Pierre Auger Observatory: The scientific achievements

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The challenge: what are we looking for?

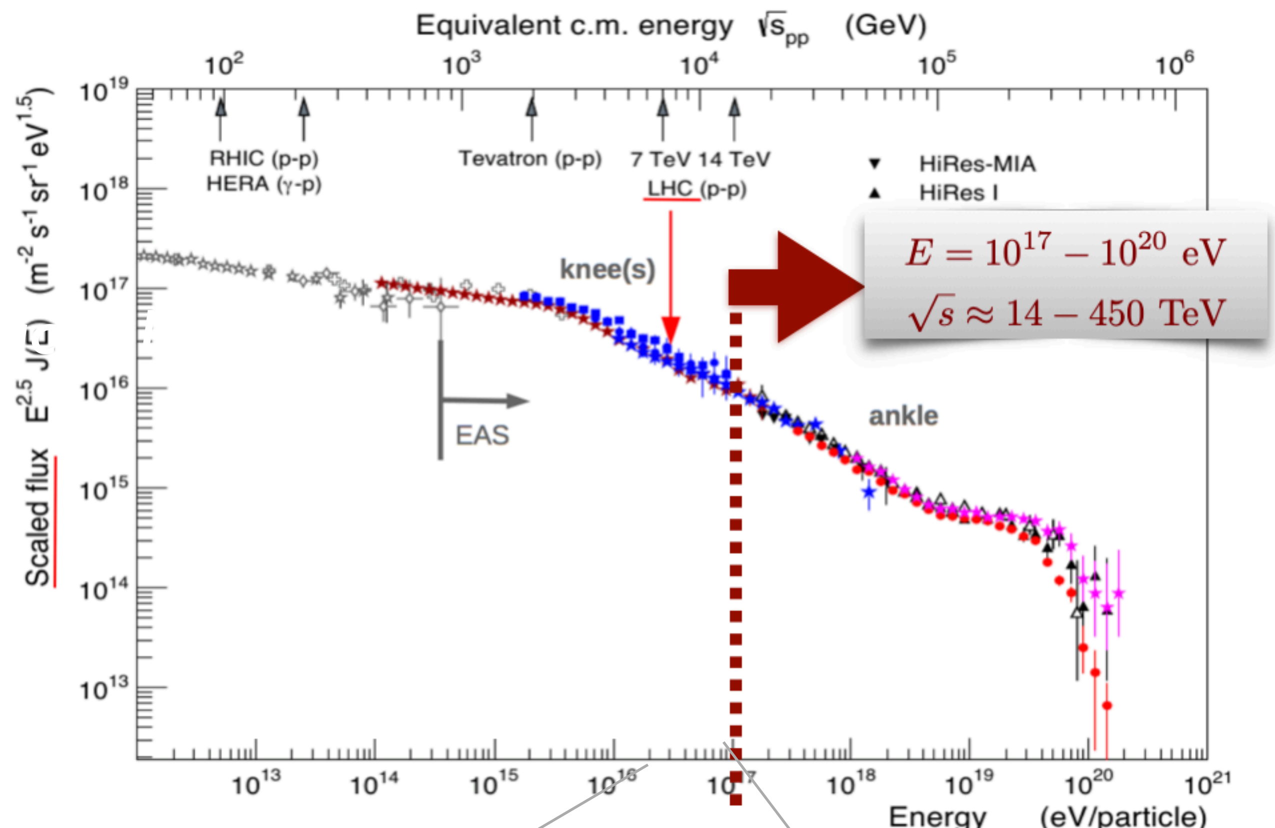
UHECRs : particles with energies up to 10^{20} eV and beyond

- UHECR production rate per Galaxy ~ 10^{31} UHECR/sec
- LHC reach ~ 10^{19} protons/sec

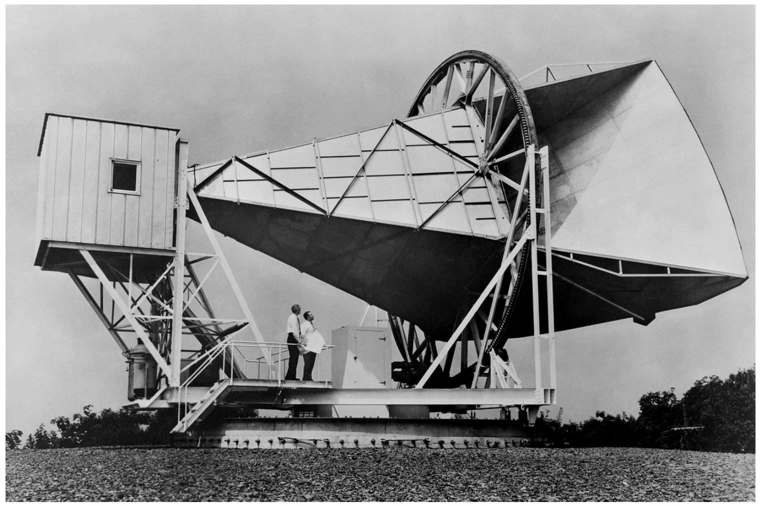
The sources must be

able to accelerate particles to energies far above those reached at LHC

luminous enough

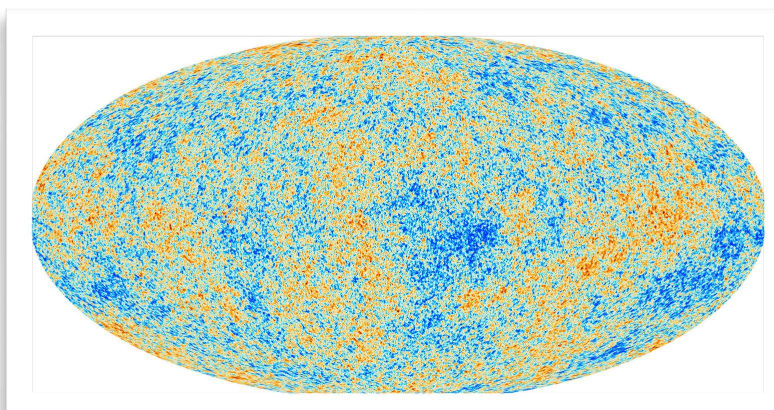


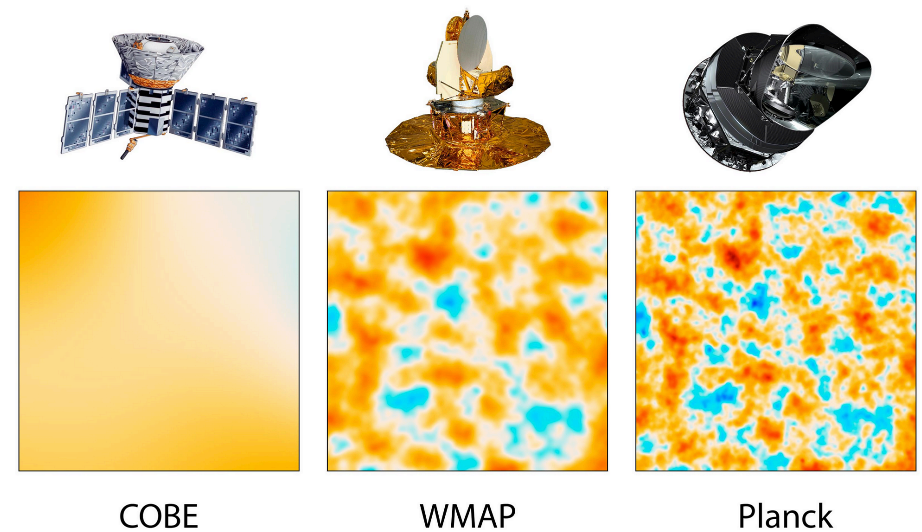
The challenge: energy losses



Cosmic microwave background: a relic from the Big Bang

- Predicted in 1948 to be ~5^0K [Alpher, Herman]
- Measured in 1964 : $(3.5\underline{+}1)^0$K [Penzias and Wilson]
- COBE mission (1989-96) and many others





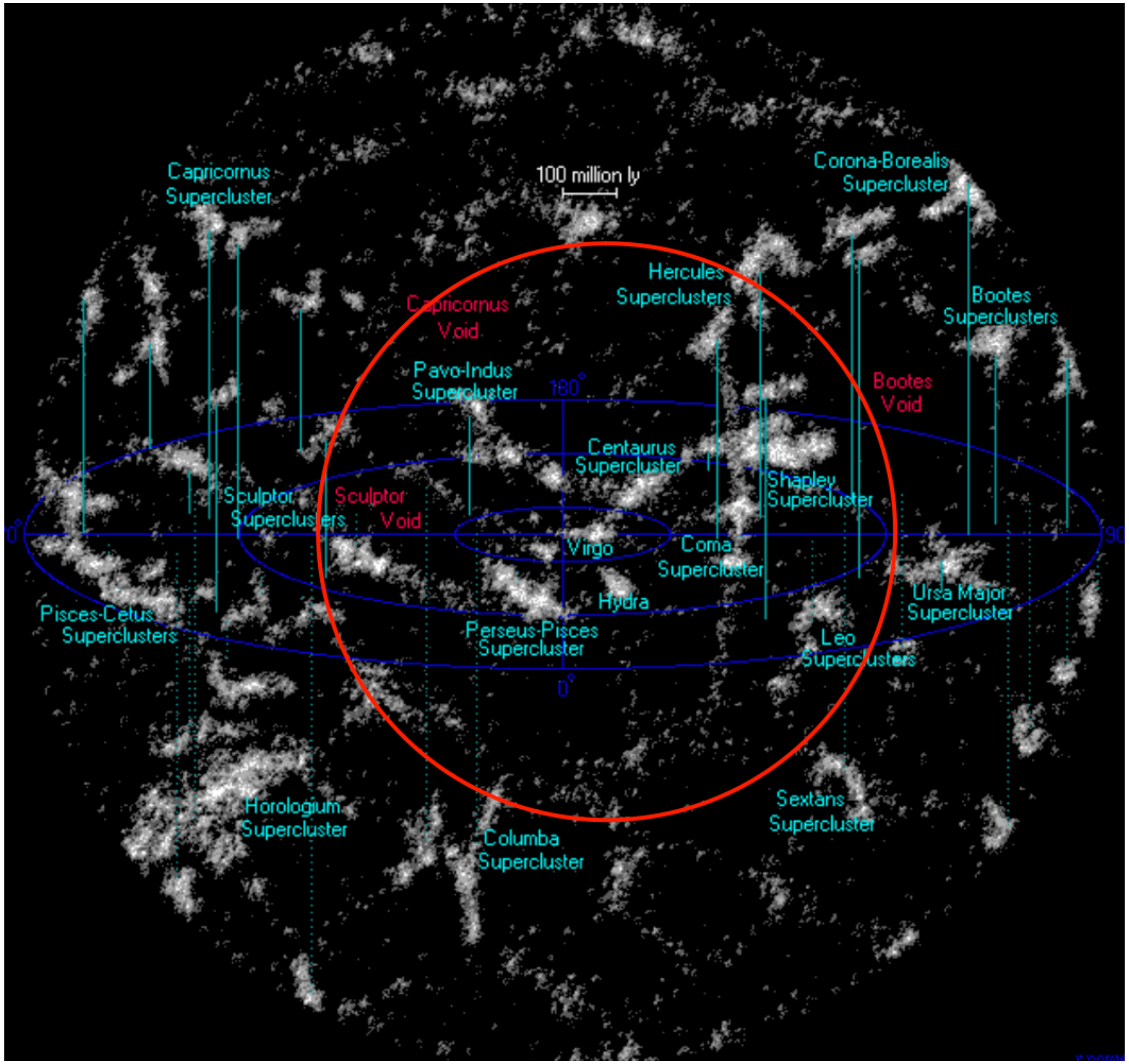
1966: The GZK effect
(Greisen, Zatsepin, Kuzmin)
Protons (or nuclei) lose energy in collisions with the cosmic microwave background above an energy of ~10^{20} eV.

PHYSICAL REVIEW LETTERS

VOLUME 16, NUMBER 17 25 APRIL 1966

END TO THE COSMIC-RAY SPECTRUM?

The GZK cutoff



the vast majority of protons above ~60 EeV come from distances D< 200 Mpc (~600 million light years)

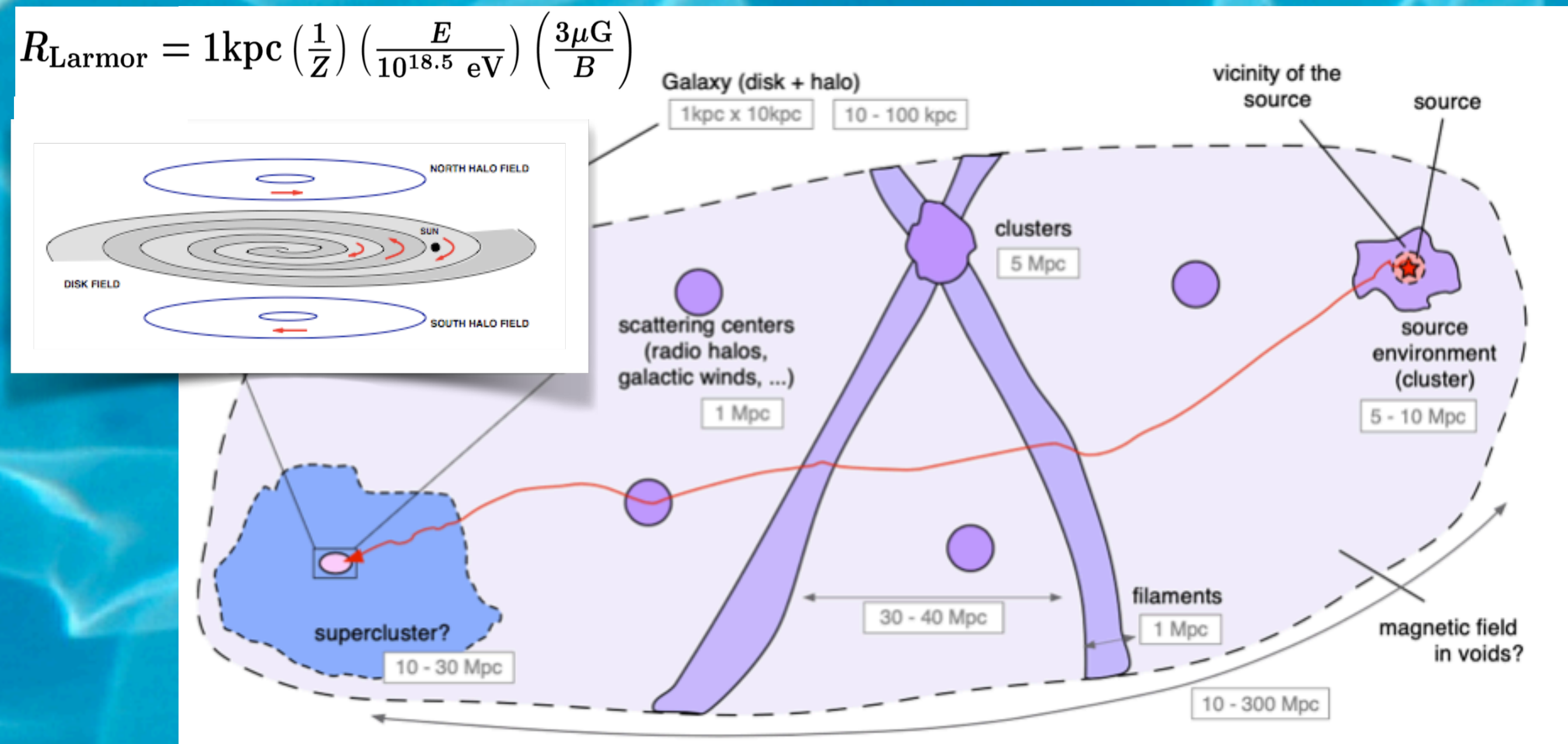
the contribution of distant sources is thus eliminated:

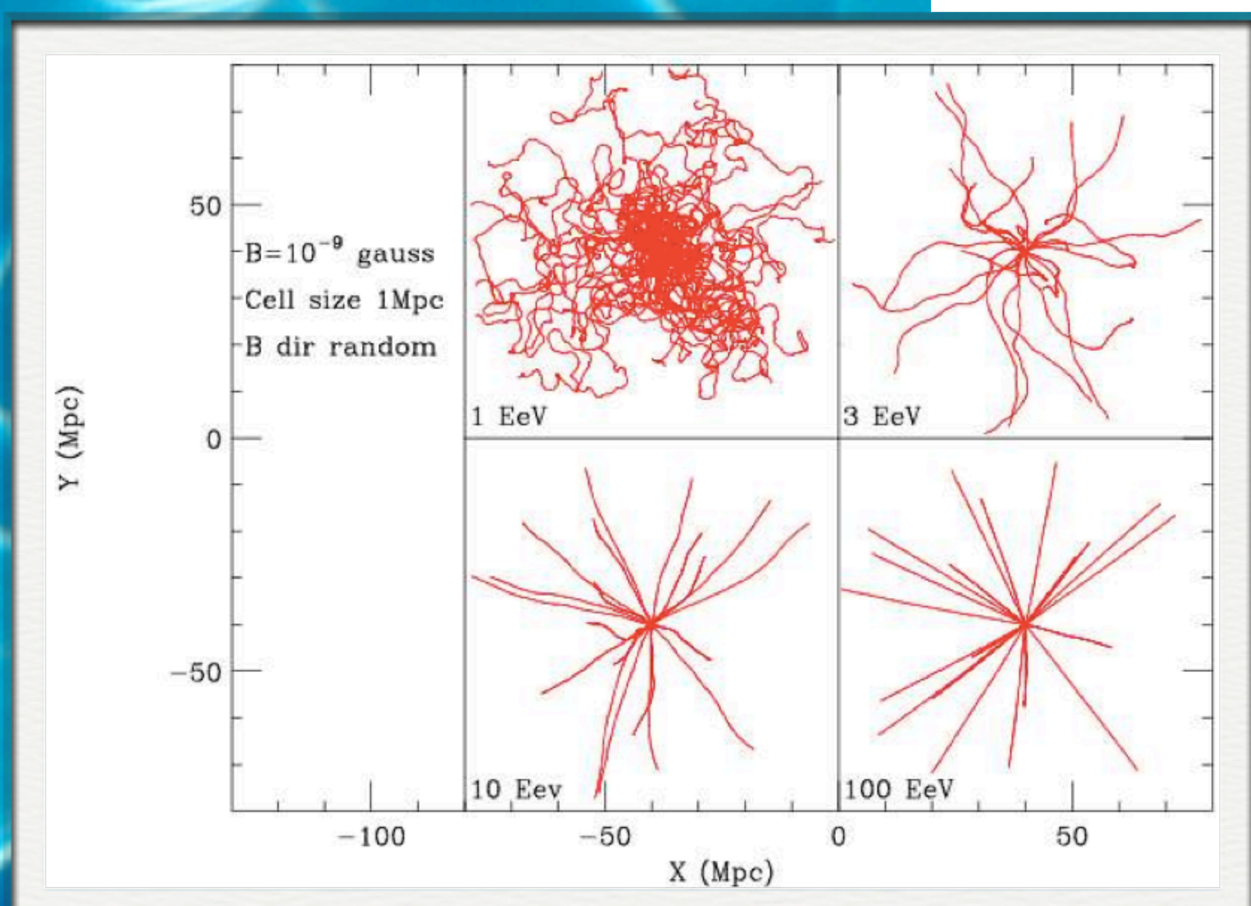
the higher the energy, the smaller the size of the collection region

[Note: 6 10^{19} eV ~9 Joule in one proton (~9 10^{16} m radius !)]

The challenge: magnetic fields

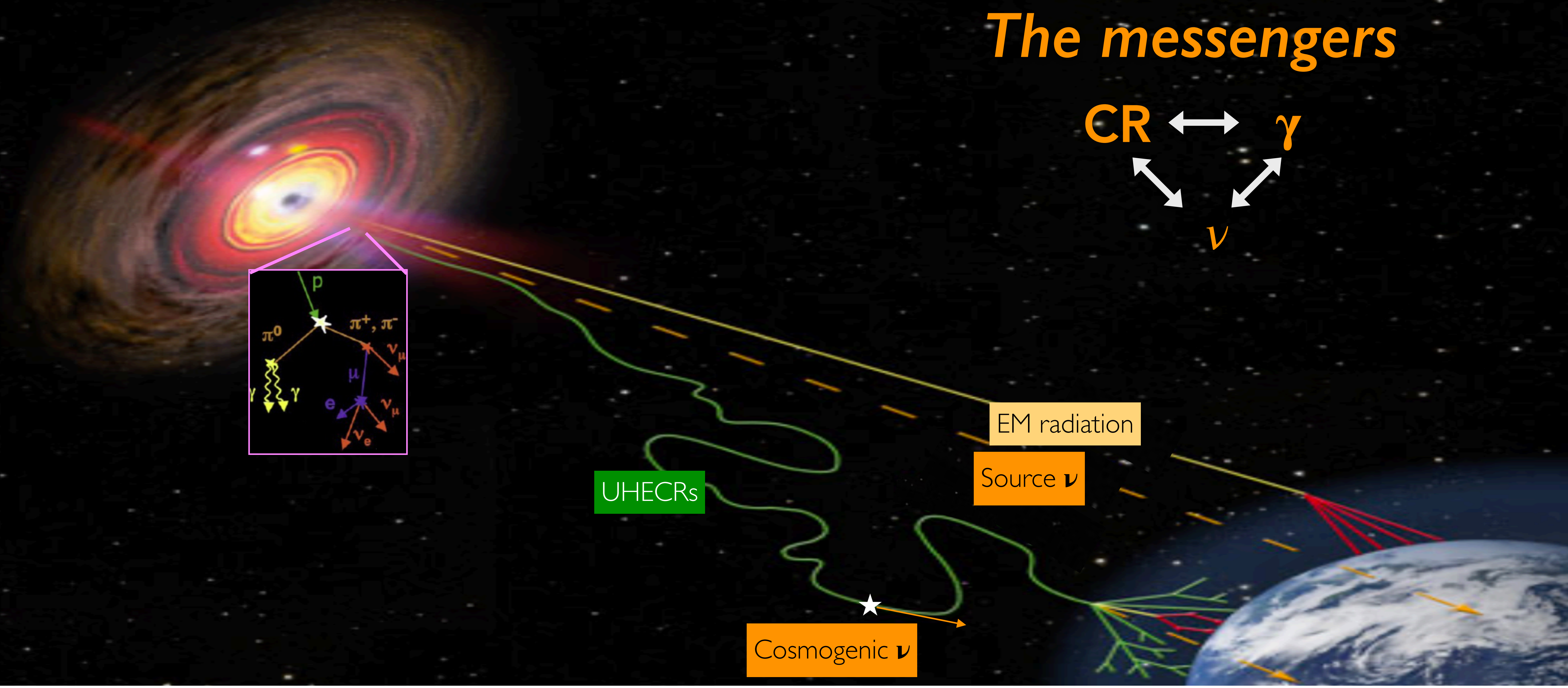
$$R_{\text{Larmor}} = 1\text{kpc}\left(\frac{1}{Z}\right)\left(\frac{E}{10^{18.5}\ \text{eV}}\right)\left(\frac{3\mu\text{G}}{B}\right)$$





Galactic and Extragalactic magnetic fields effect on charged particles

Deflections proportional to Z/E:
less deviation for lower mass and higher energy



The experimental observables

➡ Air shower measurements

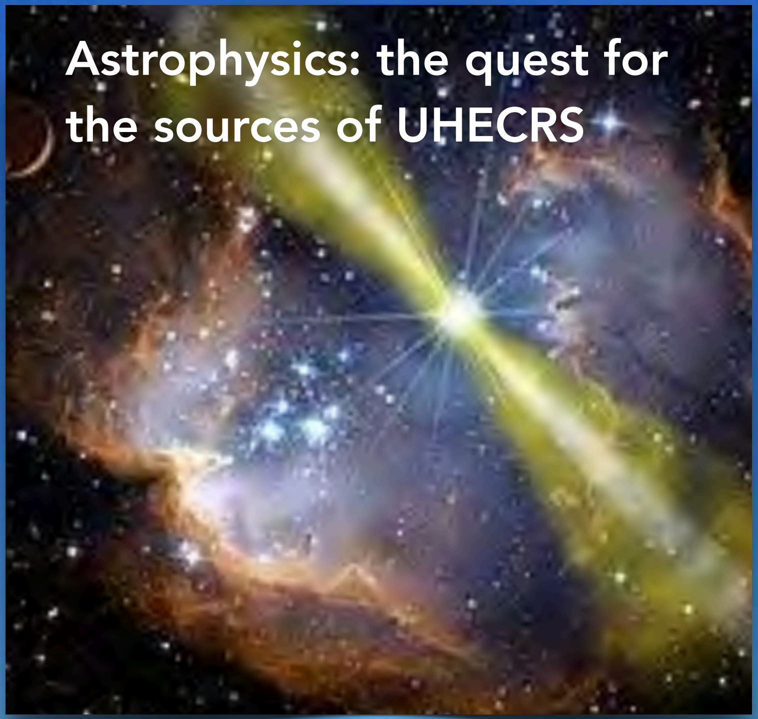
- Flux of particles
- Mass composition related quantities
- Arrival direction distribution
- Secondary particles and multi-messenger observations

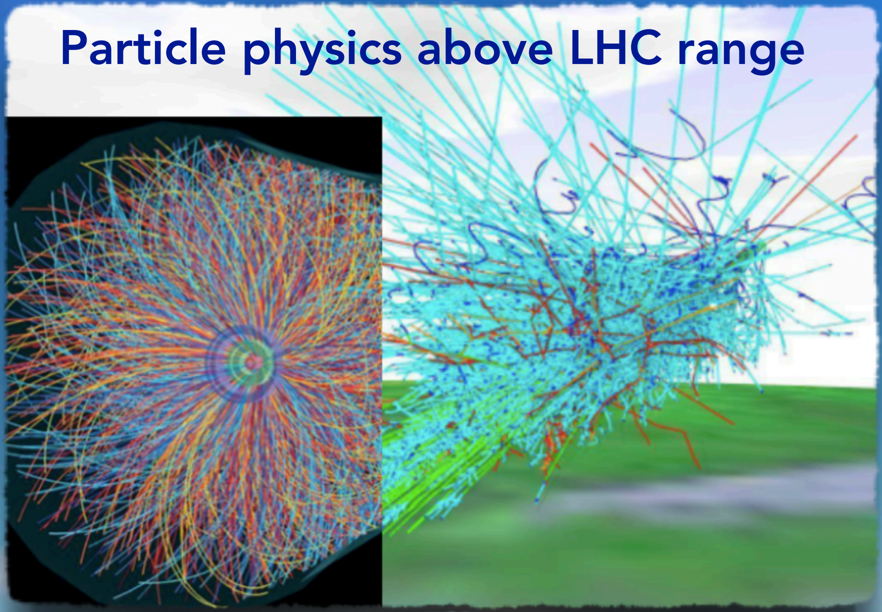
Theory
Model predictions

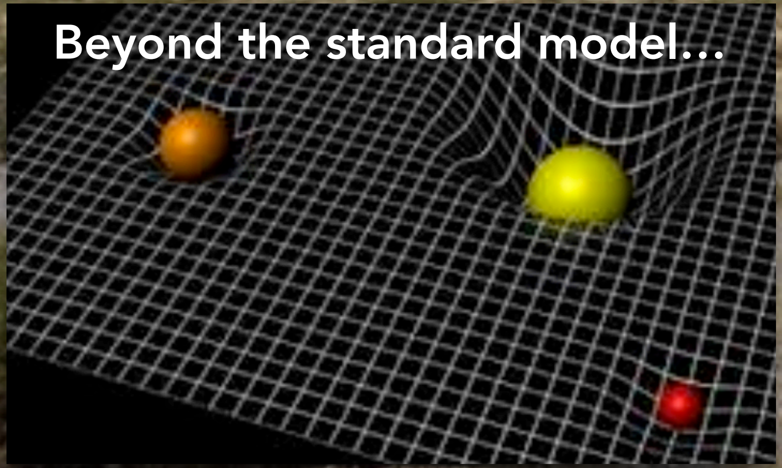
External input from
astro and particle physics

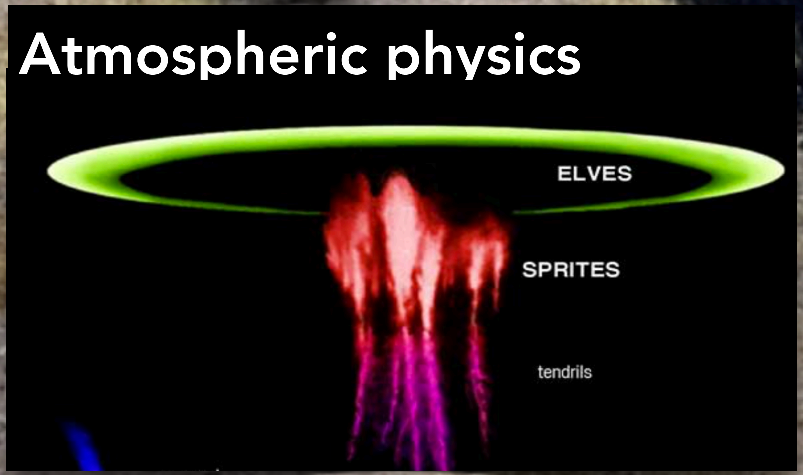
Phenomenological studies
Theory/models vs. data
Combination of different data sets

The Pierre Auger Observatory

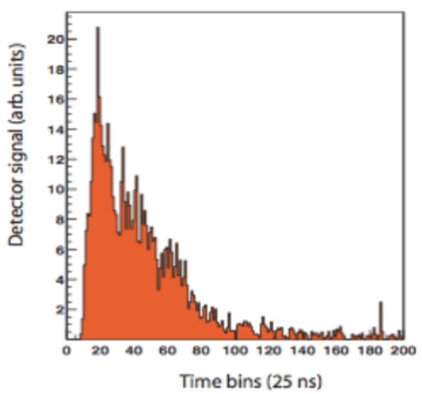


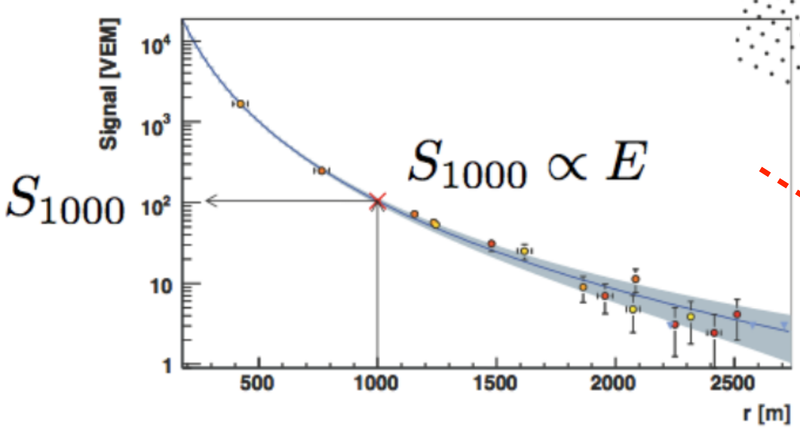


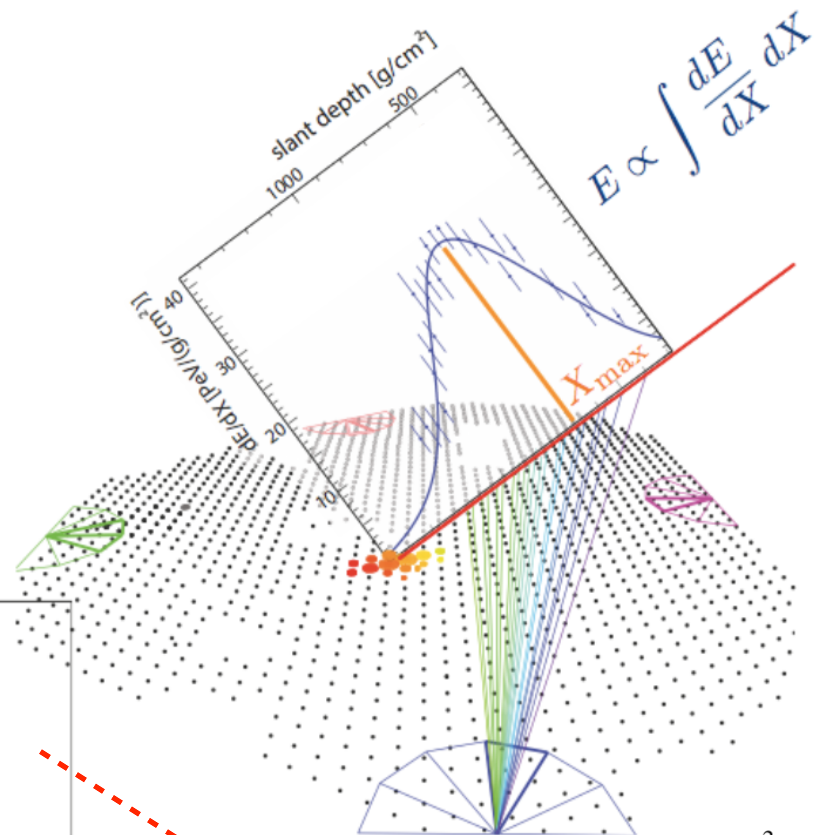




Energy calibration







FD: calorimetric energy measurement (13% duty cycle)

$$E_{Cal} = \int_0^\infty dX \, \frac{dE}{dX}$$

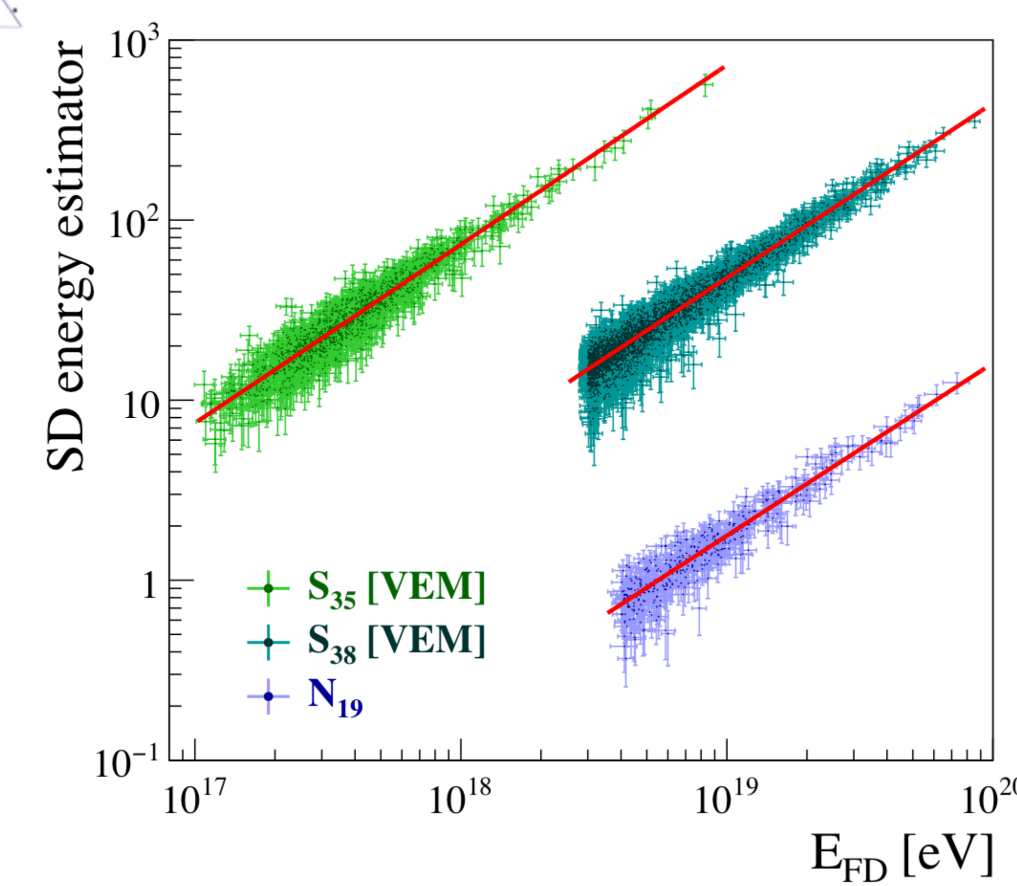
$$E_{Tot} = E_{Cal} + \underline{E_{Inv}}$$

(evaluated from data, as $E_{Inv} \propto N_\mu$)

$\sigma(E_{FD})/E_{FD} \sim 8\%$

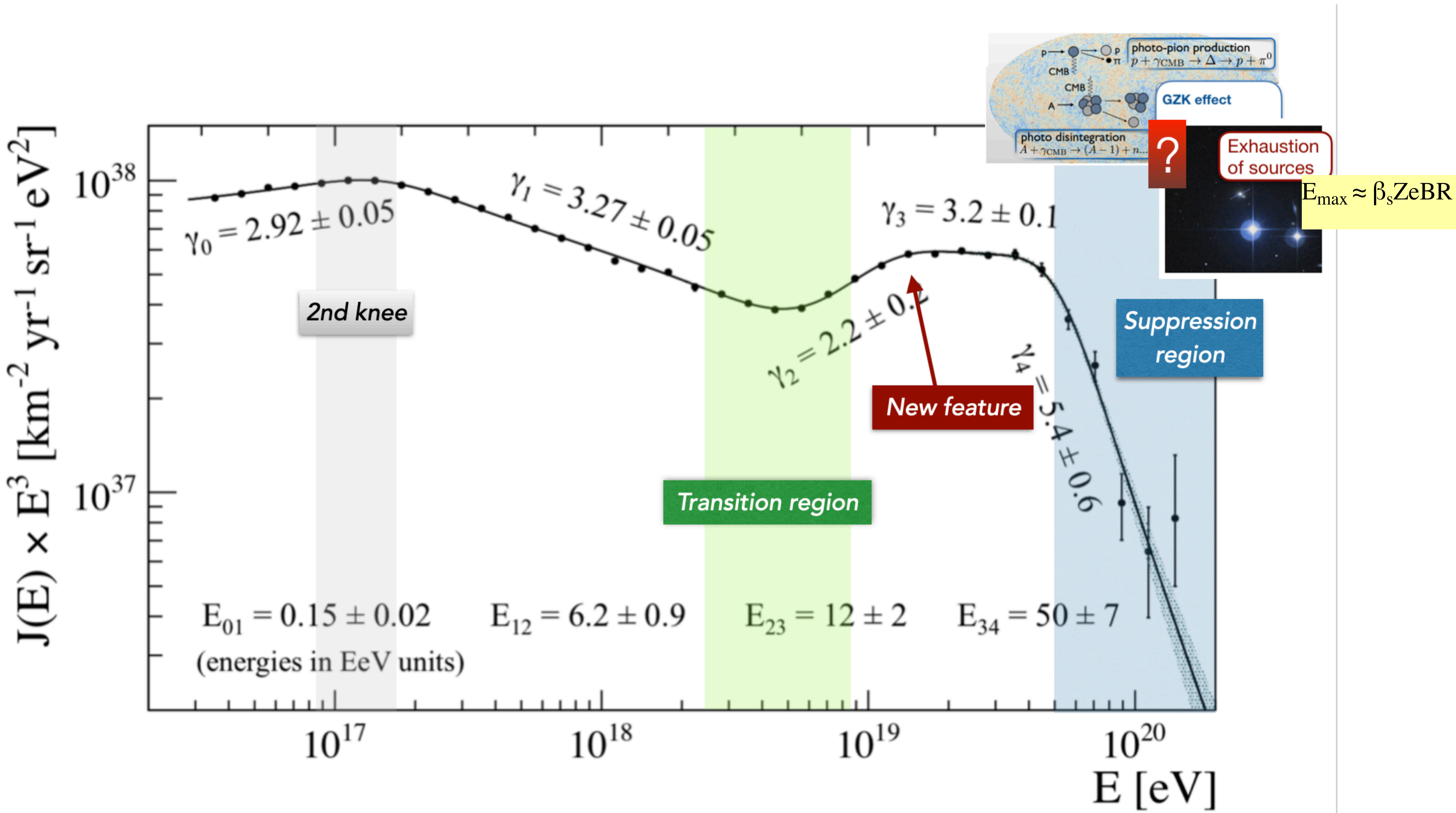
Systematic uncertainty 14%

SD: shower size at ground as energy estimator



Hybrid events: absolute calibration of the full SD sample

The energy spectrum

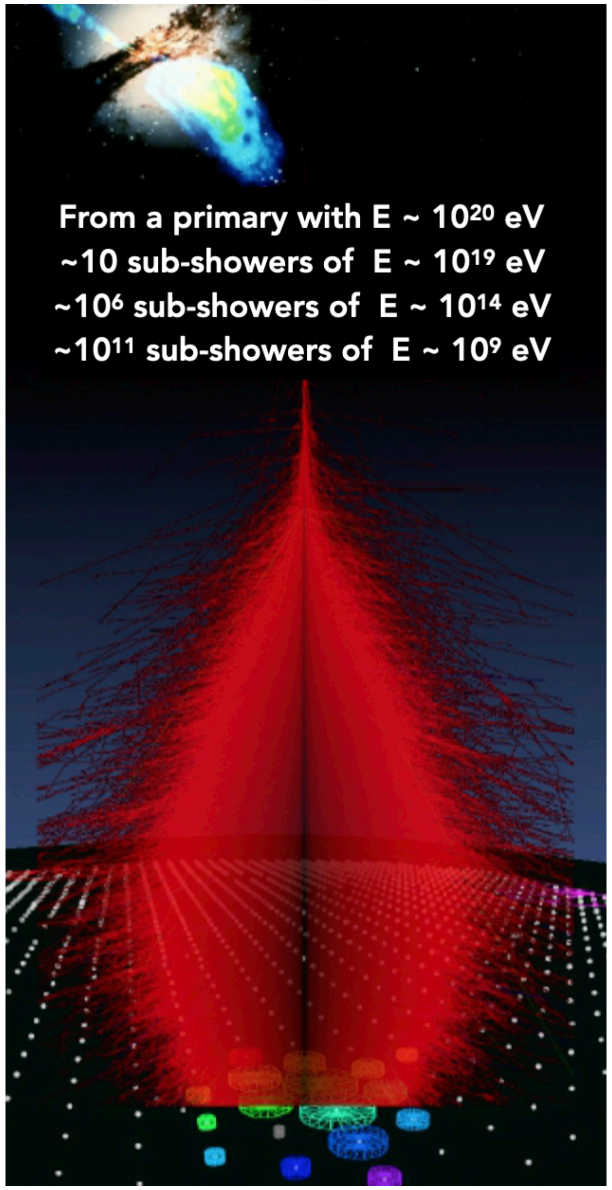


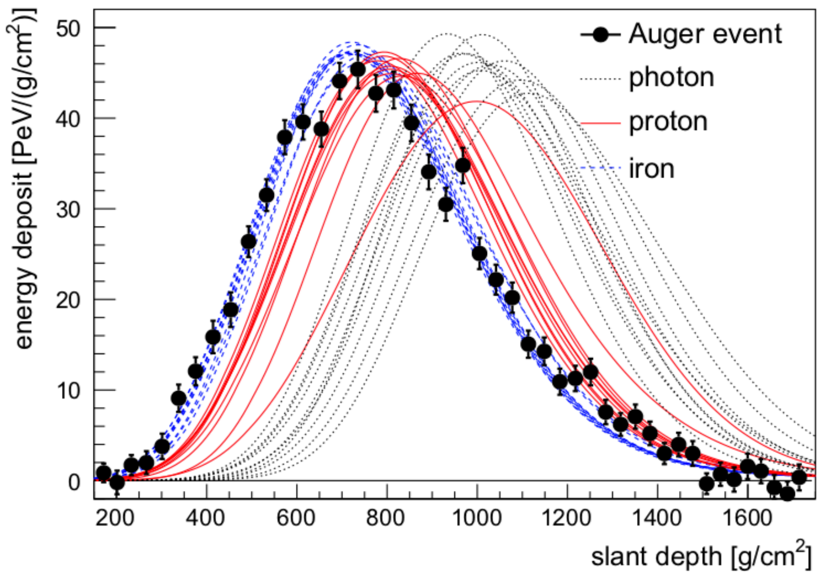
✓ UNPRECEDENTED EXPOSURE ! *Clearly established suppression* above $10^{19.5}$ eV

✓ Propagation or exhaustion of sources? Need data on mass composition in suppression region

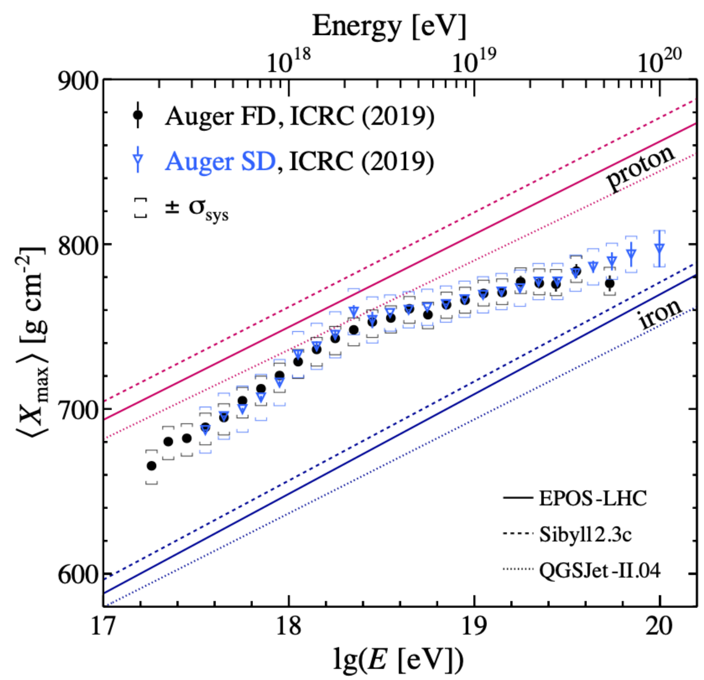
✓ Smoking gun : *we expect anisotropy* as particles with ultra-high energies should come from nearby sources

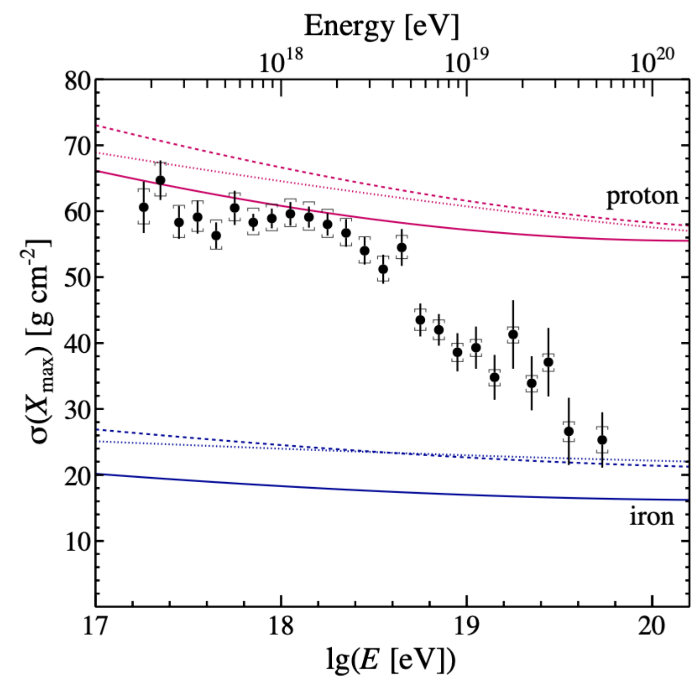
Light or heavy ? Measuring the mass composition





The distribution of the shower development in atmosphere give info on the nature of UHECR





Air shower+hadronic interaction models required to convert the info from the X_{max} distributions to A

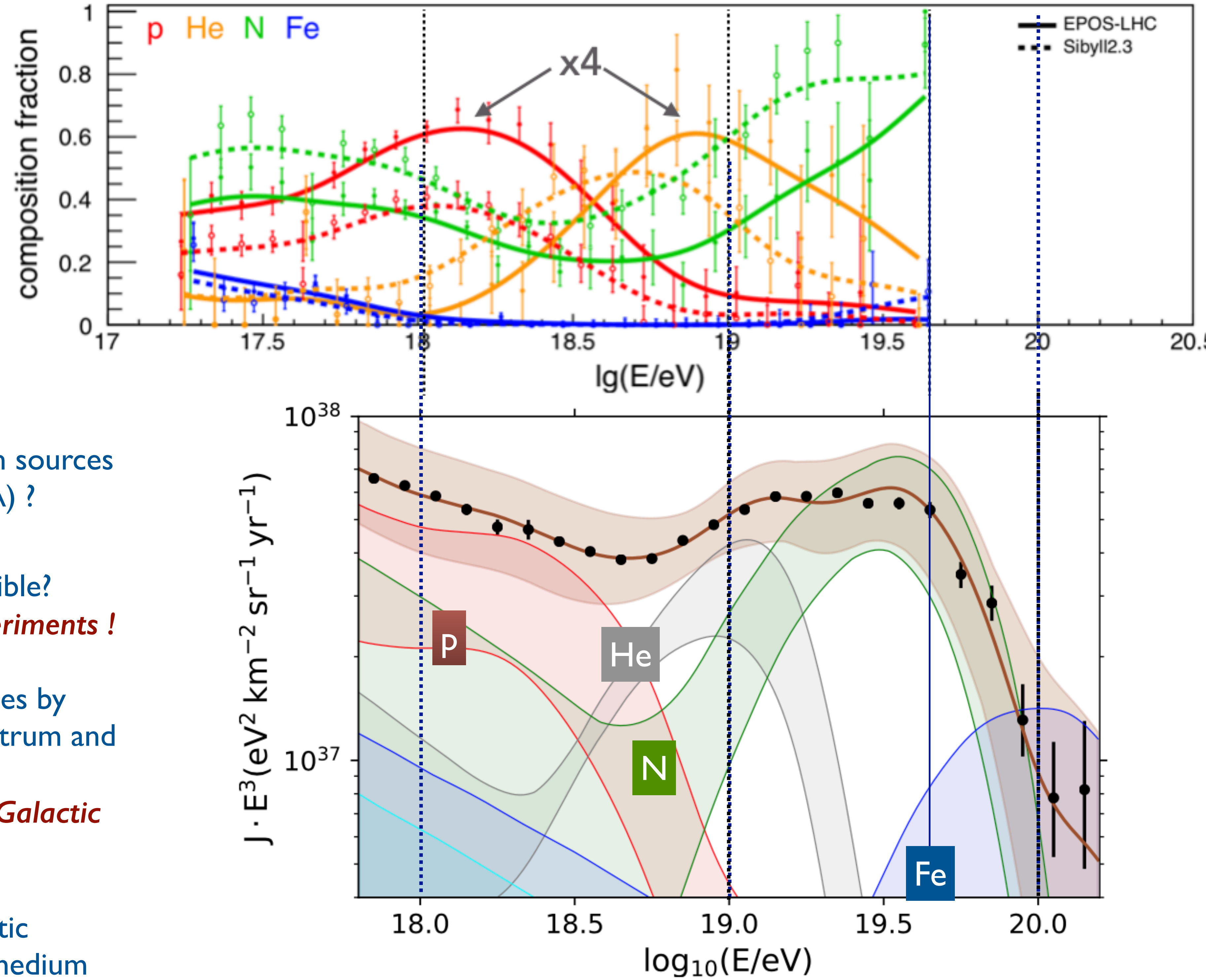
Model uncertainty = maximum contribution to systematics

Need to extrapolate what we know from accelerators to much higher energy and different projectile-target

Light or heavy ?

A VERY UNEXPECTED RESULT !

The composition is mixed and evolving with energy

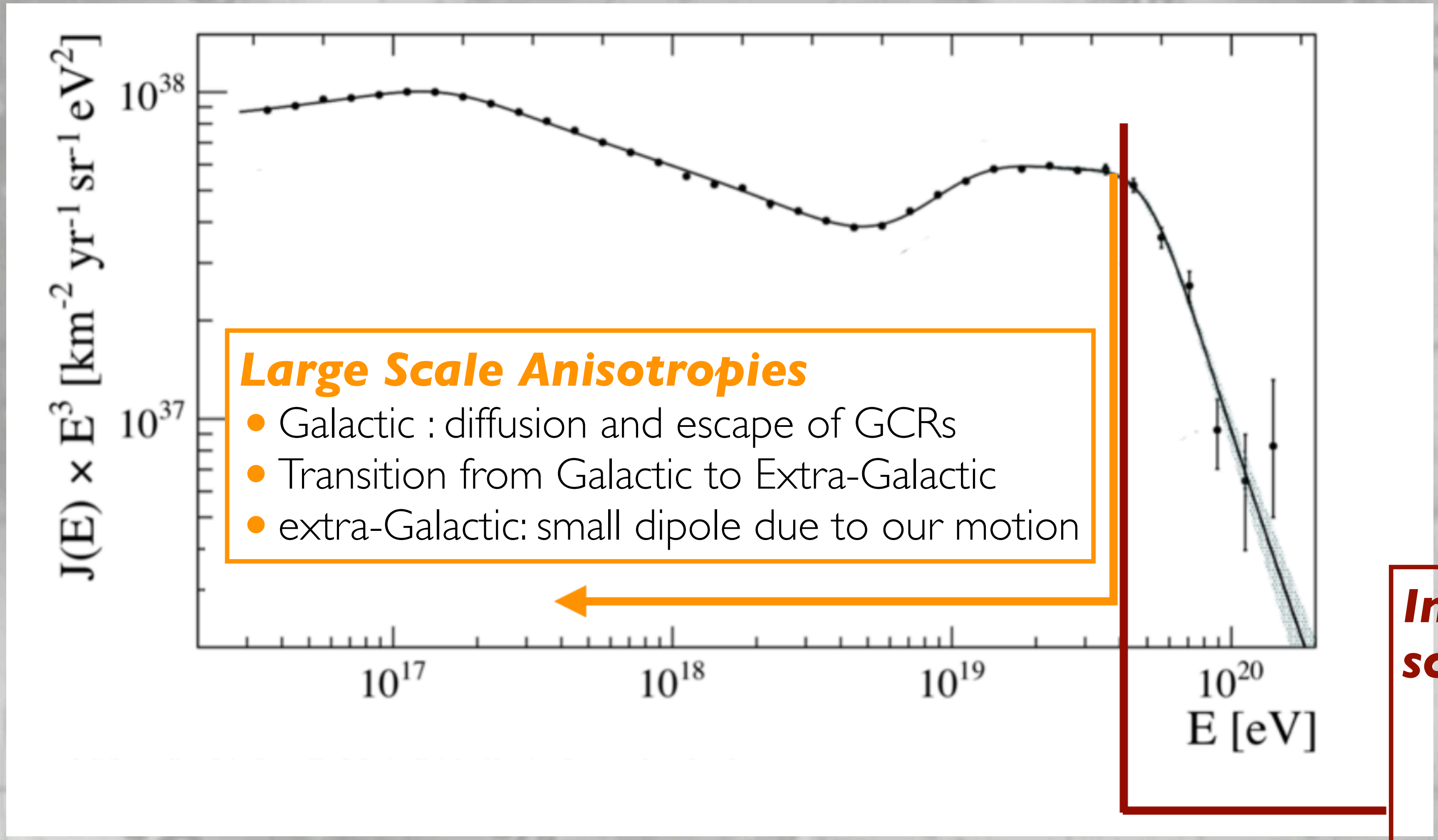


- ✓ Suppression due to energy exhaustion in sources (∝ E/Z) or to propagation effects (∝ E/A) ?
- ✓ Would then anisotropy searches be feasible? *Important for upgrades and future experiments !*
- ✓ Explore the characteristics of the sources by comparing expected and measured spectrum and composition at Earth: *two extragalactic contributions plus possibly a secondary Galactic one*
- ✓ Important hints on the end of the Galactic contribution: secondary contribution - medium composition

The arrival directions

γ, ν messengers for which directional astronomy is possible

charged CRs arrival directions and energy are measurable
further complications : magnetic fields deflections, heavier nuclei



Large Scale Anisotropies

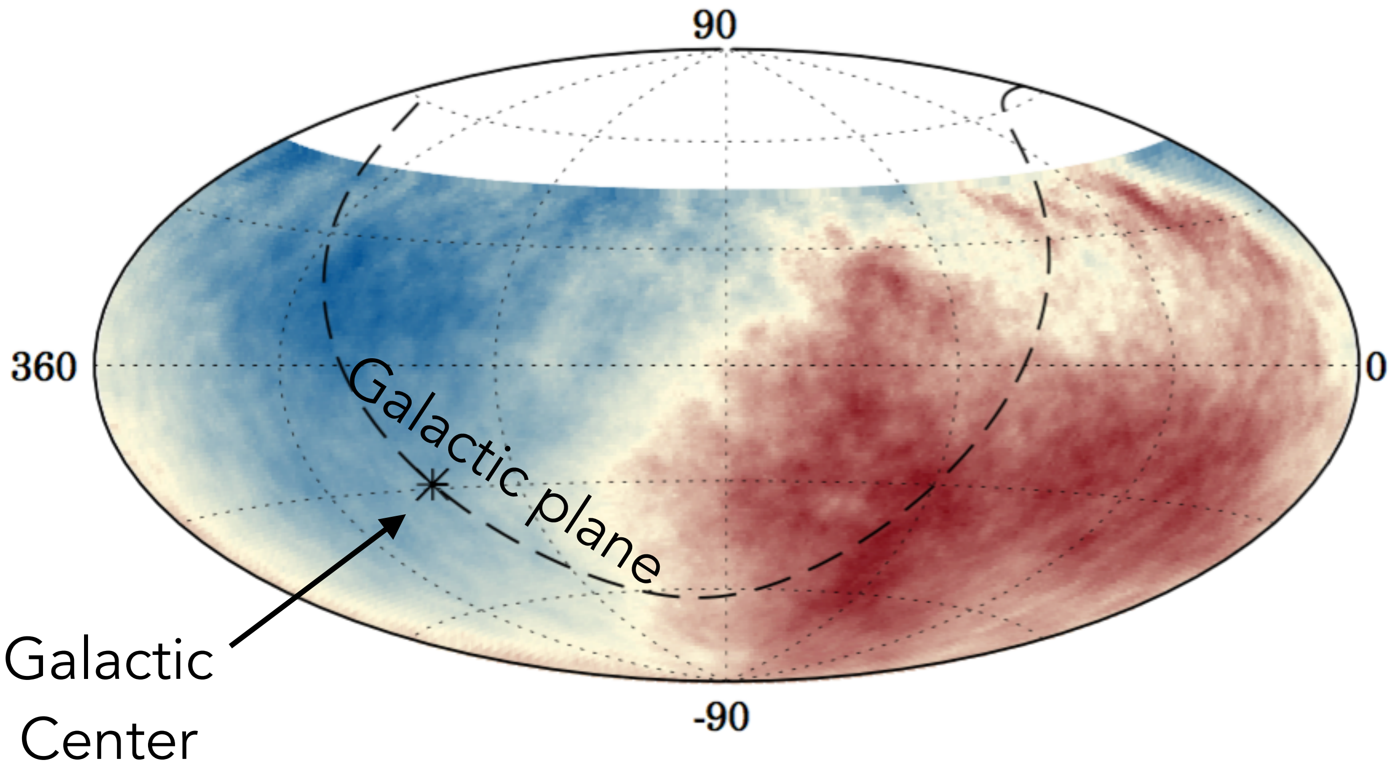
- Galactic : diffusion and escape of GCRs
- Transition from Galactic to Extra-Galactic
- extra-Galactic: small dipole due to our motion

Intermediate/small scale anisotropies

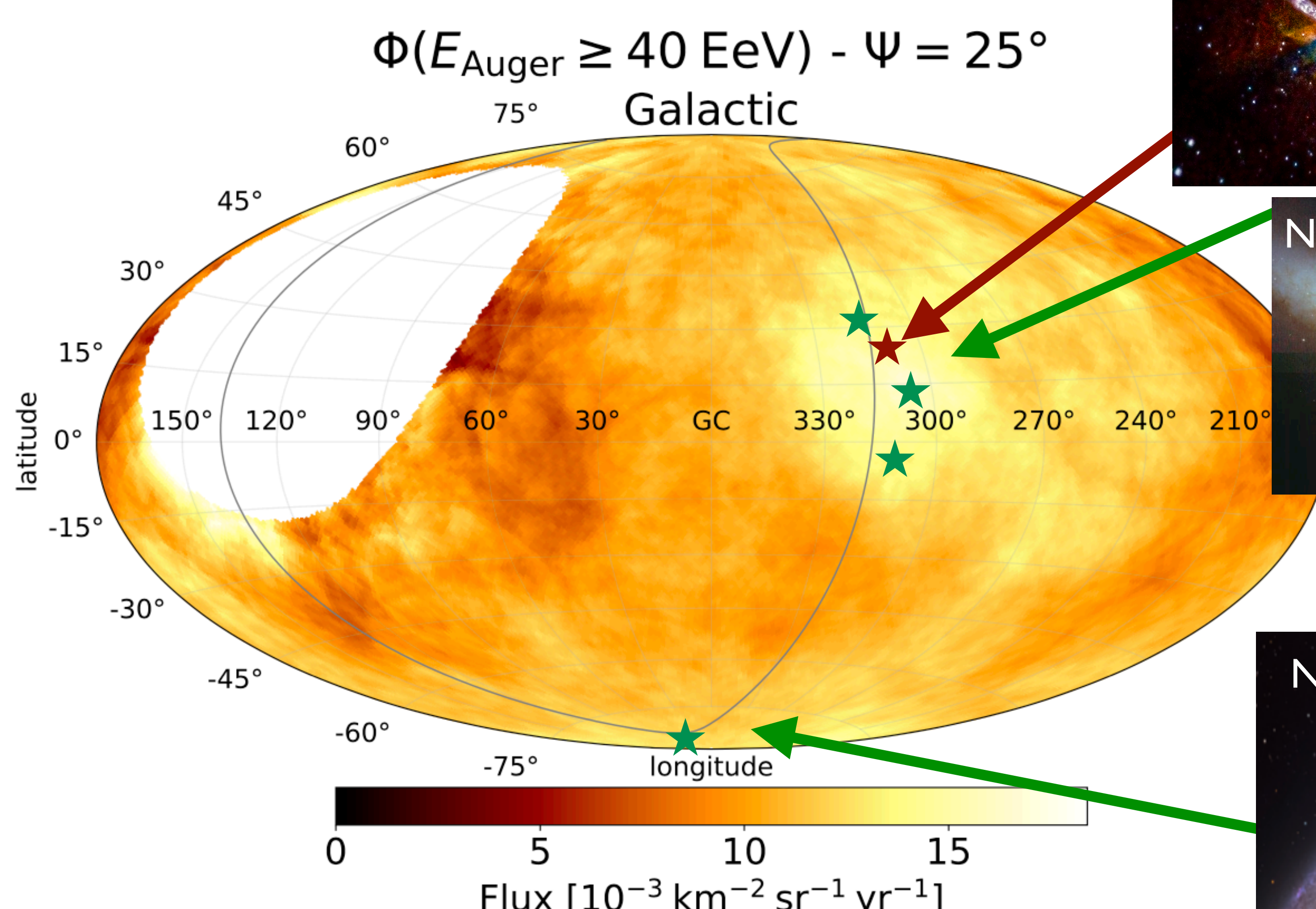
- high rigidity, nearby sources
- clustering of events from the same source
- correlation with a population of sources

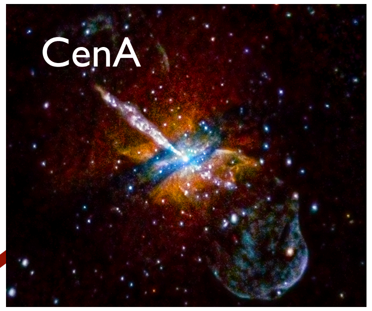
VERY difficult, as a deep and strong control of the experimental conditions is required
(we search for tiny anisotropies, need to avoid spurious effects)

The arrival directions



A dipolar anisotropy shows that *CRs above 8 10^{18} eV are indeed extragalactic !*





CRs with extreme energies >4 10^{19} eV
seem to *come preferentially from Starburst Galaxies, very close to us (few Mpc)*

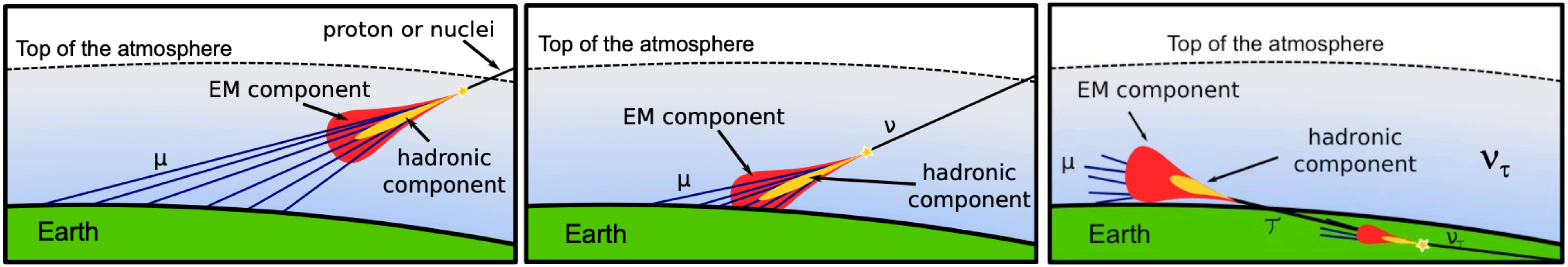
Are there any neutral messengers?

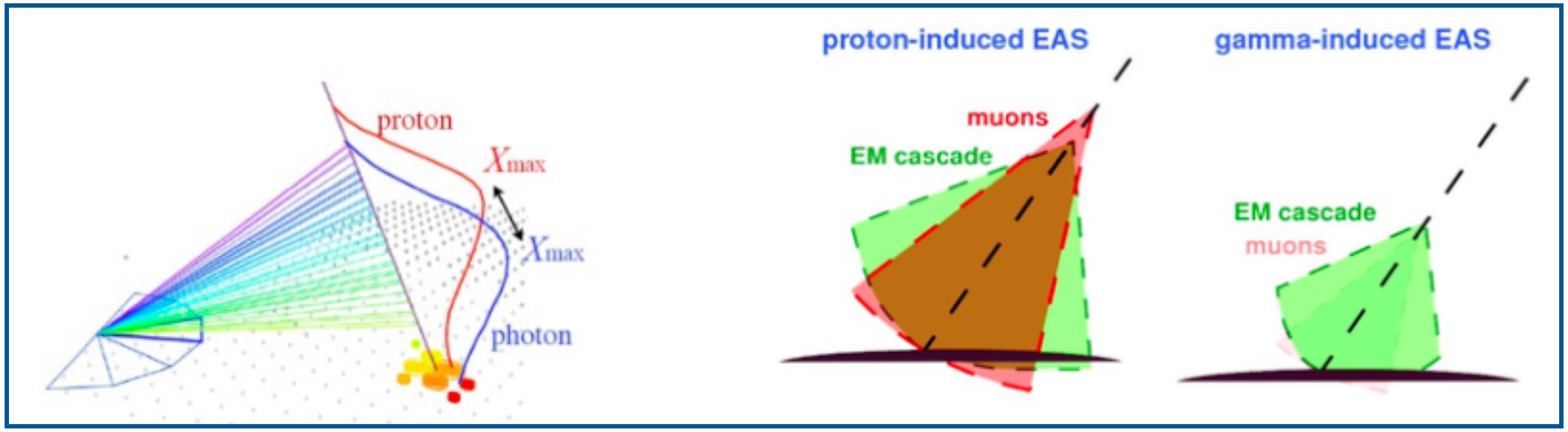
UHE neutrinos

- ✓ Astrophysical : produced in the sources (AGN, GRB) or in the source environment (SBG, Galaxy clusters)
- ✓ Cosmogenic: produced during propagation

UHE photons

- ✓ Astrophysical produced in the sources
- ✓ Cosmogenic: produced during propagation
- ✓ From top-down models





Both can be discriminated from hadrons
thanks to the different shower characteristics

UHE Photons and Neutrinos?

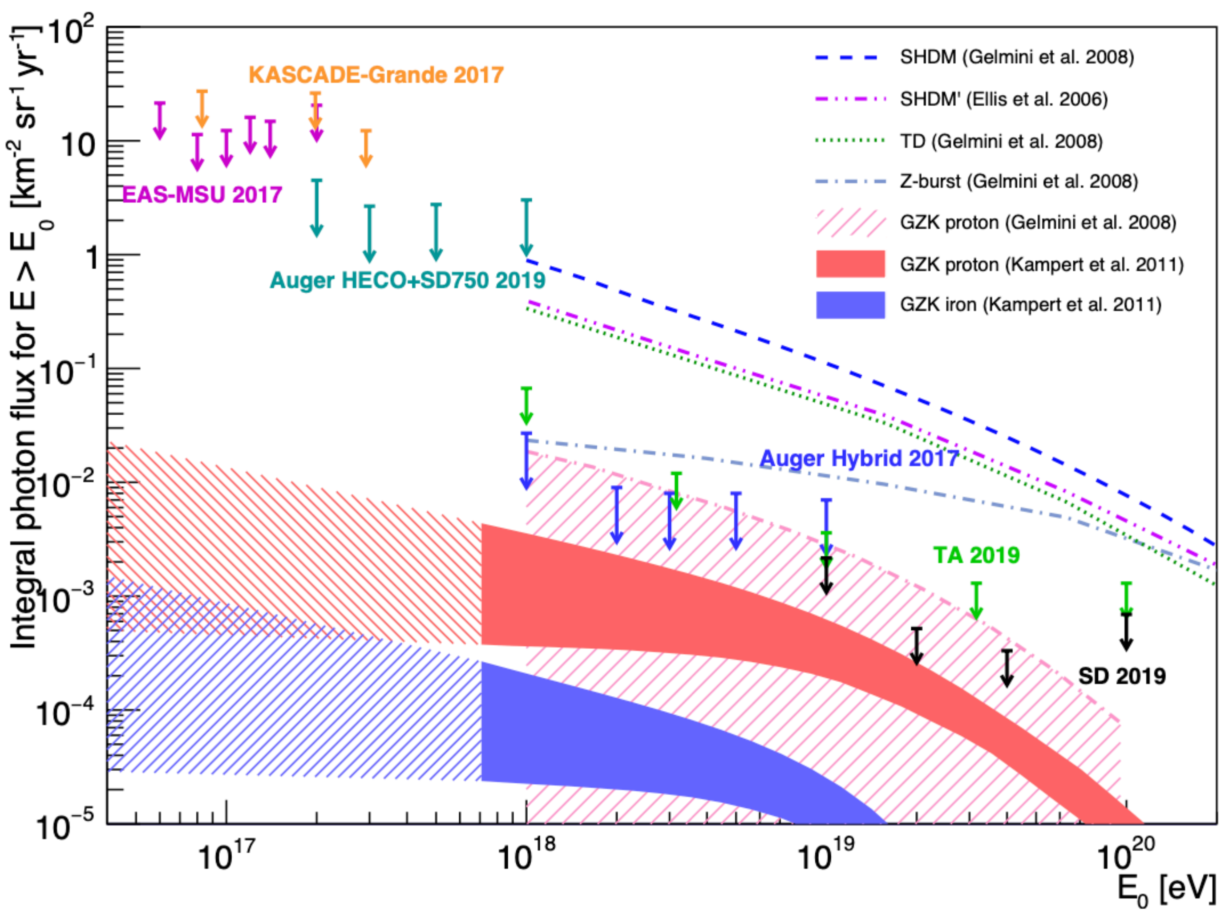
The detection of even one UHE neutrino or photon would 'per se' be a great discovery !
BUT… even a non-detection is full of information

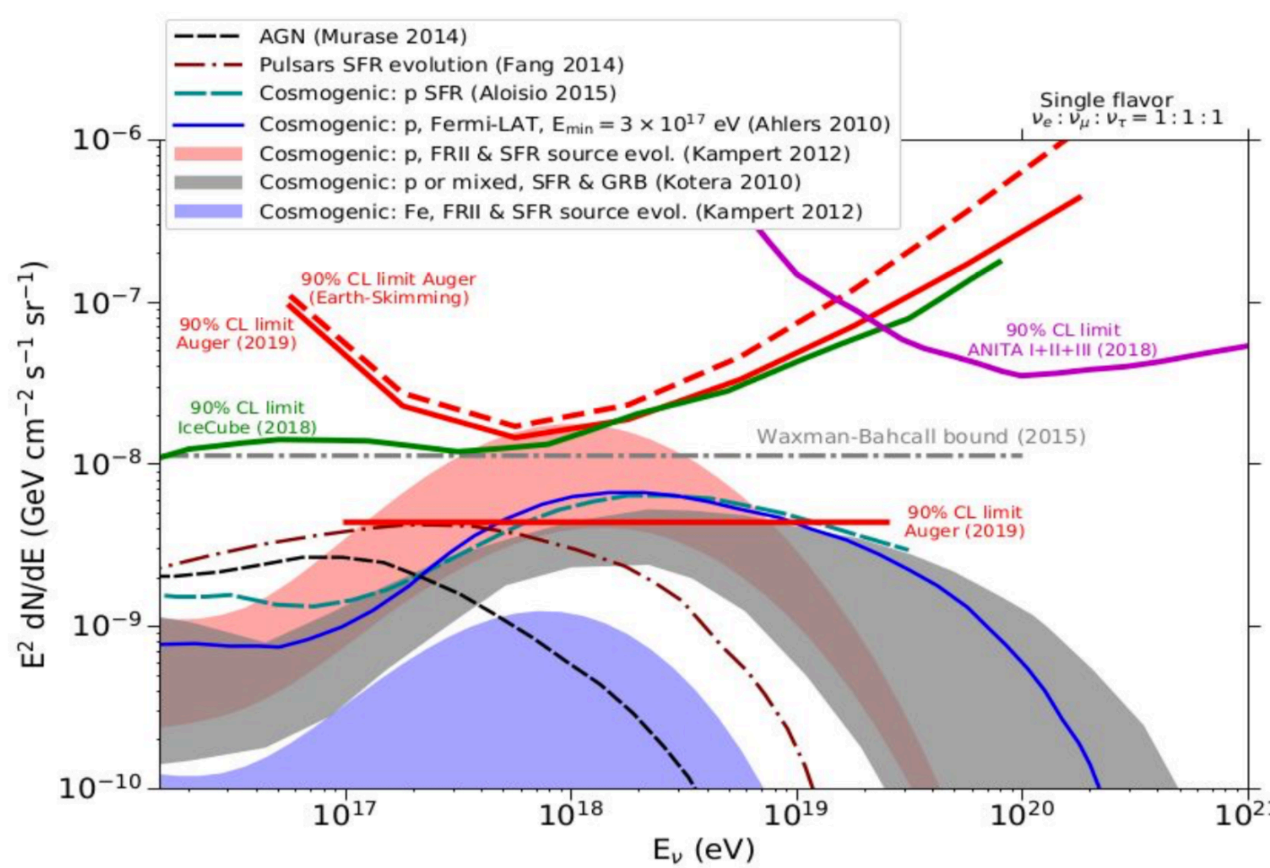
No cosmogenic photons found

- ✓ Top-down models ruled out
- ✓ Models with production of light elements only ruled out
- ✓ Constraints on super-heavy dark matter

No cosmogenic neutrinos found

- ✓ different models of cosmogenic and astrophysical neutrino production are excluded, other are disfavoured
- ✓ Energy range complementary to that of IceCube and Antares for point-like sources

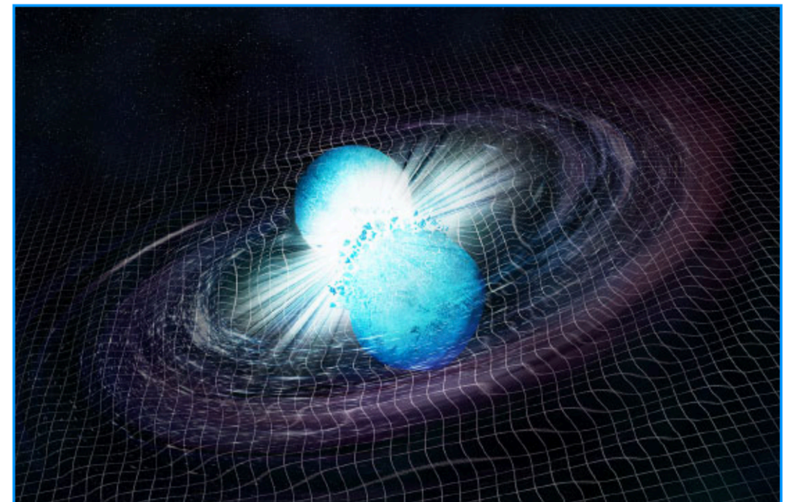


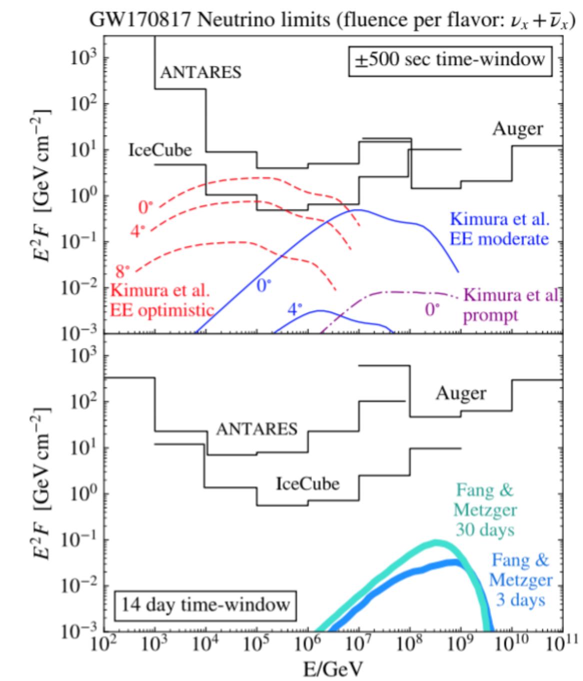


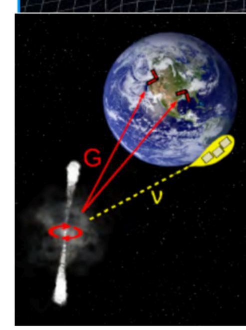
UHE Photons and Neutrinos? Some example

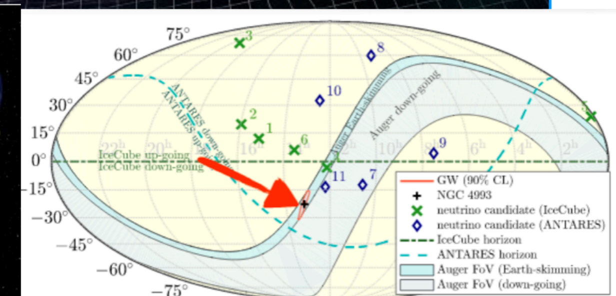
No UHE neutrino candidate found in coincidence with gravitational wave emission during Neutron stars or black holes merging

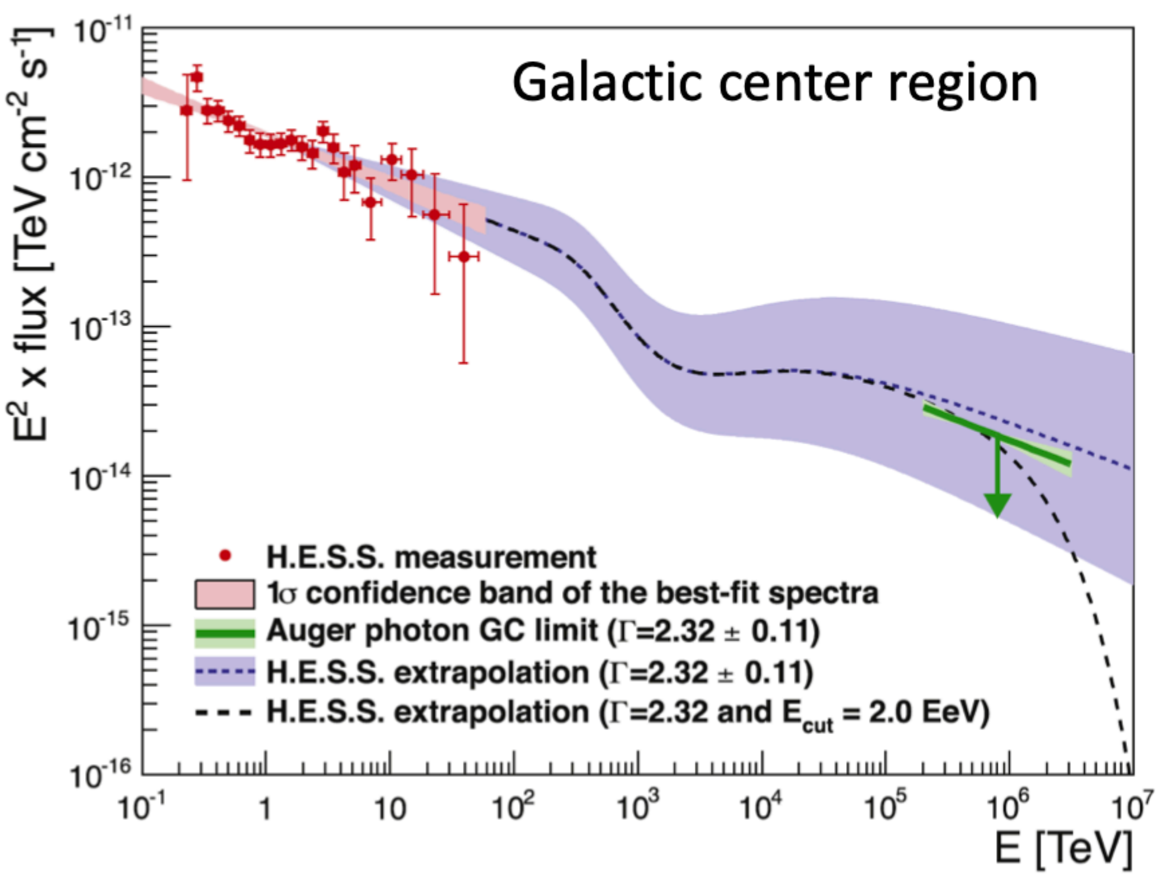
✓ Upper limits to the flux of neutrinos in the merger at UHE
✓ Constraints on models of merging







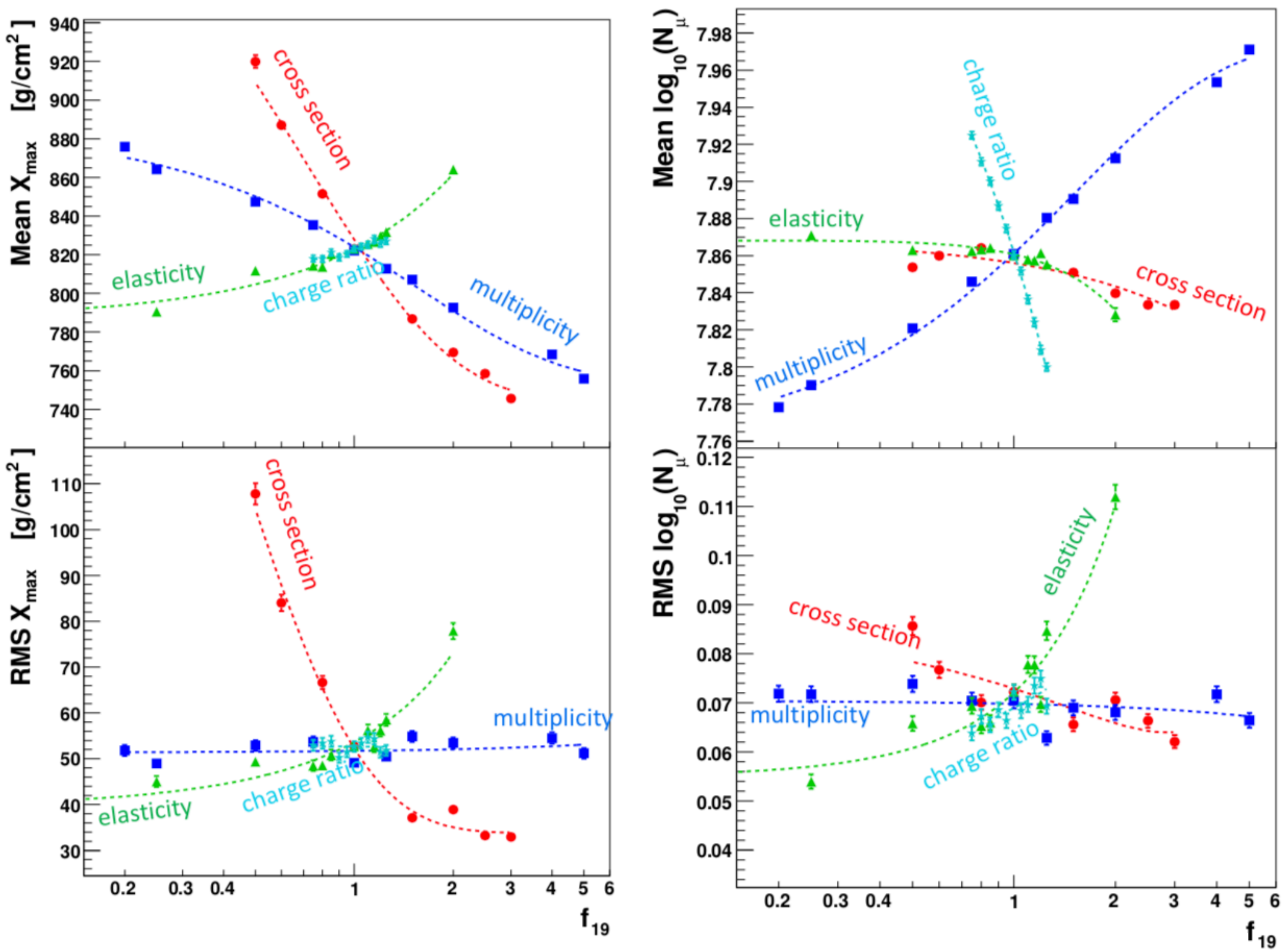




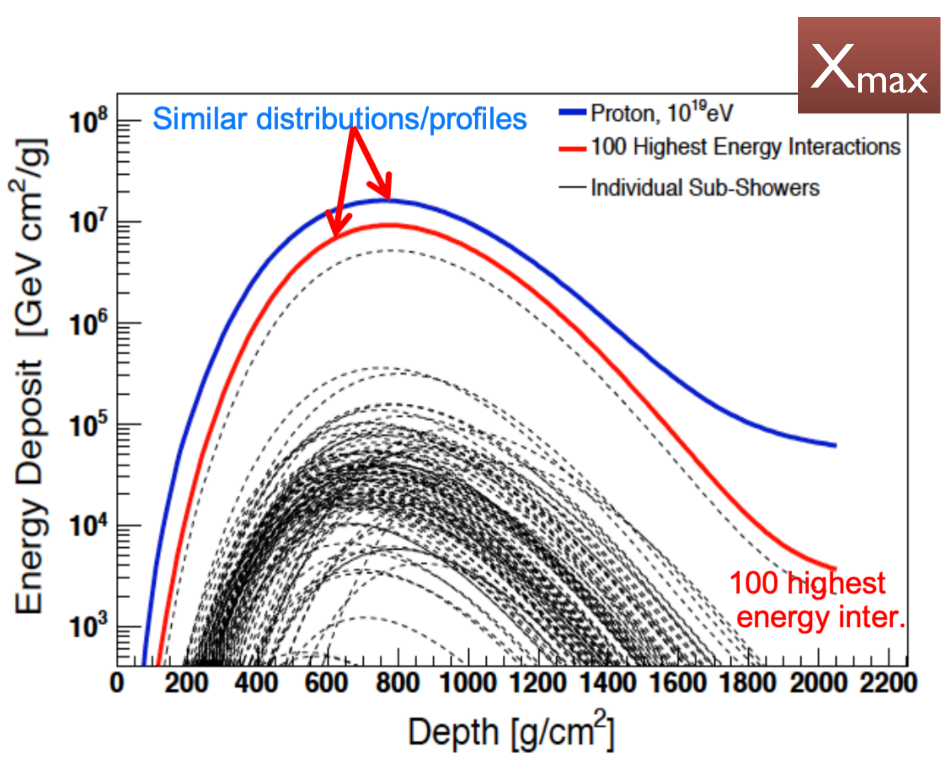
Photon sources

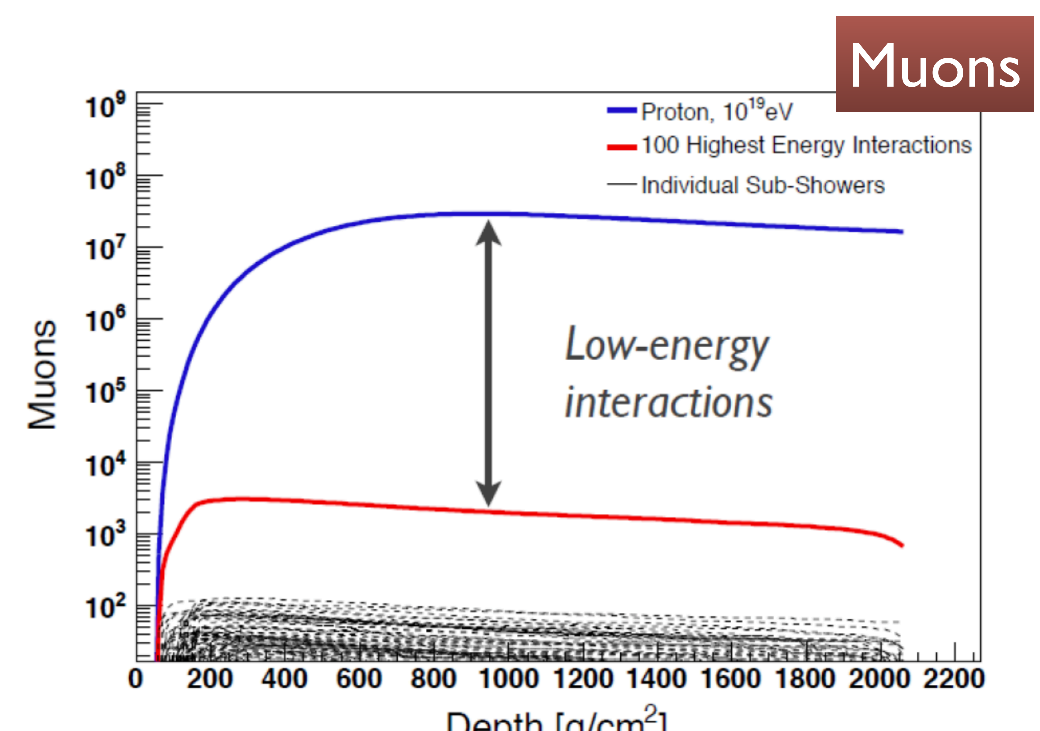
✓ no significant excess
✓ constrains on the allowed parameter space for the allows the extrapolation of the HESS flux
✓ upper limit on cut-off at ~ 2 EeV

Particle physics

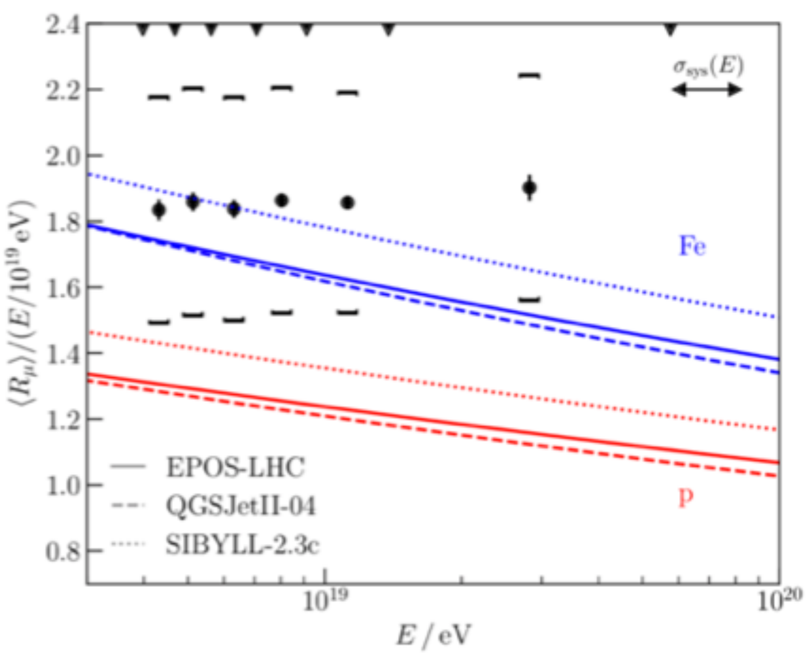


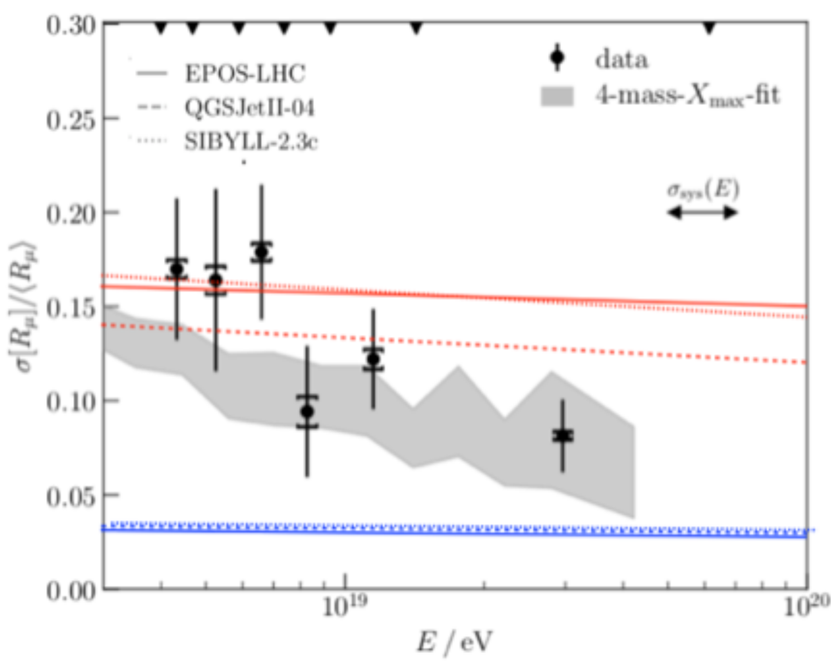
The observables measured with EAS from UHECRs are sensitive to the individual hadronic interaction features





Particle physics



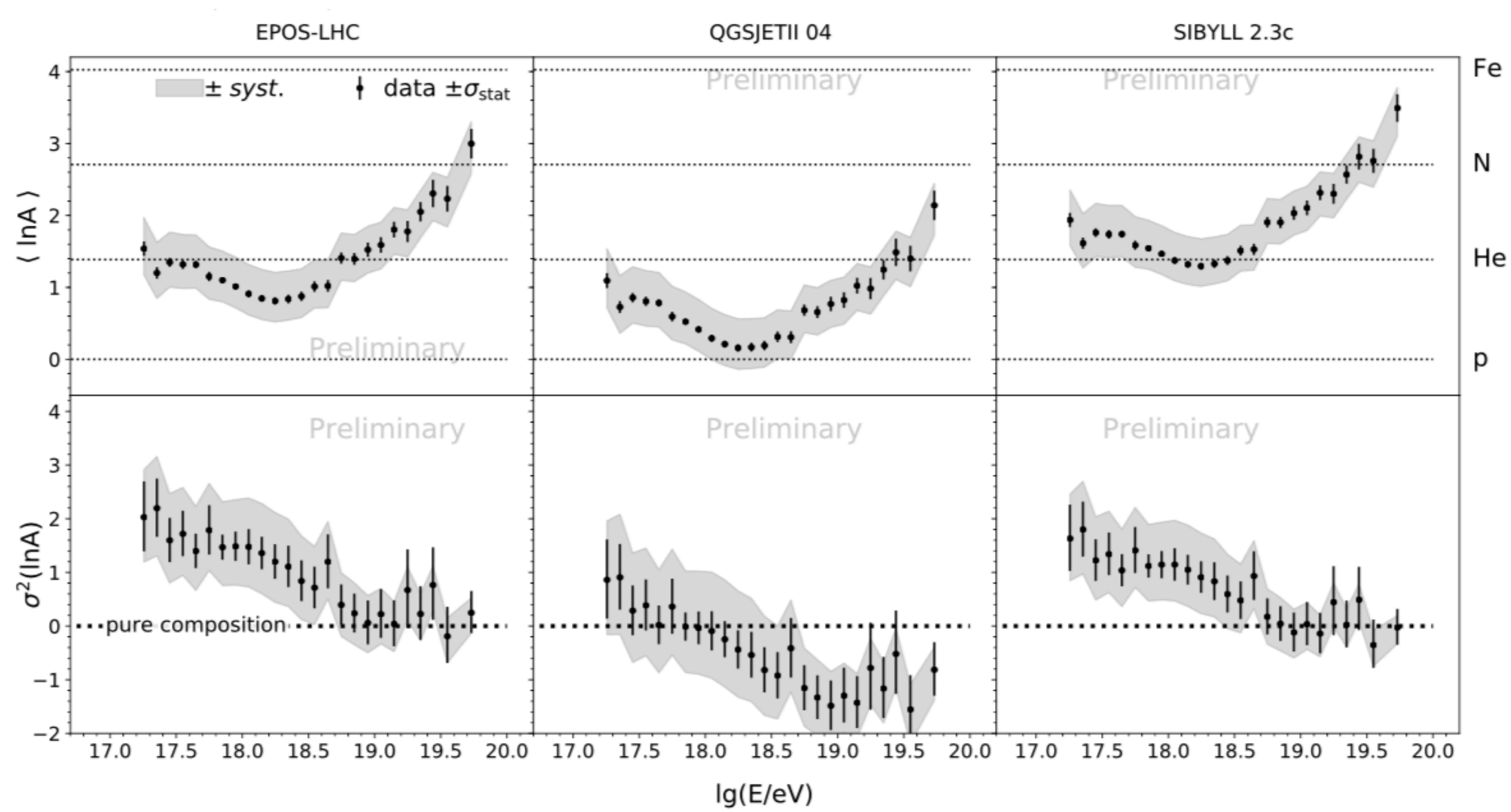


- ✓The hadronic interaction models underestimate the number of muons at UHE
- ✓<Fluctuations in the Muon number probe the first interactions at UHE

$$\langle X_{\max} \rangle = \langle X_{\max} \rangle_{\mathrm{p}} + f_E \langle \ln A \rangle$$

$$\sigma^2(X_{\max}) = \langle \sigma_{\mathrm{sh}}^2 \rangle + f_E^2\, \sigma^2(\ln A)$$

- ✓<ln A> and σ^2(ln A) vary depending on hadronic interaction models
- ✓QGSJET-II.04 predicts shower-to-shower fluctuations larger than mass range considered: X_{max} distributions not well predicted, leading to unphysical results.

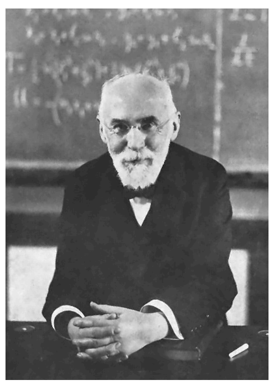


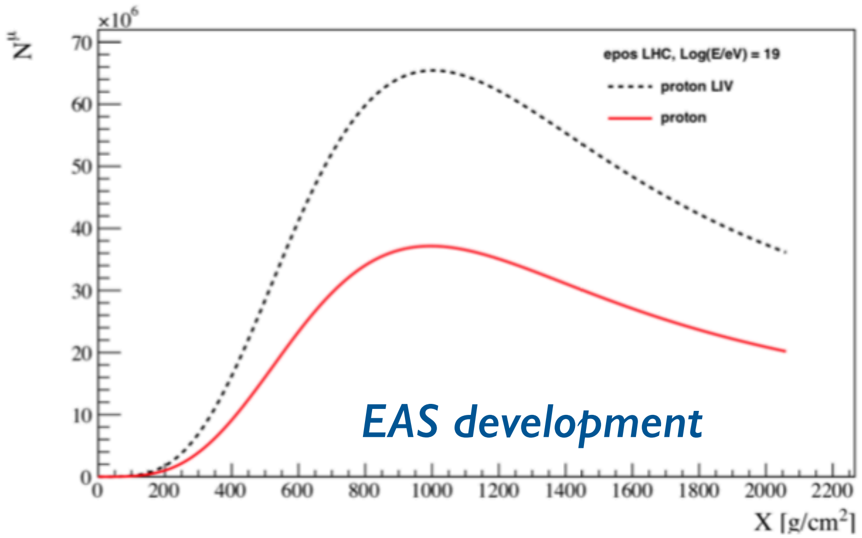
Beyond the standard model

Search for Lorentz invariance violation

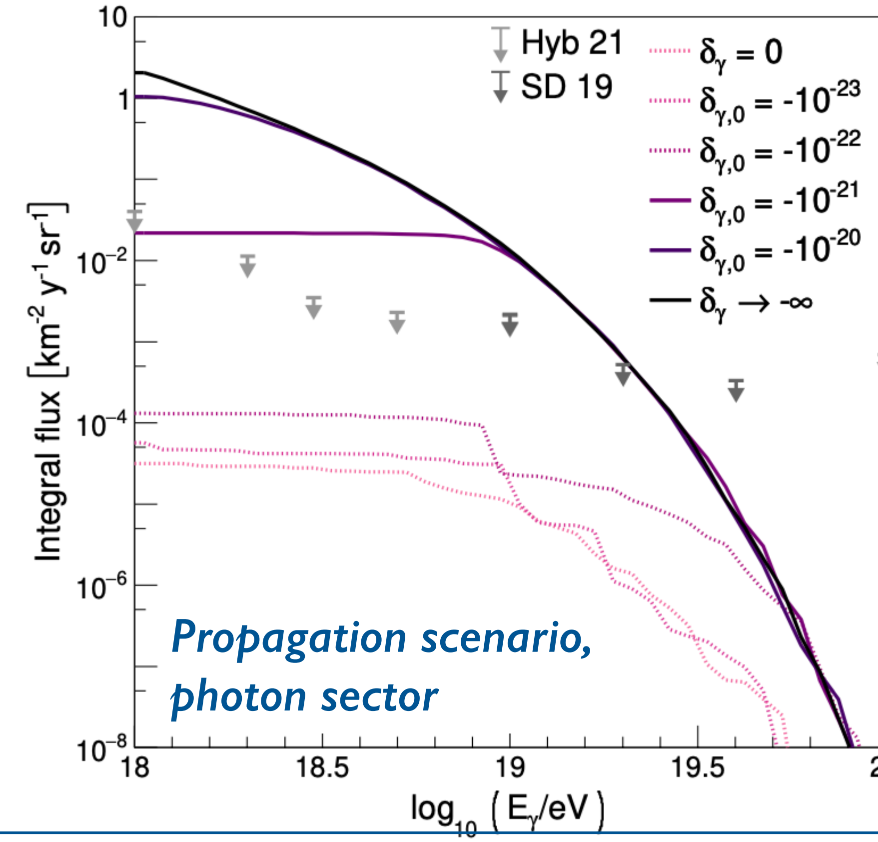
$$E_i^2 - p_i^2 = m_i^2 + \sum_{n=0}^{N} \delta_i^{(n)} E_i^{2+n} = m_i^2 + \eta_i^{(n)} \frac{E_i^{2+n}}{M_{Pl}^n}$$

Effects suppressed for low energy and short travel distances : UHECRs !!!

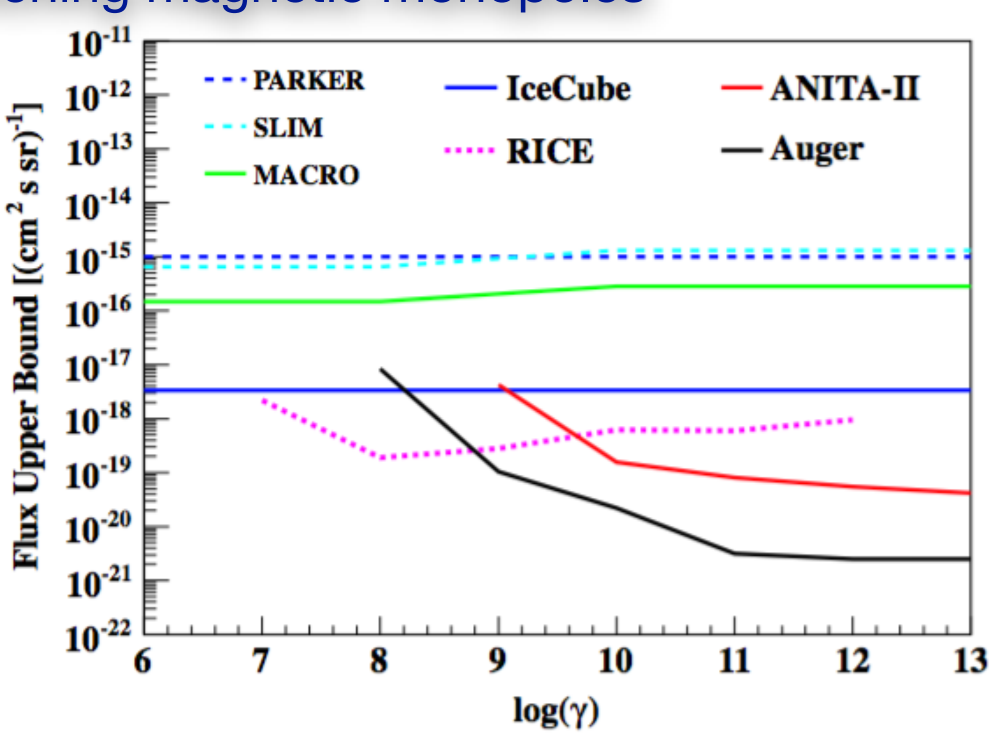


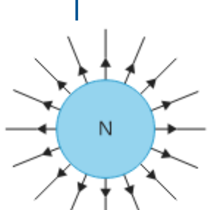


~ Factor 2 in number of muons

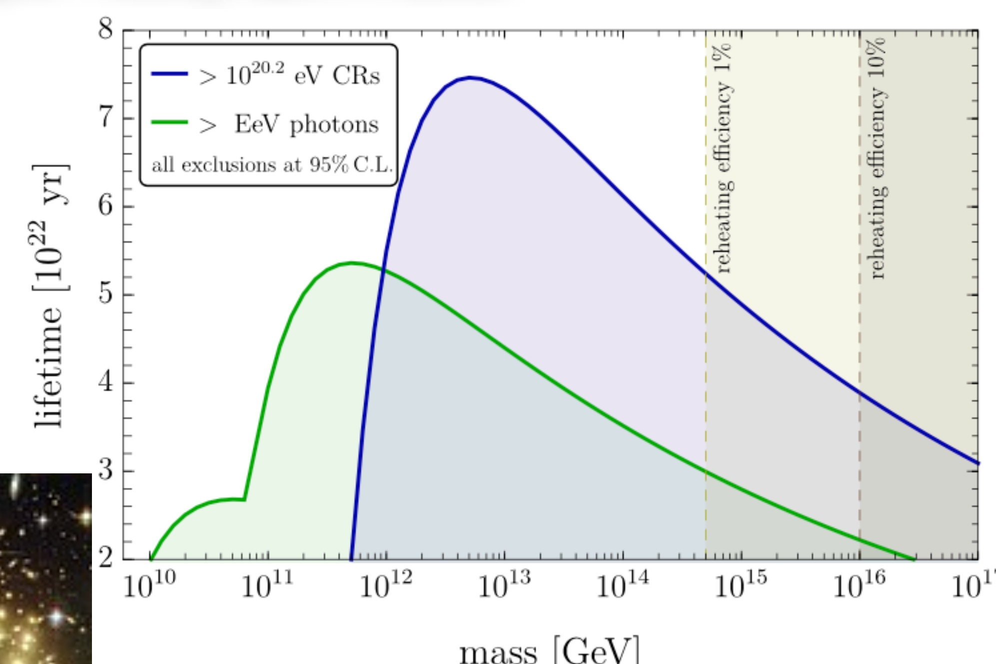


Searching magnetic monopoles



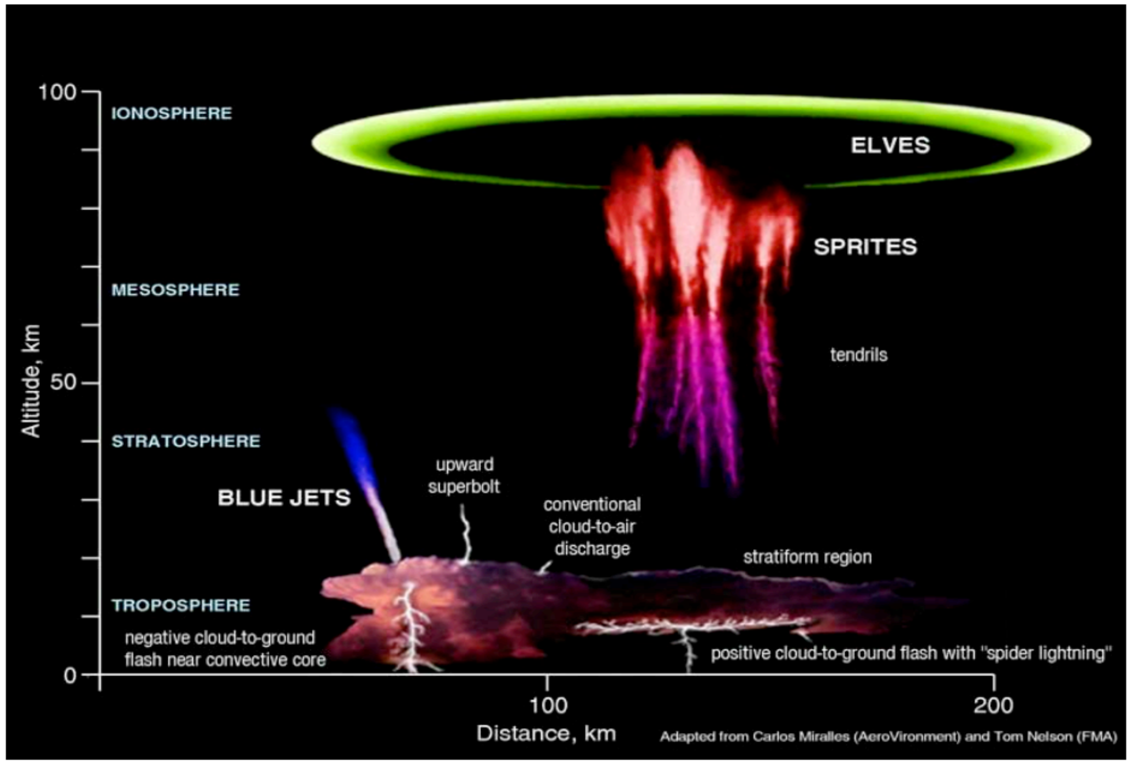


Super-heavy dark matter



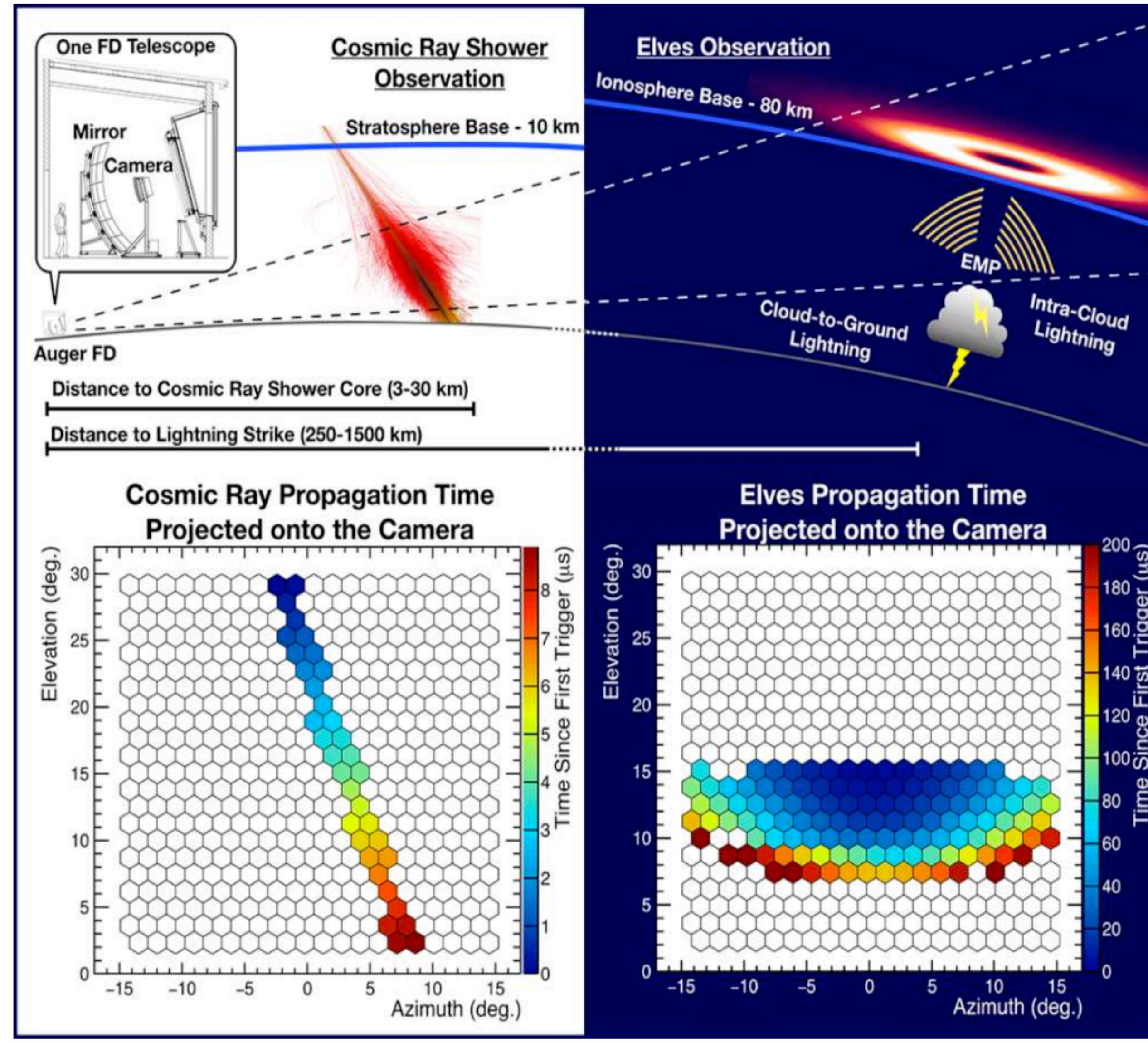
Atmospheric physics

What are the ELVES?



ELVES : *Emissions of Light and Very low frequency perturbations due to Electromagnetic pulse Sources.*

Predicted in the early 1990s [1] and discovered one year later [2], ELVES are transient luminous events (TLEs) occuring at an altitude H_{emis} ≈ 90 km when an intense electromagnetic pulse (EMP) emitted during the development of lightning reaches the base of the ionosphere. ELVES were observed for the first time in Auger data in 2005 [4]. A dedicated online trigger algorithm was developed in the following years [5].



1,598 elves, from 2014 to 2016, recorded with unprecedented time resolution (100 ns) on 10^6 km^2
Auger is the only facility on Earth that measures elves with year-round operation and full horizon coverage

information on the dynamics of plasma accelerators on our planet

Public Data Release

The Pierre Auger 2021 Open Data is the public release of 10% of the Pierre Auger Observatory cosmic-ray data presented at the 36th International Cosmic Ray Conference held in 2019 in Madison, USA, following the Auger Collaboration Open Data Policy. The release also includes 100% of weather and space-weather data collected until 31 December 2020.

This website hosts the datasets for download. A brief overview of the Pierre Auger Observatory and of the Auger Open Data is set out below. An online event display to explore the released cosmic-ray events, and example analysis codes are provided. An outreach section dedicated to the general public is also available.

Datasets
the released datasets and their complementary data

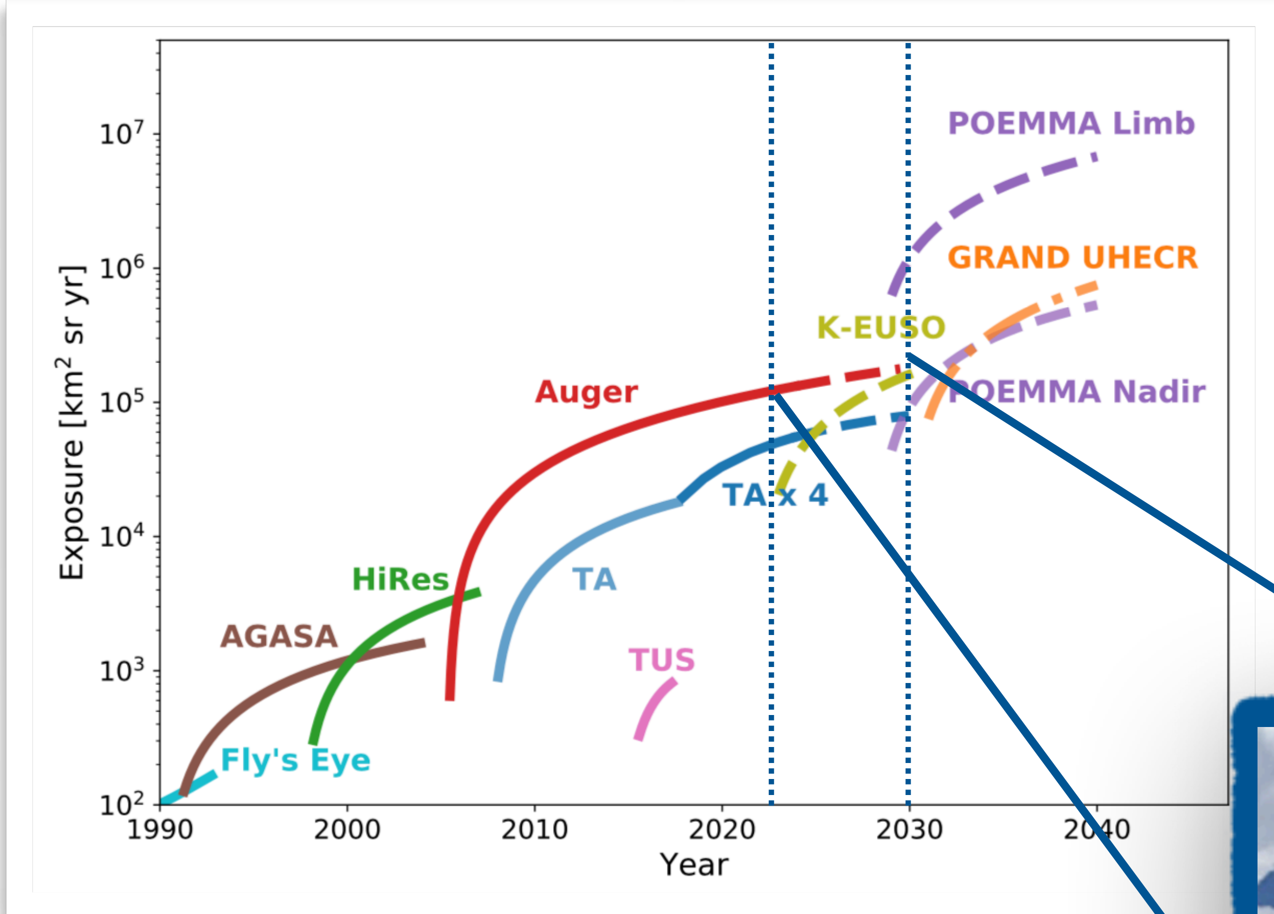
Visualize
an online look at the released pseudo raw cosmic-ray data

Analyze
example analysis codes in online python notebooks to run on the datasets

Outreach
a page dedicated to the general public

https://opendata.auger.org/

The future



The next challenges

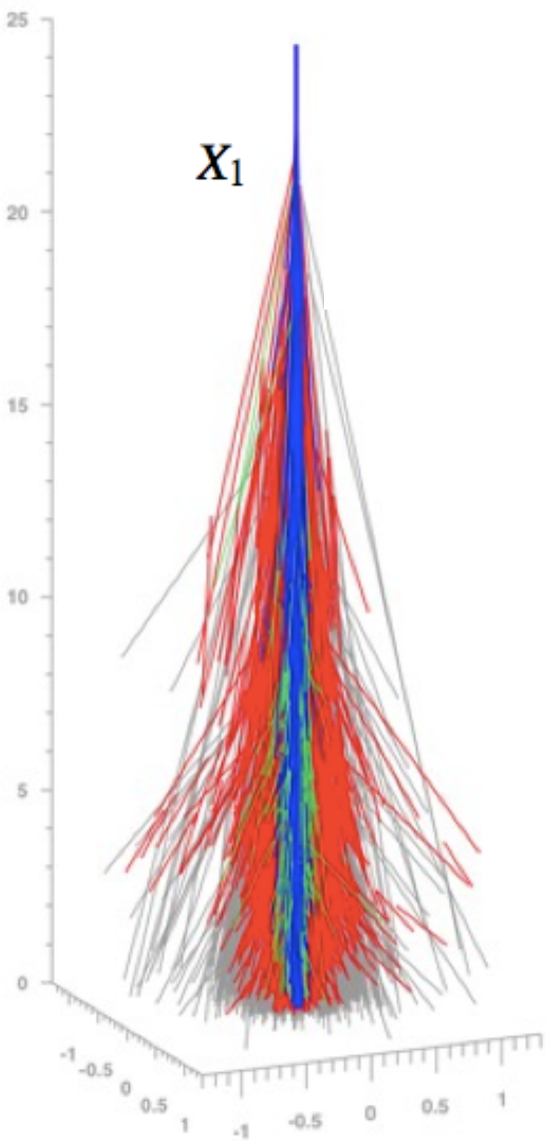
- measure the light nuclei fraction in the suppression region
- reduce the systematics due to hadronic interaction models
- understand the origin of the flux suppression
- increase the knowledge of magnetic fields
- analysis methods involving all observables (improved combined fits, machine learning)

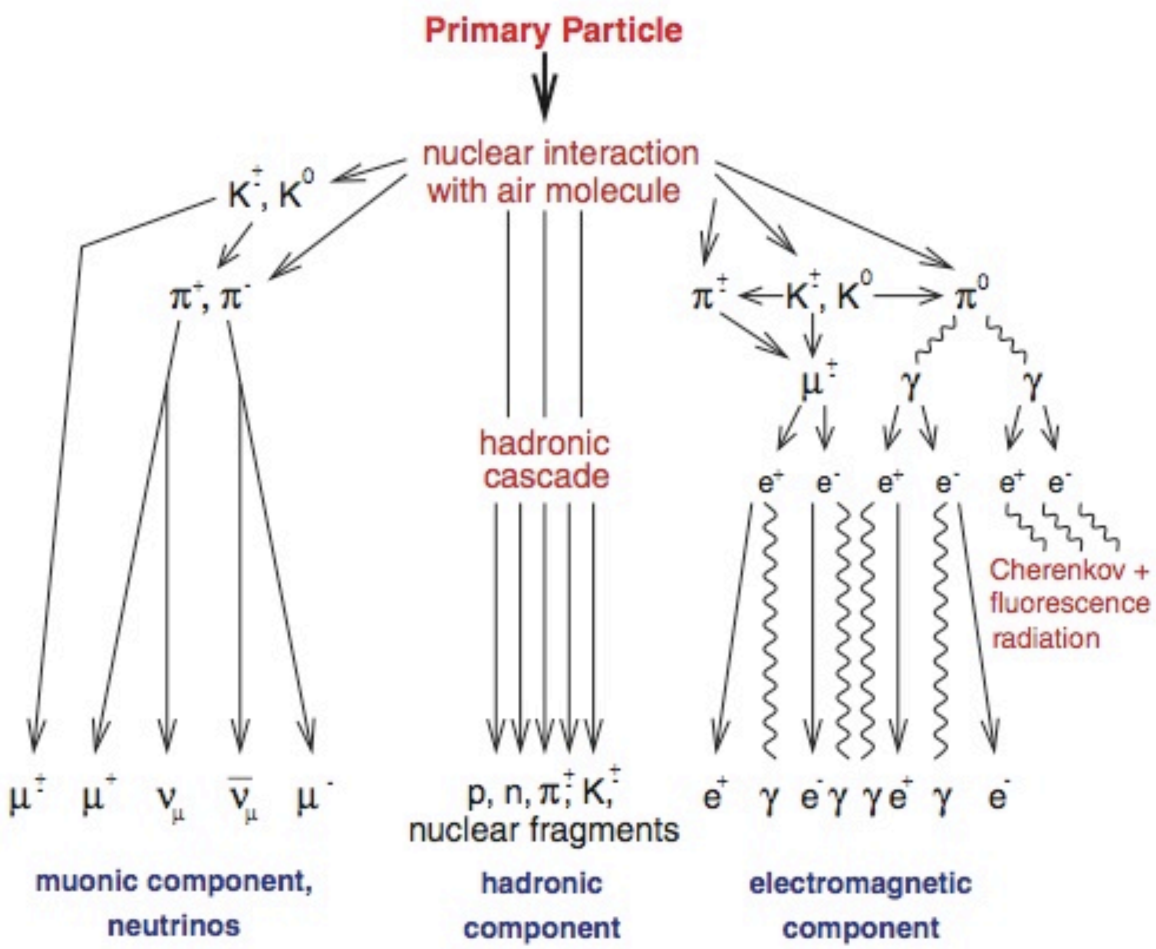
New opportunities

- up to 2030: upgrades of the present Observatories (***AugerPrime***, TAx4):
  - increasing the statistics
  - add composition-sensitive observables
  - exploit complementary techniques (Radio)
- next decade: new and complementary projects from ground and space
- p+O runs at LHC
- new data on GMF + models

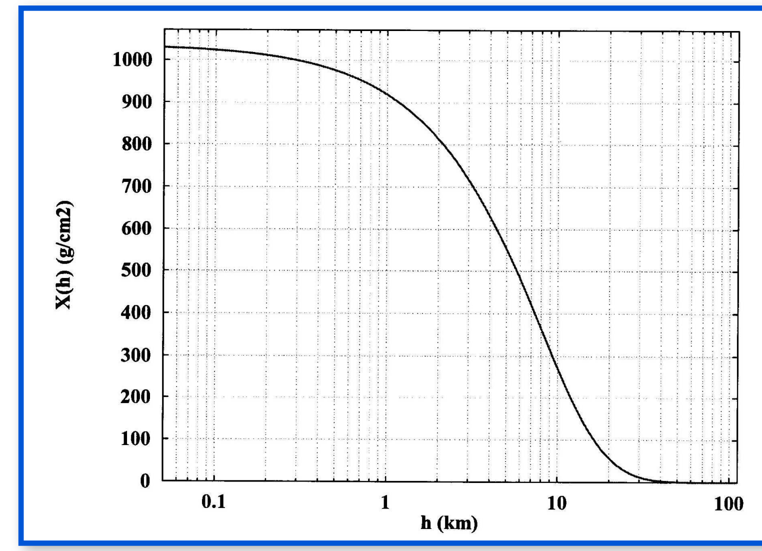
Backup slides

Extensive Air Showers





Atmospheric Thickness: 1035 g/cm²
≈ 11 λ_I (hadr. interact. lengths)
≈ 27 X_0 (radiation lengths)



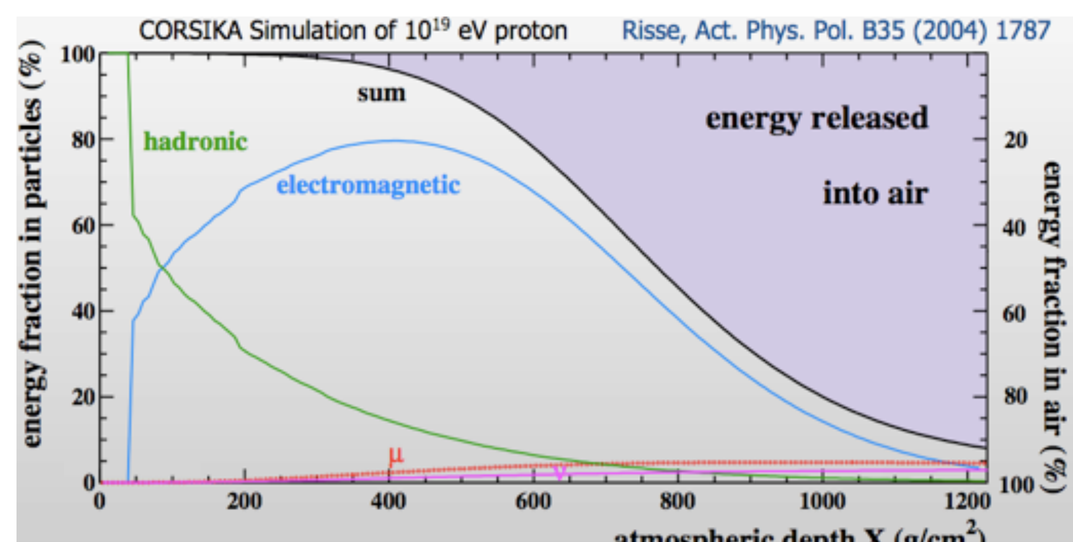
$$X_V = \int_h^\infty \rho(h')\, dh' \; g\ cm^{-2}$$

$$p + N \longrightarrow \pi^\pm, \pi^0, K^\pm, K, p, n, +....(exotic)$$

$$\pi^0 \longrightarrow \gamma\gamma \qquad \tau_\pi = 1.8 \cdot 10^{-16} s$$

$$\pi^\pm \longrightarrow \mu^\pm \nu_\mu \qquad \tau_\pi = 2.5 \cdot 10^{-8} s$$

$$\mu^\pm \longrightarrow e^\pm \nu_e \nu_\mu \qquad \tau_\pi = 2.2 \cdot 10^{-6} s$$



Full efficiency
SD1500 : >3 10^{18} eV
SD750 >3 10^{17} eV

SD	
SD annual exposure, $\theta < 60°$	$\sim$5500 km^2 sr yr
T3 rate	0.1 Hz
T5 events/yr, $E > 3$ EeV	$\sim$14,500
T5 events/yr, $E > 10$ EeV	$\sim$1500
Reconstruction accuracy (S_{1000})	22% (low E) to 12% (high E)
Angular resolution	1.6° (3 stations)
	0.9° (> 5 stations)
Energy resolution	16% (low E) to 12% (high E)
FD	
On-time	$\sim$15%
Rate per building	0.012 Hz
Rate per HEAT	0.026 Hz
Hybrid	
Core resolution	50 m
Angular resolution	0.6°
Energy resolution (FD)	8%
X_{max} resolution	< 20 g/cm^2