Towards locating the ultra-high energy cosmic ray accelerators?

O. Deligny (CNRS/IN2P3 - IPN Orsay)

i) Introduction

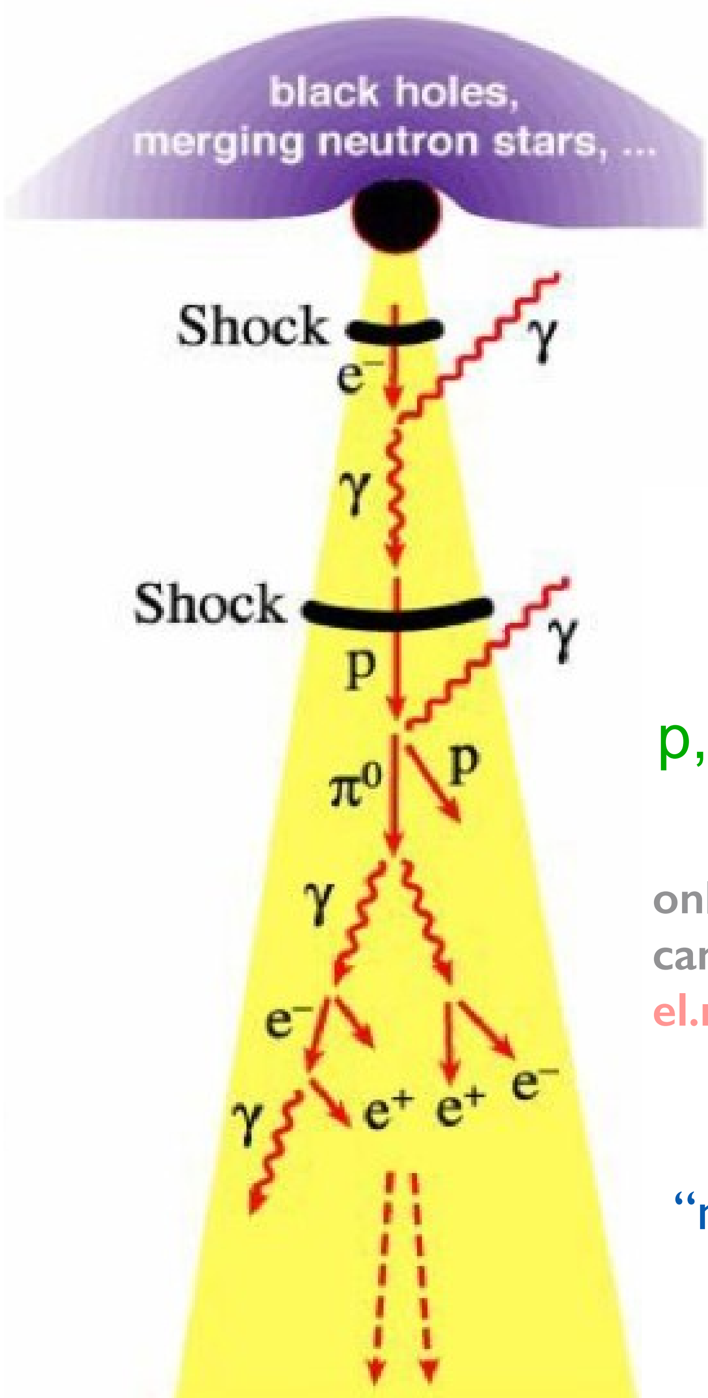
ii) The Pierre Auger Observatory

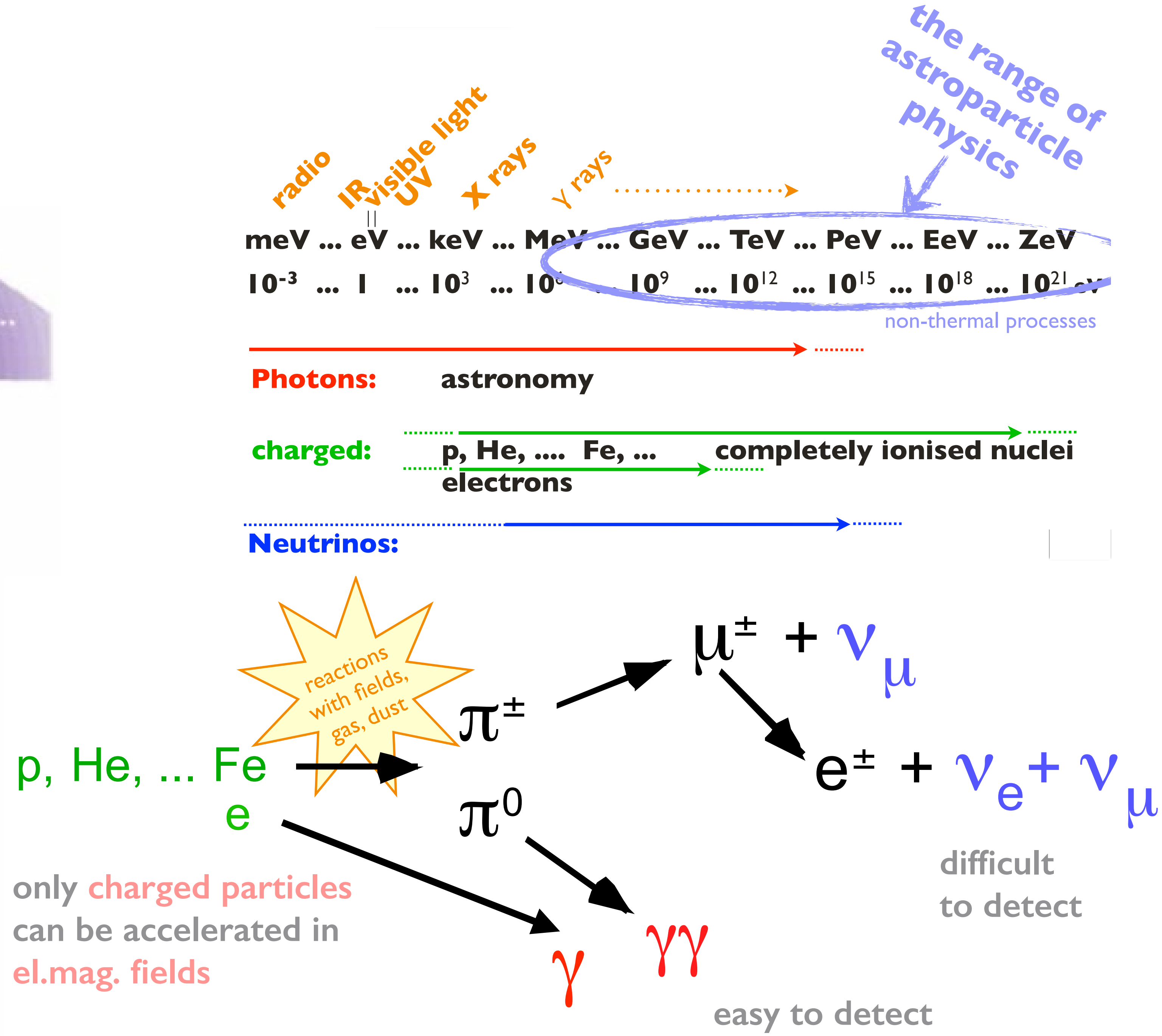
iii) The energy spectrum and mass composition: the rise of the rigidity-dependent scenario for the maximal acceleration energy

iv) Extragalactic pattern of cosmic-ray arrival directions above 8×10^{18} eV

v) Correlation of UHECR arrival directions with the flux pattern of nearby star-forming galaxies

Generic cosmic-ray accelerators





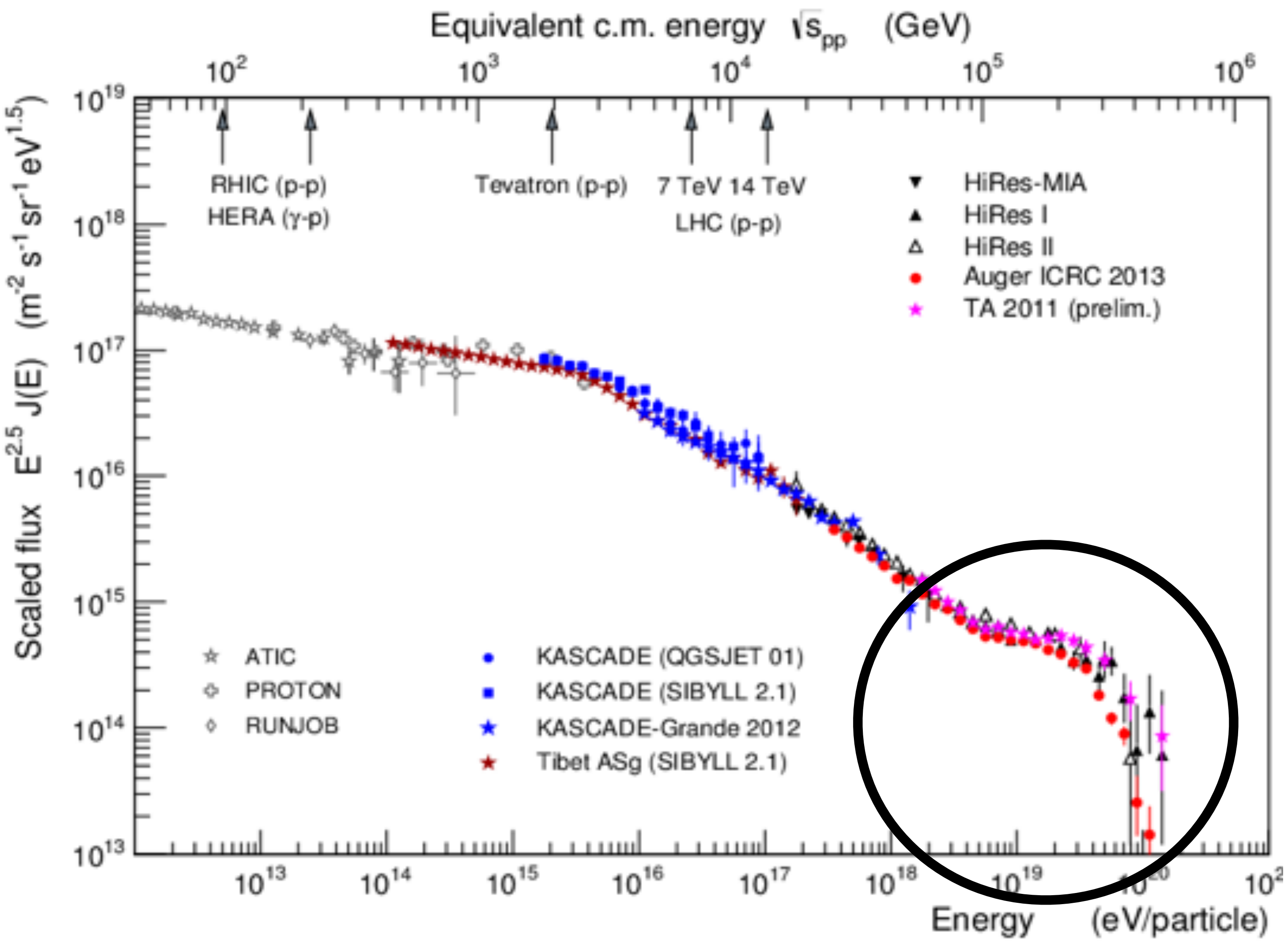
"multi-messenger astrophysics"

but gamma rays are currently
the most "productive" messengers.

γ, ν

point back to sources
(good for astronomy)
but serious backgrounds

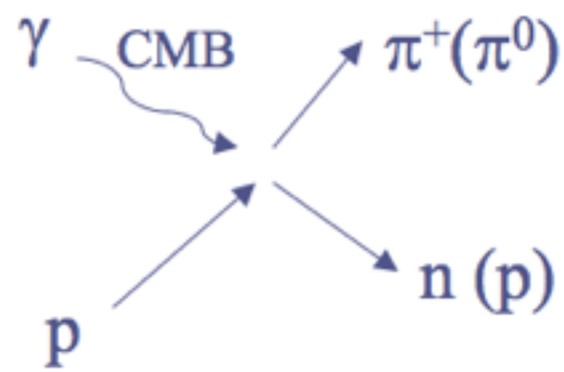
Ultra-high energy cosmic rays: contemporary questions



- Gal/xGal transition?
- Origin of the ankle?
- Origin of the UHE steepening?
- Composition at UHE?
- Sources?

NB: From neutrinos/photons upper limits, the bulk of UHECRs are accelerated particles in astrophysical objects

The GZK cutoff

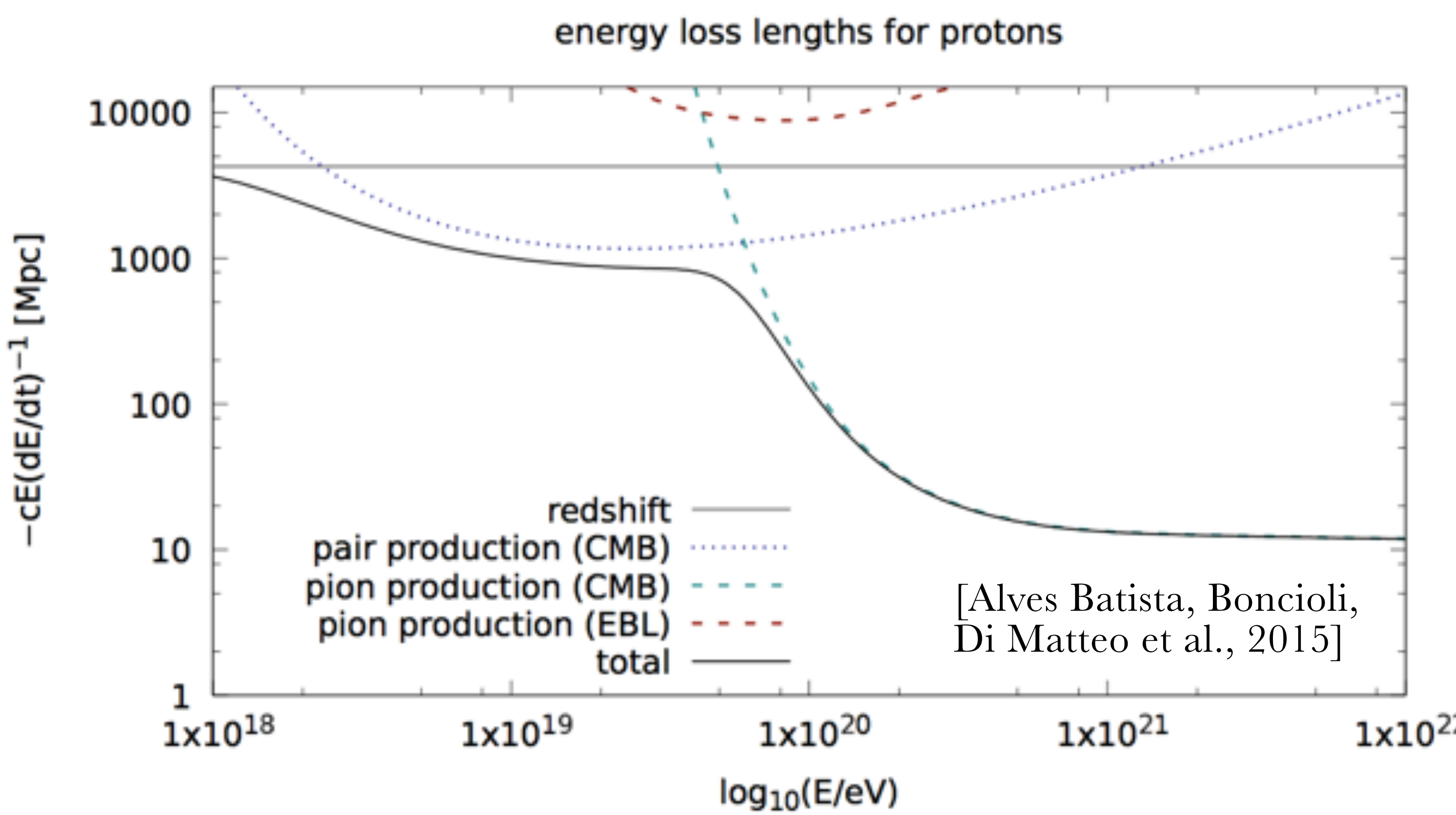


Example with protons

$$\varepsilon_\gamma > \frac{m_\pi m_p}{\varepsilon_p} \sim 10^{-3}\varepsilon_{20}^{-1}\ \mathrm{eV} \Rightarrow \quad n_\gamma \sim \frac{400}{\mathrm{cm}^3}\exp\left[1-\frac{3}{\varepsilon_{20}}\right]$$

$$\lambda_E \sim \frac{m_p}{m_\pi}\frac{1}{n_\gamma \sigma_{\gamma p}}$$

$$\sim 11\exp\left[\frac{3}{\varepsilon_{20}}-1\right] \quad \mathrm{Mpc}$$

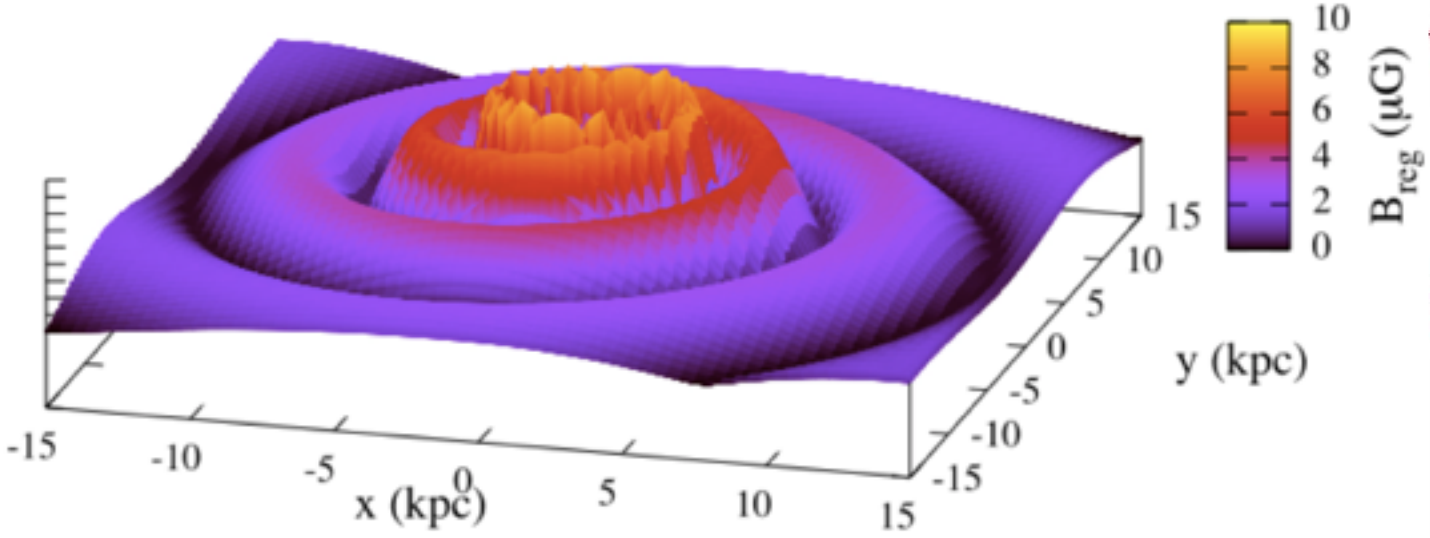


[Alves Batista, Boncioli, Di Matteo et al., 2015]

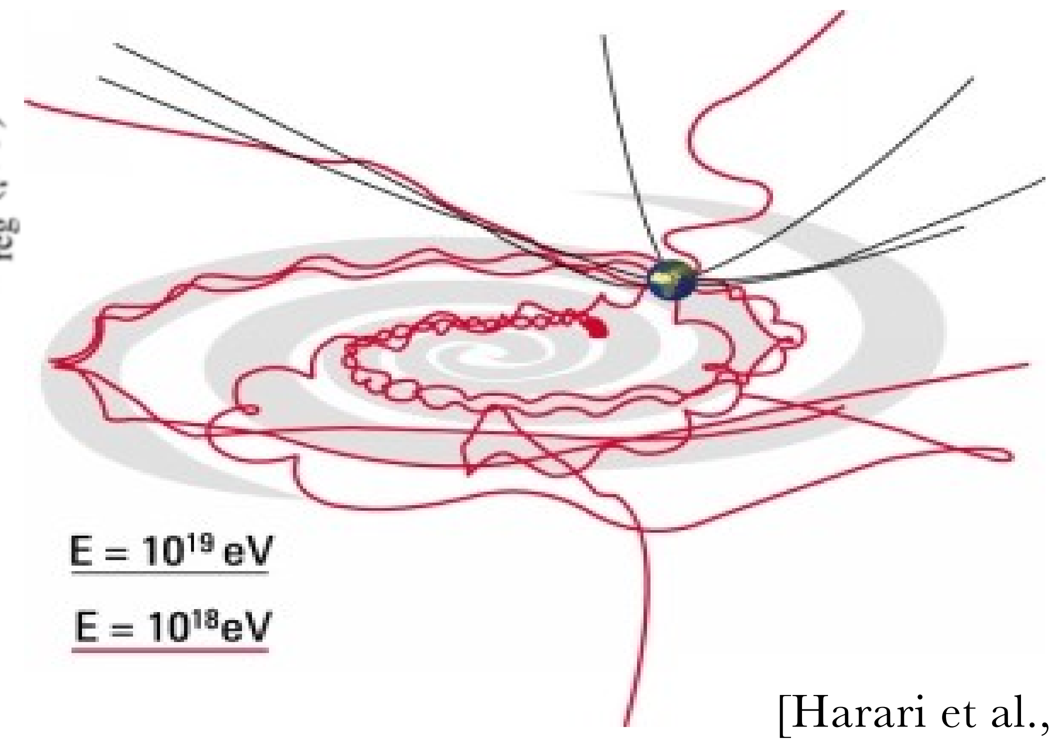
Same phenomenon with nuclei (photo-disintegration)

➡ Sudden reduction of the CR horizon at UHE

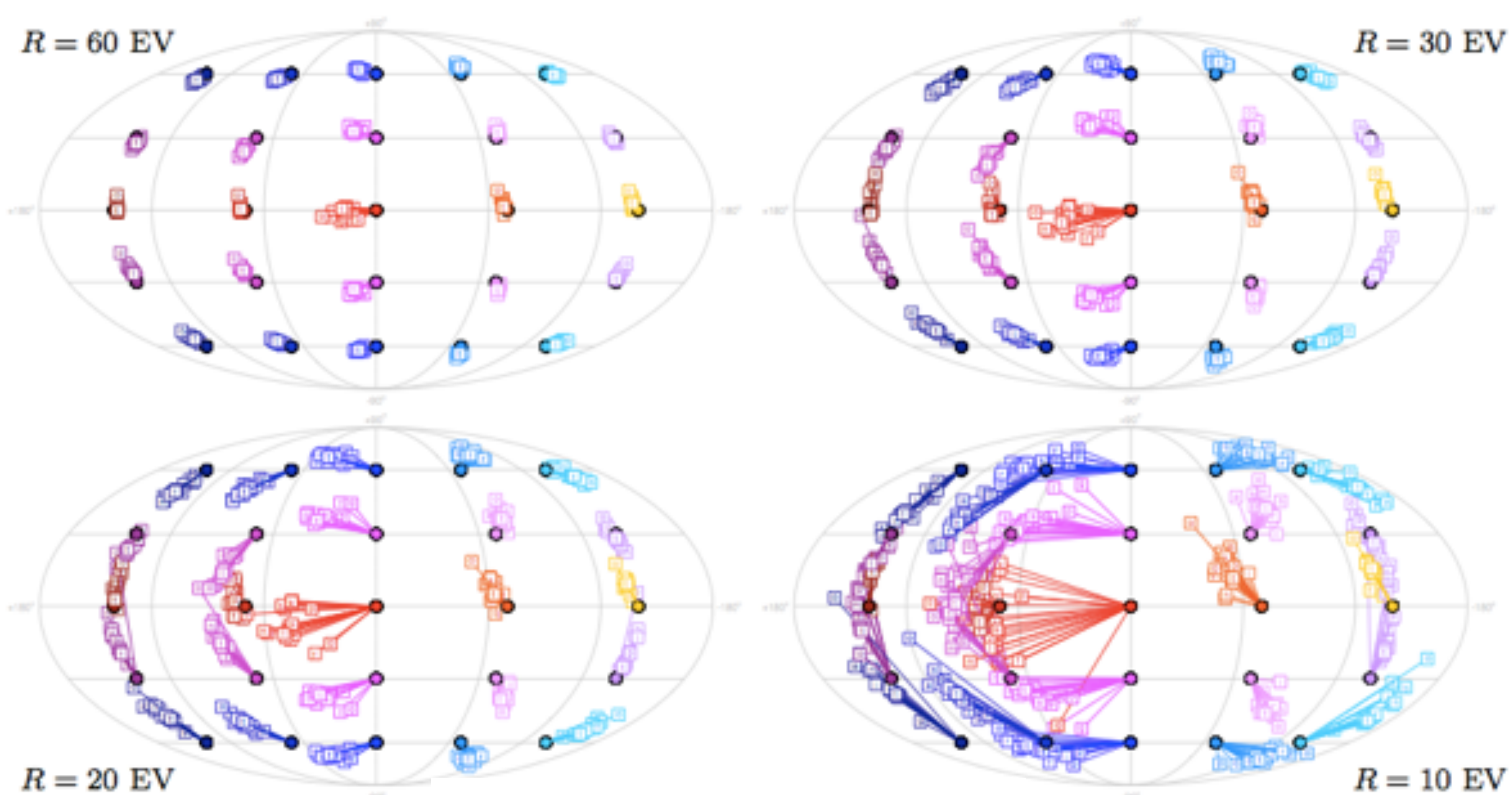
Magnetic deflections



[Jansson & Farrar 2012]



[Harari et al., 1999]



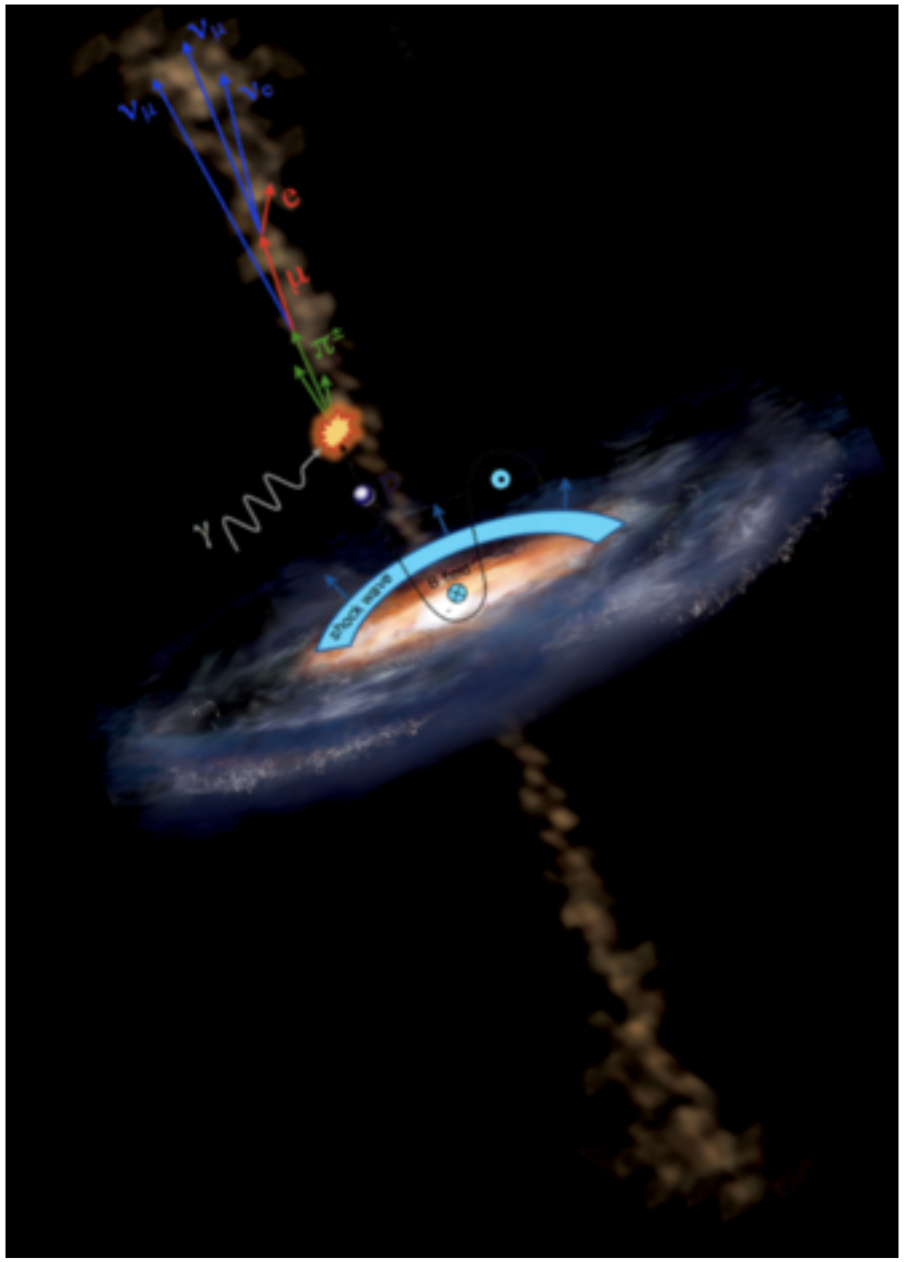
[Unger & Farrar 2017]

At UHE, CRs may be rigid enough to point back to their sources within a few degrees

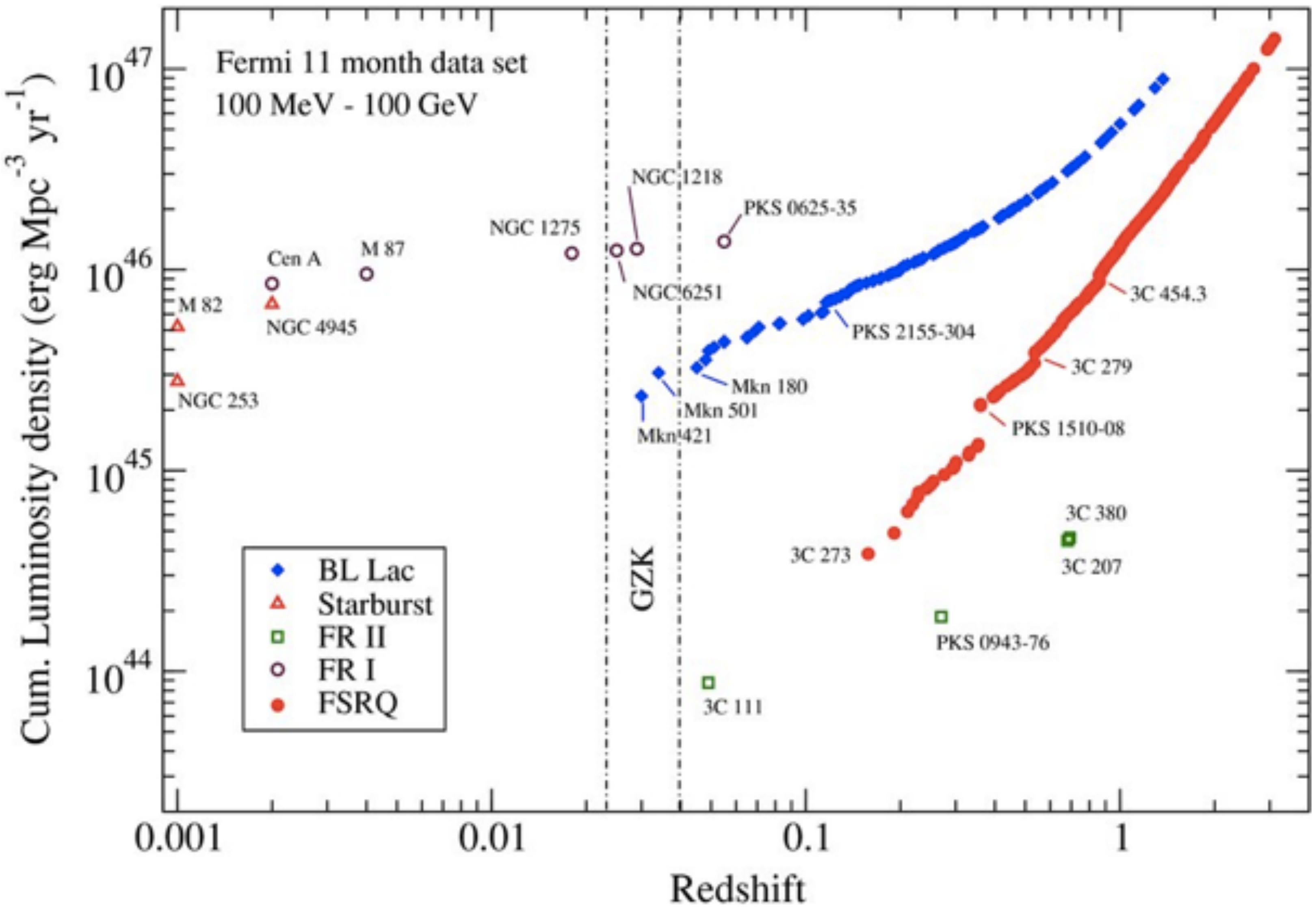
+ Reduced horizon

➡ Possibility to identify nearby sources?

Multi-messenger connection?



[Dermer & Razzaque 2010]



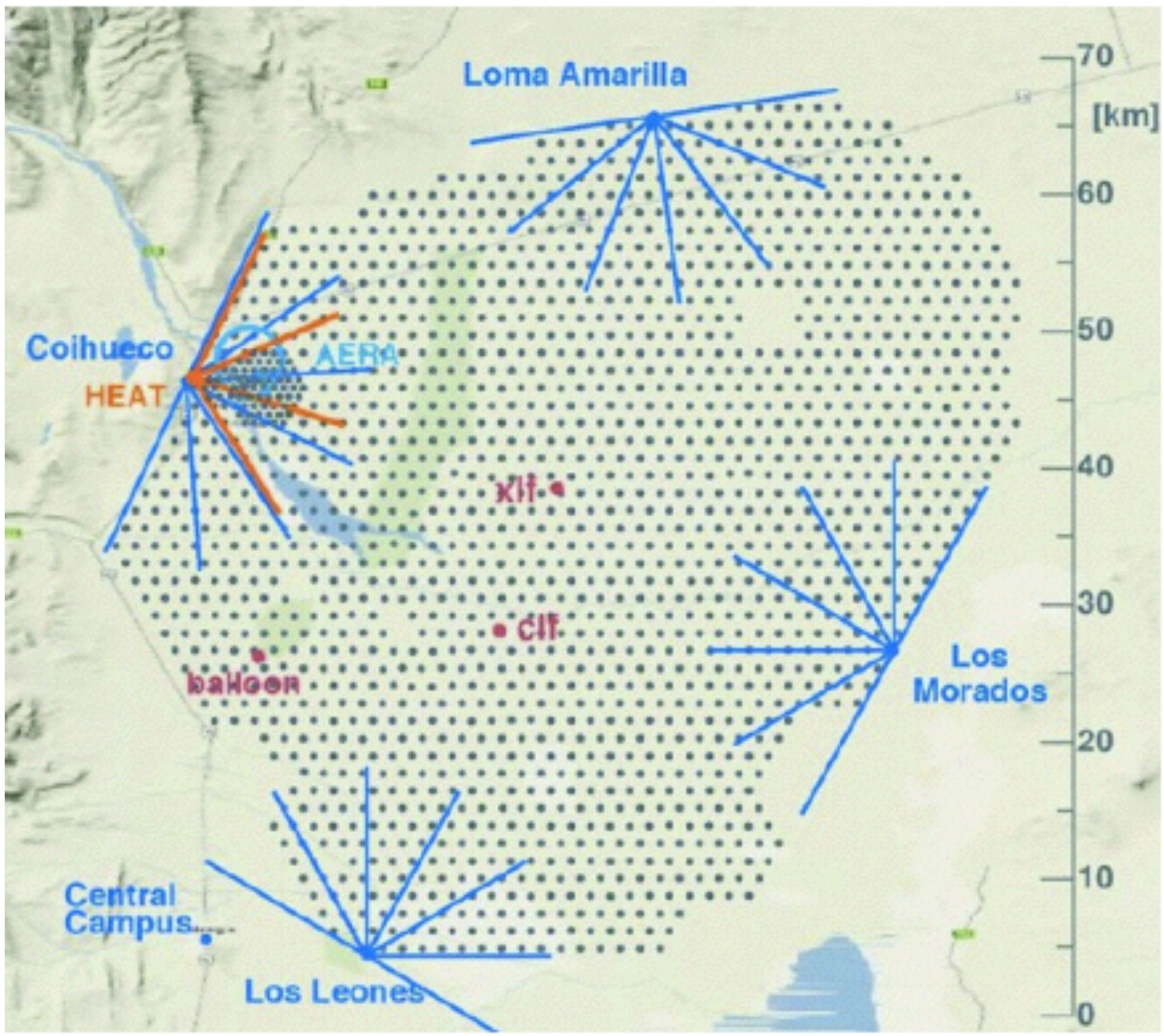
 

ii) The Pierre Auger Observatory

[NIM A 798 (2015) 172-213]

The Pierre Auger Observatory

Located in Argentina, province of Mendoza



Hybrid detector:

- Surface detector array (SD):
  - SD-1500:

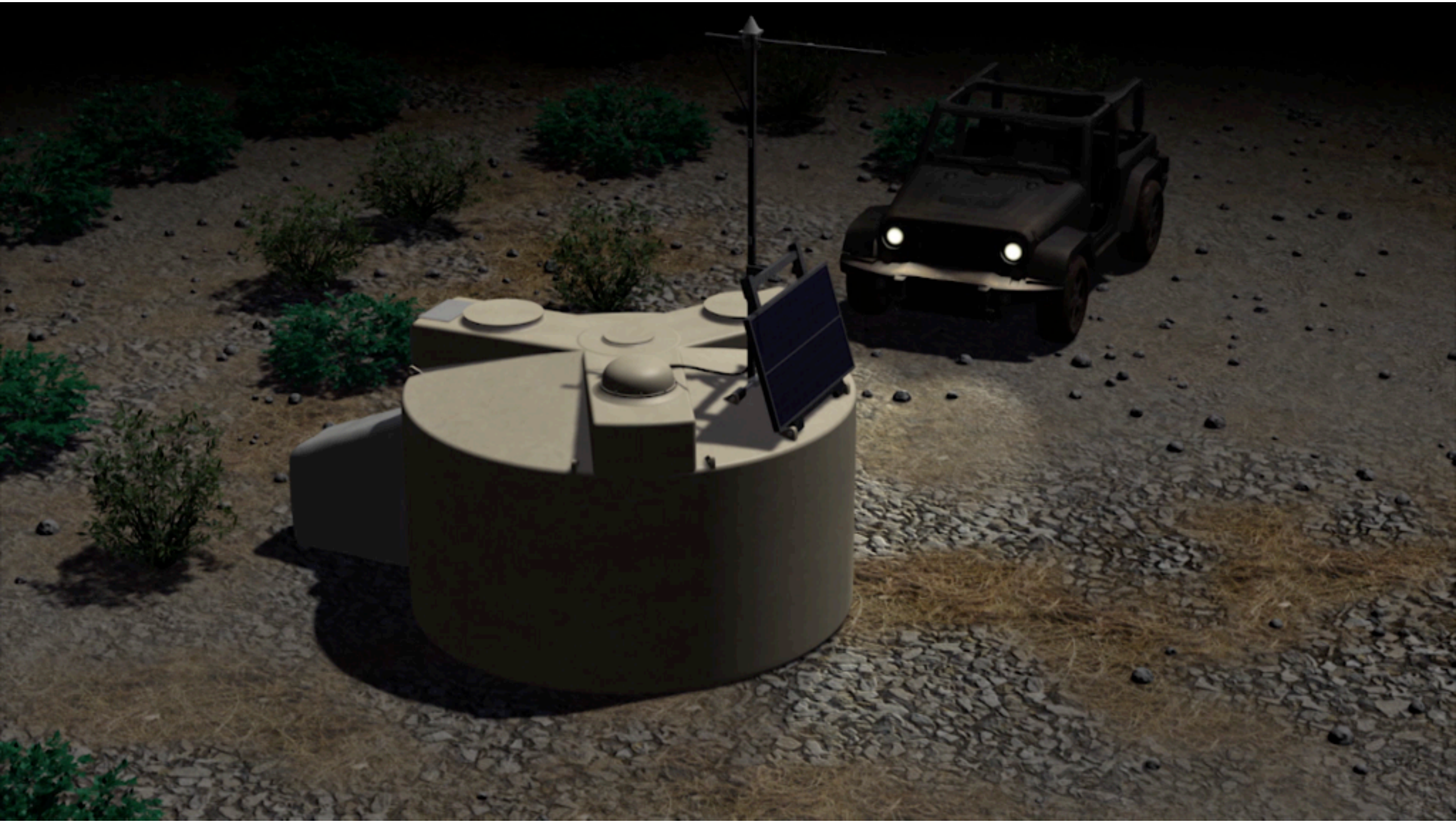
    1660 spaced by 1.5 km
    ~ 3000 km^2
  - SD-750:

    49 spaced by 750 m
    ~ 24 km^2
- Fluorescence detector (FD):

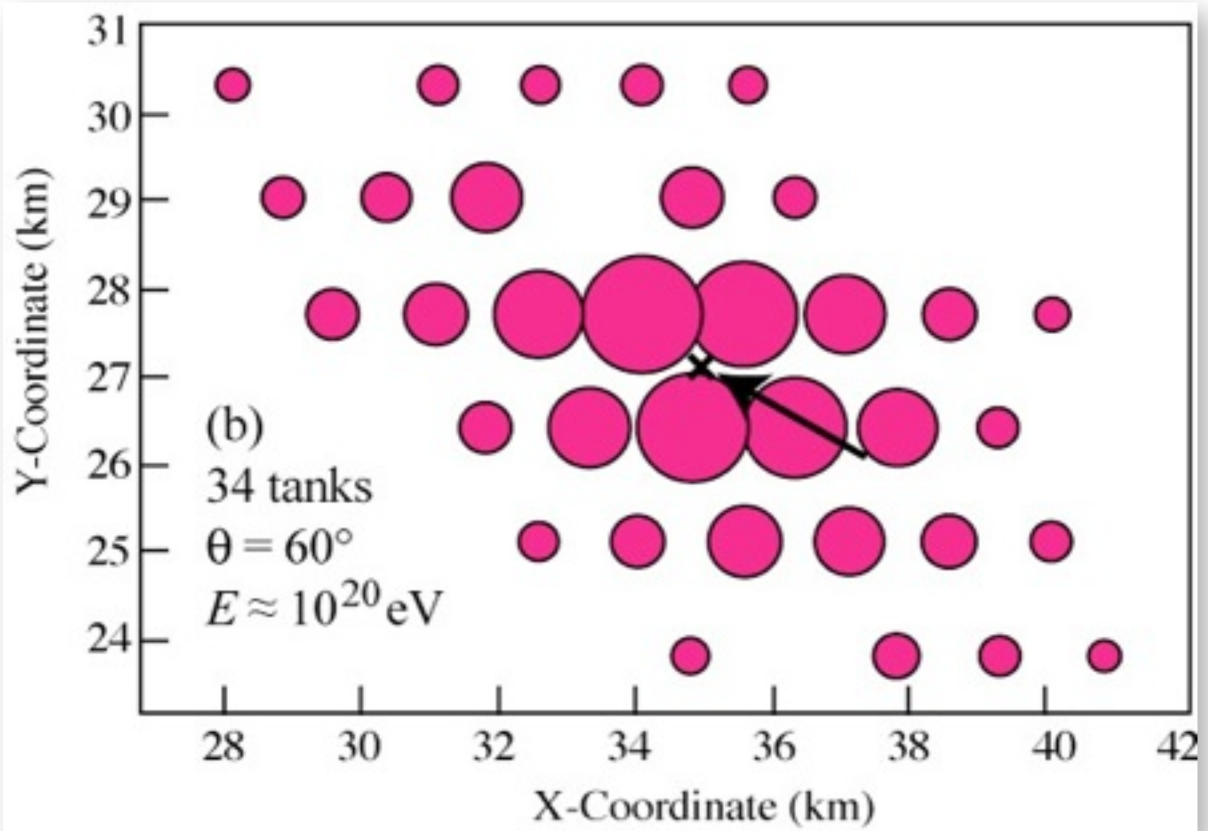
  27 fluorescence telescopes in 5 buildings

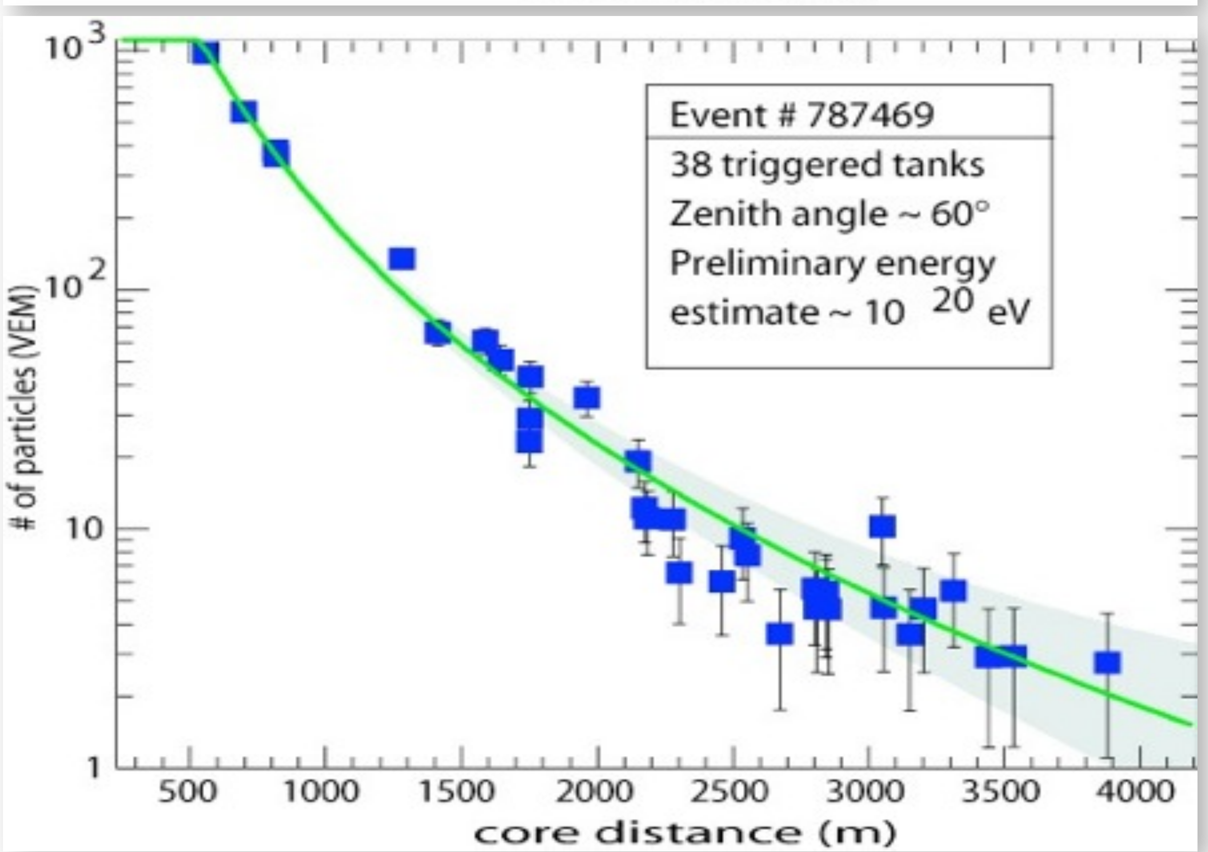
Surface detectors

Surface detectors



Surface detectors





Footprint of the shower at ground = lateral sampling

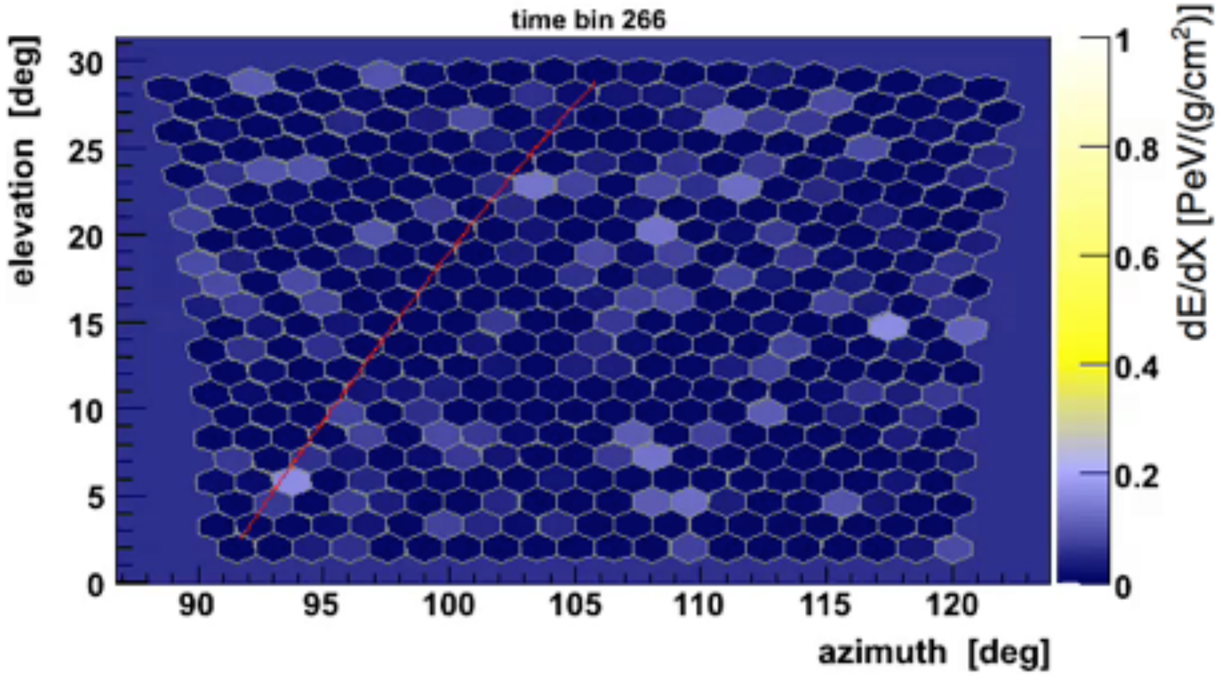
arrival direction + 'size' of the shower

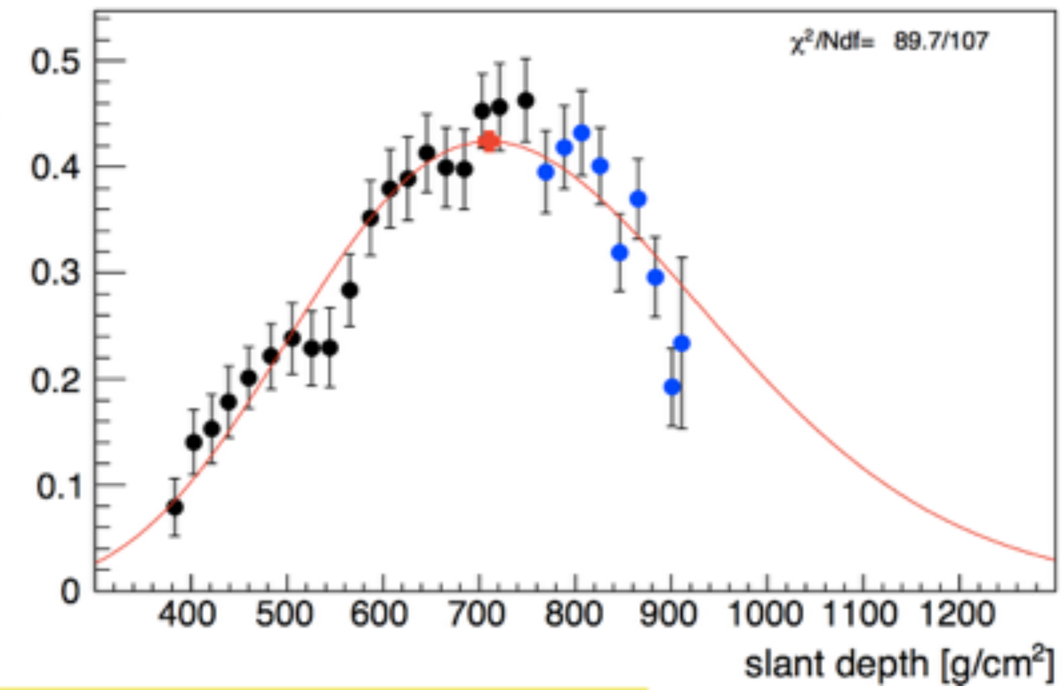
~100% duty cycle

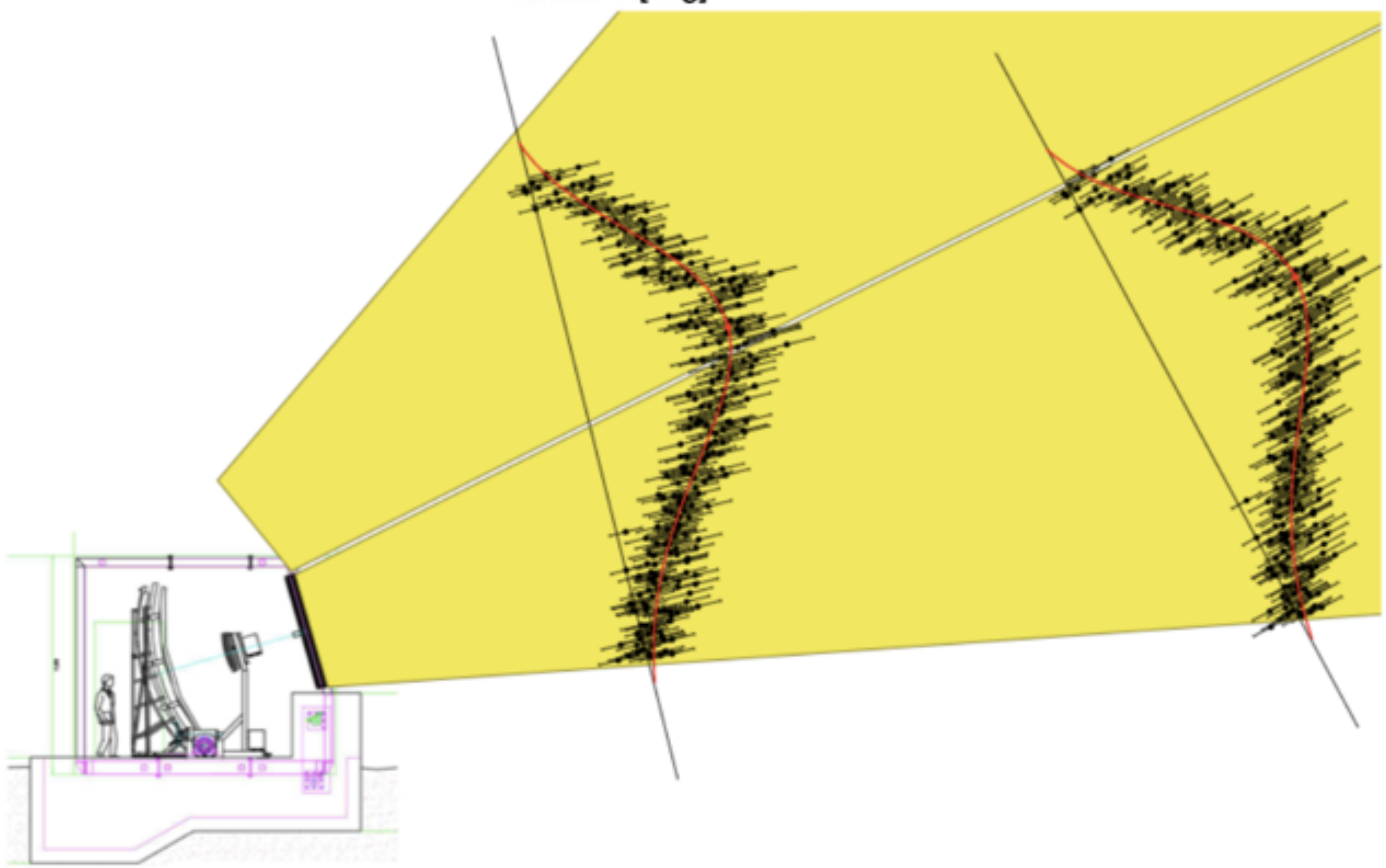
Fluorescence detectors

Fluorescence detectors

Fluorescence detectors



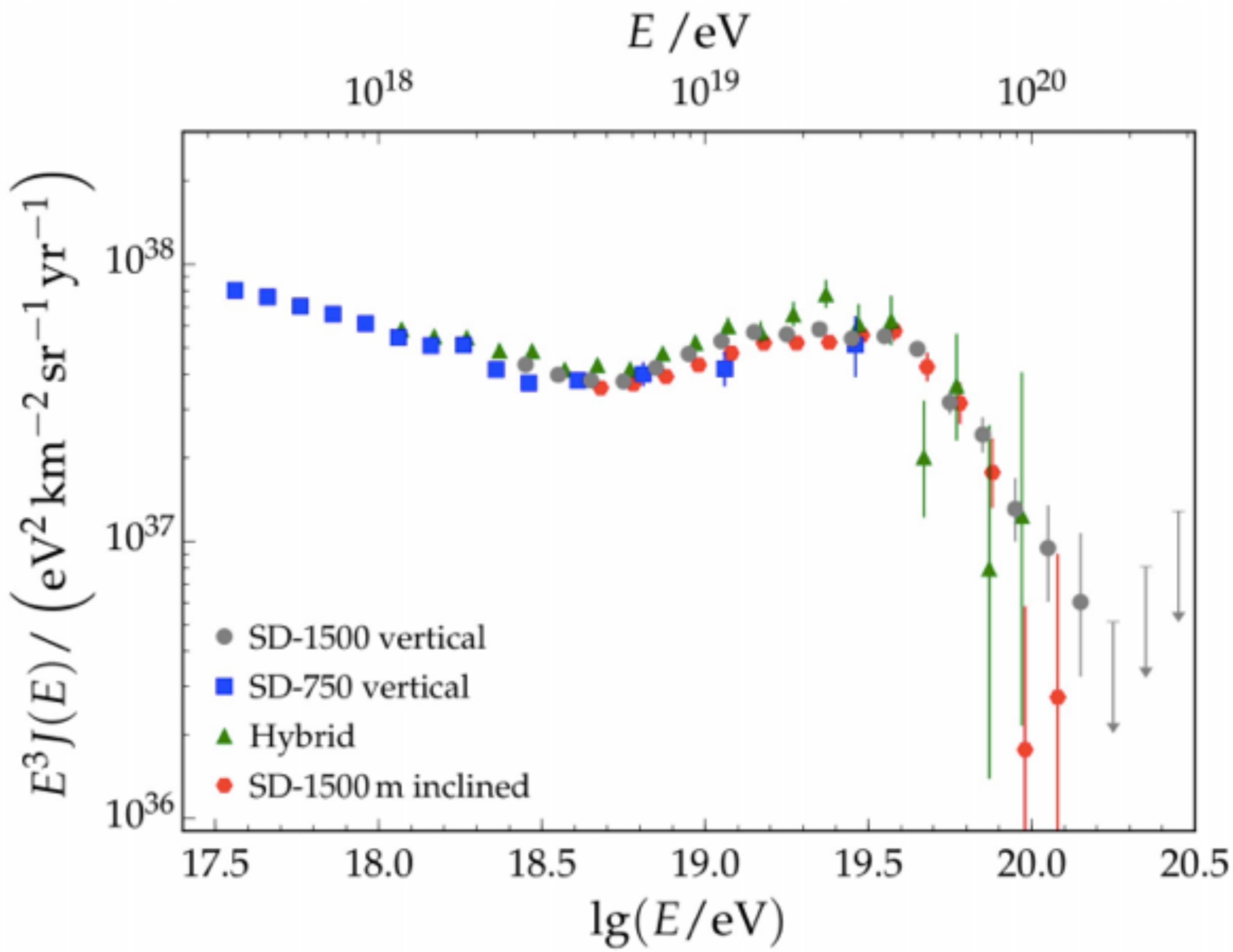




~13% duty cycle

iii) The energy spectrum and mass composition: the rise of the rigidity-dependent scenario for the maximal acceleration energy

Energy spectrum measurements



Energy systematic uncertainty
(dominated by the FD energy scale)

14%

Hybrid
11680 events
log(E)>18
Exposure: 1946 km^2 sr yr @ 10^{19} eV
(25% increase wrt 2015)

Flux uncertainty: 10%

SD-1500 inclined
19602 events
log(E) >18.5
Exposure: 15121 km^2 sr yr
(38% increase wrt 2015)

Flux uncertainty: 5%

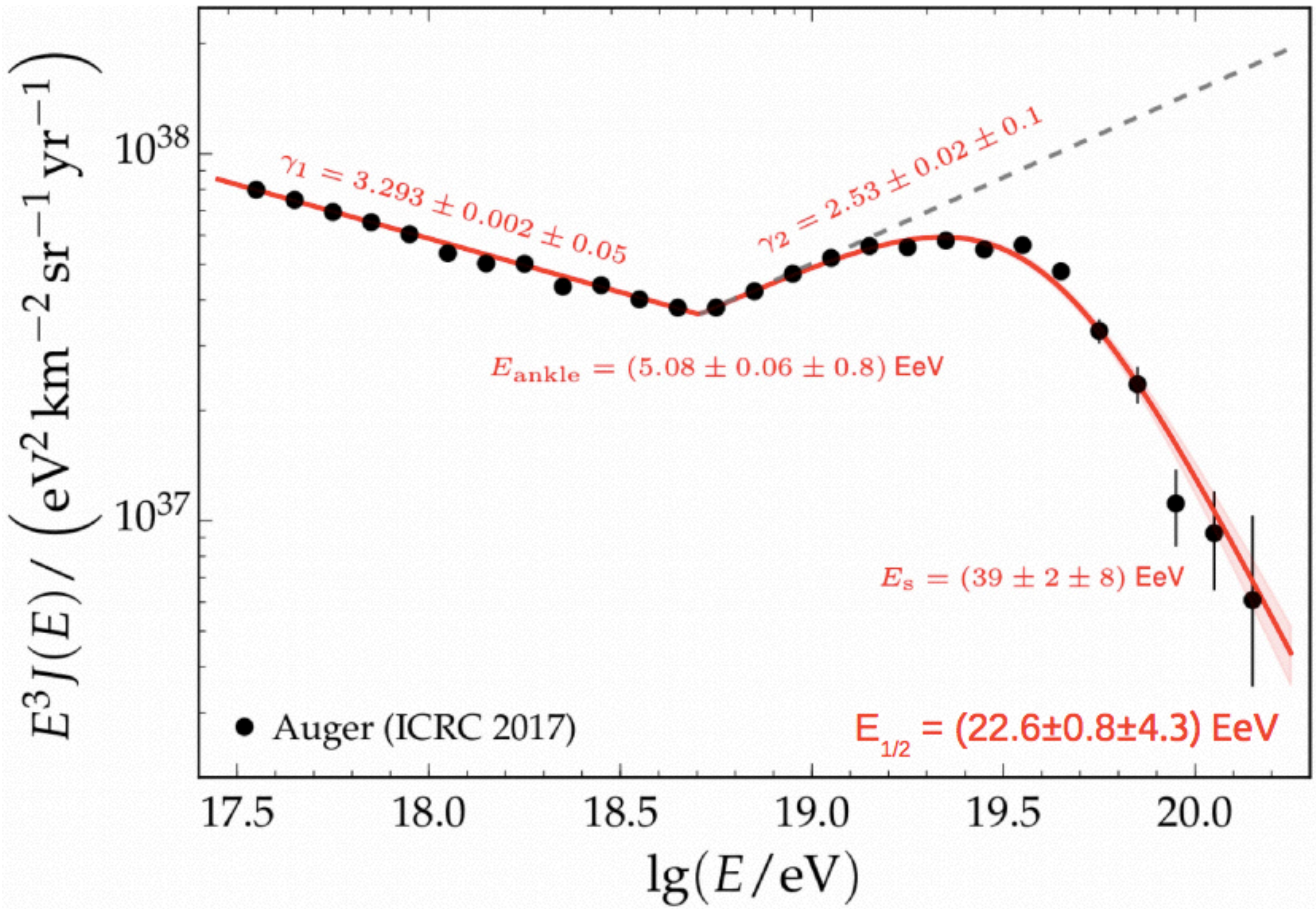
SD-1500 vertical
183332 events
log(E)>18.4
Exposure: 51588 km^2 sr yr
(20% increase wrt 2015)

Flux uncertainty: 5.8%

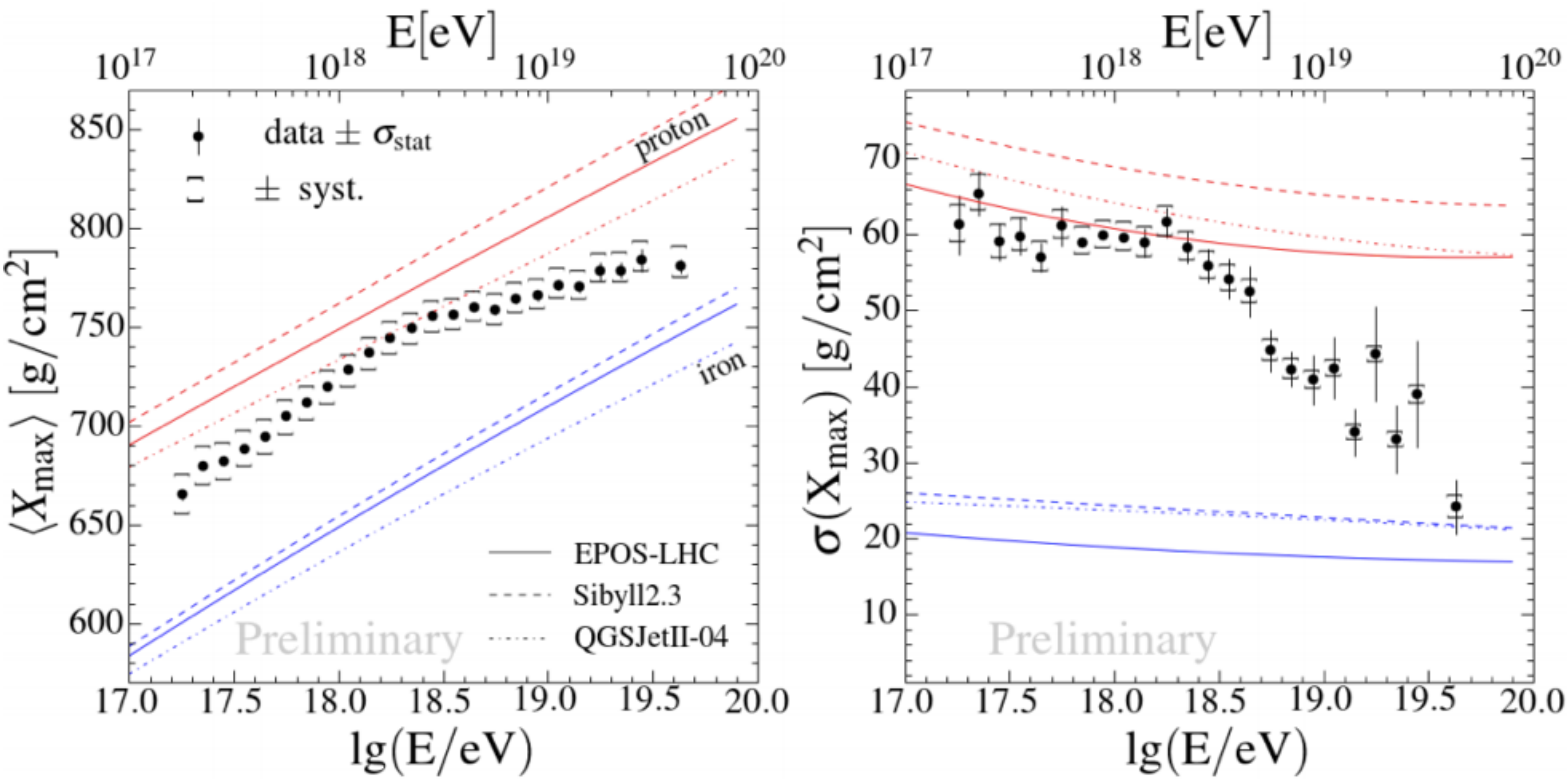
SD-750 vertical
87402 events
log(E)>17.5
Exposure 228 km^2 sr yr
(50% increase wrt 2015)

Flux uncertainty 14 – 7% @ (0.3 – 3) EeV

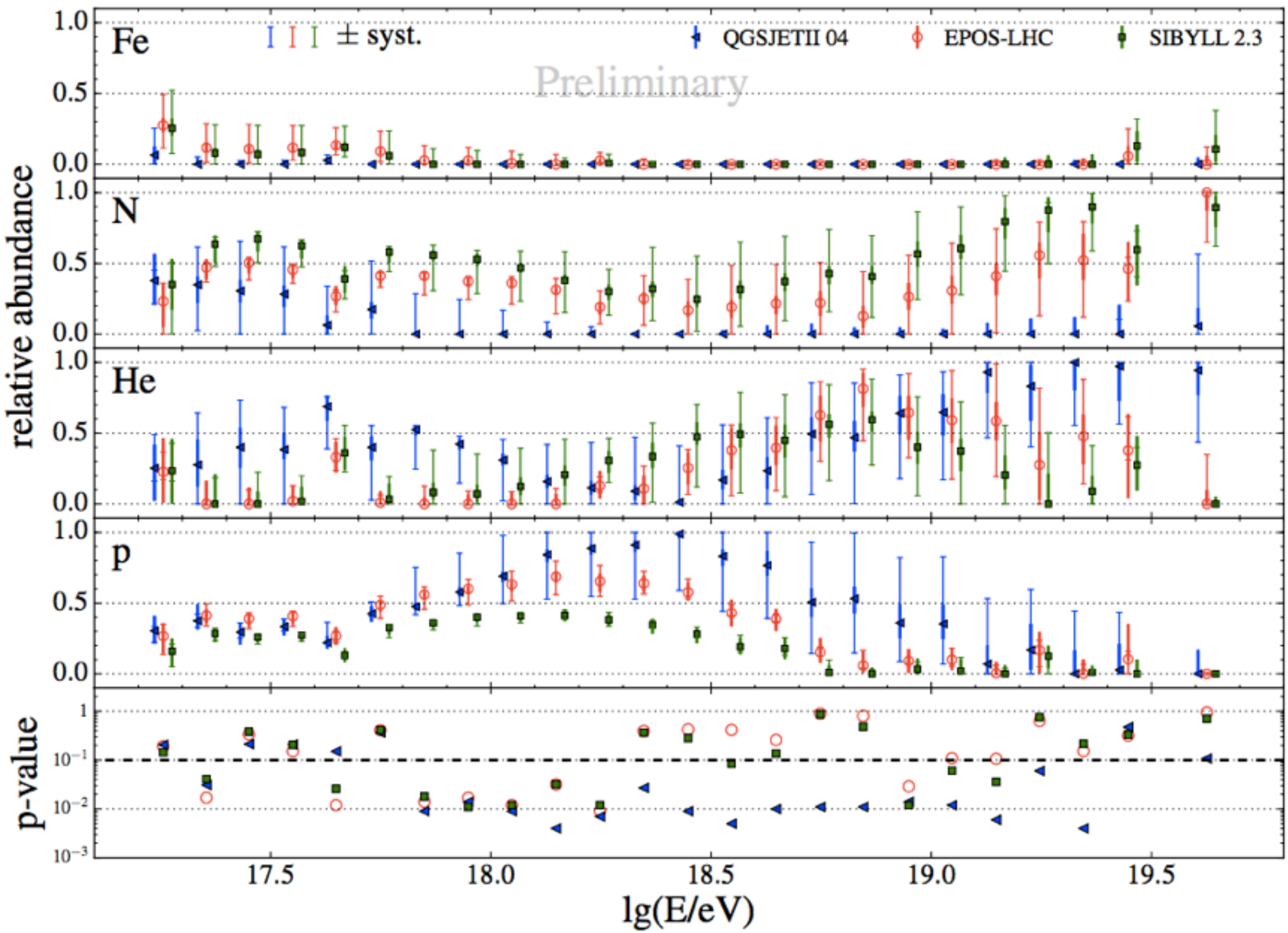
Energy spectrum



$X_{\max}$ moments



X_{max} distributions



Interpretation of spectrum and $X_{\max}$ data

[Auger coll., JCAP 04(2017)038 — see also Aloisio, Berezinsky & Blasi, JCAP 1410(2014)10]

✦ The $X_{\max}$ measurements suggest a scenario with a **rigidity-dependent** maximum acceleration energy at the sources

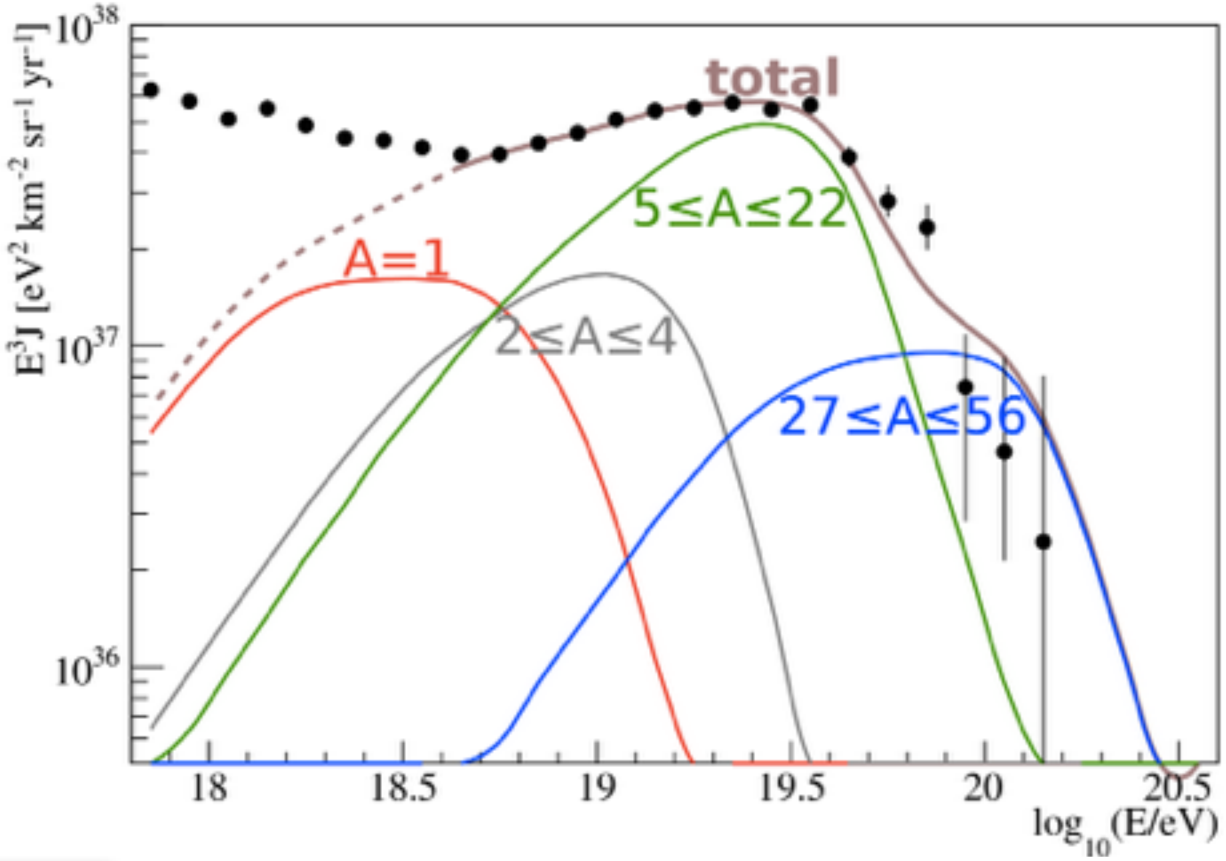
➡ Fit > $10^{18.7}$ eV both the energy spectrum and the $X_{\max}$ measurements following a simple astrophysical scenario:

- Identical sources homogeneously distributed in a comoving volume
- Injection consisting only of ^{1}H, ^{4}He, ^{14}N, ^{56}Fe (approximately equally spaced in ln$A$)
- Power-law spectrum at the sources with rigidity-dependent broken exponential cutoff:

$$\frac{\mathrm{d}N_{\mathrm{inj},i}}{\mathrm{d}E} = \begin{cases} J_0 p_i \left(\frac{E}{E_0}\right)^{-\gamma}, & E/Z_i < R_{\mathrm{cut}} \\ J_0 p_i \left(\frac{E}{E_0}\right)^{-\gamma} \exp\left(1 - \frac{E}{Z_i R_{\mathrm{cut}}}\right), & E/Z_i > R_{\mathrm{cut}} \end{cases}$$

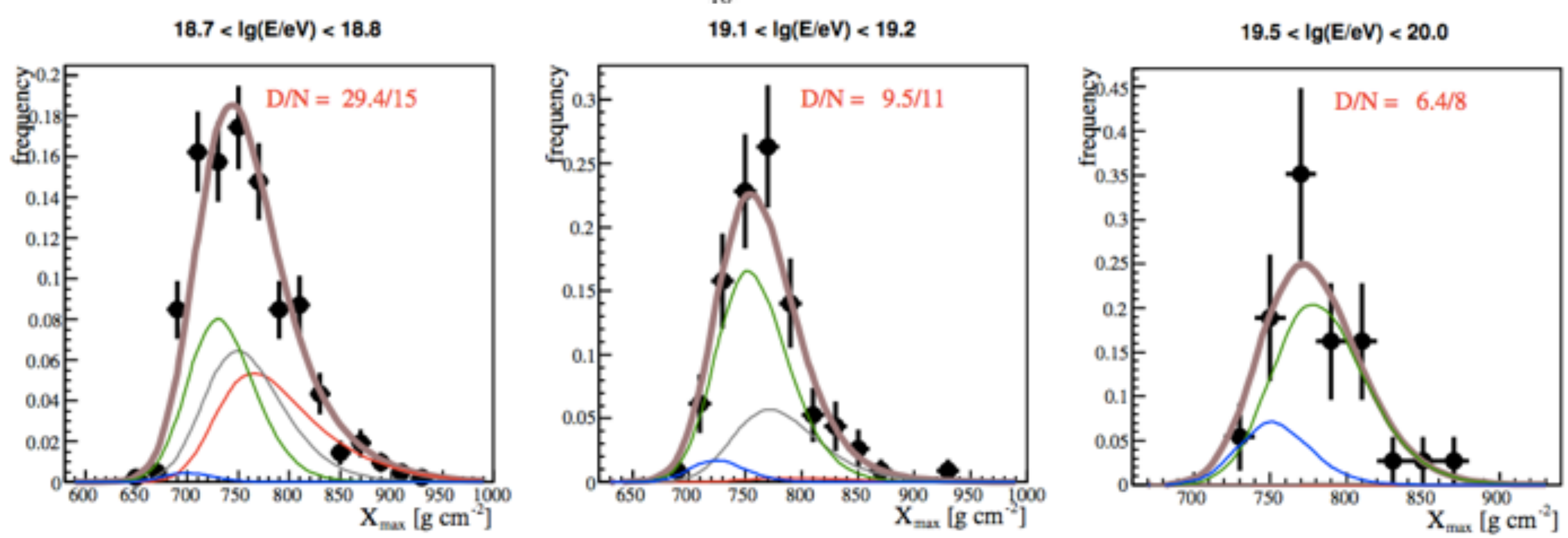
➡6 free parameters: $(J_0, \gamma, R_{\mathrm{cut}}, p_{\mathrm{H}}, p_{\mathrm{He}}, p_{\mathrm{N}})$; $p_{\mathrm{Fe}} = 1 - p_{\mathrm{H}} - p_{\mathrm{He}} - p_{\mathrm{N}}$

Energy Loss vs Max. Acceleration Energy



- ➡ Hard spectral index, meal-rich injection, low cutoff (R_{cut}~$10^{18.7}$ V)
- Mainly due to narrow X_{max} distributions (little mixing of different masses at the same energy)

- **NB: Relies on extrapolations of the mass at UHE**



- red: $A = 1$
- gray: $2 \leq A \leq 4$
- green: $5 \leq A \leq 22$
- blue: $A \geq 23$
- thick brown: total
- **black dots:** Auger data

iv) Extragalactic pattern of cosmic-ray arrival directions above 8×10^{18} eV

All extragalactic?

THE

PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics

VOL. 47, No. 11 JUNE 1, 1935 SECOND SERIES

An Apparent Effect of Galactic Rotation on the Intensity of Cosmic Rays

ARTHUR H. COMPTON, *University of Chicago and Oxford University* AND IVAN A. GETTING, *Oxford University*

(Received April 12, 1935)

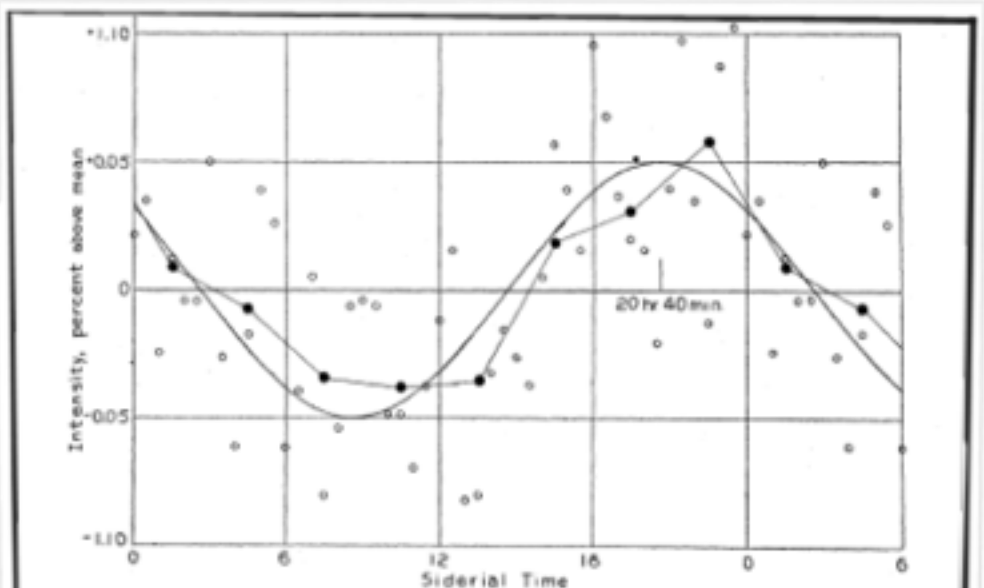


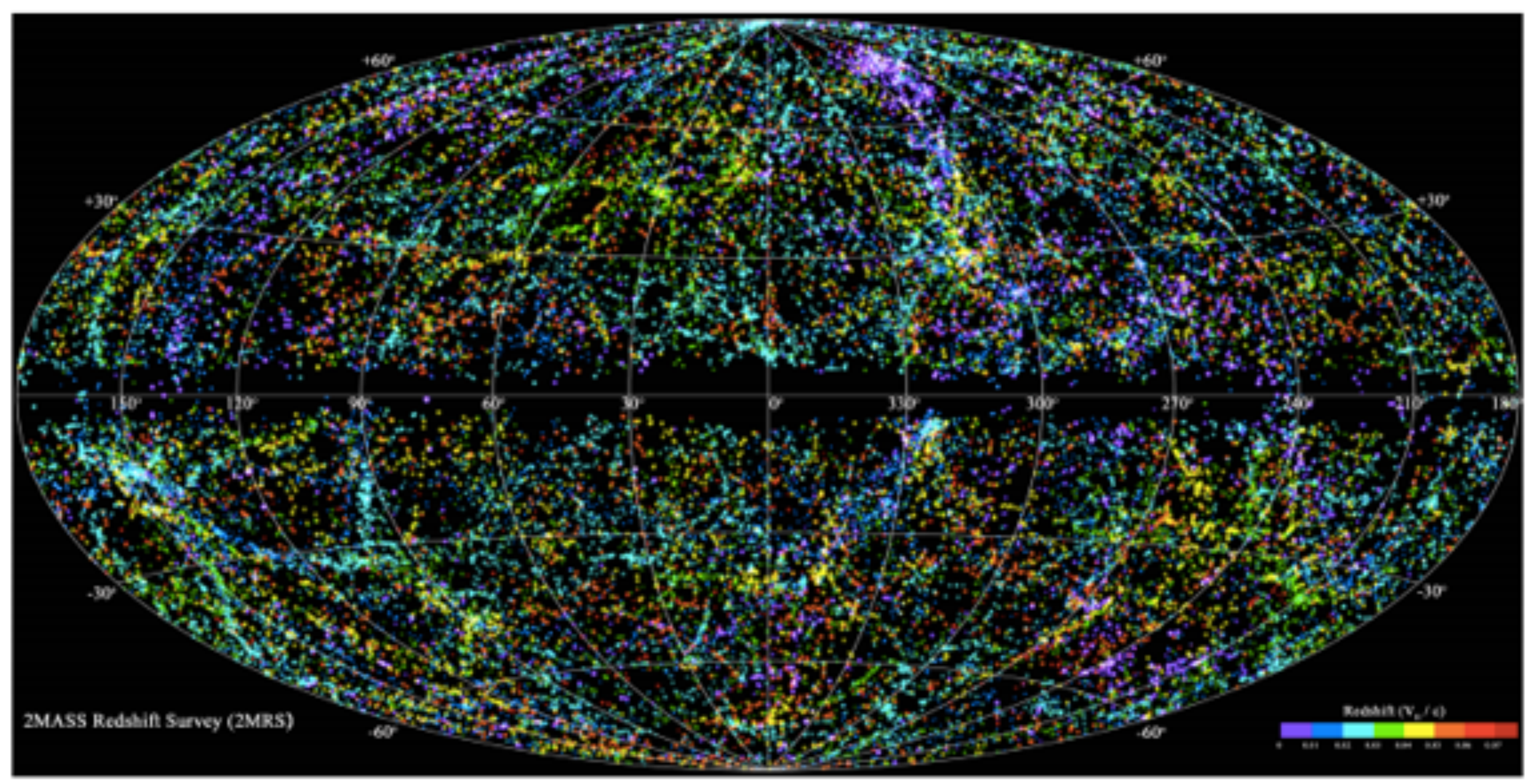
FIG. 2. Percentage variation in intensity of the cosmic rays with sidereal time. Curve, predicted effect due to galactic rotation. Data, Hess and Steinmaurer; open circles, half-hour means; solid circle, 3-hour means.

While we must await some such measurements before we can consider the effect due to the rotation of the galaxy as established, the quantitative agreement with the predictions as shown in Fig. 2 gives a strong presumption in its favor. Its existence would imply that an important part of the cosmic rays originates outside of our galaxy. If its magnitude is found to be as great as we have predicted, it will imply that practically all the cosmic radiation has an extragalactic origin.

Large-scale anisotropies

- Galactic origin: strong anisotropies suggestive of the Milky way structure
- Extragalactic origin: inhomogeneous large-scale distribution of nearby sources
- Many dependences: source distribution, CR composition, nearby dominating sources, magnetic fields…

2MASS redshift survey



Harmonic analysis

- **Weighted harmonic analysis**

$$a^x = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \cos x_i \quad , \quad b^x = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \sin x_i$$

α: right ascension

ϕ: azimuth

x = α or ϕ $\qquad \mathcal{N} = \sum_{i=1}^{N} w_i$

weights $\longrightarrow$ **small variations in coverage and tilt of the array**

[ApJ suppl. 203 (2012) 34]

$$r^\alpha = \sqrt{(a^\alpha)^2 + (b^\alpha)^2} \ , \ \varphi^\alpha = \text{atan} \frac{b^\alpha}{a^\alpha}$$

Amplitude and phase of the first harmonic modulation

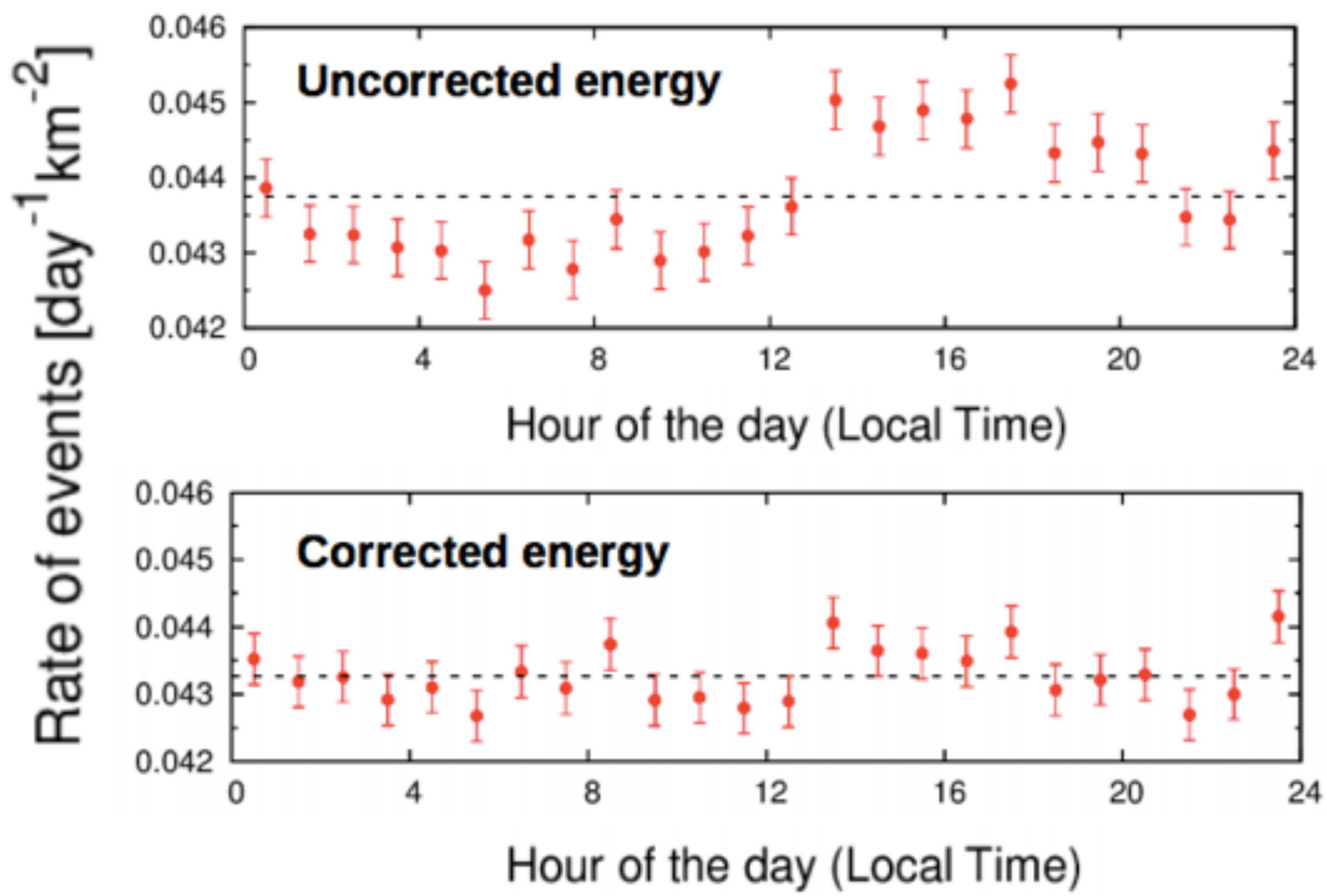
- **p.d.f. for amplitude/phase known for isotropy/anisotropy** [Linsley, 1975]

Control of the event rate

- **Energies corrected by atmospheric changes for θ < 60º**
  - Air-density ⟶ lateral distribution of EM component
  - Pressure ⟶ longitudinal depth of observation

  [Auger Coll. JINST 12 (2017) P02006]

Induces modulations of ±1.7% in solar frequency



Negligible effects at 60º < θ < 80º (EM component suppressed)

- **Geomagnetic field breaks circular symmetry of showers**

Effect accounted in energy estimation
[Auger Coll. JCAP 11 (2011) 022]

azimuth spurious modulation ~0.7%

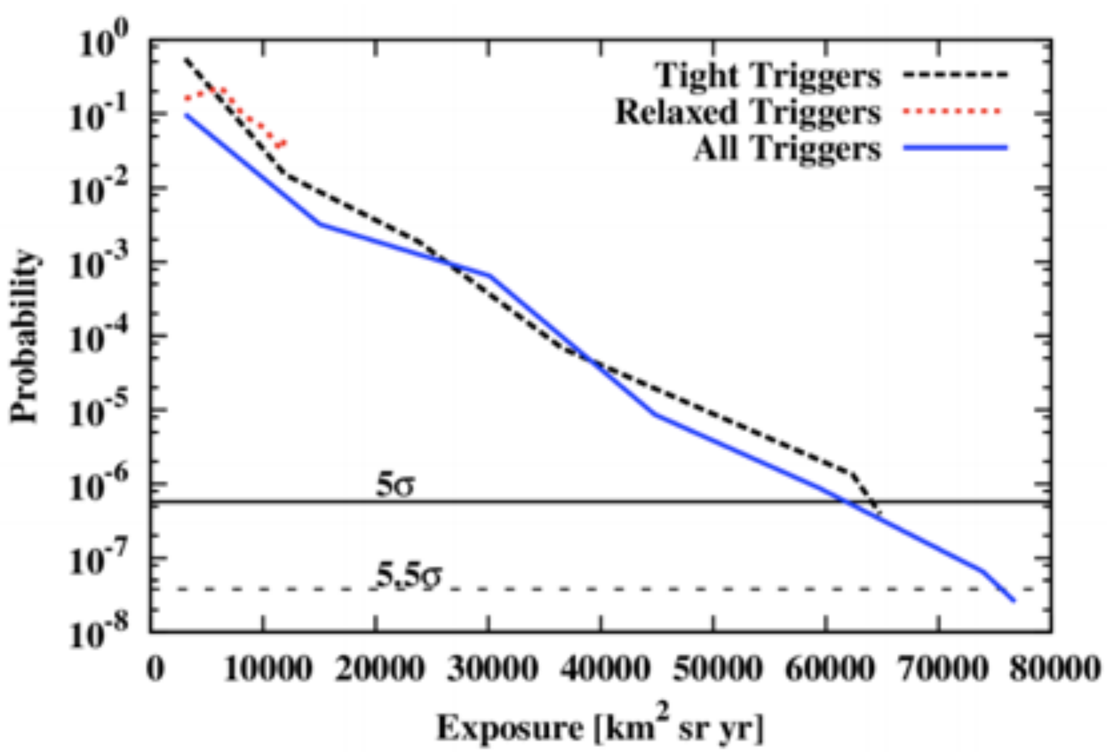
First harmonic in right ascension

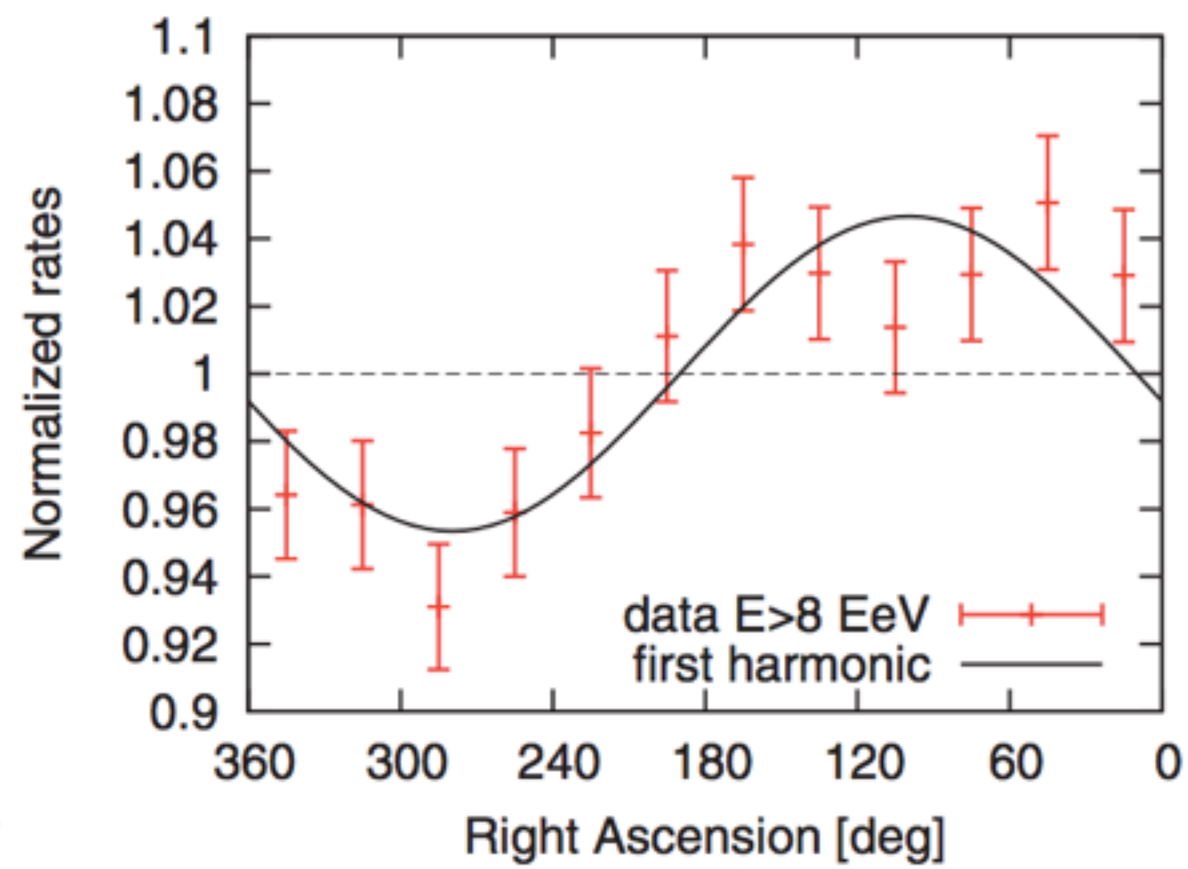
E [EeV]	N	a^α	b^α	r^α	φ^α [°]	$P(\geq r^\alpha)$
4 - 8	81 701	0.001 ± 0.005	0.005 ± 0.005	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
≥ 8	32 187	-0.008 ± 0.008	0.046 ± 0.008	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

Table 1: Results of the first harmonic analysis in right ascension.

[4 – 8] EeV: compatible with isotropy → $r^\alpha < 0.012$ @ 95% CL

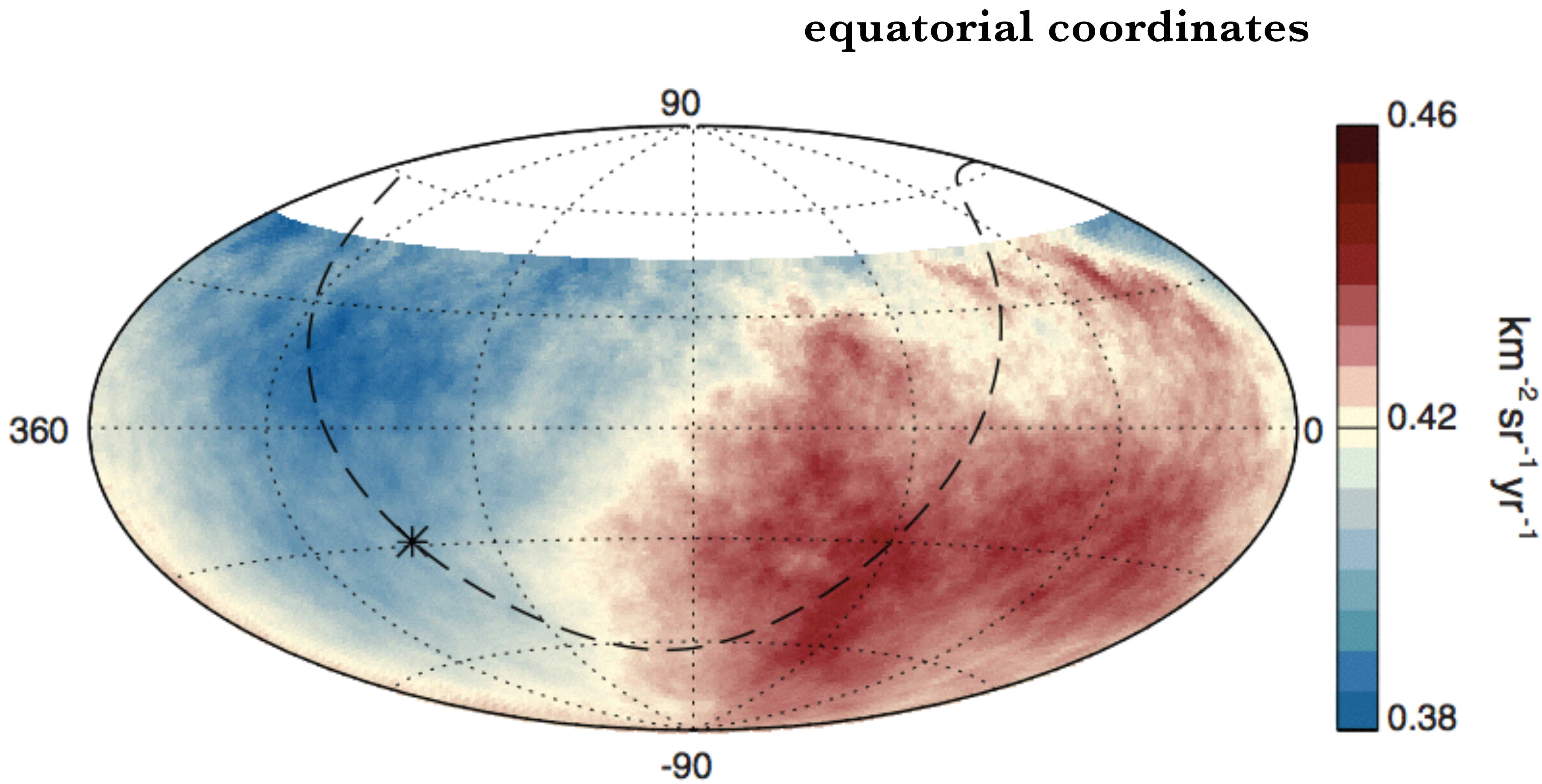
E > 8 EeV: significant modulation @ 5.6σ → *p*-value ~20 times smaller than the 5σ discovery limit[1]





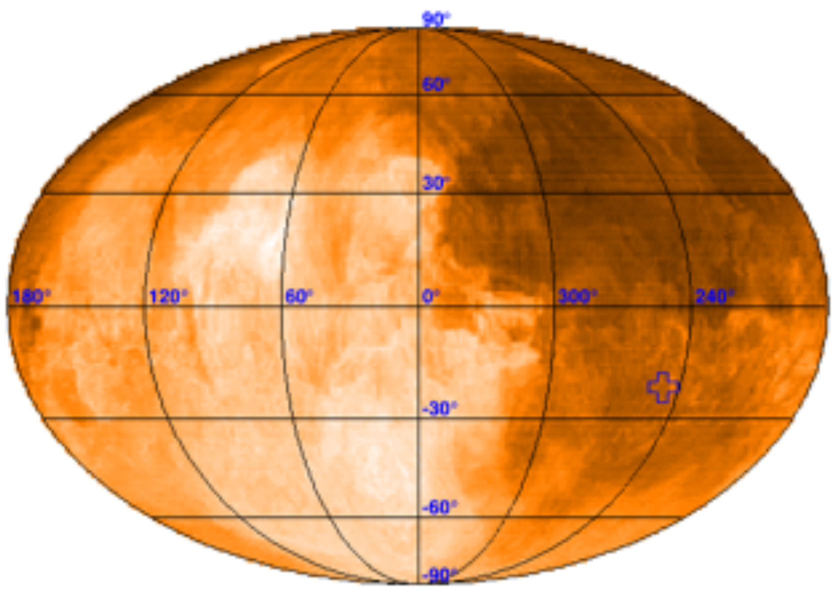
[1]penalizing for the energy bins explored → significance above 5.2σ

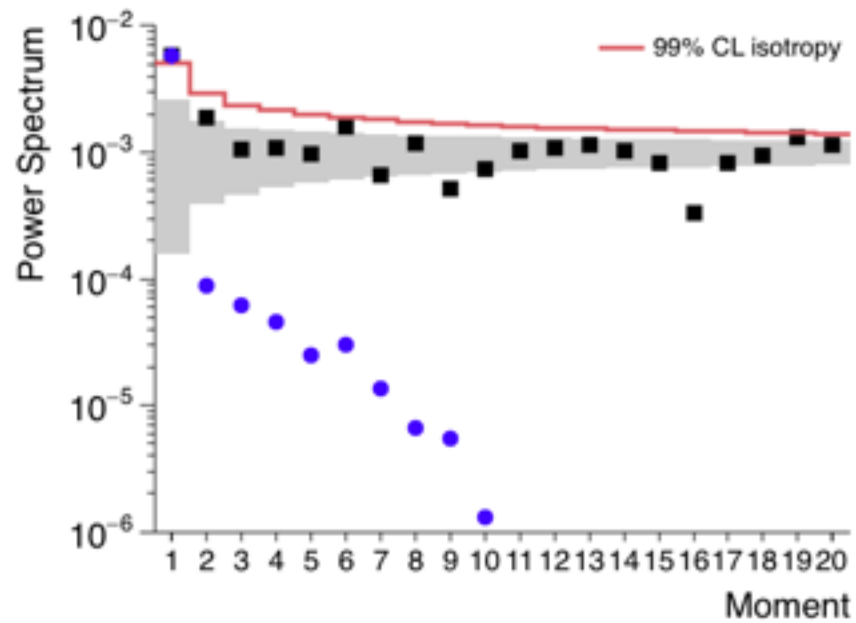
Flux pattern on the sphere



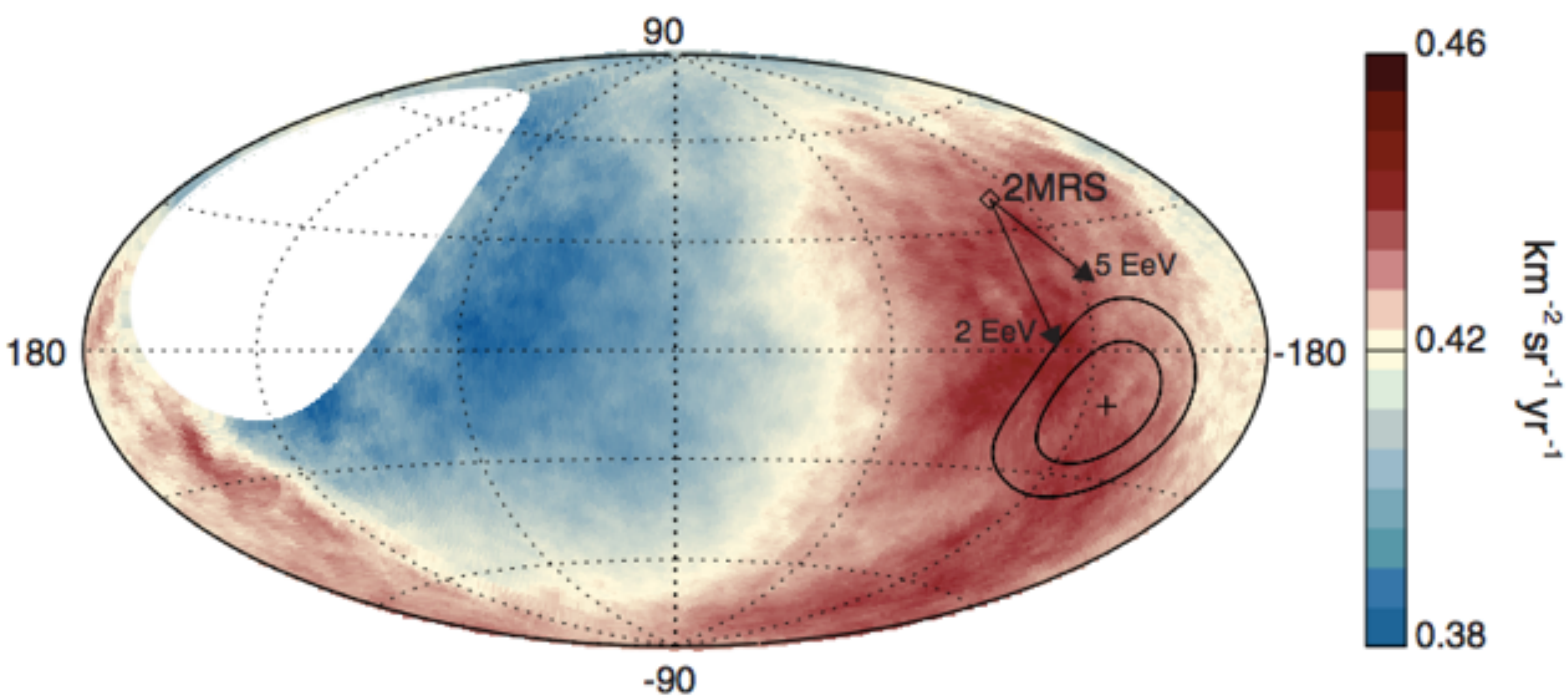
Observational evidence of extragalactic UHECRs

Benchmark-scenario: Dipole at the entrance of the Galaxy





- Dipole not ‘destroyed’ by the GMF (JF12 model here)
- Detection of higher orders: probe of the extragalactic CR density outside from the Galaxy



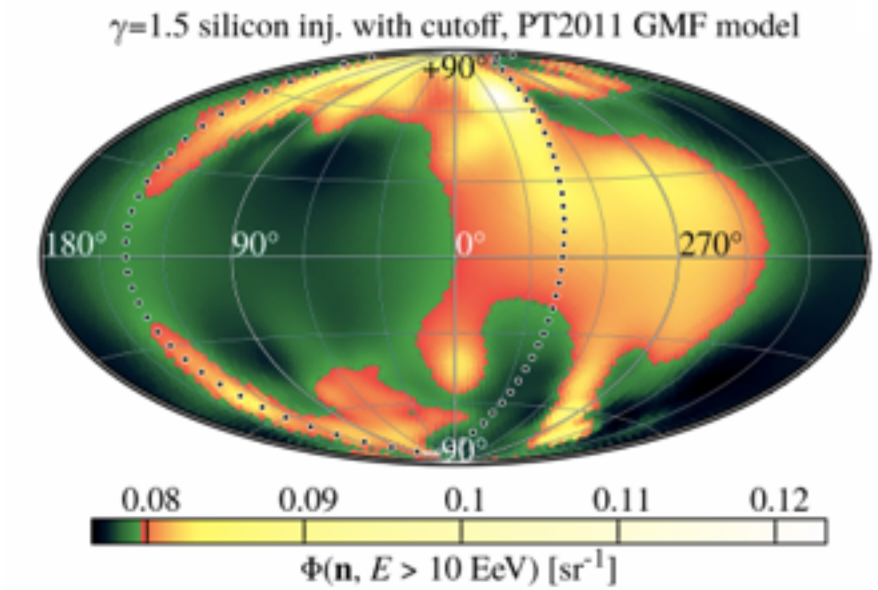
Accounting GMF deflections
[Jansson and Farrar ApJ 757 (2012) 14]
Z ~ 1.7 – 5 at 10 EeV ⟶ E/Z ~ 2 – 5 EeV
[Auger Coll. PRD 90 (2014) 122006]

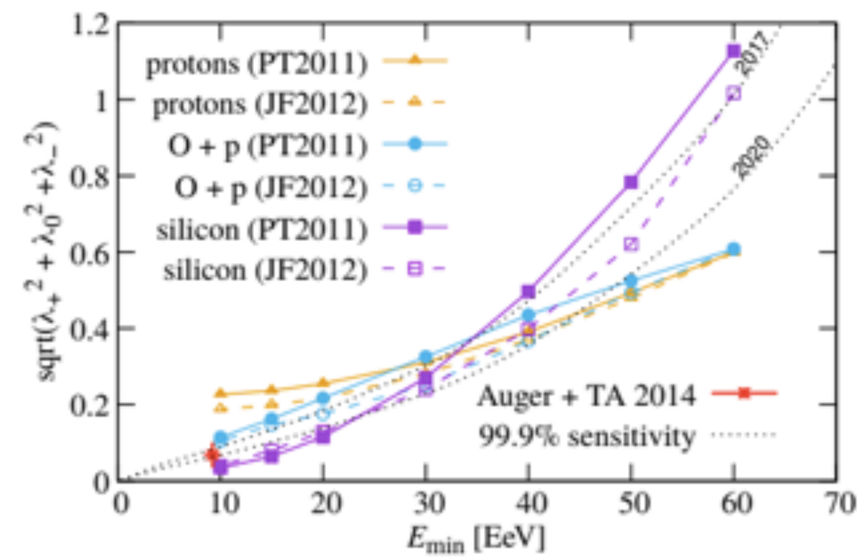
Flux pattern on the sphere

Higher order multipole signatures to constrain further models?

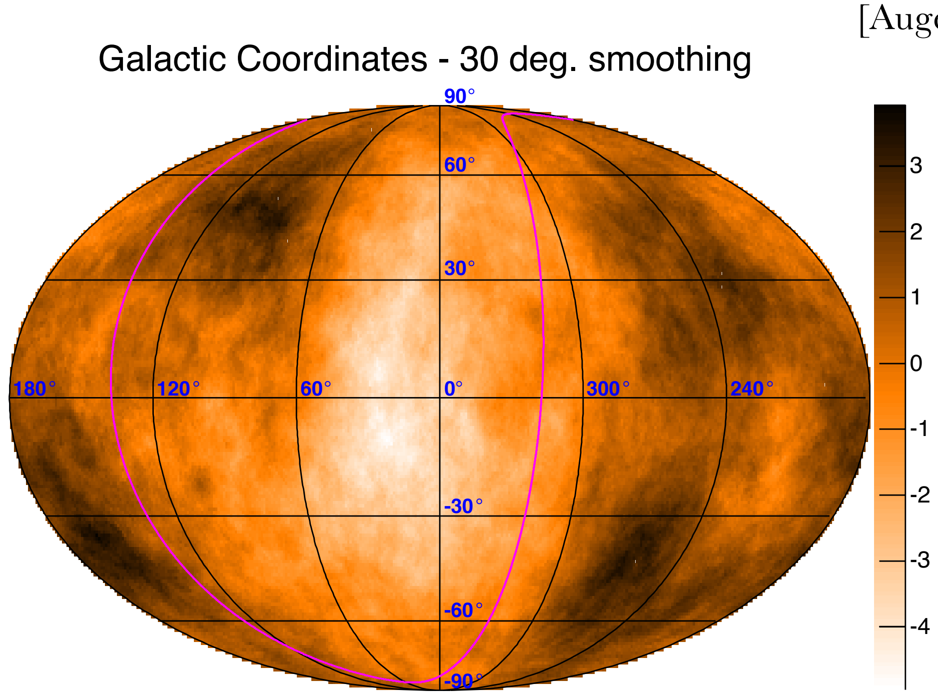
Requires full-sky coverage — joint Auger/TA analyses

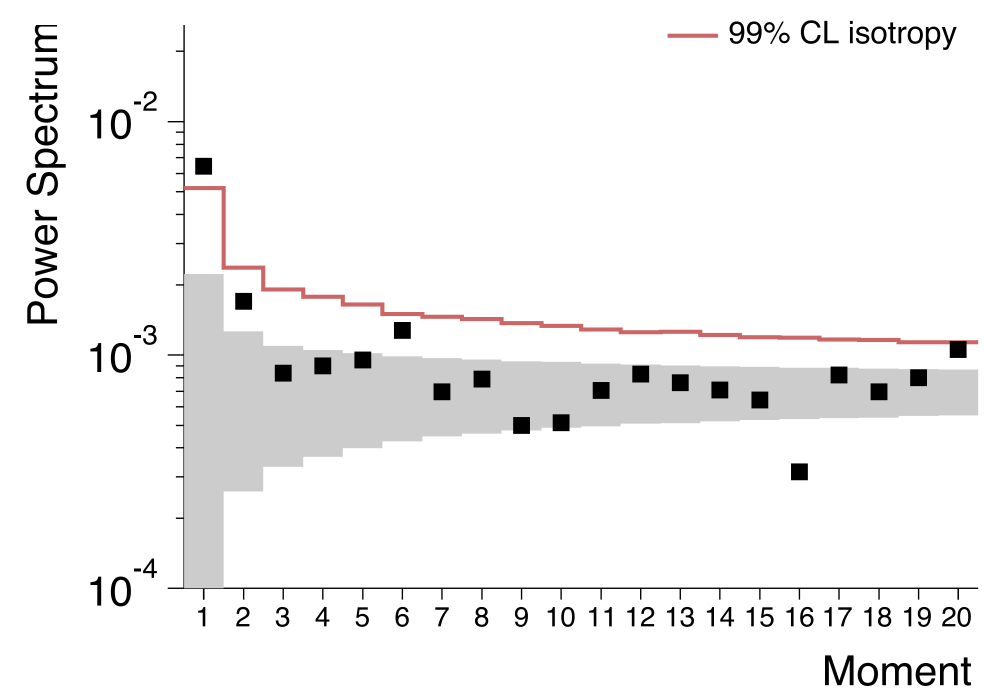
[Di Matteo & Tyniakov, arXiv:1706.02534]





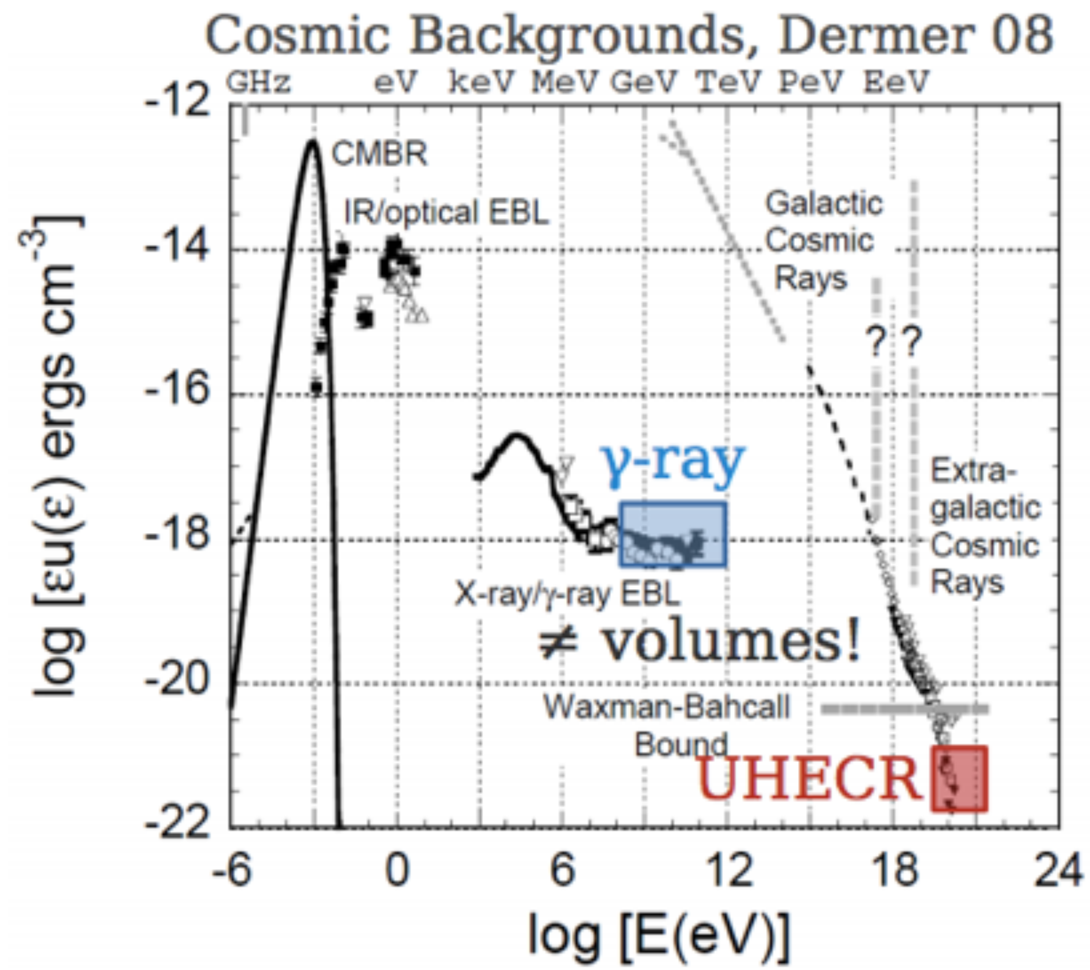
[Auger/TA coll., ICRC15]



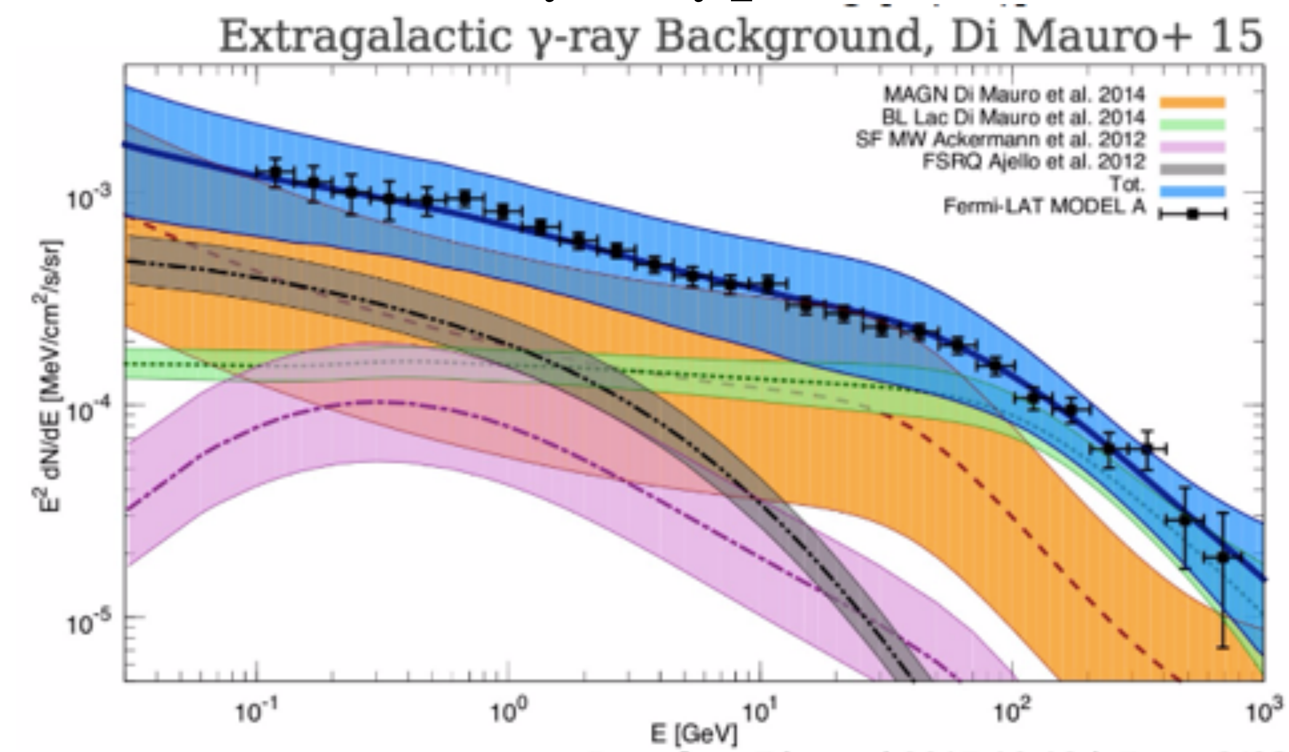


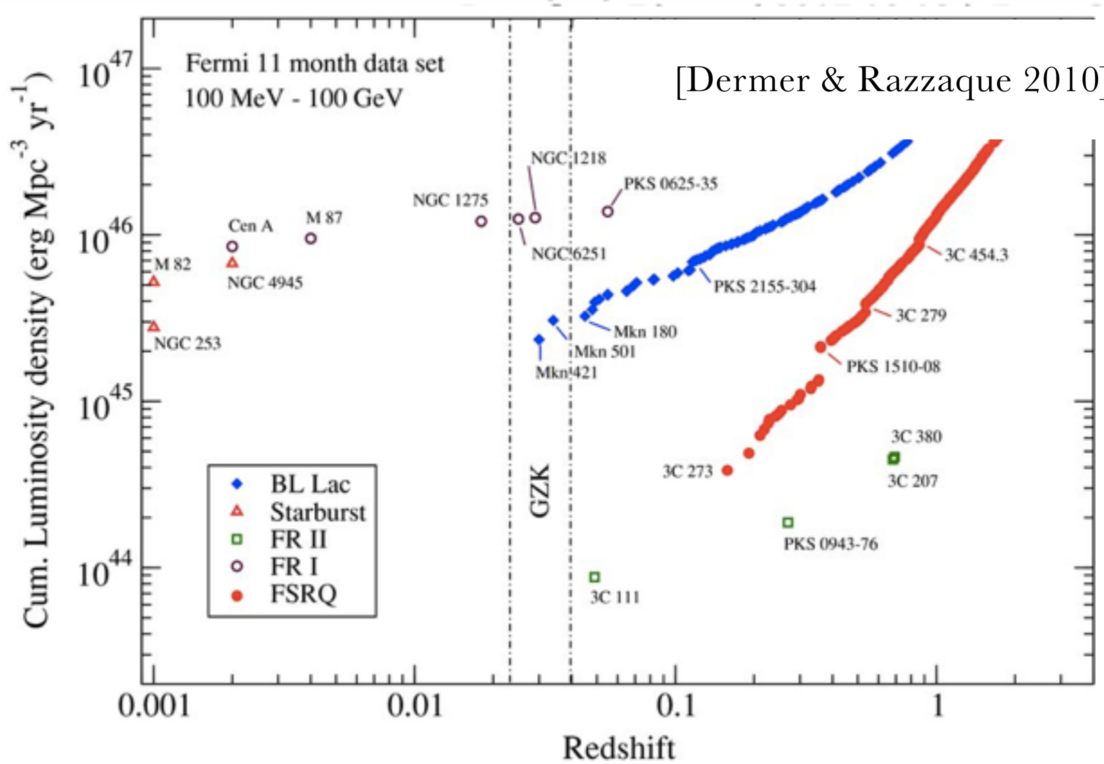
v) Correlation of UHECR arrival directions with the flux pattern of nearby star-forming galaxies

Extragalactic gamma-ray background



Extragalactic γ-ray background dominated by 2 types of sources:





UHECR source candidates: requirement on power

- >1 EeV, energy production rate close to 10^{45} erg Mpc^{-3} yr^{-1}
- Both local SBGs & AGNs match this requirement

Selection of *non-thermal* sources

Selected from the 2FHL catalog (*Fermi*-LAT, >50 GeV), within 250 Mpc
[Ackermann *et al.*, 2016]
(leptonic processes preferred)

Selected from *Fermi*-LAT search list (HCN survey) within 250 Mpc, with radio flux>0.3 Jy
[Gao & Salomon, 2005]
(hadronic processes preferred)

Assumption: UHECR flux $\propto$ non-thermal photon flux

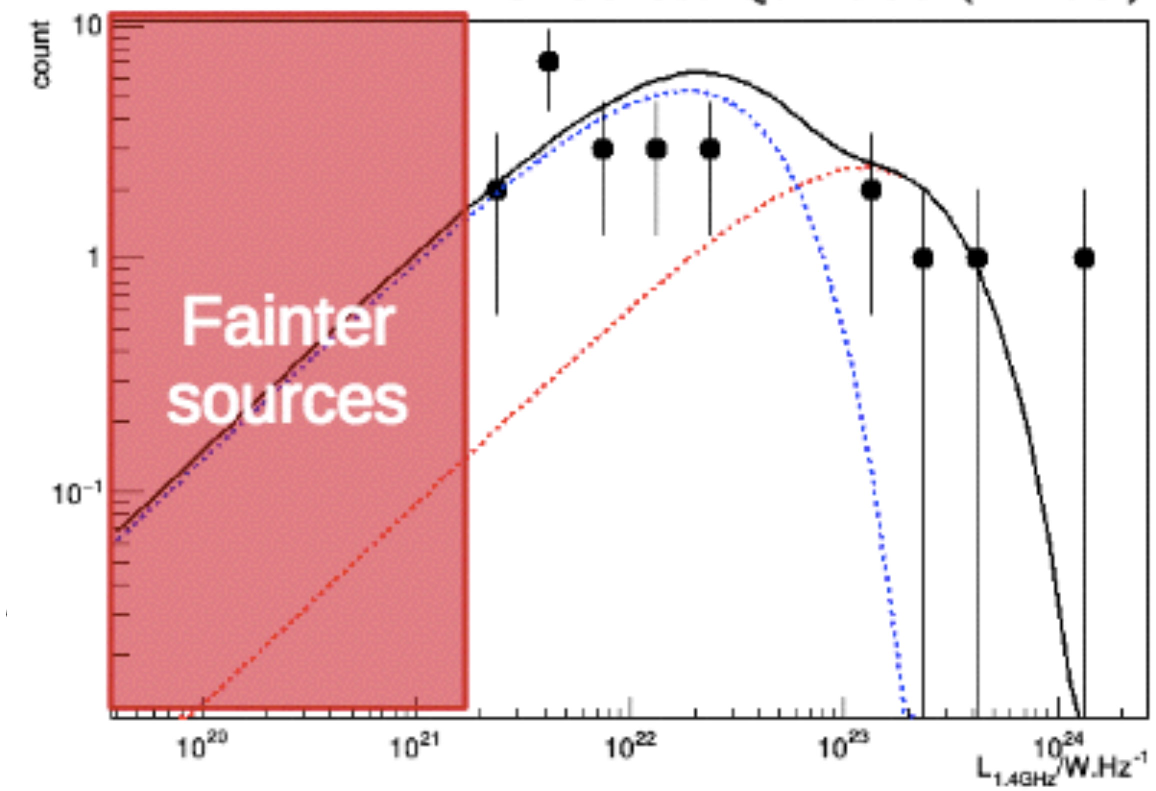
Catalog of star-forming galaxies

GeV—TeV observations

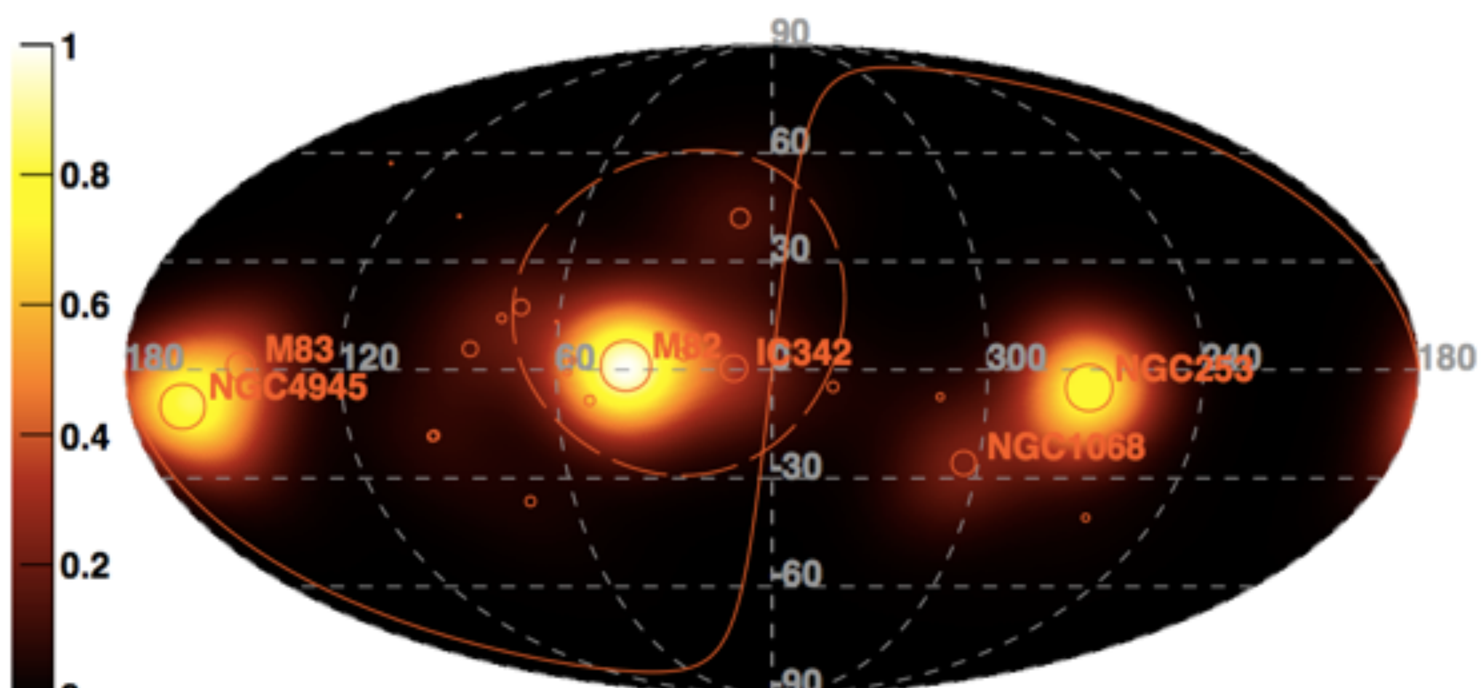
- **TeV**: M 82 (0.9% Crab), NGC 253 (0.2% Crab), NGC 4945 ⊘, NGC 1068 (<5%), M 83 (<2%)
- **GeV**: M 82, NGC 253, NCG 4945, NGC 1068 firmly detected. GeV/FIR/radio correlation

➡ Flux at 1.4 GHz used as a **proxy** for the UHECR flux

Credits: Q. Luce (IPNO)



Model Flux Map - Starburst galaxies - E > 39 EeV



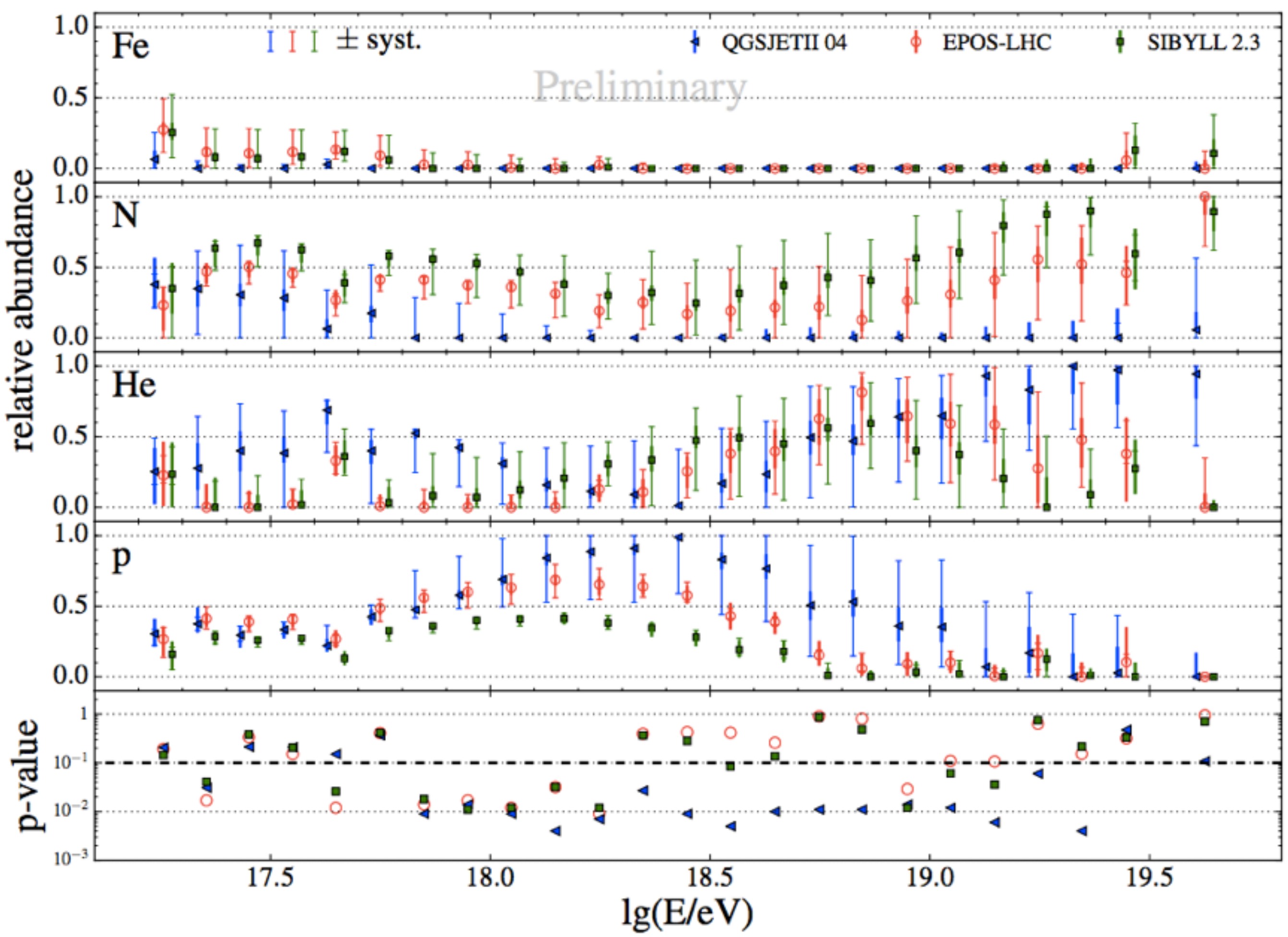
supergalactic coordinates

Selected catalog

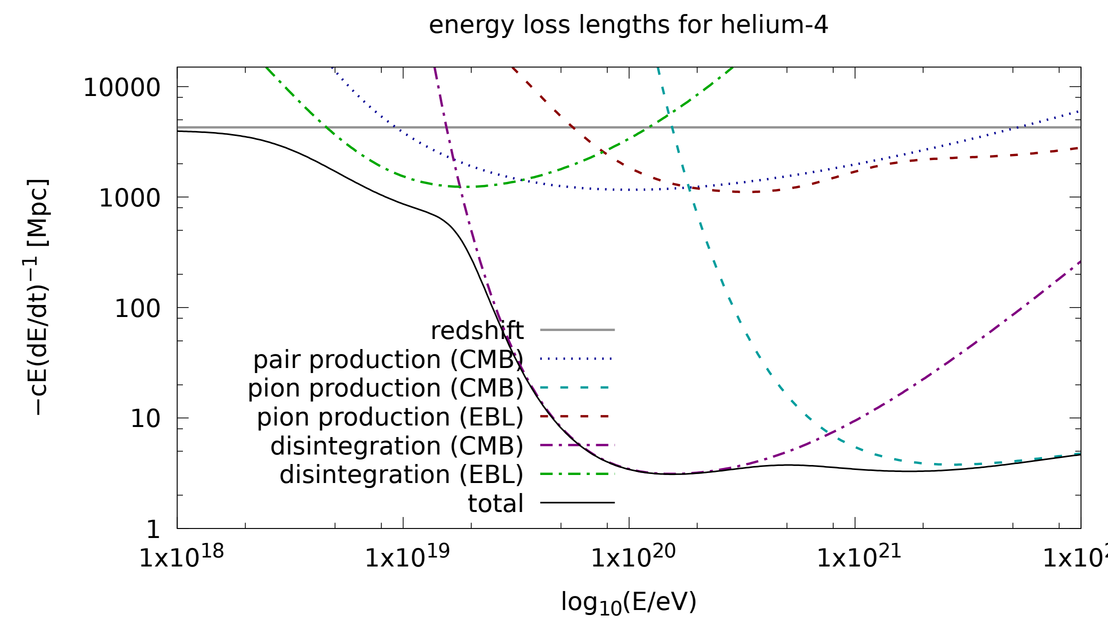
- ApJ 755, 164 (2012)
- Cut @ 0.3 Jy to maximize the completeness
- Cut that matches a ~200 Mpc GZK horizon: take the most luminous source in the sample, place it as far away as you can to detect it above 0.3 Jy → 173 Mpc
- 23 brightest (/63) — ~80% of total flux

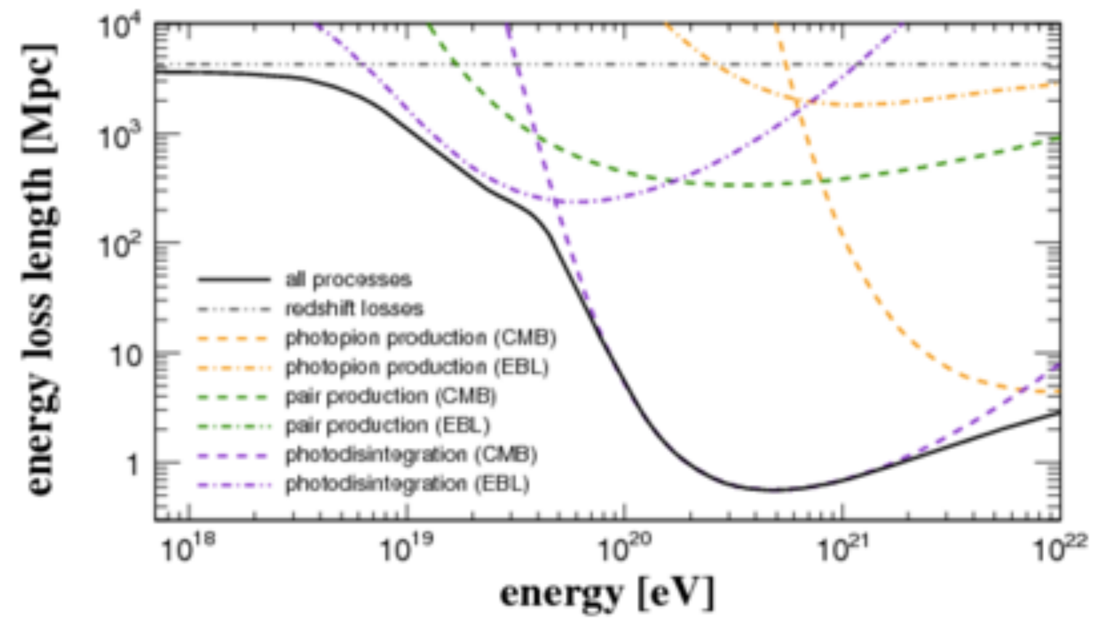
UHECR horizons

A mixture of He/CNO nuclei
in the energy range of interest



[Alves Batista, Boncioli, Di Matteo et al., JCAP10(2015)063]





☞ Small horizons already @ 30-40 EeV

Test statistics of alternative vs null

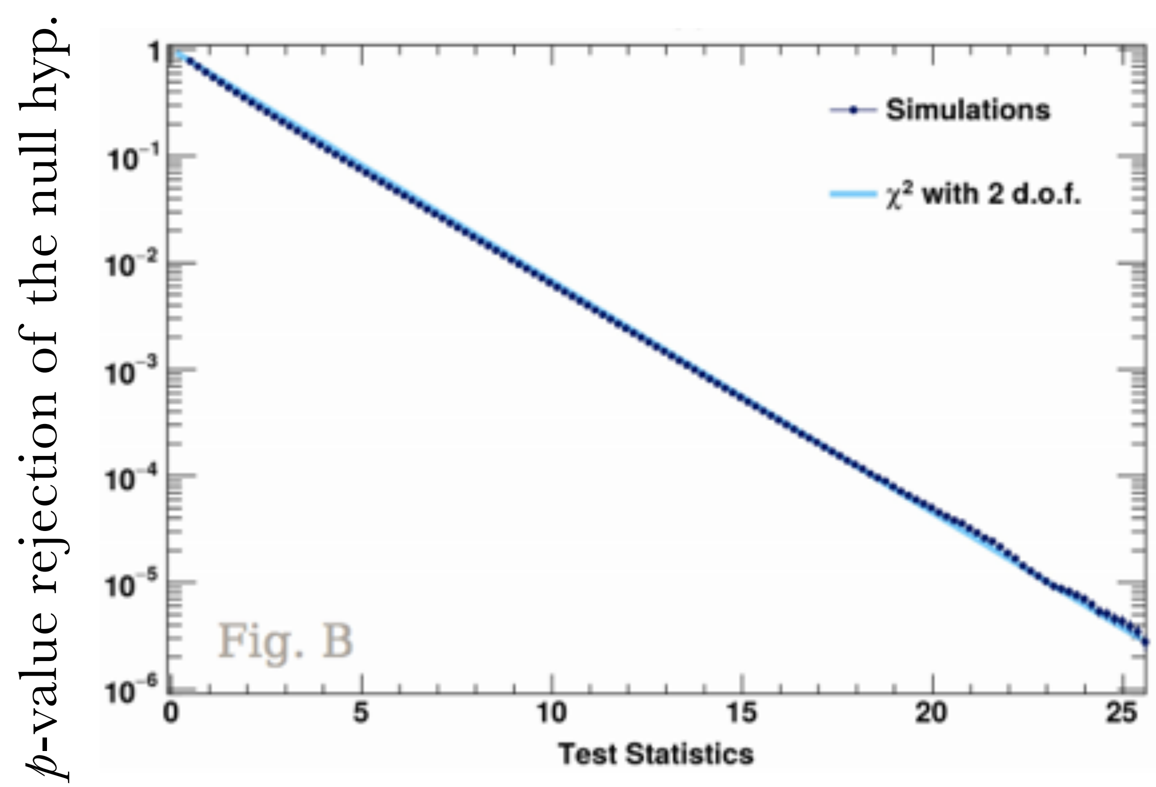
Luminosity distribution: **non-equal** sources,
flux may be dominated by strong local sources

☞ Analysis method: test arrival directions vs **density maps**

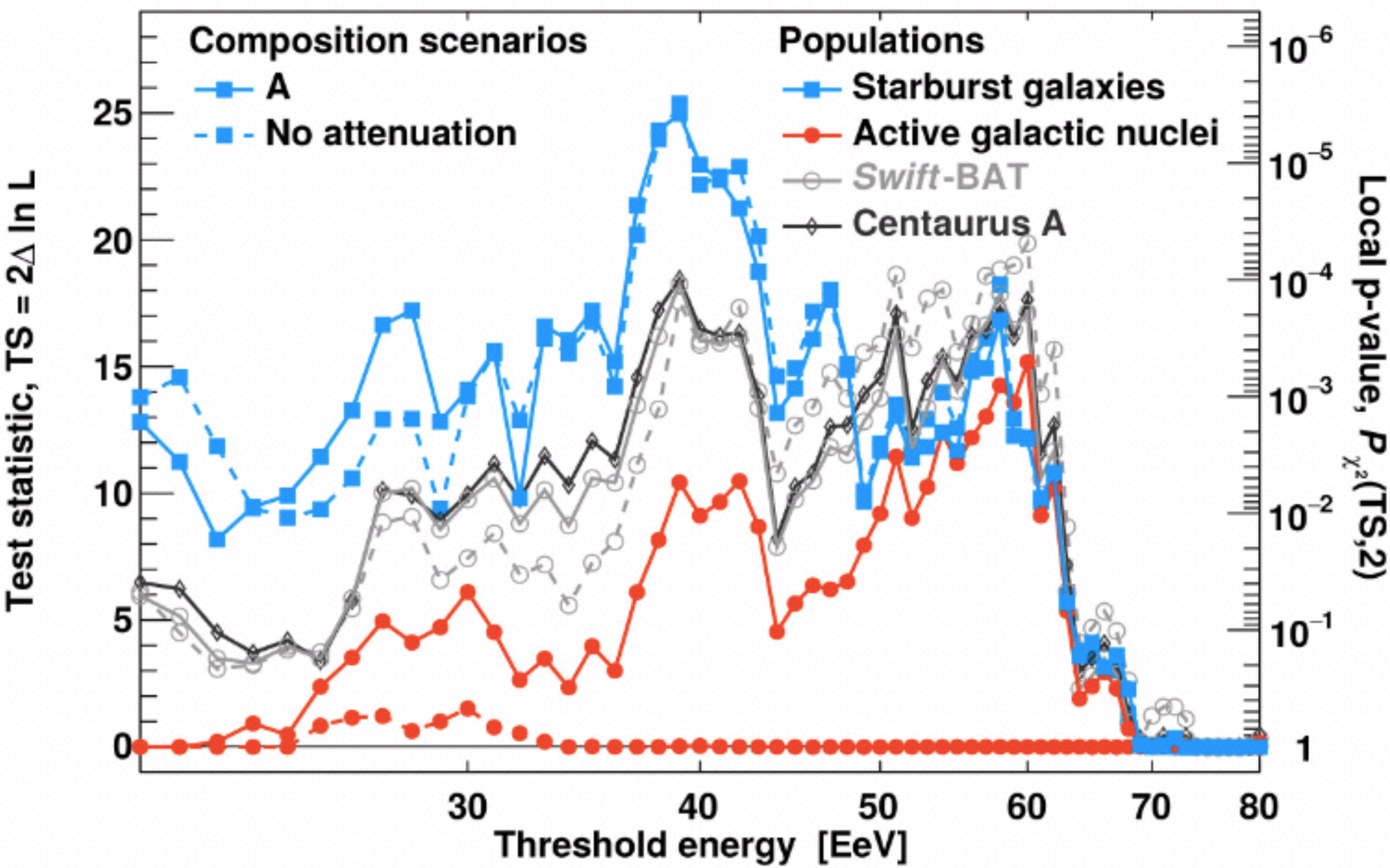
null	***alternative***
$L(-,0)=\Pi_{\text{events}}[\text{exposure}](\mathbf{n}_i)$	$L(\vartheta,\alpha)=\Pi_{\text{events}}[\text{exposure} \times \text{model}(\vartheta,\alpha)](\mathbf{n}_i)$ α: signal fraction ϑ: search radius (no magnetic offset) model: $[\alpha \times \text{sources} + (1-\alpha) \times \text{isotropy}] \otimes \text{Gauss}(\vartheta)$

Test statistics (TS): likelihood ratio

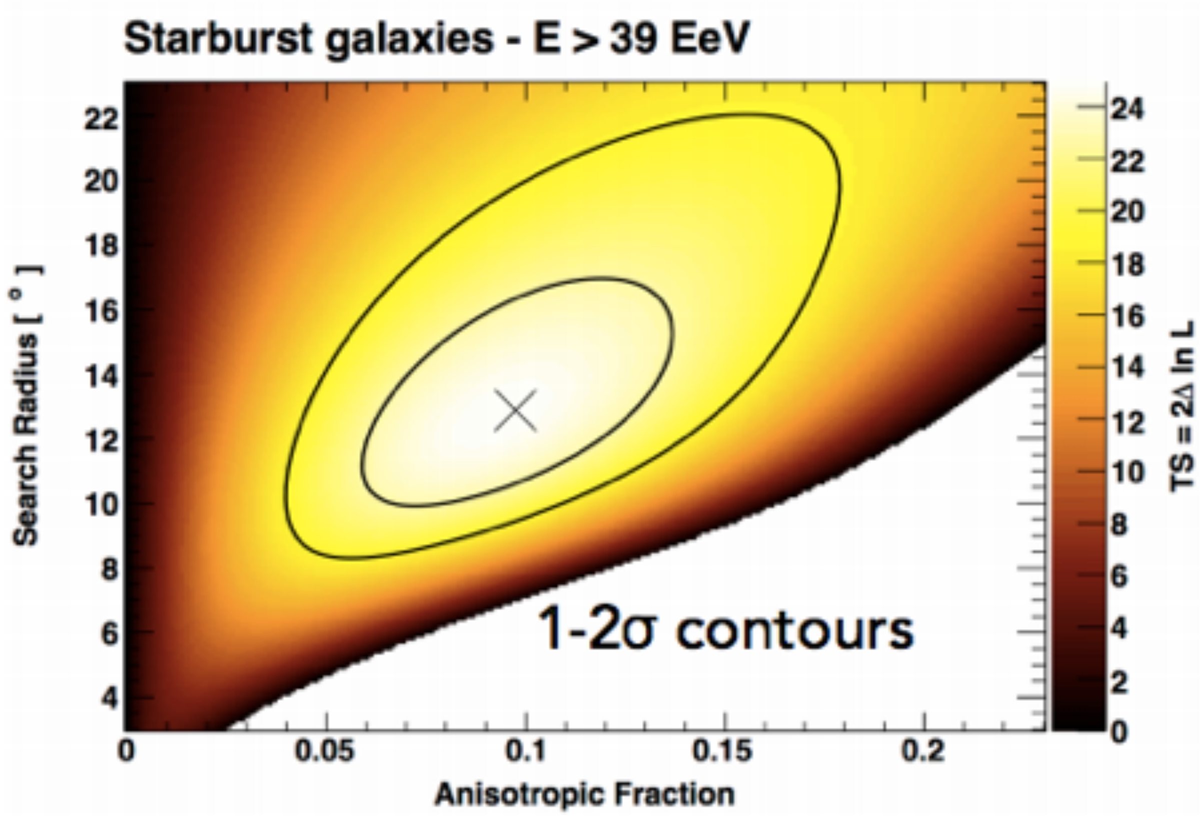
- $TS = 2 \ln(L(\vartheta,\alpha)/L(-,0))$
- **Nested** hypotheses: TS is $\boldsymbol{\chi}^2$-distributed with 2 d.o.f. (2 free parameters ϑ,α)

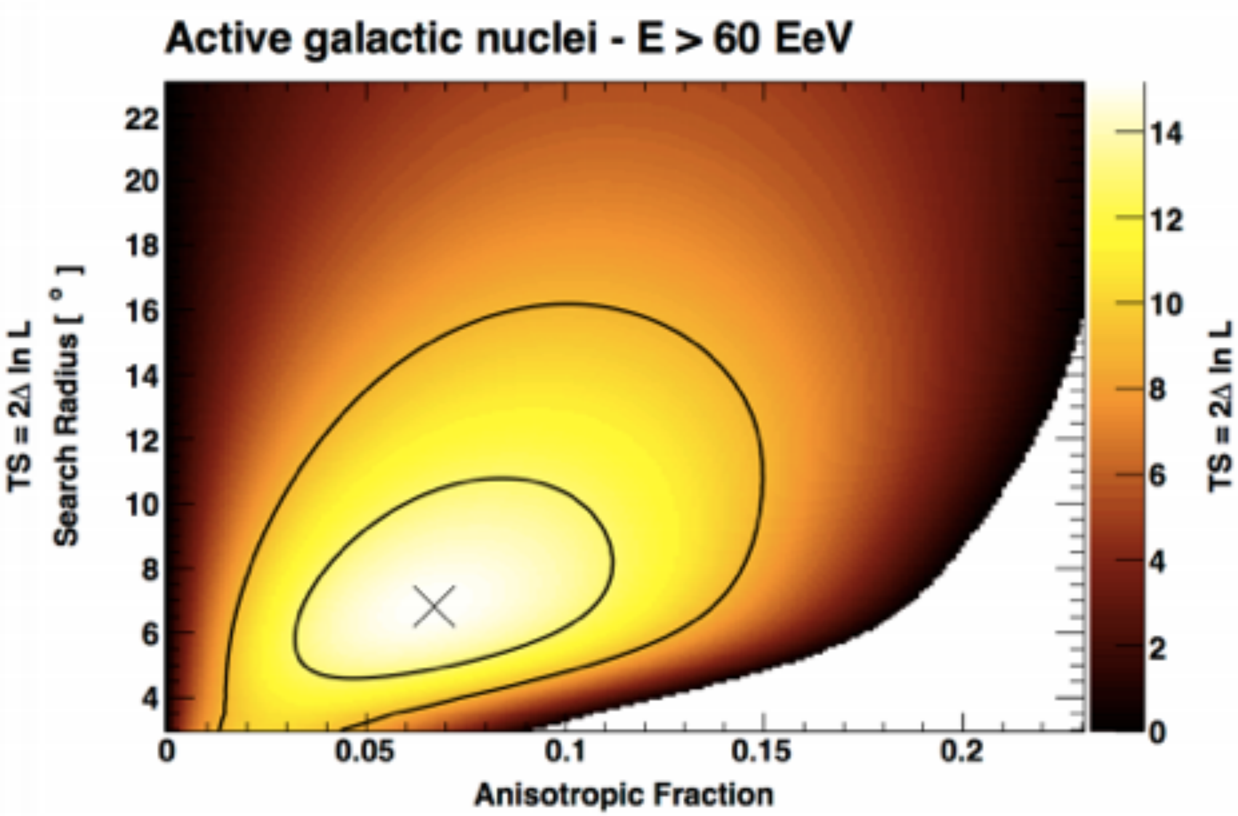


Results: test statistics vs energy threshold



Best fit parameters





Starburst Galaxies

$f_{ani} = 10\%$, $\Psi = 13°$

TS = 24.9 → *p-value* 3.8×10^{-6}

Post-trial probability

3.6×10^{-5} (~4 σ)

(fraction of isotropic simulations that have a greater TS under the same energy scan)

γ-ray detected AGNs

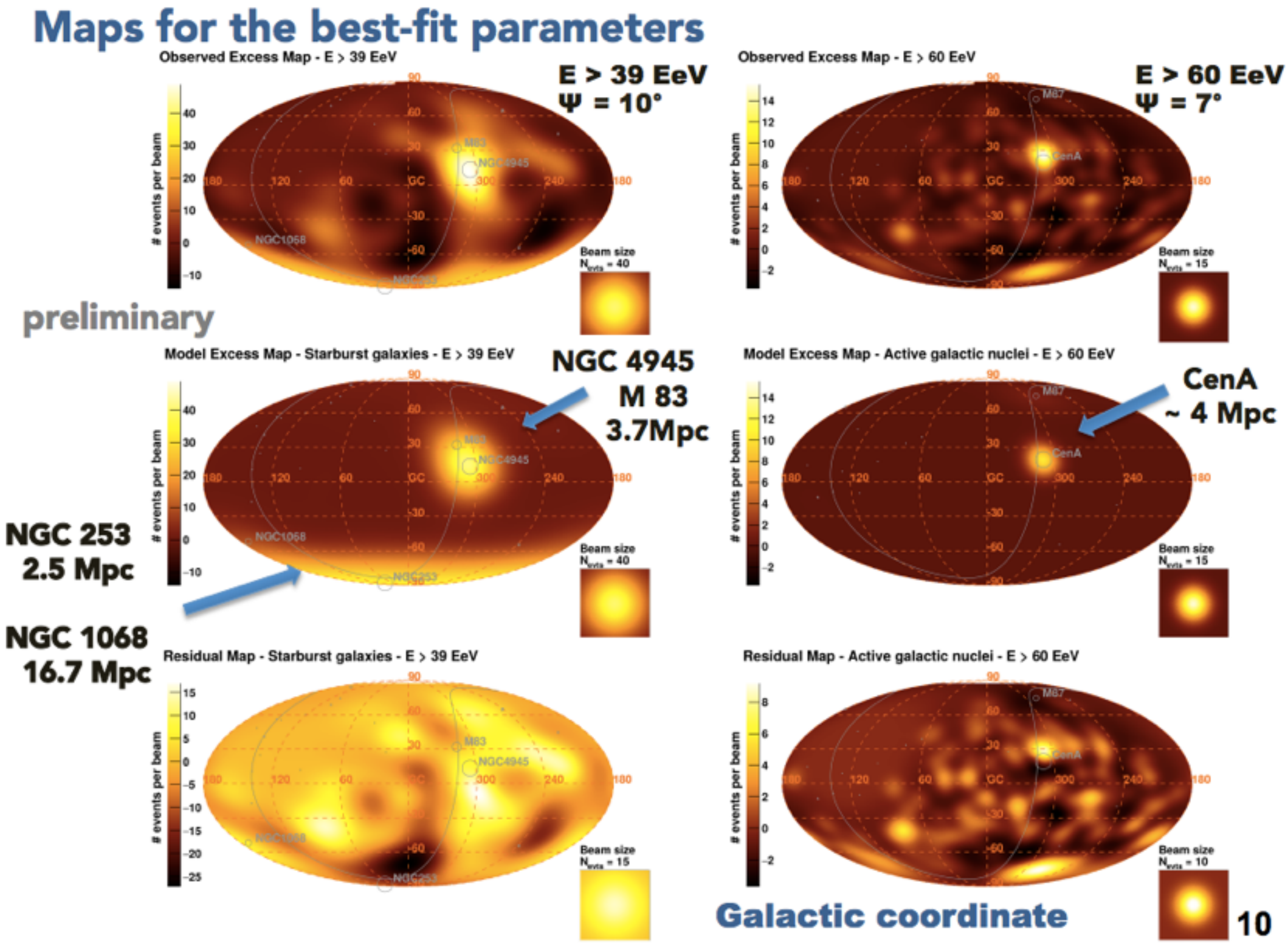
$f_{ani} = 7\%$, $\Psi = 7°$

TS = 15.2 → *p-value* 5.1×10^{-4}

Post-trial probability

3×10^{-3} (~ 2.7 σ)

Best fit and residual maps (through Auger f.o.v.)



SBGs vs γ-AGNs

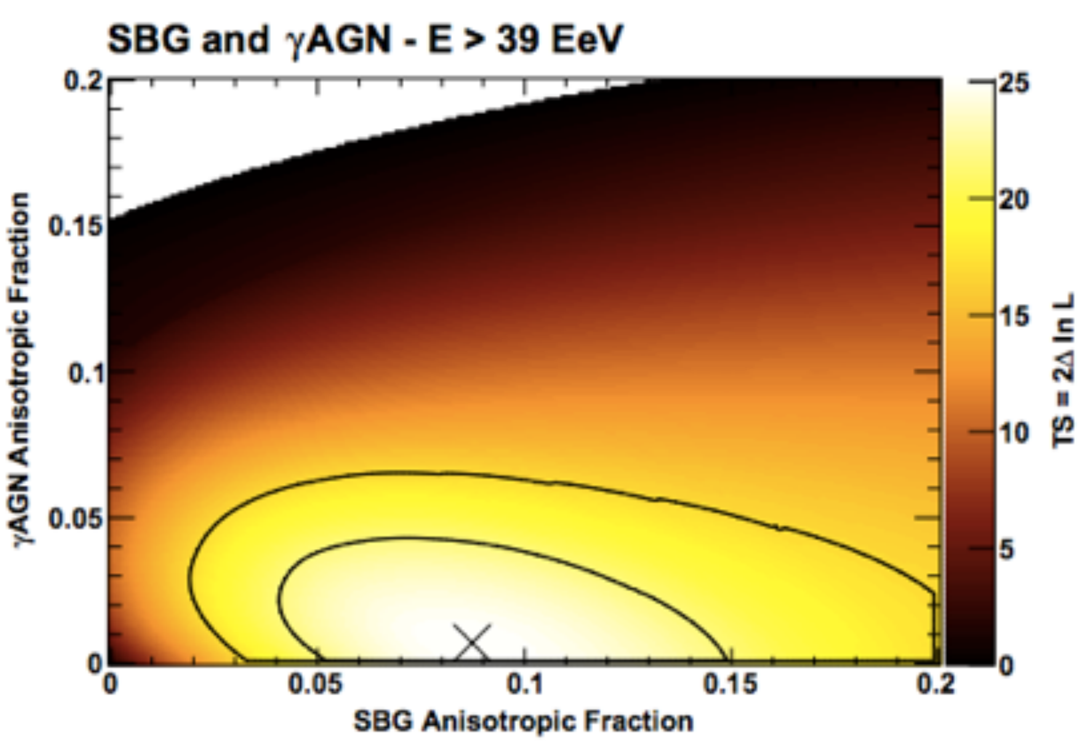
Table 1. Results obtained above 39 EeV and 60 EeV

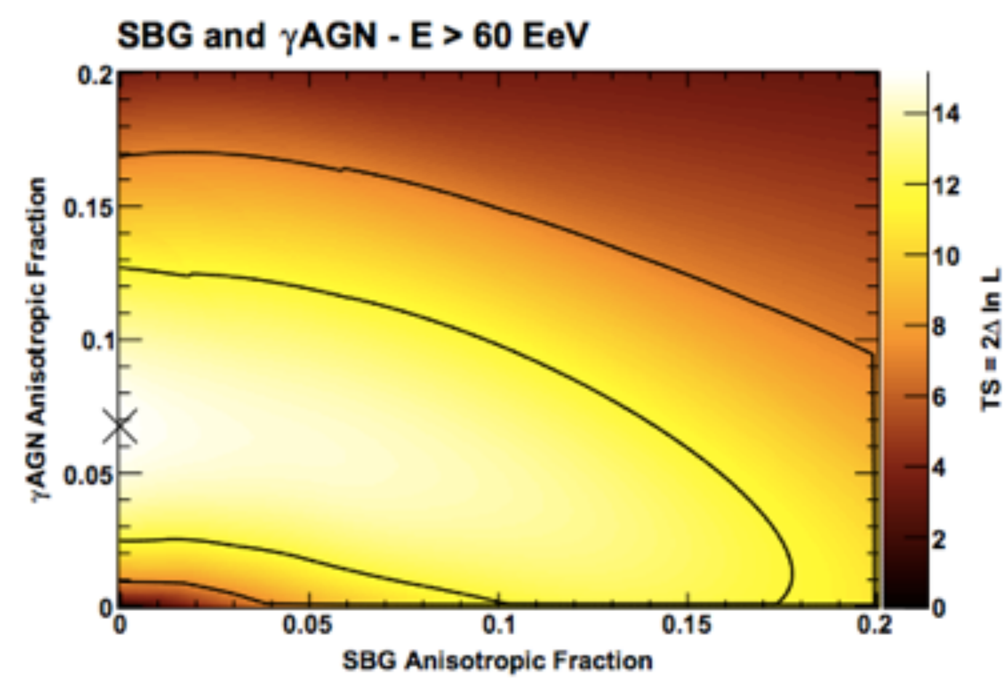
Test hypothesis	Null hypothesis	Threshold energy[a]	TS	Local p-value $\mathcal{P}_{\chi^2}(\mathrm{TS},2)$	Post-trial p-value	1-sided significance	AGN fraction	SB fraction	Search radius
SBG + ISO	ISO	39 EeV	24.9	3.8×10^{-6}	3.6×10^{-5}	$4.0\,\sigma$	N/A	9.7 %	12.9°
γAGN + ISO	ISO	39 EeV	10.4	5.4×10^{-3}	N/A	N/A	3.8 %	N/A	10.0°
γAGN + SBG + ISO	SBG + ISO	39 EeV	0.2	N/A	0.66	$-0.4\,\sigma$	0.7 %	8.7 %	12.5°
γAGN + SBG + ISO	γAGN + ISO	39 EeV	14.7	N/A	1.3×10^{-4}	$3.7\,\sigma$	0.7 %	8.7 %	12.5°
γAGN + ISO	ISO	60 EeV	15.2	5.1×10^{-4}	3.1×10^{-3}	$2.7\,\sigma$	6.7 %	N/A	6.9°
SBG + ISO	ISO	60 EeV	12.2	2.5×10^{-3}	N/A	N/A	N/A	13.7 %	12.0°
γAGN + SBG + ISO	γAGN + ISO	60 EeV	0.003	N/A	0.96	$-1.7\,\sigma$	6.8 %	0.0 %[b]	7.0°
γAGN + SBG + ISO	SBG + ISO	60 EeV	3.0	N/A	0.08	$1.4\,\sigma$	6.8 %	0.0 %[b]	7.0°

[a] For composite model studies, no scan over the threshold energy is performed.

[b] Maximum TS reached at the boundary of the parameter space.

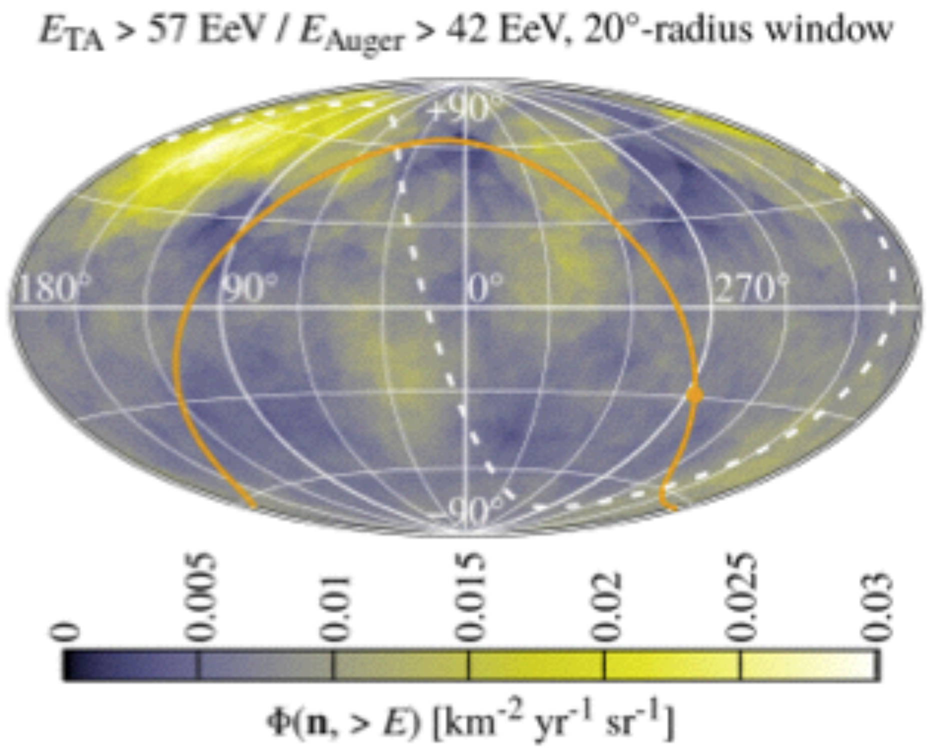
ISO: isotropic model.

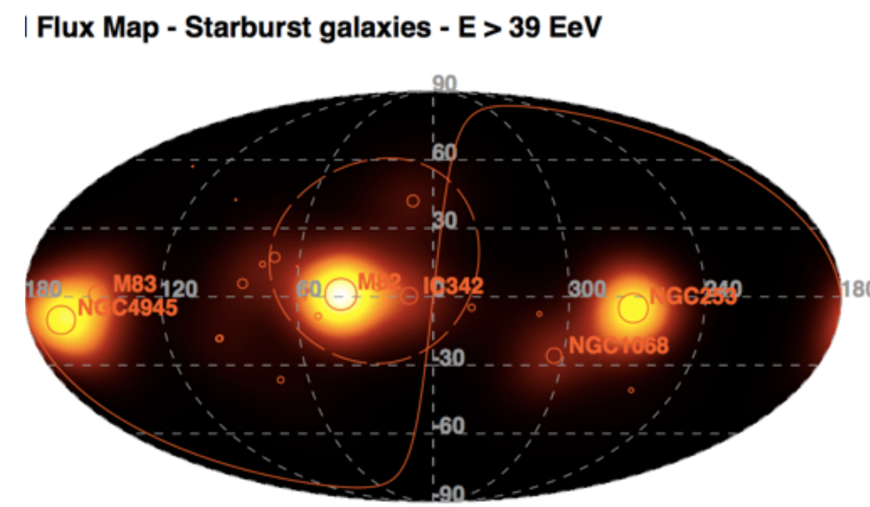




Perspectives

• Full-sky survey





[Auger/TA coll., UHECR16]

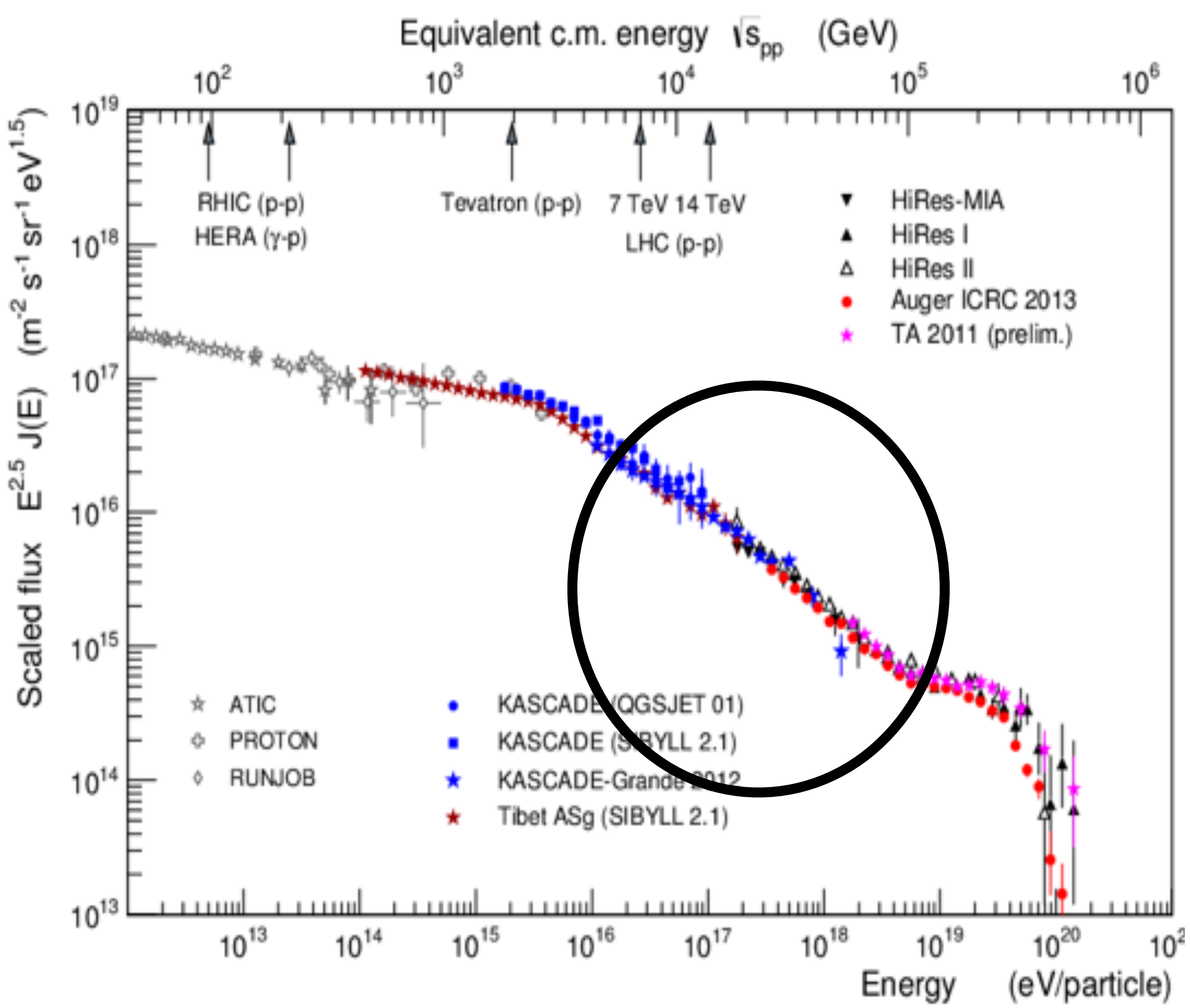
• Include galactic magnetic models in the picture

• Rigidity-dependent analyses — upgrade of the Auger Observatory

• Global picture spectrum/mass/anisotropies?

vi) **Backup**

End of Galactic CRs



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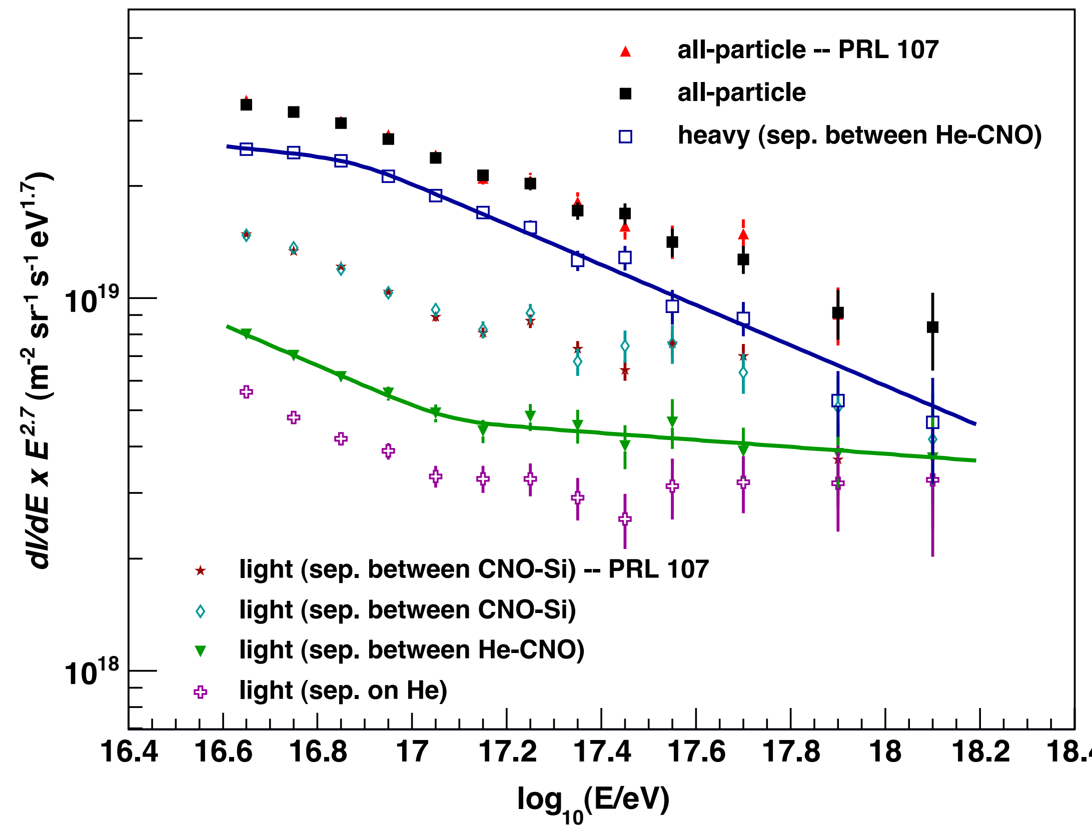
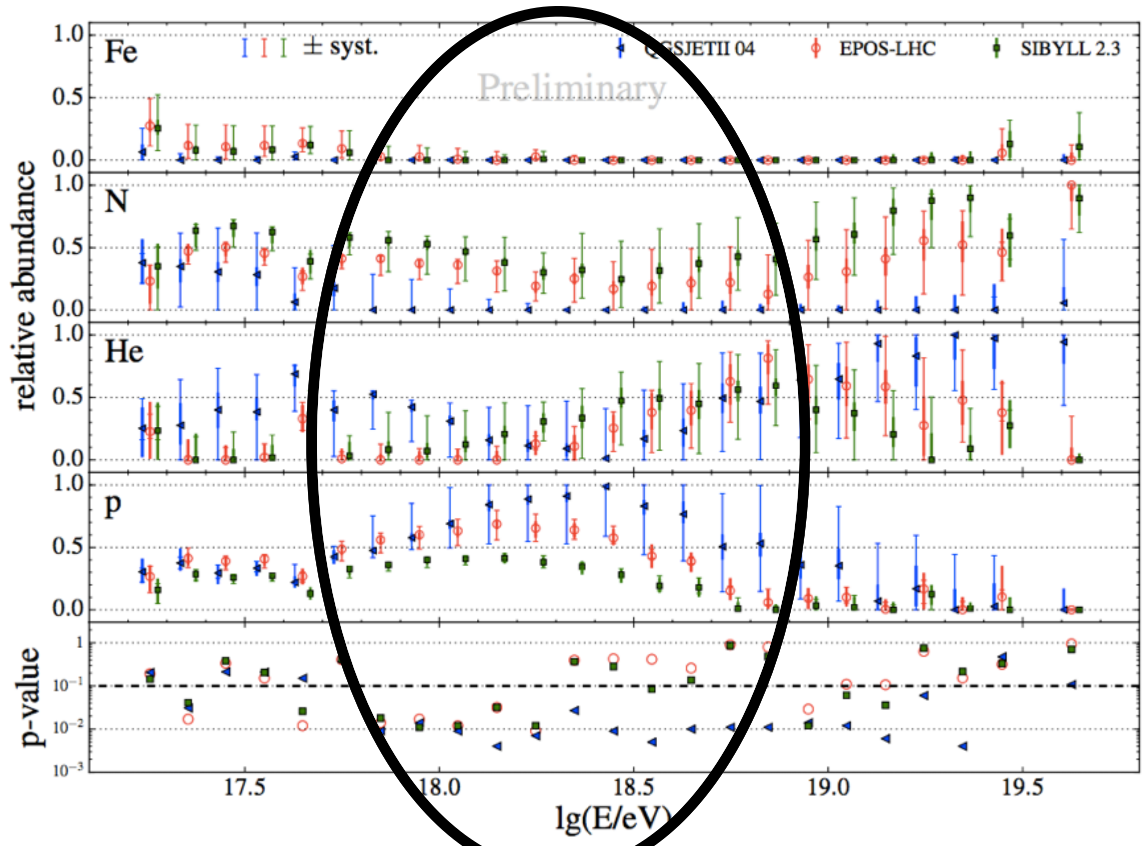


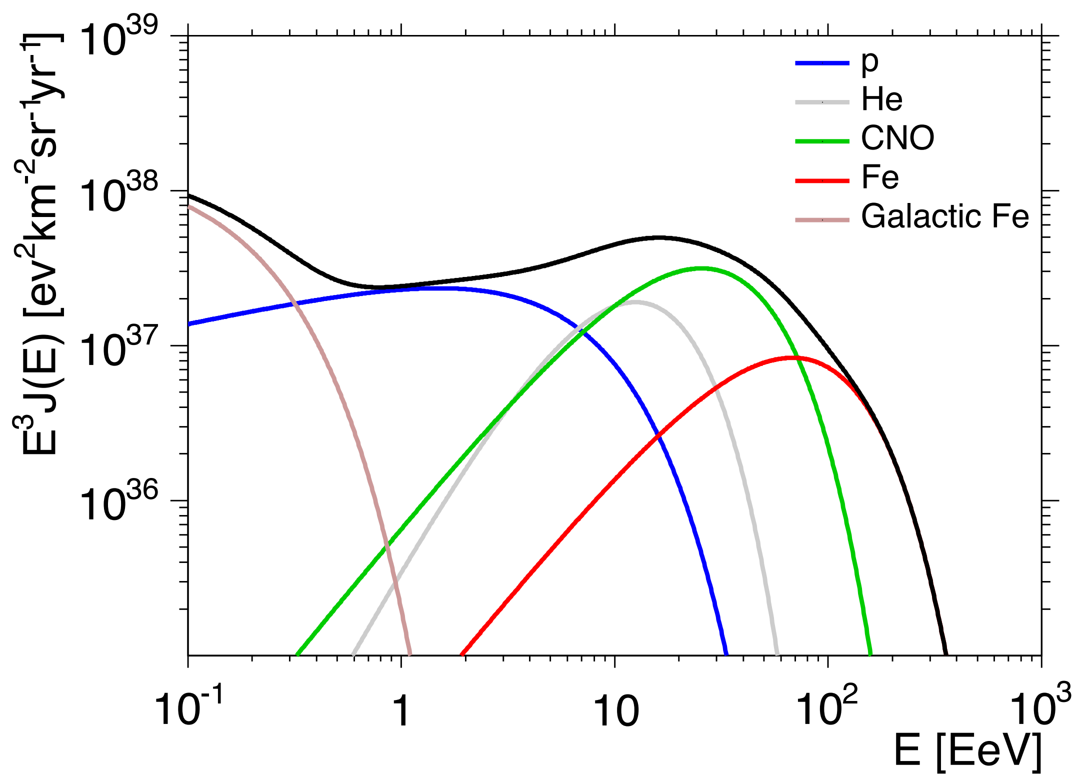
- Rigidity-dependent scenario for GCRs
- « Knees » = maximum acceleration energies
- Extragalactic protons entering progressively

The Ankle?

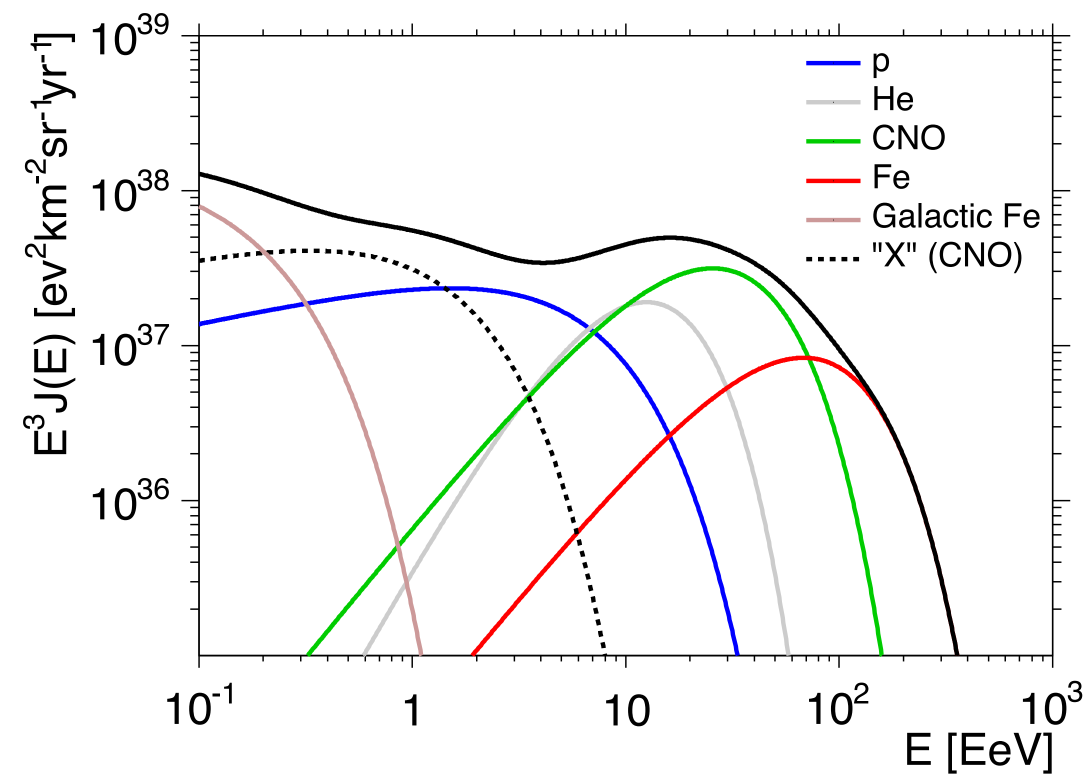


➡ In addition to (extragalactic) protons, EeV CRs are from the CNO group, not Fe!

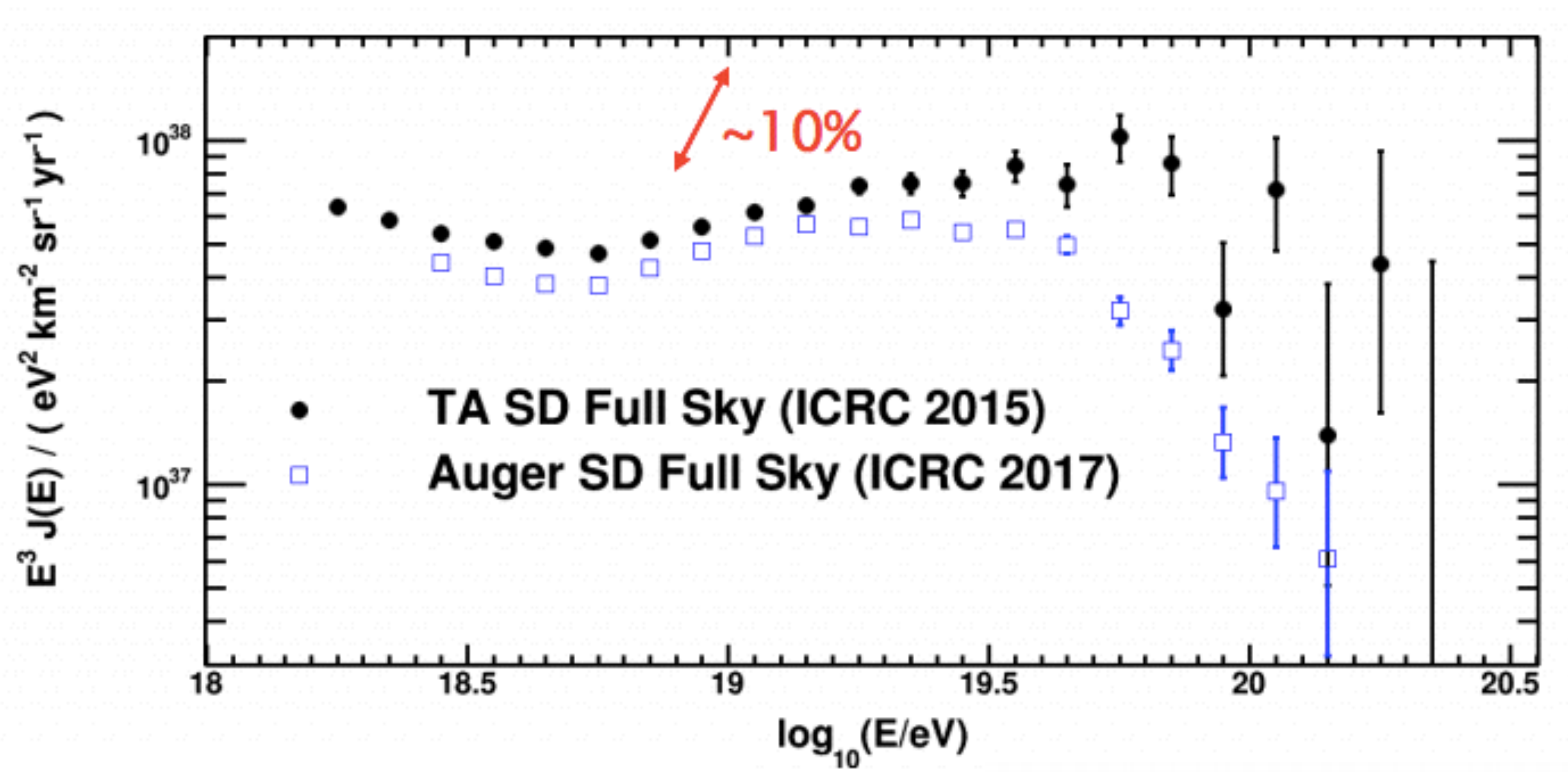
Gal/xGal scenario

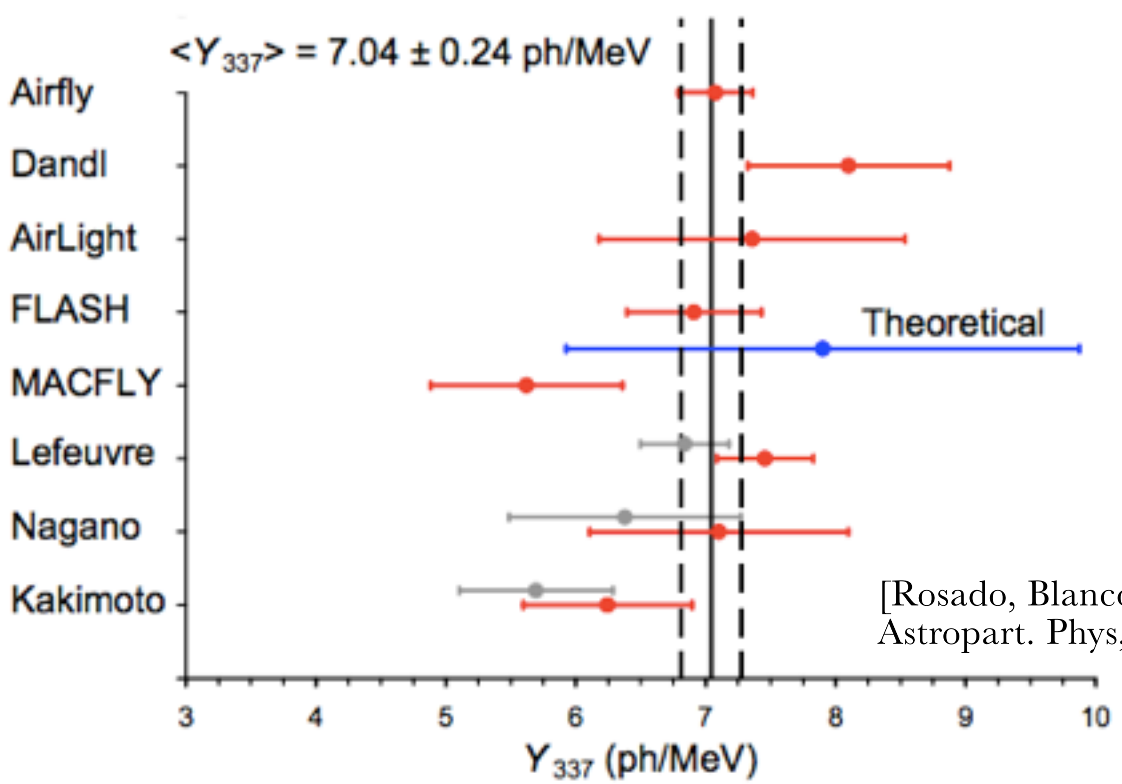


Observed scenario

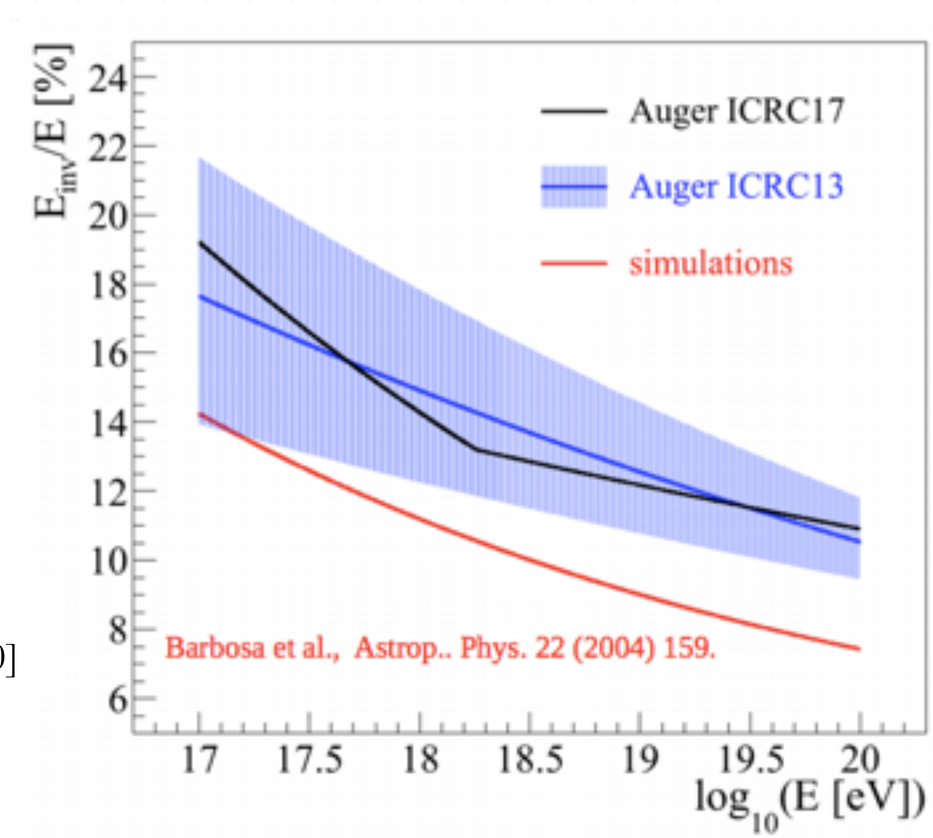


Energy spectrum: Auger vs Telescope Array

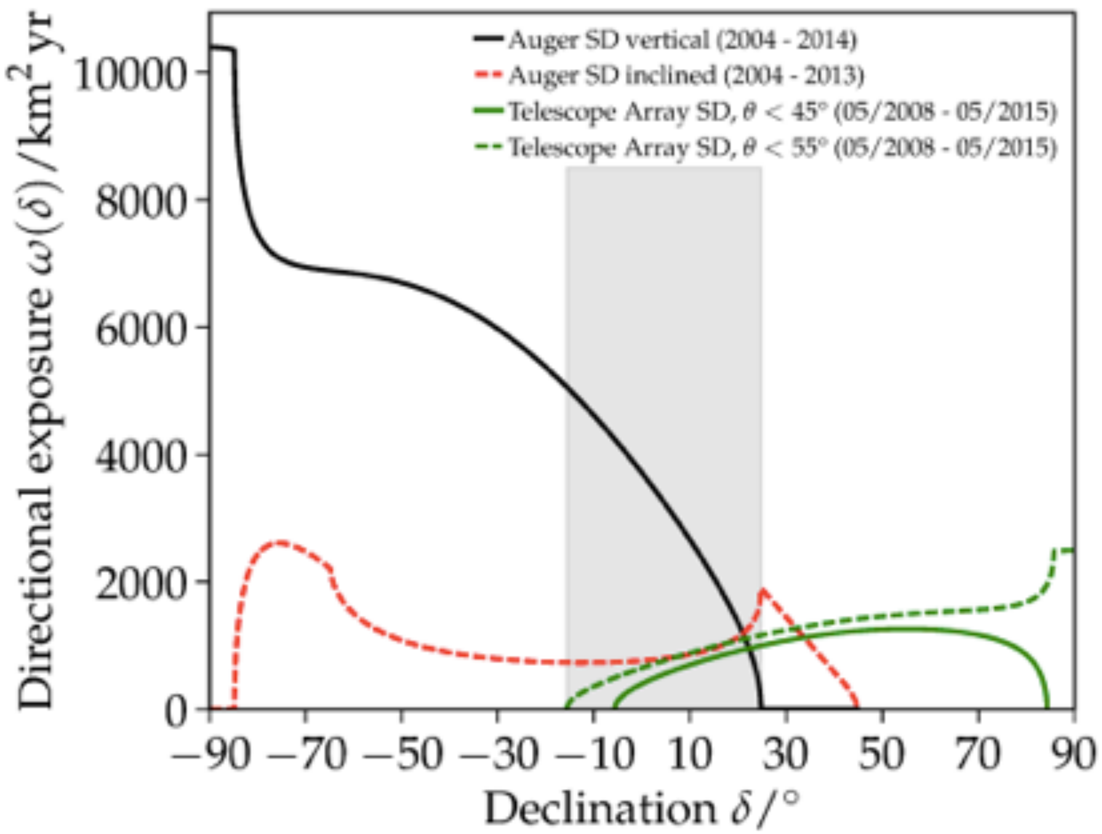




[Rosado, Blanco & Arqueros, Astropart. Phys, arXiv:1401.4310]



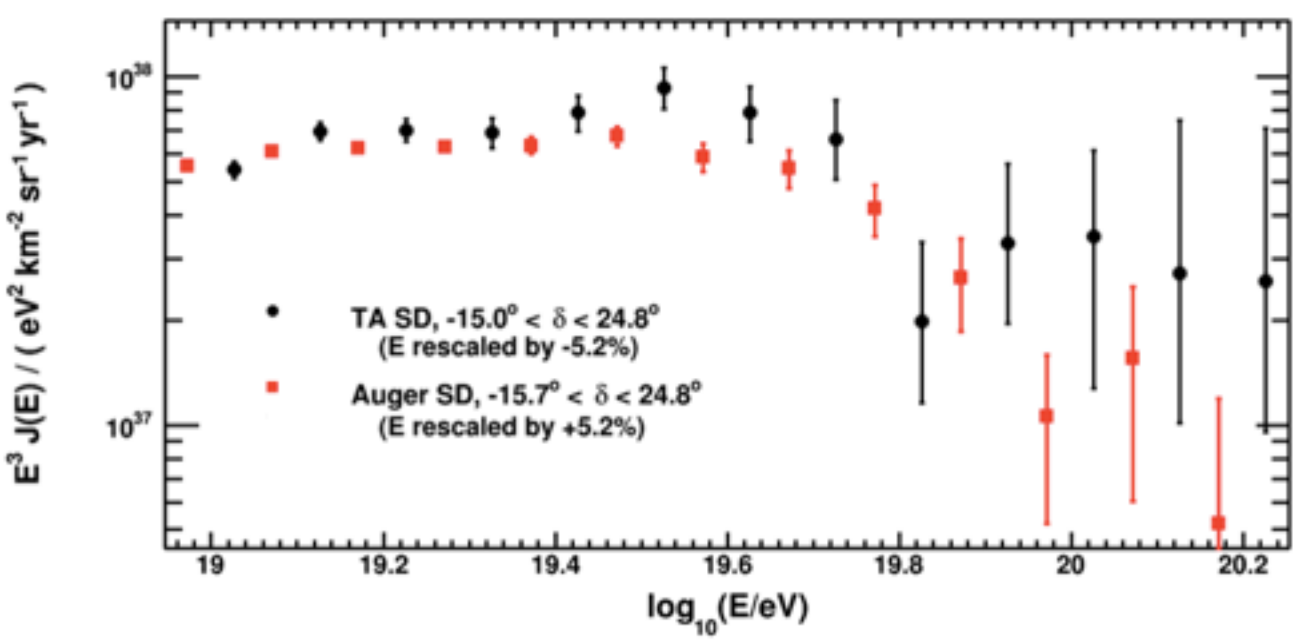
Auger vs Telescope Array: common sky

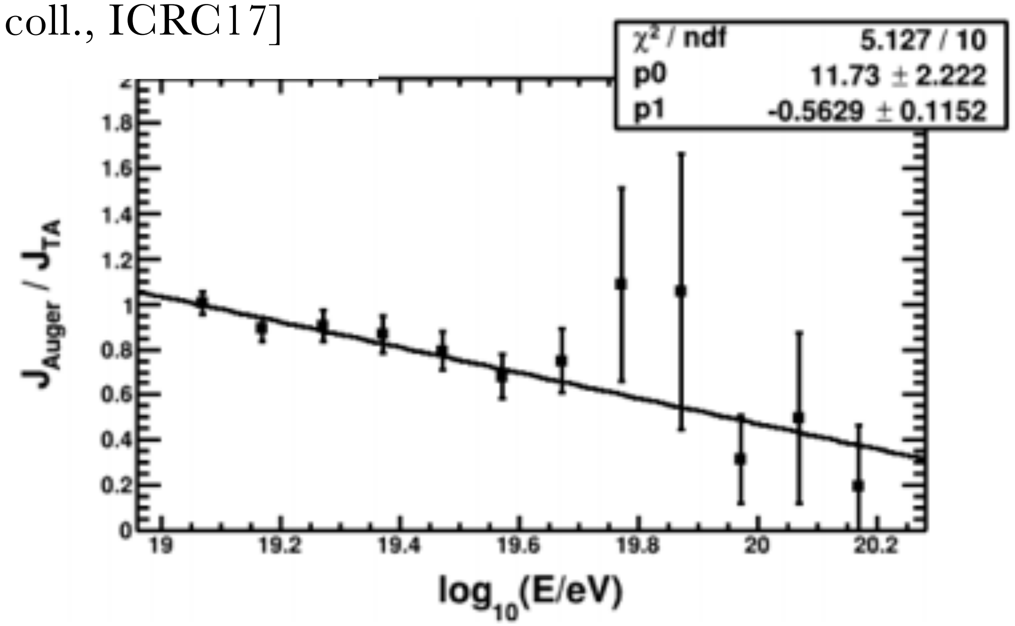


$$J_{1/\omega}(E) = \frac{1}{\Delta\Omega\Delta E}\sum_{i=1}^{N}\frac{1}{\omega(\delta_i)}$$

➡ Remove distortions induced from different directional exposures in case of anisotropies

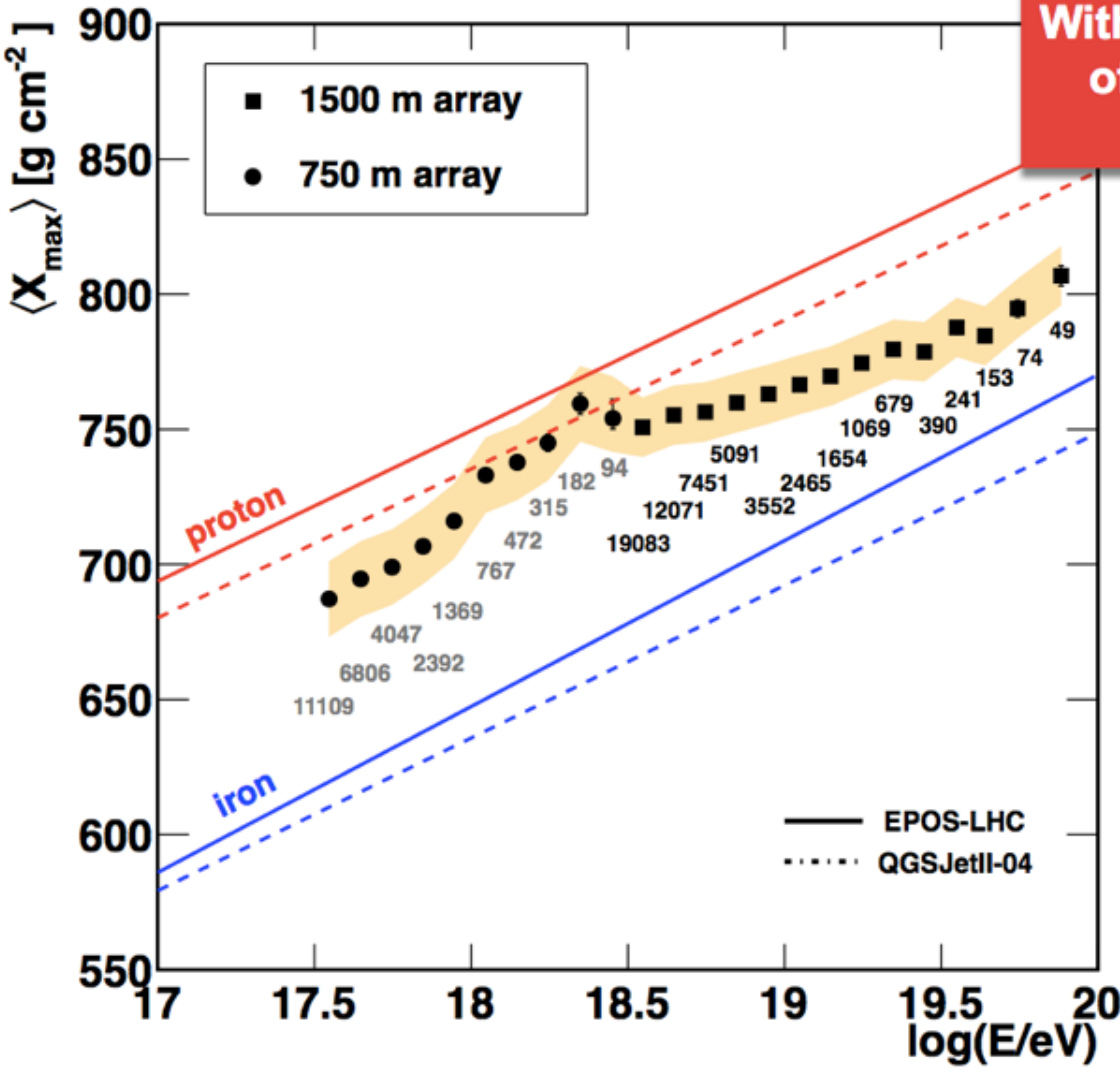
[Ivanov for Auger/TA coll., ICRC17]





➡ Energy-dependent systematics…

<X_{max}> with SD events



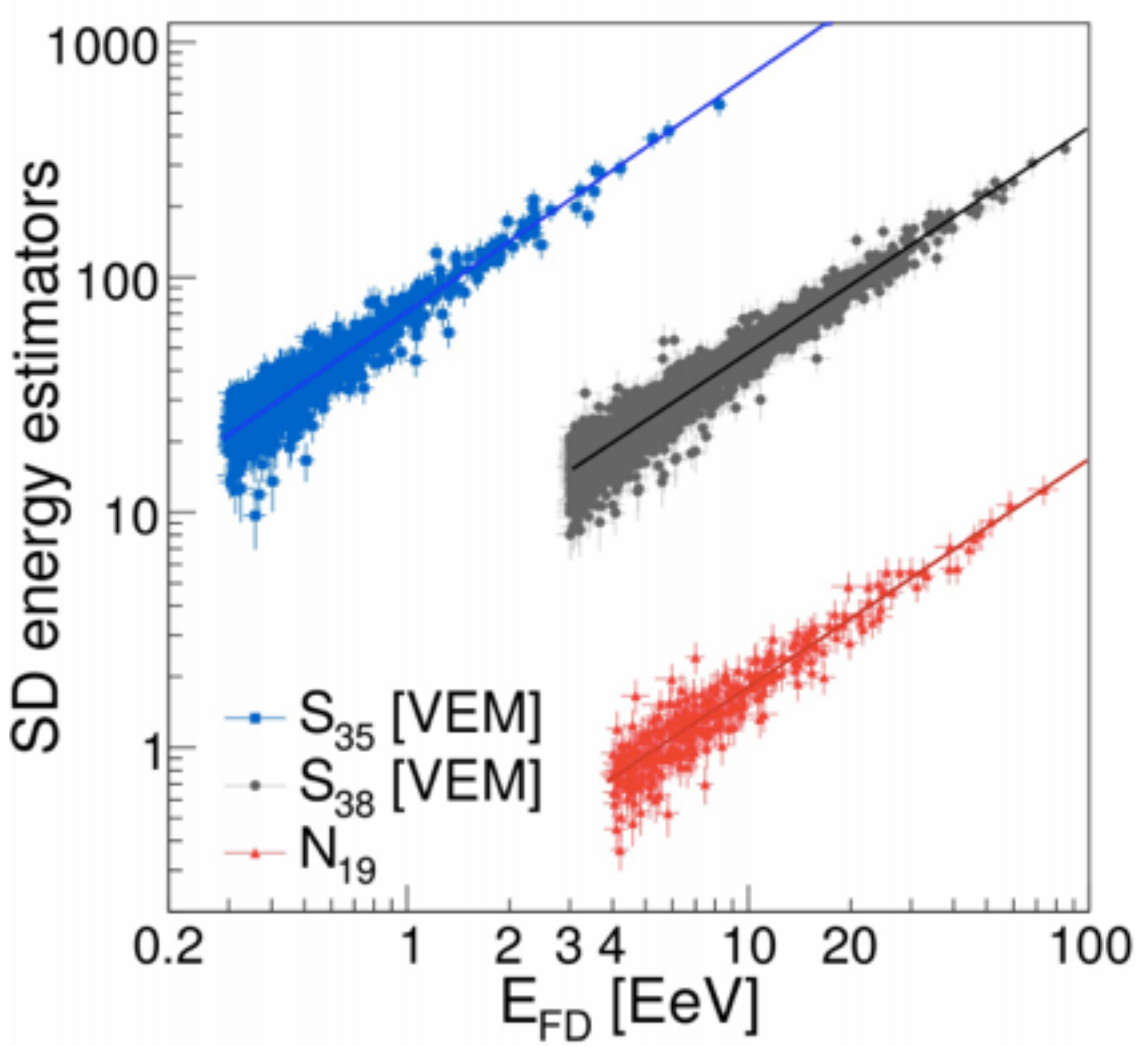
With the SD we obtain a measurement of ⟨ X_{max} ⟩ that covers more than 2 orders of magnitude in energy

- Systematics 11-14 g cm^{-2}
- First composition analysis with data of the 750 m array
- We add 3 energy bins at the highest energies compared to the FD

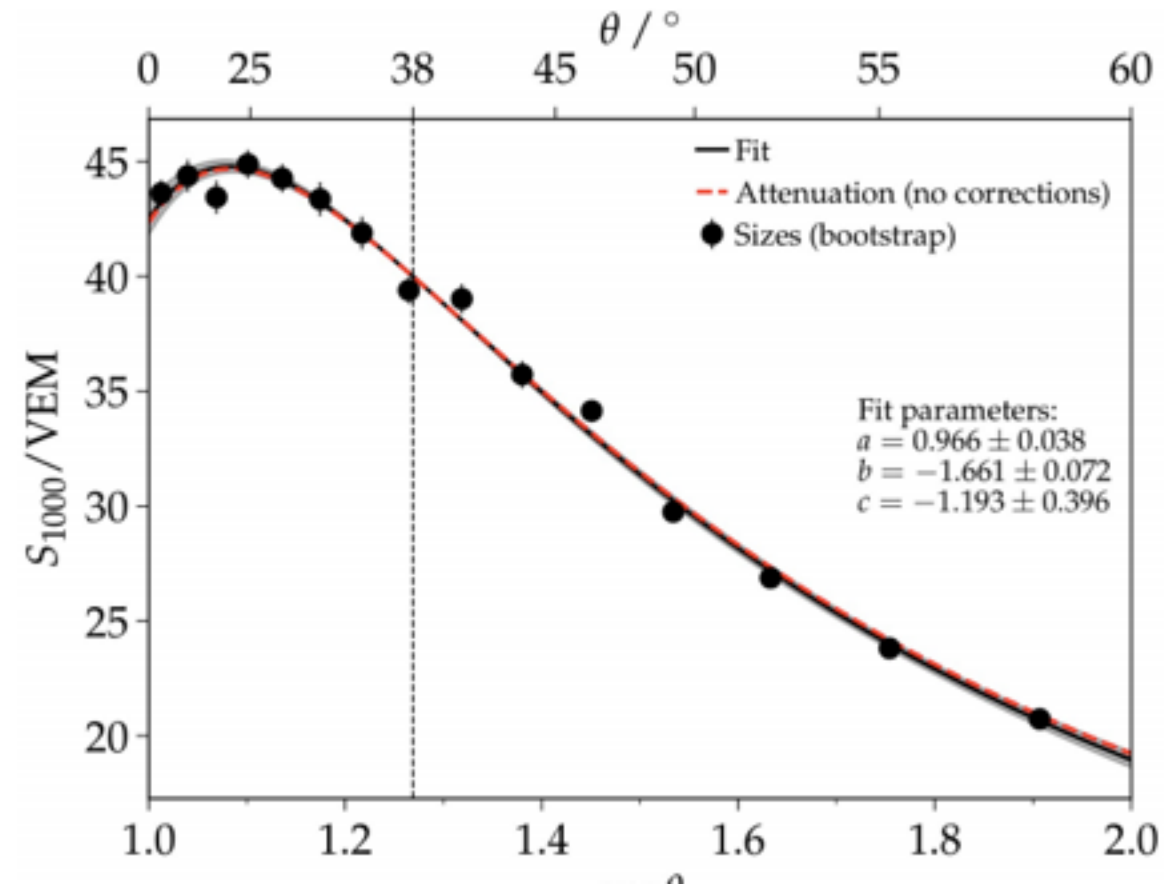
This SD analysis has 517 events above $10^{19.5}$ eV, nearly 10 times more events than the FD measurements in this energy range

SD-energy calibration

Measurement of the attenuation through 'constant intensity cut'



Resolution:
SD–1500 ~ 15%
SD-750 ~ 13%
SD-1500 inclined ~ 17%
FD ~ 7%



High quality hybrid events (2661 events for S_{38})

$$E_{FD} = A\,\hat{S}^B$$

$$\hat{S} = S_{38}, S_{35}, N_{19}$$