Astroparticle Physics at the highest energies

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Amazing two decades

- **Cosmology** and **particle astrophysics**: tremendous progress in the last two decades.
- Constructive **interplays** between observational/ experimental **data** and theoretical concepts have greatly enhanced our **fundamental** understanding of the universe.
- Such advancement in turn triggers **new questions** to be further addressed.
- We are currently living in an era of **renaissance** in **cosmology** and **particle astrophysics.**

Amazing two years 2012-2013

★ **Planck results**

Excluding many inflation models

B mode detection

New robust limits on Neff, Σm_ν

Whole sky dark matter maps

★ **Neutrinos**

U_{MNSP} $\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$

Conventional longbaseline experiments can measure the mass hierarchy independently of the value of δCP

★ **Higgs**

A triumph . Higgs found where expected.

No signs of SUSY yet.

2012-2013 extraordinary years

The **Astroparticle theme** after LHC/PLANCK/ν
two fundamental questions:

- ★ Intermediate scales between the EW and Inflation? how many? where are they?
  - ★ **Dark matte**r and energy
  - ★ Neutrino properties and proton decay

- ★ How particles and fields of the intermediate scales shape cosmic structures ?
  - ★ **High energy photons, neutrinos, CR**
  - ★ Gravitational waves

2012-2013 extraordinary years

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Ultra High Energy Cosmic Rays

THE HIGH ENERGY FRONTIER

Two persistent questions about UHECRs:

★ What are those particles with energies that can reach $E > 10^{20}$ eV = 100 EeV ?

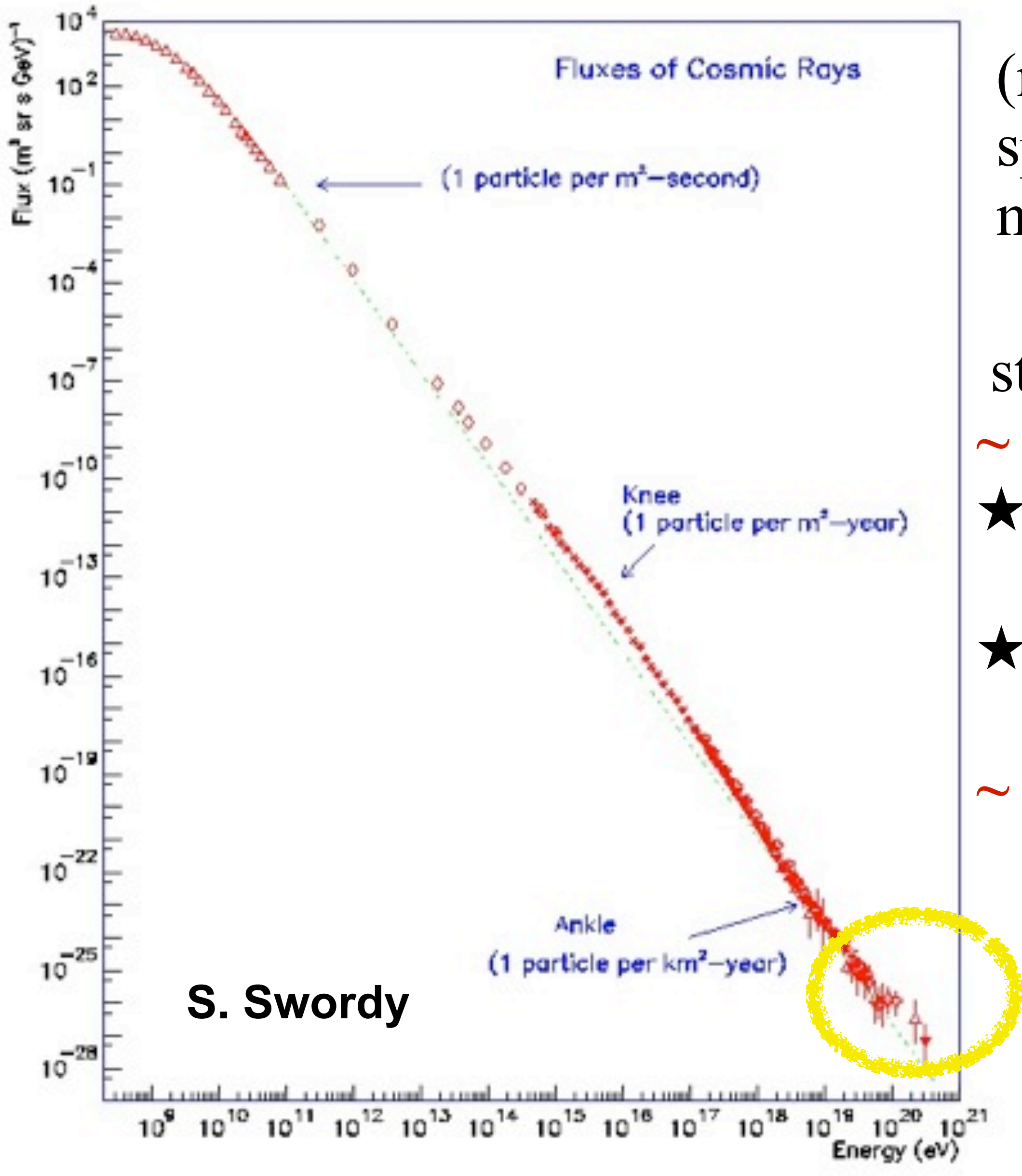
★ Where do they come from?

Their study has impact on

★ Astrophysics

★ Particle Physics

Cosmic rays flux vs. Energy



(nearly) uniform **power-law** spectrum , **10** orders of magnitude in **E** and **32** in **flux**!

structures :

~ 3 10^{18} eV: ankle

★onset of the extragalactic CR component

★energy losses of extragalactic protons by pair production

~ GZK "cuttof "

UHECR

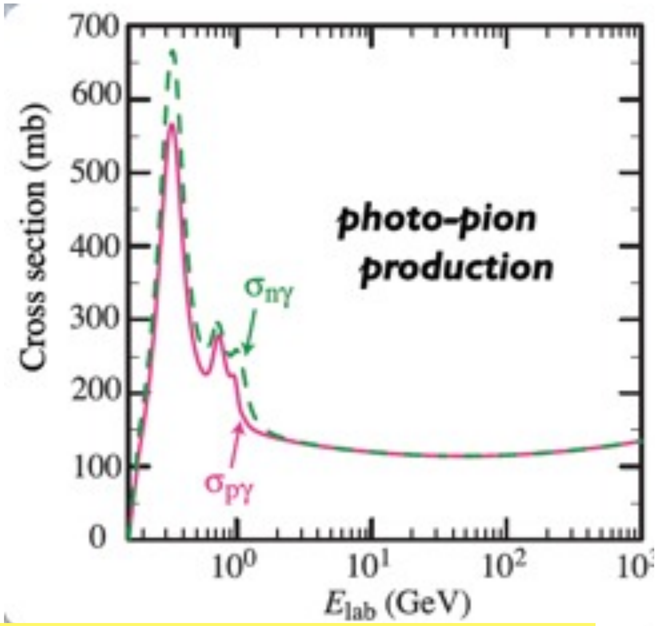
- **one particle / century / km^2**
- **many interesting questions**

GZK suppression

- Cosmic rays $E = 10^{20}$ eV interact with 2.7 K photons

- In the proton frame $E_\gamma = 300\,\mathrm{MeV}$

Photon-pion production



$$p + \gamma_{3k} \to \Delta^+ \to p + \pi^0$$

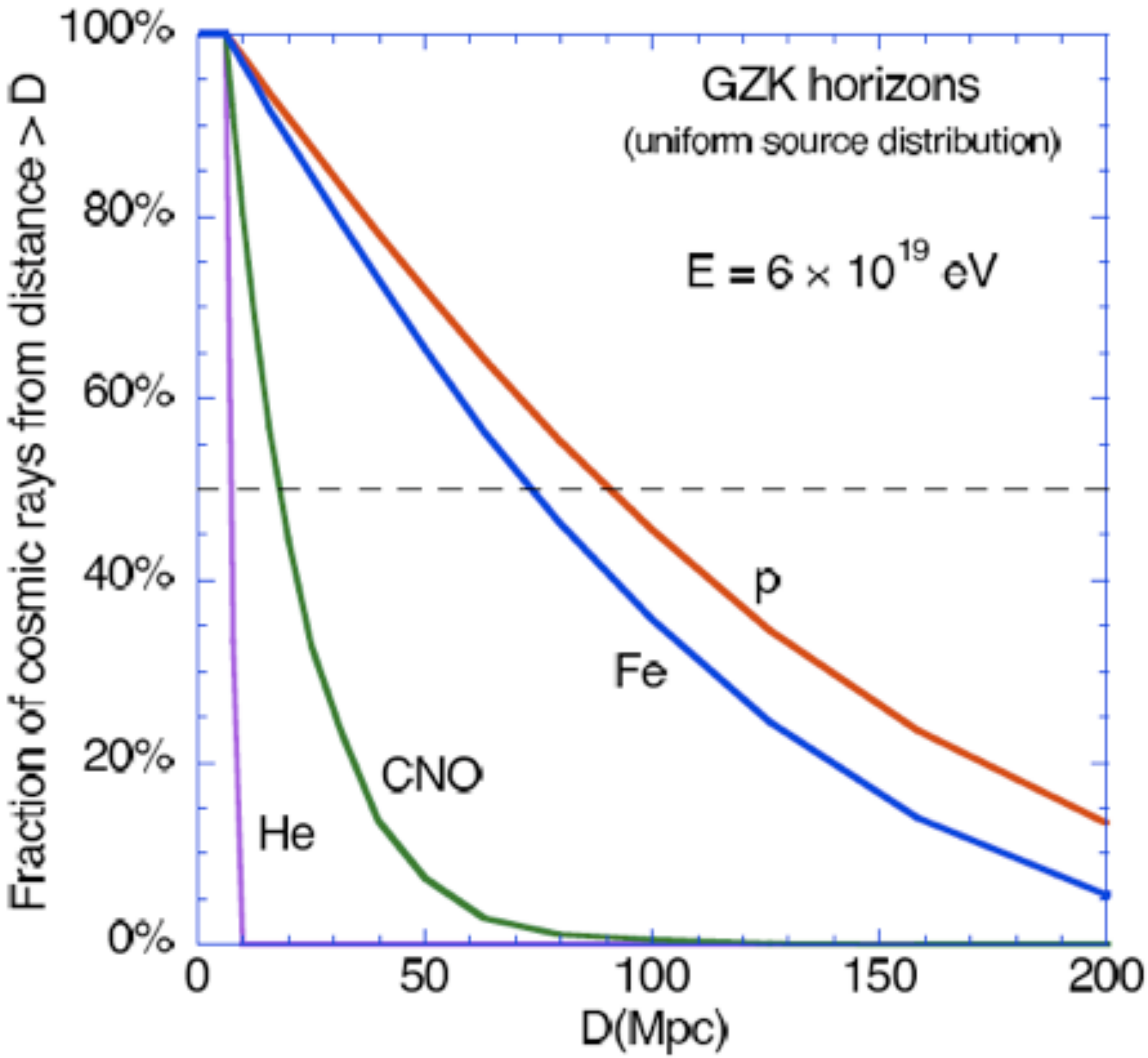
$$\to n + \pi^+$$

$$p + \gamma_{3k} \to \Delta^+ \to p + e^+ + e^-$$

- Proton looses energy, eventually below cutoff energy $E_{GZK} = 5\text{x } 10^{19}$ eV

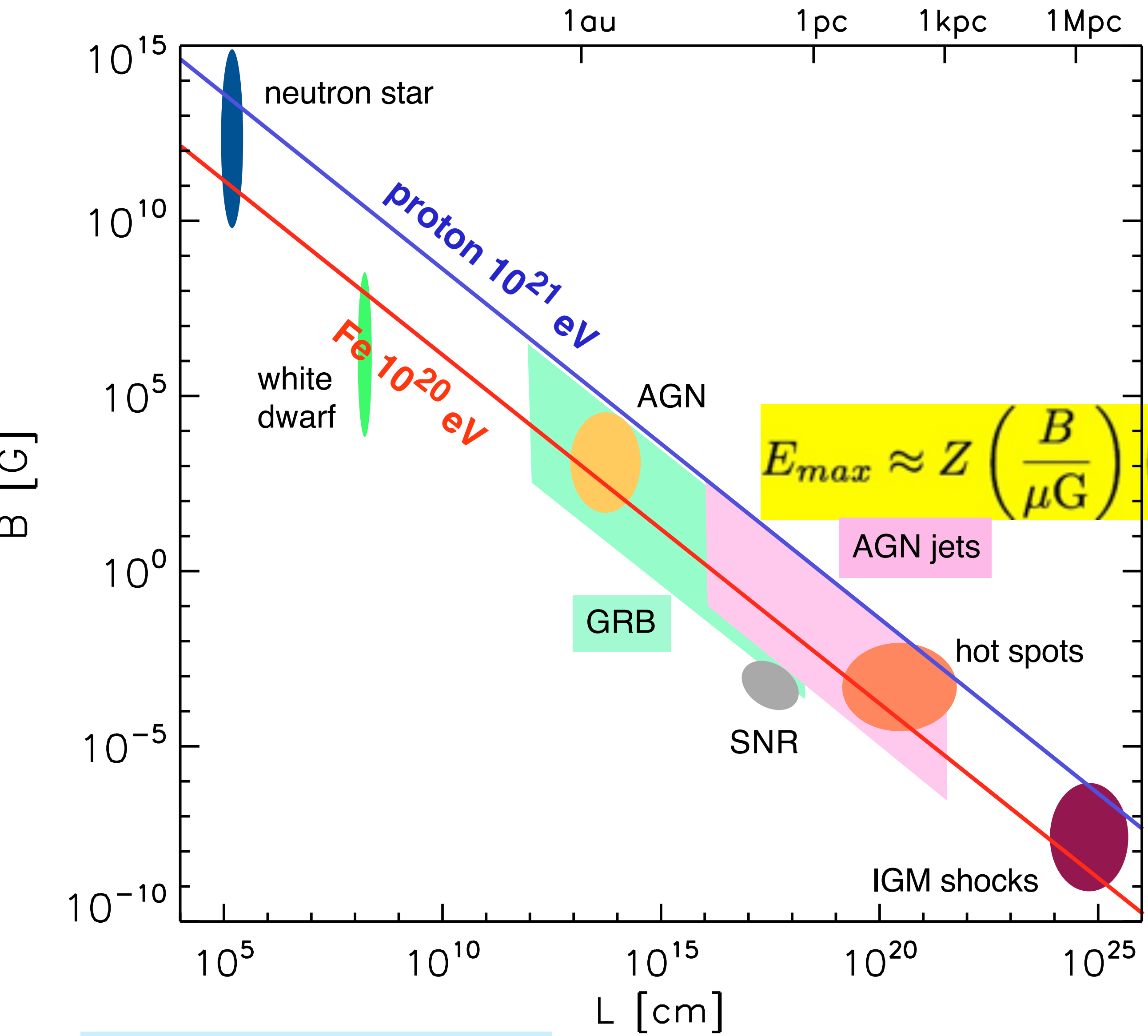
Universe is opaque for E > E_{GZK} !
Direct test of Lorentz transformations at extreme energies!

GZK horizons



Allard et al,2008

Hillas plot



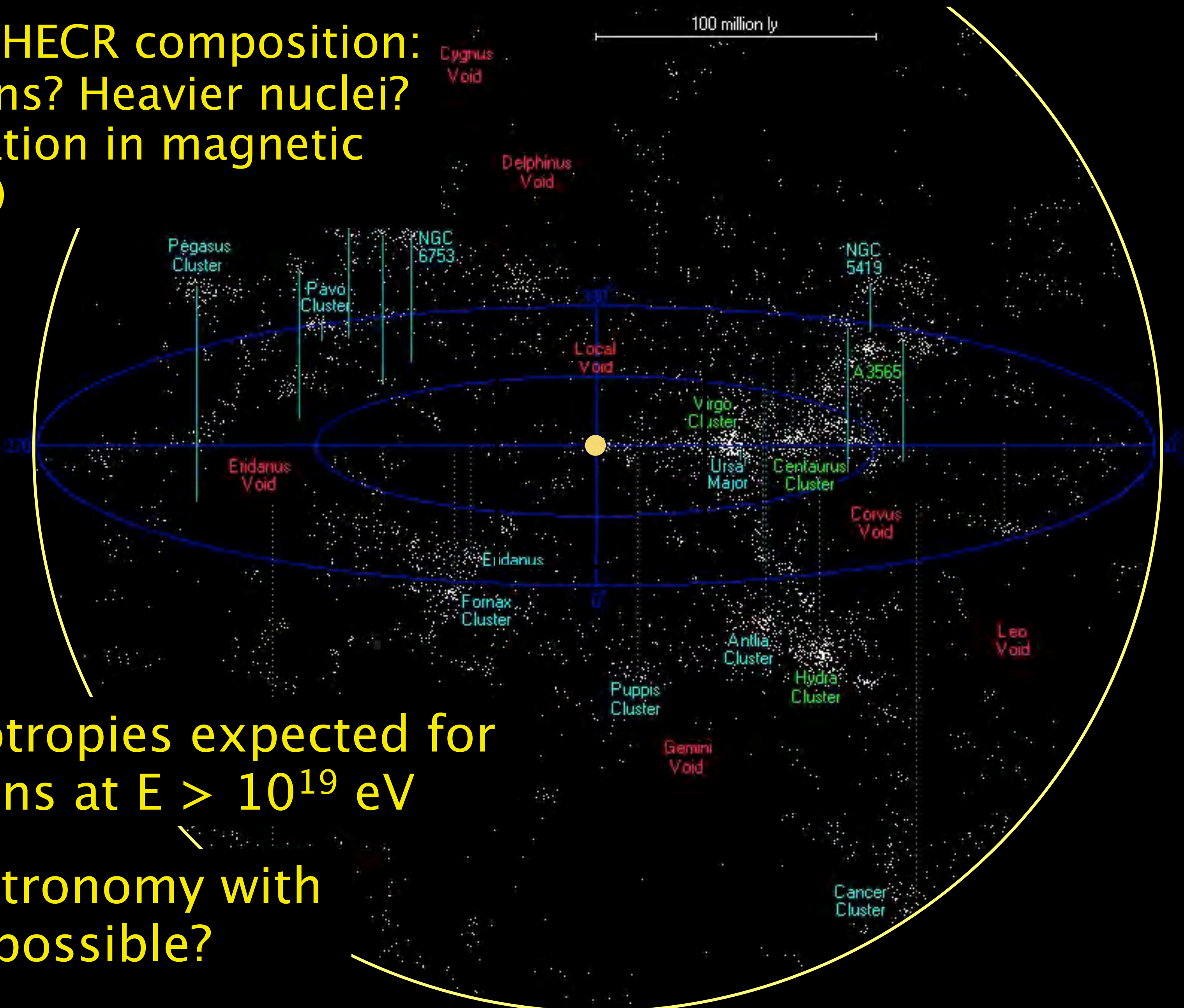
Kotera, Olinto 2010

acceleration site: **containment** of the accelerated cosmic ray **Larmor radius**

$$E_{max} \approx Z \left(\frac{B}{\mu G}\right)\left(\frac{R_{source}}{\text{kpc}}\right) \times 10^9 \text{GeV}$$

Anisotropies and Composition

The UHECR composition: protons? Heavier nuclei? (deviation in magnetic fields)

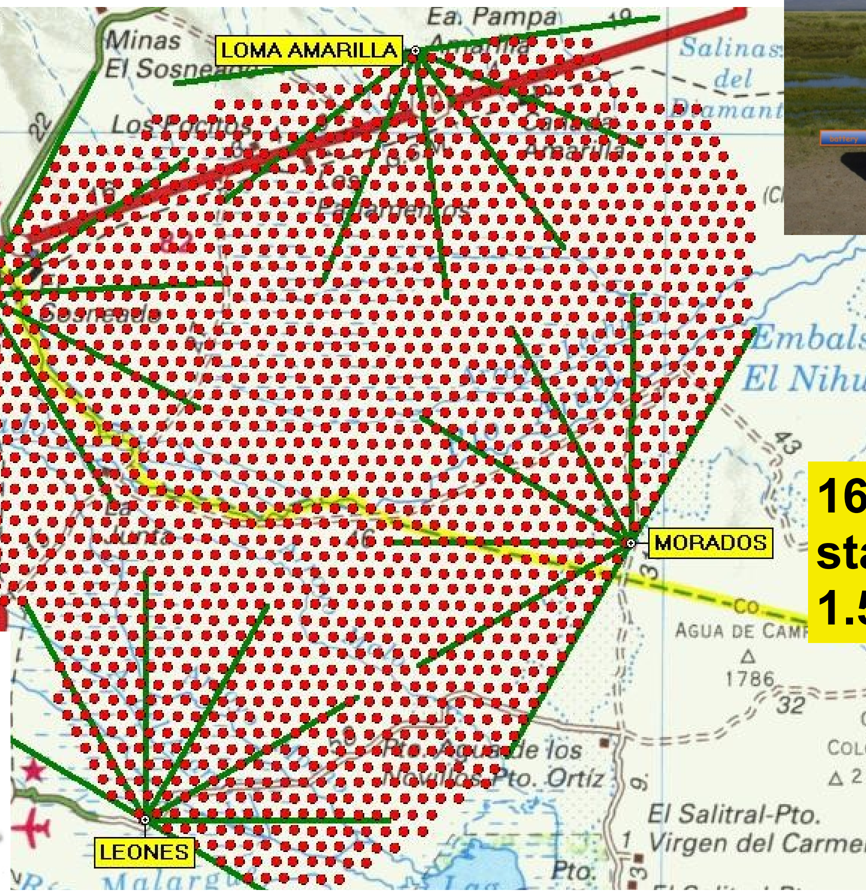


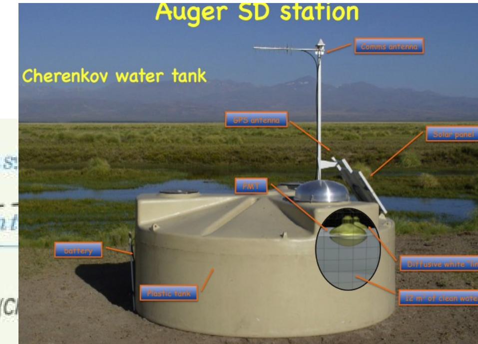
Anisotropies expected for protons at $E > 10^{19}$ eV

Is astronomy with CR possible?

Pierre Auger Observatory

3000 km^2





Fluorescence Detector

27 telescopes overlooking the array

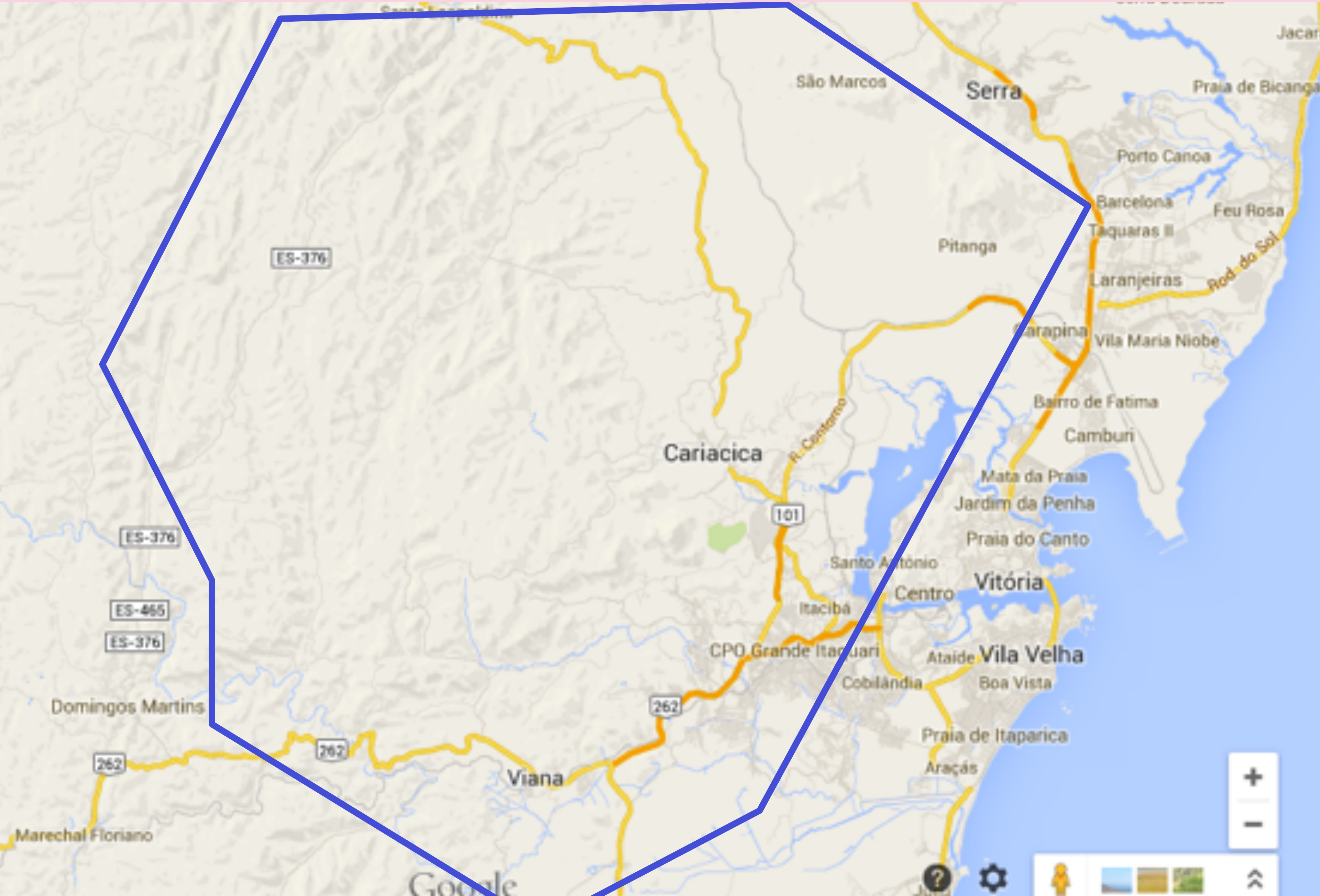
Surface Detector

1660 Cherenkov stations, in a grid of 1.5 km

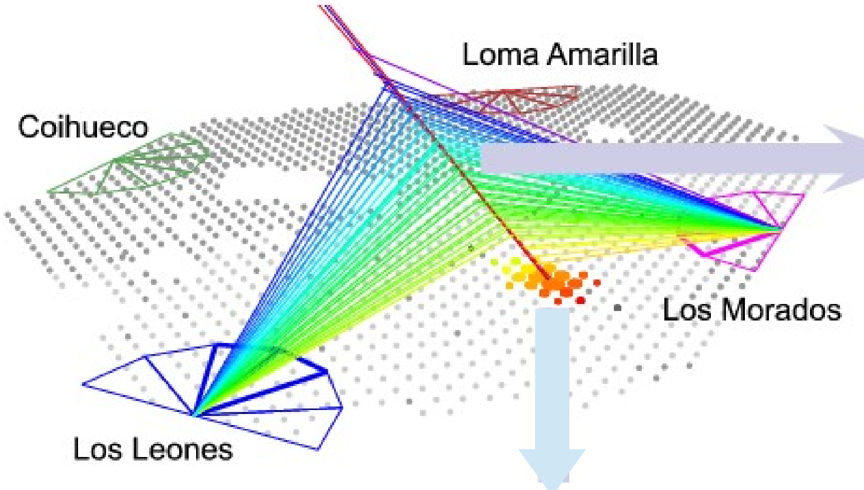
17 countries, ~ 500 physicists

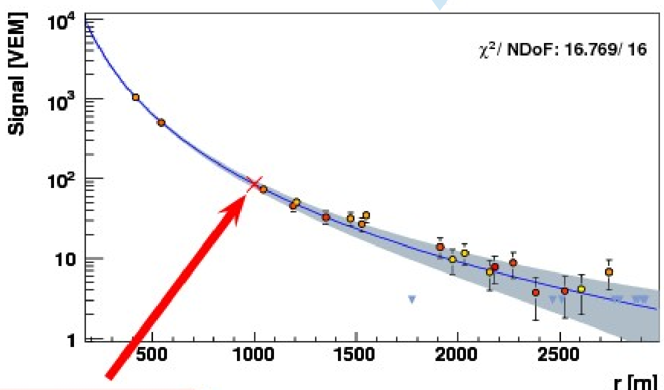
Hybrid detector: improve precision and reduce dependence on models

Pierre Auger Observatory in Vitória



Detecting UHECRs





S_{1000}

$E_{\mathrm{surface}} = f(S_{1000}, \theta)$

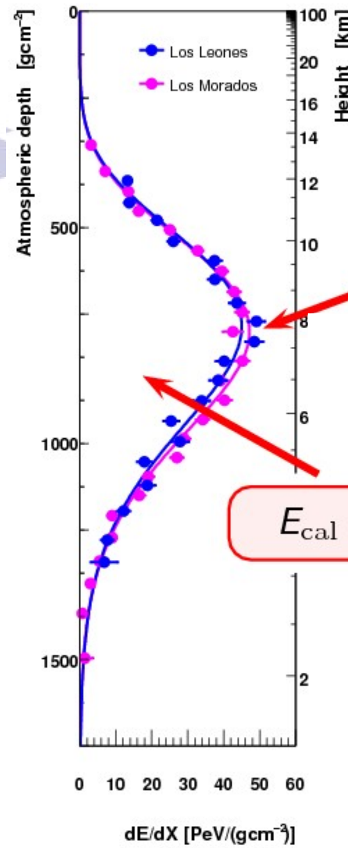
Surface Detector

Sample shower particles at ground

★100% duty cycle (statistics

★Energy threshold (full eff.) 3 EeV

★Geometrical aperture (no MC, no mod.)



Fluorescence Detector

UV photons (4 ph/particle/m) emitted in the de-excitation of the atmospheric nitrogen

X_{max}

Direct measurement of X_{max} (mass composiition)

$E_{\mathrm{cal}} = \int \mathrm{d}X \, \frac{\mathrm{d}E}{\mathrm{d}X}$

★Calorimetric energy meas. (model independent)

★10% duty cicle (moonless)

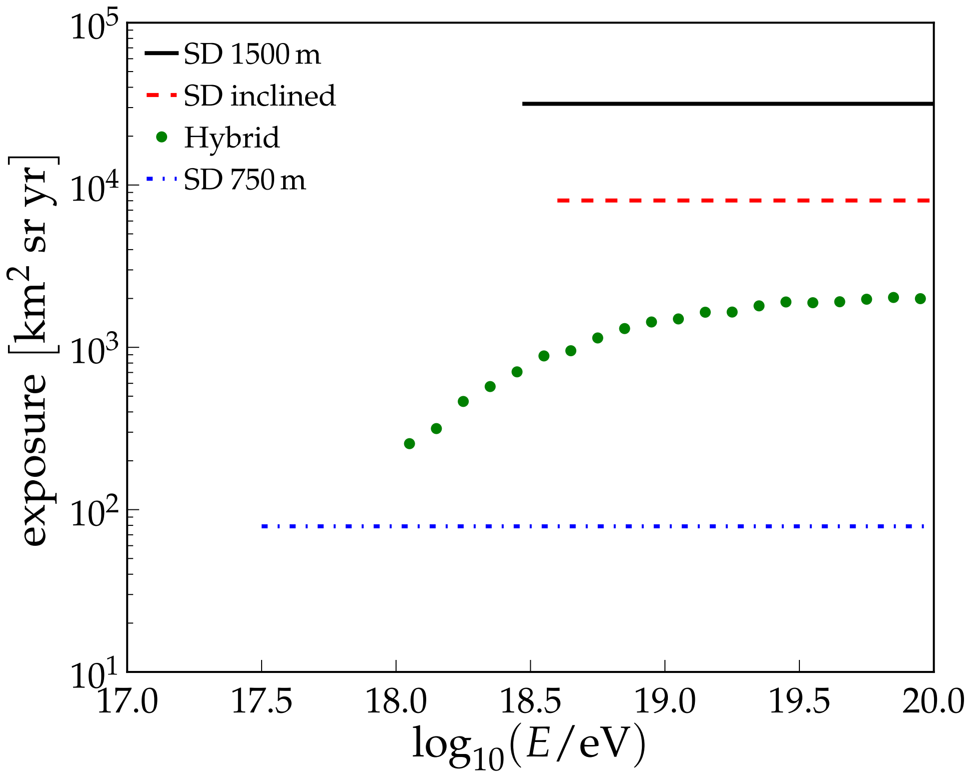
★lower energy threshold

“Golden hybrid” data sample:

★detector cross-calibration

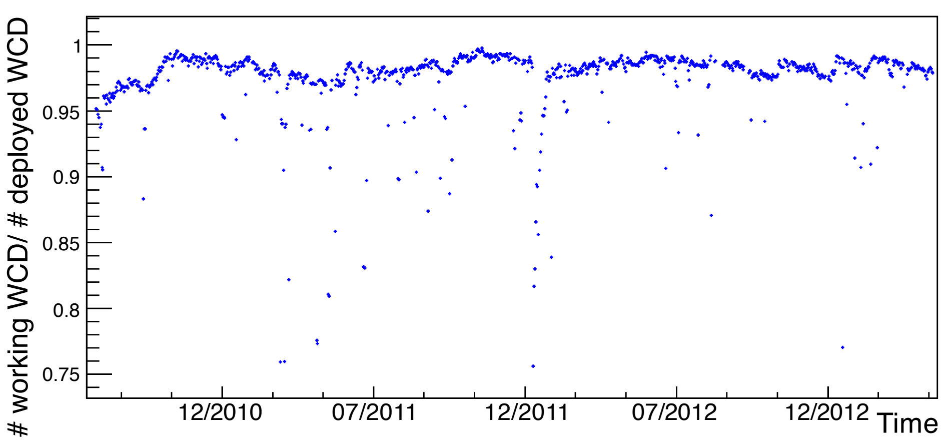
★systematics , cross-checks, etc

Detector Performance



32000 km^2 sr yr
about **5000** km^2 sr yr
each year

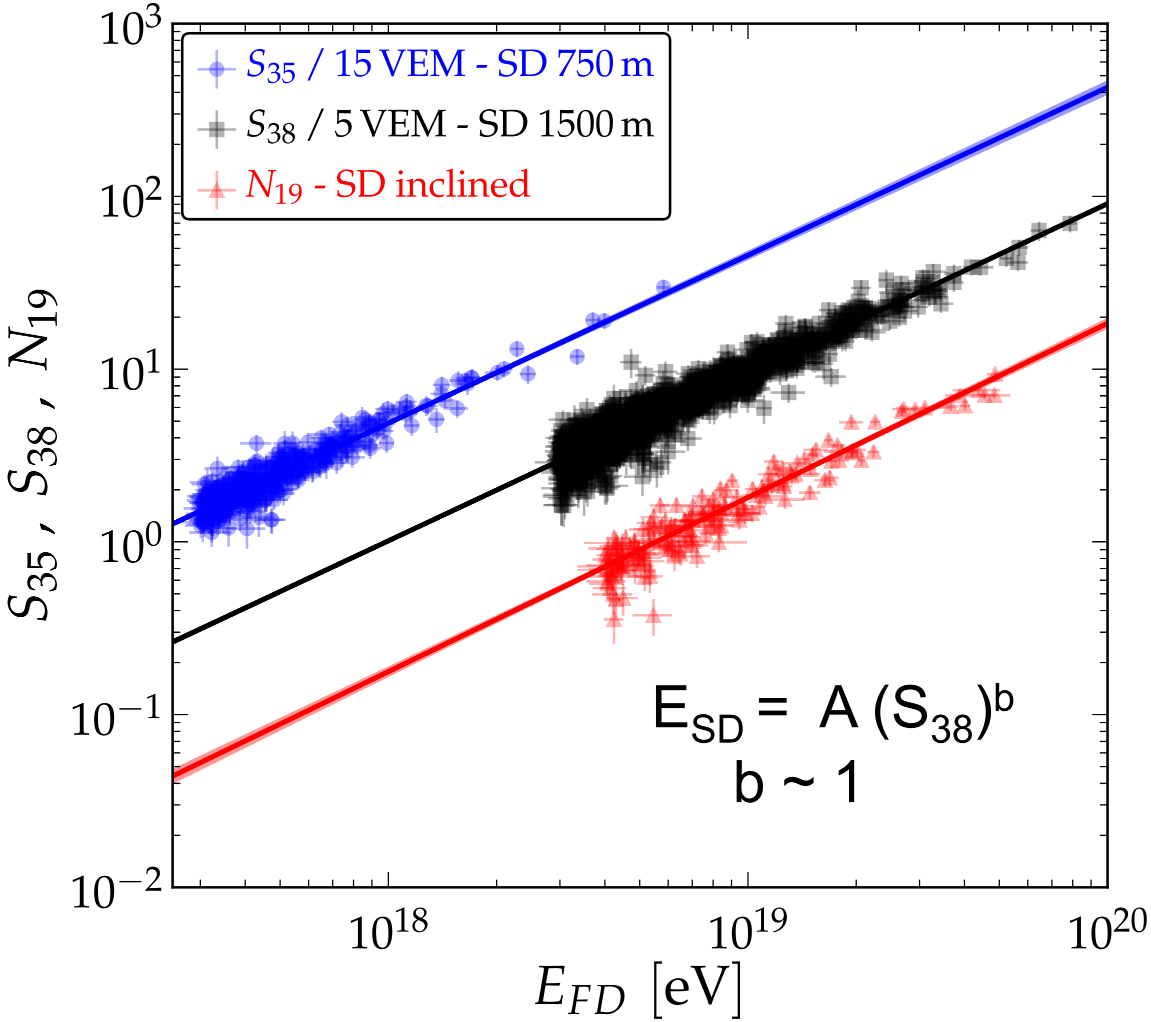
The SD exposures are illustrated only for the energy range of **full trigger efficiencies**.

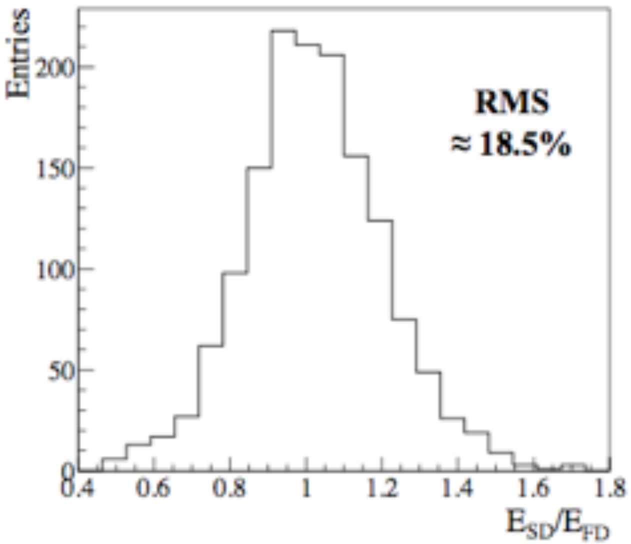


Number of **active WCDs** normalised to the nominal number of WCDs in the array, as a function of time

Bonifazi for Auger Collab, ICRC 2013

Auger energy measurements





SD energy resolution < 12% above 10 EeV

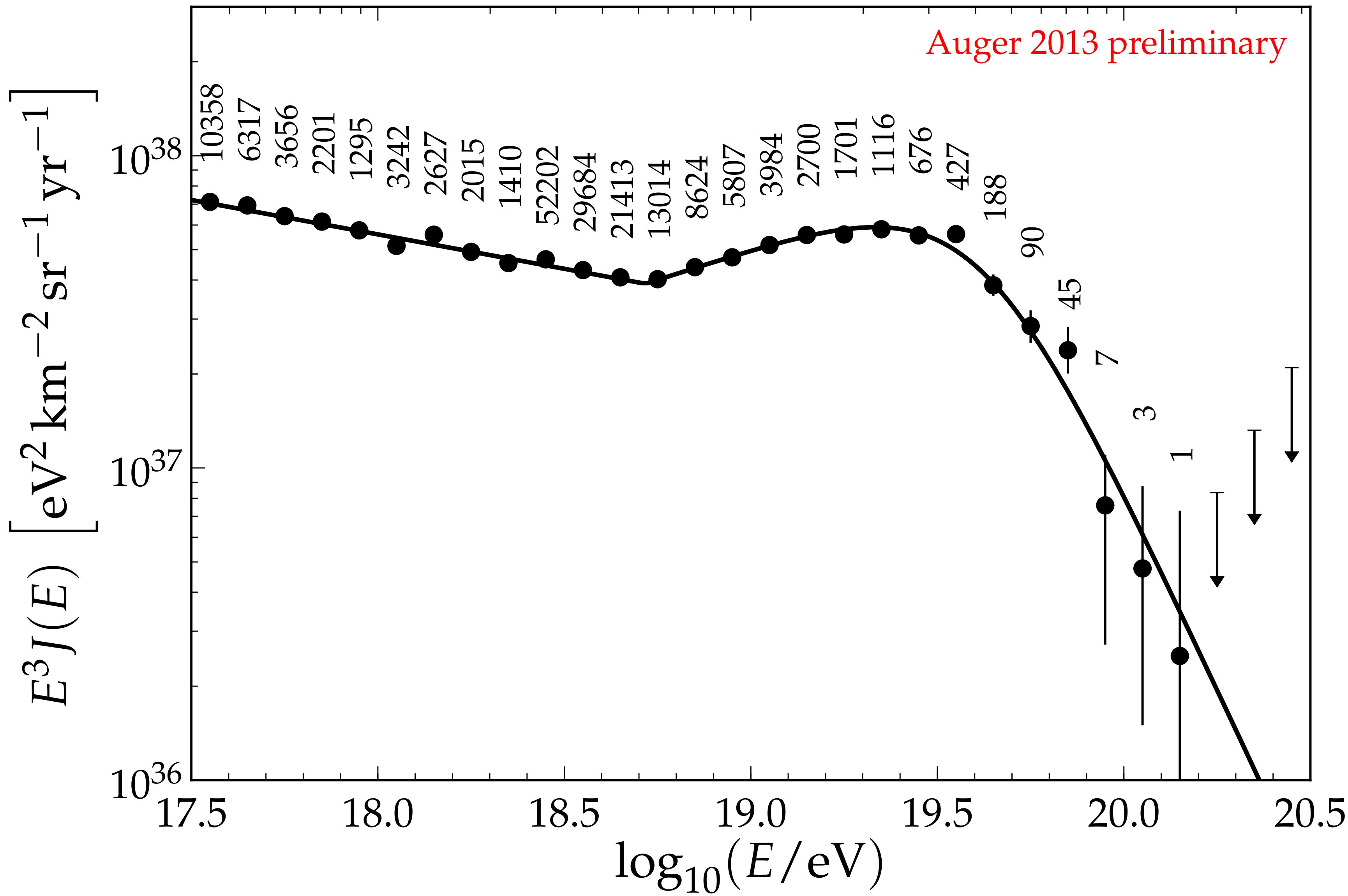
SD angular resolution < 1° above 10 EeV

Energy calibrations to FD energies for all three SD measurements from the energy estimators

Auger combined spectrum

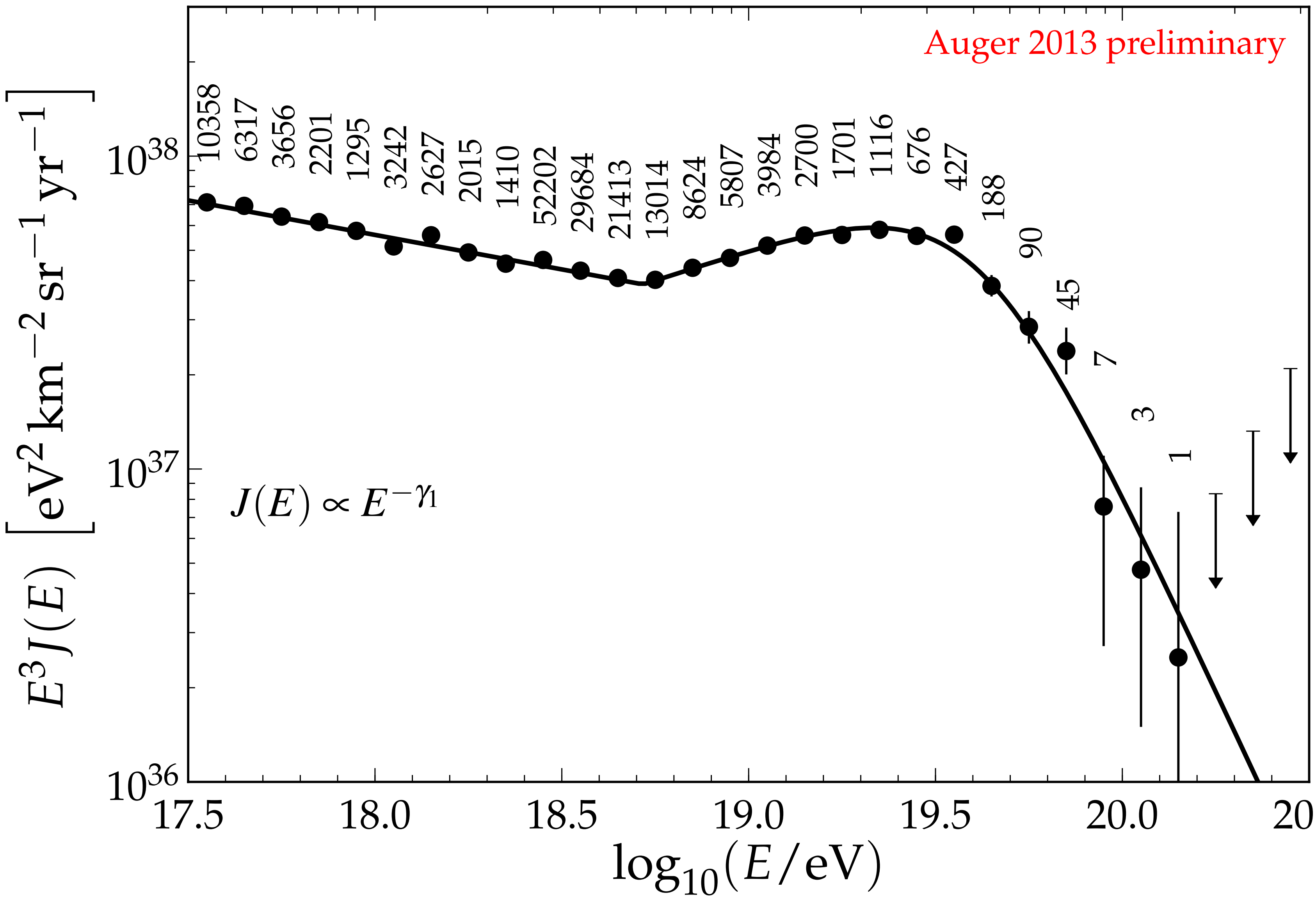
Schulz for Auger Collab, ICRC 2013

Auger combined spectrum



Schulz for Auger Collab, ICRC 2013

Auger combined spectrum



Schulz for Auger Collab, ICRC 2013

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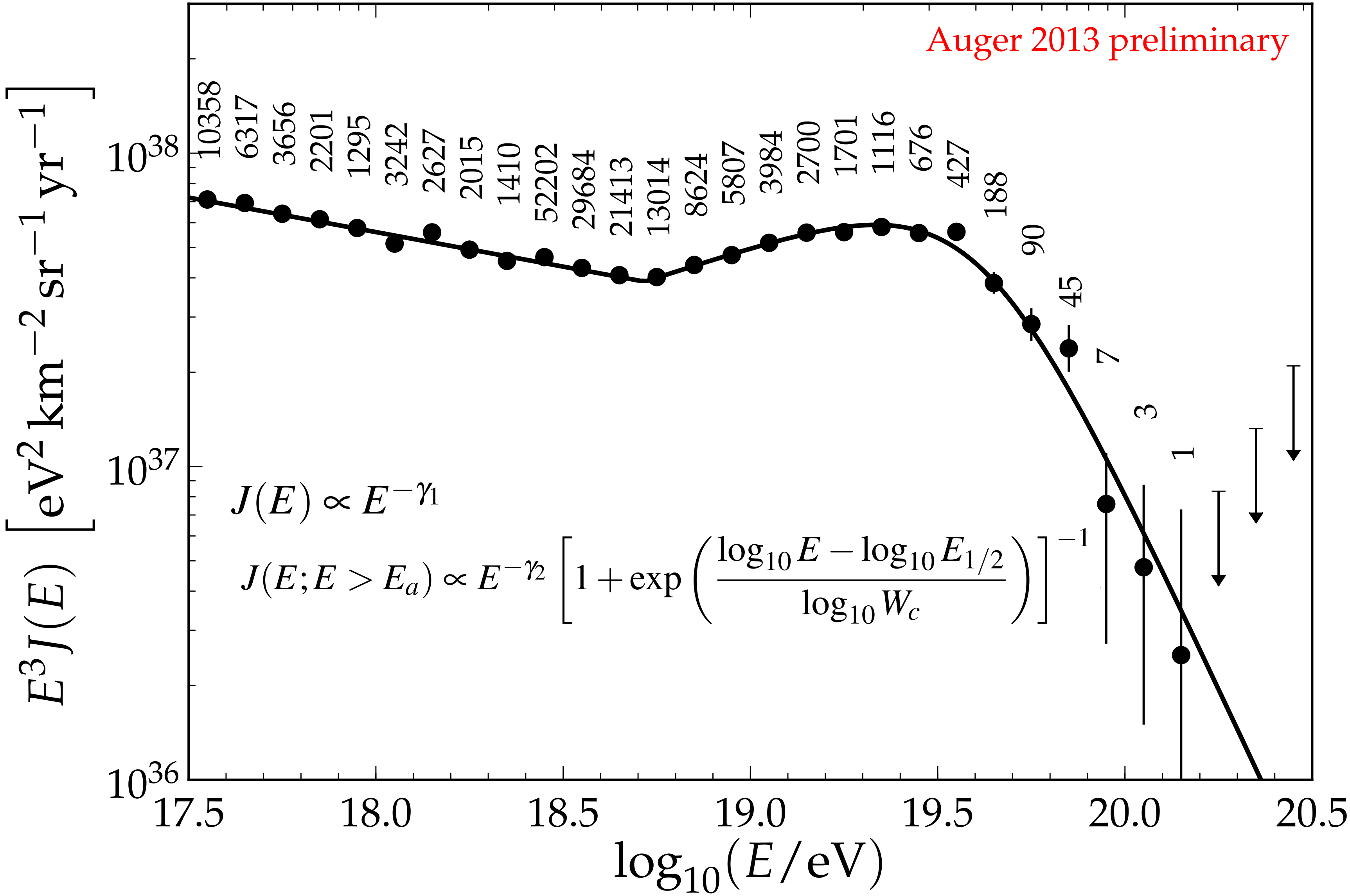

Schulz for Auger Collab, ICRC 2013

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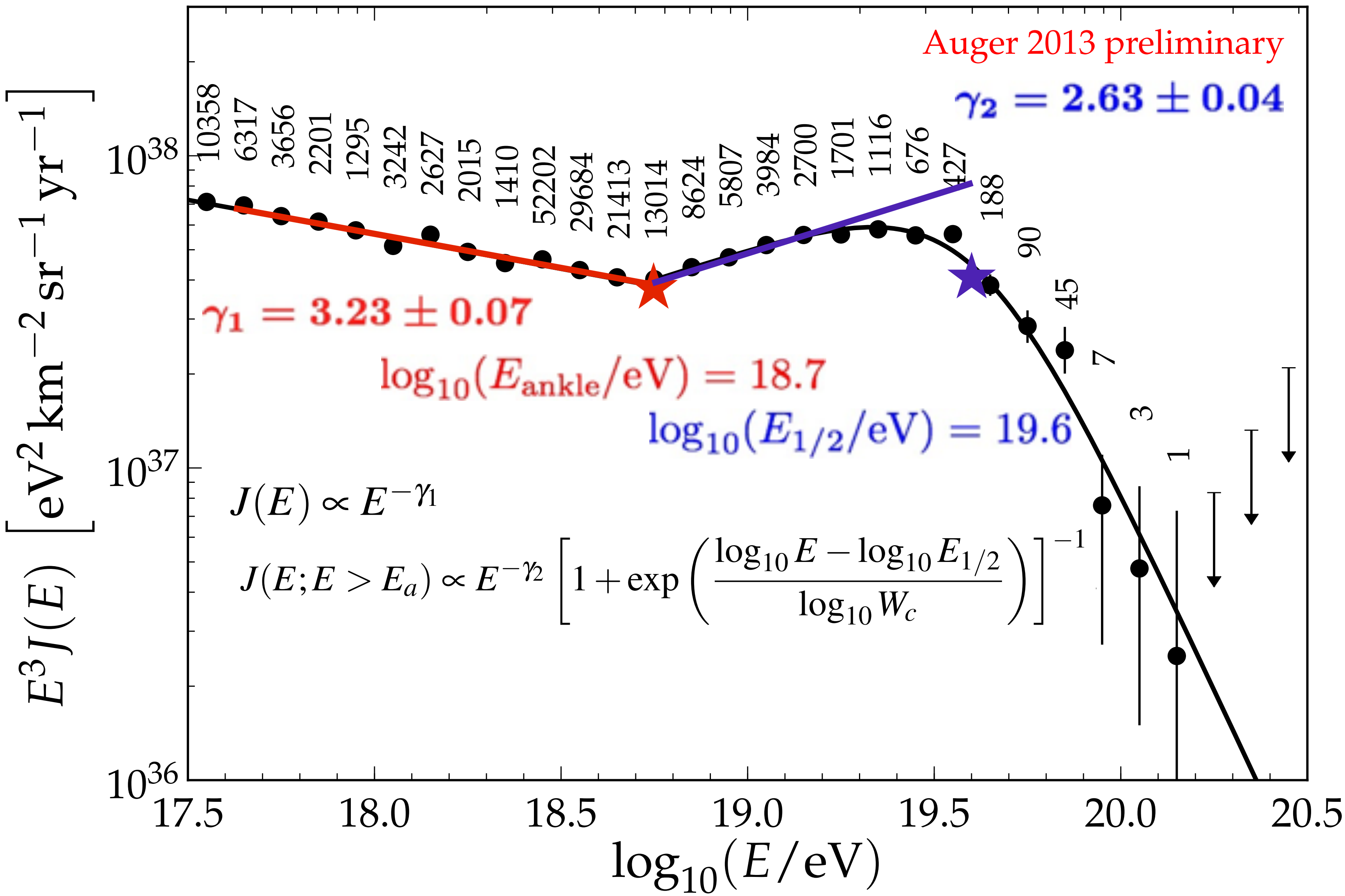
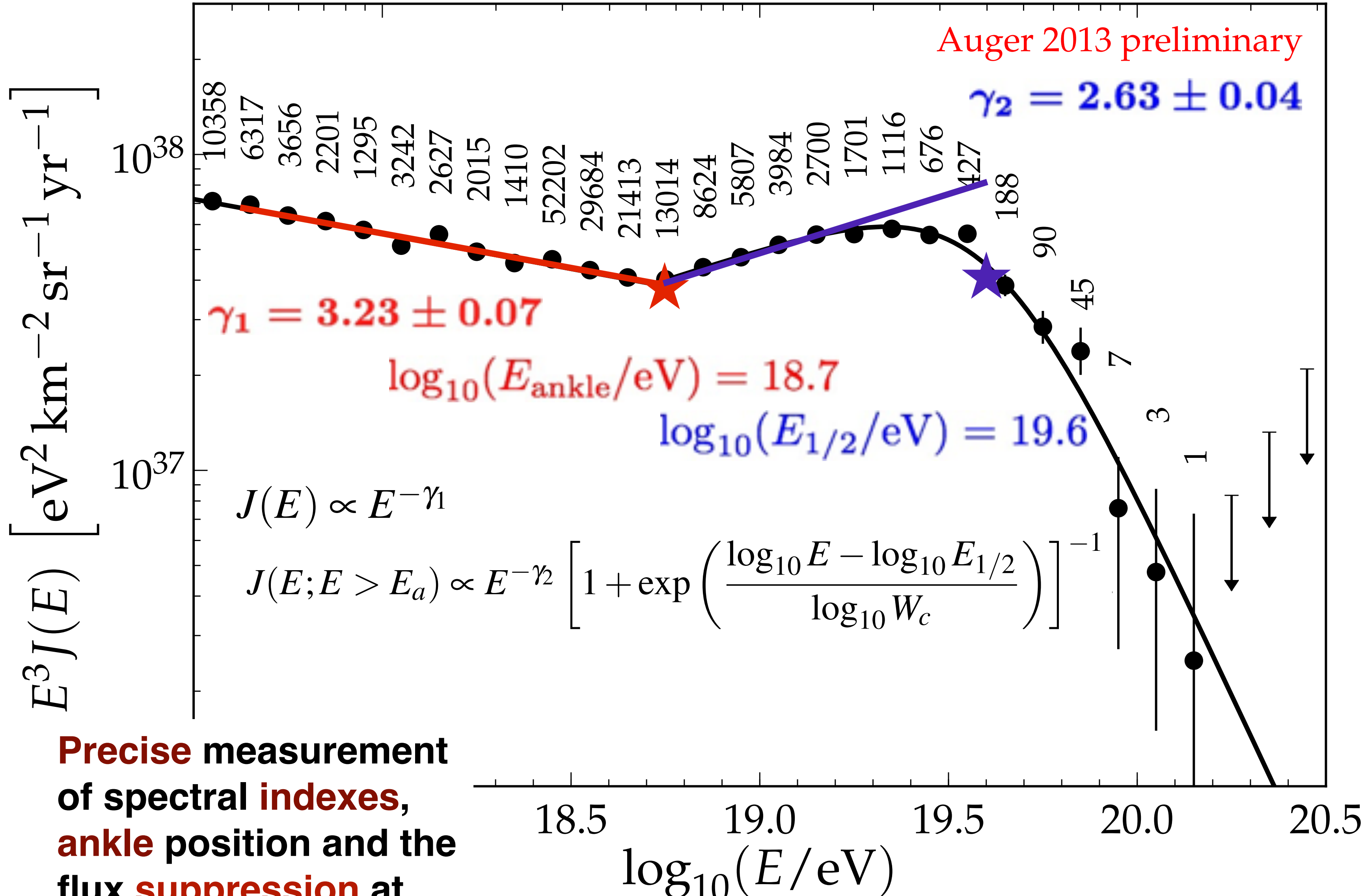


Schulz for Auger Collab, ICRC 2013

Auger combined spectrum



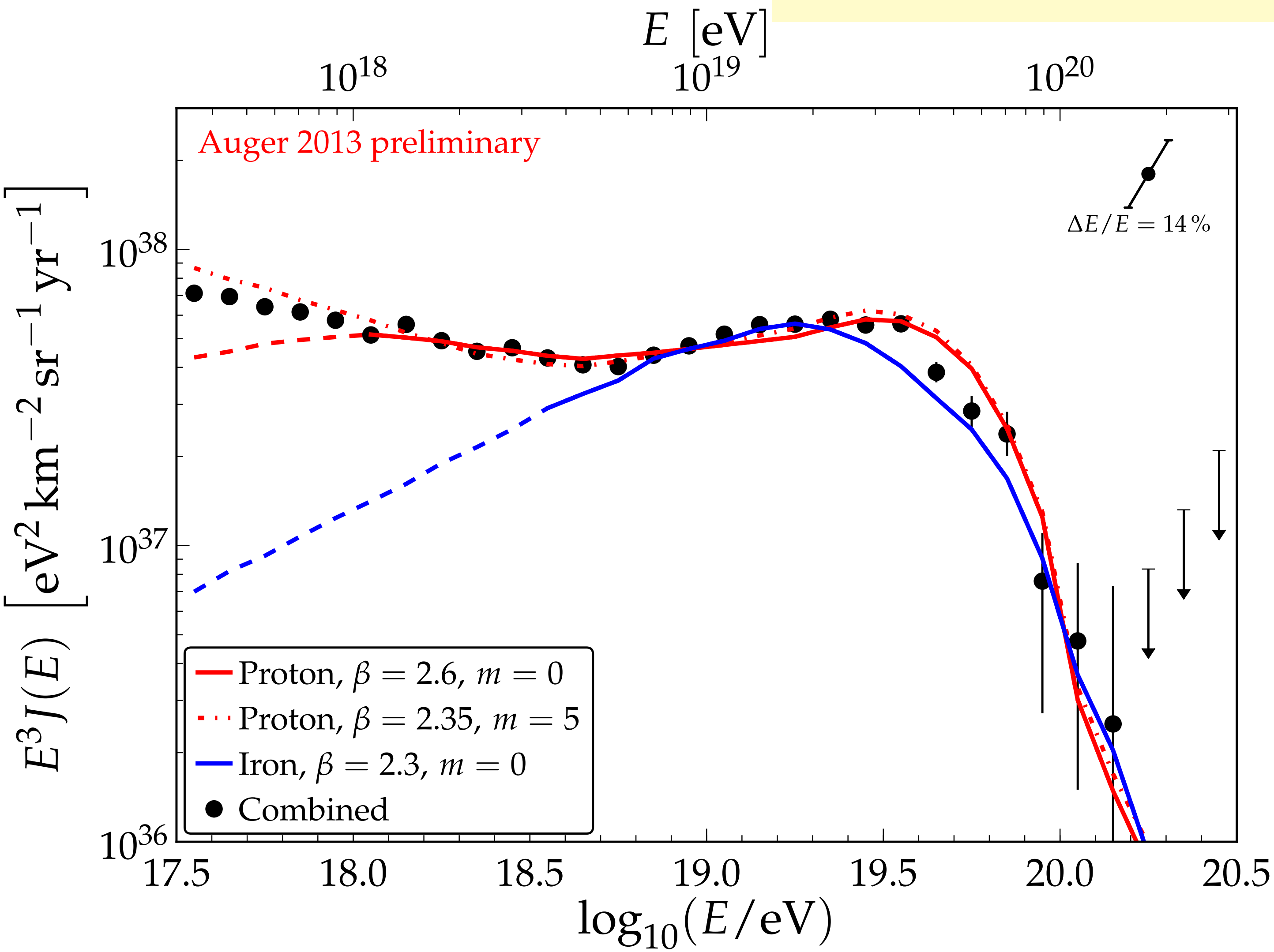
Precise measurement of spectral indexes, ankle position and the flux suppression at highest energies

Schulz for Auger Collab, ICRC 2013

Auger combined spectrum

GZK or **sources** running out of **power**?

$$\phi(E) \propto E^{-\beta} \cdot (1+z)^{m}$$

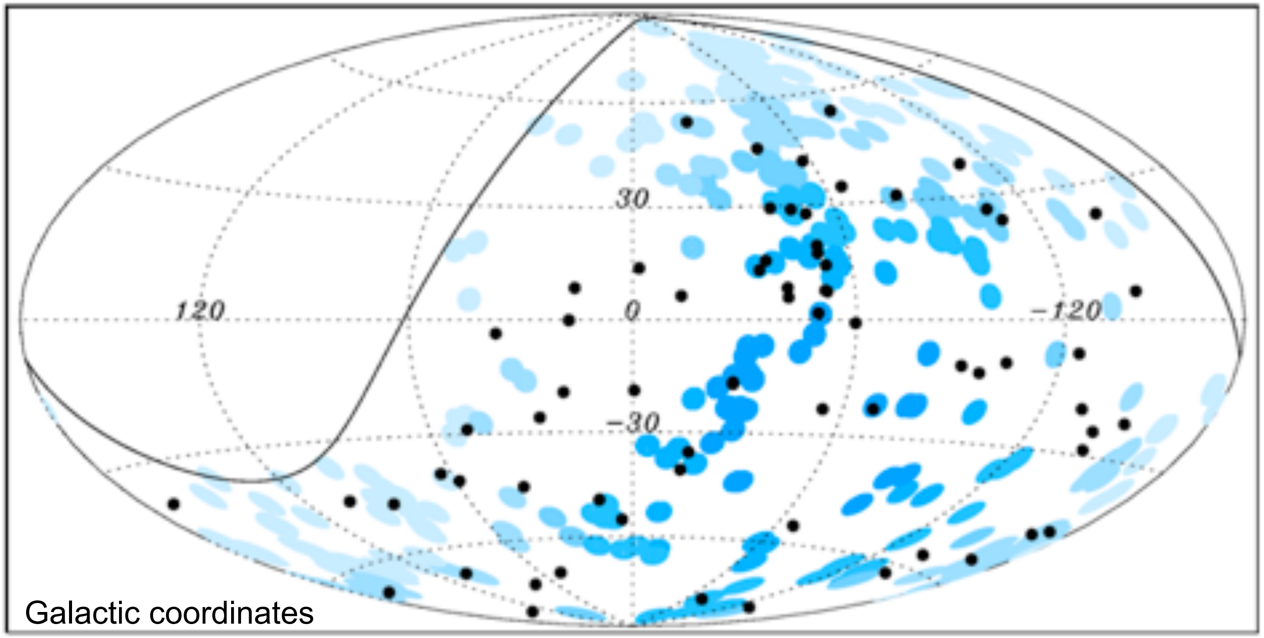


Simple models: vary particle type, source injection spectrum index and source evolution fit the data surprisingly well.

Constraining models need composition measurement.

Anisotropy

Auger High Energy Sky 2010
Aitoff projection galactic coordinates



blue dots: AGN
position within **3.1°**
black dot: CR

84 events
E > 5.7 · 10^{19} eV

★ Correlation with AGN as tracers of extragalactic sources 33±5 %, p= 0.006

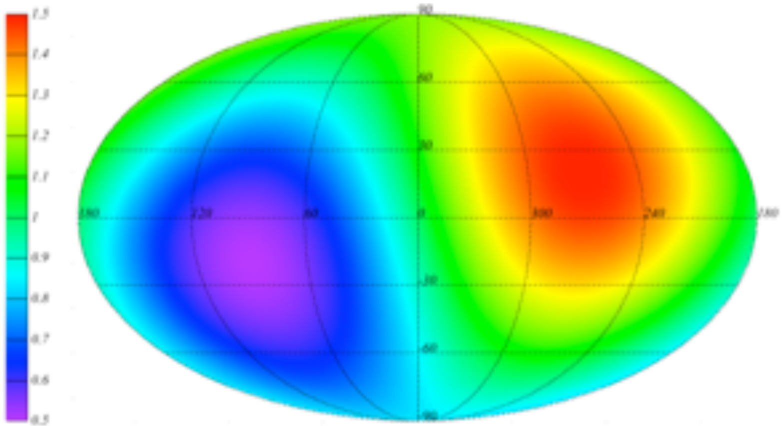
★ 21% expected for an isotropic distribution

★ 2007 correlation 68%...

★ Isotropy of UHECR rejected at 99% CL

Auger Collab, Astrop. Phys. 34 (2010)
K. Kampert , Proceedings for ICRC 2011: highlight Auger talk

Large scale anisotropy

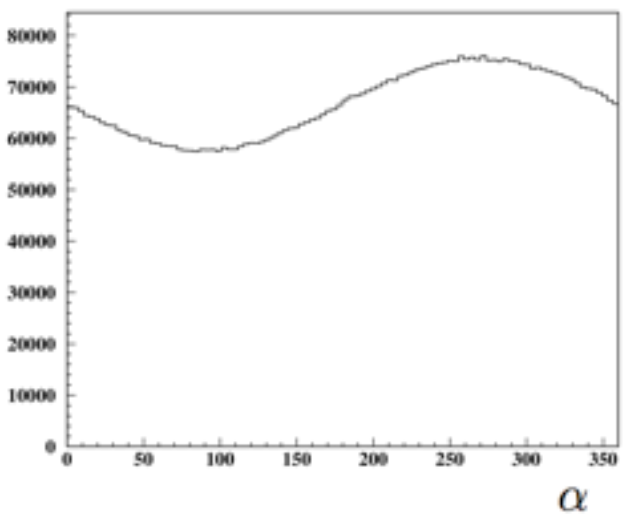


Multipole expansion of the CR flux

$$\Phi(\delta', \alpha) = \sum_{l,m} a_{lm} Y_l^m(\delta', \alpha) \qquad \delta' = \pi/2 - \delta$$

$$\Phi(\alpha, \delta) = \frac{\Phi_0}{4\pi}\left(1 + d\,\hat{d}\cdot\hat{n}\right) \qquad l = 1 \quad \text{dipole}$$

(α_d, δ_d)



Rayleigh analysis

First harmonic

$$\Phi(\alpha) = \sum_N c_i e^{in2\pi\alpha} = \Phi_0 + (1 + r\cos(\alpha - \phi) + r'\cos(2(\alpha - \phi')) + \ldots)$$

$$r = \left|\frac{\langle\cos\delta\rangle d_\perp}{1 + \langle\sin\delta\rangle d_\parallel}\right| \qquad \alpha_d$$

★ If cosmic rays have a **galactic** origin, their escape from the Galaxy might generate a **dipolar large-scale pattern** as seen from the Earth.

★ For **isotropic extragalactic** cosmic rays, a **dipole** anisotropy may exist due to our **motion** with respect to the frame of extragalactic isotropy.

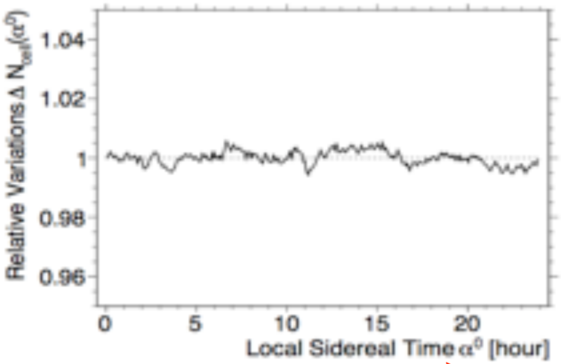
Courtesy P. Privitera

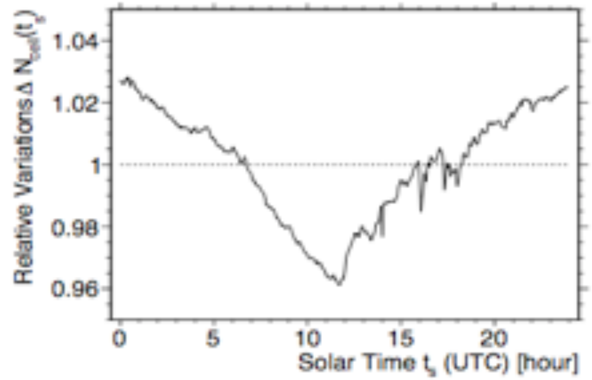
Subtle detector effects

exposure

$$\frac{dN_{obs}}{d\Omega\, dE\, dt} = \Phi(\mathbf{n}, E)\, \omega(\mathbf{n}, E)$$

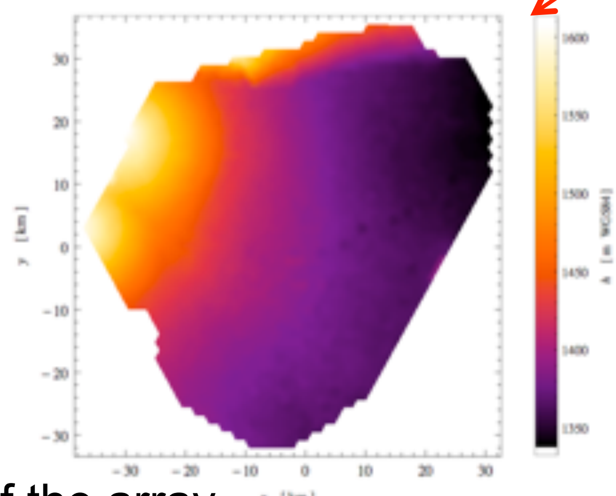
To detect a % level anisotropy, subtle detector effects must be kept under control





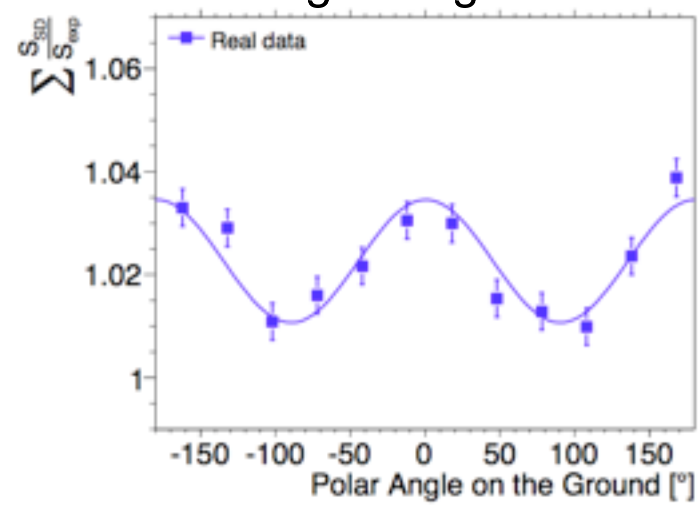
$$\omega(t, \theta, \phi, S_{38^\circ}) = n_{\text{cell}}(t) \times a_{\text{cell}} \cos\theta \times \epsilon(S_{38^\circ}, \theta, \phi),$$

Examples

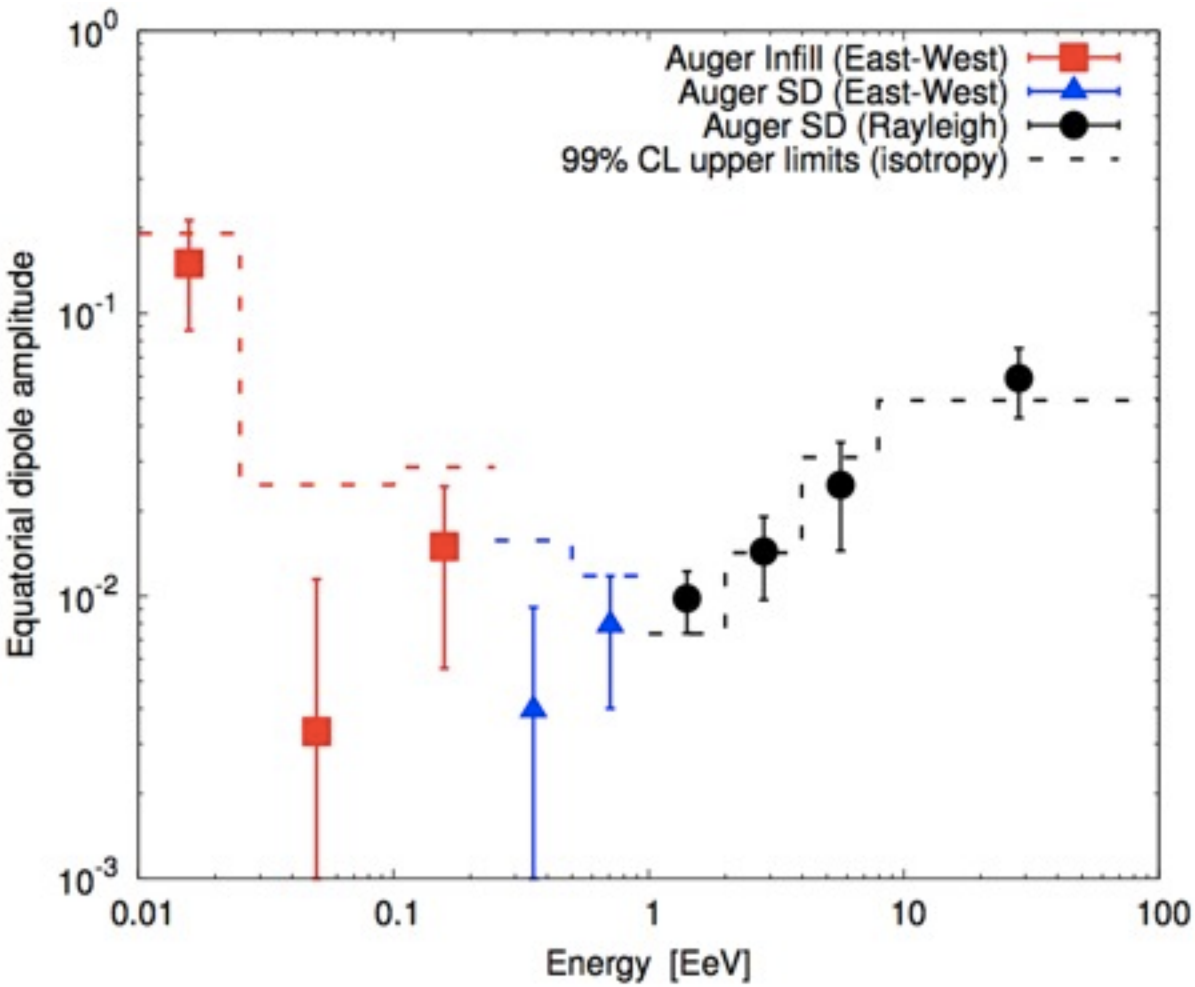


Tilt of the array

geomagnetic field



Dipole amplitude



Three energy bins above 1 EeV with probability < 1% to come from isotropy

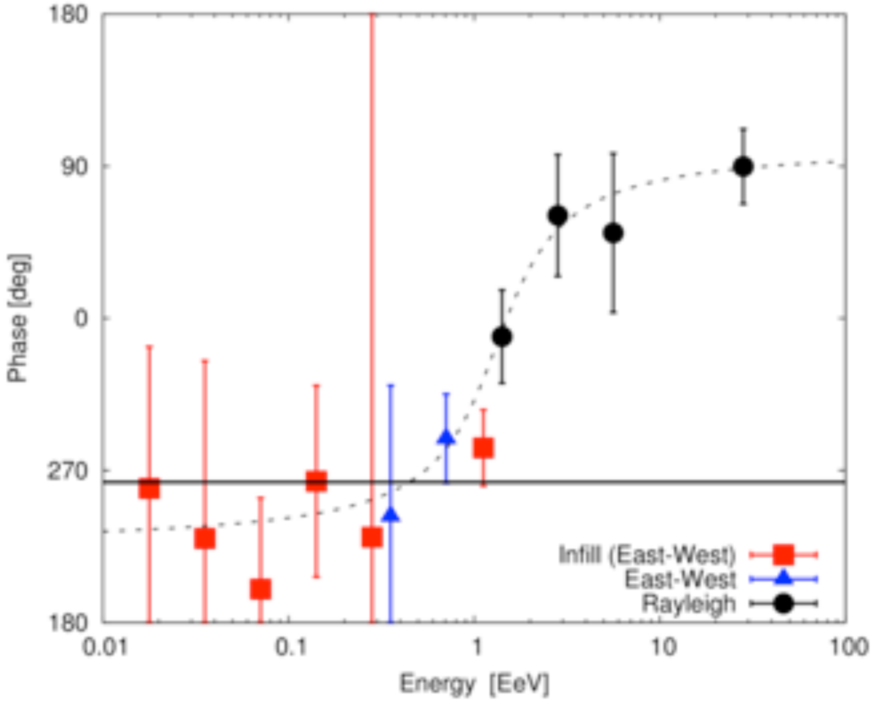
★ We can see **hints** for large scale anisotropies

★ important to further scrutinize it with **independent** data;

Sidelnik for Auger Collab, ICRC 2013

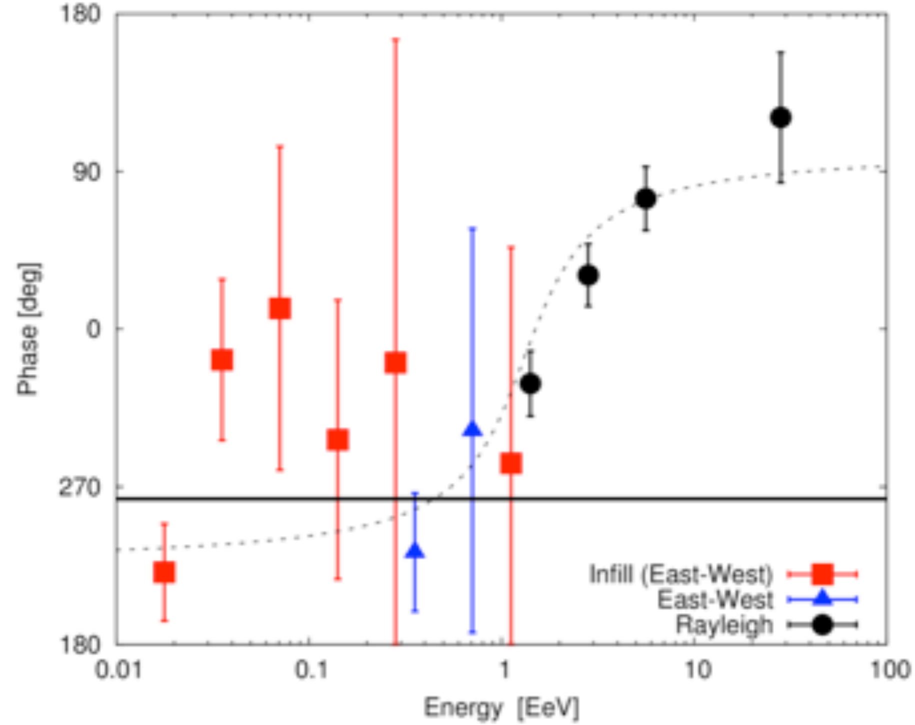
Dipole phase

Data up to Dec 2010 (April 2011)



New data

Prescription status:
18 more months to go



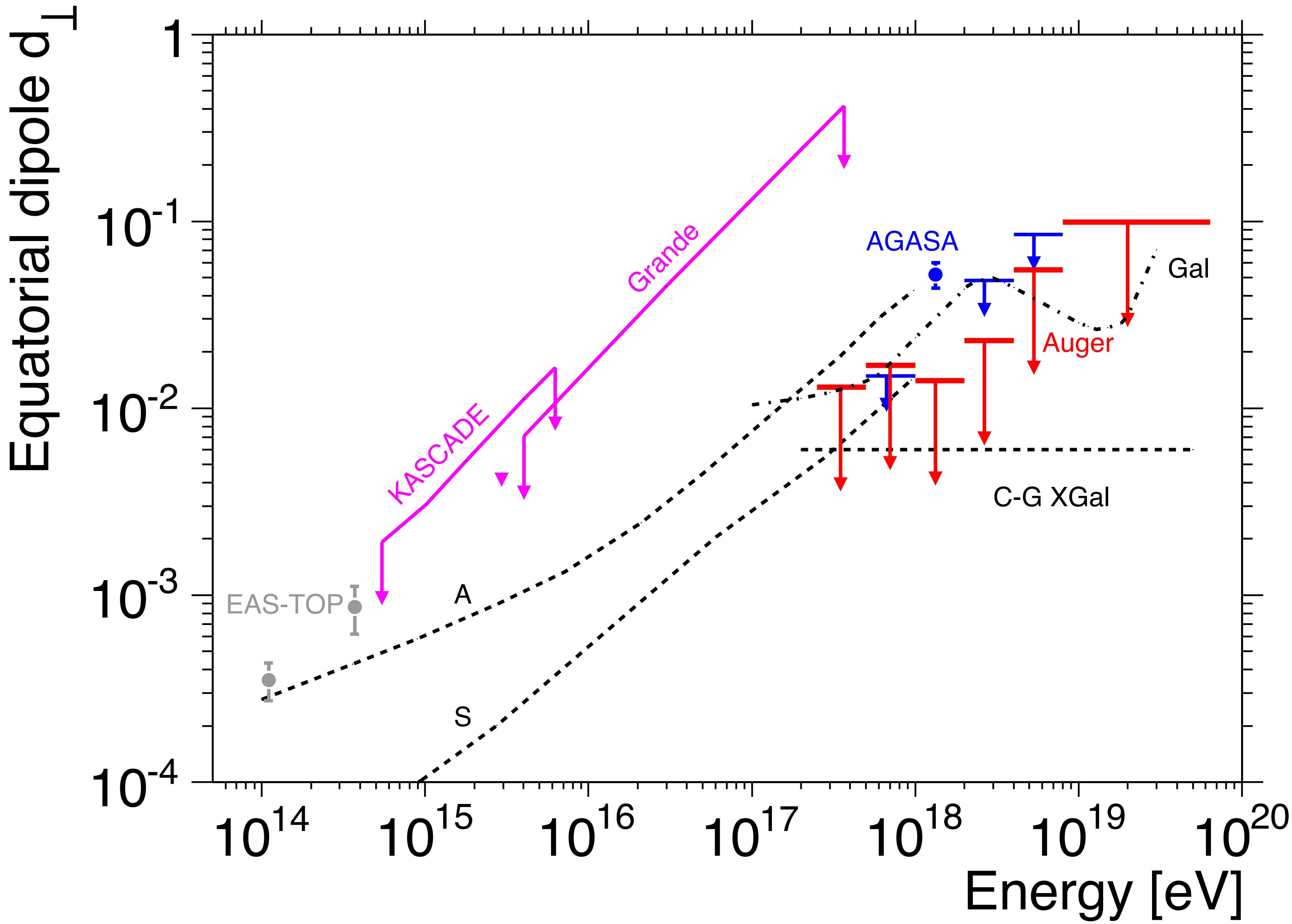
★For isotropic distribution, expect uniform distribution, uncorrelated in energy

Prescription to check with new data at 99% CL: constancy of phase at E<1 EeV with the Infill data, Transition in phase at high energies

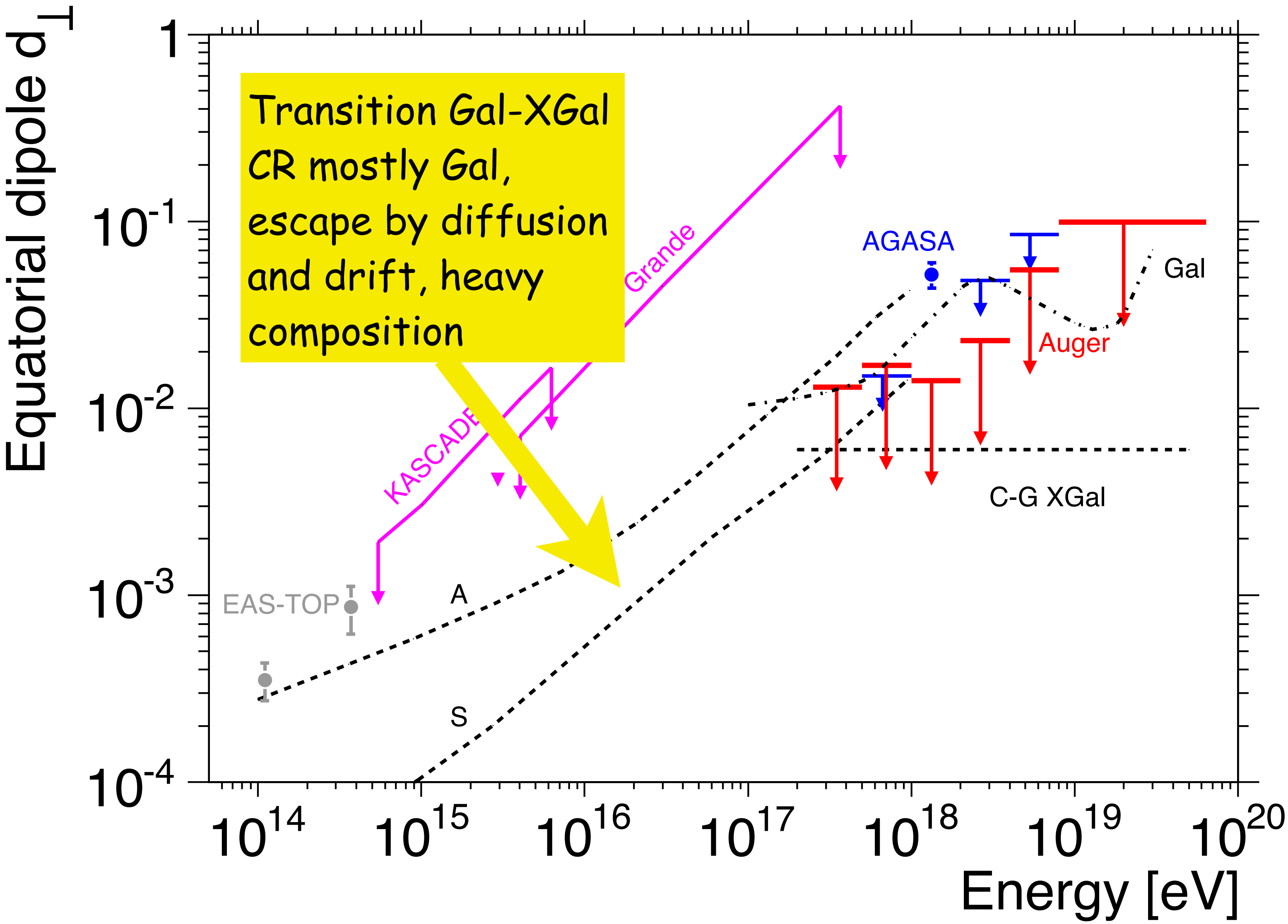
NOTE: galactic center $\alpha = 268.4^o$

Sidelnik for Auger Collab, ICRC 2013

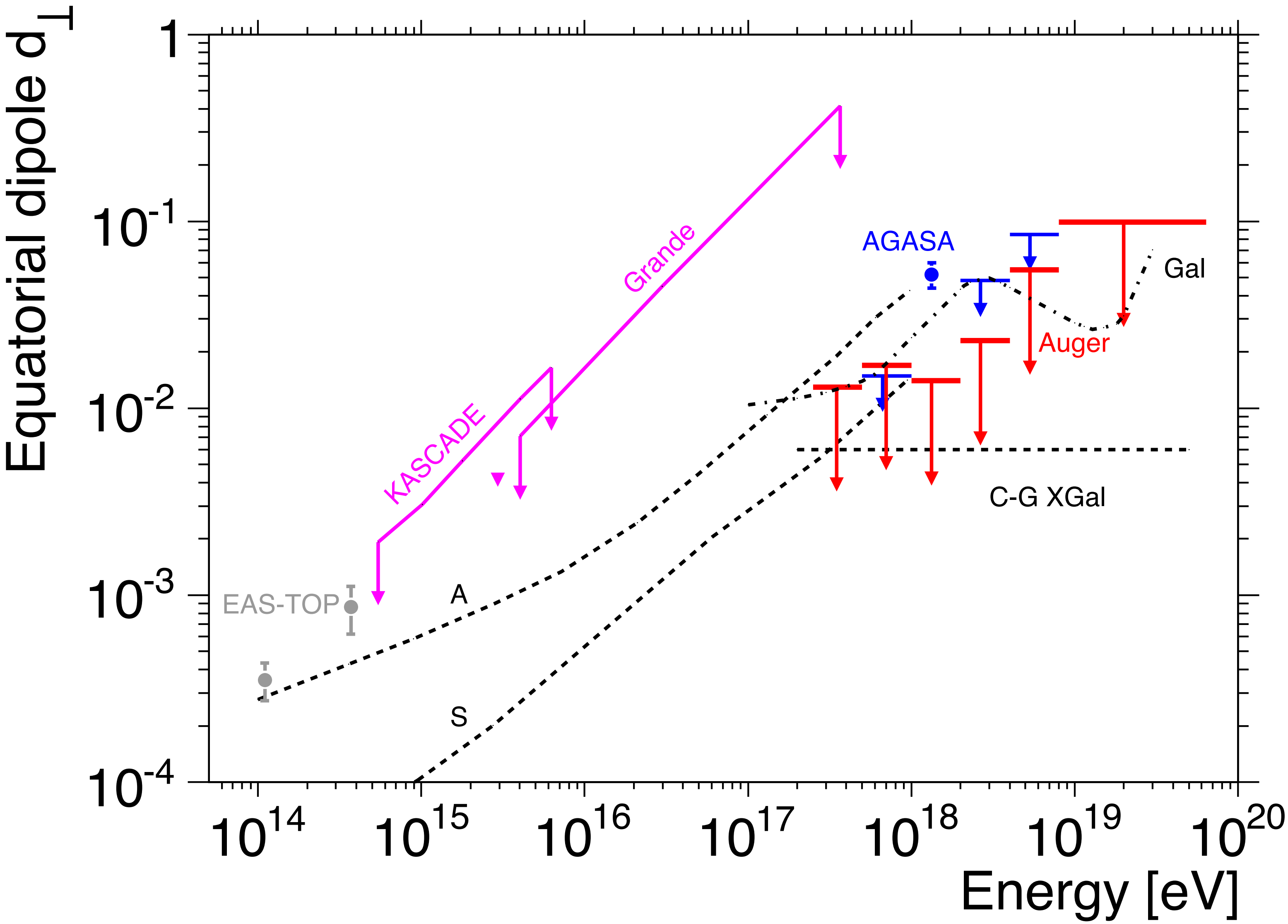
Dipole amplitude and models



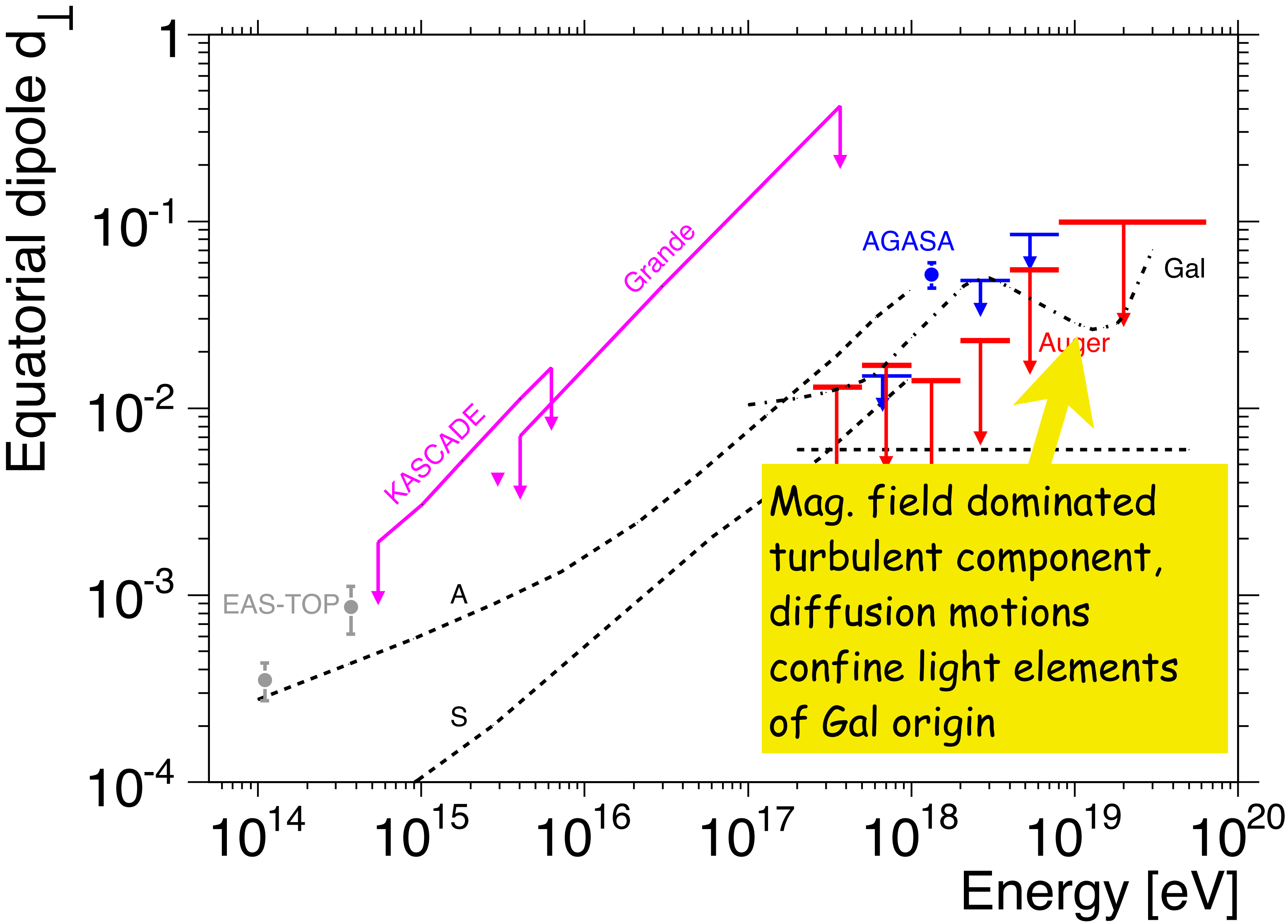
Dipole amplitude and models



Dipole amplitude and models



Dipole amplitude and models



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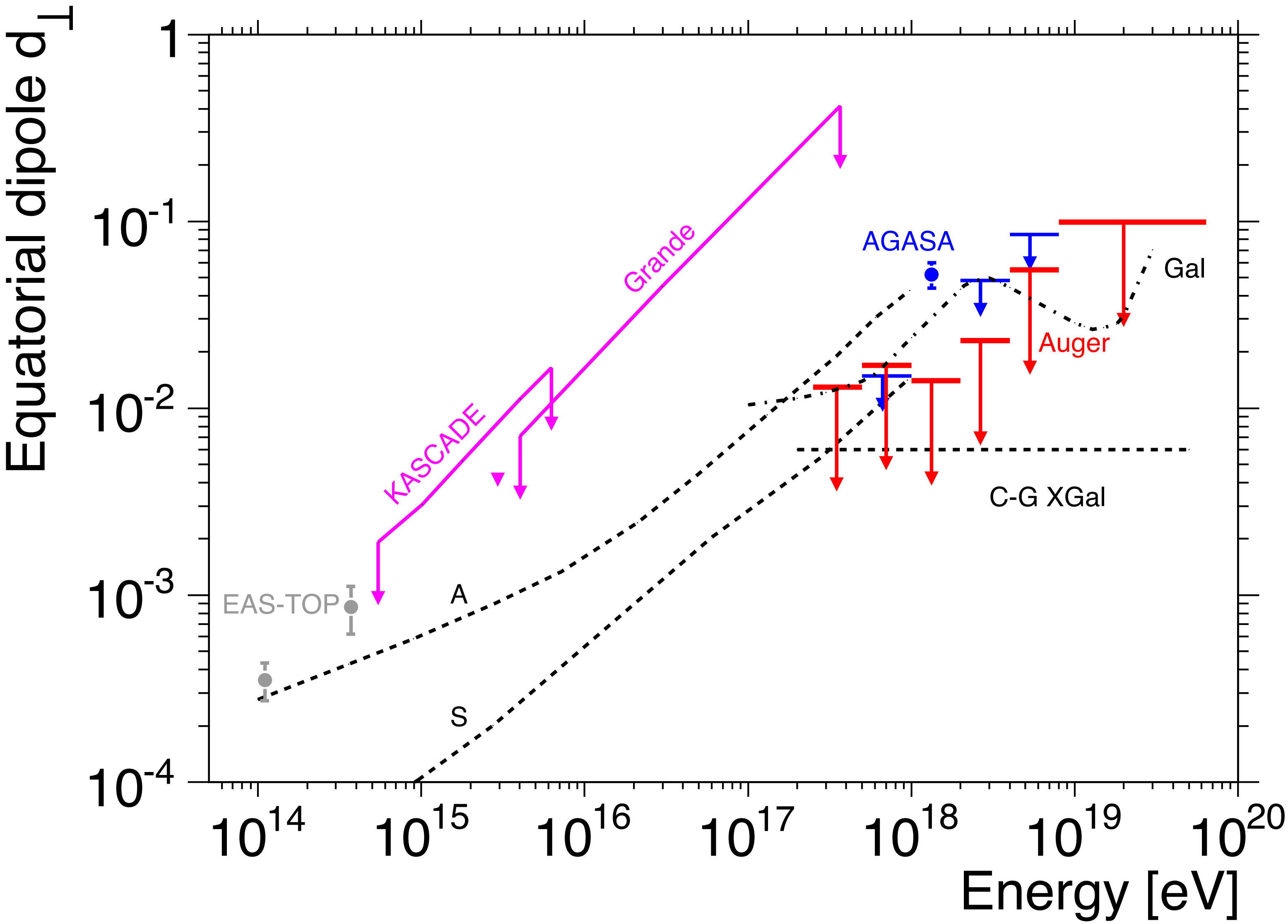

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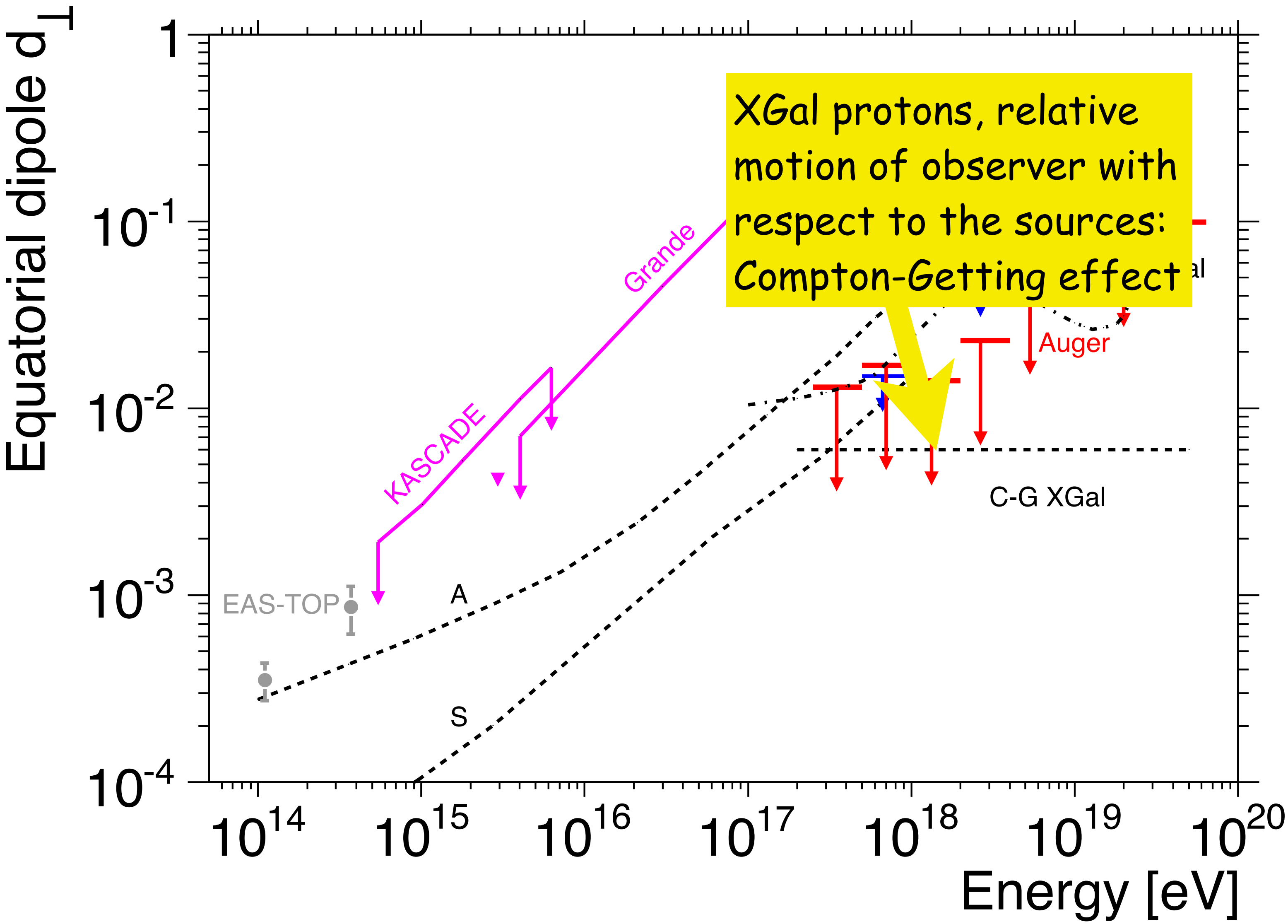
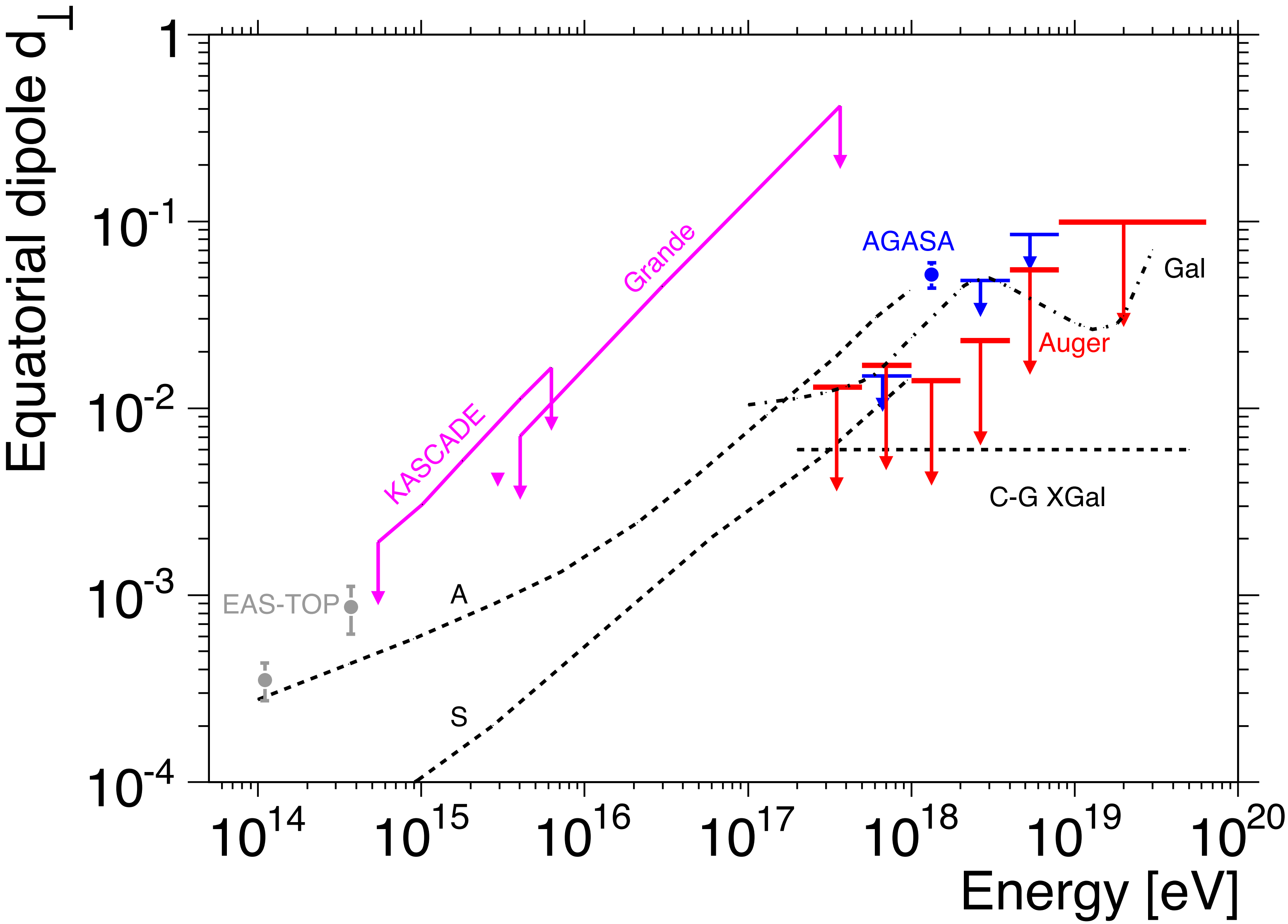


Dipole amplitude and models



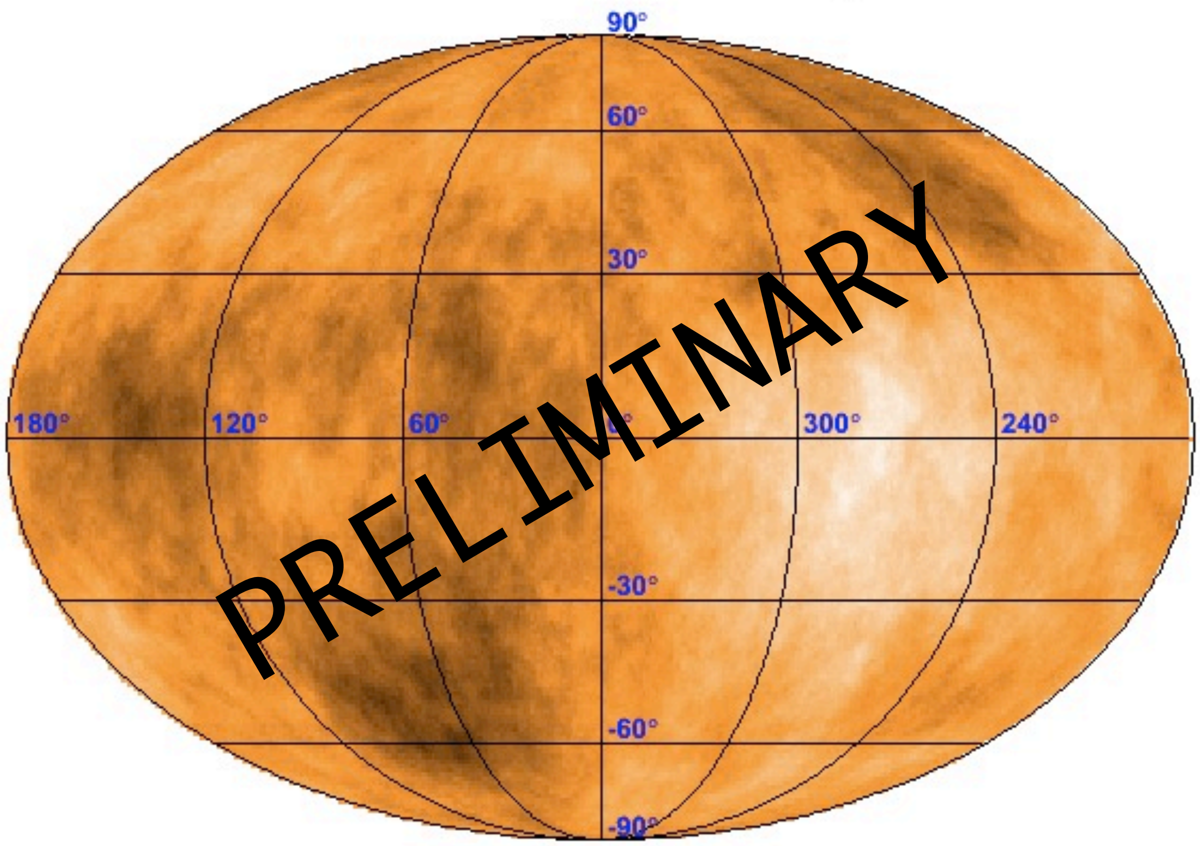
Full Sky Map E > 10 EeV

(30° smoothing)

Auger and Telescope Array joint analysis, ICRC, 2013 (Deligny)

N_{TA}~1800

N_{Auger}~10900



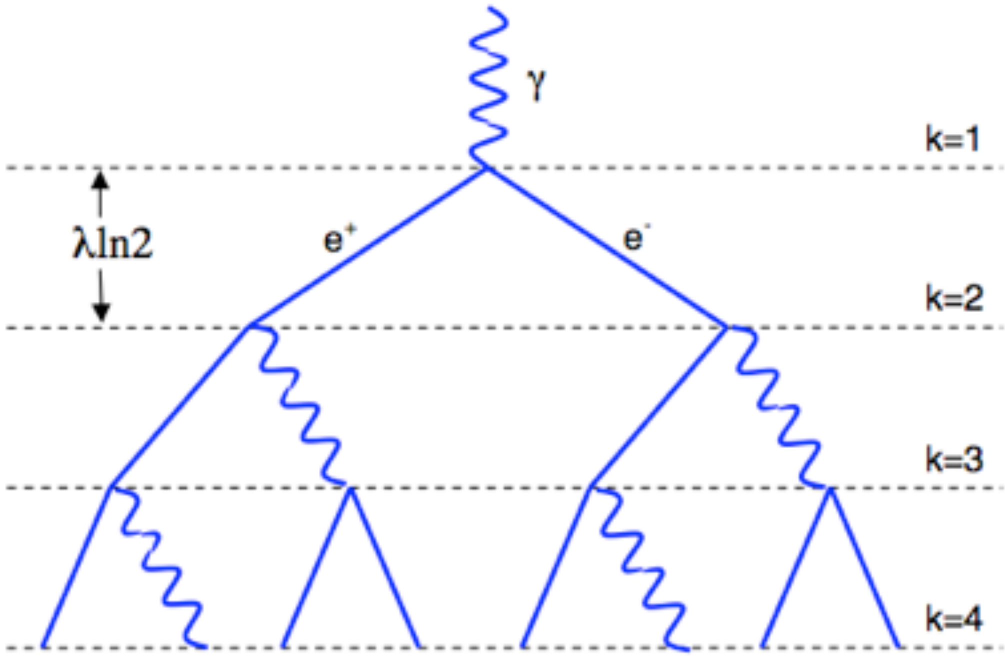
In the overlap :

N_{TA}~650

N_{Auger}~3400

Electromagnetic cascade

λ = 37g/cm^2
(radiation length)



After n generations

$$X = n\lambda$$

$$N_{part} = 2^n = 2^{X/\lambda}$$

$$E_{part} = \frac{E_0}{N_{part}}$$

Cascade stops when:

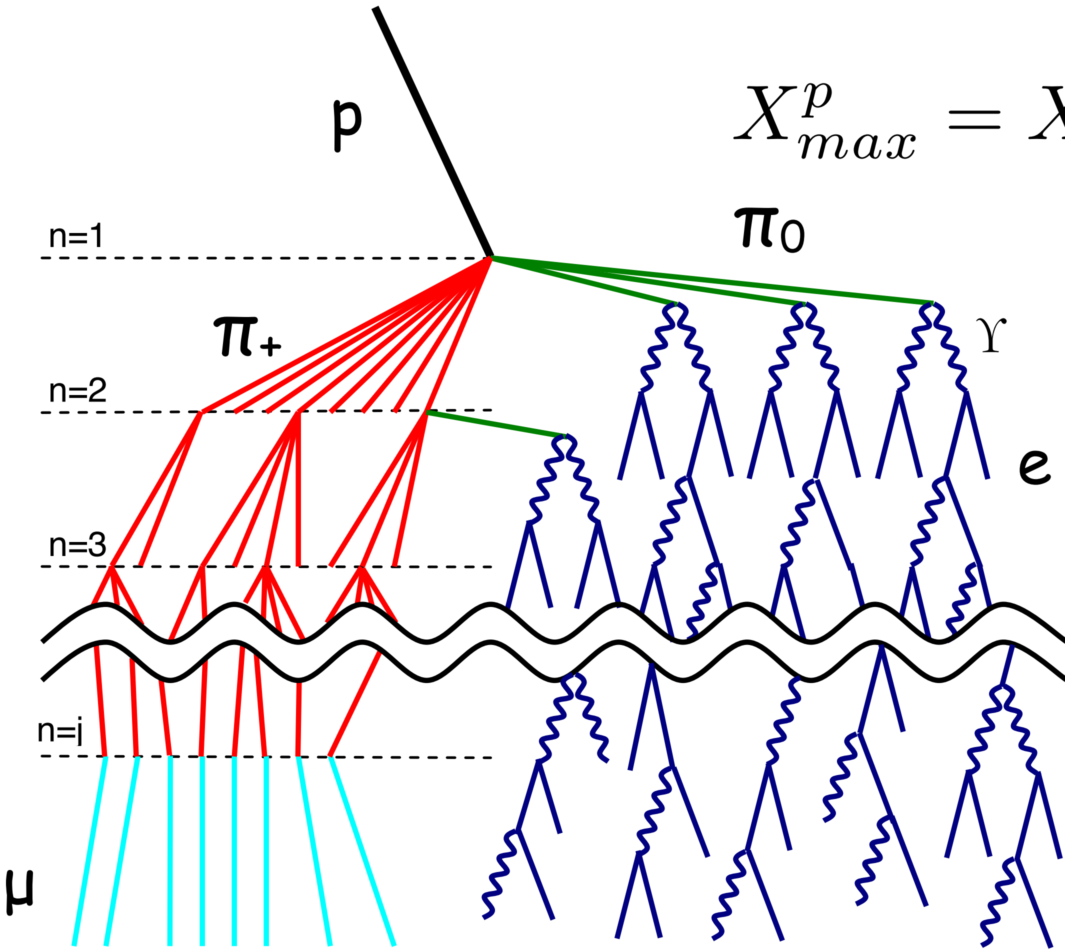
$$E_{part} < \epsilon_0 = 100 \text{ Mev}$$

$$N_{max} = \frac{E_0}{\epsilon_0}$$

$$X_{max} \sim \lambda \frac{ln(E_0/\epsilon_0)}{ln2}$$

Heitler, The Quantum Theory of Radiation ,3rd Ed., (1954), p.386.

Hadronic cascade



$$X^{p}_{max} = X_0 + \lambda \ln[E_0/(6N_\pi \epsilon_0)]$$

$$\frac{d\,X_{max}}{d\,\log E} = 62\ \mathrm{gm/cm^2}$$

Elongation rate

Good agreement with Monte Carlo simulations!

Matthews, Astropart. Phys. 22 (2005) 387

X_{max} observables

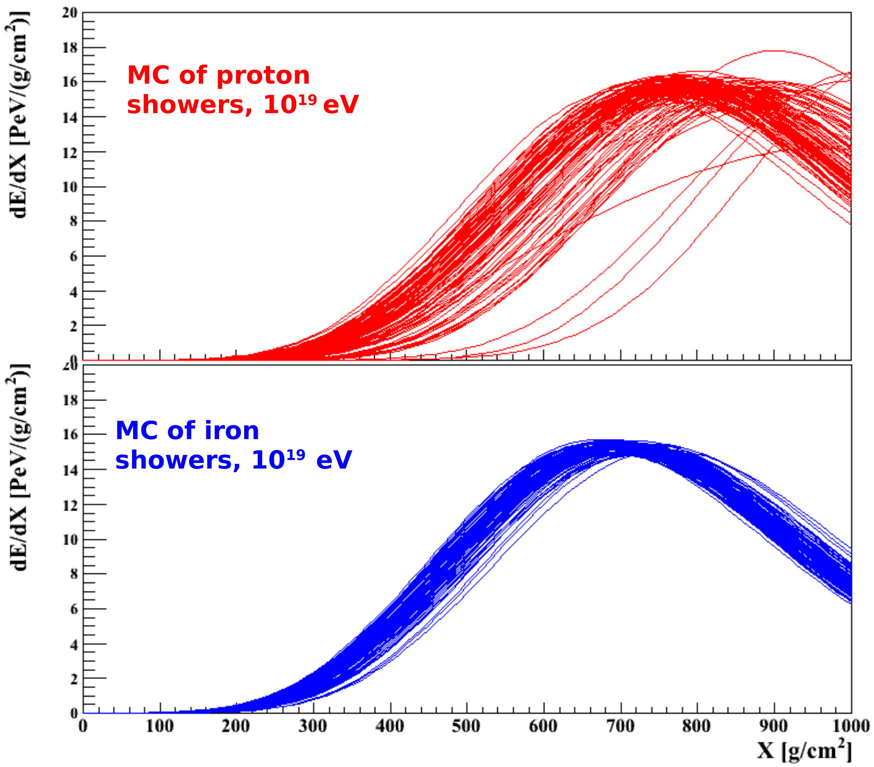
Mixed primary composition: p, Fe, etc

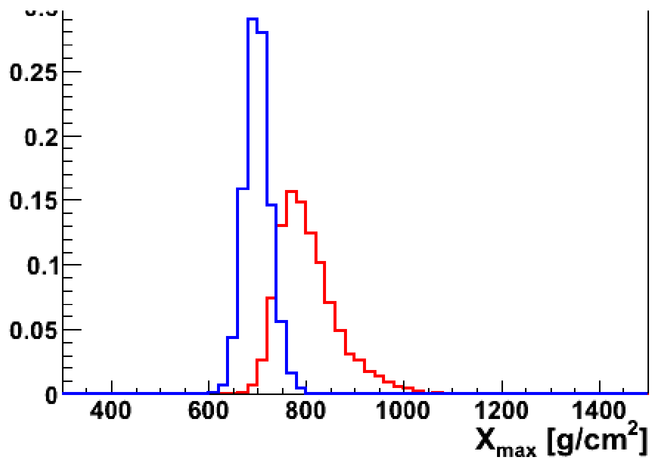
- superposition principle
- Shower produced by nucleus with energy E_A, mass A: modeled by A proton showers each with A^{-1} of the nucleus energy

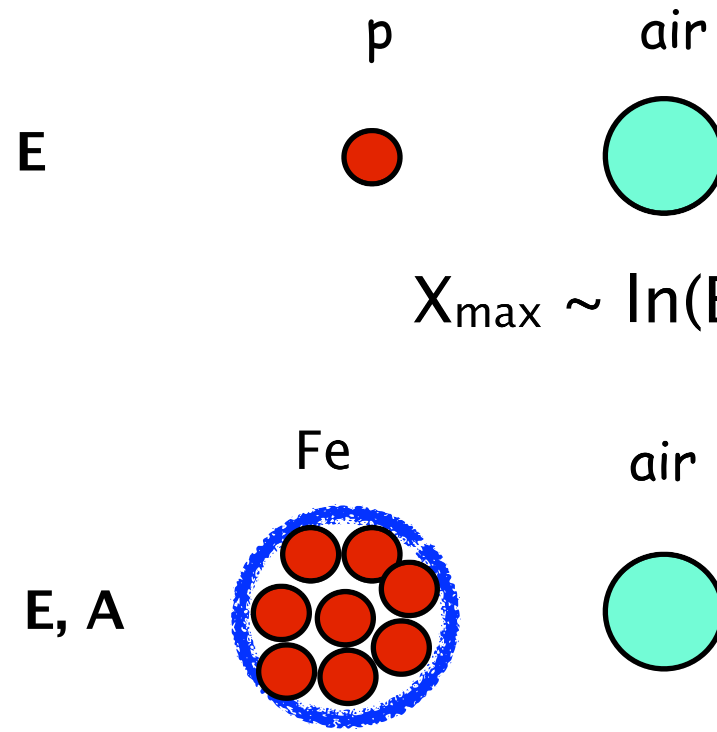
$$X_{max} \sim \ln(E_0/A)$$

$$\frac{d\,X_{max}}{d\,\log E} = \lambda(1-B)\left[1 - \frac{\partial < \ln A >}{\partial \ln E}\right]$$

Composition measurement





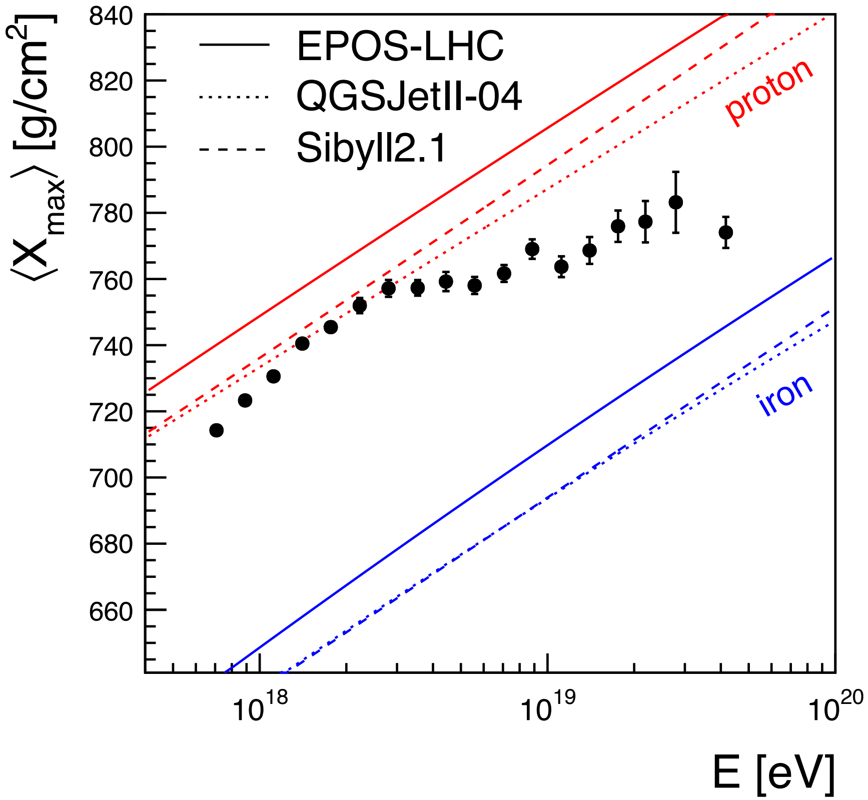


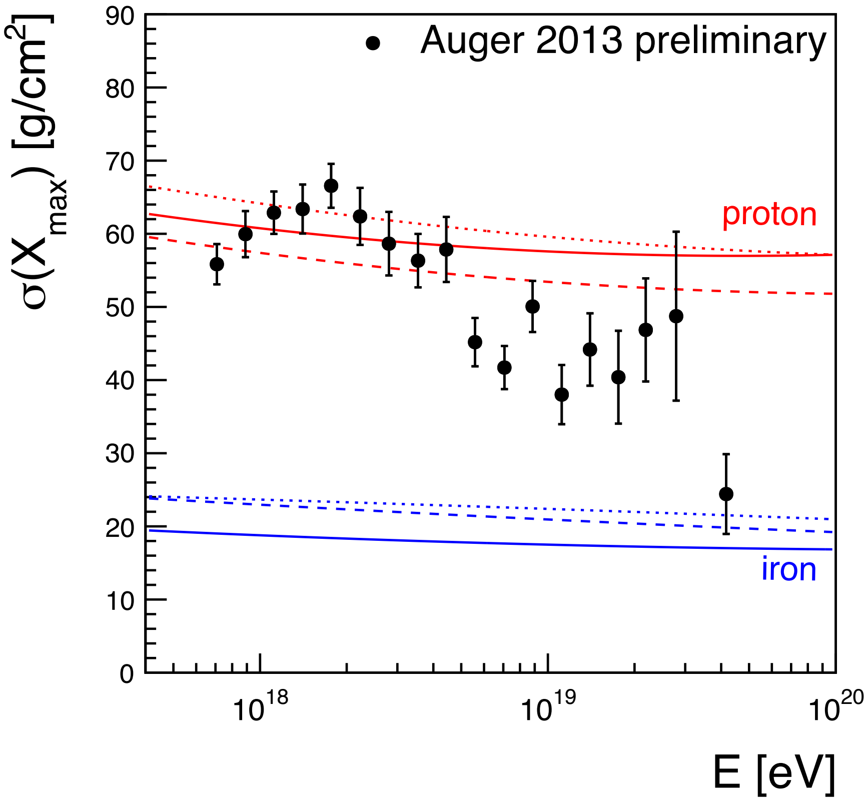
$X_{max} \sim \ln(E)$

$X_{max} \sim \ln(E/A)$

mean X_{max} and $RMS(X_{max})$ are sensitive to **composition**

Composition measurement





At the **highest energies** **<X_{max}>, $\sigma(X_{max})$, muon production depth** and **shower depth from asymmetry of risetimes** show **consistently** that our data better resemble the **simulations** of **heavier primaries** than pure protons.

V. de Souza, Auger Collab, ICRC 2013

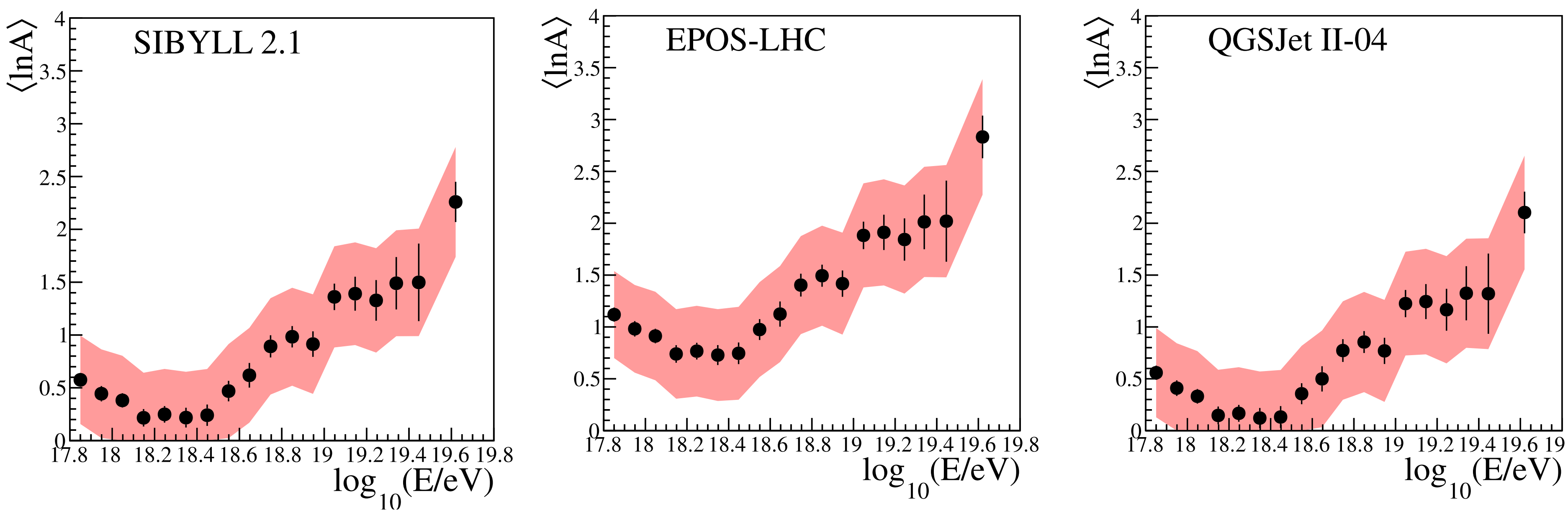
Auger Collab., PRL 104 091101, 2010

From <Xmax> and σ(Xmax) to <lnA> and σ(lnA)

$$\langle X_{\max} \rangle \approx \langle X^{p}_{\max} \rangle - D_p \, \langle \ln A \rangle$$

$$\sigma(X_{\max})^2 \approx \langle \sigma_i^2 \rangle + D_p^2 \, \sigma(\ln A)^2$$

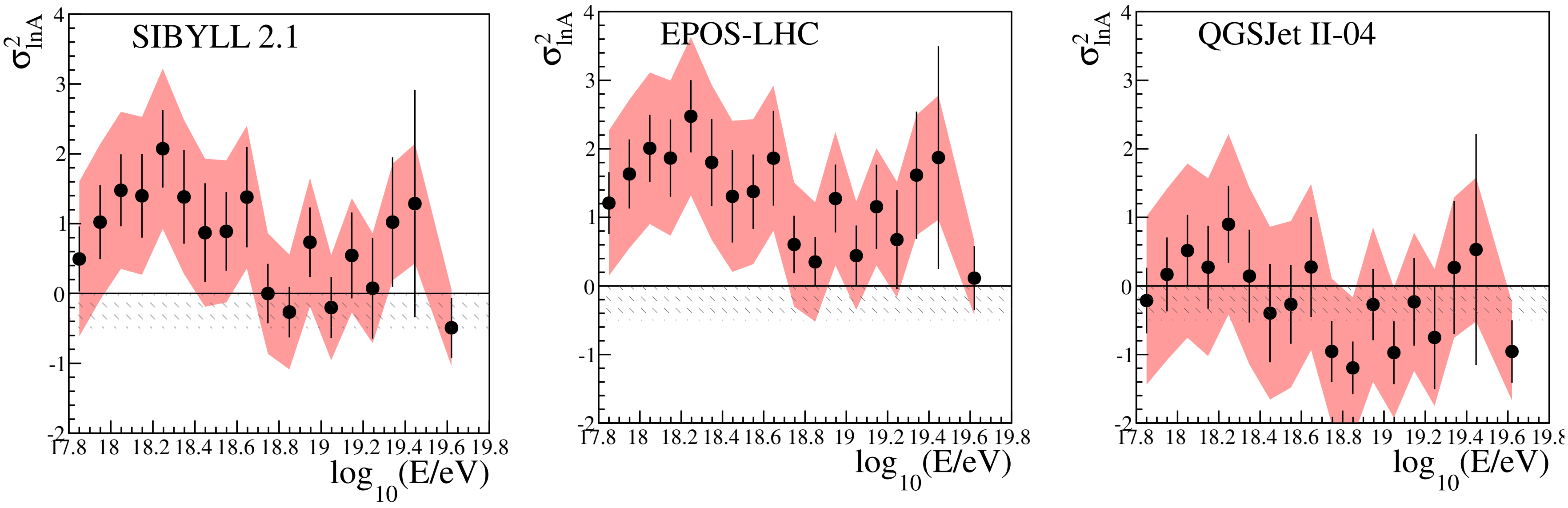
one-to-one relation between the **experimental observables** to the **moments of the mass distribution** on the top of the atmosphere



transition: **medium → light → heavy** ?

Ahn for Auger Collab, ICRC 2013

From <X_{max}> and σ(X_{max}) to <lnA> and σ(lnA)

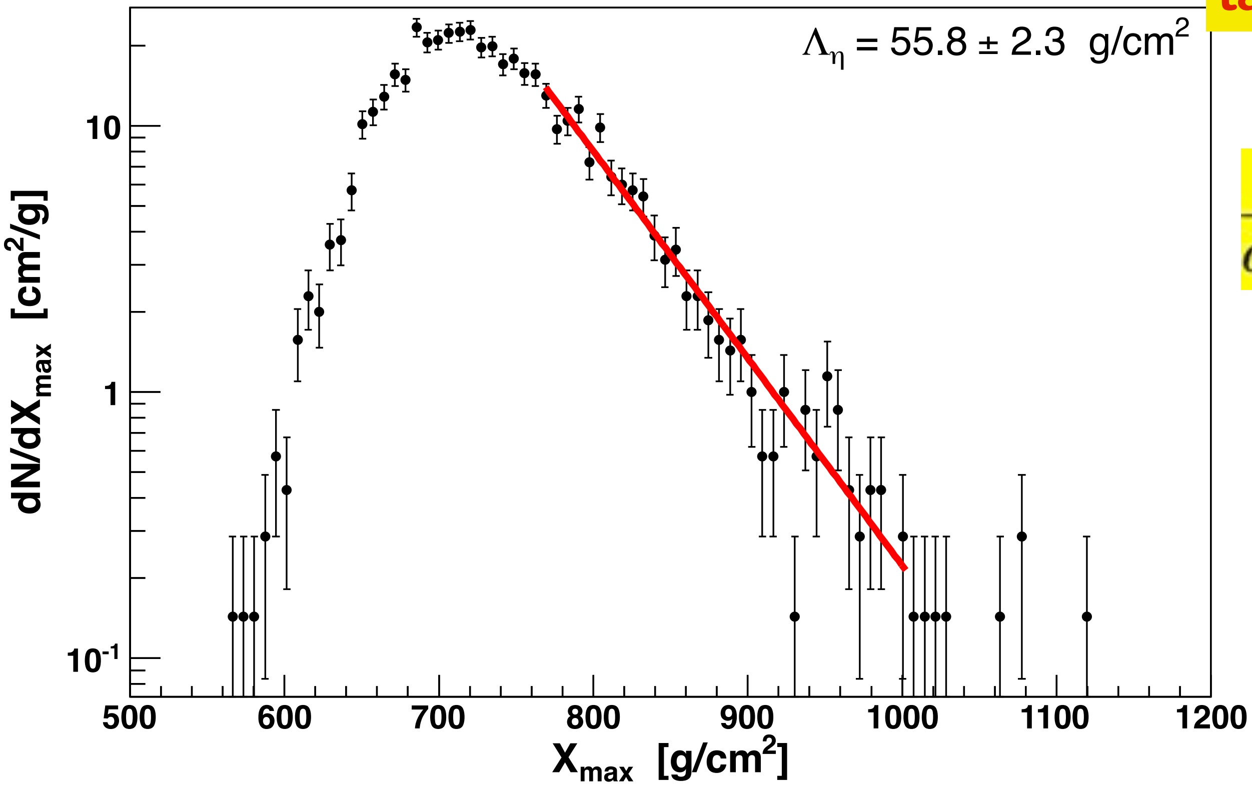


transition: **mixed → pure** ?

Auger Collab.,JCAP 1302(2013)02

E.J.Ahn, Auger Collab, ICRC 2013

p-Air & pp Cross-Section at 57 TeV



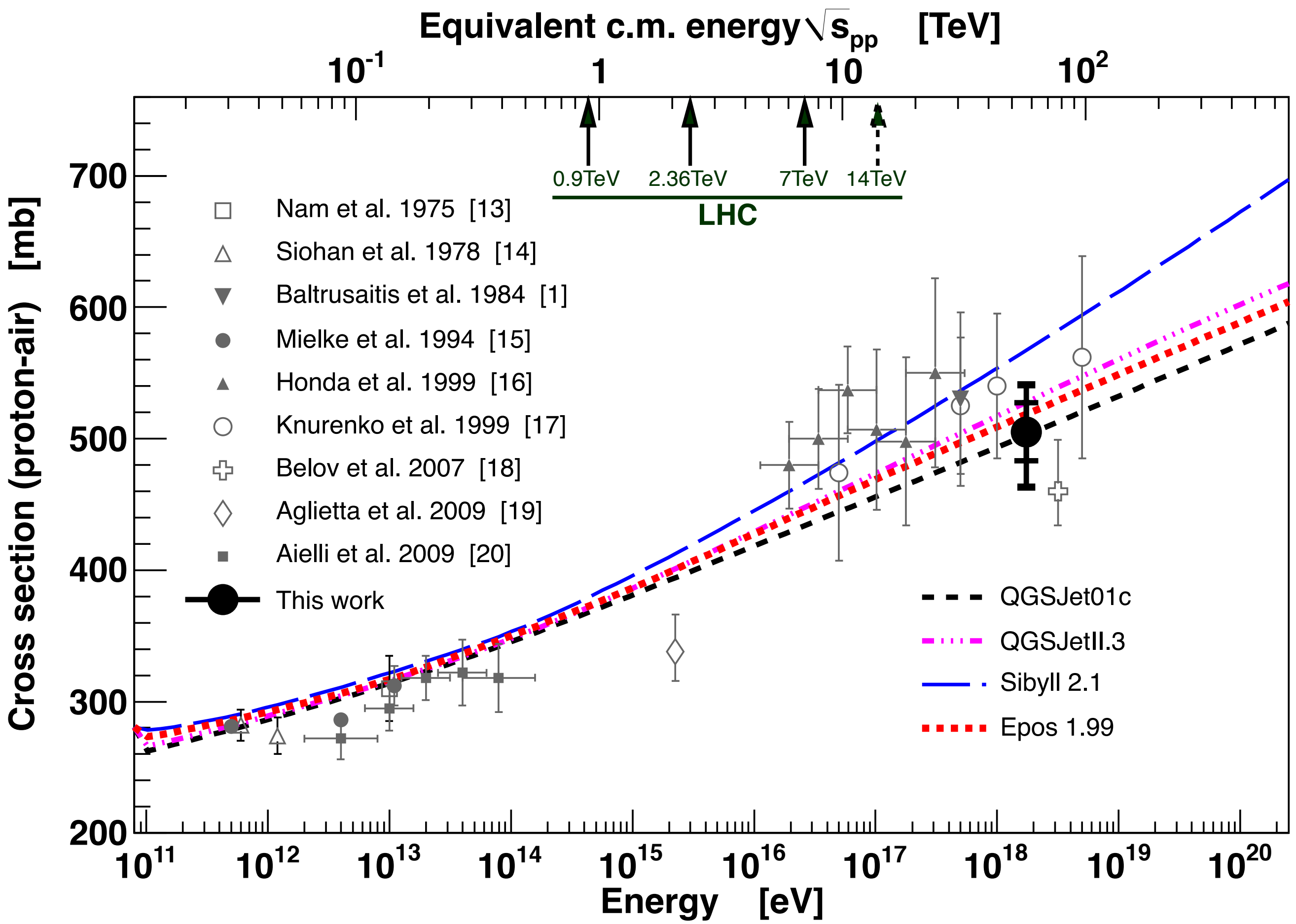
10^{18} eV < E < $10^{18.5}$ eV
tail dominated by protons

$$\frac{dN}{dX_{max}} \sim \exp\left(-\frac{X_{max}}{\Lambda_\eta}\right)$$

$\Lambda_\eta \rightarrow \sigma_{p\rightarrow Air}$
by tuning models
to reproduce tail
seen in data

Auger Collab. Phys. Rev. Lett, 2012

p-Air Cross-Section

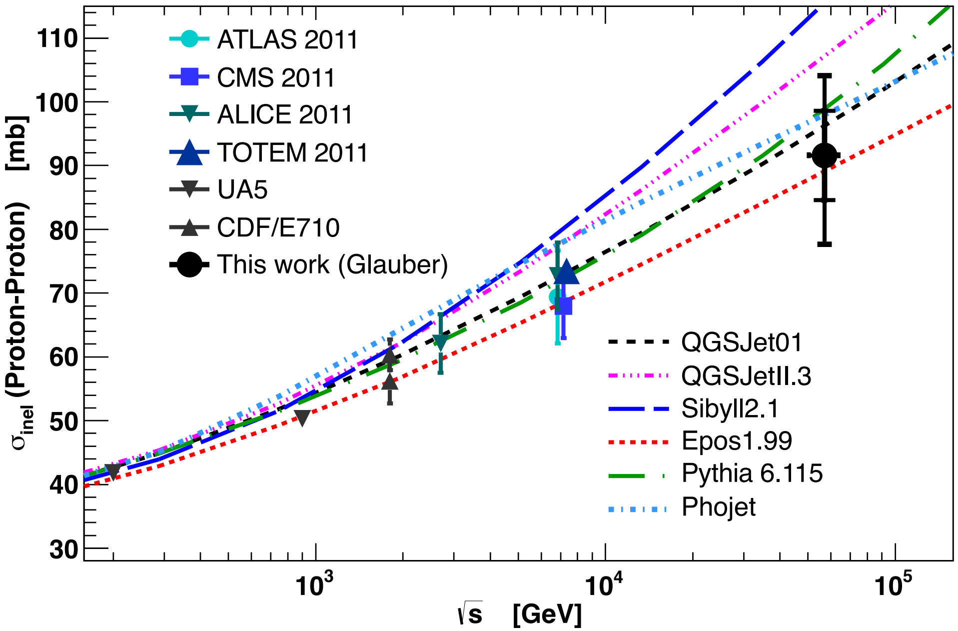


systematic uncertainties
< 0.5% photons
< 25% He

$$\sigma_{p\text{-air}}^{\text{prod}} = \left[505 \pm 22(\text{stat})\,{}^{+28}_{-36}(\text{sys})\right] \text{ mb}$$

UHECRs and LHC

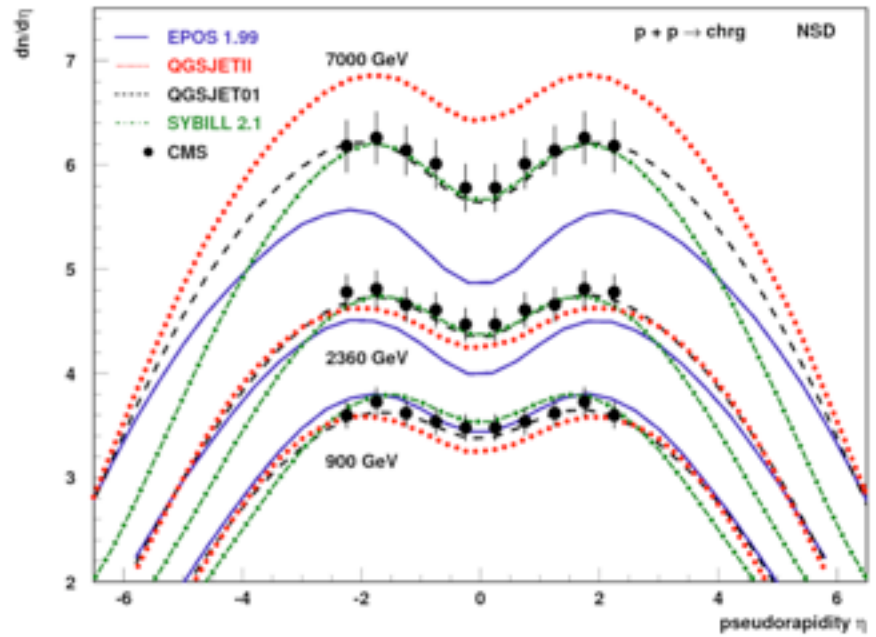
Inelastic pp Xsec at 57 TeV: standard Glauber theory + propagation of modeling uncertainties



$$\sigma_{pp}^{\rm inel} = \left[92 \ \pm 7({\rm stat}) \ ^{+9}_{-11}({\rm sys}) \ \pm 7({\rm Glauber})\right] \ {\rm mb}$$

$$\sigma_{pp}^{\rm tot} = \left[133 \ \pm 13({\rm stat}) \ ^{+17}_{-20}({\rm sys}) \ \pm 16({\rm Glauber})\right] \ {\rm mb}$$

Pseudo-rapidity distributions at LHC and Monte Carlo simulations



★ central distributions well **bracketed** by the model predictions,

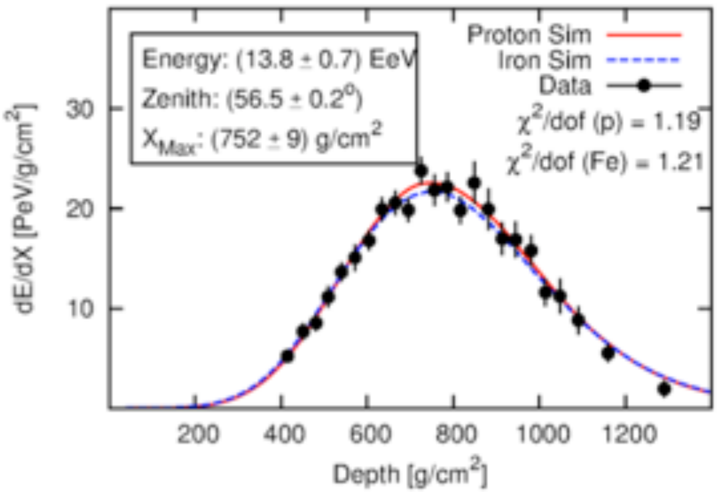
★ **true predictions** as the models were tuned years before LHC data became available

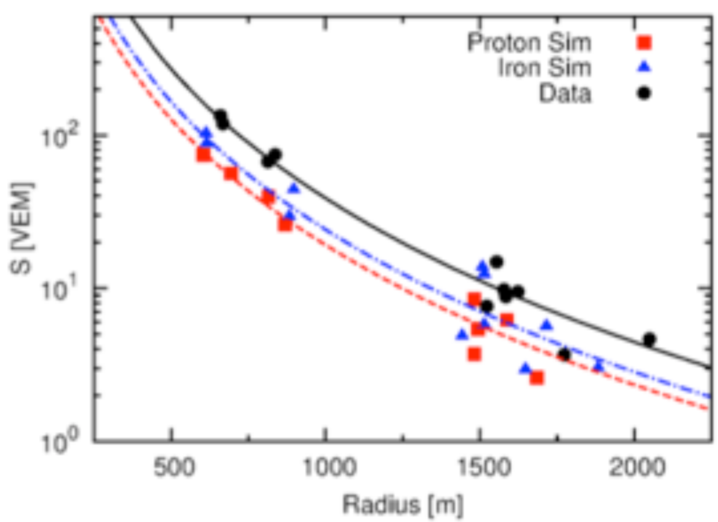
Auger Collab. Phys. Rev. Lett, 2012

UHECRS 2012 Hadronic Interactions report

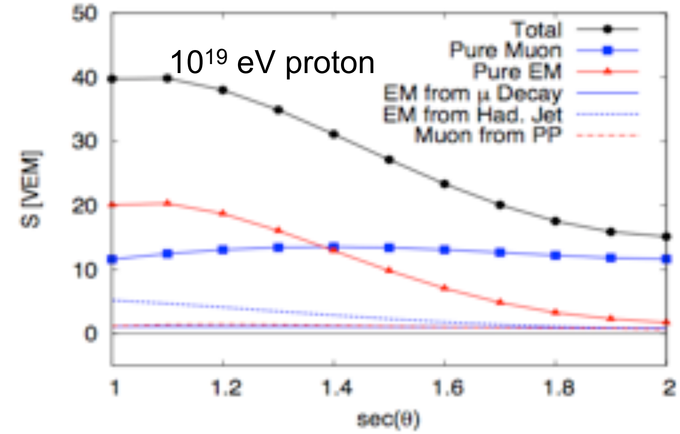
Hadronic interactions and muons

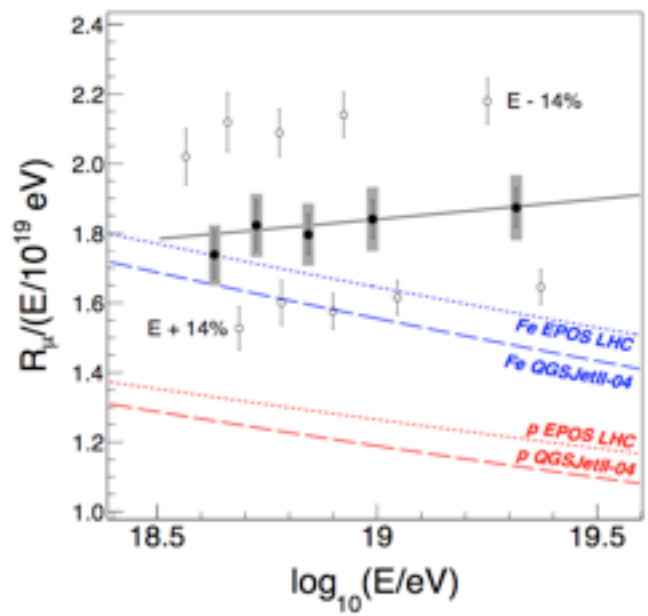
Hybrid events (both FD and SD)





Signal dominated by muons for inclined showers





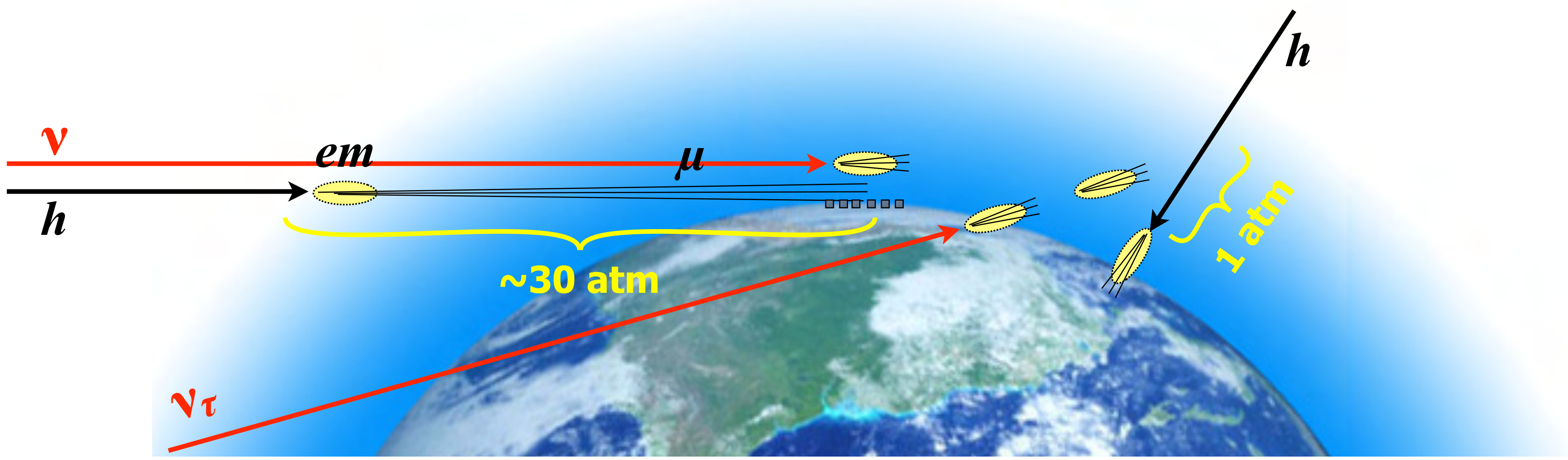
Muon excess (over hadronic models predictions) consistently observed

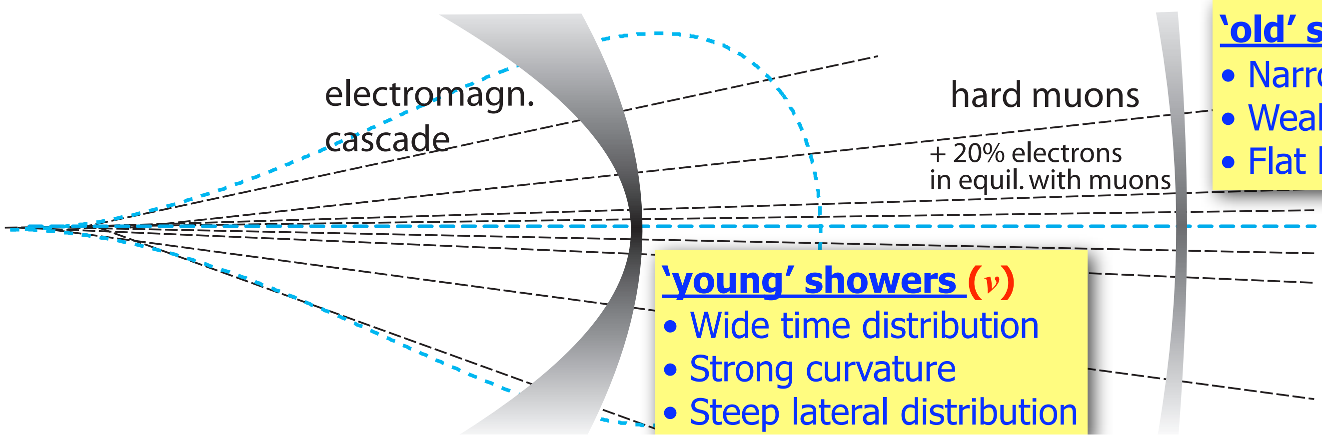
Neutrino induced showers

- ★Neutrino observations are a **unique** probe of the universe's highest-energy phenomena.
- ★Neutrinos are able to **escape** from dense astrophysial environments that photons cannot and are unambiguous **tracers** of cosmic ray acceleration.
- ★As protons and nuclei are **accelerated**, they interact with gas and background light near the source to produce subatomic particles such as charged pions and kaons, which then **decay**, emitting neutrinos.

Neutrino induced showers

Only a neutrino can induce a young horizontal shower !

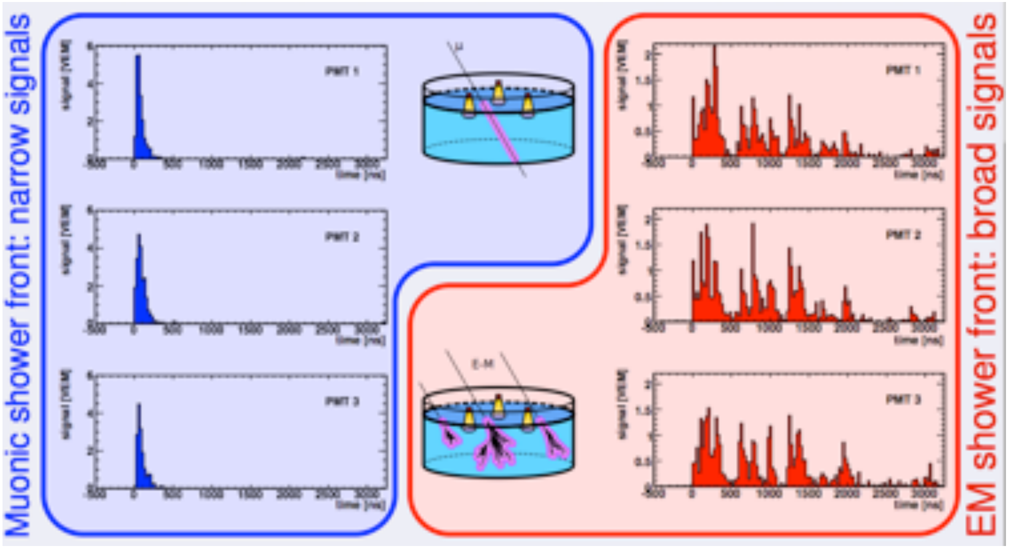


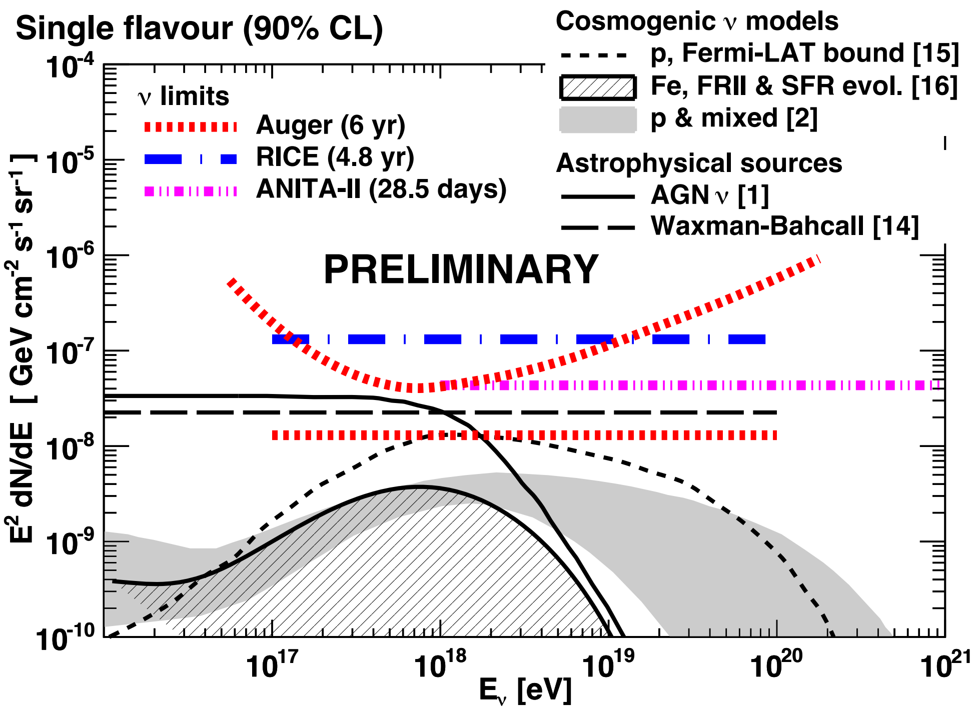


'old' showers (*h*)
- Narrow time distribution
- Weak curvature
- Flat lateral distribution

'young' showers (*ν*)
- Wide time distribution
- Strong curvature
- Steep lateral distribution

Auger neutrino limits





young ν induced showers

- ★ wide time distribution in surface stations
- ★ elongated footprint of inclined shower
- ★ propagation speed of shower front at ground

Limits start to dig into potential sources and cosmogenic "GZK" neutrinos

Auger Collab. Astrop. J. Lett, 2012

Pieroni, Auger Collab. ICRC, 2013

ICECUBE extraterrestrial neutrinos

ICECUBE extraterrestrial neutrinos

Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

IceCube Collaboration*

ICECUBE extraterrestrial neutrinos

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Science AAAS

ICECUBE extraterrestrial neutrinos

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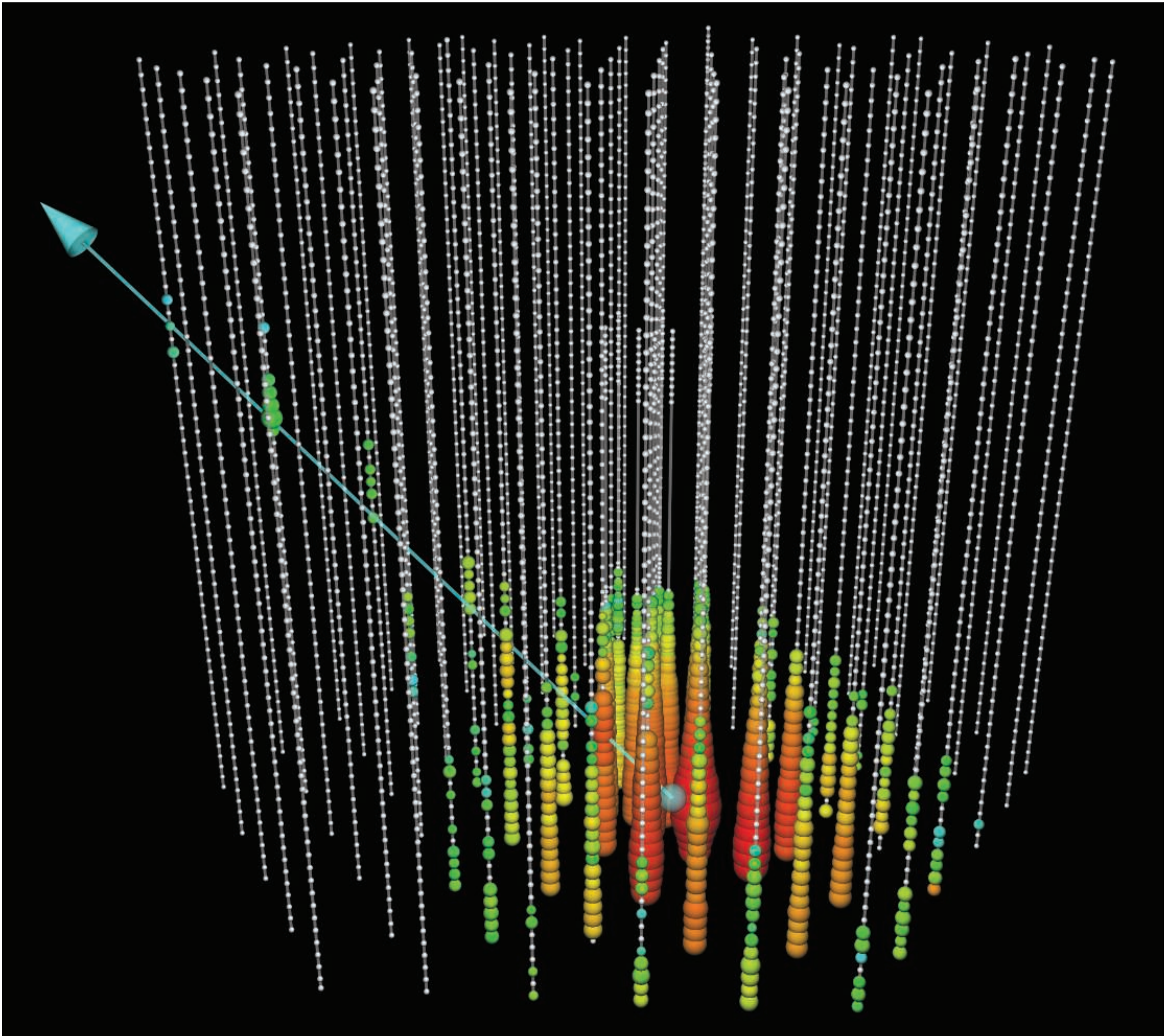
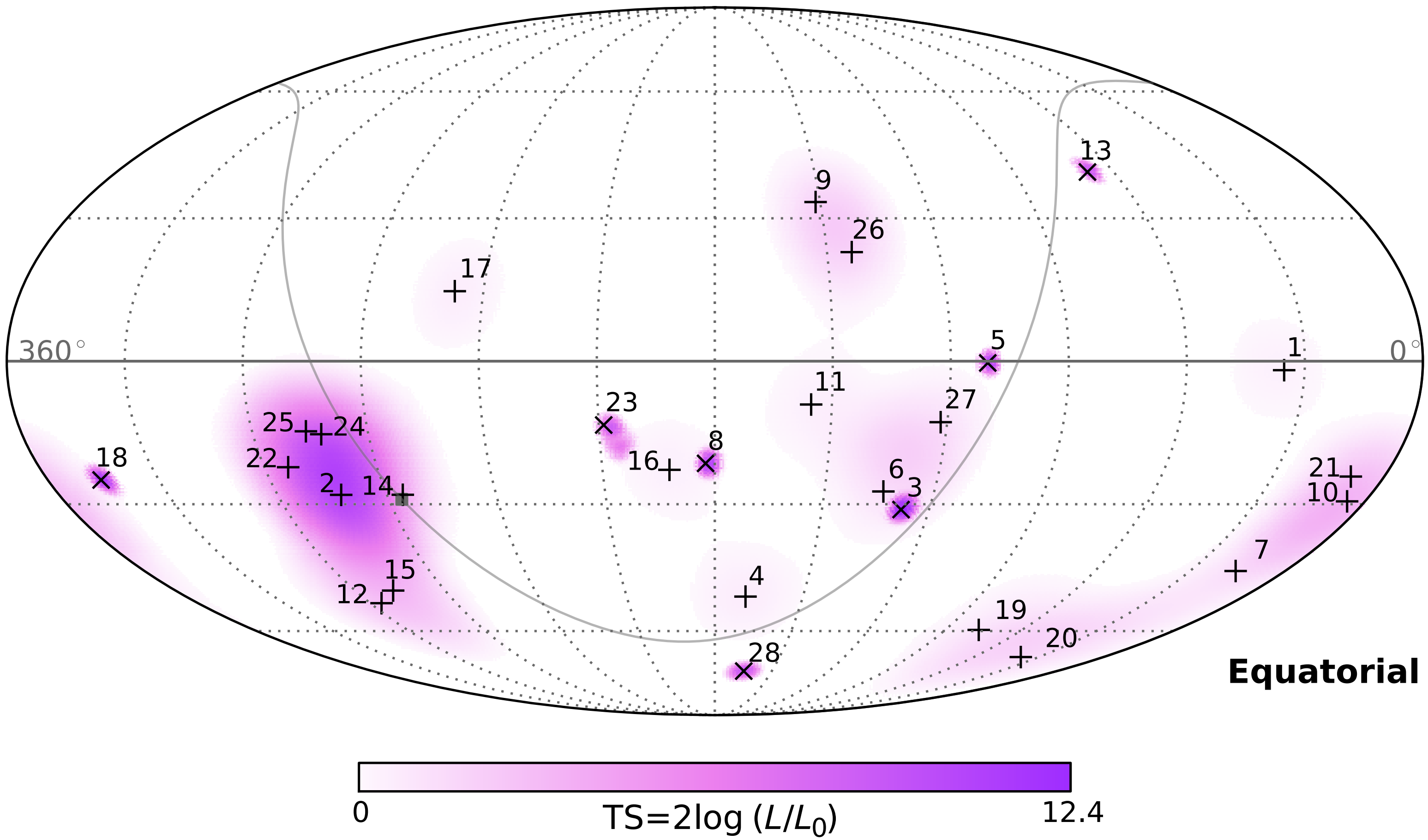


ICECUBE extraterrestrial neutrinos



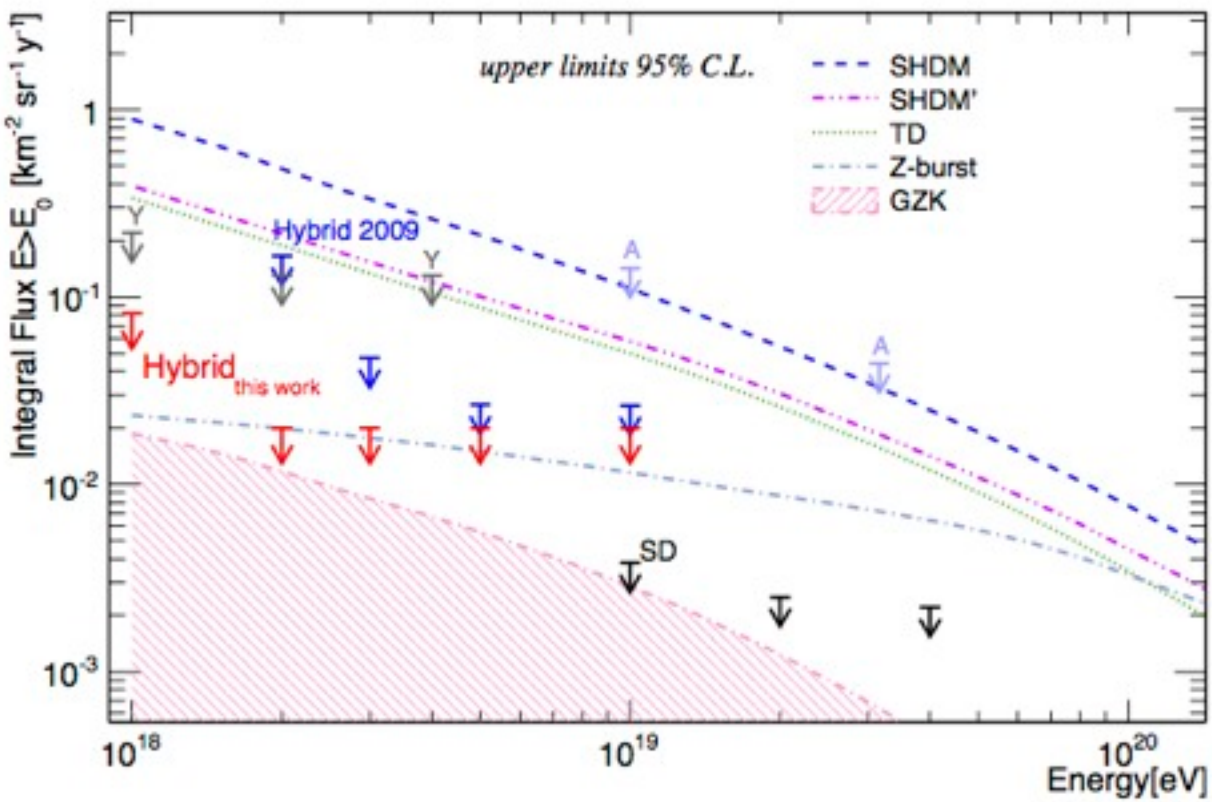
★ It is the birth of neutrino astronomy?
★ More statistics is needed before sources are identified.

Top down models

- **acceleration models (astrophysics):**
  - active galactic nuclei, gamma-ray bursts...
  - not easy to reach > 100 EeV;
  - ***photon fractions typically < ~ 1%***

- **non-acceleration models (particle physics)**
  - **UHECR: decay products of high-mass particles (> 10^{21}eV)**
  - super-heavy dark matter (SHDM): from early universe and concentrated on the halo of galaxies and clusters of galaxies
  - topological defects (TD) produced throughout the universe
  - **UHECR produced as secondary particles (hadronization process) and are most photons and neutrinos, with minority of nucleus**
  - ***photon fraction typically > ~ 10%***

Upper limits on flux of photons



Photons characterised by:
- ★ **deep Xmax in FD**
- ★ **small signal in SD**

The observation of a photon flux compatible with the cosmogenic prediction could provide an independent proof of the GZK process

disfavour exotic "particle physics" origin of UHECR

- ★ **Models disfavoured down to 1 EeV**
- ★ (optimistic) **GZK in reach**

Auger Collab, Astrop. Phys (2009)
M. Settimo, Auger Col., ICRC 2011

Scientific landscape

- The measurement of the GZK suppression together with photon limits and other recent measurements: ***the scientific landscape is deeply modified!***
- The study of the UHECR is now **predominantly** an essential branch of the High Energy Astrophysics!
- Speculations and searches for **"New Physics"** effects can and will continue.
- Some interesting ideas have been put forward and their test and study remain valid goals:
  - Violation of Lorentz invariance
  - Search for exotic states of matter - strangelets, disoriented chiral condensates, etc...
  -

Perspectives: AUGER next 10 years

- ★ Keep acquiring more data (next 10 years: three times our current statistics)
- ★ add more mass information in the UHE region (muons)
- ★ construct a world observatory (10 times the Auger exposure)

Perspectives: Astroparticle group IF - UFRJ next 5 years

- ★ Keep working in Auger (upgrade)
- ★ Direct dark matter search (DAMIC?)

Conclusion

- ★ 2012-2013 extraordinary years for astroparticle physics!
- ★ The Pierre Auger experiment is complete since 2008 and it is taking data since 2004
- ★ Very robust hybrid technique to detect CRs at the highest energies

Many interesting results on astrophysics and particle physics

- Measurement of the spectrum suppression: GZK?
- Large scale anisotropy:
  - ★Most stringent upper limits at present on the amplitudes
  - ★Phase does not follow a random distribution
  - ★With higher statistics the galactic/extragalactic transition may be stablished
- Weak correlation with VCV catalogue
  - ★Correlation is stabilizing
- Very competitive neutrino limits
- Stringent limits on photon primaries and top-down models
- Measurement of p-air cross section at 57 TeV
- Direct DM search: conflicting results, need more statistics and inovative experimental techniques

Thank you