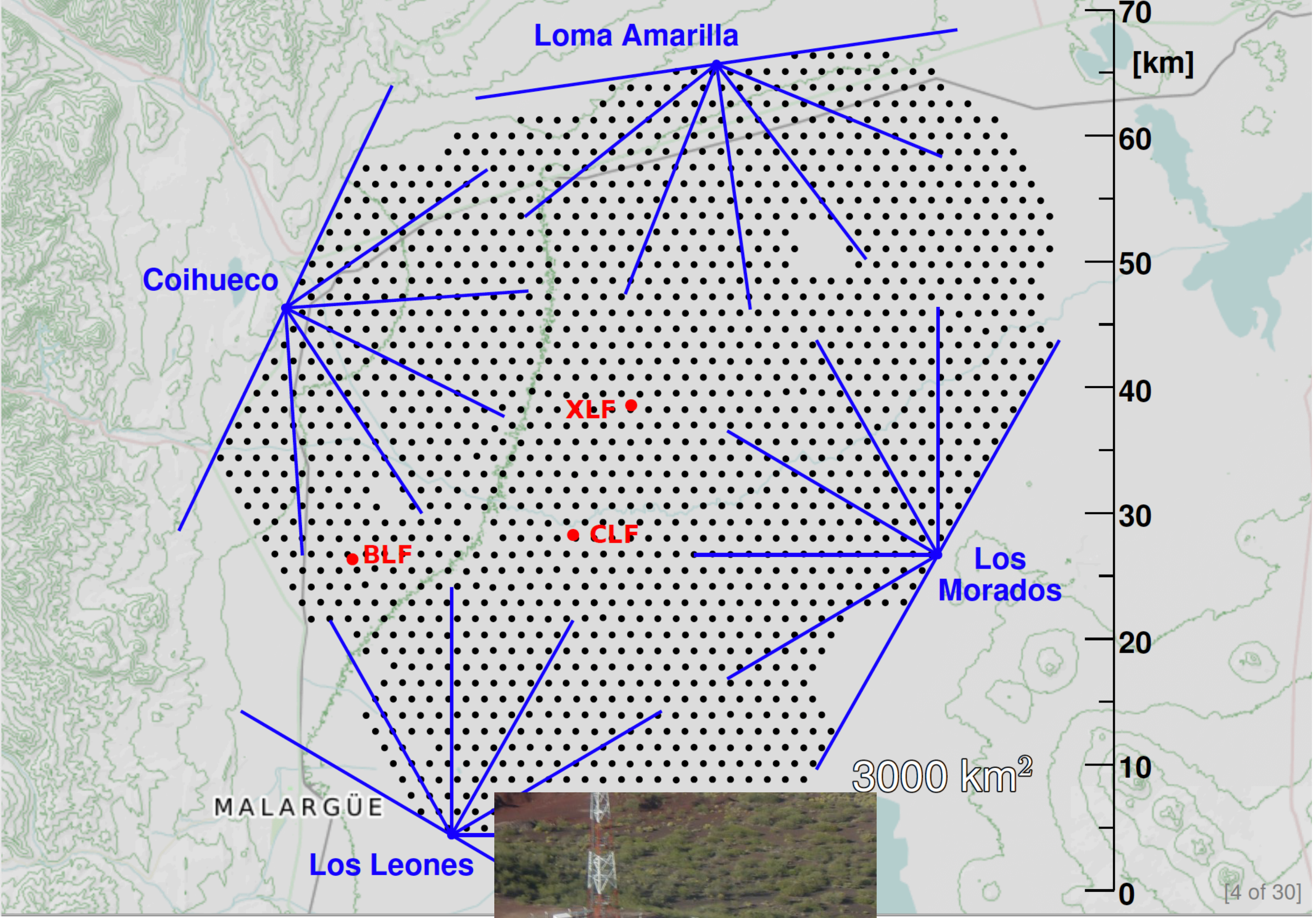
Results from the Pierre Auger Observatory

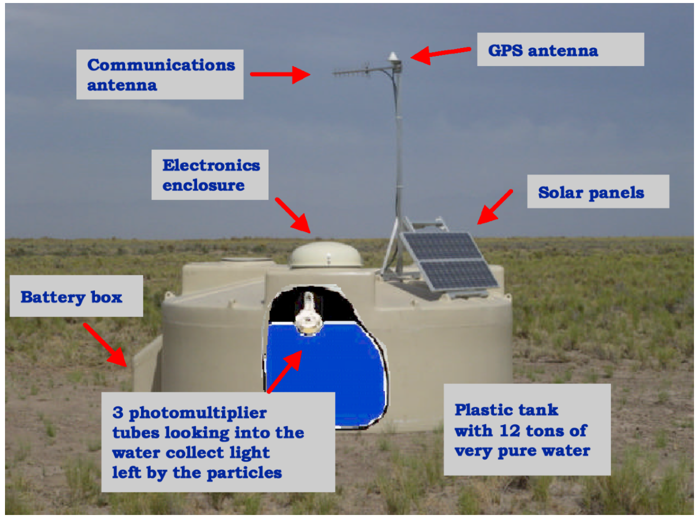
Sergio Petrera, *GSSI and INFN, L'Aquila, Italy*



The Pierre Auger Observatory

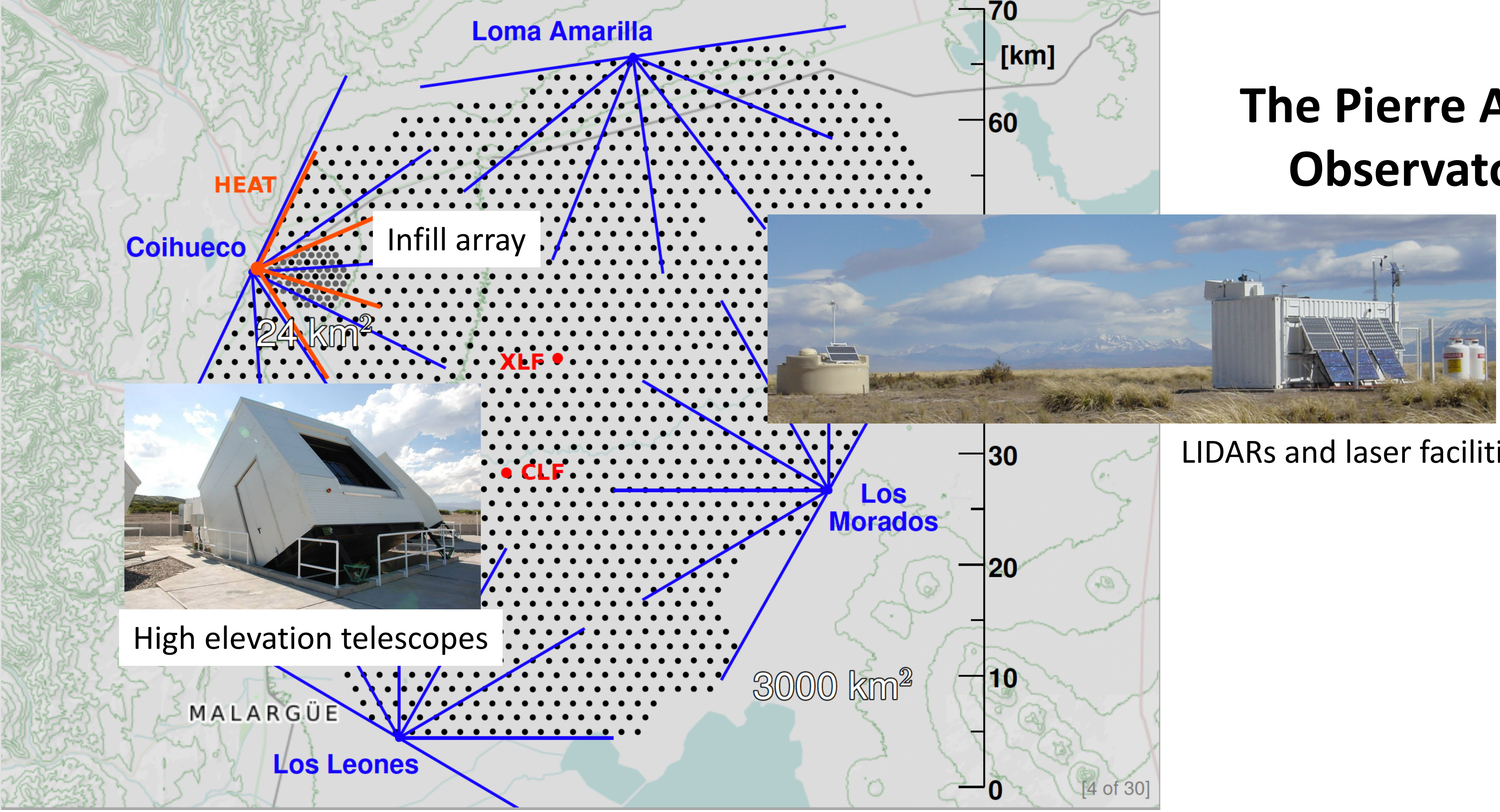
Province Mendoza
Argentina

1665 surface detectors:
water-Cherenkov tanks
(grid of 1.5 km, 3000 km^2)

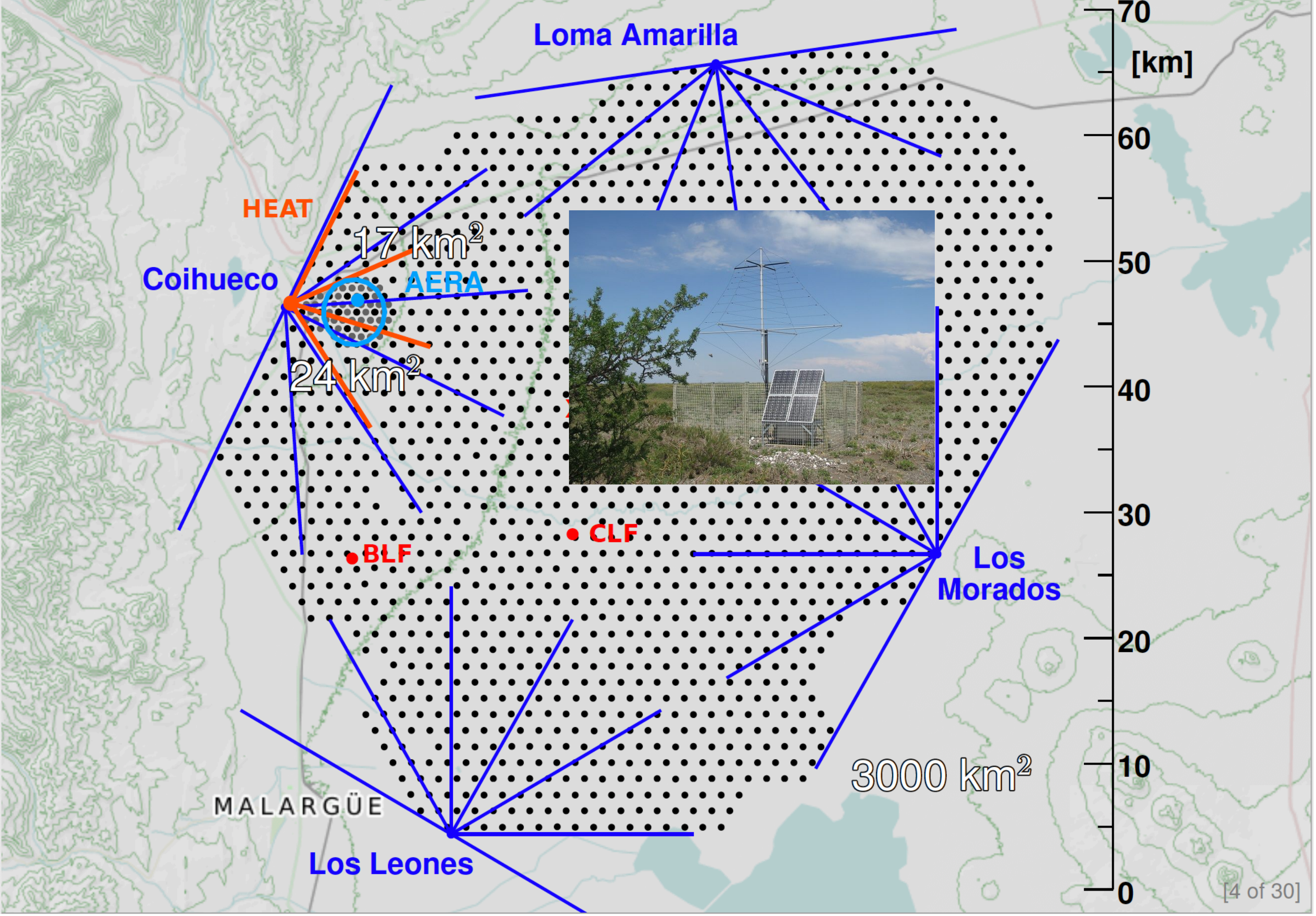


4 fluorescence sites
(24 telescopes in total)

The Pierre Auger Observatory



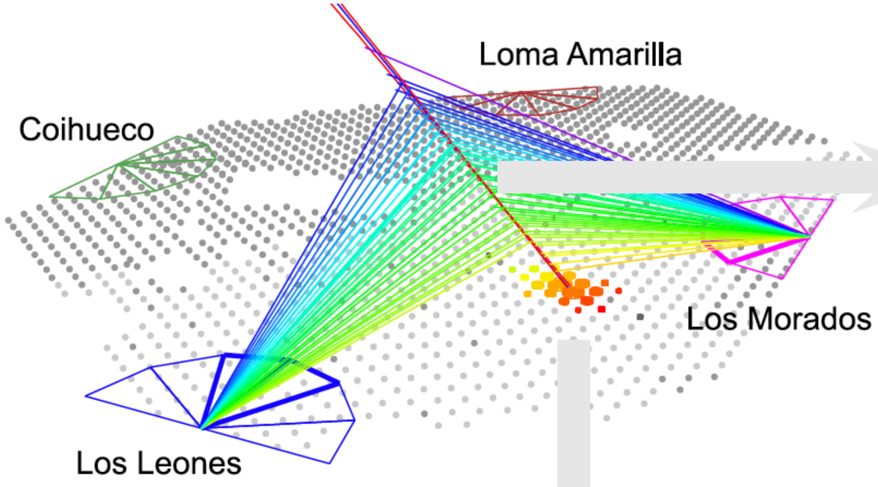
LIDARs and laser facilities

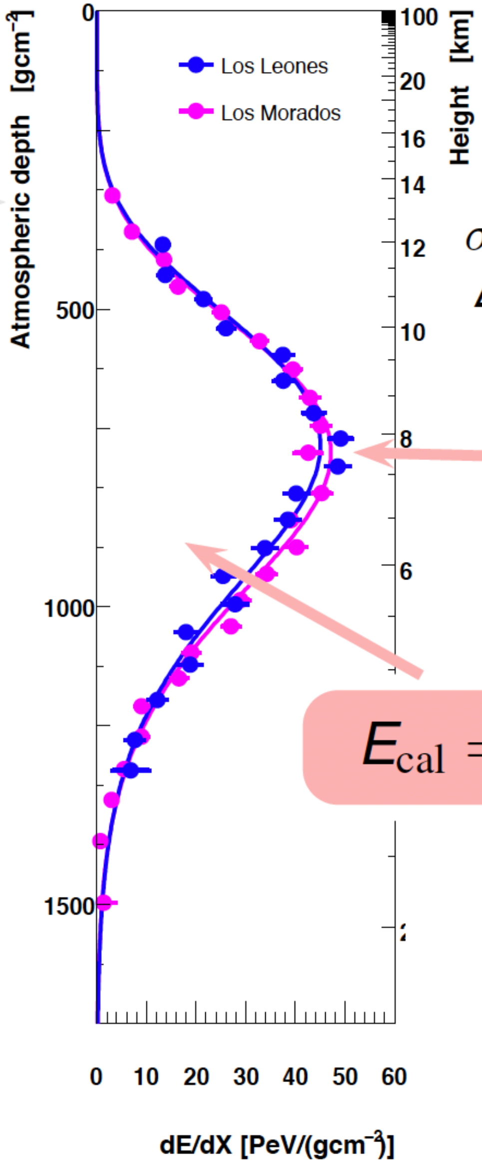


The Pierre Auger Observatory

AERA: radio antenna array

Hybrid detection of air showers



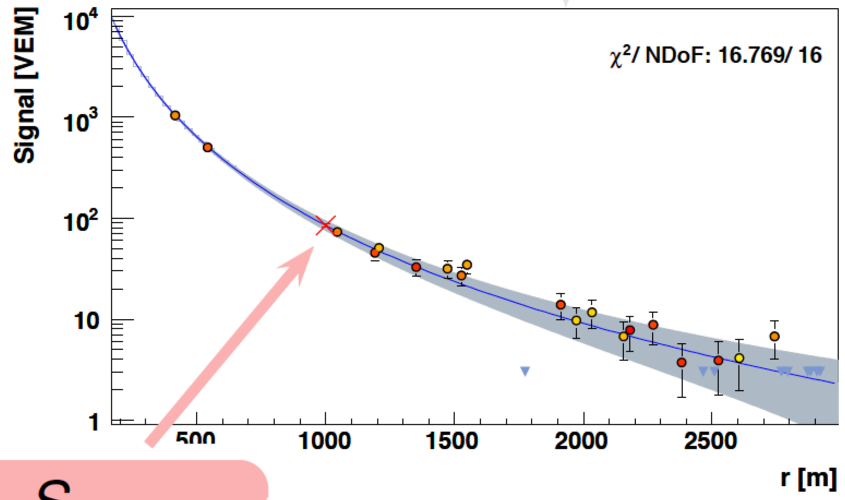


$\sigma X_{\mathrm{max}} \leq 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \leq 10\,\mathrm{g/cm^2}$

X_{max}

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

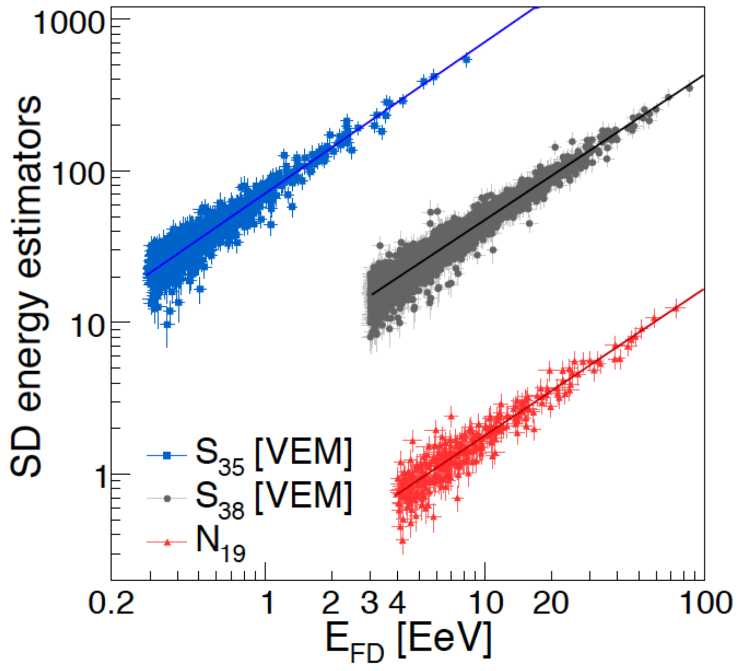
$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 15\,\%$

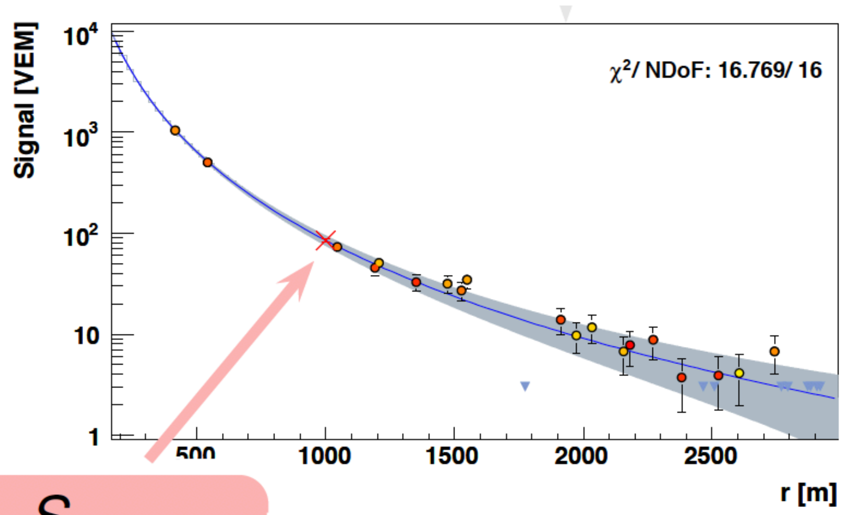


S_{1000}

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

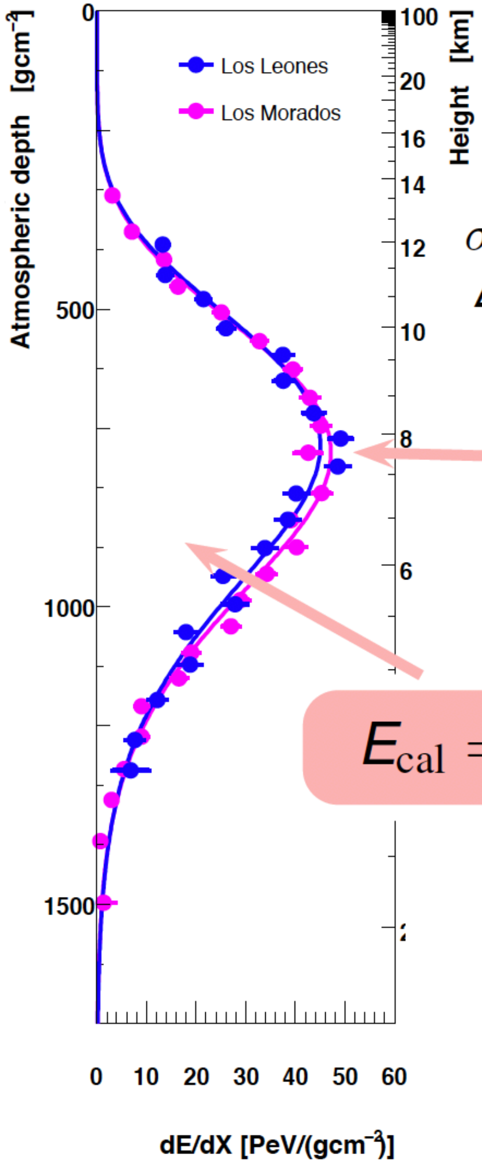
Energy calibration





S_{1000}

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



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$X_{\rm max}$

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$\sigma_E / E \sim 8\,\%$
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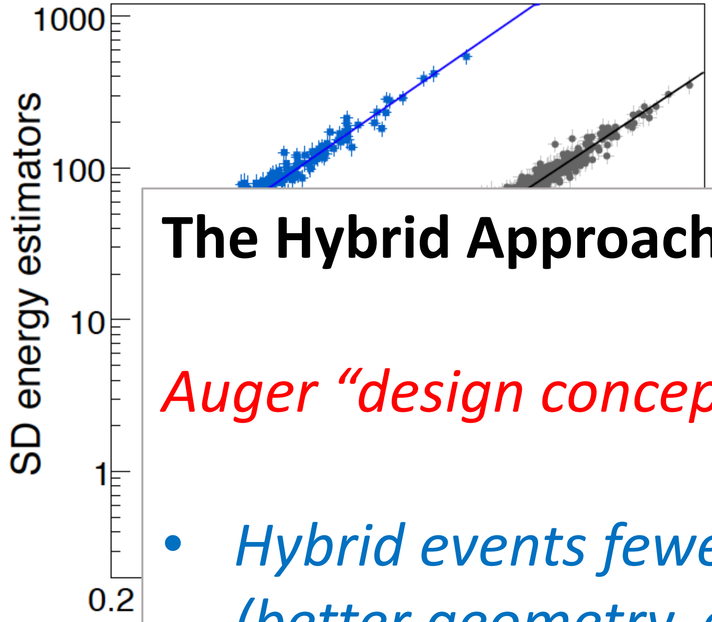
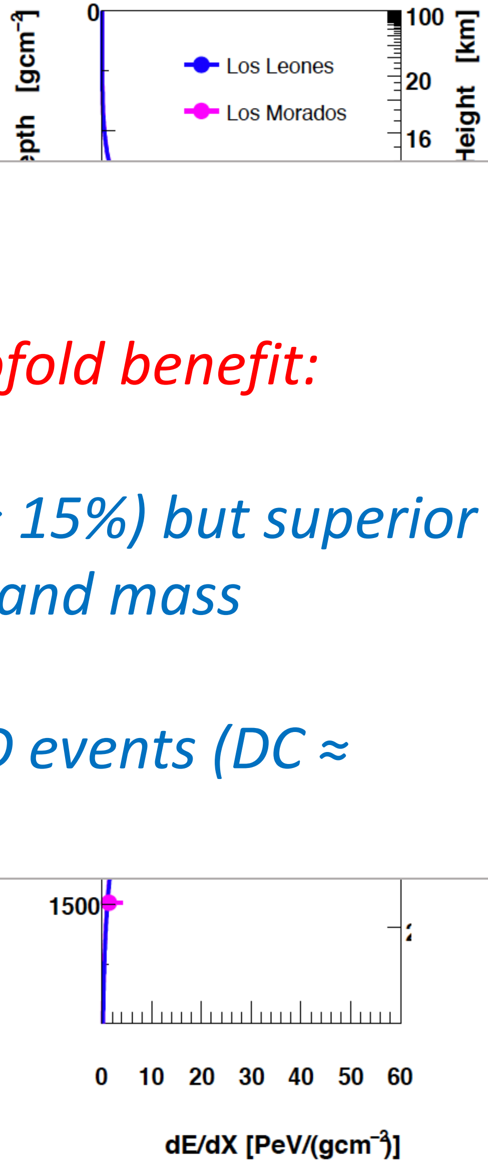
Energy calibration





The Hybrid Approach

Auger "design concept". Twofold benefit:

- *Hybrid events fewer (DC ≈ 15%) but superior (better geometry, energy and mass determination)*
- *Hybrid events calibrate SD events (DC ≈ 100%)*

$X_{\max} \lesssim 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \lesssim 10\,\mathrm{g/cm^2}$

$X_{\max}$

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

$\sigma_E/E \sim 8\,\%$
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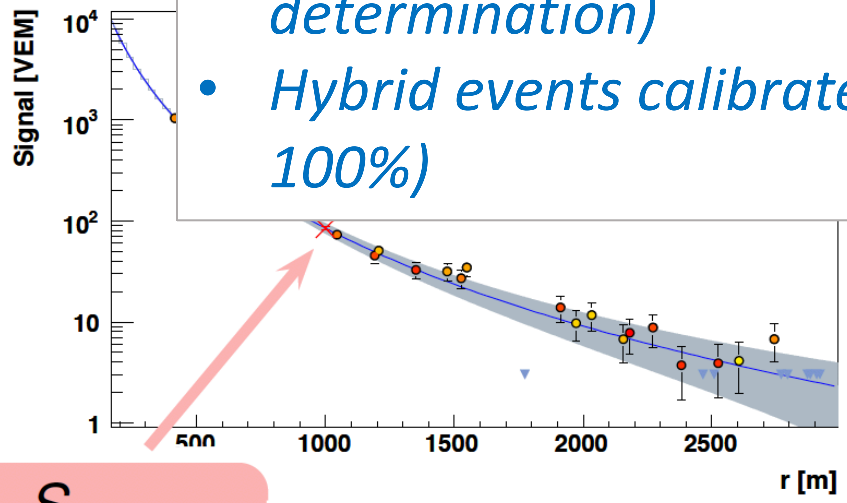
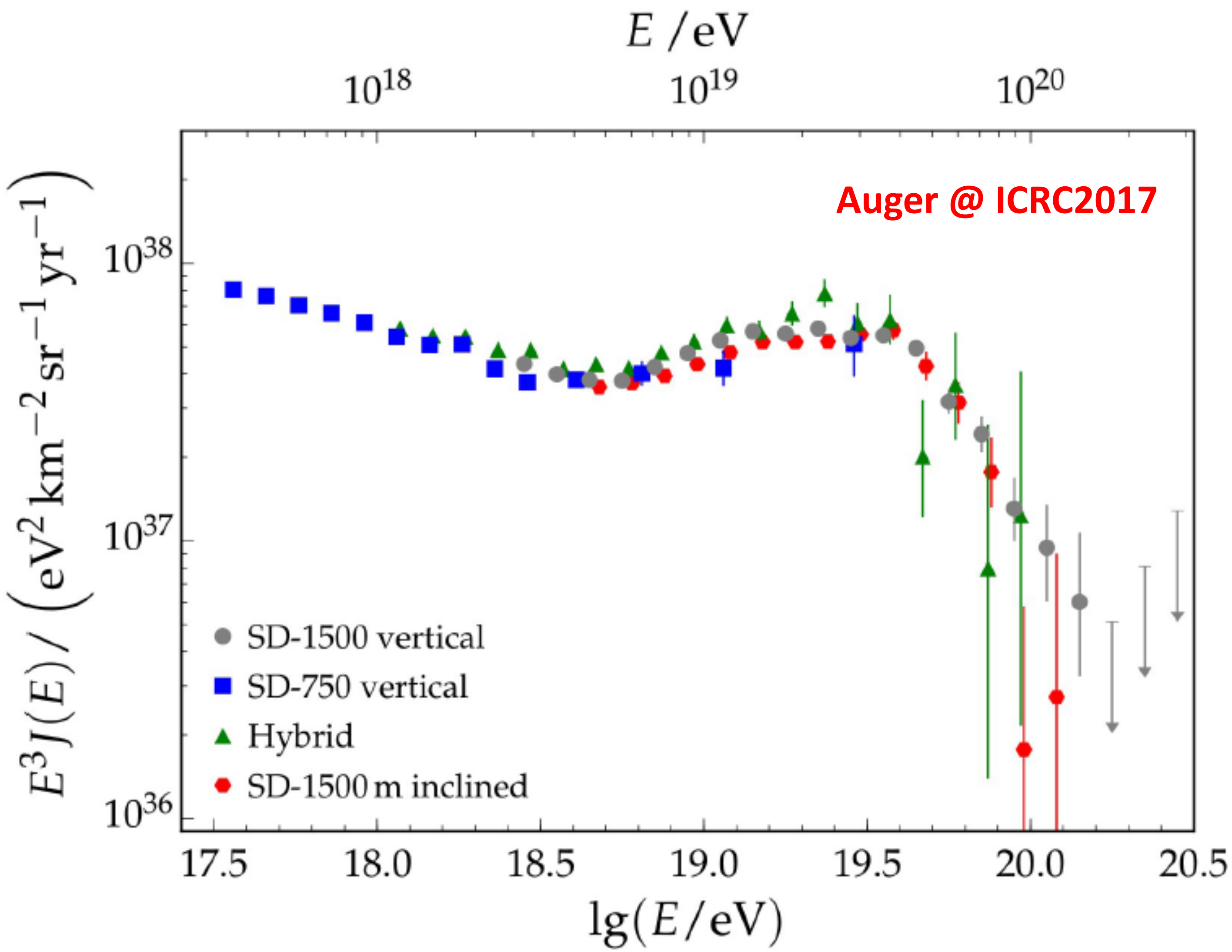


S_{1000}

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

Energy spectrum (all-particle flux)



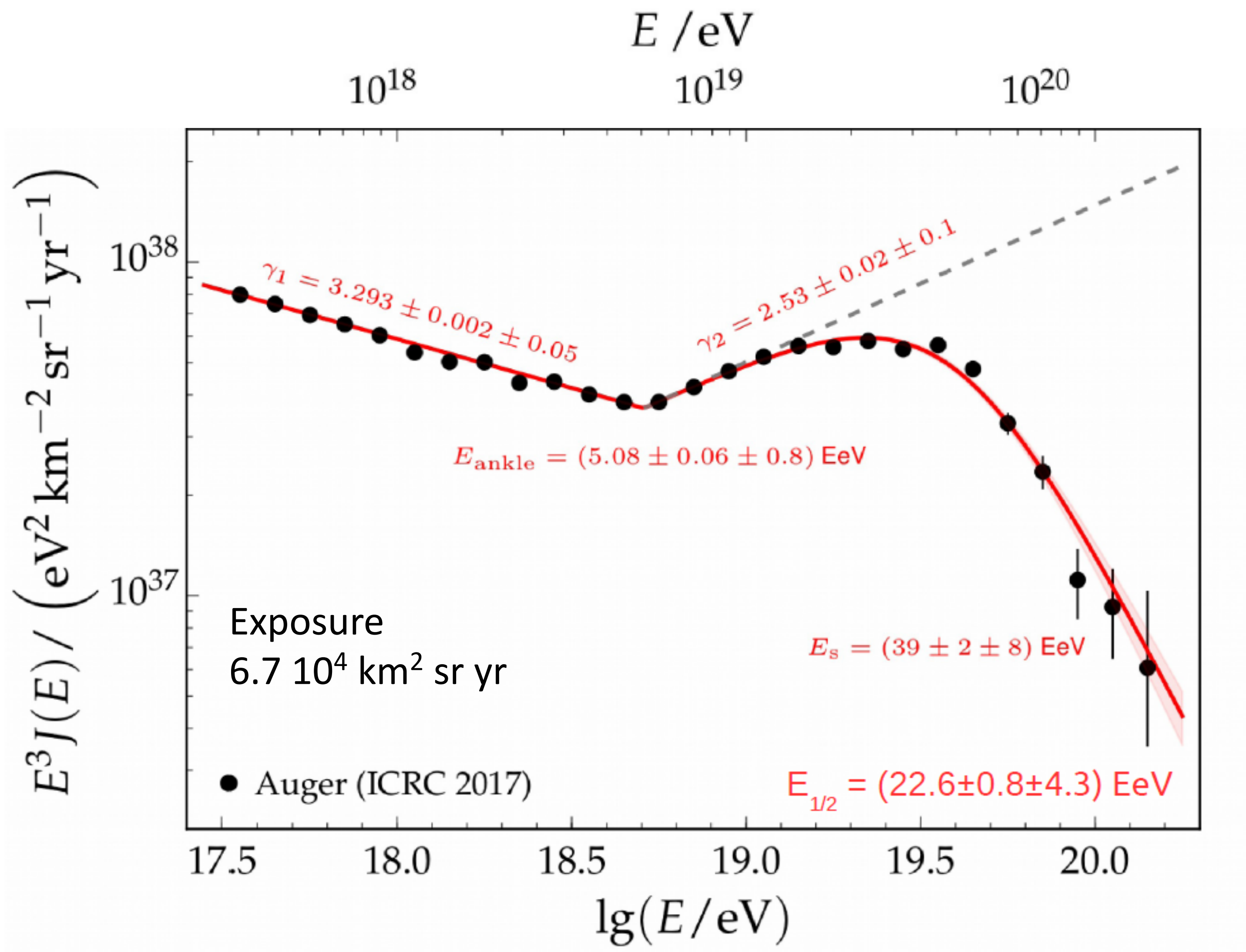
Four independent measurements

Flux uncertainties:
7-14% SD dense array
6% SD vertical (< 60°)
5% SD inclined (60°-80°)
10% Hybrid vertical (< 60°)

Energy resolution
13% SD dense array
15% SD vertical (< 60°)
19% SD inclined (60°-80°)
10% Hybrid vertical (< 60°)

14% Energy scale uncertainty

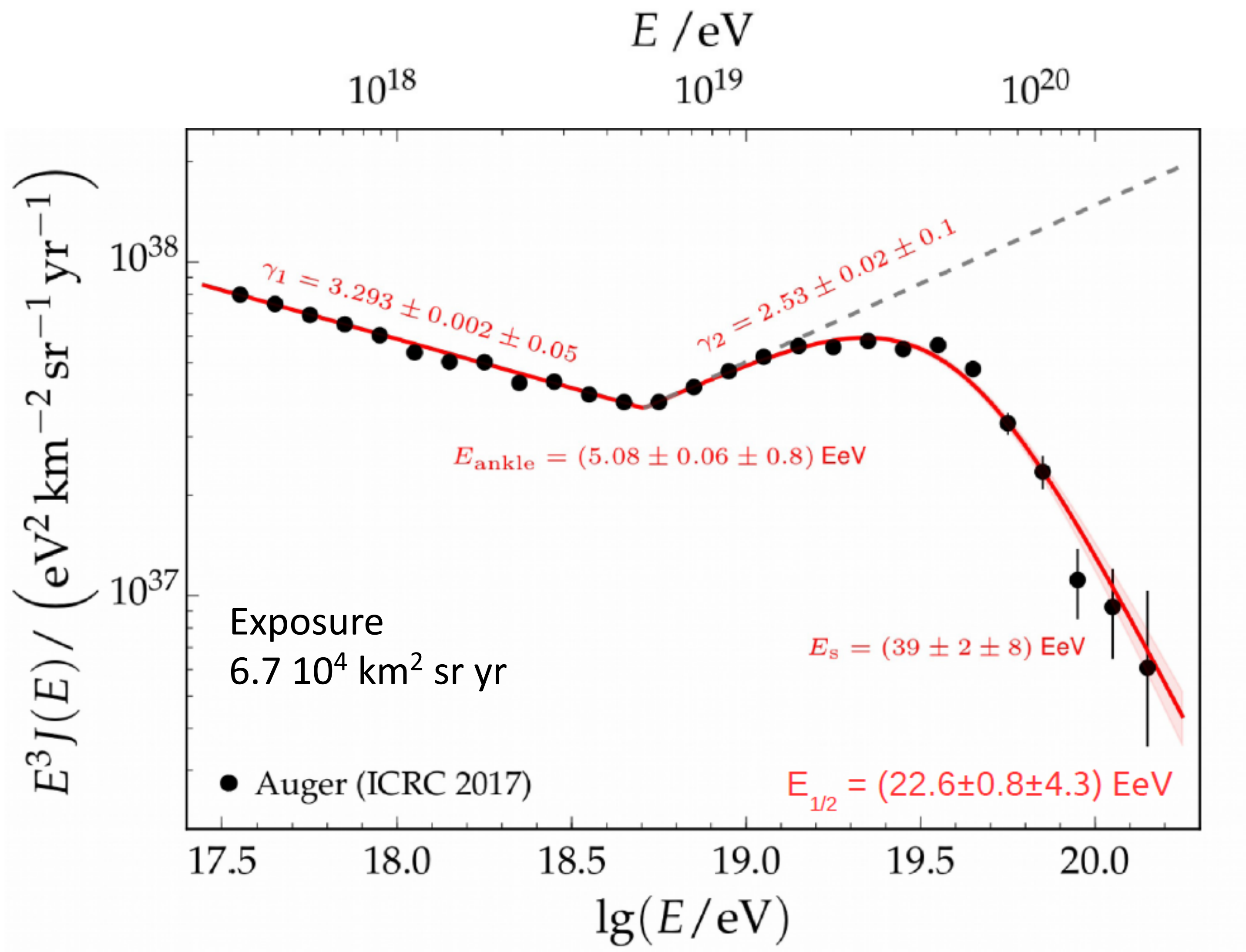
Energy spectrum (all-particle flux)



Exposure
6.7 10^4 km^2 sr yr

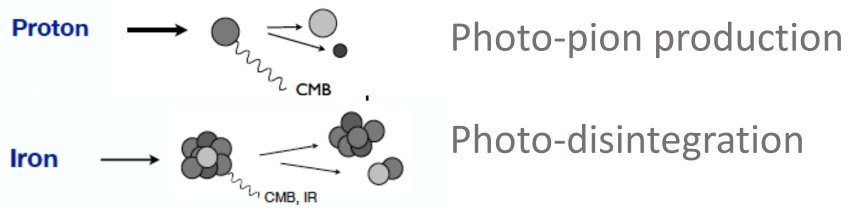
$E_{1/2}$ = (22.6±0.8±4.3) EeV

Energy spectrum (all-particle flux)



What is the origin of the flux suppression?

- *Propagation effect?*
  "Greisen-Zatsepin-Kuzmin"



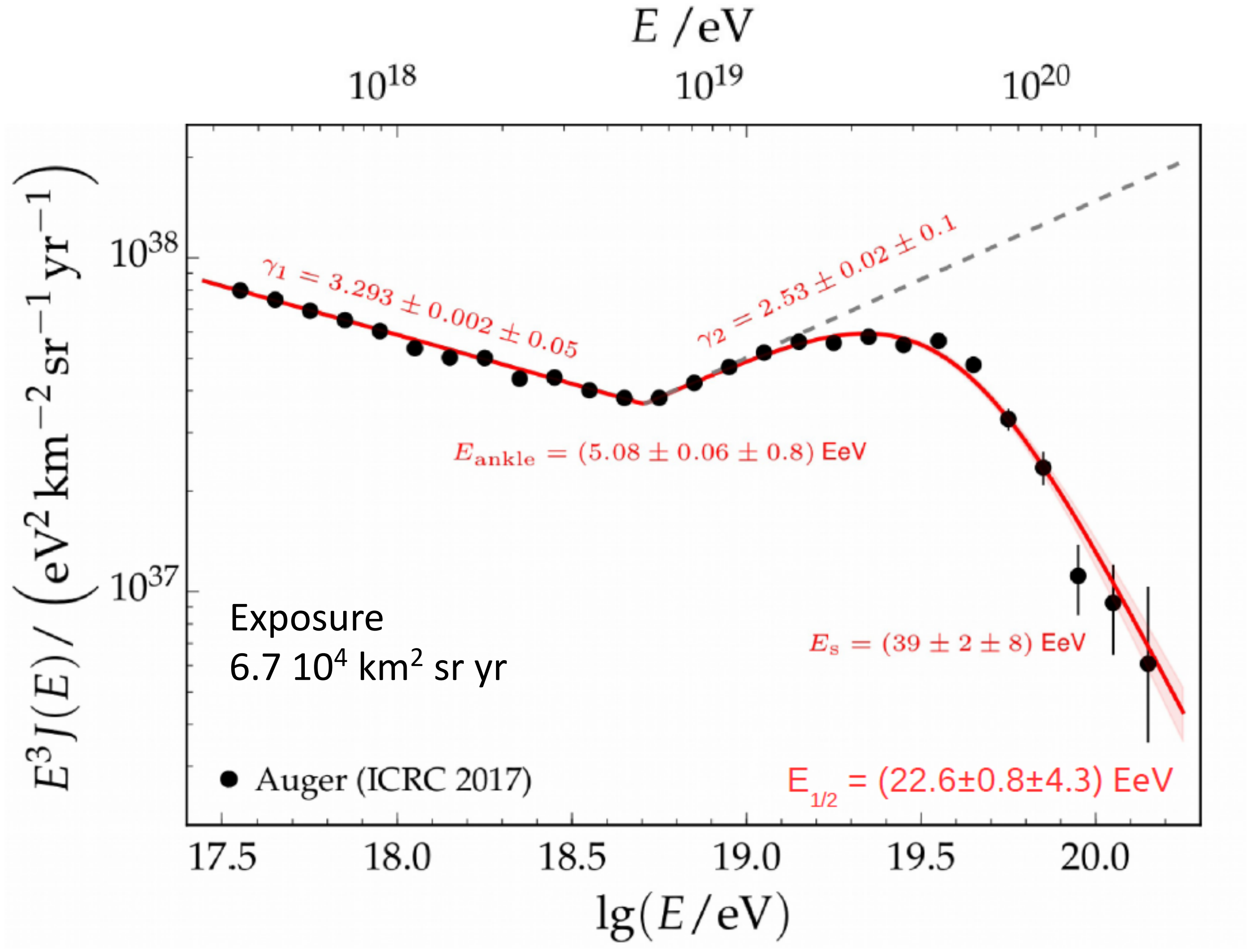
- *Maximum injection energy?*

What is the origin of the ankle?

- *Propagation effect?*

- *Transition effect?*
- *Interactions in the source environment?*

Energy spectrum (all-particle flux)



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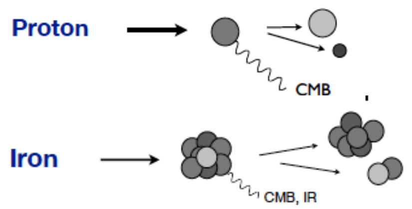


Photo-pion production

Photo-di...

- *Maxi... energy?*

W... the origin of the ankle?

Energy spectrum alone remains ambiguous concerning interpretations

- *Propagation effect?*

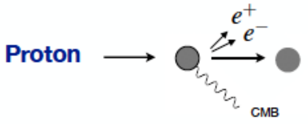
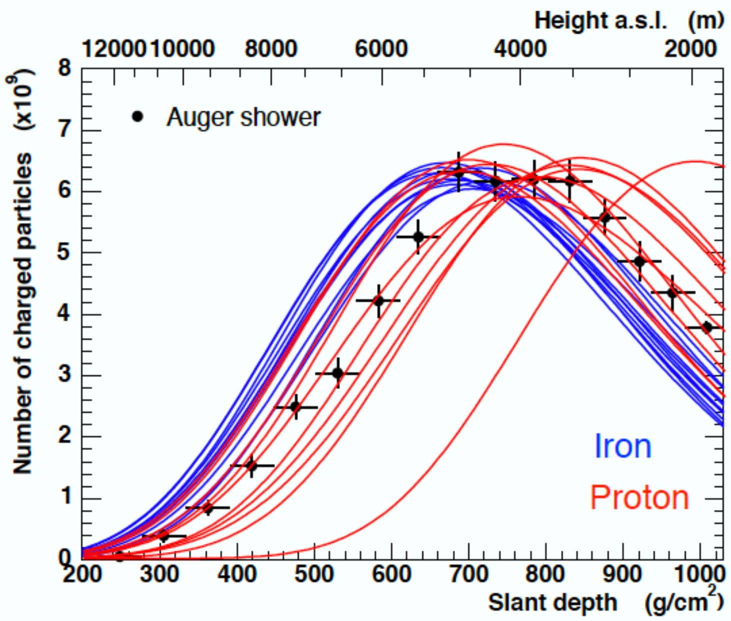
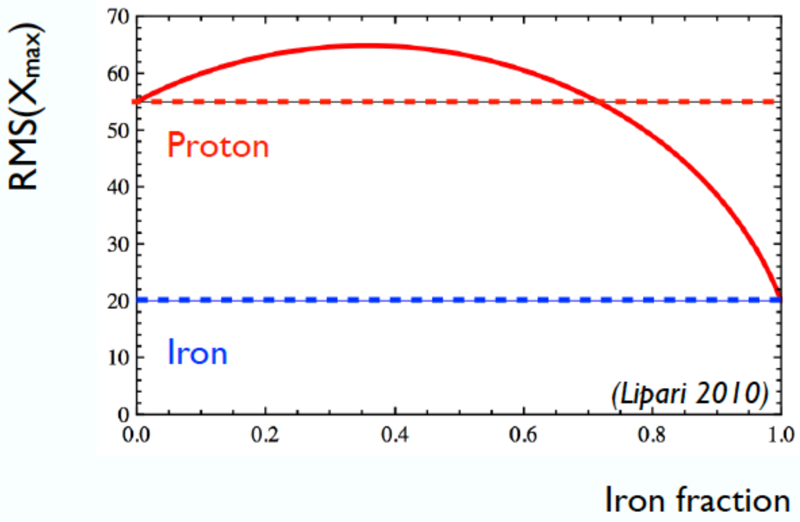


Photo-pair production

- *Transition effect?*
- *Interactions in the source environment?*

Depth of shower maximum

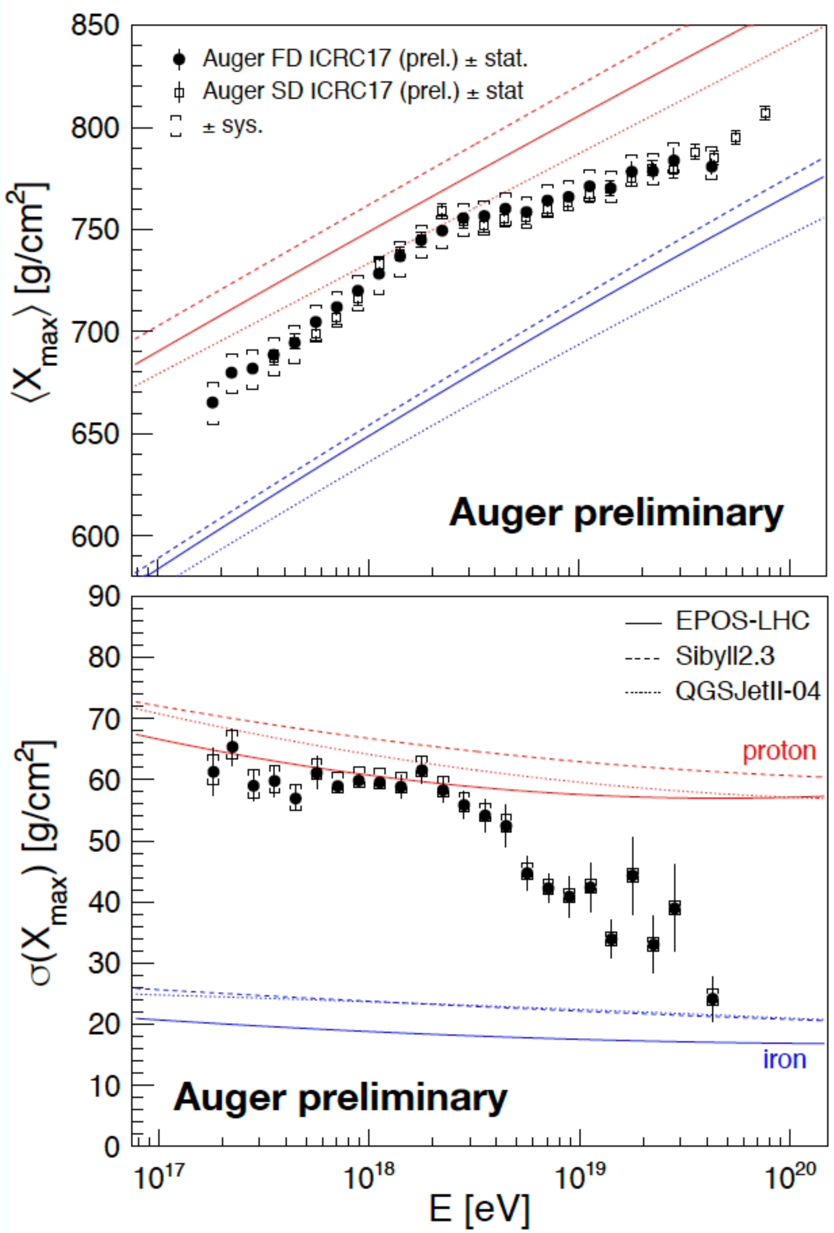




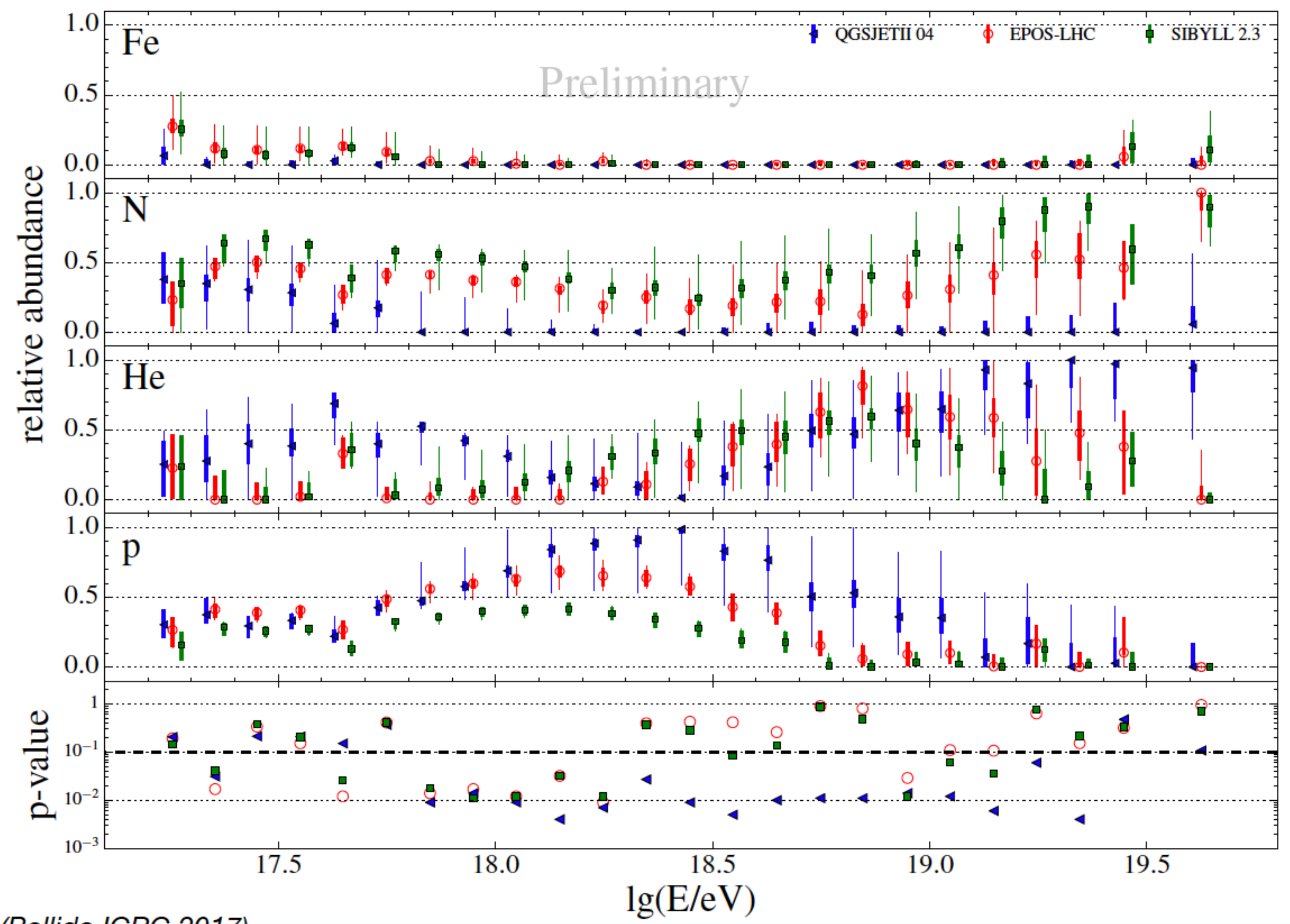
p-induced showers ***develop deeper than*** **Fe-induced ones** ***and have larger fluctuations***

Break in the elongation rate just below the ankle

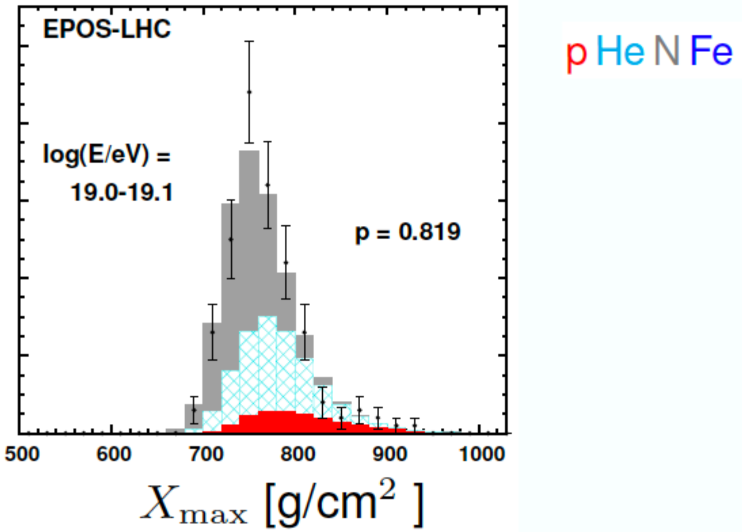
Xmax fluctuations very small



Mass composition @ Earth (top of the atmosphere)



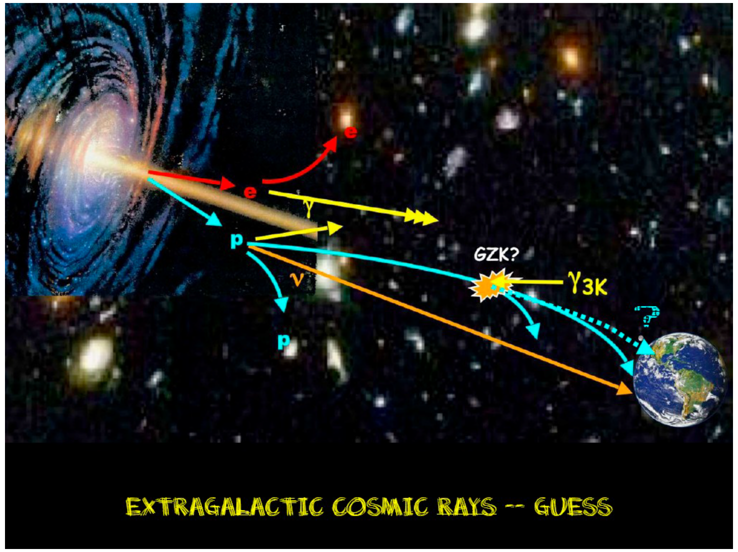
(Bellido ICRC 2017)



- **Xmax distributions fitted with four-mass CONEX showers from LHC-tuned interaction models.**
- **Fit quality not always good (QGSJet worse).**
- **Large proton fractions below the ankle.**
- **Iron almost absent.**

What is the mass composition at the sources? What are the injected fluxes?

Propagation of CR nuclei in the cosmic photon fields



Astrophysical interpretation possible for simple scenarios:

- 1D propagation;
- Homogeneous distribution of identical sources of p, He, N (, Si) and Fe nuclei;
- CR injection = power-law + rigidity cutoff.

Same basic scenario used in many interpretation papers, e.g. Aharonian, Ahlers, Allard, Aloisio, Berezinsky, Blasi, Hooper, Olinto, Parizot, Taylor, …:

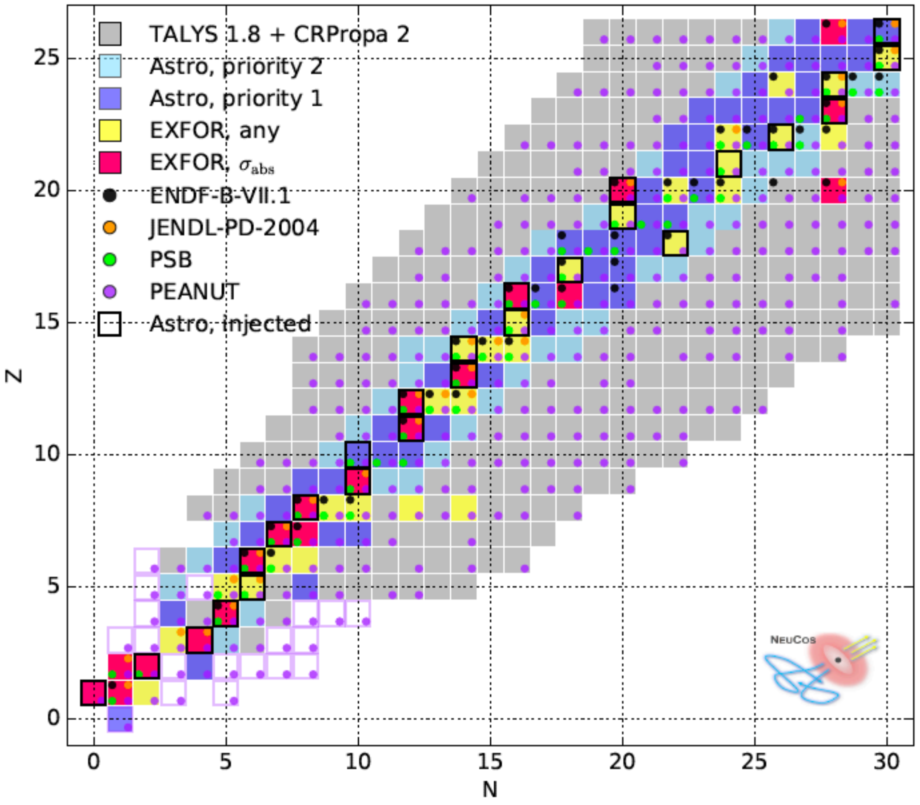
Hard/very-hard injection unless nearby sources assumed

Auger combined fit of spectrum and composition data *JCAP 04 (2017) 038*
A comprensive study of model and data uncertainties

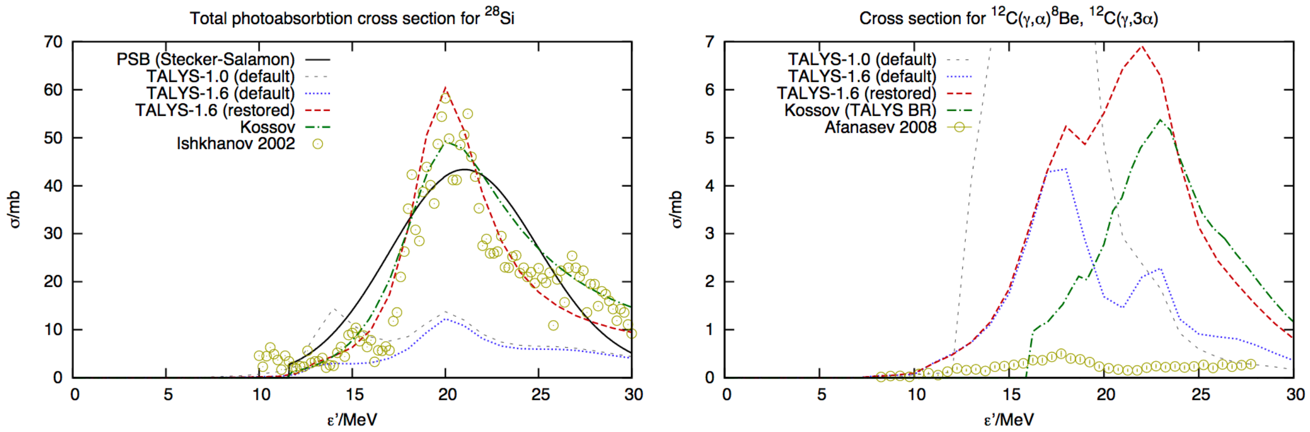
Model dependence:

- Propagation codes
- Cross-sections
- EBL models

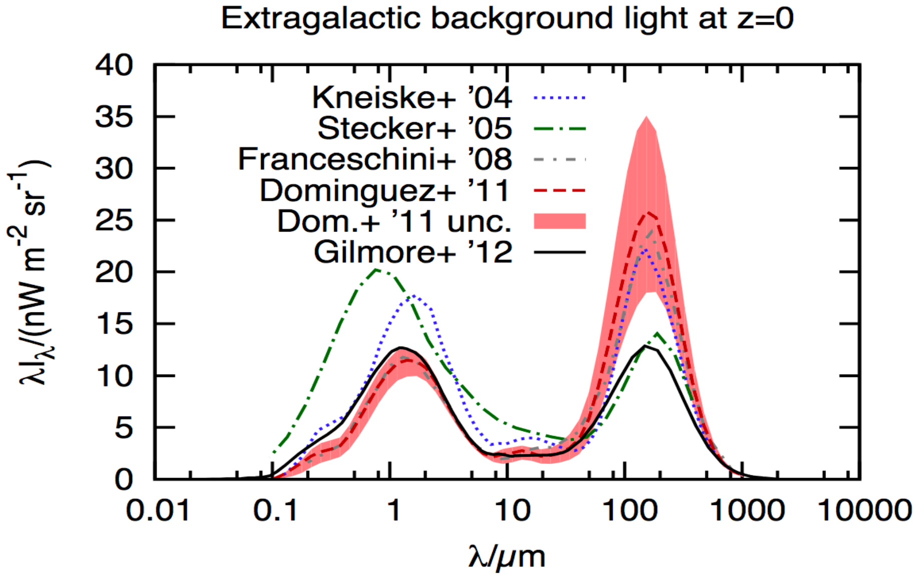
Involved nuclei



Boncioli, Fedynitch, Winter, et al., Sci. Rep., 7, 4882 (2017)



Alves Batista et al., JCAP 10 (2015) 063



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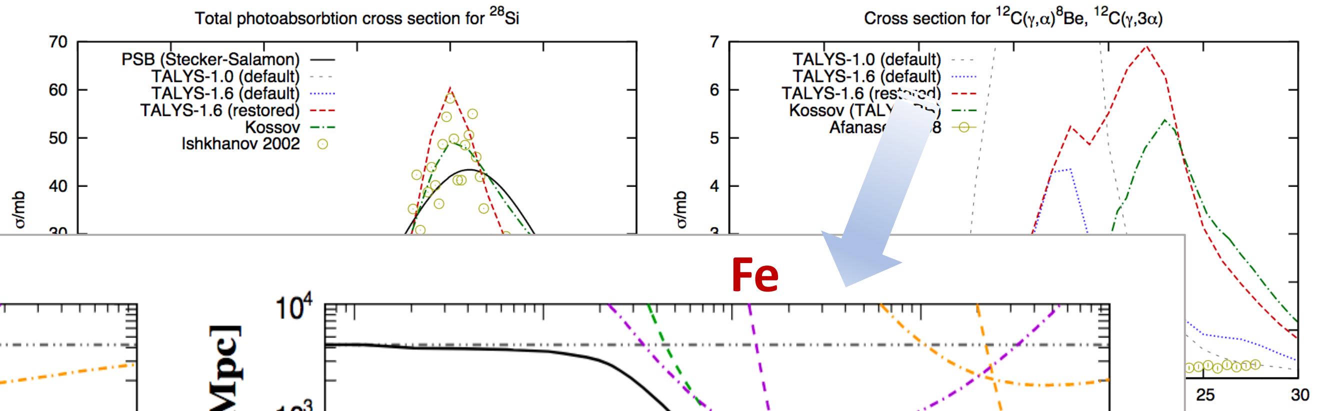
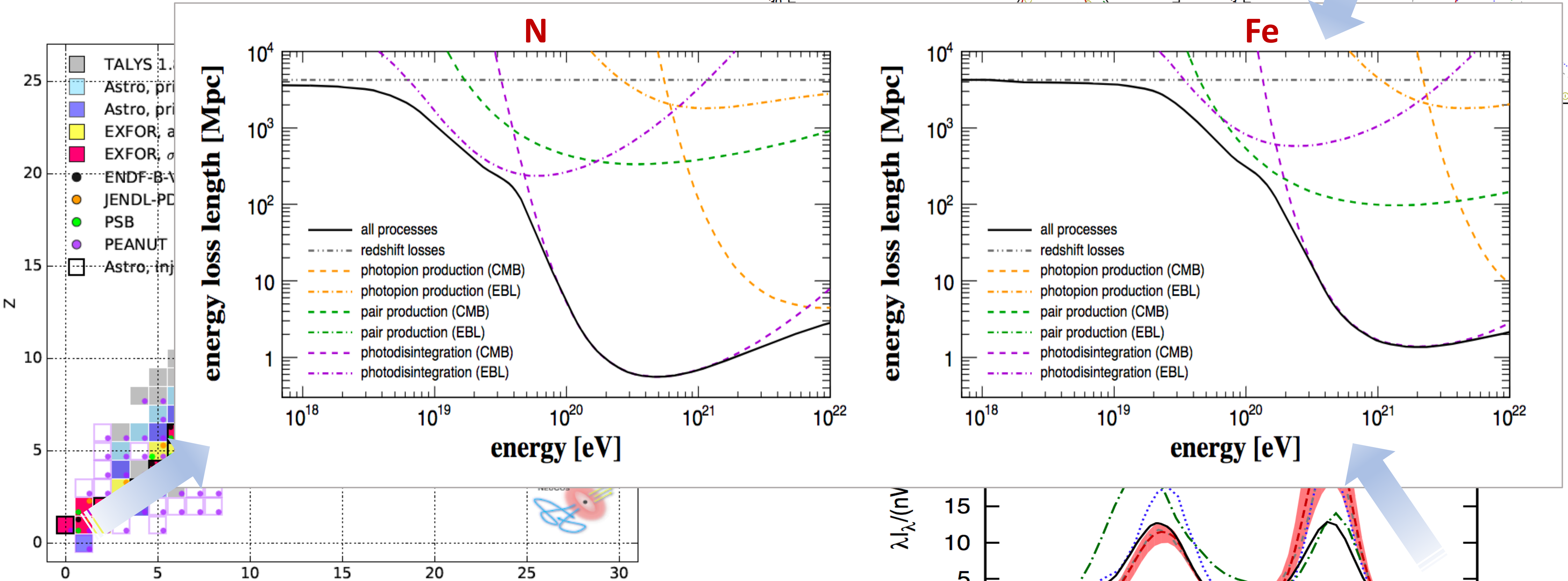
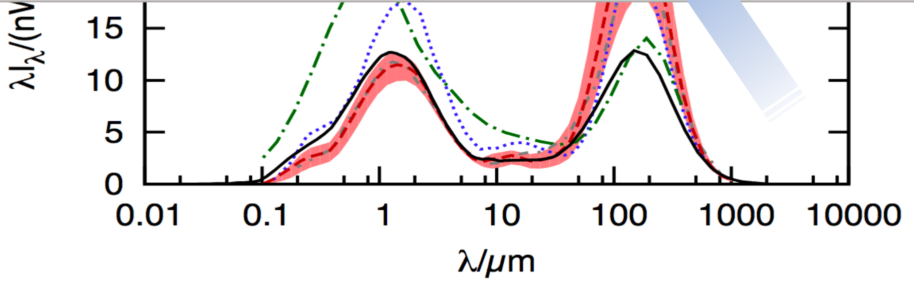






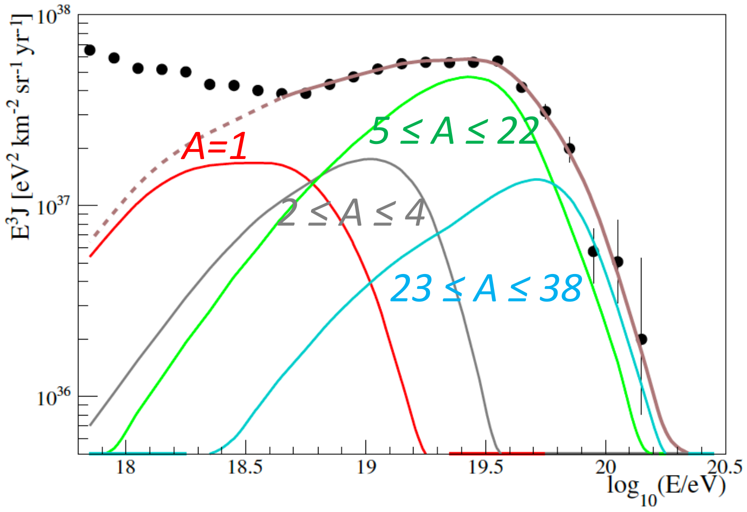
Boncioli, Fedynitch, Winter, et al., Sci. Rep., 7, 4882 (2017)

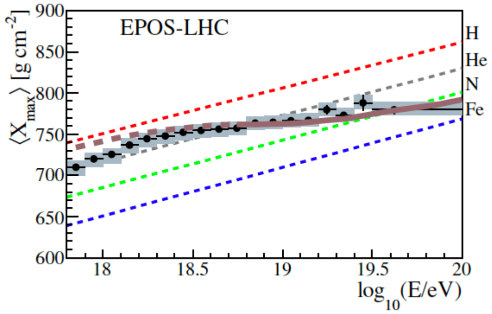
Best fit results for reference model

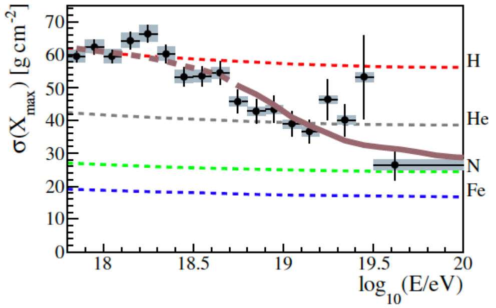
SPG (SimProp, PSB x-sect, Gilmore '12 EBL) + EPOS-LHC

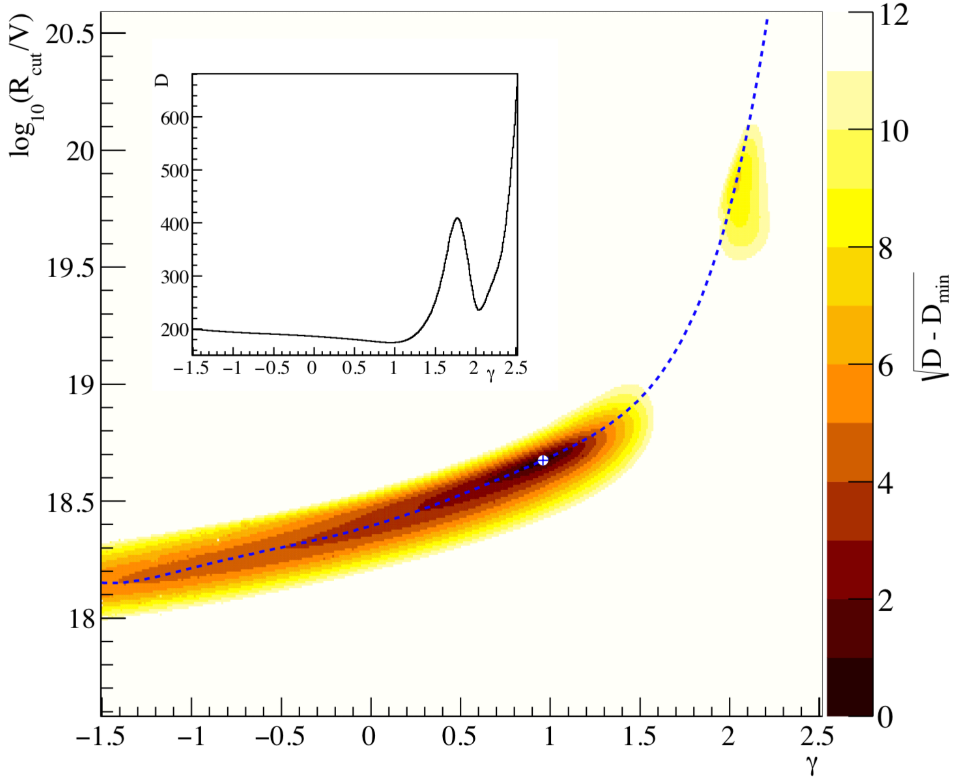
$$\frac{dN}{dE} = J_0 \sum_\alpha f_\alpha E_0^{-\gamma} \begin{cases} 1 & \text{for} \quad E_0/Z_\alpha < R_{cut}\,, \\ \exp(1 - \frac{E_0}{Z_\alpha R_{cut}}) & \text{for} \quad E_0/Z_\alpha \geq R_{cut} \end{cases}$$

reference model	best fit	average	shortest 68% int.
γ	1.22	1.27	$1.20 \div 1.38$
$\log_{10}(R_{cut}/V)$	18.72	18.73	$18.69 \div 18.77$
$f_H(\%)$	6.4	15.1	$0.0 \div 18.9$
$f_{He}(\%)$	46.7	31.6	$18.9 \div 47.8$
$f_N(\%)$	37.5	42.1	$30.7 \div 51.7$
$f_{Si}(\%)$	9.4	11.2	$5.4 \div 14.6$
$\Delta X_{max}/\sigma_{syst}$	−0.63	−0.69	$-0.90 \div -0.48$
$\Delta E/\sigma_{syst}$	+0.00	+0.12	$-0.57 \div +0.54$
D/n	166.5/117		
$D\ (J)$, $D\ (X_{max})$	12.9, 153.5		





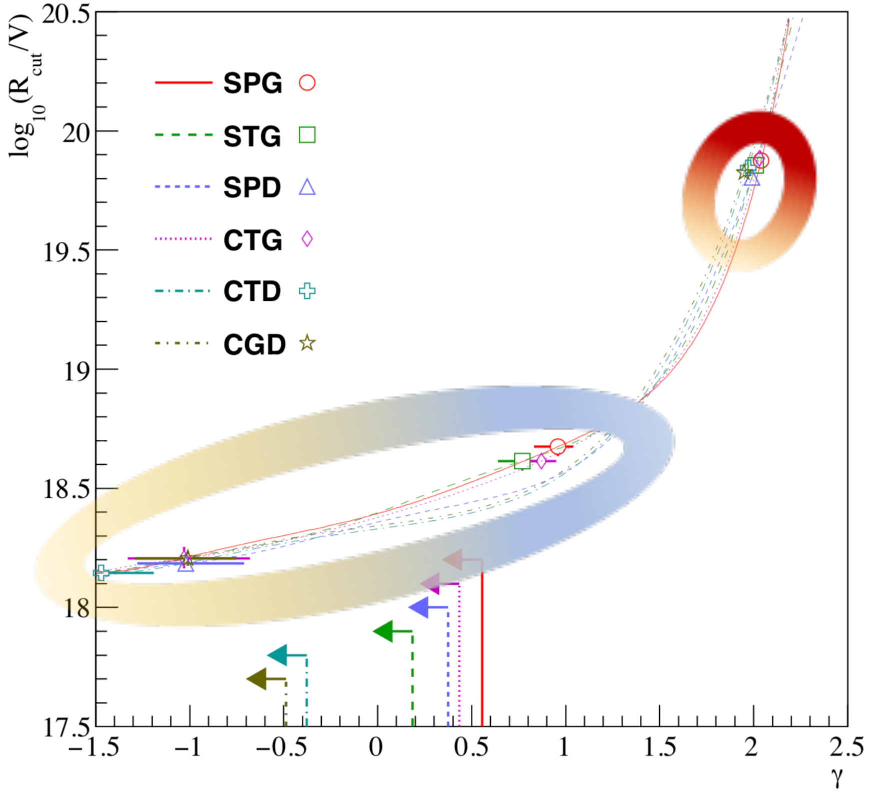




JCAP 04 (2017) 038

Changing model parameters

	MC code	$\sigma_{\text{photodisint.}}$	EBL model
SPG	SimProp	PSB	Gilmore 2012
STG	SimProp	TALYS	Gilmore 2012
SPD	SimProp	PSB	Domínguez 2011
CTG	CRPropa	TALYS	Gilmore 2012
CTD	CRPropa	TALYS	Domínguez 2011
CGD	CRPropa	Geant4	Domínguez 2011



Best minimum for γ < 1: ***here the position depends strongly on model parameters;***

Local minimum at $\gamma \approx 2$: ***almost independent of model parameters***

Changing model parameters

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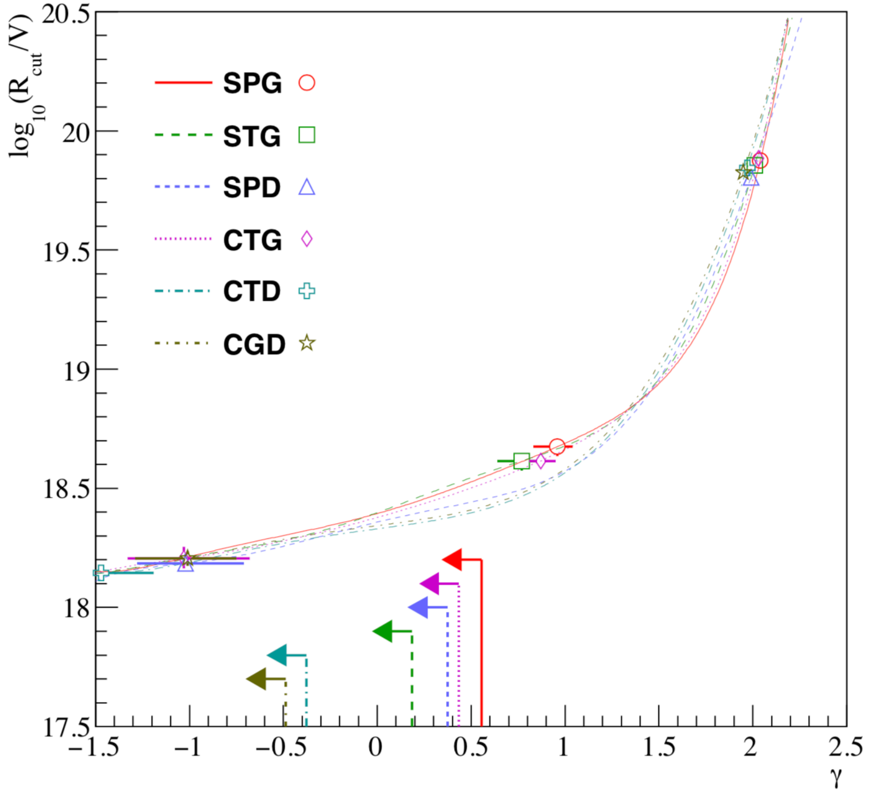
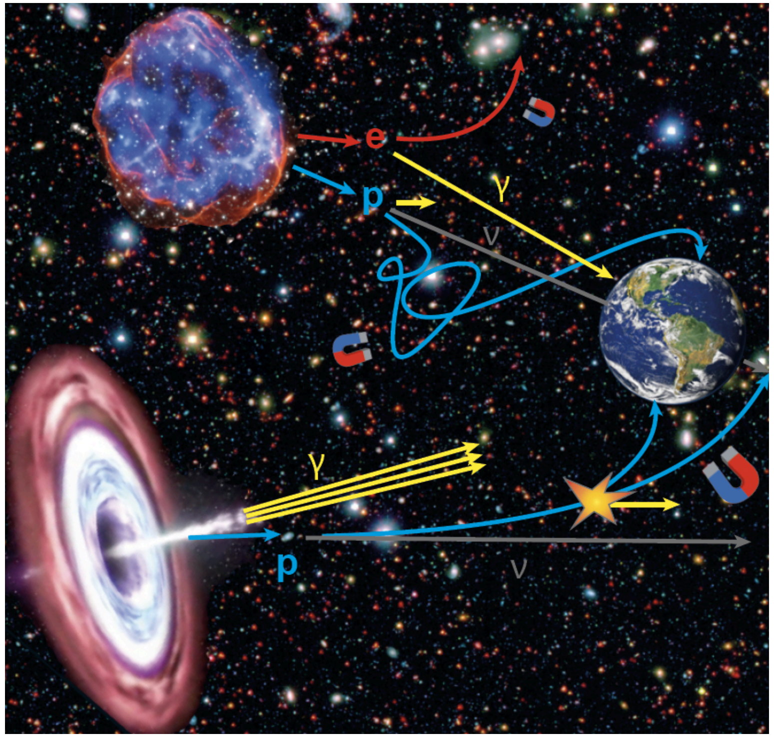


Changing interaction model

EPOS-LHC gives the best agreement
(initial tests with Sibyll 2.3 c …)

model	γ	$\log_{10}(R_{\text{cut}}/\text{V})$	D	$D(J)$	$D(X_{\max})$
EPOS-LHC	$+0.96^{+0.08}_{-0.13}$	$18.68^{+0.02}_{-0.04}$	174.3	13.2	161.1
Sibyll 2.1	$-1.50^{+0.05}$	$18.28^{+0.00}_{-0.01}$	243.4	19.7	223.7
QGSJet II-04	$+2.08^{+0.02}_{-0.01}$	$19.89^{+0.01}_{-0.02}$	316.5	10.5	306.0
	$-1.50^{+0.02}_{*}$	$18.28^{+0.01}_{-0.00}$	334.9	19.6	315.3

Making the astrophysical model more realistic



4D propagation using CRPropa3

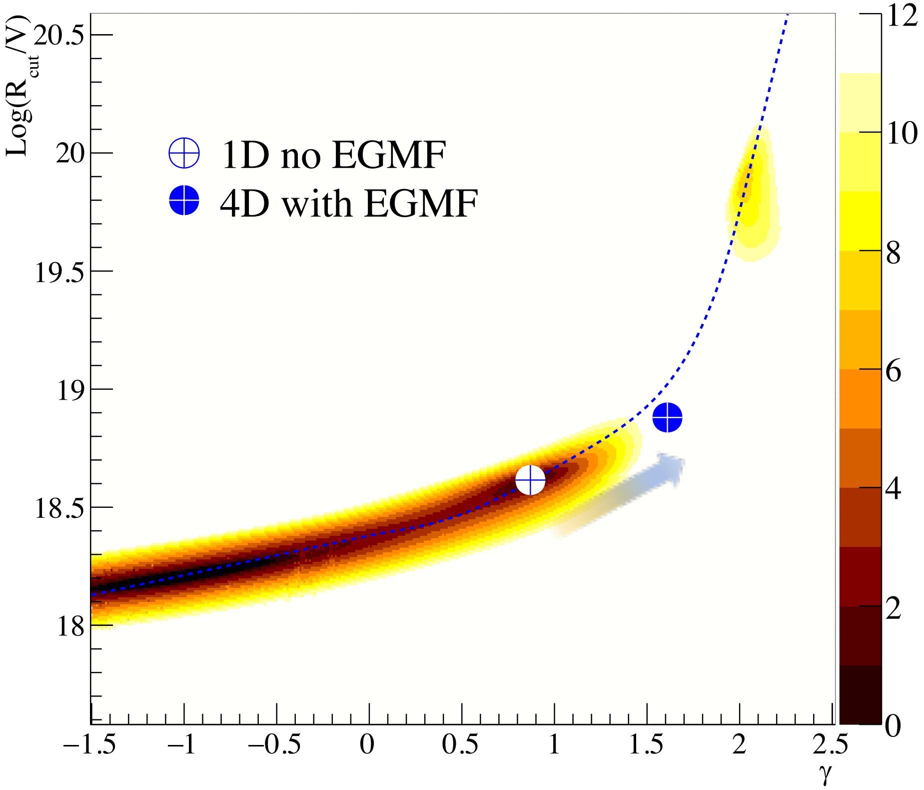
Large scale structure for CR sources *(Dolag '12)*

Results for a single model (CTG + EPOS-LHC):
Wittkowski ICRC 2017

Source properties	4D with EGMF	4D no EGMF	1D no EGMF[1]
γ	1.61	0.61	0.87
$\log_{10}(R_{cut}/\mathrm{eV})$	18.88	18.48	18.62
f_H	3 %	11 %	0 %
f_{He}	2 %	14 %	0 %
f_N	74 %	68 %	88 %
f_{Si}	21 %	7 %	12 %
f_{Fe}	0 %	0 %	0 %

[1] Homogeneous source distribution, see [A. Aab et al., JCAP 2017, 038 (2017)]

Making the astrophysical model more realistic



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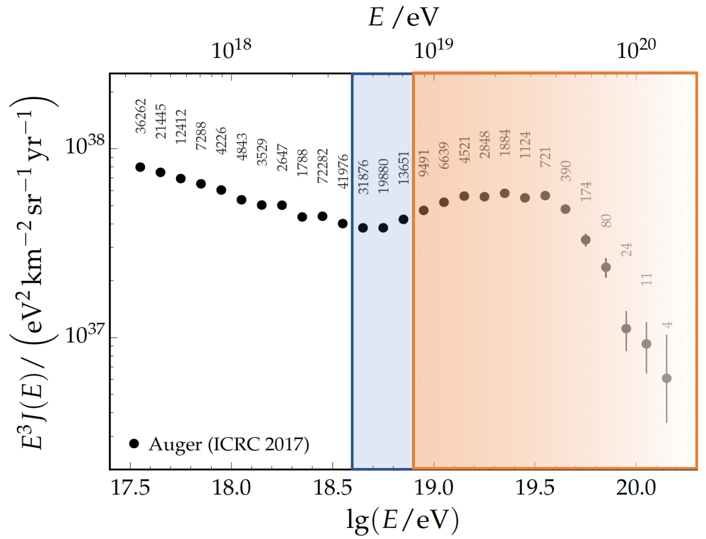
Anisotropy: Large scale



Combination of vertical and inclined showers

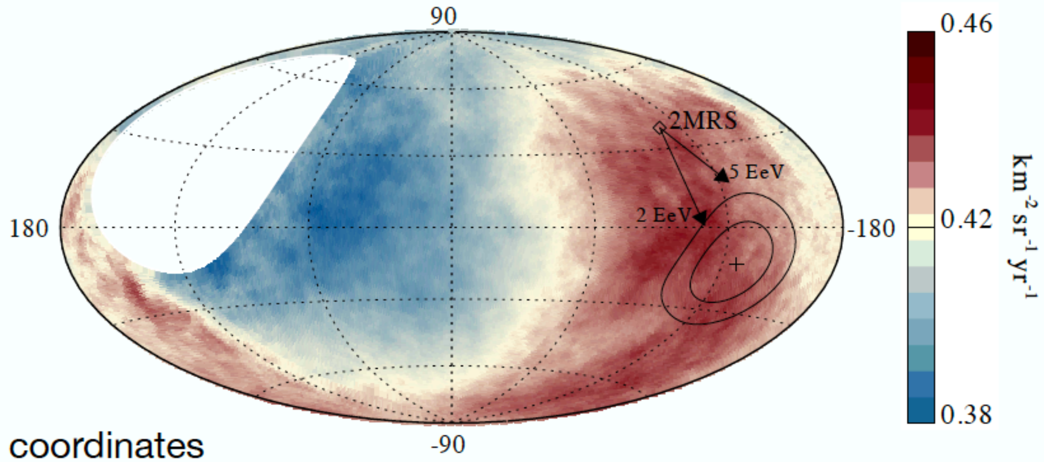
Harmonic analysis in right ascension α

	E [EeV]	events	amplitude r	phase [deg.]	$P(\geq r)$
→	4-8	81701	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
→	> 8	32187	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

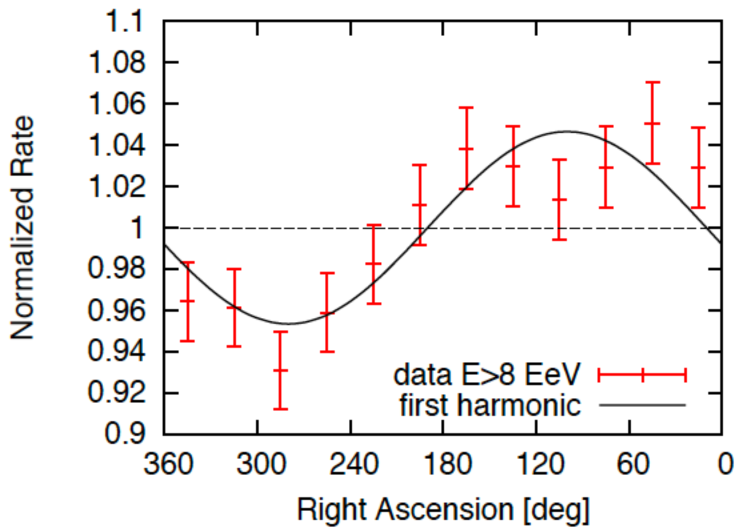
significant modulation at 5.2σ (5.6σ before penalization for energy bins explored)

3-d dipole above 8 EeV:

$(6.5^{+1.3}_{-0.9})\%$ at $(\alpha, \delta) = (100°, -24°)$ $(l, b) = (233°, -13°)$



gal. coordinates



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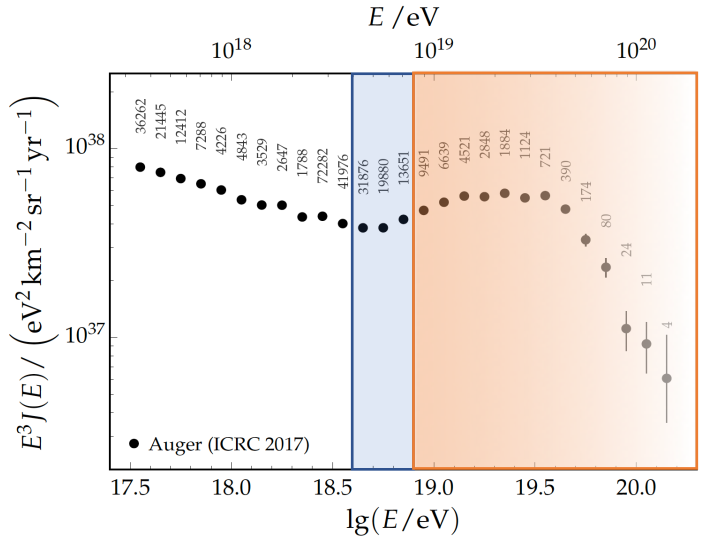

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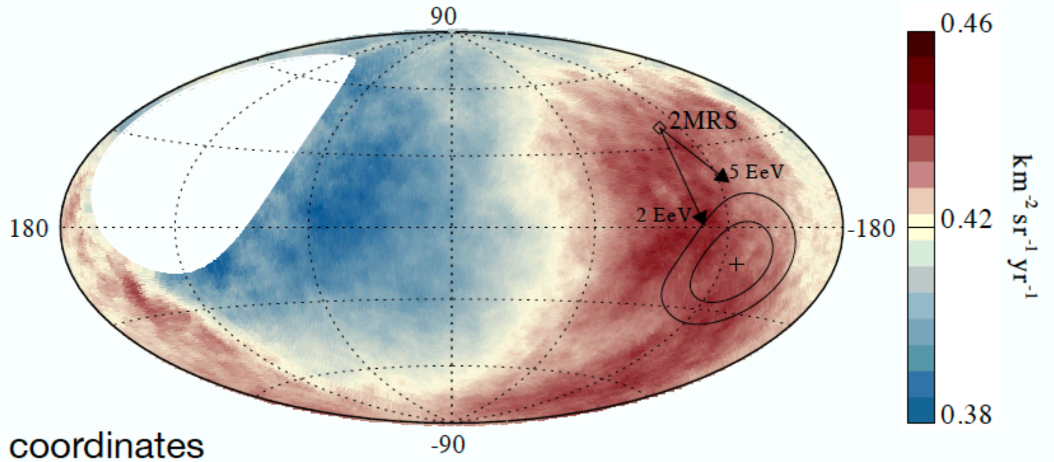
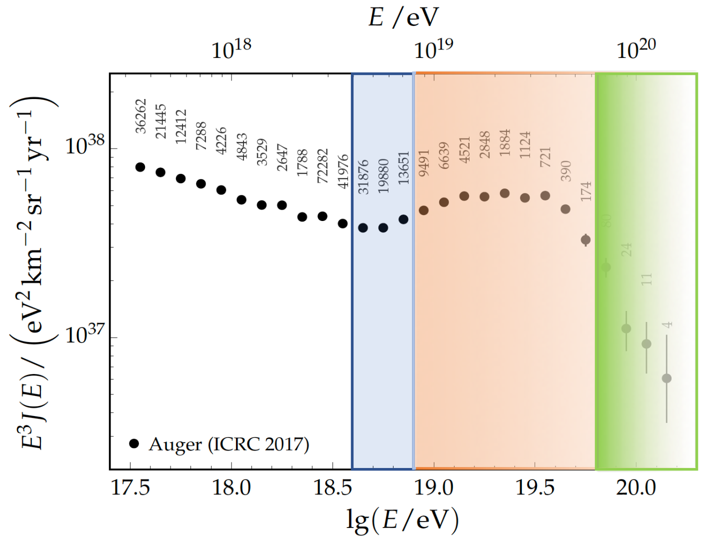


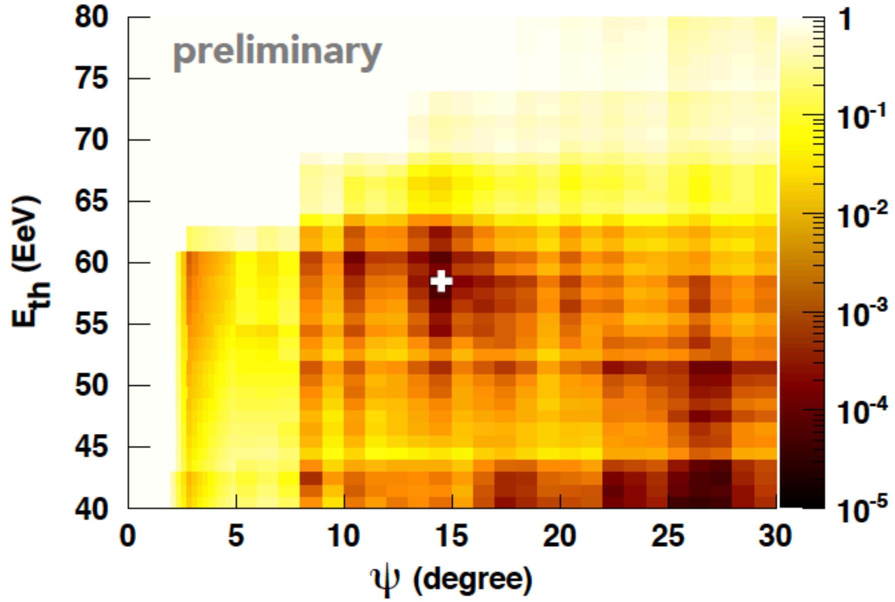
gal. coordinates

- Expected if cosmic rays diffuse to Galaxy from sources distributed similar to near-by galaxies *(Harari, Mollerach PRD 2015, 2016)*
- Deflection of dipolar pattern due to Galactic magnetic field
- Strong indication for extragalactic origin dipole direction ~ 125° from GC

Anisotropy: Intermediate scale

- Compare the cumulative number of observed (n_{obs}) events with the expected on average from isotropic simulations (n_{exp})
- Compute the cumulative binomial probability (P) to measure n_{obs} given $<n_{exp}>$
- Scan in parameters: *E_{th} in [40; 80] EeV in steps of 1 EeV*
  Ψ in [1°; 30°] in steps of 0.25° up to 5°, 1° for larger angles





(Giaccari ICRC 2017)

Largest excess

E_{th} = 58 EeV, Ψ = 15°

n_{obs} = 19, n_{exp} = 6.0

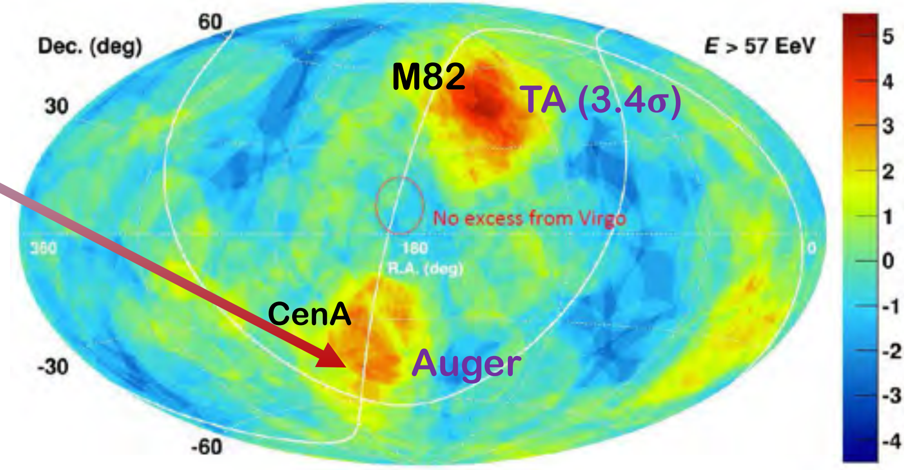
P **~ 1.1 × 10^{-5}**

Post-trial probability

~ 1.1 × 10^{-3}

(fraction of isotropic simulations that have a smaller probability under the same scan)

Region of secondary minima above ~40 EeV



Anisotropy: Correlation with catalogs

[Auger Coll., Ap.J. 853 (2018) L29]

Active Galactic Nuclei (γ-AGN)

- *Selected from 2FHL Catalog (Fermi-LAT, 360 sources):*
  Φ(> 50 GeV) ---> proxy for UHECR flux.
- *Selection of the 17 objects within 250 Mpc.*
- *Majority blazars of BL-Lac type and radio-galaxies of FR-I type.*

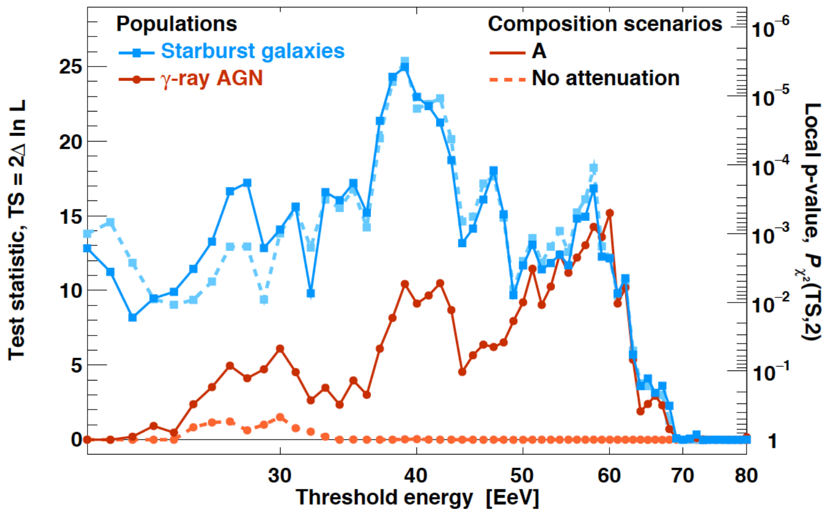
Starburst Galaxies

Use of Fermi-LAT search list for star-formation objects (Ackermann+ 2012)

- *63 objects within 250 Mpc, only 4 detected in gamma rays:*
  correlated Φ(> 1.4 GHz) ---> proxy for UHECR flux
- *Selection of brightest objects (flux completeness) with Φ(> 1.4 GHz) > 0.3 Jy*
- *23 objects, size similar to the gamma-ray AGN sample*

Assumption UHECRs flux proportional to non thermal photon flux

E > 60 EeV: f_{ani} = 7%, Ψ = 7°
TS = 15.2 $\Rightarrow$ After penalization ~2.7 σ



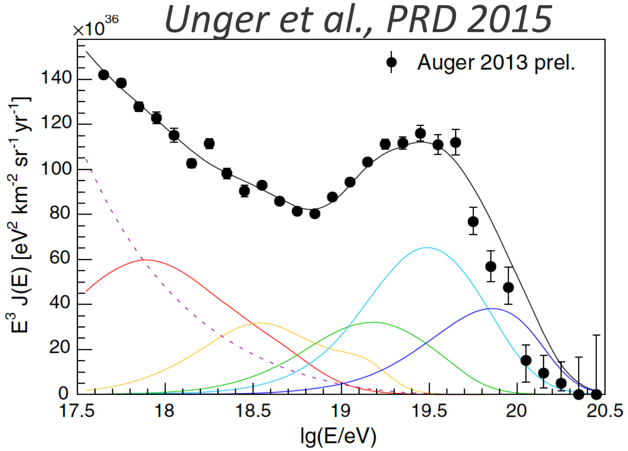
E > 39 EeV: f_{ani} = 10%, Ψ = 13°
TS = 24.9 $\Rightarrow$ After penalization ~4.0 σ

Some remarks

- ***Complicated and unexpected picture of UHECR emerging***

- ***Source models have to be more sophisticated than simple power laws*** *(e.g. large scale structure, different sources, interaction in the photon environment,…)*

Unger et al., PRD 2015



Some remarks

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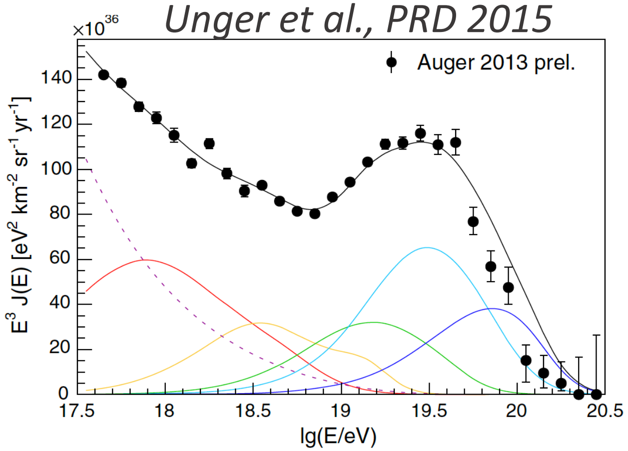
Unger et al., PRD 2015



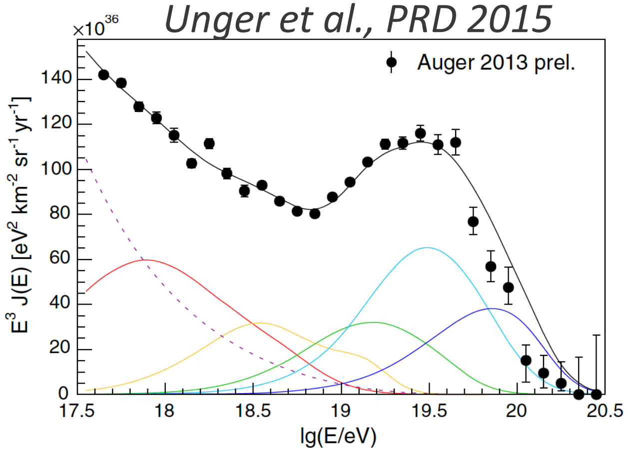
- ***Several model uncertainties*** *(EBL, ph-dis cross sections, hadronic interactions,…)*

- ***Need to have a comprehensive knowledge in the suppression region*** *(composition and possibly composition-enhanced anisotropy studies)*

Some remarks

- ***Complicated and unexpected picture of UHECR emerging***
- ***Source models have to be more sophisticated than simple power laws*** *(e.g. large scale structure, different sources, interaction in the photon environment,…)*

Unger et al., PRD 2015



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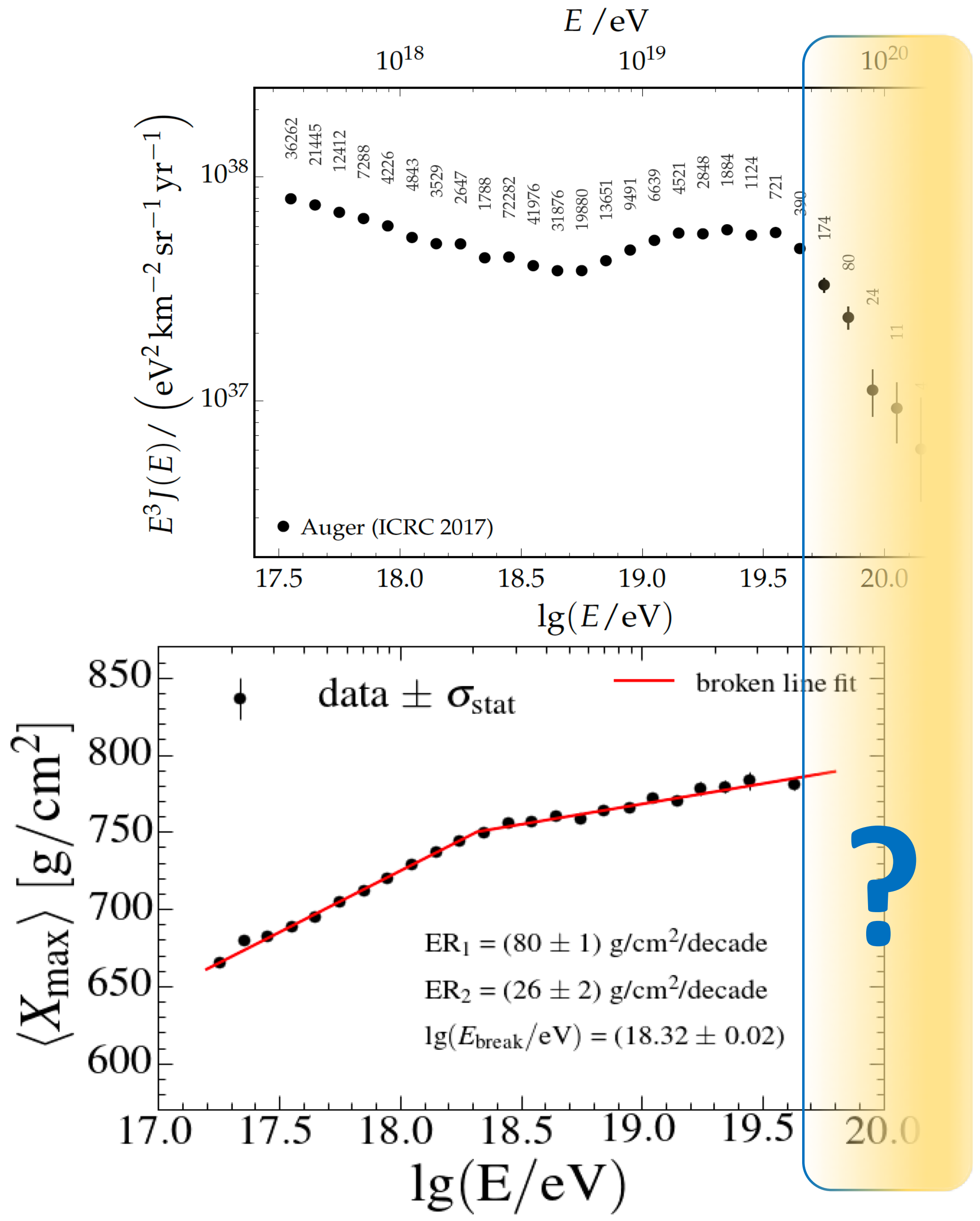
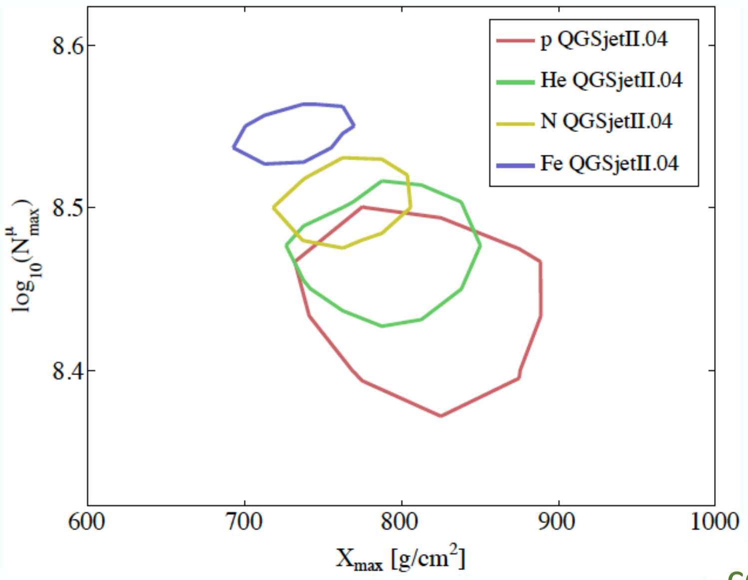



"Non est ad astra mollis e terris via"
"There is no easy way to the stars from the earth."
Hercules Furens - Seneca
Which possible direction?

Upgrade of the Pierre Auger Observatory: *AugerPrime*

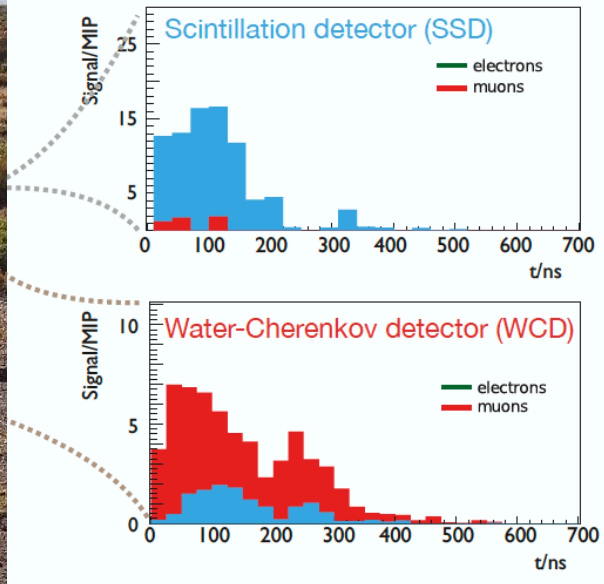
To increase exposure with composition sensitive data Surface array needed!

Duty cycle: 100% (SD) vs 15% (FD)



(AugerPrime design report 1604.03637)

complementarity of light responses used to discriminate e.m. and muonic components



$$S_{\mu,\mathrm{WCD}} = a\,S_{\mathrm{WCD}} + b\,S_{\mathrm{SSD}}$$
$$S_{\mathrm{em,WCD}} = c\,S_{\mathrm{WCD}} + d\,S_{\mathrm{SSD}}$$

Upgrade of the Pierre Auger Observatory: *AugerPrime*

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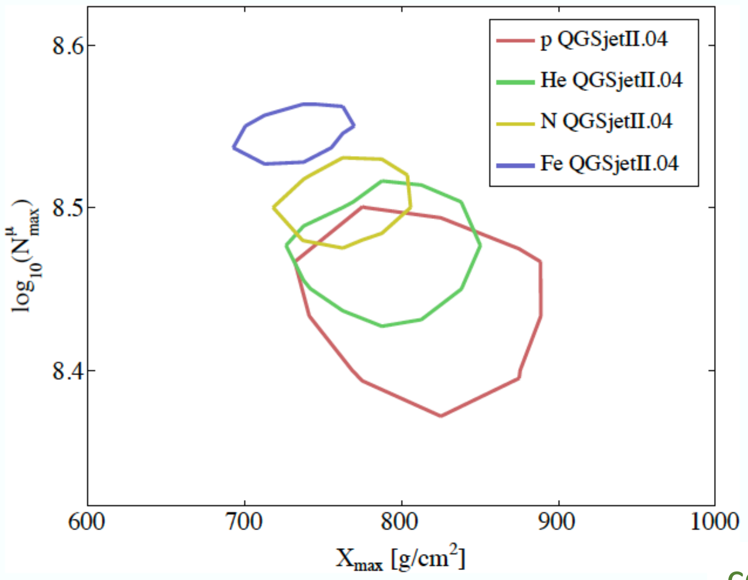
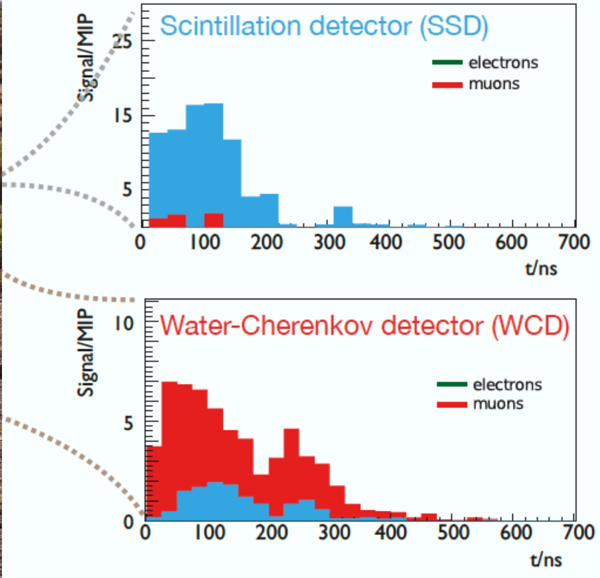


(AugerPrime design report 1604.03637)



complementarity of light responses used to discriminate e.m. and muonic components

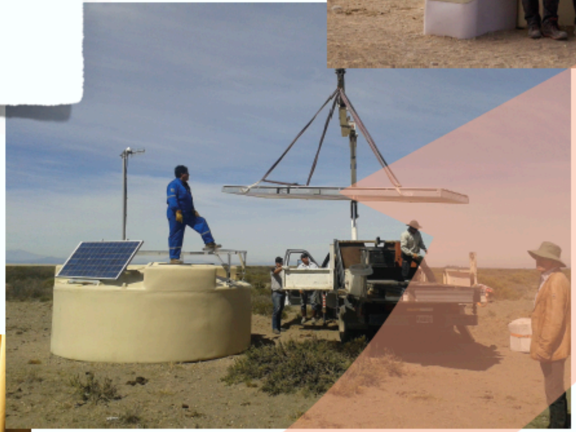
Moreover

- Upgraded and faster electronics
- Extension of the dynamic range
- Cross check with underground buried AMIGA detectors
- Extension of the FD duty cycle

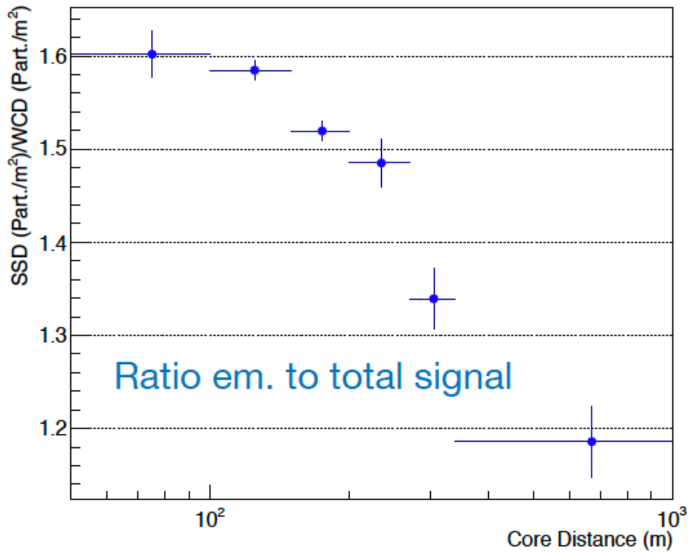
Status and plans for *AugerPrime*

- **Composition measurement at 10^{20} eV**
- **Composition selected anisotropy studies**
- **Particle physics with air showers**

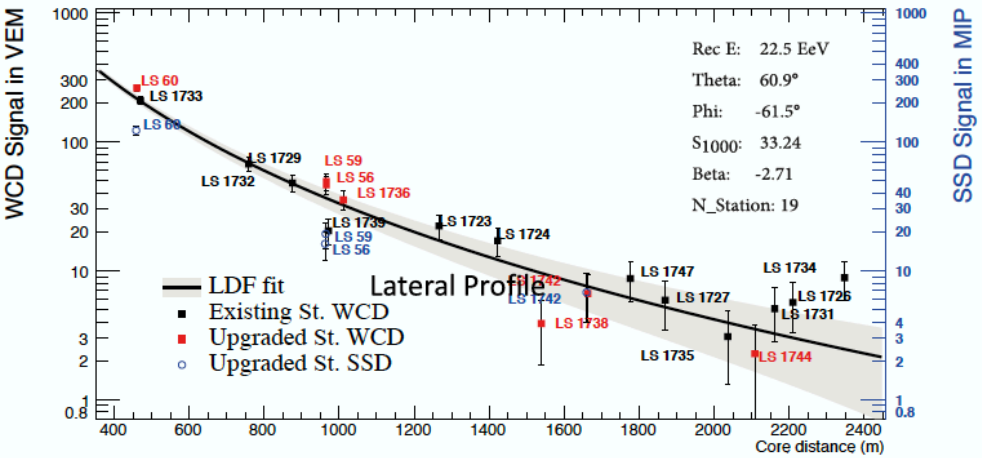
Deployment fast: ~ 5 -10 stations per day



2016: engineering array; 12 stations
2018-19: deployment
2019-25: data taking (40,000 km2 sr yr)

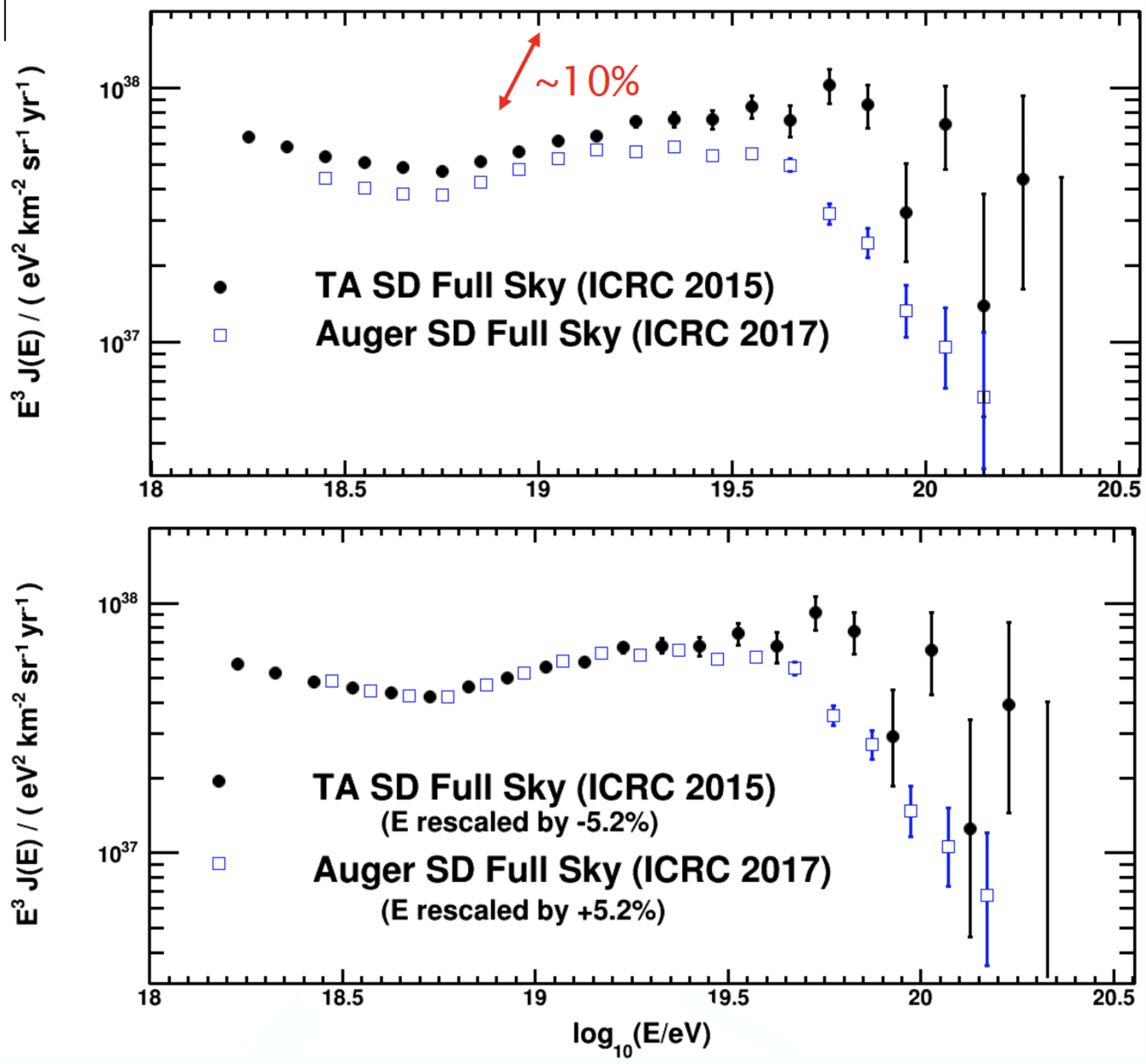


LDF of Ev.163076179300




Thanks

Energy spectrum:
Auger vs TA



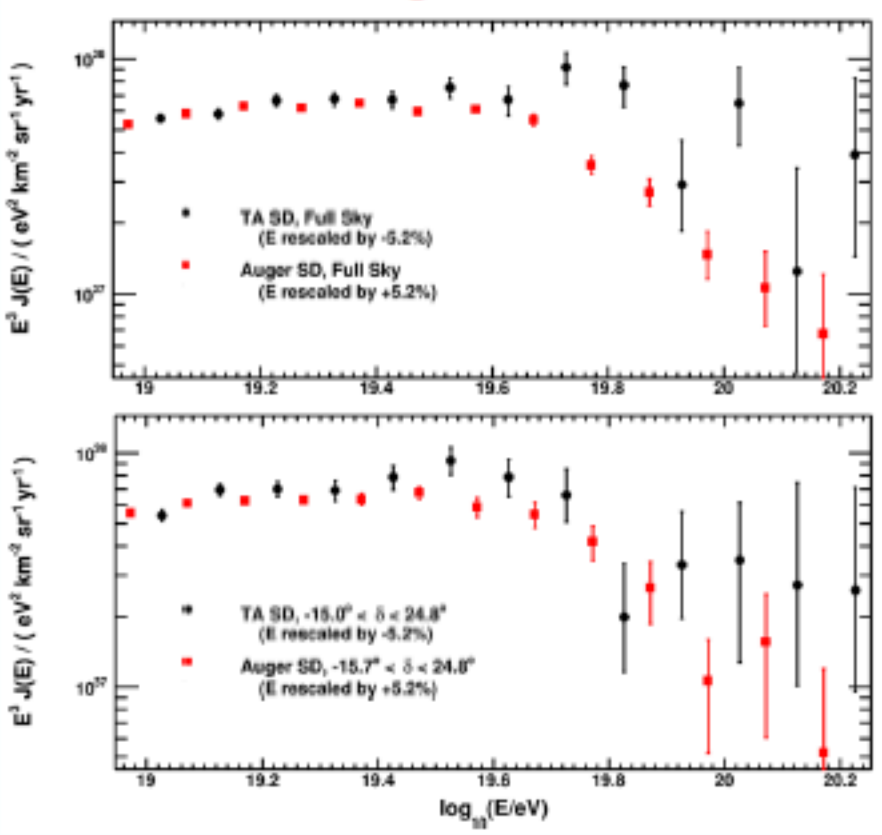
(Auger-TA Spectrum Working Group)

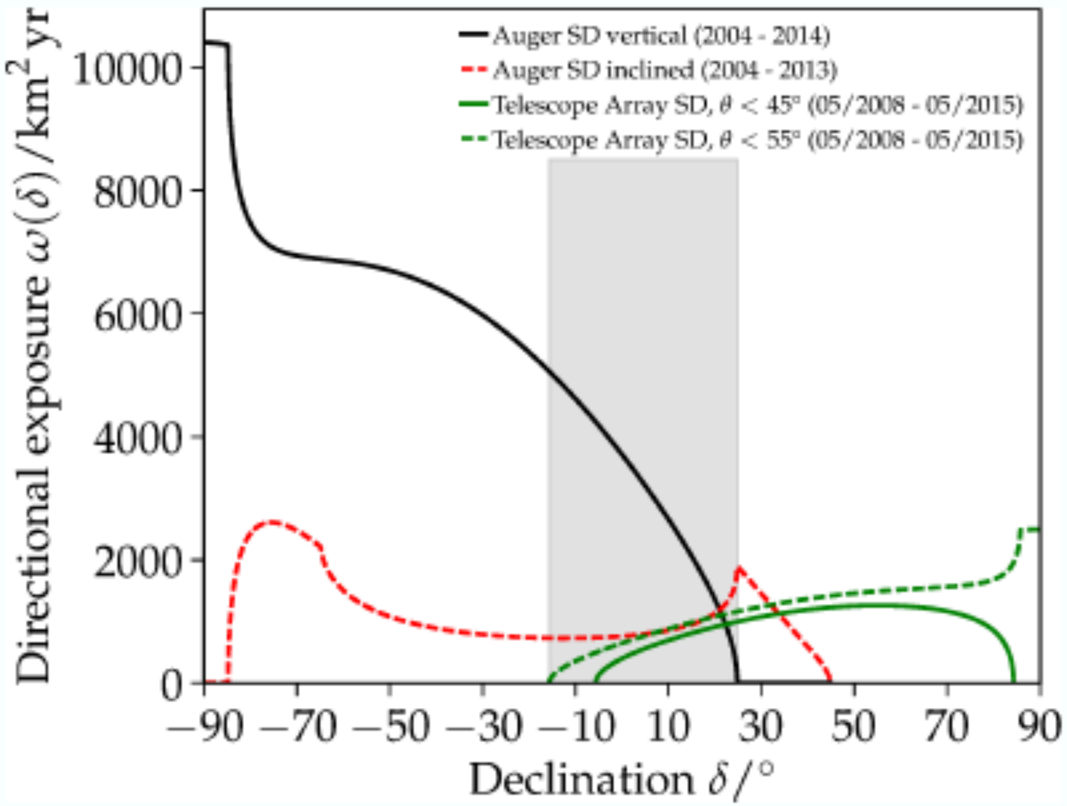
Are the spectra consistent with each other?

Auger vs TA

All sky

Common declination band





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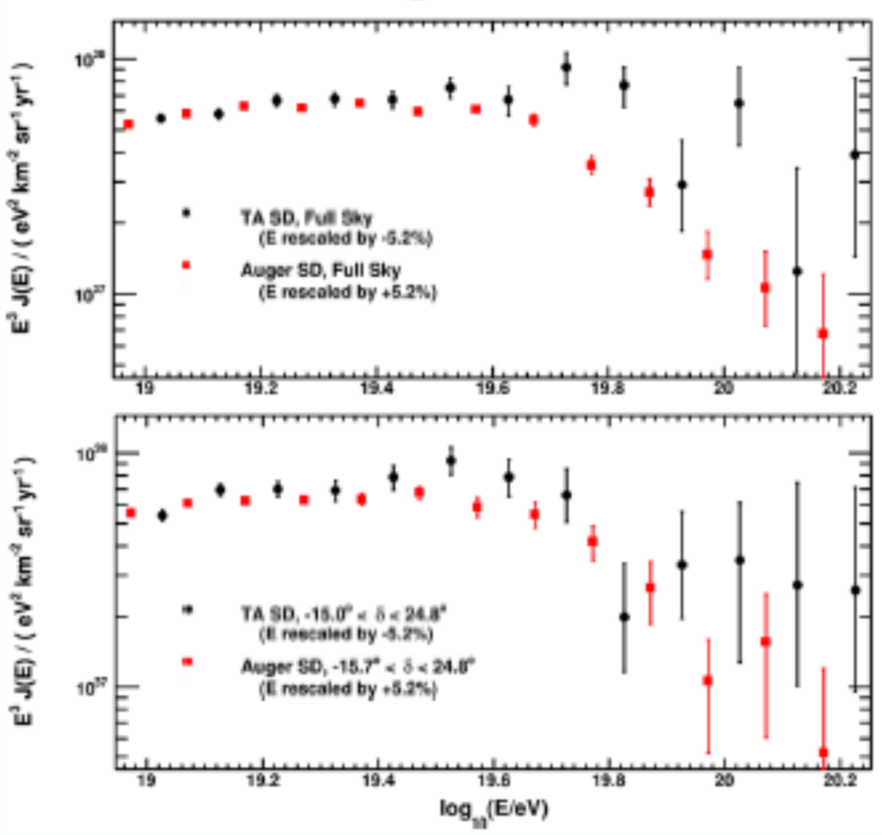
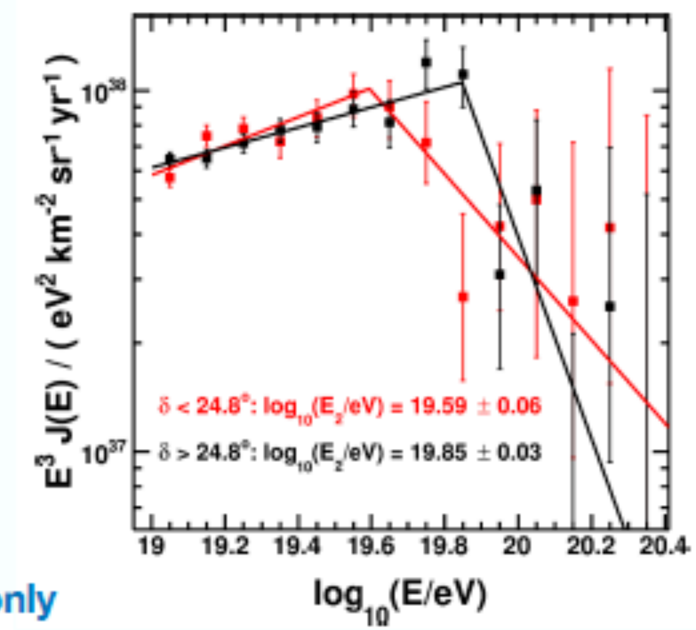
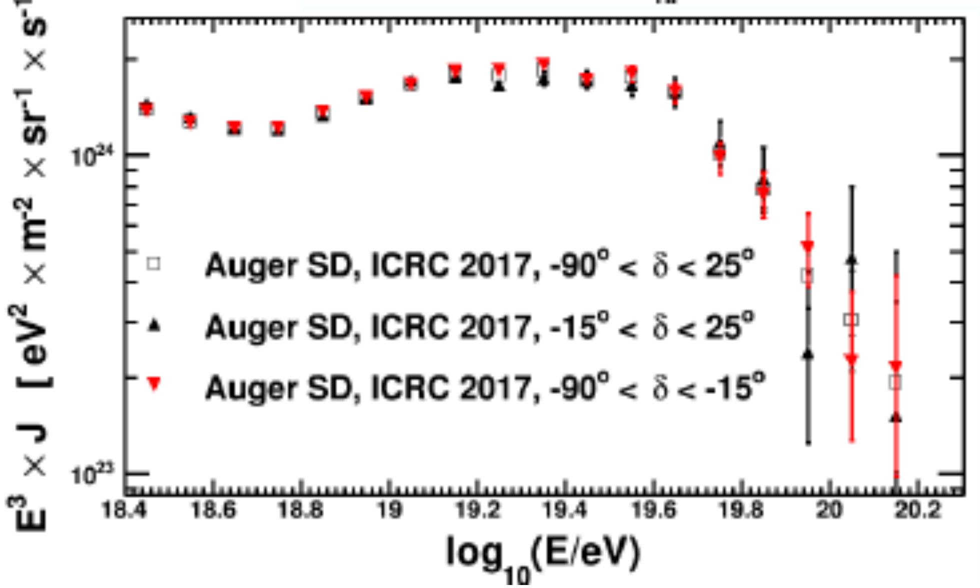


TA only



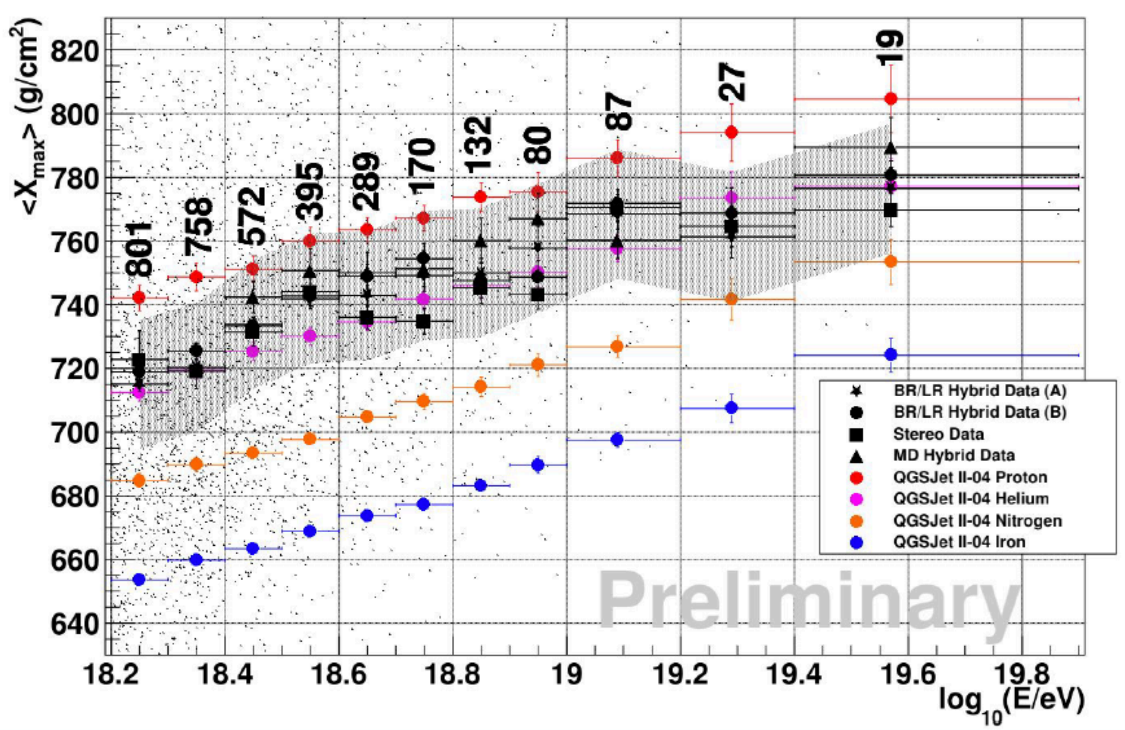
Auger only



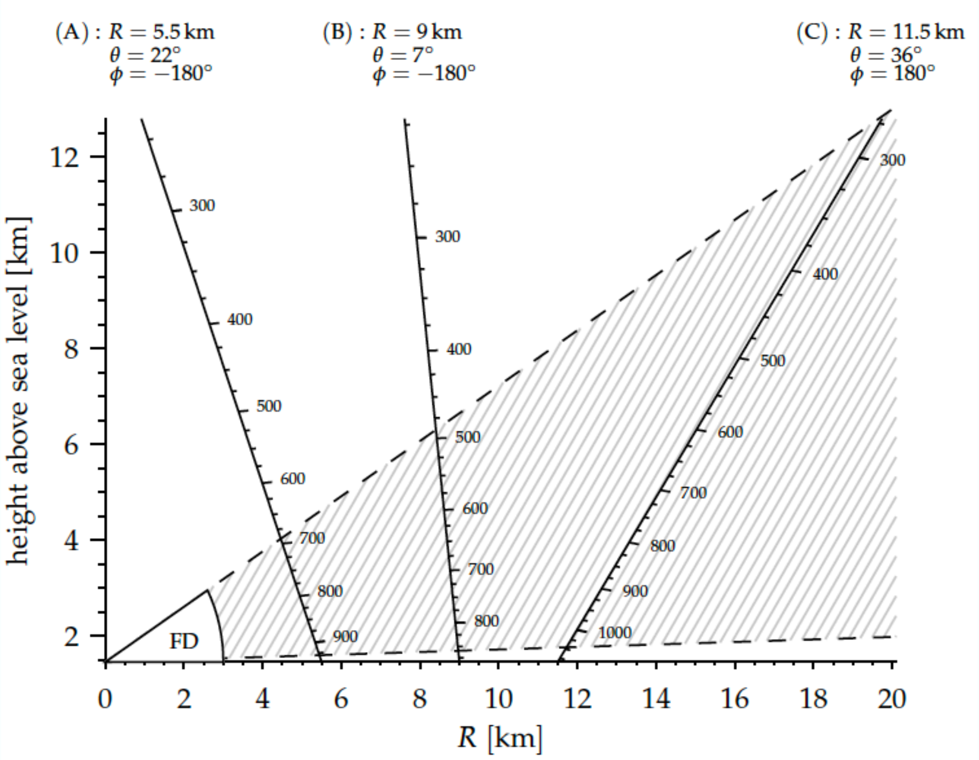
Better agreement if only common declination band considered – anisotropy !

Comparison with TA results

(TA composition summary, Hanlon, ICRC 2017)



Data cannot be compared directly due to different FoV treatment



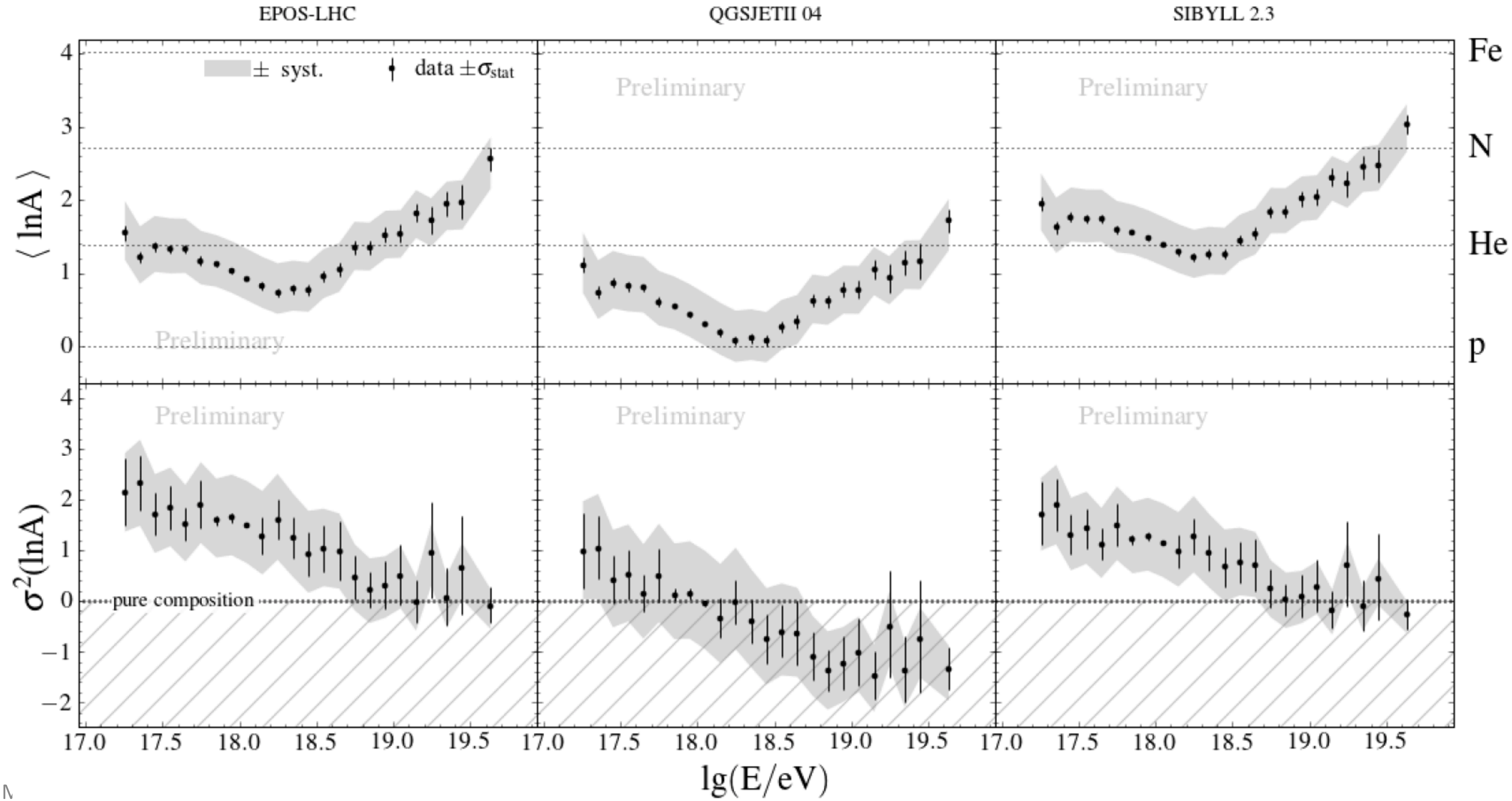
Auger: only shower geometries for which all X_{max} values visible

TA: all showers with X_{max} in field of view (bias due to detector acceptance)

Auger-TA Working Group: data of the two experiments in agreement within the exp. uncertainties (E < 10^{19} eV)

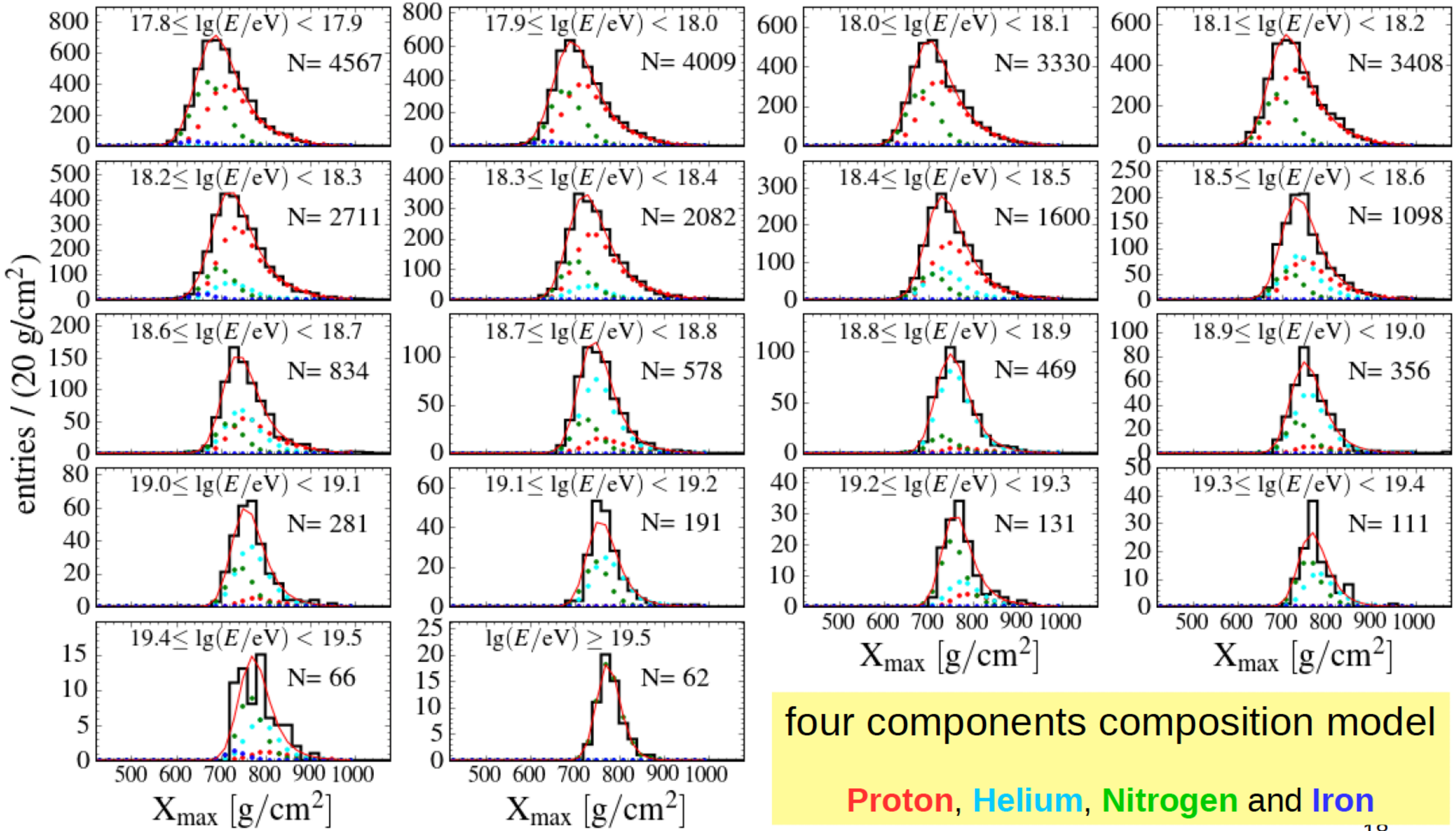
lnA moments

(estimated using X_{max} moments, for the method see JCAP **1302** (026), 2013)



X_{max} distributions (FD)

Interpreting X_{max} distributions with **EPOS-LHC**



four components composition model

Proton, **Helium**, **Nitrogen** and **Iron**

18

Sum of four components

Depth of shower maximum: Cross section

$$\frac{\mathrm{d}P}{\mathrm{d}X_1} = \frac{1}{\lambda_{\text{int}}} e^{-X_1/\lambda_{\text{int}}}$$

$$\sigma_{\text{p-air}} = \frac{\langle m_{\text{air}} \rangle}{\lambda_{\text{int}}}$$

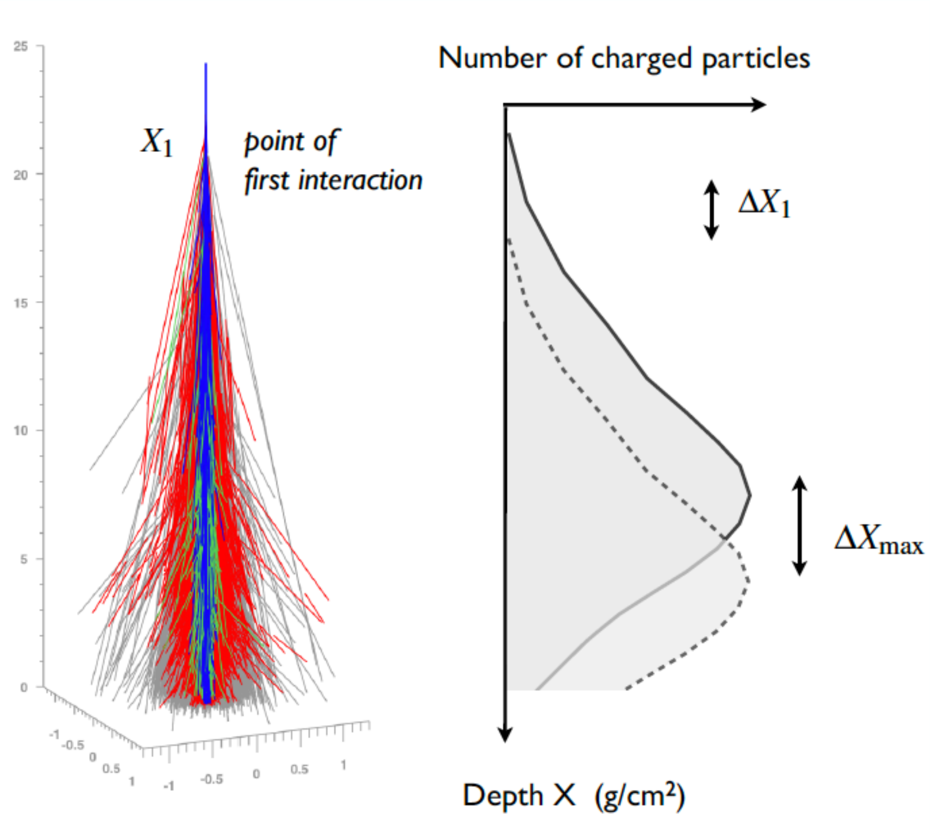
$$\text{RMS}(X_1) = \lambda_{\text{int}}$$

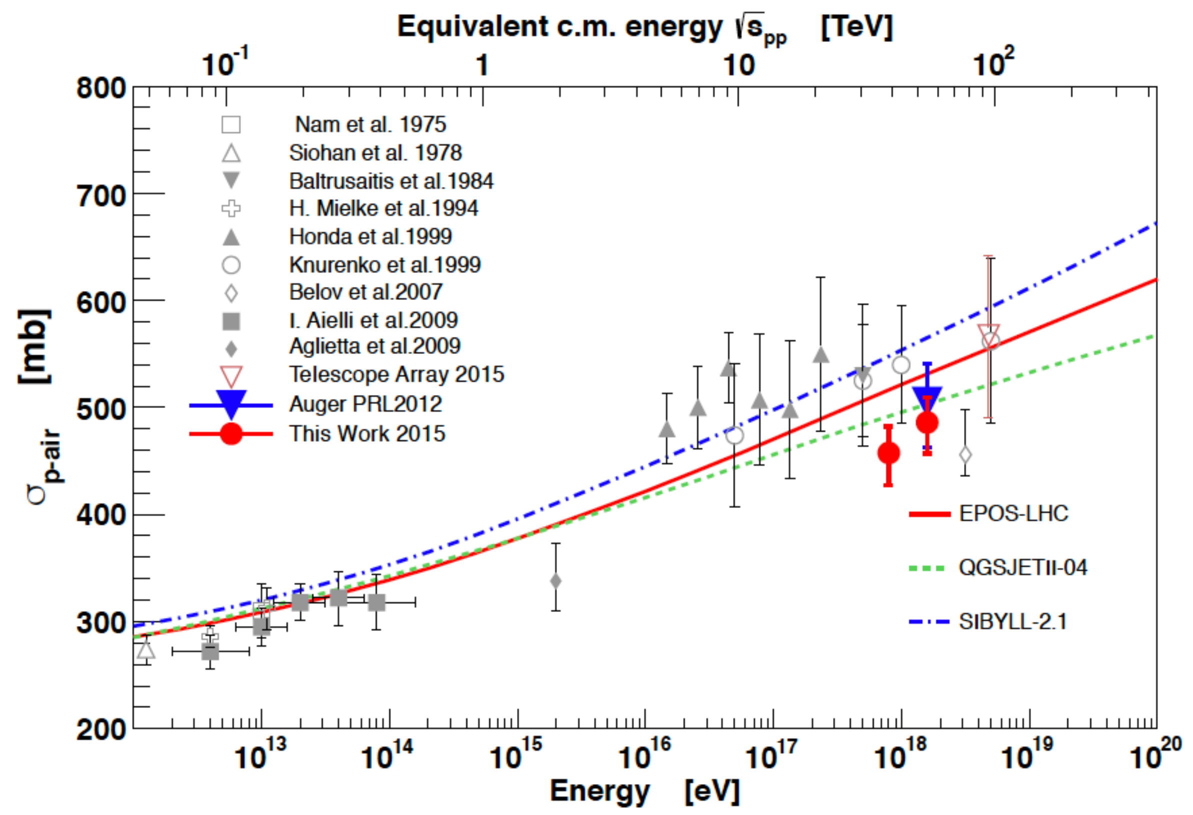
Difficulties

- Mass composition
- Fluctuations in shower development (model needed for correction)

$$\text{RMS}(X_1) \sim \text{RMS}(X_{\max} - X_1)$$

- Experimental resolution ~20 g/cm^2





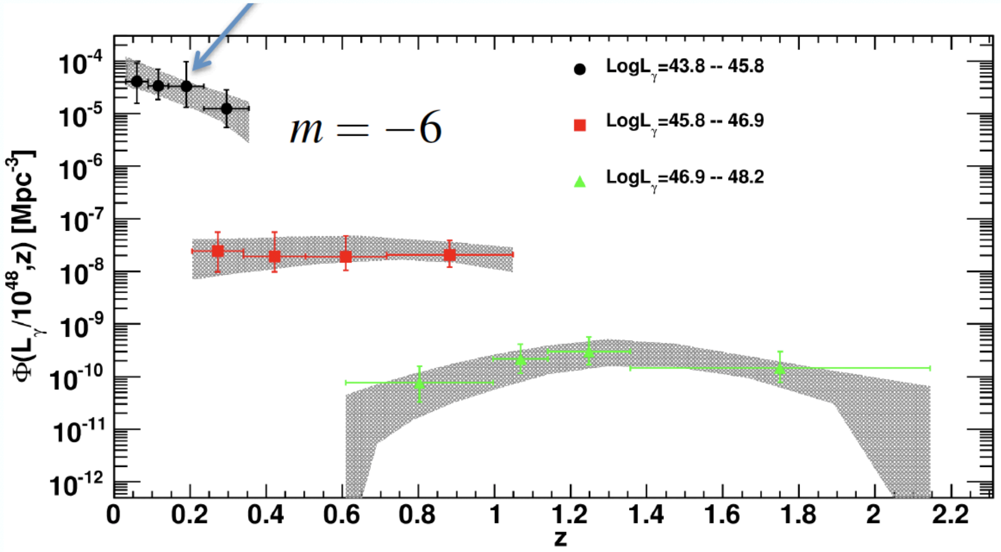
Source distribution and evolution

source evolution		γ	$\log_{10}(R_{cut}/V)$	D	$D(J)$	$D(X_{max})$
$(1+z)^m$	$m=+3$	$-1.40^{+0.35}_{-0.09}$	$18.22^{+0.05}_{-0.02}$	179.1	7.5	171.7
	$m=0$	$+0.96^{+0.08}_{-0.13}$	$18.68^{+0.02}_{-0.04}$	174.3	13.2	161.1
	$m=-3$	$+1.42^{+0.06}_{-0.07}$	$18.85^{+0.04}_{-0.07}$	173.9	19.3	154.6
	$m=-6$	$+1.56^{+0.06}_{-0.07}$	18.74 ± 0.03	182.4	19.1	163.3
	$m=-12$	$+1.79 \pm 0.06$	18.73 ± 0.03	182.1	18.1	164.0
$z \leq 0.02$		$+2.69 \pm 0.01$	$19.50^{+0.08}_{-0.07}$	178.6	15.3	163.3

Table 10. Best fit parameters (reference model) corresponding to different assumptions on the evolution or spatial distribution of sources.

More negative evolution and
closer source dominance ⇒
best fit approaches Fermi acceleration

Fermi: low-luminosity, high-synchrotron peaked (HSP) BL Lacs



(Taylor, ICRC 2017)

Ajello et al. (2014), 1310.0006

Adding a sub-ankle component

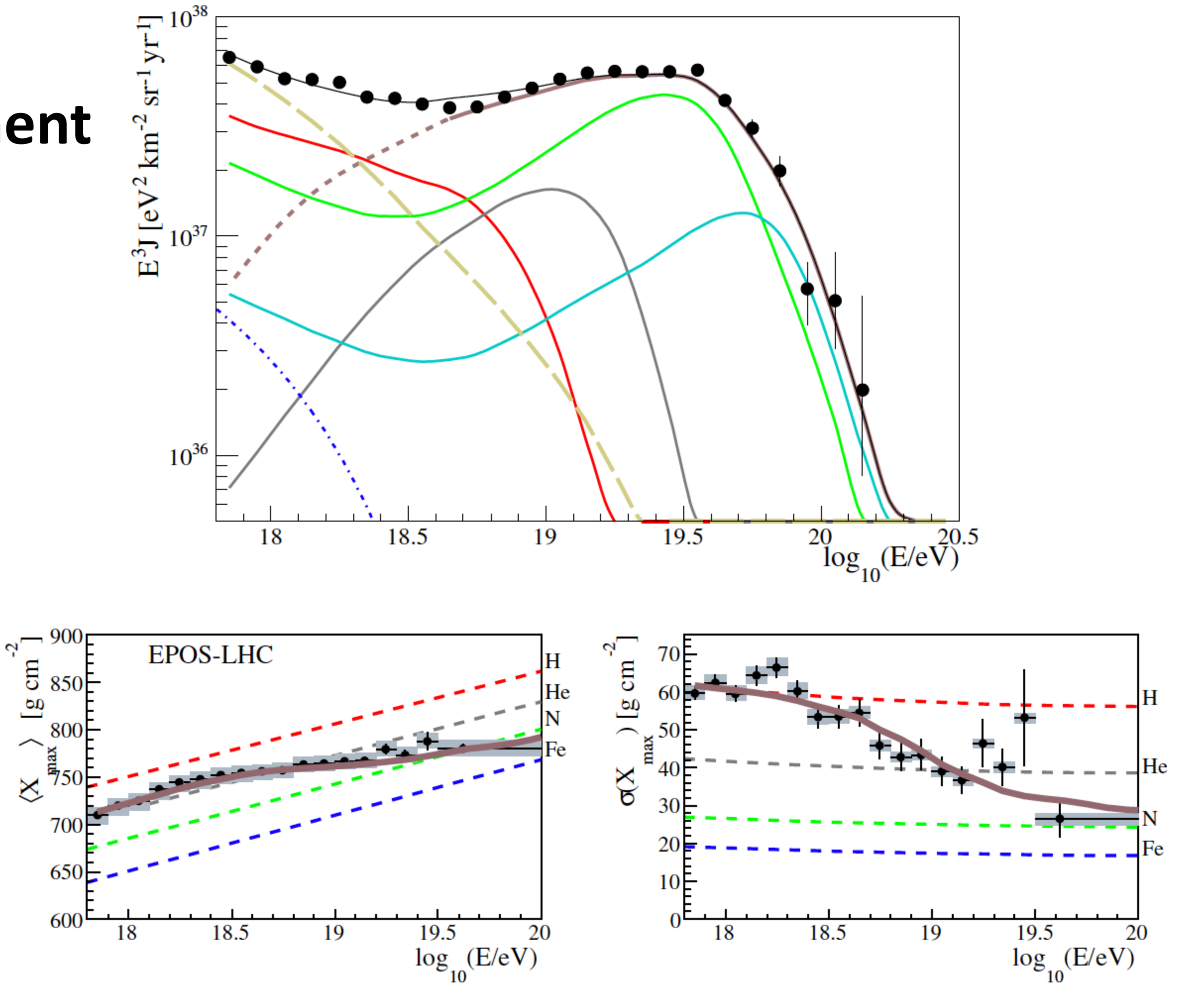


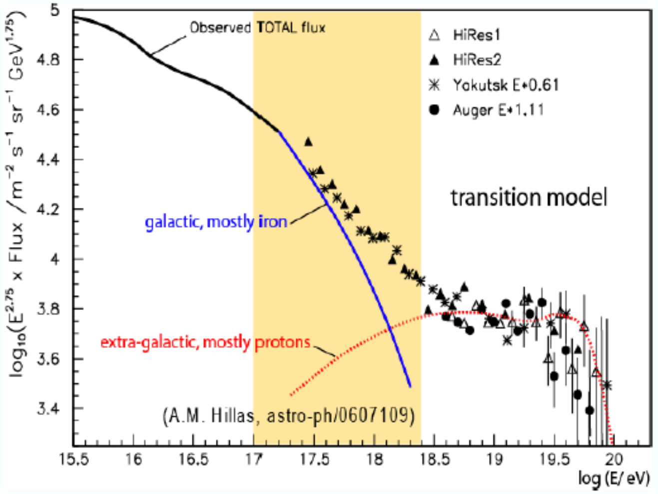
Figure 14. Top: simulated energy spectrum of UHECRs (multiplied by E^3) at the top of the Earth's atmosphere, best-fit parameters for model SPG, along with Auger data points. Partial spectra are grouped as in figure 2. The dashed (yellowish) line shows the sub-ankle component obtained as described in the text. The dot-dashed (blue) shows the KASCADE-Grande electron-poor flux, here assumed to be only iron. Bottom: average and standard deviation of the X_{max} distribution as predicted (assuming EPOS-LHC UHECR-air interactions). Markers and colours as in figures 2, 3.

JCAP04(2017)038

Transition from galactic to extragalactic cosmic rays

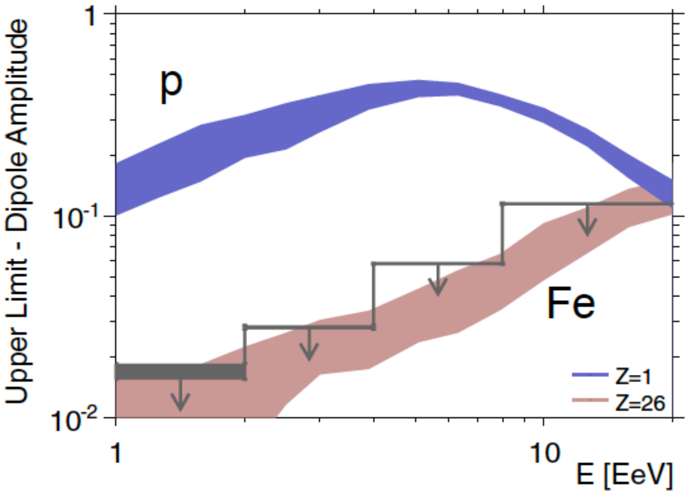
Ankle model:
- Ankle is transition region
- Injection spectrum dN/dE ~ $E^{-2.3}$

Hillas, Wolfendale et al.



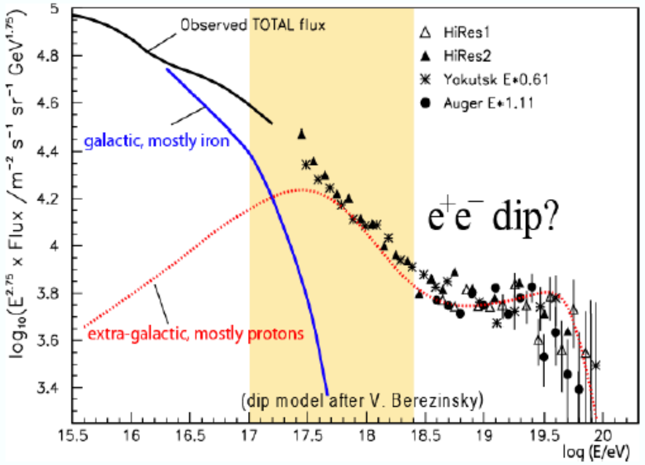
(Auger, ApJ 203, 2012, Giacinti et al., JCAP 2012, 2015)

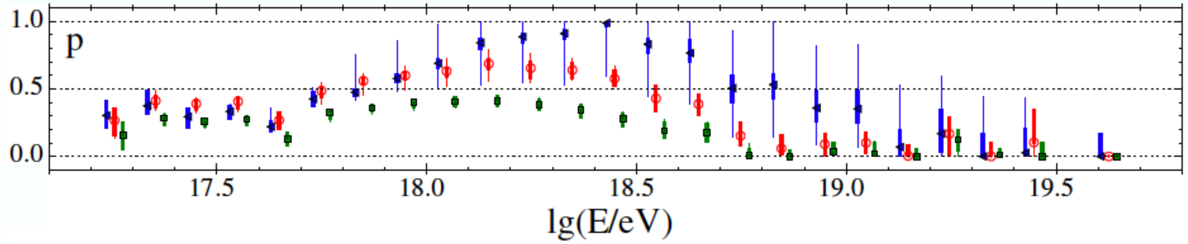
Simulation:
Sources in galactic plane



Dip model:
- Ankle is feature due to extragal. proton propagation
- Injection spectrum dN/dE ~ $E^{-2.7}$

Berezinsky et al.





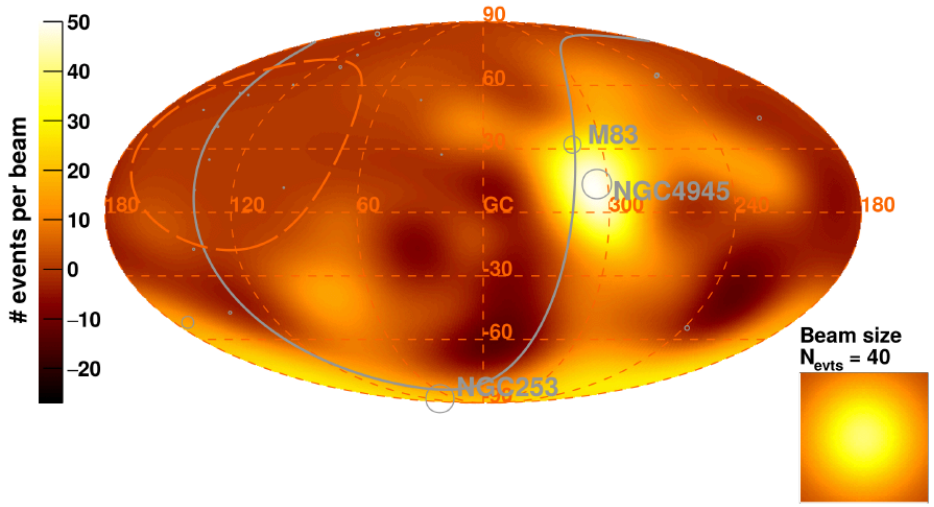
Transition energy ~10^{18} eV

39

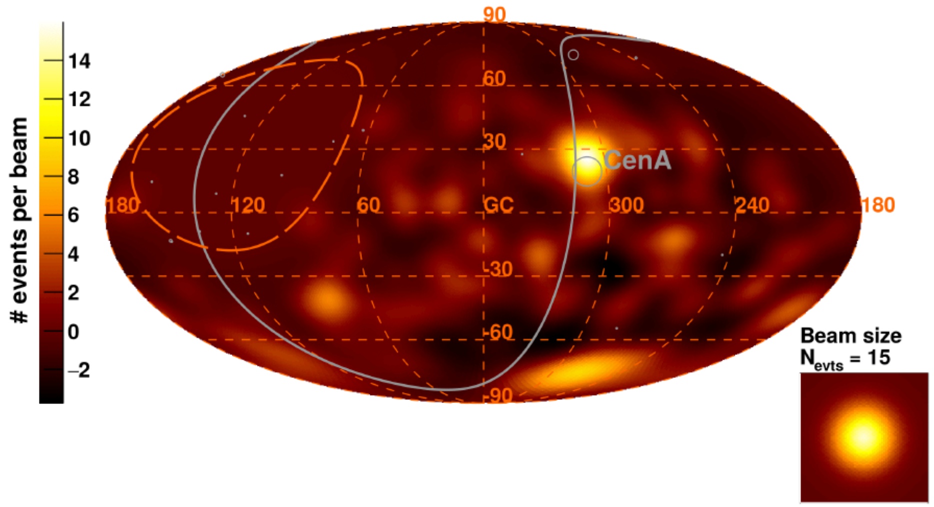
SBG

γAGN

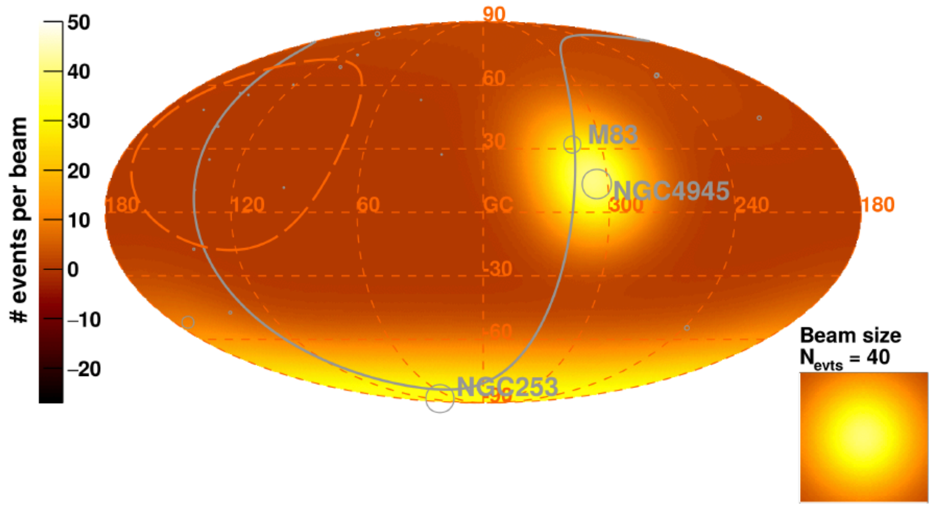
Observed Excess Map - E > 39 EeV



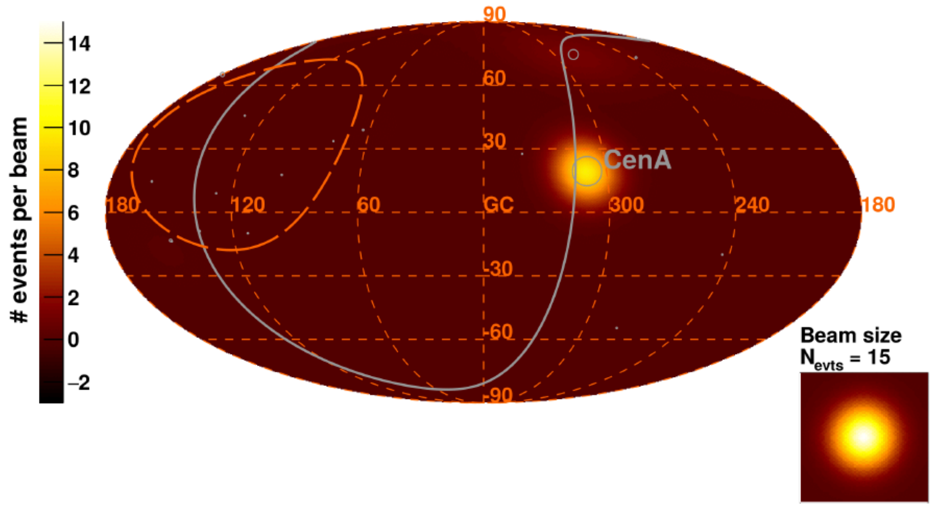
Observed Excess Map - E > 60 EeV



Model Excess Map - Starburst galaxies - E > 39 EeV



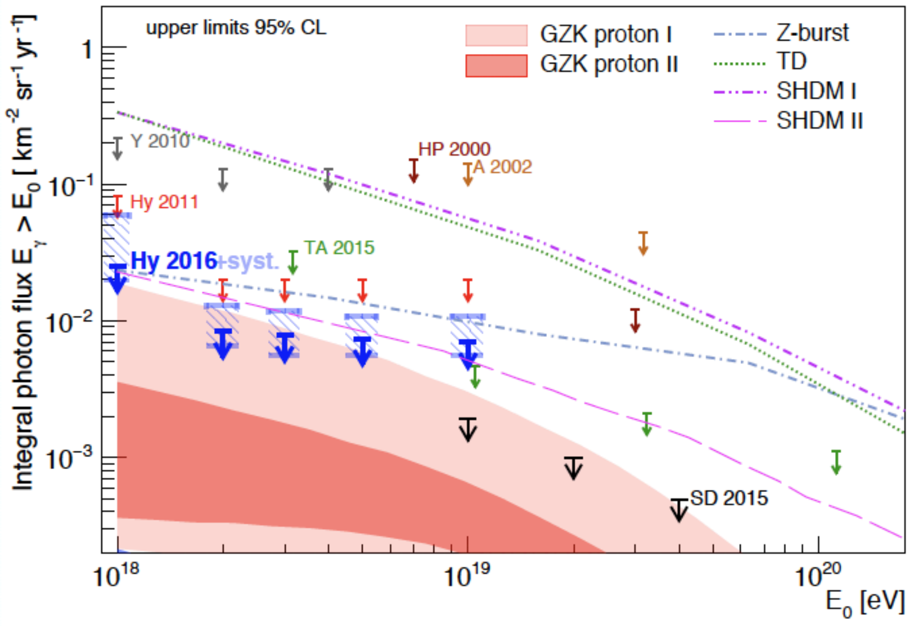
Model Excess Map - Active galactic nuclei - E > 60 EeV

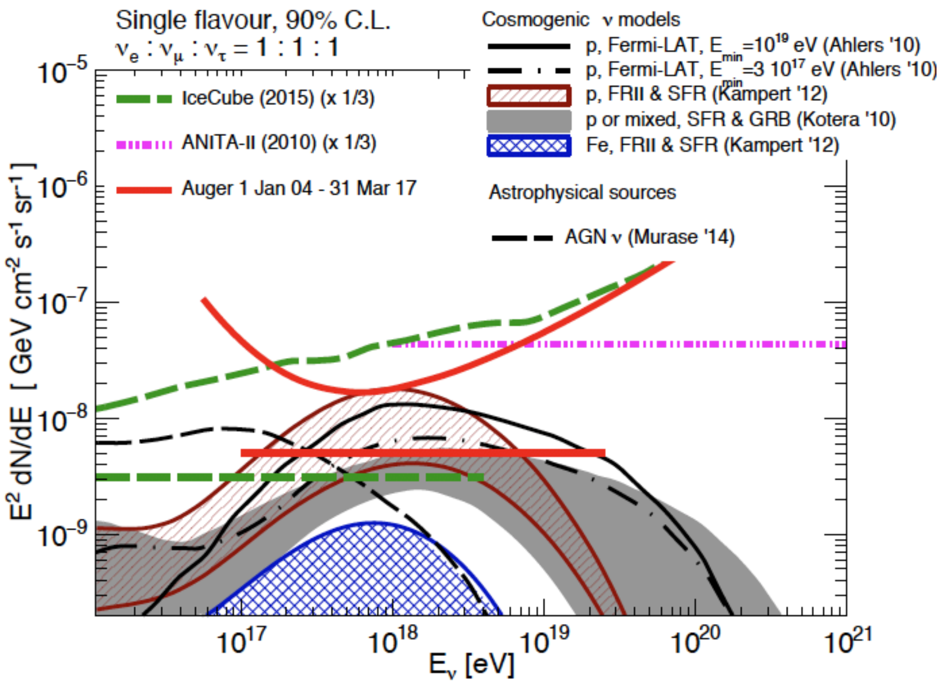


Searches for Cosmogenic Photons and Neutrinos

$$p + \gamma_{\mathrm{CMB}} \rightarrow p + \pi^0 \searrow \gamma\gamma$$

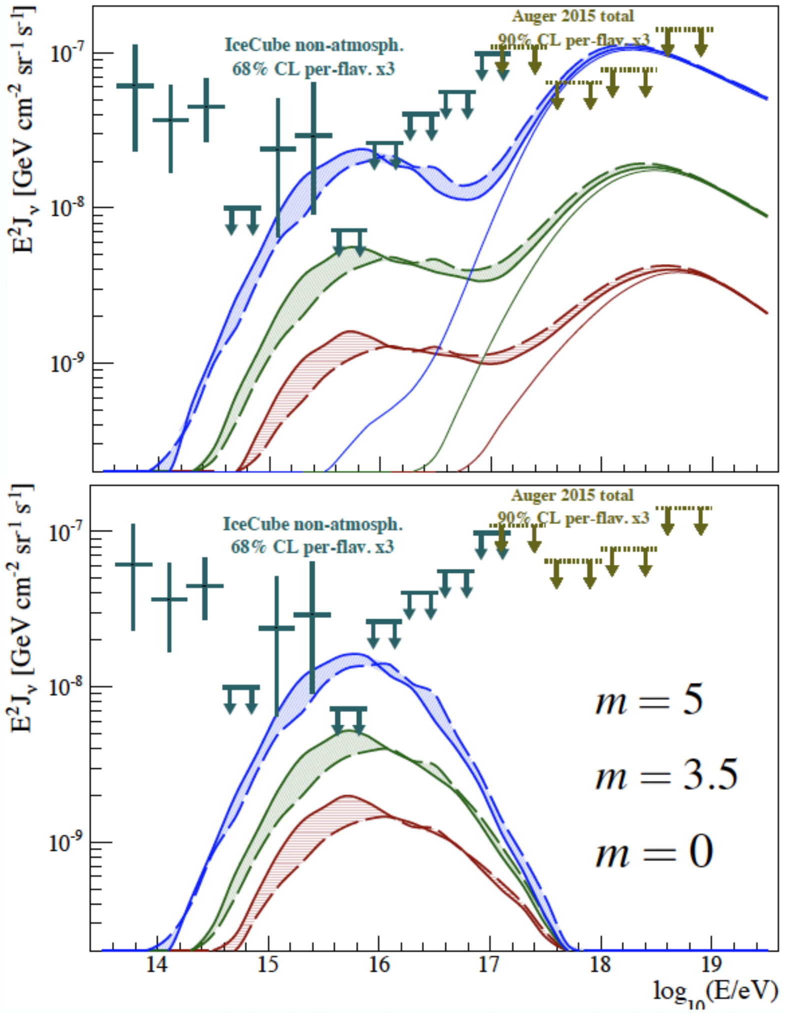
$$p + \gamma_{\mathrm{CMB}} \rightarrow n + \pi^+ \searrow e^+ + 3\nu$$





Neutrino and gamma-ray fluxes

Neutrinos



(Aloisio et al. JCAP 2015) *(Ahlers, Heinze et al.)*

Complementarity

Cosmic ray flux local

Neutrino flux from large distances

GZK neutrinos probe E > 10^{20} eV

Very low neutrino flux likely

Nuclei with small GZK losses?

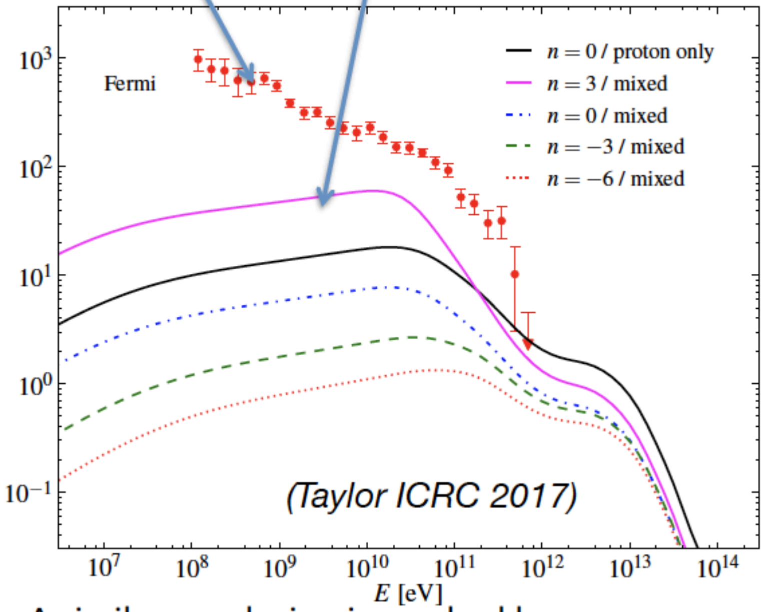
Negative evolution of sources?

Local overdensity?

Photons

IGRB (EGB with resolved points sources removed)

n=3 to -6 evolution scenarios give rise to between **40%** and **12%** of Fermi limit



A similar conclusion is reached by **Gavish et al. (2016), 1603.04074**

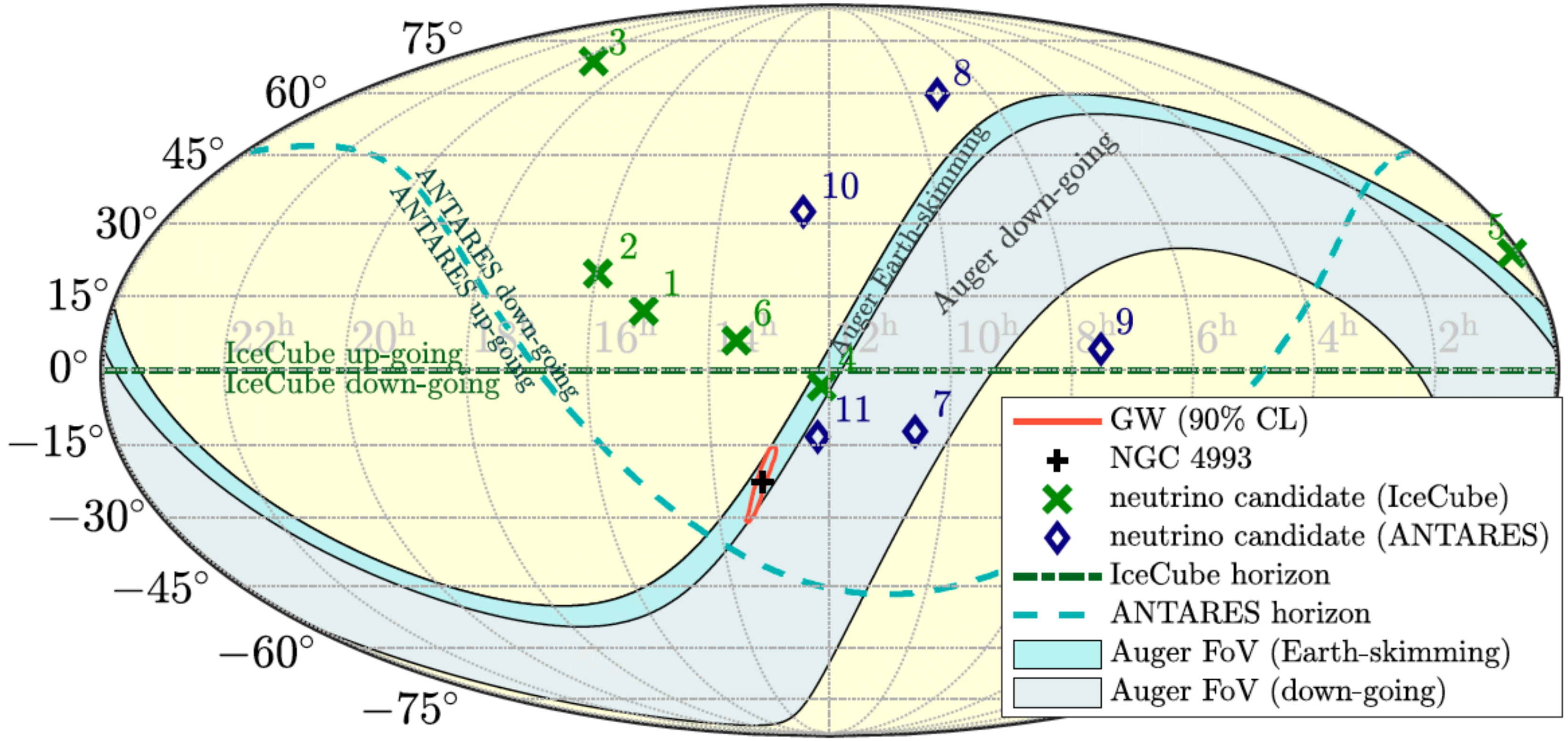


Figure 4 – Localization of GW170817 in equatorial coordinates together with the sensitive sky areas at the time of the event for the three experiments - ANTARES, IceCube and Pierre Auger Observatory. The zenith angle of NGC 4993 at the merger detection time was 91.9° for the Pierre Auger Observatory.