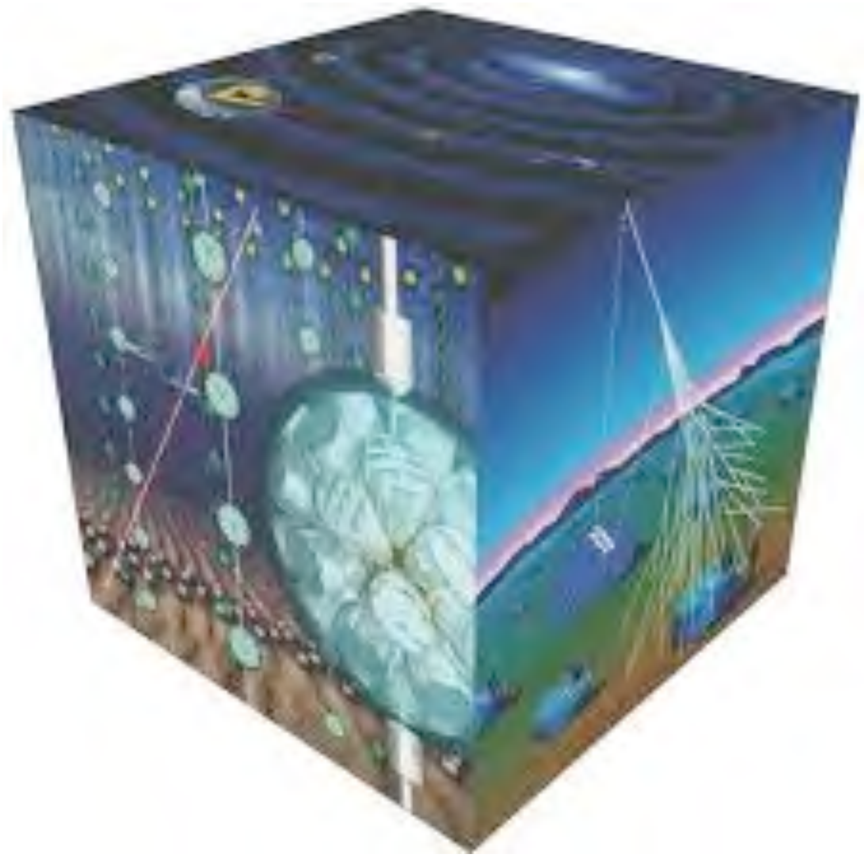
Astroparticle Physics



Cosmic rays

Gamma rays

Neutrinos

Gravitational waves

???

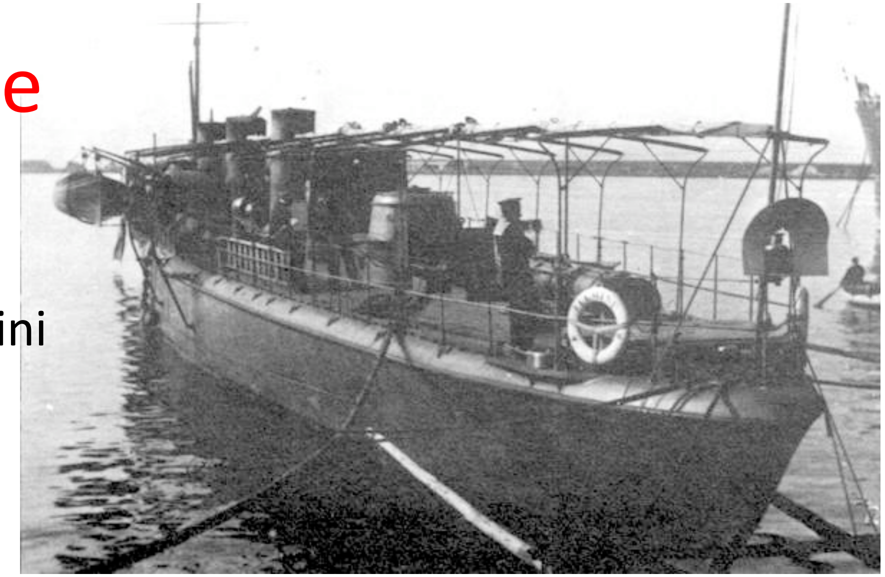
Alessandro De Angelis Mário Pimenta
Asiago, June 2017

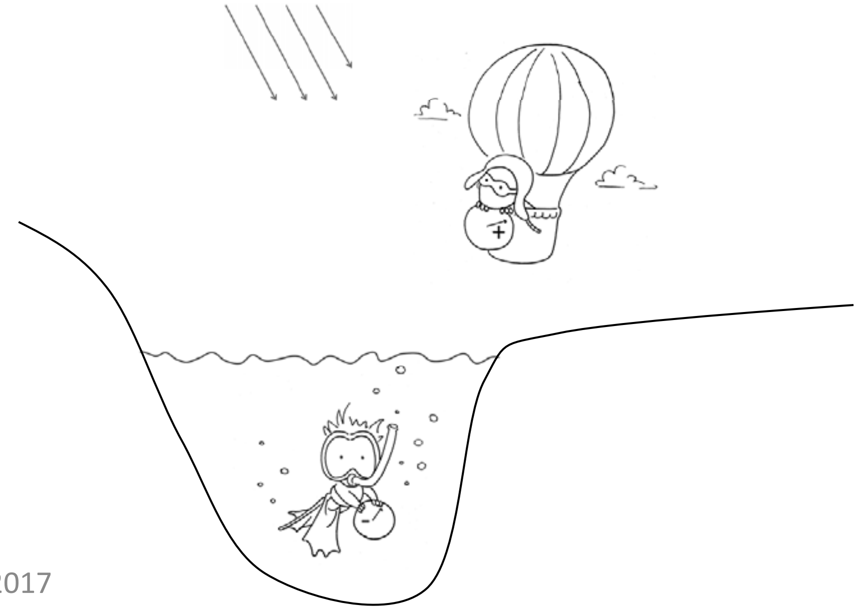
I- Introduction

Messengers from the Universe

1911/12: Domenico Pacini and Victor Hess perform two complementary experiments: Pacini discovers that ionizing radiation decreases underwater, and Hess that it increases at high altitudes

- 20% of the natural radiation at ground is due to cosmic radiation!!! Can we use these **"cosmic rays"** for science?



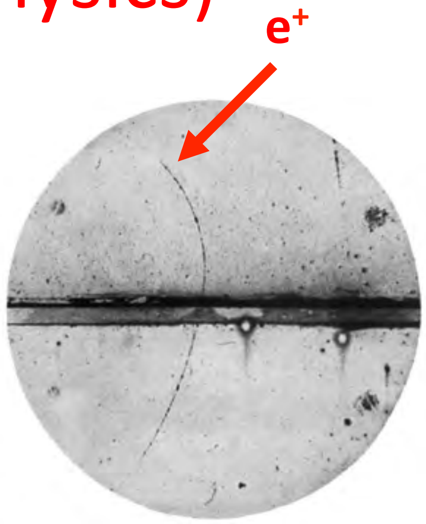


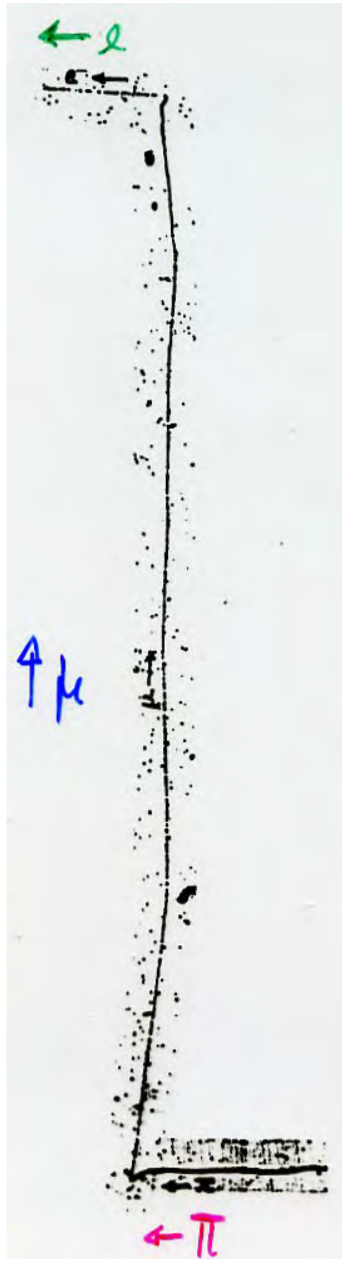
YES (the birth of Particle Physics)

Positron (Anderson 1932)

Antimatter! (Dirac)

$\gamma \rightarrow e^+e^-$ (Einstein)



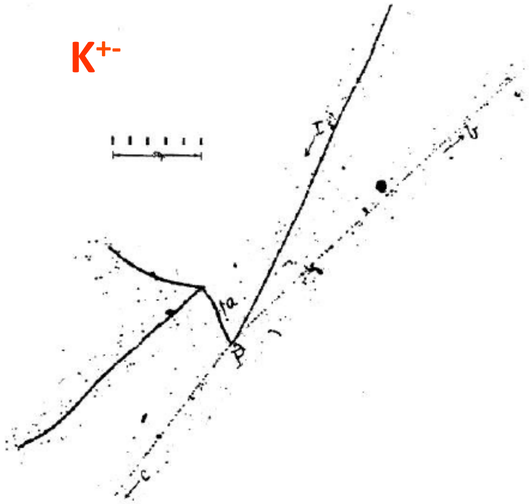


μ (Anderson 1937)

Rossi, 1940:
Muon life time.
Time dilation!

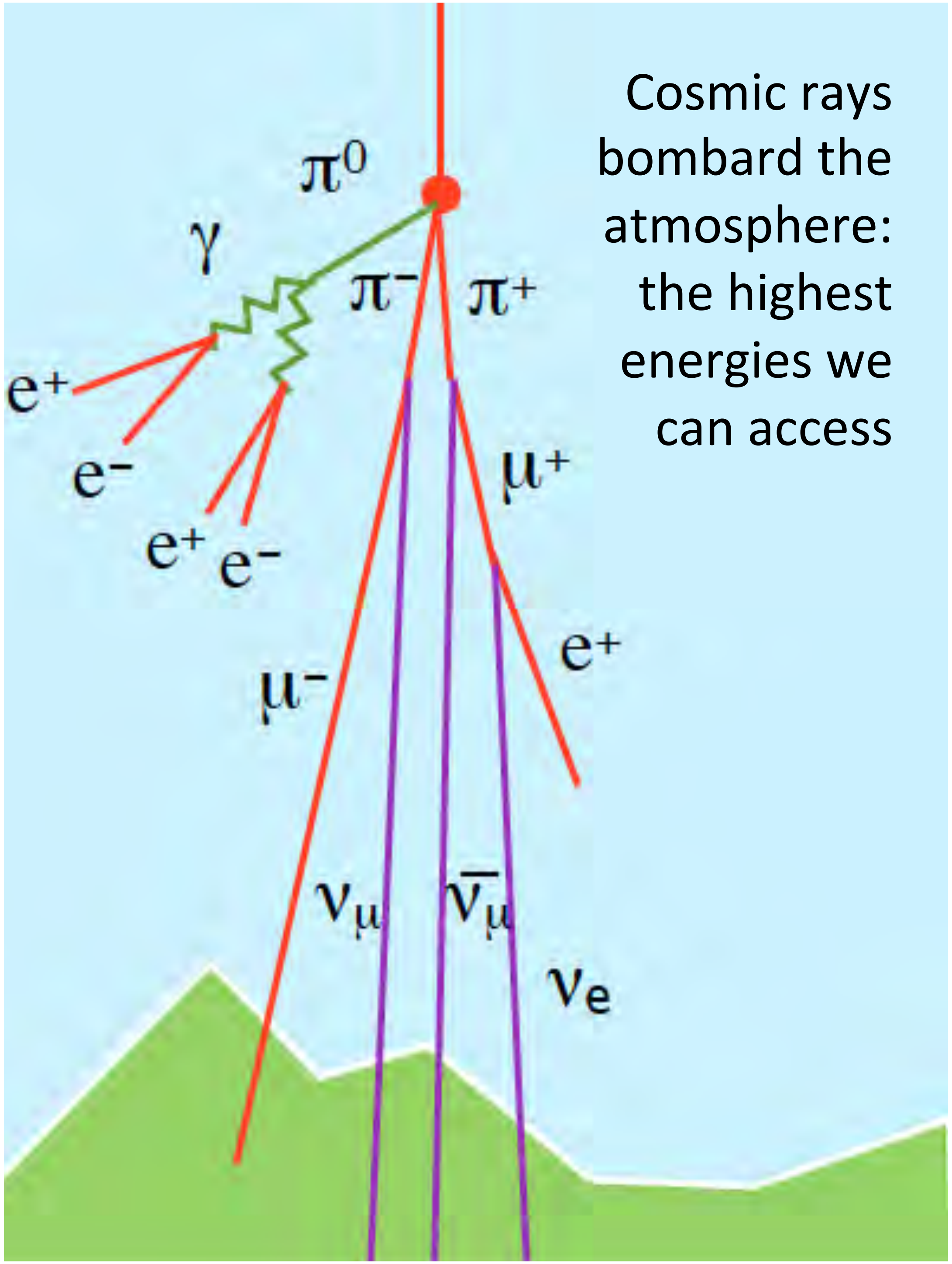
π (Lattes, Powell 1947)

Strong interactions (Yukawa)



K, Λ, ... (Leprince Ringuet 1944, Rochester , Butter 1947, ...)

Strangeness



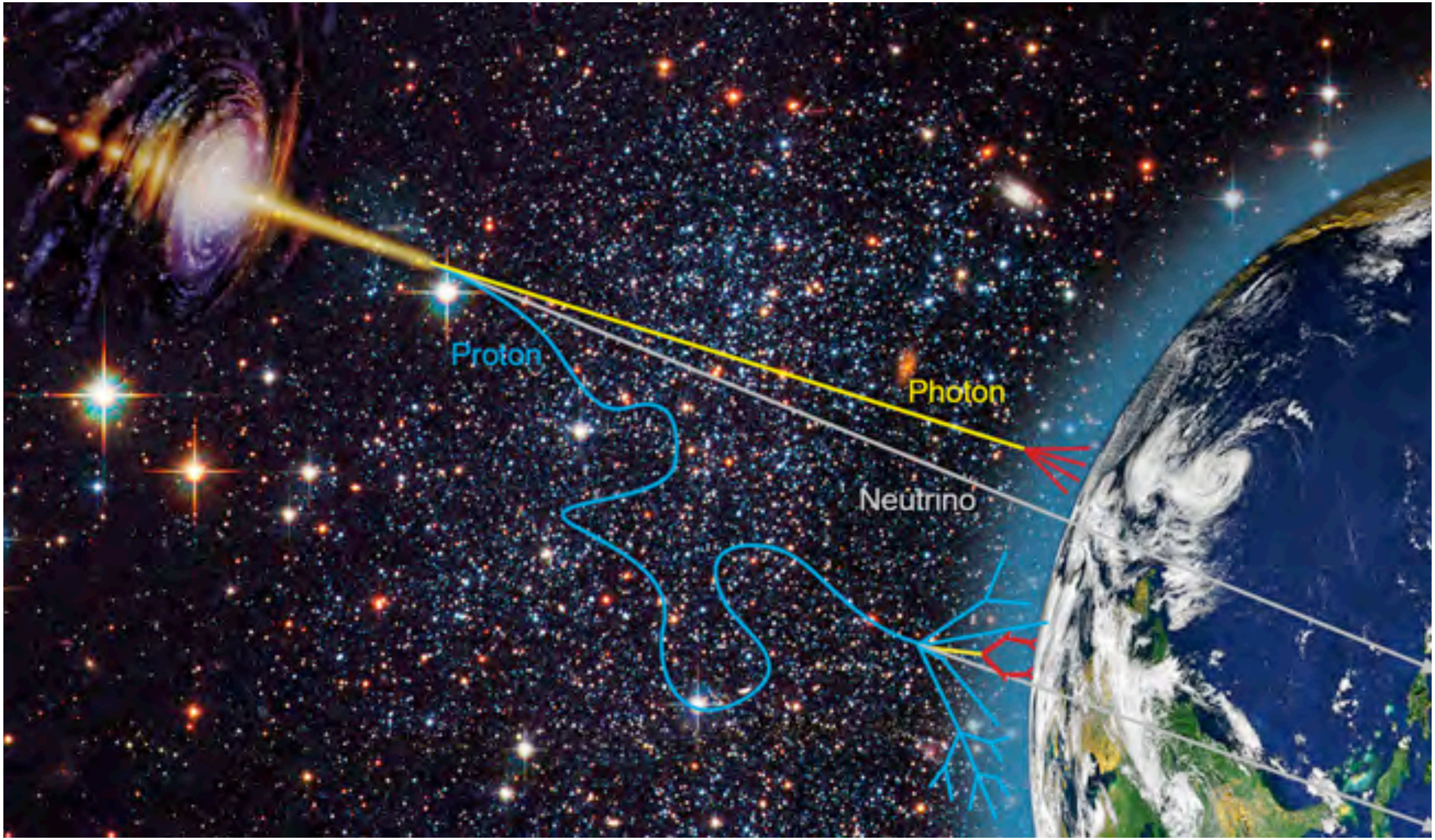
YES, and it allows accessing the highest energies

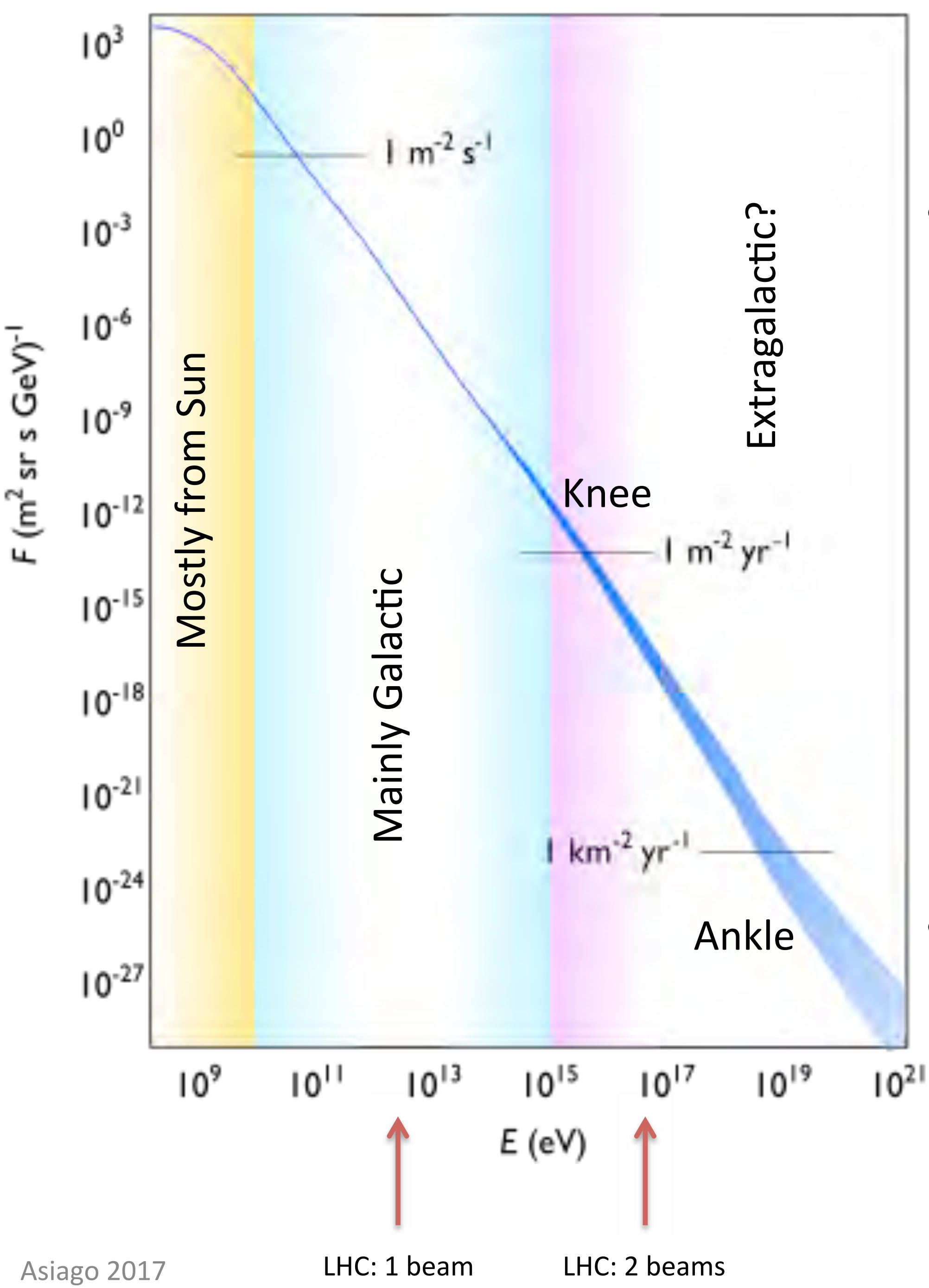
Detected protons 10^8 times more energetic than LHC

Detected gamma-rays 10000 times more energetic than human-made

Detected neutrinos 10^5 times more energetic than human-made

YES, and it allows understanding high-energy astrophysics (physics under extreme conditions)





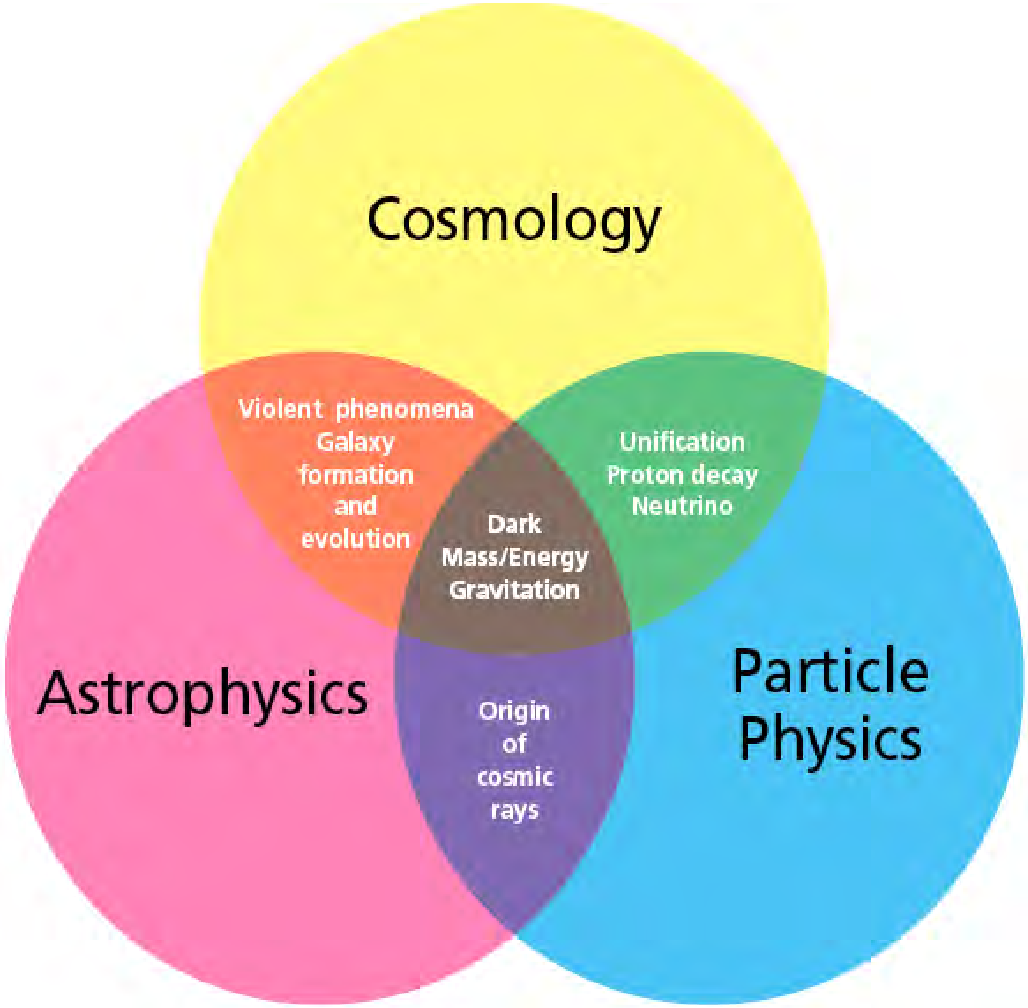
Cosmic Rays ("astroparticles")

- Once per second per cm^2 a high-energy particle from the sky hits the Earth
  - Mostly (~89%) protons
  - He (~9%) nuclei and heavier (~1%);
  - Electrons are ~1%
  - 0.01% - 1% are gamma rays

$$\frac{dN}{dE} \simeq 1.8 \times 10^4 \left(\frac{E}{\text{GeV}}\right)^{-2.7} \frac{\text{particles}}{\text{m}^2\,\text{s}\,\text{sr}\,\text{GeV}}$$

- The flux falls as ~E$^{-2.7}$ as energy increases
  - 10^{21} eV once per second on Earth
    - The highest energies

Astroparticle physics



A multimessenger science

1. ***HE gammas***
2. ***HE neutrinos***
3. ***HE protons/nuclei***
4. ***Gravitational waves***

Several possible fundamental physics objectives

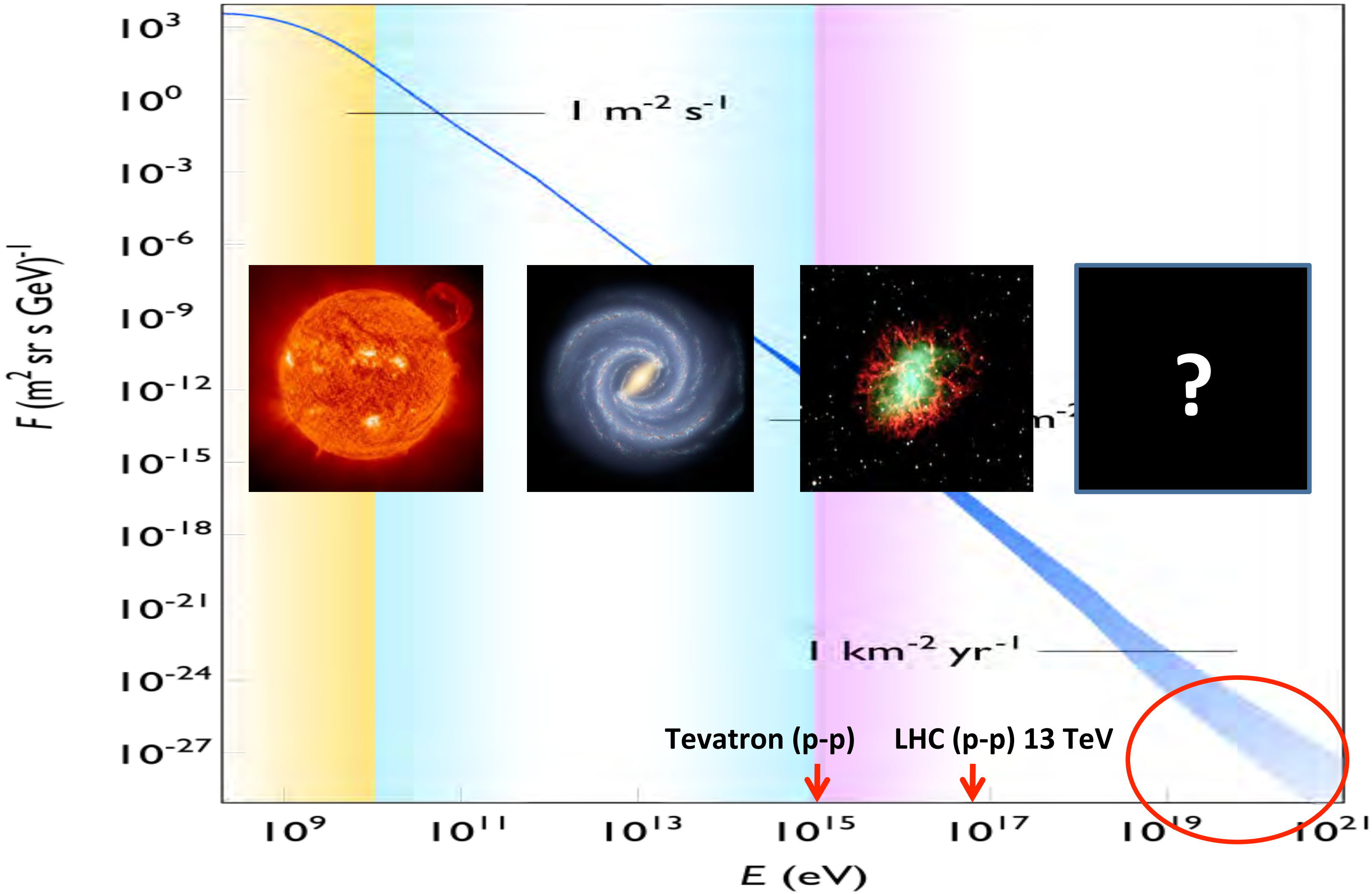
1. ***Extremely high energy collisions***
2. ***Dark matter/energy***
3. ***Axions, ALPs***
4. ***Neutrino mass***
5. ***Neutrino mixing***
6. ***CMB***

And of course, astrophysics

1. ***Behavior of physics near (SM)BHs***
2. ***Acceleration mechanisms***

II- Production

Origin ! ?



10^3
10^0
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
10^{-18}
10^{-21}
10^{-24}
10^{-27}
F (m^2 sr s GeV)$^{-1}$
1 m^{-2} s^{-1}
?
1 km^{-2} yr^{-1}
Tevatron (p-p)
LHC (p-p) 13 TeV
10^9
10^{11}
10^{13}
10^{15}
10^{17}
10^{19}
10^{21}
E (eV)

Possible UHECR Sources: **2 scenarios**

Bottom-Up Acceleration

(Astrophysical Acceleration Mechanisms)

UHECR's are accelerated in extended objects or catastrophic events (supernova remnants, rotating neutron stars, AGNs, radio galaxies)

Experimental evidence:

- ✓ anisotropy in arrival directions
- ✓ Photons < ≈1%

Top–Down Decay

(Physics Beyond the Standard Model)

Decay of topological defects
Monopoles Relics
Supersymmetric particles
Strongly interacting neutrinos
Decay of massive new long lived particles
Etc.

Experimental evidence:

- ✓ isotropy in arrival directions
- ✓ Photons > ≈10%

IIa- Charged particle acceleration

Origin (E ~<10^{15} eV)?

Energy density (cosmic rays)

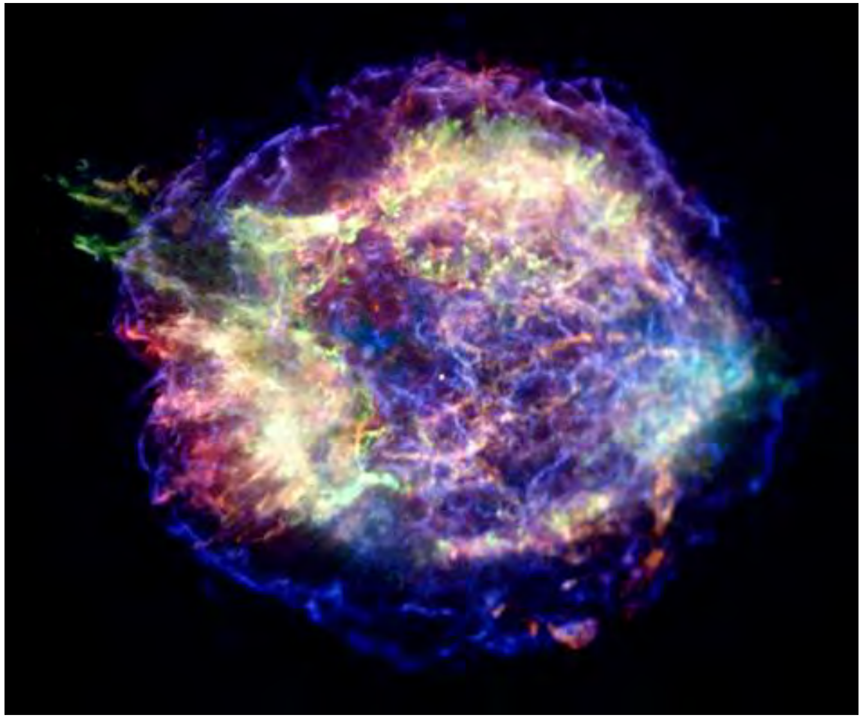
$$\rho_E \sim \int E \frac{dN}{dE} dE \sim 10^{-12}\, \mathrm{erg}/cm^3$$

$$\sim 1\, \mathrm{eV}/cm^3$$

$$P \sim \frac{\rho_E V_{galaxy}}{\tau_{esc}} \sim 5.10^{40} erg/s$$

For example, power dissipated by a Supernova (the remnant of a collapsed star) of 10 $M_{sun.}$

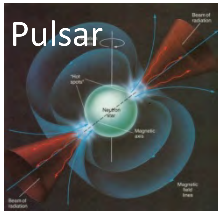
E ~10^{53} erg

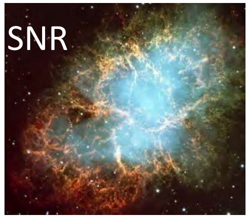


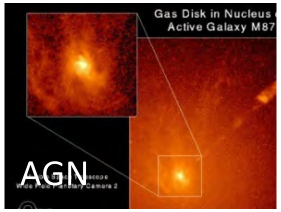
Supernovae in our Galaxy

1 SN ~30 Years ~10^{-9} s^{-1}

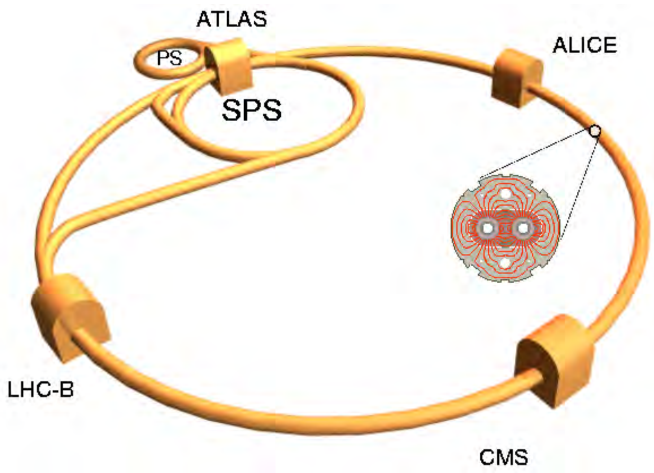
Where can be these accelerators in the Universe?





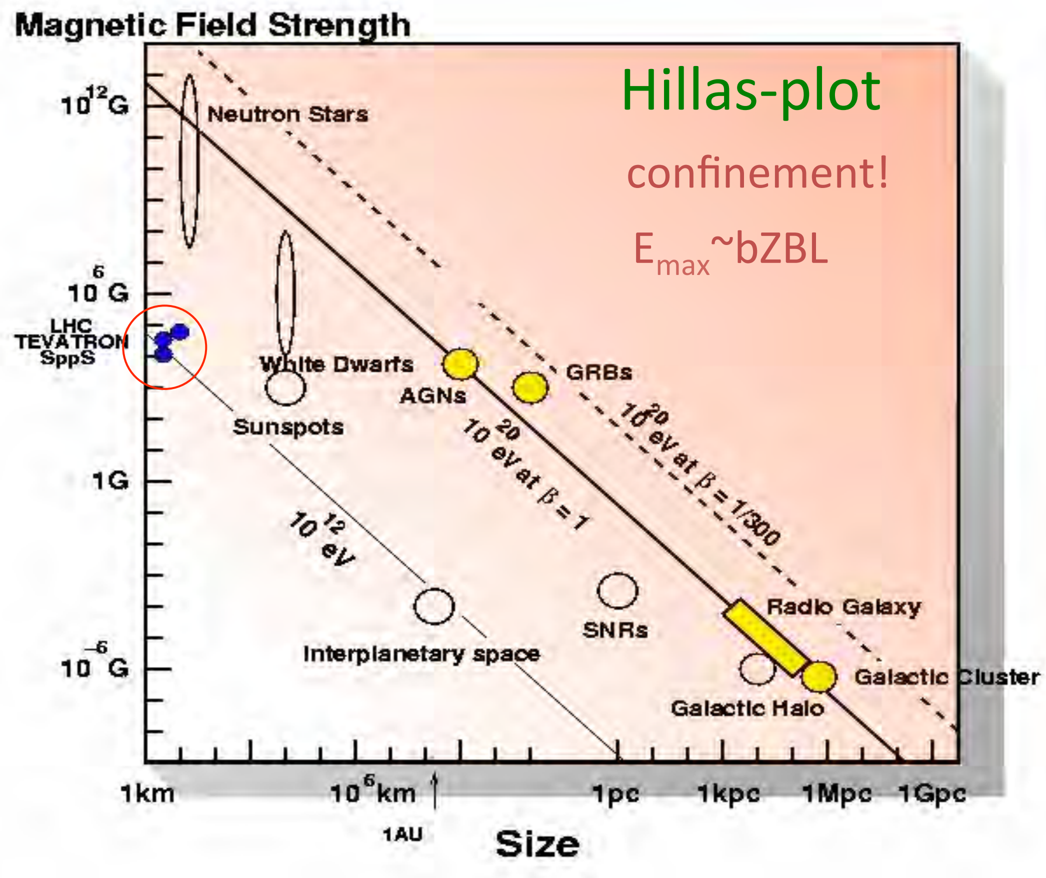


Large Hadron Collider



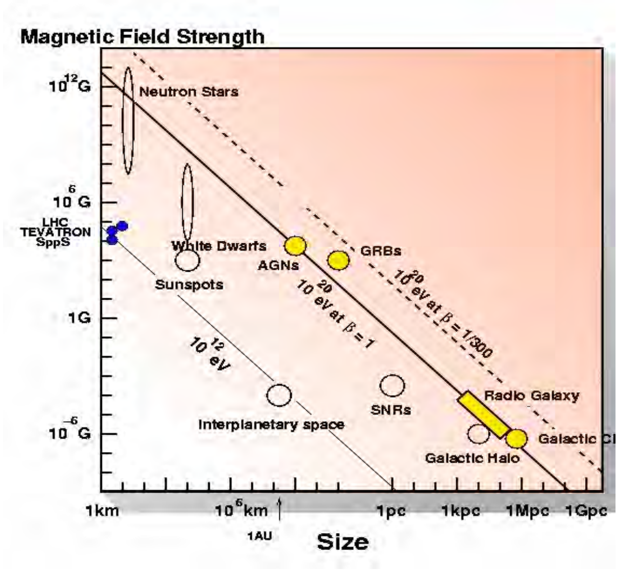
E ∝ BR

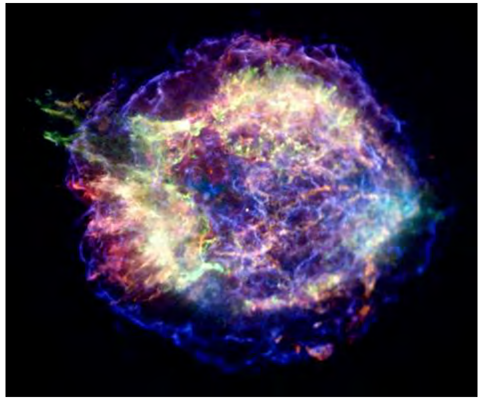
R ~ 10 km, B ~ 10 T
E ~ 10 TeV



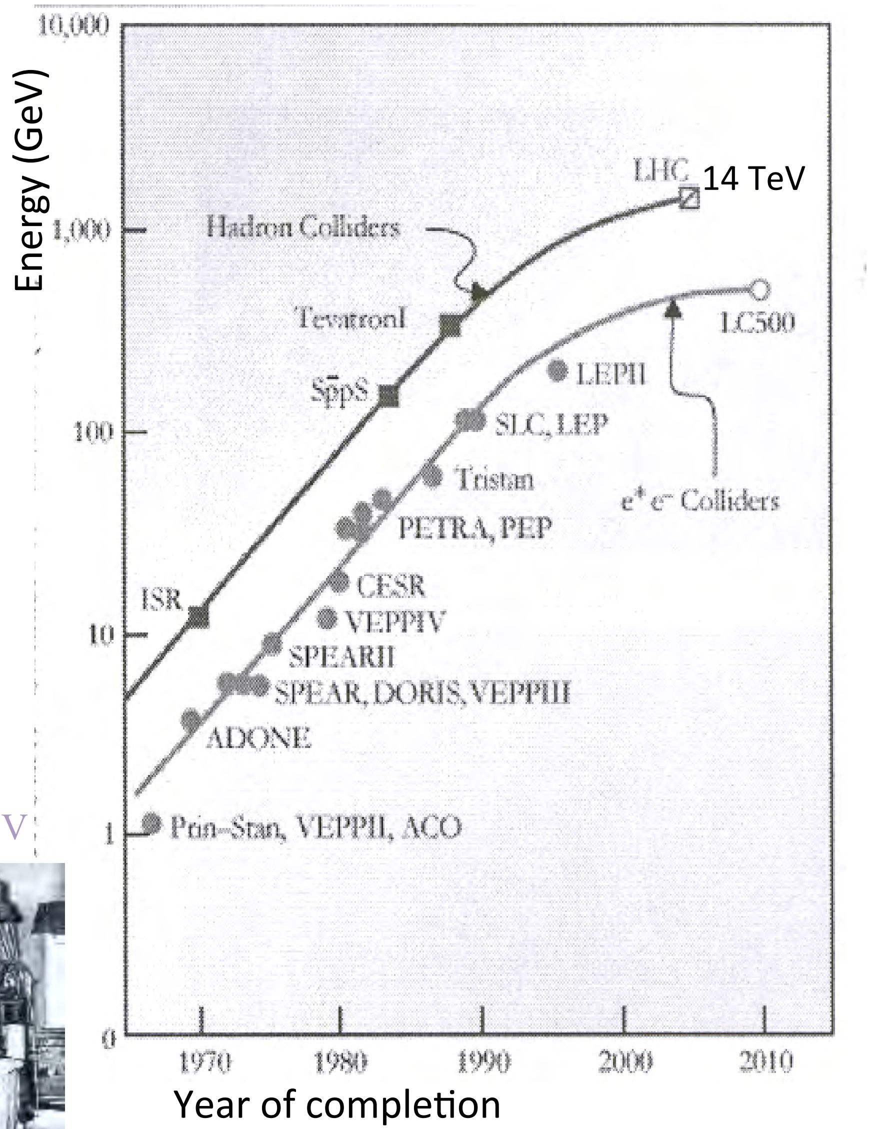
A few new terms

- Stellar end-products. A star heavier than the Sun collapses at the end of its life into a neutron star (R ~ few km, which can be pulsating – a pulsar) or into a BH, and ejects material in an explosion (SuperNova Remnant).
  - Very large B fields are in the pulsar; magnetic fields also in the SNR
- The centres of galaxies host black holes, often supermassive (millions or even billion solar masses). They might accrete at the expense of the surrounfing matter, and accelerate particles in the process. When they are active, they are called Active Galactic Nuclei.



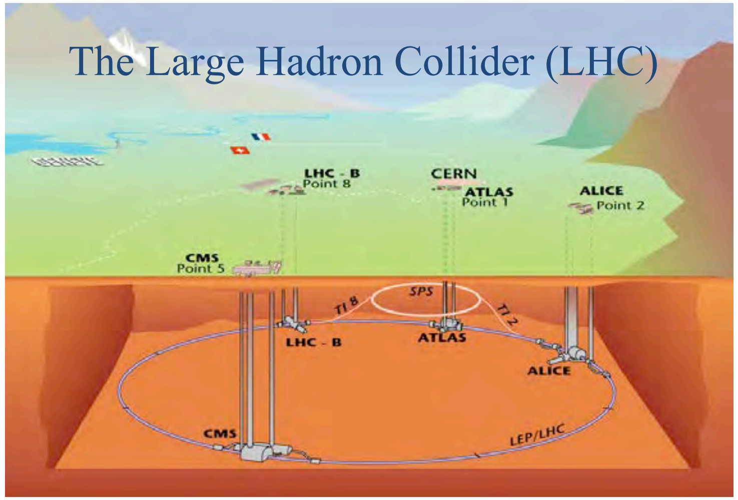


They surpass human-made accelerators



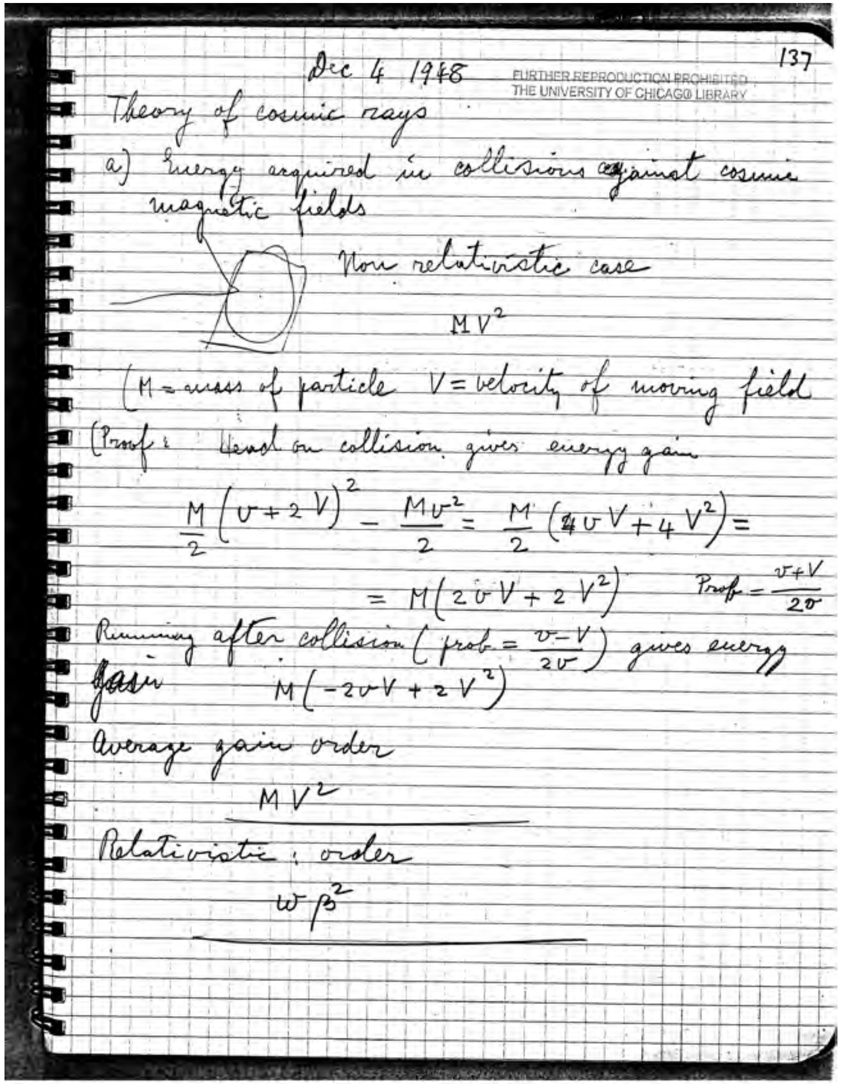
~ 10 MeV

1930



High Luminosity
Sophisticated detectors
Central region
Energy limited

How to generate bottom-up energies much higher than thermal?



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Dec 4 1948

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Theory of cosmic rays

a) Energy acquired in collisions against cosmic magnetic fields

Non relativistic case

MV^2

(M = mass of particle V = velocity of moving field

(Proof: Head on collision gives energy gain

$$\frac{M}{2}(v+2V)^2 - \frac{Mv^2}{2} = \frac{M}{2}(4vV+4V^2) =$$

$$= M(2vV+2V^2) \qquad \text{Prob} = \frac{v+V}{2v}$$

Running after collision $\left(\text{prob} = \frac{v-V}{2v}\right)$ gives energy gain

$$M(-2vV+2V^2)$$

Average gain order

$$MV^2$$

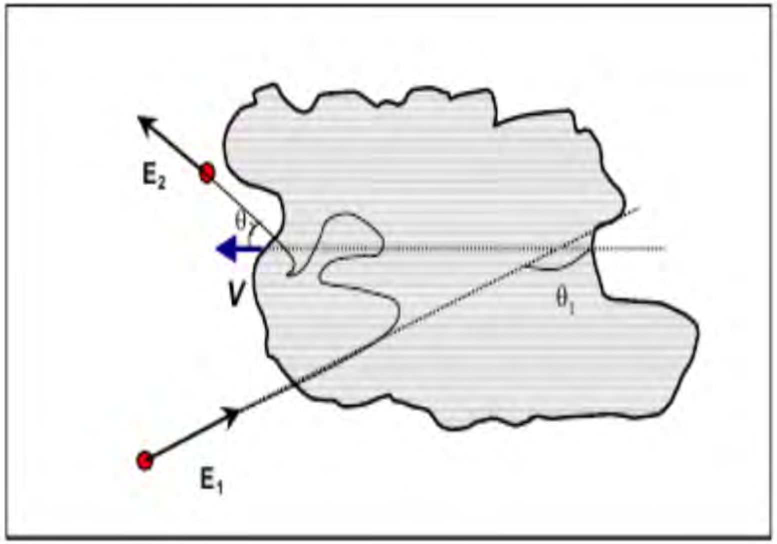
Relativistic: order

$$w\beta^2$$

Acceleration mechanism

Fermi 2nd order (1949)

particles accelerated in stochastic collisions with massive interstellar clouds (collisions to a moving diffusive wall!)



In the cloud reference frame

$$E_1^* = \gamma\, E_1(1 - \beta\cos\theta_1)$$
$$E_2^* = E_1^*$$

Back to the Lab reference frame

$$E_2 = \gamma\, E_2^*\,(1 + \beta\cos\theta_2^*)$$

Then:

$$\frac{\Delta E}{E} = \frac{1 - \beta\cos\theta_1 + \beta\cos\theta_2^* - \beta^2\cos\theta_1\cos\theta_2^*}{1-\beta^2} - 1$$

But:

$$\langle\cos\theta_2^*\rangle = 0$$

$$\langle\cos\theta_1\rangle = \frac{\int_{-1}^{1}\cos\theta_1\overbrace{(1-\beta\cos\theta_1)}^{\text{Probability}}\,d\cos\theta_1}{\int_{-1}^{1}(1-\beta\cos\theta_1)\,d\cos\theta_1} = -\frac{\beta}{3}$$

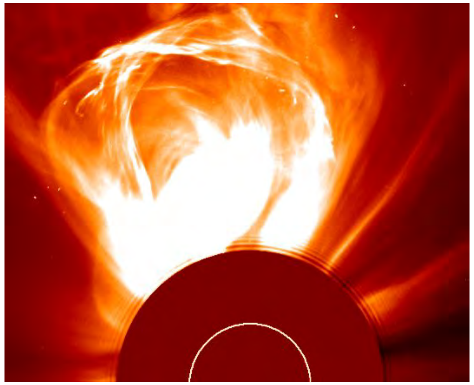
$$\langle\frac{\Delta E}{E}\rangle \simeq \frac{4}{3}\beta^2$$

$\beta \sim 10^{-4}$!!!

Acceleration mechanism

Fermi 1st order

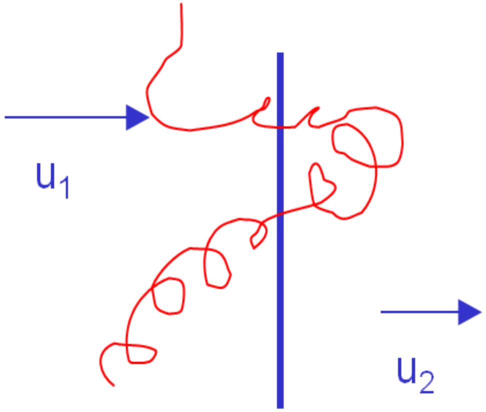
Solar coronal mass ejection 9 Mar 2000



Shock formation :

- Sudden release of Energy (CMEs, SNRs, GRBs,…)
- Supersonic flow hits an obstacle (AGNs jets, pulsar winds, …)

Particles gain energy by consecutive crossings of the shock front!



Crossing probability α cos(θ)

$$\frac{\Delta E}{E} = \frac{1 - \beta\cos\theta_1 + \beta\cos\theta_2^* - \beta^2\cos\theta_1\cos\theta_2^*}{1-\beta^2} - 1$$

Now (plane shock front):

$$\langle\cos\theta_1\rangle = \frac{\int_{-1}^{0}\cos^2\theta_1\, d\cos\theta_1}{\int_{-1}^{0}\cos\theta_1\, d\cos\theta_1} = -\frac{2}{3}$$

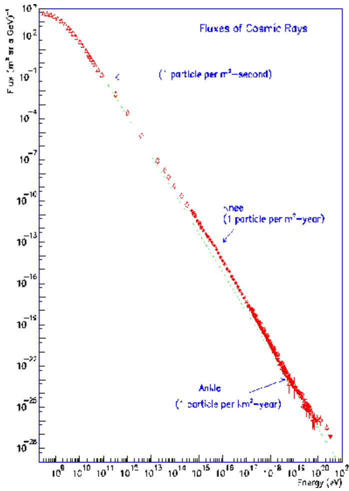
$$\langle\cos\theta_2^*\rangle = \frac{\int_{0}^{1}\cos^2\theta_2^*\, d\cos\theta_2^*}{\int_{0}^{1}\cos\theta_2^*\, d\cos\theta_2^*} = \frac{2}{3}$$

$$\left\langle\frac{\Delta E}{E}\right\rangle \simeq \frac{4}{3}\beta$$

The power law

$$\frac{dN}{dE} \propto E^{-\gamma}$$

$$(N > E) \propto E^{-\gamma+1}$$



In each cycle the particle gains a small fraction of energy ε. After n cycles:

$$E_n = E_0 (1+ \varepsilon)^n$$

Or the number of cycles to attain an energy E is:

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

The particle may escape from the shock region with some probability P_i .Then the probability to escape with $E>E_n$ is:

$$P_{E_n} = P_i \sum_{j=n}^{\infty} (1-P_i)^n = (1-P_i)^n$$

and

$$\frac{N}{N_0} = P_{E_n} = \left(\frac{E}{E_0}\right)^{-\alpha}$$

$$\alpha = -\frac{\ln(1-P_i)}{\ln(1+\epsilon)} \cong \frac{P_i}{\epsilon}$$

$$\frac{dN}{dE} \propto \left(\frac{E}{E_0}\right)^{-\gamma} \qquad \gamma=\alpha+1$$

$$\left(\frac{dN}{dE}\right)_{Source} \approx E^{-2}$$

$$\left(\frac{dN}{dE}\right)_{Earth} \propto \left(\frac{dN}{dE}\right)_{Source} .\tau_{esc}(E) \propto E^{-2.7}$$

Zwicky conjectures (1933)

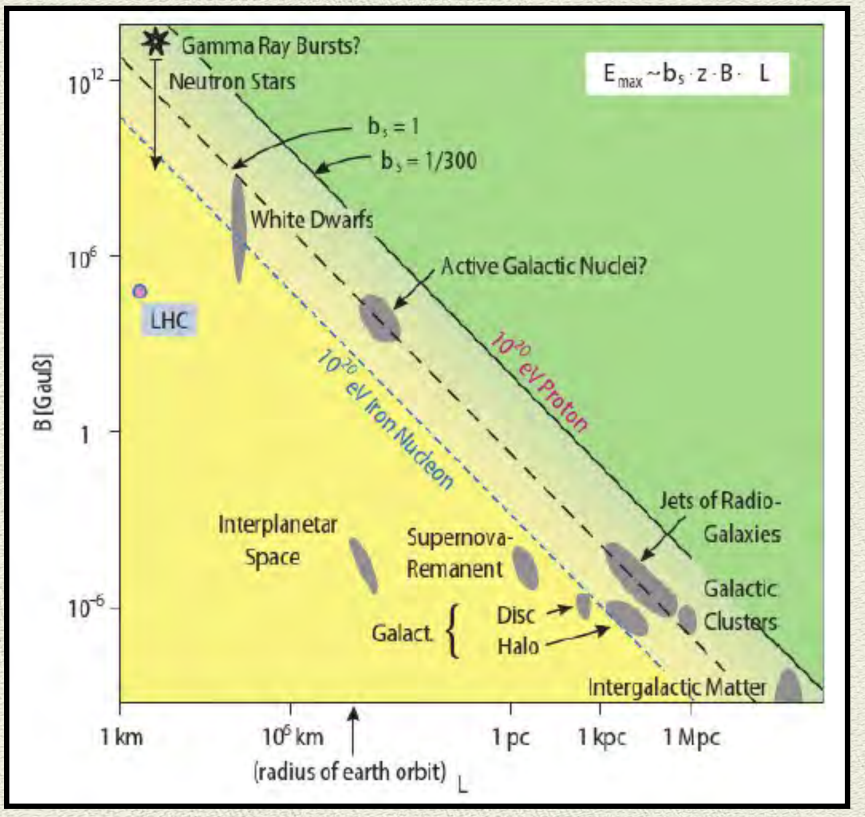
1. Heavy enough stars collapse at the end of their lives into super-novae
2. Implosions produce explosions of cosmic rays
3. They leave behind neutron stars

(Zwicky in1930)

Bottom-up models

Where do they come from?

r_L must be smaller than the dimension of the source L to remain confined.



$$r_L = \frac{E_{15}}{Z B_{\mu G}} [\mathrm{pc}]$$

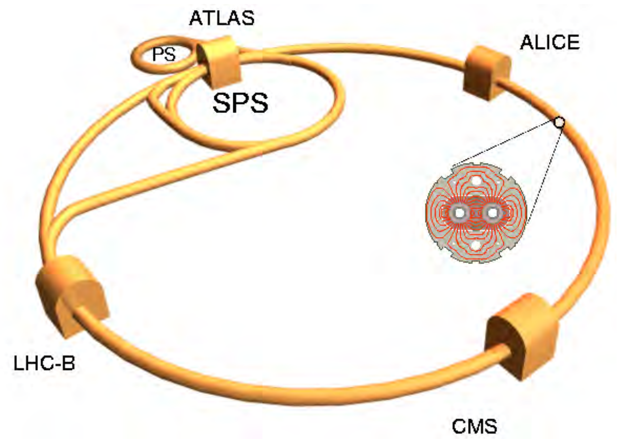
$$E_{max} \simeq ZeBL\beta$$

One should consider also energy losses at the source

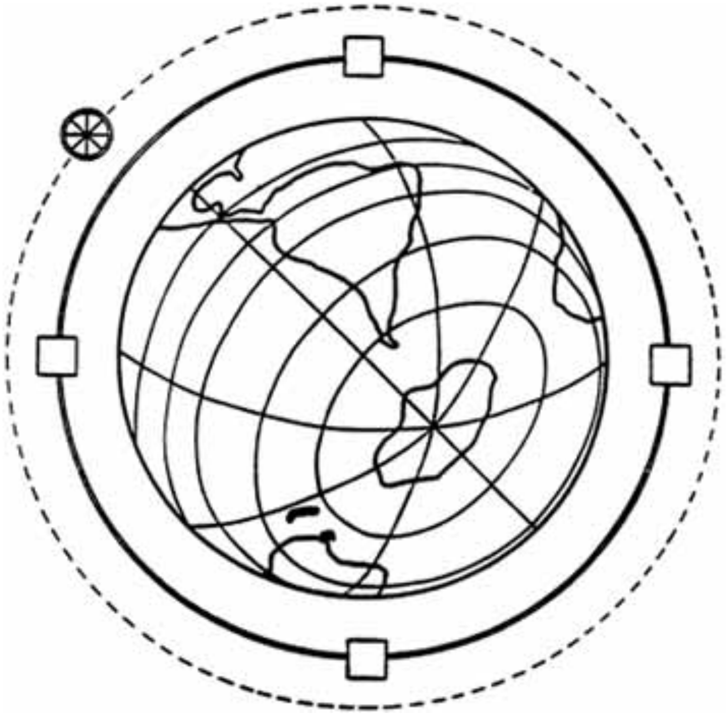
$E = k\,BR$

Whatever is the acceleration mechanism…

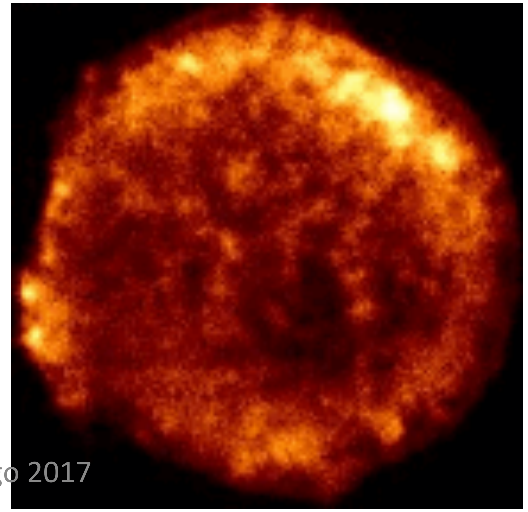
Large Hadron Collider



R ~ 10 km, B ~ 10 T
⇒ E ~ 10 TeV



Tycho SuperNova Remnant

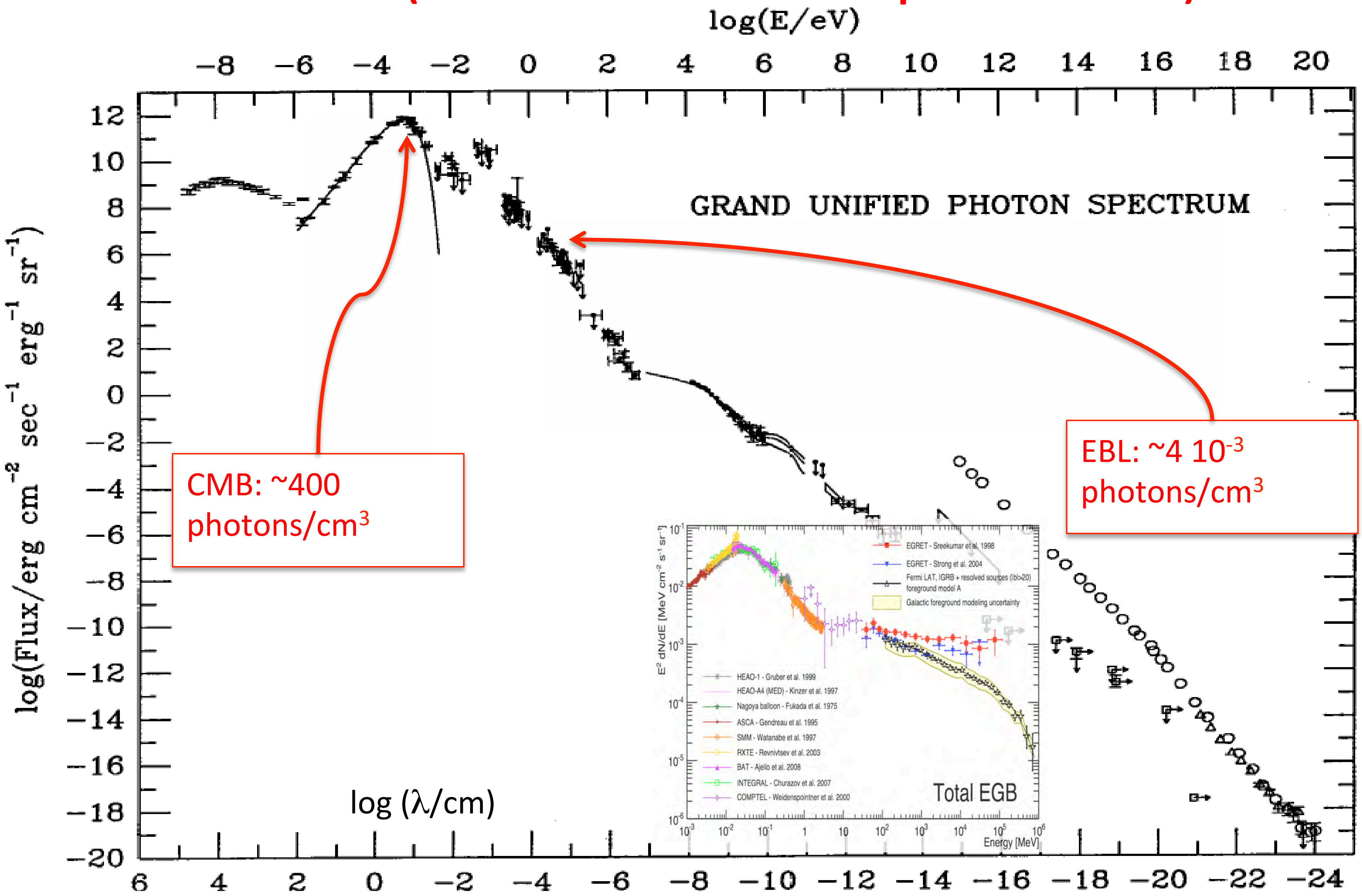


R ~ 10^{15}km, B ~ 10^{-10}T
⇒ E ~ 1000 TeV

The maximum energy possible on Earth is ~ 5000 TeV

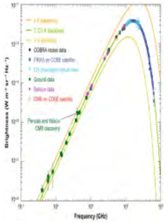
IIb- Production of high energy photons (and neutrinos)

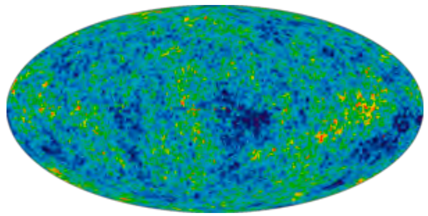
The observed photon spectrum extends over 30 decades (measurements up to 1 TeV)



Thermal radiation: Blackbody Spectra

CMB:
2.7 K



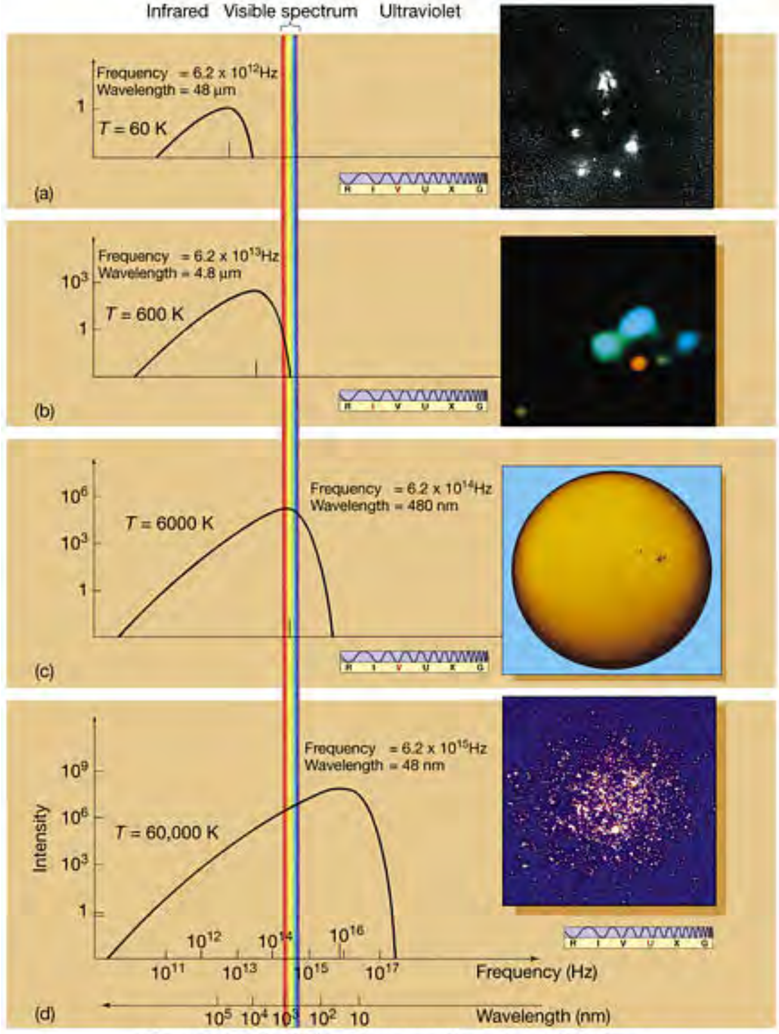


A Galactic gas cloud
60 K

Dim star in the Orion Nebula:
600 K

The Sun:
6000 K

Cluster of very bright stars, Omega Centauri:
60 000 K



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Accretion near BHs: ~ the keV

γ rays: non-thermal Universe

- Particles accelerated in extreme environments interact with medium
  - Gas and dust; Radiation fields – Radio, IR, Optical, …;
    Intergalactic Magnetic Fields, …
- Gamma rays traveling to us!

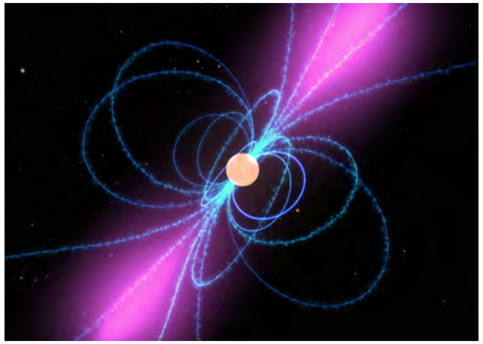
- No deflection from magnetic fields, gammas point ~ to the sources
  - Magnetic field in the galaxy: ~ 3μG
    Gamma rays can trace cosmic rays at energies ~10x
- Large mean free path
  - Regions otherwise opaque can be transparent to X/γ

Studying Gamma Rays allows us to see different aspects of the Universe

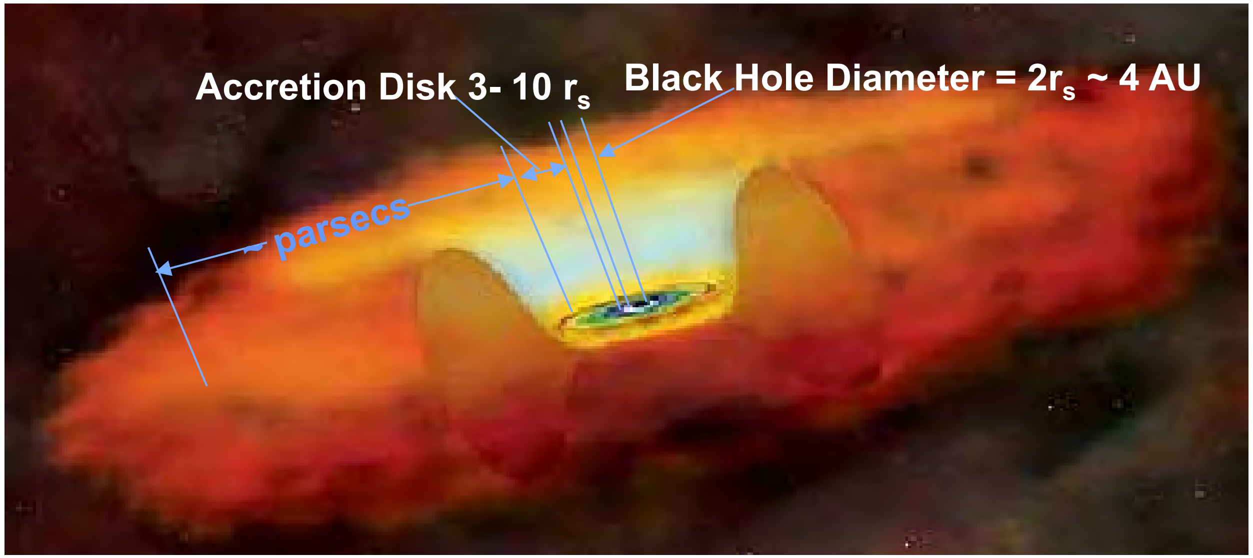
Examples of known extreme environments

GRB

SuperNova Remnants
Pulsars



Active Galactic Nuclei



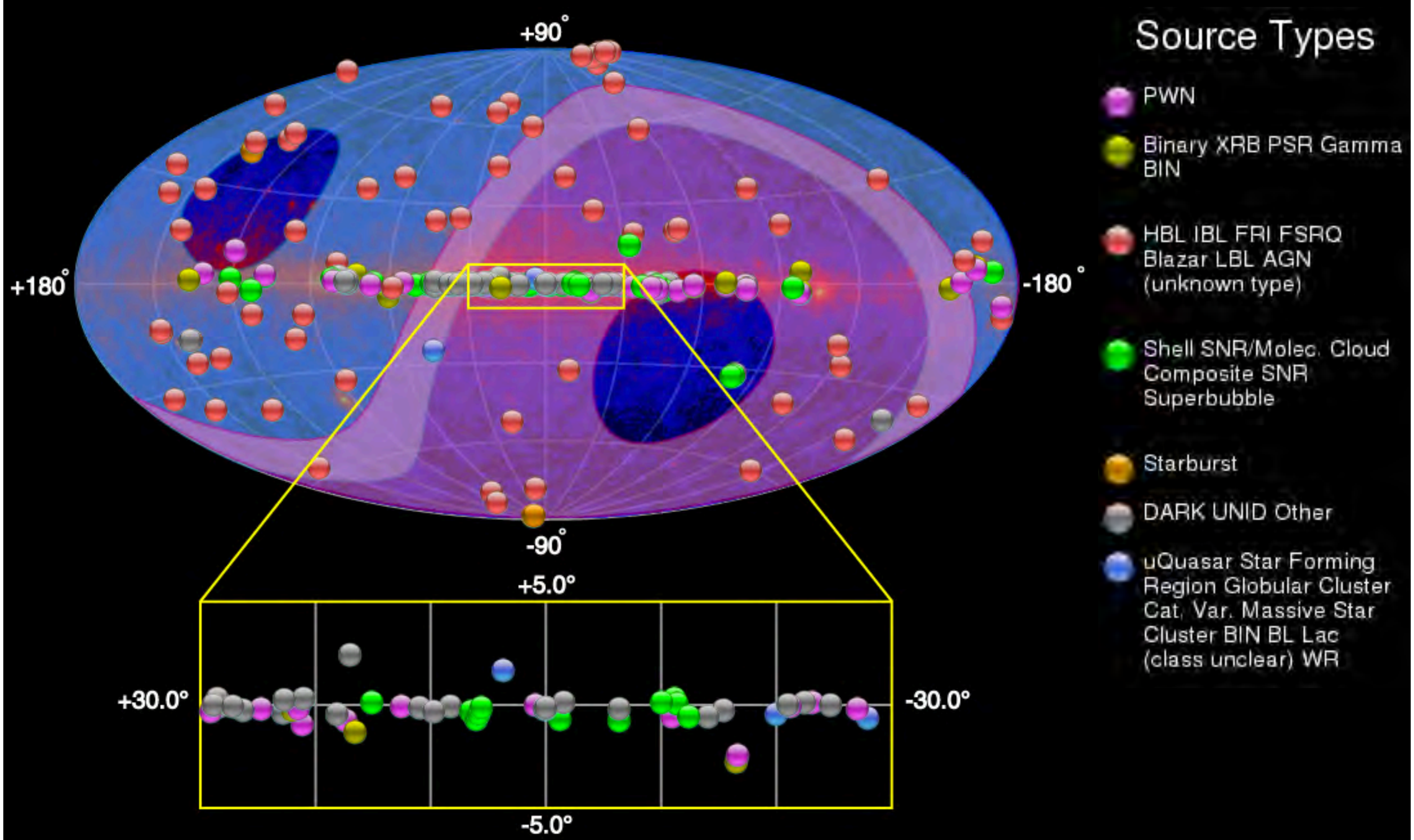
Energies above the thermal regions

- (LE) or MeV : 0.1 (0.03) -100 (30) MeV
- HE or GeV : 0.1 (0.03) -100 (30) GeV
- VHE or TeV : 0.1 (0.03) - 100 (30) TeV
- UHE or PeV : 0.1 (0.03) -100 (30) PeV

- LE,HE domain of space-based astronomy
- VHE+ domain of ground-based astronomy

- When no ambiguity, we call “HE” all the HE and VHE+

>3k HE and >200 VHE photon emitters

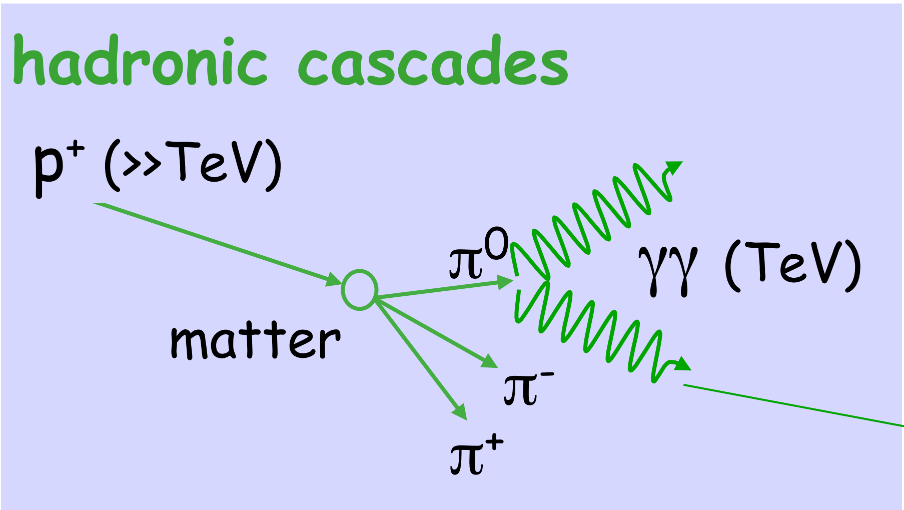


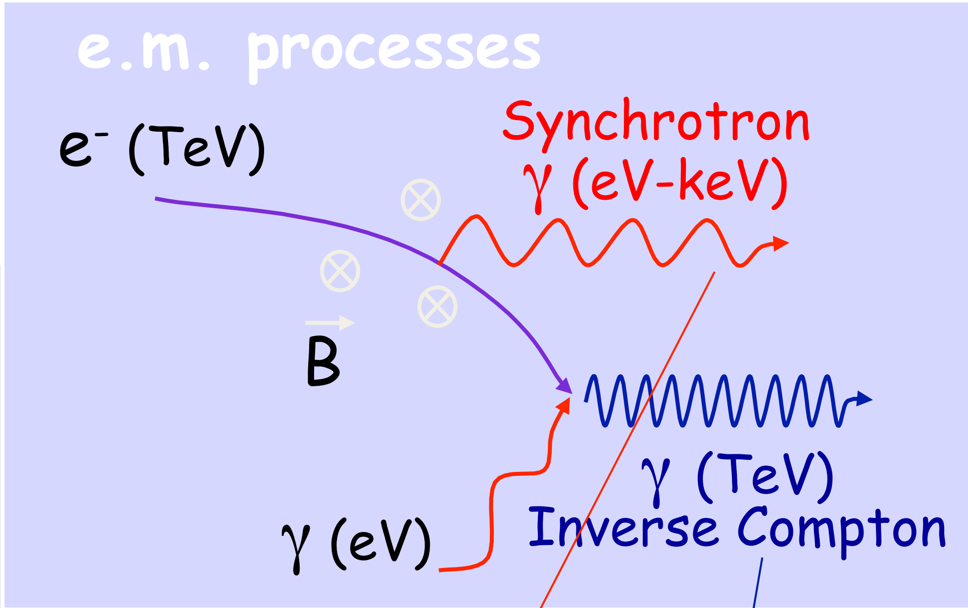
(1) Bottom-up: Interaction of accelerated particles with radiation and matter fields

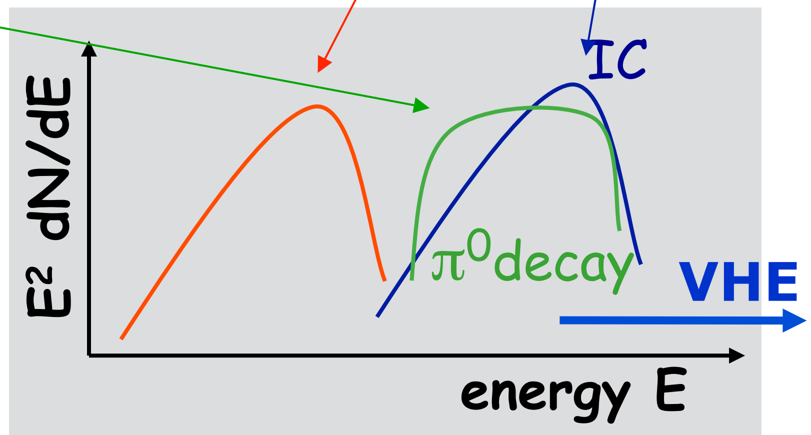
- Gamma-ray production and absorption processes: several but well studied
- These phenomena generally proceed under extreme physical conditions in environments characterized by
  - huge gravitational, magnetic and electric fields,
  - very dense background radiation,
  - relativistic bulk motions (black-hole jets and pulsar winds)
  - shock waves, highly excited (turbulent) media, etc.
- They are related to, and their understanding requires knowledge of,
  - nuclear and particle physics,
  - quantum and classical electrodynamics,
  - special and general relativity,
  - plasma physics, (magneto) hydrodynamics, etc.
  - astronomy & astrophysics

Leptonic and hadronic production of gamma rays

50 TeV gamma-rays hadronically produced track a pupulation of protons of energy ~ 1 PeV



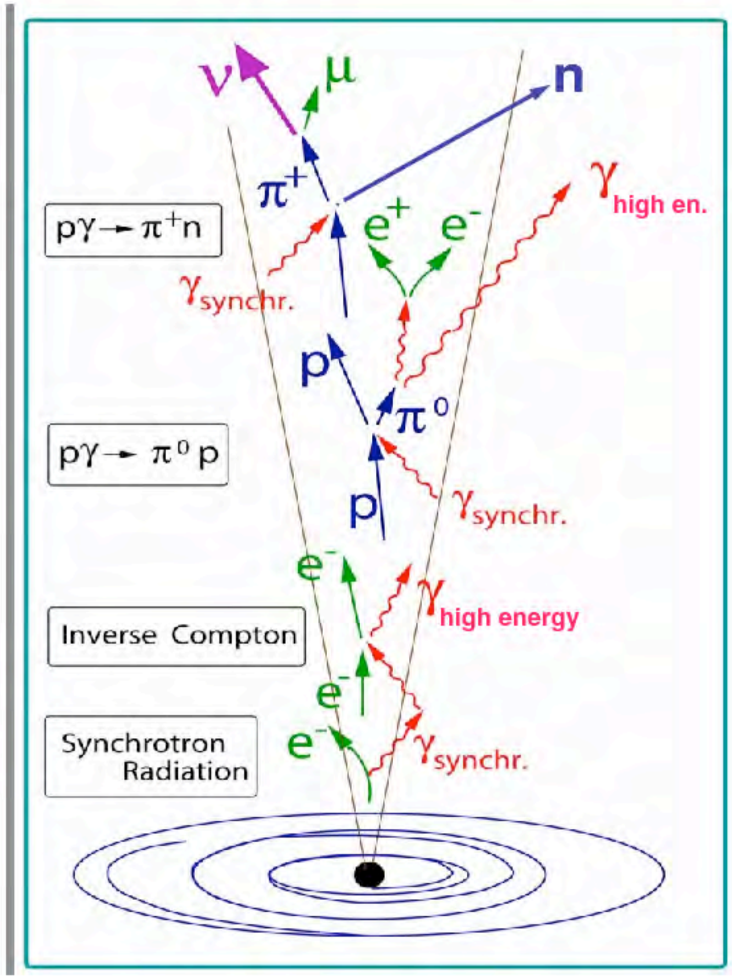




In the VHE region,
$dN/dE \sim E^{-\Gamma}$ (Γ: spectral index)

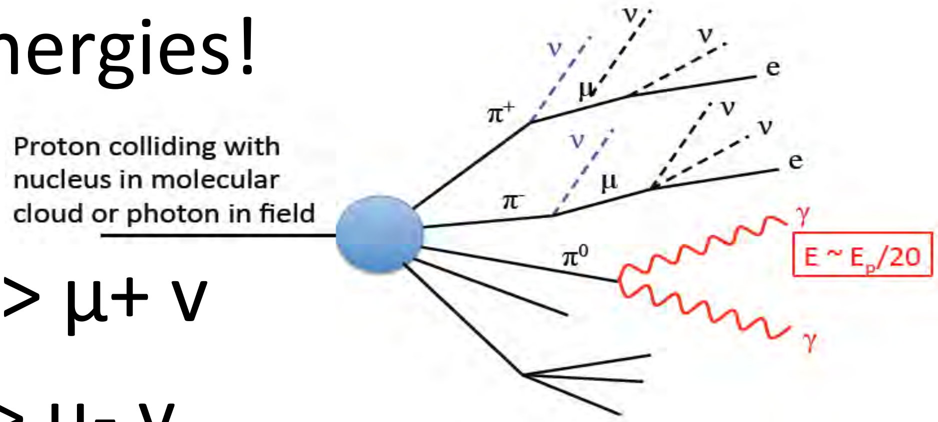
To distinguish between hadron/leptonic origin study Spectral Energy Distribution (SED):
(differential flux) · E^2

The hadronic mechanism is at work also for neutrinos…



In a hadronic process (isospin symmetry)

- N(π+) ~ N(π-) ~ N(π^0) Same energies!

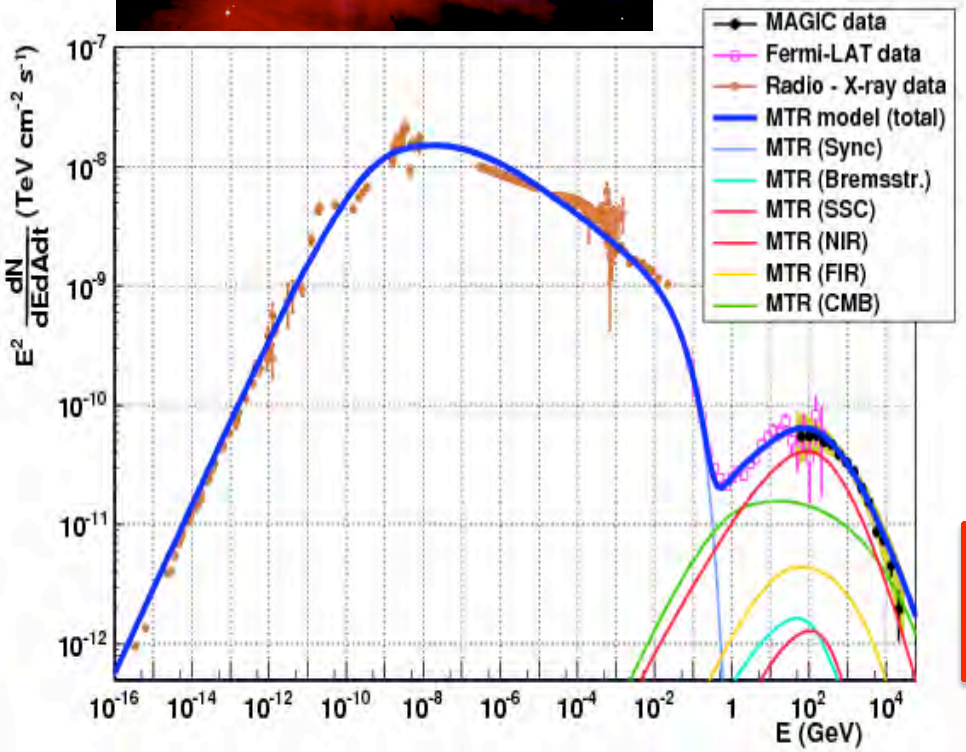


π+ -> μ+ ν

π- -> μ- ν

π^0 -> γγ

A "typical" (V)HE γ source: Crab Nebula

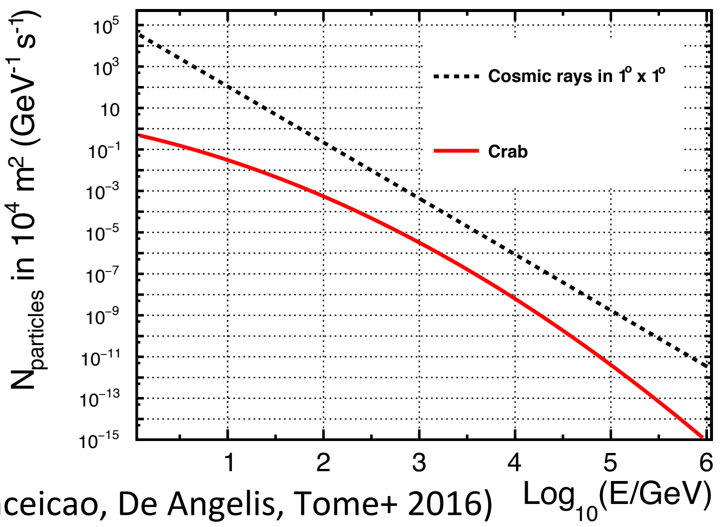


- The Crab Nebula is a nearby (~2 kpc away) PWN and the first source detected in VHE gamma-rays [Weekes 1989].
- It is the brightest steady VHE gamma-ray source, therefore it has become the so-called "standard candle" in VHE astronomy.
  - Recent observation of flares in the GeV range have however shown that occasionally the Crab flux can vary.

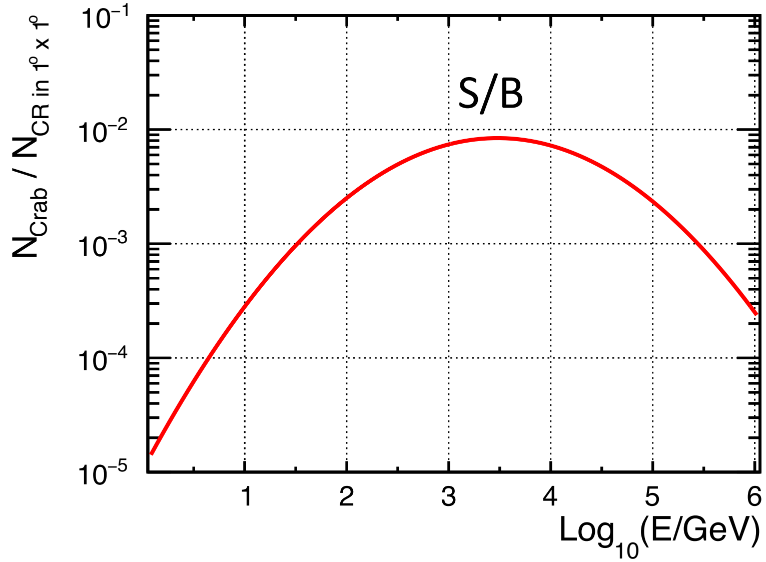
$$\frac{dN_\gamma}{dE} \simeq 3.23 \times 10^{-11} \left(\frac{E}{\mathrm{TeV}}\right)^{-2.47-0.24\left(\frac{E}{\mathrm{TeV}}\right)} \mathrm{TeV}^{-1}\mathrm{s}^{-1}\mathrm{m}^{-2}$$

γ-ray detection: signal vs. background

- Is Crab Nebula easy to detect?
- Suppose to have a 100 x 100 m^2 detector with a resolution of 1 square degree:



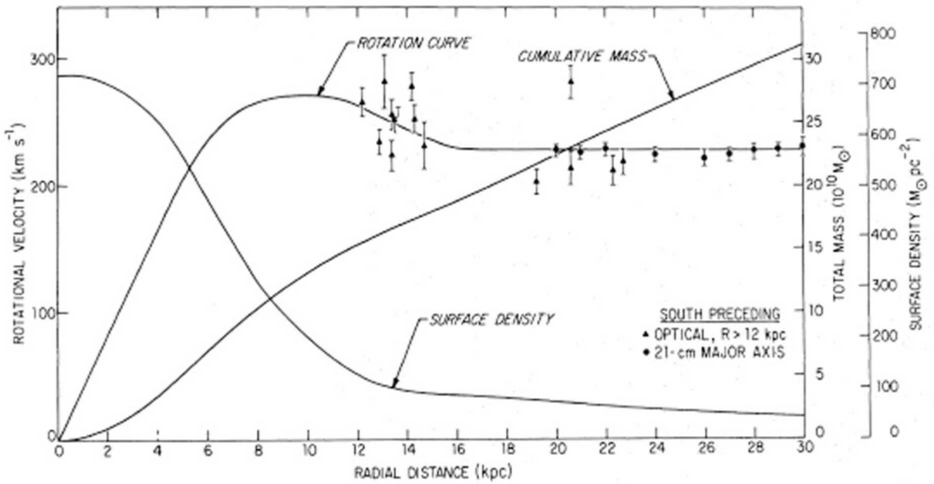
Conceicao, De Angelis, Tome+ 2016)



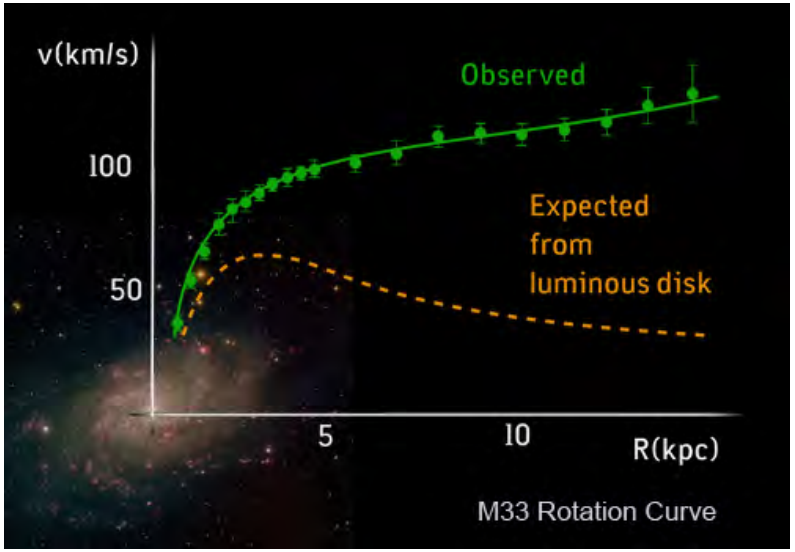
Conclusion: you need large effective area, good angular resolution, proton rejection

(2) Top-down: are there new (heavy) particles which can produce HE photons?

- Rotation curves of spiral galaxies



  – flat at large radii: if light traced mass we would expect them to be Keplerian at large radii, $v \propto r^{-1/2}$, because the light is concentrated in the central bulge
    - and disc light falls off exponentially
    - Zwicky had already noted in 1933 that the velocities of galaxies in the Coma cluster were too high to be consistent with a bound system
    - Observed for many galaxies, including the Milky Way



The currently favored solution

To assume that in and around the Galaxies there is

Dark Matter

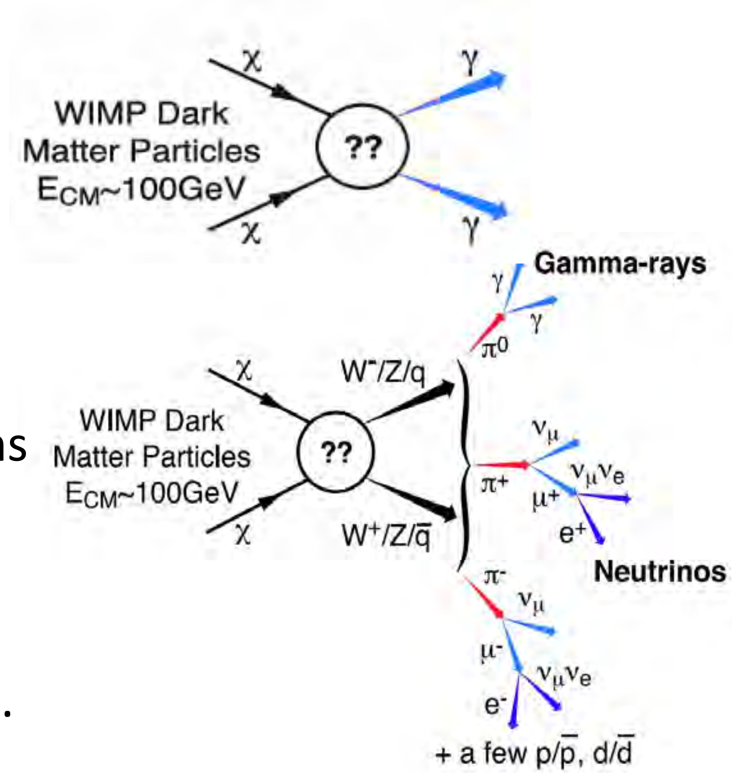
subject to gravitational interaction but no electromagnetic interaction

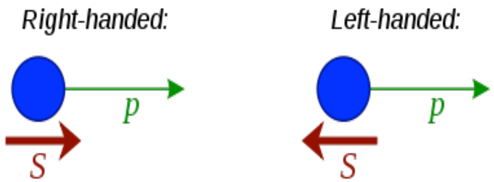
$$M(r) \propto r \Rightarrow v_{rot} = \sqrt{\frac{GM(r)}{r}} = const.$$

– Must be "cold", i.e., non-relativistic (it is trapped by the gravitational field), and "weakly" interacting: WIMP
– The hypothesis is not odd: remember that the existence of Neptune was suggested on the basis of the irregular motions of Uranus
– How much DM do we need? results to be <u>5 times more than luminous matter (astrophysics, evolution of the Universe)</u>

How do WIMPs produce photons?

- The energy “blob” from χχ annihilation might decay:
  - Directly into 2γ, or into Zγ if kinematically allowed. Clear experimental signature (photon line), but not very likely (requires one loop). In SUSY, the BR depends on what is the lightest neutralino composition.
  - Into a generic f-fbar pair, then generating a hadronic cascade with π^0 decaying into photons in the final state. Remind that flavors are left-handed and anti-flavors are right-handed with amplitude $[1+|p|/(E+m_f)]/2 \sim v/c$, and in this case for an s-wave you need to “force” one of the decay products to have the “wrong” elicity.





$$M_{fi} \propto \frac{1}{2}\left(1 - \frac{|p|}{E + m_f}\right) = \frac{m_f}{2m_\chi + m_f}$$

=> The χχ pair will prefer to decay into the heaviest available pair – i.e., if 20 GeV < m_χ < 80 GeV, into b-bbar

III- Propagation

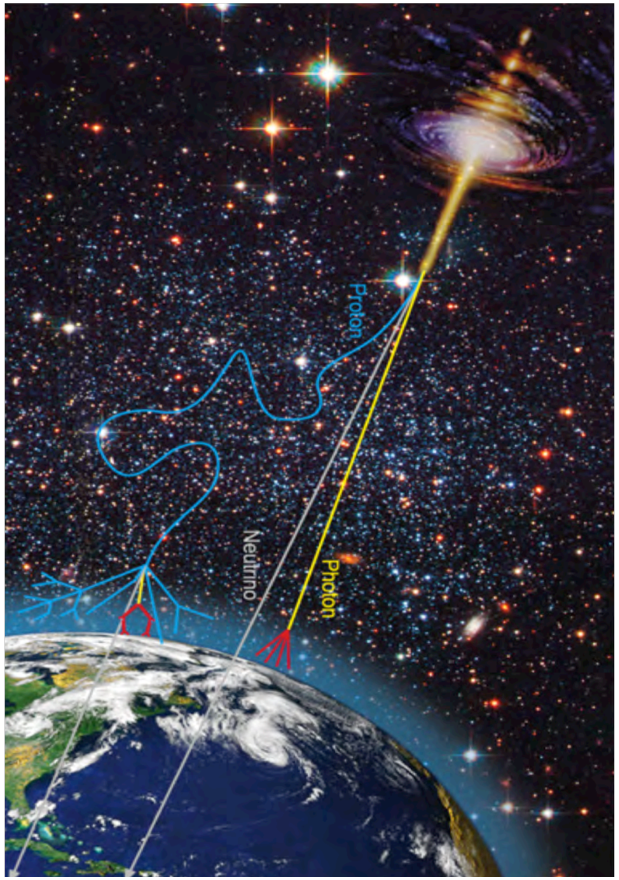
Propagation of charged CR in the Universe

- Gyroradius

  B in the Galaxy: a few μG; outside the Galaxy: 1nG > B > 1 fG

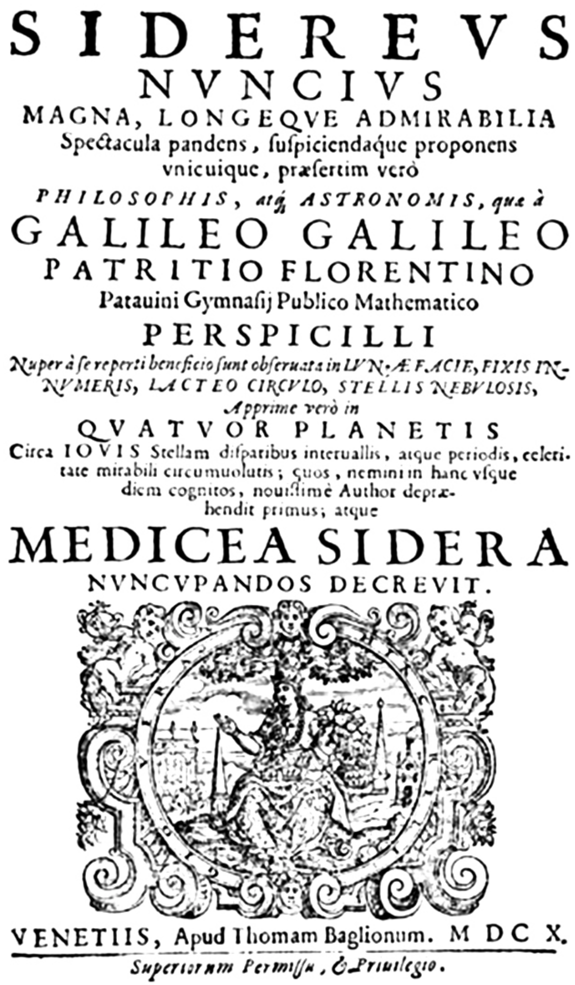
$$\frac{r}{1\ \text{pc}} \cong \frac{\frac{E}{1\ \text{PeV}}}{\frac{B}{1\ \mu\text{G}}}$$

- If you want to look at the GC (d ~ 8 kpc) you need E > 2 10^{19} eV
  - But only 1 particle / km^2 / year
  - *And no galactic emitters expected at this energy*
- But in principle one could look outside the galaxy, were B is smaller and there are SMBHs…
  - *No: the resonant interaction with the CMB (GZK effect) provides a cutoff at E ~ 10^{19} eV*
- Conclusion: extremely difficult to use charged CR for astrophysics



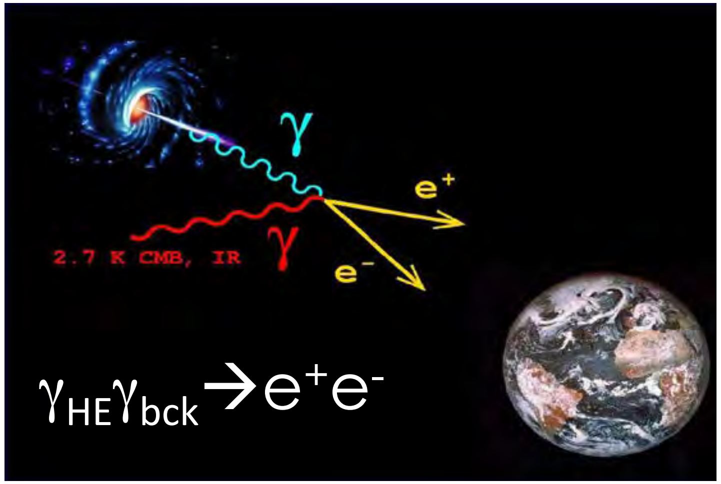
Neutral messengers must be used for astronomy & astrophysics

- Neutrinos: very difficult to detect due to the small interaction cross section (despite a km^3 detector in Antarctica, the only cosmic sources localized up to now are SN1987A, the Sun, and the Earth)
  - <10 neutrinos per year from astrophysical sources identified by IceCube (1km^3)!
- Gravitational waves: just started
- Photons: they have a long tradition in astronomy since millennia... And they are the "starry messangers" by default since 1610 at latest...


SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Nuper à se reperti beneficio sunt observata in LVNÆ FACIE, FIXIS INNVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeritate mirabili circumuolutis; quos, nemini in hanc vsque diem cognitos, nouissimè Author depræhendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.
VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permissu, & Priuilegio.

IIIa- Propagation of photons

Attenuation of γ–rays

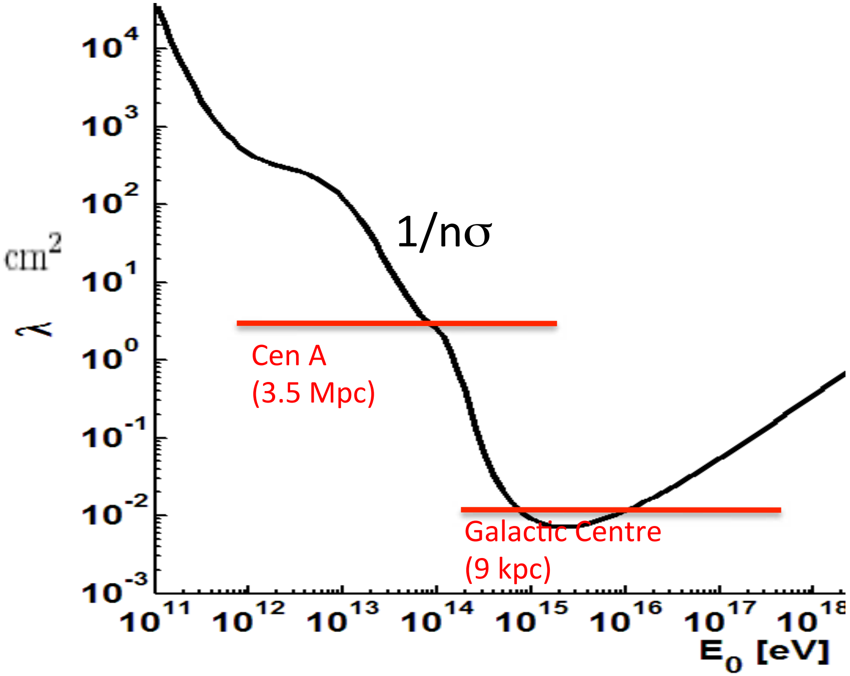


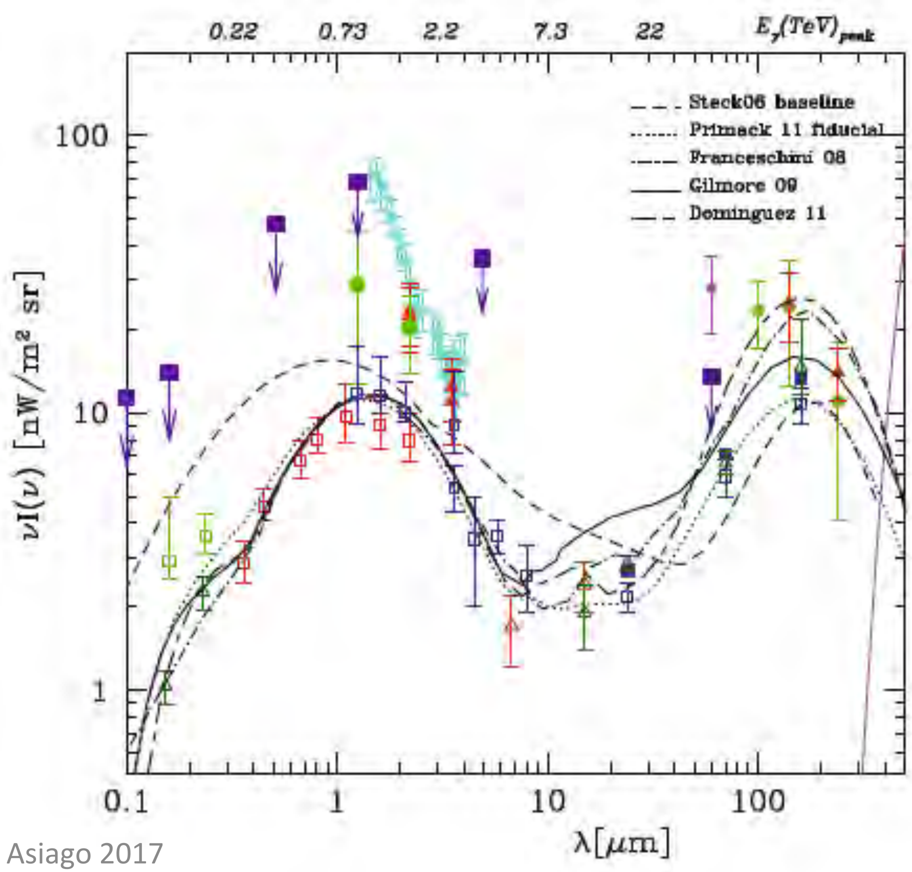
- γ-rays are effectively produced in EM and hadronic interactions
  - Energy spectrum at sources E^{-2}
- are effectively detected by space- and ground-based instruments
- effectively interact with matter, radiation ($\gamma\gamma \rightarrow e^+e^-$) and B-fields
- The interaction with background photons in the Universe attenuates the flux of gamma rays
- The "enemies" of VHE photons are photons near the optical region (Extragalactic Background Light, EBL)

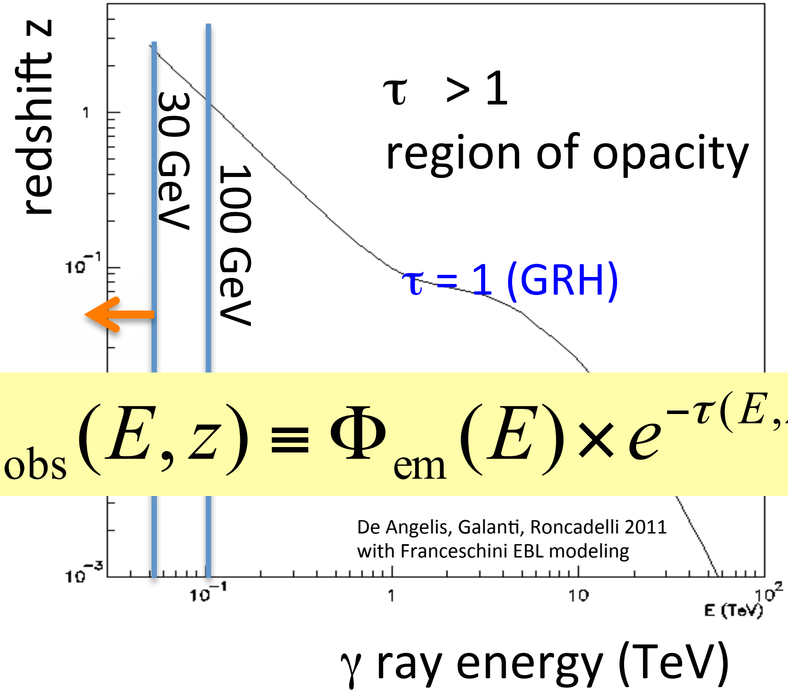
$$\gamma_{VHE}\gamma_{bck} \rightarrow e^+e^-$$

$\sigma(\beta)$ ~ $$1.25 \cdot 10^{-25}(1-\beta^2)\cdot\left[2\beta(\beta^2-2)+(3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right]\ \mathrm{cm}^2$$

Max for: $$\epsilon \simeq \frac{2m_e^2c^4}{E} \simeq \left(\frac{500\ \mathrm{GeV}}{E}\right)\mathrm{eV}$$



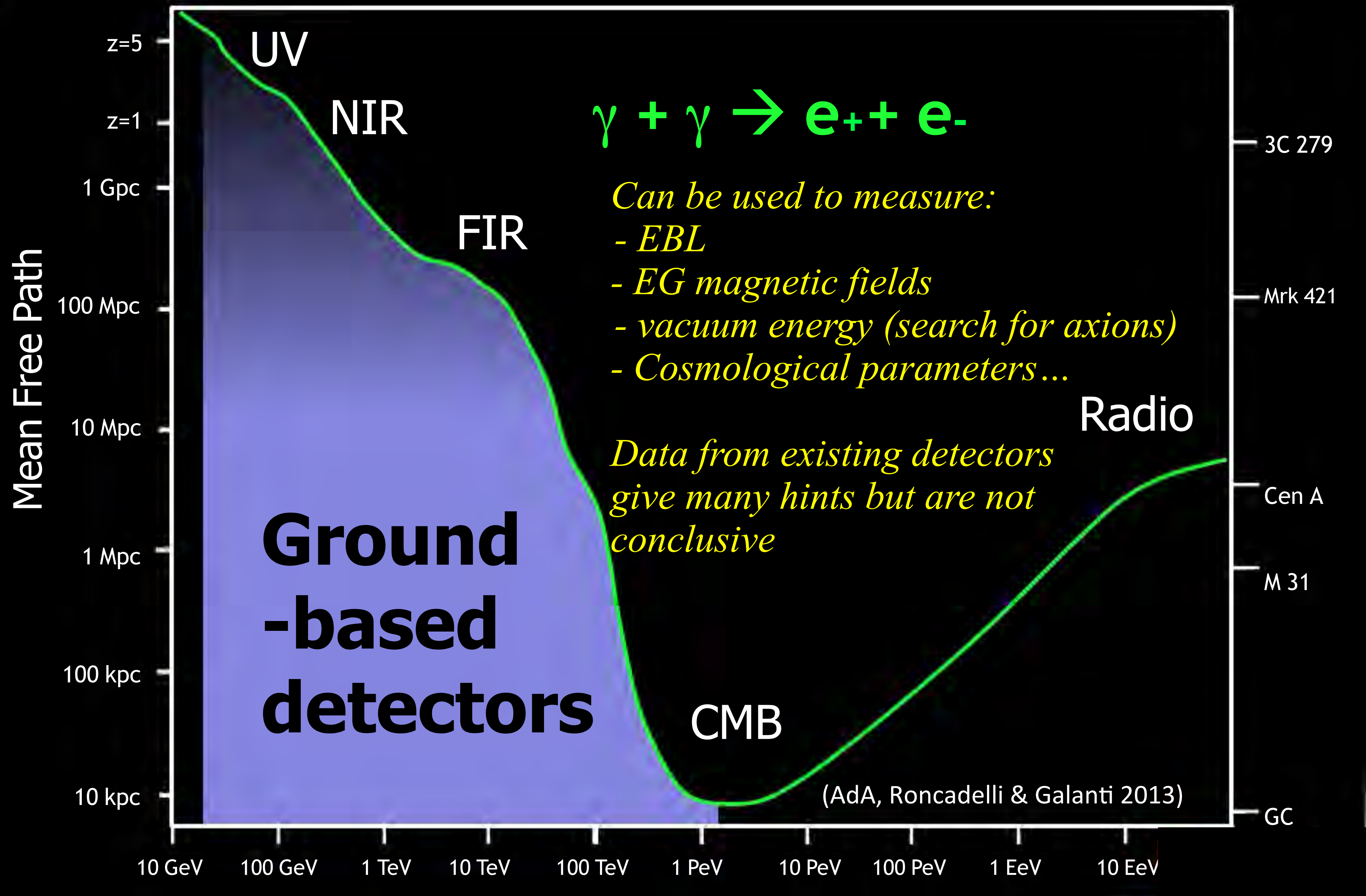




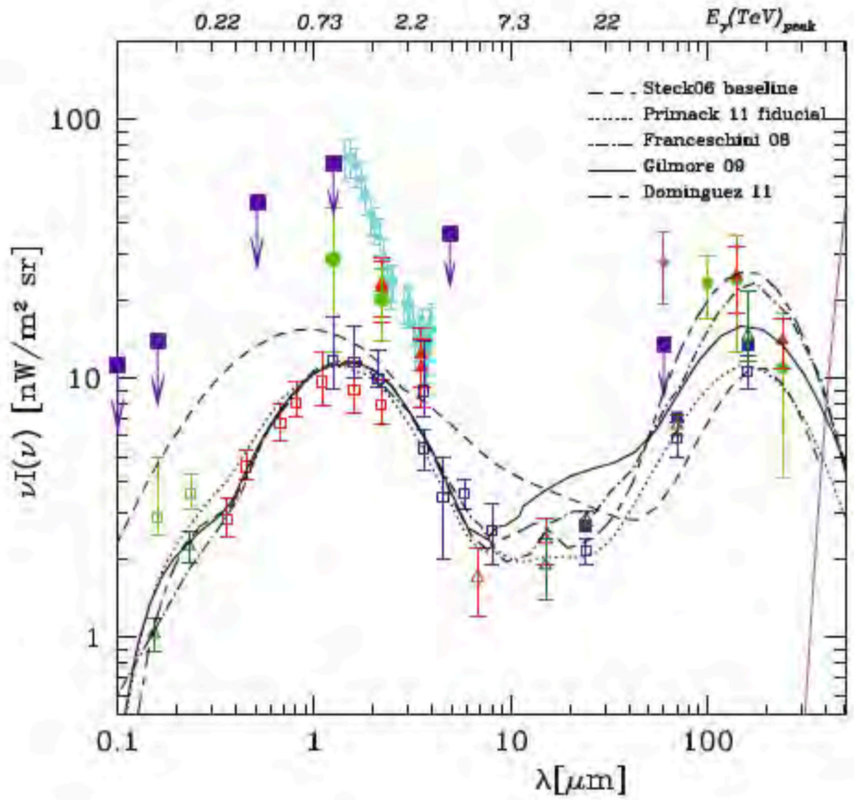
$$\Phi_{obs}(E,z) \equiv \Phi_{em}(E)\times e^{-\tau(E,z)}$$

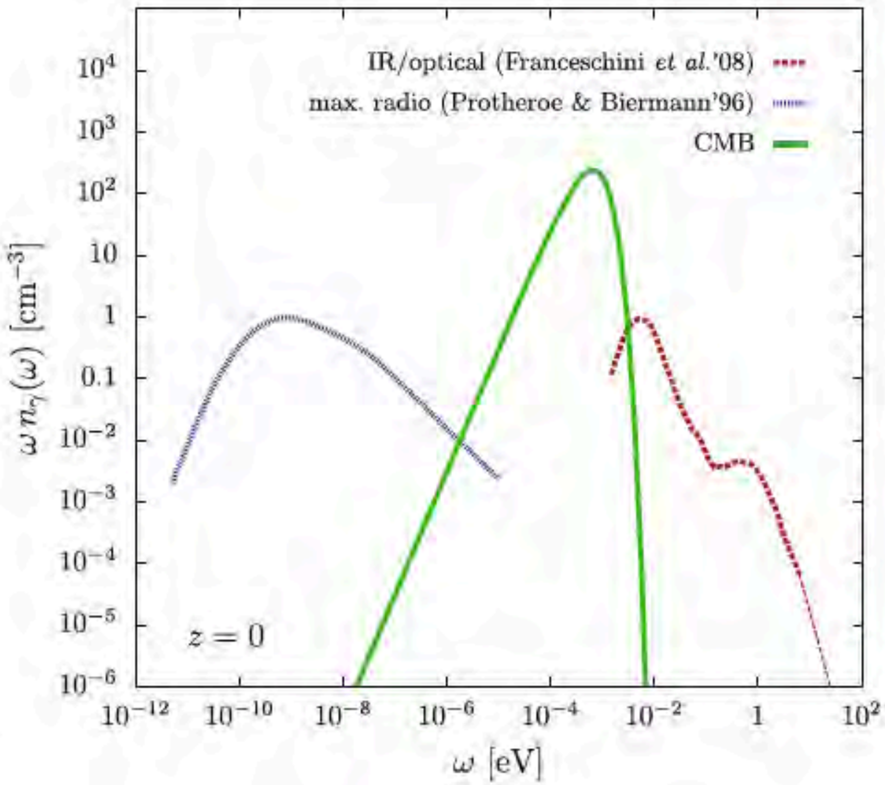
- The diffuse extragalactic background light (EBL) is all the accumulated radiation in the Universe due essentially to star formation processes
- This radiation covers a wavelength range between ~0.1 and 600 μm (consider the redshift and the reprocessing)
- After the CMB, the EBL is the second-most energetic diffuse background
- The understanding of the EBL is fundamental
  - To know the history of star formation
  - To model VHE photon propagation for extragalactic VHE astronomy. VHE photons coming from cosmological distances are attenuated by pair production with EBL photons. This interaction is dependent on the SED of the EBL.
- Therefore, it is necessary to know the SED of the EBL in order to study intrinsic properties of the emission in the VHE sources.

The γ horizon: nuisance and resource



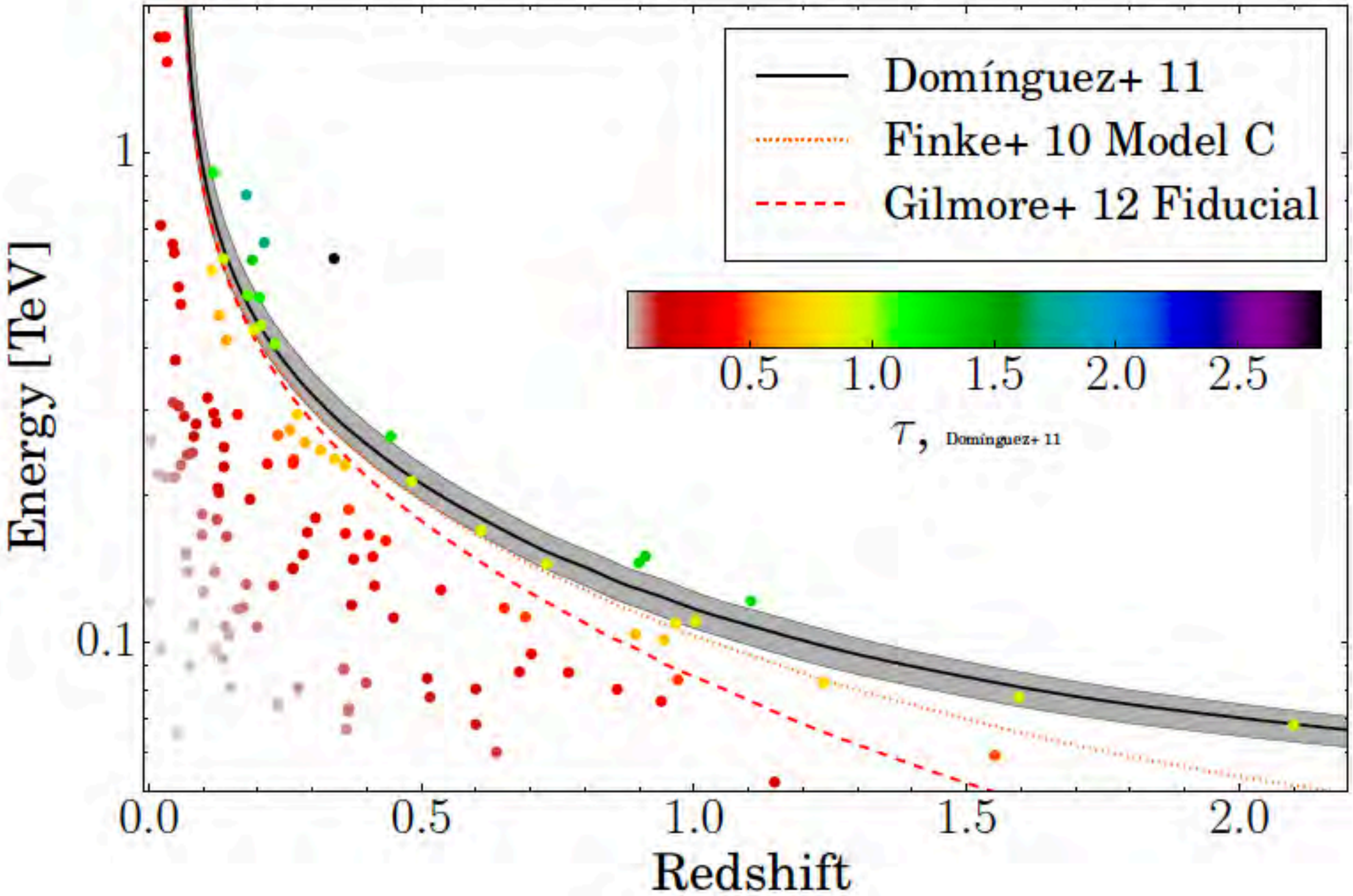
EBL



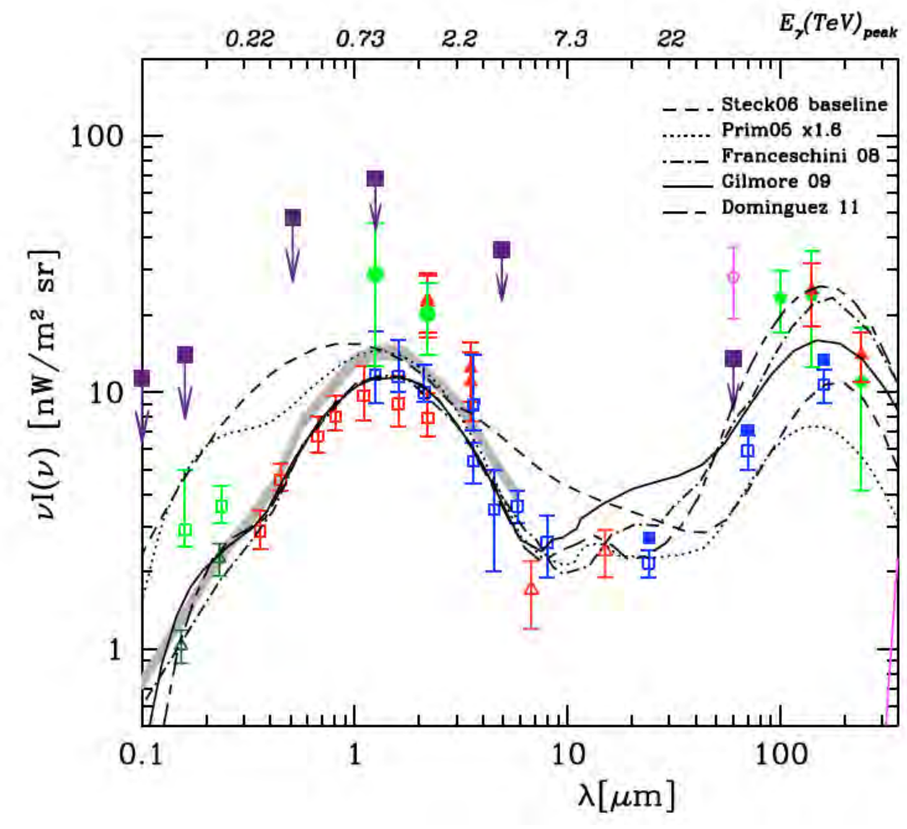


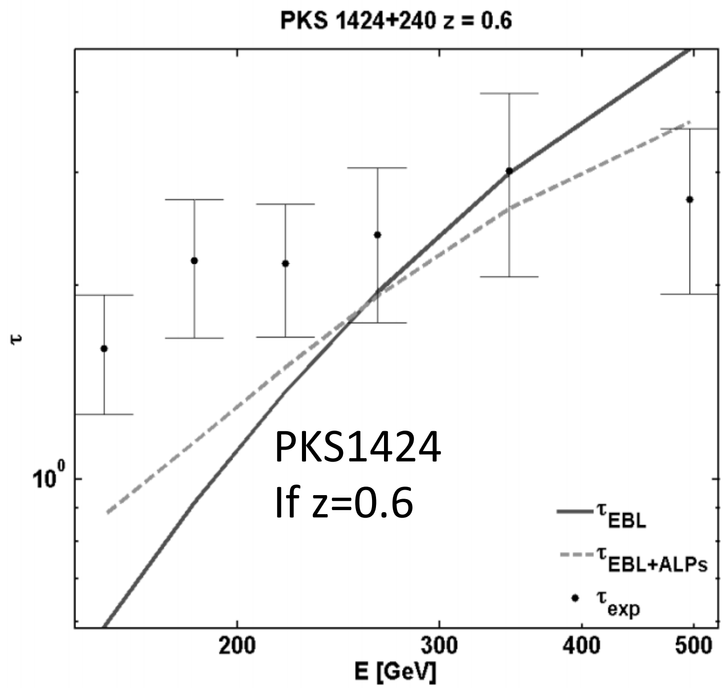
The EBL affects in particular the signal from extragalactic sources

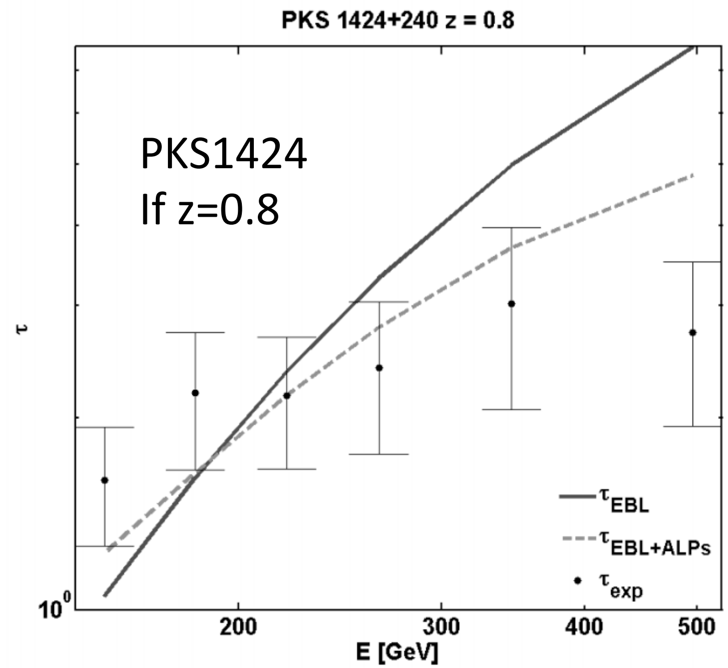
Fermi 2FHL and gamma horizon



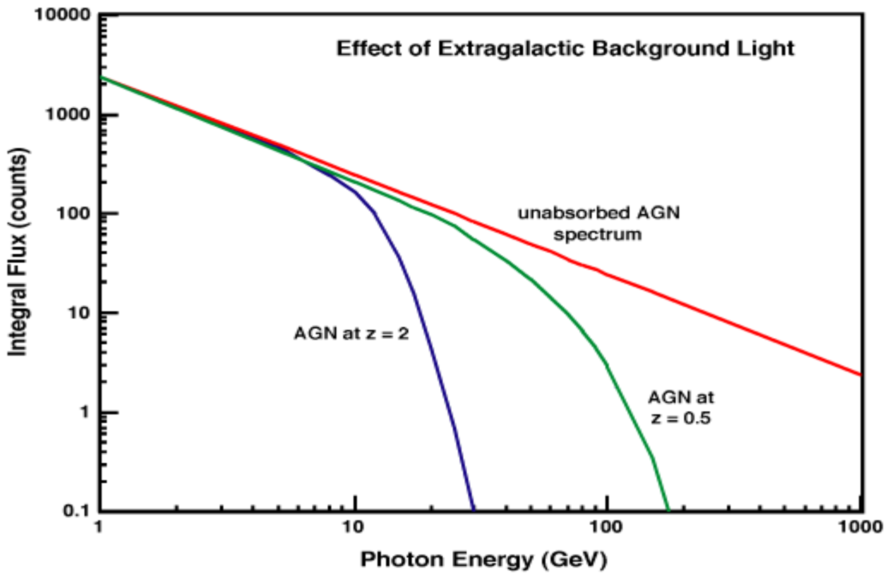
A reminder: EBL rather well constrained, and SED extrapolation from Fermi is possible

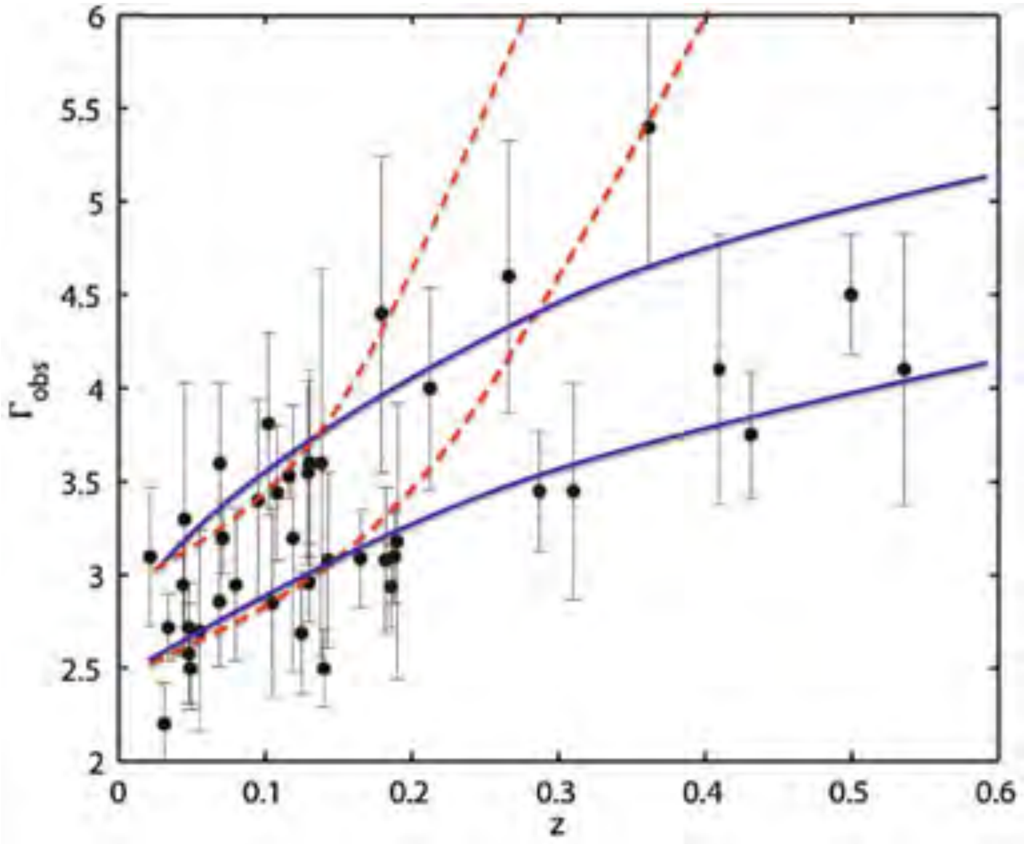






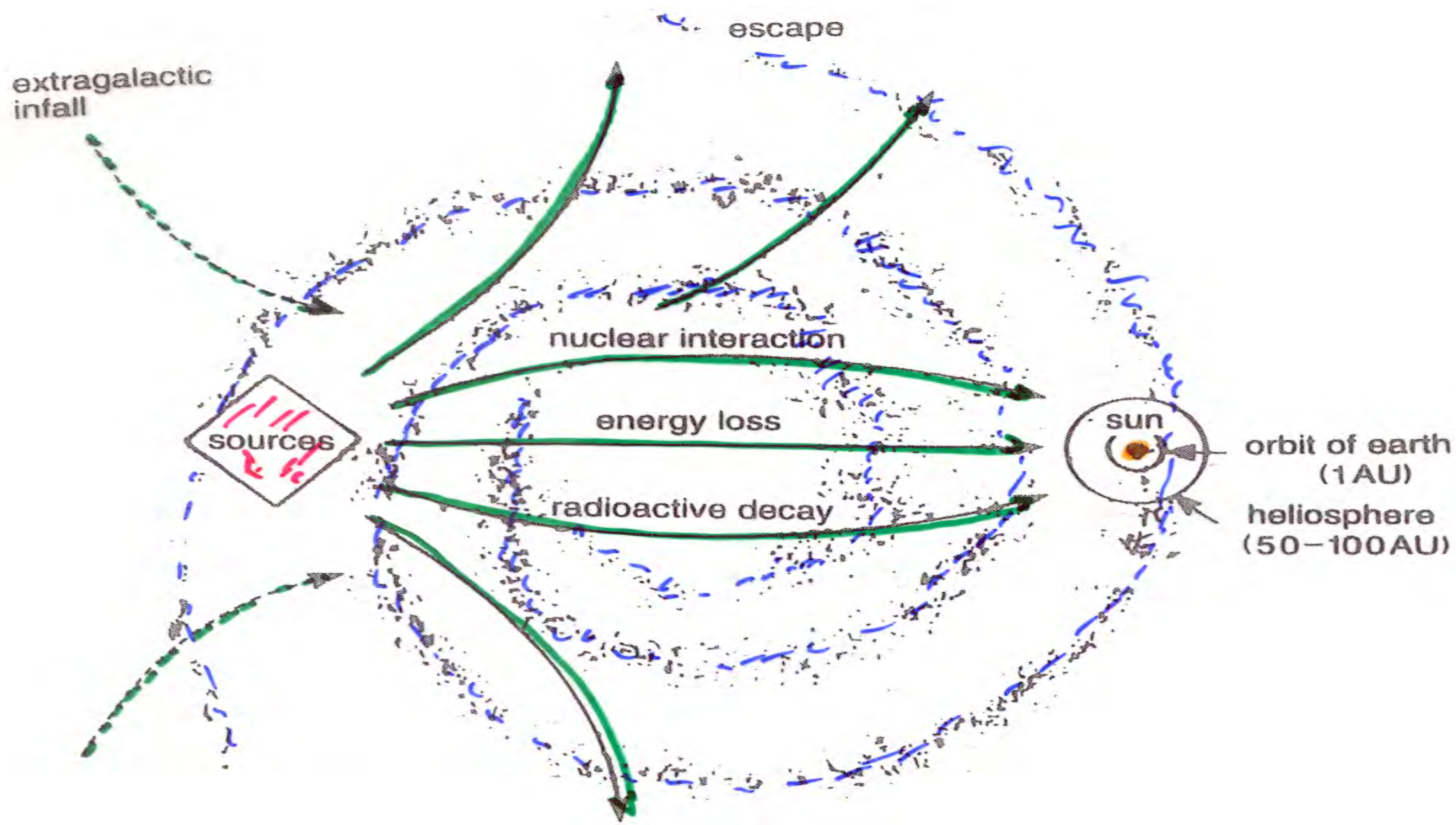
Spectral index of AGN



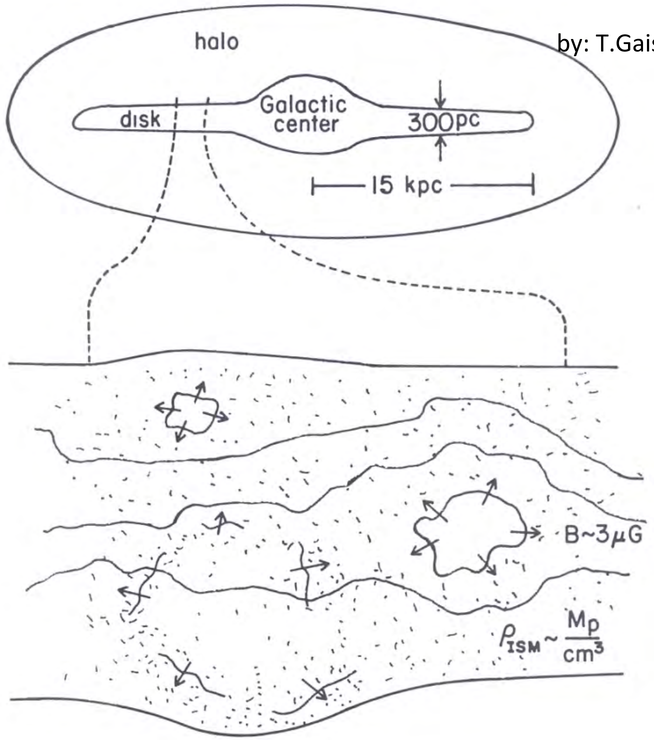


IIIb- Propagation of charged particles

The propagation in our galactic



Propagation



by: T.Gaisser

Charged cosmic rays diffuse and interact in the Galactic randomly magnetized ISM . Confinement times are quite long ($\tau \sim 10^7$ years) and directions become basically isotropic.

Transport equation :

$$\frac{\partial N_i}{\partial t} = Q_i + \vec{\nabla} \cdot \left(D\, \vec{\nabla} N_i - \vec{V} N_i \right) + \frac{\partial}{\partial E} \left(b(E) N_i \right) - \frac{N_i}{\tau_i} + \sum_{j>i} \frac{P_{ji} N_j}{\tau_j}$$

Sources

Diffusion

Convection

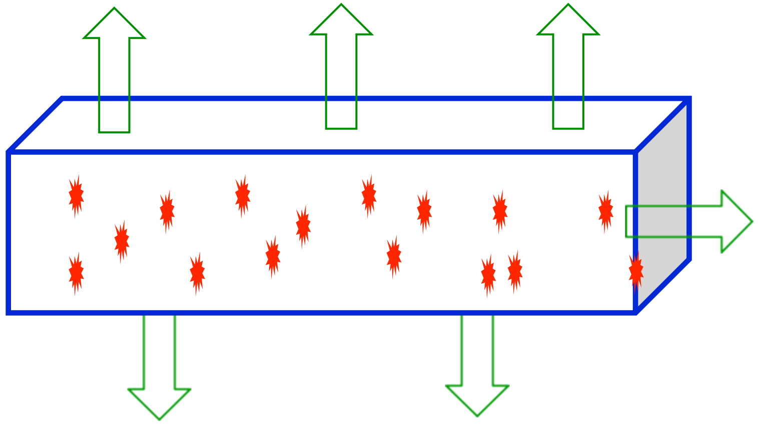
Energy gains and losses

Spallation and decay losses

Spallation gains

Leaky-Box

A box where charged cosmic rays freely propagates having however some probability to escape by the walls. The sources are uniformely distributed.



Simplified stationary equation :

$$0 = Q_i + \sum_{j>i} N_j \left\{ \rho\beta c\, \sigma_{ji}^{spall} + \frac{1}{\gamma\tau_{ji}^{decay}} \right\} - N_i \left\{ \rho\beta c\, \sigma_{i}^{spall} + \frac{1}{\gamma\tau_{i}^{decay}} + \frac{1}{\tau_{i}^{esc}} \right\}$$

Sources

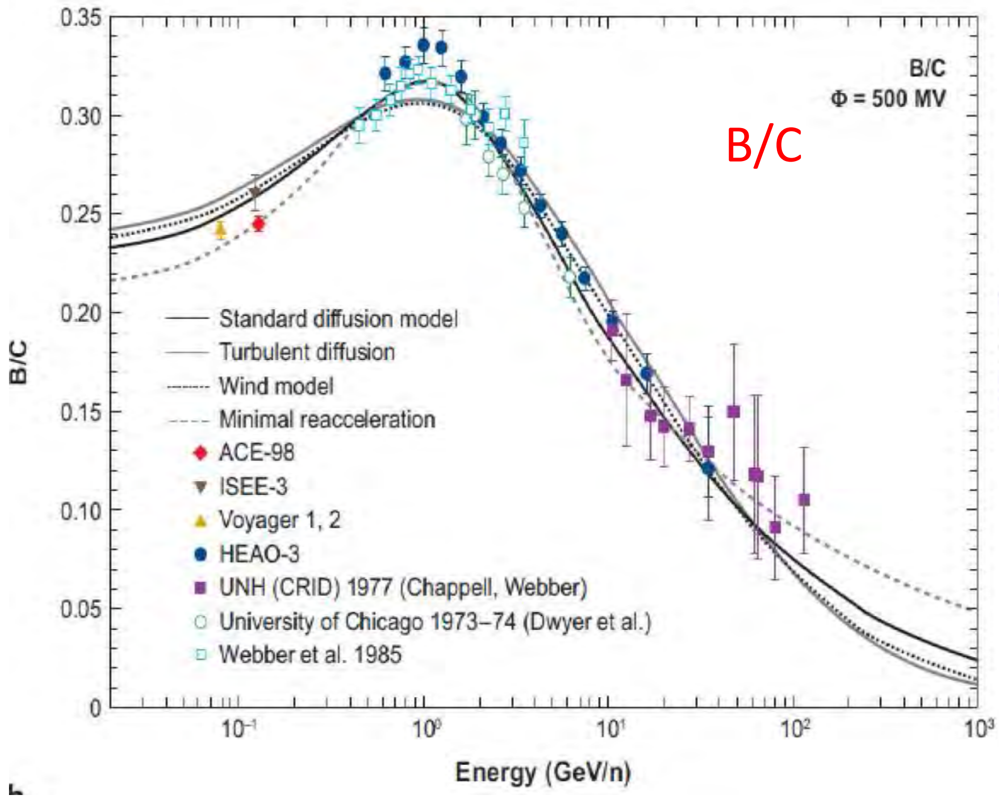
Spallation and decays gains

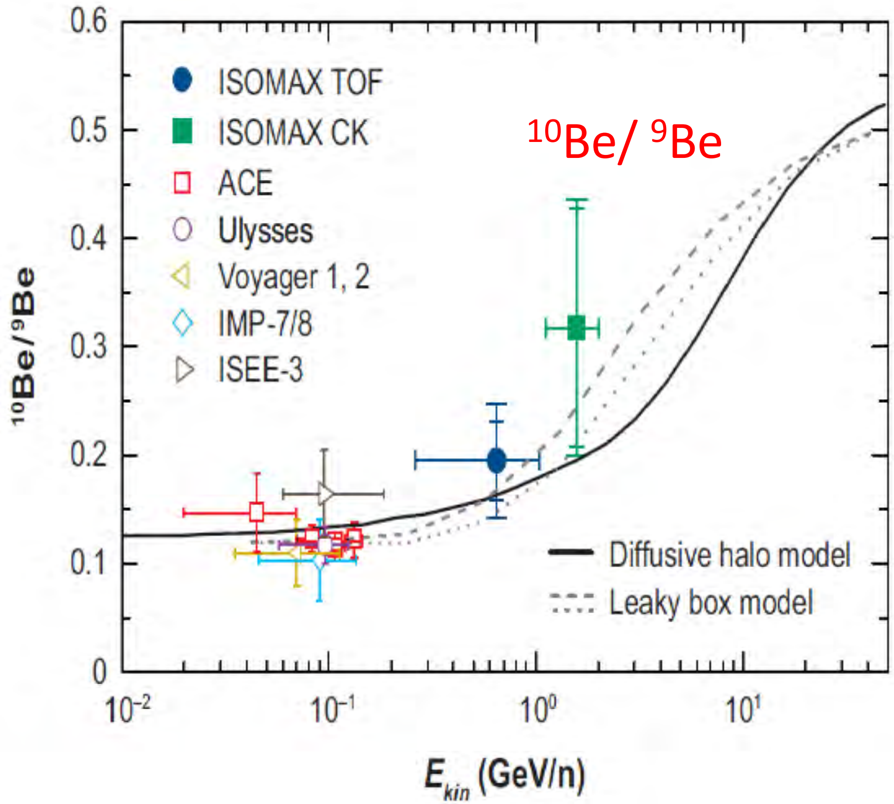
Spallation, decays and escape losses

Constraining propagation models

Secondary/primary ratios

Unstable/stable isotopos



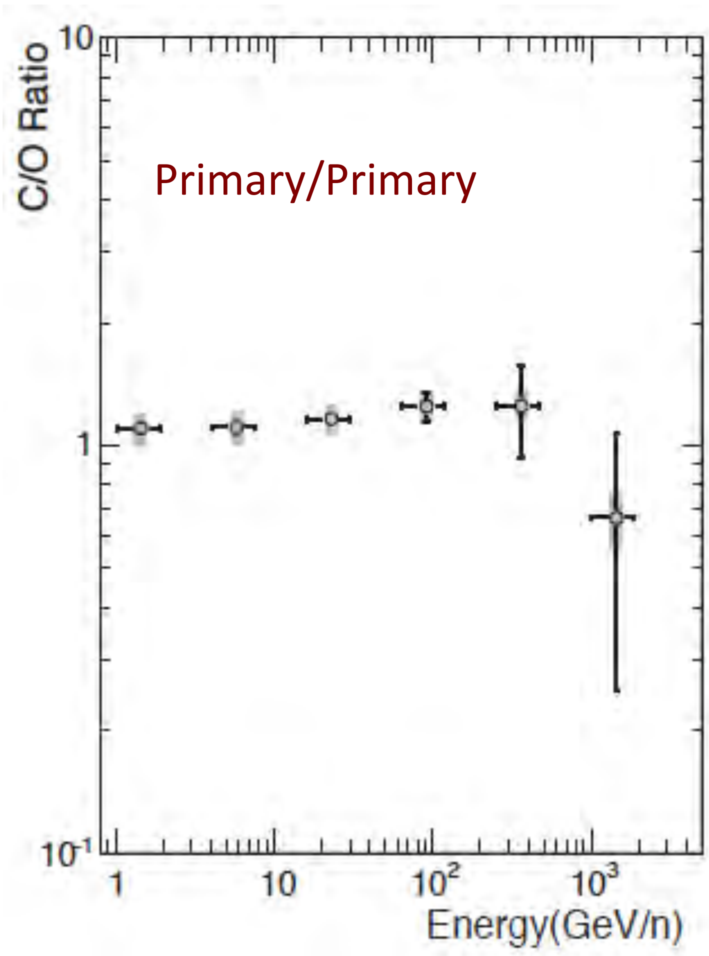


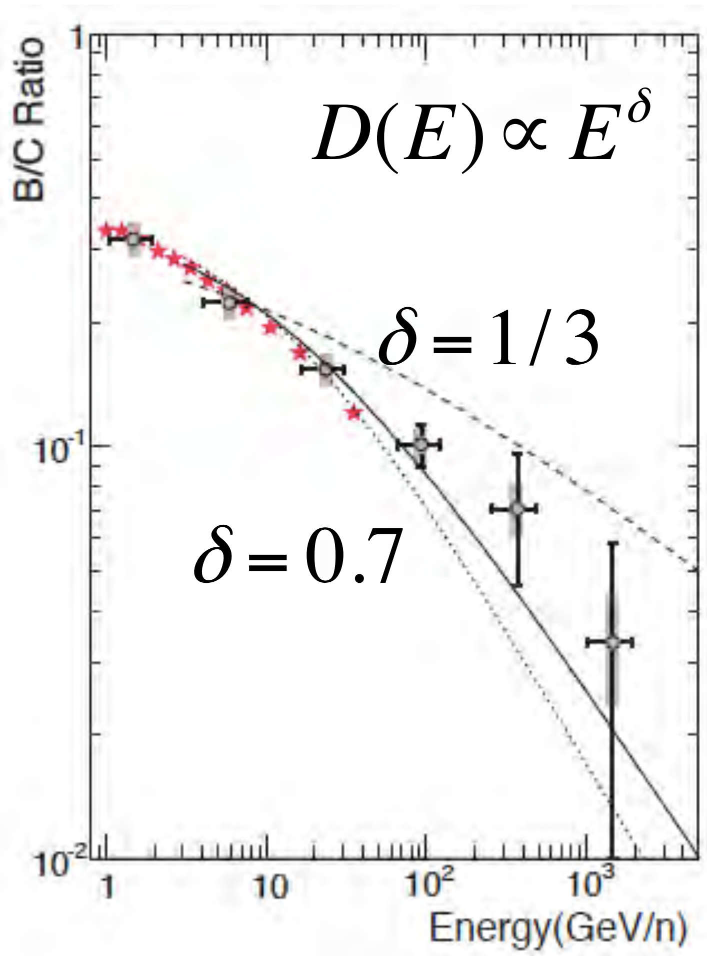
Box size, Diffusion coef., escape time, ...

Radioactive clocks

Energy dependence (τ_{sc})

CREAM 2008





Confinement and composition

Magnetic Field:

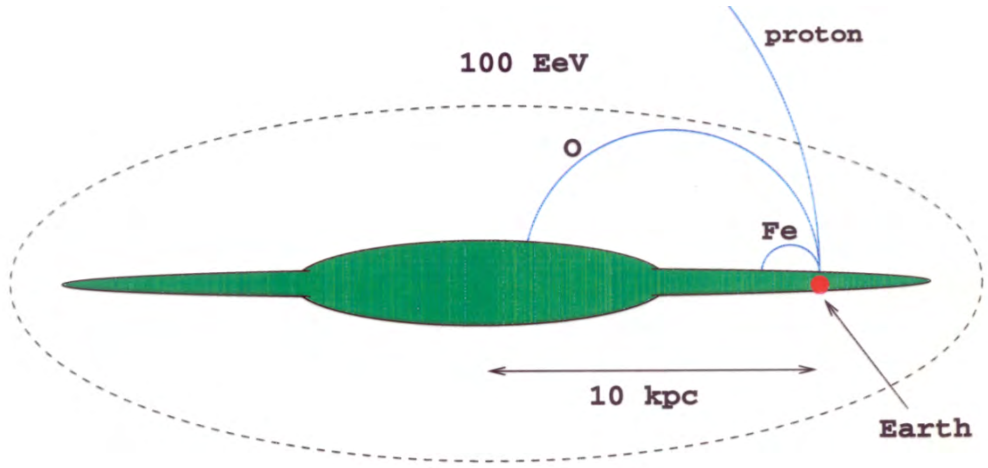
Galactic ~ 1-3 μG

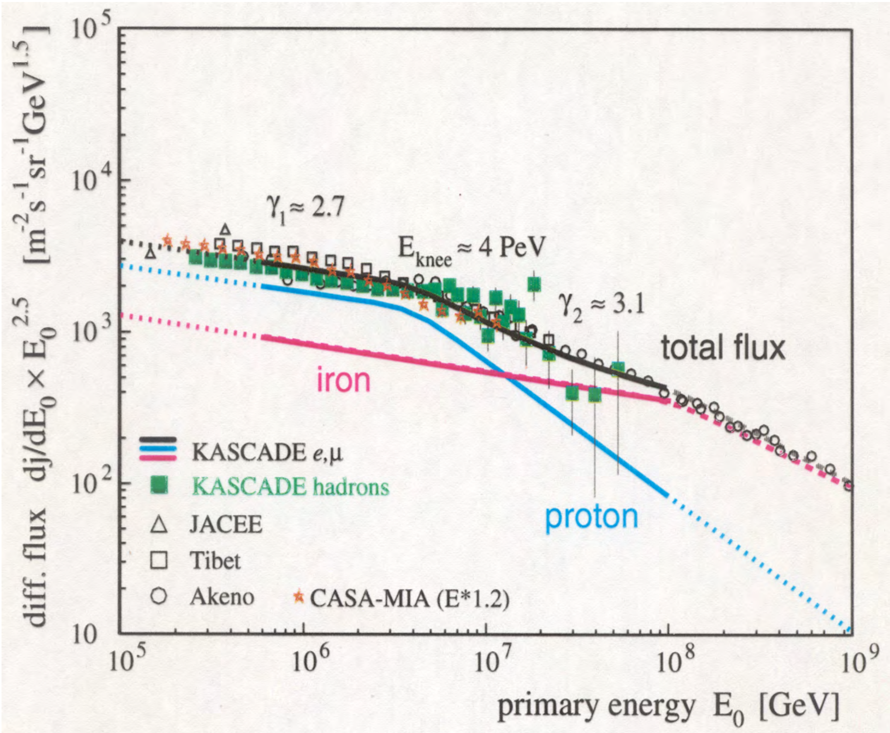
Intergalatic 1 nG > B > 1fG

Larmor Radius:

$$R = \frac{E}{ZeB}$$

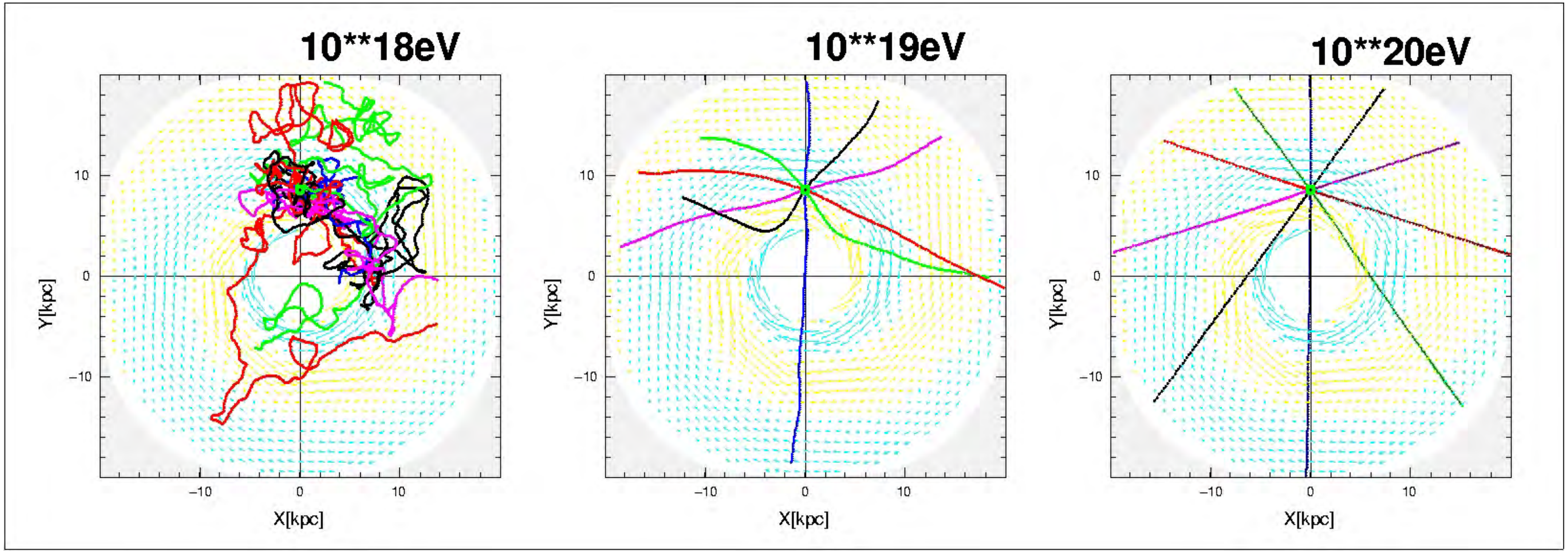
Several knees?





Galactic Magnetic Field deflection (p)

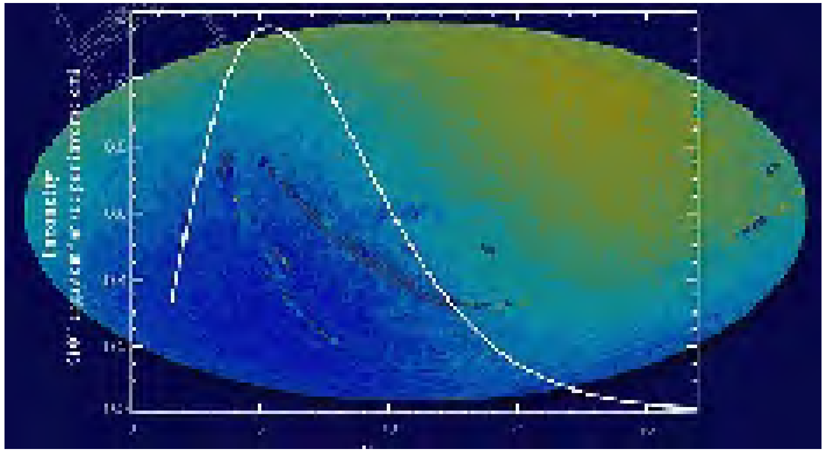
T.Stanev

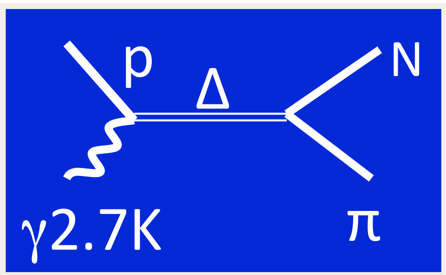


Above 10^{19} : Astronomy !

An unique opportunity to measure the galactic magnetic field ?

The Greisen-Zatsepin-Kuzmin (GZK) cutoff

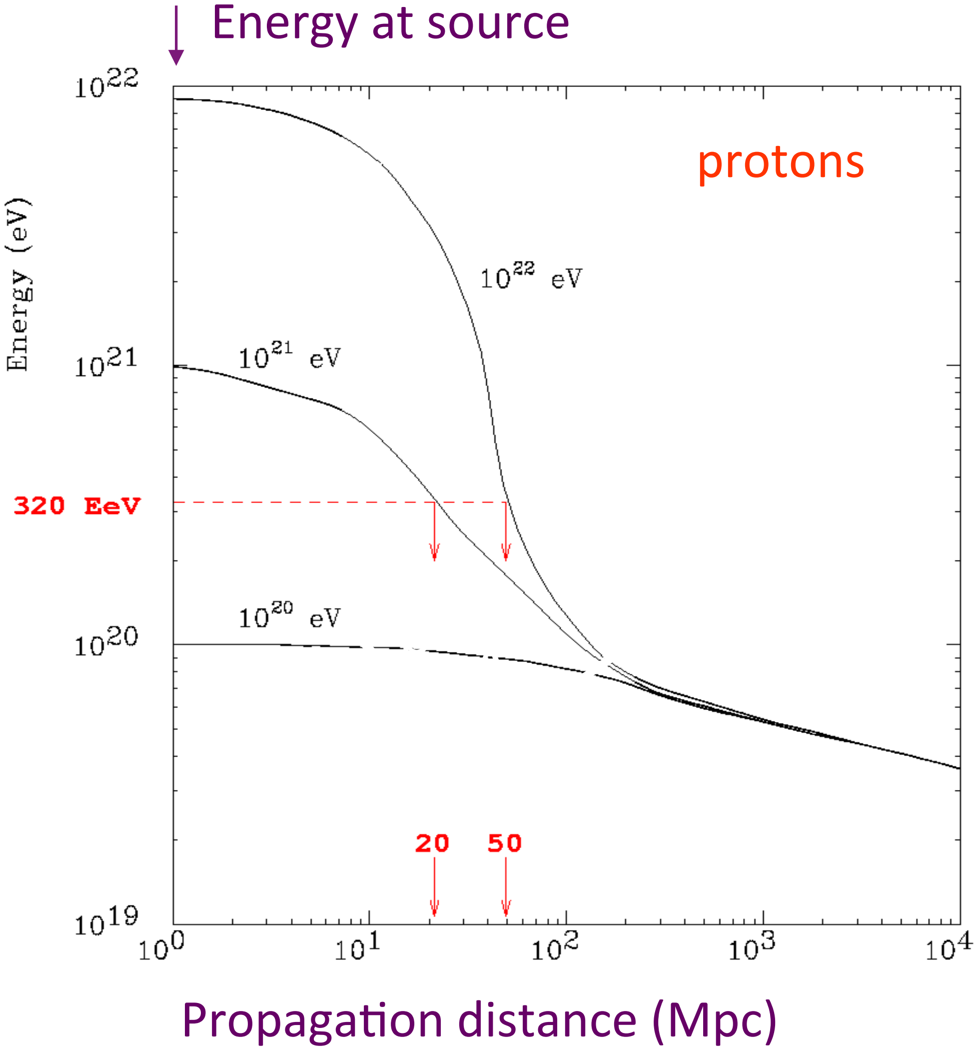




$$E_p \approx 10^{20}\,\mathrm{eV}$$

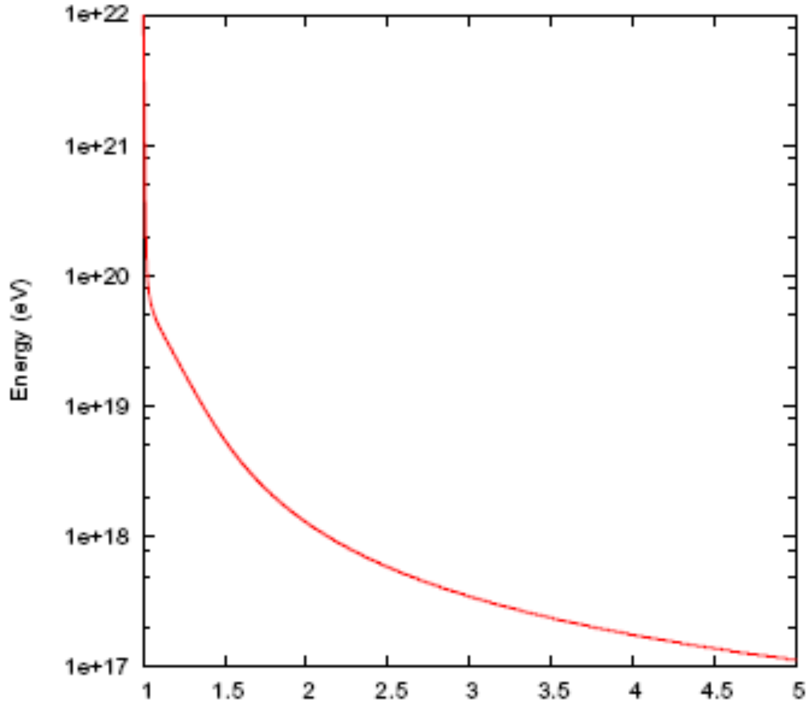
$$\lambda = \frac{1}{\sigma_{p\gamma}\,\rho_{CMB}}$$

$$\approx 6\ \mathrm{Mpc}$$



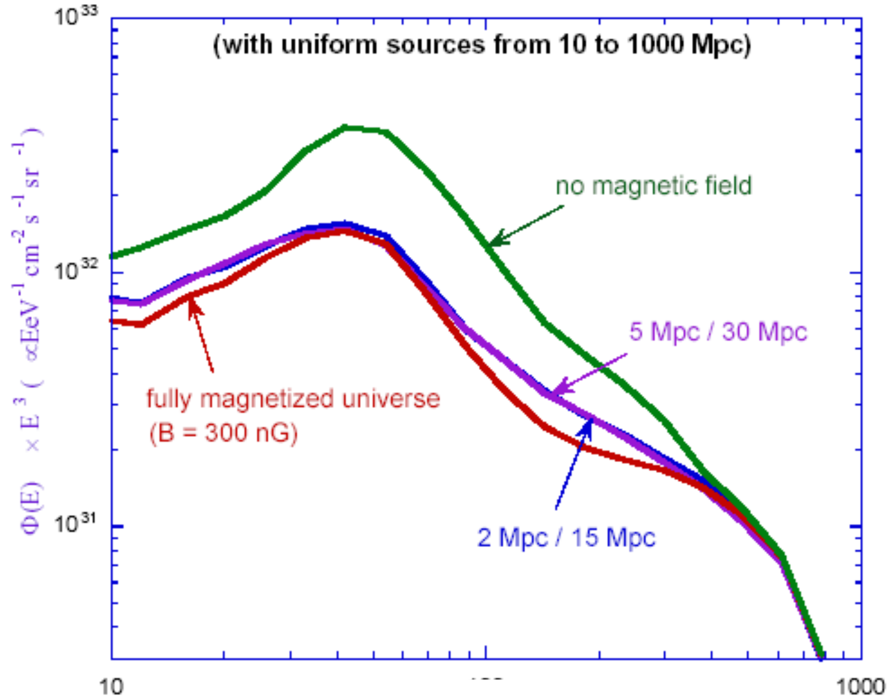
GZK is model dependent

GZK cutoff Energy – Stecker and Scully



1 + z

GZK and magnetic fields (protons)
Deligny, Parizot, Letessier-Selvon



Energy (in EeV)

Sources type and distribution

Primary composition

Magnetic fields

Not a true cutoff !

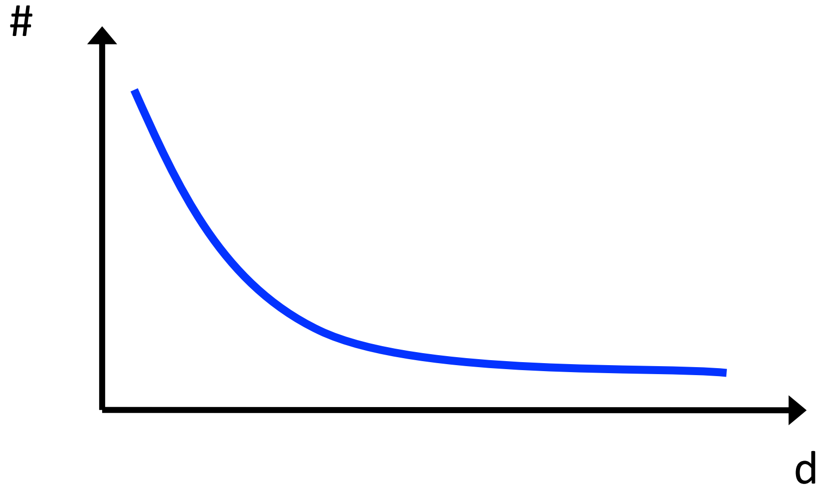
Pileup

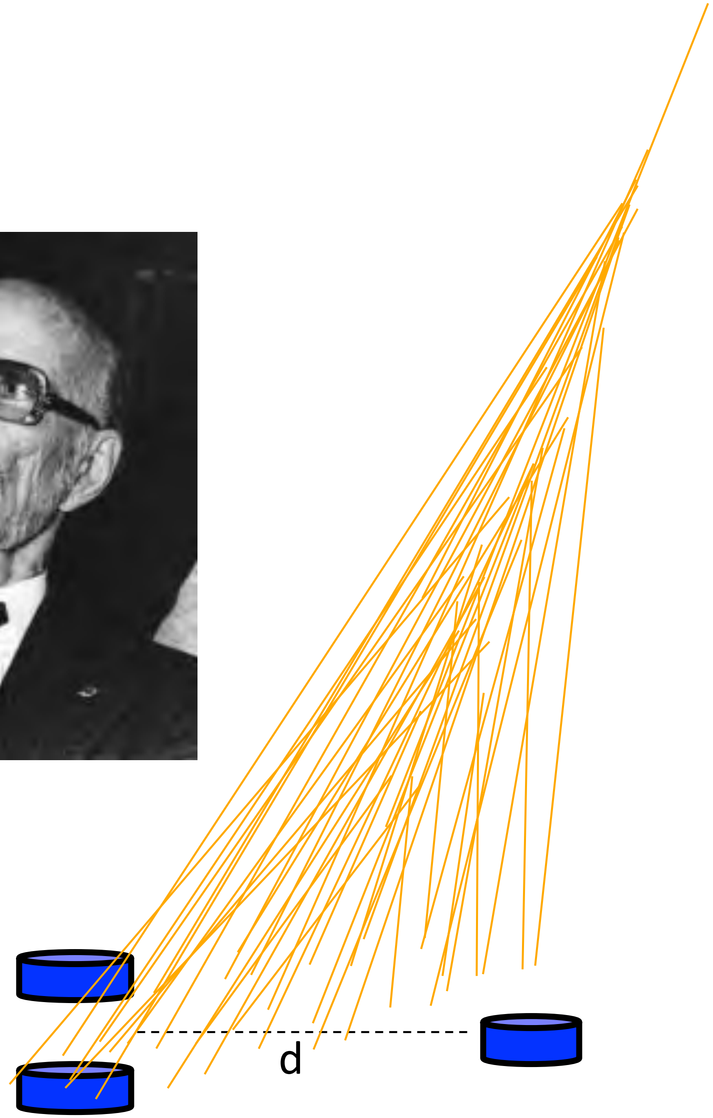
Recovery of the spectrum at higher energies ?

Particle showers

Pierre Auger, 1938

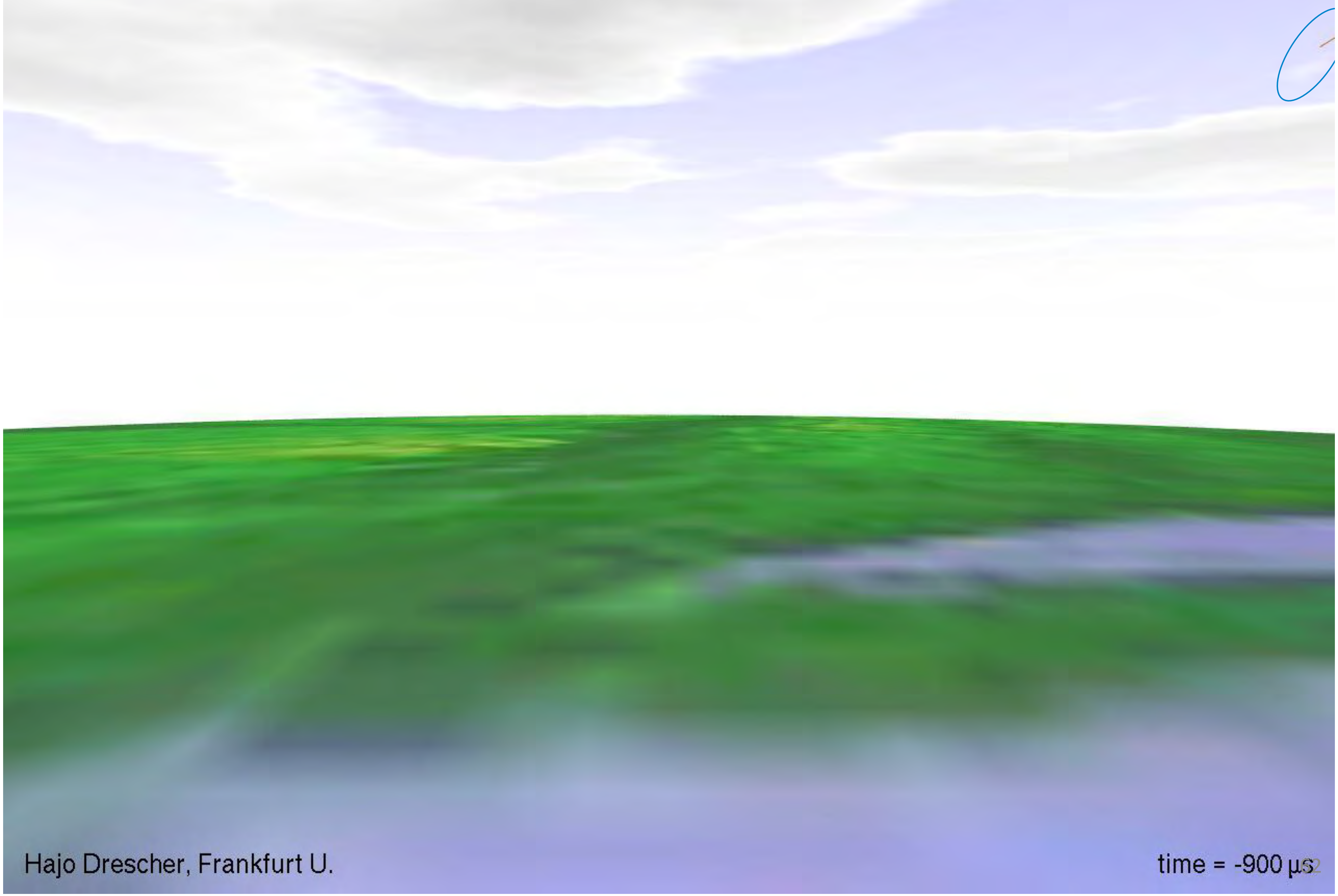
Coincidences



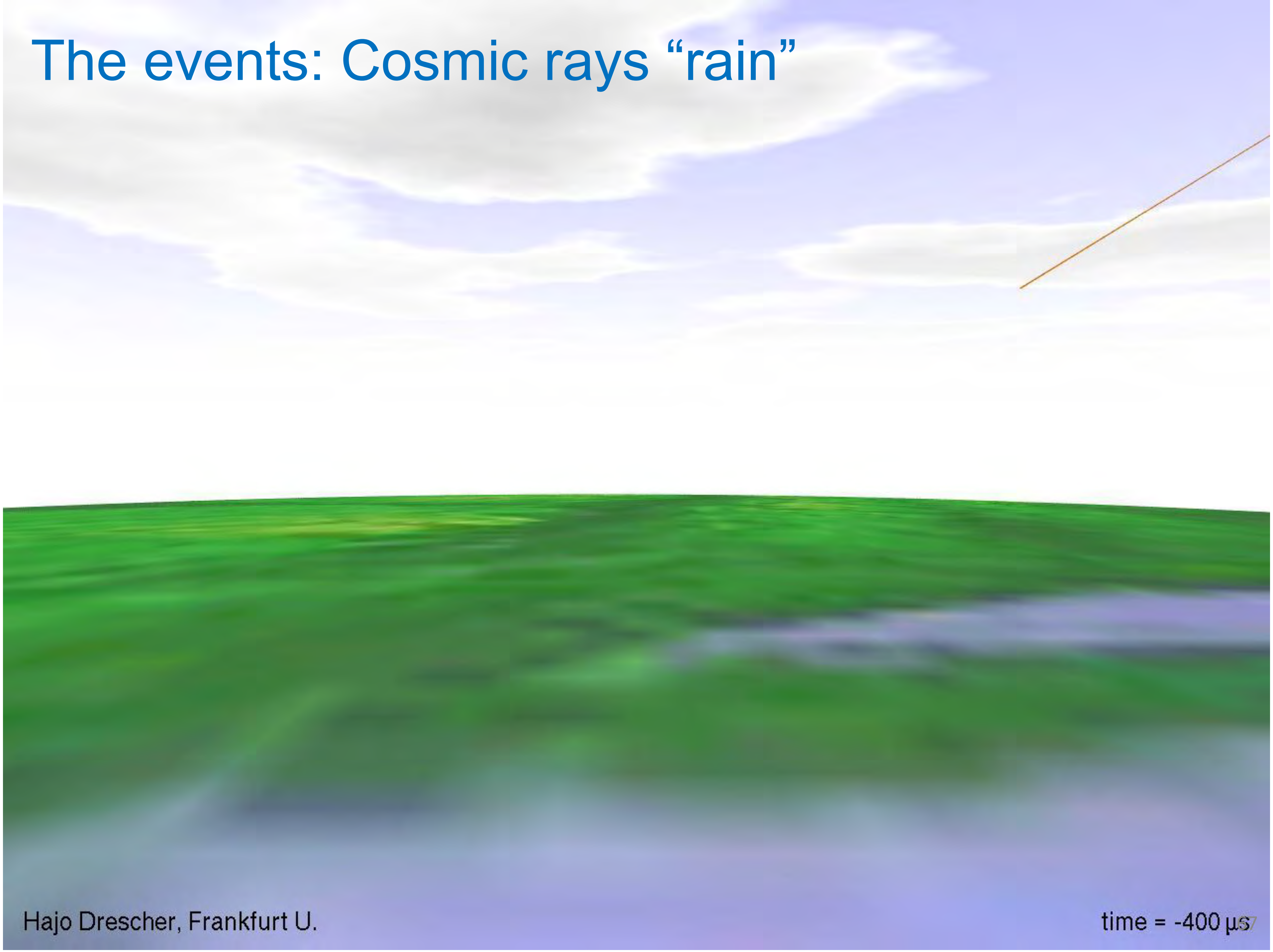


First shower energy estimates !

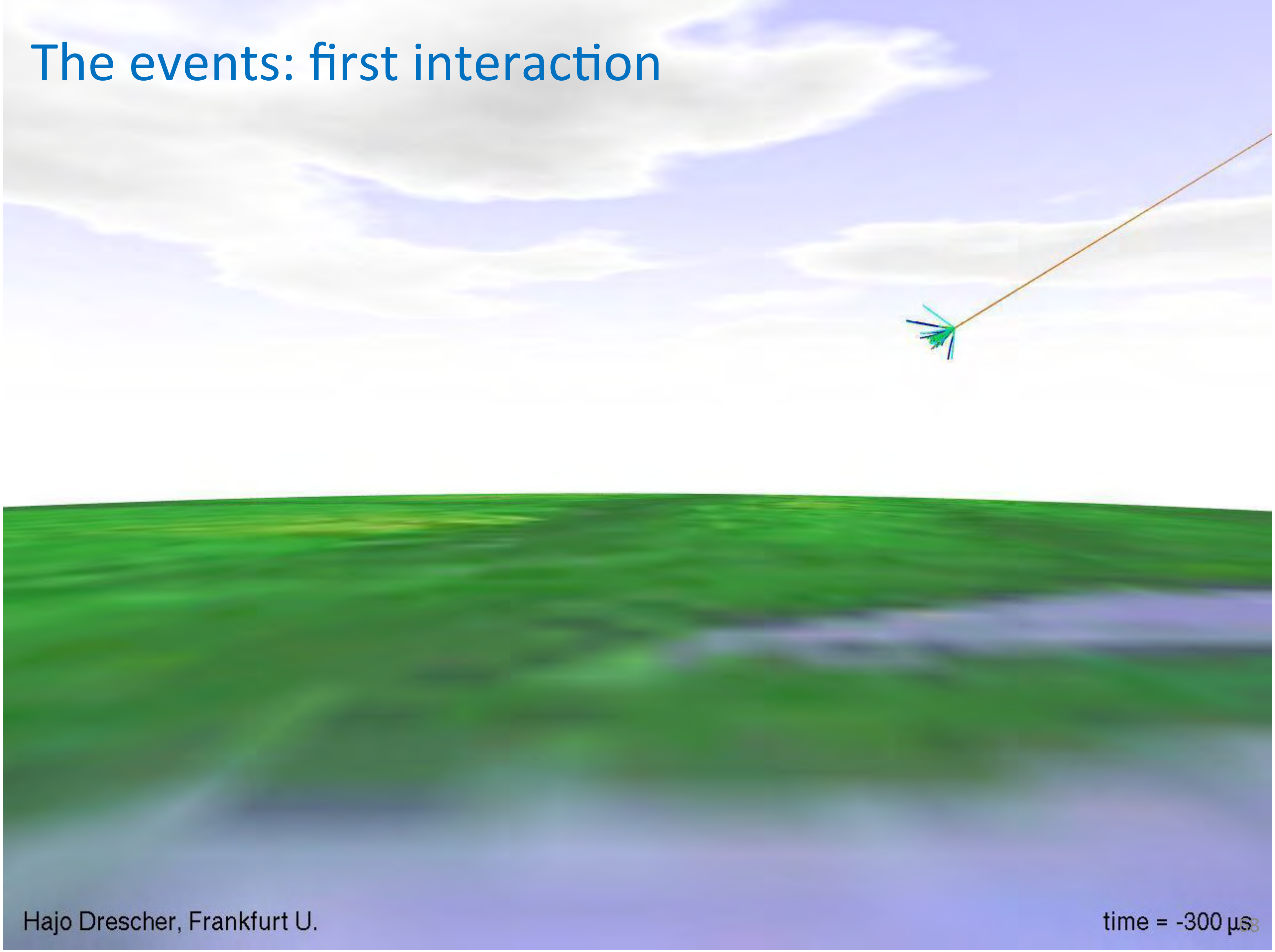
The events: Cosmic rays “rain”



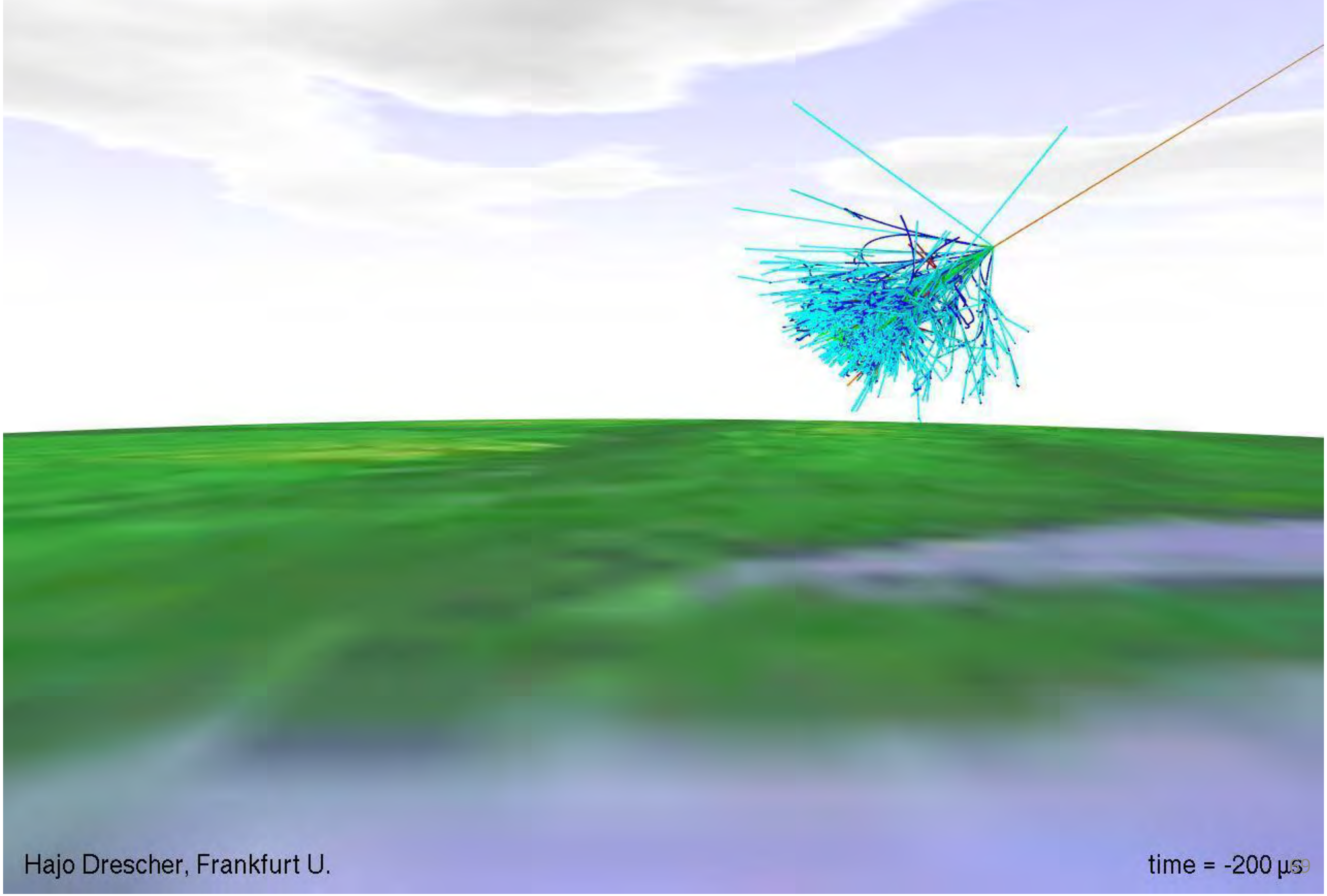
The events: Cosmic rays “rain”



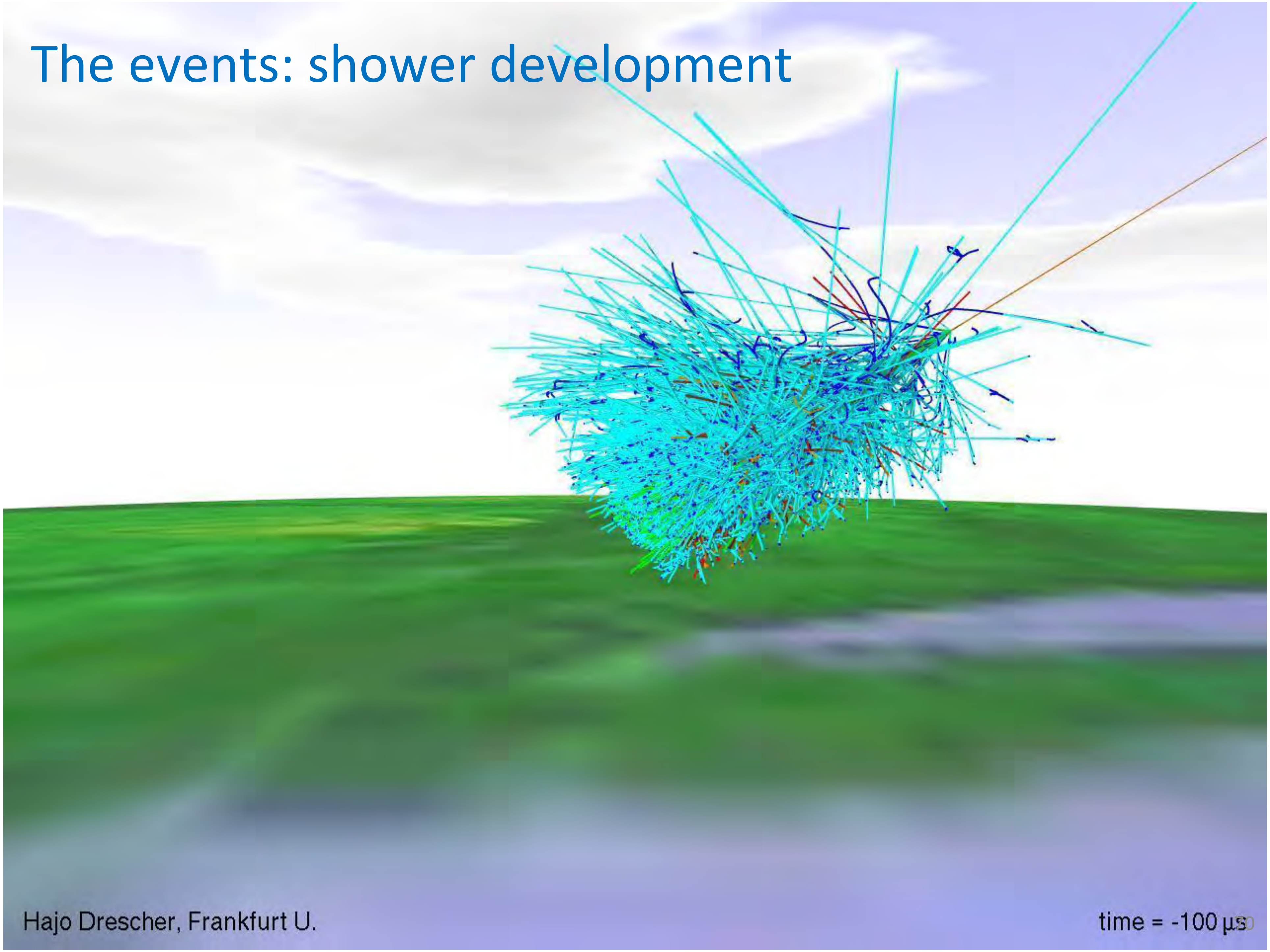
The events: first interaction



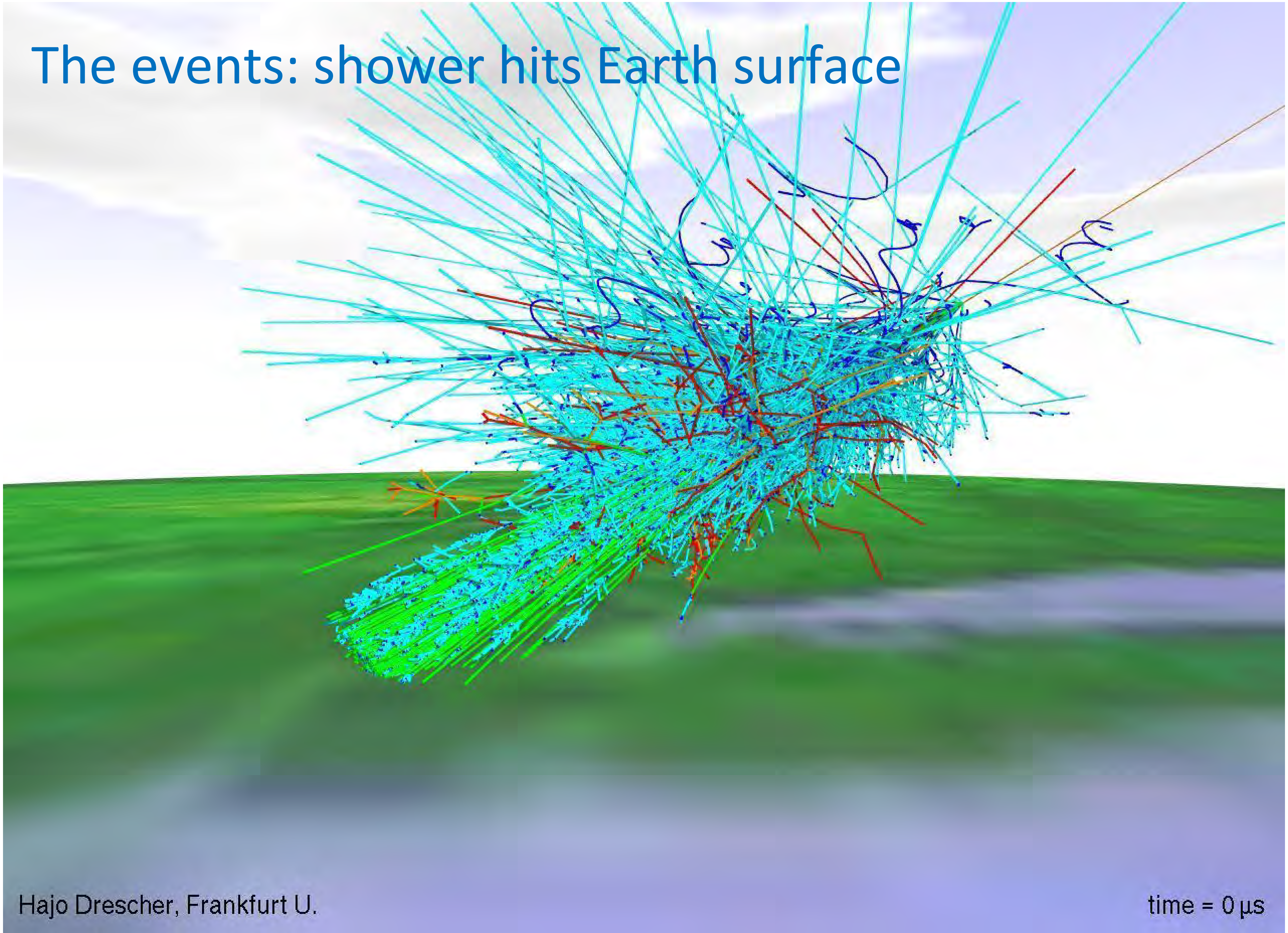
The events: shower development



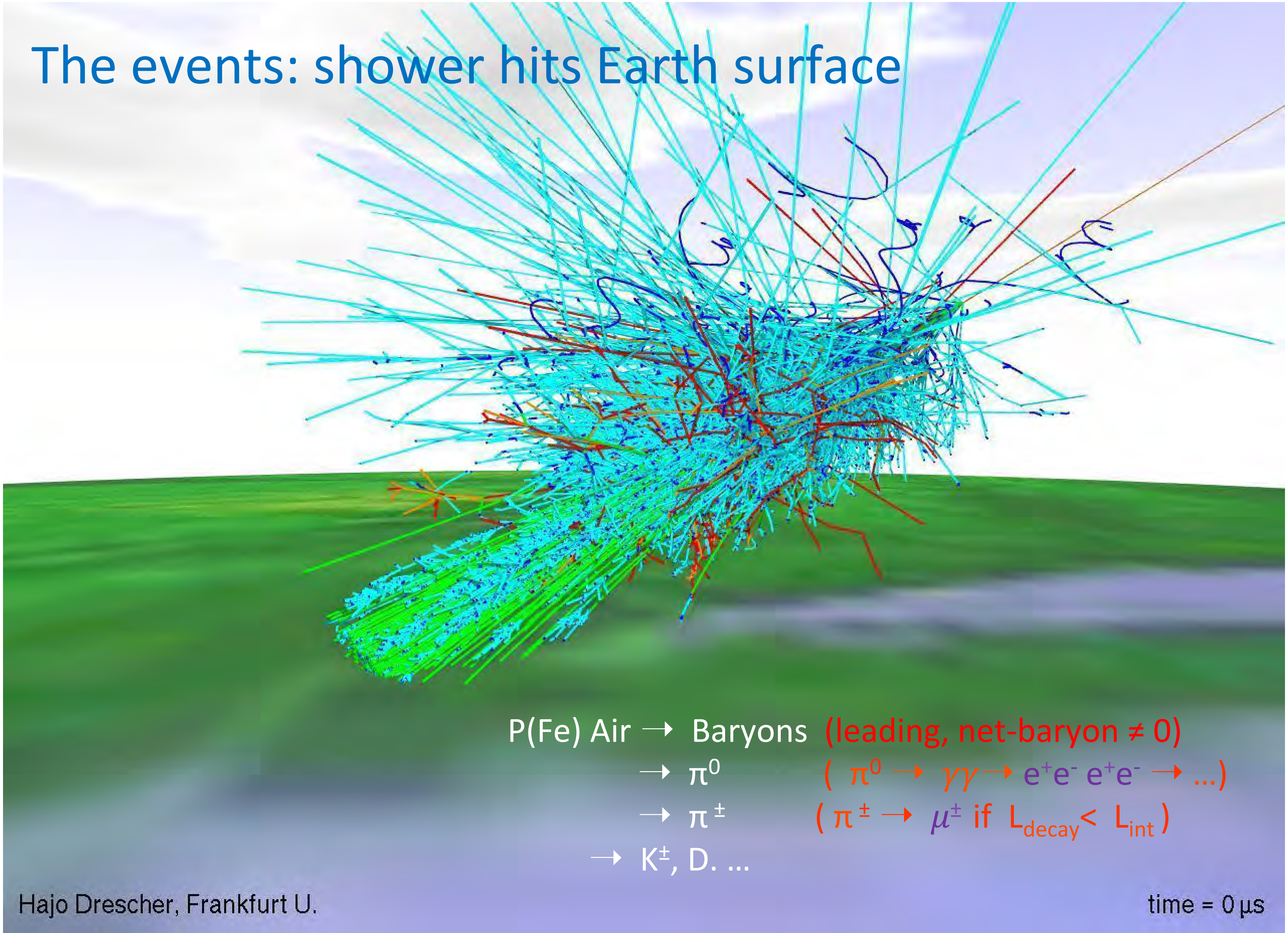
The events: shower development



The events: shower hits Earth surface



The events: shower hits Earth surface



P(Fe) Air → Baryons (leading, net-baryon ≠ 0)

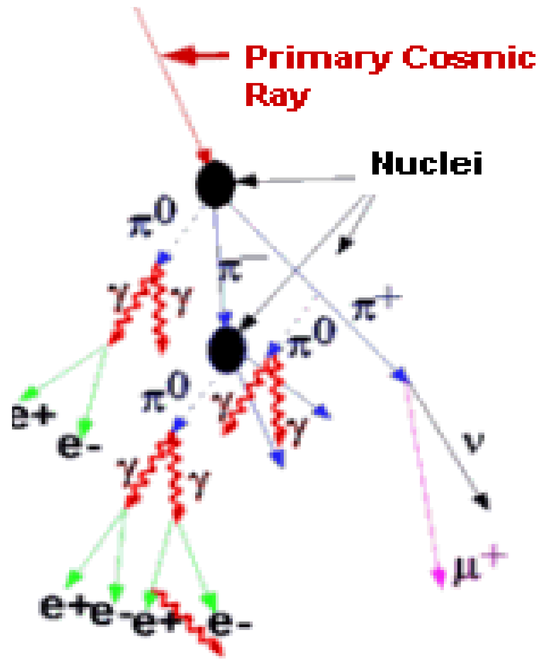
→ π^0 ($\pi^0 \rightarrow \gamma\gamma \rightarrow e^+e^- e^+e^- \rightarrow ...$)

→ $\pi^\pm$ ($\pi^\pm \rightarrow \mu^\pm$ if $L_{decay} < L_{int}$)

→ $K^\pm$, D. …

Particle interactions

P(Fe) Air → Baryons (leading, net-baryon ≠ 0)
→ π^0 ($\pi^0 \rightarrow \gamma\gamma \rightarrow e^+e^- e^+e^- \rightarrow \dots$)
→ $\pi^\pm$ ($\pi^\pm \rightarrow \mu^\pm$ if $L_{decay} < L_{int}$)
→ $K^\pm$, D. …



e.m. and weak interations

- well known !

hadronic interations

- large uncertainties !
- forward region, small p_t, very high $\sqrt{s}$
- main parameters: σ_{in}, k_{in}, <n>, (fraction π^0, Nb of Baryons, …)

Nuclear fragmentation

- Nuclei are not just a superposition of nucleons !

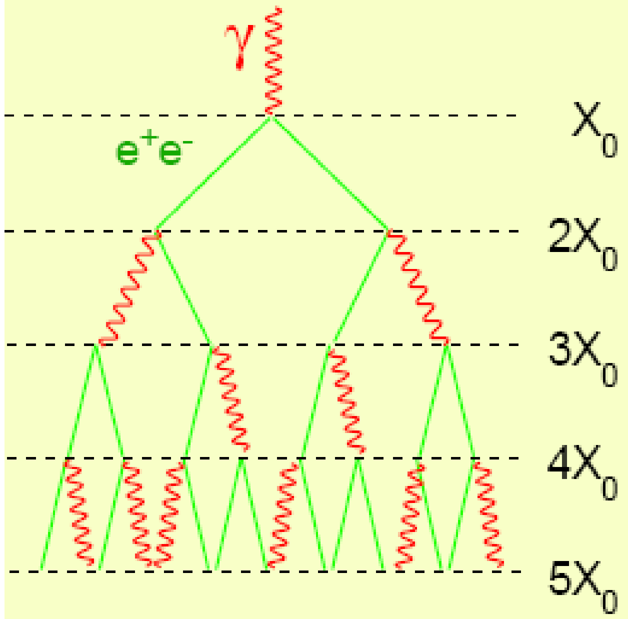
Missing Energy

- 5% to 10% …

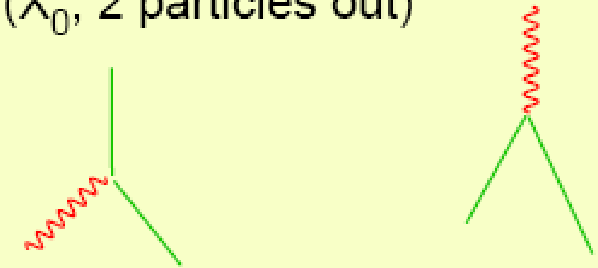
Electromagnetic interactions

J. Knapp

A simple (el.mag.) shower model:



Bremsstrahlung & Pair production
(X_0, 2 particles out)



$N(t) = 2^t$ t is depth in X_0

$E(t) = E_0/2^t$

$N_{max} = E_0/E_{crit} = 2^{t_{max}}$

$E_{crit} = E_0/N_{max} = E_0/2^{t_{max}}$

$t_{max} = \ln(E_0/E_{crit}) / \ln 2$

... reproduces shower behaviour rather well

but: X_0 for bremsstrahlung, 0.78 X_0 for pair production,
both processes produce energy spectra,
δ-electrons, ionization, scattering ...

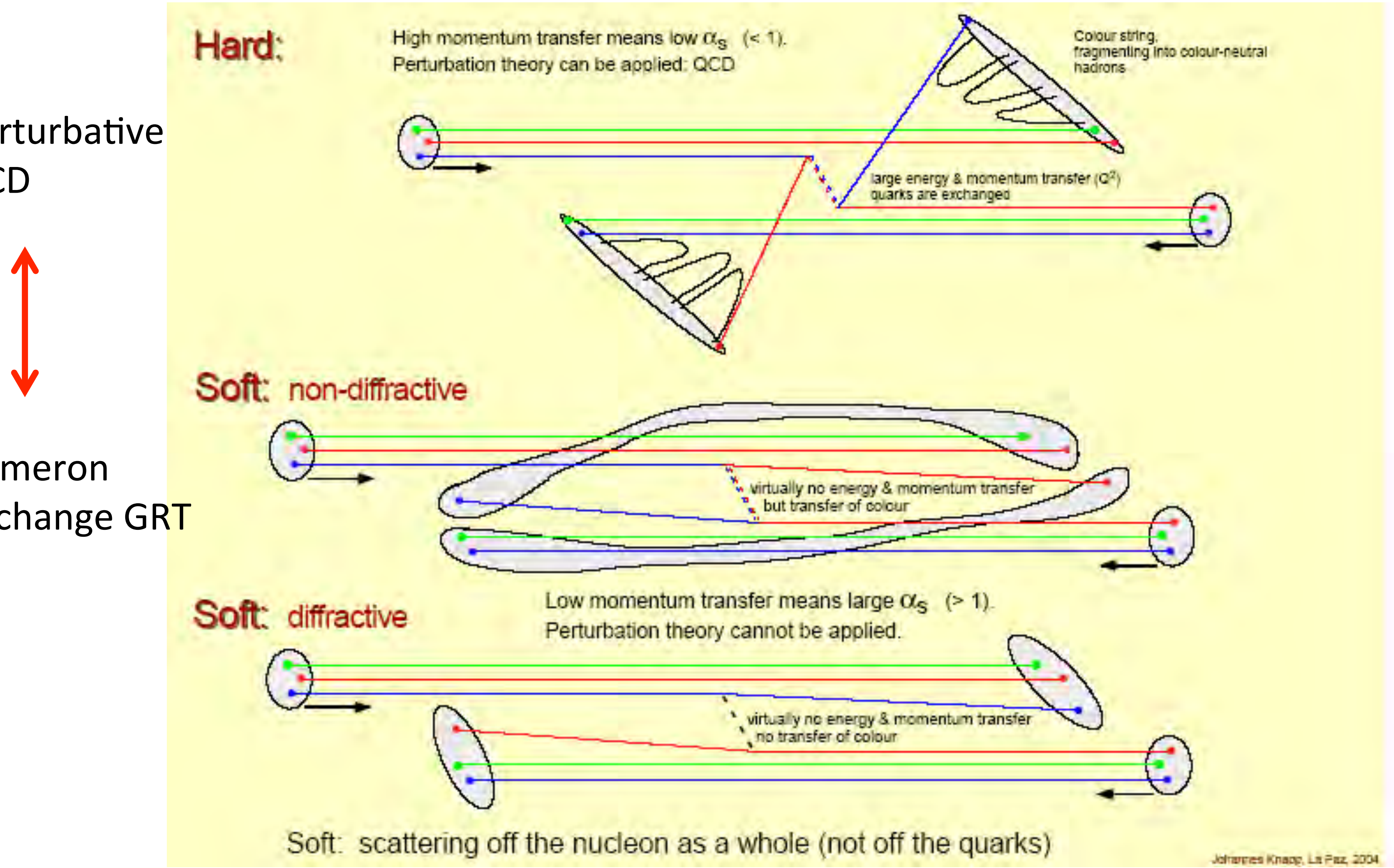
Reality is more complicated, ... needs a MC simulation.

Hard and soft hadronic interactions

J. Knapp

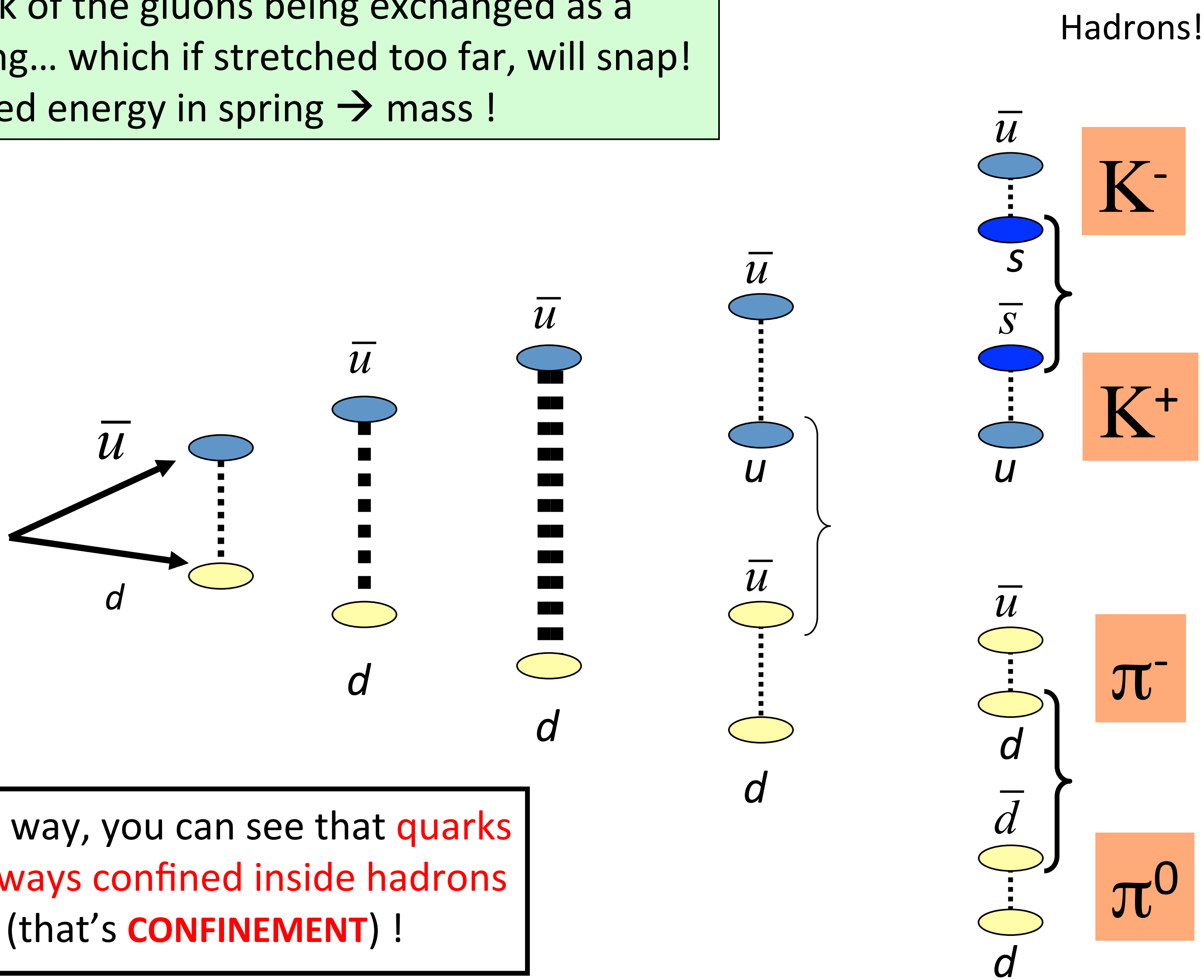
Perturbative QCD

Pomeron exchange GRT



String fragmentation

Think of the gluons being exchanged as a spring… which if stretched too far, will snap! Stored energy in spring → mass !



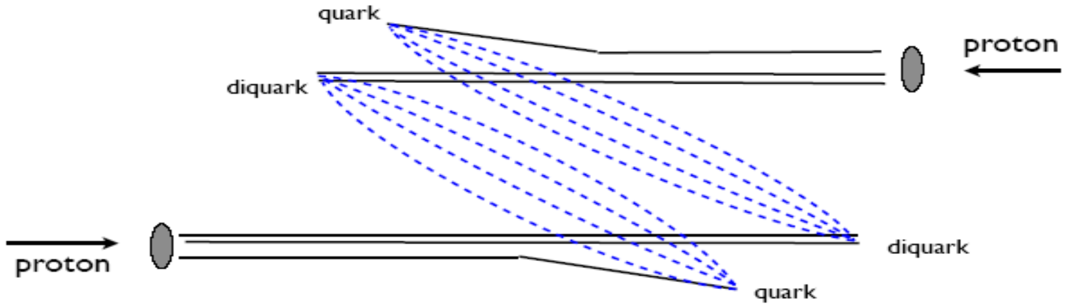
In this way, you can see that quarks are always confined inside hadrons (that's **CONFINEMENT**) !

“Standard” Hadronic models (low pt)

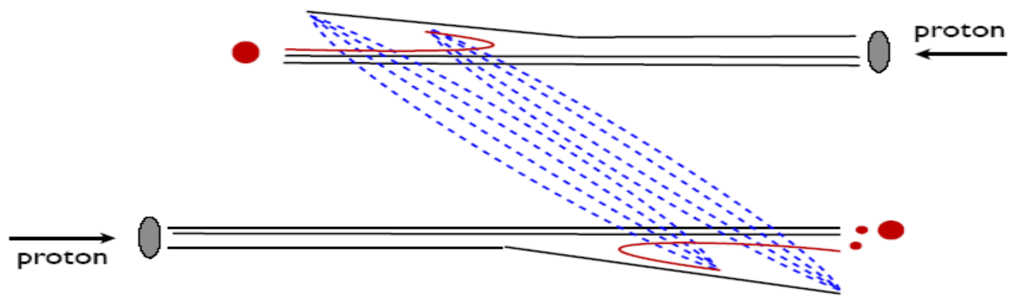
Minimum string configuration

Ralph Engel

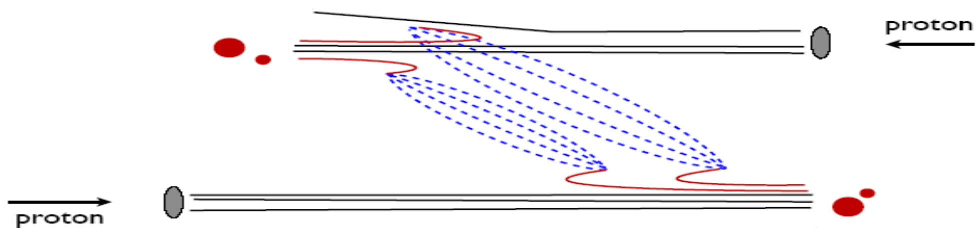
SIBYLL



QGSJET



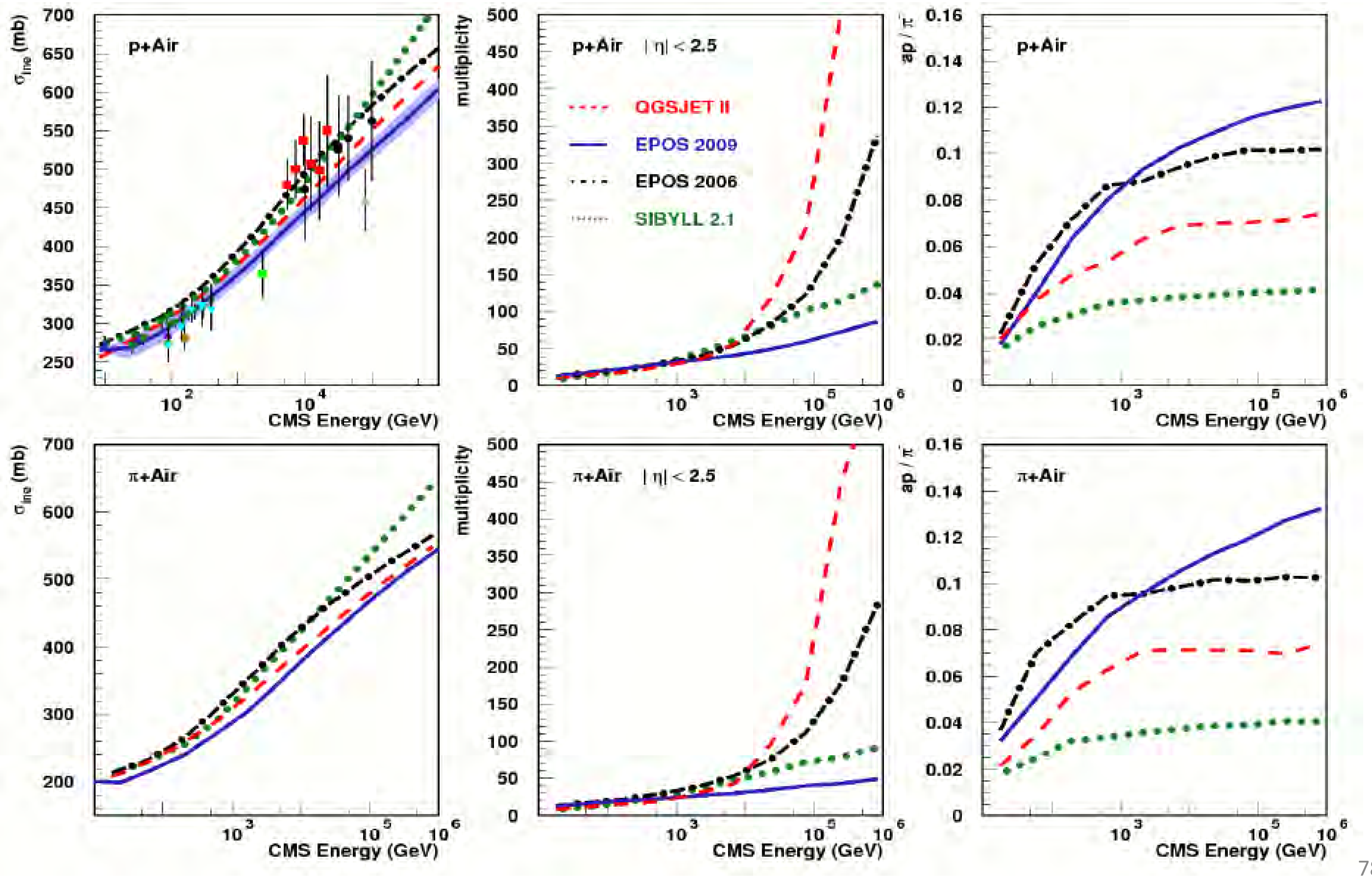
EPOS



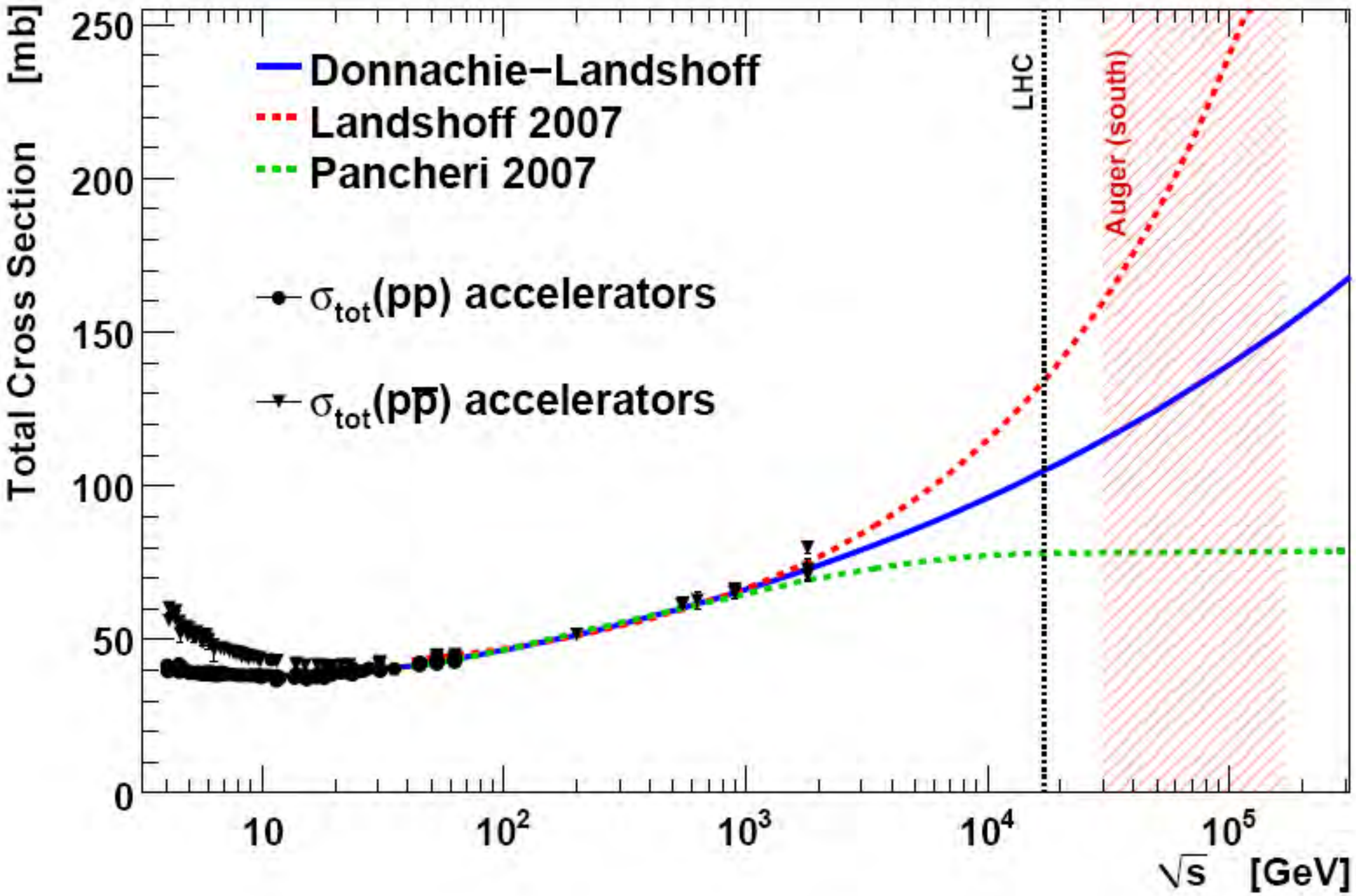
Hadronic models parameters

P.Tanguy

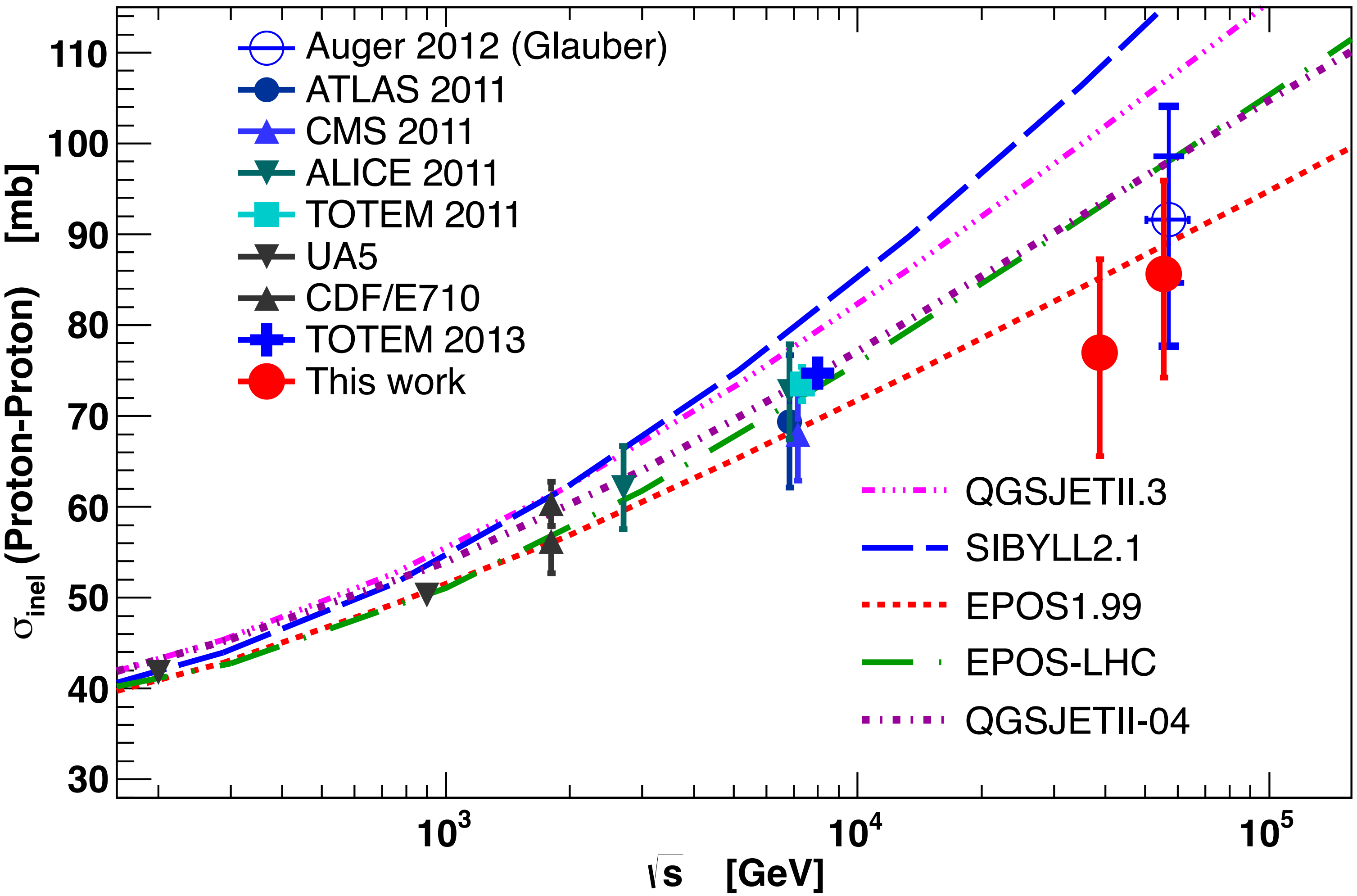
p air



Cross sections extrapolations (before LHC)

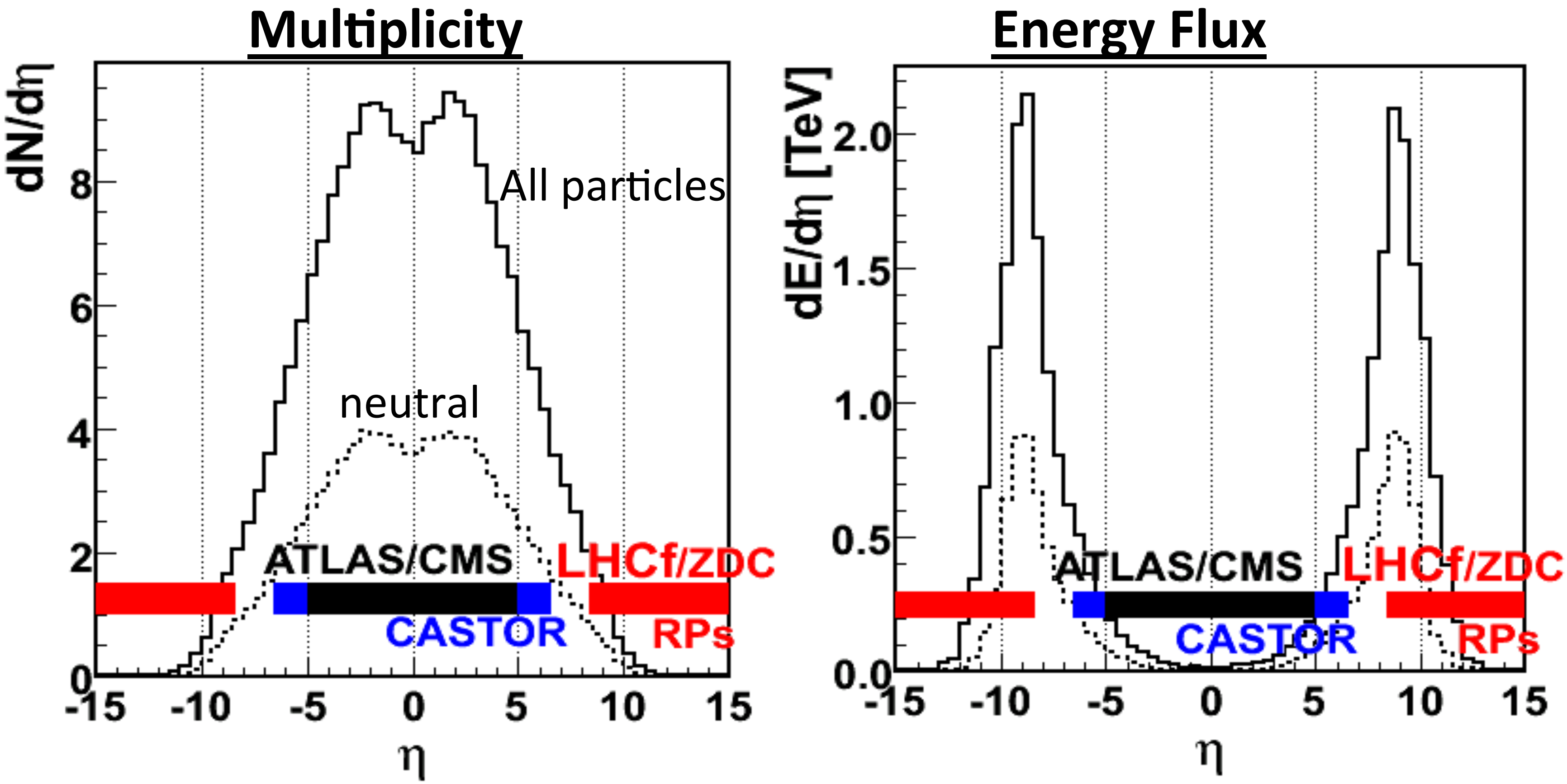


Cross sections extrapolations (after LHC)



LHC Kinematics (14 TeV)

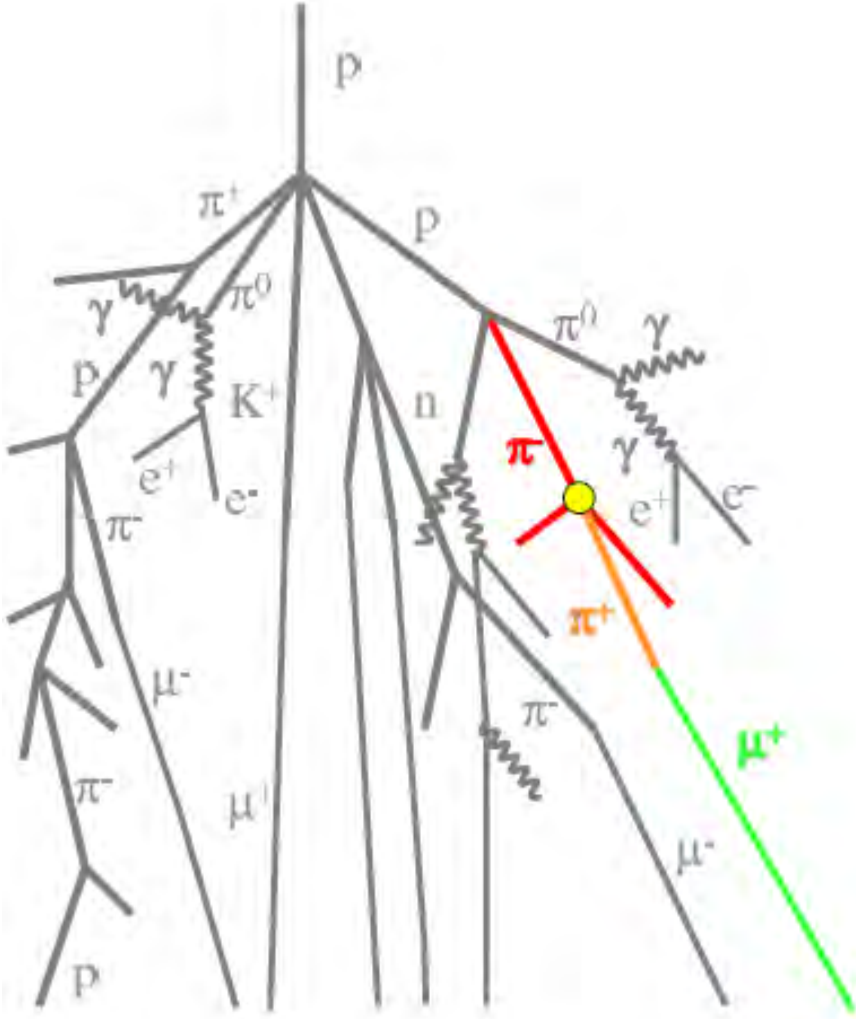
Takashi SAKO



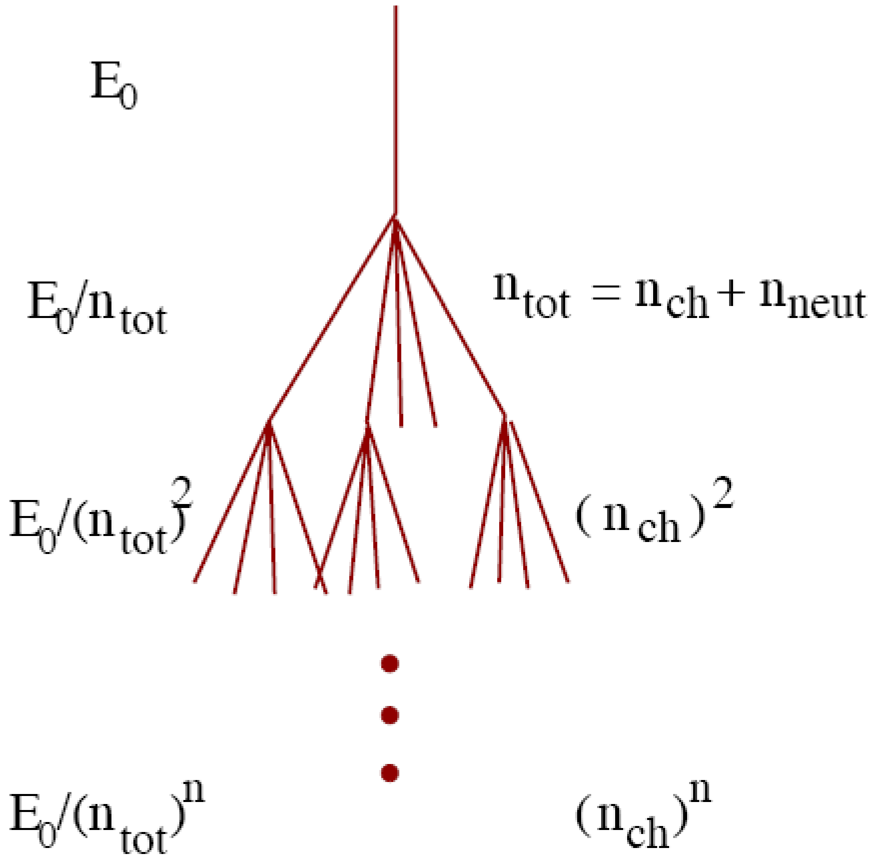
pseudo-rapidity; $\eta = -\ln(\tan(\theta/2))$

Most of the energy flows into very forward region

The μ_s



Muon production



Primary particle proton

π^0 decay immediately

$\pi^{\pm}$ initiate new cascades

$$N_\mu = \left(\frac{E_0}{E_{dec}}\right)^\alpha$$

$$\alpha = \frac{\ln n_{ch}}{\ln n_{tot}} \approx 0.82 \ldots 0.95$$

Assumptions:

- cascade stops at $E_{part} = E_{dec}$
- each hadron produces one muon

(Matthews, Astropart.Phys. 22, 2005)

Muon spectrum at Earth Surface

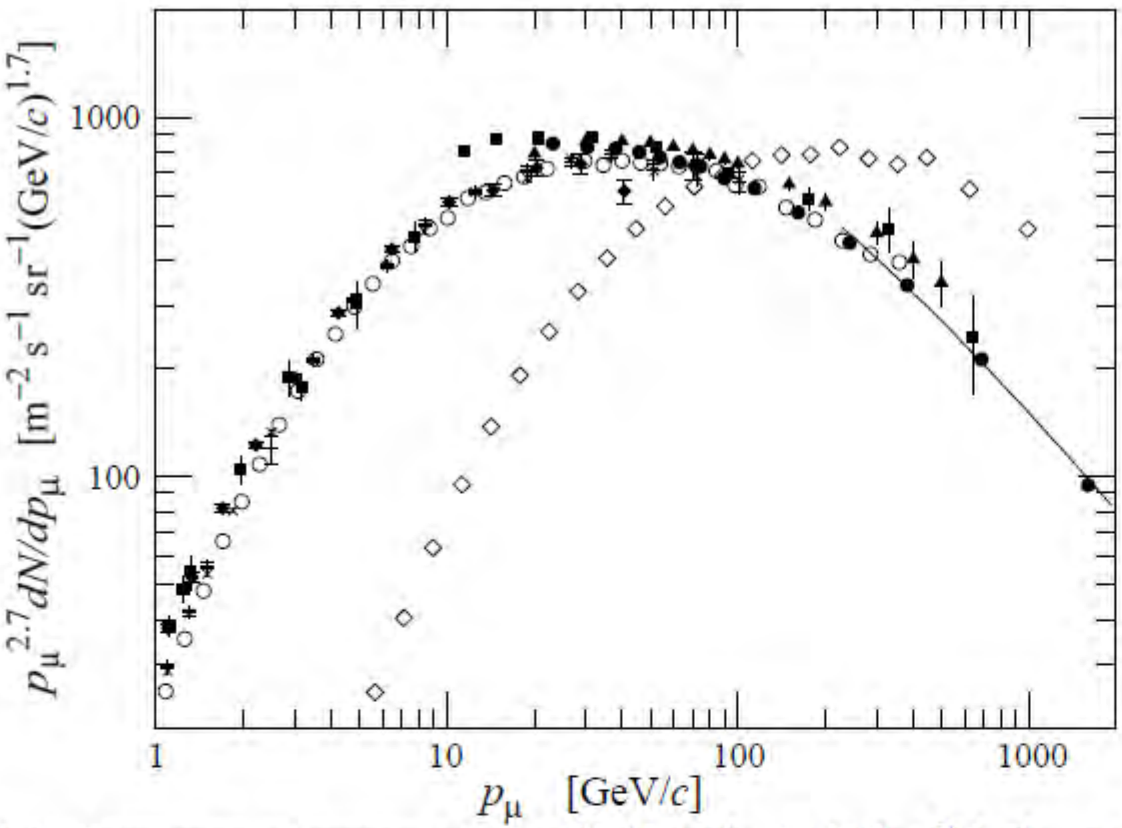


Figure 26.4: Spectrum of muons at $\theta = 0°$ (♦ [41], ■ [46], ▼ [47], ▲ [48], ×, + [43], ○ [44], and • [45] and $\theta = 75°$ ◊ [49]) . The line plots the result from Eq. (26.4) for vertical showers. **J. Beringer et al (PDG) PR D86 010001 (2012)**

Fluxes in the atmosphere

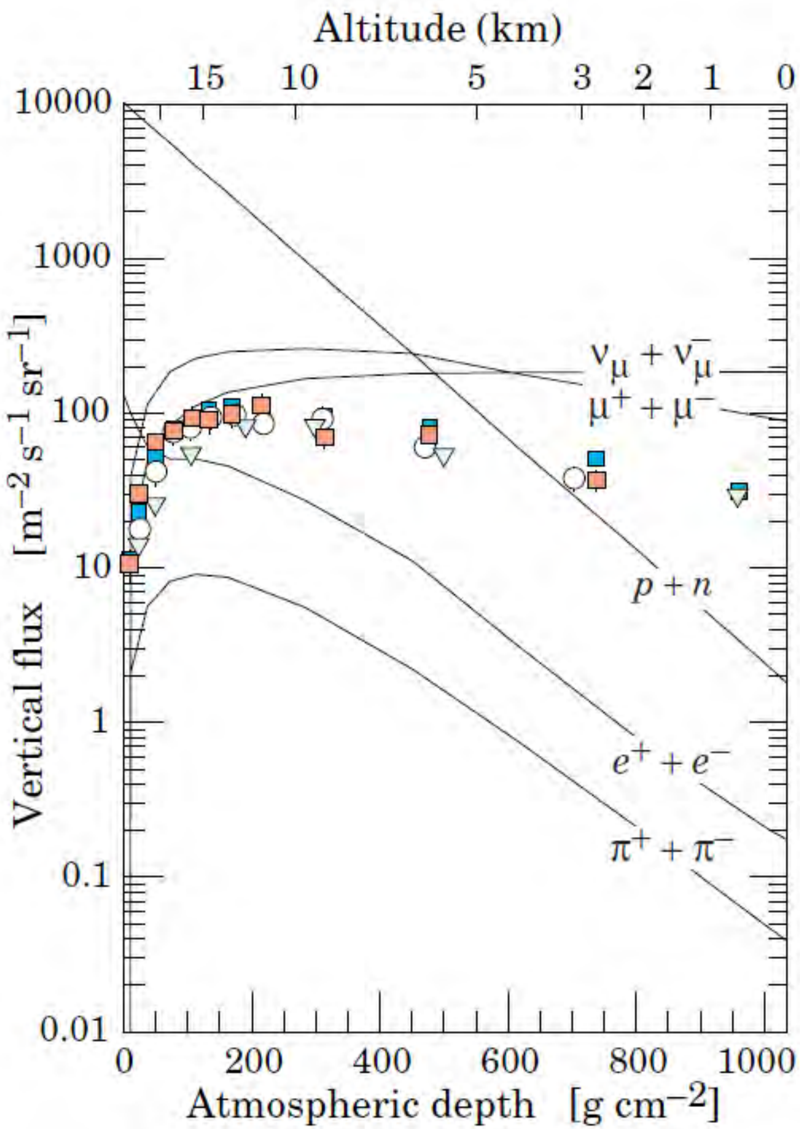


Figure 26.3: Vertical fluxes of cosmic rays in the atmosphere with $E > 1$ GeV estimated from the nucleon flux of Eq. (26.2). The points show measurements of negative muons with $E_\mu > 1$ GeV [32–36].

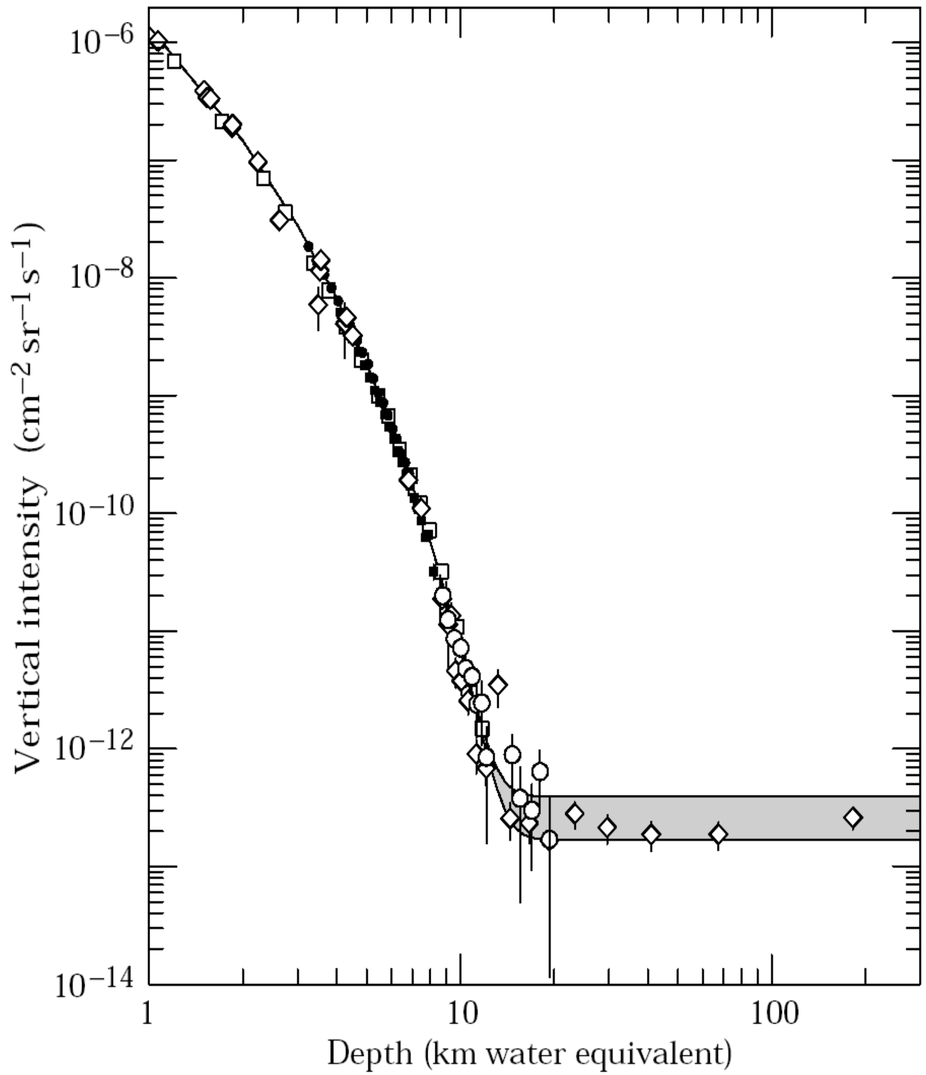
J. Beringer et al (PDG) PR D86 010001 (2012)

Under Earth

At the Earth surface :

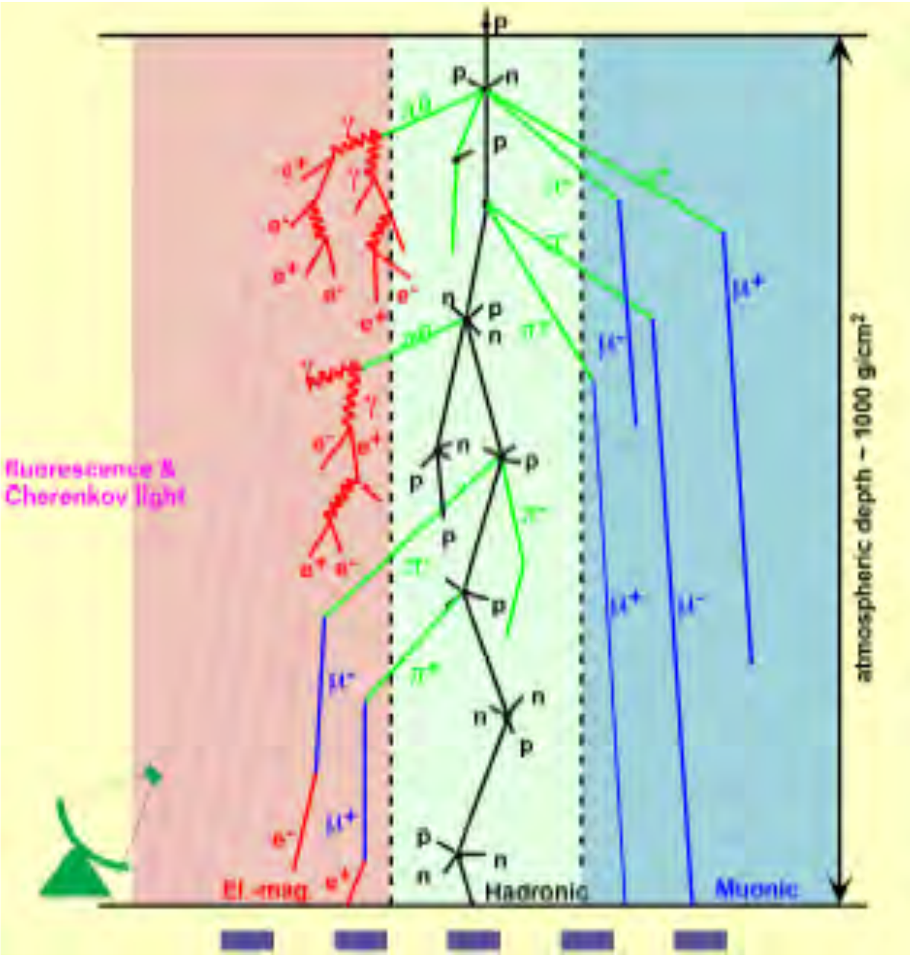
~70 m^{-2} s^{-1} sr^{-1}

~1 cm^{-2} min^{-1} ($\Omega \sim \pi$)

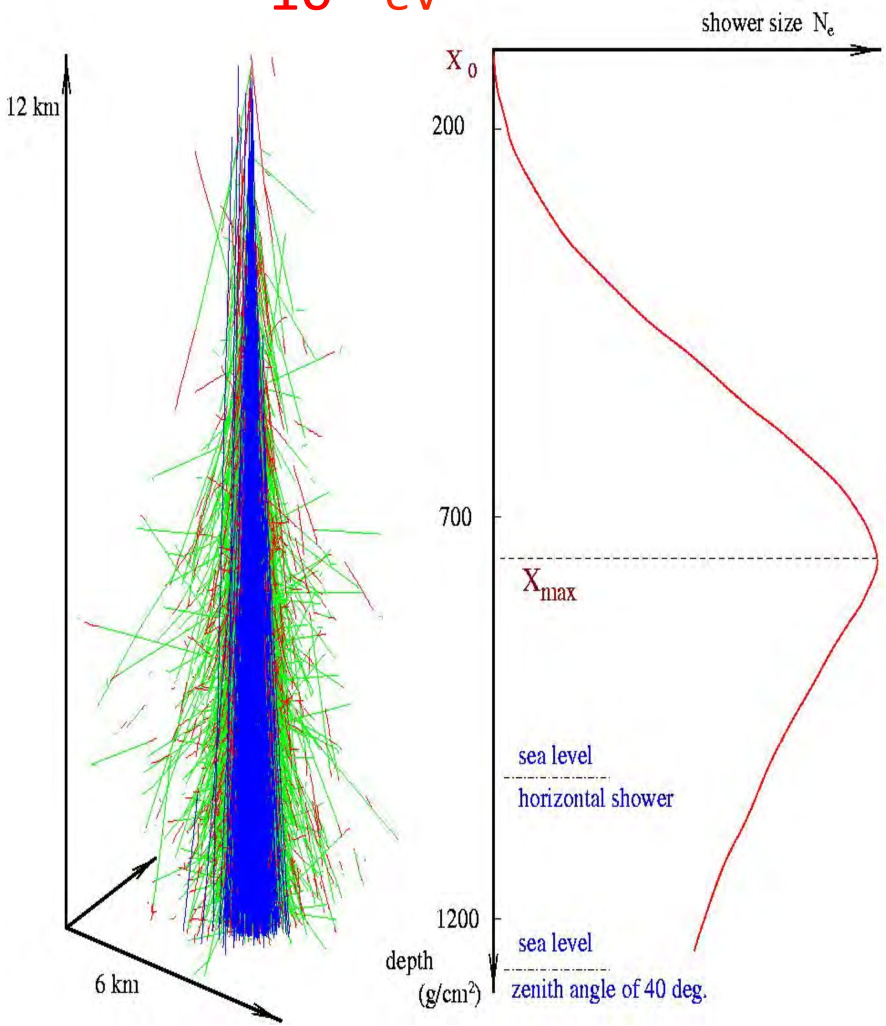


Place	Depth(KmWater)	Threshold(TeV)
Mt.Blanc	~ 5	~ 3
GranSasso	~ 3.5	~ 2
Kamiokande	~ 2.7	~ 1

Extensive Air Showers (EAS)



10^{19} eV



EAS transverse profiles

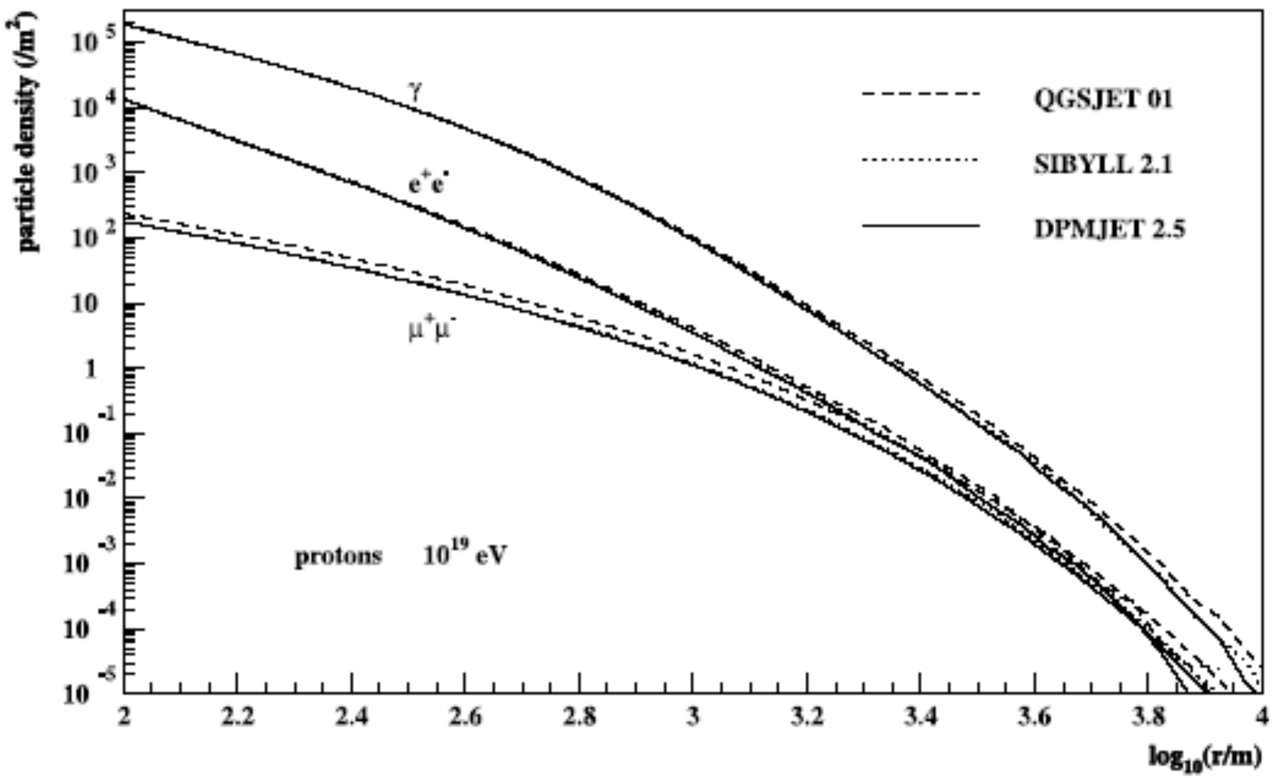
NKG (Nishimura, Kamata, Greisen)

$$\rho(r) = c(s)N_e / r_0^2 (r/r_0)^{s-2}(1+r/r_0)^{s-4.5}$$

r_0: Moliére radius

s : shower age

J. Knapp et al. / Astroparticle Physics 19 (2003) 77–99



P_t distributions
Multiple Coulomb scattering

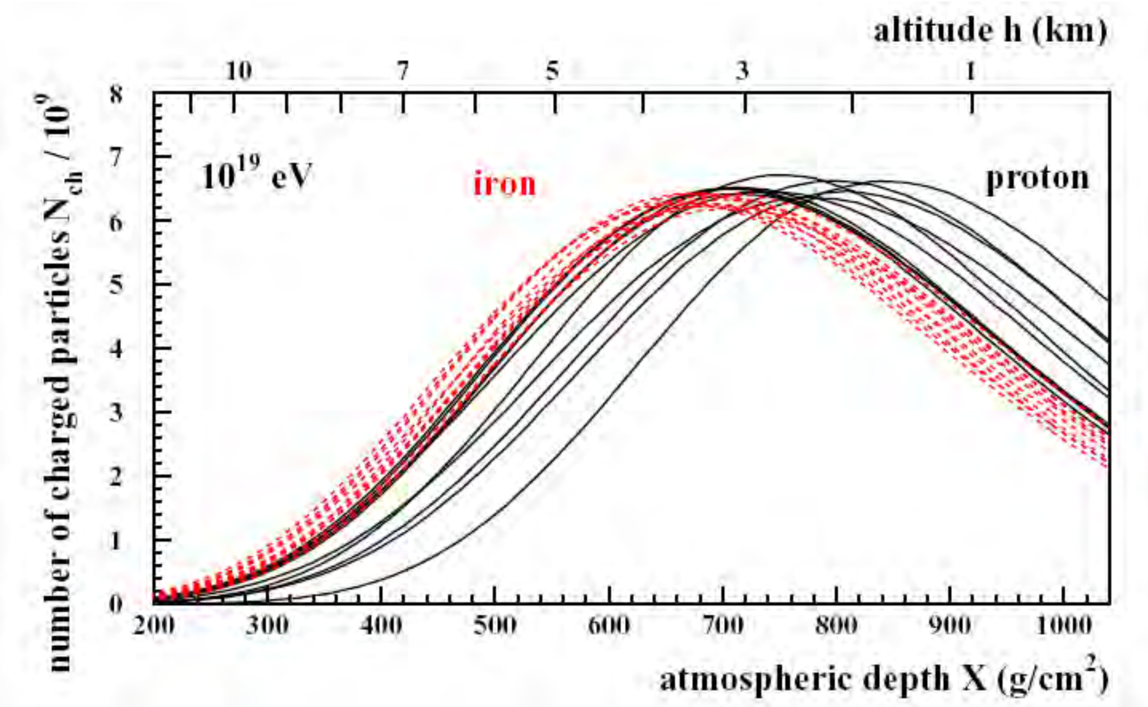
EAS longitudinal profiles

Gaisser

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

$N_e^{max} \propto E$

$X_{max} \propto \ln E$

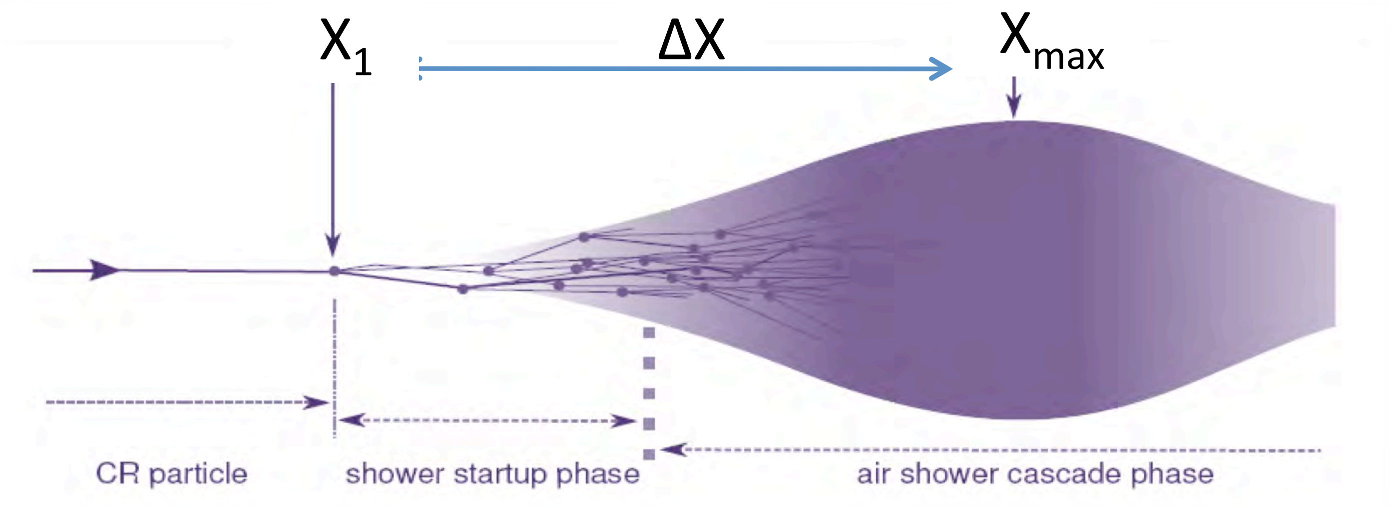


Iron ~ 56 nucl(E/56)

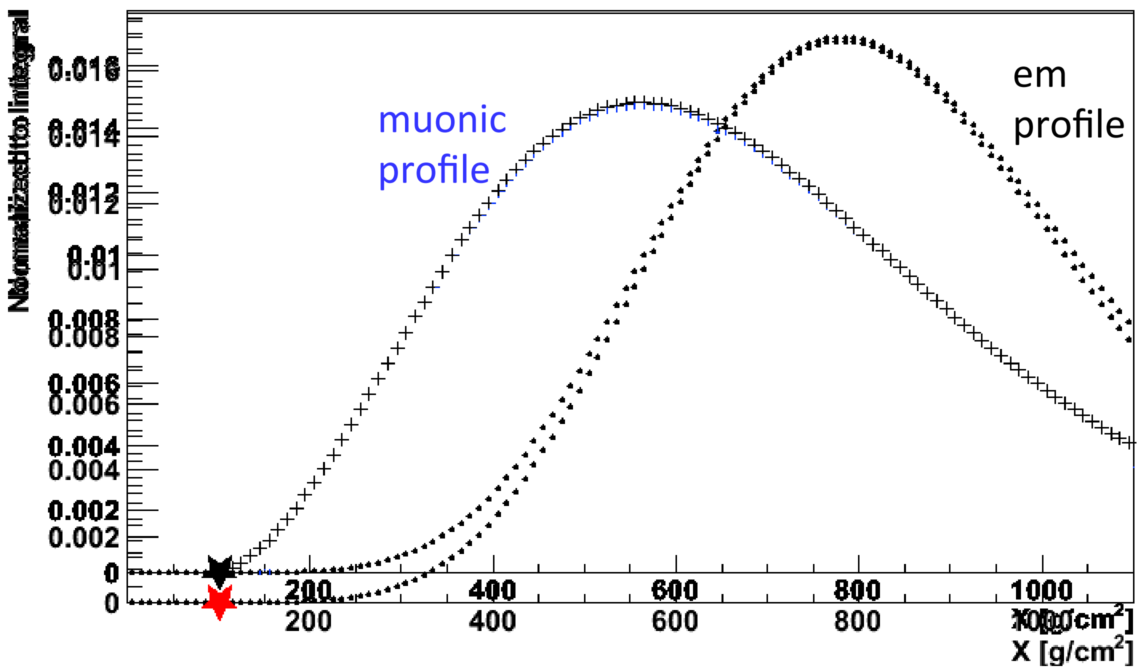
Smaller fluctuactions

Smaller X_{max}

Shower development



$$X_{max} = X_1 + \Delta X$$



$E \propto Ne$

$$\propto \int \frac{dN_e}{dX} dX$$

$$N_\mu \propto \int \frac{dN_\mu}{dX} dX$$