Experimental Astroparticle

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Subatech

Let there be light

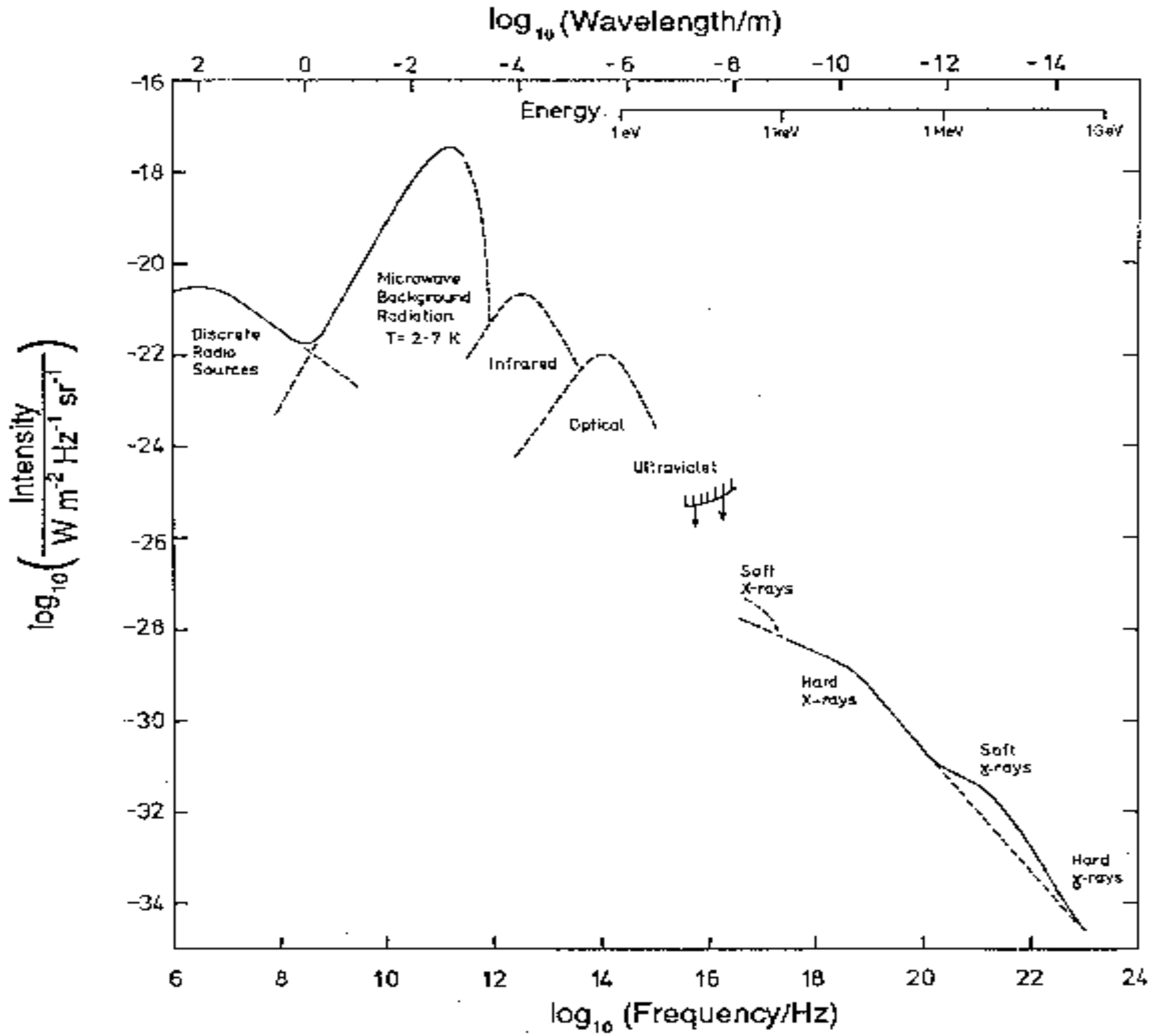
All what we know is astrophysics is thanks to the light !

- 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…

A multiwavelength Sky

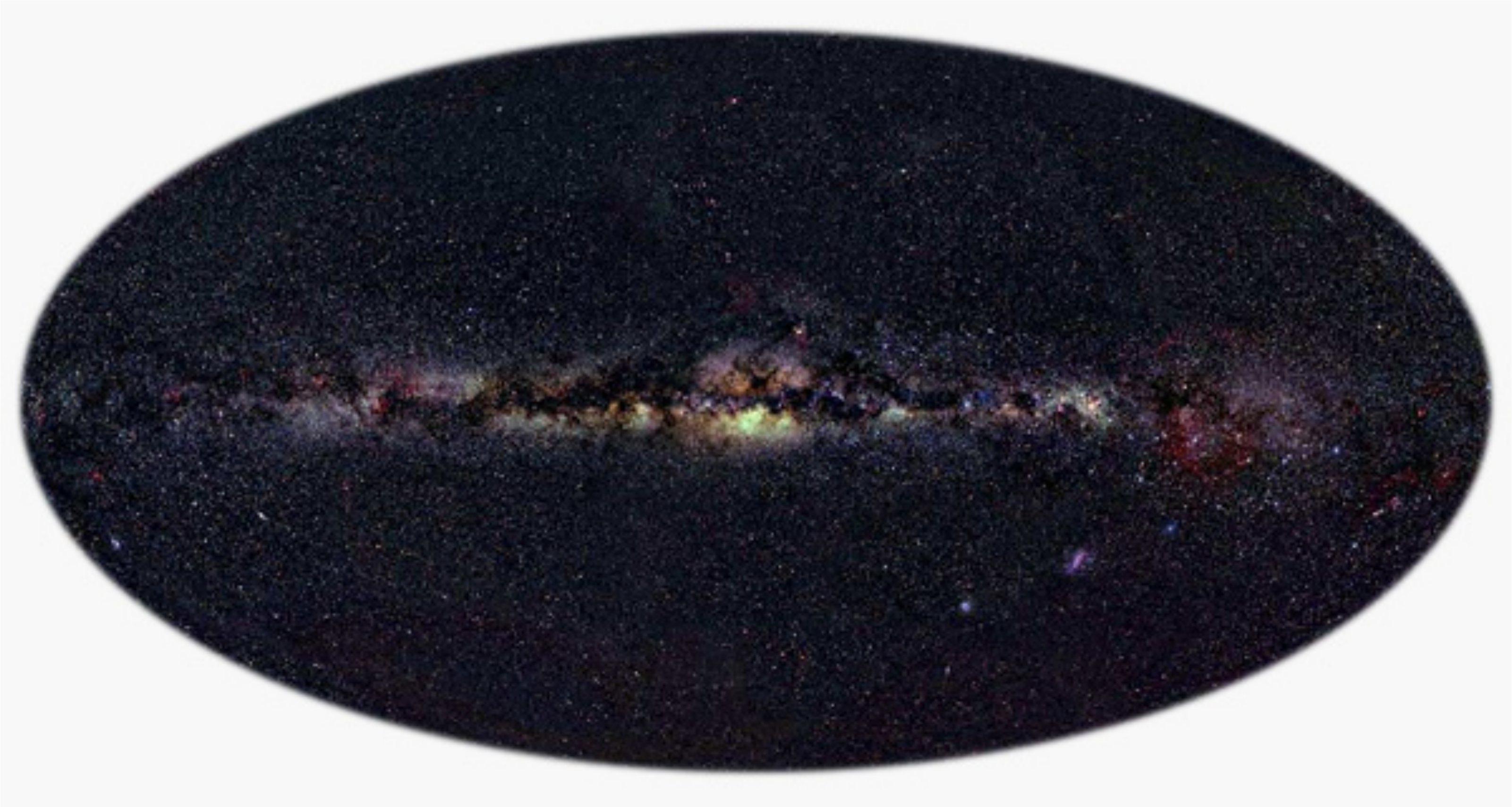


Our galaxy

The optical Milky Way

Our galaxy

Visible Light
460 10^3 GHz / 400 - 700 nm / 1 eV

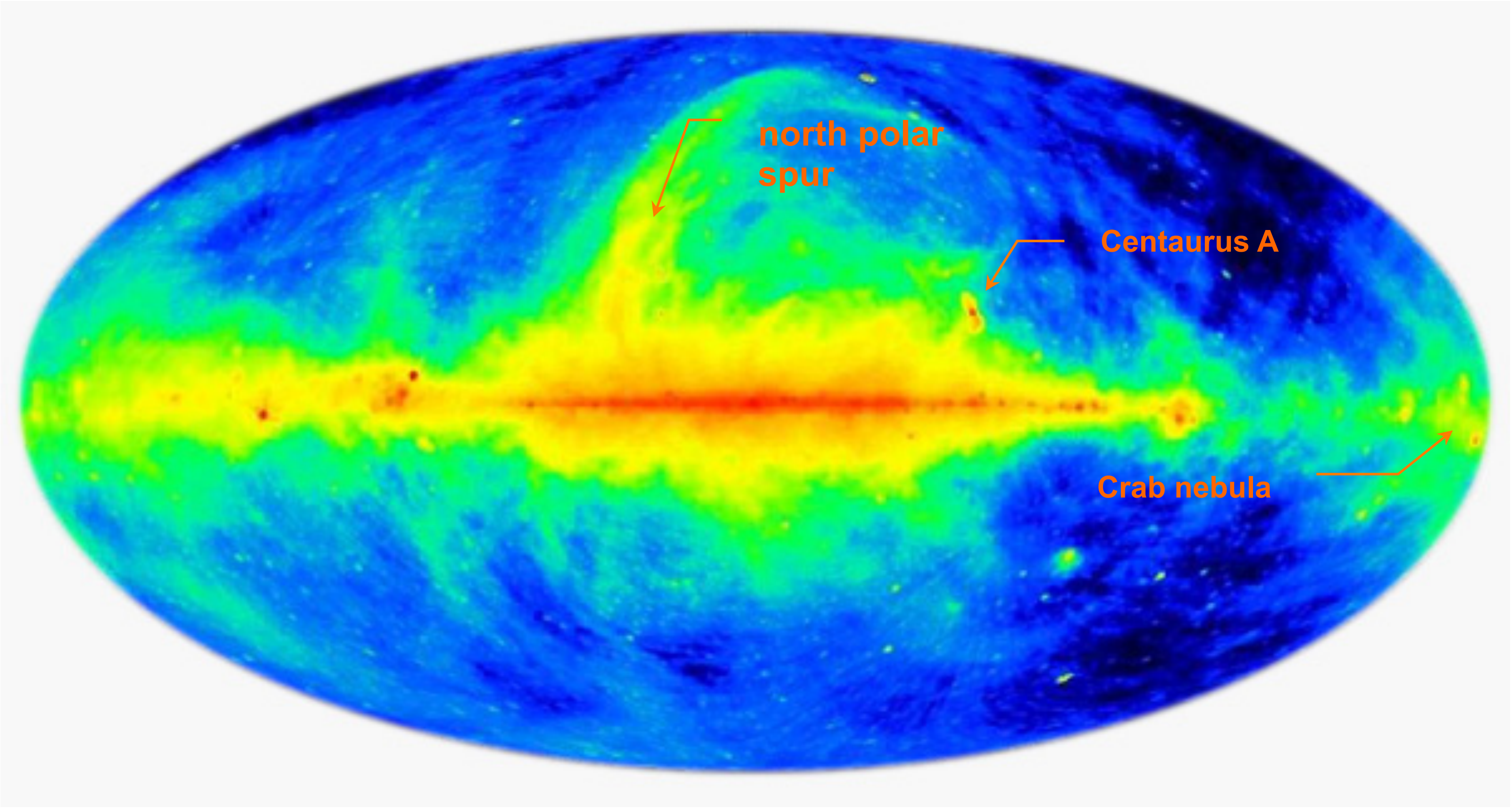


Visible light is absorbed by interstellar dust clouds.
Only stars close enough to the solar system (few parsec) are seen.

Our galaxy

Milky Way : Radio at 73 cm

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

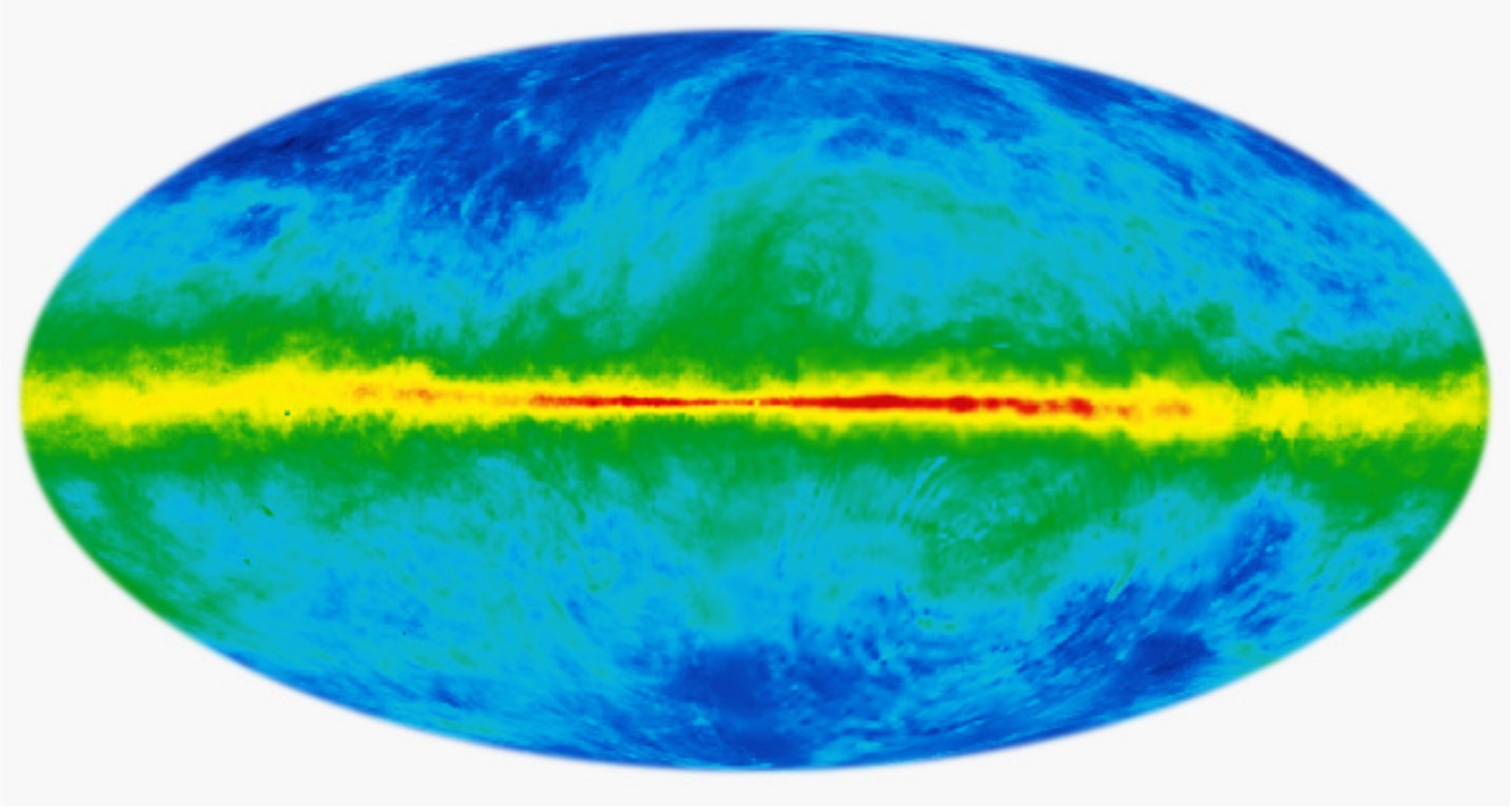


Radio wave essentially from the movement of ultra relativistic electrons probably issue from supernovae remnants in the galactic magnetic field.

Our galaxy

Milky Way : Radio at 21 cm

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

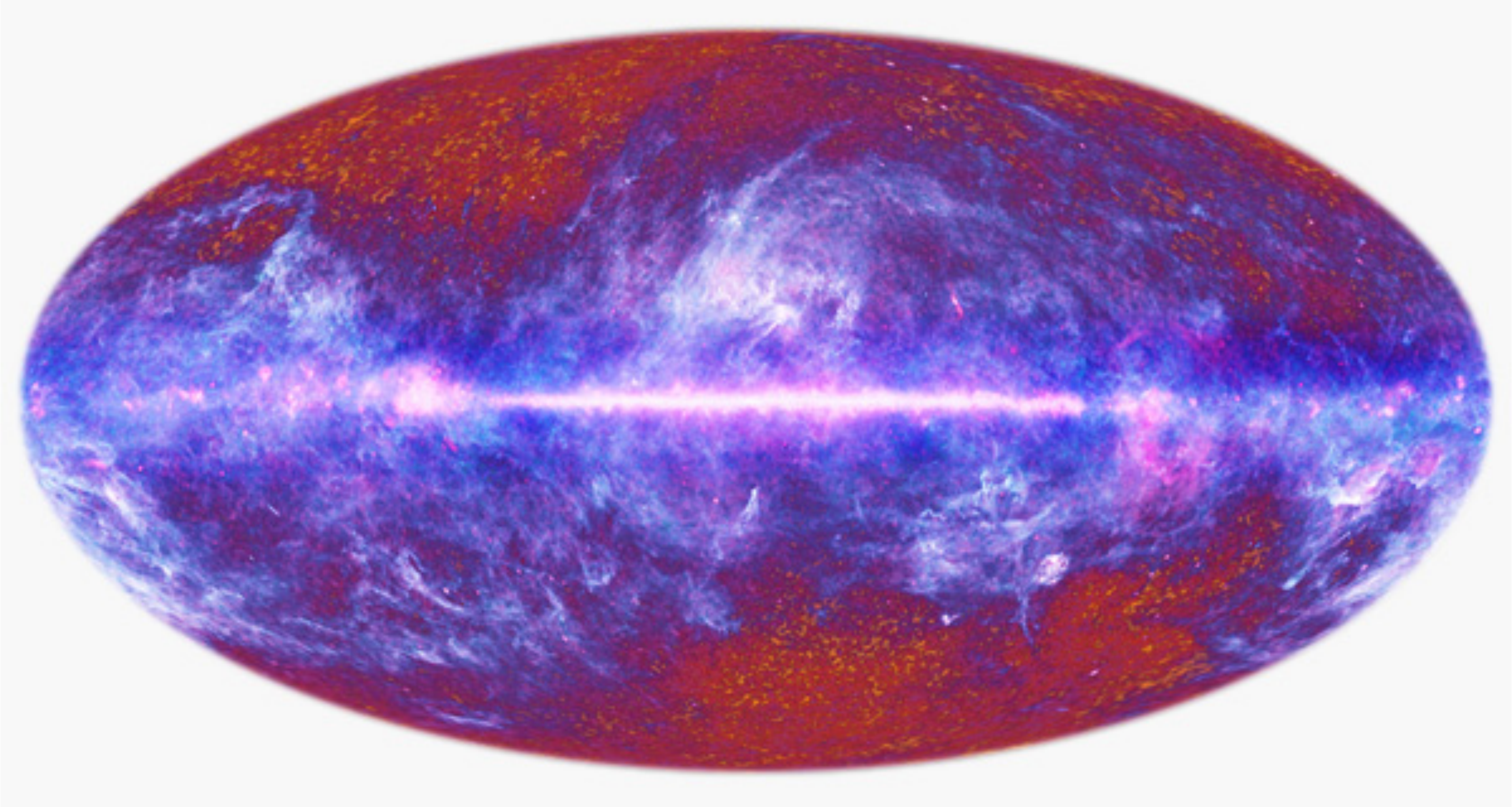


Hyperfine transition of hydrogen, neutral at low temperature. Structures are due to the column density of atomic hydrogen clouds along the line of sight showing the presence of interstellar clouds.

Our galaxy

Microwave

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

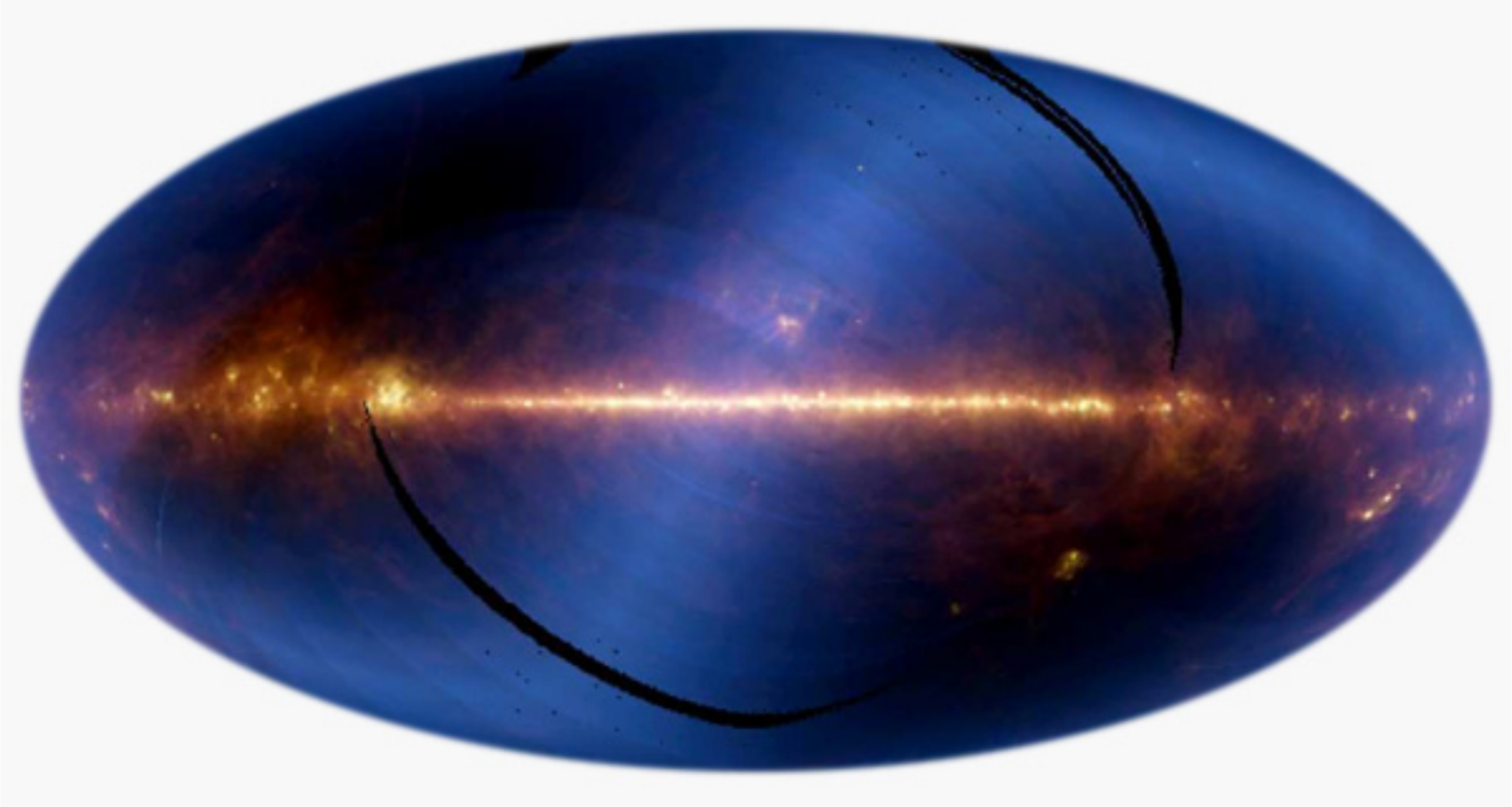


Red clumpy spots : Cosmic Microwave Background

Foreground : Magnetic field in the galaxy (synchrotron effect on electron)

Our galaxy

Far Infrared
10.10^3 GHz / 100 µm / 0.05 eV)



Thermal emission, due to interstellar dust heated by starlight.

Our galaxy

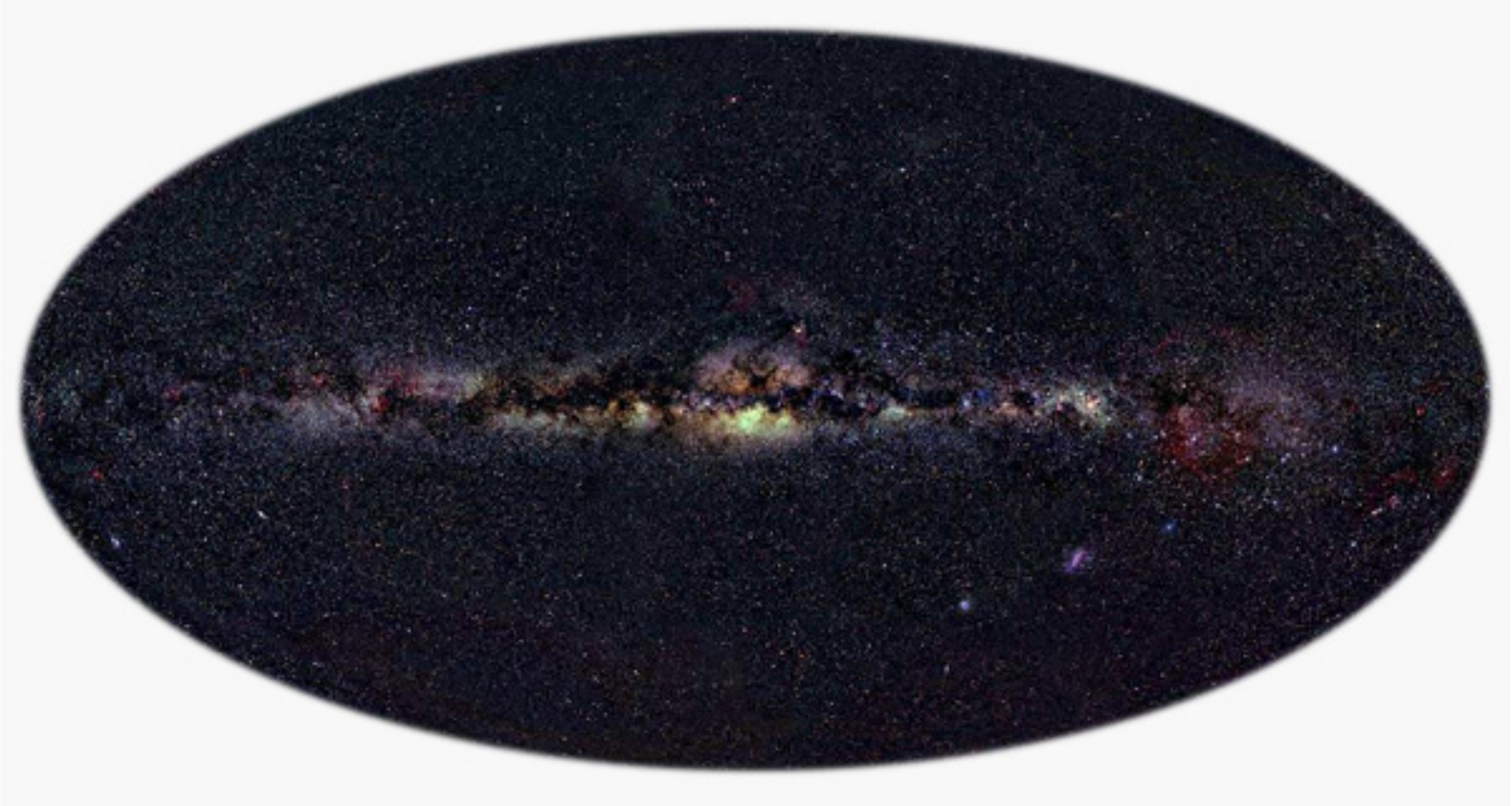
Infrared Sky
100.10^3 GHz / 2 µm / 0.5 eV

Giant stars emission in the disk and in the bulb

Our galaxy

Visible Light

460 10^3 GHz / 400 - 700 nm / 1 eV

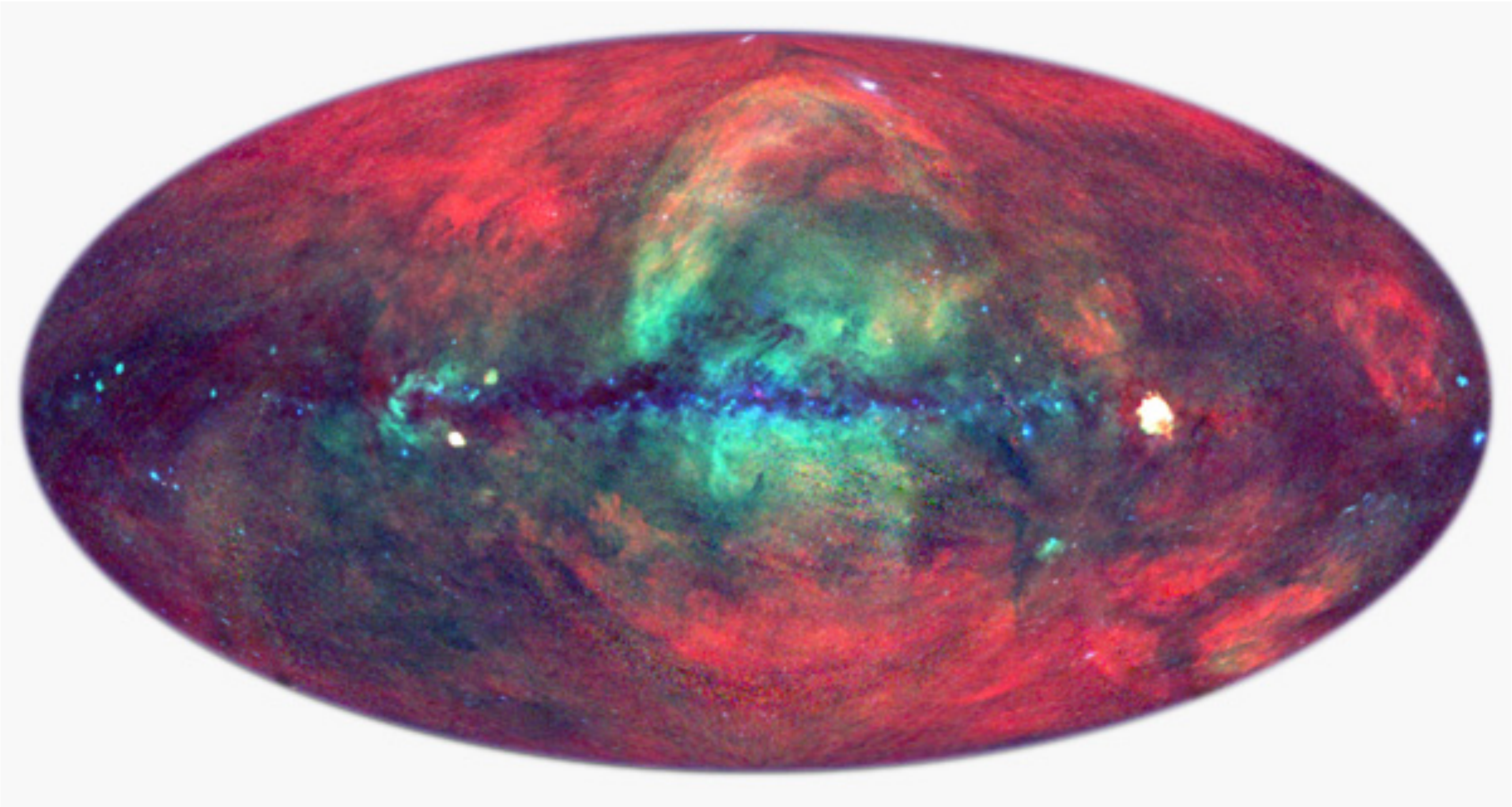


Visible light is absorbed by interstellar dust clouds.

Only stars close enough to the solar system (few parsec) are seen.

Our galaxy

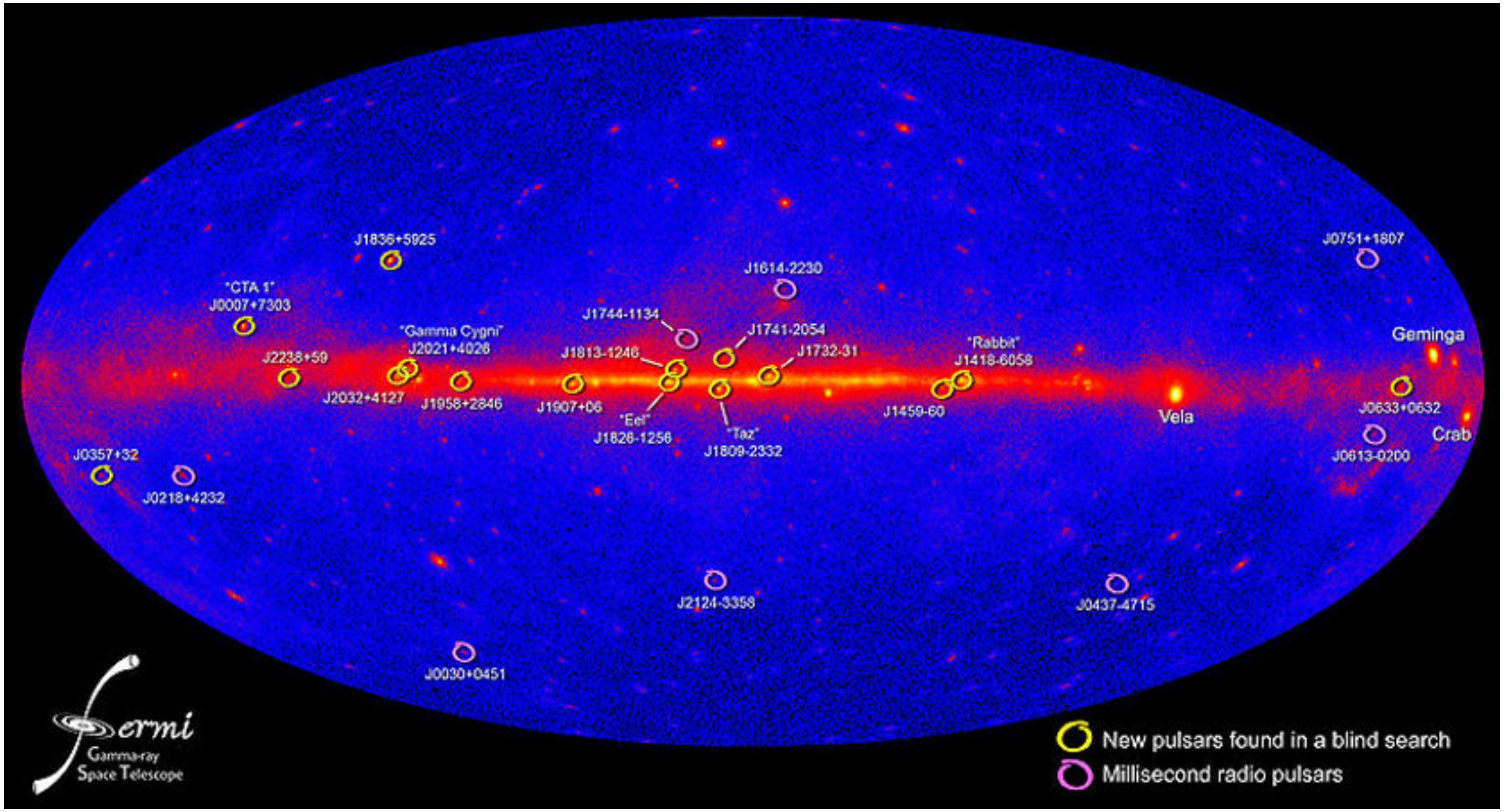
X-Rays
360 GHz / 8.3 nm / 1.5 keV



Diffuse X-ray emission from overheated and shocked gas.
The dark band shows the absorption from cold gaz of our galaxy.

Our galaxy

High Energy Sky
Gamma rays (>100 MeV)



The gamma emission is due to collision between cosmic rays (atoms and relativistic particles) and interstellar clouds, to bremsstrahlung and inverse Compton process

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- Nuclear reactions, galactic and extragalactic hydrodynamics, MHD, explosions, nucleosynthesis,
  past, future… EVERYTHING !

Well, almost everything…

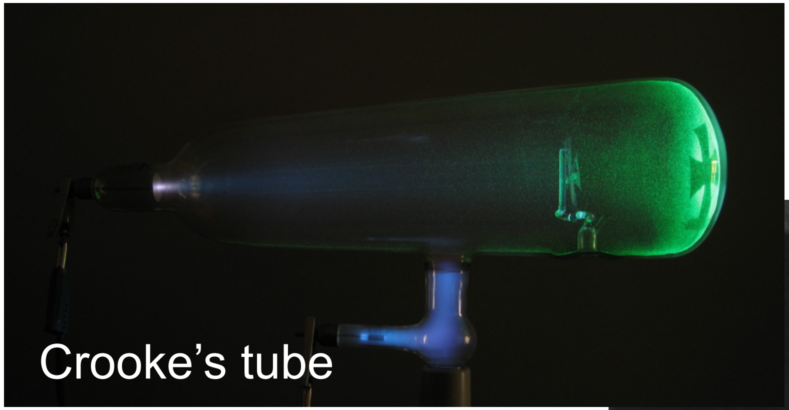
- Non-luminous messengers : Cosmic Rays !
- Rare but precious : **~ 4 CR/cm²/s**
  ~30 μg/s on entire earth (**1kg** per year !)

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

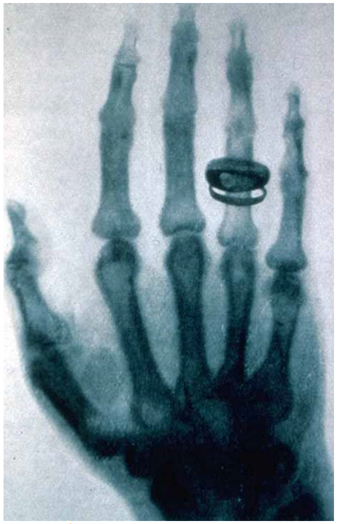
- …but not astrophysics !
- Energy spectra and chemical composition tells us a lot…

Big Discoveries in 19th century

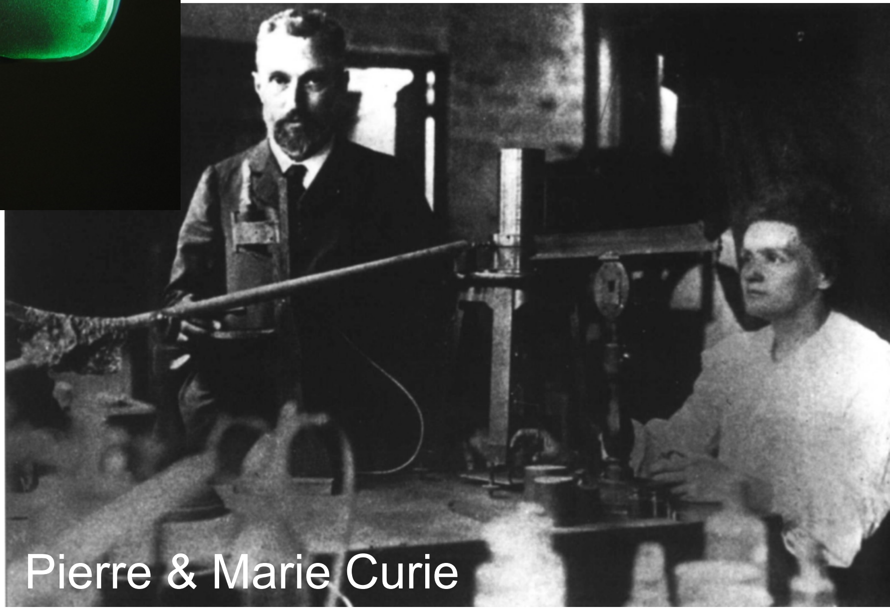
- 1885: Discovery of the cathode's rays (electron) Jean Perrin
- 1895: Discovery of the X rays Röntgen
- 1886: Discovery of the natural radioactivity Henry Bequerel
- 1898: Discovery of the Radium Pierre & Marie Curie



Crooke's tube



1st radiography :
hand of Ms Röntgen



Pierre & Marie Curie

The electroscope

The electroscope

- Charged up electroscope → the "arms" repel each other

The electroscope

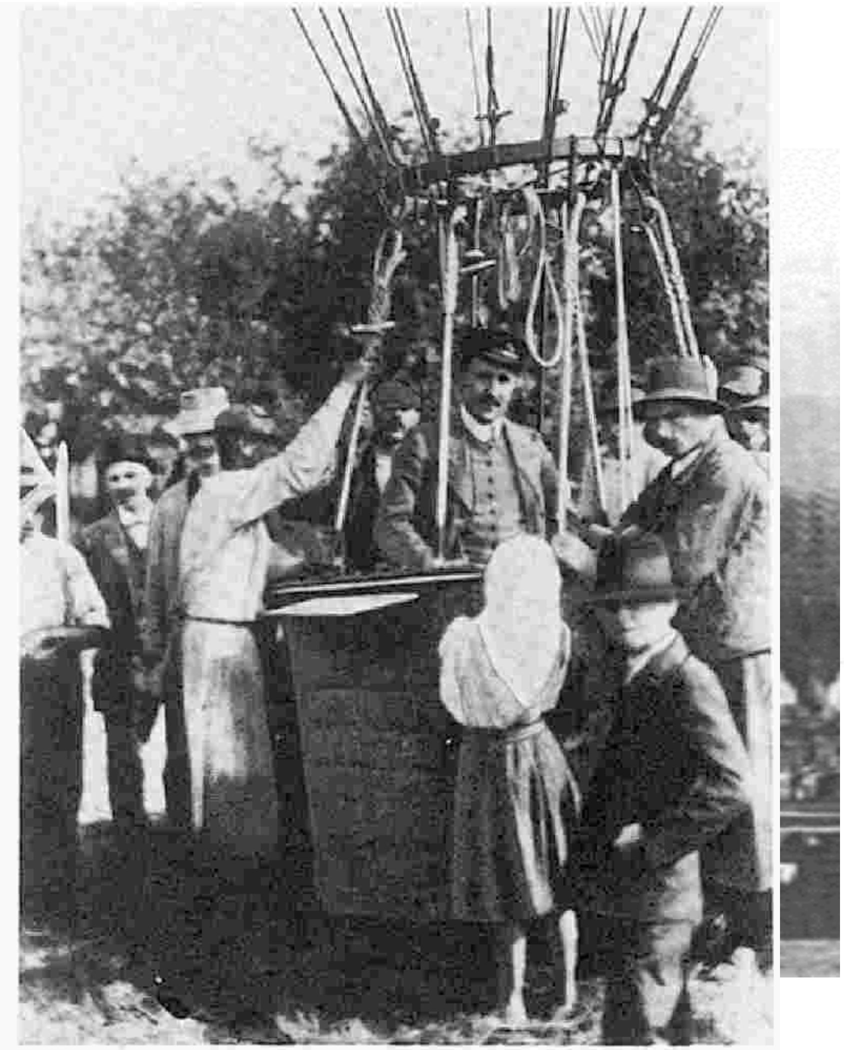
- Charged up electroscope → the "arms" repel each other
- Under ionizing radiations, the air is partially ionized and the electroscopes discharges.
- The more intense the radiation is, the faster the electroscope discharges.

Fast discharge

- 1901 : Wilson notice the time of discharge is the same on the ground and underground remarque que la décharge est identique sur Terre et sous un tunnel (environ 7 divisions par heure).
- Rutherford demonstrate that natural radioactivity (rock and equipment) is not responsible.
- 1910 : the priest Théodore Wulf (built the best electroscope) did study on the top of the Eiffel Tower


The Eiffel Tower
important ...
Enigme
3,5 ions/cm³
...
for Science
Height: 300m
→ Flux/15
6 ions/cm³

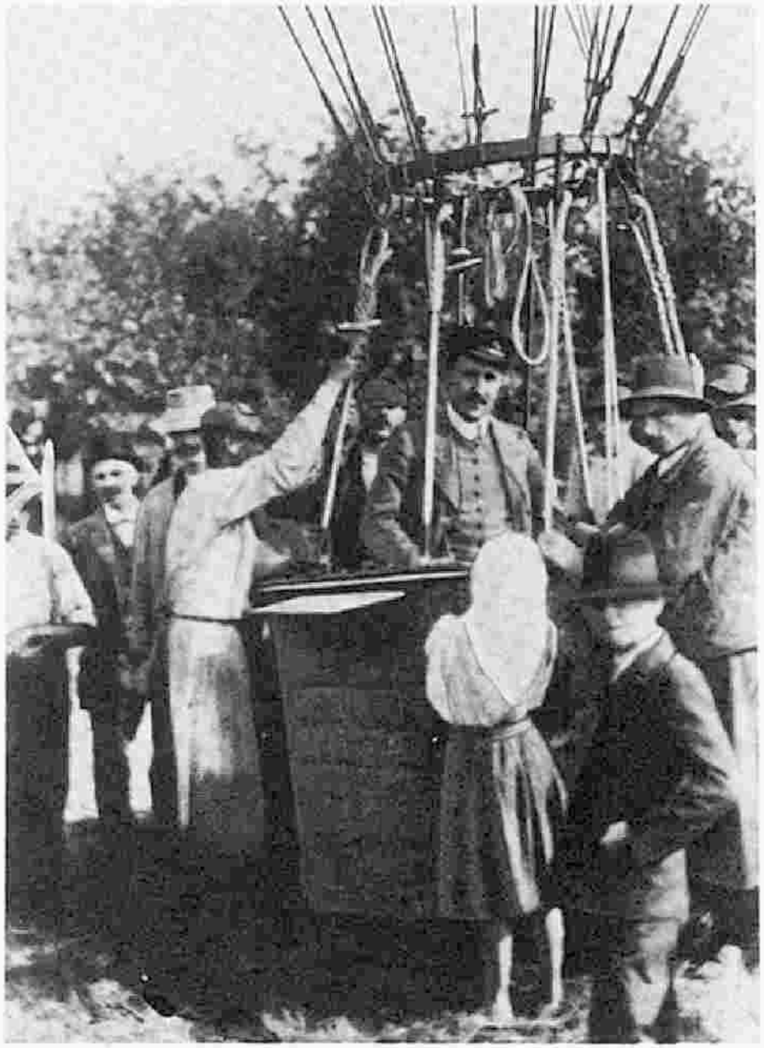
Lets go higher !



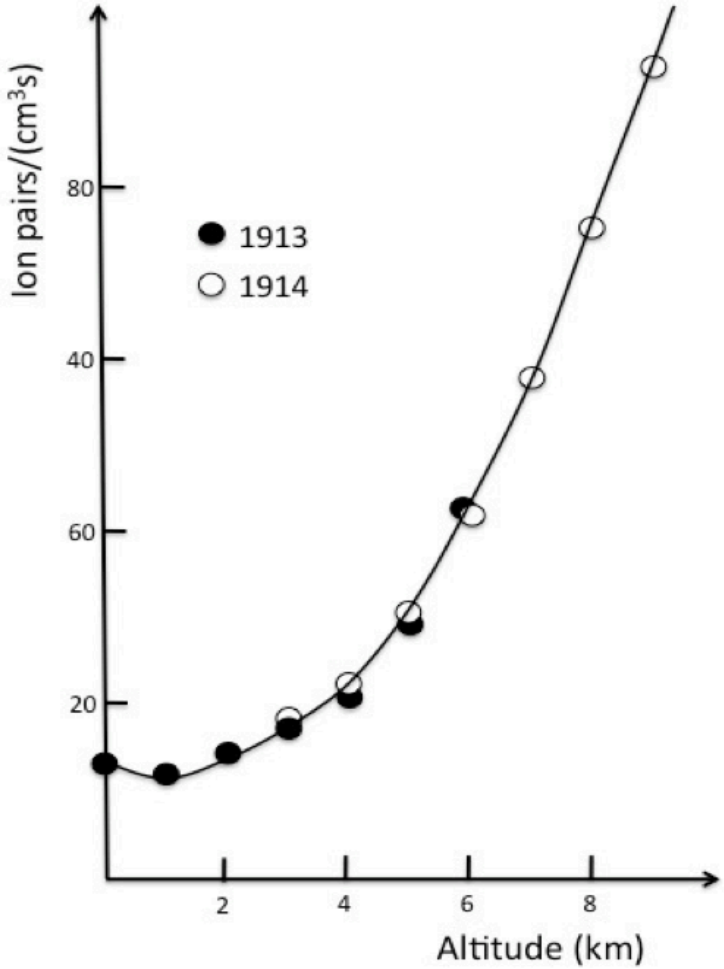
Hess bei Ballonlandung (1912).

Route des Entdeckungsfluges der kosmischen Strahlung.

Lets go higher !



Hess bei Ballonlandung (1912).



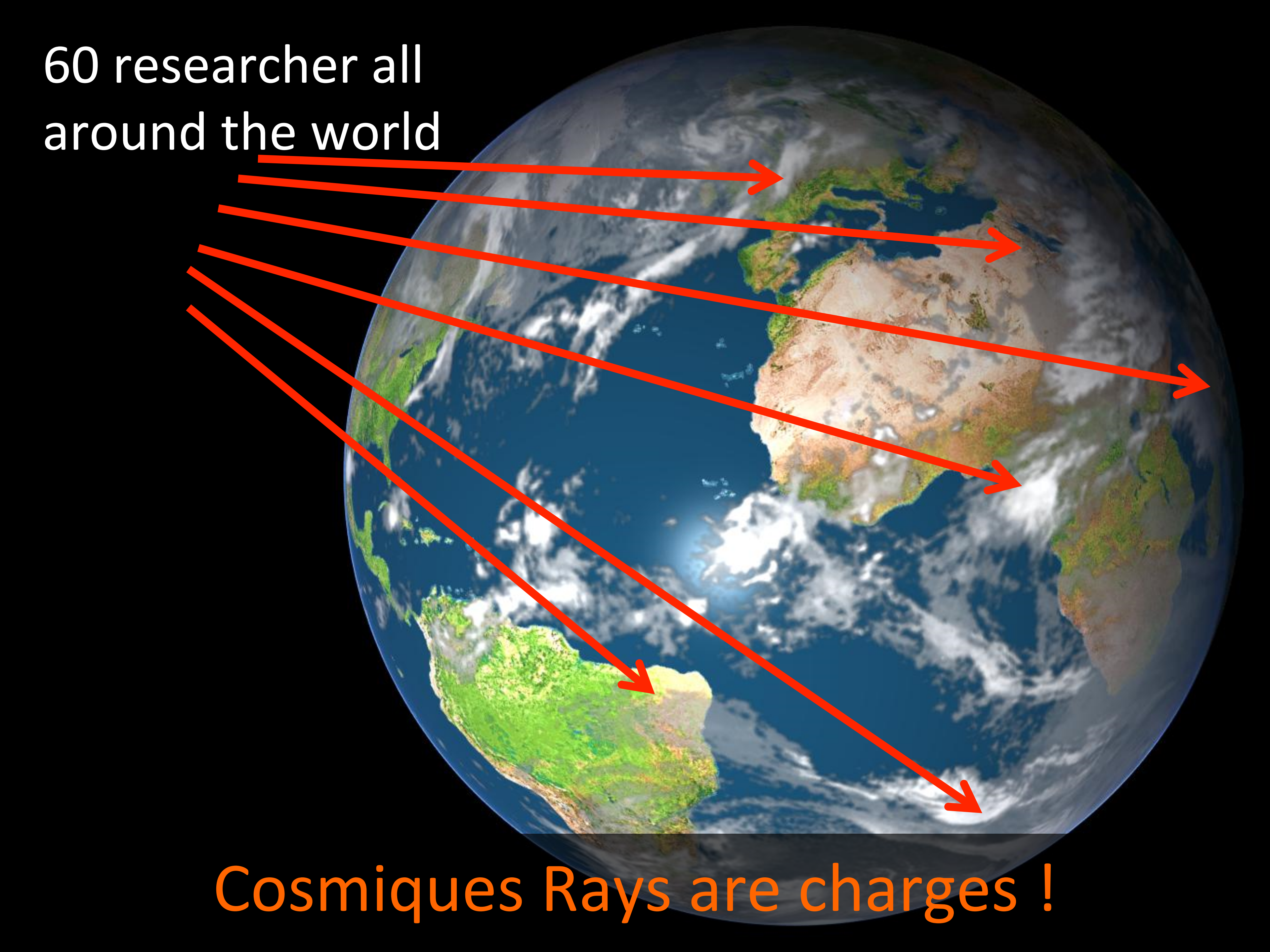
« The result of these observations seems to be explained in the simplest manner by assuming that an extremely penetrating radiation enters the atmosphere from above » (V. Hess)

17 years

From 1912 to 1928, not that much happens:

- Robert Millikan lead the game and he believes that the Hess rays are very high energy gammas thus there name (→1925 : « Cosmic Rays »).
- In 1929 : Bothe and Kohlörster work with Geiger counters and show that Hess rays are charges !
- D. Skobeltzyn, who works with bubble chambers finds curved tracks in magnetic field as well.

But Millikan resist and refute these conclusions...


60 researcher all
around the world
Cosmiques Rays are charges !

Summary

In 1932, Millikan admits CR are "Cosmic" and there are charges.


The New York Times

MILLIKAN RETORTS HOTLY TO COMPTON IN COSMIC RAY CLASH

Debate of Rival Theorsts Brings Drama to Sessicn of Nation's Scientists.

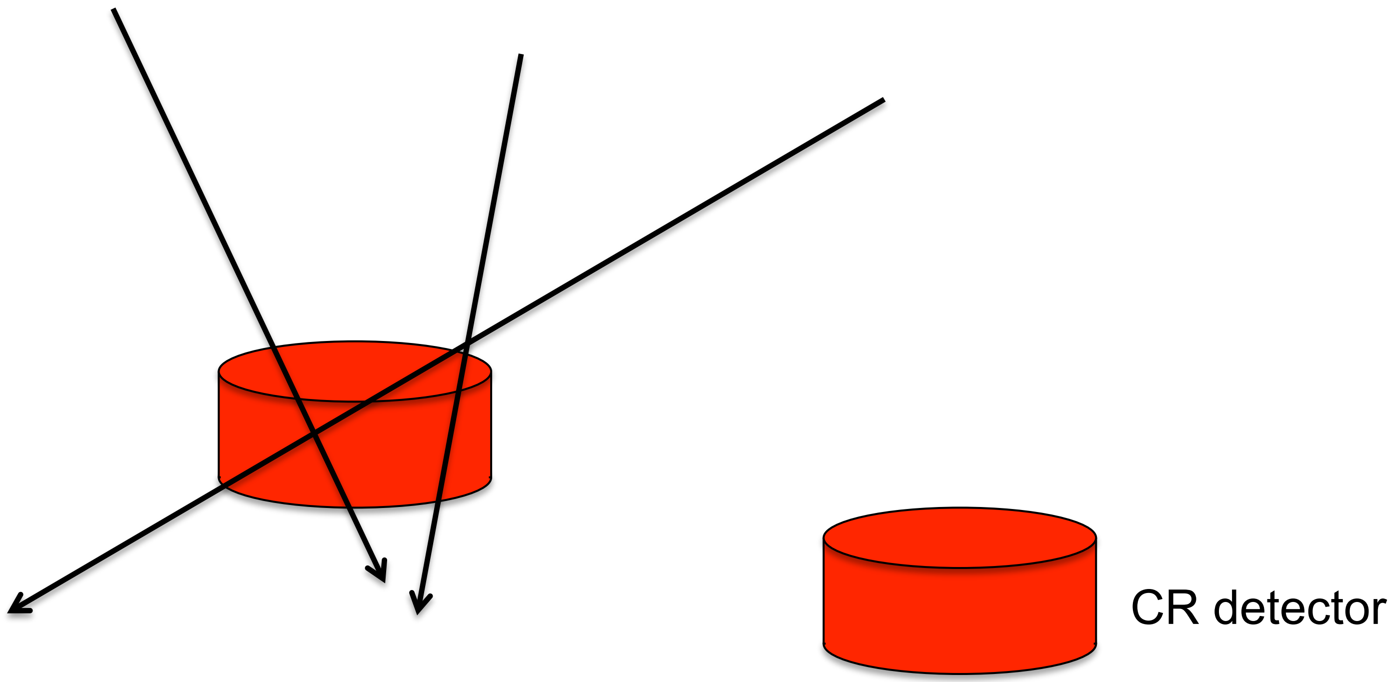
THEIR DATA AT VARIANCE

New Findings of His Ex-Pupil Lead to Thrust by Millikan at 'Less Cautious' Work.

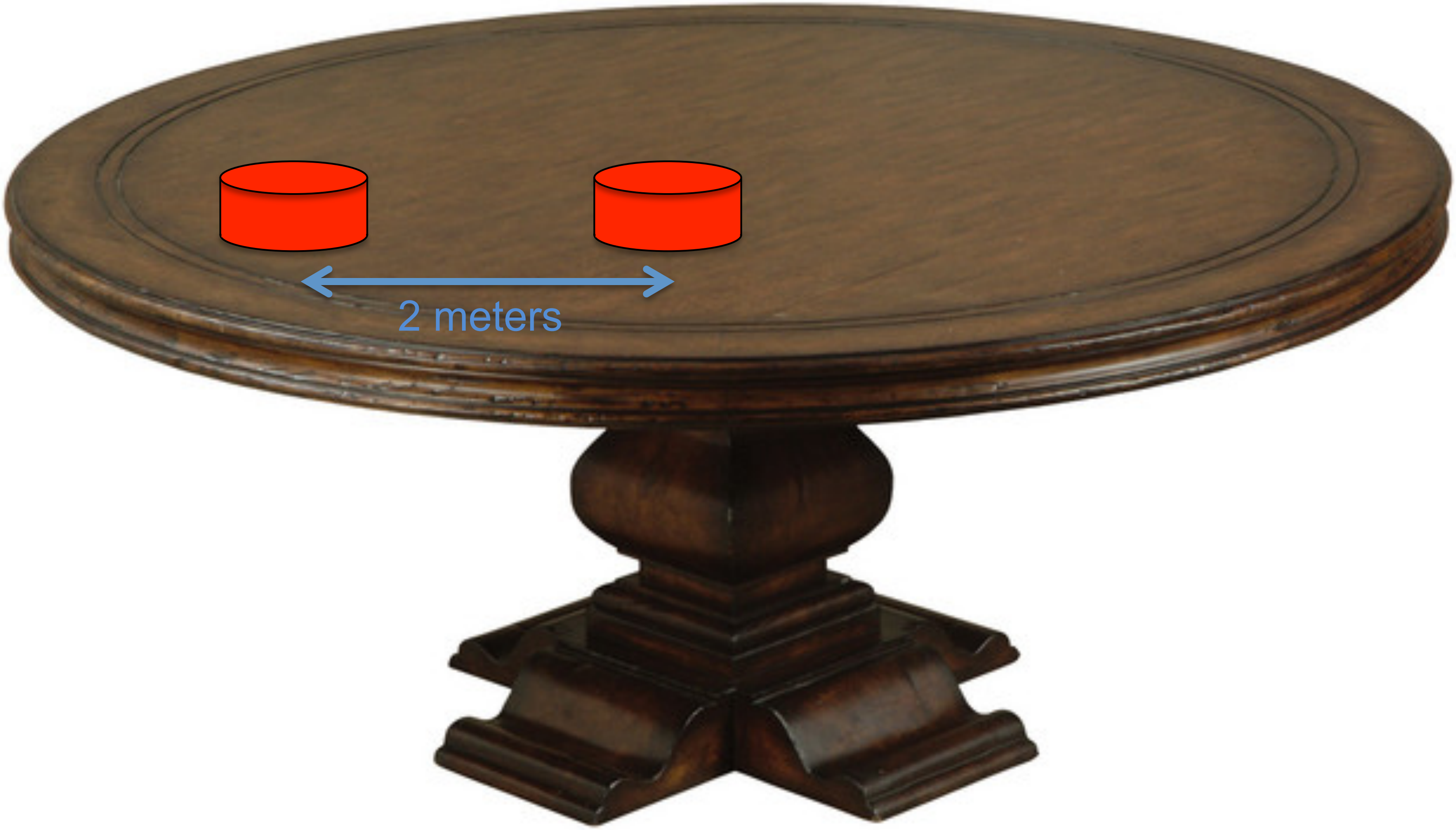
Measurements on CR say,
it is not depending on :

- The Sun
- The Milky Way
- Other region of the sky
- The intensity is constant and come from all directions
- At the ground we observe only secondary particles

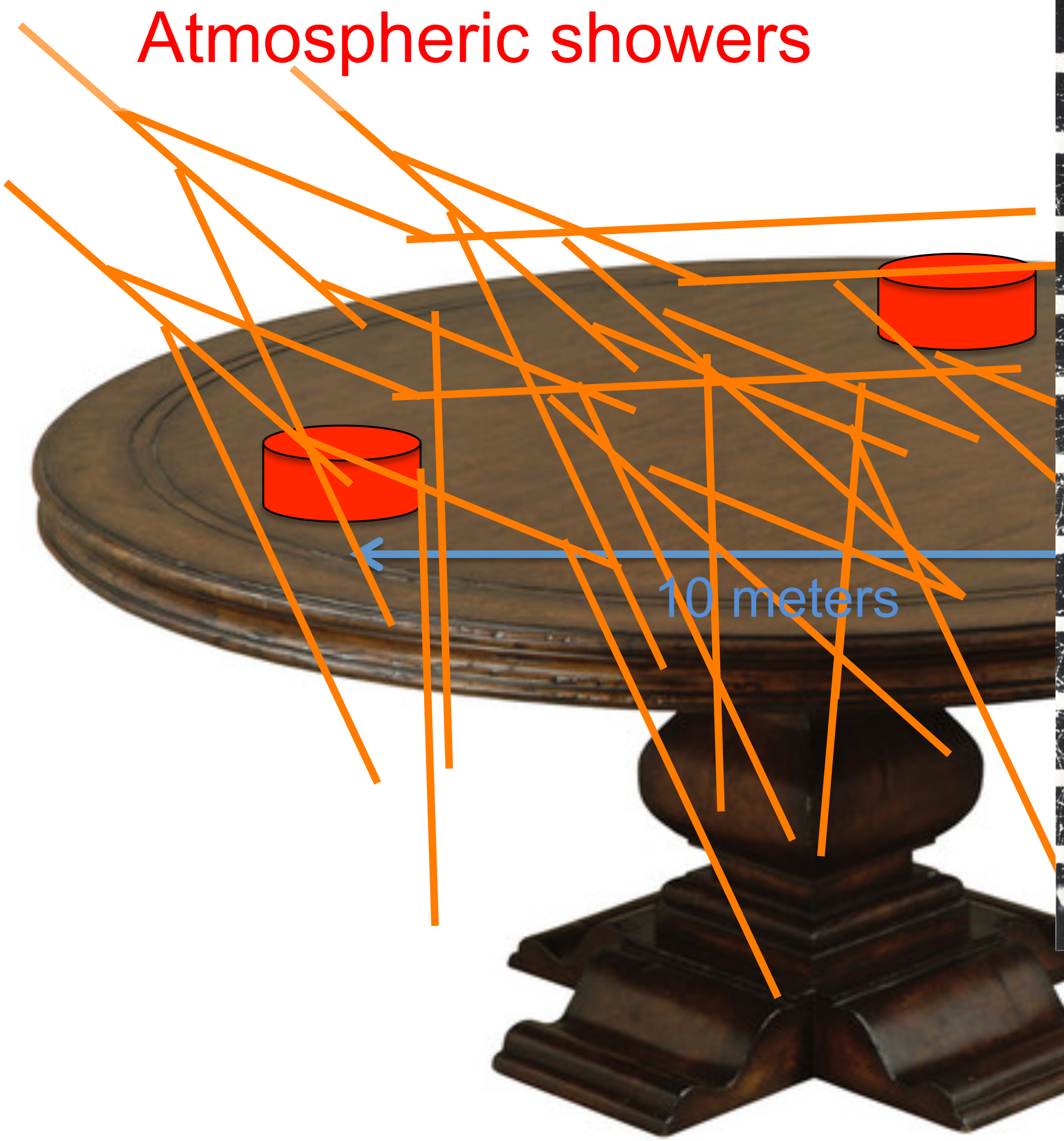
Pierre Auger and the atmospheric showers

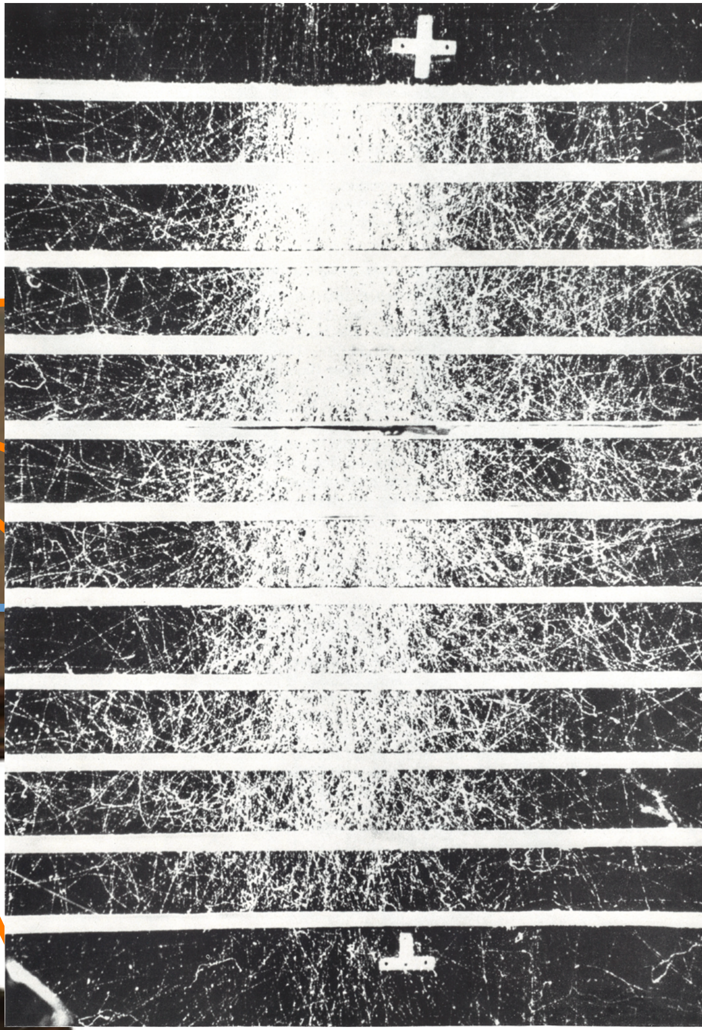


Detection in coincidence

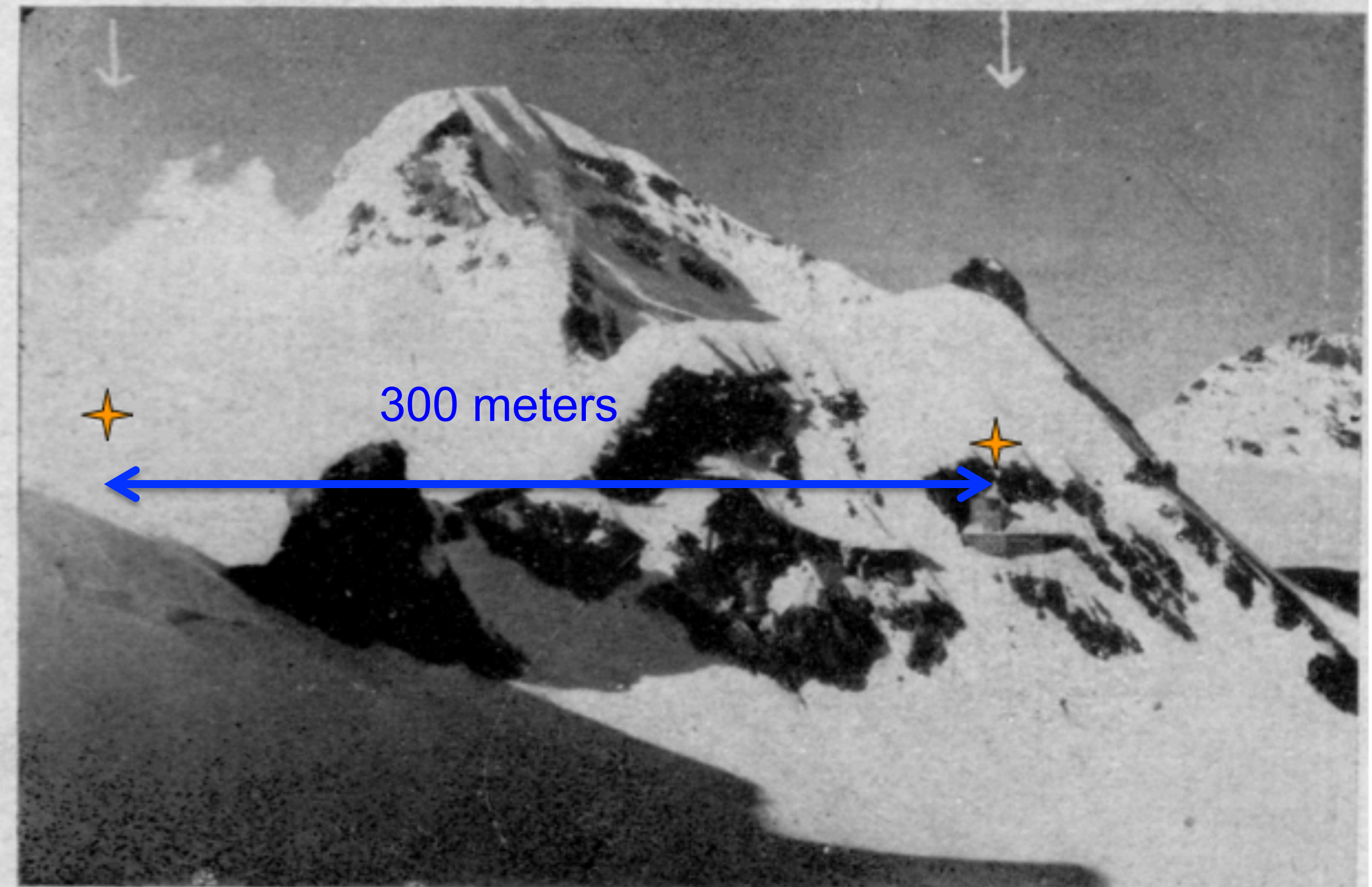


Detection in coincidence





Atmospheric showers



Cliché Auger et Daudin.

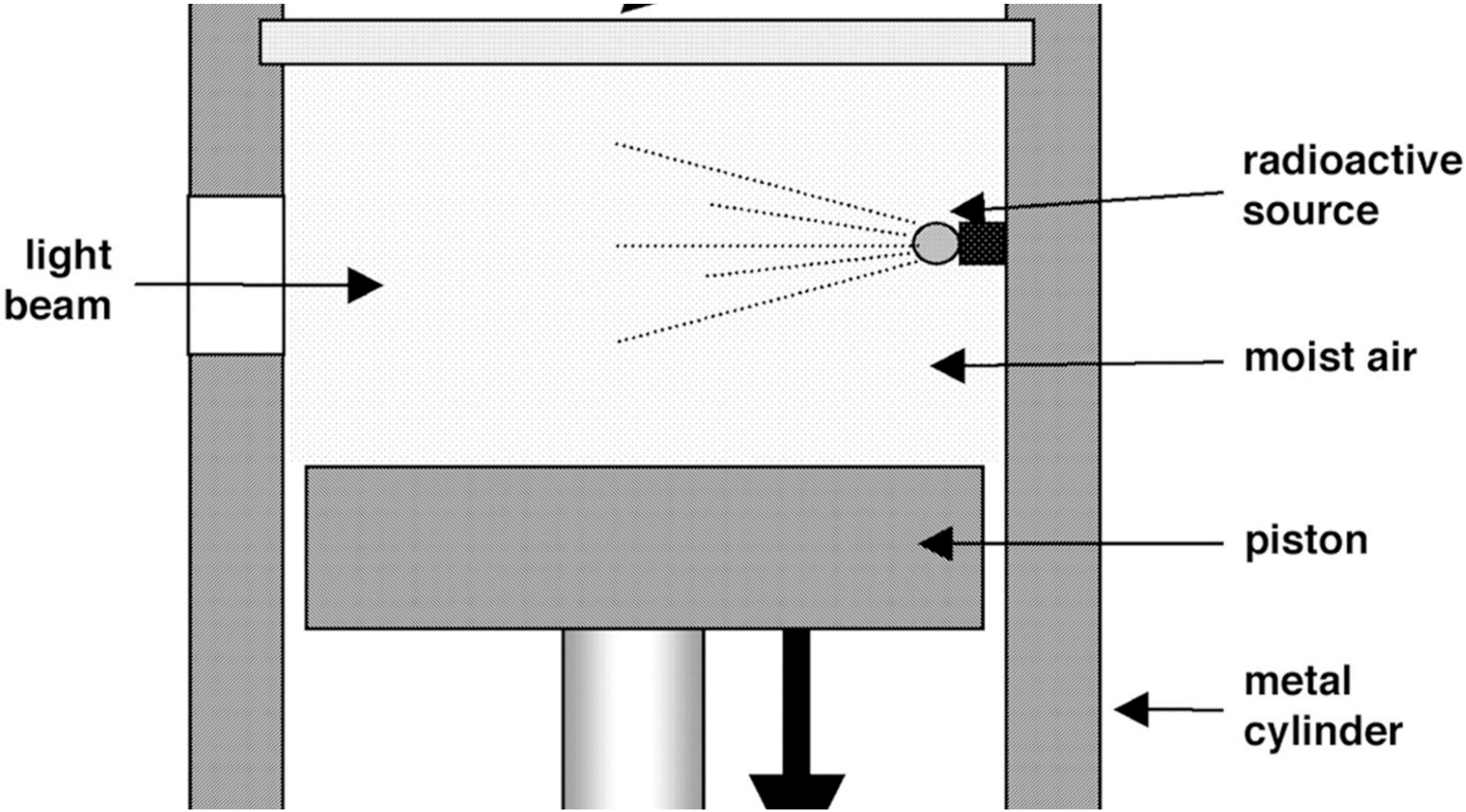
Vue du col de la Jungfrau, où les grandes gerbes ont été décelées sur une base de 300 m. Le laboratoire est sous la flèche de droite, marqué d'une croix, il contient un des compteurs. La croix de gauche indique l'emplacement du second compteur, sur la glace du col. La montagne située derrière est le Mönch.

The Cloud Chamber

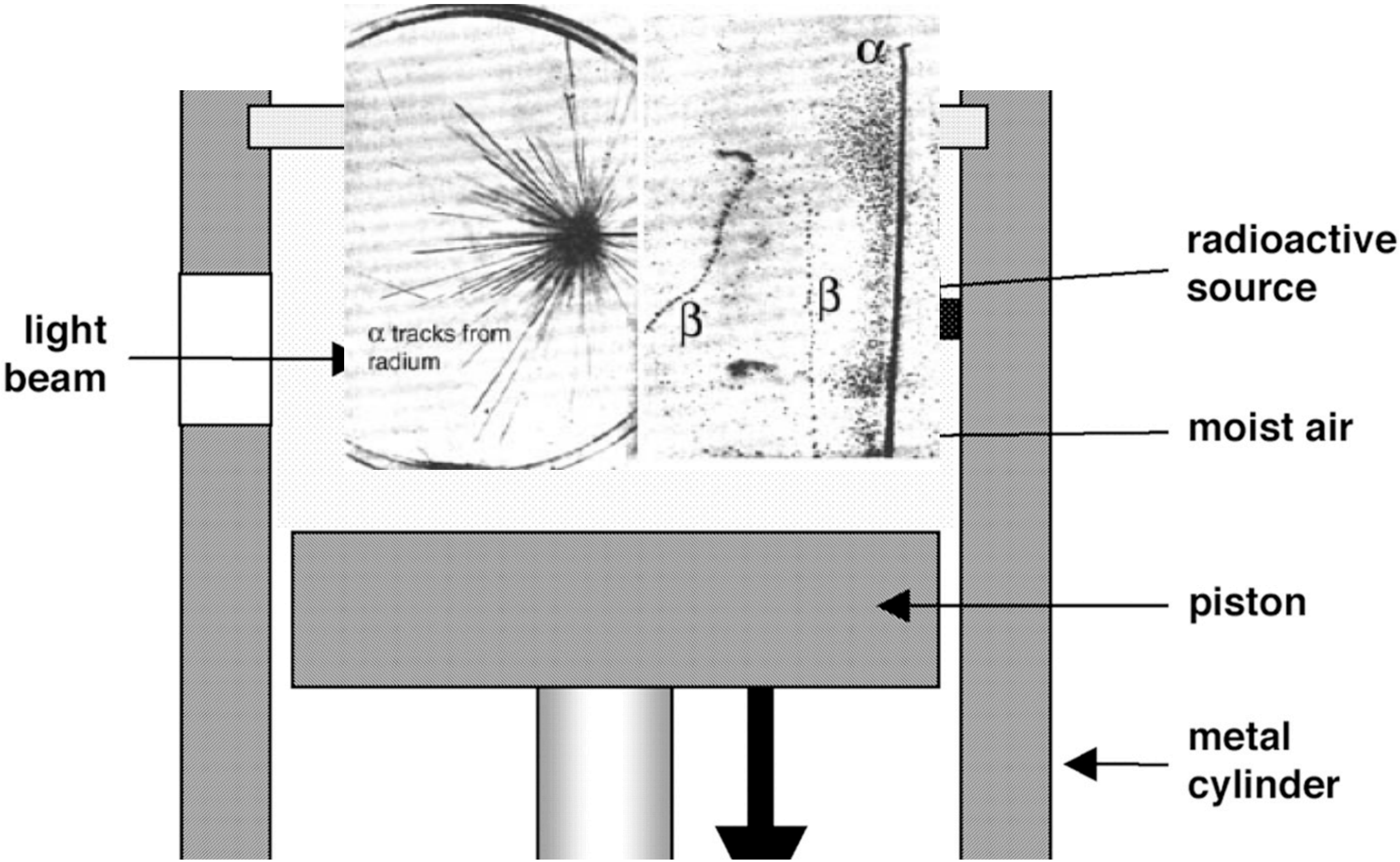
C.T.R. Wilson

1927 Tack of CR in clould chamber (RV are matter !)
Skobeltzyn

The Cloud Chamber



The Cloud Chamber



Positron identification

1932 Carl Anderson 

Detector: Cloud chamber and high magnetic field (B~2.5T)

How ? charged particles are deflected on the magnetic field depending on their charge sign

Lorentz force :

$$\vec{F} = \pm q.\vec{v} \times \vec{B}$$

What ? The particle momentum can be measured from the track curvature

Hypothesis:

- Milikan : photons
- Compton : electron ejected from the atom

Positive and negative tracks were observed !!

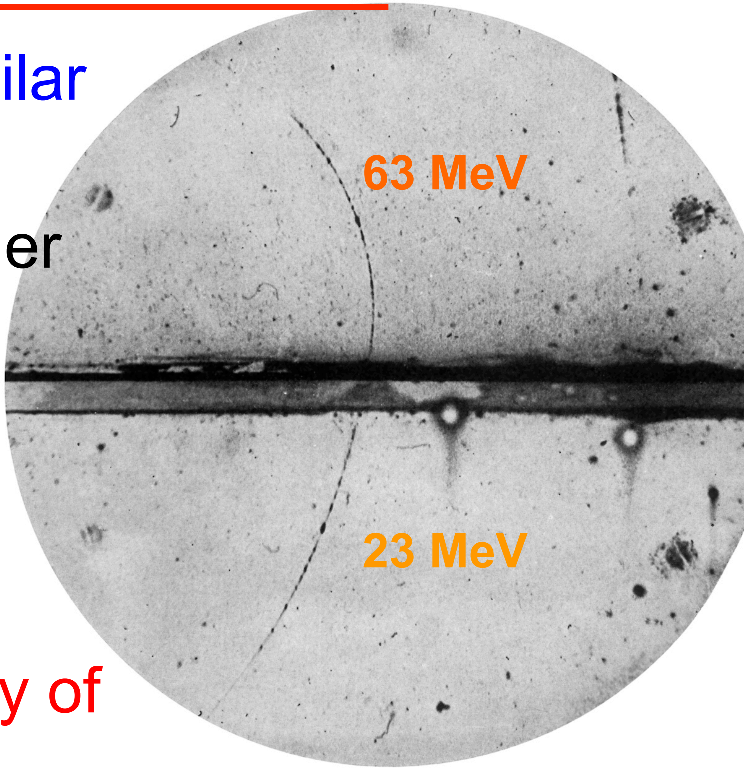
Positron identification

- Positron and proton curvature are similar
- For similar curvature particles (same momentum) the energy deposit is larger by the slowest (proton)

$$\frac{dE}{dx} \propto \frac{1}{\beta^2} \propto \left(1 + \left(\frac{m}{p}\right)^2\right)$$

Proton track are thicker as the density of droplets is large

- Negative tracks from below and positive particles from above have similar curvature



First track of positron (predicted by Dirac in 1930

➔ Anderson inserted a lead plate in the cloud chamber to distinguish particle direction !

A lot of new particles !

1932 Positron → Antimatter

1936 Muon

1949 Pion

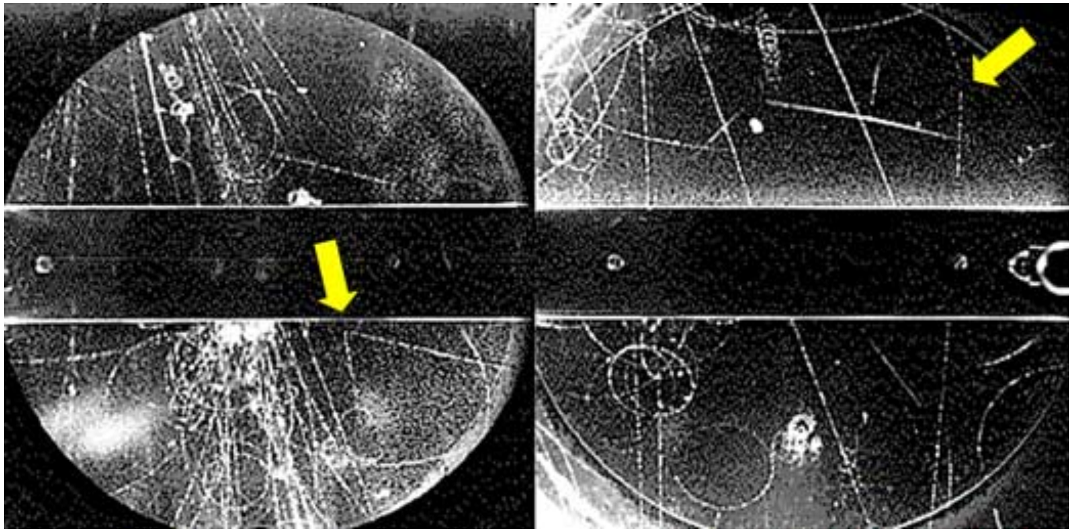
1949 Pions (π)

1949 Kaons (K)

1949 Lambda (Λ)

1952 Xi (Ξ)

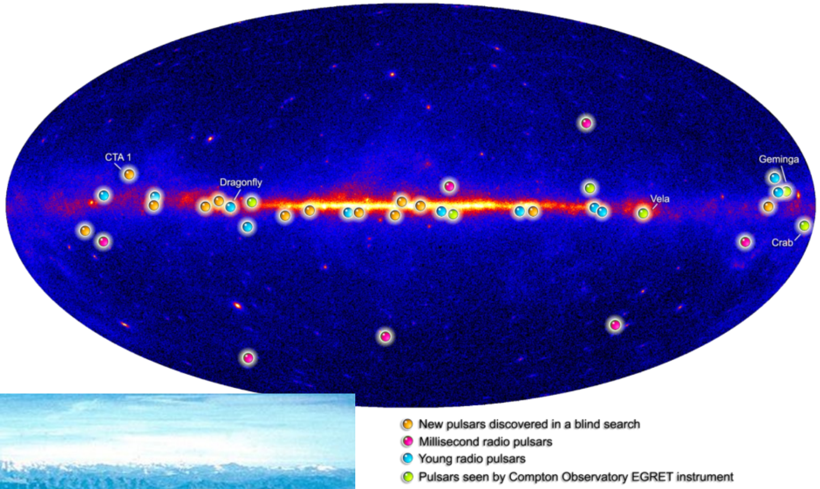
1953 Sigma (Σ)



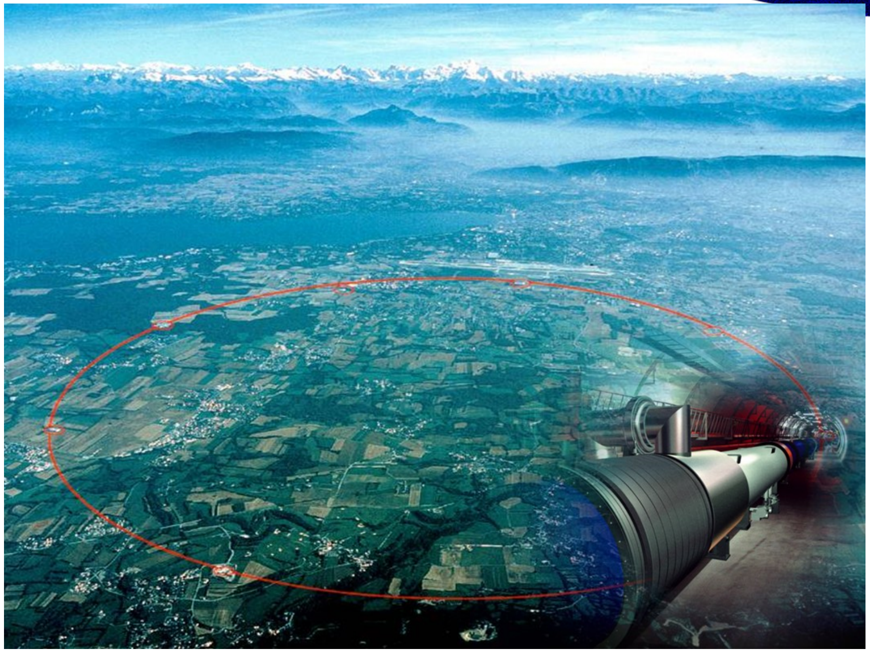
A new science is born :

Particle Physics !

Cosmic Rays

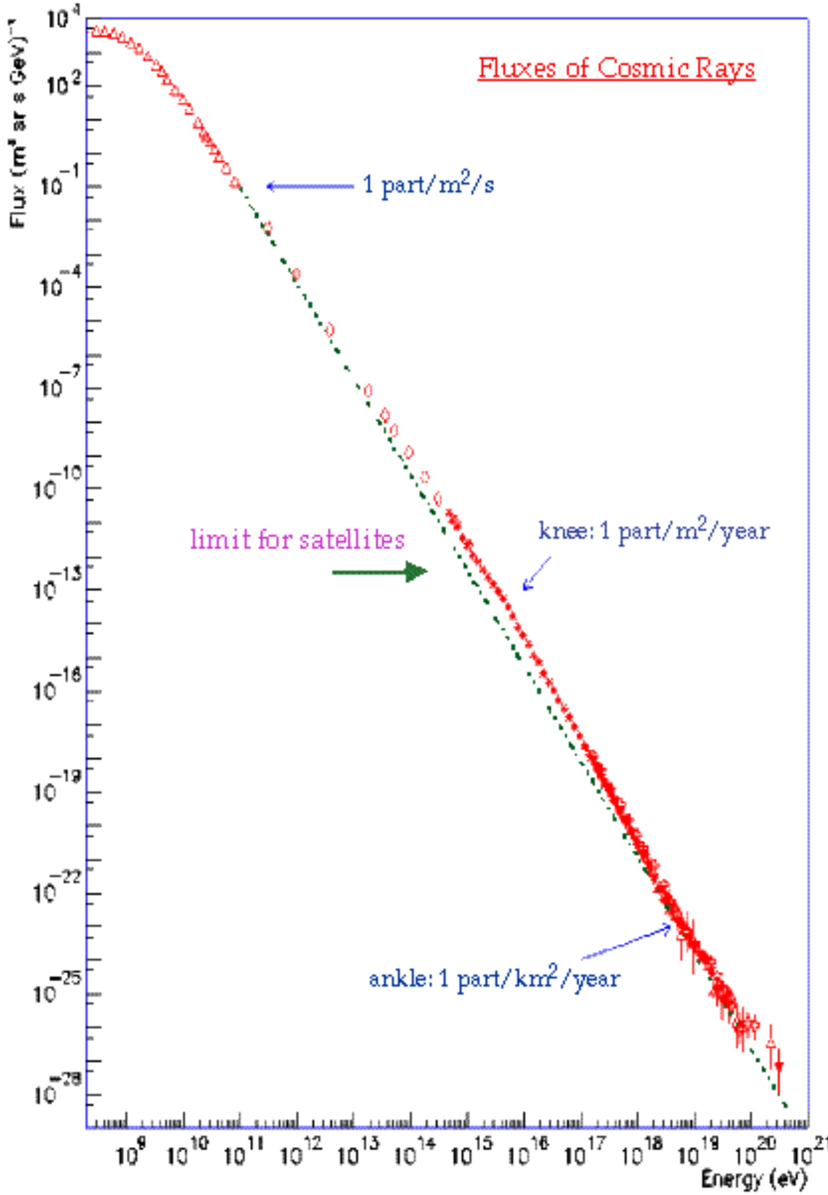


Astrophysic



Particle Physics

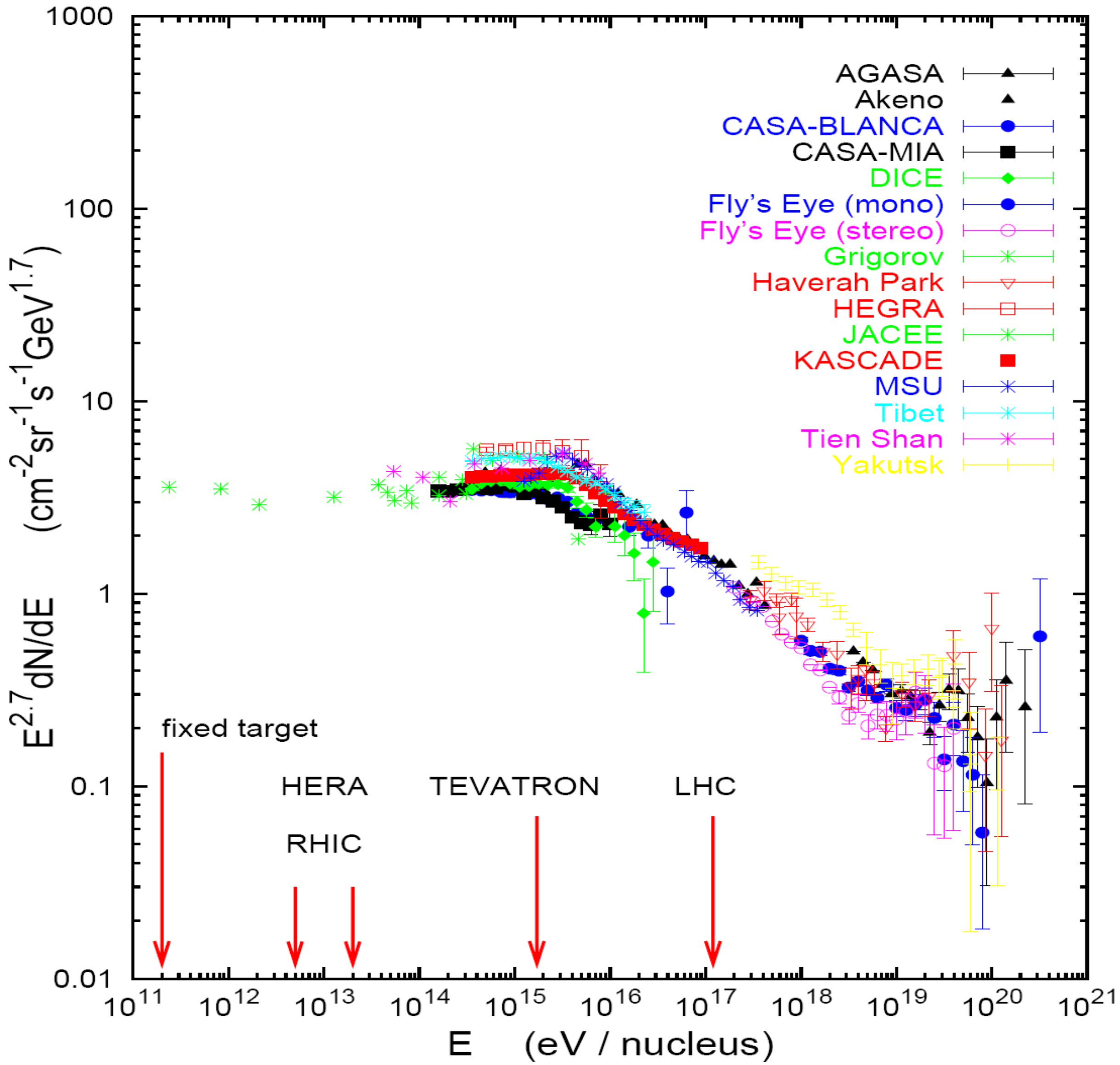
The “all” paticle sectrum



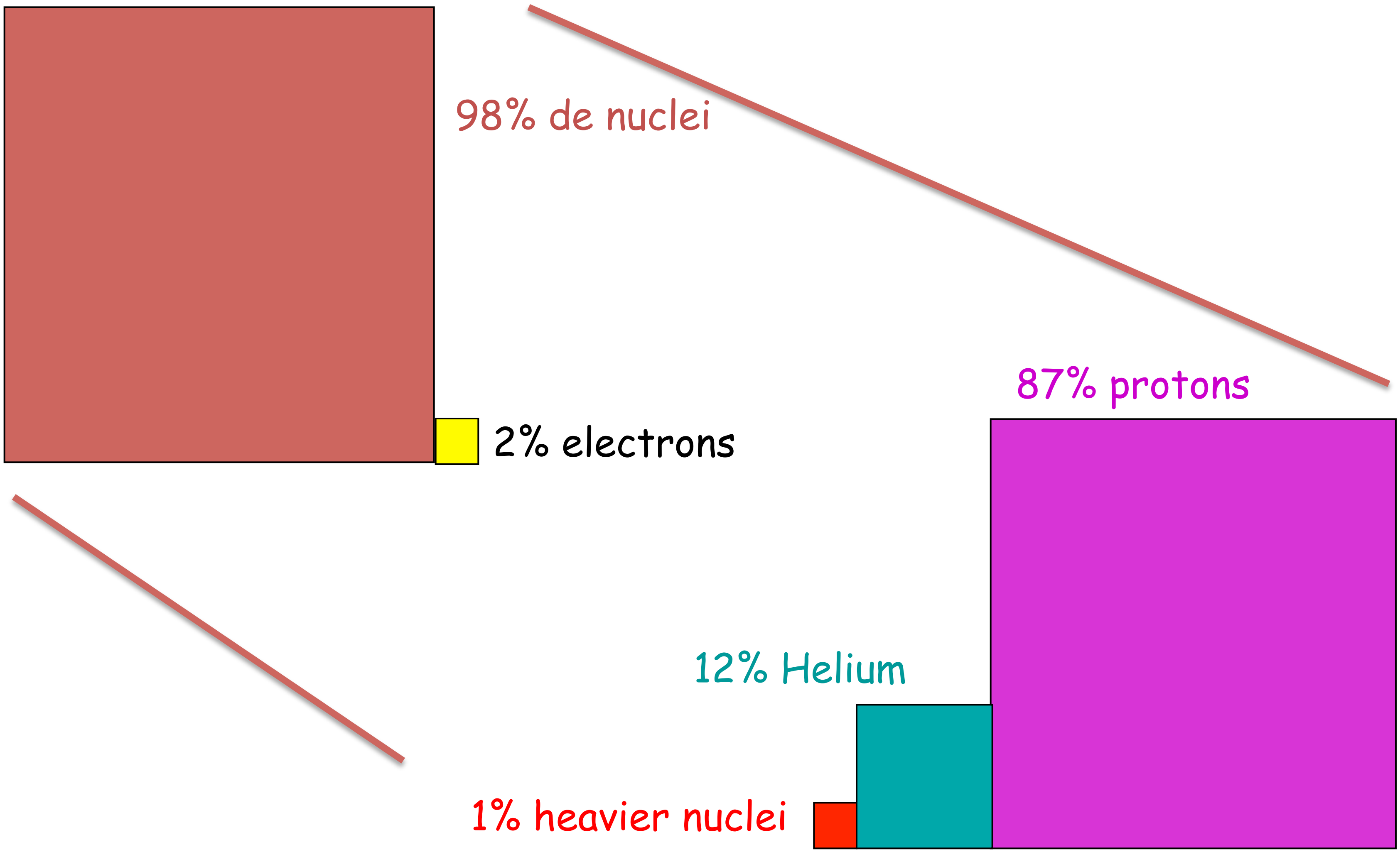
$$\frac{dI}{dE} \propto E^{-\gamma} \quad ou \quad I(>E) \propto E^{-(\gamma-1)}$$

- 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…

The “all” paticle sectrum

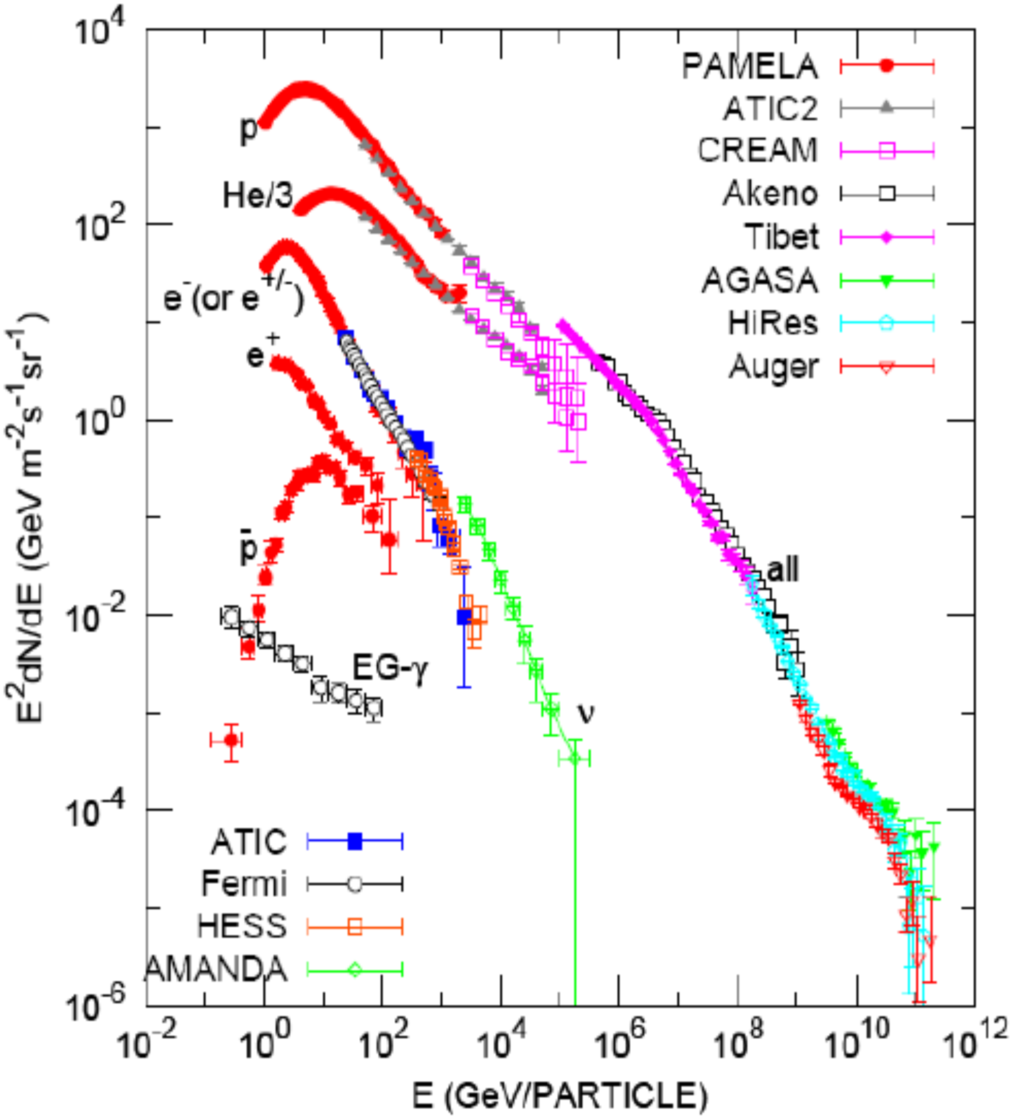


Composition



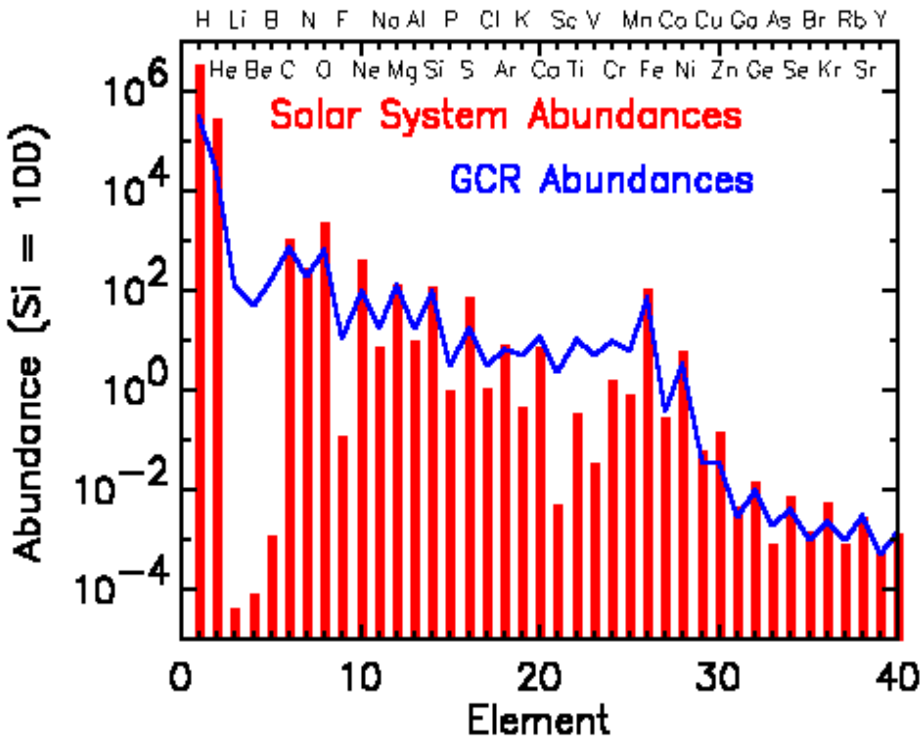
Flux : 4 RC/cm^2/s $\Rightarrow$ 1 kg/year << 40 000 ton/year (meteorites)

Composition



Abundance

- Comparing relative abundances of elements in cosmic rays and in solar system, we notice important difference for some nucleus:
  - Li, Be , B
  - Sc, Ti, V, Cr, Mn
- This nucleus are not produce by stellar nucleosynthesys but from fragmentation of C, N, O (for Li, Be, B) and iron (for Sc, Ti, V, Cr, Mn) with nuclear reactions called spallation, on protons of the interstellar medium.



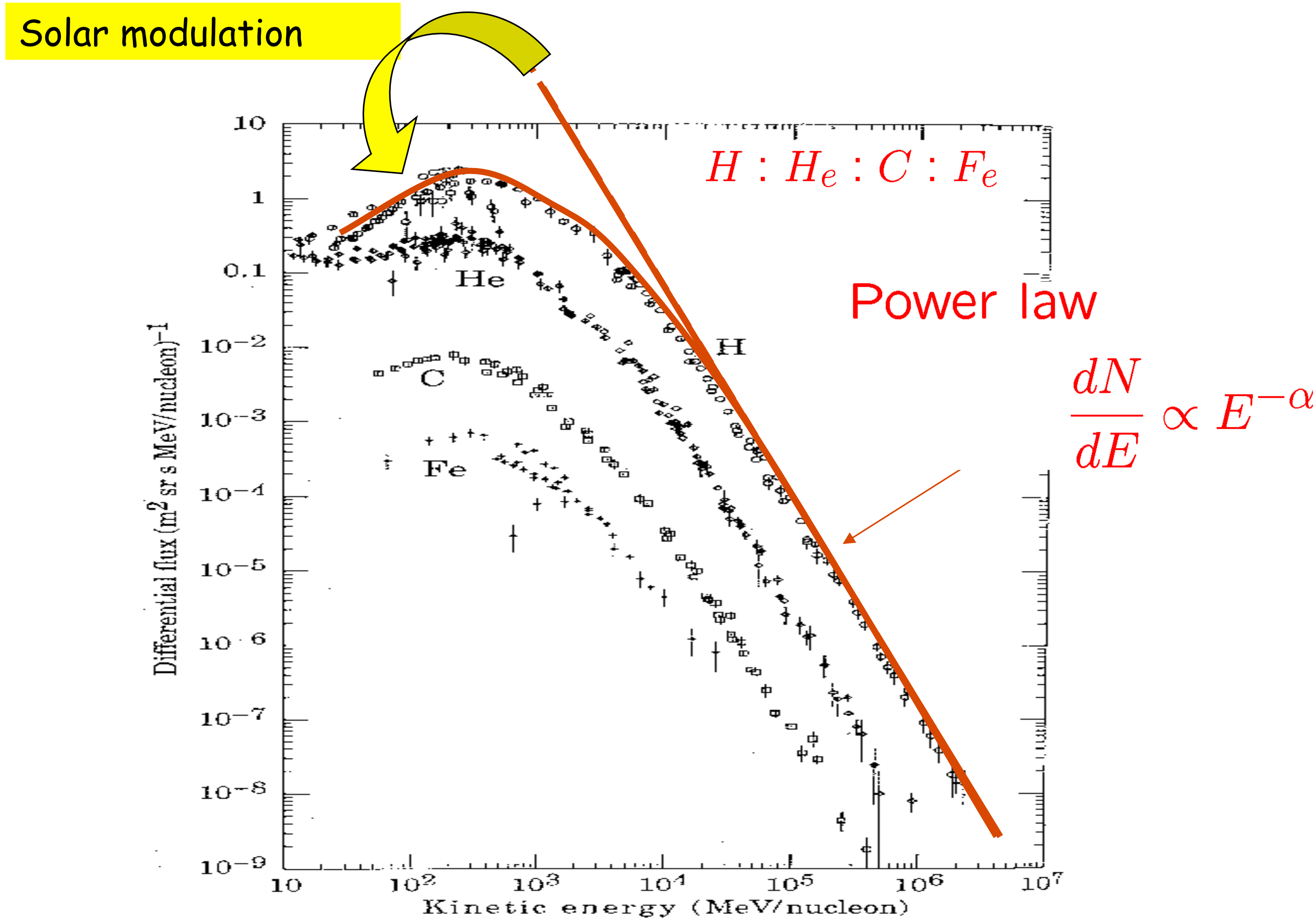
Effect of propagation

- The rate of products of spallation (Li, Be, B etc.) gives the mean depth of matter crossed by a cosmic ray (brownian propagation) between the source and the earth
$\approx$ 5 à 10 g cm^{-2}.

- Spectrum of products of spallation are steaper (less events at high energy) because the mean depth of matter dependent on the rigidity = energy/charge $R=E_0/(ze)$. Particles with a higher rigidity (higher radius) escape faster.

- Radioactive products of spallation with a medium life time (^{10}Be, $\tau = 3{,}9\times10^6$ years) compute the ratio with their stable isoptope (^{9}Be et ^{7}Be) to know the time scale of a cosmic ray in the galaxy $T \approx 10^7$ années.

Solar modulation



How to identify cosmic accelerators ?

- Use neutral and stable messenger propagating in straight line :
  - non thermical photons : the most energetics
    - Presence of accelerated protons /nucleus ($\pi^0 \rightarrow \gamma\gamma$) or accelerated electrons (inverse Compton effect
    - Observations in radio, X, gamma at lower energies showing accelerated electrons (synchrotron and inverse Compton effect)
  - neutrinos giving hints of accelerated protons /nucleus ($\pi^\pm \rightarrow \mu^\pm \nu_\mu$ et $\mu^\pm \rightarrow e^\pm \nu_\mu \nu_e$) .

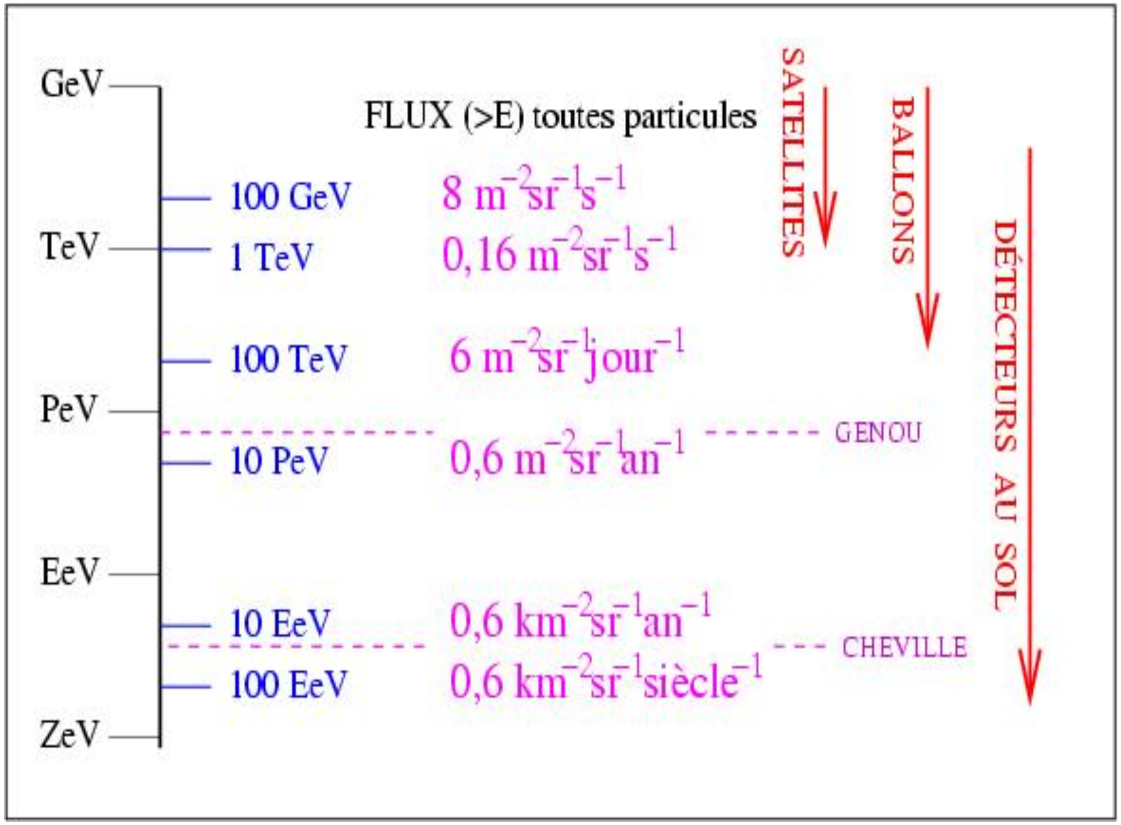
- Use charged particles with a propagation radius in the galactic magnetic filed (~ $\mu G = 10^{-10}$ T) est >> dimension de la Galaxie (10^4 parsecs)> Size of the galaxy (10^4 parsecs)
  $E > 10^{19}$ eV

$$R / parsec = \frac{E/(10^{15} eV)}{B/(10^{-10} T)}$$

What are the cosmic accelerators ?

- Objects with non-thermal spectrum (radio, X, gamma):
  - Supernovae remanent, pulsars, pulsars wind nebulae
  - binary systems
  - Active galactic nuclei, gamma ray burst
- This object are composed by a shock (Supernovae remanent) or huge electromagnetic fields (pulars)
  ➔ Fermi mechanism
- System with accretion-ejection aroud a compact object (neutron star, black hole). They compose binary systems, active galactic nuclei, gamma ray burst
- Still complicated to explain the acceleration up to 10^{20} eV. Gamma ray burst is the most probable candidate.

What type of detector ?



How to characterise a particle ?

• Mass	m
• Electric charge	$z.e$
• Speed	$v = \beta.c$
• Lorentz factor	$\gamma = E/(mc^2)$
• Momentum	$p = mc\ \beta\gamma$
• Cinetic energy	$T=mc^2(\gamma-1)$

Observables given by the AMS detector

Detector	Measured observable	Link with the particle
Magnetic spectrometer	- Rigidity - Sign of z	
Time of flight	Speed/c	β
- Proportionnal counters - Scintillators - Ionisation chamber	Ionisation	$dE/dx = z^2 f(\beta)$
Cherenkov effect	Density of Cherenkov photons	$dN/dx = z^2 g(\beta)$
Transition radiation	Nomber of X photons	$N = z^2 h(\gamma)$
Calorimeter	Deposit Energy	$mc^2(\gamma-1)$

Two important radiations

- Two effets of polarization induced by charged particle in dielectrics :
  - Cherenkov radiation if $v > n.c$
    - Sensitive to $\beta = v/c$
  - Transition radiation : if one (or more) interface between different dielectrics
    - Sensitive to $\gamma = E/(mc^2)$

Cherenkov radiation

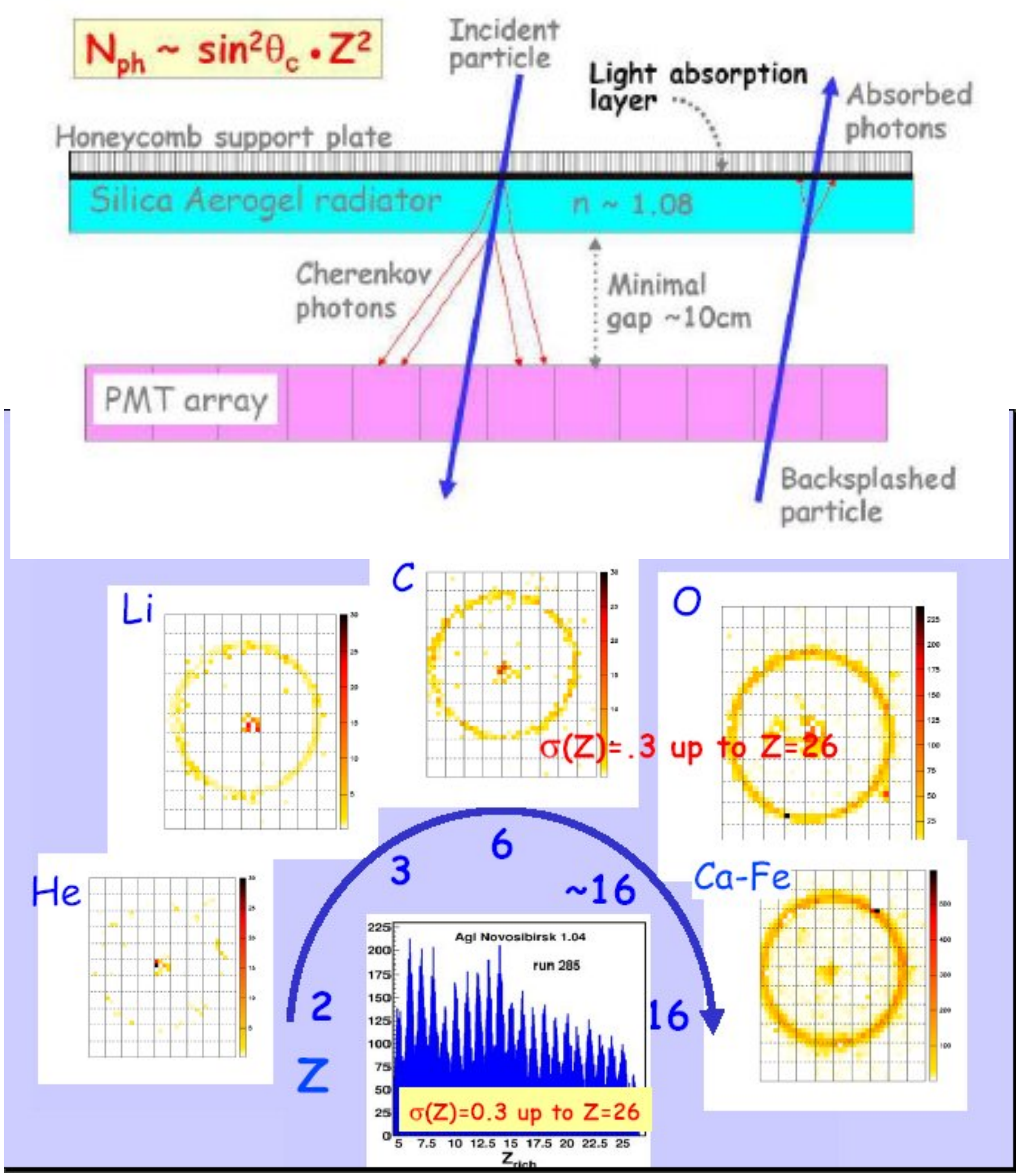
- Emit on a cone along the trajectory of the particle with an opening angle θ_c with $\cos\theta_c = 1/(\beta\, n(\omega))$
- Threshold in β given by $\cos\theta_c < 1$
- Emission in all wavetlength with $n(\omega) > 1$ (from UV to radio)

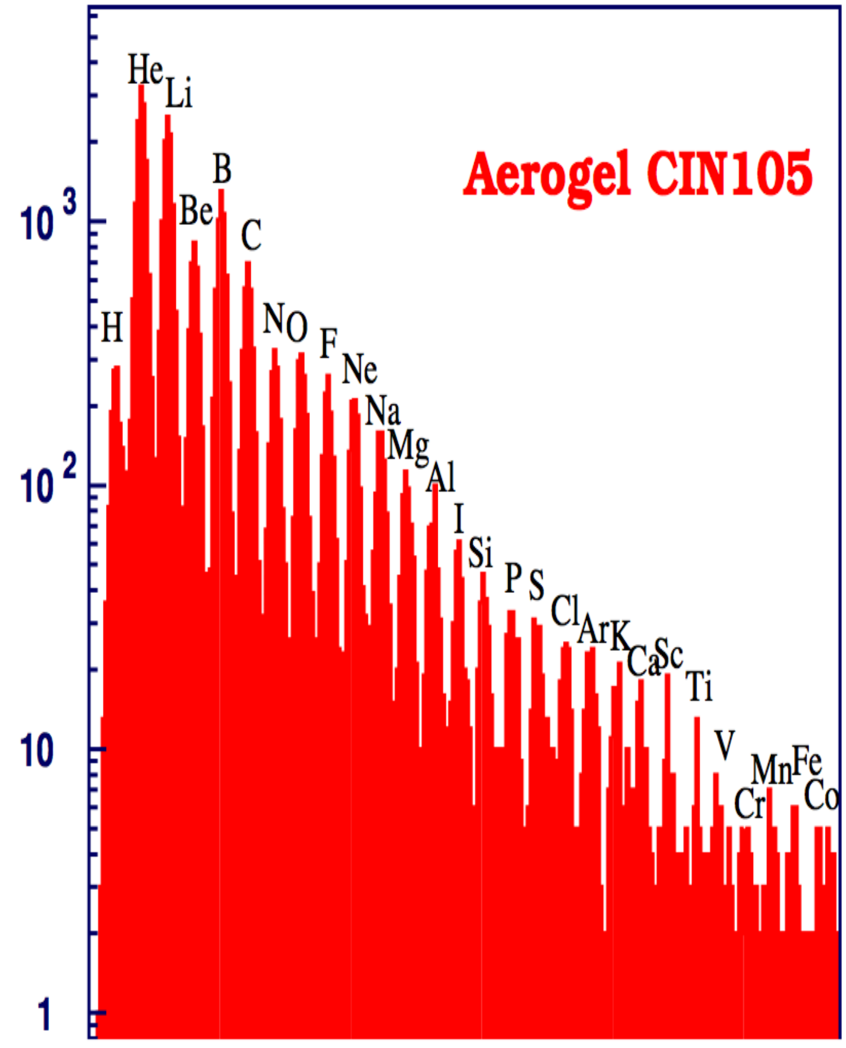
Generally detected in UV

$$\frac{d_2 N}{dx\, d\omega} = \frac{\alpha}{c} z^2 \sin^2\theta_c$$

- Discriminated between two particules with the same momentum with different masses
- Give the direction of the particle
- « Ring Imaging Cherenkov » detector or RICH : give a precise measurement of the charge.

Cherenkov radiation





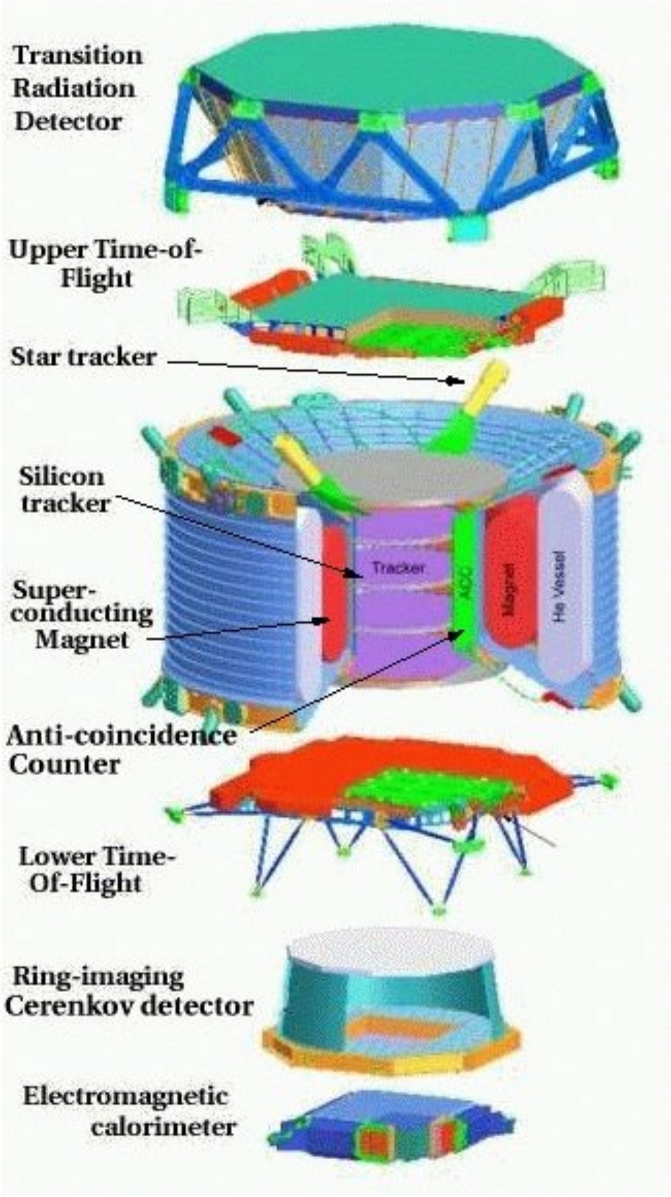
Transition radiation

- A "radiation of transition" is emitted when a charged particle cross a medium with discontinuity id the refraction index (ex : vacuum – dielectric)

- Some (complex) electromagnetism calculus tell us:
  - The emitted energy is α to γ
    → mainly electrons
  - The number of emitted photons is low
    → Needs of many layer : sandwitch
  - keV radiation is emitted with an angle $\theta \sim 1 / \gamma$

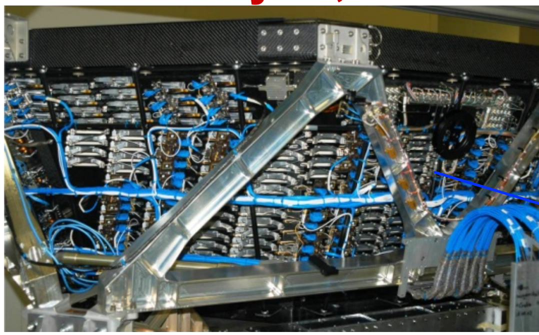
AMS02 : Alpha Magnetic Spectrometer

Particle	Energy range
p, He	E < 1 TeV
e^-	E < 1 TeV
e^+	E< 300 GeV
D, ^{3}He, ^{9}Be, ^{10}Be	E<10 GeV/nucl.
Elements Z≤26	E<1TeV/nucl.

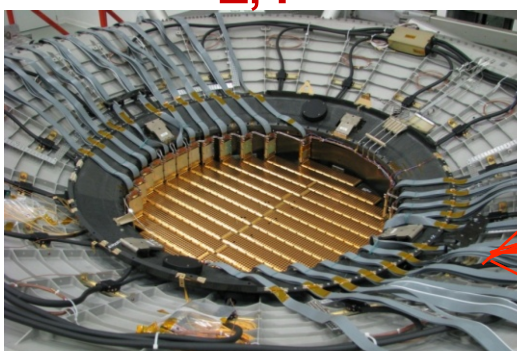


AMS02 : Alpha Magnetic Spectrometer

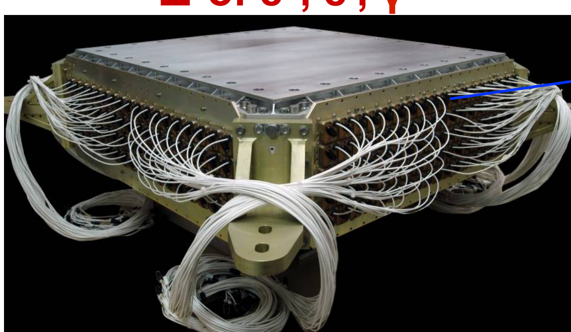
TRD
Identify e^+, e^-

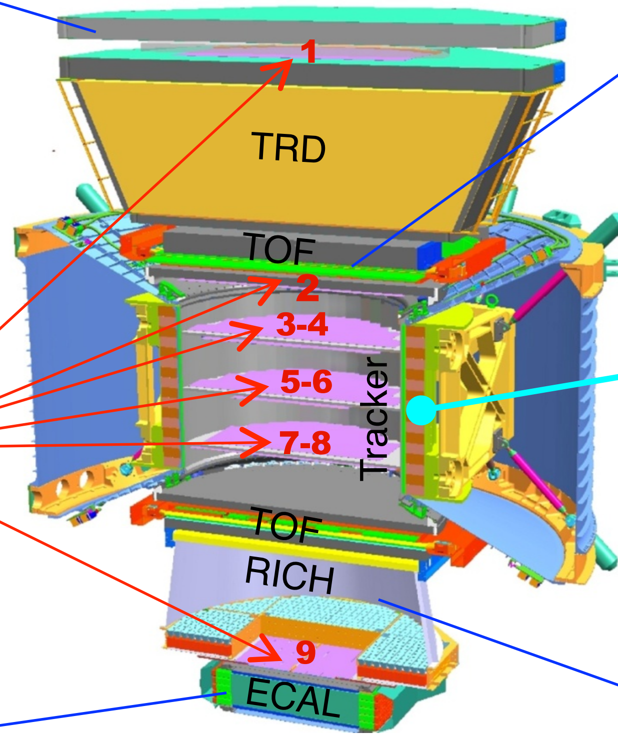


Silicon Tracker
Z, P



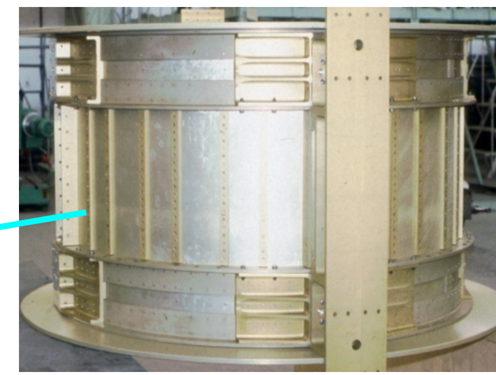
ECAL
E of e^+, e^-, γ



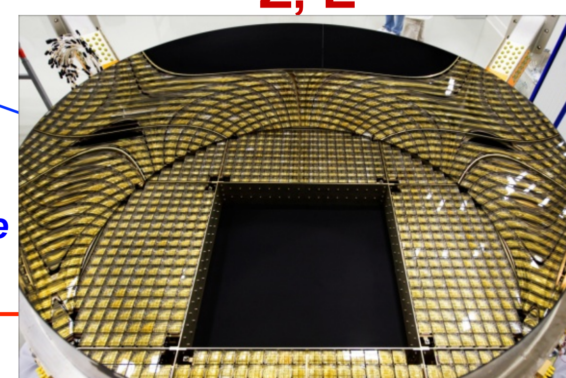


TOF
Z, E

Magnet
±Z

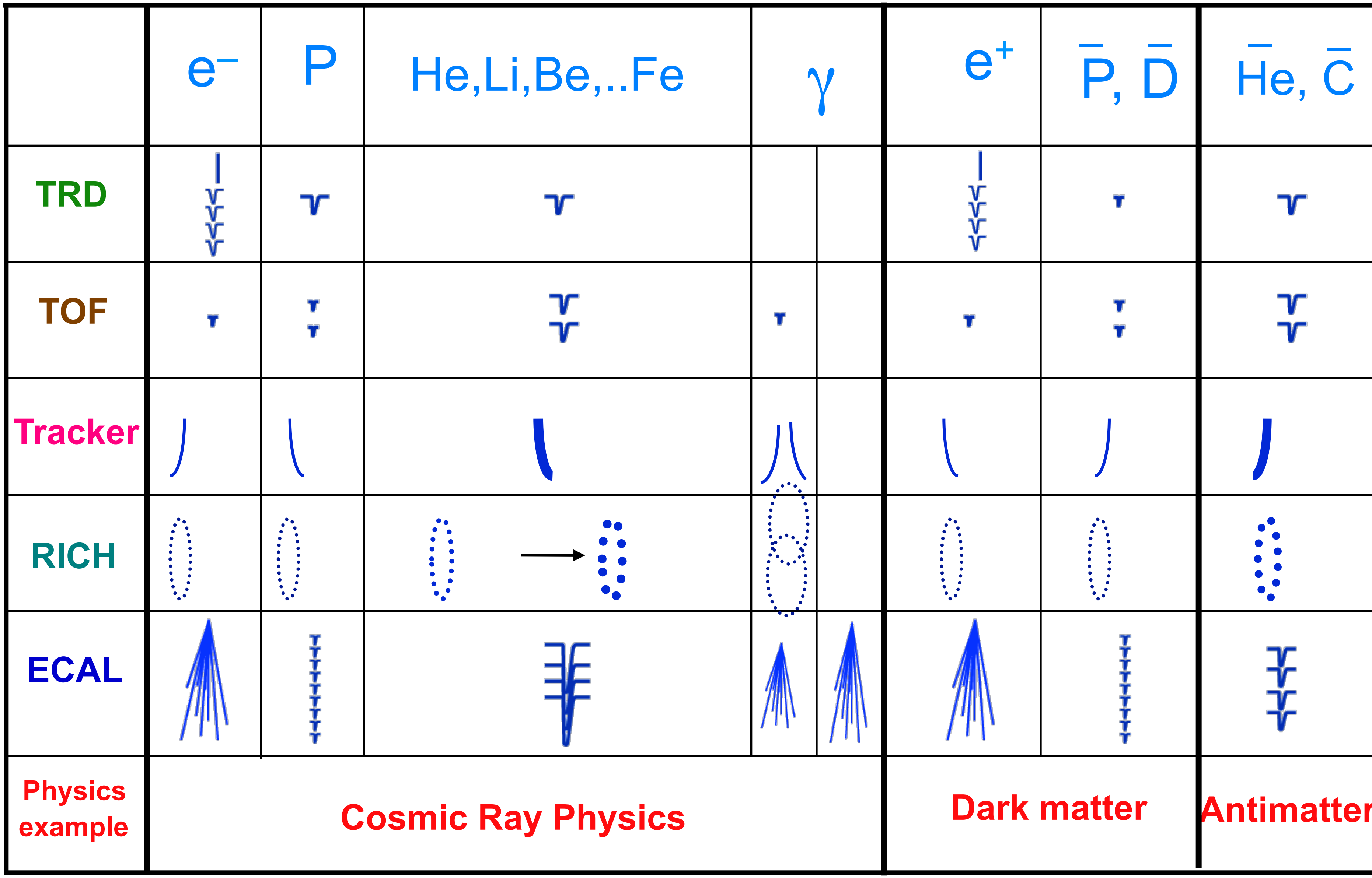


RICH
Z, E



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

AMS02 : Alpha Magnetic Spectrometer



Some results

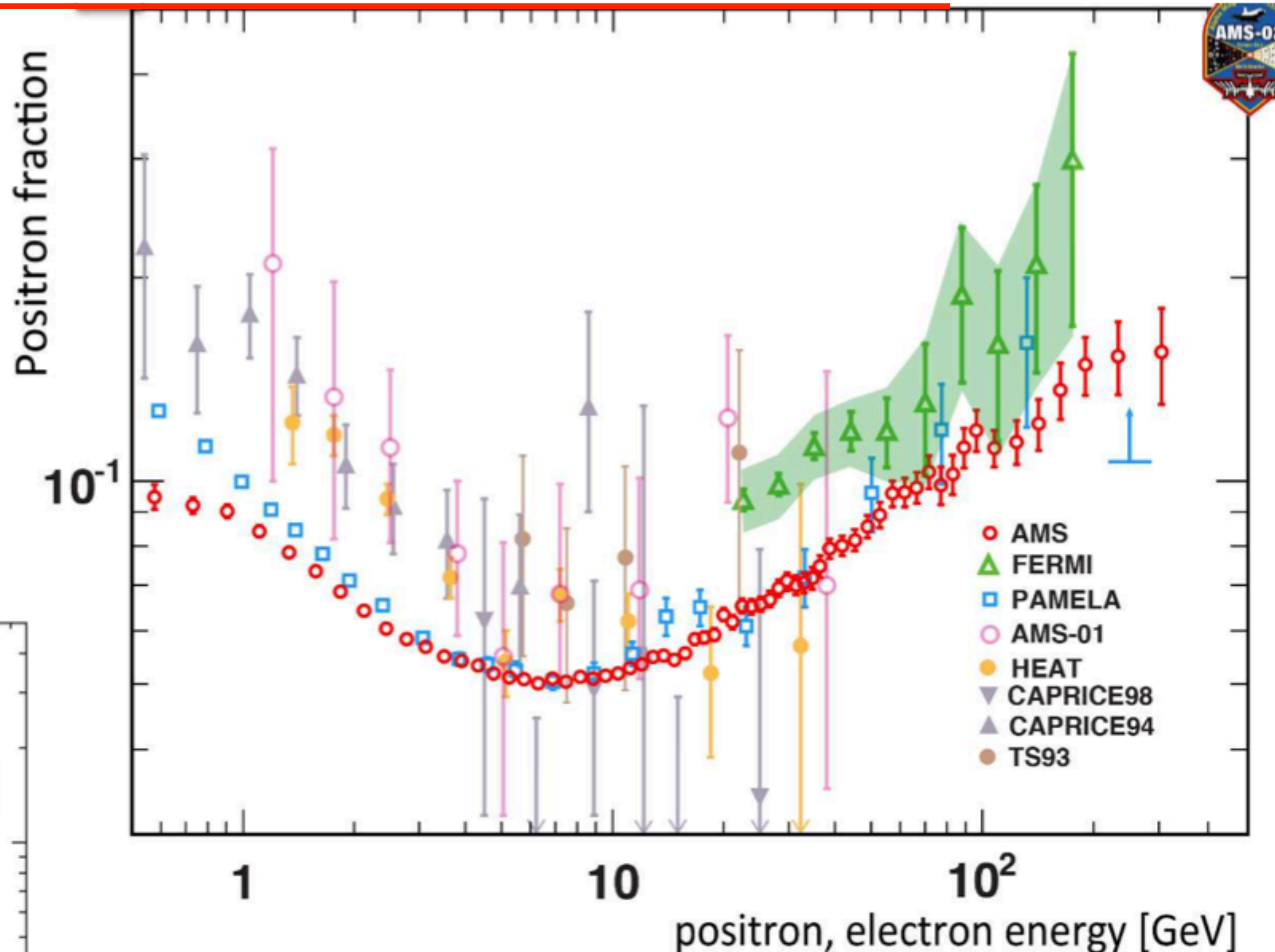
The positron fraction

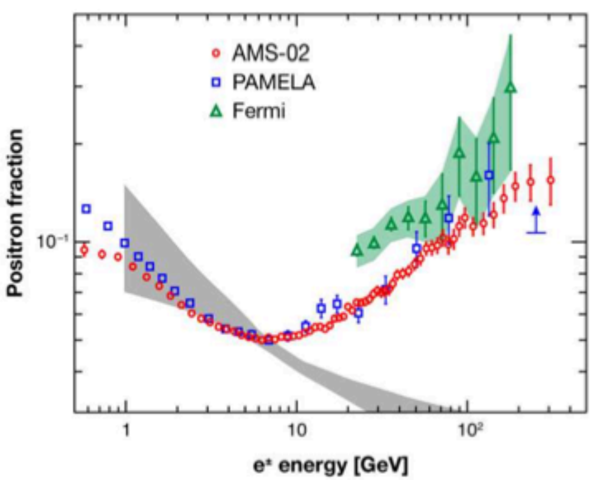
$$r_{e+} = \frac{N_{e+}}{N_{e+} + N_{e-}}$$

2 years of data

$\sim 74000 e^{+}$ events

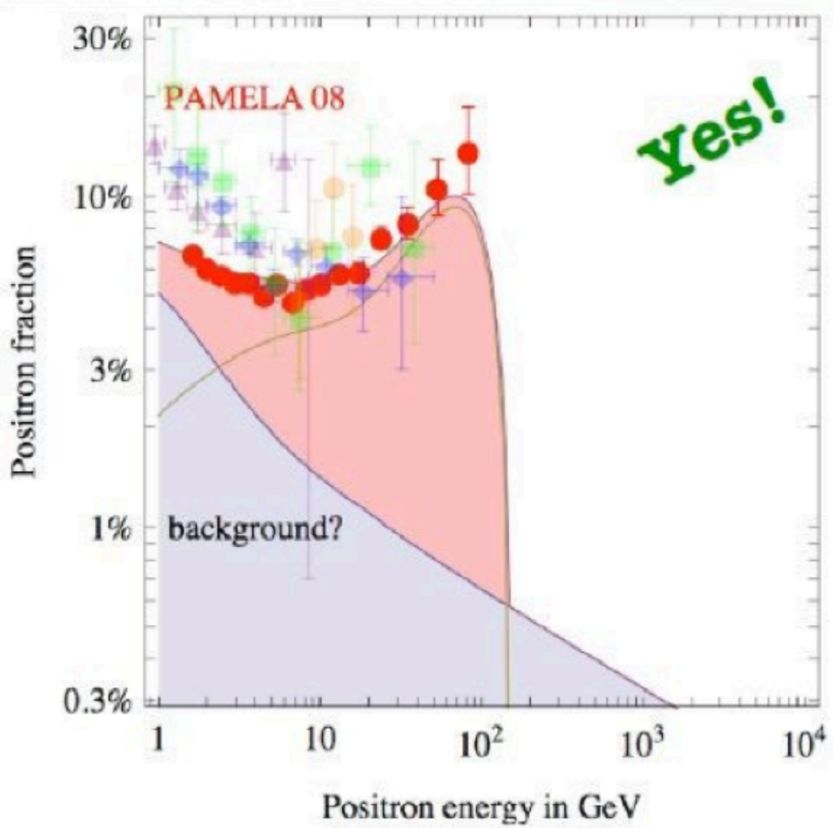
72 events on last energy bin (260-350)GeV

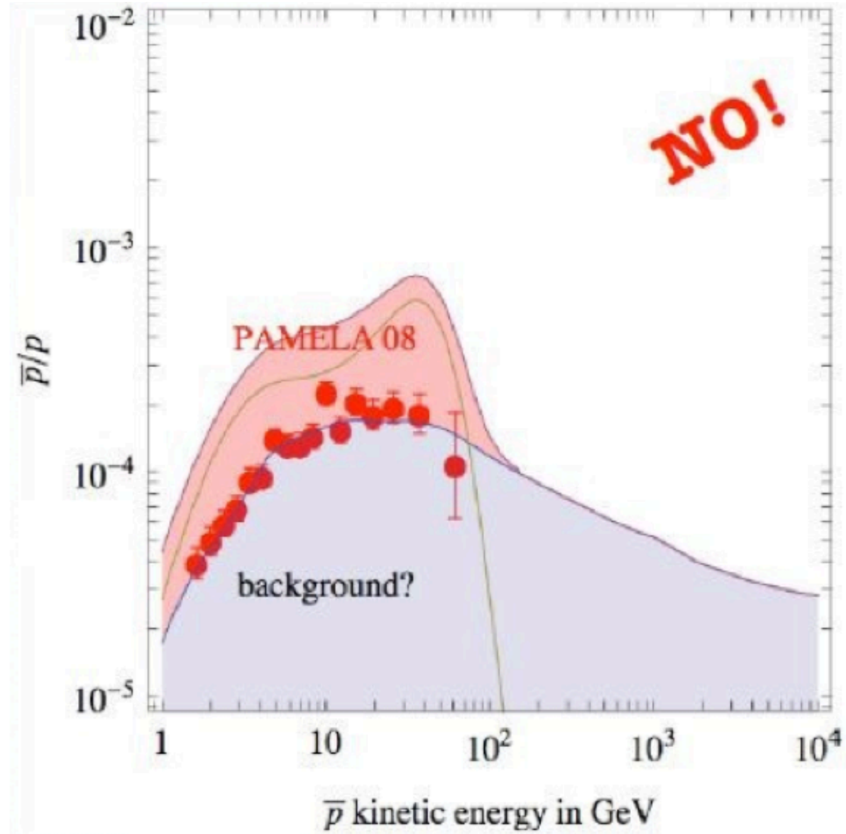




e^{+} secondary production is exptected to decrease monotonically while results indicate a persistent rise !

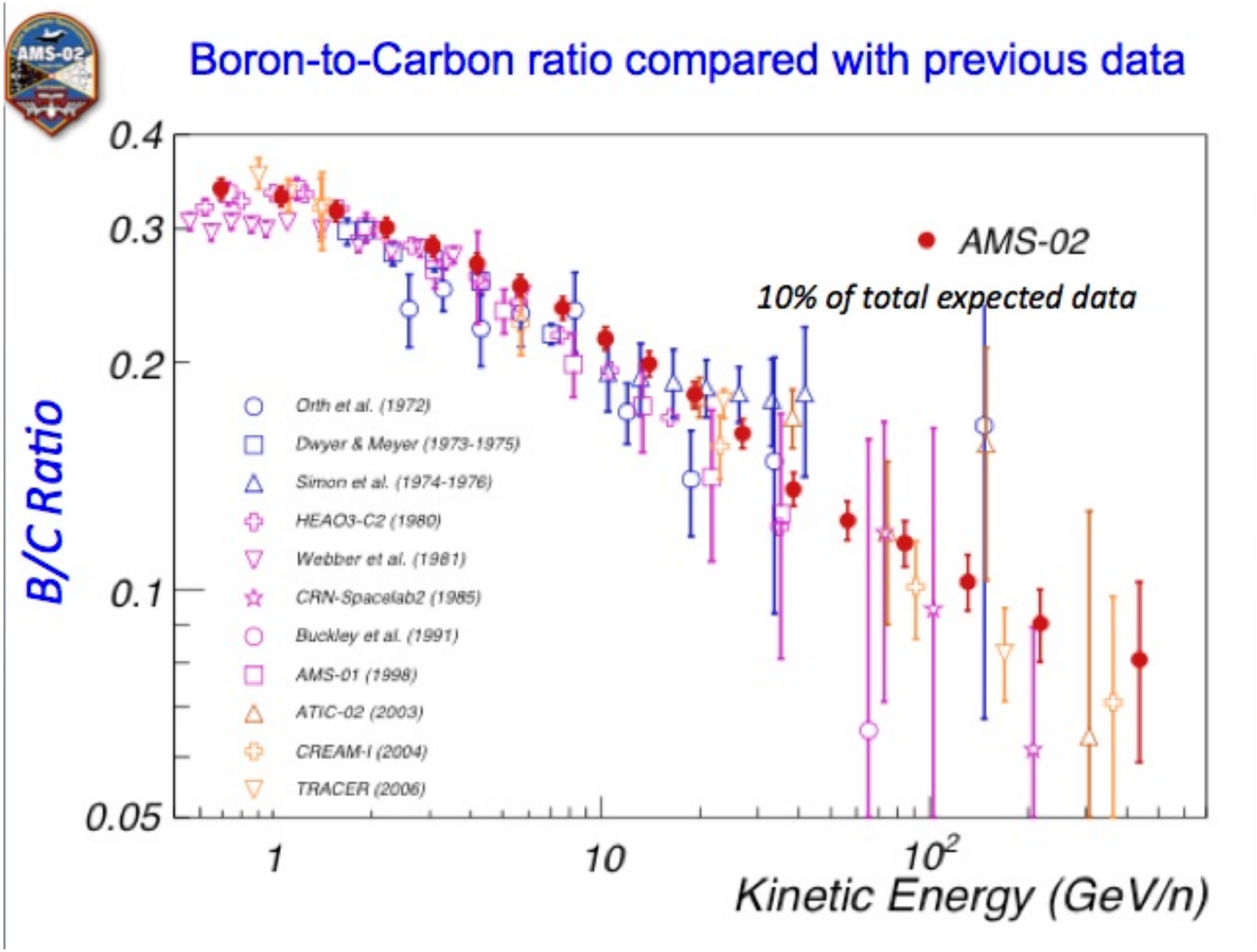
Some results (PAMELA)





- A wino ($\omega\omega \rightarrow W^+W^-$) of 150 GeV can explain positrons fraction, but not anti-protons
- Much larger mass (~10TeV) needed to explain antiproton, compatible with relic density
- Very exotic annuhilation into lepton only ($\mu^+\mu^-$)

Some results (AMS02)



Balloon Experiments

Charged particles (1 TeV → few 100 TeV)

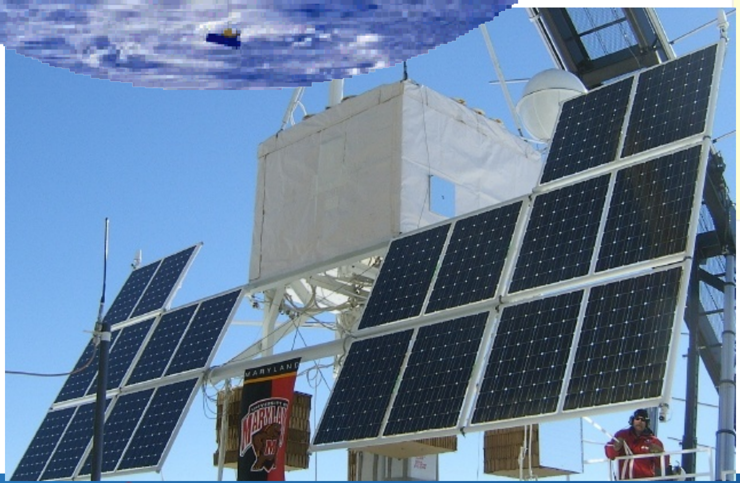
- Very high altitude flights: 40 km ´ 3,9 g cm^{-2}
- Load: up to ≈ 270 kg and 10 m^3
- Many former flights:

JACEE (USA + Japon) ; RUNJOB (Russie + Japon) etc.

using emulsion chambers !

- Recently: Ultra Long Duration Balloon (ULDB) Flights
  60-100 jours (NASA, Antarctic) → the CREAM experiment
  (Cosmic Ray Energetics and Mass)

CREAM



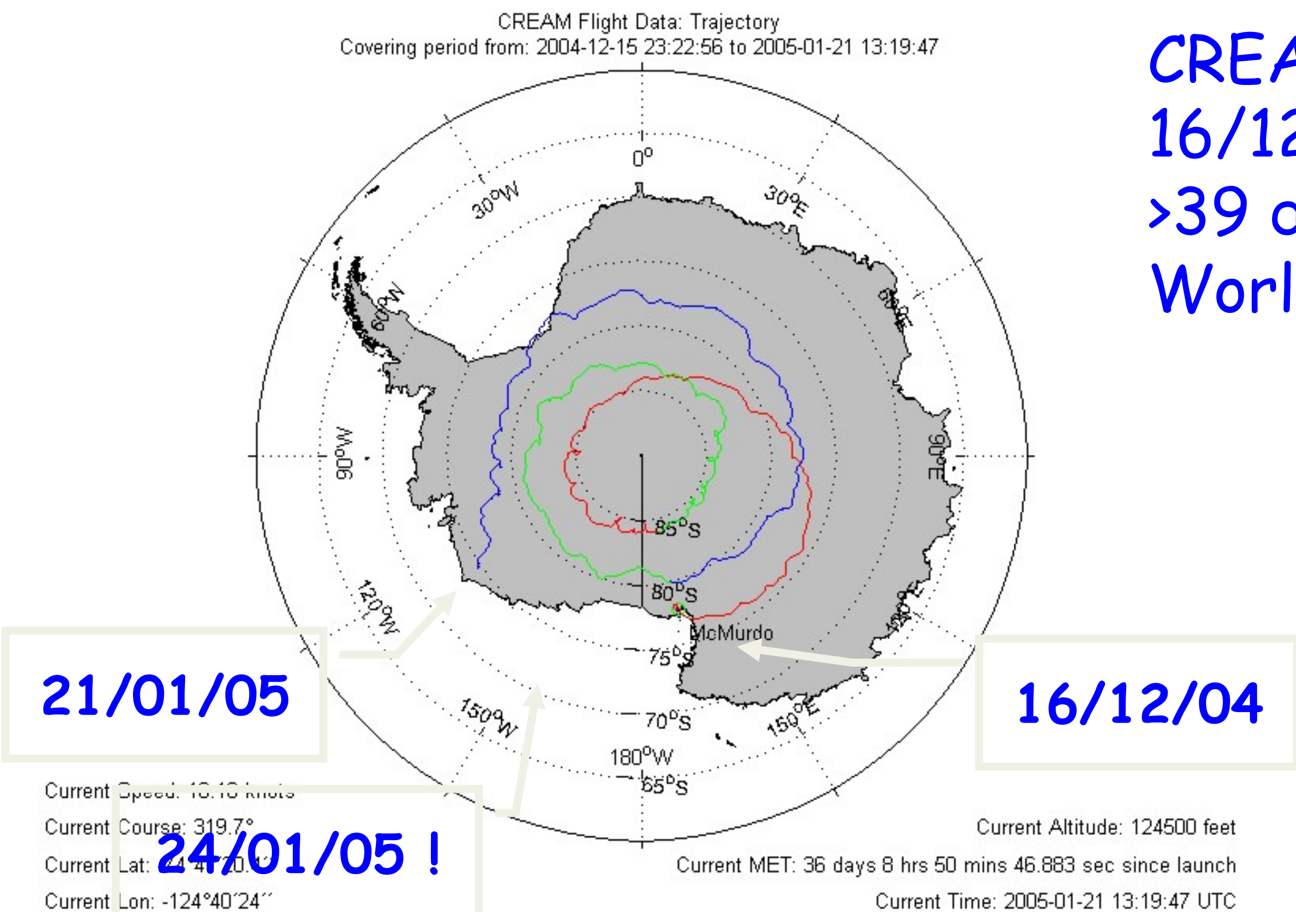
Ultra Long Duration Balloon

ULDB Proj., Adv.Sp.Res33,1633(2004) :

NASA project to develop

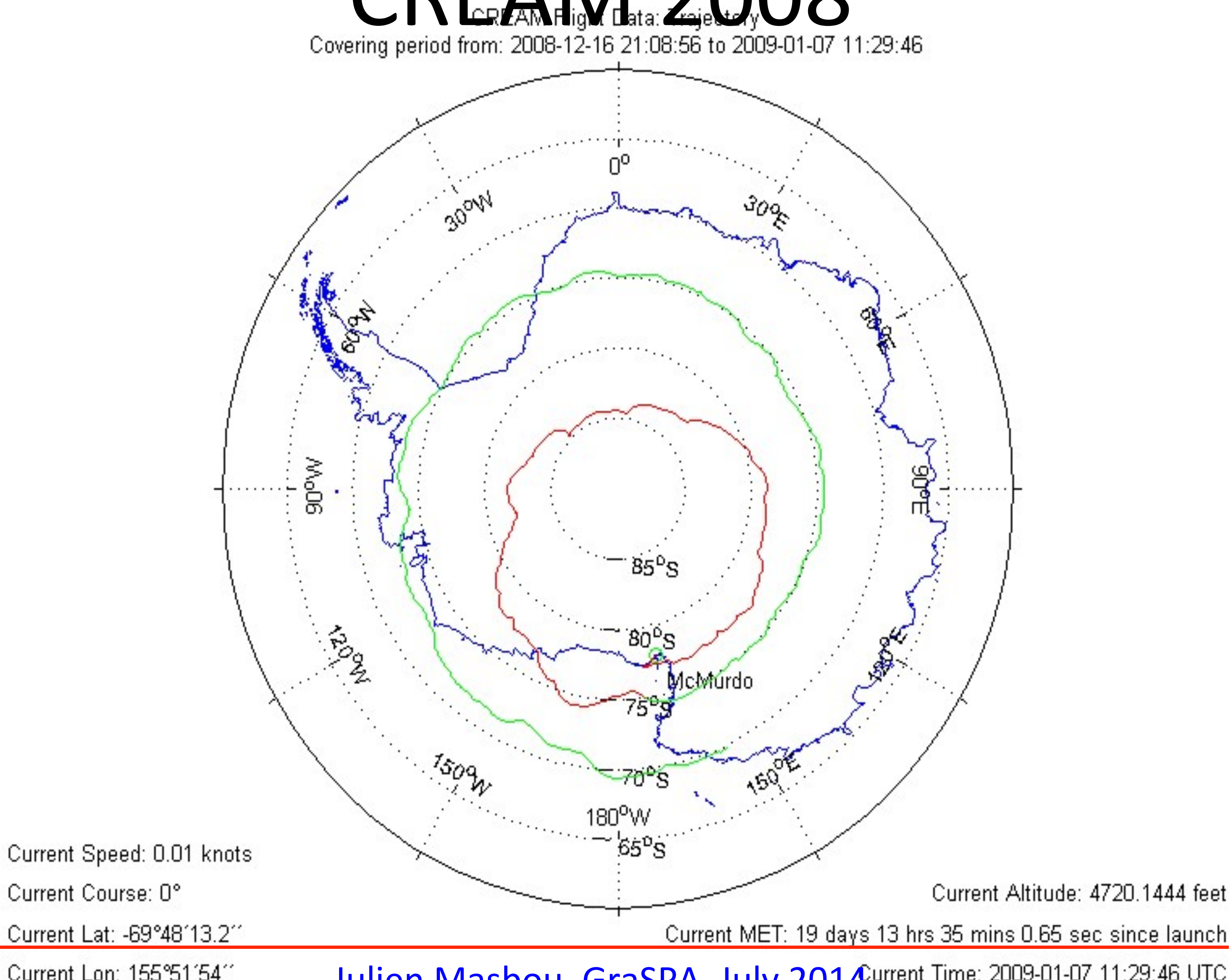
- Flight of < 100 days
- Payload · 2 tons
- Alt 33000 meter
- CREAM n° 1 : 2006 (2005/LDB)

CREAM 2004



CREAM I:
16/12/04 - **/01/05
>39 days flight
World Record

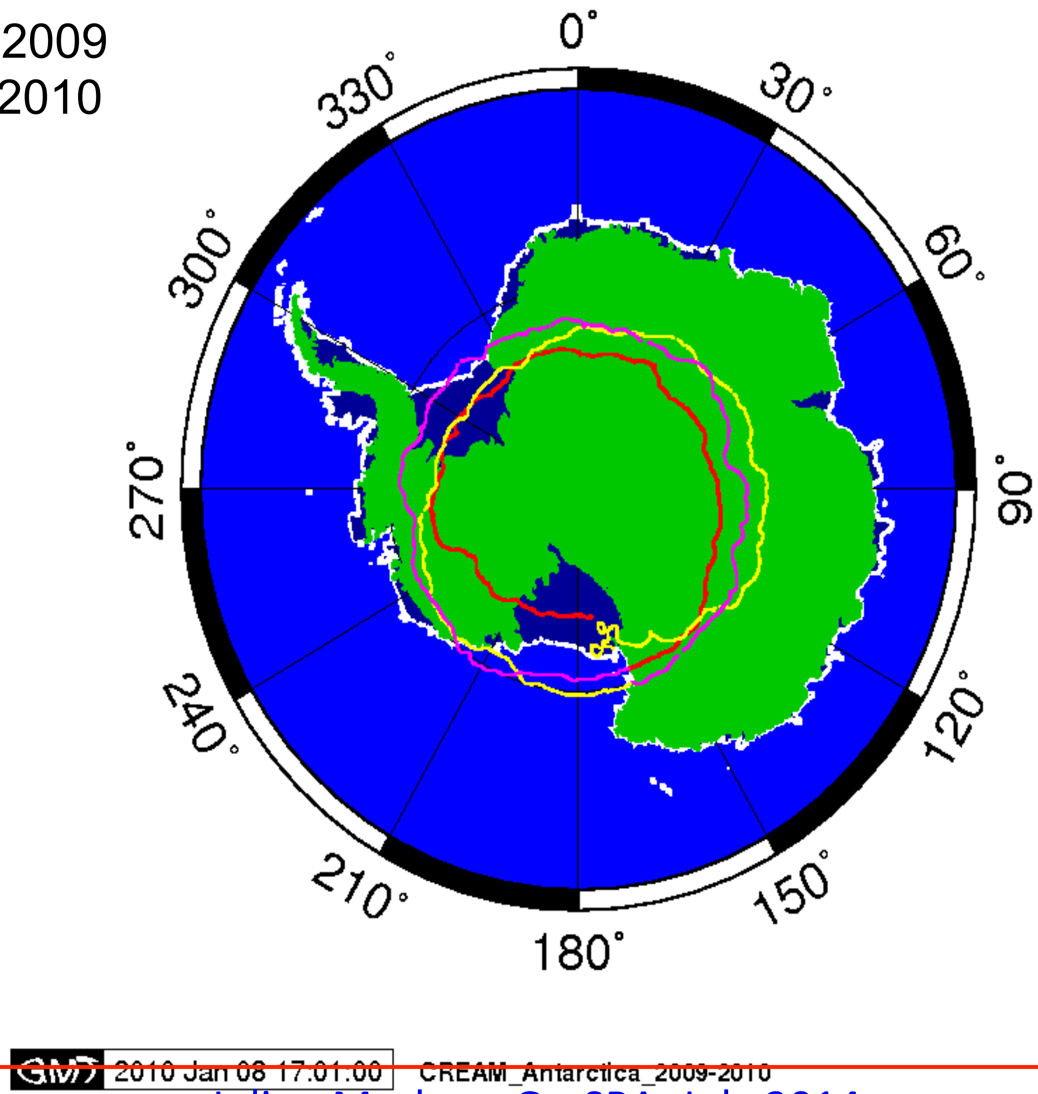
CREAM 2008



CREAM Flight Data: Trajectory
Covering period from: 2008-12-16 21:08:56 to 2009-01-07 11:29:46
0°
30°W
30°E
60°W
60°E
90°W
90°E
120°W
120°E
150°W
150°E
180°W
85°S
80°S
75°S
70°S
65°S
McMurdo
Current Speed: 0.01 knots
Current Course: 0°
Current Lat: -69°48′13.2′′
Current Lon: 155°51′54′′
Current Altitude: 4720.1444 feet
Current MET: 19 days 13 hrs 35 mins 0.65 sec since launch
Current Time: 2009-01-07 11:29:46 UTC

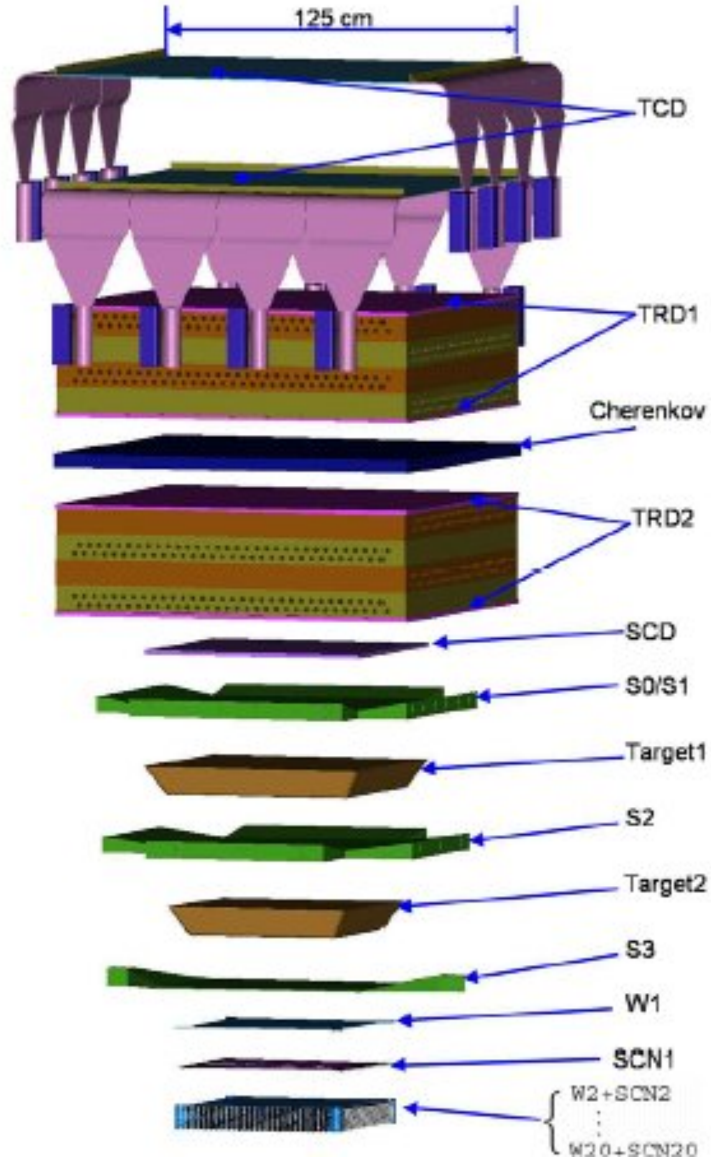
CREAM 2009

1 décembre 2009
au 8 janvier 2010

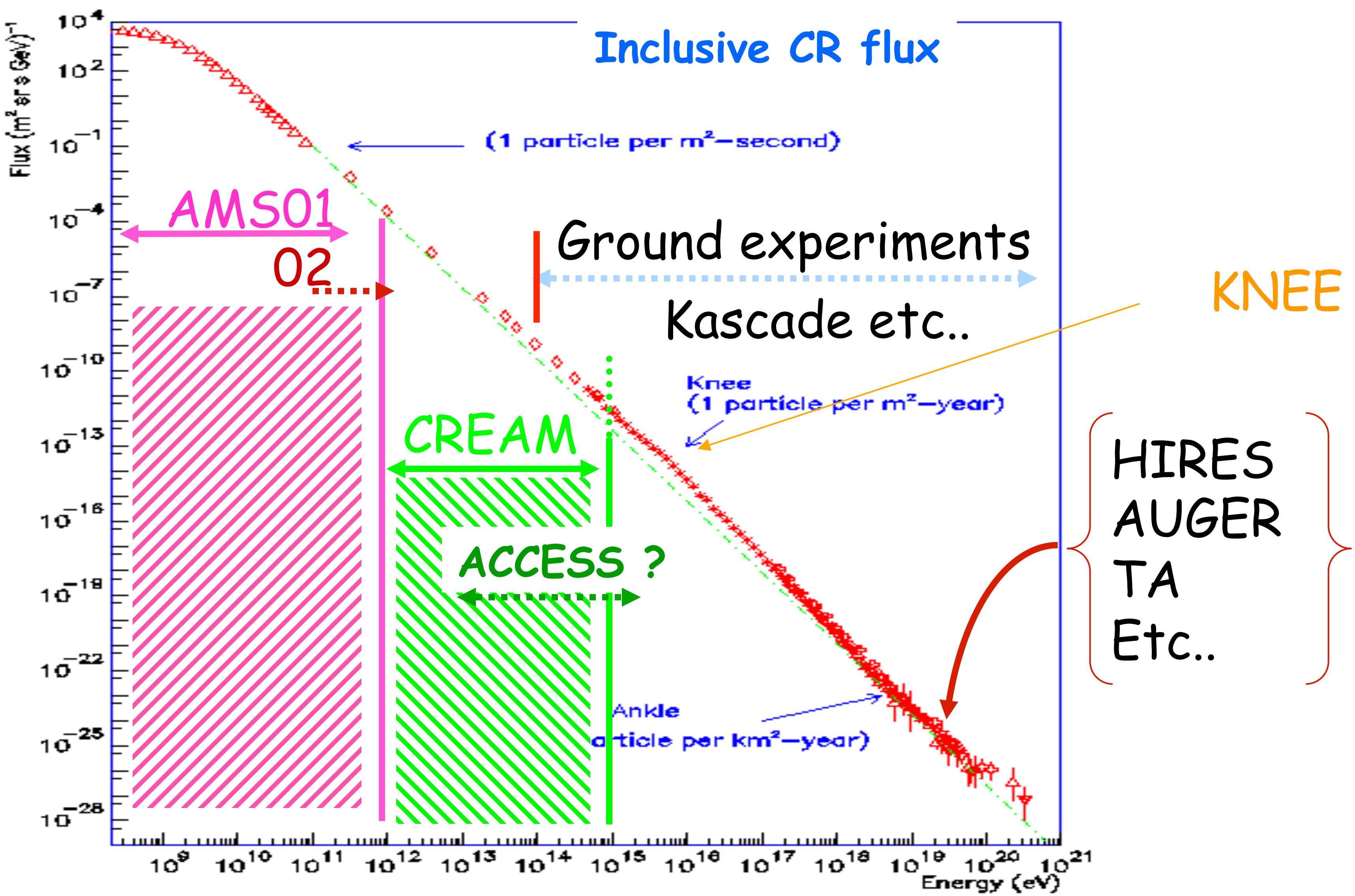


CREAM : Cosmic Ray Energetics and Mass

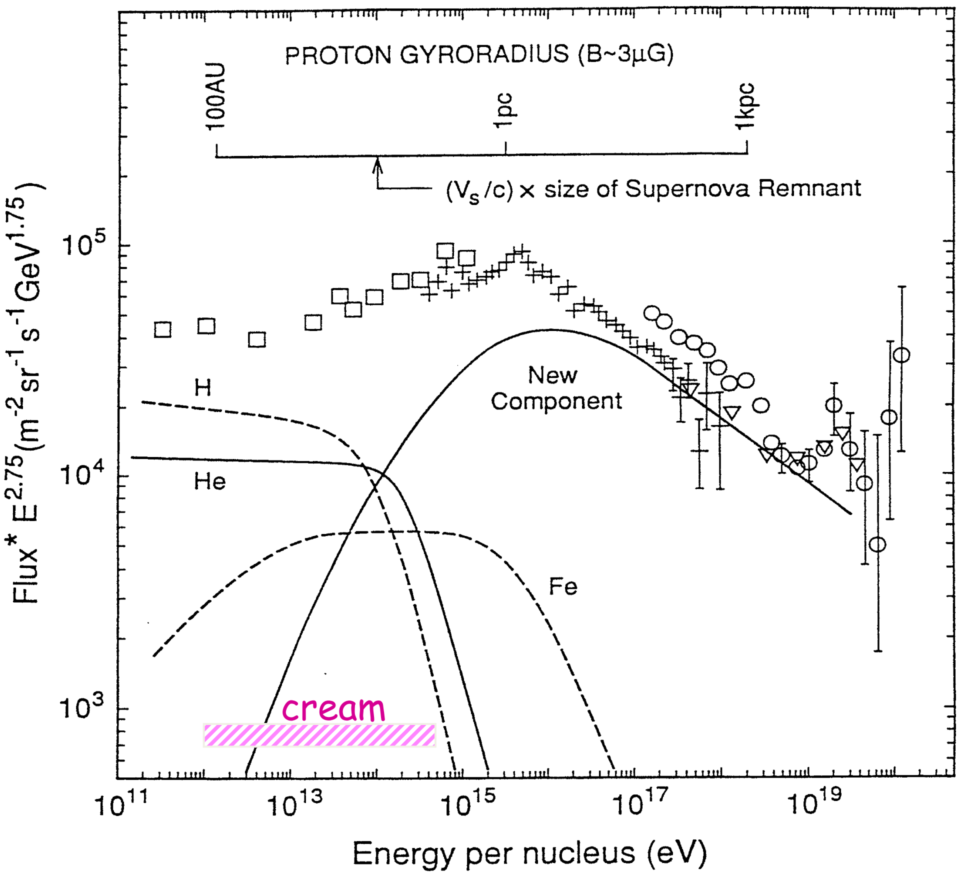
- Objectives :
  CR composition and spectrum of the different elements
  (from TeV to ~500 TeV)
- Acceptance : 2,2 m^2 sr
- Energy measurement:
  - Calorimeter 20 X_0 (W + scint. fibres)
  - Transition Radiation Detector
- Identification :
  - TRD
  - Cherenkov detector "CHERCAM" similar to AMS-2



Experimental context



The knee

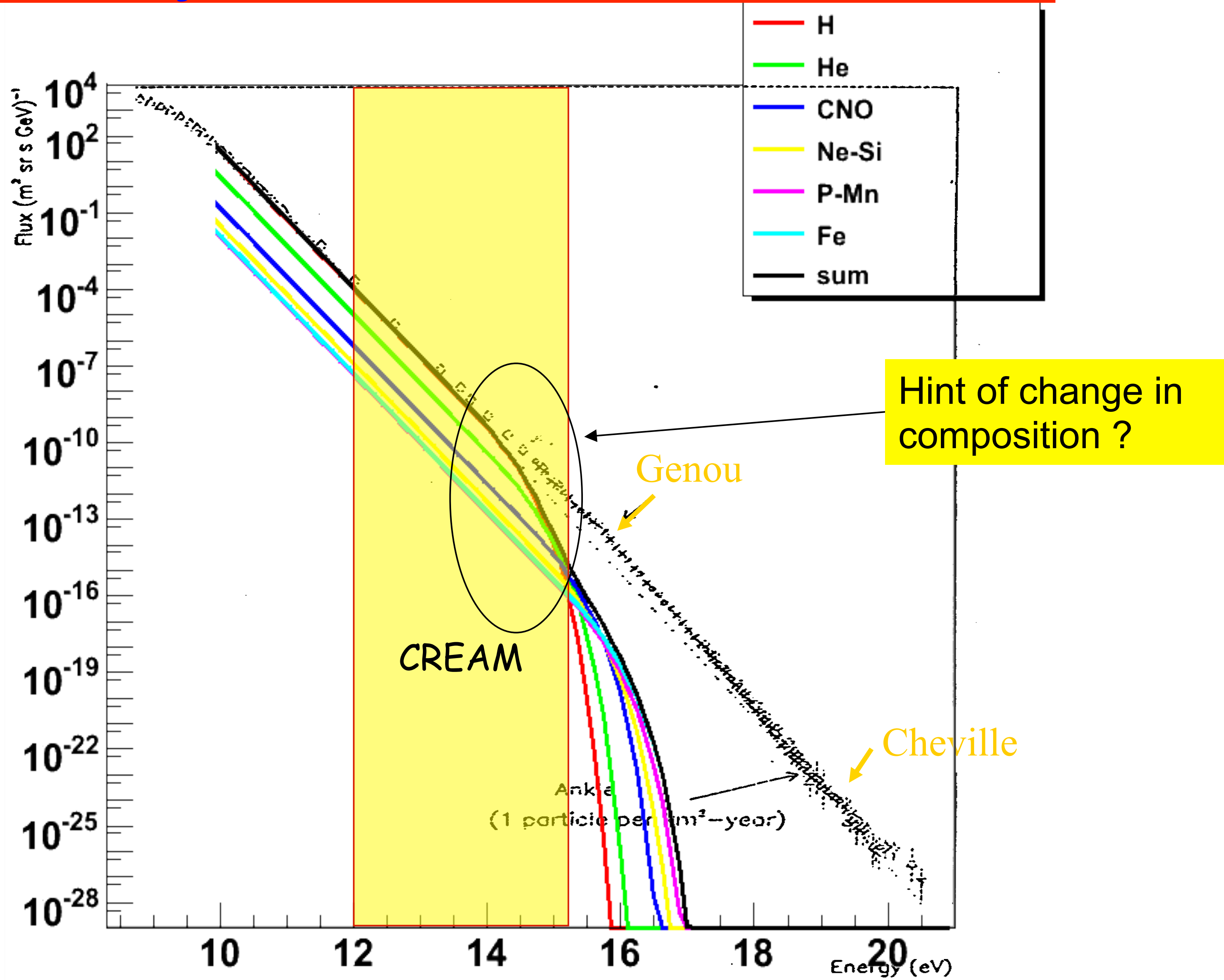


•Is the knee due to:
- Acceleration mechanisms
or to changes :
- in propagation?
- in CR sources?
- in interaction properties (threshold) ?

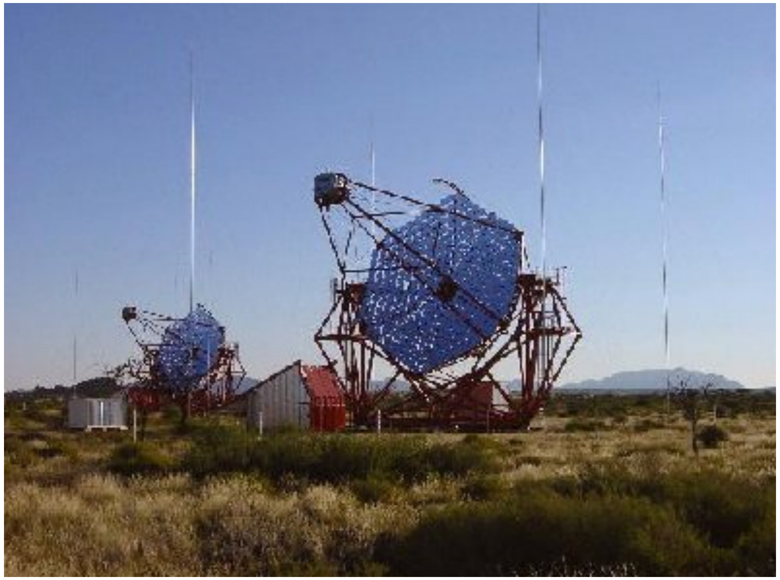
⇨ A diffuse SNR shock acceleration with E_{max} implies a change in composition around ~10^{14} eV.

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

Composition of the knee



The atmosphere as a detector



H.E.S.S.

Pierre Auger Observatory

Observables from the ground

- Only secondary particles of the shower reaches the ground
- Depending on the energy and the altitude:
  - Few residuals hadrons, because hadronic components quickly absorbed
  - $e^{\pm}$: the most numerous at the maximun of the shower
  - $\mu^{\pm}$: reach (almost) always the grounds, very penetrating up to underground !
  - Secondary γ detected after $e^{+}e^{-}$ conversion (Chrenkov effect in water)

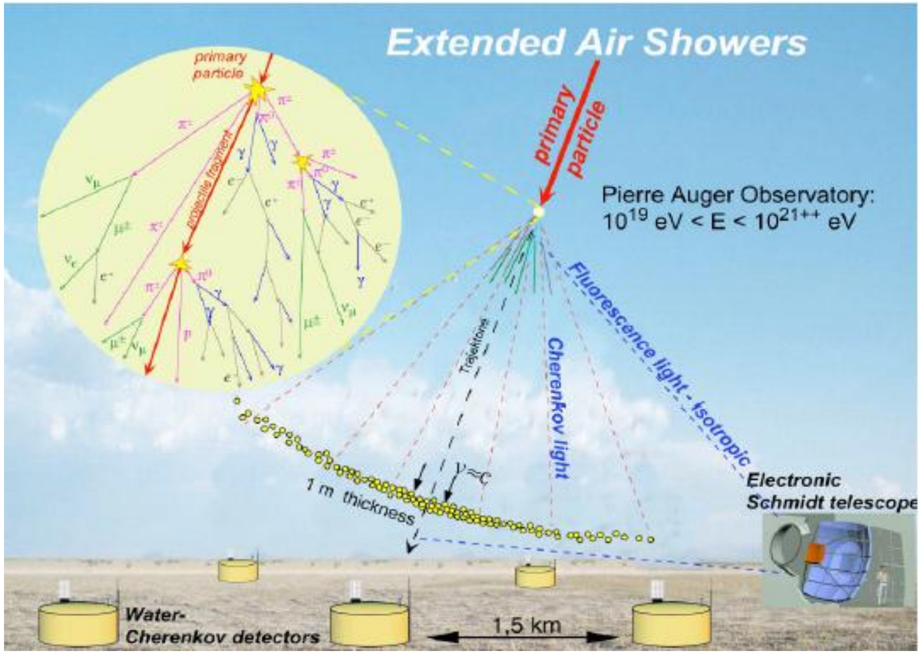
- Photons emitted along the development of the shower (Cherenkov or fluorescence)

  → 3D calorimetric information

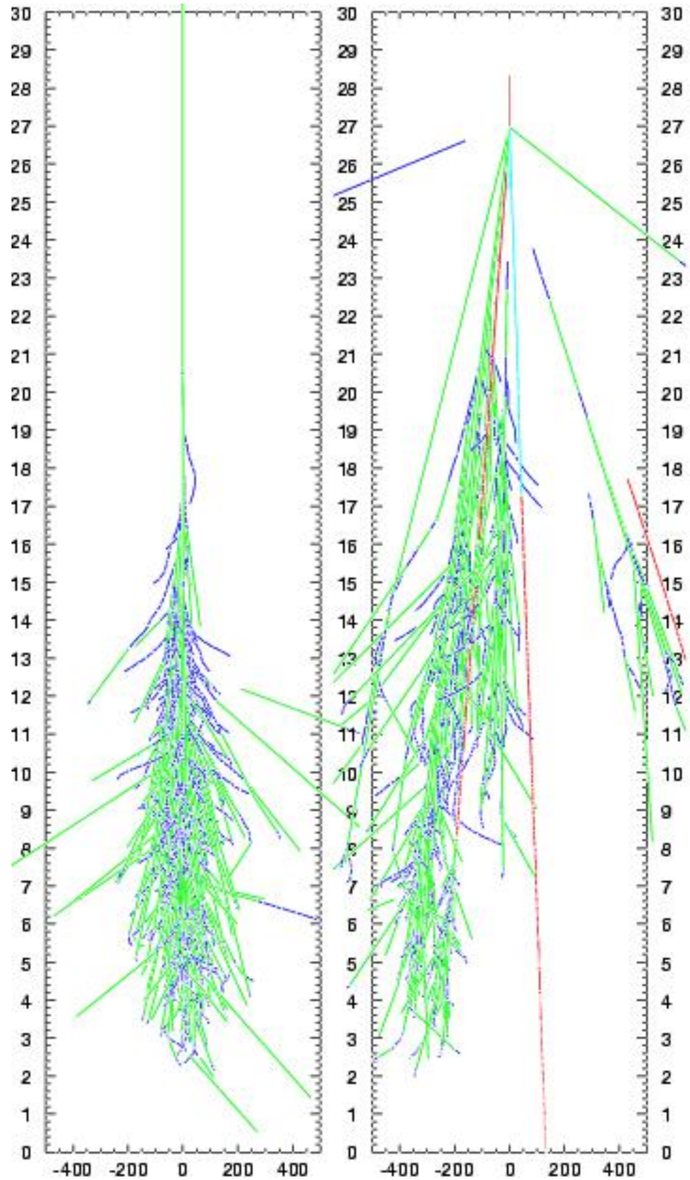
- Radio emission from the particles

Temploral aspect

- During the shower development, a thin layer of charged particle move to the ground
- A bit “curved”
- ~10m thick



Electromagnetic / hadronic Showers

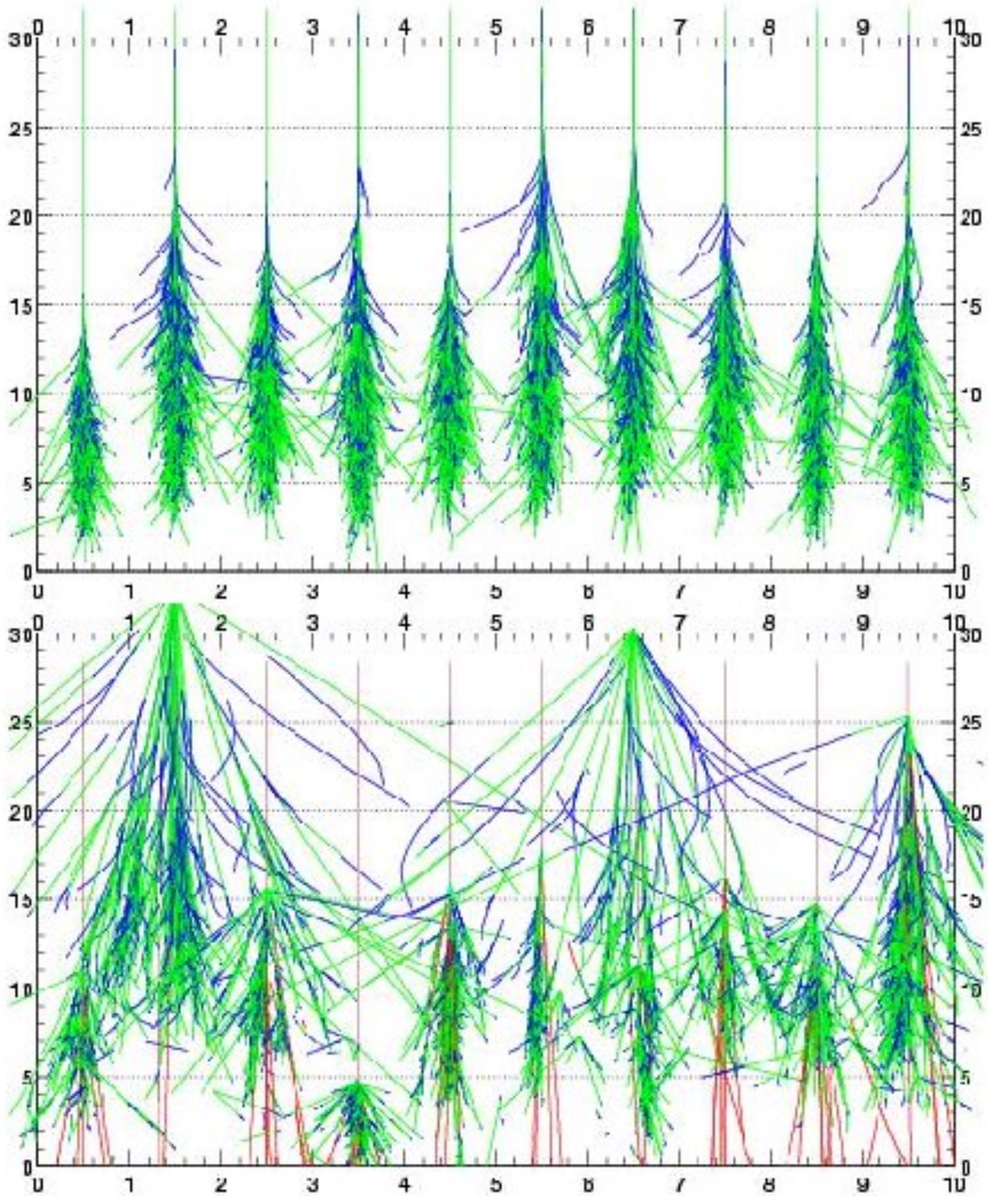


Shower from γ of 300 GeV	Shower from proton of 300 GeV
Symmetry of revolution	
Small transverse momentum	Big transverse momentum
Few muons	Presence of muons
Mainly e^+e^- and γ	Possibility of sub-electromagnetic showers

Electromagnetic / hadronic Showers

10 γ of 300 GeV

10 protons of 300 GeV



The atmosphere as a detector

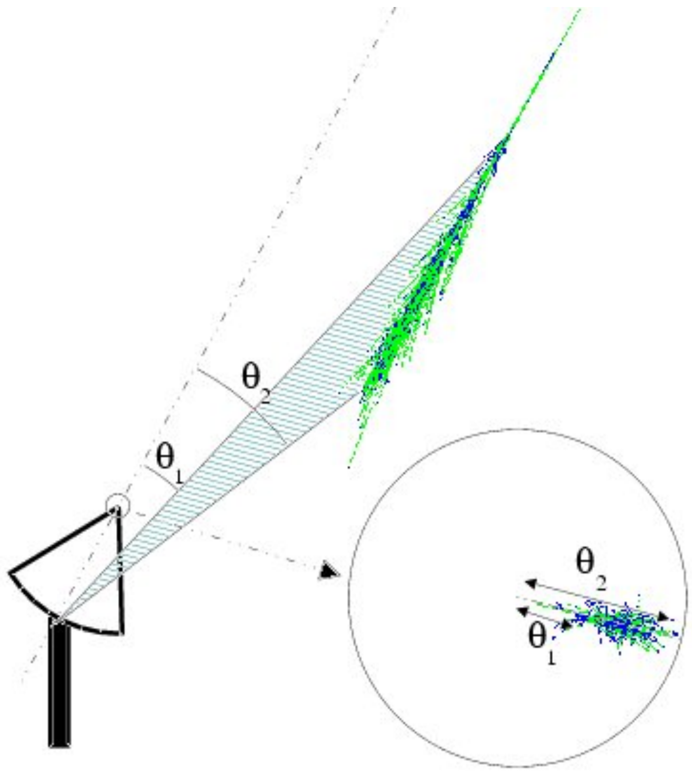
- Gamma-ray astronomy > 100 GeV
  - Cherenkov experiments (HESS, MAGIC, CANGAROO, VERITAS)
  - Wide field of view experiments (MILAGRO, TIBET-ARGO)

- Ultra High Energy Cosmic Ray Experiment
  - An hybride detector (Pierre Auger Observatory)

The atmosphere as a detector

- Atmospheric Cherenkov telescope
  - Limited field of view (5° for H.E.S.S.)
    - Follow the travel of the source in the sky
  - Can work only during night time, no moon and good weather
  - High discrimination power between gamma and hadron
- Surface detectors (secondary particles on the ground)
  - Large field of view (~ 1 sr)
  - High working time
  - Low discrimination

Atmospheric Cherenkov telescope



Cherenkov telescopes

MAGIC 2 :

2 telescopes

Ø 17m (3.5˚)

E > 60 GeV

Veritas :

4 telescopes

Ø 12m (3.5˚)

E > 85 GeV

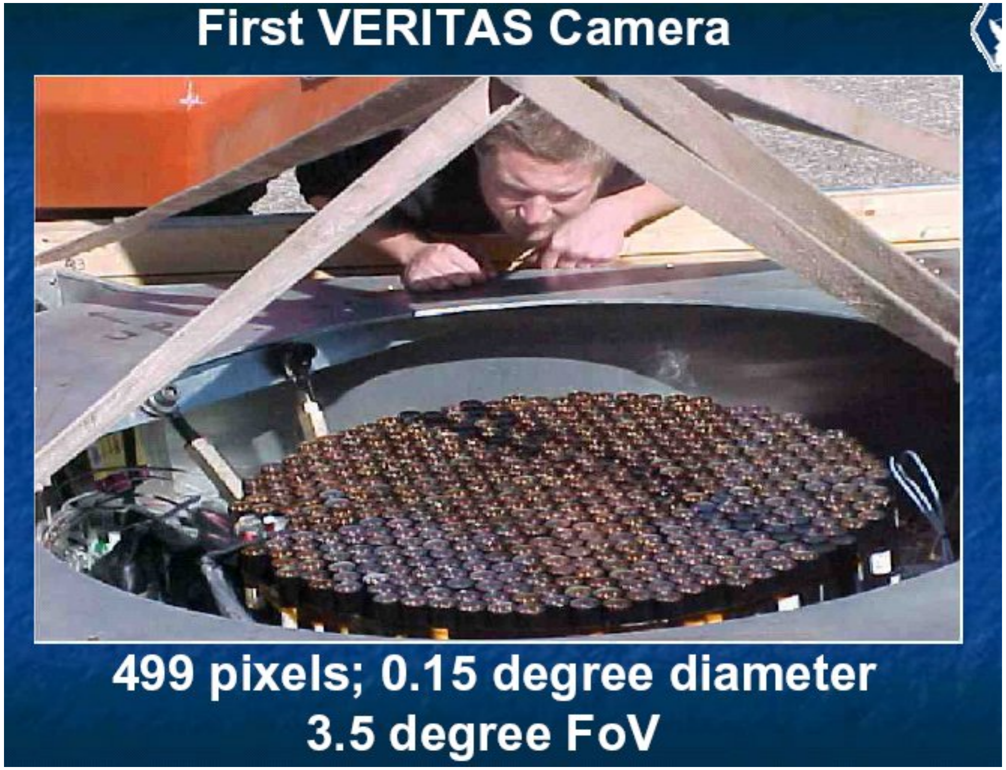
H.E.S.S. 2 :

4 telescopes +1

Ø 13m (5˚) + Ø 28m

E > 20 GeV

Camera properties



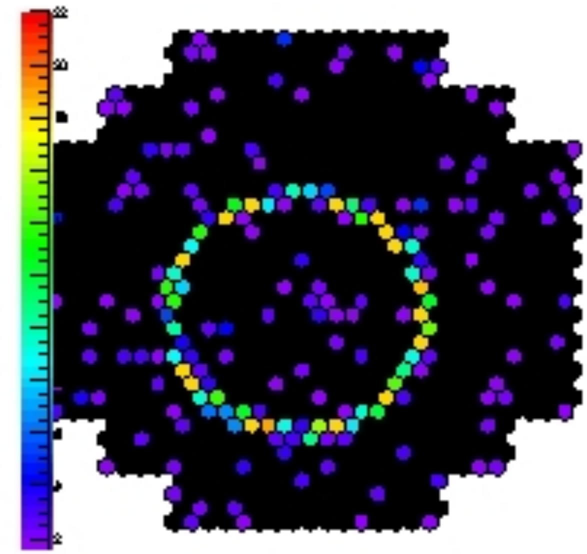
VERITAS **MAGIC**

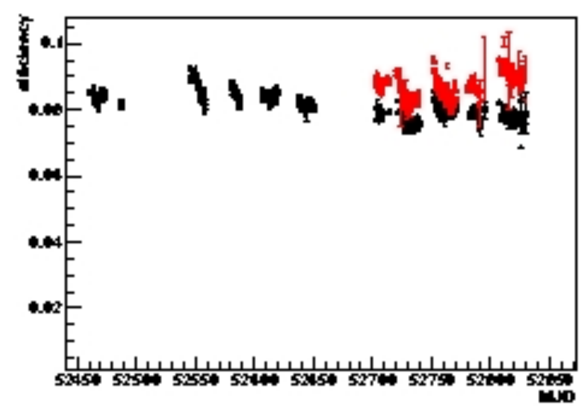
Muons for monitoring the detector

- Muons falling on the miroir of a telescope create an annulus, its equation is perfectly known

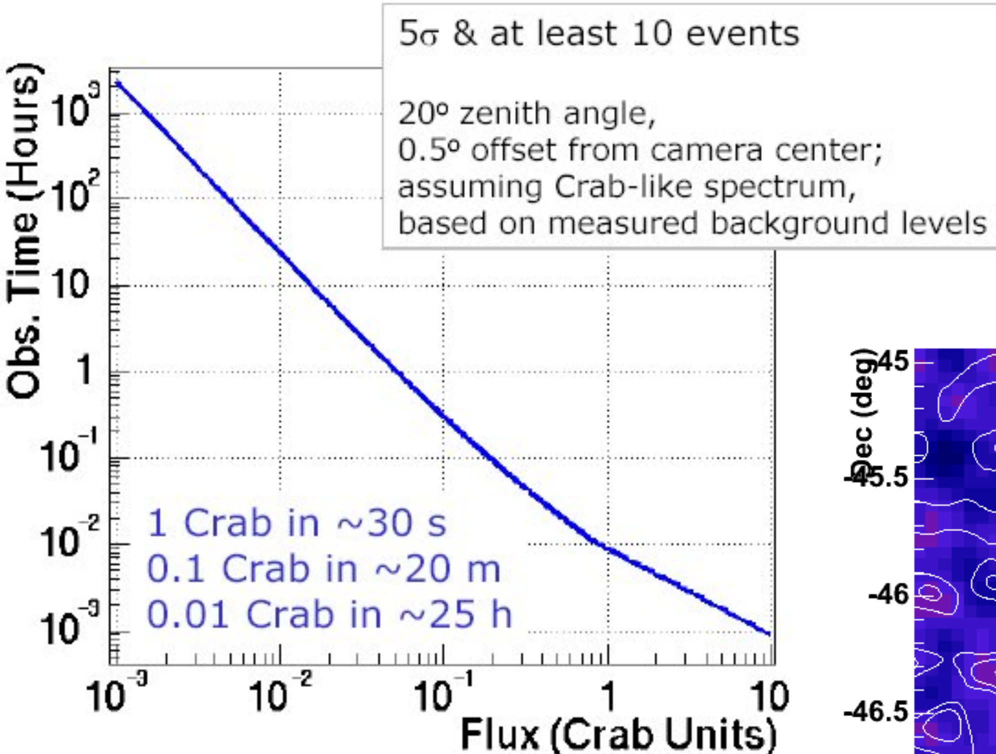
- Comparaison with real signal gives the global efficiency including :
- absorption in the atmosphere
- Reflectivity of miroirs
- Quantum efficiencies of PMTs

- The evolution of the detector as function of the time is automatically taken into account in the analysis.



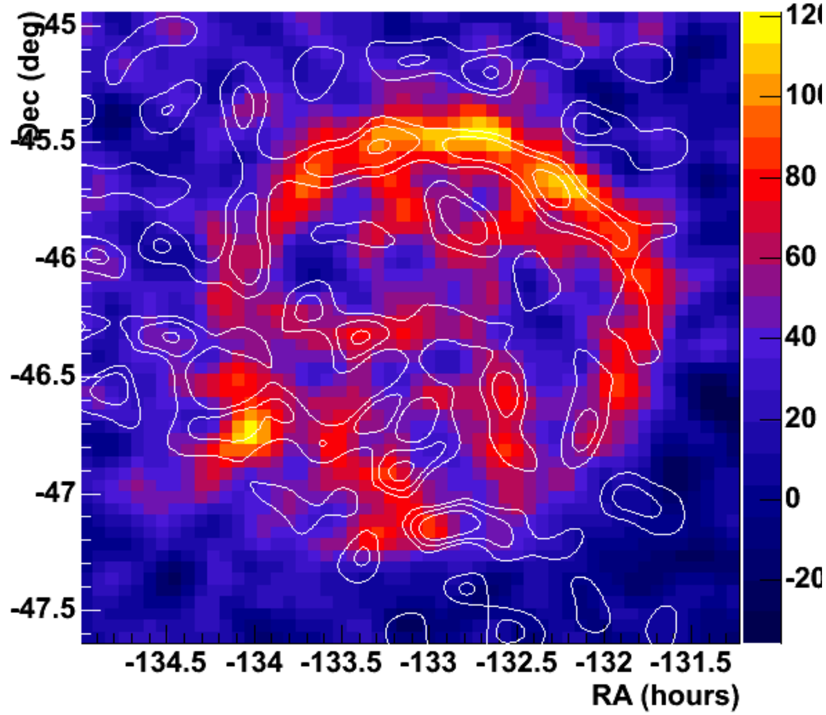


Sensitivity to gamma sources



Large sources:

Vela Junior
(diameter 2°)

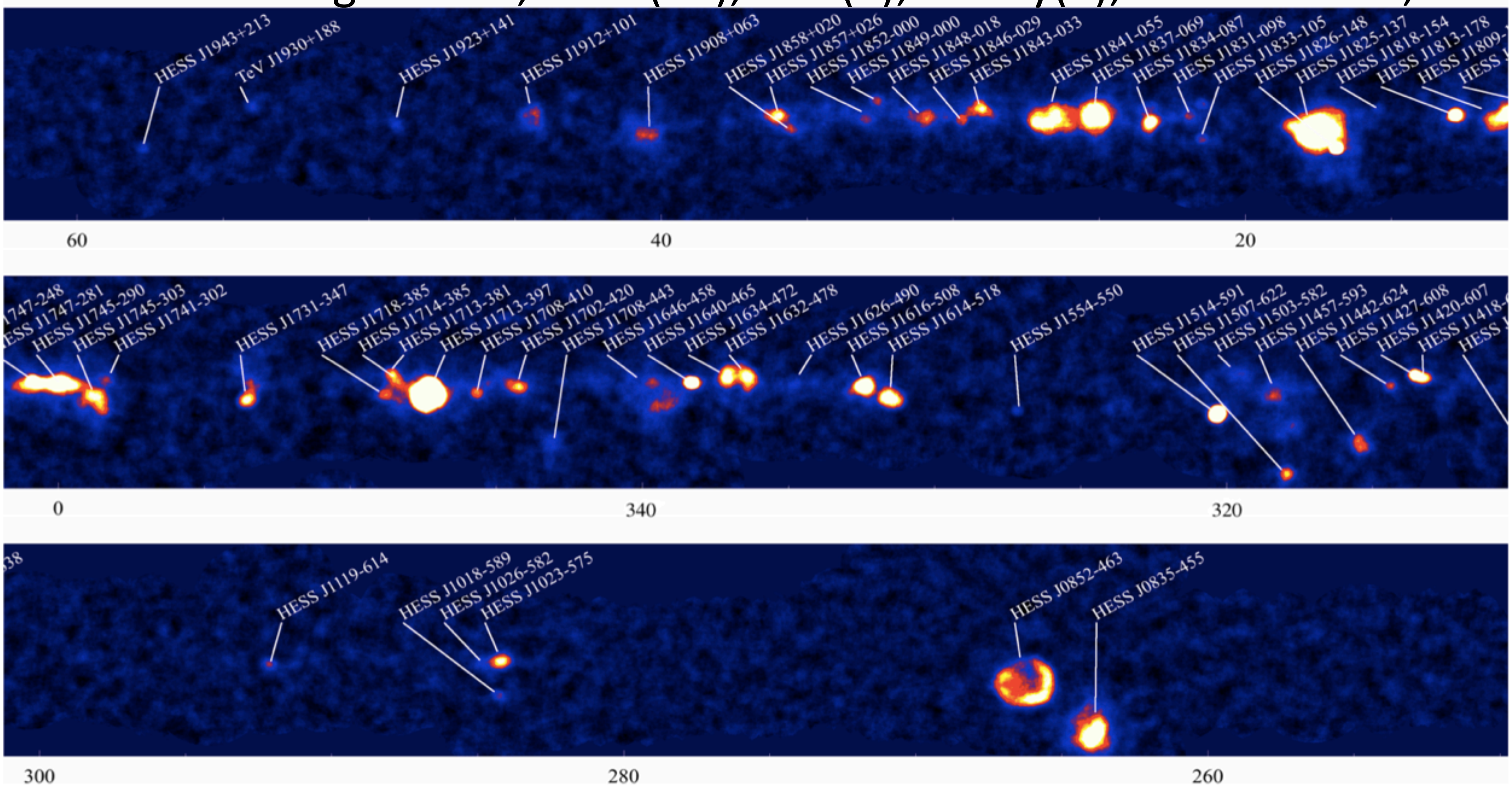


- > 100 sources in 2012
- 6 in 2006

H.E.S.S. Galactic Plan Survey

- Inner part of the Galaxy, 1400 h of data + dedicated pointing on 56 sources

→ Molecular gaz scale, PWN(29), SNR(9), binary(3), Dark sources,…



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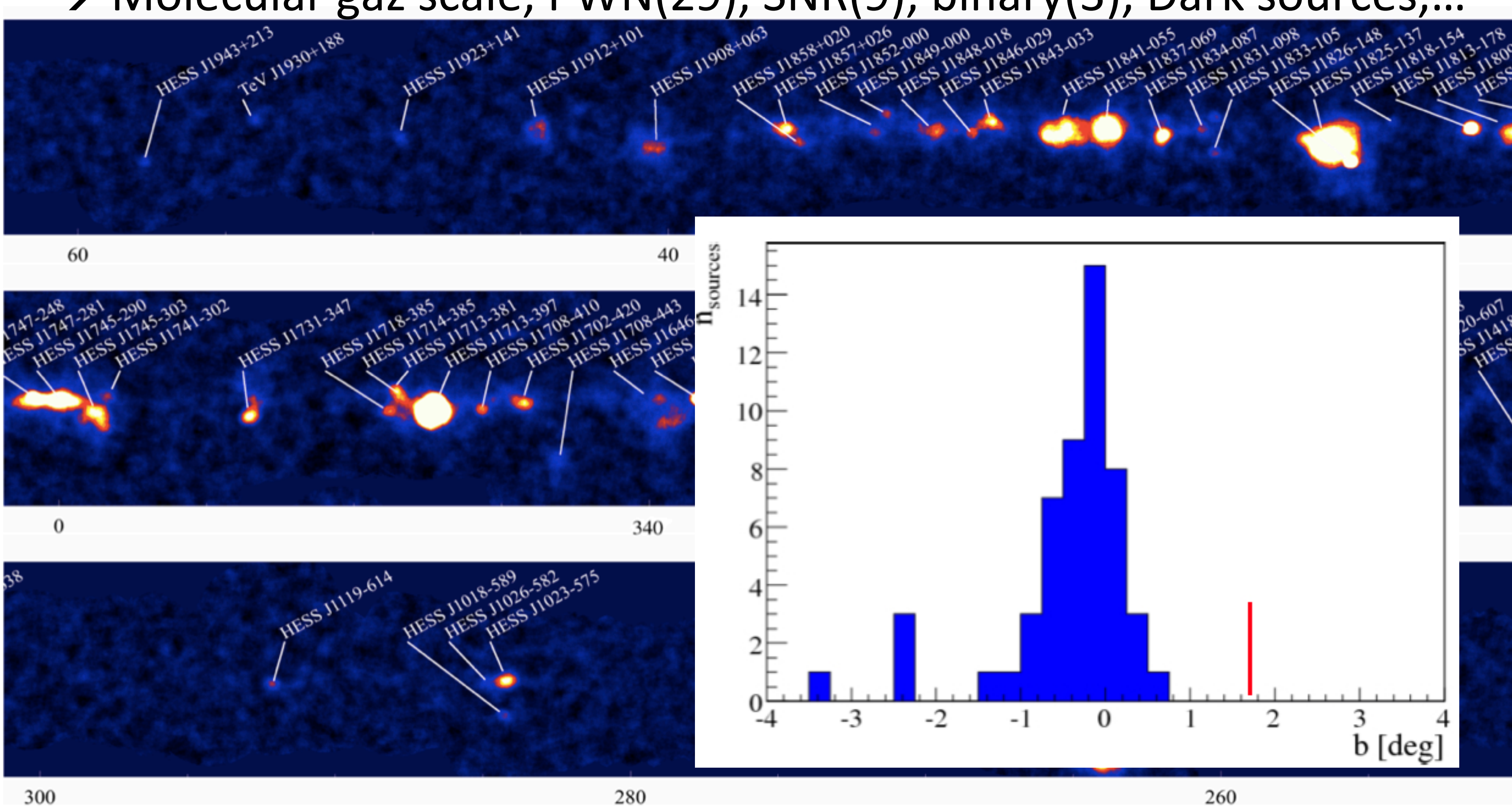


The Galactic Center

In principle the best option :

- Very near, and high DM concentration expected

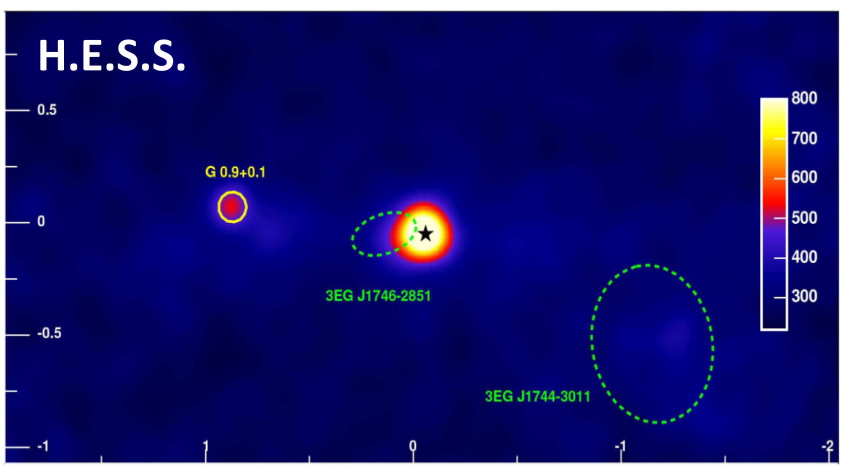
  → Flux should be high.

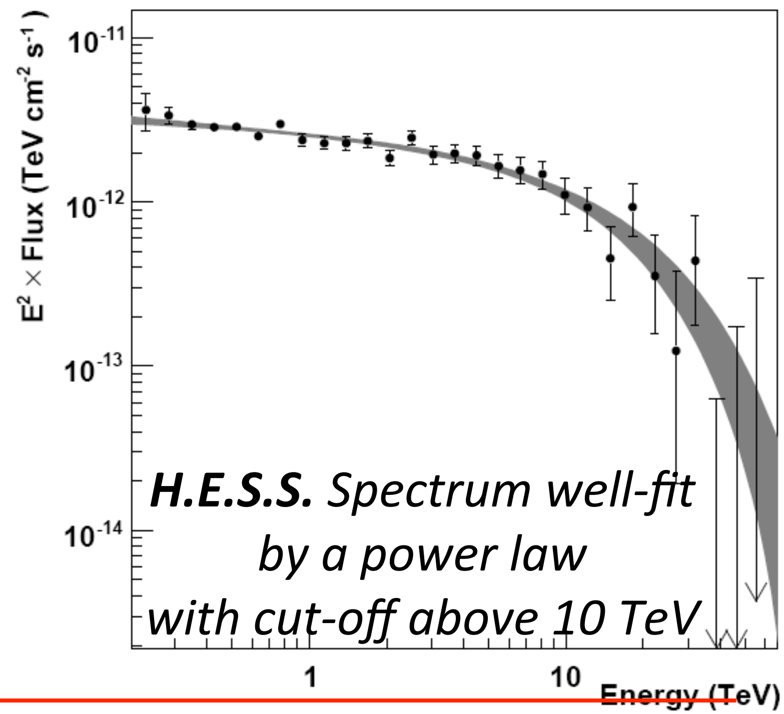
- HESS and MAGIC reported a point-like source

a very massive neutralino, not compatible with WMAP cosmology.

Aharonian et al. (H.E.S.S., 2004) P.R.L., 97221102 / A&A 503 (2009)

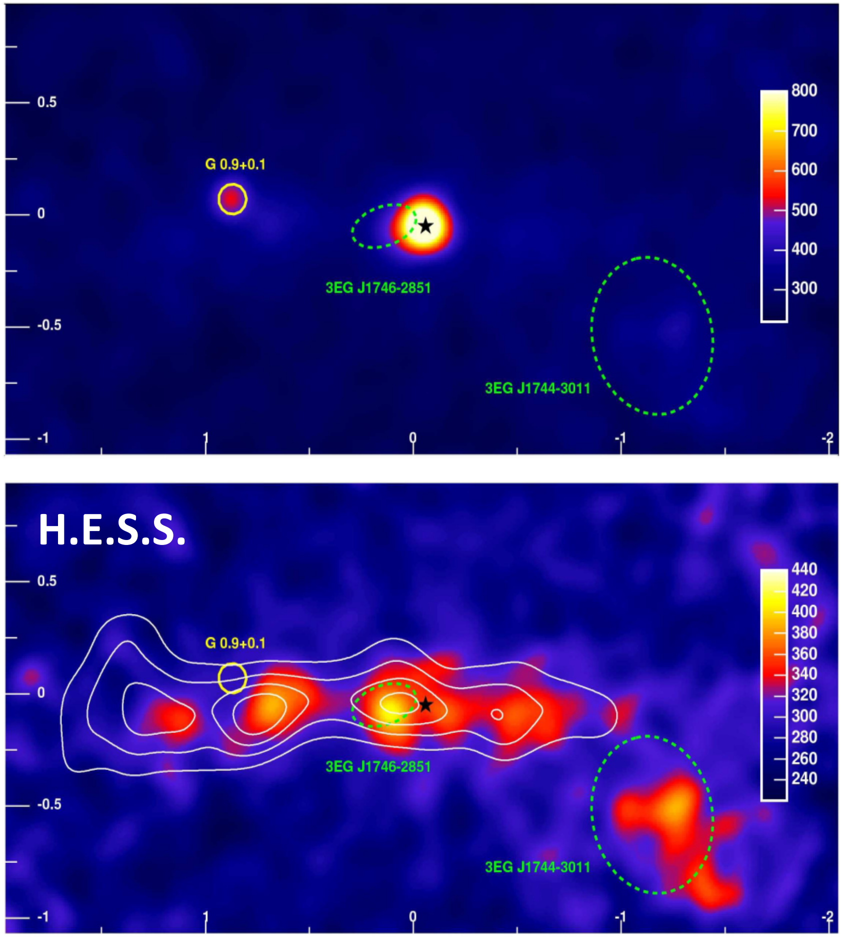
Albert et al. (MAGIC, 2005) A.J., 638





H.E.S.S. *Spectrum well-fit by a power law with cut-off above 10 TeV*

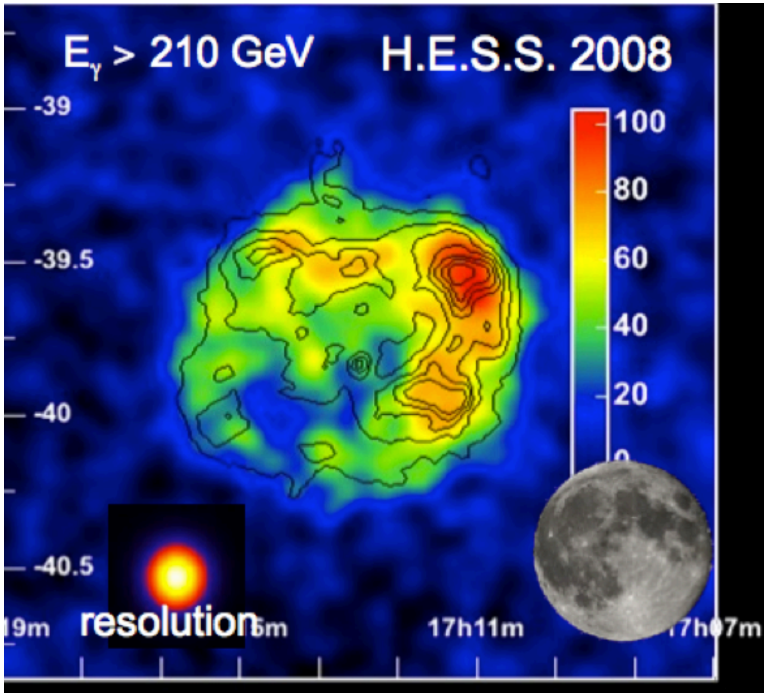
The Galactic Center



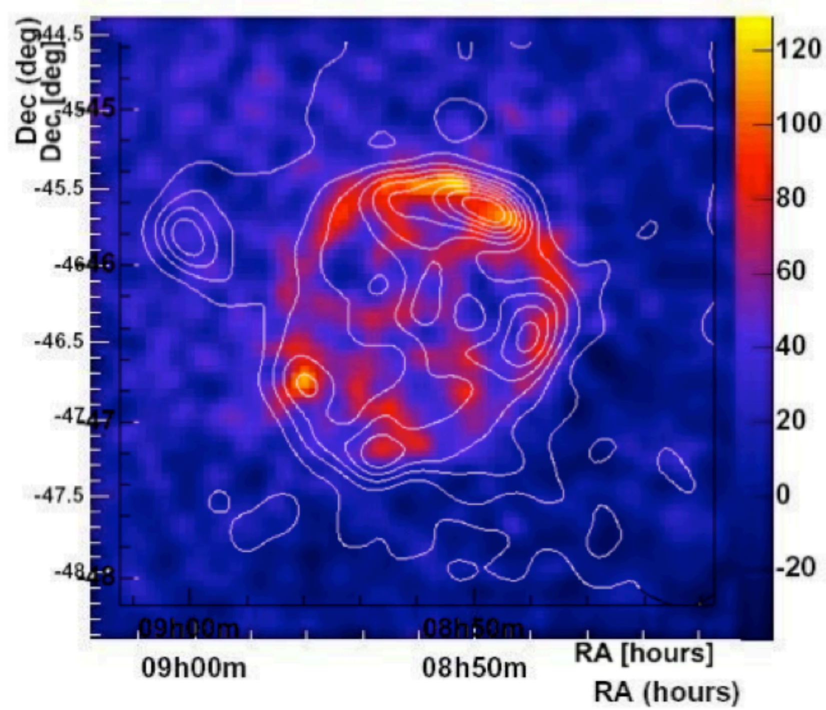
Later on an extended emission was discovered,
but associated to the galactic plane and molecular clouds.

Aharonian et al. (H.E.S.S., 2006), Nature 439

Supernovae remanent



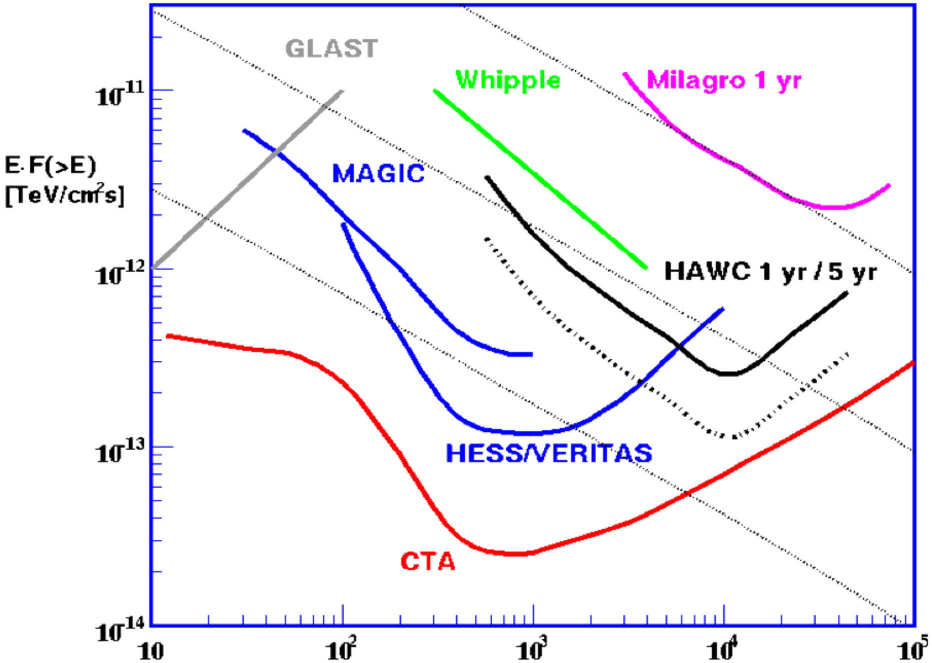
RX J1713.7-3946



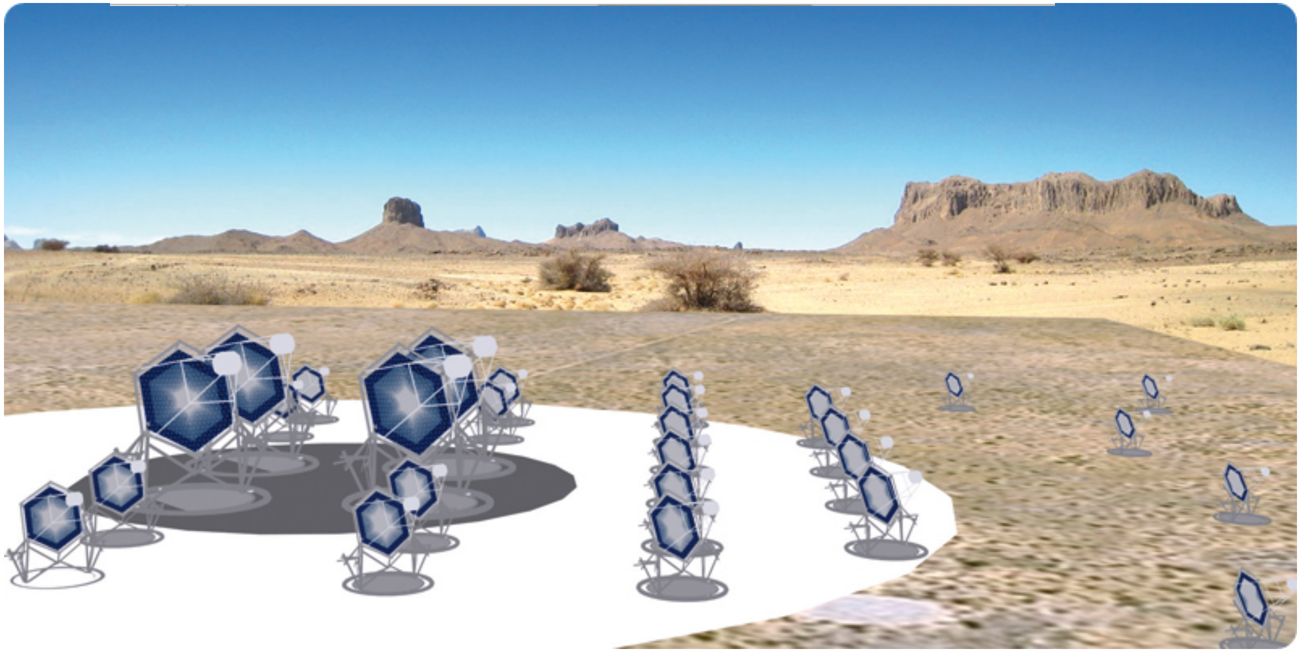
RX J0852.0-4622

- Striking correlation between X-ray and γ-ray emission
- SNRs are proved to accelerated particules up to 100 TeV
- Type of particle unknown

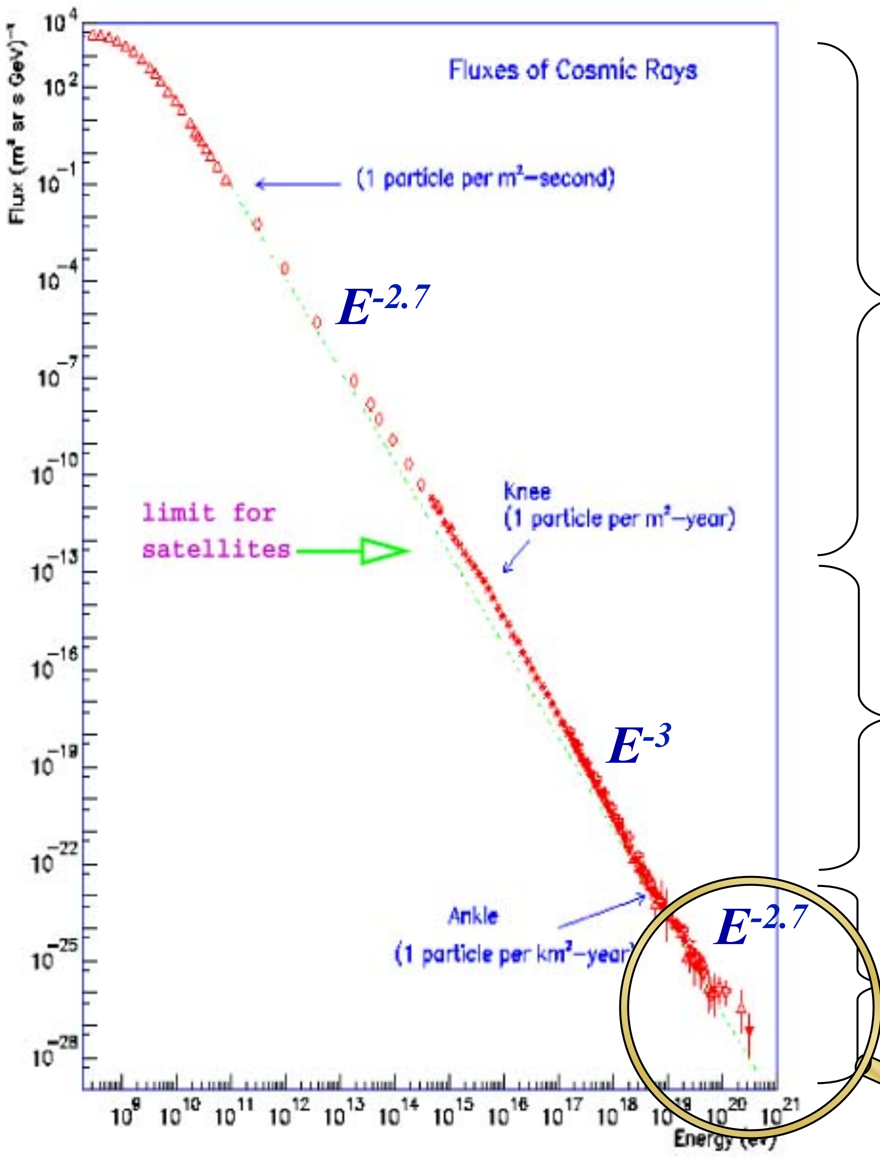
Future



GLAST
Whipple
Milagro 1 yr
MAGIC
HAWC 1 yr / 5 yr
HESS/VERITAS
CTA
E·F(>E)
[TeV/cm²s]
10^{11}
10^{12}
10^{13}
10^{14}
10
10^{2}
10^{3}
10^{4}
10^{5}



The Ankle



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

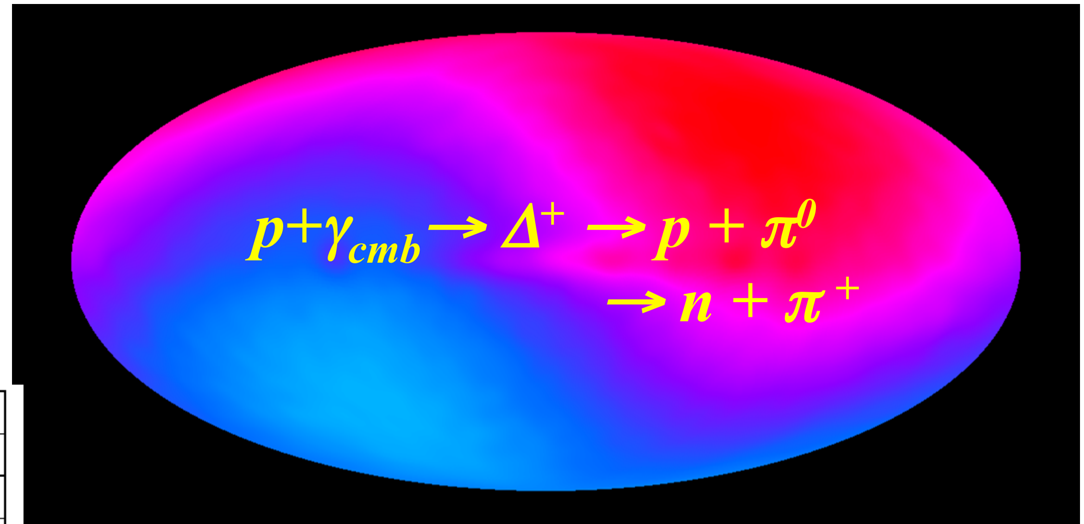
Galactic ?
SuperNovae? Superbubles?
reacceleration?
Heavier nuclei → protons ?

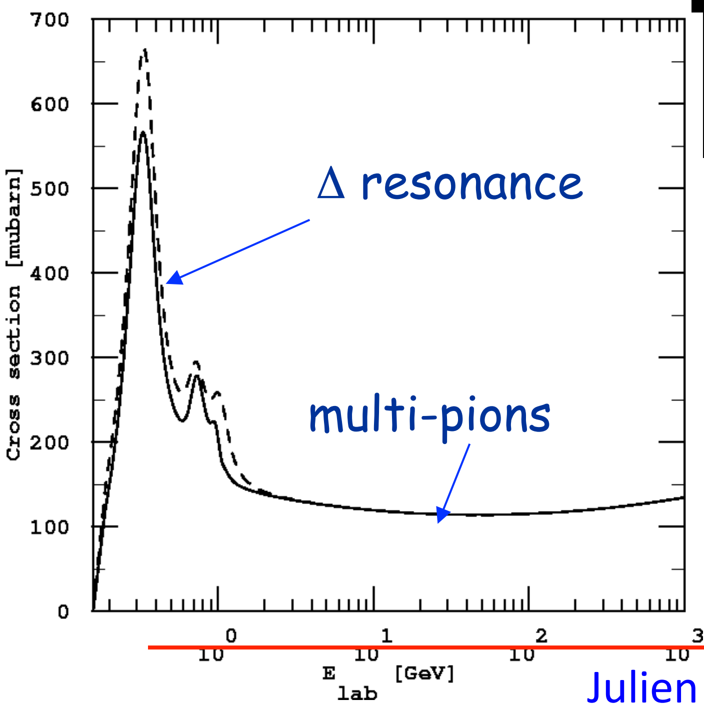
Extragalactic ?
source ?, composition ?

UHECR, terra incognita

GZK Cutoff

An extrem case of relativistic kinematics !!!



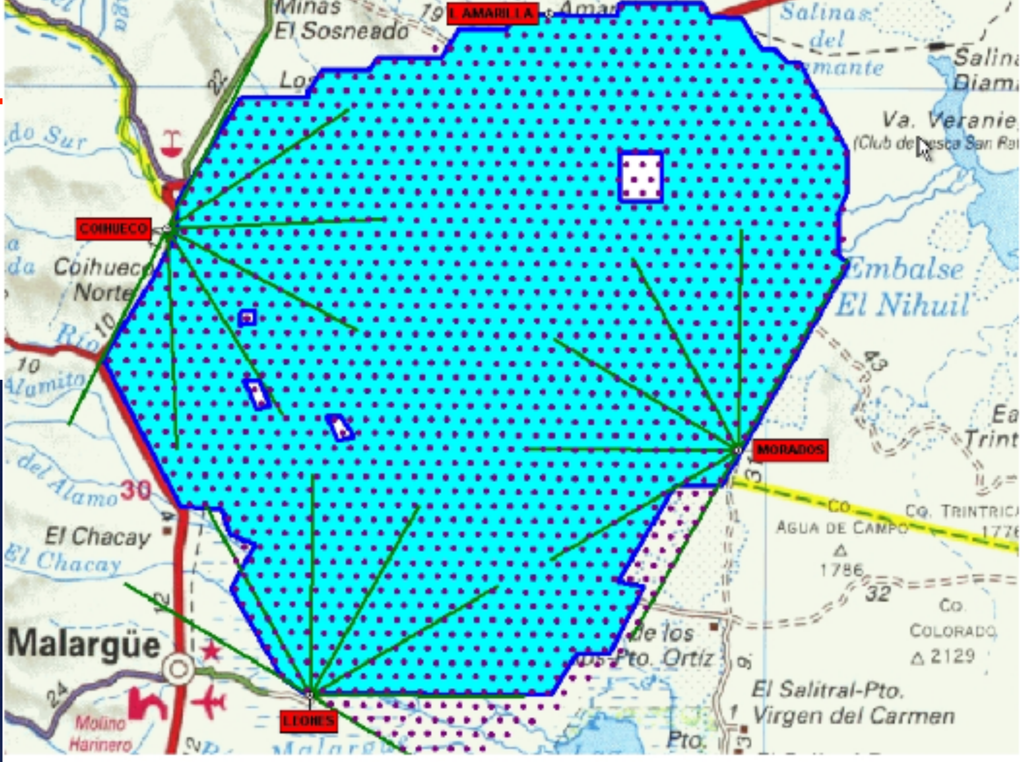


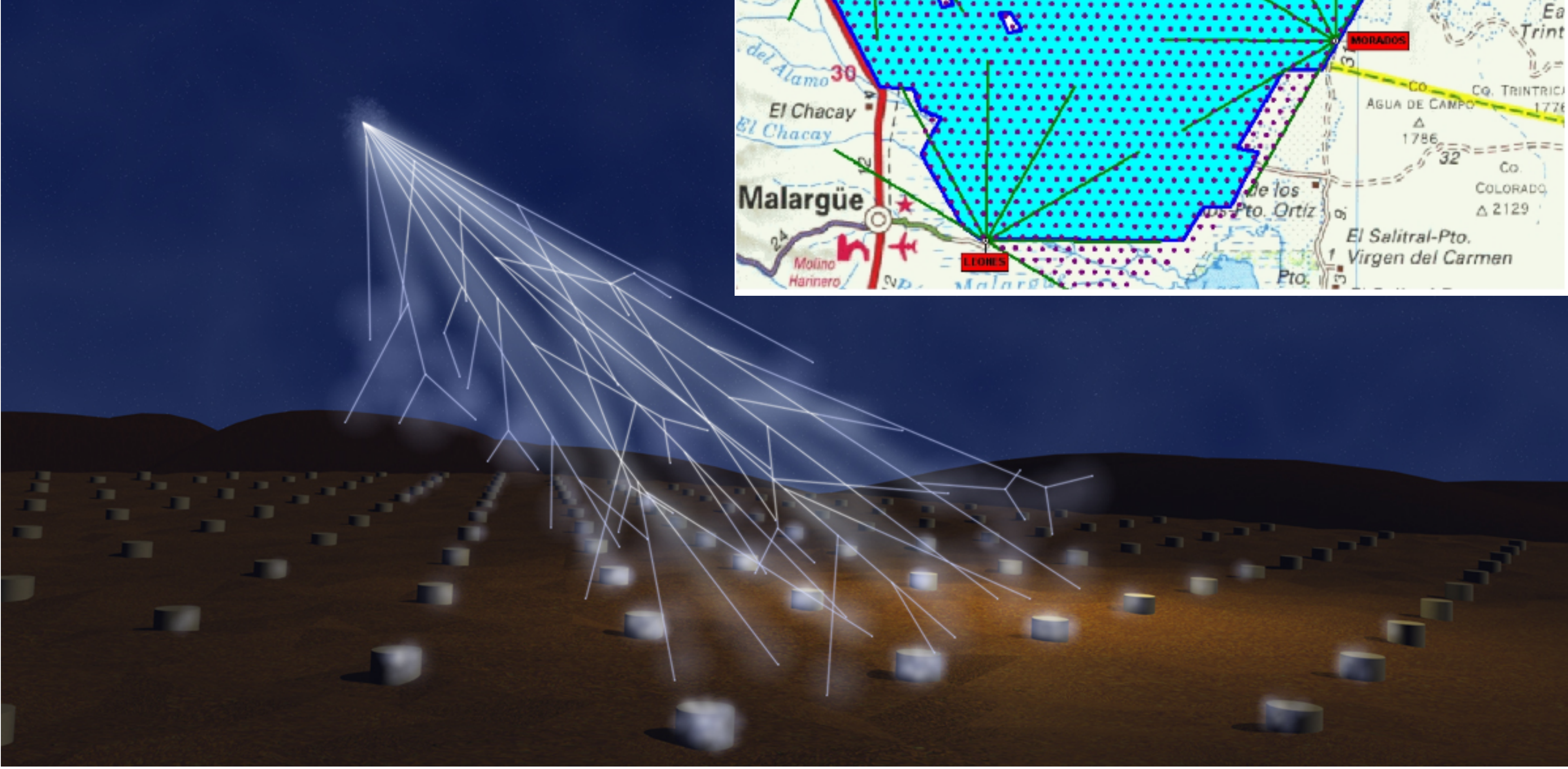
GZK "cutoff"

Greisen '66, Zatsepin & Kuzmin '66

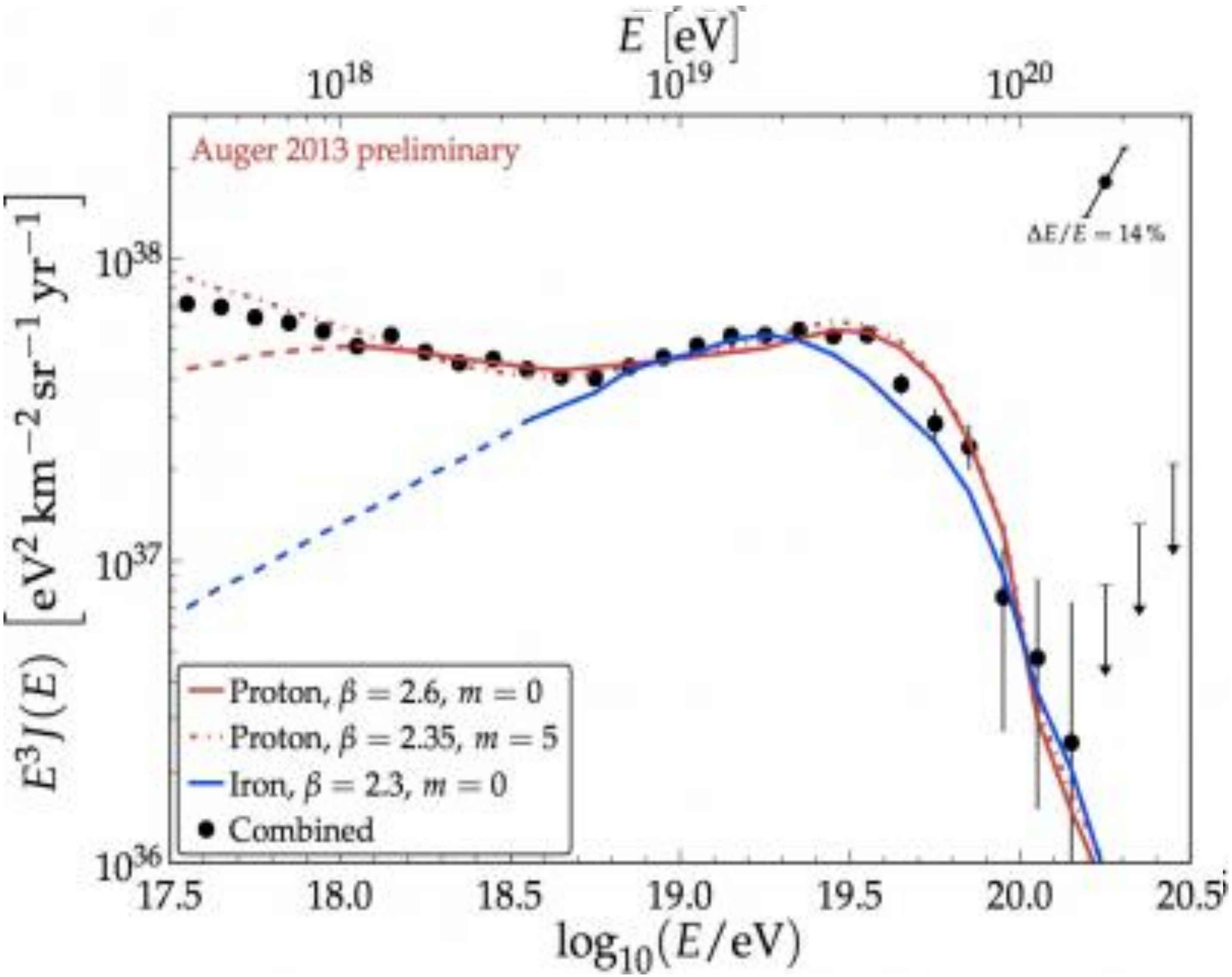
Pierre Auger Observatory

3000m^2 / 1600 tanks





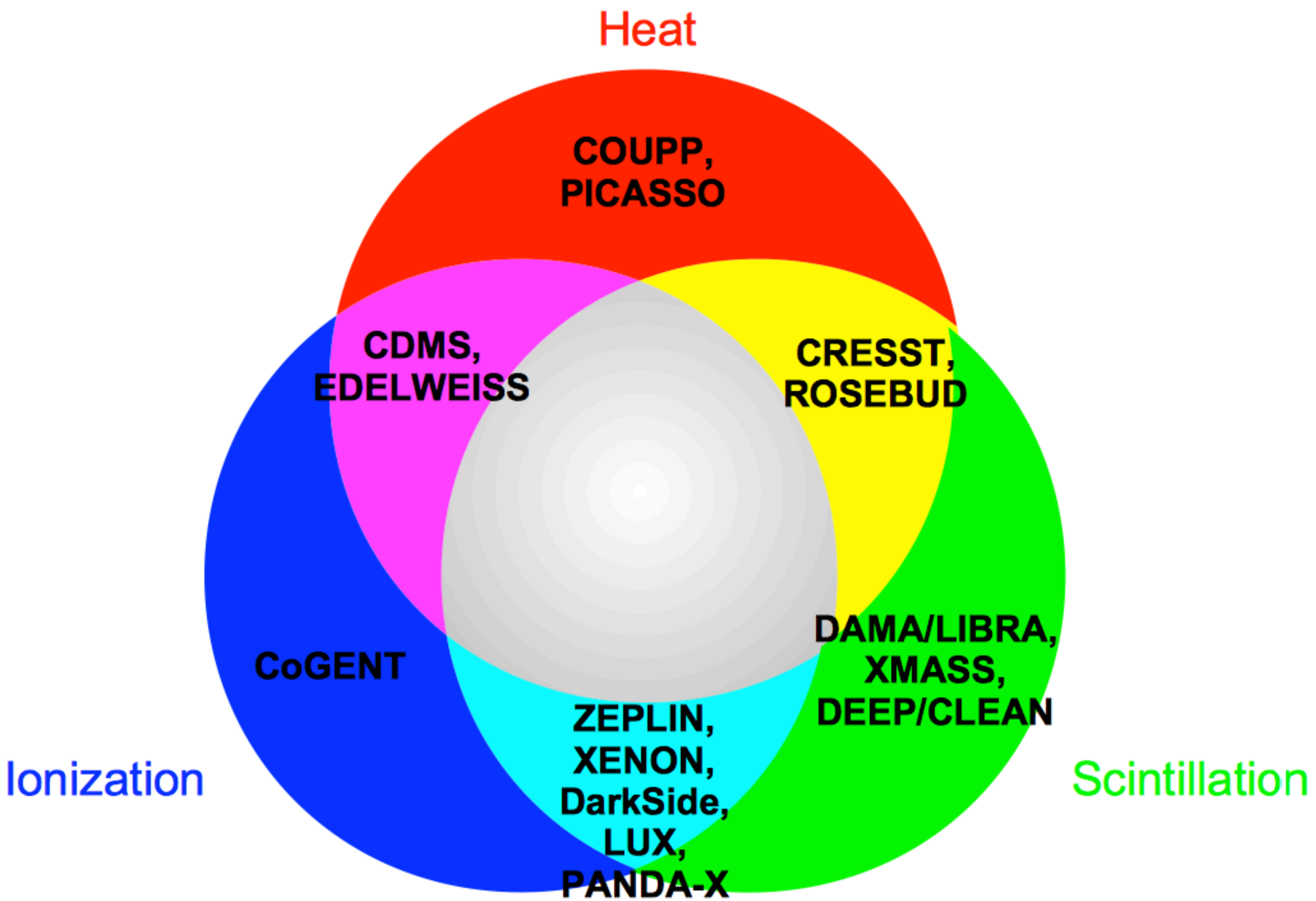
GZK Cutoff



E [eV]
10^18
10^19
10^20
Auger 2013 preliminary
ΔE/E = 14%
10^38
10^37
10^36
E^3 J(E) [eV^2 km^-2 sr^-1 yr^-1]
Proton, β = 2.6, m = 0
Proton, β = 2.35, m = 5
Iron, β = 2.3, m = 0
Combined
17.5
18.0
18.5
19.0
19.5
20.0
20.5
log10(E/eV)

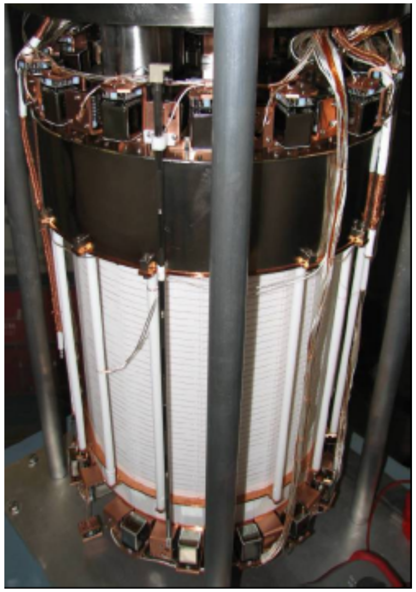
Detection techniques

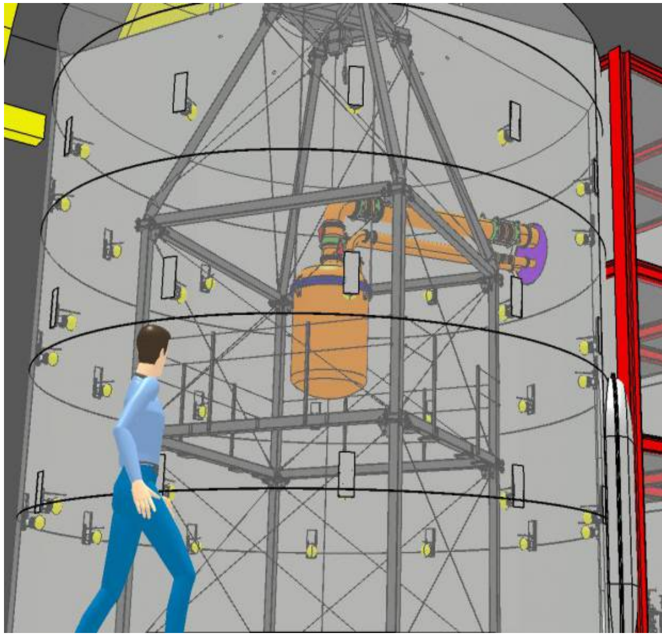
Various targets are used (Ge, Xe, Ar, Ne, . . .)
Energy recoil is transferred to three possible phenomena: **scintillation**, **ionization**, **heat**
One (or two) among these three signals are used for particle detection.



Direct detection with xenon

The XENON Dark Matter Program





XENON10
Achieved (2007)
σ_{SI} = 8.8 · 10^{-44} cm² @ 100 GeV/c²
Phys.Rev.Lett. 100 (2008) 021303

Light DM:
σ_{SI} = 7 · 10^{-42} cm² @ 7 GeV/c²
Phys.Rev.Lett. 107 (2011) 051301

XENON100
Achieved (2012)
σ_{SI} = 2.0 · 10^{-45} cm² @ 55 GeV/c²
E. Aprile et al. (XENON100),
Phys. Rev. Lett. 109 (2012)
arXiv:1207.5988

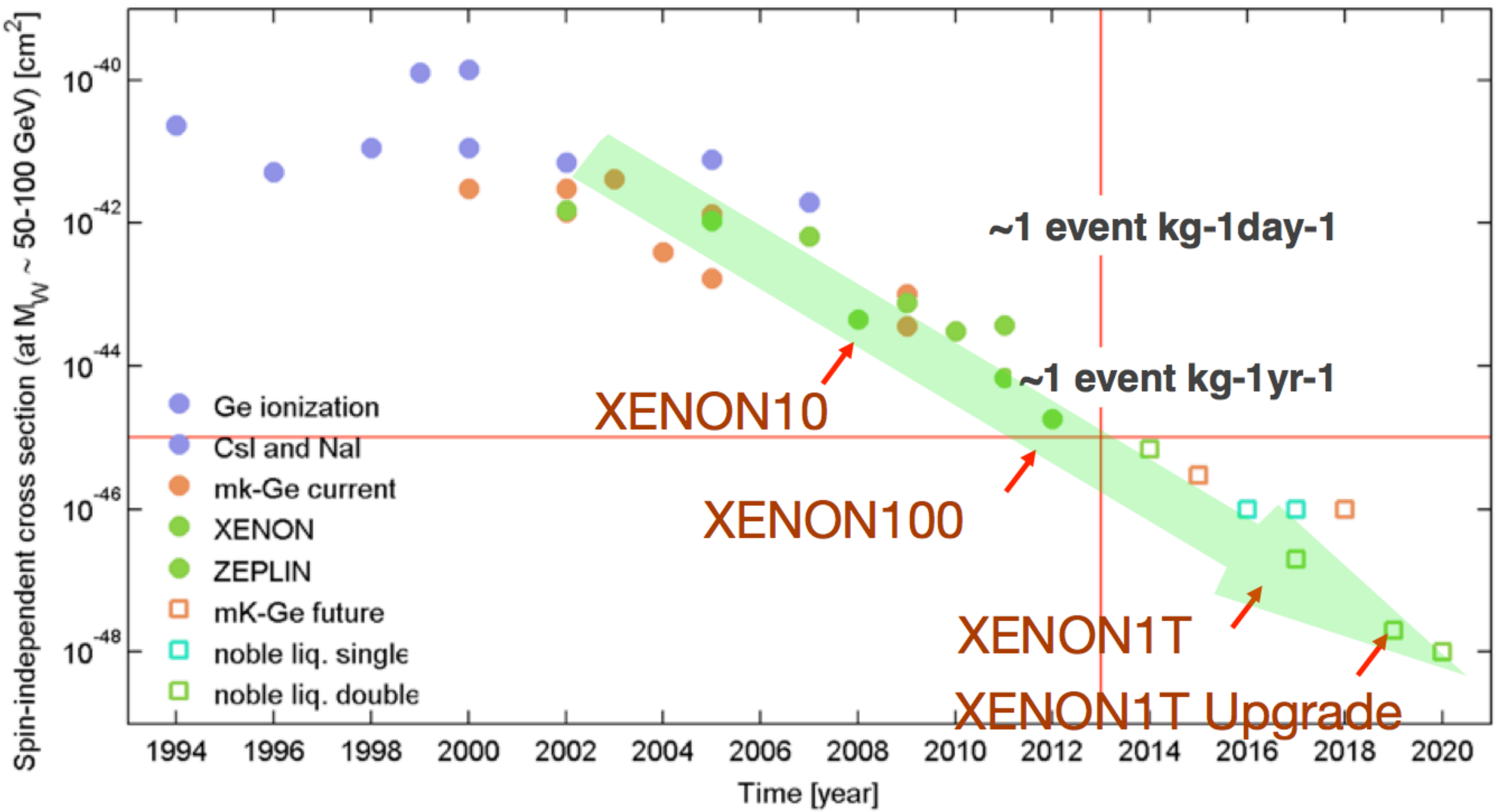
In operation since 2009

XENON1T
Projected (2017)
σ_{SI} = ~ 10^{-47} cm²

Construction started in 2013

Upgrade : XENONnT
σ_{SI} = ~ 10^{-48} cm²

Direct detection : progress over time



Background Suppression

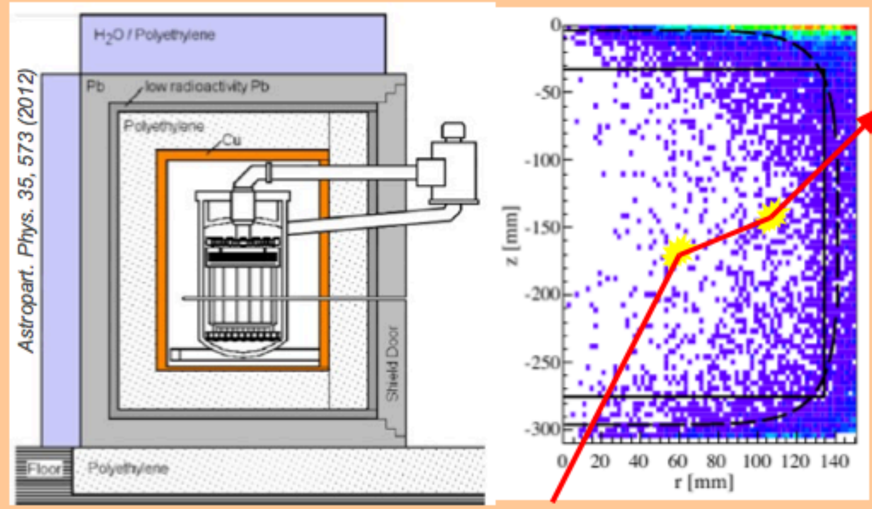
A Avoid Backgrounds

Use of radiopure materials

Shielding

deep underground location
large shield (Pb, water, poly)
active veto (μ, γ coincidence)

self Shielding → fiducialization



B Use knowledge about expected WIMP signal

WIMPs interact only once

→ single scatter selection
require some position resolution

WIMPs interact with target nuclei

→ nuclear recoils
exploit different d*E*/dx from
signal and background

Scintillation Pulse Shape

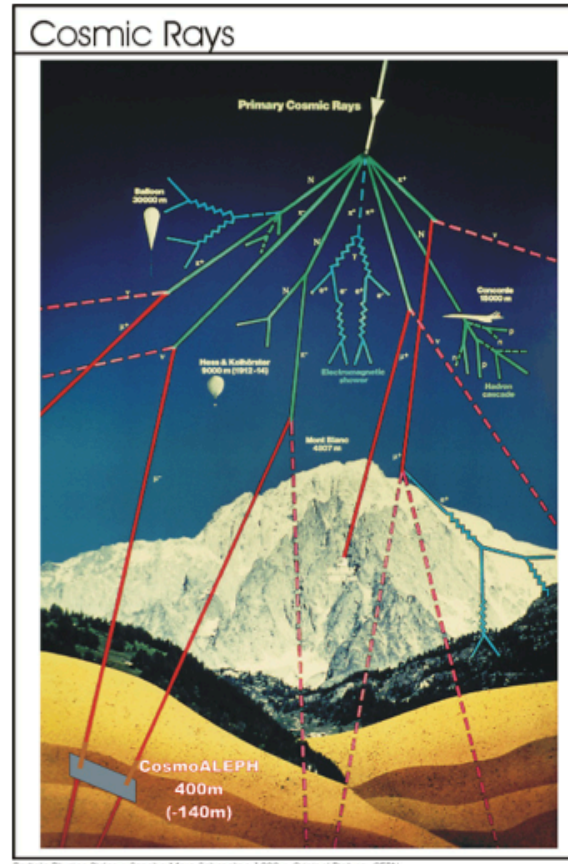
Signal Quenching

Cosmic Rays

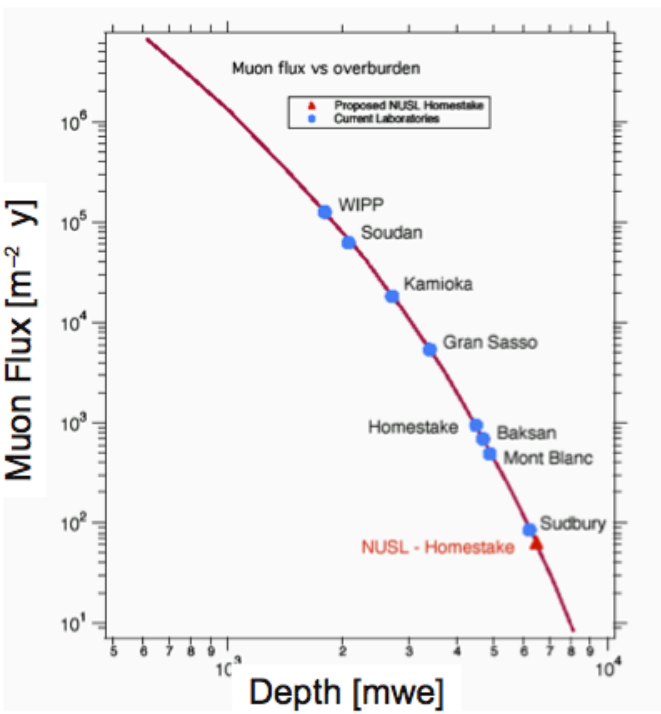
Cosmic rays and secondary/tertiary particles which they create in reactions can be reduced by going to underground laboratories

The hadronic component (n, p) is already reduced significantly after a few meters rock

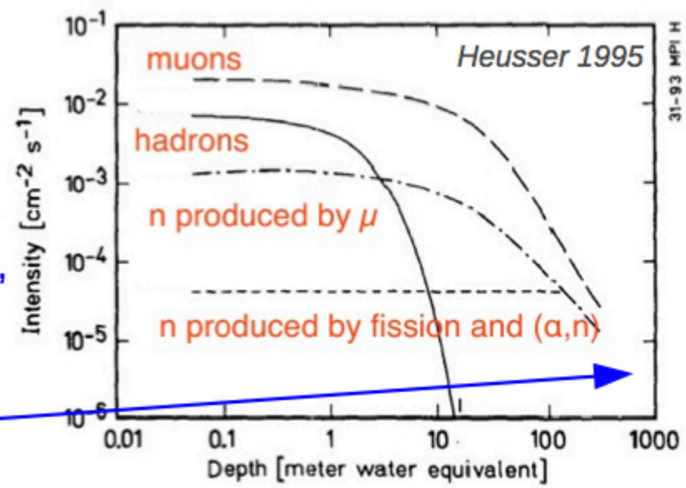
Shielding thickness (rock, soil) given in „meter-water-equivalent“ (mwe) to allow for comparison between different laboratories



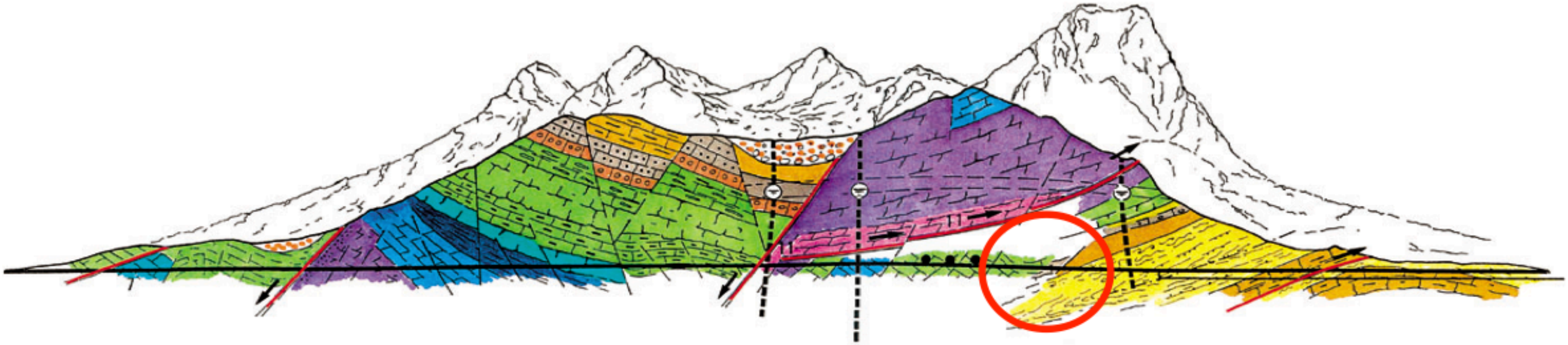
Particle Physics Slides • Sascha Marc Schmeling 1999 • Original Picture: CERN

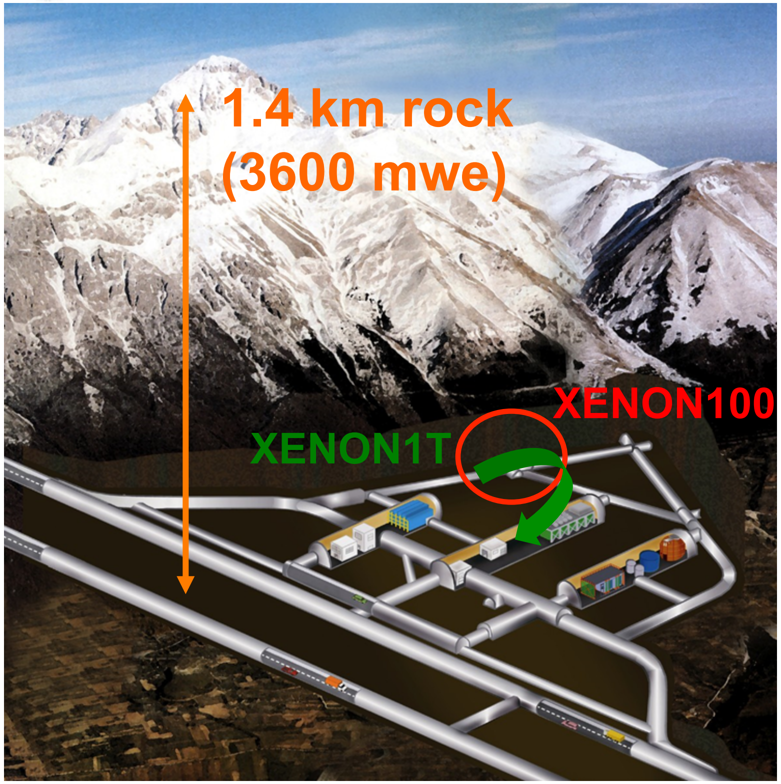


in deep laboratories, only muons remain which cause e/m showers and also generate neutrons



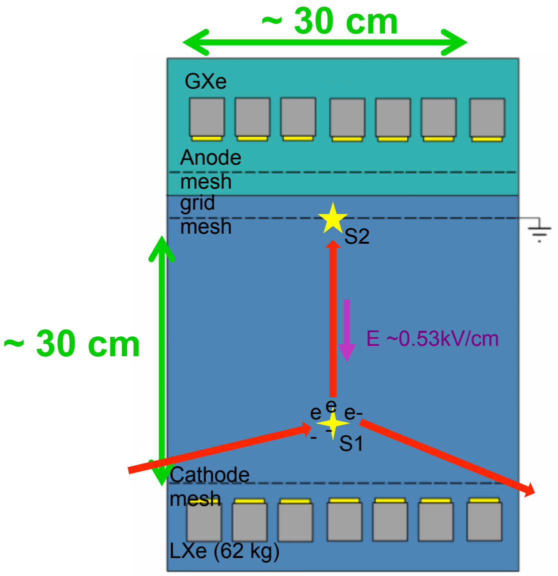
Location of the XENON experiment

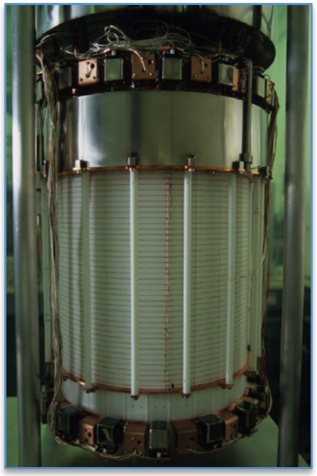


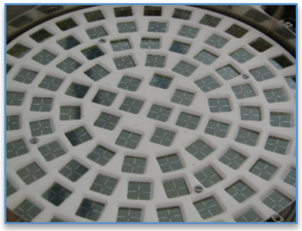


Two phase XENON TPC principle

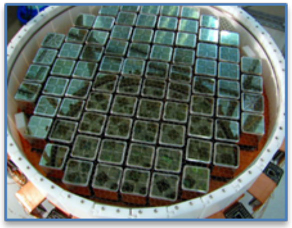
E. Aprile et al. (XENON100), Astropart. Phys. 35, 573-590 (2012)



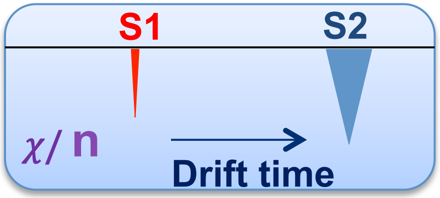




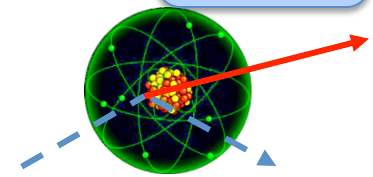
Top array
98 PMTs

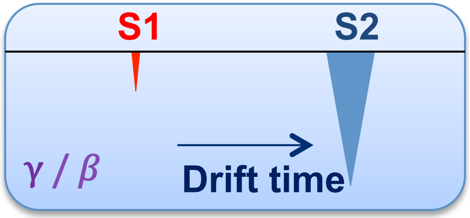


Bottom array
80 PMTs

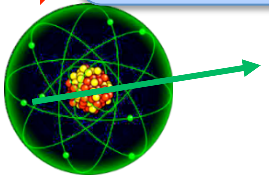


Nuclear Recoil





Electronic Recoil

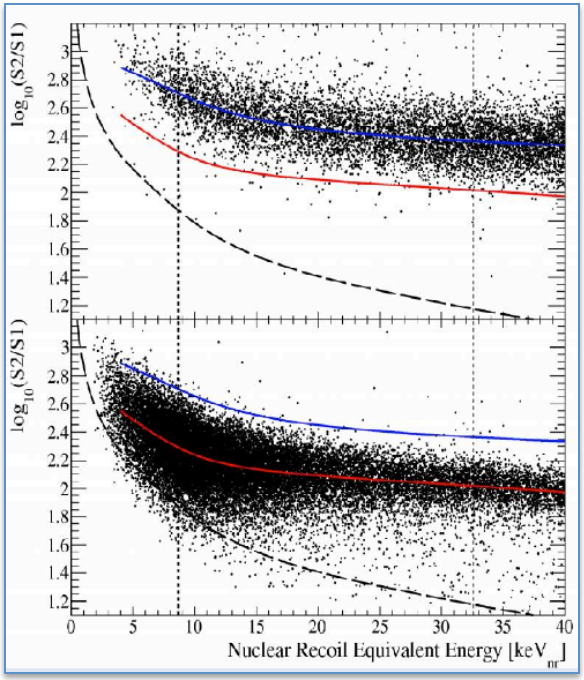


- Materials selected for low radioactivity
- Scintillation (S1) and Charge (S2) Signals
  - ER / NR discrimination
- 3D Reconstruction for fiducialization:
  - **(XY)** – Top PMTs hit pattern (± 3 mm)
  - **(Z)** – Drift time (± 0.3 mm)
- Multiple scattering rejection

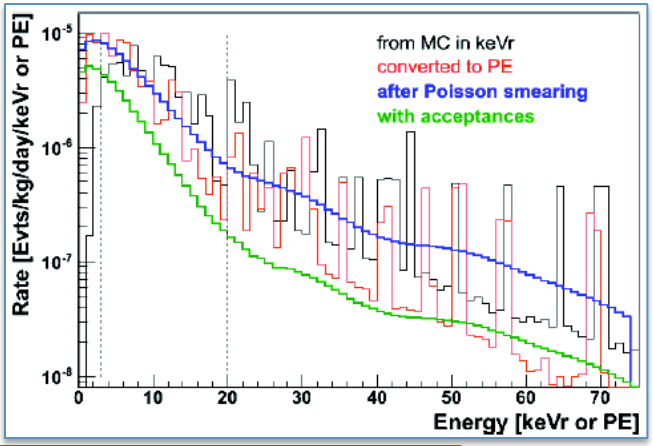
Background expectation

E. Aprile et al. (XENON100), arXiv:1207.3458

- **Electronic recoil background:**
  - Electronic recoil estimation done with ^{60}CO and ^{232}Th Data collected all the time for a total of 40 effective days
  - 35 times more statistics than in data used for Dark Matter search
  - Expected events in a benchmark region : **0.79±0.16**



- **Neutron recoil background:**
  - Calibration done with ^{241}AmBe exposure
    Two exposure campaigns:
    one at beginning and one at the end of run
  - Nuclear recoil estimation done with Geant4 simulation
  - Expected events in a benchmark region : $\mathbf{0.17^{+0.12}_{-0.07}}$



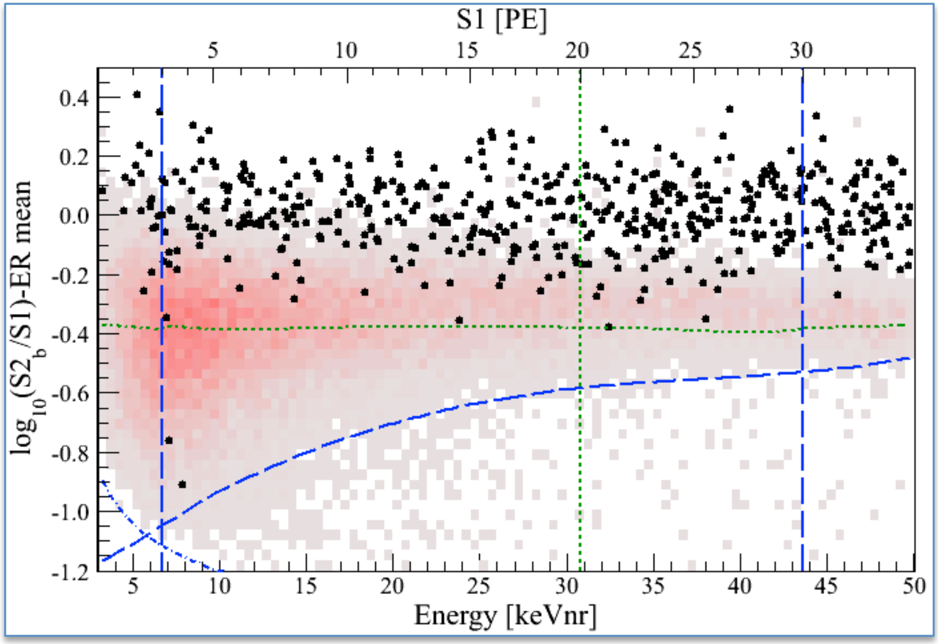
- **Total background:**

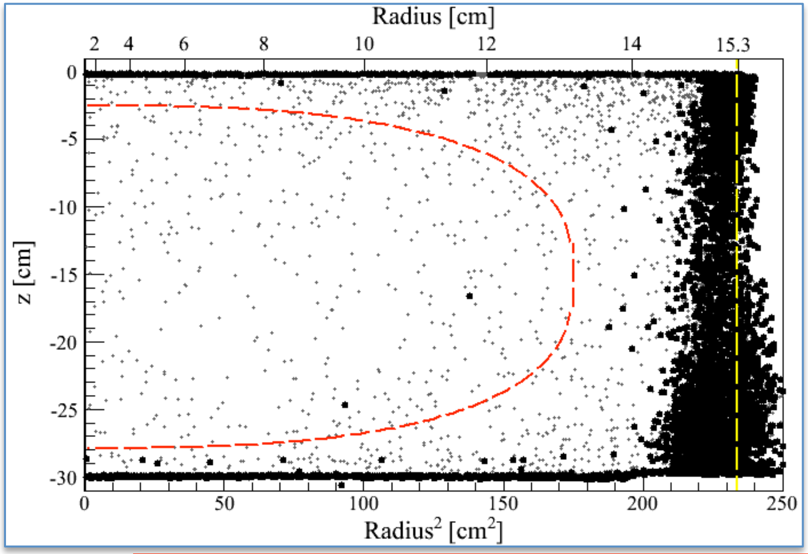
- In the benchmark region we expect in **total**
  1.0±0.2 events

E. Aprile et al. (XENON100), Phys. Rev. Lett. 109, 181301 (2012)

Blind analysis

- XENON100 did a blind analysis
- Event discrimination by S2/S1 separation
- Defined WIMP searching region:
  - S1 with benchmark region (3 - 30 pe)
  - S2 threshold cut (S2 > 150 pe)
  - 99.75 % ER rejection line

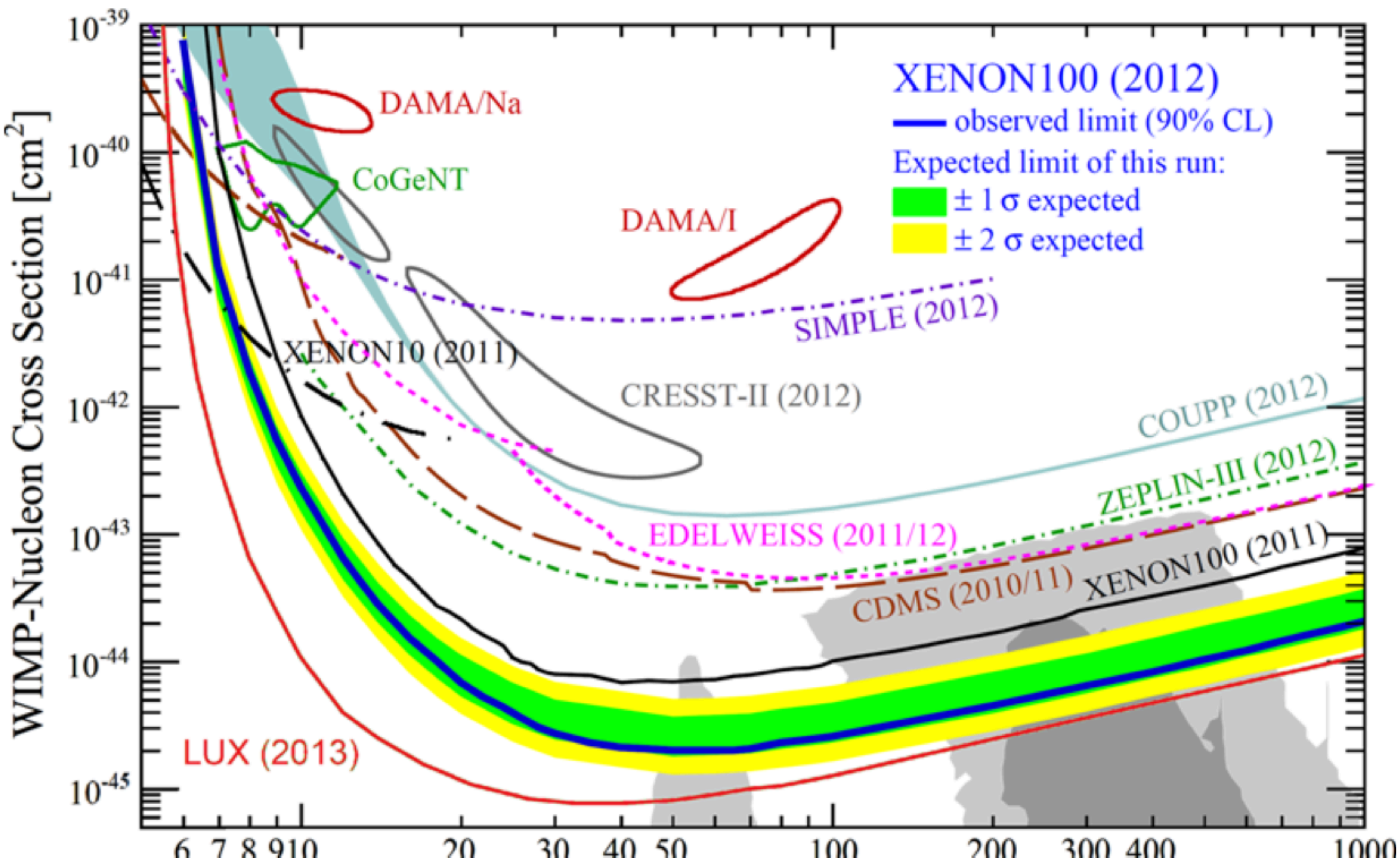




- Event rejection by defining a 34kg super-ellipse
- Double scatters excluded

Probability that 2 events fluctuate over the background expectation is 26.4%

Dark Matter Spin independent limits



XENON100:
2x10^{-45}cm^2
@50GeV
Blinded Analysis

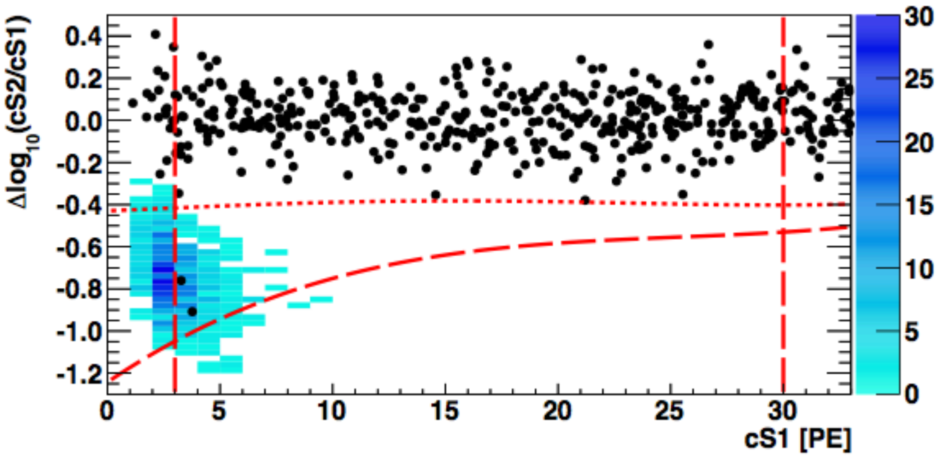
LUX:
7.6x10^{-46}cm^2
@33GeV

XENON100 Collaboration, Phys. Rev. Lett. 109, 181301 (2012)
LUX Collaboration, Phys. Rev. Lett. 112, 091303 (2014)

Predictions for light WIMPs

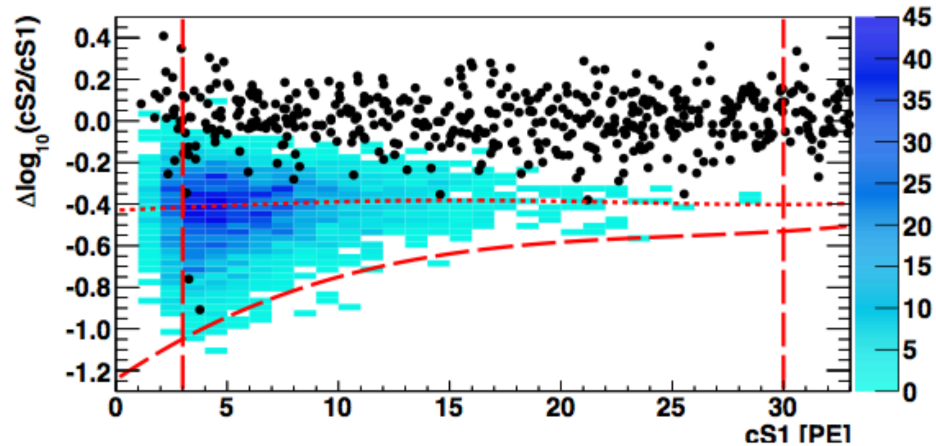
- How would signal claims of other experiments look like in XENON100's Run10 data?

WIMP with m_W = 8 GeV



WIMP-nucleon cross section : 3×10^{-41} cm^2

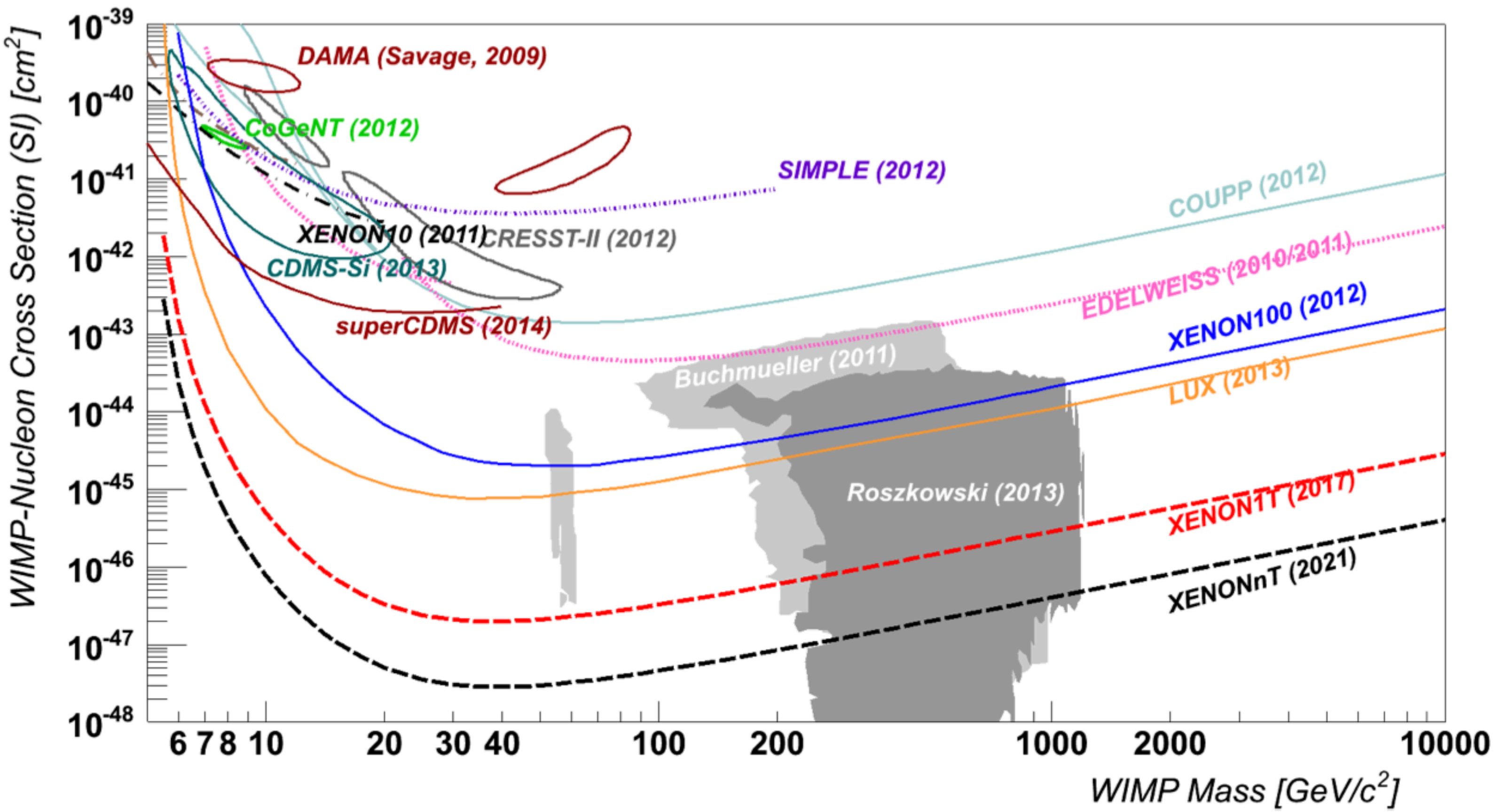
WIMP with m_W = 25 GeV



WIMP-nucleon cross section : 1.6×10^{-40} cm^2

XENONnT : limits

No WIMP Dark Matter found yet
(apart several hints at low masses not supported by other experiments)
Increase the fiducial volume by building a bigger TPC and cryostat



XENON10 → XENON100 → **XENON1T** → XENONnT