Latest Results from the Pierre Auger Observatory

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The University of Adelaide, Australia

Photo: Steven Saffi, University of Adelaide

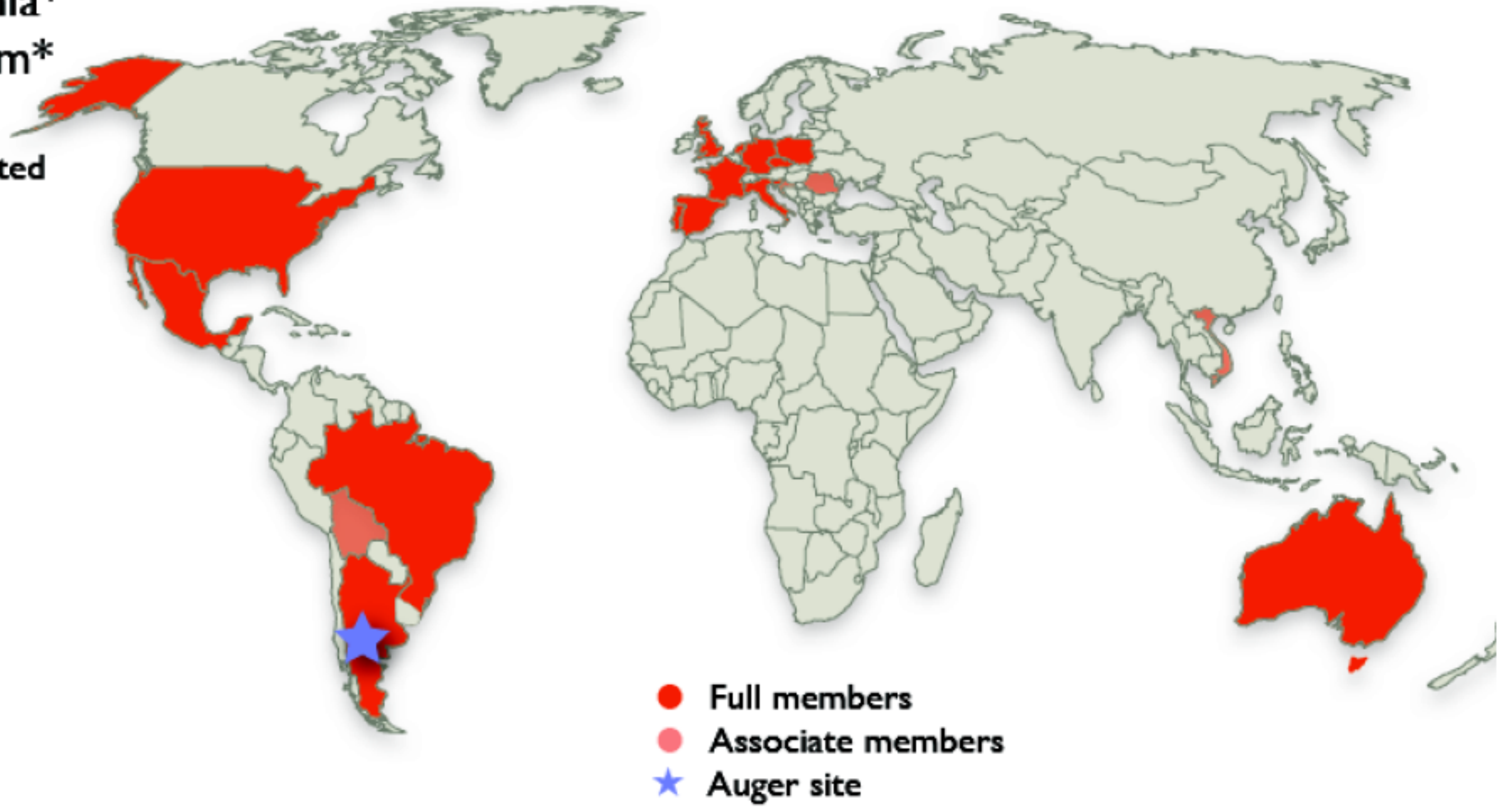
Pierre Auger Collaboration

About 500 members from 19 countries

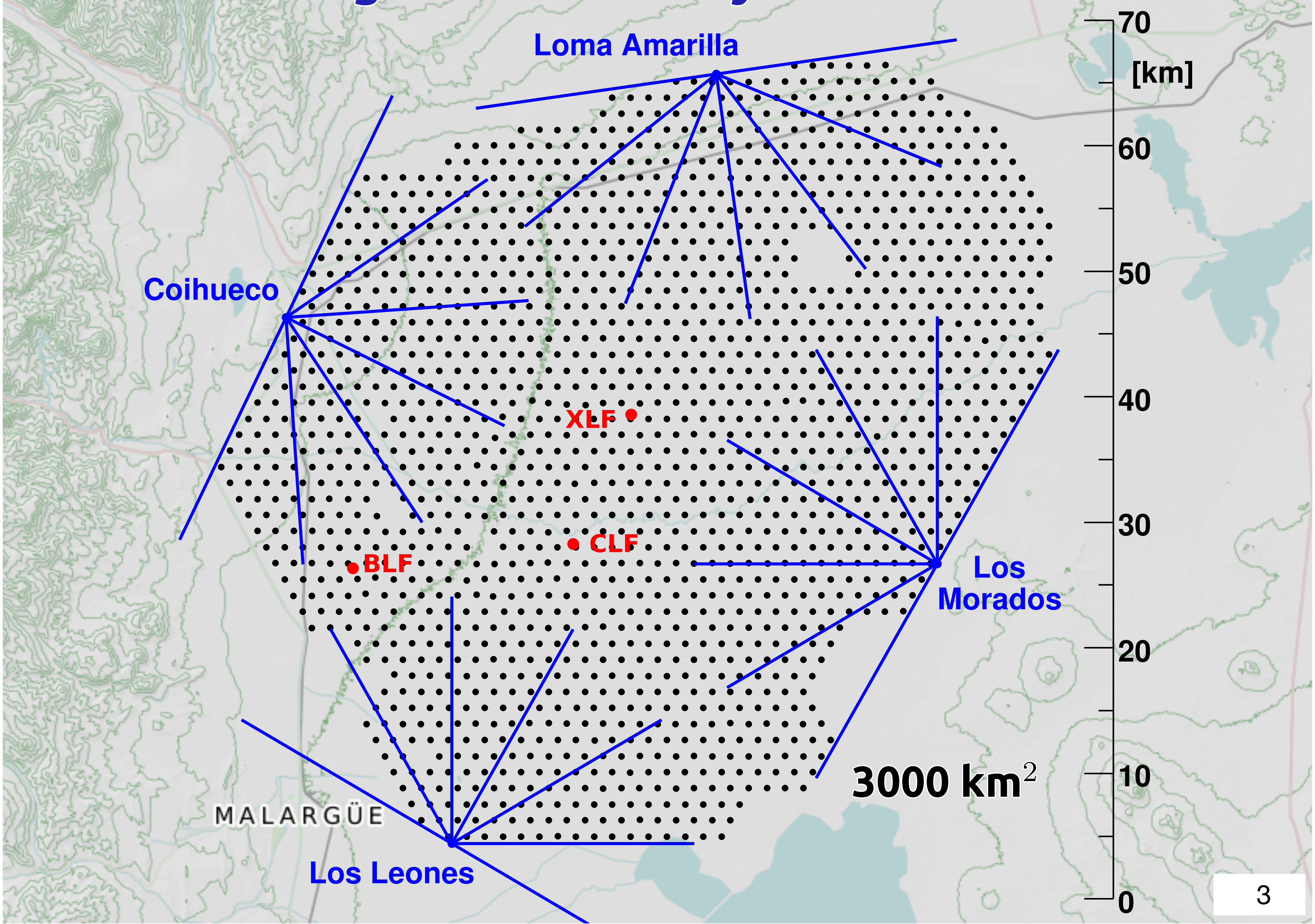
Argentina
Australia
Brazil
Croatia
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Slovenia
Spain
United Kingdom
USA

Bolivia*
Romania*
Vietnam*

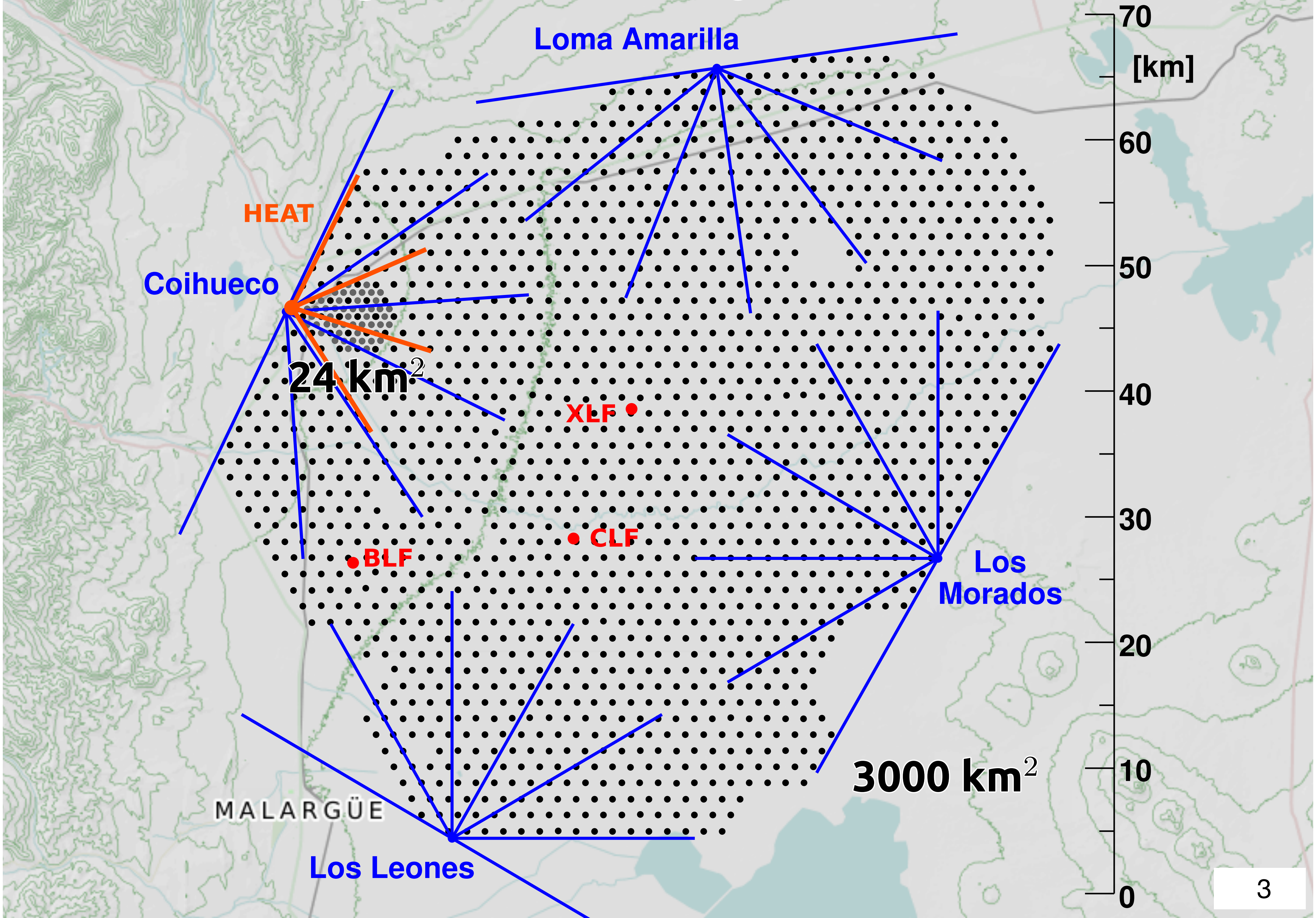
*Associated

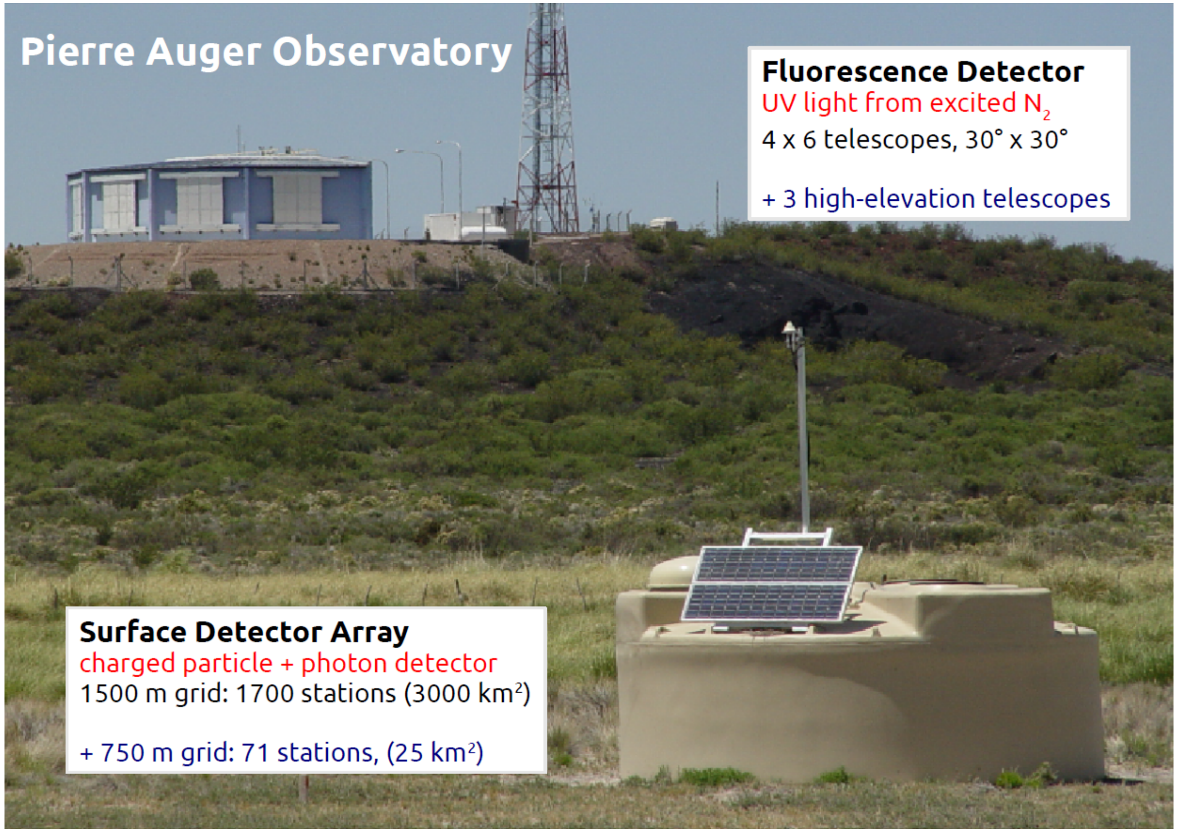


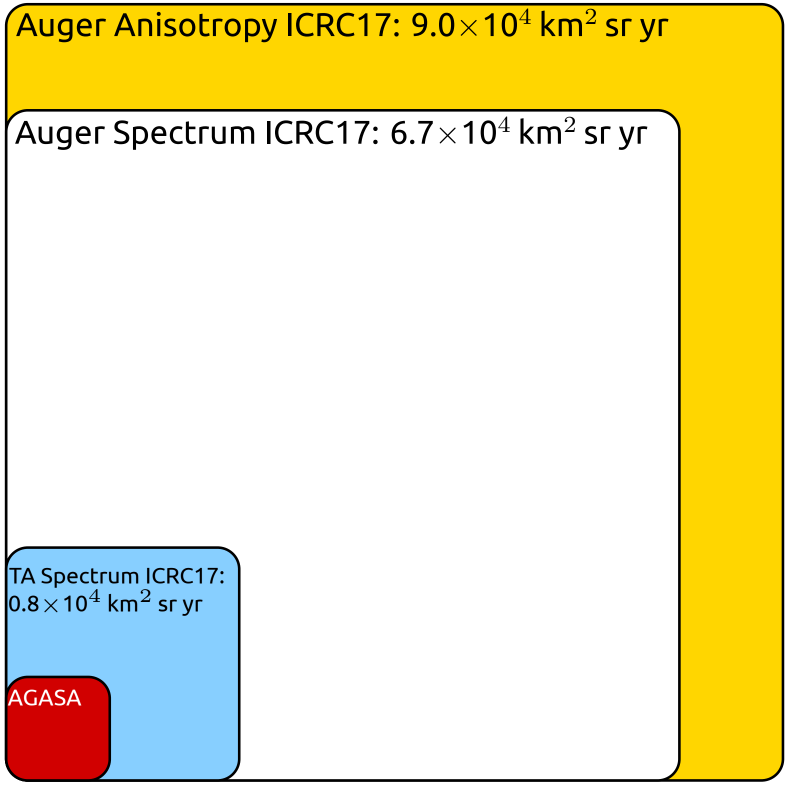
The Pierre Auger Observatory



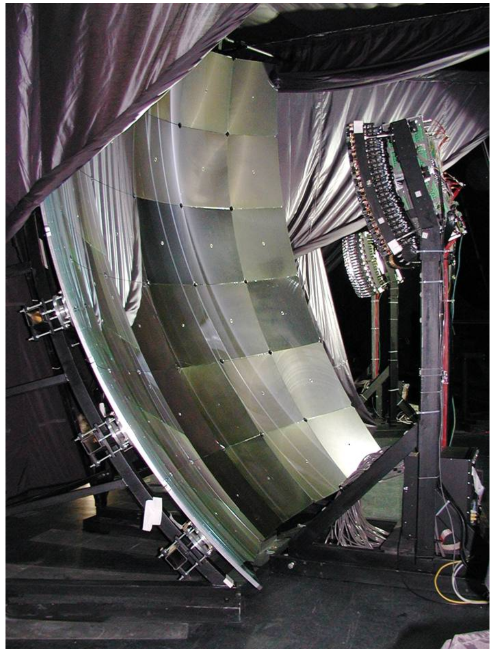
The Pierre Auger Observatory



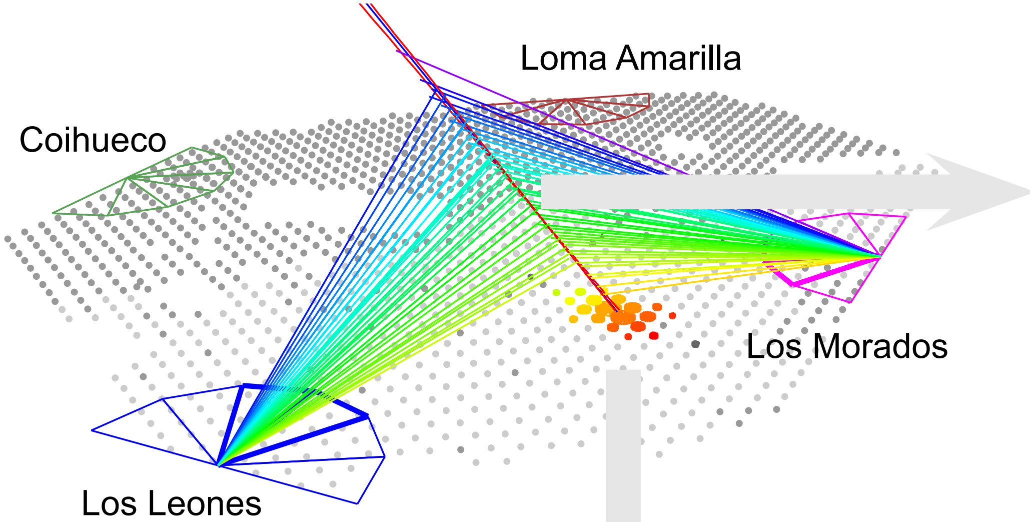


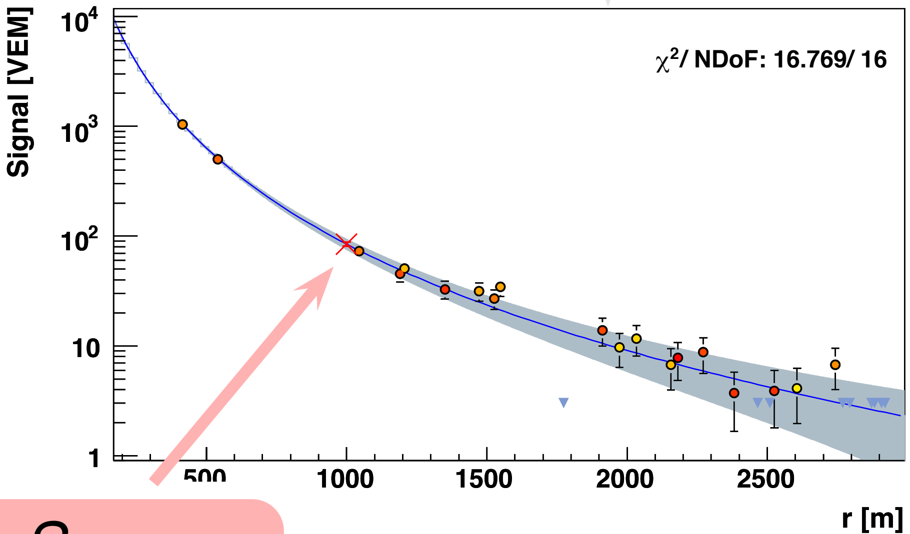


Exposure dominated by SD array.



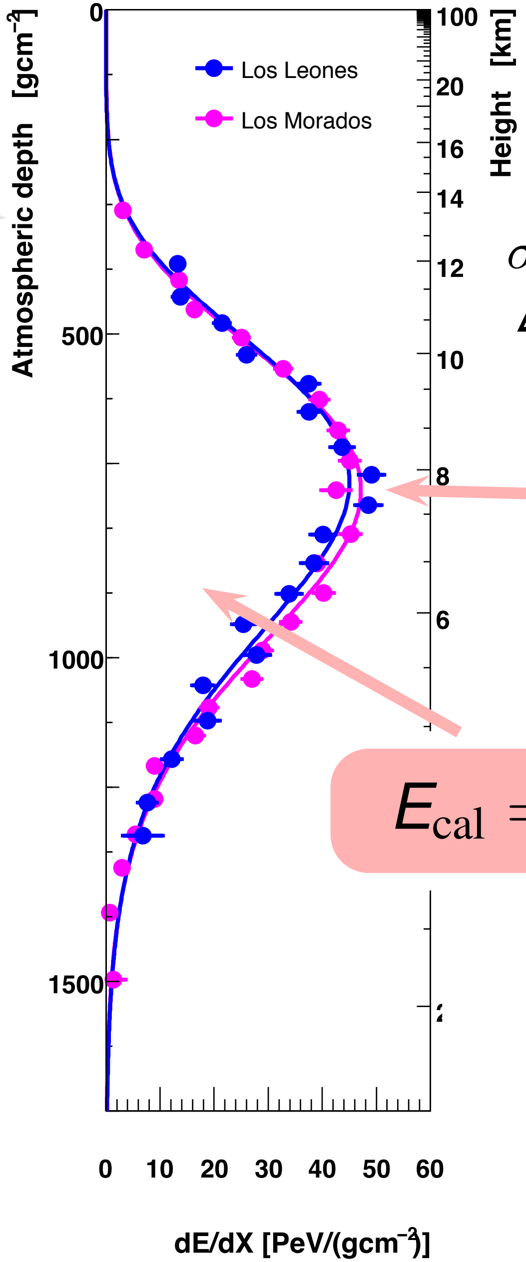
Auger is a Hybrid detector - FD calibrates SD energy scale





S_{1000}

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



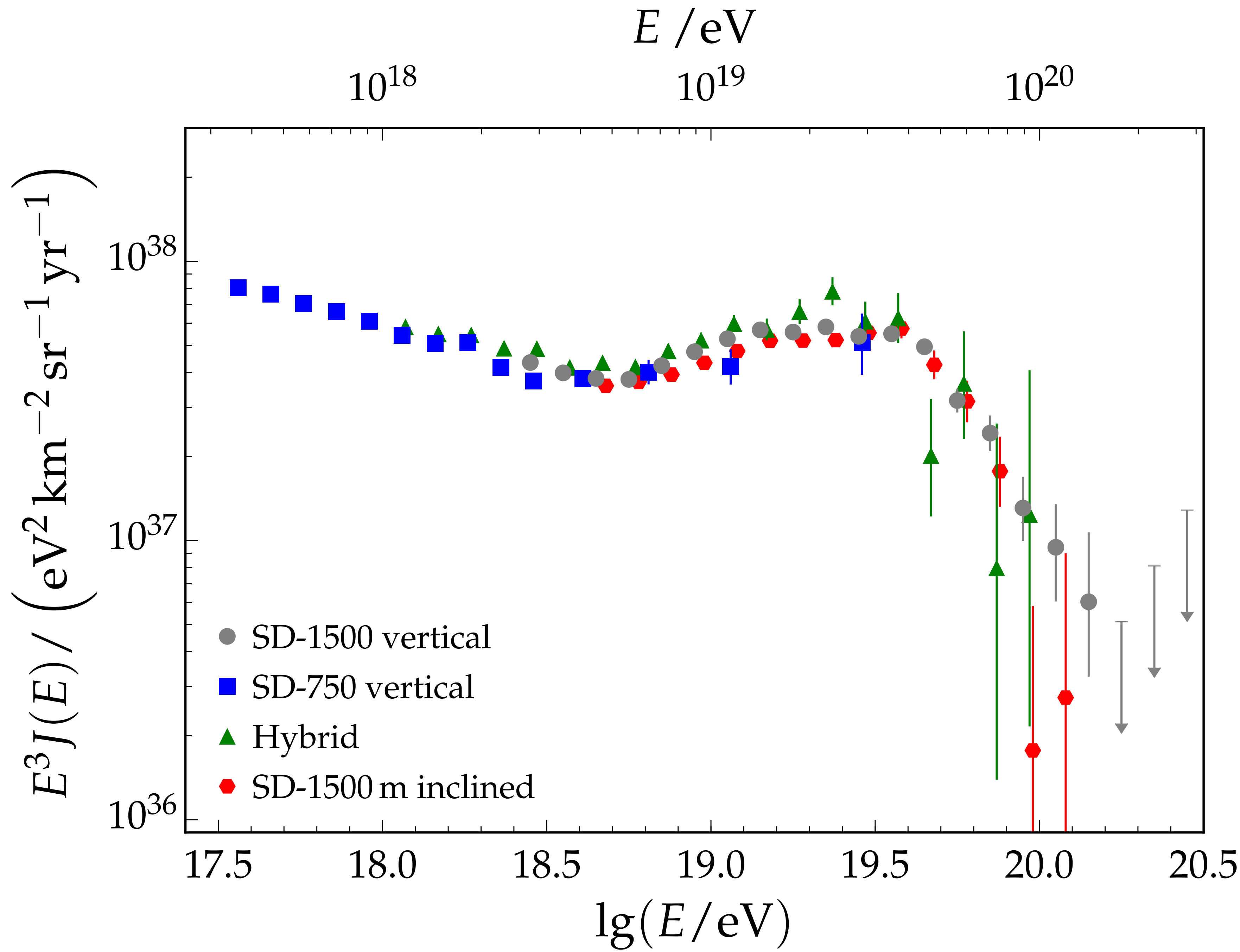
$$\sigma_{X_{\rm max}} \leq 20\ {\rm g/cm^2}$$
$$\Delta_{\rm sys} \leq 10\ {\rm g/cm^2}$$

$X_{\rm max}$

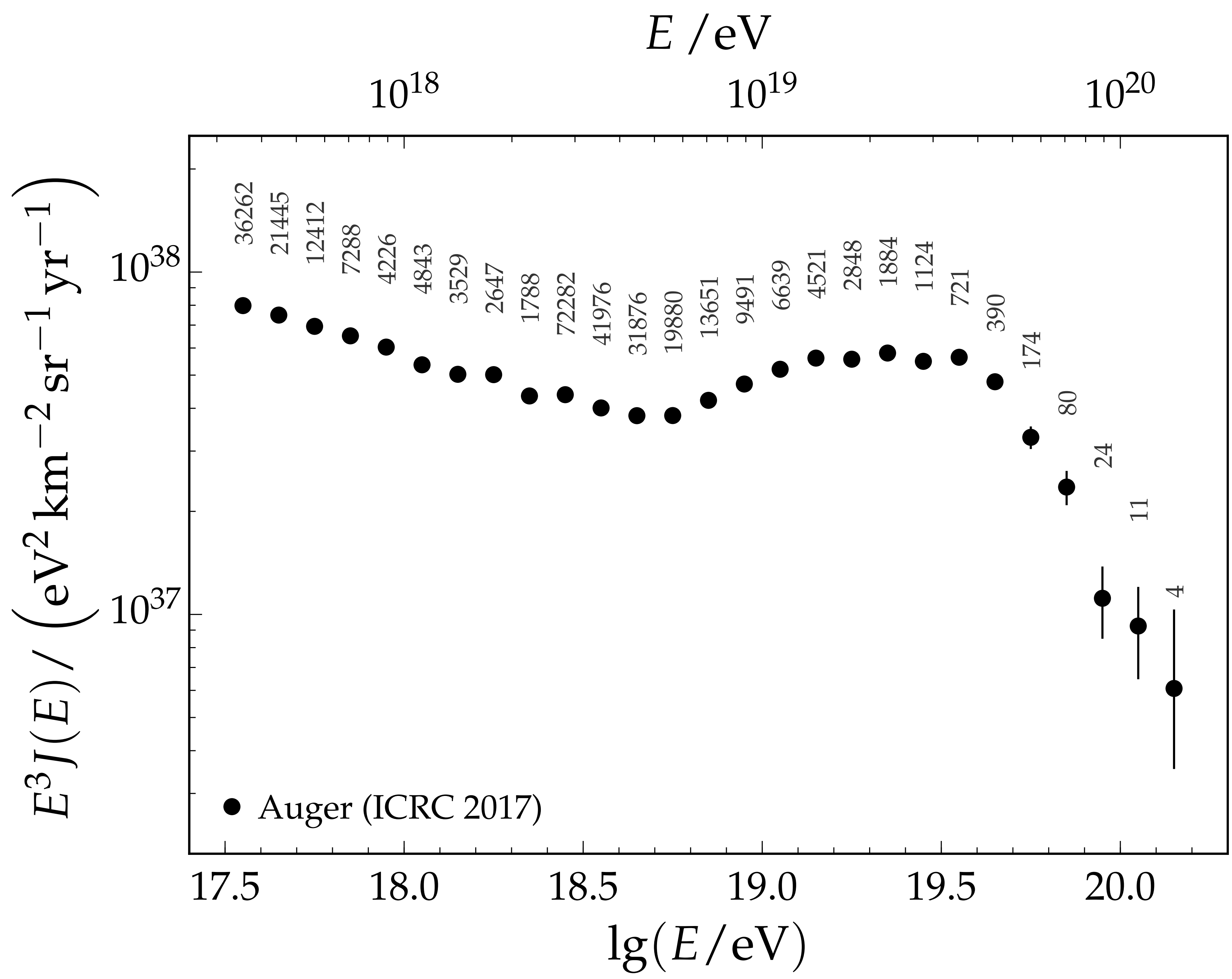
$$E_{\rm cal} = \int \frac{{\rm d}E}{{\rm d}X}\,{\rm d}X$$

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

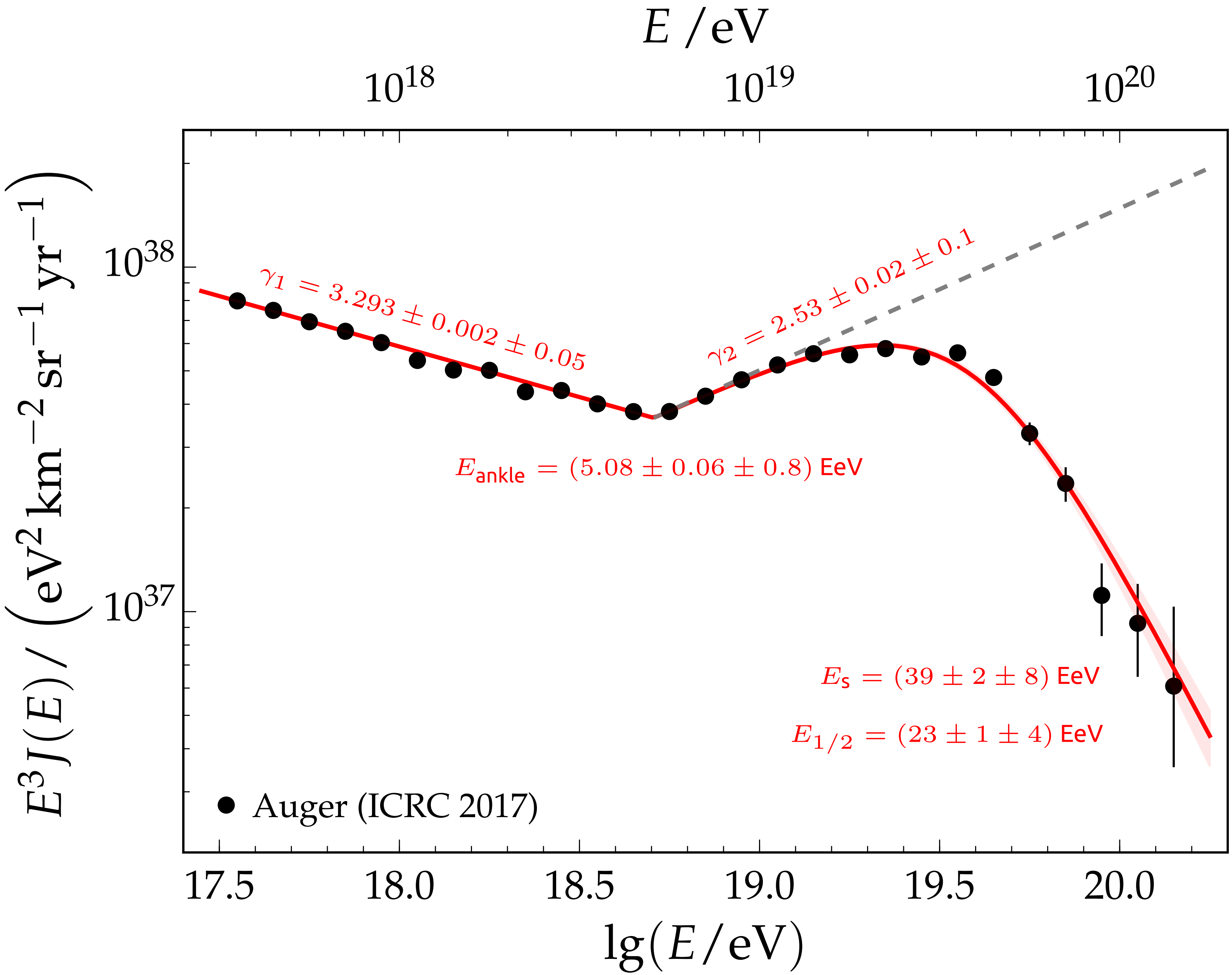
Energy Spectrum



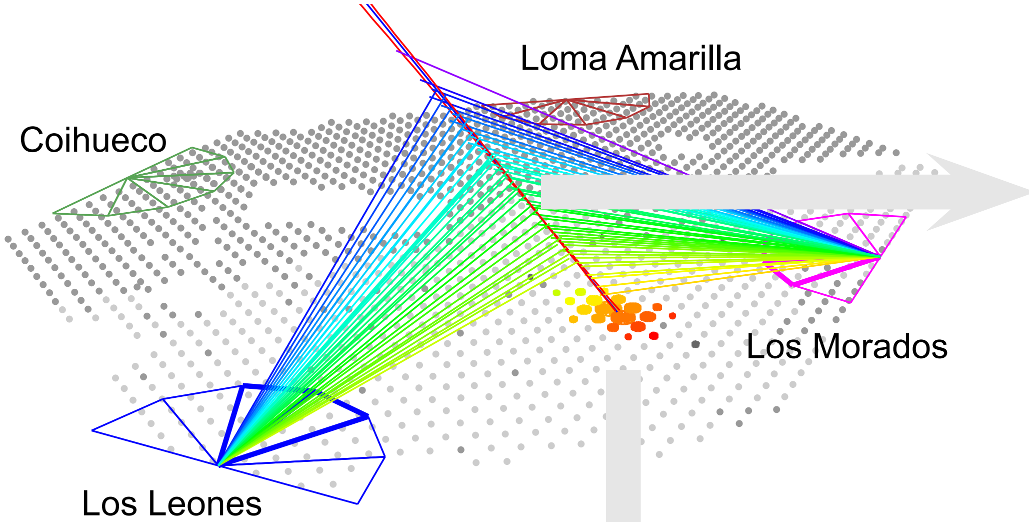
Combined Energy Spectrum

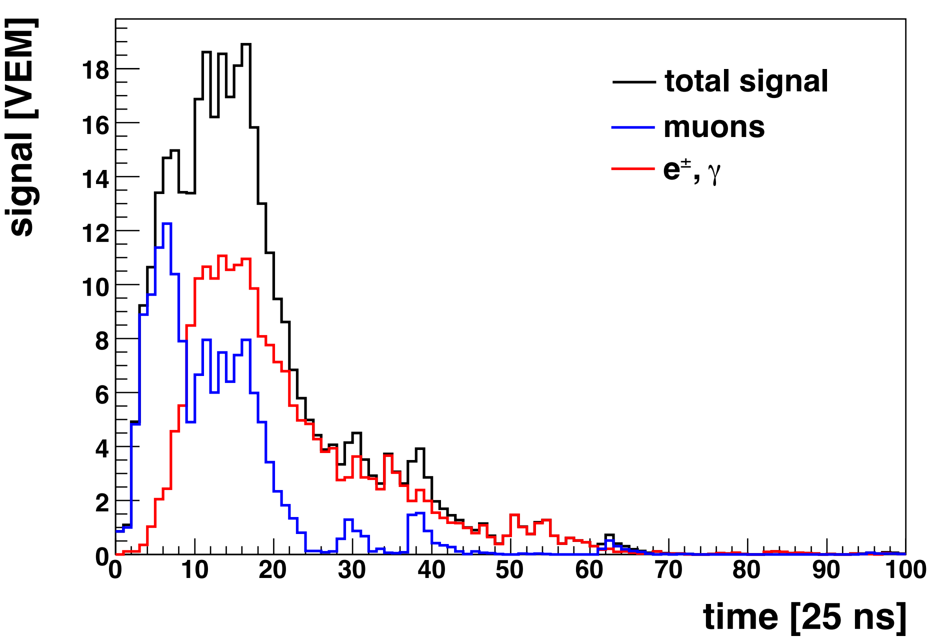


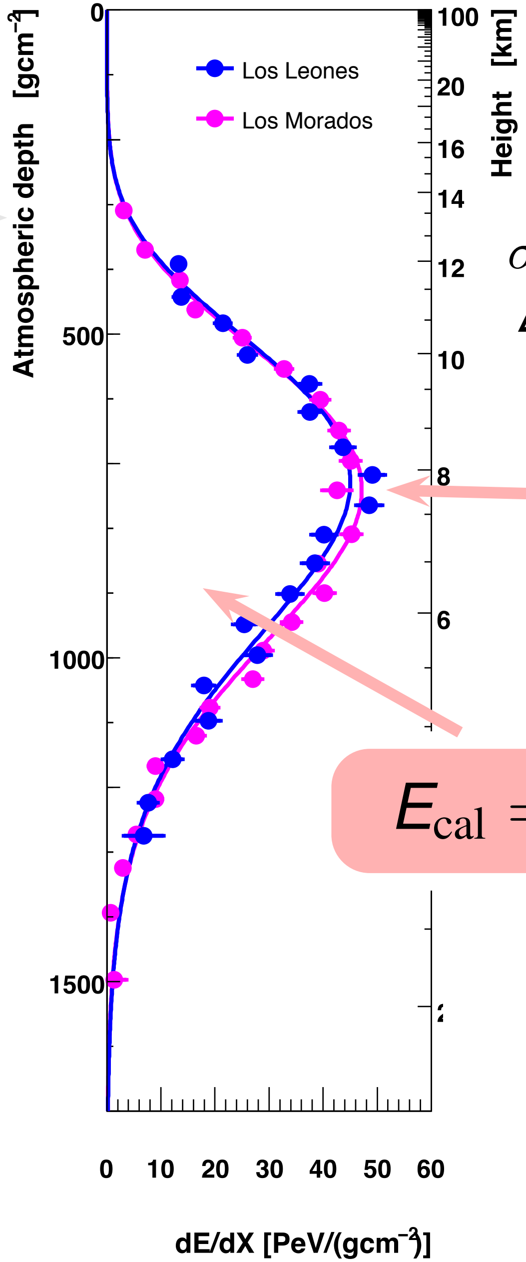
Combined Energy Spectrum



Mass composition







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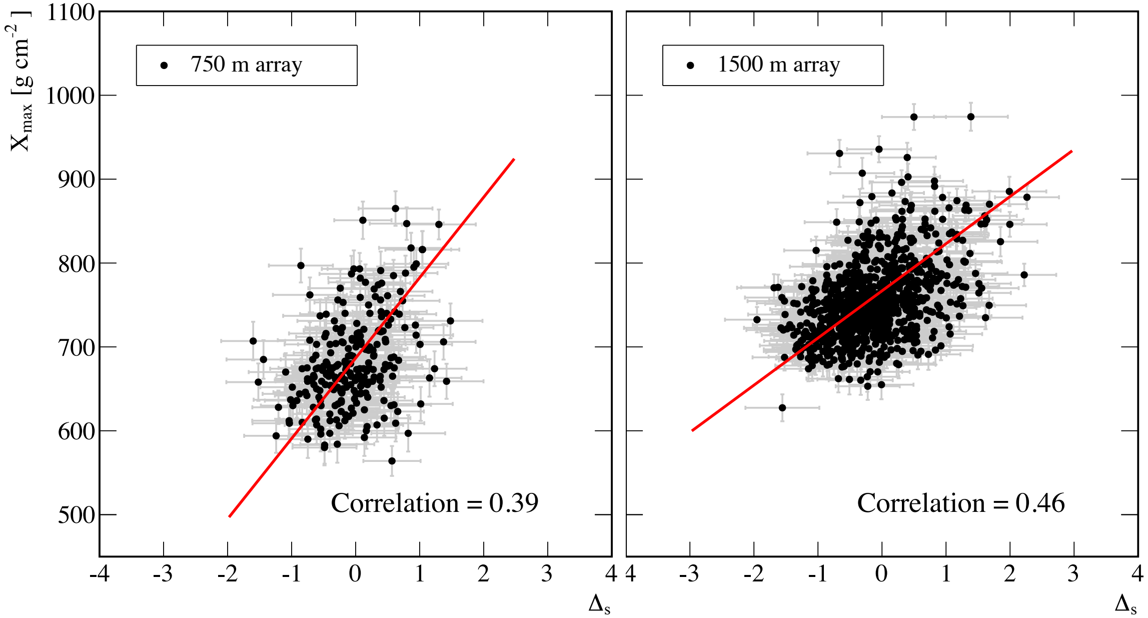

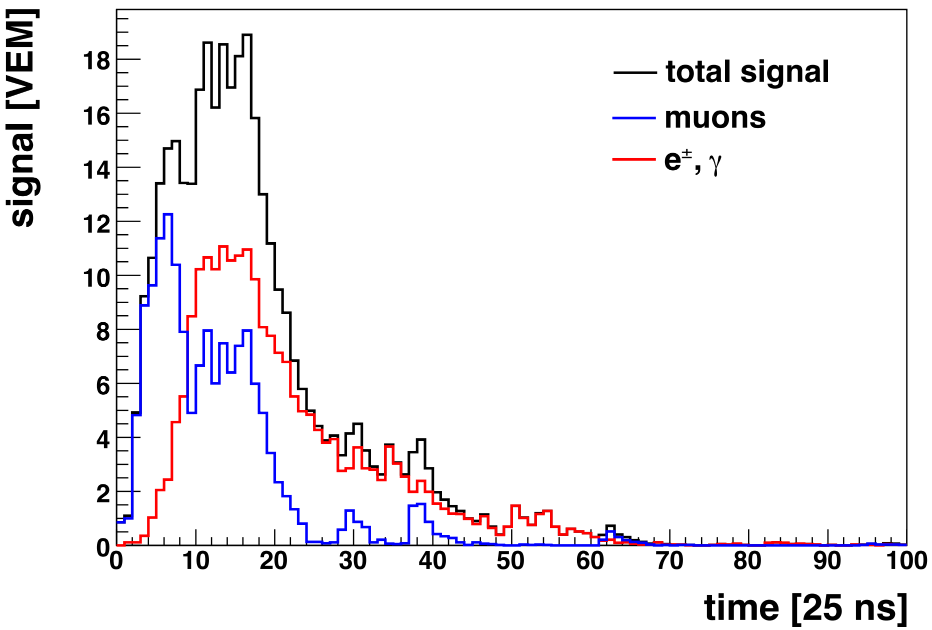

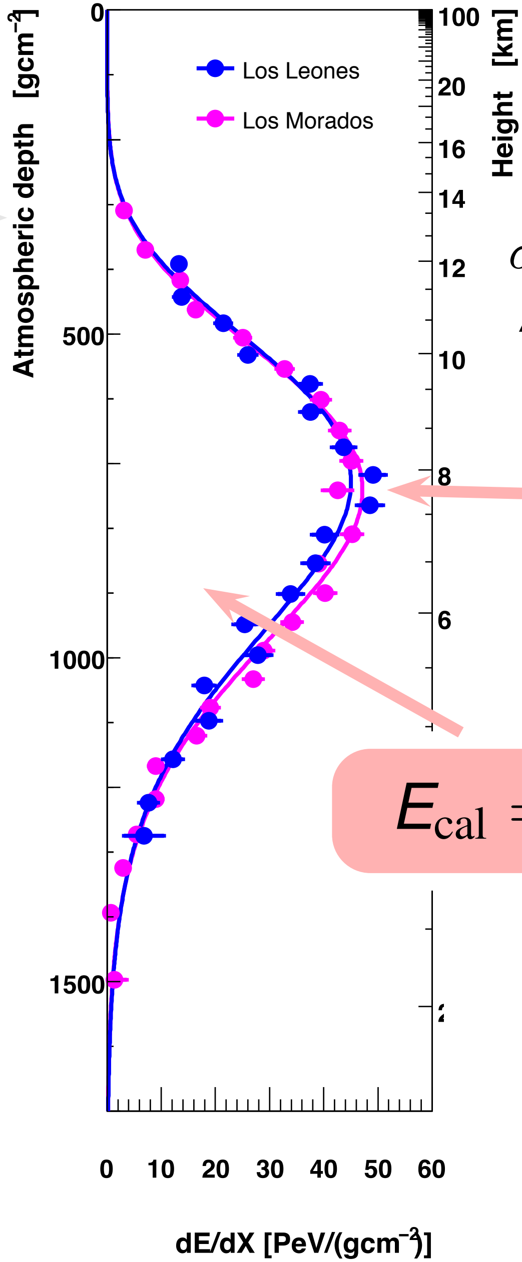

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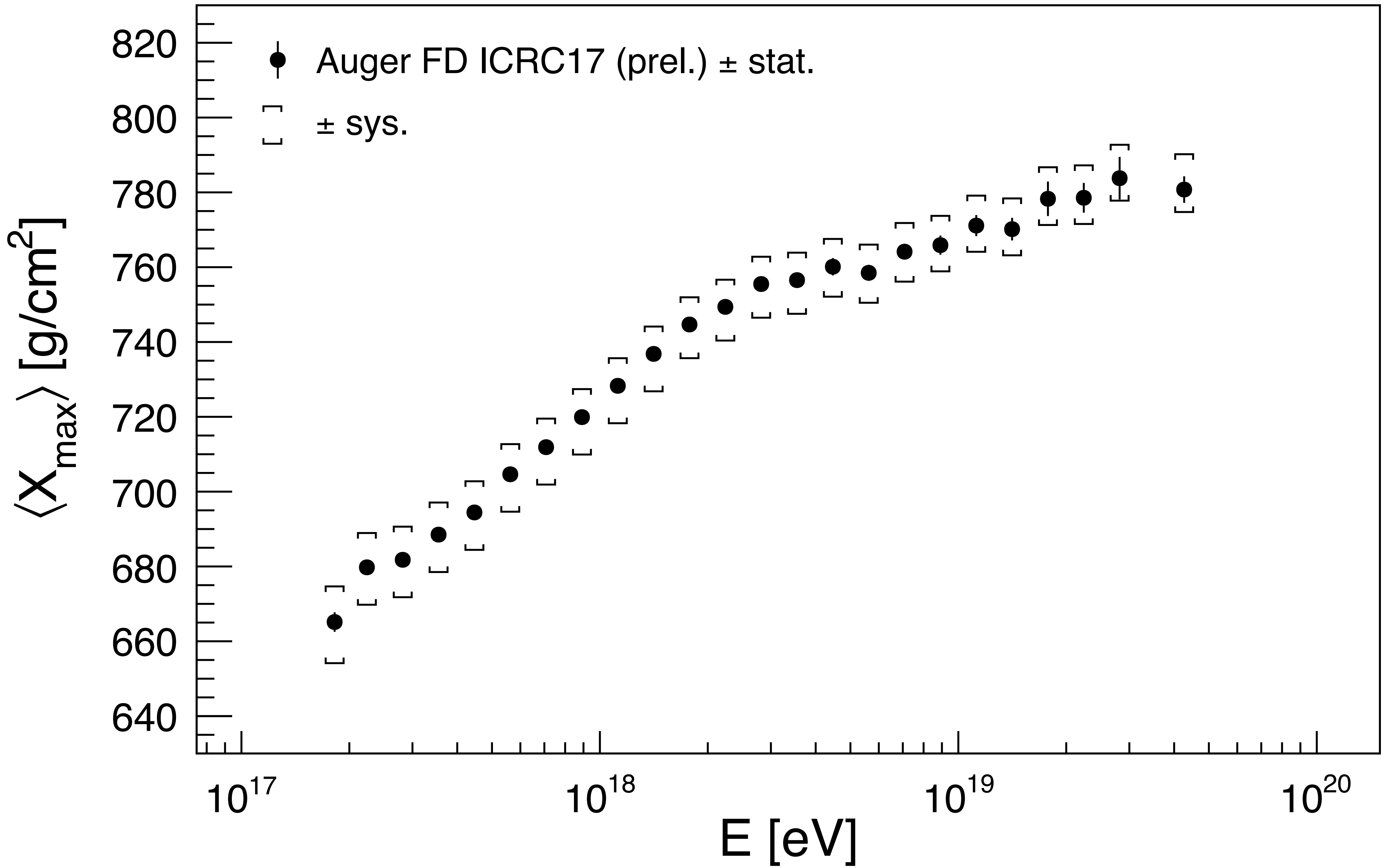
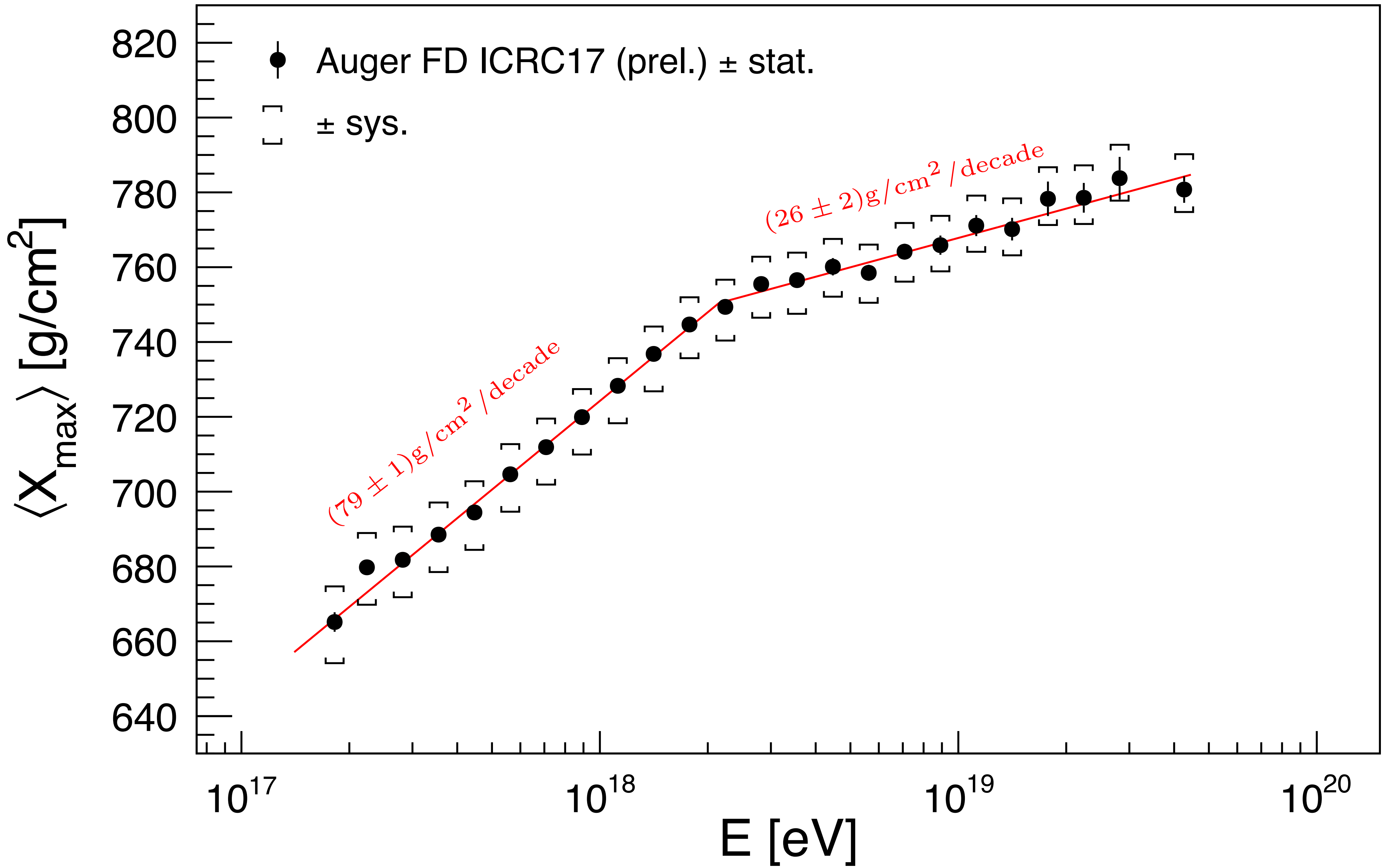
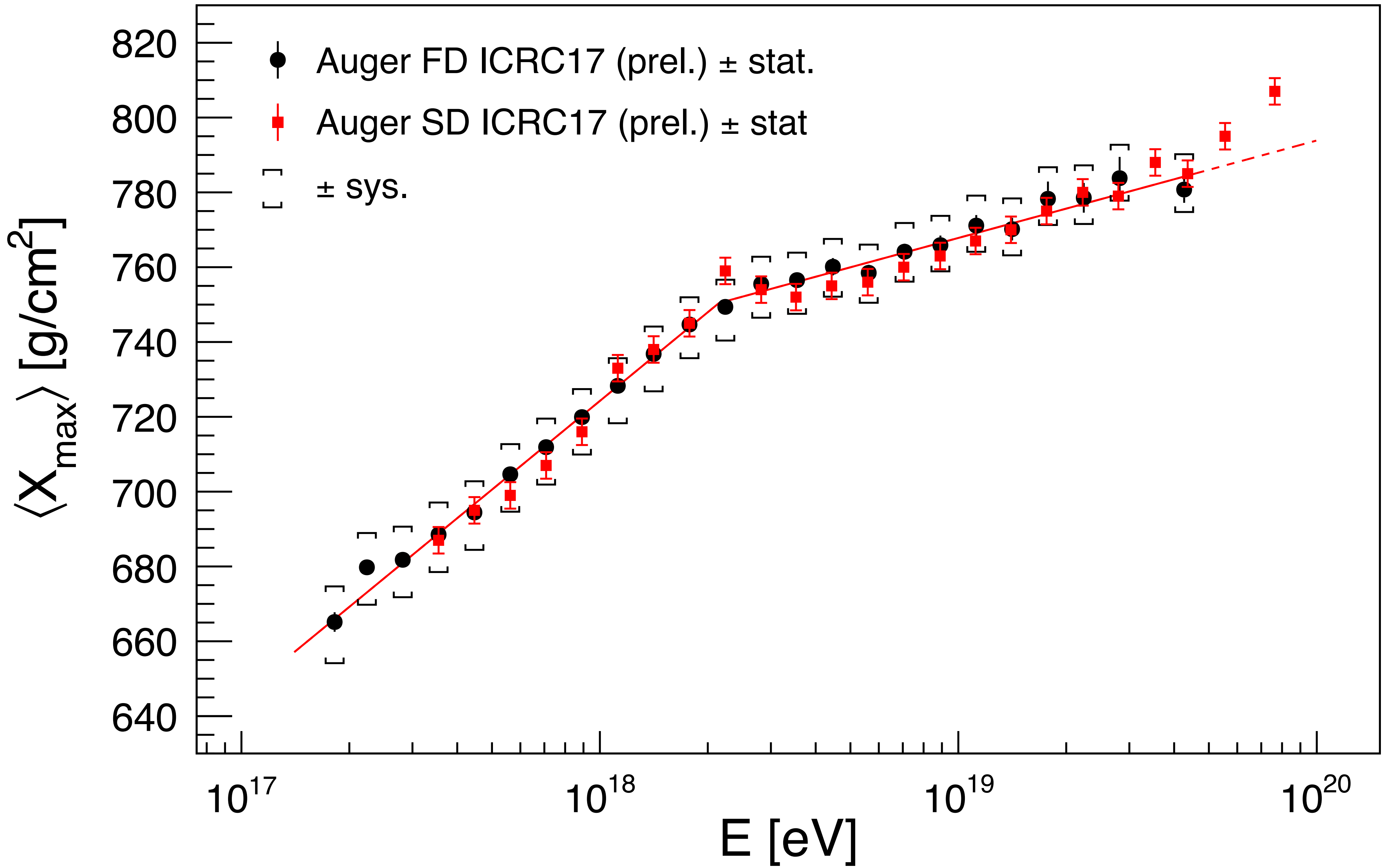
Mean X_{max} from fluorescence detectors



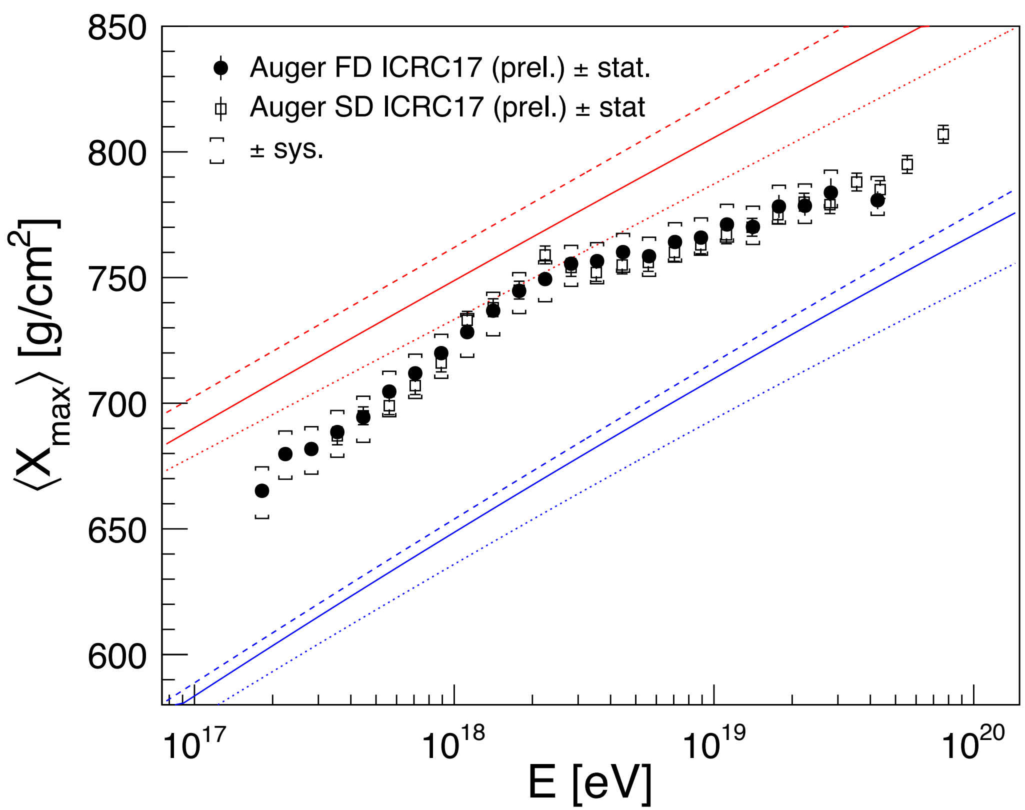
Mean X_{max} from fluorescence detectors

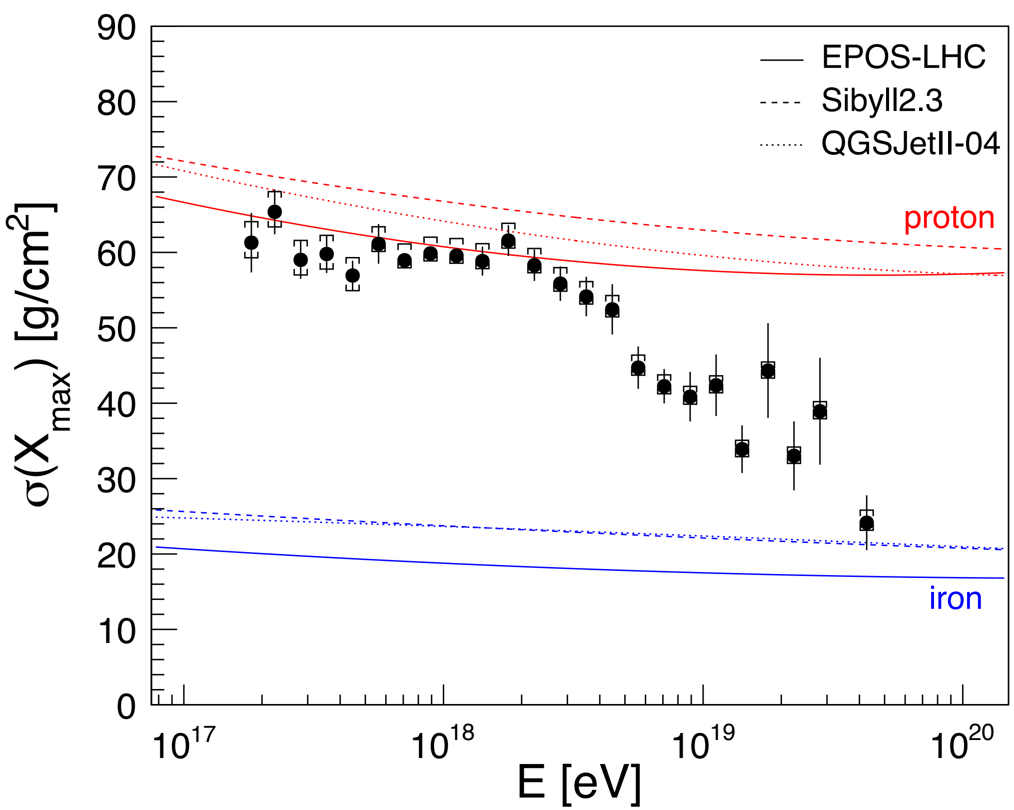


Mean X_{max} from fluorescence and surface detectors



Mean X_{max} and fluctuations in X_{max} (latter from from fluorescence detectors only)



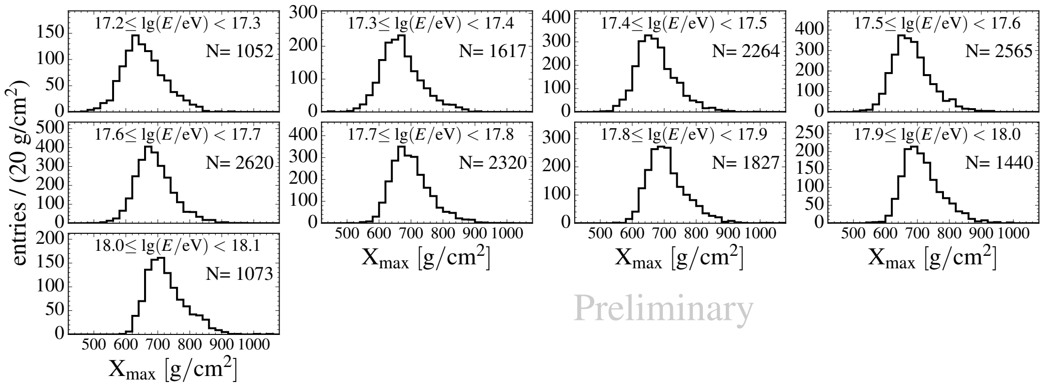


lines: air shower simulations using post-LHC hadronic interaction models

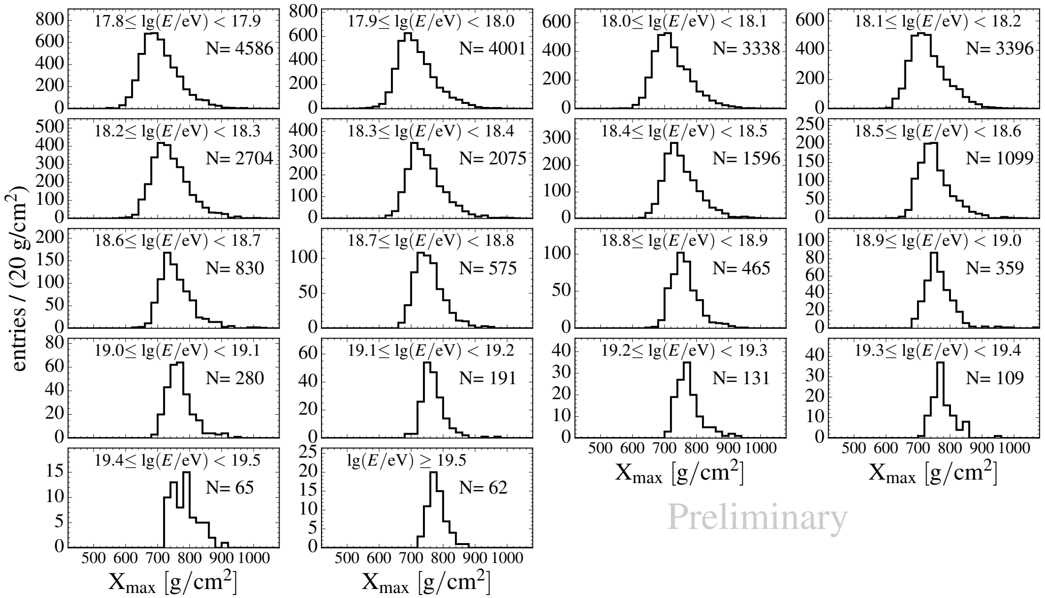
Fits of full X_{max} distributions with (p-He-N-Fe) mixtures

From FD

$\lg(E/\mathrm{eV}) = 17.2 \ldots 18.1$

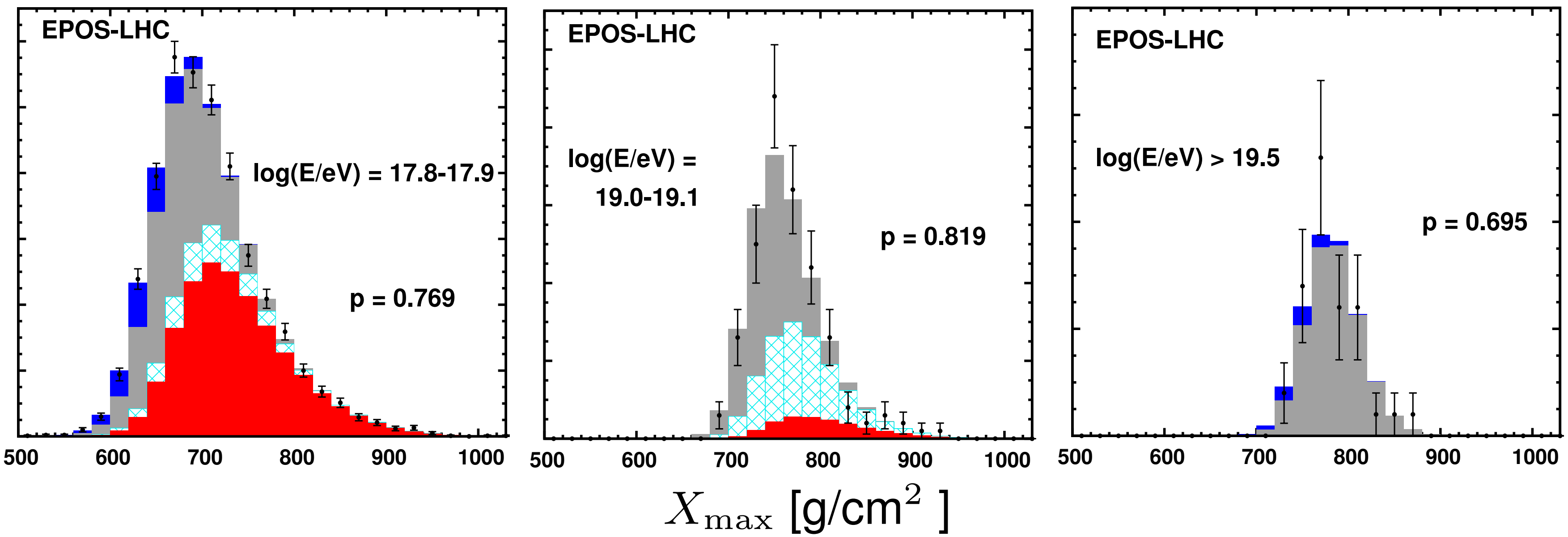


$\lg(E/\mathrm{eV}) = 17.8 \ldots > 19.5$

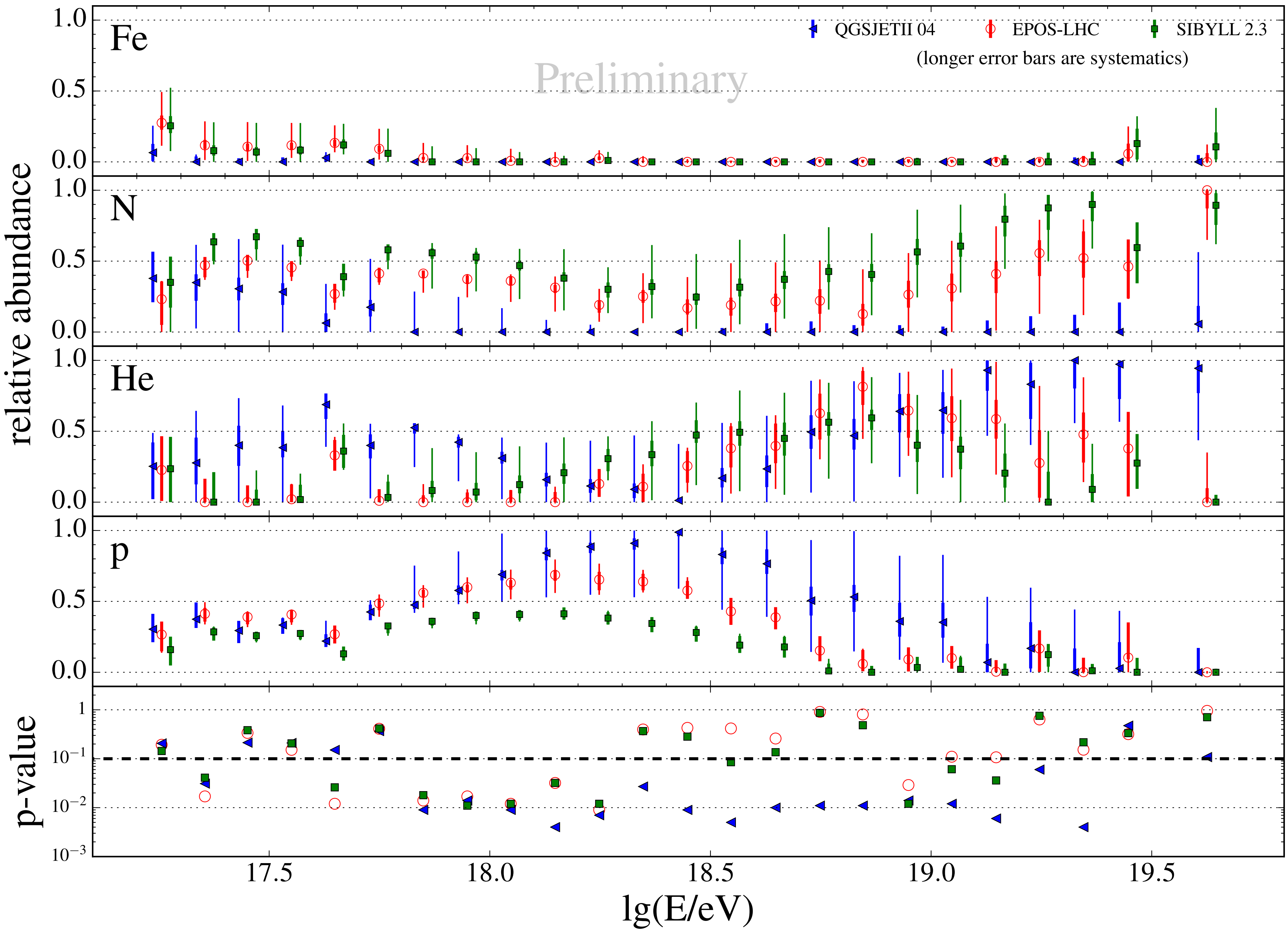


Examples of 4-component fit:

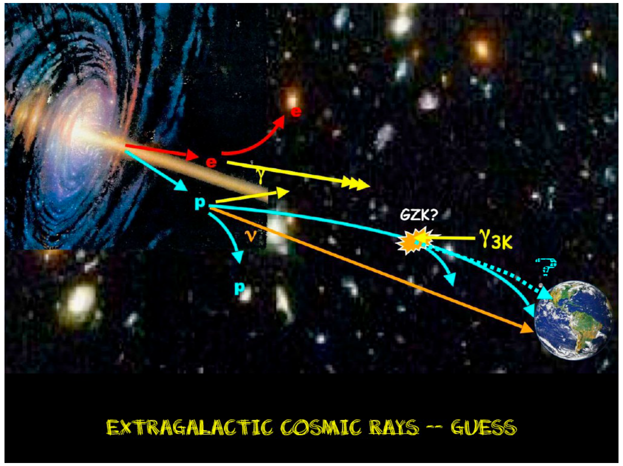
p He N Fe



Mass fractions



Astrophysical interpretation: very simple models



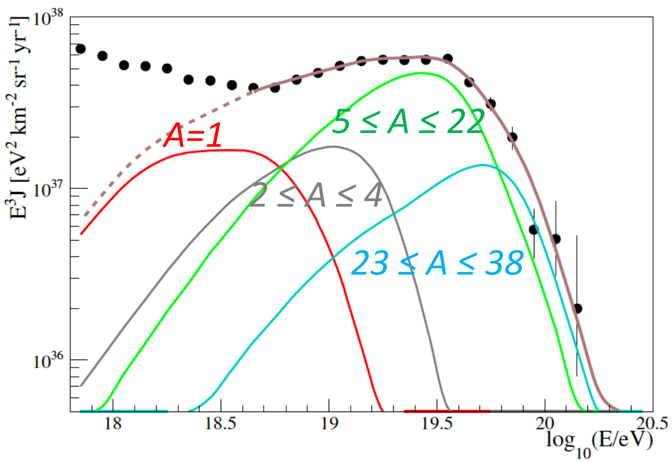
Simulate propagation of CR particles in cosmic photon fields

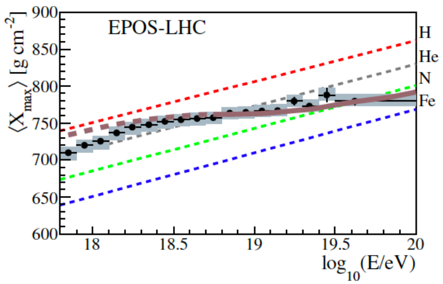
- match to measured spectrum and mass composition at Earth
- 1D propagation through photon fields
- Homogeneous distribution of identical sources of p, He, N, (Si), Fe
- CR injection = power law + rigidity cutoff

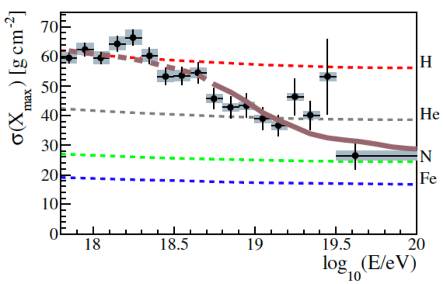
Similar scenarios studied by Aharonian, Ahlers, Allard, Aloisio, Berezinsky, Blasi, Hooper, Olinto, Parizot, Taylor, …

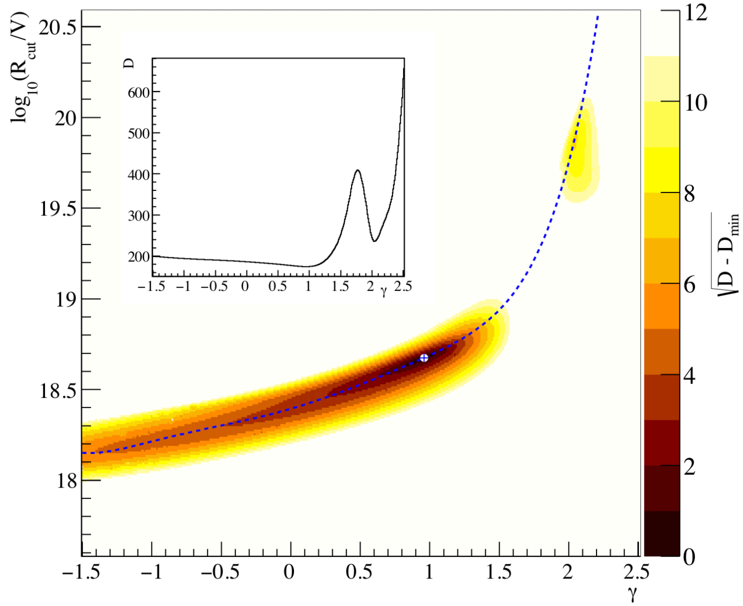
Results: hard/very hard injection spectrum unless nearby sources assumed.

Full study incl. model and data uncertainties:
Aab et al. [Auger Collab.] JCAP (2017) 1704, 038.





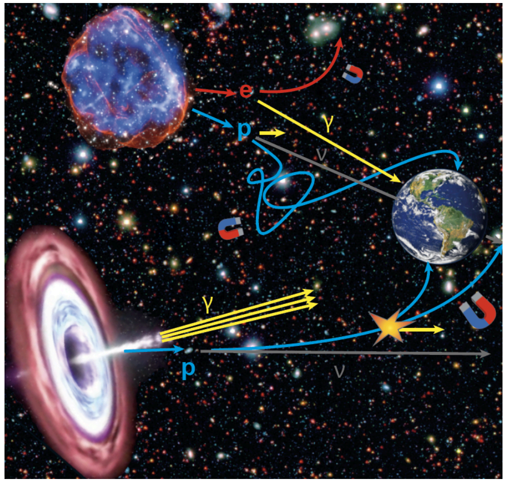




$$\frac{dN}{dE} = J_0 \sum_{\alpha} f_\alpha E_0^{-\gamma} \begin{cases} 1 & \text{for} \quad E_0/Z_\alpha < R_{\rm cut}\,, \\ \exp(1 - \frac{E_0}{Z_\alpha R_{\rm cut}}) & \text{for} \quad E_0/Z_\alpha \geq R_{\rm cut} \end{cases}$$

"Reference" model: SimProp, PSB x-sect, Gilmore '12 EBL, EPOS-LHC

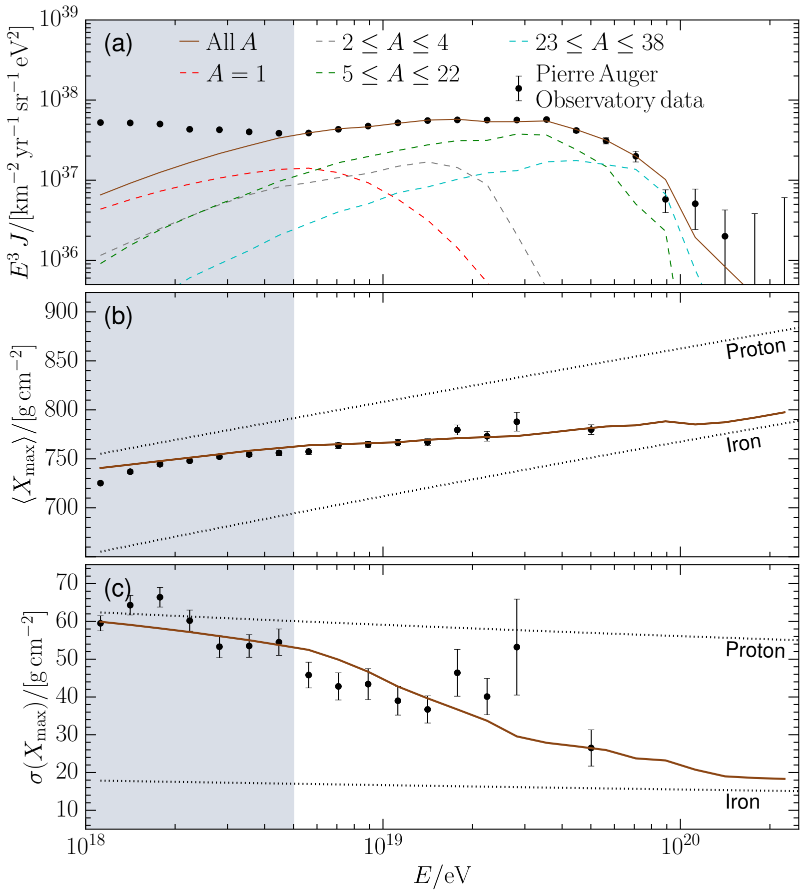
Astrophysical interpretation: adding some extra reality

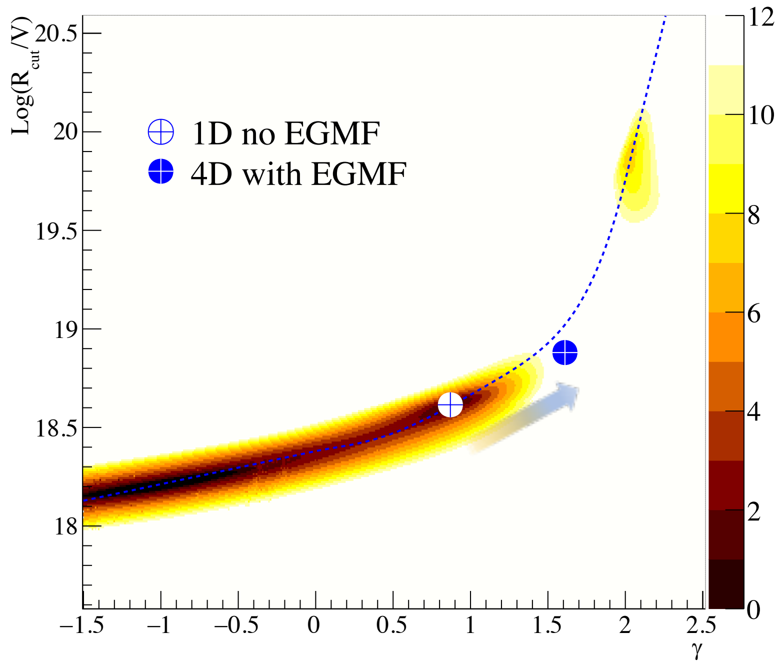


- e.g. Wittkowski [Auger Collab.] ICRC 2017
- 4D propagation (incl. source evolution) with CRPropa3
- extragalactic B fields, large scale structure (Dolag `12), Gilmore `12 EBL, EPOS-LHC

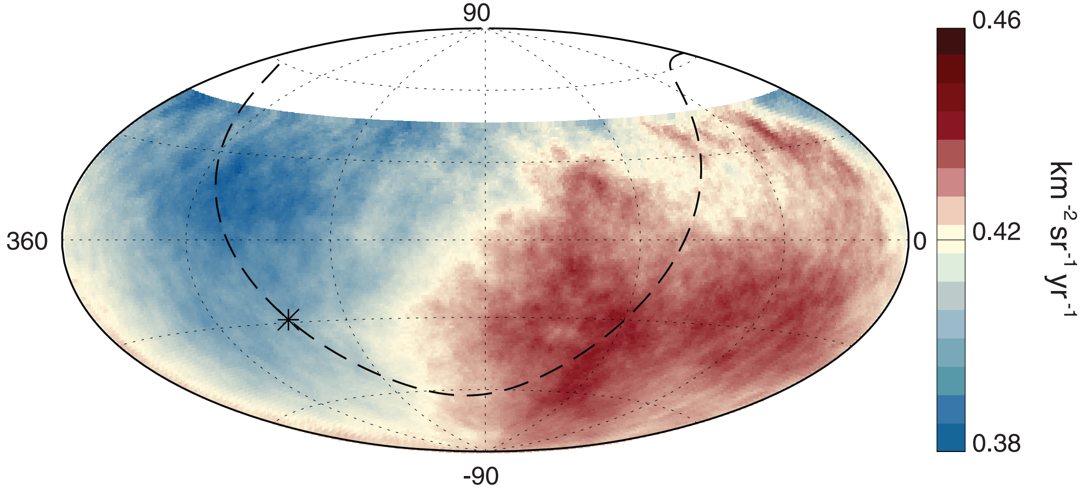
Source properties	4D with EGMF	4D no EGMF	1D no EGMF[1]
γ	1.61	0.61	0.87
$\log_{10}(R_{cut}/eV)$	18.88	18.48	18.62
f_H	3 %	11 %	0 %
f_{He}	2 %	14 %	0 %
f_N	74 %	68 %	88 %
f_{Si}	21 %	7 %	12 %
f_{Fe}	0 %	0 %	0 %

previous slide



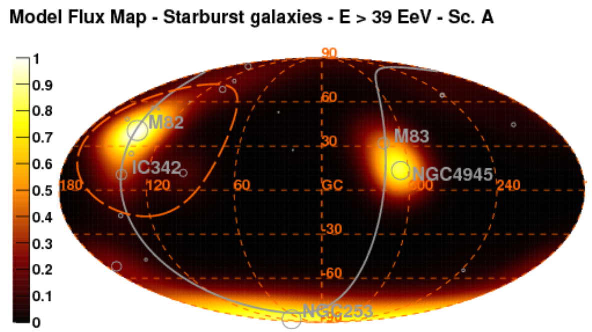


Anisotropy



Indication of Intermediate-scale Anisotropy

A. Aab et al. [Auger Collab.] ApJ. Lett. **833** (2018) L29



Analysis strategy:

- arrival direction data, D
- sky model from source candidates, M_i

  $M_i = (\text{flux model}) \times (\text{attenuation model}) \times (\text{angular smearing}) \times (\text{exposure})$
- null hypothesis: isotropy M_0
- single population signal model

  $M = (1 - \alpha) M_0 + \alpha M_i$

- test statistic:
  - ratio of likelihoods of model-data comparison

    $\mathrm{TS} = 2 \ln \left(P(D \,|\, M) / P(D \,|\, M_0) \right)$

    think: $\Delta\chi^2$ of (isotropy + signal) vs isotropy
  - p-value from Wilks' theorem: $p(\mathrm{TS}) = p_{\chi^2}(\mathrm{TS}, \Delta\mathrm{ndf})$
  - a large TS means
    - M describes D much better than M_0
    - M_0 excluded at p (not: M "proven" at p)

UHECR Source “Suspects”

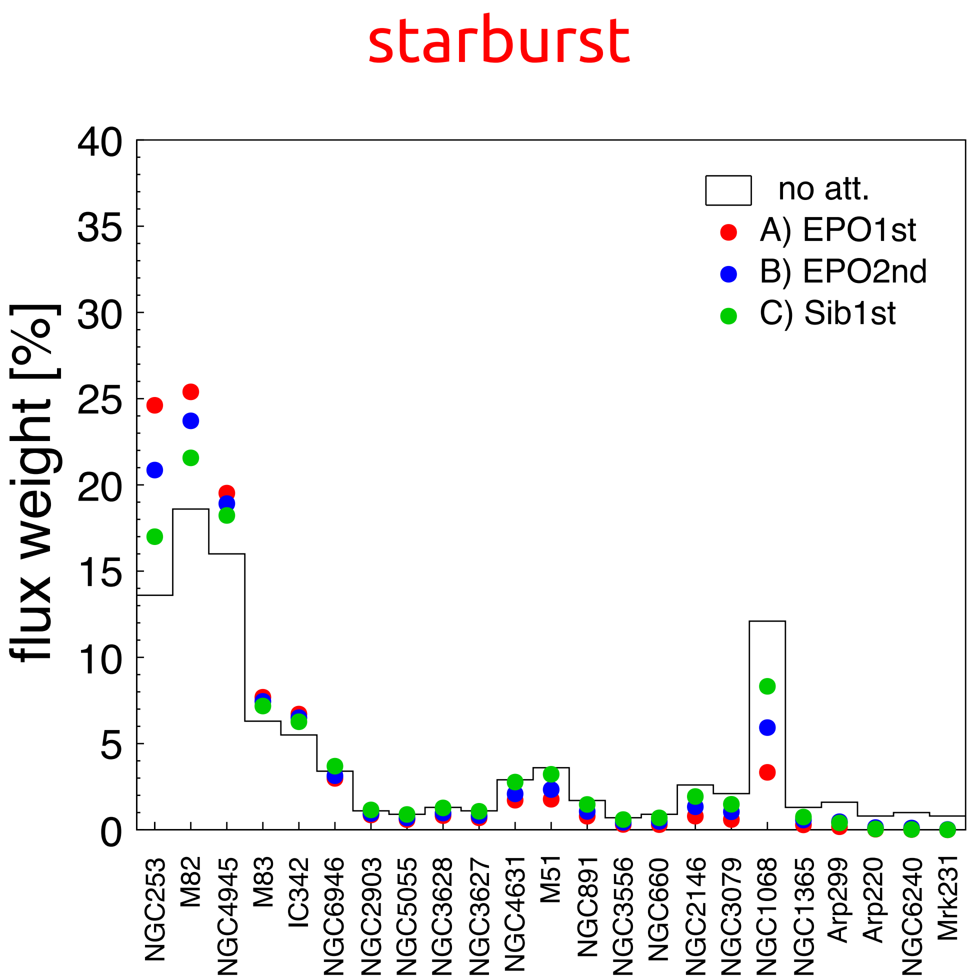
Credit: M. Unger

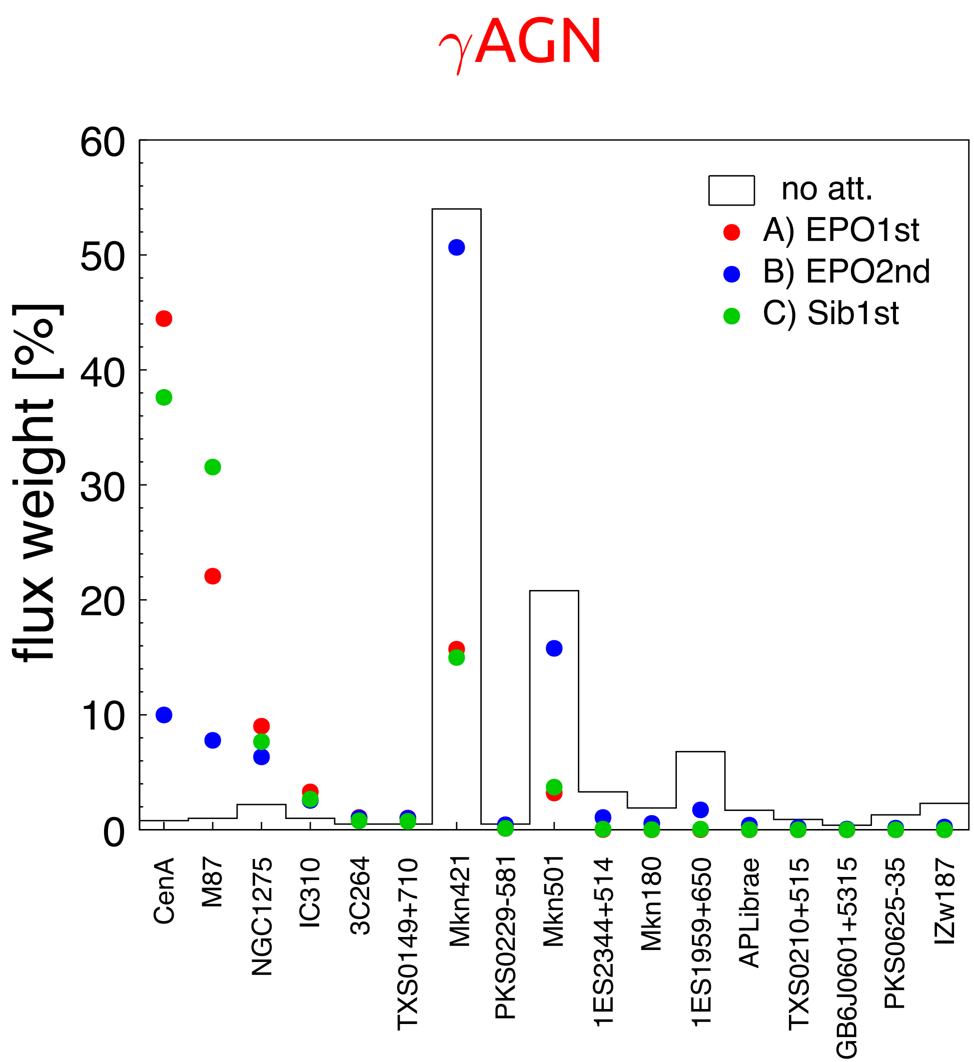
Swift-BAT 2MRS SBG γAGN ~~VCV~~

- *Swift*-BAT X-ray-selected galaxies, $D < 250$ Mpc, $\Phi > 1.3 \cdot 10^{-11} \frac{\text{erg}}{\text{cm}^2\ \text{s}}$, w : 14-195 keV
- 2MRS IR-selected galaxies, $D > 1$ Mpc, w : K-band
- SBG: 23 nearby starburst galaxies, $\Phi > 0.3$ Jy, w : radio at 1.4 GHz
- γAGN: 17 2FHL blazars and radio galaxies, $D < 250$ Mpc, w : γ-ray 50 GeV-2 TeV.

w : UHECR flux proxy, *Swift*-BAT and 2MRS previously tested (ApJ **804** (2015) 172), extragal. γ-ray sources γAGN and SBG.

Flux attenuation: depends on mass fractions, distance

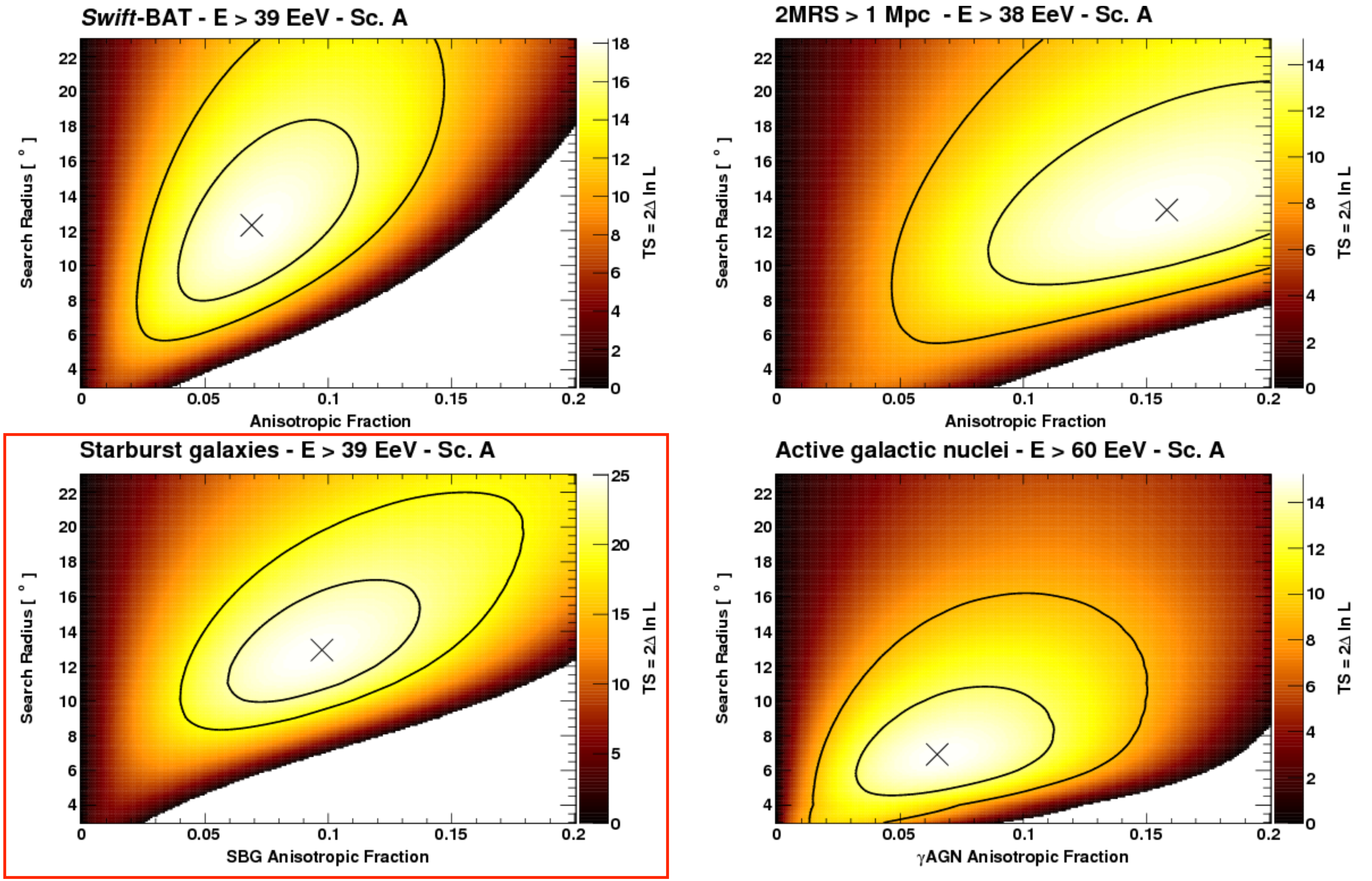




composition scenarios from Pierre Auger Coll., JCAP **1704** (2017) 038 + CRPropa3

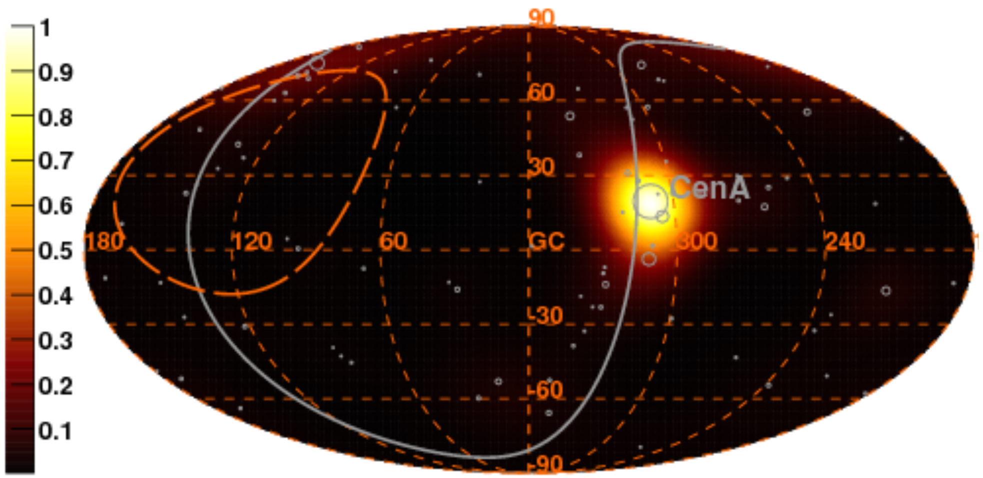
name	$\lg(R_{max}/V)$	f_p	f_{He}	f_N	f_{Si}	γ
EPO1st	18.68	0.000	0.673	0.281	0.046	0.96
EPO2nd	19.88	0.000	0.000	0.798	0.202	2.04
Sib1st	18.28	0.702	0.295	0.003	0.000	-1.50

Data-Model fit: angular smearing and anisotropic fraction

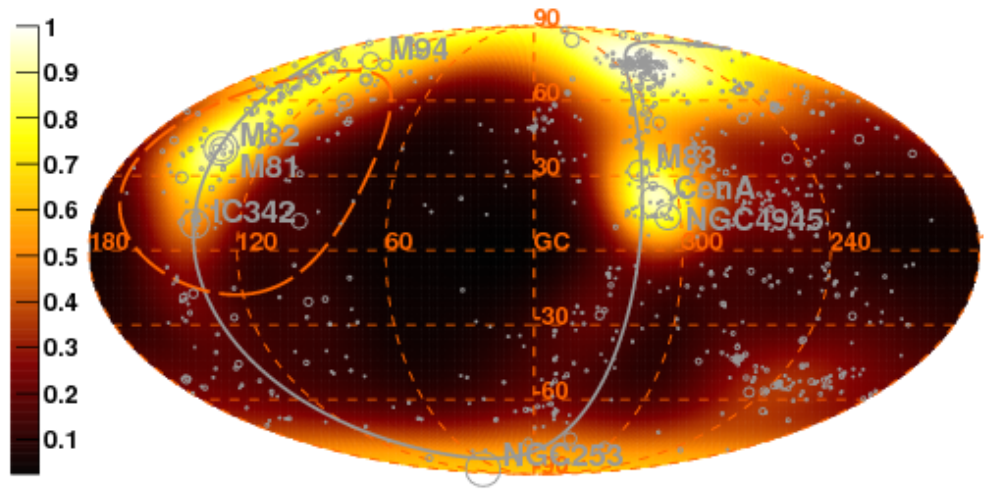


Sky Model (flux) × (attenuation model)$_A$ × (angular smearing), gal. coord.

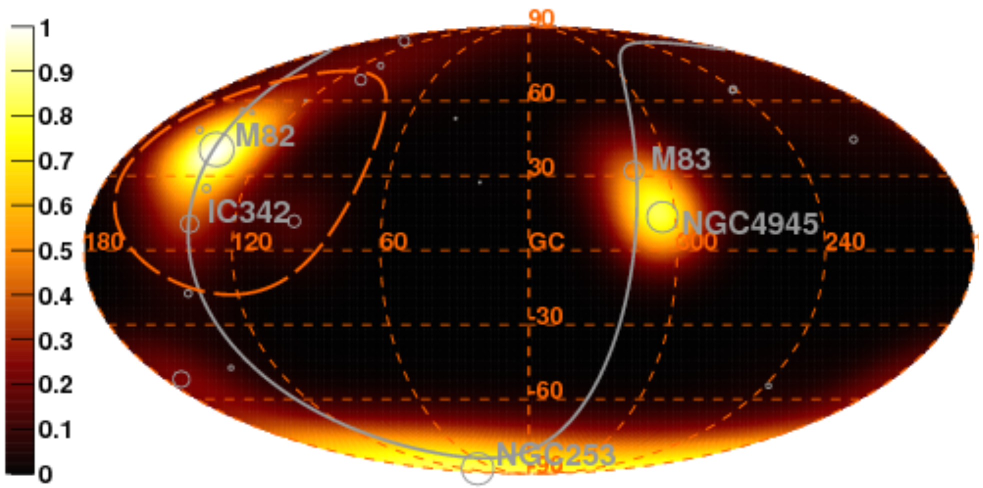
Model Flux Map - *Swift*-BAT - E > 39 EeV - Sc. A



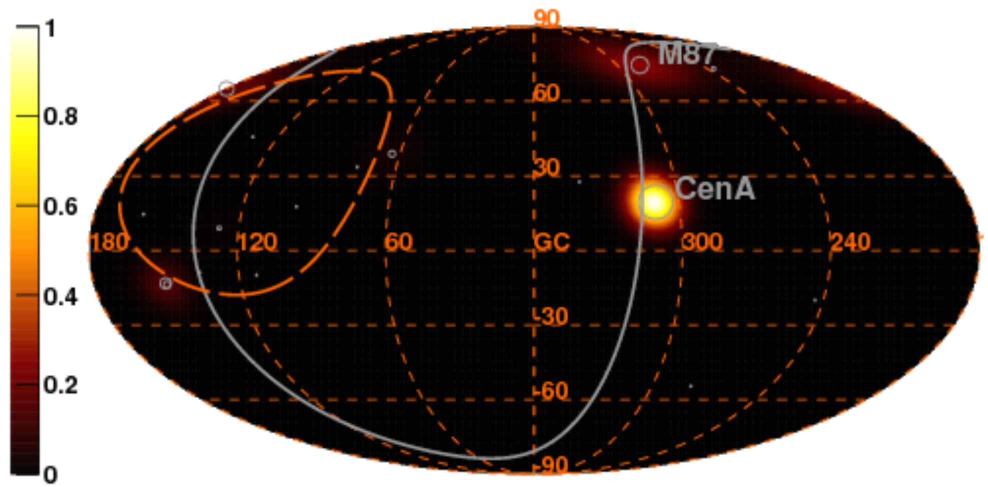
Model Flux Map - 2MRS > 1 Mpc - E > 38 EeV - Sc. A



Model Flux Map - Starburst galaxies - E > 39 EeV - Sc. A



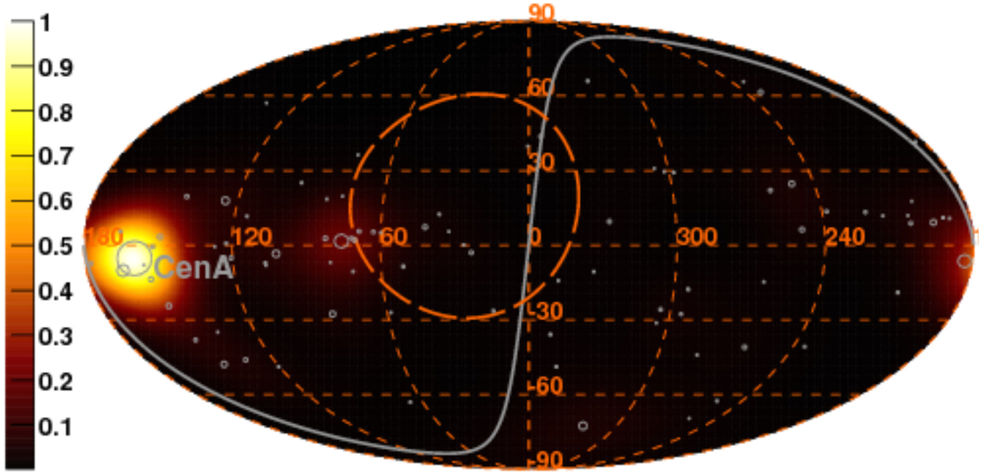
Model Flux Map - Active galactic nuclei - E > 60 EeV - Sc. A



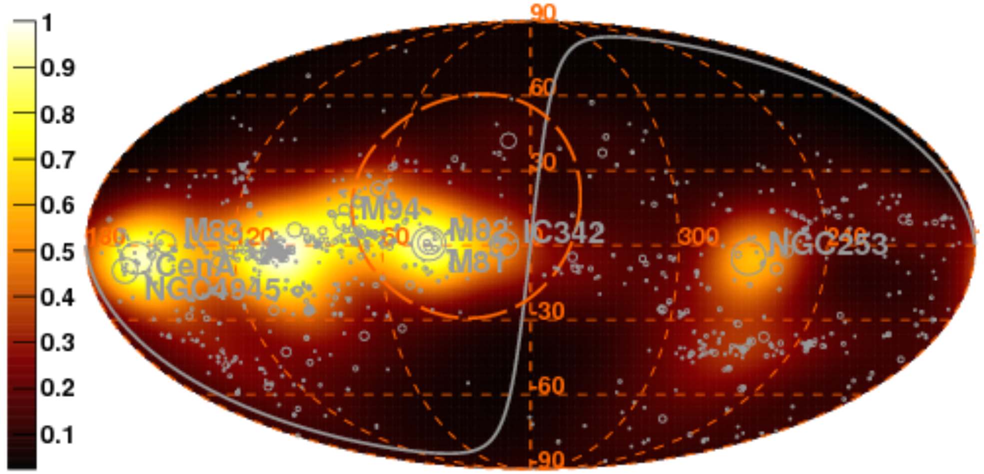
note region with zero exposure

Sky Model (flux) × (attenuation model)$_A$ × (angular smearing), super-gal. coord.

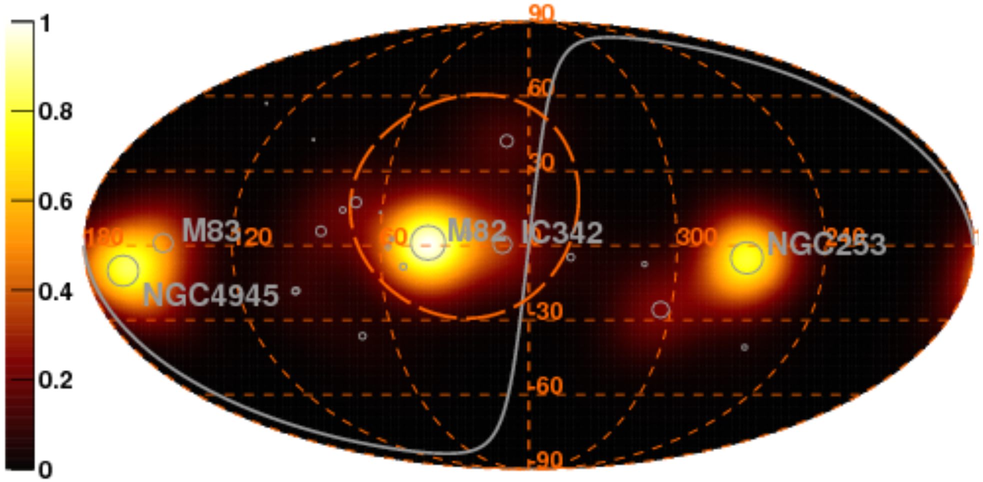
Model Flux Map - *Swift*-BAT - E > 39 EeV - Sc. A



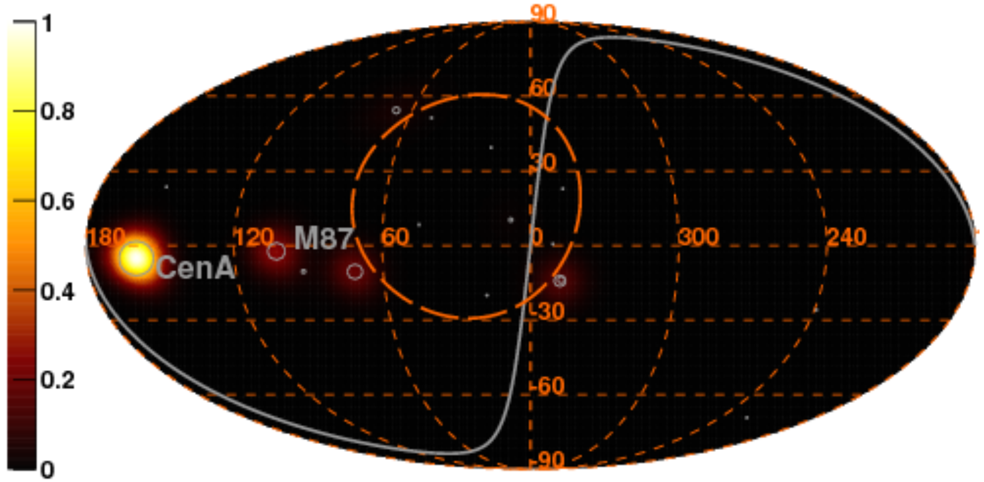
Model Flux Map - 2MRS > 1 Mpc - E > 38 EeV - Sc. A



Model Flux Map - Starburst galaxies - E > 39 EeV - Sc. A



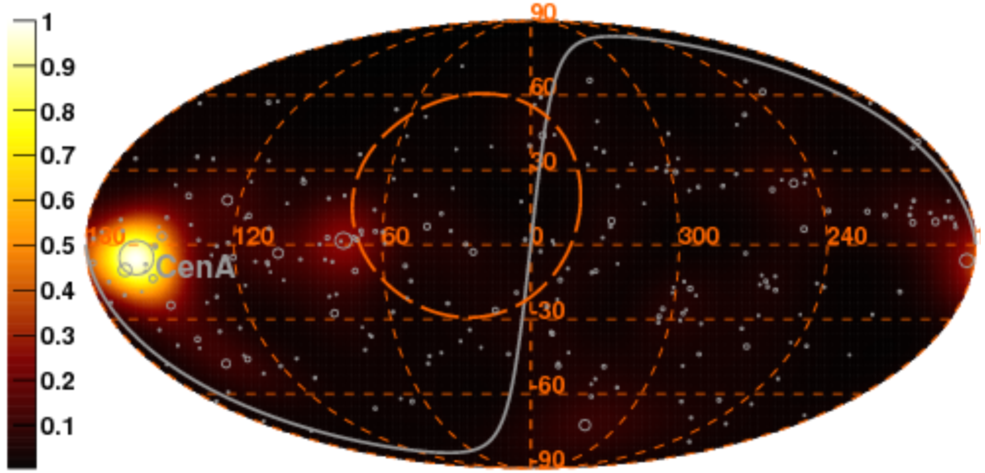
Model Flux Map - Active galactic nuclei - E > 60 EeV - Sc. A



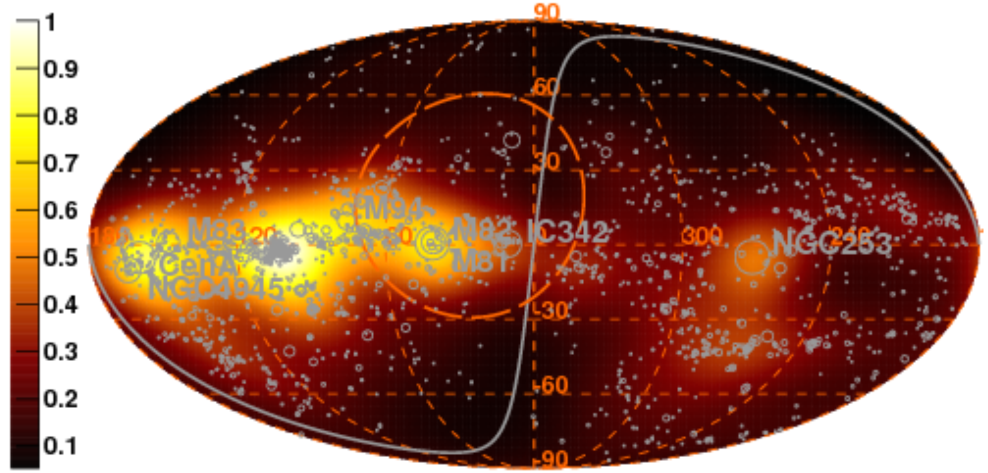
note region with zero exposure

Sky Model (flux) $\times$ (attenuation model)$_B$ $\times$ (angular smearing), super-gal. coord.

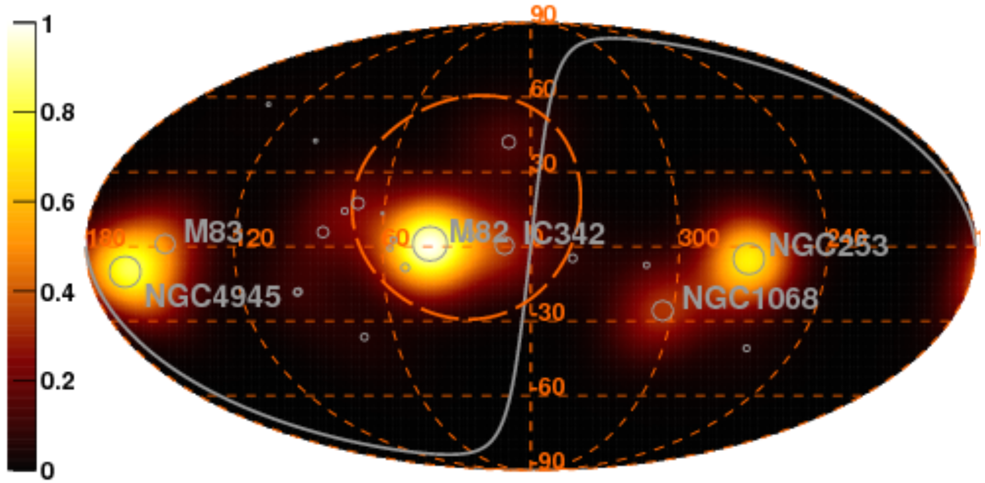
Model Flux Map - *Swift*-BAT - E > 39 EeV - Sc. B



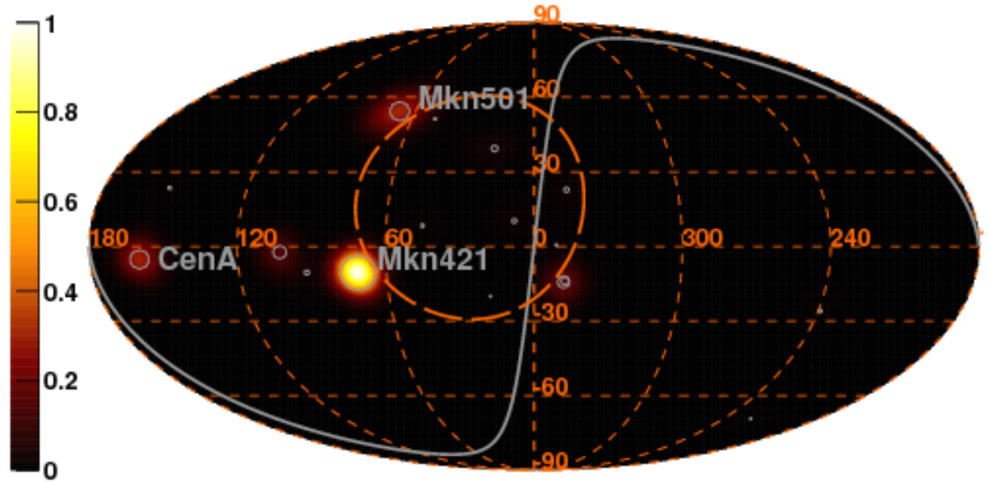
Model Flux Map - 2MRS > 1 Mpc - E > 38 EeV - Sc. B



Model Flux Map - Starburst galaxies - E > 39 EeV - Sc. B

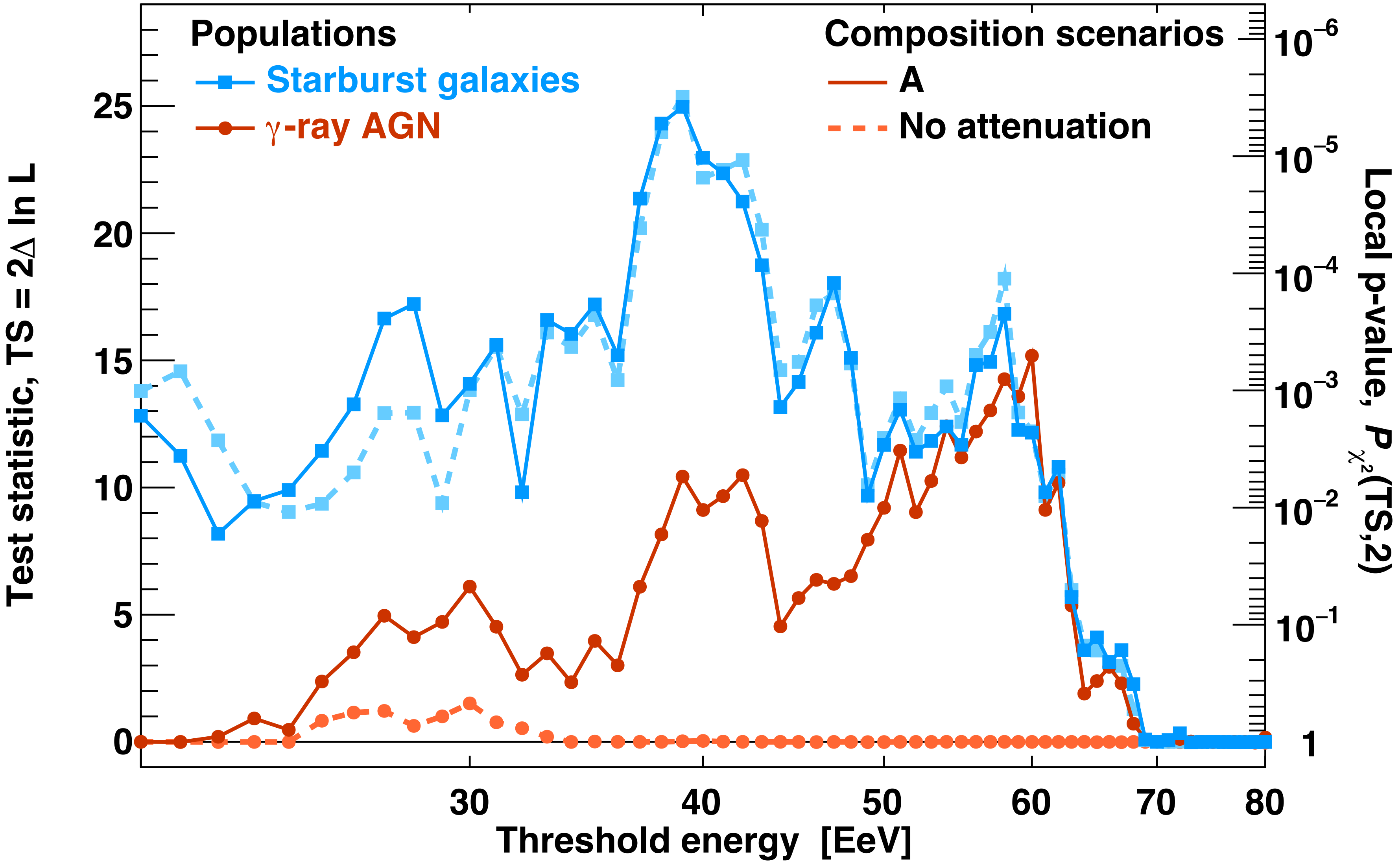


Model Flux Map - Active galactic nuclei - E > 60 EeV - Sc. B



note region with zero exposure

Test Statistic (TS) vs Energy



starburst model fits data better than isotropy, significance of 4 σ^*.

* P_{χ^2} (TS, 2) penalized for energy scan

Detail of results of the sky models

A. Aab et al. [Auger Collab.] ApJ. Lett. **833** (2018) L29

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/other fraction	SBG 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 + 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°
γAGN + SBG + ISO	SBG + ISO	60 EeV	3.0	N/A	0.08	$1.4\,\sigma$	6.8 %	0.0 %[b]	7.0°
Swift-BAT + ISO	ISO	39 EeV	18.2	1.1×10^{-4}	8.0×10^{-4}	$3.2\,\sigma$	6.9 %	N/A	12.3°
Swift-BAT + SBG + ISO	*Swift*-BAT + ISO	39 EeV	7.8	N/A	5.1×10^{-3}	$2.6\,\sigma$	2.8 %	7.1 %	12.6°
2MRS + ISO	ISO	38 EeV	15.1	5.2×10^{-4}	3.3×10^{-3}	$2.7\,\sigma$	15.8 %	N/A	13.2°
2MRS + SBG + ISO	2MRS + ISO	39 EeV	10.4	N/A	1.3×10^{-3}	$3.0\,\sigma$	1.1 %	8.9 %	12.6°

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

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

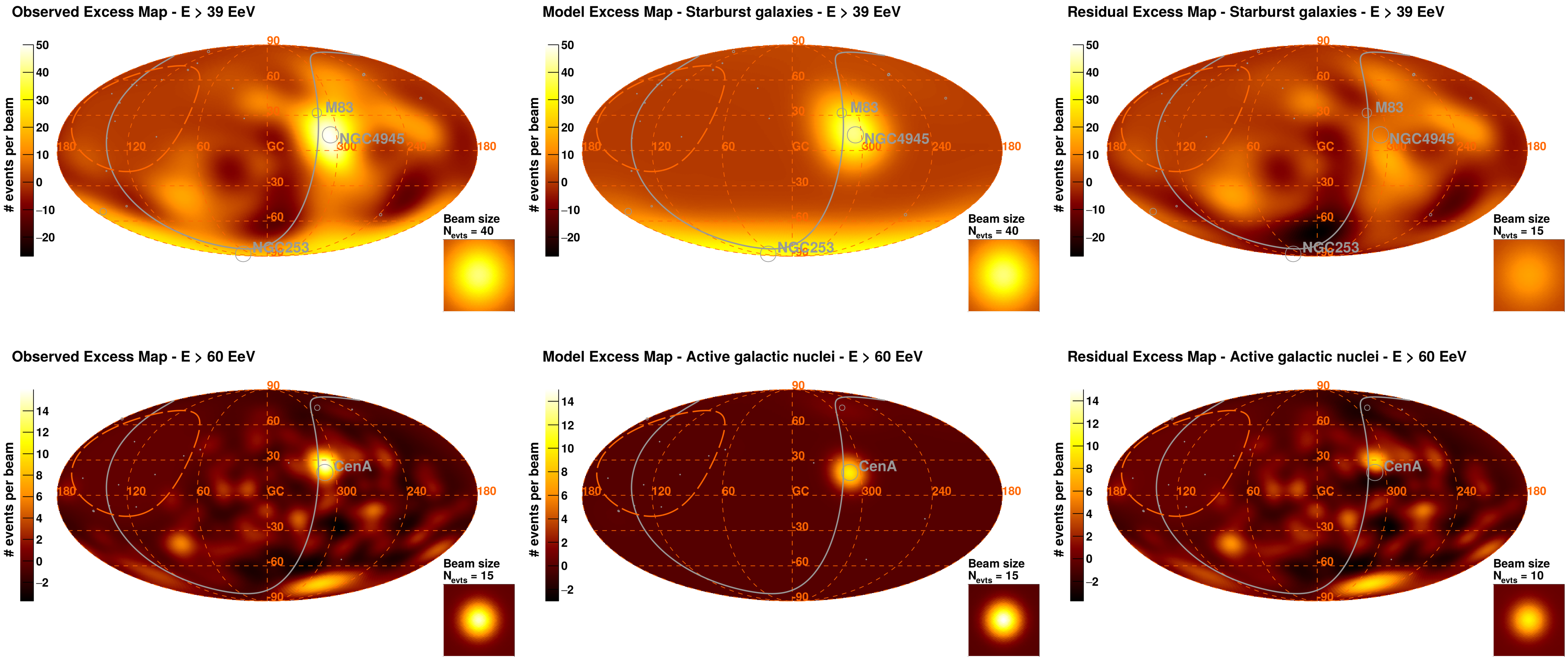
ISO: isotropic model.

starburst model fits data better than isotropy, significance of 4 σ^*.

* $P_{\chi^2}(\mathrm{TS},\ 2)$ penalized for energy scan

Data vs Model for SBG and γAGN (galactic coords)

top: starburst galaxies

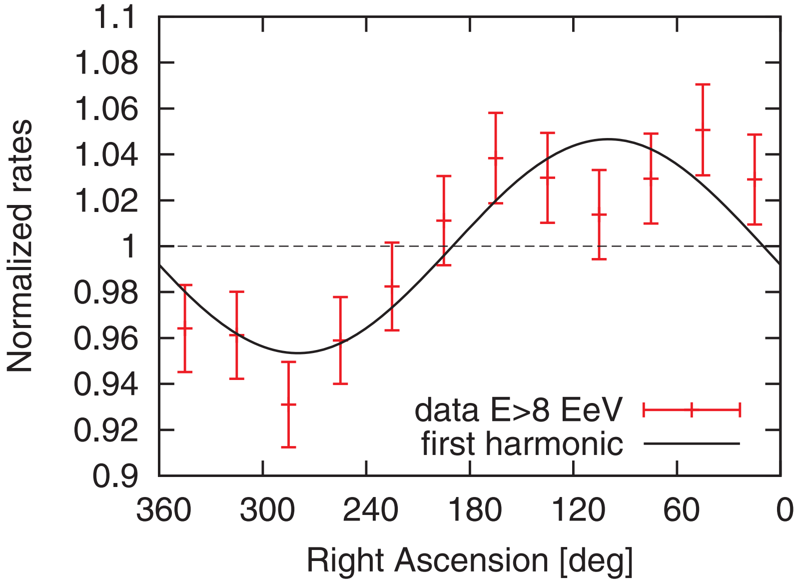


bottom: γAGN

All are "excess" maps: best-fit isotropic component is subtracted.

Observation of Dipolar Anisotropy above 8 EeV

A. Aab et al. [Auger Collab.] Science **357** (2017) 1266

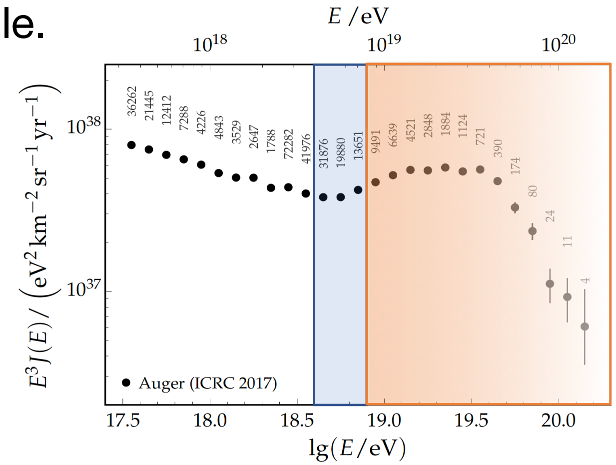


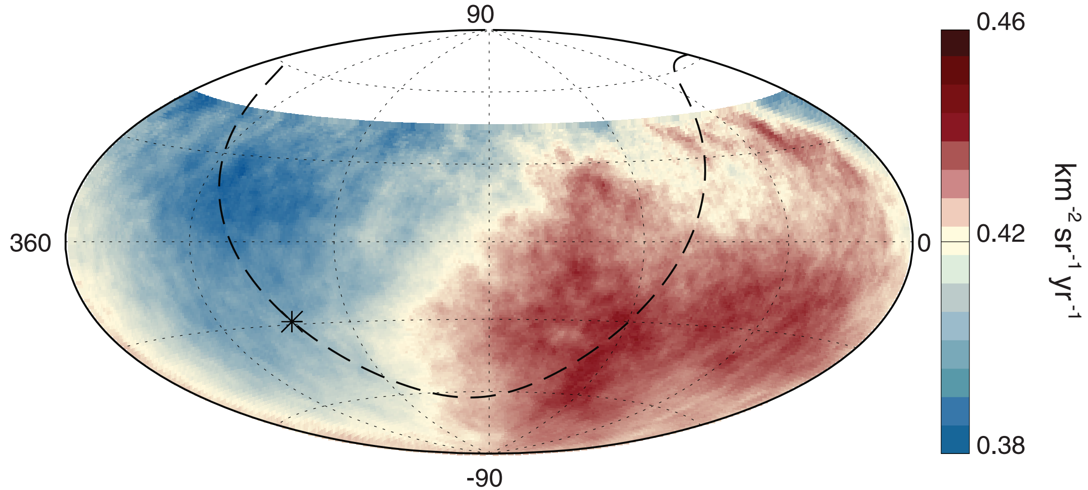
Harmonic Analysis in right ascension (RA)

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 5.2σ

very close to a pure dipole.





3D dipole above 8 EeV

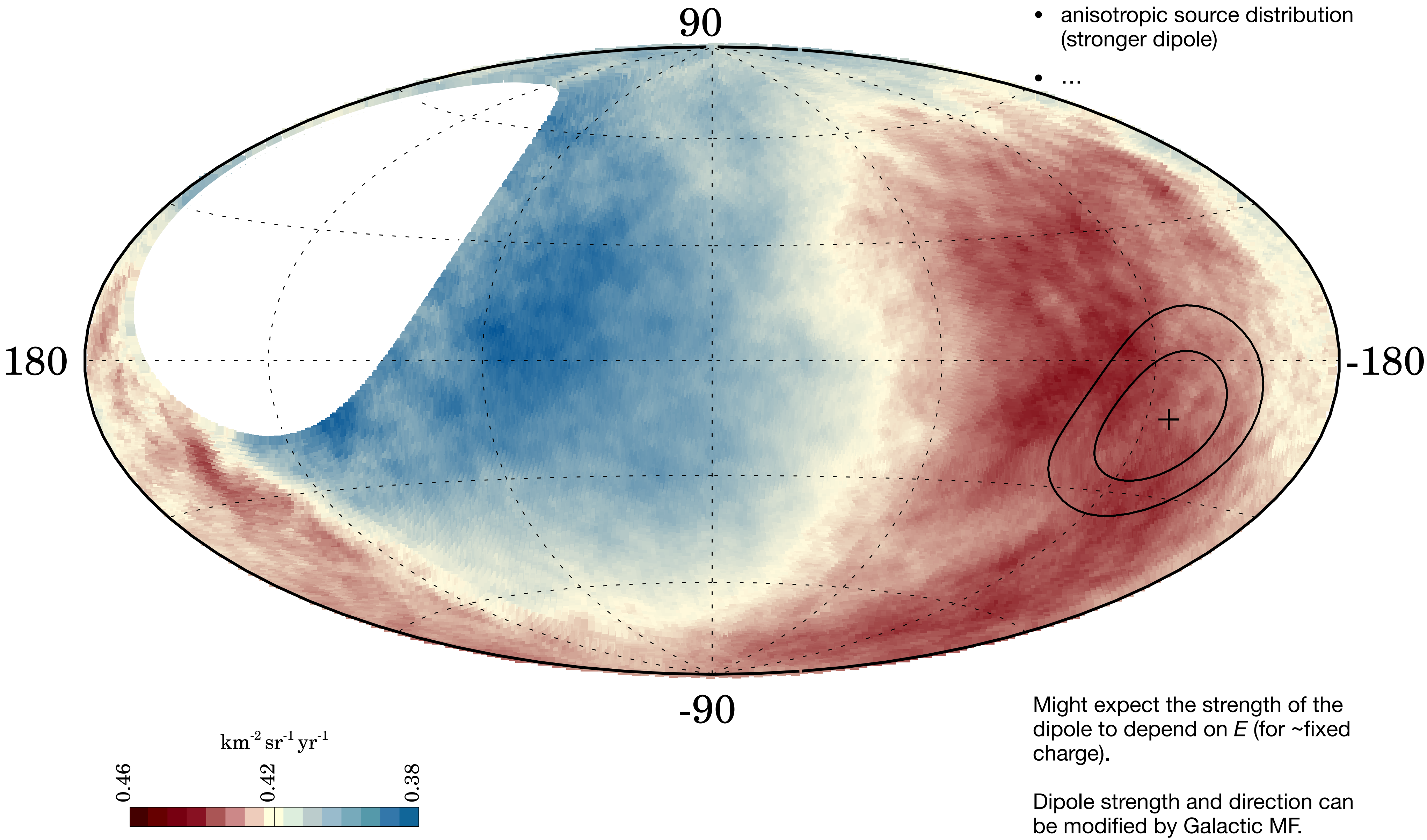
$(\alpha, \delta) = (100°, -24°)$, amplitude $6.5^{+1.3}_{-0.9}$ %

Dipole in galactic coordinates

Strong evidence for extragalactic origin at these energies
- dipole direction 125 degrees from GC.

Dipole could be the result of

- single source + diffusion
- isotropic source distribution (some sources always closer)
- anisotropic source distribution (stronger dipole)
- ...

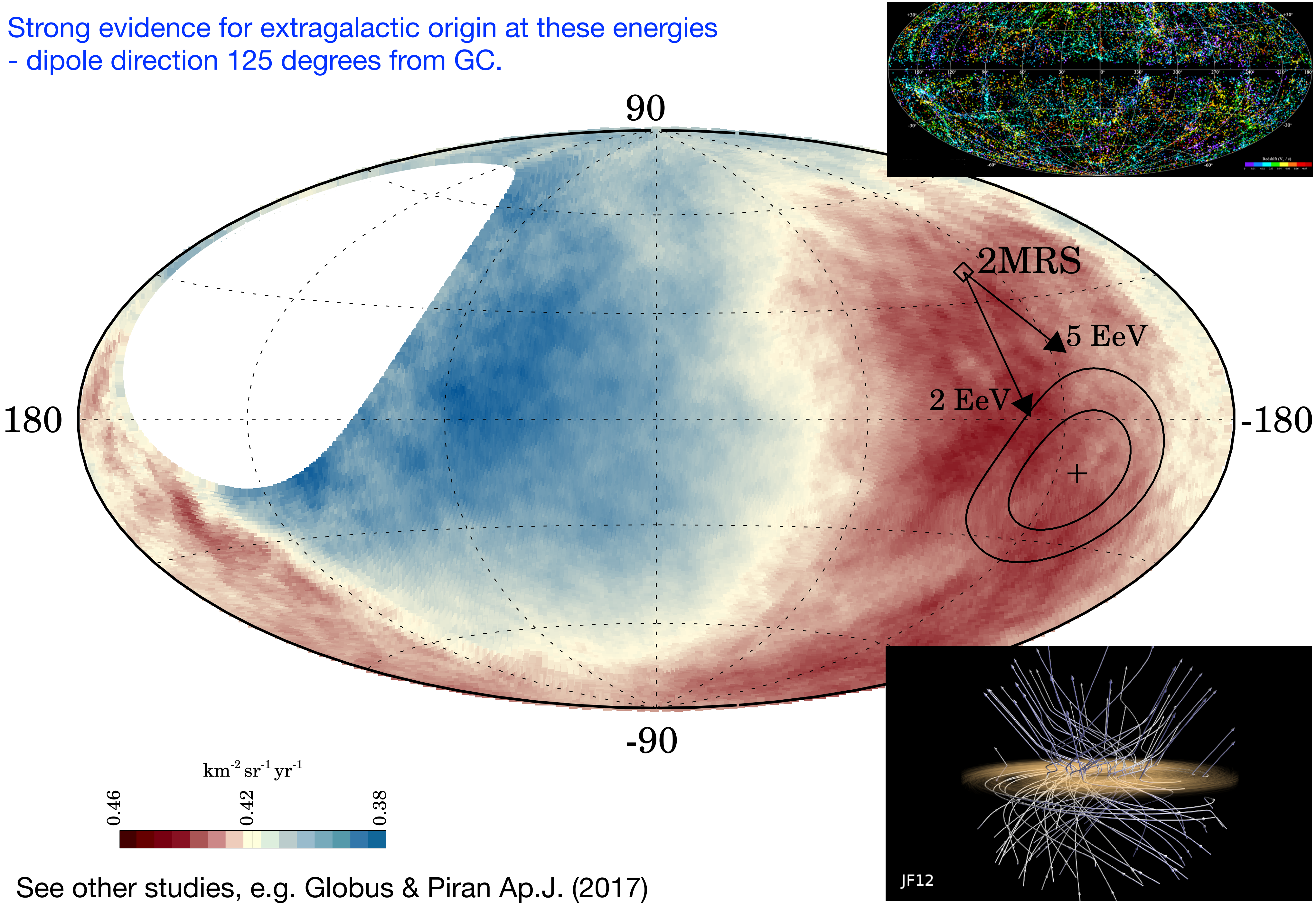


Might expect the strength of the dipole to depend on *E* (for ~fixed charge).

Dipole strength and direction can be modified by Galactic MF.

Dipole in galactic coordinates

Strong evidence for extragalactic origin at these energies
- dipole direction 125 degrees from GC.

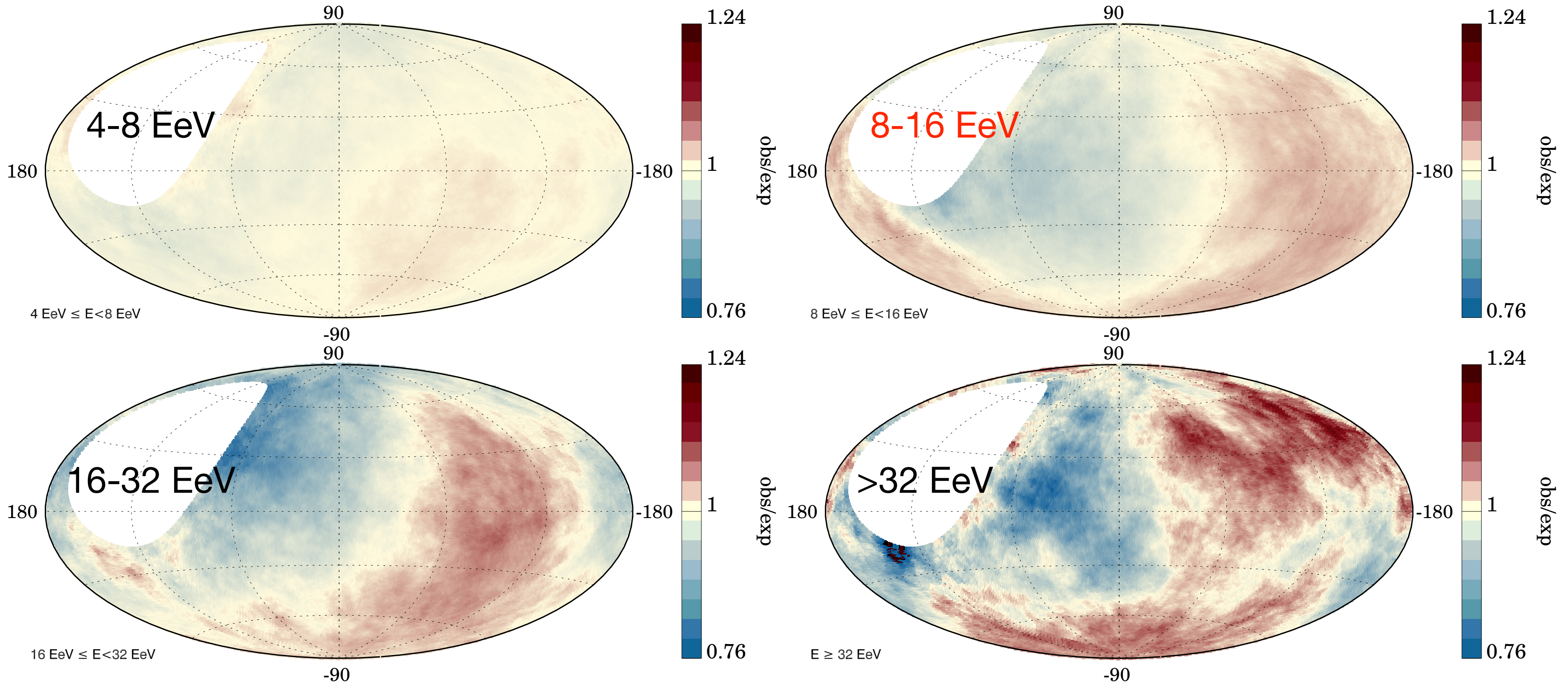


See other studies, e.g. Globus & Piran Ap.J. (2017)
- Noemie's talk this afternoon!

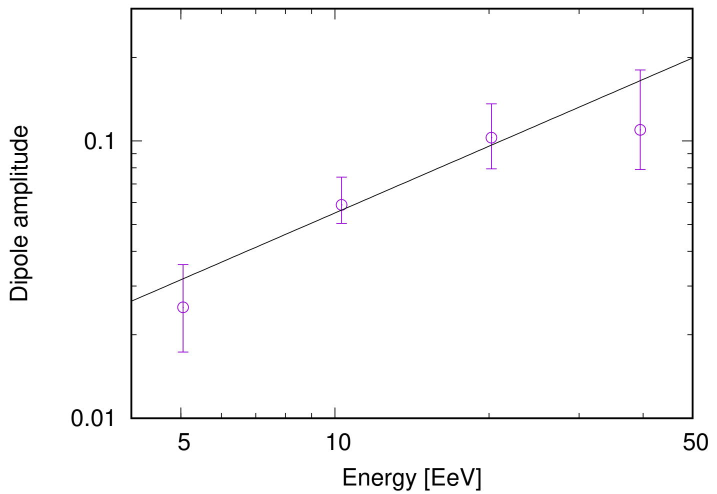
Dipole - some energy dependence?

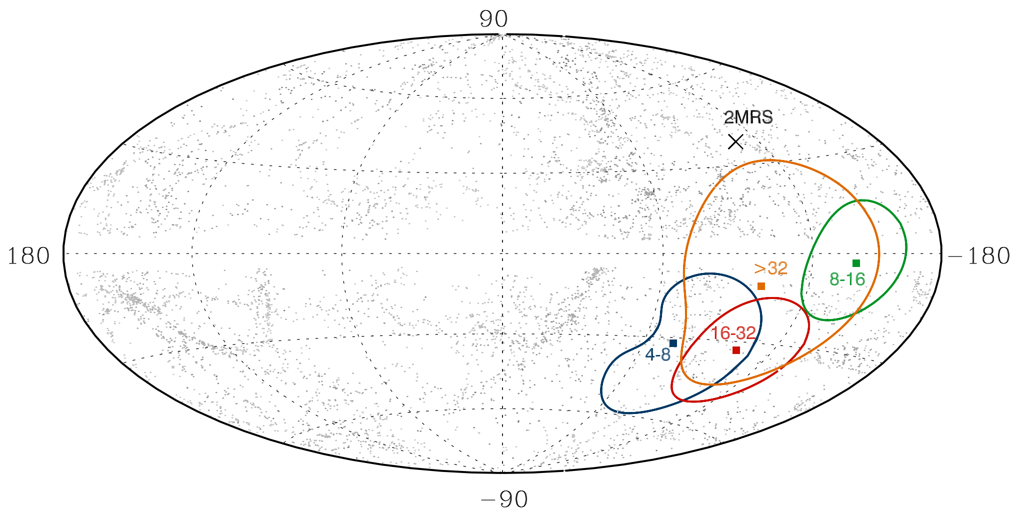
A. Aab et al. [Auger Coll.] Submitted to ApJ (2018)
arXiv:1808.03579

same fractional excess scale on each plot



(only 8-16 EeV bin has a statistically significant result)



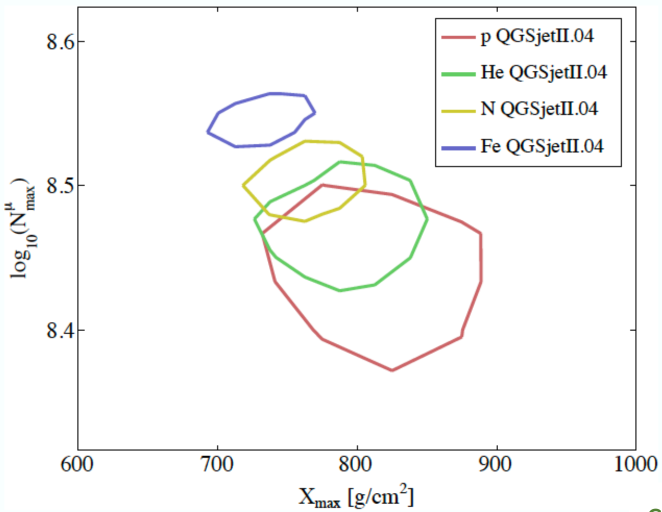


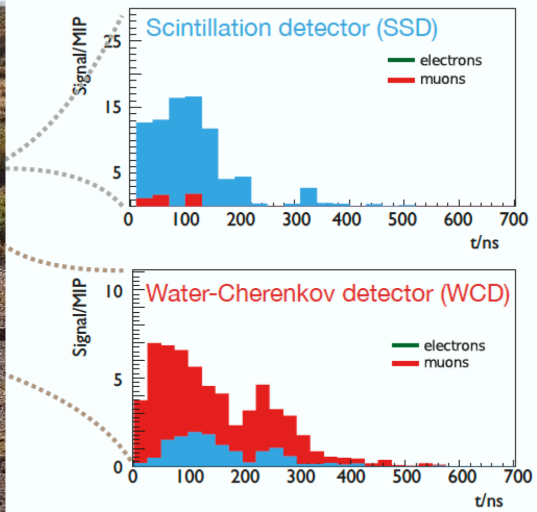
Upgrade to the Auger Observatory - AugerPrime

- mass composition information for every event

To increase exposure with composition sensitive data Surface array needed!

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





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

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

(AugerPrime design report 1604.03637)

Upgrade to the Auger Observatory - AugerPrime

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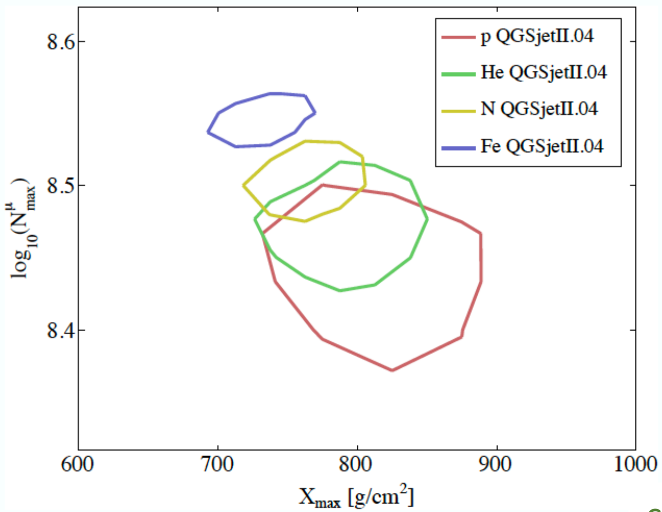
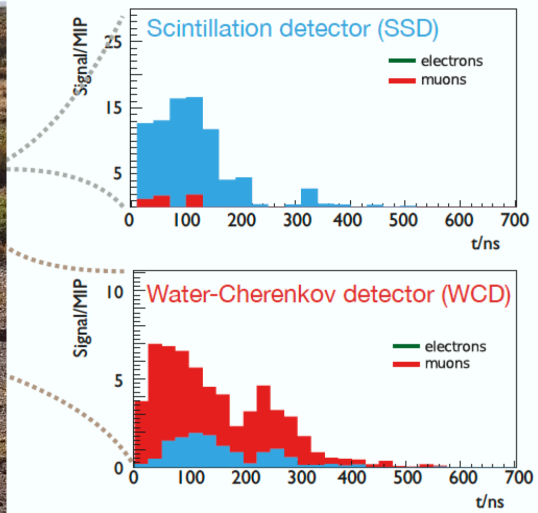


(AugerPrime design report 1604.03637)



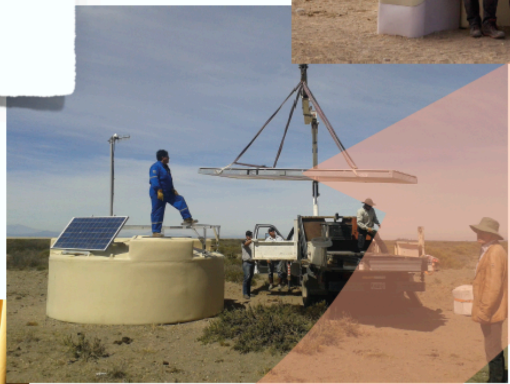
complementarity of light responses used to discriminate e.m. and muonic components

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

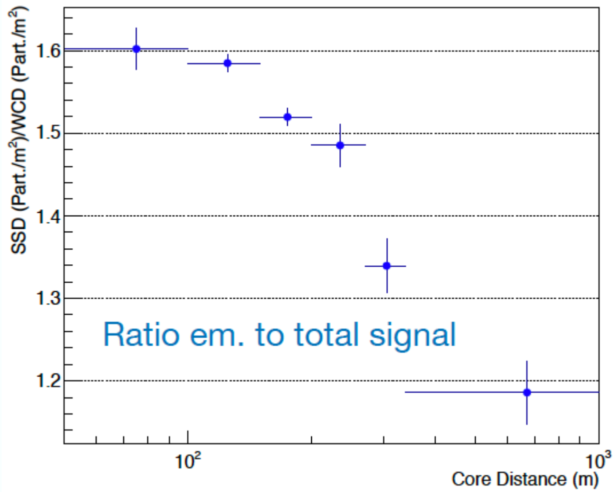
Upgrade to the Auger Observatory - AugerPrime

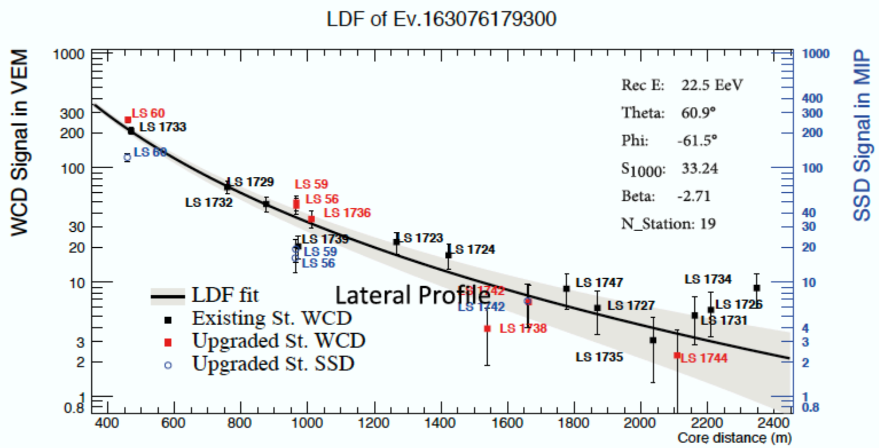
Status and plans for *AugerPrime*

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



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





Summary

- Spectrum and composition
  - highest exposure measurement of spectrum , strong flux suppression
  - Composition with FD and SD
    - light composition at ankle
    - mixed composition at UHE
    - hints of galactic Fe at lowest energies?
  - compatible with rigidity-dependent cut-off at sources

- Anisotropy
  - observation of dipole anisotropy E > 8 EeV
  - indication of medium-scale anisotropy, E > 39 EeV

- Other results (no time)
  - UHE Neutrino and gamma-ray limits constraining proton-dominated sources
  - Hadronic interactions (normal UHE cross-sections, muon deficits in models)

- AugerPrime Upgrade