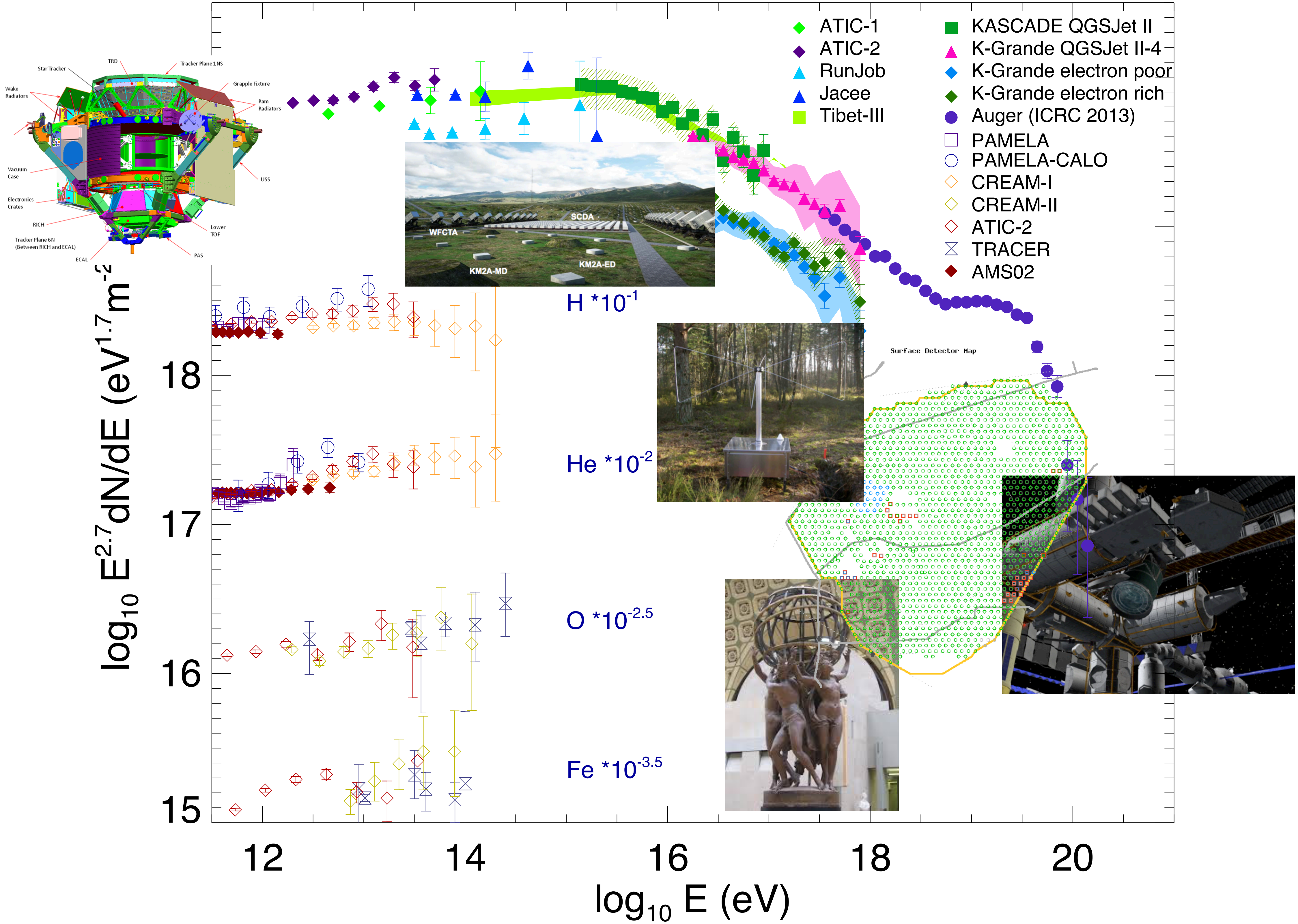
Very-high and ultra-high-energy cosmic-rays : recent observations and perspectives



Outline

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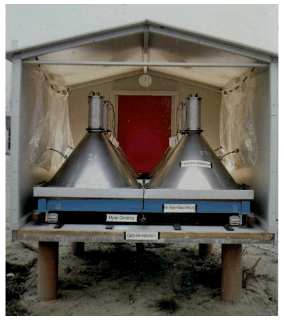
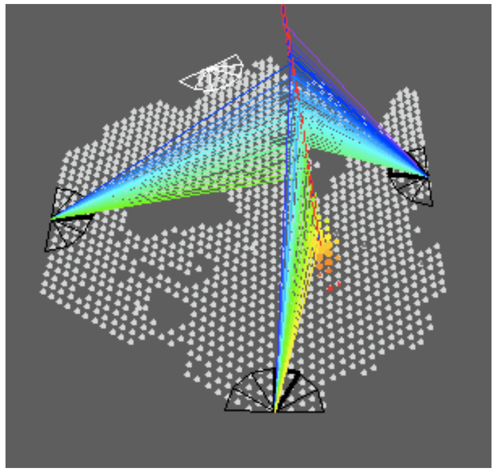
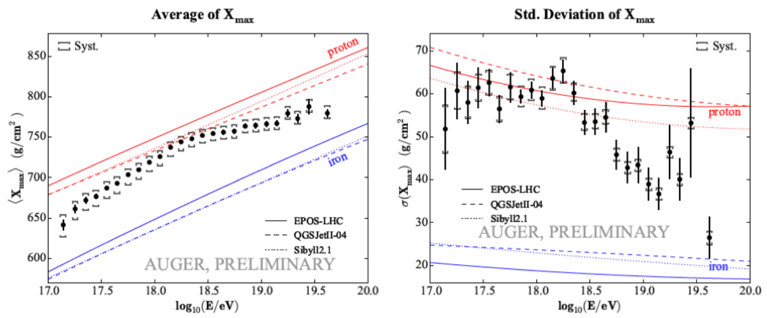
❖ The knee and beyond : KASCADE-Grande, the heavy knee and the light ankle



❖ Auger the giant hybrid observatory
 – spectrum
 – composition
 – air shower properties
 – anisotropies
 – comparison with Telescope Array





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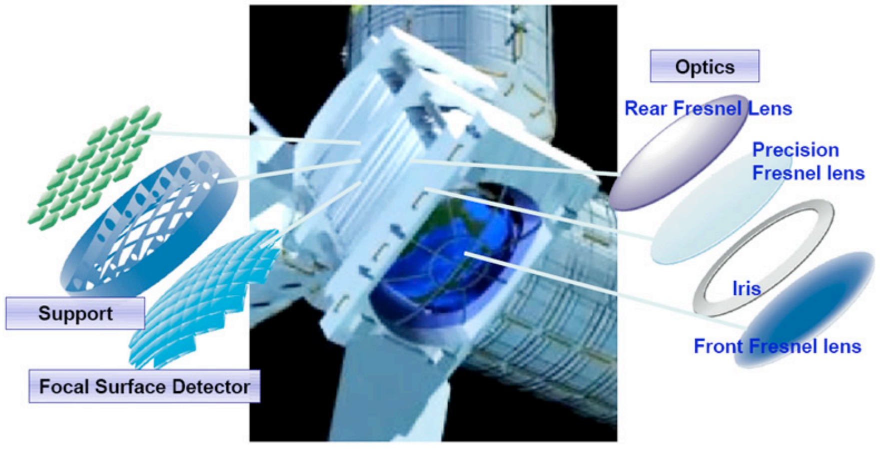

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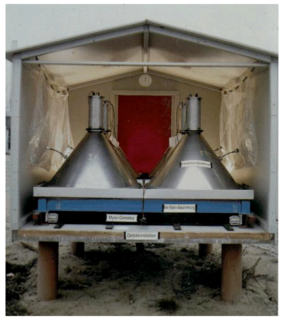

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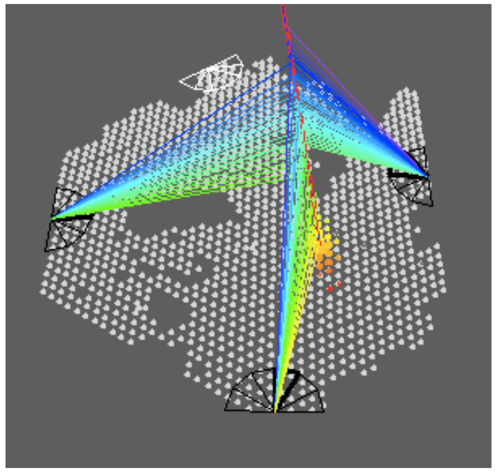

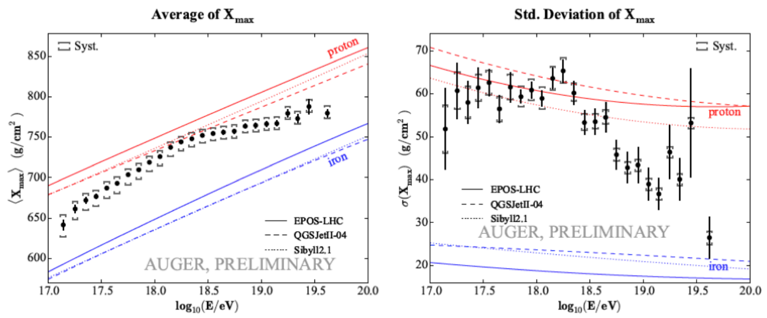

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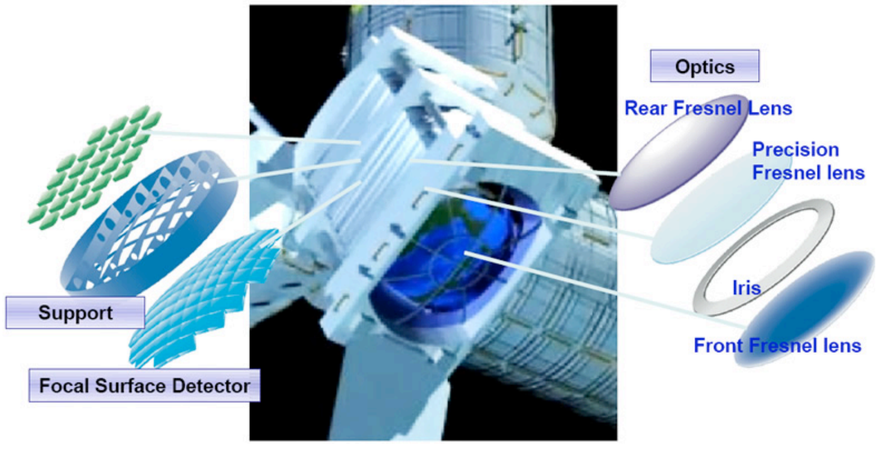


Cosmic-rays at very-high and ultra-high energies

Why do we care?
We know for many decades that cosmic-rays of extraordinary energies are produced in the universe and eventually reach the Earth…
How are they produced/accelerated, how energetic can they become ? What are their sources in the Galaxy? What are their sources outside of the Galaxy?

❖To understand cosmic-ray one needs to measure the cosmic-ray spectrum, composition and arrival directions

❖ Above ~10^{14} eV cosmic-rays are detected indirectly by reconstructing the properties of air showers they initiate in the atmosphere

Mainly two detection methods :

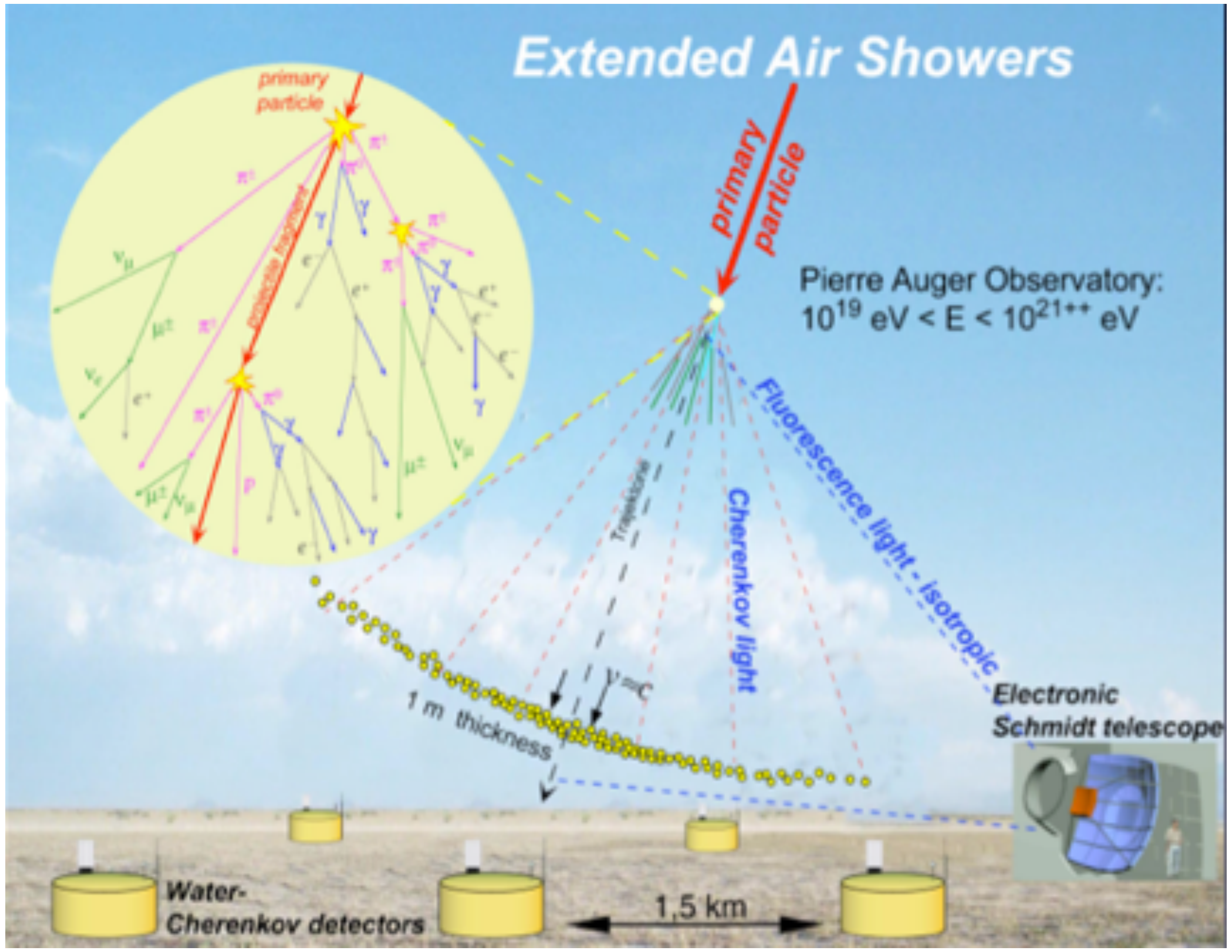
Ground arrays (sampling of the shower's particle content at ground level)

Fluorescence telescope (detection of the longitudinal development of the shower)

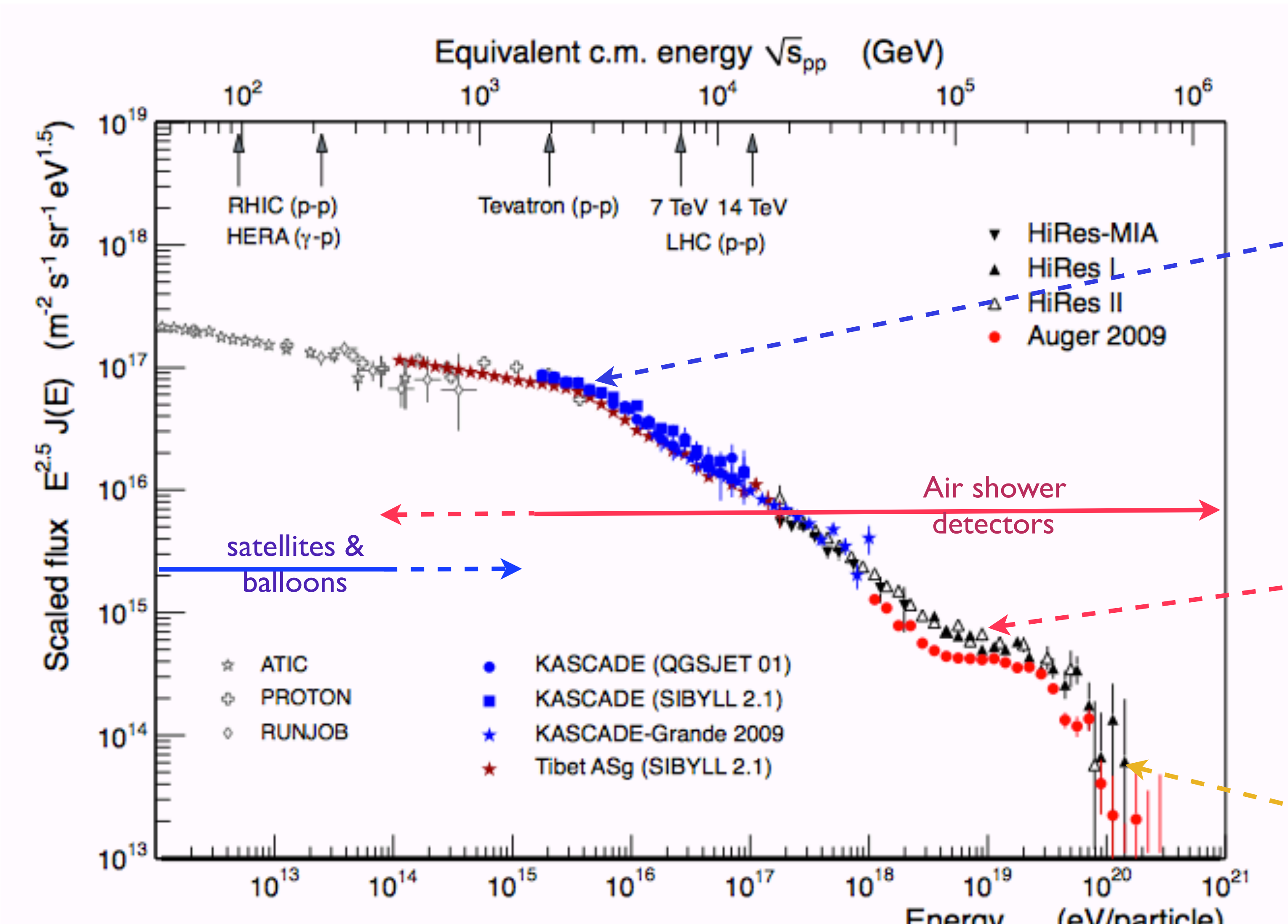
The most difficult aspect of CR indirect detection is to infer CR composition because of :

- air showers intrinsic fluctuations

- uncertainties on hadronic interactions taking place during the shower development



The cosmic-ray spectrum



Pierog, 2012

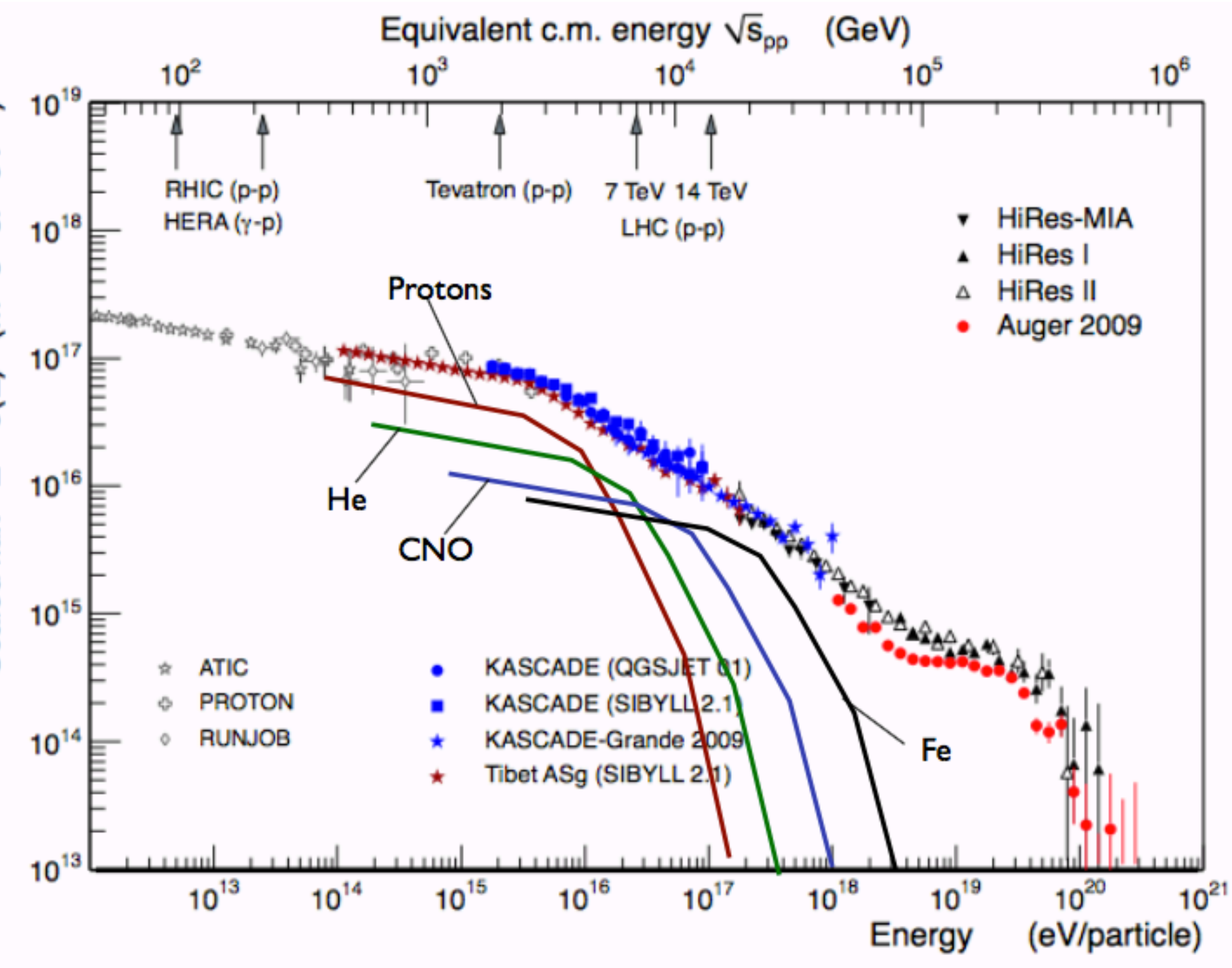
The knee
E~3-4.10^{15} eV

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

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

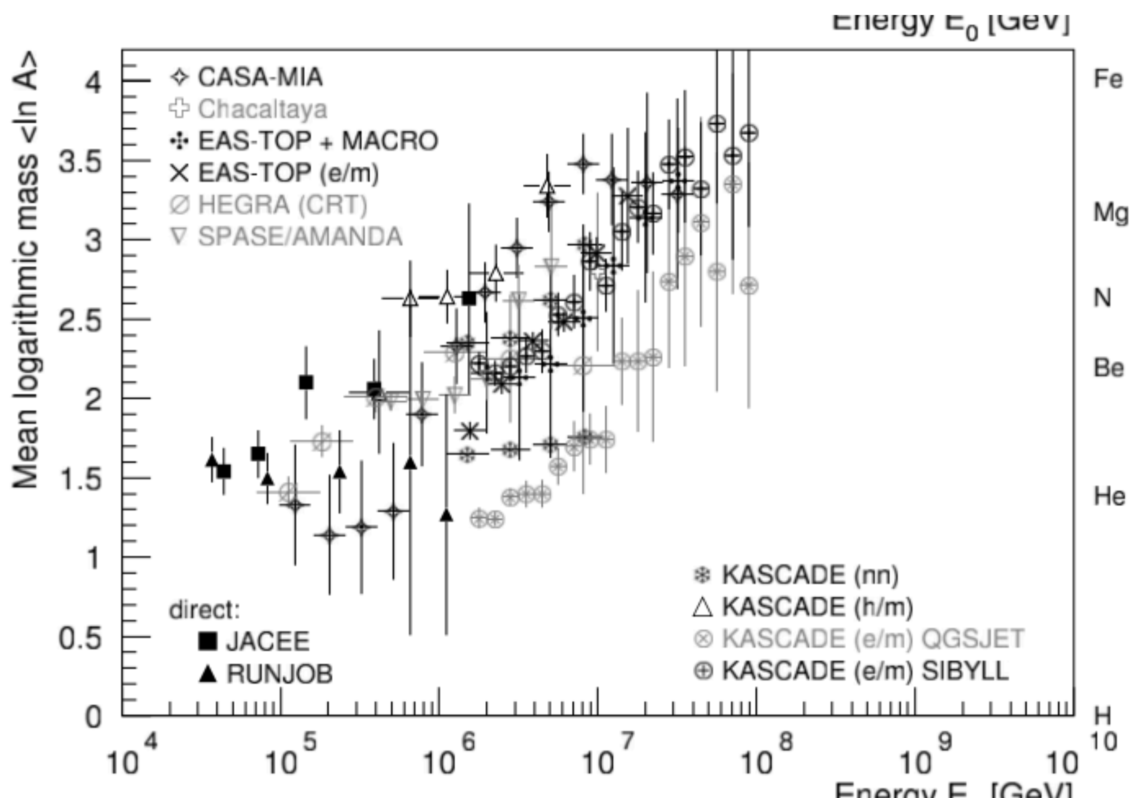
Situation at the beginning of 2010, three major features in the VHE and UHE cosmic-ray spectrum :
The knee and the ankle were known for a long time
The high energy cut-off was revealed a few years before at the end of the controversy between HiRes and AGASA

The cosmic-ray spectrum



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

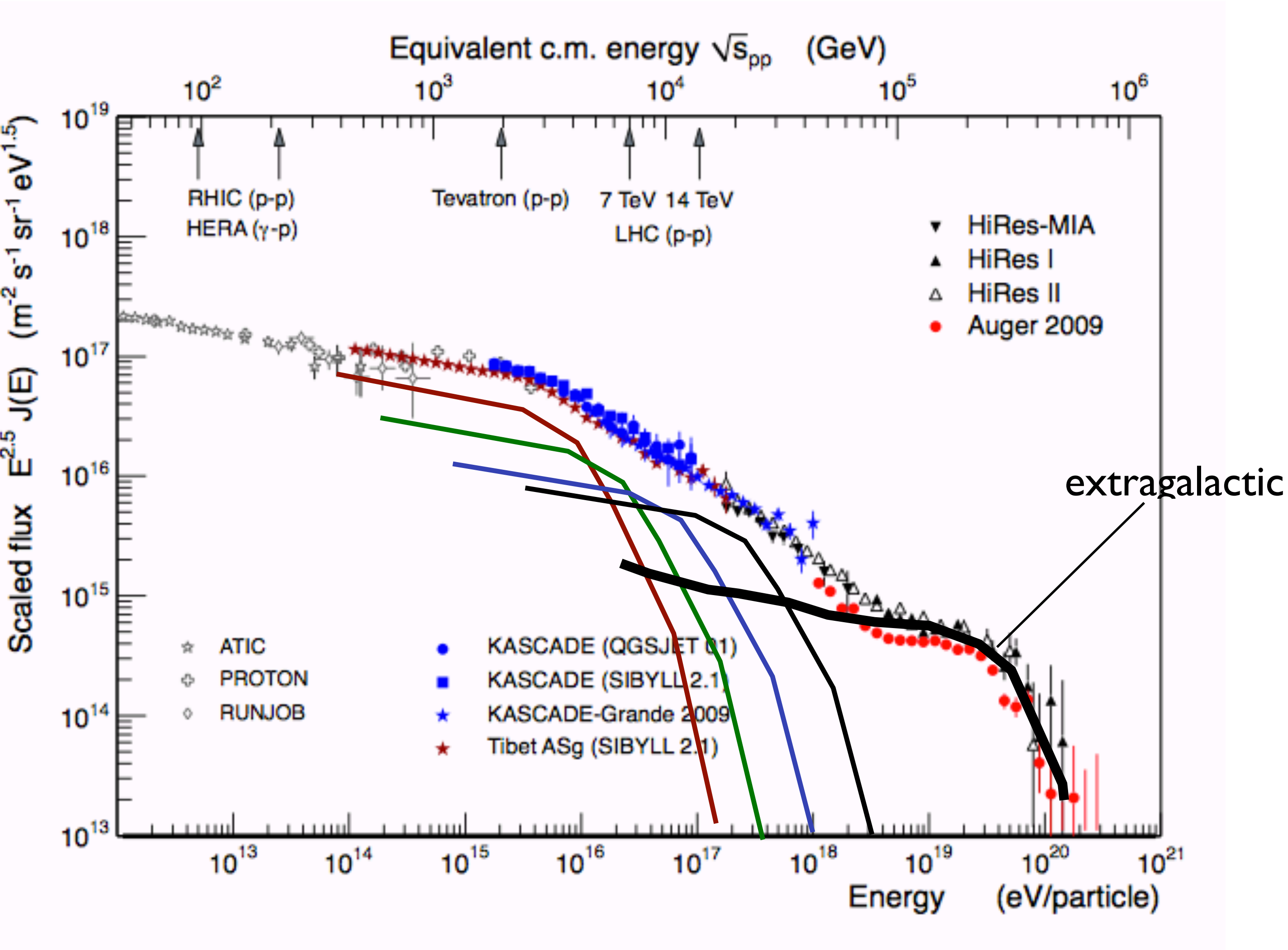
Mainly two physical mechanisms invoked to explain the knee :

(i) maximum rigidity in Galactic accelerators is reached

(ii) rigidity at which Galactic cosmic-rays start to leak faster from the Galaxy

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

The cosmic-ray spectrum



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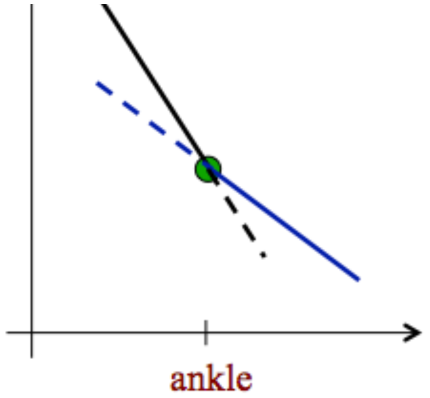
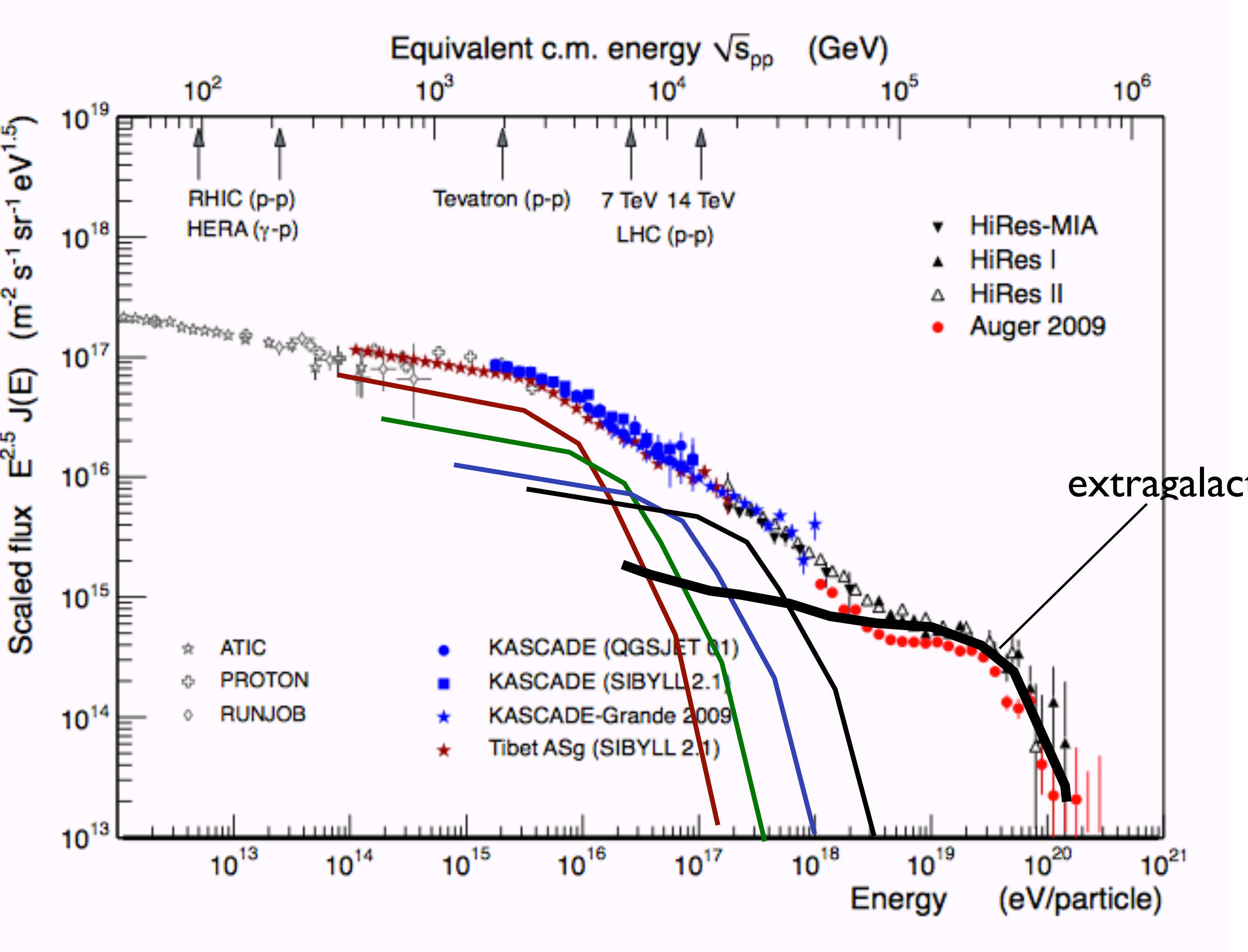


ankle : transition from a softer to a harder component

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

(but other interpretations have been proposed)

The cosmic-ray spectrum



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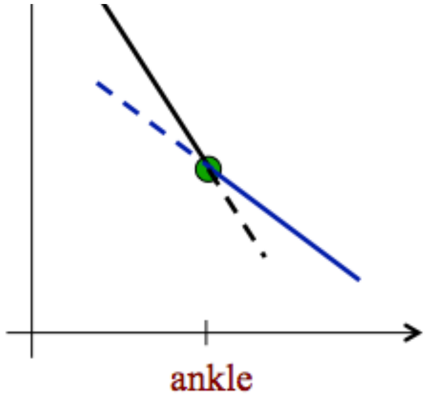

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KASCADE-Grande designed as an extension of KASCADE to measure the cosmic-ray spectrum and composition between ~10^{16} eV and ~10^{18} eV
constraints expected on :

- the knee of the heavy elements
- the transition from Galactic to extragalactic

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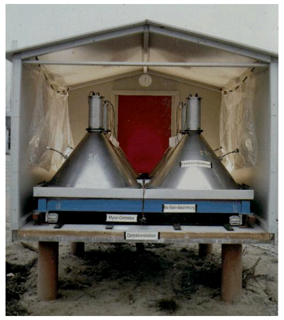

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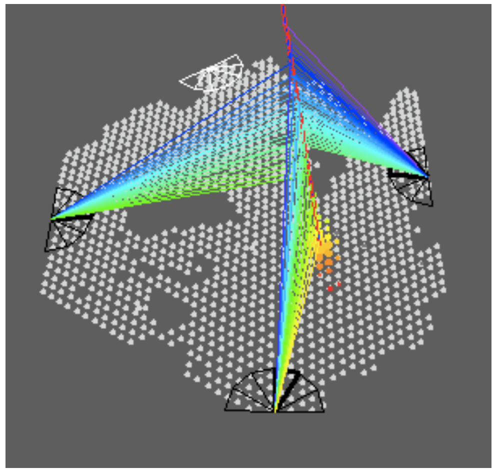

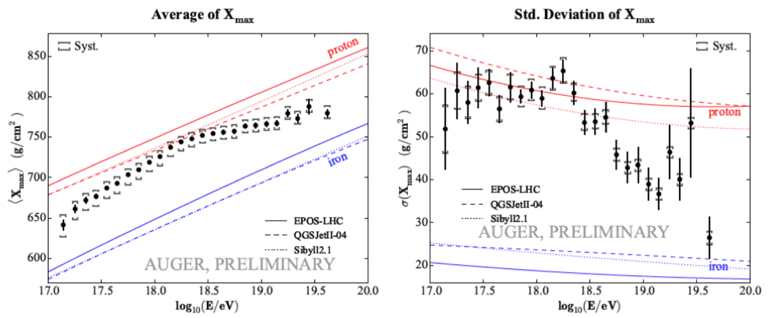

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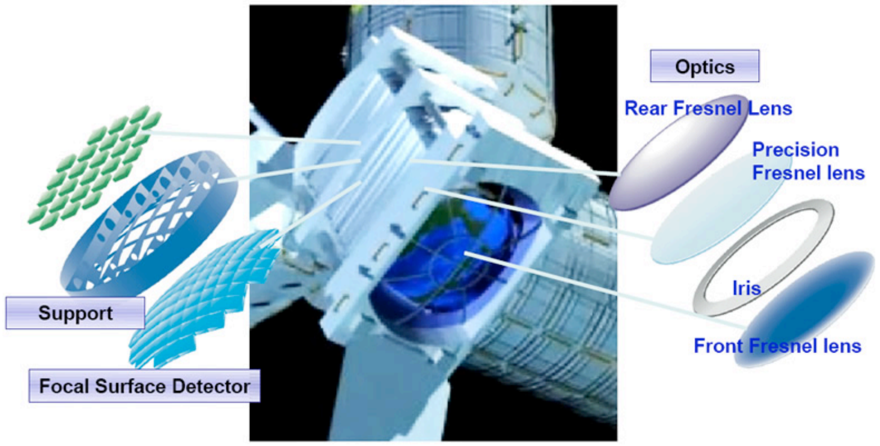
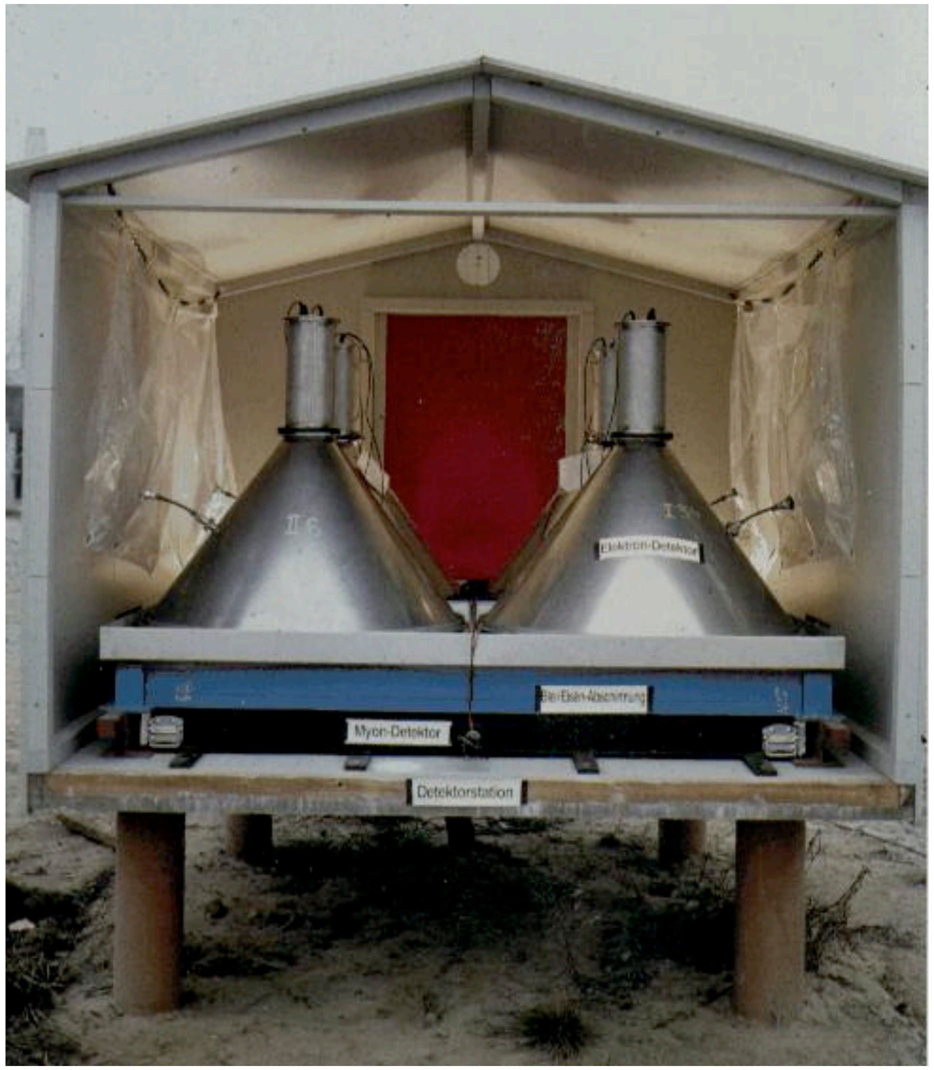


KASCADE and KASCADE-Grande

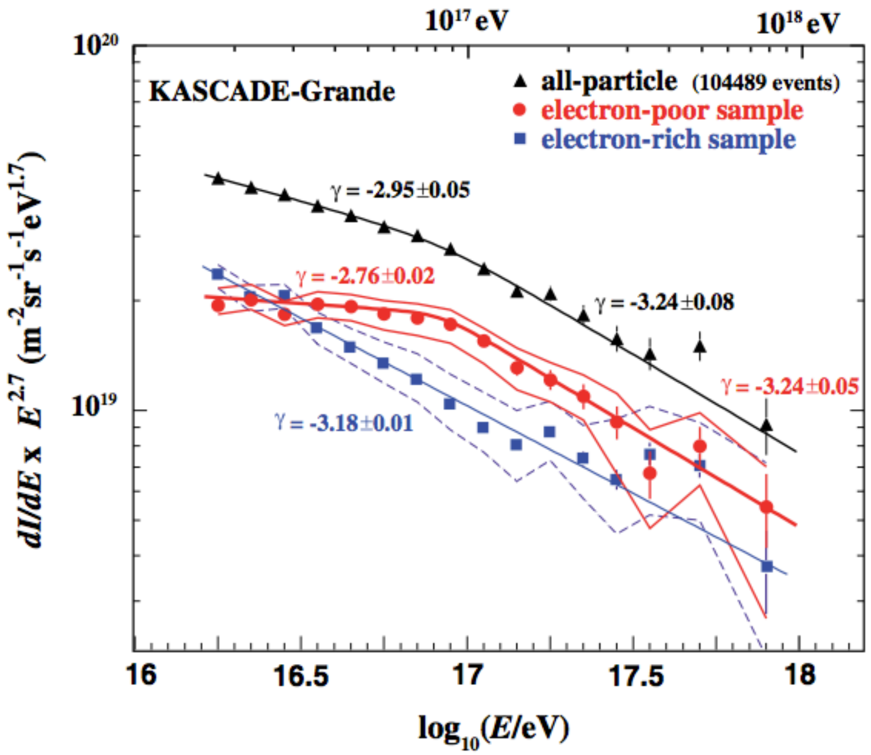
Kascade

Kascade-Grande

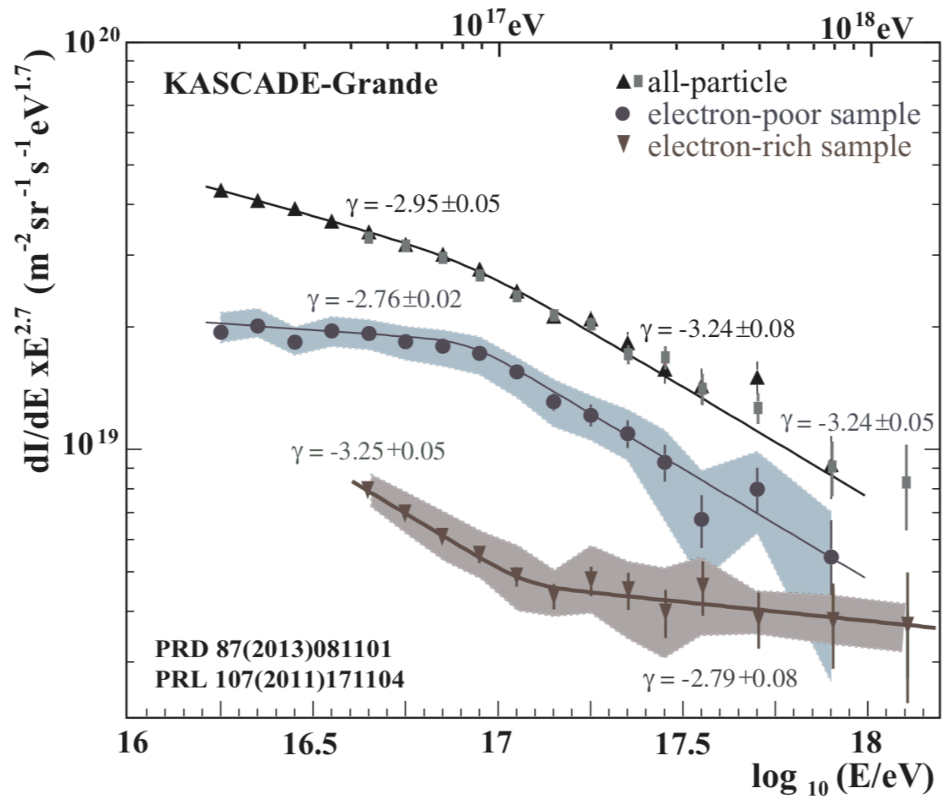


liquid scintillators => e^+e^-
shielded plastic scintillators => muons

Kascade-Grande : Heavy knee and light ankle



KG collab, Phys. Rev. Lett., 2011



• Significant break of the heavy component (supposed to be Si+Fe)
• Moderate change of spectral index ~0.5
• 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
• 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)

• A similar analysis showed evidence for an "ankle" in the light component

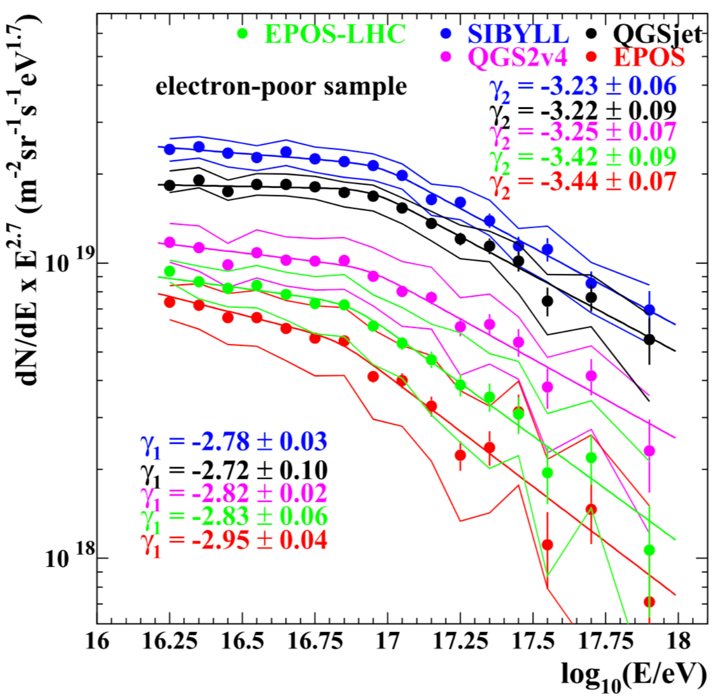
• The spectral index before the "light ankle" is compatible with the post knee spectral index of the heavy component

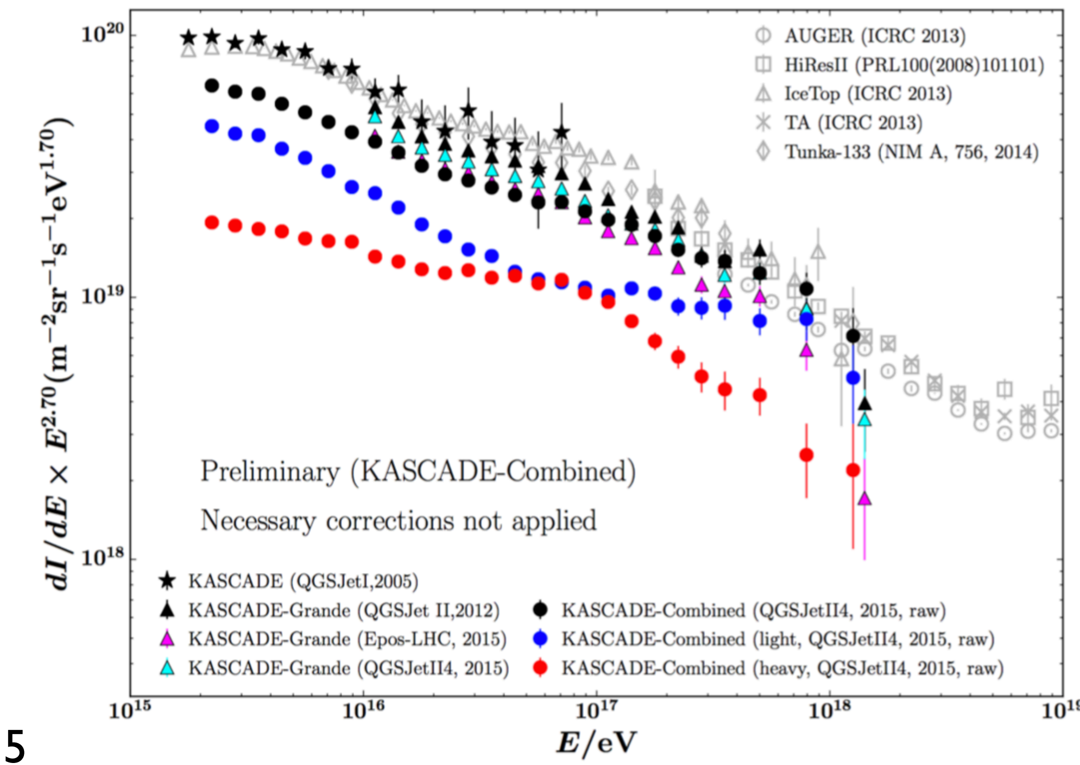
• Likely explanation : an extragalactic light component is starting to emerge on top of the light galactic component
==> smooth knee for the light component too ==> post knee protons at ~10^{17} eV (?)

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

Constraining for the transition from Galactic to Extragalactic cosmic-rays
Constraining for Galactic sources ---> "more than pevatrons" needed?

Kascade-Grande : Heavy knee and light ankle





KG collab, ICRC 2015

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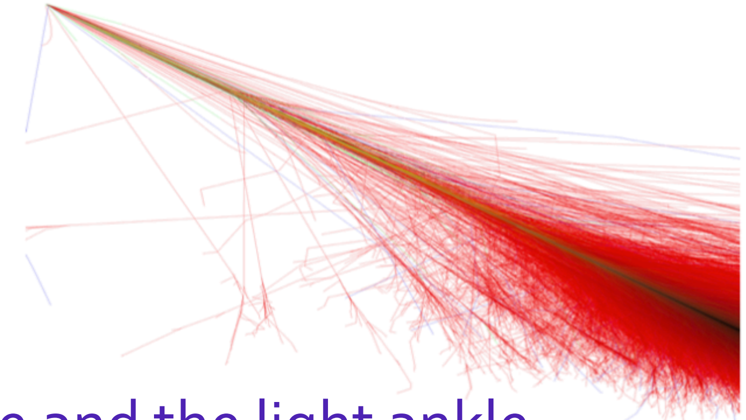

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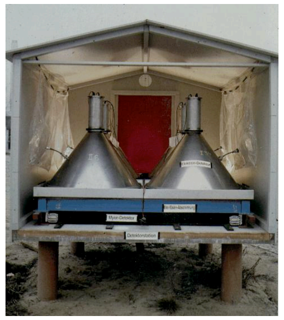

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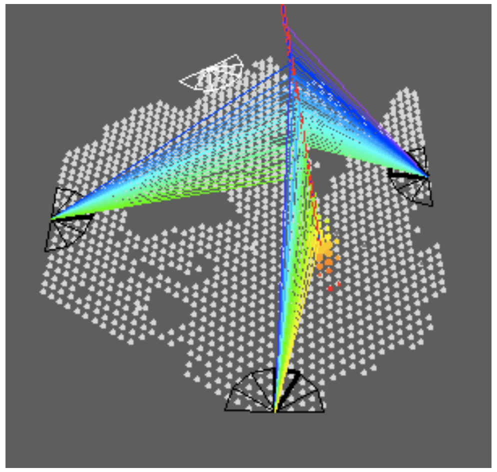

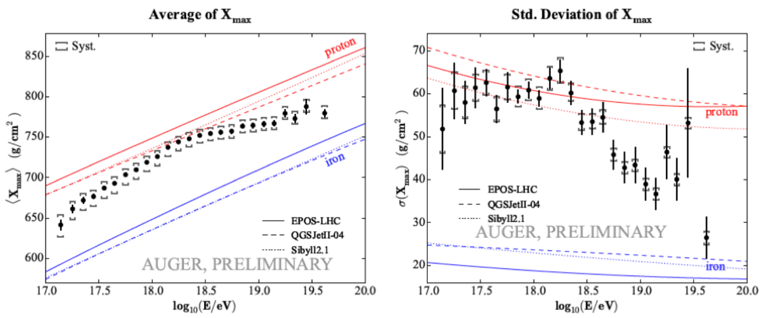

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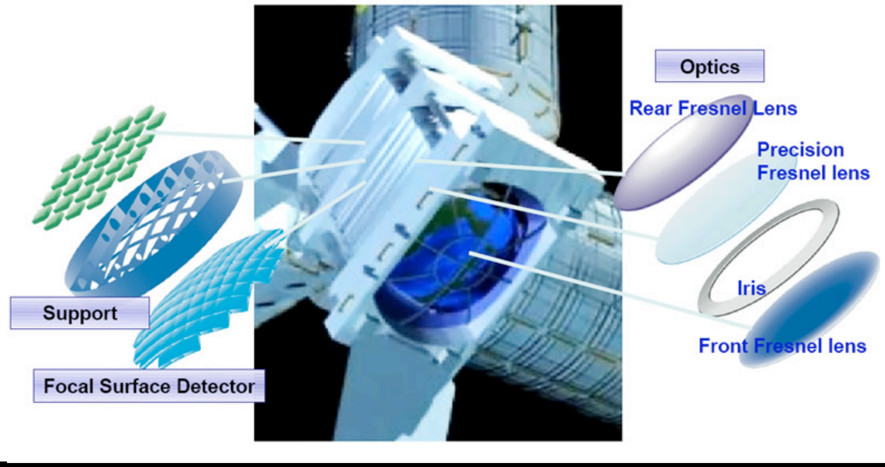


Auger the largest cosmic-ray observatory in the world

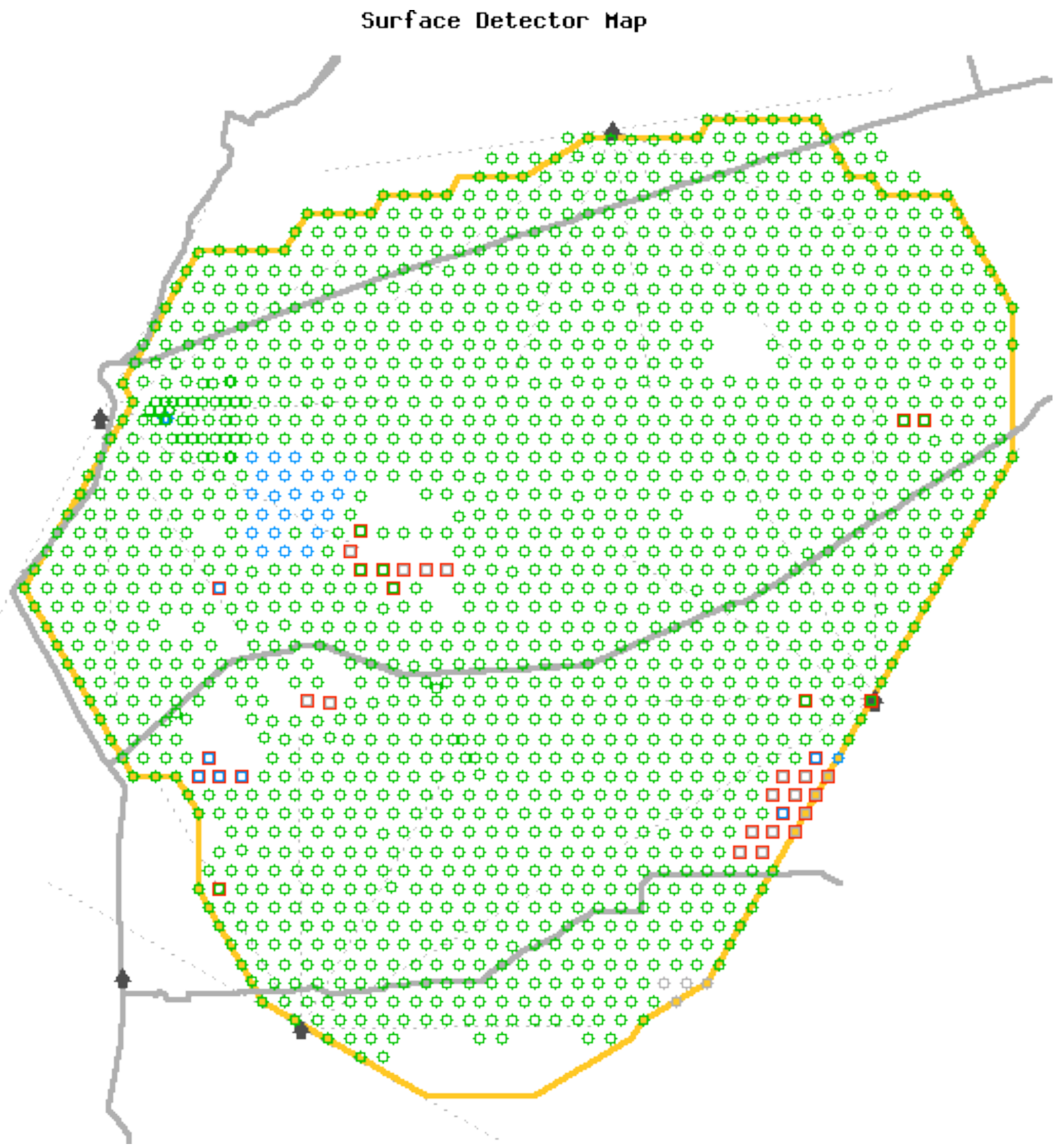
- Located in Malargue (Mendoza, Argentina, 1400m a.s.l
- 1600 Water Cerenkov Tanks, spacing 1500 m

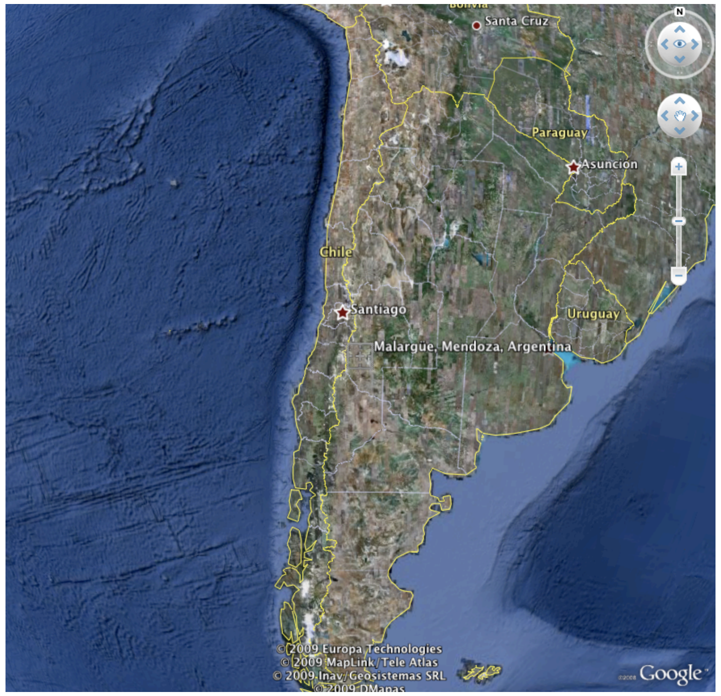
-> ground array surface 3000 km^2

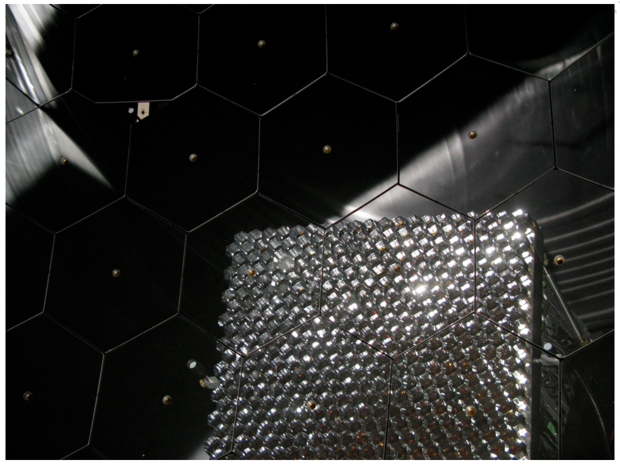
- 4 Fluorescence detectors overlook the array

Huge surface for an unprecedented statistics above 10^{18} eV
+ low energy extension to study cosmic-ray physics down to 10^{17} eV
Hybrid detection for a good understanding of air-shower physics
A few percent of hybrid events allow :

- energy calibration almost independent of air shower simulations
- unprecedented resolution for composition studies
- cross check of the hadronic physics used in air shower simulations

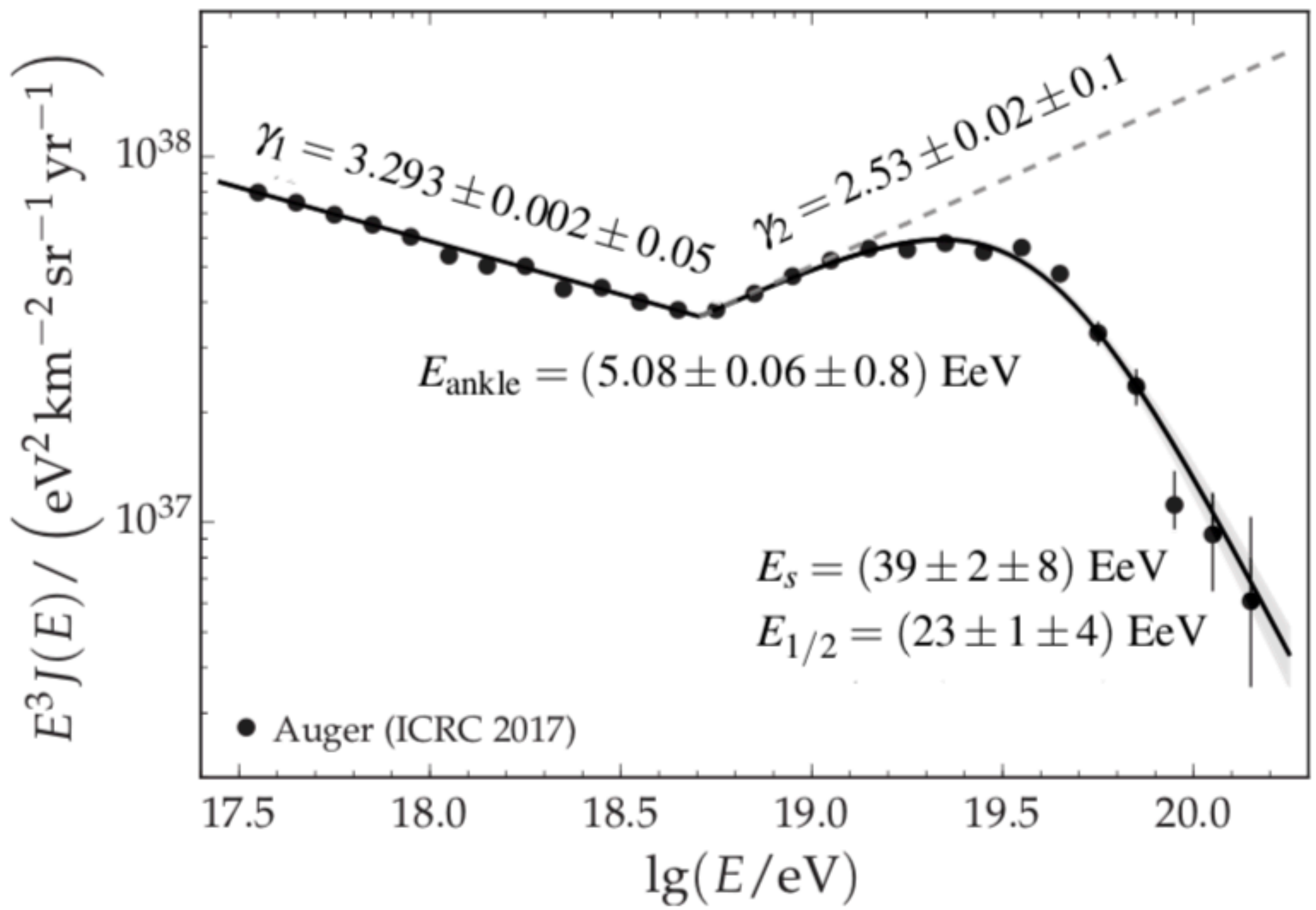






Auger UHECR spectrum

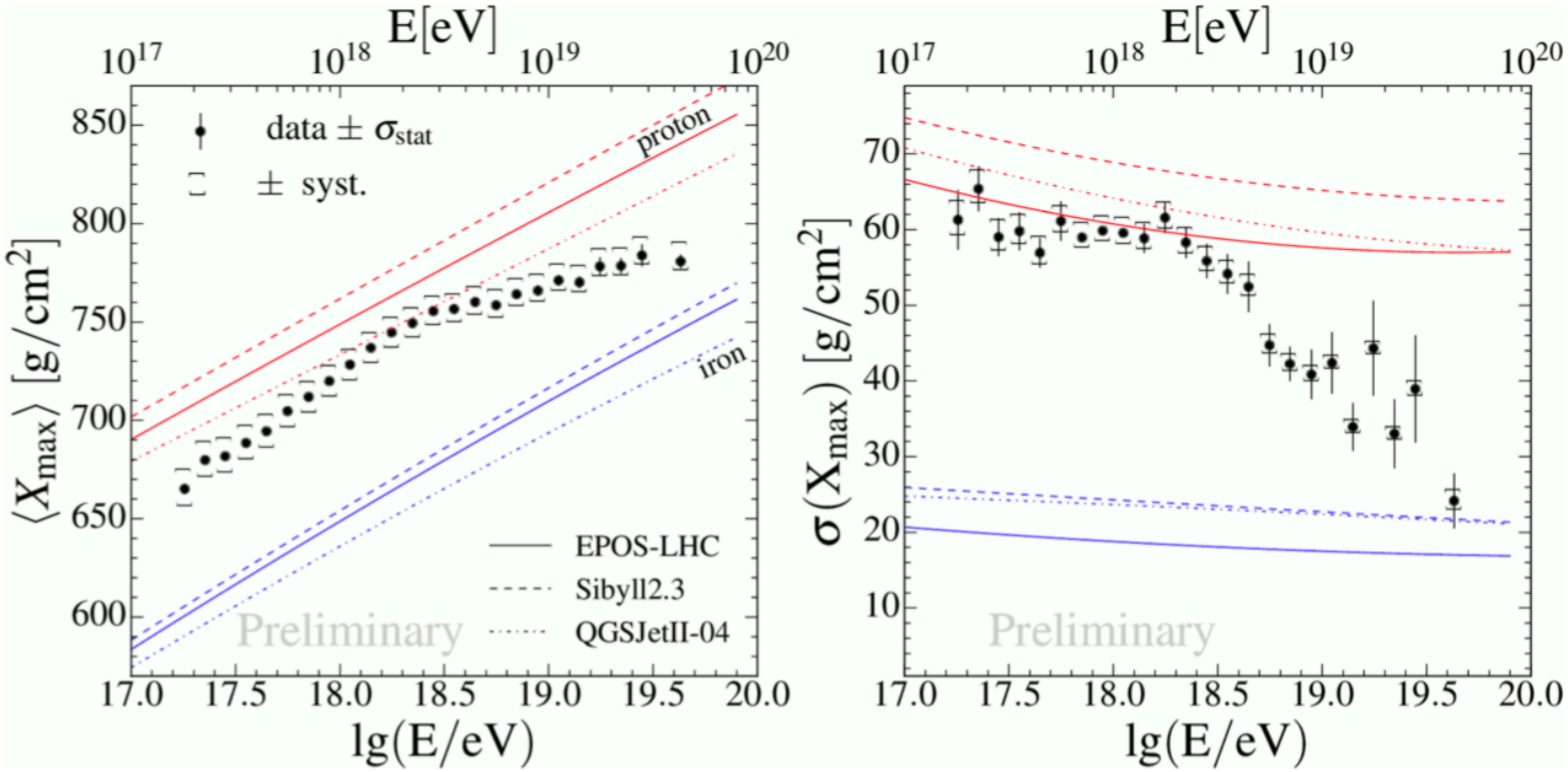
- Energy calibration relies on the calorimetric measurements of fluorescence detectors
- Statistics relies on the huge exposure of the surface array



- confirms the presence of the ankle and the high energy cut-off with unprecedented statistics and resolution (14 events above 10^{20} eV)

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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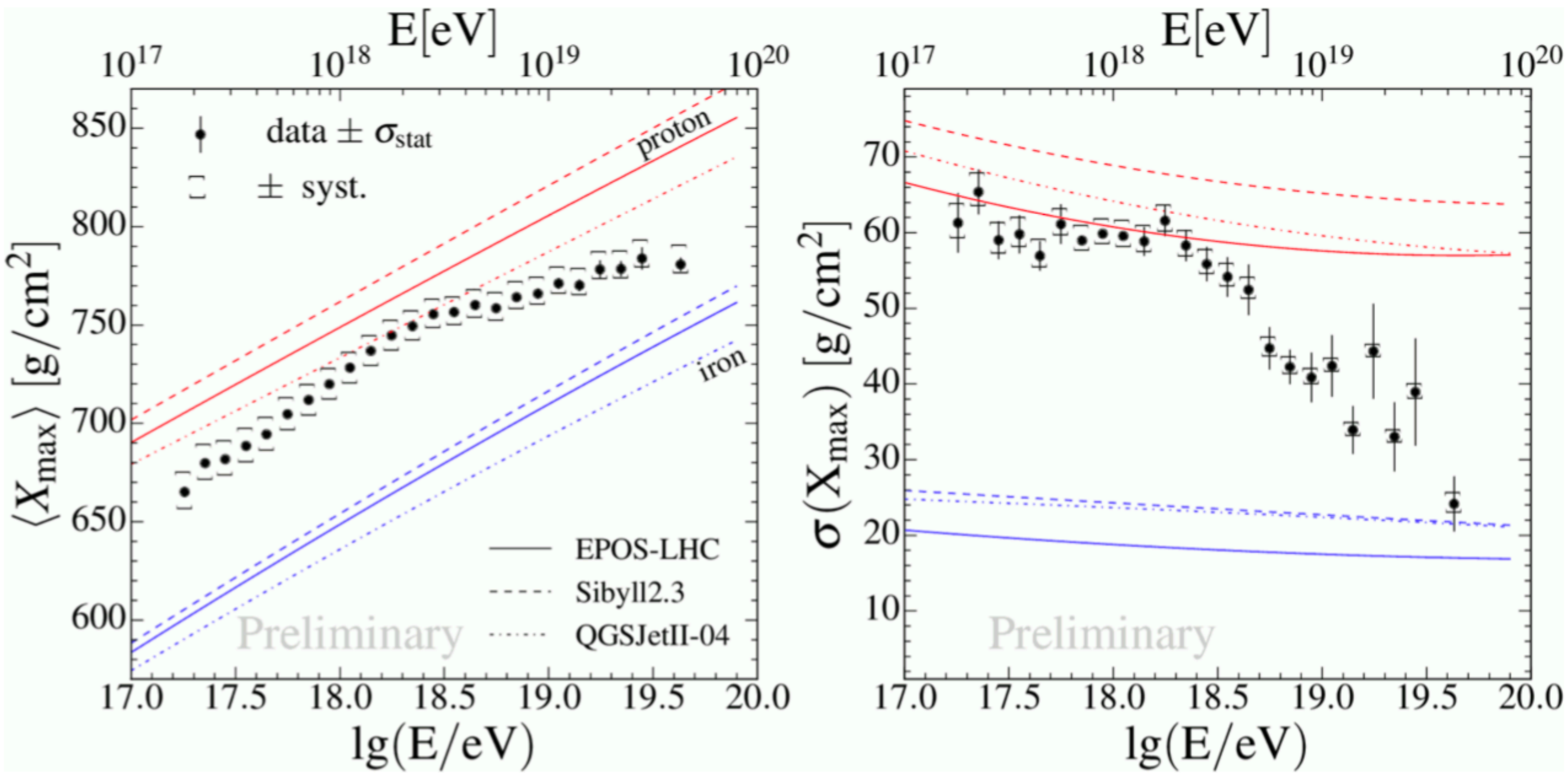

Auger collab, ICRC 2017

—> 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

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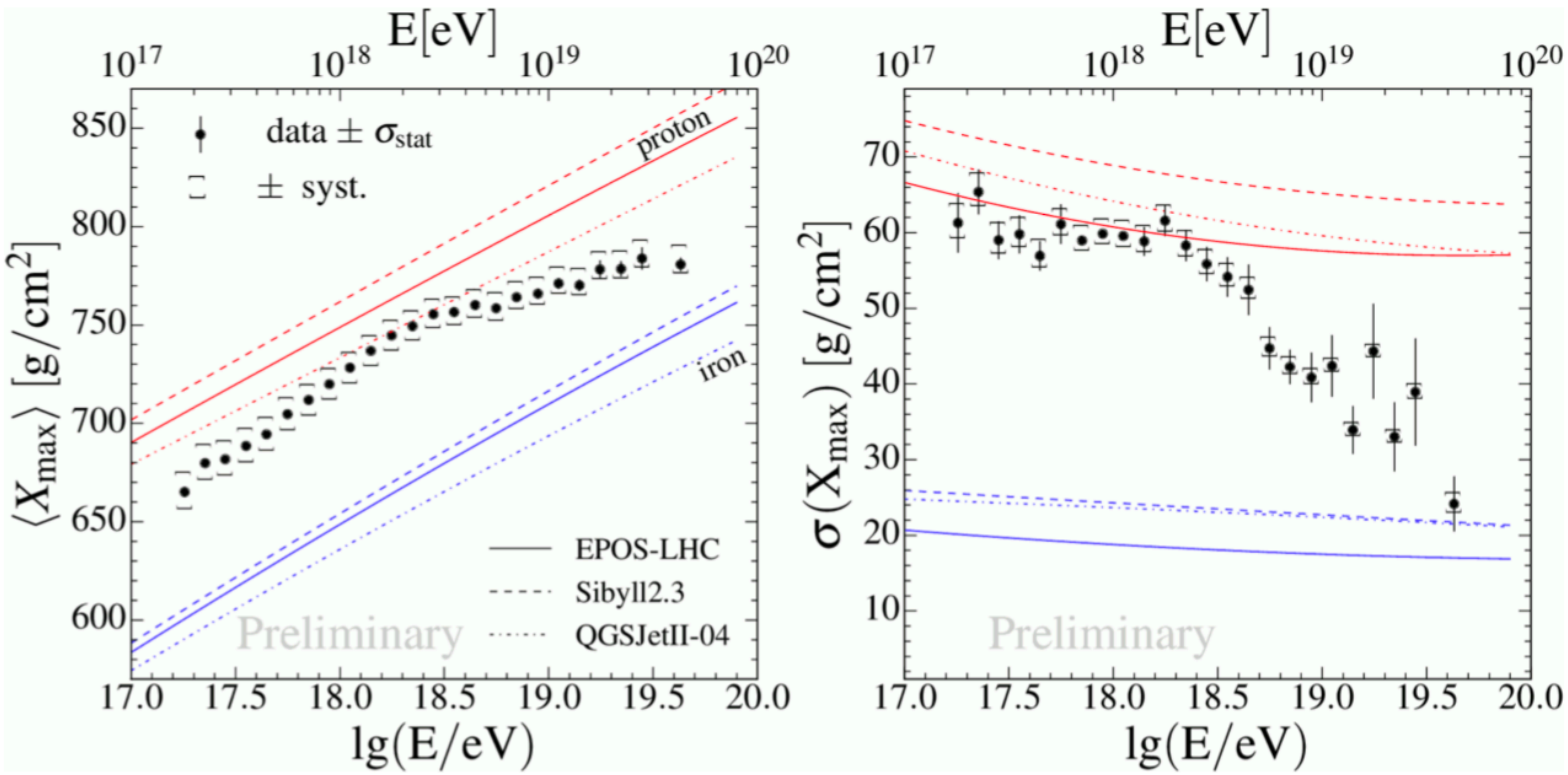


Auger collab, ICRC 2017

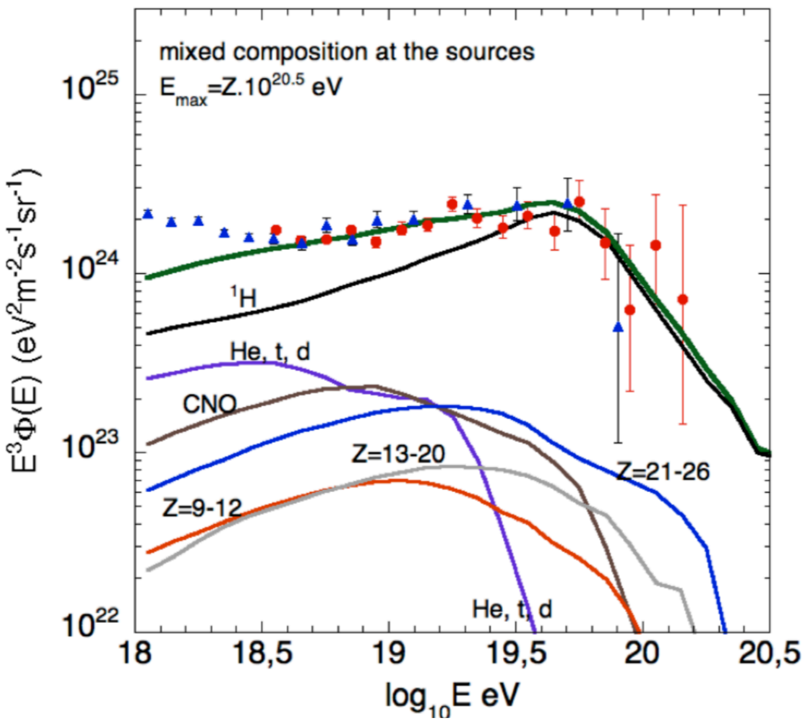
What can be concluded from the observation of a composition getting heavier above the ankle?

Let us place ourselves in the framework of an extragalactic origin of the cosmic-rays above the ankle

Implications of the evolution of the composition above the ankle

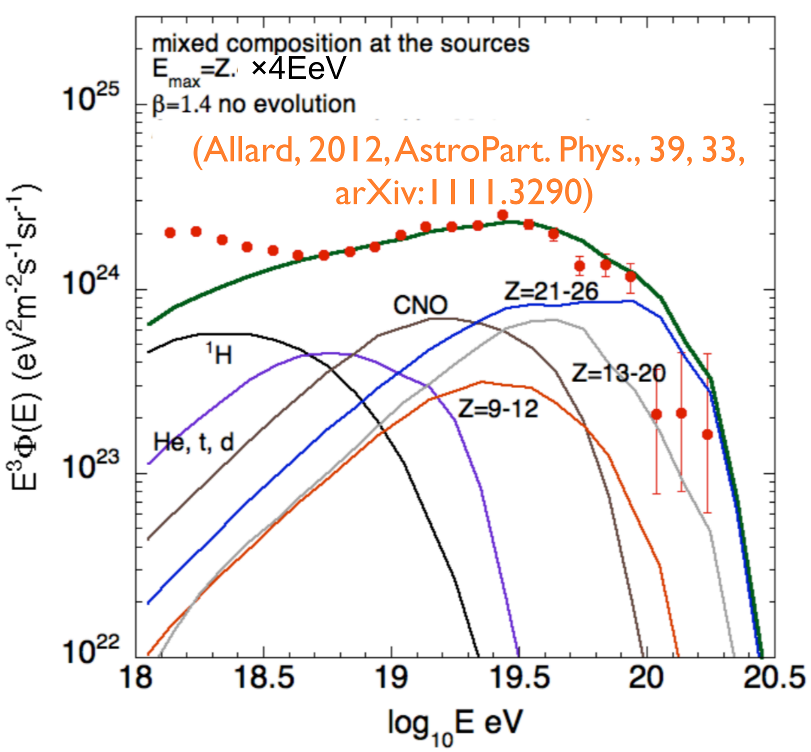
Assuming the maximum energy per nucleon is above 10^{20} eV (what most people thought until ~2010) mixed composition similar to that of low energy galactic cosmic-rays :

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



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)
(Allard et al., 2007, AstroPart. Phys., 27, 61, astro-ph:0512345)
(Allard et al., 2008, JCAP, 10, 033, arXiv:0805.4779)

But the evolution of the composition implied by Auger composition analyses strongly suggest that the composition is becoming heavier as the energy increases
—> most likely explanation 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 $N(E) \propto E^{-\beta}$, $\beta=1.4$, $E_{max}(Z)=Z \times E_{max}^{proton}$, $E_{max}^{proton}=4.10^{18}$ eV

—> allows to reproduce the high energy composition trend

—> high energy cut-off explained by the combined effect of the maximum energy at the sources and the interaction of nuclei with photon backgrounds

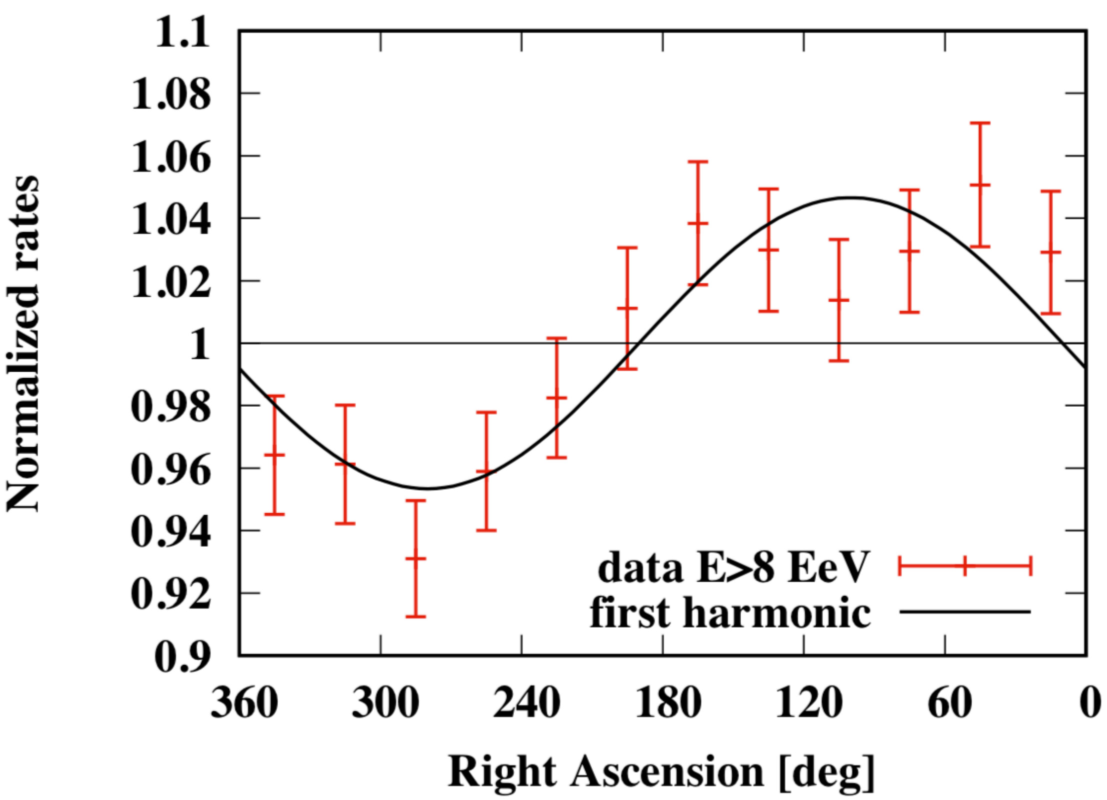
—> strong implications for UHE cosmogenic neutrinos predictions

(Globus et al., 2017, ApJ 839L, 22, arXiv:1703.04158; Decerprit & Allard, 2011, A&A 535A, 66)

—> conservative conclusion : accelerators capable of accelerating protons well above 10^{19} eV must be rare in the local universe

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
≥ 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 at the highest energies (E>40 EeV)

Auger Collab, Astrophysical Journal, 804:15 (18pp), 2015 May 1,

General anisotropy tests above 40 EeV :

- Search for localised excess (scan in energy, location and angular scale)
  —> strongest Li-Ma significance 4.3σ in a 12° window not far from CenA
  —> 69% chance to have a stronger excess under the same scan with isotropic simulations

- Autocorrelation of events (2pt correlation function), scan in energy and angular scale
  —> strongest departure from isotropy for a separation angle of 1.5° above 42 EeV
  —> 70% chance to have such a strong excess of pairs with isotropic simulations

No sign of intrinsic anisotropies

No correlation with the supergalactic plane or the galactic center

Most cross-correlation studies with flux limited samples are inconclusive

Only hints of signal in the direction of CenA and with Swift bright AGNs (these two studies were updated at the last ICRC)

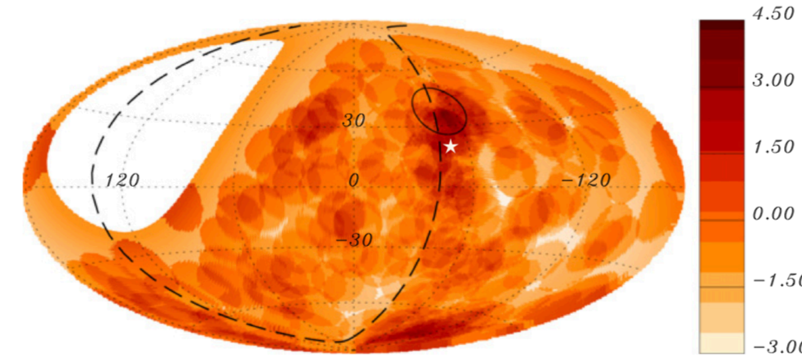


Figure 1. Map in Galactic coordinates of the Li–Ma significances of overdensities in 12°-radius windows for the events with $E \geqslant 54$ EeV. Also indicated are the Super-Galactic Plane (dashed line) and Centaurus A (white star).

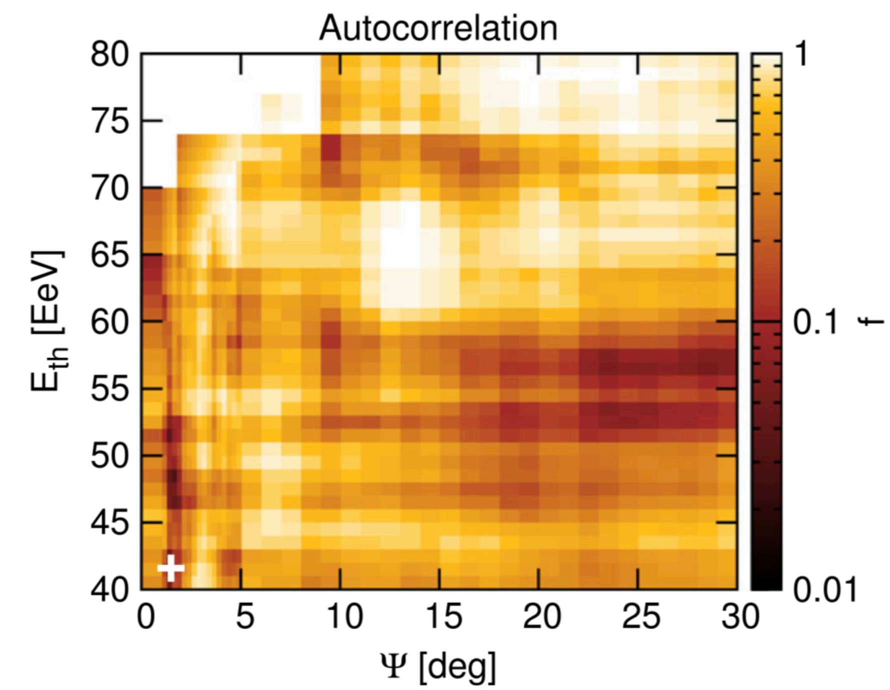
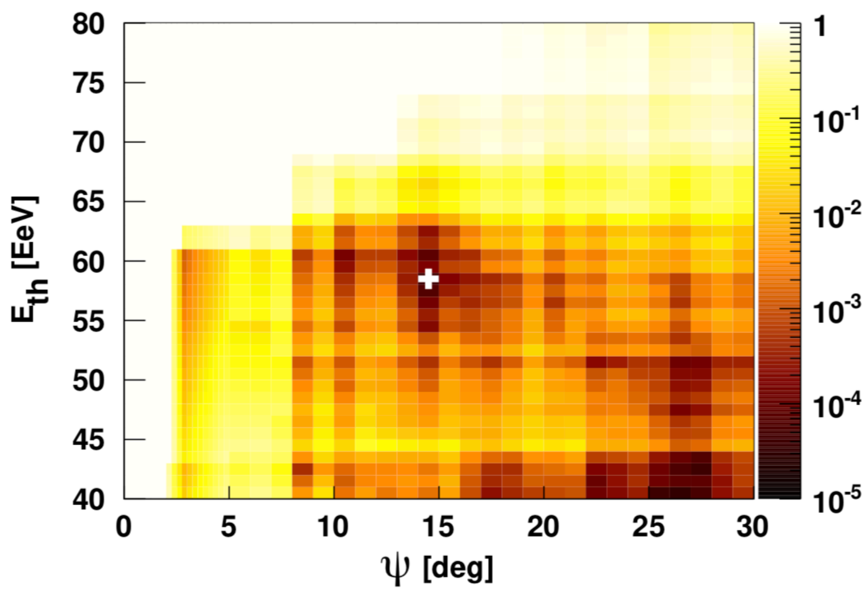


Table 1
Summary of the Parameters of the Minima Found in the Cross-correlation Analyses

Objects	E_{th} (EeV)	Ψ (°)	D (Mpc)	$\mathcal{L}_{min}$ (erg s^{-1})	f_{min}	$\mathcal{P}$
2MRS Galaxies	52	9	90	…	1.5×10^{-3}	24%
Swift AGNs	58	1	80	…	6×10^{-5}	6%
Radio galaxies	72	4.75	90	…	2×10^{-4}	8%
Swift AGNs	58	18	130	10^{44}	2×10^{-6}	1.3%
Radio galaxies	58	12	90	$10^{39.33}$	5.6×10^{-5}	11%
Centaurus A	58	15	…	…	2×10^{-4}	1.4%

Anisotropies at the highest energies, latest updates (ICRC 2017)

- The CenA region
—> strongest departure from isotropy above 58 EeV, for an angular scale of 15°, 19 events (over 203) observed, 6 expected
—> 3.1σ once penalized
—> secondary minimum at 40 EeV (~25°)



Anisotropies at the highest energies, latest updates

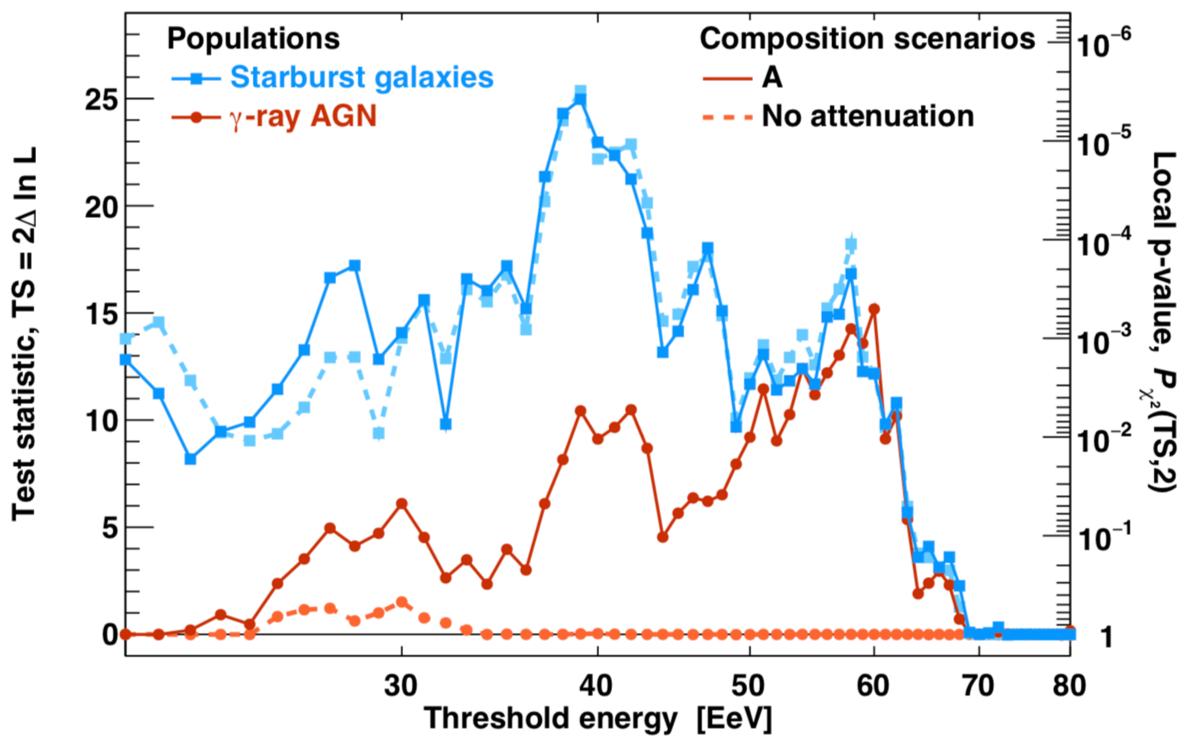
(Auger Collab, 2018ApJ, 853L29A)

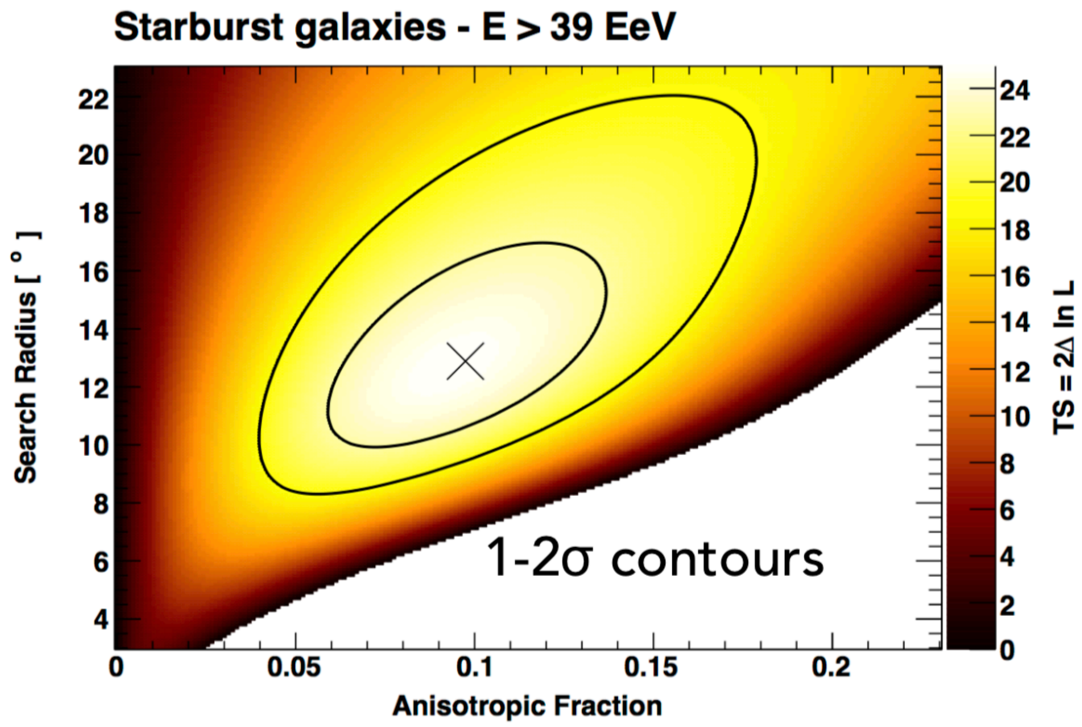
A different method for cross-correlation studies with astrophysical catalogues

- 4 catalogues considered : star-forming galaxies (Ackerman et al., 2012, ApJ 755, 164), Fermi γ-ray AGN, 2MRS and Swift Bat

- Build cosmic-ray arrival direction maps by :
  - weighting each source by its flux in a given wavelength
  - apply a gaussian blurring of the arrival directions (the blurring angle ψ being a free parameter)
  - superimpose an isotropic distribution (the isotropic fraction f being a free parameter)

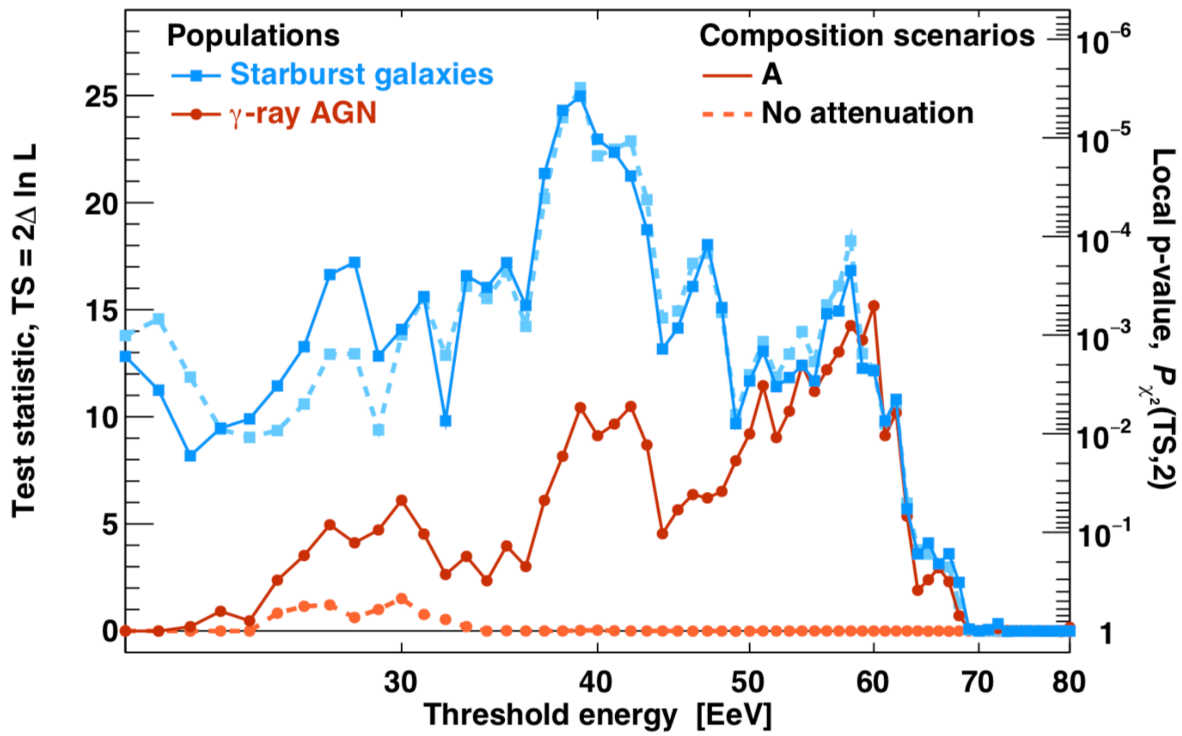
- A scan in energy is performed to find the blurring ψ and fraction f which maximize the agreement with the data (and reject isotropy most significantly)
  NB : UHECR "attenuation" due to energy losses is corrected for

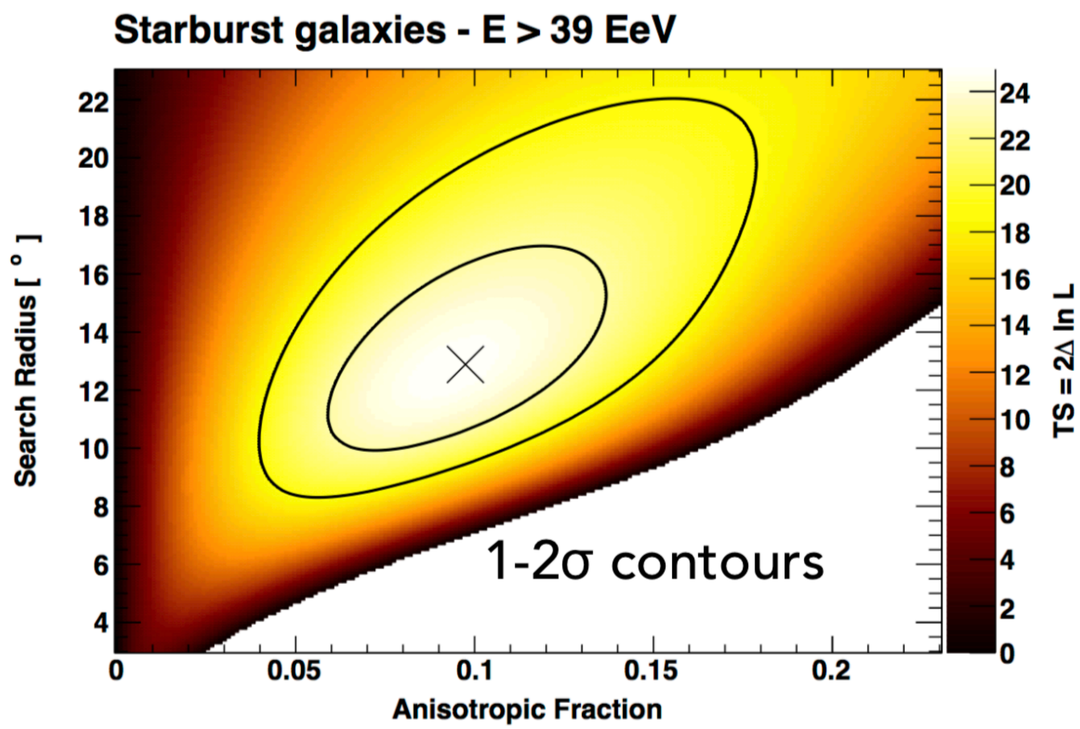




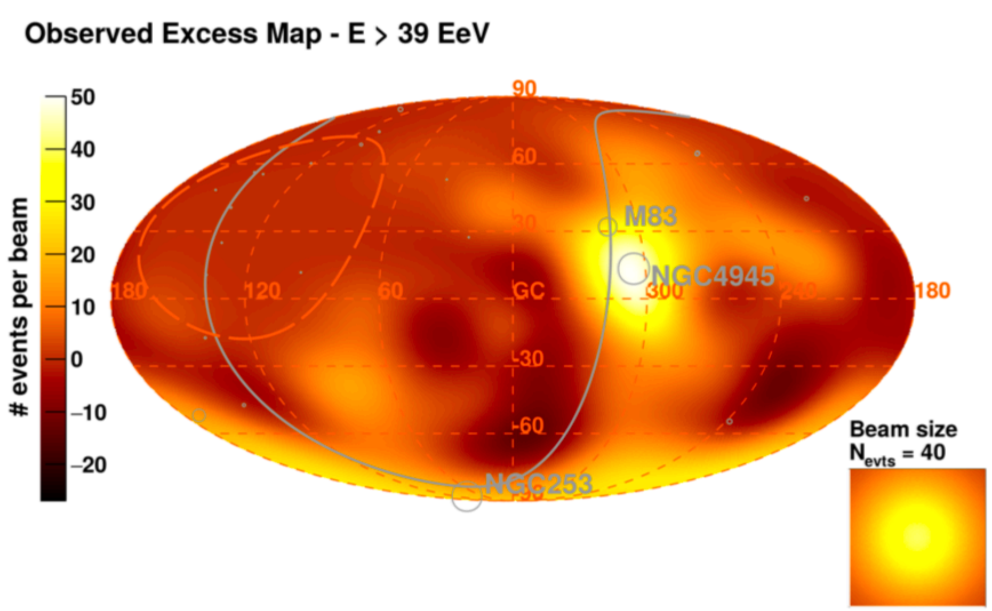
Anisotropies at the highest energies, latest updates

(Auger Collab, 2018ApJ, 853L29A)





4σ deviation from isotropy once penalized for the scan in energy (but not penalized for the use of several catalogues)



NB : a large part of the signal comes from the "CenA region" represented by the nearby M83 and NGC 4945 in the SFG catalog

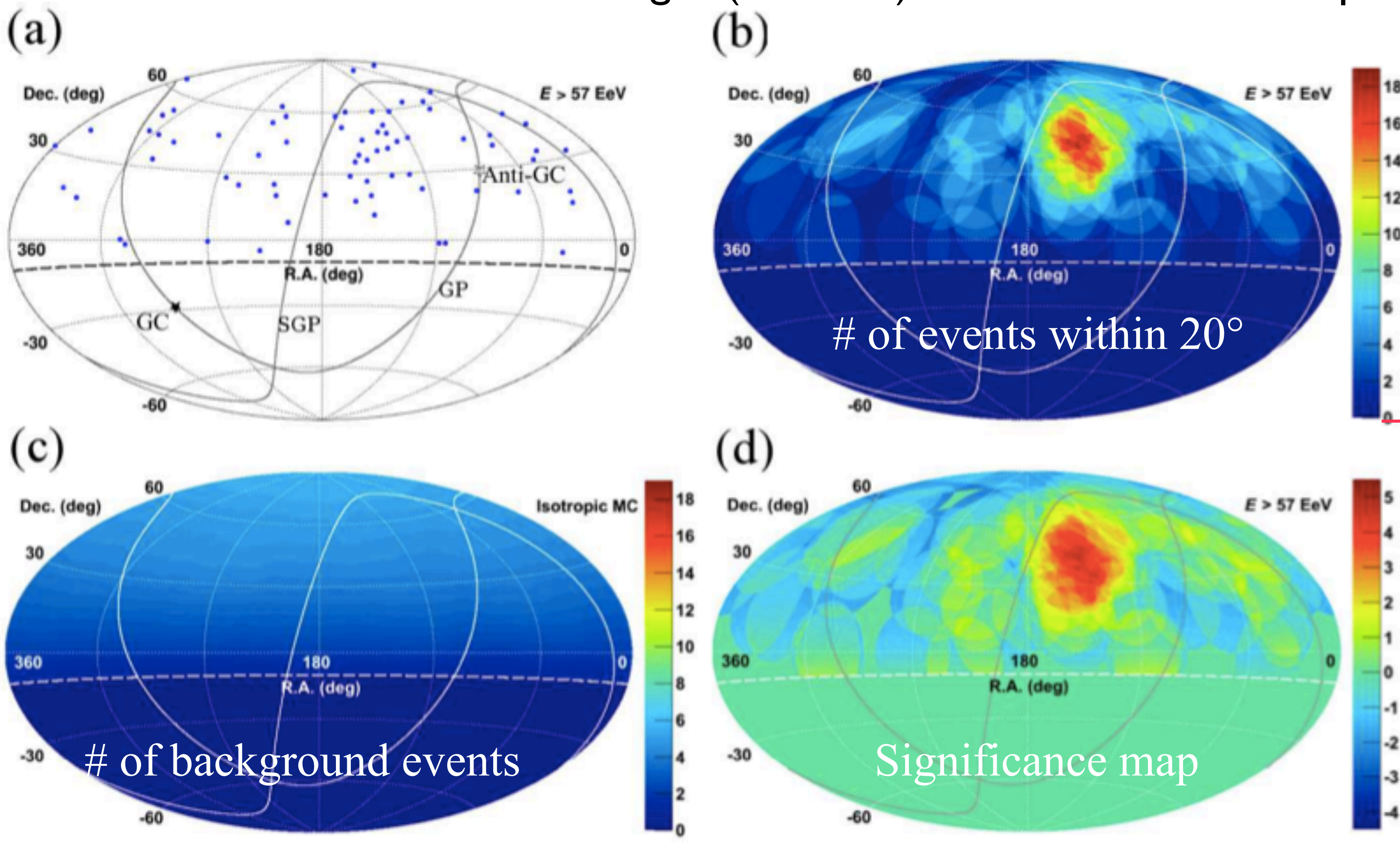
(the energy of the maximum departure from isotropy correspond to the second minimum of the CenA region analysis)

A Slight excess at the south galactic pole explained by the nearby NGC 253 brings the additional significance

—> Auger analyses at high-energy suggest the presence of a moderate anisotropy it is probably too early to fully understand its origin

Anisotropies in TA sky

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



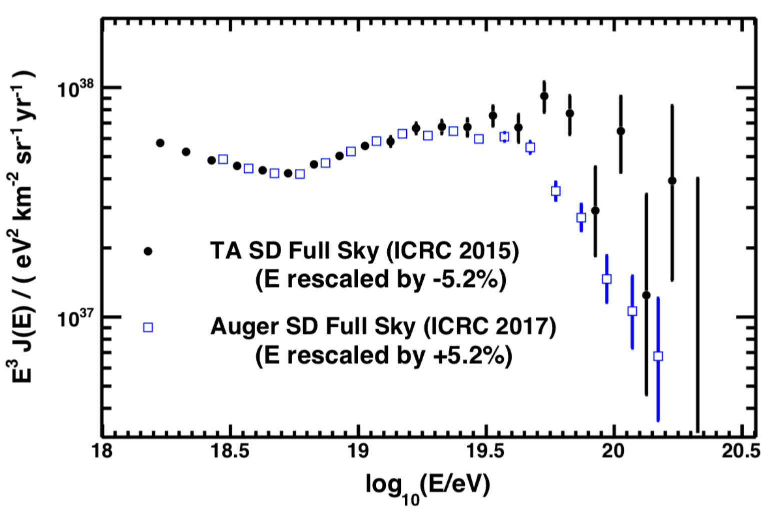
Abbasi et al., ApJ Letters, 2014

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)



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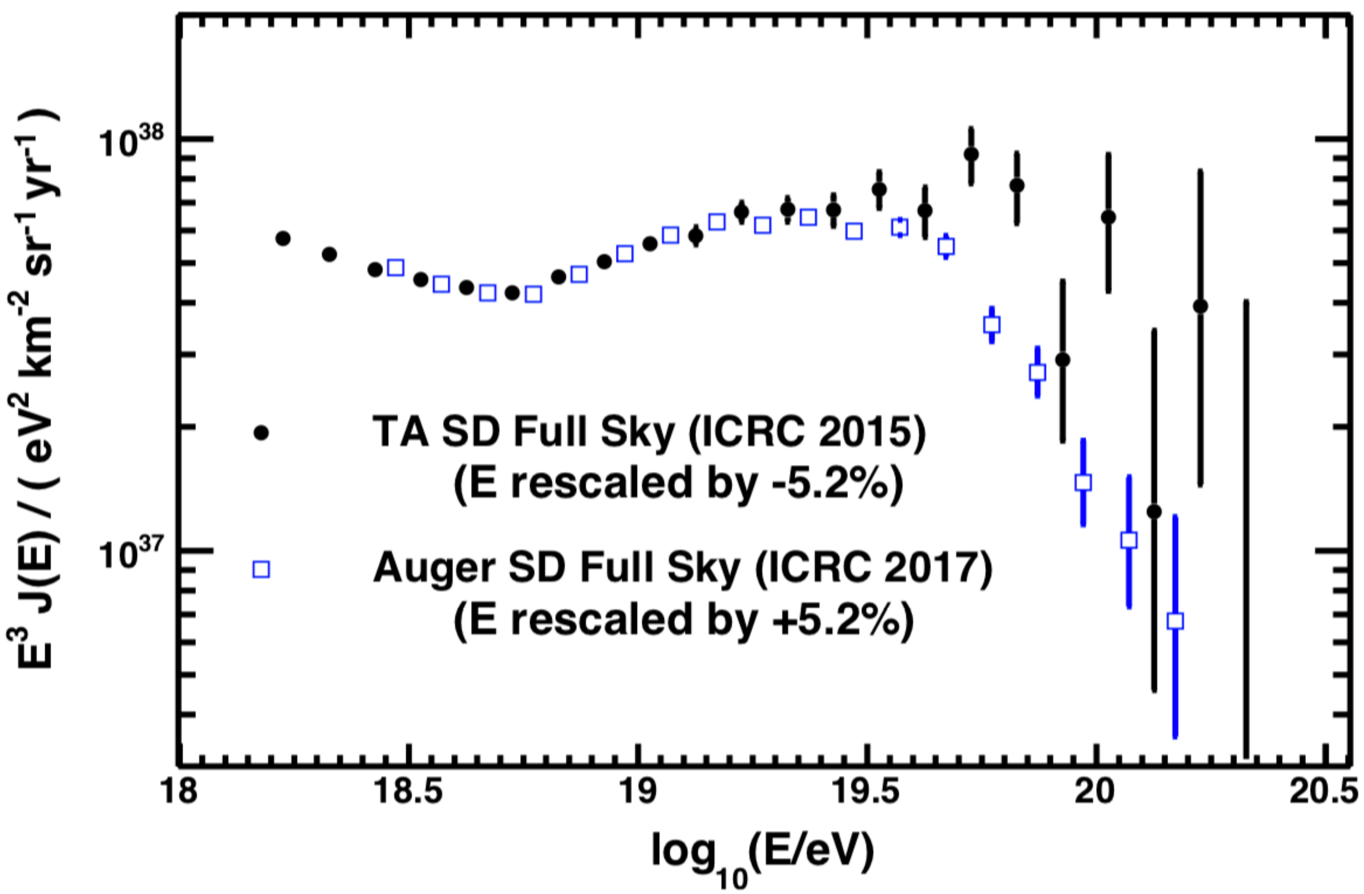

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However :
- the significance of the cluster has decreased in the past years (now ~3σ)
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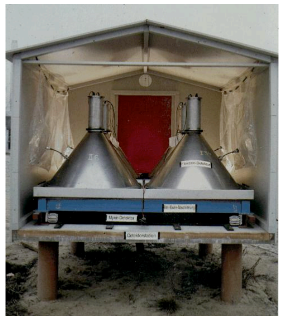
When comparing the spectra a significant excess of events appears in TA dataset above ~50 EeV (even after rescaling the energy scale)
~ factor of 2 more events than expected
—> if it is a systematic effect, it should affect the anisotropy dataset of at least one of these experiments
—> if this excess of events is physical then why is the anisotropy in TA sky so moderate?
(see Globus N. et al., 2017, ApJ)
—> it is very non trivial to combine different part of the sky observed by different

Outline

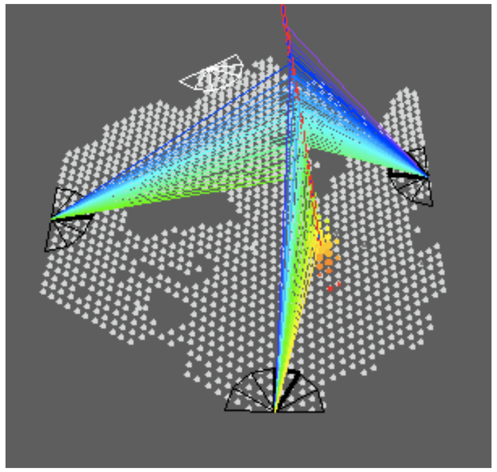
❖ Indirect detection of cosmic-rays : a short introduction

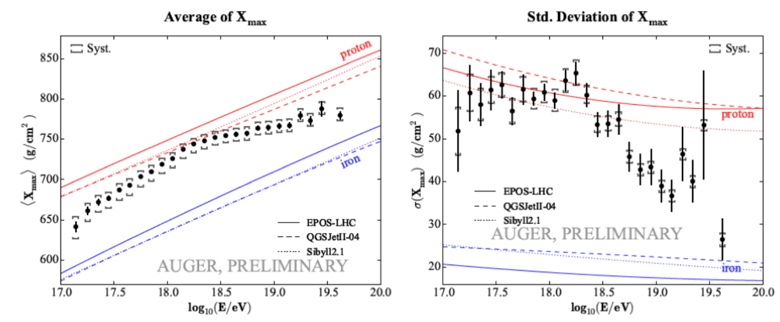
❖ The knee and beyond : KASCADE-Grande, the heavy knee and the light ankle



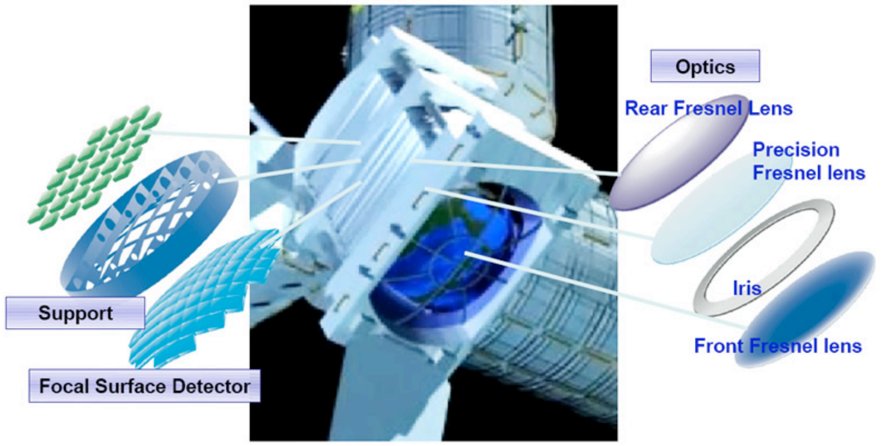
❖ Auger the giant hybrid observatory

- spectrum
- composition
- air shower properties
- anisotropies
- comparison with Telescope Array





❖ Future experiments (mid term and long term future)



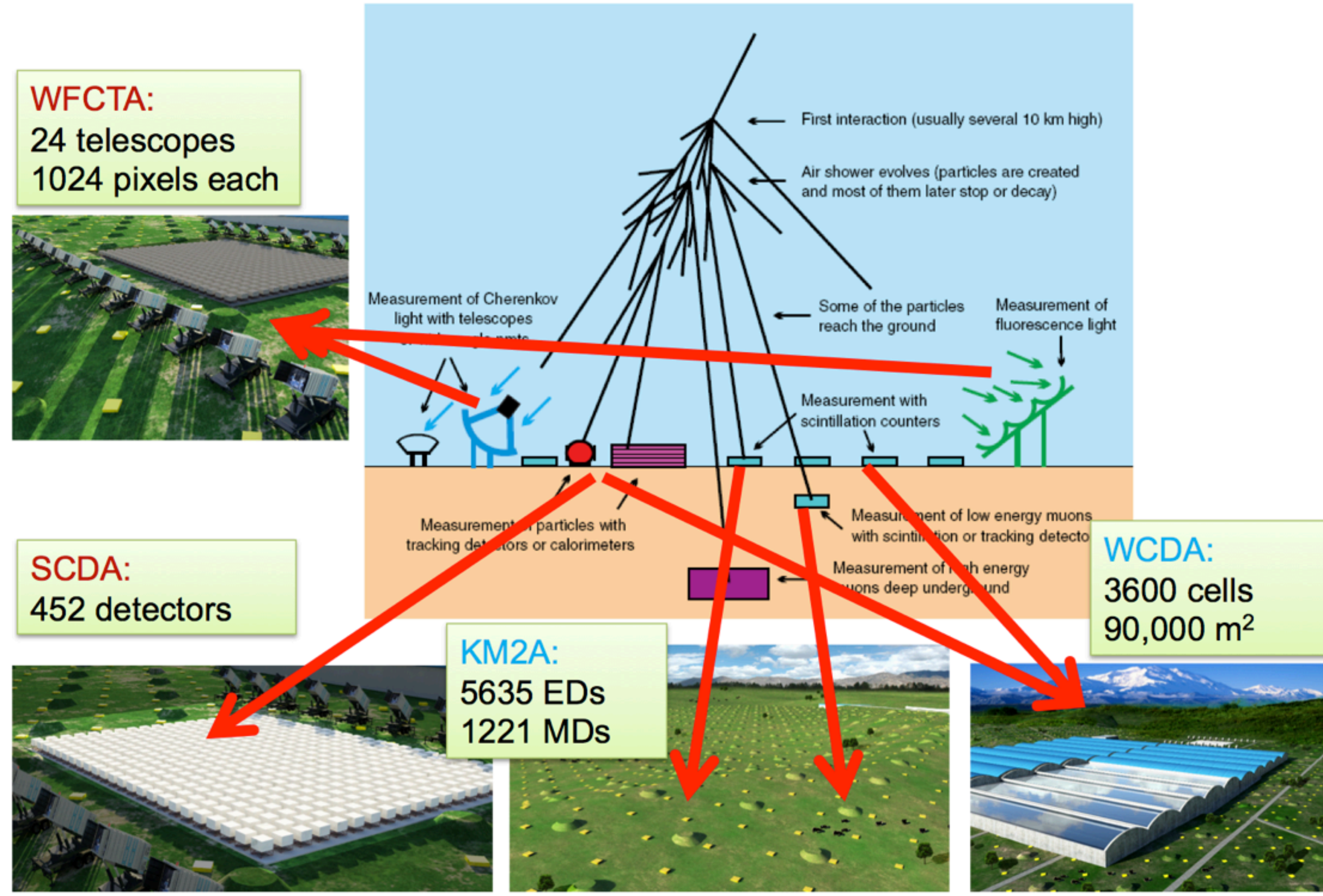
The future in the knee region : LHAASO

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

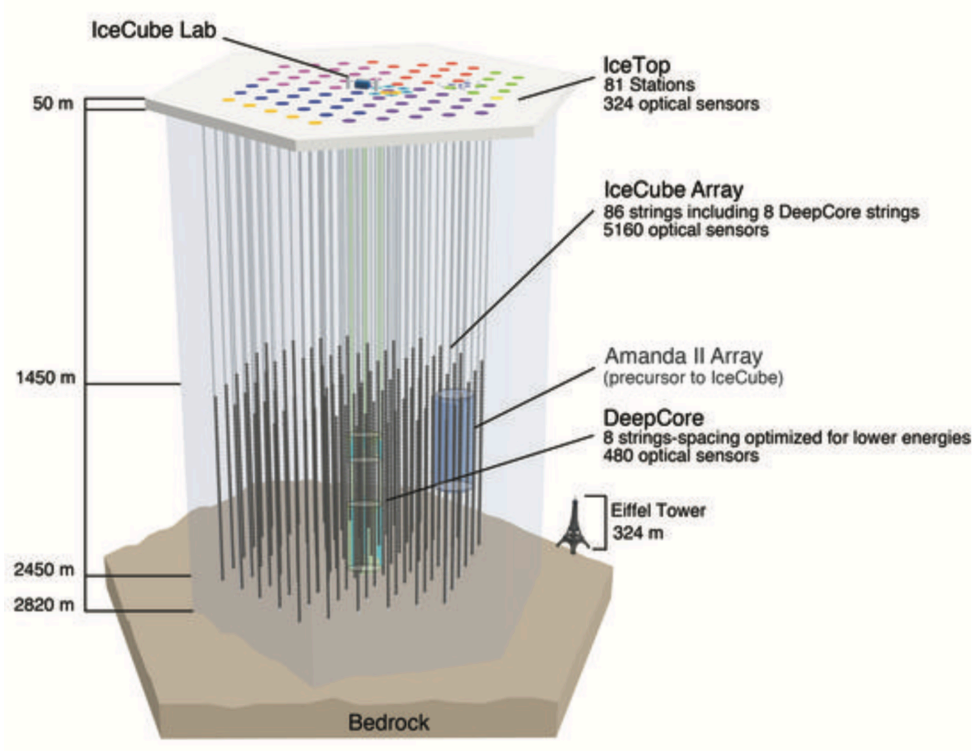
✳ high resolution measurements of air showers particle content ---> sensitivity to the cosmic-ray mass

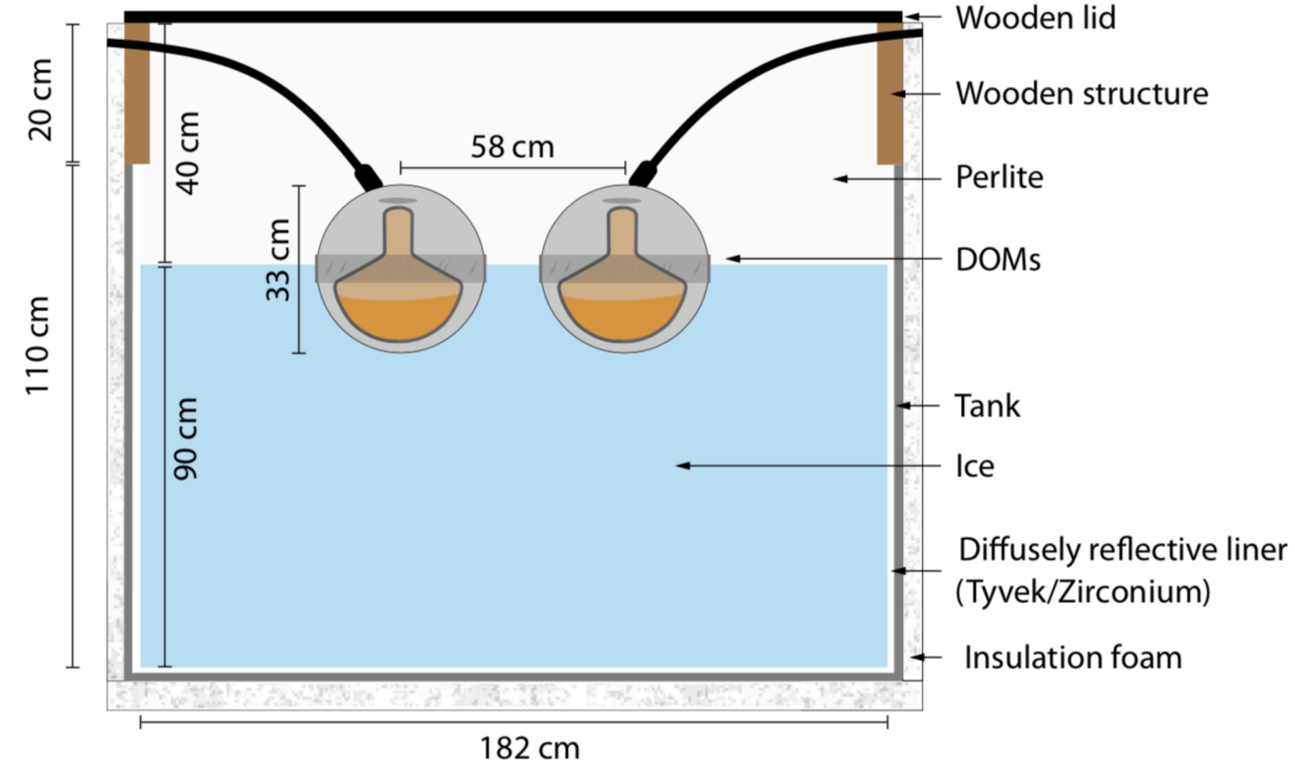
✳ MILAGRO-like gamma-ray detector (complementary to CTA above 30 TeV) ---> useful to search (multi-)Pevatrons



- Instrument almost completely funded by China
- Deployment ongoing (1/4 of the instrument should be deployed within the next two years)
- France already has a foot in the LHAASO collaboration :
  - ✳ Part of the IPNO Auger team involved
  - ✳ A front end board for the Cherenkov telescopes has been delivered by IPNO and the Omega platform
  - ✳ Student exchange program between France and China (thesis defended last October)
  - ➡ Very interesting science case

The future in the knee region : IceTop/IceCube





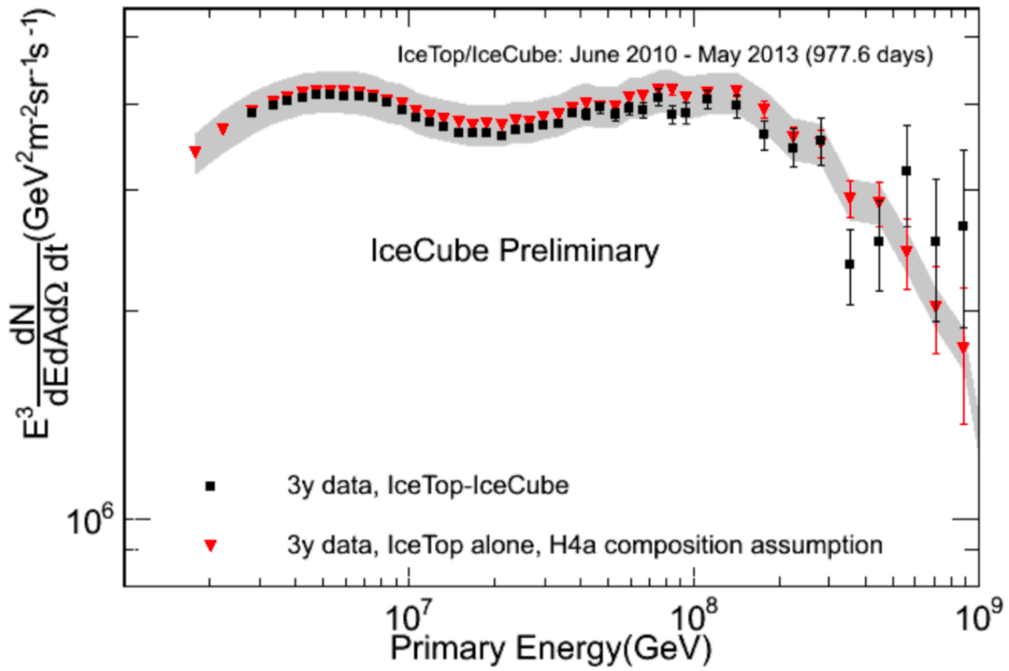
IceTop already in operation at the south pole

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

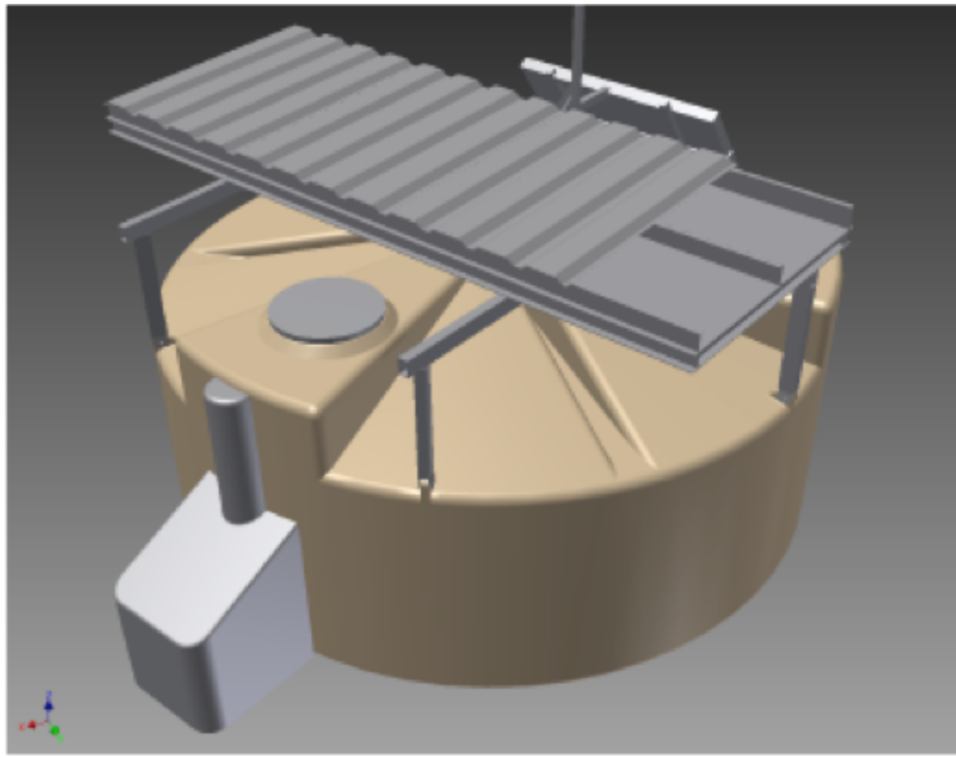
—> sensitive to composition and air shower properties

—> 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

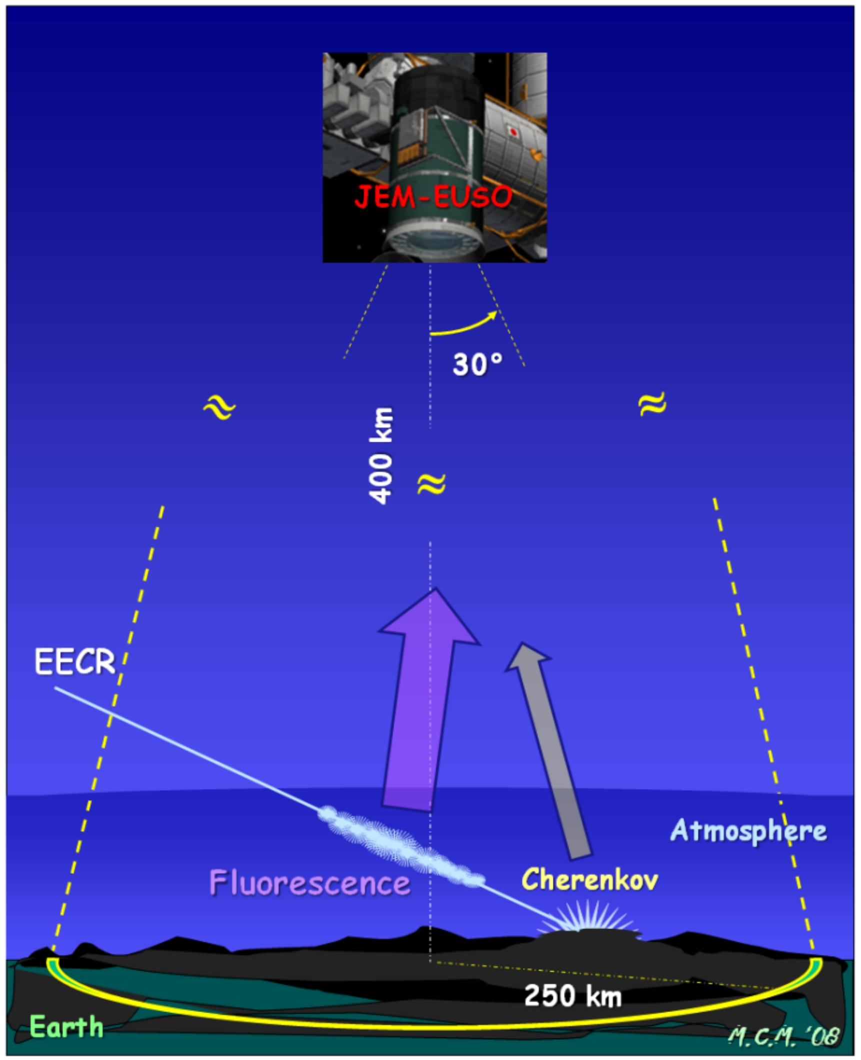
- increase of the FD duty cycle by 50% (by operating in brighter background sky conditions, switch the photodetectors to lower gains)

---> increase of the hybrid events statistics

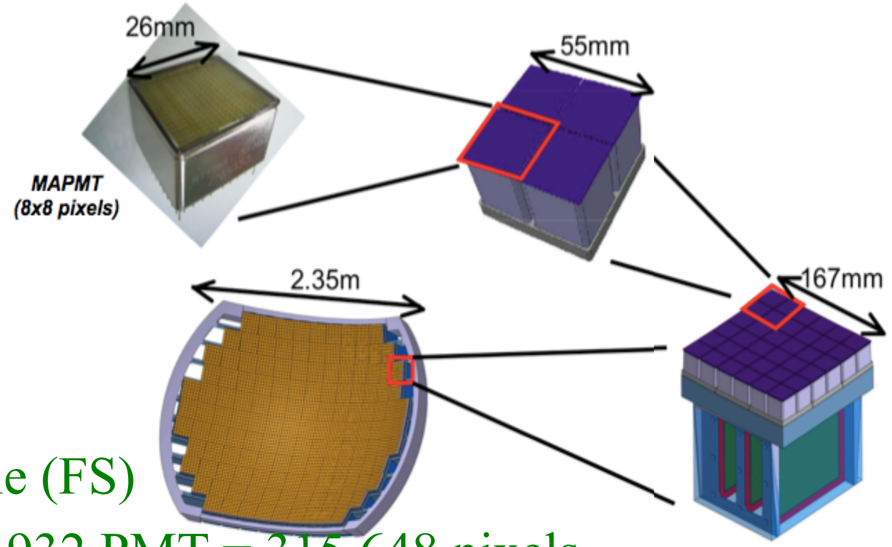
12 scintillators already installed in the infilled array
first light presented at the ICRC2017

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
If TA hotspot is real, one of the lessons is that 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



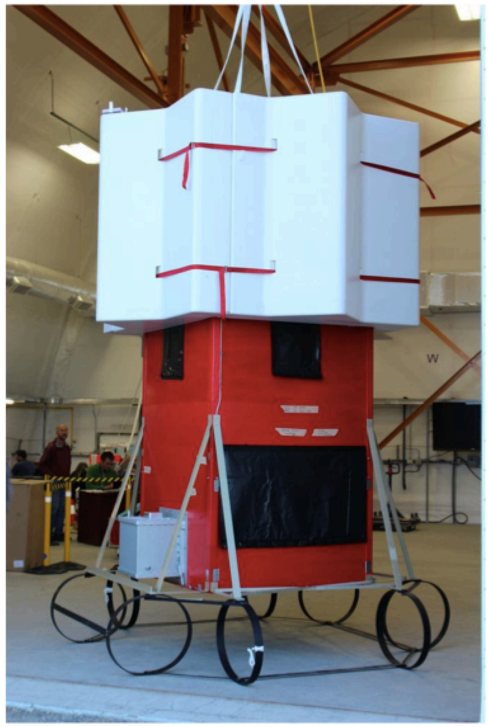
The idea is to observe air showers from space :
- Telescope with 30 deg opening angle observing the earth from the ISS (400 km altitude)
---> huge area covered on the ground
---> drawback of the fluorescence technique ~19% duty cycle
---> still annual exposure ~10 times that of Auger above ~5.10^{19} 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

JEM-EUSO pathfinders

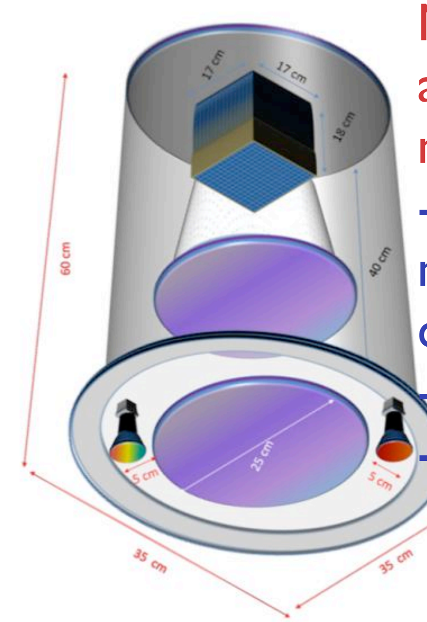
Several prototypes have been built or are planed to serve as proof of concept and prototypes for JEM-EUSO :



EUSO balloon (CNES) :
a one night flight in northern Canada in August 2014
--> small lens (1 m^2) and a single PDM in the focal plane
--> sky background measurements and successful measurement and reconstruction of laser shots but no autonomous trigger

EUSO Super Pressure Balloon:
Improved version of EUSO-balloon with an autonomous trigger
—>~ one month long flight expected
—> launched in March 2017 from New Zeland
—> prematurely crashed after 13 days due to leak in the balloon
—> ongoing data analysis

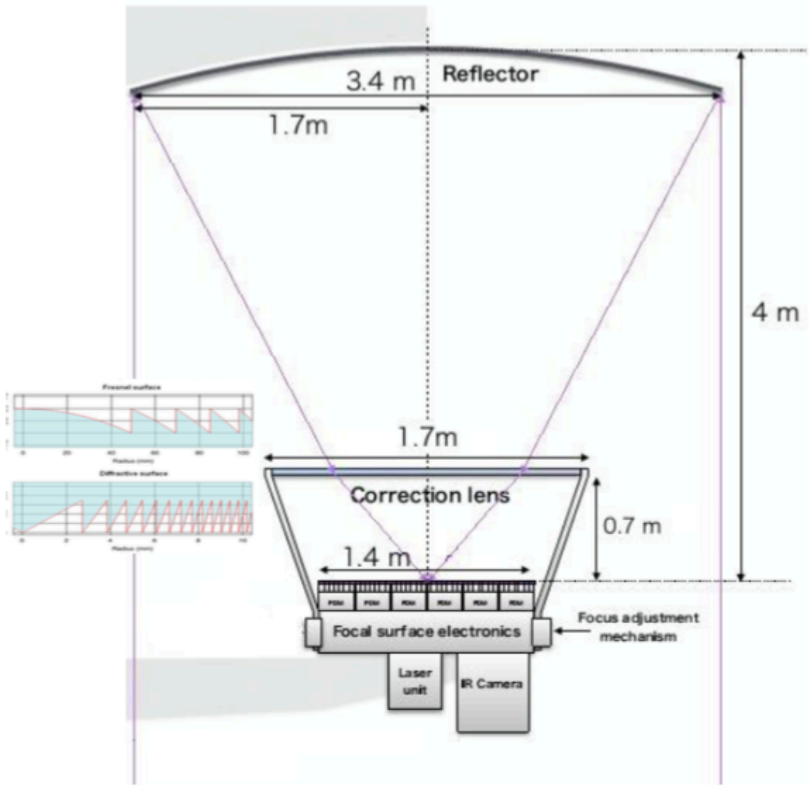
TA-EUSO :
~Same optics as EUSO-ballon installed and operating on the TA site
--> detection of real air showers with an autonomous trigger
--> validation of the JEM-EUSO trigger strategy



Mini EUSO : accepted by ROSCOSMOS and ASI to be installed on the Russian module of the ISS in 2018:
--> Complete background measurements from space in the same conditions as the full mission
--> atmospheric phenomena
--> meteorites

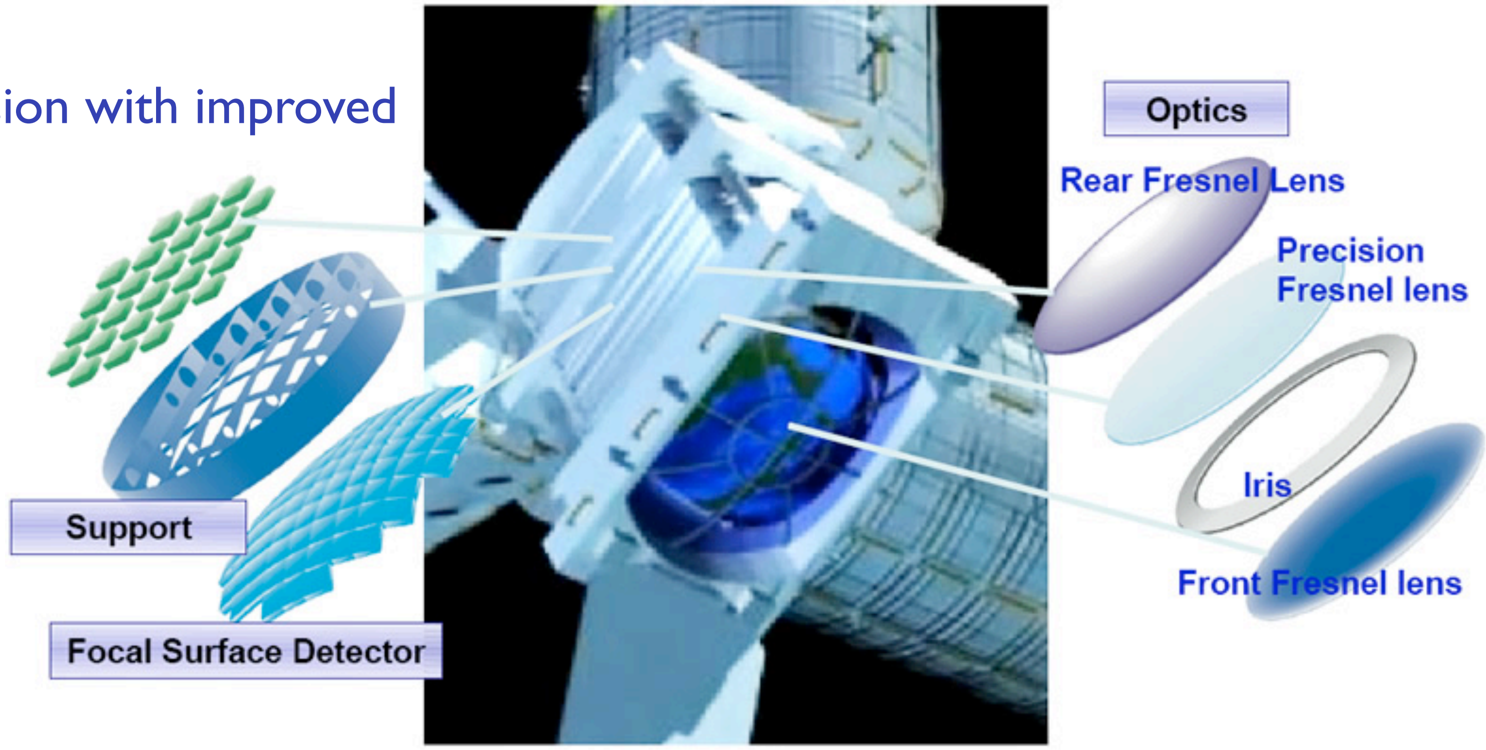
The future of JEM-EUSO

Klypve-EUSO (AKA K-EUSO) concrete effort toward a full JEM-EUSO mission :
--> accepted by ROSCOMOS
--> to be installed on the ISS (2023)
--> annual exposure expected to be similar to that of Auger
--> first UHECR large exposure full sky coverage experiment



Full JEM-EUSO mission postponed sine die :

- the alternative solution is to propose a free flyer mission with improved performances
—> POEMMA (UHECR+neutrinos)
—> Exploratory phase founded by NASA
—> EUSO SPB2 expected in 2022 expected to be a pathfinder for POEMMA



Thank you for your attention !!!!

and many thanks to

-Andreas Haungs

-Tanguy Pierog

-Francesco Fenu

- Etienne Parizot