frac{3t-1}{t+2y}$$

- The number of particle with energy E is maximal for $s = 1$

Taking into account ionization energy losses: the "age" parameter

- Approximation A is not valid anymore when the electron mean energy is close to the cricital energy E_c.

- One can modify the above results:

$$y = \ln\left(\frac{E_0}{E_c}\right) \quad \text{et} \quad s = \frac{3t}{t+2y}$$

- Semi empirical formula given by Greisen for an incident γ, for the mean number of electrons after traversing t radiation length:

$$\bar{N}_t = \frac{0.31}{\sqrt{y}} \exp\left[t\left(1 - \frac{3}{2}\ln s\right)\right]$$

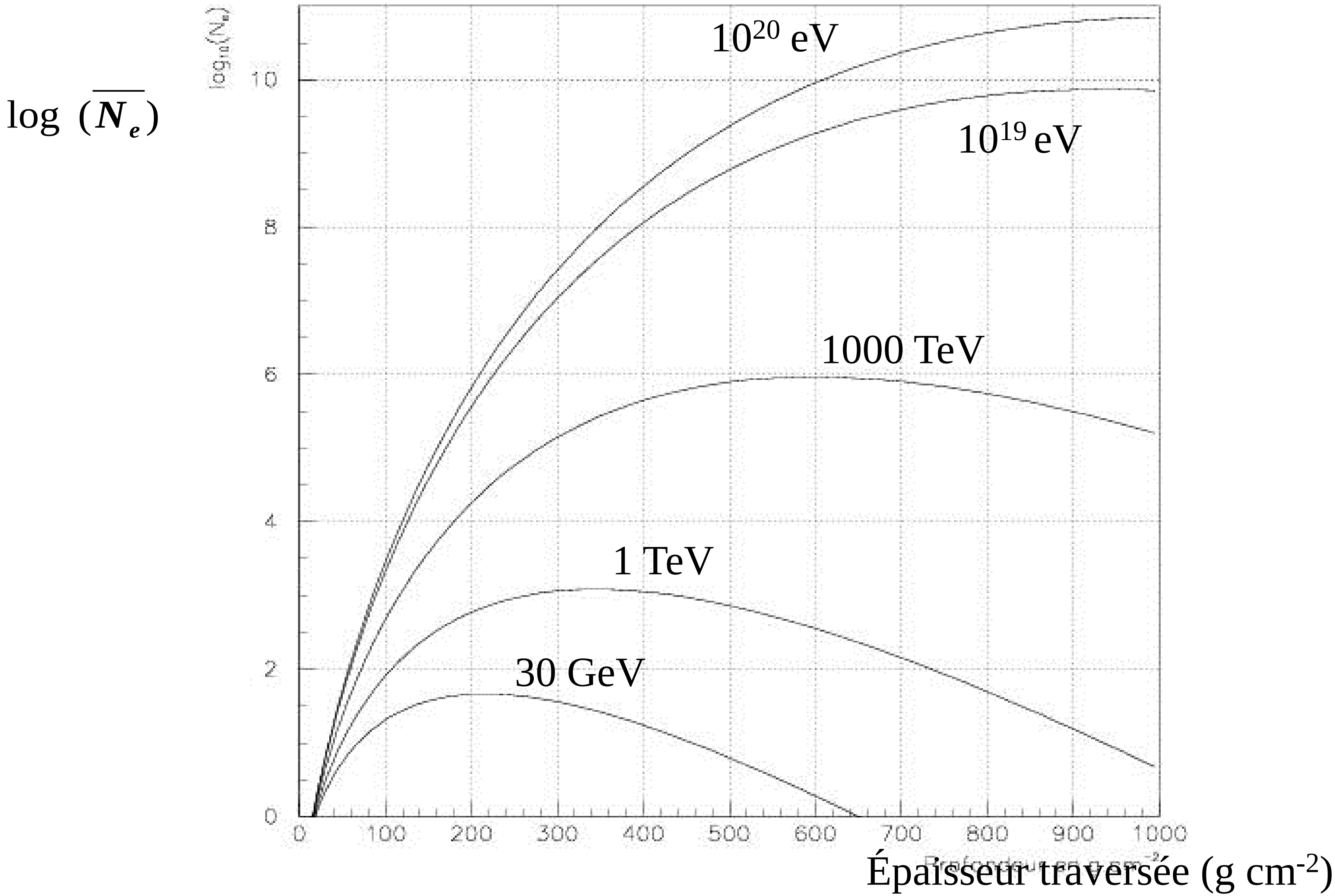
- The parameter s increase with t. It is < 1 during the development phase, reaches 1 at the maximal development stage for $t_{max} = y = \ln(E_0/E_c)$ and is > 1 during the extinction phase.

- s is called the "age".

EM showers : some orders of magnitude

Primary γ energy E_0	Thickness traverse $t_{max}\, X_0$ (g cm^{-2})	Altitude (m)	$N_e(t_{max})$
30 GeV	216	12000	50
1 TeV	345	8000	1200
1000 TeV	600	4400	$0{,}9 \times 10^6$
10^{19} eV	936	1200	$7{,}4 \times 10^9$
10^{20} eV	1021	0	$7{,}0 \times 10^{10}$

EM shower average profiles

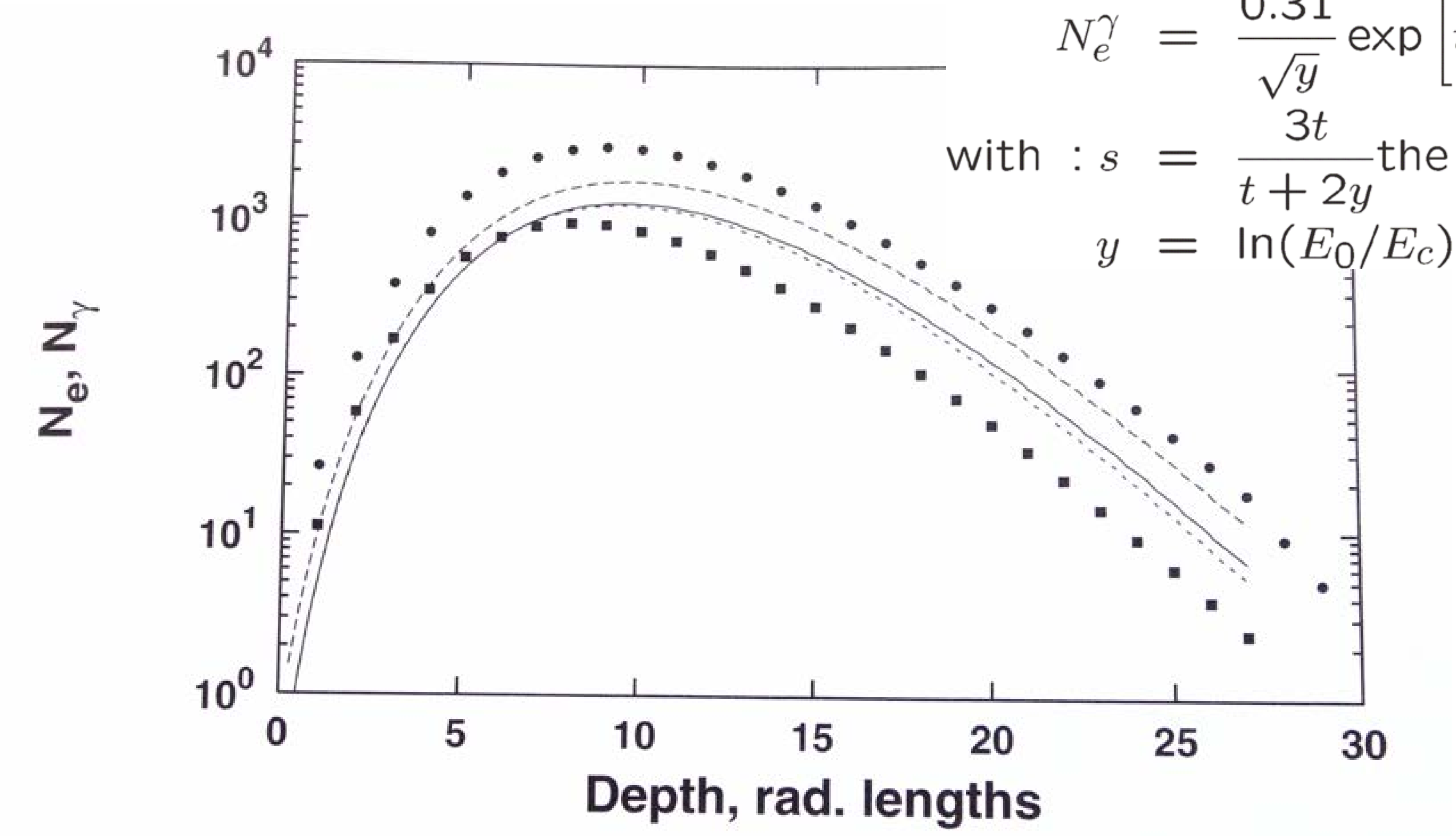


EM cascades (Rossi & Greisen)

$$N_e^\gamma = \frac{0.31}{\sqrt{y}} \exp\left[t(1 - \frac{3}{2}\ln s)\right]$$

$$\text{with}: s = \frac{3t}{t+2y} \text{ the shower age}$$

$$y = \ln(E_0/E_c)$$



Parametrization (Greisen) and Monte Carlo (EGS4)
photons 1TeV, E_c=10MeV

Shower size
i.e. number of electrons at ground level
as an energy estimator

- At maximal development level, the mean number of electrons is proportionnal to the primary energy ($y = \ln(E_0/E_c)$.

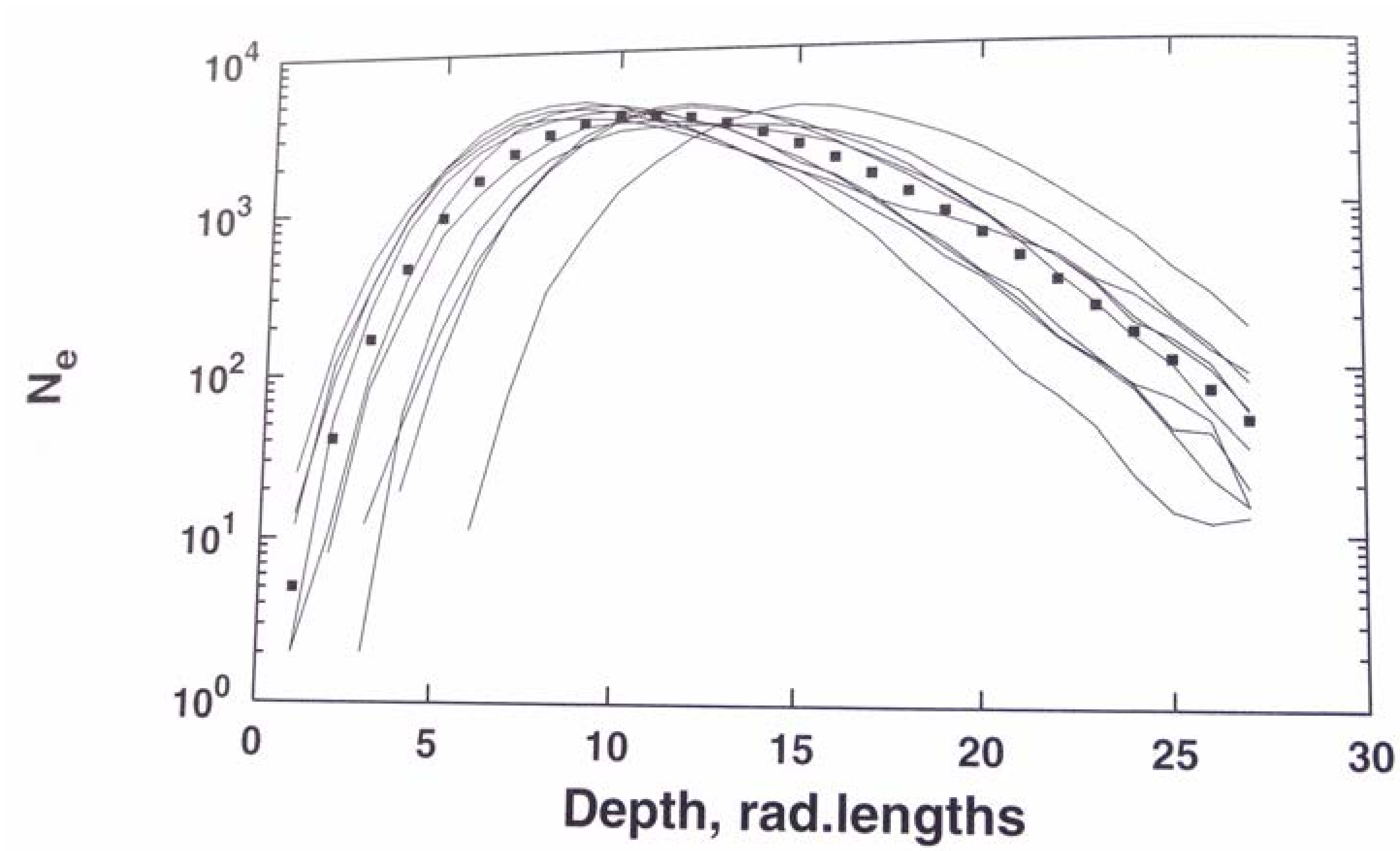
- Fluctuations on N_e:

  - Fluctuations on the depth of first interaction (exponential law)
  - Fluctuations in the shower development (approximatly log-normal because of the multiplicative behaviour)
  - Sampling fluctuations (depends on the type of detectors, their arrangement on the ground etc.)

- If the altitude of the maximal development is known (direct optical measurement), or if one can estimate the age independently (from lateral distribution of the electrons) one can avoid the first kind of fluctuations.

- Fluctuations are minimal at the maximum of development.

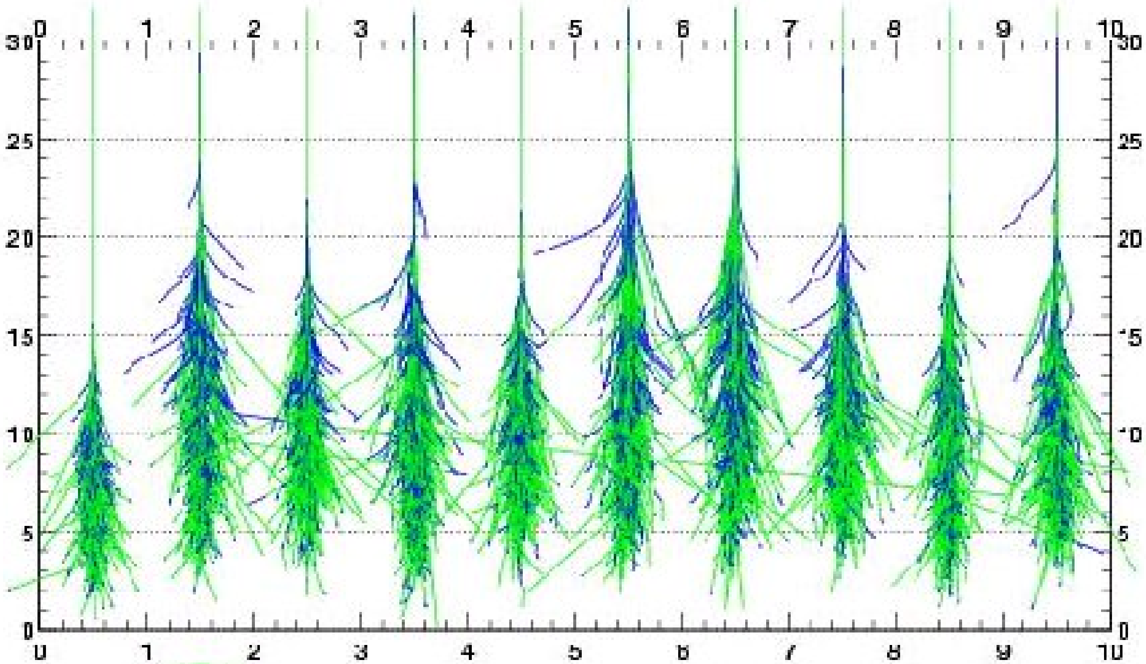
Cascades EM (Rossi & Greisen)



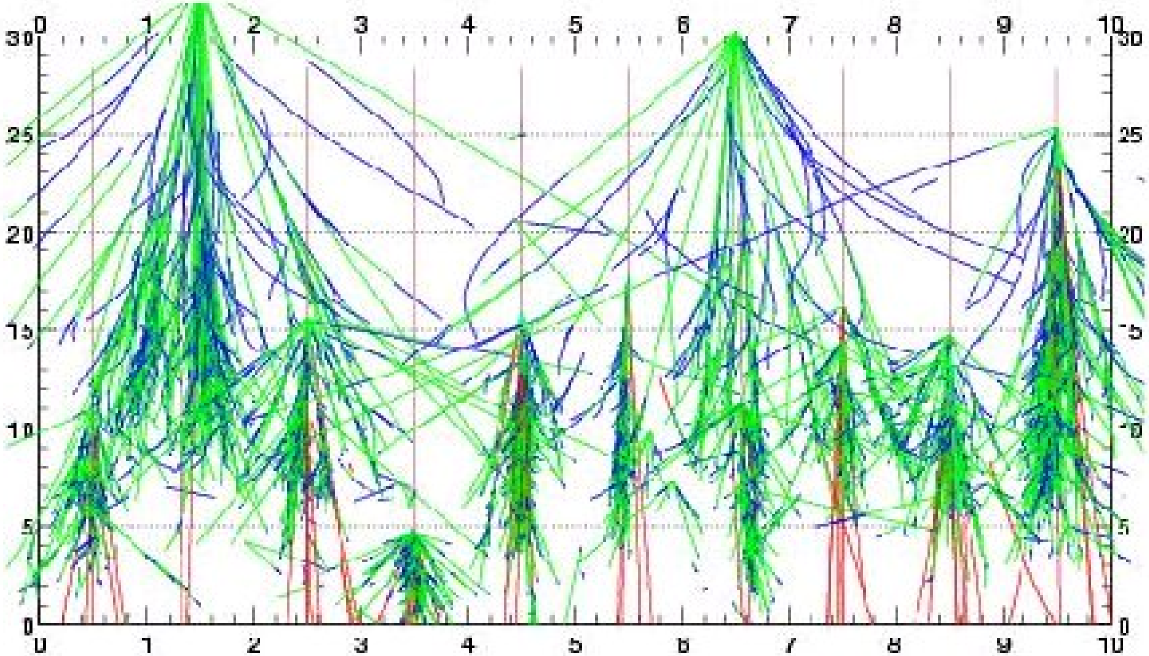
Shower to shower fluctuations
10 showers at 10^{14}eV compared to the average of 100 showers.

GAMMA-RAY (EM) INDUCED SHOWERS

10 γ
300 GeV



10 protons
300 GeV



Simulations de

M. de Naurois

Electromagnetic showers
($e^{\pm}$ or γ primary)

Dominating phenomena

- Radiation processes:
  - Bremsstrahlung of $e^{\pm}$
  - Pair production (>MeV) e^+e^- pairs
- Multiple scattering (small angular deflections) of $e^{\pm}$
- Energy losses by $e^{\pm}$
  - par ionization
  - atomic excitation

} In the Coulomb field of nuclei

γ induced
shower 300 GeV

Roughly
symmetric
around the axis

Small transverse
dispersion
(multiple scattering)

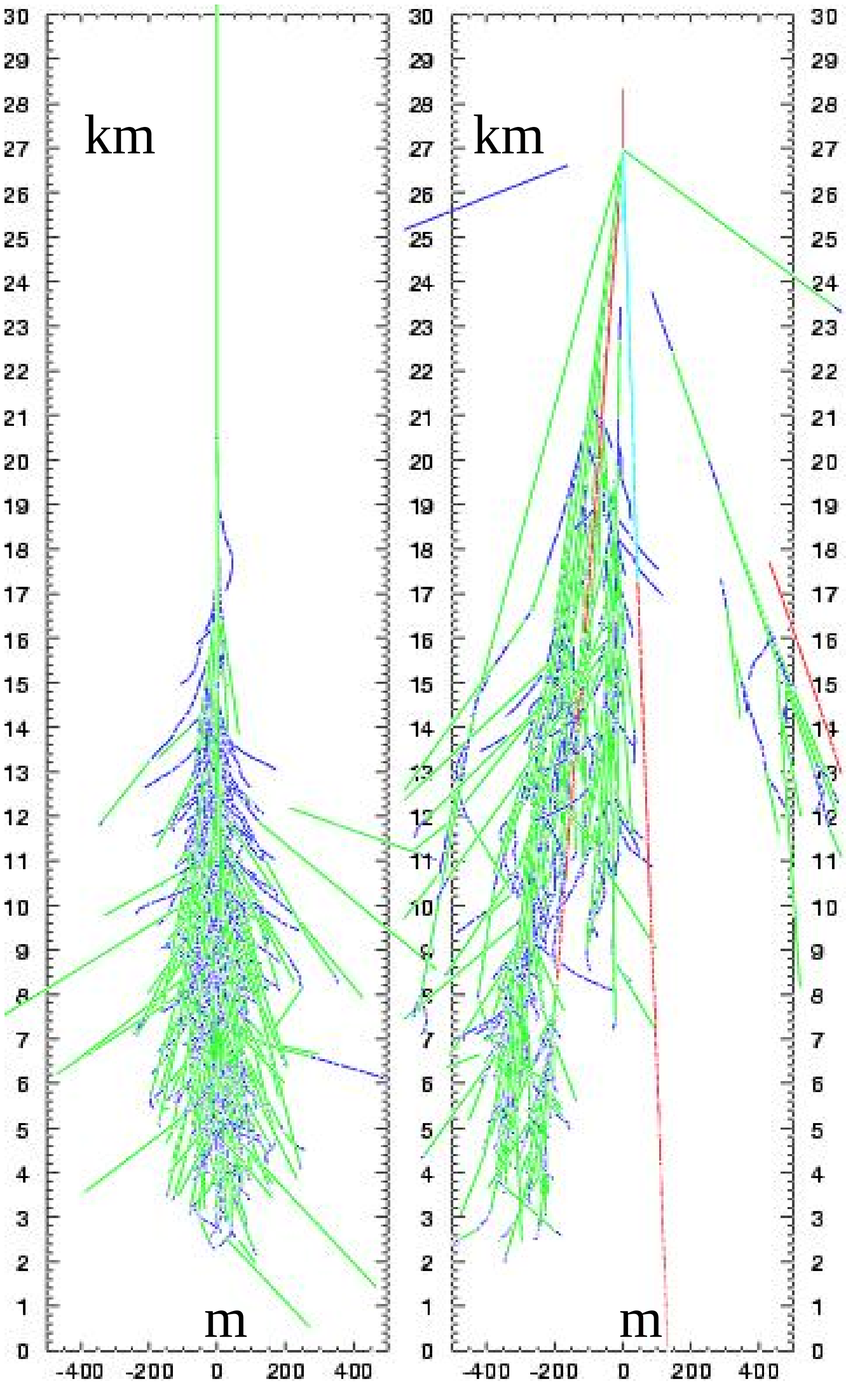
(almost) no muons

…

(unless E_0>1 PeV)

Essentially

e+ e- and γ
secondaries



proton induced
shower 300 GeV

Large transverse
momentum

Muon component
(from mesons decays)

A hadronic shower
does contain
EM sub-showers

Optical photon emission by showers

- Showers charged particles emit light:
  - Cherenkov light : very collimated along the shower axis (Cherenkov angle at 1 Atm. ≈ 1°) threshold depending on the altitude : at ground 22 MeV for $e^{\pm}$ et 4.5 GeV for $\mu^{\pm}$

    (20 photons per m per $\beta \approx 1$ charged particle at 1 atm)

    Essentially used for gamma-ray astronomy
  - Nitrogen fluorescence: isotropic emission

    (≈ 4 photons per electron per m)

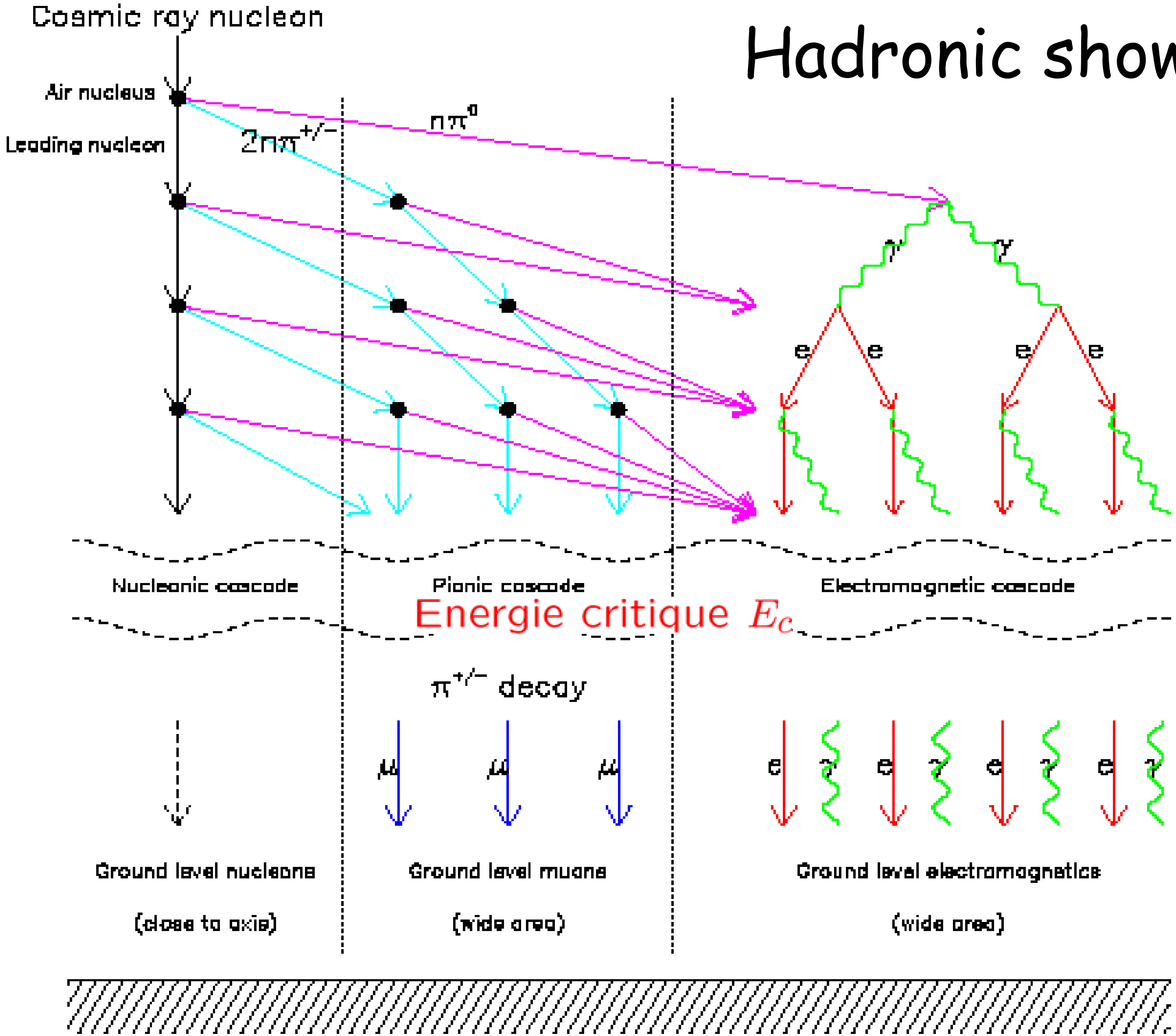
    Essentially used at UHE ≥ 10^{18}eV.

→ Lecture on Imaging & Cherenkov Detectors

- This light detected by ground telescopes gives us very rich information on the 3D development of the showers. It give a quasi calorimetric reliable measurement of the energy.
- … but optical detectors can only work during moonless clear sky nights (≈ 10% duty cycle).

HADRONIC SHOWERS MODELS AND DETECTION

Hadronic showers



"Hadronic" showers (protons or nuclei primaries)

- Great complexity implying the use of numerical simulations:
  - Many length scales : nucleon interaction length, pion interaction length, EM radiation length, atmosphere density height scale…
  - Superposition of a nuclear cascade, a pionic cascade and an electromagnetic cascade (the later from π^0 decay γ).
  - Large fluctuations in the multiplicity of secondaries.
- But simulations are subject to many uncertainties:
  - p+N or N+N interactions: sensitivity to nuclear models.
  - Energy range unexplored by accelerators and colliders : sensitivity to nucleon structure functions (parton distributions) and fragmentation functions extrapolated far from the measured regions.
  - The inelasticity and in general the very forward diffractive physics is not well measured in fixe target experiment (even worse at colliders).

Still, the main behavior observed on EM showers remains valid.

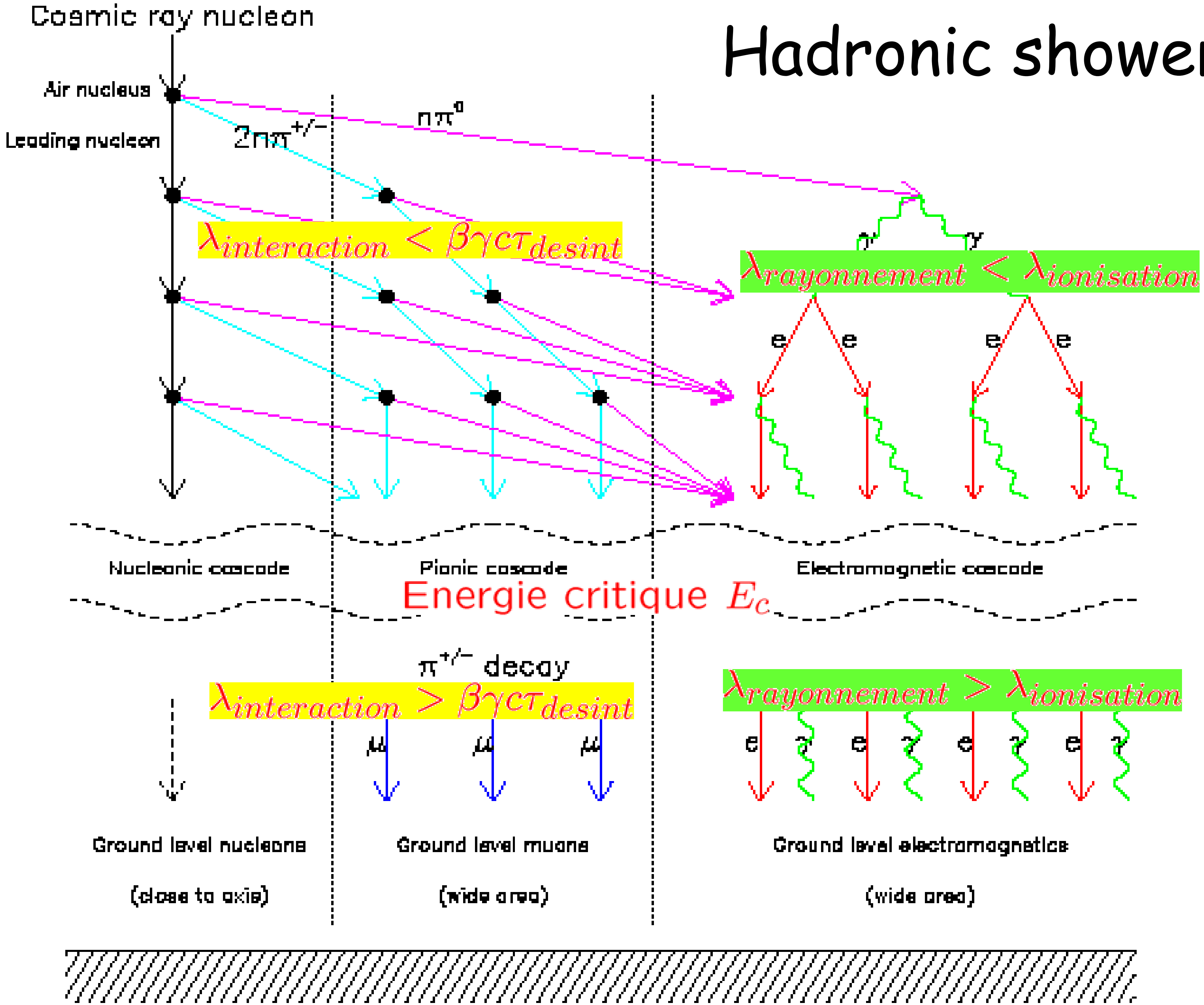
From EM to Hadronic showers

- The main observables are the same:
  - Number of electrons, gamma but also muons at ground and their lateral distributions.
  - Longitudinal profile and maximal dev. altitude (optical detectors).
  - Number of muons at ground level and lateral distribution of muons.

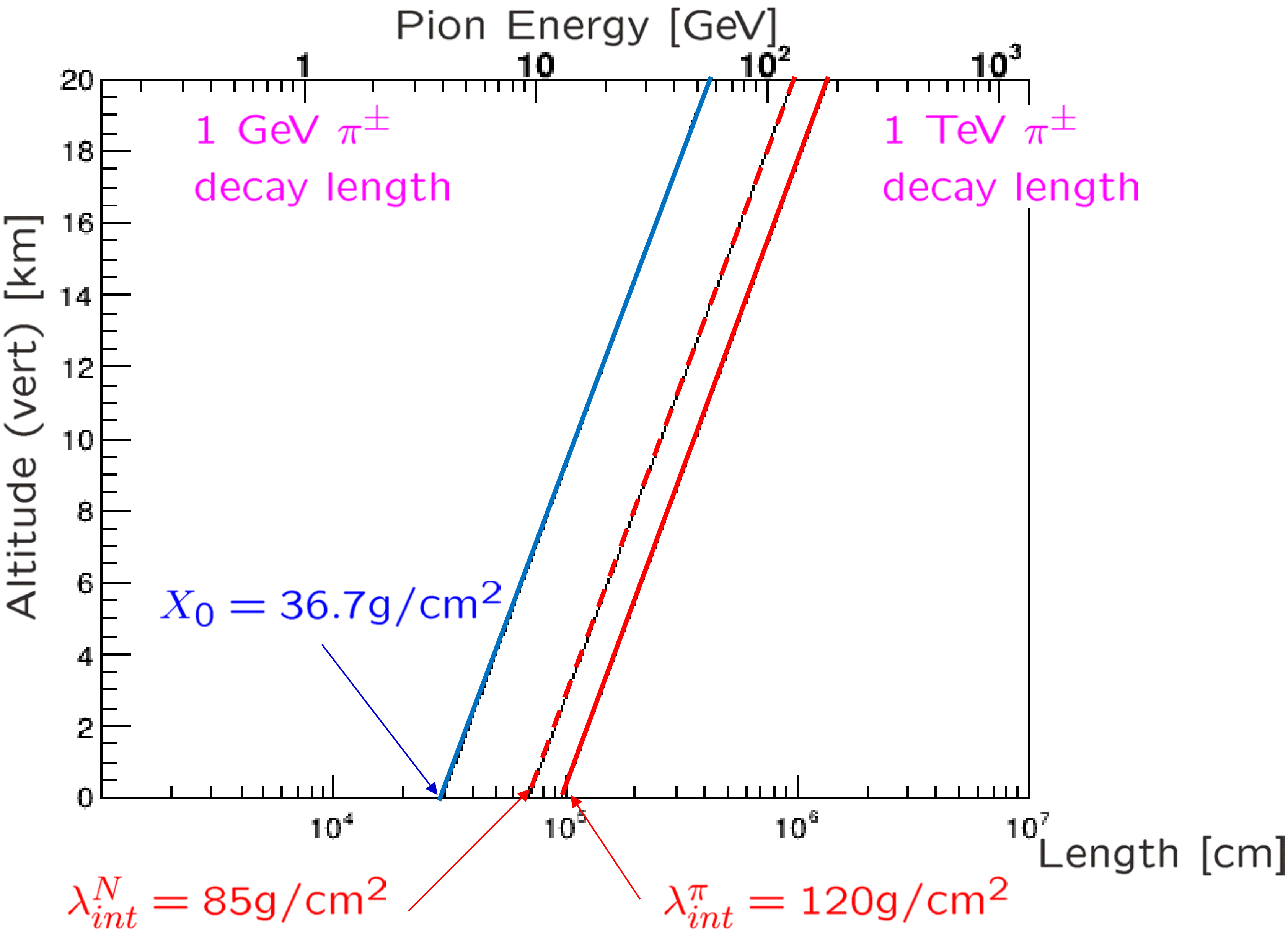
- Feynman scaling is rather well verified in the fragmentation: it plays an role analogue to that of Bethe-Bloch formulae for EM showers (absence of mass/energy scale).

- Simulations have allowed to establish empirical formulae inspired by EM showers useful for quick estimates *(T.K. Gaisser, A.M. Hillas)*

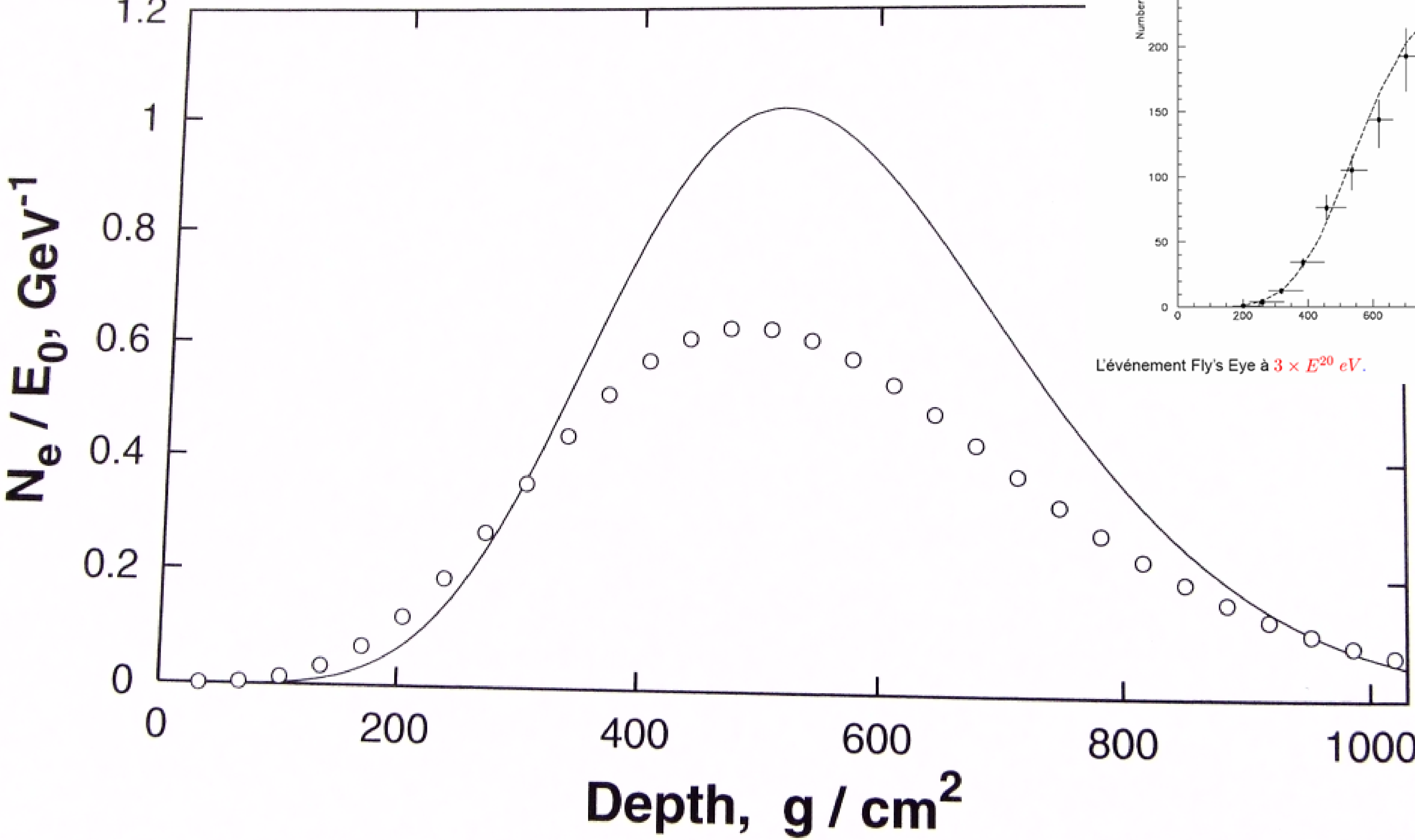
Hadronic showers

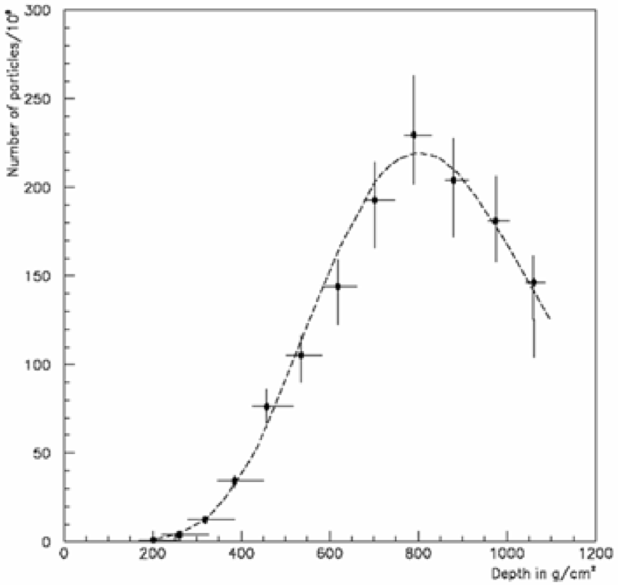


Interaction and radiation lengths in atmosphere



Development of Hadronic vs EM showers





L'événement Fly's Eye à $3 \times E^{20}\ eV$.

Gaisser longitudinal Parametrization

Gaiser Hillas formulae :

$$N_e(X - X_1) = N_e^{max} e^p \left(\frac{X - X_1}{X_{max} - \lambda}\right)^p \exp - \left(\frac{X - X_1}{\lambda}\right)$$

$$\text{with } p = \frac{X_{max} - \lambda}{\lambda}$$

Averaging on X_1 depth of 1^{st} interaction :

$$\bar{N}_e(X) = N_e^{max} \frac{p}{p+1} e^p \left(\frac{X}{X_{max} - \lambda}\right)^{p+1} \exp - \left(\frac{-X}{\lambda}\right)$$

$$X_{max} = X_0 \log\left(\frac{E_0}{\epsilon_0}\right)$$

$$N_e^{max} = \frac{E_0}{\omega}$$

Radiation length : $\approx 36.7\text{g/cm}^2$

Cricital energy : $\epsilon_0 \approx 74\text{eV}$

Empirical relation between size and energy: $\omega \approx 1.7\text{GeV}$

Incident nucleus interaction length (of energy E_0) $\lambda_N \approx 70\text{g/cm}^2$

Longitudinal development

Xmax and energy :

$$X_{max} \approx X_0 \log\left(\frac{E_0}{\epsilon_0}\right)$$
$$\Rightarrow 80g/cm^2 \text{ per energie decade}$$

Nuclei :

Superposition principle : a nucleus ^AN is equivalent to A protons.

Thus :

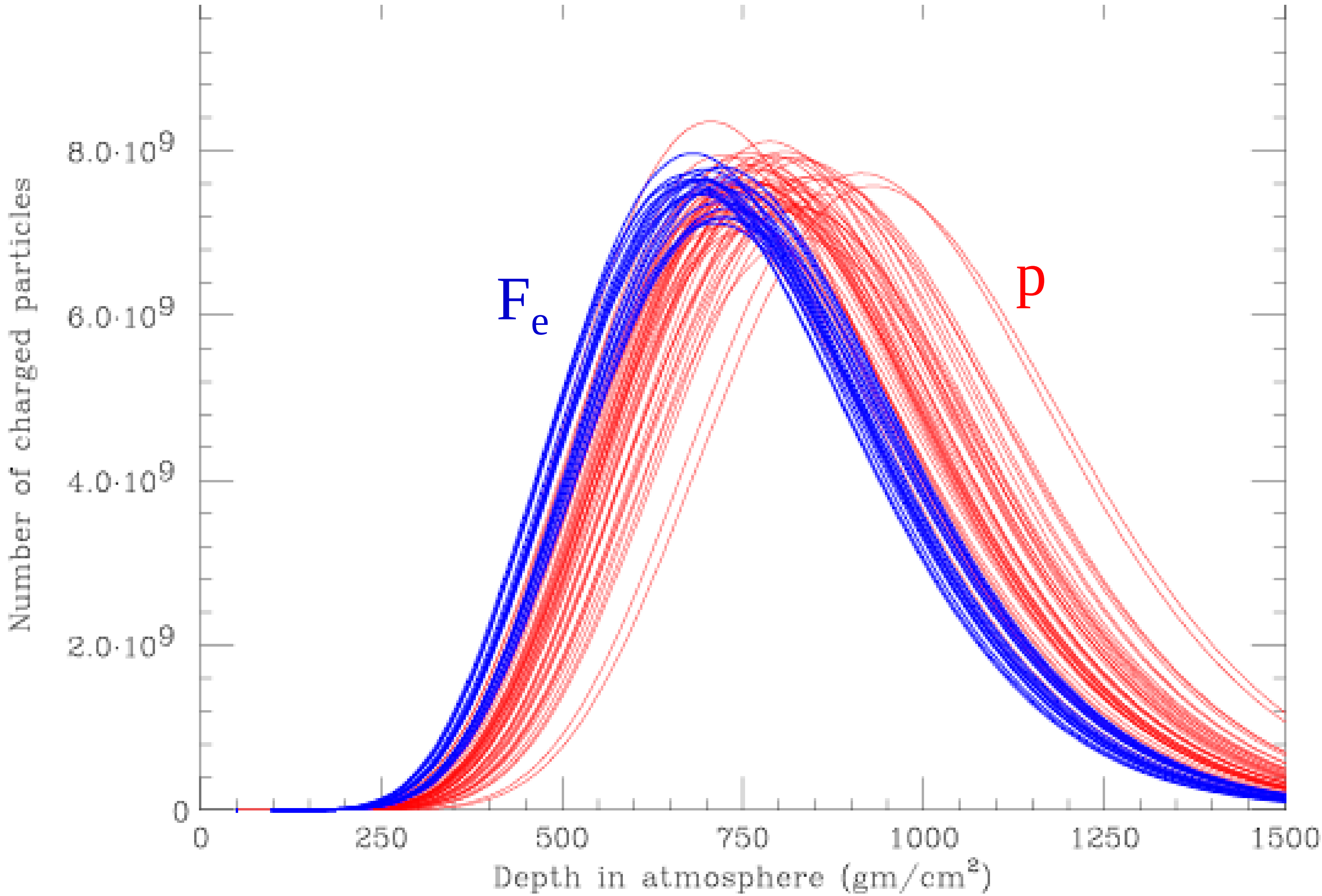
$$X_A^{max} = X_0 \log\left(\frac{E_0}{A\epsilon_0}\right)$$
$$= X_p^{max} - X_0 \log(A)$$

For example iron/proton $A = 56$:

$$X_0 \log(A) = 36.7 \log(56) = 148g/cm^2$$

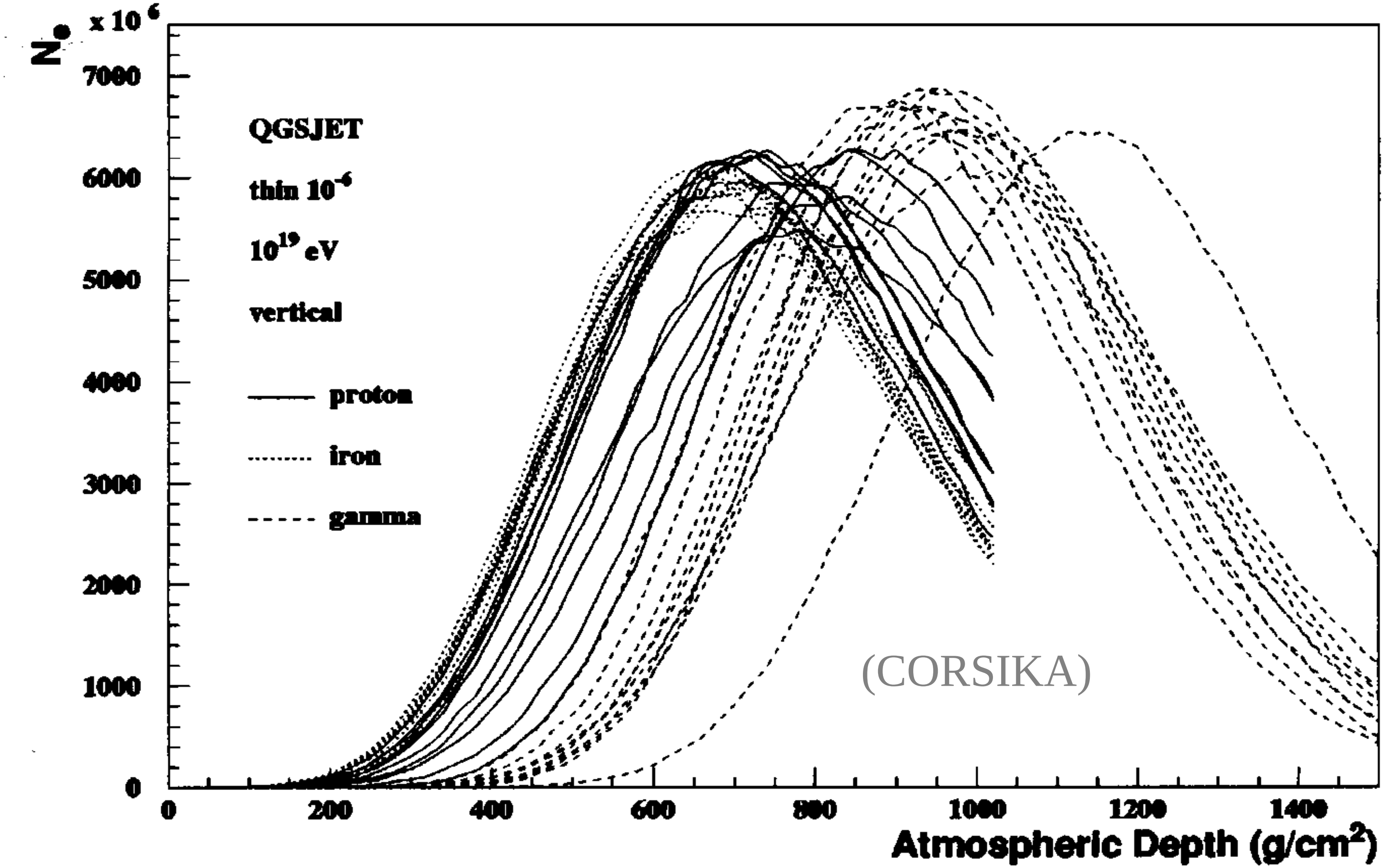
Structure in space

Shower to shower fluctuations largely due to the depth of the first interaction.

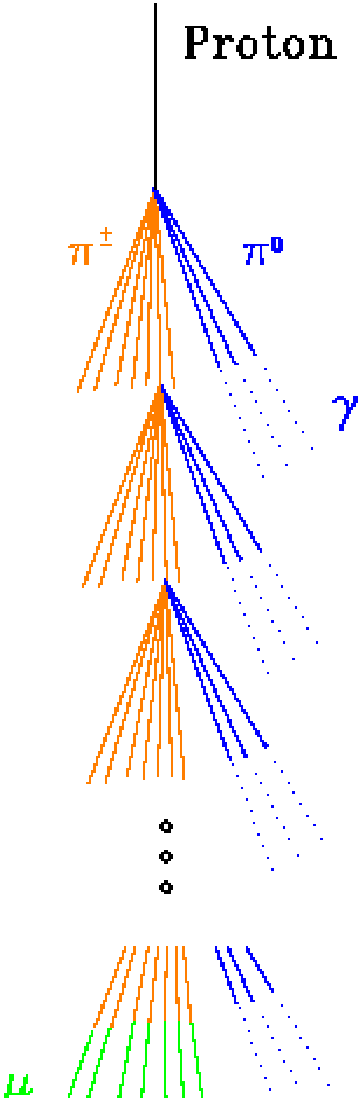


Primary identification

- Requires a good statistics and a good knowledge of the initial energy, the shower angle (+ systematic corrections because of atmospheric attenuation)



A simplified development model



Energy per pion	$N_{\pi^\pm}$
$E_0/10$	$\frac{2}{3}10$
$E_0/100$	$(\frac{2}{3}10)^2$
$E_0/1000$	$(\frac{2}{3}10)^3$
⋮	⋮
$E_c = E_0/10^{n_c}$	$(\frac{2}{3}10)^{n_c}$

⇒ tutorials

A simplified development model

The size (number of electrons at max) is proportional to the primary energy:

$$N_e^{max} \approx S_0 E_0/\epsilon_0 = E_0/(1.7\text{GeV})$$

The depth of max is proportional to the log of the energy:

$$X_{max} \approx X_0 \log(E_0/\epsilon_0) \Rightarrow 80\text{g/cm}^2 \text{ par décade}$$

Showers from heavier nuclei produce more muons than lighter ones.

$$N_\mu^{Fe} \approx 2 \times N_\mu^p(E)$$

Shower from heavier nuclei start higher up and reach max higher up too.

$$X_{max}^{Fe} < X_{max}^p$$

Radial extension

The radial distribution is determined by the mean transverse momentum (P_T) from hadronic interactions and by multiple scattering. In air, the Molière radius is ≈ 75m.

Molière radius (~1/4 of the radiation length) :

$$\langle \delta\theta^2 \rangle = \left(\frac{21\,\text{MeV}}{E}\right) \delta X$$

$$r_1 = \left(\frac{E_s}{E_c}\right) X \approx 9.3\ \text{g/cm}^2$$

Nishimura, Kamata, Greisen :
multiple scattering + transverse momentum

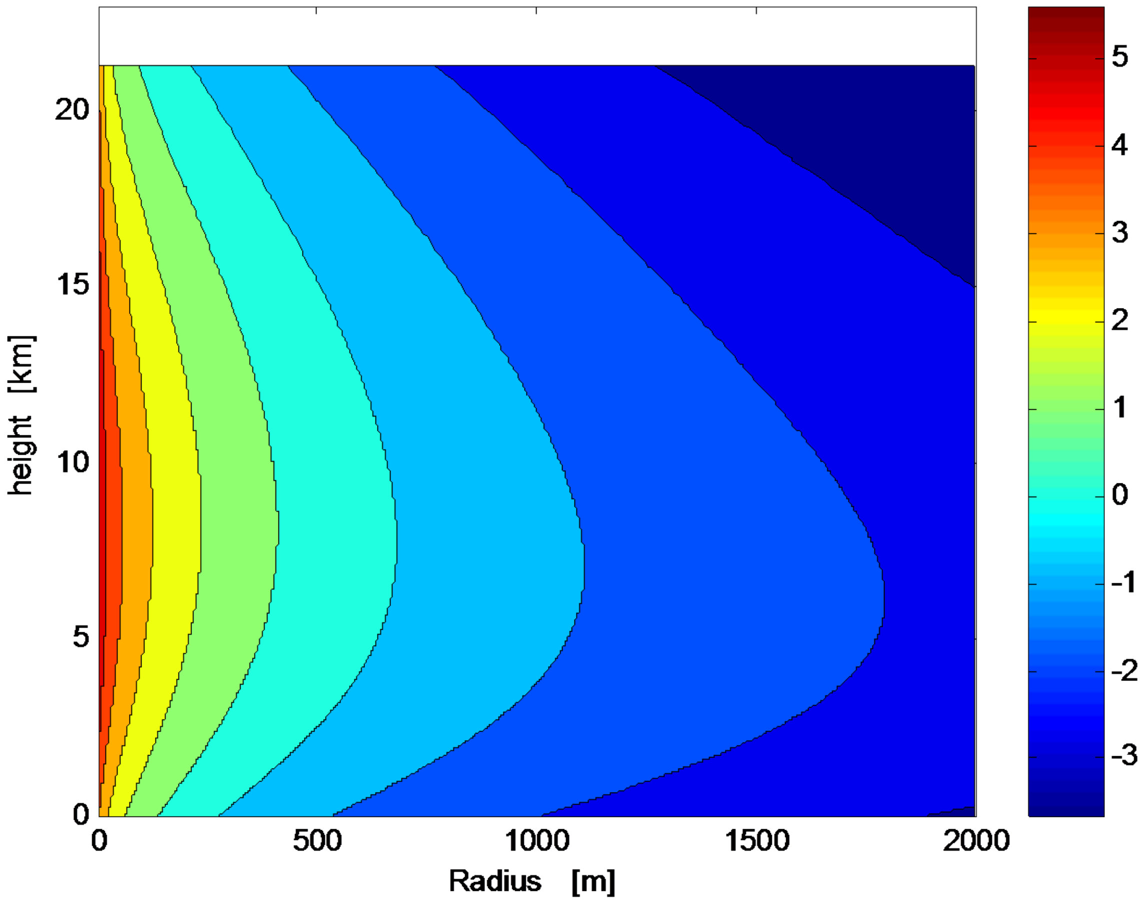
$$xf(x) = C(s)x^{(s-1)}(1+x)^{(s-4.5)}$$

$$\text{with} : x = \frac{r}{r_1}$$

normalization such as :

$$2\pi \int_0^\infty xf(x)dx = 1$$

$e^+ + e^-$ lateral density



$\log_{10}$ of the number of $(e^+ + e^-)$ per m^2

Proton de 10^{14}eV

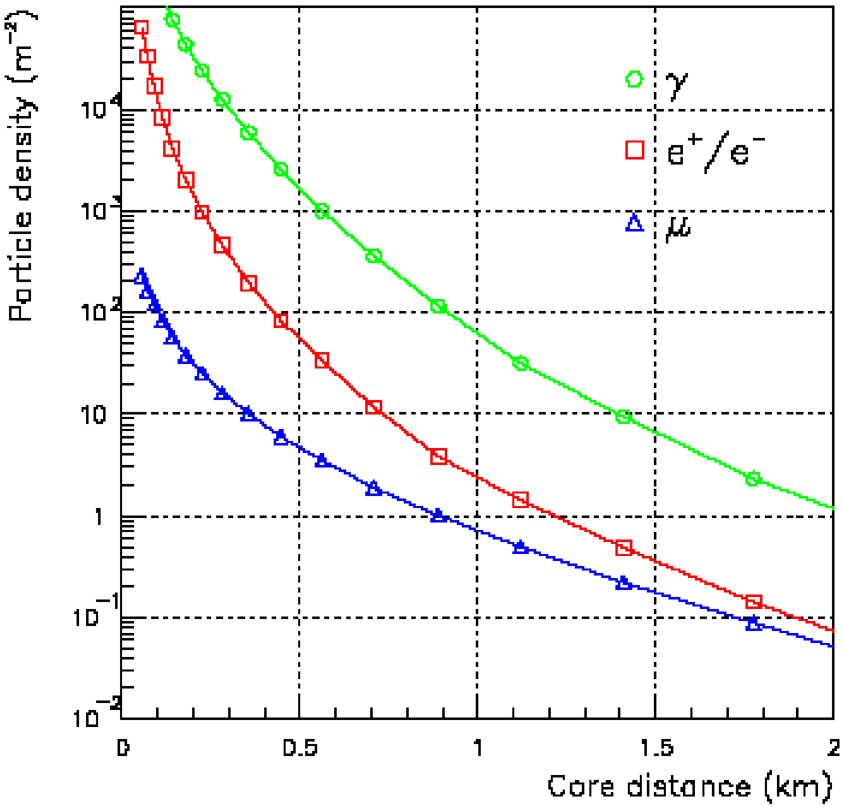
Lateral evolution

The density as a function of the distance to the center of the shower is characterized by a lateral density function (LDF)

$$\rho(r) \propto k \times r^{-[\eta + f(r)]}$$

where f et k depends on the type of the detectors used where η depends on the incident angle of the shower and the primary energy.

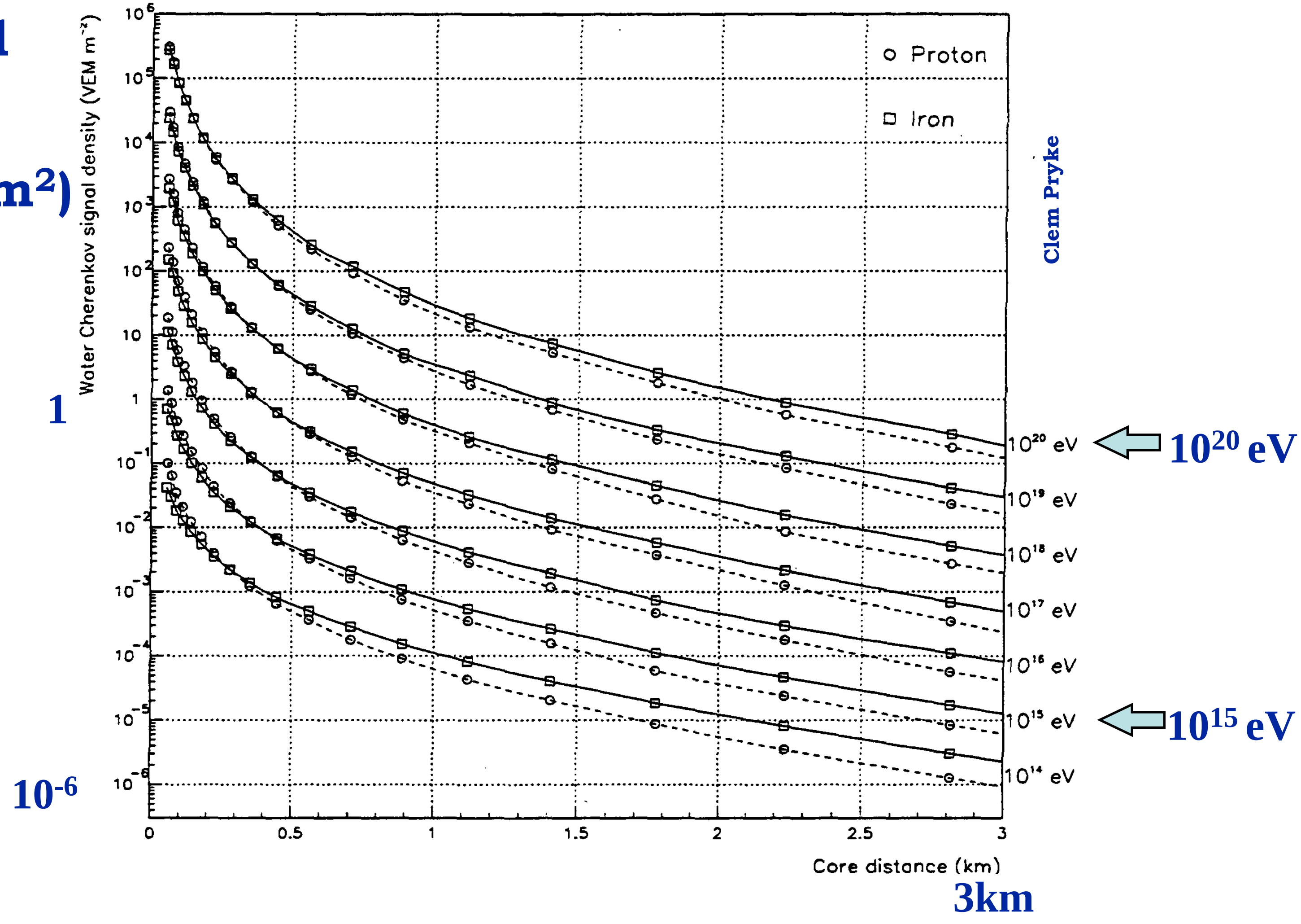
For $r >$ 800m this (empirical) expression must be modify as $(r/800)^{1.03}$



Shower Density Lateral Distribution (simulation)

Detector Signal Density

(equiv.muons/m²)

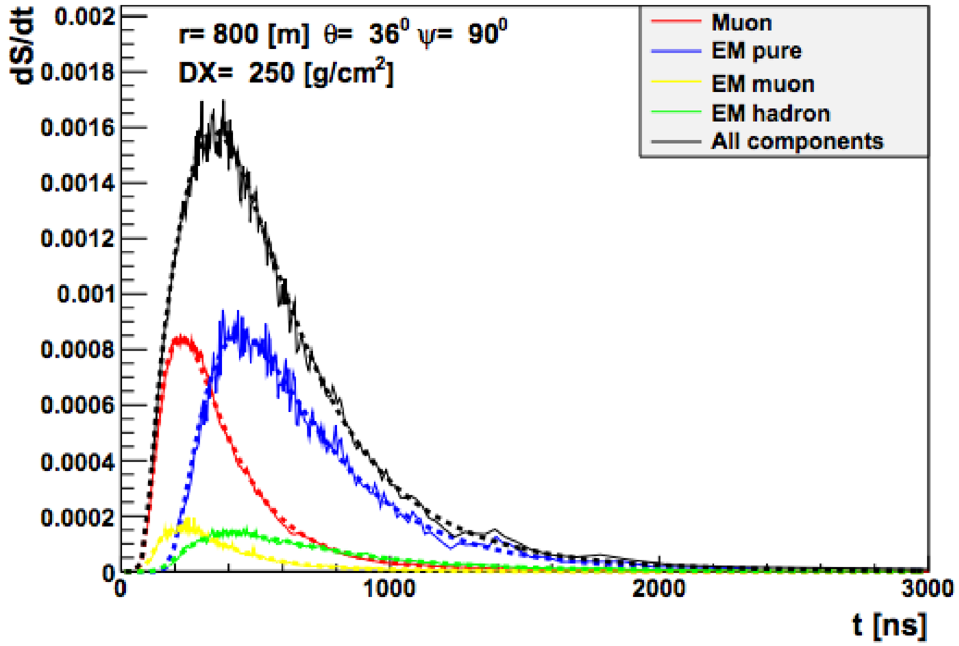


Core Distance (km)

Shower universality

- Owing to the extremely large number interactions involved in the EM component of the showers, its development can be described in a universal way from only a few macroscopic parameters (similarly to a black body spectrum that can be described knowing the temperature only).

- The hadronic/muonic part of the shower is a priori not as universal but simulation studies for energies above $E > 10^{17.5}$ eV show that a universal description of the shower profiles (longitudinal, lateral and timewise) can be achieved knowing only a reduced set of macroscopic variables E, X_{max}, N_{μ}



Particle energy distribution

Rossi Greisen :

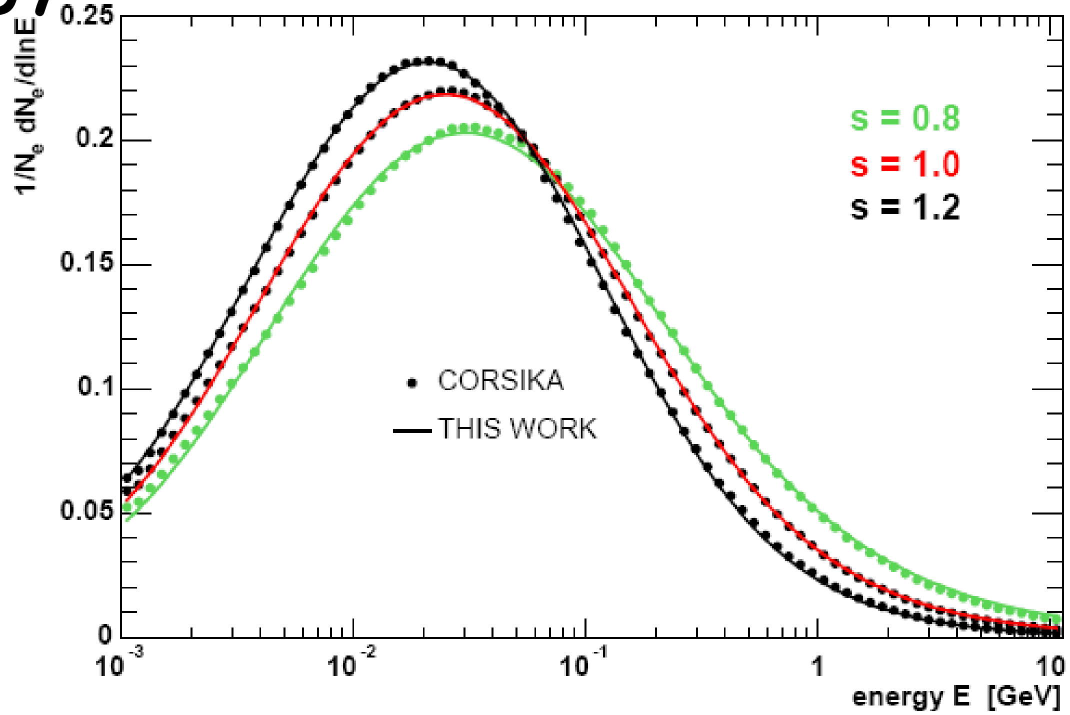
$$\frac{dN}{d(\log E)} \approx \frac{1}{E^{s+1}}$$

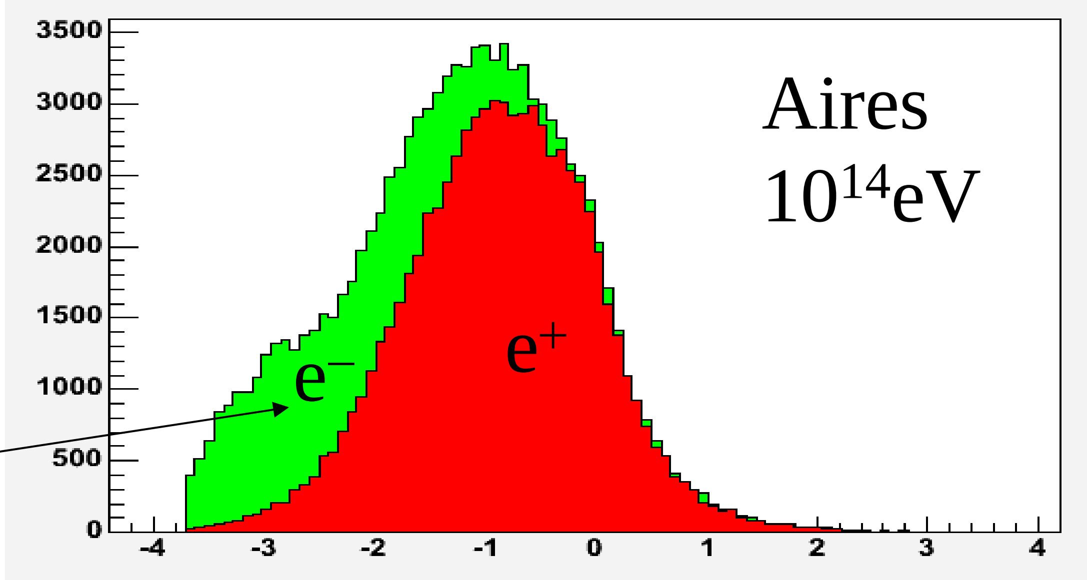
E.Nerling (thesis) :

$$f_e(E,s) = a_0 \frac{E}{(E+a_1)(E+a_2)^s}$$
$$a_1 = 6.42522 - 1.53183.s$$
$$a_2 = 168.168 - 42.1368.s$$

E en MeV

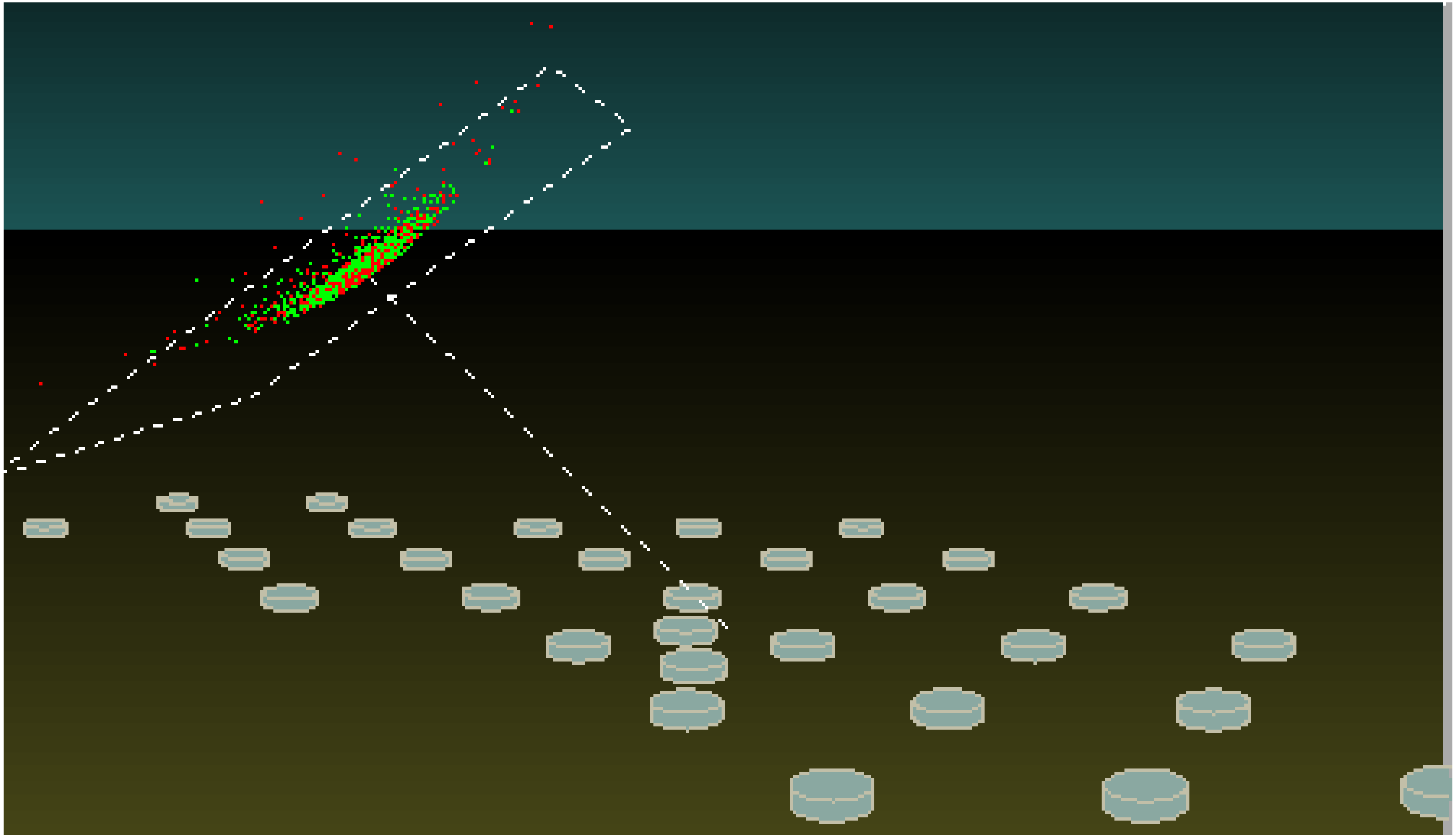
$$a_0^{-1} = \int_{\log E_{cut}} f(E,s)d(\log E)$$





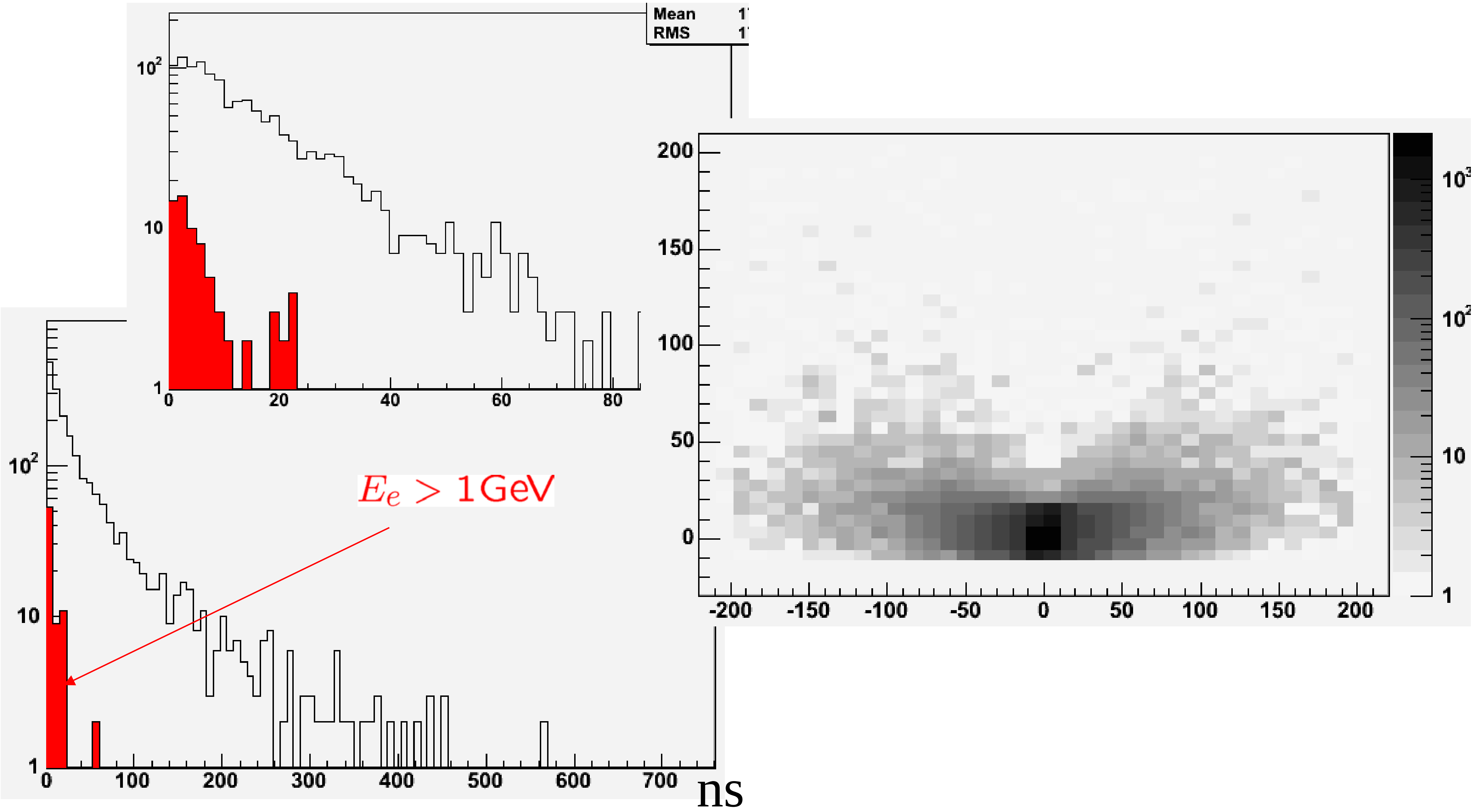
Excess e⁻ at low energy (ionization)

Time structure



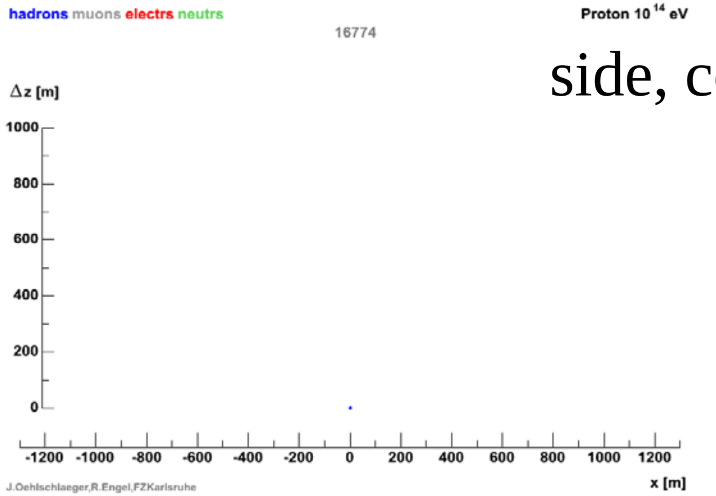
Fine galette (quelques dizaines de ns) de particules traversant le ciel avec une vitesse $v \sim c$.

Time structure

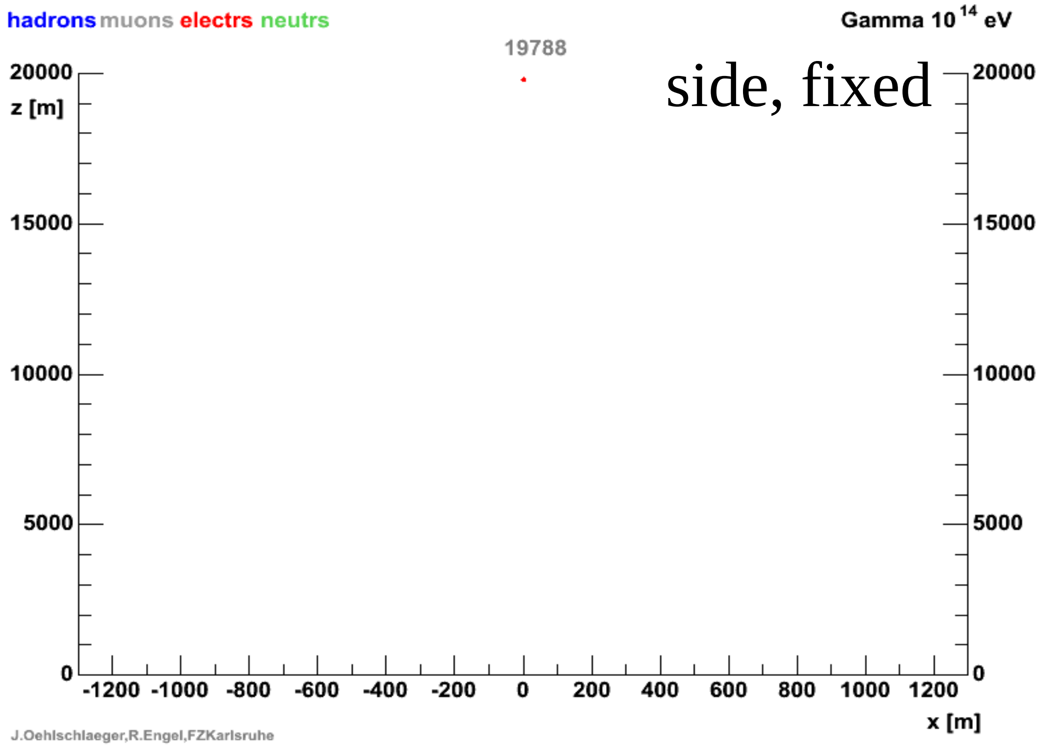


List of CORSIKA shower movies

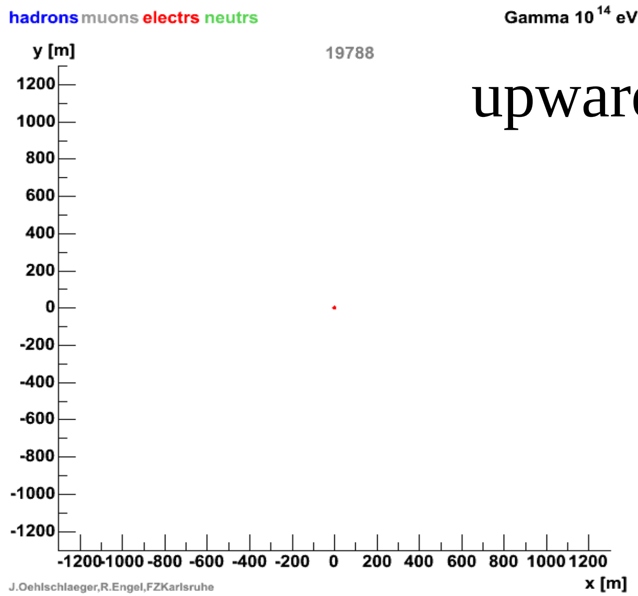
Movie	Initiating Particle, Energy, Zenith Angle	Viewing, Observer	Energy Cut	Remarks
sanga14zx13.gif sanga14xz13.gif sanga14yx13.gif	gamma 100 TeV, vertical	side, co-moving side, fixed upwards, co-moving	0.1 GeV	coloured particle types, actual altitude [m] displayed



side, co-moving



side, fixed

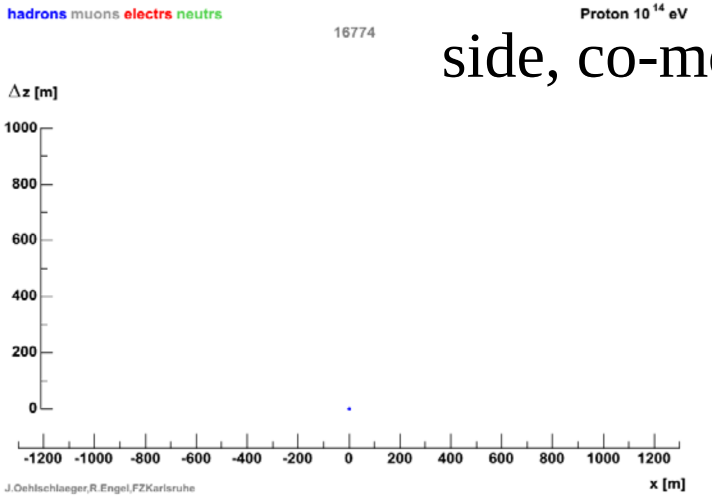


upwards, co-moving

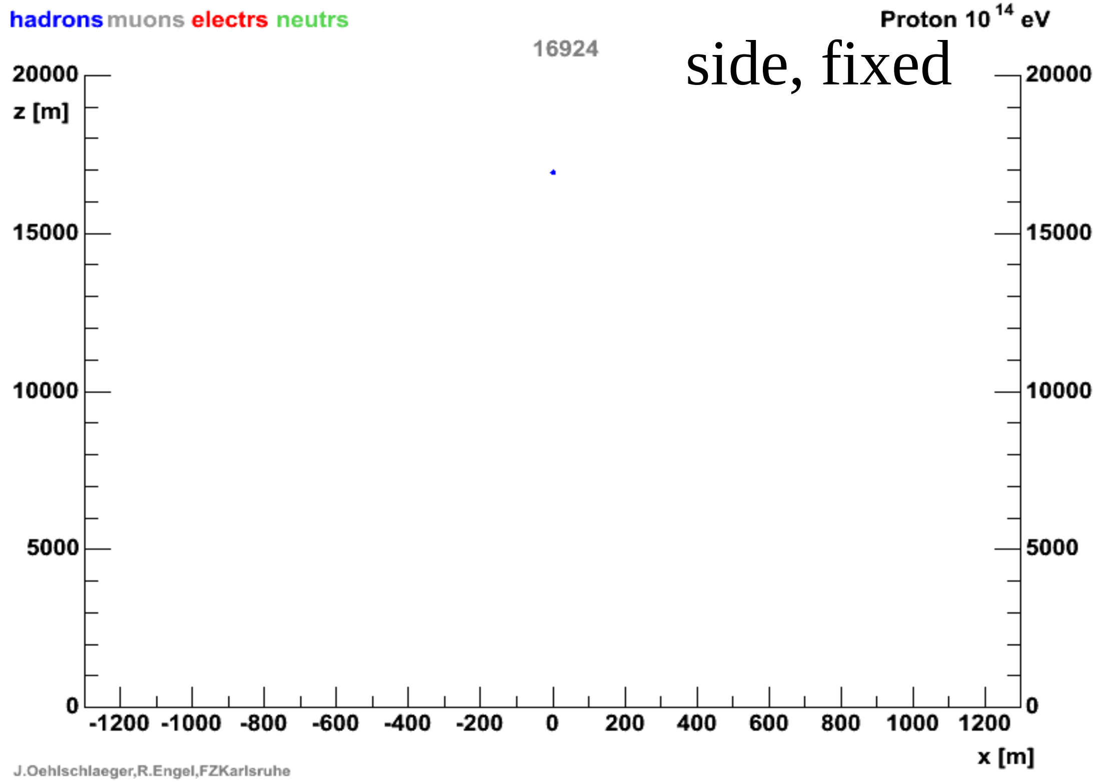
gamma, 100 TeV, vertical

List of CORSIKA shower movies

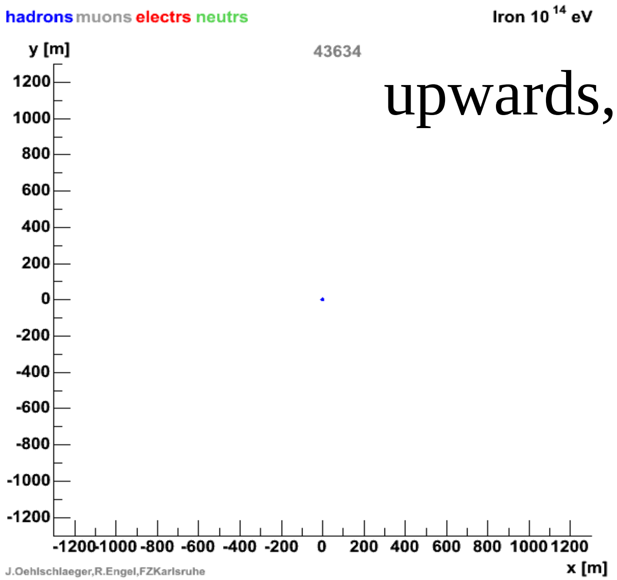
Movie	Initiating Particle, Energy, Zenith Angle	Viewing, Observer	Energy Cut	Remarks
sanpr14zx13.gif sanpr14xz13.gif sanpr14yx13.gif	proton 100 TeV, vertical	side, co-moving side, fixed upwards, co-moving	0.1 GeV	coloured particle types, actual altitude [m] displayed



side, co-moving



side, fixed

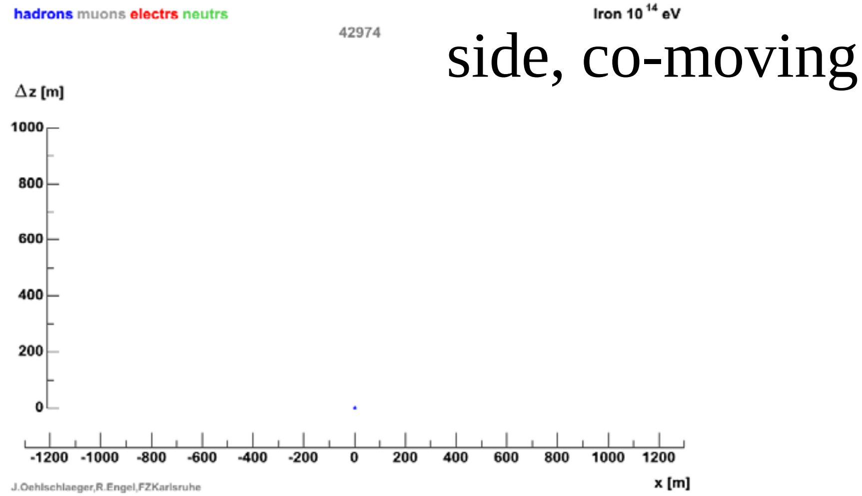


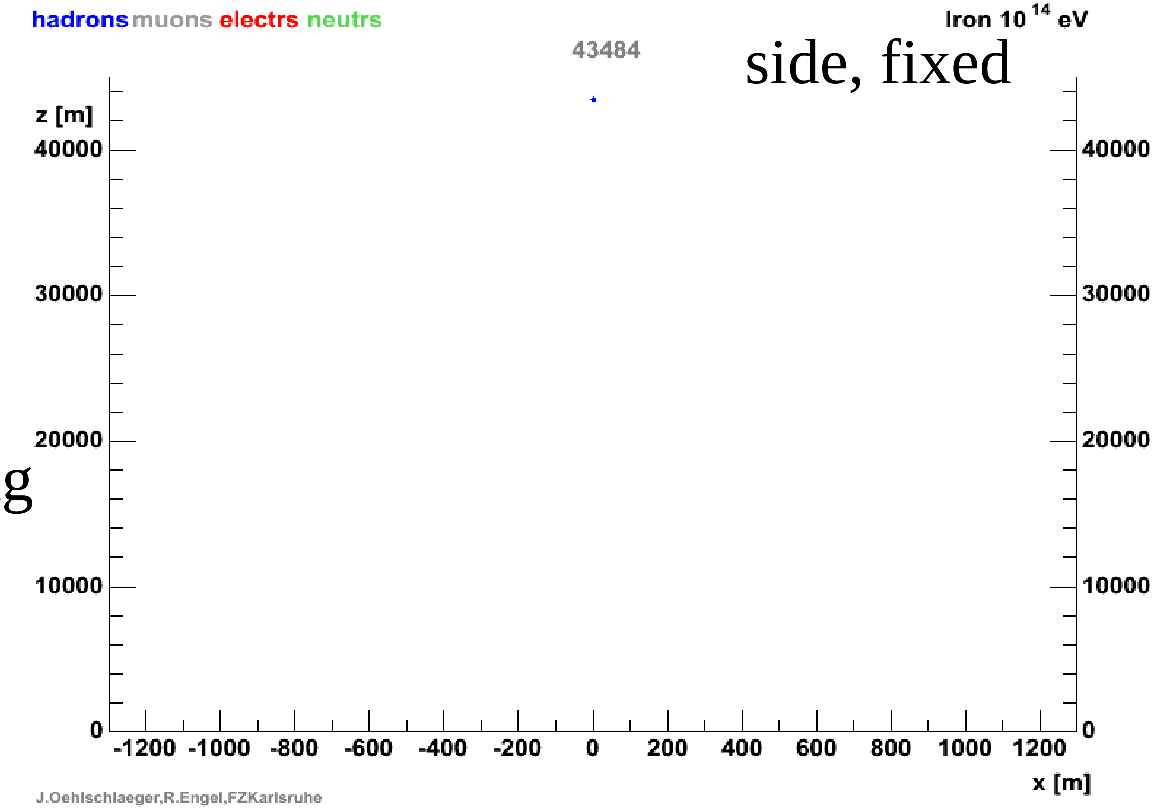
upwards, co-moving

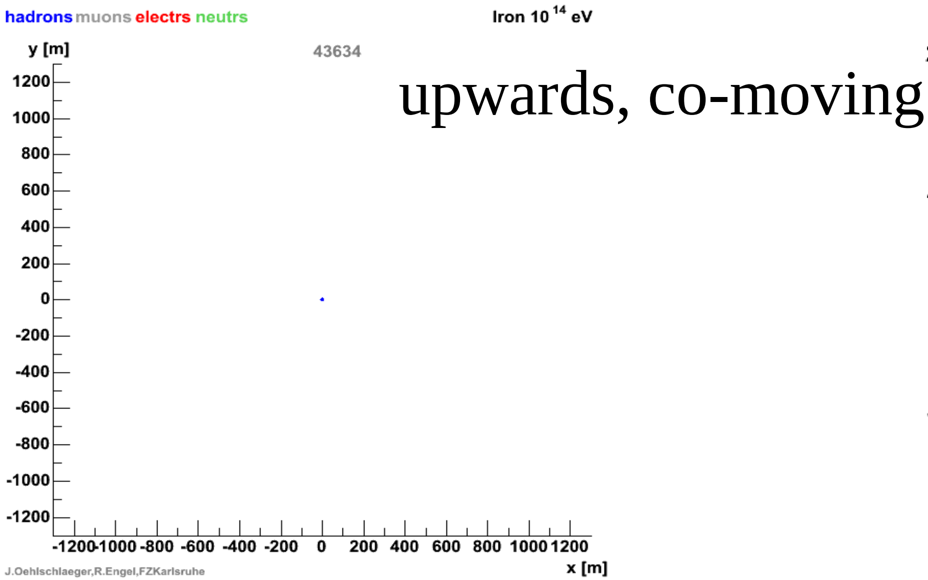
Proton, 100 TeV, vertical

List of CORSIKA shower movies

Movie	Initiating Particle, Energy, Zenith Angle	Viewing, Observer	Energy Cut	Remarks
sanfe14zx13.gif sanfe14xz13.gif sanfe14yx13.gif	iron 100 TeV, vertical	side, co-moving side, fixed upwards, co-moving	0.1 GeV	coloured particle types, actual altitude [m] displayed



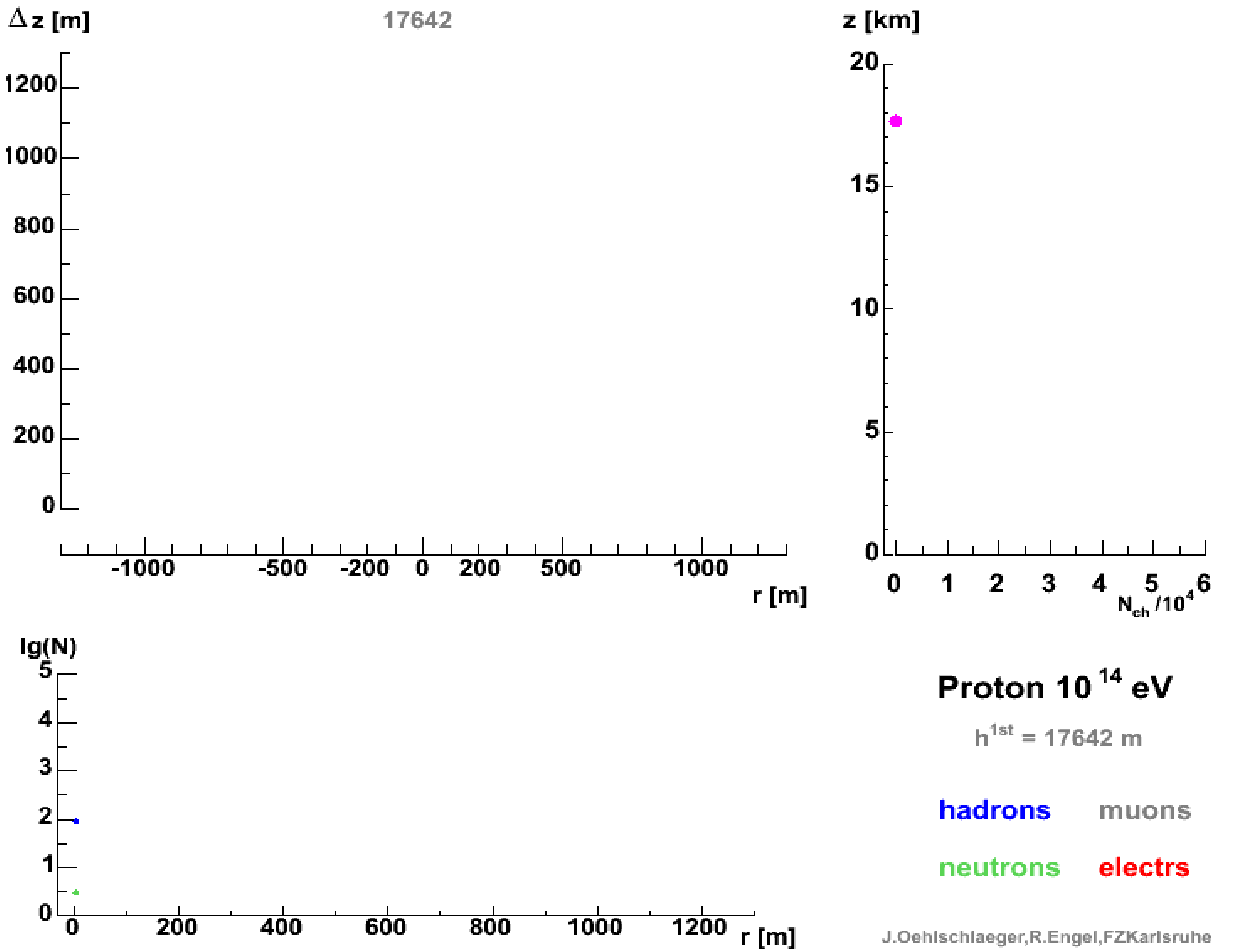




Iron, 100 TeV, vertical

List of CORSIKA shower movies

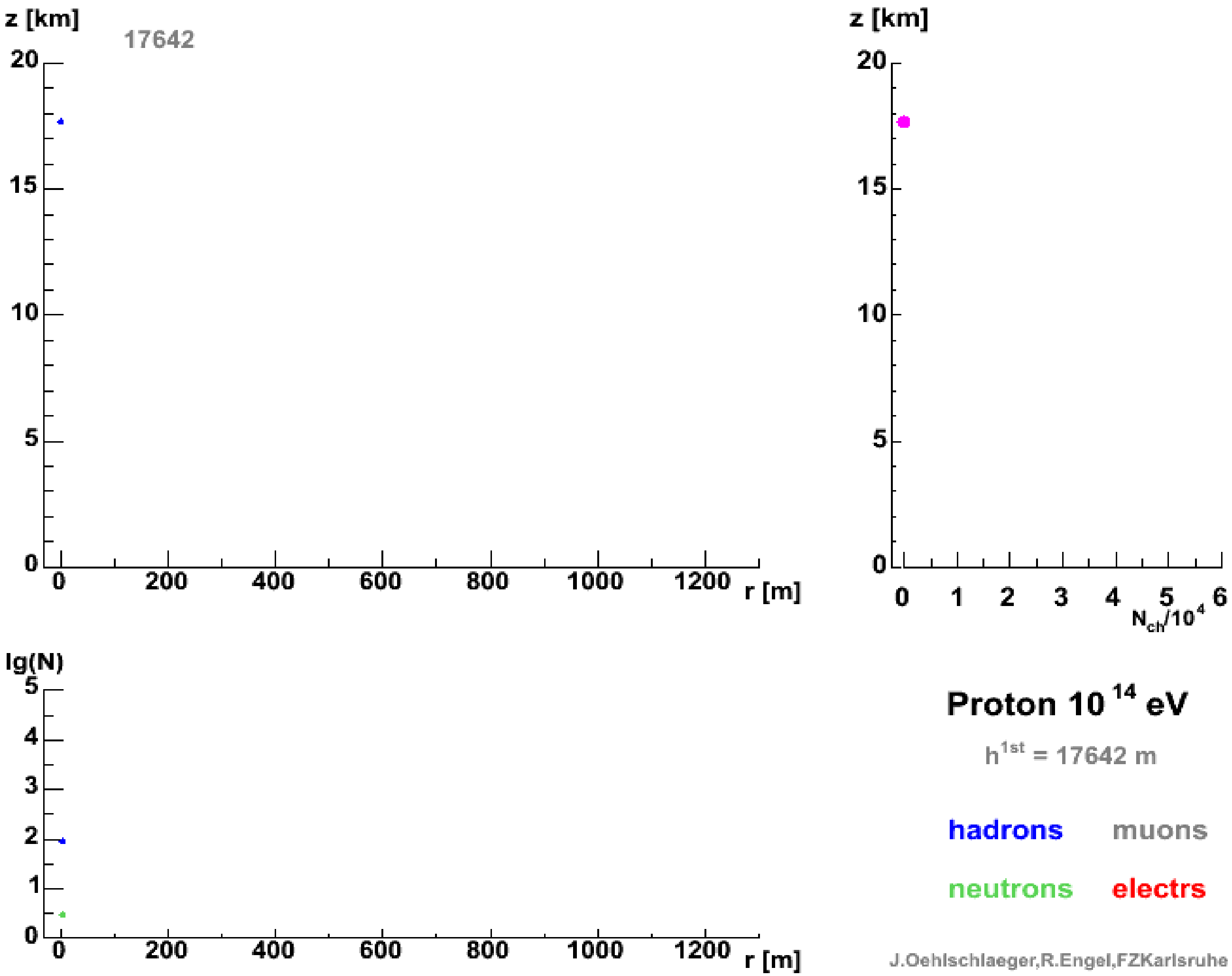
Movie	Initiating Particle, Energy, Zenith Angle	Viewing, Observer	Energy Cut	Remarks
nchargedzx03.gif nchargedrz03.gif nchargedxz03.gif nchargedyx03.gif	proton 100 TeV, vertical	side, co-moving side, fixed side, fixed upwards, co-moving	0.1 GeV	coloured particle types, actual altitude [m] displayed, including longitudinal and actual lateral distribution



Proton, 100 TeV, vertical

List of CORSIKA shower movies

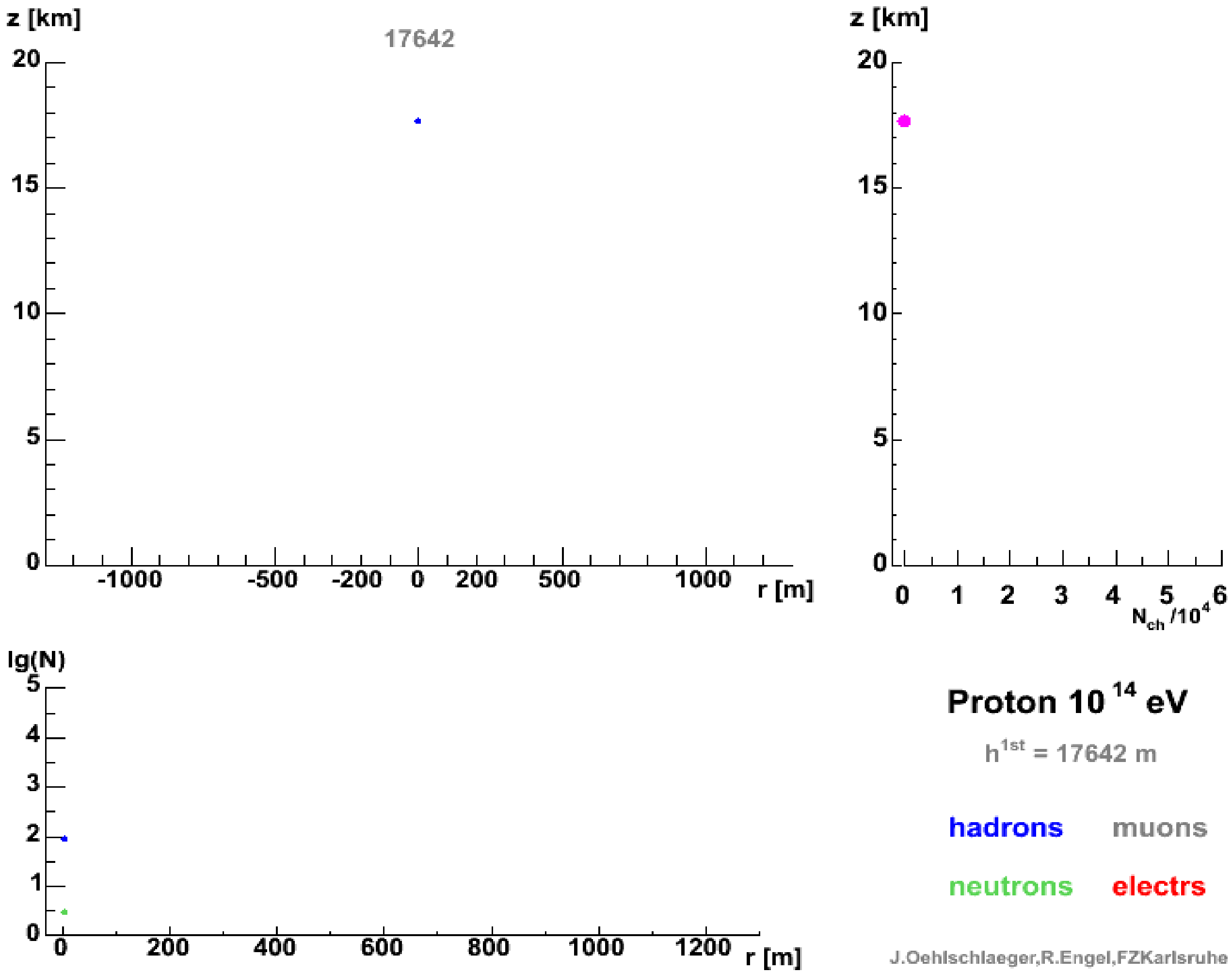
Movie	Initiating Particle, Energy, Zenith Angle	Viewing, Observer	Energy Cut	Remarks
nchargedzx03.gif nchargedrz03.gif nchargedxz03.gif nchargedyx03.gif	proton 100 TeV, vertical	side, co-moving side, fixed side, fixed upwards, co-moving	0.1 GeV	coloured particle types, actual altitude [m] displayed, including longitudinal and actual lateral distribution



Proton, 100 TeV, vertical

List of CORSIKA shower movies

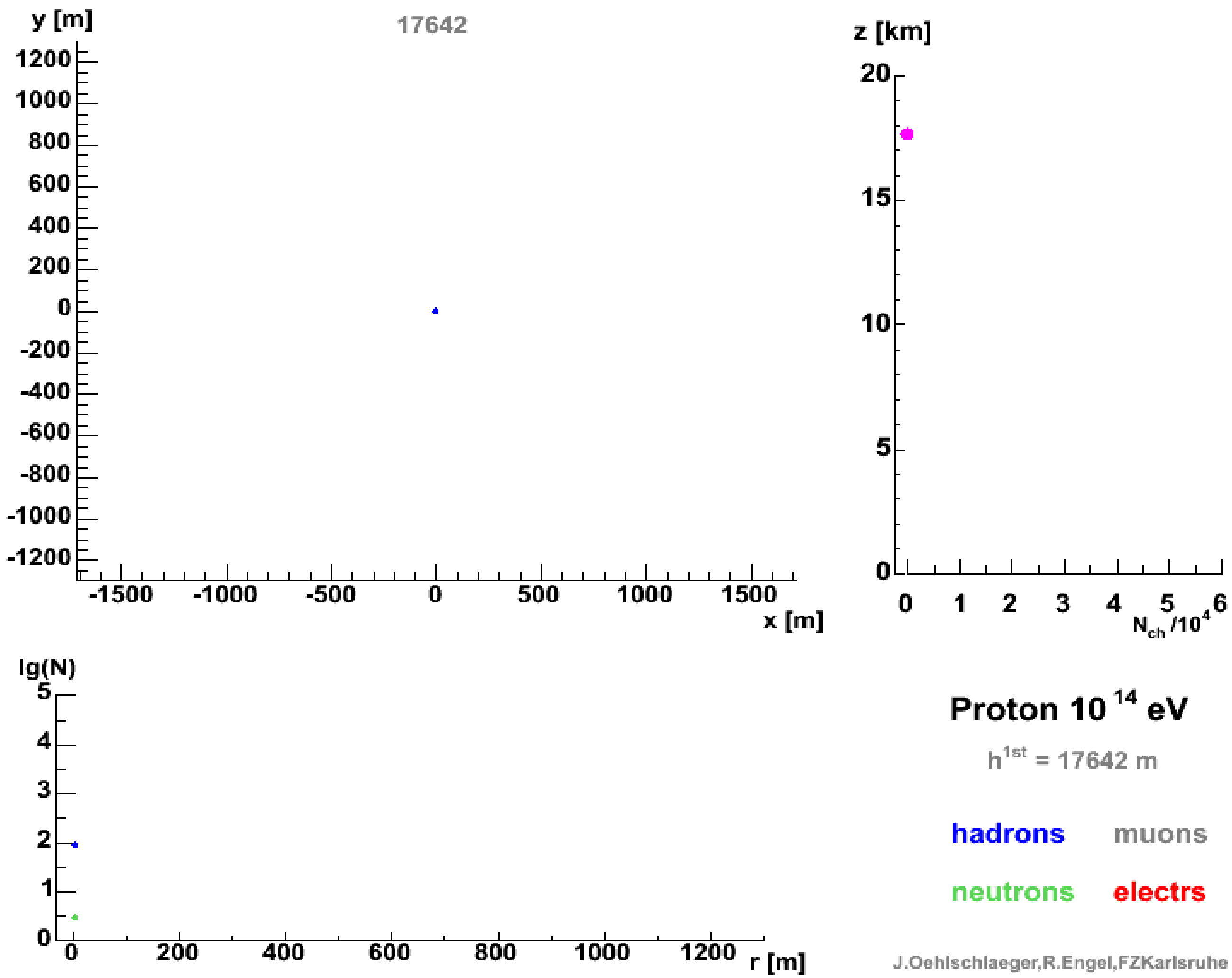
Movie	Initiating Particle, Energy, Zenith Angle	Viewing, Observer	Energy Cut	Remarks
nchargedzx03.gif nchargedrz03.gif nchargedxz03.gif nchargedyx03.gif	proton 100 TeV, vertical	side, co-moving side, fixed side, fixed upwards, co-moving	0.1 GeV	coloured particle types, actual altitude [m] displayed, including longitudinal and actual lateral distribution



Proton, 100 TeV, vertical

List of CORSIKA shower movies

Movie	Initiating Particle, Energy, Zenith Angle	Viewing, Observer	Energy Cut	Remarks
nchargedzx03.gif nchargedrz03.gif nchargedxz03.gif nchargedyx03.gif	proton 100 TeV, vertical	side, co-moving side, fixed side, fixed upwards, co-moving	0.1 GeV	coloured particle types, actual altitude [m] displayed, including longitudinal and actual lateral distribution



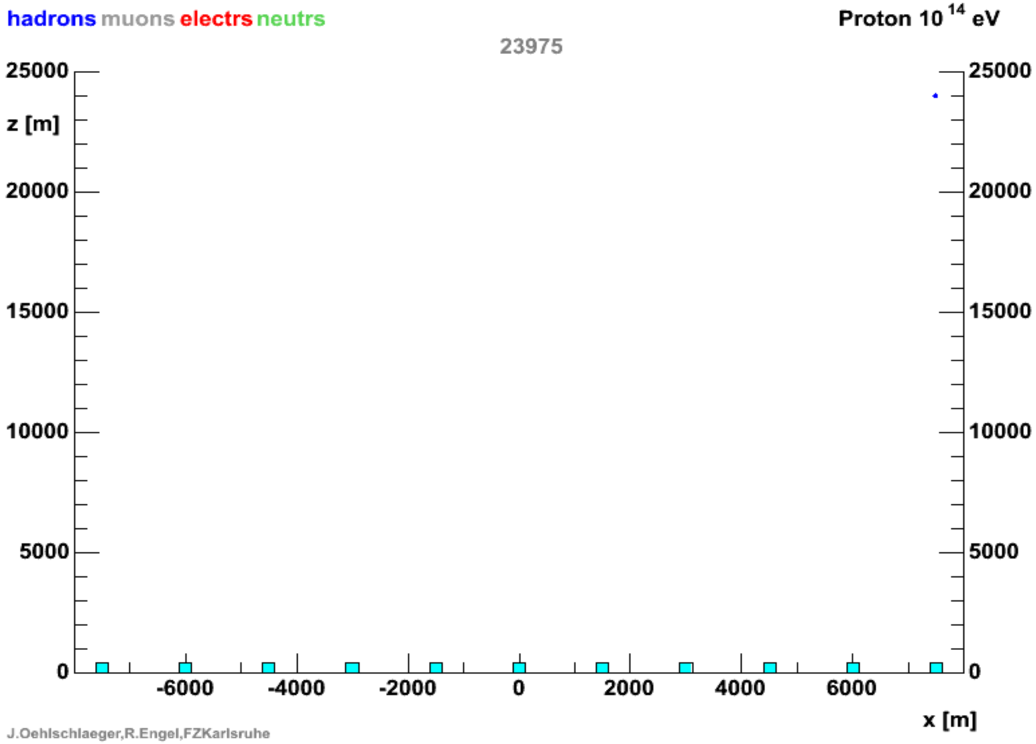
Proton, 100 TeV, vertical

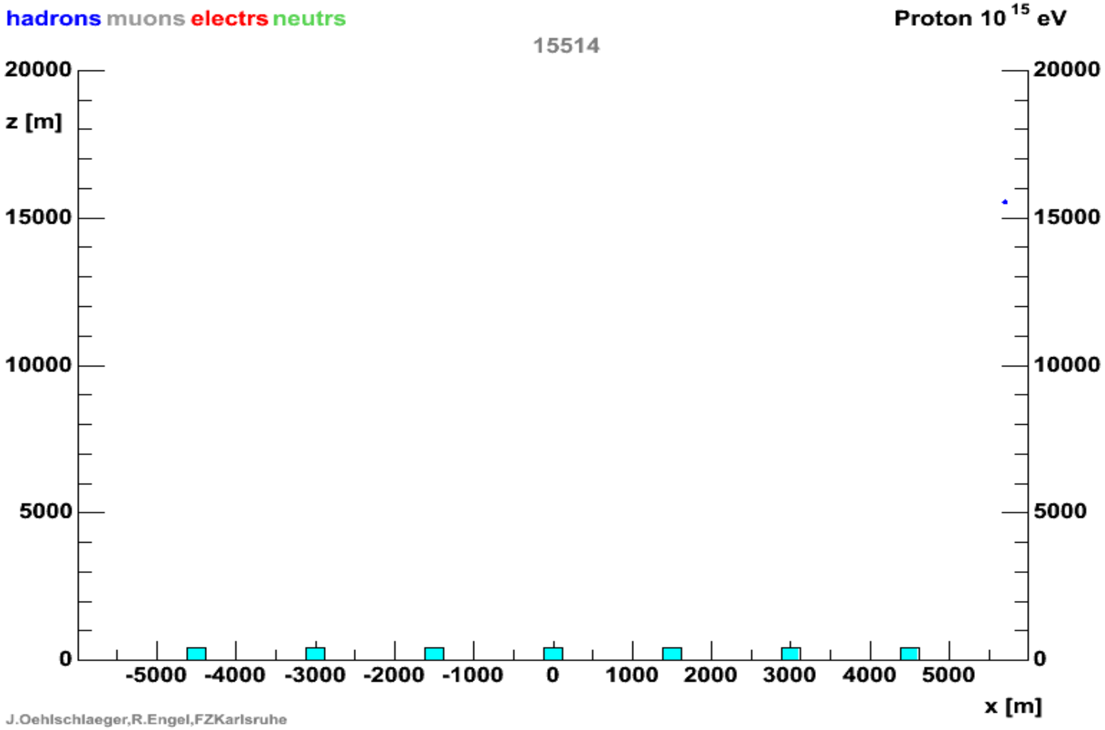
List of CORSIKA shower movies

Movie	Initiating Particle, Energy, Zenith Angle	Viewing, Observer	Energy Cut	Remarks
sincpr14xz03.gif sincpr15xz03.gif	proton, 100 TeV, 30 deg proton, 1 PeV, 30 deg	side, fixed	0.1 GeV 1 GeV	coloured particle types, actual altitude [m] displayed, hit detectors flashing

Proton, 100 TeV, 30 deg

Proton, 1 PeV, 30 deg



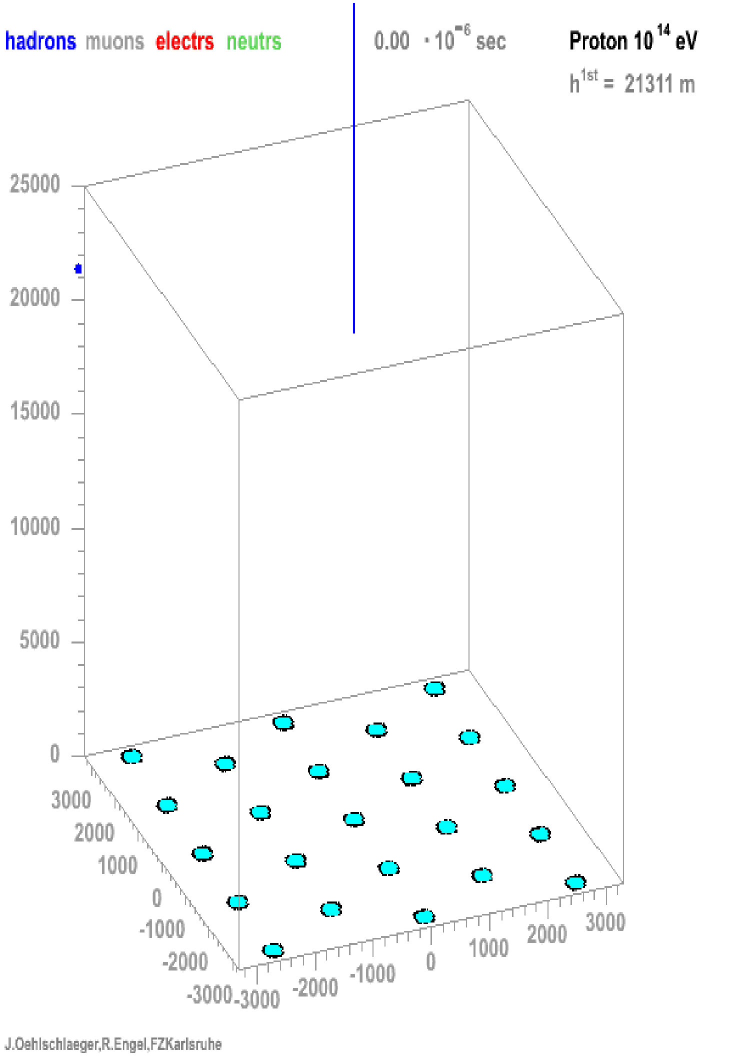


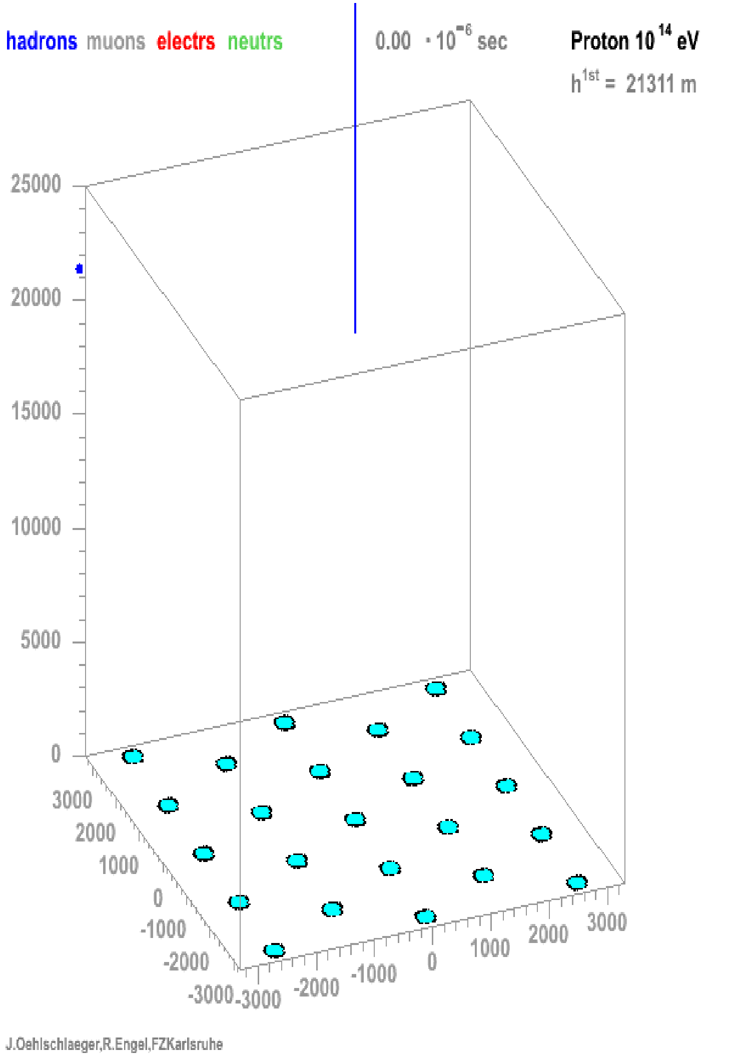
Beware ! not at same vertical scale

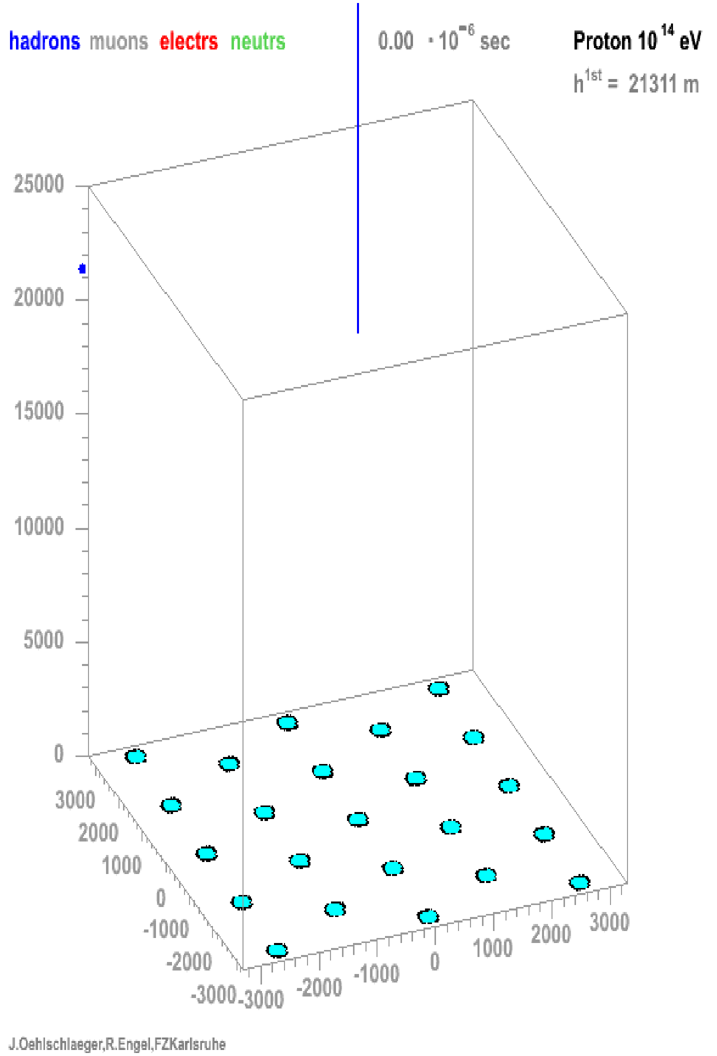
List of CORSIKA shower movies

Movie	Initiating Particle, Energy, Zenith Angle	Viewing, Observer	Energy Cut	Remarks
trafix14prh.gif trafix14prhm.gif trafix14prhme.gif	proton, 100 TeV, vertical	perspective, fixed	0.1 GeV	traces of hadrons traces of hadrons & muons traces of hadrons & muons & electrons

Proton, 100 TeV, vertical





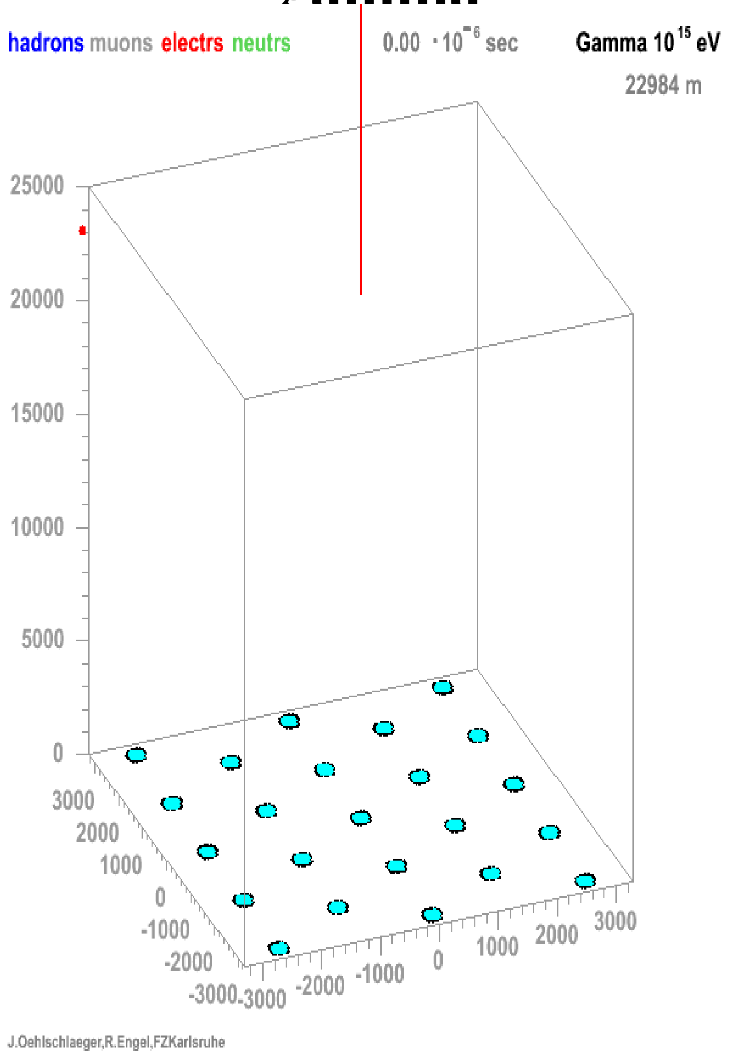


List of CORSIKA shower movies

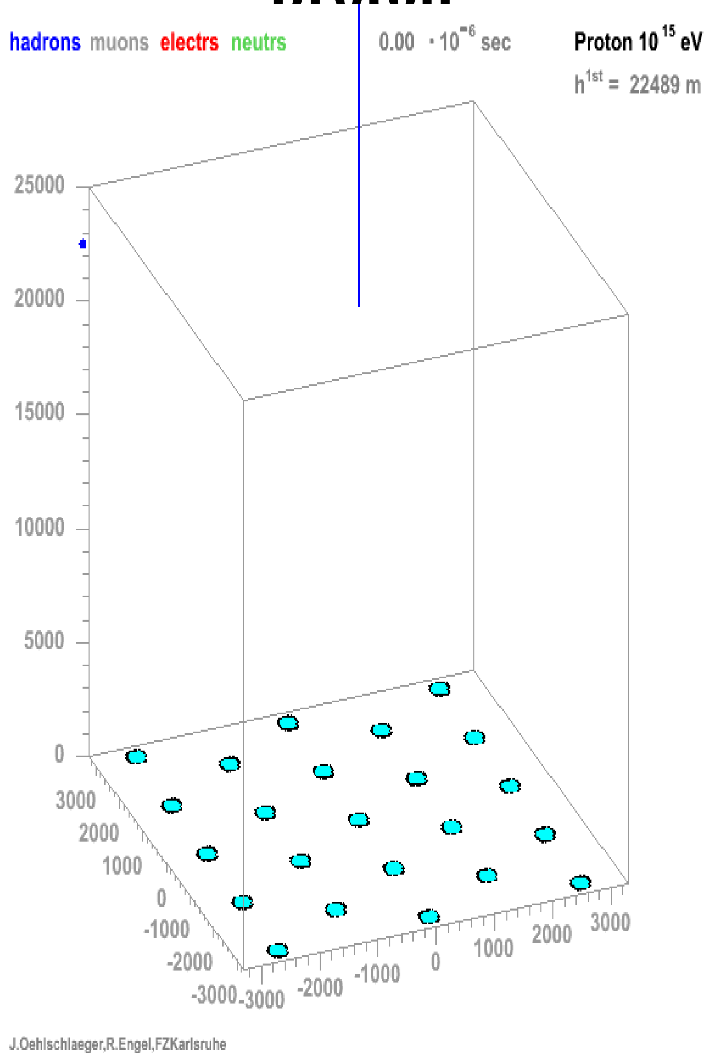
Movie	Initiating Particle, Energy, Zenith Angle	Viewing, Observer	Energy Cut	Remarks
trafix15ga05.gif trafix15pr05.gif trafix15fe05.gif	gamma, 1 PeV, vertical proton, 1 PeV, vertical iron, 1 PeV, vertical	perspective, fixed	1 GeV	traces of hadrons & muons & electrons

1 PeV, vertical

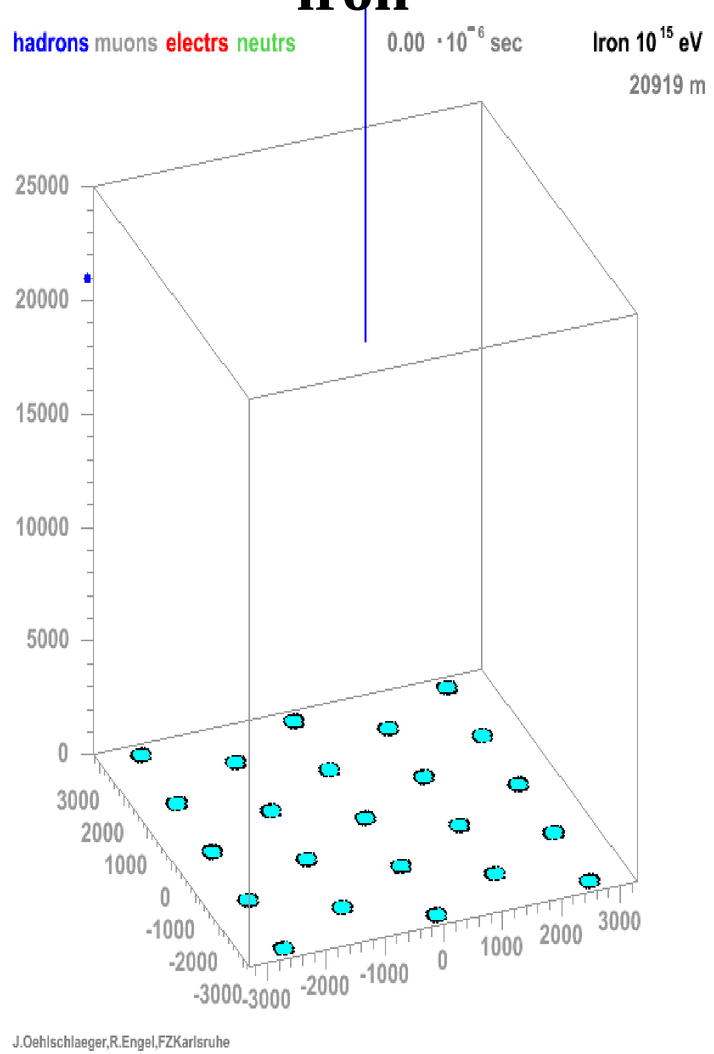
gamma



proton



iron



UHECR detection

Lecture on
Imaging & Cherenkov
Detectors

Lecture on
Imaging & Cherenkov
Detectors