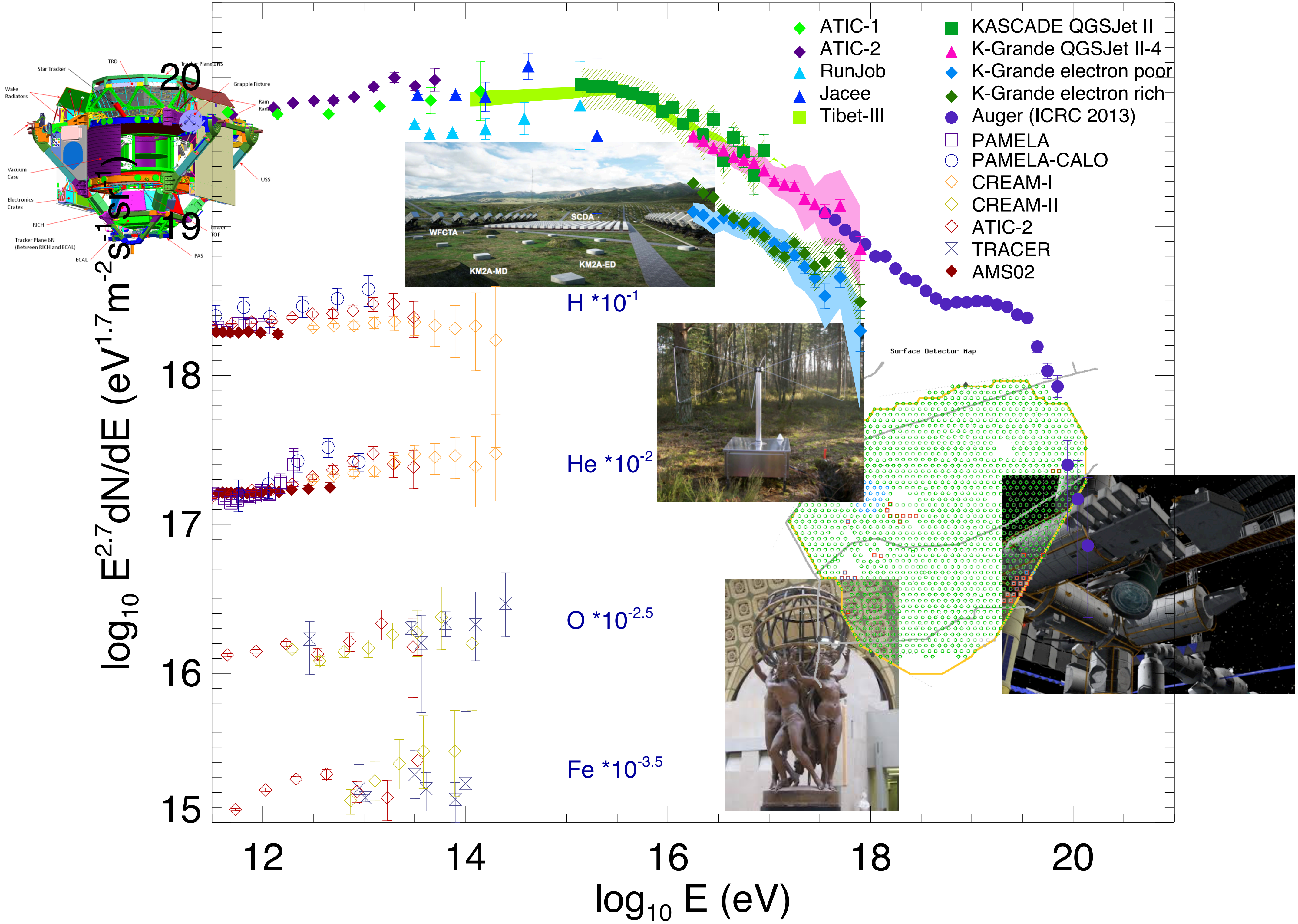
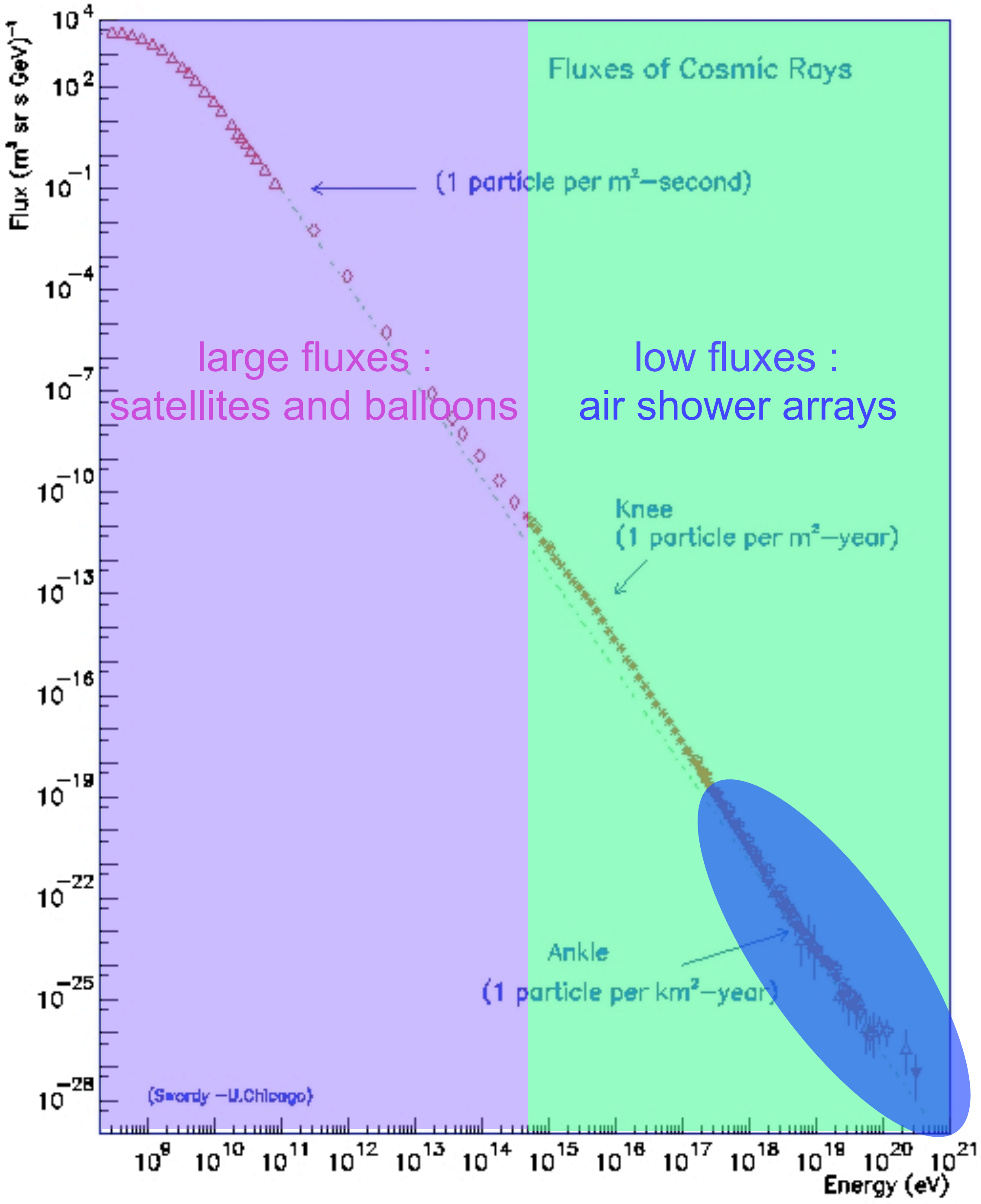
The physics of UHECRs

(focused on detection and extragalactic propagation)



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 (<$10^{13\text{-}14}$ 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 (~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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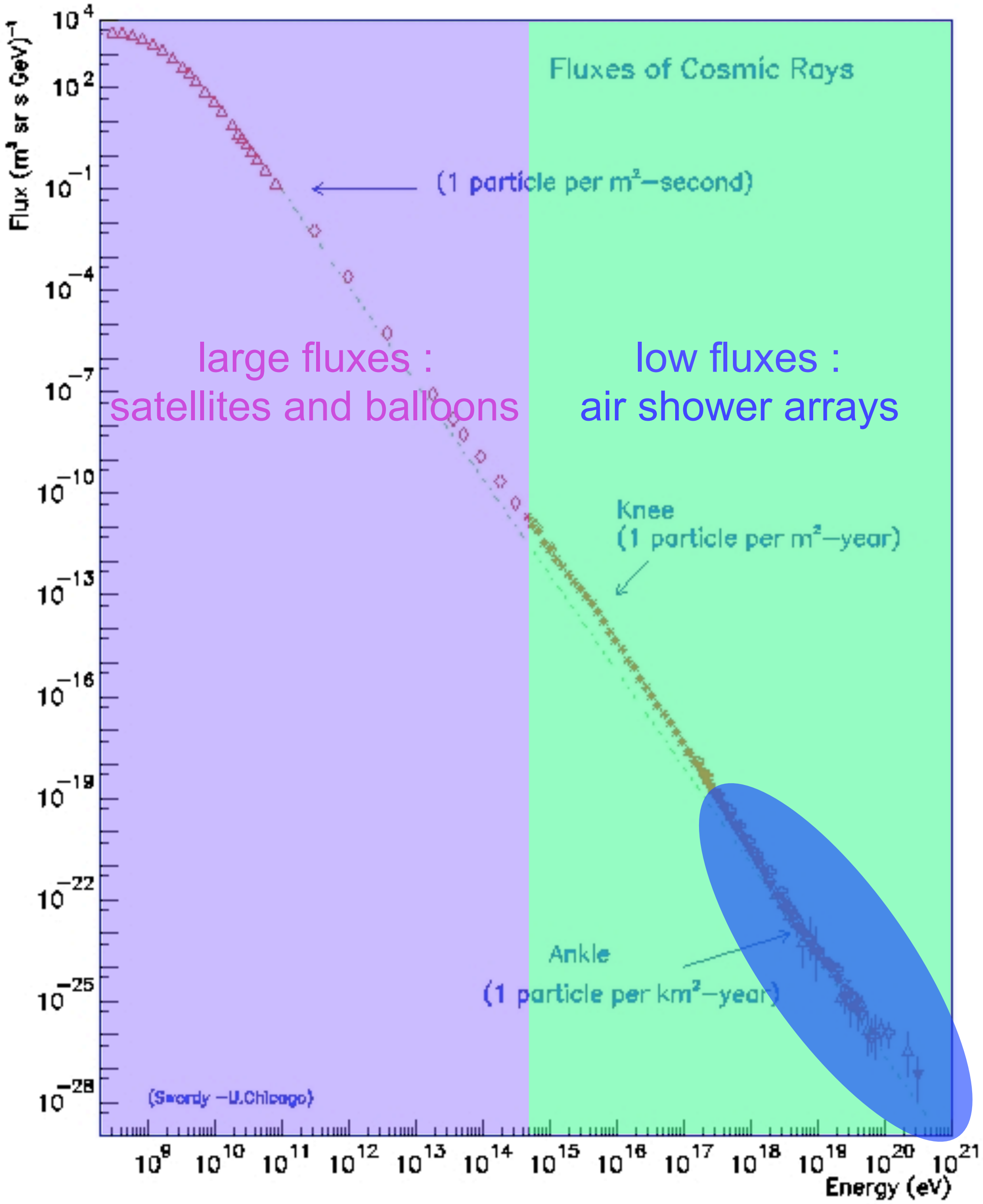

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NB : these particles are simply the most energetic particles known to exist in the universe

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

Angular spectrum

Arrival directions

2

Energy spectrum

Flux as a function of the energy

3

Mass spectrum

composition

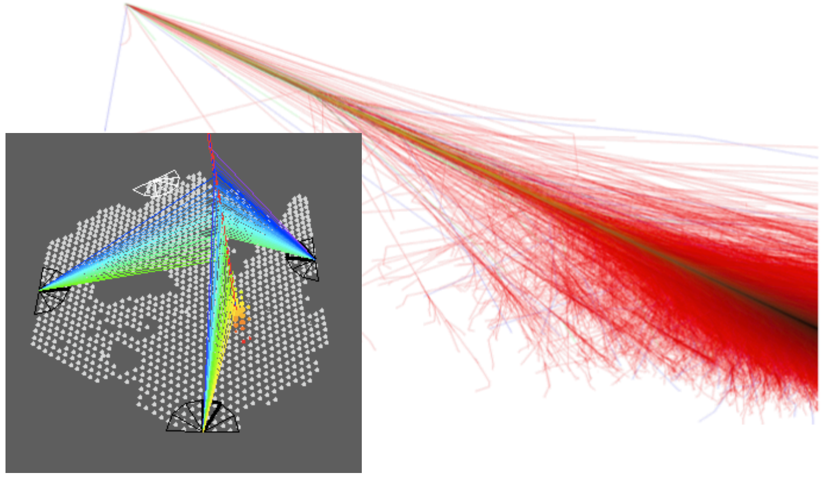
Outline

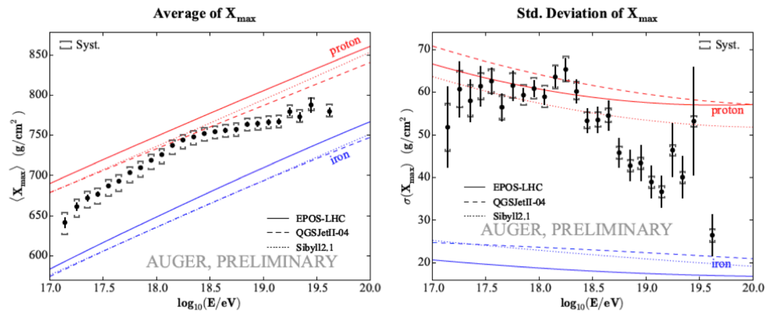
- Indirect detection of cosmic-rays, a brief introduction
  - Detection techniques (ground arrays and fluorescence detectors)

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

- Extragalactic cosmic-rays phenomenology
  - Propagation of protons and nuclei

- Key results obtained in the last few years and their possible interpretation
  - Auger composition results
  - Anisotropies
  - How does PANDORA fit in this picture?





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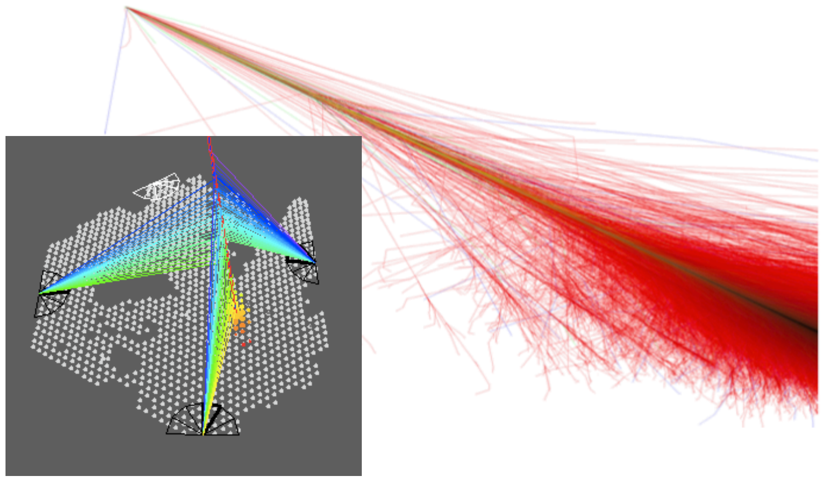

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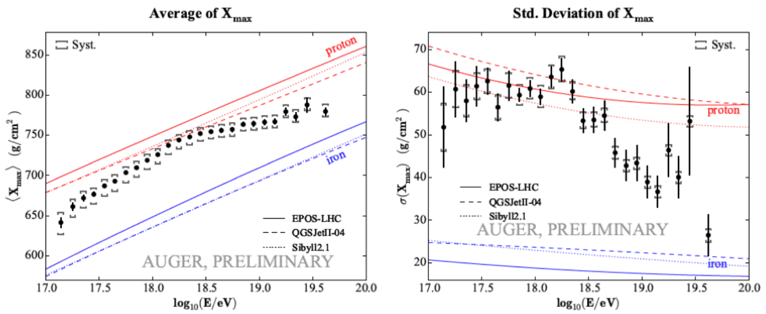
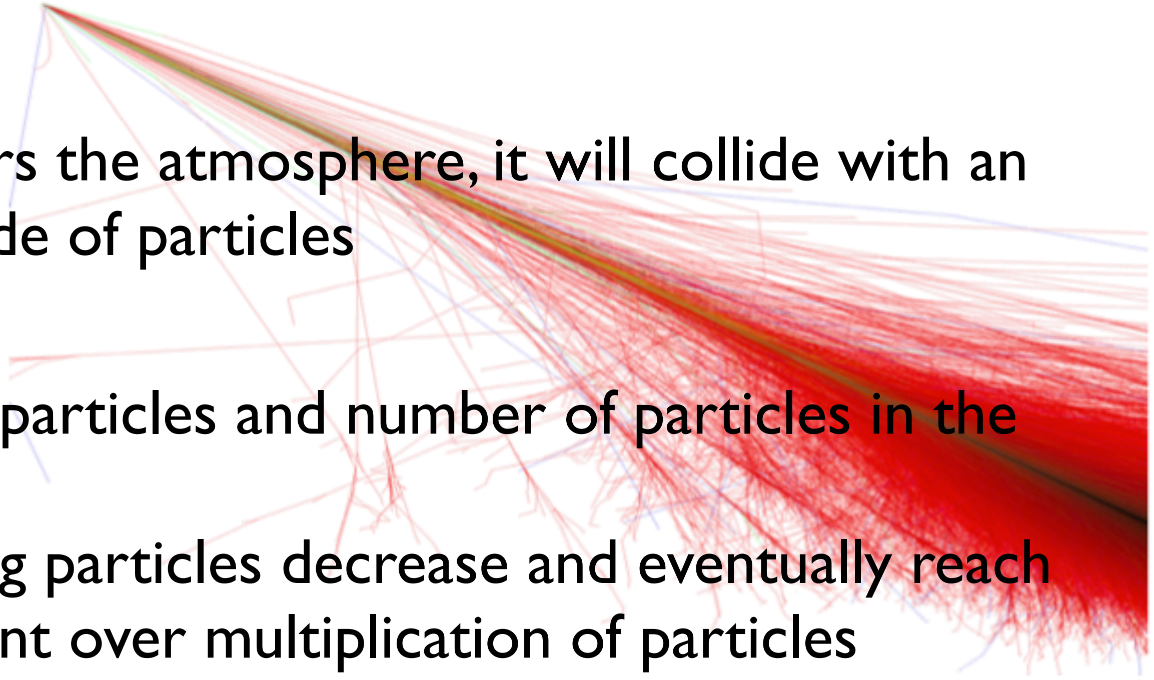


A few simple facts about air showers



- 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

- 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

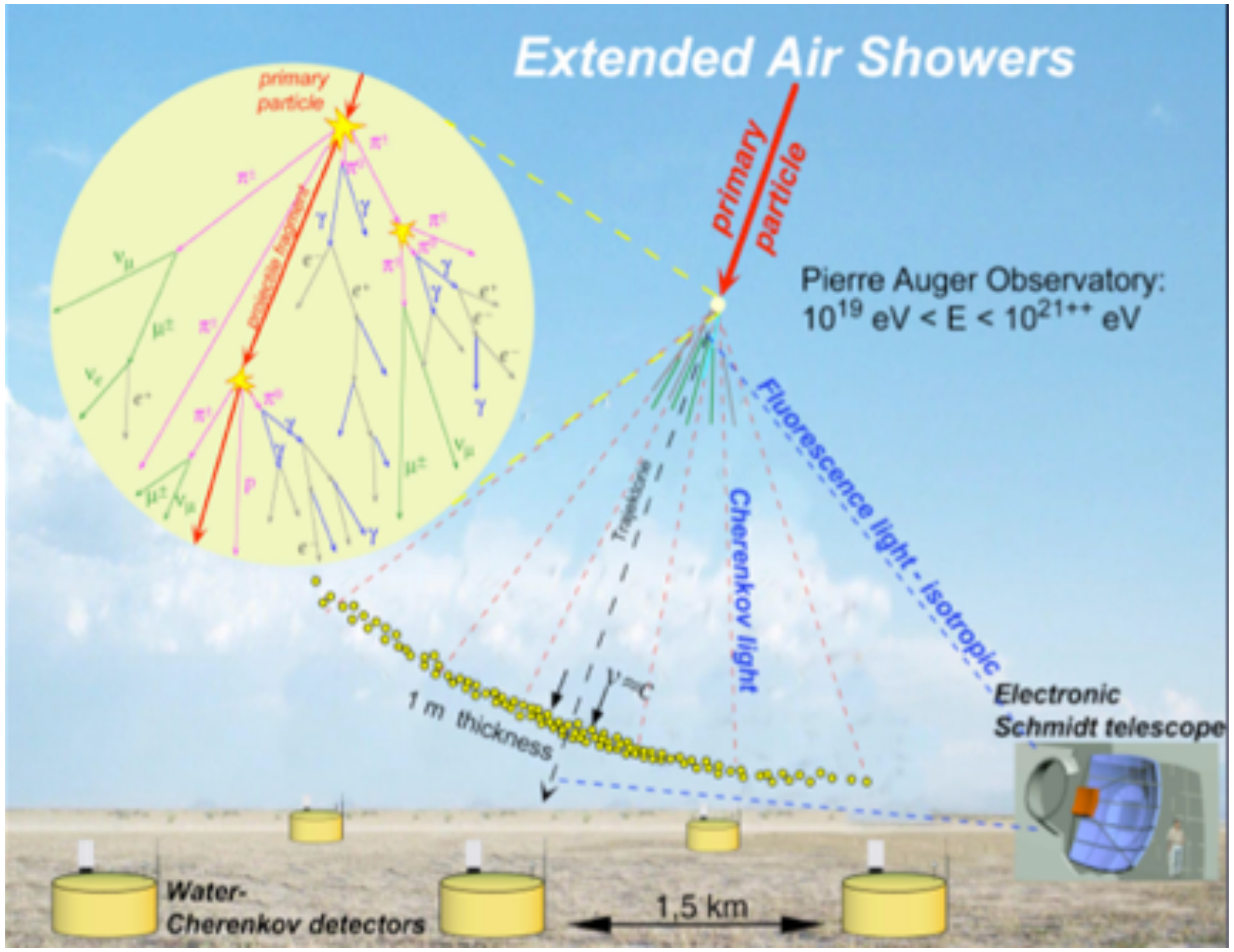
- at ground level (usually well beyond the shower maximum) the shower is mostly composed of γ, $e^{+/-}$ (electromagnetic component of the shower) and $\mu^{+/-}$ (hadronic component of the shower)

—> **by measuring the properties of air showers we aim at reconstructing/ estimating the energy, the direction and the nature of primary cosmic-ray**

Detection of VHE and UHE cosmic-rays

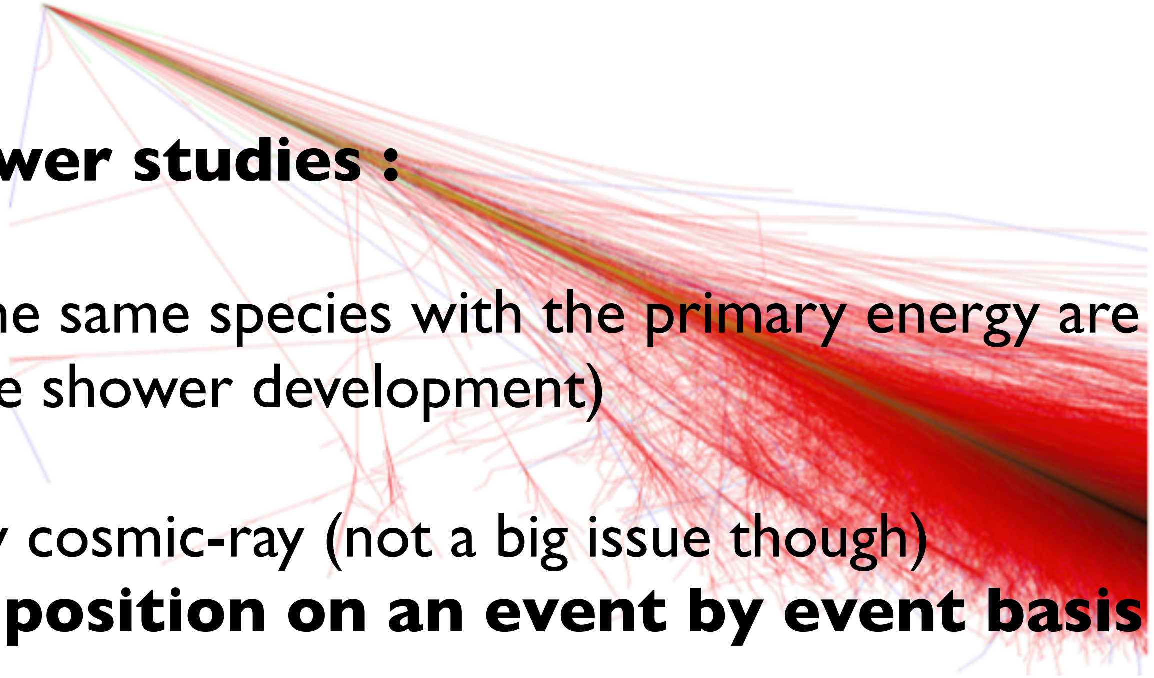
•At low energy cosmic-rays detected directly by satellites in space or balloons in the upper atmosphere —> very good energy, direction and mass reconstruction —> isotope separation is even possible

—> up to a few TeV at least, composition dominated by protons, then He and significant presence of heavier nuclei up to Fe (now clear evidence for energy dependent relative abundances but we won't discuss that…)



- 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

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
—> limits the resolution on the energy of the primary cosmic-ray (not a big issue though)
—> **“forbids” the determination of the composition on an event by event basis**

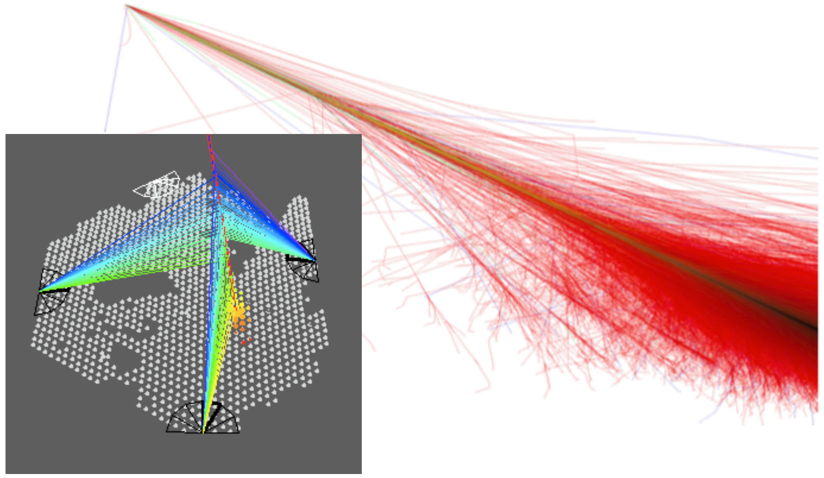
(ii) Part of the interactions taking place during an air shower development (especially at the first stages of VHE or UHE showers) are beyond the reach of artificial particles accelerators and thus poorly constrained

—> 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

Outline



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  - **- The knee and the ankle**

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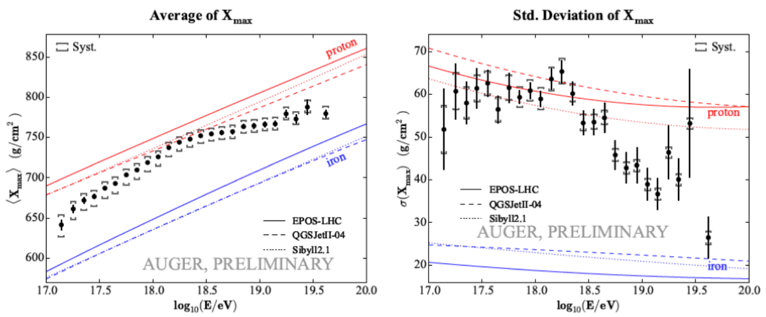
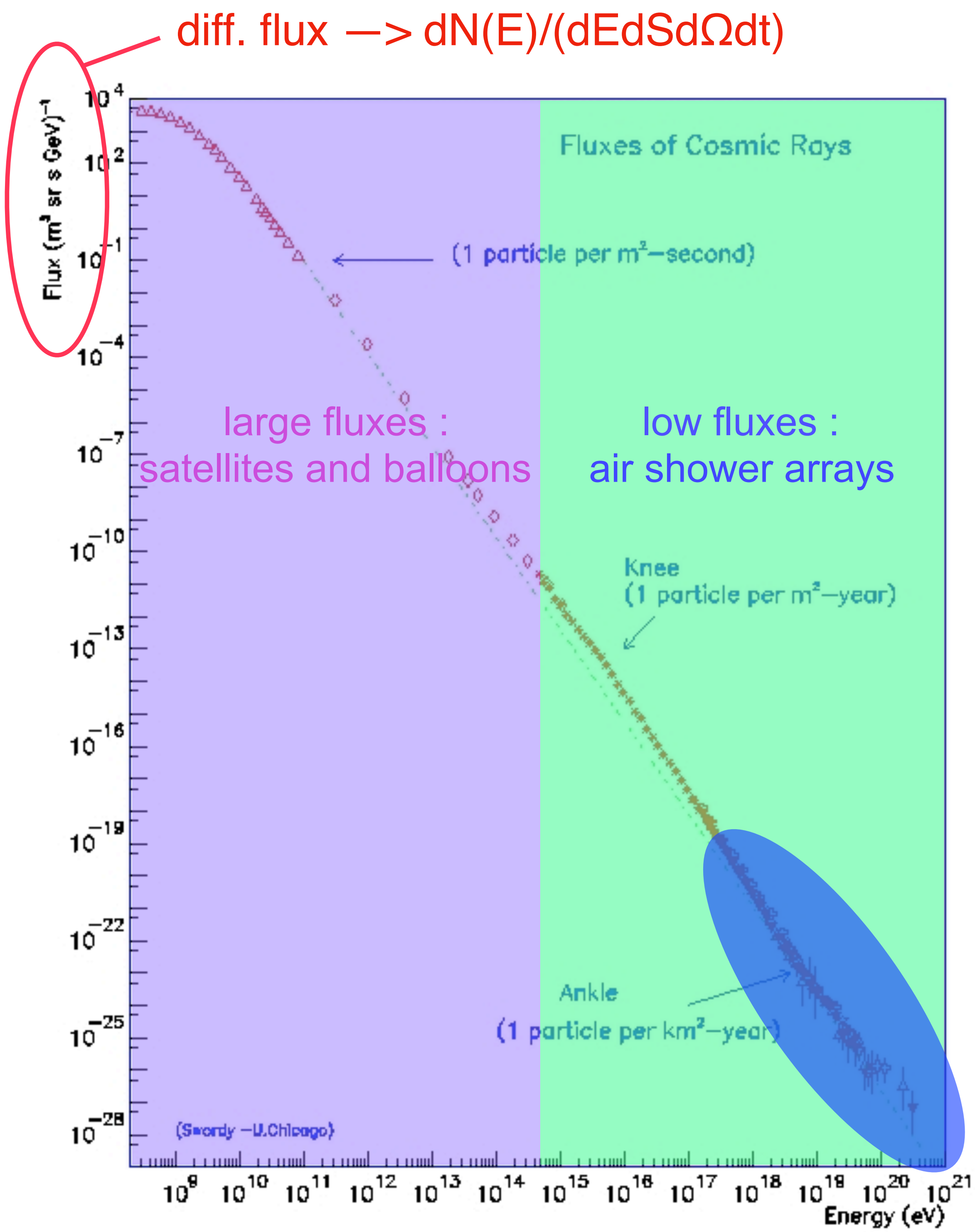
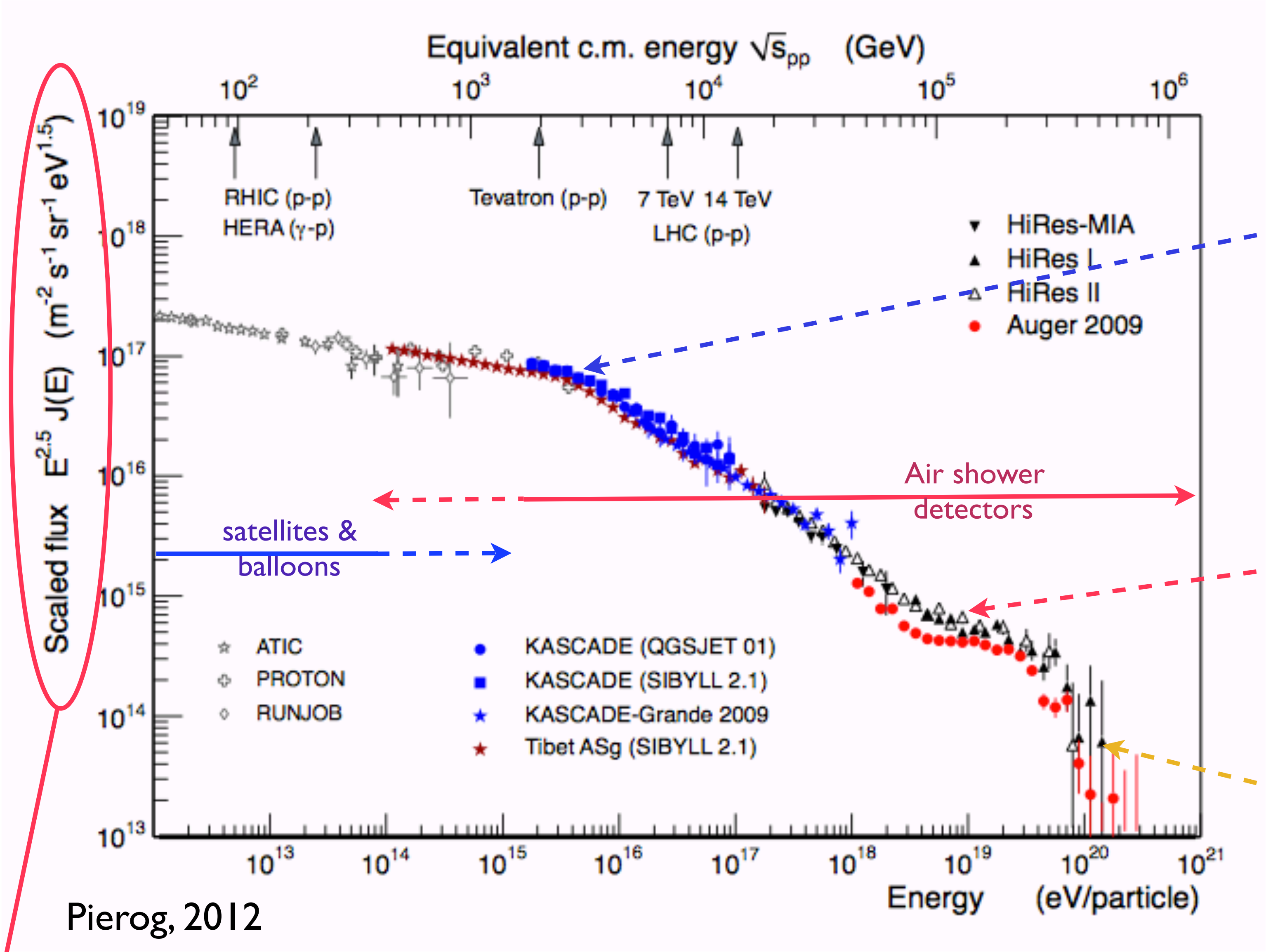


Let us come back to the cosmic-ray spectrum



Presented that way the CR spectrum looks almost featureless but…

Let us come back to the cosmic-ray spectrum



Pierog, 2012

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

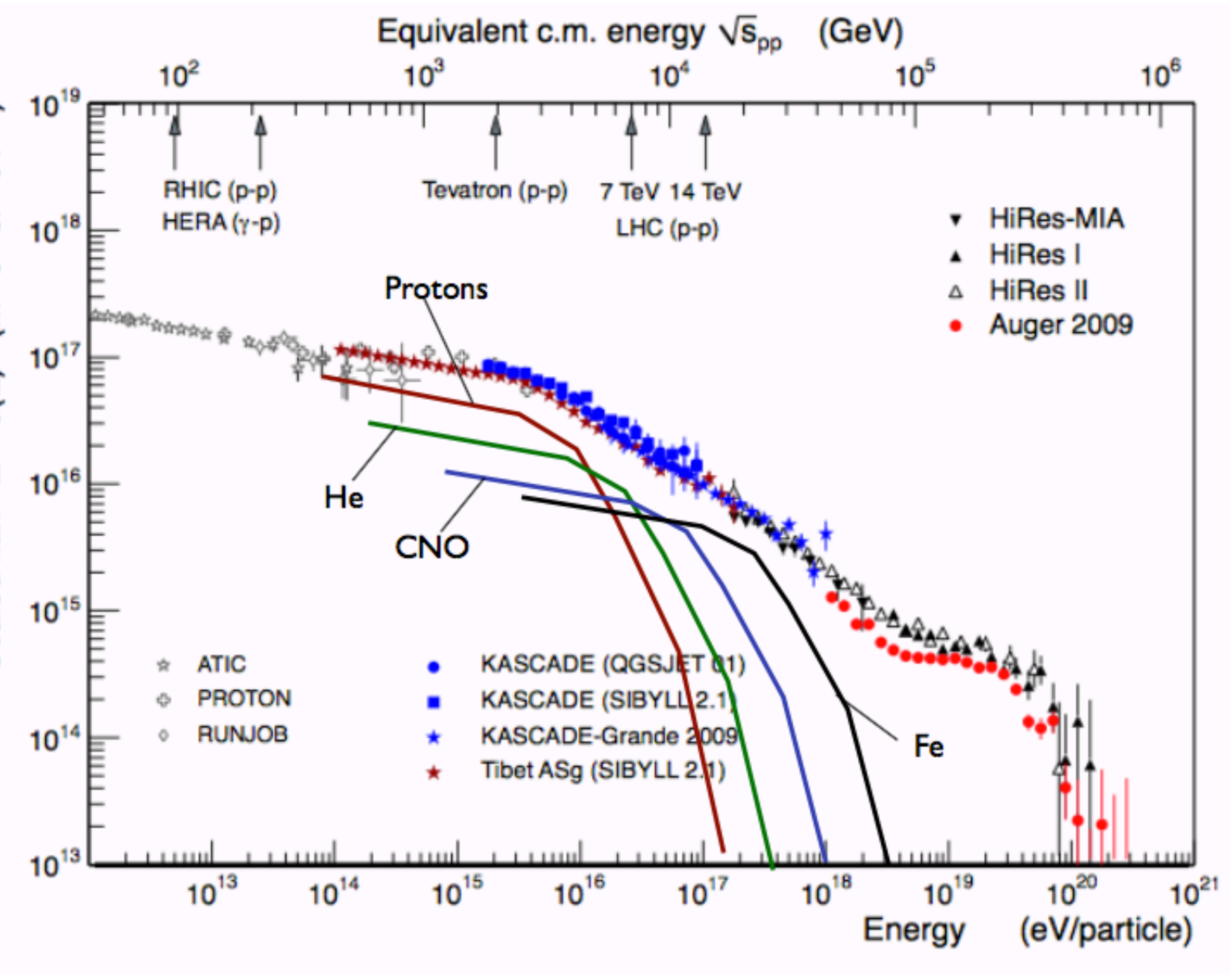
The ankle
E~3-4.10^{18} eV

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

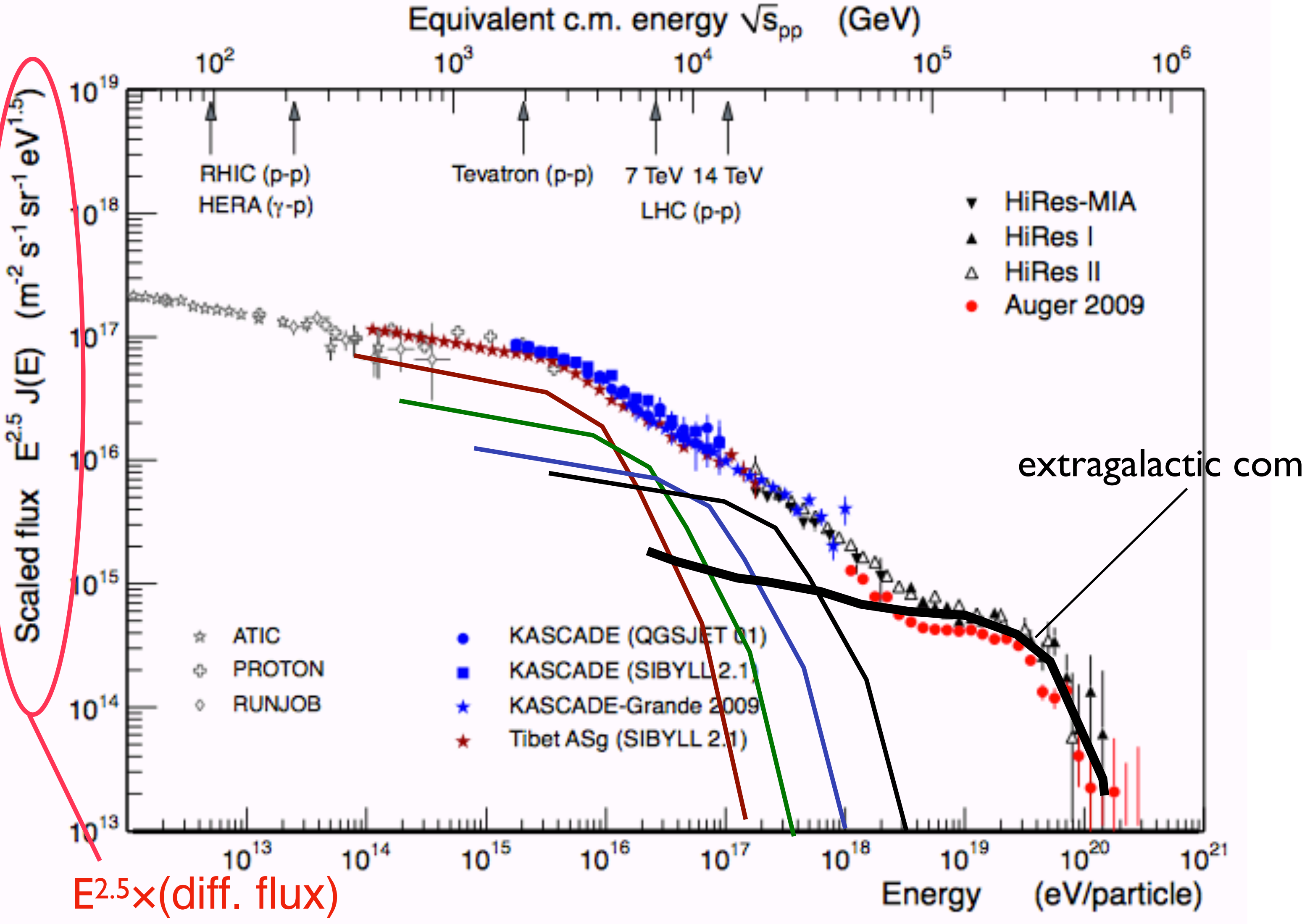


The knee first seen in the late 50's very soon suspected to be an inflection of the light galactic component

==> one expects the composition is getting heavier in the energy decade following the knee
==> indeed confirmed by most experiments including KASCADE

Most popular explanation :
The maximum energy/rigidity in Galactic accelerators is reached
==> in this case, the knees of the different species expected at energies proportional to their charge
(**consequence of cosmic-ray acceleration mechanisms and cosmic-ray confinement in the sources**)

The ankle



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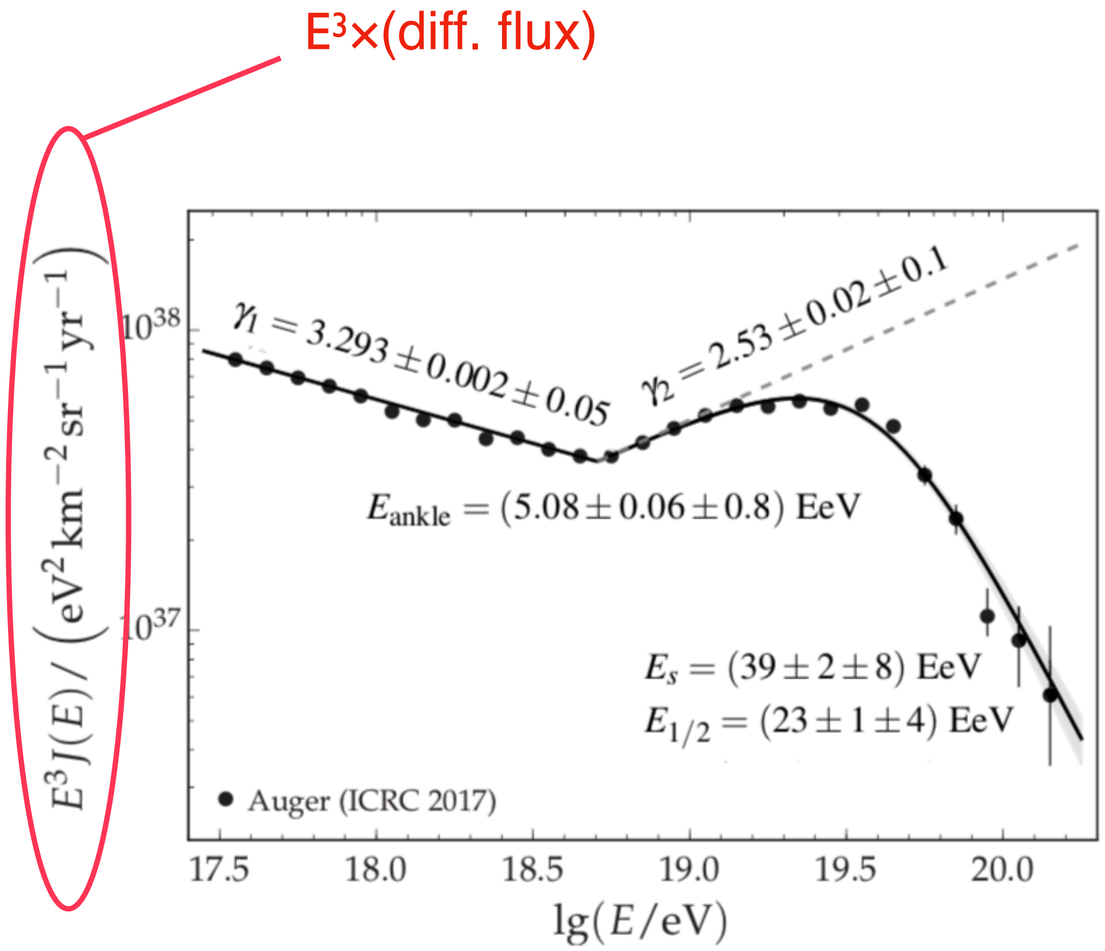
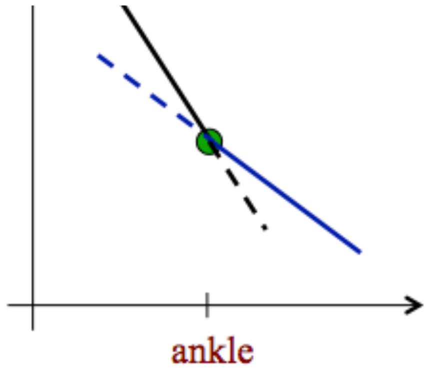
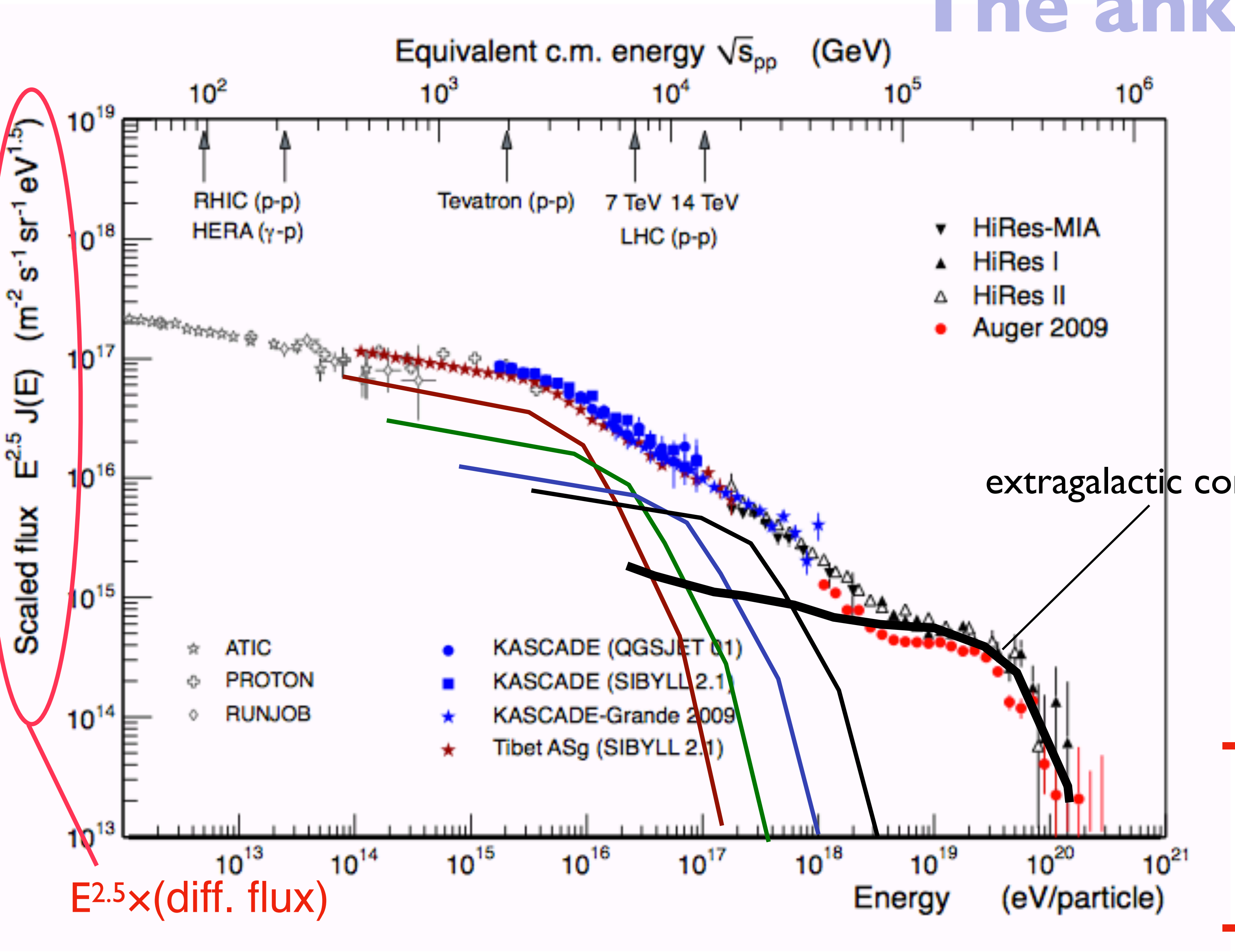




ankle : transition from a softer to a harder component

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

The ankle



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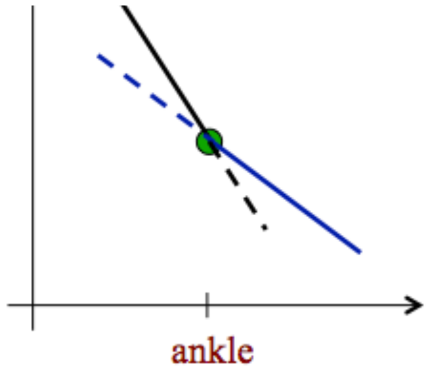
Why should the component taking over be extragalactic?

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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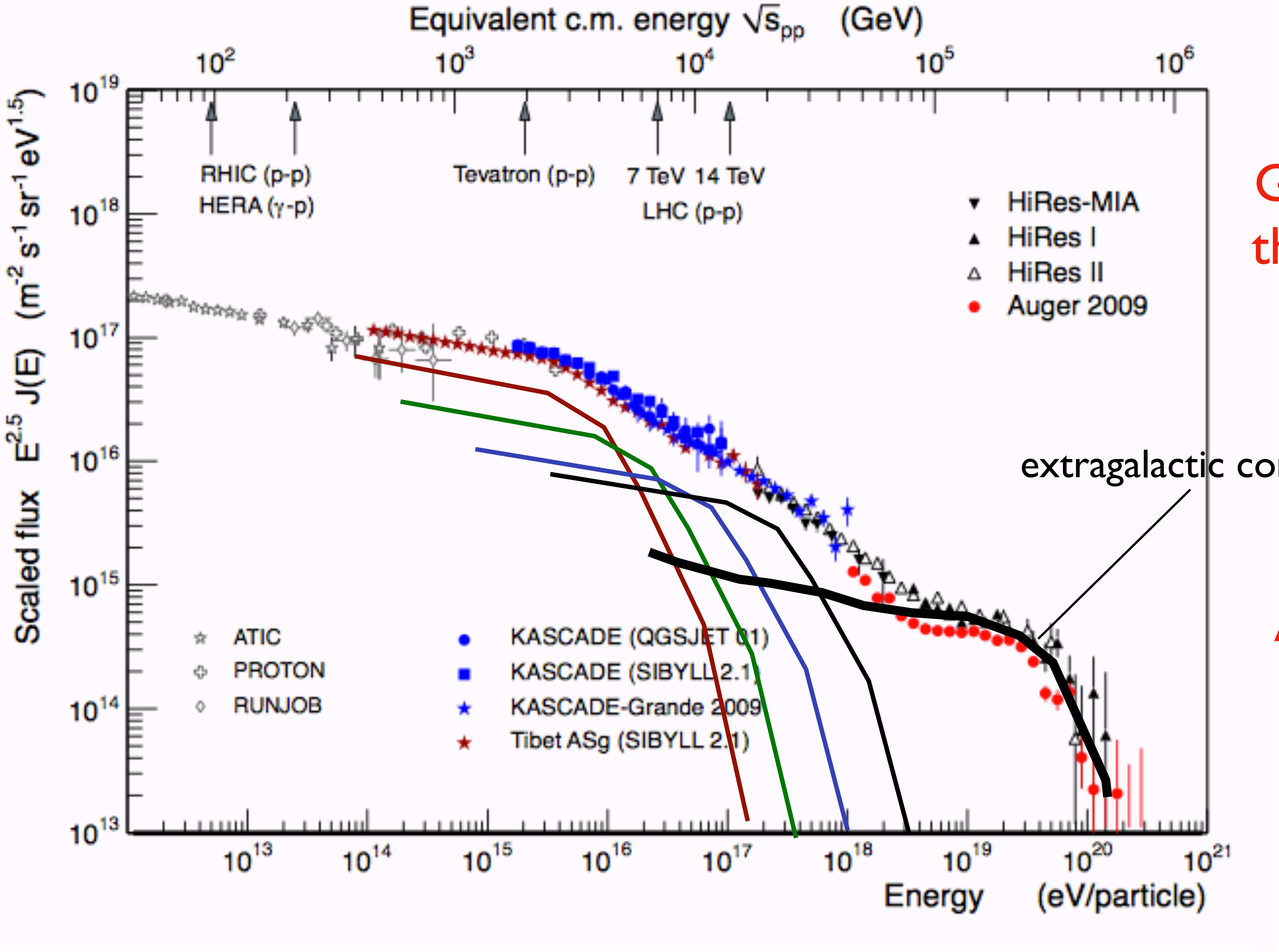


extragalactic component

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?

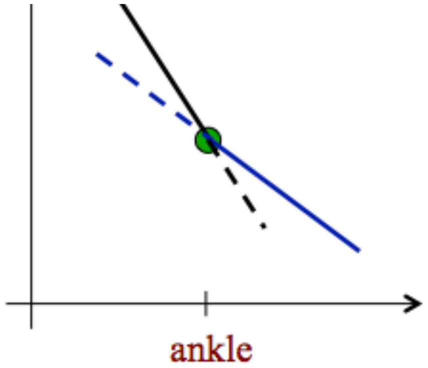
Extragalactic sources :

AGNs, GRBs, galaxy clusters, young neutron stars…

NB :

If UHECR sources are extragalactic then the spectrum and composition should be modified during the propagation between the sources and the Earth !!

—> modelling of the propagation necessary (the more accurate the better)



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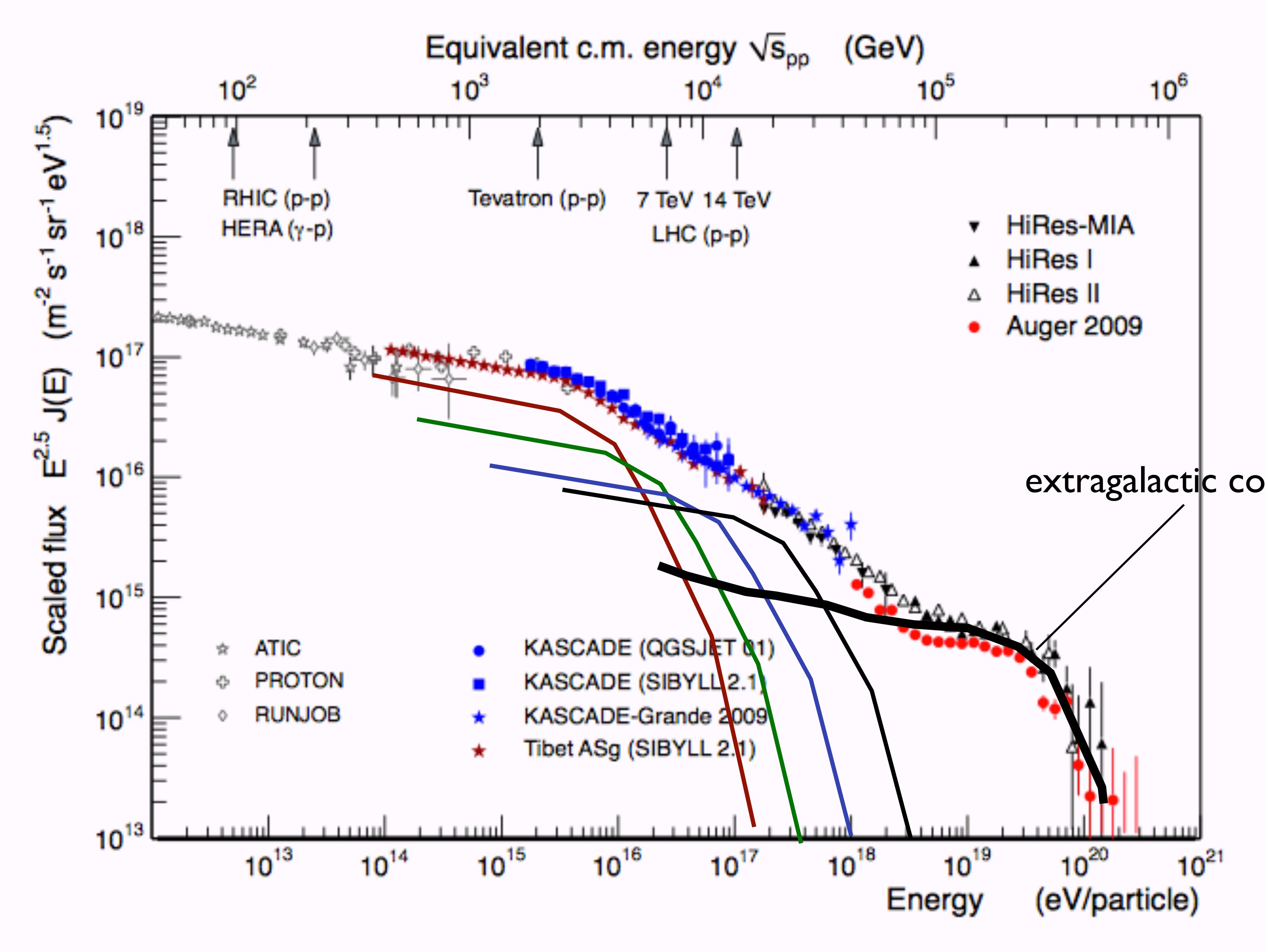
A consistent picture ?



extragalactic component

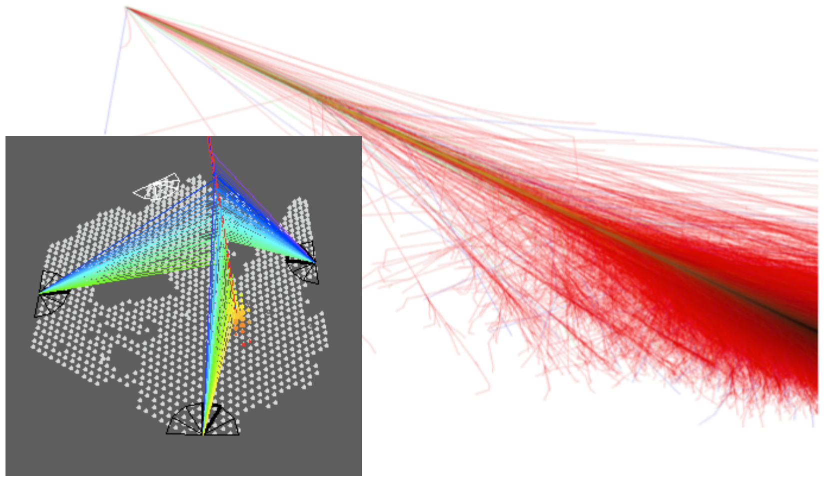
Pierog, 2012

Tantalizing picture !

(i) What CR data have to say about it?

(ii) Can we get some hints of the phenomenology of this possible extragalactic component by studying UHECR propagation?

Outline



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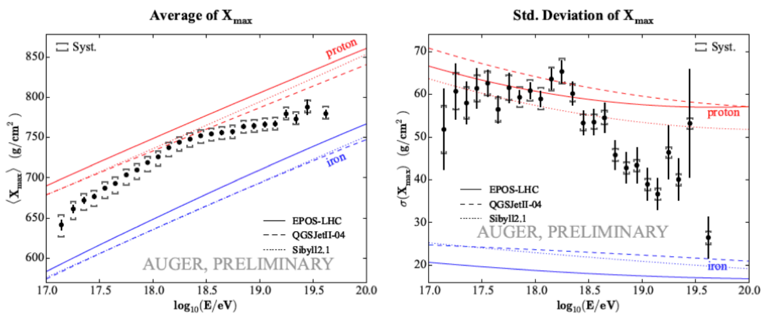
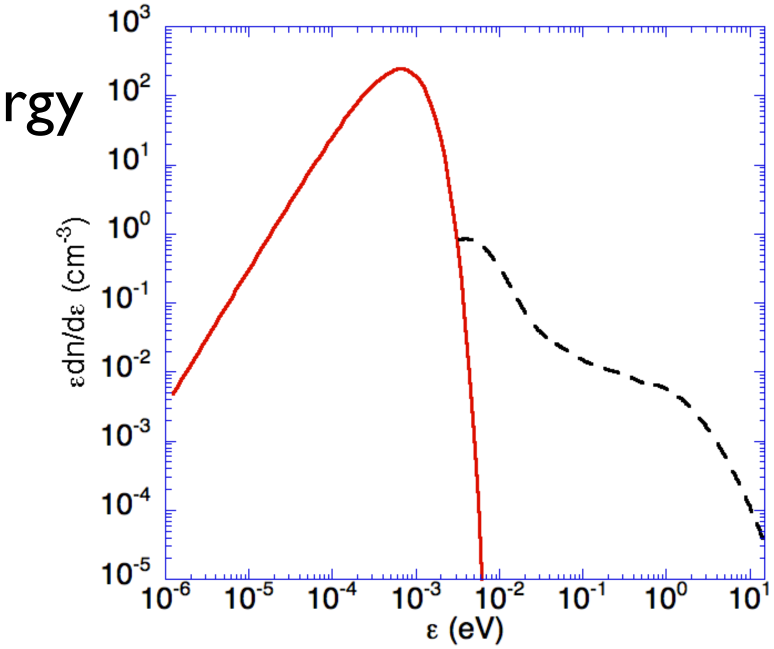


Extragalactic cosmic-ray propagation (above 10^{17} eV)

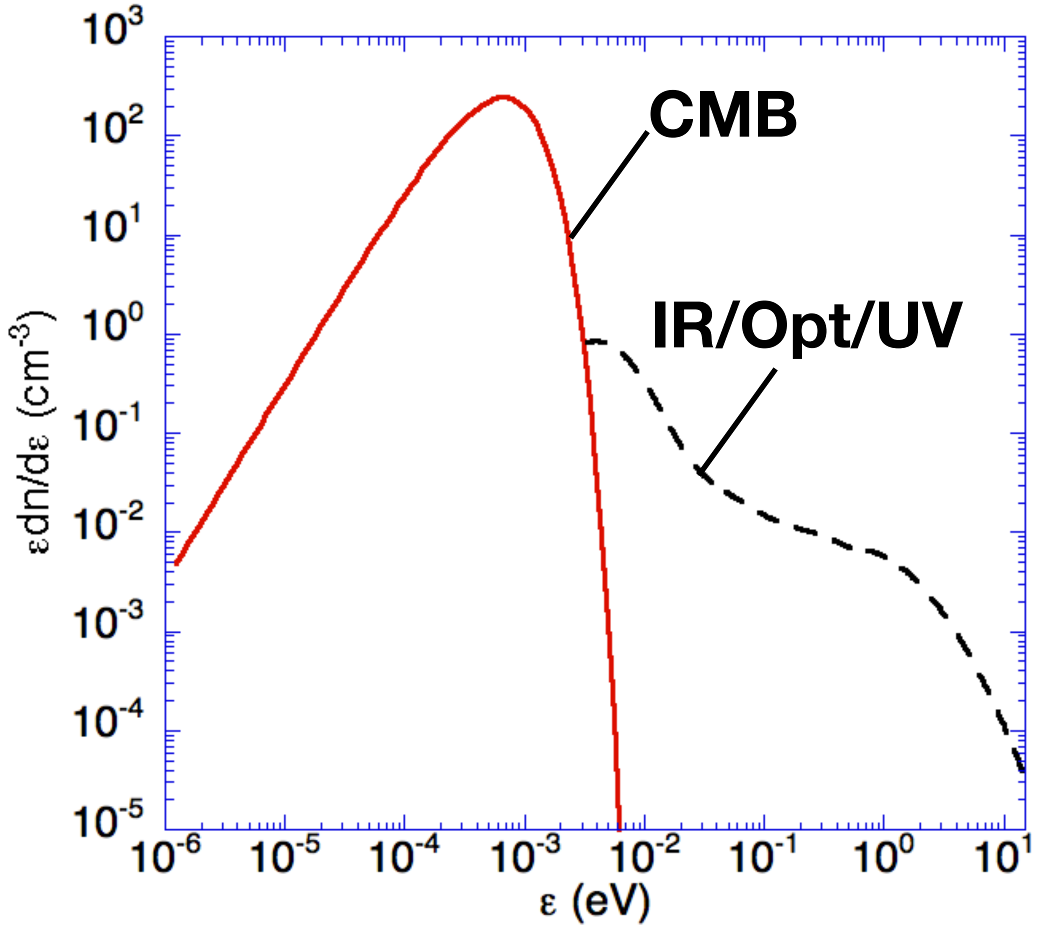
- The universe is essentially empty (except in galaxies and galaxy clusters)
- The average density is around 10^{-6} proton.cm^{-3}
- $t_{int,pp}$ ~2.1×10^{13} yr >> $t_{universe}$ ==> negligible
- we expect extragalactic cosmic-rays to loose energy because of the expansion of the universe
- There are photon backgrounds in the universe, the CMB being the densest (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 UHE cosmic-rays 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 **Densest photon background** today $\langle E_{cmb} \rangle \sim 6\times10^{-4}$ eV (say 10^{-3} eV)
  - At higher energy : Infra-red, optical, ultra violet backgrounds (IR/OPT/UV)



* Higher energy backgrounds at the scale of the Universe are negligible

* The IR/Opt/UV backgrounds and their time evolutions are not as well known as the CMB (but not a major source of uncertainty for propagation)

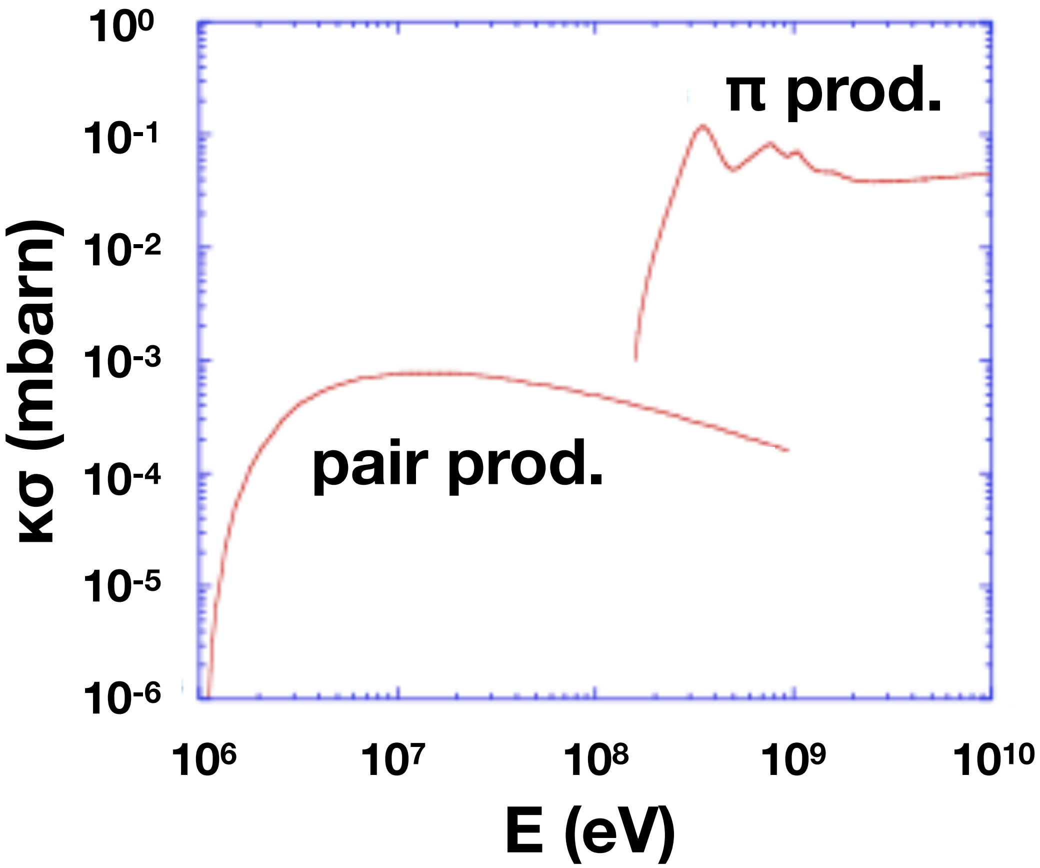
IR/OPT/UV backgrounds are very important for nuclei propagation

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%)



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

How can photon backgrounds with such low energies produce pairs and πs??!!

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) look like γ-rays !

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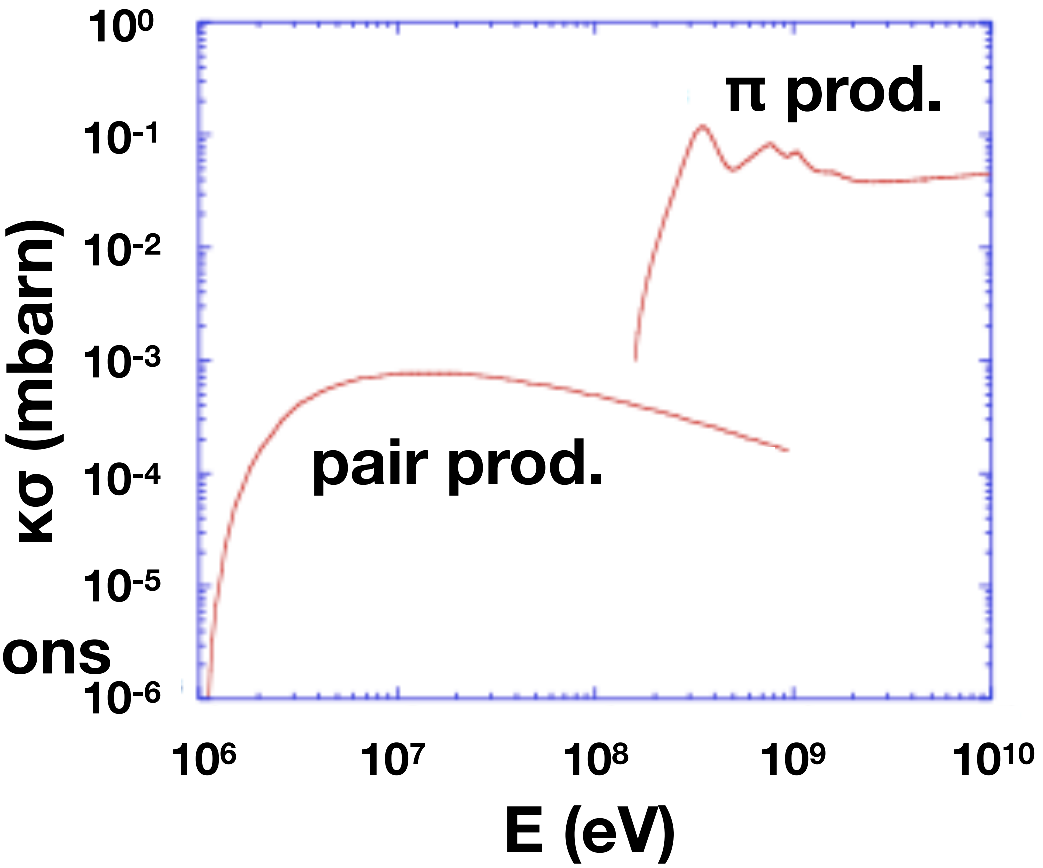


UHECR protons interaction threshold with CMB photons

Pair prod :

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

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

Pion prod :

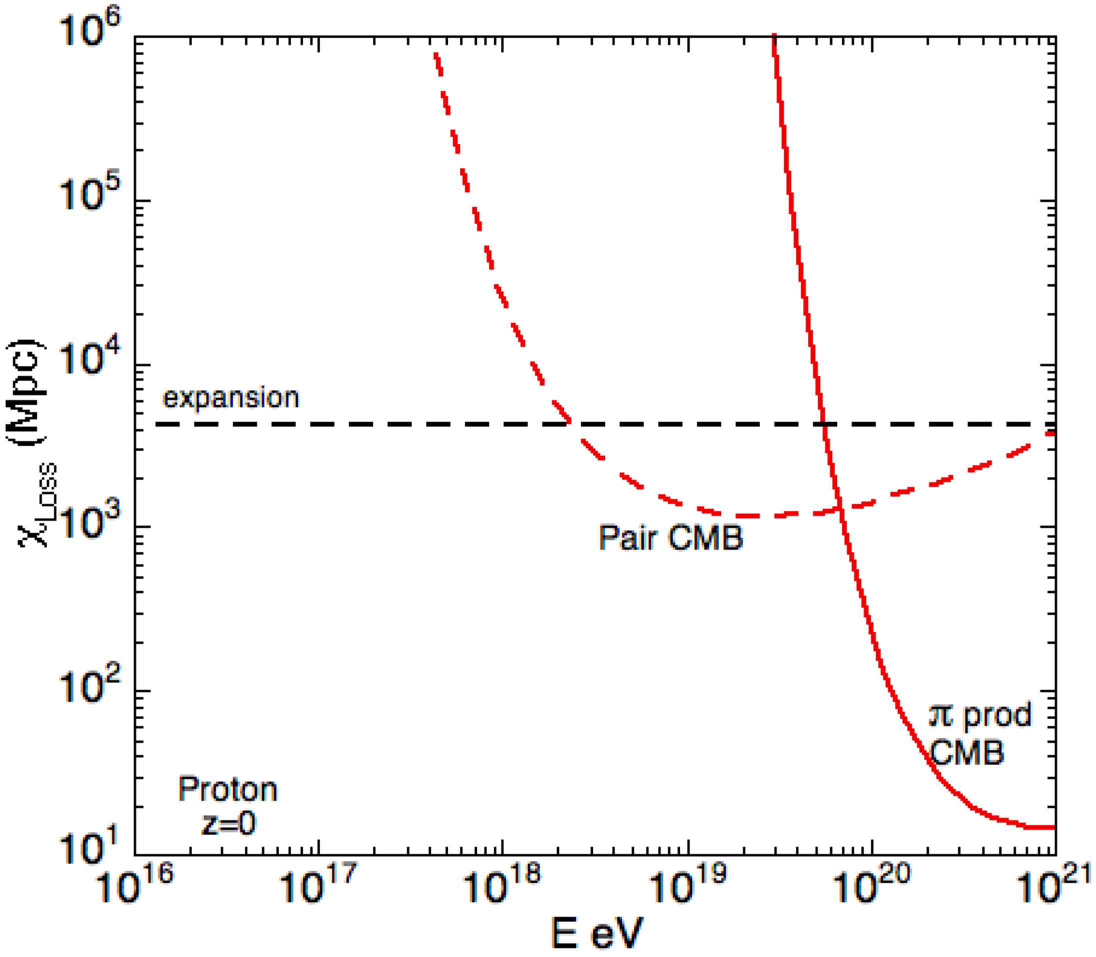
$$for\ E_\gamma \simeq 10^{-3} eV ==> E_{p,th} \simeq 7\times10^{19} eV$$

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

Proton attenuation length (or loss length)

χ_{loss} : energy loss length (or attenuation length), the typical distance over which a UHE particle losses its energy

$\chi_{loss} \sim \lambda / \kappa$



(GZK stands for Greisen, Zatsepin and Kuzmin the three scientists who first pointed out this expected feature)

Proton attenuation length :

- expansion below ~10^{18} eV

- then pair production with CMB photons

- strong decrease around ~10^{20} eV due to pion production

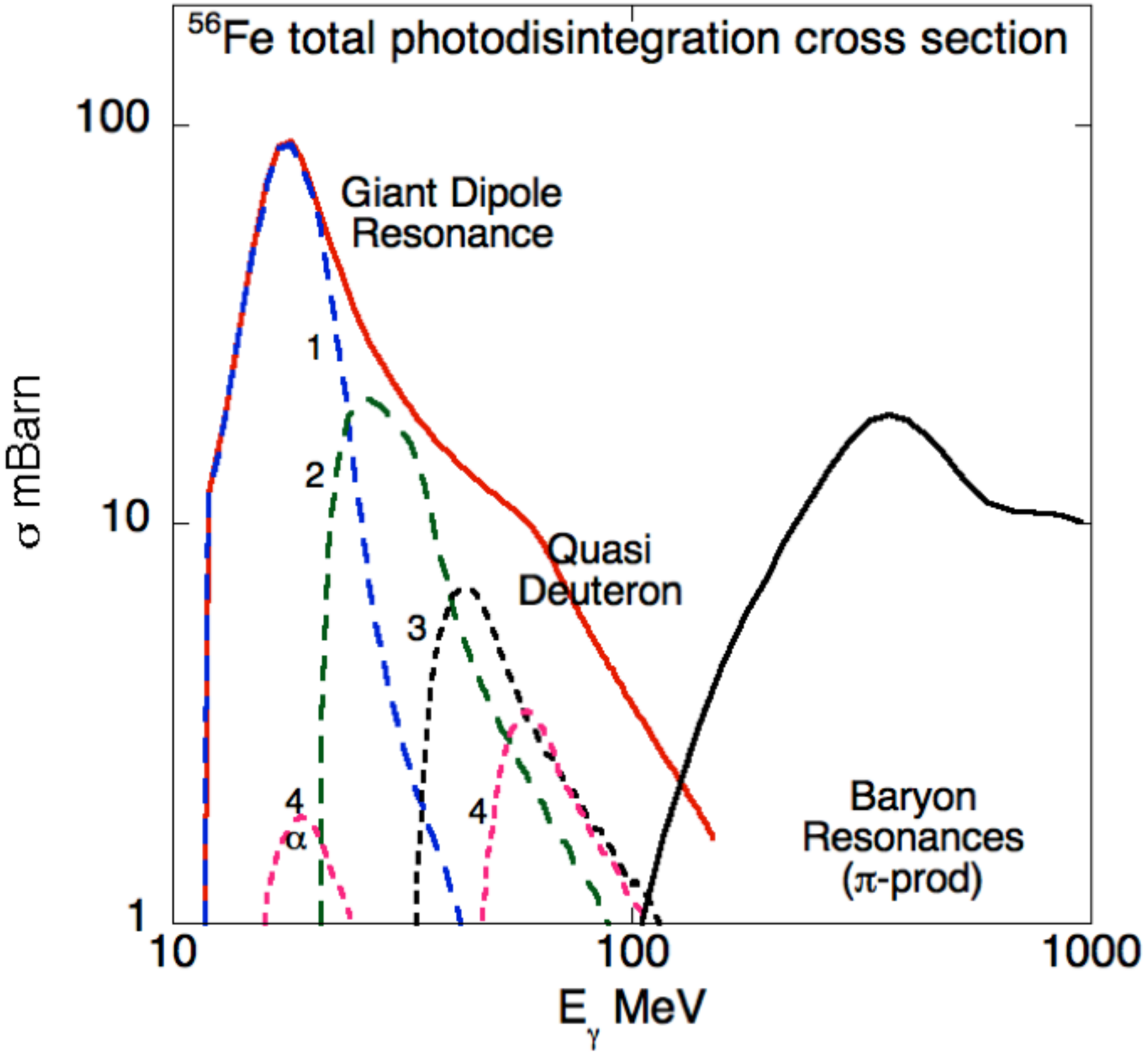
the universe becomes extremely opaque to UHE protons —> the spectrum is expected to drop severely at the highest energies —> GZK cut-off

Photo-interactions of nuclei

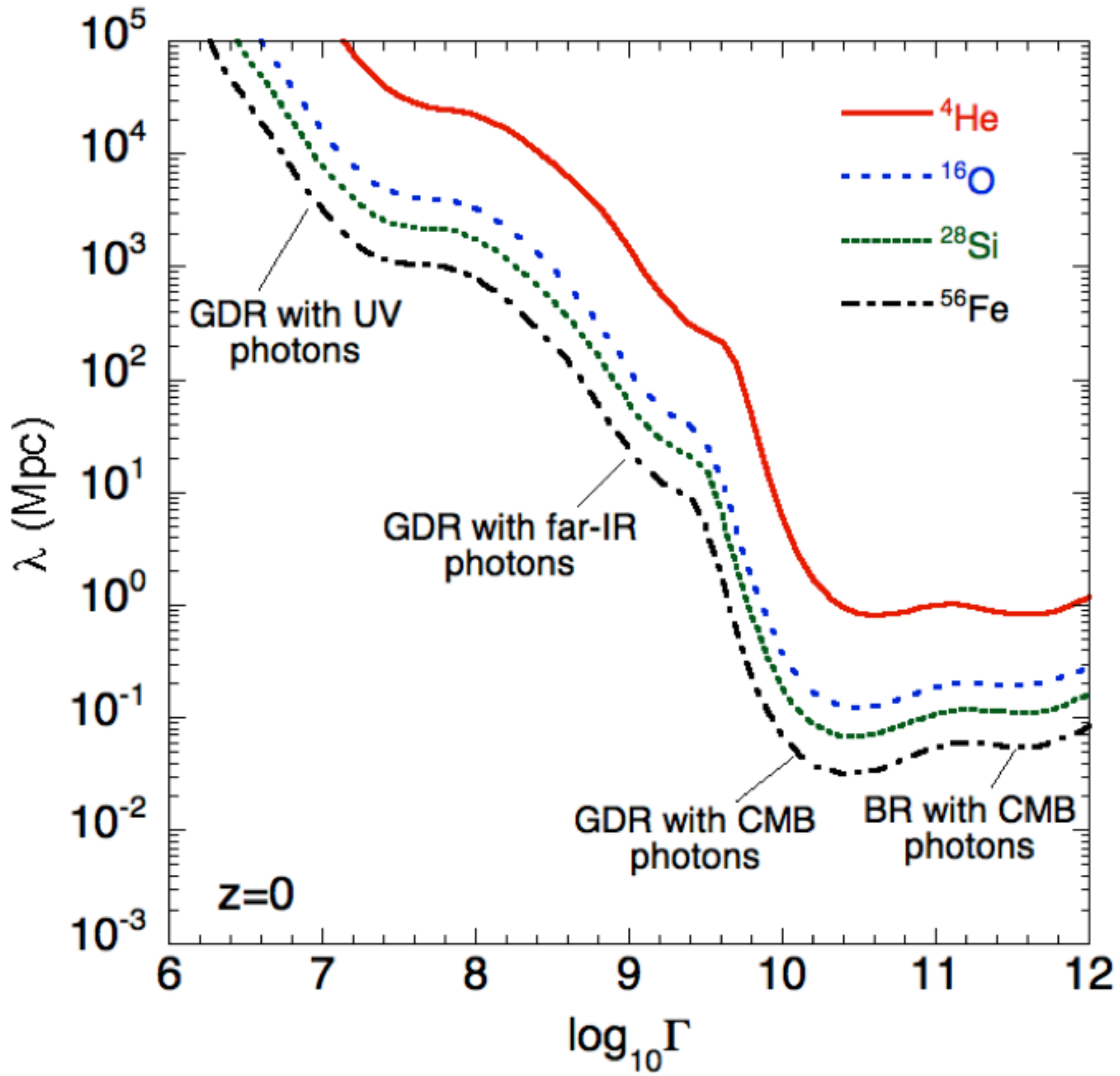
Nuclei (heavier than protons) :

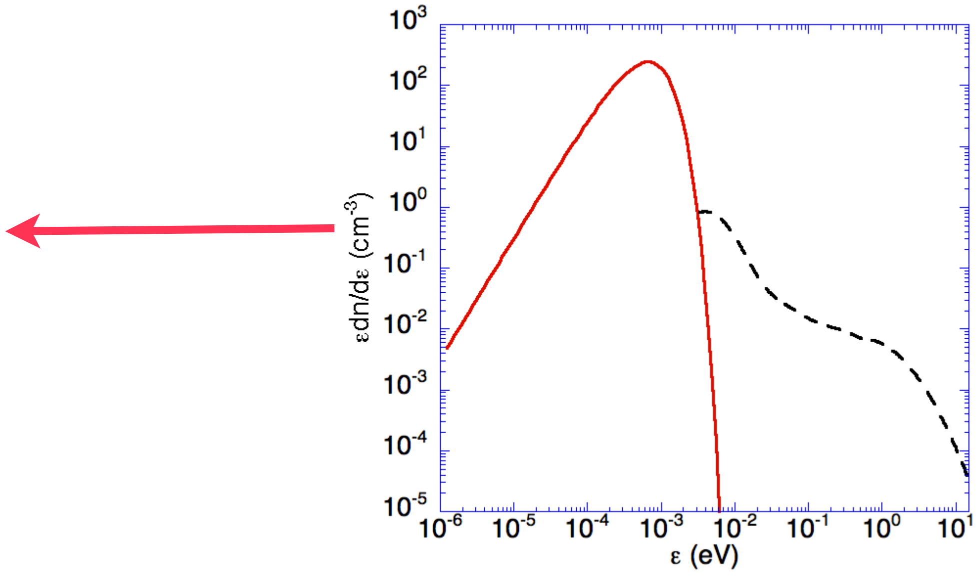
Two types of processes

- 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 (Talys used since Khan et al., 2005)
  - Quasi-Deuteron process (QD);
    threshold ~ 30 MeV
  - Pion production (BR); threshold ~ 135 MeV



Nuclei mean free path for photodisintegration





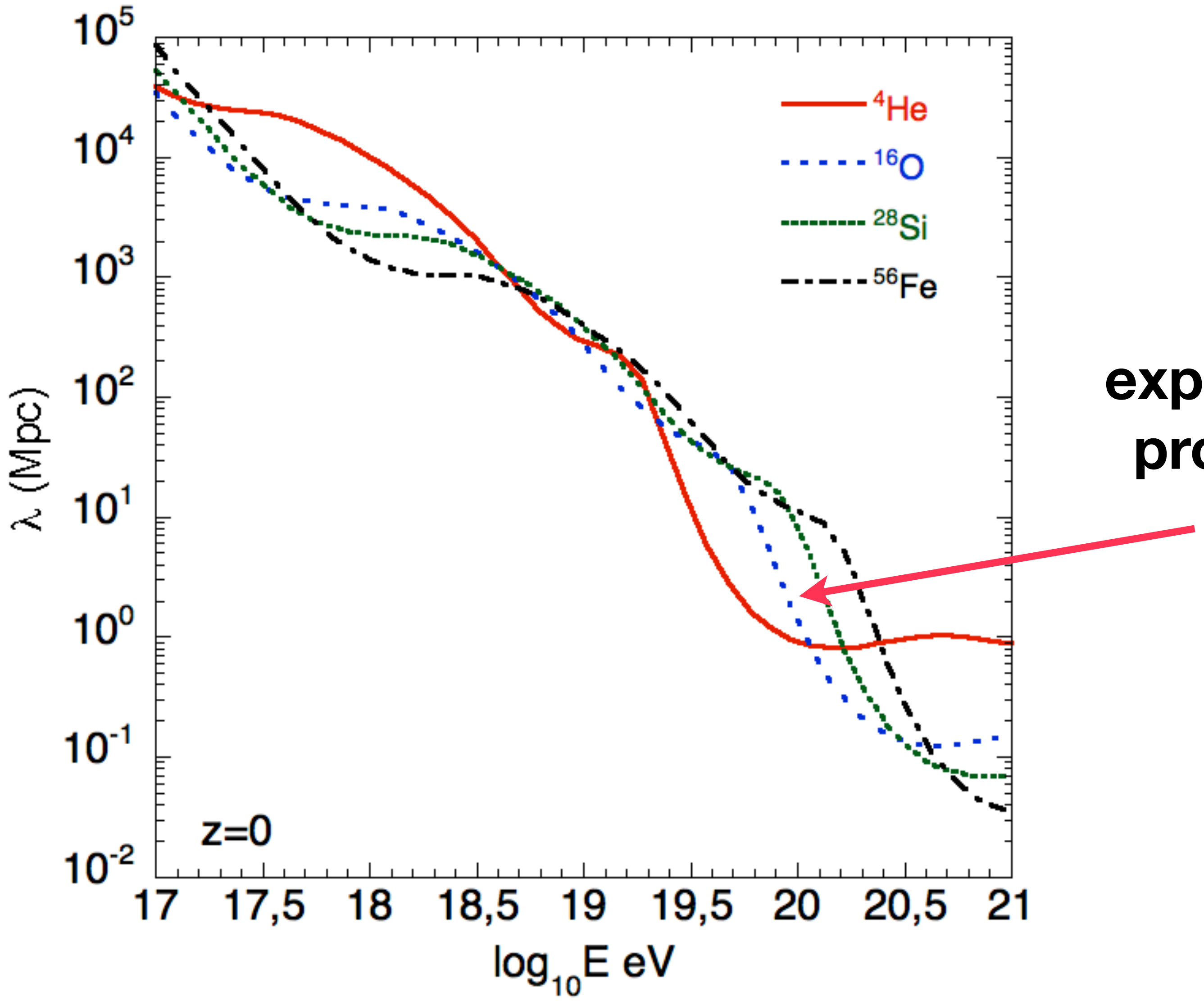
Nuclei photodisintegration mean free path :

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



The GZK cut-off for nuclei is expected to take place at energies ~ proportional to their mass starting around 10^{19} eV for He

Nuclei photodisintegration mean free path :

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What do we need to propagate UHECR?

We want to follow the energy and mass evolution of UHECR of various primary energies and mass, emitted by source at various distances and propagated throughout extragalactic photon background until it reaches the Earth

- at every moment of the propagation we need to be able to compute the competition between the different energy loss and decay processes and the different reaction channel of a given process (in particular the GDR) of an UHECR at its current energy and mass

—> we need to GDR cross sections and branching ratios for the whole nuclear chart up to ^{56}Fe

—> knowing the photon background cross sections can be used to calculate mean free paths of any reaction channel for any isotope at any energy

—> around 380 isotopes are currently considered in particular all the isotopes with a lifetime longer than 1s

Simplest calculations of extragalactic UHECR diffuse spectra

We assume :

- a source composition
- source spectrum (usually a power law, same for all the species)
- maximum energy ($Z \times E_{max}^{proton}$)
- a spatio-temporal distribution of the sources in the universe (we will assume they are uniformly distributed in the few examples we will show)

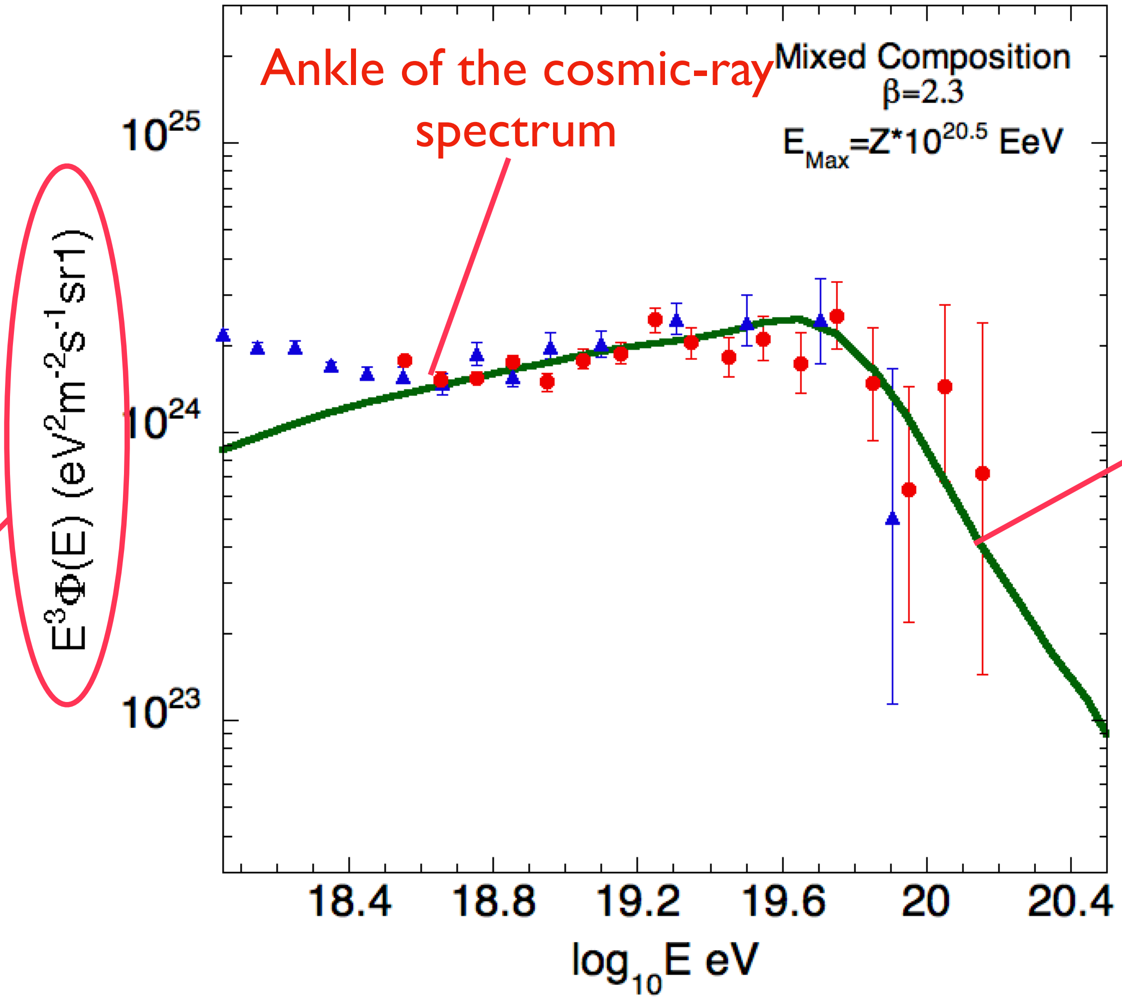
- We adjust the best spectral index on UHECR data

A "good" model should reproduce the observed UHECR spectrum
It should also reproduce the observed UHECR composition

simple 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



Ankle of the cosmic-ray spectrum

E³×(diff. flux)

Predicted suppression above 5.10^{19} eV
—> unrelated to the maximum energy at the sources
—> GZK effect

The UHECR spectrum can be well reproduced above the ankle

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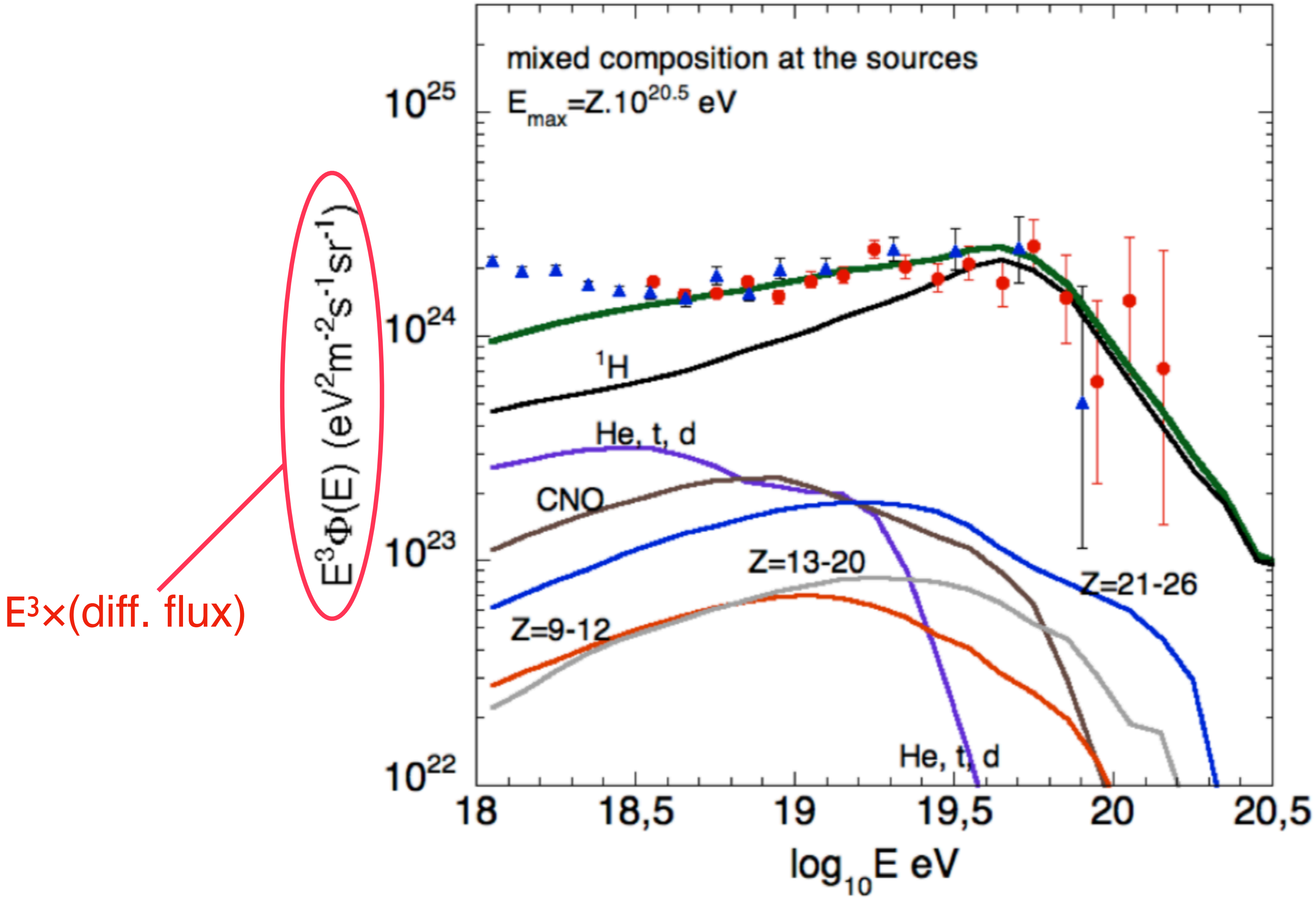
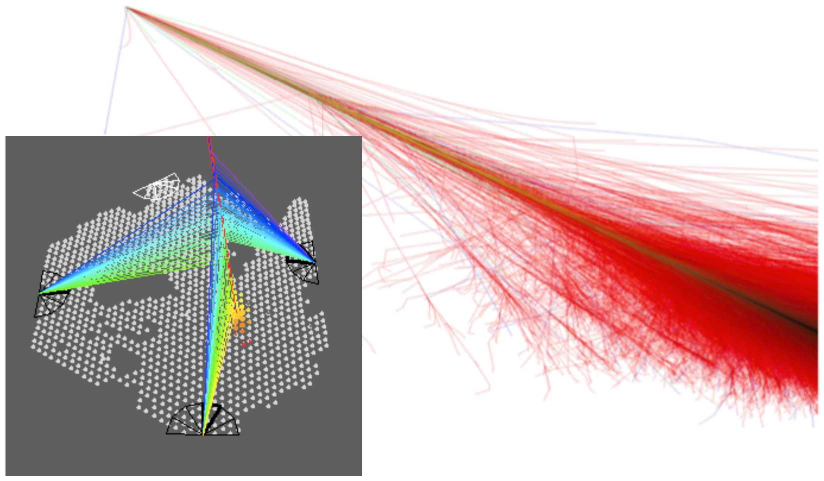


When all the species are assumed to be accelerated above 10^{20} eV, the composition is expected to get lighter (i.e proton richer) above 10^{19} eV (photodisintegration of composed species)

Outline



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  - Detection techniques (ground arrays and fluorescence detectors)

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  - The knee and the ankle

- Extragalactic cosmic-rays phenomenology
  - Propagation of protons and nuclei

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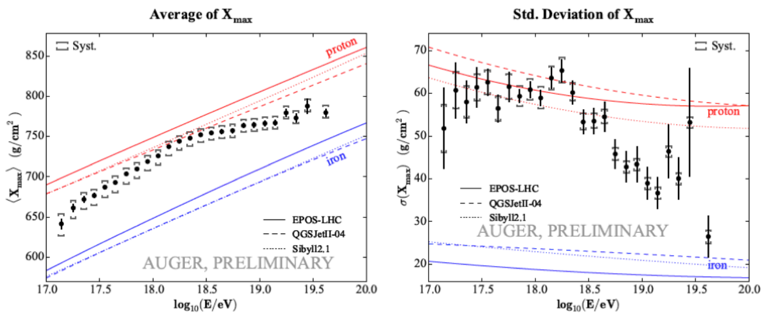
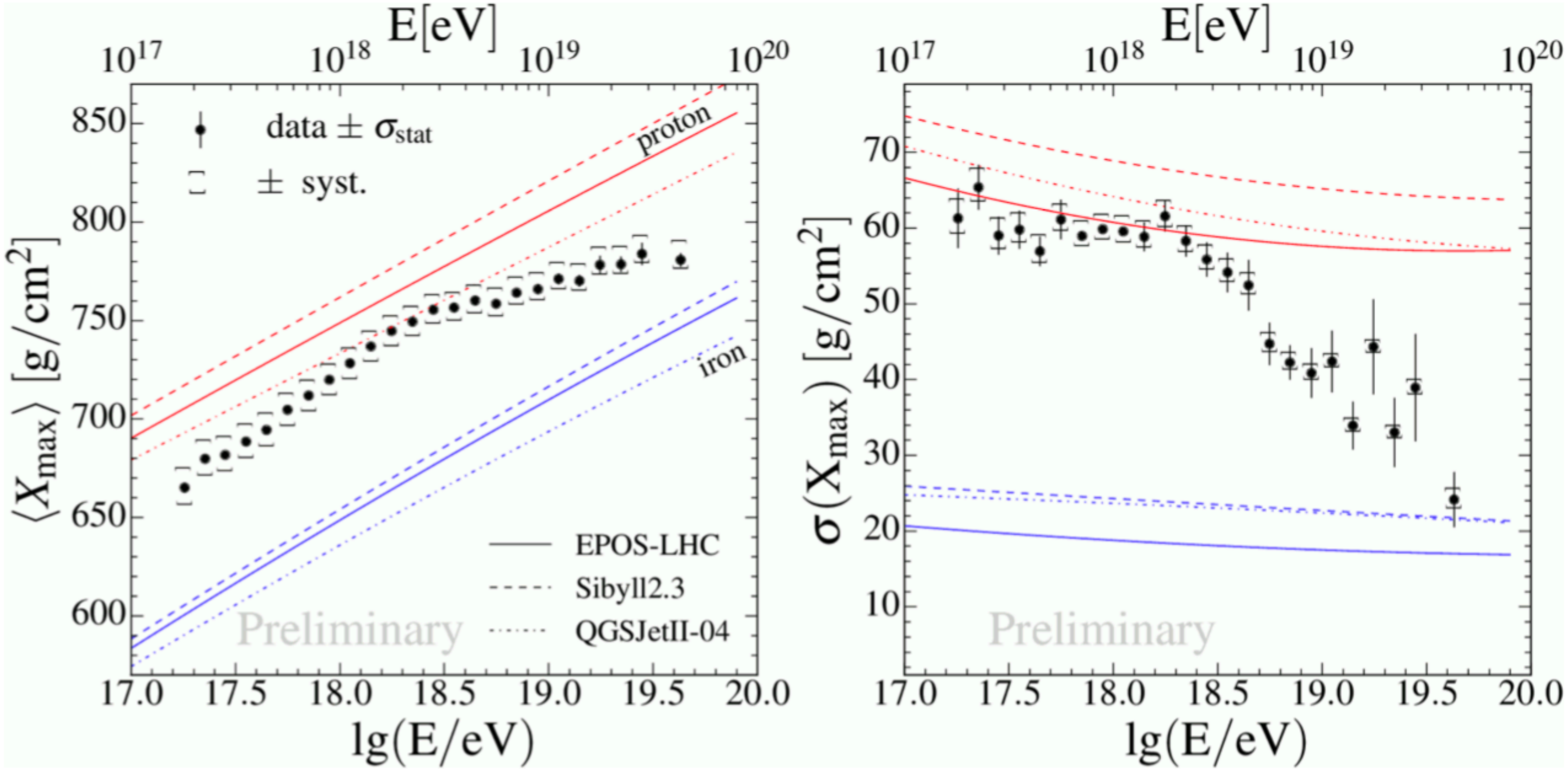
  - **Auger composition results**
  - **Anisotropies**
  - **How does PANDORA fit in this picture?**



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

- **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

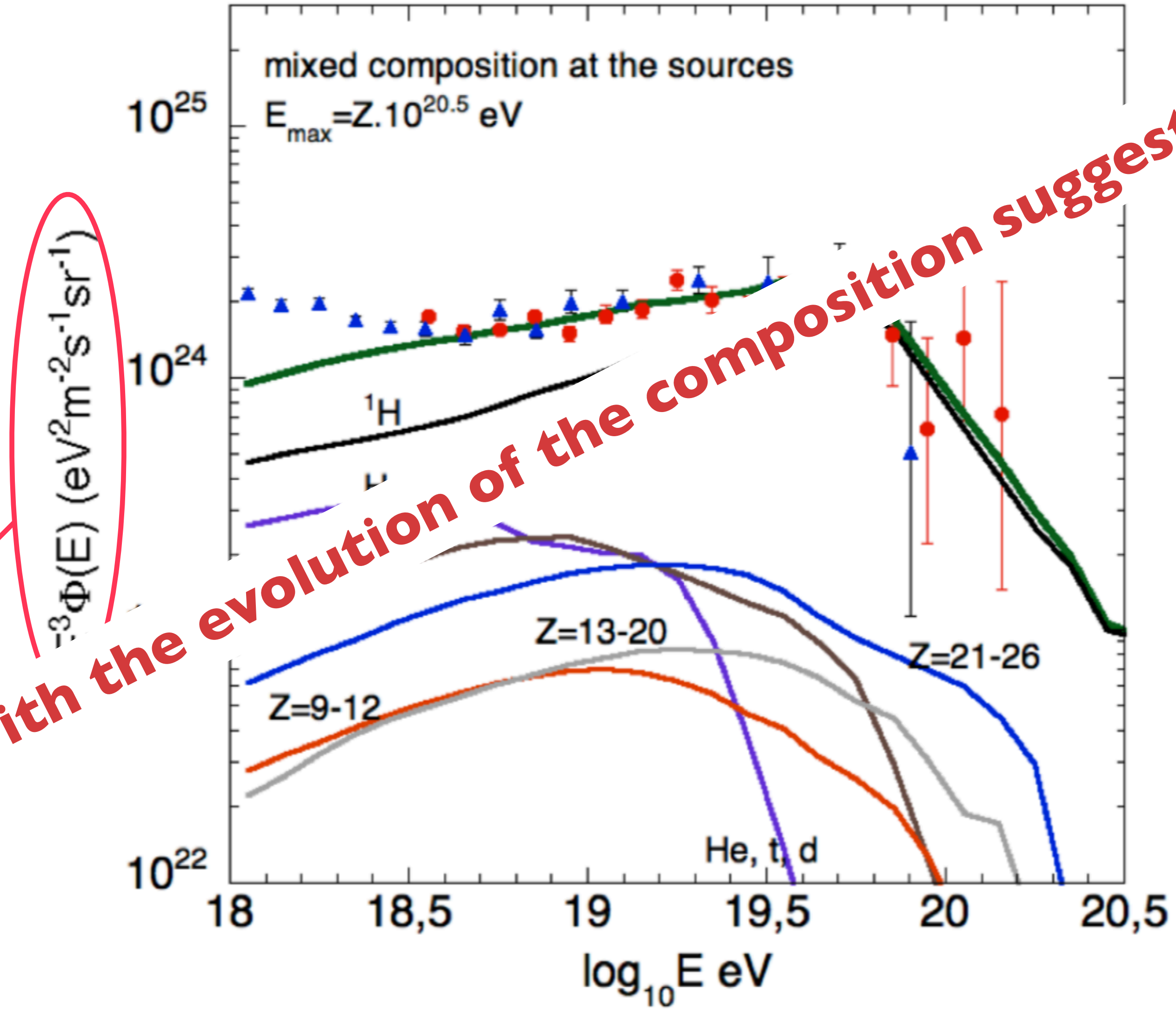
—> model independent evidence for a composition getting heavier and proton poorer above the ankle

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)

Incompatible with the evolution of the composition suggested by Auger data !

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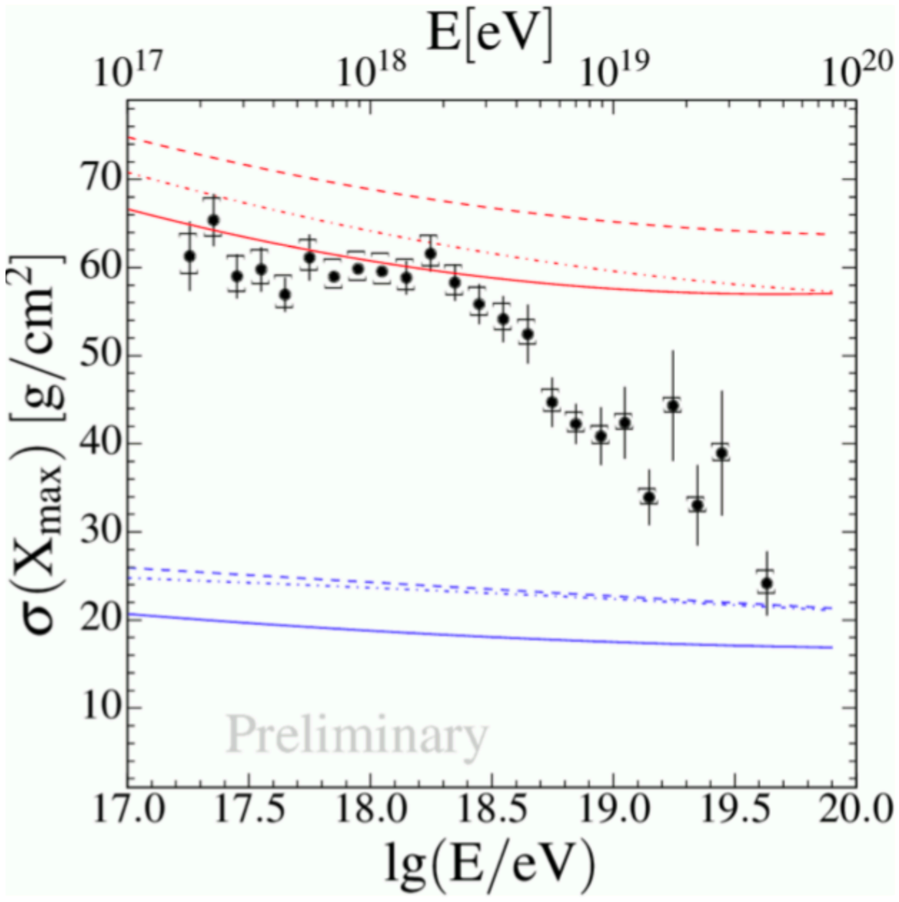
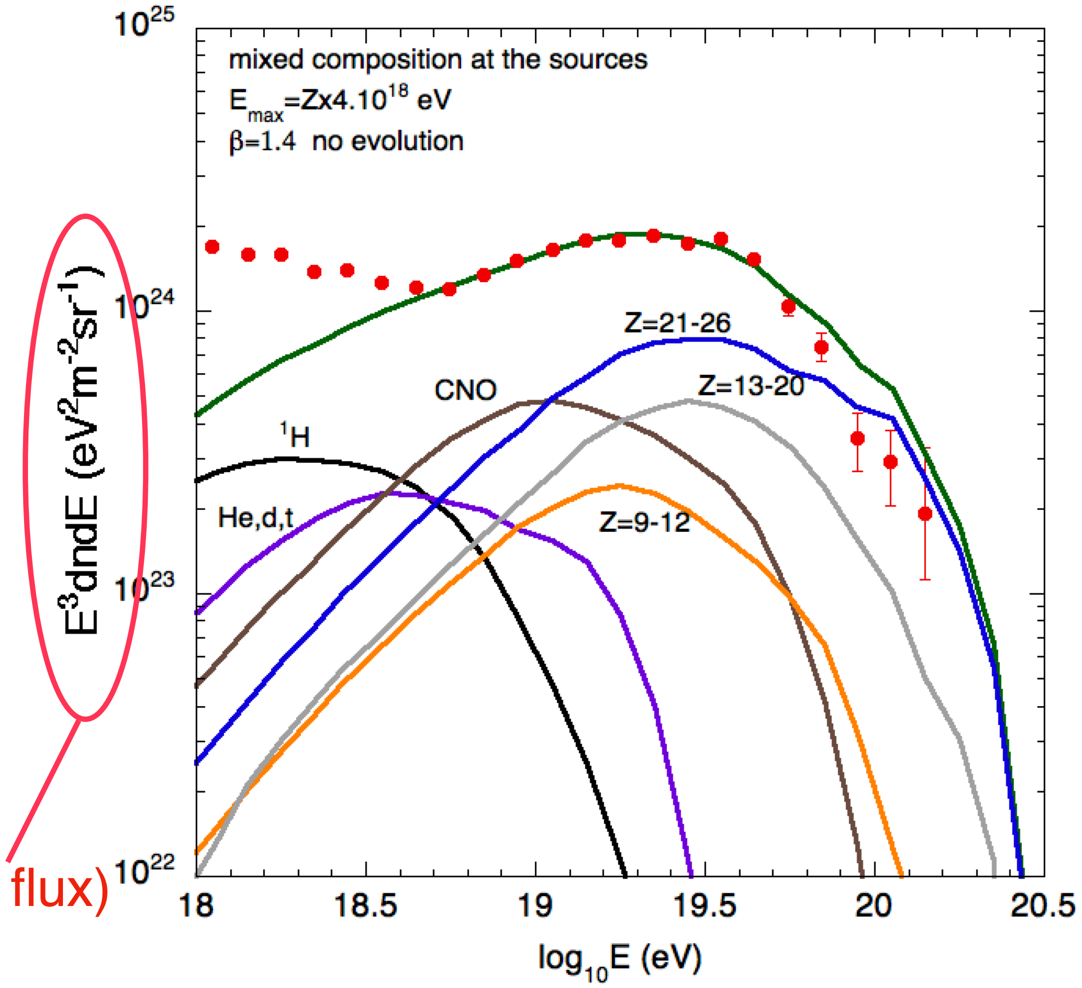
Implications of Auger composition measurements



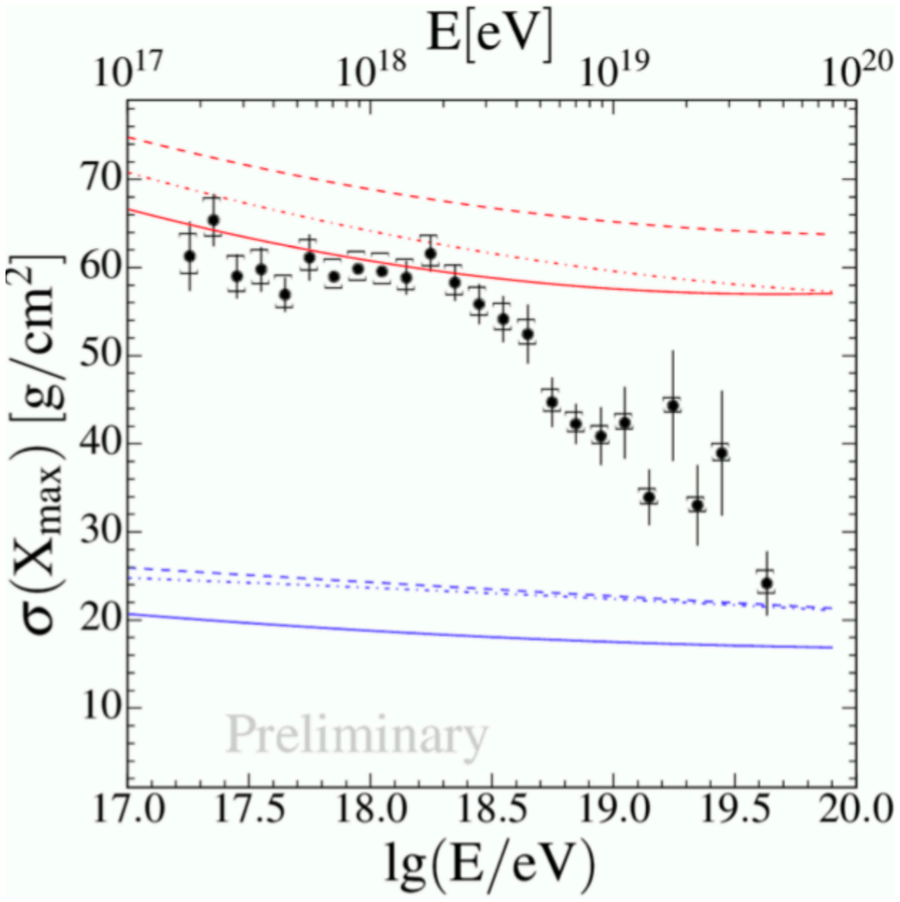


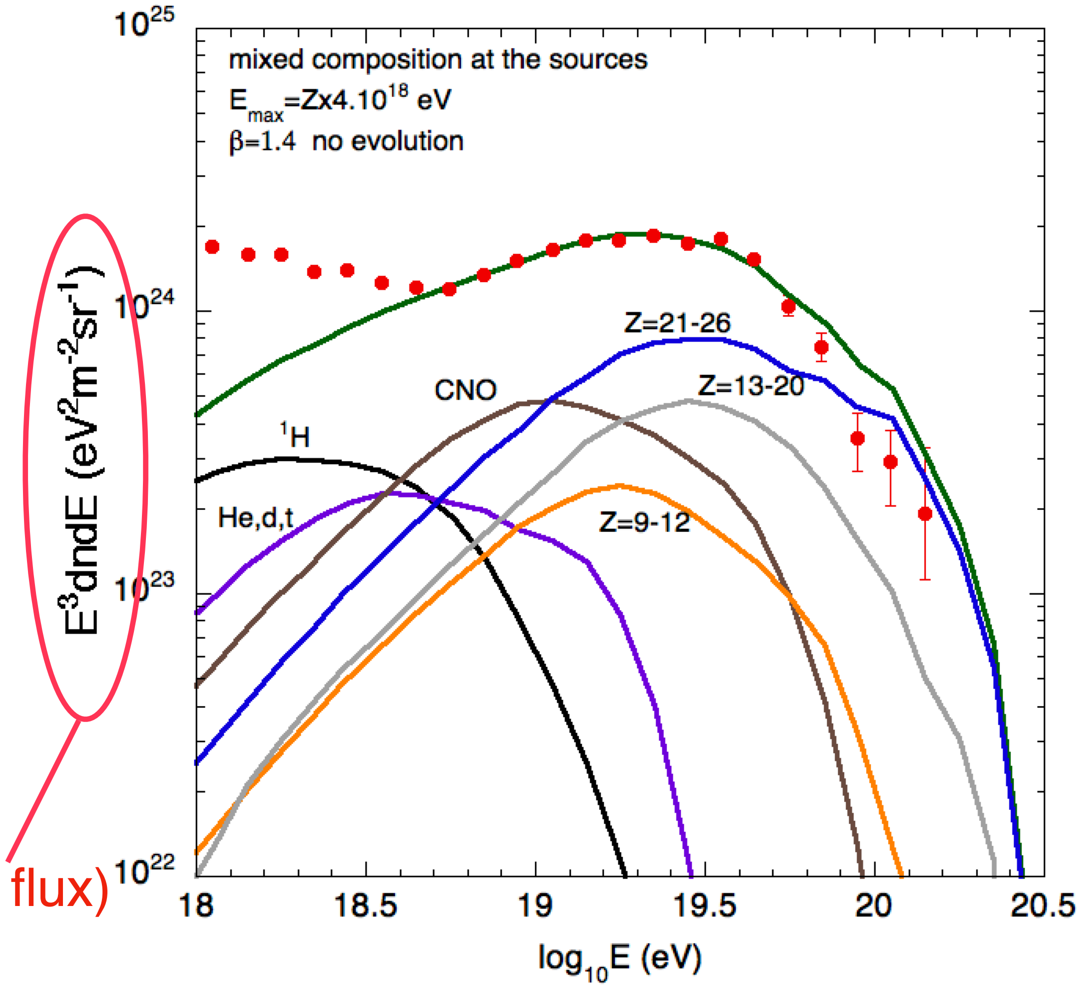
E³×(diff. flux)

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 $N(E) \propto E^{-\beta}$, $\beta=1.4$, $E_{max}(Z)=Z\times E_{max}^{proton}$, $E_{max}^{proton}=4\mathrm{x}10^{18}$ eV
—> The hierarchy between the complex species remains more or less unchanged
—> The protons are cut at the sources and so the composition on Earth gets proton poorer as the energy increases

Implications of Auger composition measurements





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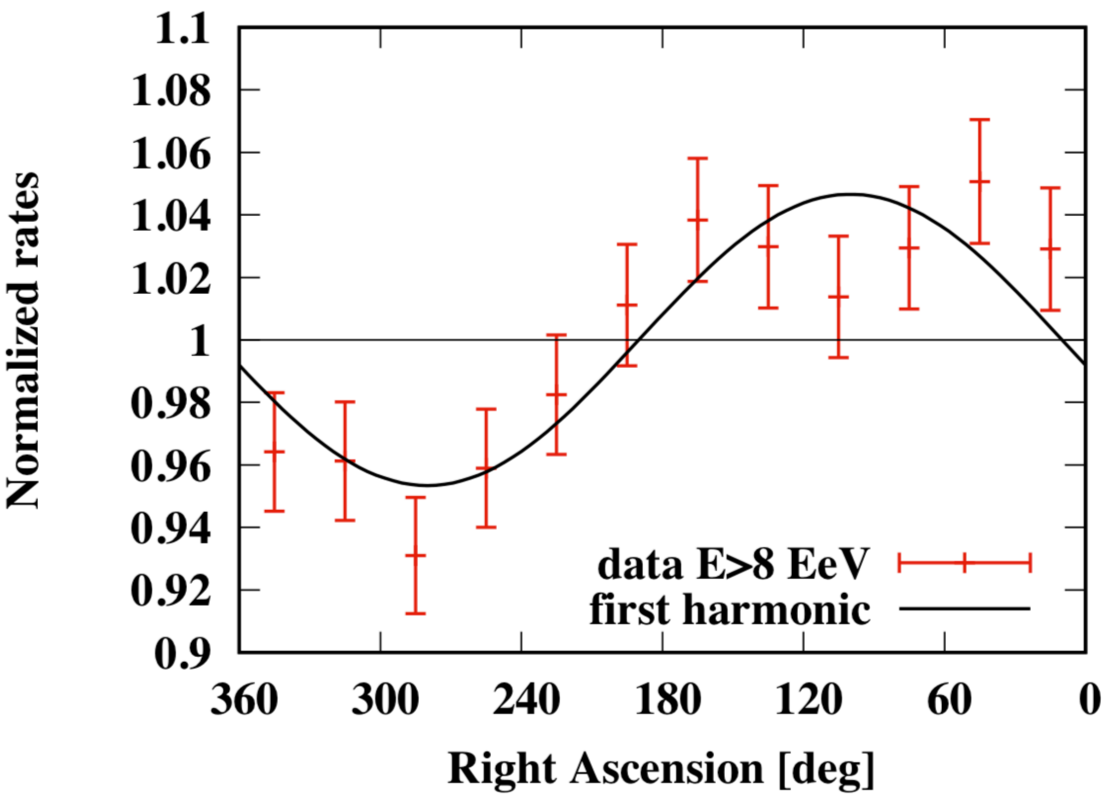
here $N(E) \propto E^{-\beta}$, $\beta=1.4$, $E_{max}(Z)=Z\times E_{max}^{proton}$, $E_{max}^{proton}=4.10^{18}$ eV
obviously not a good news for anisotropy expectations and secondary ν and γ emission

Anisotropies : discovery of a large scale anisotropy above 8 EeV

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
$\geq$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

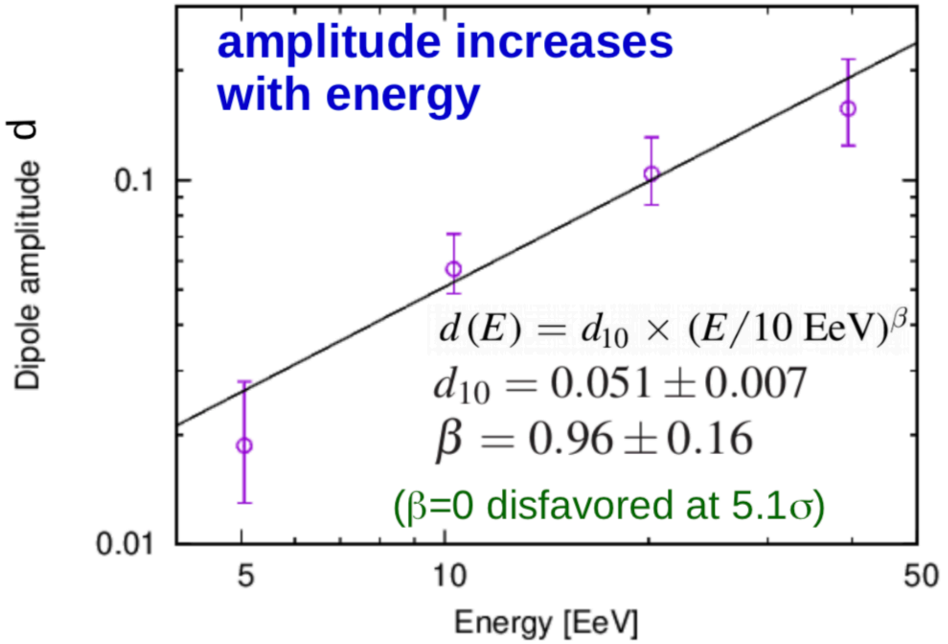
—> but probably does not prove by itself that cosmic-rays in this energy range are purely extragalactic

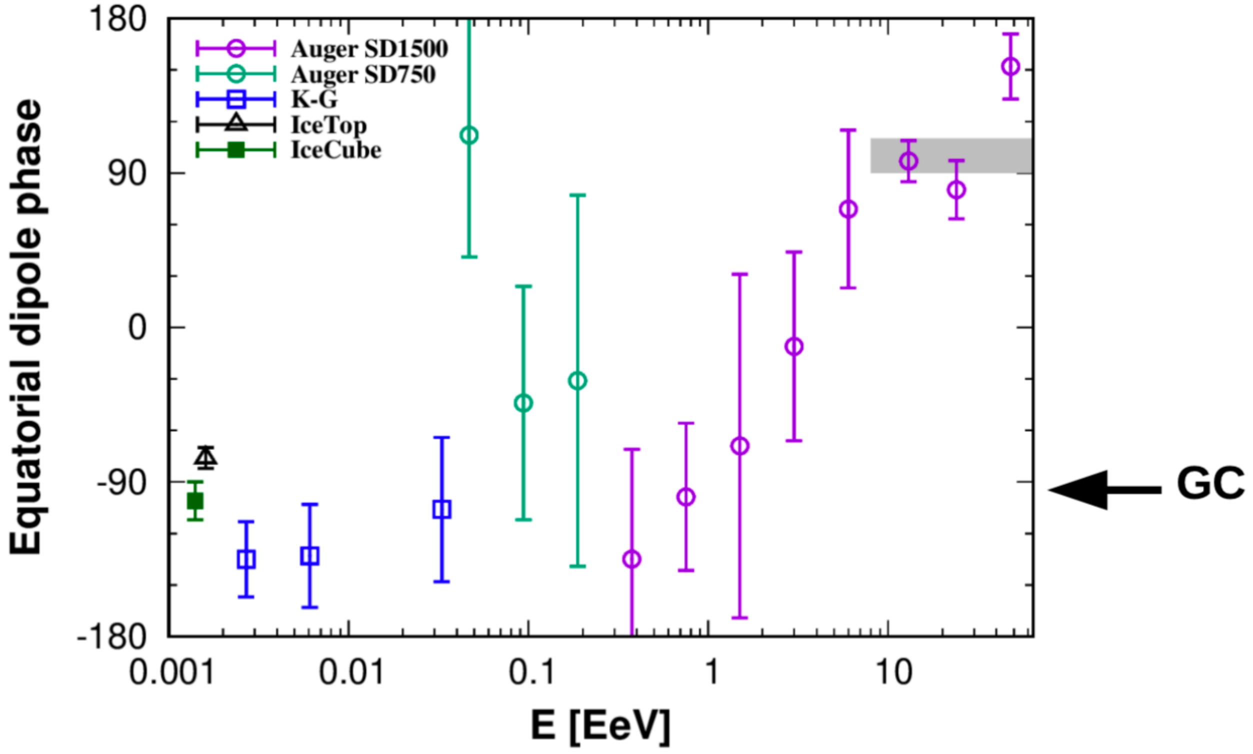
—> what is the origin of the dipole? source distribution? contribution of a dominant source?

—> 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

Taken from Esteban Roulet's talk at ICRC 2019





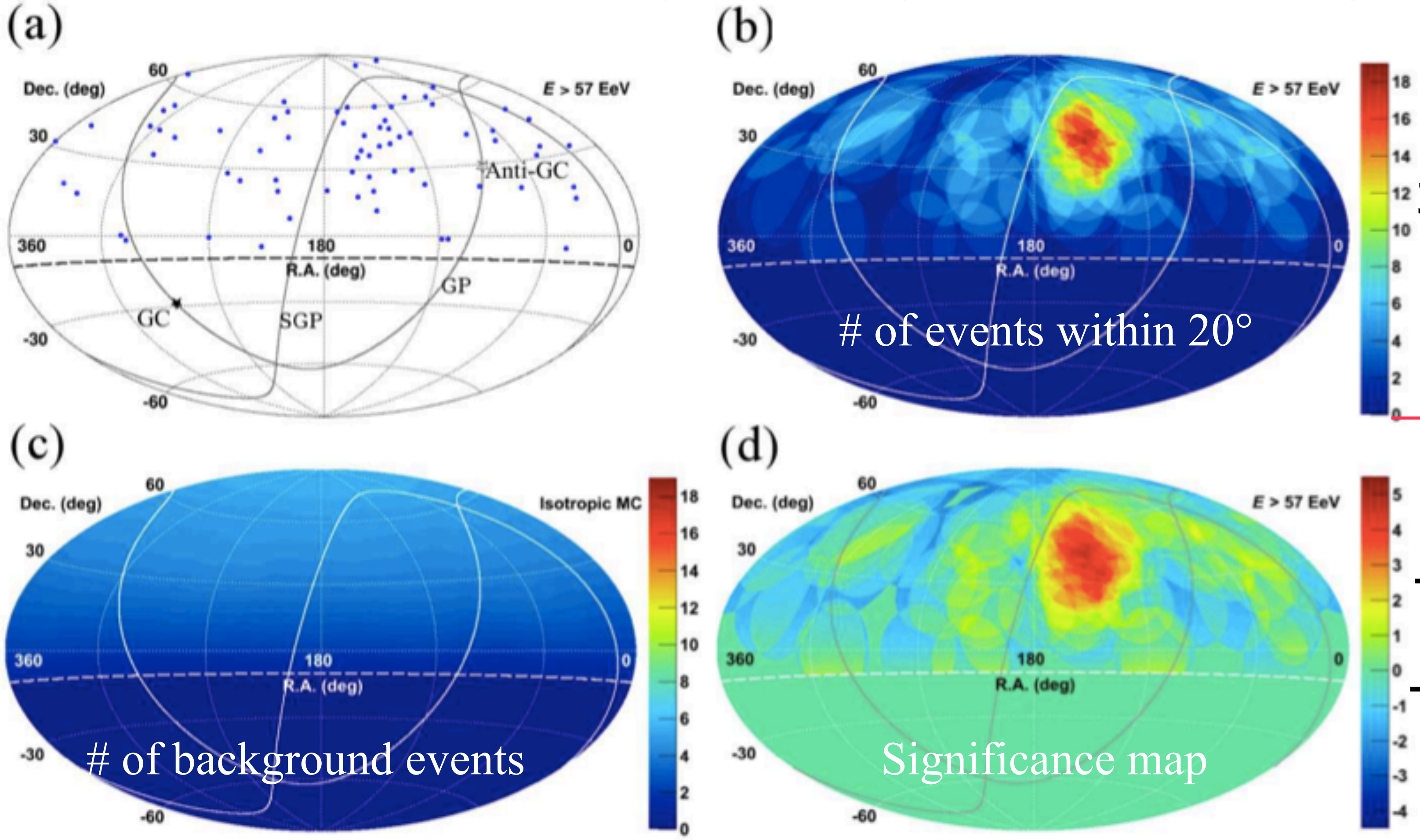
Arguments given :
reconstructed dipole with a right ascension close to that of the galactic center at low energy (below 10^{18} eV) moving away from it as energy increases
—> transition toward and extragalactic origin
(argument would be stronger if the dipoles measured between a few PeV and 8.10^{18}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

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

Anisotropies in Telescope Array sky

TA a smaller version of Auger (700 km²) in the northern hemisphere claims a significant anisotropy signal



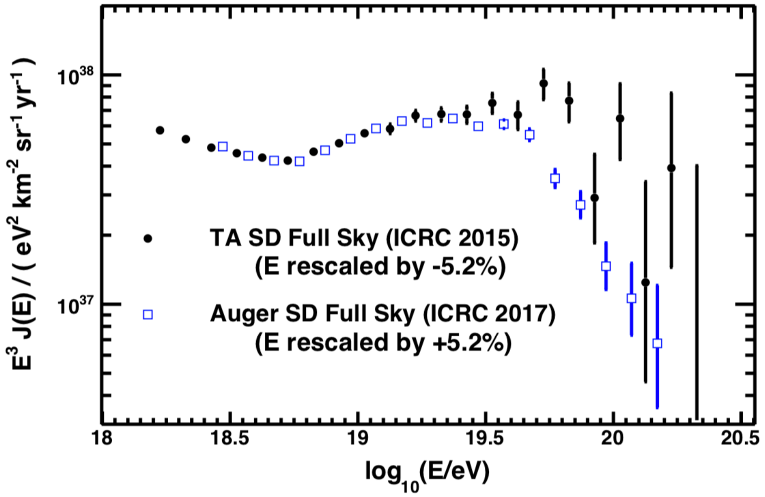
Abbasi et al., ApJ Letters, 2014

Initial claim : Cluster of events,
angular scale ~ 20 deg
3.4 sigmas (once penalized), ~20% of the events above 57 EeV in the cluster
location of the center of the cluster ~20° away from M82

—> very tempting association especially regarding recent Auger studies with SFG samples

However :

- the significance of the cluster has decreased in the past years (now ~3σ)
- at lower energy a significant deficit of events is claimed at ~ the same location (cold spot)



Consequences of anisotropy measurements

- The presence of anisotropies in the UHECR sky is now established

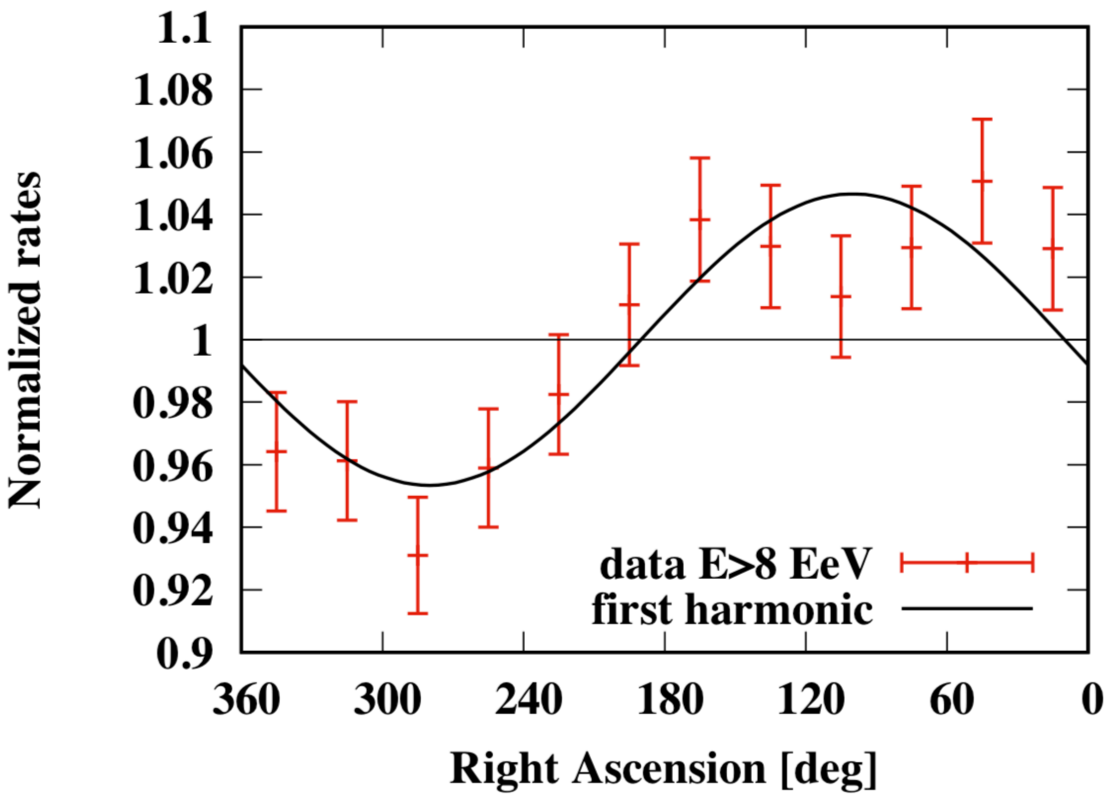
- These anisotropies are quite weak and so far only detected at large and intermediate angular scales

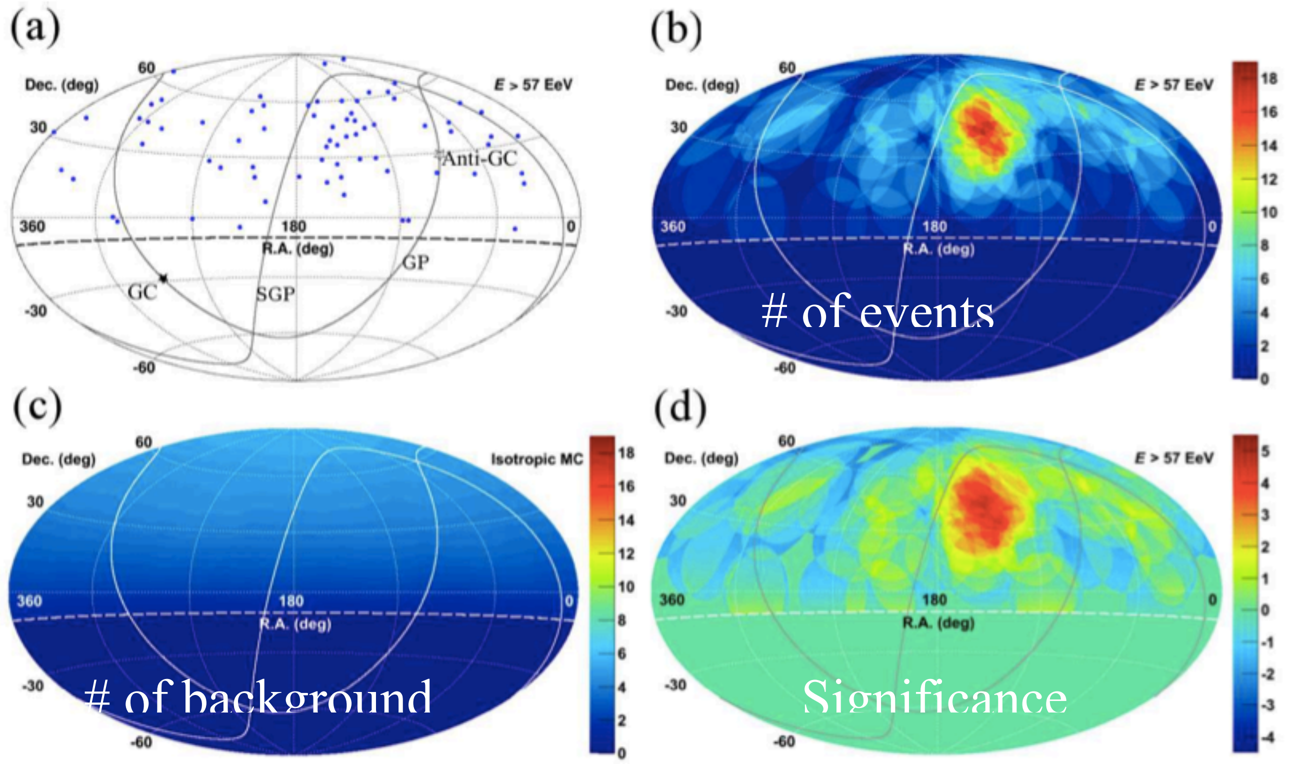
—> intuitively consistent with the composition getting heavier with the energy

- The association of these anisotropies with single sources is not obvious (and actually quite unlikely in my opinion)

—> We are not close to measuring the spectrum and composition of single sources

—> We only have access to the diffuse spectrum and composition (the finer structure is currently unaccessible)





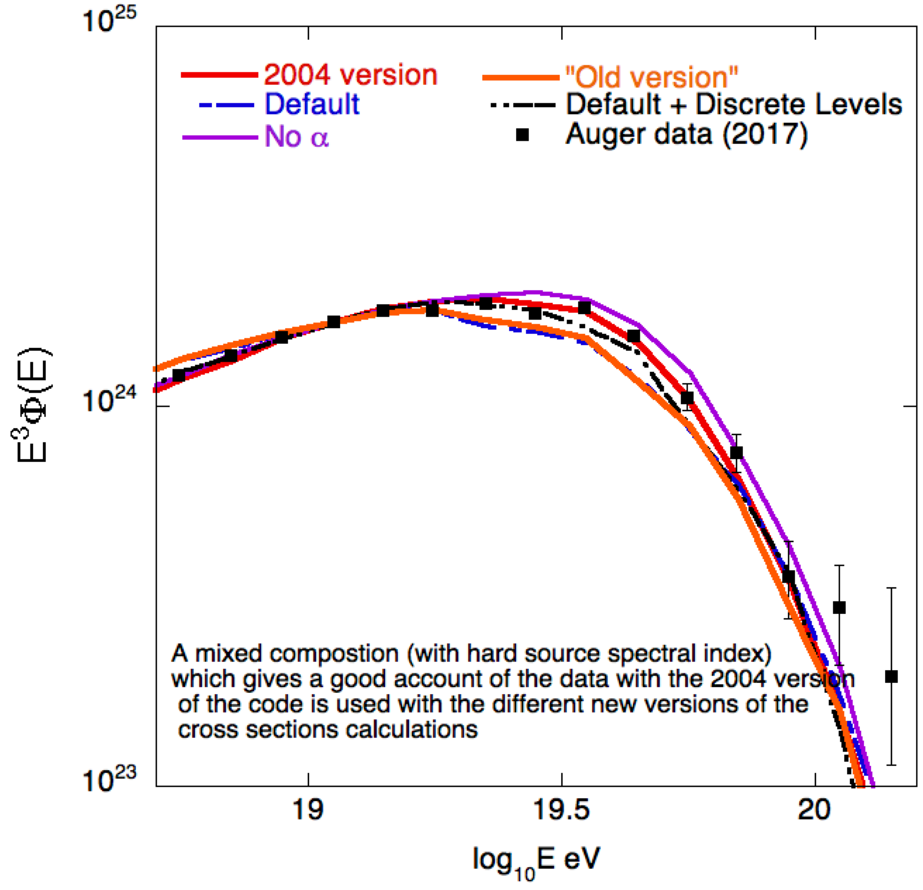
Impact of TALYS settings on the UHECR spectrum and composition after propagation

Assuming :

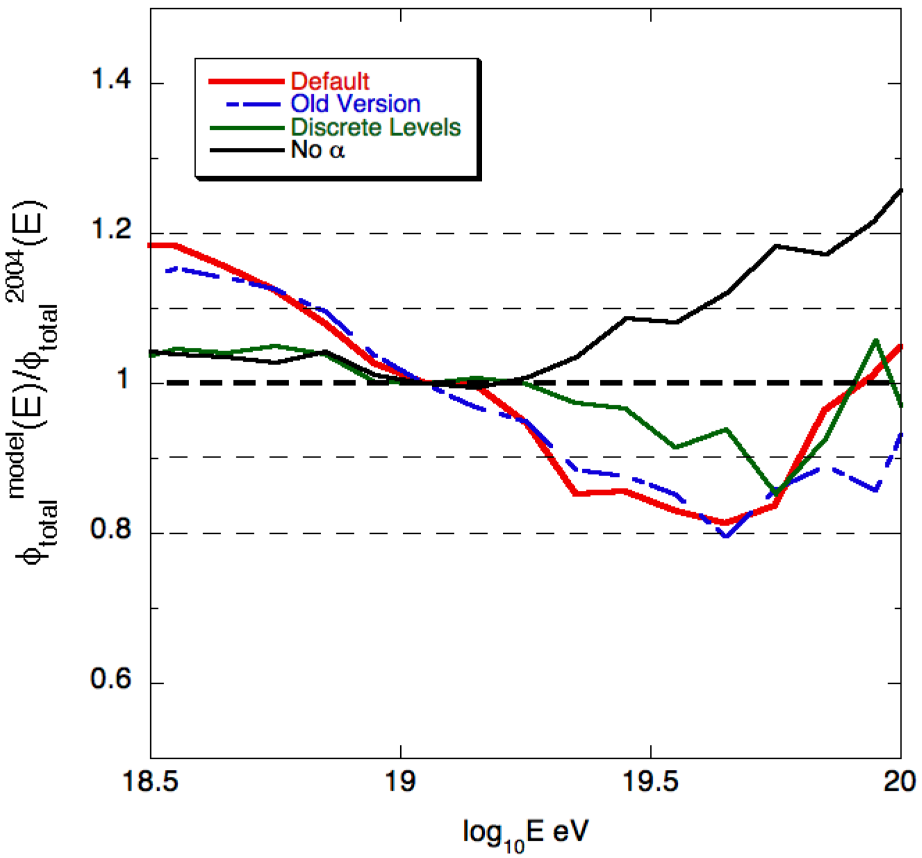
(i) a uniform distribution of extragalactic sources
(ii) standard candle sources emitting a power law spectrum of UHECRs (i.e $N(E) \sim E^{-\beta}$)

A set of parameters which allows a satisfactory reproduction of the UHECR spectrum and composition are (for the code used in Allard et al., 2005) :

(i) a source spectral index β=0.61
(ii) a low maximum energy at the sources $E_{max}(Z)=Z \times 4.10^{18}$eV where Z is the charge of the nucleus
(iii) relative abundances : H=0.1, He=0.15, CNO=0.68, Si=0.07, Fe=0.002 (NB : no astrophysical motivations)



A mixed compostion (with hard source spectral index) which gives a good account of the data with the 2004 version of the code is used with the different new versions of the cross sections calculations



* The different settings result in different branching ratios for the different reaction channels (differences especially strong for the α channels of light nuclei

—> sizeable difference between the different settings however a good agreement with the data can be found for each setting by somewhat modifying the astrophysical parameters (without changing strongly the global picture)

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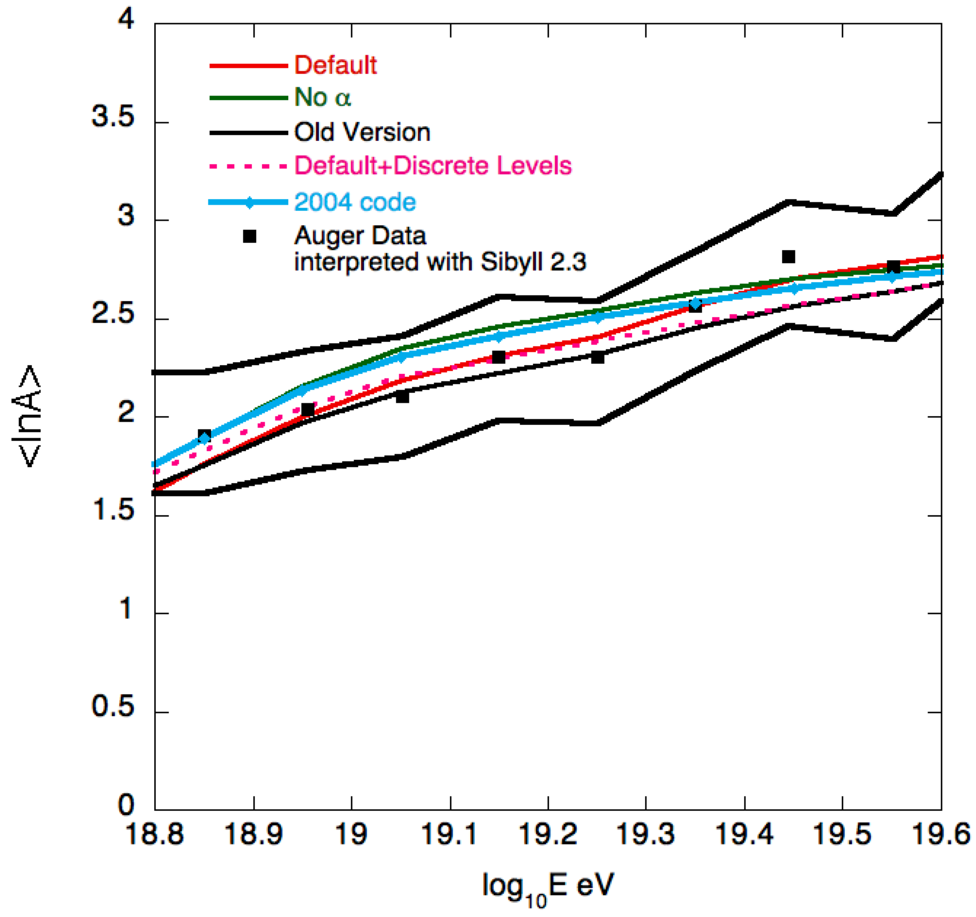
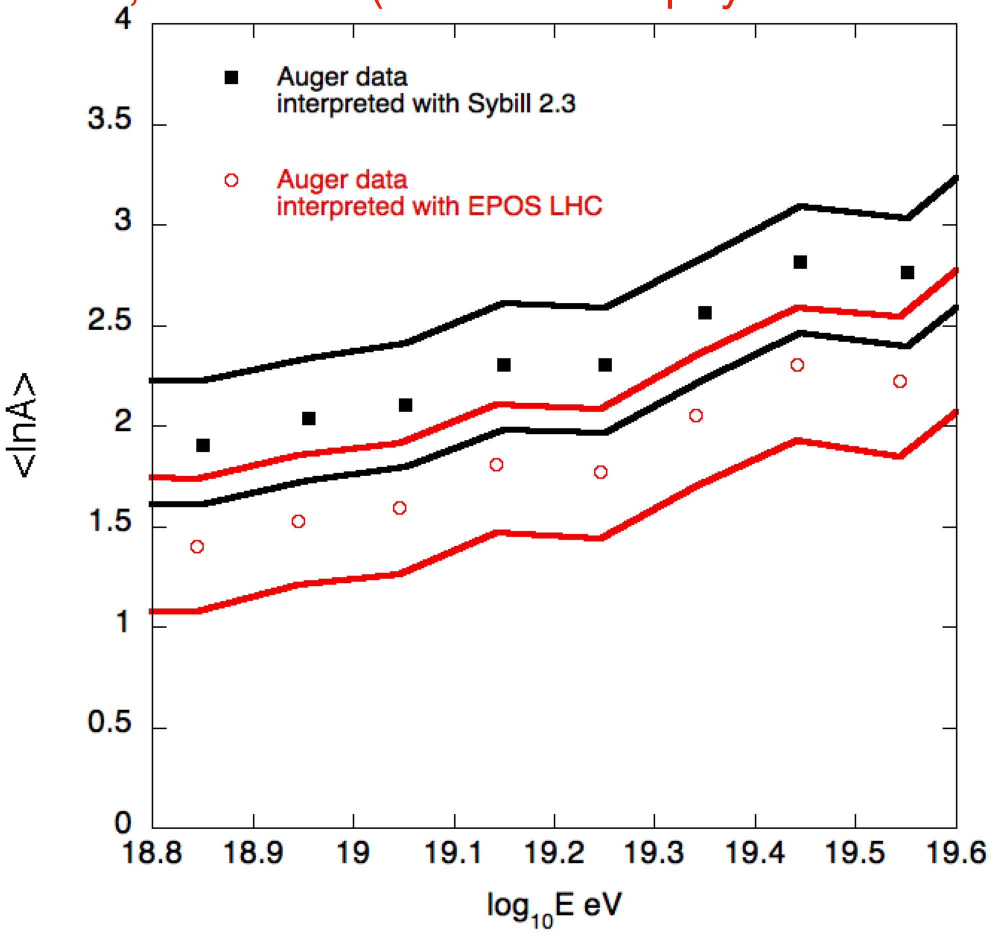




When looking at the energy evolution of <lnA>, one sees that the different settings are very close to each other

—> The differences are small compared to the systematics of the UHECR measurements and to the uncertainties due to hadronic models used to interpret cosmic-ray data

How does PANDORA fit in this picture?

(i) The accuracy with which UHECR observatories can measure the composition is limited (shower to shower fluctuation, modelling of hadronic interactions)

(ii) We have only access to the diffuse UHECR spectrum and composition due to the low level of the anisotropies detected so far

(iii) The current conclusion we can draw from the evolution of the diffuse spectrum and composition (i.e the fact that the maximum energy at the source should be low) does not require very precise GDR cross sections

—> There are currently limitations to our understanding of UHECR physics which are stronger than the uncertainties on GDR cross sections

—> At first sight, new measurements and better modelling of cross sections are not going to change drastically our understanding of UHECR physics

—> **However** new measurements can give better constrains, especially for light nuclei GDR cross sections (which are difficult to model theoretically at least in TALYS) —> can only make UHECR propagation calculations more robust

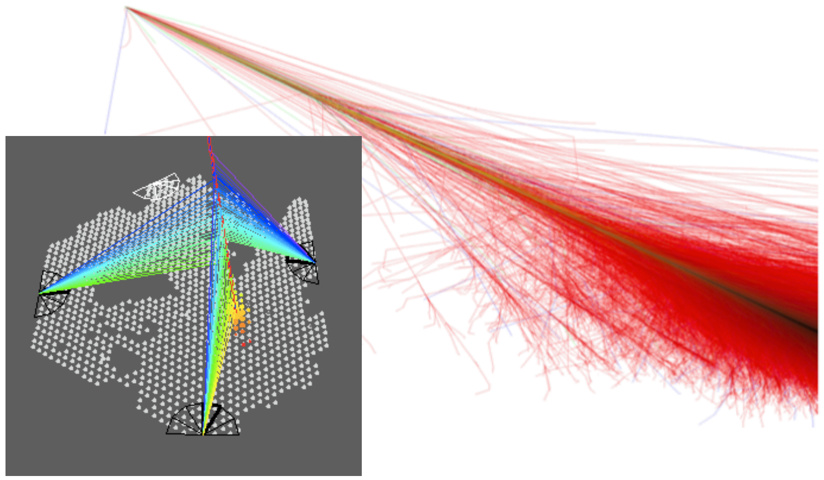
—> Also true for UHECR acceleration calculations

(not mentioning that the current most important limitations, mentioned above, could be alleviated in the years to come)

Thank you !

Backup

Outline



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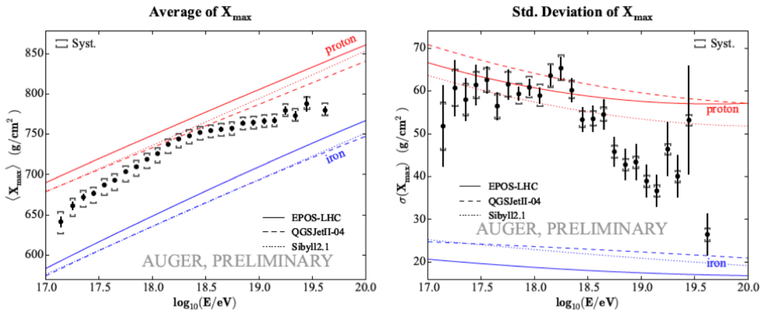
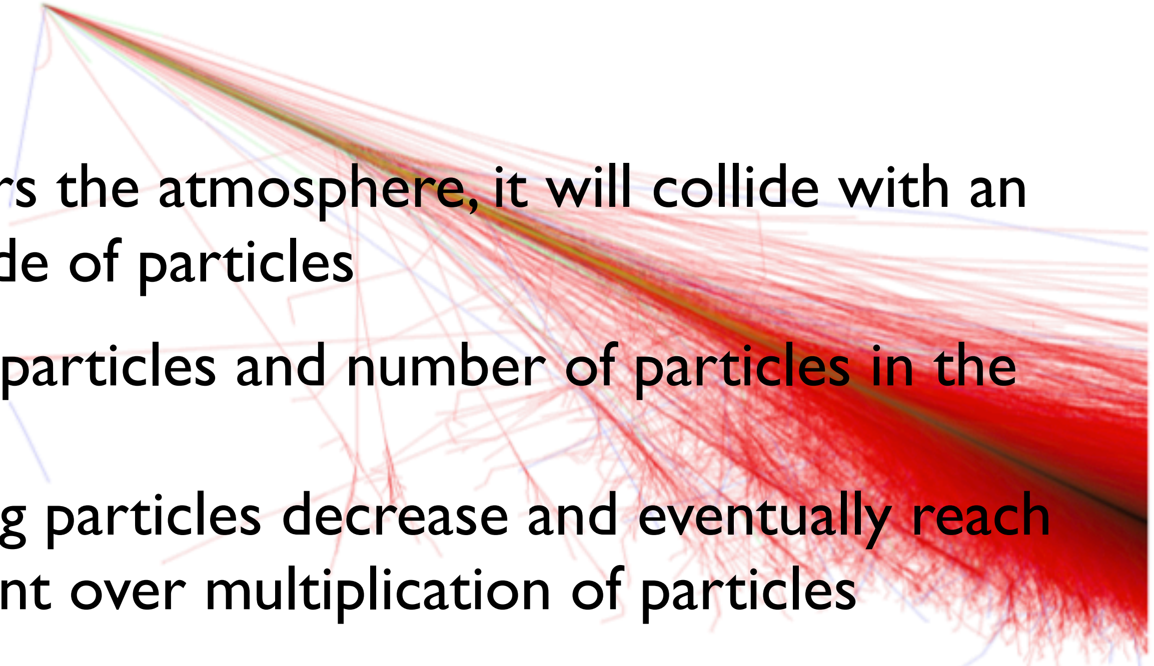


A few simple facts about air showers



- 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

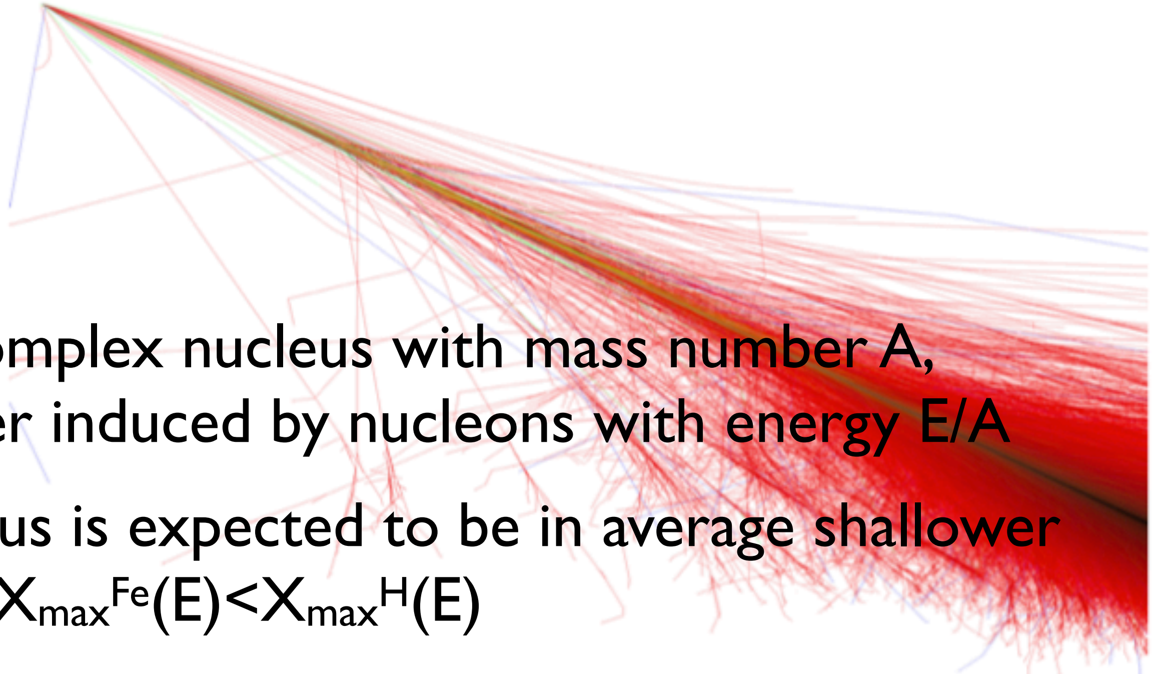
- The shower will develop over many generations of particles and number of particles in the shower increase before reaching a maximum
—> as the development goes, the energy of the leading particles decrease and eventually reach a critical energy at which absorption becomes dominant over multiplication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

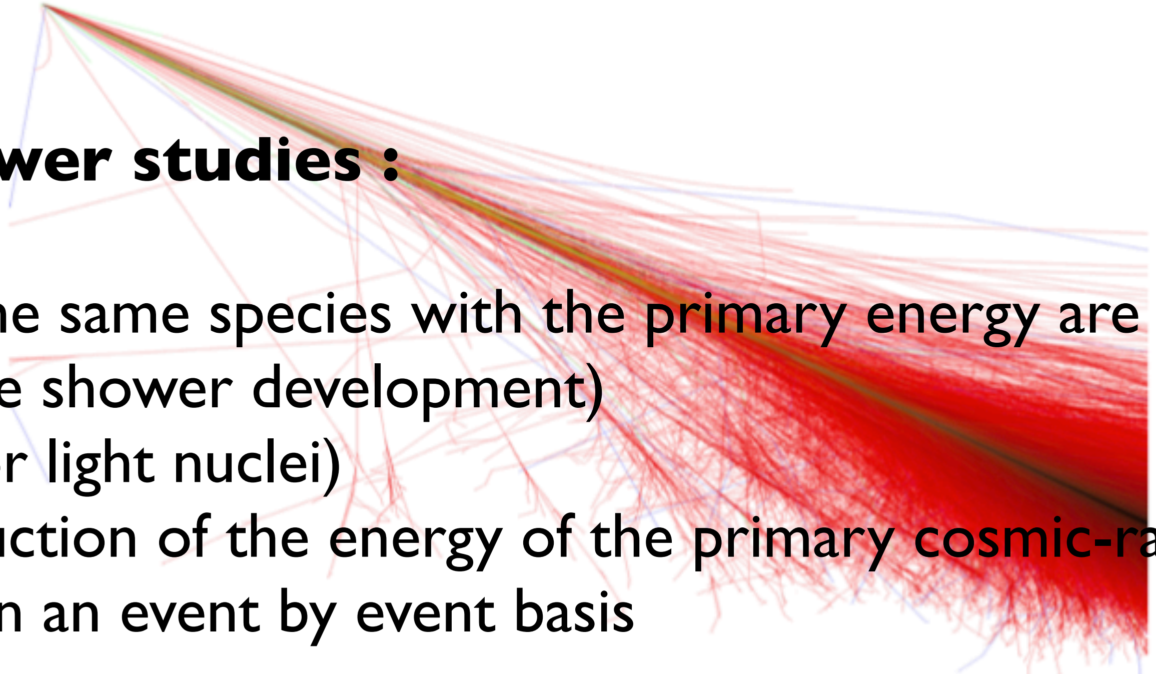
—> the development of a shower induced by a nucleus is expected to be in average shallower than that of a proton with the same initial energy, e.g, $X_{max}^{Fe}(E)<X_{max}^{H}(E)$

—> 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, $N_{\mu}^{Fe}(E)<N_{\mu}^{H}(E)$

—> **X_{max} and N_{μ}** (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)

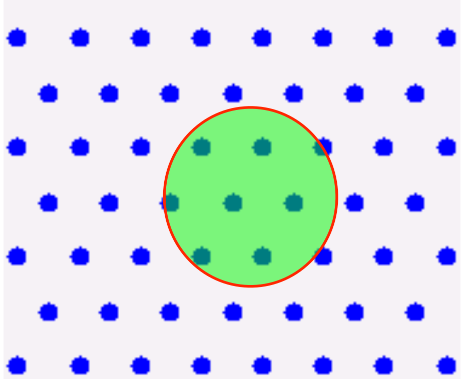
—> hadronic model dependence is also currently a strong limitation for composition studies of VHE and UHE cosmic-rays

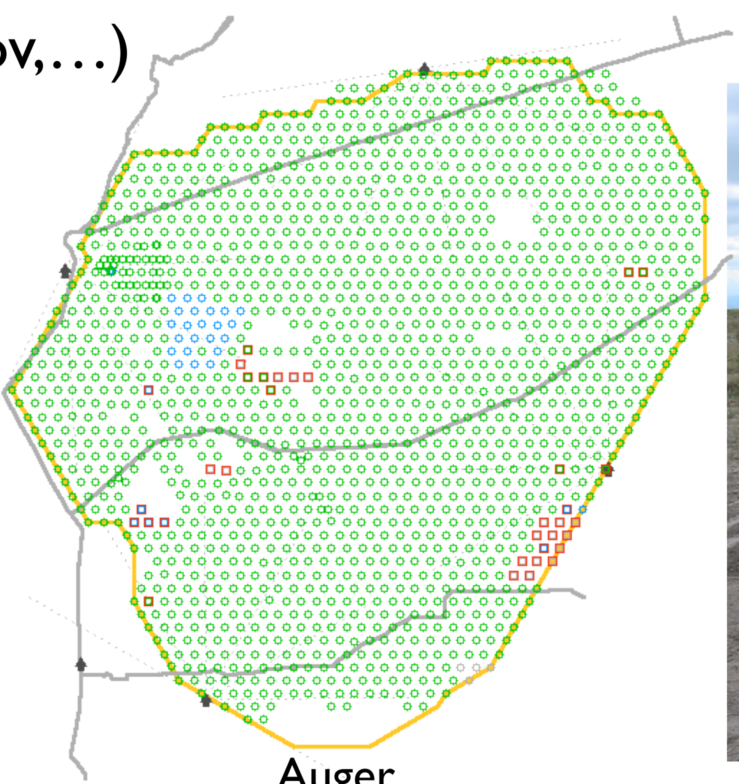
due to the conjonction of (i) and (ii) the best that can be done for CR composition is to separate large datasets into light/intermediate/heavy CR components and search for features which seem not to depend on the hadronic model used

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
  - Auger, Telescope array ($10^{18.5}$- >10^{20} eV) : surface 3000 km^2, 1600 detectors, spacing 1500 m

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

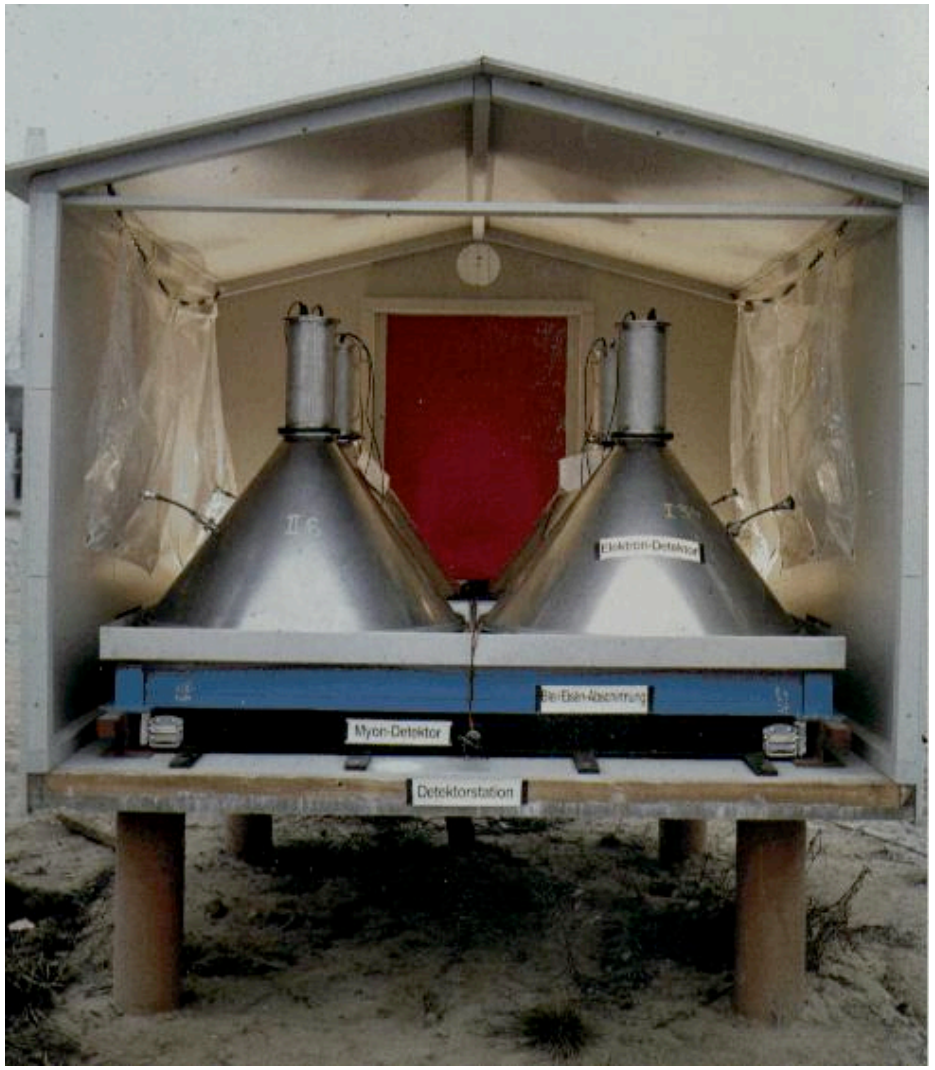




Auger

Kascade

Ground array detectors



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

Kascade

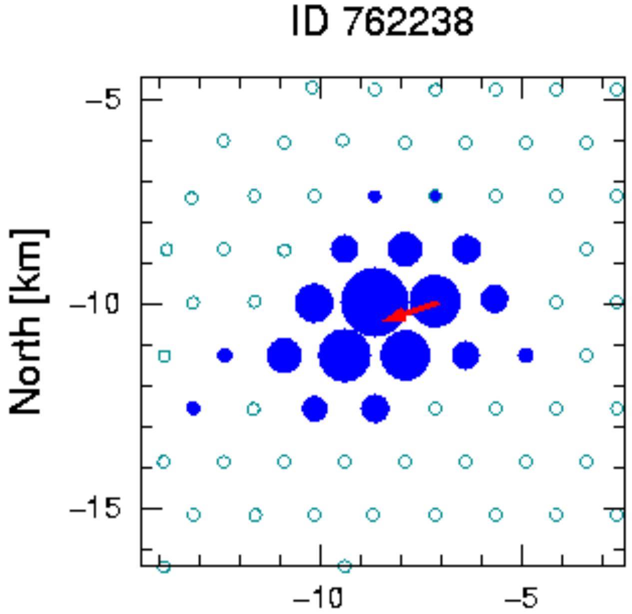
KIT campus

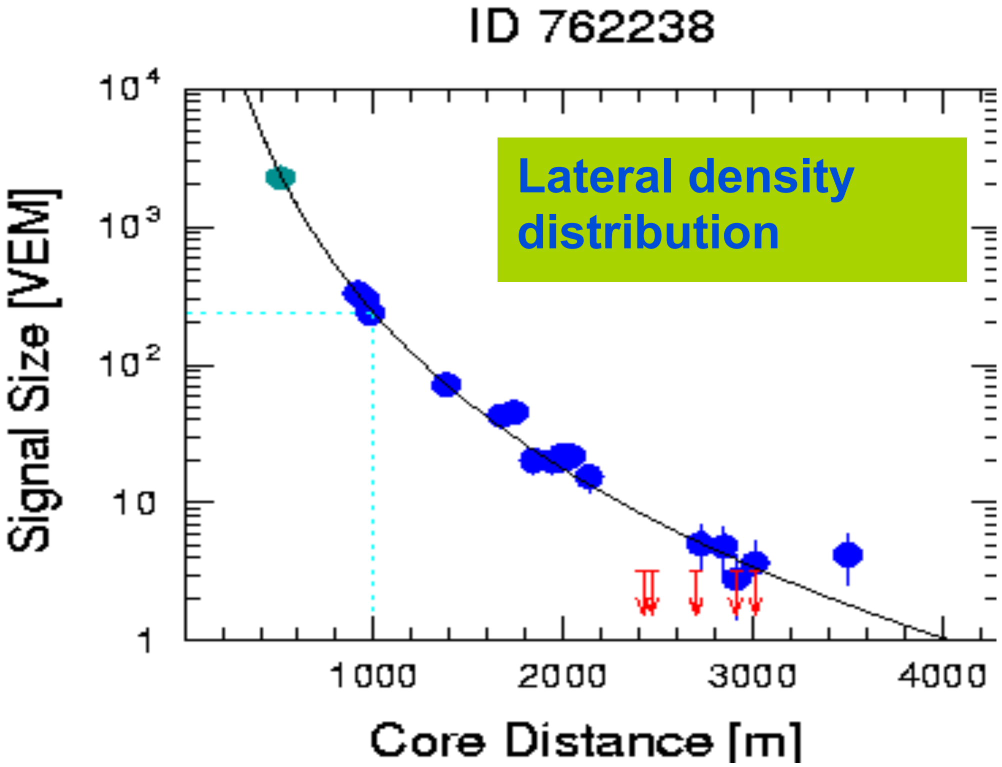
Ground array detectors

- 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

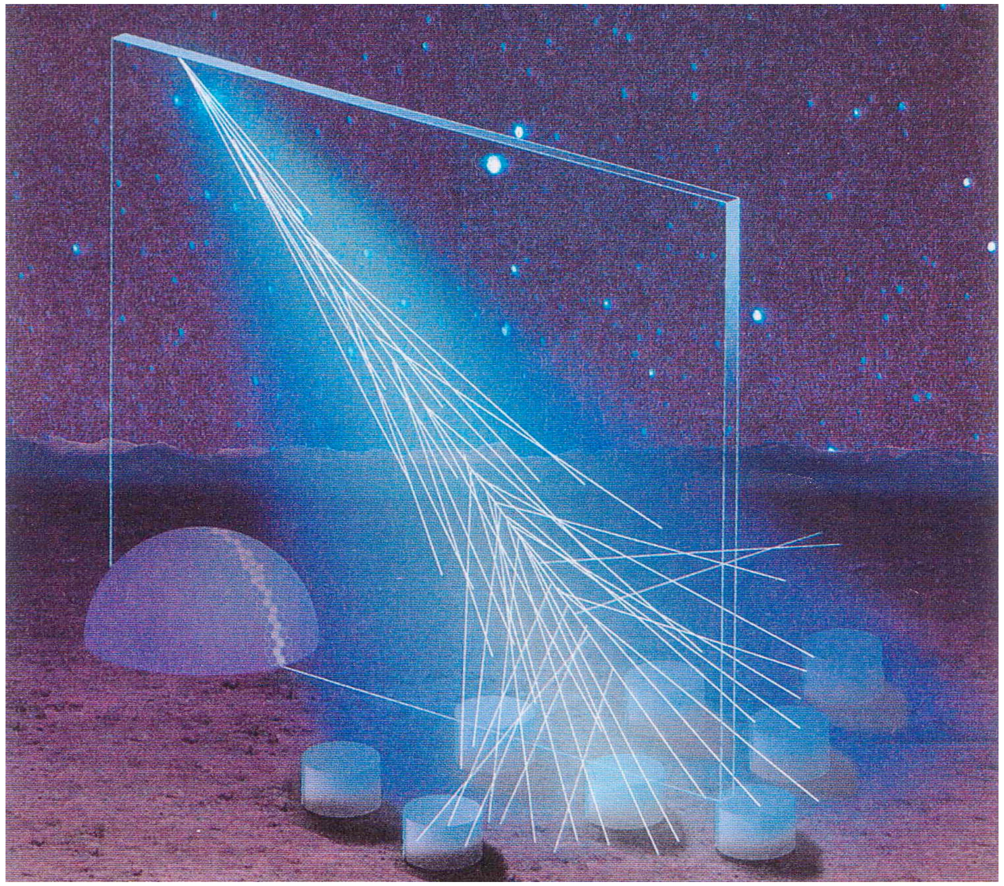
The relation muon number/composition is extracted from air shower simulations

—> Hadronic model dependent





Fluorescence detectors



- The fluorescence (UV) emitted by N_2 molecules exited by the air shower e^+e^- is detected

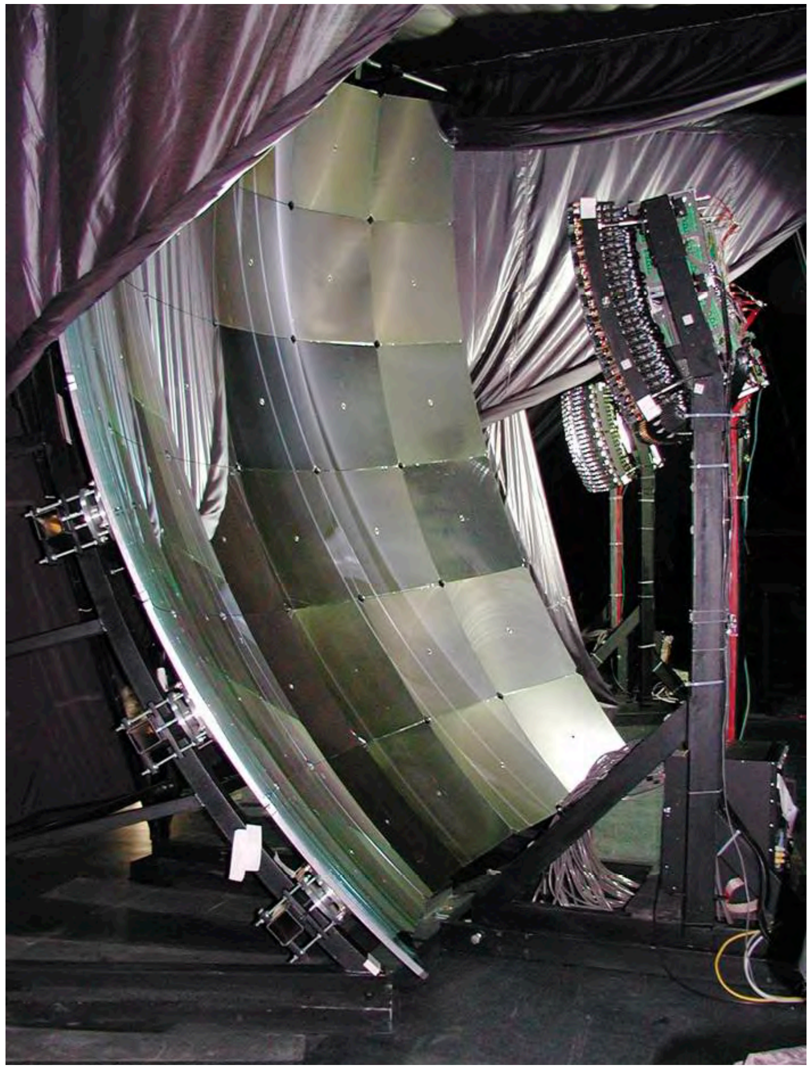
- Fluorescence light proportional to the number of electromagnetic particles in the shower

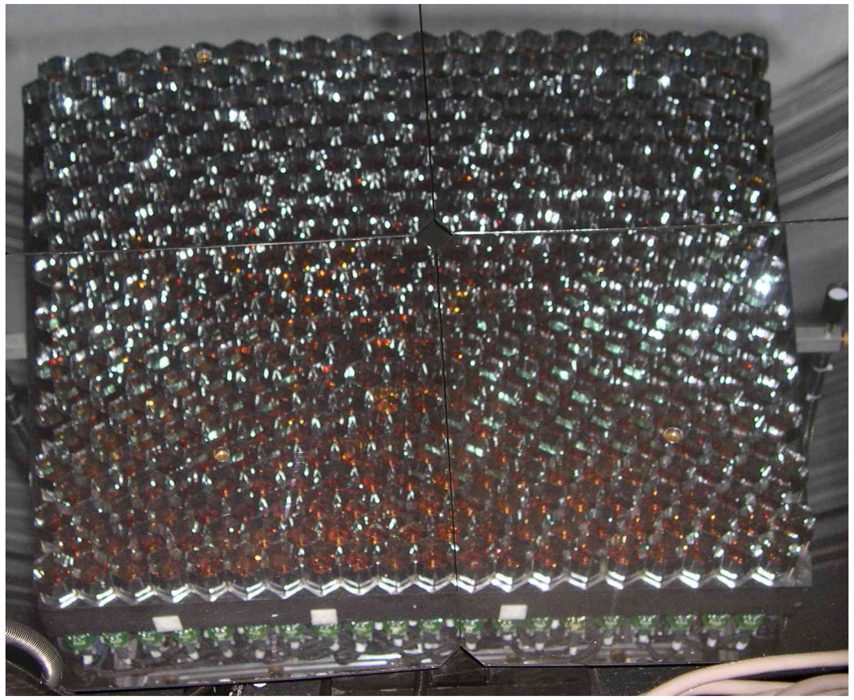
-> proportional to the energy of the cosmic-ray

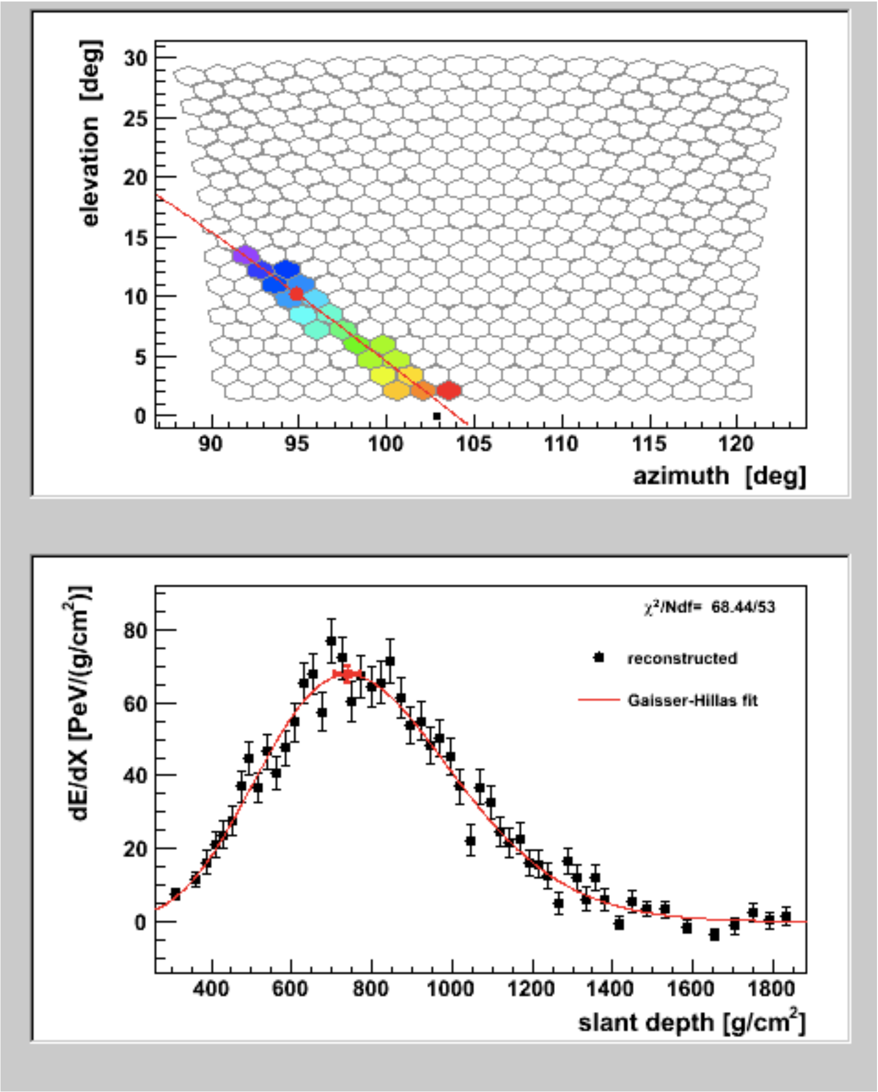
- UV light can only be detected by moonless nights -> ~15% duty cycle
- Calorimetric measurement -> less dependent on shower simulations
- Technique pioneered by the Fly's eye experiment in the 80's (now used by Auger and TA !)

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

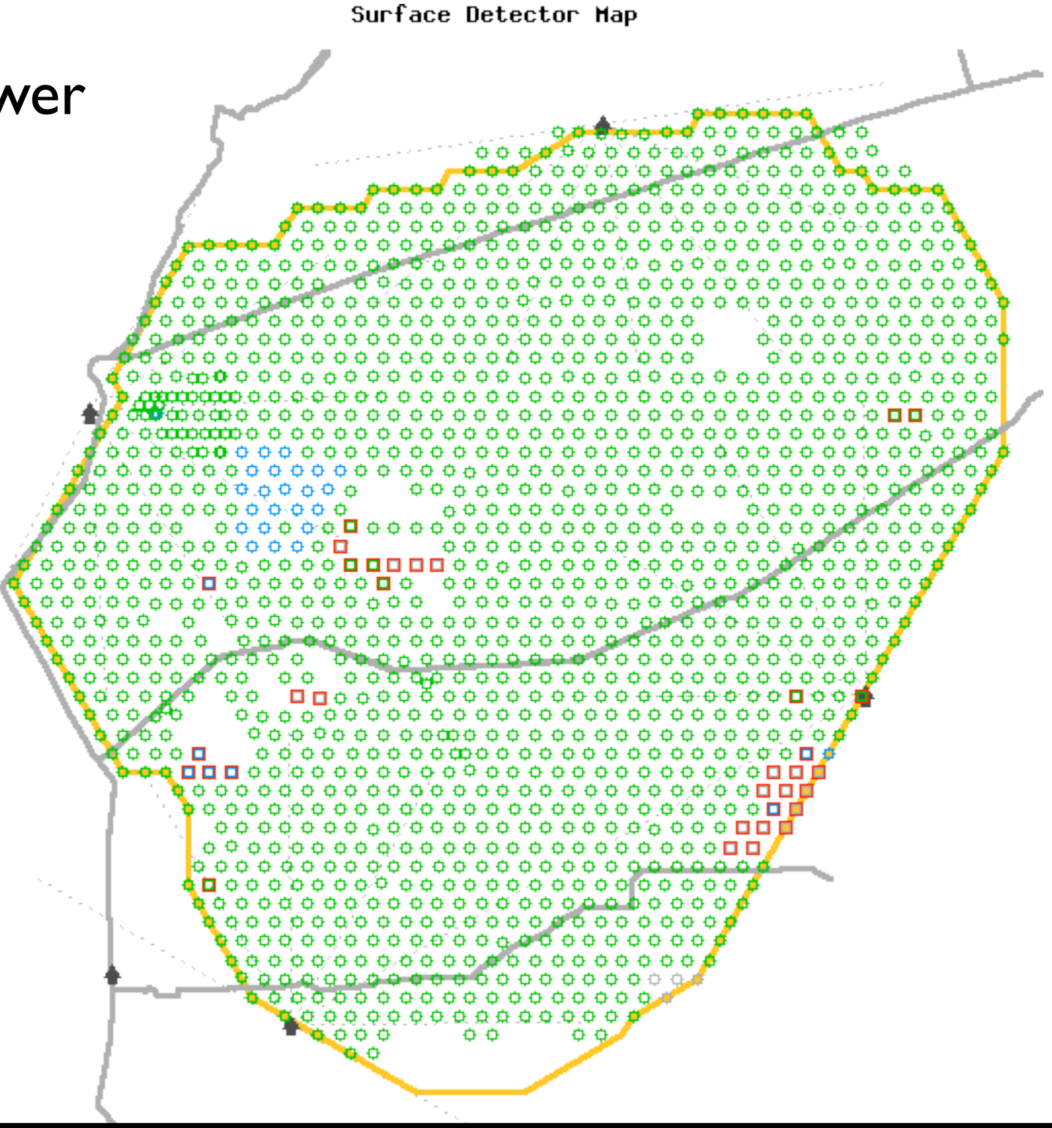
(Telescope Array is based on a similar principle)

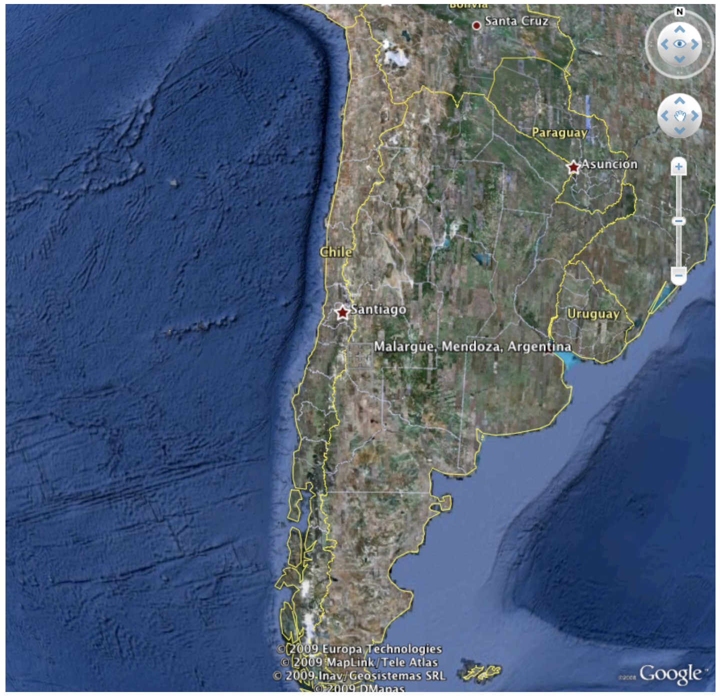
- Located in Malargue (Mendoza, Argentina, 1400m a.s.l
- 1600 Water Cerenkov Tanks, spacing 1500 m

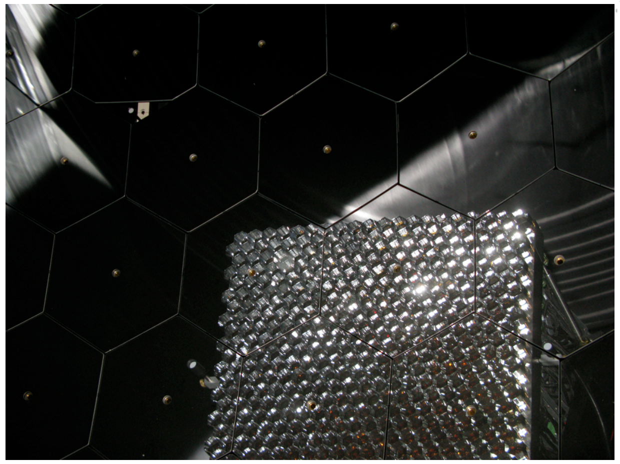
-> ground array surface 3000 km^2

- 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

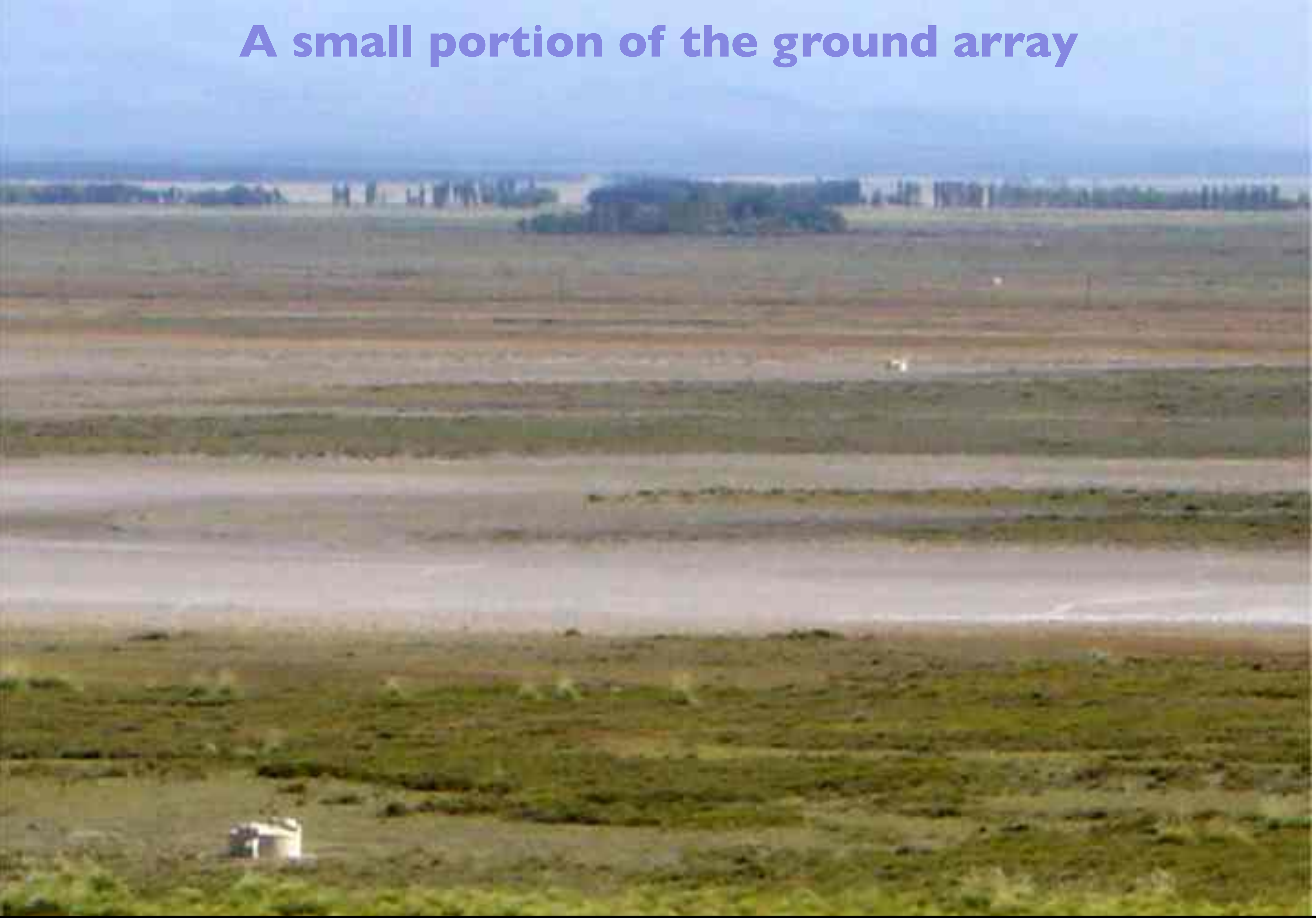




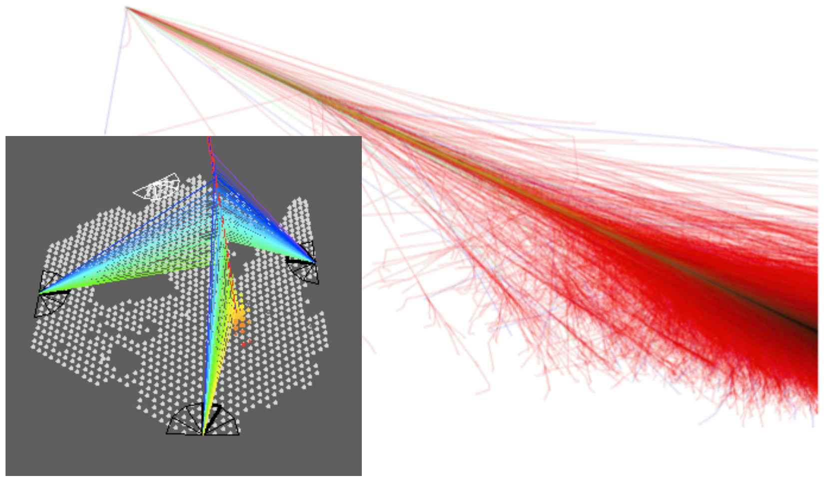


Pierre Auger Observatory the hybrid giant

A small portion of the ground array



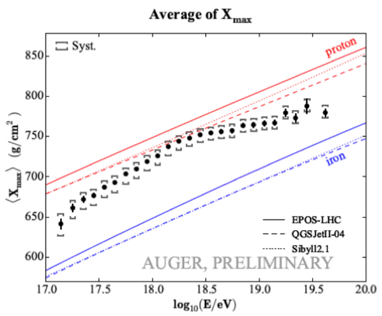
Outline

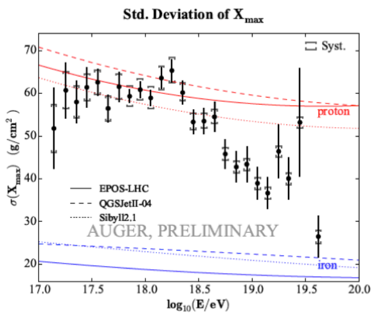


- Indirect detection of cosmic-rays, a brief introduction
  - Detection techniques (ground arrays and fluorescence detectors)

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

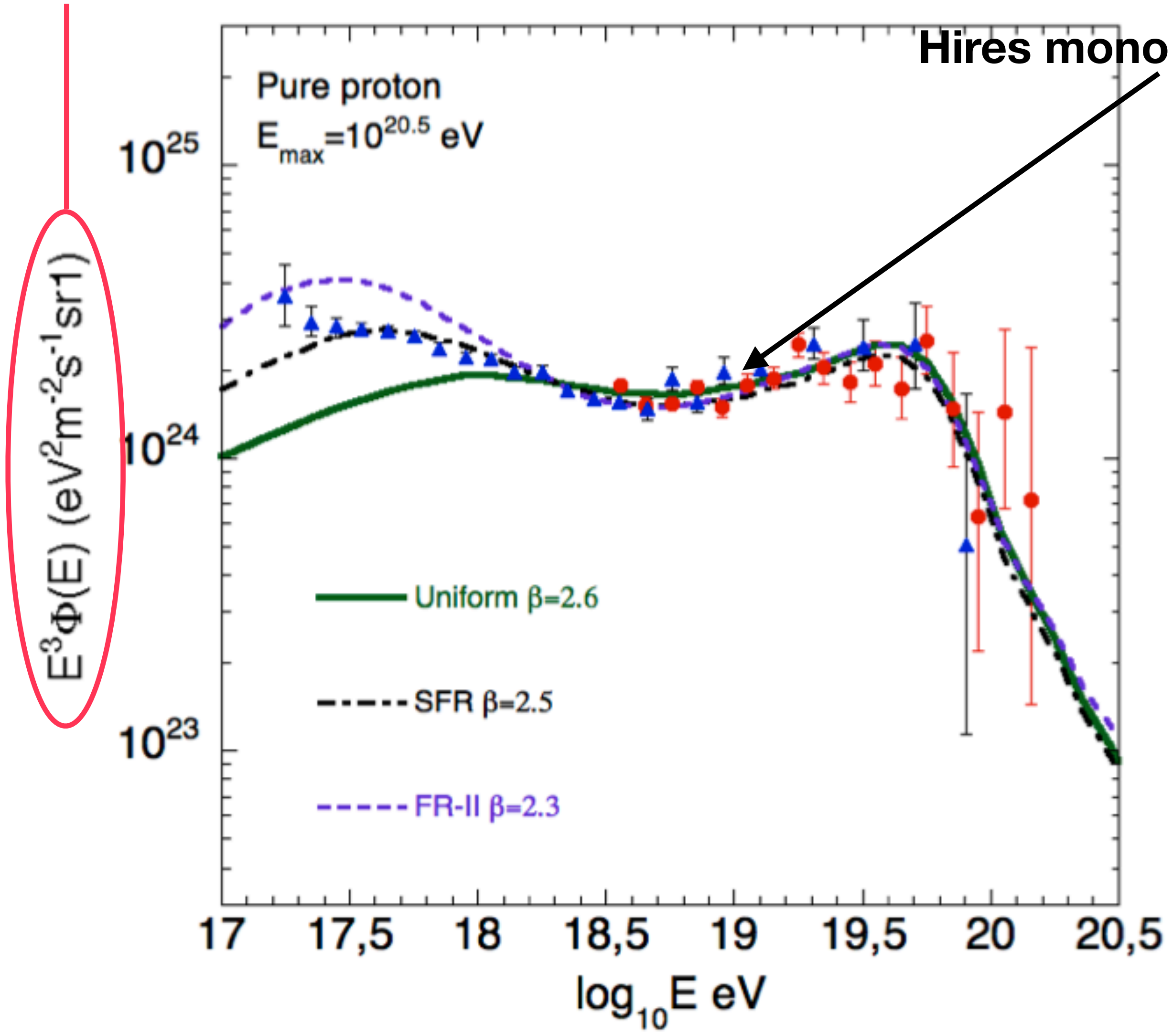
- **Extragalactic cosmic-rays phenomenology**
  - **Propagation of protons and nuclei**





- Key results obtained in the last few years and their possible interpretation
  - Auger composition results
  - Anisotropies
  - How does PANDORA fit in this picture?

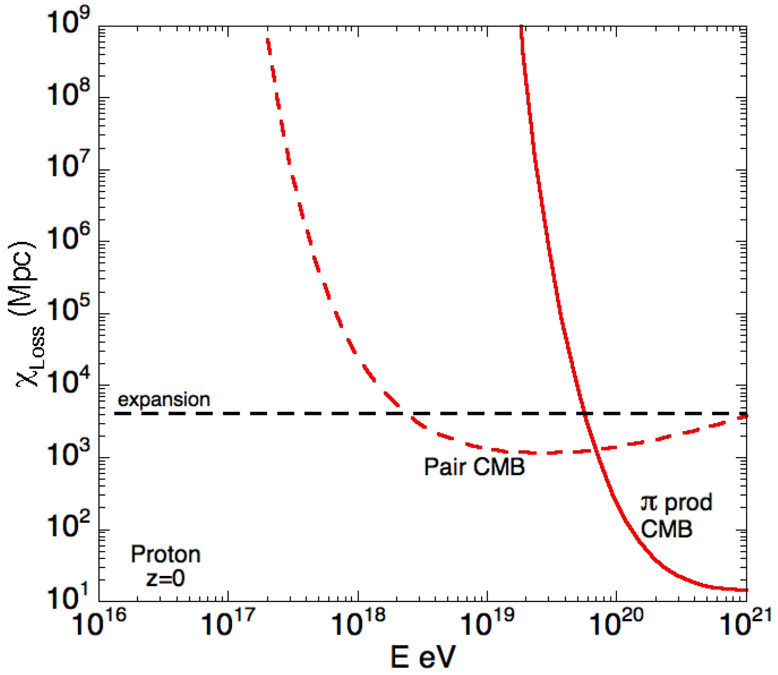
A special case : pure proton composition



E³×(diff. flux)

Hires mono spectrum (2005)

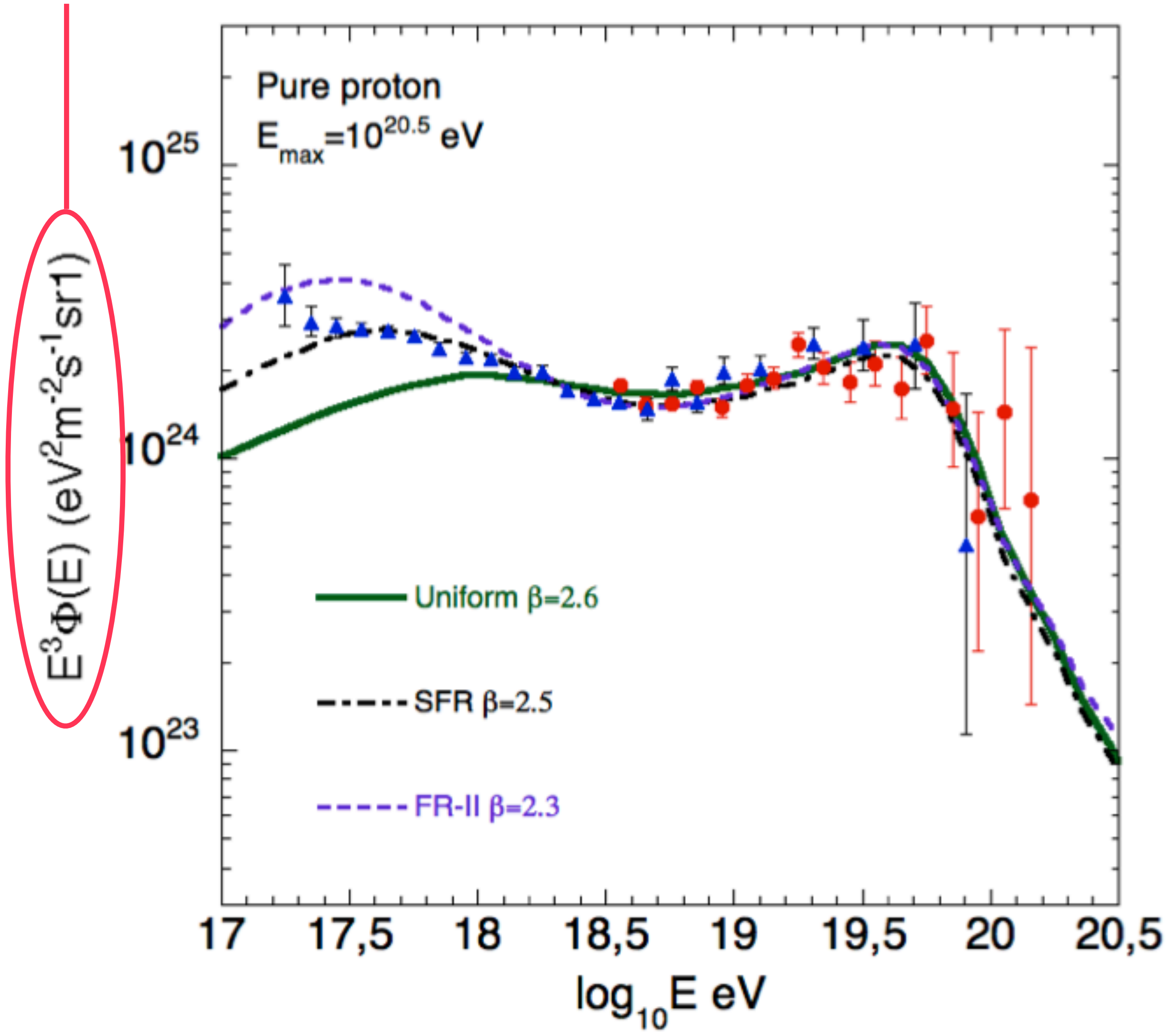
The ankle can be fitted by the extragalactic component itself : pair production dip->the ankle feature has nothing to do with the transition (model developed by Berezinsky et al., 2002-2007)



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

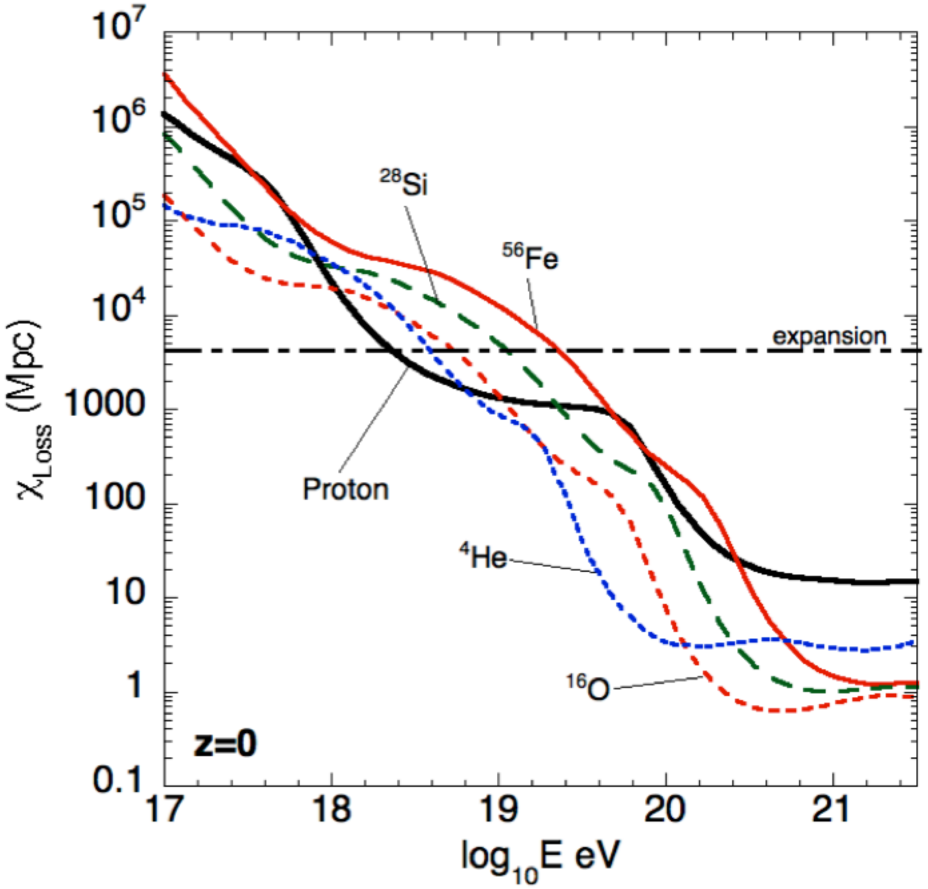
A special case : pure proton composition

BUT



E³×(diff. flux)

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 attenuation length evolution is different for nuclei
A small added fraction (already ~10%) of heavier (complex) nuclei erases the dip

4 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

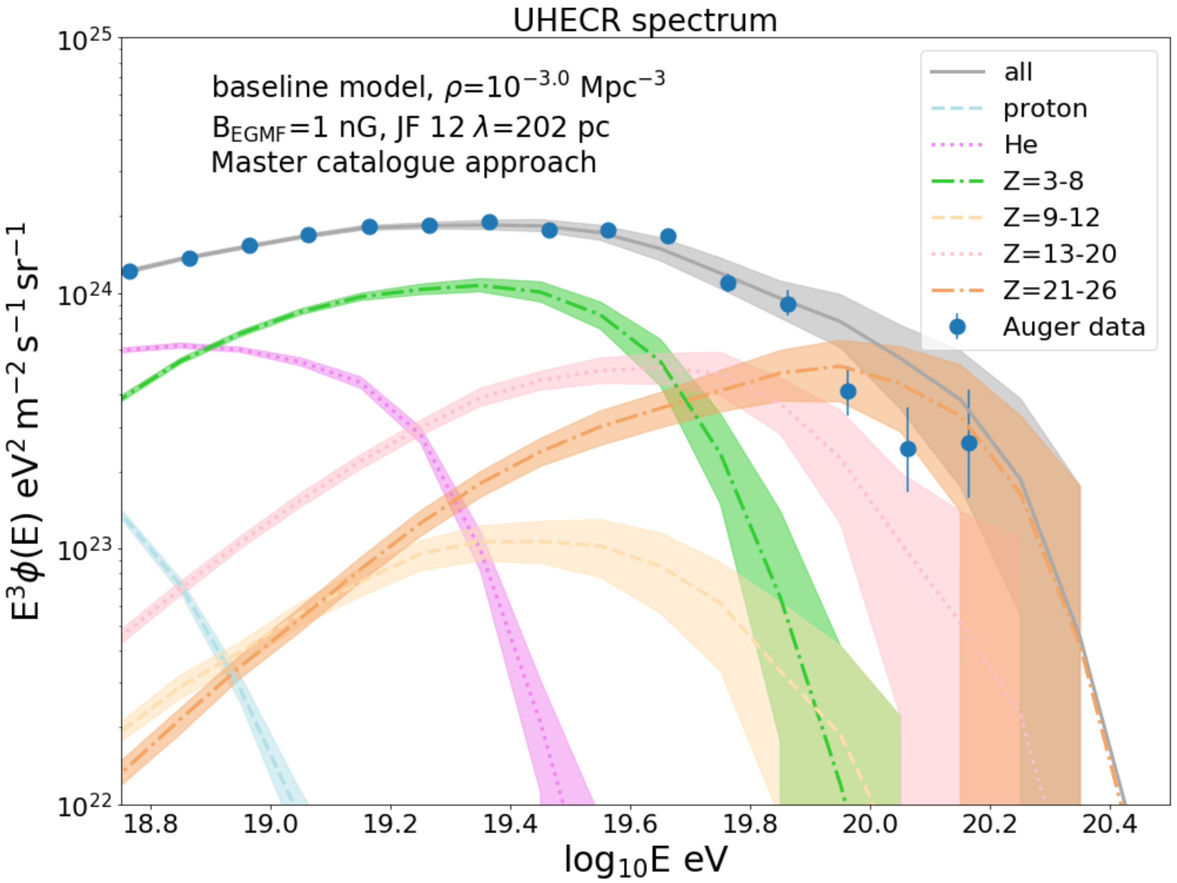
composition

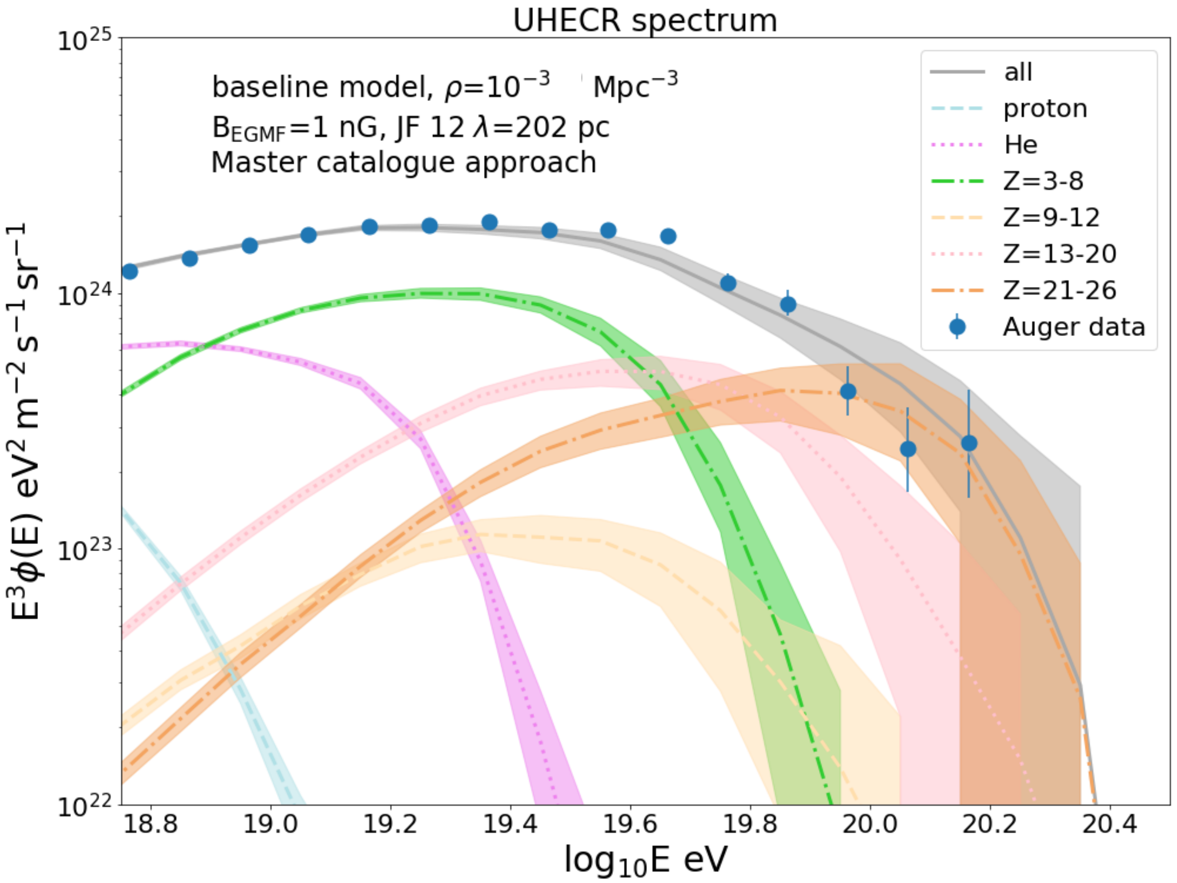
4

Multi-messenger counterparts

cosmogenic γ and ν

Influence of other astrophysical parameters





Same source spectrum and composition model, same maximum energy, same source density but… Sources are picked in 2MRS on the left panel, source are picked in a homogenous and isotropic distribution on the right panel

—> good model in the case of 2MRS which presents an overdensity in local universe, results in a spectrum too soft at the highest energies for the homogenous case

—> amplitude of the difference similar to what we encountered with the different TALYS settings