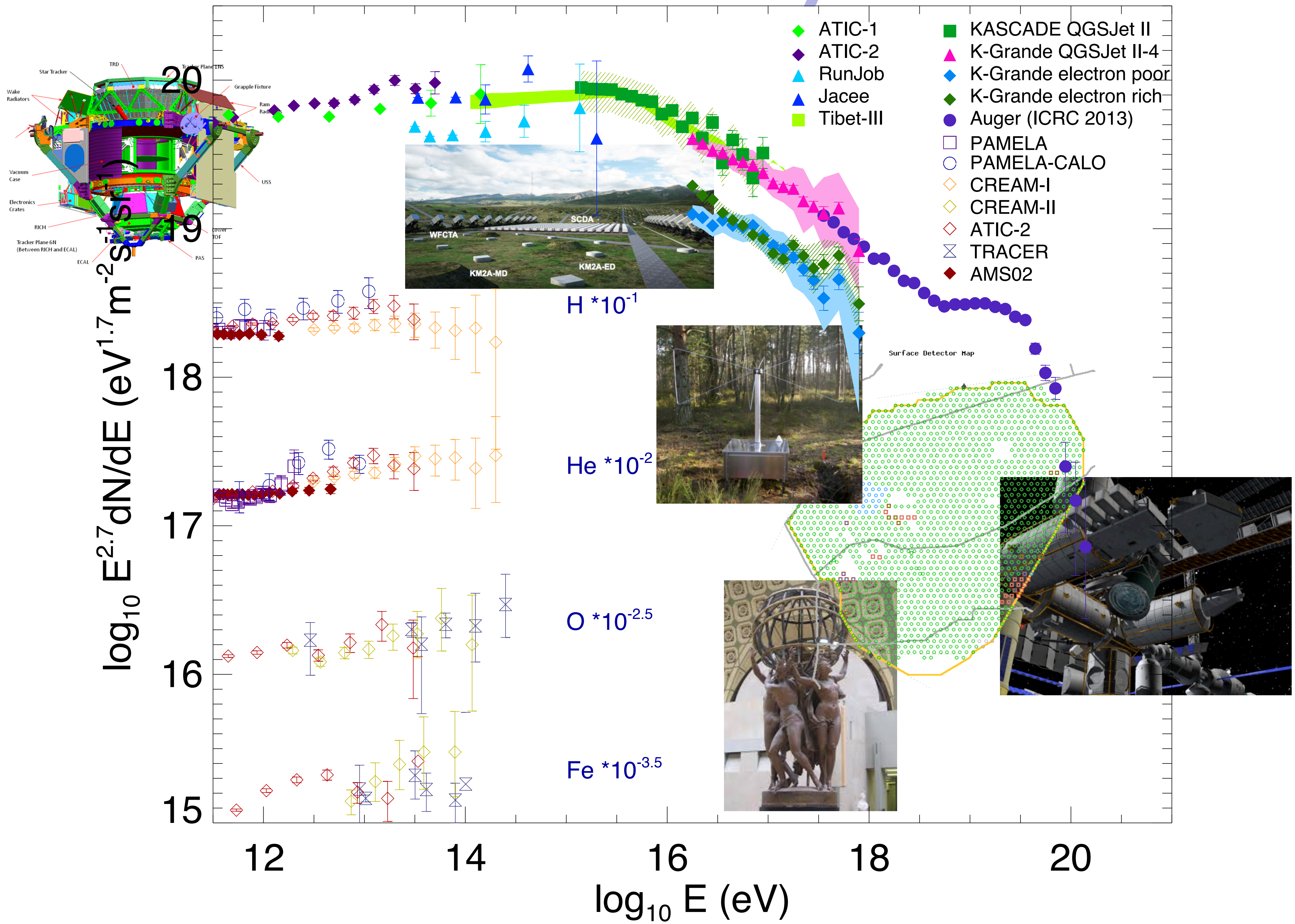
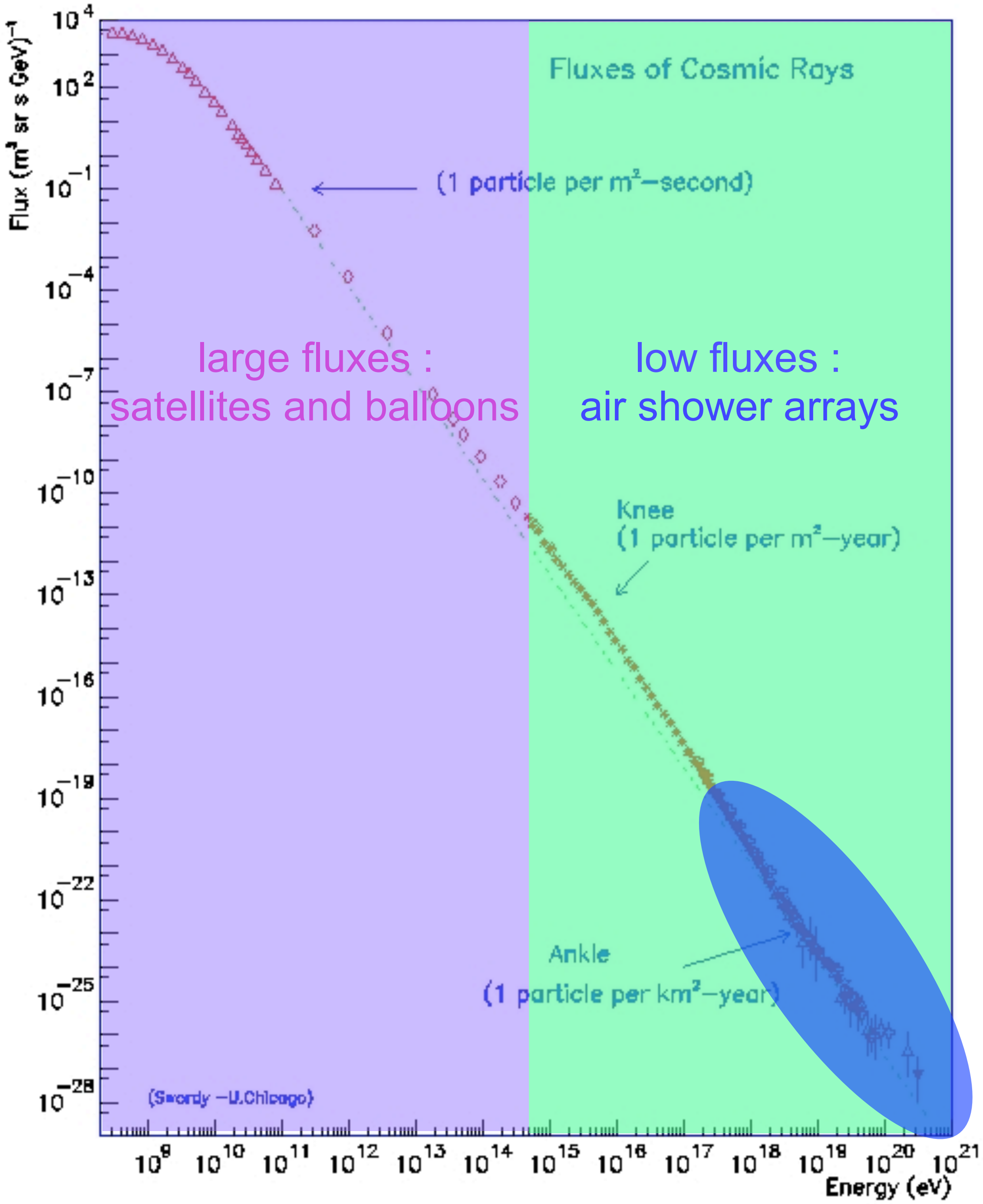
The transition from Galactic to extragalactic cosmic-rays



Denis Allard - CNRS

The cosmic-ray spectrum
(a wonder of high-energy astrophysics)



Spectrum measured on 12 orders of magnitude in energy and 32 in flux

- At low energy ($<10^{13-14}$ eV) the fluxes are large
-> domain of satellite and atmospheric balloons

- At high energies (low fluxes) one uses air shower properties to detect cosmic-ray
-> domain of ground based air shower observatories

- At the highest energies ($\sim 10^{20}$ eV), extremely low fluxes (<1 CR.km^{-2}.kyr^{-1})
-> domain of giant air shower detectors
NB : these particles are simply the most energetic particles known to exist in the universe

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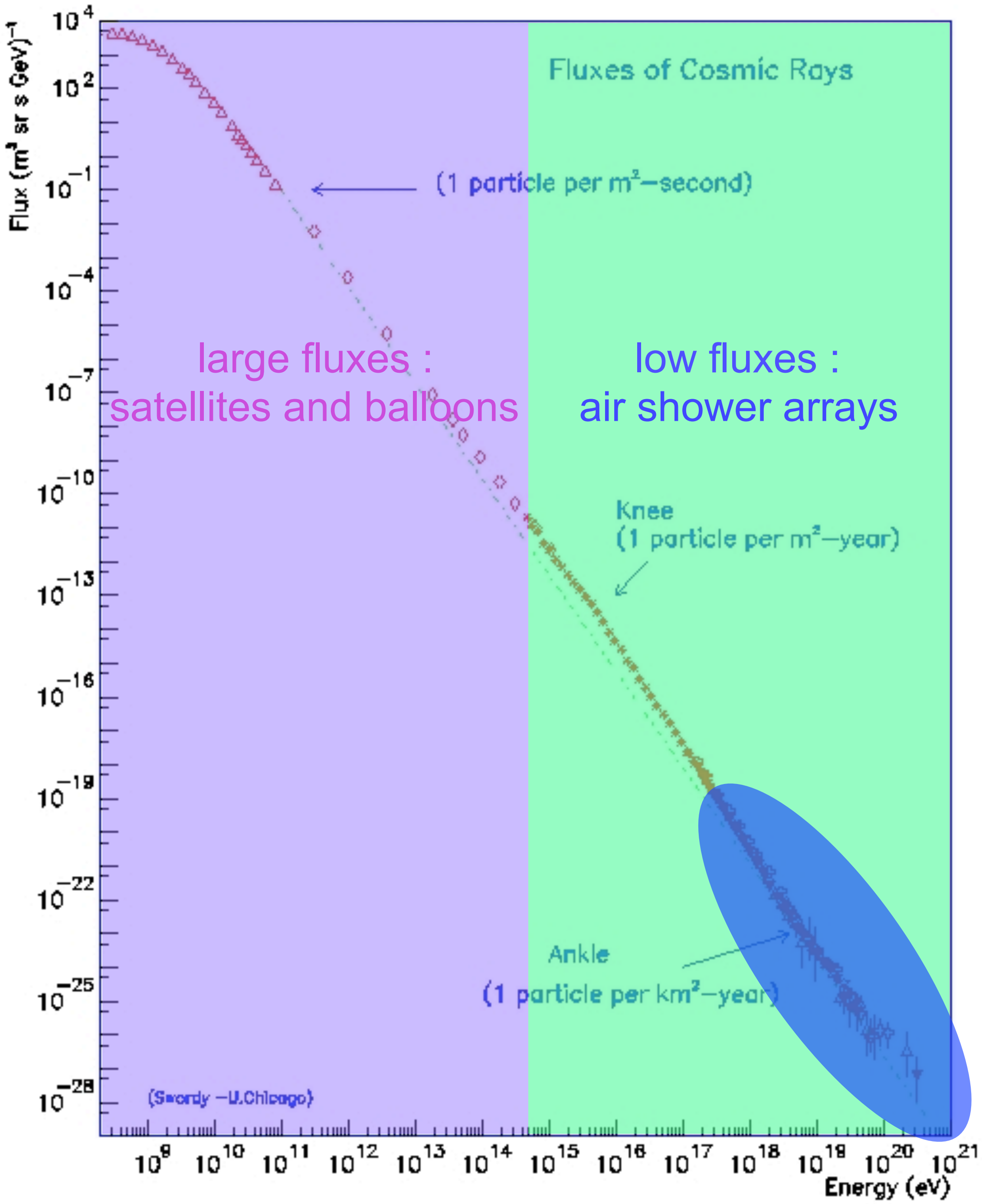

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We know cosmic-rays are accelerated in astrophysical sources but we do not know much more about their origin (long standing question for high-energy astrophysics)

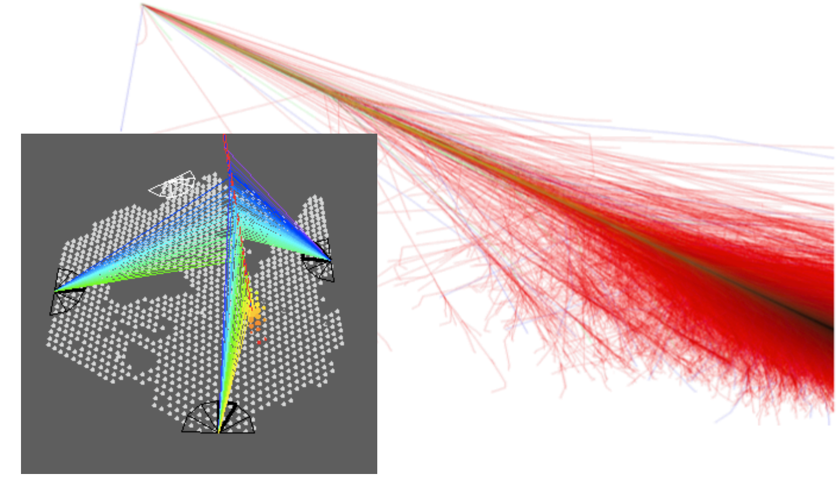
3 key observables to understand the origin of cosmic-rays

1	2	3
Angular spectrum	Energy spectrum	Mass spectrum
↓	↓	↓
Arrival directions	Flux as a function of the energy	composition

4 key observables to understand the origin of cosmic-rays

1	2	3	4
Angular spectrum	Energy spectrum	Mass spectrum	Multi-messenger counterparts
↓	↓	↓	↓
Arrival directions	Flux as a function of the energy	composition	cosmogenic γ and ν

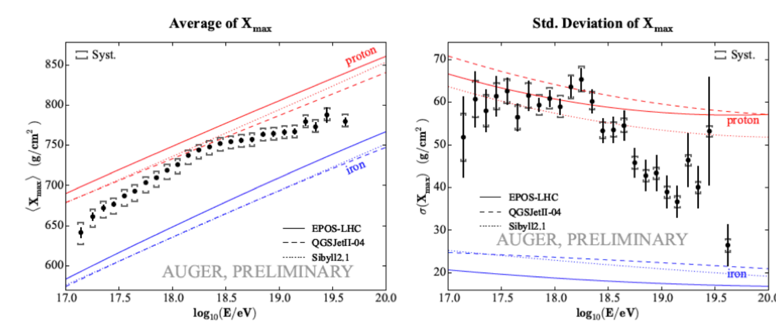
Outline



- Indirect detection of cosmic-rays, a brief introduction
  - A few facts about air showers
  - Detection techniques (ground arrays and fluorescence detectors)
  - More emphasis on KASCADE and the Pierre Auger Observatory

- A closer look to the cosmic-ray spectrum
  - The knee and the ankle

- Hints from extragalactic cosmic-rays phenomenology
  - Propagation of protons and nuclei



- Key results obtained in the last few years and their possible interpretation
  - KASCADE-Grande's heavy knee and light ankle
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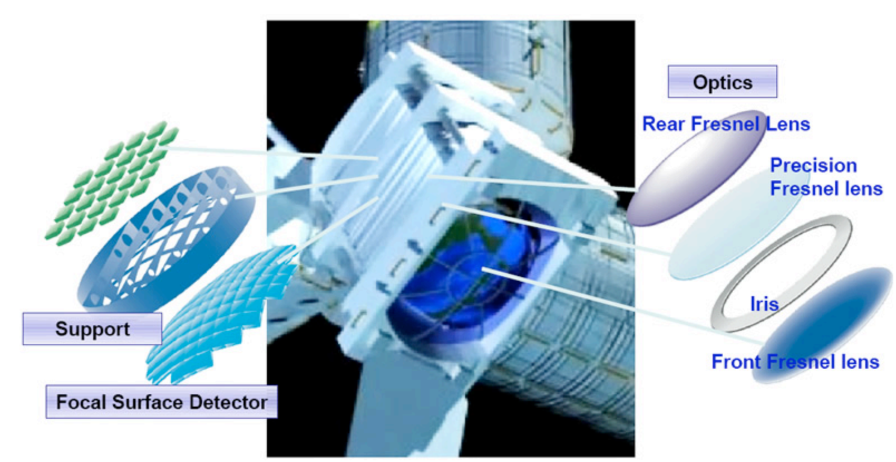
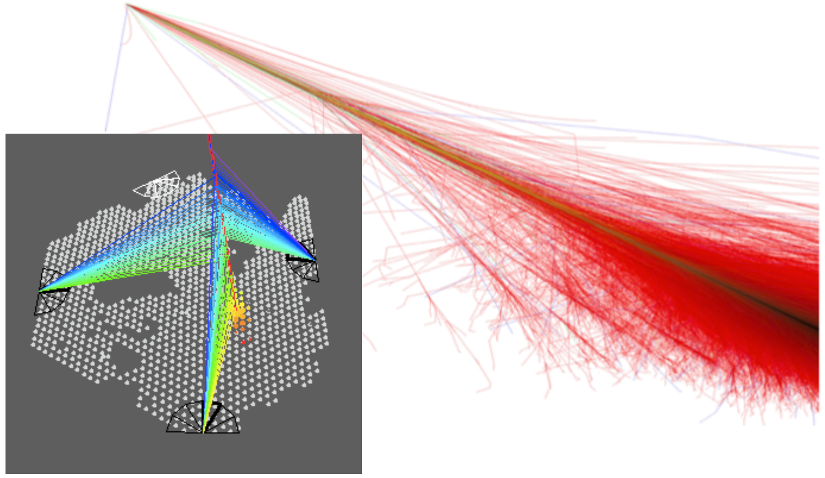


- Can a consistant picture emerge?
  - Still a few stones in the shoe…

- A few key future experiments

Outline



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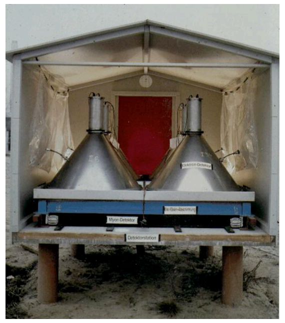

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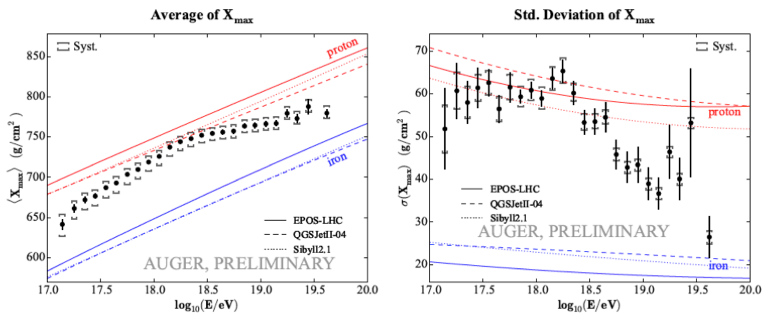

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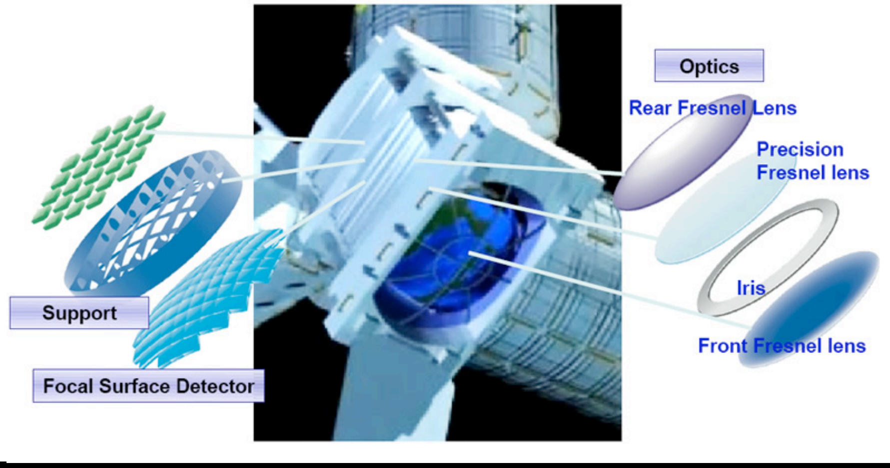
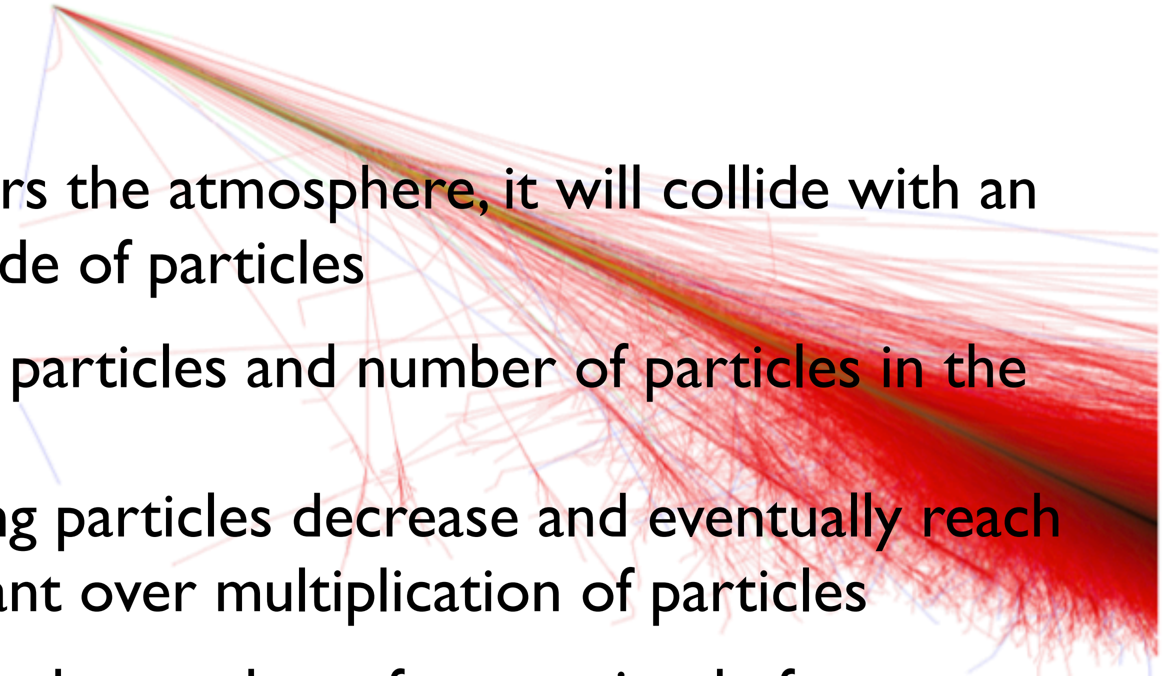


A few simple facts about air showers



- Whenever a high energy a cosmic-ray nucleus enters the atmosphere, it will collide with an ambiant nucleus and initiate the production of a cascade of particles

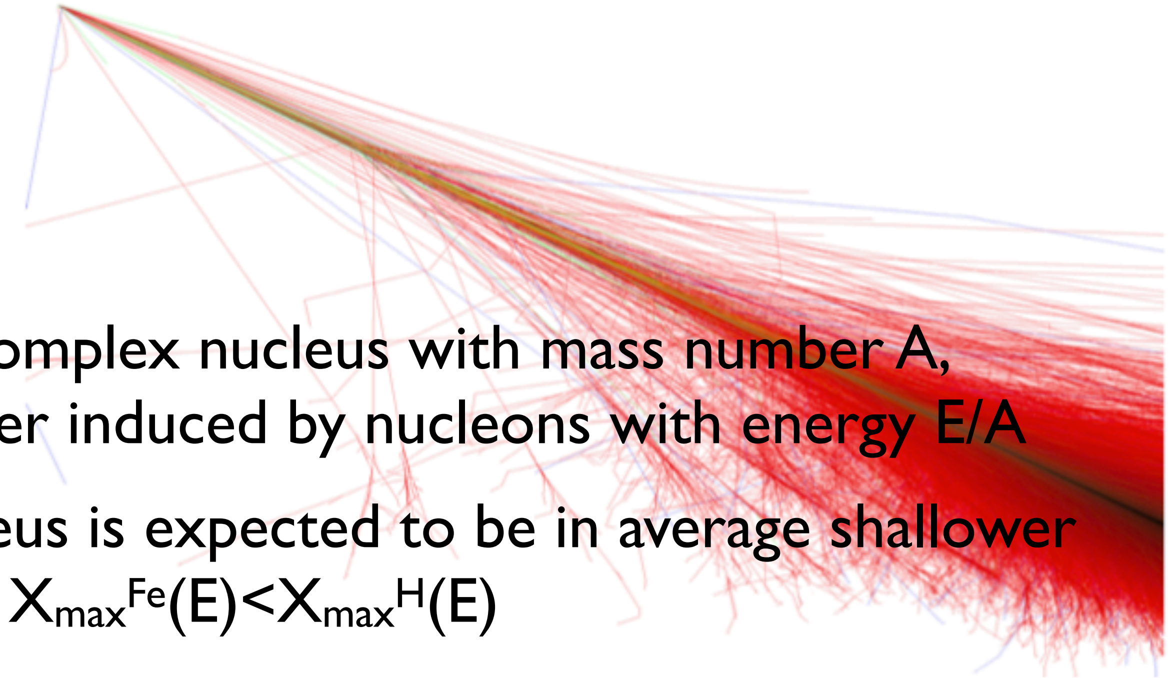
- The shower will develop over many generations of particles and number of particles in the shower increase before reaching a maximum
—> as the development goes, the energy of the leading particles decrease and eventually reach a critical energy at which absorption becomes dominant over multiplication of particles

- For a proton, the higher the initial energy, the larger the number of generation before reaching the critical energy, the deeper in the atmosphere the shower will develop, the larger the number of particles at the shower maximum

—> important quantities : $\mathbf{X_{max}}$ the depth of atmosphere crossed before reaching its maximum; $\mathbf{N_{max}}$ the number of particles in the shower at the maximum (in good approx proportional to the energy)
NB : use of X rather than l; X in $g.cm^{-2}$ (same idea as the grammage for CR propagation)

- at ground level (usually well beyond the shower maximum) the shower is mostly composed of γ, $e^{+/-}$ (electromagnetic component of the shower) and $\mu^{+/-}$ (hadronic component of the shower)

A few simple facts about air showers



- Superposition principle : A shower induced by a complex nucleus with mass number A, behave approximately as the superposition of A shower induced by nucleons with energy E/A

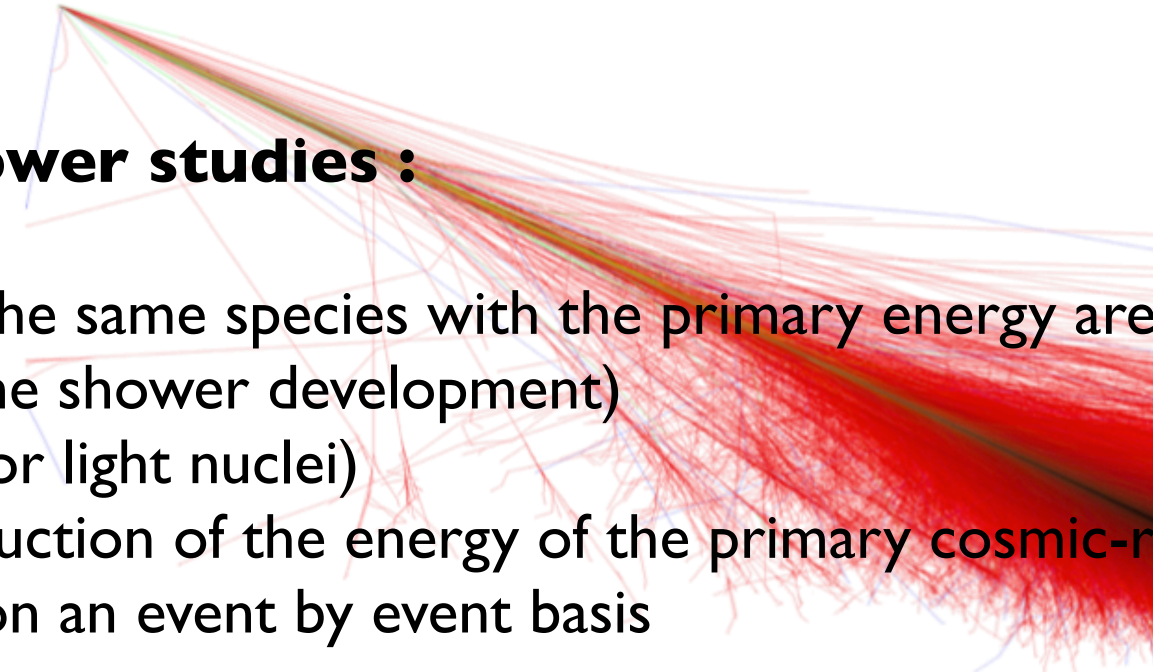
—> the development of a shower induced by a nucleus is expected to be in average shallower than that of a proton with the same initial energy, *e.g*, $X_{max}^{Fe}(E)<X_{max}^{H}(E)$

—> the shower to shower fluctuations for heavy nuclei are expected to be lower than those of light nuclei and all the more protons

—> the number of muons expected in average in showers induced by heavy nuclei is larger than that of light nuclei induced showers, *e.g*, $N_{\mu}^{Fe}(E)<N_{\mu}^{H}(E)$

—> $\mathbf{X_{max}}$ **and** $\mathbf{N_{\mu}}$ (or similarly the "muon to electron ratio") are very important composition sensitive parameters of the air shower

A few simple facts about air showers



Two very important limitations of Air shower studies :

(i) The properties of several air showers initiated by the same species with the primary energy are expected to differ (stochastic processes involved in the shower development)
—> shower to shower fluctuations (especially large for light nuclei)
—> in particular limits the resolution of the reconstruction of the energy of the primary cosmic-ray
—> "forbids" the determination of the composition on an event by event basis

(ii) Part of the interactions taking place during an air shower development (especially at the first stages of VHE or UHE showers) are beyond the reach of artificial particles accelerators and thus poorly constrained

—> interpretations of showers observables in terms of energy or mass of the primary cosmic-ray must rely the predictions of ***different hadronic models*** which model particles interactions beyond the measurable limits (currently the most widely used are QGSJet, EPOS and SIBYLL)

—> hadronic model dependence is also currently a strong limitation for composition studies of VHE and UHE cosmic-rays

due to the conjonction of (i) and (ii) the best that can be done for CR composition is to separate large datasets into light/intermediate/heavy CR components and search for features which seem not to depend on the hadronic model used

Detection of VHE and UHE cosmic-rays

Above ~10^{14} eV, fluxes are too low for satellites and balloons detection

Ground based observatory detect atmospheric air showers

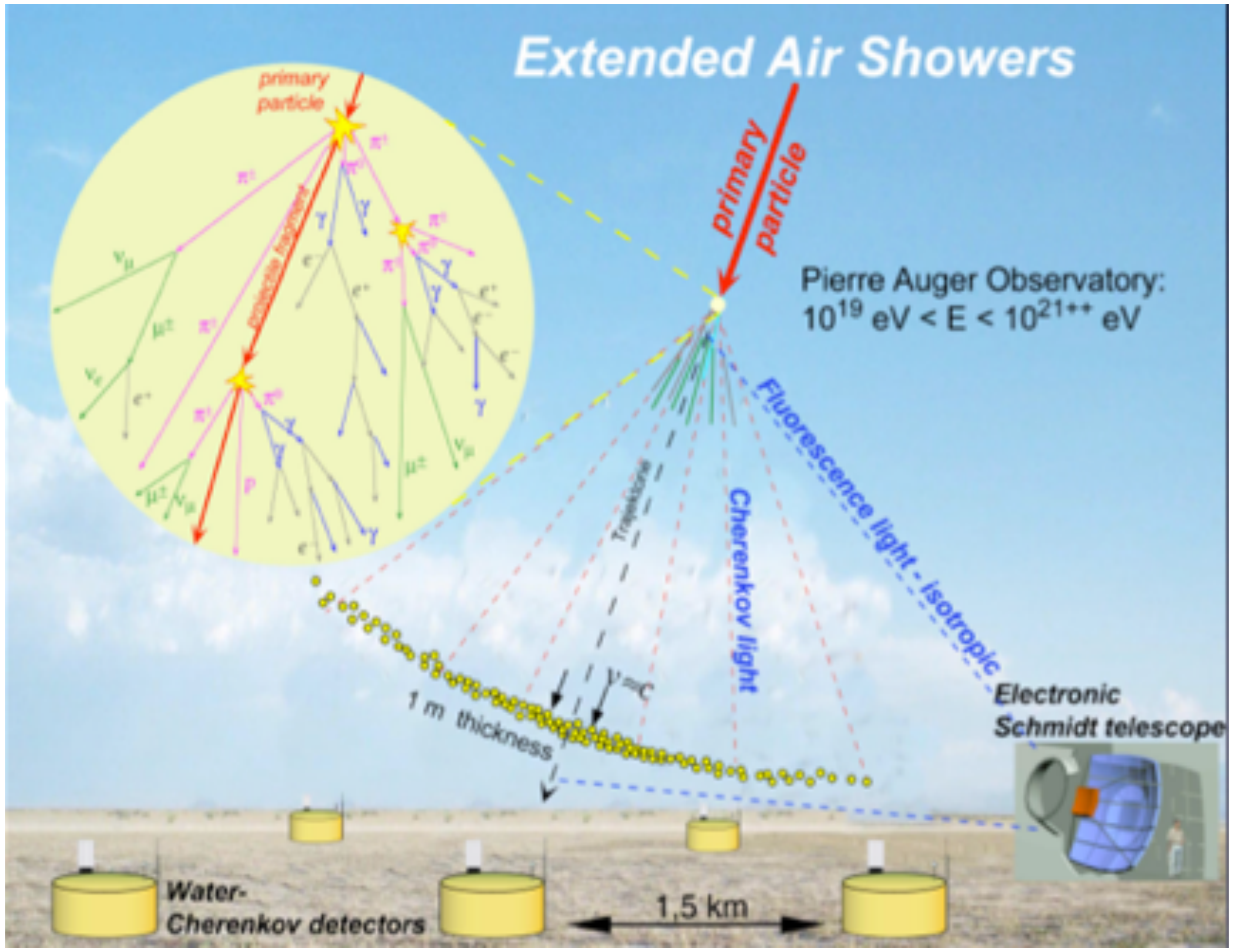
Principle : detect secondary particles in order to reconstruct the properties of the primary cosmic-ray

Mainly two detection methods :

Ground arrays

Fluorescence telescope

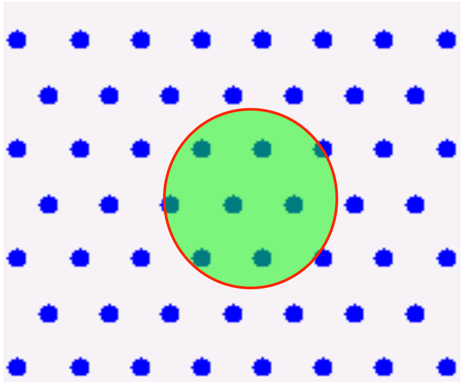
KASCADE (Germany; ~10^{15} to 10^{18} eV) and Auger (argentina; >10^{17} eV), Telescope Array (US, UHECR) are two examples of ground based cosmic-ray observatories but there are many others



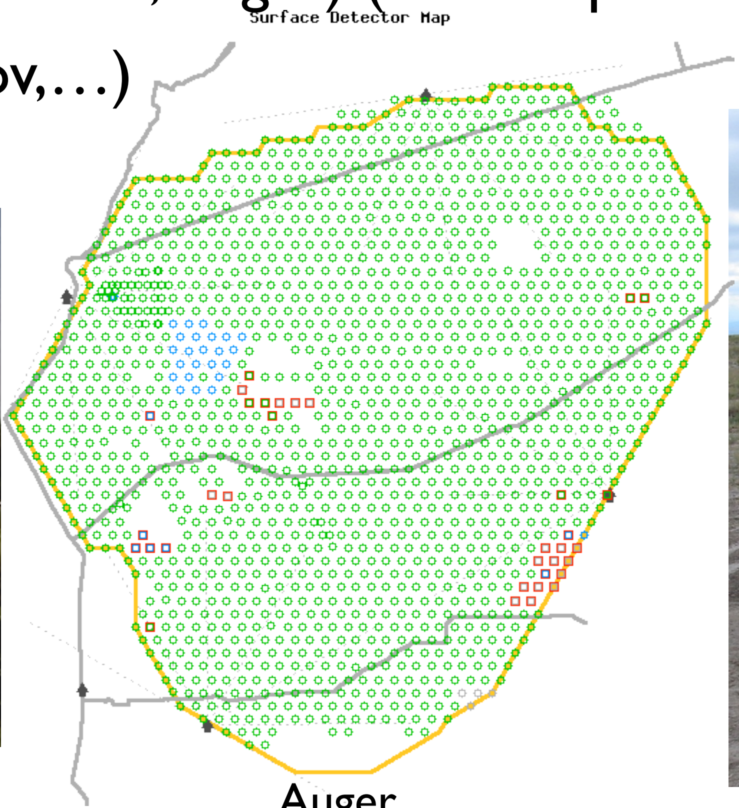
Ground array detectors

- Sampling air shower particles at ground level
- Surface covered and detector spacing depends on the targeted energy range :
  - Kascade (10^{15}-10^{17} eV) : surface 40000 m^2, 252 detectors, spacing 13m
  - Kascade Grande (10^{16}-10^{18} eV) : surface 0.5 km^2, 37 detectors, spacing 130m
  - Auger ($10^{18.5}$- >10^{20} eV) : surface 3000 km^2, 1600 detectors, spacing 1500 m

- Different type of detectors :
  - Scintillators (Kascade, AGASA) (==> electrons)
  - Shielded scintillators (AGASA, Yakutzk) (==> muons)
  - Water Cerenkov Tanks (Haverah Park, Auger) (==> all particles)
  - And many more (radio, Cerenkov,…)

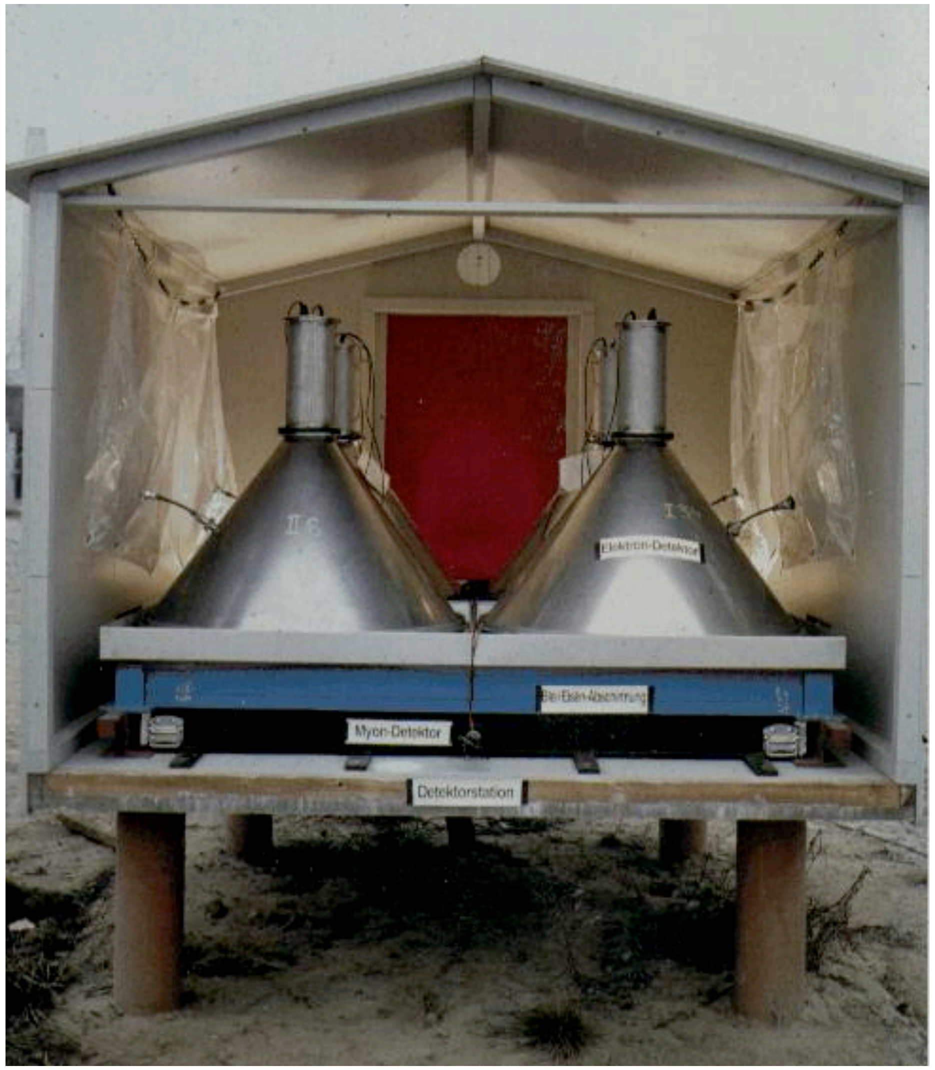


Kascade



Auger

Ground array detectors



liquid scintillators => e^+e^-
shielded plastic scintillators => muons

Kascade

Kascade-Grande

Ground array detectors

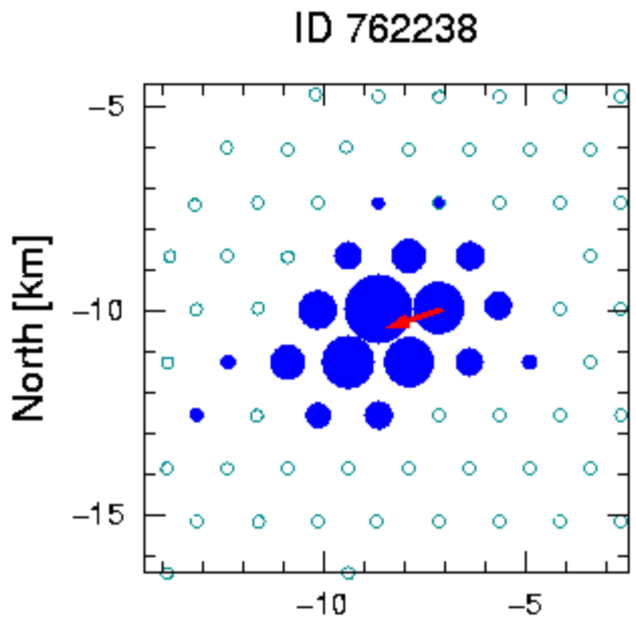
- Reconstruction methods :
  - Direction estimated using the time structure of the shower front
  - Energy reconstructed using the evolution signal size (Number of particles) as a function of core distance
  - Nature estimated mainly using the number of muons or the muon to electron ratio

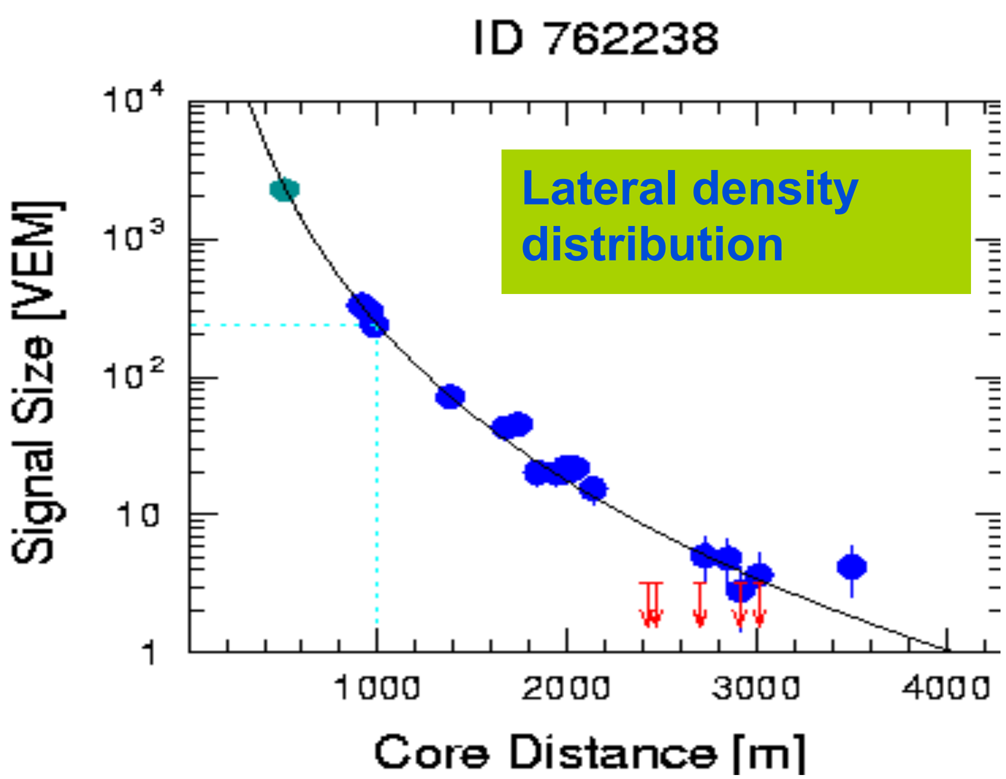
The relation Signal size/Energy is extracted from air shower simulations

-> Hadronic model and composition dependent

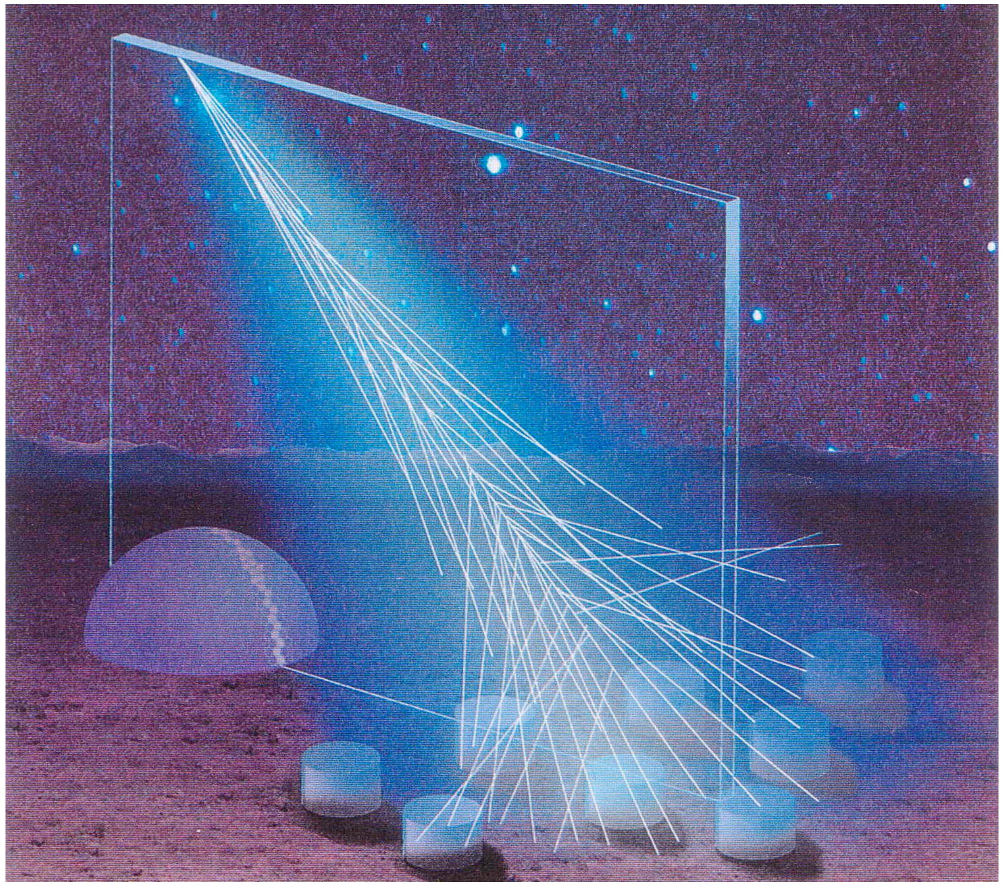
The relation muon number/composition is extracted from air shower simulations

-> Hadronic model dependent





Fluorescence detectors

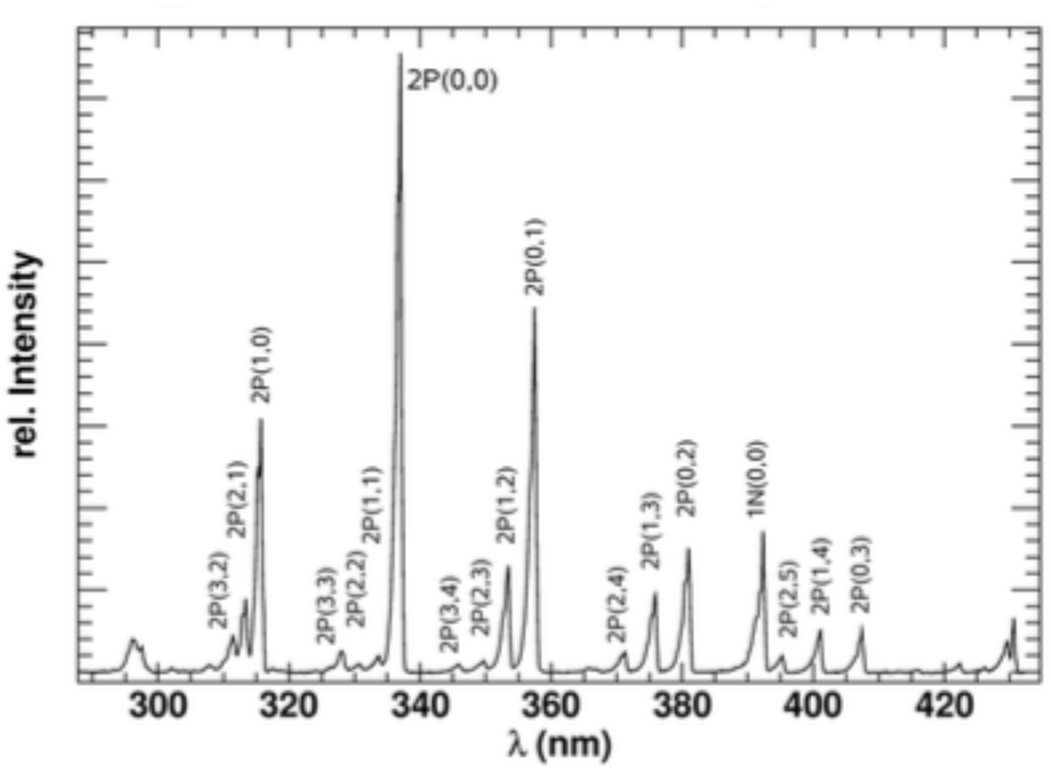


- The fluorescence (UV) emitted by N_2 molecules exited by the air shower e^+e^- is detected
- Fluorescence light proportional to the number of electromagnetic particles in the shower

-> 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
- Systematic uncertainty mainly due to the fluorescence yield
- Energy dependent aperture

Fluorescence detectors



Spectrum of Fluorescence emitted by a 3 MeV e^- in air

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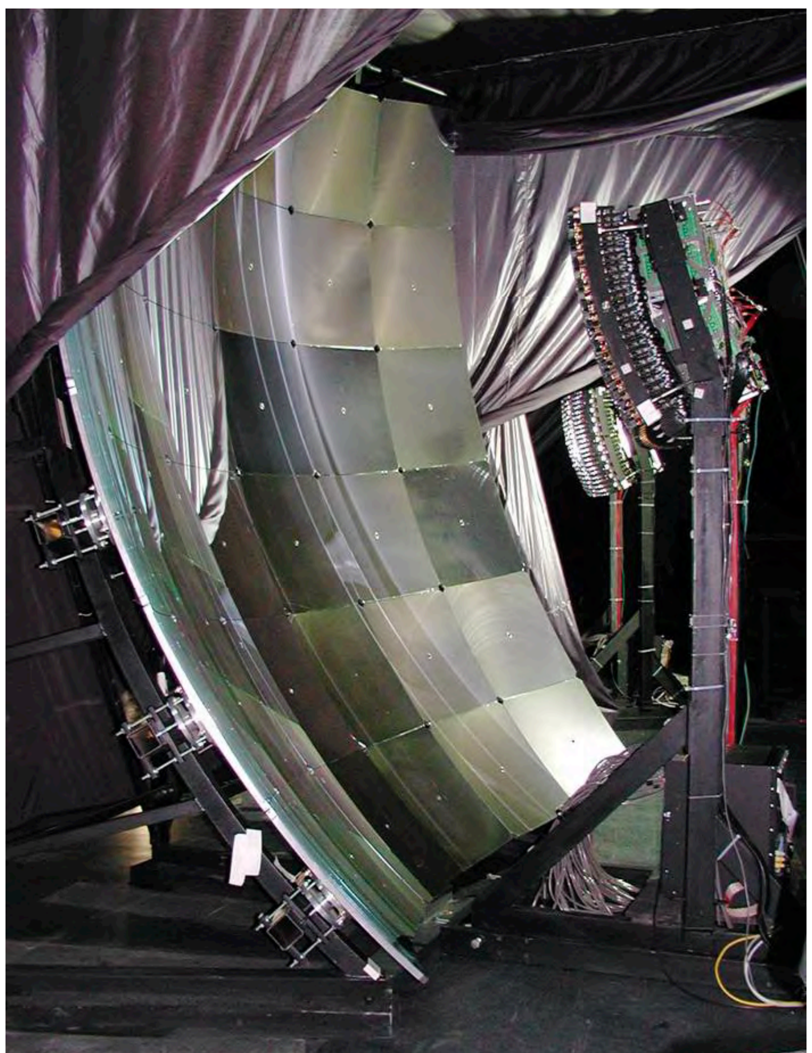
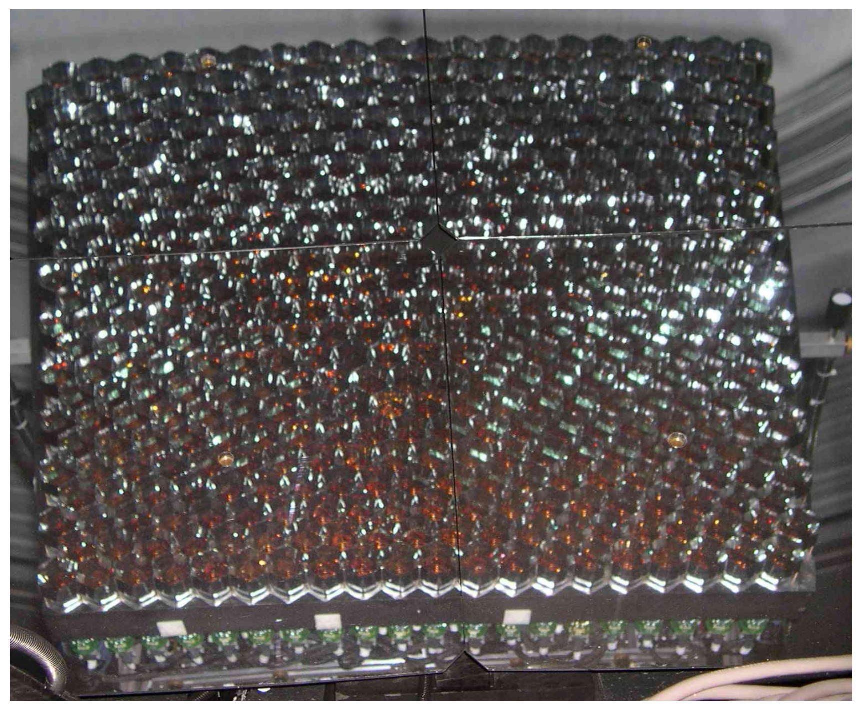
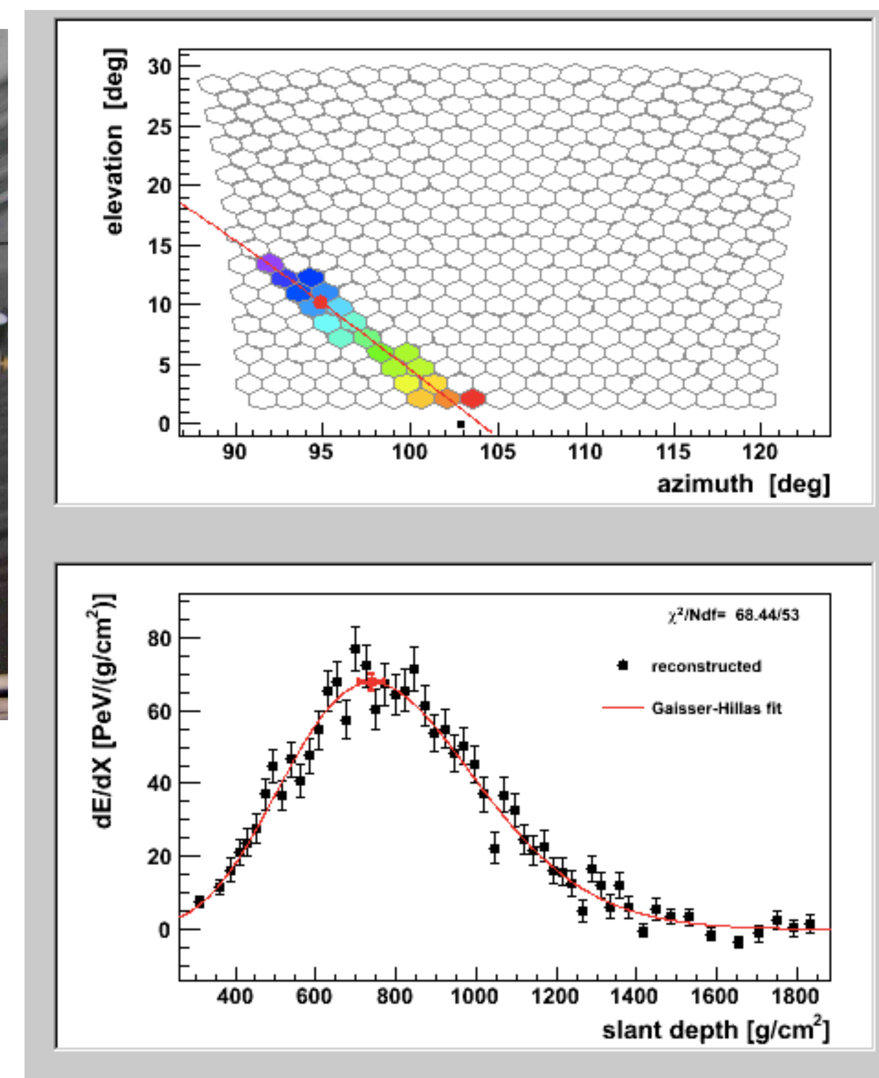
Fluorescence detectors

- 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)







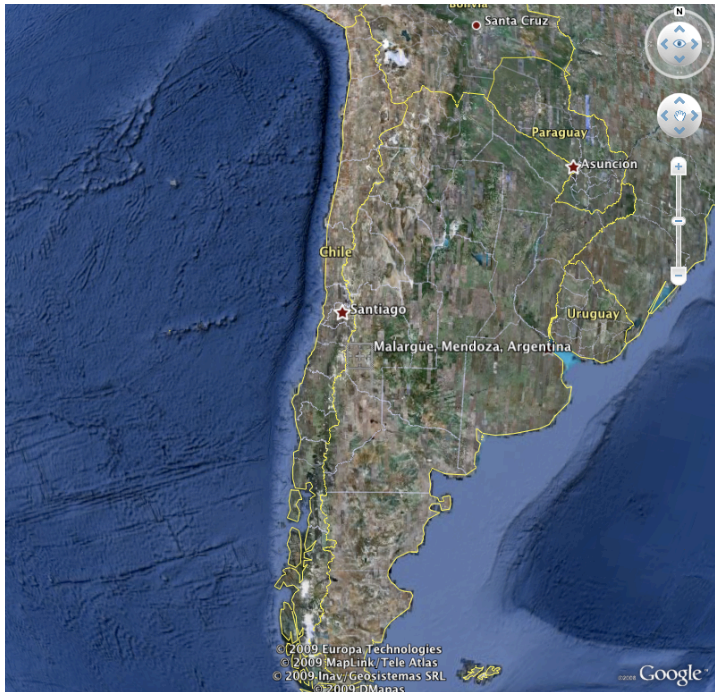
The Pierre Auger Observatory : hybrid detection

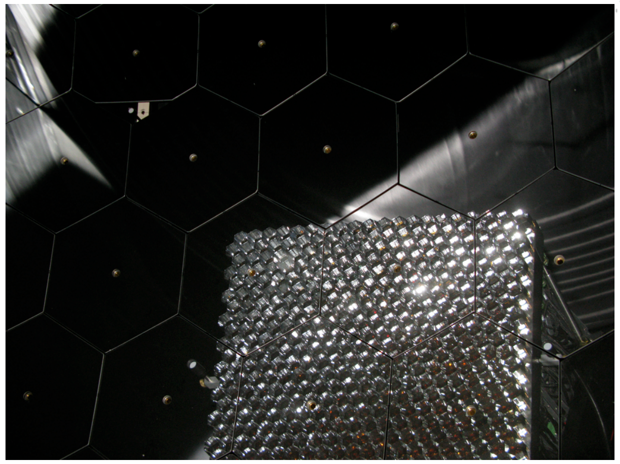
- Located in Malargue (Mendoza, Argentina, 1400m a.s.l
- 1600 Water Cerenkov Tanks, spacing 1500 m

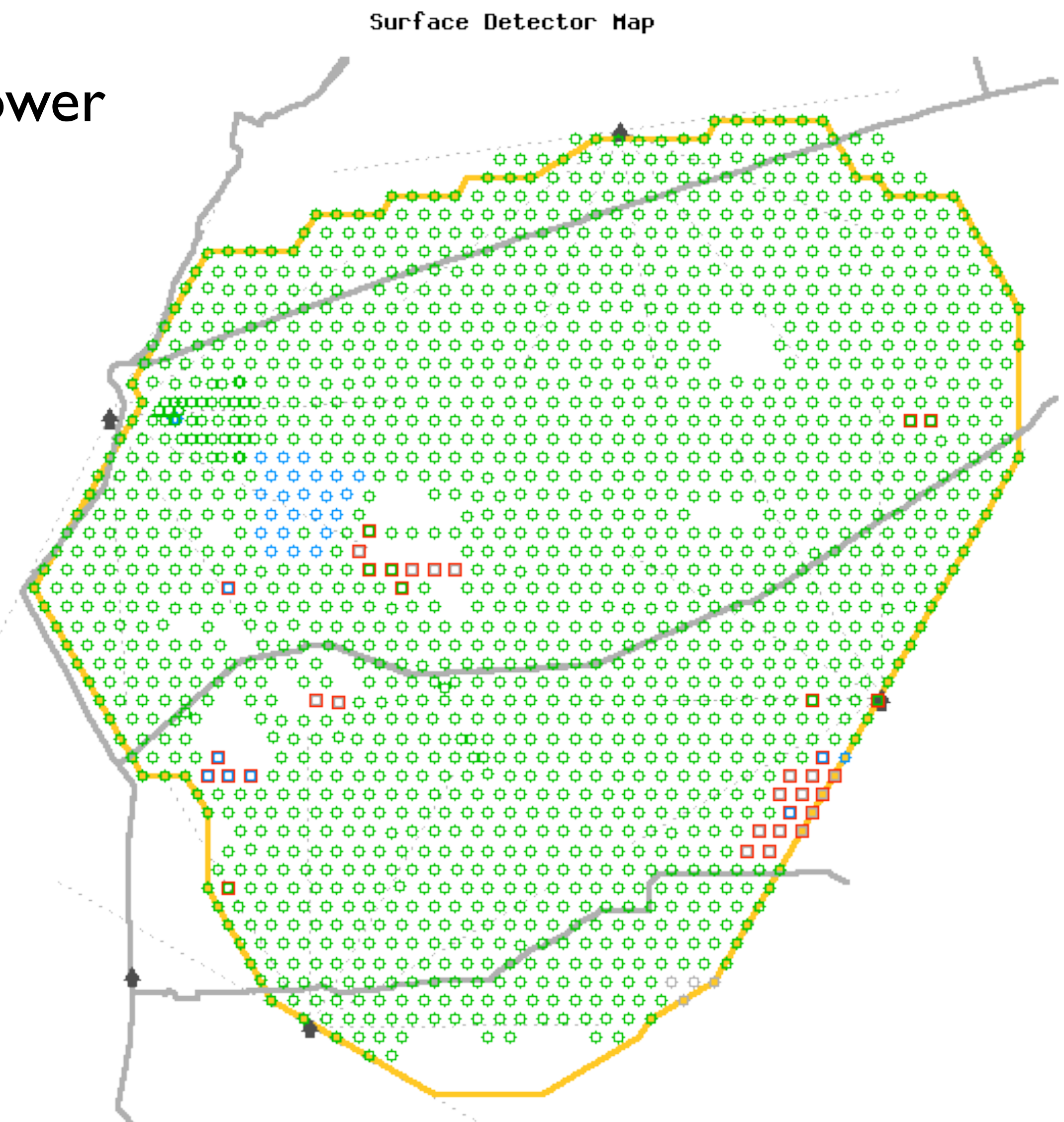
-> ground array surface 3000 km^2

- 4 Fluorescence detectors overlook the array

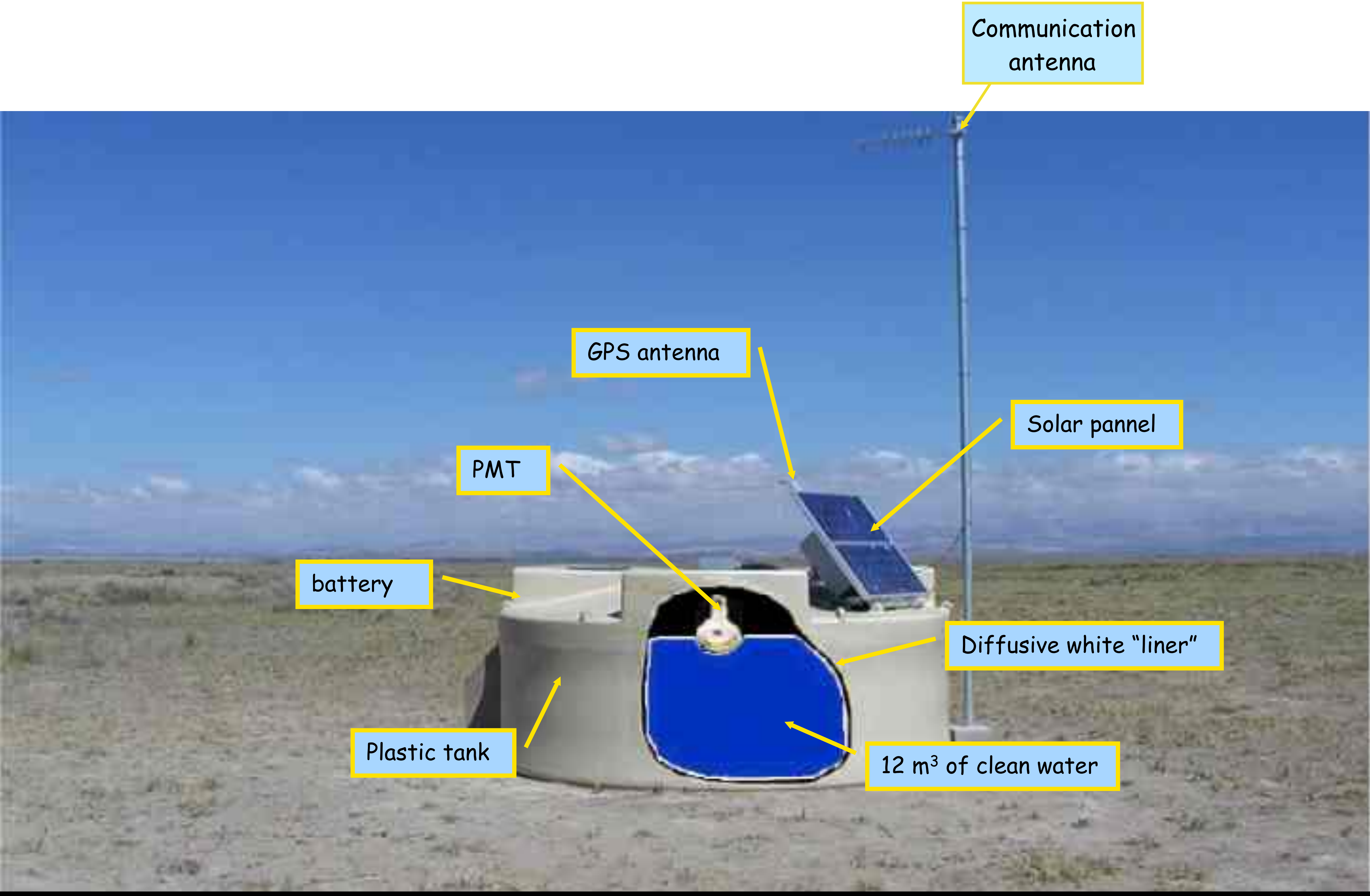
→ Huge surface for an unprecedented statistics above 10^{19} eV
Hybrid detection for a good understanding of air-shower physics







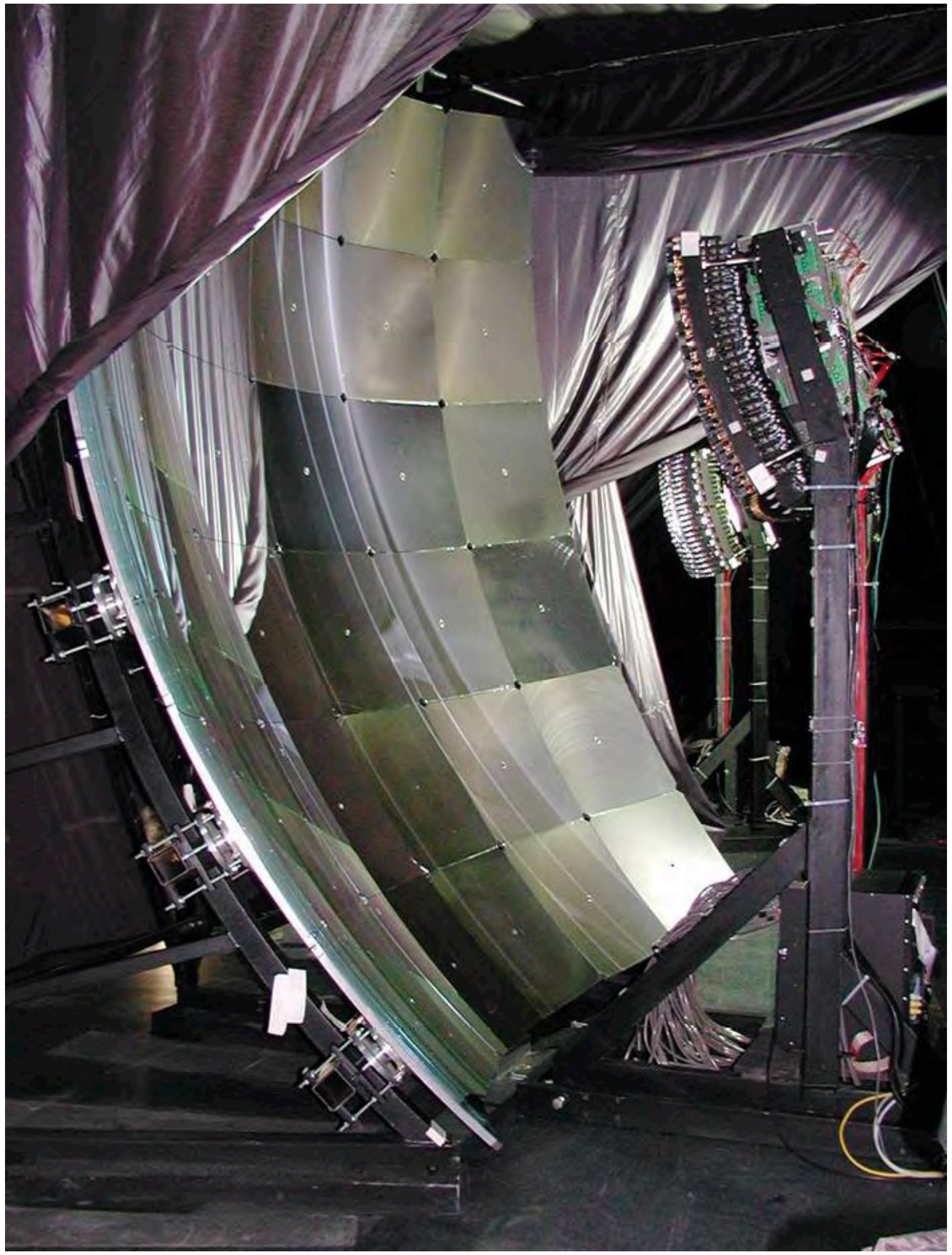
A water Cerenkov tank

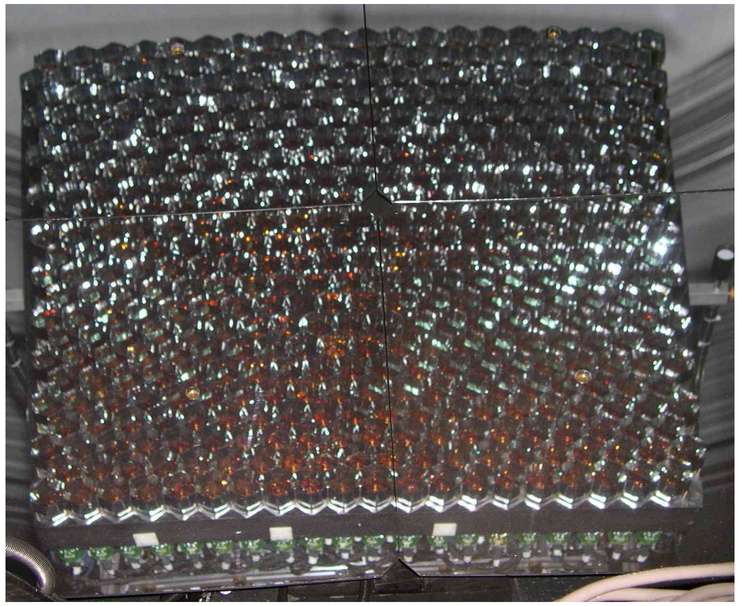


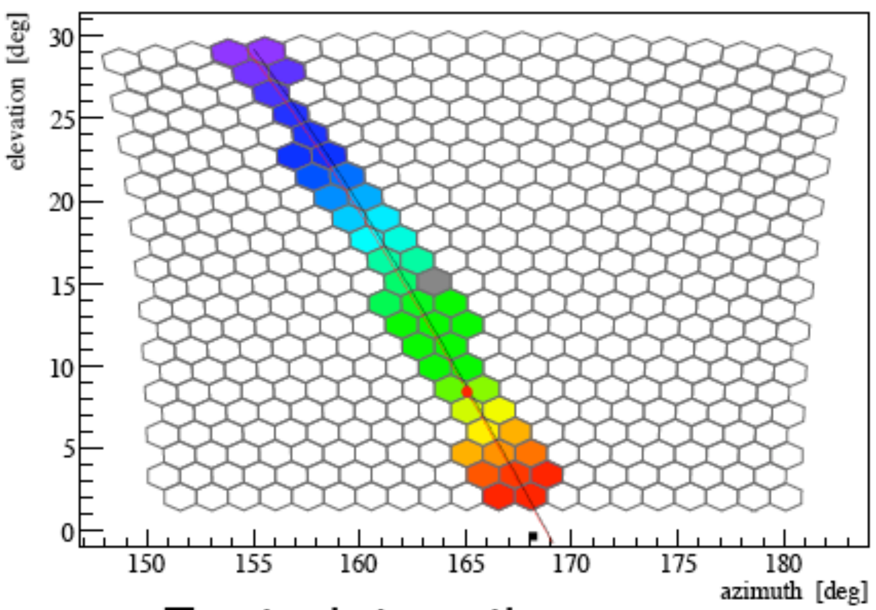
A small portion of the ground array

4 sites of 6 fluorescence telescope overlook the array

A fluorescence telescope







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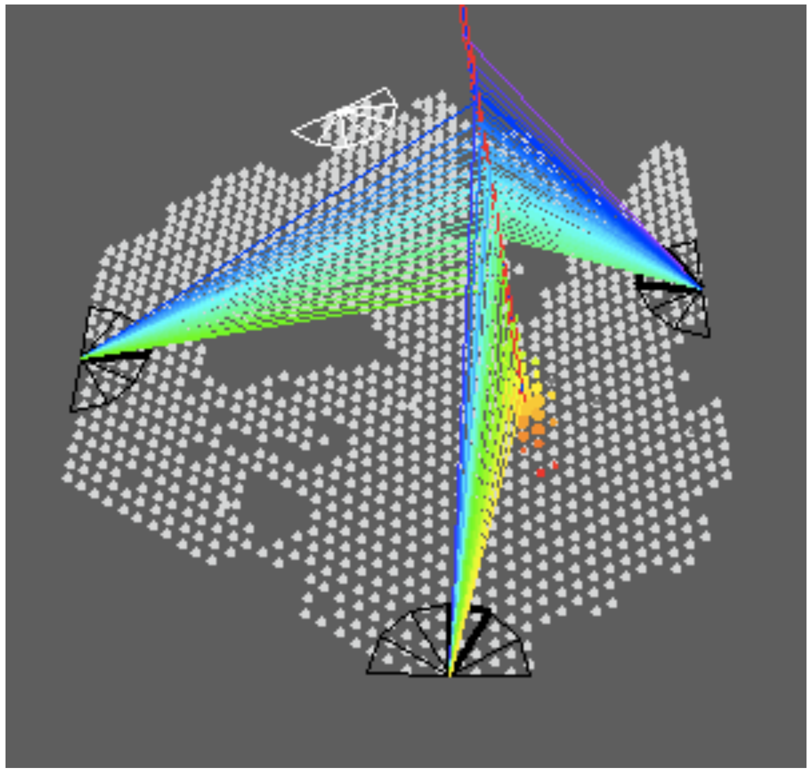
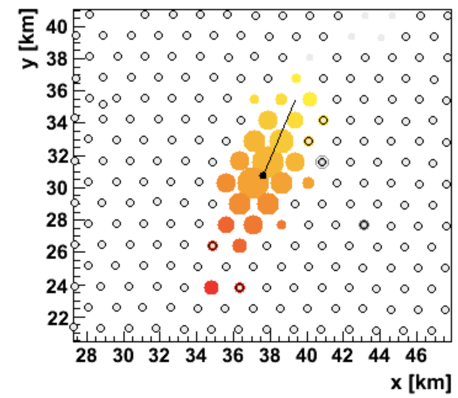
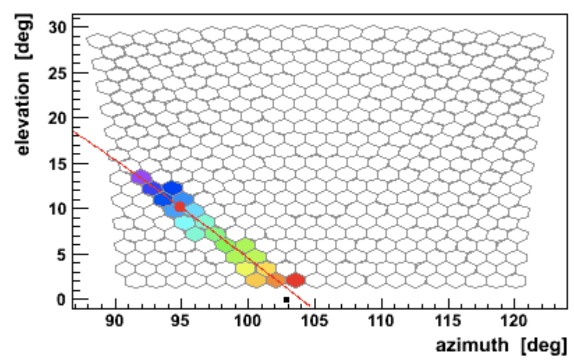
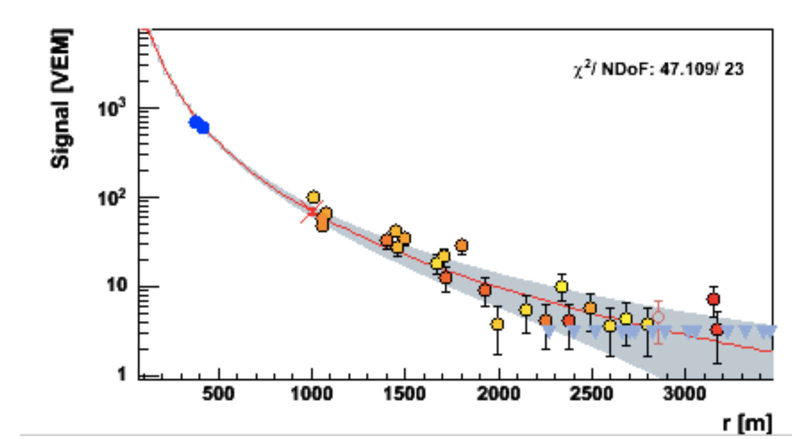
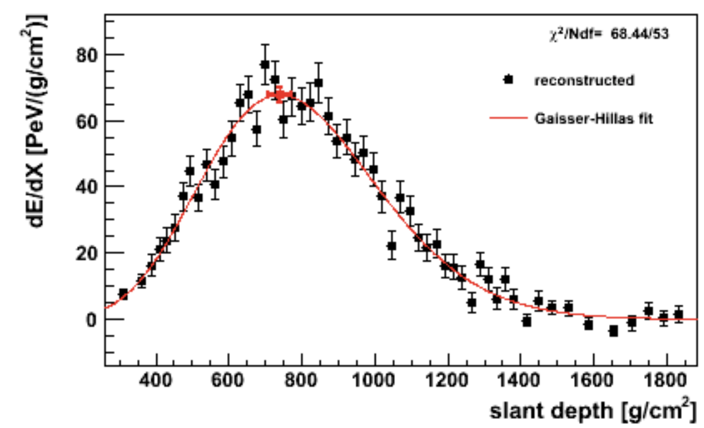


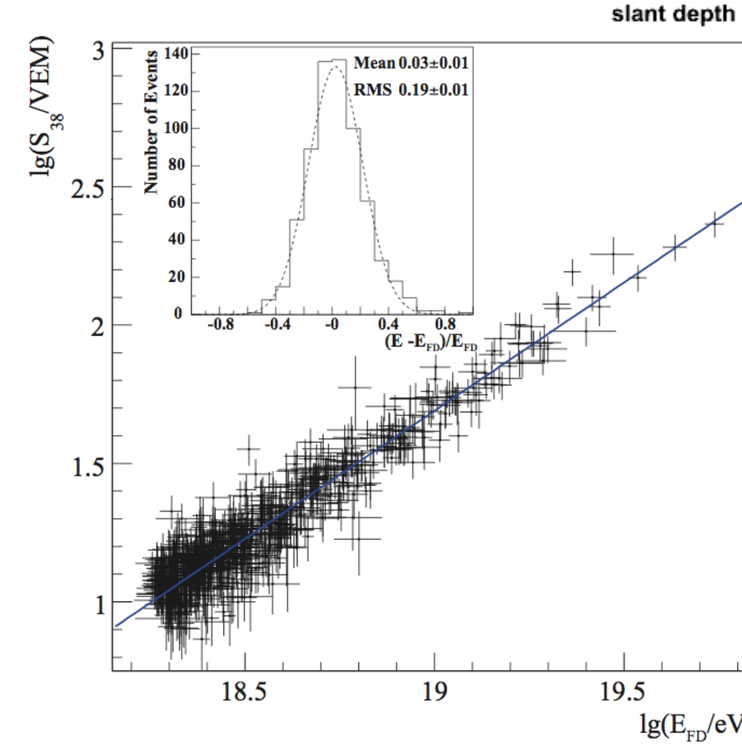








- One can calibrate the relation E/Signal using hybrid events
  - SD gives S1000
  - FD gives a calorimetric measurement of the energy
- Energy evolution measured without using simulations
  - No hadronic model dependence
  - Composition changes handled naturally
  - Spread measured



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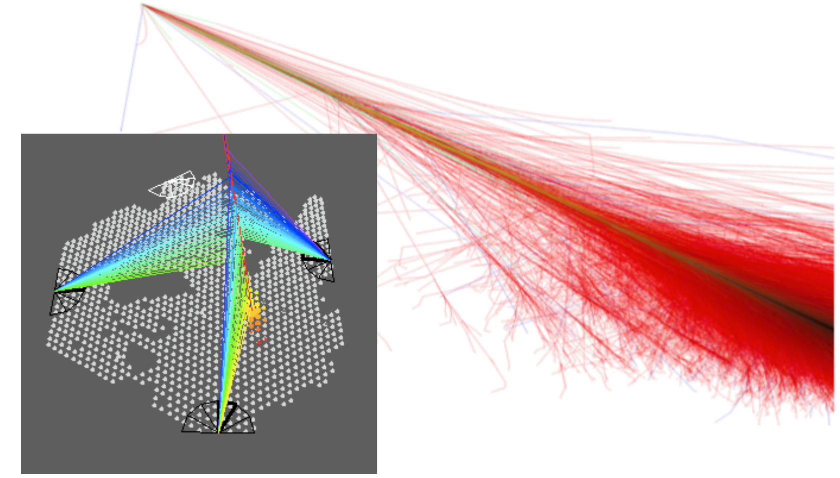

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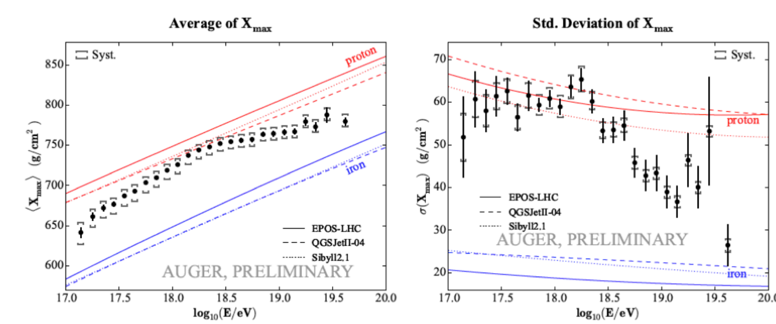

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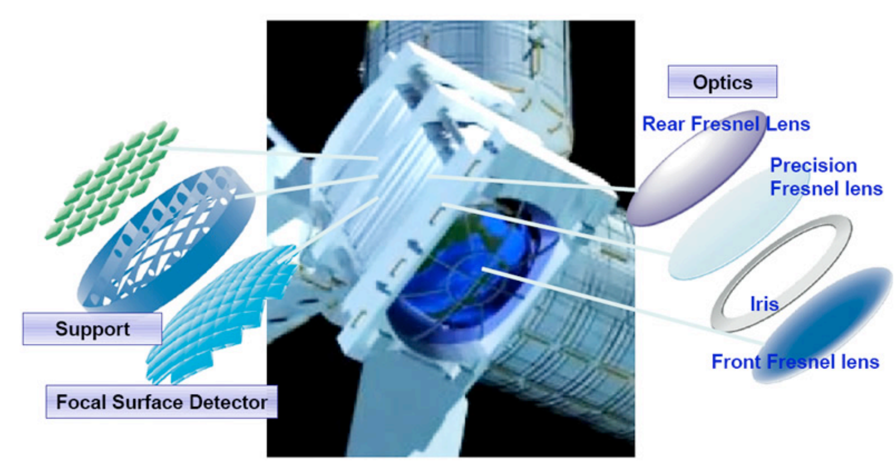
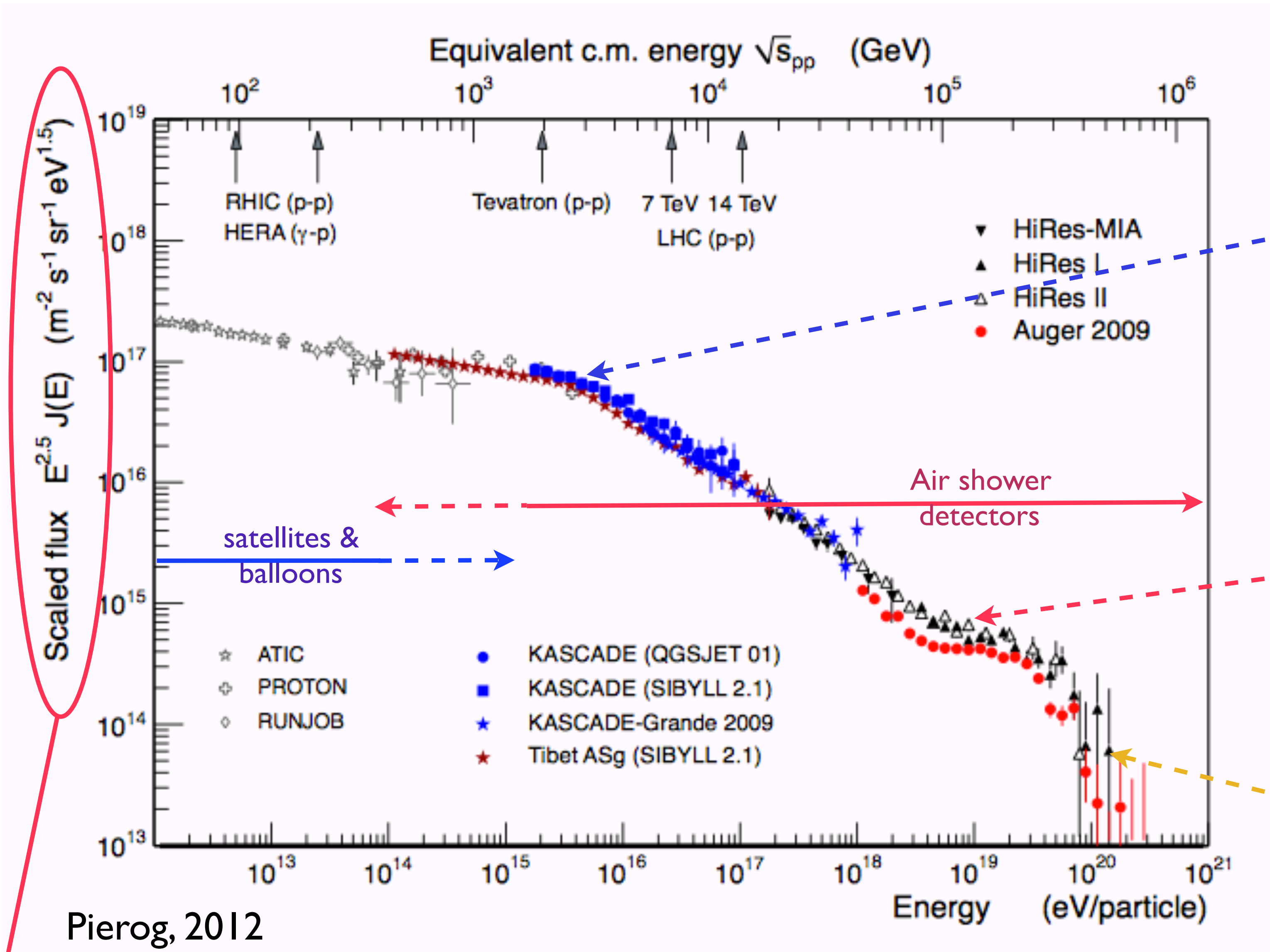


Let us come back to the cosmic-ray spectrum



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

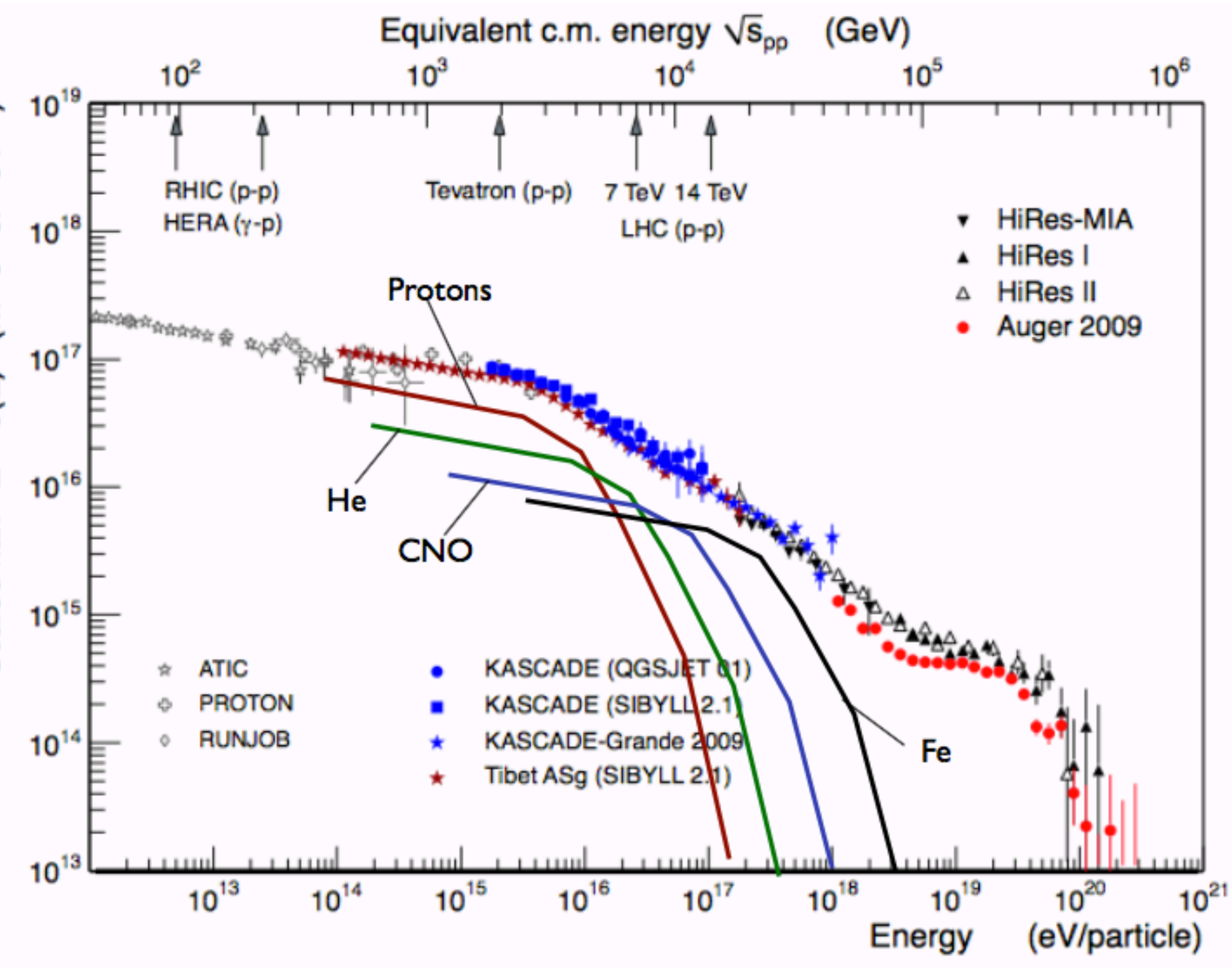
The ankle
E~3-4.10^{18} eV

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

$E^{2.5}$×(diff. flux)

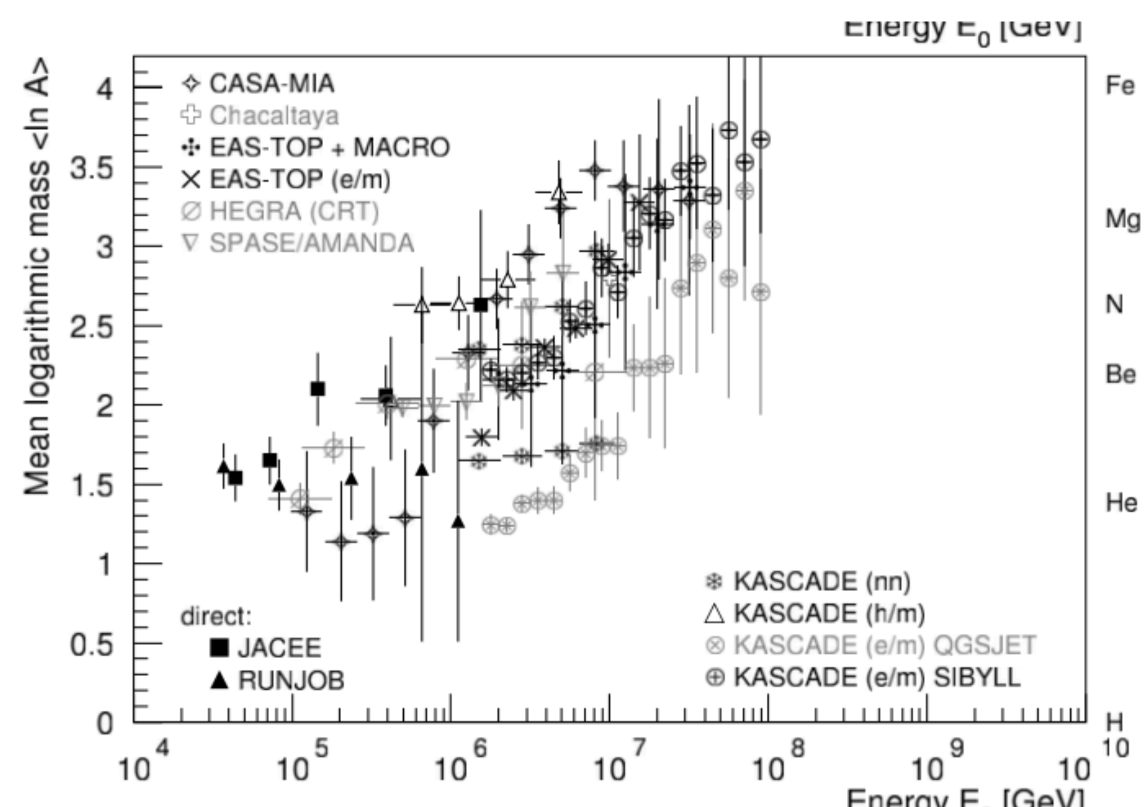
Three major features in the VHE and UHE cosmic-ray spectrum :
The knee and the ankle (known for a long time)
A high energy cut-off (established only a few years ago)

The knee



The knee first seen in the late 50's very soon suspected to be an inflection of the light galactic component

==> one expects the composition is getting heavier in the energy decade following the knee confirmed by most experiments including KASCADE(see Blumer et al., 2009; Unger & Kampert, 2012)



compilation by Blumer et al., 2009

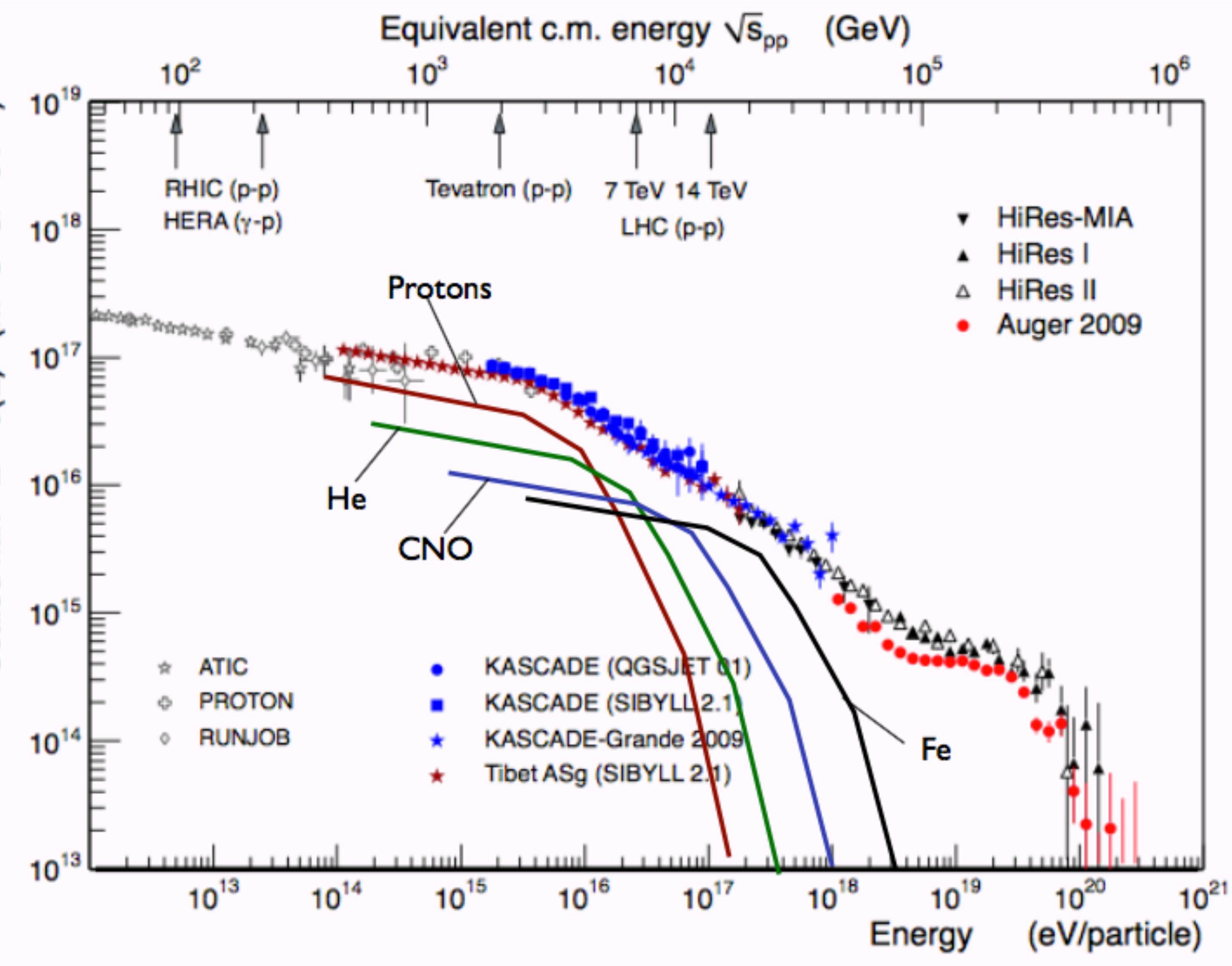
Mainly two physical mechanisms invoked to explain the knee :

(i) maximum rigidity in Galactic accelerators is reached

(ii) rigidity at which Galactic cosmic-rays start to leak faster from the Galaxy (see for instance Gianciti et al., 2015)

==> in both cases knees of the different species expected at energies proportional to their charge

The knee



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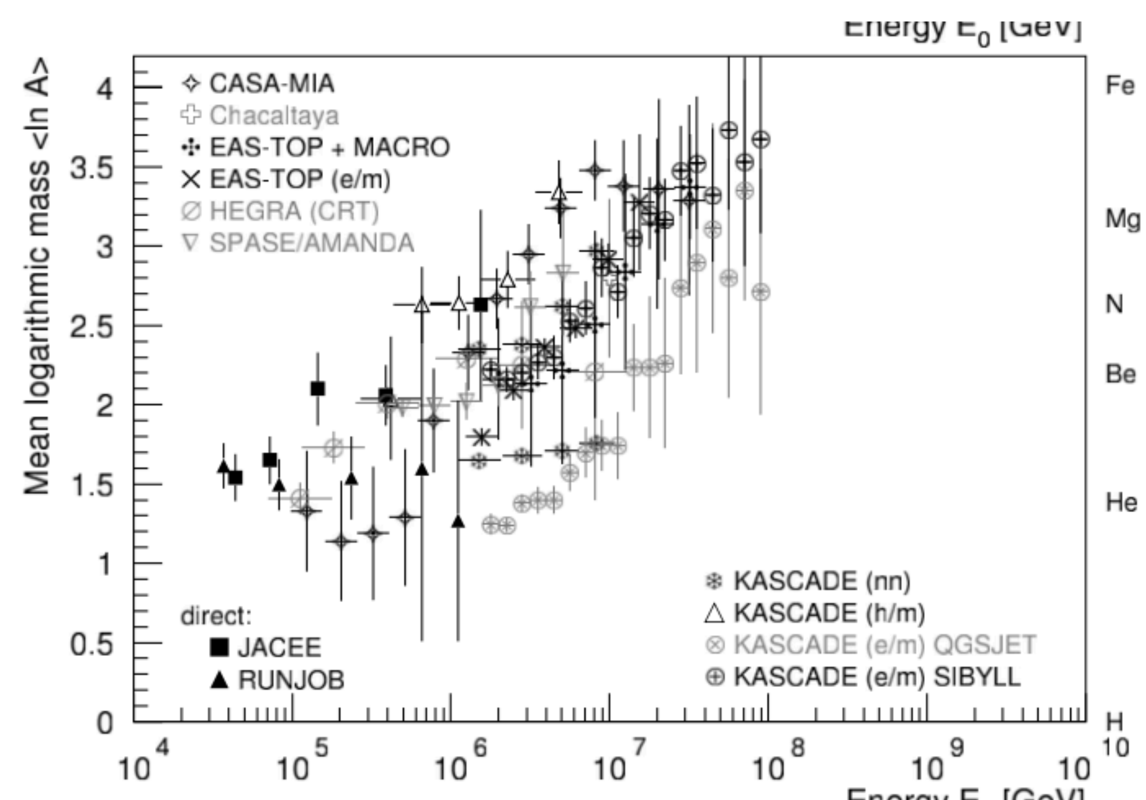
==> by separating between electron rich (so muon poor and thus produced mostly by light nuclei) and electron poor showers (so muon rich and produced mostly by heavy nuclei), the KASCADE collaboration showed that only the electron rich sample was presenting a break in its spectrum at the knee (see e.g Astropart. Phys 16 (2002))



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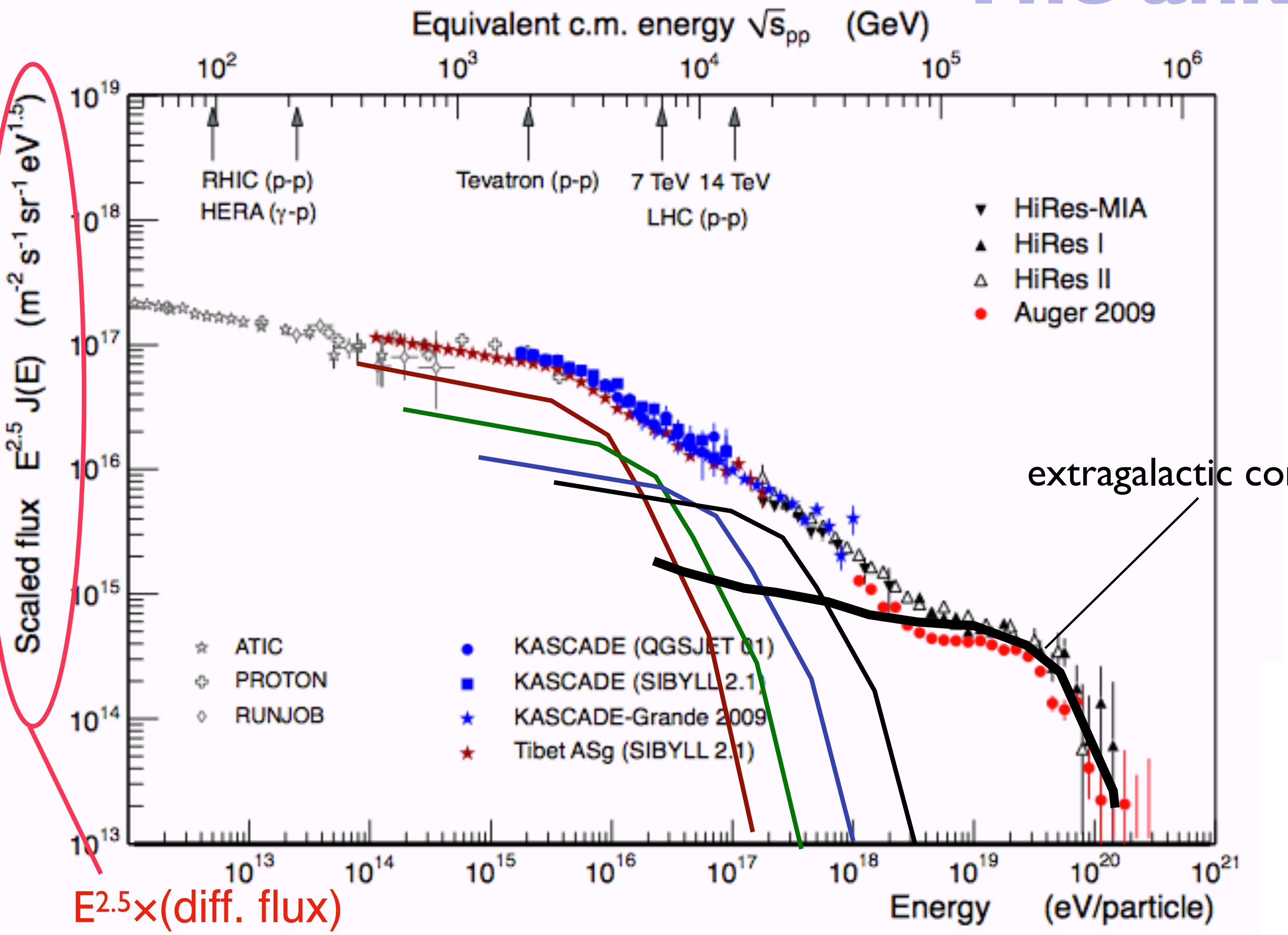
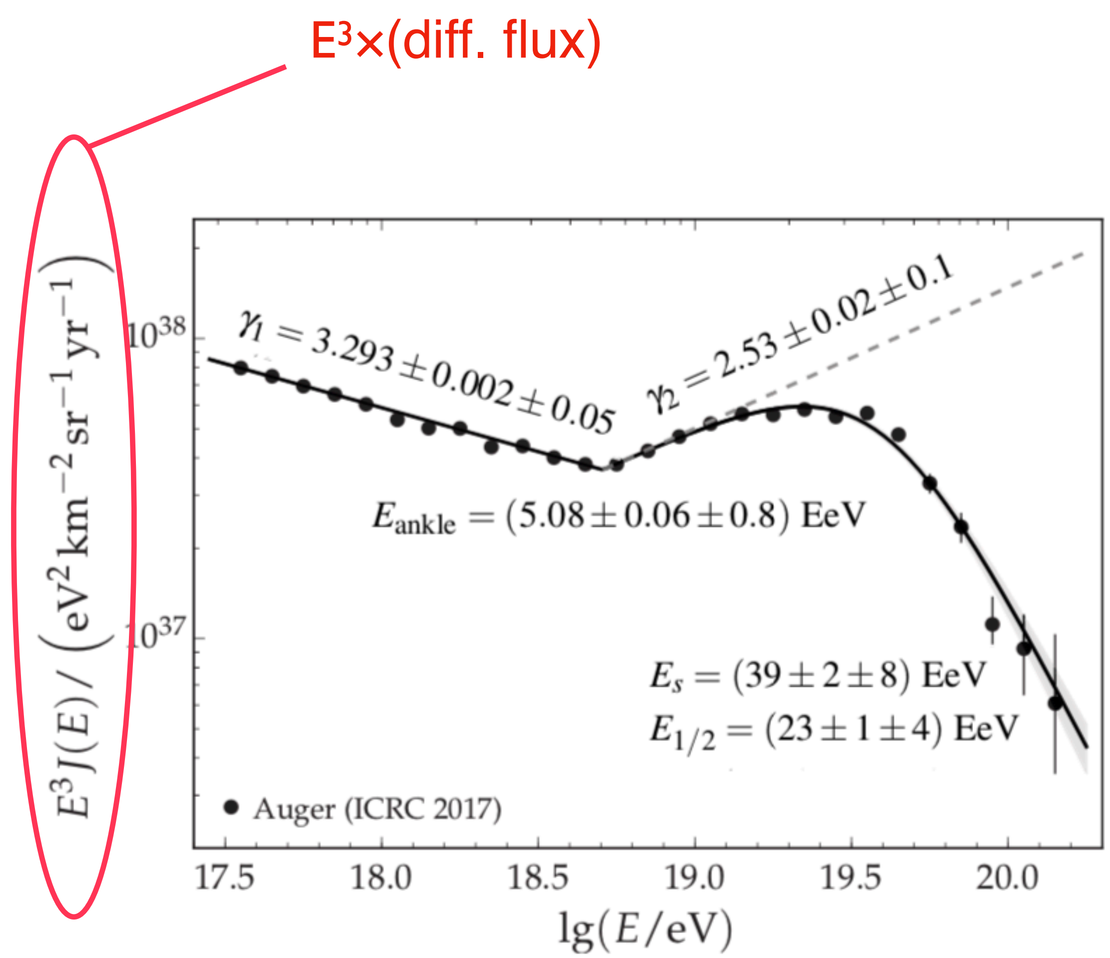
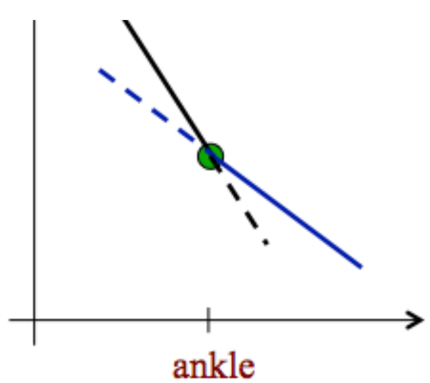
The ankle



The knee first seen in the late 50's very soon suspected to be an inflection of the light galactic component

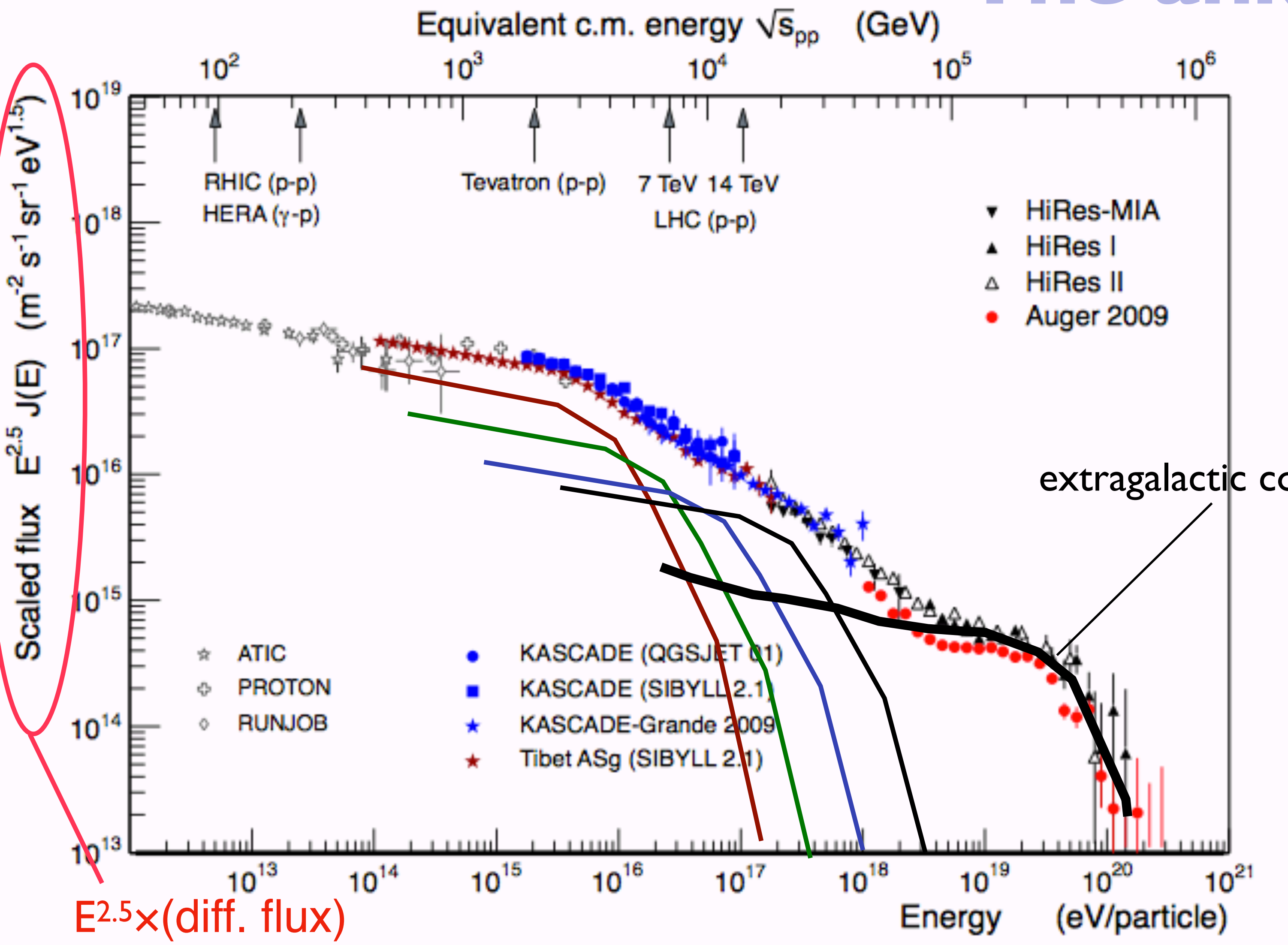




ankle : transition from a softer to a harder component

==> very natural feature for the transition from galactic to extragalactic cosmic-ray

The ankle



The knee first seen in the late 50's very soon suspected to be an inflection of the light galactic component

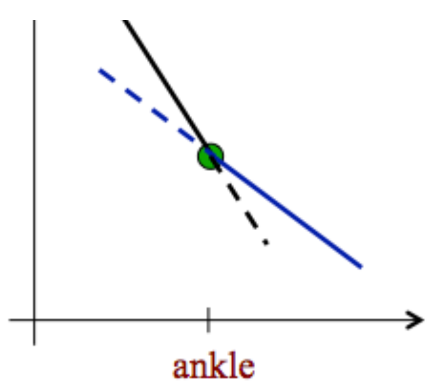
Why should the component taking over be extragalactic?

Several argument are usually invoked :

- No galactic accelerator expected to be powerful enough to reach the highest energies
- Anisotropies in the direction of the galactic disk would be naively expected

➡ Strong belief that the highest energy cosmic-ray are of extragalactic origin but there is no definitive proof of it

➡ we will assume the UHECR are extragalactic in the following



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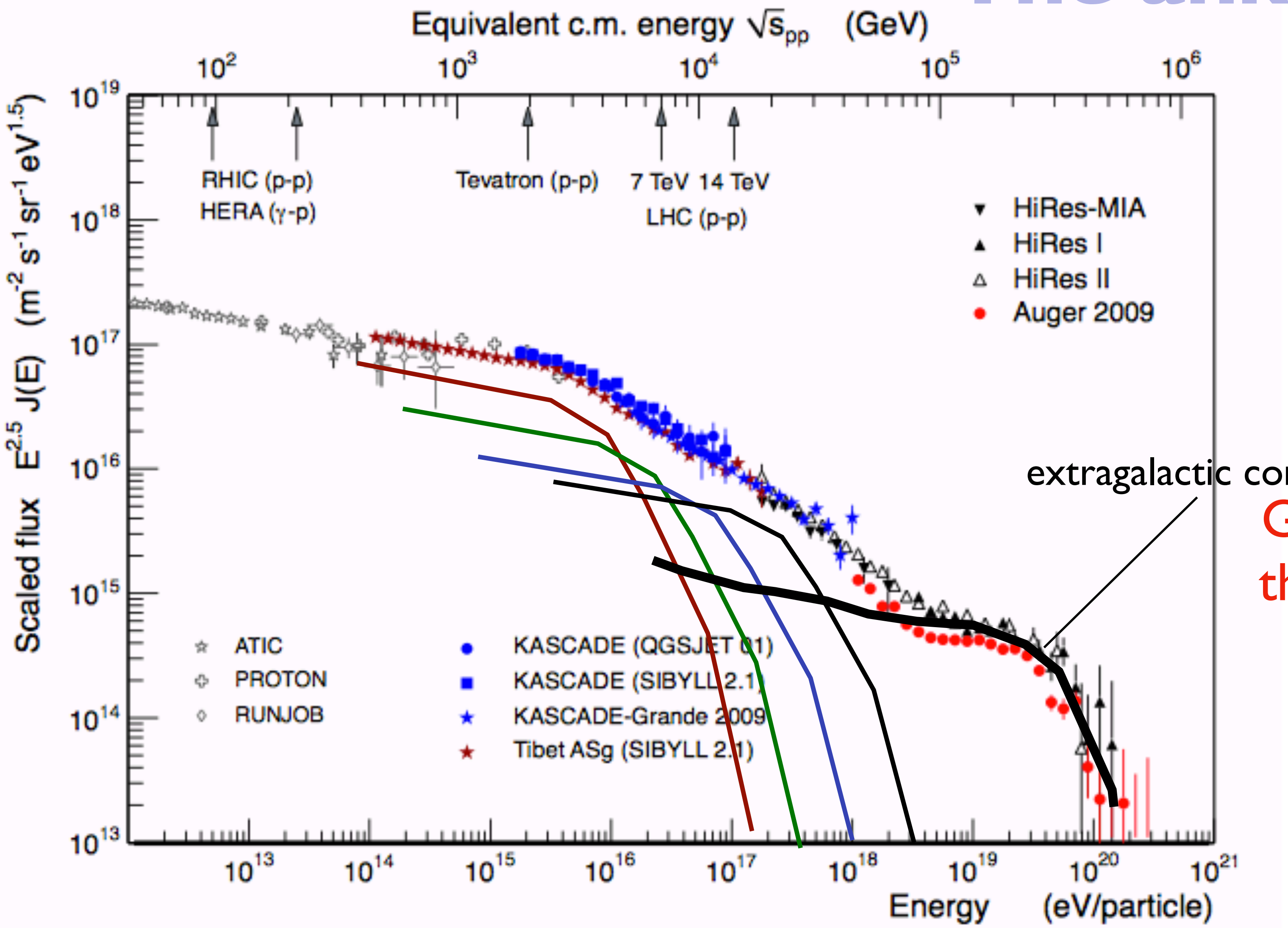
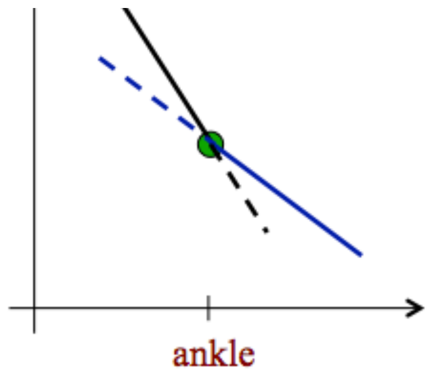


The knee first seen in the late 50's very soon suspected to be an inflection of the light galactic component

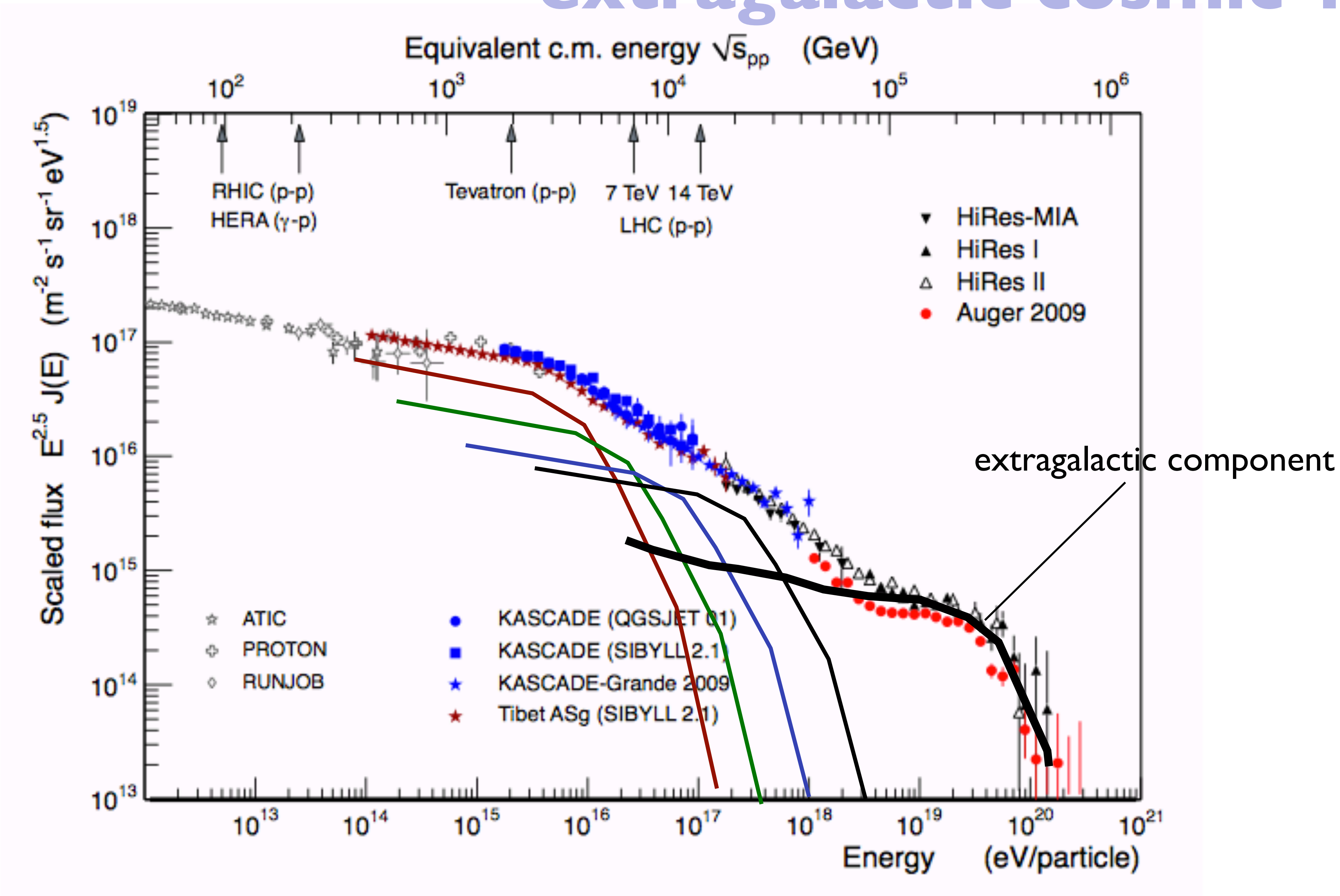
Galactic sources :
Galactic cosmic-ray origin probably related to the end of the life or the explosion of massive stars (stellar winds, supernova remnants, superbubbles, pulsars, PWNs)
Galactic center?

Extragalactic sources :
AGNs, GRBs, galaxy clusters, young neutron stars which are "on top" of the Hillas diagram often mentioned



ankle : transition from a softer to a harder component
==> very natural feature for the transition from galactic to extragalactic cosmic-ray

A consistent picture of the transition from galactic to extragalactic cosmic-rays?



Pierog, 2012

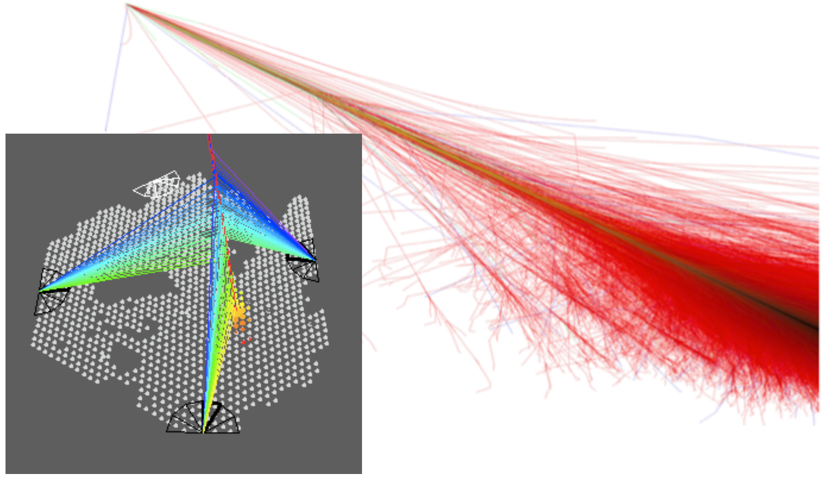
Tantalizing picture !

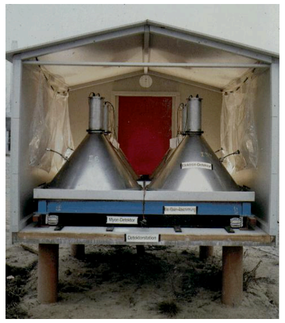
Main difficulty : there are three orders of magnitude between the knee and the ankle

What CR data have to say about it?

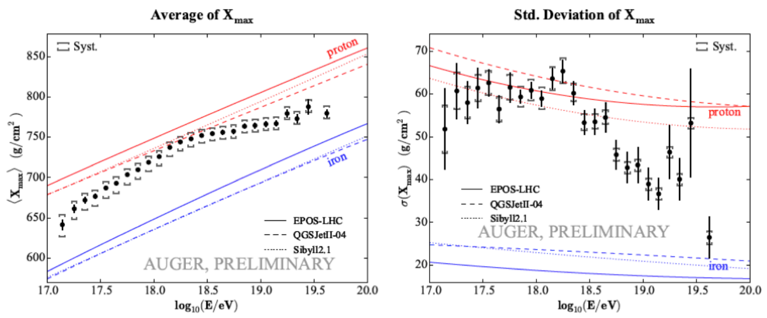
Can we get some hints of the phenomenology of the transition by studying UHECR propagation?

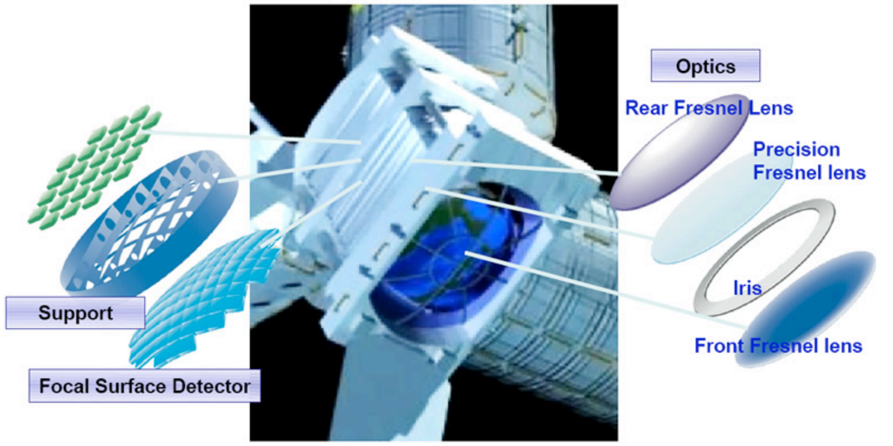
Outline





- ❖ Indirect detection of cosmic-rays, a brief introduction
  - – A few facts about air showers
  - – Detection techniques (ground arrays and fluorescence detectors)
  - – More emphasis on KASCADE and the Pierre Auger Observatory
- ❖ A closer look to the cosmic-ray spectrum
  - - The knee and the ankle
- ❖ **Hints from extragalactic cosmic-rays phenomenology**
  - - **Propagation of protons and nuclei**
- ❖ Key results obtained in the last few years and their possible interpretation
  - - KASCADE-Grande's heavy knee and light ankle
  - - Auger composition results
  - - possible interpretations
- ❖ Can a consistant picture emerge?
  - - Still a few stones in the shoe…
- ❖ A few key future experiments





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

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

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

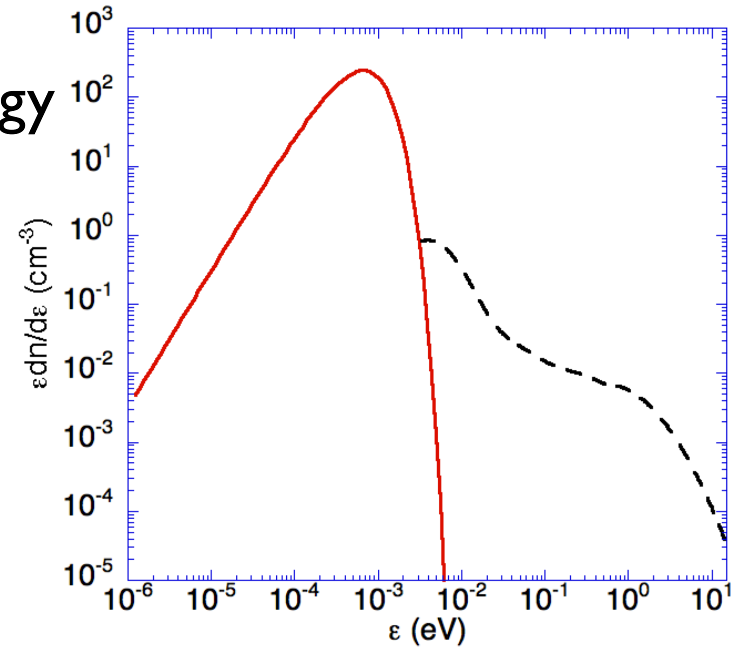
- $t_{int,pp} \sim 2.1\times10^{13}$ yr >> $t_{universe}$ ==> negligible

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

- 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 expansion losses, extragalactic cosmic-ray will loose energy by photo-interactions

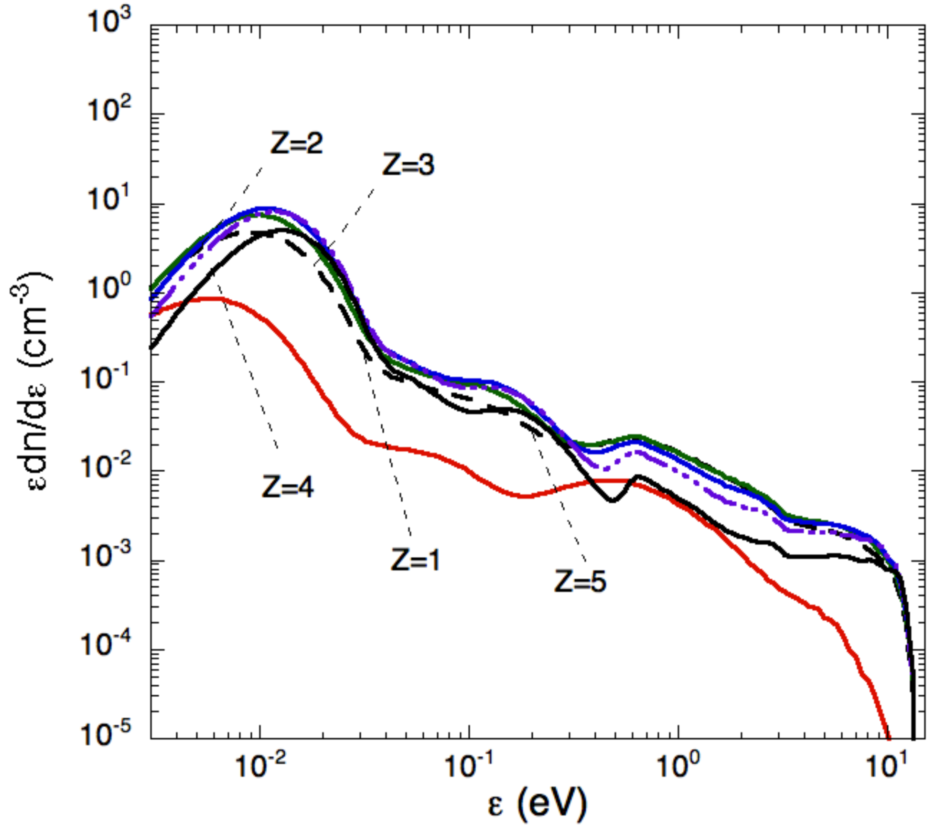


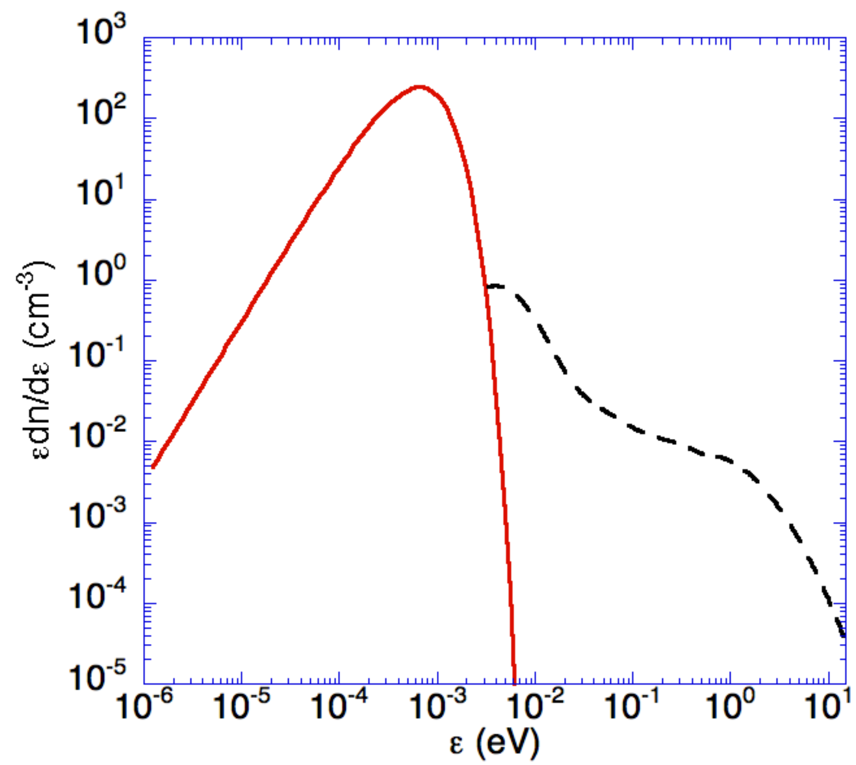
Photon backgrounds

- 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

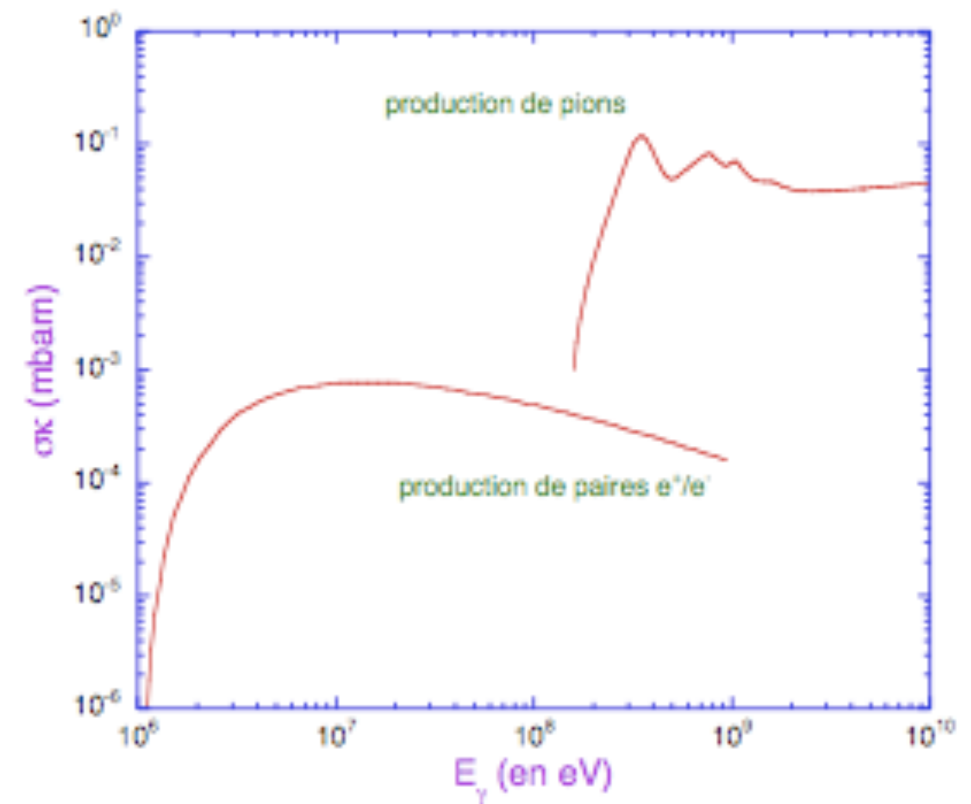
Photo-interactions of protons

Protons :

- pair production: $P+\gamma \rightarrow p+e^+/e^-$ - low inelasticity process
- Pion and meson production :

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

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



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

The energy threshold for π production in the proton rest frame is $\sim m_\pi \sim 140$ MeV

If the proton is energetic enough (i.e a large Lorentz factor in the lab frame) then in its rest frame even CMB photons (10^{-3} eV) could look like γ-rays !

Photo-interactions of protons

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

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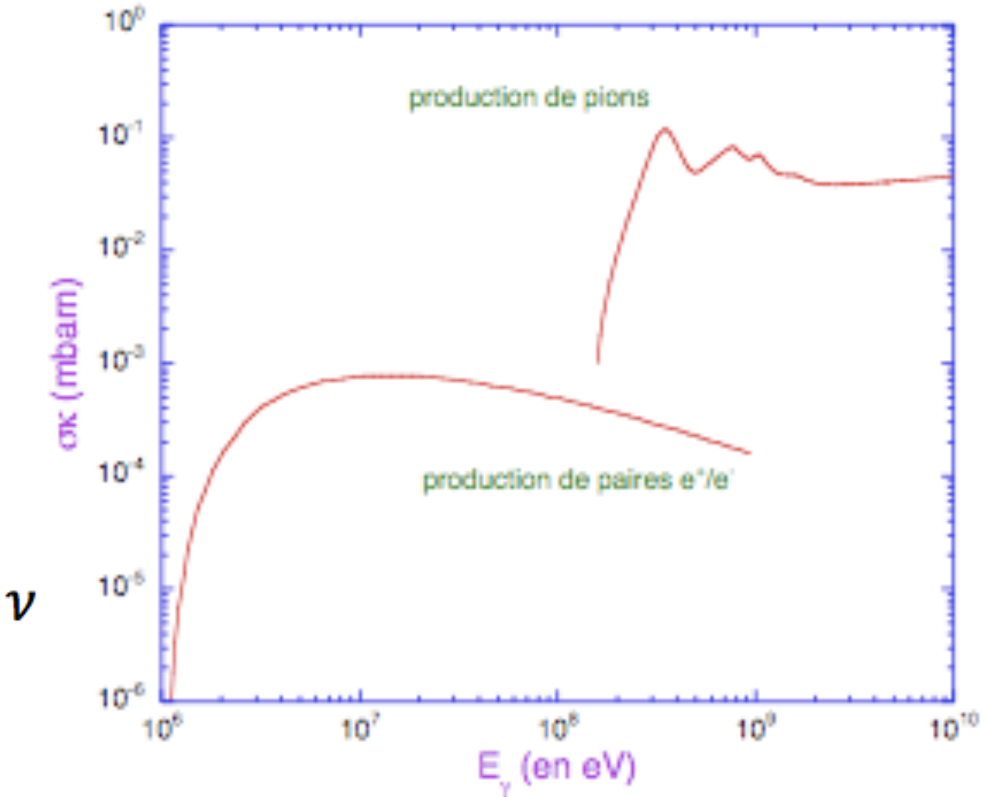


Pair prod :

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

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

$$\gamma_{p,th} \simeq 5{\times}10^{8}$$

Pion prod :

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

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

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

Photo-interactions of nuclei

Nuclei (heavier than protons) :

Two types of processes

- Processes triggering a decrease of the Lorentz Factor
  - expansion 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

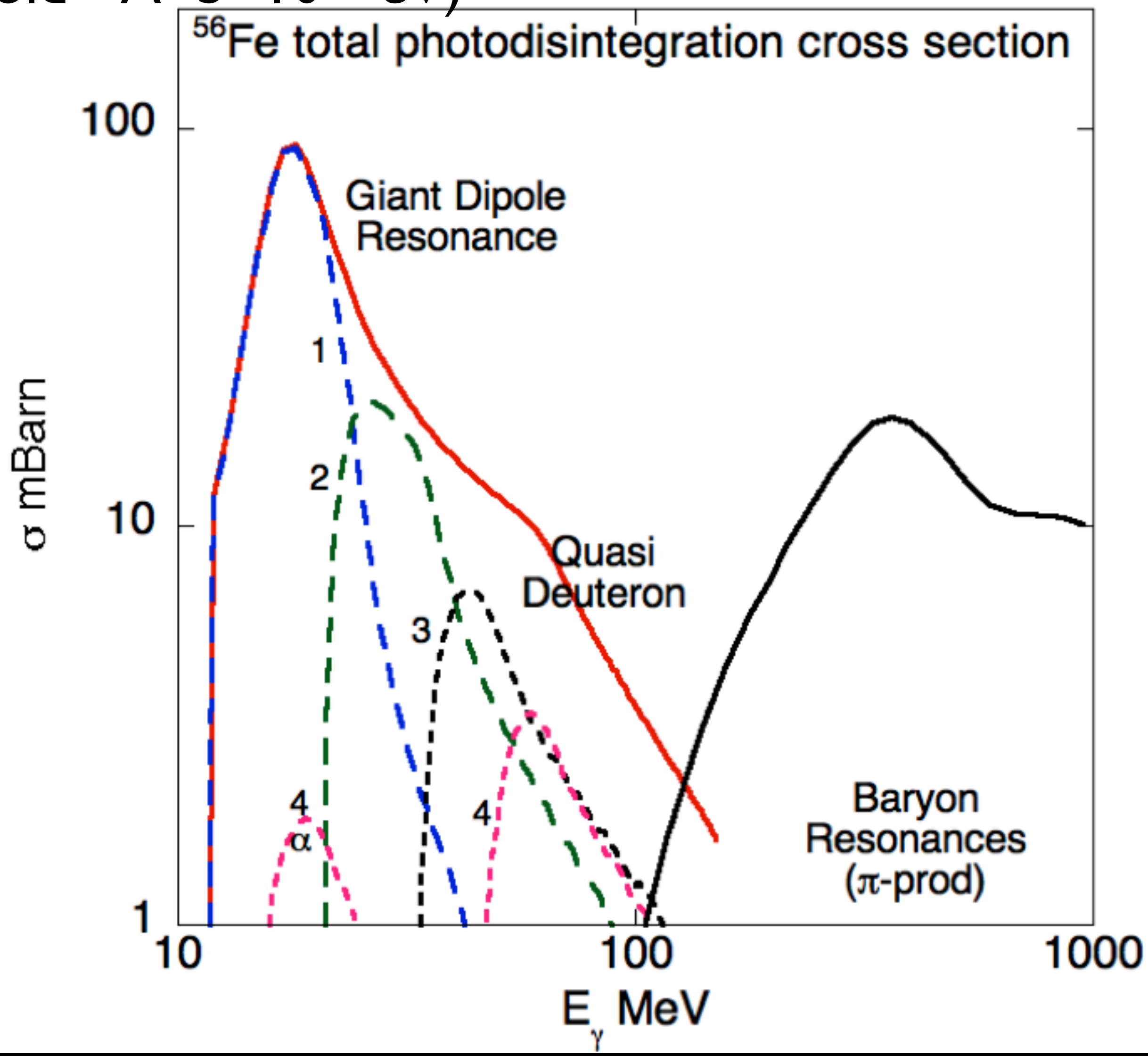


Photo-interactions of protons and nuclei

We know the interaction processes of protons and nuclei as well as the photon backgrounds with which they interact

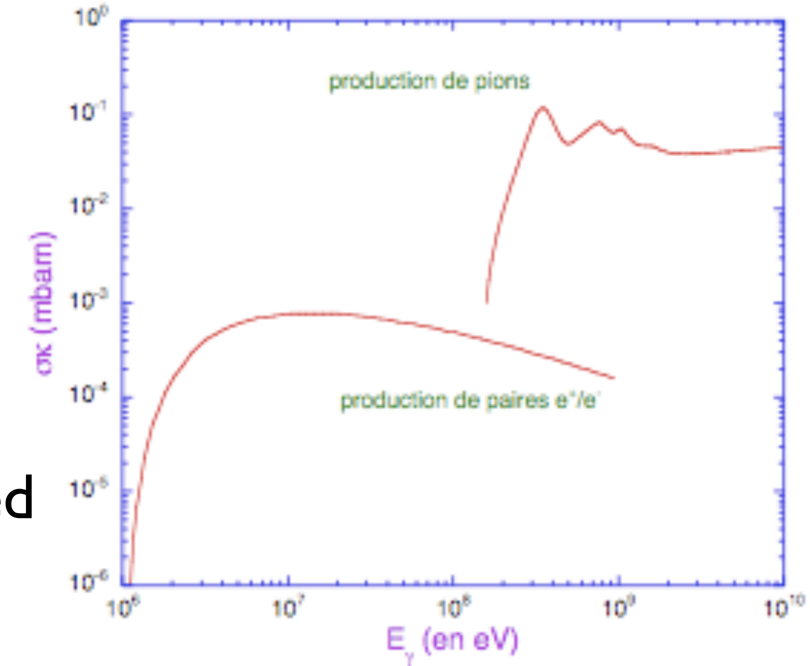
—> We can calculate the energy (or Lorentz factor) evolution of :

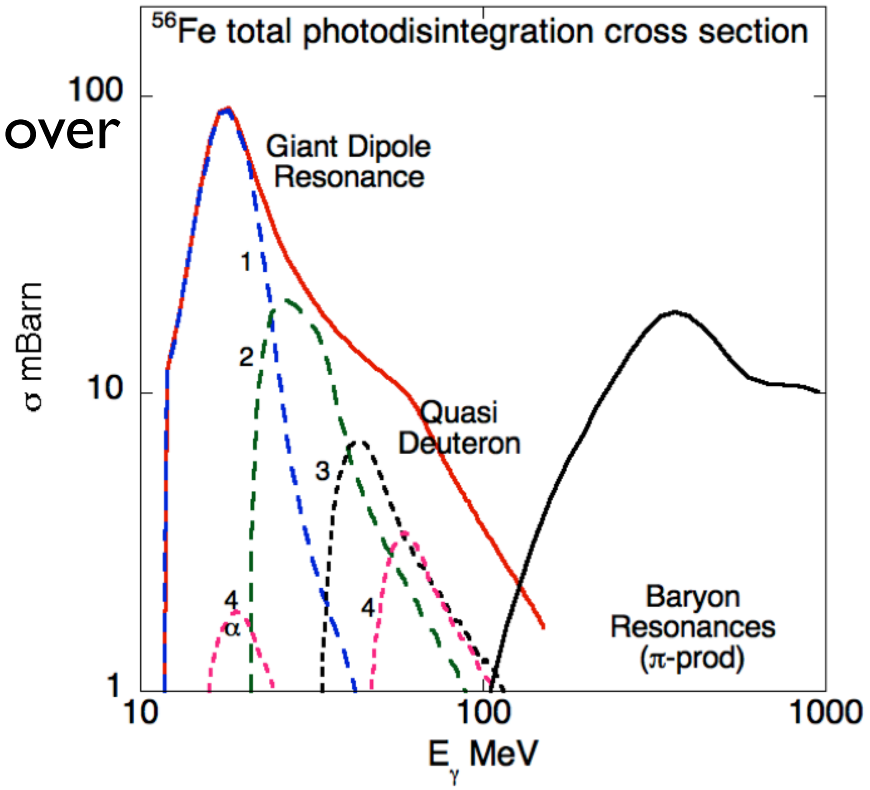
- the mean free path or interaction lenght λ, average distance traveled before interacting

$\lambda=(n\times\sigma)^{-1}$

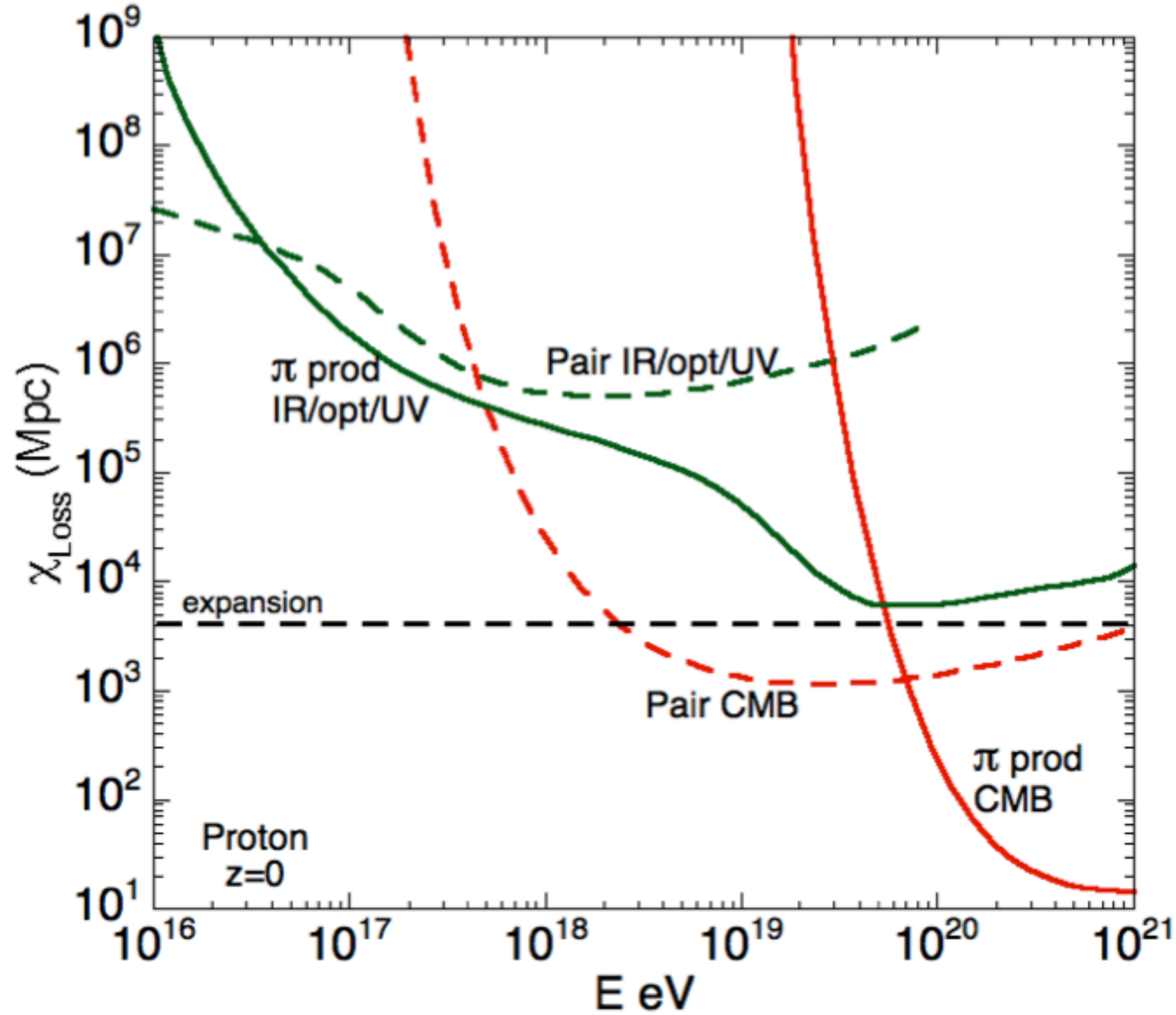
- the energy loss length (or attenuation length), the typical distance over which a UHE particle losses its energy χ

$$\chi_{loss} = c \times \left(\frac{1}{E} \times \frac{dE}{dt}\right)^{-1} \simeq \frac{\lambda}{\kappa}$$





Proton attenuation length (or loss length)



Proton attenuation length :

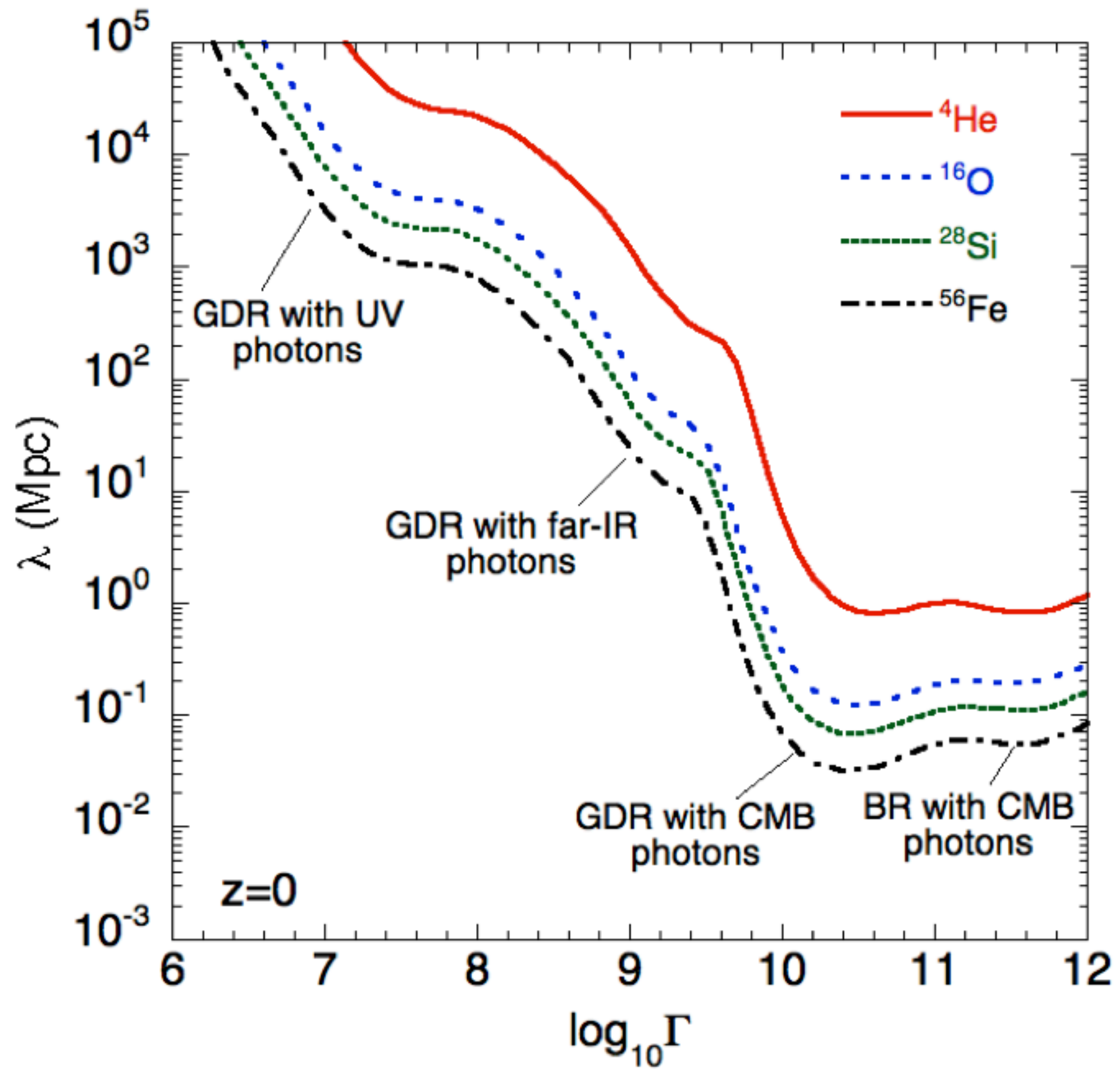
- expansion below ~10^{18} eV

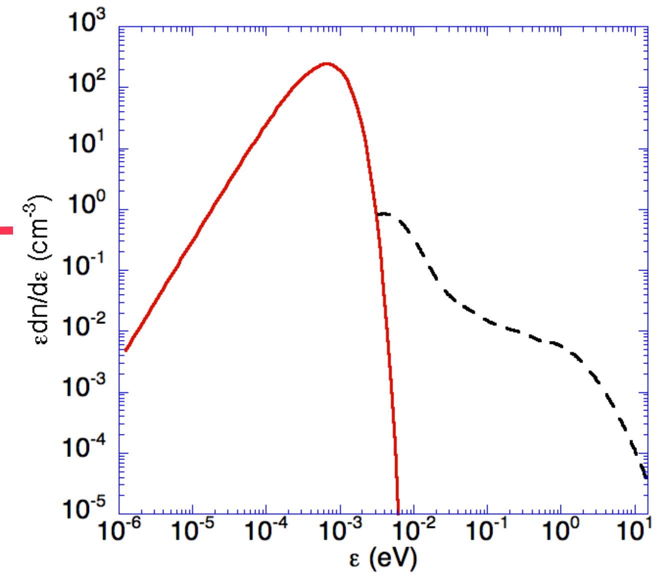
- then pair production with CMB photons

- 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





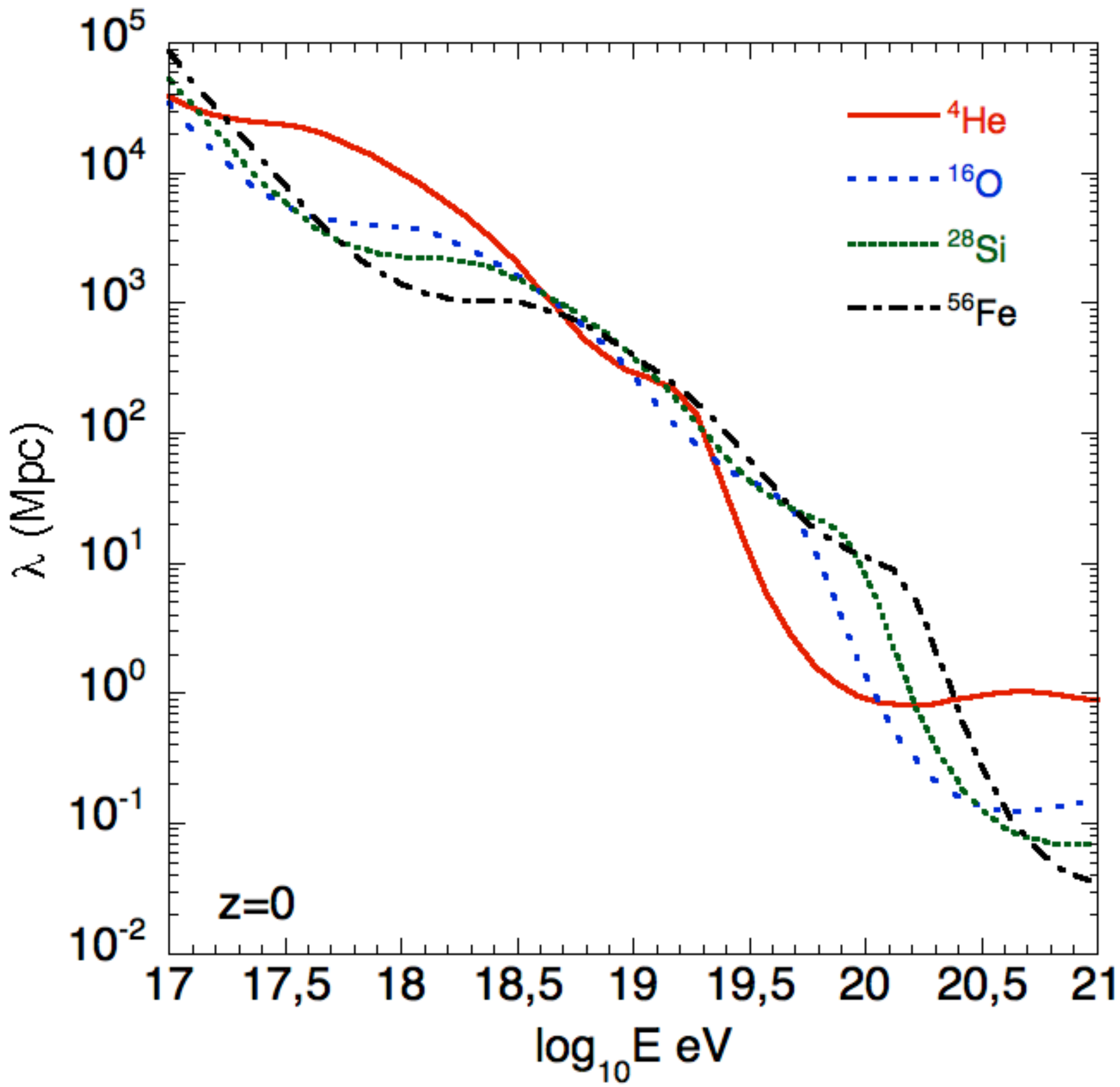
Nuclei photodisintegration mean free path :

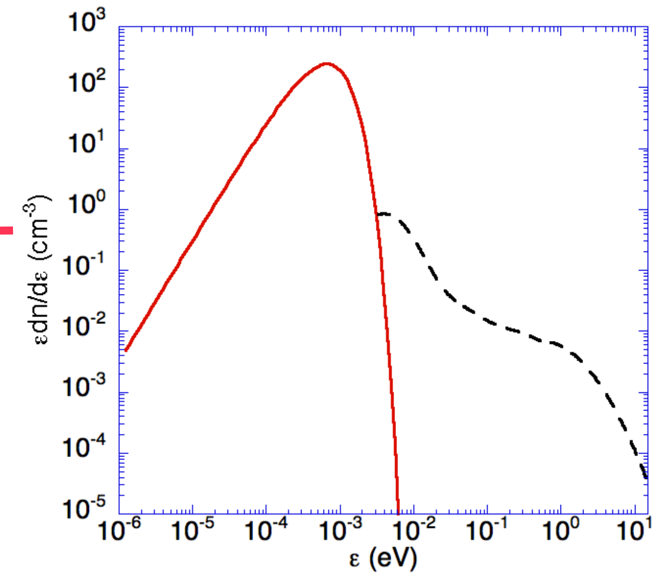
- species have similar threshold for GDR in the NRF (except He and Be) -> interaction threshold at ~ the same Lorentz factor -> Energy threshold proportional to the mass

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

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

Nuclei mean free path for photodisintegration





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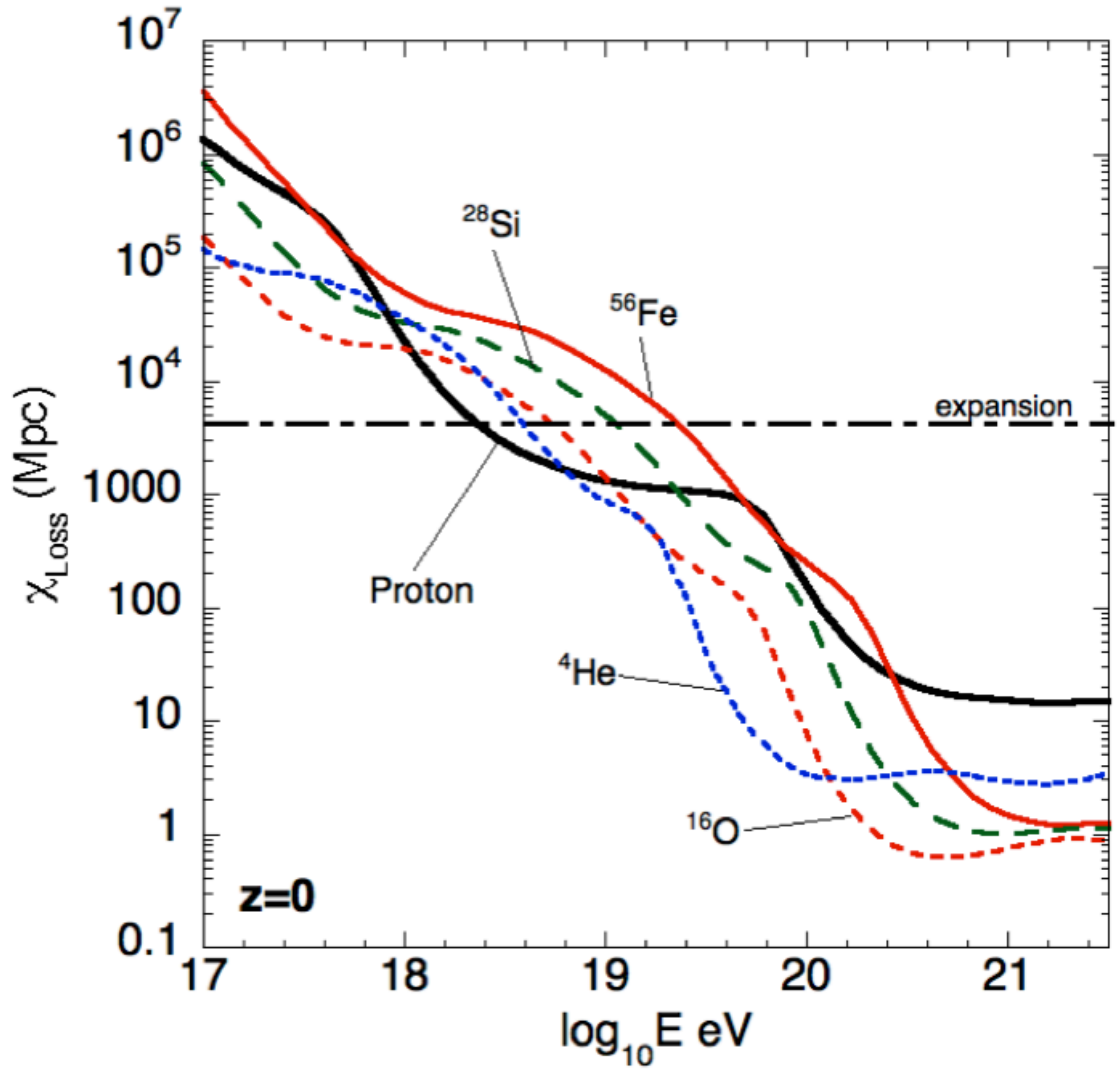
Proton and nuclei loss length



proton and nuclei attenuation length :

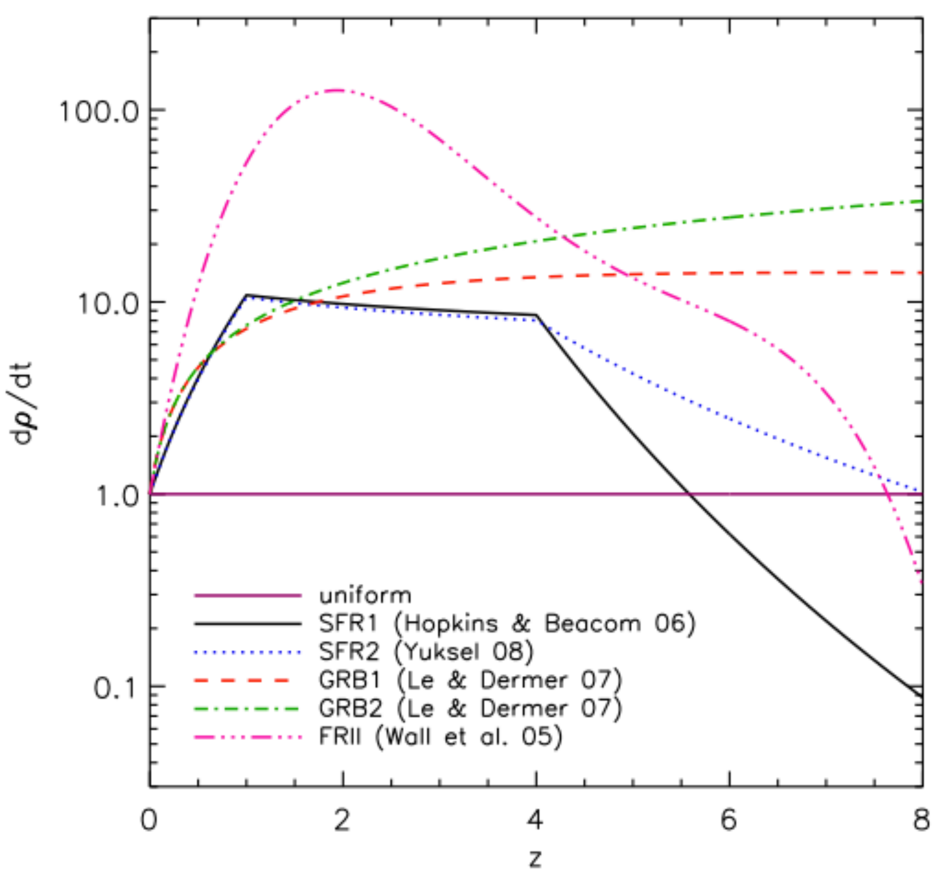
- similar shape of the attenuation length curve for complex nuclei (same processes) shifted in energy
- different shape for protons (important implications)
- hard to survive above 10^{19} eV for low and intermediate mass nuclei
- mostly protons and heavy nuclei expected at the highest energies

Calculations of extragalactic UHECR spectra

(and secondary neutrino and photon fluxes)

We assume :

- a source composition
- source spectrum (usually a power law, same for all the species)
- maximum energy ($Z \times E_{max}^{proton}$)
- physically meaningful cosmological evolution of the sources luminosity (uniform, SFR, FR-II, GRBs...)



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

A "good" model should reproduce the measured UHECR spectrum

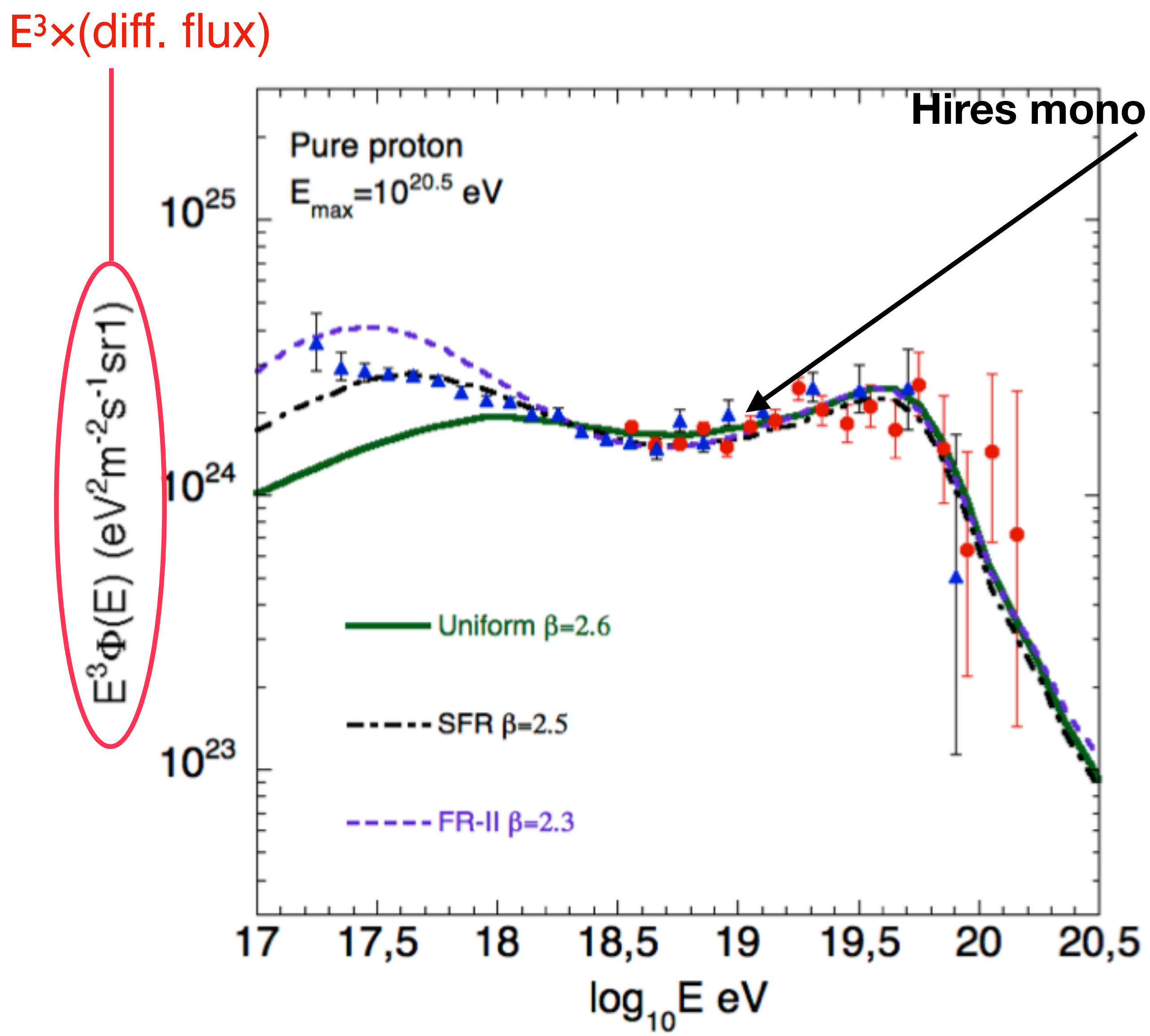
➡ normalisation for the secondary ν and γ fluxes

➡ νs and γs must not overshoot IceCube UHEν sensitivity and Fermi-LAT isotropic gamma-ray background (IGRB)

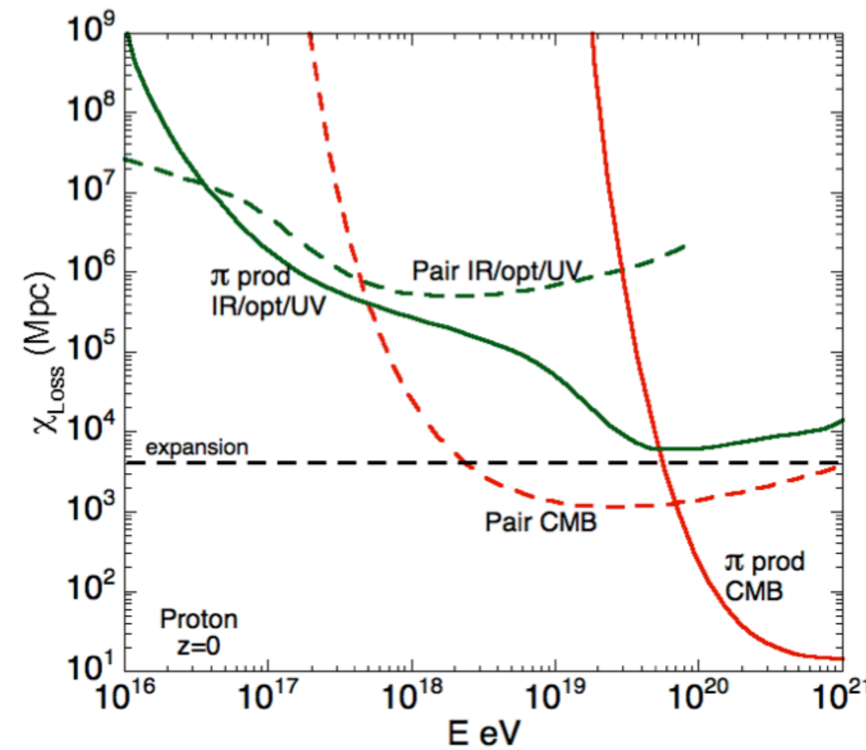
NB : it should also reproduce the observed UHECR composition

- In the next few slides we will discuss models for which we assume that all the species present in the source composition are accelerated above 10^{20} eV (what most people believed before ~2010)

A special case : pure proton composition



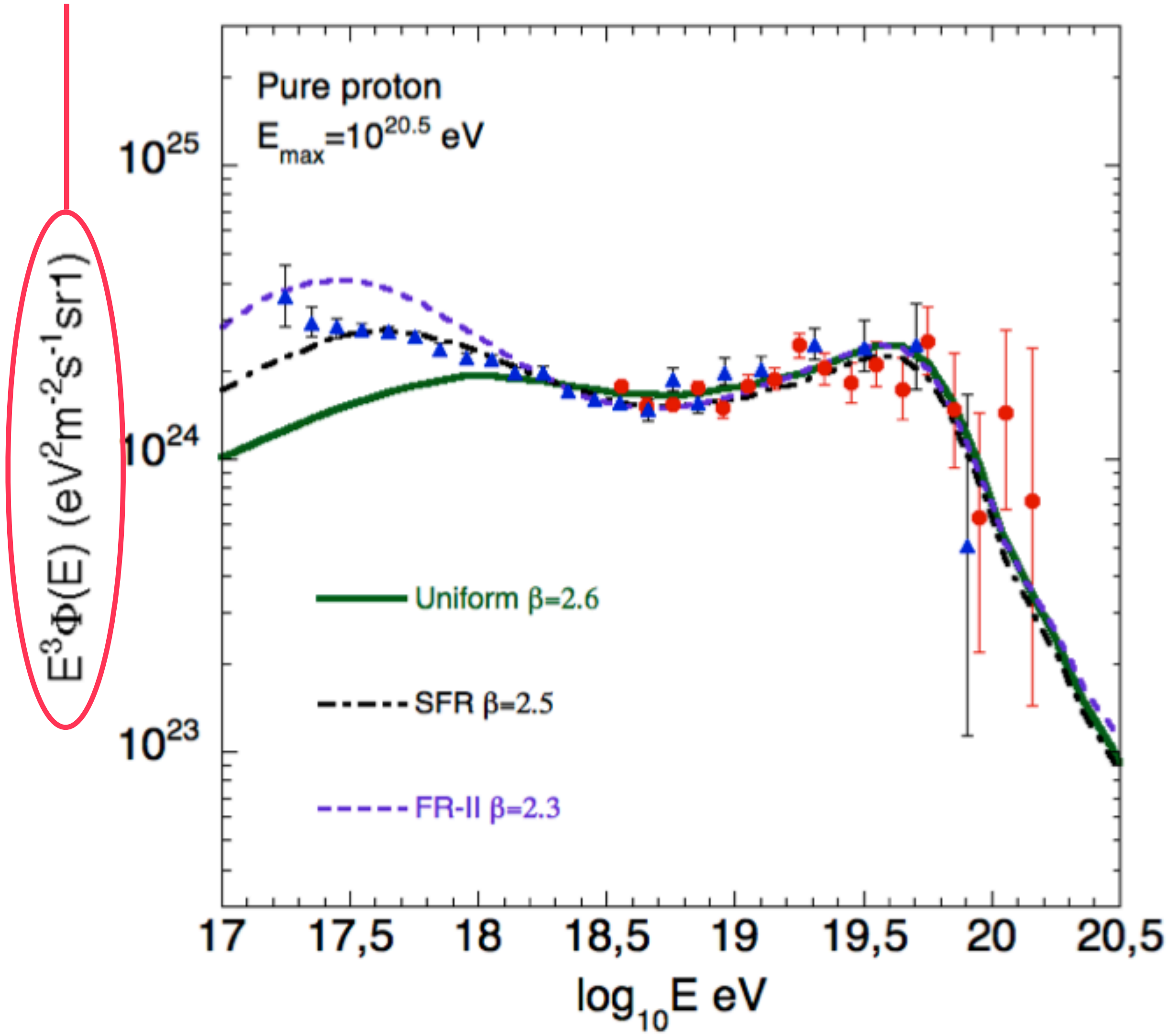
The ankle can be fitted by the extragalactic component itself : pair production dip->the ankle feature has nothing to do with the transition (model developed by Berezinsky et al., 2002-2007)



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

A special case : pure proton composition

E³×(diff. flux)



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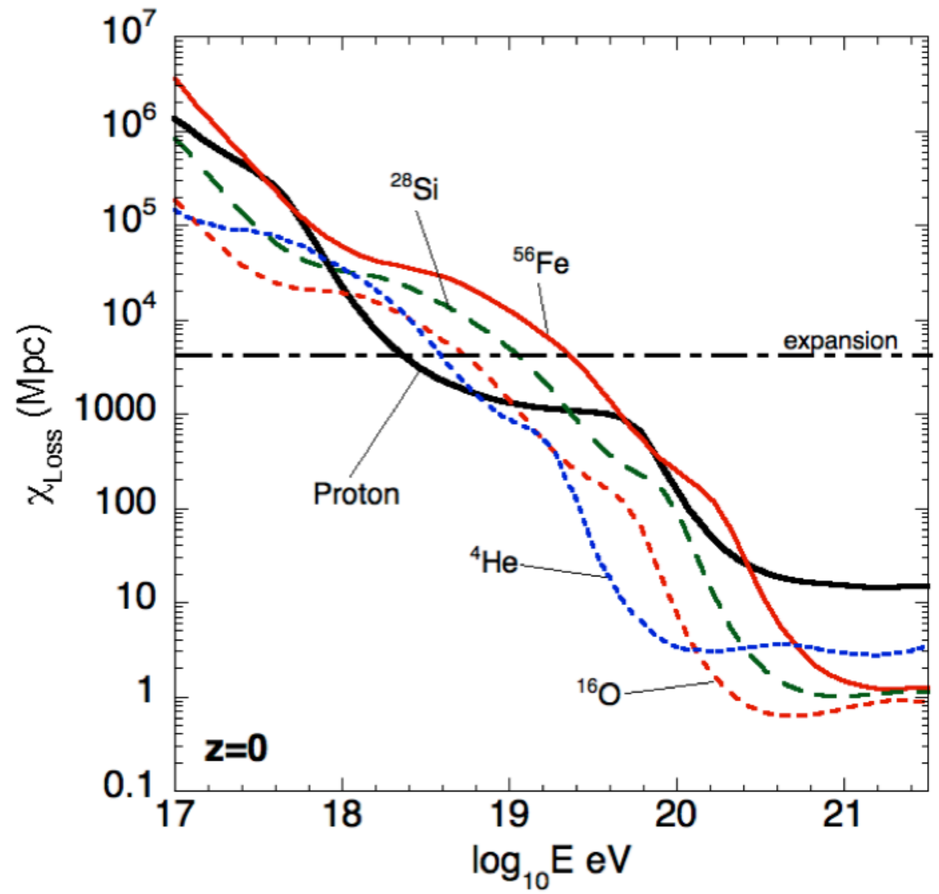
BUT



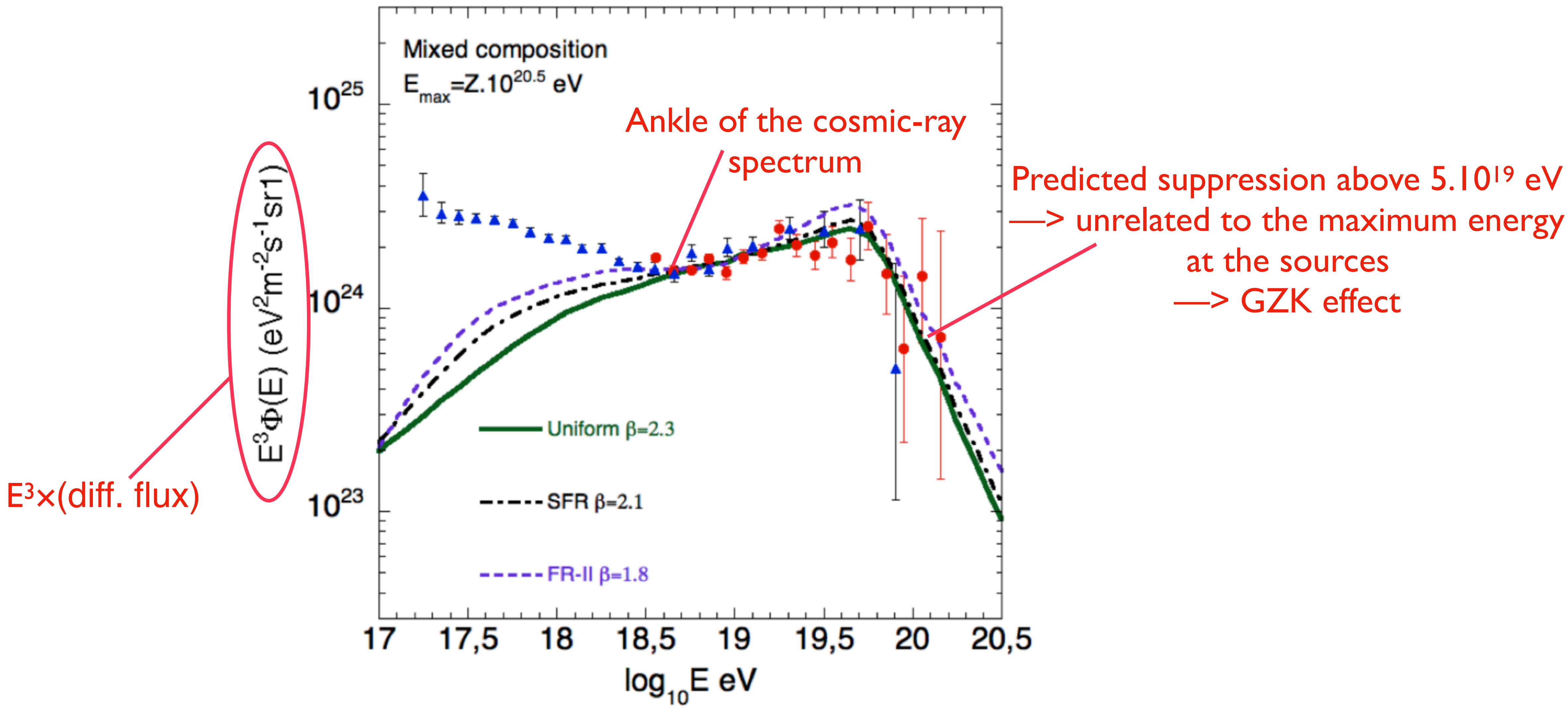
The attenuation length evolution is different for nuclei

A small added fraction (already ~10%) of heavier (complex) nuclei erases the dip

One example : mixed composition assumed at UHECR sources

Assuming the maximum energy per nucleon is above 10^{20} eV (what most people thought until ~2010) mixed composition similar to that of low energy galactic cosmic-rays :

$N(E) \propto E^{-\beta}$, $E_{max}(Z)=Z\times E_{max}^{proton}$, $E_{max}^{proton}=10^{20.5}$ eV



The UHECR spectrum can be well reproduced above the ankle
—> the ankle is interpreted in this case as a signature of the transition between Galactic and extragalactic cosmic-rays (more precisely the end of the transition)

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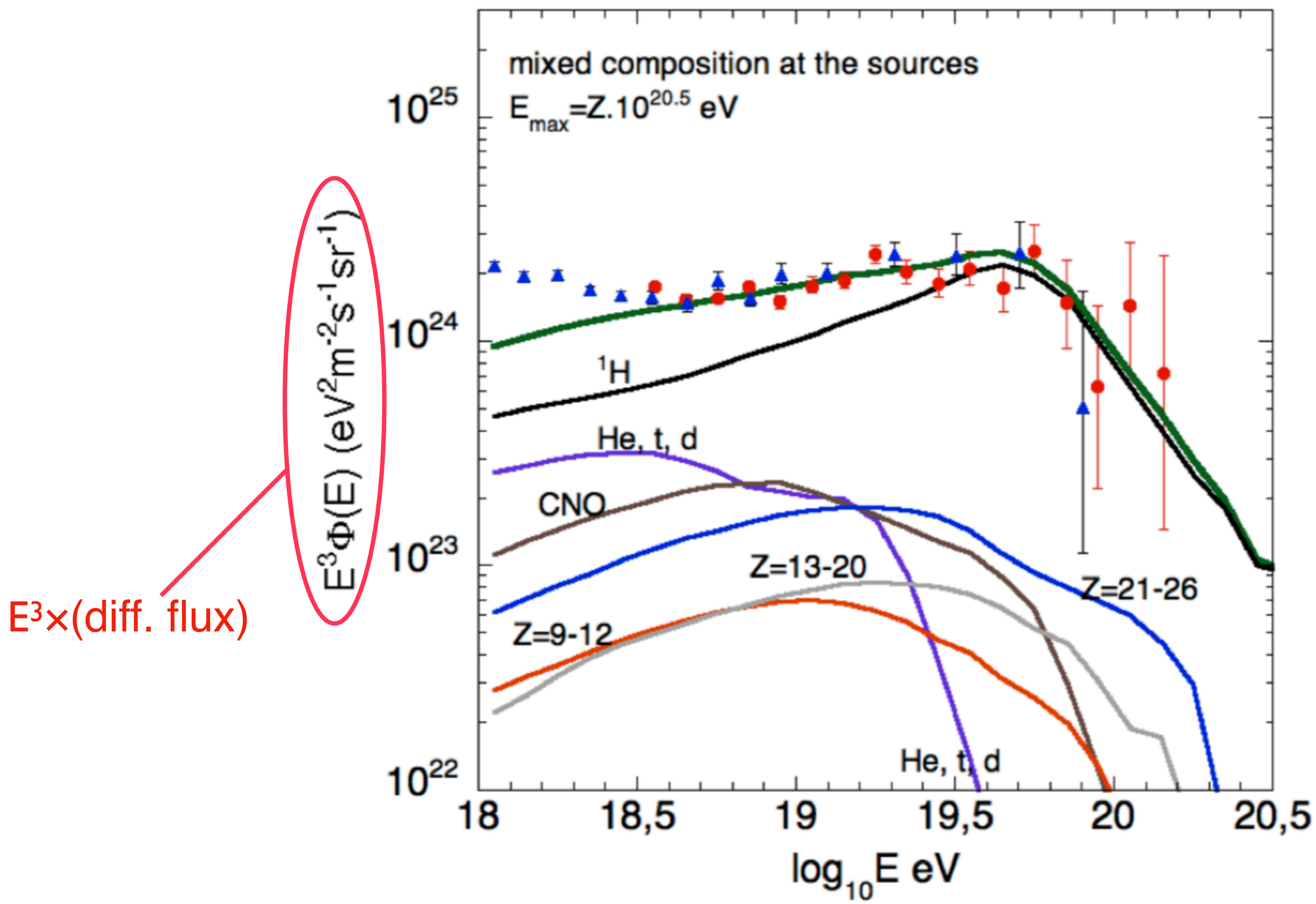
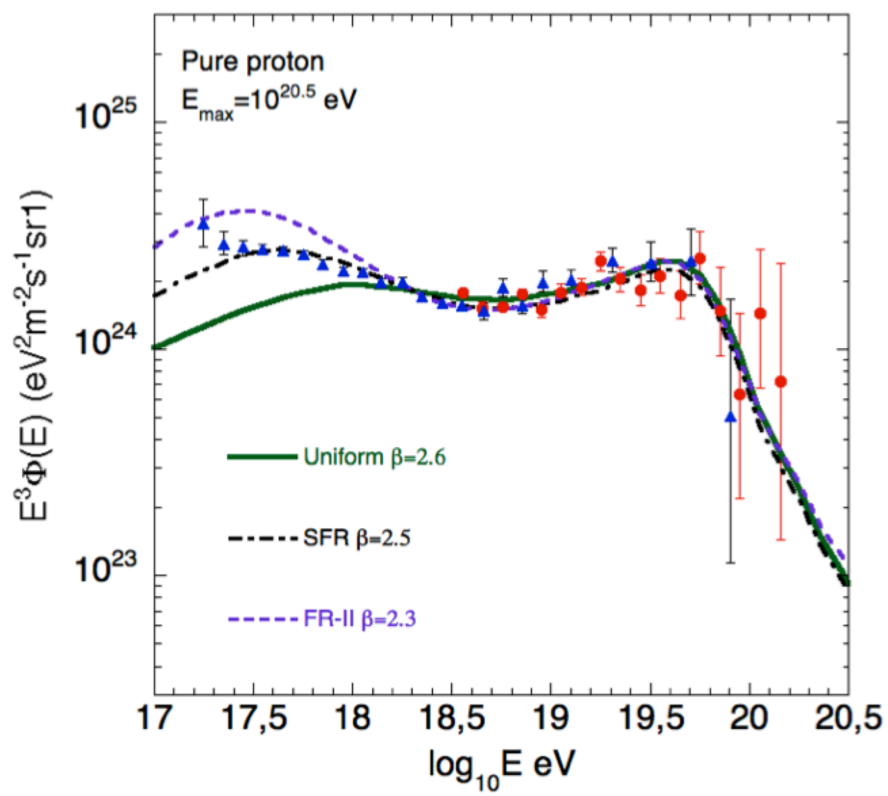
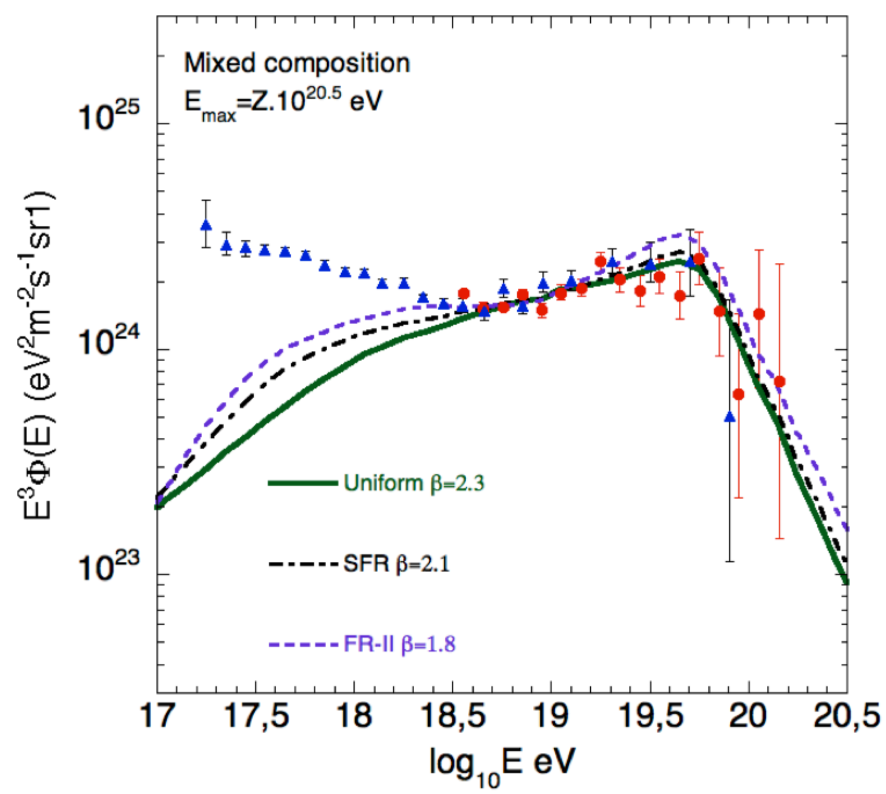


When all the species are assumed to be accelerated above 10^{20} eV, the composition is expected to get lighter (i.e proton richer) above 10^{19} eV (photodisintegration of composed species)

Consequences for the GCR to EGCR transition



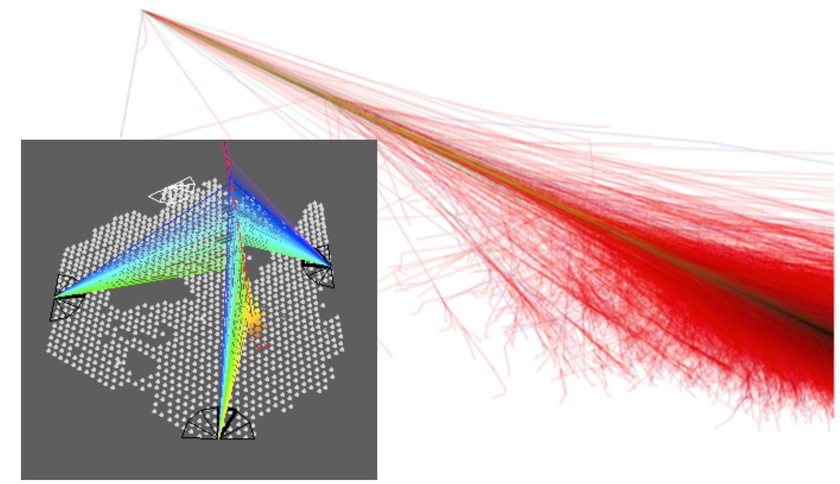


pure proton (dip model) : the galactic component ends earlier, does not requires a significant proton galactic component above a ~few 10^{16} eV (elemental spectra rapidly falling above their knees)

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

Outline



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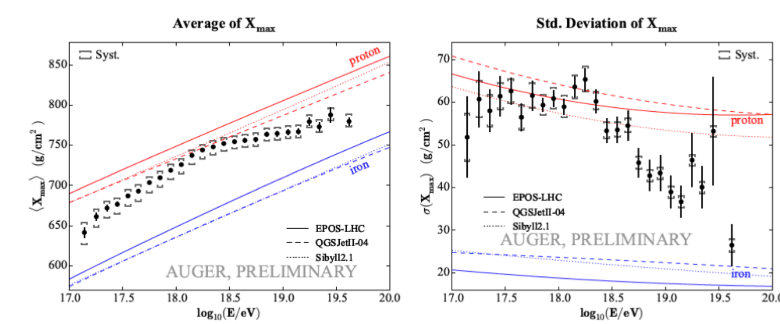
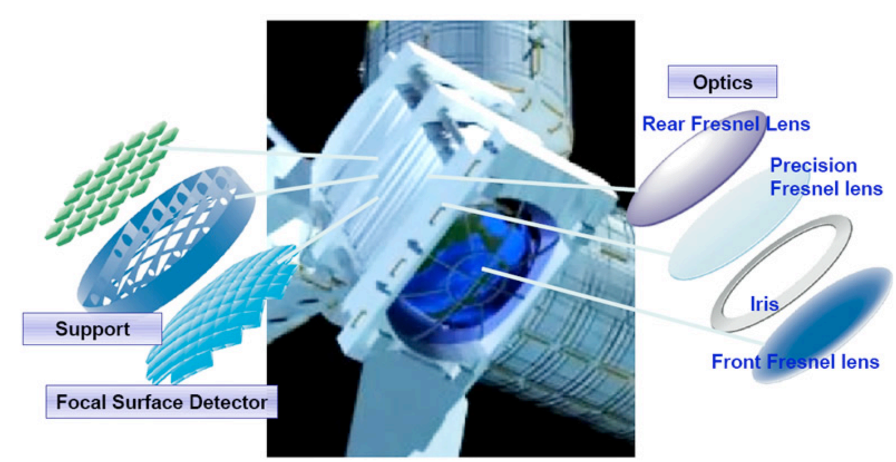
  - **Auger composition results**
  - **possible interpretations**



- Can a consistant picture emerge?
  - Still a few stones in the shoe…

- A few key future experiments

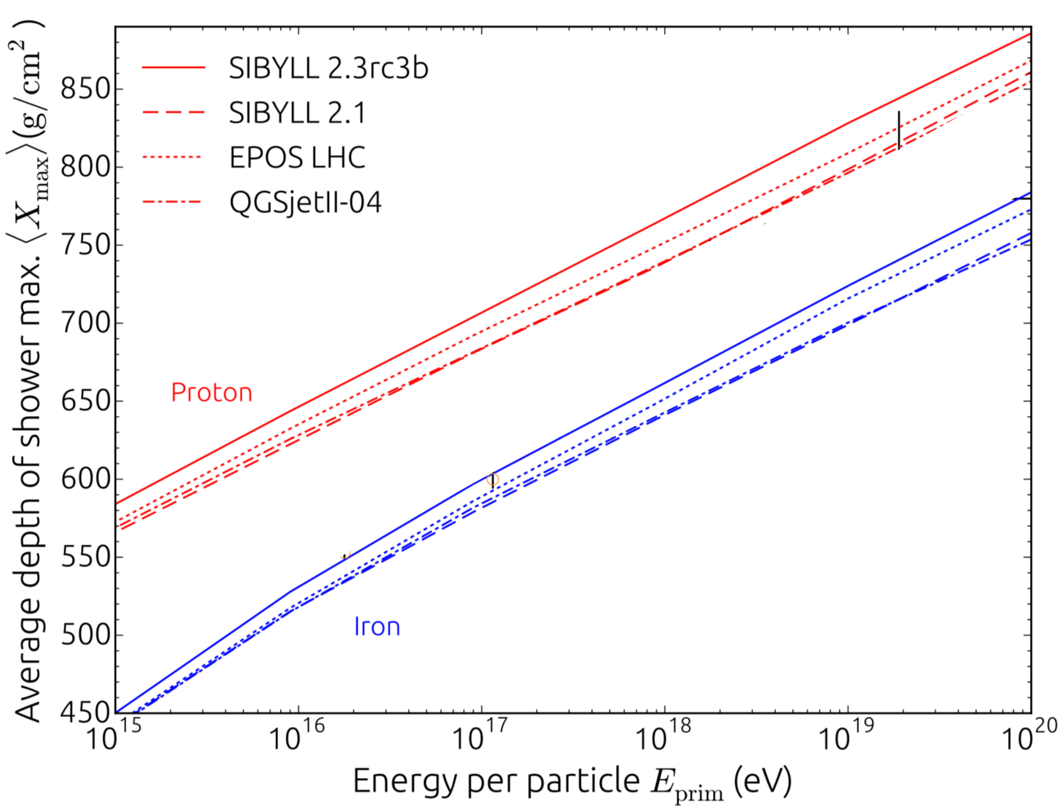


Brief summary of the properties of hadronic showers and their dependence on composition

- More muons at a given energy for nuclei than for protons

- Deeper shower maximum for proton showers than for nuclei showers at a given energy

- The spread of the distribution of X_{MAX} for proton showers at a given energy is expected to be larger than for nuclei



adapted from Engel et al., ICRC 2015 proceedings

==> example of models predictions for the energy evolution of X_{MAX} for proton, iron and photon showers

==> the trends we discussed qualitatively are model independent but precise predictions are not

==> precise quantitative interpretation of data always depend on the model used to describe the properties of air shower

==> only approximative trends can be derived from the data and never on the basis of a single shower but by analyzing a large sample of showers at a given energy

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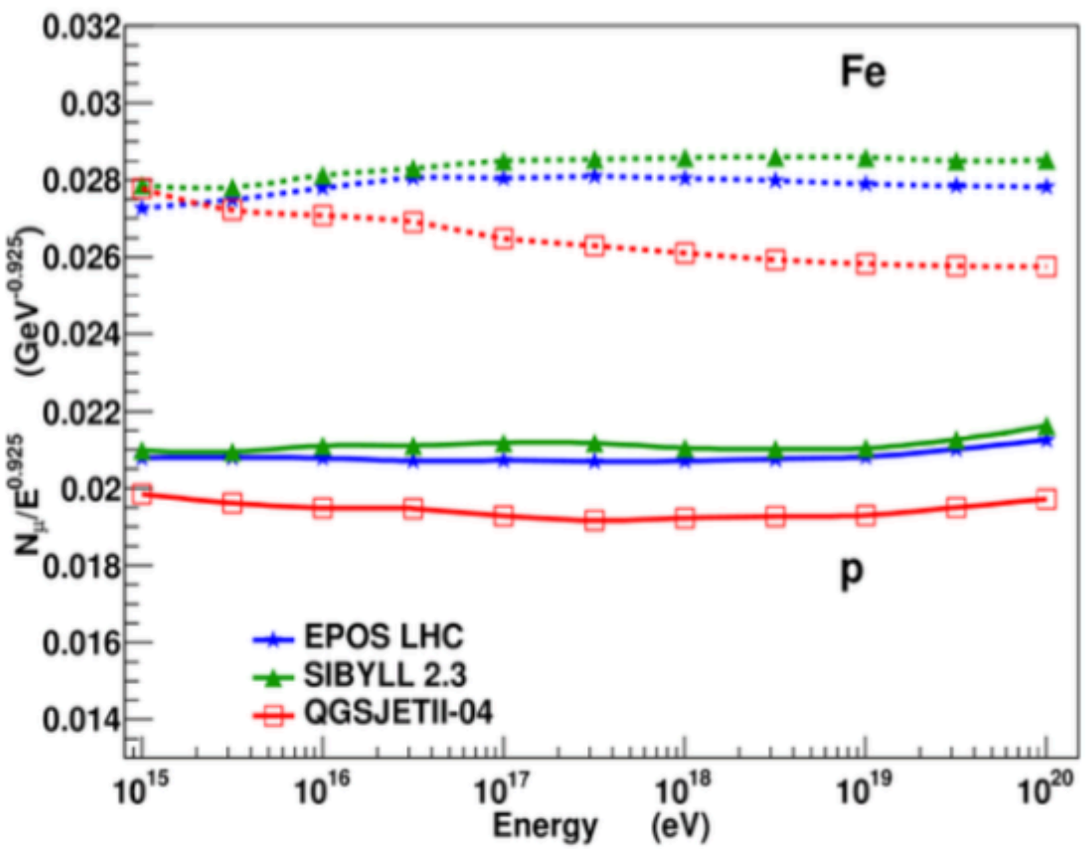

Pierog, UHECR 2016

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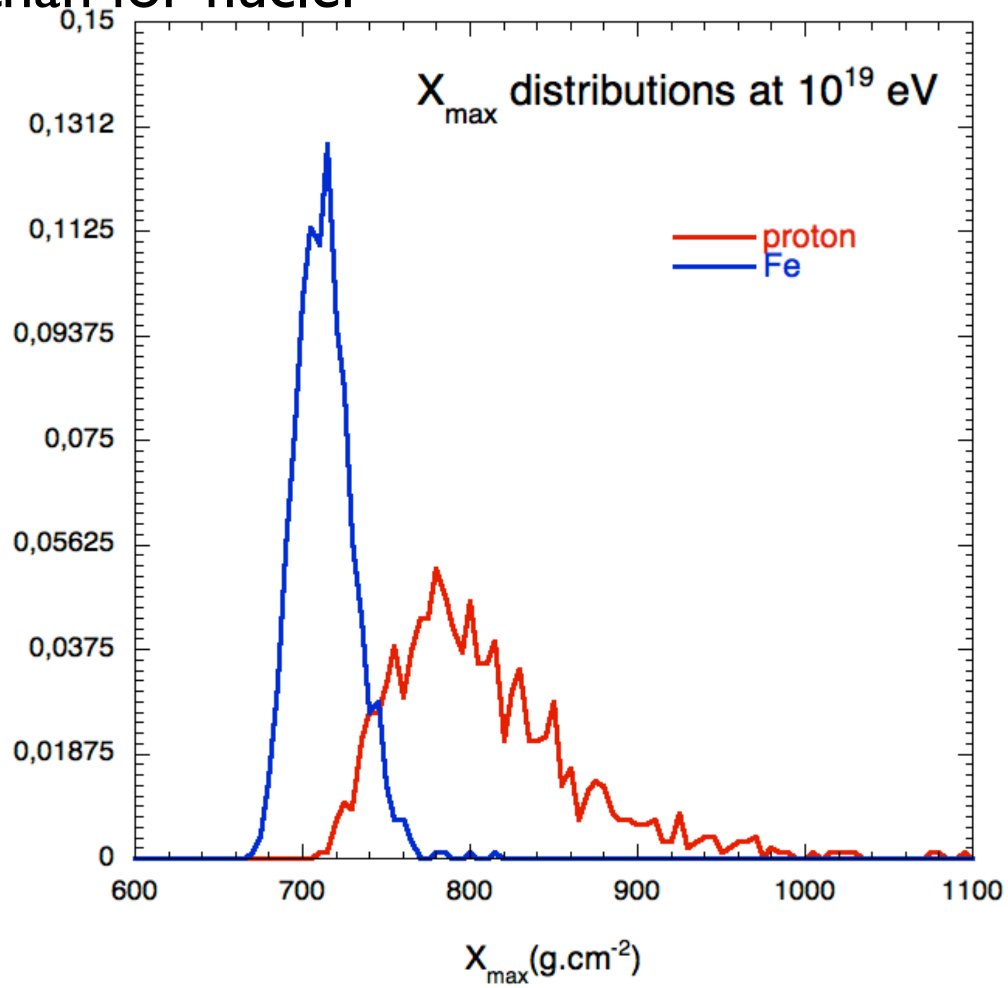


==> example of models predictions for the energy evolution of X_{MAX} for proton, iron and photon showers

==> the trends we discussed qualitatively are model independent but precise predictions are not

==> precise quantitative interpretation of data always depend on the model used to describe the properties of air shower

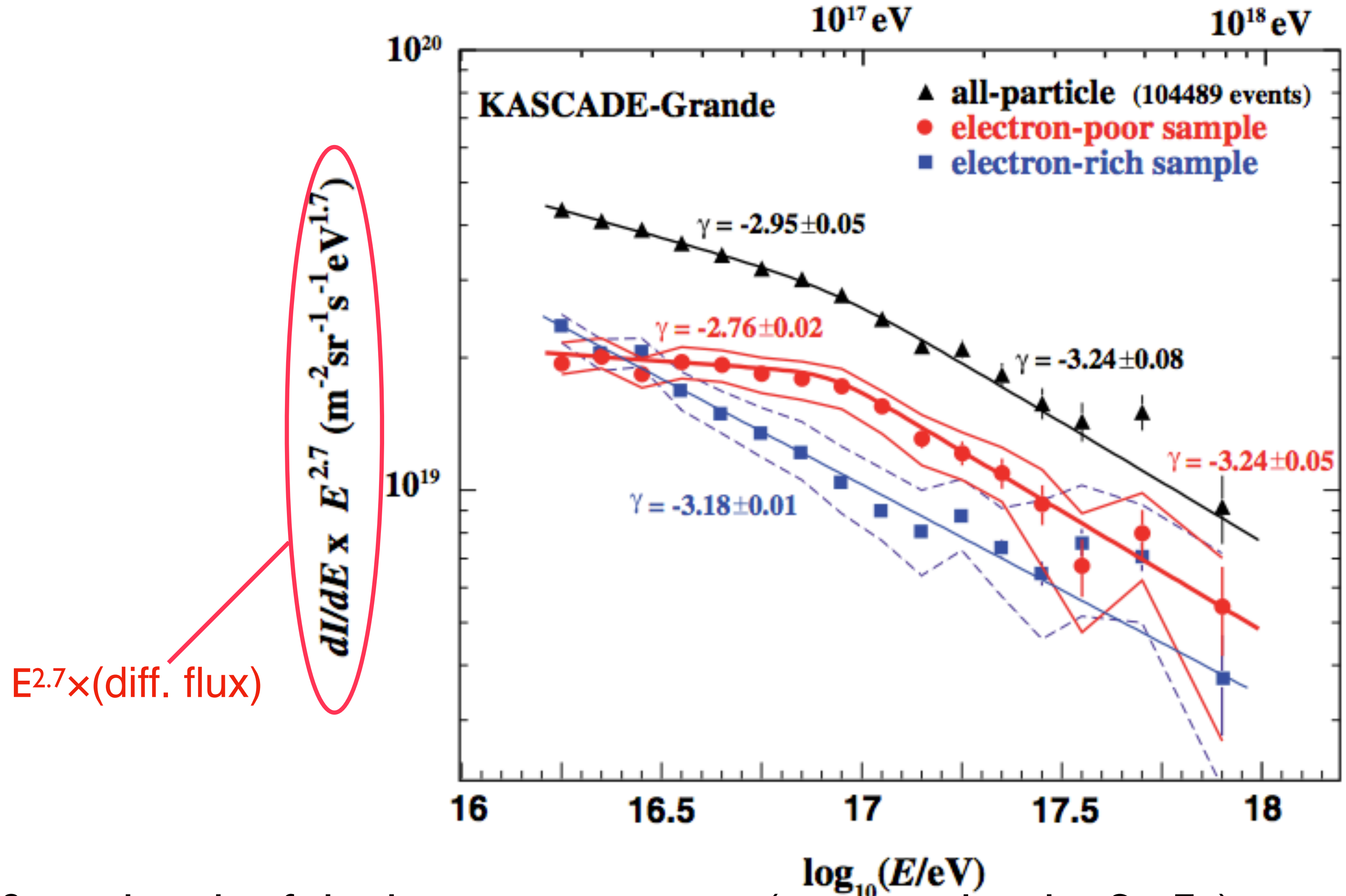
==> only approximative trends can be derived from the data and never on the basis of a single shower but by analyzing a large sample of showers at a given energy

KASCADE-Grande spectrum and composition analyses

• The Kascade-Grande collaboration released composition analyses claimed to be robust (i.e the main conclusions do not depend strongly of hadronic models)

• Based on the estimate of the muon to electron ratio
—> on the separation between electron rich (light CRs) and electron poor (heavy CRs) showers at a given energy

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)

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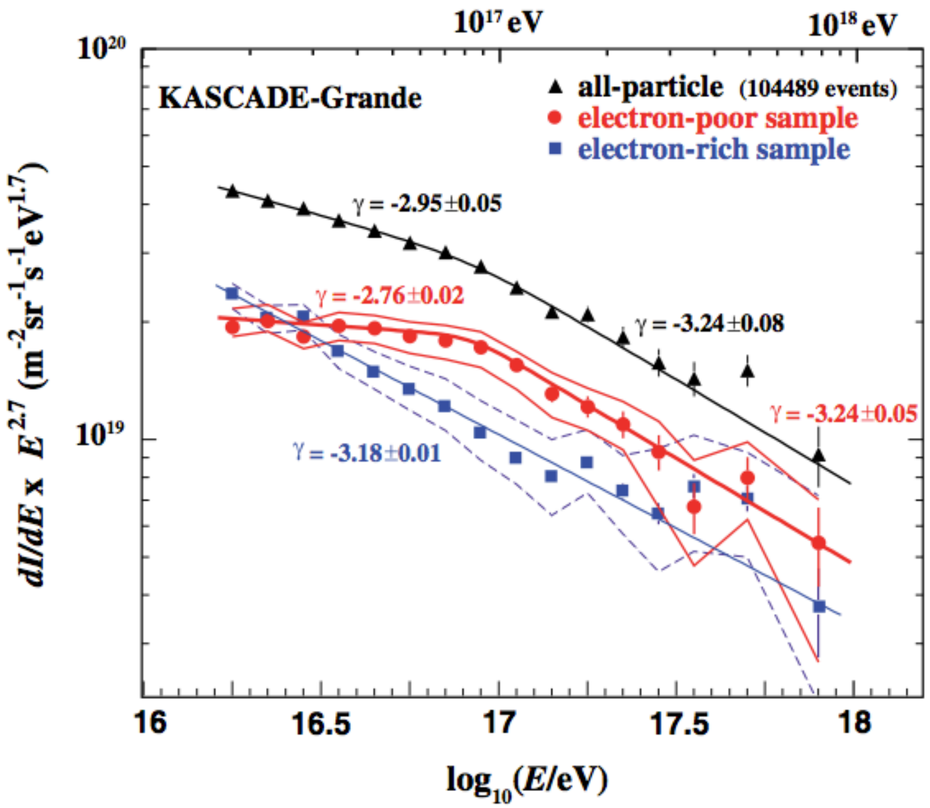
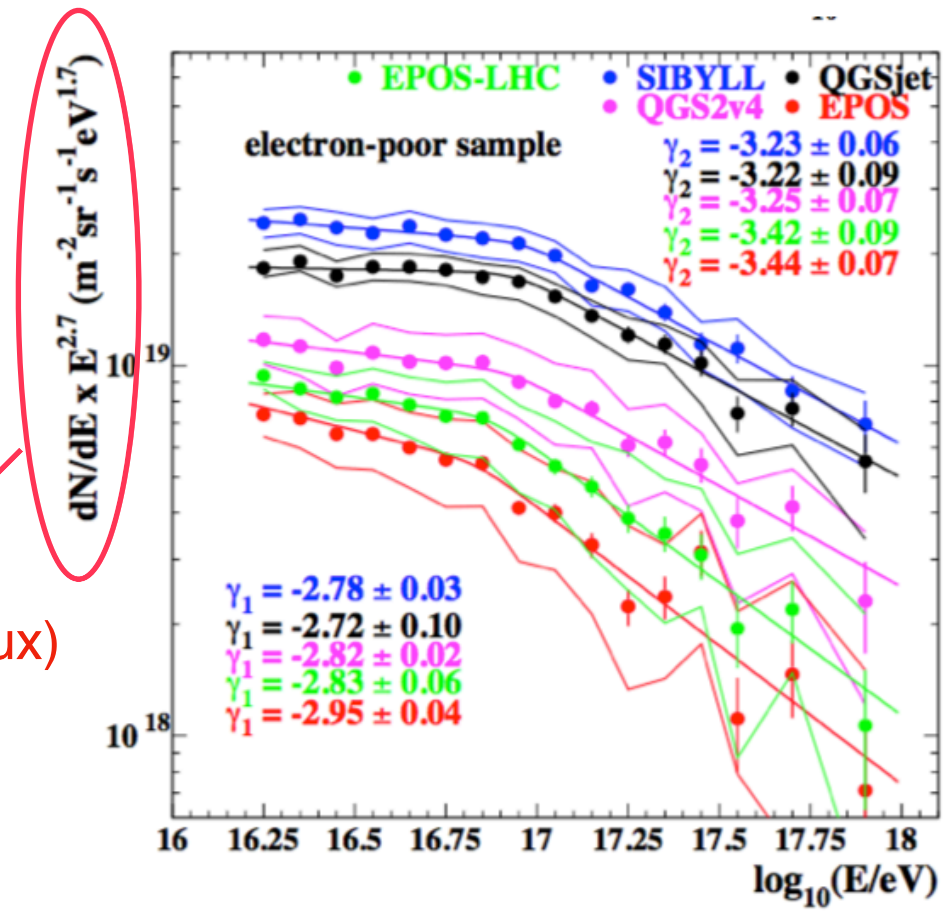


KG collab, Phys. Rev. Lett., 2011



$E^{2.7}$×(diff. flux)

KG collab, ICRC 2015

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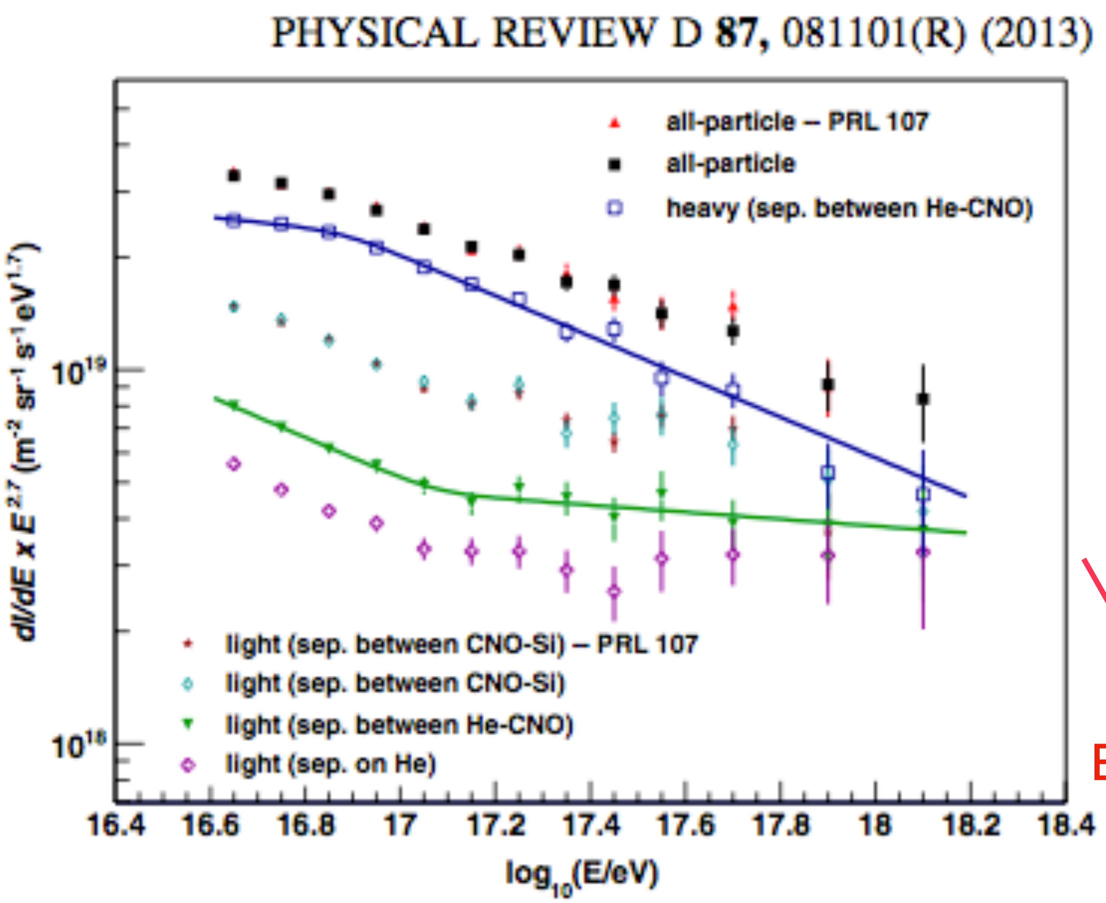
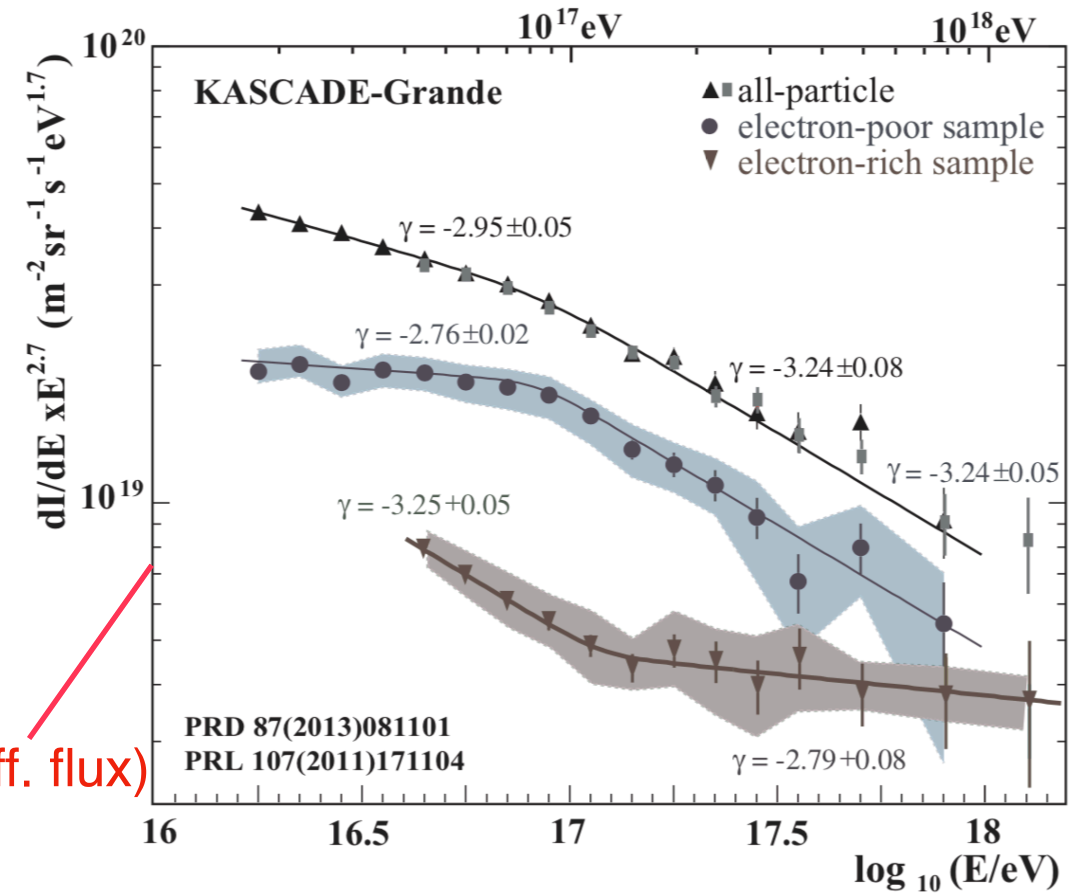
Evidence for a “Light Ankle”



$E^{2.7}$×(diff. flux)



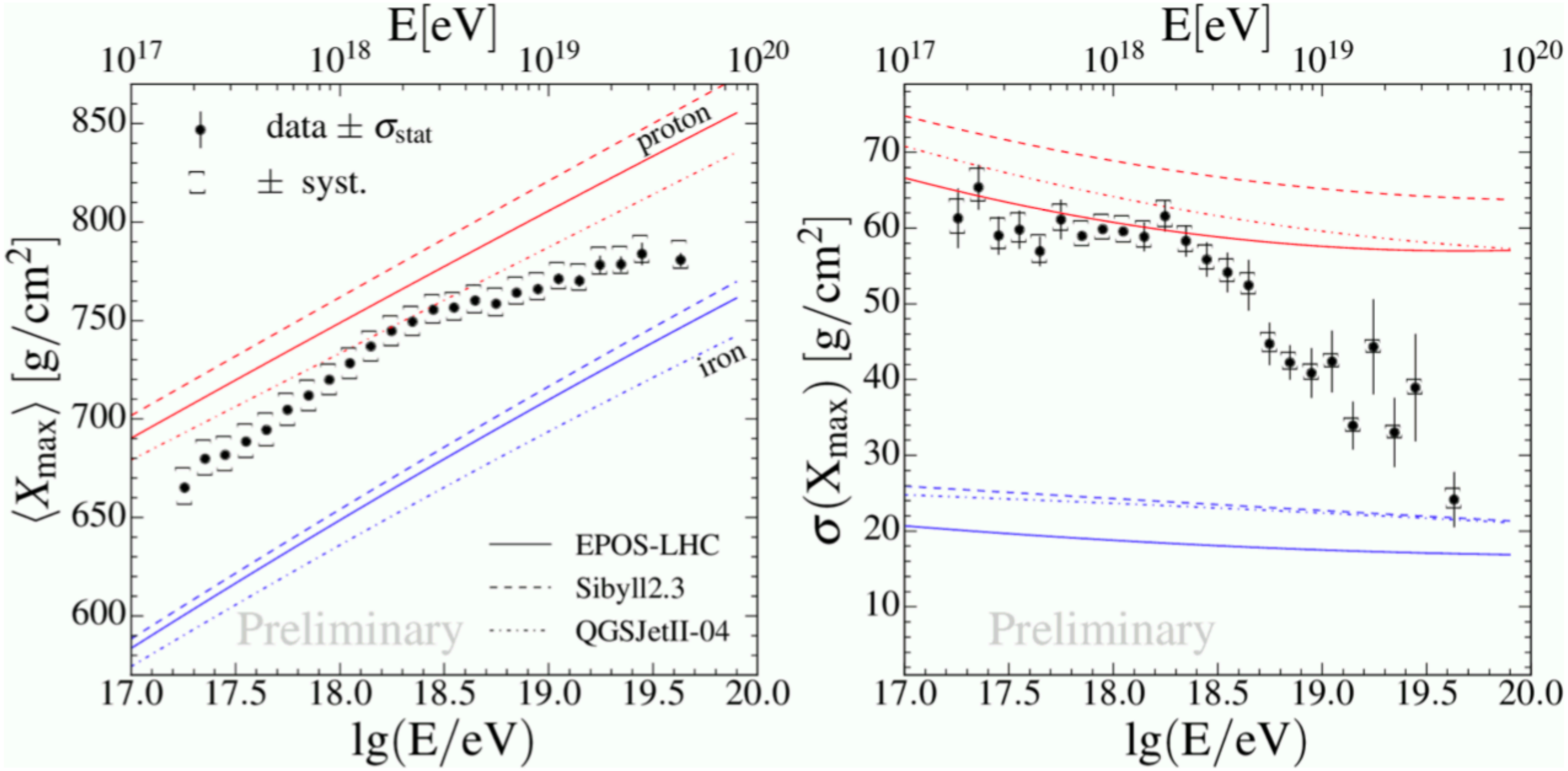
- A similar analysis showed evidence for an “ankle” in the light component
- The spectral index before the “light ankle” is compatible with the post knee spectral index of the heavy component
- Likely explanation : an extragalactic light component is starting to emerge on top of the light galactic component

==> smooth knee for the light component too ==> post knee protons at ~10^{17} eV (?)

- Cross check with other hadronic models ==> the result seems to be confirmed

Auger composition analyses

• Most reliable estimates of the UHECR composition are based on the measurement of the depth of the maximum of air shower development Xmax
—> energy evolution of the < Xmax> and its spread σ_{Xmax} are powerful probes for the evolution of the composition



Auger collab, ICRC 2017

- up to a few 10^{18} eV : $<X_{max}>$ evolution steeper than predicted for pure compositions
  —> indication of a composition getting lighter
  —> transition toward a light dominated extragalactic component
- above a few 10^{18} eV (in particular above the ankle)
  (i) $<X_{max}>$ evolution flatter than predicted for pure compositions
  (ii) σ_{Xmax} decreases strongly with the energy

—> model independent evidence for a composition getting heavier and proton poorer above the ankle

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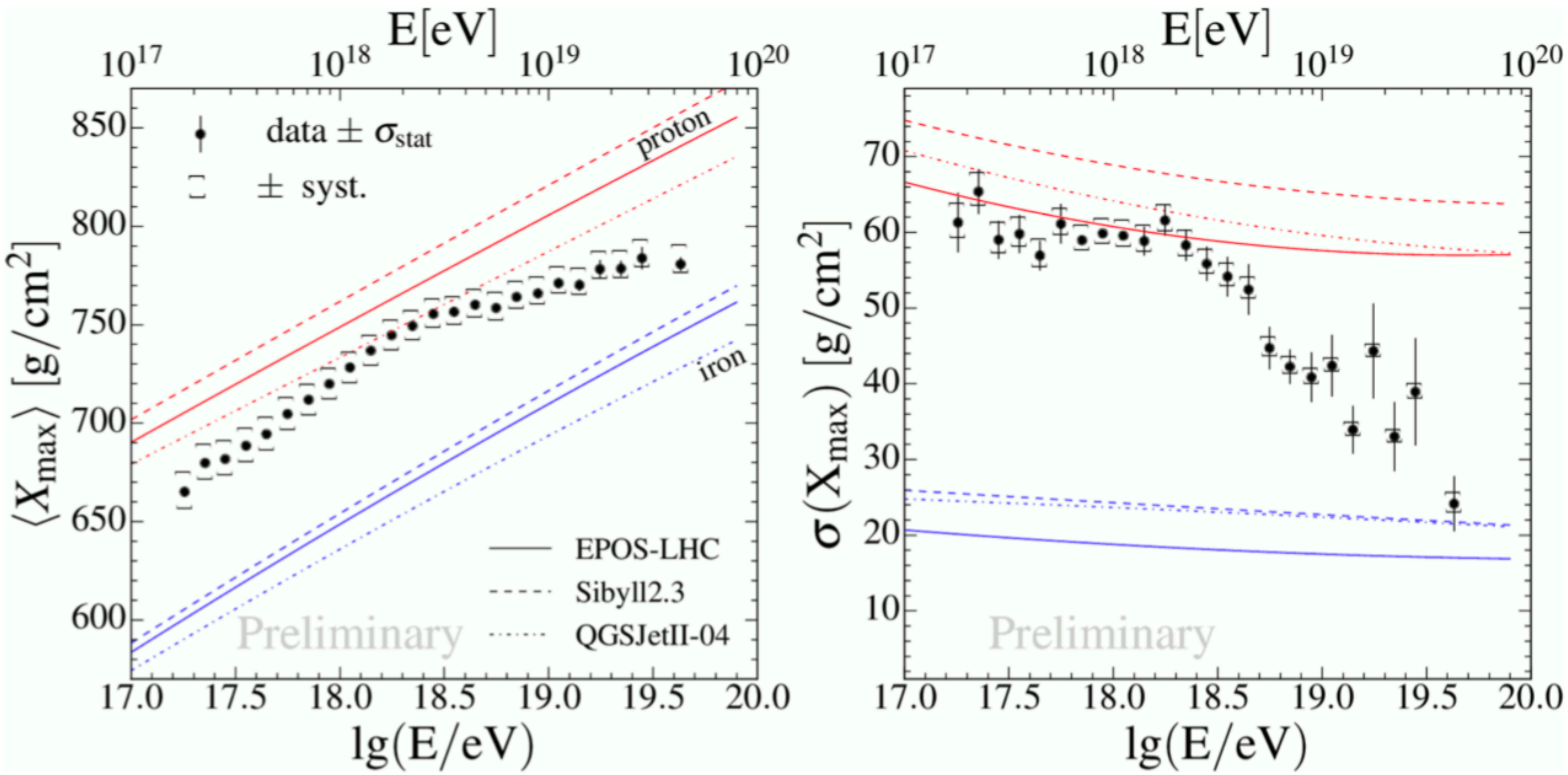

Auger collab, ICRC 2017

—> Most probably the extragalactic component goes from light dominated at the ankle to intermediate dominated above 10^{19} eV

—> study of the correlation between the ground and X_{max} confirm that the composition is mixed and that intermediate nuclei are required (Auger collab, Physics Letters B 762 (2016) 288–295)

—> pure protons and almost pure proton models extragalactic models are ruled out

—> pair production dip as and interpretation of the ankle ruled out

Auger composition analyses

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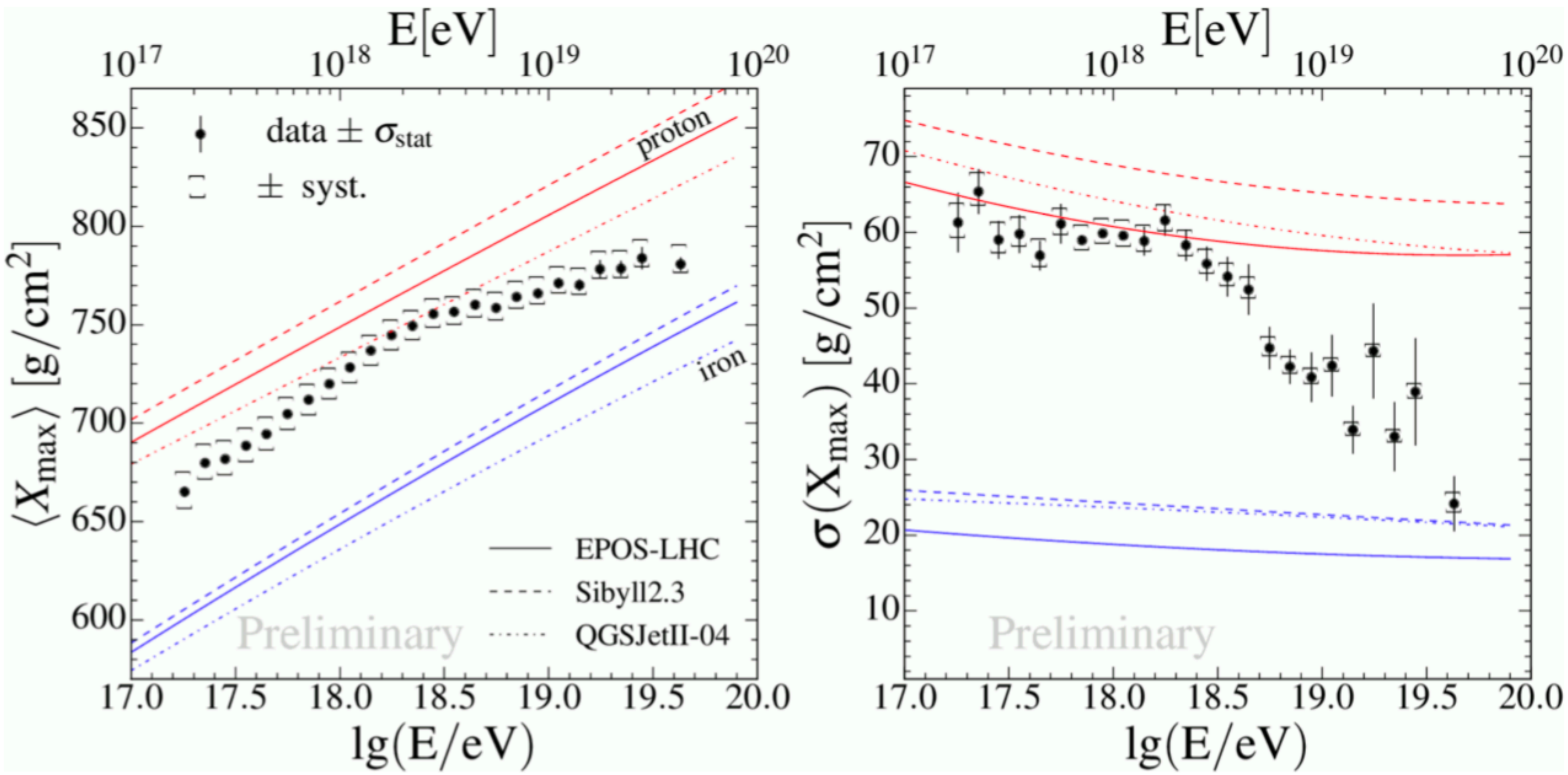


Auger collab, ICRC 2017

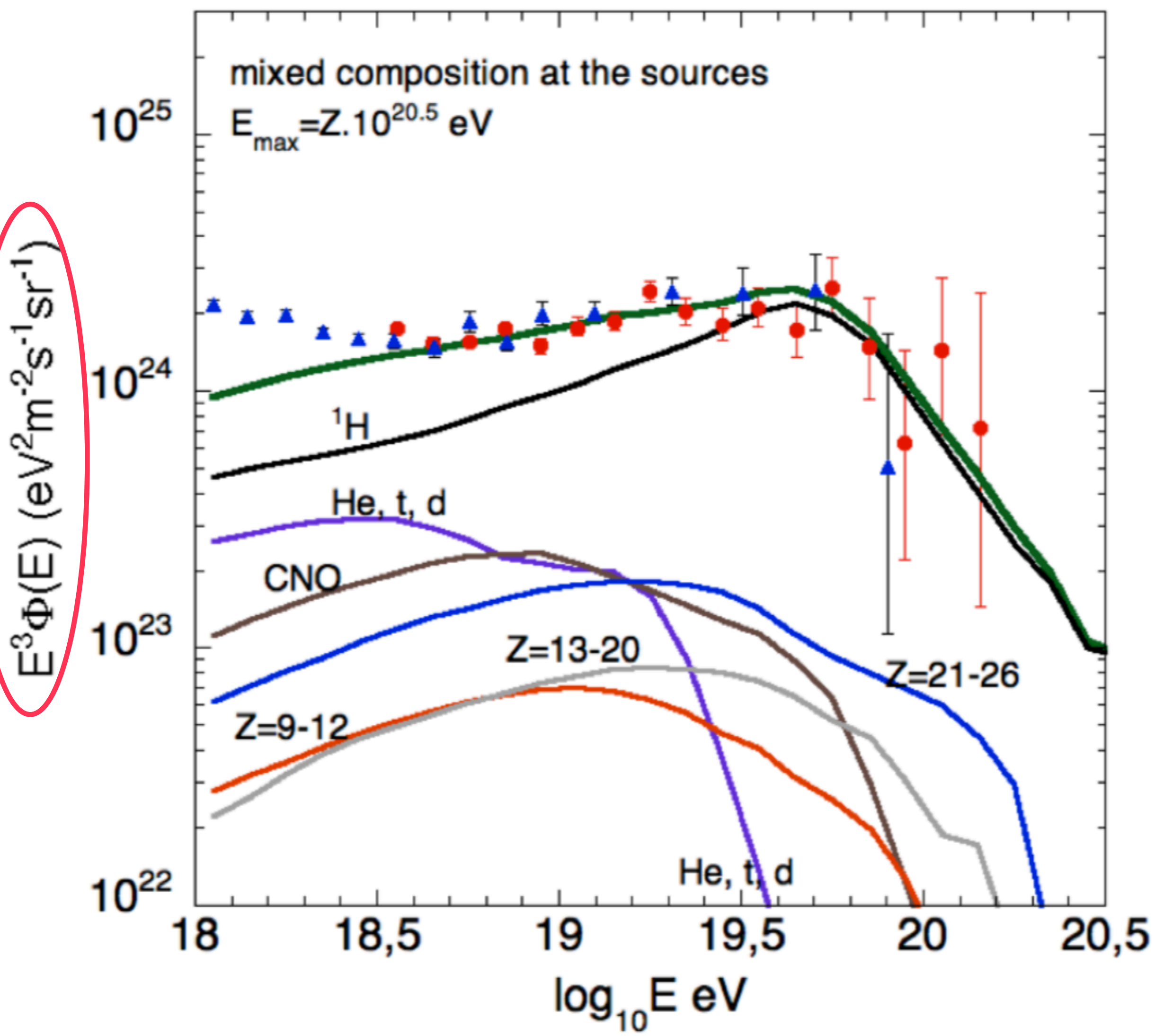
What can be concluded from the observation of a composition getting heavier above the ankle?

One example : mixed composition assumed at UHECR sources

Assuming the maximum energy per nucleon is above 10^{20} eV (what most people thought until ~2010) mixed composition similar to that of low energy galactic cosmic-rays :

$N(E) \propto E^{-\beta}$, $E_{max}(Z) = Z \times E_{max}^{proton}$, $E_{max}^{proton} = 10^{20.5}$ eV

E³×(diff. flux)



When all the species are assumed to be accelerated above 10^{20} eV, the composition is expected to get lighter (i.e proton richer) above 10^{19} eV (photodisintegration of composed species)

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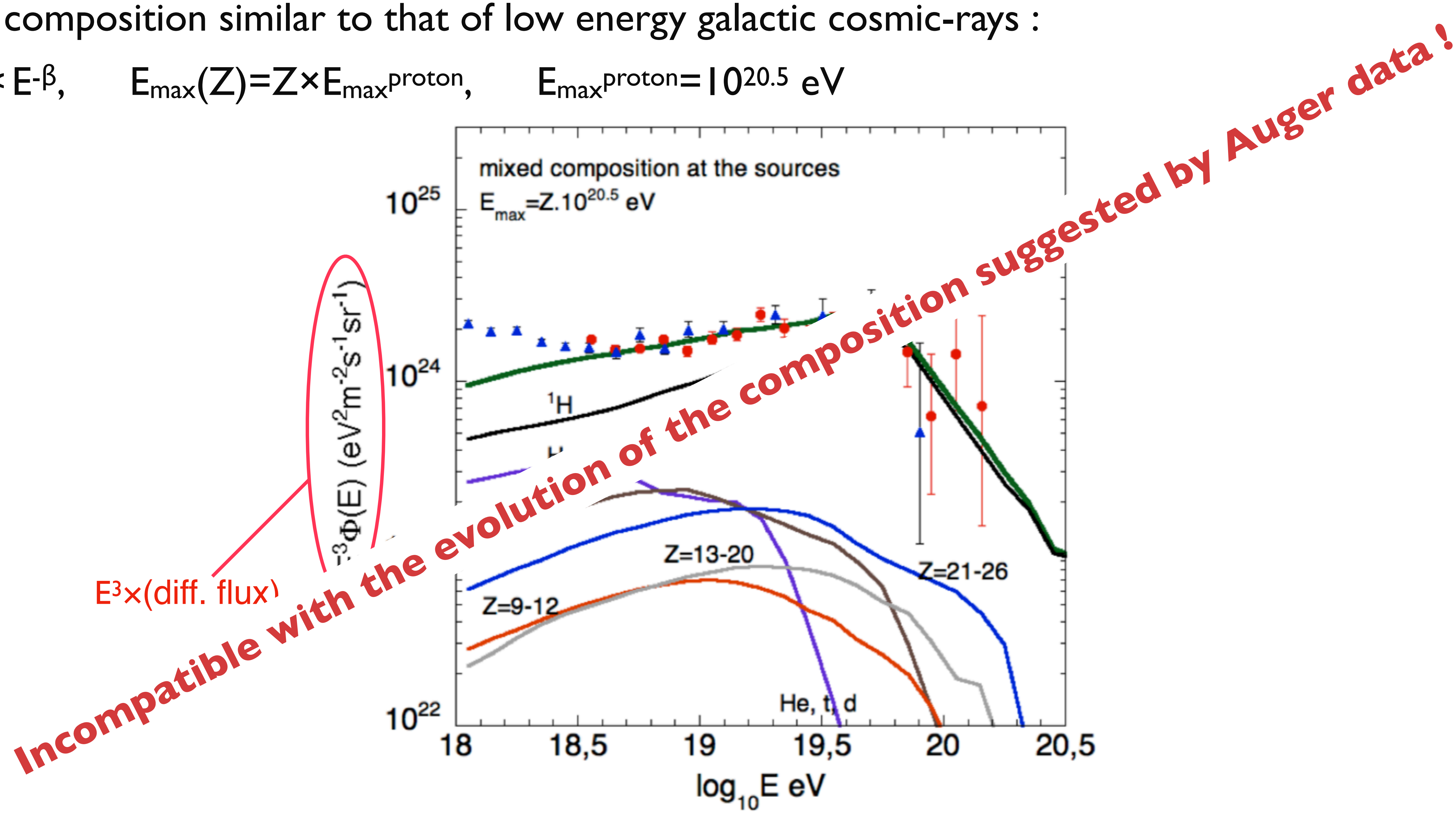

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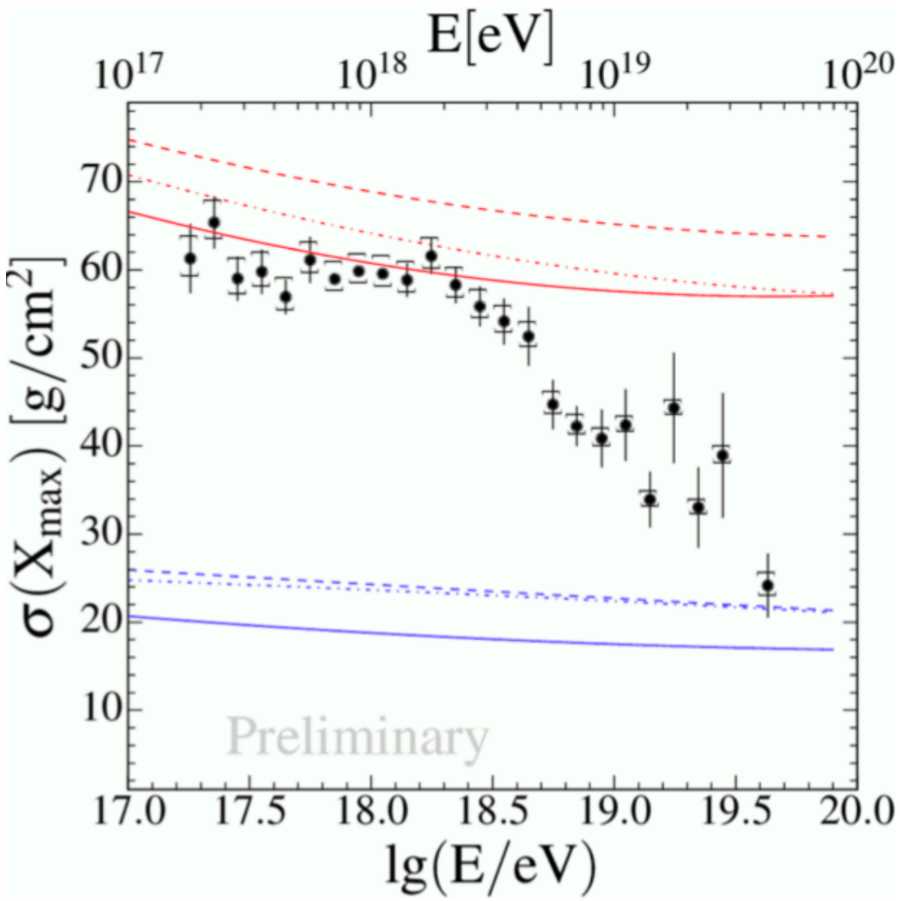
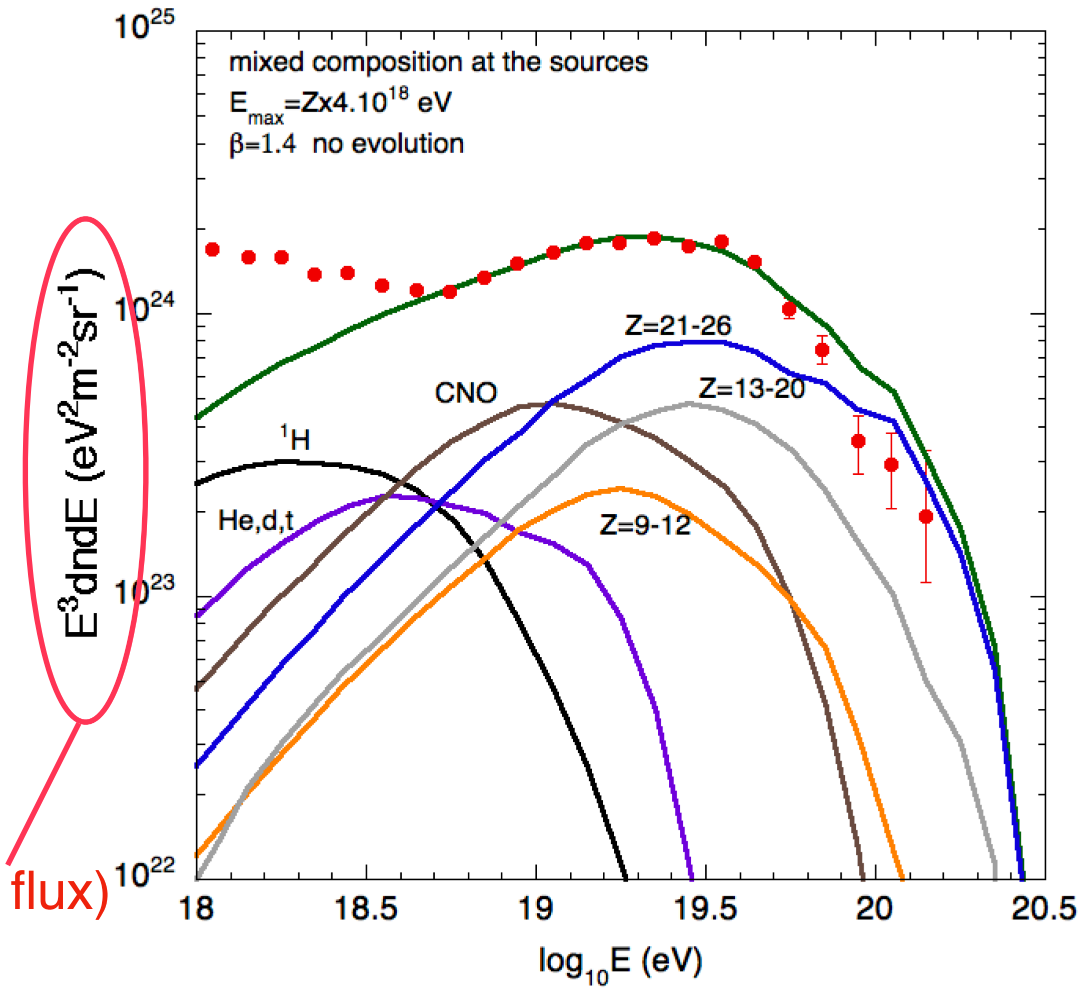
Implications of Auger composition measurements





The evolution of the composition implied by Auger composition analyses strongly suggest that the composition is light at the ankle and becoming heavier as the energy increases
—> dominant sources of UHECR do not accelerate protons to the highest energies

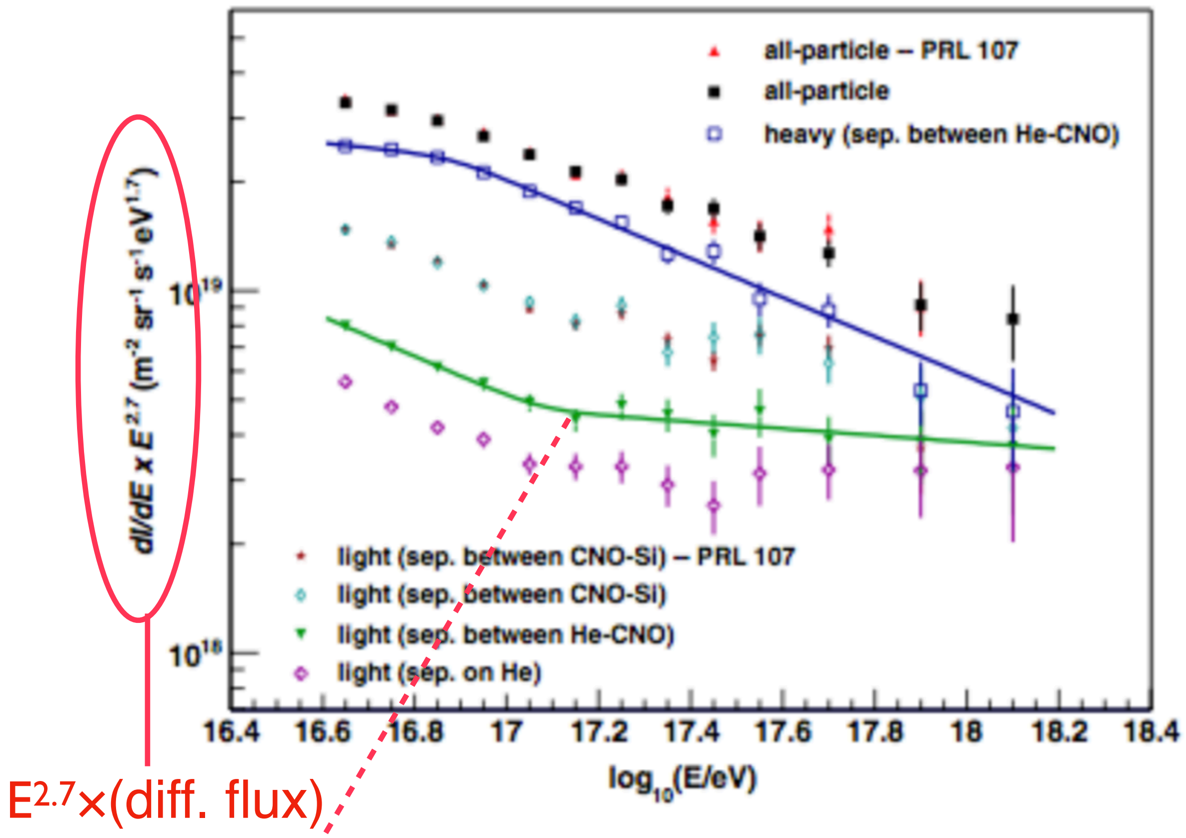
Low maximum energy per nucleon (a few EeV to 10^{19} eV, well below the pion production threshold with CMB photons) and hard source spectral indexes required

here $N(E) \propto E^{-\beta}$, β=1.4, $E_{max}(Z)=Z\times E_{max}^{proton}$, $E_{max}^{proton}=4.10^{18}$ eV

obviously not a good news for UHE cosmogenic neutrinos predictions

KASCADE-Grande's light ankle

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

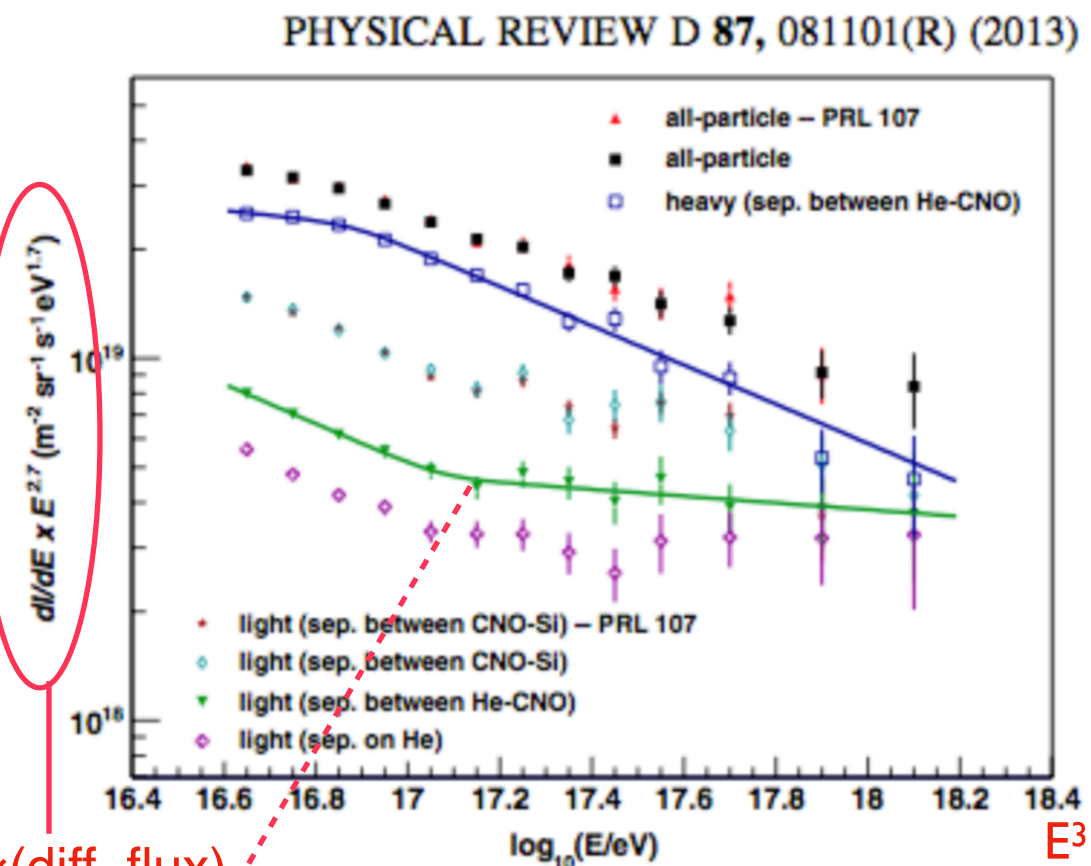


KASCADE-Grande's light ankle, equivalent to the ankle of the cosmic-ray spectrum but for the light component (H-He), around 10^{17} eV

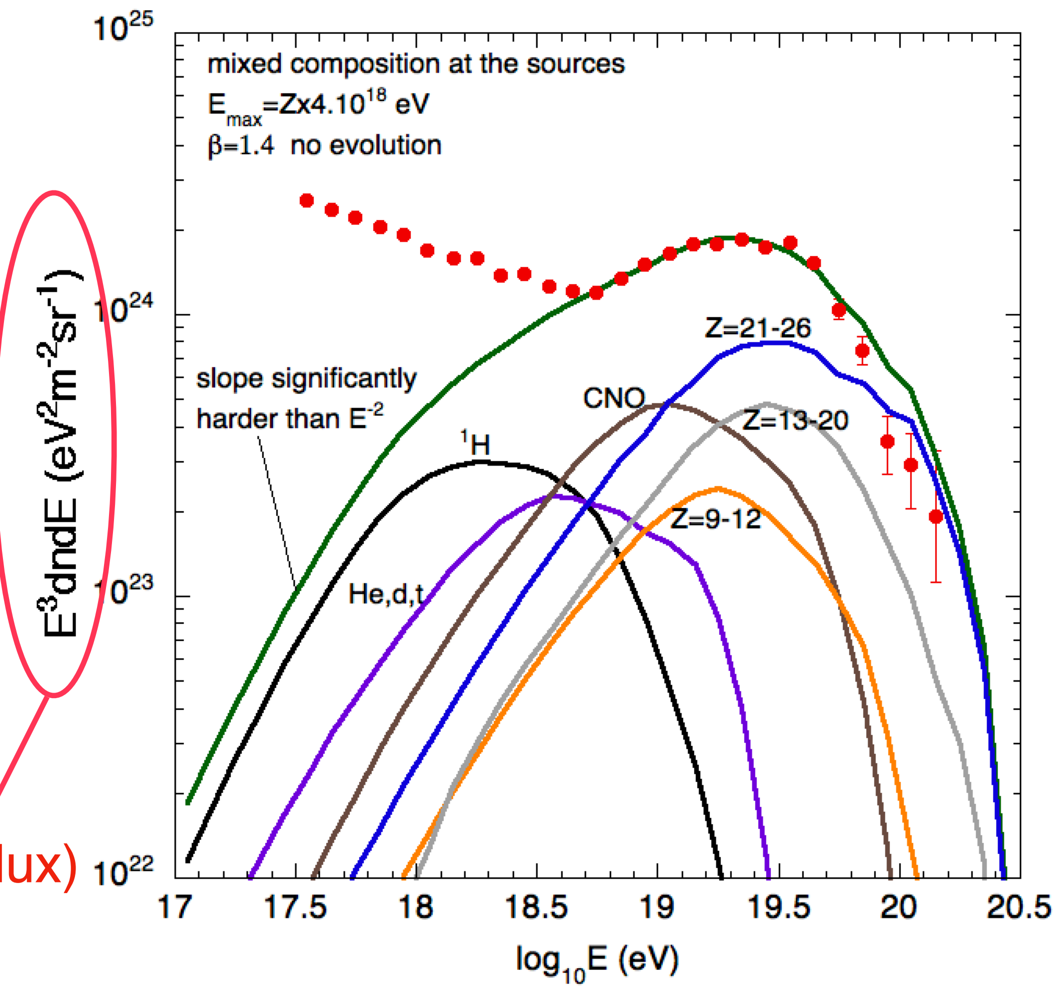
—> most probably implies that extragalactic light component starts to be significant already at 10^{17} eV

—> light component quite soft above 10^{17} eV (~2.7)

KASCADE-Grande's light ankle



E$^{2.7}$×(diff. flux)



E^3×(diff. flux)

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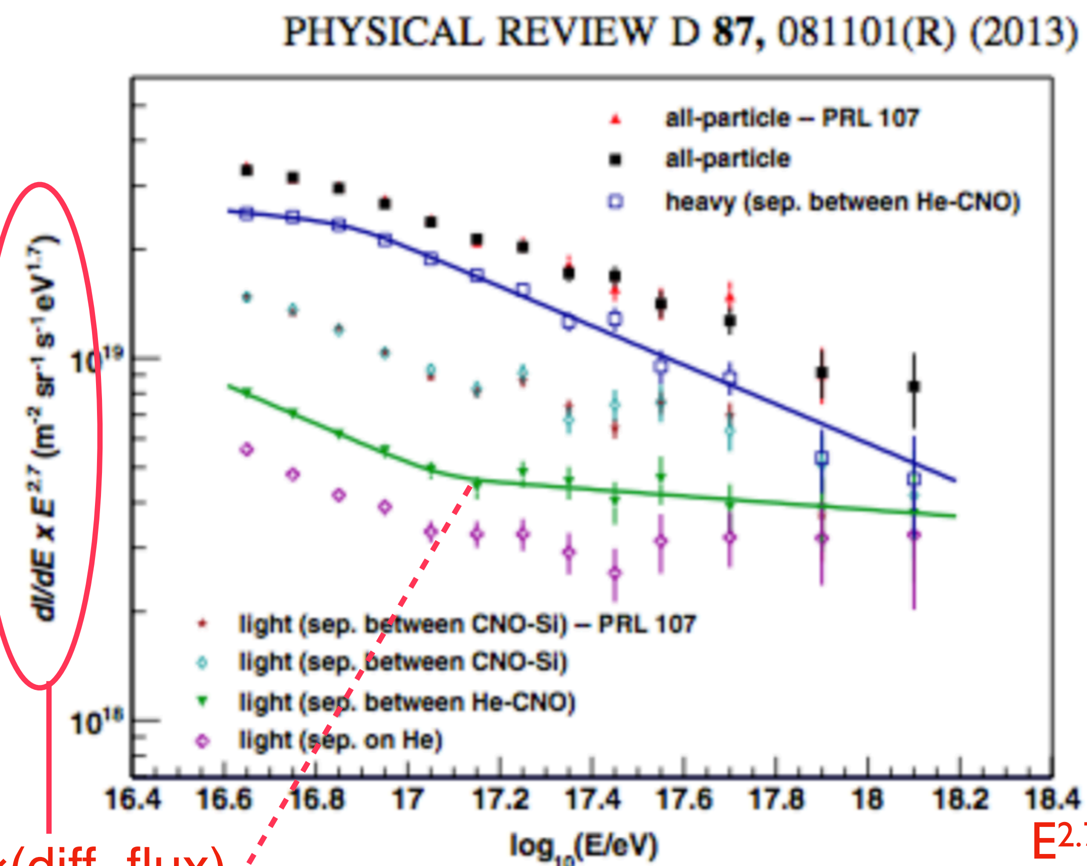
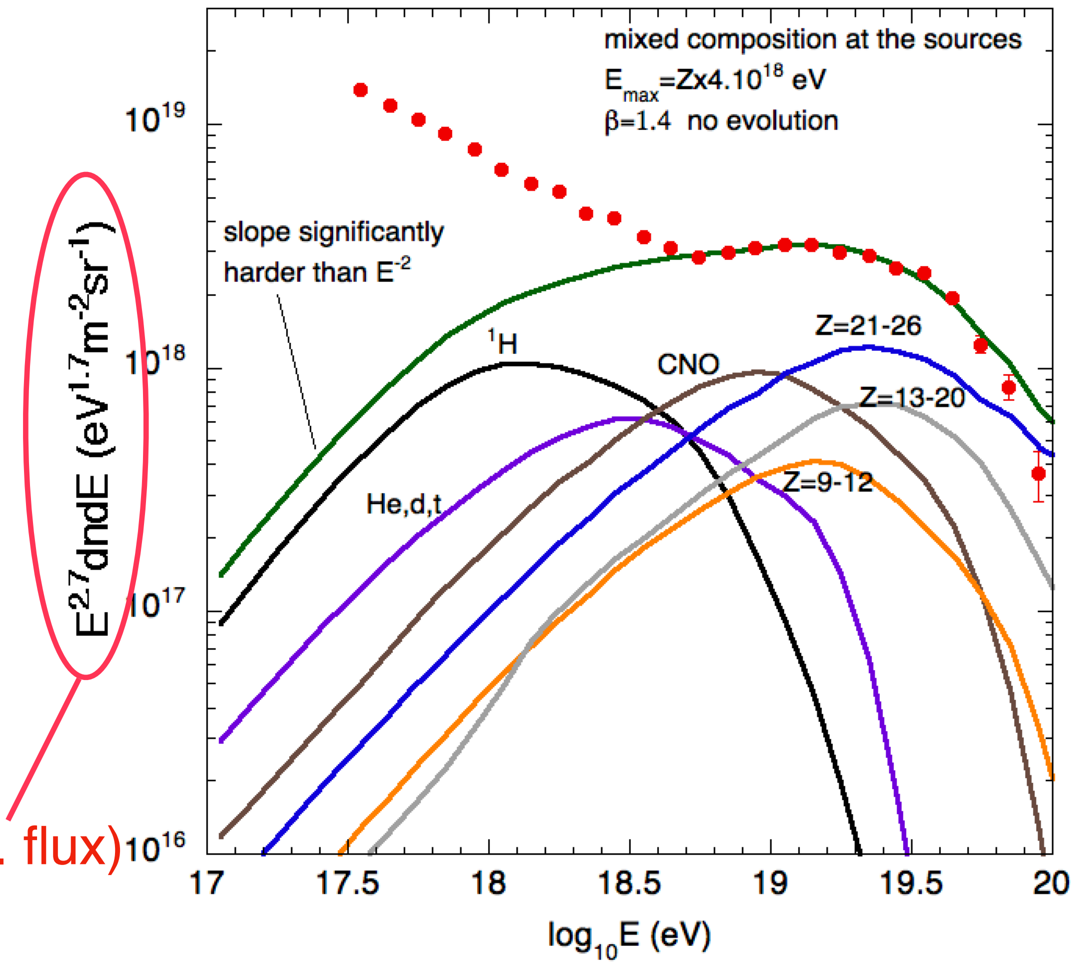
Difficult to make a consistent picture of the Auger composition + the light ankle with the above phenomenological model

One would need a much softer spectrum for the light nuclei

KASCADE-Grande's light ankle



E$^{2.7}$×(diff. flux)



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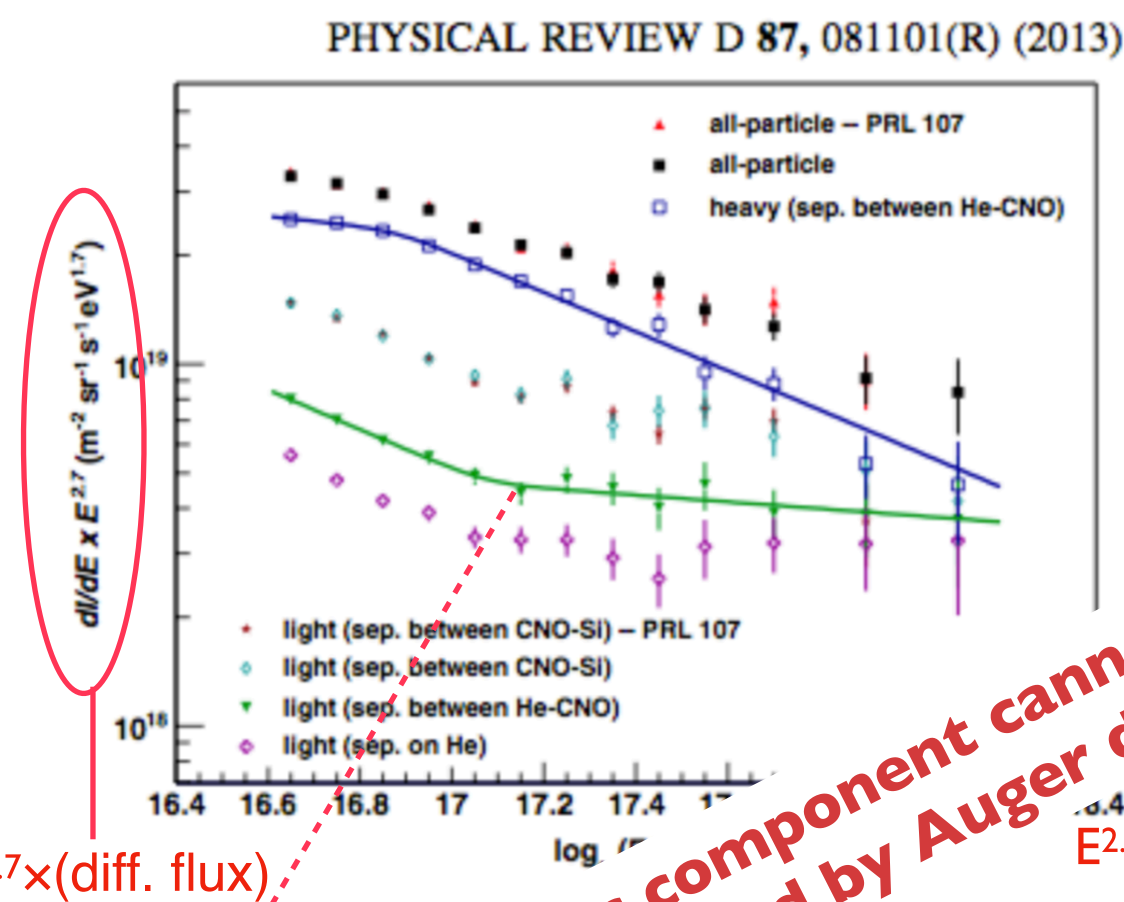
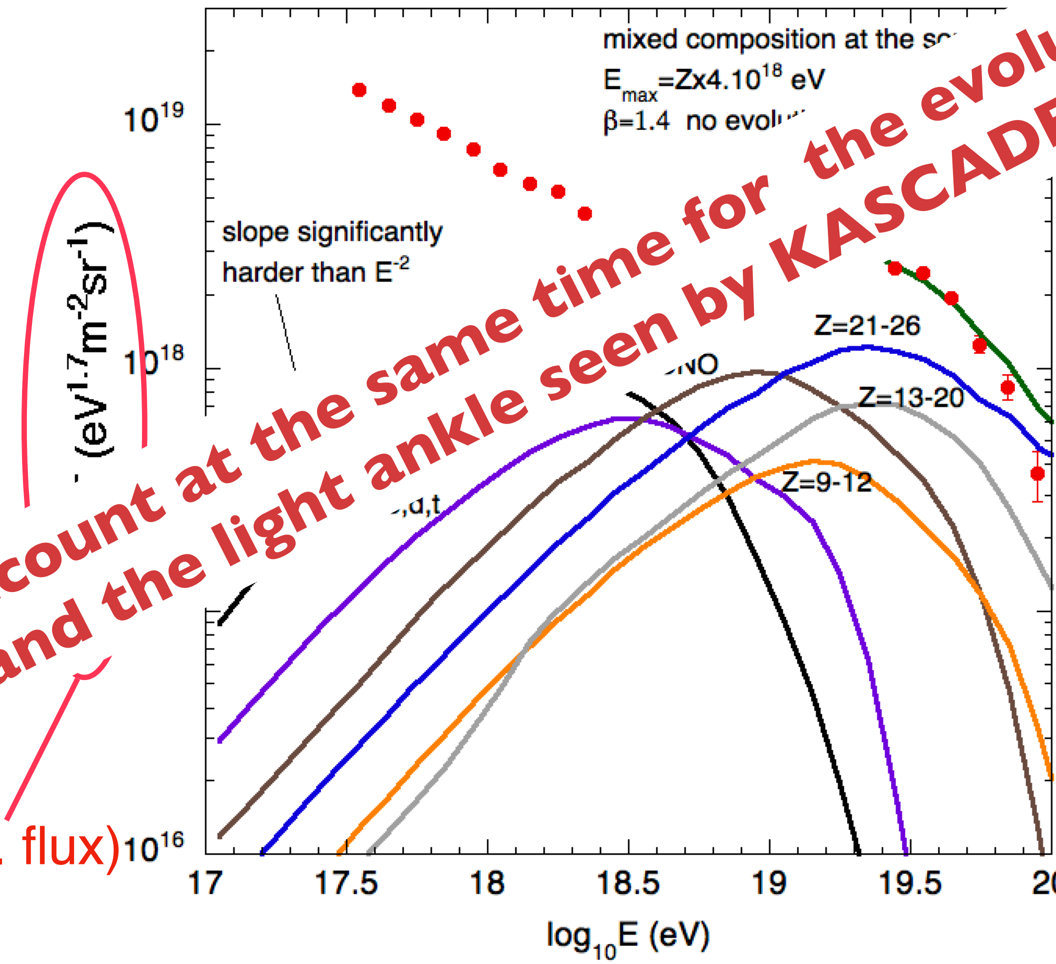




Such an extragalactic component cannot account at the same time for the evolution of the composition suggested by Auger data and the light ankle seen by KASCADE-Grande

KASCADE ankle, equivalent to the ankle of the cosmic-ray spectrum but for the light comp , around 10^{17} eV

ably implies that extragalactic light component starts to be significant already at 10^{17} eV

- component quite soft above 10^{17} eV (~2.7)

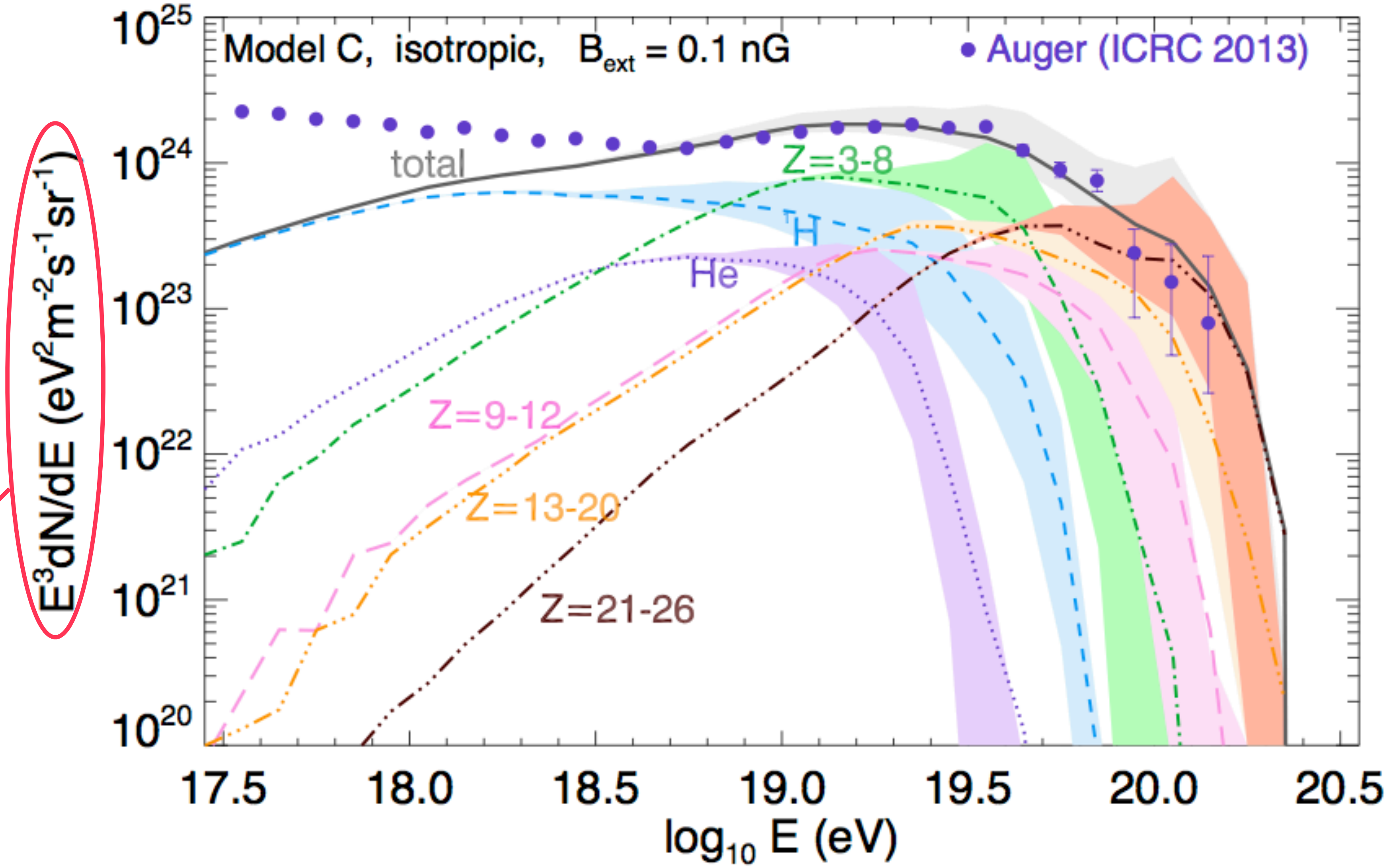
Phenomenological model of UHECR acceleration as a solution to the soft proton spectrum issue

Model of UHECR acceleration at GRB internal shocks (Globus et al. 2015) can reproduce UHECR data (Auger spectrum and composition)

- if most of the energy dissipated is communicated to accelerated cosmic-rays
- the composition injected at the shock has ~ 10 times galactic CR metallicity

NB : Spectrum on earth, sum of the contributions of all GRB after propagation in the extragalactic medium

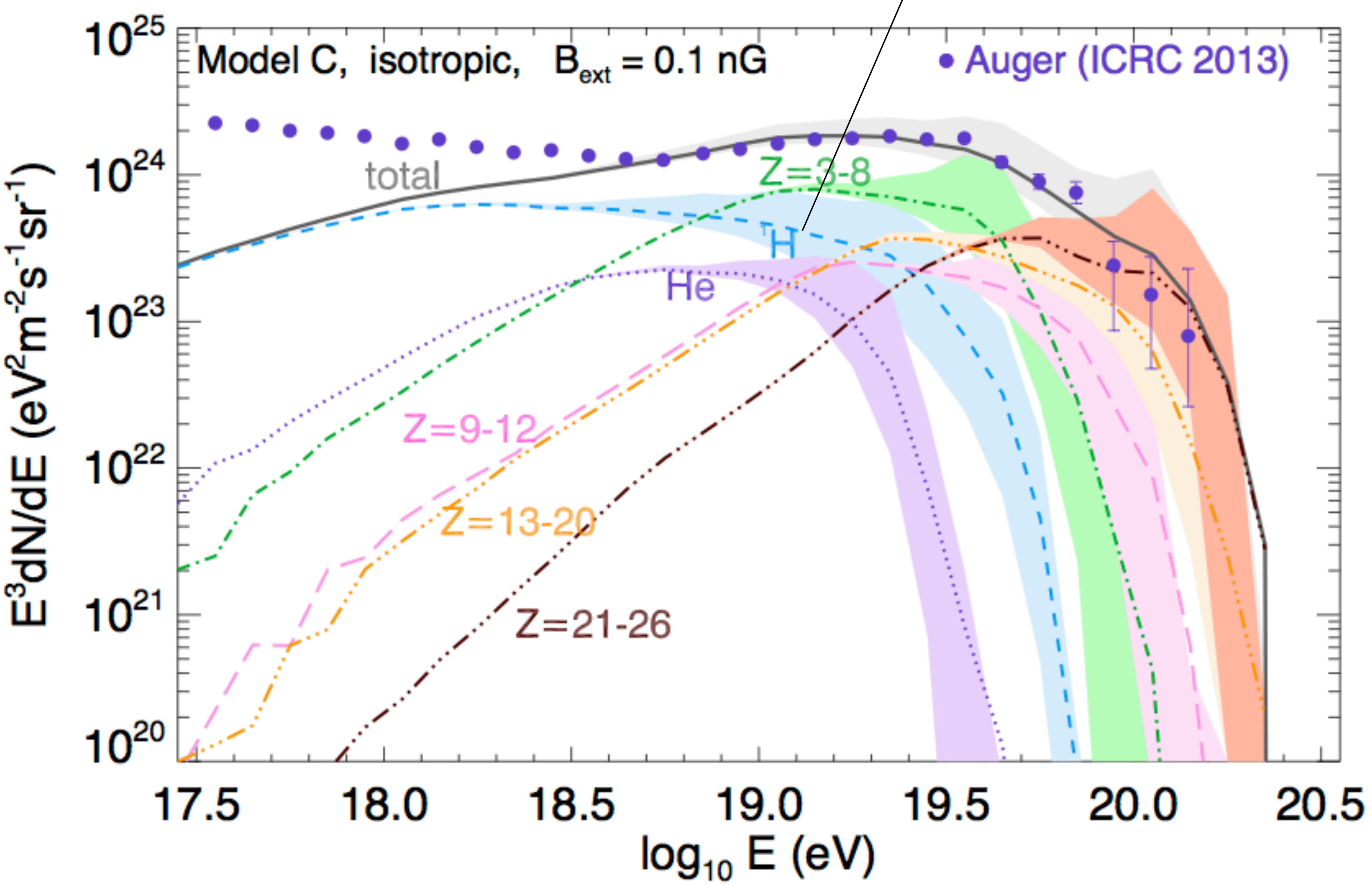
E³×(diff. flux)



N. Globus et al., MNRAS, 2015

Phenomenological model : implications for the GCR to EGCR transition

low proton maximum energy
—> composition getting heavier as the energy increases



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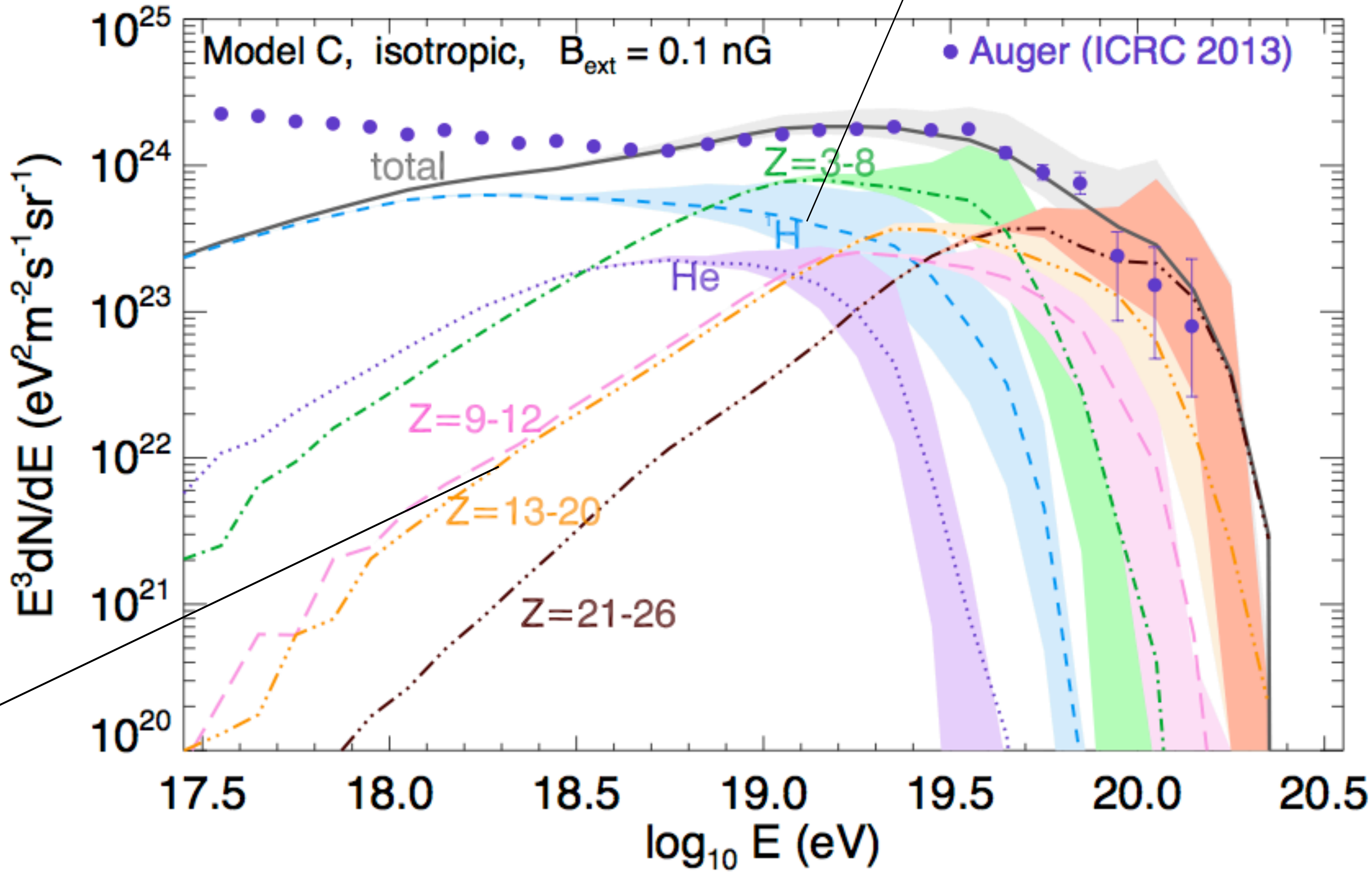
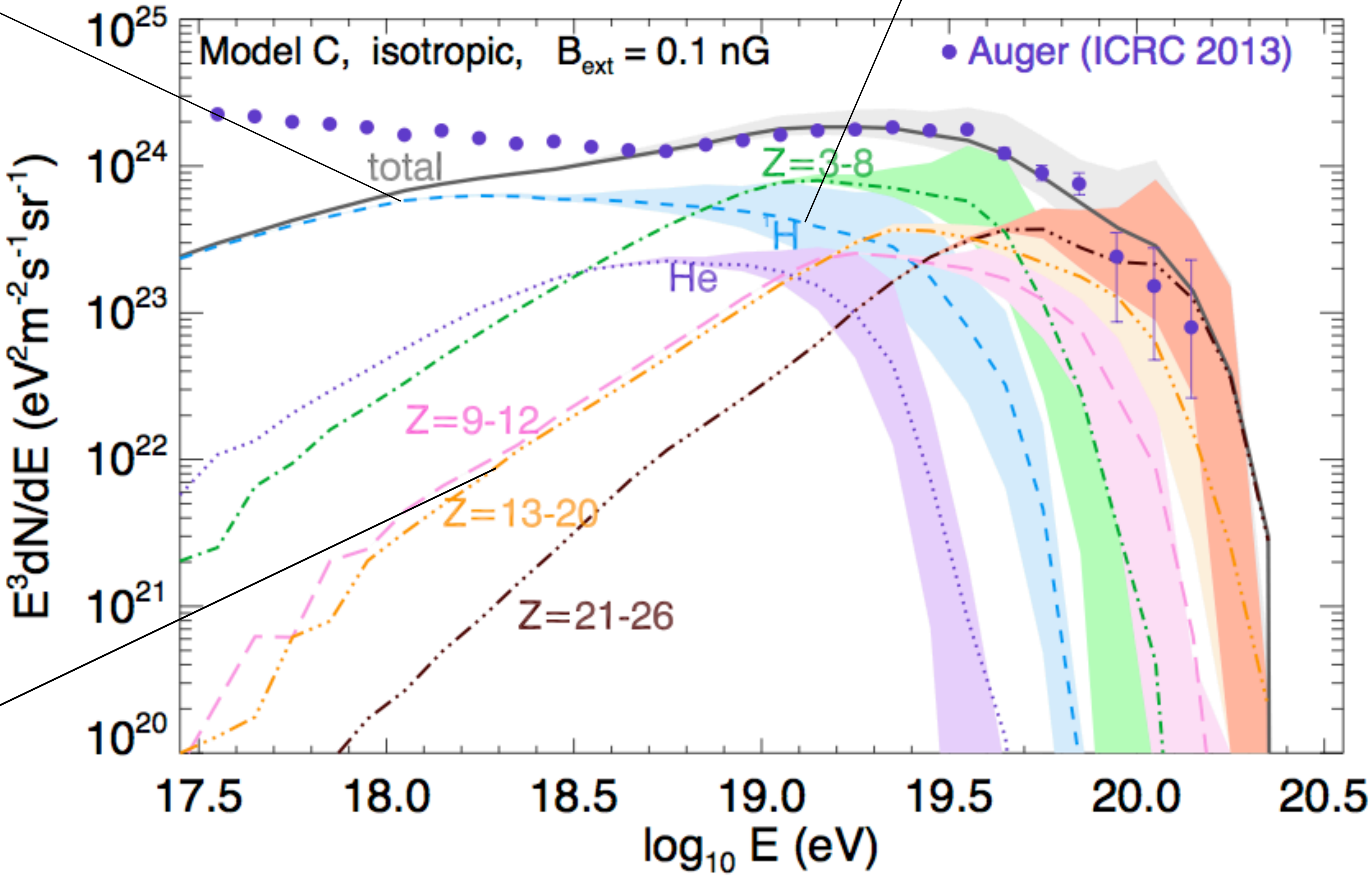


Heavier nuclei spectrum : Very hard due to the high-pass filter effect of the escape process
—> Hard nuclei spectrum required to fit Auger composition at high energy

Phenomenological model : implications for the GCR to EGCR transition

Proton spectrum : Soft due to the efficient escape of neutrons from the source (secondary neutron from the photodisintegration of nuclei within the source)
—> Allows the proton component to extend down to the light ankle seen by KASCADE-Grande

low proton maximum energy
—> composition getting heavier as the energy increases



Heavier nuclei spectrum : Very hard due to the high-pass filter effect of the escape process
—> Hard nuclei spectrum required to fit Auger composition at high energy

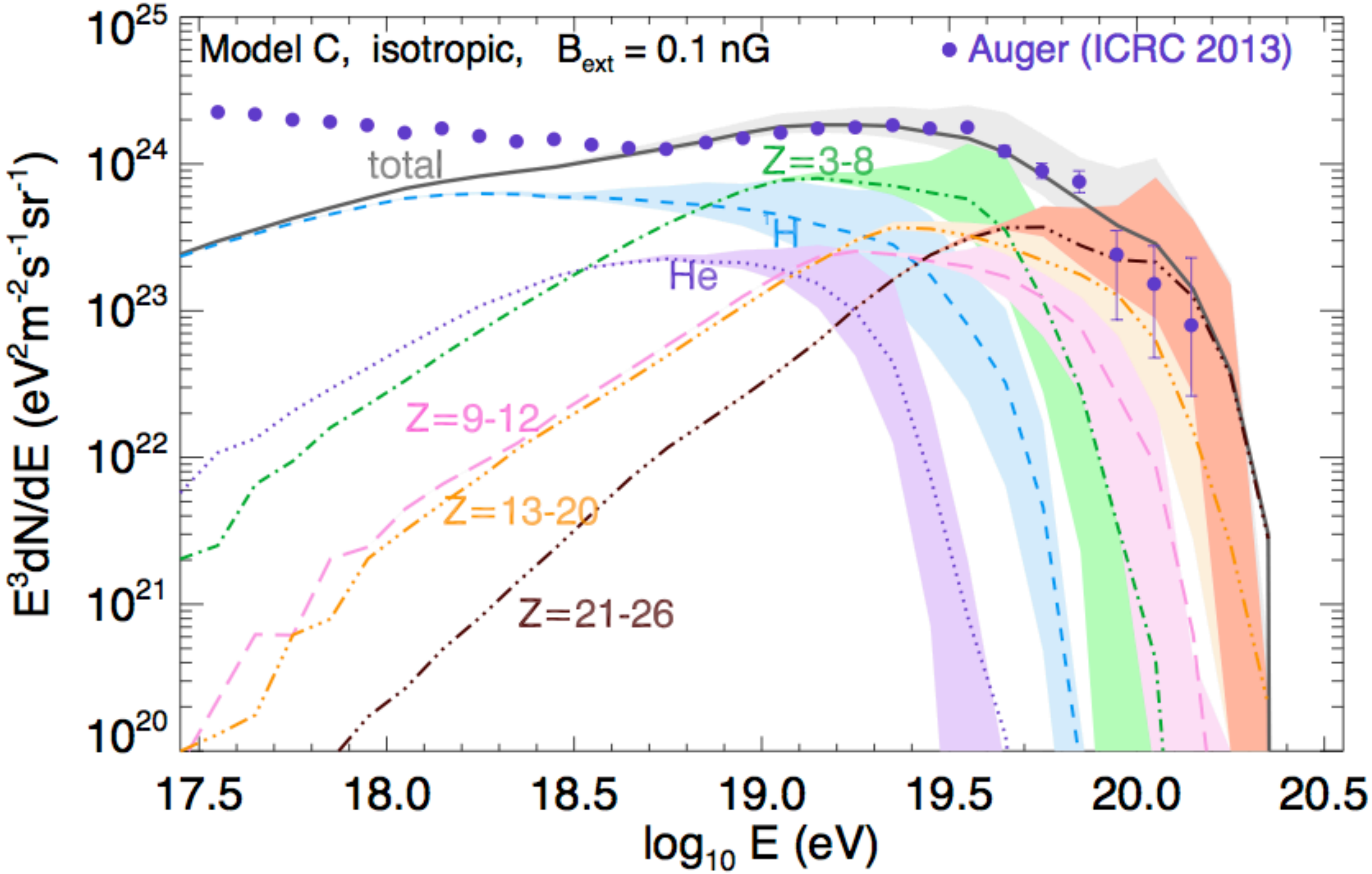
Phenomenological model : implications for the GCR to EGCR transition

The difference in shape between the proton and nuclei spectra arises from the fact that the source environment is strongly magnetized and harbours dense radiation fields

—> should not be a distinctive feature of GRB sources

An extragalactic component presenting these spectral features is able to account for the light ankle and the evolution of the composition measured by Auger

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

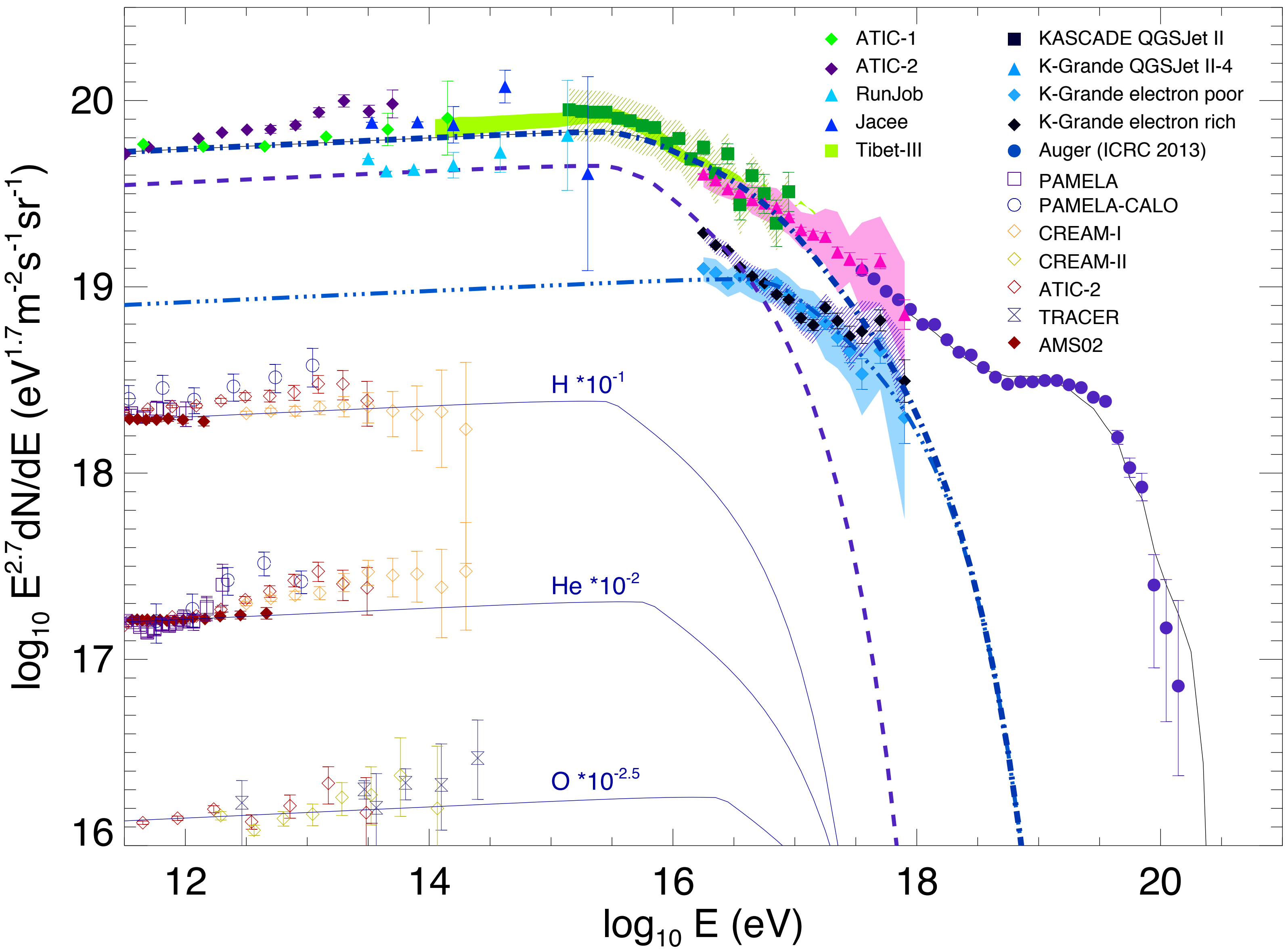


Galactic component

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

==> we assume the same broken power laws (index x) for the different species (break at the respective knees)

We normalize the different components 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})

Globus et al. 2015, PRD rapid com.

Galactic + extragalactic components

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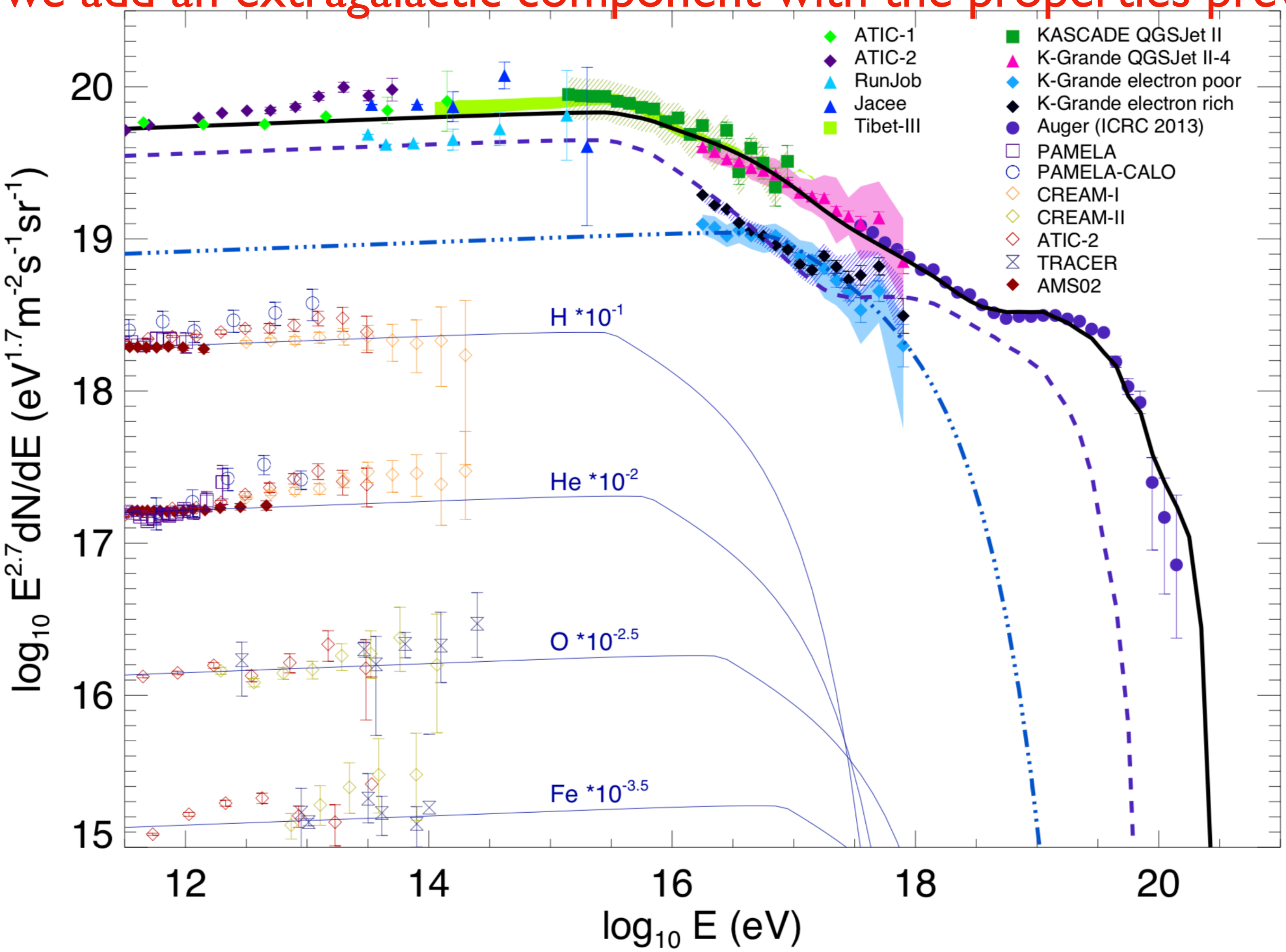
+ we add an extragalactic component with the properties previously discussed



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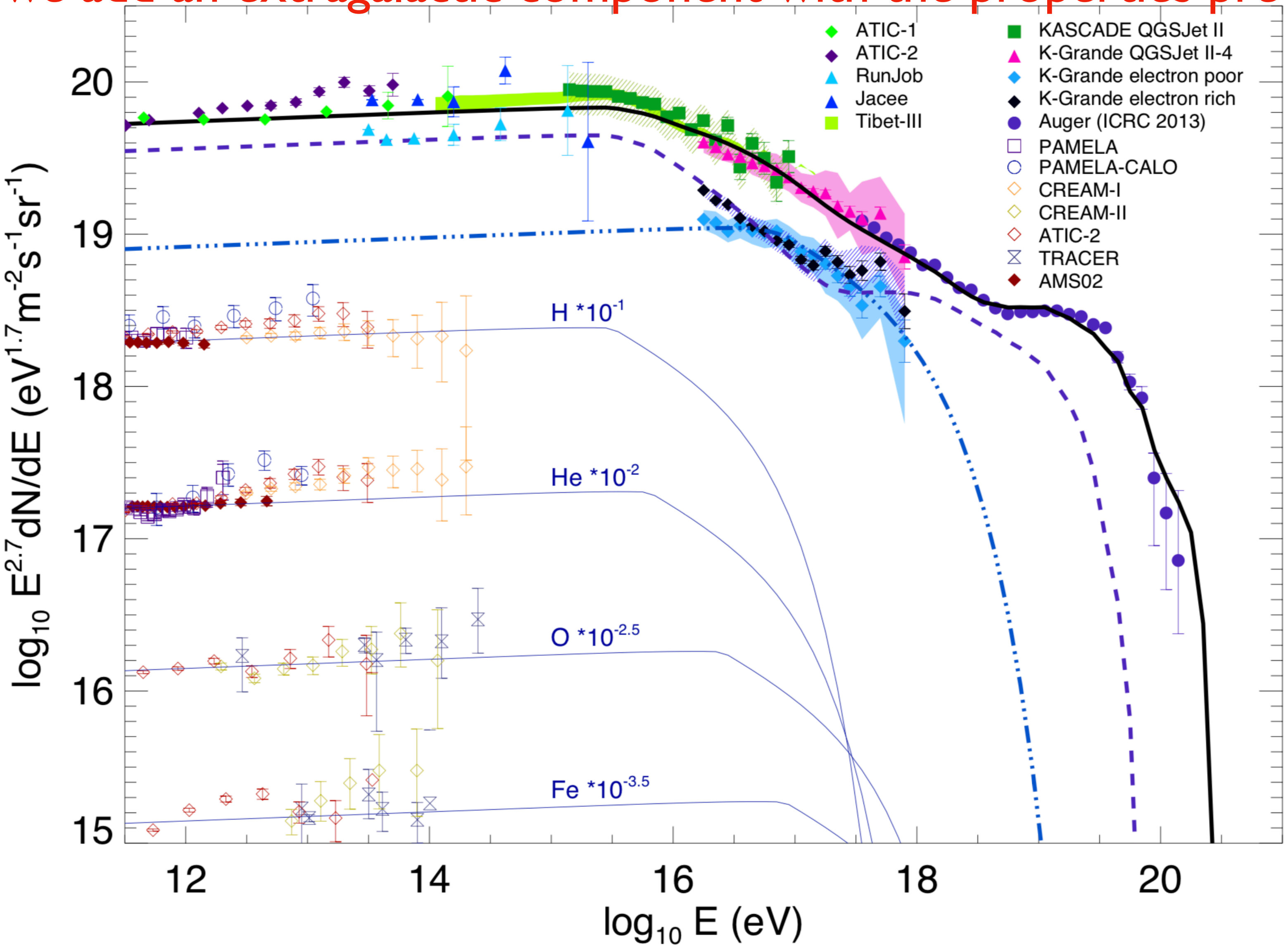

Good reproduction of the light ankle, the ankle and the composition trend found in Auger data

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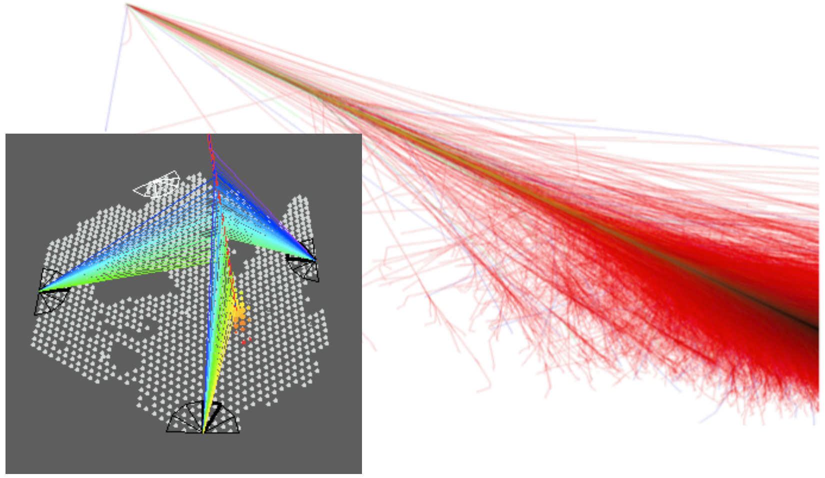
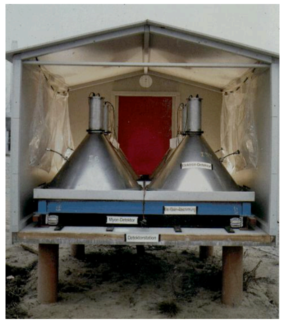
Outline



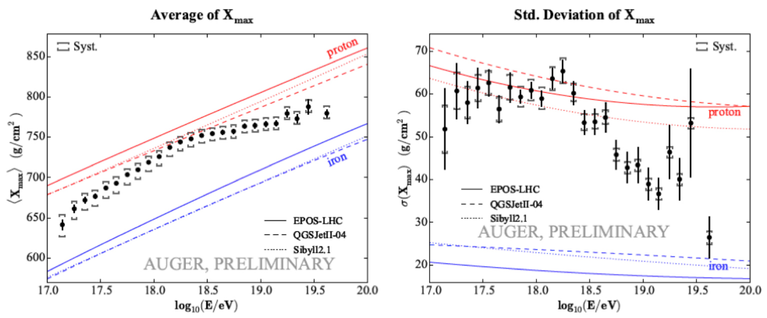


❖ Indirect detection of cosmic-rays, a brief introduction
- A few facts about air showers
- Detection techniques (ground arrays and fluorescence detectors)
- More emphasis on KASCADE and the Pierre Auger Observatory

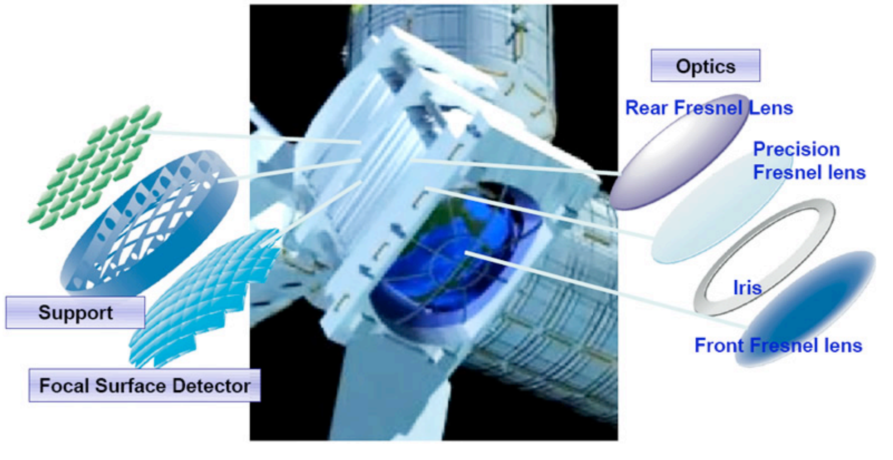
❖ A closer look to the cosmic-ray spectrum
- The knee and the ankle

❖ Hints from extragalactic cosmic-rays phenomenology
- Propagation of protons and nuclei

❖ Key results obtained in the last few years and their possible interpretation
- KASCADE-Grande's heavy knee and light ankle
- Auger composition results
- possible interpretations



❖ **Can a consistant picture emerge?**
- **Still a few stones in the shoe…**



❖ A few key future experiments

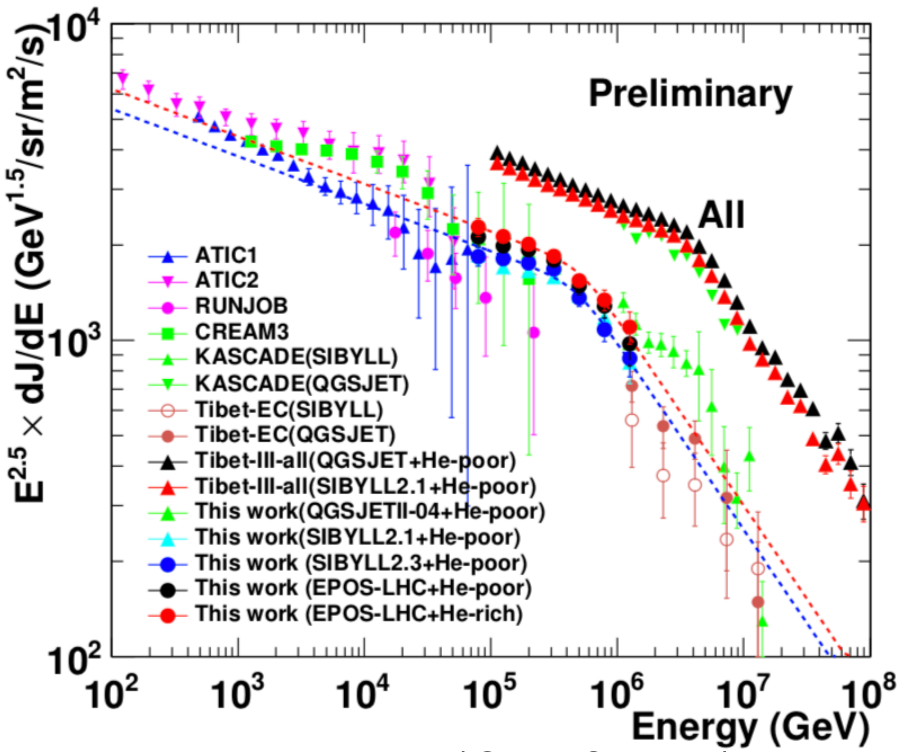
A few stones in the shoe…

- A lot of caution is required since there is a claimed discrepancy between the predictions of hadronic models and the observed properties of air showers with multi-component detectors
—> in particular in Auger and KASCADE data
(possibly not dramatic, but currently prevents making solid statements about relative abundances of particular elements or even group of elements)

- Sometimes very different interpretations from different experiments
—> Recent examples

Auger Vs Telescope Array (at the highest energies)

Tibet Vs IceCube/IceTop (at the knee)

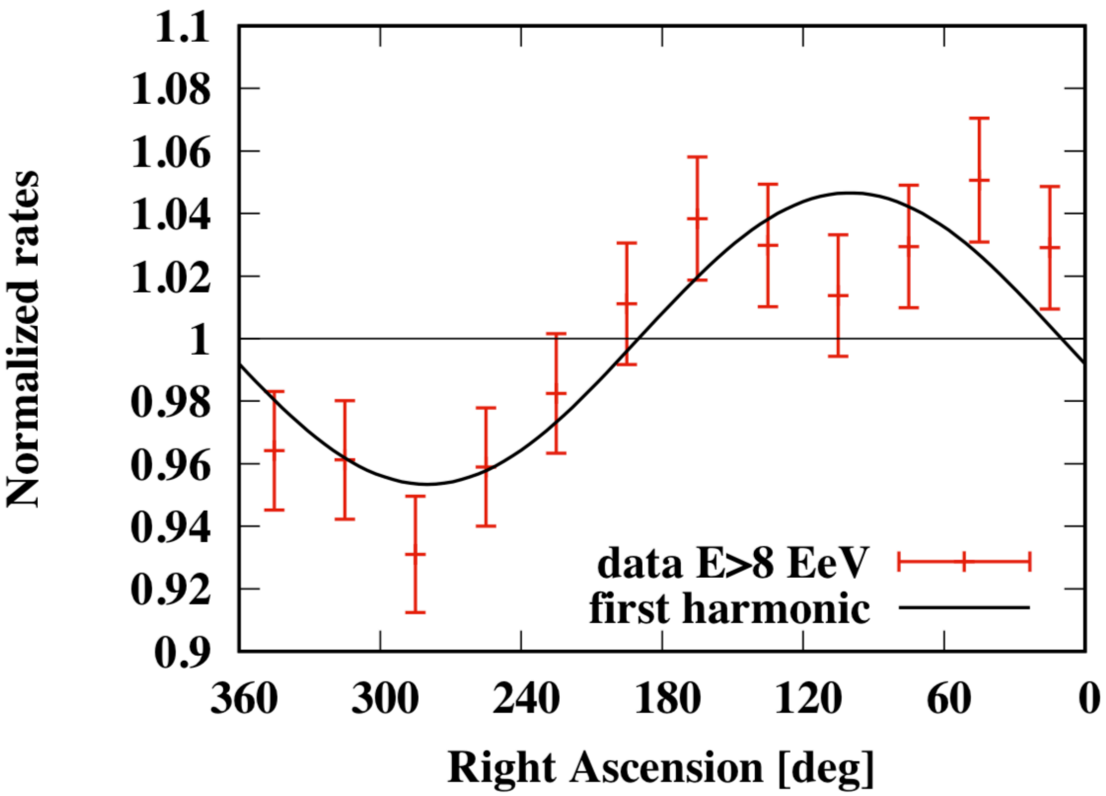


Tibet collab, 2019 (ISVHECR2018)

While IceCube/IceTop most recent study (PhysRevD2019) supports the dominance of H and He at the knee, latest results from Tibet go in a radically different direction : P+He knee around 400 TeV and P+He abundance <30% at the knee (which is thus caused by other elements)

Are the highest energy cosmic-rays really extragalactic?

Auger collab, Science 357 (22 September 2017) 1266, arXiv:1709.07321



Energy [EeV]	Number of events	Fourier coefficient a_α	Fourier coefficient b_α	Amplitude r_α	Phase φ_α [°]	Probability $P(\geq r_\alpha)$
4 to 8	81,701	0.001 ± 0.005	0.005 ± 0.005	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
≥ 8	32,187	-0.008 ± 0.008	0.046 ± 0.008	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

Dipolar modulation in right ascension above 8 EeV, isotropy rejected at 5.2 σ after penalization
Nothing significant below this energy
no significant higher order multipole

Energy [EeV]	Dipole component d_z	Dipole component $d_\perp$	Dipole amplitude d	Dipole declination δ_d [°]	Dipole right ascension α_d [°]
8	-0.026 ± 0.015	$0.060^{+0.011}_{-0.010}$	$0.065^{+0.013}_{-0.009}$	-24^{+12}_{-13}	100 ± 10

observed dipole: (l, b) = (233°,-13°)

—> far from the Galactic center —> disfavour a Galactic origin of the dipole signal

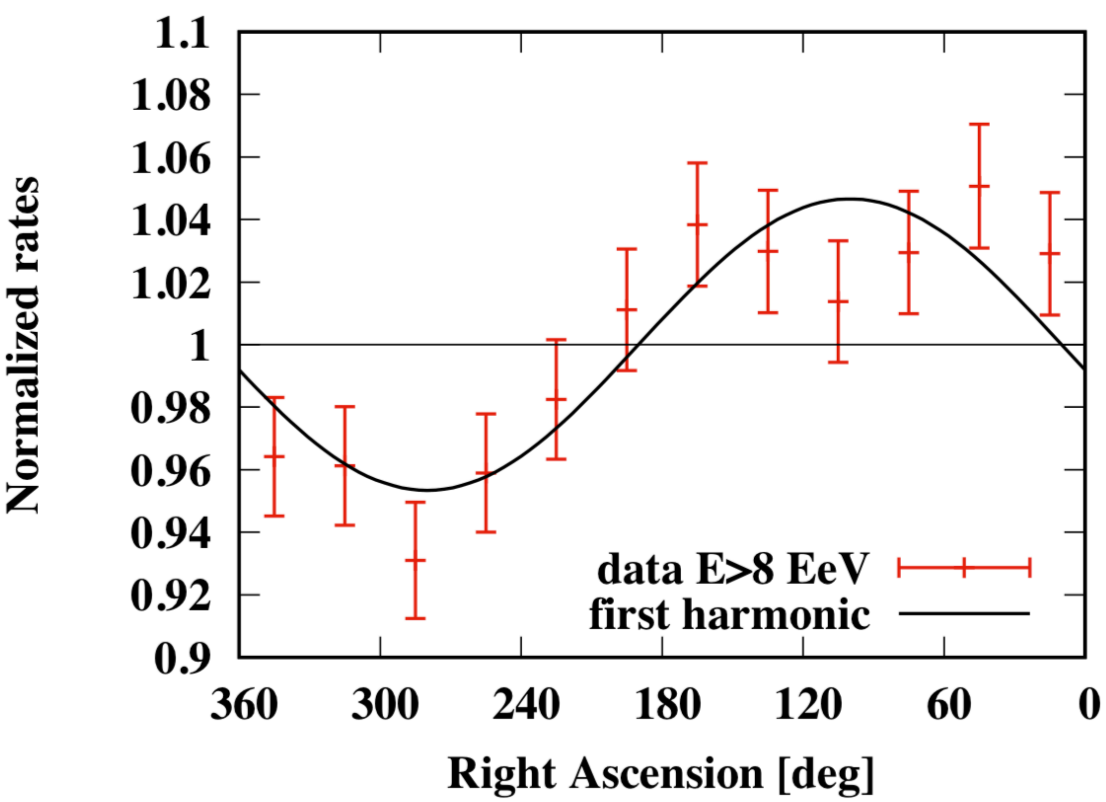
—> but probably does not prove by itself that cosmic-rays in this energy range are purely extragalactic

—> what is the origin of the dipole? source distribution? contribution of a dominant source?

—> first anisotropy study to pass the 5σ discovery threshold, certainly a milestone in UHECR observation history but it does not answer many questions

Anisotropies : discovery of a large scale anisotropy above 8 EeV

Auger collab, Science 357 (22 September 2017) 1266, arXiv:1709.07321



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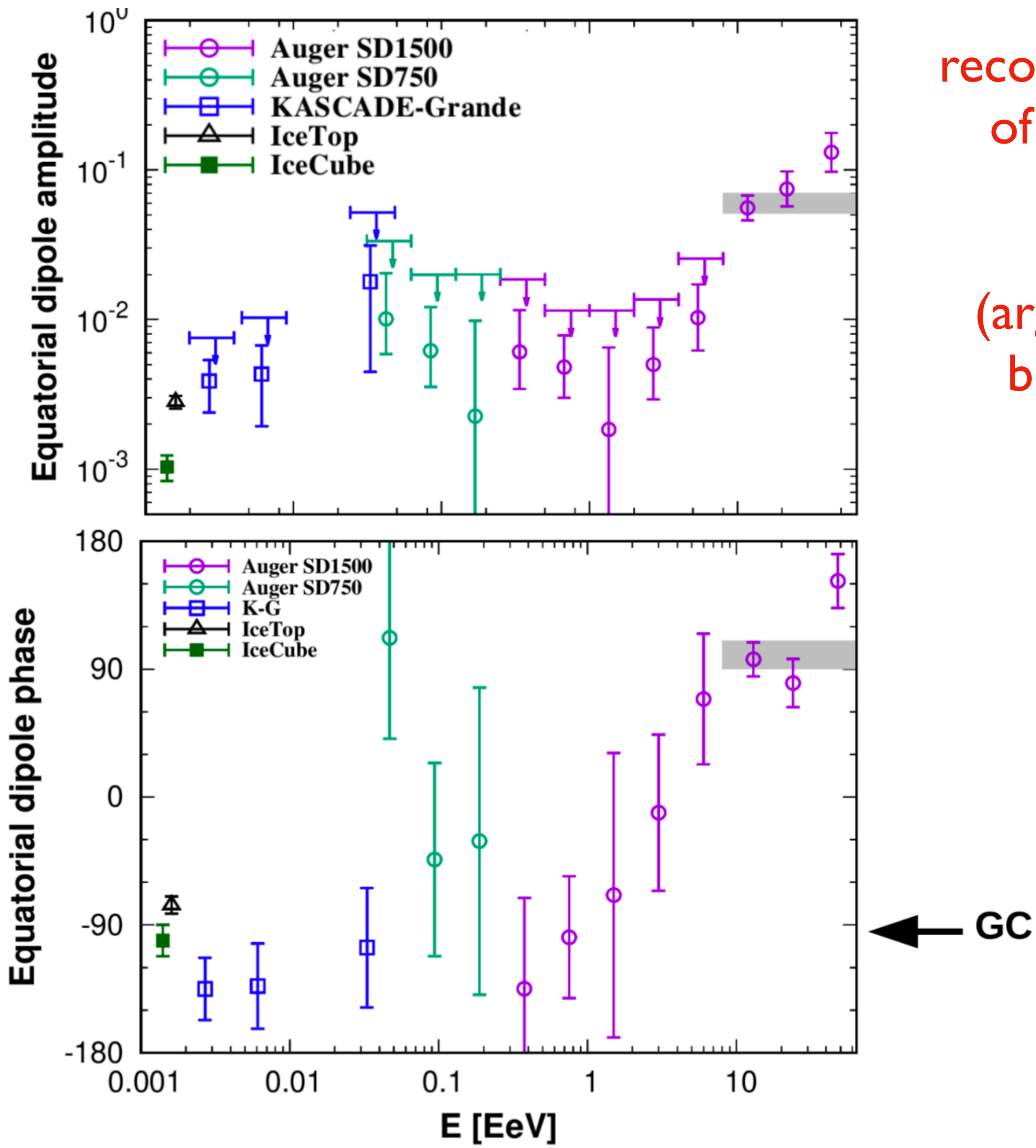
Anisotropies : discovery of a large scale anisotropy above 8 EeV

Taken from Esteban Roulet's talk at ICRC 2019
(Auger collaboration)

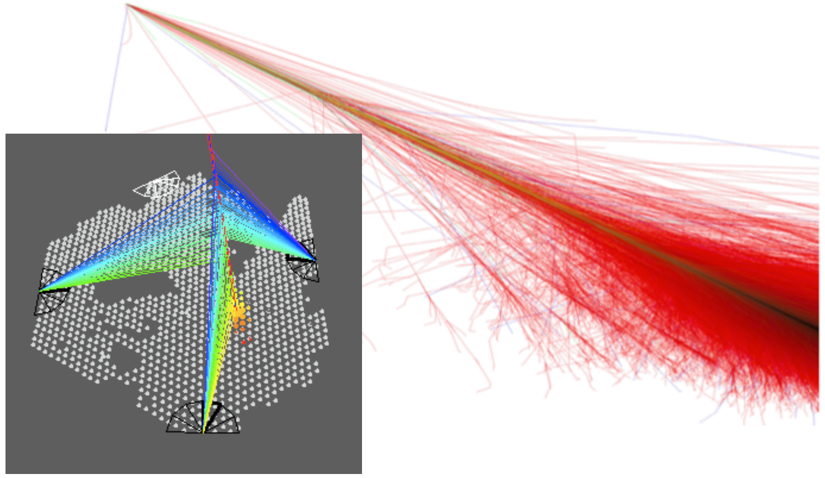


Argument given :
reconstructed dipole with a right ascension close to that of the galactic center at low energy (below 10^{18} eV) moving away from it as energy increases
—> transition toward and extragalactic origin
(argument would be stronger if the dipoles measured between a few PeV and 8.10^{18} eV were significant)

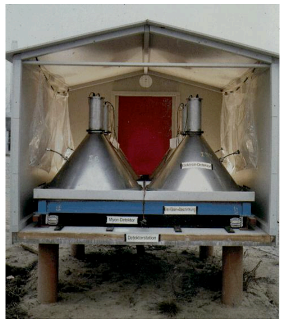
Other possible hints of intermediate scales anisotropies (20 to 30 degrees "warm spots") at the highest energies (~40 to 50 EeV) are claimed by Auger and TA
—> Auger, in a region of the sky close to CenA
+ hint of a correlation with a SFG catalogue
(see results for ICRC 2019 and 2018ApJ, 853L29A)
—> TA in the Ursa Major region (Abbasi et al., ApJ Letters, 2014)

—> Not at the 5σ level yet but would be an important argument in favor of an extragalactic origin if confirmed

Outline



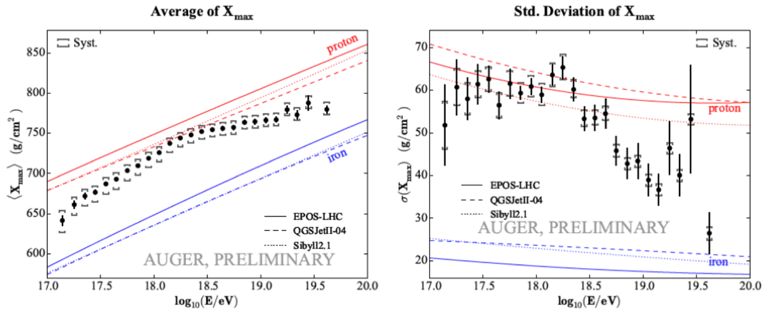
- ❖ Indirect detection of cosmic-rays, a brief introduction
  - – A few facts about air showers
  - – Detection techniques (ground arrays and fluorescence detectors)
  - – More emphasis on KASCADE and the Pierre Auger Observatory



- ❖ A closer look to the cosmic-ray spectrum
  - - The knee and the ankle

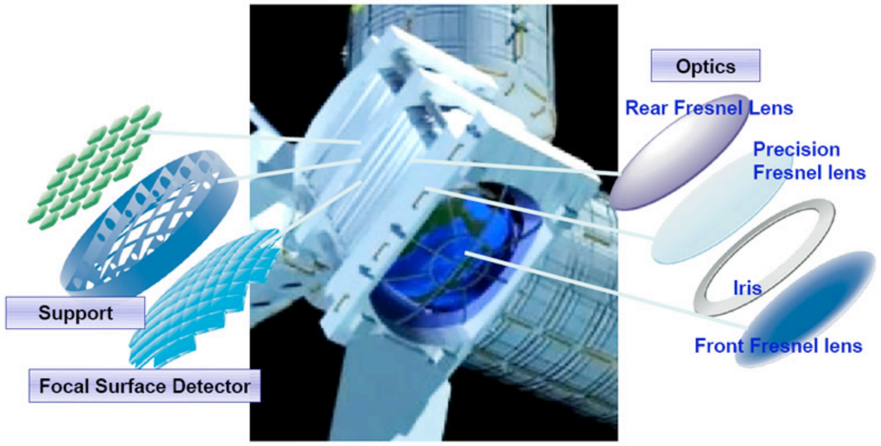
- ❖ Hints from extragalactic cosmic-rays phenomenology
  - - Propagation of protons and nuclei

- ❖ Key results obtained in the last few years and their possible interpretation
  - - KASCADE-Grande's heavy knee and light ankle
  - - Auger composition results
  - - possible interpretations



- ❖ Can a consistant picture emerge?
  - - Still a few stones in the shoe…

- ❖ **A few key future experiments**



The future in the knee region and beyond : LHAASO

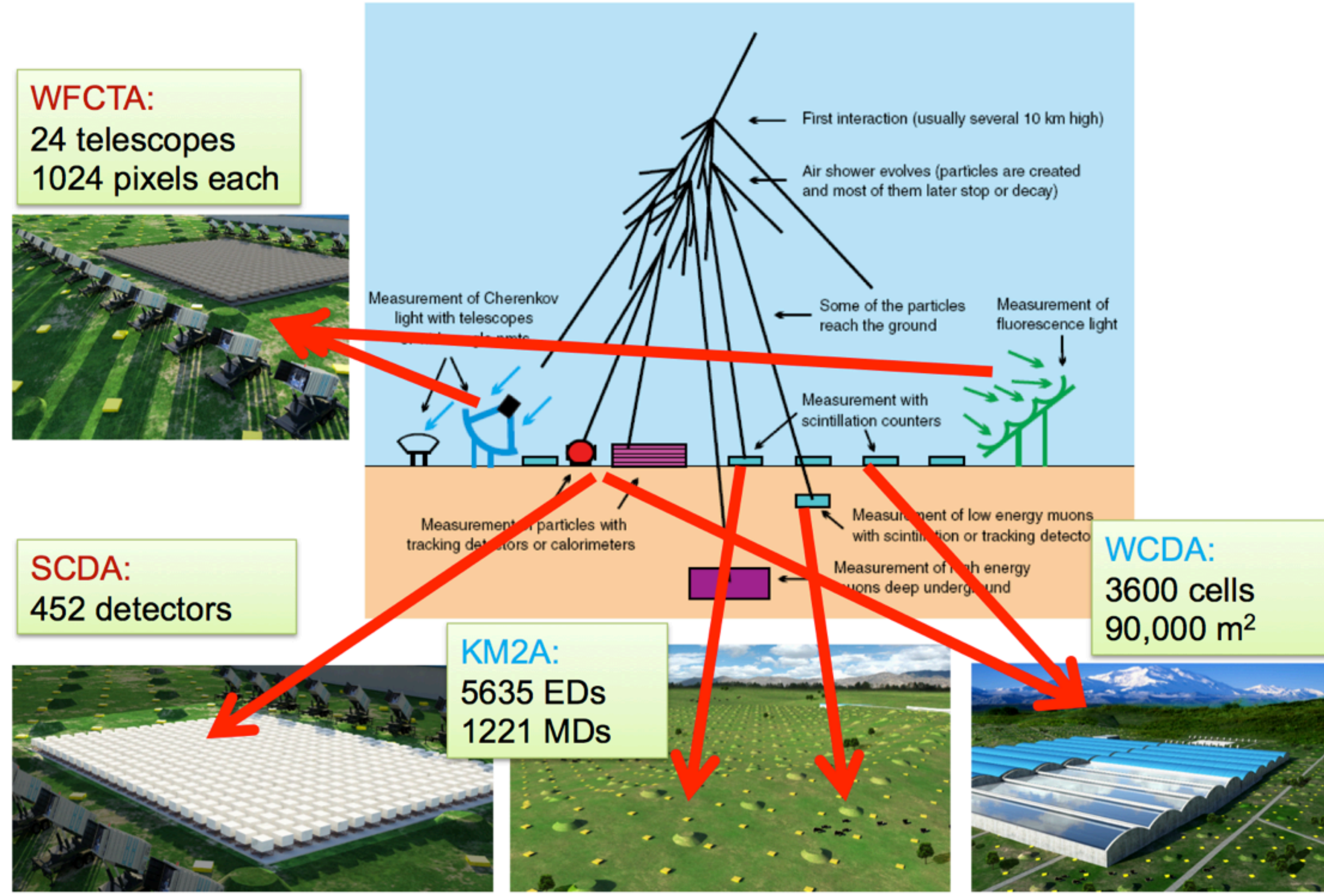
Hybrid (multidetector) VHE cosmic-ray and gamma-ray observatory to be installed in the Sichuan province 4400 m a.s.l

High altitude + multidetector :

✳ very low energy threshold (30 TeV) ---> good overlap with direct measurements

✳ high resolution measurements of air showers particle content ---> sensitivity to the cosmic-ray mass

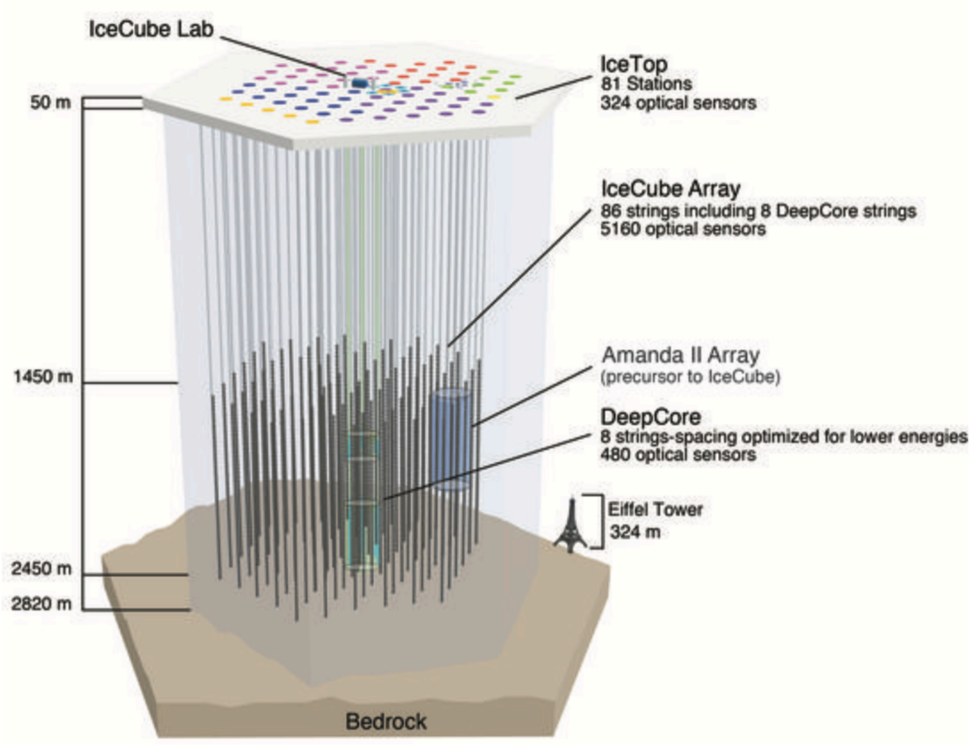
✳ MILAGRO-like gamma-ray detector (complementary to CTA above 30 TeV) ---> useful to search (multi-)Pevatrons

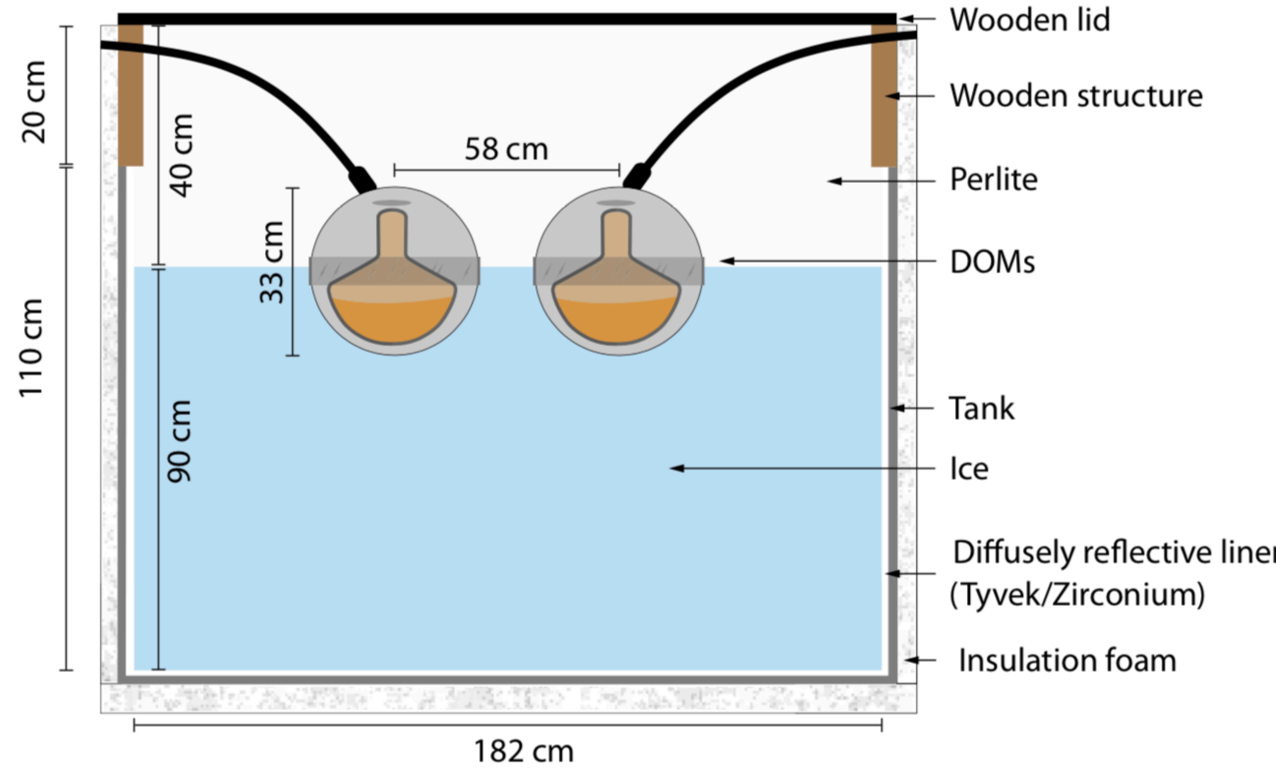


- Instrument almost completely funded by China
- Deployment ongoing

➡ Very interesting science case

The future in the knee region and beyond : IceTop/IceCube





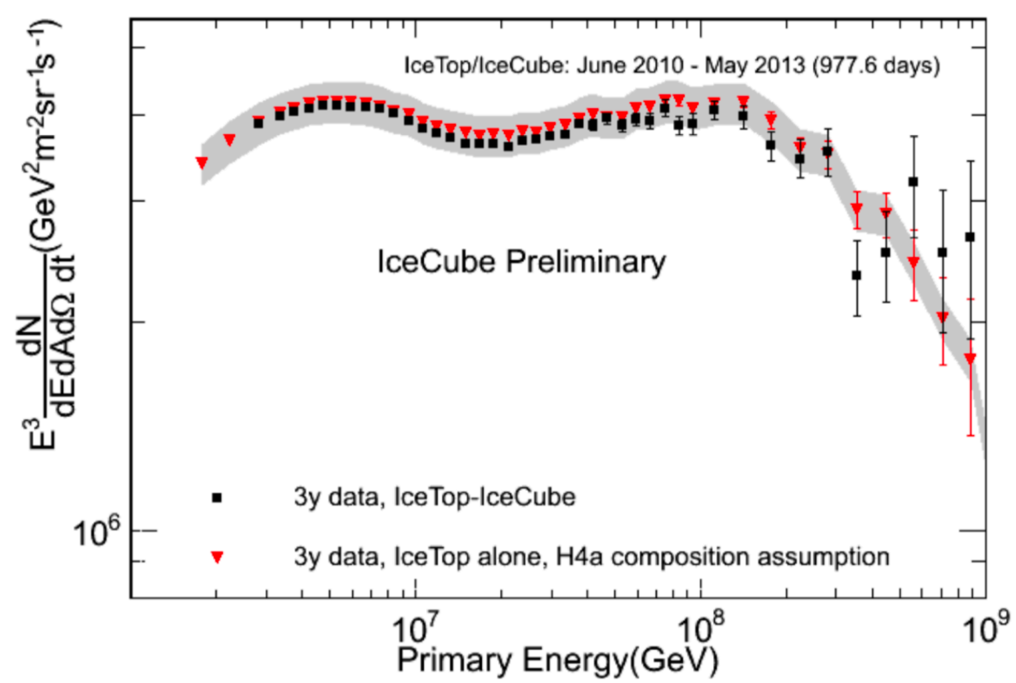
IceTop already in operation at the south pole

- Ice Cerenkov Tank
  —> charged particles content of air showers
- IceCube array
  —> very energetic muons (TeV)

—> sensitive to composition and air shower properties

—> larger array enhanced by scintillators for IceCube-Gen2

—> very large statistics and improved sensitivity to composition and shower properties expected



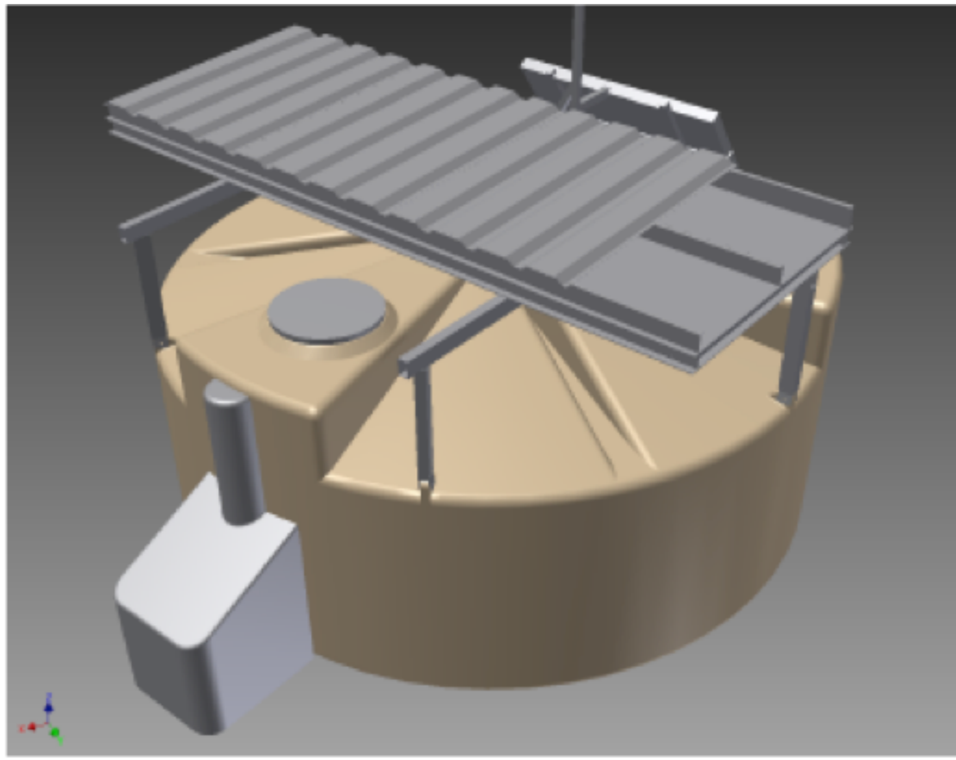
Short term future of Auger : “Auger Prime”

The Auger collaboration proposes a significant upgrade of their detectors for the period 2018-2025 of data taking :
- improved electronics for the surface detector faster ADCs
- larger dynamic-range PMTs (useful to avoid detector saturation)
- scintillator detectors on top of the water tanks

---> better separation of the muonic and electromagnetic components for the surface detector
---> better constrain of the muon content of air showers
---> better constrains on the composition for the surface detector
---> hope to better constrain/isolate the light component of UHECRs
---> improved sensitivity to photons and neutrinos

- increase of the FD duty cycle by 50% (by operating in brighter background sky conditions, switch the photodetectors to lower gains)

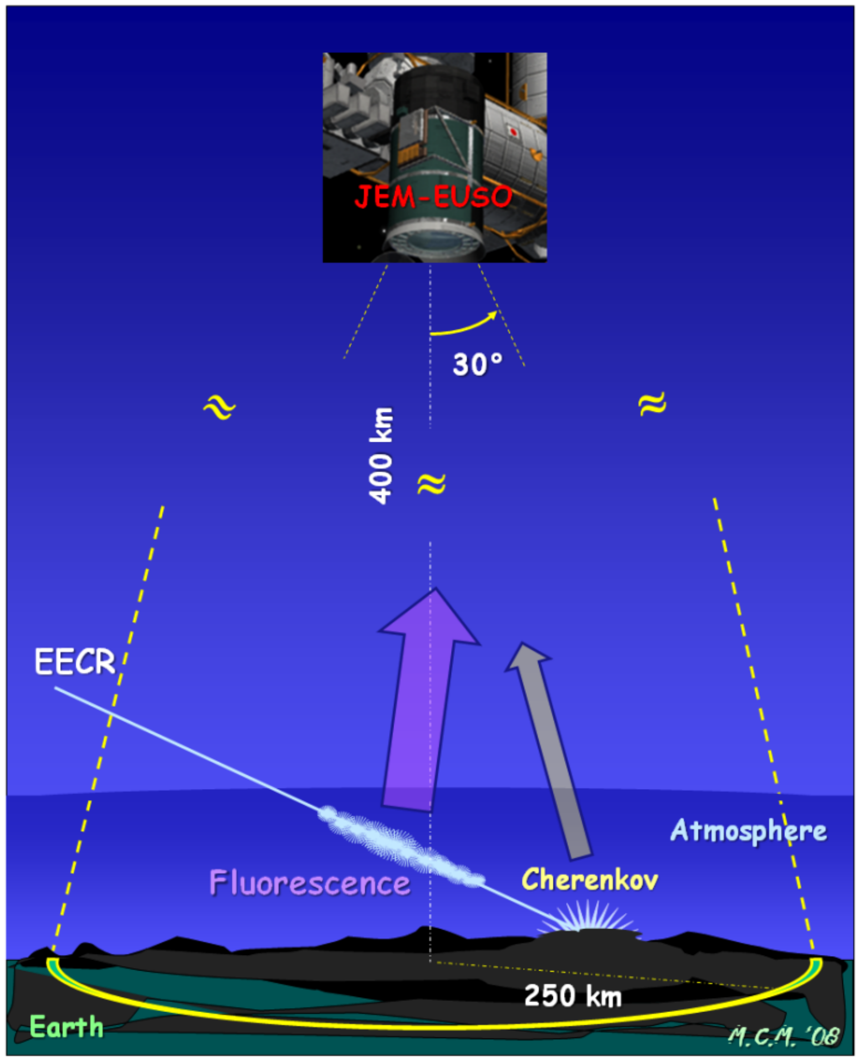
---> increase of the hybrid events statistics



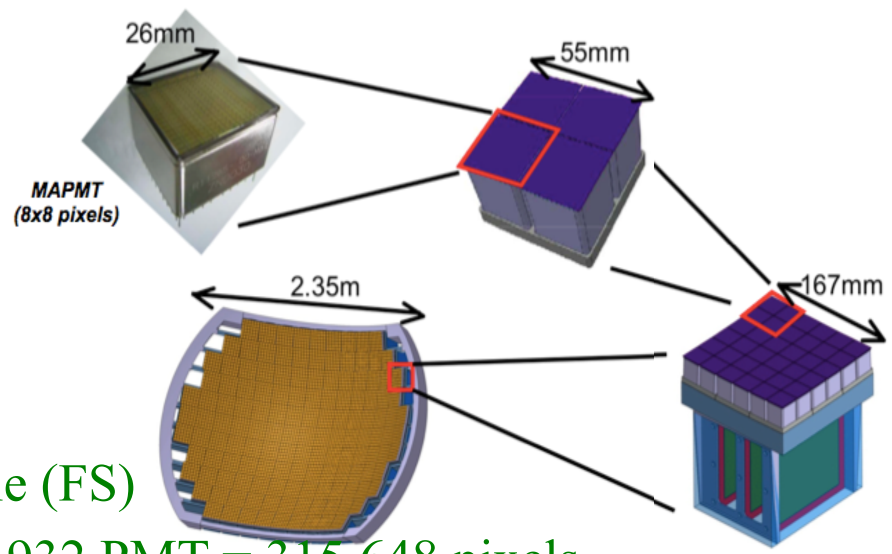
scintillators already installed in the infilled array
first light presented at the ICRC2017

Longer term future of UHECR observations : JEM-EUSO

Current statistics at UHE only give hints for the presence of anisotropies
--> these anisotropies are crucial to better constrain UHE origin, a significant increase of the statistics will be needed.
A milestone would be to approach exposures of the order of 10^6 km^2.sr.yr
Moreover full sky coverage is crucial
Detection from space is currently the only credible possibility to obtain both a significant increase of statistics and full sky coverage



The idea is to observe air showers from space :
- Telescope with 30 deg opening angle observing the earth from the ISS (400 km altitude)
---> huge area covered on the ground
---> drawback of the fluorescence technique ~19% duty cycle
---> still annual exposure ~10 times that of Auger above ~5.10^{19} eV in nadir mode
- need for a large Fresnel lens (2.5 m) to focus the faint shower fluorescence light on finely pixelized



Surface focale (FS)
137 PDM = 4932 PMT = 315 648 pixels