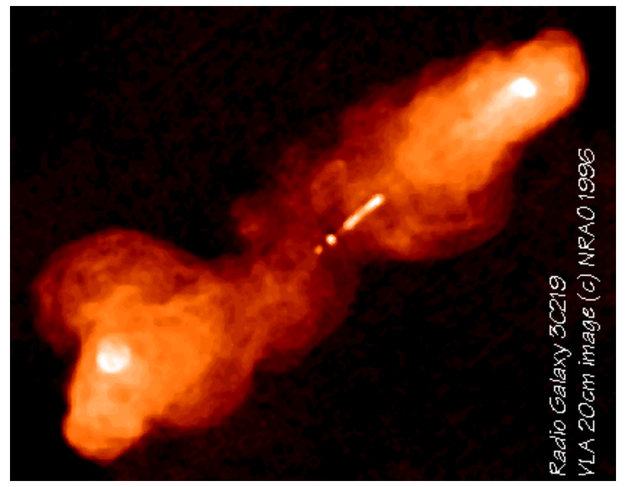
What have we learned from the Pierre Auger Observatory for future UHECR observatories

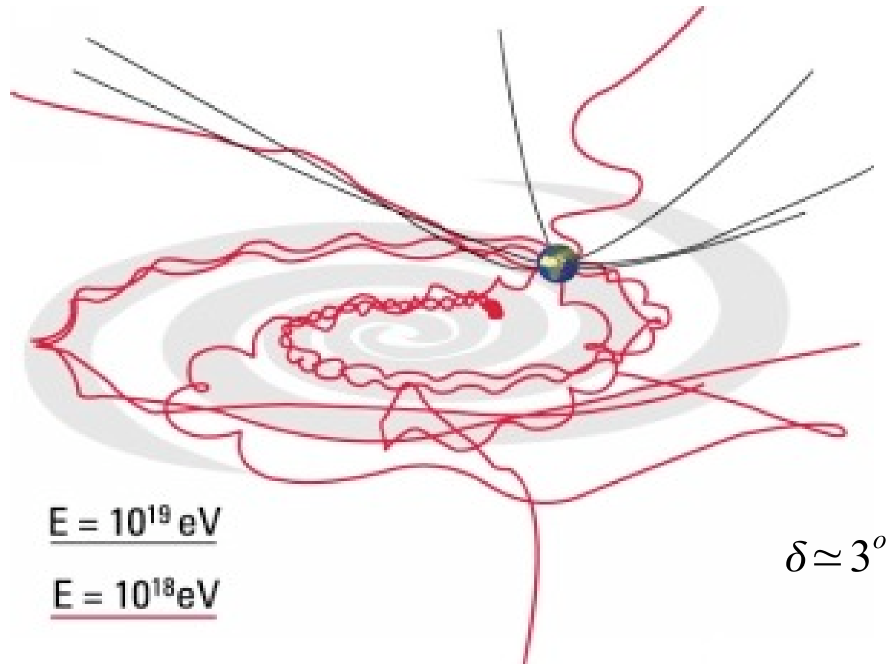
Ralph Engel, for the Pierre Auger Collaboration

(picture curtesy S. Saffi)

Most important research goals



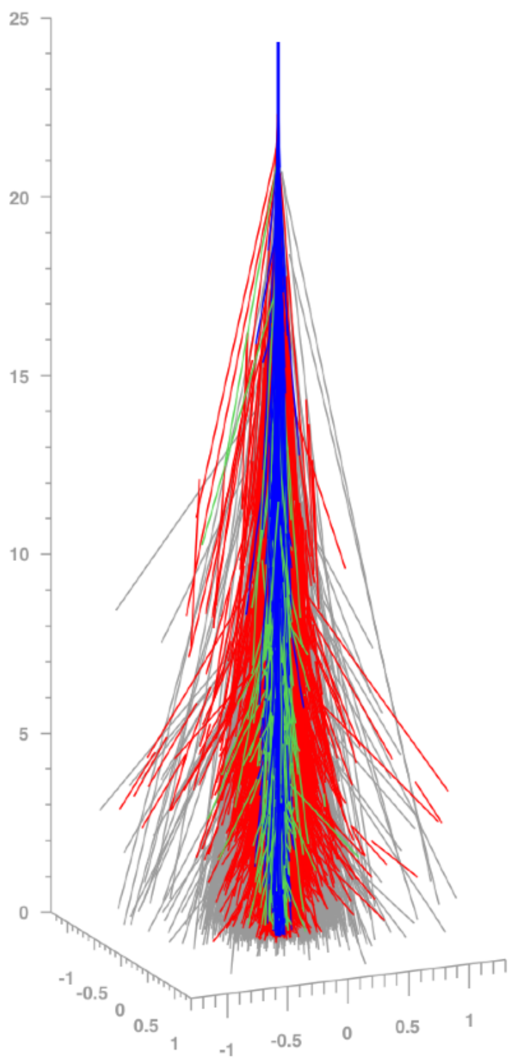
- Identification of sources and/or source regions
- Determination of acceleration (or other) mechanism to produce particles of extreme energies
- Study of astrophysics of source objects/regions
- Investigation of cosmic ray propagation
- Multi-messenger studies (neutrinos, gamma-rays)



$$\delta \simeq 3^o \frac{B}{3\,\mu G}\frac{L}{kpc}\frac{6\times10^{19}\,eV}{E/Z}$$

- Input for prediction of secondary particle fluxes

- Measurement of or placing limits on magnetic fields
  - in clusters and filaments
  - in intergalactic regions and voids
  - in our Galaxy

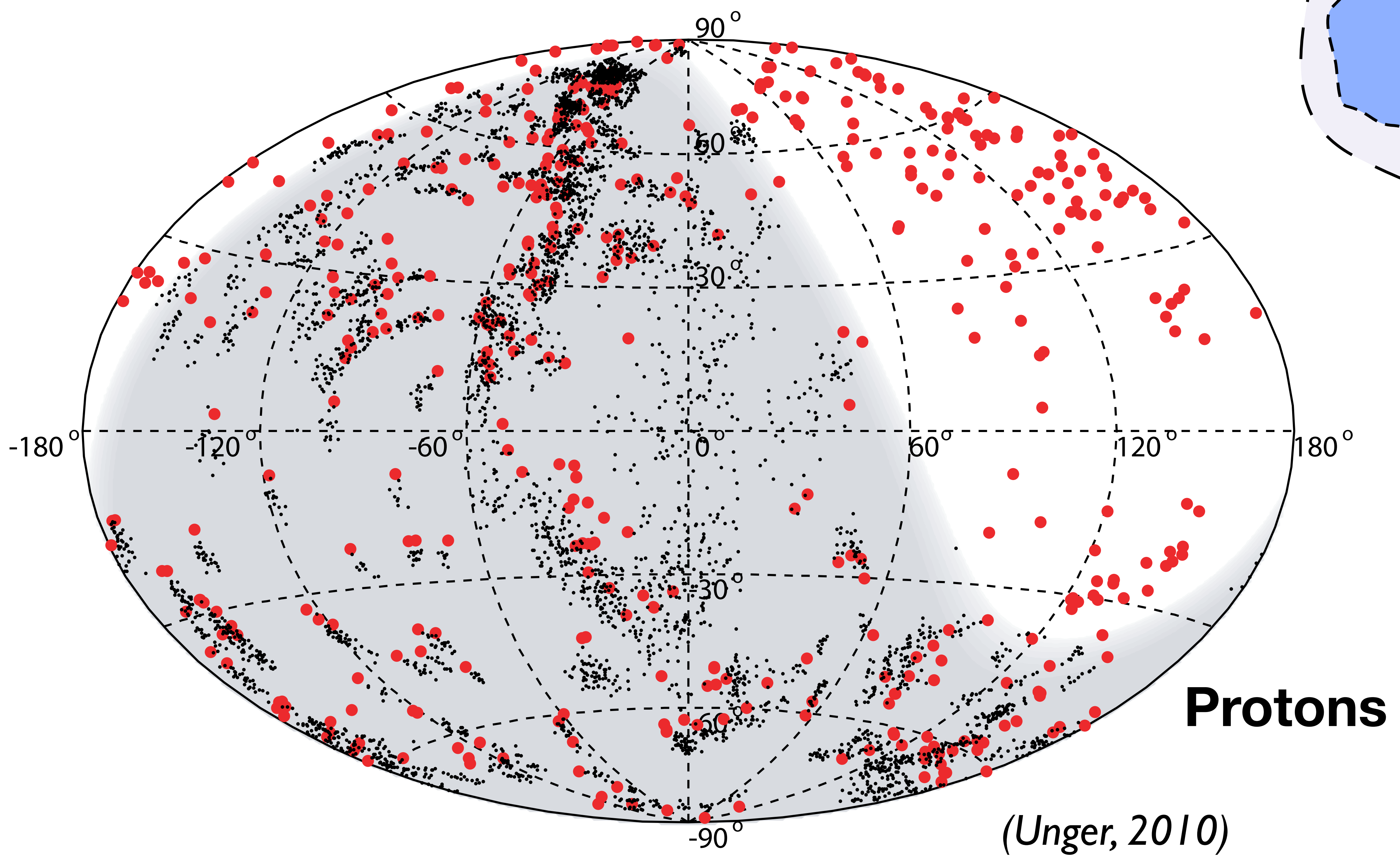


- Study of fundamental physics under extreme conditions such as space-time structure (LIV)
- Study of shower physics and hadronic interactions at extreme energies
- Multi-purpose applications: atmospheric physics, geophysics

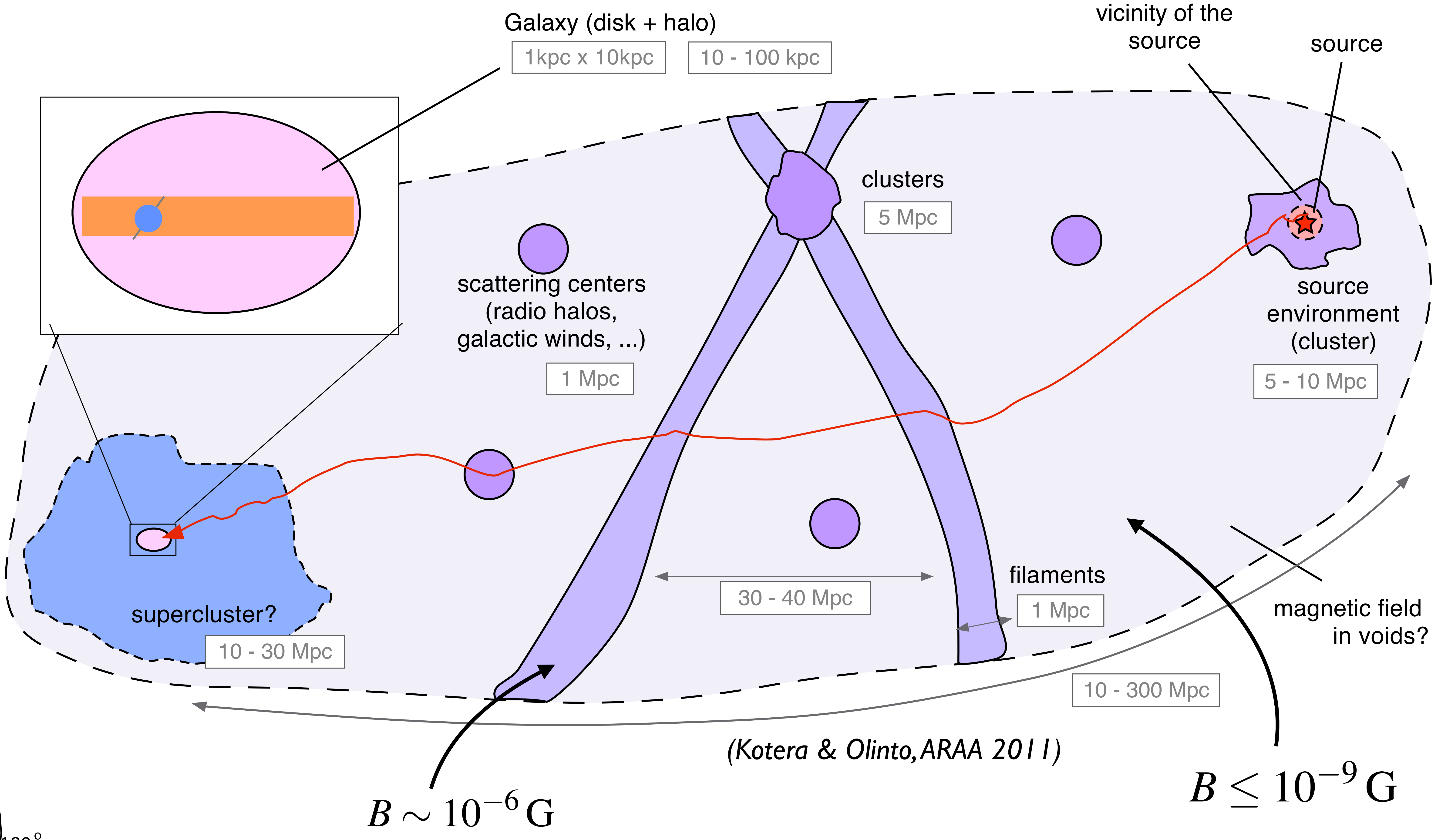
Source identification of UHECRs

Deflection in Galactic and extragalactic mag. fields

$$\delta \simeq 3^o \frac{B}{3\,\mu G} \frac{L}{kpc} \frac{6\times10^{19} eV}{E/Z}$$



(Unger, 2010)



(Kotera & Olinto, ARAA 2011)

Anisotropy in arrival direction distribution on small, intermediate and large scales

Multi-messenger signals (gamma-rays and neutrinos)

Source identification of UHECRs

Deflection in Galactic and extragalactic mag. fields

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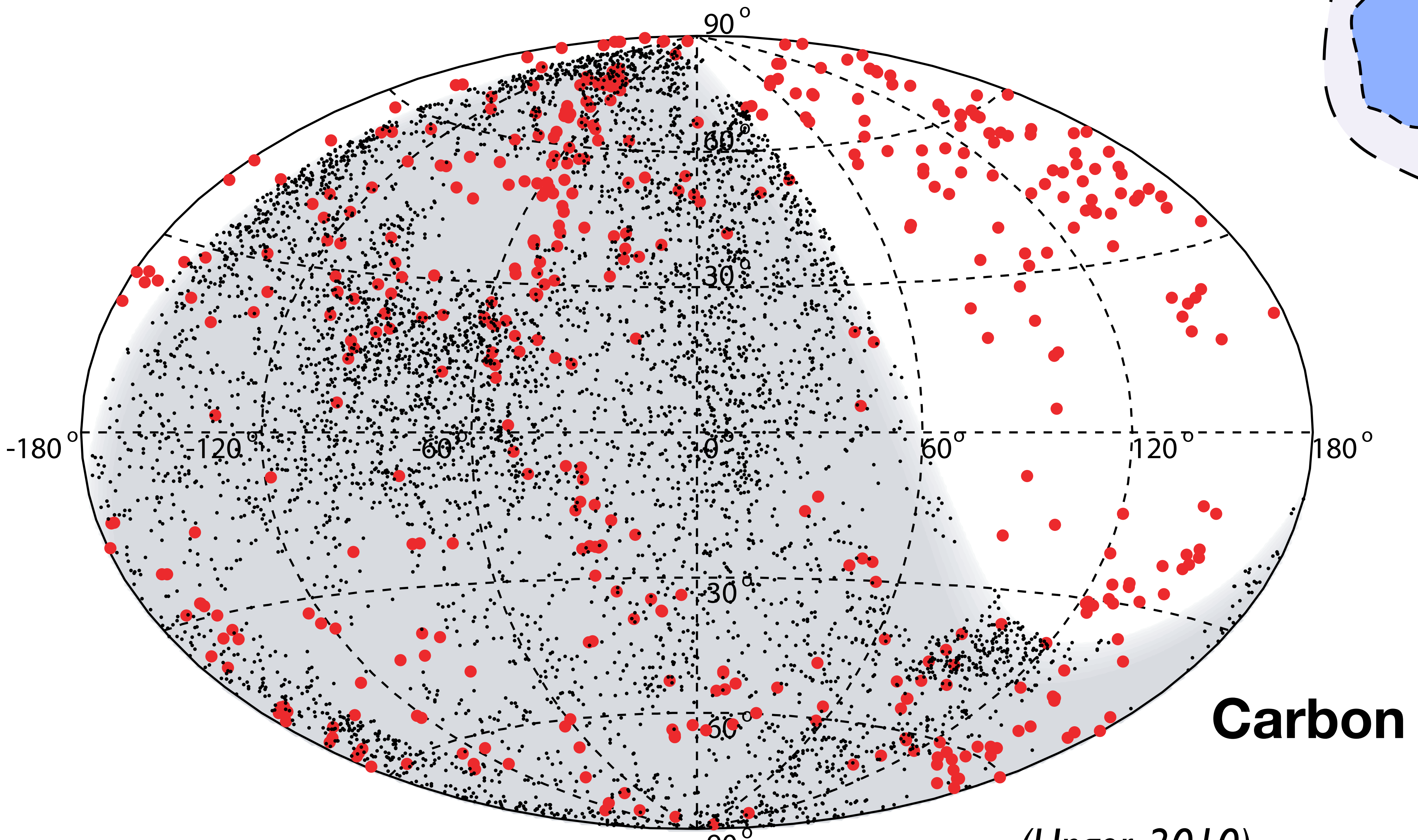

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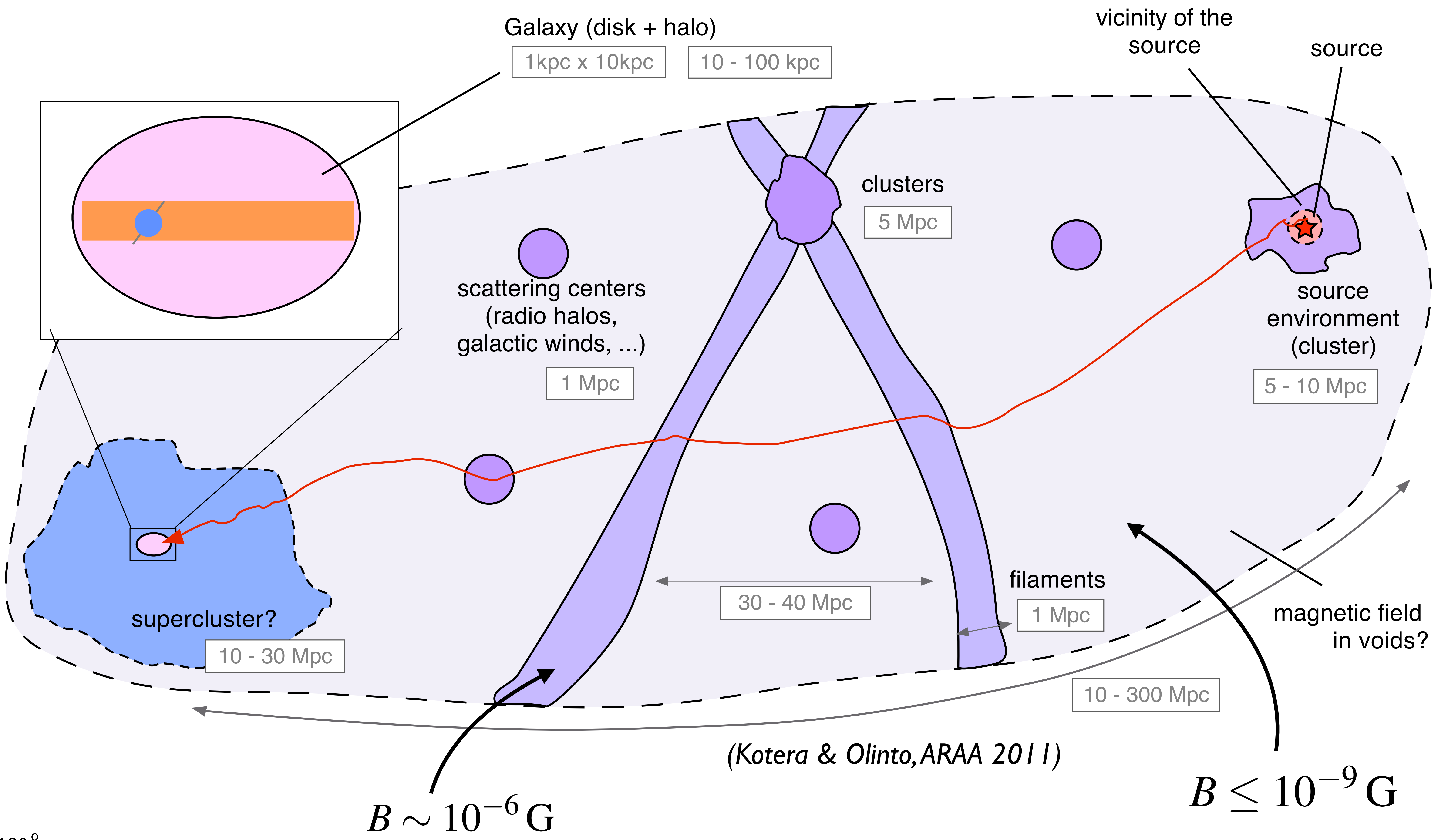

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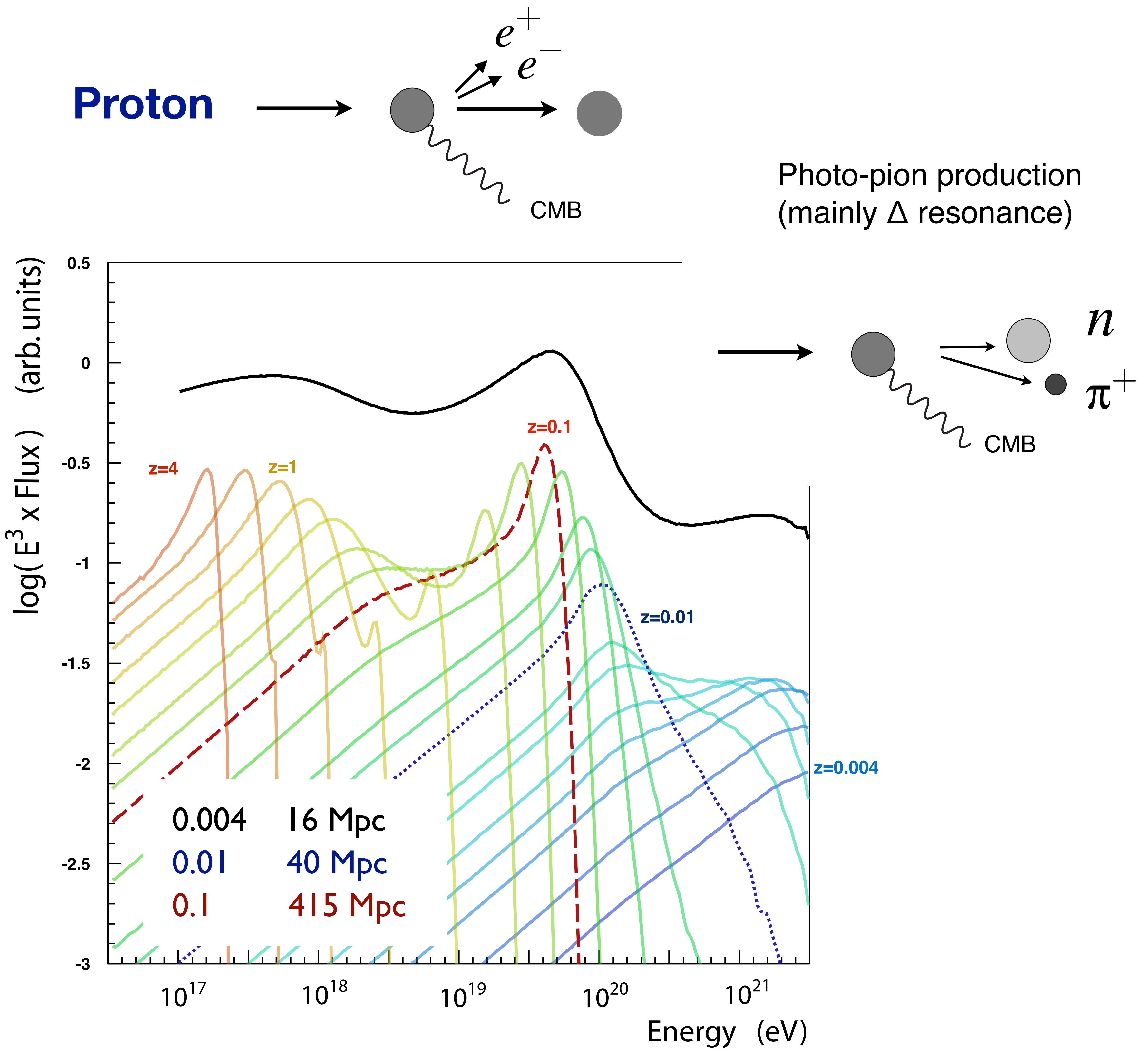
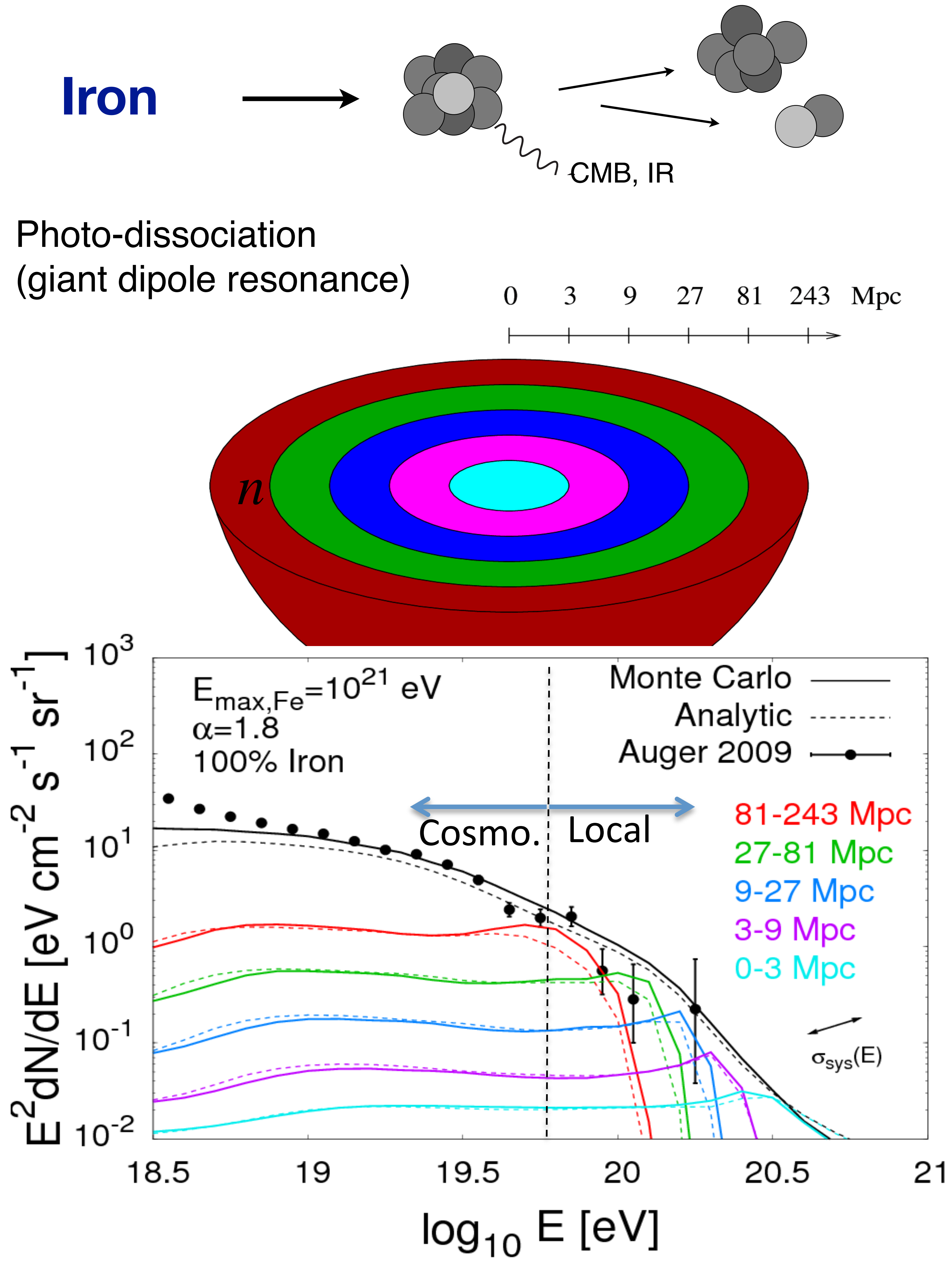
Anisotropy in arrival direction distribution on small, intermediate and large scales

Multi-messenger signals (gamma-rays and neutrinos)

Typical propagation distances and secondaries



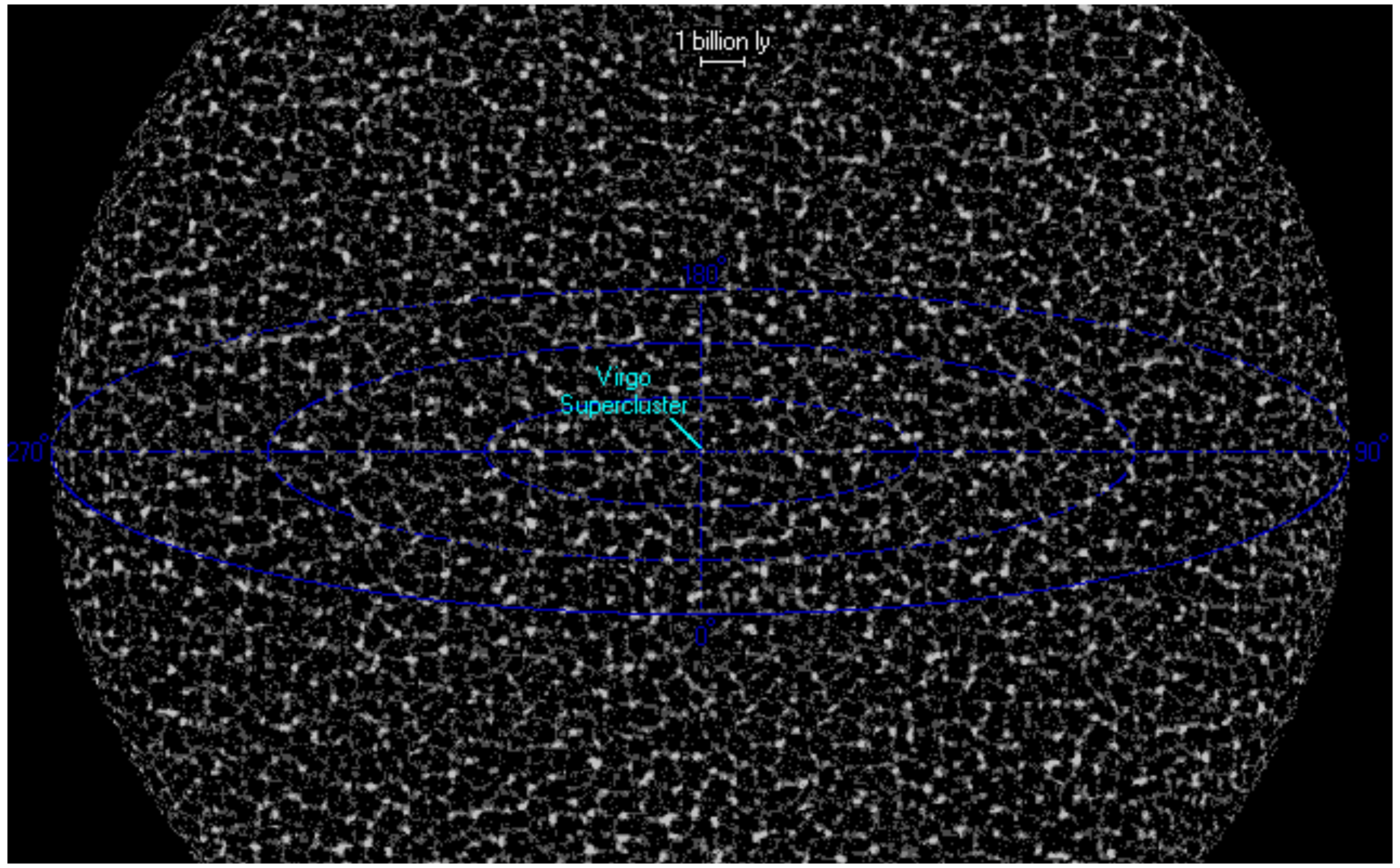
(Bergmann et al., PLB 2006)

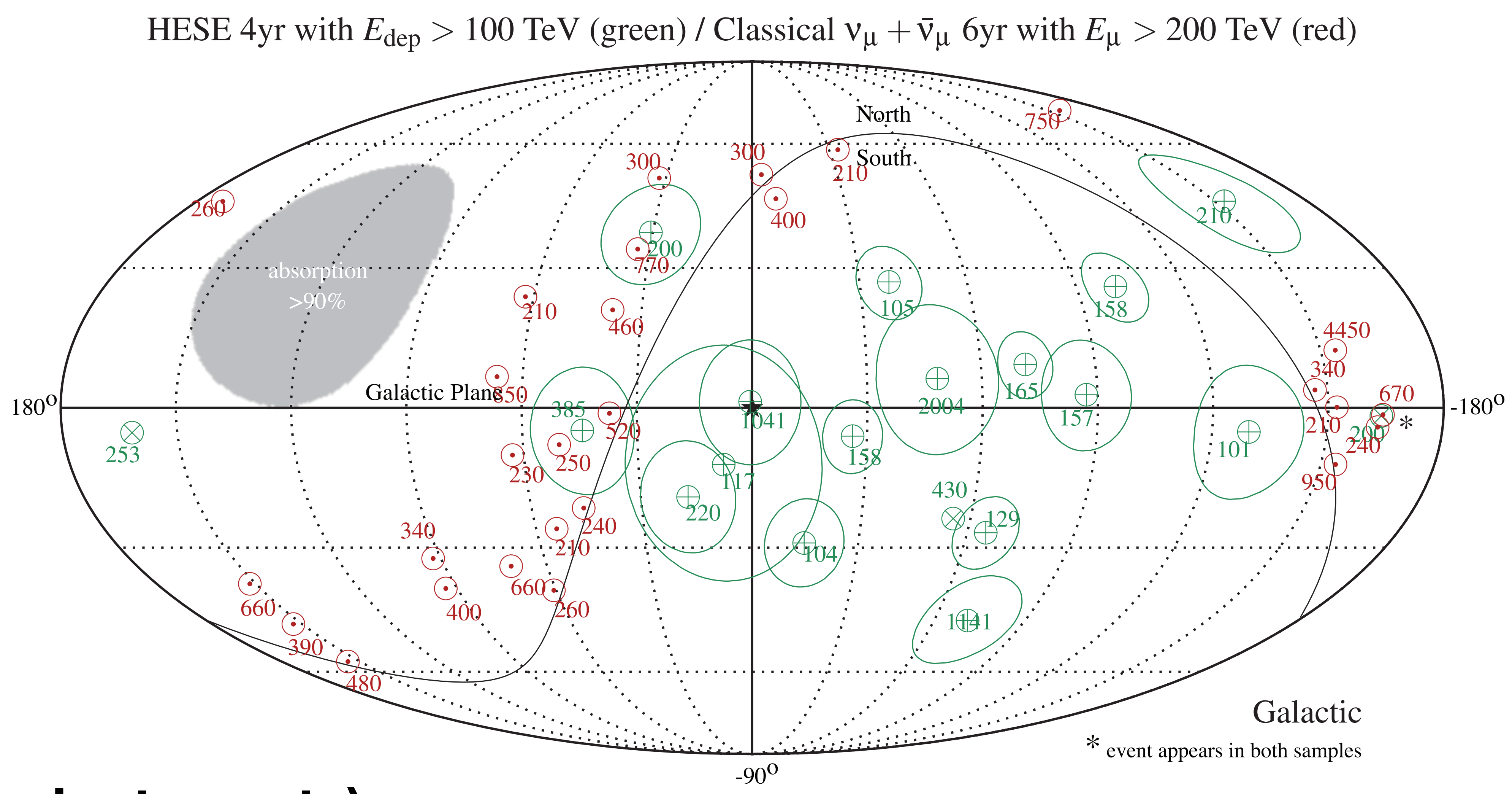


(Hooper, Taylor et al., PRD 2008)

Greisen-Zatsepin-Kuzmin (GZK) effect, 1966

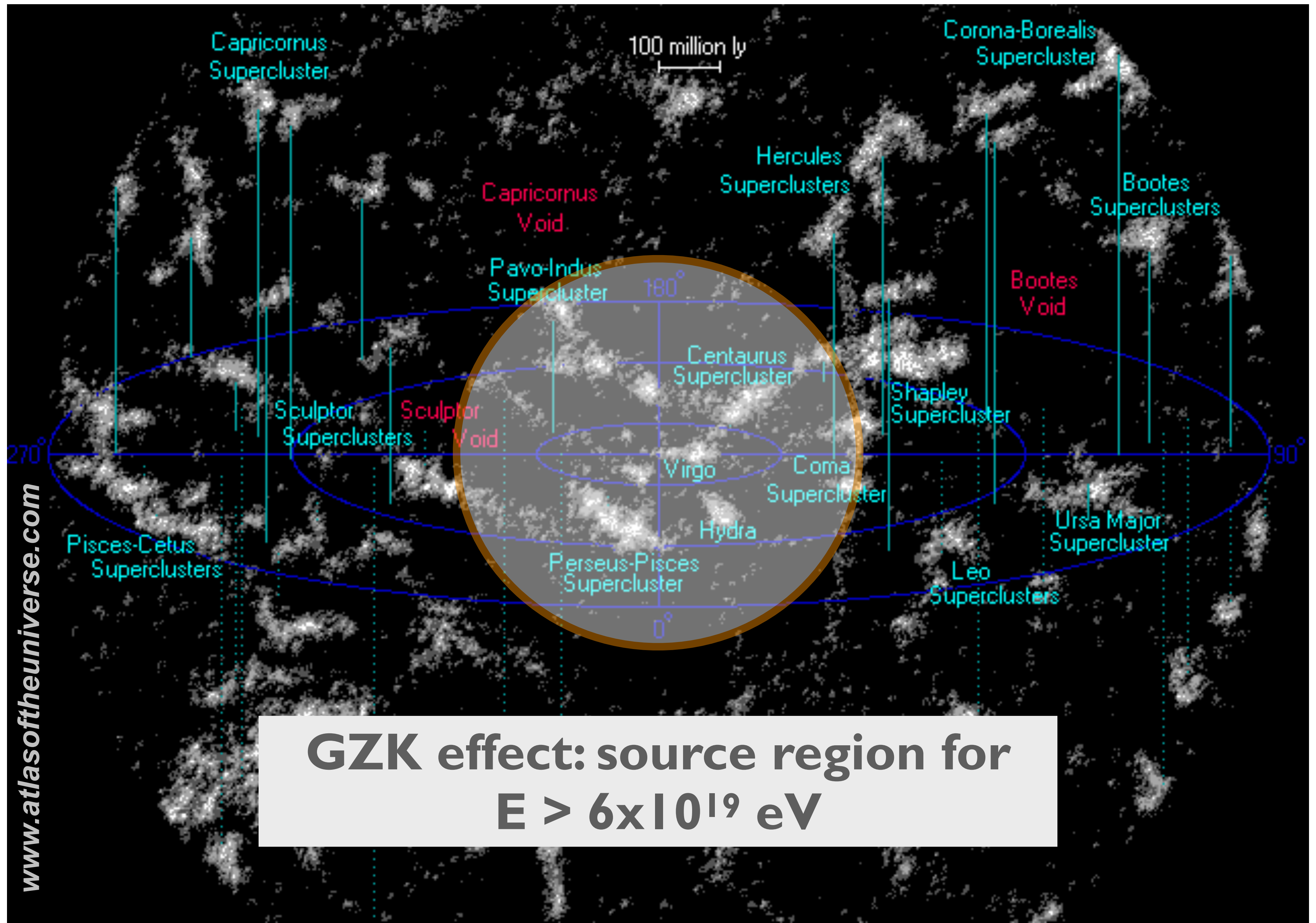
Complementarity of UHE cosmic rays and neutrinos

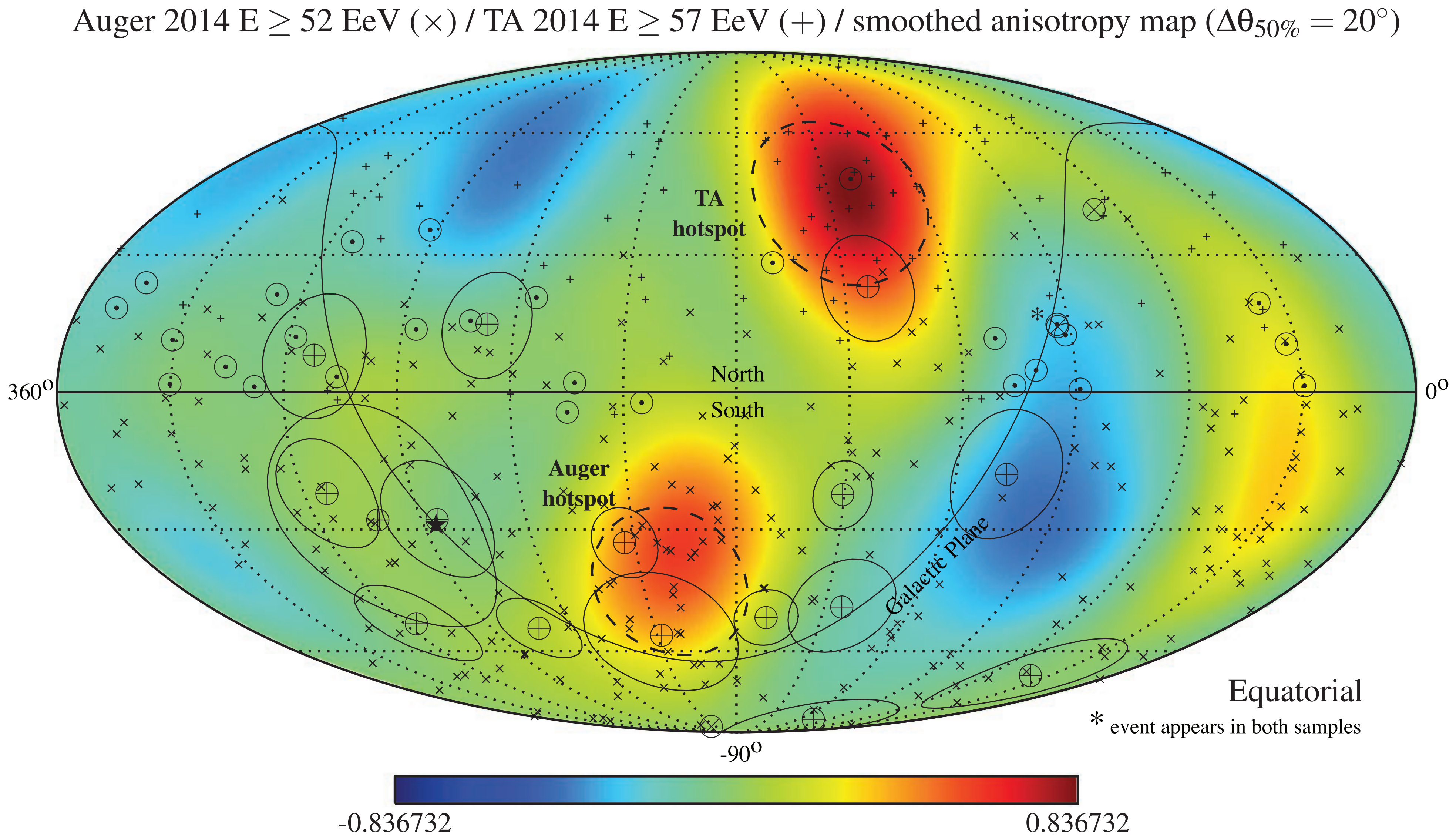




Neutrinos (transient events)

(Ahlers & Halzen, PTEP 2017)





Cosmic rays (back-tracking)

Baseline procedure to make progress

- Flux of particles
- Mass composition
- Arrival direction distribution
- Secondary particles and multi-messenger observations
- Air shower measurements

- Atmospheric phenomena and geophysics

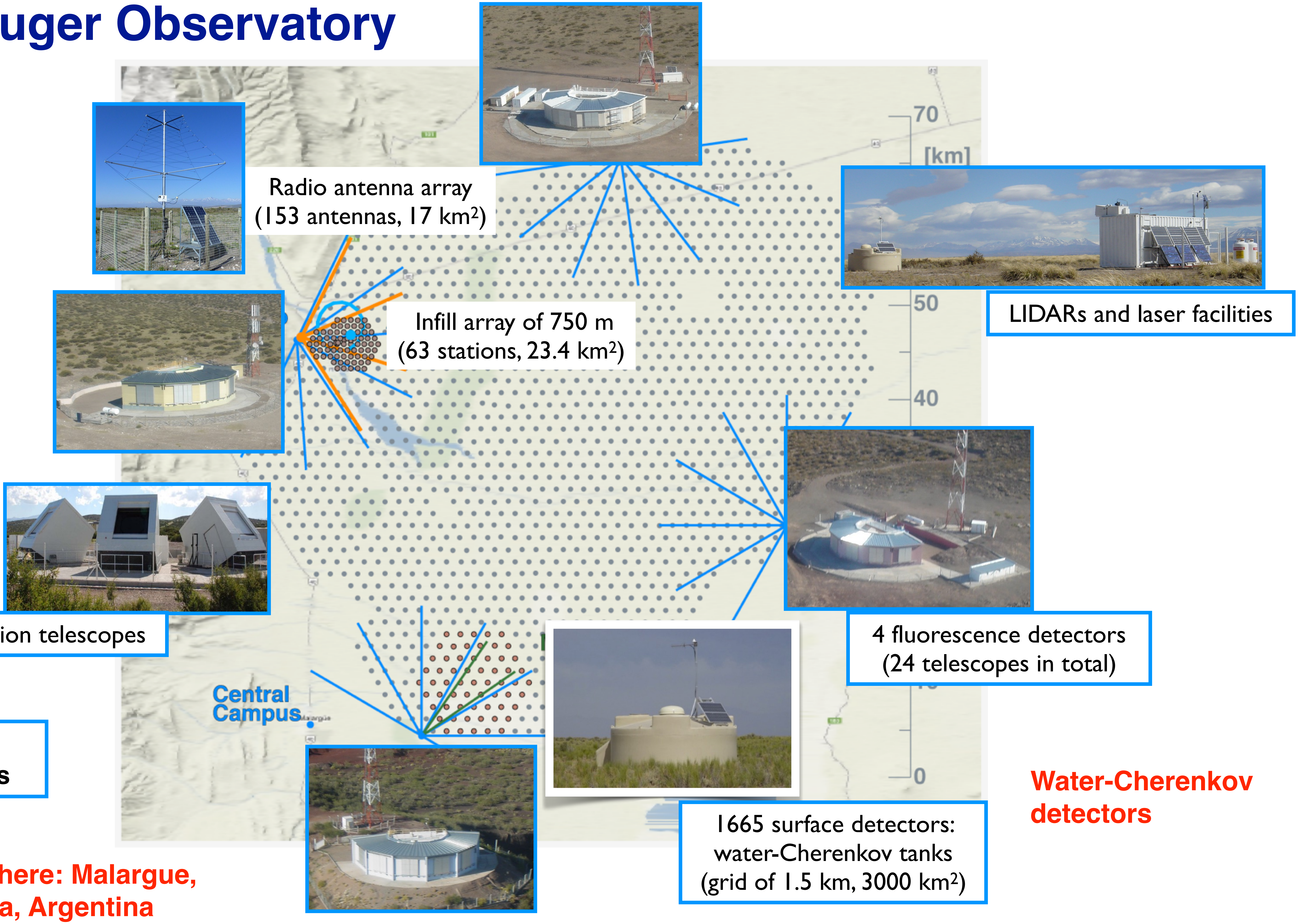
Theory
Model predictions

External input from
astro and particle physics

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

The Pierre Auger Observatory

Pierre Auger Observatory
Province Mendoza, Argentina



More than 400 members,
98 institutes, 17 countries

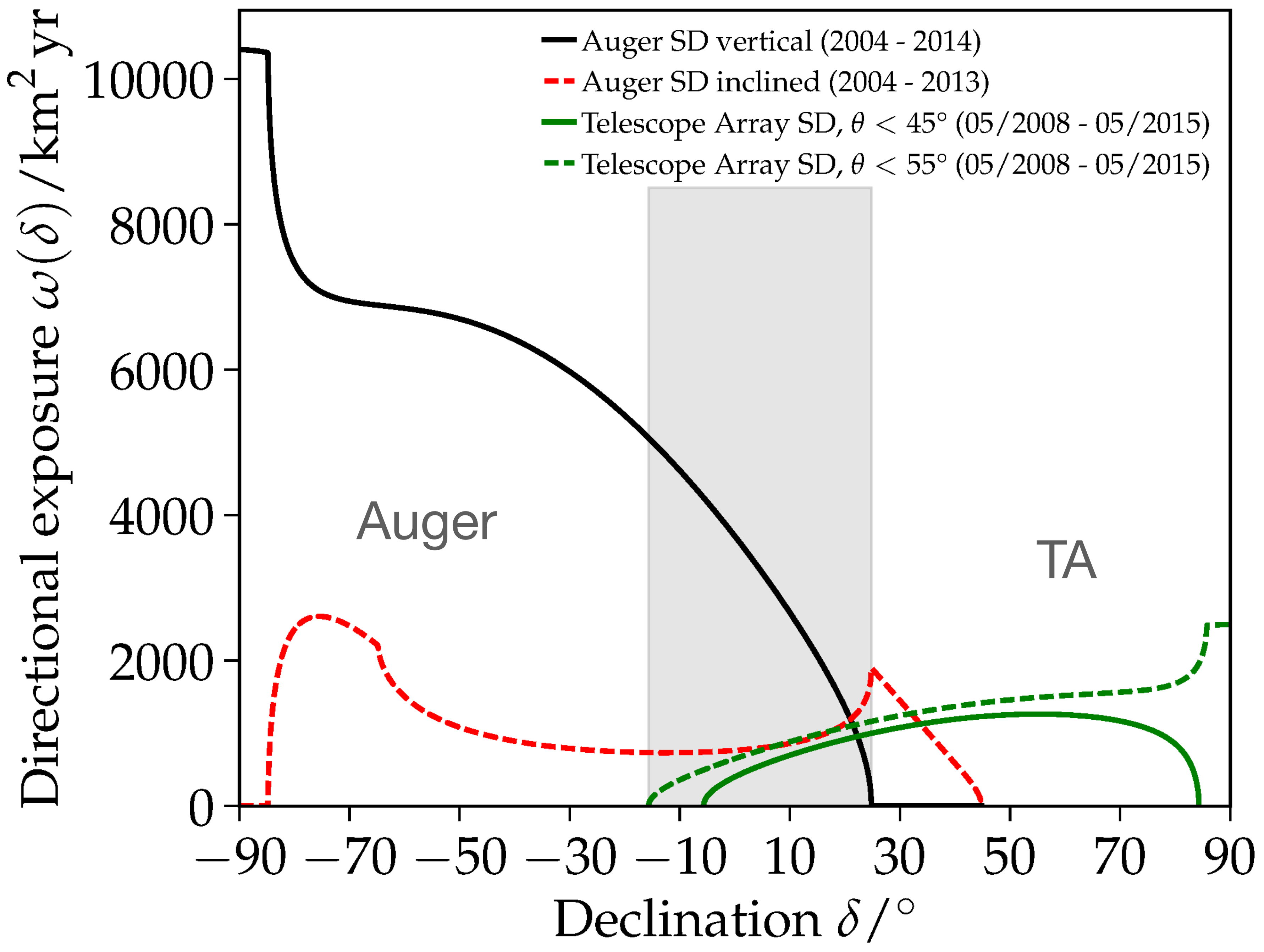
Water-Cherenkov detectors

Southern hemisphere: Malargue, Province Mendoza, Argentina

Pierre Auger Observatory and Telescope Array

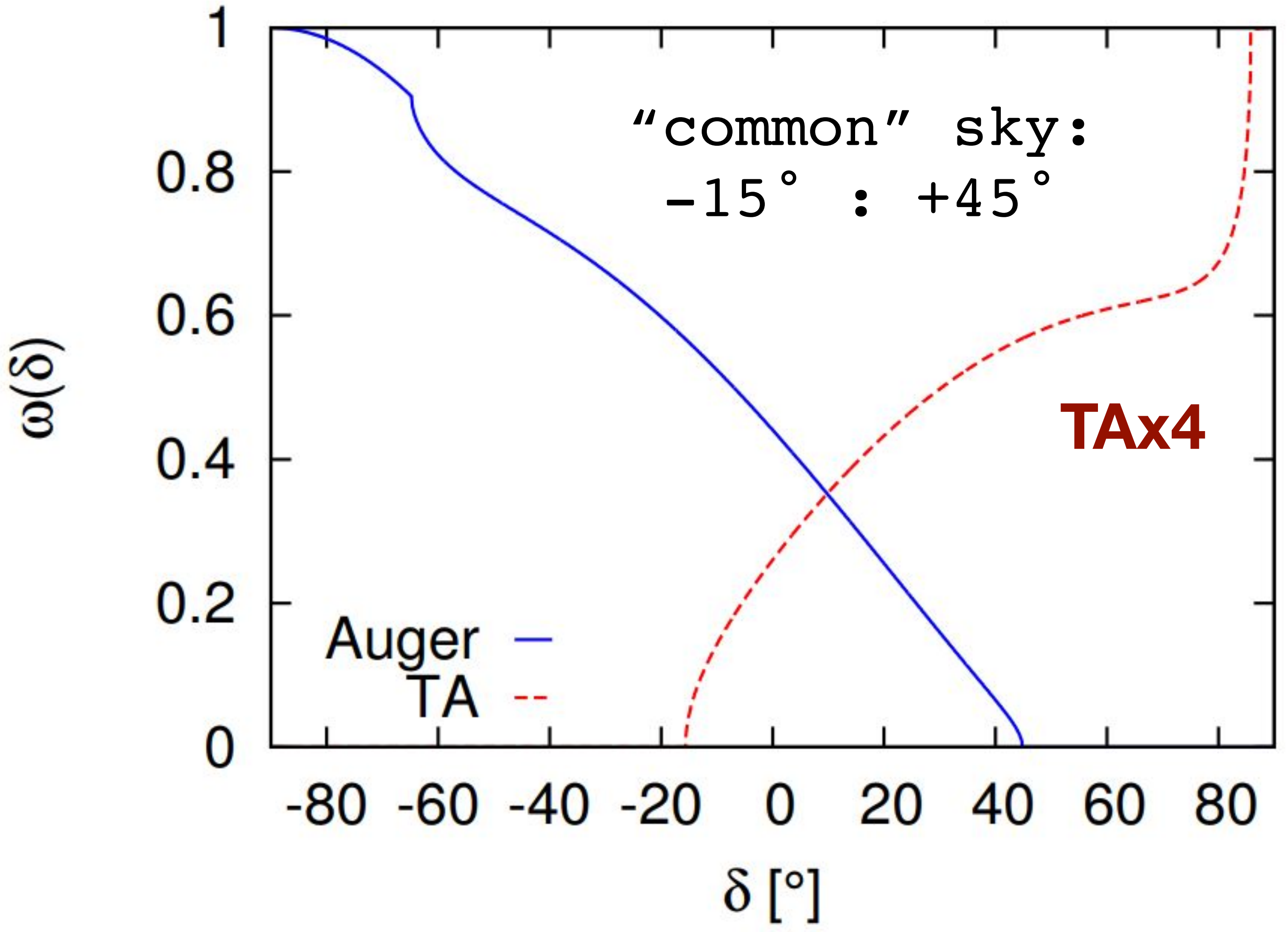
Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km^2
36 fluorescence telescopes

Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km^2
27 fluorescence telescopes

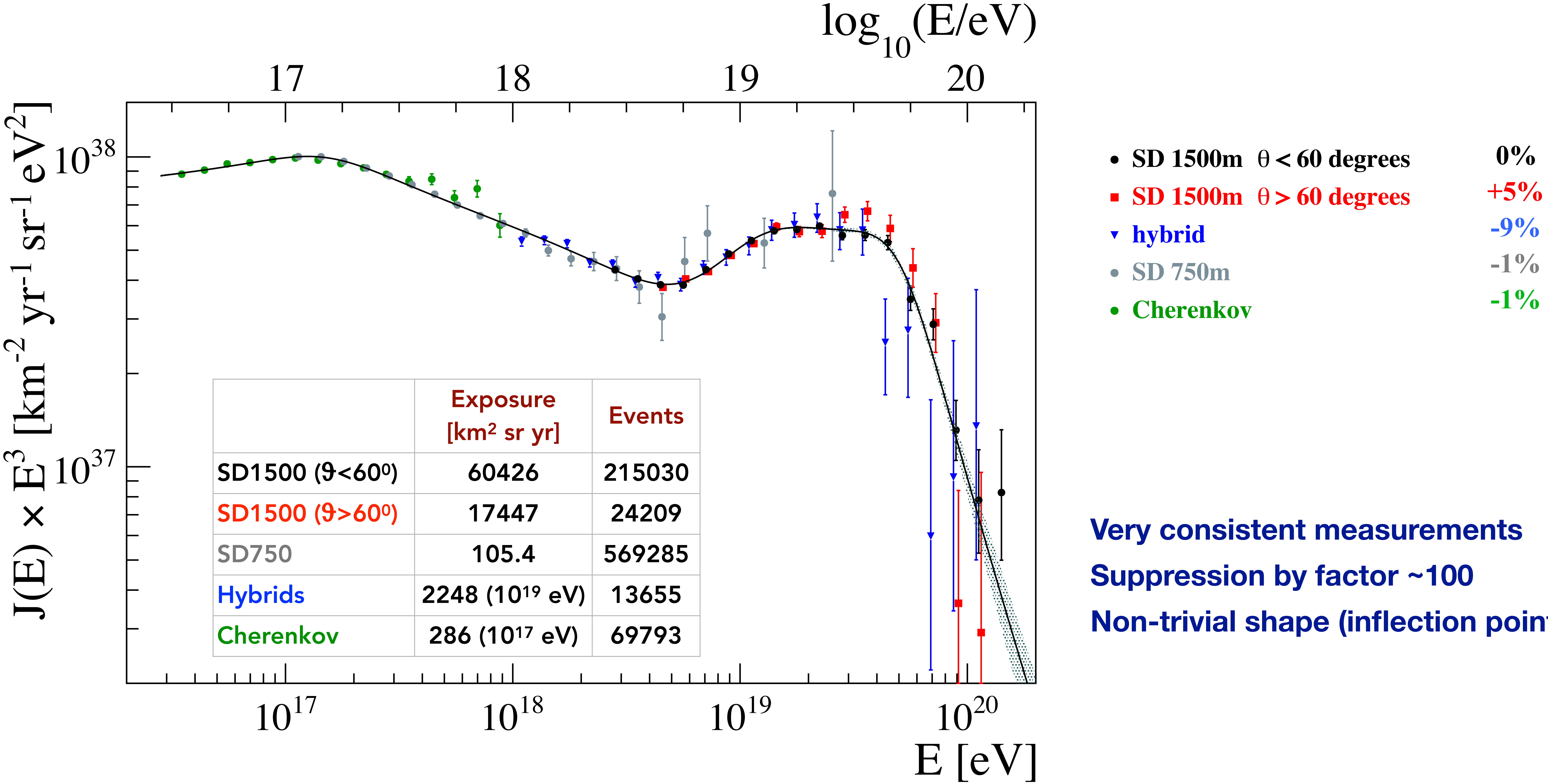


Together full sky coverage,
but exposures **1:8 – 1:6**

Overlap region can be used for cross-checks and cross-calibration



1. Energy spectrum – Auger results



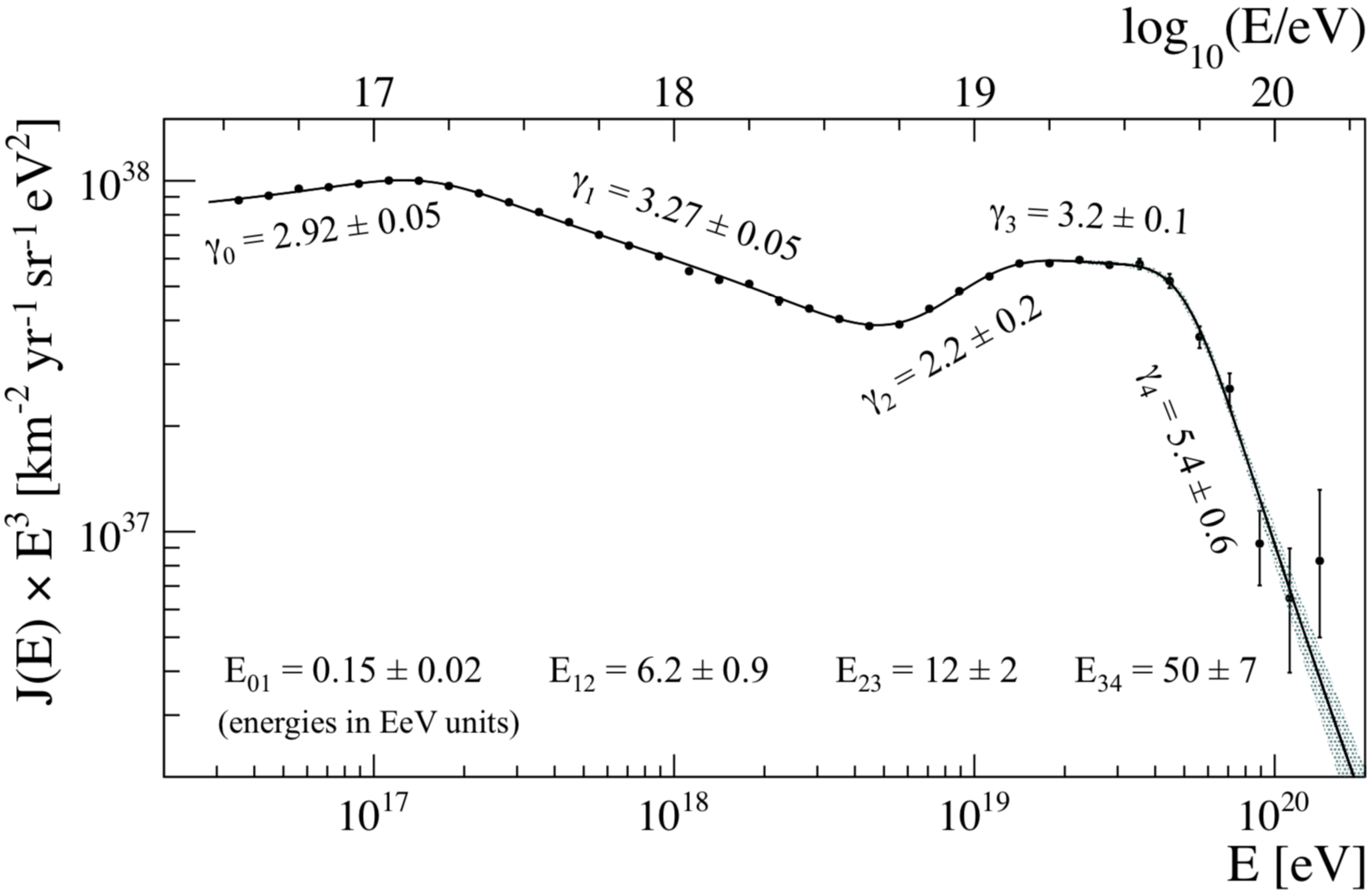
	Exposure [km² sr yr]	Events
SD1500 (ϑ<60⁰)	60426	215030
SD1500 (ϑ>60⁰)	17447	24209
SD750	105.4	569285
Hybrids	2248 (10^{19} eV)	13655
Cherenkov	286 (10^{17} eV)	69793

Very consistent measurements

Suppression by factor ~100

Non-trivial shape (inflection point)

Combined energy spectrum



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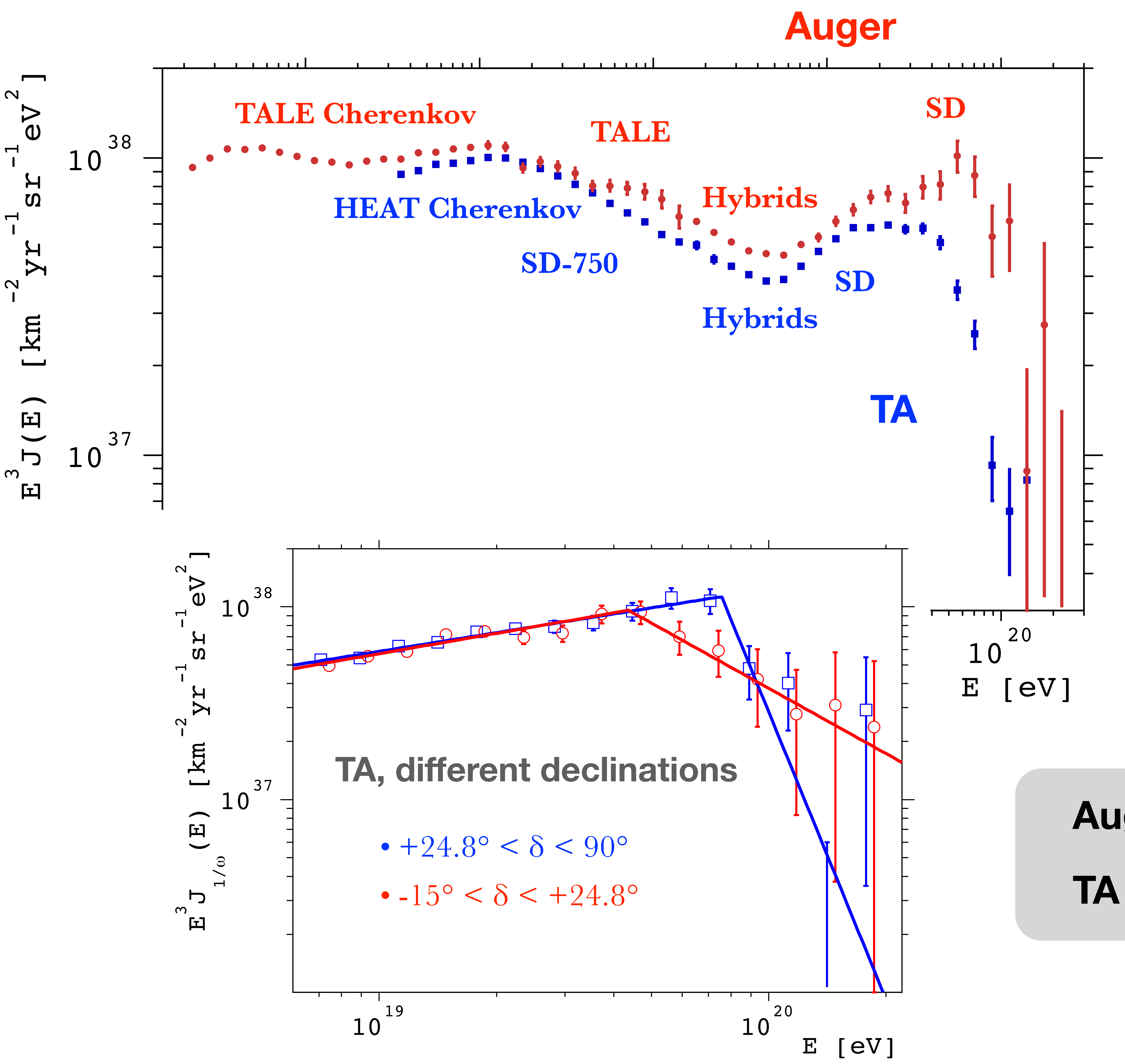
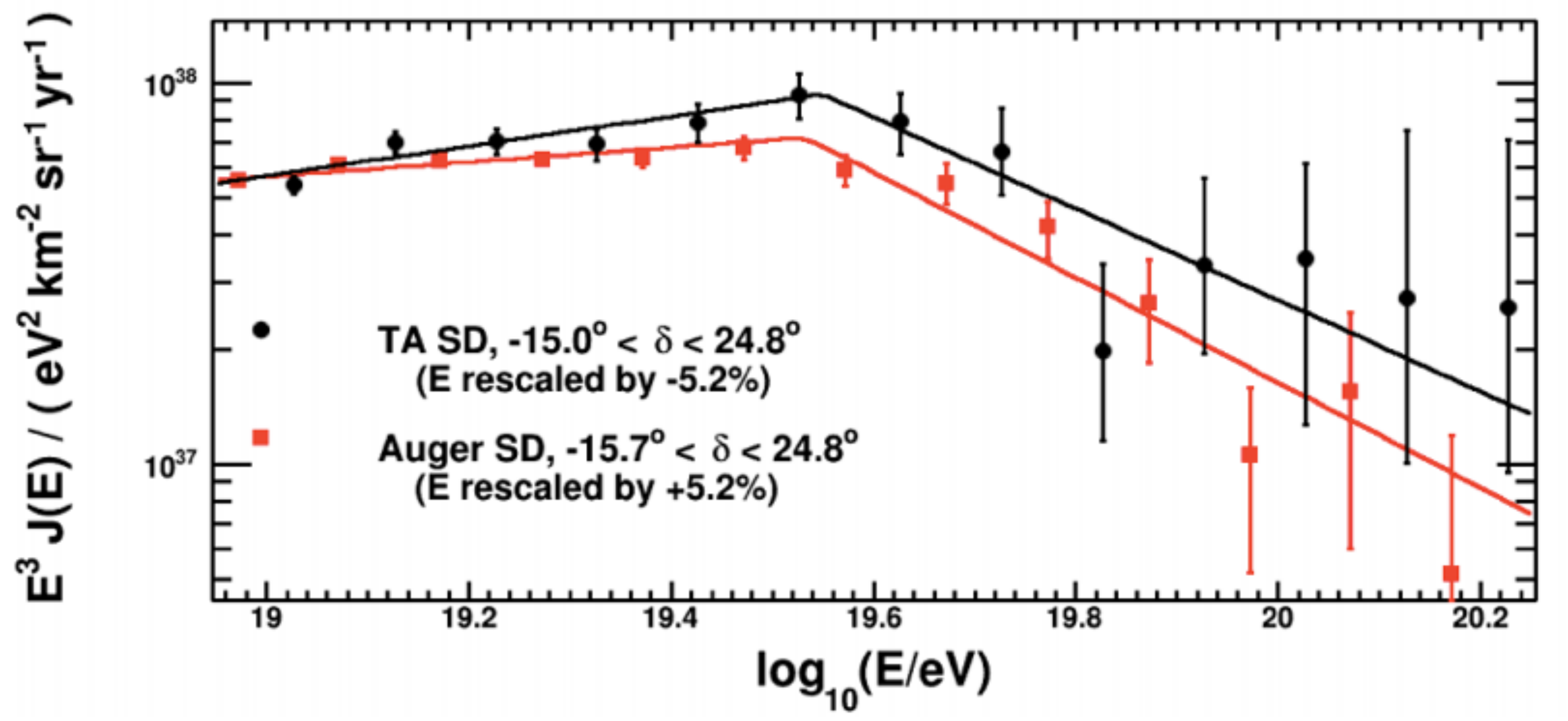
Stat. uncertainty very small

Sys. uncertainty dominating

Comparison of energy spectra of Auger and TA



Spectrum in common declination band

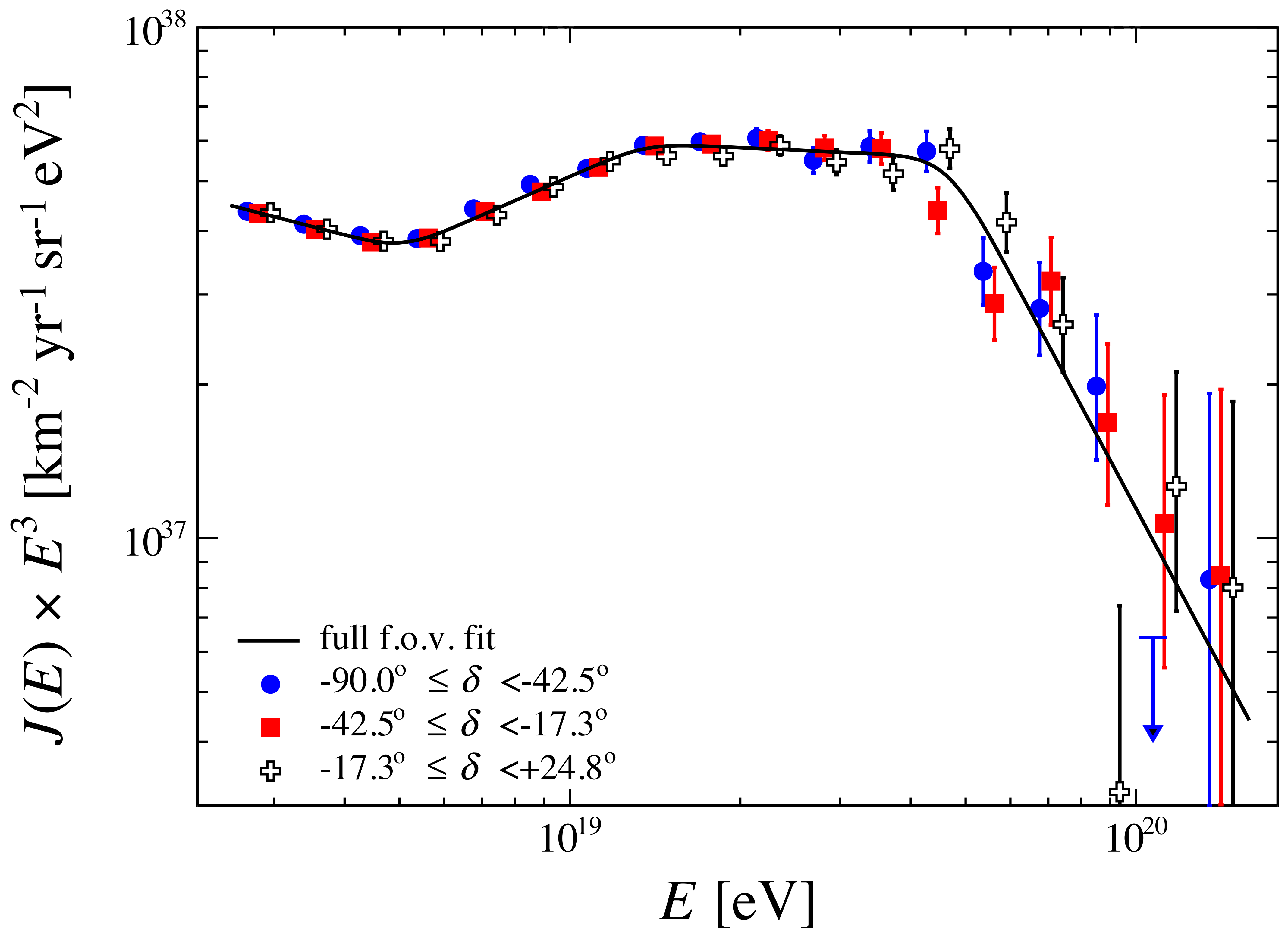


Smaller but systematic differences

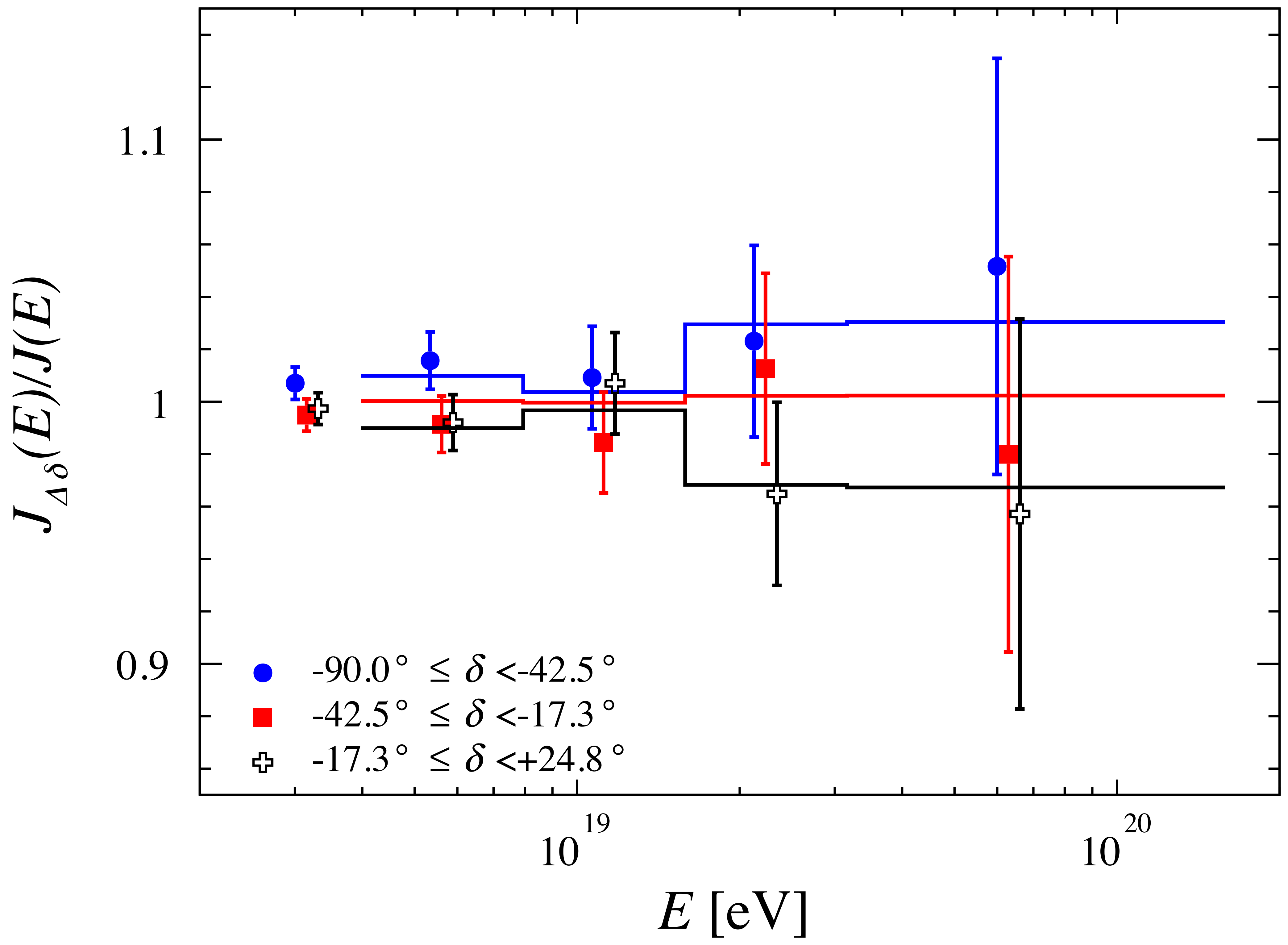
Auger	$\Delta E/E = 14\%$
TA	$\Delta E/E = 21\%$

(Auger-TA Spectrum Working Group ICRC 2019 & TA, arXiv:1801.07820)

Declination dependence in range accessible by Auger



Lines: expectation according to dipole

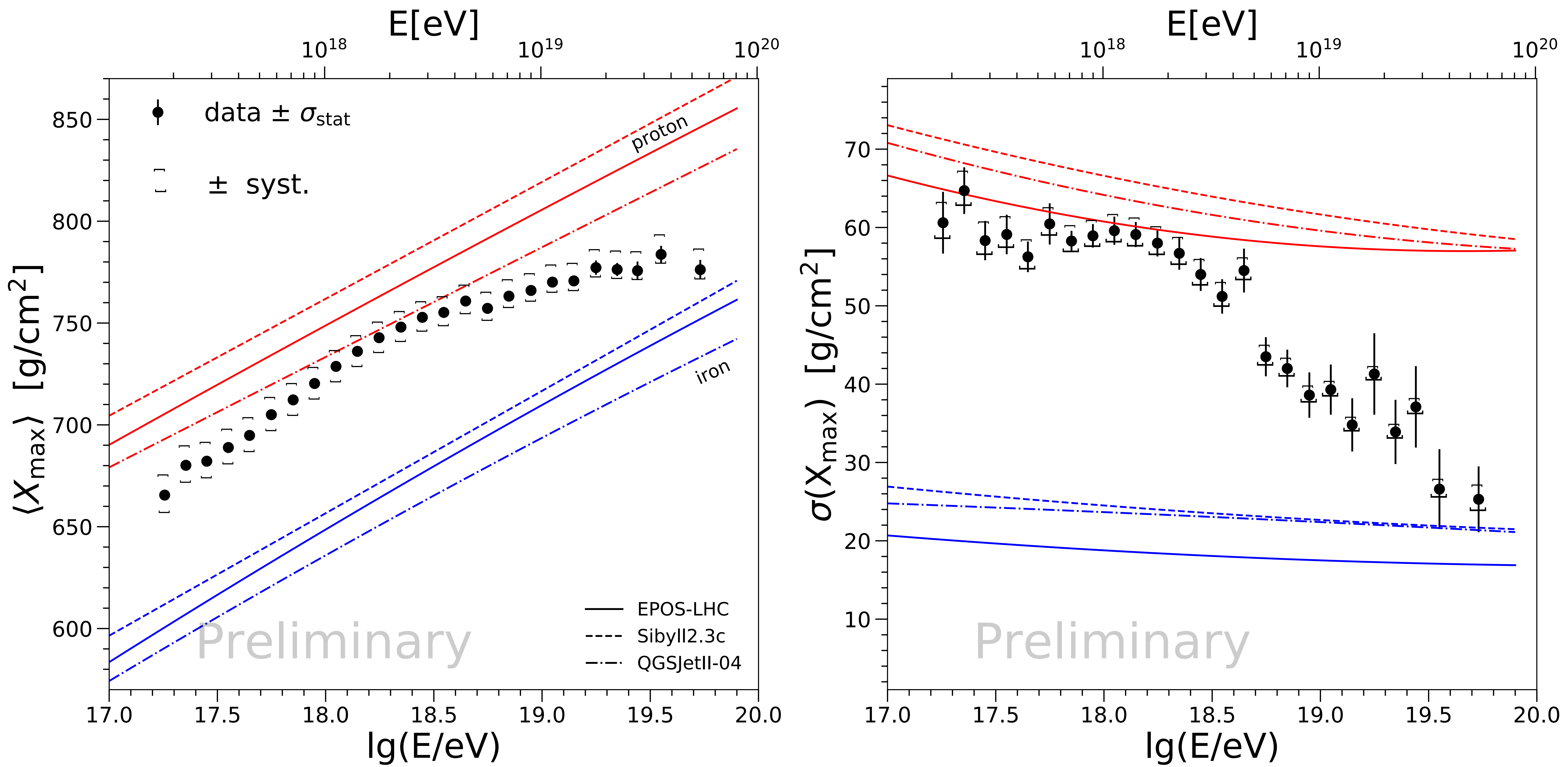


Declination dependence also seen in Auger data, but much smaller

Imprint of differences of local source distribution?

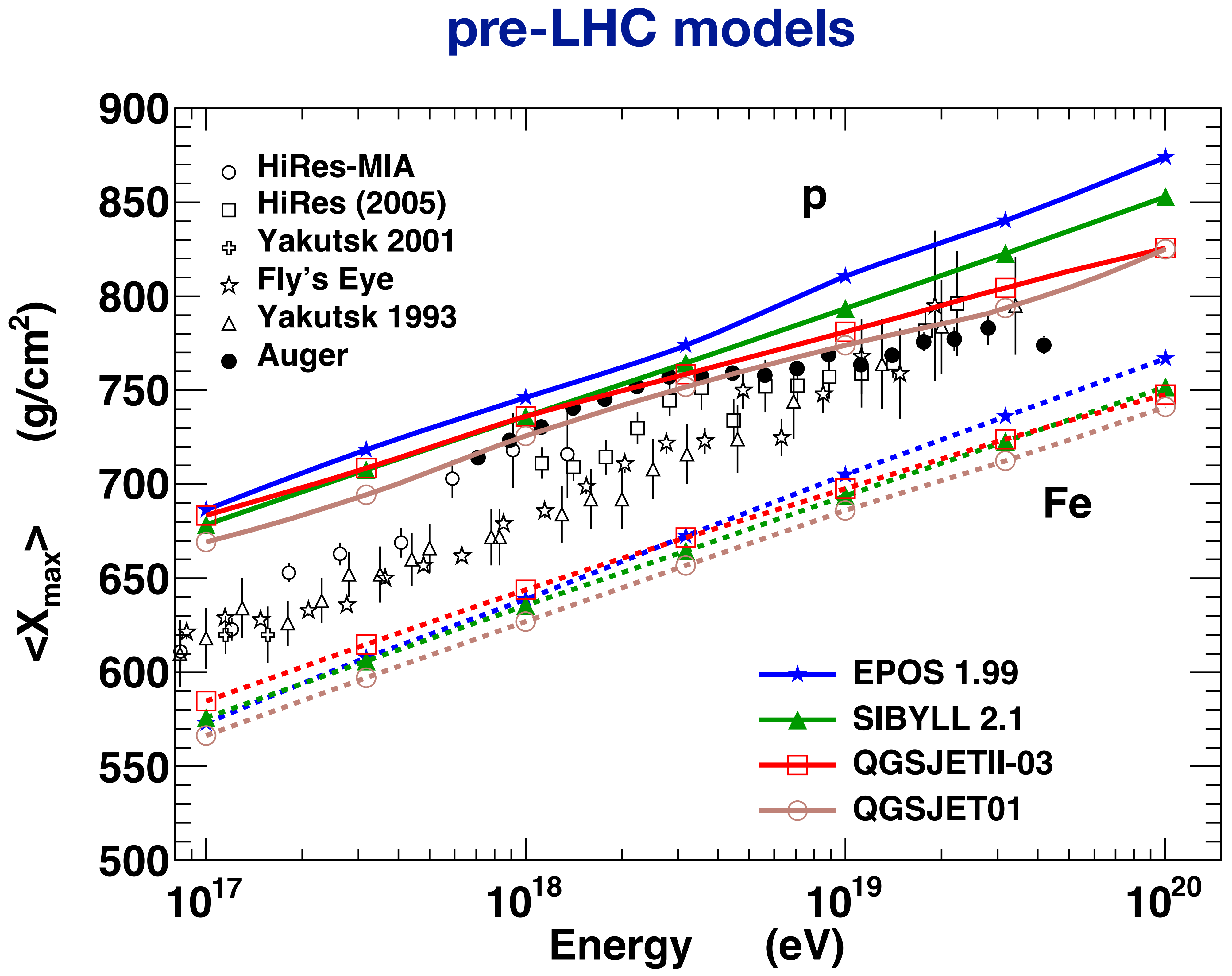
(Auger, Phys. Rev. Lett. 125 (2020) 121106 & Phys. Rev. D. 102 (2020) 062005)

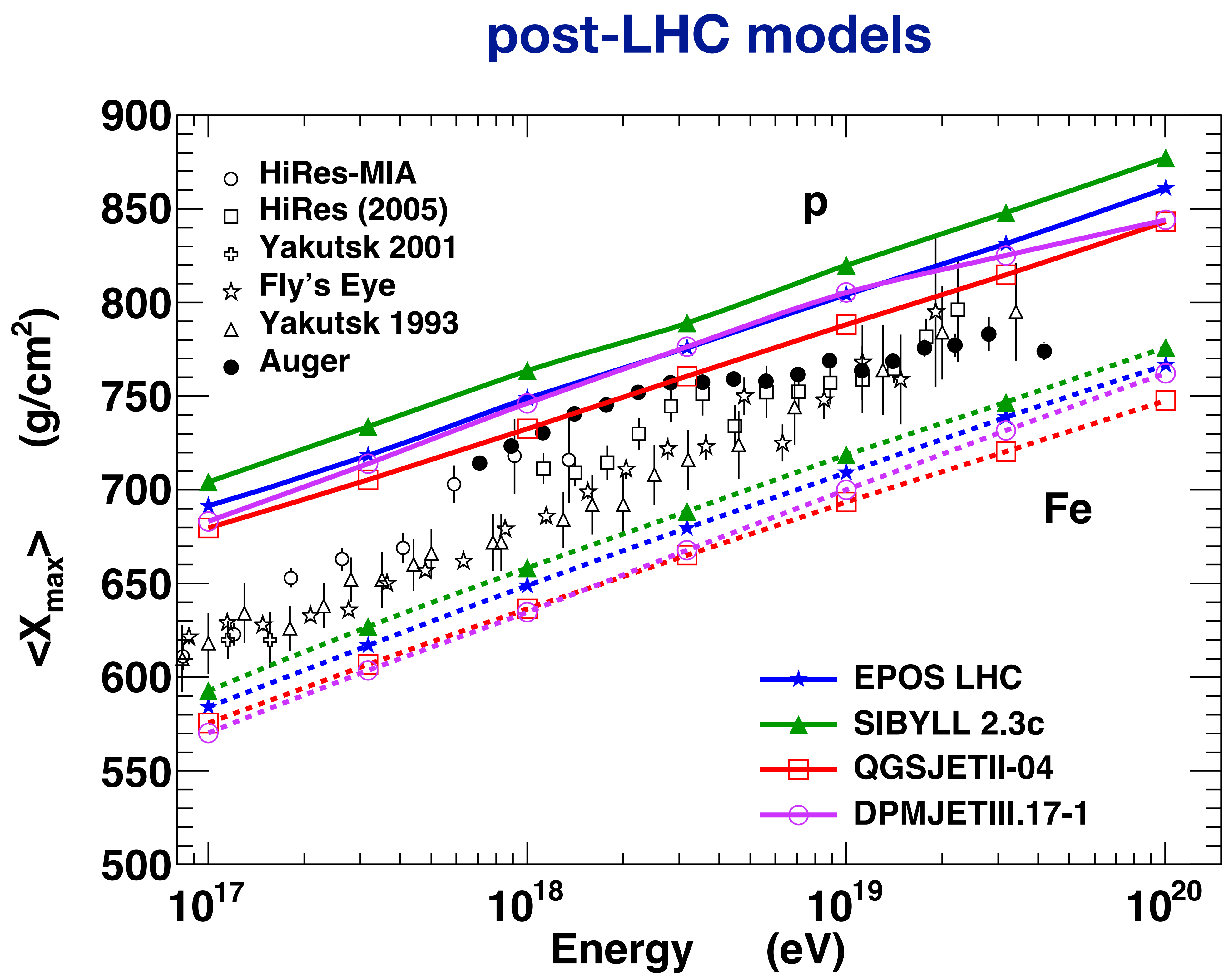
2. Mass composition – Auger fluorescence data



(Auger ICRC 2019)

Change of model predictions thanks to LHC data





(Pierog, ICRC 2017)

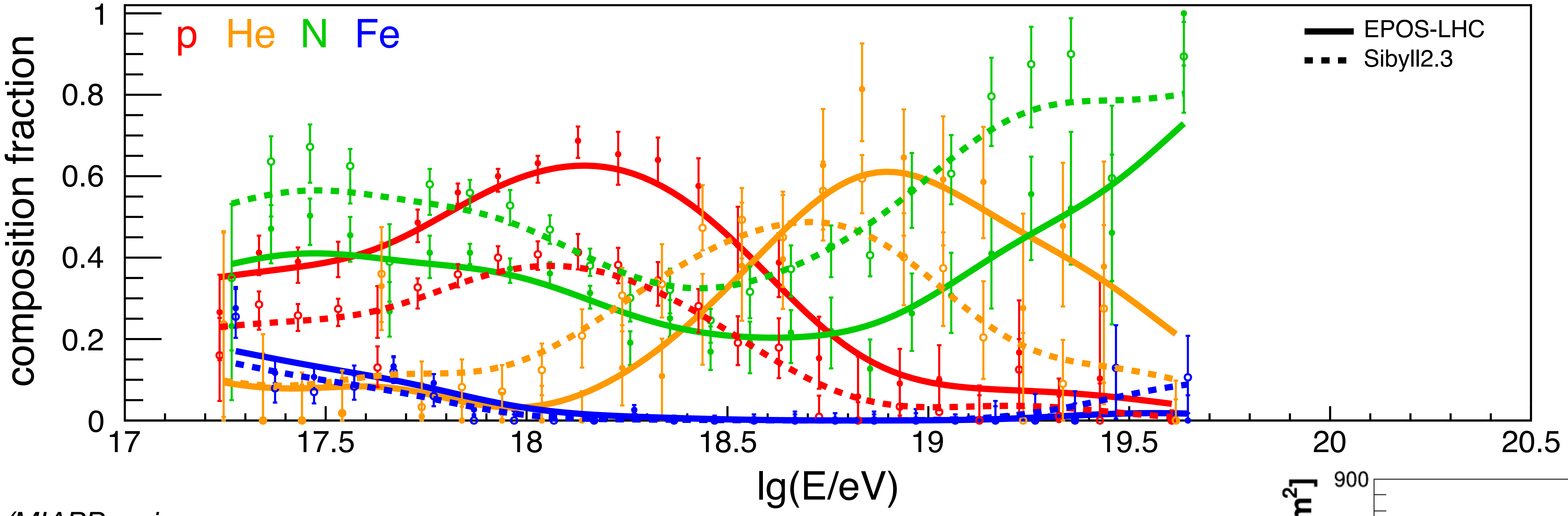
Sys. X_{max} uncertainty Auger: $\Delta X_{\rm max} = -10\,{\rm g/cm^2}\ +8\,{\rm g/cm^2}$

TA: $\Delta X_{\rm max} = \pm 20\,{\rm g/cm^2}$

LHC-tuned models should be used for data interpretation

(see also discussion Lipari, Phys.Rev.D 103 (2021) 103009)

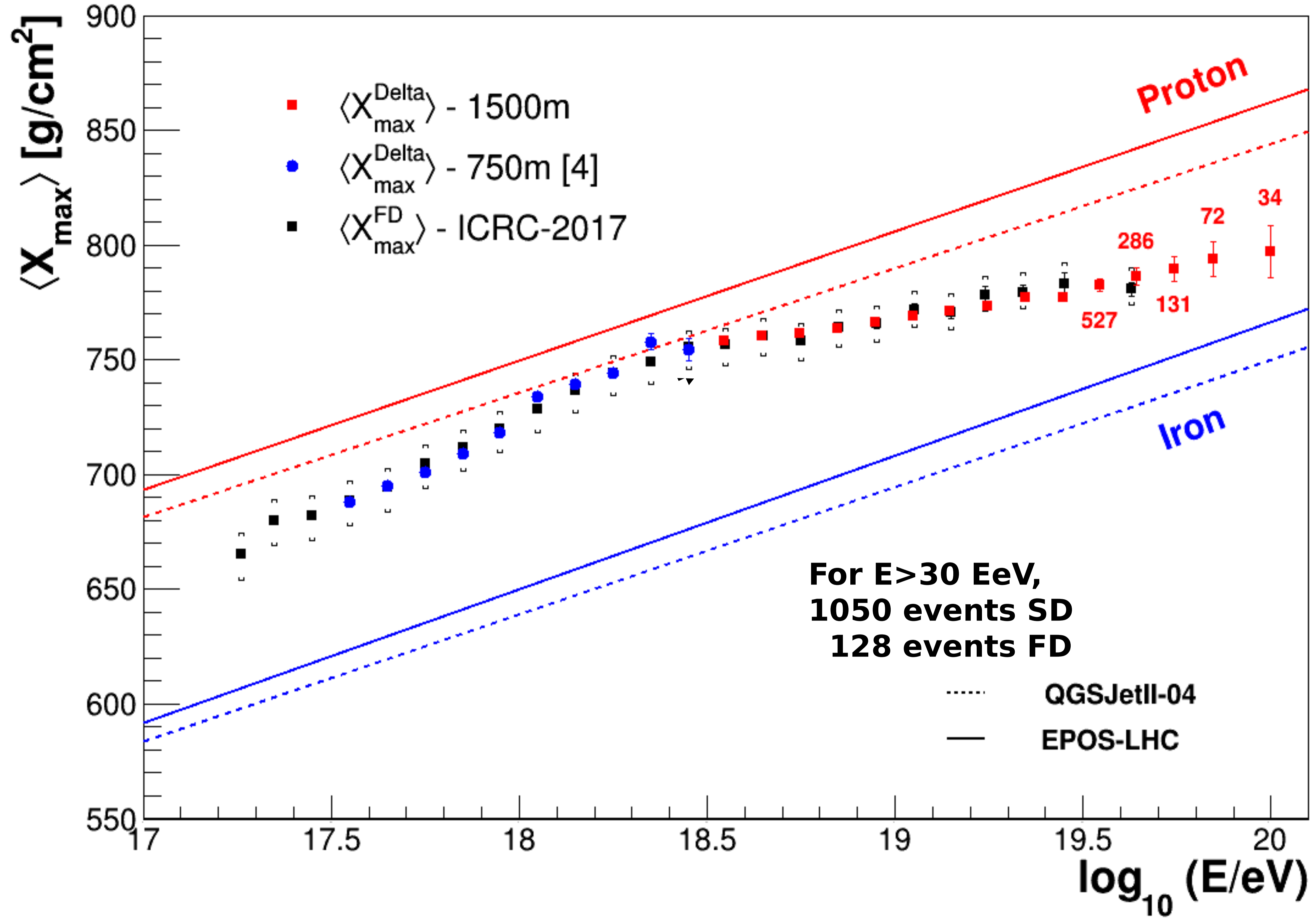
Mass composition – data analysis



(MIAPP review,
Front. Astron. Space Sci. 2019)

$\log_{10}$(E/eV)	SD
18.5-18.6	45872
18.6-18.7	27783
18.7-18.8	17011
18.8-18.9	11631
18.9-19.0	7960
19.0-19.1	5489
19.1-19.2	3582
19.2-19.3	2290
19.3-19.4	1473
19.4-19.5	864
19.5-19.6	527
19.6-19.7	286
19.7-19.8	131
19.8-19.9	72
>19.9	34
Total	125005

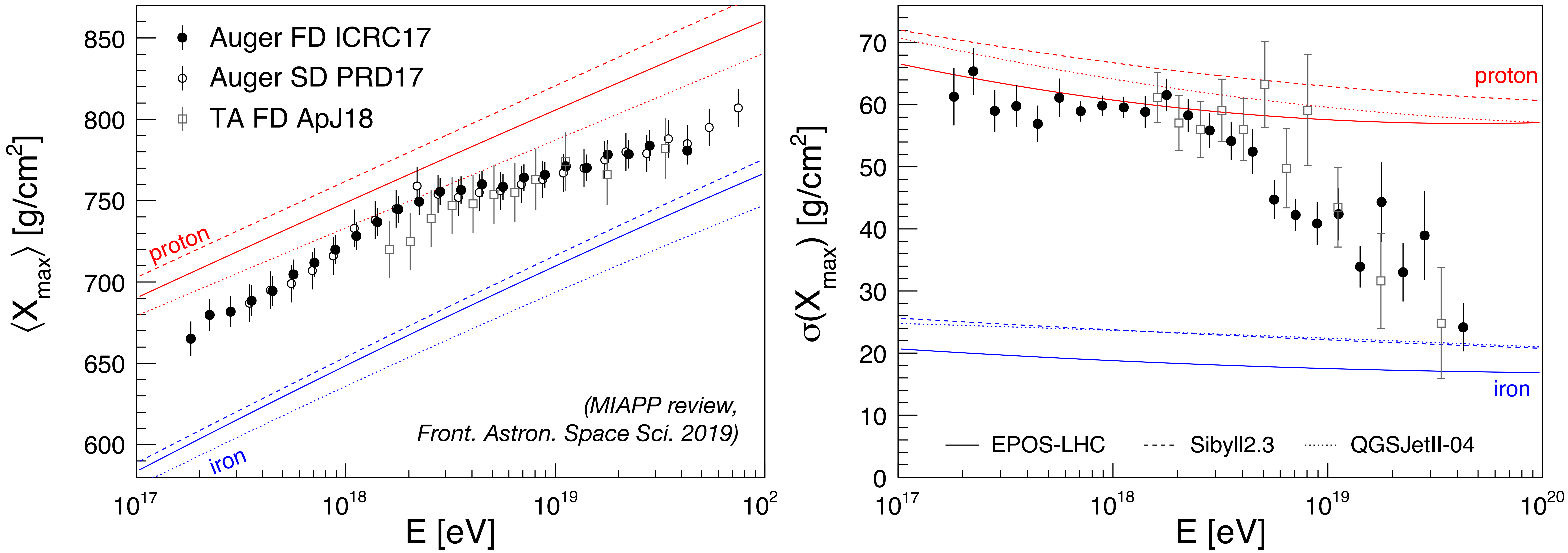
Surprising pattern of changes in mass composition

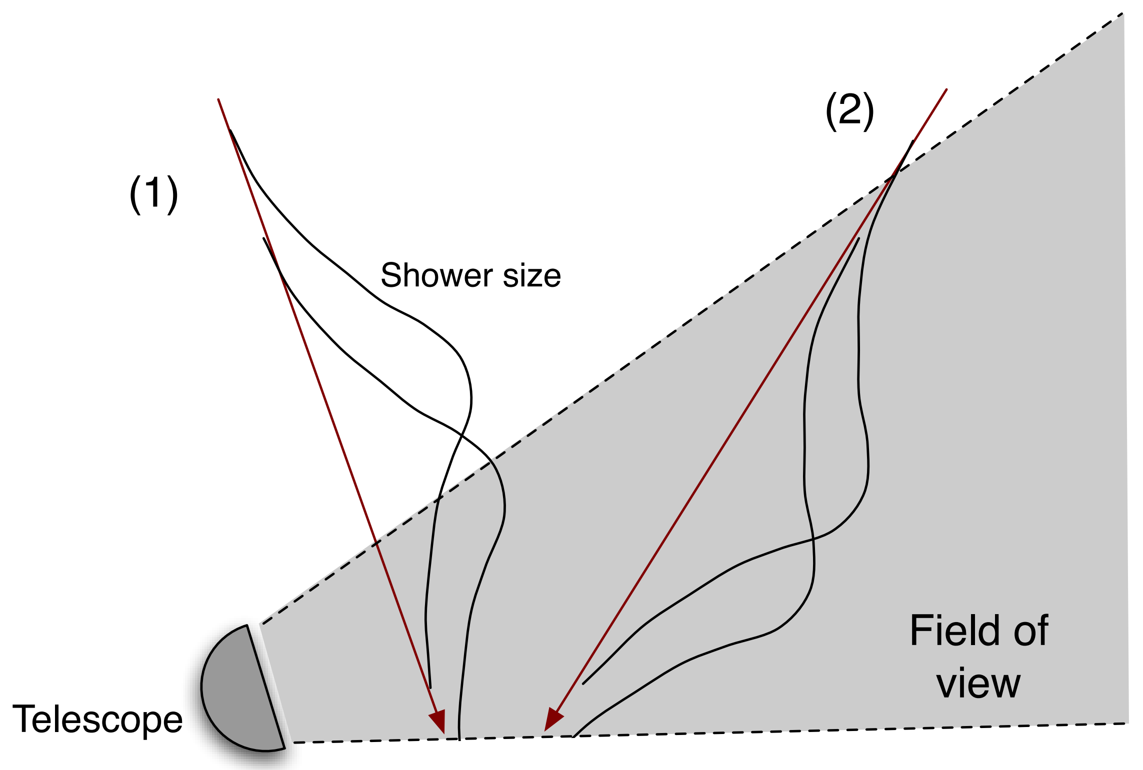


Surface detector data:
only average composition

(Auger ICRC 2019)

Comparison of Xmax data of Auger and TA

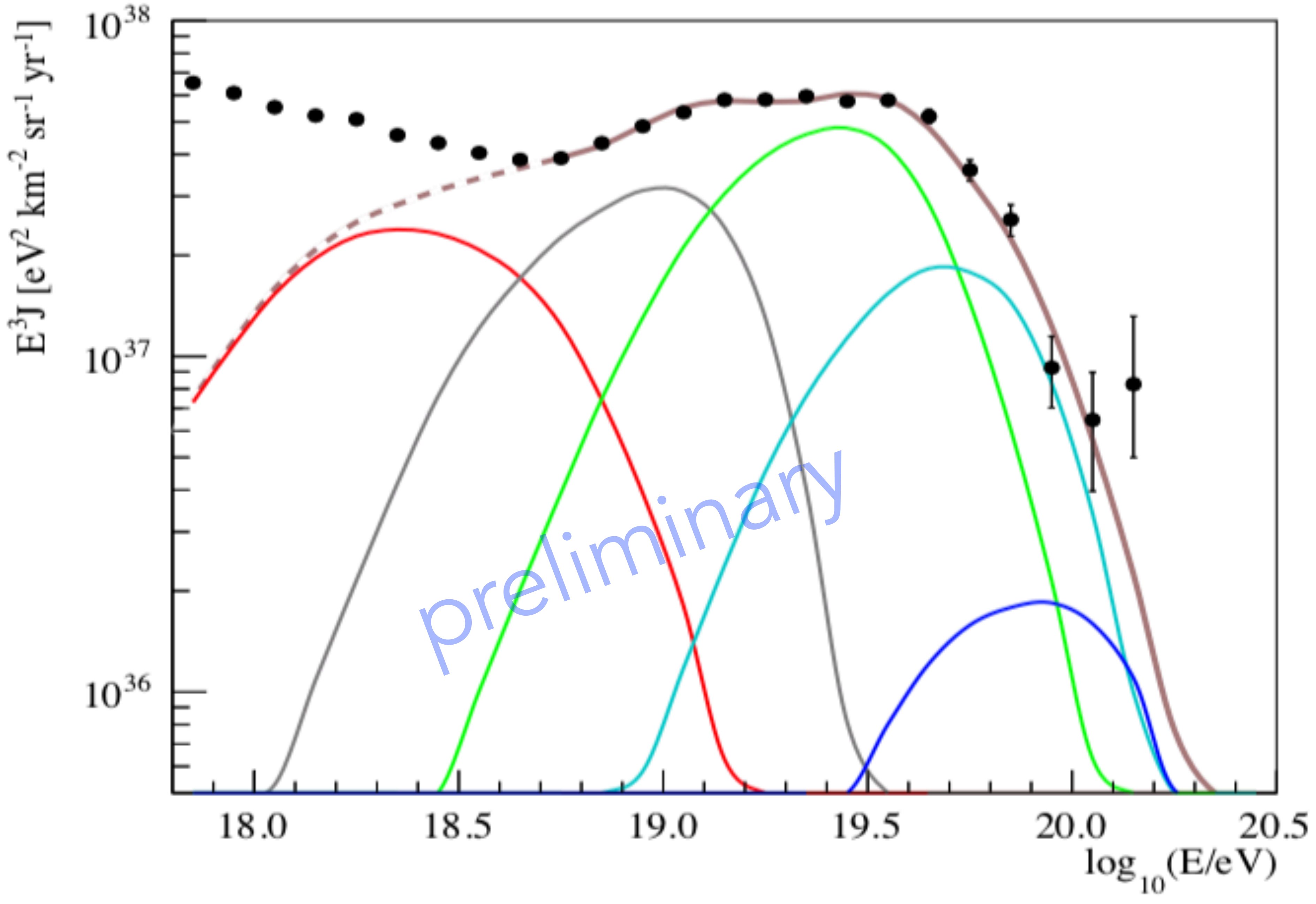




Work in progress:
data consistent in energy range with sufficient statistics

(Auger-TA Xmax Working Group, UHECR 2018)

Interpretation: spectrum and composition



A=1

A=2-4

A=5-22

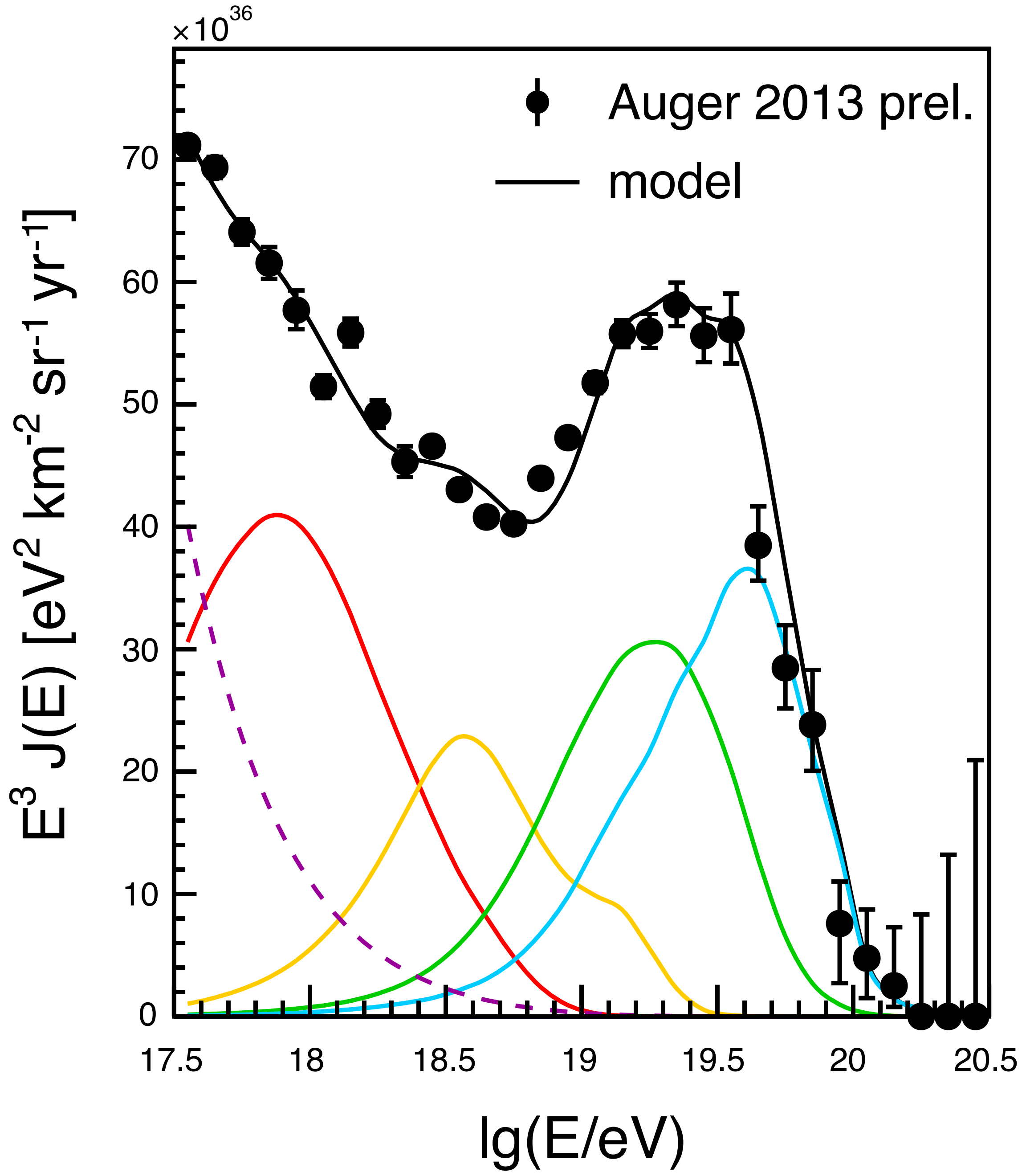
A=23-38

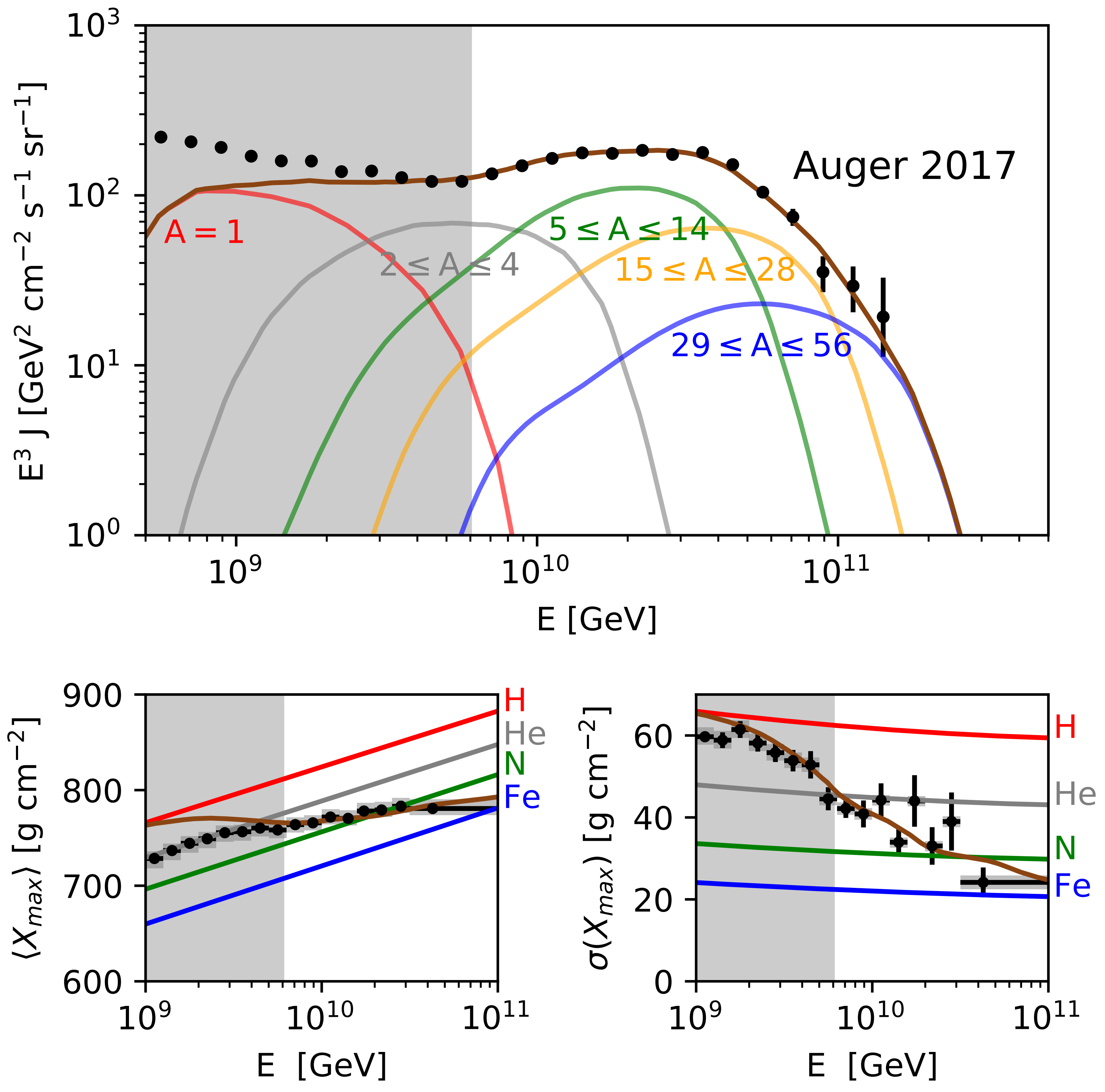
A>38

(Auger ICRC 2019)

Physics in source region

(Aloisio et al. 2014,
Taylor et al. 2015,
Globus et al. 2015,
Unger et al. 2015,
Fang & Murase 2017)



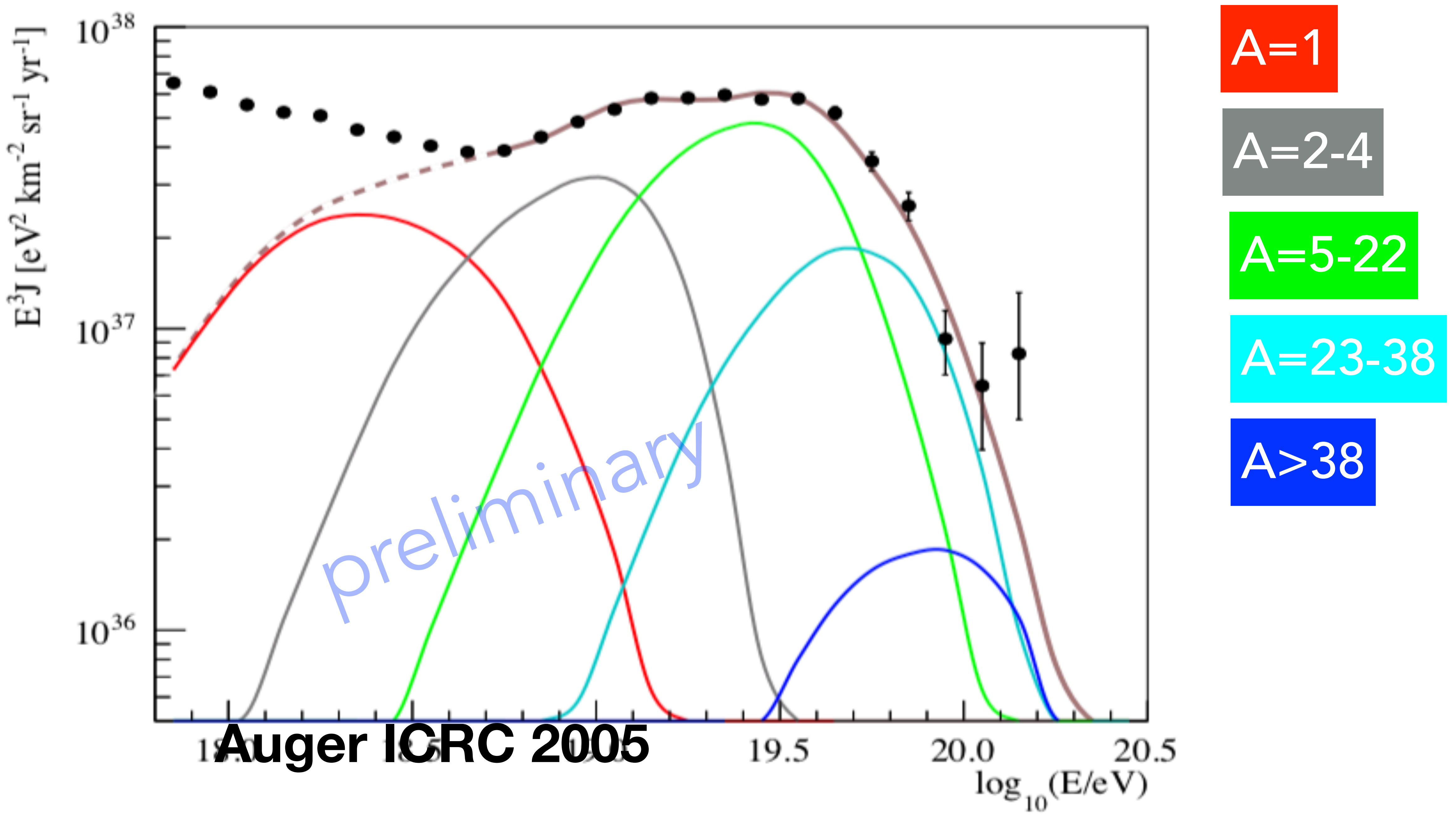


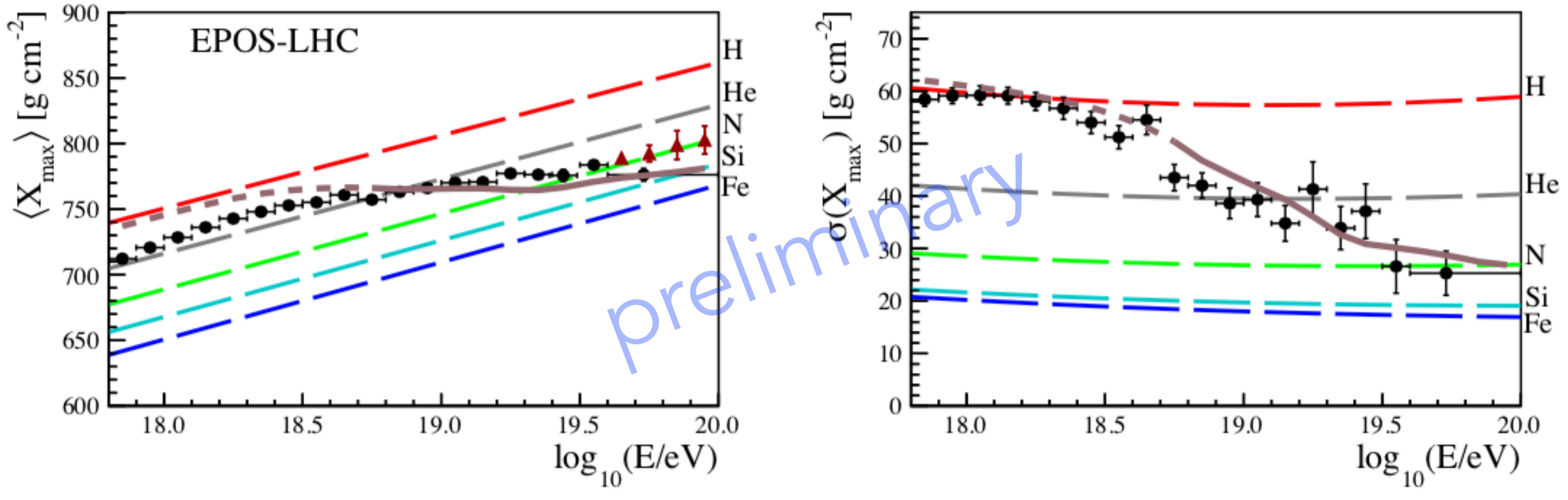
(Heinze et al. ApJ 873 (2019) 88)

Inflection point natural feature in models with scanning composition

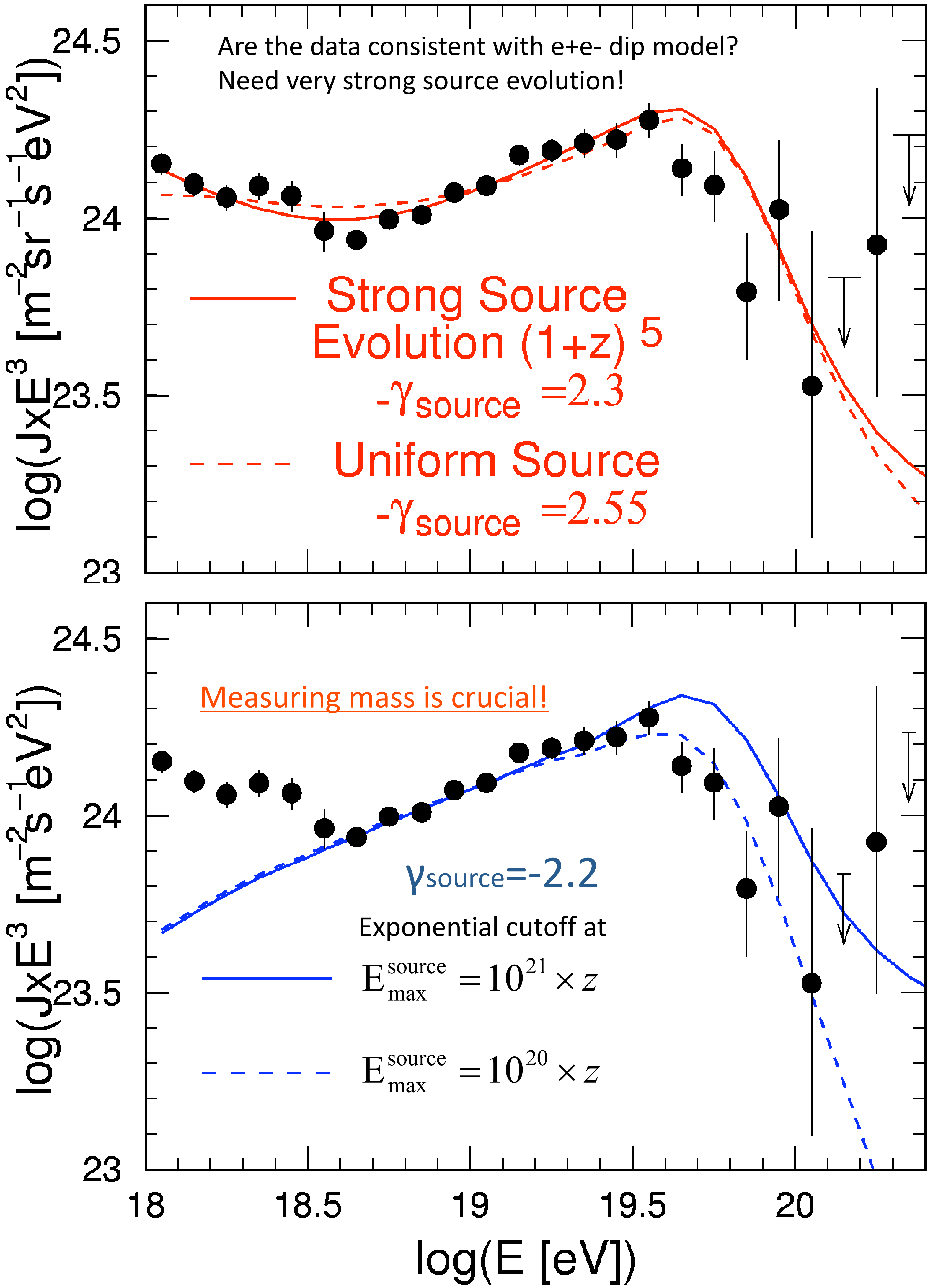
Interpretation of flux and composition data

Auger 2019





Auger 2007



(Auger, ICRC 2019)

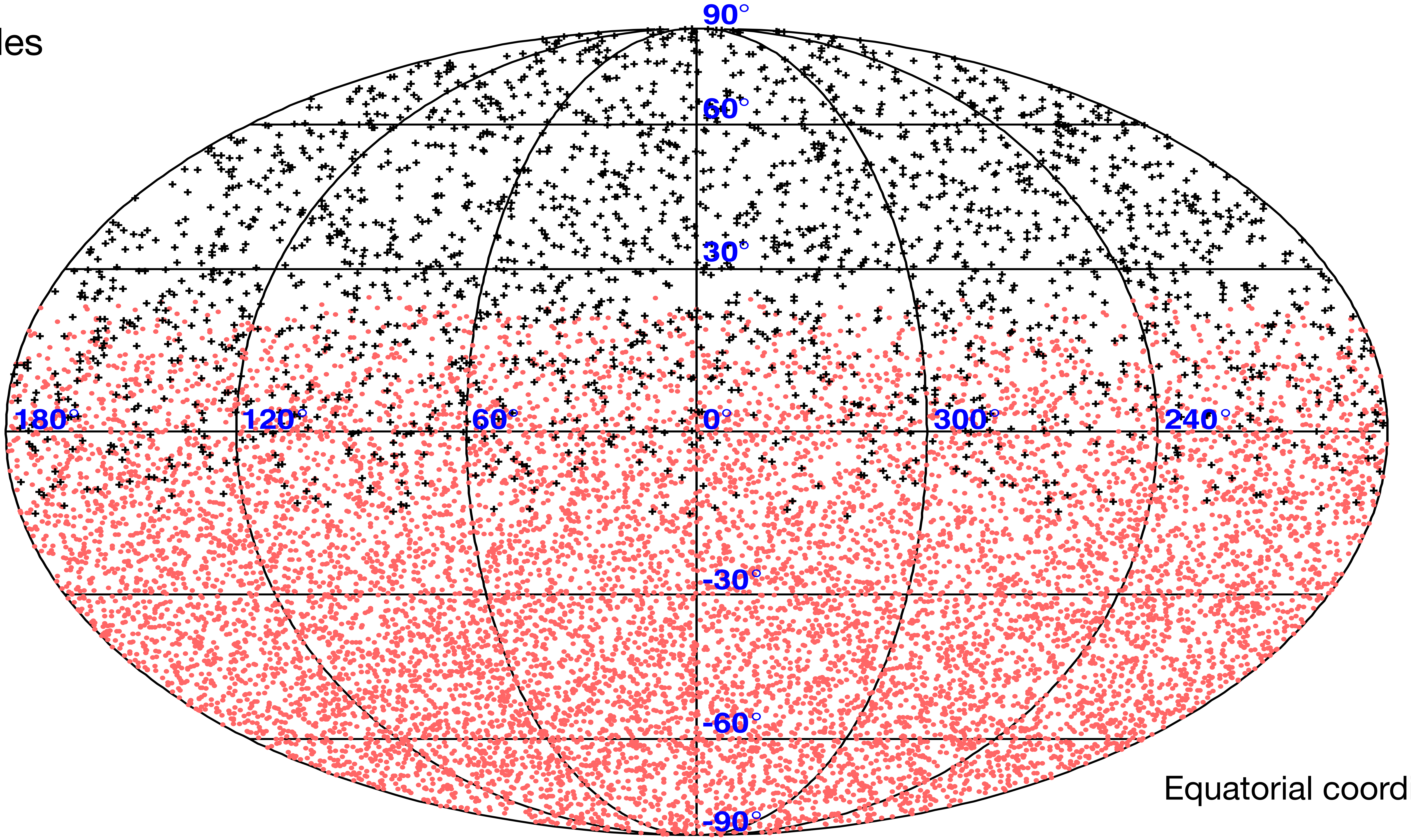
3. Arrival direction distribution

Different exposures and energy scales of Auger Observatory and Telescope Array

$$E > 10^{19}\,\mathrm{eV}$$

After unification of energy scales in overlap region:

No anisotropy found in 2014

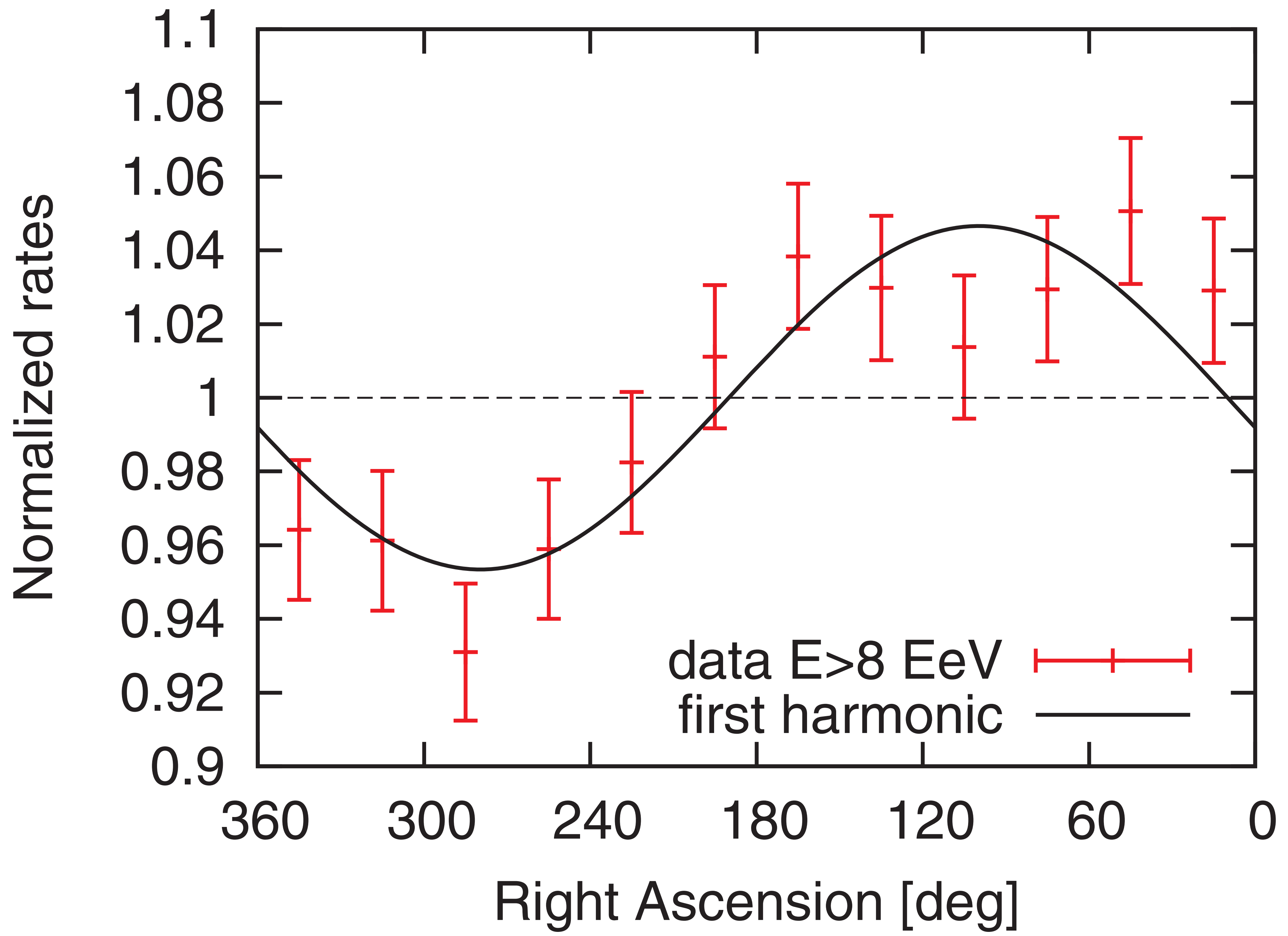


Equatorial coordinates

Pierre Auger and TA Collaborations, ApJ **794** (2014) 2, 172

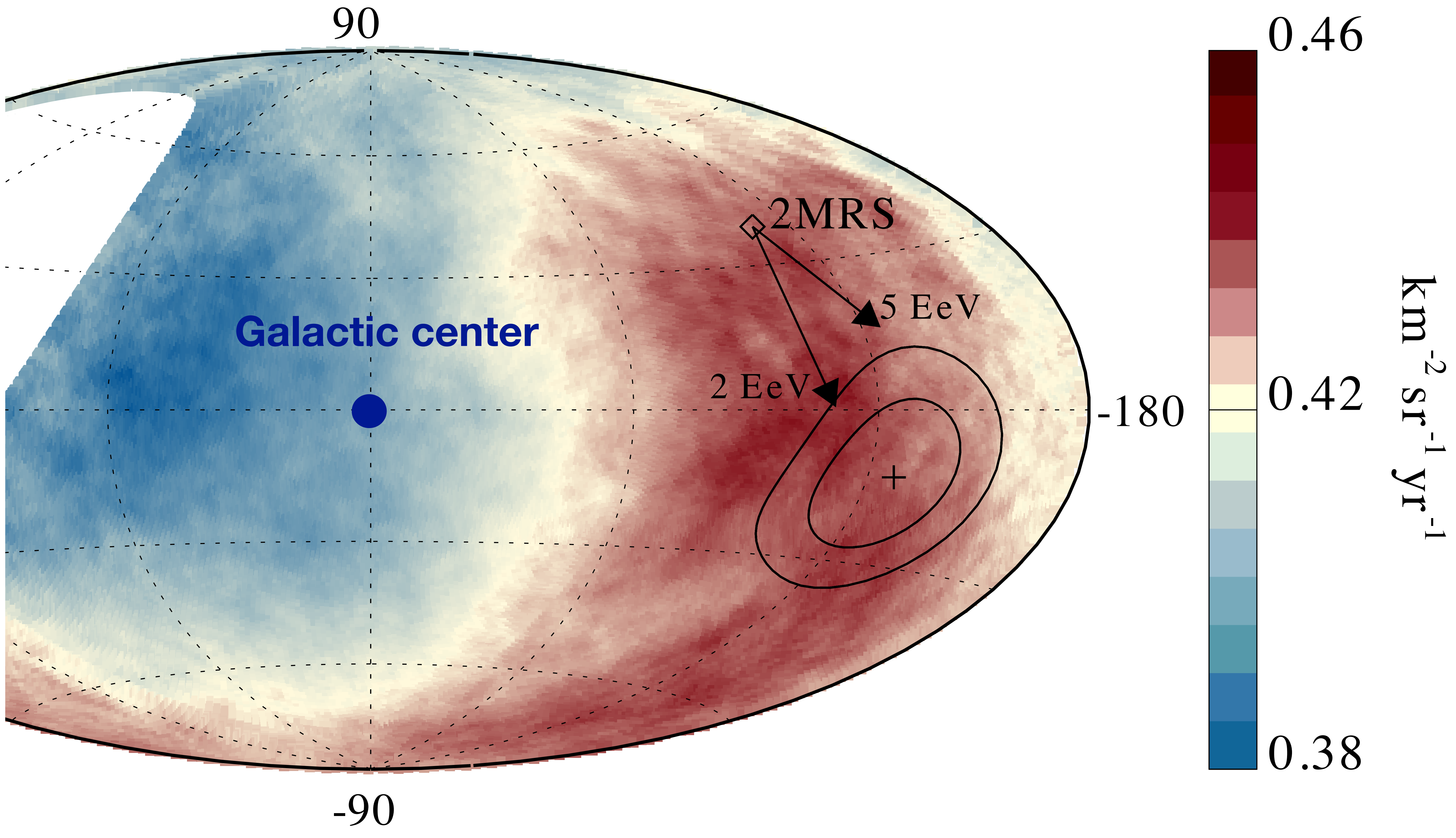
Arrival directions – Auger results on large angular scales

6.5% dipole at 5.2 sigma
Science 357 (2017) 1266



$E > 8 \times 10^{18}\,\mathrm{eV}$

Estimated deflection in galactic mag. field



Arrival directions follow mass distribution of near-by galaxies: extragalactic origin of sources

Arrival directions – Auger results on large angular scales

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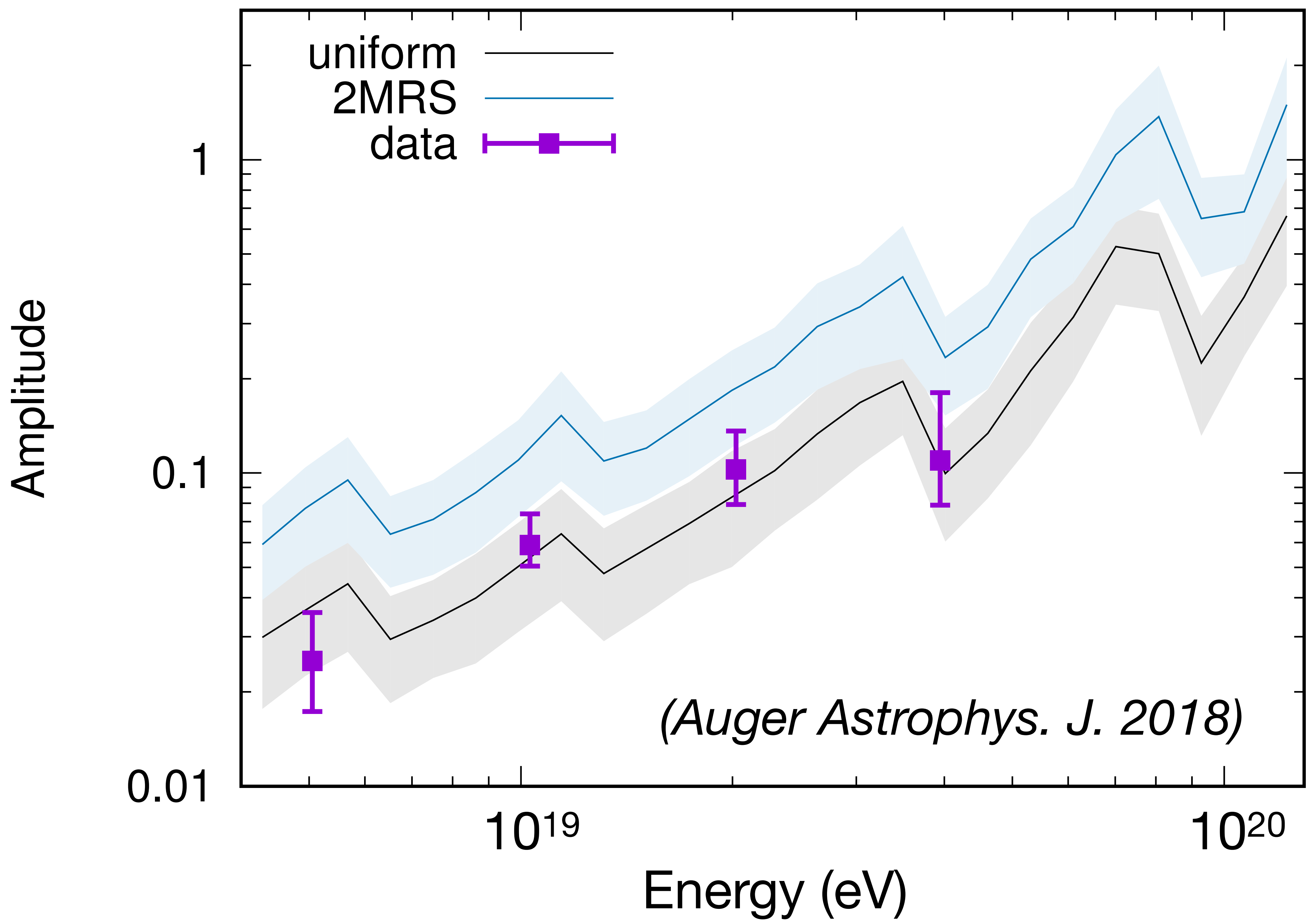
Science AAAS

Energy-dependence of amplitude (ApJ 2018)



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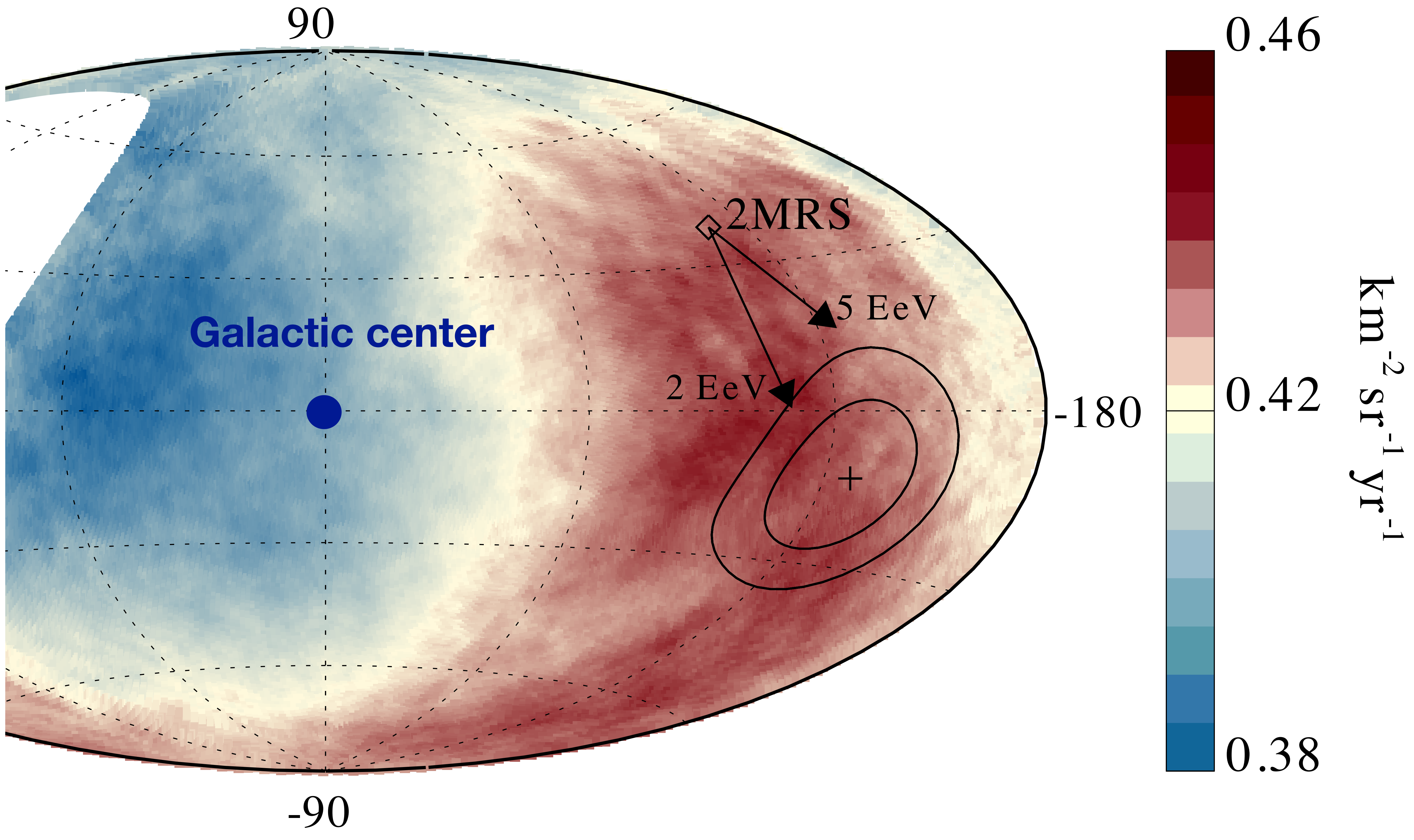
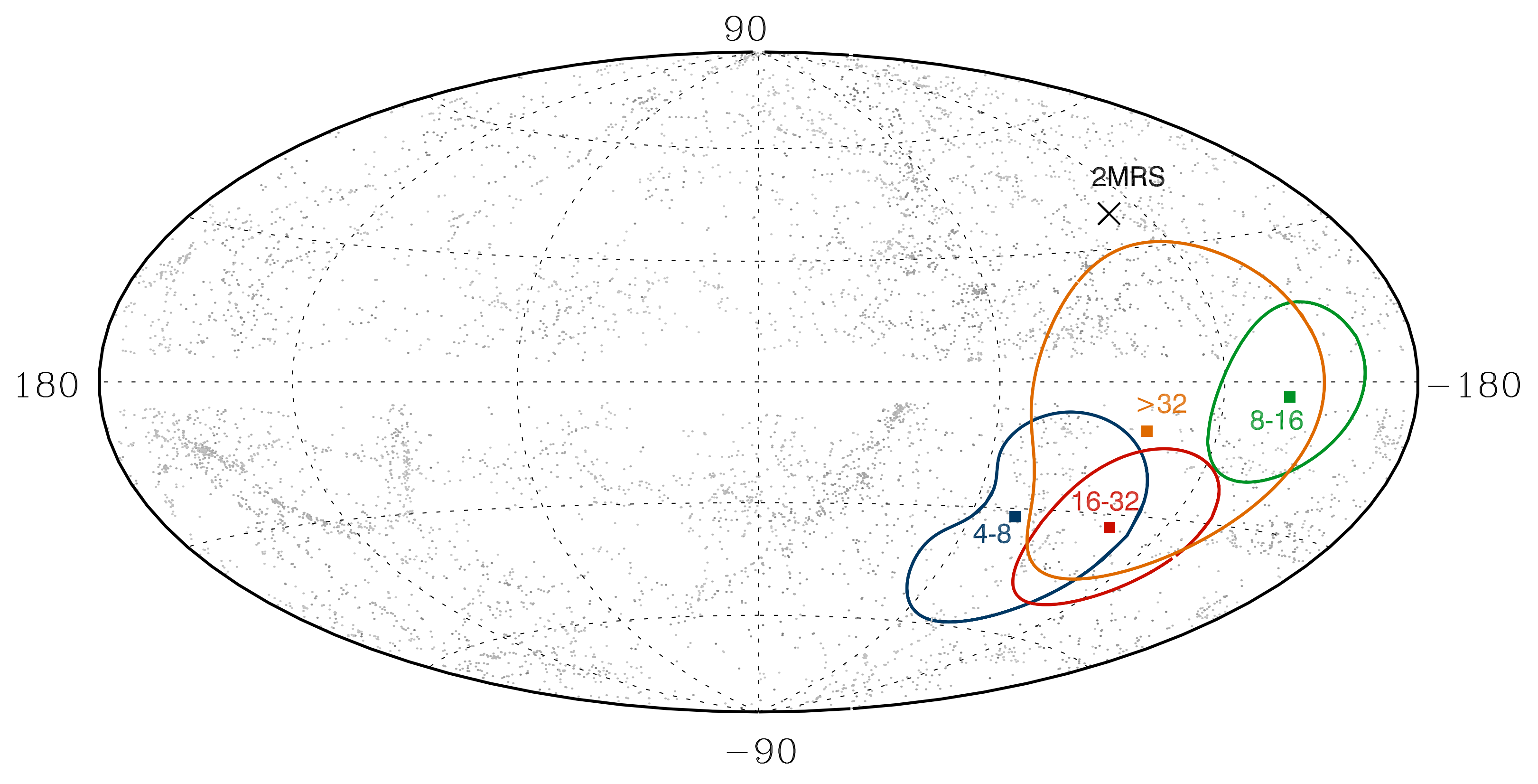
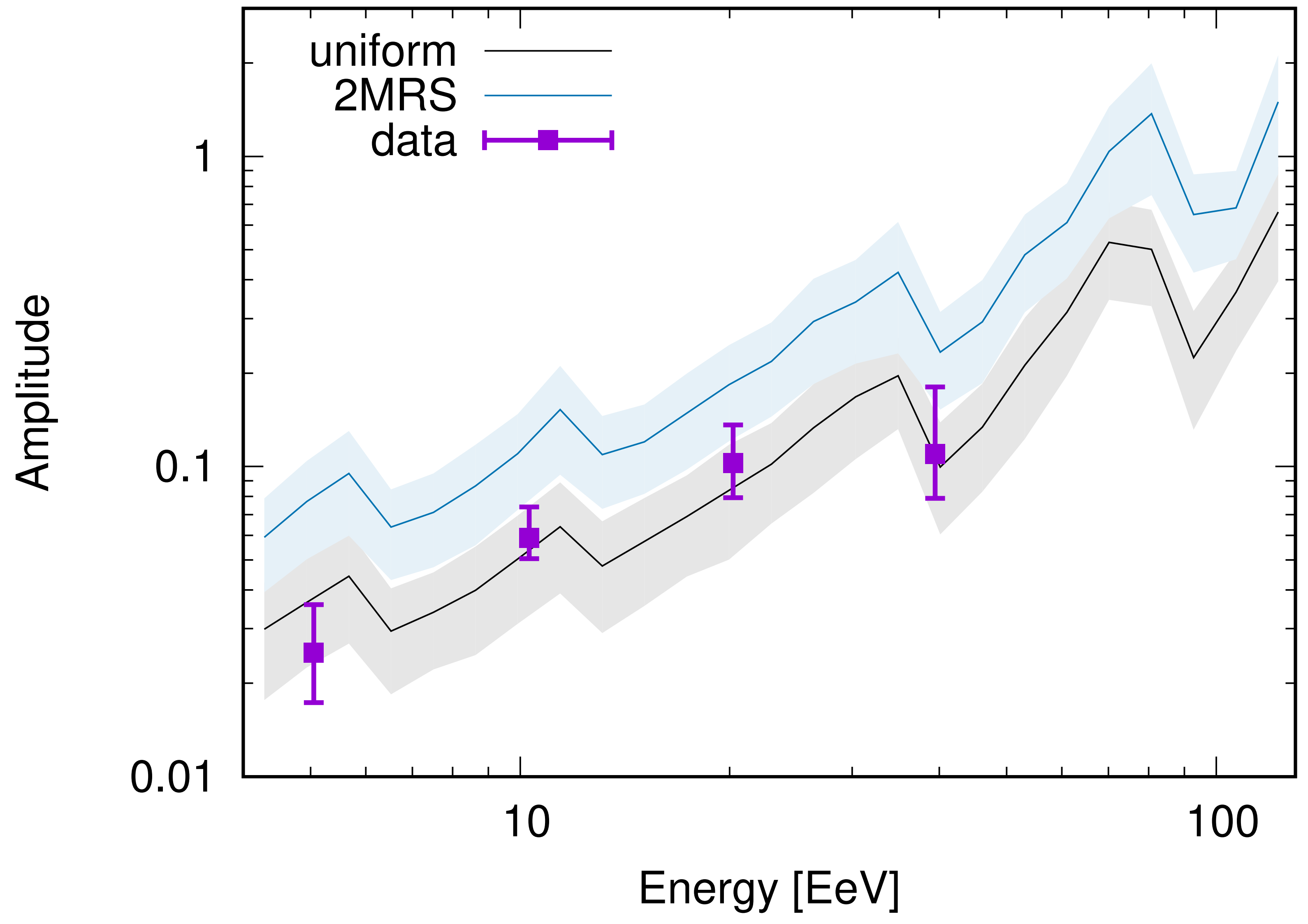


Arrival directions follow mass distribution of near-by galaxies: extragalactic origin of sources

Dipolar anisotropy – interpretation

(Auger Astrophys. J. 2018)





Energy-dependence of amplitude and direction

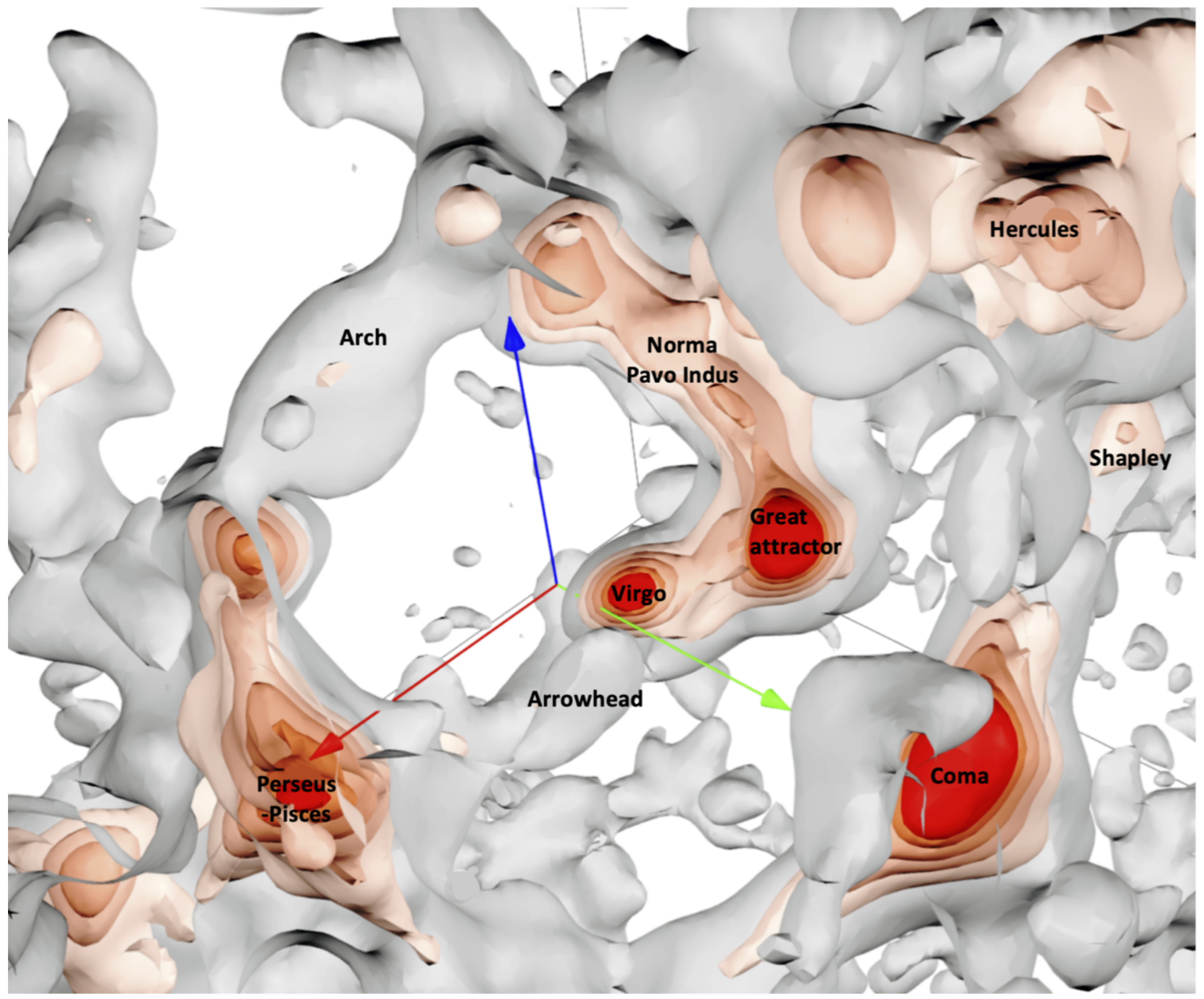
Globus, N., Piran, T. 2017, ApJL, 850, L25
Hackstein, S., et al. 2016,MNRAS, 462, 3660
Hackstein, S., et al. 2018,MNRAS, 475, 2519
Harari, D., Mollerach, S., Roulet, E. 2010, JCAP, 11 033
Harari, D., Mollerach, S., Roulet, E. 2014, PRD, 89, 123001
Harari, D., Mollerach, S., Roulet, E. 2015, PRD, 92, 063014

Extensive theoretical work (prediction and interpretation)

model: mixed composition
$R_{\text{max}} = 6$ EeV, $\rho = 10^{-4}$ Mpc^{-3}

Non-trivial interplay of mass composition, mag. horizon and local source distribution

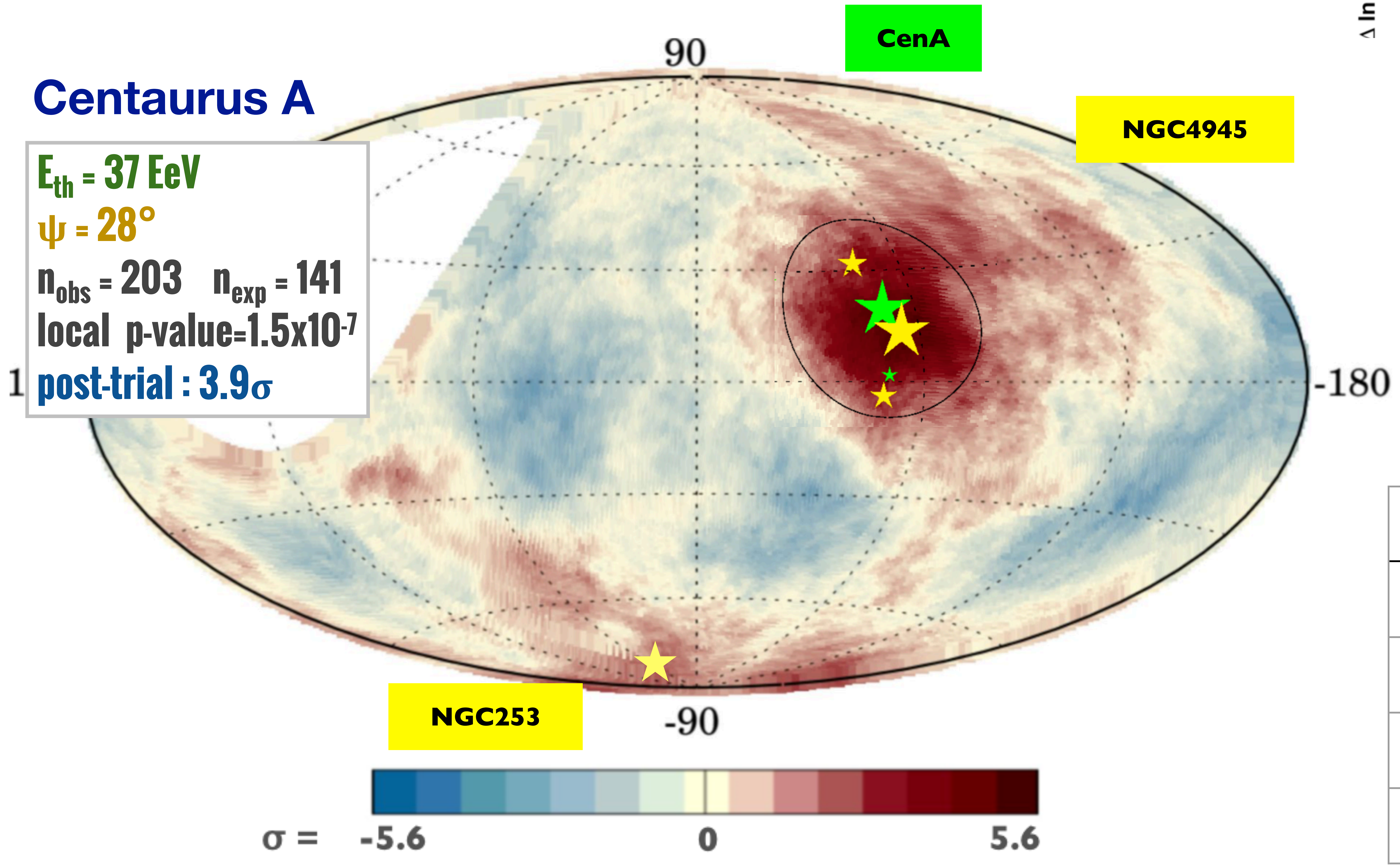
(Ding, Globus & Farrar 2101.04564)

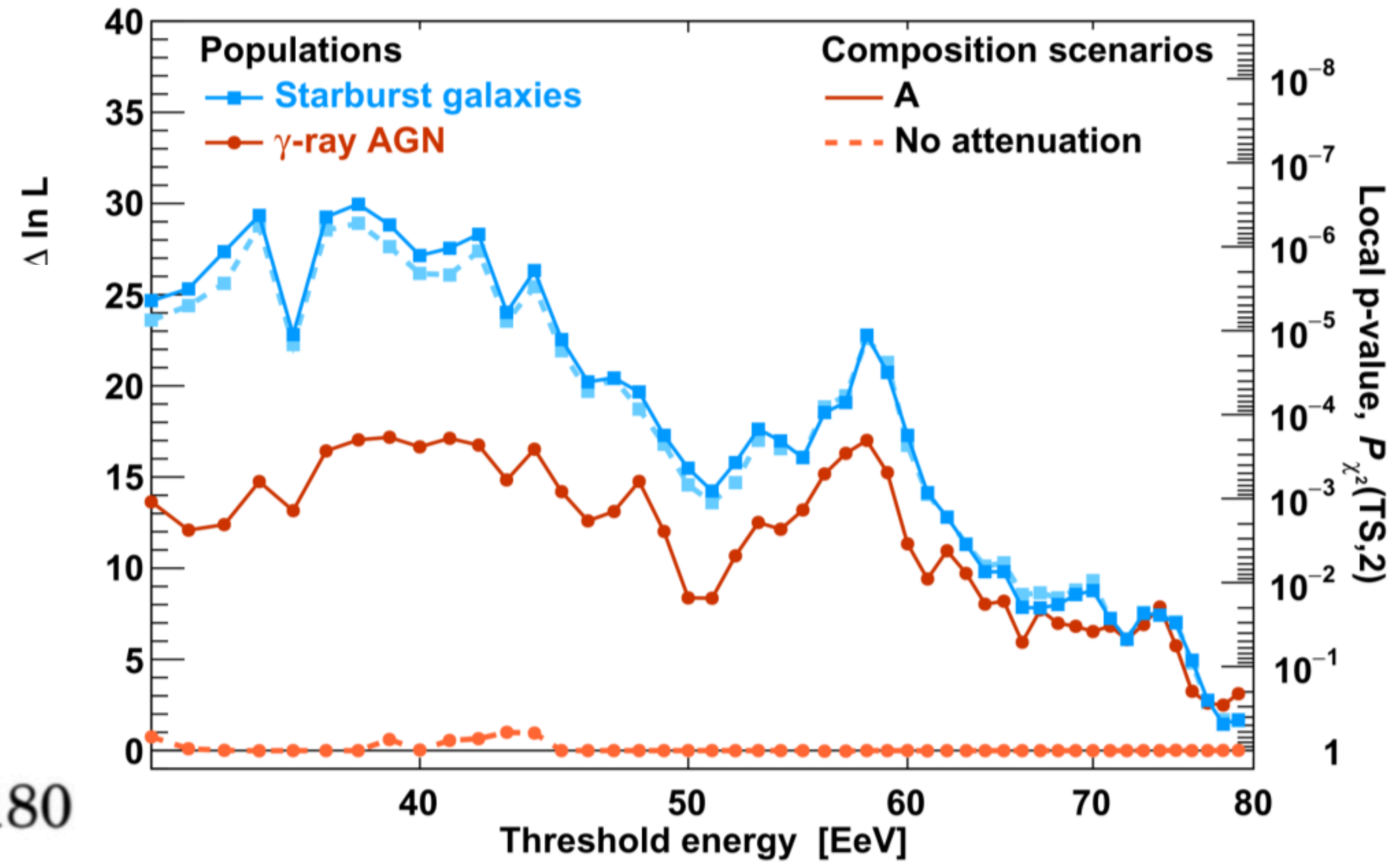


Arrival directions – catalog searches

Total SD events with E>32 EeV : **2157**

Total exposure: **101,400 km² sr yr**

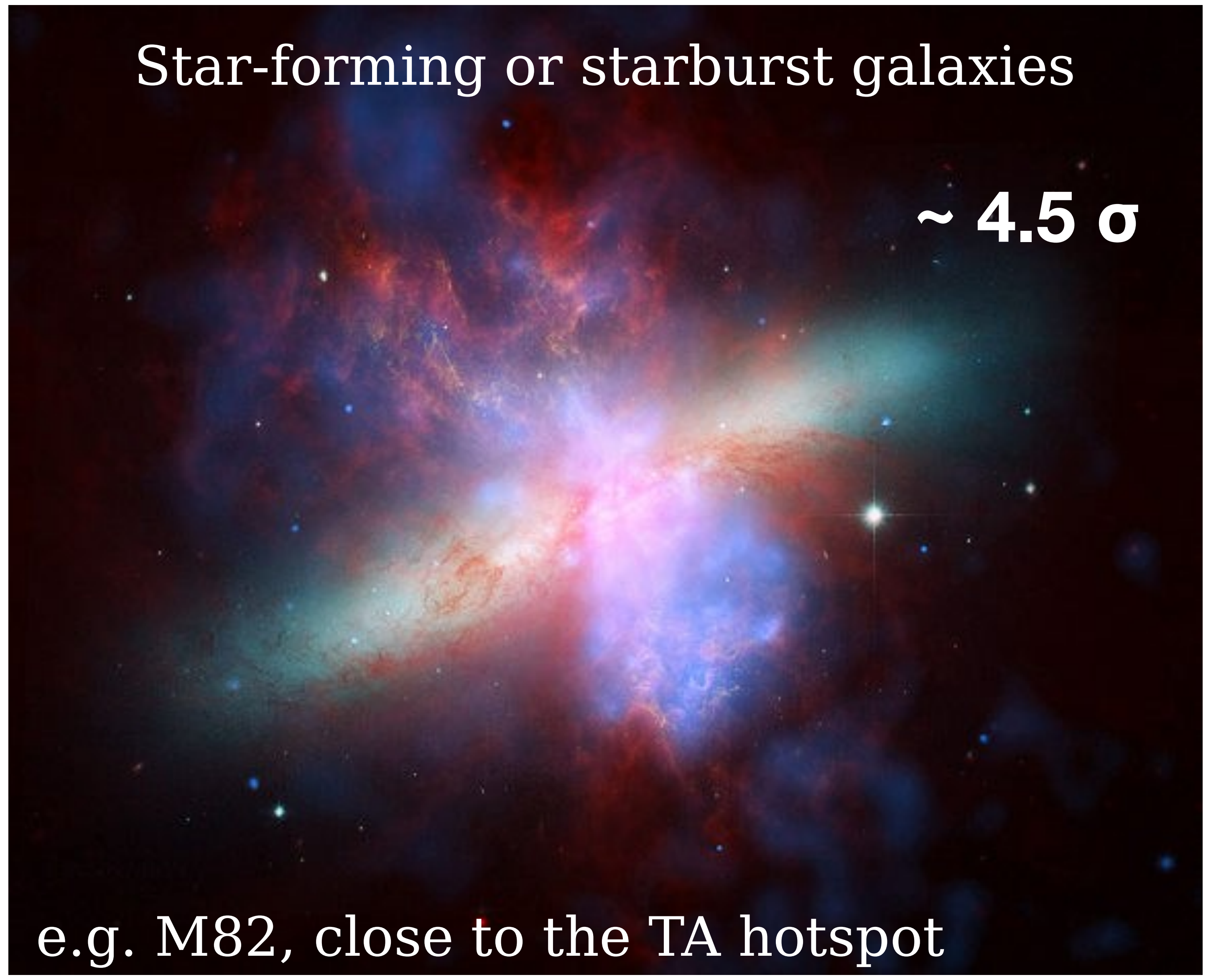


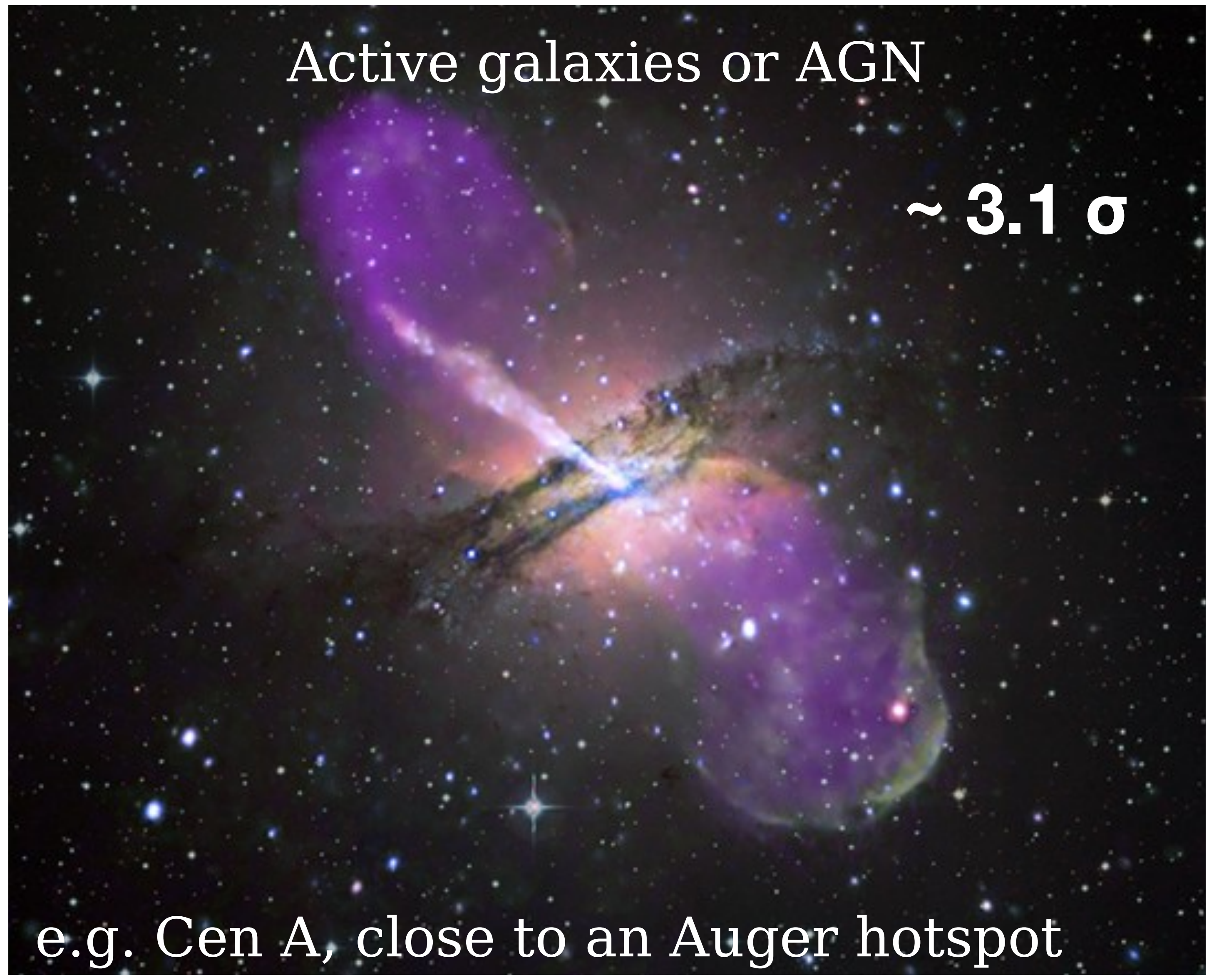


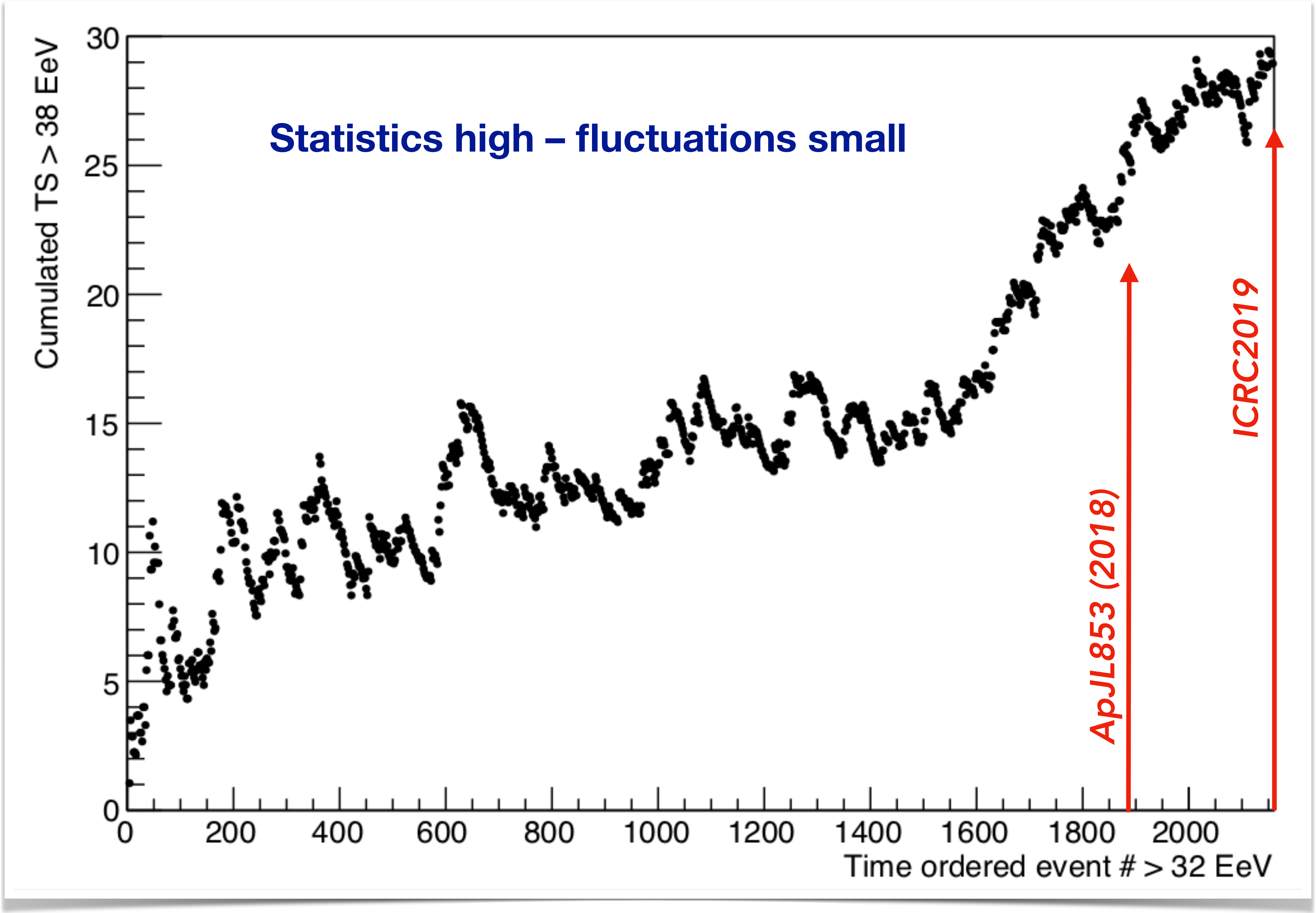
Catalog	E_{th}	θ	f_{aniso}	TS	Post-trial
Starburst	38 EeV	15^{+5}_{-4}°	11^{+5}_{-4}%	29.5	4.5 σ
γ-AGNs	39 EeV	14^{+6}_{-4}°	6^{+4}_{-3}%	17.8	3.1 σ
Swift-Bat	38 EeV	15^{+6}_{-4}°	8^{+4}_{-3}%	22.2	3.7 σ
2MRS	40 EeV	15^{+7}_{-4}°	19^{+10}_{-7}%	22.0	3.7 σ

(Auger Astrophys. J.2018, ICRC 2019)

Catalog searches – outlook



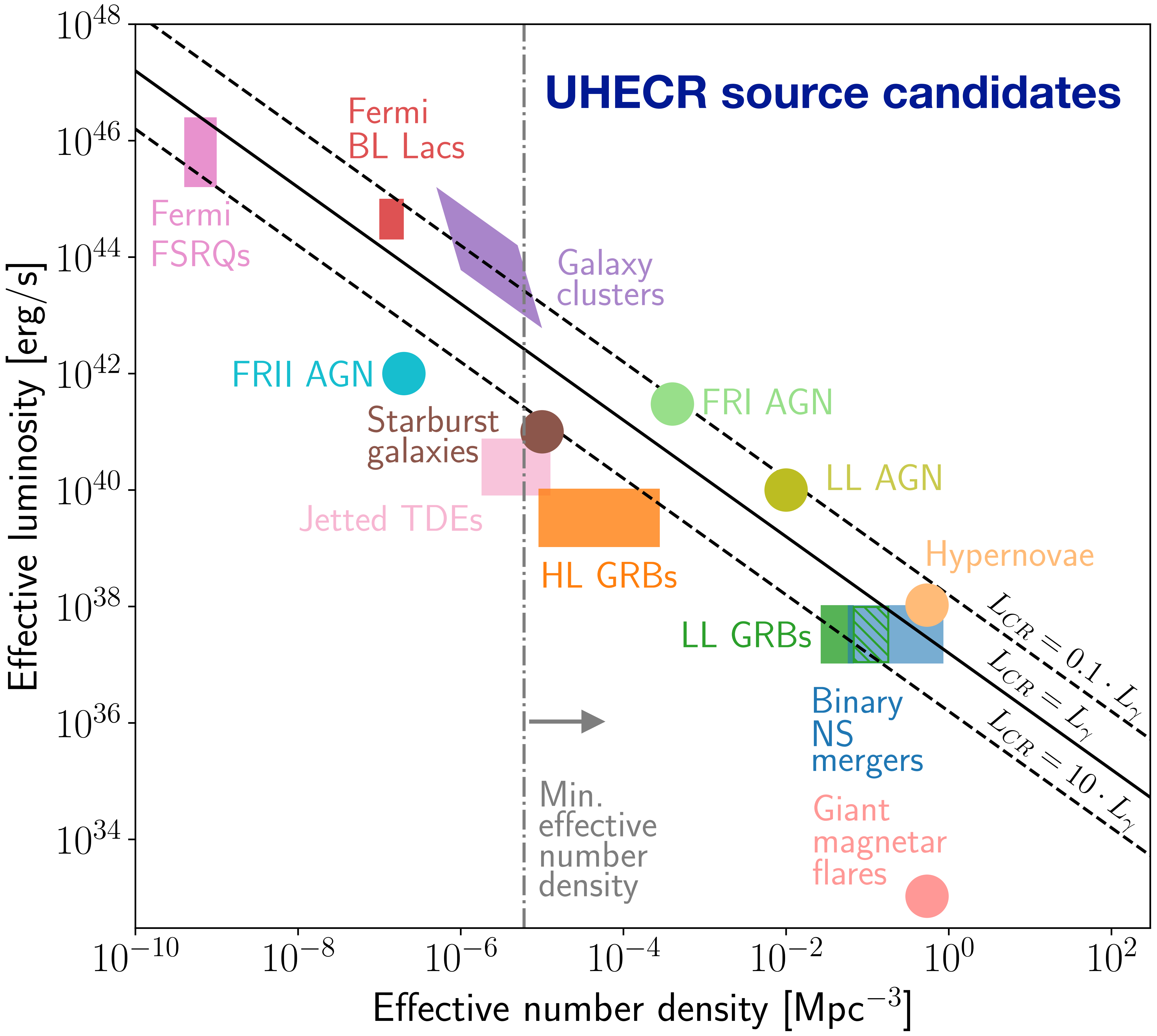


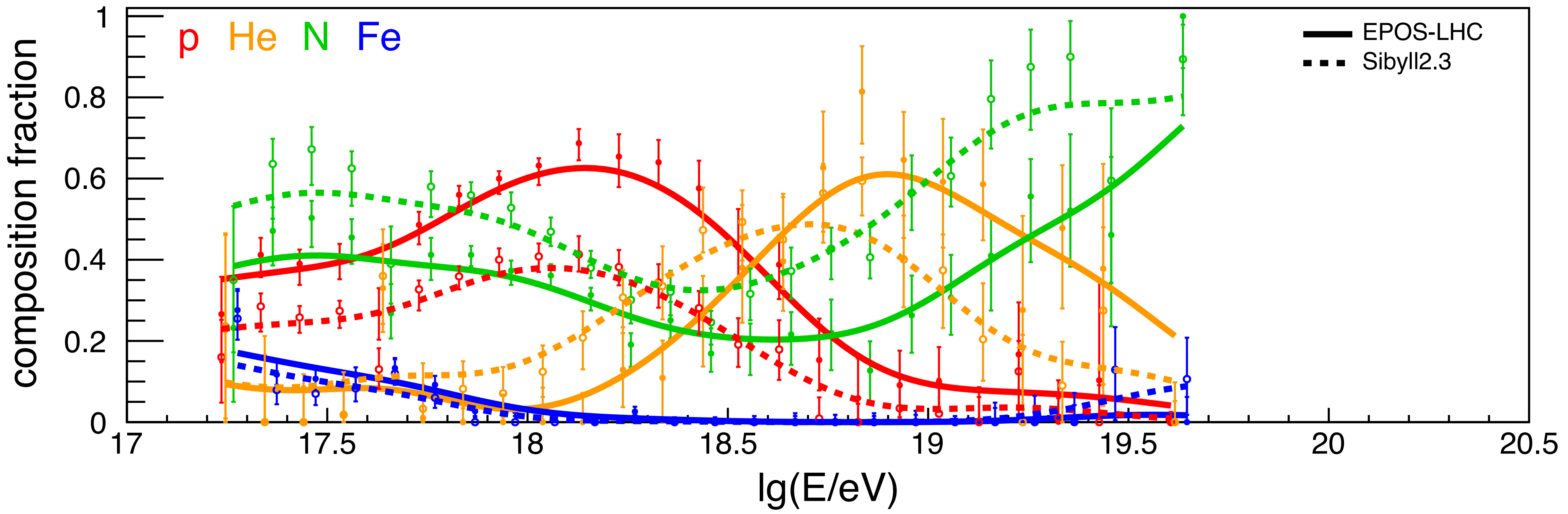


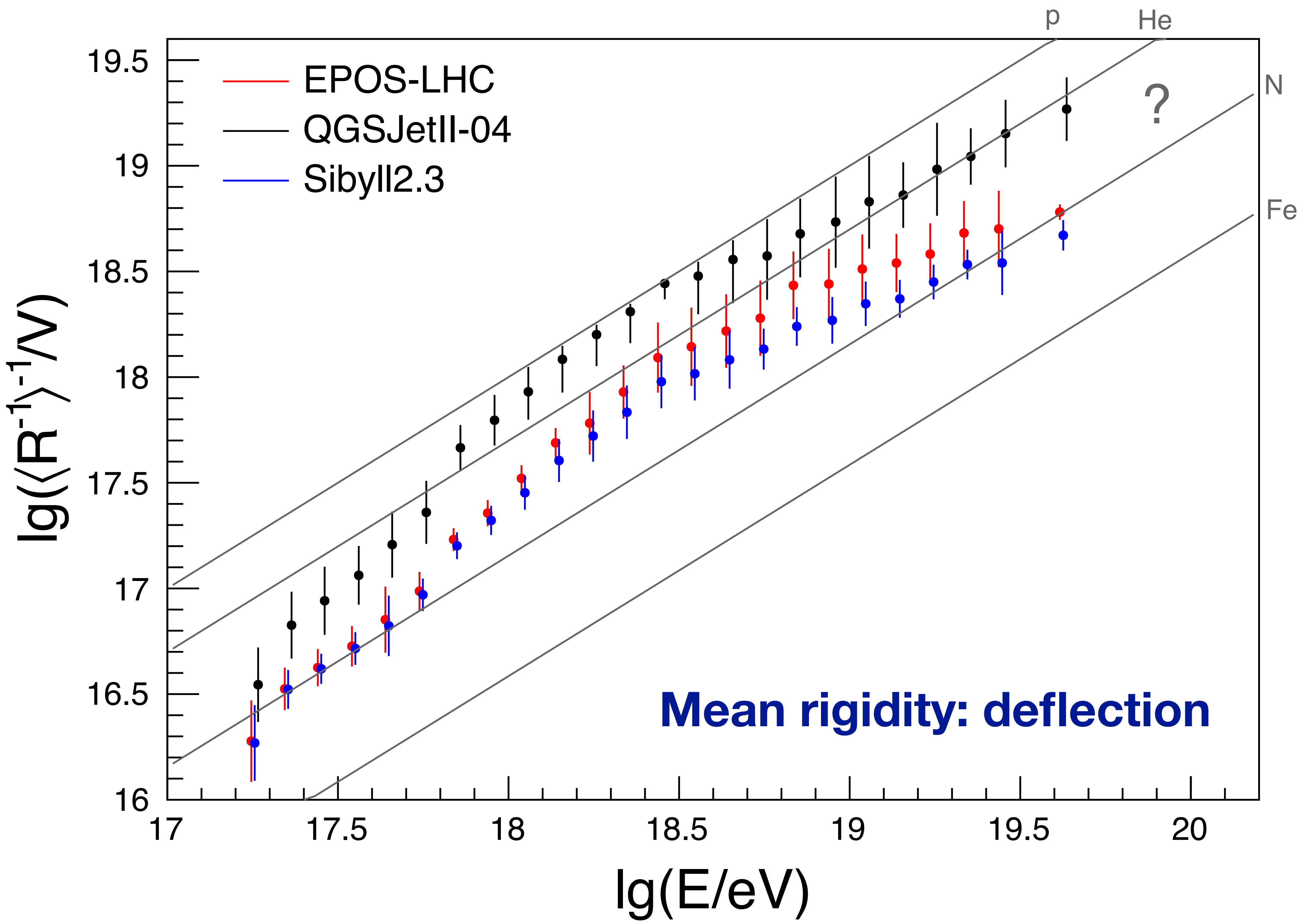
(Auger, ICRC 2019)

General prospects for finding sources

(Alves Batista et al, MIAPP review, 1903.06714)

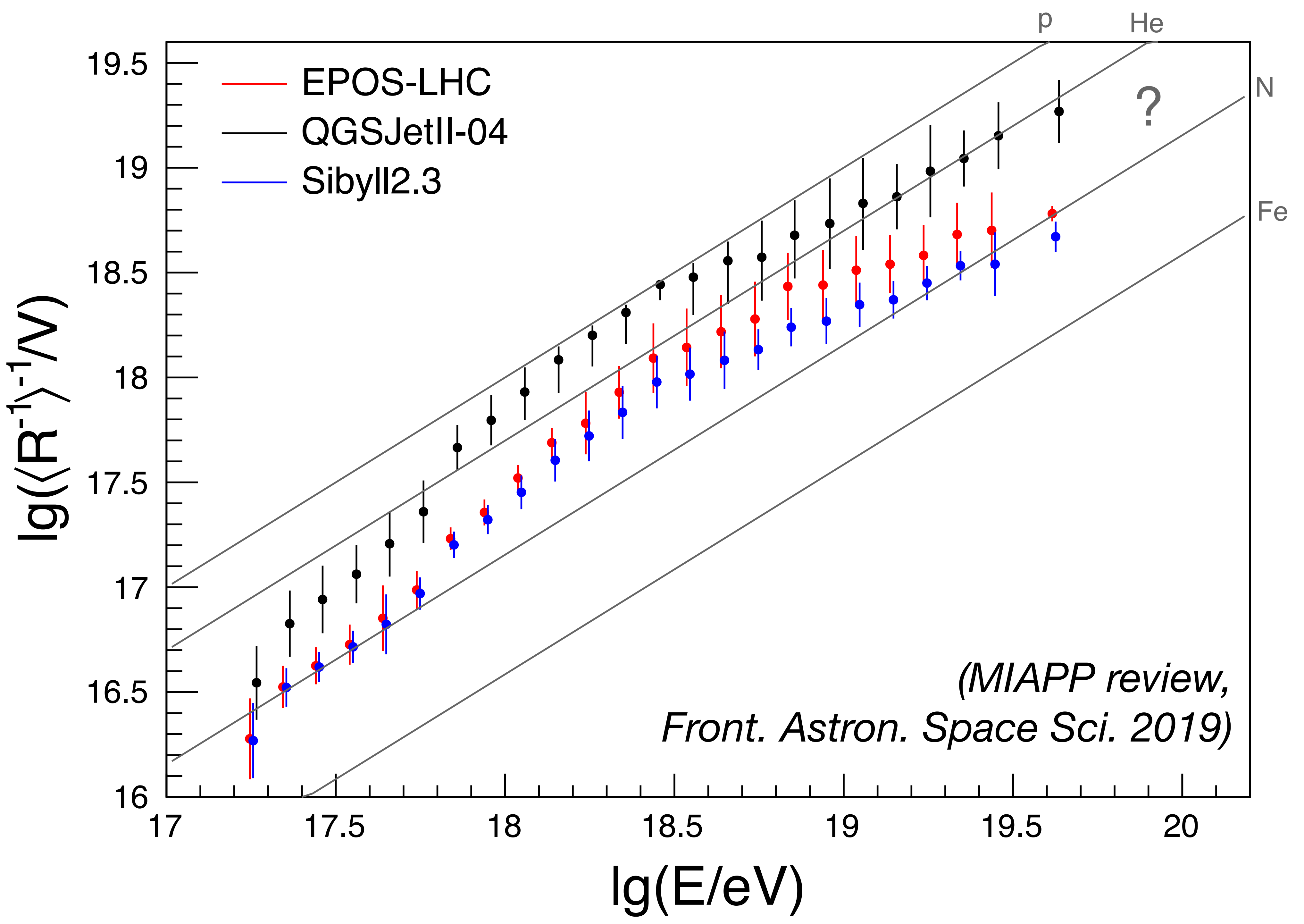






Higher energy: mean deflection similar, but reduced source volume

Accounting for magnetic field deflection needed



Average rigidity derived from Auger data

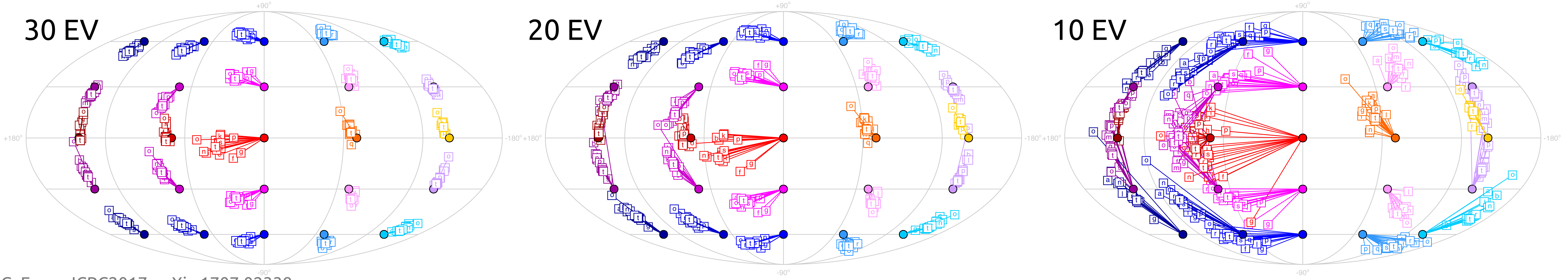
Agnostic view:

particles with smaller charge are less deflected

Full sensitivity:

use knowledge of galactic magnetic fields

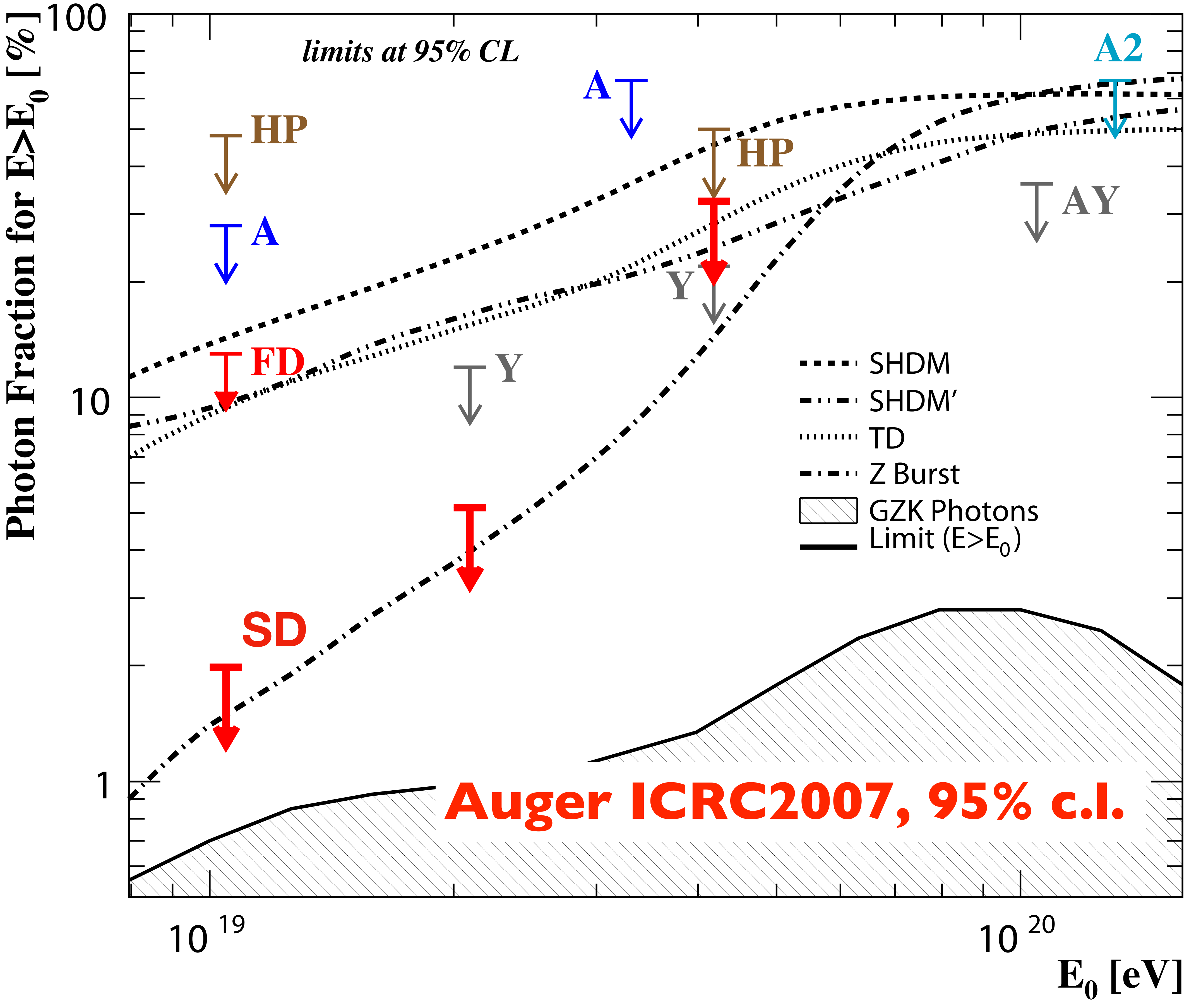
backtracking through magnetic field model variations at different rigidities $R = E/Z$



MU&G. Farrar ICRC2017, arXiv:1707.02339

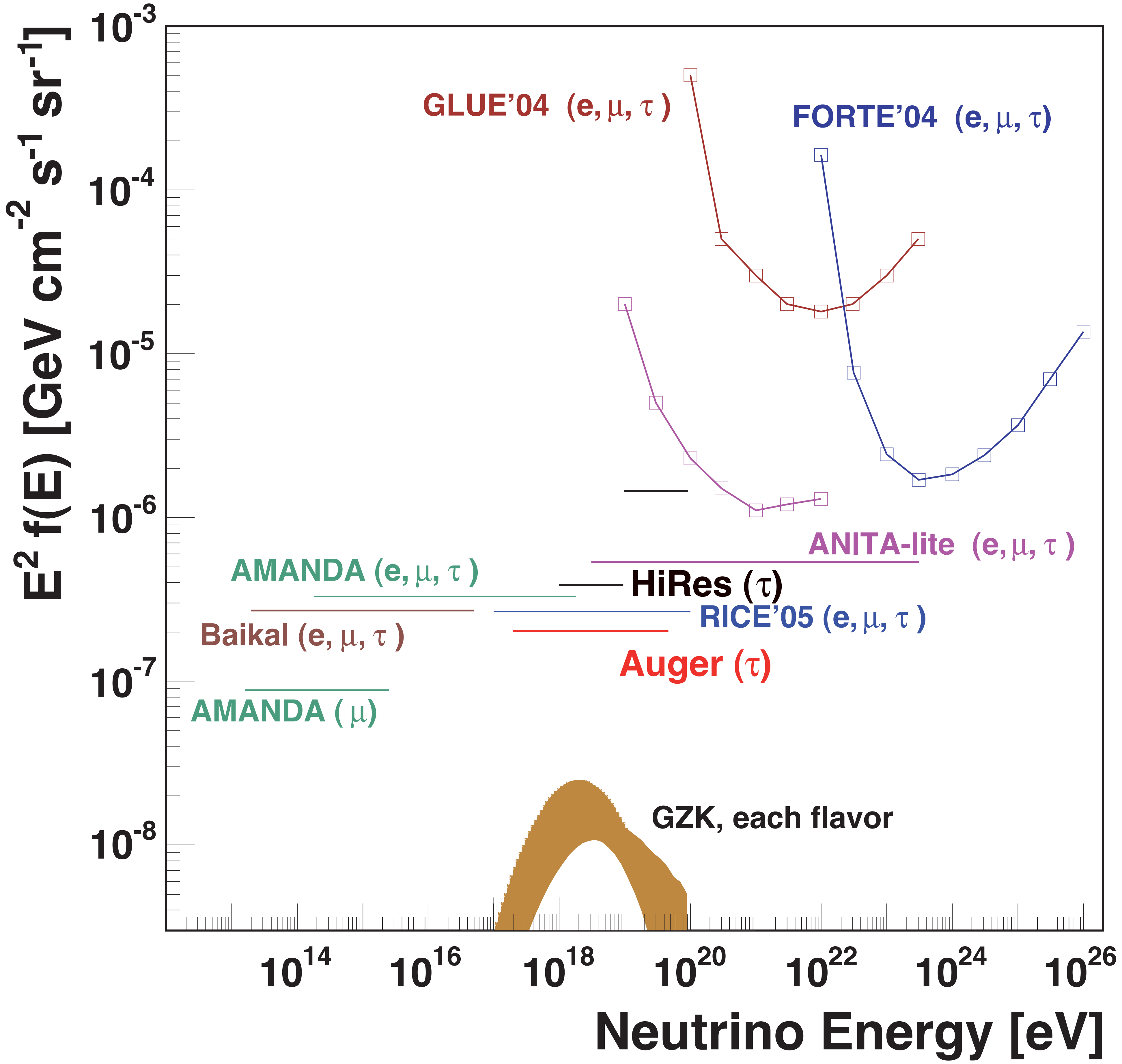
4. Multi-messenger physics – early Auger results

Integral photon flux limit



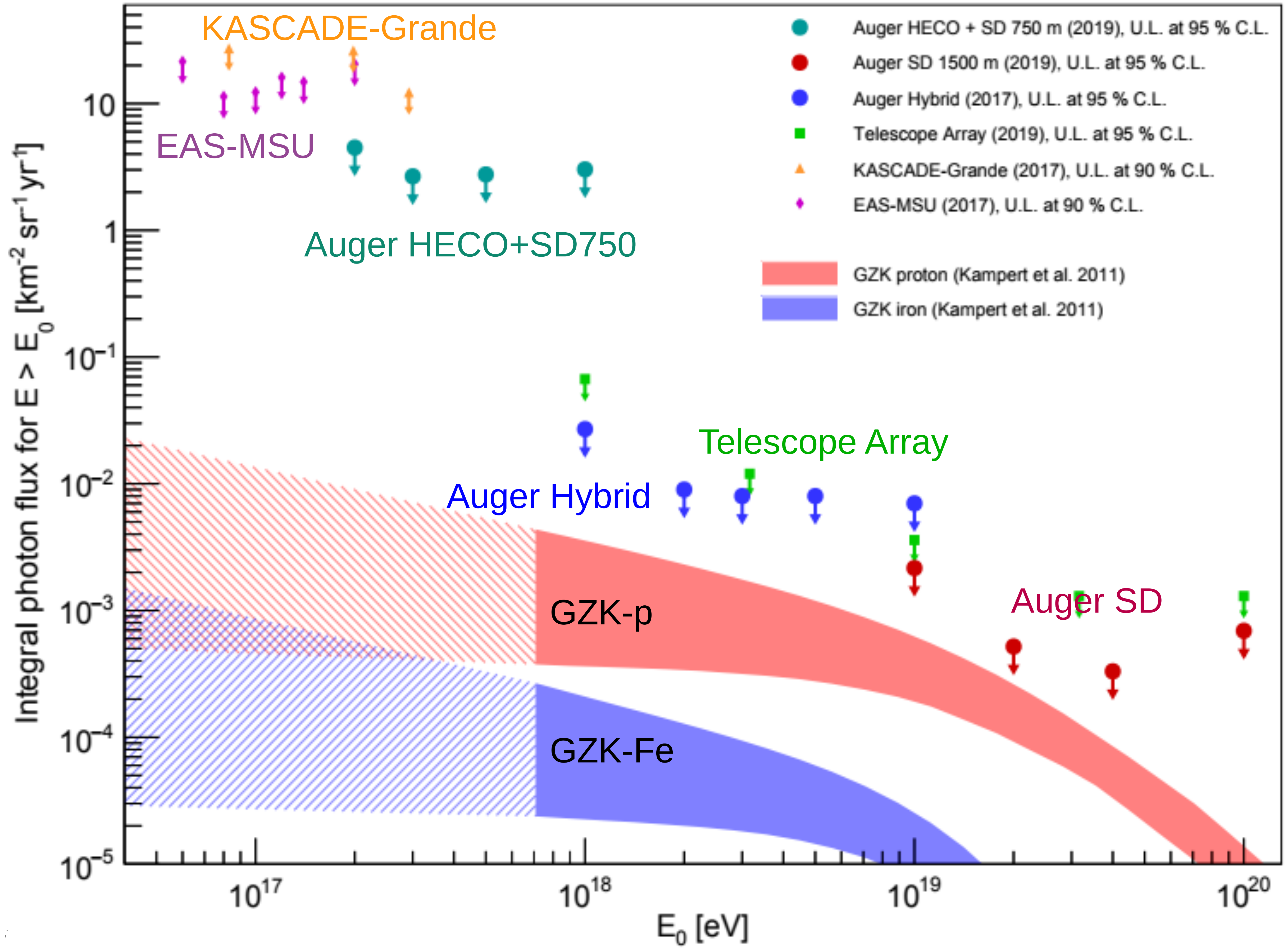
(Auger, Astropart. Phys 2007, 2008)

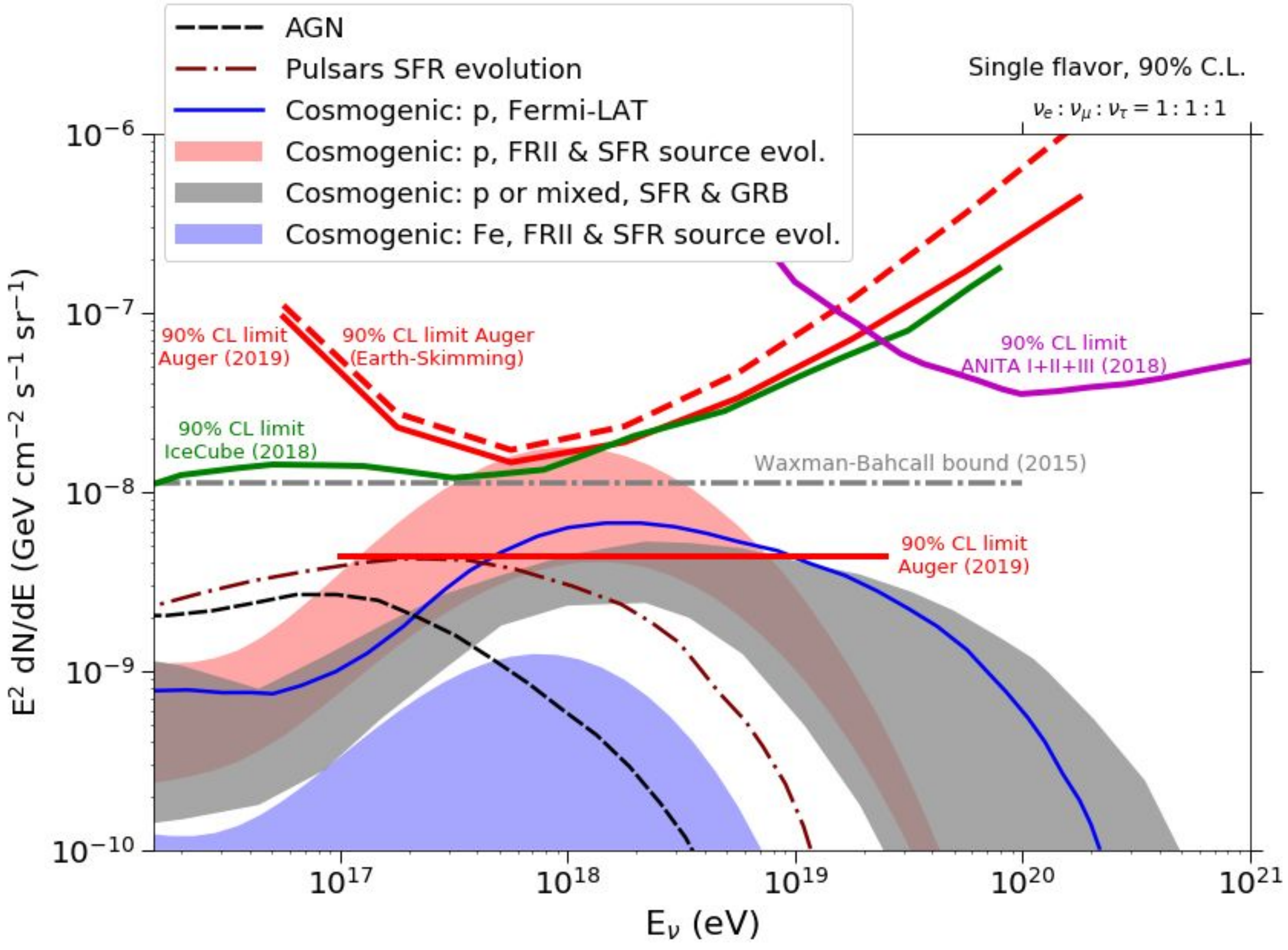
Neutrino flux limit



(Auger, Phys. Rev. Lett. 2008)

4. Multi-messenger physics – Auger results today

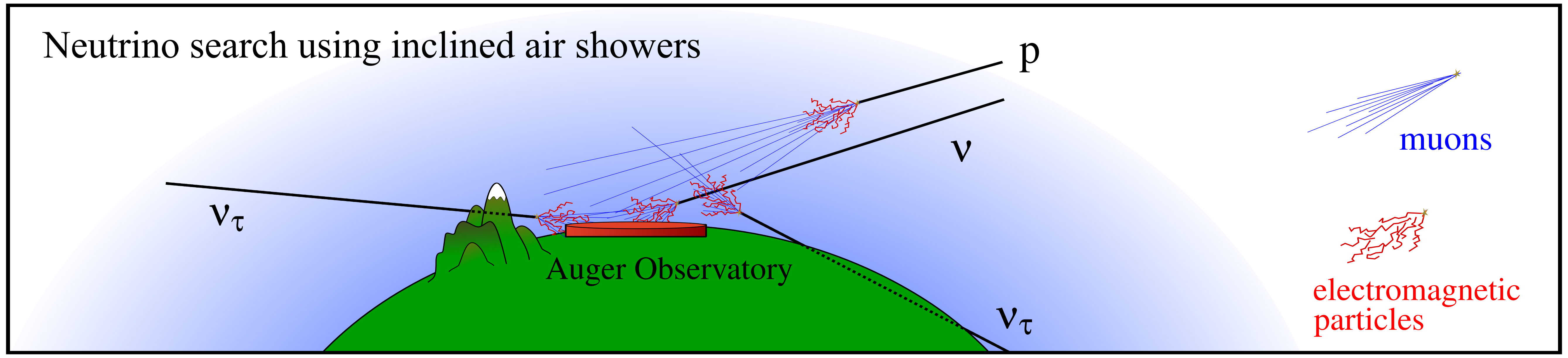




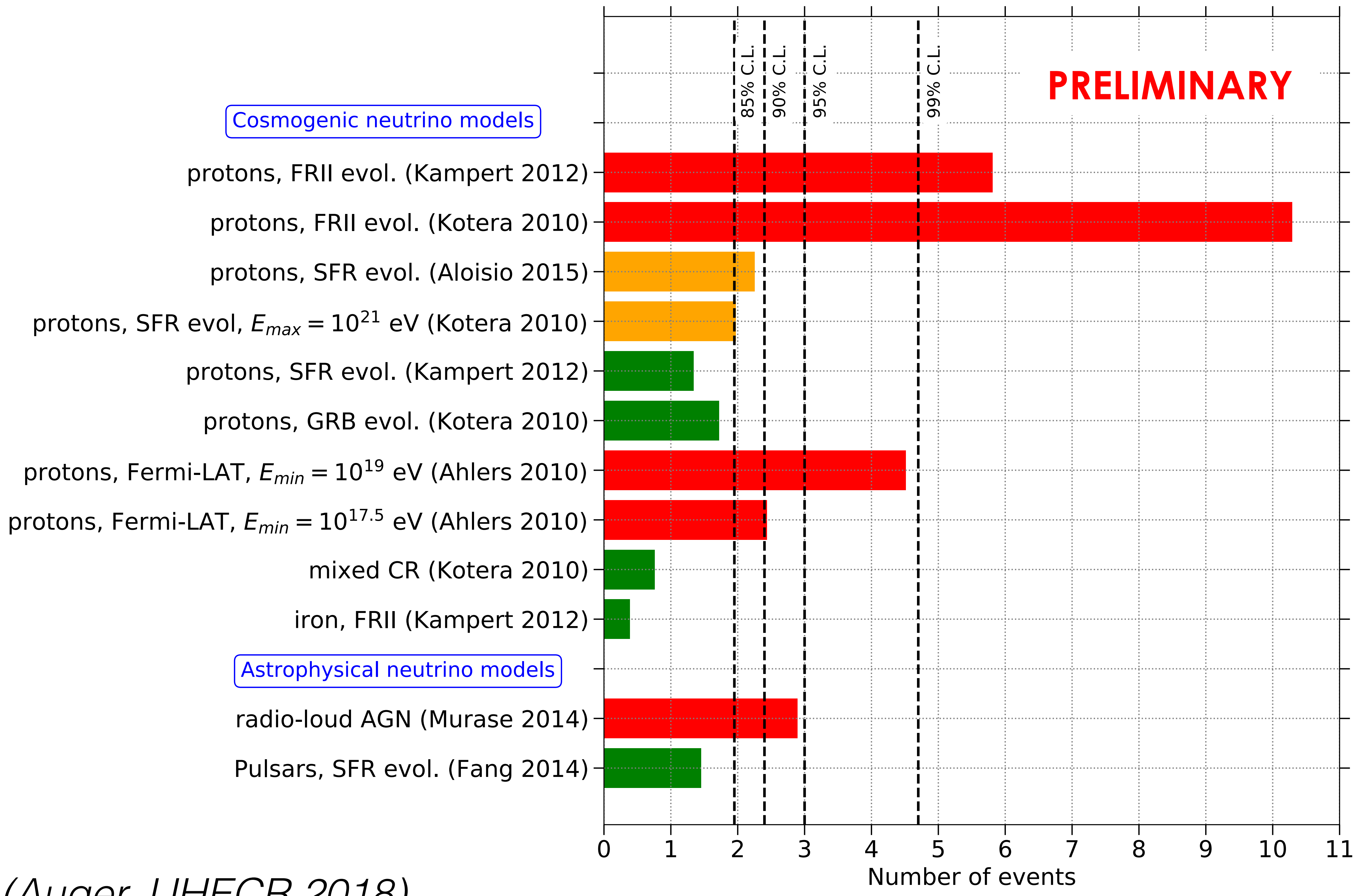
Limits have reached GZK predictions for protons

(Auger ICRC 2019) *(Auger JCAP 2019)*

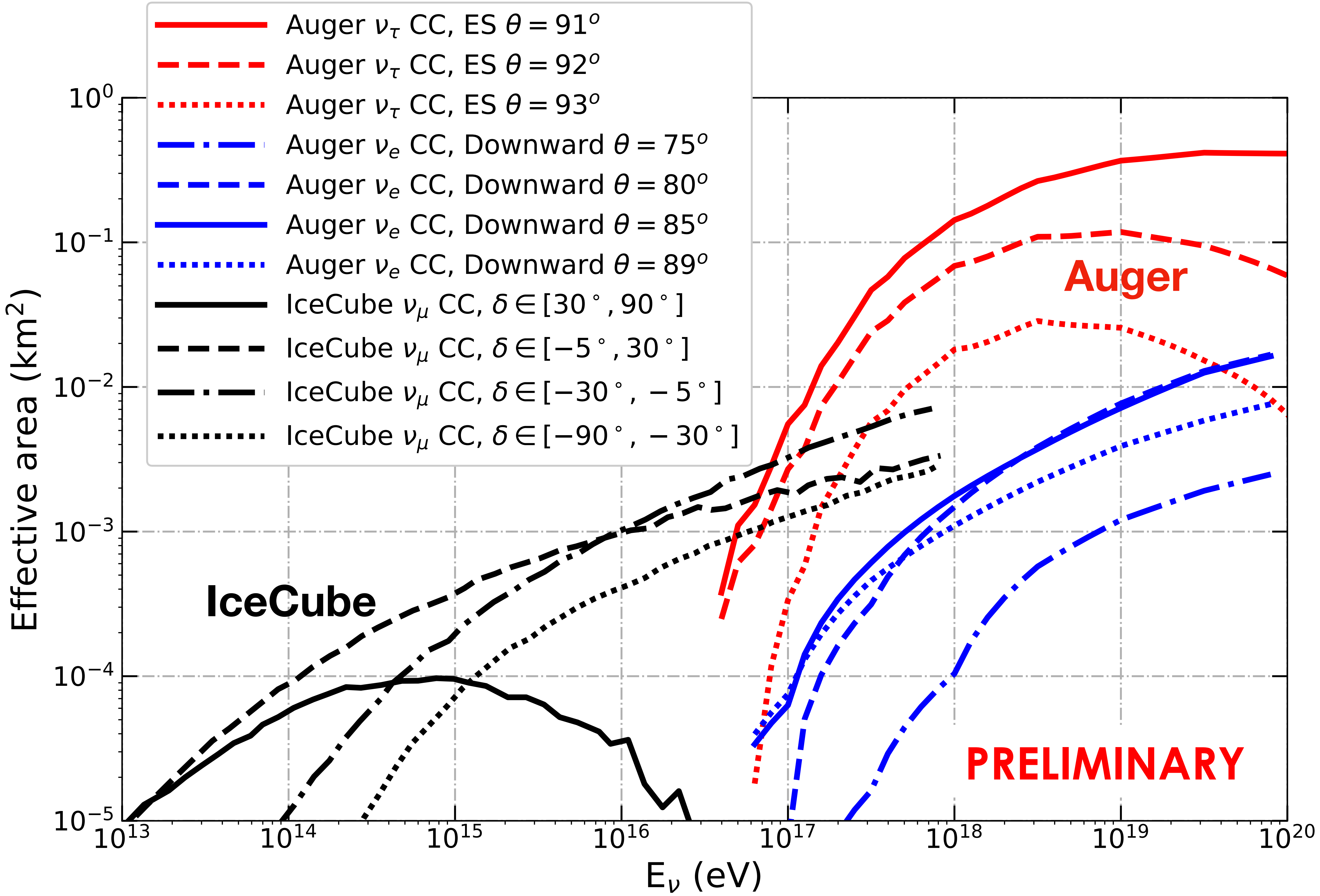
Waiting for the first EHE neutrino (background-free)...



Expected number of events



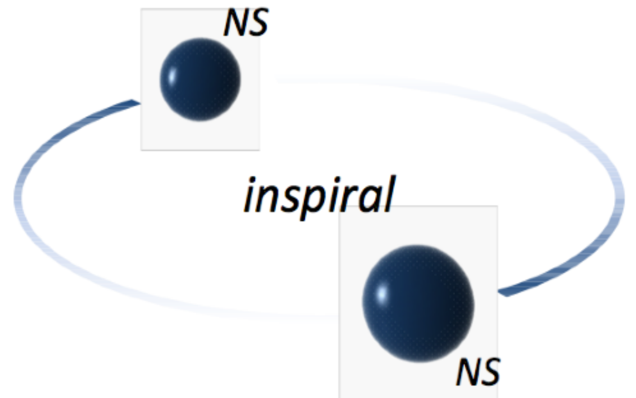
Effective neutrino aperture

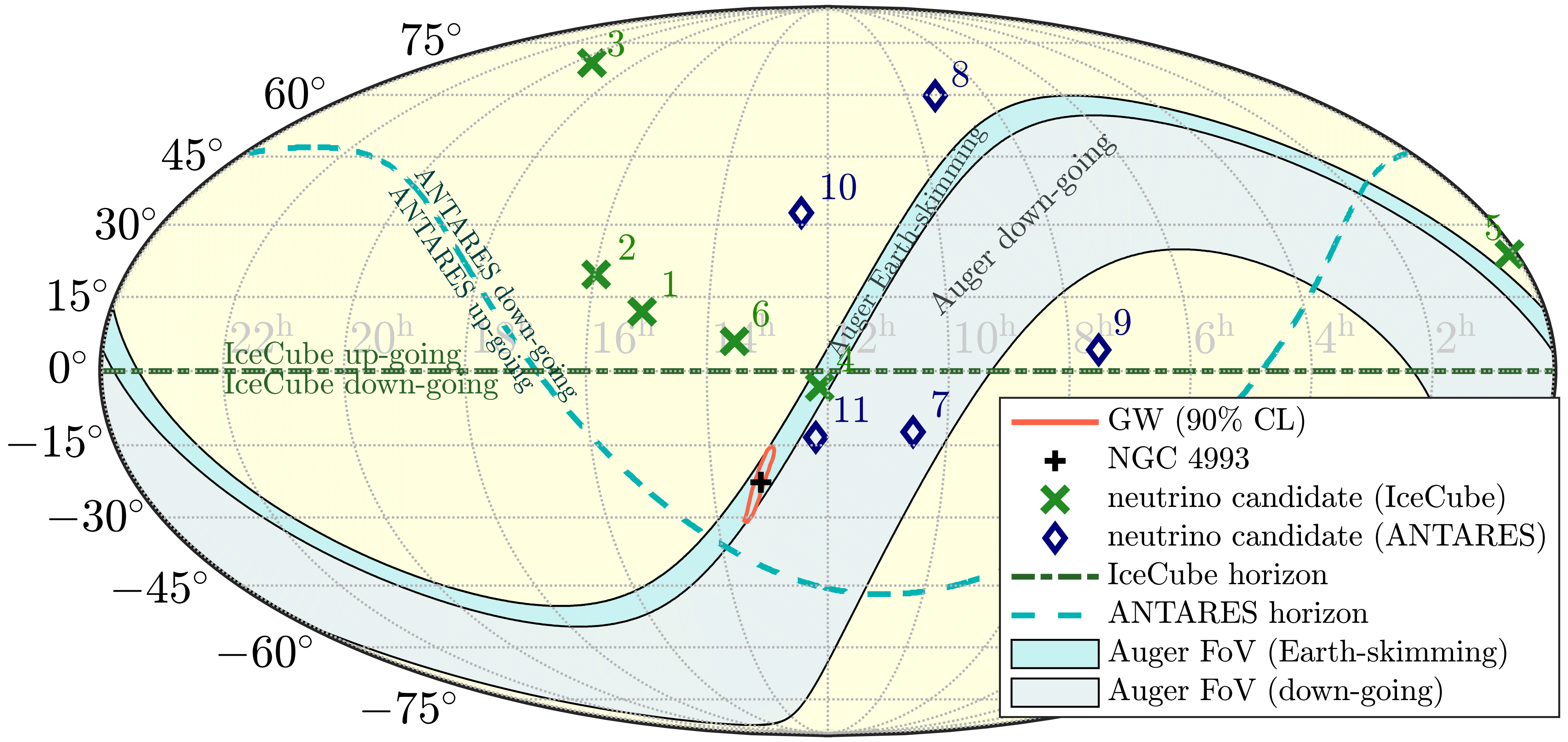


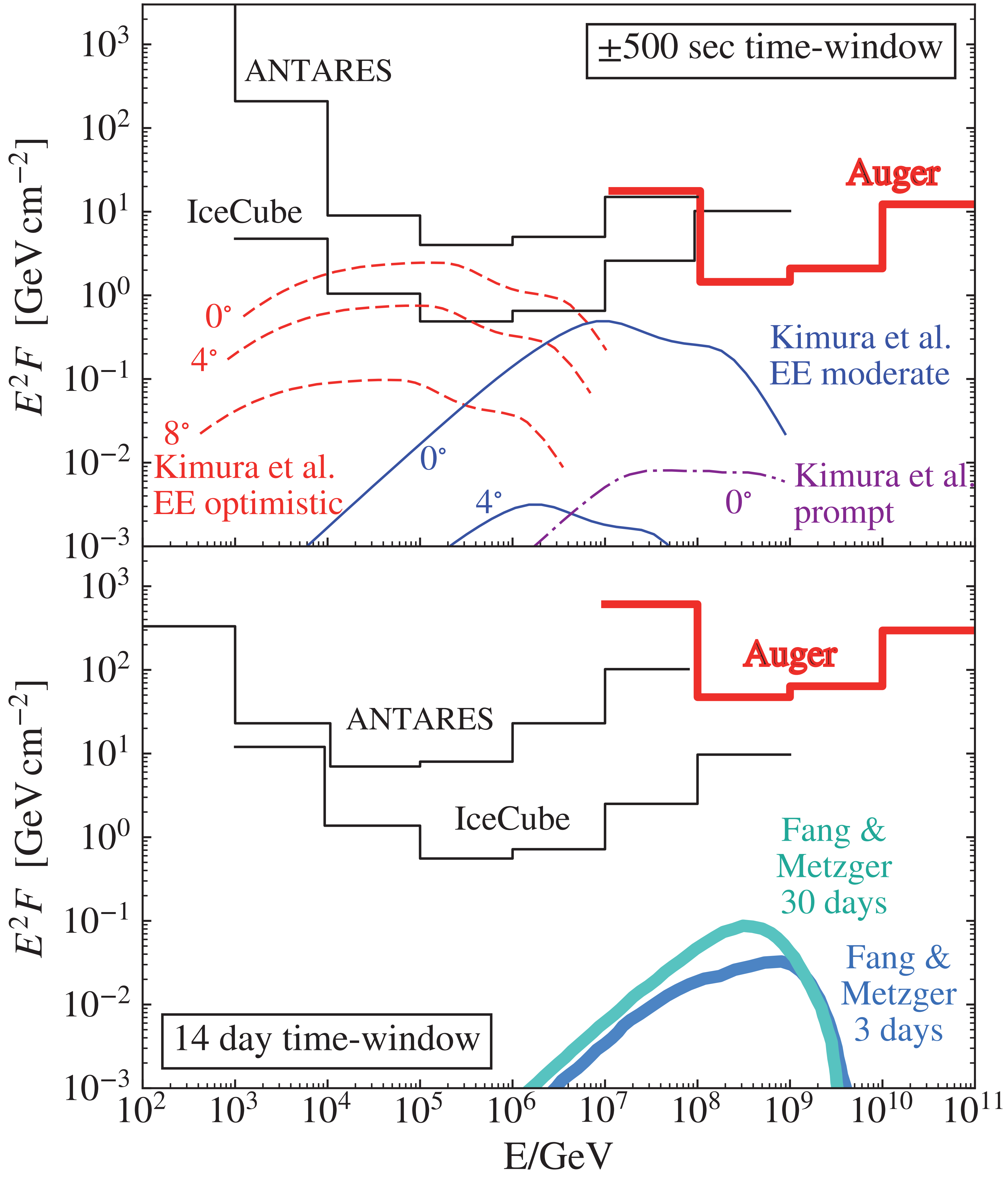
(Auger, UHECR 2018)

Multi-messenger physics – transient events

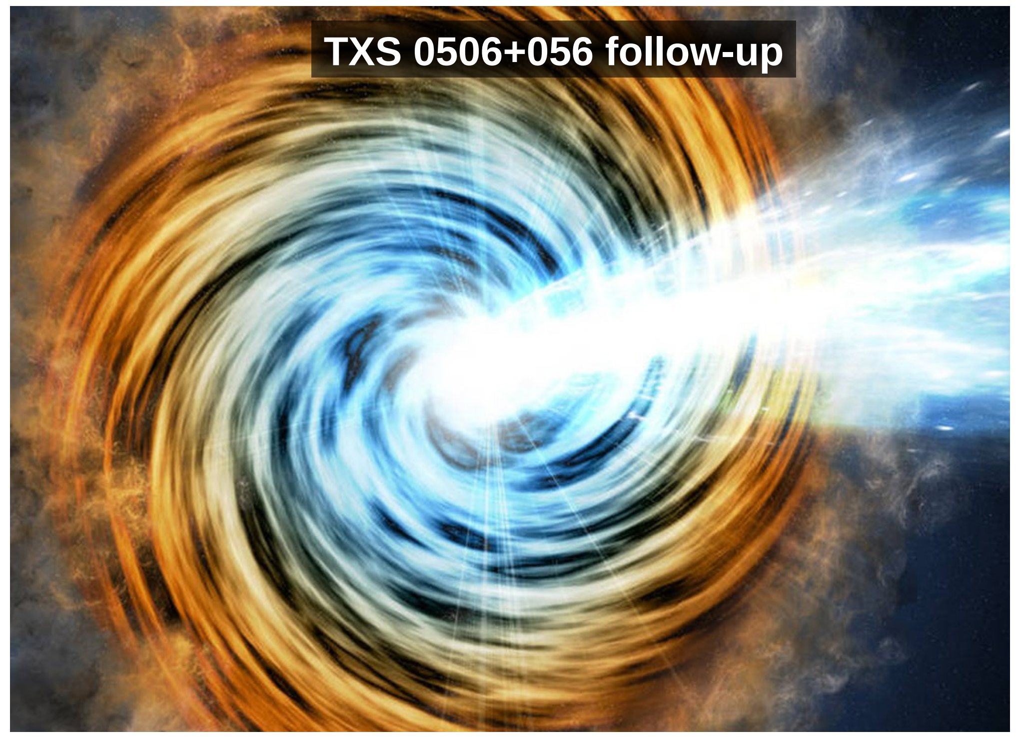
GW170817

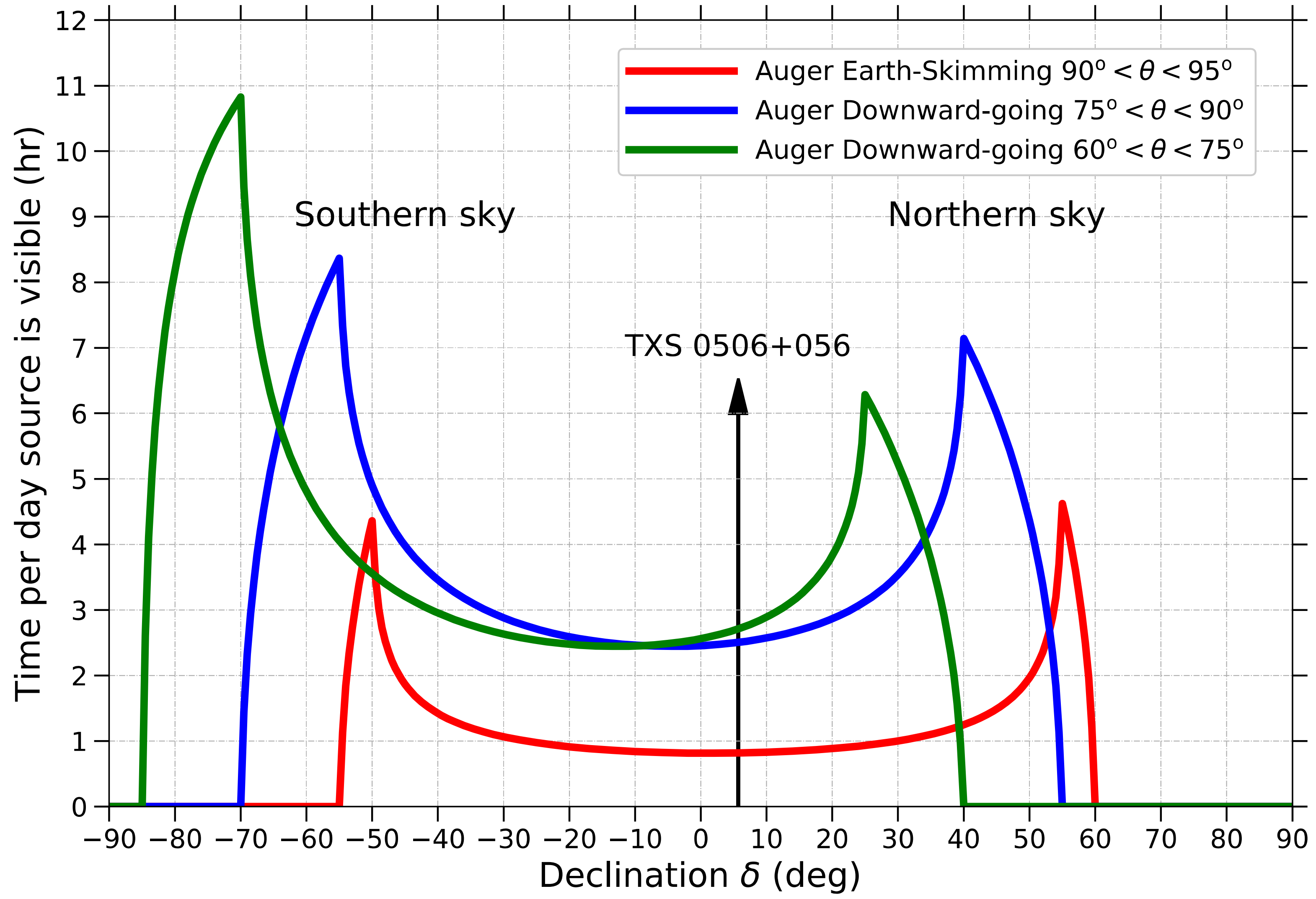






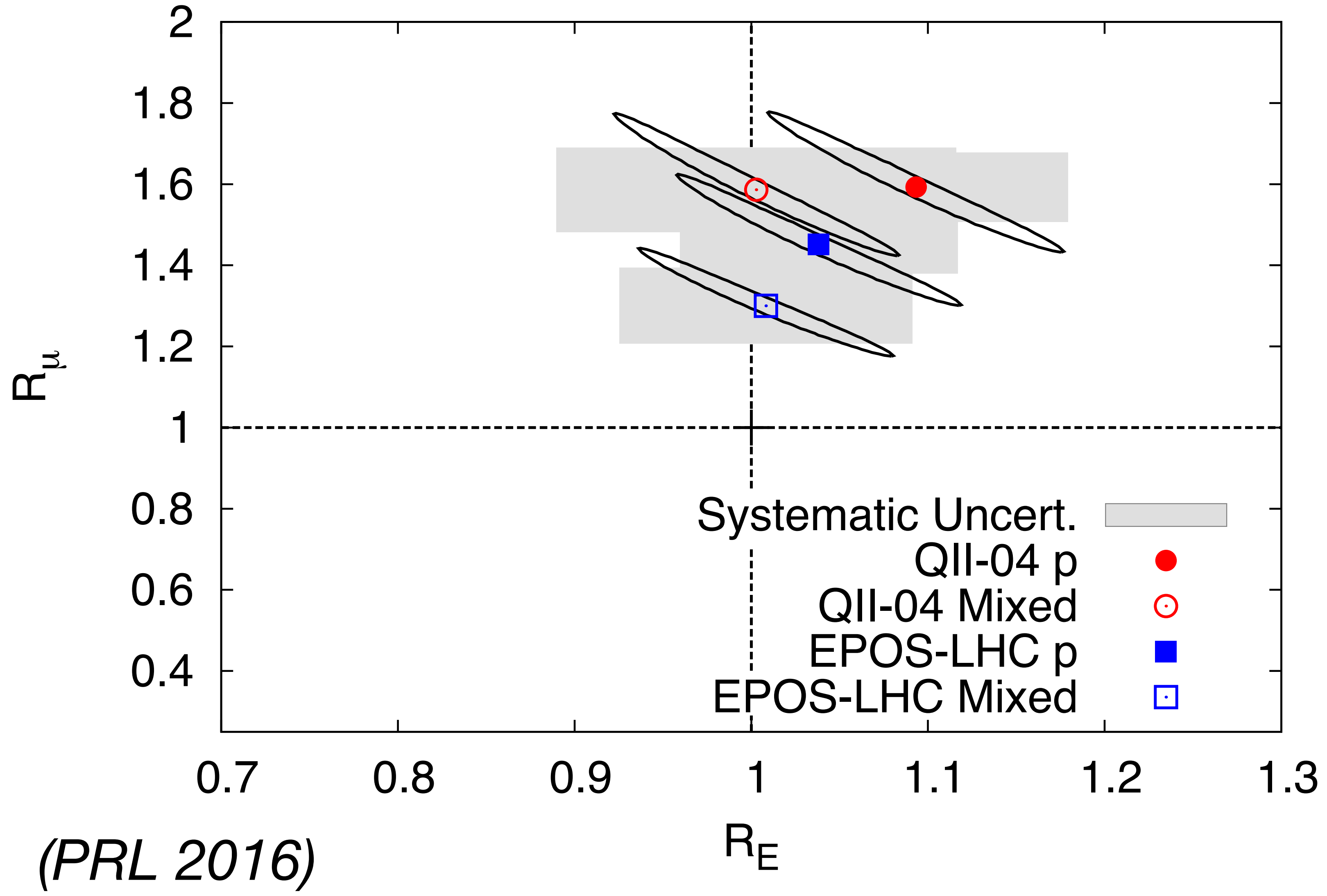
TXS 0506+056





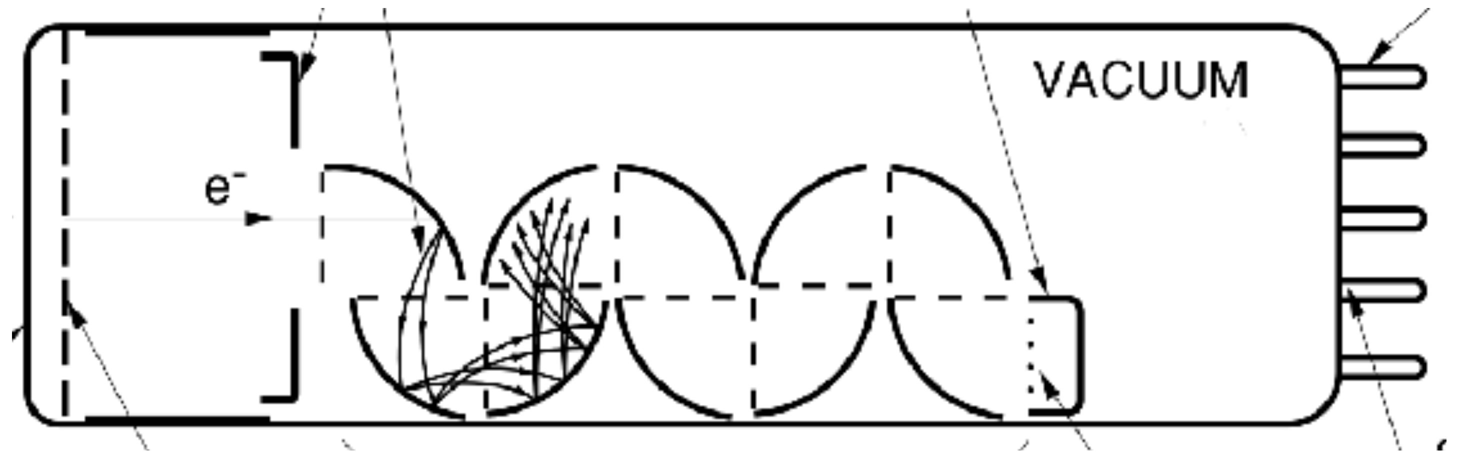
ApJL (2017), special issue (70 collaborations)

5. Hadronic interactions – Auger results

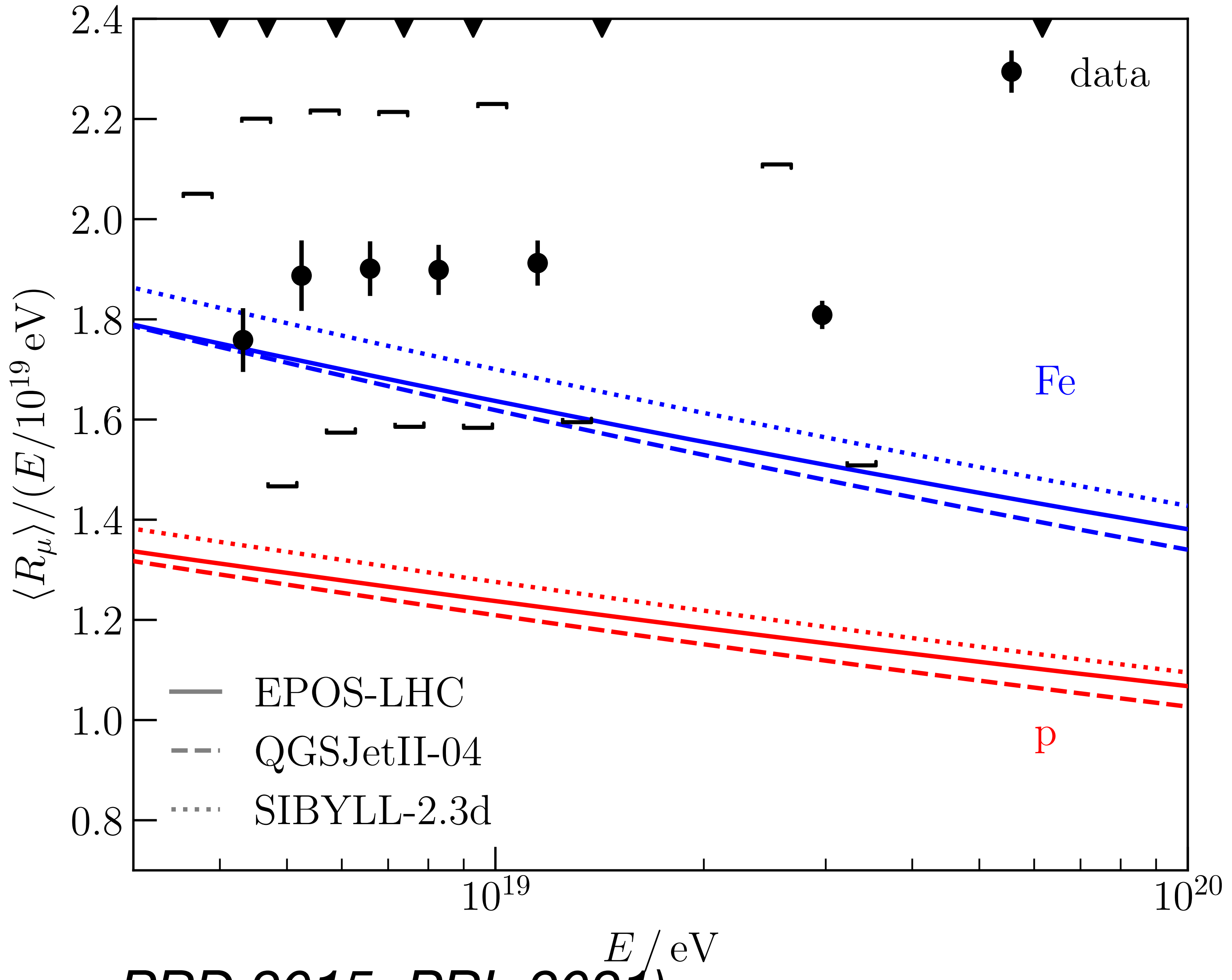


(PRL 2016)

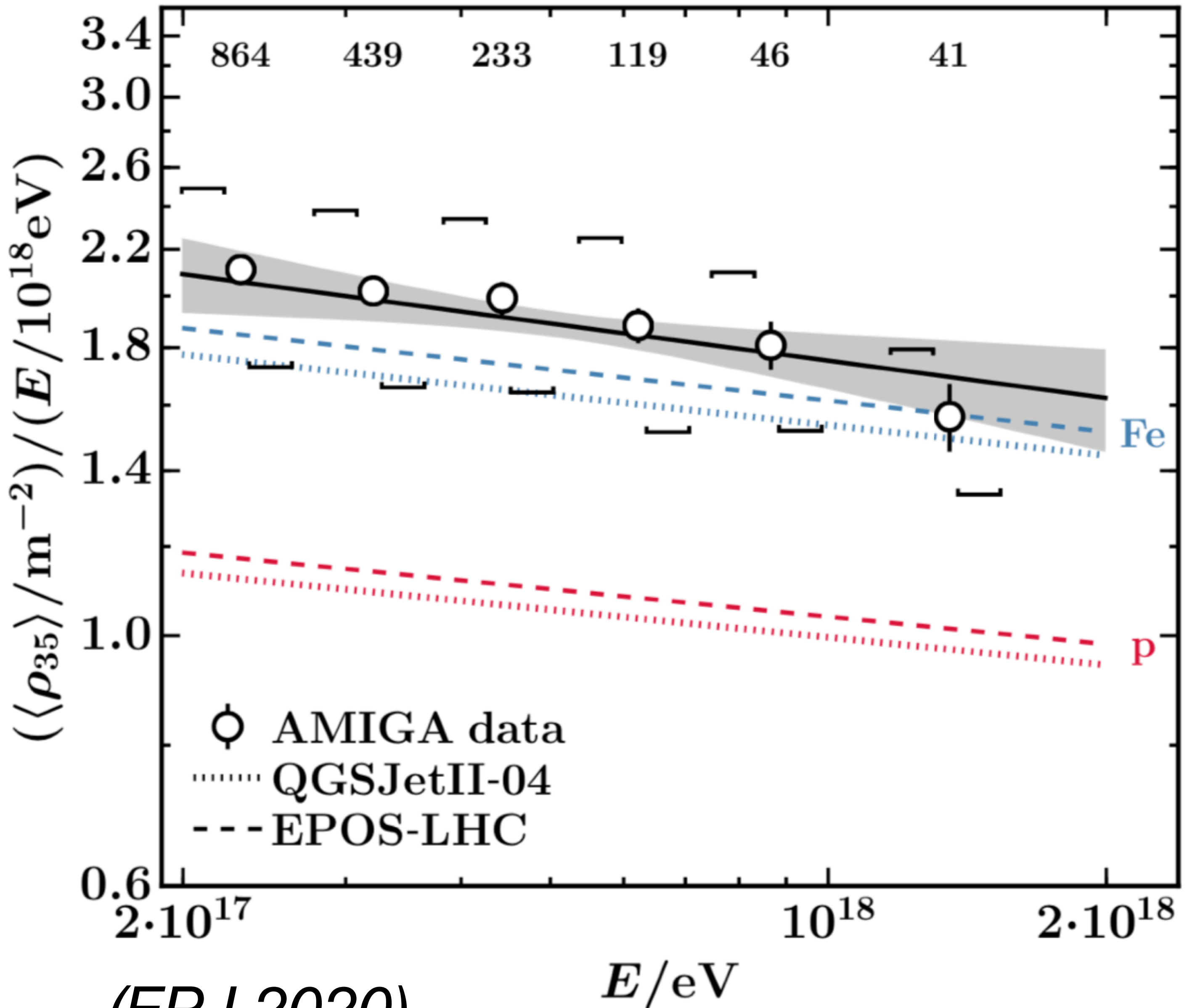
PMT analogy to shower



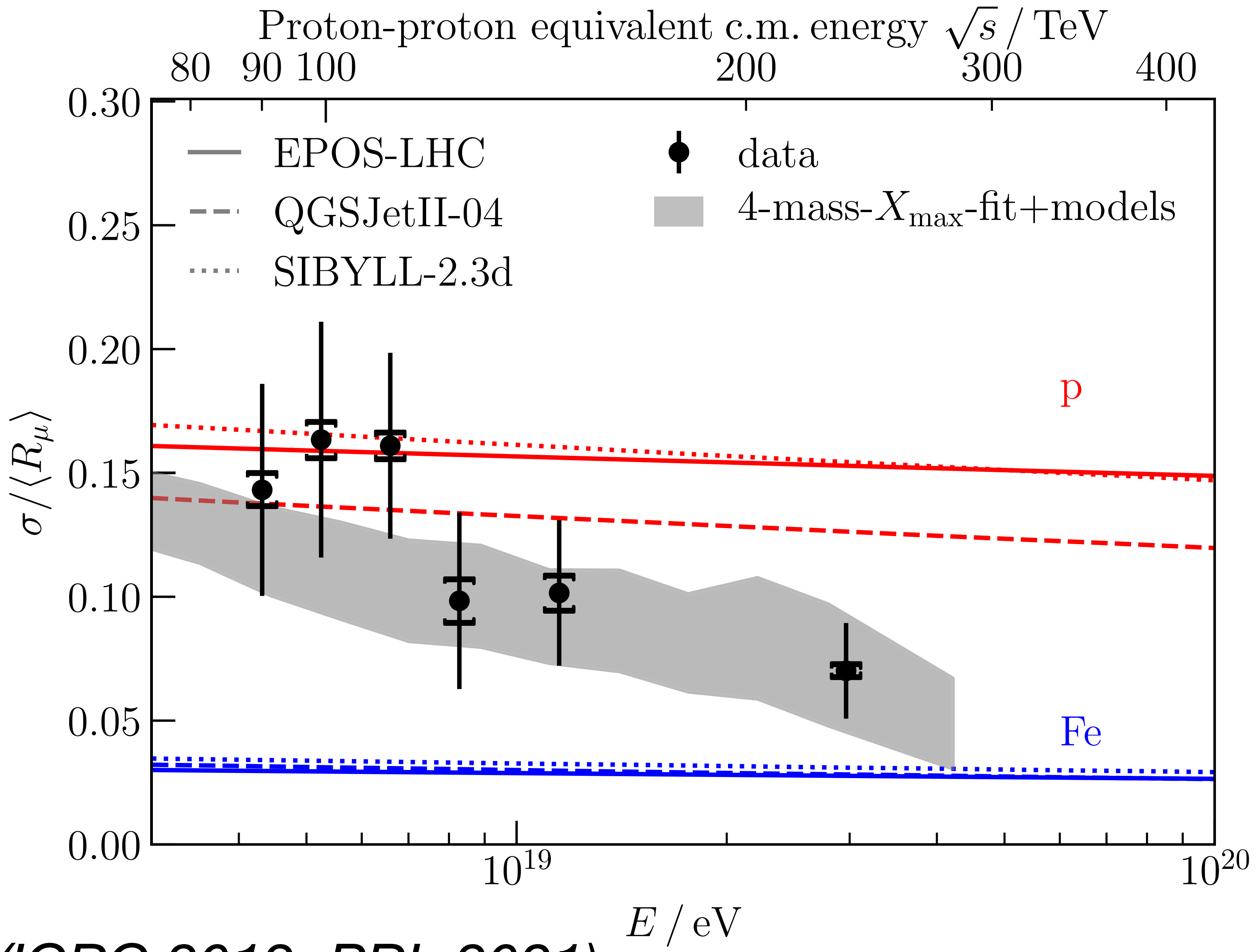
Shower-to-shower fluctuations



(Auger PRD 2015, PRL 2021)

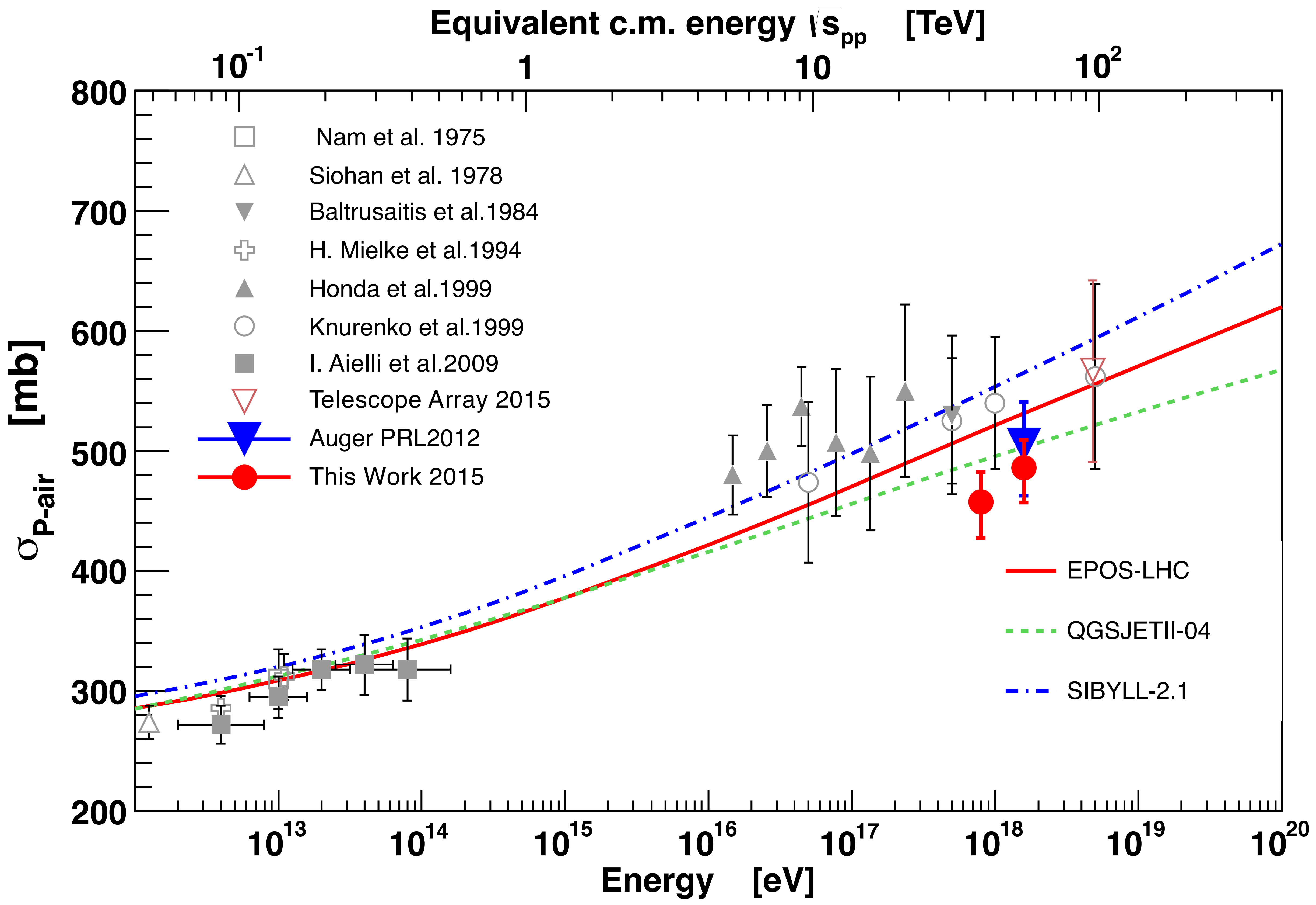


(EPJ 2020)



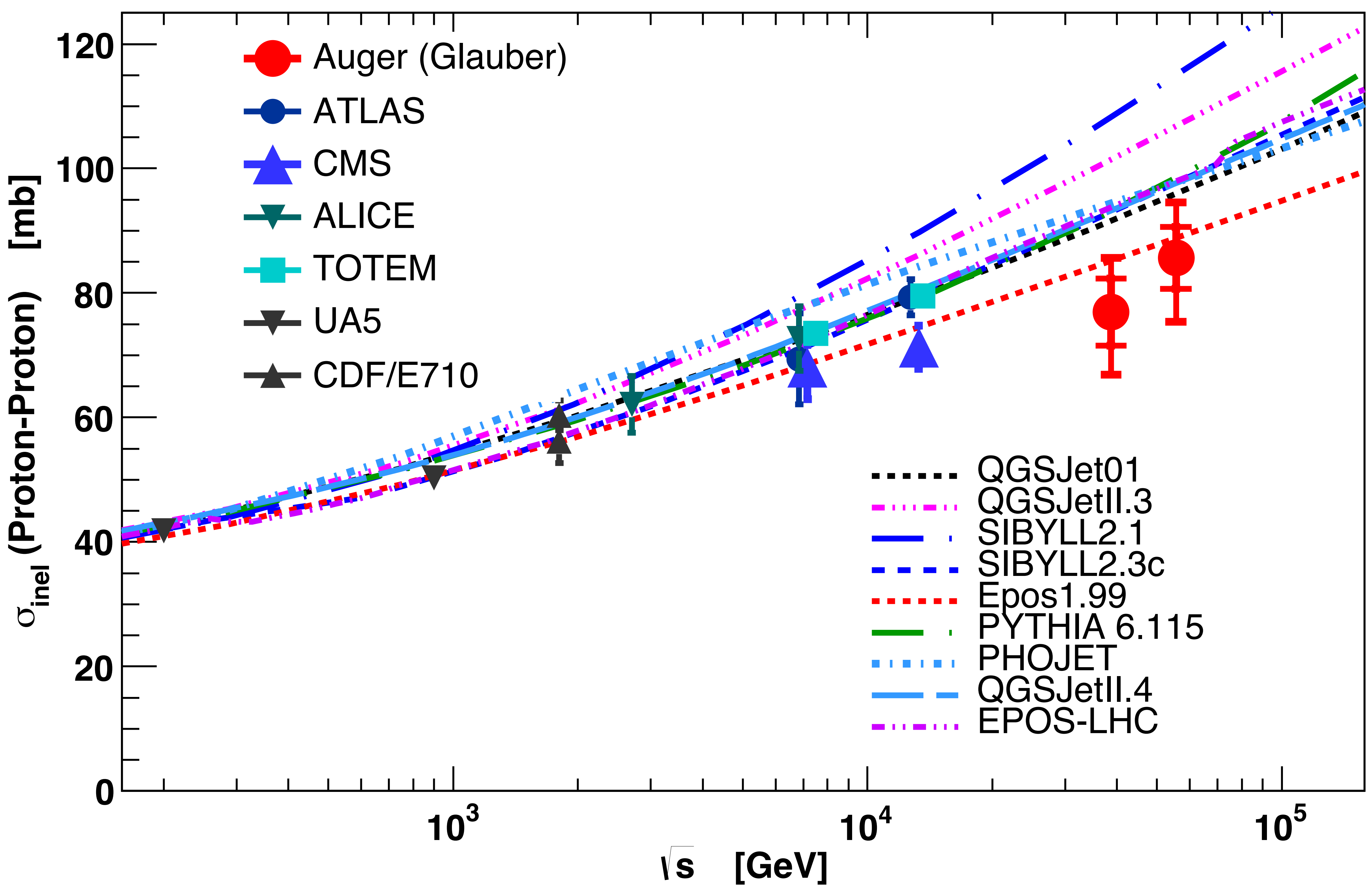
(ICRC 2019, PRL 2021)

Proton-air cross section measurement



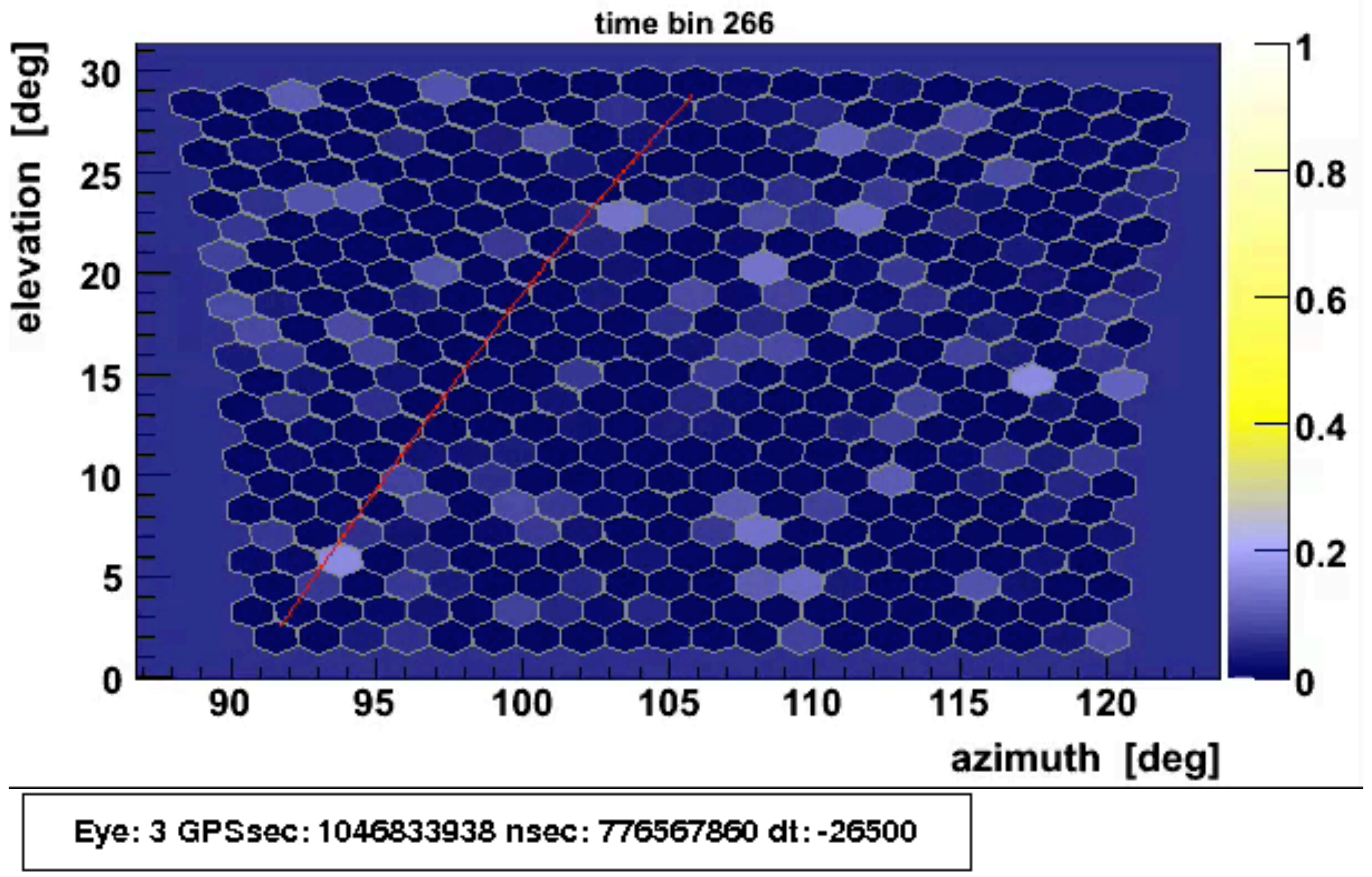
Models, collider data, Auger (derived) cross sections

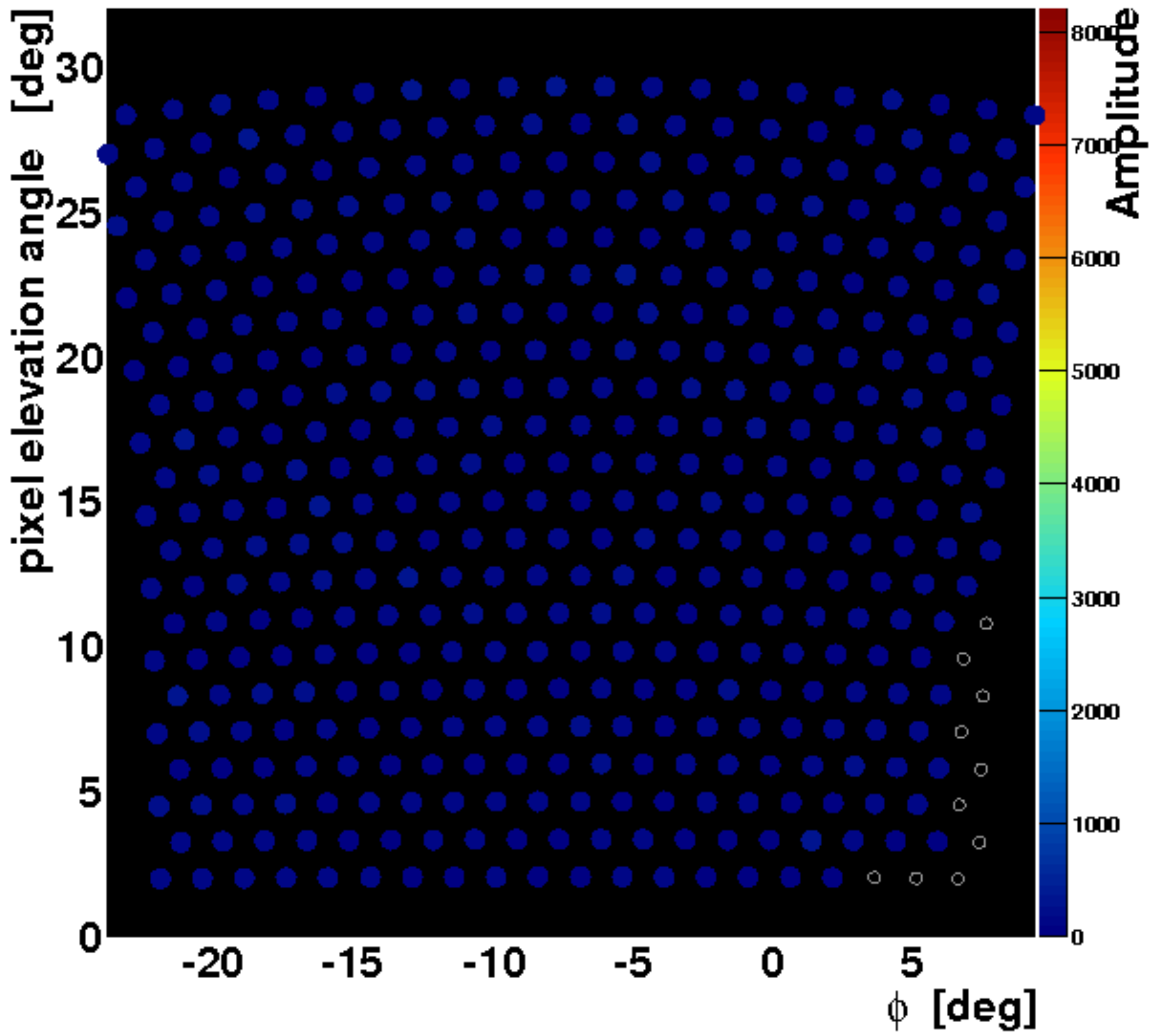
Glauber model (multiple scattering approximation)

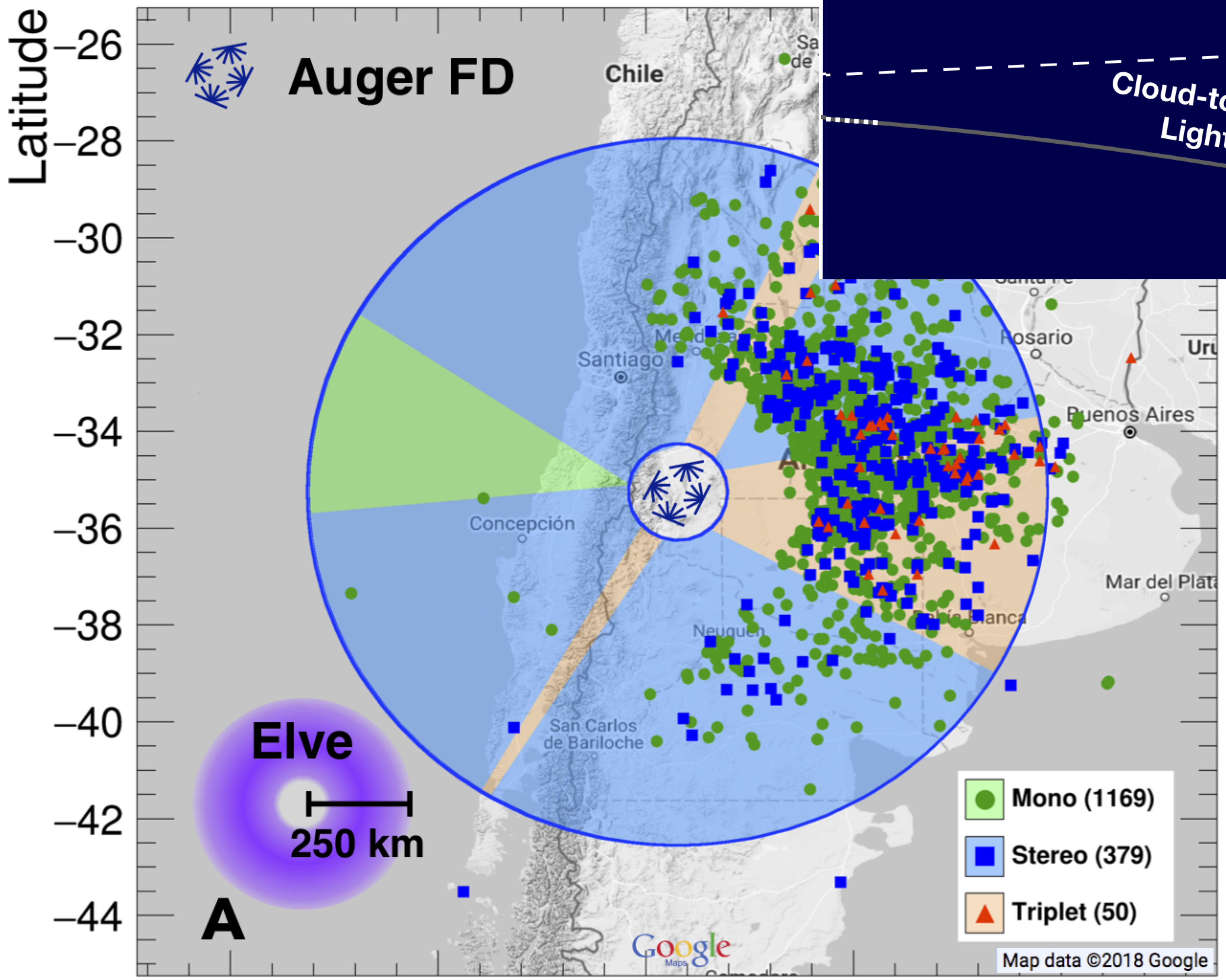


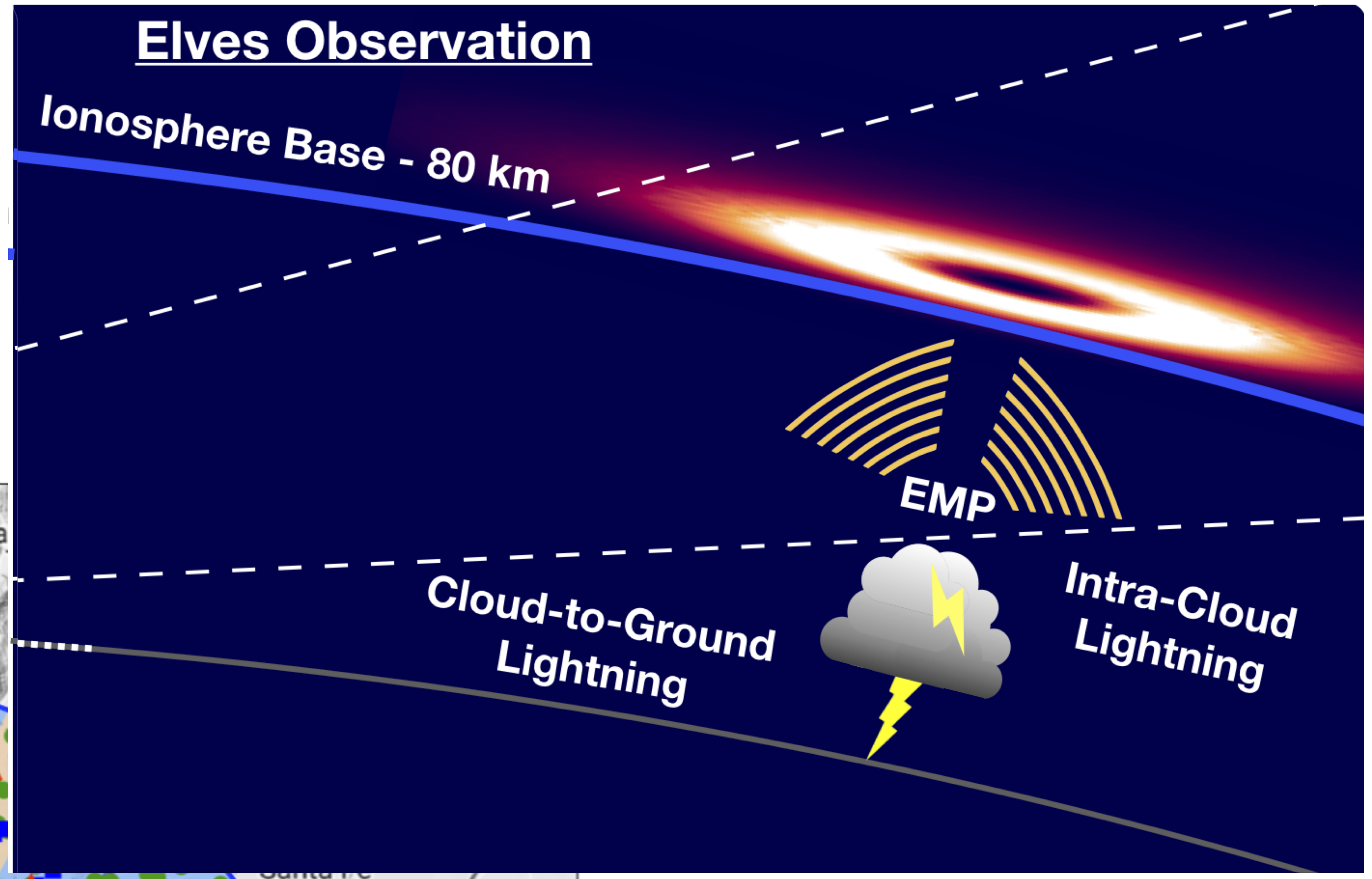
(Auger, Phys. Rev. Lett. 2012, ICRC 2017 , see also discussion Lipari, Phys.Rev.D 103 (2021) 103009)

6. Atmospheric and geo-physics observations









1600 elves observed

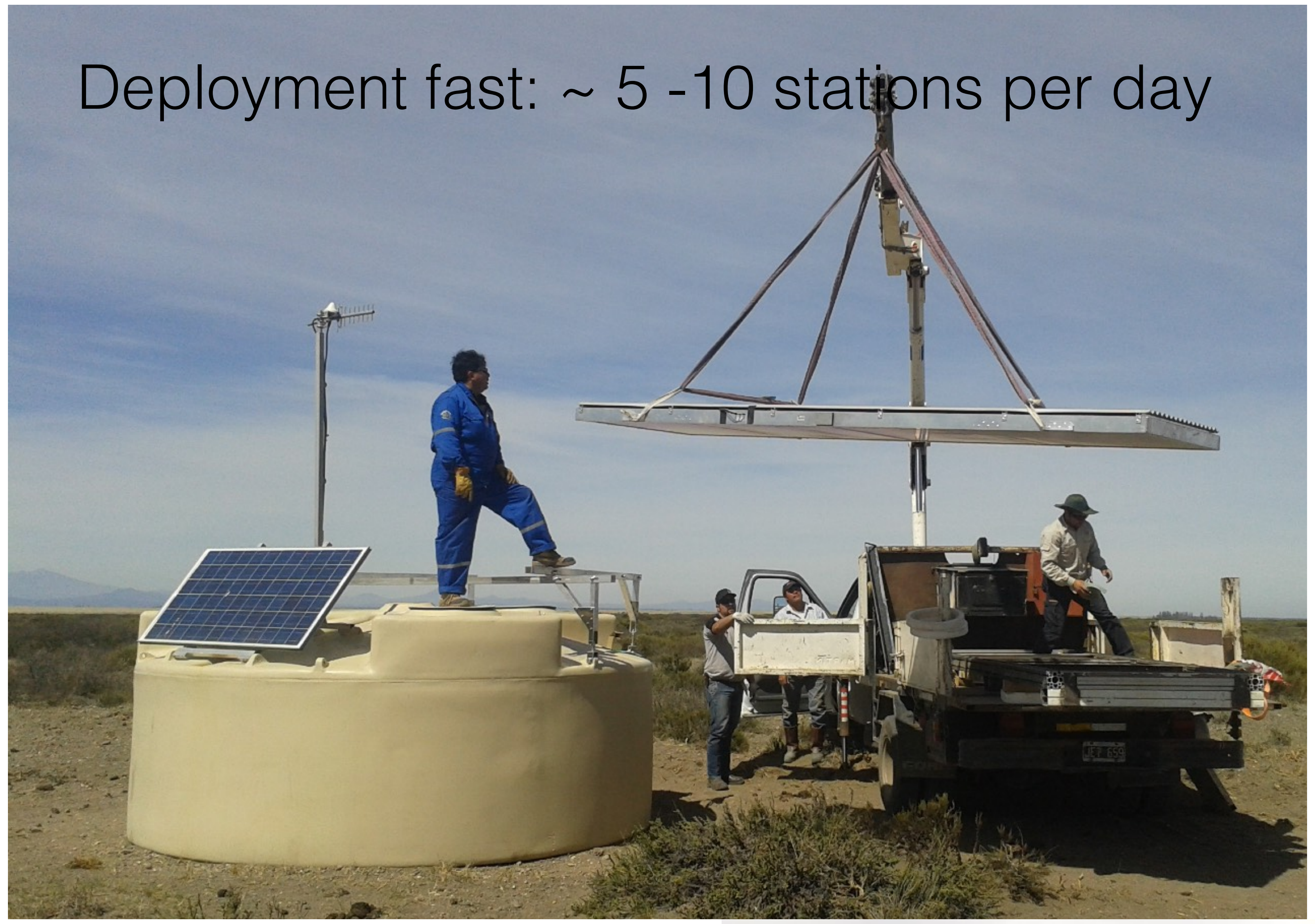
(Earth and Space Sciences, 2020)

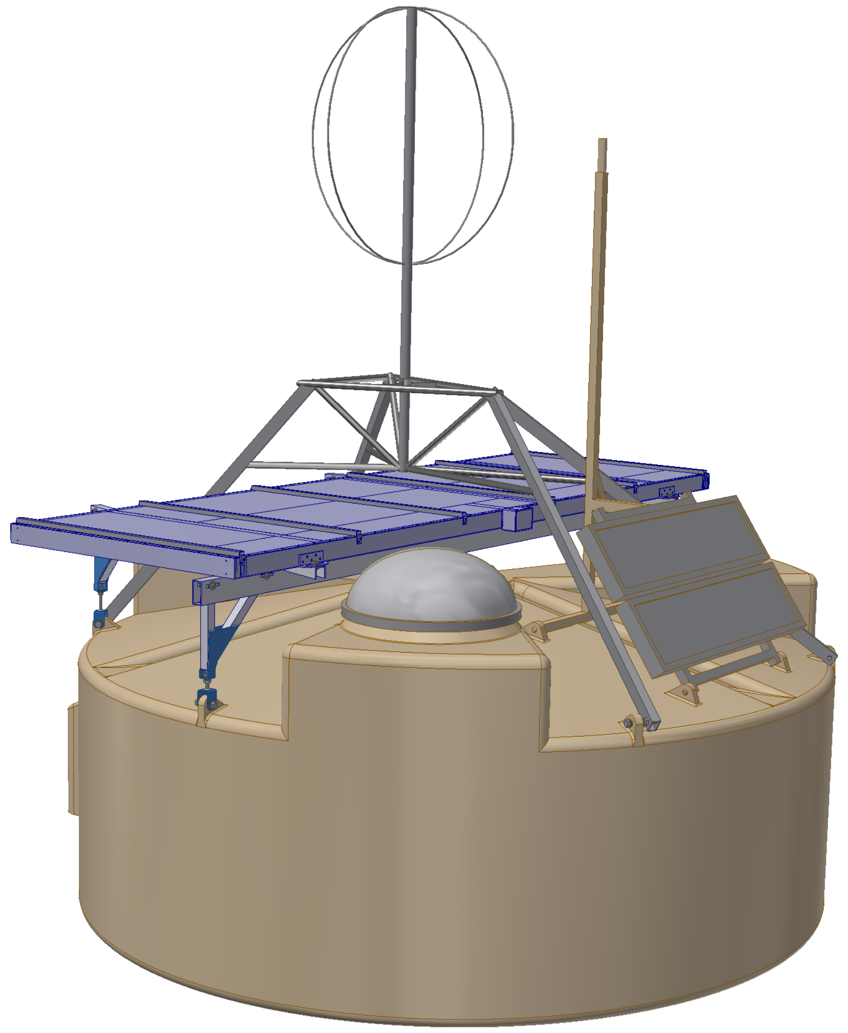
AugerPrime – the upgrade of the Pierre Auger Observatory

Upgrade of Auger Observatory: scintillators

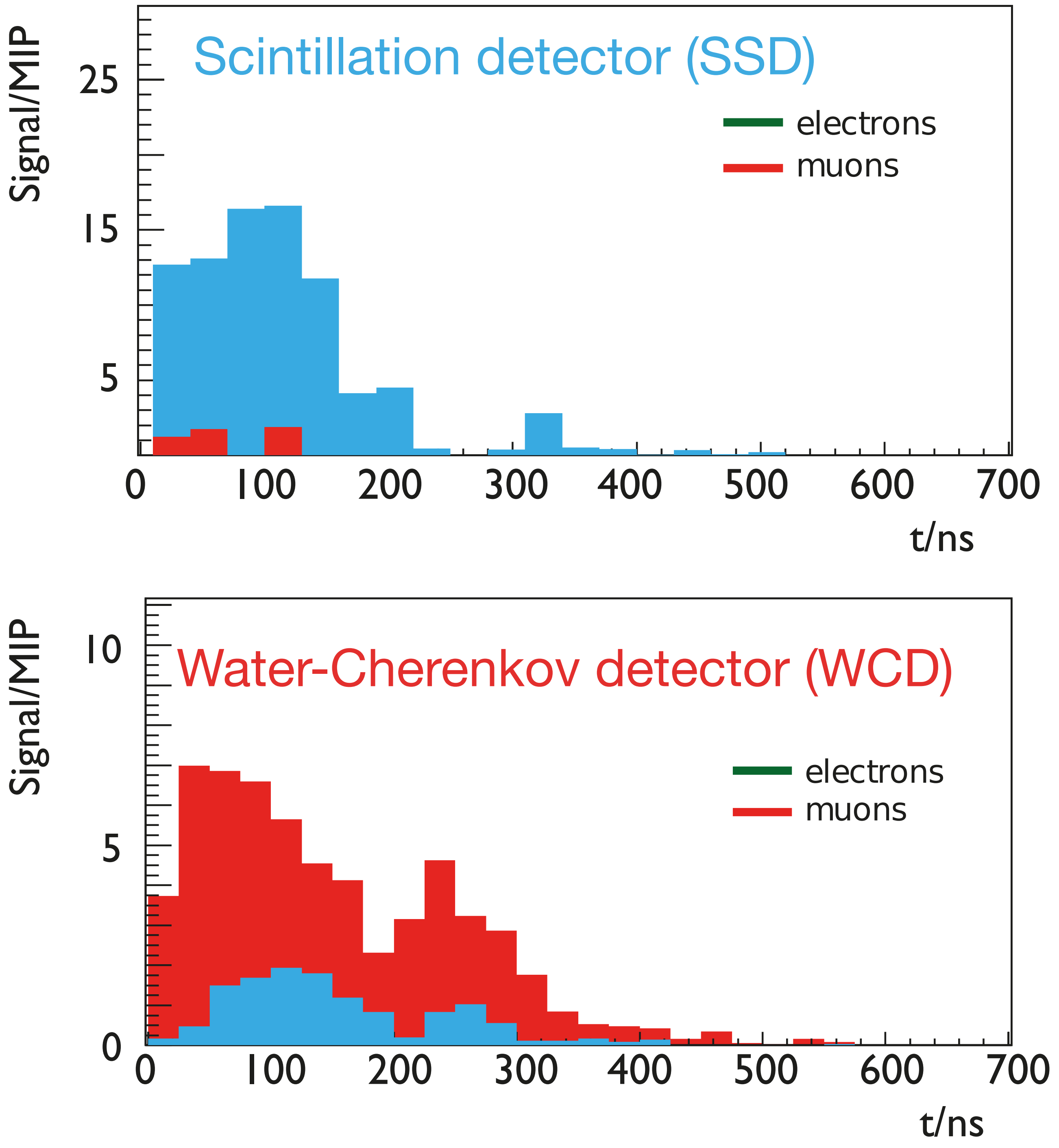
15% duty cycle

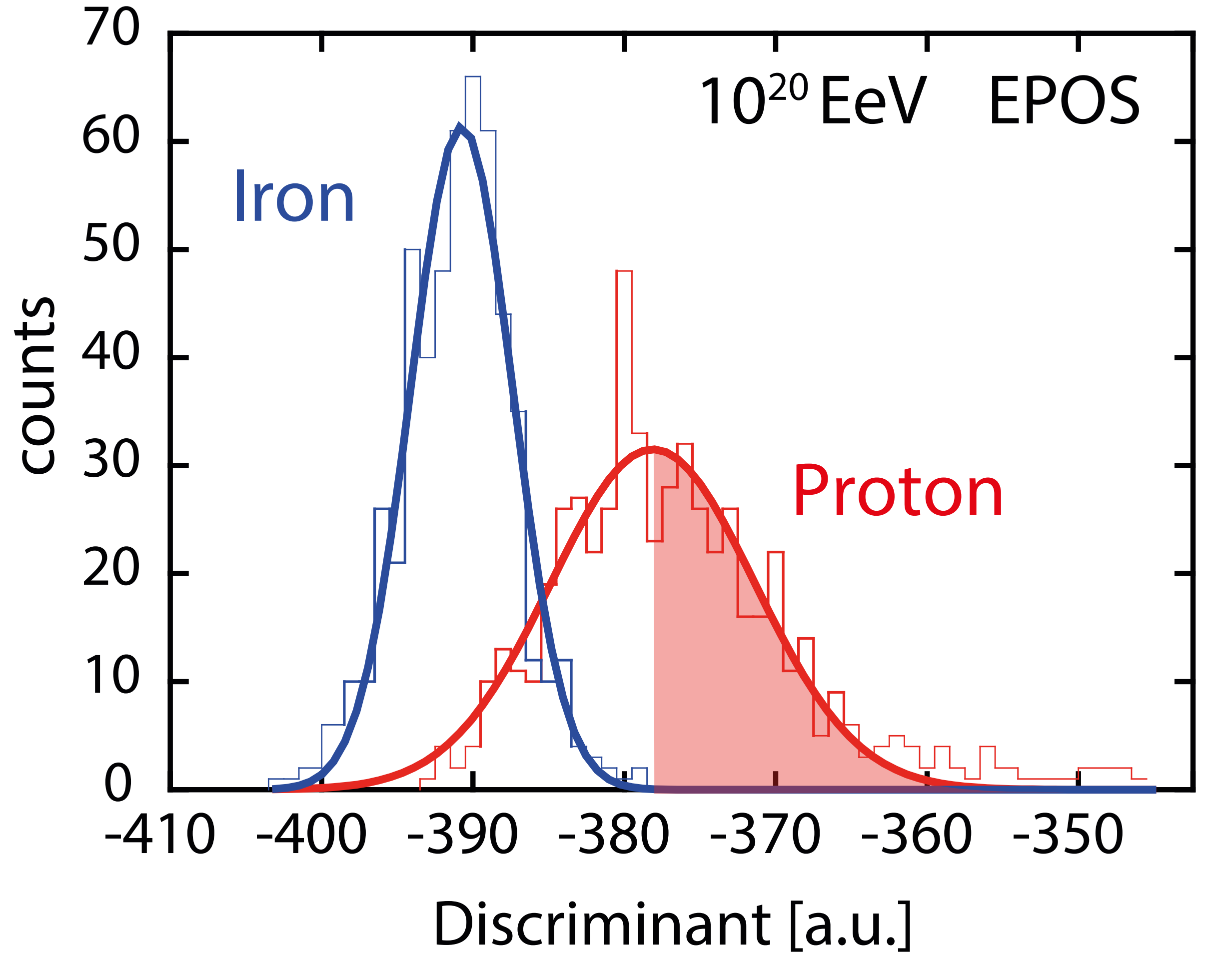
100% duty cycle





Radio antennas for inclined showers





- **Scintillators (3.8 m²) and radio antenna on top of each array detector**
- **Composition measurement up to 10^{20} eV**
- **Composition selected anisotropy**
- **Particle physics with air showers**

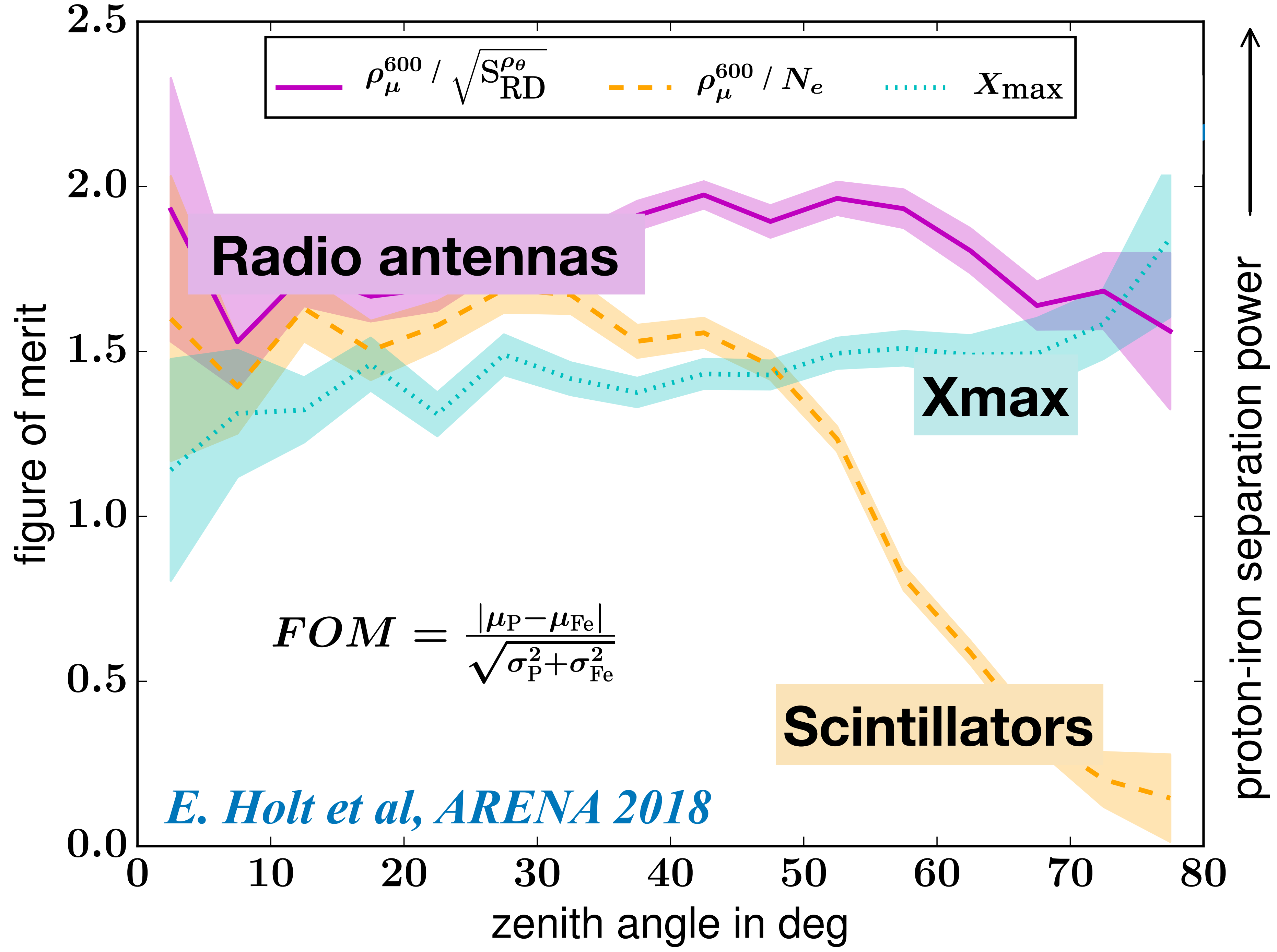
(AugerPrime design report 1604.03637)

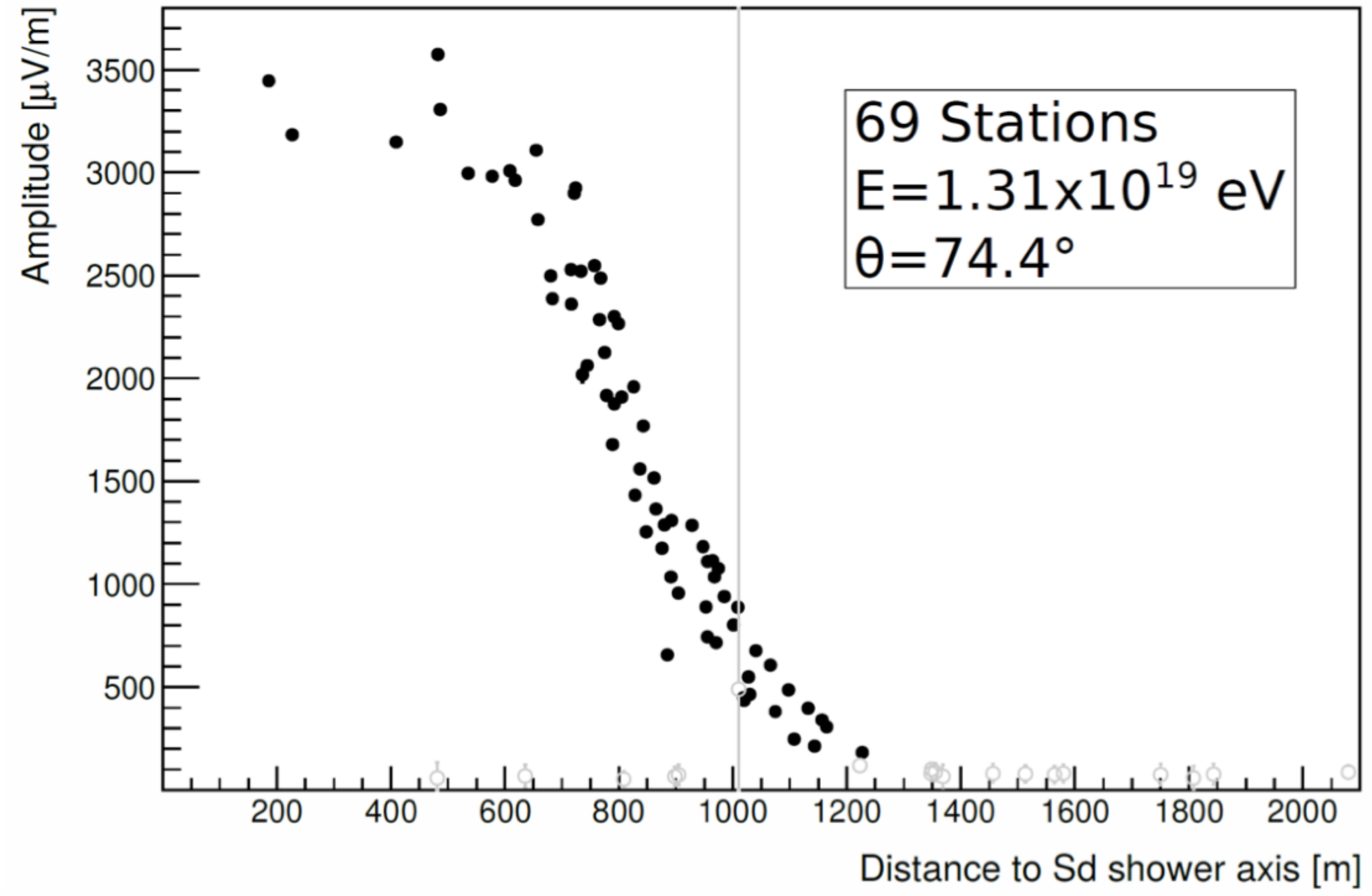
Upgrade of Auger Observatory: radio antennas

Composition information for inclined / horizontal showers (calorimetric)
Larger field of view for anisotropy studies, neutrino and gamma-ray search

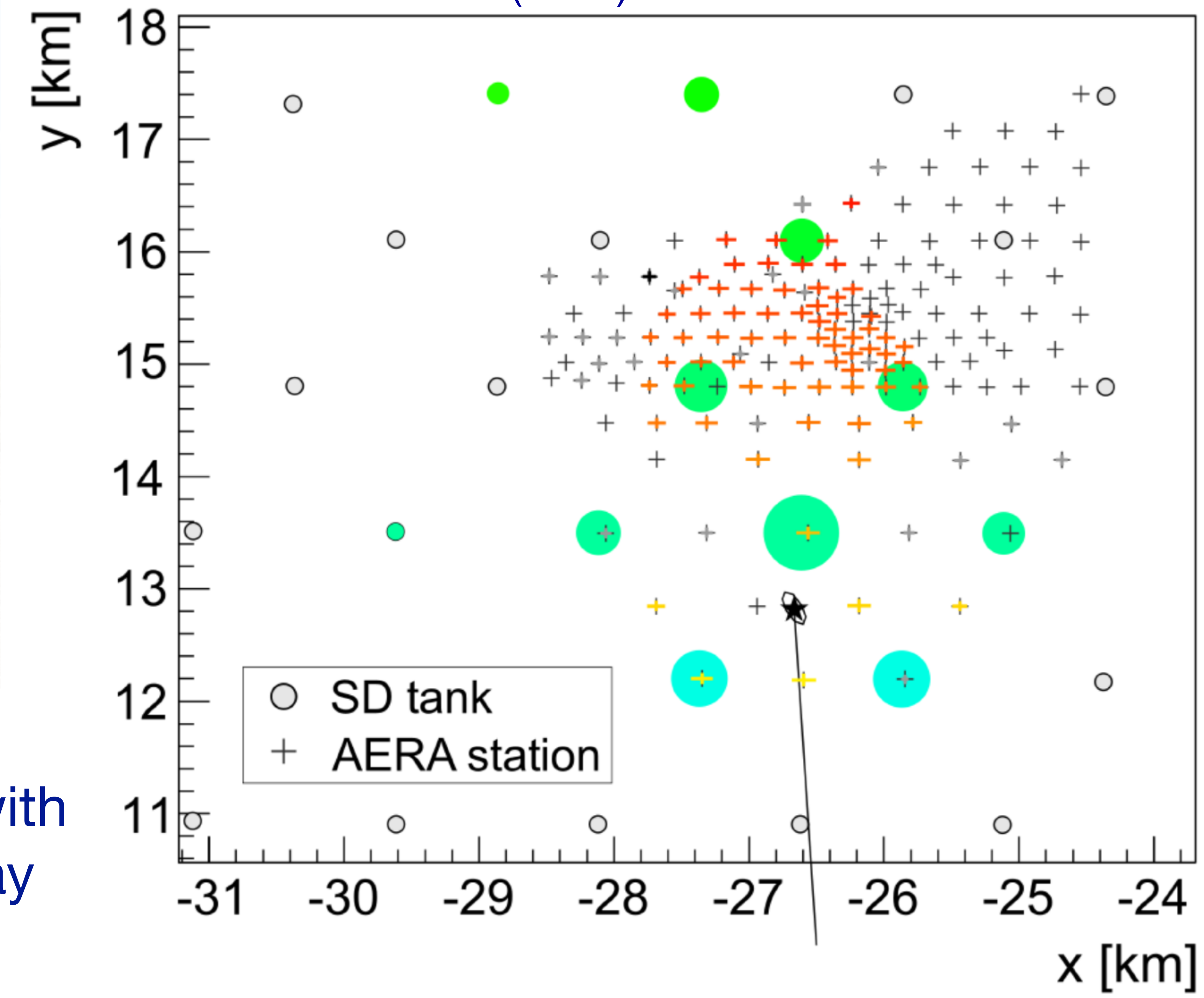
Prototype station in field (Jan. 2019)

Theoretically possible sensitivity



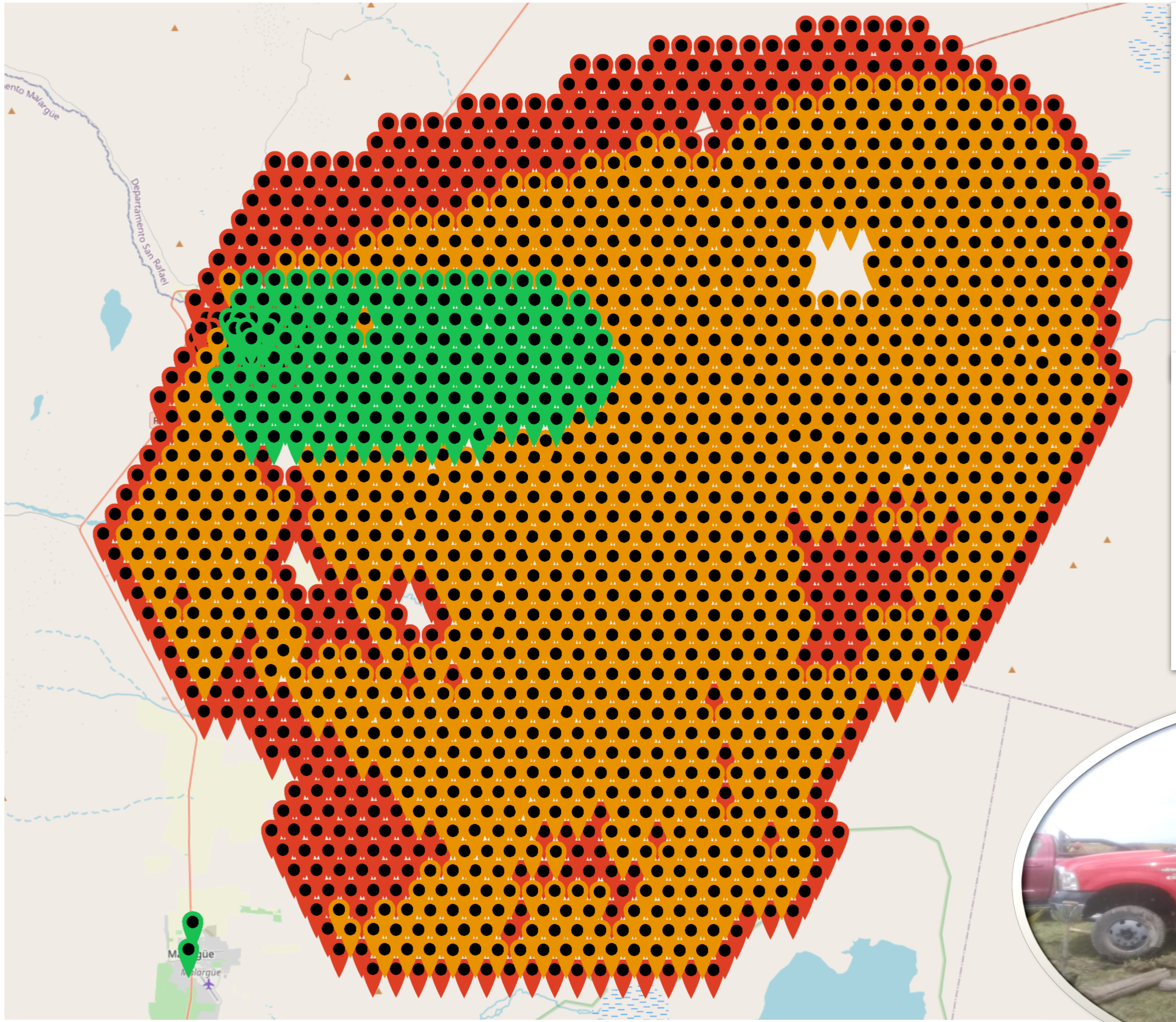


EPJ WoC. 135(2017)01015



Event observed with existing radio array (AERA, 17 km²)

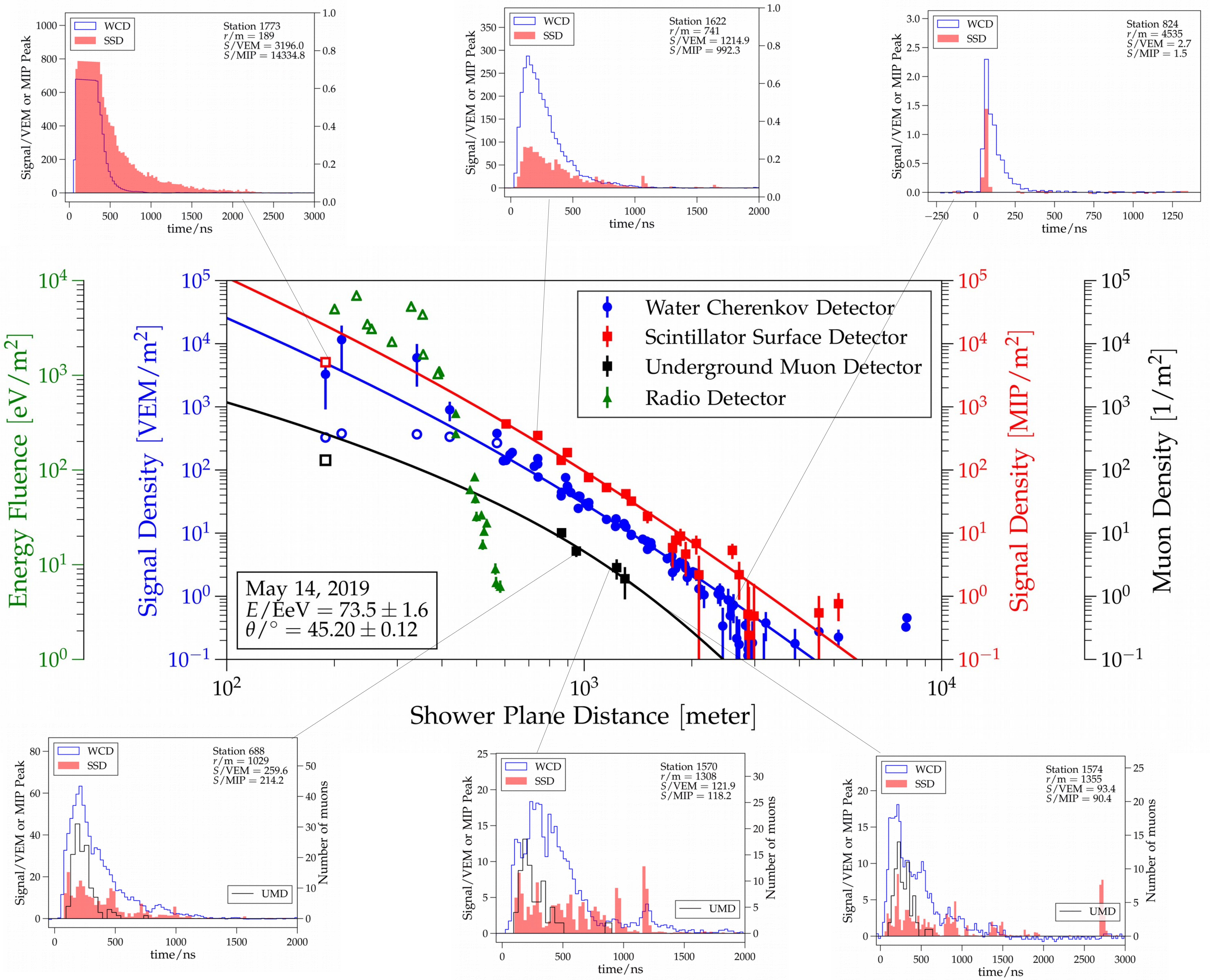
Status of detector deployment



SSD installed (1199 detectors) with PMT (152 detectors) w/o PMT (1047 detectors)

Deployment of scintillator modules and electronics progressing well, radio antennas to follow, to be completed in 2023

New quality of data – multi-hybrid measurements



Physics with the upgraded Observatory

Auger exposures for comparison

Spectrum (2004 – 2018, 6T5, $\theta < 60°$): 60,400 km^2 sr yr

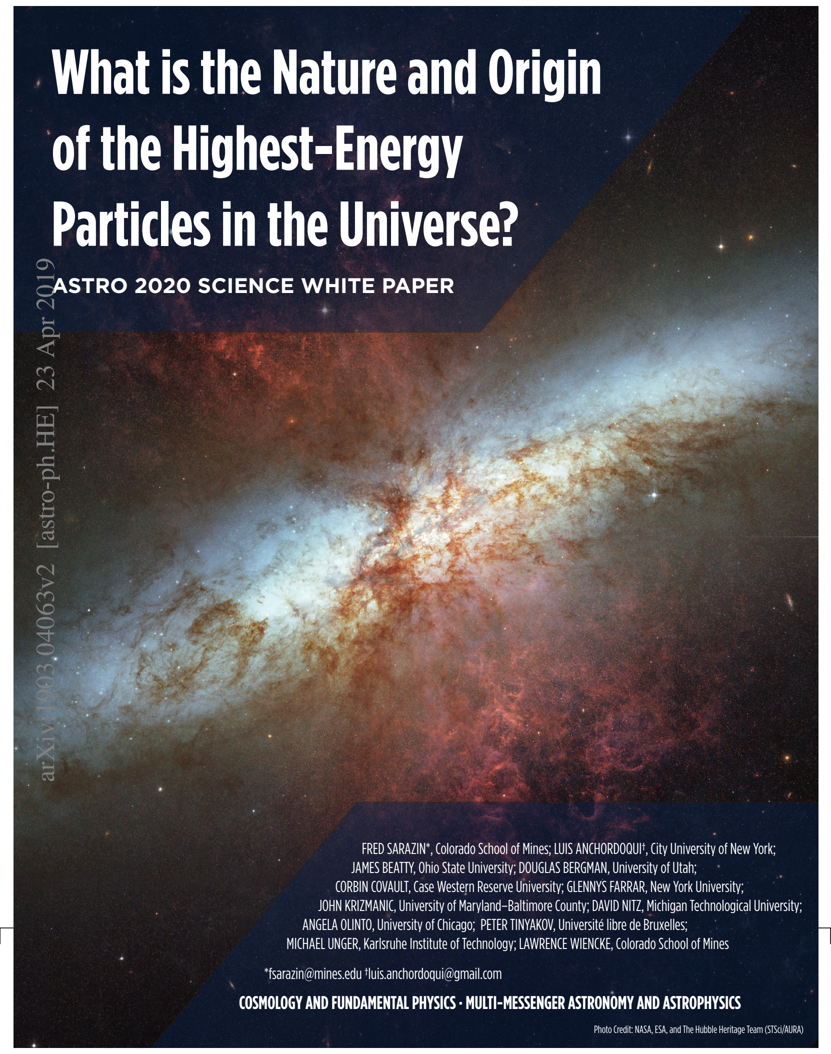
Collect every year ~5300 km^2 sr yr (6T5, $\theta < 60°$)

Anisotropy (2004 – 2020, all angles): ~ 120,000 km^2 sr yr (4T5 pos/2)

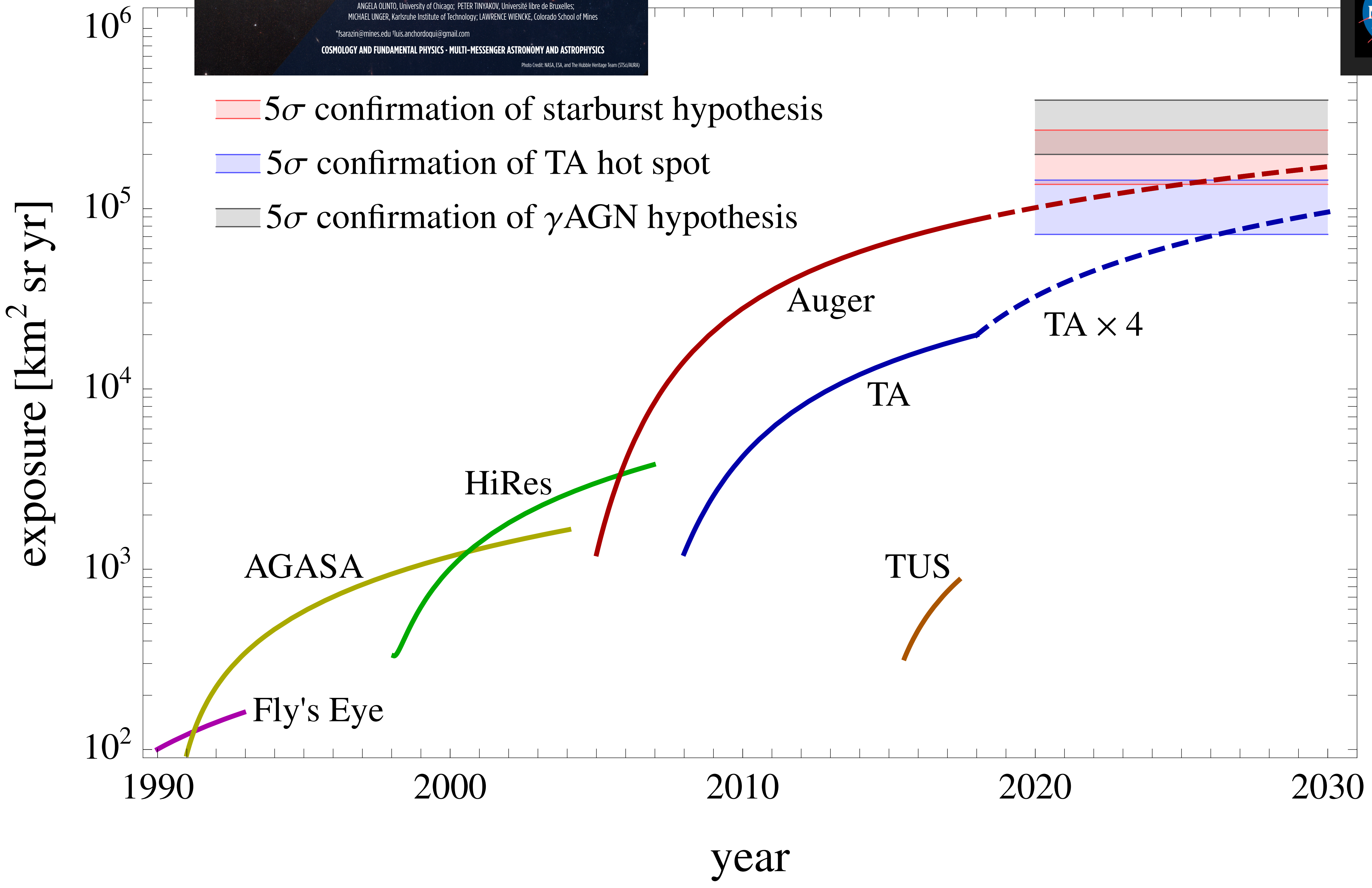
AugerPrime (7-8 years, $\theta < 60°$): ~ 40,000 km^2 sr yr

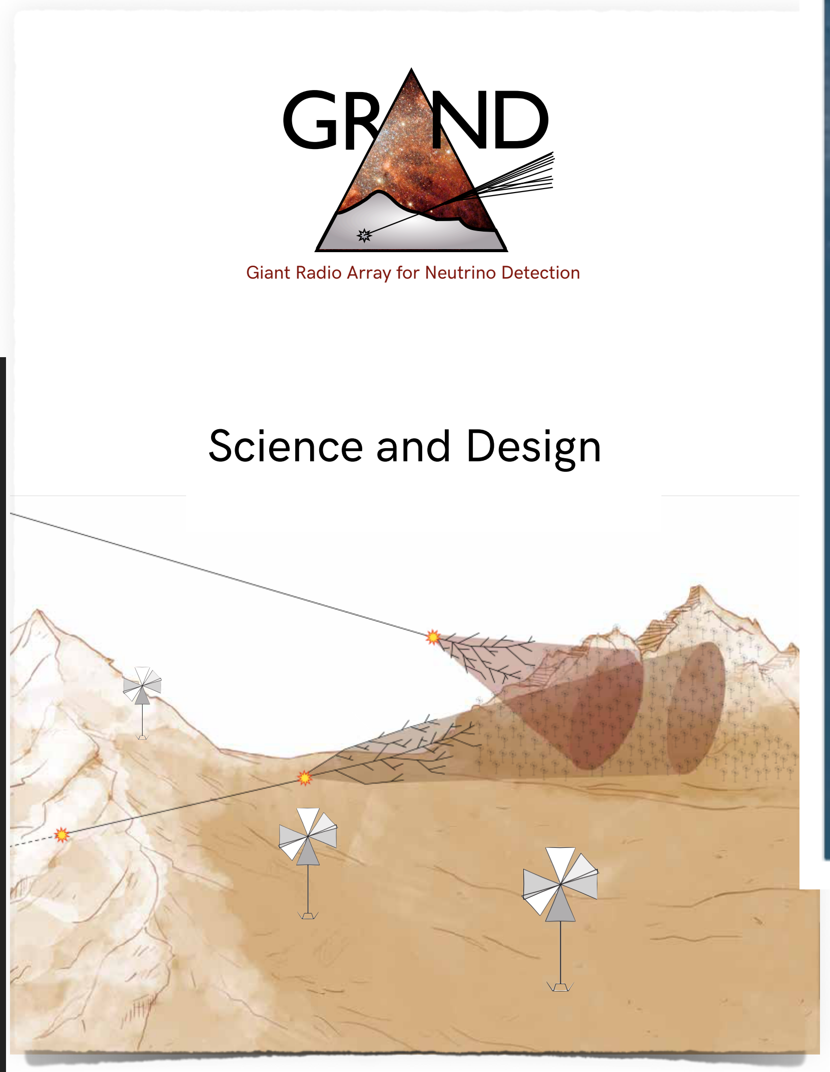
1. Extend **energy range of mass-sensitive measurements** (lower and higher end)
2. New measurements / observables that fully exploit **event-by-event charge/mass** estimates
3. **Multi-hybrid events** to verify our understanding (reconstruction, hadronic interactions)
4. Reduction of **systematic uncertainties** at single event level (fluctuations)
5. Improve our triggers for **neutrinos, exotic events,** atmospheric phenomena
6. Learning for our Phase I data set: **re-analysis of full data** set with new knowledge (DNN, …)

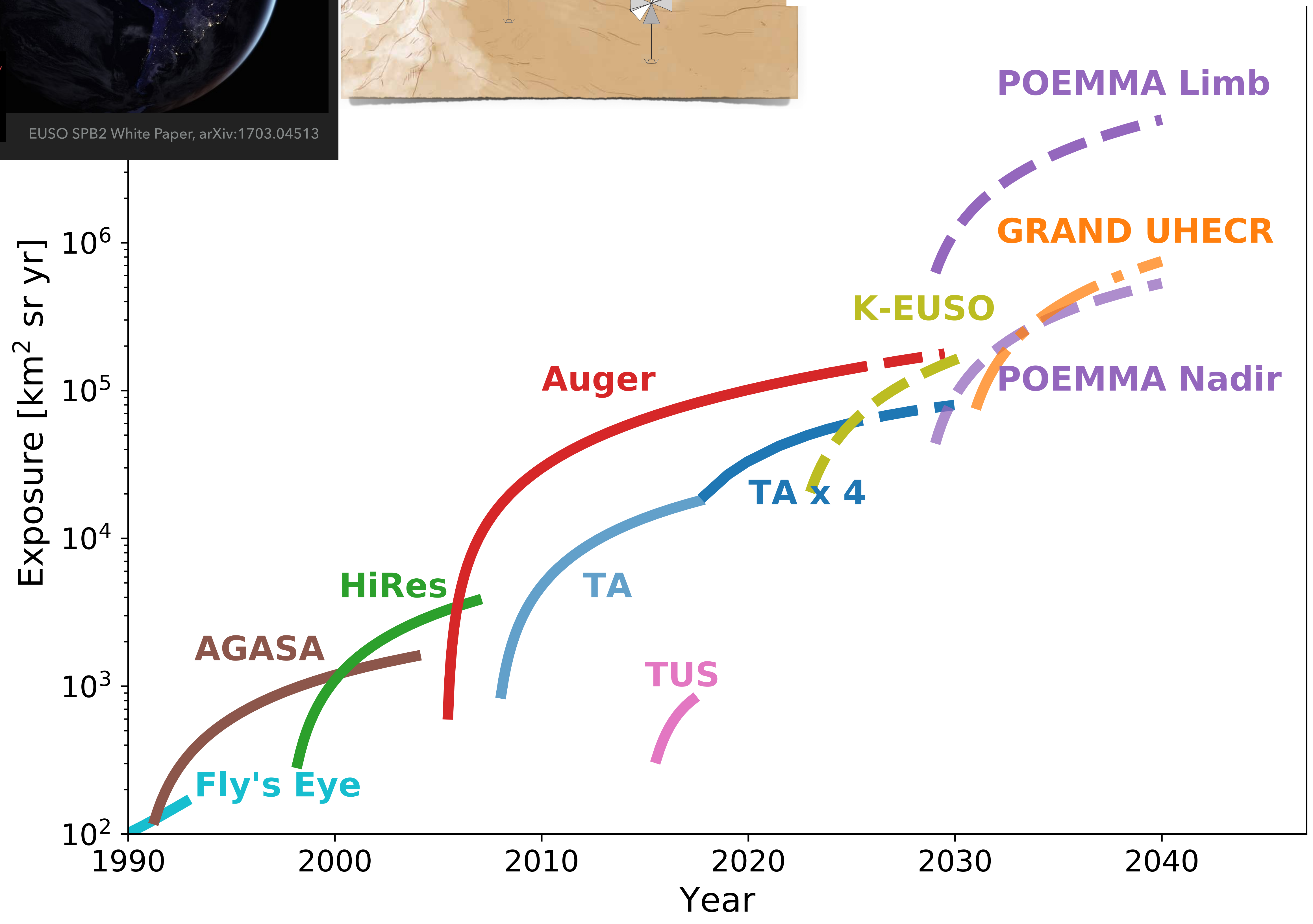
Outlook



(Sarazin et al, 1903.04063)

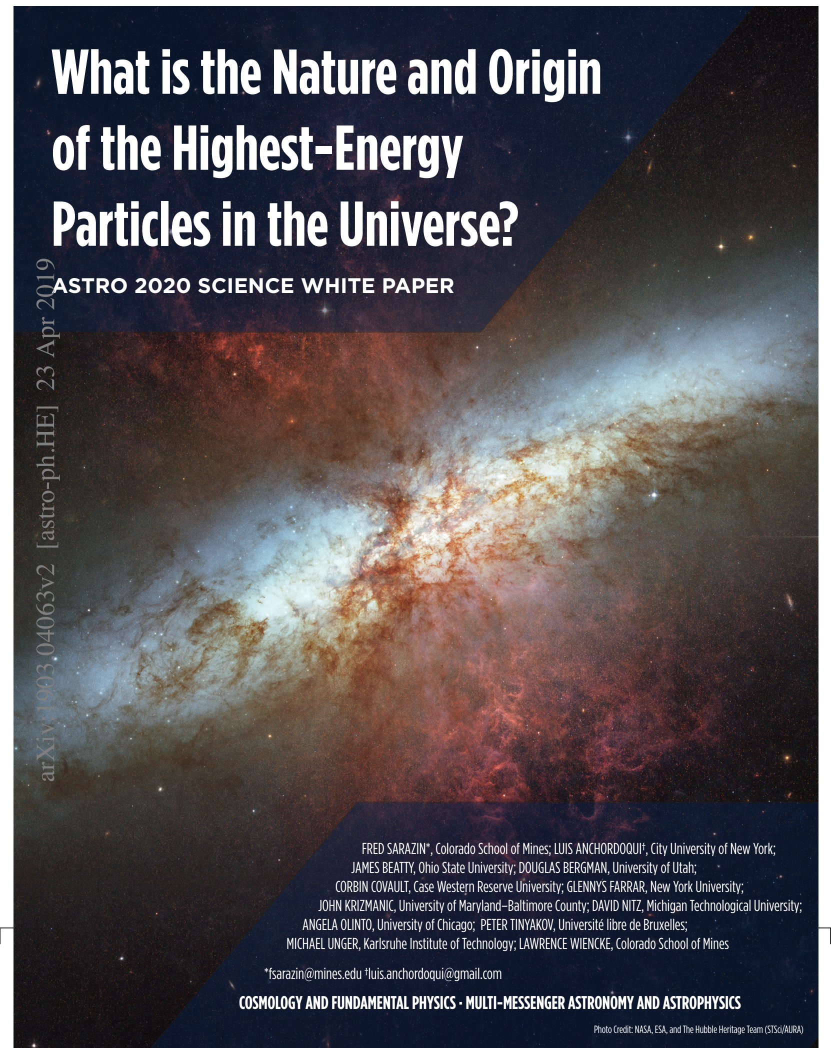




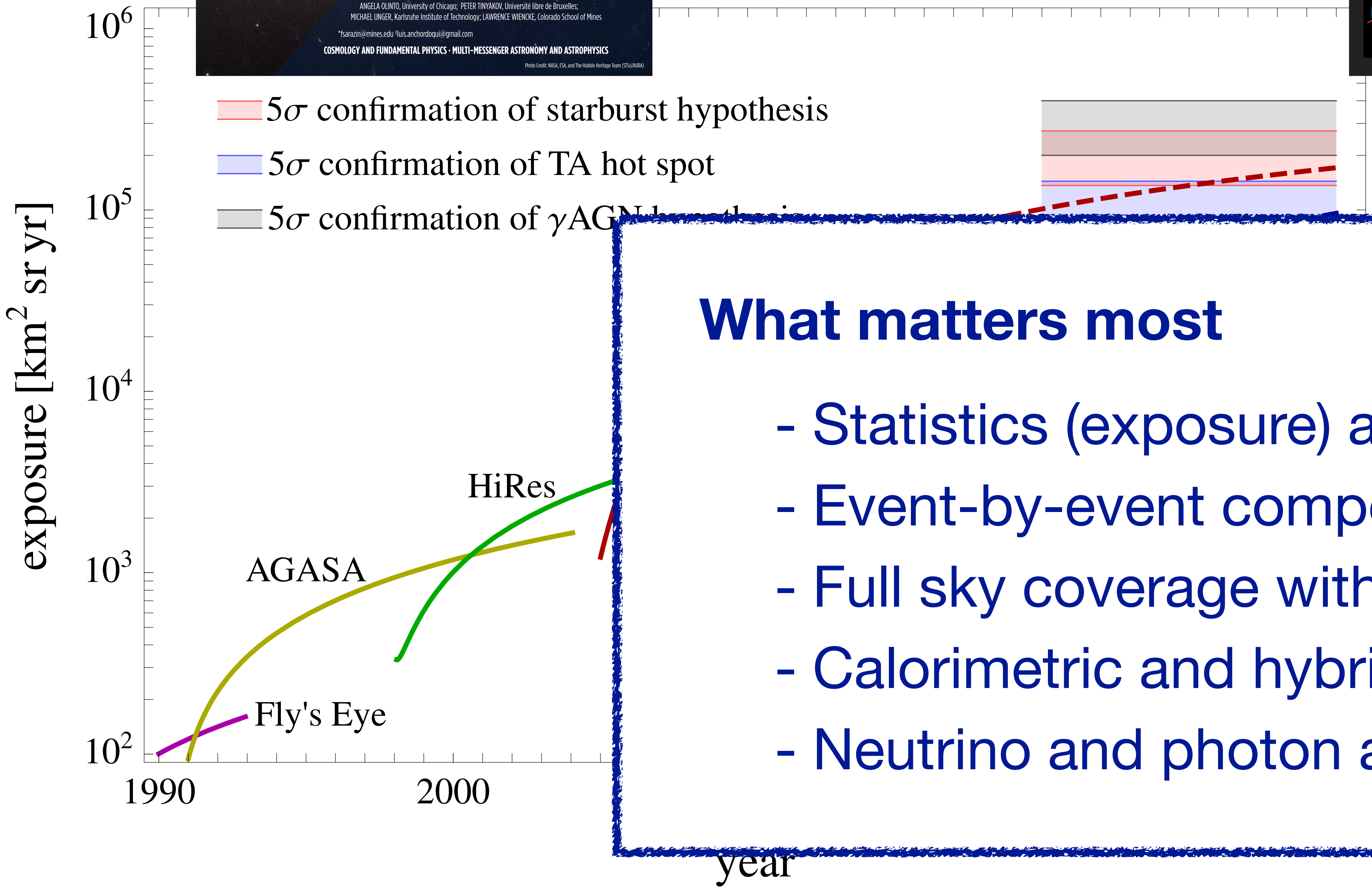


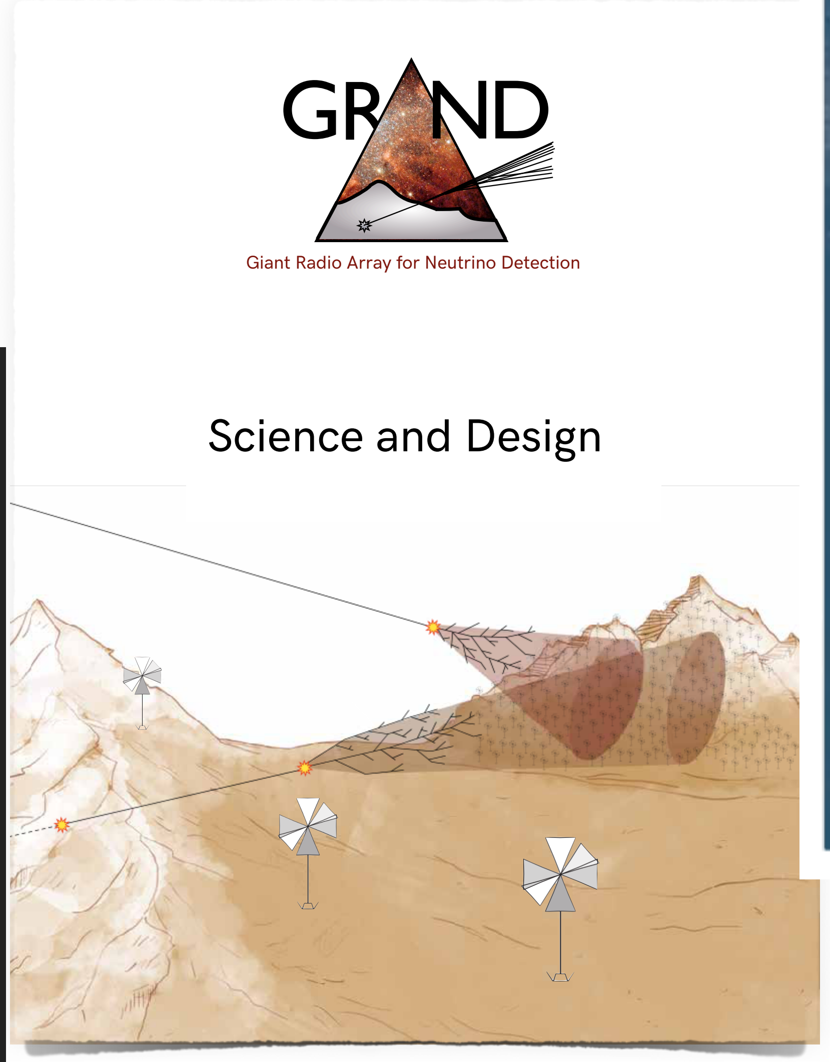
(Alves Batista et al, 1903.06714)

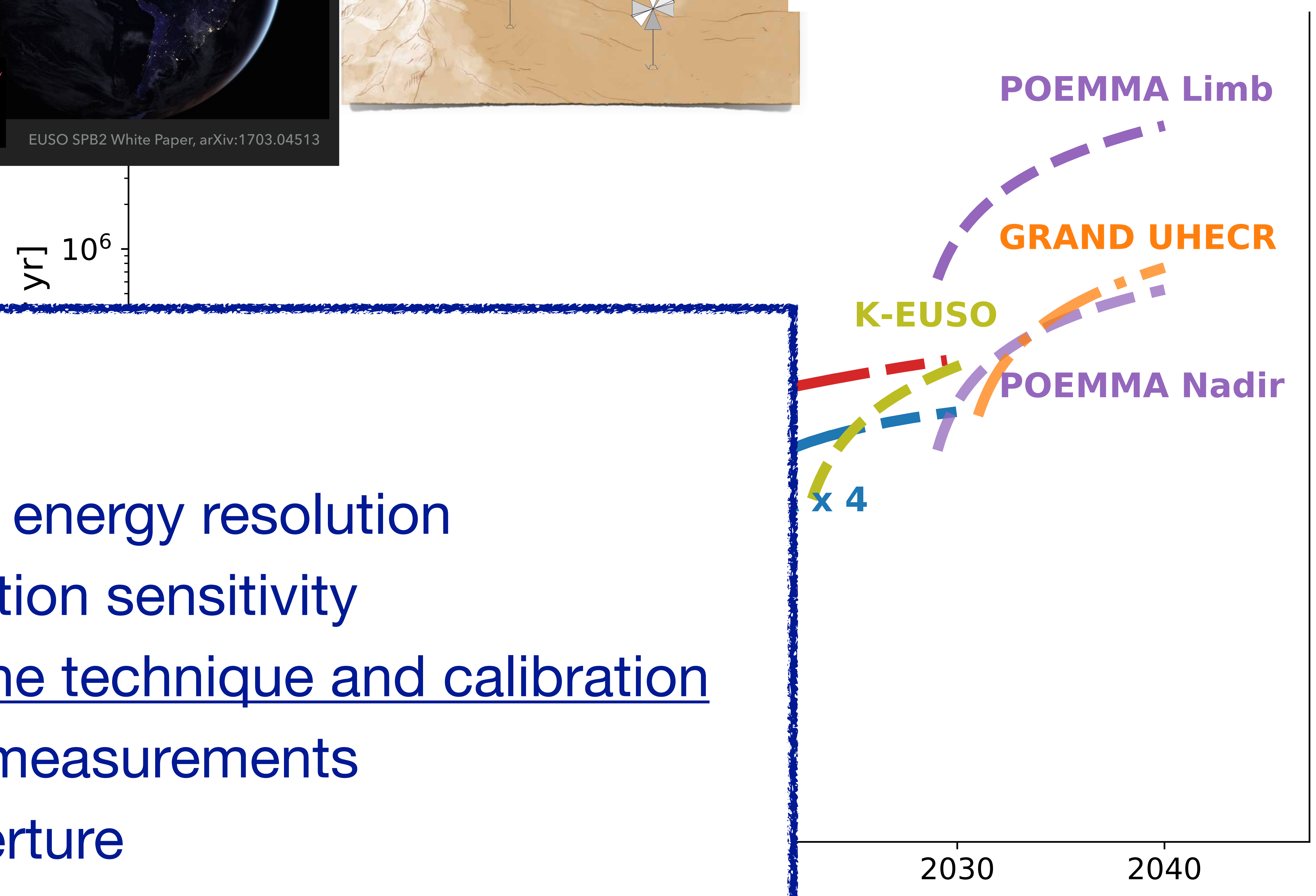
Outlook



(Sarazin et al, 1903.04063)







What matters most

- Statistics (exposure) and energy resolution
- Event-by-event composition sensitivity
- Full sky coverage with <u>one technique and calibration</u>
- Calorimetric and hybrid measurements
- Neutrino and photon aperture

(Alves Batista et al, 1903.06714)