Non thermal nucleosynthesis :
on the importance of nuclear reactions in cosmic-ray astrophysics

Denis Allard - Laboratoire AstroParticule et Cosmologie (APC)

30/09/2016 - Ecole Joliot-Curie

Outline

• High energy astrophysics is multi-wavelength and multi-messenger
(what is a cosmic-ray?)

• The history of cosmic-ray physics

• The cosmic-ray spectrum - a wonder of the cosmos
(a three dimensional problematics)

• Cosmic-ray acceleration (a very simple introduction)

• What do we know about "low energy" Galactic cosmic-rays
-> the key role of light elements nucleosynthesis

• Very high and ultra-high energy cosmic-ray

• Extragalactic cosmic-rays phenomenology
-> the key role of nuclei photo-interactions

• Main results at ultra-high energy (UHE composition)

• Open questions and conclusions

High energy astrophysics is multi-wavelength and multi-messenger

During the second half the 20th century multiwavelength astronomy developed rapidly and allowed to discover many new extraordinary astrophysical objects, some of them were totally unexpected

➡ pulsars

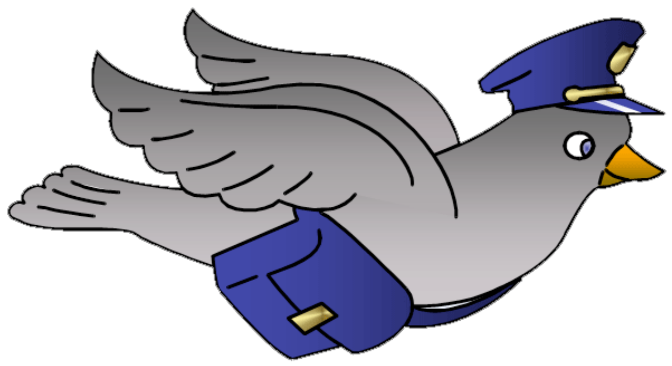
➡ Active galactic nuclei

➡ accretion phenomena

➡ gamma-ray bursts

➡ star-forming galaxies

➡ solar systems in formation



Fantastic progress in the knowledge of the universe. However modern high-energy astrophysics is more than multiwavelength photon astronomy. It is a multimessenger science

Besides photons there are different astrophysical “messengers” starting with cosmic-rays (discovered a century ago). Neutrino astronomy and gravitational wave astronomy have just emerged in the past years. These messengers are of different natures and each of them are expected to provide a new window on the universe.

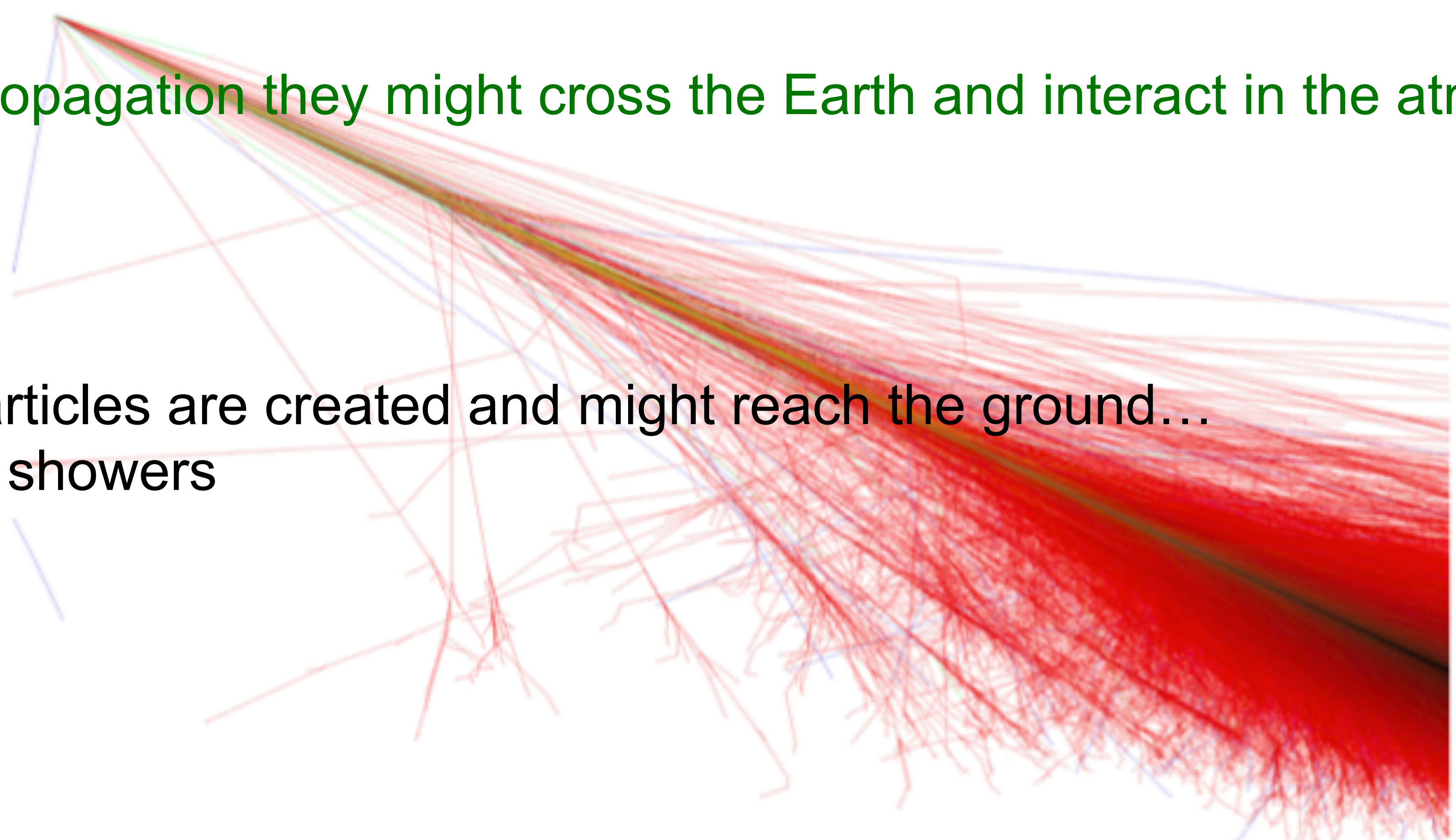
What is a cosmic-ray ?

★ High energy particles “traveling” throughout the Galaxy and even throughout the intergalactic space

★ They are Atomic Nuclei : Protons plus other nuclei and some electrons with various energies
(Helium, Carbon, Oxygene, Iron, mostly very small abundances of heavier nuclei)

★ During their propagation they might cross the Earth and interact in the atmosphere

★ Secondary particles are created and might reach the ground…
---> extensive air showers



History of cosmic-ray physics : a few milestones

- Charged electroscope : the arms repel each other

- The air is partially ionized due to some ionizing radiation => charges on the electroscope are evacuated when the electroscope is in contact with air

- 1785: Coulomb notices the spontaneous discharge of electroscopes and understands it is due to the air

- Confirmed by Faraday

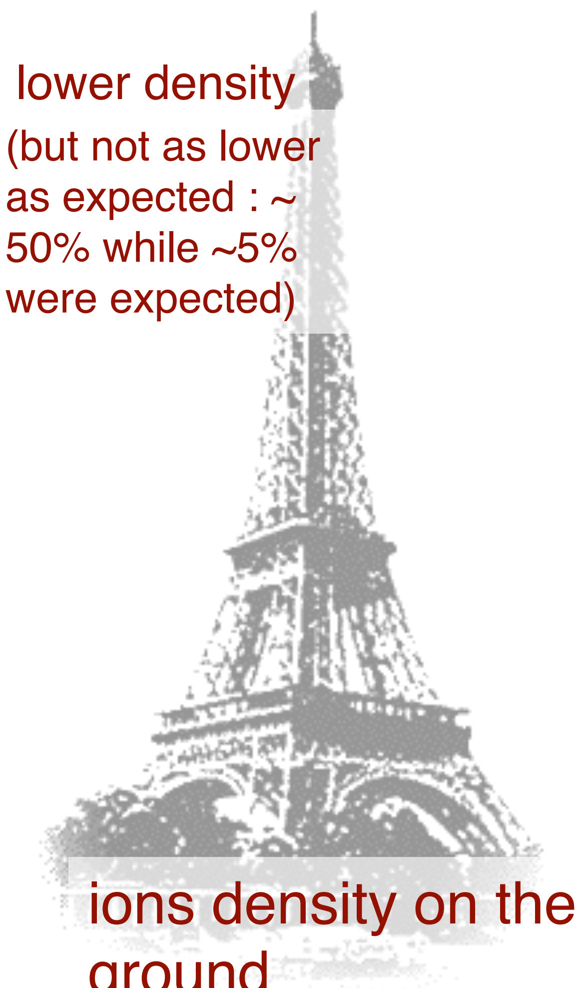
History of cosmic-ray physics : a few milestones

End of the XIXth century, radioactivity is discovered by Becquerel

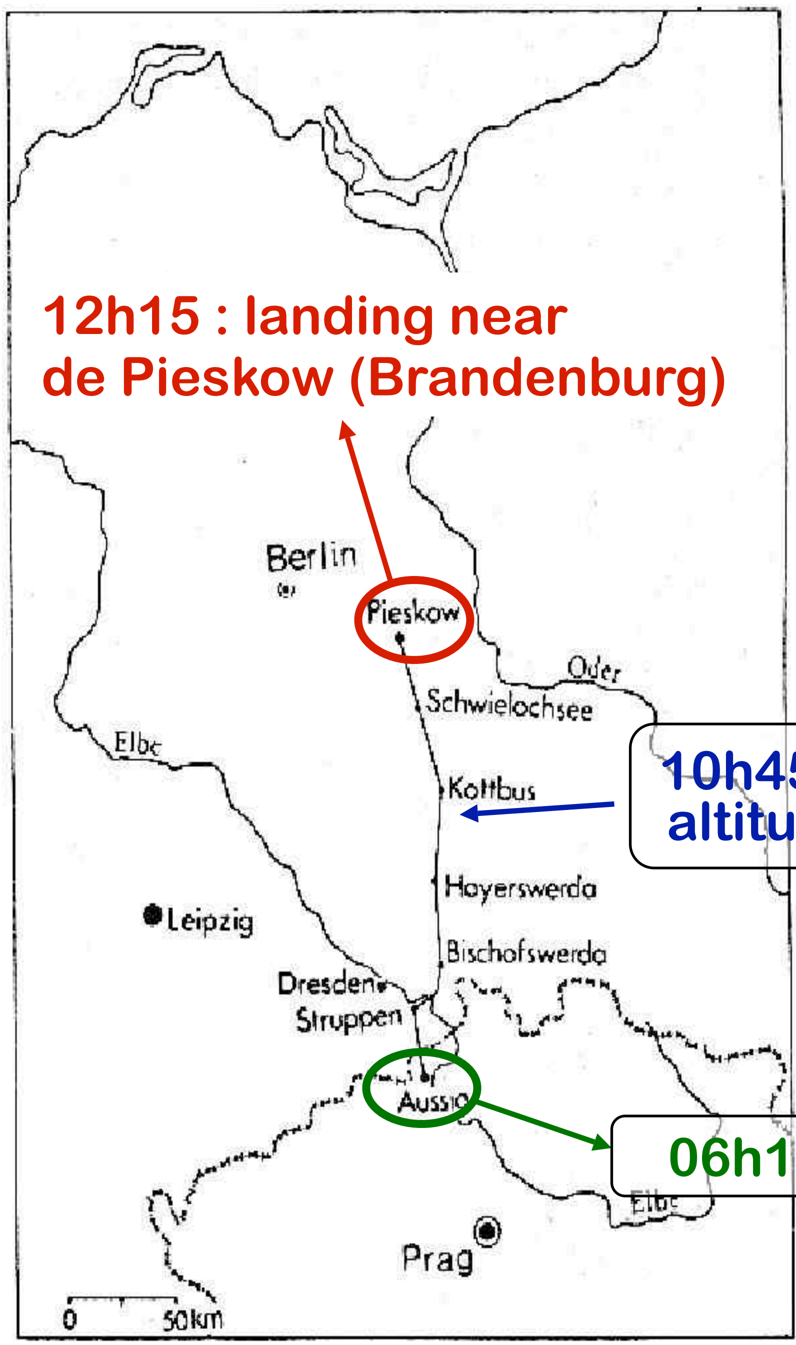
- 1901: Wilson measured the discharge of electroscopes underground : identical to what measured at ground level

➡ Rutherford showed that the ionization of the atmosphere at ground level is mostly due to natural radioactivity

- 1910: Theodore Wulf (jesuit priest and amateur physicist expert in the conception of very precise electroscopes) takes measurements on top of the Eiffel tower



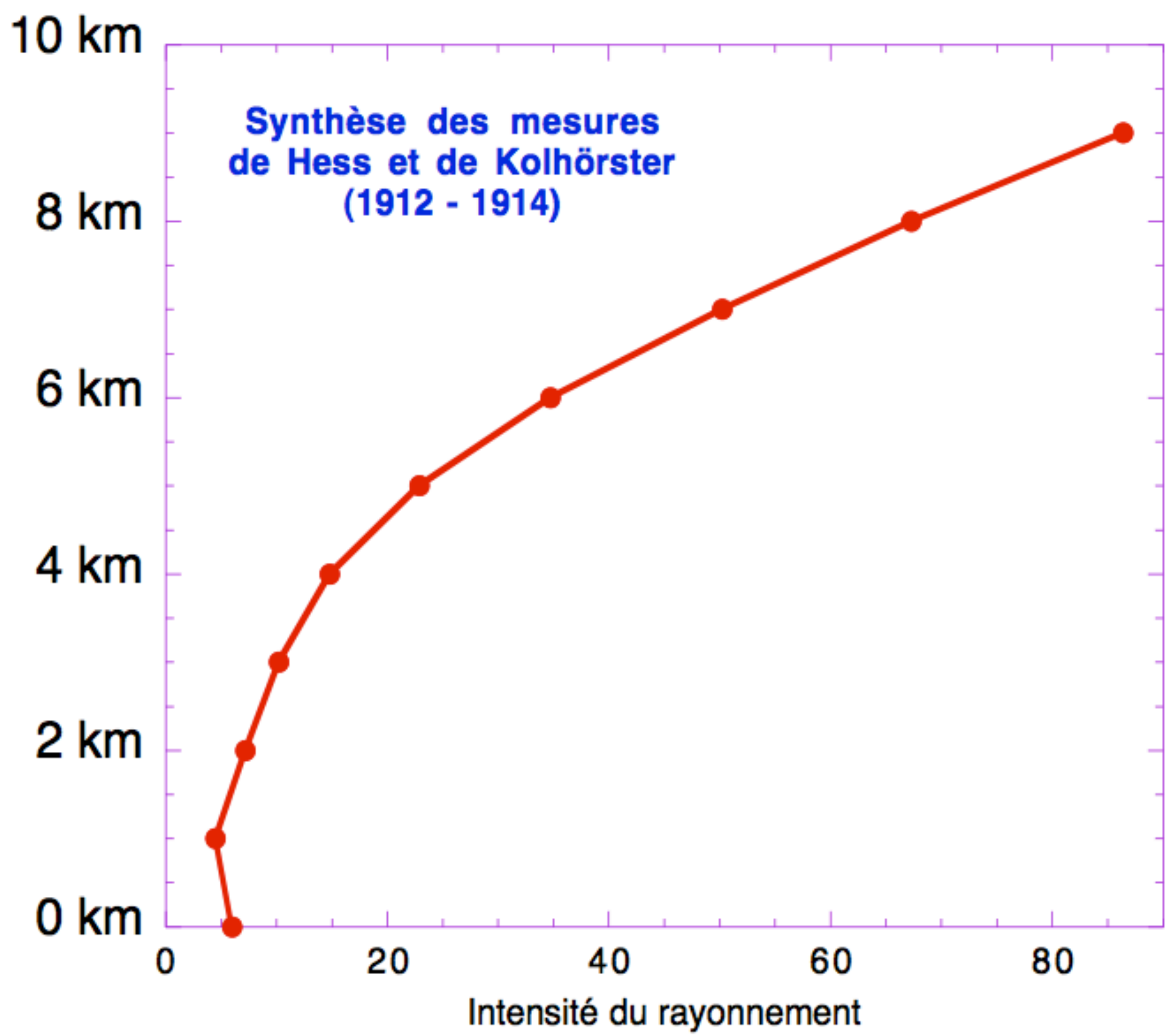
Hess Balloon flights - flight of August 7, 1912



Route des Entdeckungsfluges der kosmischen Strahlung.

Hess bei Ballonlandung (1912).

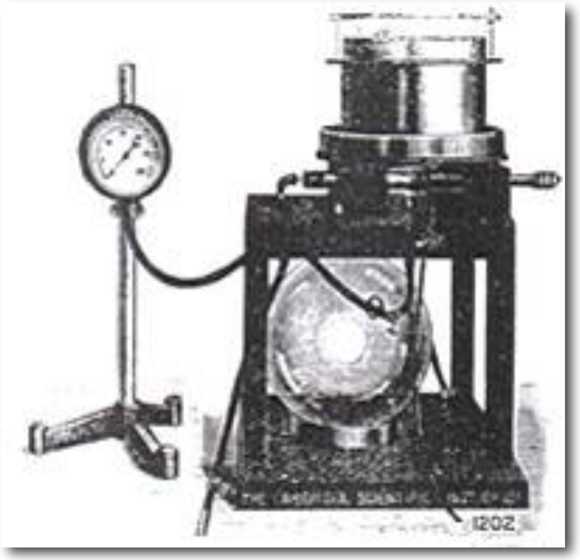
Summary of balloon measurements



15 years of confusion!

✦Light ? Matter ? From 1912 to 1929, the situation remains confuse.

✦Robert Millikan things that Hess ionizing particles are very high energy gamma-rays (1925 : « cosmic-rays »).

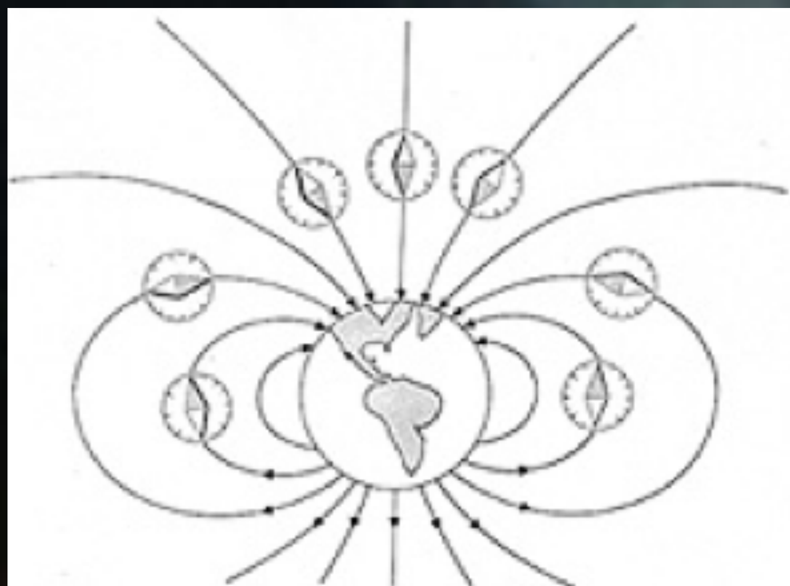


• Problem : the nature of the particles is unknown, particle detectors are not mature yet (Geiger counters and cloud chambers have only been invented invented a few years earlier)!

• Only access to secondary particles

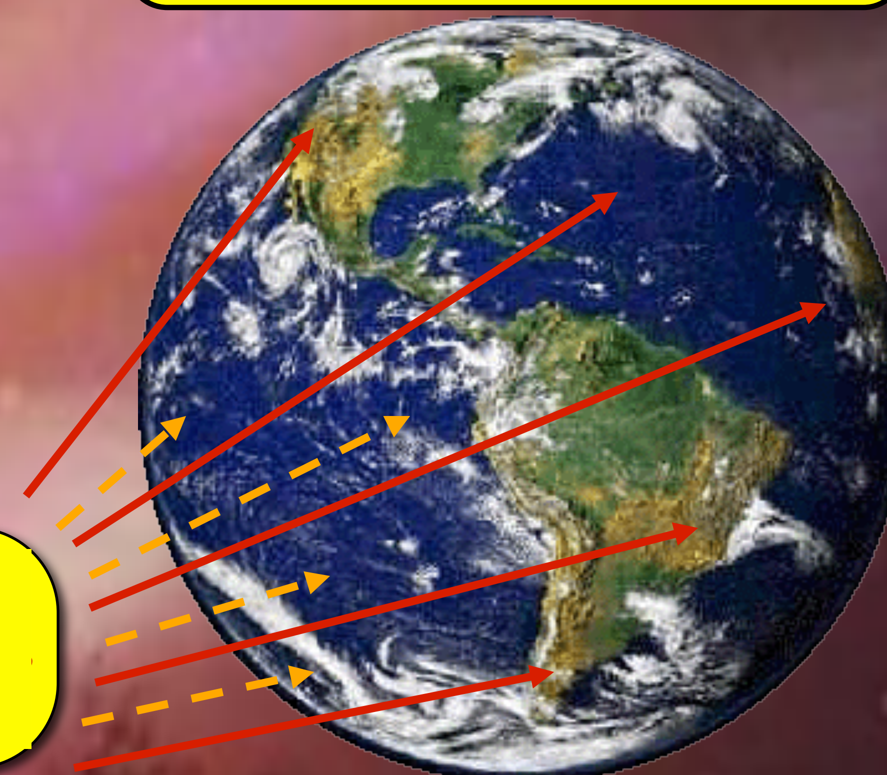
• 1929 : Several experimental setups showed the presence of charged particles among the ionizing radiation
D. Skobeltzyn working with cloud chambers and magnets finds ---> that the detected particles are curved by magnetic fields ---> at least a fraction of the ionizing particles are charged

What about primary cosmic-rays!



Latitude effect
(first observed by Clay
in 1928)

1930 : Compton's famous
series of expeditions



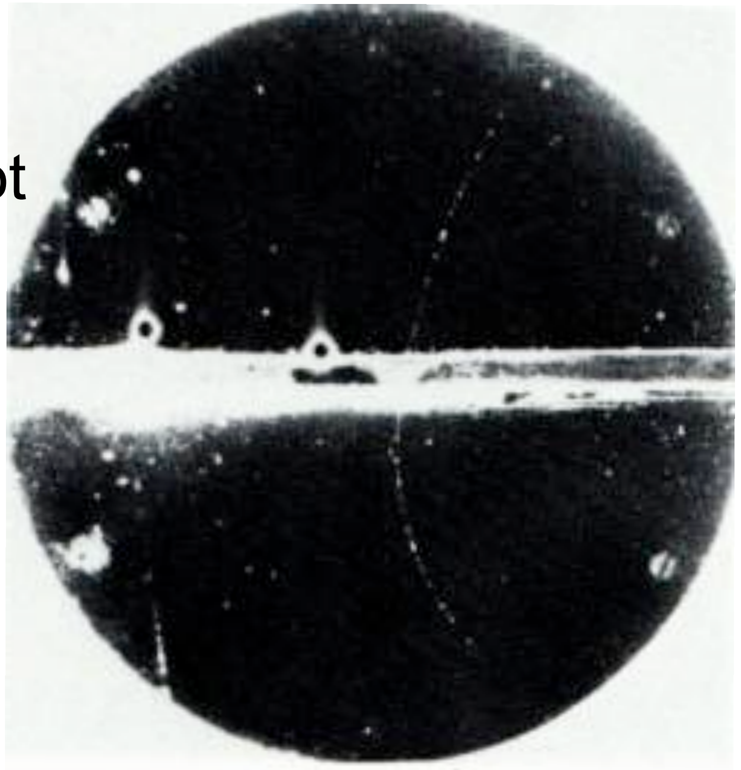
60 physicists
around the world

The full series of measurements shows evidence for a variation of the flux with the latitude

➡ Primary cosmic-rays are charged particles !!

Cosmic-rays and particle physics

Well before the dawn of accelerators, experimental particle physics started with the observation of secondary particles, a lot of unknown particles have been discovered !

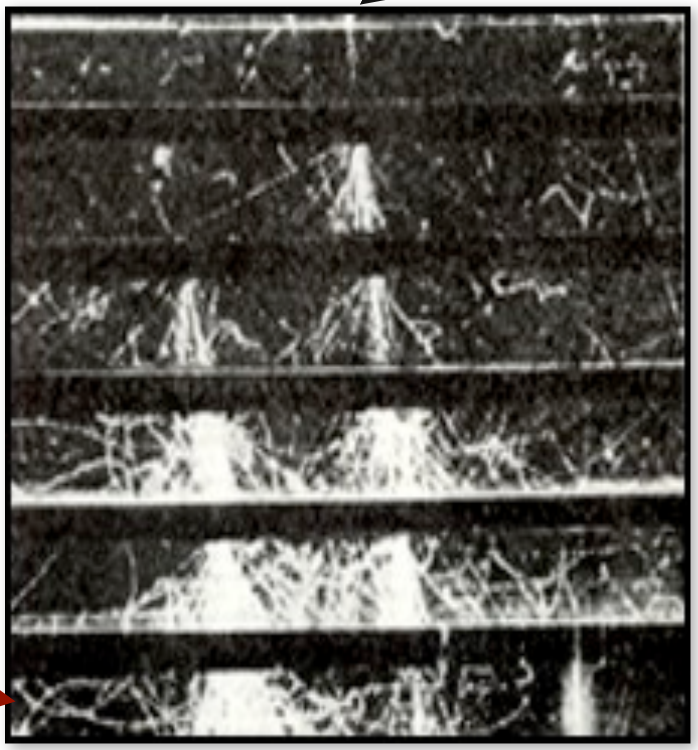


- 1932: Anderson discovers the positron (anti-electron, predicted in 1930 by Dirac) in cosmic-ray tracks

  1936: Neddermeyer et Anderson discover the muon

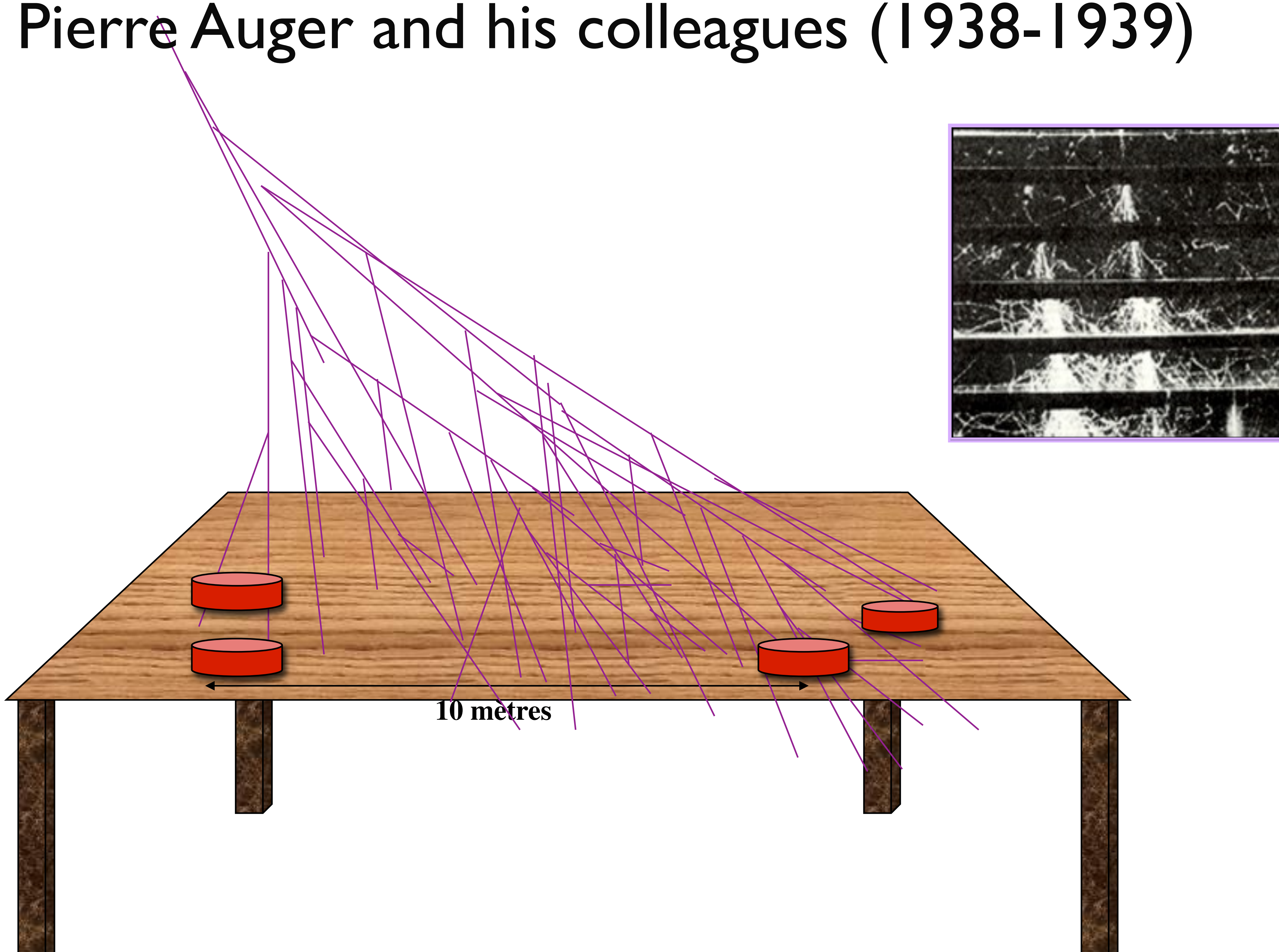
- 1947: Powel discovers the pion (predicted by Yukawa in 1936)

+ discovery of strange particles, etc...



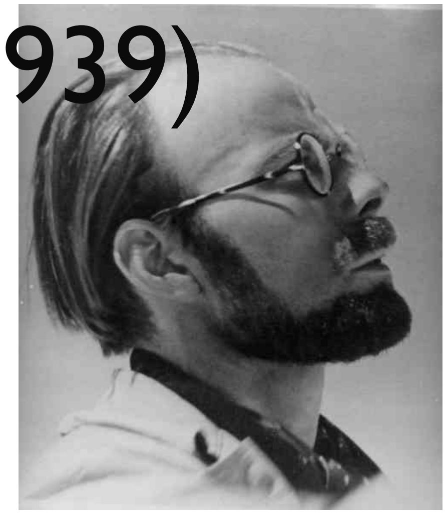
Observation of showers (cascades) of particles

Experimental discovery of extensive air showers by Pierre Auger and his colleagues (1938-1939)



Pierre Auger and his colleagues used temporal coincidences between detectors separated by increasing distances : 2 then 5 then 10... then 100m

Experimental discovery of extensive air showers by Pierre Auger and his colleagues (1938-1939)



- progresses of electronics allow for the first time to study coincidences at the microsecond scale
- ➡ low probability for random coincdences

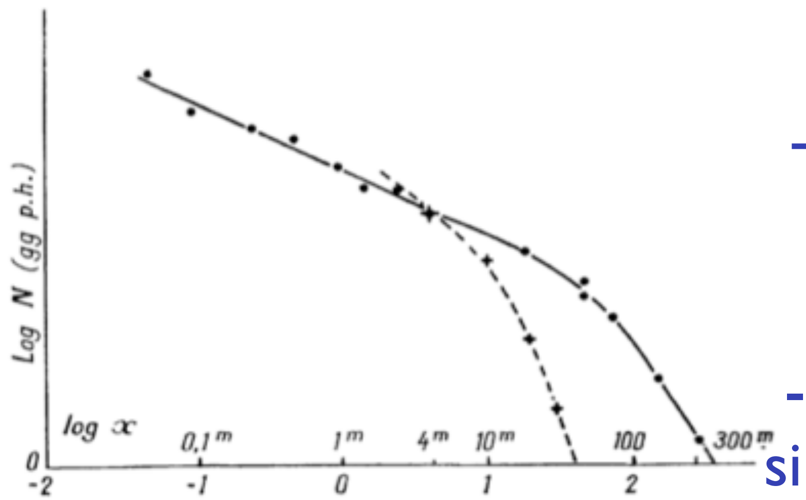
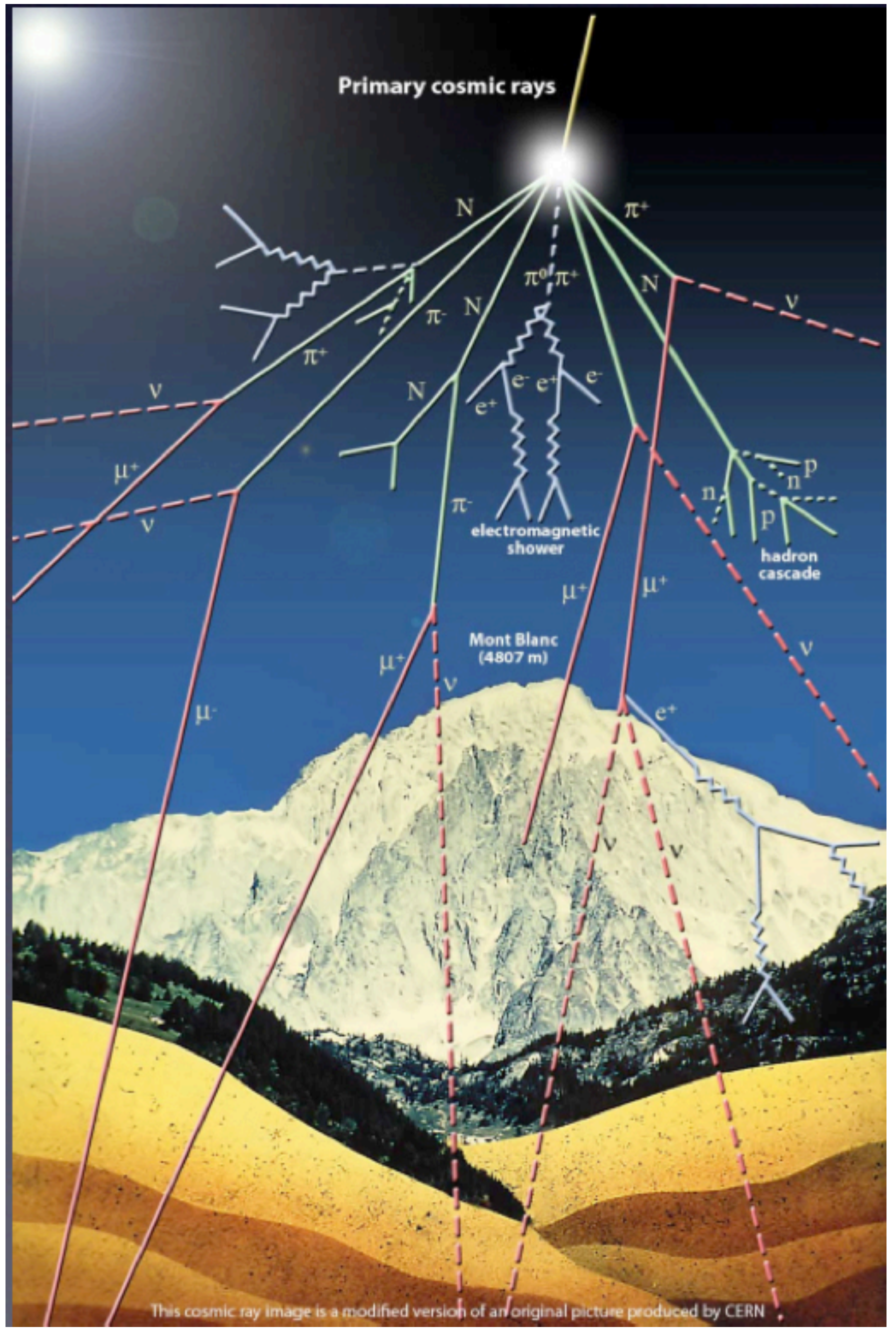


Fig. 14. — Décroissance du nombre N des gerbes atmosphériques avec l'écartement X des compteurs. Coordonnées logarithmiques (- - - calcul.)

The number of coincidences is well above the background of random events
-> particles triggering the detectors simultaneously have a common origin



- The excess of coincidence proves that air showers exist
- The ionizing particles are secondary particles
- Coincidences are observed for detector separations >100 m corresponds to primary cosmic-ray energies > 10^{15} eV

1953 : the schism

• important distinction :

★ Cosmic-rays : very energetic charged particles (mostly protons and nuclei from He to Fe and a small fraction of electrons) -> cosmic messengers -> targets for astrophysicists

★ Secondary particles : created by the interaction of cosmic-rays with the atmosphere -> targets for particle physicists

• After 1953, particle physicists left the study of secondary particles and turned to “artificial” accelerators (conference of Bagnères de Bigorre)

• Cosmic-rays started to be studied by astrophysicists as cosmic messengers

Cosmic-rays as astrophysical messengers

4 cosmic-rays / cm^2 / second

1 kg/yr << 40 000 tons/yr (meteorites)

⇒ new astronomy !

≠ multi-wavelength astronomy

→ Mass spectrum

3 key observables to understand the origin of cosmic-rays

1. **Angular spectrum** → Arrival directions

2. **Energy spectrum** → Flux as a function of the energy

3. **Mass spectrum** → composition

"A new astronomy" with cosmic-rays?

Yes !

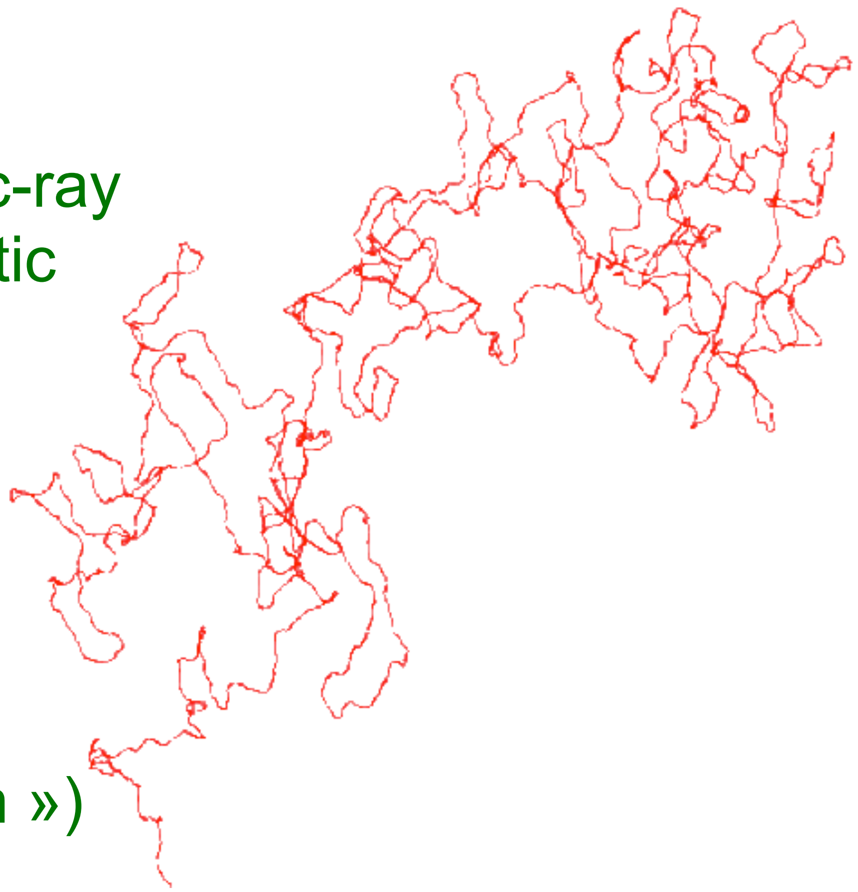
detection of extra-terrestrial matter and even extra-galactic !

No !

No source pointing, unfortunately !

Charged particle + magnetic = deflexion !

Trajectory of a cosmic-ray in the galactic magnetic field



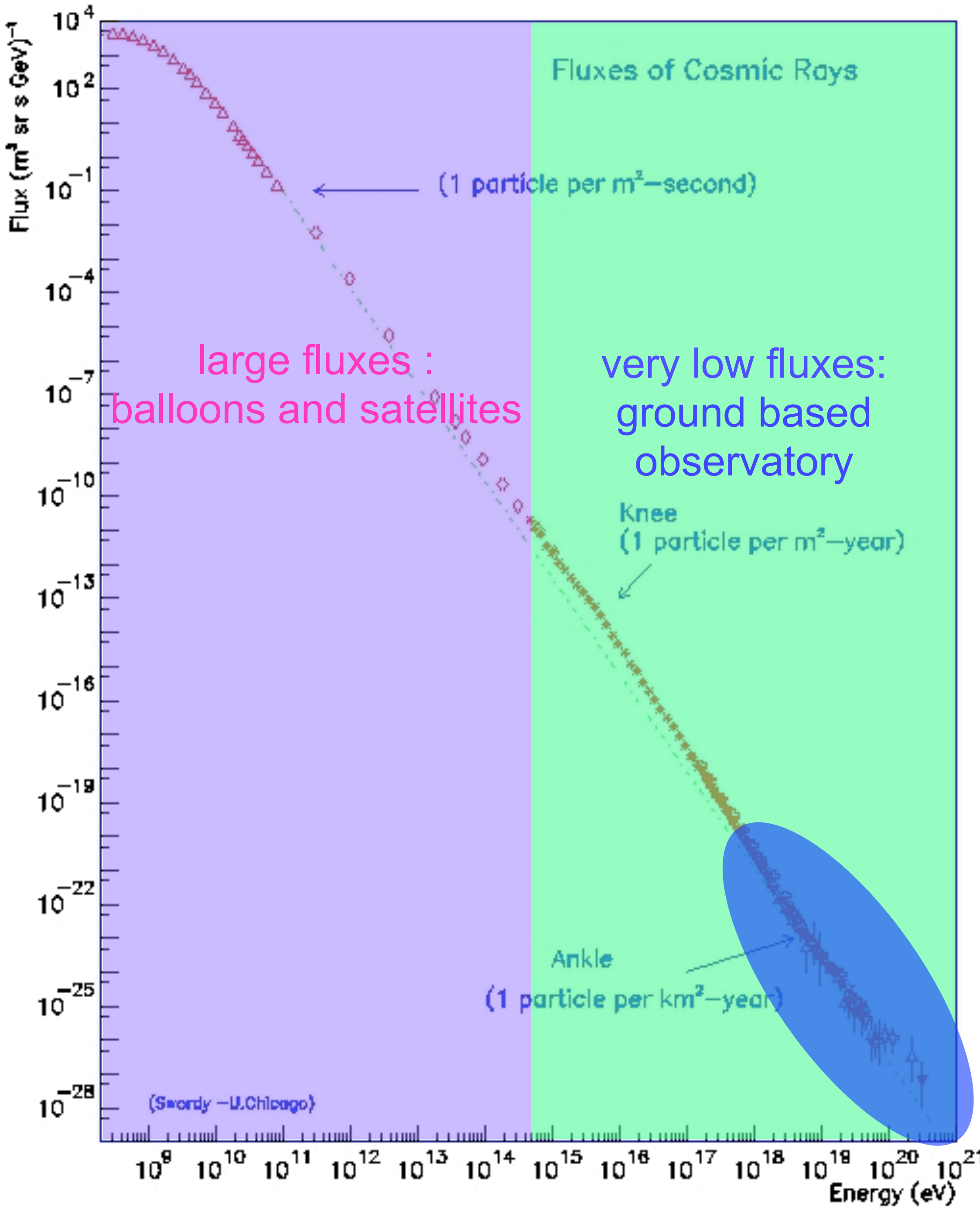
(« isotropization »)

→ Impossible to infer the direction of the source

→ no astronomy !

→ Cosmic-ray sources are still unknown !

The cosmic-ray spectrum (a wonder of the cosmos)



Extraordinary regularity over 12 orders of magnitude in energy and 32 in flux
-> a common kind of mechanism must be at the origin of cosmic-rays at all energies

Strong energy evolution of the flux
1 part/m^2/s at 10^{10} eV
<1 part/km^2/century at 10^{20} eV
-> different detectors are used in different energy ranges

$E<10^{14}$ eV :
direct detection in space or at very high altitude in the atmosphere

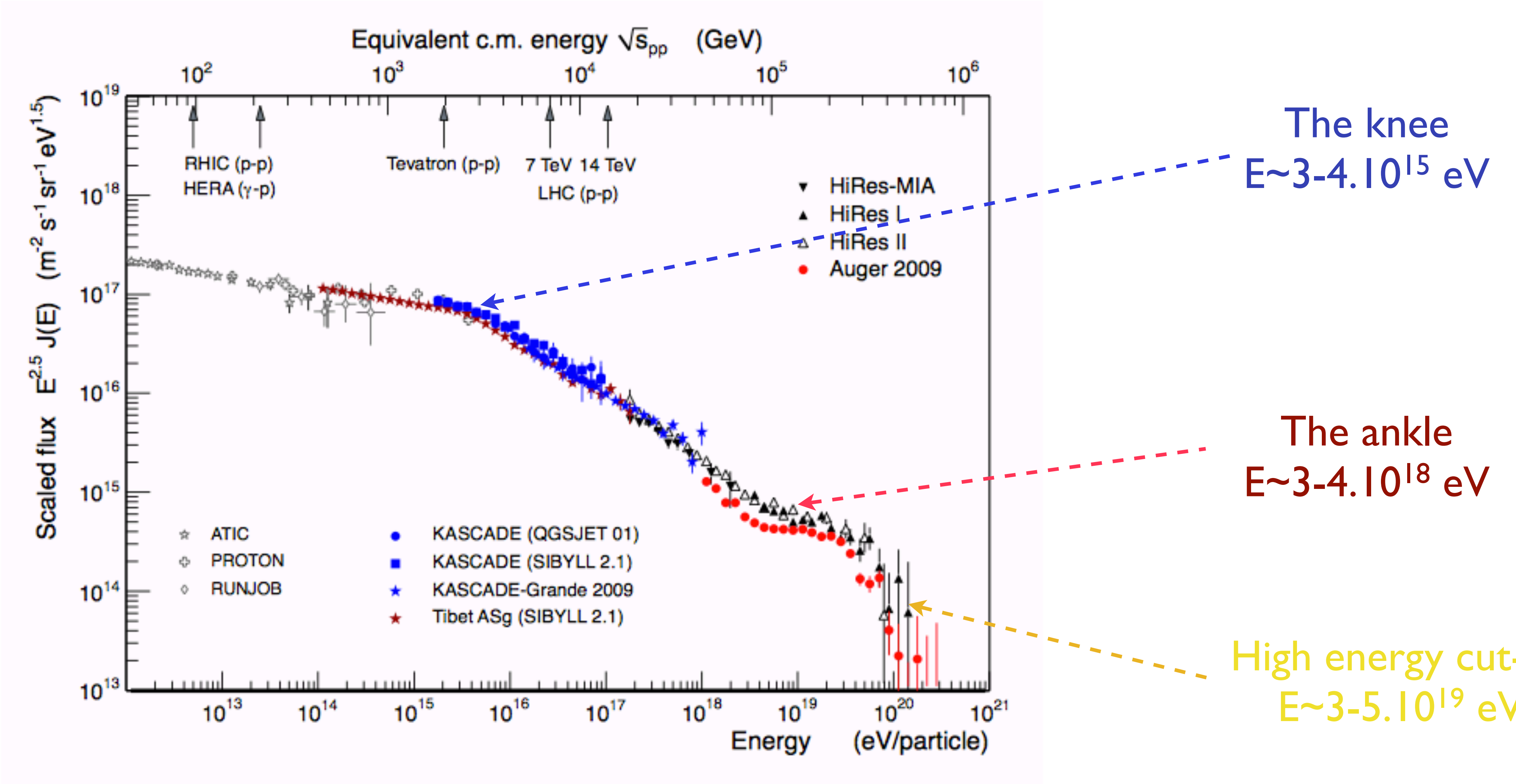
$E>10^{14}$ eV :
indirect detection from the ground (detection and reconstruction of extensive air showers)

Not only 10^{15} eV cosmic-ray exist (100 times LHC), but some of them reach more than 10^{20} eV !!

The highest energy cosmic-rays are extraordinarily rare, but how are they produced ?

➡ They are accelerated in astrophysical sources

Another view of the spectrum : some imperfections key for our understanding



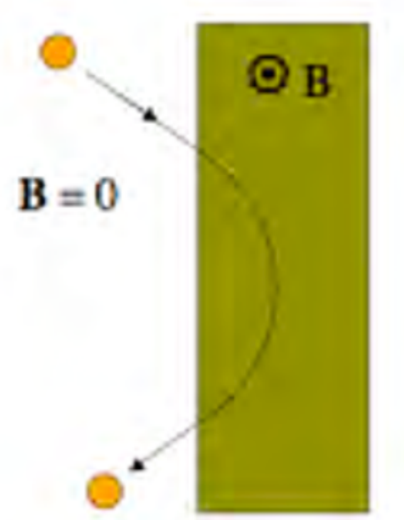
Pierog, 2012

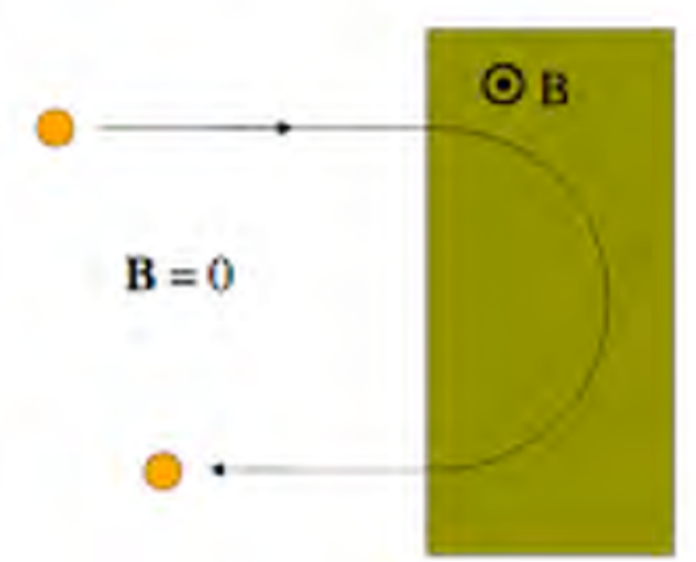
The understanding of the origin of the knee and the ankle is crucial for the global understanding of cosmic-rays

How to accelerate cosmic-rays?

- Cosmic-rays are charged particles, it is highly likely that electromagnetic fields present in many astrophysical objects are responsible for the acceleration process

- In 1949, Enrico Fermi proposed a mechanism allowing to accelerate nuclei and electrons and to produce power law spectra
--> original scenario : reflection of charged particles by moving magnetic clouds
(gas clouds in motion in the Galaxy carrying a magnetic field larger than in the average galactic medium)

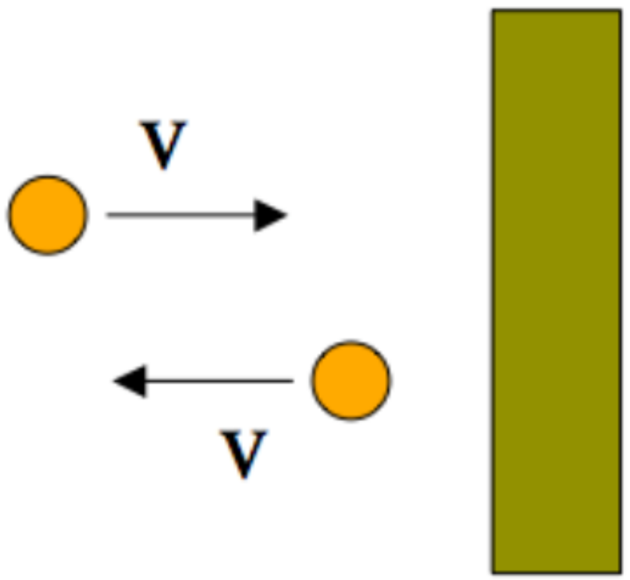




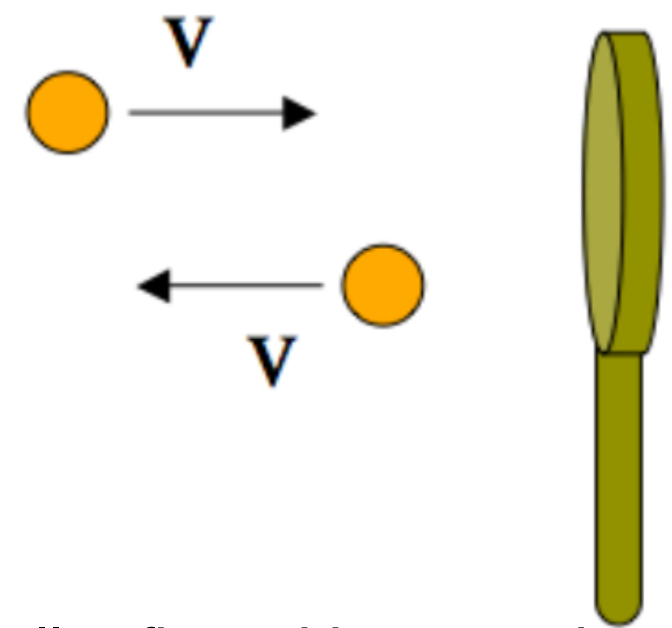
Charged particles can be reflected by “magnetic clouds”

if the cloud is at rest, the energy is conserved

Idealized tennistic analogy!

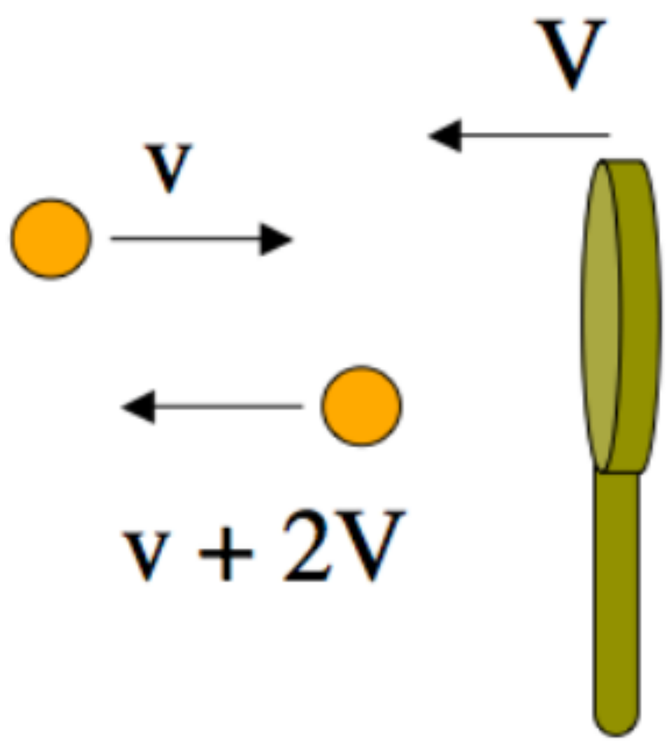


Ball reflected by a wall



Ball reflected by a steady racquet

Now the racket is moving !

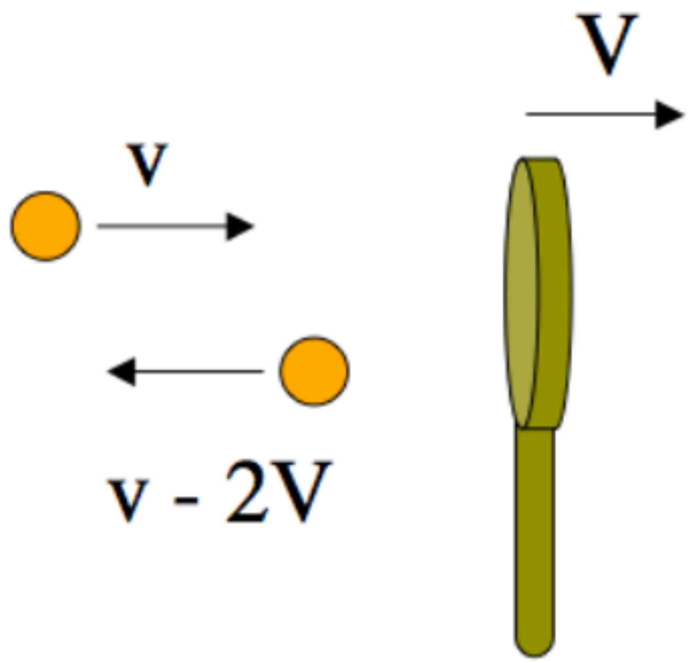


Before the shock :
- court frame the ball has velocity v
- racquet frame, the ball has a velocity v+V

After the shock :
- racquet frame the ball has a velocity v+V
- back to the court frame, the ball has a velocity v+2V

➡ Acceleration by double change of frame during frontal shock between the ball and the racquet

Idealized tennistic analogy!



Drop shot : this time the racquet is going away from the ball !

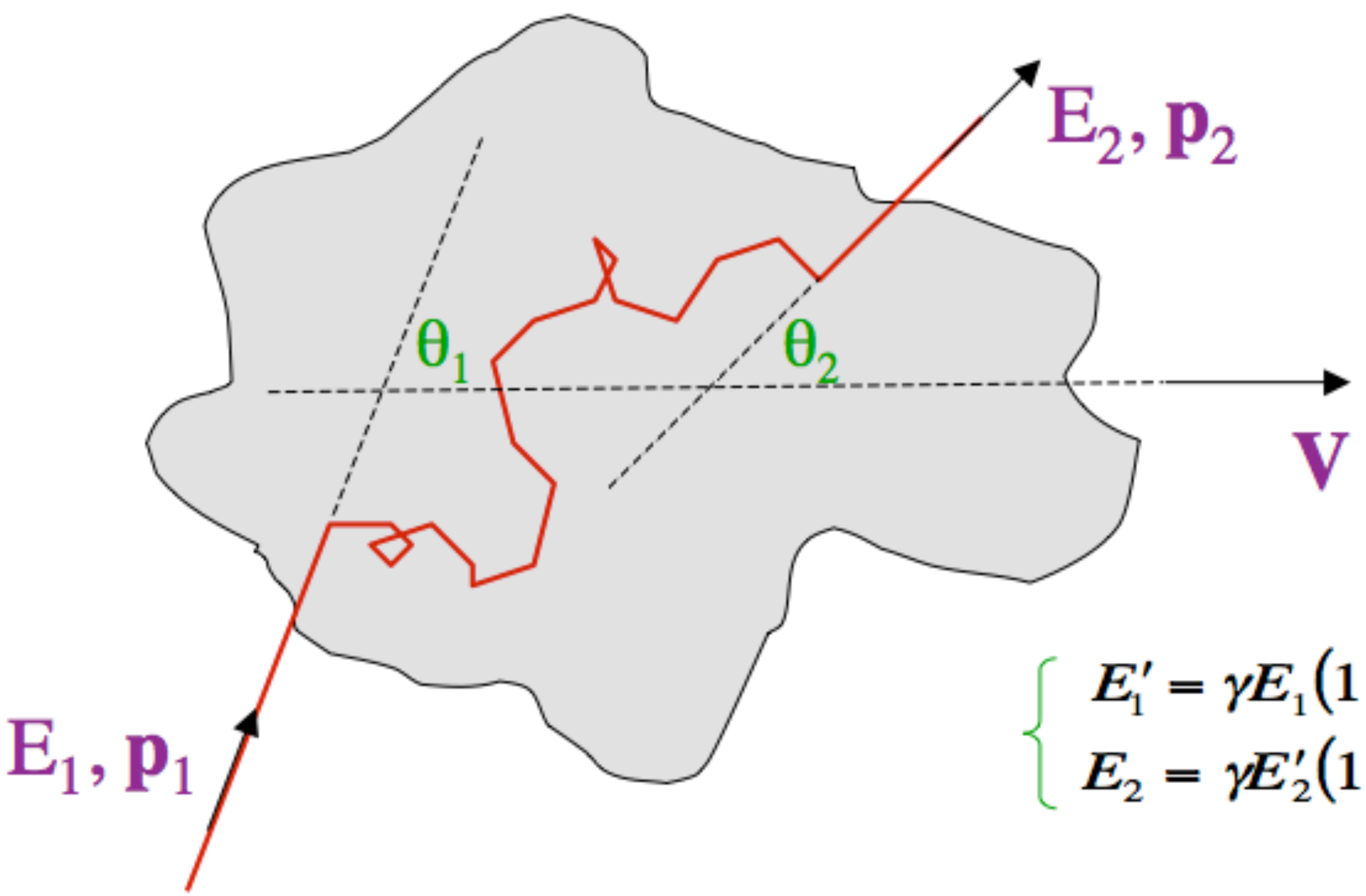
➡ Deceleration by double change of frame when the racquet is going away from the ball

Fermi mechanism :
- Magnetic cloud <=> tennis racquet
- Charged particle <=> tennis ball

- When the particle encounters a magnetic cloud coming toward it => energy gain

- When the particle encounters a magnetic cloud going away from it => energy loss

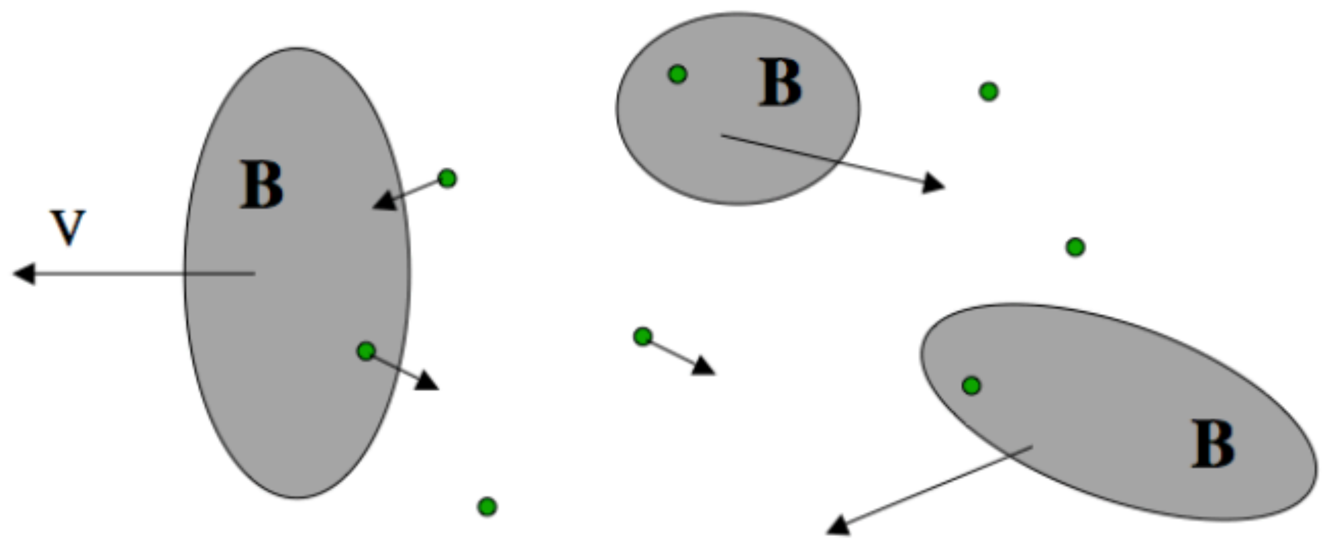
More realistic picture of the particle behavior in the magnetic cloud



$$
\begin{cases}
E_1' = \gamma E_1 (1 - \beta \cos\theta_1) \\
E_2 = \gamma E_2' (1 - \beta \cos\theta_2')
\end{cases}
$$

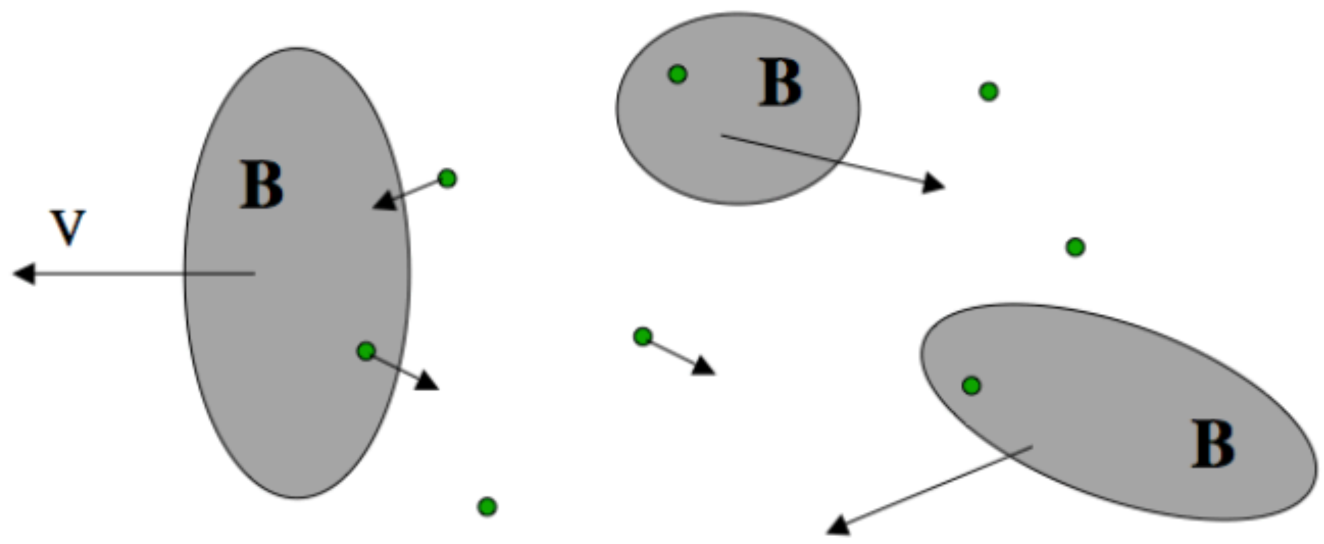
inside the cloud particles directions are randomized (isotropized) by the (turbulent) magnetic fields in the cloud (and not simply reflected)

Original Fermi mechanism



In the galaxy, one expects that a particle should encounter magnetic clouds in every direction. Shouldn't energy gain and energy losses compensate each other ?

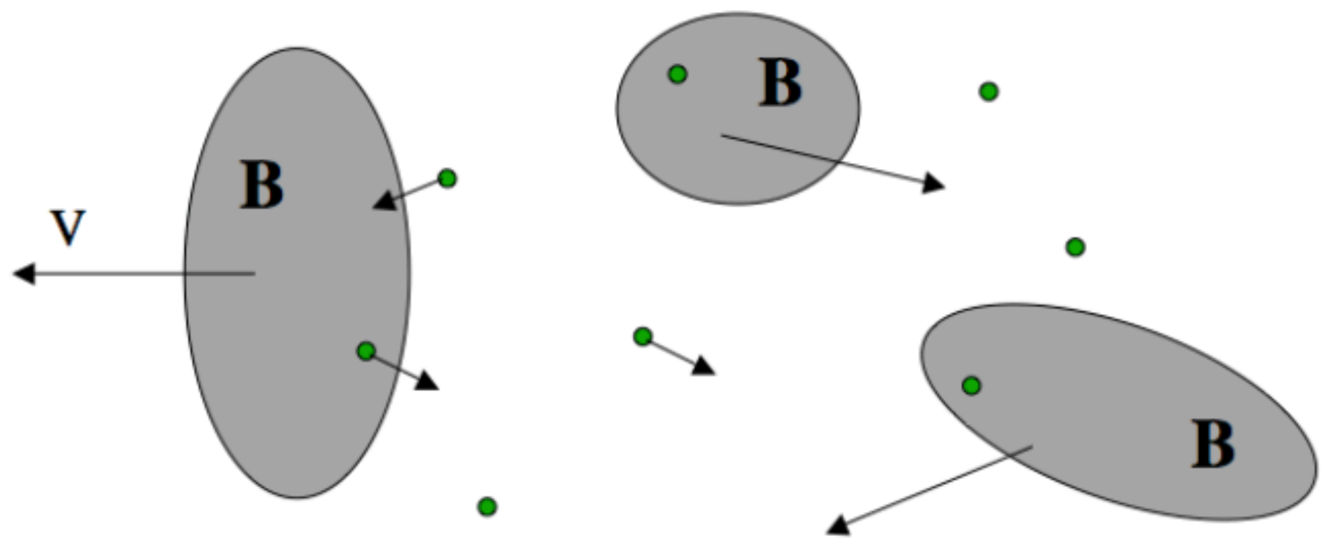
Original Fermi mechanism



In the galaxy, one expects that a particle should encounter magnetic clouds in every direction. Shouldn't energy gain and energy losses compensate each other ?

No! Highway analogy !

Original Fermi mechanism

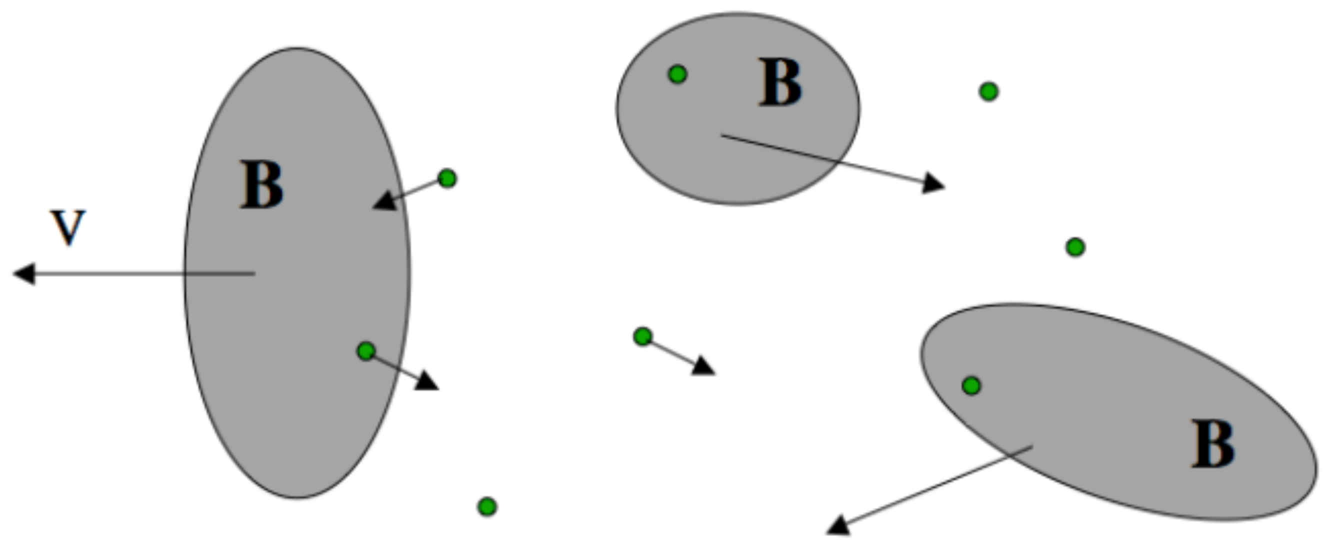


In the galaxy, one expects that a particle should encounter magnetic clouds in every direction. Shouldn't energy gain and energy losses compensate each other ?

No! Highway analogy !

One can show that frontal collisions are in average more frequent and that this mechanism leads to an energy gain in average (fractional energy gain $\propto \beta_{cloud}{}^2$)

Original Fermi mechanism



In the galaxy, one expects that a particle should encounter magnetic clouds in every direction. Shouldn't energy gain and energy losses compensate each other ?

No! Highway analogy !

One can show that frontal collisions are in average more frequent and that this mechanism leads to an energy gain in average (fractional energy gain $\propto \beta_{cloud}{}^2$)

Problem :"magnetic clouds" present in the Galaxy are too slow (β_{cloud}~10^{-4}) and their separation in space too large (~pc)

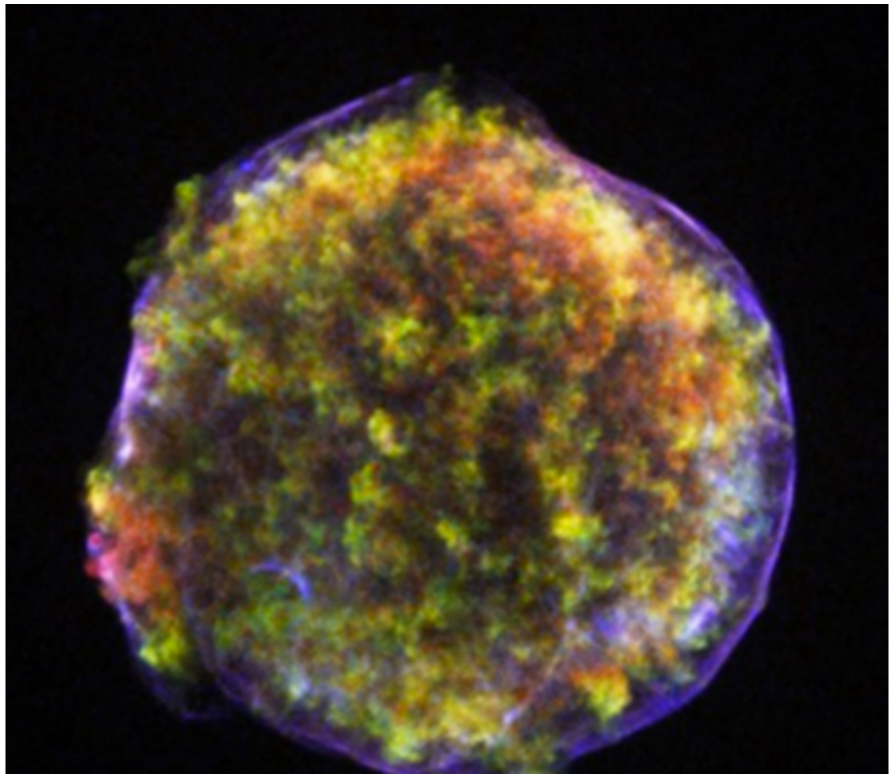
➡ The original Fermi mechanism is too "slow" to explain cosmic-ray acceleration above a few 10^9 eV

➡ A modern mechanism based on the same kind of intuition (reflection by moving magnetized structures) and involving astrophysical shock waves gives much better results (kept the name of Fermi mechanism)

Astrophysical shock waves and cosmic-ray acceleration

shock waves are very common in astrophysics they can be found in supernova remnants, active galactic nuclei, even in the solar system

they form as soon a supersonic wind/plasma propagates in an ambient medium

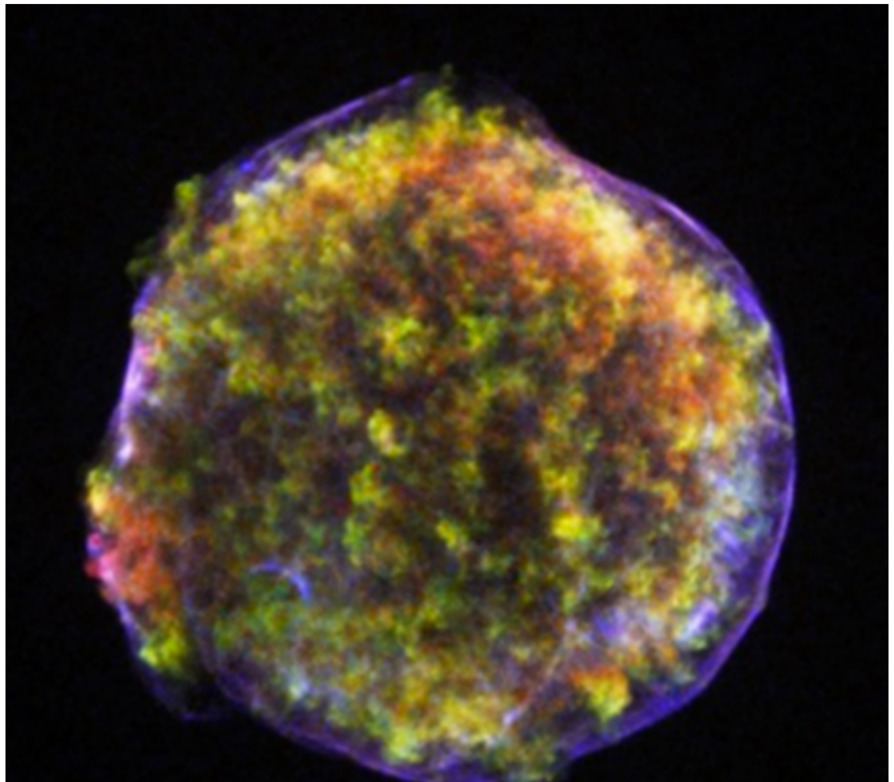


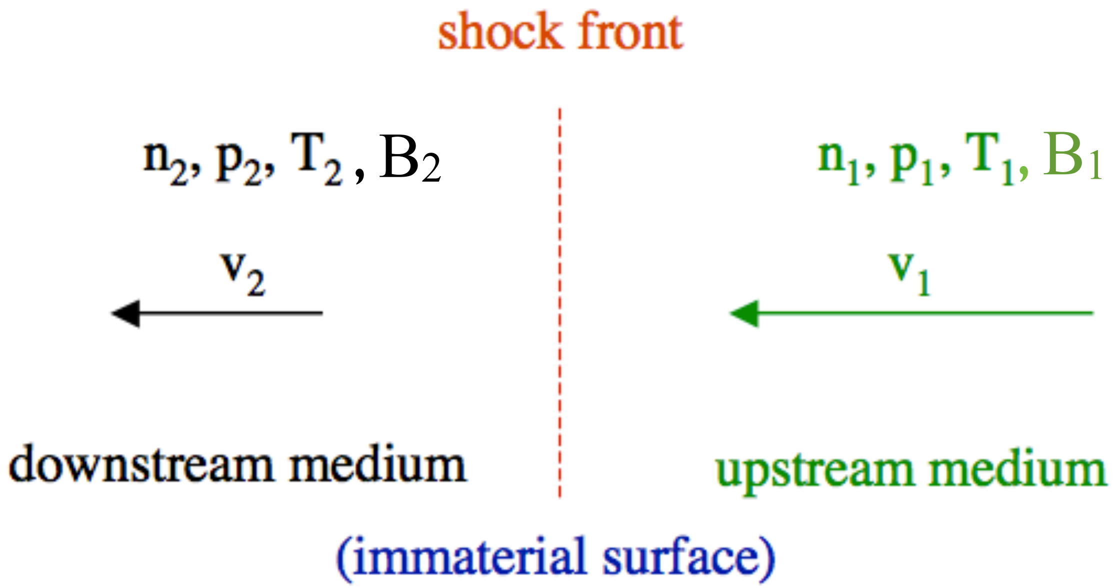
Tycho supernova remnant (1572) in X-rays

Radio image of the Cygnus A radiogalaxy (VLBA 1984)

The principle of *diffusive shock acceleration* is very similar to the original Fermi mechanism

Astrophysical shock waves and cosmic-ray acceleration


Tycho supernova remnant (1572) in X-rays



The principle of *diffusive shock acceleration* is very similar to the original Fermi mechanism

➡ The magnetized media upstream and downstream of the shock play the role of magnetic clouds

Astrophysical shock waves and cosmic-ray acceleration

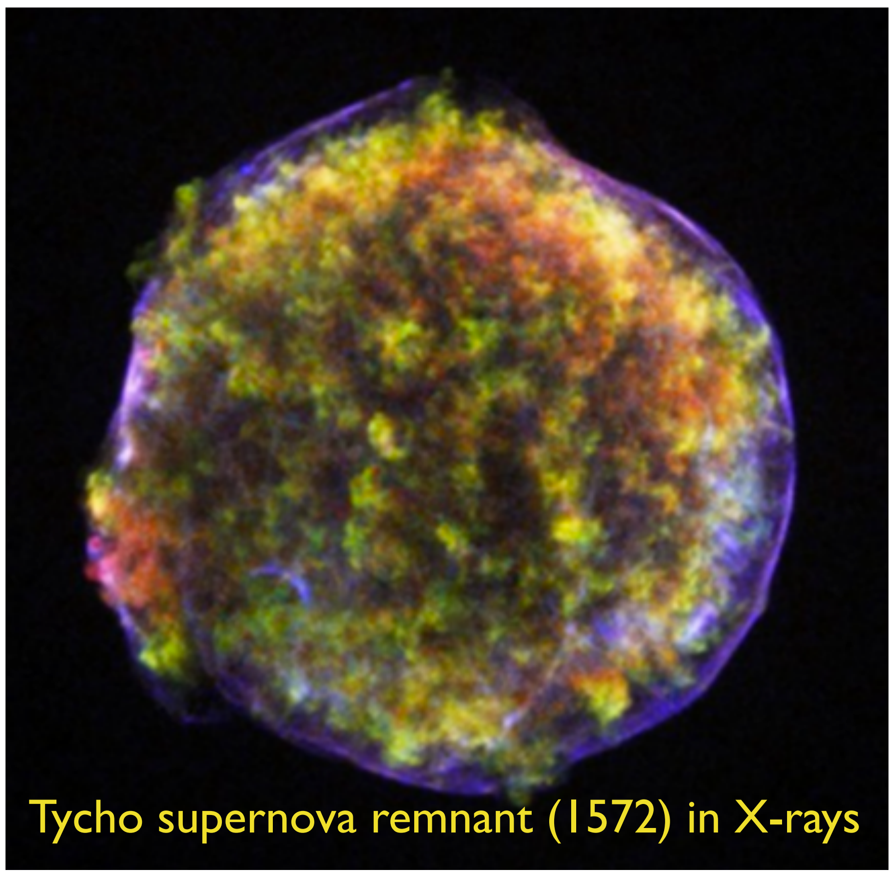
quantities in the downstream frame are determined using conservation relations across the shock : mass, momentum and energy and magnetic flux conservation (jump conditions)

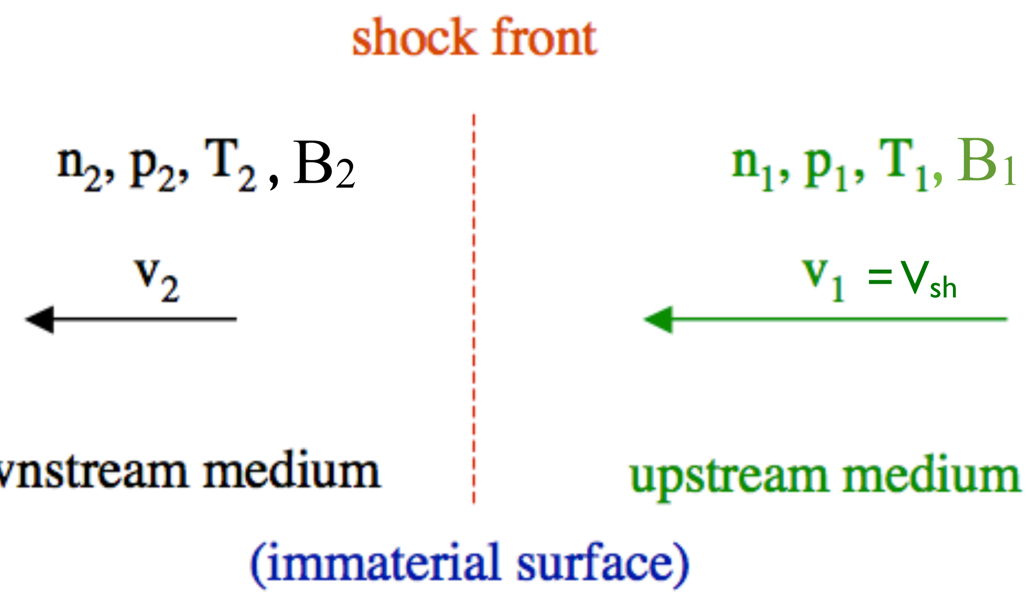
in particular :

$n_2 = r \times n_1$

$v_2 = v_1 / r$

with r the shock compression ratio r=4 for strong shocks

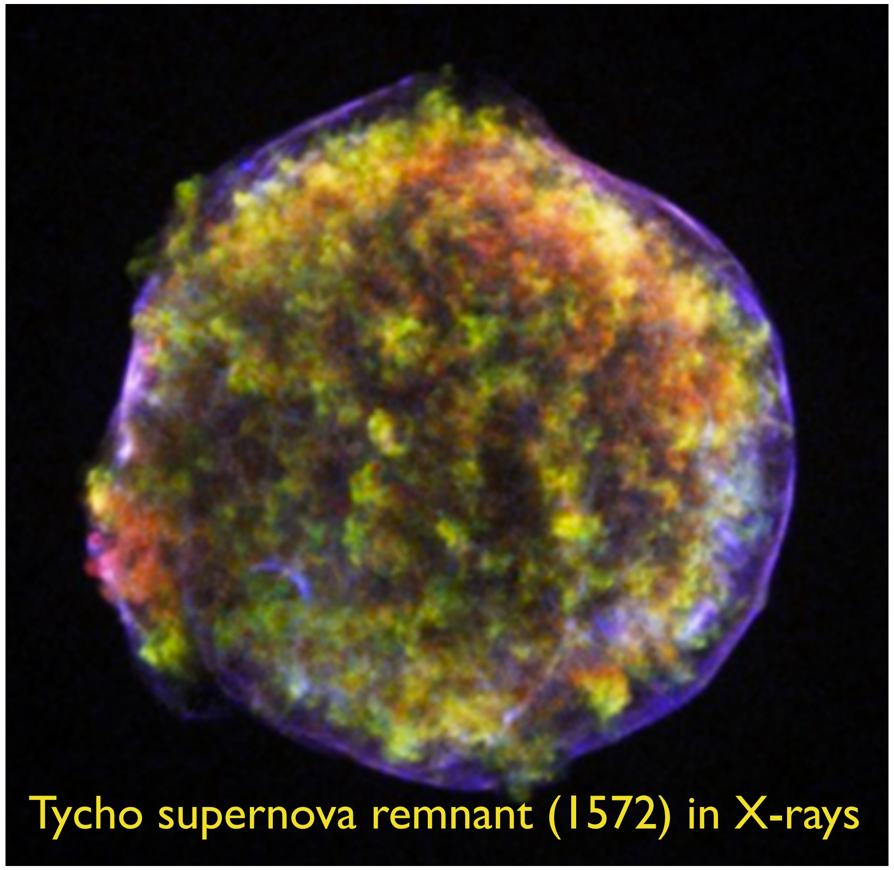

Tycho supernova remnant (1572) in X-rays

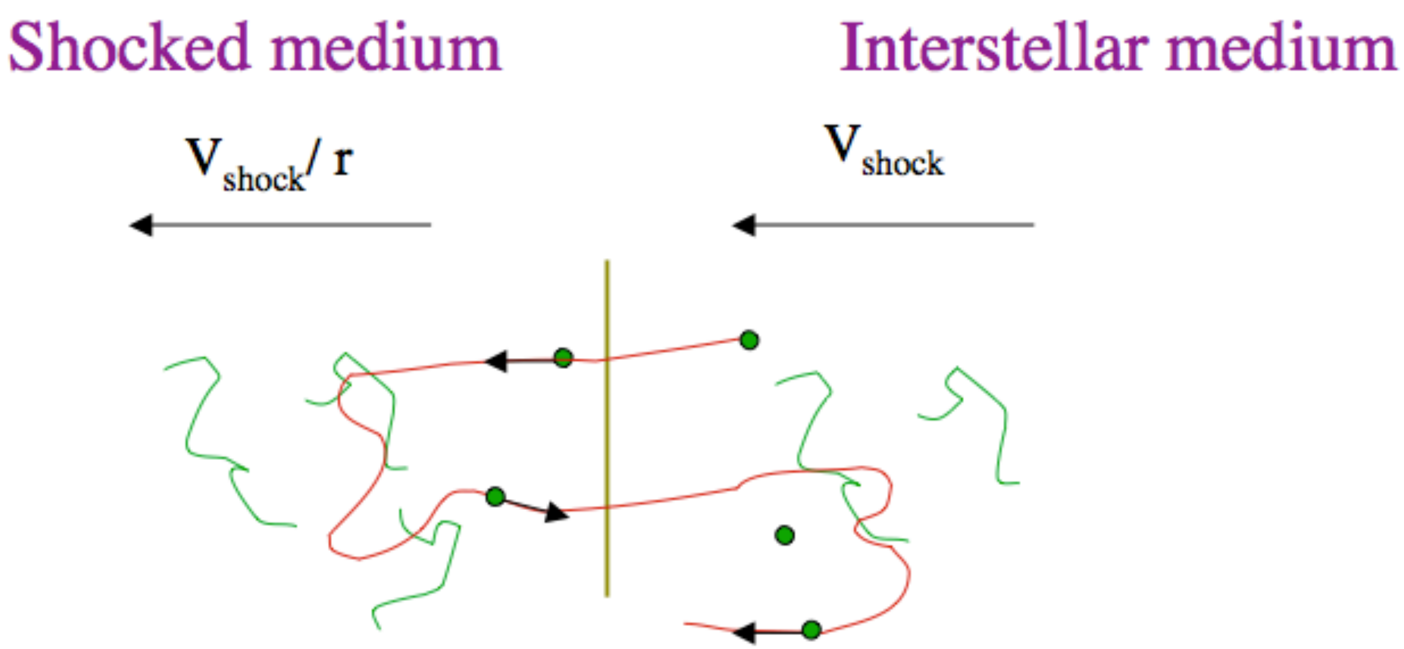


The principle of *diffusive shock acceleration* is very similar to the original Fermi mechanism

➡ The magnetized media upstream and downstream of the shock play the role of magnetic clouds

Astrophysical shock waves and cosmic-ray acceleration



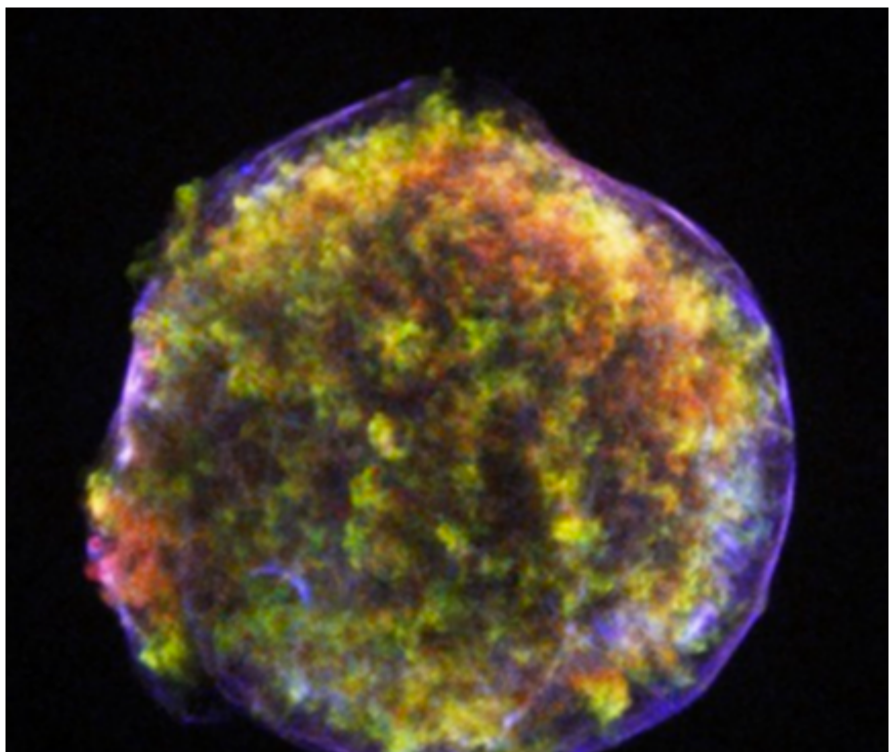


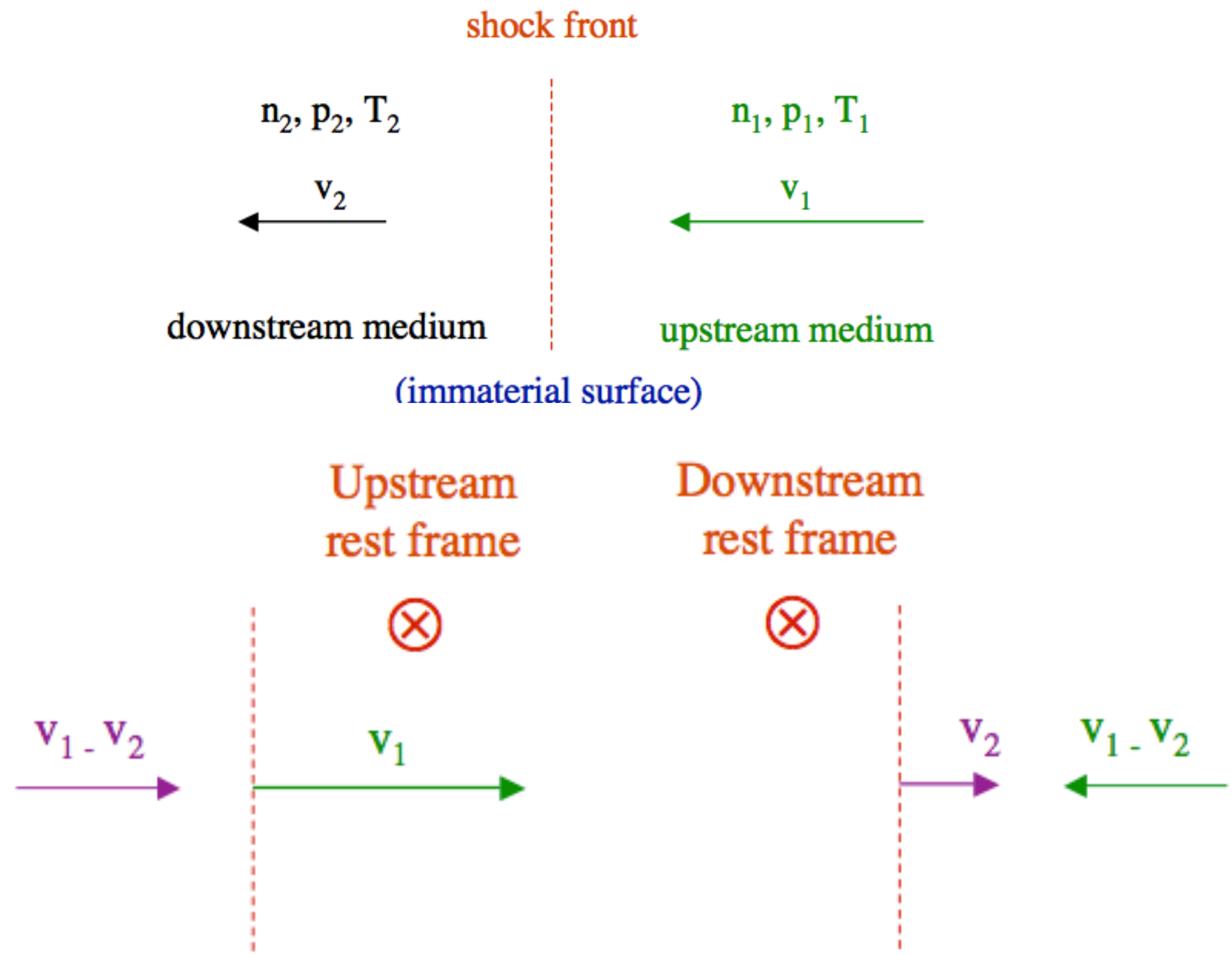
The principle of *diffusive shock acceleration* is very similar to the original Fermi mechanism

➡ The magnetized medium upstream and downstream of the shock play the role of magnetic clouds

➡ charged particles can perform cycles from upstream then to downstream to upstream and so on

Astrophysical shock waves and cosmic-ray acceleration


Reste de la supernova de Tycho (1572) en rayon X



The principle of *diffusive shock acceleration* is very similar to the original Fermi mechanism

➡ The magnetized medium upstream and downstream of the shock play the role of magnetic clouds

➡ charged particles can perform cycles from upstream to downstream to upstream and so on

➡ each encounter with a magnetized medium (either upstream or downstream) is frontal

➡ Energy gain at each cycle

Astrophysical shock waves and cosmic-ray acceleration

➡ Only frontal collisions => mechanism much more efficient than the original scenario by Fermi

Energy gain $\propto \beta_{shock}$ with β_{shock}~0.01-0.05

➡ Bonus : naturally produces a power-law spectrum for the accelerated particles

Why a power law spectrum of accelerated particles ?

Astrophysical shock waves and cosmic-ray acceleration

➡ Only frontal collisions => mechanism much more efficient than the original scenario by Fermi
Energy gain $\propto \beta_{shock}$ with β_{shock}~0.01-0.05

➡ Bonus : naturally produces a power-law spectrum for the accelerated particles

Why a power law spectrum of accelerated particles ?

➡ because at each cycle there is a probability to leave the system rather than crossing the shock front again

➡ the larger the number of cycles, the higher the energy, but the lower the number of particles remaining in the system

➡ the full (quite straightforward) calculation gives a power law spectrum
==> the spectral index depends only on the compression ratio
==>universal value for strong shocks : $n(E) \propto E^{-2}$

Does that mean arbitrarily large energies can be reached ?

Astrophysical shock waves and cosmic-ray acceleration

➡ Only frontal collisions => mechanism much more efficient than the original scenario by Fermi

Energy gain $\propto \beta_{shock}$ with β_{shock}~0.01-0.05

➡ Bonus : naturally produces a power-law spectrum for the accelerated particles

Why a power law spectrum of accelerated particles ?

➡ because at each cycle there is a probability to leave the system rather than crossing the shock front again

➡ the larger the number of cycles, the higher the energy, but the lower the number of particles remaining in the system

➡ the full (quite straightforward) calculation gives a power law spectrum

==> the spectral index depends only on the compression ratio

==>universal value for strong shocks : $n(E) \propto E^{-2}$

Does that mean arbitrarily large energies can be reached ?

➡ No !

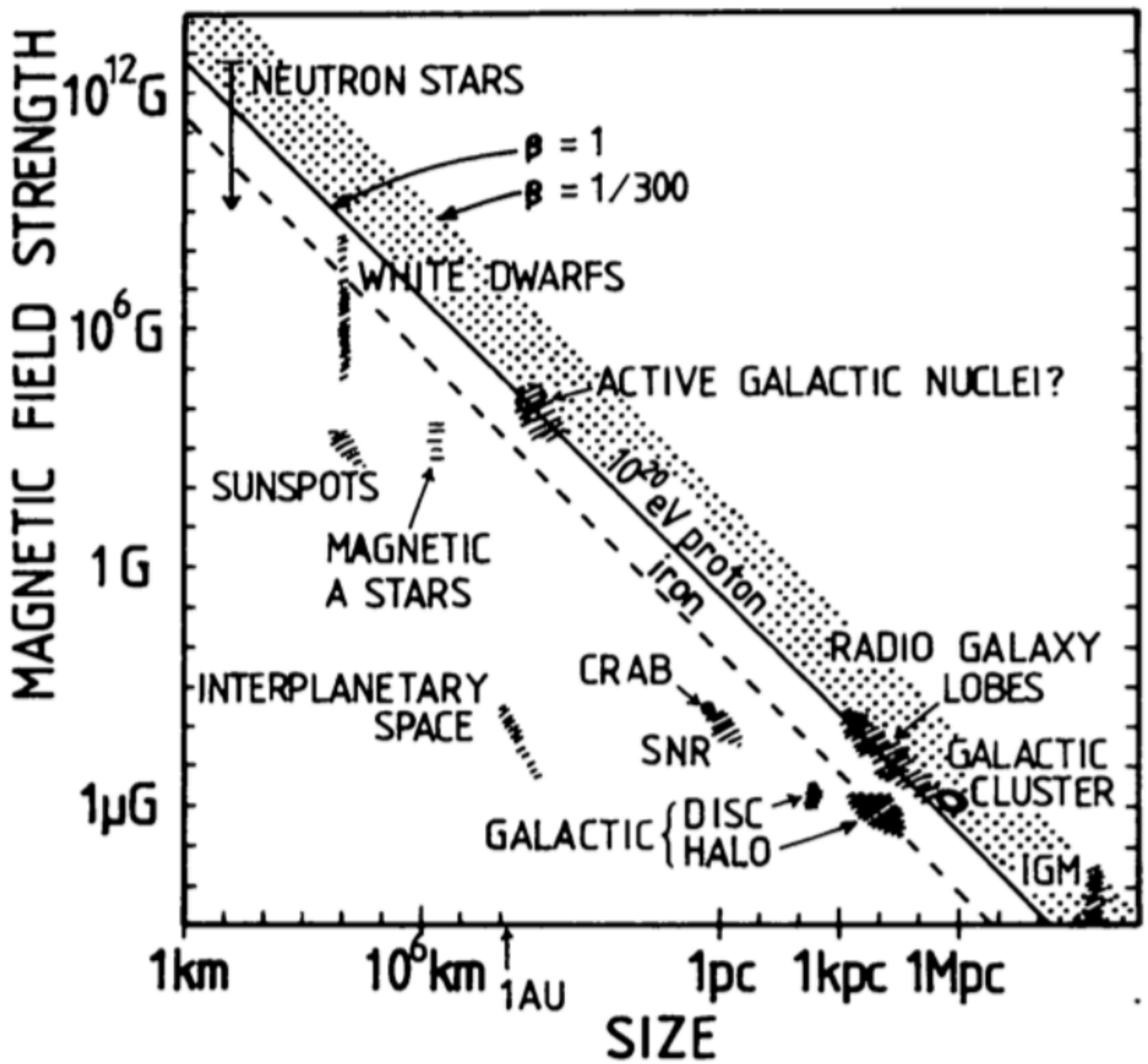
➡ The maximum energy depends on the ability of the source to confine particles :$R_L < L_{source}$

Same R_L for particles with the same rigidity R=Pc/Z~E/Z !

➡ One of the consequence of this argument is that the maximum energy is expected to be proportional to the charge of the nucleus

One expects oxygen (Z=8) or iron (Z=26) nuclei to be accelerated to energies respectively 8 and 26 times larger than the maximum energy reached by protons

Hillas diagram



How to attack the problem : three key observables

1

Angular spectrum

→ Arrival Directions (to find the sources)

2

Energy Spectrum

→ Measure the flux as a function of the energy

3

Mass spectrum

→ composition

Angular distribution

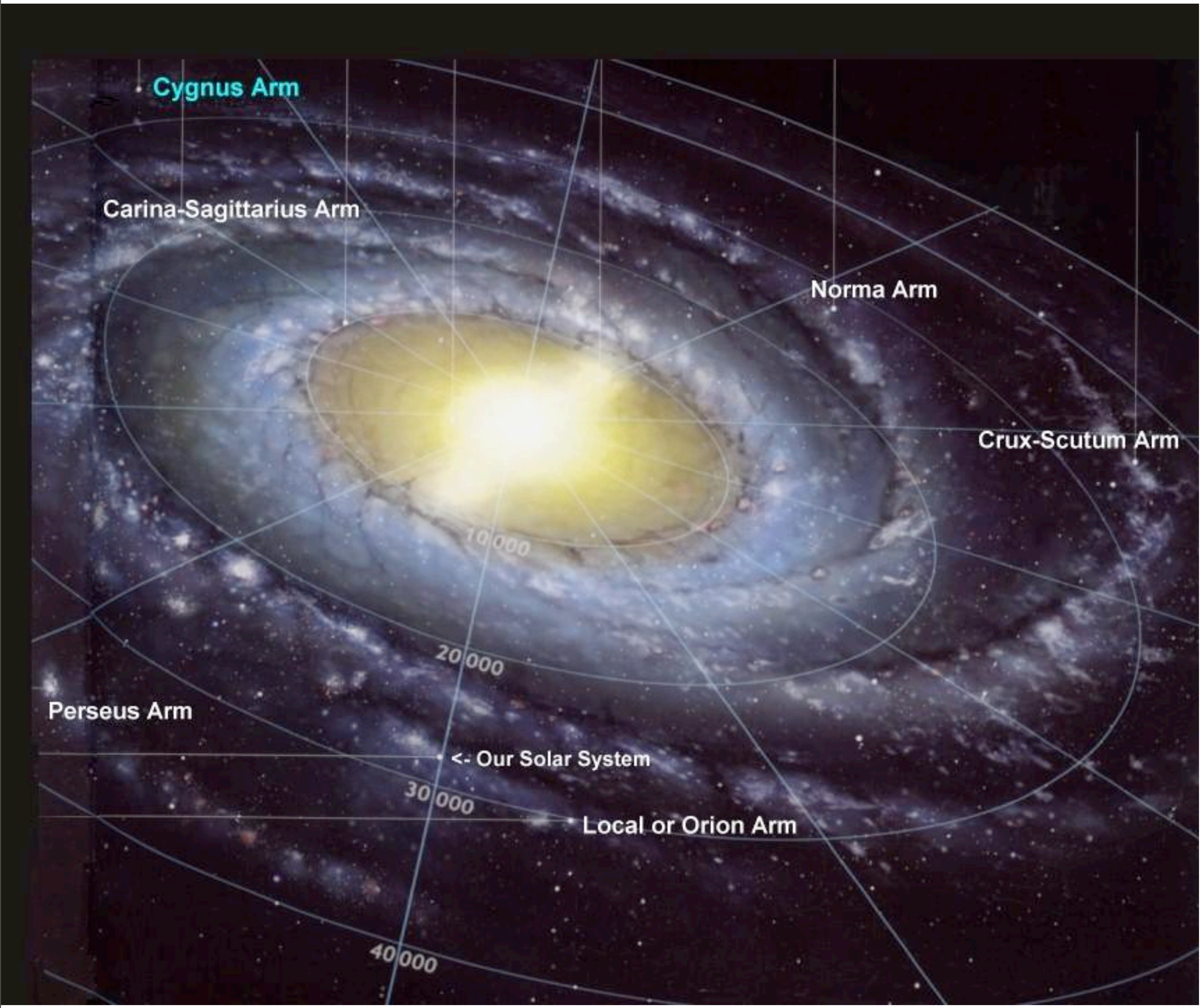
High resolution picture of the cosmic-ray sky below 10^{19} eV

Isotropic

we do not see any source

Why is that so?

parenthesis about the galaxy



Mass : 10^{12} M_{sun} (M_{sun}=2.10^{30} kg),
N_{stars}~4.10^{11}
Galactic disk :
- diameter ~30 kpc,
- thickness 300 pc
surrounded by a halo

★ <gas density> ~ 1 cm^{-3} in the disk

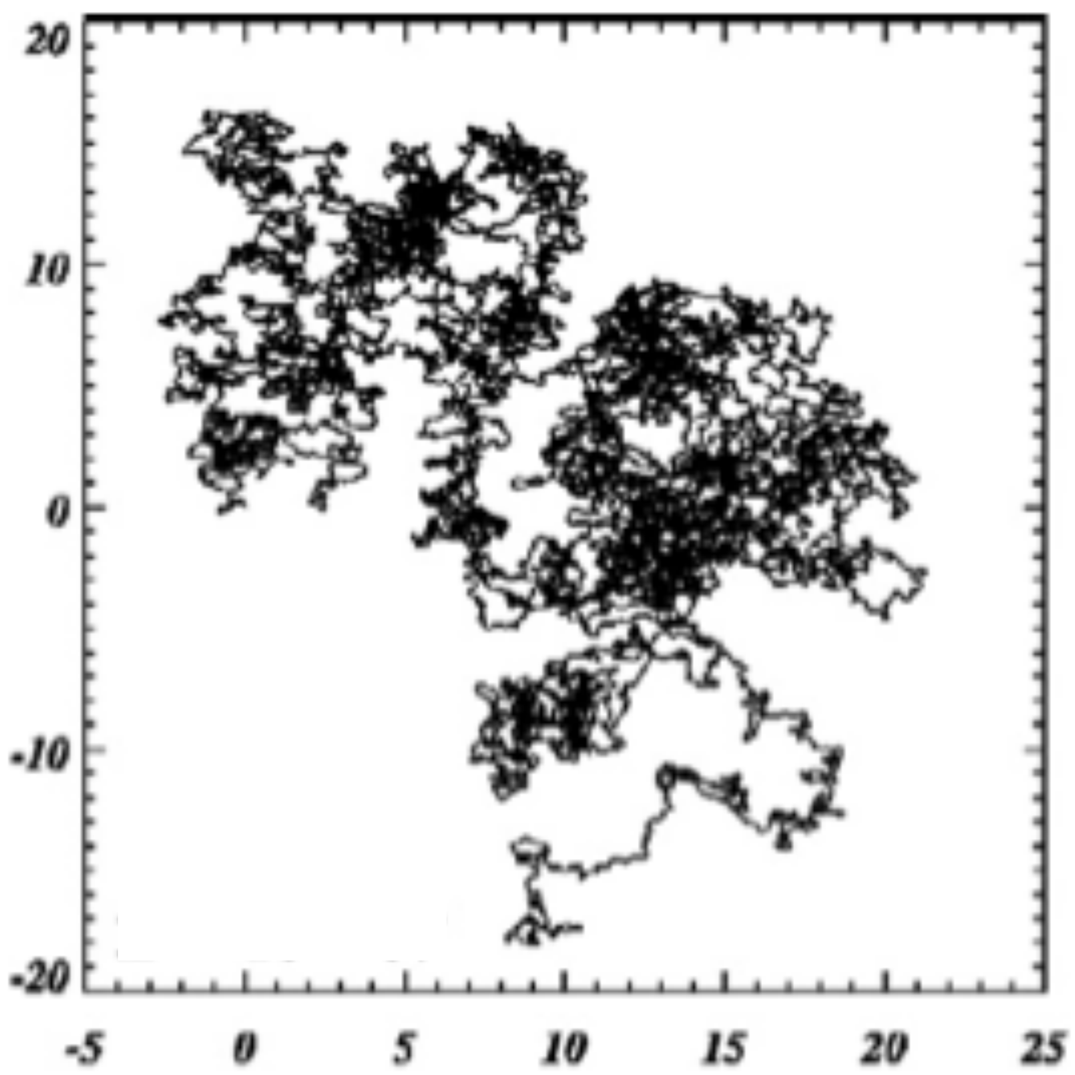
★ much lower density in the halo

✤ Magnetic Field non uniform and partly turbulent
B~ a few μG (1G=10^{-4} T) in the disk

✤ magnetic field most probably extending well above the disk in the galactic halo

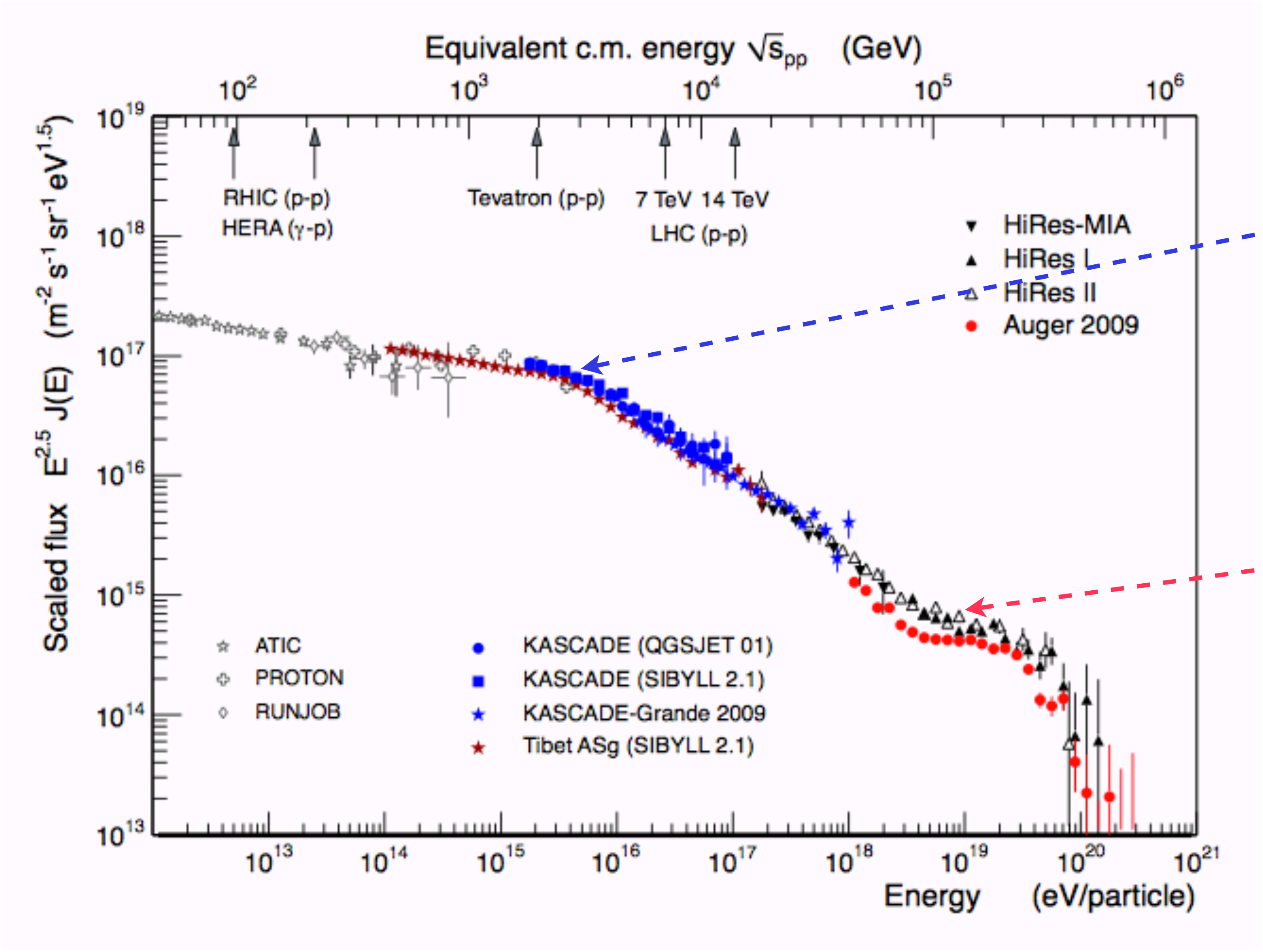
Charged particles behavior in the galactic turbulent magnetic fields

The strength of the Galactic magnetic field is more than large enough to completely isotropize cosmic-rays below 10^{15} eV (and certainly well above)
==> diffusive propagation



- ✤ The diffusive propagation is characterized by the diffusion D(R) --> particle with the same R~E/Z propagate the same way in a given field
  $D(R) \propto R^{\alpha}$
  (α characteristic of the type of turbulence)

How to understand the shape of the observed spectrum



Pierog, 2012

The knee
E~3-4.10[15] eV

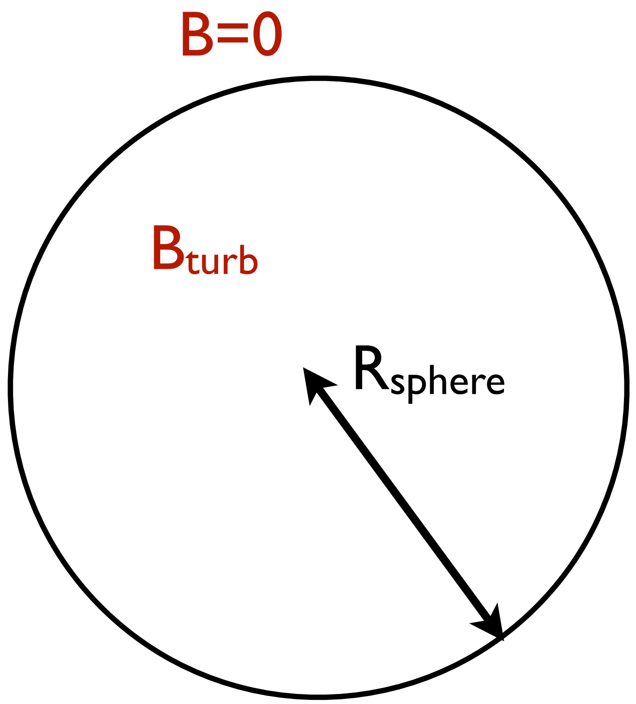
The ankle
E~3-4.10[18] eV

Below the knee the shape of the spectrum is ~ $n(E) \propto E^{-2.7}$

Should not it simply be the shape of the spectrum at the sources ?

No !!!

Escape from a finite sphere of radius R_{sphere}



What is the time needed for a particle with rigidity R to escape from the sphere?

One can show in diffusion theory :

$$\langle t_{esc} \rangle (R) \propto \frac{R^2_{sphere}}{D(R)}$$

$$\Rightarrow \quad \langle t_{esc} \rangle (R) \propto R^{-\alpha}$$

Leaky box approximation

Let us consider the Galaxy as a whole and treat the escape term as a loss term with typical timescale $\langle\tau_{esc}\rangle$ (leaky box approximation)!

$$\frac{\partial N}{\partial t}(R) = q(R,t) - \frac{N(R)}{\tau_{esc}(R)}$$

leaky box equation with a source term and an escape term

$$P(t) = \frac{1}{\tau_{esc}} \exp\left(-\frac{t}{\tau_{esc}}\right) \quad \langle t\rangle = \int_0^{\infty} \frac{t}{\tau_{esc}} \exp\left(-\frac{t}{\tau_{esc}}\right) dt = \tau_{esc}$$

==> The mean escape time, is also the mean confinement/residence time (i.e the mean age) of the cosmic-rays in the Galaxy

==> it also correspond to the "age" of the cosmic-rays detected on Earth

Leaky box approximation

Let us consider the Galaxy as a whole and treat the escape term as a loss term with typical timescale <τ_{esc}> (leaky box approximation)!

$$\frac{\partial N}{\partial t}(R) = q(R,t) - \frac{N(R)}{\tau_{esc}(R)}$$

leaky box equation with a source term and an escape term

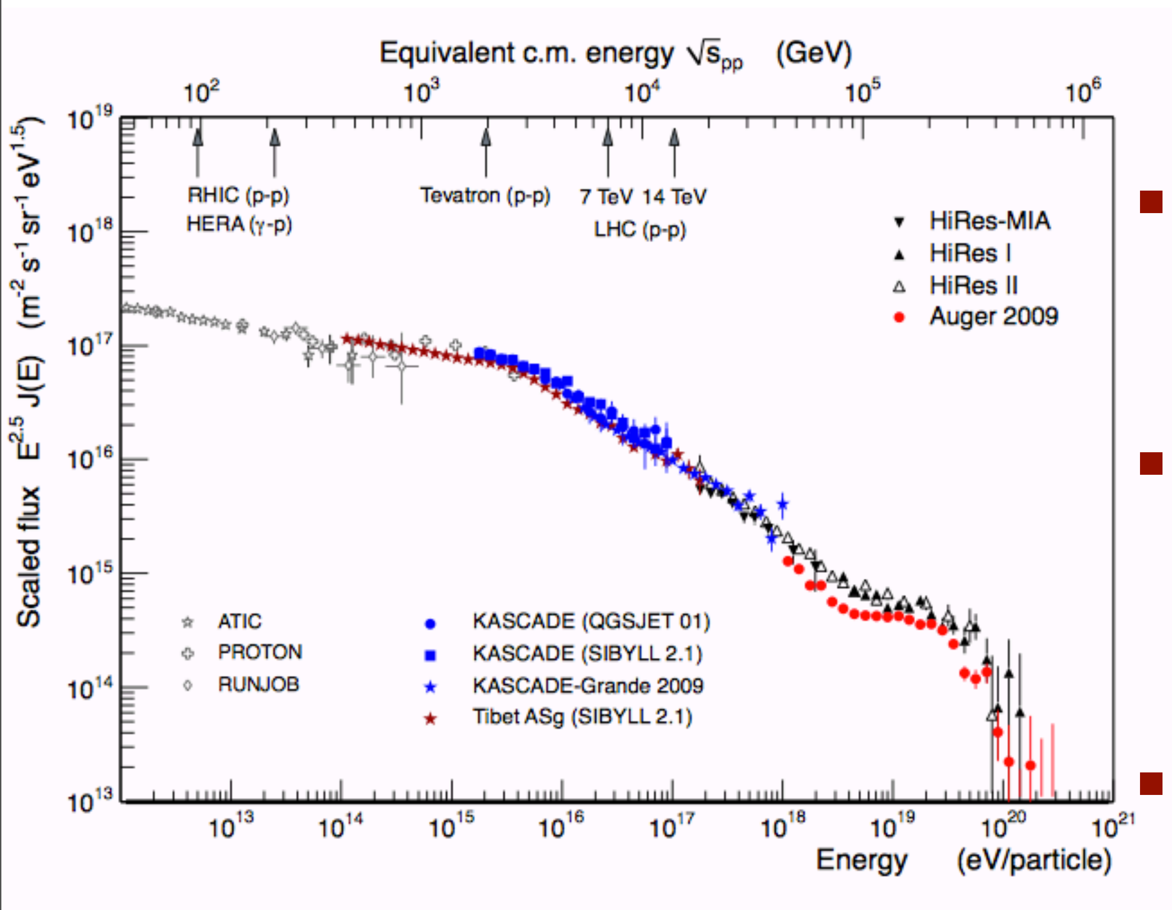
$$q(R) - \frac{N(R)}{\tau_{esc}(R)} = 0$$

steady state assumption : CR density does not vary with time (reasonable assumption)

$$N(R) = q(R) \times \tau_{esc}(R)$$

Trivial solution !!!
==> very interesting consequences

Interpretation of the shape of the spectrum : slope steepening



- Confinement time of cosmic rays of rigidity R:

$$\langle \tau_{esc} \rangle (R) \propto R^{-\alpha}$$

- Injection rate in the whole Galaxy (spectrum at the sources):

$$q(R) \propto R^{-\beta}$$

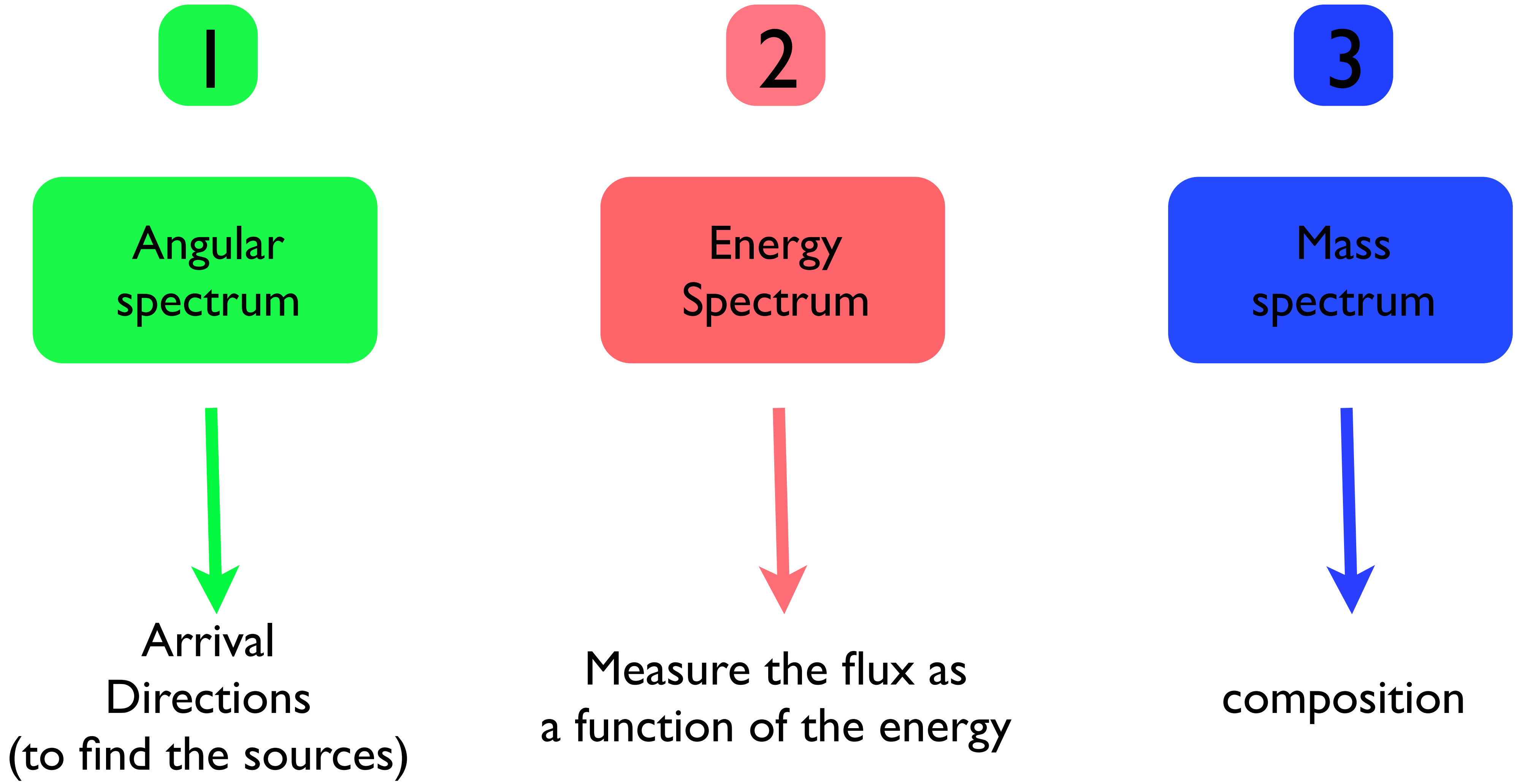
- Resulting spectrum in the Galaxy (steady-state)

$$N(R) \propto R^{-(\beta+\alpha)}$$

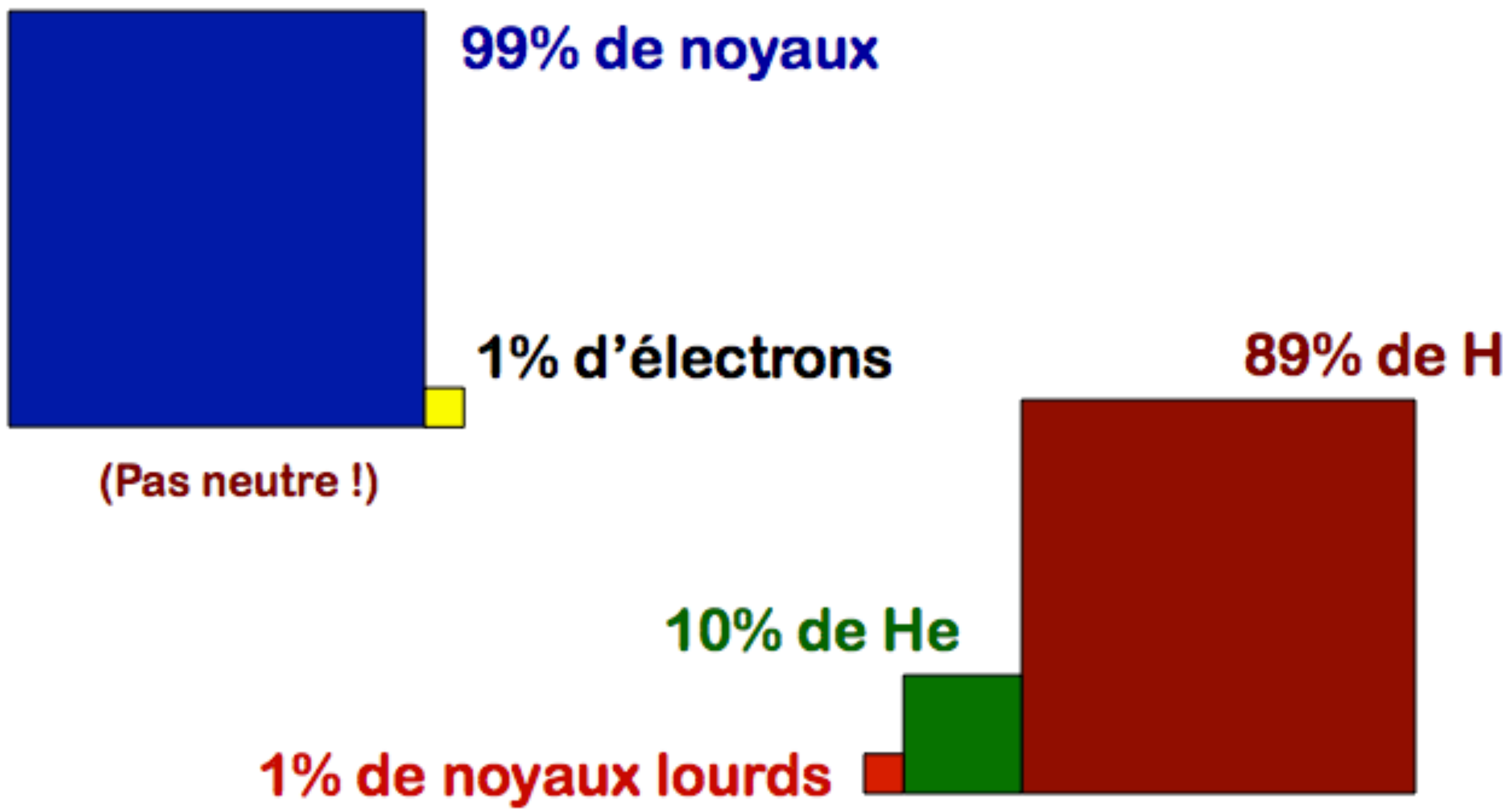
slope steepening

- Measurements give: $\boxed{\beta+\alpha \simeq 2.7}$

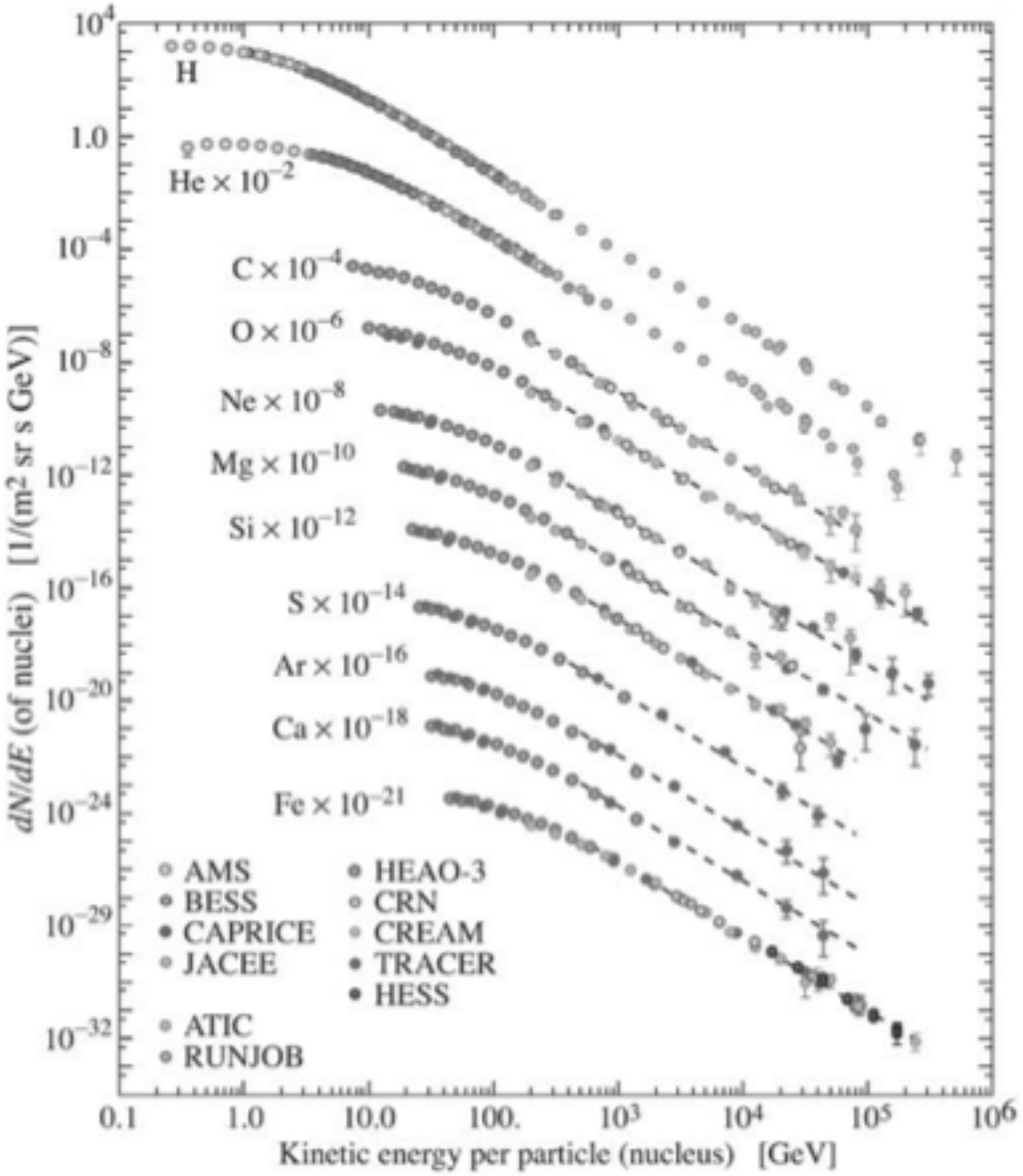
How to attack the problem : three key observables



composition



composition

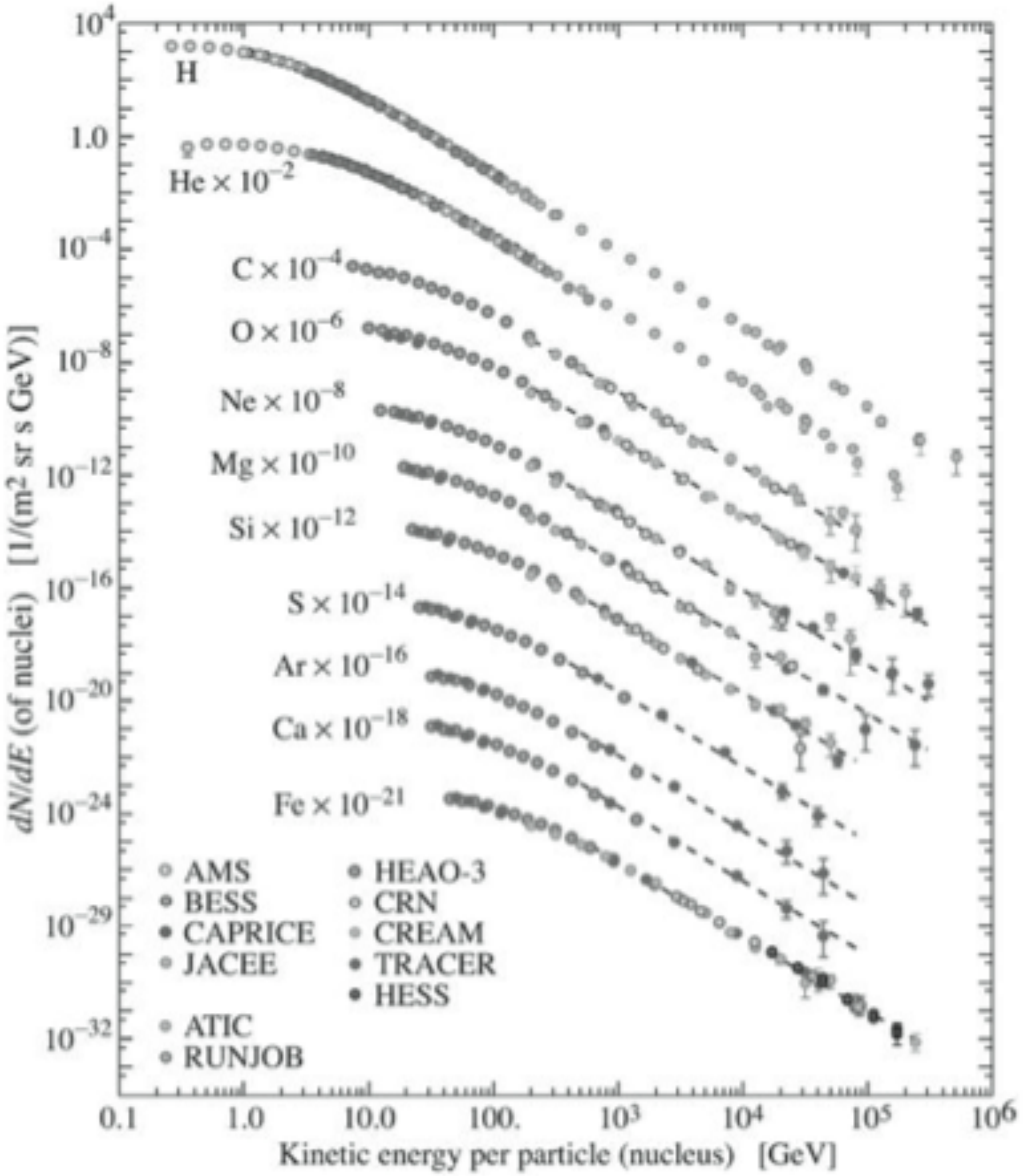


composition very well measured by balloons and satellites on a wide energy range

===> approximately the same shape for the different species

===> all type of nuclei acceleration in the same sources by the same mechanism

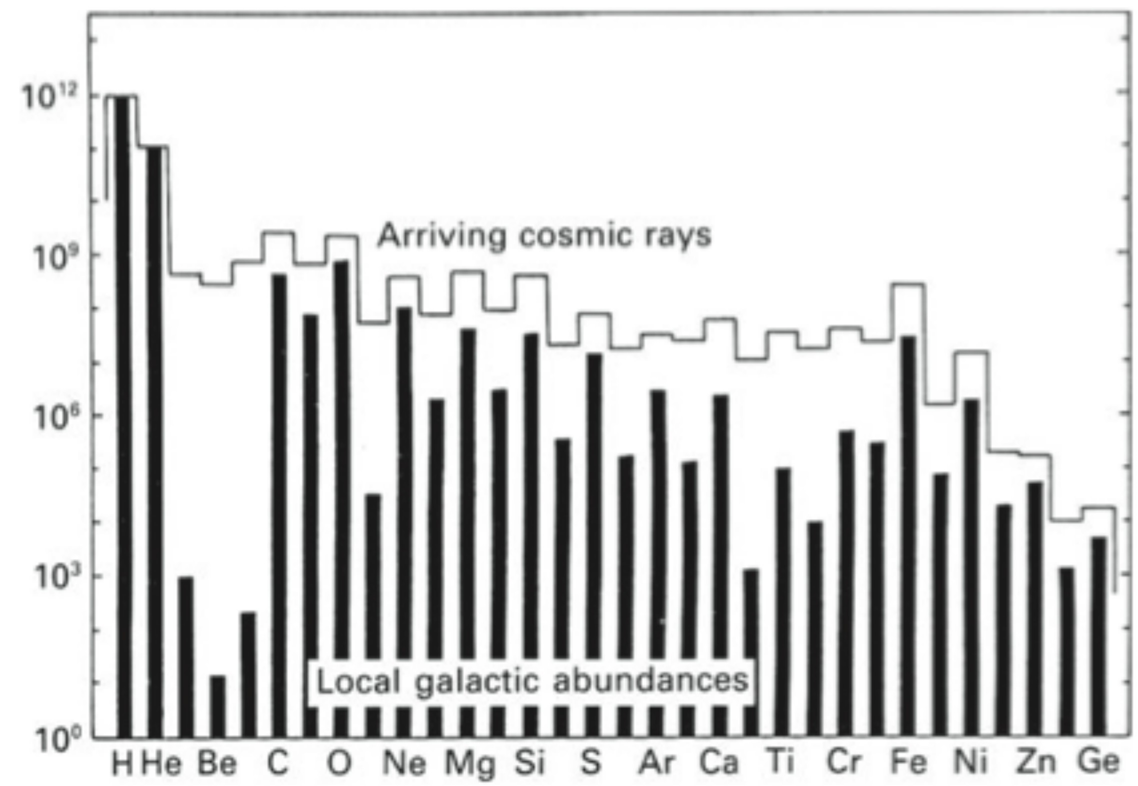
composition



composition very well measured by balloons and satellites on a wide energy range

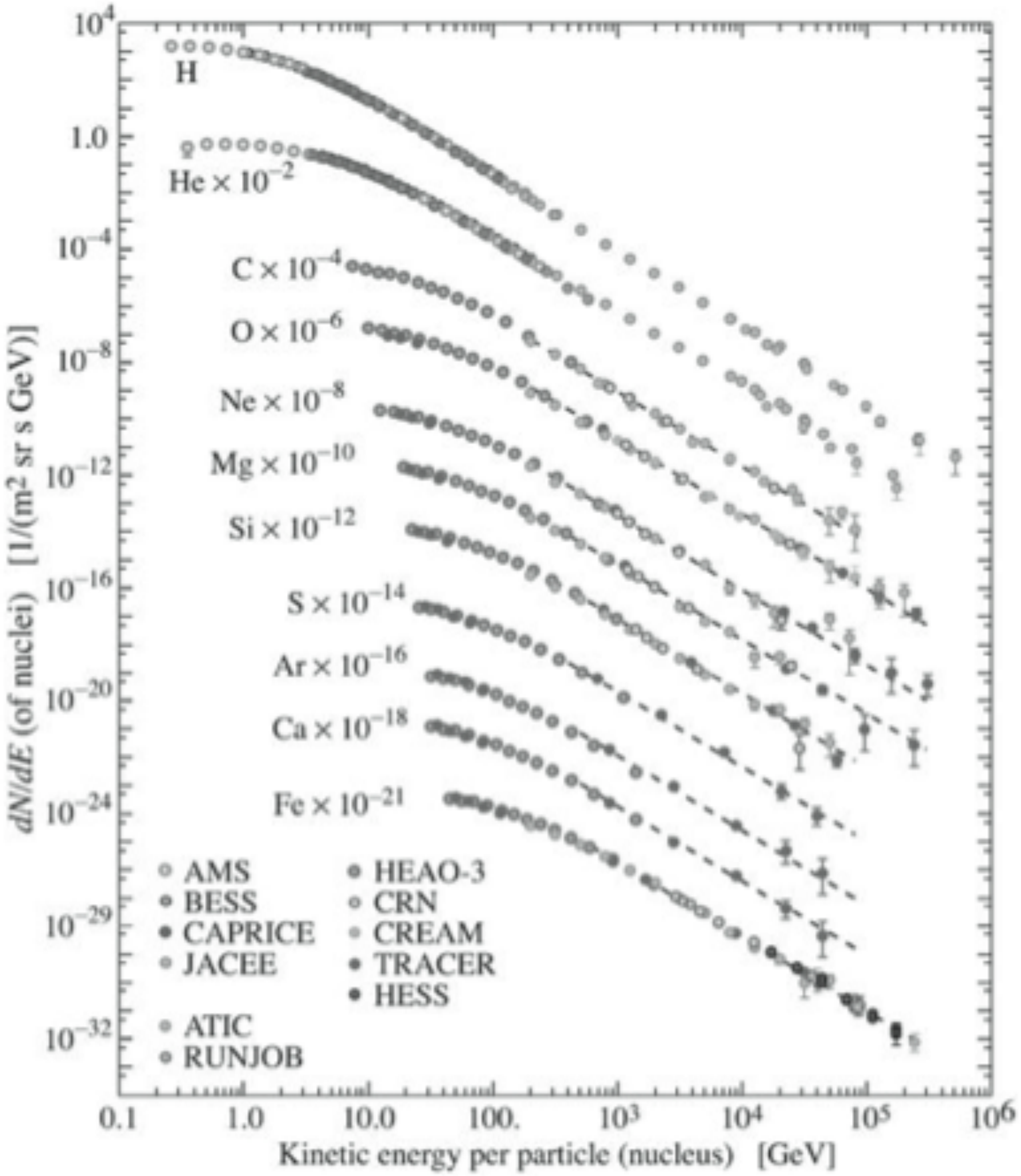
===> approximately the same shape for the different species

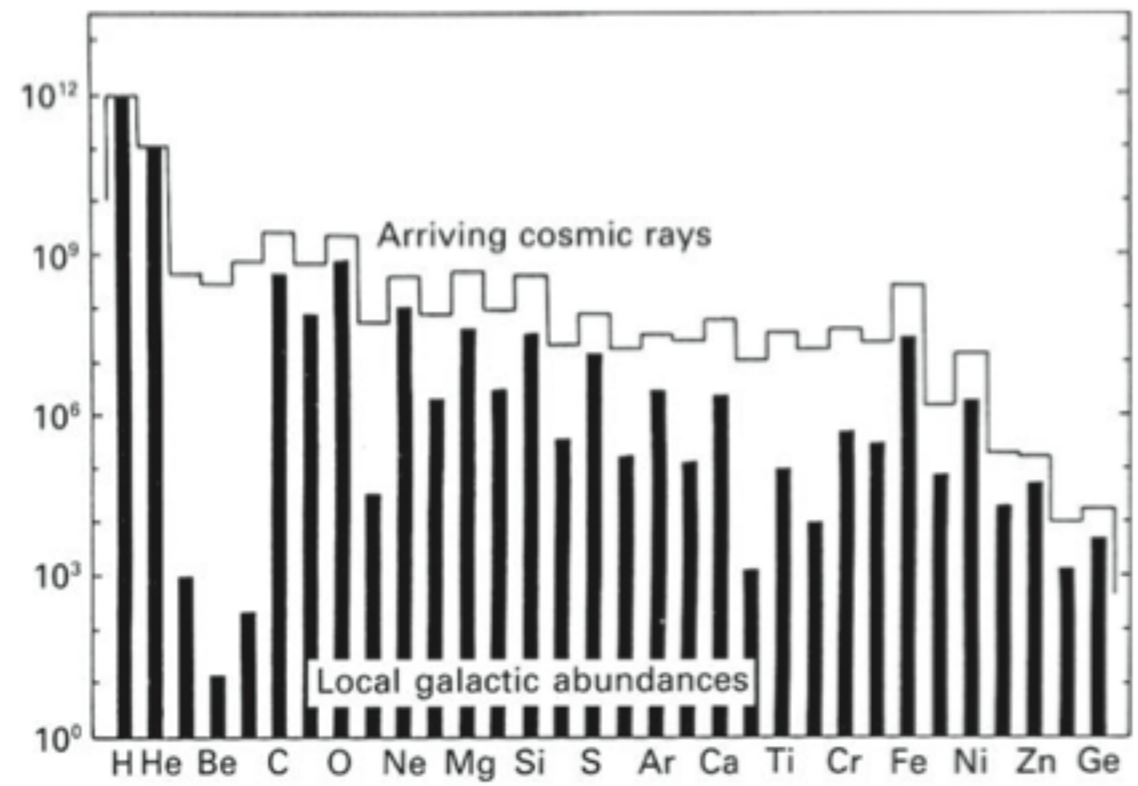
===> all type of nuclei acceleration in the same sources by the same mechanism



at the lowest energies ~ GeV/nucleon Li-Be-B with low abundance in the interstellar medium, not produced in stars are overabundant in cosmic-rays

composition





composition very well measured by balloons and satellites on a wide energy range

===> approximately the same shape for the different species

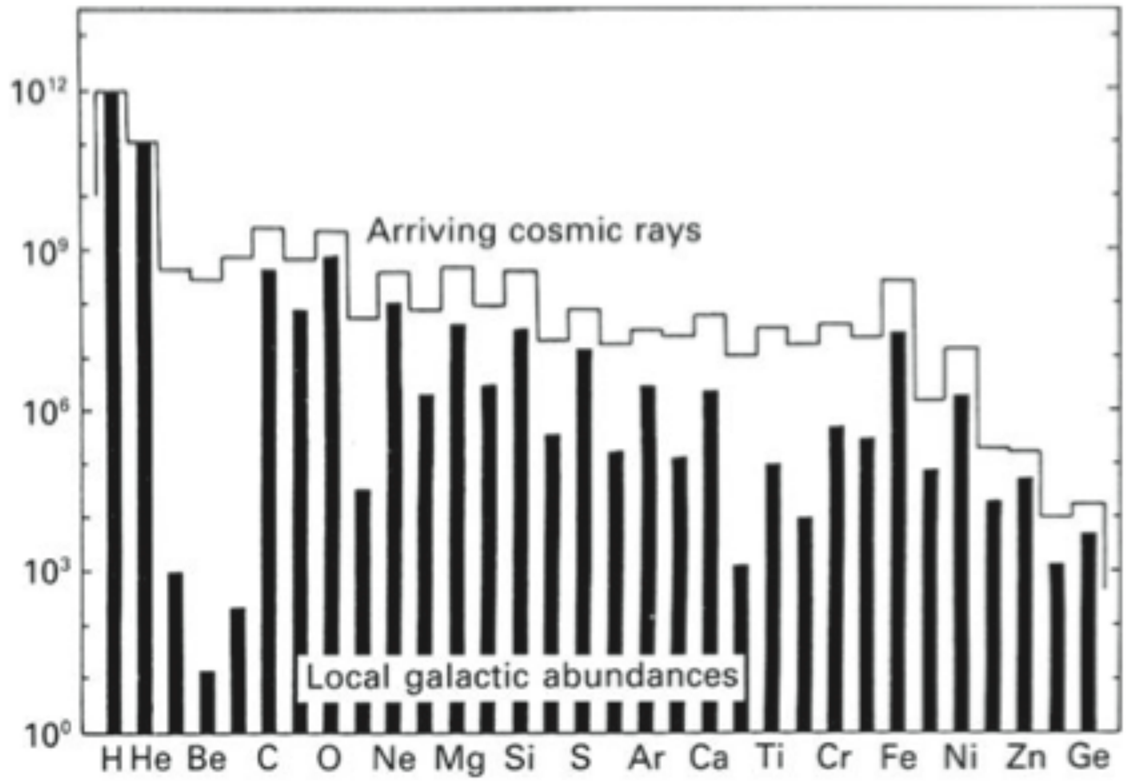
===> all type of nuclei acceleration in the same sources by the same mechanism

at the lowest energies ~ GeV/nucleon
Li-Be-B with low abundance in the interstellar medium, not produced in stars are overabundant in cosmic-rays

===> they are produced by spallation of CNO cosmic-rays during their propagation in the galaxy

===> spallative nucleosynthesis

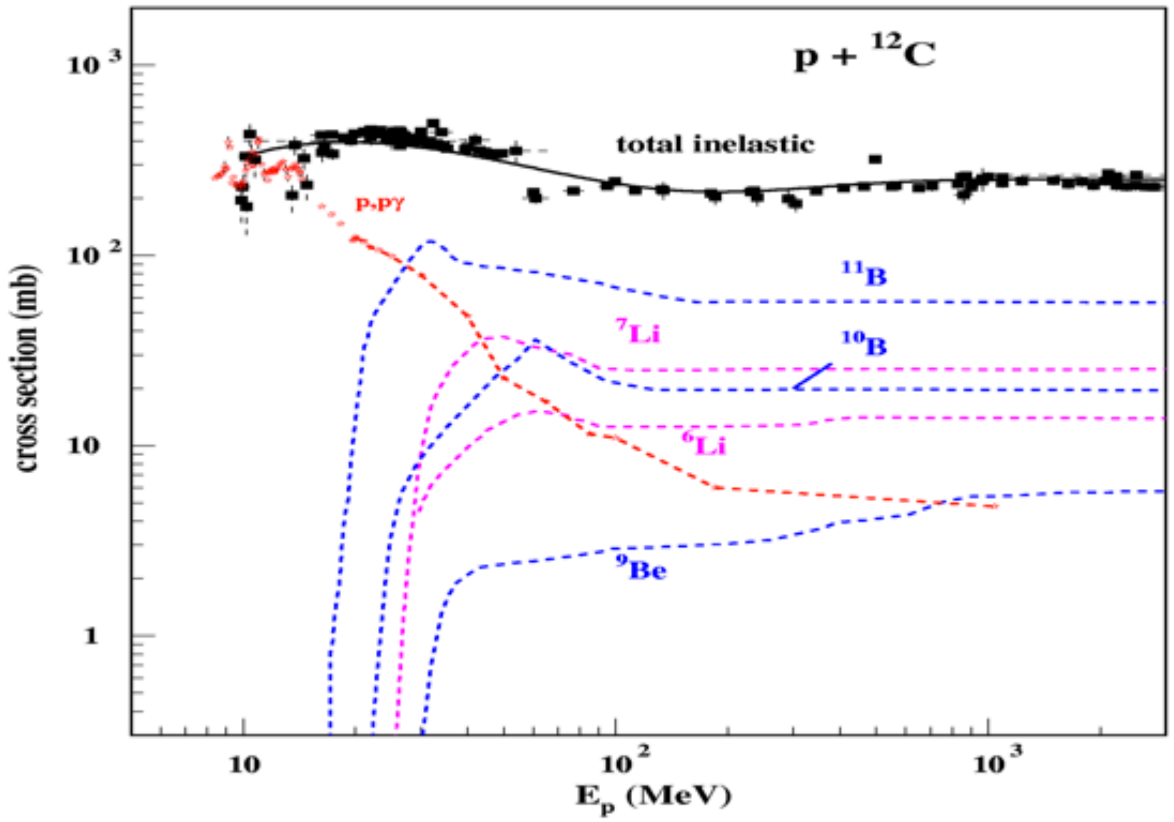
nuclear cross section



LiBeB nuclei in cosmic-rays are secondary nuclei mostly produced by the spallation of CNO cosmic-rays (projectile) by interstellar H, He nuclei (target) ---> spallation (or inverse spallation)

NB : LiBeB nuclei in the interstellar matter are mostly LiBeB cosmic-rays which have been later thermalized

knowing the cross section for their production and taking into account they can also be destroyed by spallation one can calculate the propagation time needed for LiBeB to be produced with such abundances



Leaky box approximation with production and destruction terms

branching ratio

$$0 = q_i(R) - \frac{N_i(R)}{\tau_{esc}(R)} - \frac{N_i(R)}{\tau_{spall,\,i}(R)} + \sum_j P_{j\to i} \frac{N_j(R')}{\tau_{spall\,,j}(R')}$$

destruction term　　　　production term

with $\tau_{spall,\,i}(R) = \left(\sigma^i_{spall}(R) n v\right)^{-1}$ mean spallation time (inverse of the spallation rate)

Can we really obtain the time cosmic-rays have propagated by measuring LiBeB nuclei abundances ?
No !

✤ The Galactic medium is inhomogenous, we do not no where the sources are
---> we do not know the average density of matter crossed by cosmic-rays during their propagation :
- assuming a density *n* and a propagation time *t*, the same number of created LiBeB nuclei would be obtained with a propagation in a medium of density *2n* during a time *t/2*
===> sensitive to the product *nt*

✤ Change of variable : let us define the grammage *X* (units $g.cm^{-2}$)

$X = \bar{m} n v t$ with $\bar{m} \simeq 1.4 m_p$

Leaky box approximation with production and destruction terms

✤ Change of variable : let us define the grammage X (units g.cm^{-2})

$$X = \bar{m} n v t \quad \text{with} \quad \bar{m} \simeq 1.4 m_p$$

$$\tau_{spall,\,i} \rightarrow X_{spall,\,i} \text{ where } X_{spall,\,i} = \bar{m} n \tau_{spall,\,i} c = \bar{m}/\sigma^i_{spall}$$

$$\tau_{esc} \rightarrow X_{esc}$$

NB : we assume the cross sections and branching ratios do not depend on E to simplify the equations in the following

Let us rewrite the leaky box equation with new variable X for the primary (CNO) and secondary nuclei (LiBeB) making the following (quite justified) approximations

(i) We will consider CNO as one single species and LiBeB as well as one single species

(ii) We will consider CNO as a purely primary nucleus, *i.e* we will neglect the CNO produced by spallation of heavier nuclei

(iii) We will consider LiBeB as a purely secondary nucleus, *i.e* we will neglect the LiBeB emitted by the sources (the source term q_{LiBeB} will be neglected)

Leaky box approximation with production and destruction terms

Let us rewrite the leaky box equation with new variable *X* for the primary (CNO) and secondary nuclei (LiBeB)

(i) For the CNO nuclei (we use the index "p" referring to "primary")

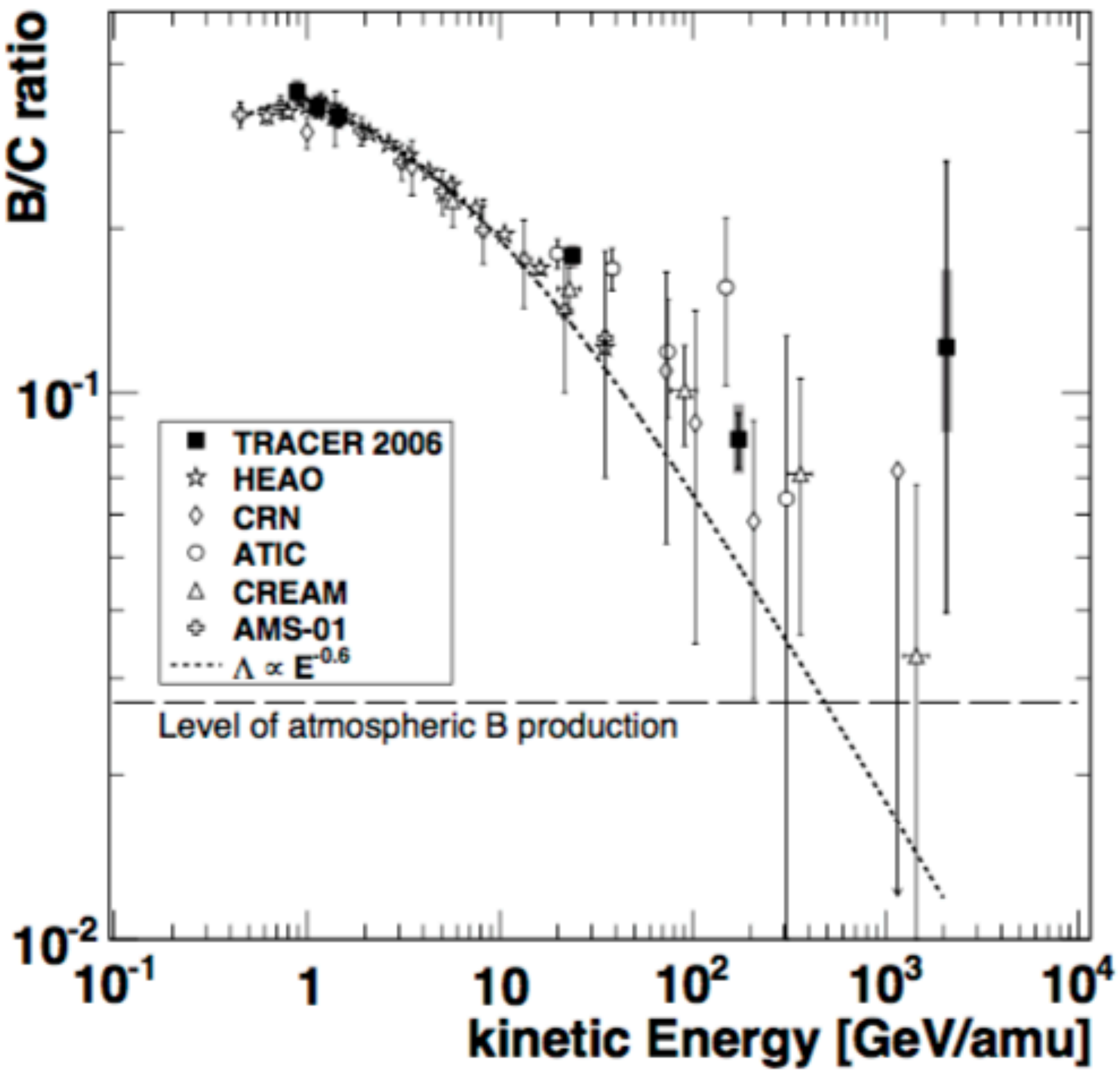
$$0 = q_p(R) - \frac{N_p(R)}{X_{esc}(R)} - \frac{N_p(R)}{X_{spall,\,p}}$$

(ii) For the LiBeB nuclei (we use the index "s" referring to "secondary")

$$0 = -\frac{N_s(R)}{X_{esc}(R)} - \frac{N_s(R)}{X_{spall,\,s}} + P_{p\to s}\frac{N_p(R')}{X_{spall,\,p}}$$

$$\longrightarrow \quad \frac{N_s(R)}{N_p(R')} = \frac{P_{p\to s}}{X_{spall,\,p}\left(\frac{1}{X_{esc}} + \frac{1}{X_{spall,\,s}}\right)}$$

Leaky box approximation with production and destruction terms

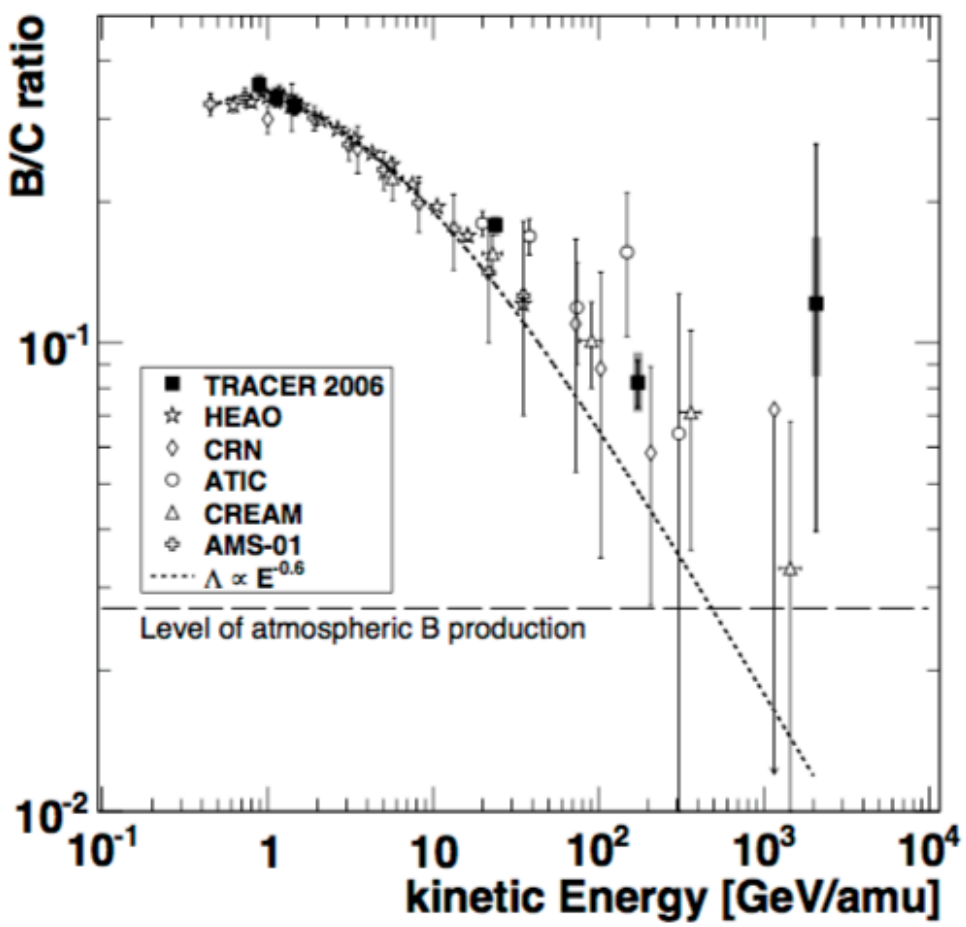


TRACER collaboration 2012

$$\frac{N_s(R)}{N_p(R')} = \frac{P_{p\rightarrow s}}{X_{spall,\,p}\left(\frac{1}{X_{esc}} + \frac{1}{X_{spall,\,s}}\right)}$$

⇒ on average, at ~ 1 GeV/nucleon CRs have gone through a grammage of **X_{RC} ~5 g/cm²** from their sources to the Earth

energy evolution



$$\langle t_{esc} \rangle (R) \propto R^{-\alpha}$$

the residence time is expected to decrease as the energy/rigidity increases
at some point we should have

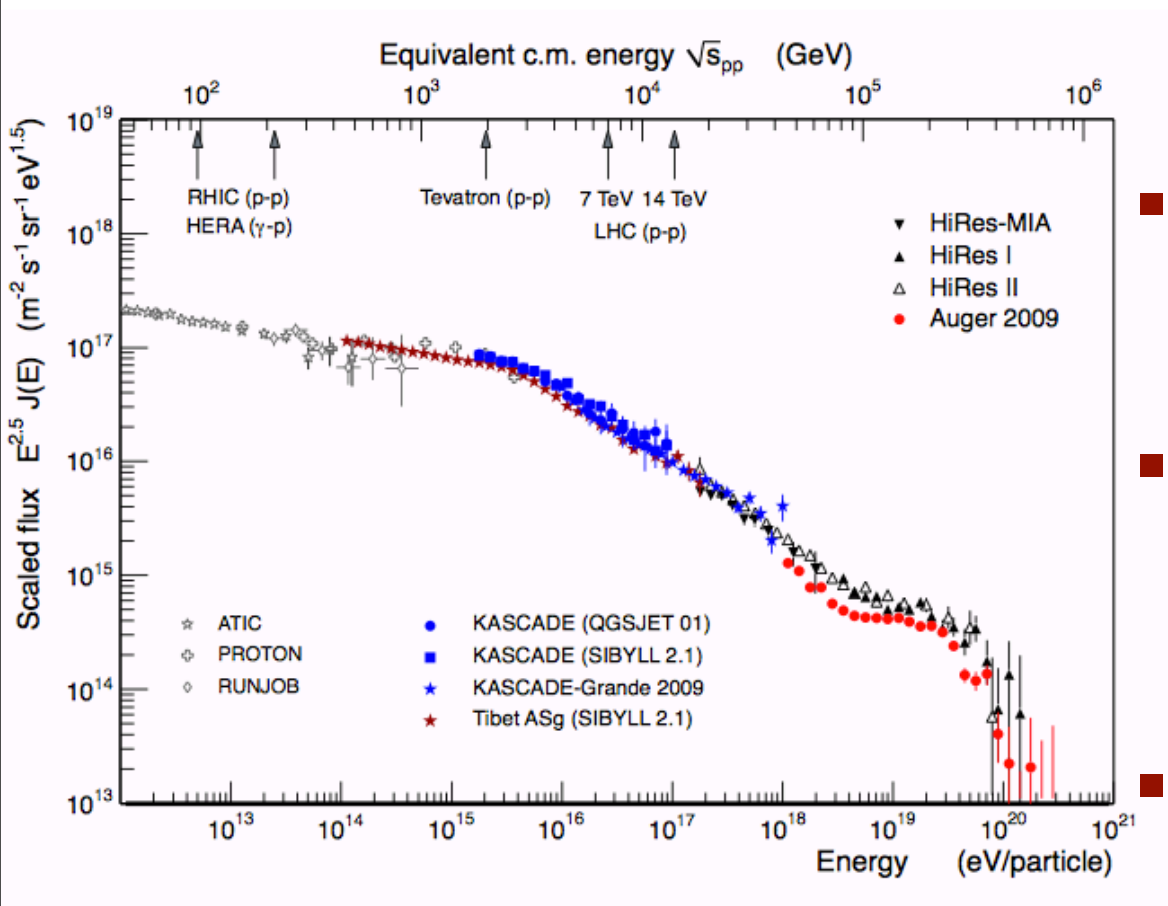
$$X_{spall,\, i} >> X_{esc}$$

$$\frac{N_s(R)}{N_p(R')} = \frac{P_{p \to s}}{X_{spall,\, p} \left(\frac{1}{X_{esc}} + \frac{1}{X_{spall,\, s}} \right)}$$

$$\frac{N_s(R)}{N_p(R')} = \frac{P_{p \to s}}{X_{spall,\, p}} X_{esc}(R)$$

The energy/rigidity evolution can be deduced from the evolution of the secondary to primary ratio !
===> energy evolution of the diffusion coefficient
===> the shape of the source spectrum can be inferred

Interpretation of the shape of the spectrum : slope steepening



- Confinement time of cosmic rays of rigidity R:

$$\langle \tau_{esc} \rangle (R) \propto R^{-\alpha}$$

- Injection rate in the whole Galaxy (spectrum at the sources):

$$q(R) \propto R^{-\beta}$$

- Resulting spectrum in the Galaxy (steady-state)

$$N(R) \propto R^{-(\beta+\alpha)}$$

slope steepening

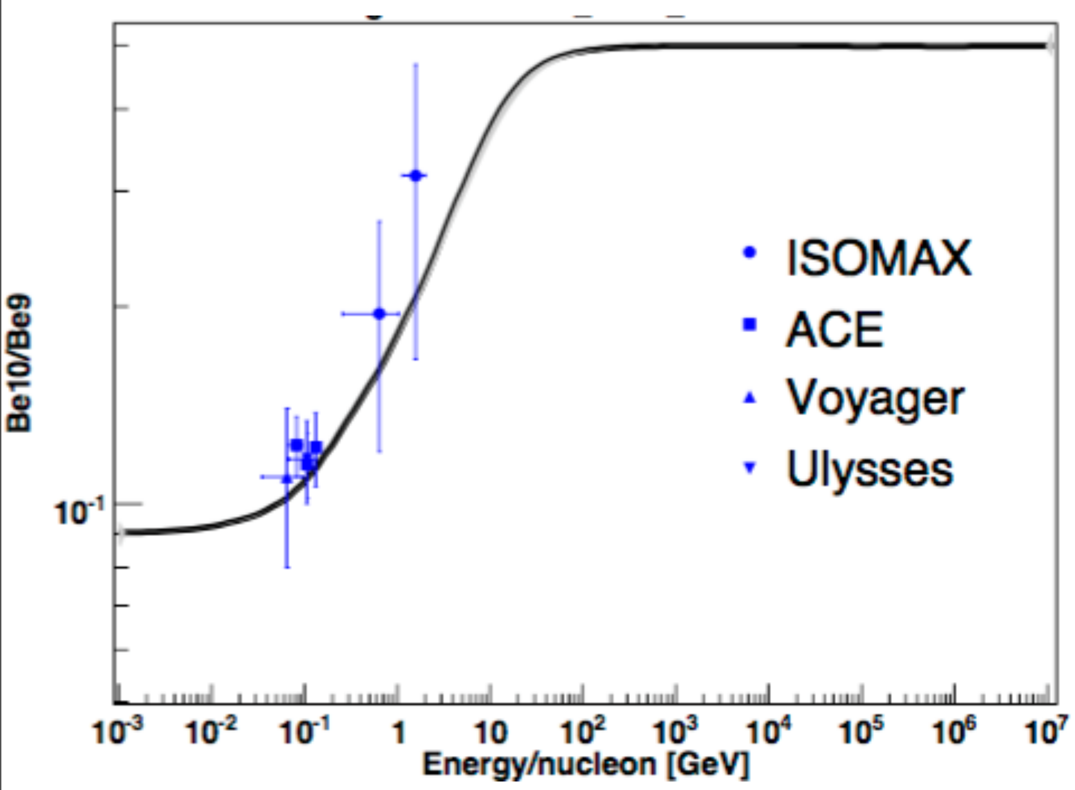
- Measurements give: $\beta+\alpha \simeq 2.7$

From secondary to primary ratios one gets α ≈ 0.3-0.6 (0.6 preferred value)

===> β ≈ 2.1-2.4

cosmic clocks (or how to get access to the propagation time)

- $^{12}C + H \rightarrow {}^{9}Be$ (stable secondary nucleus)
  $^{12}C + H \rightarrow {}^{10}Be$ (unstable secondary nucleus: ~ 1.5 Myr)



Gebauer and W. de Boer (2009)

For a purely secondary (q=0) radioactive element *"rad"*

$$0 = -\frac{N_{rad}(R)}{X_{esc}(R)} - \frac{N_{rad}(R)}{X_{spall,\,rad}} + P_{p\rightarrow rad}\frac{N_p(R')}{X_{spall,\,p}} - \frac{N_{rad}(R)}{X_{decay,\,rad}}$$

$$X_{decay,\,rad} = \bar{m} n \gamma \tau_0^{rad} c$$

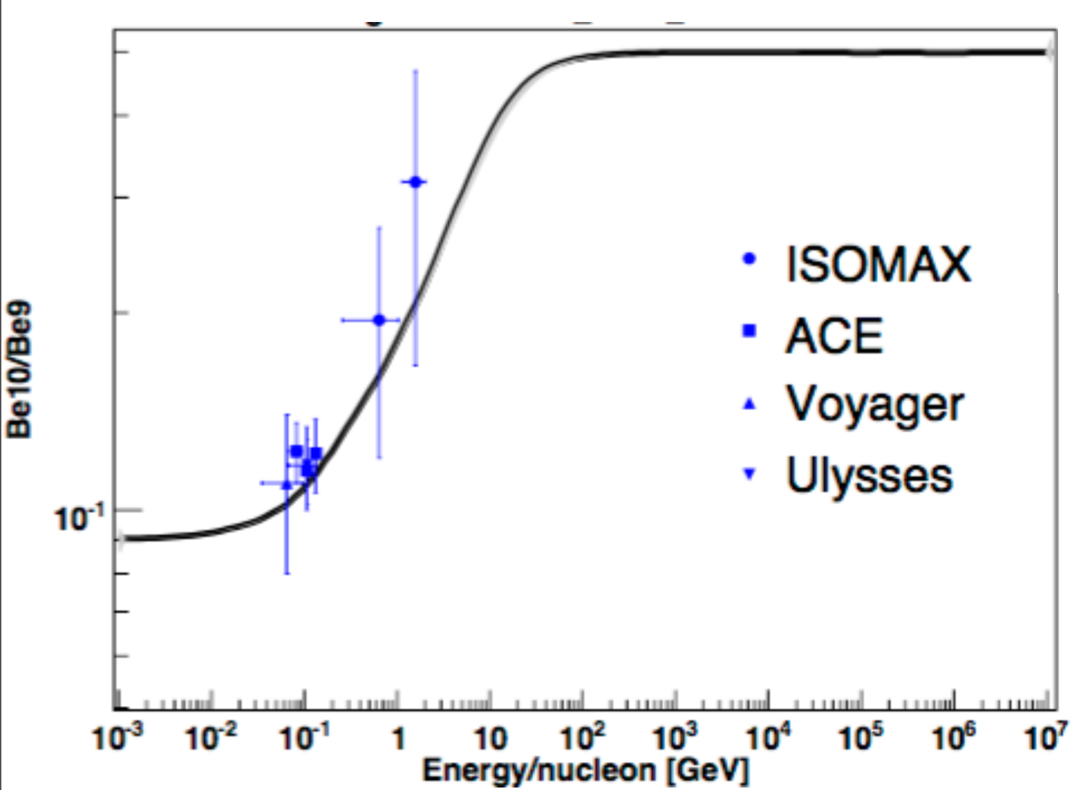
$$\frac{N_{rad}(R)}{N_p(R')} = \frac{P_{p\rightarrow rad}}{X_{spall,\,p}\left(\frac{1}{X_{esc}} + \frac{1}{X_{spall,\,rad}} + \frac{1}{X_{decay,\,rad}}\right)}$$

$$\frac{N_{rad}(R)}{N_{stable}(R)} = \frac{P_{p\rightarrow rad}}{P_{p\rightarrow s}} \frac{\left(\frac{1}{X_{esc}} + \frac{1}{X_{spall,\,s}}\right)}{\left(\frac{1}{X_{esc}} + \frac{1}{X_{spall,\,rad}} + \frac{1}{\bar{m} n \gamma \tau_0^{rad} c}\right)}$$

everything is known or measured but *n* (the mean density of the medium crossed) !!!
at ~ 1 GeV/nucleon $\langle X_{esc} \rangle \sim 5$ g.cm^{-2} ==> $n \sim 0.3$ cm^{-2}

cosmic clocks (or how to get access to the propagation time)

- $^{12}C + H \rightarrow\ ^{9}Be$ (stable secondary nucleus)
  $^{12}C + H \rightarrow\ ^{10}Be$ (unstable secondary nucleus: ~ 1.5 Myr)



Gebauer and W. de Boer (2009)

$$\frac{N_{rad}(R)}{N_{stable}(R)} = \frac{P_{p\to rad}}{P_{p\to s}} \frac{\left(\frac{1}{X_{esc}} + \frac{1}{X_{spall,\,s}}\right)}{\left(\frac{1}{X_{esc}} + \frac{1}{X_{spall,\,rad}} + \frac{1}{\bar{m}n\gamma\tau_0^{rad}c}\right)}$$

everything is known or measured but *n* (the mean density of the medium crossed) !!!

at ~ 1 GeV/nucleon $<X_{esc}>\sim 5$ *g.cm*$^{-2}$ ==> *n*~0.3 *cm*$^{-2}$

from $X = \bar{m}nvt$

we get τ_{esc} **~ 2 10^{7} years around 1 GeV/nucleon**

Interpretation of the value of *n* :
in the Galactic disk the mean density is ~ 1 cm^{-3}
if the cosmic had propagated exclusively in the disk, we should have found ~ 1 cm^{-3}
===> a good fraction (2/3rd)of their propagation time must have been spent in emptier regions
===> in the Galactic halo

[+ ^{26}Al, ^{36}Cl, ^{53}Mn, ^{54}Mn, ^{59}N]

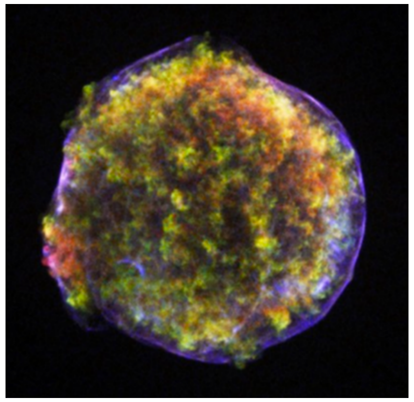
what are the sources?

- ~1 eV/cm^3 in a confinement volume of 15kpc radius and ~5 kpc of vertical scale (halo), renewed every 2 10^7 years
  L_{CR}~10^{41} erg.s^{-1}
- 1 SN of 10^{51} erg every 30 years
  L_{SN}~10^{42} erg.s^{-1}

⇒ ~10% of the SN energy goes to cosmic-rays

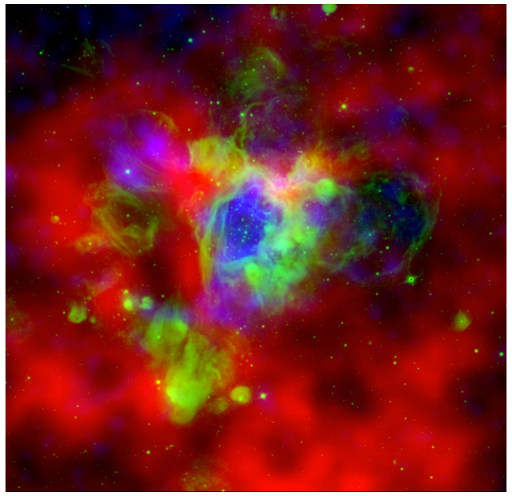
Supernova/cosmic-ray connexion, an energetic argument :
10-20% of the luminosity released by supernovae in the galaxy would by enough to produce all the galactic cosmic-rays

➡ "standard" model : supernova remnants are the sources of galactic cosmic-rays



This hypothesis has however some problem :
- maximum energy
- some aspects of the composition of low energy cosmic-rays

Superbubbles could be an attractive alternative but the role played by collective effect is not well understood



Life is more complicated

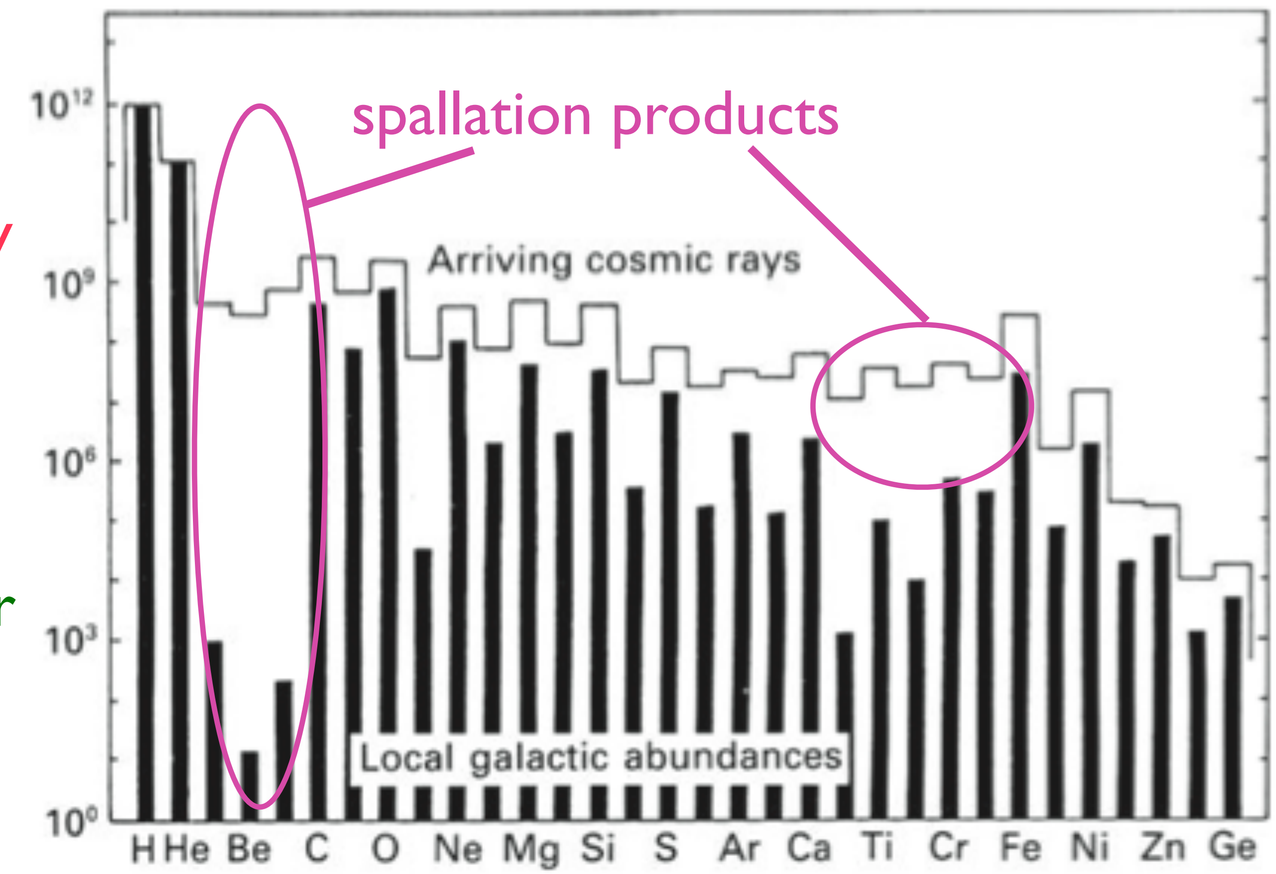
✤ We saw that most of the LiBeB nuclei we see in the Galaxy originate from cosmic-ray spallation

✤ These "secondary" nuclei give us a wealth of information about the propagation of Galactic cosmic-rays

✳ Reality is of course much more complex than the toy model we have built !

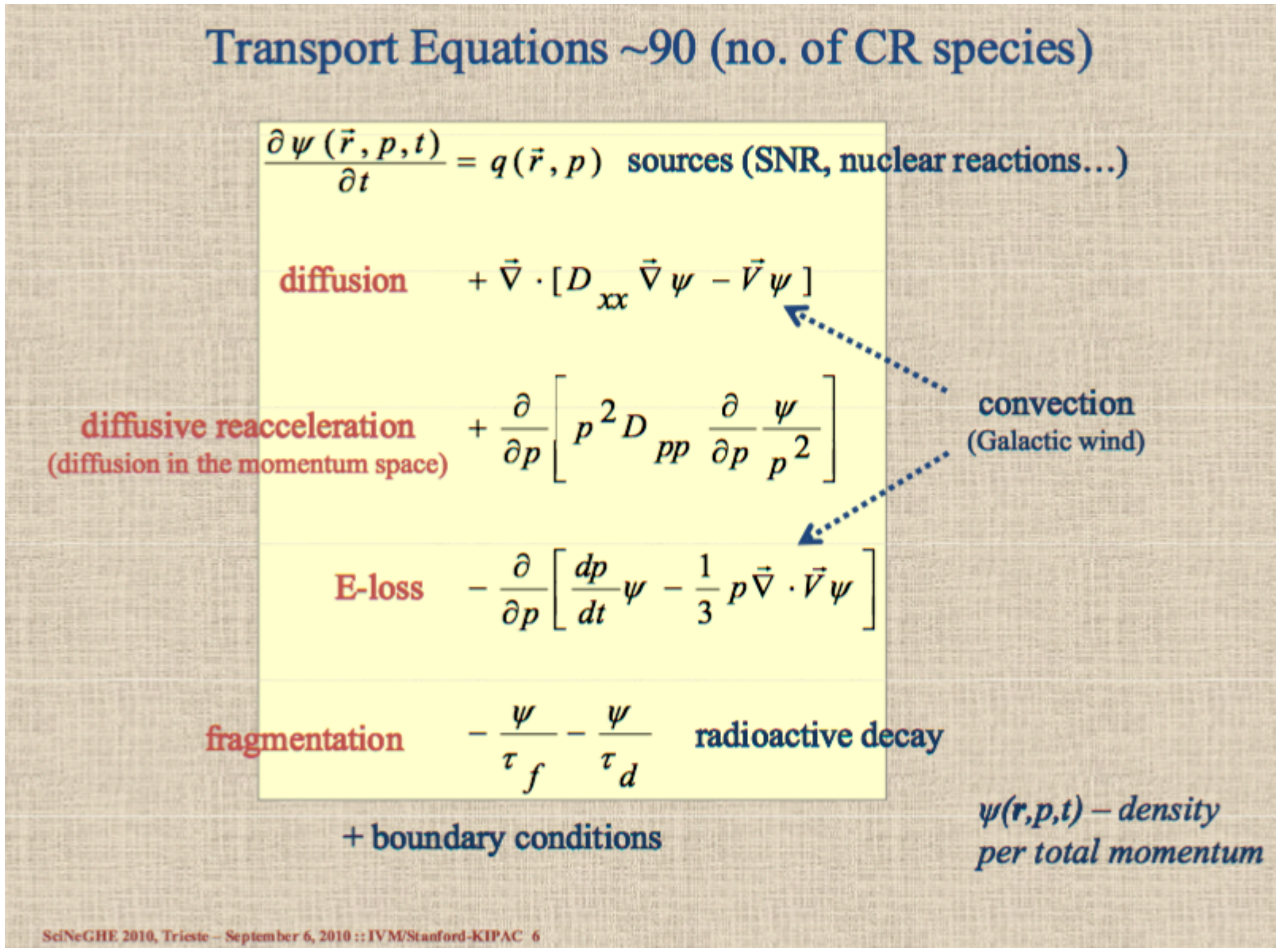
The same informations (X_{esc}, n, t_{esc}) can be obtained by analyzing sub-Fe group elements (also produced almost exclusively by spallation)

===> the results obtained should be consistent with all the different measurements especially for the other "purely secondary nuclei" and the cosmic clocks



[+ ^{26}Al, ^{36}Cl, ^{53}Mn, ^{54}Mn, ^{59}N]

Life is more complicated



Slide from a talk of I. Moskalenko coauthor of the GALPROP simulation framework

To get more constraints on Galactic cosmic-ray origin, one must solve a system of coupled very complicated diffusion equations and build/use elaborated models for :

- the spatial distribution of the sources in the Galaxy
- the cosmic-ray spectrum emitted from the sources (and ideally the source to source variability)
- the spatial variation of the diffusion coefficients
- the spatial variation of matter density in the Galaxy
- nuclear interactions

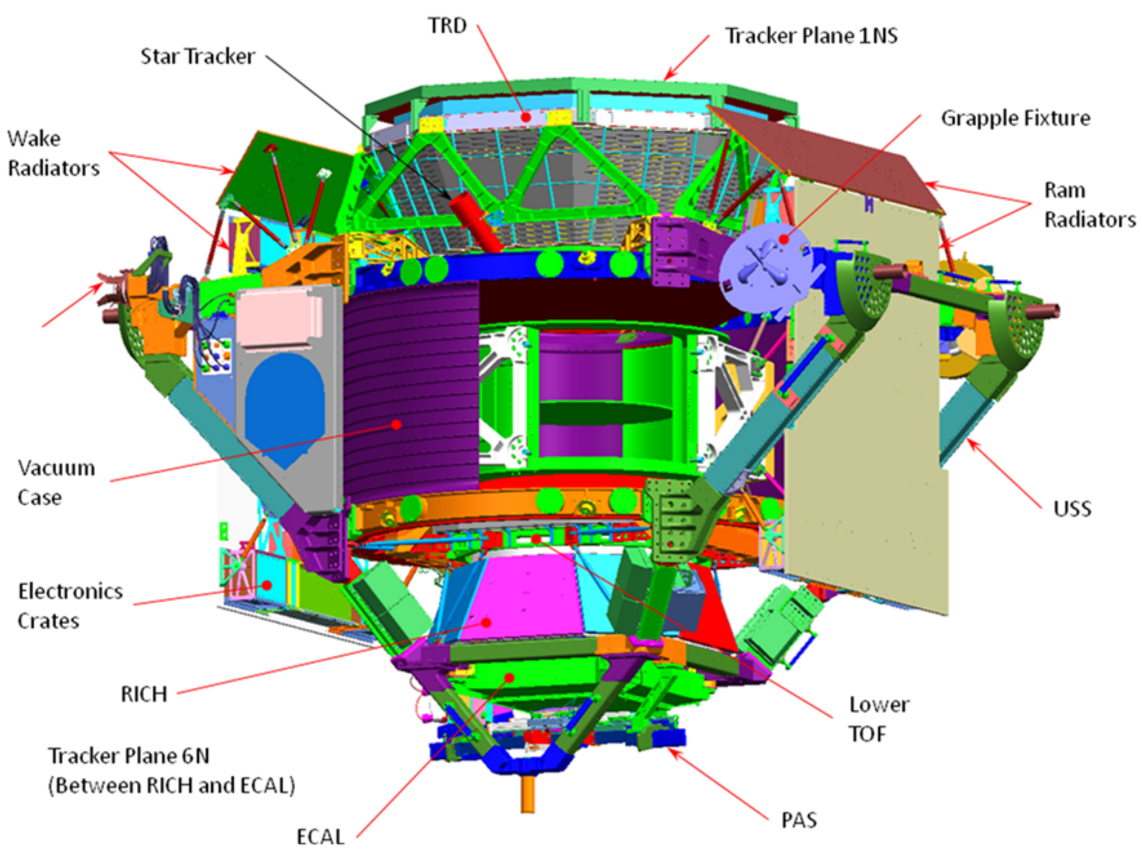
Satisfying models must reproduce the cosmic-ray spectrum and composition observed on earth as well as secondary observations (Galactic gamma-ray background measured by FERMI)

Very complicated numerically, simplifying assumptions (spatial evolution of the diffusion coefficient, continuous source distributions, standard candles, etc...)

===> puzzle of Galactic cosmic-rays not yet solved

===> interesting constraints expected from gamma-ray observations of SNRs and superbubbles

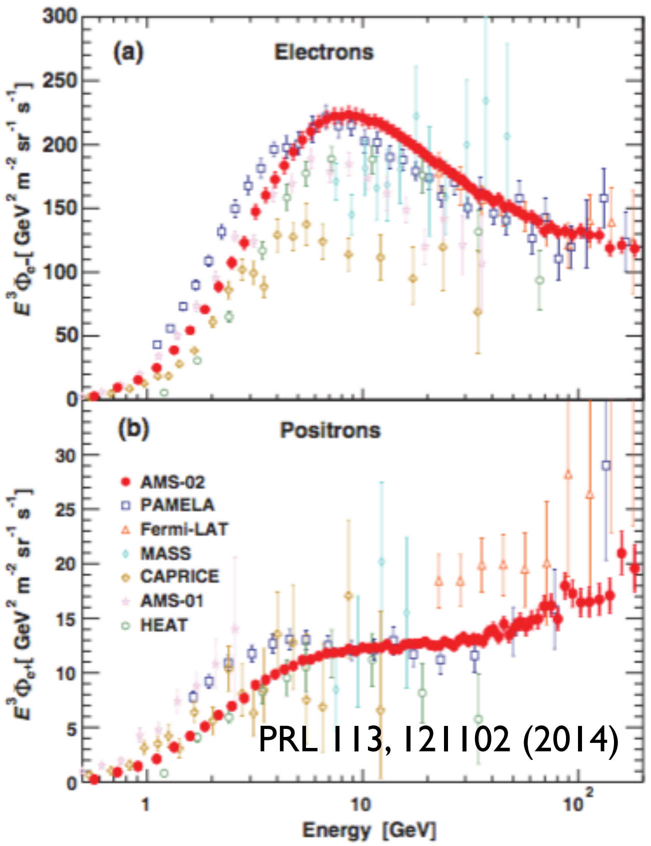
AMS02 : the most advanced cosmic-ray detector ever sent to space

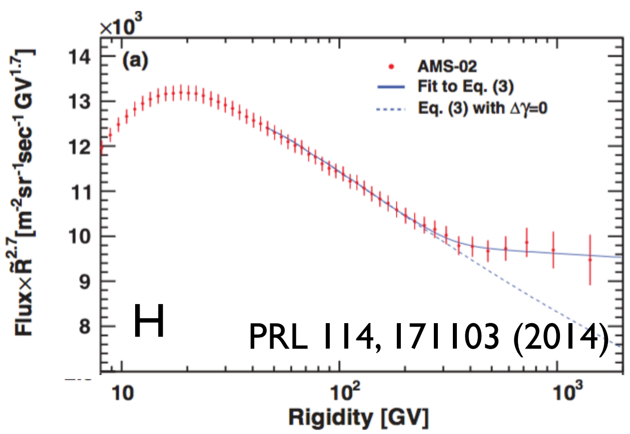


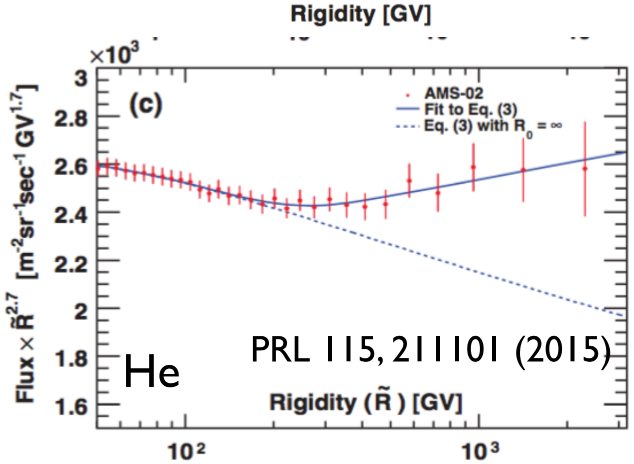
- 1998 AMS01 flight in the space shuttle
- AMS program on hold after Columbia's crash in 2003
- AMS back in Nasa's program in 2010
- AMS02 installed on the ISS in May 2011

- ~ 40 millions triggers per day -> 16 billions per year
- 39 TB of data per year
- 60 billions events collected so far
- High statistics and high resolution measurement of CR nuclei and e^+e^- from ~1 GV to ~2 TV
- publication of the first results started in 2013

AMS02 : first physics results



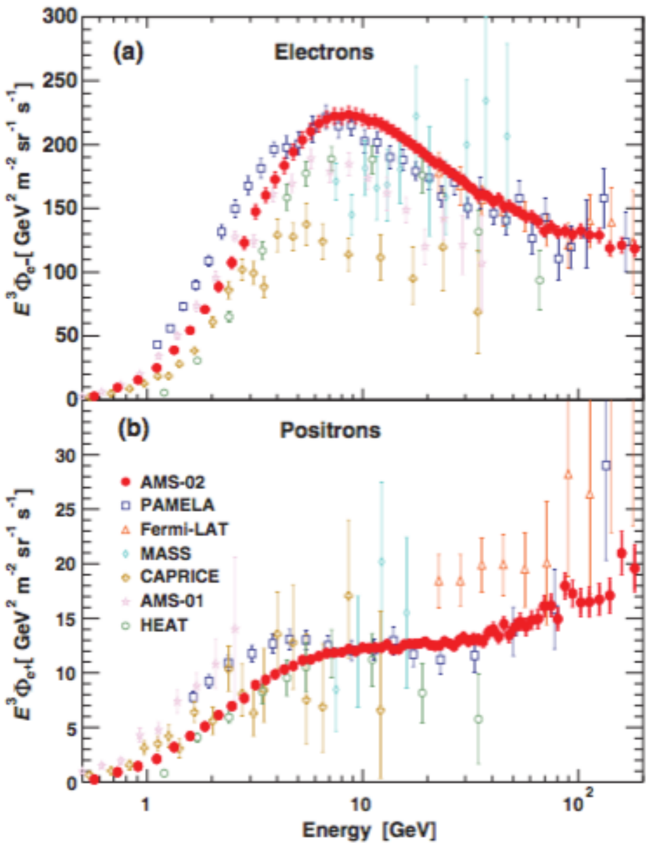




Measurements of the flux and spectrum of e^+ and e^-
first strong evidence for a significantly harder spectrum for positrons at high energy
--> already strong constrains on astrophysical (local source(s)) and dark matter scenarios
--> of course statistics will improve

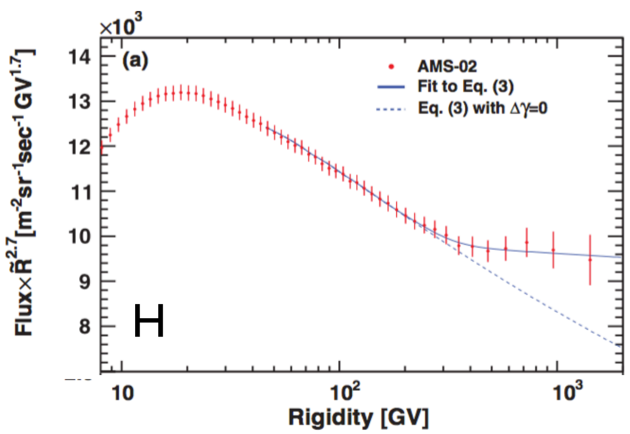
Measurements of the flux of H and He CRs
- confirmation of the presence of a spectral hardening around ~200 GV
(already claimed by PAMELA but measured by AMS02 with a higher resolution and statistics)
- difference of the spectral shape of H and He
---> very intriguing result, constraining for astrophysical models !
---> a lot of theoretical/phenomenological efforts dedicated to understand these features (acceleration, propagation, local sources)

AMS02 : more to come



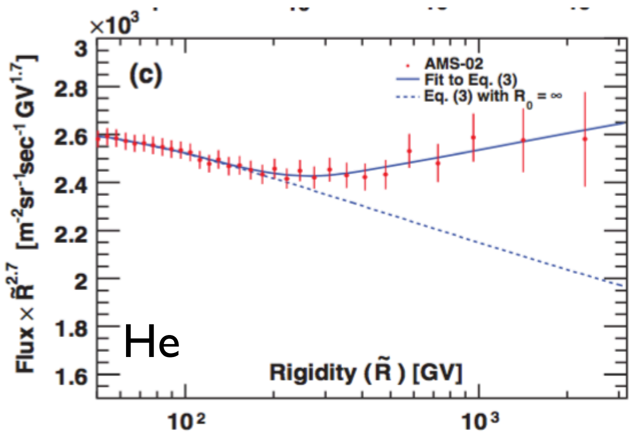
Other new analyses expected to be released soon (some results were hinted at the conference "AMS days at CERN"):

- Li
- C,O
- B/C (secondary to primary ratio)
- heavier nuclei
- isotopic ratios

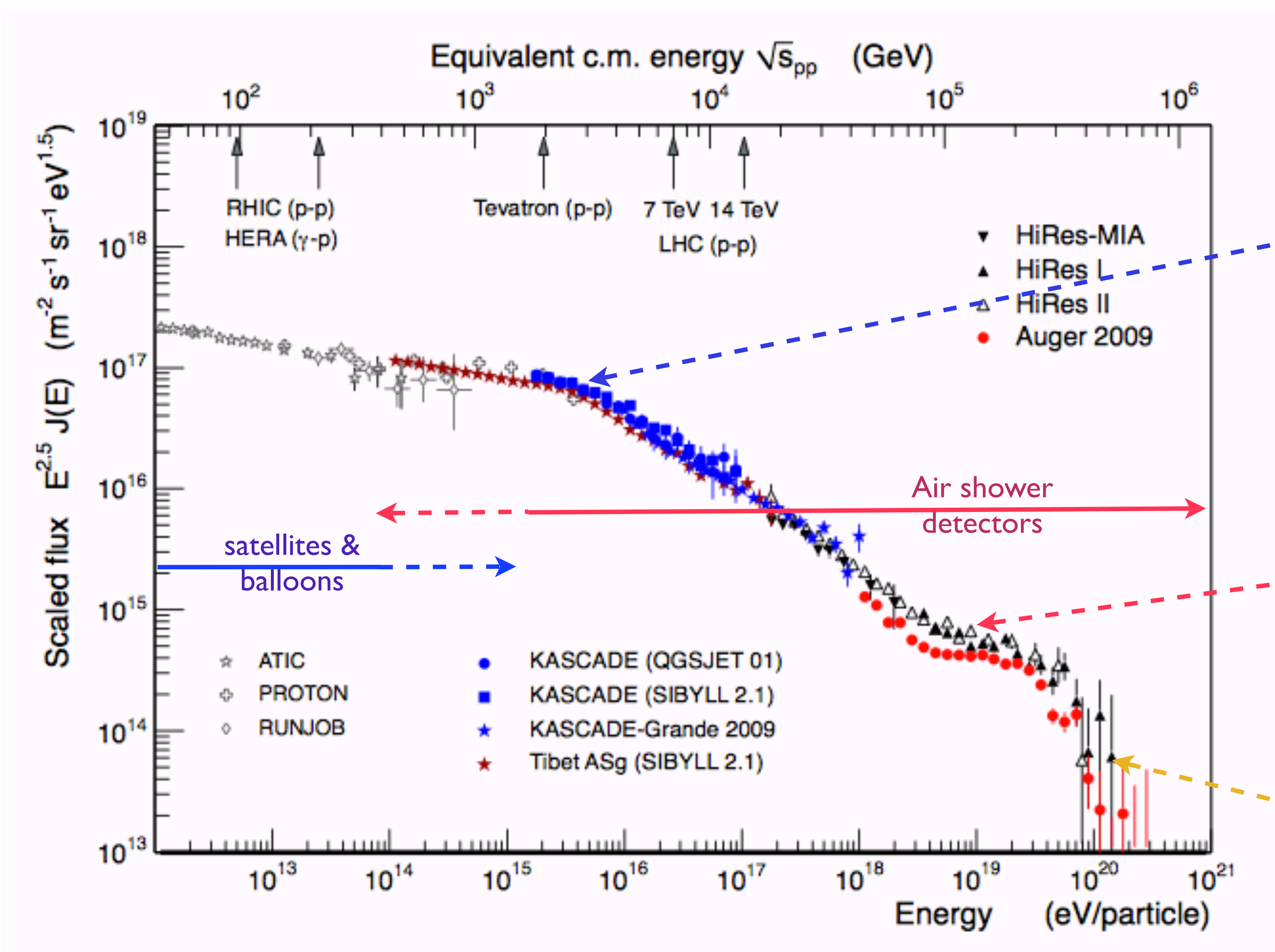


--> do heavier nuclei present the same hardening as H and He?

--> high resolution measurements of secondary nuclei at high energy important to constrain astrophysical scenarios



Very high and ultra-high energy cosmic-rays

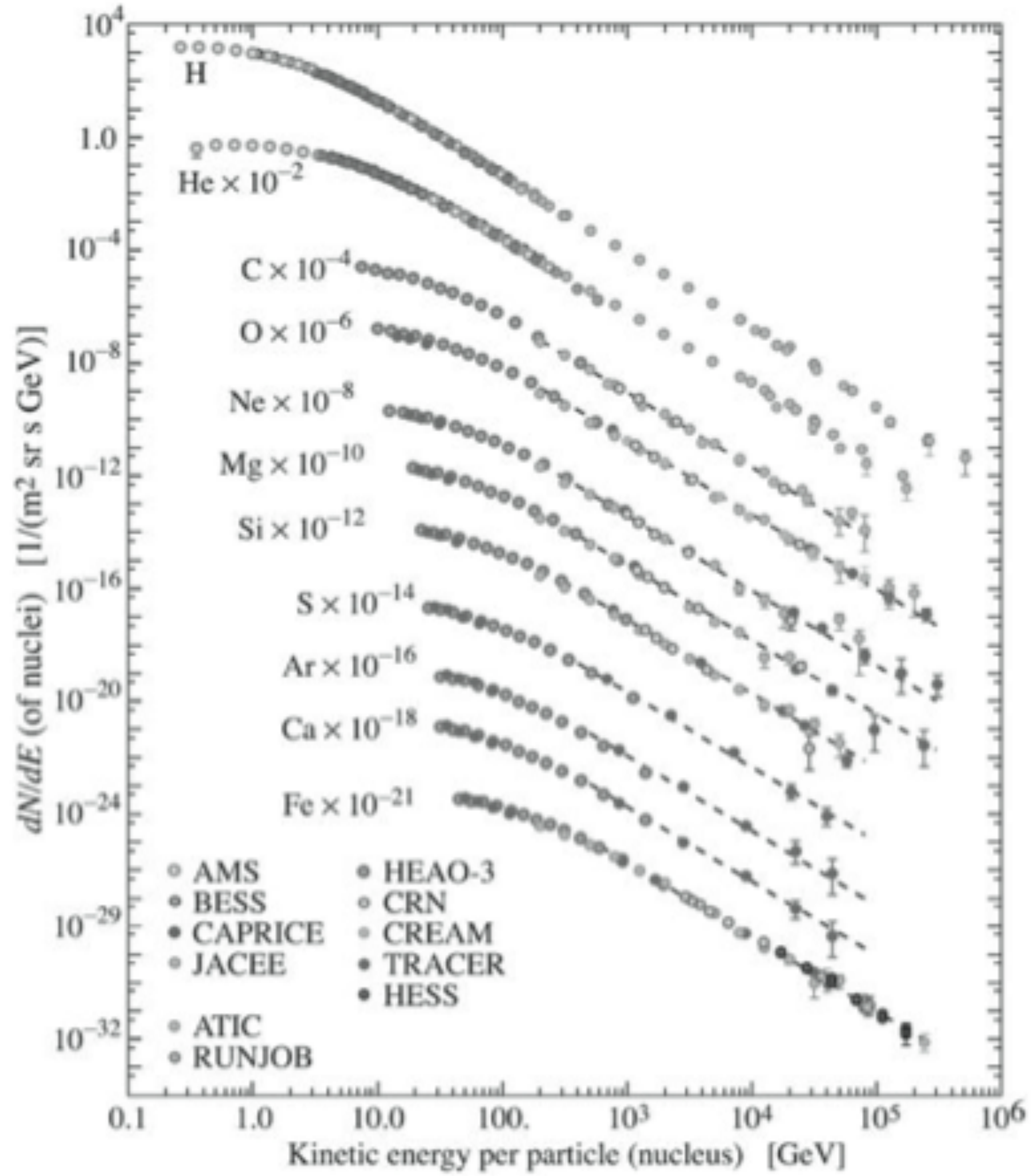


The knee
$E{\sim}3\text{-}4.10^{15}$ eV

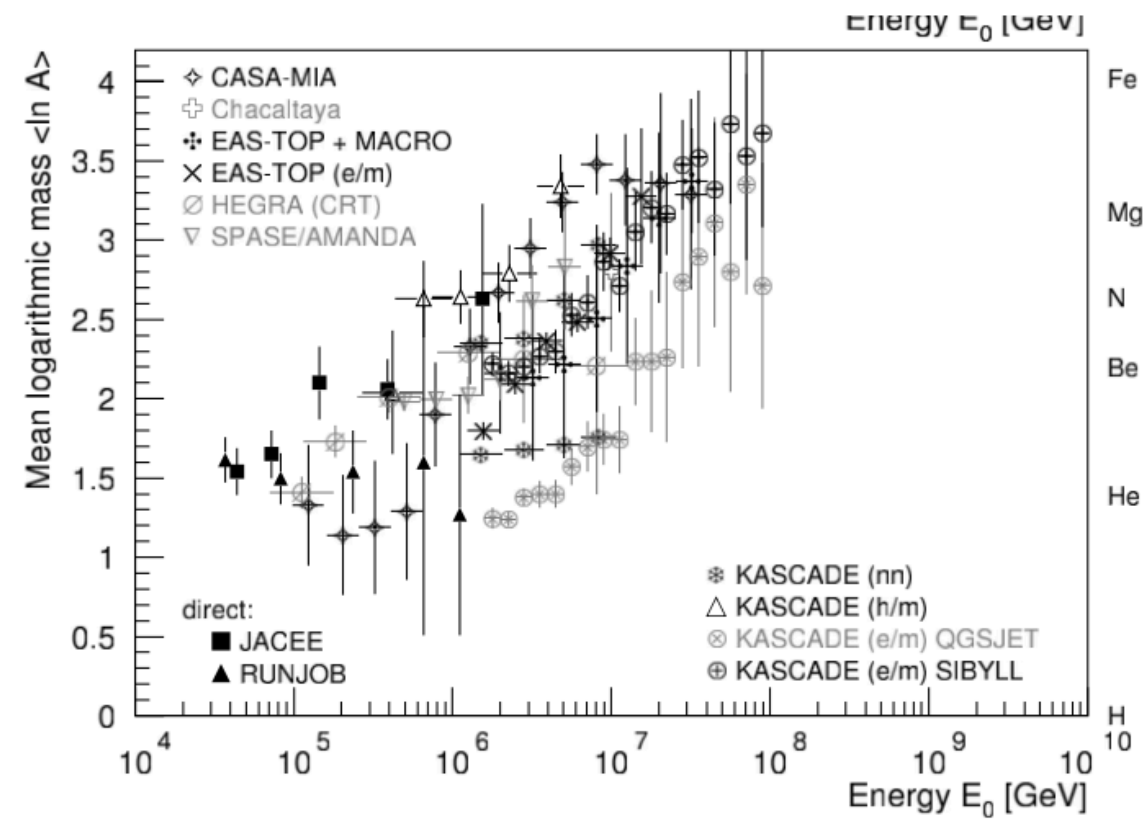
The ankle
$E{\sim}3\text{-}4.10^{18}$ eV

High energy cut-off
$E{\sim}3\text{-}5.10^{19}$ eV

Situation below the ankle



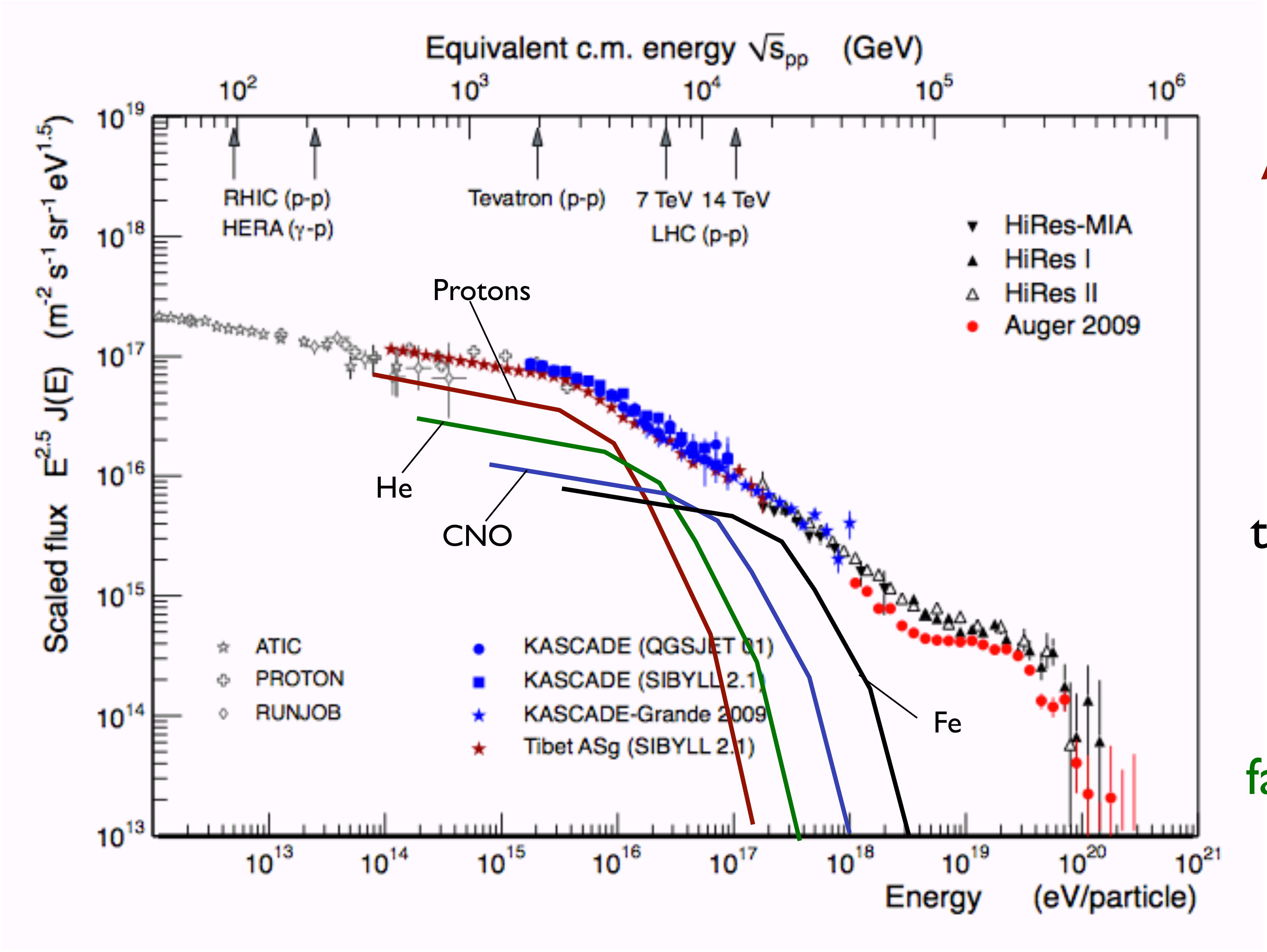
Composition between 10^{10} and 10^{14} eV
(balloons et satellites)
Spectra of the different elements ~ parallel
relative abundances do not evolve strongly
with the energy



compilation par Blumer et al., 2009

Composition between 10^{14} and 10^{17} eV
(only from the ground above ~ 10^{15} eV)
composition clearly becoming heavier in
knee region and above

How to understand a composition getting heavier above the knee ?



Pierog, 2012

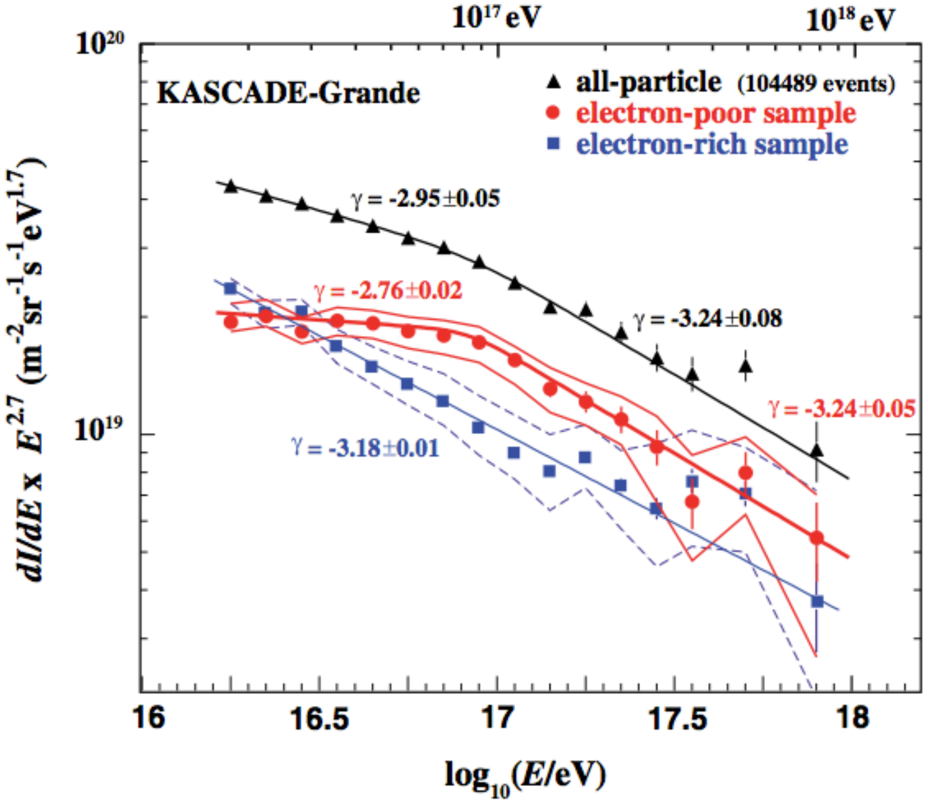
A logical interpretation would be that the knee marks the energy at which most galactic sources become unable to accelerate protons

The other elements follow the same trend at energies proportional to their charge

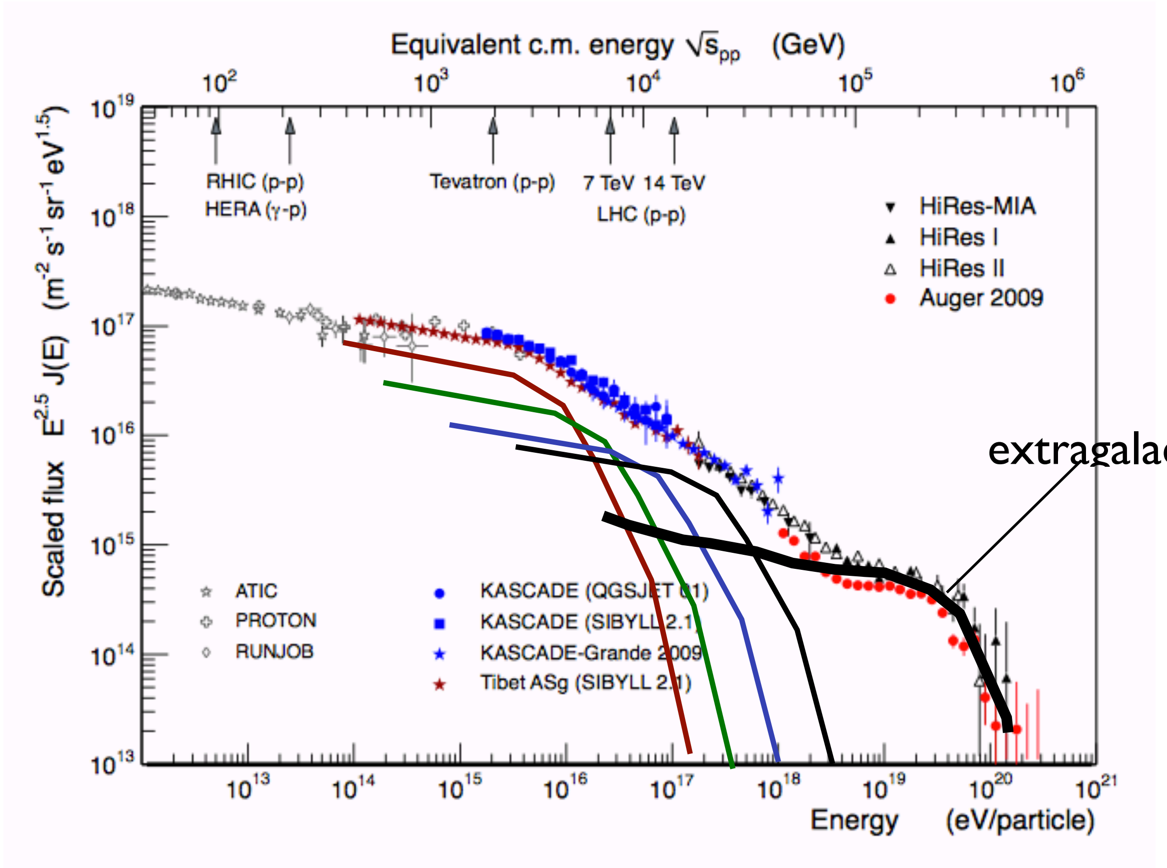
the galactic component decreases faster above the knee but not as fast as if there were only protons

quite logical interpretation, but a few other exist (with the same implication for the evolution of the composition)

Evidence for a “heavy knee”

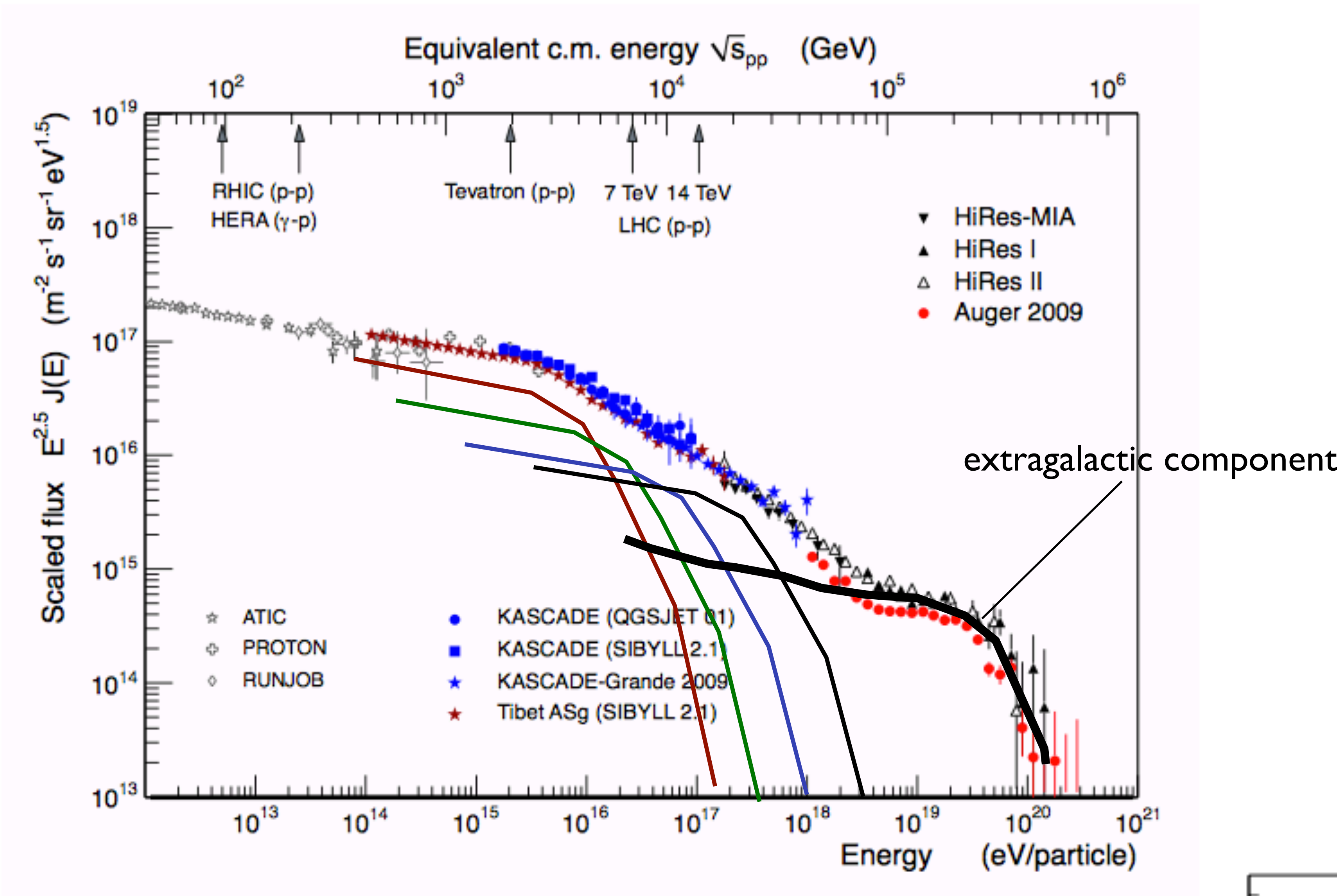


KG collab, Phys. Rev. Lett., 2011



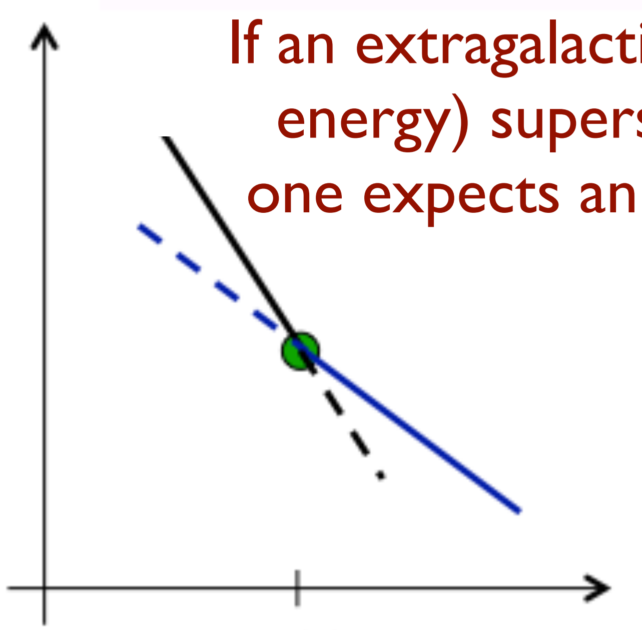
- Significant break of the heavy component (supposed to be Si+Fe) spectrum seen for all hadronic models
- Moderate change of spectral index ~0.5 in all cases
- The heavy component does not seem to disappear immediately after its knee (smooth knee rather than sharp)
- The heavy component still seems to be significantly there at 10^{18} eV in all case
- The hadronic model dependence is mostly found in the relative abundance of the heavy component (not in the existence or the sharpness of the break)

After the knee... the ankle

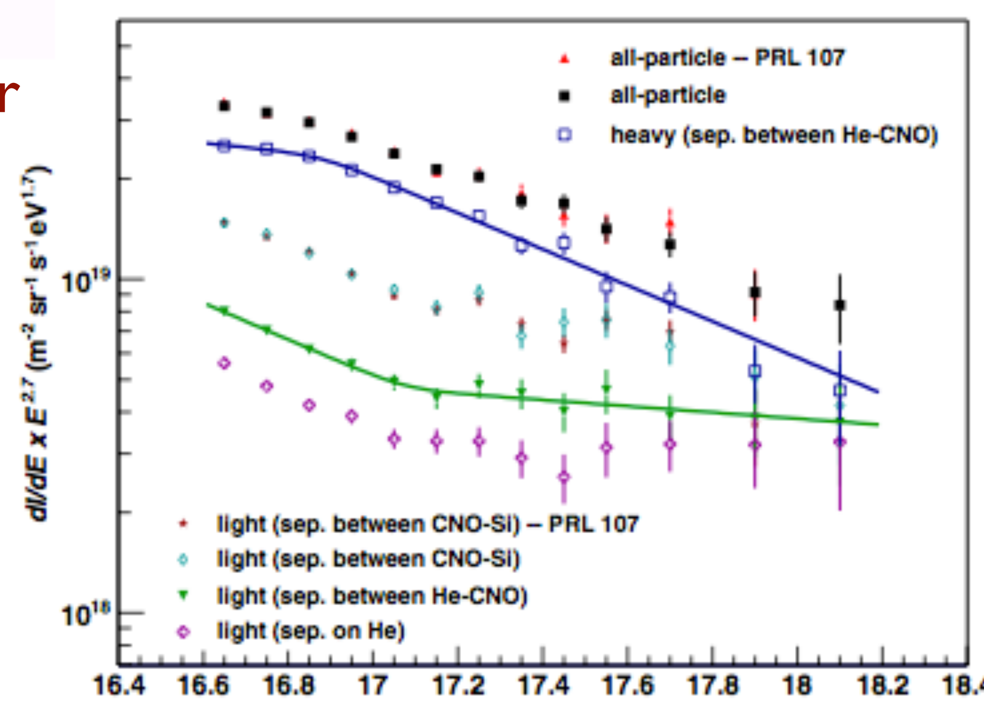


Hypothesis supported by composition analyses between 10^{17} and 10^{18} eV

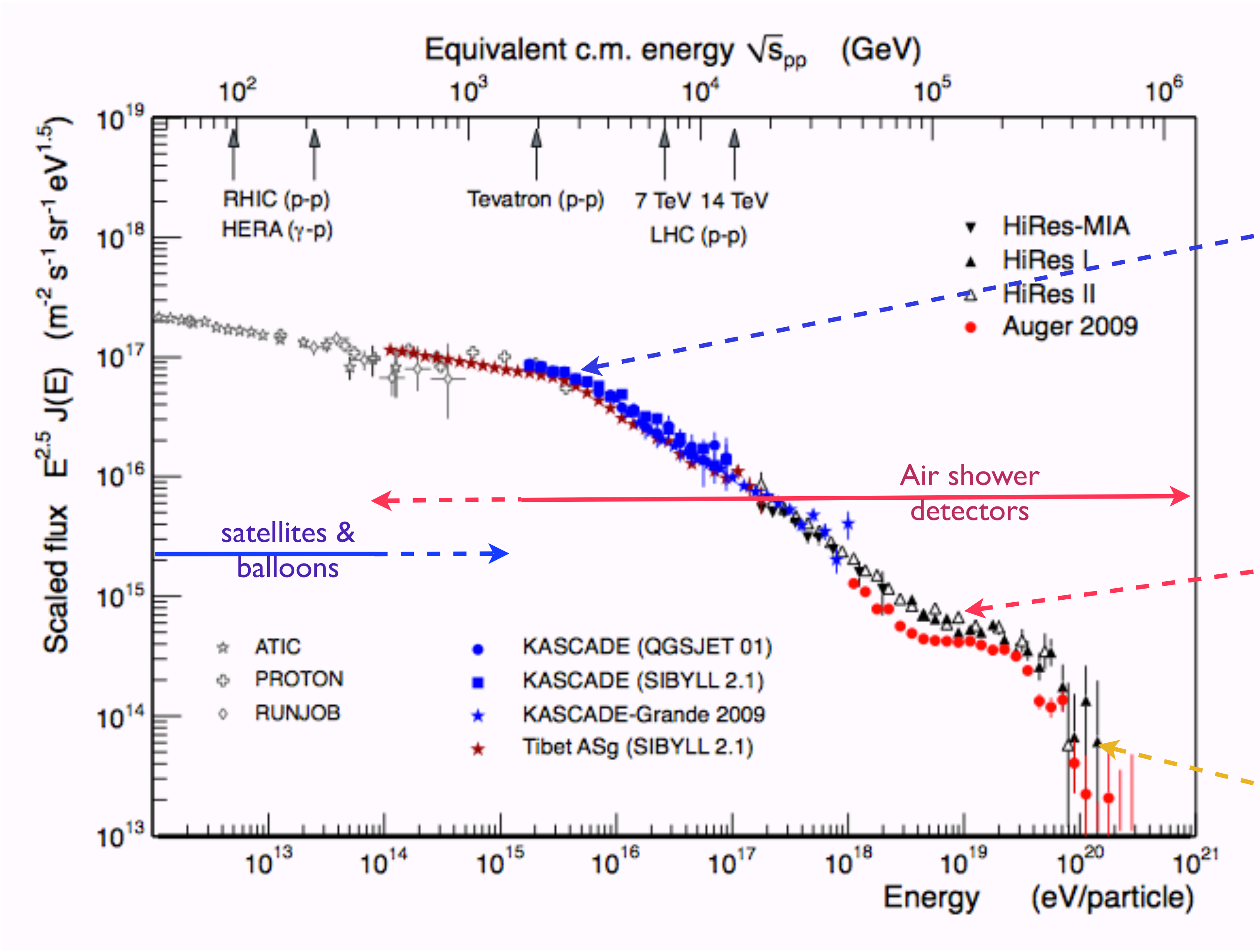
If an extragalactic component (subdominant at lower energy) supersedes the dying galactic component one expects an ankle like structure in the spectrum



PHYSICAL REVIEW D 87, 081101(R) (2013)



The cosmic-ray spectrum



The knee
E~3-4.10^{15} eV

The ankle
E~3-4.10^{18} eV

High energy cut-off
E~3-5.10^{19} eV

Pierog, 2012

There are three orders of magnitude in energy between to the knee and the ankle

what is happening on this energy range?

==> problematic of the transition from Galactic to extragalactic cosmic-rays

Detection of very high and ultra-high energy cosmic-rays from the ground

above 10^{14} eV :

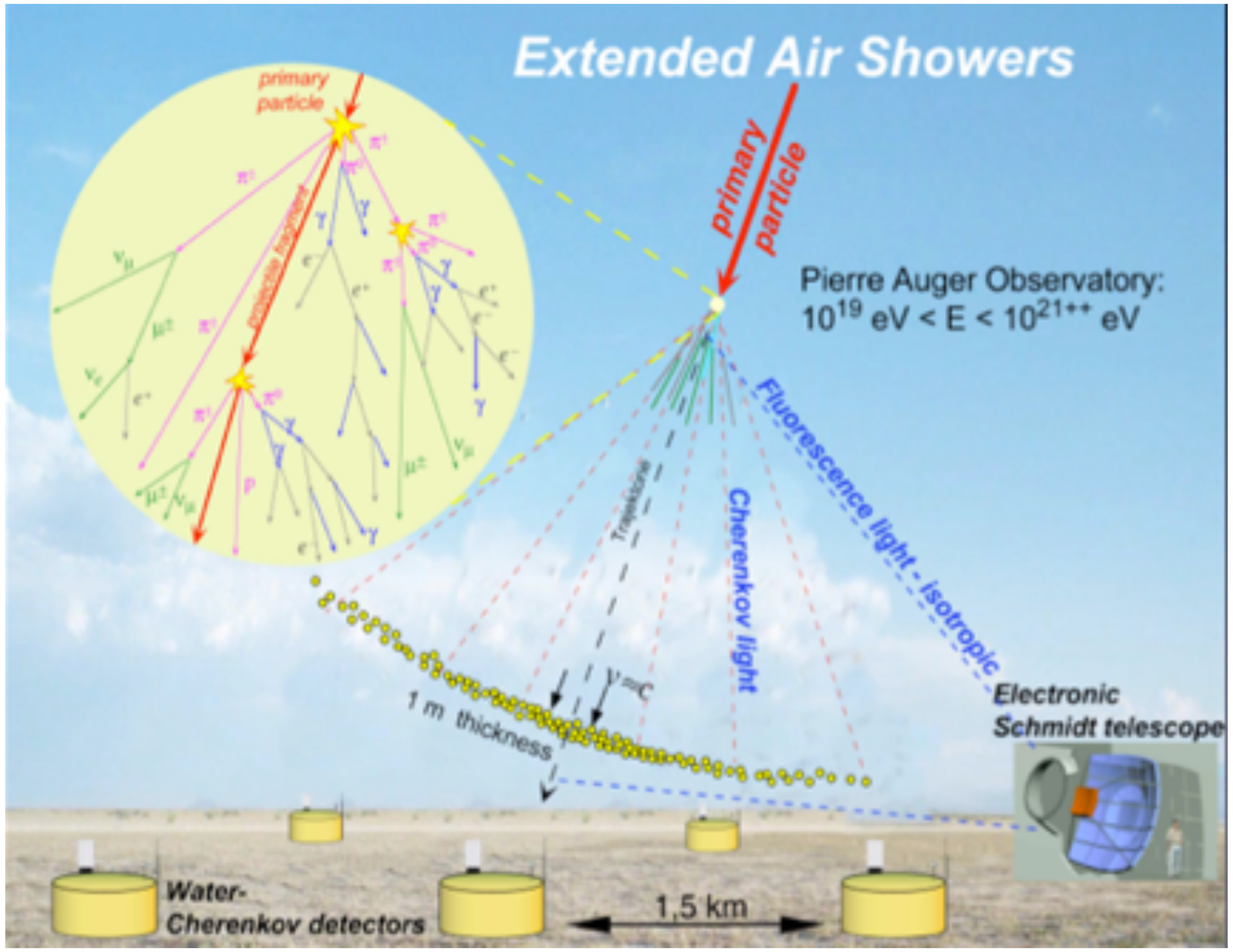
• fluxes are too low to be detected by balloons and satellites

➡ ground based observatories detect and reconstruct air showers to estimate the characteristics of the primary cosmic-rays

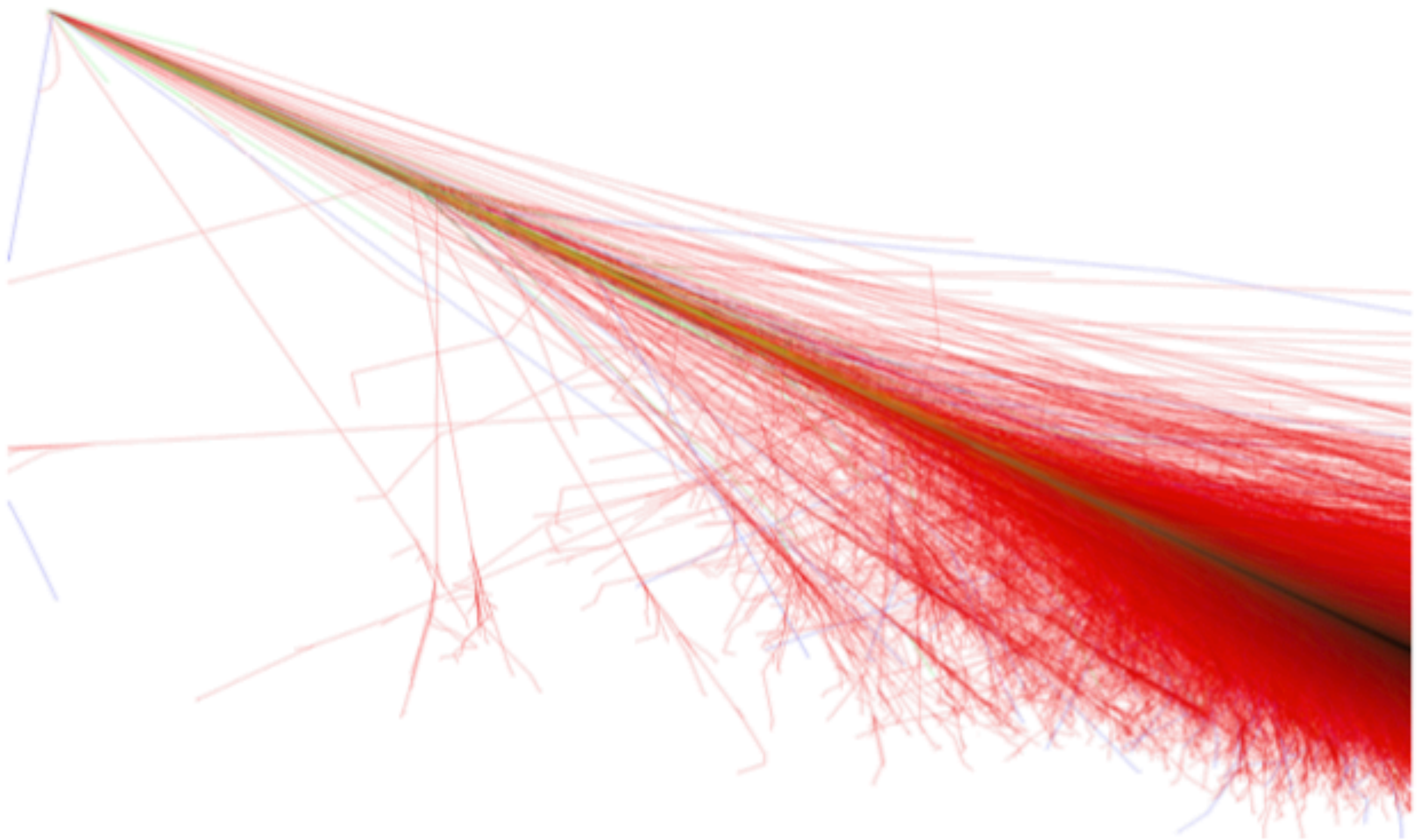
• Mainly two types of ground based detectors :

➡ surface arrays

➡ fluorescence telescopes



Air showers detection



For a single air shower
- the cosmic-ray primary energy can be reconstructed quite precisely

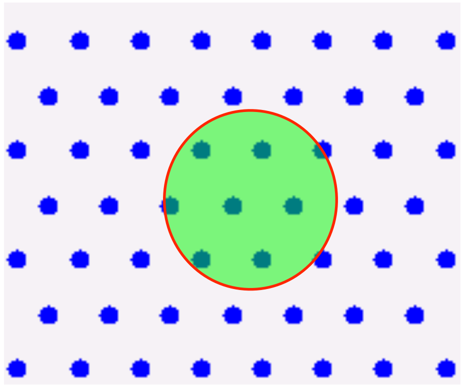
- the cosmic-ray arrival direction can also be reconstructed precisely

- the composition cannot be reconstructed on a shower by shower basis ==> "shower to shower fluctuations" ==> one needs a large dataset at a given energy to isolate subsets of "light" (proton, He), "intermediates" (CNO) or "heavy" (Si, Fe) primaries

Ground arrays

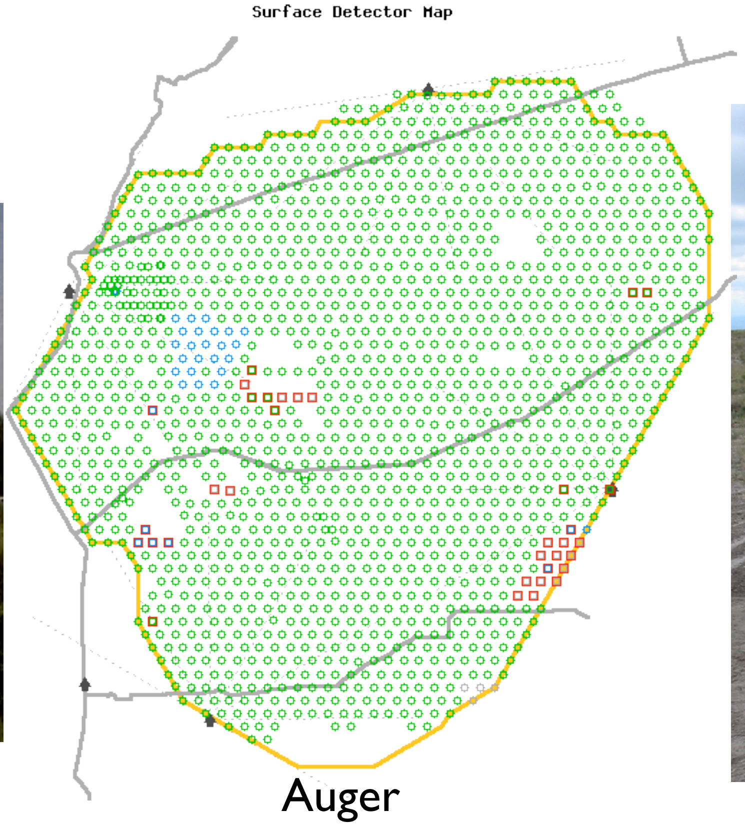
Sampling of the particle content of air showers at ground level

- The area covered and the spacing between detectors depends on the energy range studied
- Kascade (10^{15}-10^{17} eV) : area 40000 m^2, 252 detectors, spacing 13m
- Auger (10^{18}- >10^{20} eV) : surface 3000 km^2, 1600 detectors, spacing 1500 m



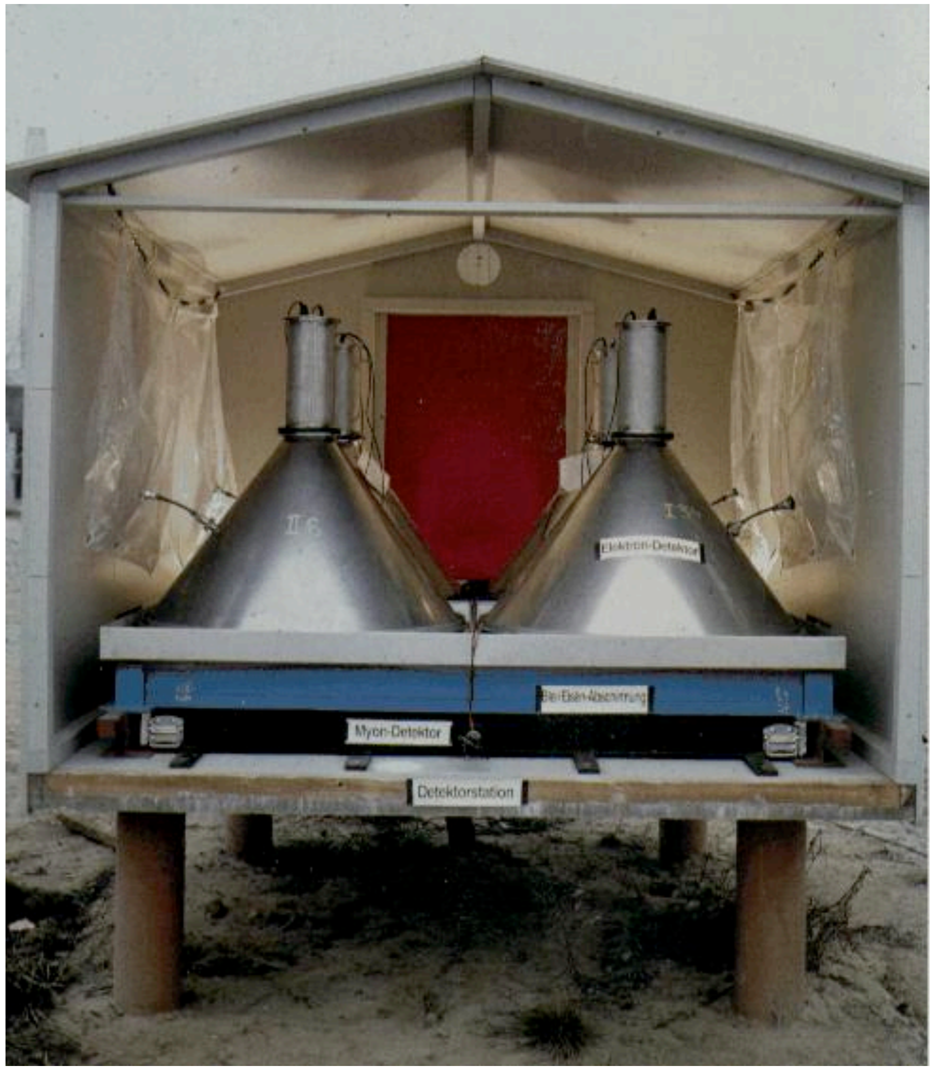
- Different types of detectors :
  - Scintillators (Kascade) (==> electrons)
  - Shielded Scintillators (Kascade) (==> muons)
  - Water Cerenkov tanks (Auger) (==> all particles)

Kascade



Auger

Ground arrays



Liquid scintillators => e^+e^-

Shielded plastic scintillators => muons

Kascade

Kascade-Grande

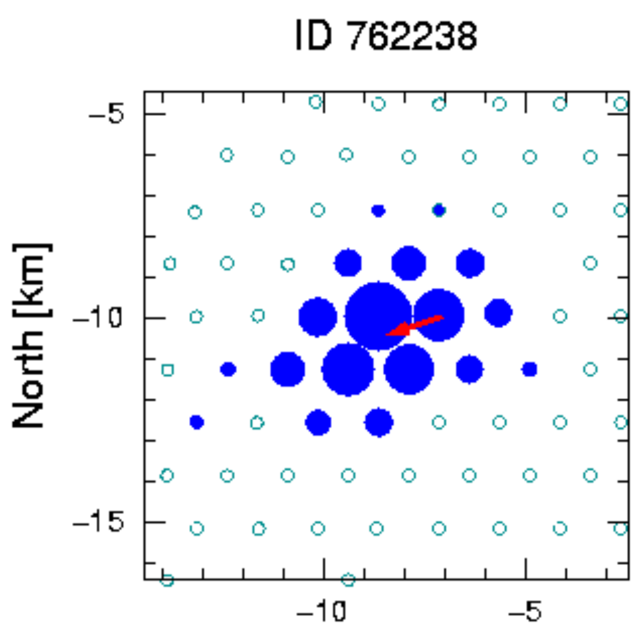
Ground arrays

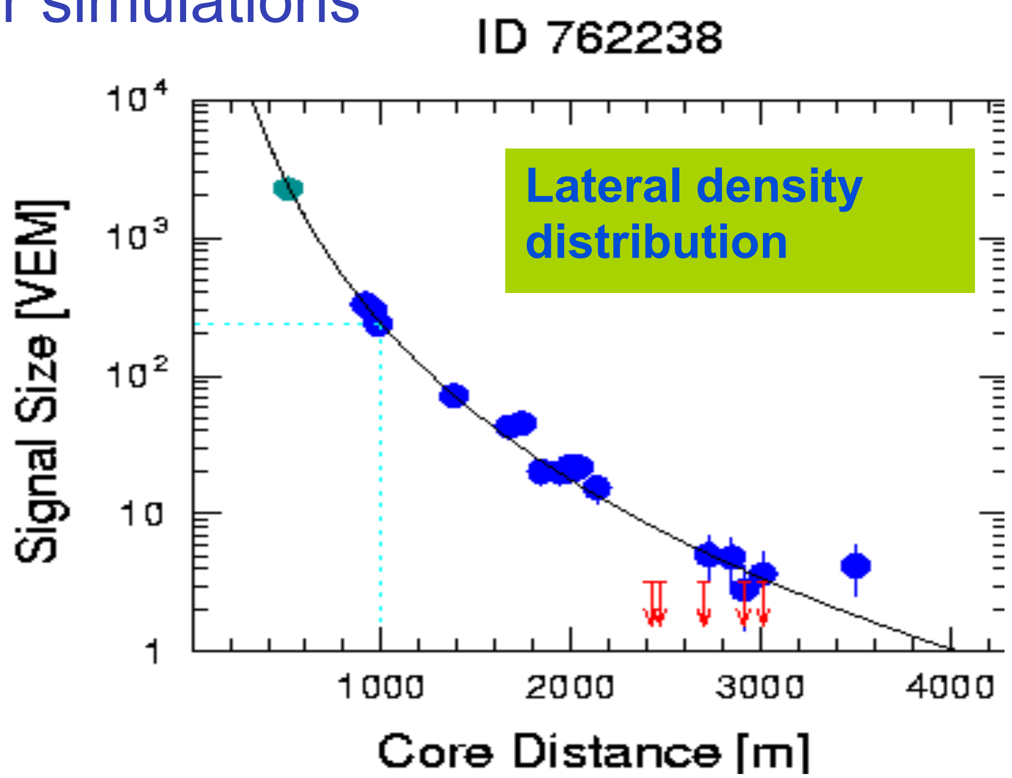
- Reconstruction method
- Direction estimated using the time structure of the shower front
- Energy reconstructed using the evolution of the signal with the distance to the shower core
- nature of the primary particle estimated using the muon number (not on a shower by shower basis)

The Signal/Energy relation is deduced from air shower simulations

The muon number/composition relation is deduced from air shower simulations

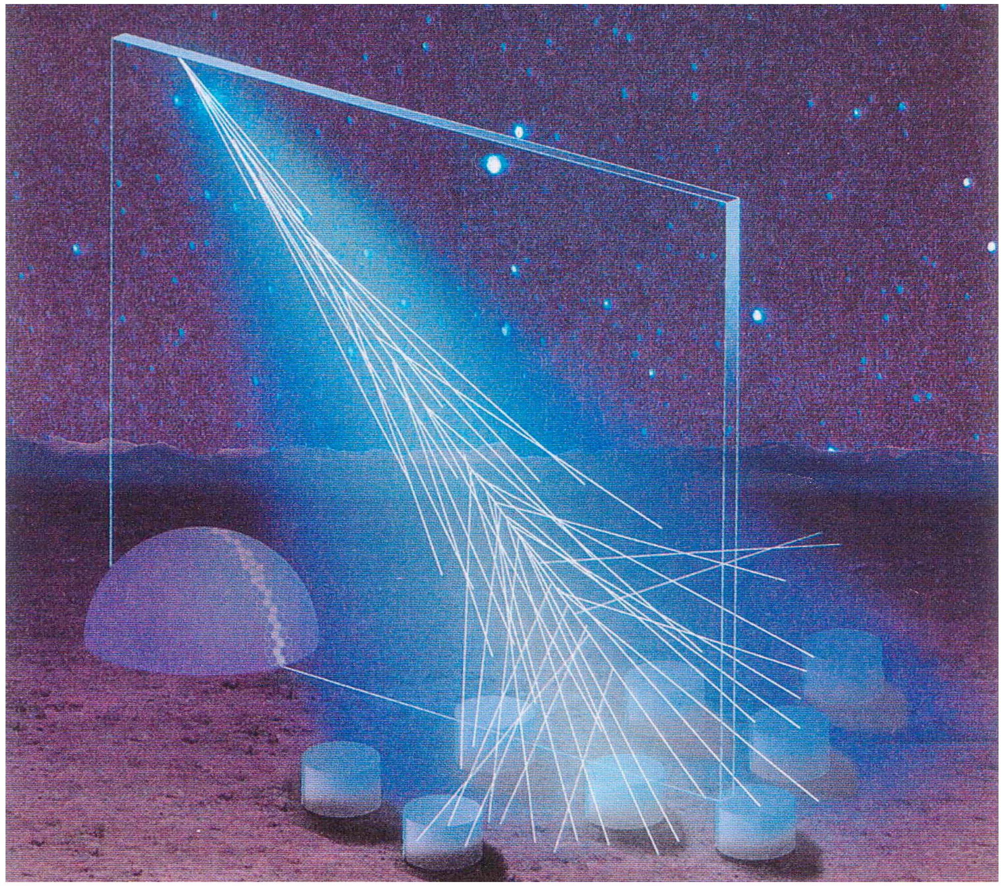
-> depends on hadronic models used in the shower simulations





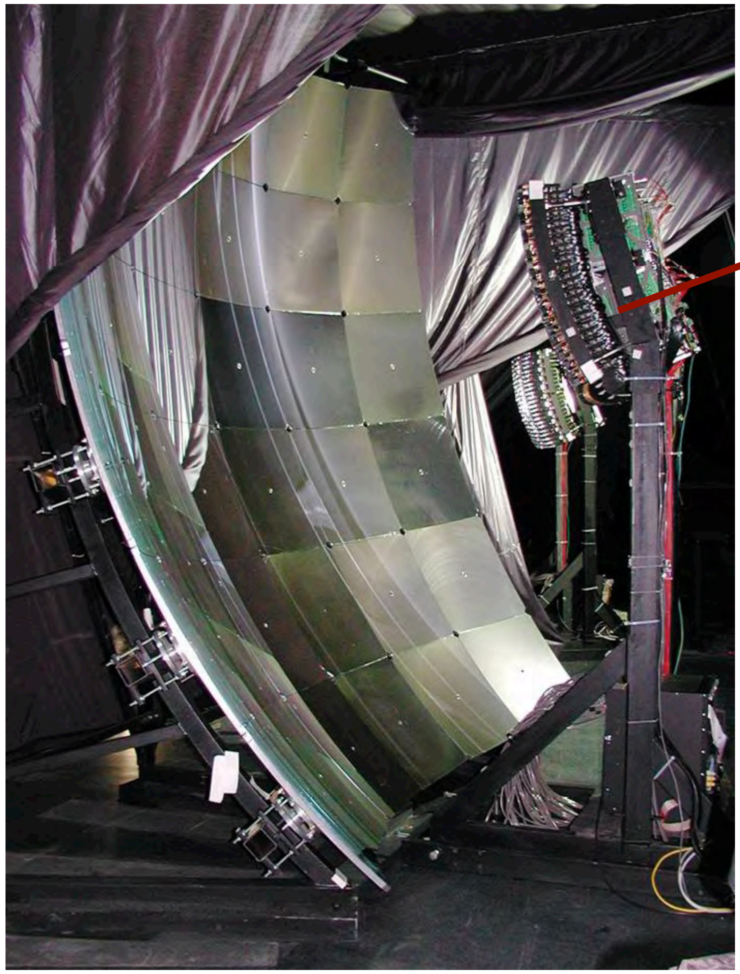
Fluorescence telescopes

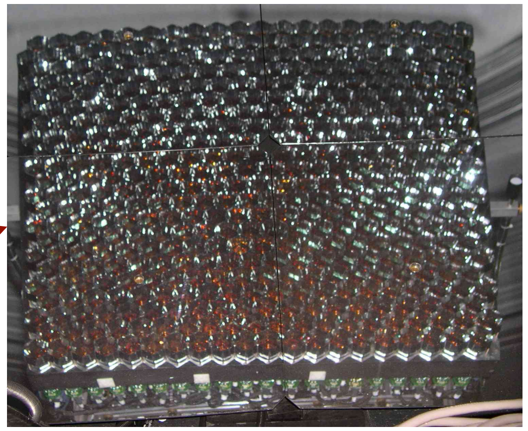
- The fluorescence (UV) emitted by N_2 molecules exited by the air shower e^+e^- is detected
- Fluorescence light proportional to the number of electromagnetic particles in the shower -> proportional to the energy of the cosmic-ray
- UV light can only be detected by moonless nights -> ~15% duty cycle
- Calorimetric measurement -> widely independent of the modeling of hadronic interaction
- Technique pioneered by the Fly's eye experiment in the 80's

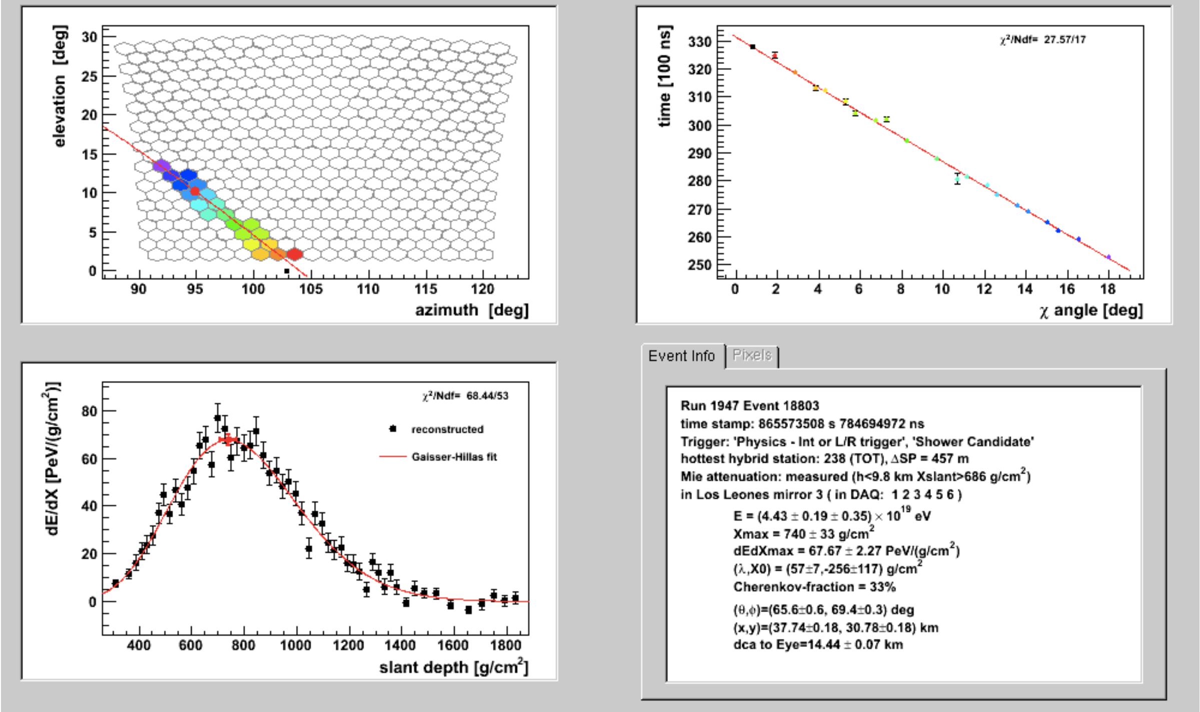


Fluorescence telescopes

- Reconstruction methods :
  - The UV picture of the shower development is captured by the PMTs
  - The timing of the different channels constrains the shower geometry
  - The energy is estimated by integrating the shower profile
  - The position of the maximum of longitudinal development (X_{max}) constrains the composition (statistical discrimination)







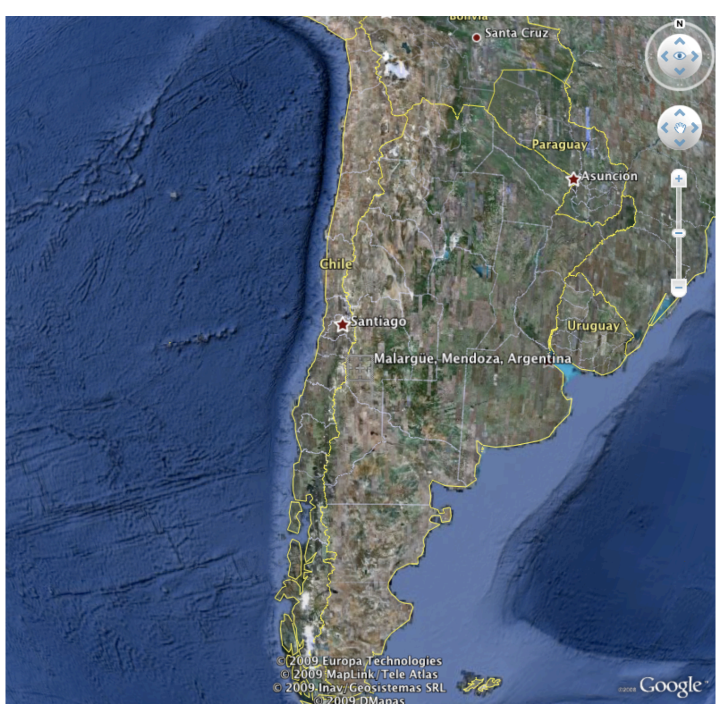
Pierre Auger observatory : the hybrid giant

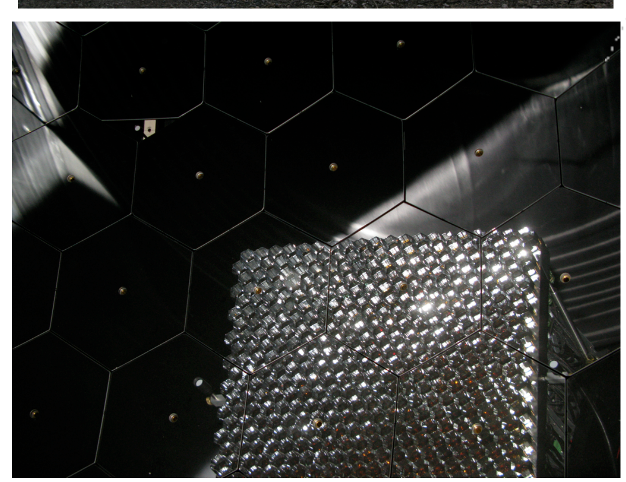
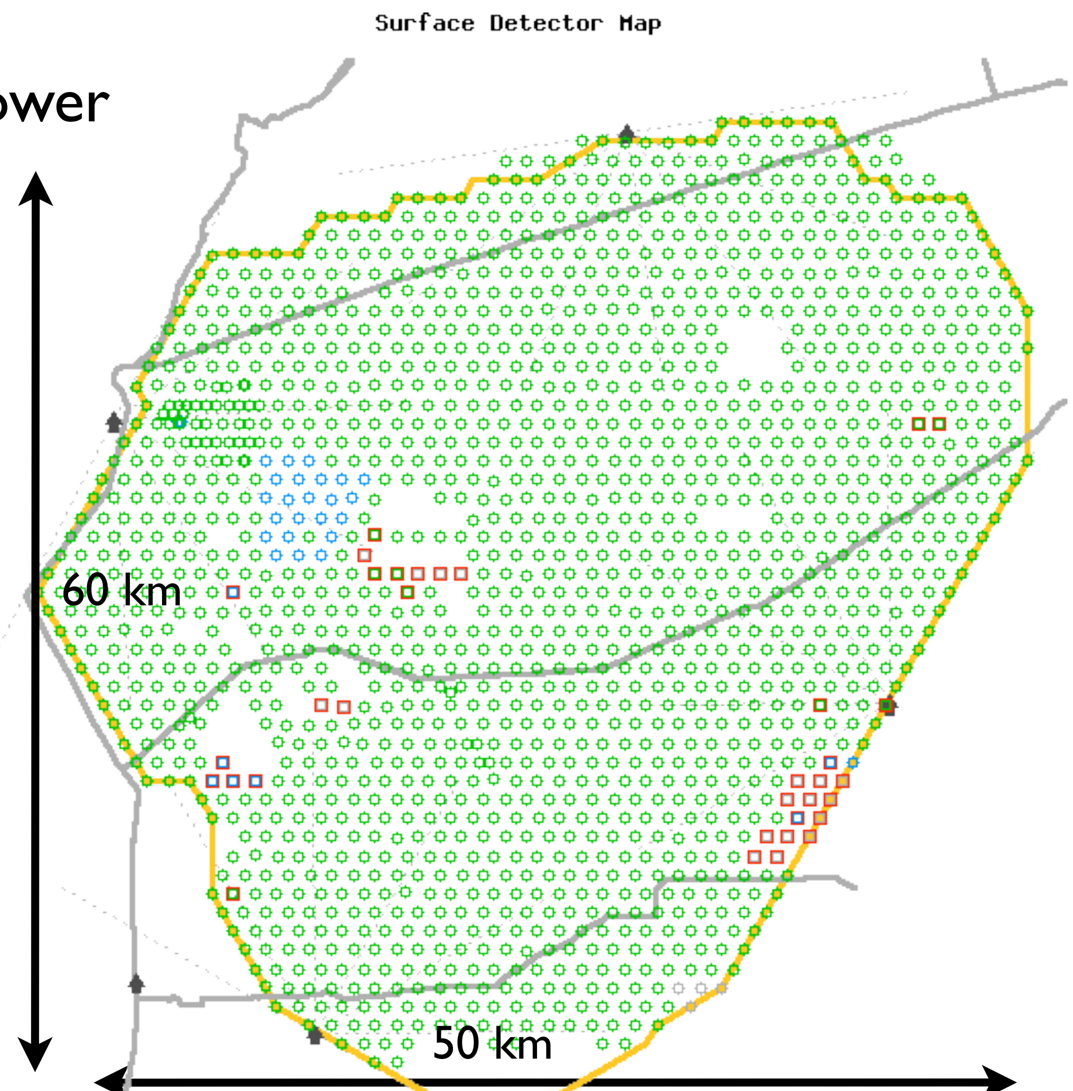
- Located in Malargue (Mendoza, Argentina, 1400m a.s.l
- 1600 Water Cerenkov Tanks, spacing 1500 m

-> ground array surface 3000 km^2

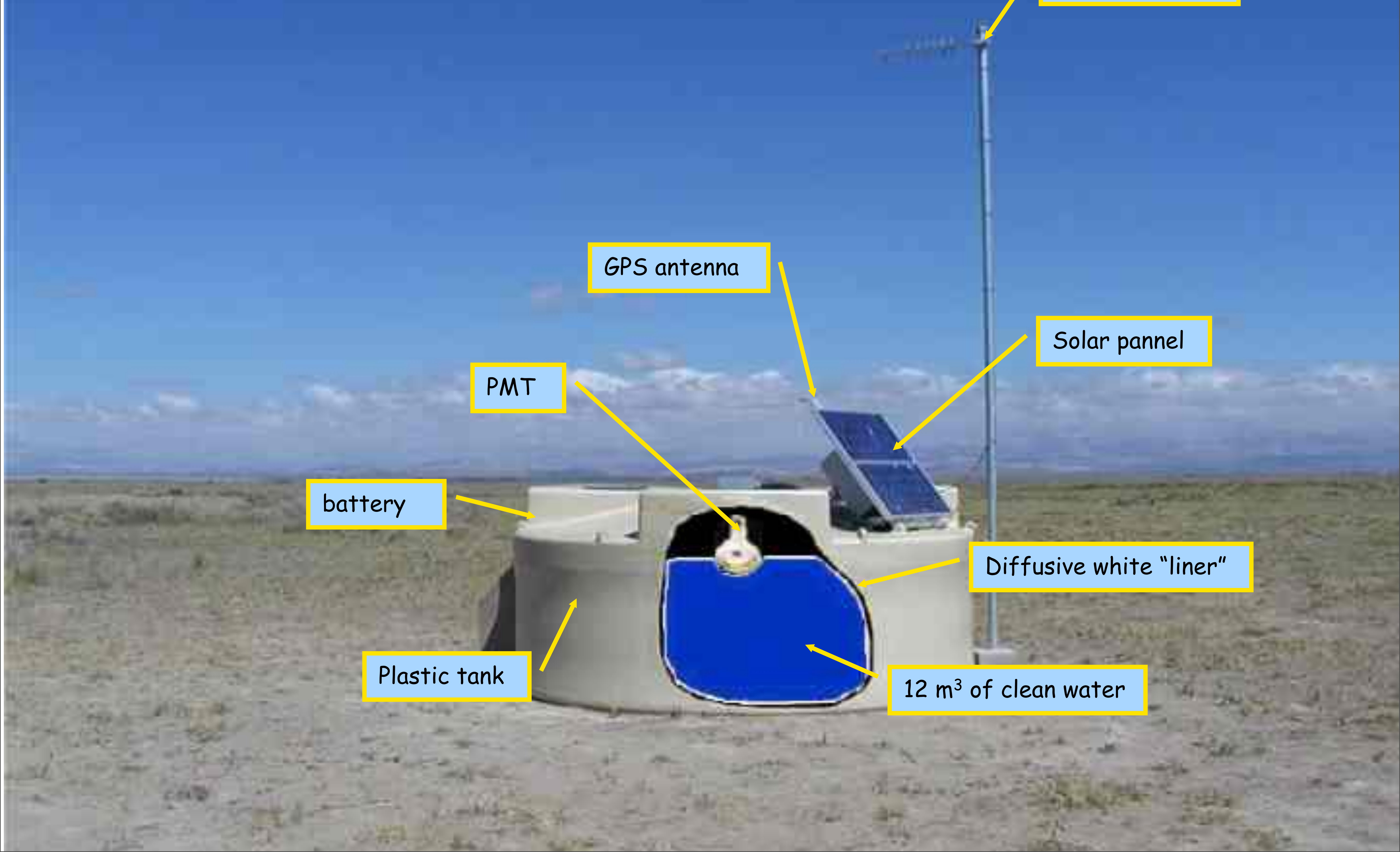
- 4 Fluorescence detectors overlook the array

Huge surface for an unprecedented statistics above 10^{19} eV
Hybrid detection for a good understanding of air-shower physics



Une des stations d'Auger
Cuve à effet (Cherenkov)

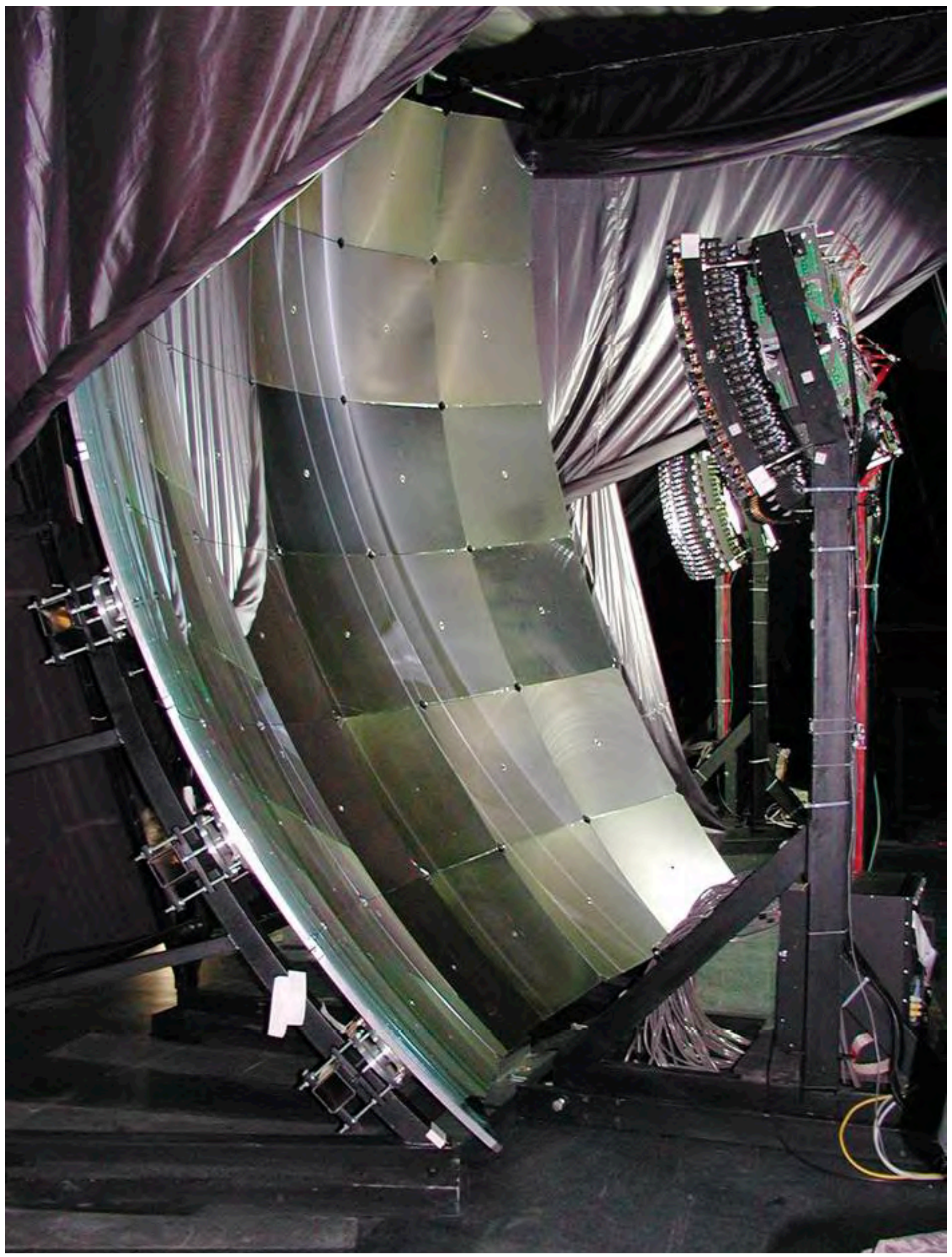


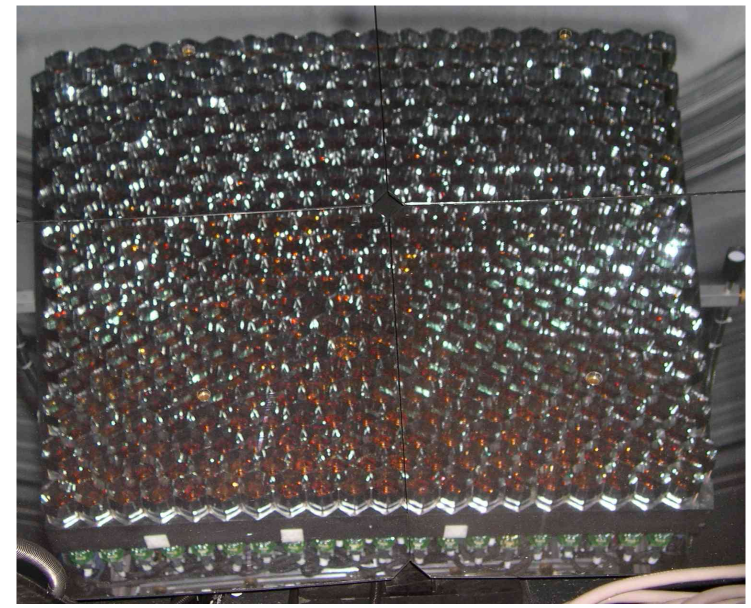
A small part of the ground array

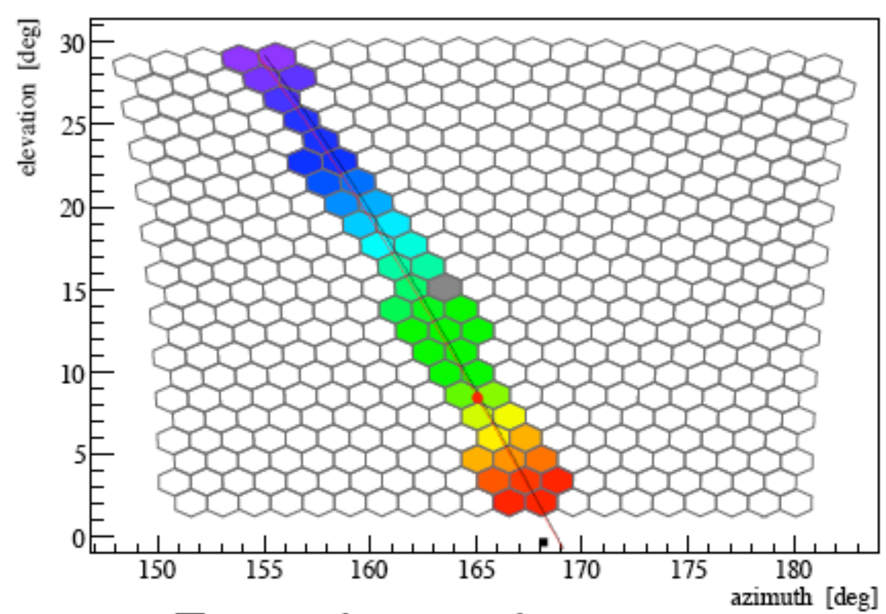
(spacing 1.5 km, total area 3000 km^2)

4 sites of 6 fluorescence telescopes overlook the array

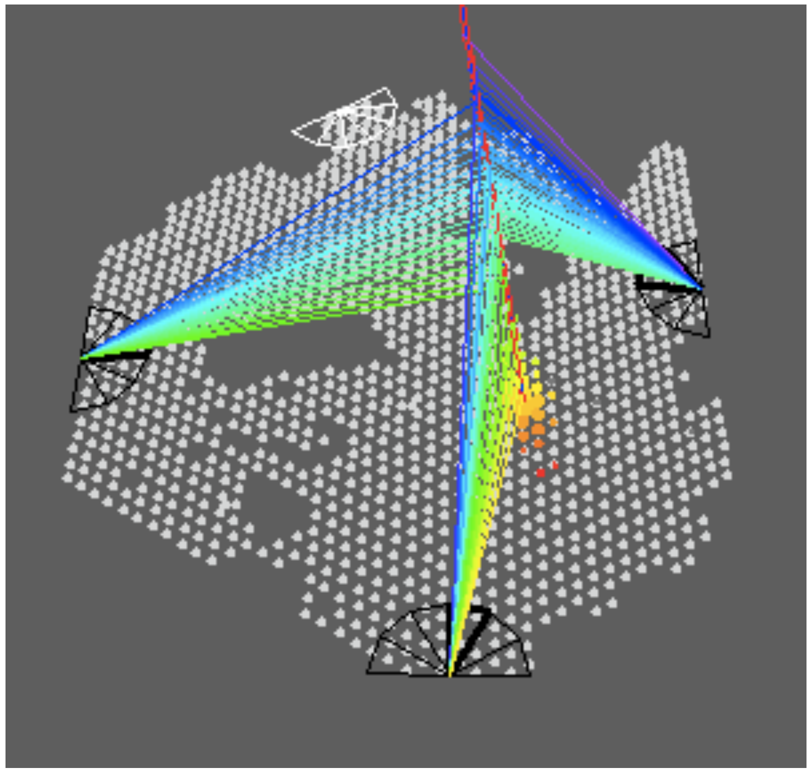
1 fluorescence telescope

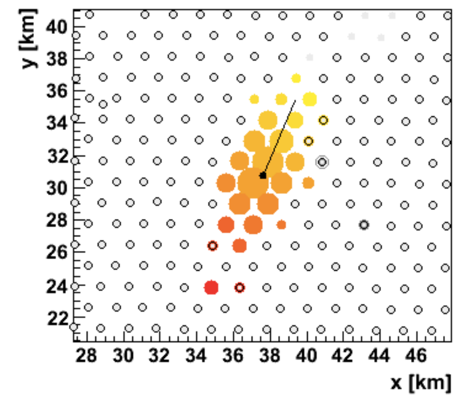


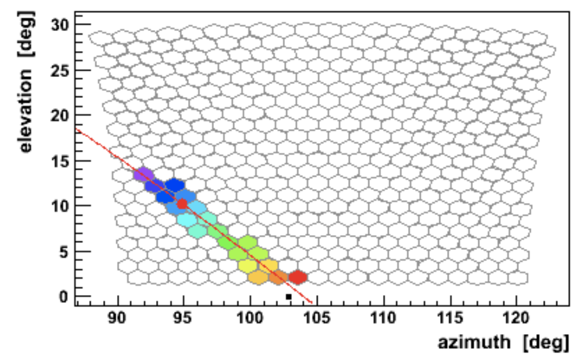


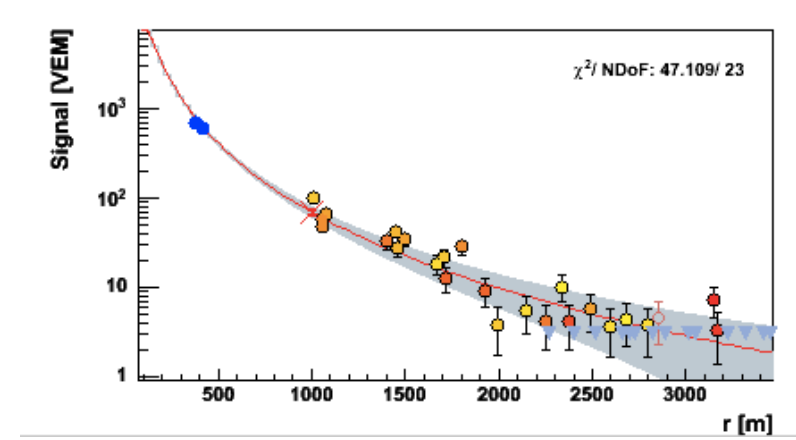


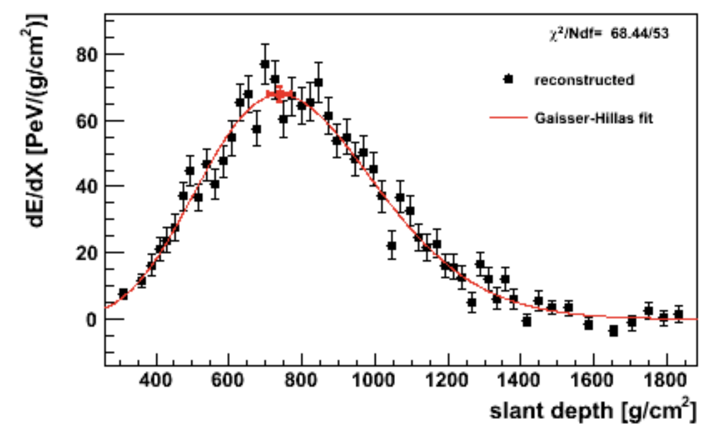
Hybrid detection





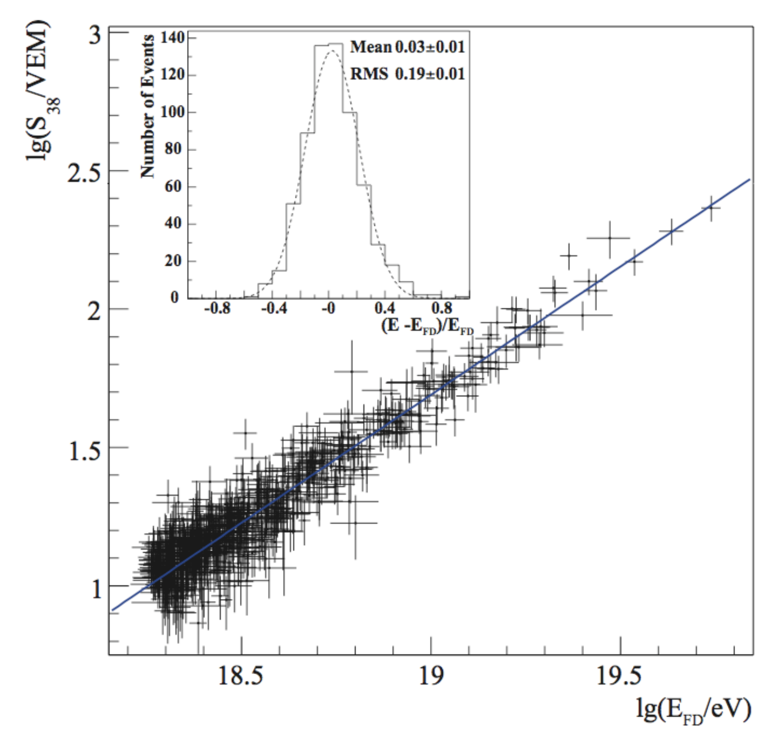




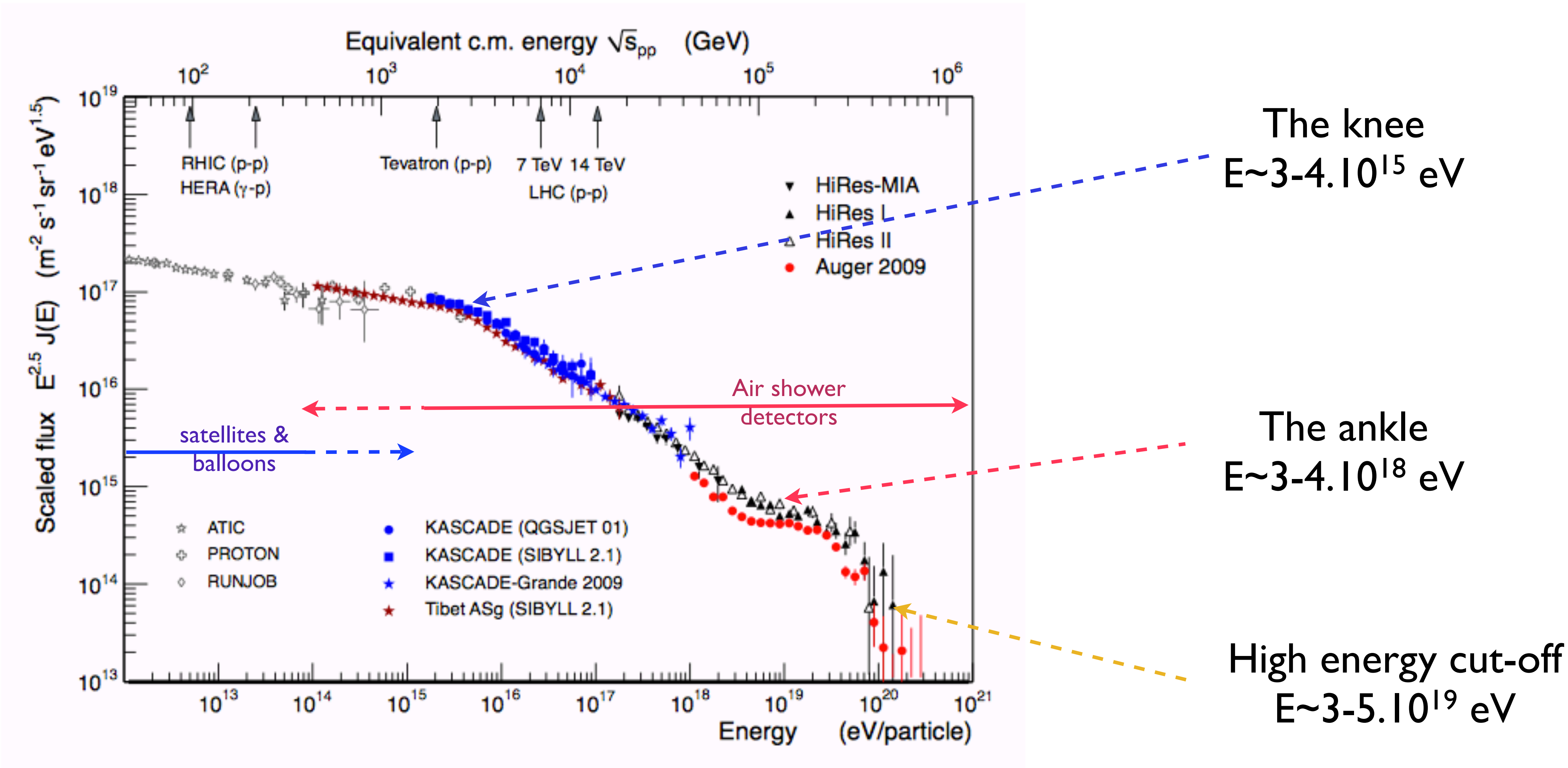


- One can calibrate the relation E/Signal using hybrid events
  - SD gives S1000
  - FD gives a calorimetric measurement of the energy
- Energy evolution measured without using simulations
  - No hadronic model dependence
  - Composition changes handled naturally
  - Spread measured

➡ takes advantage of both technique



The cosmic-ray spectrum



Pierog, 2012

There are three orders of magnitude in energy between to the knee and the ankle
what is happening on this energy range?
==> problematic of the transition from Galactic to extragalactic cosmic-rays

Extragalactic cosmic-ray propagation (above 10^{17} eV)

- The universe is essentially empty (apart in galaxies and galaxy clusters)

- The average density is around 10^{-6} proton.cm^{-3}

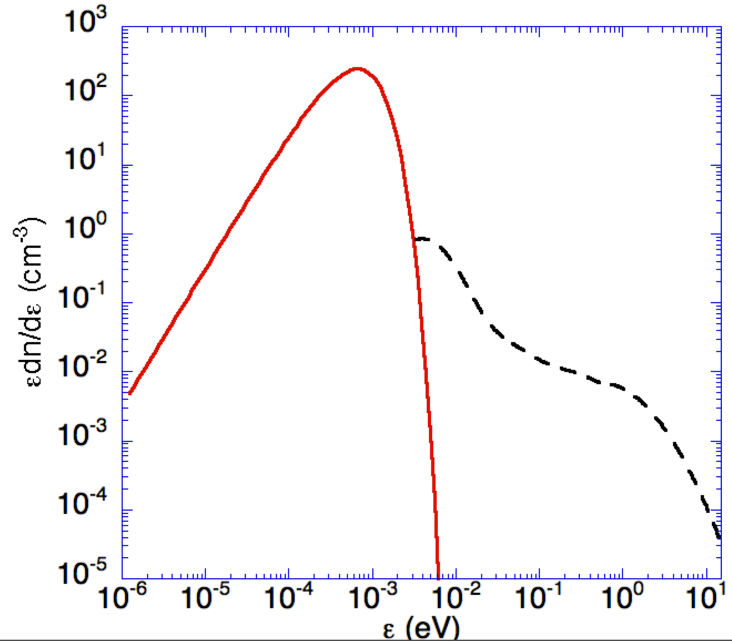
- $t_{int,pp}$ ~2.1×10^{13} yr >> $t_{universe}$ ==> negligible

- the universe is expanding so we expect extragalactic cosmic-rays to loose energy through adiabatic losses

- There are photon backgrounds in the universe, the densest of which is the CMB (410 cm^{-3})

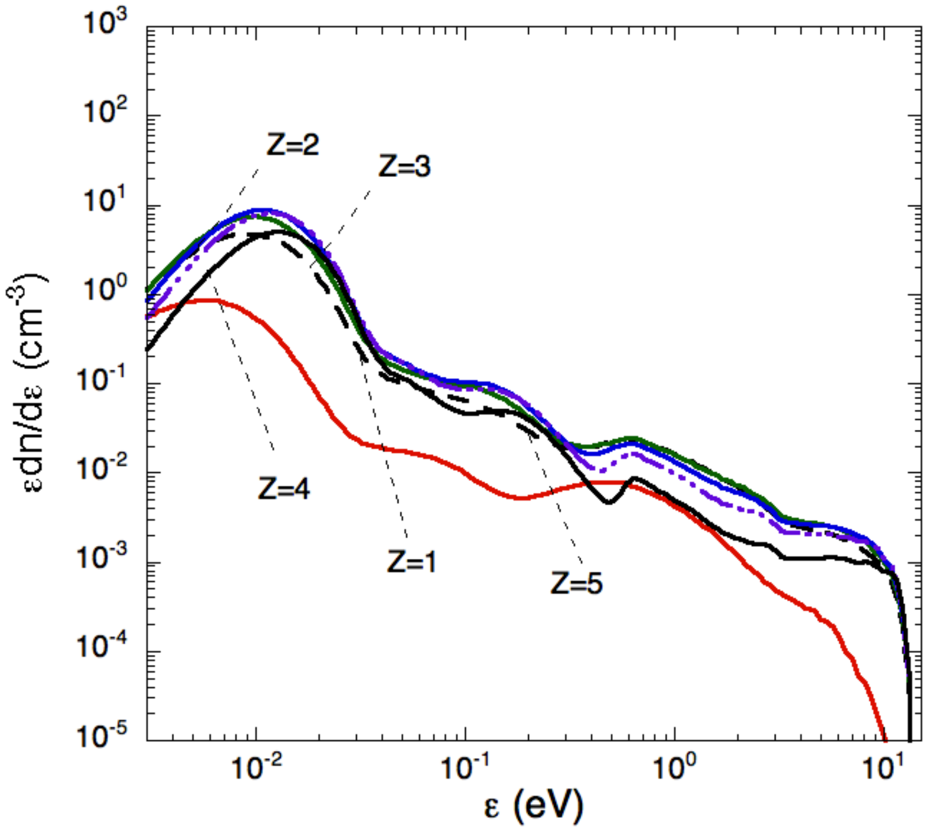
- Quite dense photon backgrounds in infra-red, optical and UV (but 2 orders of magnitude less dense than the CMB)

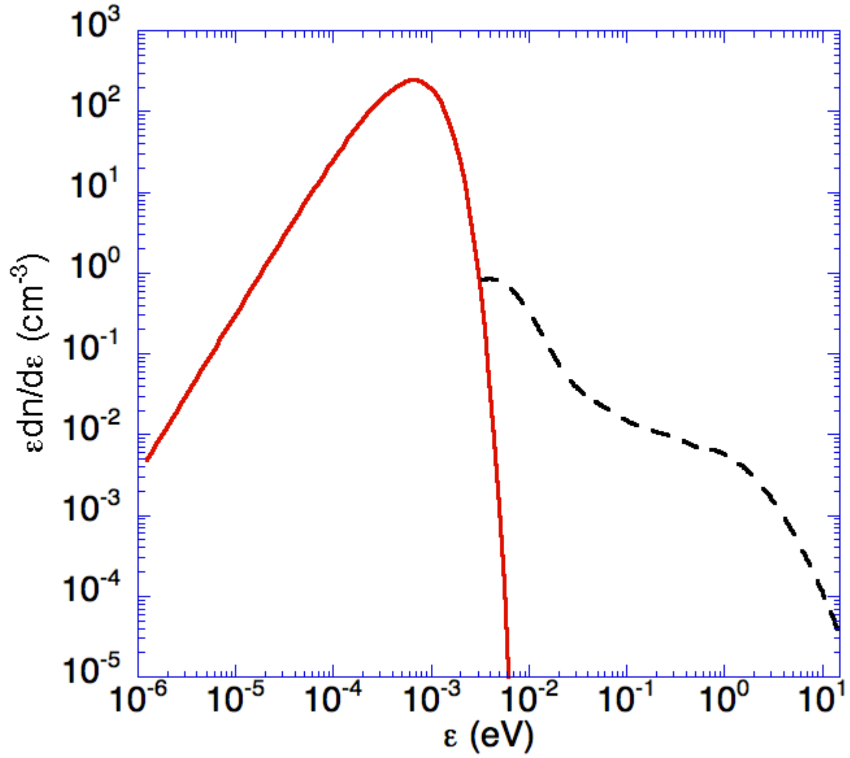
==> besides adiabatic losses, extragalactic cosmic-ray will loose energy by photo-interactions



Photon backgrounds

- In the extragalactic medium (very low density), ultra-high energy nuclei mainly interact with photon backgrounds
  - Cosmological Microwave Background, very well known T=2.726K, trivial cosmological (I.e, time) evolution $\lambda_{CR}(E_{CR},z)=\lambda_{CR}(E_{CR}\times(1+z),z=0)/(1+z)^3$ **Densest photon background today (z=0)** $<E_{cmb}>\sim 6\times 10^{-4}$ eV
  - Infra-red, optical, ultra violet backgrounds (IR/OPT/UV) from Kneiske et al., 2006





IR/OPT/UV background are very important for nuclei propagation

Photo-interactions of protons

Protons :

• pair production: P+γ→p+e⁺/e⁻ - low inelasticity process

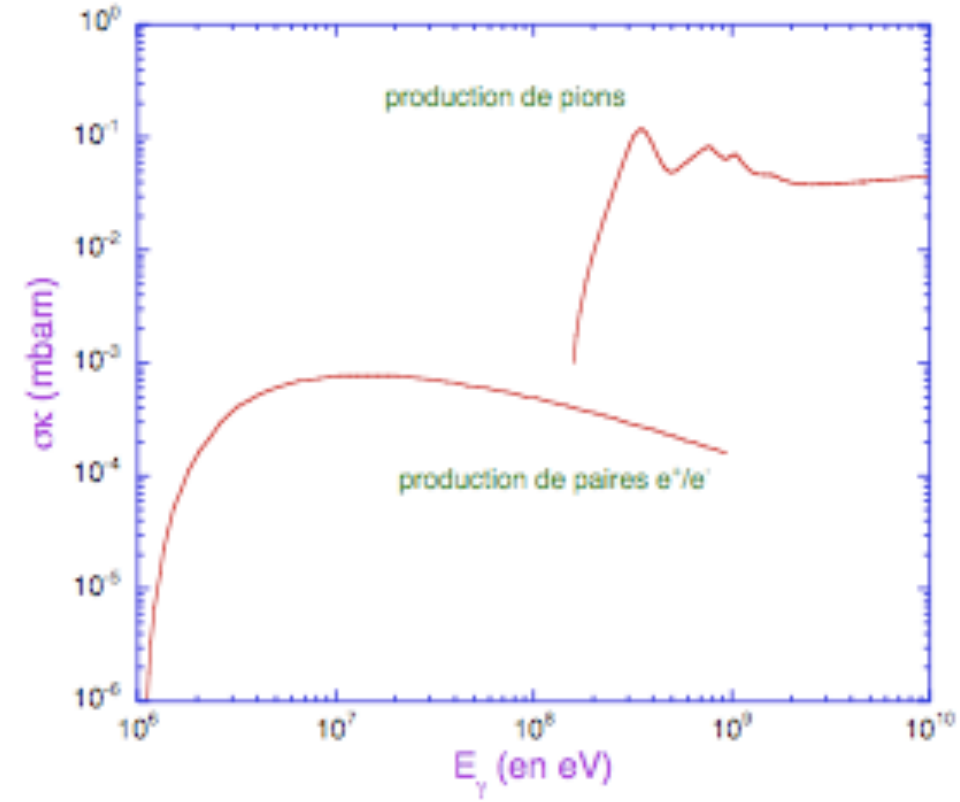
• Pion and meson production :

n+γ→n'+$\pi^{0/+/-}$ - large inelasticity process (~20%)

$\pi^0 \rightarrow 2\gamma$

$\pi^+ \rightarrow \mu^+ + \nu_\mu,\ \mu^+ \rightarrow \overline{\nu_\mu} + e^+ + \nu_e$ ==> *secondary* $e^{+/-}$, γ *and* ν

$\pi^- \rightarrow \mu^- + \overline{\nu_\mu},\ \mu^- \rightarrow \nu_\mu + e^- + \overline{\nu_e}$



The energy threshold for e^+/e^- production in the proton rest frame is ~$2m_e$ ~1 MeV

The energy threshold for π production in the proton rest frame is ~ m_π~140 MeV

But wait ! <E_{cmb}>~10^{-3} eV !!! how to produce a e^+/e^- pair with a CMB

and even more how to produce a π ??

If the proton is energetic enough (i.e a large Lorentz factor in the lab frame) then in its rest frame even CMB photons could look like γ-rays

Let us calculate the energy threshold for a proton to give a pair and/or a pion with a CMB photon !

Photo-interactions of protons

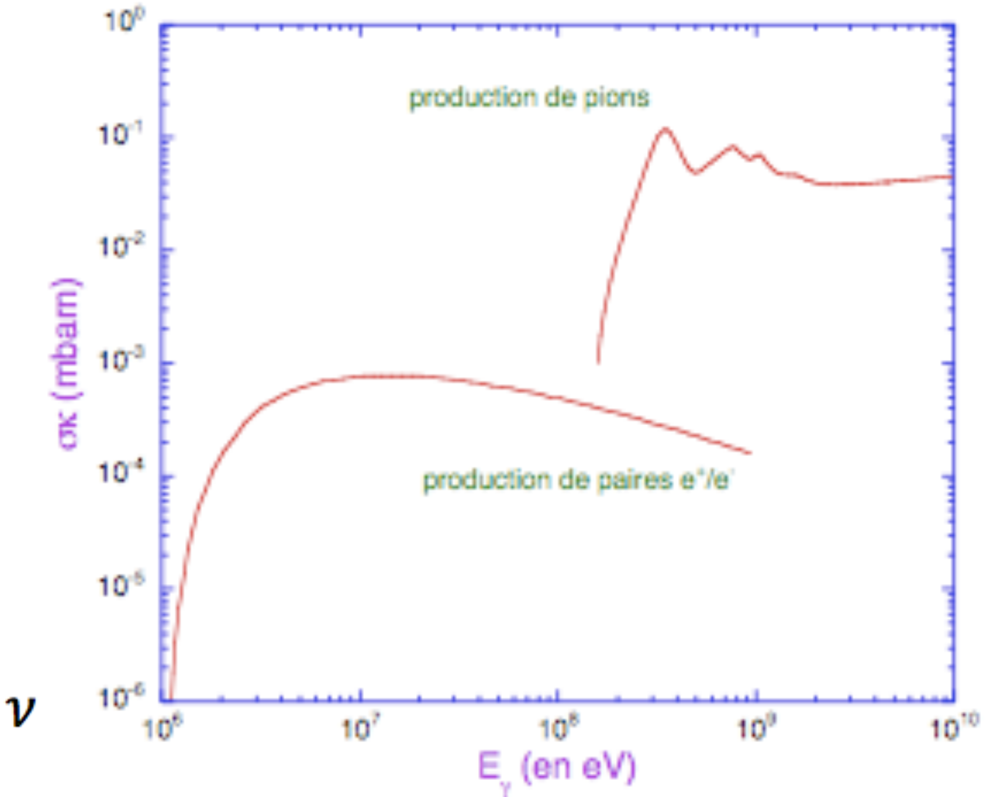
Protons :

• pair production: P+γ→p+e⁺/e⁻ - low inelasticity process

• Pion and meson production :

n+γ→n'+π$^{0/+/-}$ - large inelasticity process (~20%)

$\pi^0 \rightarrow 2\gamma$
$\pi^+ \rightarrow \mu^+ + \nu_\mu,\ \mu^+ \rightarrow \overline{\nu_\mu} + e^+ + \nu_e ==> secondary\ e^{+/-}, \gamma\ and\ \nu$
$\pi^- \rightarrow \mu^- + \overline{\nu_\mu},\ \mu^- \rightarrow \nu_\mu + e^- + \overline{\nu_e}$



Pair prod :

$$m_p^2 + 2E_\gamma E_p(1 - \cos\theta) = (2m_e + m_p)^2 ==> E_{p,th} = \frac{m_e m_p + m_e^2}{E_\gamma}$$

$$for\ E_\gamma \simeq 10^{-3} eV ==> E_{p,th} \simeq 5\times10^{17} eV$$

$$\gamma_{p,th} \simeq 5\times10^8$$

Pion prod :

$$m_p^2 + 2E_\gamma E_p(1 - \cos\theta) = (m_\pi + m_p)^2 ==> E_{p,th} = \frac{m_\pi m_p}{2E_\gamma} + \frac{m_\pi^2}{4E_\gamma}$$

$$for\ E_\gamma \simeq 10^{-3} eV ==> E_{p,th} \simeq 7\times10^{19} eV$$

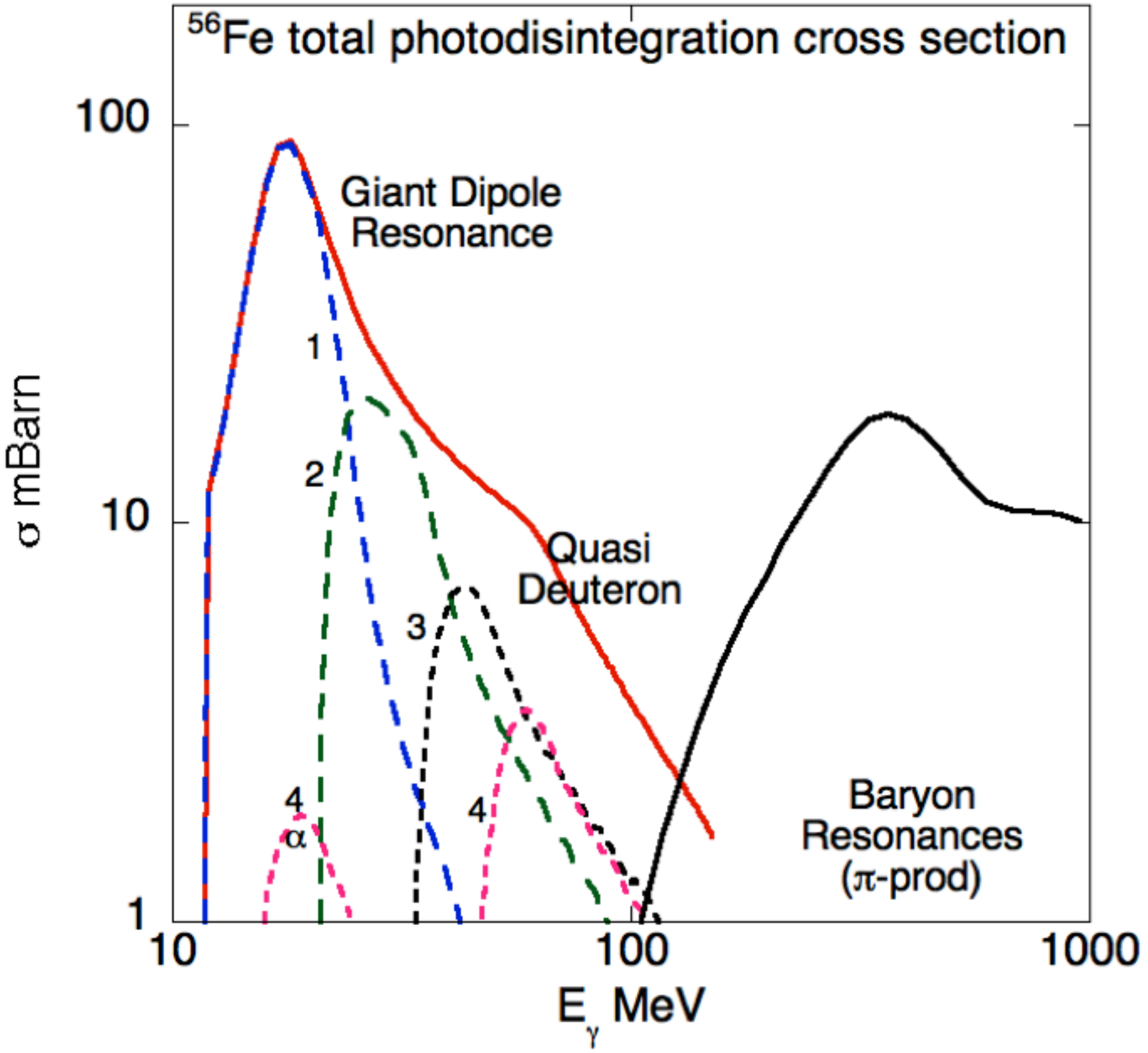
$$\gamma_{p,th} \simeq 7\times10^{10}$$

Photo-interactions of nuclei

Nuclei (heavier than protons) :

Two types of processes

- Processes triggering a decrease of the Lorentz Factor
  - Adiabatic losses
  - Pair production losses ($\gamma_{N,th} \sim 5\times10^8$ energy threshold $\sim A\times5\times10^{17}$ eV)
- Photodisintegration processes
  - Giant Dipole Resonance (GDR);
    threshold ~ 8 - 20 MeV ==> $\gamma_{N,th} \sim 5\times10^9$
    largest σ and lowest threshold (Khan et al., 2005)
  - Quasi-Deuteron process (QD);
    threshold ~ 30 MeV
  - Pion production (BR); threshold ~ 135 MeV



Neutrinos, photon and pair production channels :
π-prod of secondary p and n; β-decay of second
decay of the π produced during the BR process

Mean free path and attenuation length (or energy loss lengths)

mean free path :

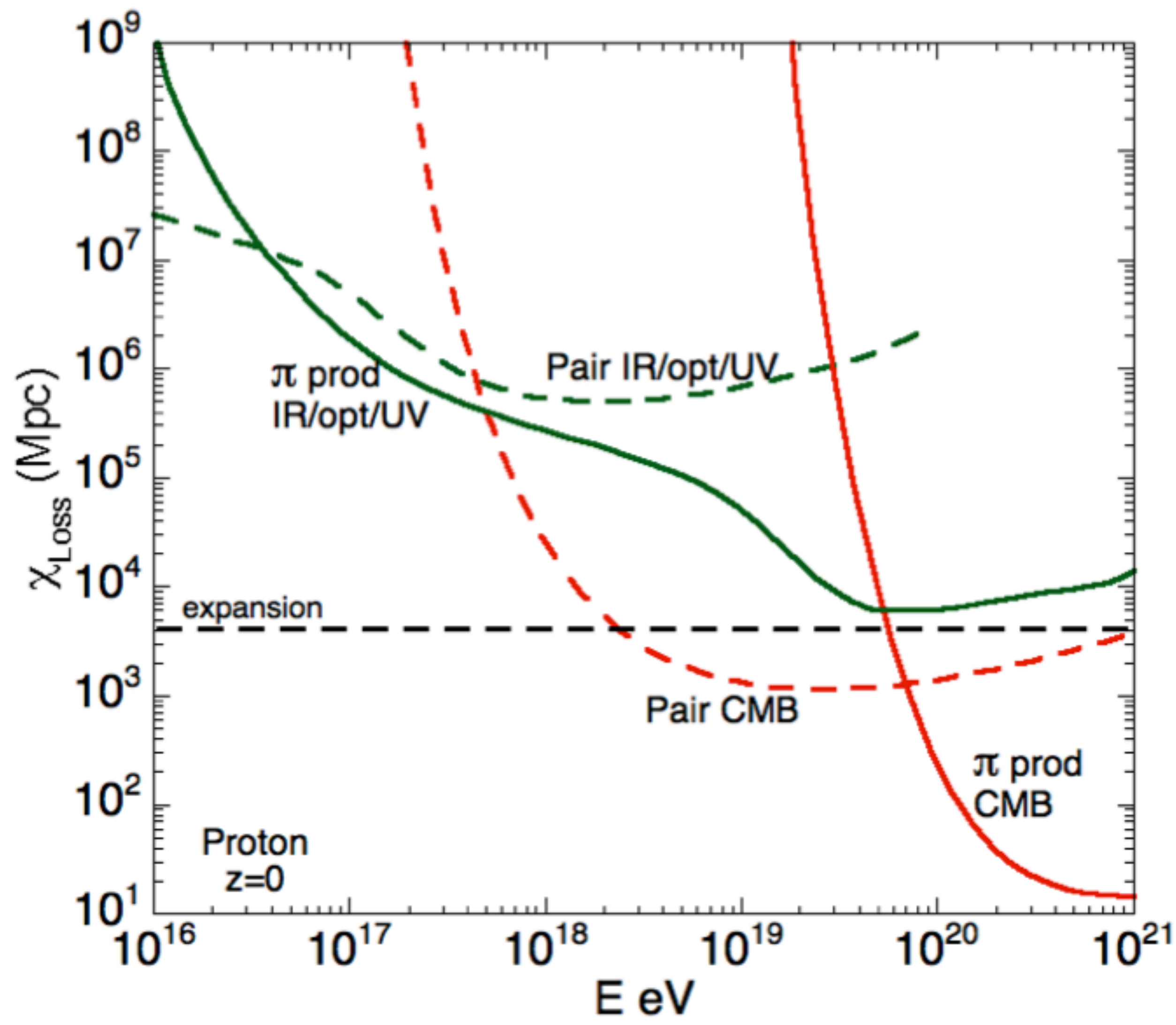
$$\lambda_{int}^{-1}(\Gamma_N) = \frac{1}{\Gamma_N}\int_{E_{th}}^{2\Gamma_N E_\gamma^{max}} \frac{dn(E'_\gamma)}{dE'_\gamma}\sigma(E'_\gamma)dE'_\gamma$$

attenuation length (or energy loss length) :

$$\chi_{loss}^{-1}(\Gamma_N) = \frac{1}{\Gamma_N}\int_{E_{th}}^{2\Gamma_N E_\gamma^{max}} \frac{dn(E'_\gamma)}{dE'_\gamma}\kappa(E'_\gamma)\sigma(E'_\gamma)dE'_\gamma$$

$\kappa(E_\gamma')$ is the inelasticity (i.e, the fraction of the initial energy lost by the nucleus in the process)

Proton attenuation length



Proton attenuation length :

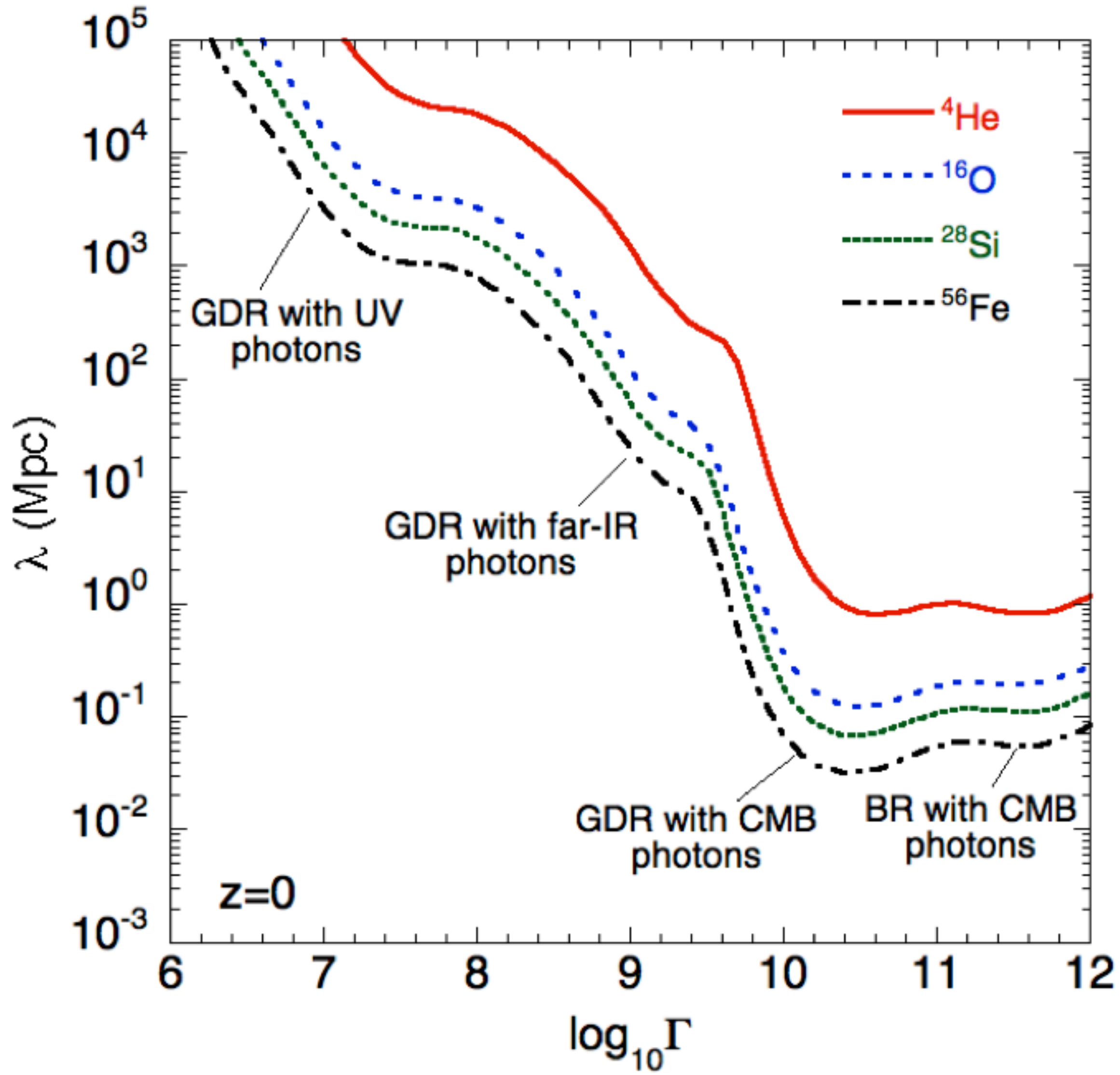
- expansion below ~10^{18} eV

- then pair production with CMB photons

- strong decrease around ~10^{20} eV due to pion production -> GZK cut-off

(minor role of the IR/opt/UV background except for neutrino production)

Nuclei mean free path for photodisintegration



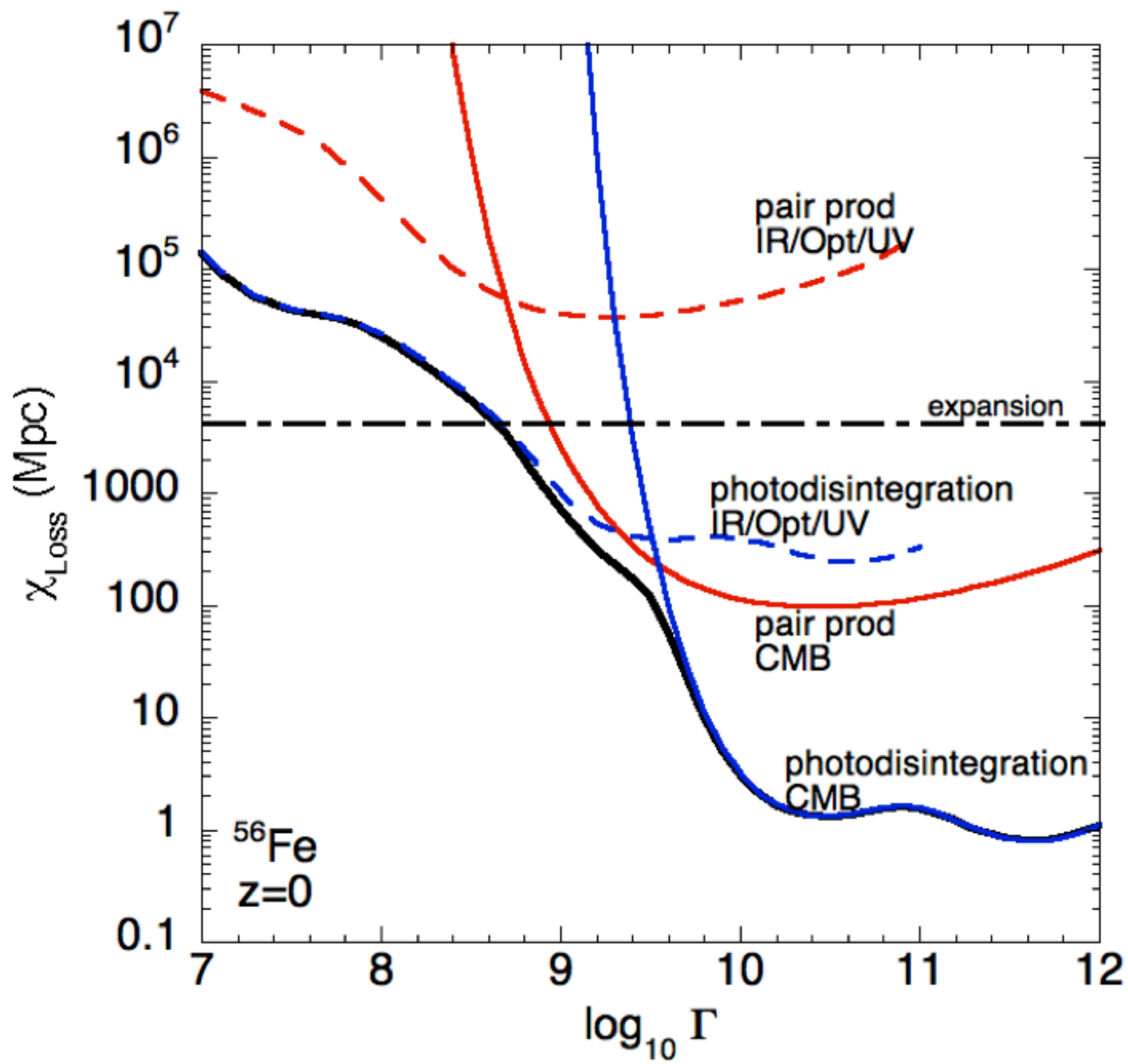
Nuclei photodisintegration mean free path :

- species have similar threshold for GDR in the NRF (except He and Be) -> interaction threshold at ~ the same Lorentz factor -> Energy threshold proportional to the mass

- cross section ~ proportional to the mass -> mean free path ~ proportional to the mass

- the GDR process dominates at all energies except the very highest

iron attenuation length

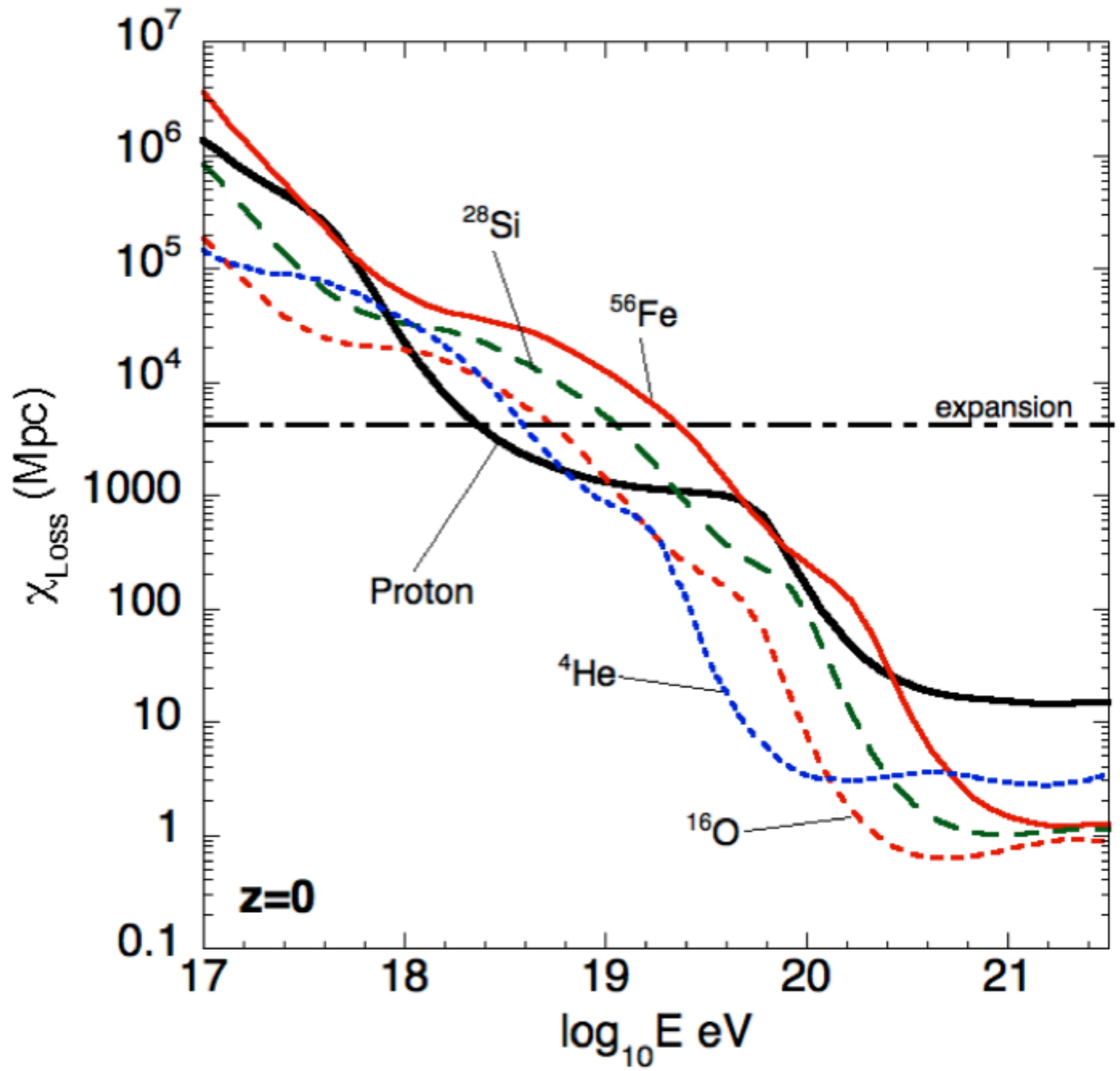


iron attenuation length :

- photodisintegration processes dominate most of the energy losses

- strong decrease above gamma~$10^{9.5}$ -> GDR with CMB photons -> GZK cut-off for nuclei

protons and nuclei loss length



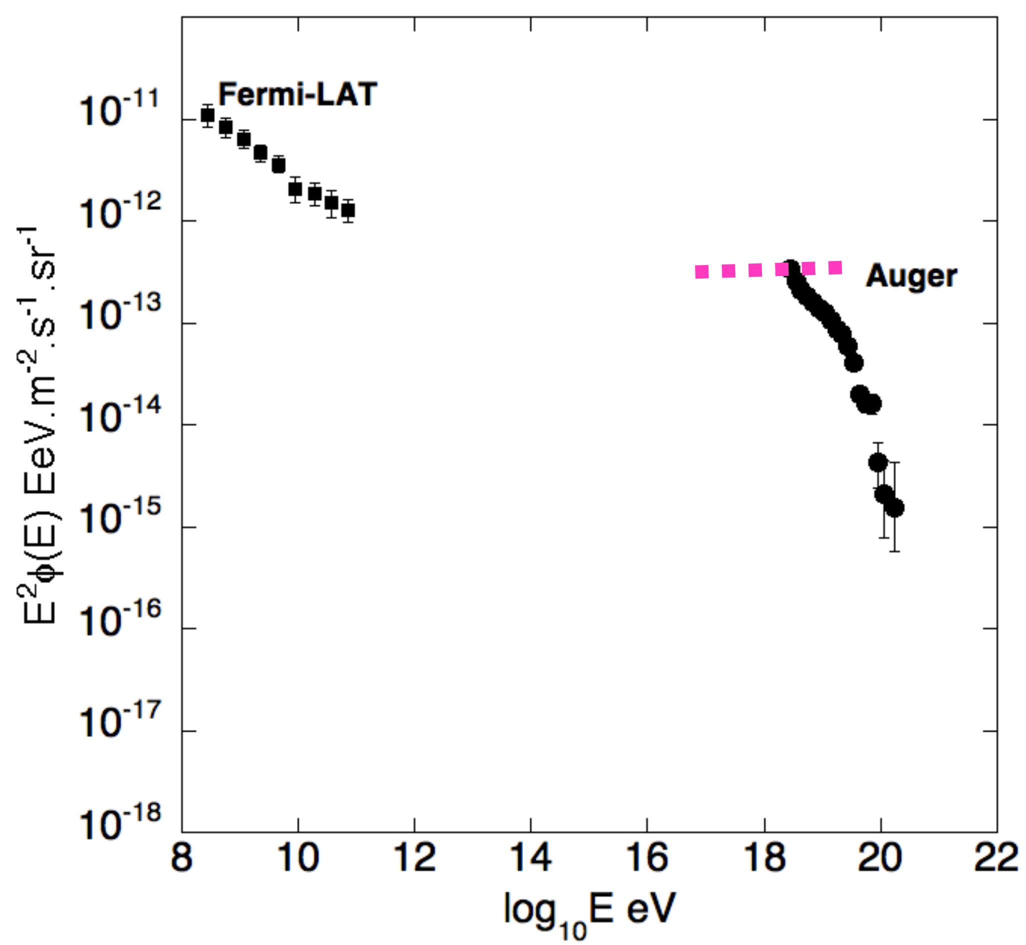
proton and nuclei attenuation length :

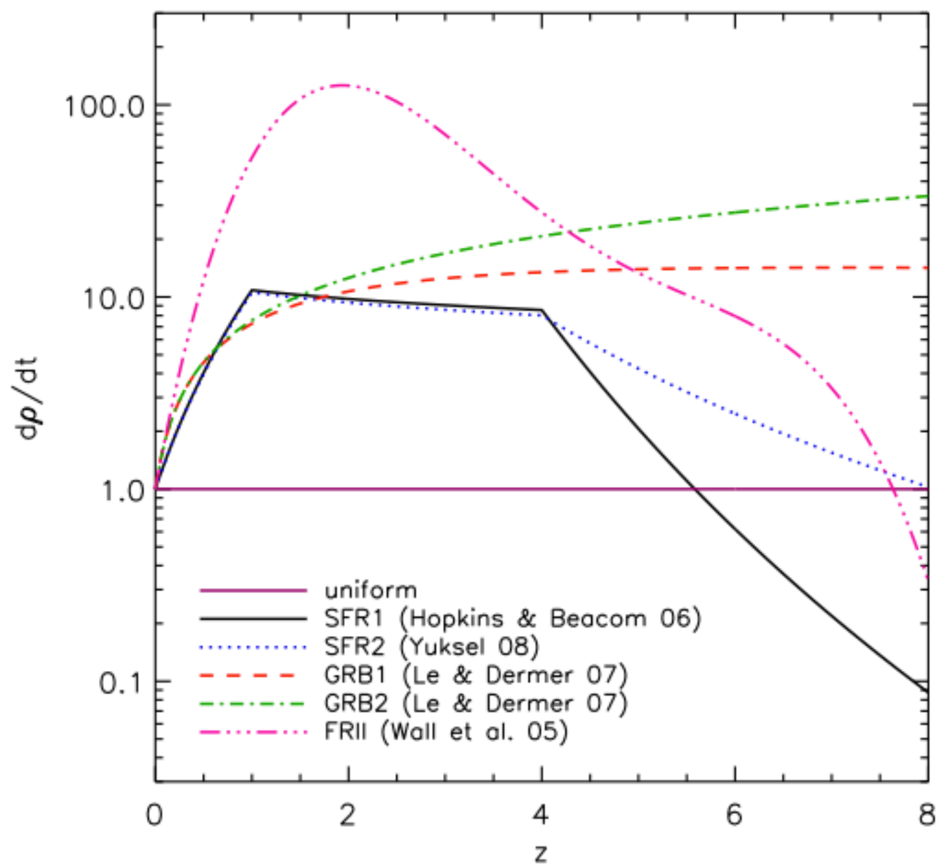
- similar shape of the attenuation length curve for complex nuclei (same processes) shifted in energy
- different shape for protons (important implications)
- hard to survive above 10^{19} eV for low and intermediate mass nuclei
- mostly protons and heavy nuclei expected at the highest energies

calculation of extragalactic UHECR spectrum and secondary neutrino and photon fluxes

We assume :

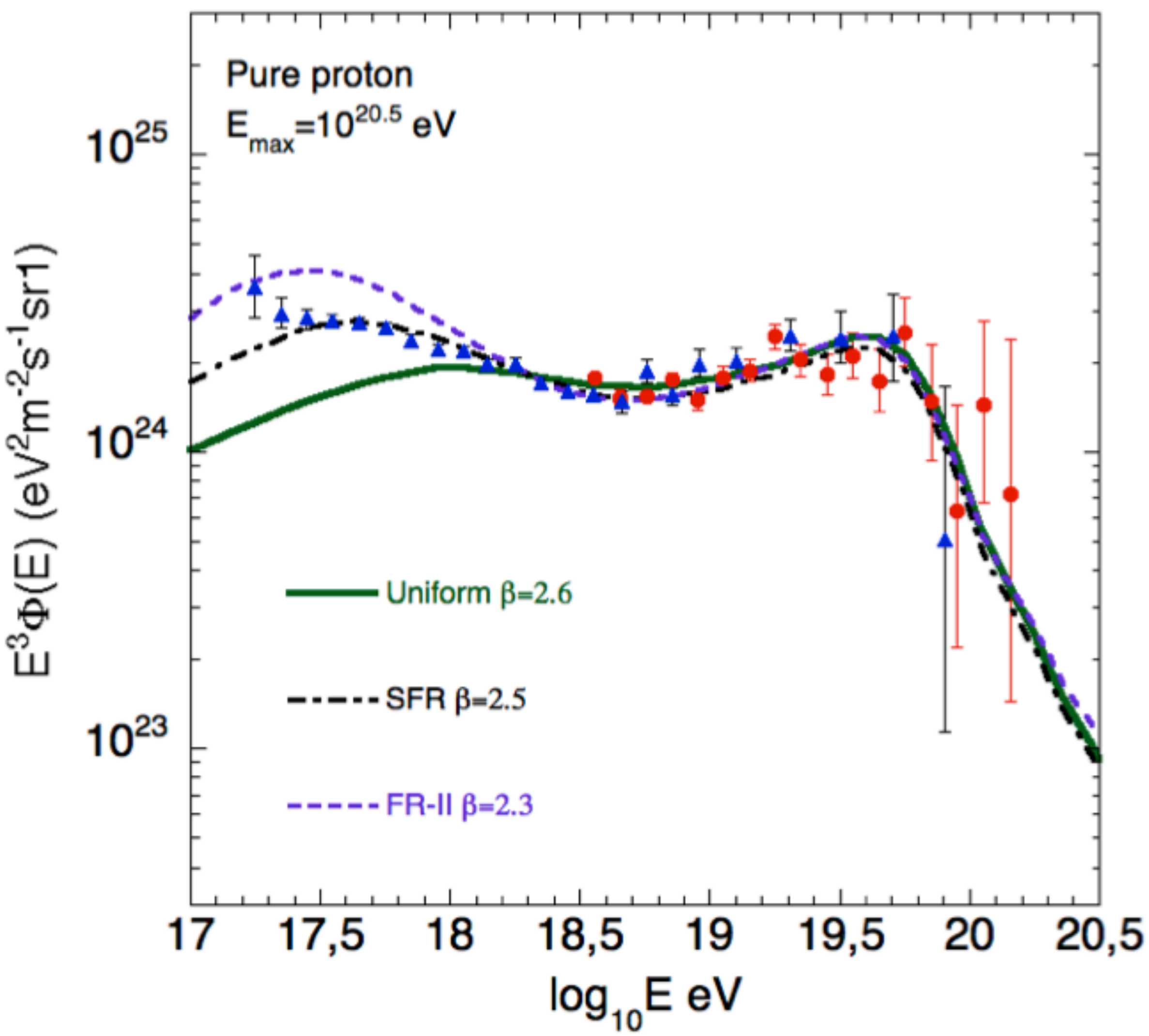
- a source composition
- source spectral index
- maximum energy ($Z \times 10^{20.5}$ eV)
- physically meaningful cosmological evolution of the sources luminosity (uniform, SFR, FR-II, GRBs...)

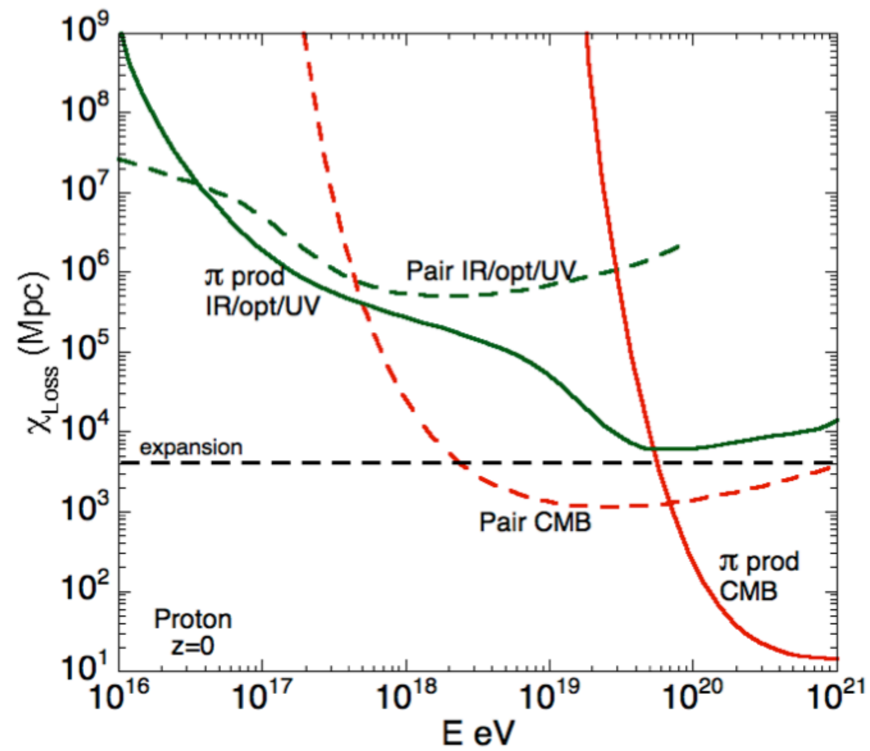




- We adjust the best spectral index on data
- We normalize the UHECR flux at 10^{19} eV using Auger
- it gives a normalization for neutrinos and photons

a special case : pure proton composition

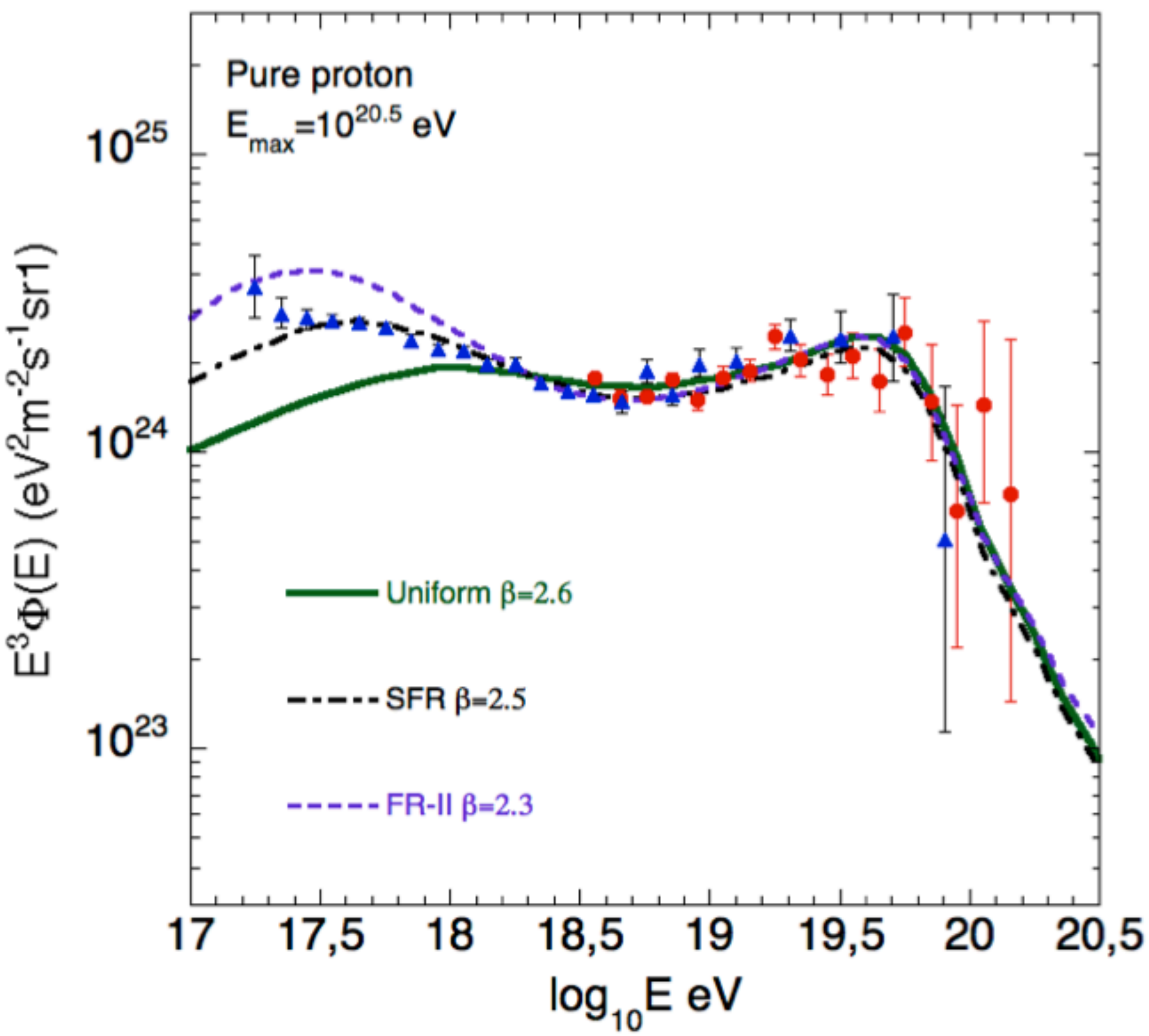




The existence of the pair production dip is due to the energy evolution of the proton attenuation length

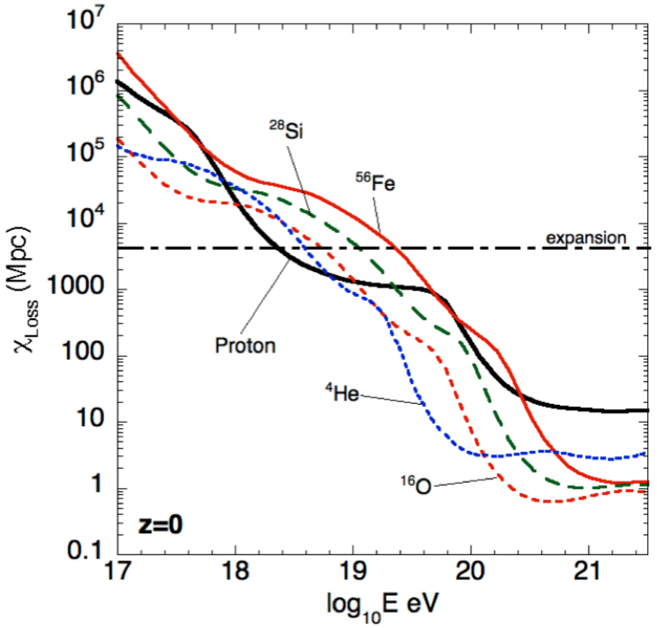
The ankle can be fitted by the extragalactic component itself : pair production dip->the ankle feature has nothing to do with the transition (model developed by Berezinsky et al., 2002-2007)

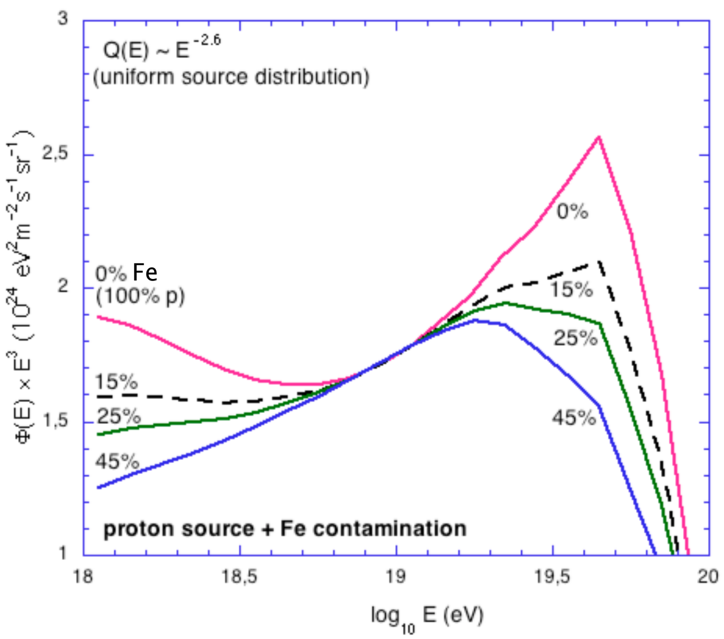
a special case : pure proton composition



The ankle can be fitted by the extragalactic component itself : pair production dip->the ankle feature has nothing to do with the transition (model developed by Berezinsky et al., 2002-2007)

BUT



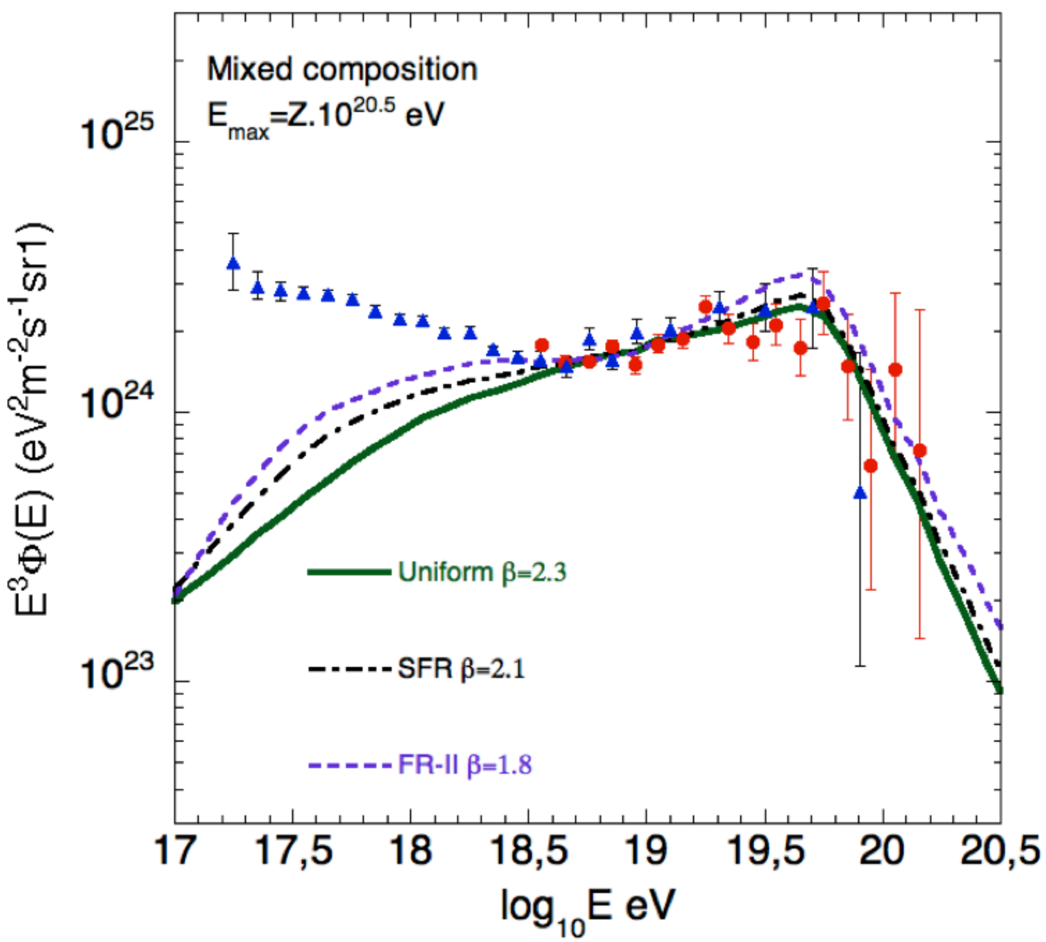


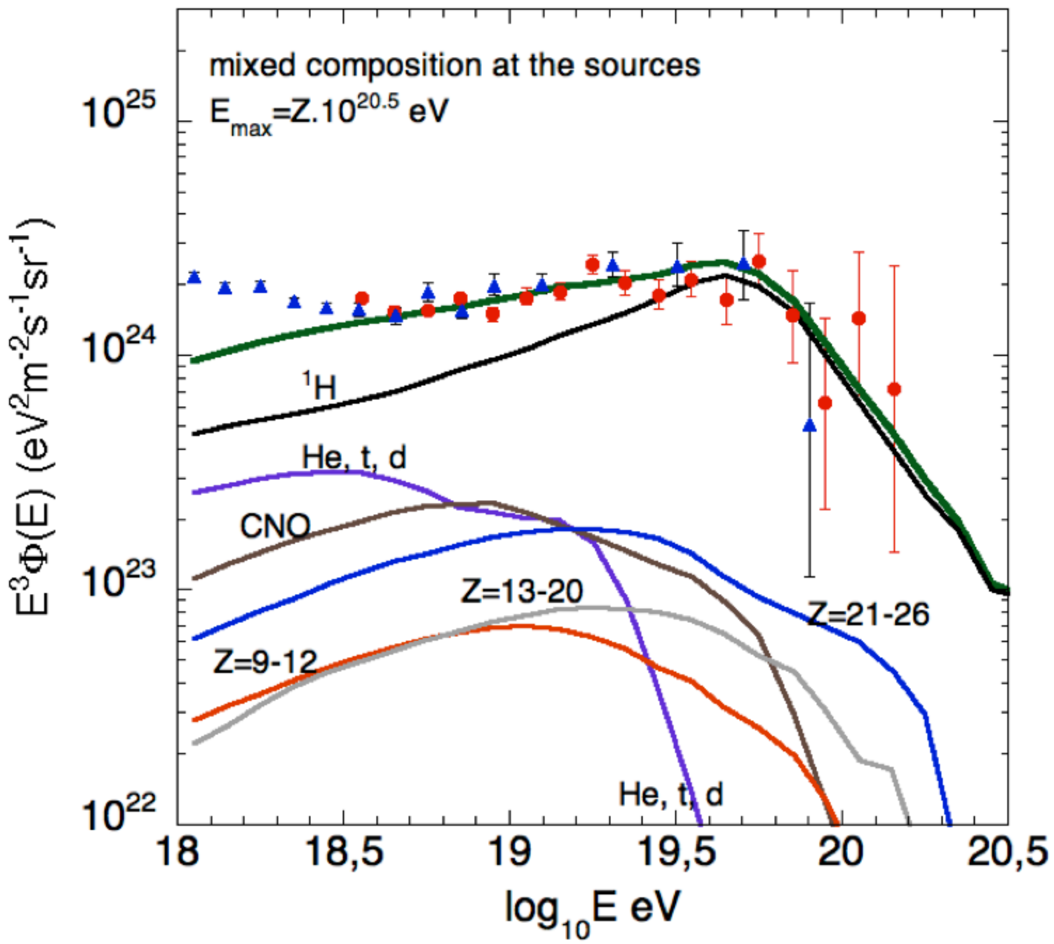
The attenuation length evolution is different for nuclei

A small admixture of nuclei erases the dip

mixed composition

We assume a mixed composition at the sources similar to the one reconstructed for low energy Galactic cosmic-rays, protons accelerated above 10^{20} eV, rigidity dependent Emax





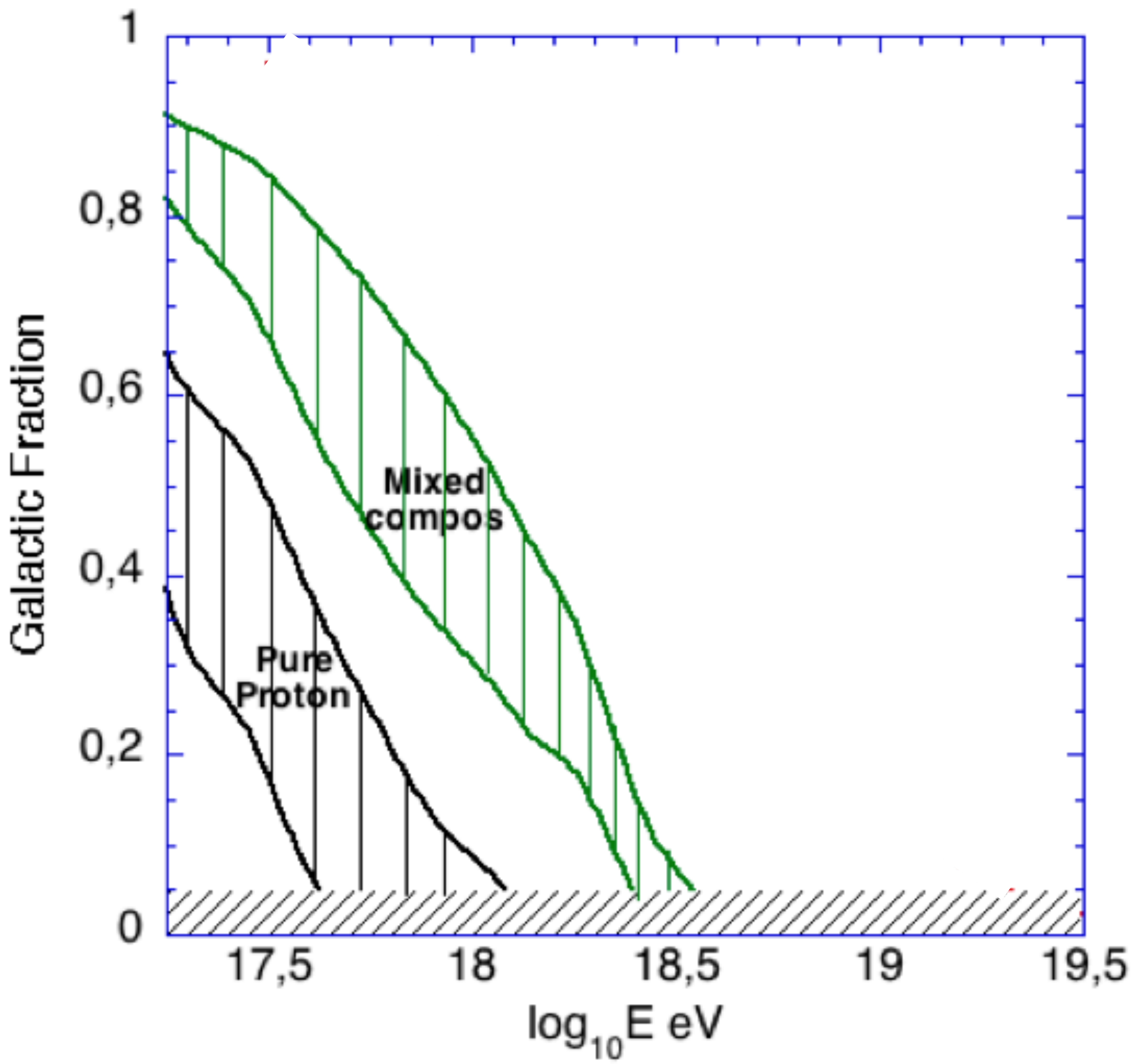
No pair production dip with a mixed composition

the ankle marks the transition from galactic to extragalactic

evolution of the composition if all the species are accelerated above :

getting lighter above 10^{19} eV

consequences on the transition from GCR to EGCR

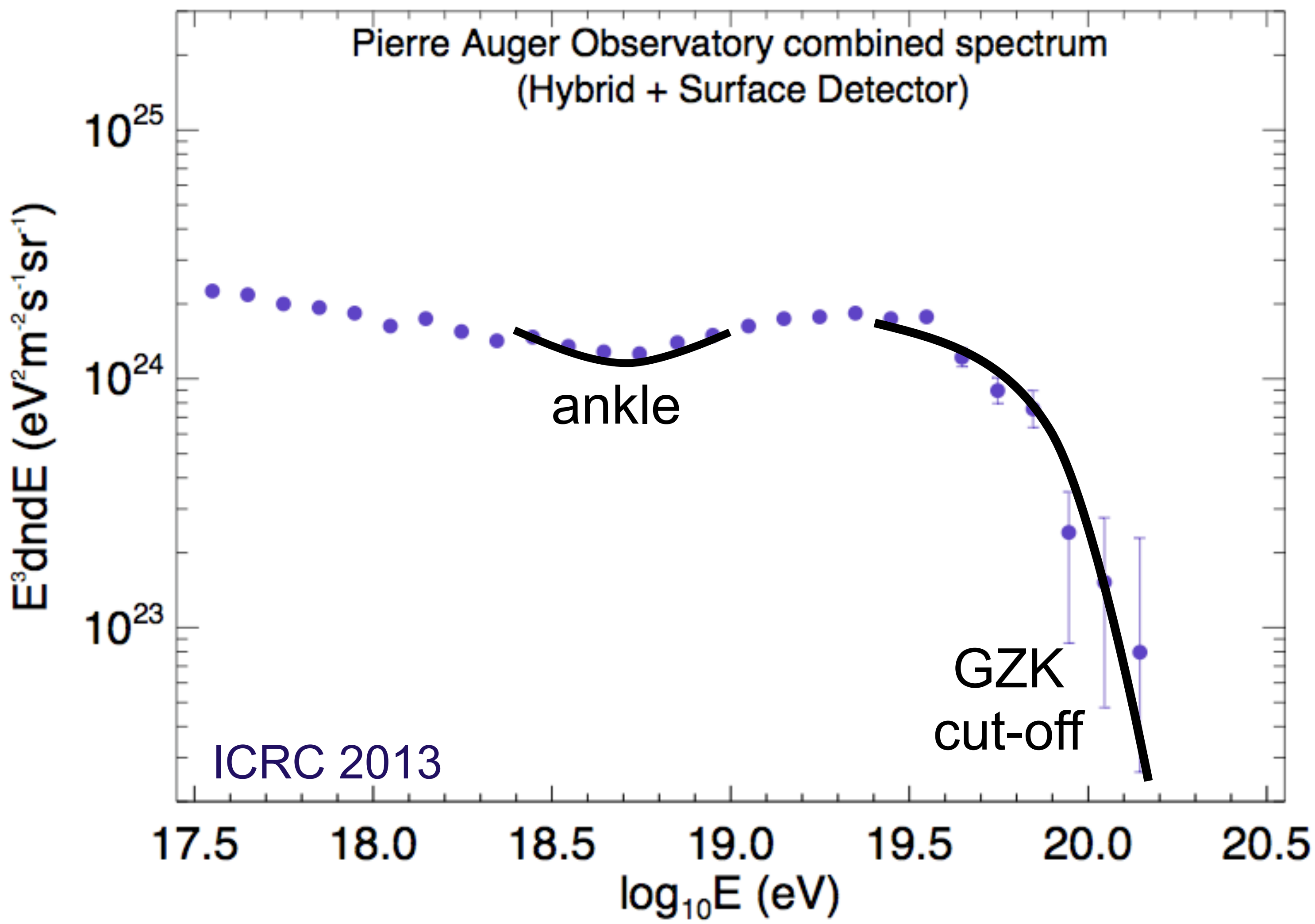


pure proton (dip model) : the galactic component ends earlier, does not requires a significant proton galactic component above a ~few 10^{16} eV (elemental spectra rapidly falling above their knees)

Mixed composition : the galactic component ends at best at the ankle
==> requires galactic Fe up ~3.10^{18} eV
==> requires galactic protons up to ~10^{17} eV

Different implications for galactic cosmic-ray sources

Main results from the Pierre Auger observatory: the energy spectrum



Observation of the ankle
and a cut-off above
$3\text{-}4.10^{19}$ eV

A long anticipated cut-off above 10^{19} eV

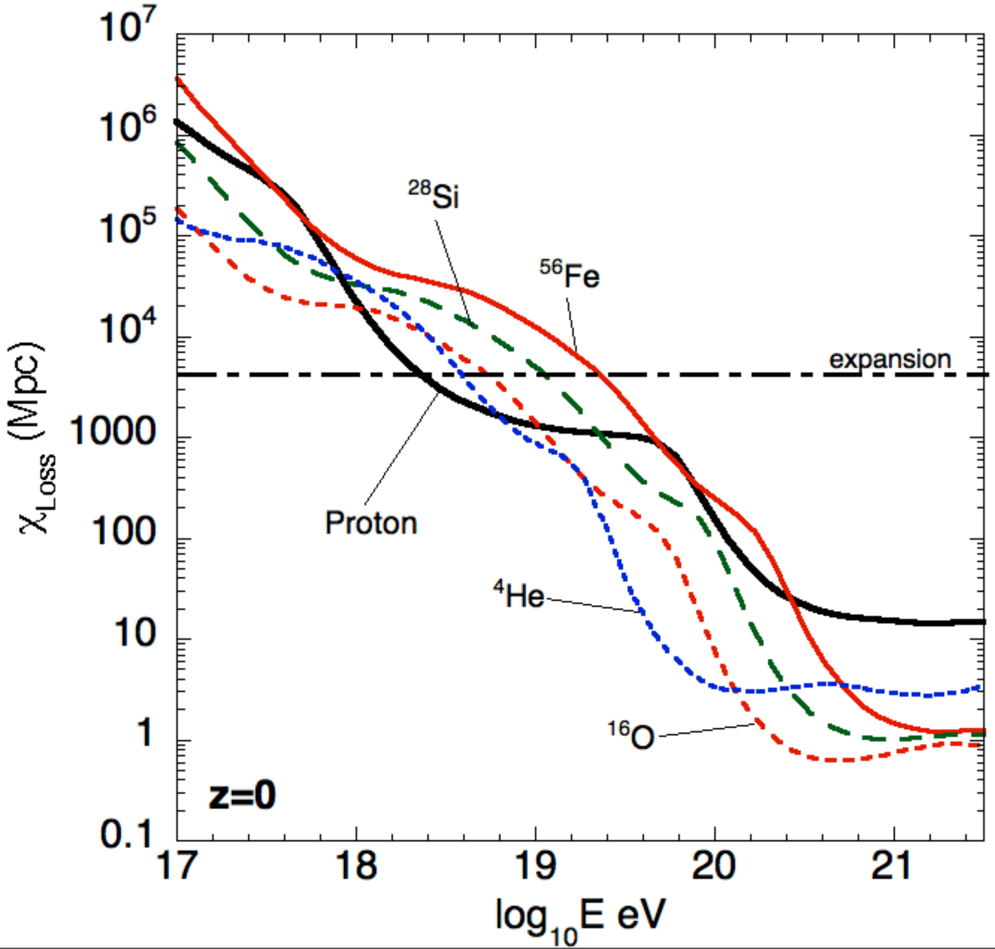
Above a few 10^{19} eV, protons and nuclei of extragalactic origin strongly interact with photon backgrounds (mostly the CMB)

- Protons loose energy

- Nuclei are photodisintegrated

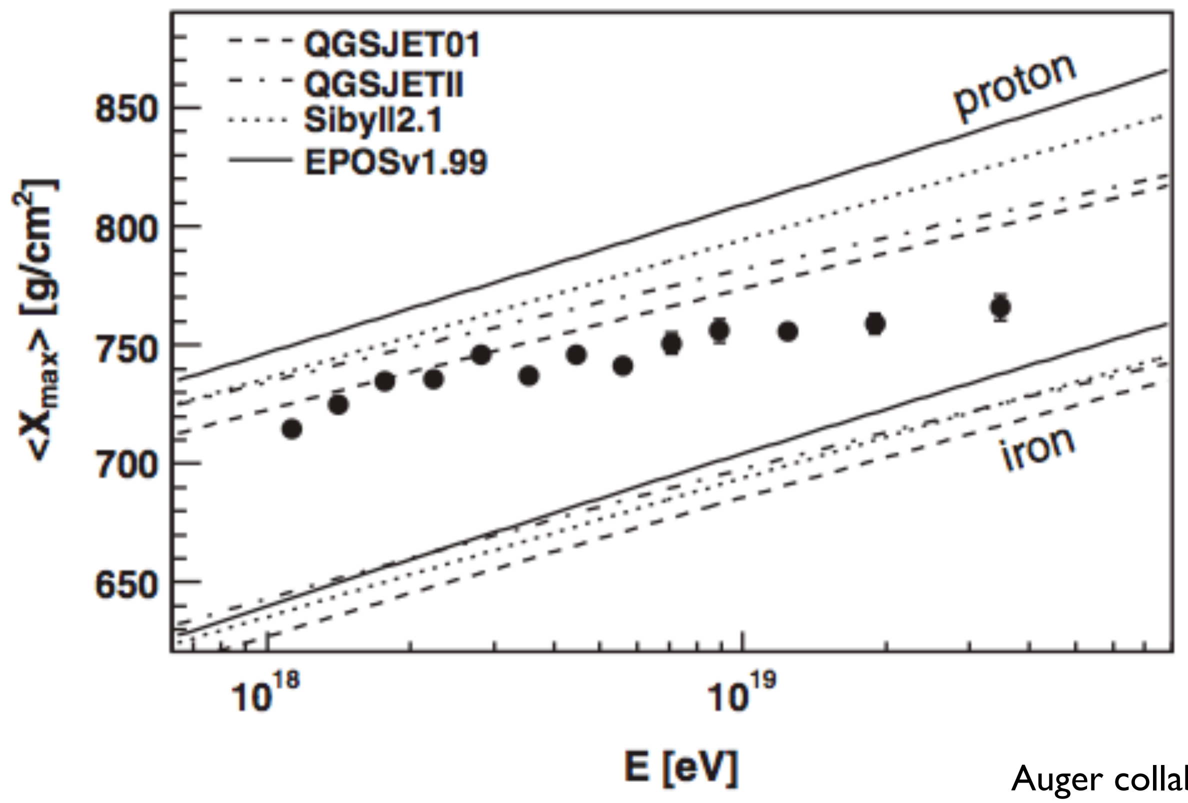
➡ above the interaction threshold, the horizon of particles is abruptly reduced

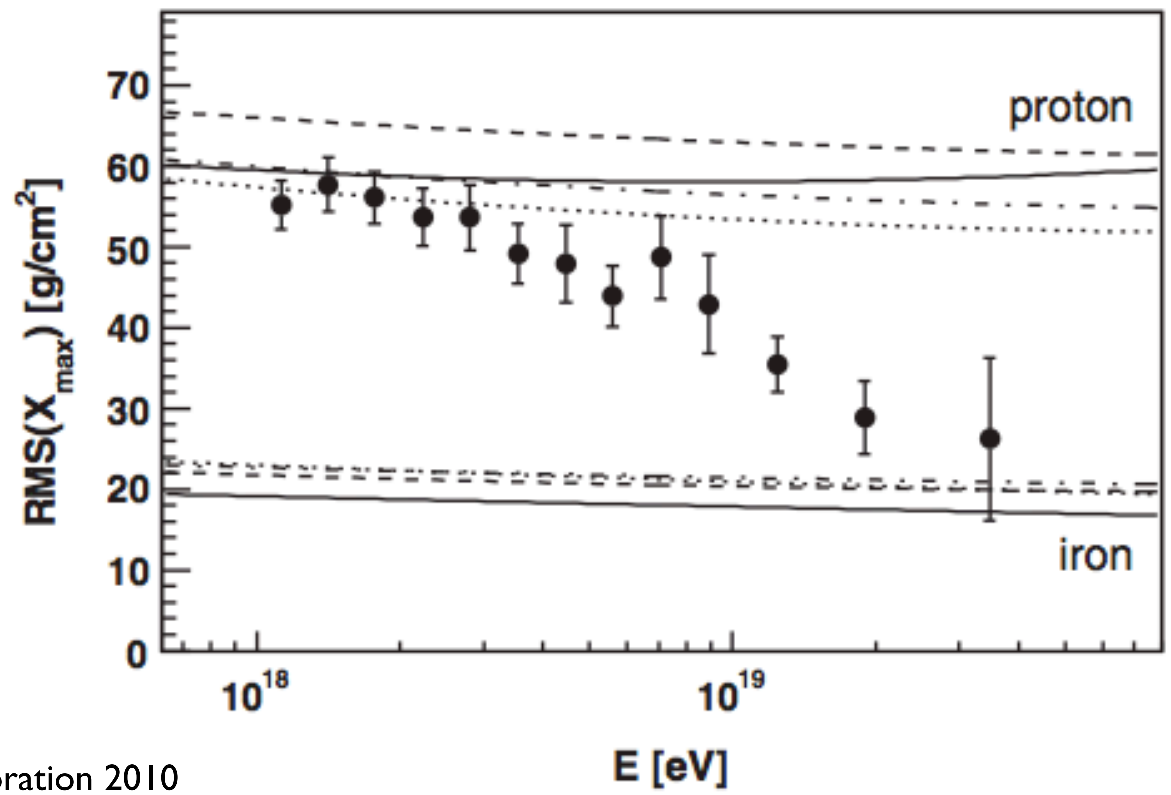
➡ only nearby sources can contribute to the flux at the highest energy
➡ a cut-off is expected in the spectrum (whatever the source composition)



GZK cut-off

Composition





Auger collaboration 2010

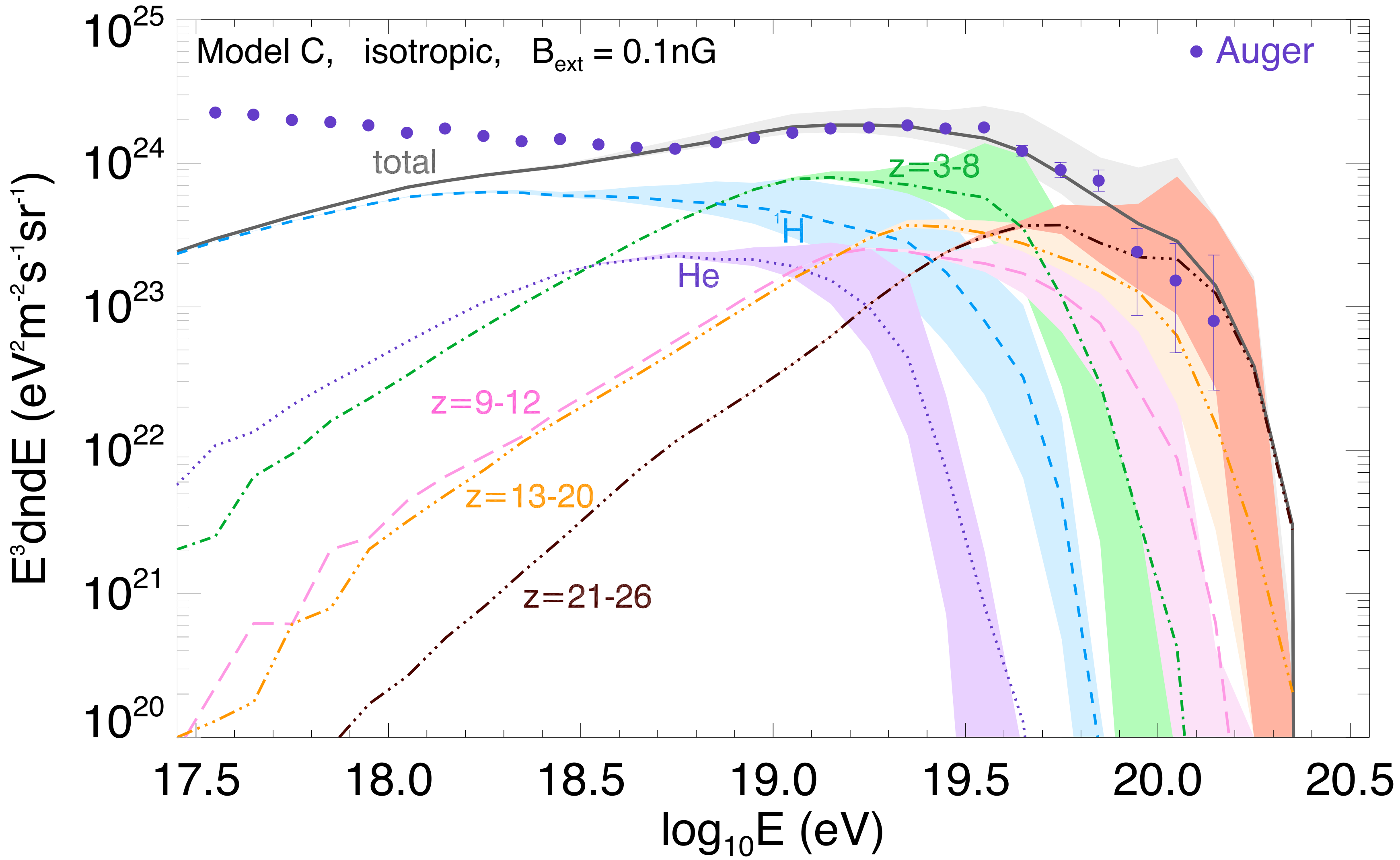
The composition which is light at the ankle becomes gradually heavier as the energy increased

➡ Most of the extragalactic sources dominating the flux on Earth are unable to accelerate protons above ~10^{19} eV

➡ Cosmic-rays above 10^{19} eV are probably heavier nuclei (maximum energy proportional to the charge)

➡ High charges at the highest energies => less promising for a rectilinear propagation

Example of a potentially successful model



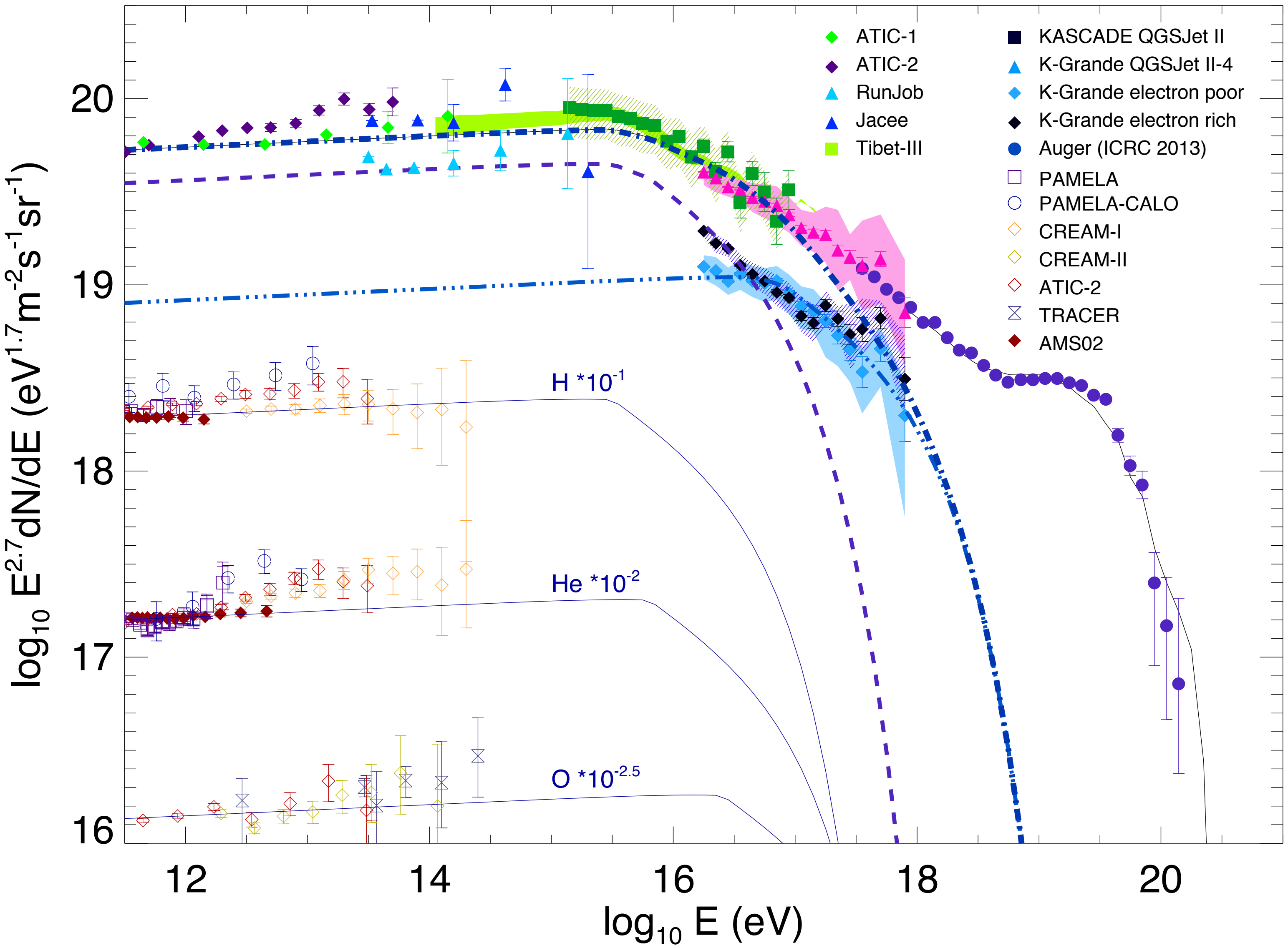
A source model involving GRBs as the sources of UHECR (there are other possibilities) :
- the sources are not able to accelerate protons above ~10^{19} eV
- heavier nuclei are able to make it to the highest energies

Galactic component

- KG does not suggest any strong asymmetry between the different components
- the knees of the different components are probably smooth

==> we same broken power law for the different species (break at the respective knees)

We normalize the different component with satellites measurements



$E_{break(p)} = 10^{15.5}$ eV,

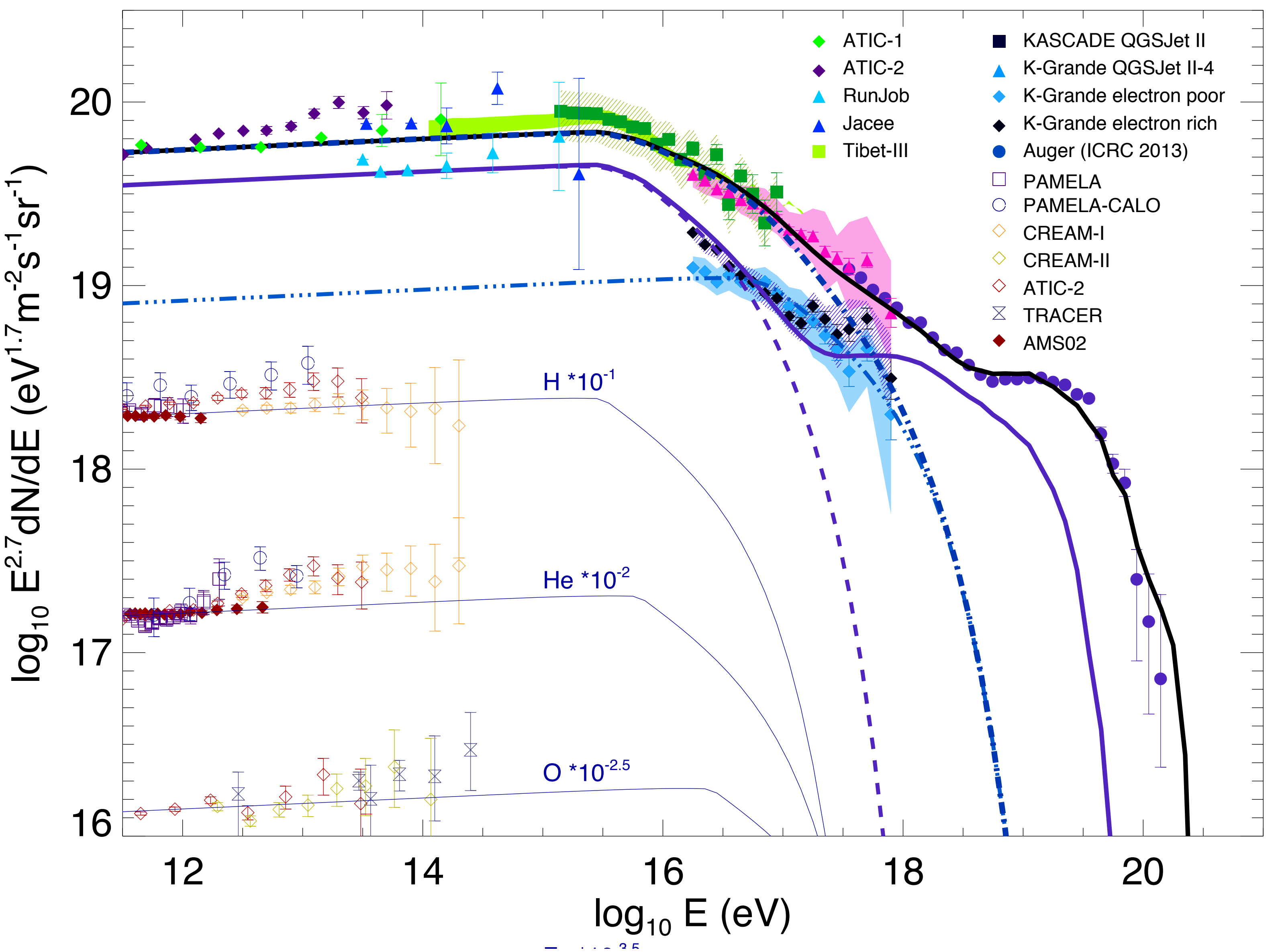
$x = 2.67$, $\Delta x = 0.45$

$E_{max(p)} = 6\,10^{16}$ eV

(exponential cutoff above E_{max})

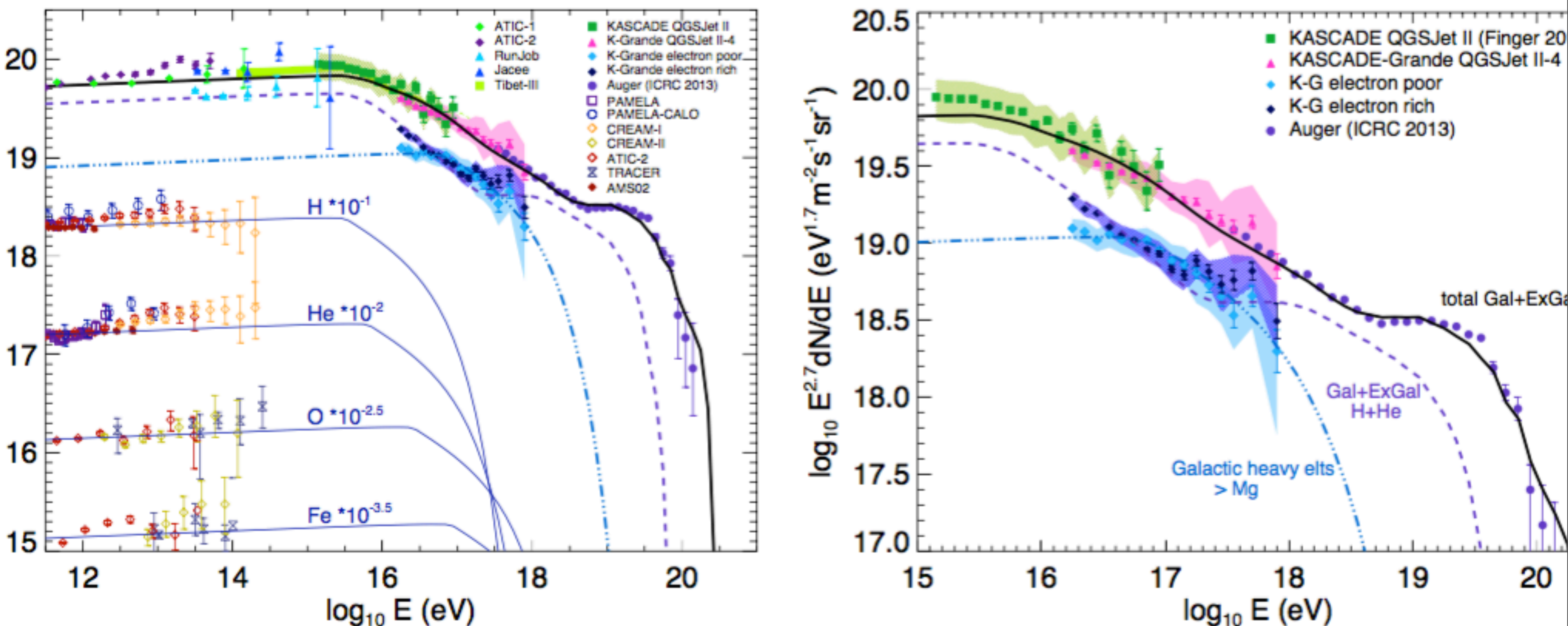
N. Globus, D. Allard, E. Parizot, Phys. Rev. D - Rapid Comm., 2015

Galactic + extragalactic component



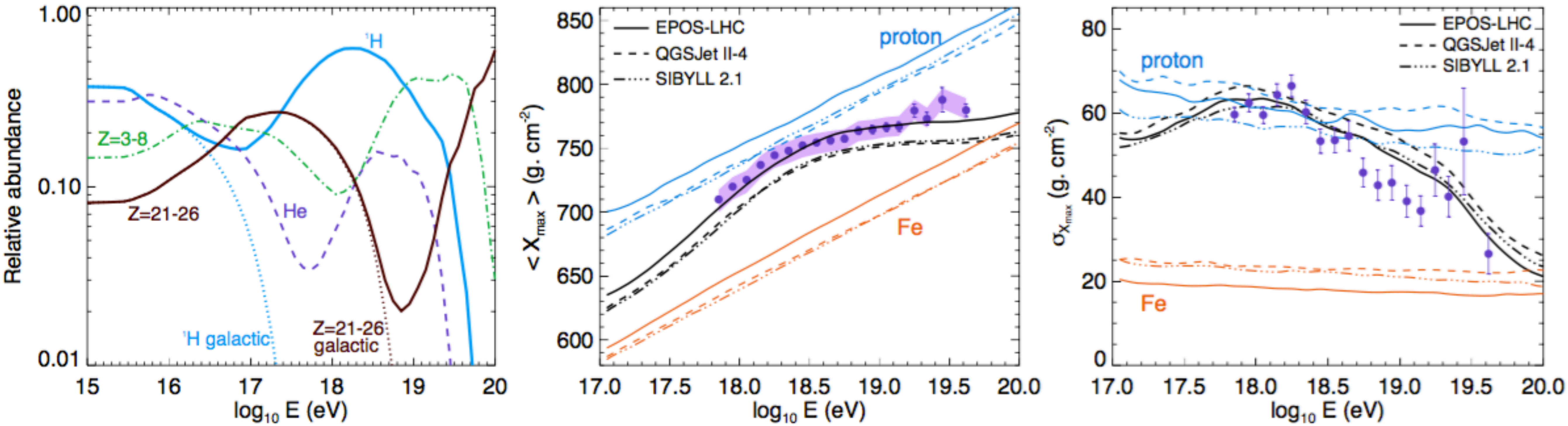
N. Globus, D. Allard, E. Parizot, Phys. Rev. D - Rapid Comm., 2015

Galactic + extragalactic component



N. Globus, D. Allard, E. Parizot, Phys. Rev. D - Rapid Comm., 2015

Evolution of the composition



- Good description of Auger composition observables when using the latest (LHC tested) hadronic models
- Good agreement with more recent Auger analyses (down to 10^{17} eV) and recent LOFAR (radio) measurements

- NB : Auger and KG composition results are fully coherent when analyzed with the most recent hadronic models

N. Globus, D. Allard, E. Parizot, Phys. Rev. D - Rapid Comm., 2015

Arrival directions

No strong evidence for significant deviation from isotropy

➡ Still in the fog

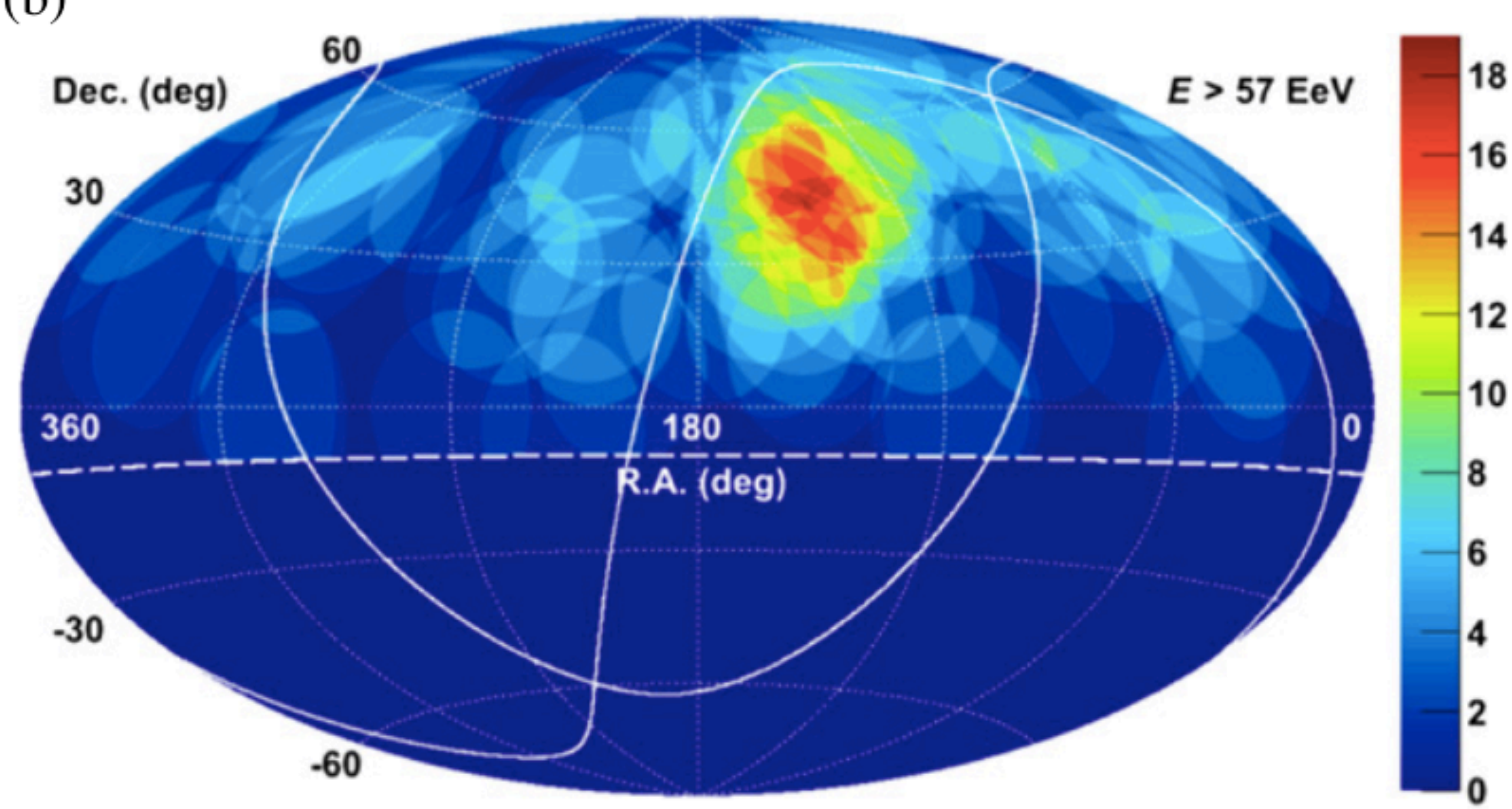
➡ Even with a huge area, Auger statistics remains too low at the highest energies (~ 150 cosmic-rays above 5.10^{19} eV)

A new hope for the north

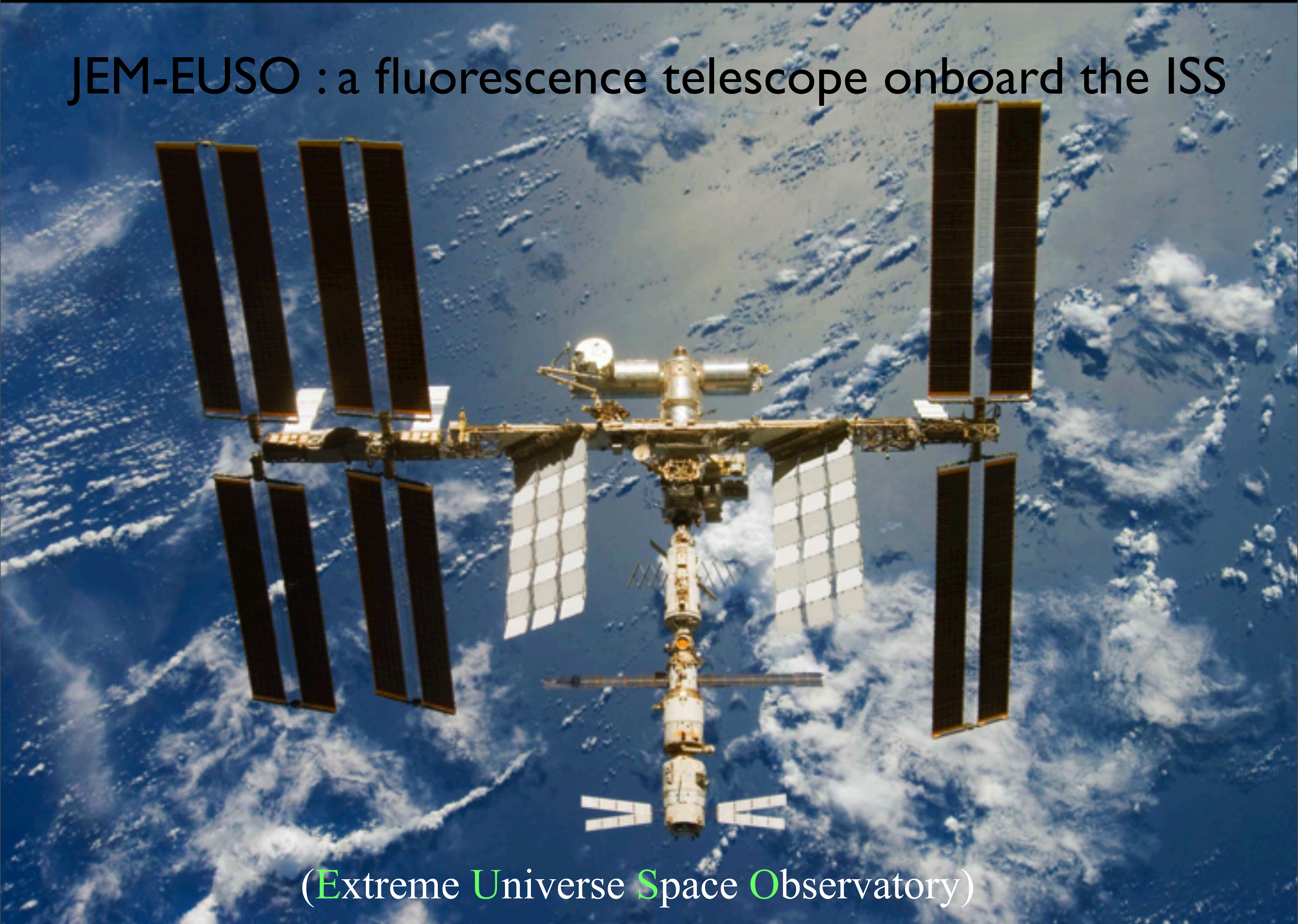
- ✧ "Telescope Array": Observatoire d'UHECRs situé en Utah, couvrant 700 km^2 (collaboration États-Unis/Japon)

- ✧ Le brouillard magnétique semble commencer à être percé, dans l'hémisphère nord !

(b)



➡ to be confirmed with larger statistics

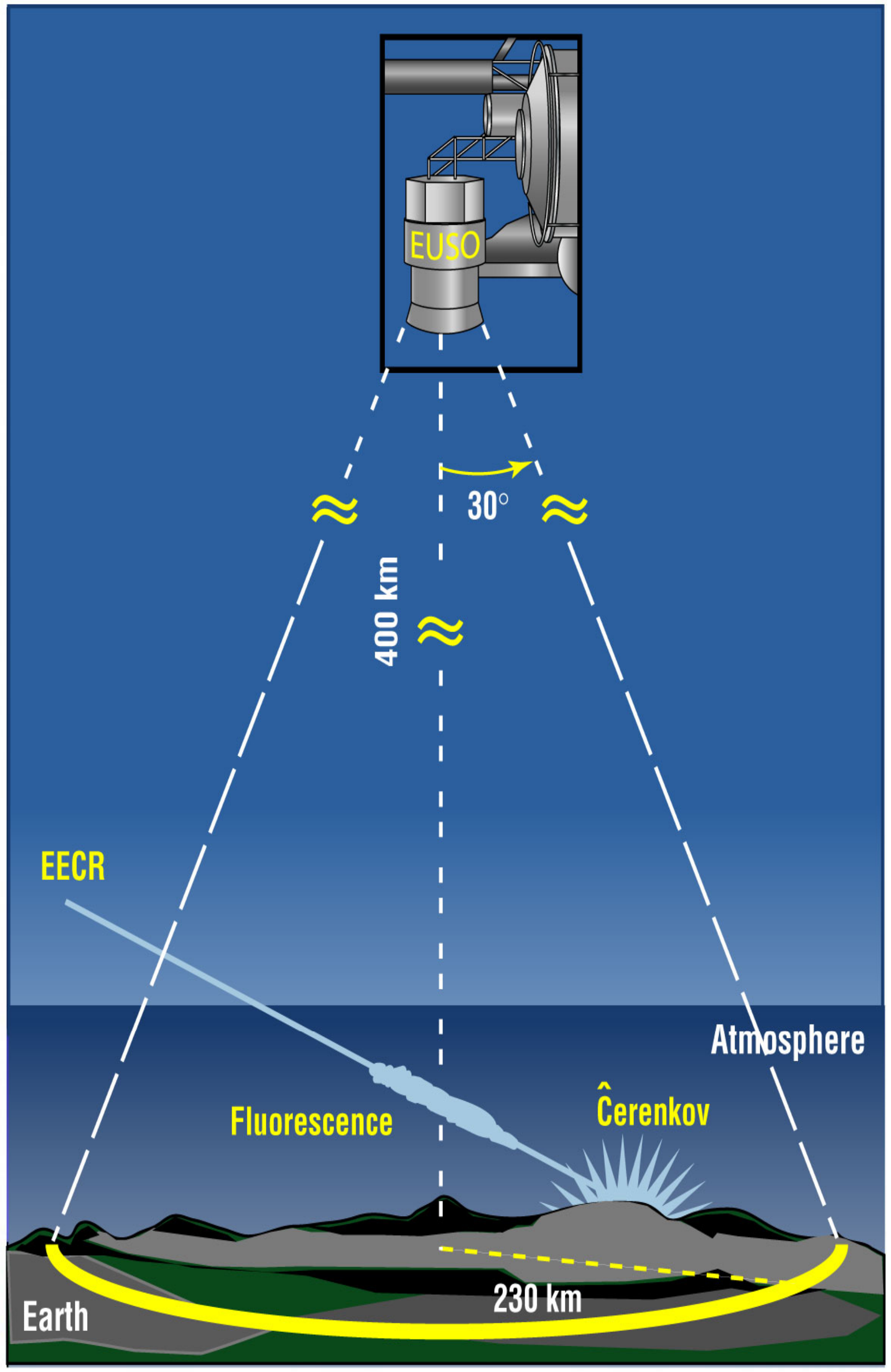

JEM-EUSO : a fluorescence telescope onboard the ISS
(Extreme Universe Space Observatory)

JEM-EUSO : doing astronomy by looking toward the ground !

At 400 km altitude, it will detect air showers above 3.10^{19} eV

Huge collection area

190 000 km^2



Requires cloudless and moonless nights

~14% duty cycle

With a 5 years mission, it should accumulate ~ 10 times the current Auger statistics above 5.10^{19} eV