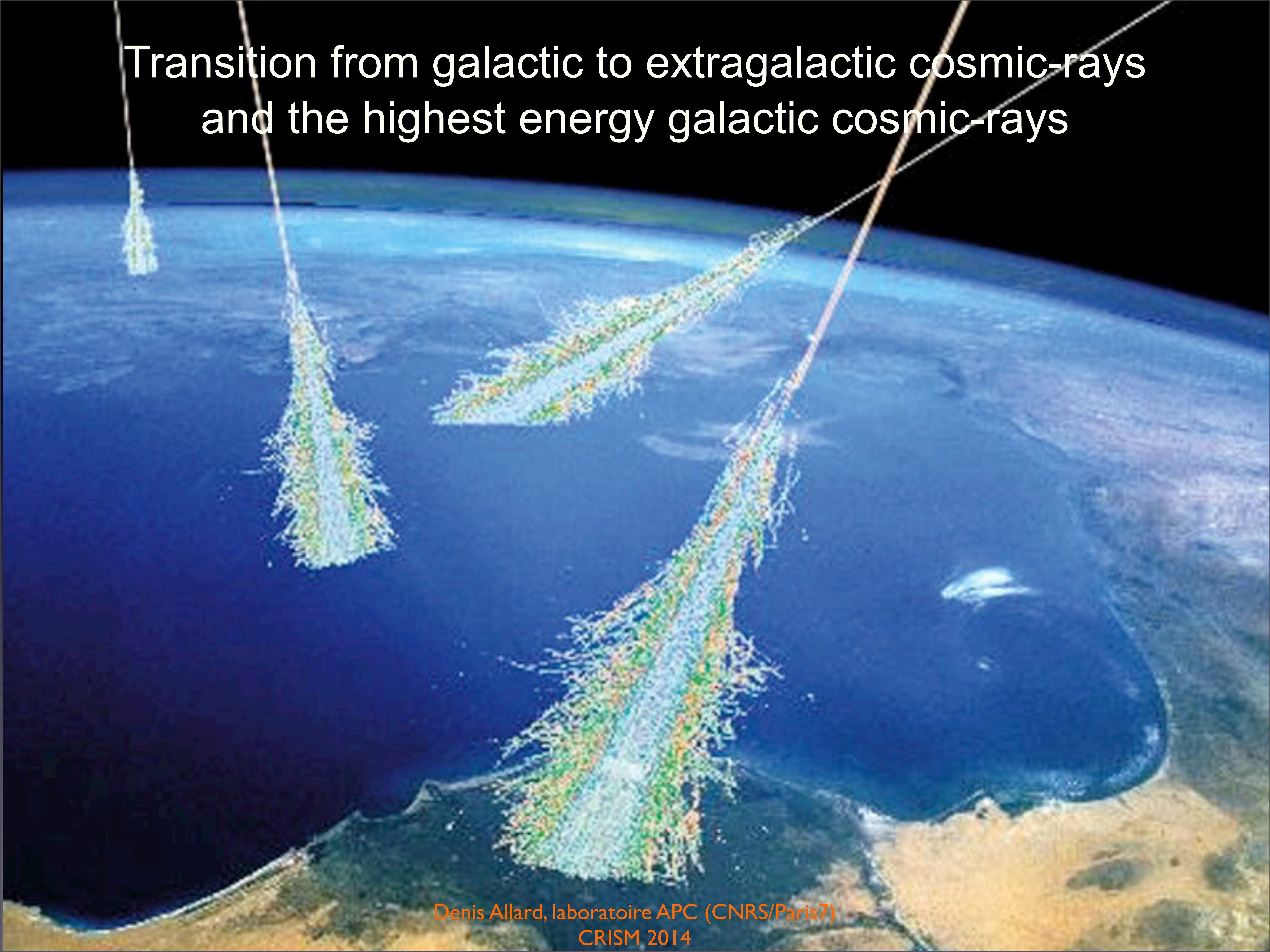
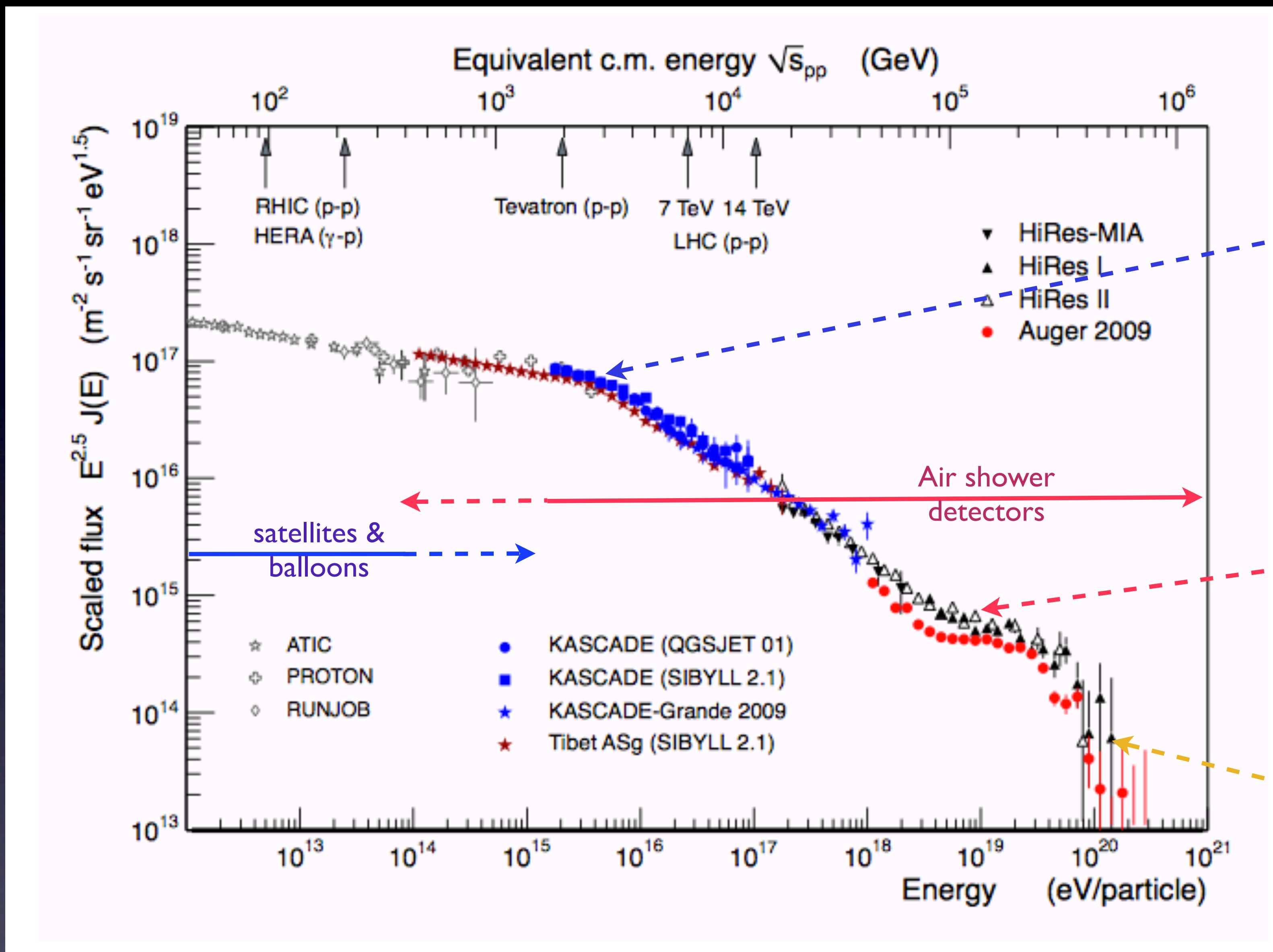
Transition from galactic to extragalactic cosmic-rays and the highest energy galactic cosmic-rays



Denis Allard, laboratoire APC (CNRS/Paris7)
CRISM 2014

The cosmic-ray spectrum



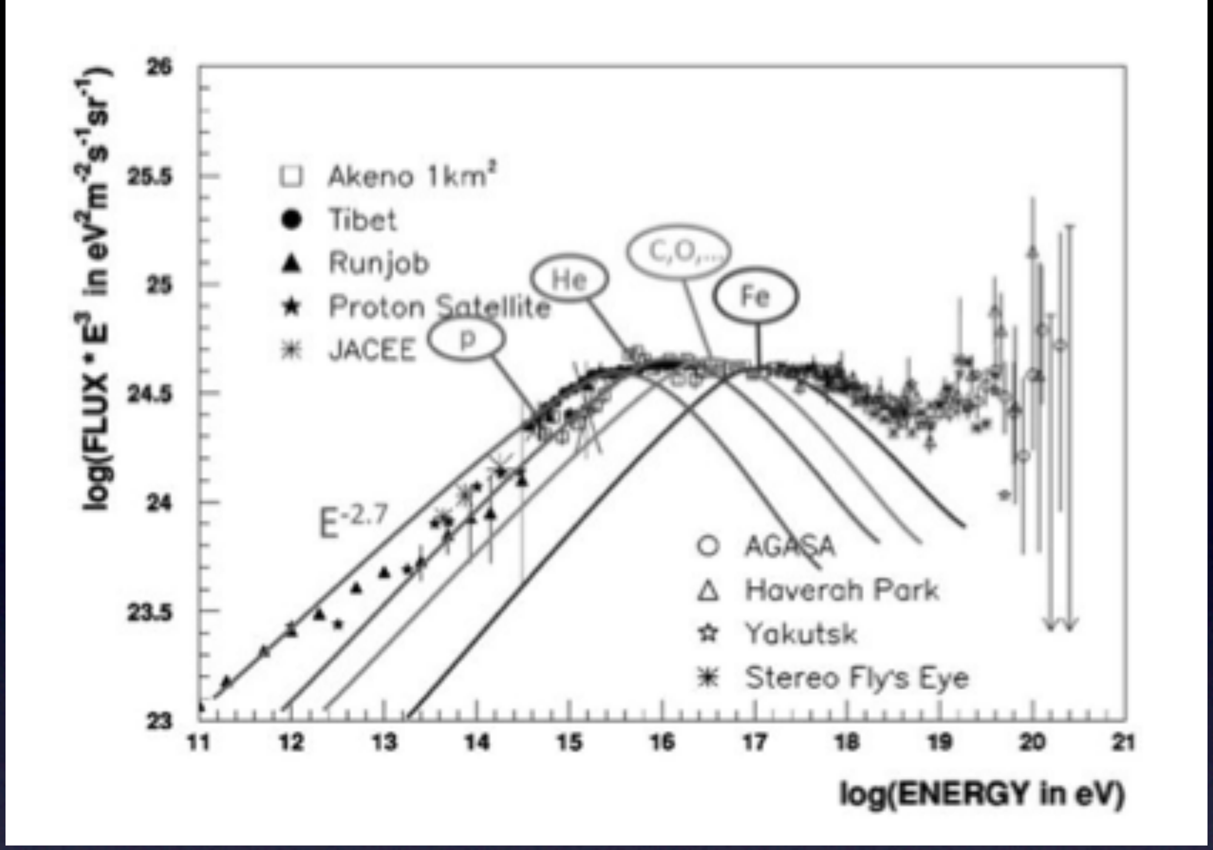
Pierog, 2012

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

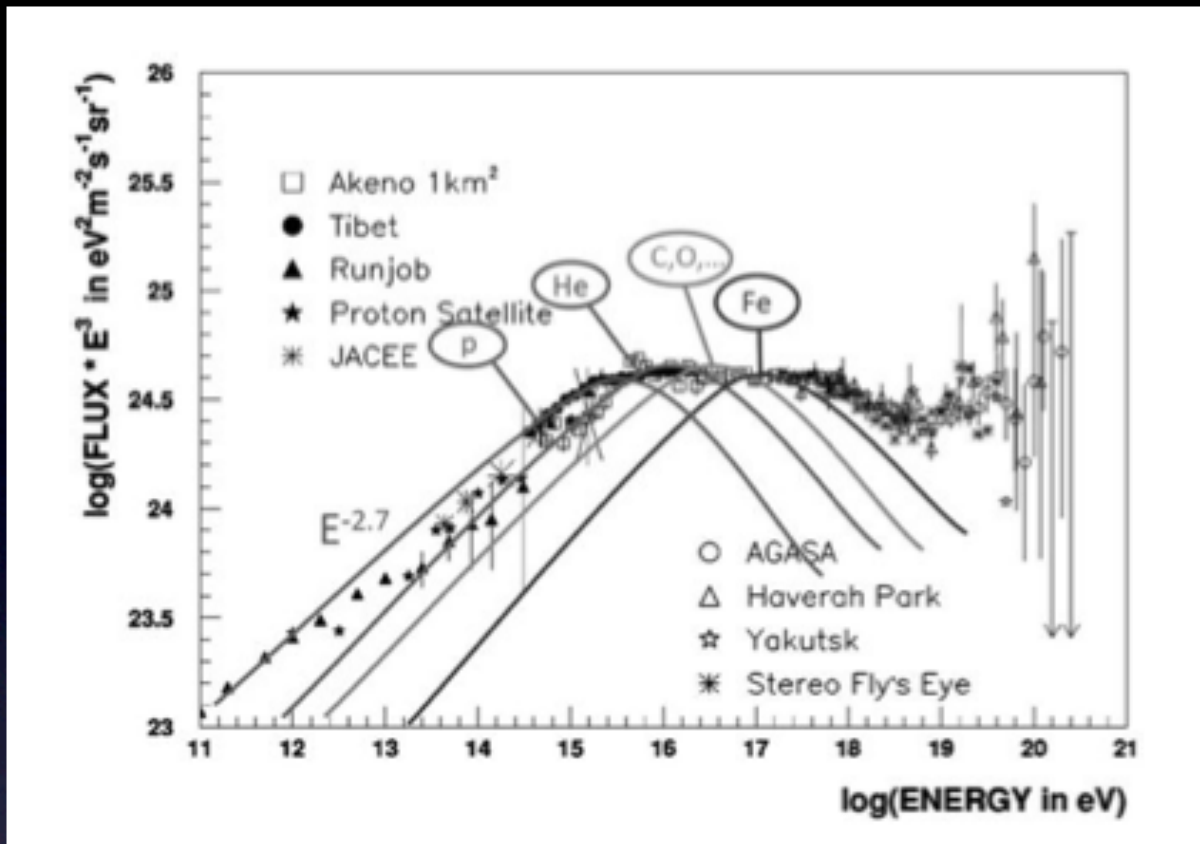
The cosmic-ray spectrum



Longair, High energy astrophysics (2011)

The knee first seen in the late 50's
very soon suspected to be an inflection
of the light galactic component
==> composition getting heavier in the
energy decade following the knee confirmed
by most experiments
(see Unger & Kampert, 2012)

The cosmic-ray spectrum



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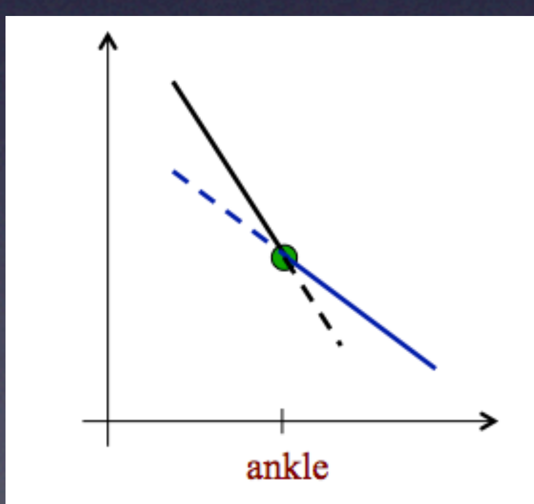
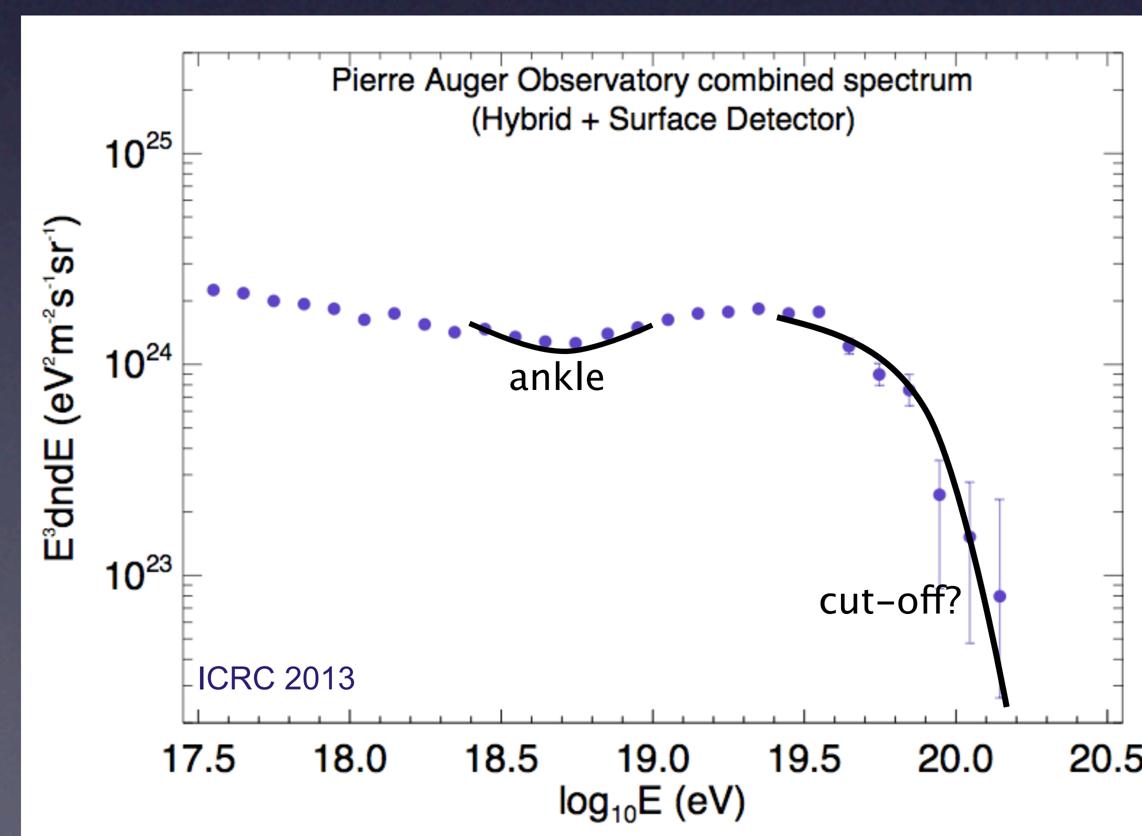


ankle : transition from a softer to
a harder component
==> very natural feature for the
transition from galactic to
extragalactic cosmic-ray



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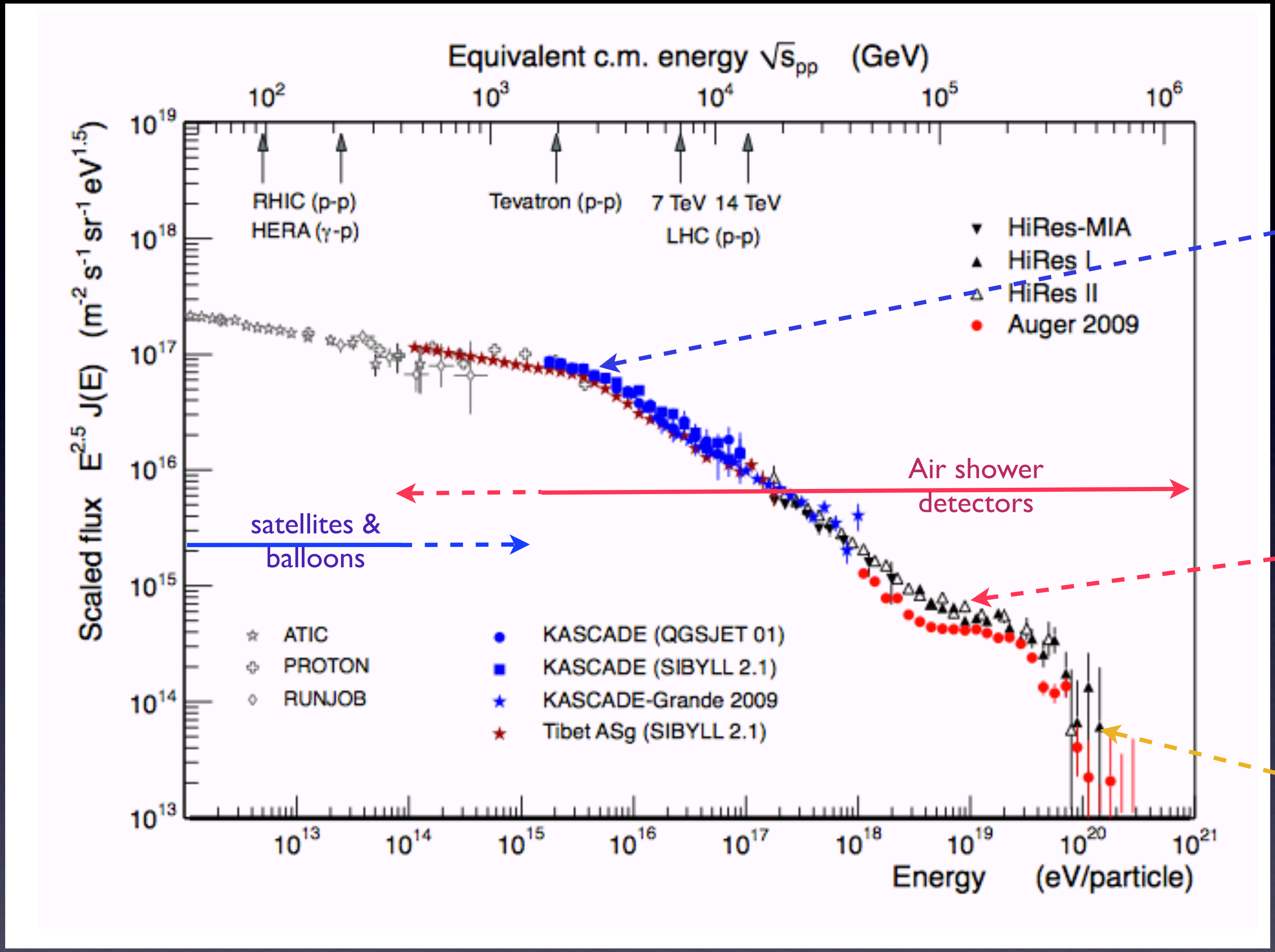

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$E \sim 3\text{-}4.10^{15}$ eV

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

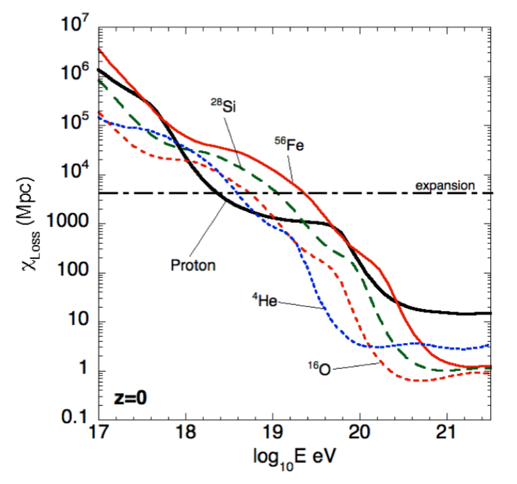
High energy cut-off
$E \sim 3\text{-}5.10^{19}$ eV

There are three orders of magnitude in energy between to the knee and the ankle
what is happening on this energy range?

Plan of the talk

• Hints from extragalactic cosmic-ray propagation :

where could an extragalactic component start to dominate? role of the composition?



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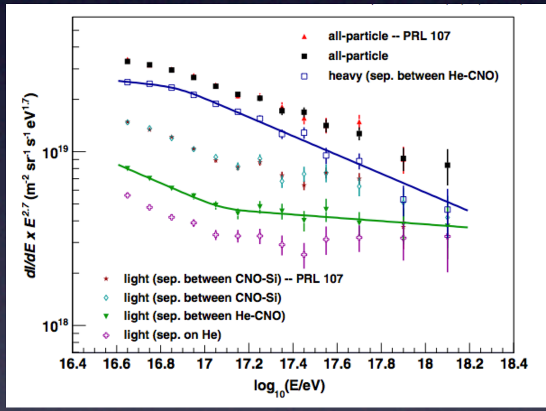
can a coherent picture emerge?



• The future :

the key experiments of the years to come (at least, two examples)

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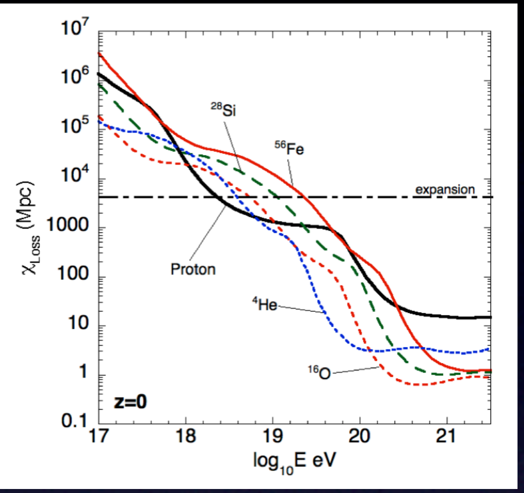

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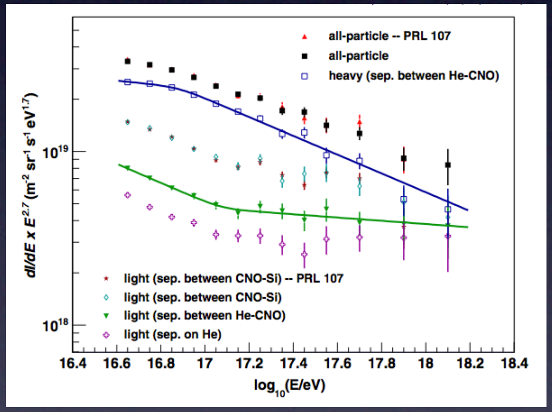
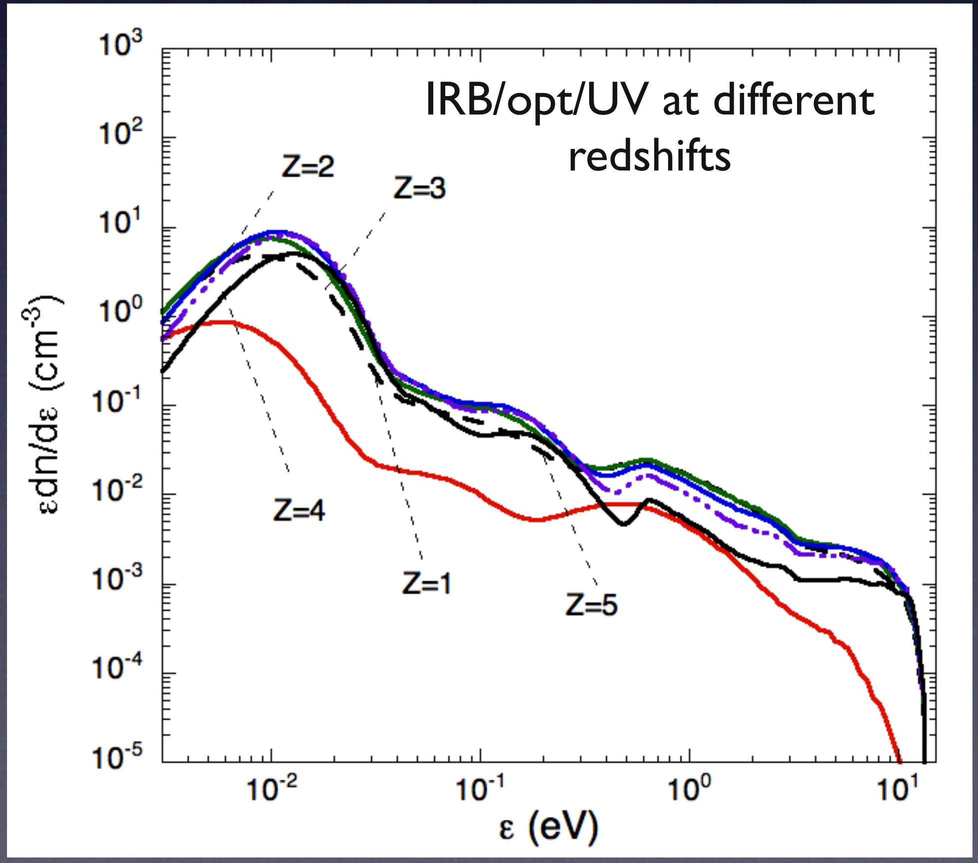


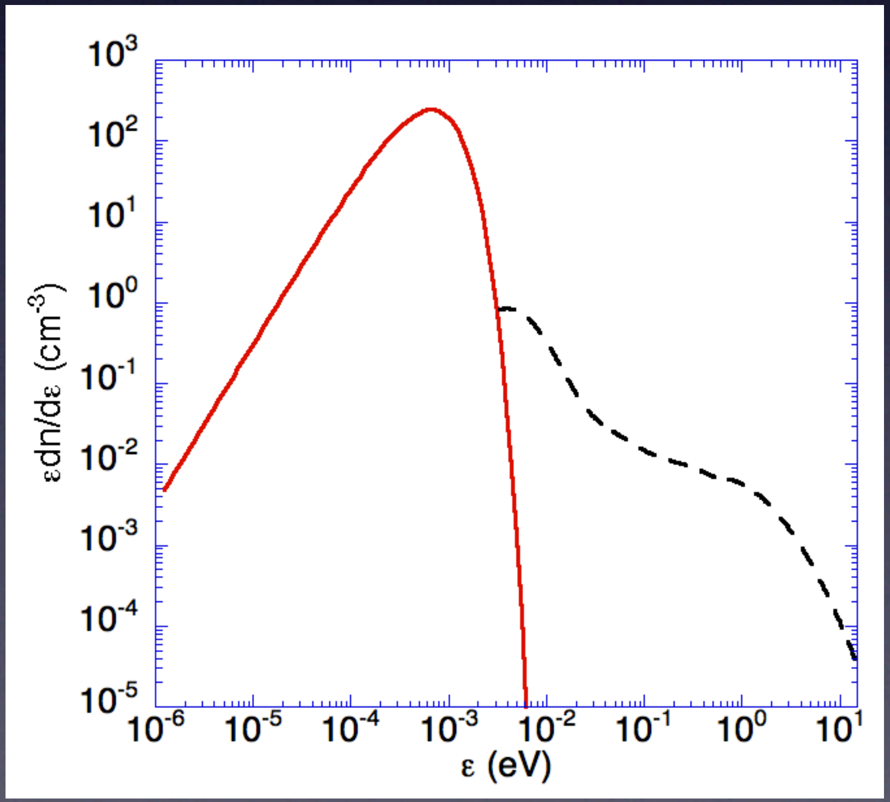
• The future :

the key experiments of the years to come (at least, two examples)

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**
  - Infra-red, optical, ultra violet backgrounds (IR/OPT/UV) from Kneiske et al., 2006





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

CR protons and nuclei interactions

Protons :

• adiabatic losses

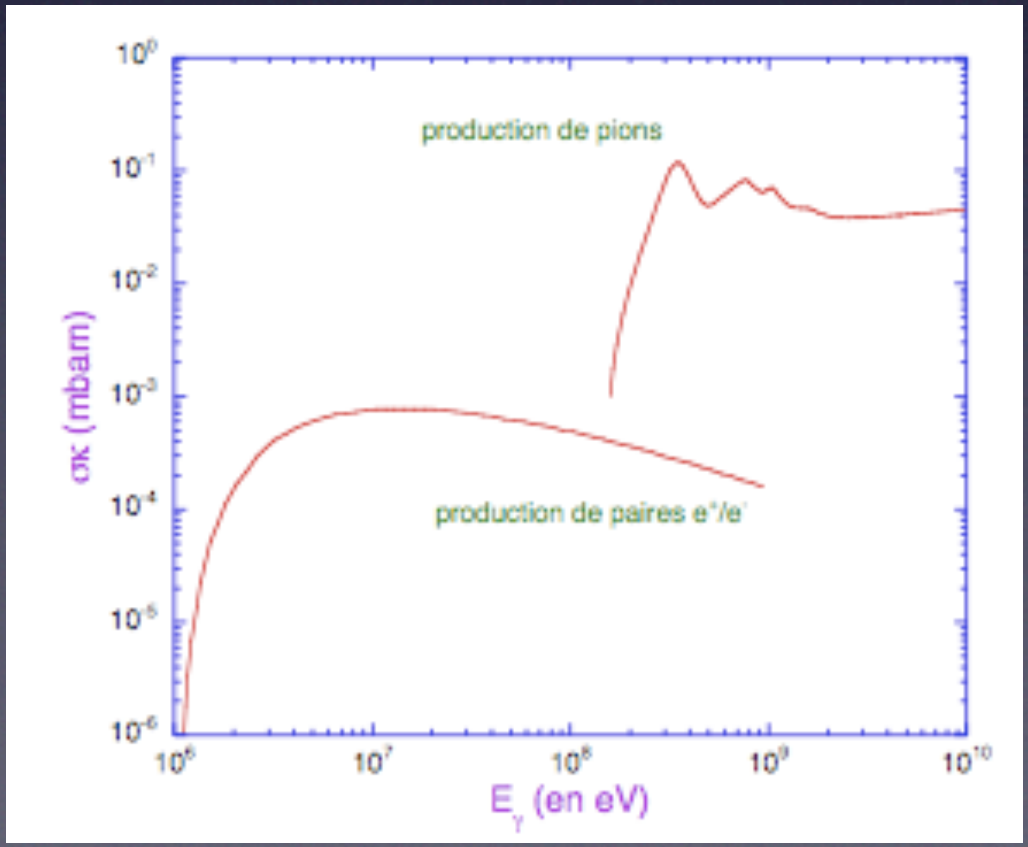
• pair production:
$P+\gamma \rightarrow p+e^+/e^-$ - low inelasticity process
Interaction with CMB photons ~ 10^{18} eV

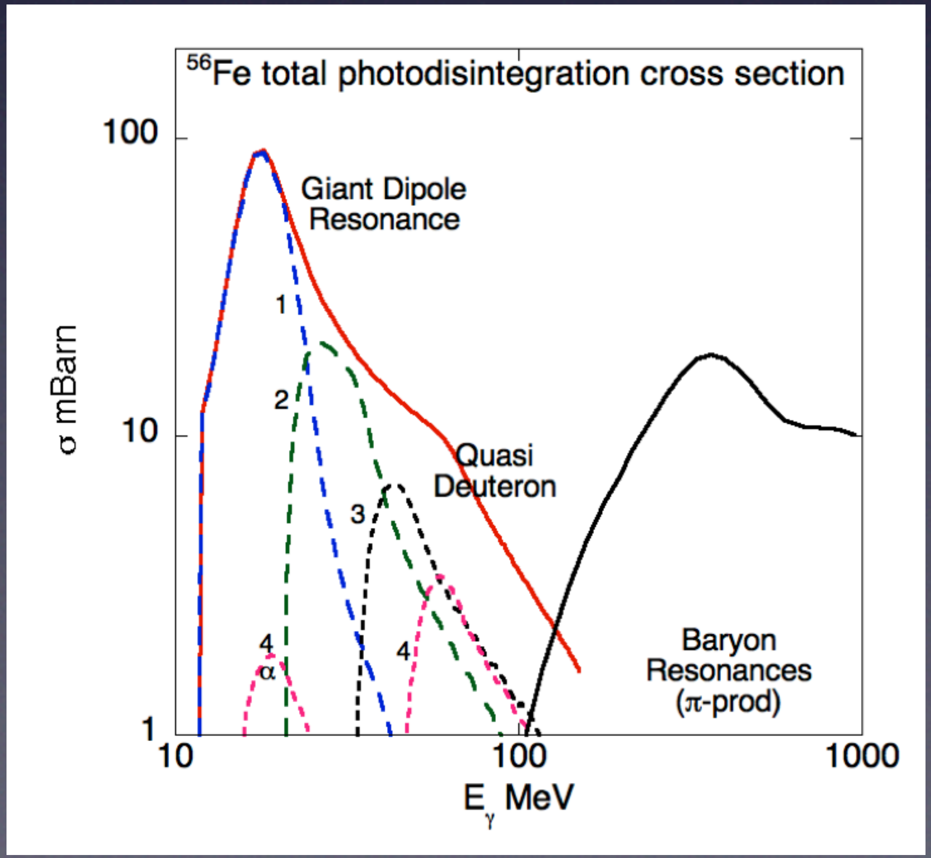
• Pion and meson production :
$n+\gamma \rightarrow n'+\Pi$ - large inelasticity process (~20%)
Interaction threshold ~7.10^{19} eV

Compound nuclei :

Two types of processes

- Processes triggering a decrease of the Lorentz Factor
  - Adiabatic losses
  - Pair production losses (energy threshold ~$A\times10^{18}$ eV)
- Photodisintegration processes
  - Giant Dipole Resonance (GDR); threshold ~ 8 - 20 MeV largest σ and lowest threshold (Khan et al., 2005)
  - Quasi-Deuteron process (QD); threshold ~ 30 MeV (Rachen 1996, PSB 1976)
  - Pion production (BR); threshold ~ 145 MeV (Rachen 1996)

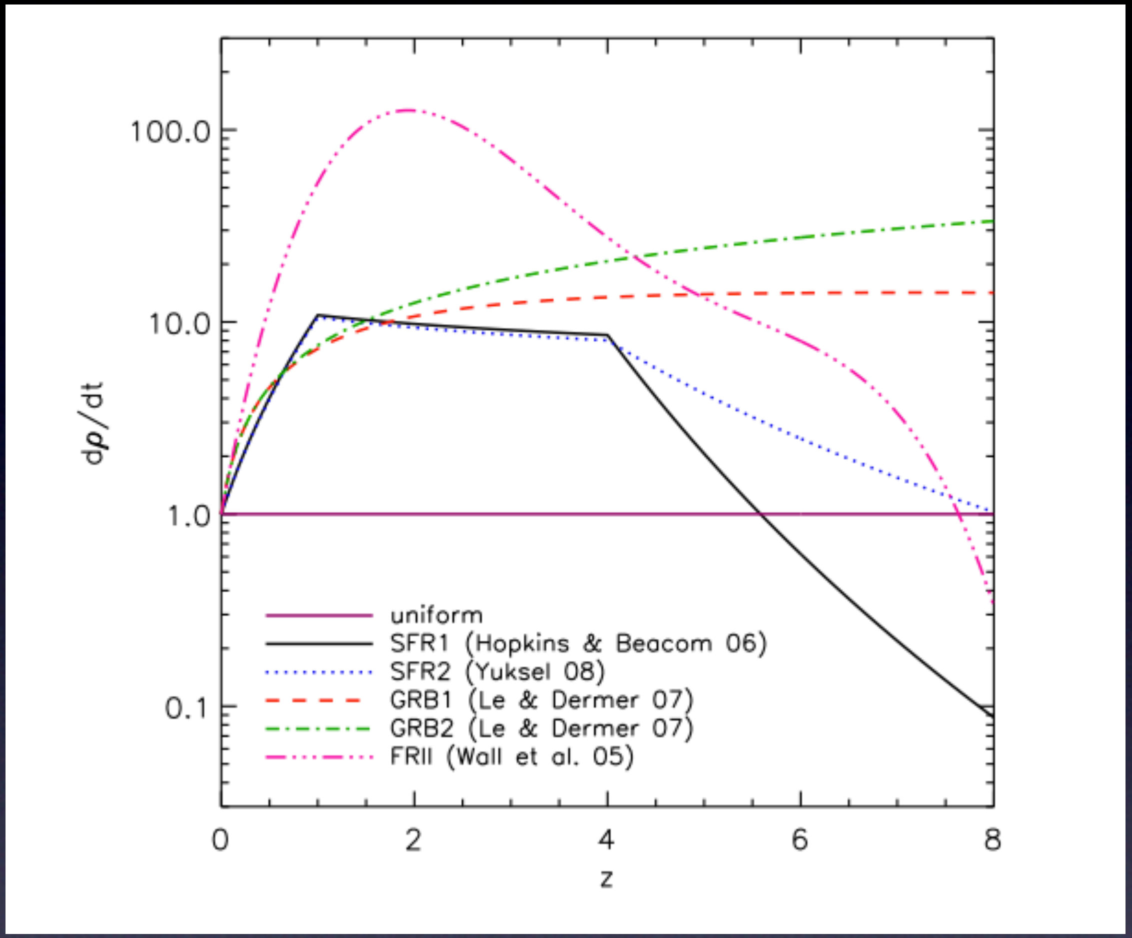




calculation of extragalactic UHECR spectrum

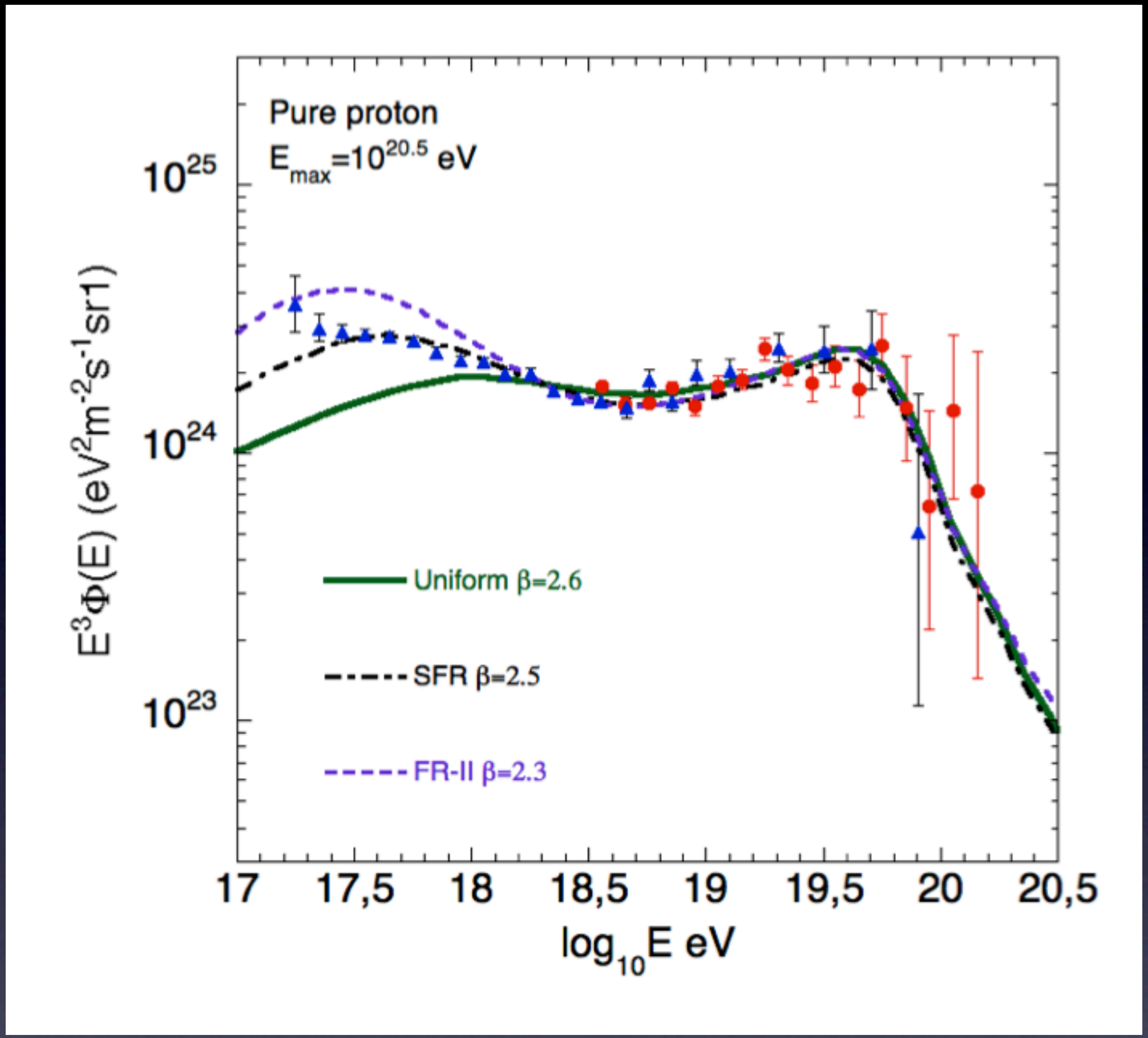
We assume :

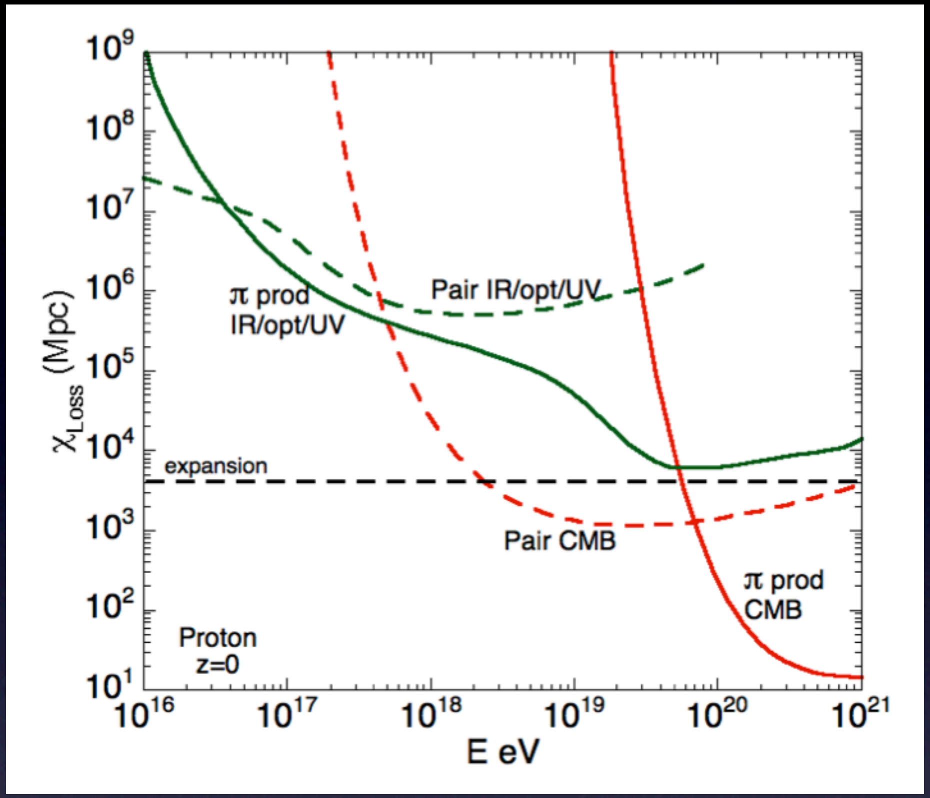
- a source composition
- source spectral index
- maximum energy ($Z \times 10^{20.5}$ eV)
- physically meaningful cosmological evolution of the sources luminosity (uniform, SFR, FR-II, GRBs...)



- We adjust the best spectral index to experimental spectra

a special case : pure proton composition

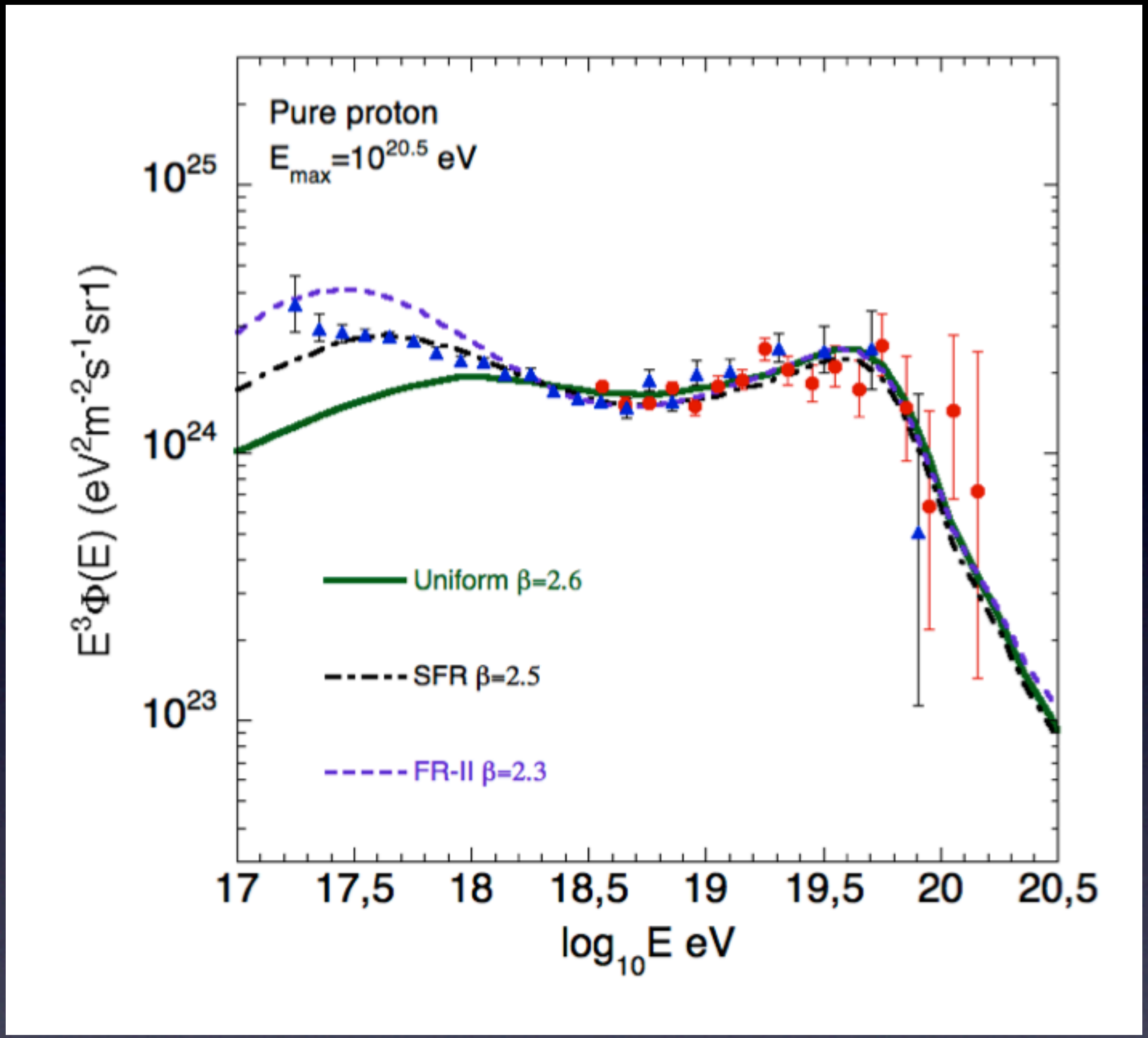




The existence of the pair production dip is due to the energy evolution of the proton attenuation length

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

a special case : pure proton composition



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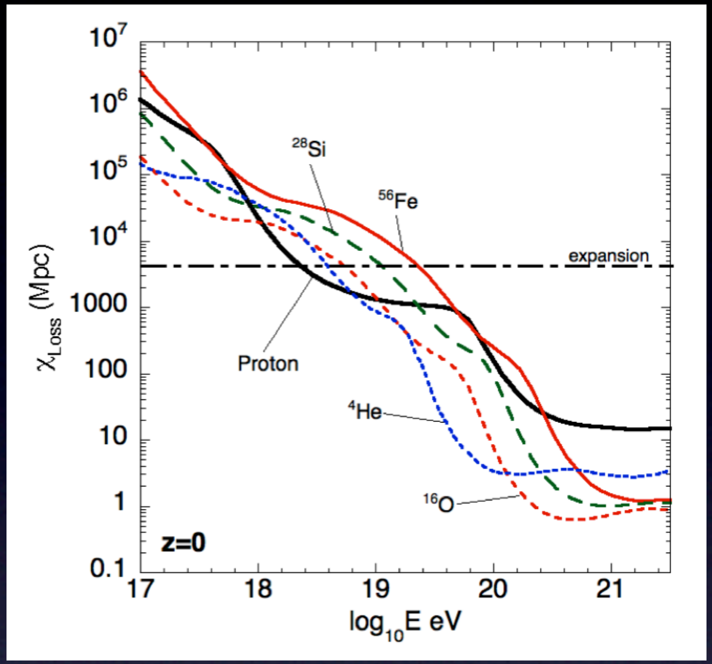

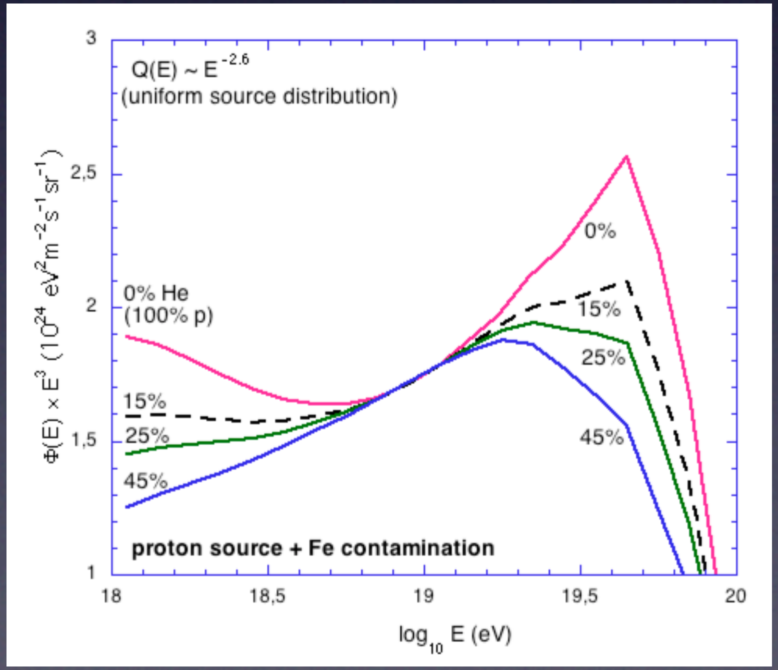

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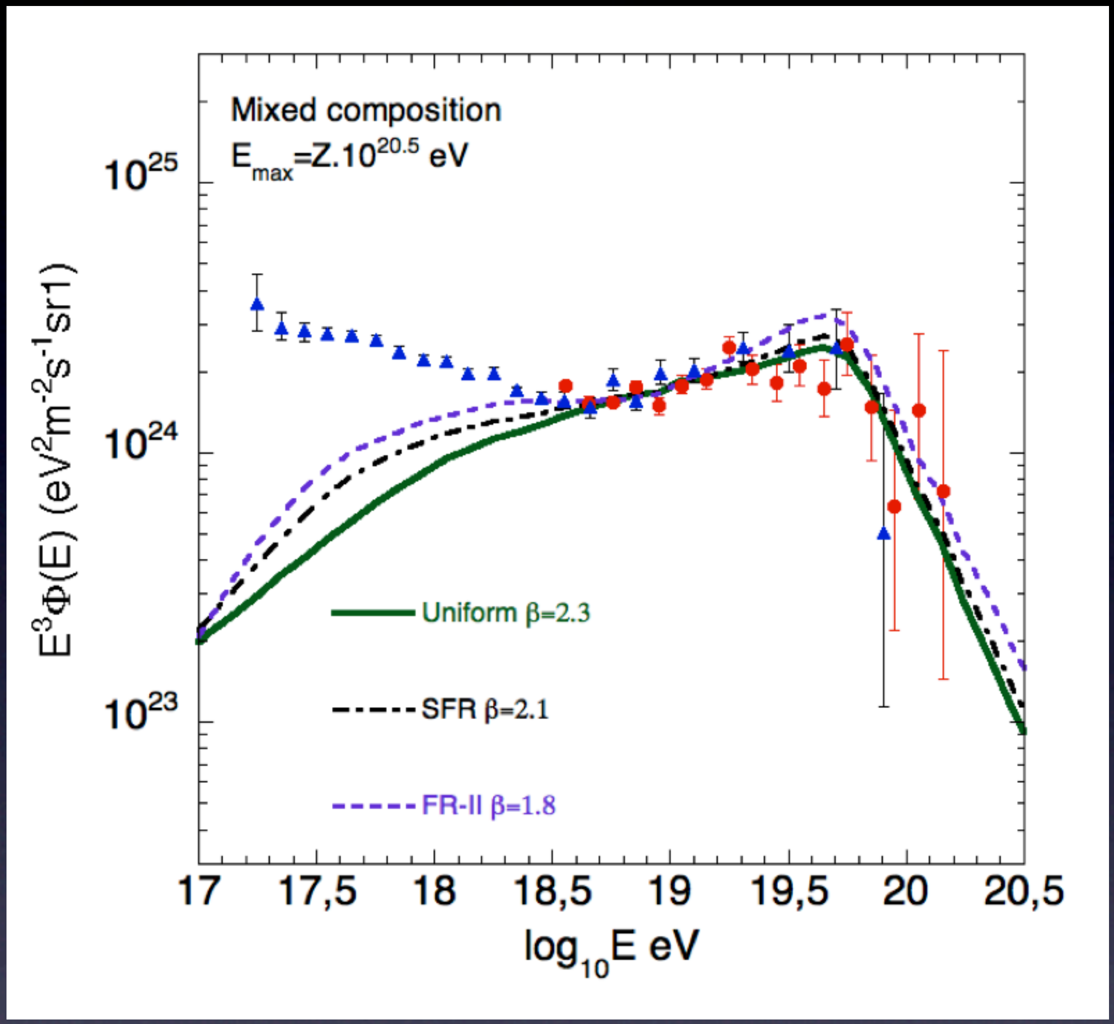
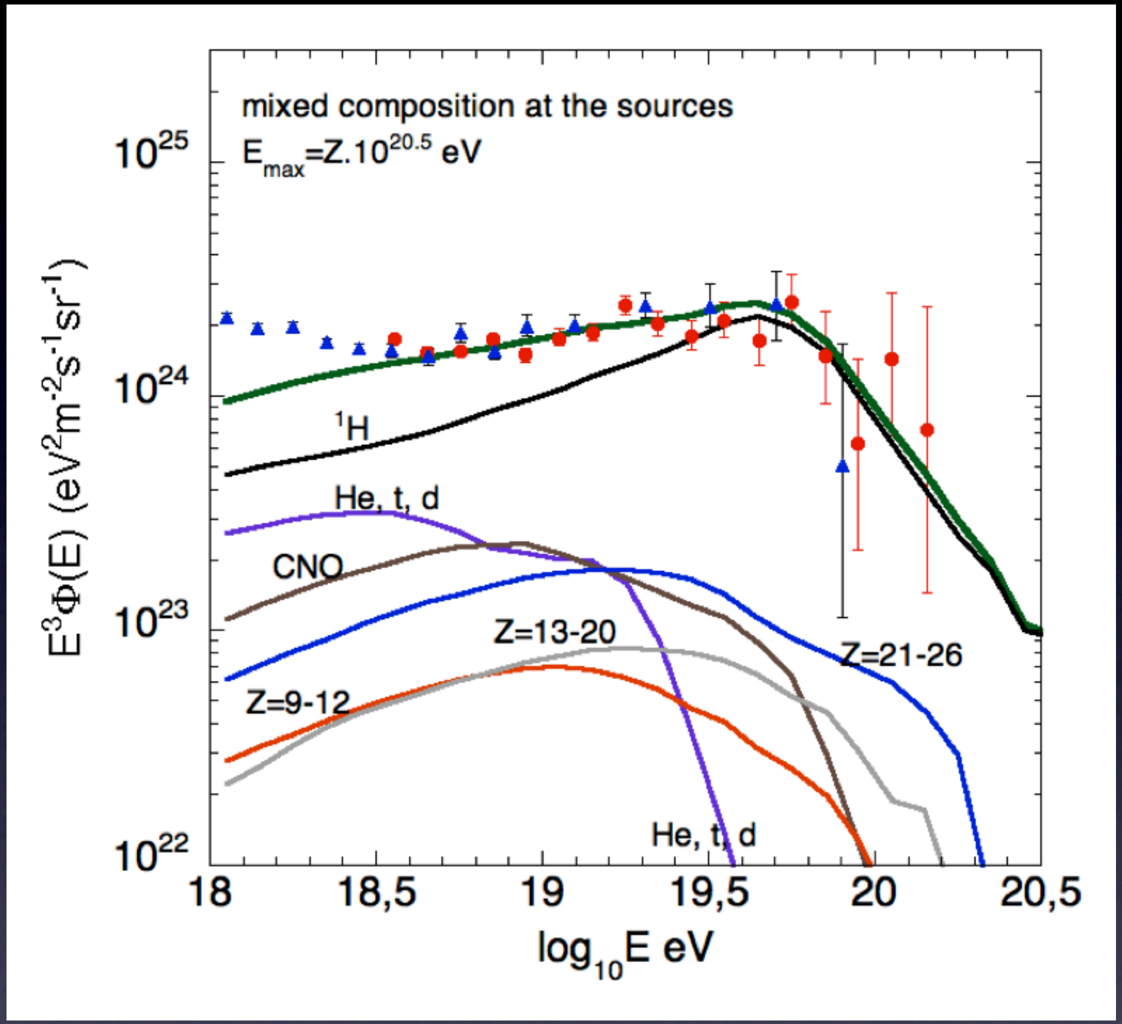
The attenuation length evolution is different for nuclei
A small admixture of nuclei erase the dip

mixed composition

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





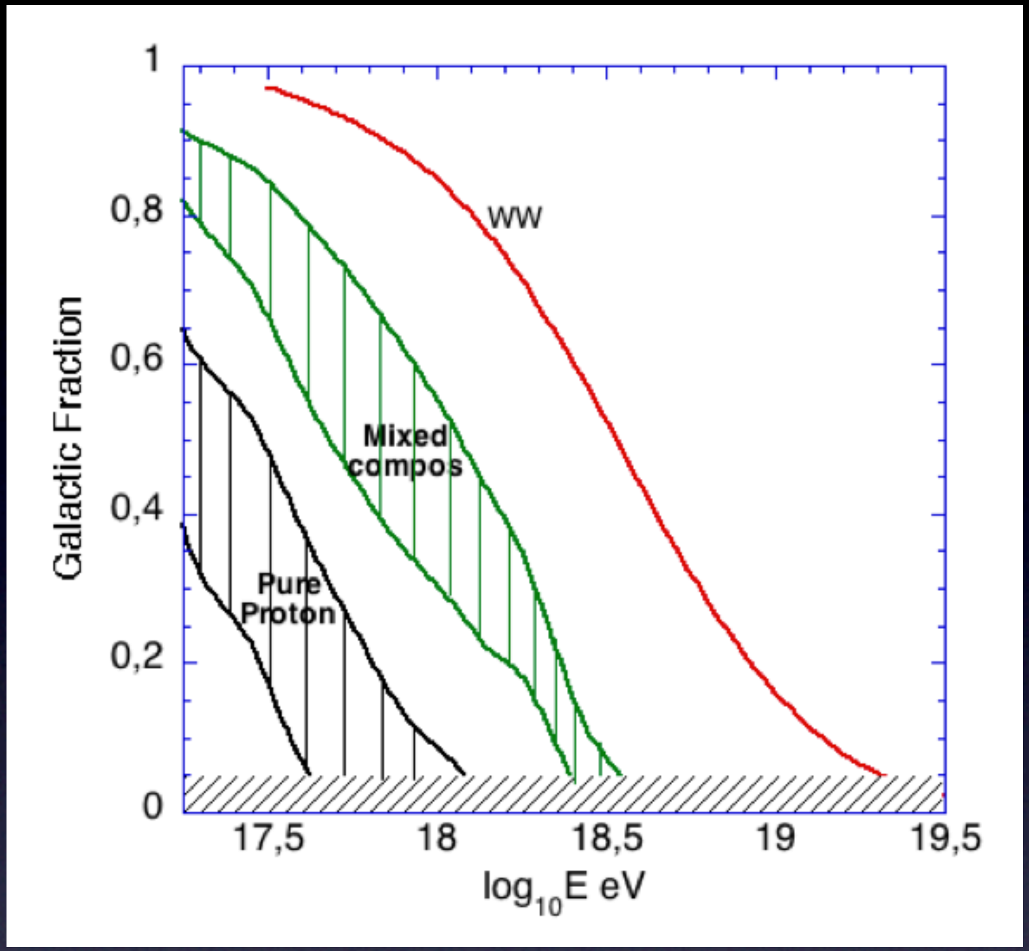
No pair production dip with a mixed composition

the ankle marks the transition from galactic to extragalactic

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

getting lighter above 10^{19} eV

consequences on the transition from GCR to EGCR



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

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

Different implications for galactic cosmic-ray sources

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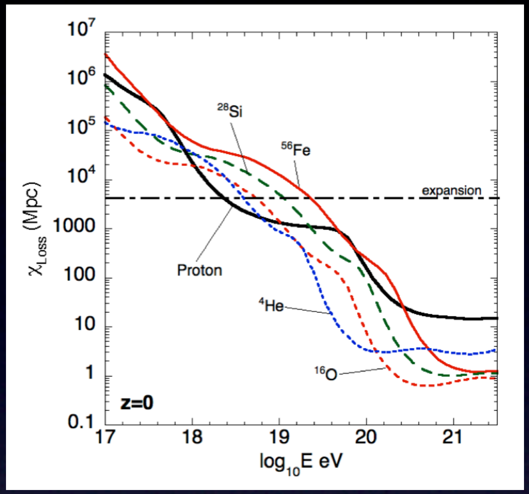

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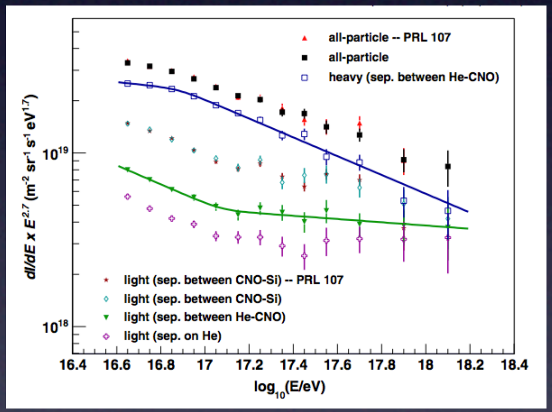
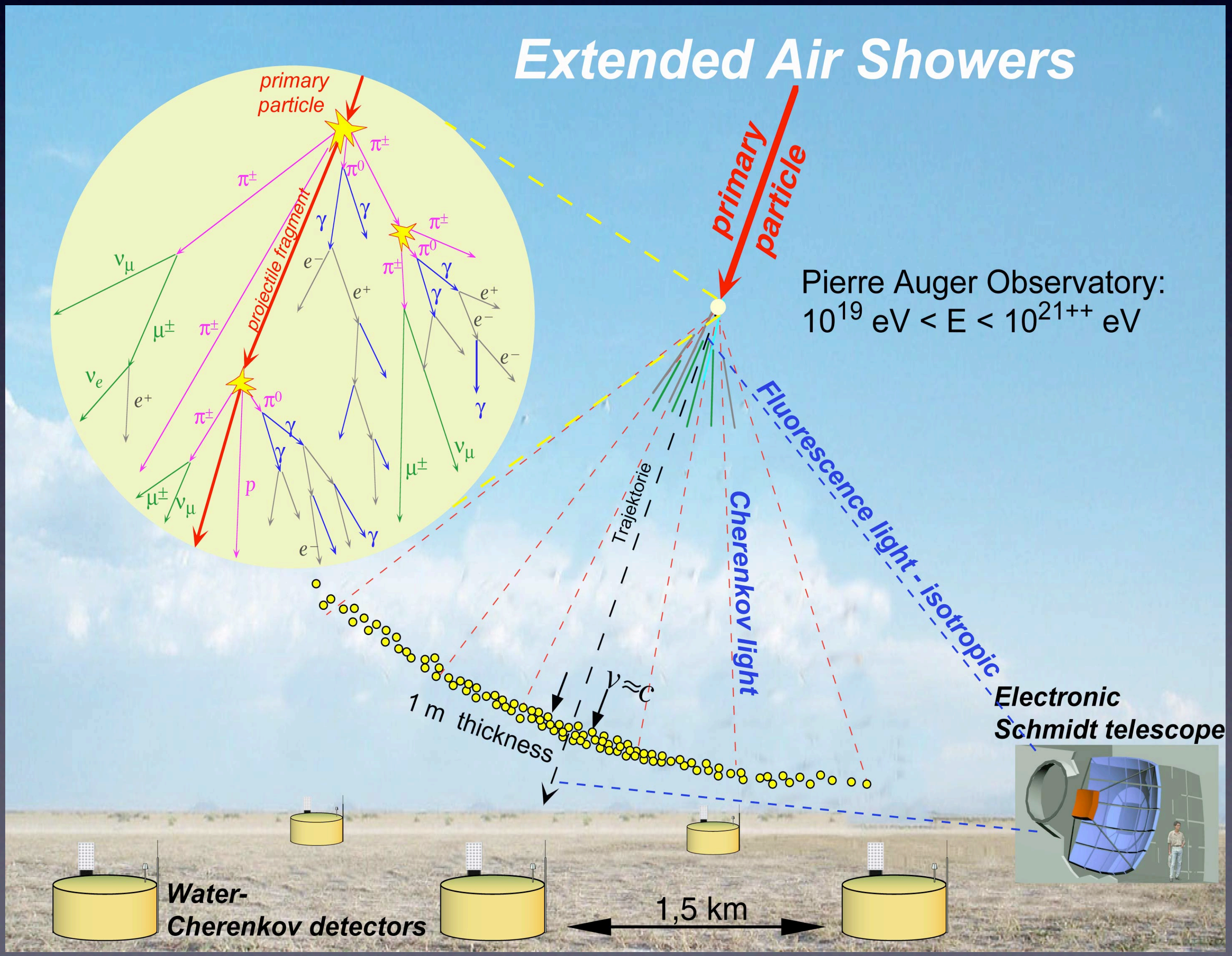


• The future :

the key experiments of the years to come (at least, two examples)

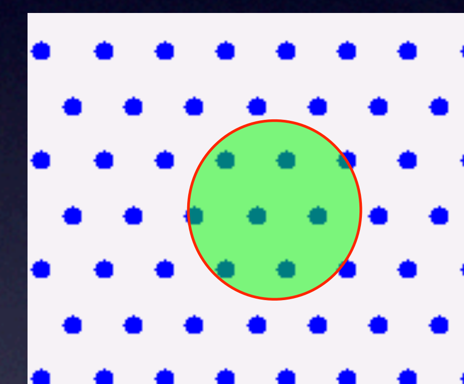
Detection of VHE and UHE cosmic-rays

- 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



Ground array detectors

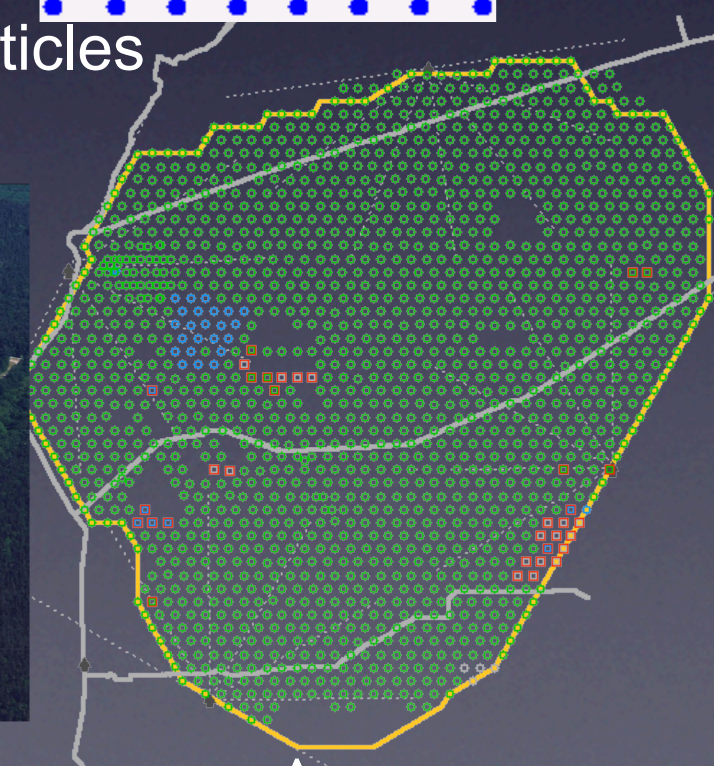
- Sampling air shower particles at ground level
- Surface covered and detector spacing depends on the targeted energy range :
  - Kascade (10^{15}-10^{17} eV) : surface 40000 m^2, 252 detectors, spacing 13m
  - Kascade Grande (10^{16}-10^{18} eV) : surface 0.5 km^2, 37 detectors, spacing 130m
  - Auger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



- Different type of detectors :
  - Scintillators (Kascade, AGASA) ==> charged particles
  - Shielded scintillators (Kascade, AGASA, Yakutzk) ==> muons
  - Water Cerenkov Tanks (Haverah Park, Auger) ==> charged particles

Kascade

Kascade-Grande



Auger

Ground array detectors

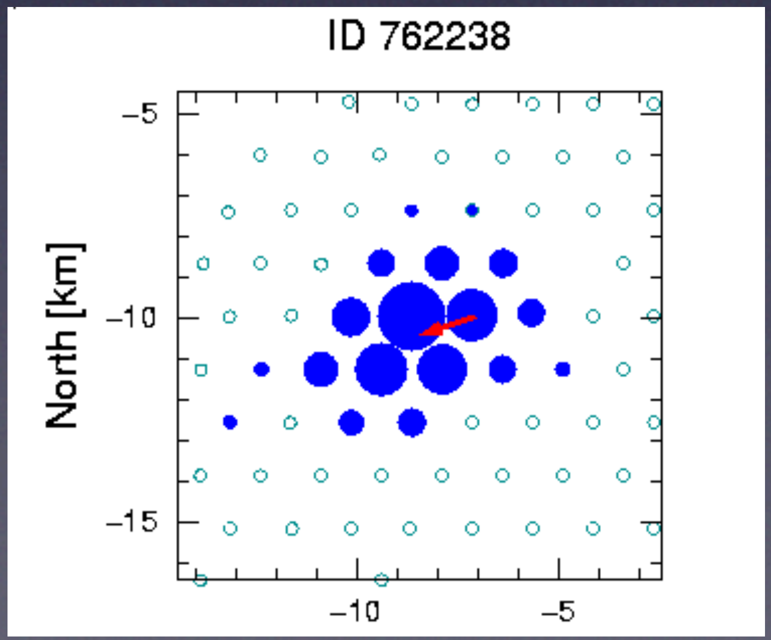
- Reconstruction methods :
  - Direction estimated using the time structure of the shower front
  - Energy reconstructed using the evolution signal size (Number of particles) as a function of core distance
  - nature estimated mainly using the number of muons or the muon to electron ratio

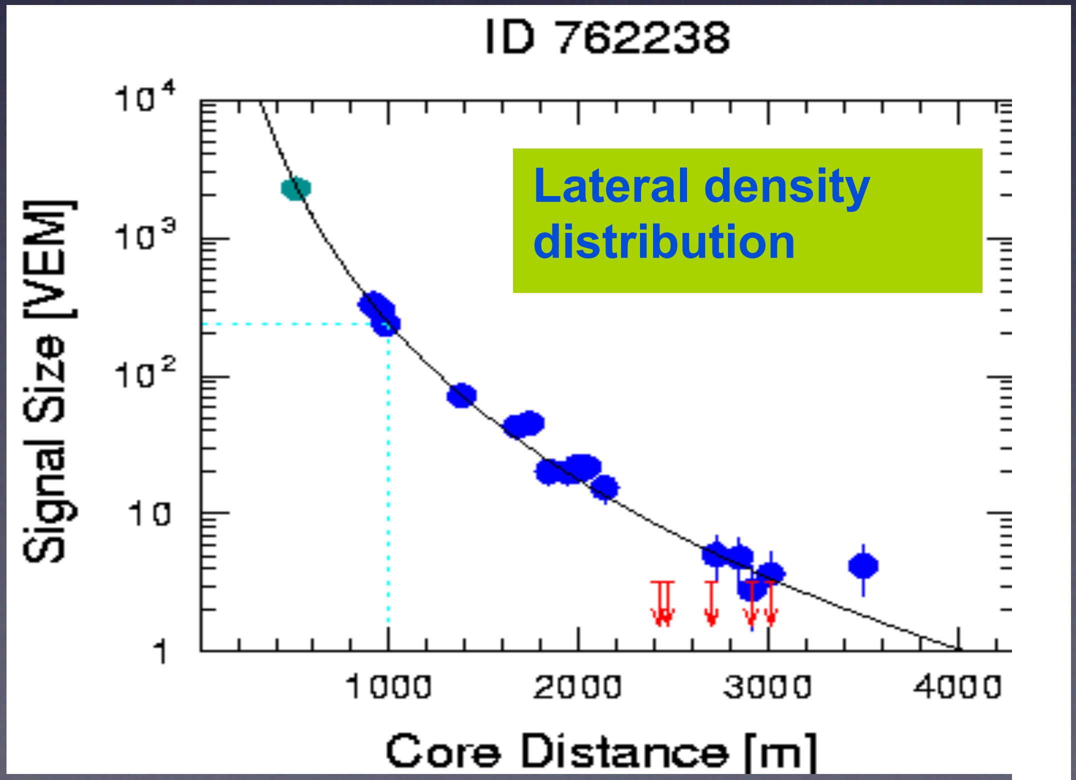
The relation Signal size/Energy is extracted from air shower simulations

-> Hadronic model and composition dependent

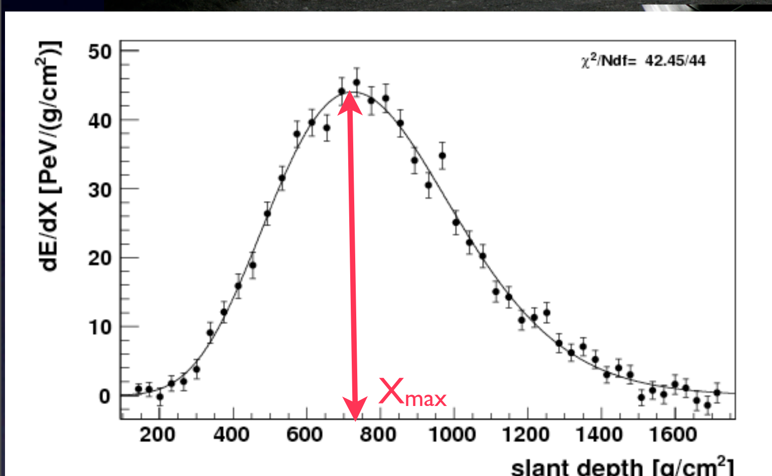
The relation muon number/composition is extracted from air shower simulations

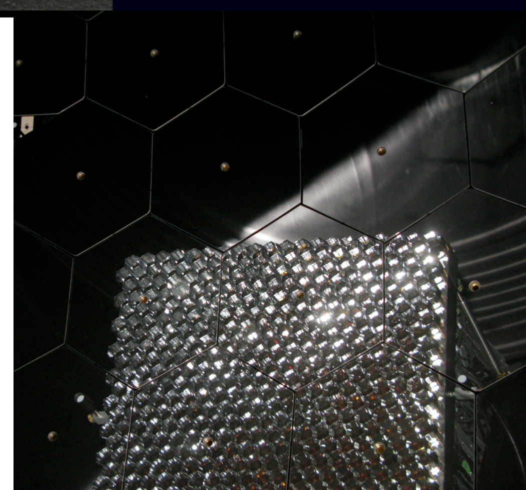
-> Hadronic model dependent

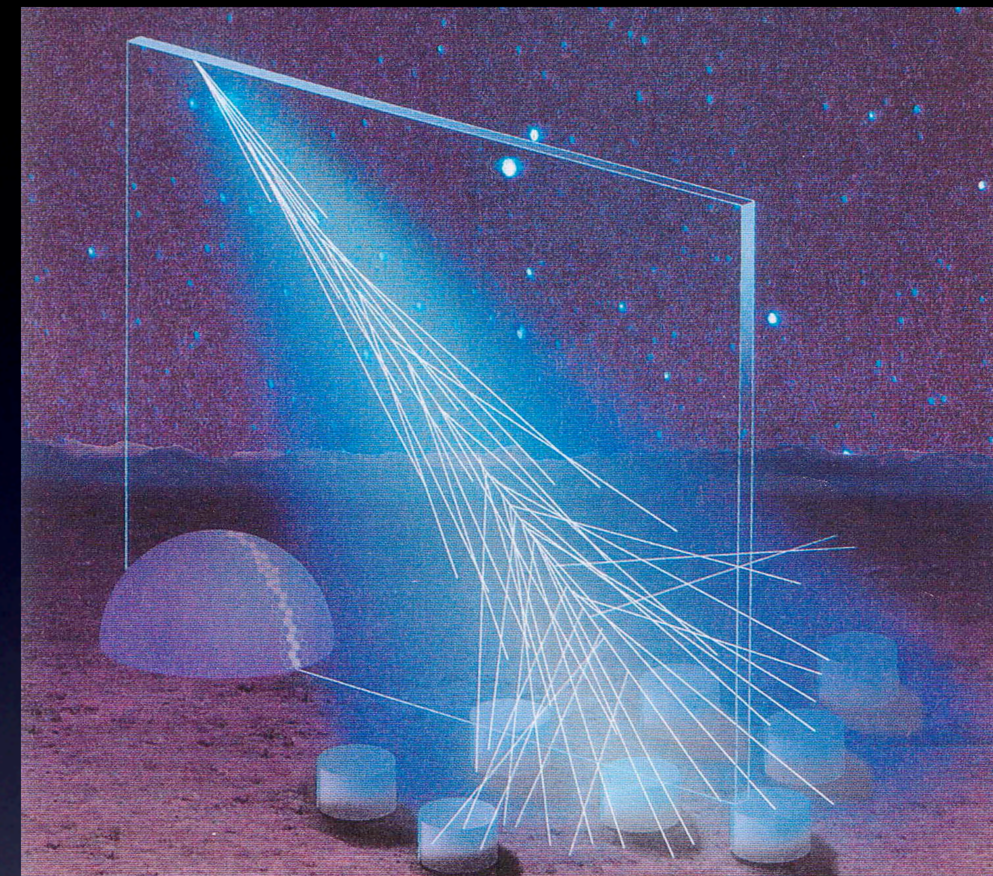




Fluorescence detectors

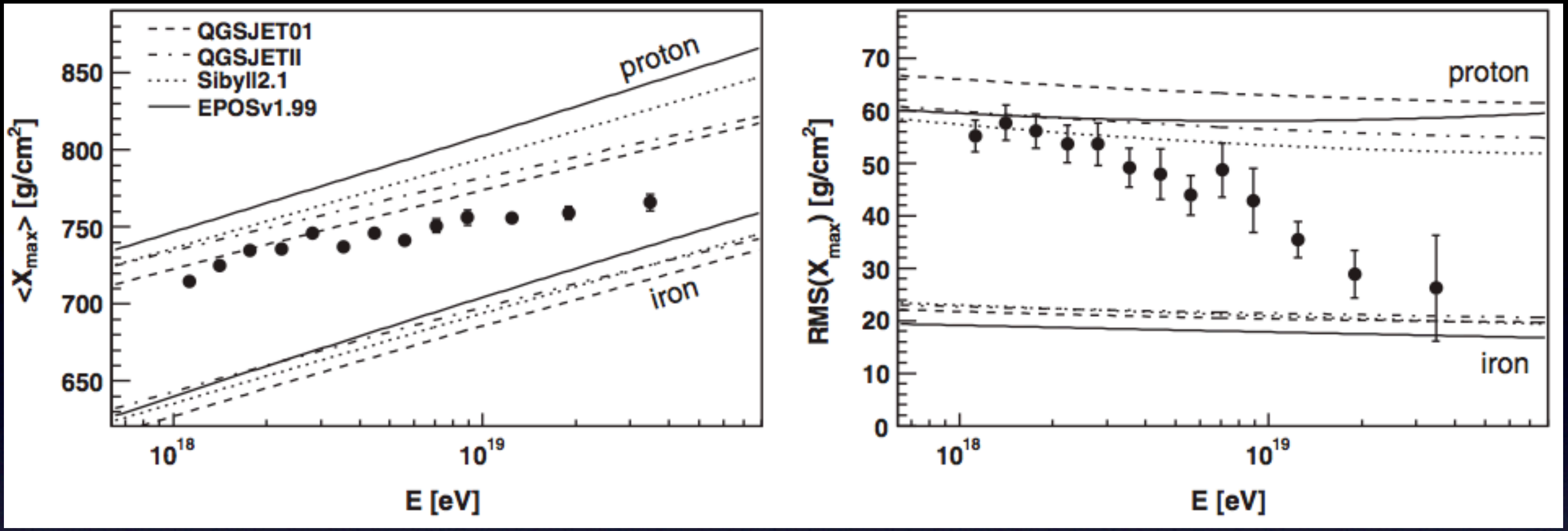






- The fluorescence (UV) emitted by N_2 molecules exited the air shower e^+e^- is detected
- Fluorescence light proportional to the number of electromagnetic particles in the shower -> proportional to the energy of the cosmic-ray
- Detectors sample the evolution of the shower size during its development (unlike ground array) ==> Energy, X_{max}
- Calorimetric measurement of the energy-> widely independent of the modeling of hadronic interaction
- Geometry more complicated, a lot of monitoring required (atmosphere, aerosols,...)

Auger composition



X_{max} and its spread can be used as a composition sensitive estimator Auger coll., 2010

Shallower showers and lower spread for heavy primaries at a given energy

X_{max} at a given energy for a given primary is hadronic model dependent

==> difficult to extract relative abundance of the different elements

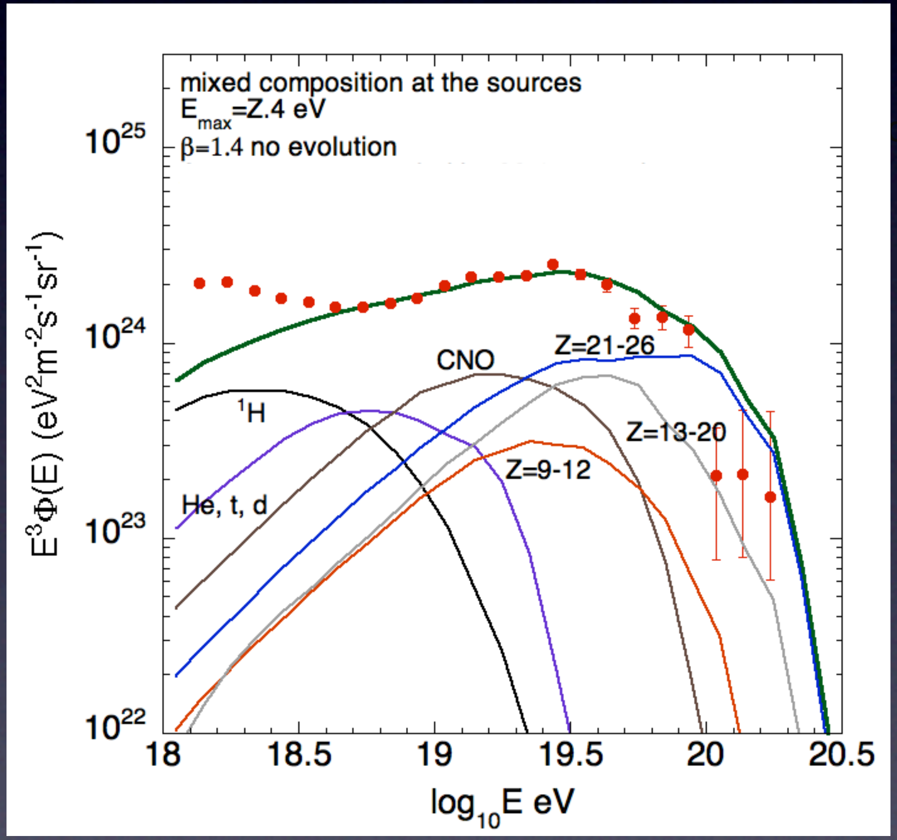
==> "model independent" evidence for a composition getting proton poorer with energy and a significant contribution of nuclei especially at the highest energies

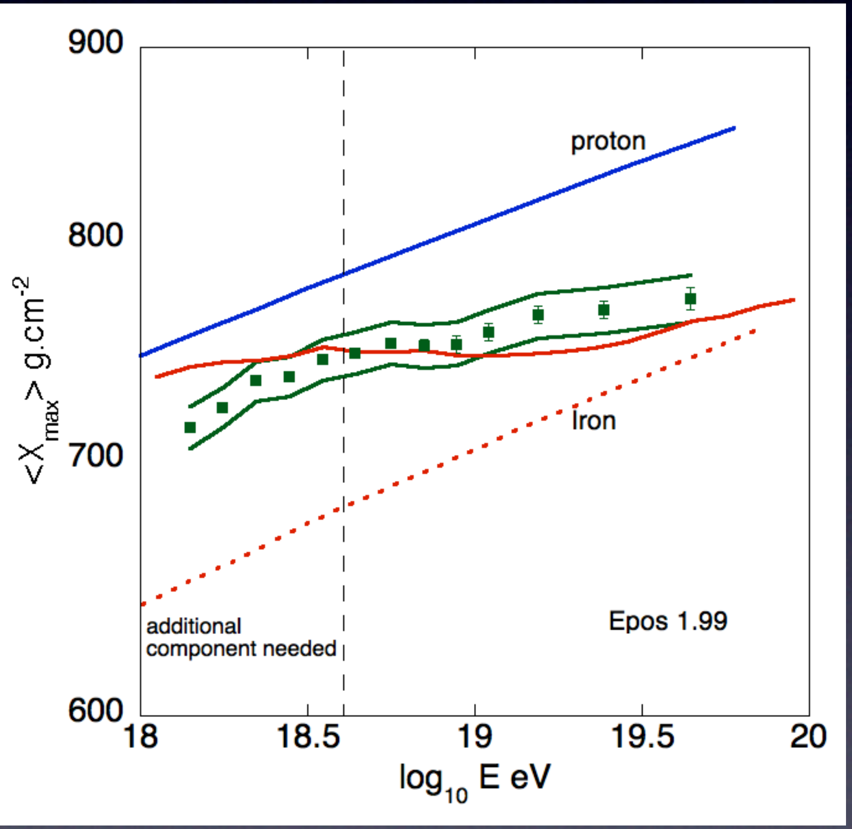
NB : hadronic physics scenarios elaborated to make this result compatible with protons (Allen & Farrar, 2013) ==> only way to save the dip model which is otherwise ruled out

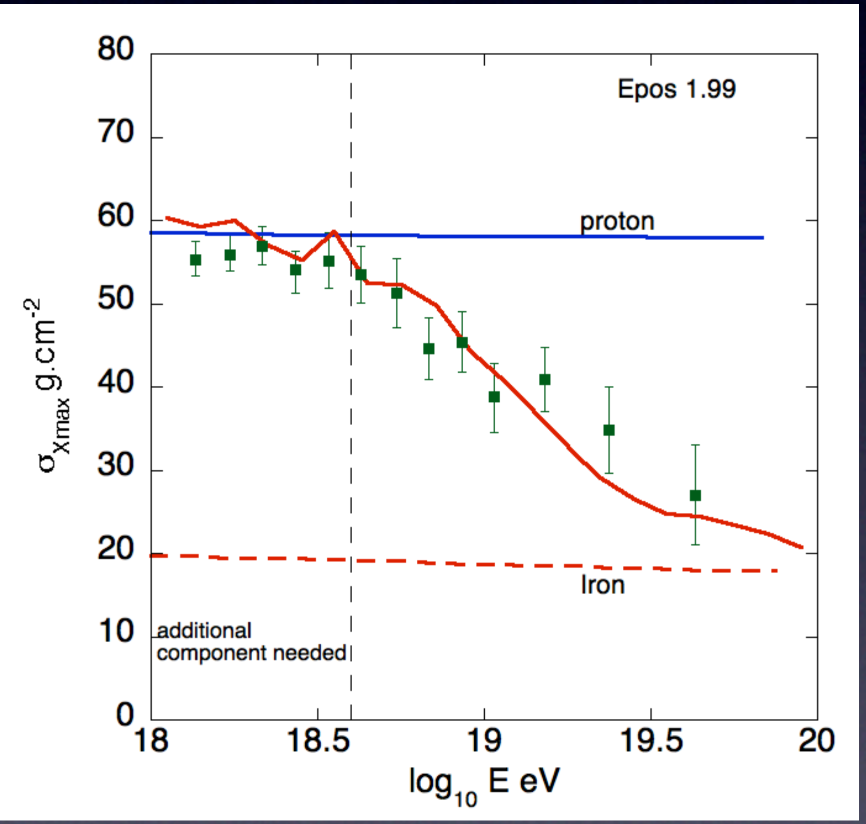
a possible solution : low E_{max} models

We assume that the sources are not able to accelerate protons above a few 10^{18} eV

but can accelerate nuclei of charge Z up to energies Z times higher
(can be expected for astrophysical acceleration mechanisms)





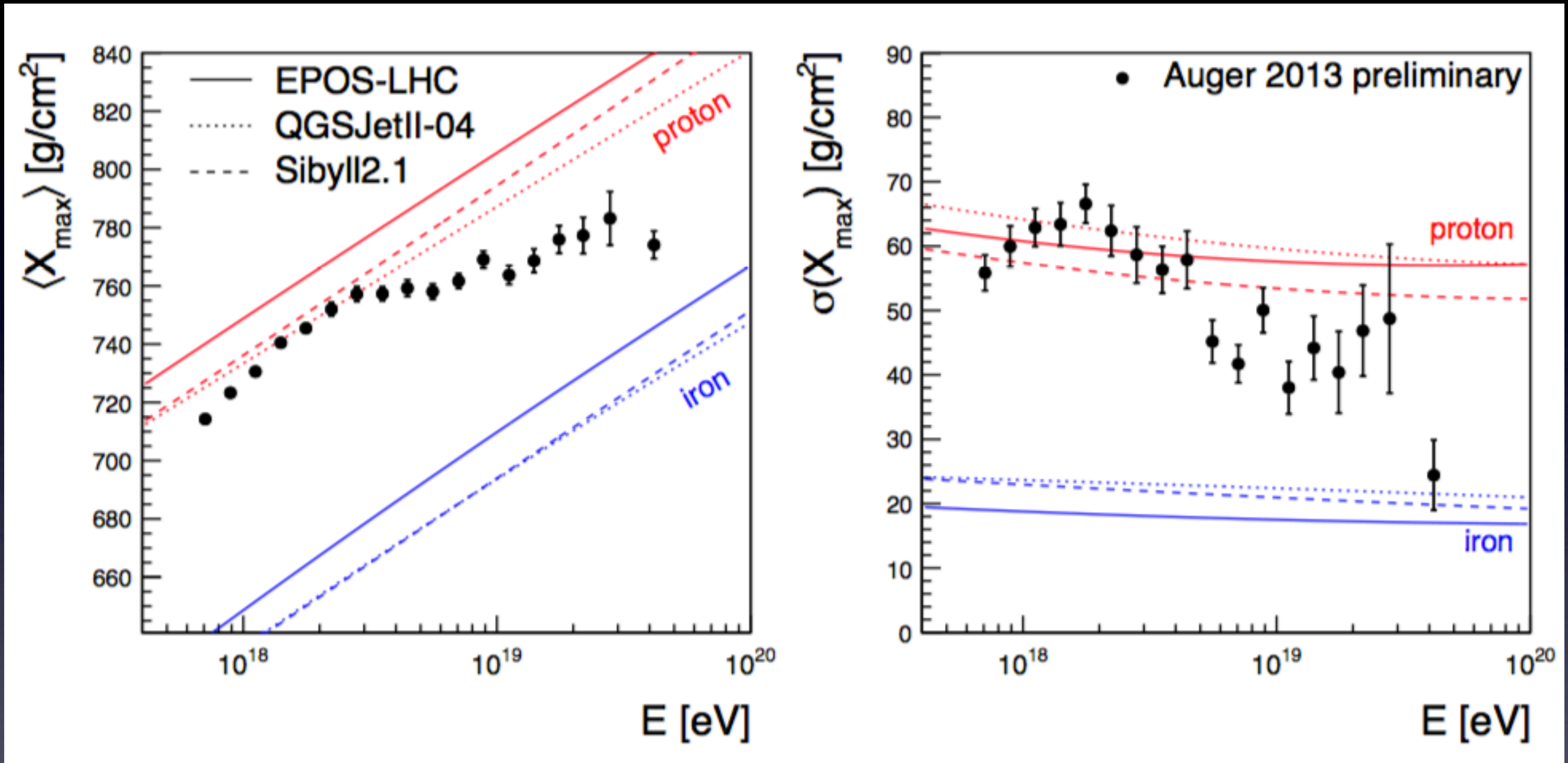


requires hard spectral indexes to fit the spectrum

relatively good description of the evolution of the composition

same ankle transition scenario but steeper (due to a harder spectral index)

Latest results



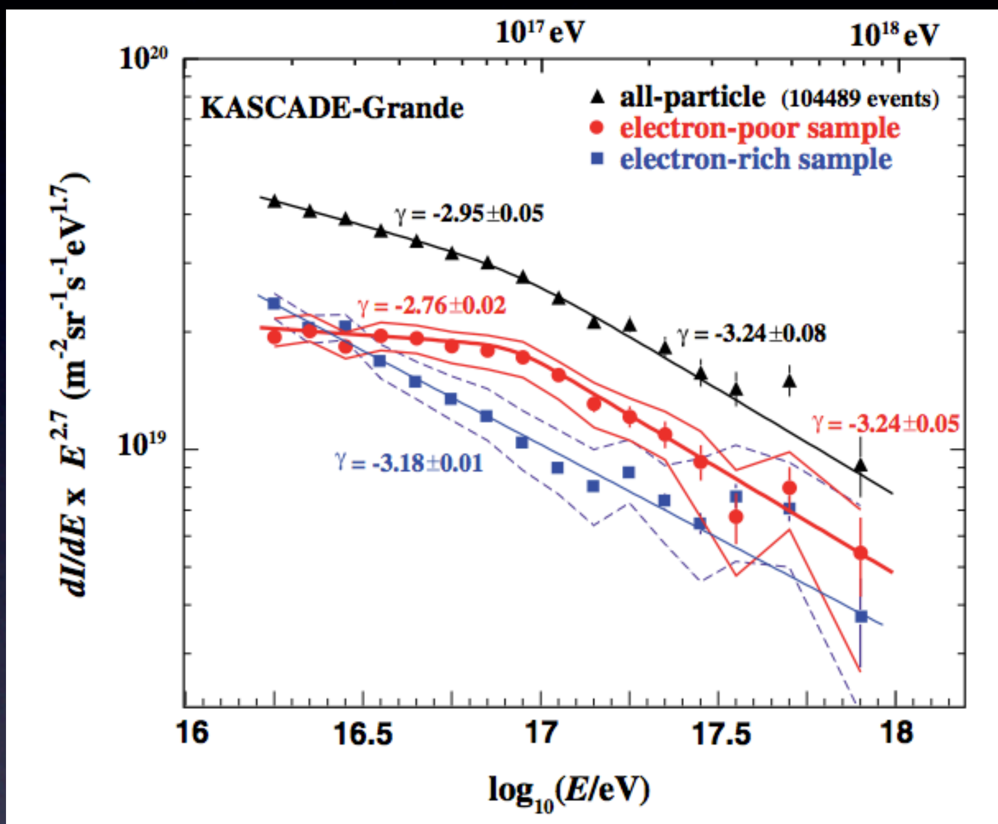
Auger collab., preliminary version presented at icrc 2013

Recent Kascade-Grande analyses

• The Kascade-Grande collaboration recently released composition analyses claimed to be more robust than Kascade elemental spectra

• Based on the separation between electron rich (light CRs) and electron poor (heavy CRs) showers at a given energy

Evidence for an “iron knee”



KG collab, Phys. Rev. Lett., 2011

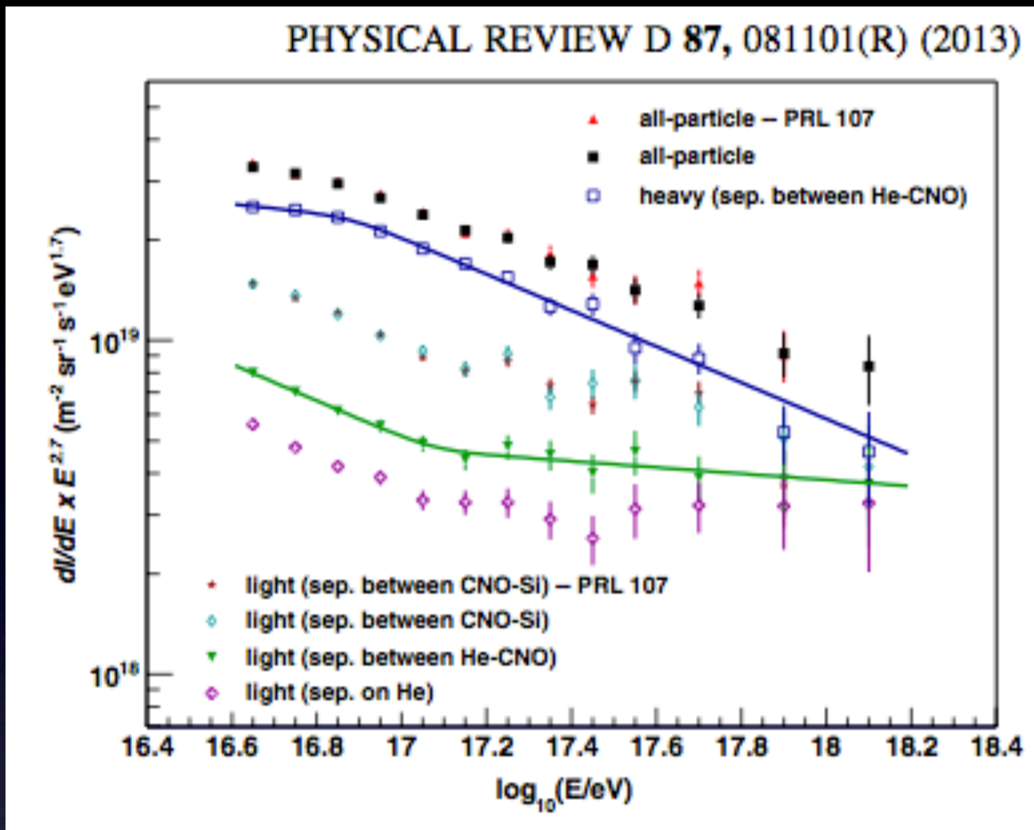
Table 3
Slope of the different spectra and break positions obtained with the three different hadronic interaction models, by applying the k parameter analysis in order to separate the spectra into different mass groups. QGSjet results are from Apel et al. (2011).

Model	EPOS	QGSjet	SIBYLL
All-particle			
γ_1	-3.00 ± 0.03	-2.95 ± 0.05	-2.98 ± 0.05
γ_2	-3.19 ± 0.04	-3.24 ± 0.08	-3.17 ± 0.05
$\log_{10}(E/eV)$	16.82 ± 0.09	16.92 ± 0.10	16.90 ± 0.12
significance (σ)	2.8	2.1	2.7
Heavy component			
γ_1	-2.98 ± 0.05	-2.76 ± 0.02	-2.79 ± 0.03
γ_2	-3.54 ± 0.10	-3.24 ± 0.05	-3.28 ± 0.07
$\log_{10}(E/eV)$	16.82 ± 0.07	16.92 ± 0.04	16.96 ± 0.04
significance (σ)	4.0	3.5	7.4
Light component			
γ	-3.05 ± 0.01	-3.18 ± 0.01	-3.21 ± 0.02

KG collab, PASR, 2014

- 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)

Evidence for an “light ankle”



$\gamma_1 = -3.25 \pm 0.05, \gamma_2 = -2.79 \pm 0.08, \log_{10}(E_{\text{break, light}}/\text{eV}) = 17.08 \pm 0.08$

- 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 appear 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 needed ==> important result if confirmed

- Very frustrating : Auger energy range starts where KG ends !!! Auger seems to be a bit lighter than KG (taking hadronic models at face value...) is it really a strong discrepancy ?

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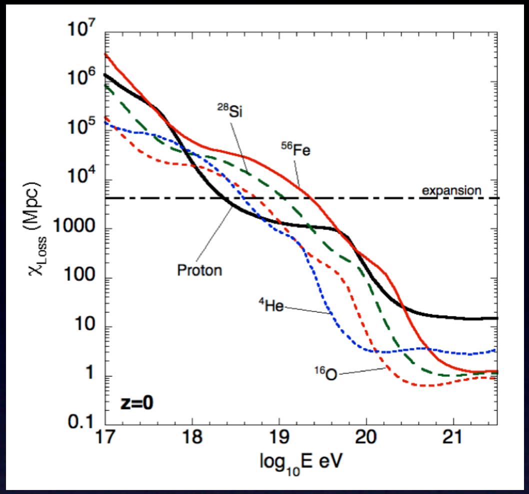

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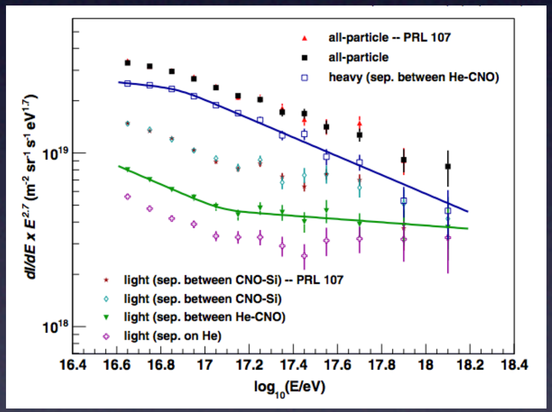

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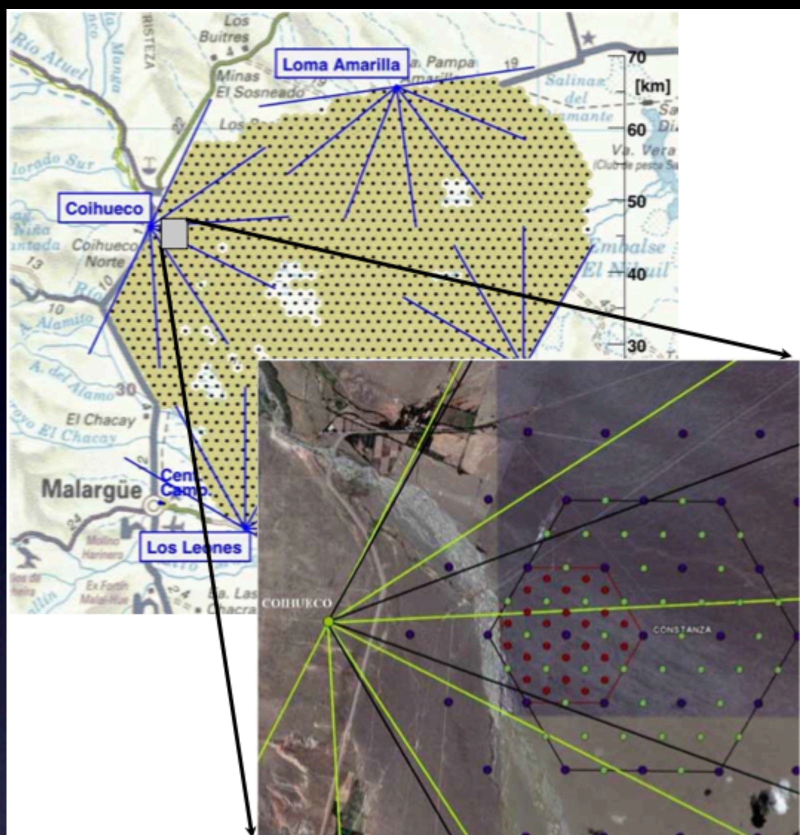
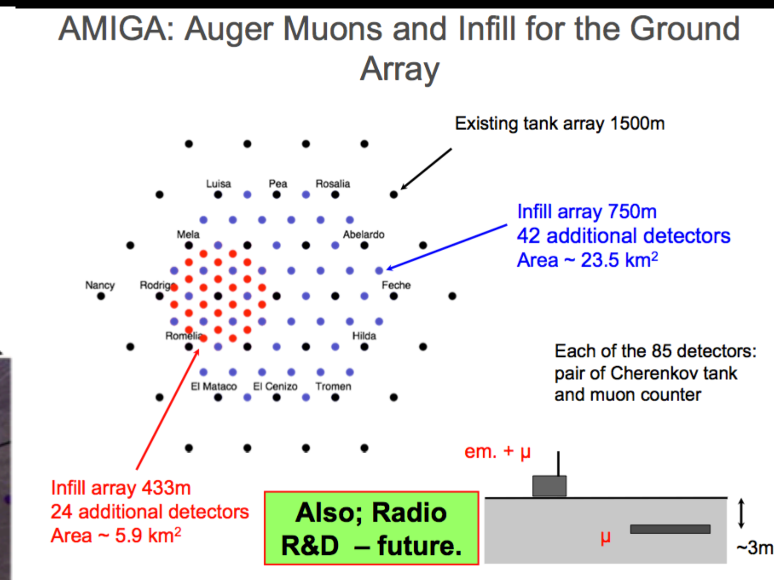
Low energy extension of the Pierre Auger Observatory



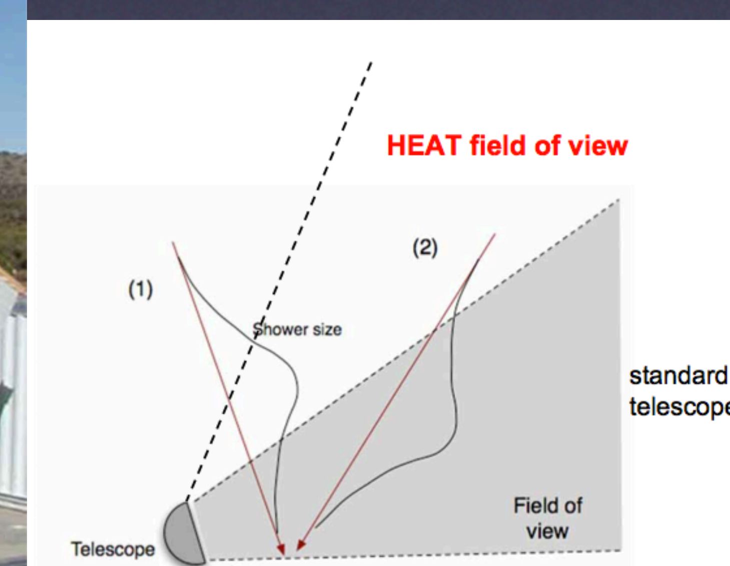


- An infilled array within the Auger ground array : lower detectors granularity ==> lower energy threshold (~10^{17} eV)

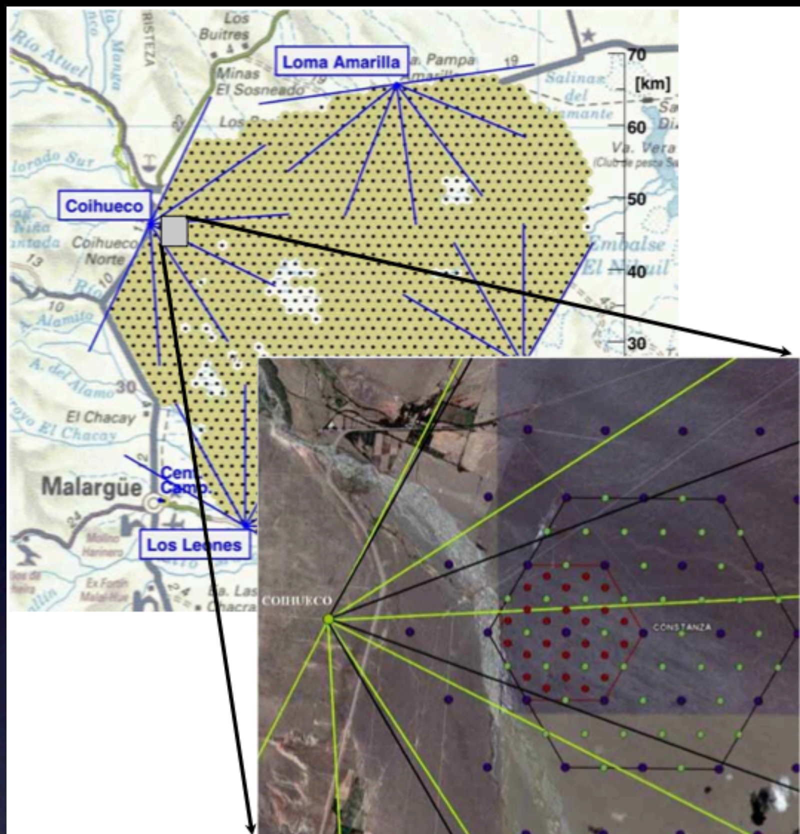
- Regular Auger detectors (water Cerenkov tanks) coupled with buried scintillators ==> better muon separation ==> KG like analyses

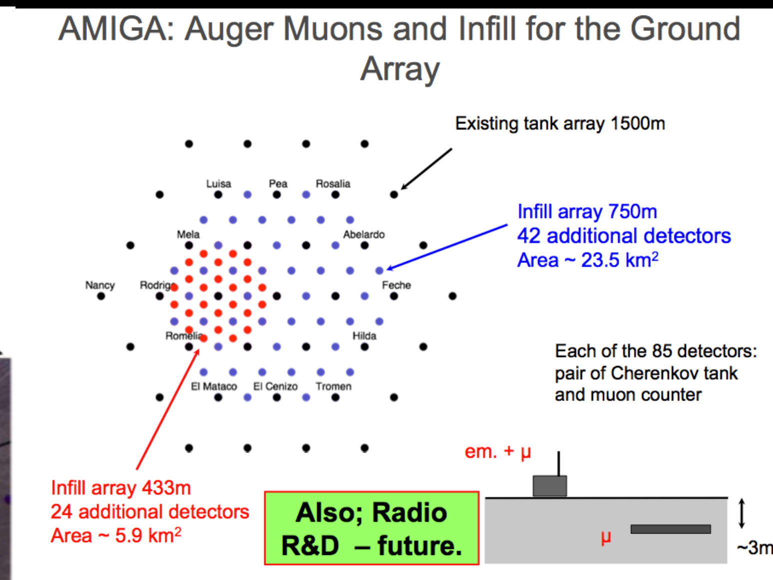
- Higher elevation fluorescence telescope ==> lower energy threshold (~10^{17} eV)

- Access to the muon number and X_{max} for the infilled events ==> multivariable composition analyses on the whole transition energy range

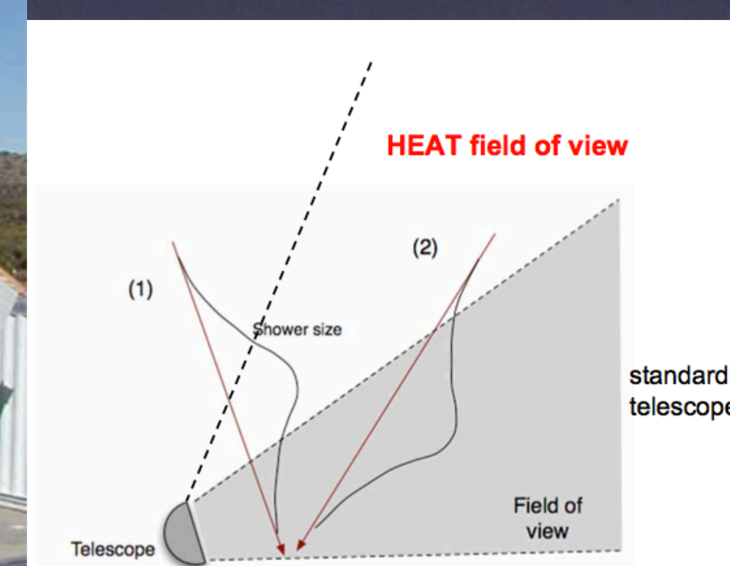


Low energy extension of the Pierre Auger Observatory

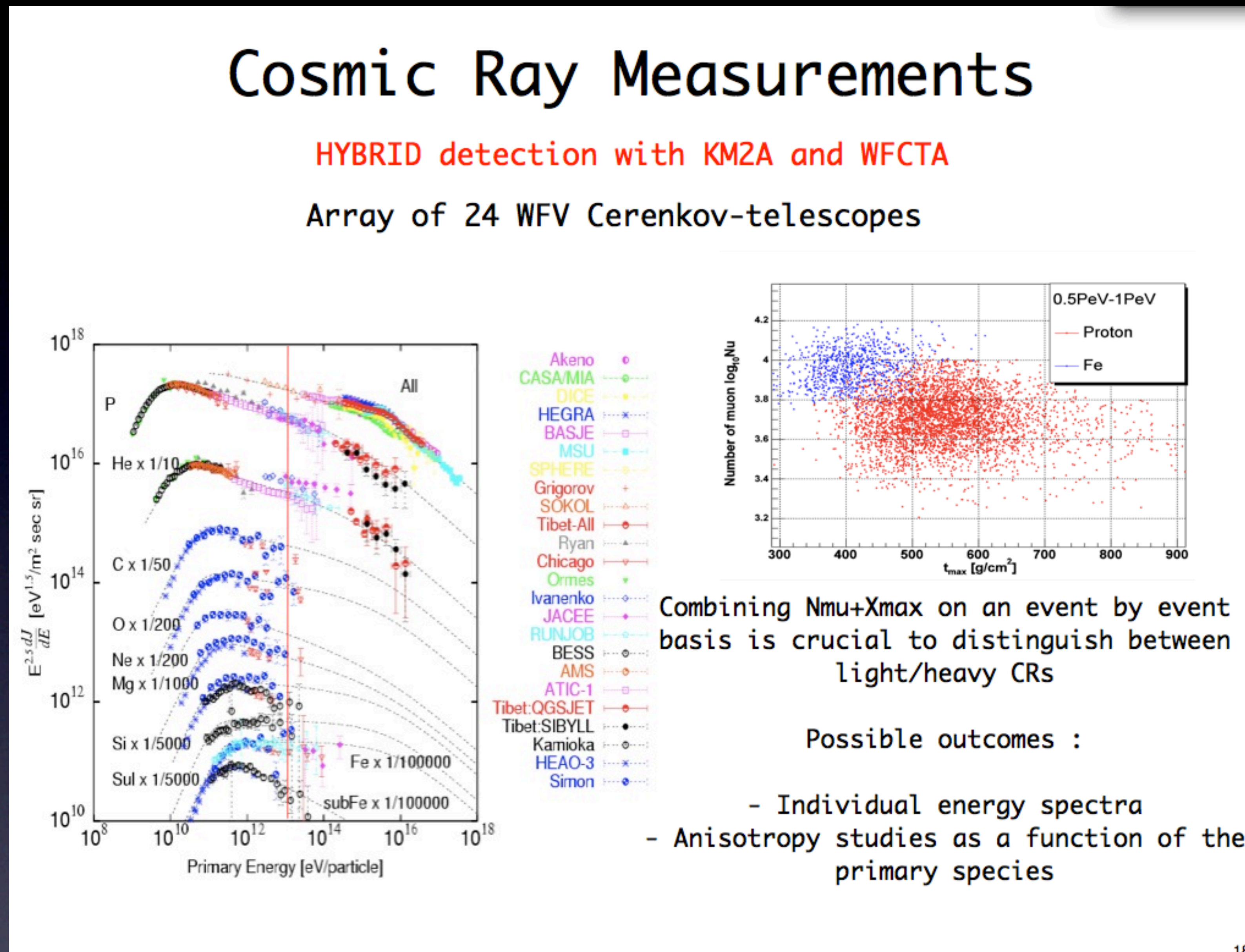




- Equivalent proposal for Telescope Array (northern hemisphere UHECR observatory) : Low energy extension TALE ==> excellent proposals to definitely understand the transition from galactic to extragalactic cosmic-rays



High resolution cosmic-ray measurement at low energy : LHAASO



Multidetector observatory at 4500 m a.s.l

Multivariable analyses of the cosmic spectrum from 10^{13} to 10^{17} eV

==> overlap with direct measurement

==> measurement at the knee and above