Taller de Altas Energías

Benasque, September 24th 2014

Cosmic Rays

Universidad de Granada

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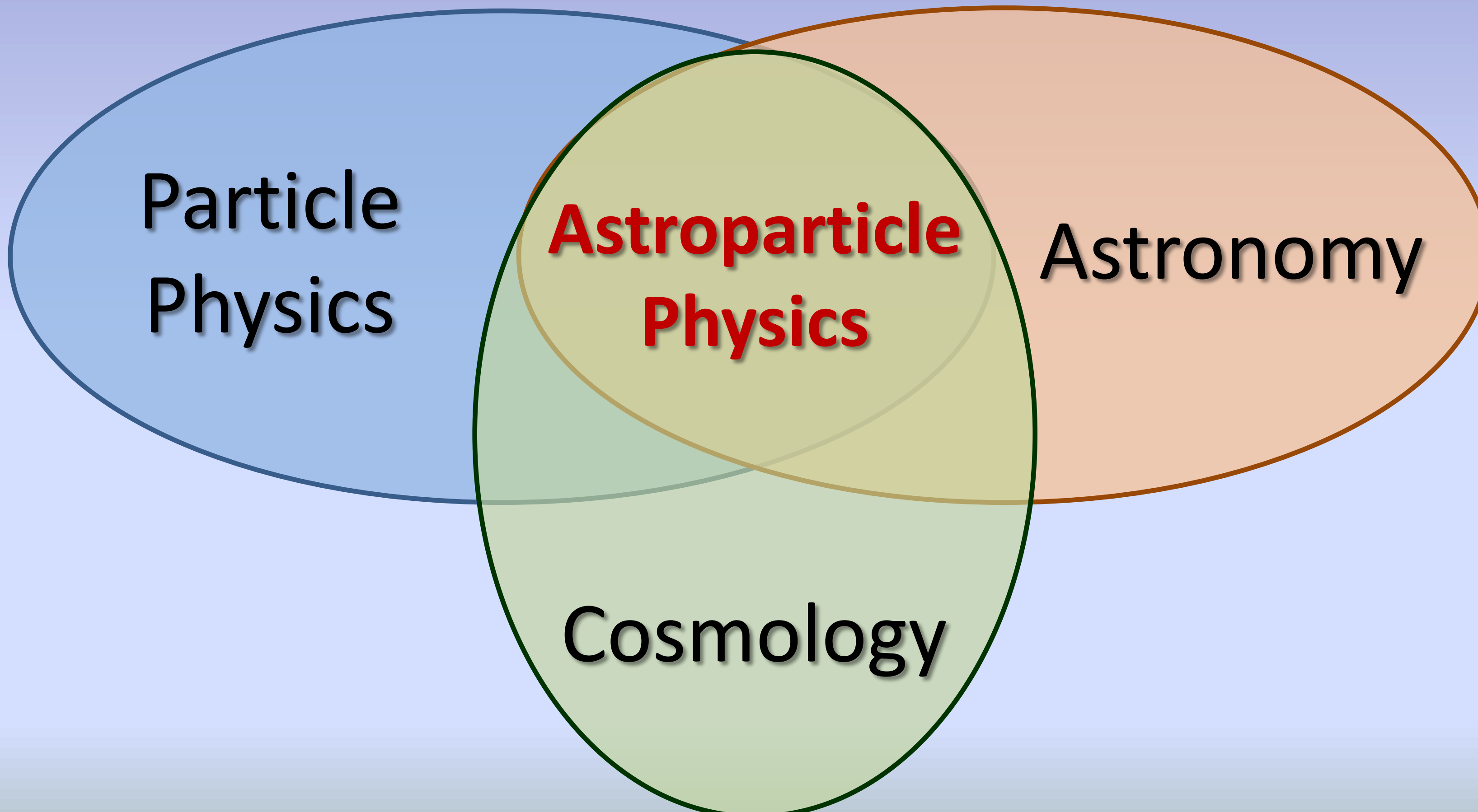
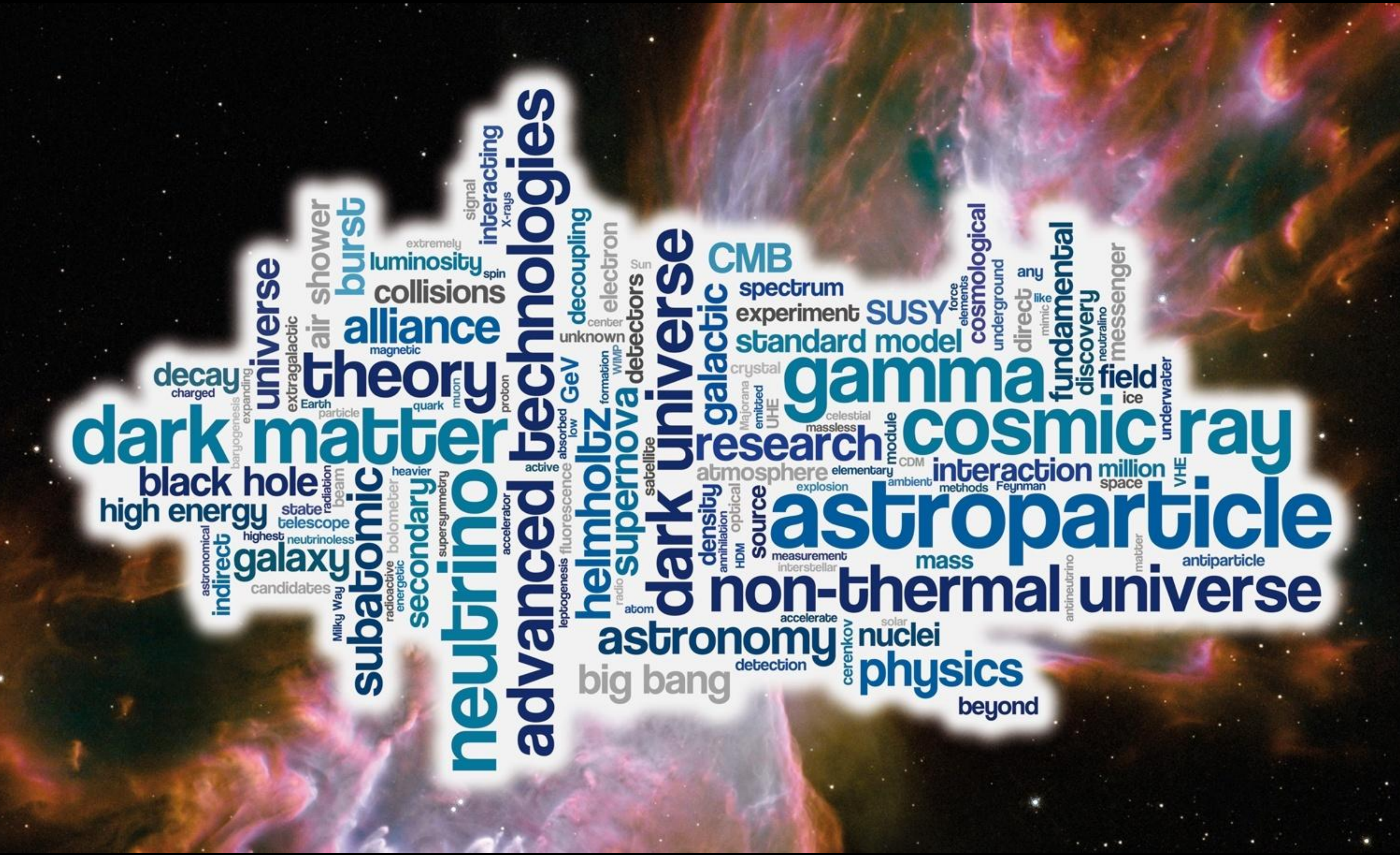
Astroparticle Physics

... is a branch of particle physics that studies elementary particles of astronomical origin and their relation to astrophysics and cosmology. It is a relatively *new field of research*...



The field covers many many topics …



Astroparticle Physics related talks:

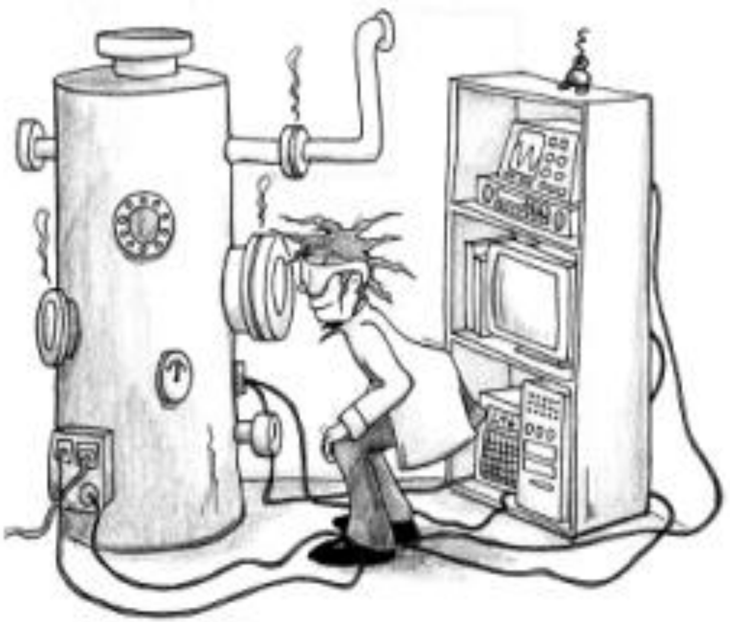
- ✓ Dark Matter ← talk by *David Cerdeño [DM]* *Tuesday 23th*
- ✓ Dark Energy
- ✓ Gamma Ray Astronomy ← talk by *Marcos López [APG]* *Friday 26th*
- ✓ Neutrino Astronomy ← talk by *Carlos Pérez [ST4]* *Thursday 25th*
- ✓ **Cosmic Rays** ← this talk *[APC]* *Wednesday 24th*
- ✓ ... etc ...
- ✓ Cosmic Microwave Background , Gravitational Waves ...
- ✓ ... etc ...

Lecture outline

- HISTORY
- Acceleration and propagation
- The observations (spectrum)
- UHECRs

BRIEF HISTORY

OF COSMIC RAY DETECTION

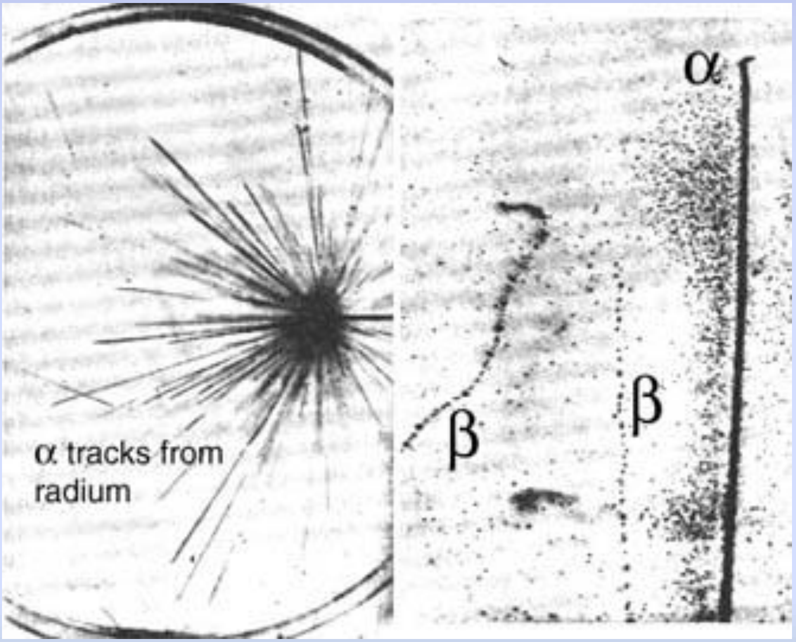



… long time ago
back in 1900 …

- 1911 CTR **Wilson**: Development of the **cloud chamber** & publication of the first pictures
- 1911 – 1912 VF Hess: balloon flights ← first evidence of CRs

1927

Original Wilson Cloud Chamber (Cavendish Museum)



C. T. R. Wilson, Proc. Roy. Soc. (London), 87, 292 (1912)

Victor F. Hess, centre, departing from Vienna about 1911, was awarded the Nobel Prize in Physics in 1936

- 1911 CTR **Wilson**: Development of the **cloud chamber** & publication of the first pictures
- 1911 – 1912 VF Hess: Calibration measurements with gamma rays
- 1911 VF Hess: First three balloon flights
- 1912 VF Hess: Six balloons flights at altitudes 150 – 2750 m (eclipse of sun, night, day, afternoon)
- 1912 VF **Hess**: Seventh balloon flight: 5350 m ← **discovery of cosmic rays**

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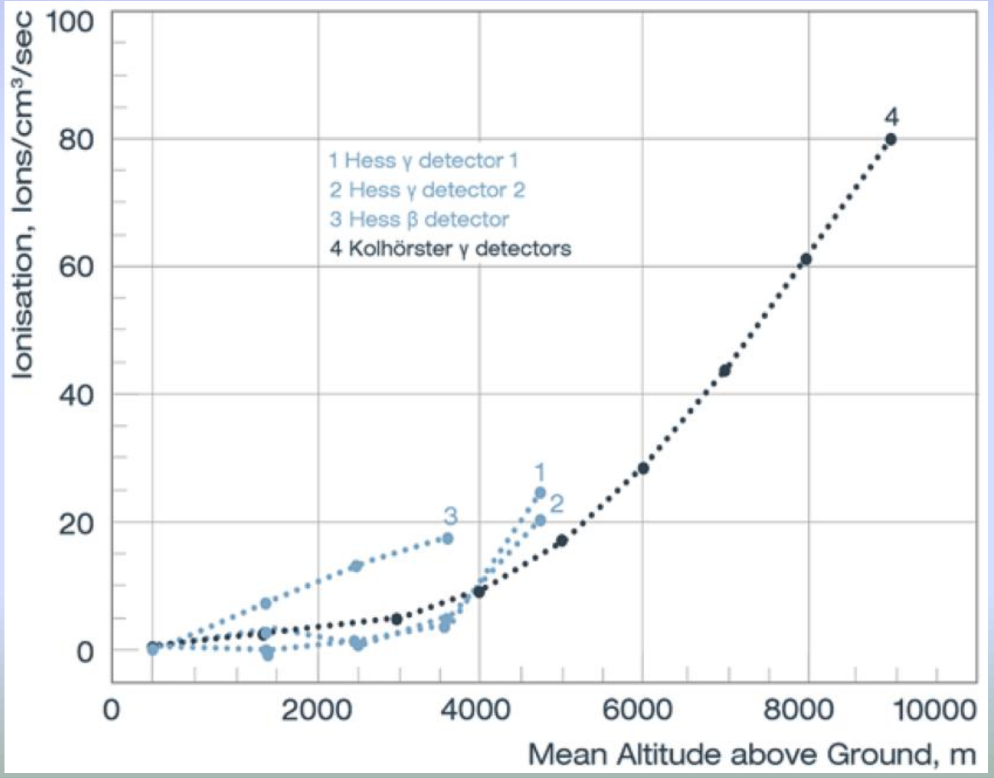
A radiation of high penetrating power hits the atmosphere from above, which can't be caused by radioactive emanations.

1936

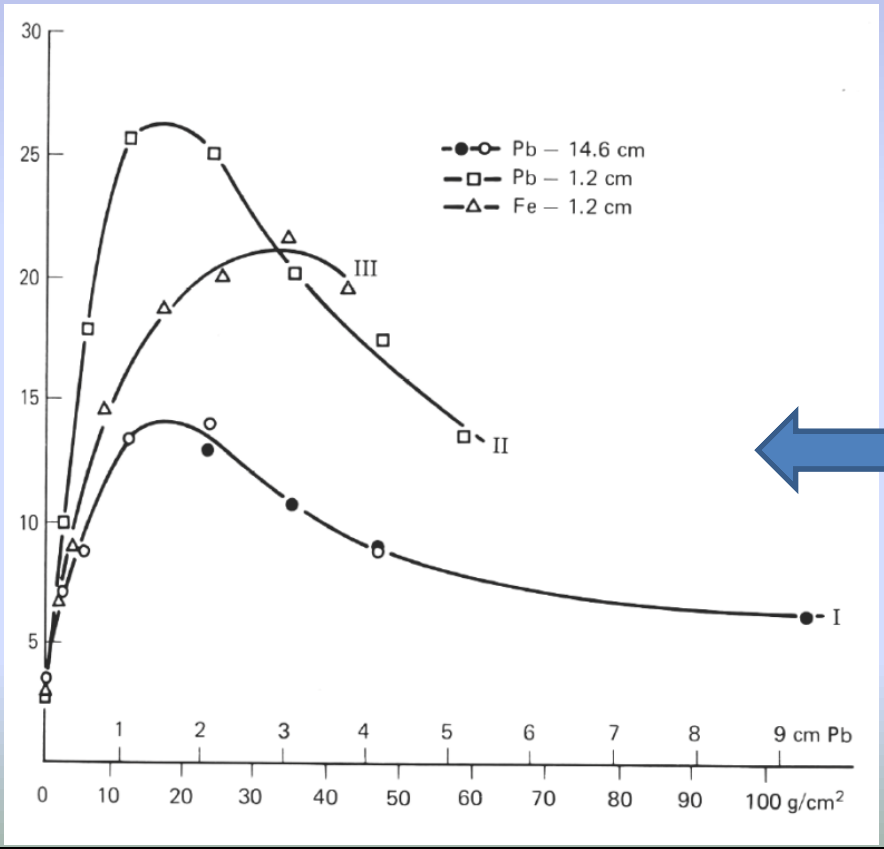


- 1929 *Bothe & Kolhörster*: show that tracks are curved by magnetic field → **CRs are charged particles**

- 1928 **Geiger-Müller counters** (development).
- 1930 *B Rossi & W Bothe*: **Coincidence technique** many channels → trigger chambers in magnetic fields.
- 1934 *Bethe & Heitler*: development of electromagnetic cascade theory → the observed particles at ground are **secondaries**.
- 1933 – 1935 *B Rossi, PMS Blanckett, G Occhialini*: Discovery of "**secondaries**" (only *p, n,* $e^{\pm}$ known!) with **coincidence Geiger-Müller counters**.

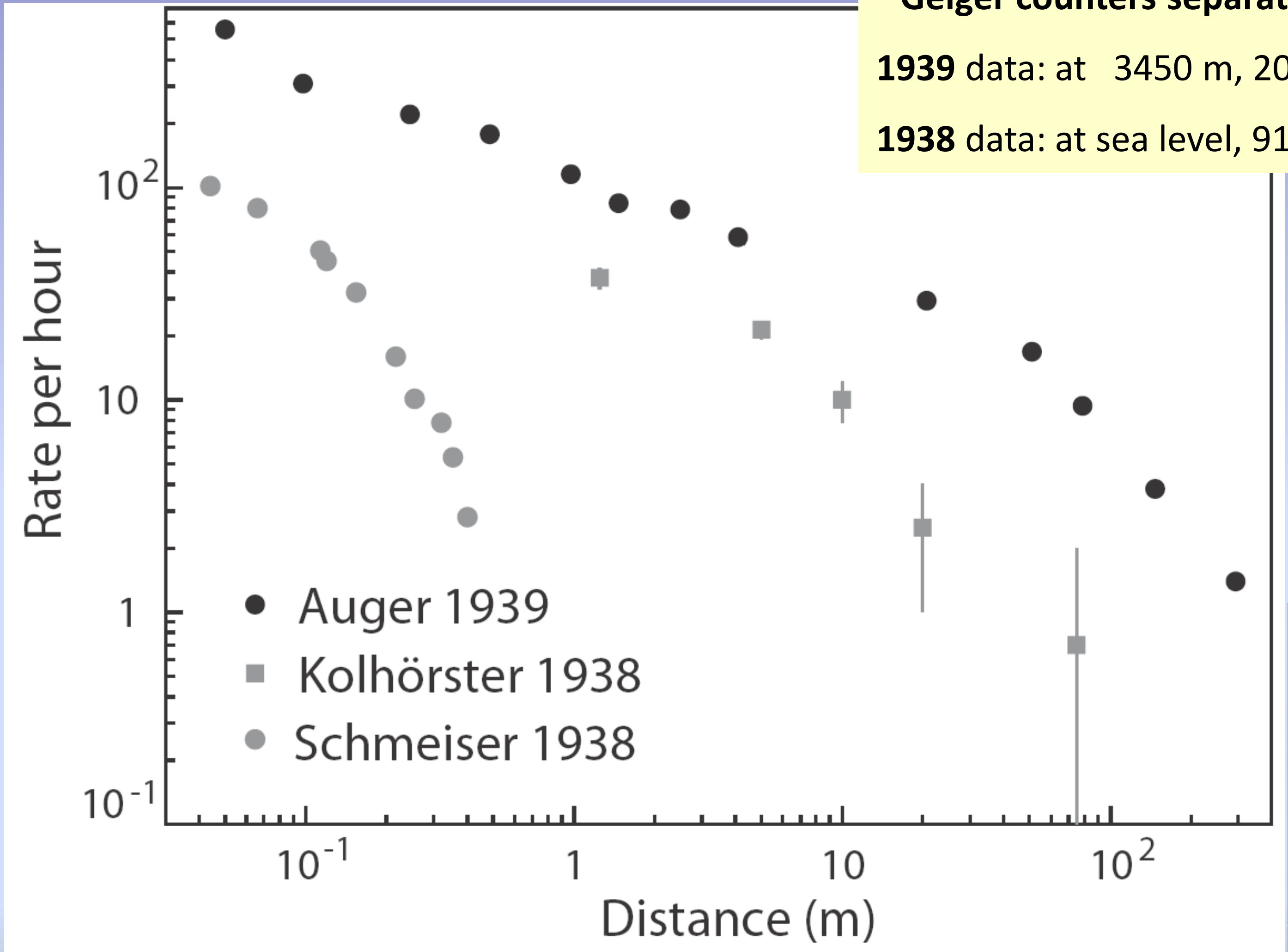
1948

- 1934 *W Baade & F Zwicky*: propose **supernovae** as possible sources of CRs.



"Rossi's transition curve" *raised doubts about the legitimacy of the coincidence method*

1938 *P. Auger*: **Extensive Air Showers** ← Geiger–Müller counters in "coincidence technique"



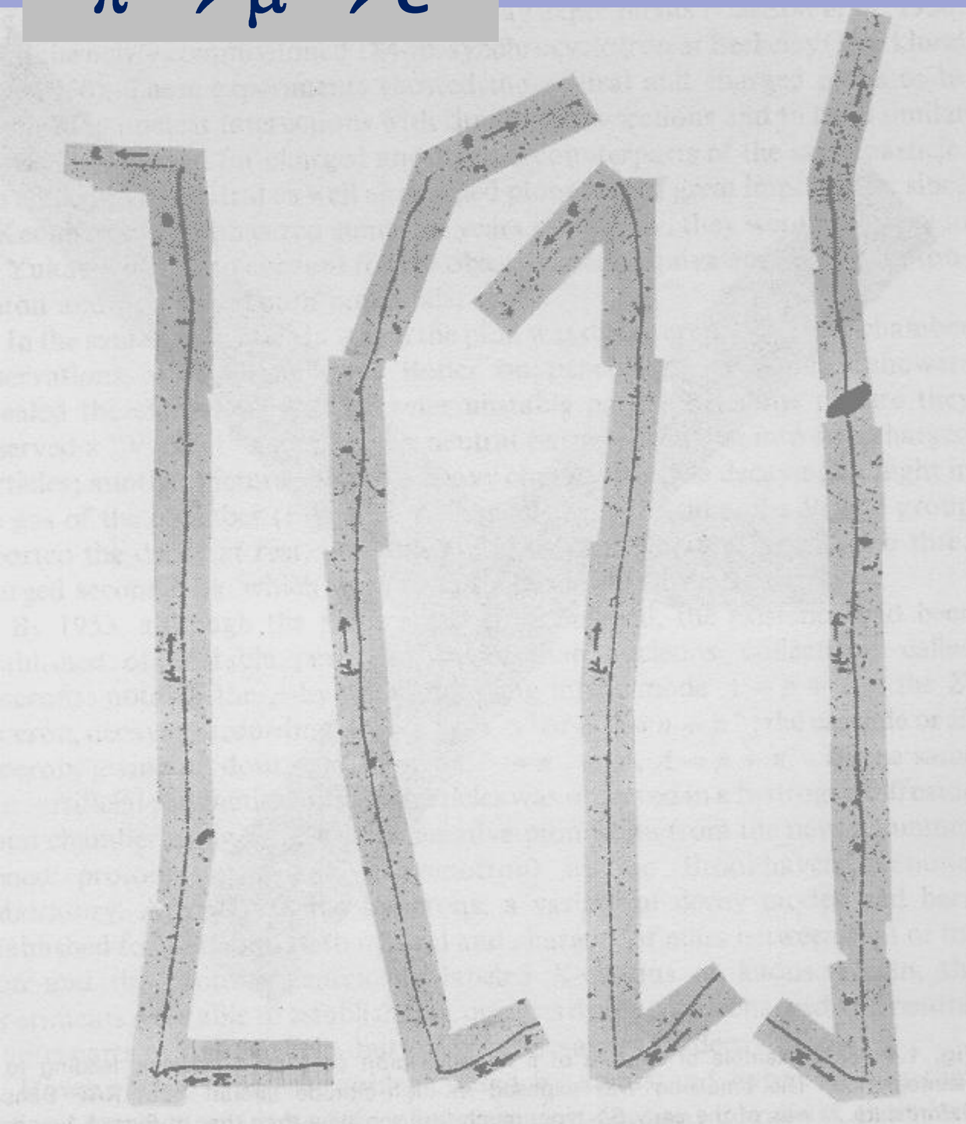
Geiger counters separated up to 300 m distance

1939 data: at 3450 m, 200 cm^2 counters

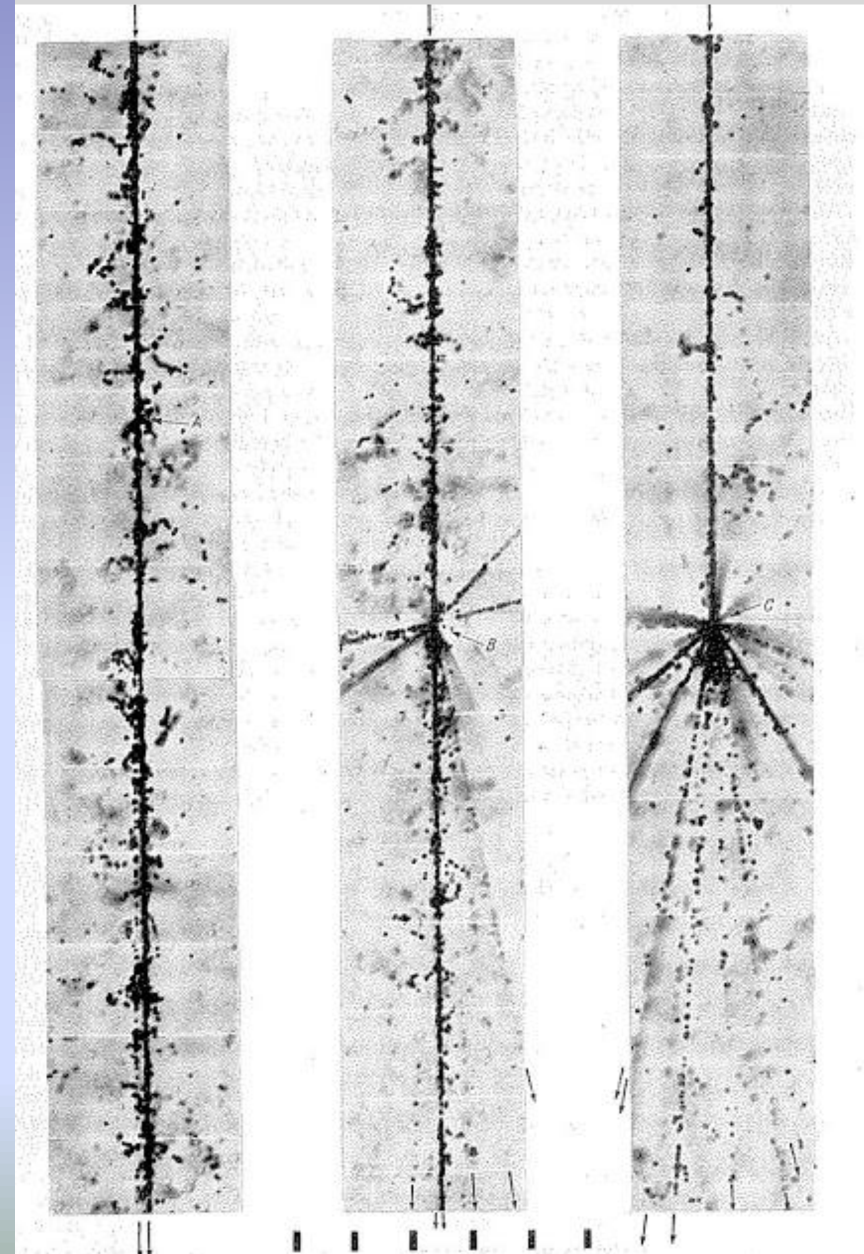
1938 data: at sea level, 91 cm^2 & 430 cm^2 counters

Photo emulsions exposed to CRs

$\pi \rightarrow \mu \rightarrow e$



“star” as a breakthrough of CR interaction with an atom of the emulsion



Results in elementary particle physics with Cosmic Rays

Year	Discovery with cosmic part.	Reference	Detector
1929	Charged secondaries	Skobeltzyn (1929)	Cloud chamber
1929	Charged secondaries	Bothe and Kolhörster (1929)	Counters and absorbers
1932	Charged primaries	Clay and Berlage (1932)	Electroscope
1932	Positron	Anderson (1933)	Cloud chamber
1937	Muon (μ)	Neddermeyer and Anderson (1938)	Cloud chamber
1947	Pion (π)	Perkins (1947)	Photographic emulsion
		Lattes et al. (1947)	Photographic emulsion
1947	Strange particles	Rochester and Butler (1947)	Cloud chamber
1947	μ-absorption and decay	Conversi et al. (1945)	Counters and absorbers
1949	K_L^o-meson	Brown et al. (1949)	Photographic emulsion
1951	Λ^o-baryon	Armenteros et al. (1951)	Cloud chamber
1952	Ξ-hyperon	Armenteros et al. (1951)	Cloud chamber
1953	Σ-hyperon	York et al. (1953)	Cloud chamber
1954	K^+, K^--meson	Menon and O'Ceallaigh (1954)	Photographic emulsion

Remarkable contribution of CRs to particle Physics.

and with first particle accelerator (184 inch synchro–cyclotron at LBL Berkeley)

1948	$\pi^\pm$-lifetime	Richardson (1948)	Photogr. emulsion / 184" SC
1949	π-energy spectrum	Richman and Wilcox (1950)	Photogr. emulsion / 184" SC
1950	$\pi^\pm$- and $\mu^\pm$-mass	Barkas et al. (1951))	Photogr. emulsion / 184" SC
1950	π^o-meson	Bjorklund et al. (1950)	Proportional counter / 184" SC
1950	π^o-mass	Panofsky et al. (1950)	Proportional counter / 184" SC

- 1948 *B Rossi (USA) and G Zatsepin (Russia)* started experiments on the structure of Auger showers. These researchers constructed the **first arrays of correlated detectors to detect air showers**.

- 1947 ***Fermi***: proposed **acceleration mechanism** by bouncing off moving magnetic clouds in the Galaxy.

- 1950's **PMTs & liquid-plastic scintillators** $\rightarrow$ 1st array of liquid scintillators AGASSIZ (1957)
- 1953 *Galbraith & Jelley* : detection of **air-Cherenkov radiation** (mirror + PMT + oscilloscope in moonless nights).
- 1958 *Porter*: 1st large surface array of **water-Cherenkov detectors**

- 1961 – 1963 **Volcano Ranch** (New Mexico) 8.1 km^2 plastic scintillation
- 1964 – 1977 **Havera Park** (Leeds, UK) 12 km^2 plastic scintillators + water-Cherenkov detectors
- 1990 – 2004 **Akeno – AGASA** 100 km^2 scintillator detectors. Optical fiber.
- 1981 – 1993 **Fly's Eye I & II** (Utah) : **Fluorescence Detection** $\rightarrow$ stereoscopic observation.
- 1997 – 2006 **HiRes I & II**: Fluorescence Detection

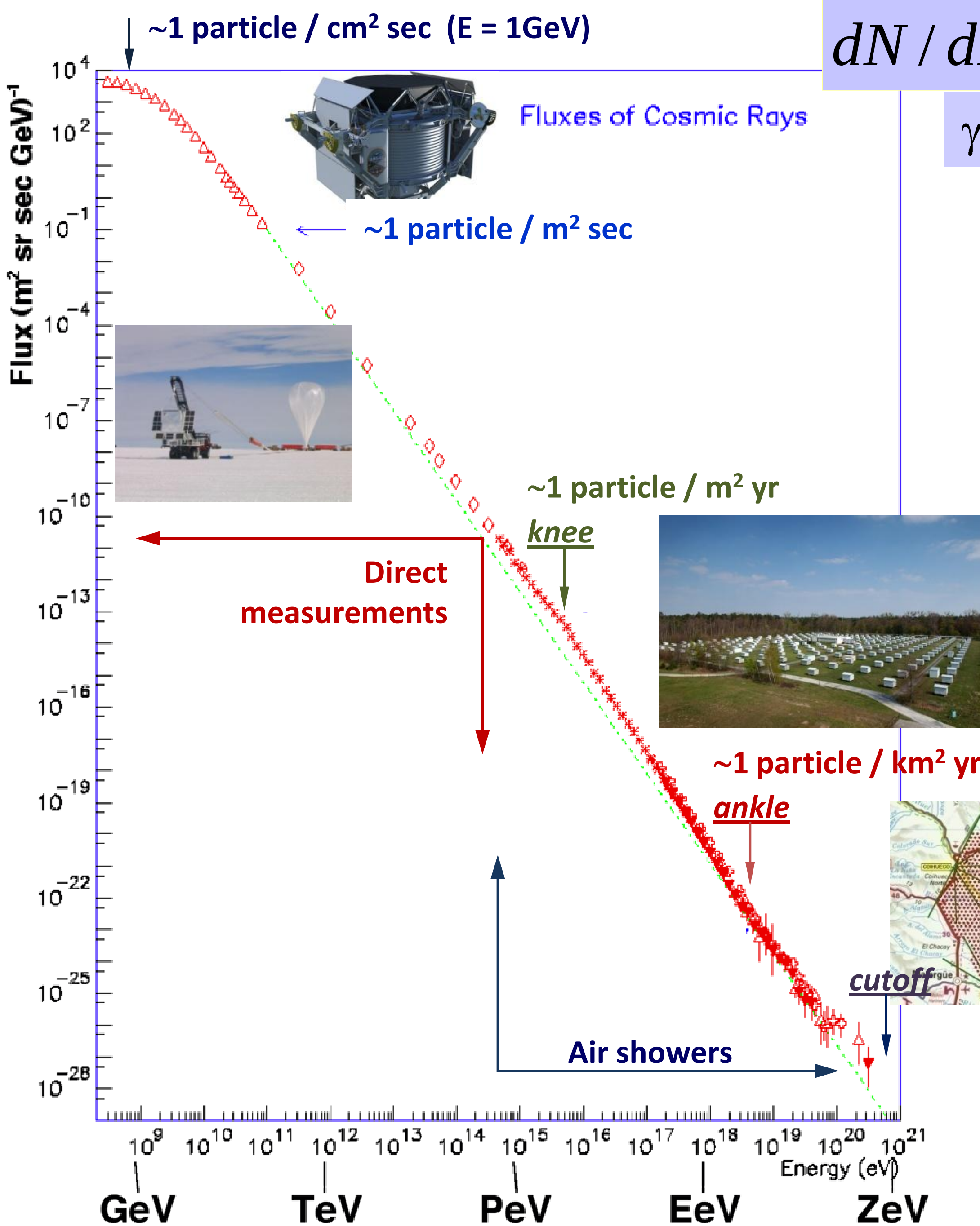
- 1996 – 2010 **KASKADE** (Germany) Surface array
- 2004 – 2015 **Pierre Auger** (Argentina) 3000 km^2 Hybrid (SD + FD)
- 2008 **Telescope Array** (Utah) : 700 km^2 Hybrid (3 FD stations . 507 SD 3 m^2 plastic scintill., 1.2 km spacing)

Cosmic Rays ??

"Cosmic Rays can be defined as massive particles striking the Earth"

- **Primary** Cosmic Rays: these entering the upper atmosphere.
- **Secondary** Cosmic Rays: those produced by the interactions of the primary CRs in the atmosphere or in the Earth.

- **Galactic** (including solar)
- **Extragalactic**



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

$\gamma \sim 2.7$

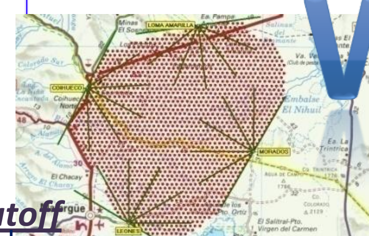
Very smooth power low spectra

32 orders of magnitude in Flux
21 explored in energy

HOW ?

WHERE ?

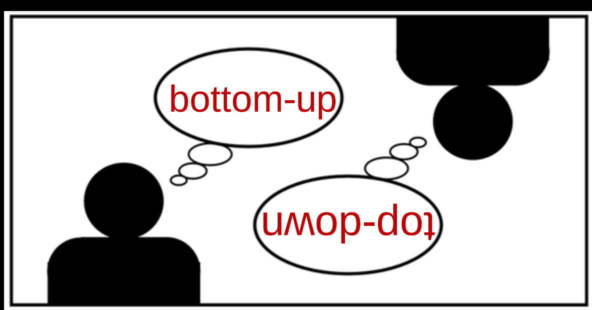
WHAT ?



Acceleration & Propagation	→	Energy Spectrum
Origin of Cosmic Rays	→	Anisotropies
Nature	→	Mass composition

One of the unsolved problems in Astrophysics is: how to give large energy to produced particles?

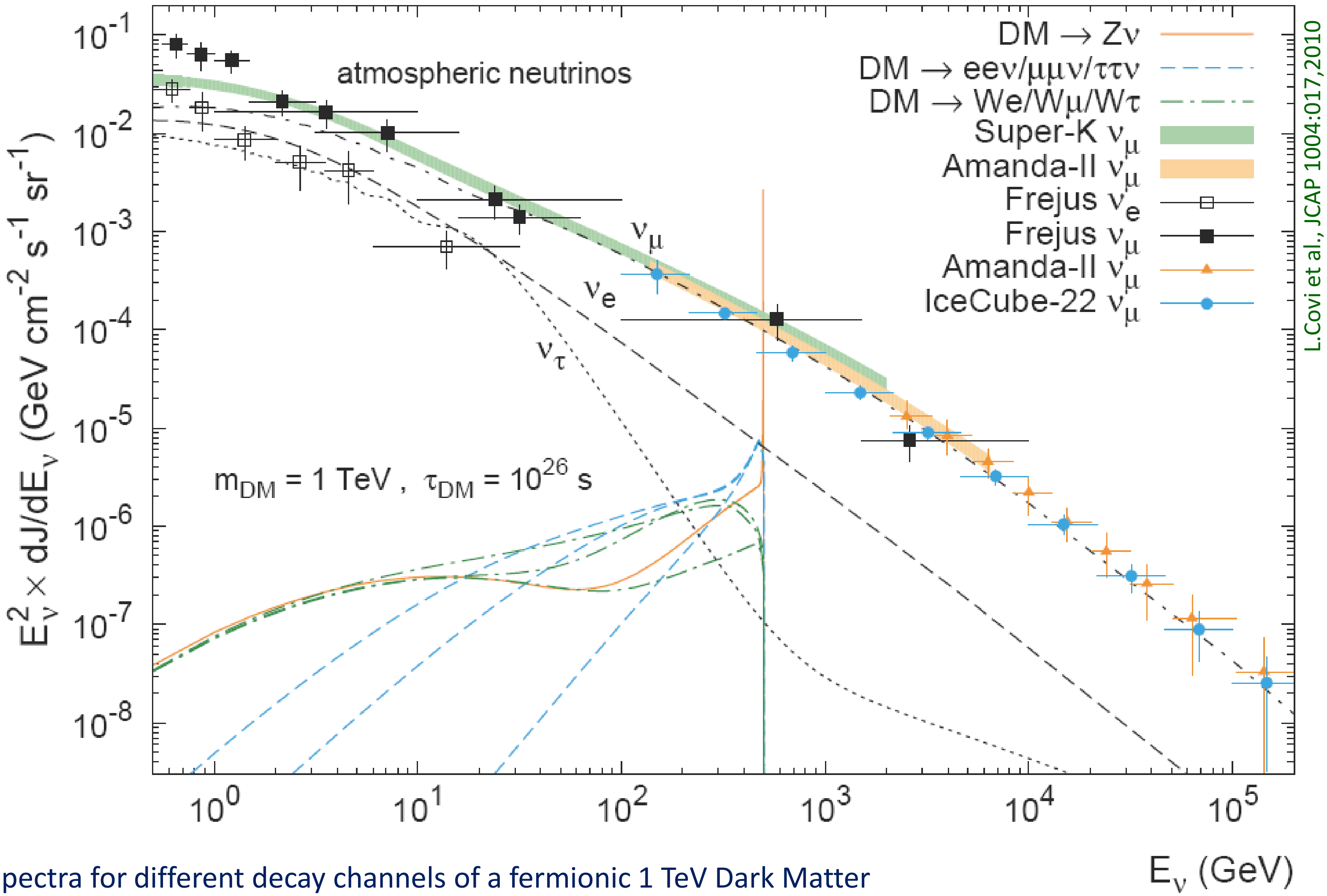
- Bottom-up models: low energy particles are accelerated via SM processes within the astrophysical objects (e.g. magnetic/electric fields)



- Top-down models: particles already generated with very high energies usually via non-SM processes (e.g. decay of very heavy "exotic" particles)

EXOTIC PARTICLE DECAY

Different daughter particles spectra depending on the number of particles in the final state.
In general "bump-like" spectrum, at least before propagation!



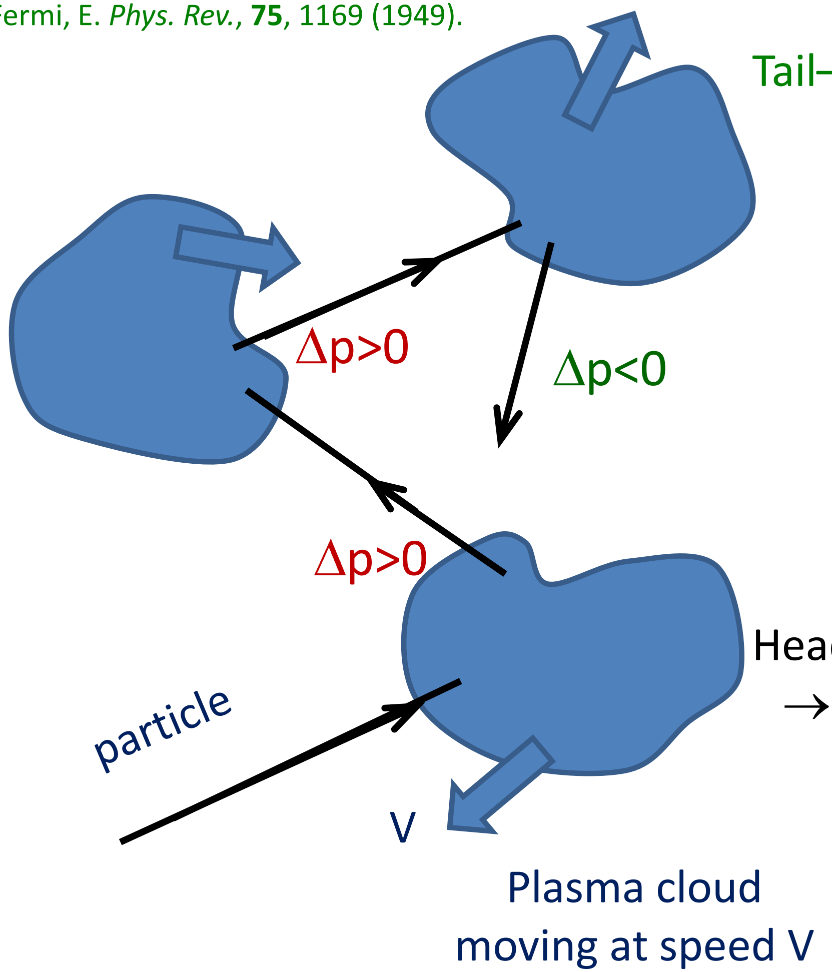
Neutrino spectra for different decay channels of a fermionic 1 TeV Dark Matter candidate compared to expected background of atmospheric neutrinos.

ACCELERATION

1949: FERMI ACCELERATION (2nd order)

Stochastic energy gain (acceleration) in "elastic scattering" with magnetized plasma clouds (magnetic inhomogeneities) moving at non-relativistic speed V

Fermi, E. *Phys. Rev.*, **75**, 1169 (1949).



On average, Head–on collisions more probable
→ Energy gain over many collisions:

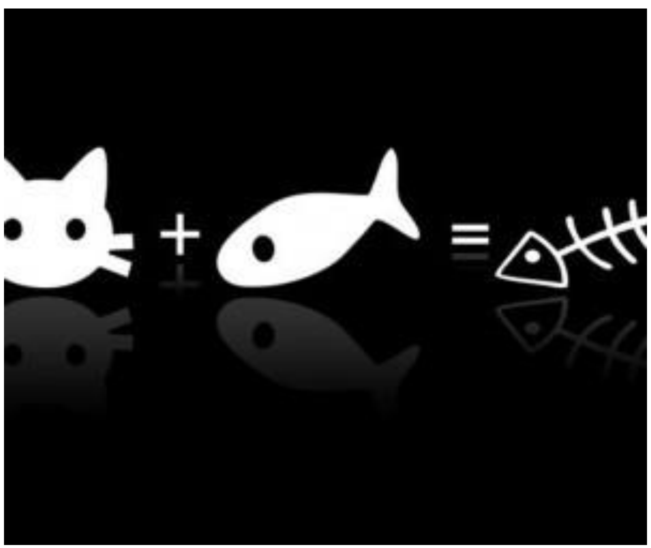
$$\Delta E / E \propto \beta^2 \qquad \beta = V/c \sim 10^{-4}$$

" 2nd order "
✓ Slow and inefficient

✓ The resulting energy spectrum strongly dependent on cloud parameters
✓ Predicted energy spectrum does not fit with data

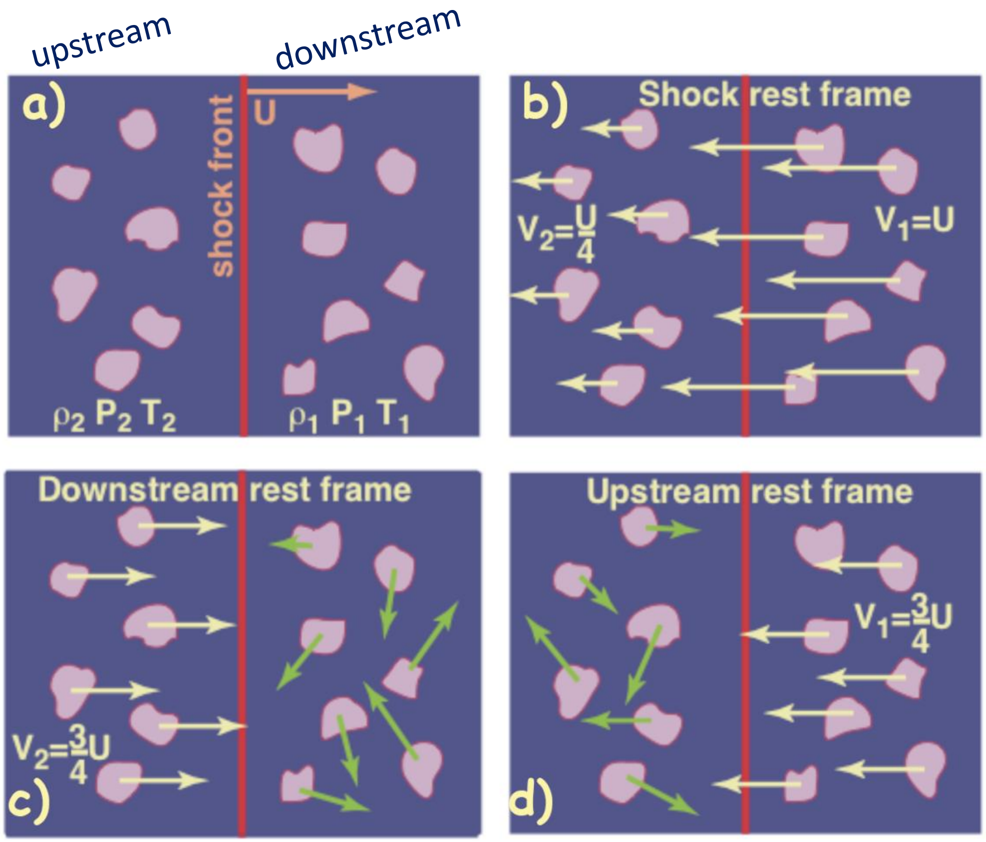
~30 years later a new idea was proposed (it requires heavier calculation) ...

R.Blandford, J.Ostriker, *Astrophys. J.,* **221**, L29 (1978)
R.Blandford, D.Eichler, *Phys. Rept*. **154**, 1-75 (1987)



1970's: FERMI ACCELERATION (1st order)

Scattering at magnetic irregularities separated by a planar strong shock waves moving with high velocity β



- Ideal fluid equations
- Conservation of Num. particles & energy:

$$\rho_1 v_1 = \rho_2 v_2$$

- Strong shock:

$$\rho_2 / \rho_1 = (\gamma+1)/(\gamma-1)$$

- Fully ionized plasma (monoatomic ideal gas):

$$\gamma = 5/3 \sim 1.7$$
$$v_1 / v_2 = 4$$

→ Rapid gain in Energy as particles repeatedly cross shock front

$$\Delta E / E \propto \beta \quad (\beta \sim 10^{-1})$$

" 1st order "

Axford, Krymsky (1977), Bell, Blandford, Ostriker (1978)
Achterberg (2001), Bell (2004)

Power law spectrum $E^{-\gamma}$ predicted !

The Fermi acceleration mechanism generates a power-law particle energy spectrum.

E_0 = initial energy of particle at source

$\zeta = \frac{\Delta E}{E}$ = energy gain after each shock-crossing (ζ<<1)

→ Energy after n crossings: $E_n = E_0 \cdot (1+\zeta)^n \Rightarrow n = \frac{\ln(E_n / E_0)}{\ln(1+\zeta)}$

P_{esc} = probability to escape the accelerating region after each shock crossing (constant & <<1)
(= ratio of the loss and crossing flux = $4v_2/c$)

→ Probability to stay in the acceleration region: $N = N_0 (1 - P_{esc})^n$

$$\frac{dN}{dE} \propto E^{-1+\frac{\ln(1-P_{esc})}{\ln(1+\zeta)}} \approx E^{-1-\frac{P_{esc}}{\zeta}}$$

✓ Predicted exponent independent of local environment / shock parameters.

✓ Observed spectrum goes like $E^{-2.7}$ → *something still missing …*

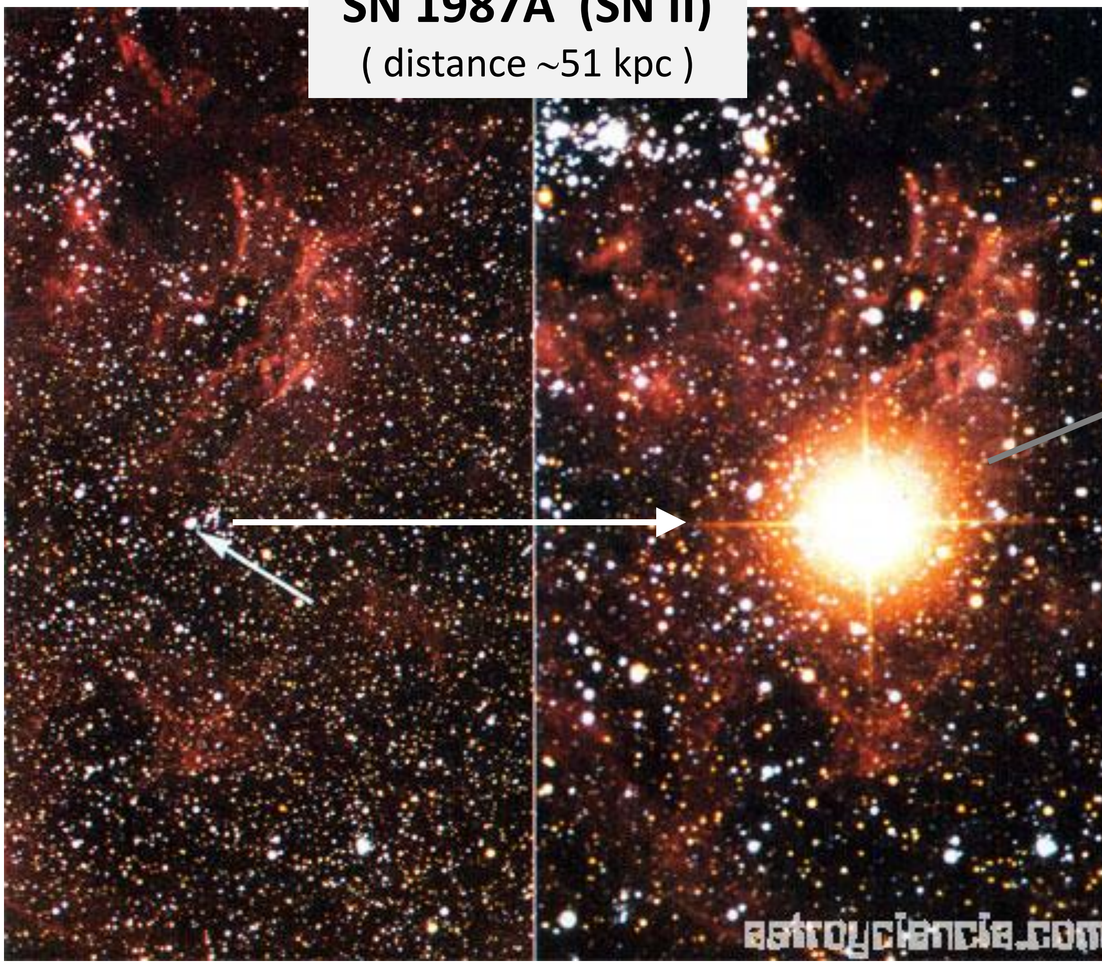
$$\frac{P_{esc}}{\zeta} \approx \frac{3}{\frac{v_1}{v_2} - 1} = (\text{strong shock limit}) = 1$$

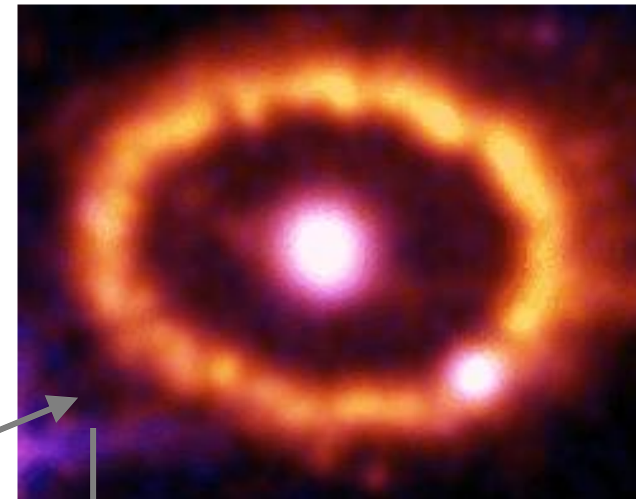
The observed flux from high energy CRs requires a steeper injection spectrum.

SOURCES

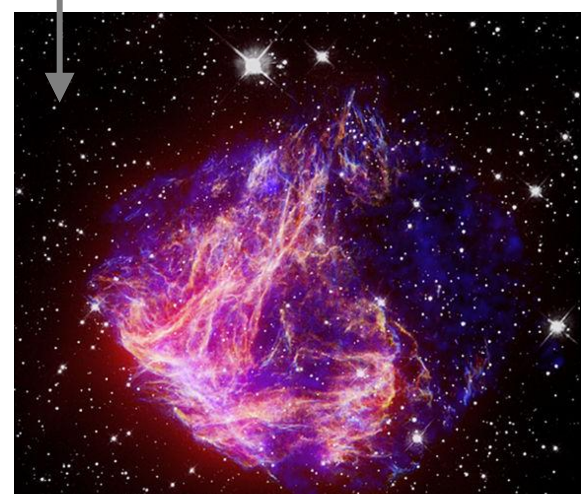
Powerful shocks in the Universe? Supernovae !

SN 1987A (SN II)
(distance ~51 kpc)



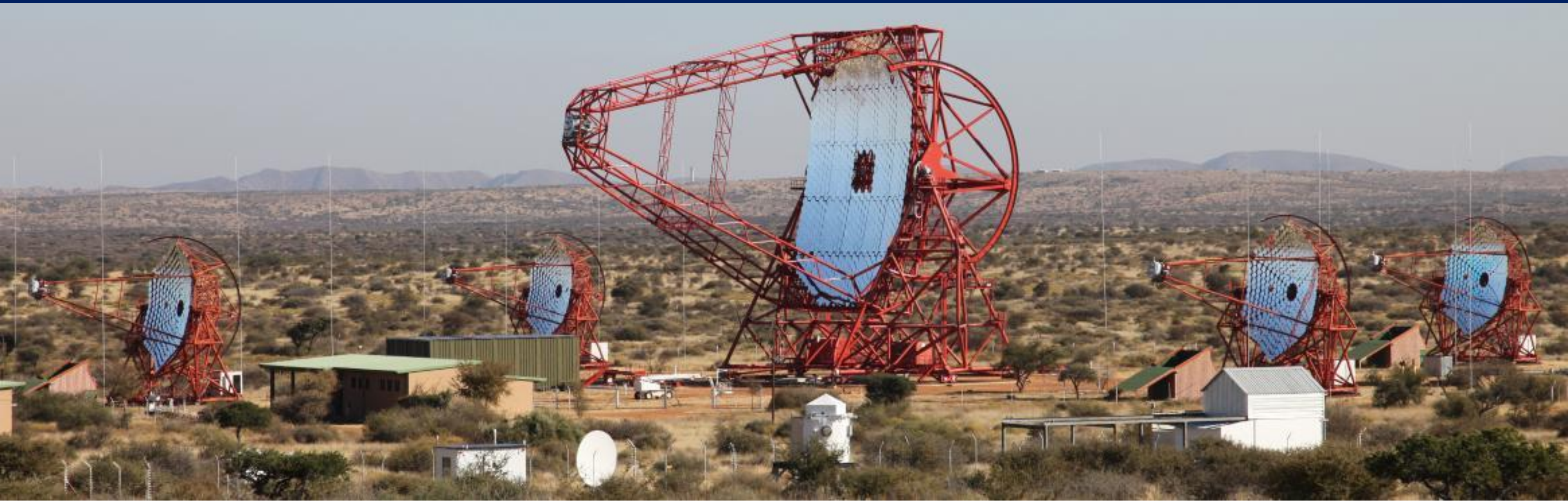


~1 SN II explosion / 50 years in each Galaxy



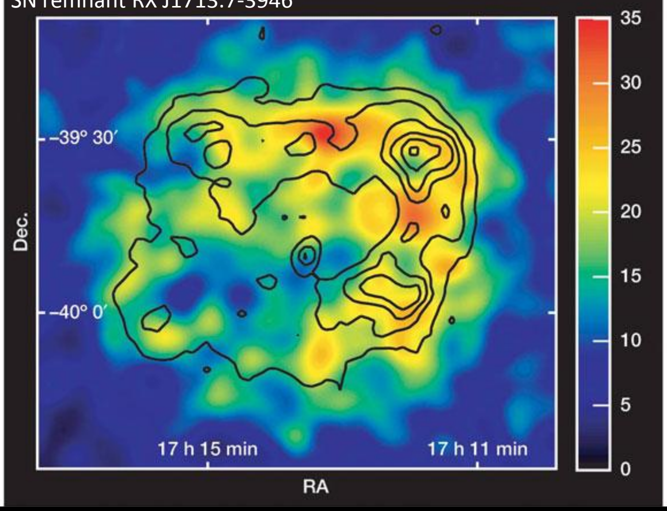
SN remnant N49 in the Large Magellanic Cloud (~48 kpc)

HESS : 1st Experimental Confirmation !



HESS (γ-ray color map E ~ 1 TeV)
ASCA (X-ray contour E ~ 1 keV)

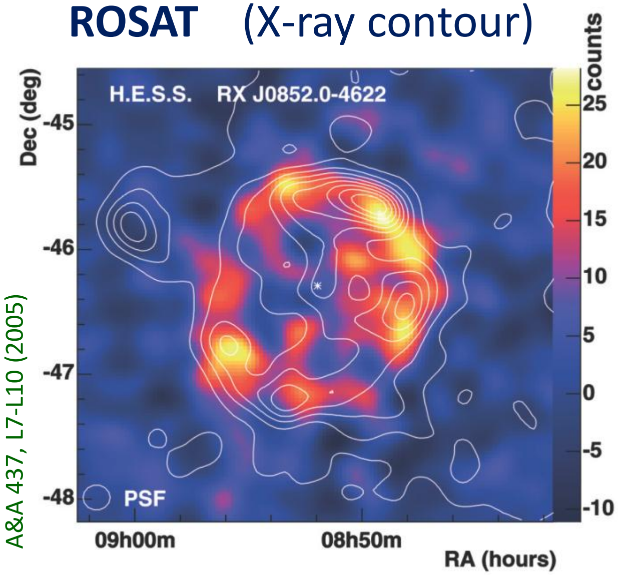
SN remnant RX J1713.7-3946



Nature 432 (2004) 75-77

High-energy particle acceleration (γ-rays) in the shell of a supernova remnant

HESS (γ-ray color map)
ROSAT (X-ray contour)

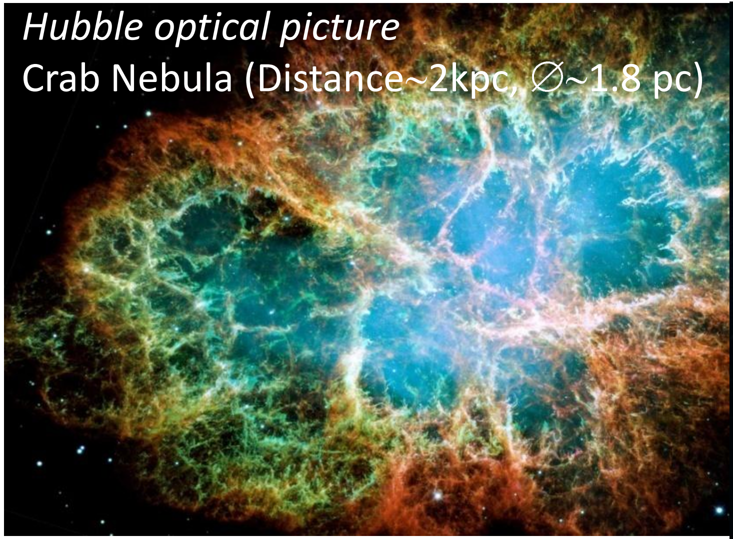


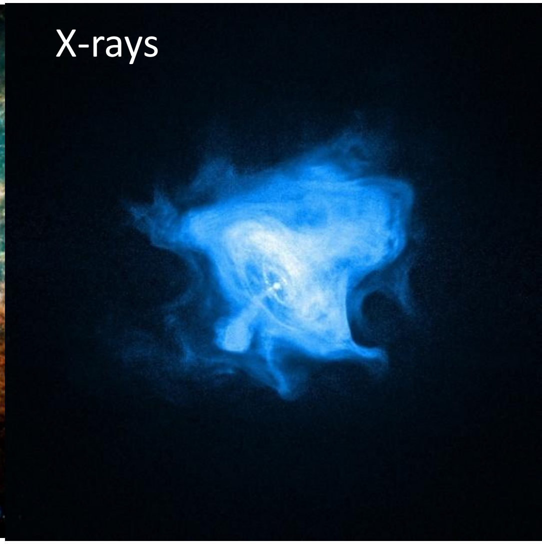
A&A 437, L7-L10 (2005)

GALACTIC sources

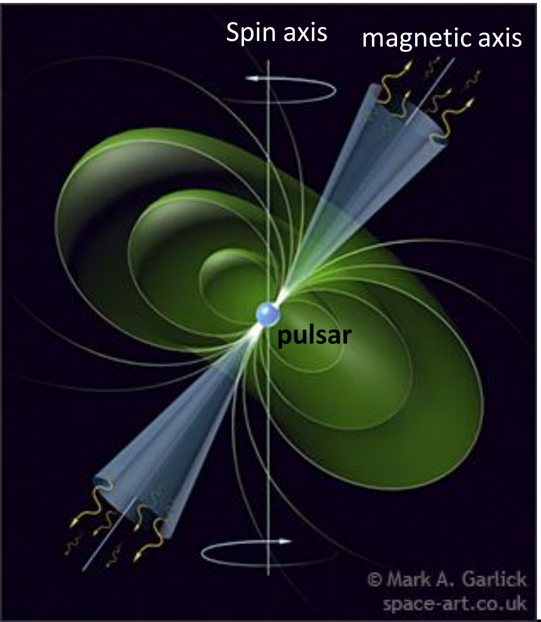
Several violent processes occur in the Universe that can act as particle's sources:

- **SuperNova Remnants (SNR)**
  – Fermi Shock Mechanism –



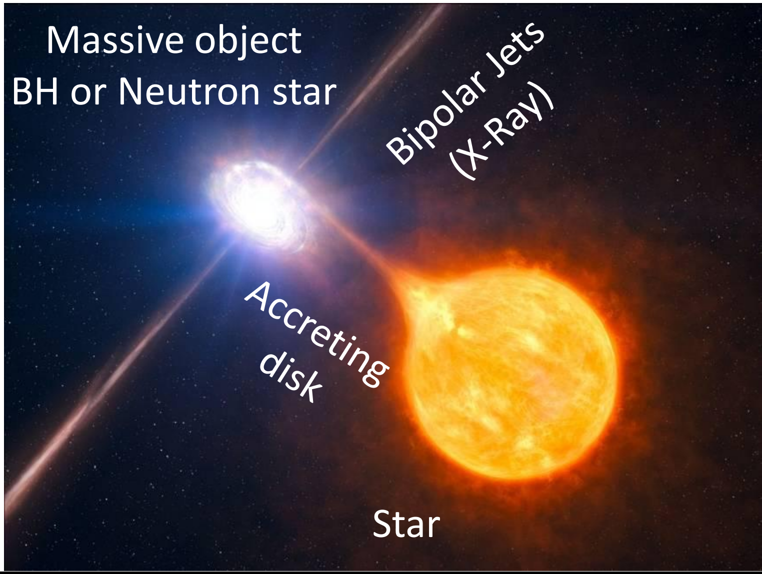


http://www.investigacionyciencia.es/noticias/el-misterio-de-la-nebulosa-del-cangrejo-10020



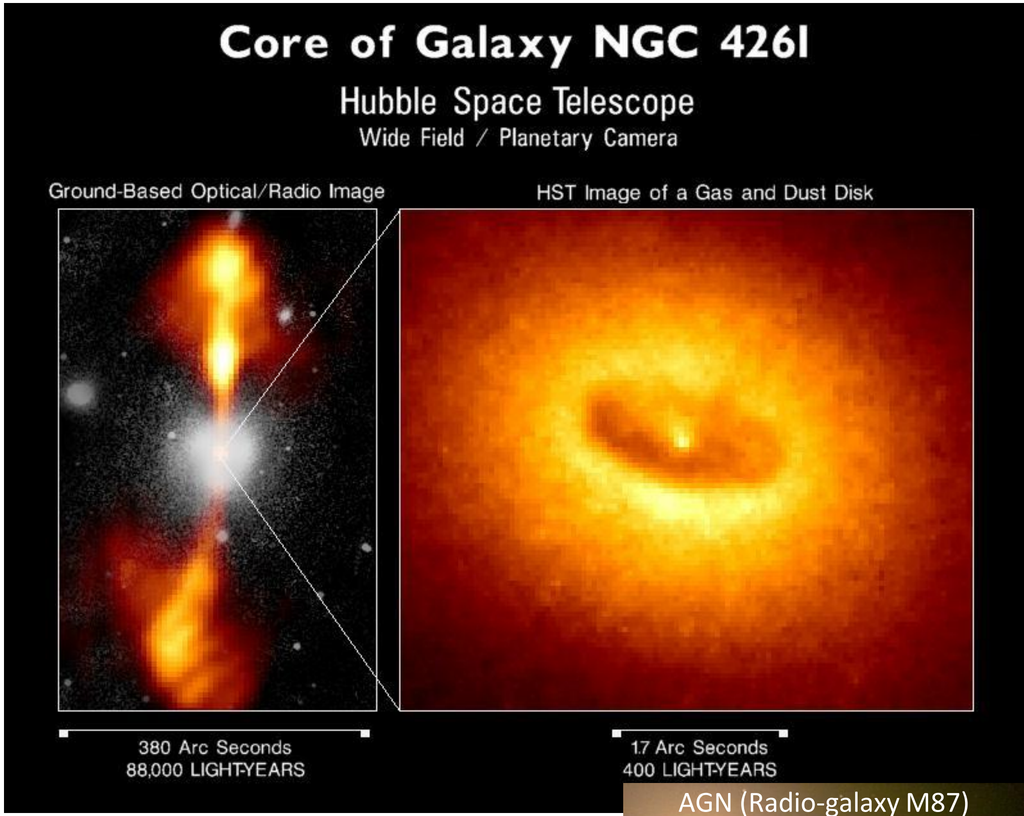
- **Neutron stars / Pulsars**
  – dense & compact objects
  high magnetic fields –
  $\sim 2M_{sun}$ ∅~20 km

- **Micro Quasars**
  – Binary systems with
  an accreting BH –



EXTRAGALACTIC sources

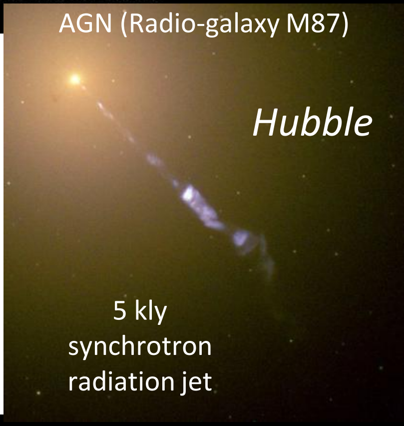
Several violent processes occur in the Universe that can act as particle's sources:



- **Active Galactic Nuclei (AGN)**

  – Quasars / Blazars: supermasive BH at center of Galaxy emitting relativistic jets –

  $\sim 10^6 - 10^9\ M_{sun}$ Distance $\sim$240 Mpc – 6 Gpc



- **Gamma Ray Bursts (GRB)**

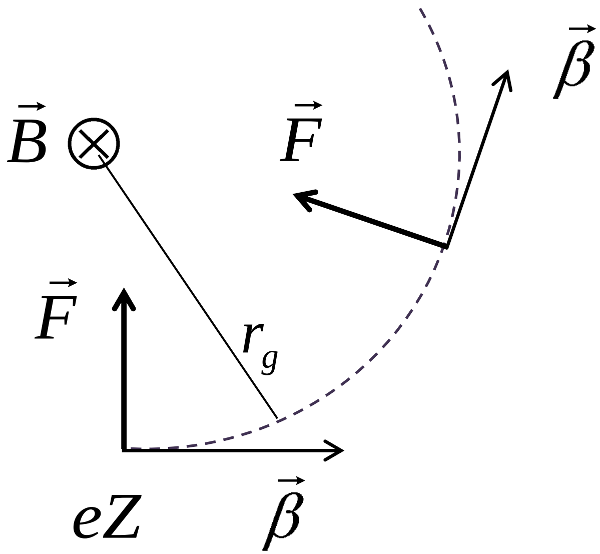
  – narrow beam of intense EM radiation –

Larmor radius & Rigidity

Charged (***eZ***) particle moving with velocity β in Uniform Magnetic Field (***B***)

$$\vec{F} = eZ \cdot (\vec{\beta} \times \vec{B})$$

← Lorentz Magnetic Force changes only β direction ($\beta \perp \boldsymbol{B}$)



Magnetic force = centripetal force

$$F = eZ \cdot \beta \cdot B = m \frac{\beta^2}{r_g}$$

gyro-radius
or
Larmor radius

Rigidity

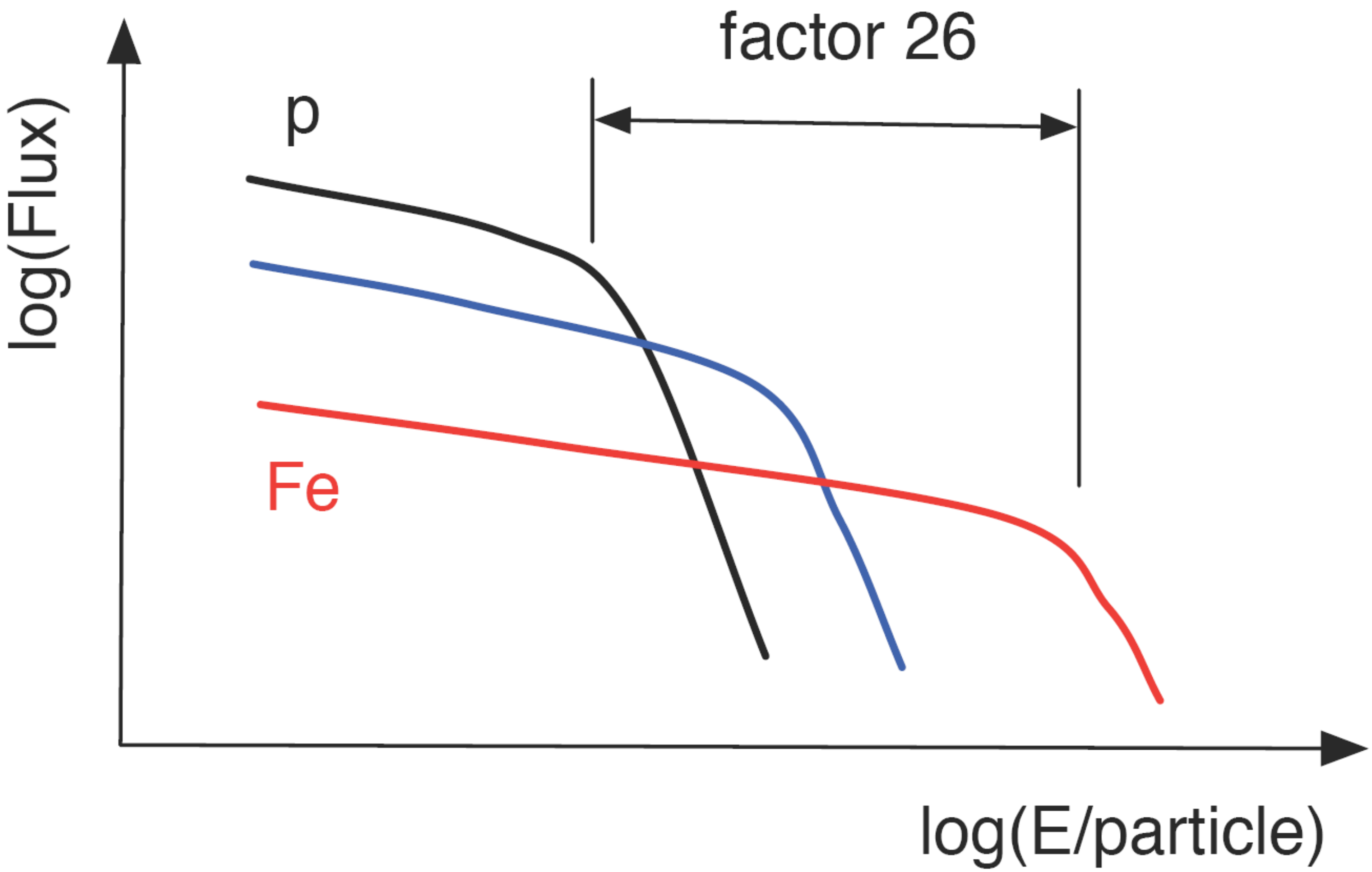
$$B \cdot r_g = \frac{p}{eZ} \quad [\text{Volts}]$$

… in order to accelerate CRs to high energies, the size of the acceleration site must be larger than the Larmor radius.

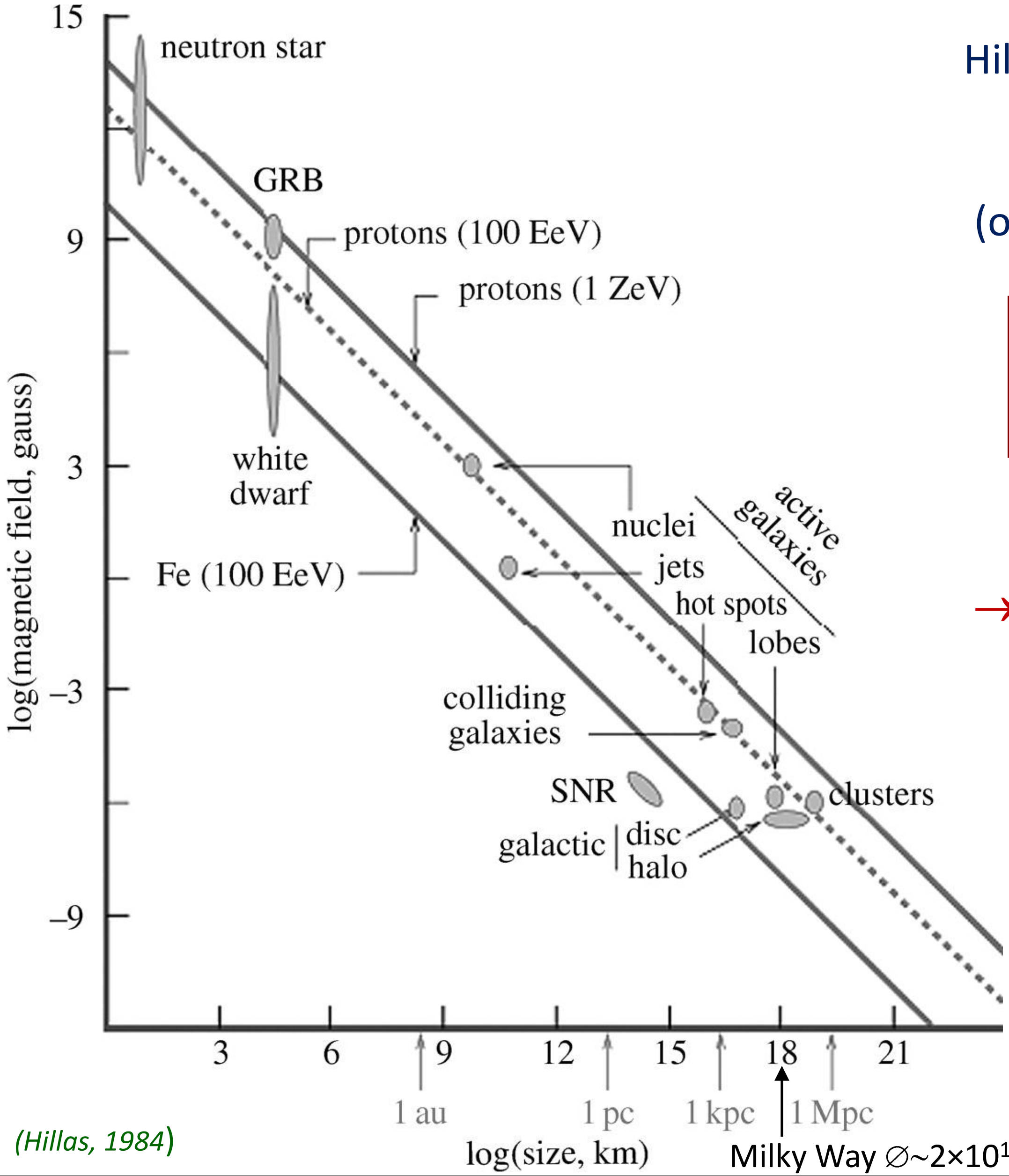
Larmor radius & Rigidity

Rigidity → $B \cdot r_g = \frac{p}{eZ}$ $\left[\text{Volts} \right]$

… a given source (fixed Rigidity) can accelerate *iron* to higher energy (× *eZ*) than *protons* !



ENERGY LIMITATION: the *Hillas plot*



(Hillas, 1984)

Milky Way ∅~2×10^18 km

Hillas Criterion: Geometrical requirement

Larmor Radius < size of accelerator

(otherwise escapes the acceleration site)

$$E_{max} \approx 10^{18}\,\mathrm{eV} \cdot Z \cdot \left(\frac{R}{\mathrm{kpc}}\right) \cdot \left(\frac{B}{\mu G}\right)$$

(no energy losses)

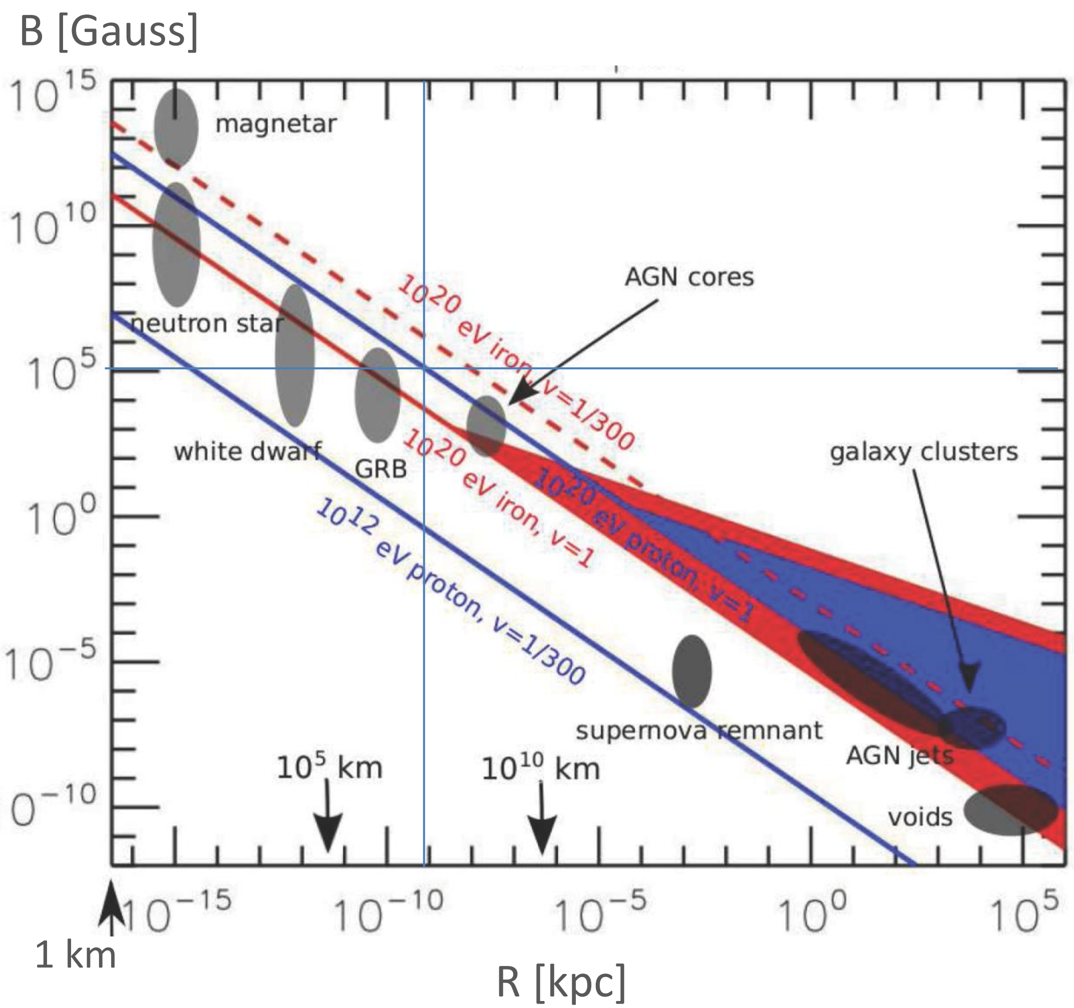
→ **Large sites (R), large magnetic fields (B)**

SN remnants: E_{max} ~10^{15} eV (*knee*)

CRs : E_{max} ~ 10^{20} eV (*cutoff*) **??**

ENERGY LIMITATION (cont.)

Relaxed for heavy nuclei !



1. ***Hillas*** Criterion (Geometrical)

$$E_{max} \approx 10^{18} \cdot Z \cdot \left(\frac{R}{kpc}\right) \cdot \left(\frac{B}{\mu G}\right) \quad eV$$

2. Minimal **power** of the Source

Induction

$$L_{min} \approx \frac{\varepsilon^2}{Z_0} \approx 10^{45} \cdot Z^{-2} \cdot \left(\frac{E_{max}}{10^{20}\,eV}\right)^2 \quad erg \cdot s^{-1}$$

Vacuum impedance

3. **Energy loss** within the Source (synchrotron radiation)

$$E_{max} \leq 3 \times 10^{16} \cdot \frac{A^4}{Z^4} \cdot \left(\frac{R}{kpc}\right)^{-1} \cdot \left(\frac{B}{G}\right)^{-2} \quad eV$$

[astro-ph] arXiv:0808.0367

PROPAGATION

Propagation of Cosmic Rays

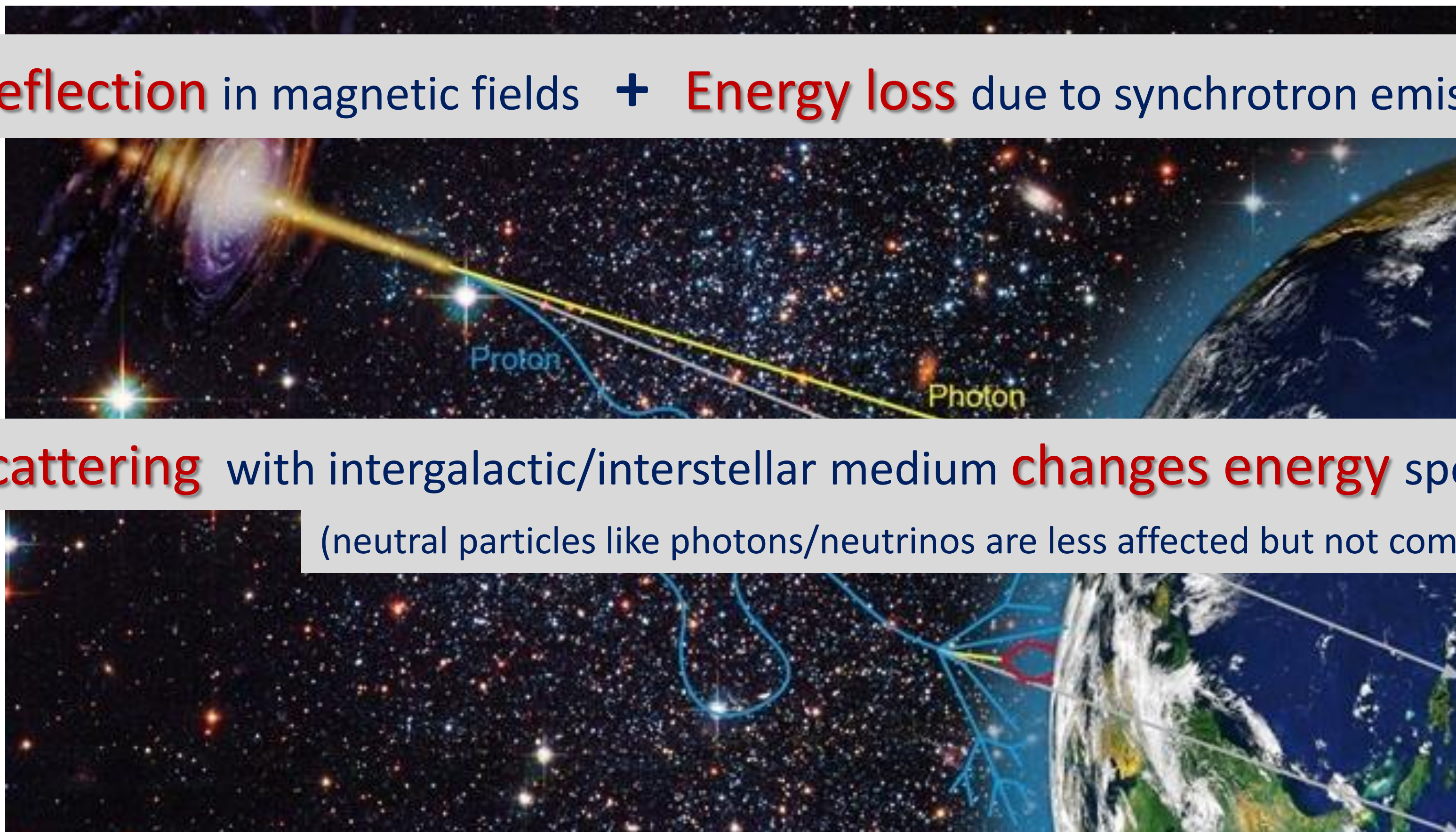
Propagation of CRs from the source to the Earth can change

the energy spectrum

AND

the direction

- **Deflection** in magnetic fields **+** **Energy loss** due to synchrotron emission



- **Scattering** with intergalactic/interstellar medium **changes energy** spectrum

  (neutral particles like photons/neutrinos are less affected but not completely safe)

Interstellar space (residence time of CRs in Galaxy ~5×10^6 years)

… the propagation of CRs resembles a random-walk in real space (*diffusion* $\rightarrow$ *isotropy*) and momentum space (*diffusive acceleration*) explained by scattering of CRs on turbulent magnetic fields in the Galactic disc.

Galactic Cosmic Rays

Galactic CRs at least up to energies around the *knee* (~ 5×10^{15} eV)

are deep in the **diffusive regime** → propagation can be described by solving numerically a

diffusion–convection–energy loss equation which is location– energy– and specie– dependent

$$\frac{\partial n_i(E,\boldsymbol{x},t)}{\partial t} - \nabla(D\nabla n_i(E,\boldsymbol{x},t)) = Q(E,\boldsymbol{x},t)$$ ← Diffusion

Inelastic scattering with gas + decays → $$- \left(c\rho\lambda^{-1}_{i,\mathrm{inel}}(E) + \lambda^{-1}_{d}\right) n_i(E,\boldsymbol{x},t)$$

Synchrotron radiation + adiabatic red-shift → $$- \frac{\partial}{\partial E}\left(\beta_i n_i(E,\boldsymbol{x},t)\right)$$

producing species *i* from spallation of *j* → $$+ \sum_k \int_E^{\infty} dE' \frac{\mathrm{d}\sigma_{ki}(E',E)}{\mathrm{d}E} n_k(E',\boldsymbol{x},t)$$

Solved numerically
with a given geometry for Galactic Disk
and compared to data

Galactic Cosmic Rays

Galactic CR spectrum injected at sources ⇔ the one observed at Earth

1. SNR observed in γ-rays with spectrum $\propto E^{-\alpha}$ with $\alpha \sim 2.2$
2. Hadronic contribution to γ-ray emission from primary nuclei interacting with ambient gas
3. Acceleration spectrum $\propto E^{-2.2}$ consistent with non-relativistic shock acceleration theory
4. Charge CR spectrum observed at Earth $n(p)$ & injected spectrum $\Phi(p) \propto E^{-p}$ related by:

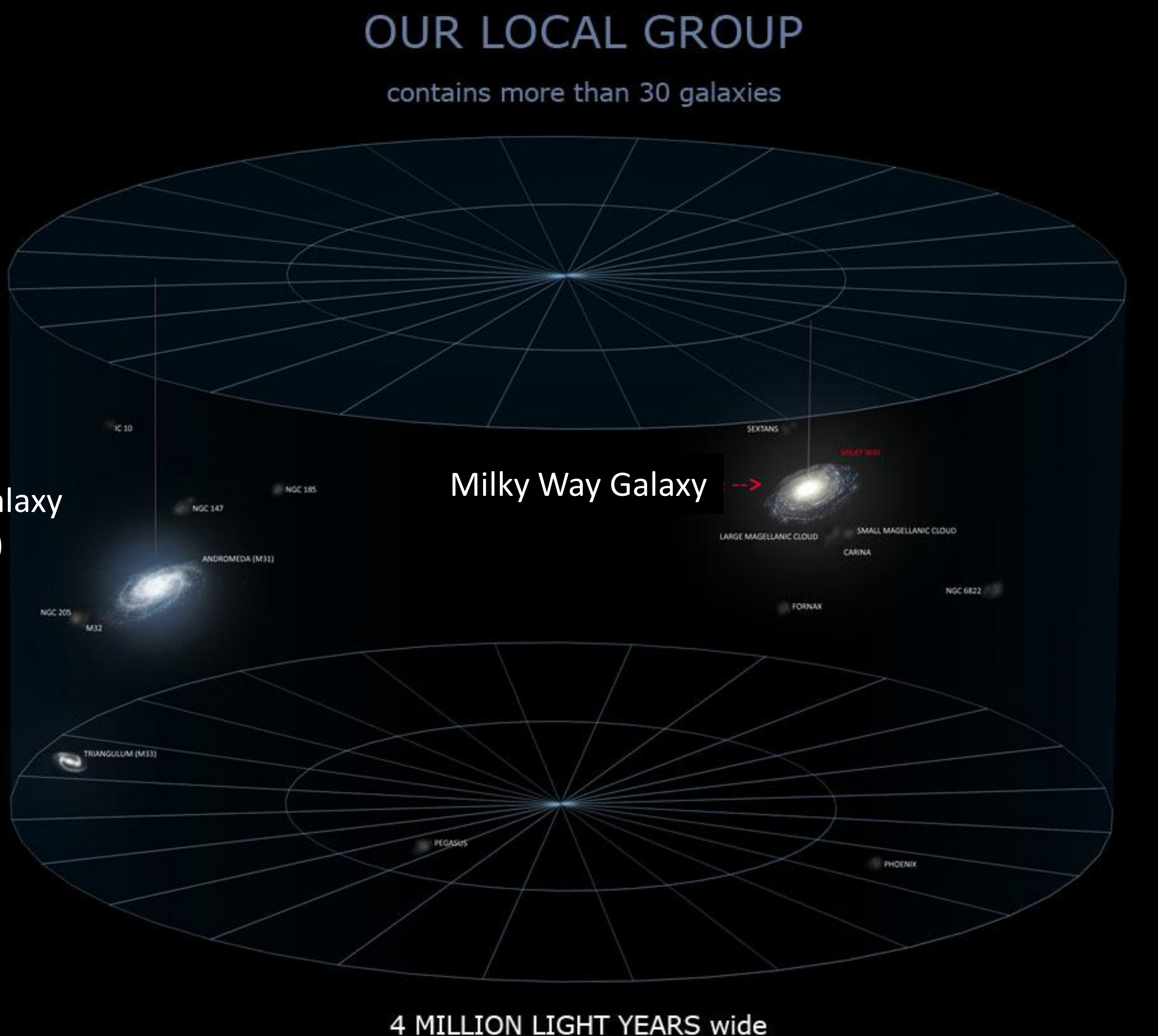
$$n(p) \propto \frac{\Phi(p)}{D(p)} \propto p^{-\alpha-\delta}$$

5. Data from secondary (N) to primary (O) CR ratios $\rightarrow \delta \sim 0.4 - 0.5 \Rightarrow$ $n(p) \propto E^{-2.7}$

Consistent with observations!

Extragalactic Cosmic Rays

Andromeda Galaxy
(~2.4 Mlyr)



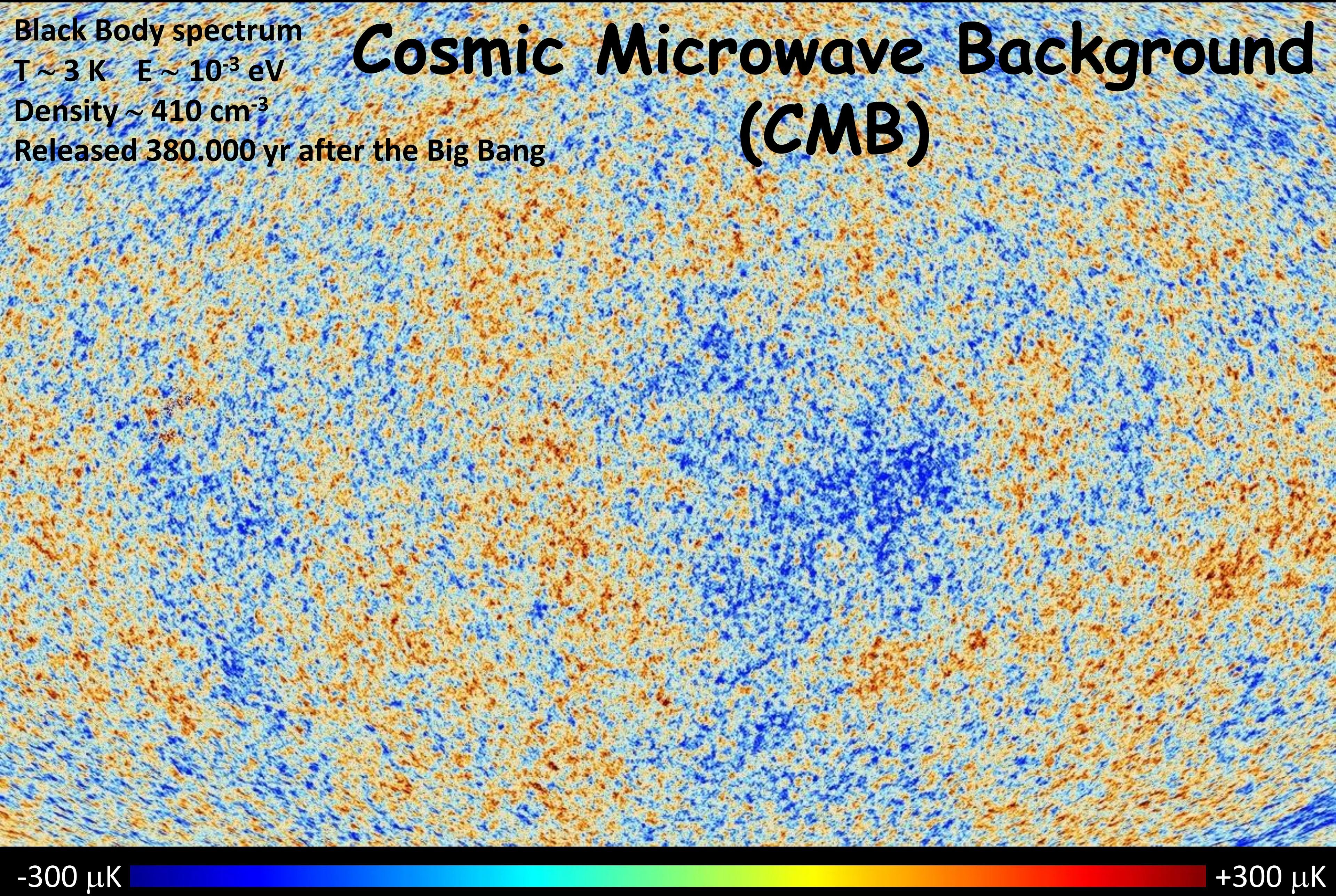
Cosmic Microwave Background (CMB)

Black Body spectrum

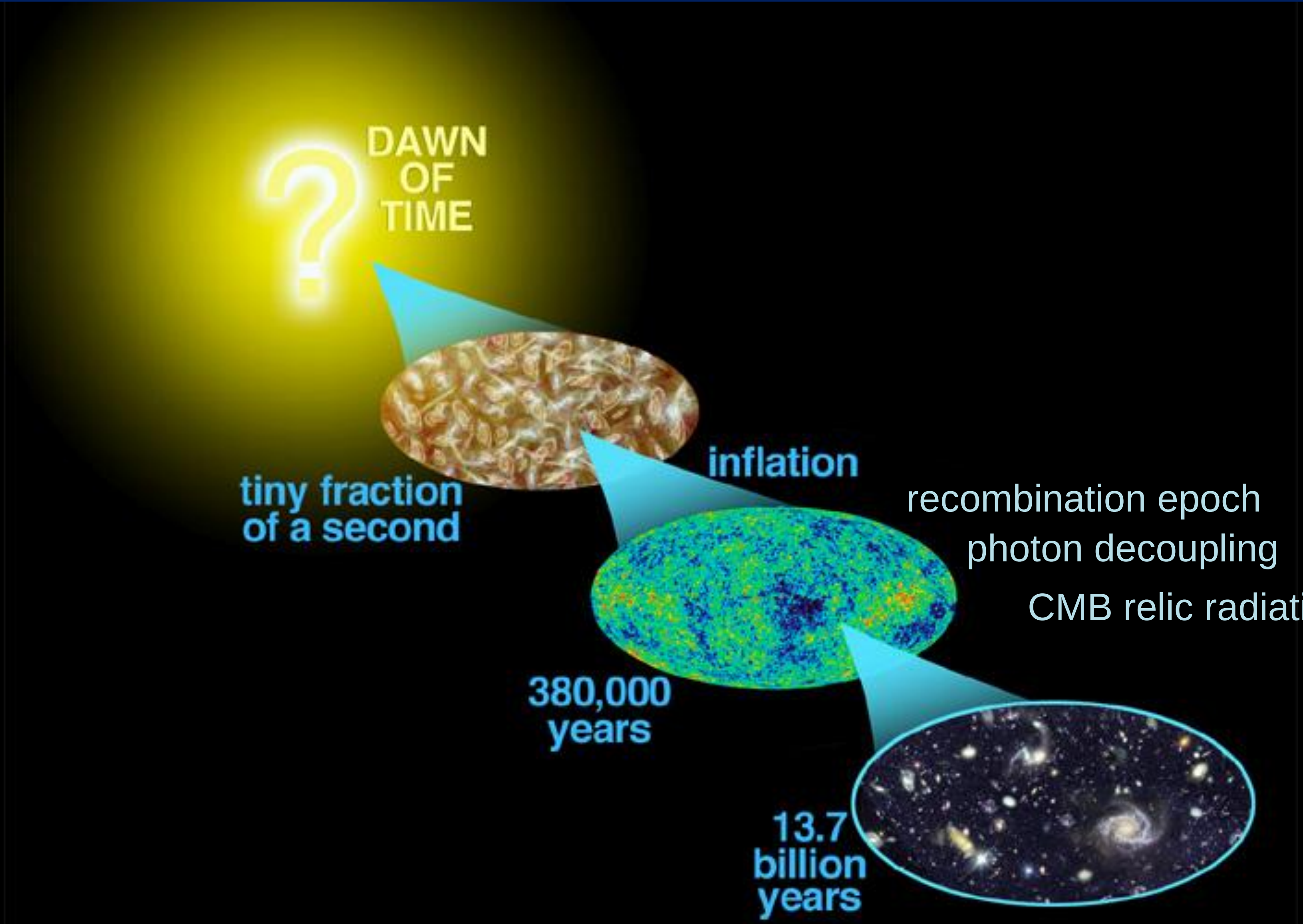
T ~ 3 K   E ~ 10^{-3} eV

Density ~ 410 cm^{-3}

Released 380.000 yr after the Big Bang



COSMIC MICROWAVE BACKGROUND



recombination epoch
photon decoupling
CMB relic radiation

Extragalactic Cosmic Rays

I. Non-relativistic baryons (gas in centers of Galaxy Clusters) $\Leftarrow$ NEGLIGIBLE !

II. Adiabatic energy loss (expansion of the Universe ≡ *redshift*) $\Leftarrow$ SMALL !

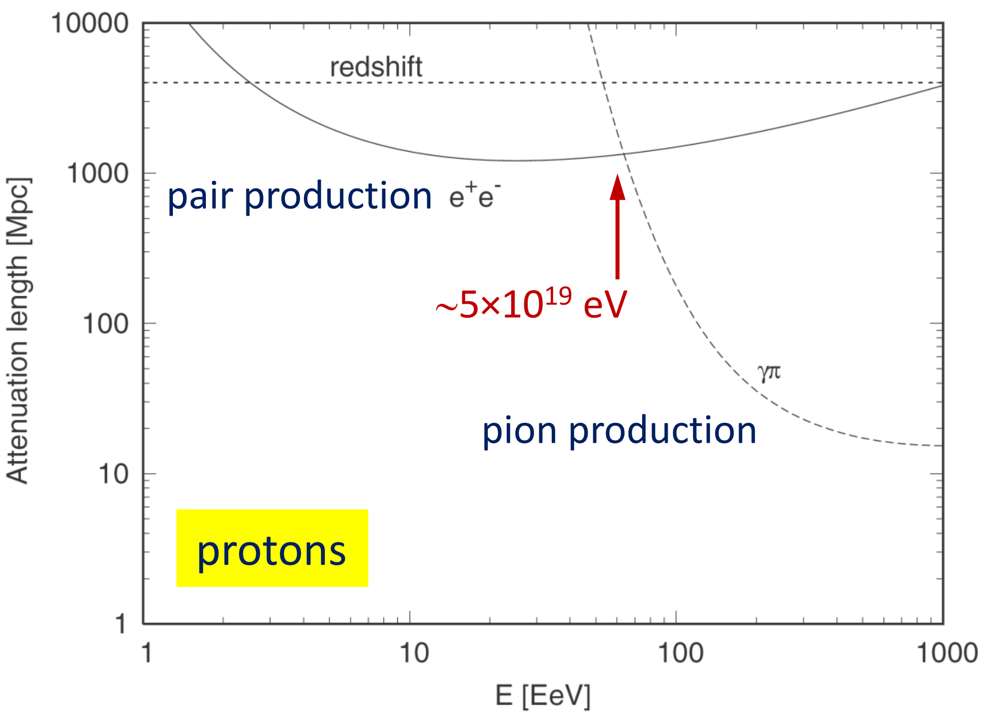
III. Low energy target photons (γ_{CMB} Cosmic Microwave Background) $\Leftarrow$ DOMINANT !

	Pair production	Photo disintegration	Pion production (GZK suppression!)
nucleons	$p + \gamma_{CMB} \rightarrow p + e^+ e^-$		$p + \gamma_{CMB} \rightarrow \Delta^+(1232) \rightarrow p + \pi^0$ $p + \gamma_{CMB} \rightarrow \Delta^+(1232) \rightarrow n + \pi^+$ **(same for neutrons)** **high inelasticity** ~20-50%
nuclei	$A + \gamma_{CMB} \rightarrow A + e^+ e^-$	$A + \gamma_{CMB} \rightarrow (A\text{-}1) + N$	**low inelasticity** ~20%/A ${}^A{}_Z X + \gamma_{CMB} \rightarrow {}^A{}_Z X + \pi^0$
$E_{threshold}$	$\sim A \times 2\times10^{18}$ **Low energy threshold**	$\sim 5\times10^{19}$ for iron	$\sim A \times 5\times10^{19}$ eV

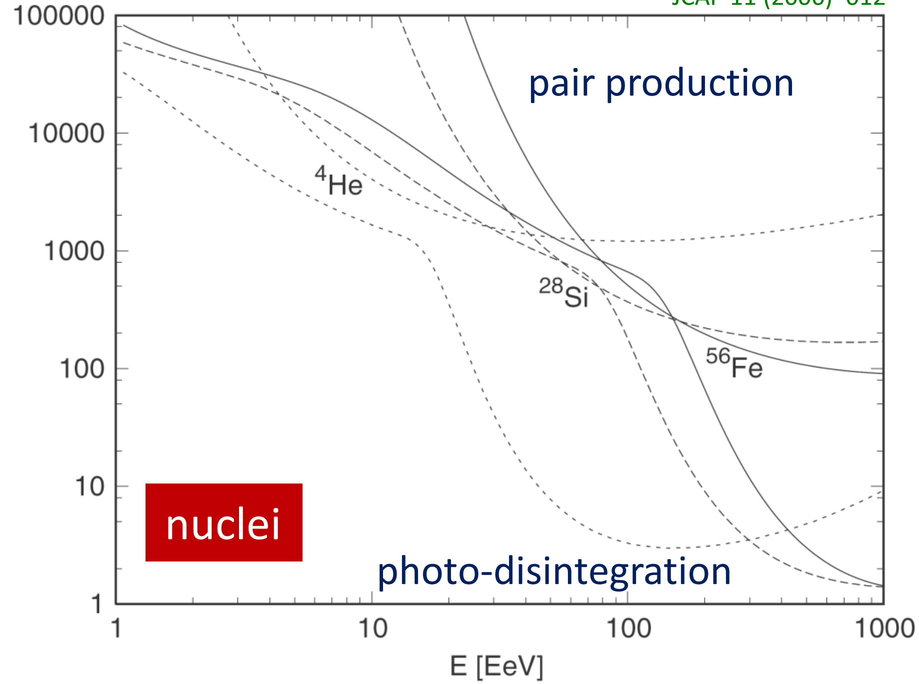
Extragalactic Cosmic Rays

Nucleons & nuclei interactions with low energy photons

γ_{CMB} Cosmic Microwave Background

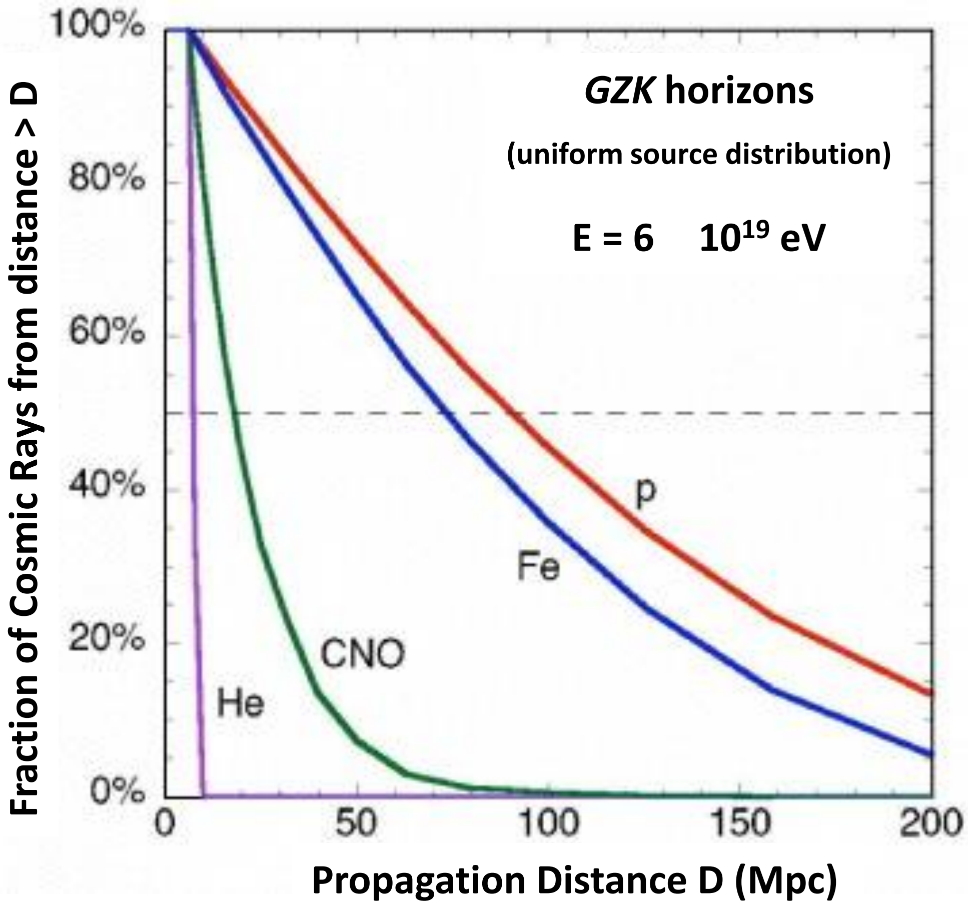


JCAP 11 (2006) 012

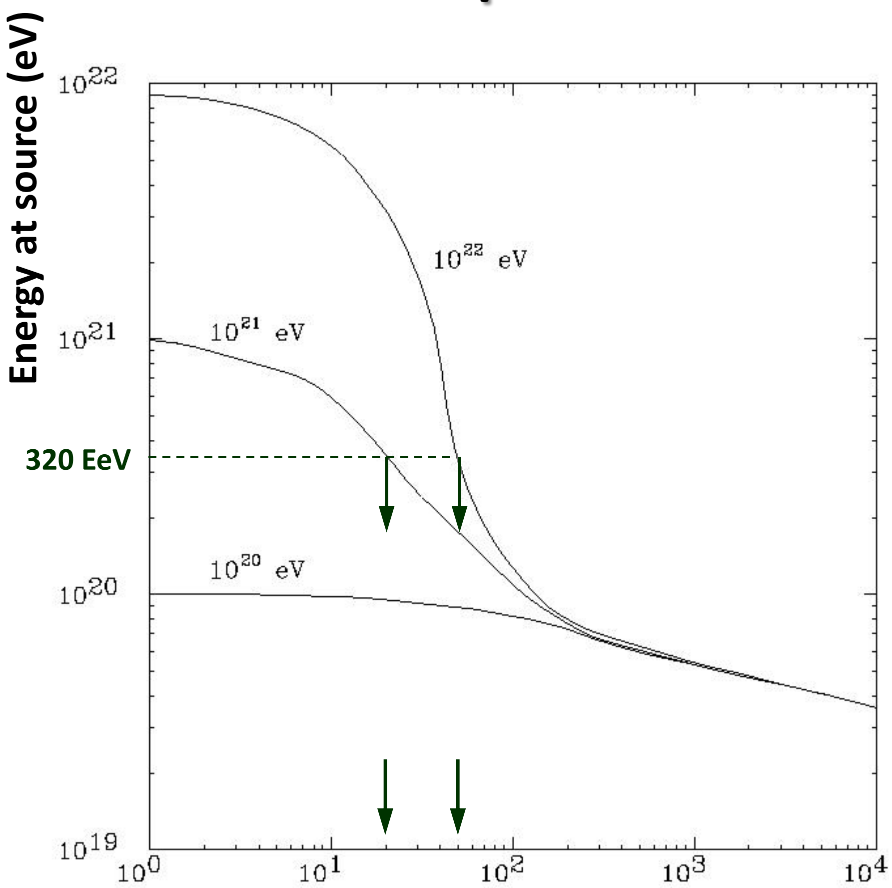


Extragalactic Cosmic Rays

Opaque space ...



Amnesic protons...



Sources with E > E_{GZK} must be at D < 100 Mpc (local cluster)

Deflection in Magnetic Fields

Deflection of cosmic rays in cosmic magnetic fields still hard to quantify (based on numerical simulations):

$$\vec{F} = q \cdot \vec{v} \times \vec{B}$$

rms deflection angle

Waxman *et al*. Astrophys. J. **472** L89 (1996)

$$\theta(\mathrm{E},\mathrm{d}) \approx \frac{\sqrt{(d\, l_c/9)}}{r_g} \approx 0.8^0 \cdot \mathrm{Z} \cdot \left(\frac{\mathrm{E}}{10^{20}\,\mathrm{eV}}\right)^{-1} \cdot \left(\frac{d}{10\mathrm{Mpc}}\right)^{-1/2} \cdot \left(\frac{l_c}{1\mathrm{Mpc}}\right)^{-1/2} \cdot \left(\frac{\mathrm{B}}{10^{-9}\,\mathrm{G}}\right)$$

B = Strength of the magnetic field coherent over a length l_c
E = cosmic ray energy traveling a distance d

Order of magnitude estimate (Galaxy):

$$l_c \approx 100\ \mathrm{pc},\ d \approx 10\ \mathrm{kpc},\ \mathrm{B} \approx 3\,\mu\mathrm{G} \quad \Rightarrow \quad \theta(\mathrm{E}) \approx 1^0 \cdot \mathrm{Z} \cdot \left(\frac{10^{20}\,\mathrm{eV}}{\mathrm{E}}\right)$$

E_{proton} ~ 60 EeV → few degrees
E_{iron} ~ 60 EeV → tens of degrees ⇒ Galactic magnetic fields are likely to destroy any possible correlation with local large scale structure in case of heavy composition

Large-scale extragalactic magnetic fields are much less known…

DETECTION

Detection of Astroparticles … a challenge !

The basic ideas are the same as for any particle physics detector. The ***"how"*** is NOT an issue:

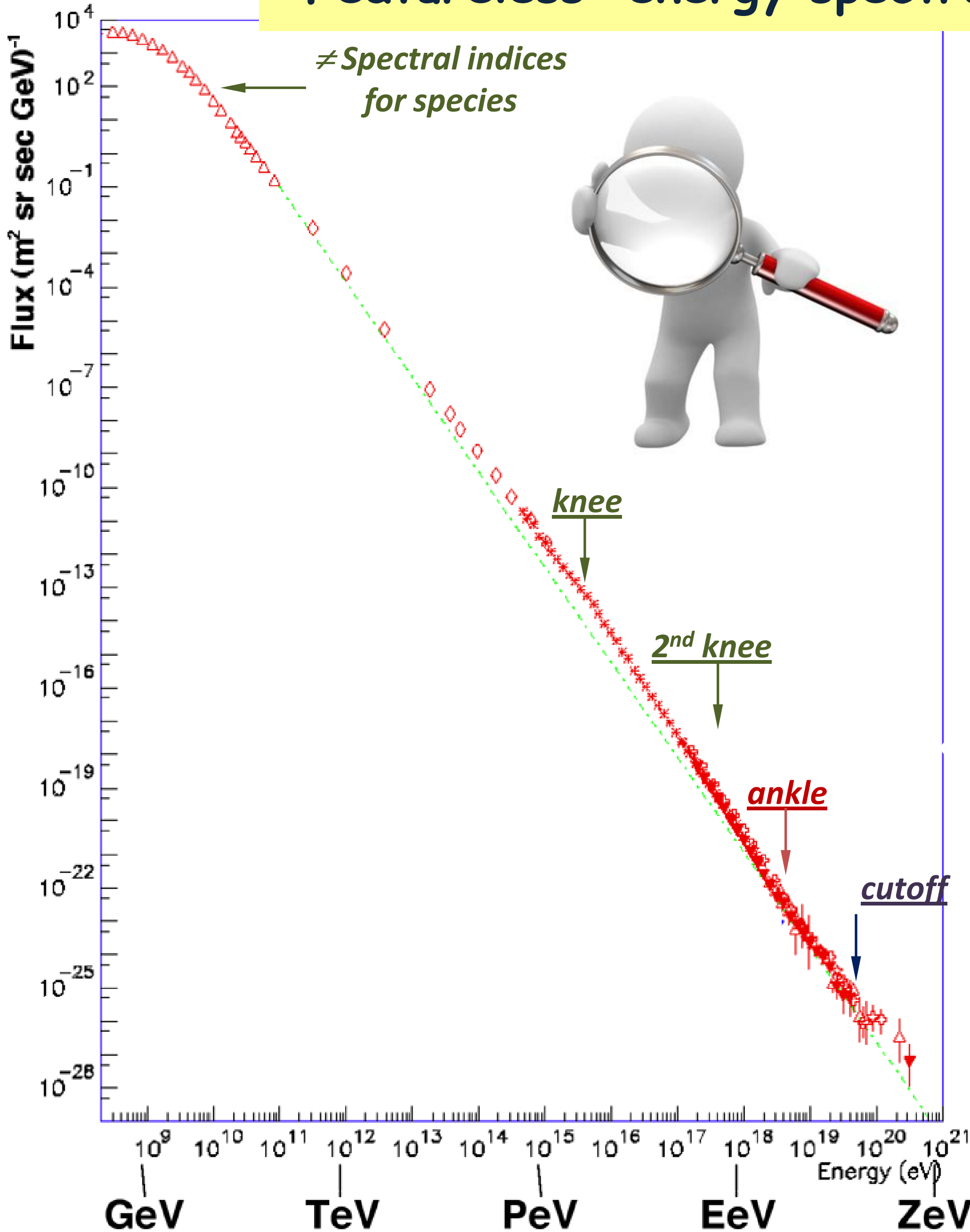
- **Charged particles:**
  - ✓ Spectrometers to reconstruct Z/M (← magnetic field)
  - ✓ Cherenkov light detectors (← highly relativistic)
  - ✓ Calorimeters to measure the energy (← atmosphere!)
  - ✓ Fluorescence Telescopes
  - ✓ …
- **Neutral particles:** turn them into charged ones and measure those…

… the main question is

"which" are the messengers I want to study (CR, γ-rays, ν)?

"which" region of the energy spectrum I want to explore?

"Featureless" energy spectrum … $\propto E^{-\gamma}$ ($\gamma \sim 2.7$)



… but, really "featureless" ?

NOT AT ALL !

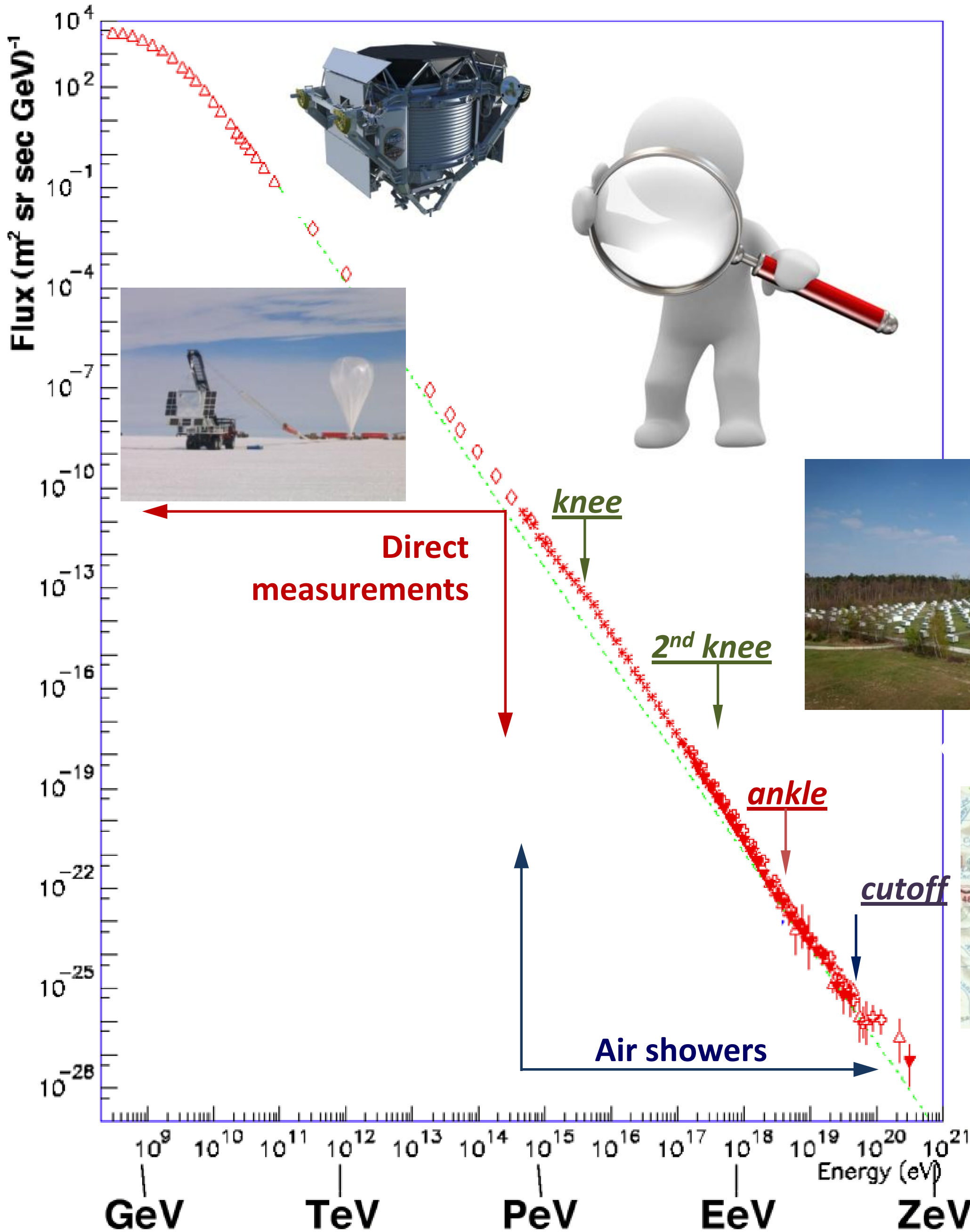
$E < 10^{15}$ $\gamma = 2.7$

$E \sim 4\times10^{15}$ $\gamma = 3$

$E \sim 4\times10^{17}$ $\gamma = 3.3$

$E \sim 5\times10^{18}$ $\gamma = 2.8$

$E \sim 5\times10^{19}$ eV – end (*suppression*)

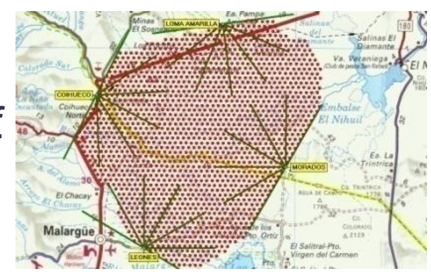


Direct (space & balloons)

&

Indirect (ground based)

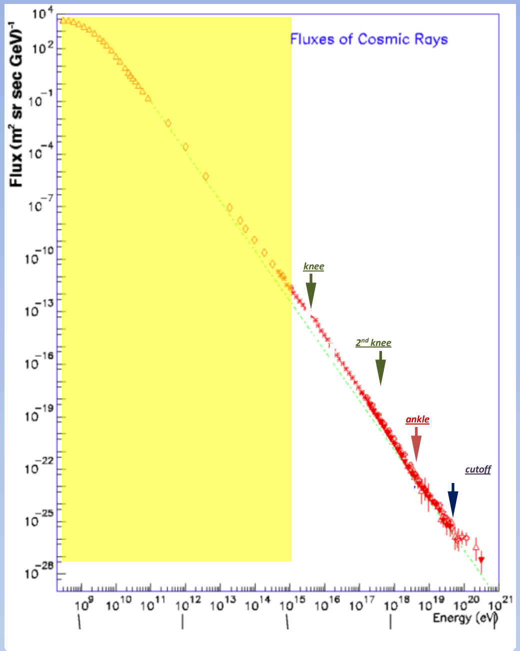
Measurements



WHERE ?

HOW ?

WHAT?

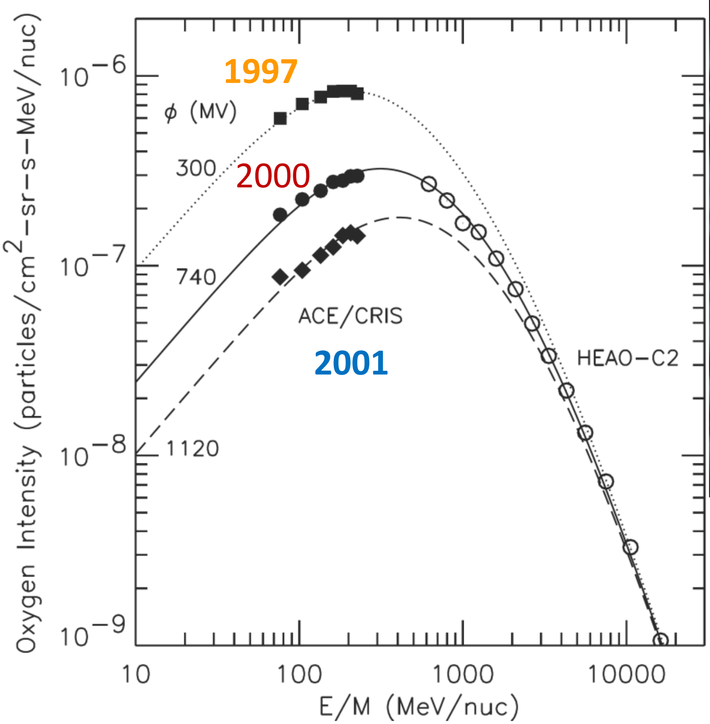


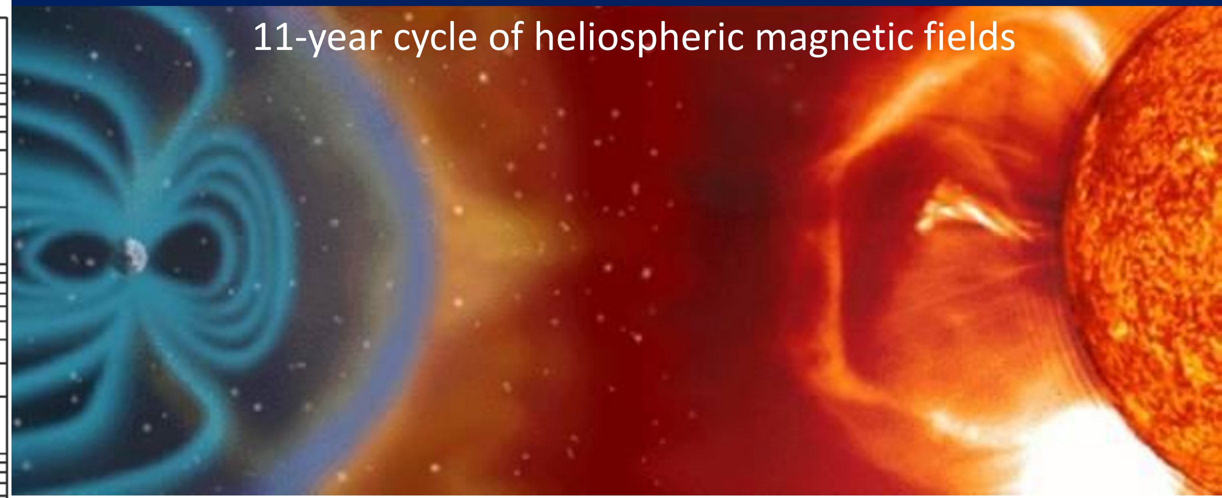
DIRECT DETECTION

(BELOW THE *KNEE*)

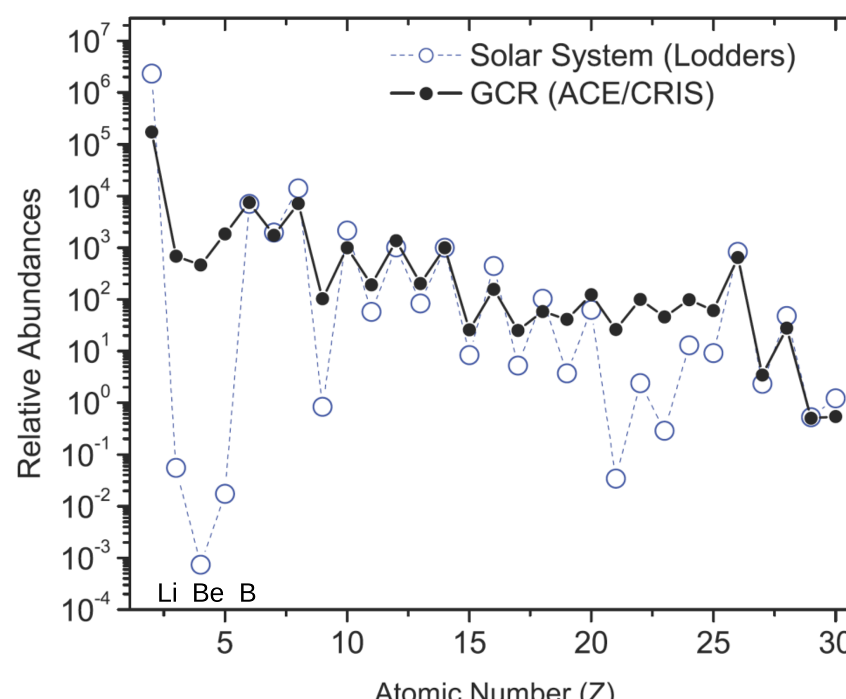
SATELLITES, STRATOSPHERIC BALLOONS…

Solar Modulations and Abundances of Elements

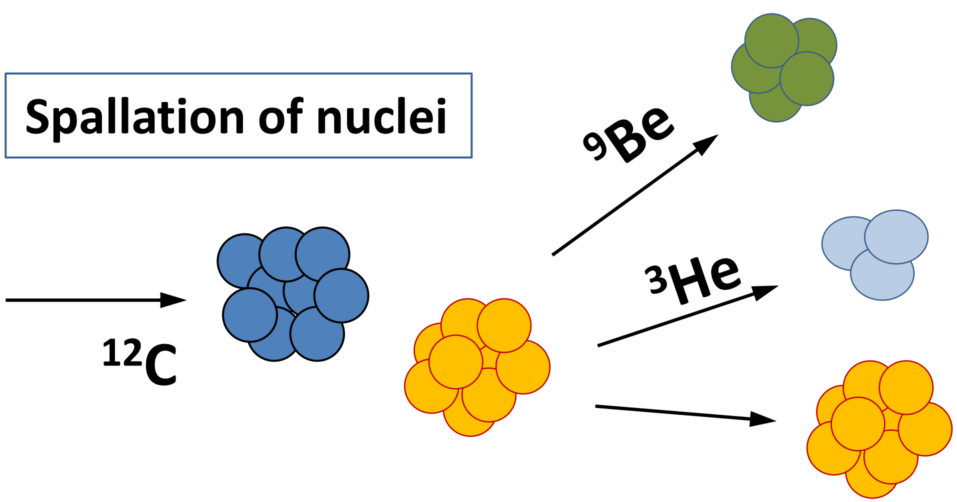




interstellar medium in Galaxy: ~1 atom/cm^3



Spallation of nuclei



DETECTORS IN SPACE

PAMELA Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

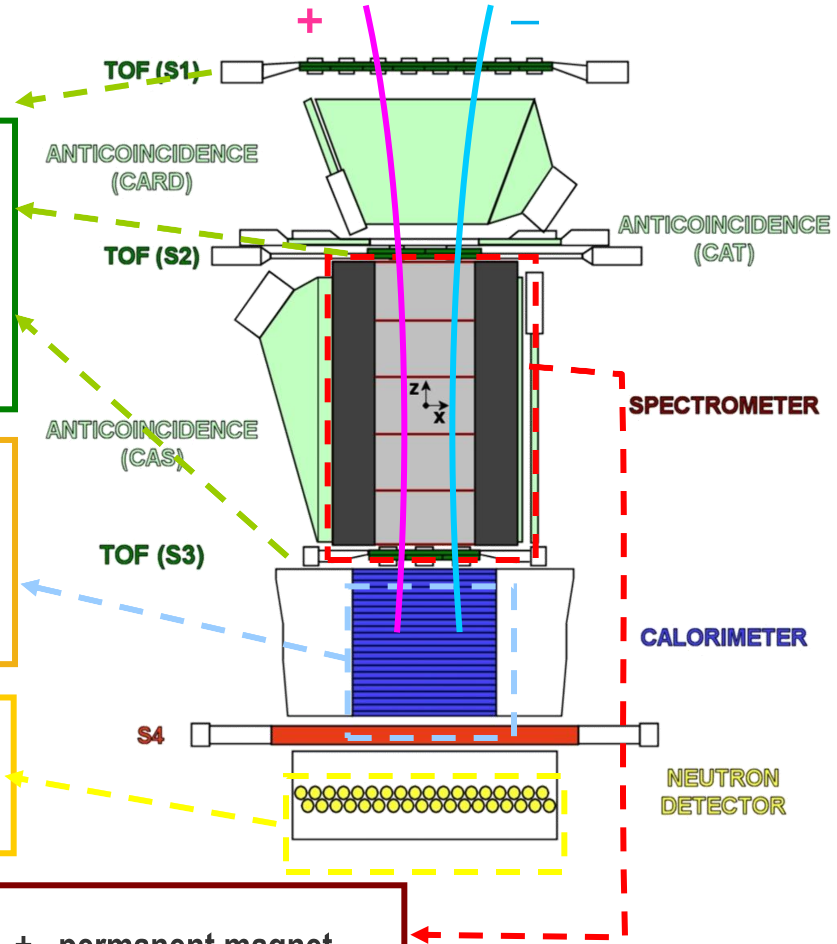
(Data 2006 – 2008)

$e^{\pm}$, p , $\overline{\text{p}}$, He
1 GeV – 1.2 TeV

Time-Of-Flight
plastic scintillators + PMT:
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX.

Electromagnetic calorimeter
W/Si sampling (16.3 X0, 0.6 λI)
- Discrimination e+ / p, anti-p / e^- (shower topology)
- Direct E measurement for e^-

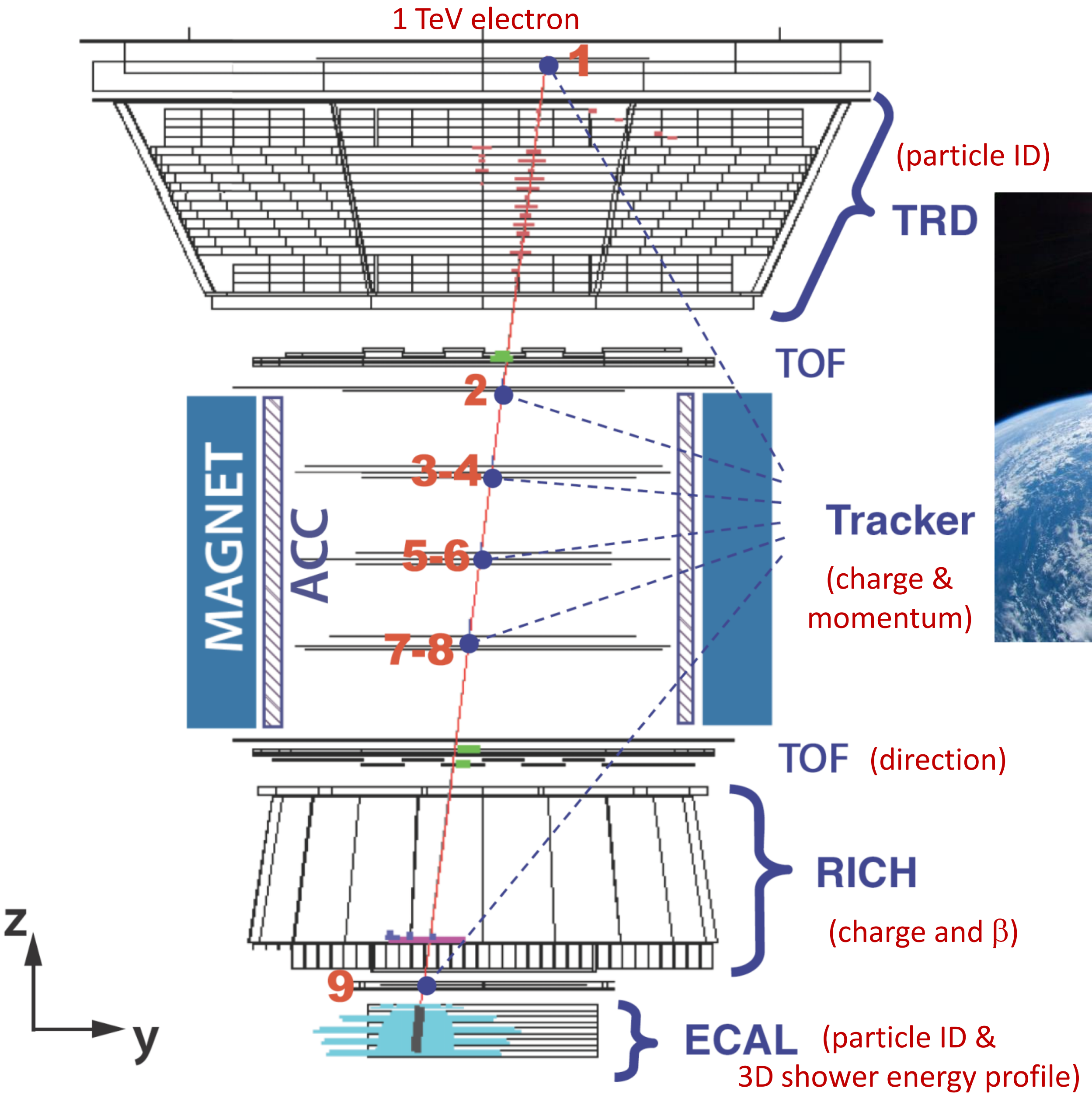
Neutron detector
36 He^3 counters :
- High-energy e/h discrimination



Spectrometer
microstrip silicon tracking system + **permanent magnet**
It provides:
- *Magnetic rigidity* → R = pc/Ze
- *Charge sign*
- *Charge value from dE/dx*

GF: 21.5 cm^2 sr
Mass: 470 kg
Size: 130x70x70 cm^3
Power Budget: 360W

DETECTORS IN SPACE

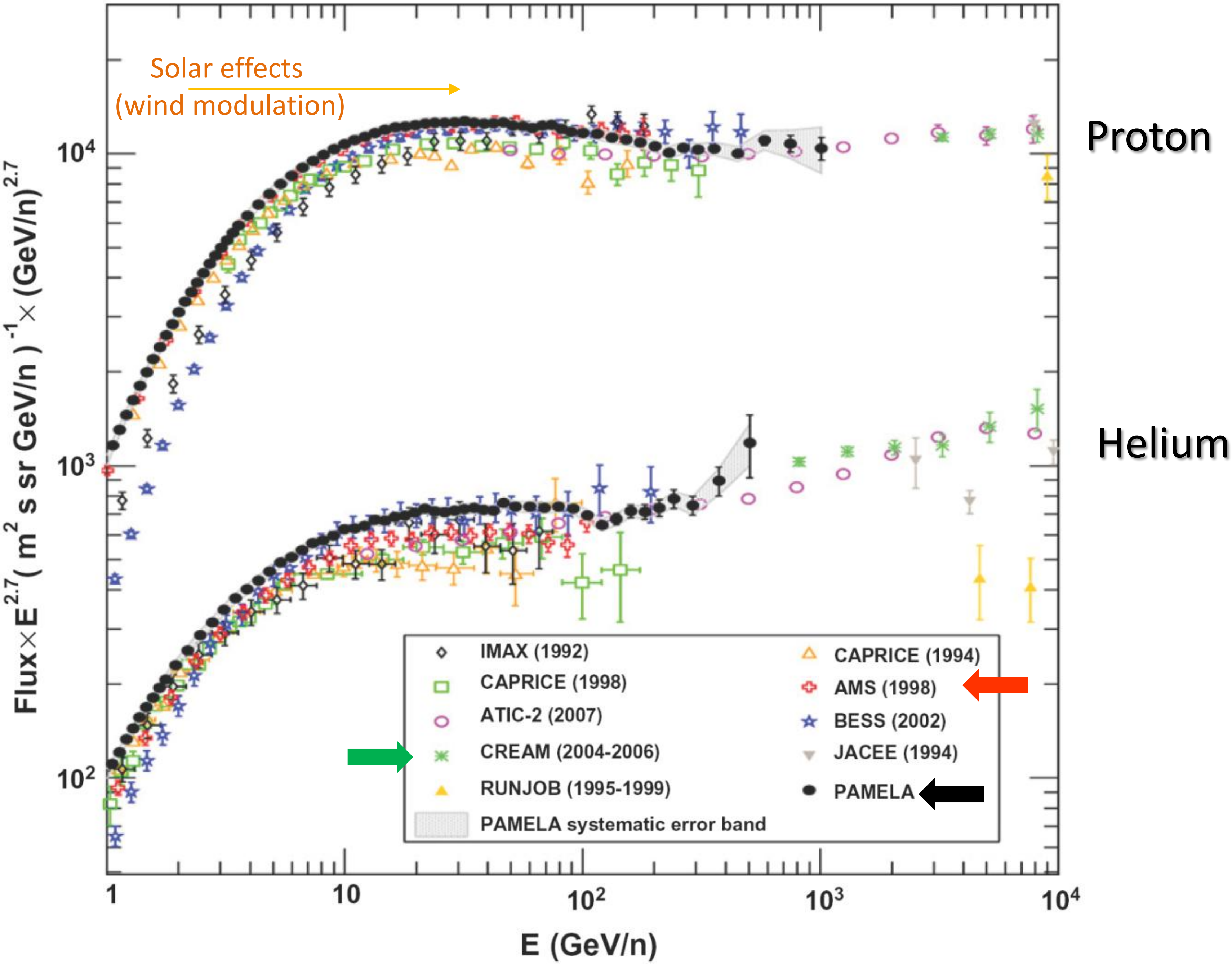


L. Accardo et al. PRL 113, 121101 (2014)

AMS-02

Alpha Magnetic Spectrometer

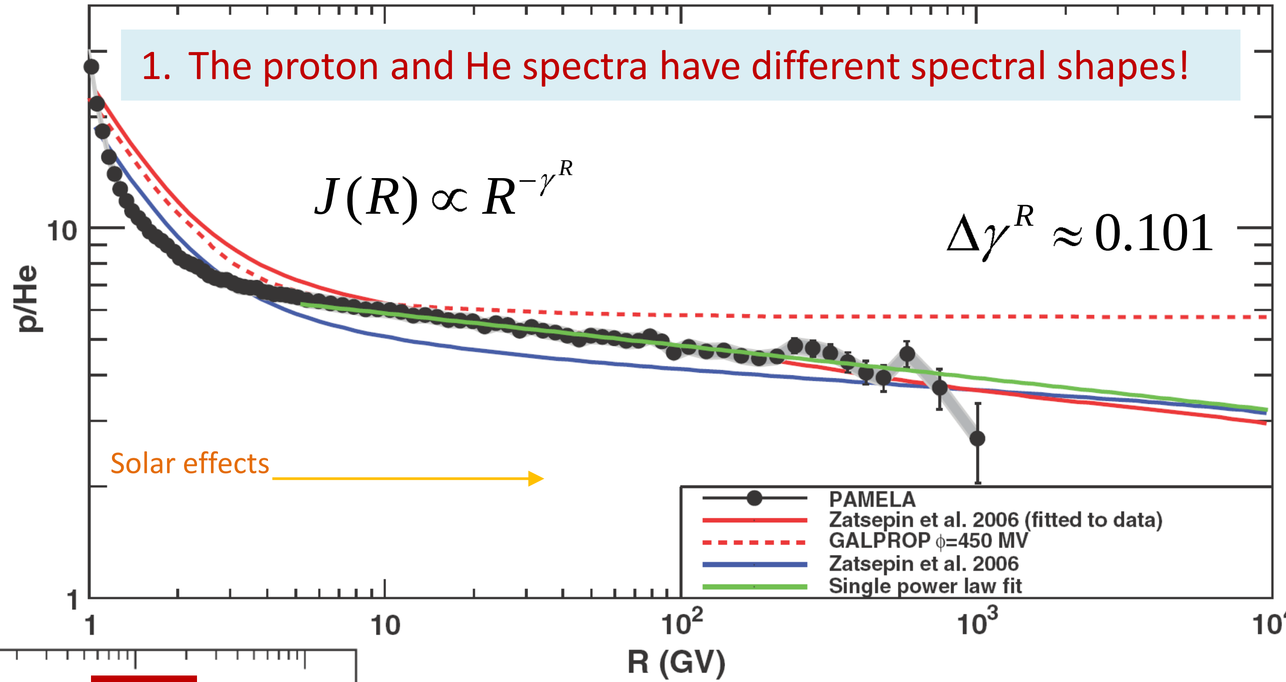
- ✓ 41 billion primary cosmic rays
- ✓ 10 million identified as e±
- ✓ E ∈ [0.5 to 500] GeV
- ✓ Increase of positrons from 8 GeV with no preferred incoming direction in space. The energy at which the e+ fraction ceases to increase ≅ 275±32 GeV.

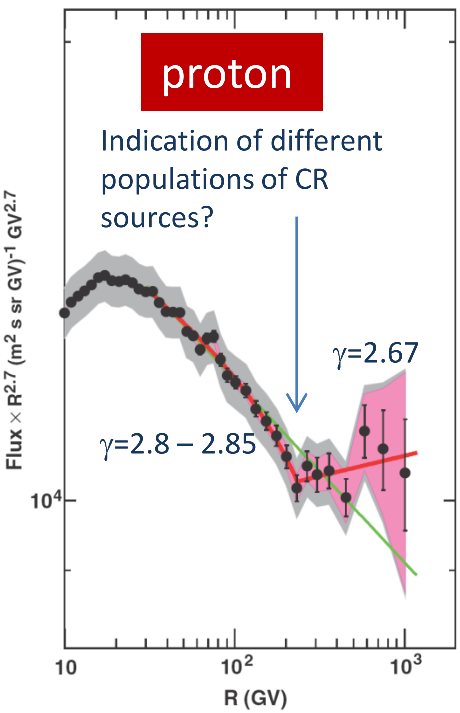

Solar effects
(wind modulation)
Proton
Helium
10^4
10^3
10^2
$Flux \times E^{2.7} (m^2\ s\ sr\ GeV/n)^{-1} \times (GeV/n)^{2.7}$
1
10
10^2
10^3
10^4
E (GeV/n)
IMAX (1992)
CAPRICE (1998)
ATIC-2 (2007)
CREAM (2004-2006)
RUNJOB (1995-1999)
PAMELA systematic error band
CAPRICE (1994)
AMS (1998)
BESS (2002)
JACEE (1994)
PAMELA

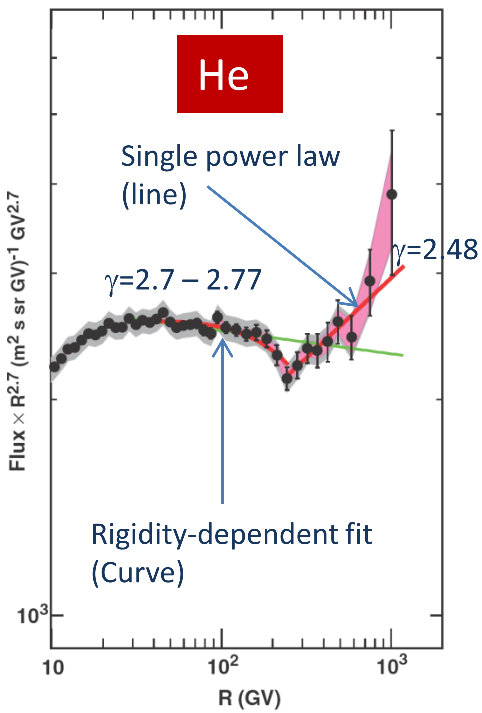
Rigidity: $R = \frac{pc}{Ze} \equiv \frac{E}{Z}$

$$\gamma^{R}_{30-100GV,p} \approx 2.820 \pm 0.005$$

$$\gamma^{R}_{30-100GV,He} \approx 2.732 \pm 0.008$$



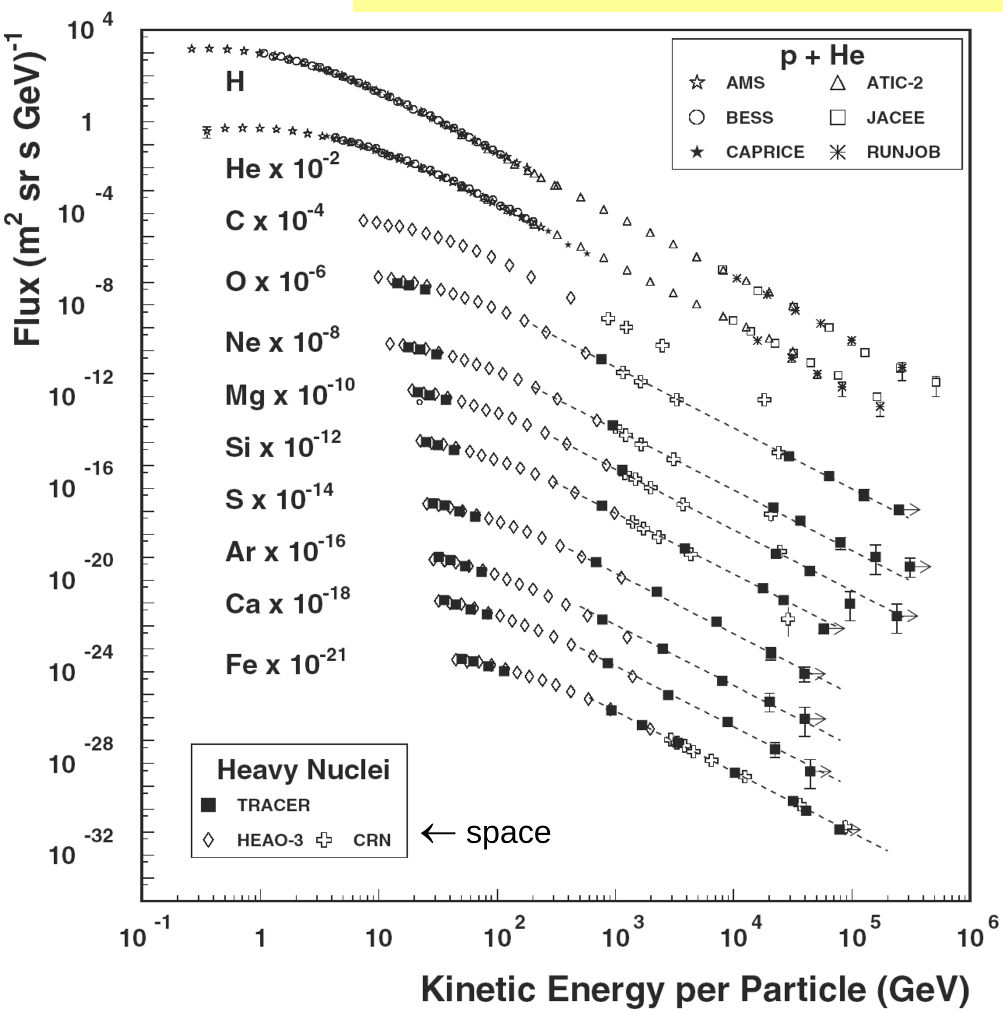


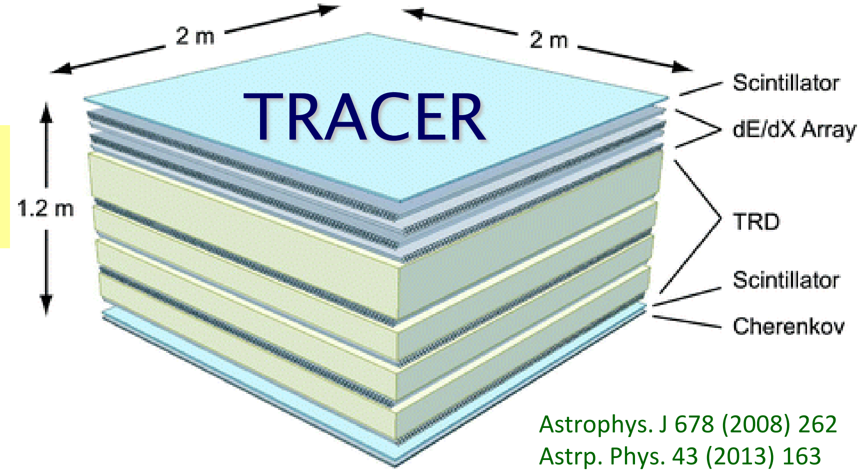


2. Clear deviation from a single-power law model

BALLOONS

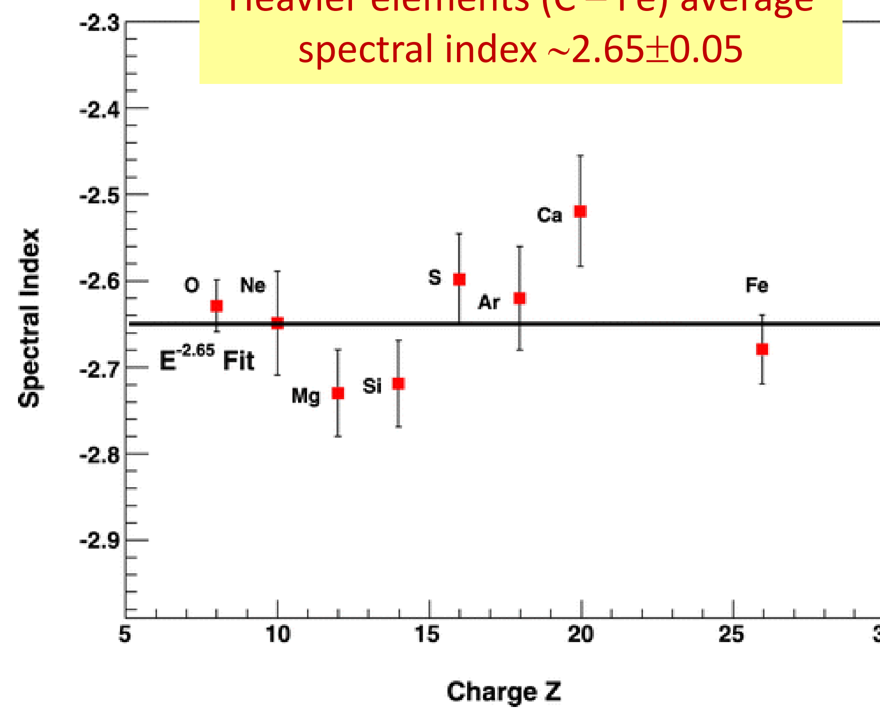
Good agreement among experiments in the regions of overlap





Astrophys. J 678 (2008) 262
Astrp. Phys. 43 (2013) 163

Heavier elements (C – Fe) average spectral index ~2.65±0.05



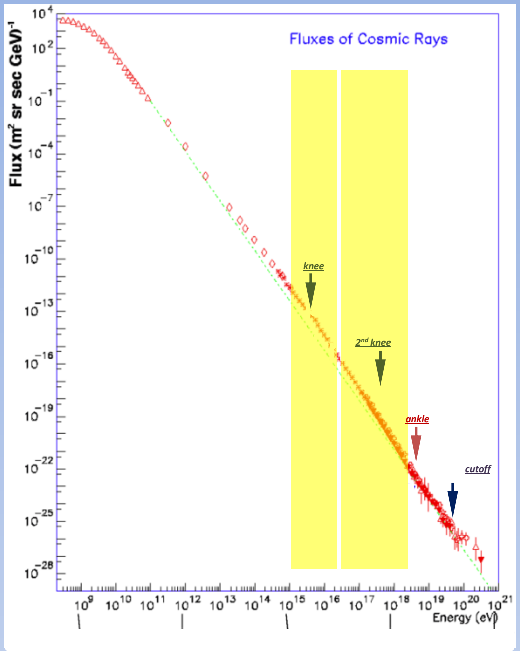
CRs "below the knee": SUMMARY

1. **Direct detection measurements:** detectors in space, stratospheric balloons…
2. **Main component** of CRs: **protons** (~85%), with additionally **He** (~10%) + other heavier elements
3. **Abundances**: ***odd–even* effect** (*even* = tighter bounded nuclei = more abundant)
4. **Spallation** effect observed: Li-Be-B produced as secondaries
5. **Low energy CR flux** suppressed and modulated by **Sun activity**
6. **"Featureless"** energy spectrum $\propto \mathbf{E^{-2.7}}$

$$\frac{dN}{dE} = \frac{1.8\times10^{4}\,(E/GeV)^{-2.7}}{m^{2}\cdot s\cdot sr\cdot GeV}$$

7. **p** and **He** (slightly) **different spectral index** and changing with Rigidity
8. **Good agreement between experiments** over may orders of magnitude in Energy.

INDIRECT DETECTION



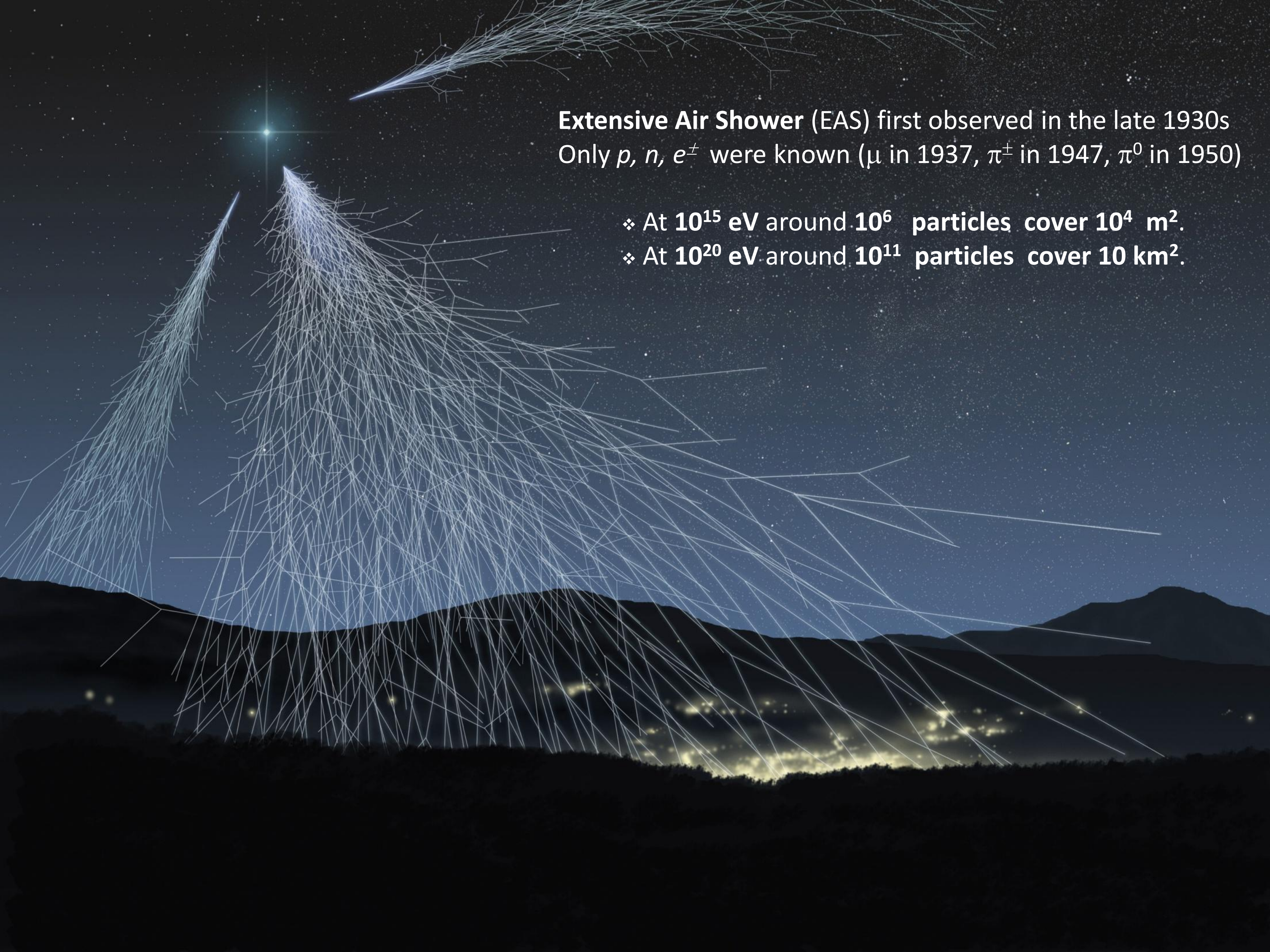
(AROUND THE *KNEE*)

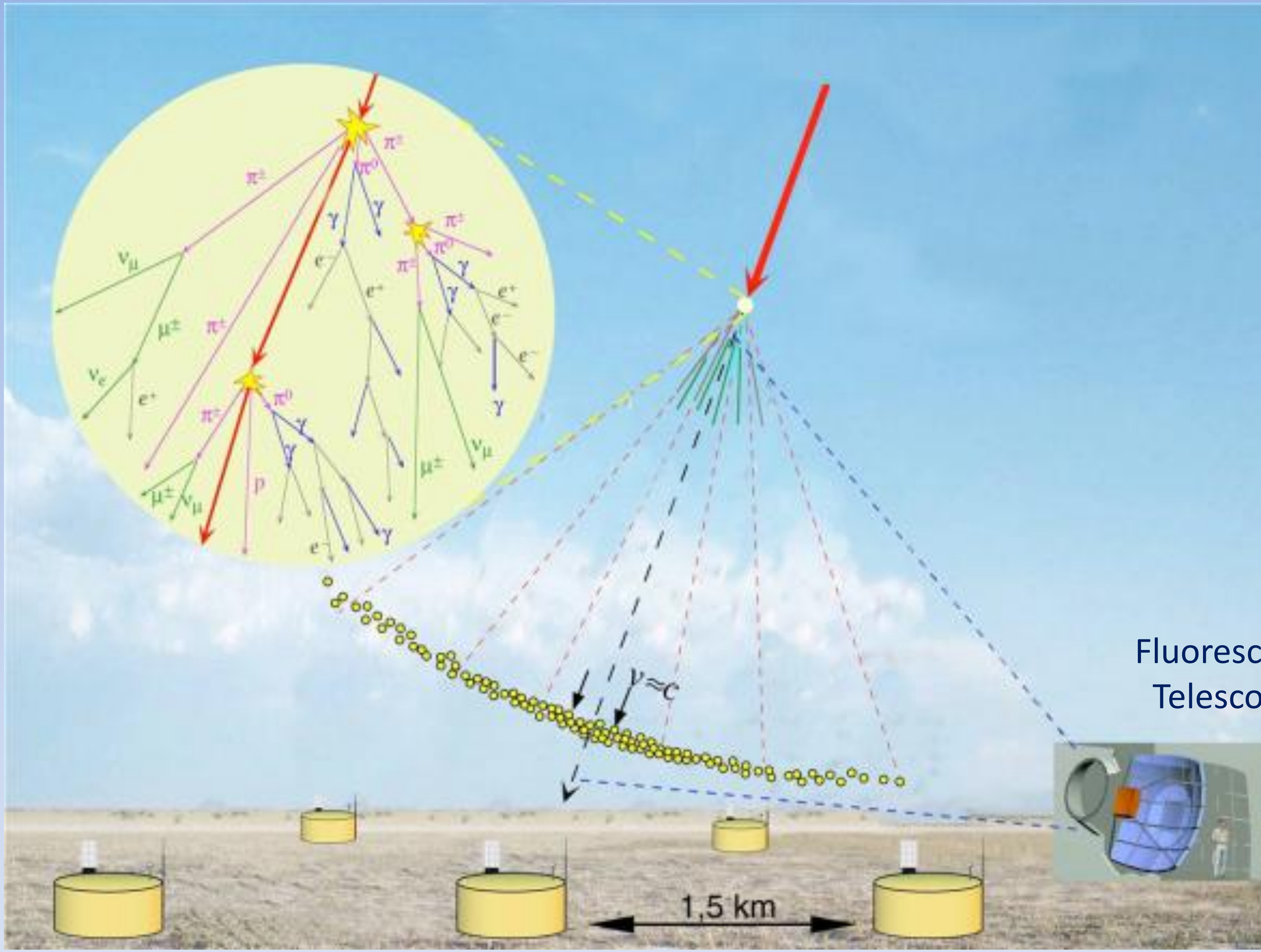
GROUND BASED DETECTORS

Extensive Air Shower (EAS) first observed in the late 1930s

Only *p, n,* $e^{\pm}$ were known (μ in 1937, $\pi^{\pm}$ in 1947, π^{0} in 1950)

- At **10^{15} eV** around **10^{6} particles cover 10^{4} m^{2}**.
- At **10^{20} eV** around **10^{11} particles cover 10 km^{2}**.





Fluorescence Telescopes

Array of Surface detectors
(water Cherenkov, scintillators, …)

Extensive Air Showers (EAS)

$\pi^\pm \to \mu^\pm + \nu_\mu$ (99.9%)

$K^\pm \to \mu^\pm + \nu_\mu$ (63.5%)

$K^\pm \to \pi^\pm + \pi^o$ (21.2%)

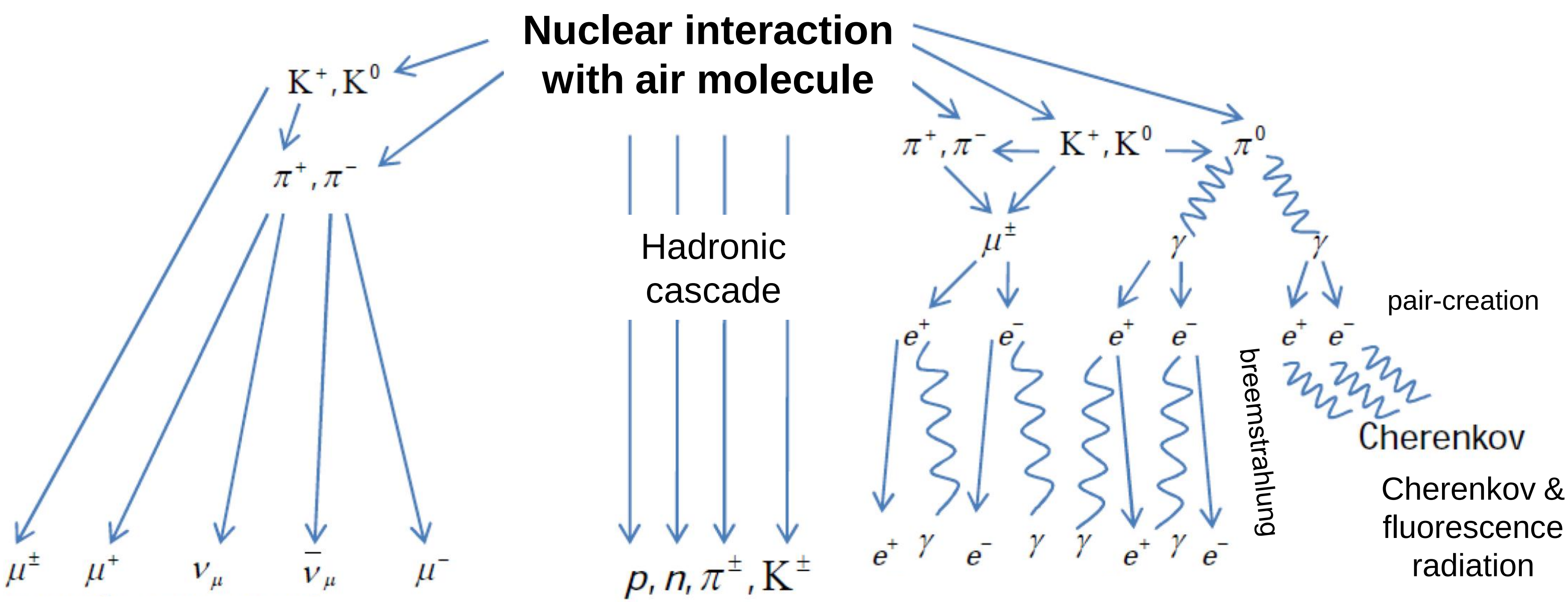
$\pi^o \to \gamma\,\gamma$ (98.8%)

$\gamma \to e^+e^-$

$e^- \to e^-\ \gamma$

Primary Particle

E_o



muonic component $\approx$**10% E_o**

neutrinos $\approx$**1% E_o**

(nuclear fragments)

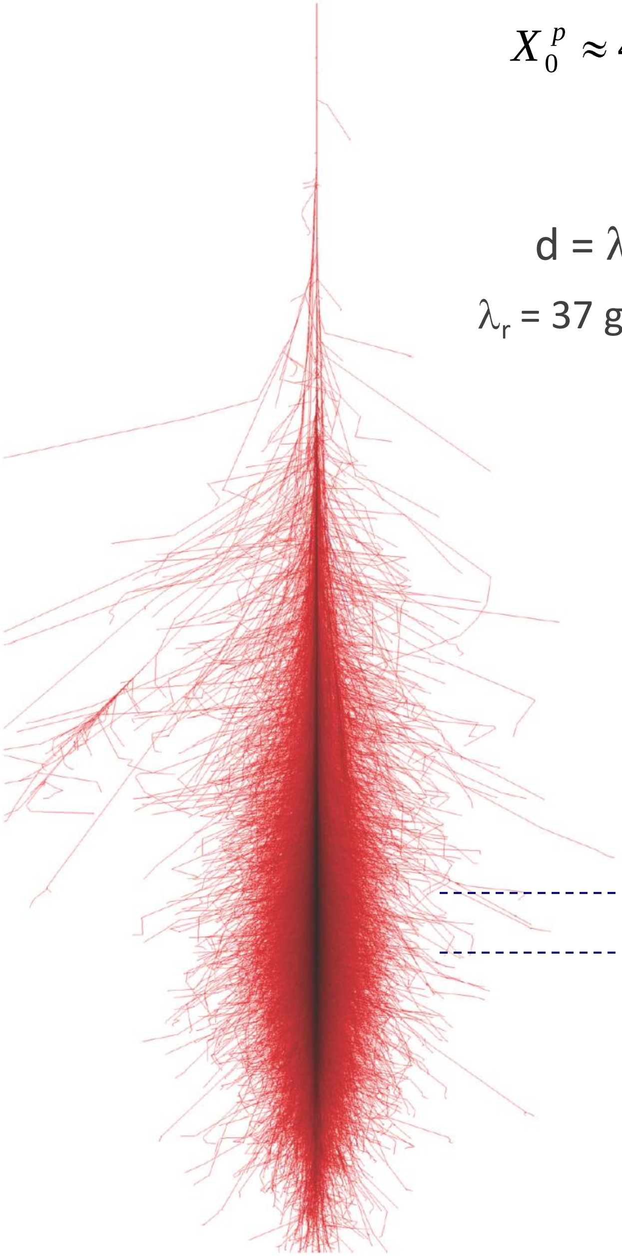
hadronic component $\approx$**4% E_o**

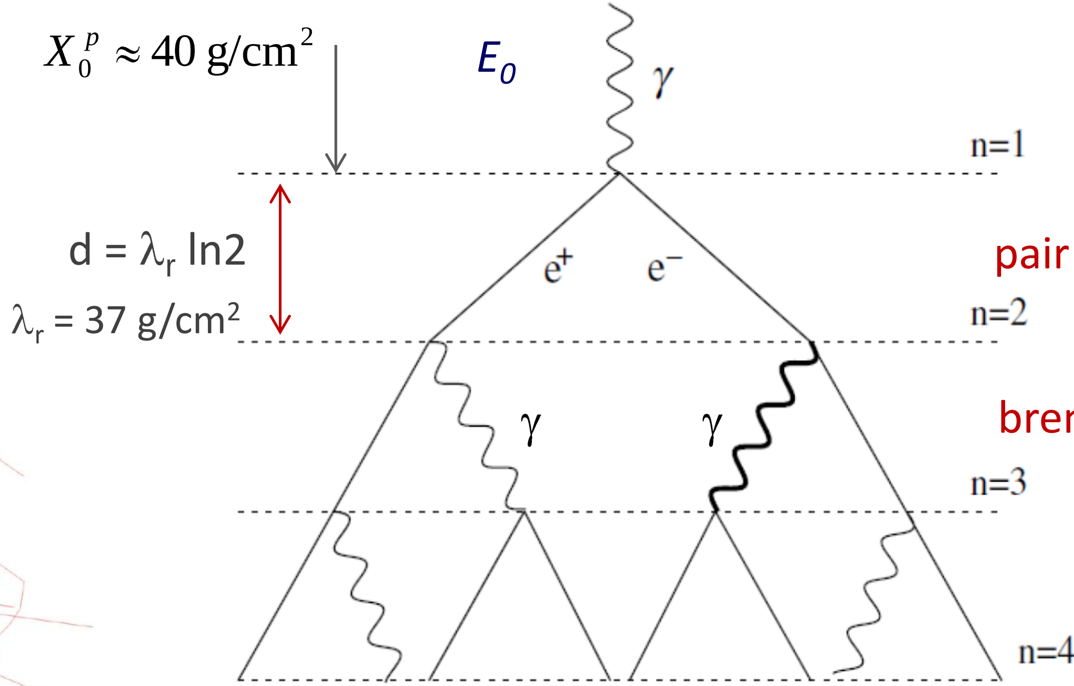
electromagnetic component $\approx$**85% E_o**

Atmosphere ≡ calorimeter of variable density (vertical thickness > **26 radiation lengths**)

(1 proton, $E=10^{18}$ eV, $\theta=0^o$) $\to$ ~10^{10} particles at sea level, few km^2 on ground

Electromagnetic EAS: the Heitler model





Particles at maximum $\propto E_0$

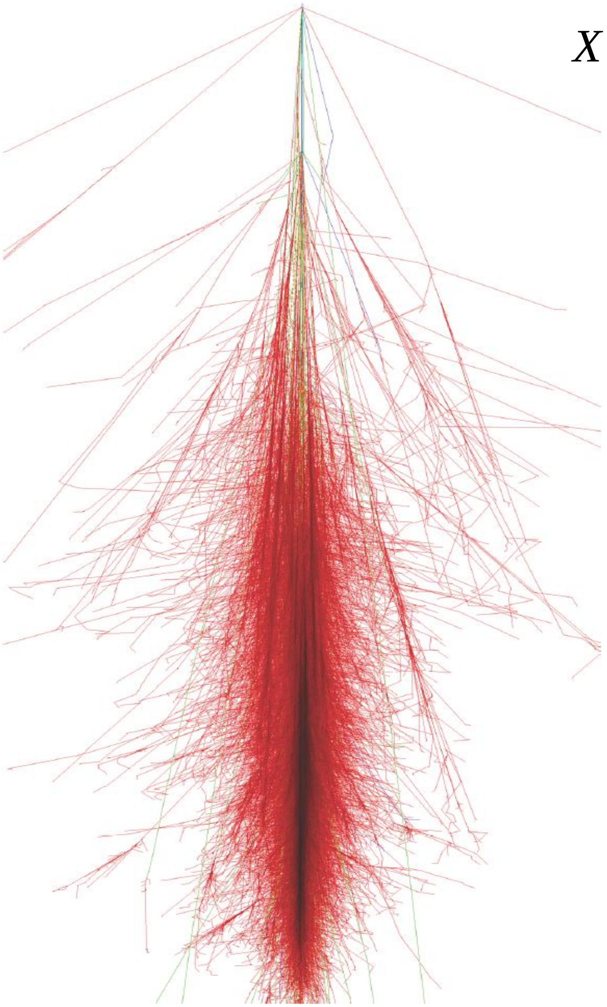
Maximum depth $\propto \ln(E_0)$

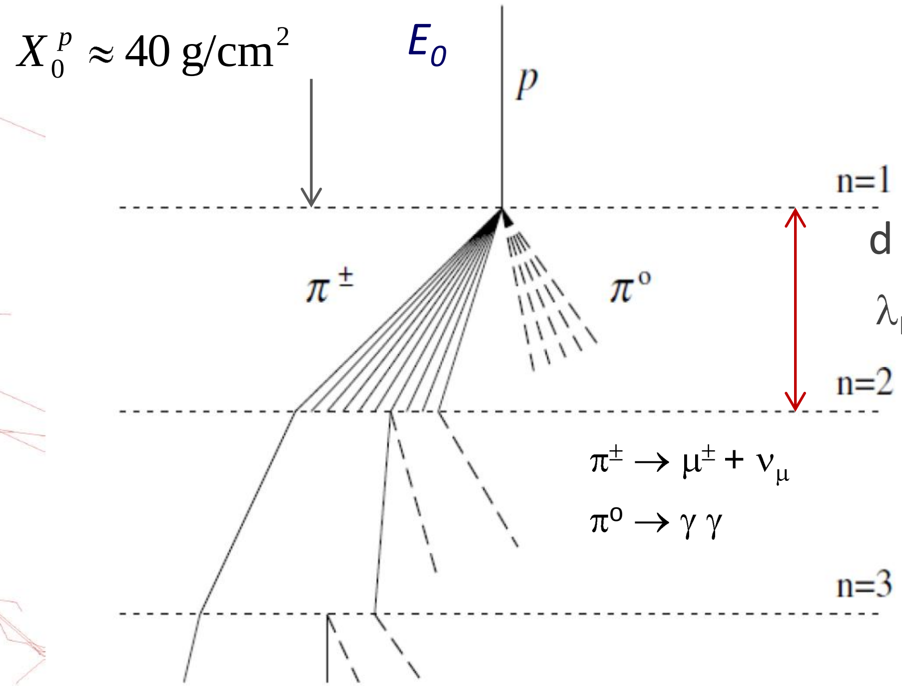
$$N_{max} = E_0 / E^{\gamma}_{critical}$$

$$X_{max} = X_0 + n_{max} \cdot d = X_0 + \lambda_r \cdot \ln\left(E_0 / E^{\gamma}_{critical}\right)$$

- After n interaction lengths there are $N_n = 2^n$ particles each with energy $E_n = E_0/N_n$ and total traversed depth is $X = n \cdot d$
- Splitting process until $E < E_{critical}$ ~80 MeV

EAS initiated by hadrons & superposition model





$\pi^\pm \to \mu^\pm + \nu_\mu$

$\pi^0 \to \gamma\,\gamma$

d = $\lambda_I \ln 2$

$\lambda_I \approx 90 - 9\log(E_0/\mathrm{EeV})\ \ \mathrm{g/cm^2}$

$$2N_{\pi^\pm} + N_{\pi^0} \approx 30$$

$$\beta = \frac{\ln(2N_\pi)}{\ln(3N_\pi)} \approx 0.9$$

$$E^\pi_{critical} \approx 10\ \ \mathrm{GeV\ at}\ 10^{17}\ \mathrm{eV}$$

$$\frac{N_{\max}}{N_\mu} \approx \mathrm{O}(1000)\ \ \text{for}\ E_0 \approx 10^{19}\ \mathrm{eV}$$

← *e.m.* cascade carries most of the shower energy!

Nuclei initiated showers compared to proton showers

$$X^A_{\max}(E_0) = X^p_{\max}(E_0) - \lambda_r \cdot \ln A$$ ← Less penetrating

$$N^A_\mu(E_0) = N^p_\mu(E_0) \cdot A^{1-\beta}$$ ← More muons

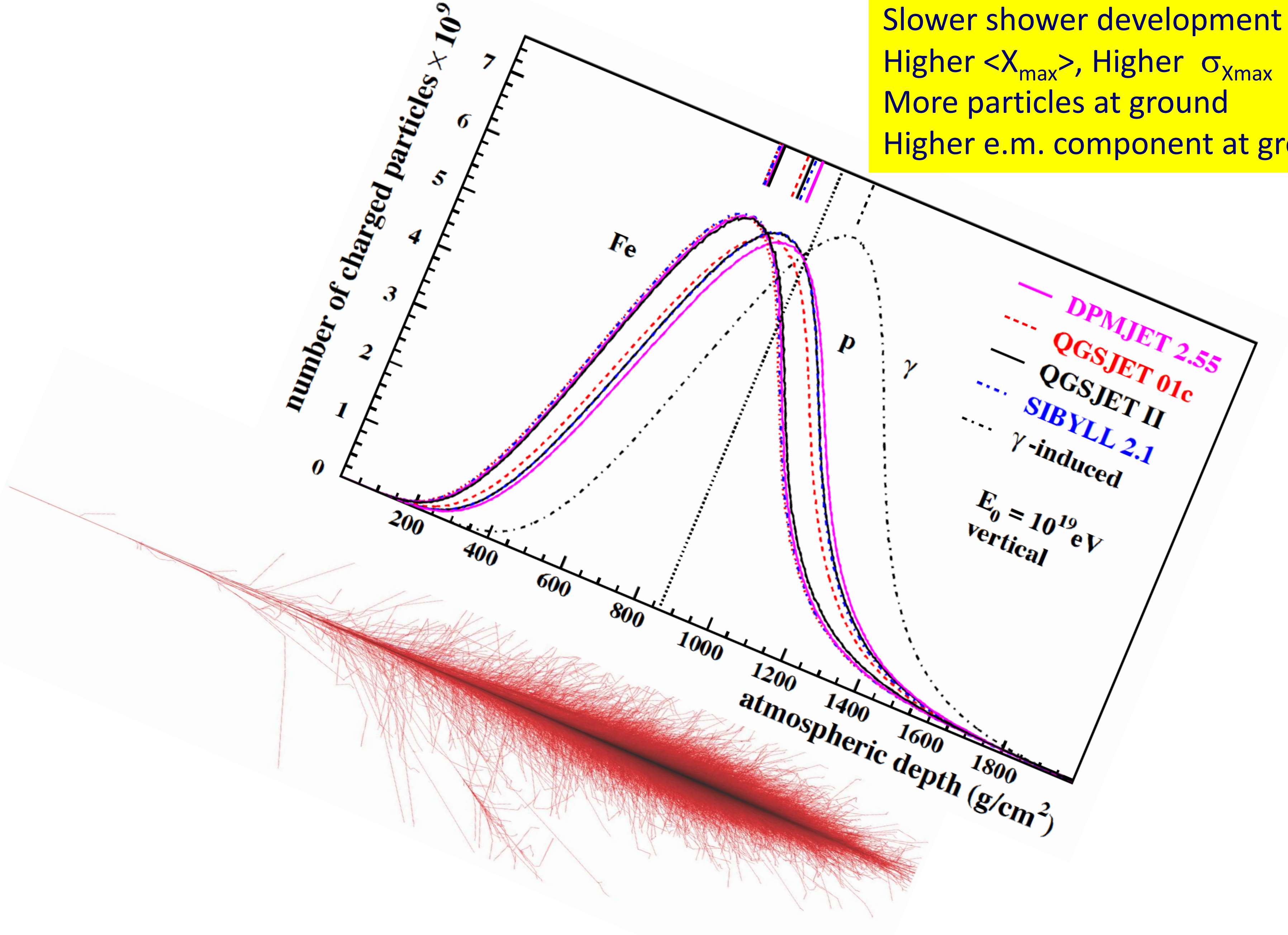
Decreasing mass:

Slower shower development

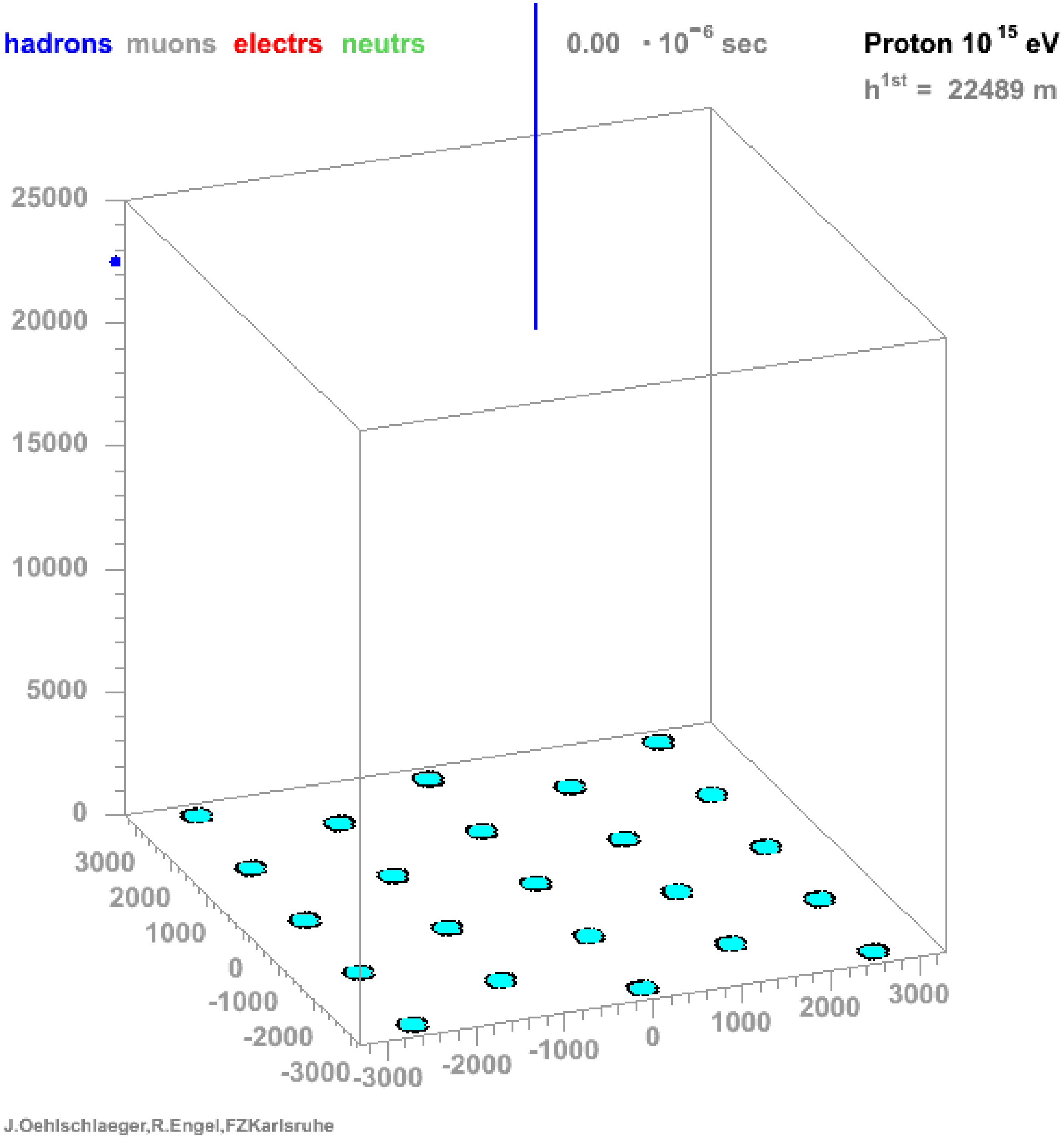
Higher <X_{max}>, Higher σ_{Xmax}

More particles at ground

Higher e.m. component at ground

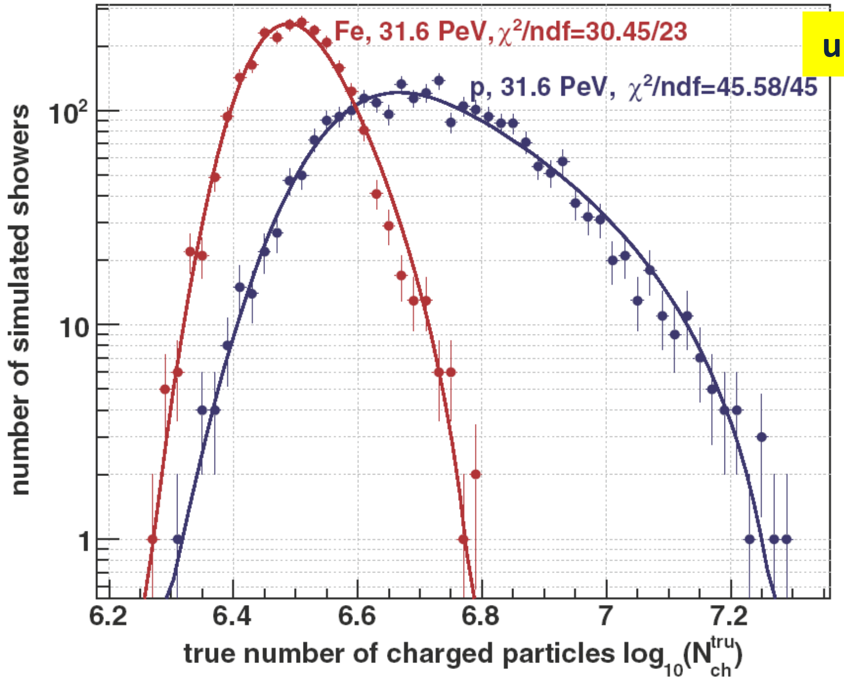


Extensive Air Showers (EAS)

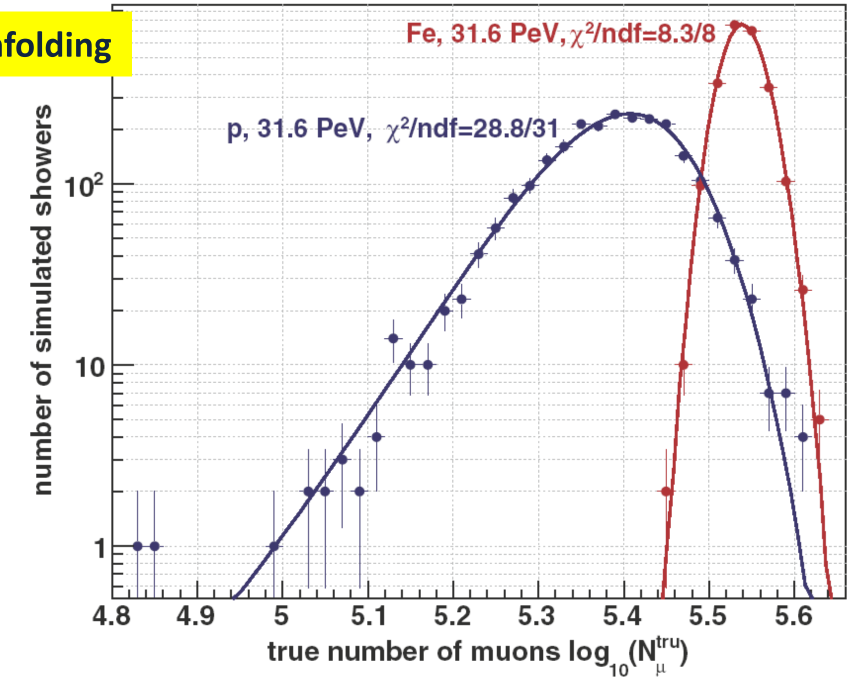


@ 10^{19} eV

$$X_{max}^{Fe} \approx 700 \text{ g/cm}^2$$
$$X_{max}^{p} \approx 800 \text{ g/cm}^2$$
$$X_{max}^{\gamma} \approx 950 \text{ g/cm}^2$$



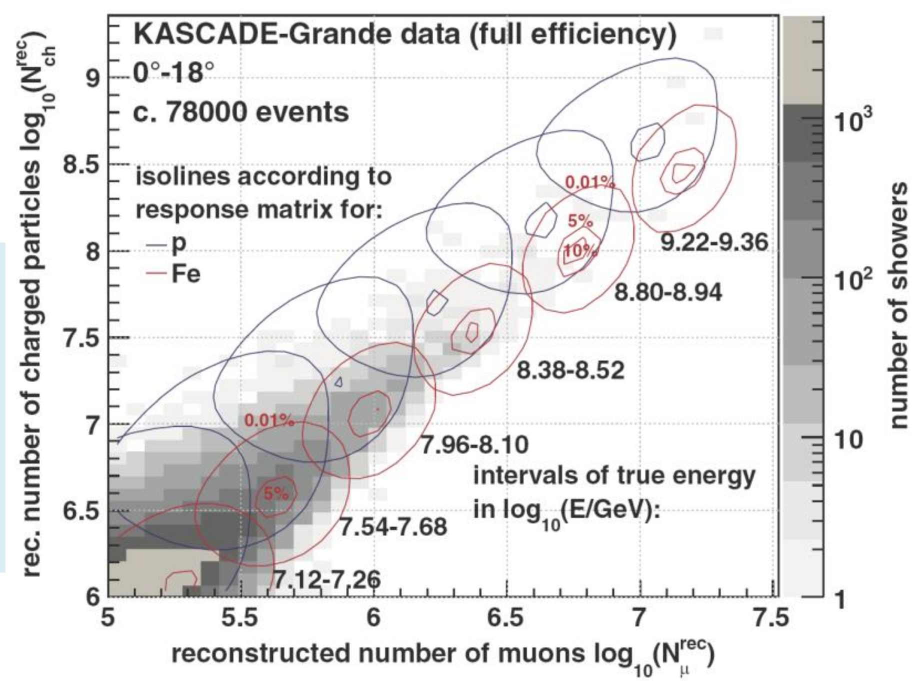
unfolding



Data can be **interpreted** in terms of primary mass by a comparison to **air shower simulations** using **hadronic interaction models**

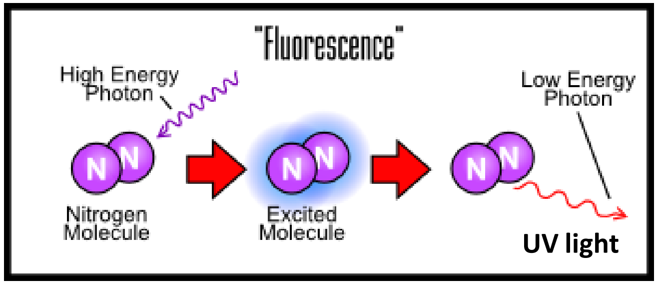
- **Protons = deeper**
  - → more charged particles (more electrons), less μ
  - → **more fluctuations**
- **Iron = less penetrating**
  - → less charged particles (less electrons), more μ
  - → **less fluctuations**

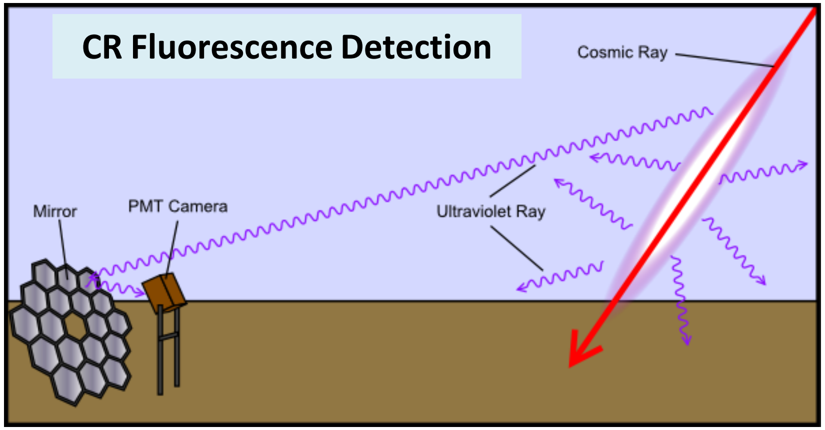
... N_μ / N_e relates to the primary **mass**

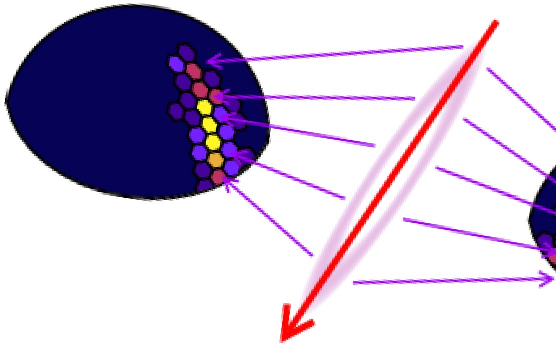


Fluorescence Telescopes

Shower Longitudinal Profile





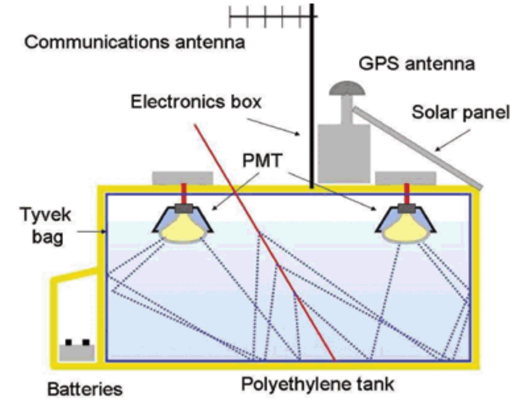


Stereoscopic Imaging

Surface Detectors

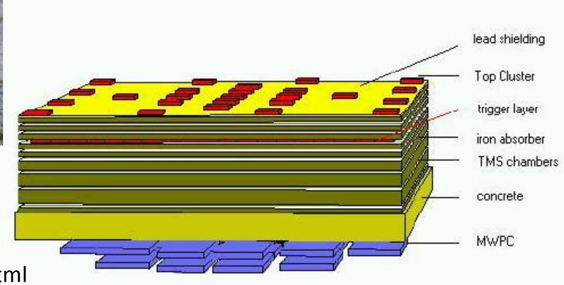
Lateral Distribution of Particles at Ground

Water Cherenkov stations



Scintillators

e/γ detector: liquid scintillator + light collector + PMT
Muon detector: plastic scintillator shielded (iron) + PMT



https://web.ikp.kit.edu/KASCADE/welcome.html

GROUND BASED DETECTORS:

DATA & INTERPRETATION

Ground Based detectors

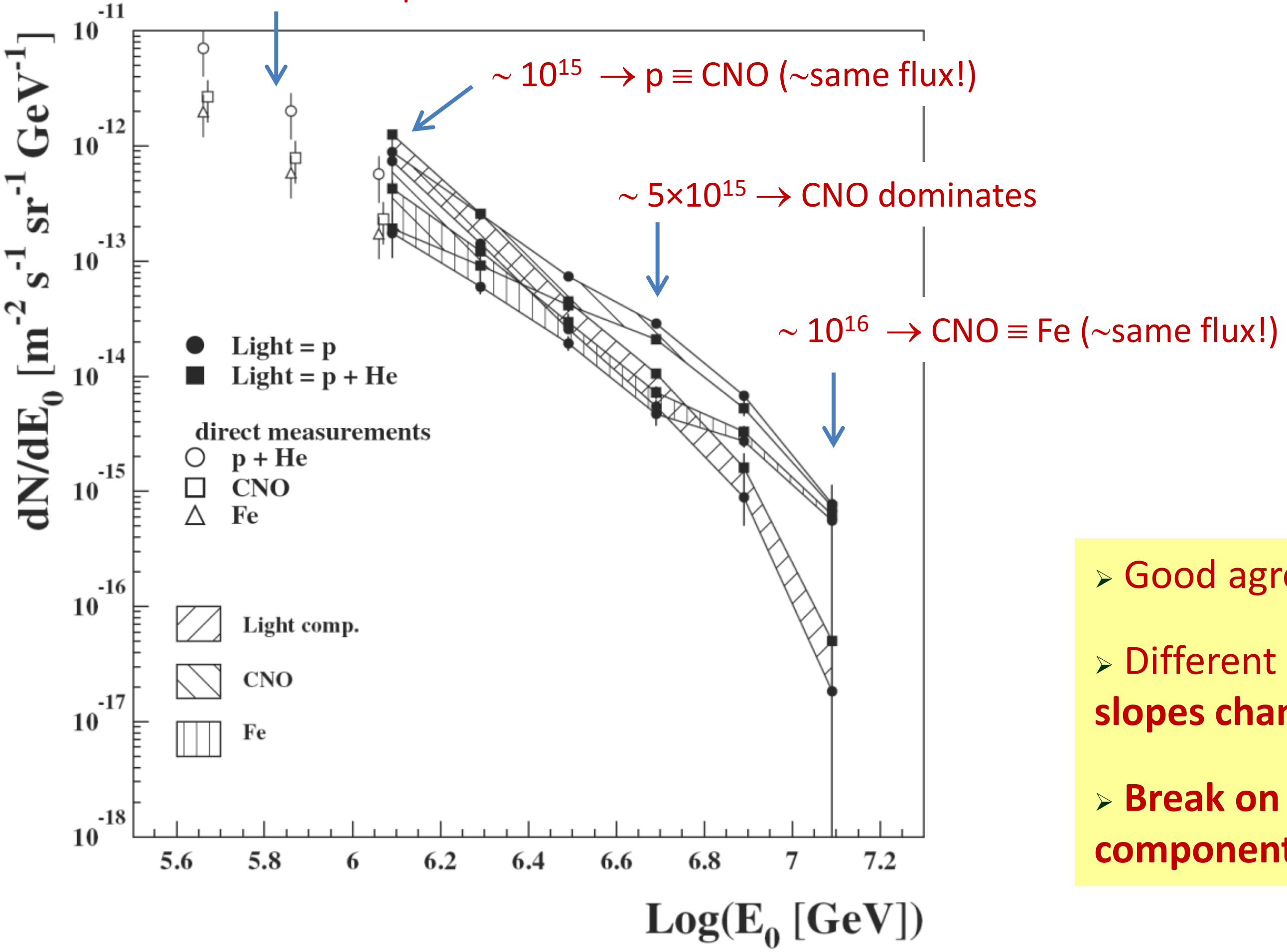
EAS–TOP

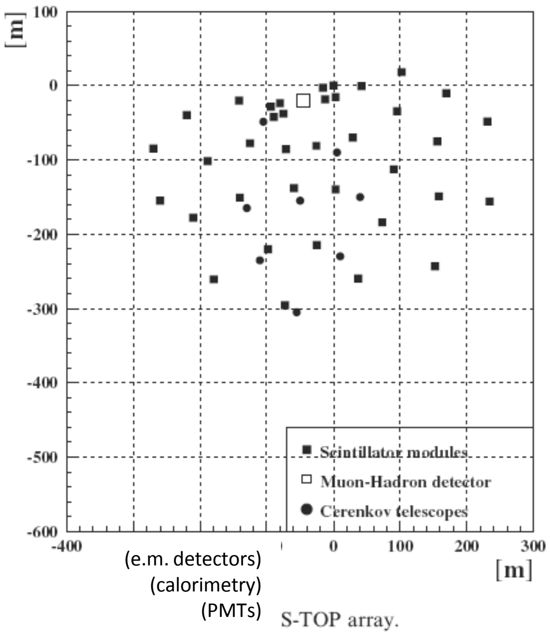
1989 – 2000

Indirect measurements in E ∈ 10^{12} – 10^{16} eV

Data divided in 3 mass groups

<10^{15} → p flux > CNO flux

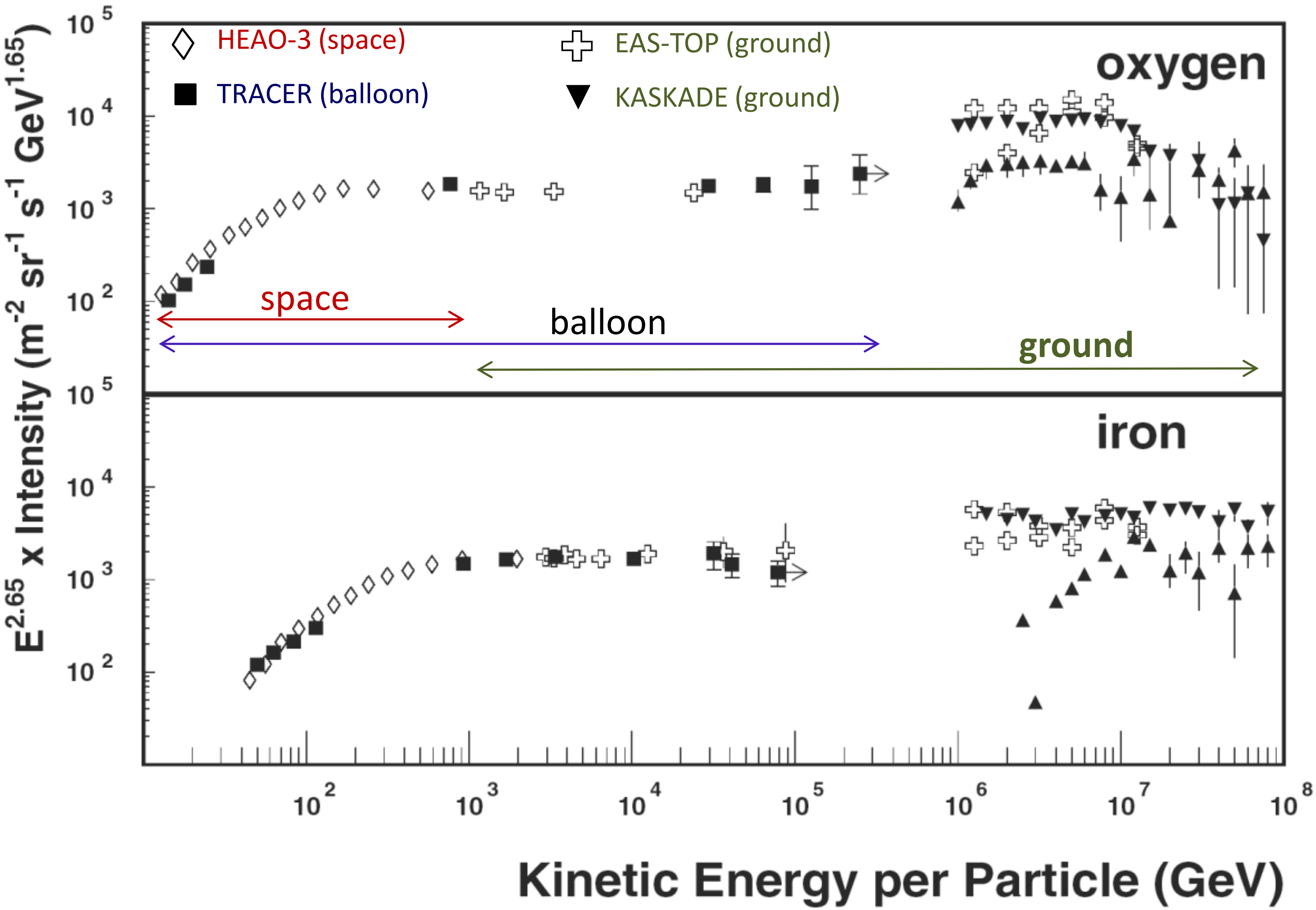




S-TOP array.

- Good agreement with low energy data
- Different spectrum for the 3 groups with **slopes changing**
- **Break on the *knee*** observed in **light components** but not in heaviest

Connection from DIRECT to SHOWER measurements



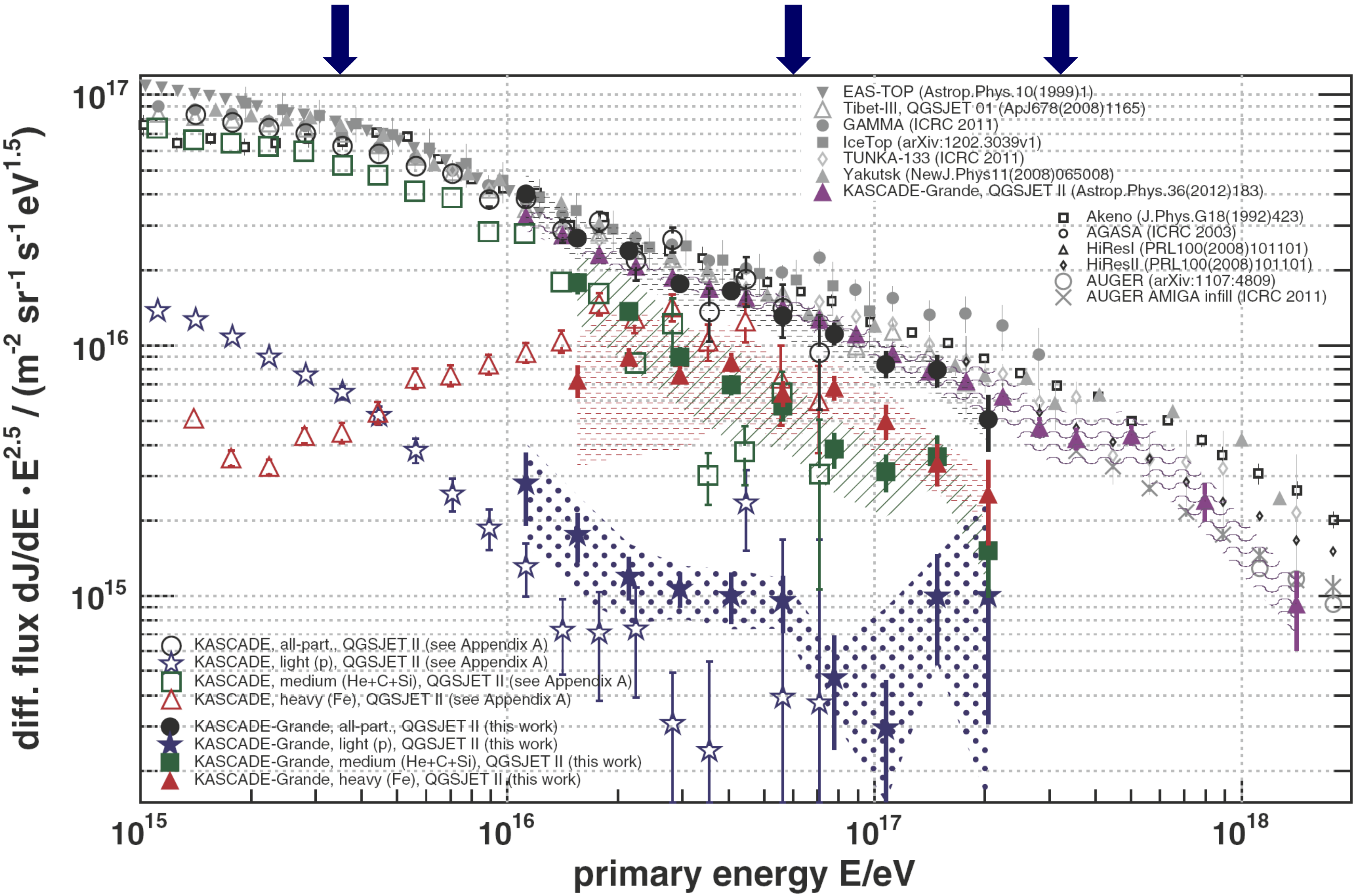
KASKADE & KASKADE-Grande

Area ~ 200×200 m²
252 stations (scintillators)
13 m spaced
E ∈ $10^{15} - 10^{17}$ eV

KASKADE –Grande →

Area ~ 700×700 m²
+ 37 stations 10 m² scintillators
>100 m spaced
E ∈ $10^{16} - 10^{18}$ eV

KASKADE & KASKADE-Grande



CRs "around the knee": SUMMARY

1. **Indirect measurements:** ground based detectors (Fluorescence, Cherenkov, Scintillators…)

2. **A good description of the all-particle spectrum found (compatible between experiments).**

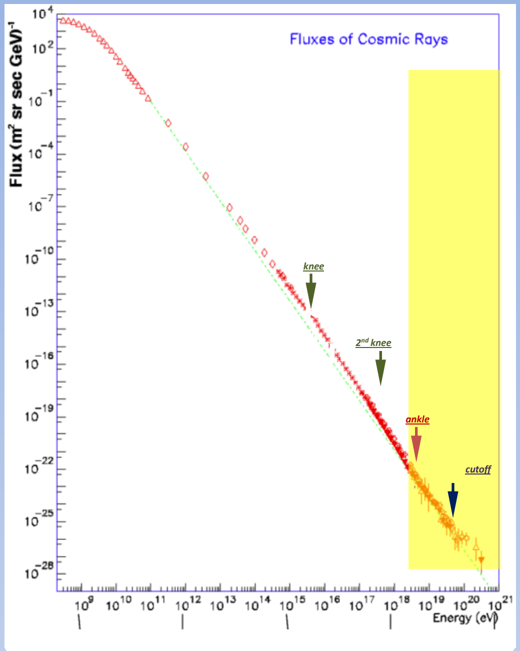
3. Data consistent with the assumption of a **rigidity** dependent change of the *knee* energy.

4. **Light** (*He* dominated) composition **at the *knee***.

5. Change towards a **heavy** composition **at higher energies**.

6. KASKADE-Grande **extends** unfolding analysis to **$E \sim 10^{18}$ eV (3 mass groups)** and Indicates **very heavy composition at $E \sim 10^{17}$ eV**.

- **At the *knee*** **$\sim 4\times10^{15}$ eV** spectral slope changes from
  $\gamma \sim 2.7$ to $\gamma \sim 3.1$ (end of Galactic "proton" flux)
- **At the 2nd *knee*** **$\sim 4\times10^{17}$ eV** **$\gamma \sim 3.1$ to $\gamma \sim 3.3$ (end of Galactic "Fe" flux)**



INDIRECT DETECTION

(FROM THE *ANKLE* TO THE *CUTOFF*)

GIANT GROUND BASED DETECTORS

The Pierre Auger Observatory

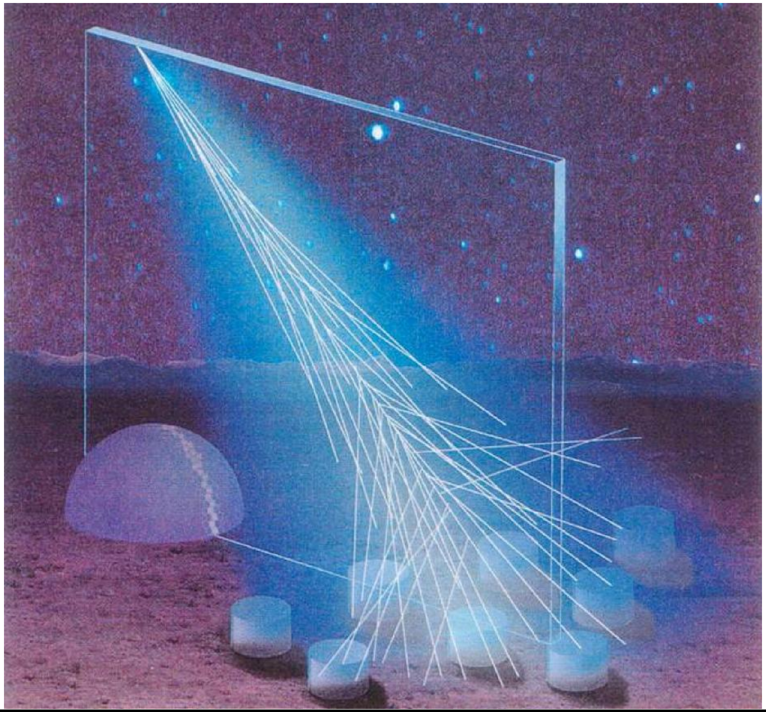
Malargüe – Argentina

(Pampa Amarilla)

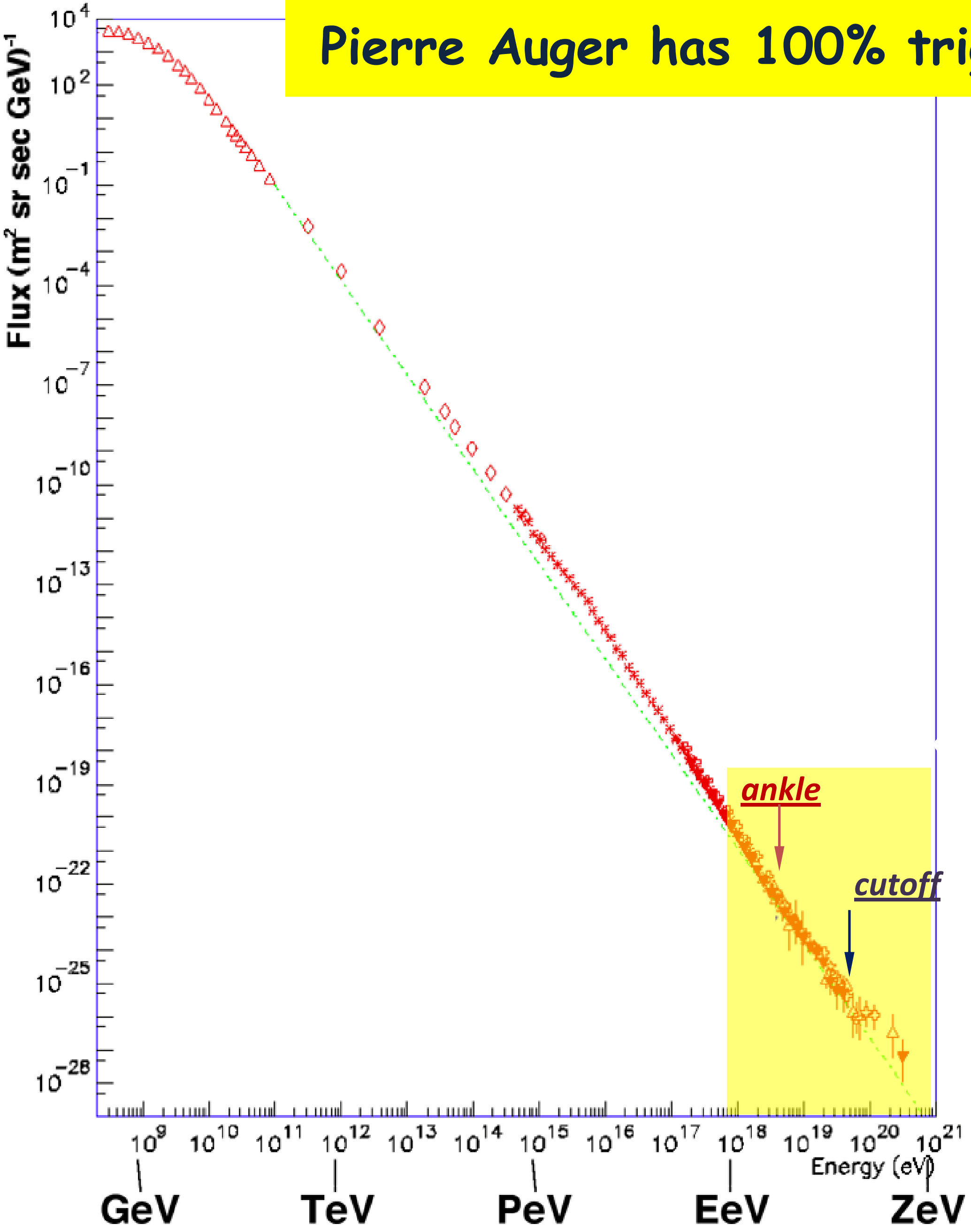
- Taking data since 2004
- Detector completed in June 2008
- ~500 members and 19 countries

Argentina, Australia, Bolivia*, Brazil, Croatia, Czech Republic, France, Germany, Italy, Mexico, Netherlands, Poland, Portugal, Romania*, Slovenia, Spain, U.K., U.S.A., Vietnam*

HYBRID detection technique

- 

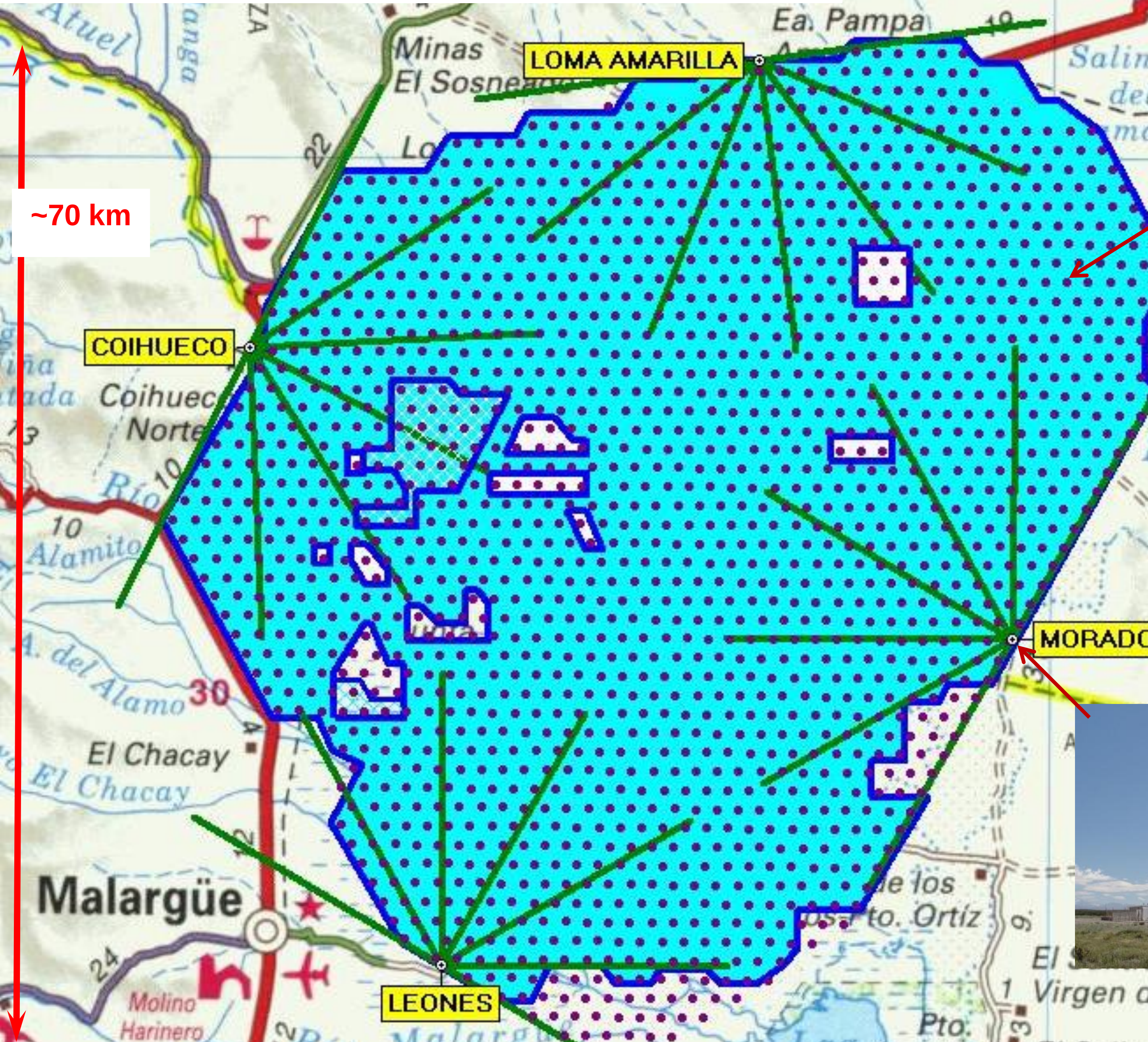
Pierre Auger has 100% trigger efficiency above 10^{18} eV

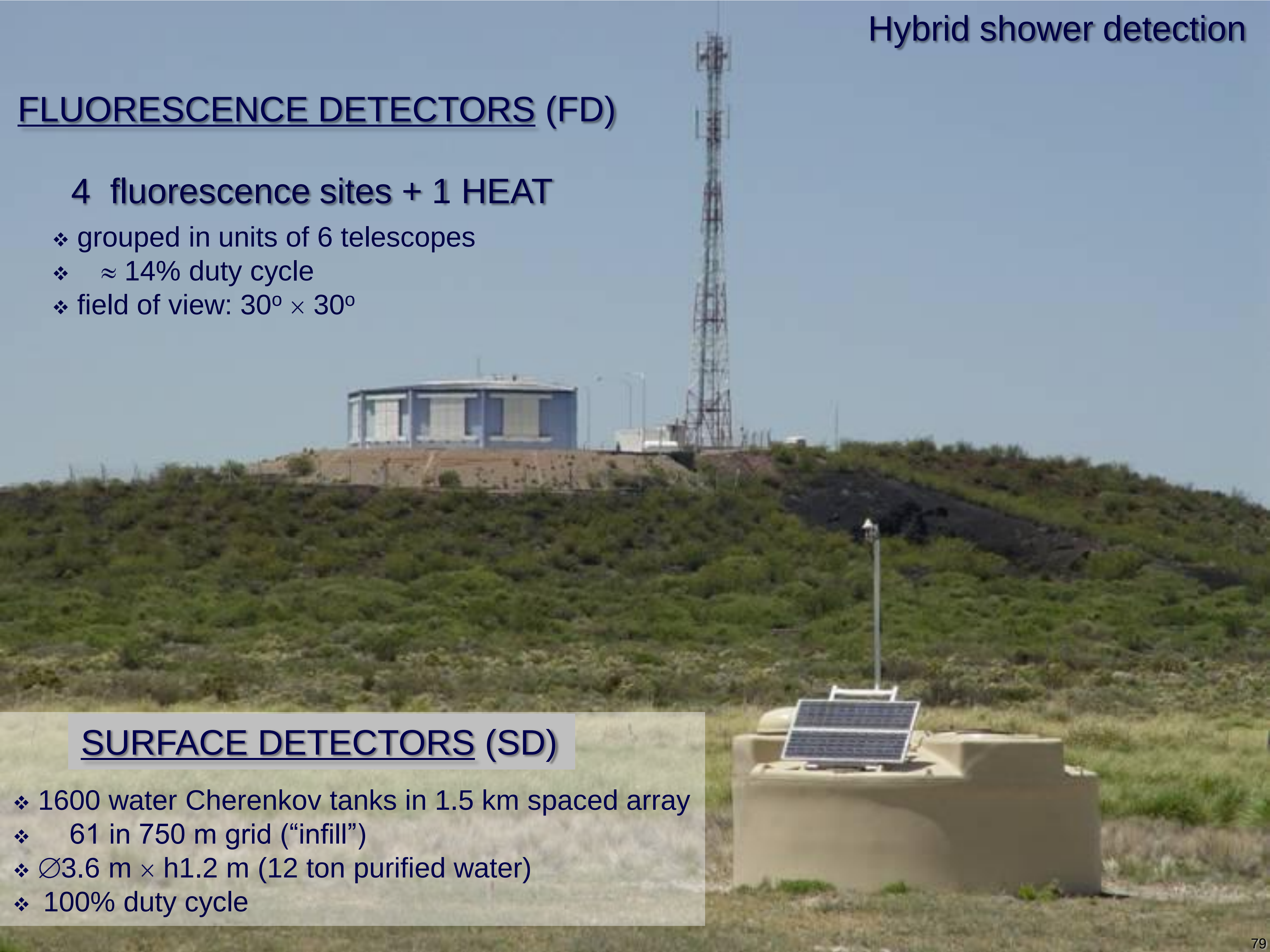


E ~ 5×10^18 γ = 2.8

E ~ 5×10^19 eV – end (*suppression*)

3000 km^2 , 1390 m altitude , 875 – 1740 g cm^{-2} (60°)





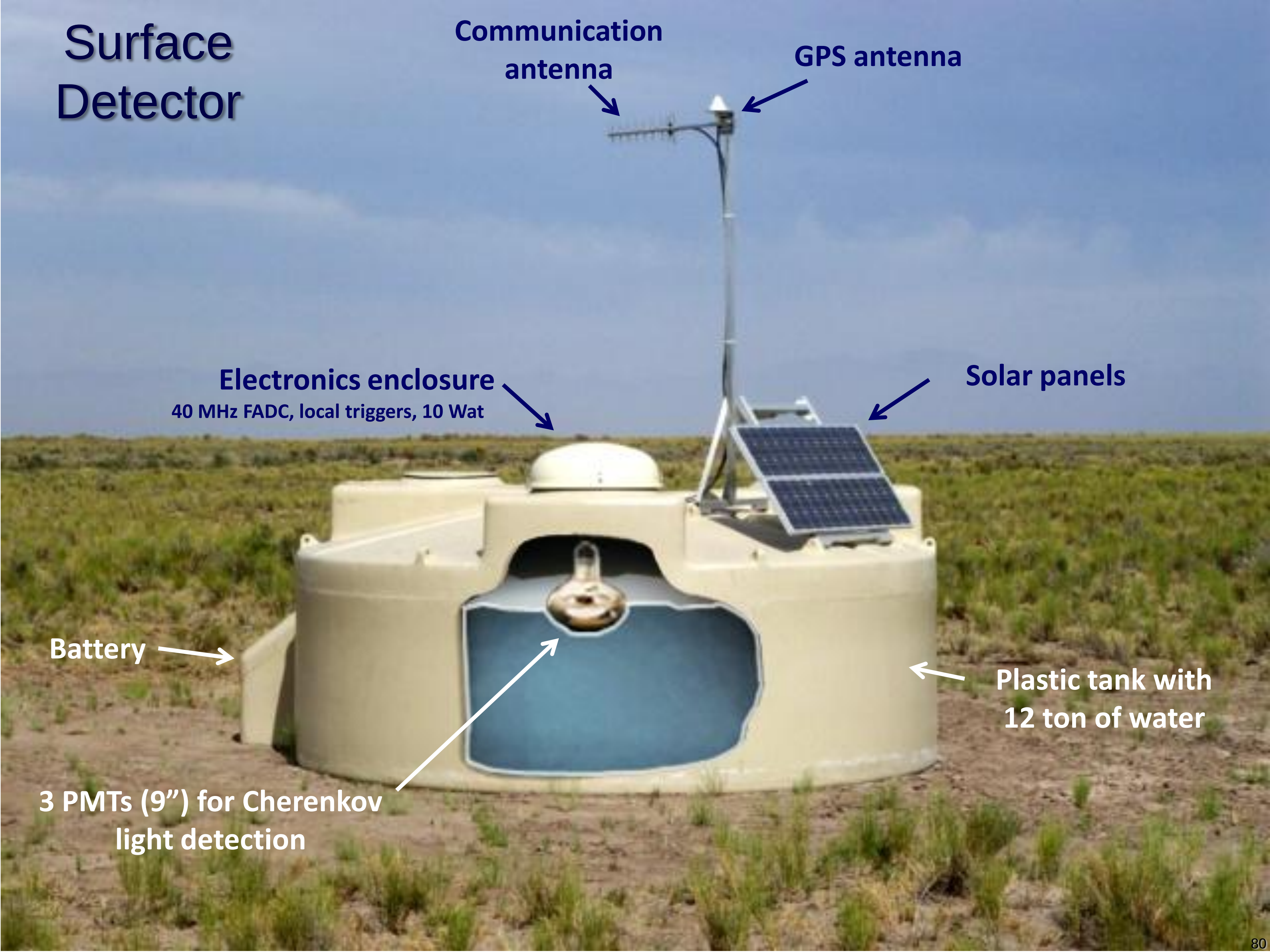
FLUORESCENCE DETECTORS (FD)

4 fluorescence sites + 1 HEAT

- grouped in units of 6 telescopes
- ≈ 14% duty cycle
- field of view: 30º × 30º

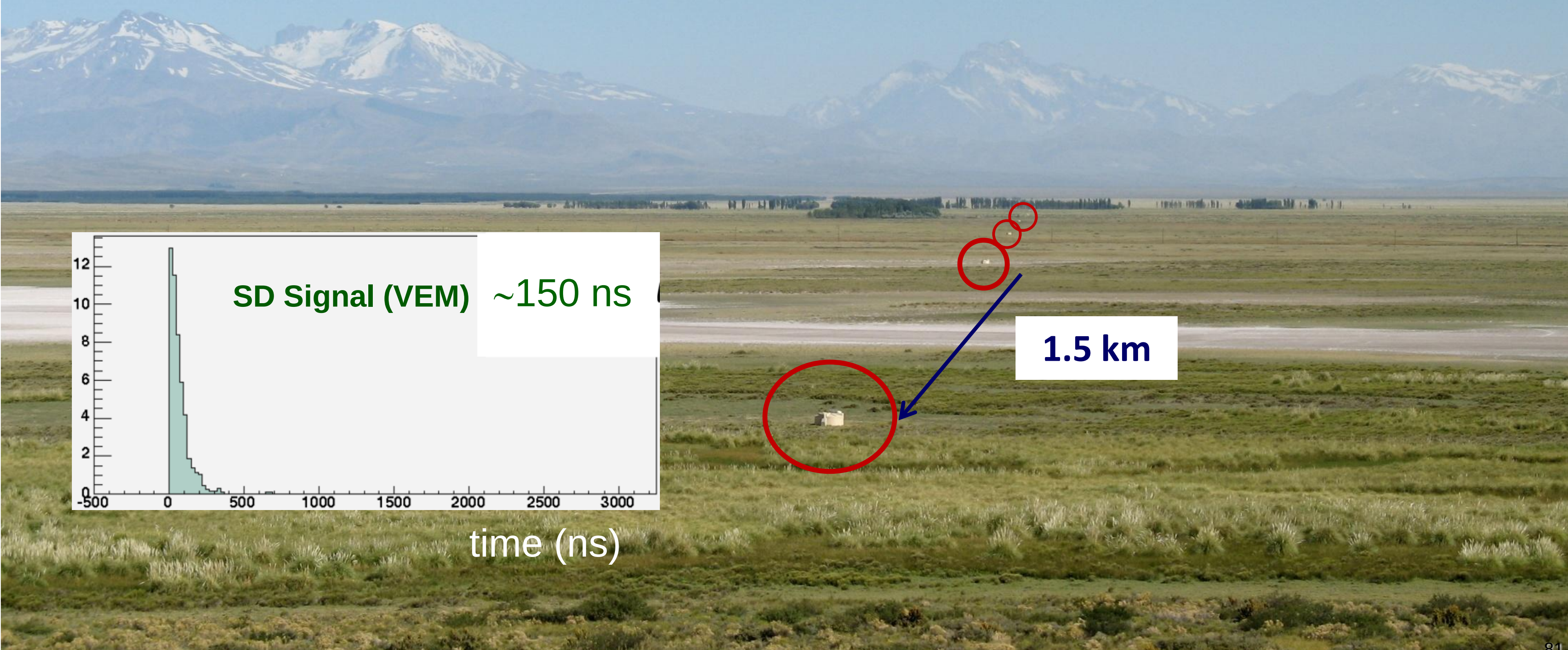
SURFACE DETECTORS (SD)

- 1600 water Cherenkov tanks in 1.5 km spaced array
- 61 in 750 m grid (“infill”)
- ∅3.6 m × h1.2 m (12 ton purified water)
- 100% duty cycle

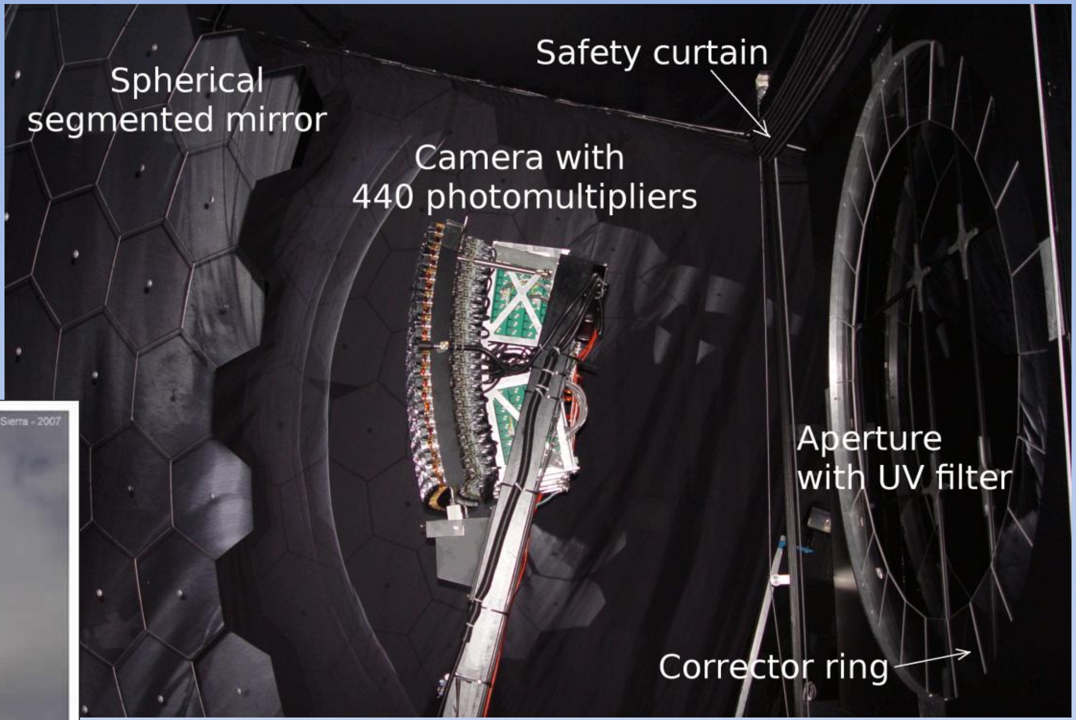


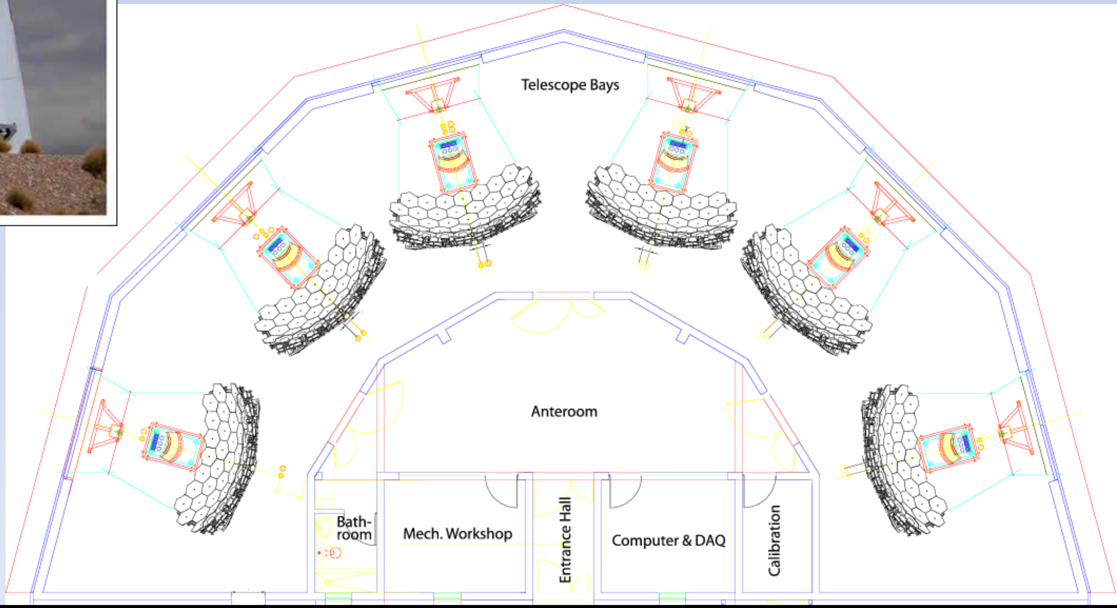
Surface Detector
Communication antenna
GPS antenna
Electronics enclosure
40 MHz FADC, local triggers, 10 Wat
Solar panels
Battery
Plastic tank with 12 ton of water
3 PMTs (9”) for Cherenkov light detection

Surface Detector array (SD)

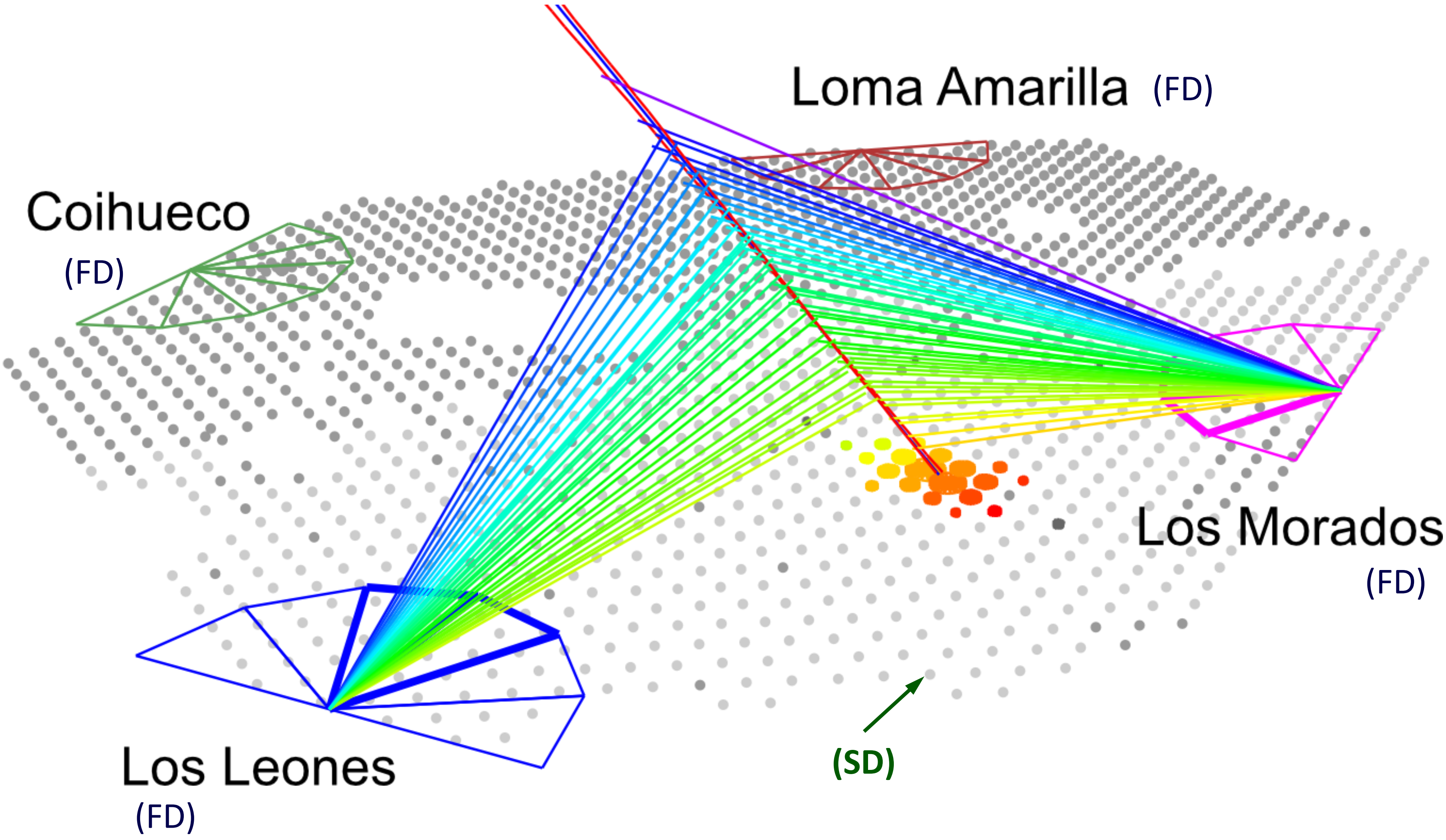


Fluorescence Detector (SD)



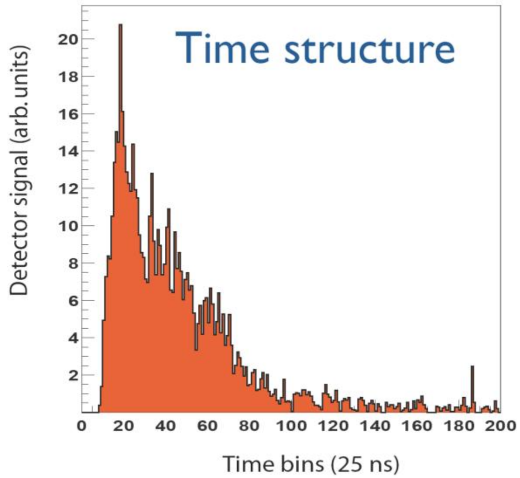


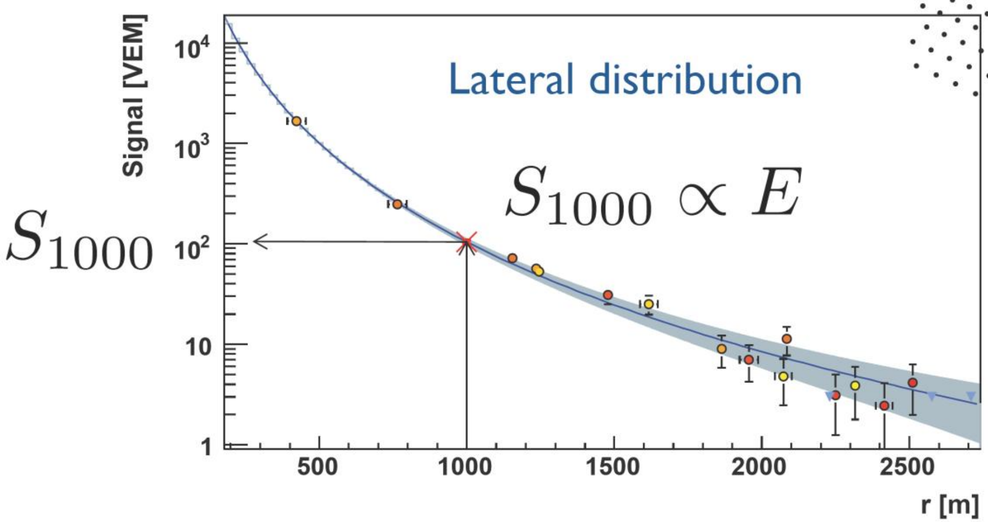
Example of “hybrid” event

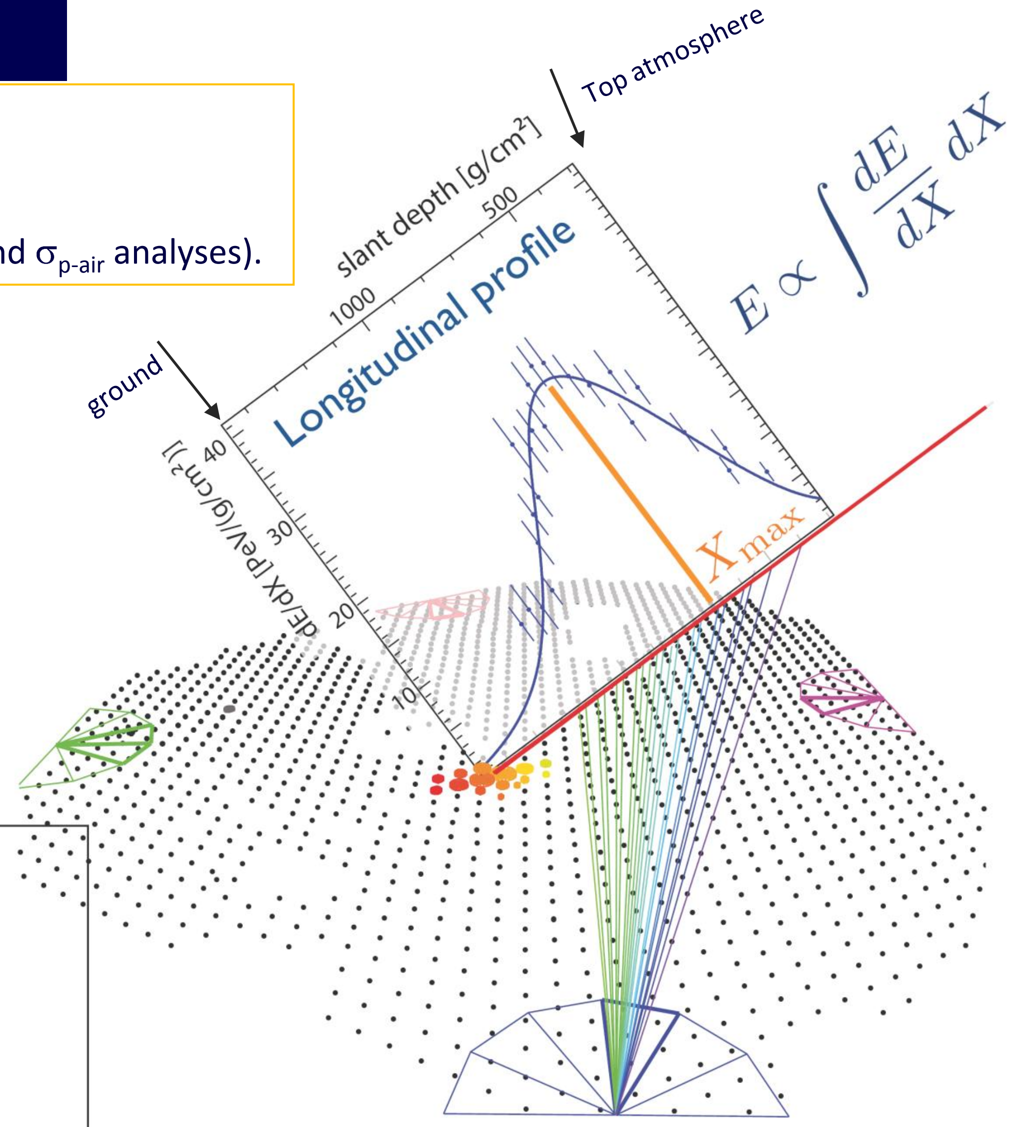


Shower Observables

Fluorescence Telescopes:
measure the shower longitudinal profile.
Calorimetric measurement of energy.
Determination of shower maximum X_{max} (primary mass and $\sigma_{p\text{-}air}$ analyses).





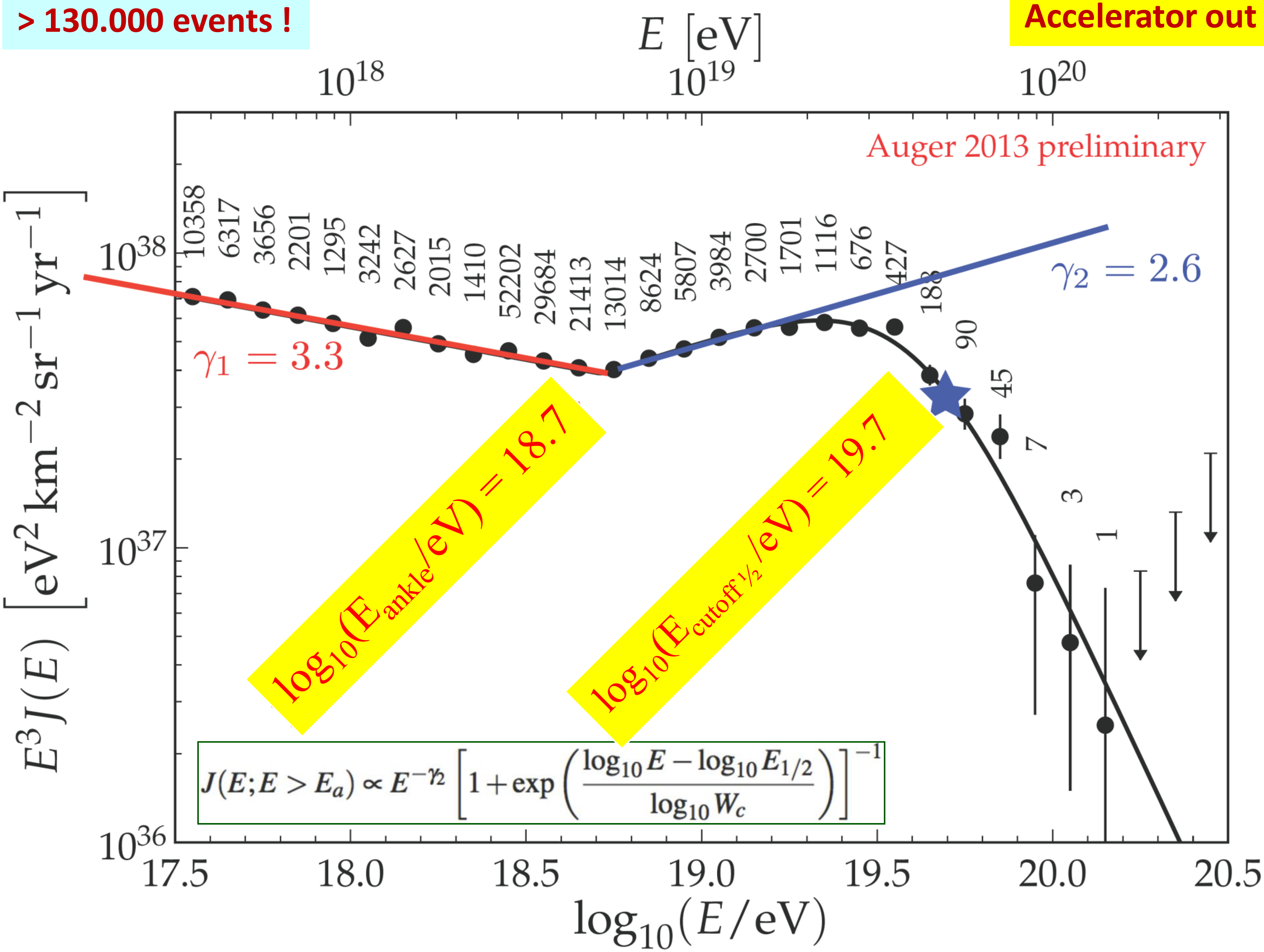


Surface Detectors:
measure the shower lateral distribution
Energy $\propto$ signal measured at 1 km from core

The Energy Spectrum

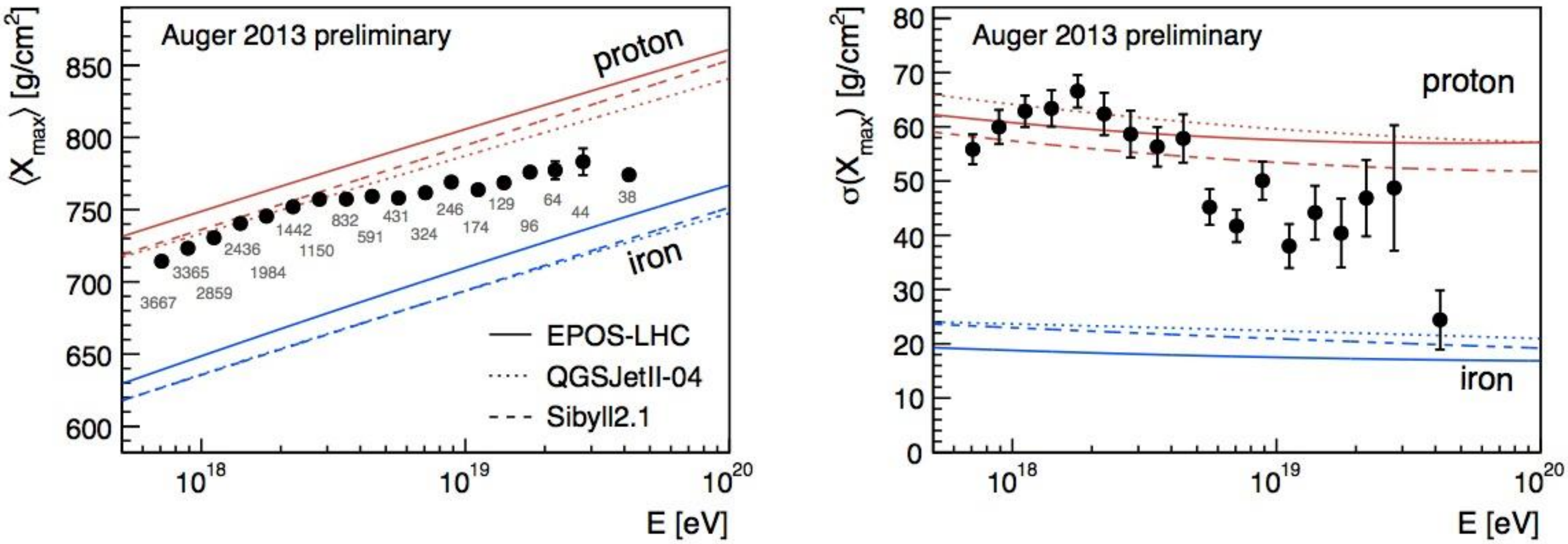
> 130.000 events !

Conclusions: ***"cutoff"***
GZK effect ?
Accelerator out of steam?



What are they ??

Single line: χ^2/ndf = 128.1/16 , p=1.15×10^{-19}
Broken line: χ^2/ndf = 10.3 /14 , p=0.74



Conclusions:

A trend towards a heavier composition at higher energies

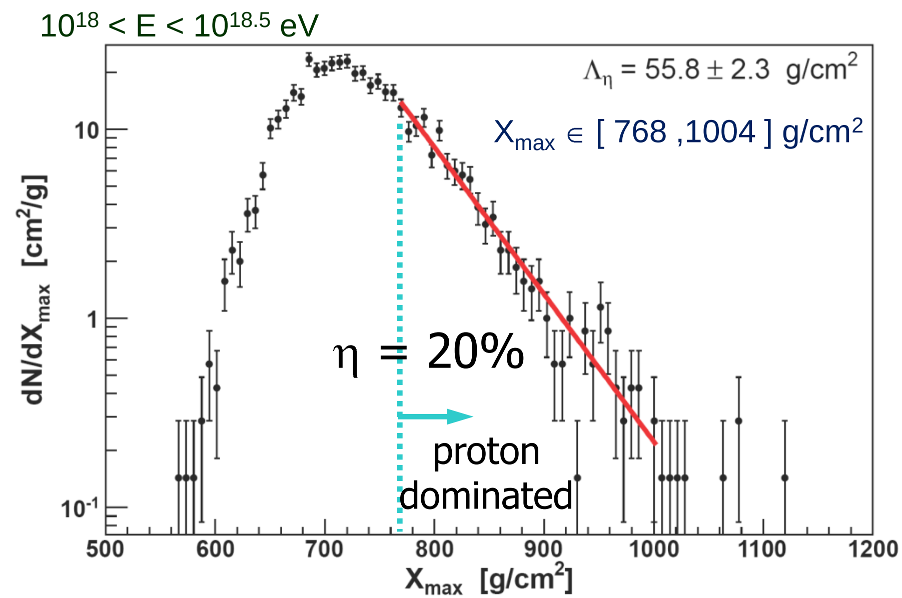
Particle Physics !

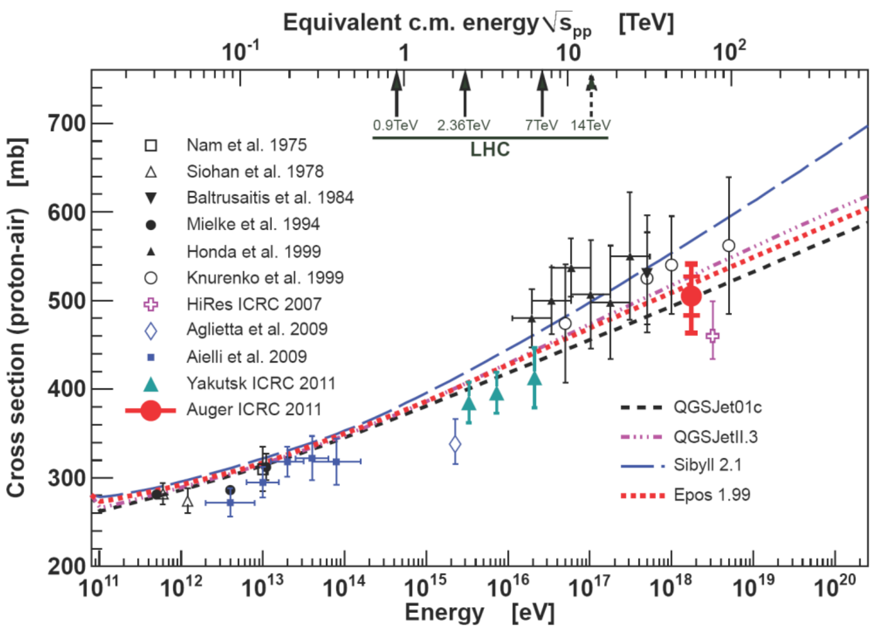
p-air cross section at $\sqrt{s}$ = 57 TeV (<E>≈1.7 EeV)

Tail of the X_{max} distribution sensitive to cross-section

$$\frac{dN}{dX_{max}} \propto \exp - \left(\frac{X_{max}}{\Lambda_\eta} \right) \qquad \sigma_{p-air} = \frac{\langle m_{air} \rangle}{\Lambda_\eta}$$

- ✓ Define Λ_η as primary observable via exponential shape
- ✓ Select a proton enriched data sample (η=20%)
- ✓ Use simulations to correlate Λ_η^{MC} with cross-section
- ✓ Λ_η^{MC} adjusted to reproduce the measured Λ_η





$$\sigma_{p-air} = (505 \pm 22\,\text{stat}\ ^{+28}_{-36}\ \text{sys})\ \text{mb}$$

Systematic uncertainties:

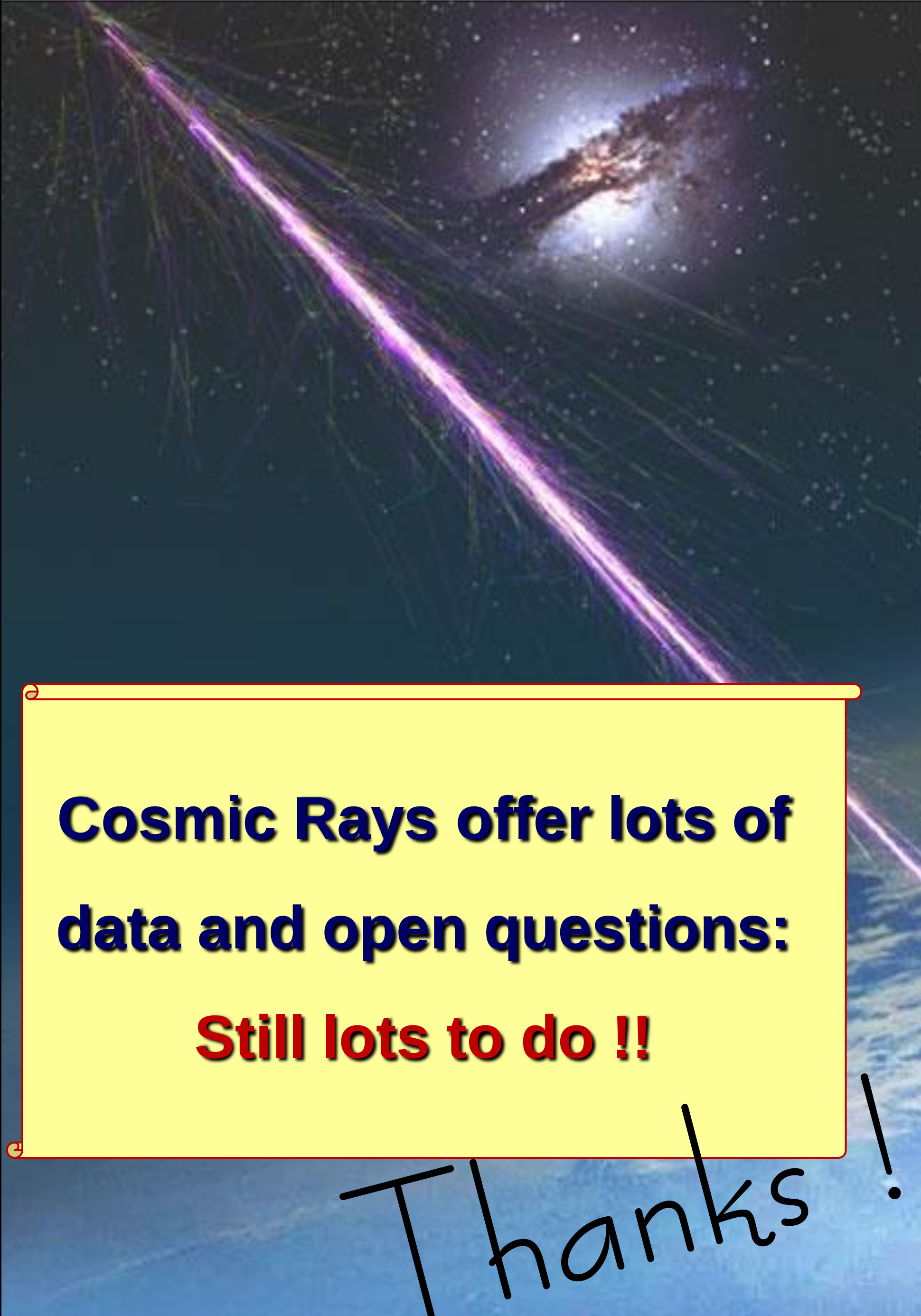
- Hadronic models
- energy scale
- simulations … total +20 mb −15 mb
- photon and helium fraction:
  - photon fraction 0.5% +10 mb
  - He fraction 25% −30 mb

CRs "end of spectrum": SUMMARY

Where do we stand ?

We observe:

- **A suppression in energy spectrum:** *GZK-effect or exhaustion of the acceleration mechanism?*
- **No GZK photons or neutrinos**
- **A trend towards a heavier composition at higher energies**
- **A weak correlation to nearby matter distribution**
- **A very isotropic sky on large scale**
- ***Particle Physics* measurements with UHECRs !**



Cosmic Rays offer lots of data and open questions:

Still lots to do !!

Thanks !

Image credit: Stan Lee / Marvel Comics