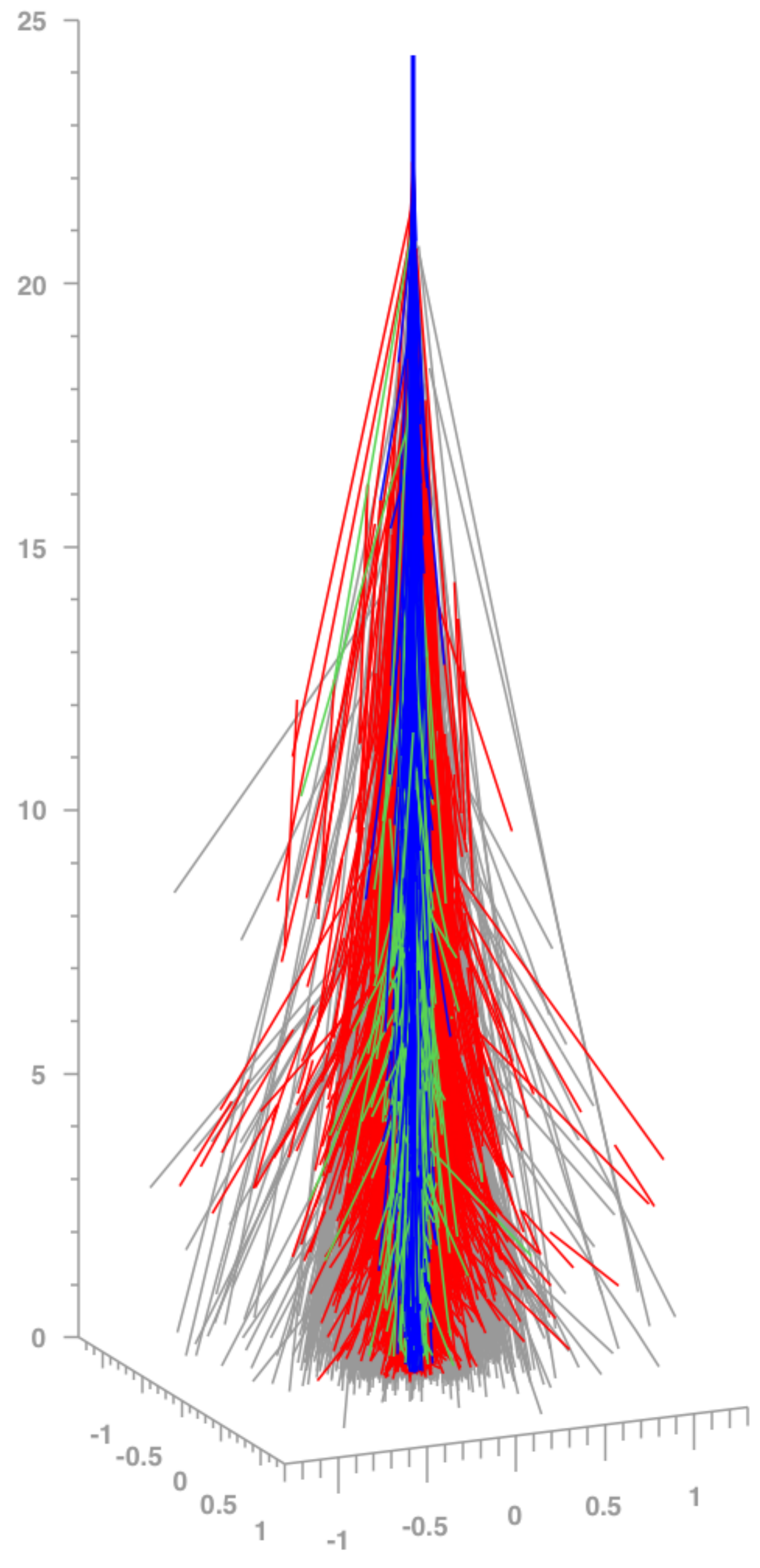
Ultra-High-Energy Cosmic Rays



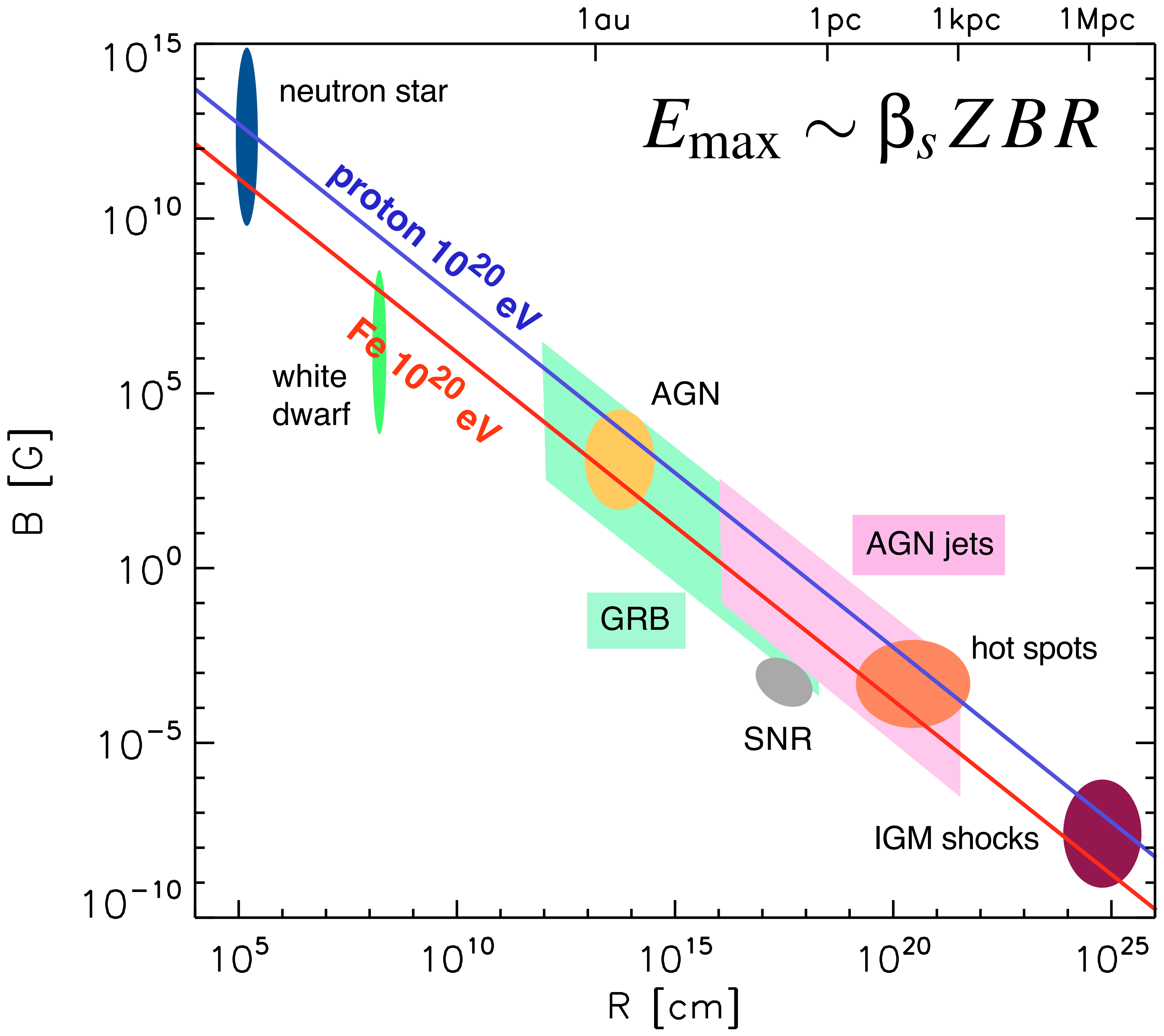
Ralph Engel, *Karlsruhe Institute of Technology*

(Many thanks due to colleagues of Auger and TA Collaborations)

Karlsruhe Institute of Technology

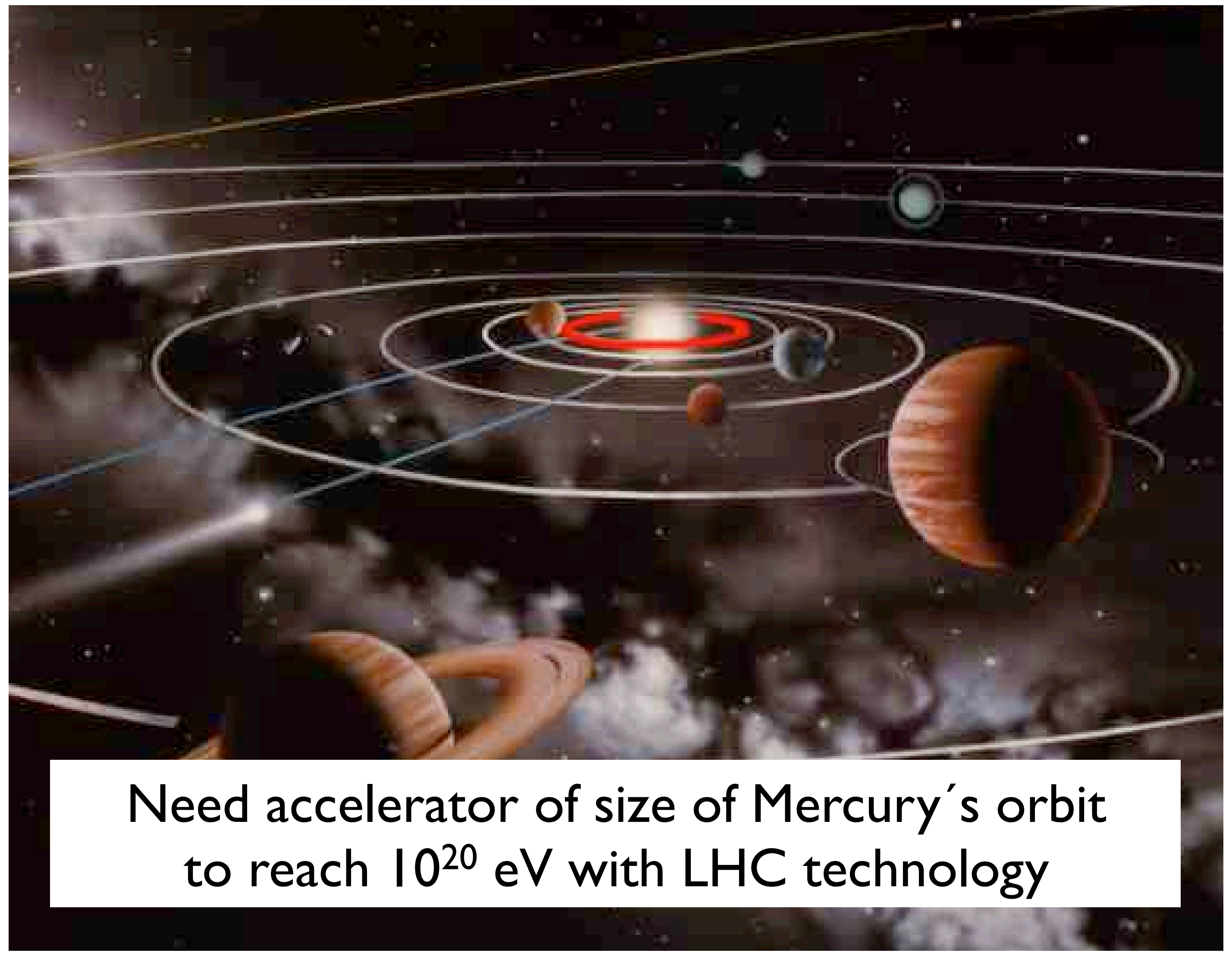
UHECRs: How to make them

Hillas plot (1984)



(Kotera & Olinto, ARAA 2011)

(Unger, 2006)

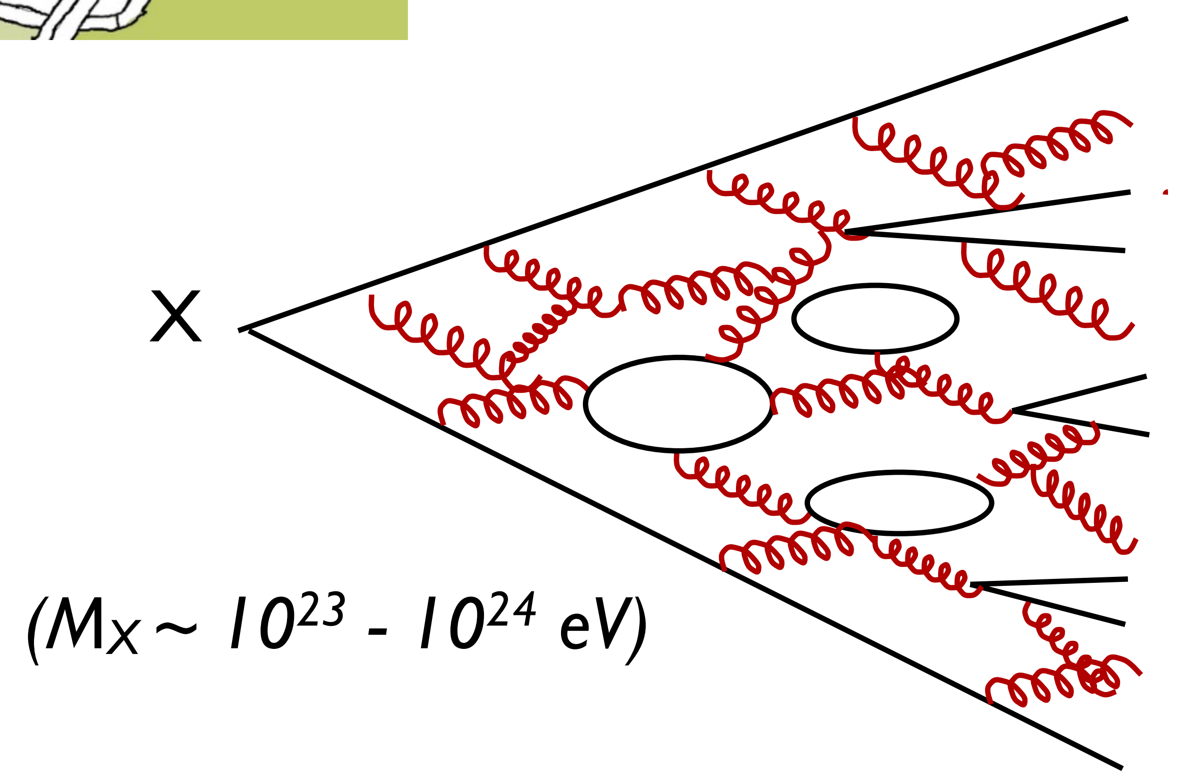


Realistic constraints more severe

- small acceleration efficiency
- synchrotron & adiabatic losses
- interactions in source region

X particles from:

- topological defects
- monopoles
- cosmic strings
- cosmic necklaces
- .....



Fragmentation function

QCD: ~ $E^{-1.5}$ energy spectrum

QCD+SUSY: ~ $E^{-1.9}$ spectrum

UHECRs: How to get them to Earth

Proton

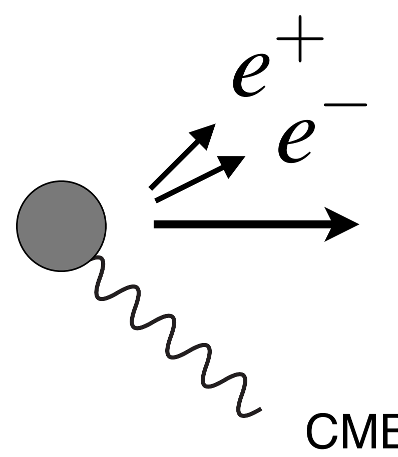
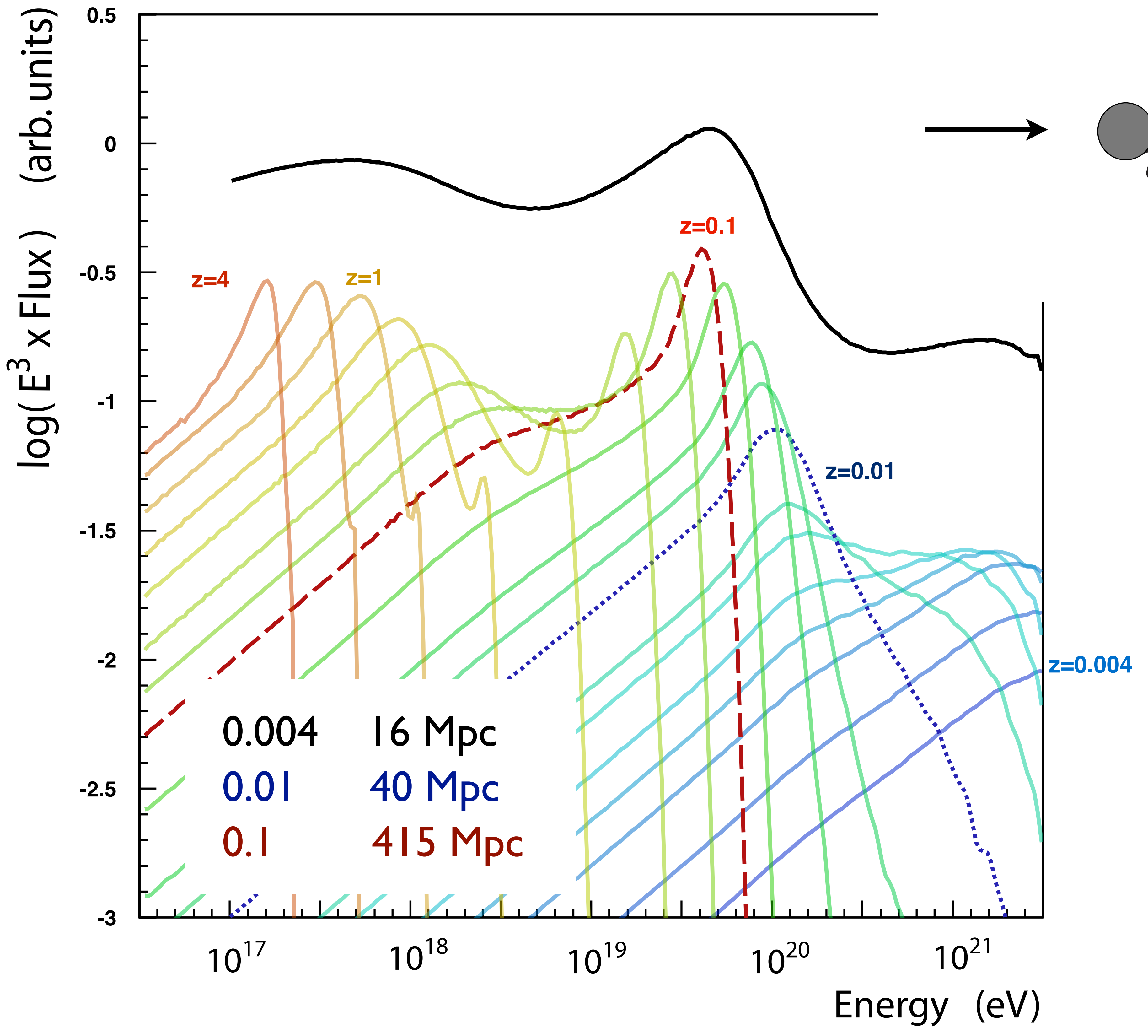
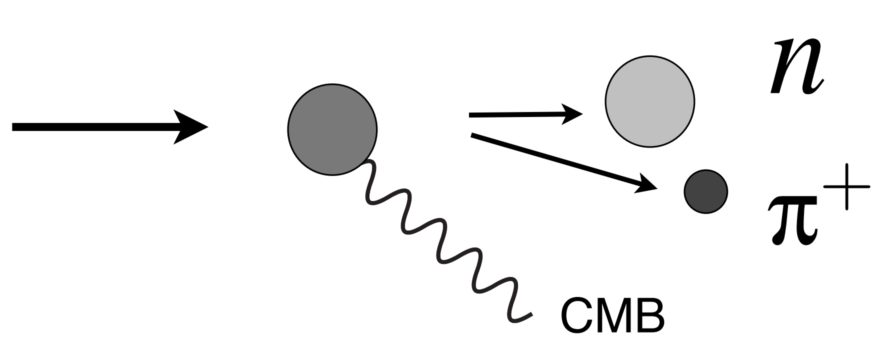


Photo-pion production
(mainly Δ resonance)





(Bergmann et al., PLB 2006)

Iron

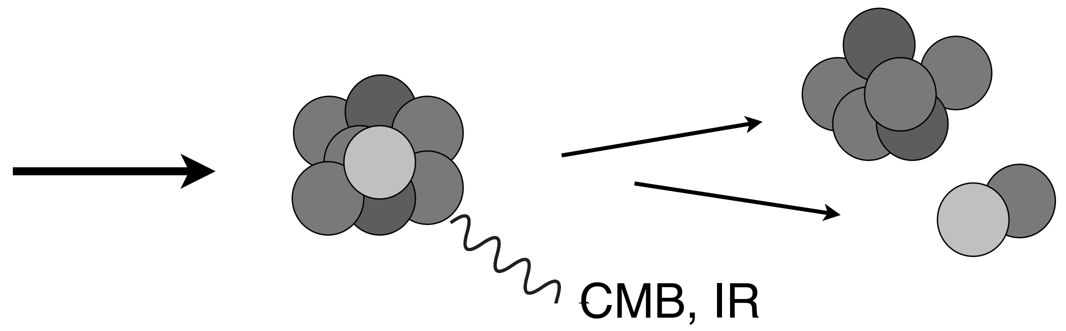
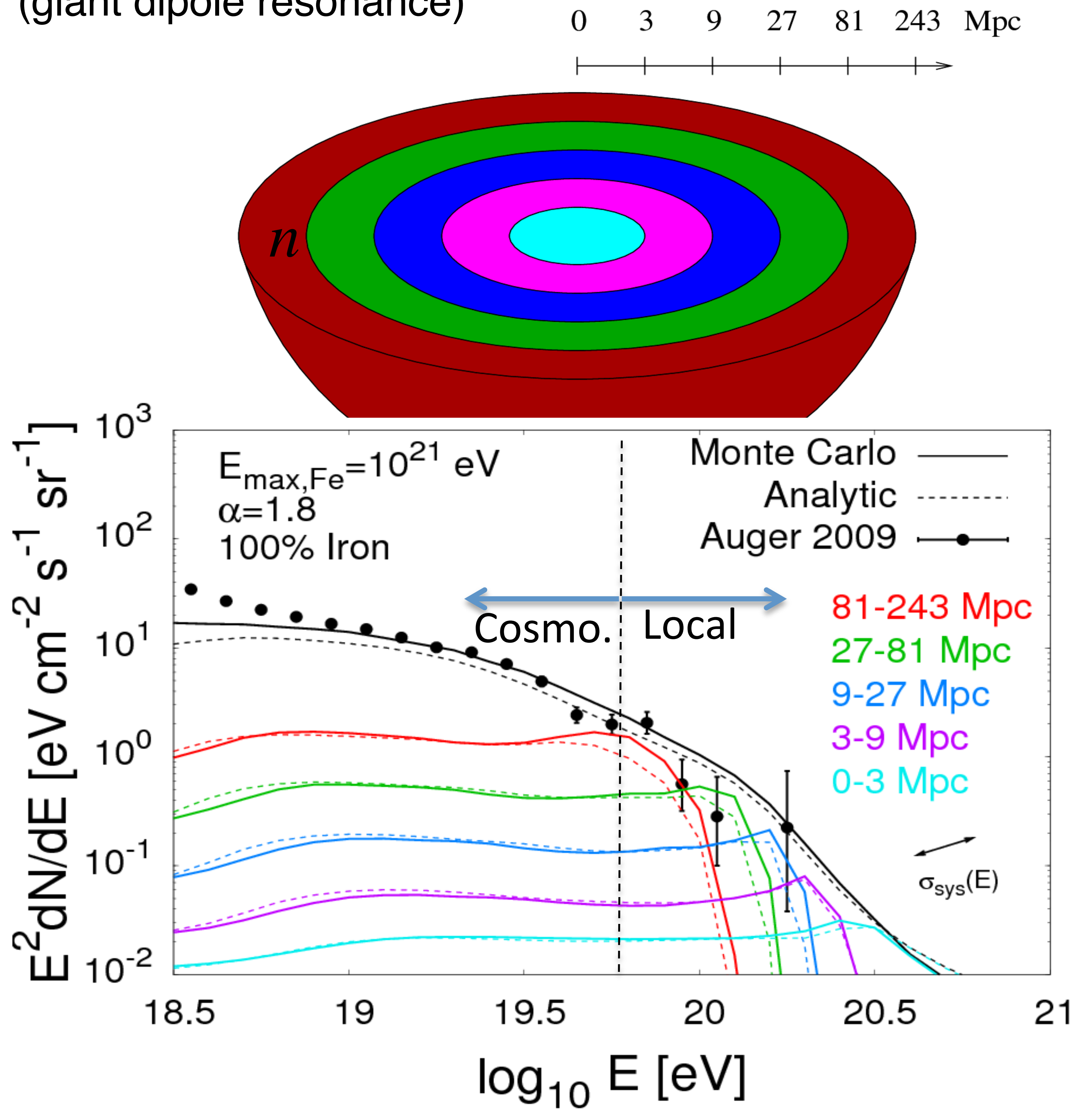


Photo-dissociation
(giant dipole resonance)

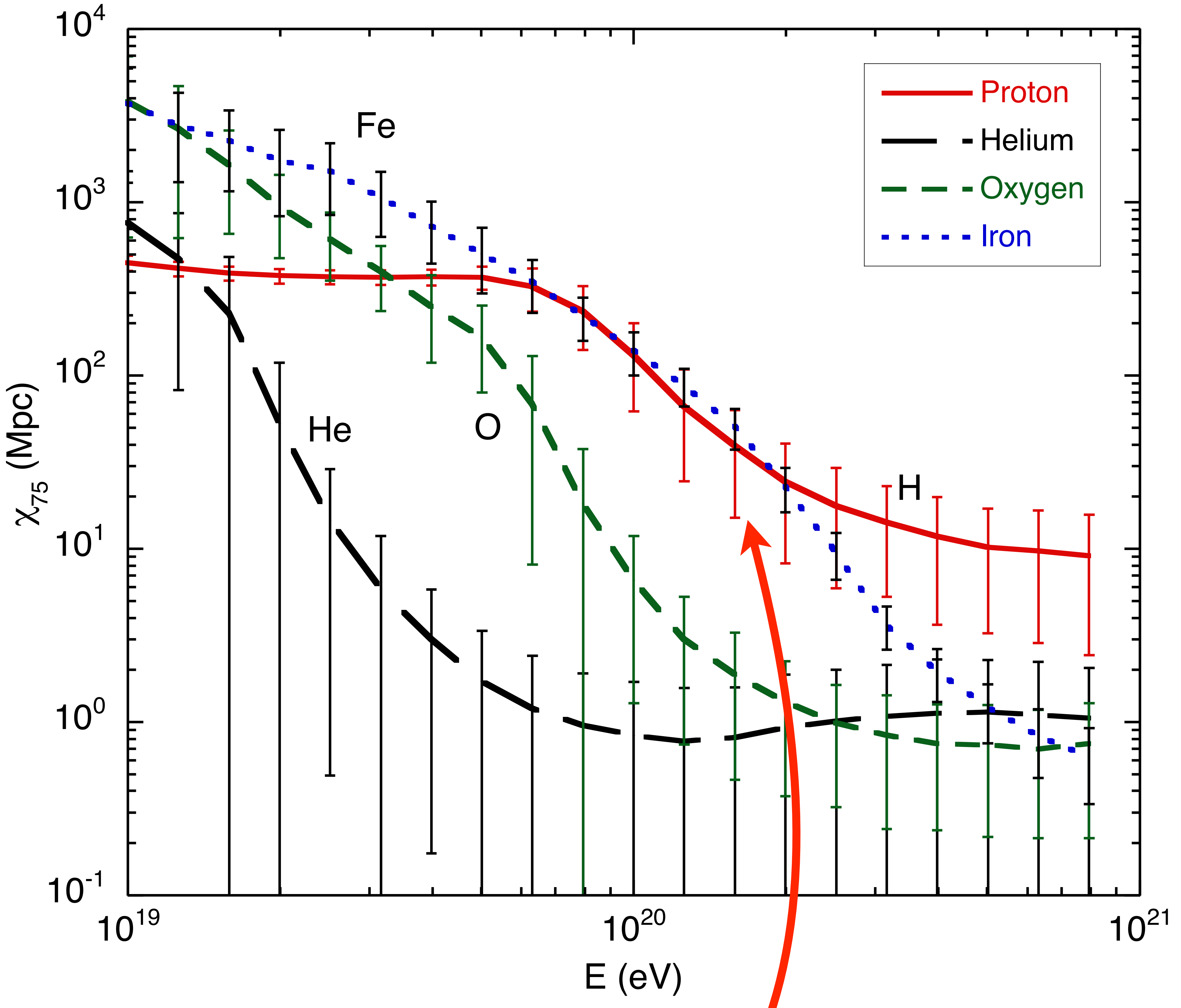


Greisen-Zatsepin-Kuzmin (GZK) effect, 1966

(Hooper, Taylor et al., PRD 2008)

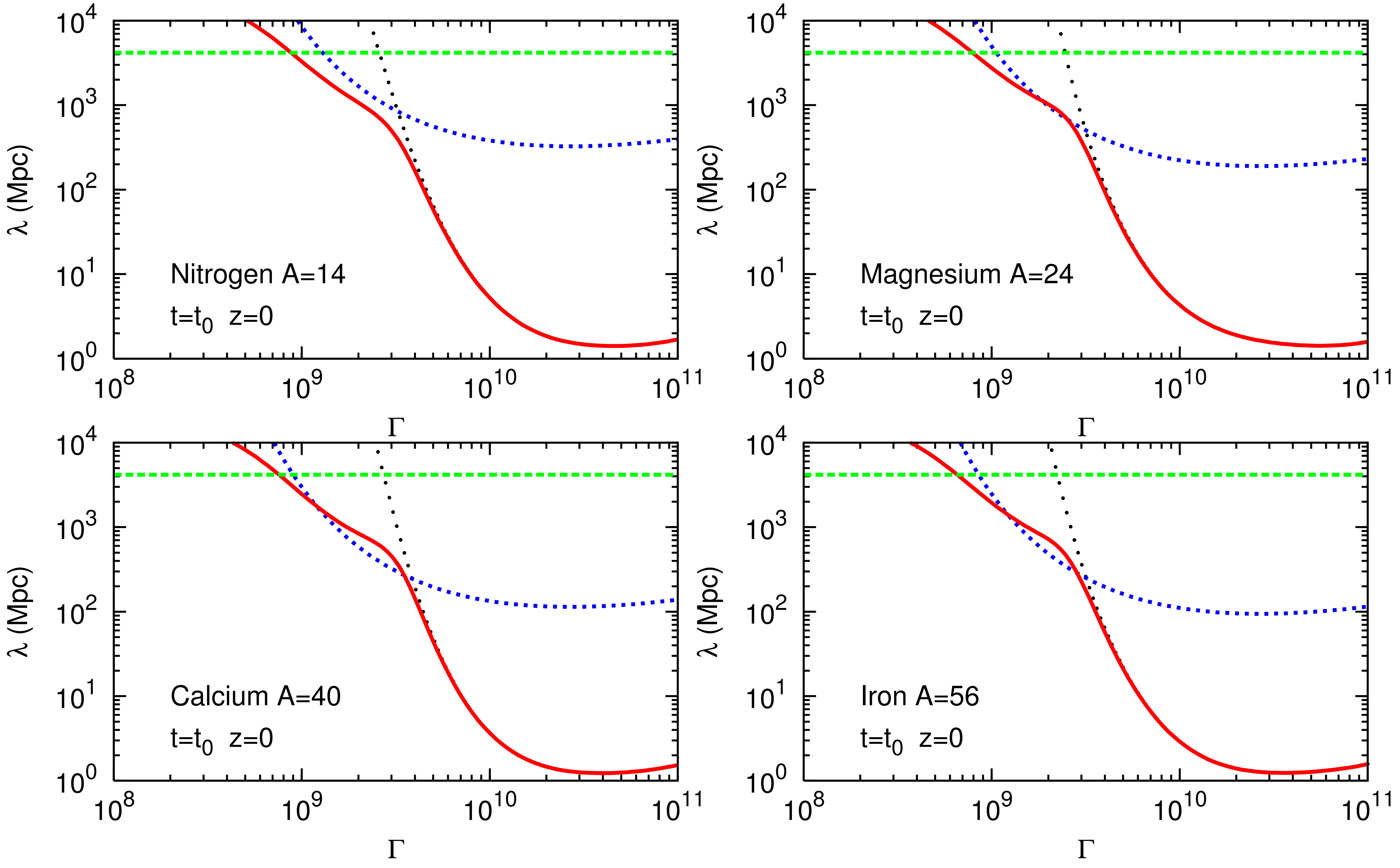
UHECRs: How to get them to Earth

(Allard et al. 2007)



Coincidence of very similar suppression energy of p and Fe

(Aloisio, PTEP 2017)



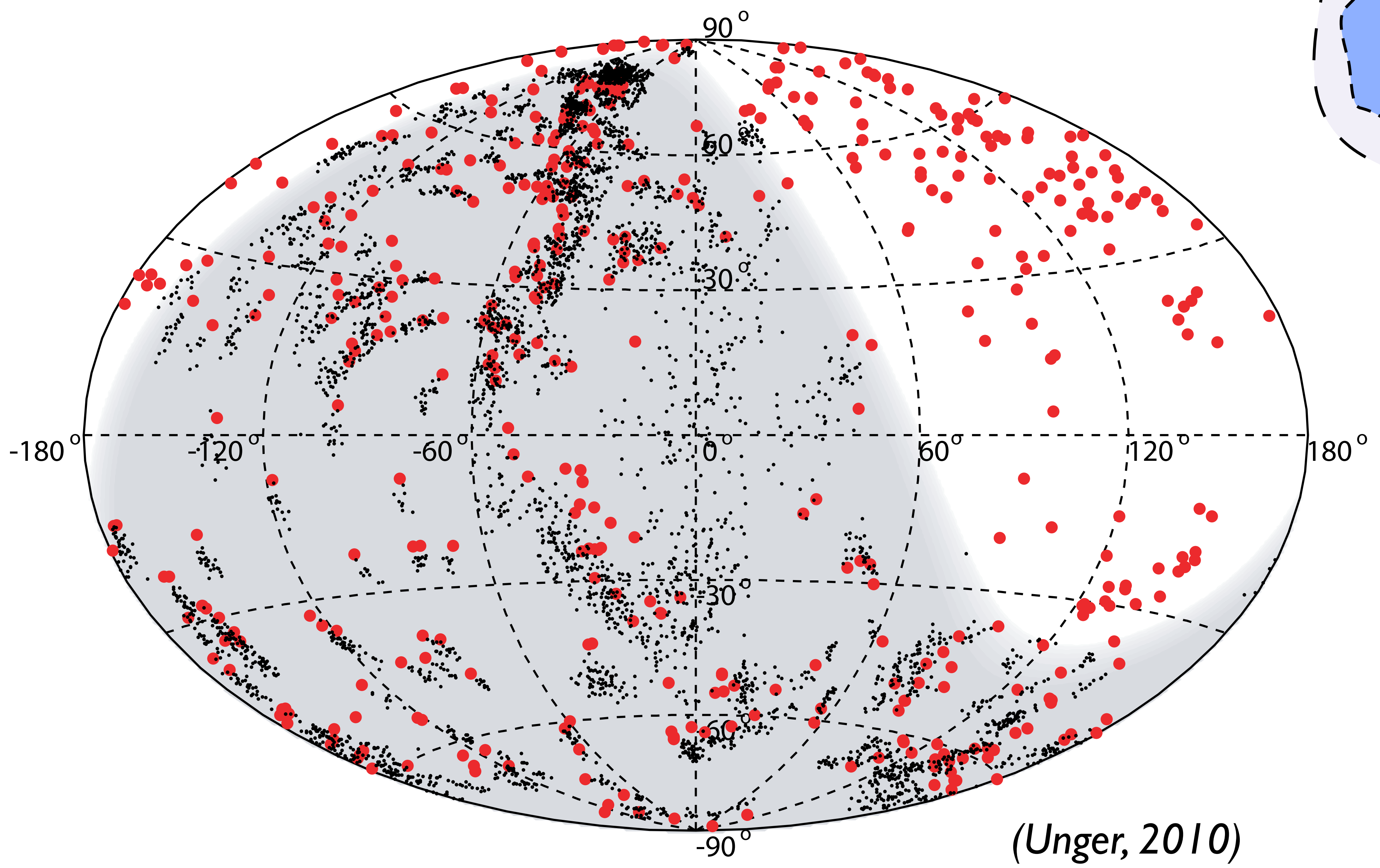
$$E = A\,\Gamma\, m_p$$

Energy threshold of suppression of nuclei scales with mass number (Giant dipole resonance at ~12 MeV lab.)

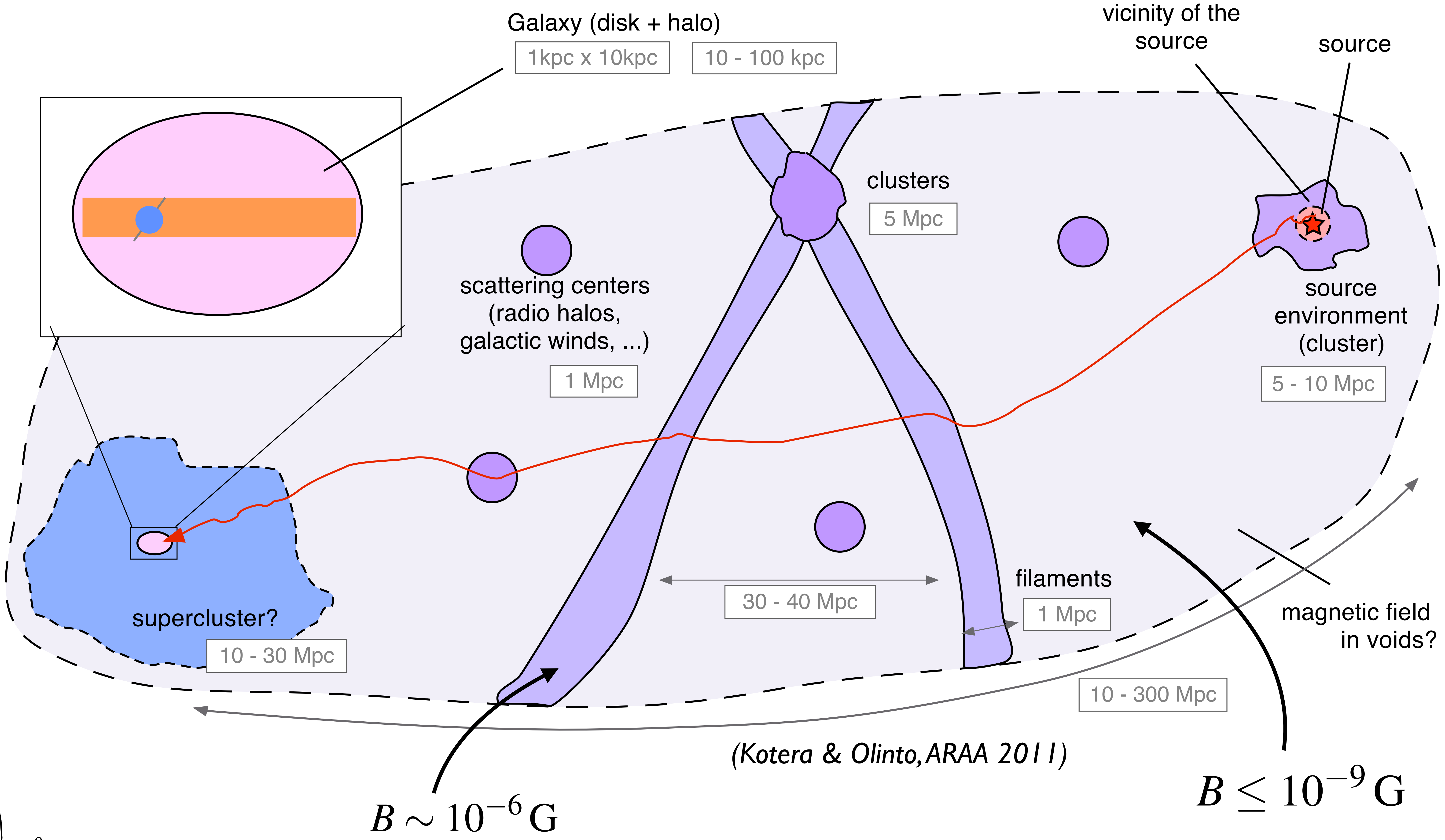
UHECRs: How to identify their sources

Deflection in Galactic and extragalactic mag. fields

$$\delta \simeq 3^o \frac{B}{3\,\mu G} \frac{L}{kpc} \frac{6\times 10^{19} eV}{E/Z}$$



(Unger, 2010)

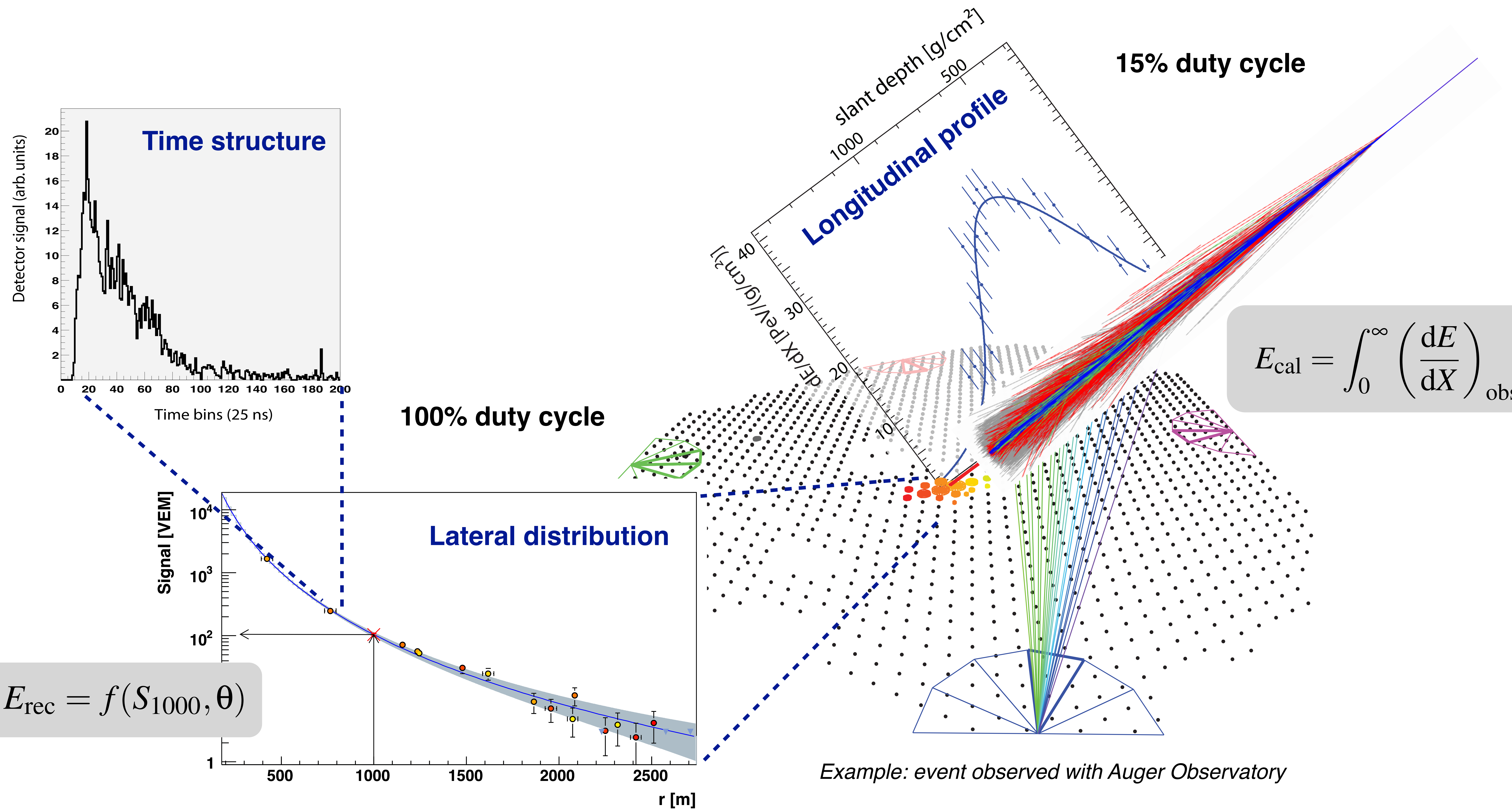


(Kotera & Olinto, ARAA 2011)

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

Multi-messenger signals (gamma-rays and neutrinos)

UHECRs: How to detect them

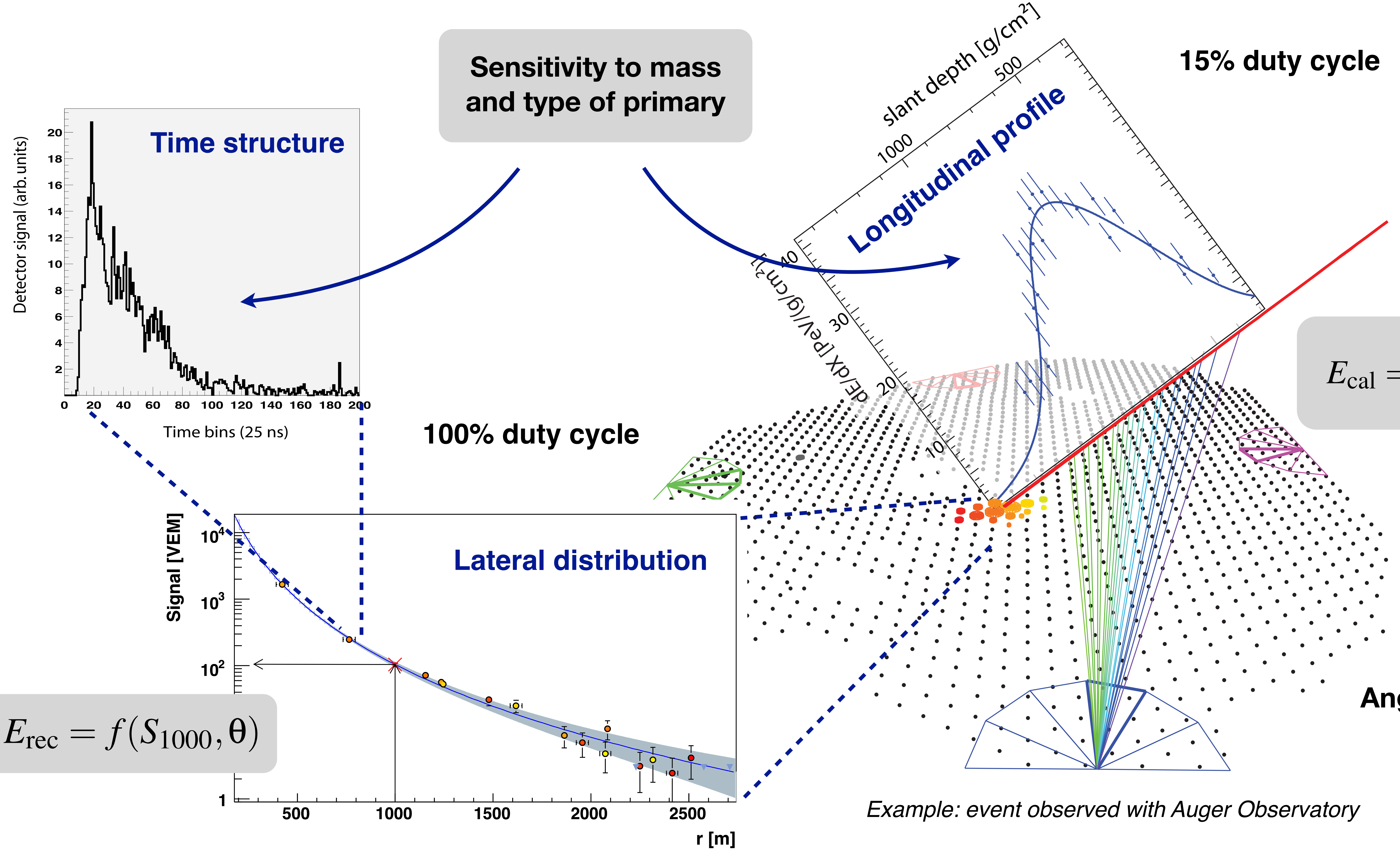


$$E_{\rm cal} = \int_0^\infty \left(\frac{{\rm d}E}{{\rm d}X}\right)_{\rm obs} {\rm d}X$$

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

Example: event observed with Auger Observatory

UHECRs: How to detect them

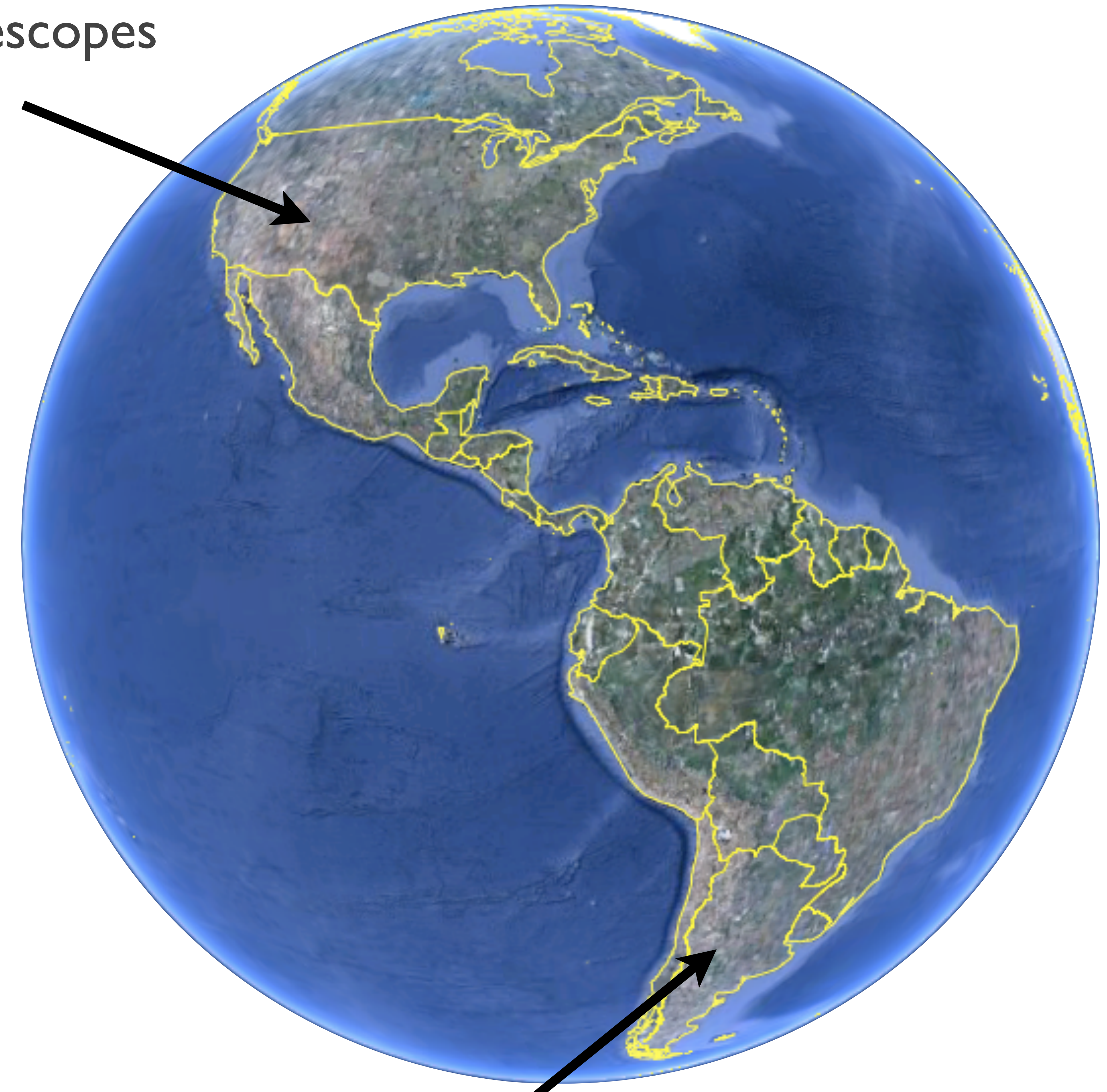


$$E_{\rm cal} = \int_0^\infty \left(\frac{dE}{dX}\right)_{\rm obs} dX$$

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

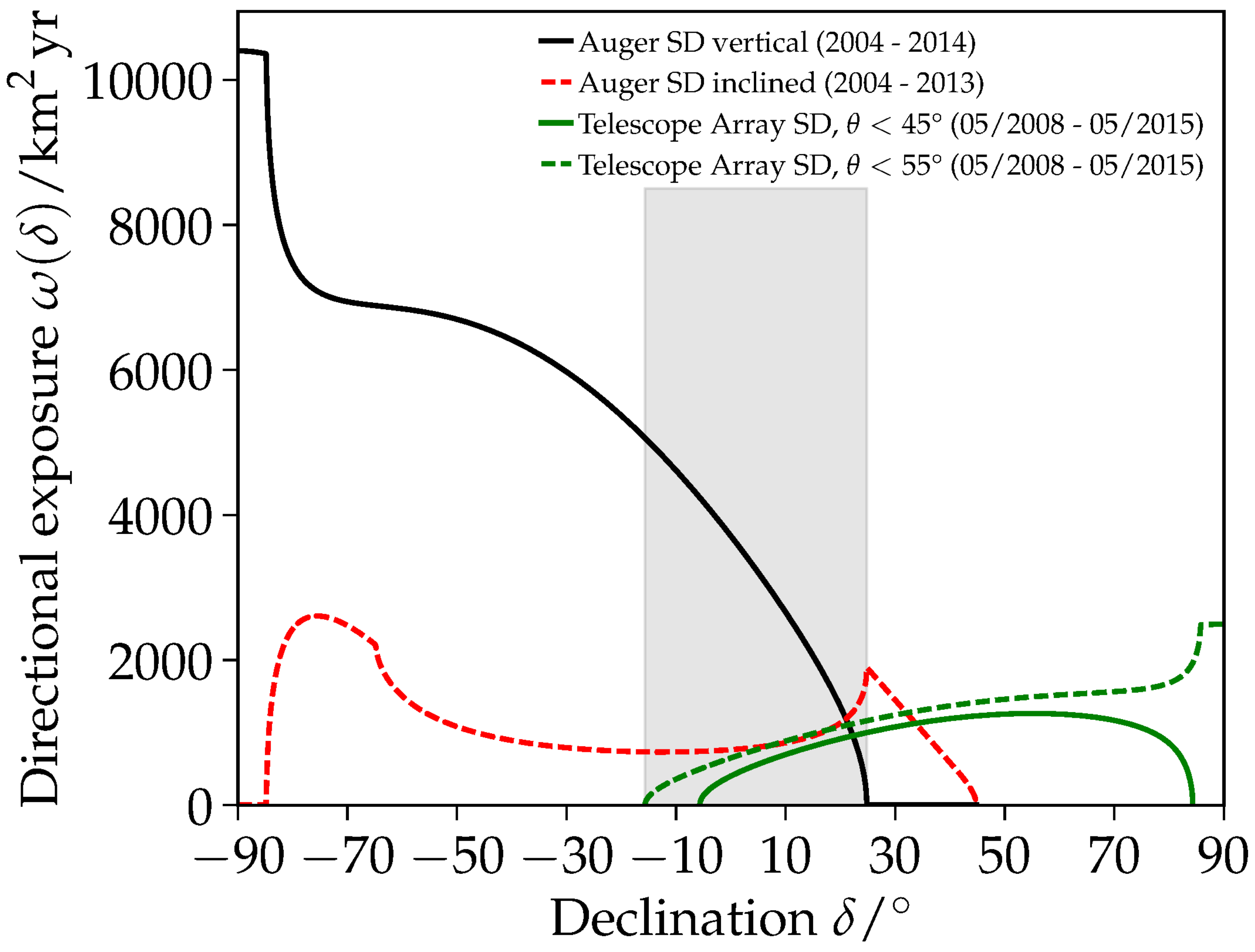
Pierre Auger Observatory and Telescope Array

Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km²
36 fluorescence telescopes



Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km²
27 fluorescence telescopes

Together full sky coverage

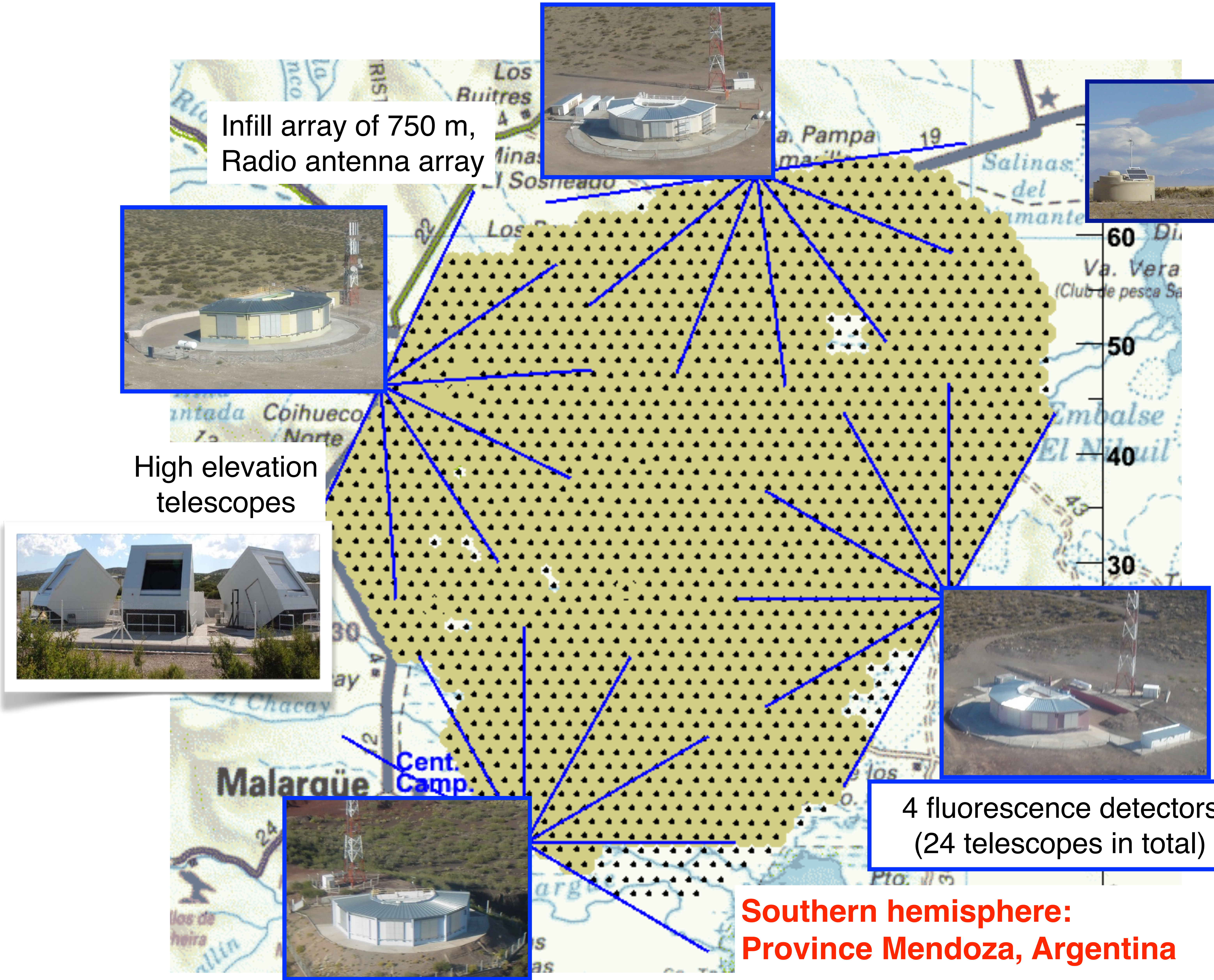


Auger:
6.7×10^4 km² sr yr (spectrum)
9×10^4 km² sr yr (anisotropy)

TA:
8.1×10^3 km² sr yr (spectrum)
8.6×10^3 km² sr yr (anisotropy)

The Pierre Auger Observatory

Talks by Smida, Coleman



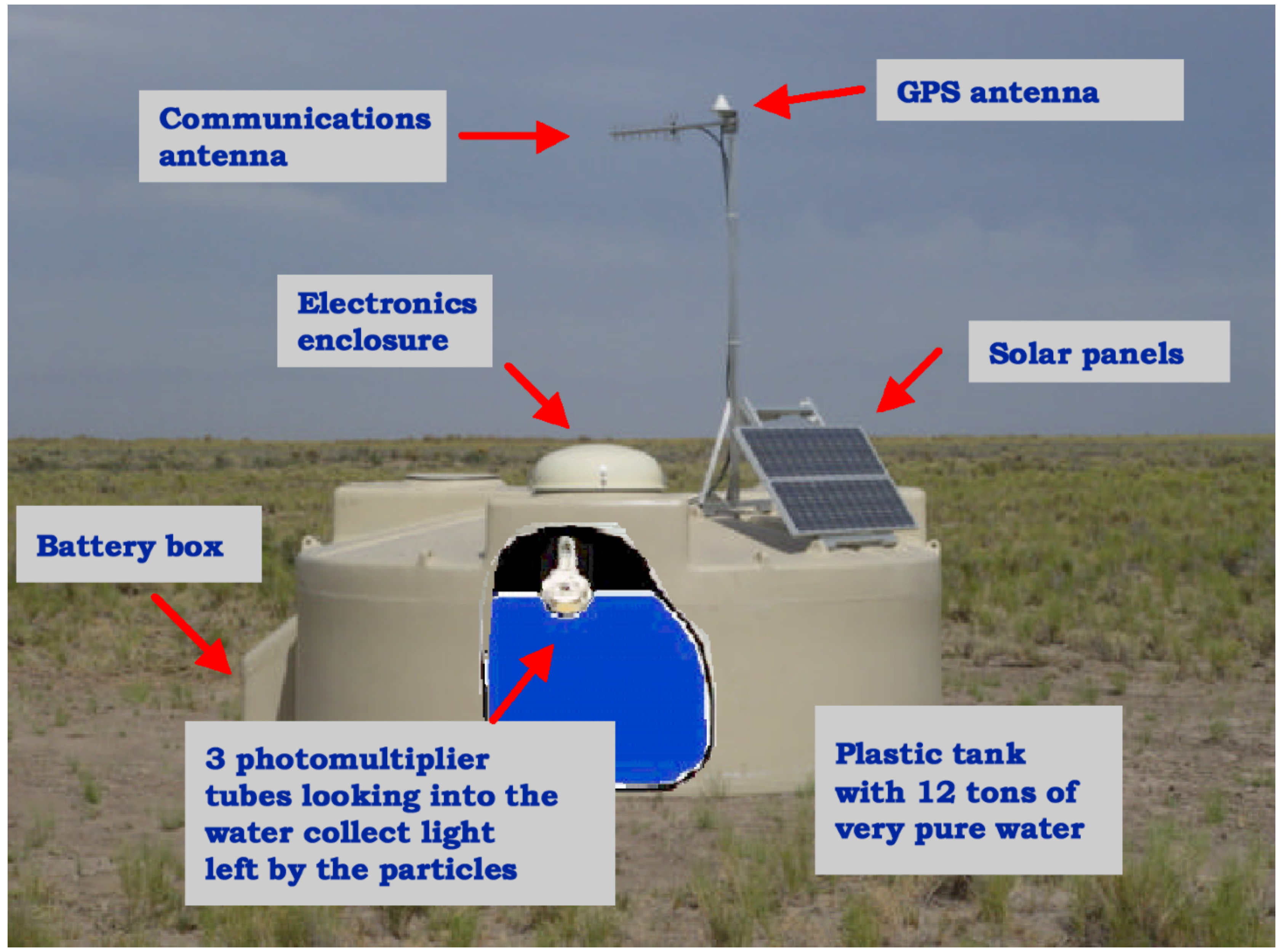
Infill array of 750 m, Radio antenna array

High elevation telescopes

4 fluorescence detectors (24 telescopes in total)

LIDARs and laser facilities

1665 surface detectors:
water-Cherenkov tanks
(grid of 1.5 km, 3000 km²)



Southern hemisphere: Province Mendoza, Argentina

Telescope Array (TA)

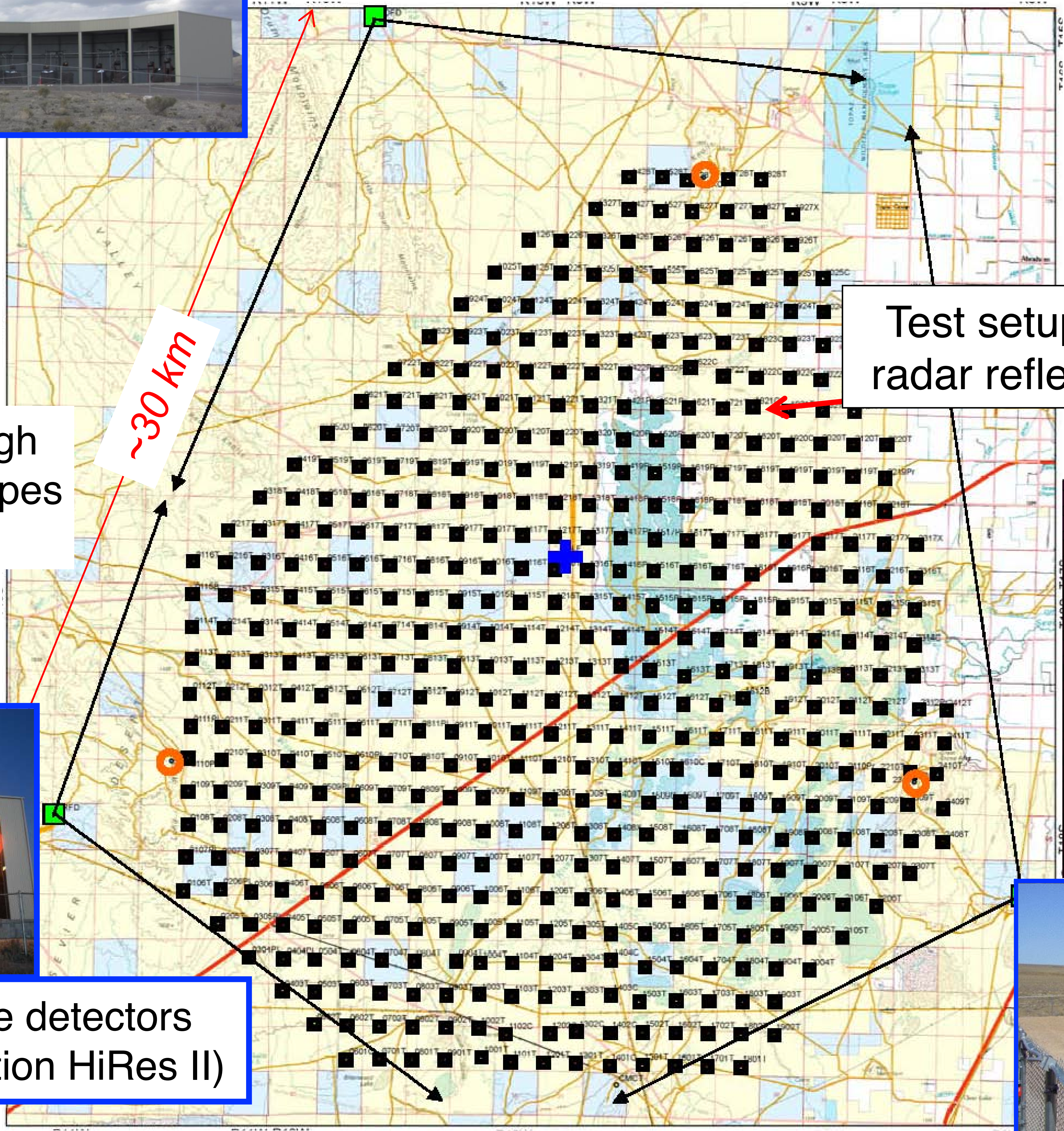
Talk by Abu-Zayyad

Middle Drum: based on HiRes II

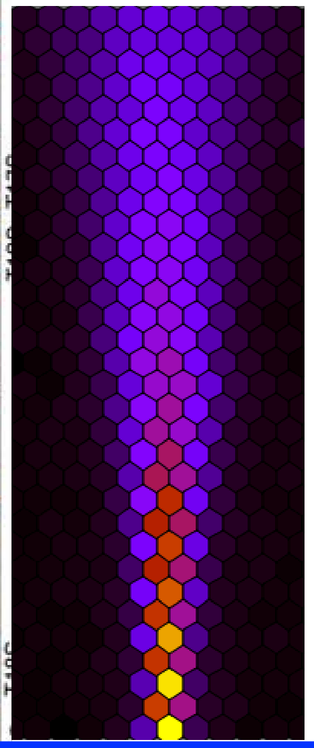
TALE (TA low energy extension)

LIDAR
Laser facility

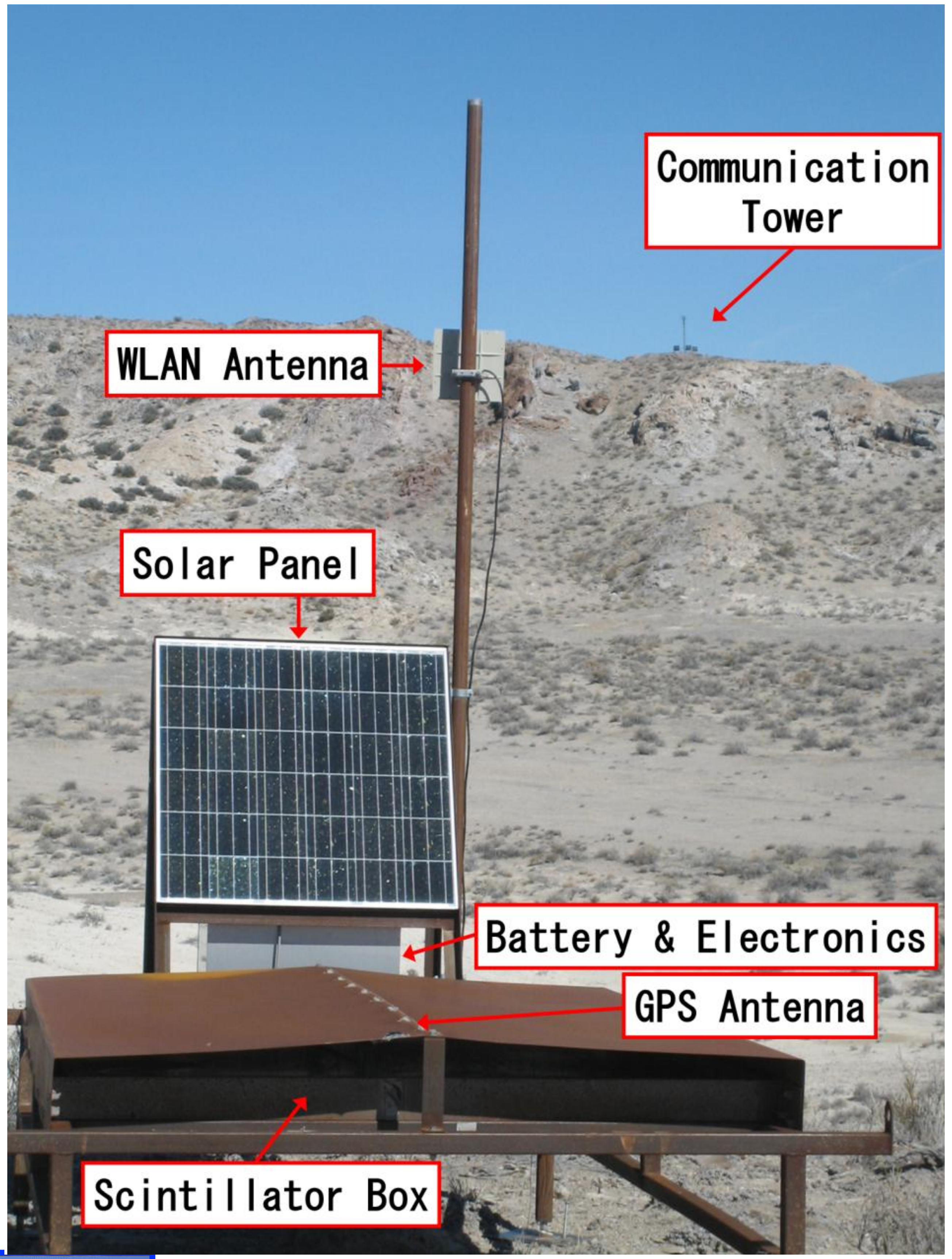
Infill array and high
elevation telescopes



3 fluorescence detectors
(2 new, one station HiRes II)



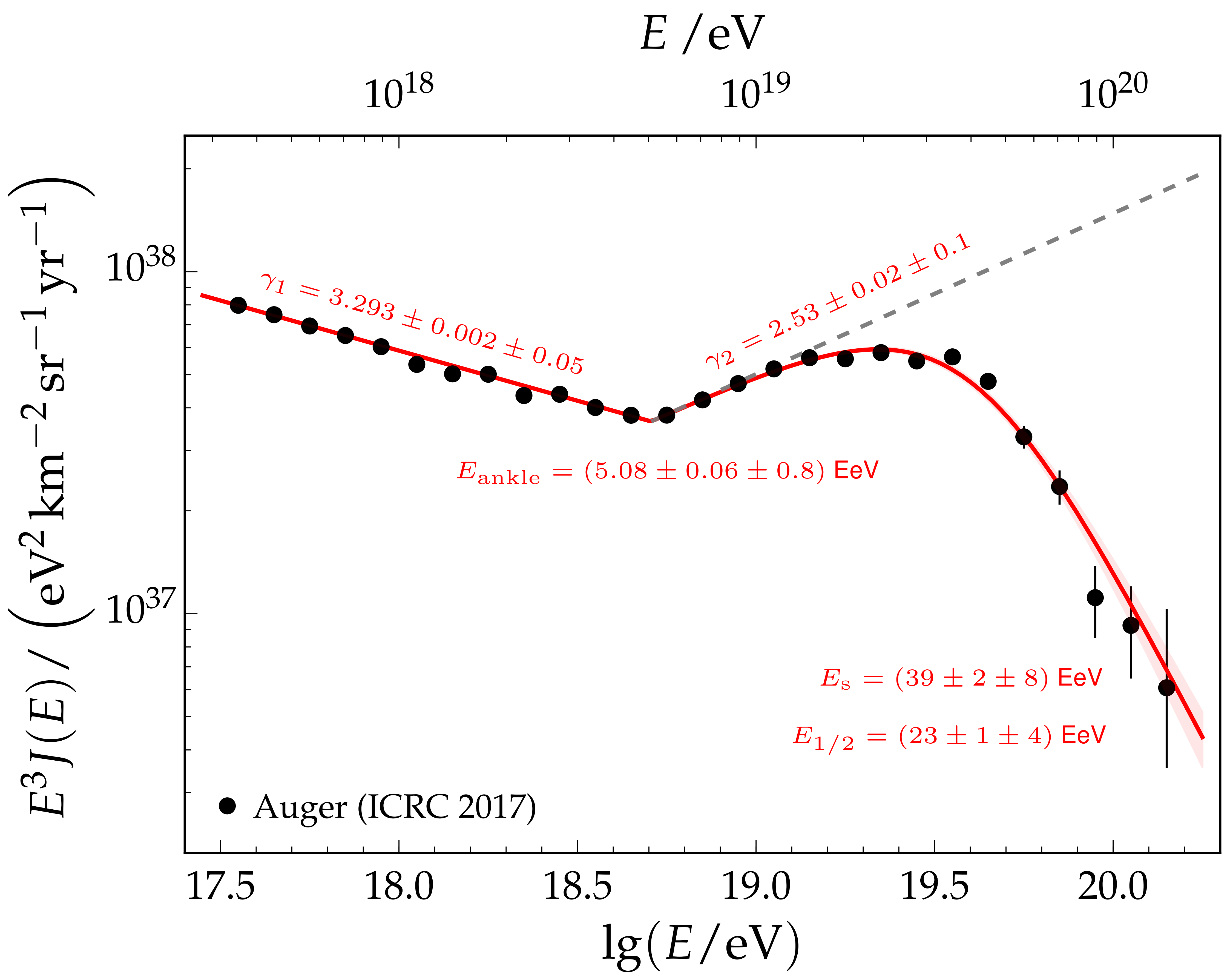
Electron light
source (ELS):
~40 MeV



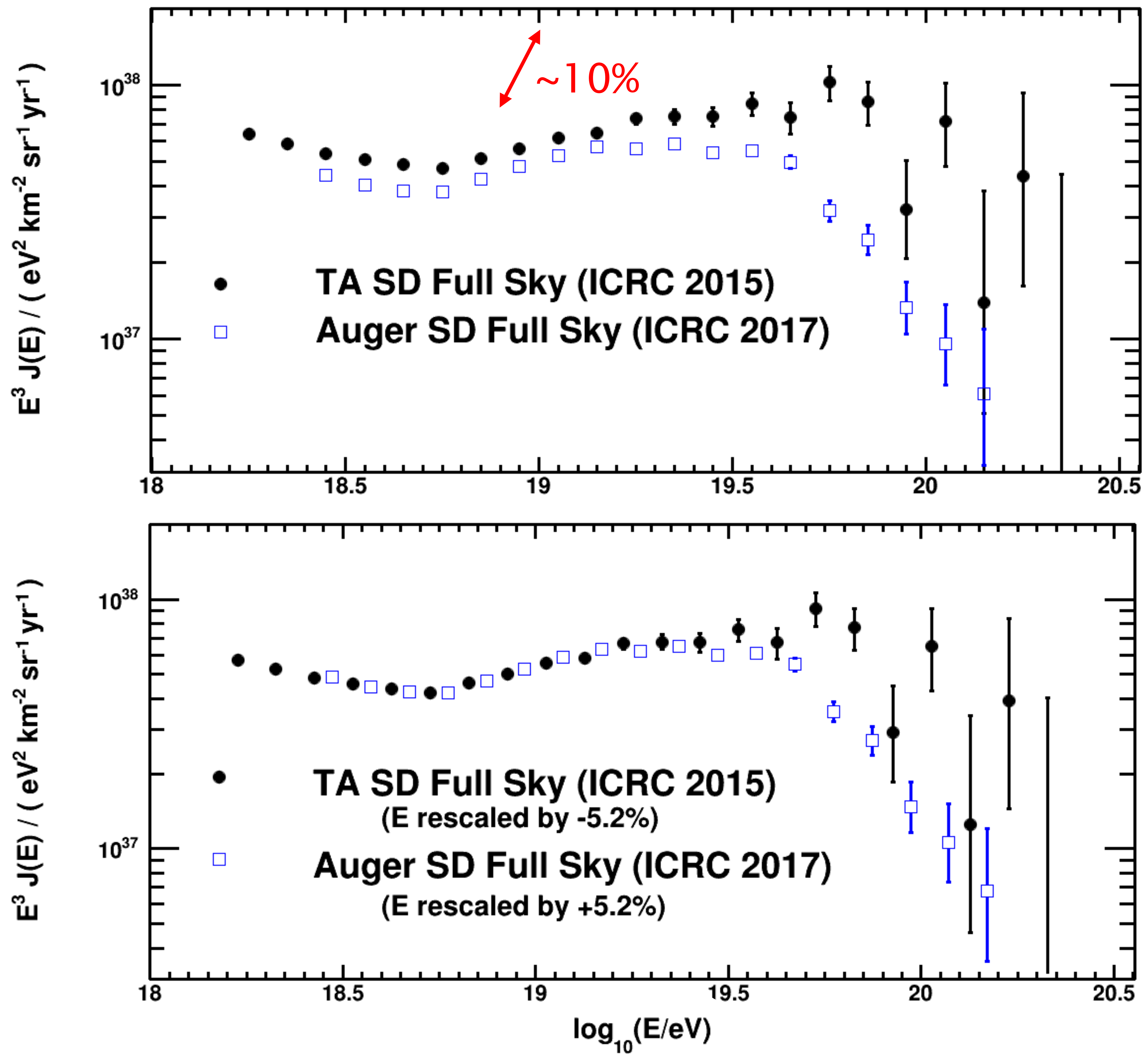
507 surface detectors:
double-layer scintillators
(grid of 1.2 km, 680 km^2)

Northern hemisphere: Utah, USA

Energy spectrum (all-particle flux)



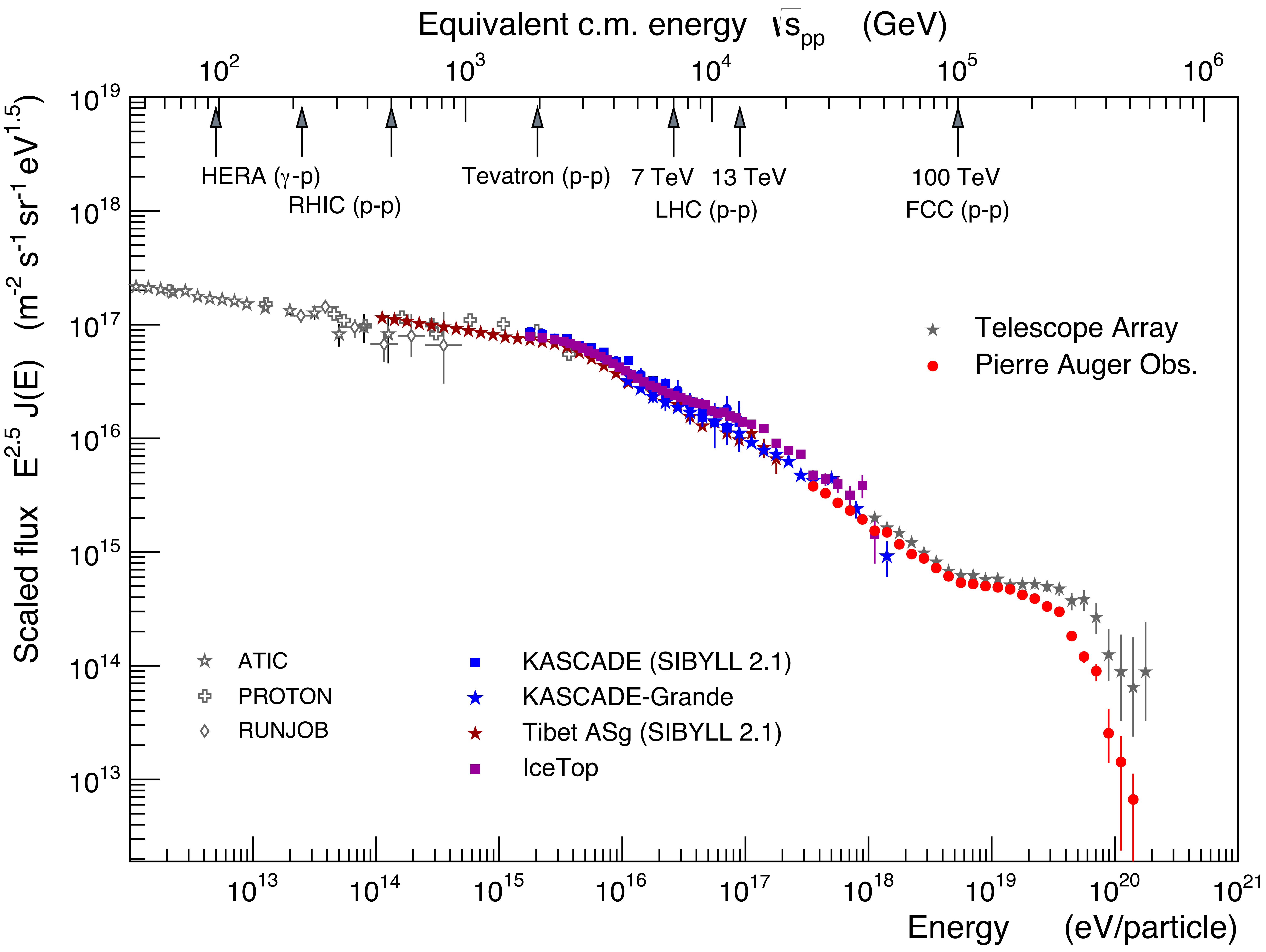
(Auger-TA Spectrum Working Group)



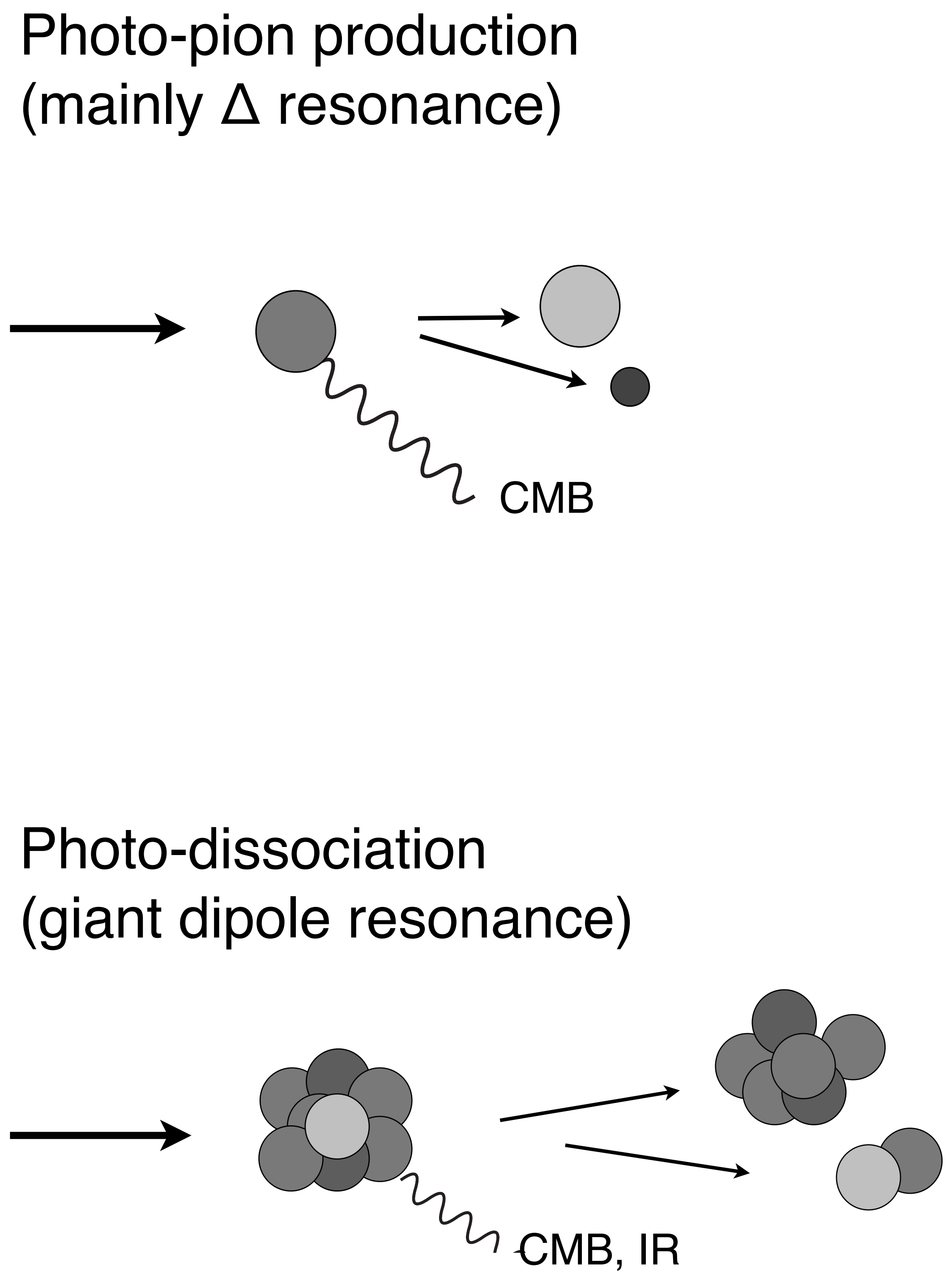
Sys. uncertainty of energy scale

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

What is the origin of the flux suppression at $6x10^{19}$ eV?

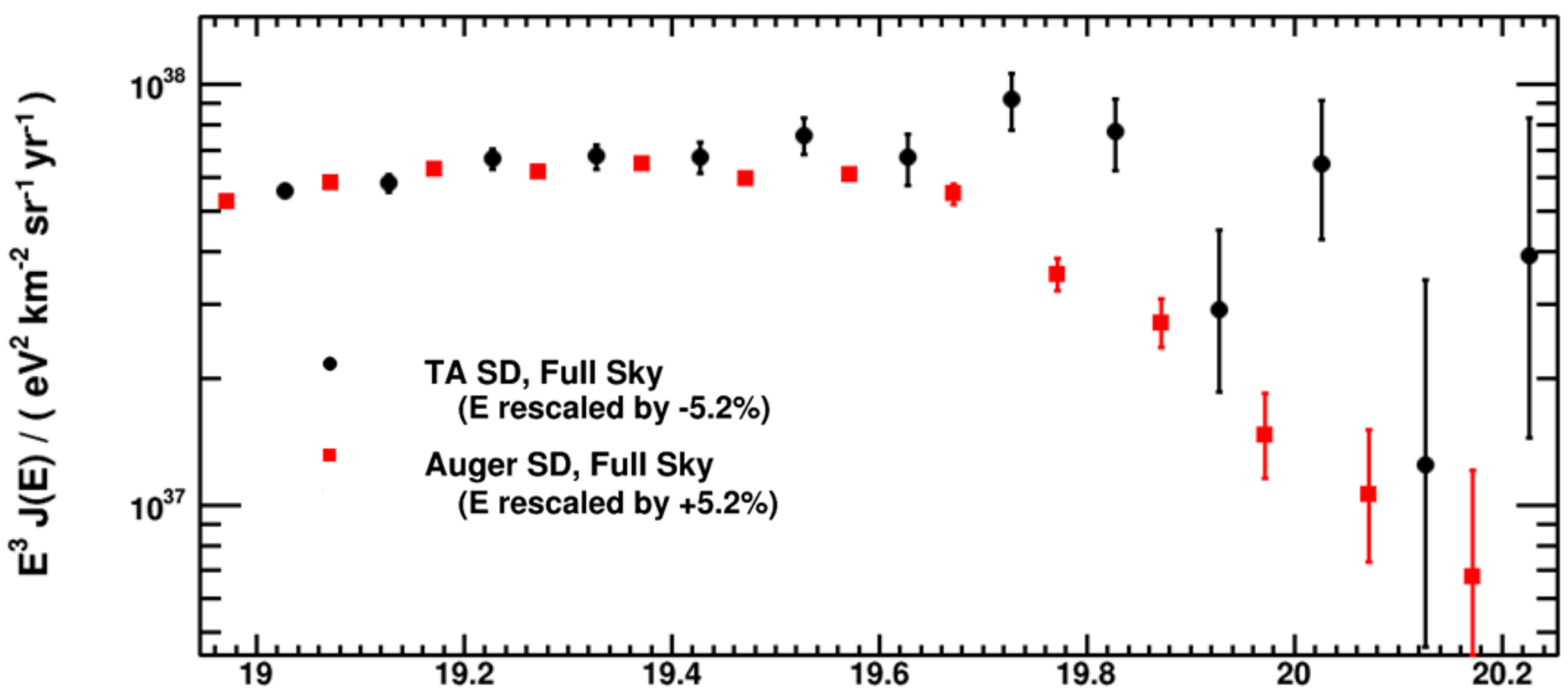


Greisen-Zatsepin-Kuzmin (GZK) effect

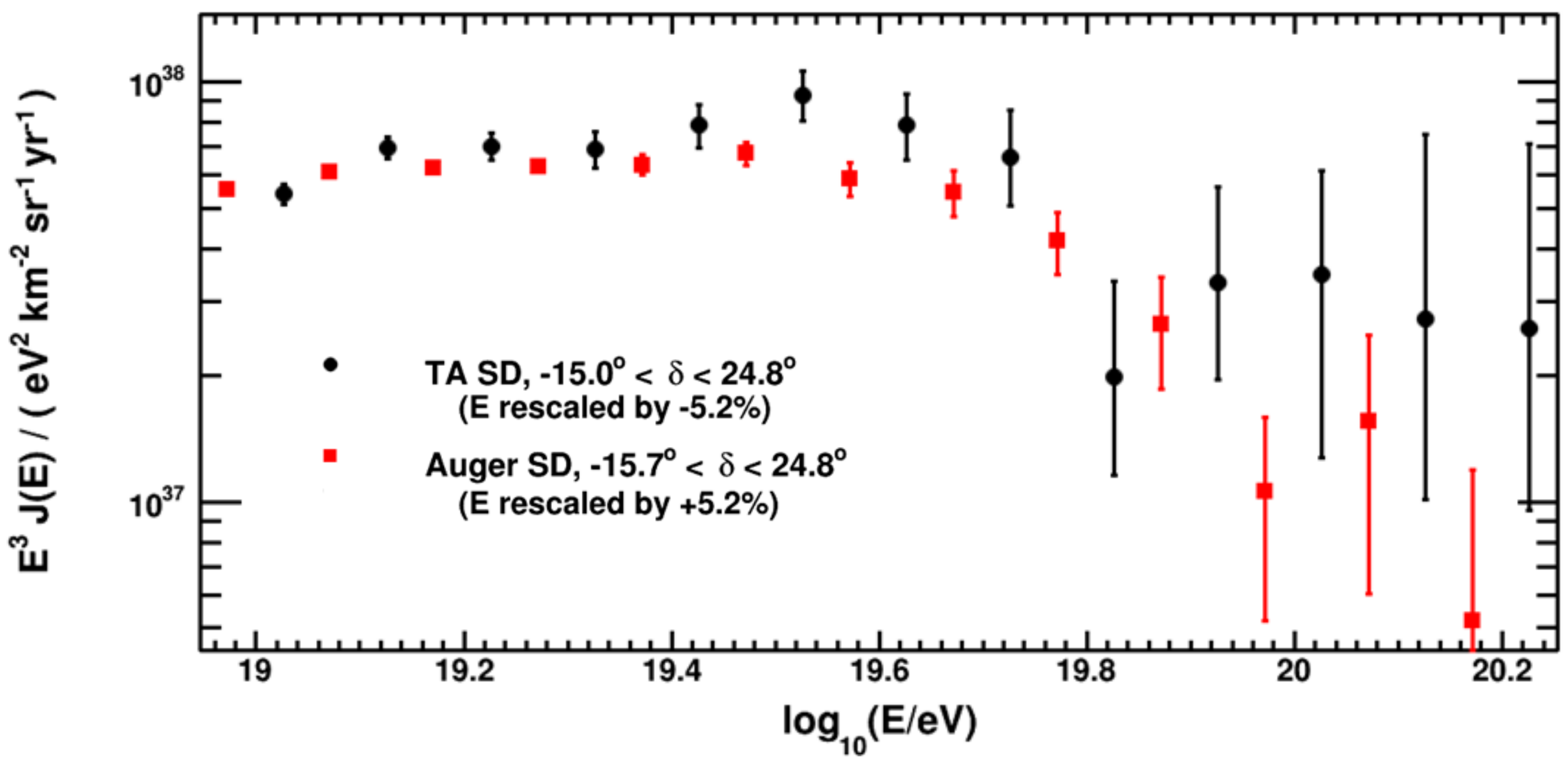


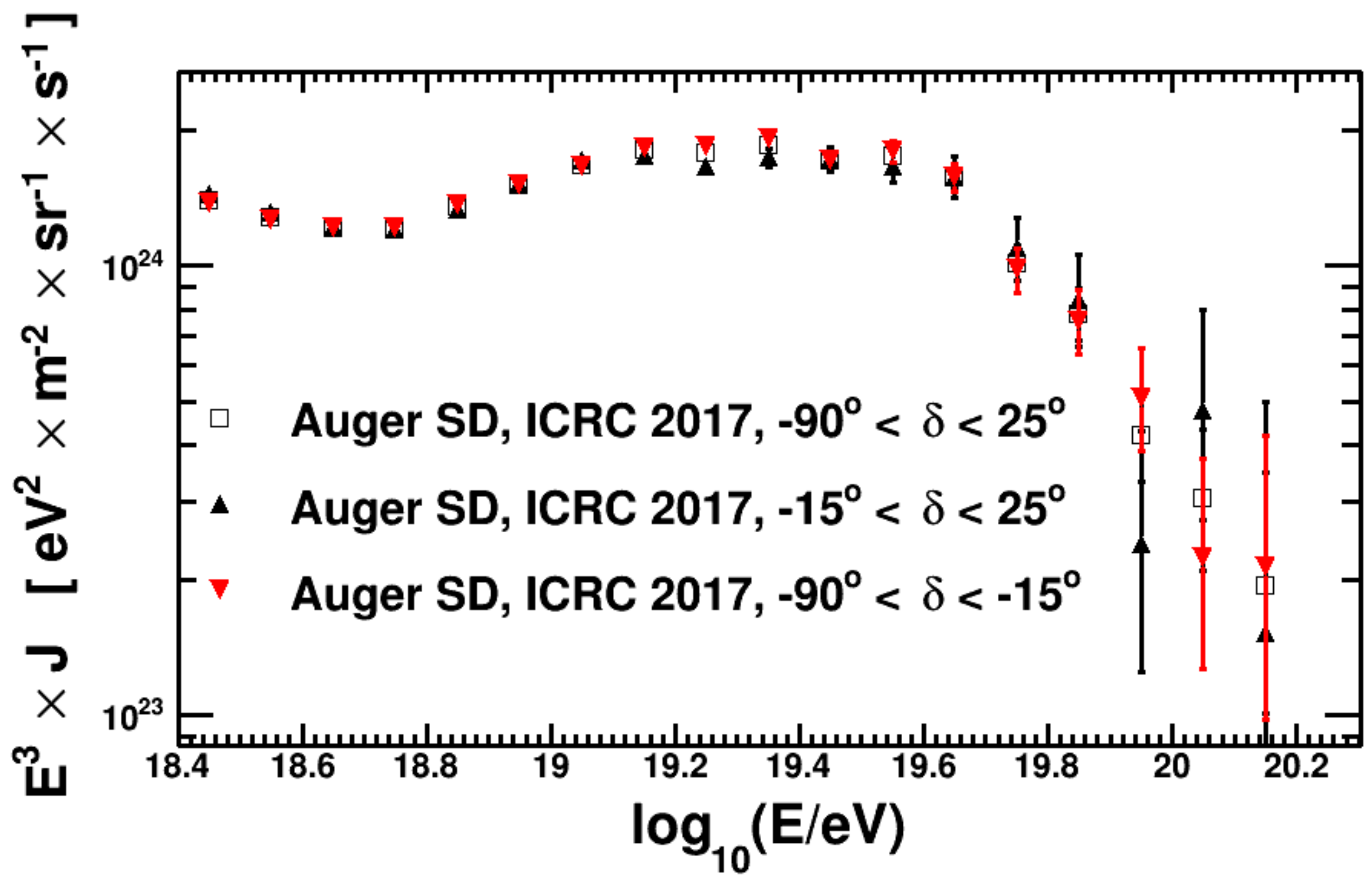
Are the energy spectra consistent with each other?

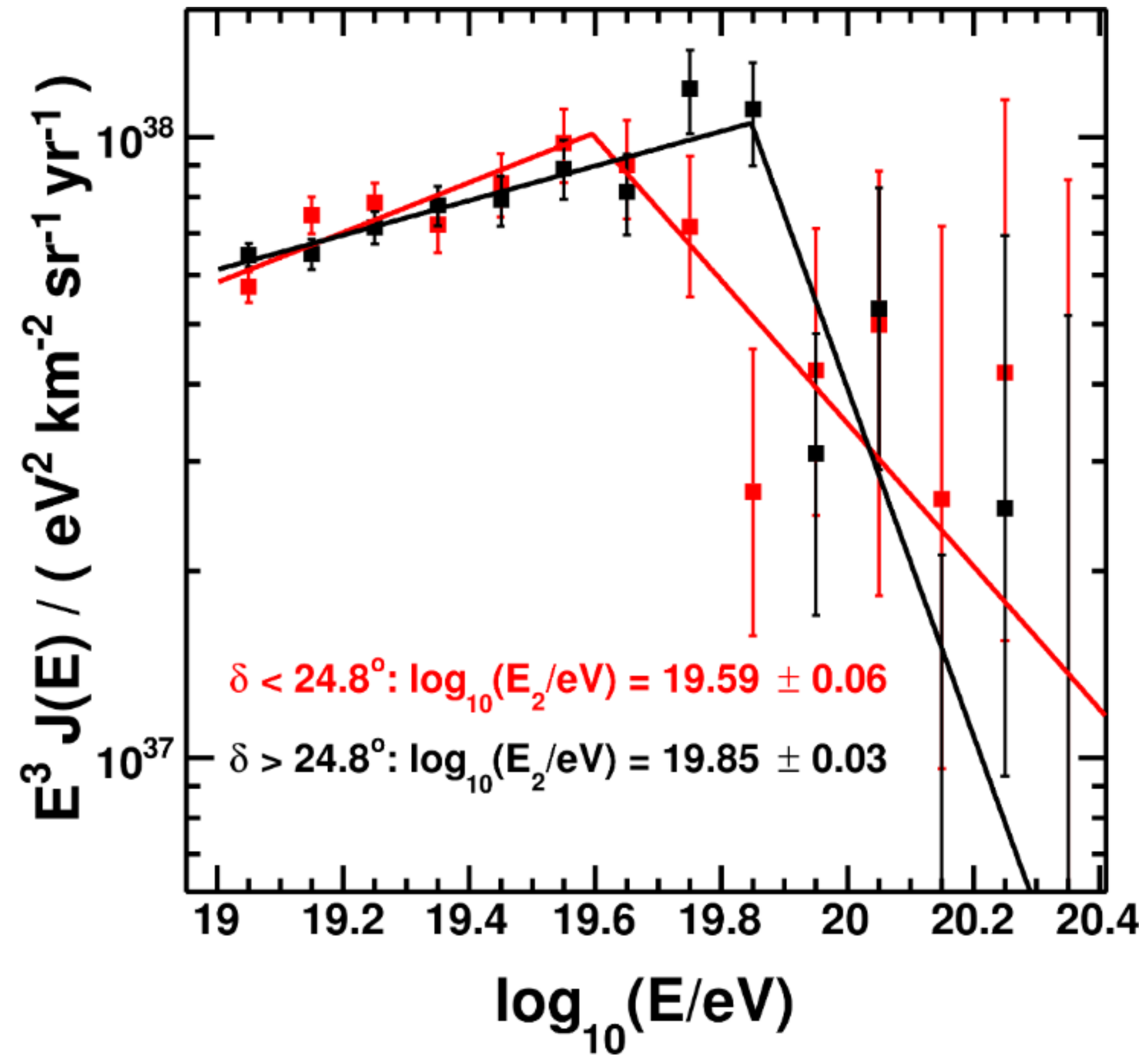
All sky



Common declination band







Better agreement if only common declination band considered – anisotropy !

Telescope Array: spectrum with TALE

(Abuzayyad, ICRC 2017)

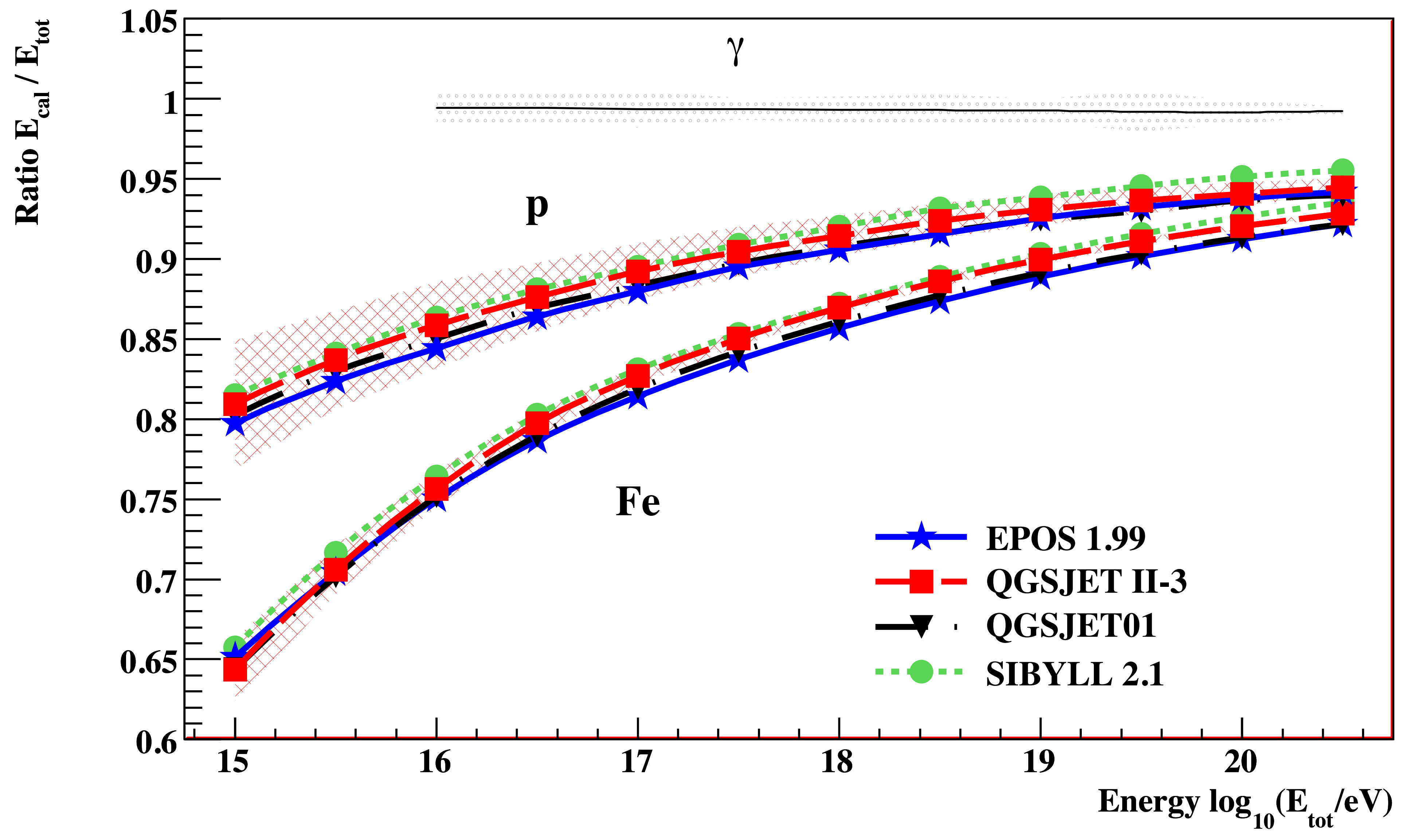
Low energy showers develop high in atmosphere

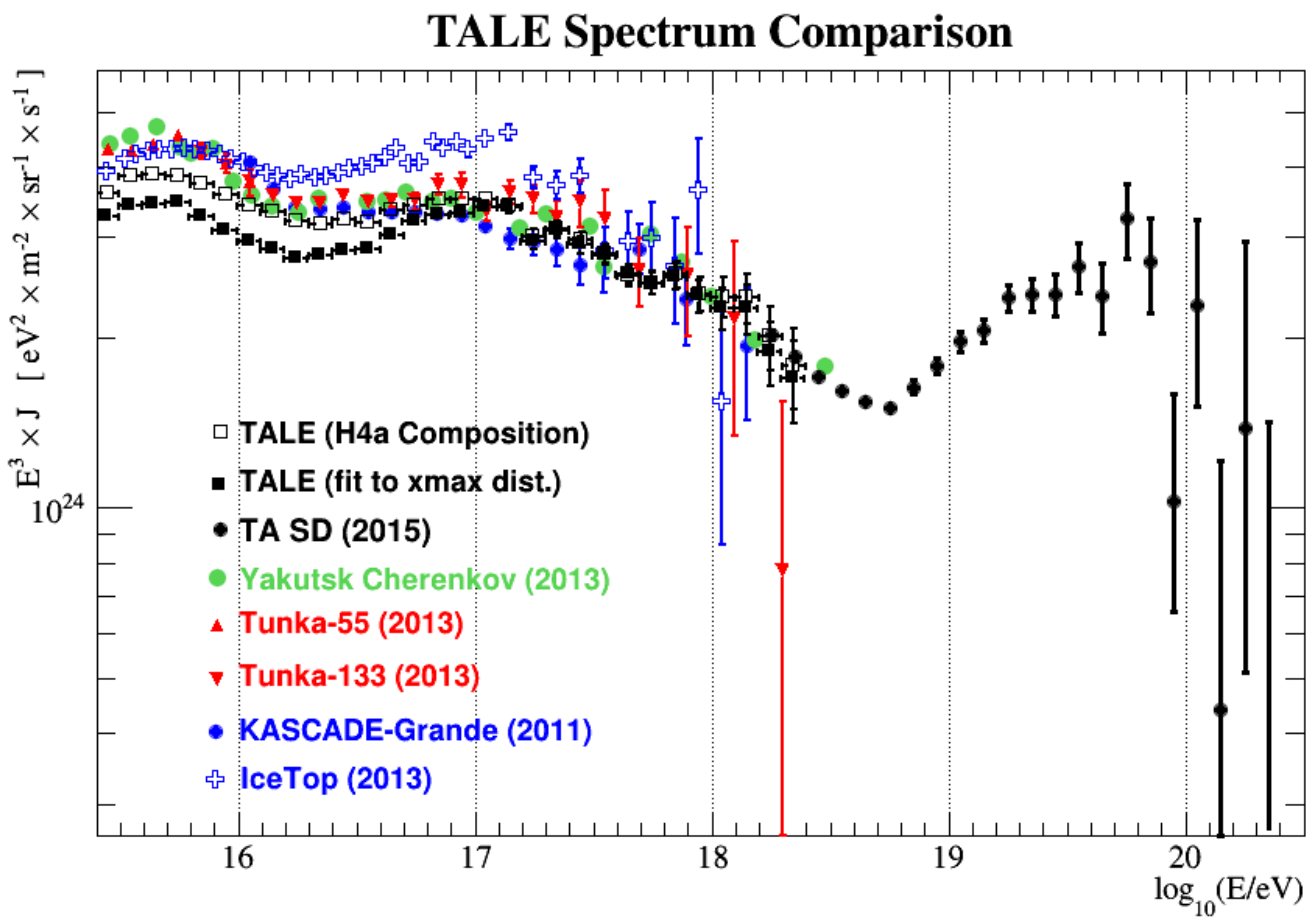
Less light produced due to smaller number of secondary particles

Viewed at small angle to shower axis

Composition-dependent correction to go from calorimetric energy to total energy

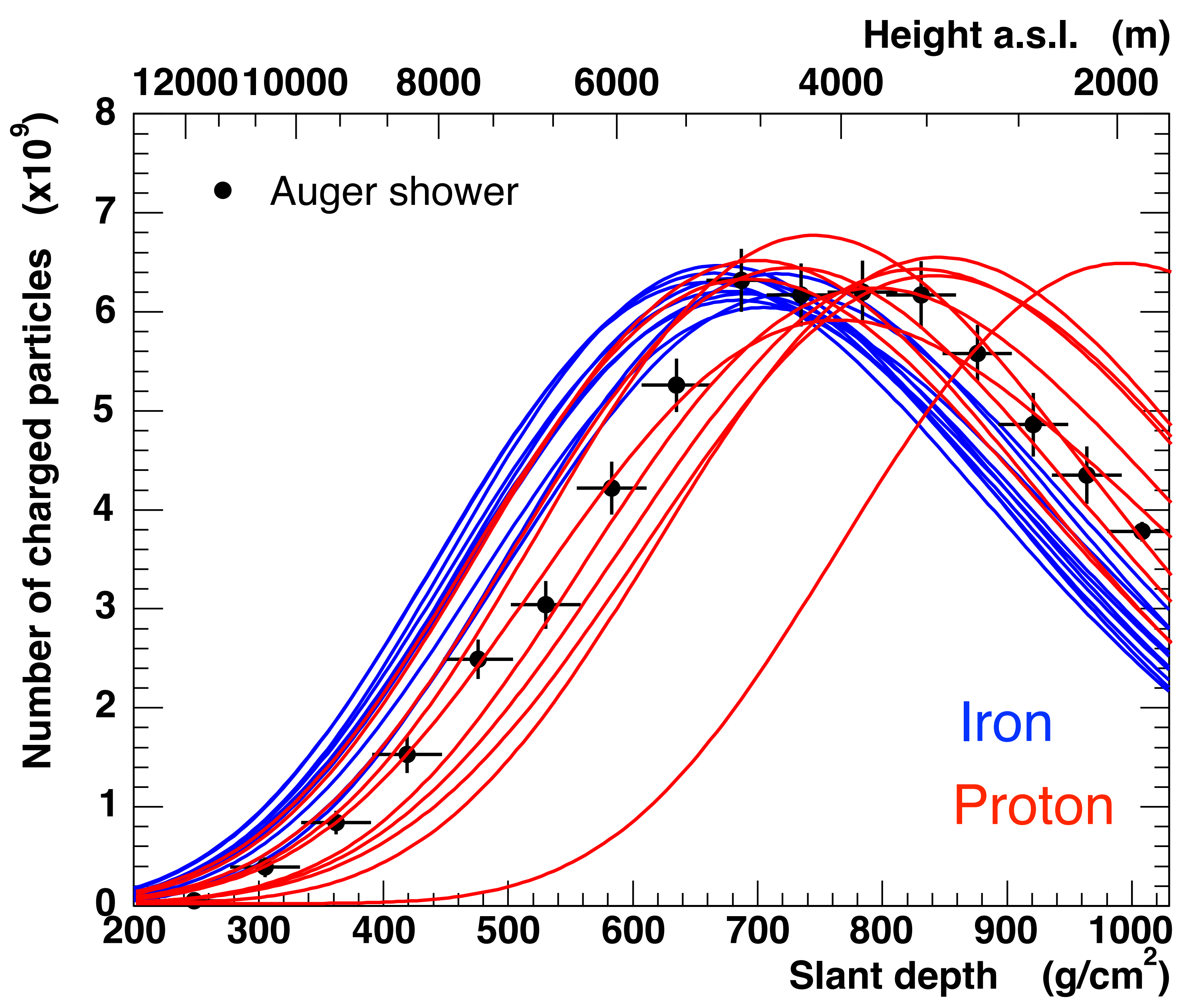
(RE et al. Ann. Rev. Nucl. Part. Phys. 2011, 61)



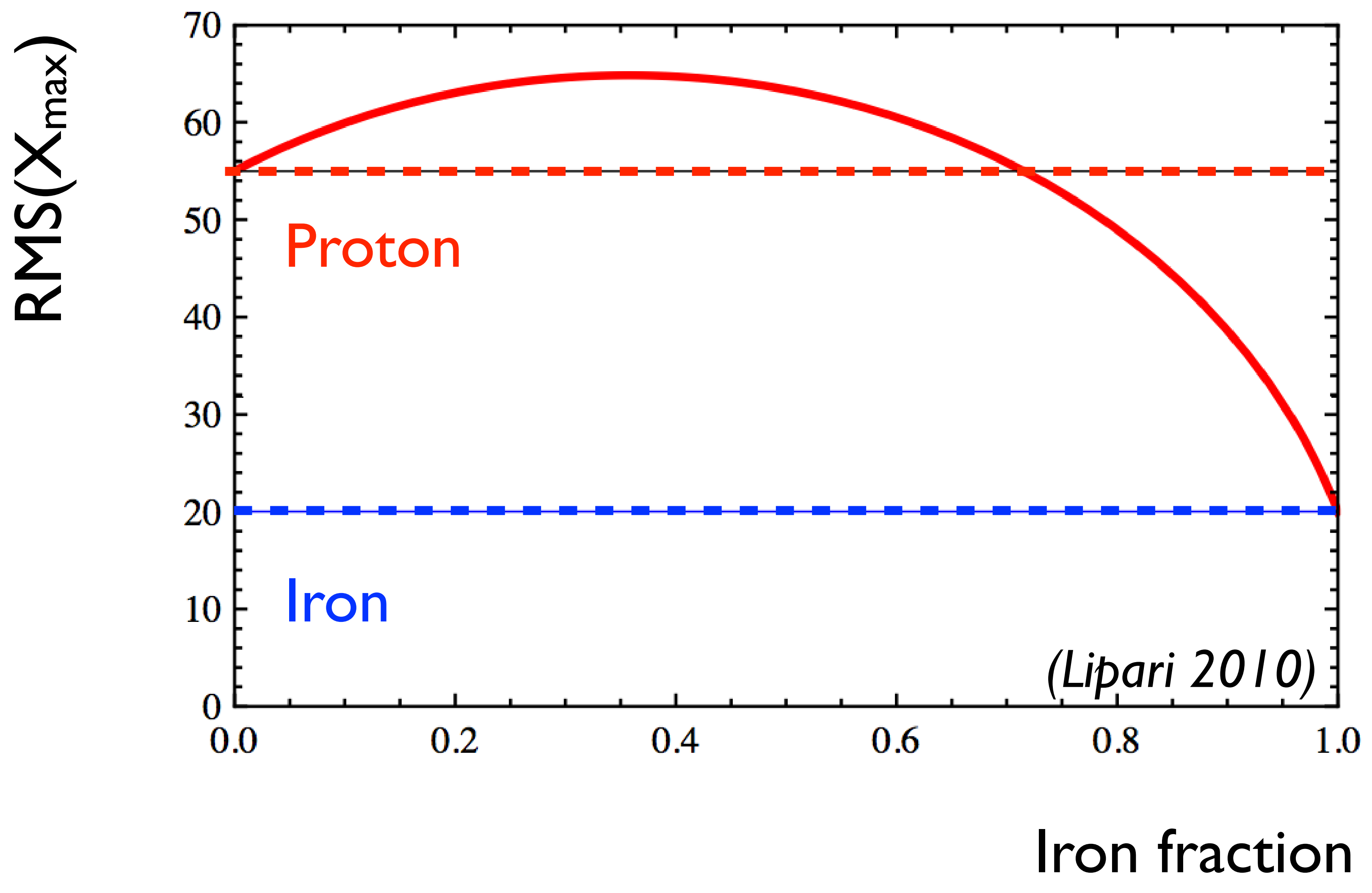


Best detection of second knee so far

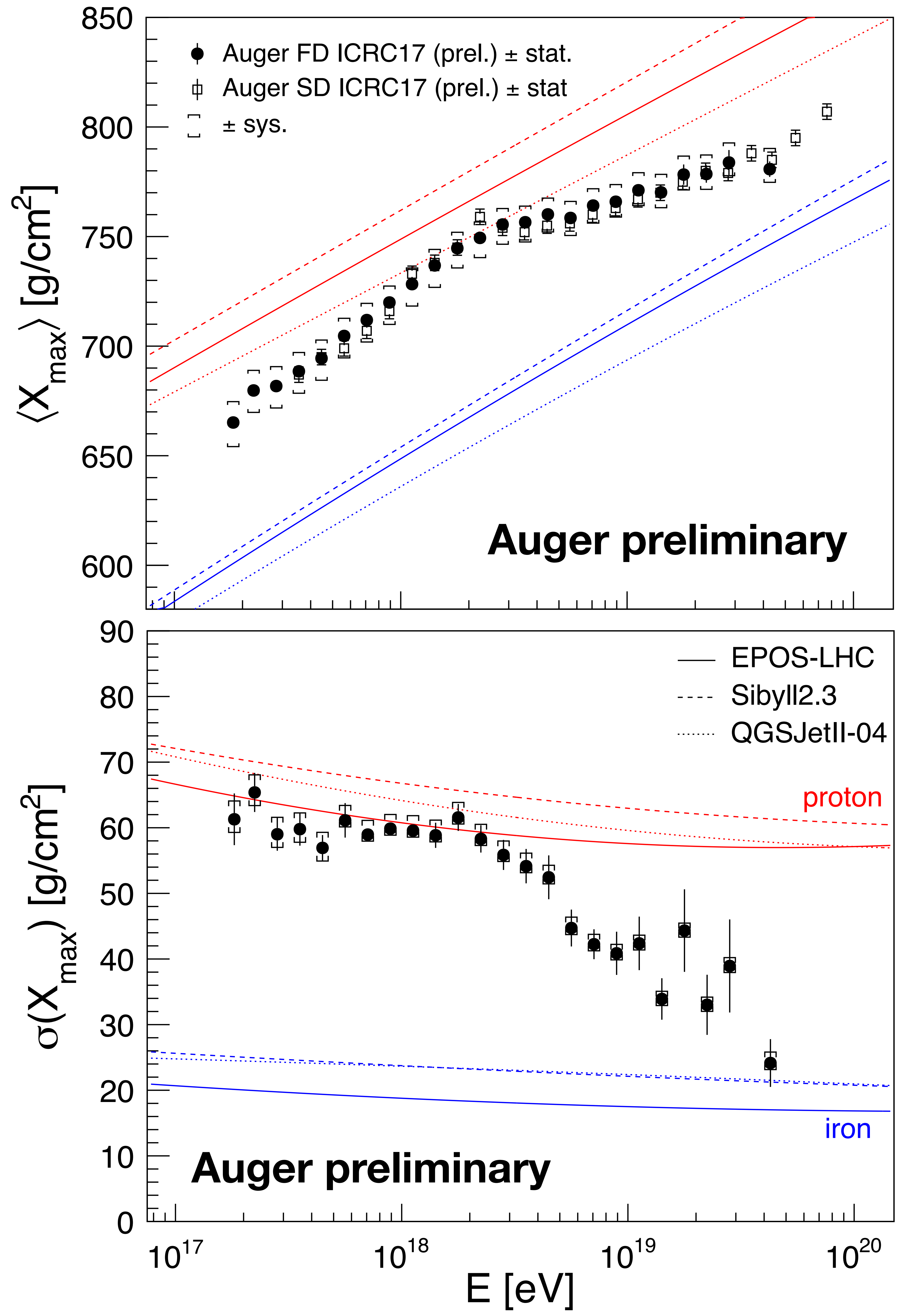
Depth of shower maximum (Auger results)



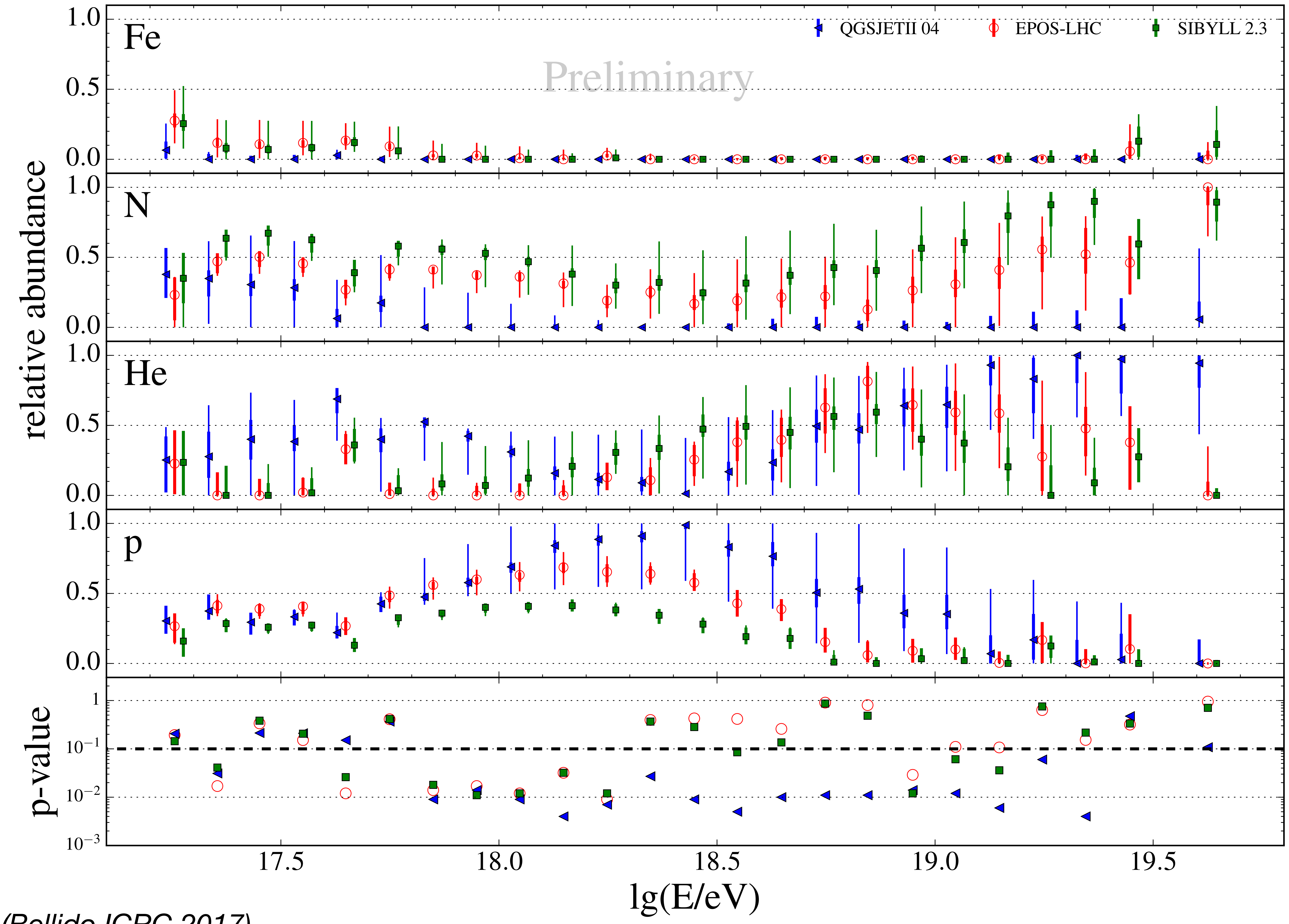
Break in elongation rate just below energy of ankle



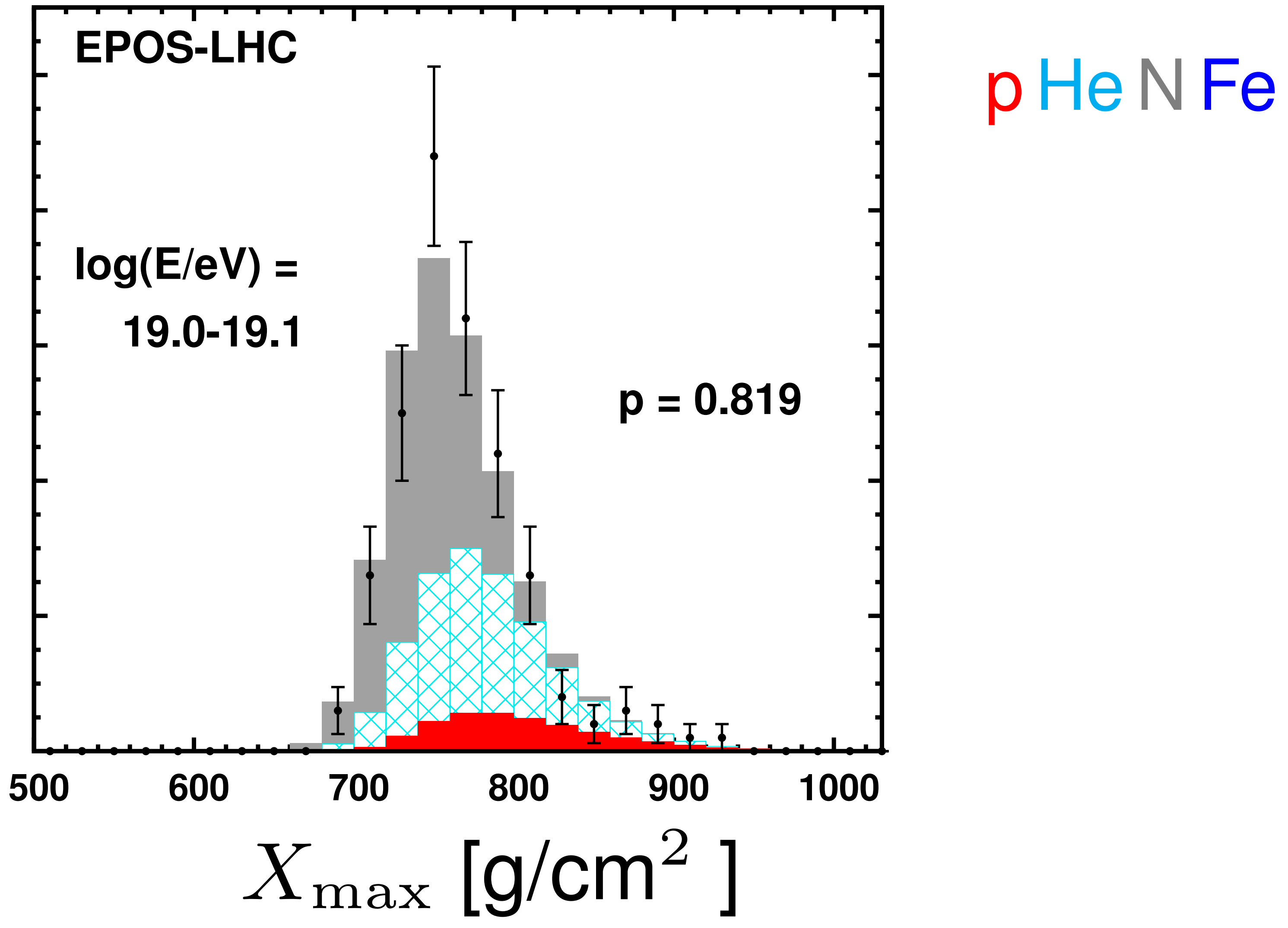
Shower-by-shower fluctuations very small



Mass composition at top of the atmosphere



(Bellido ICRC 2017)



LHC-tuned interaction models

Fit quality not always good

No iron needed for interpretation

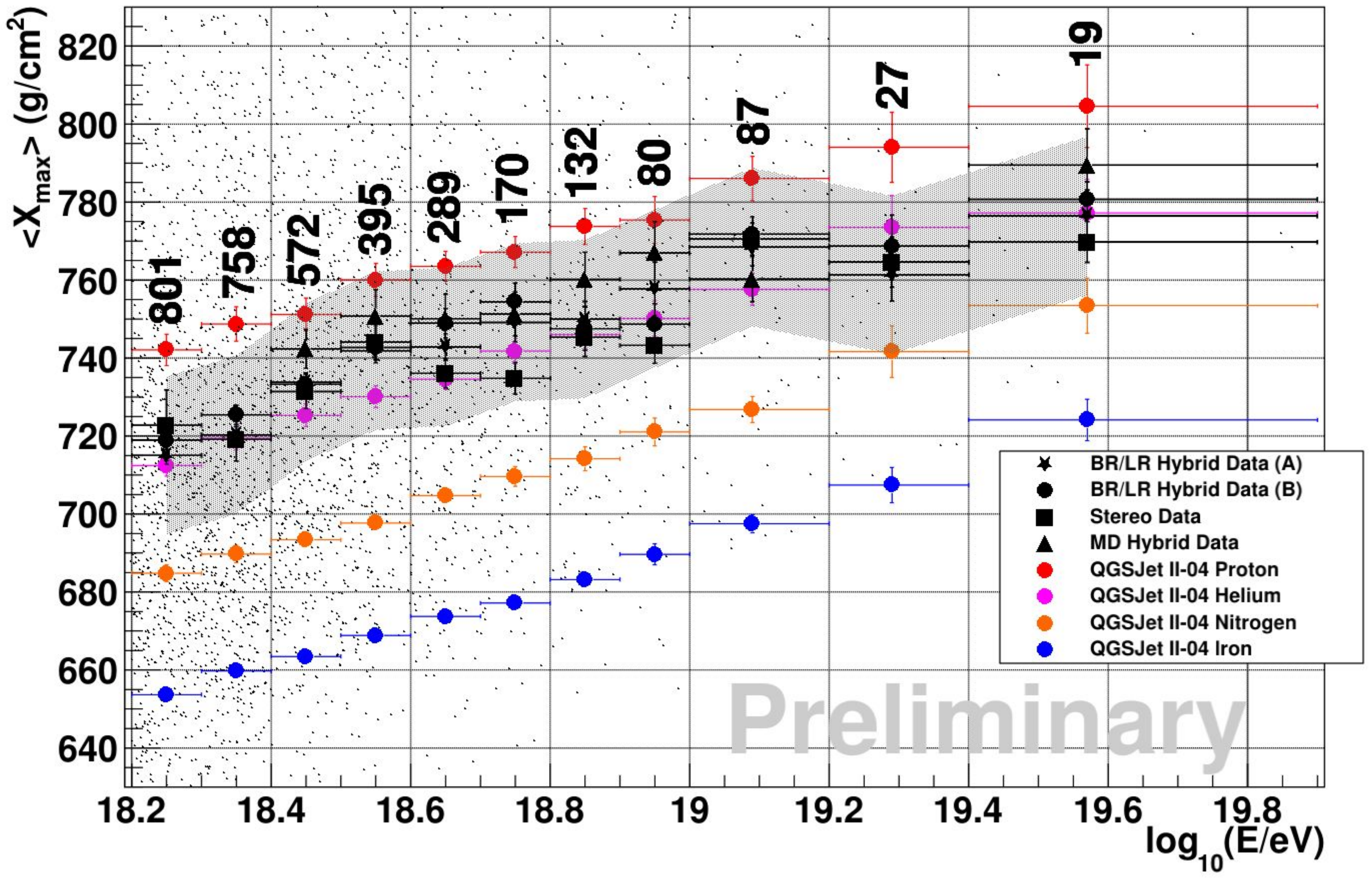
Large proton fraction below ankle

No obvious scaling with rigidity

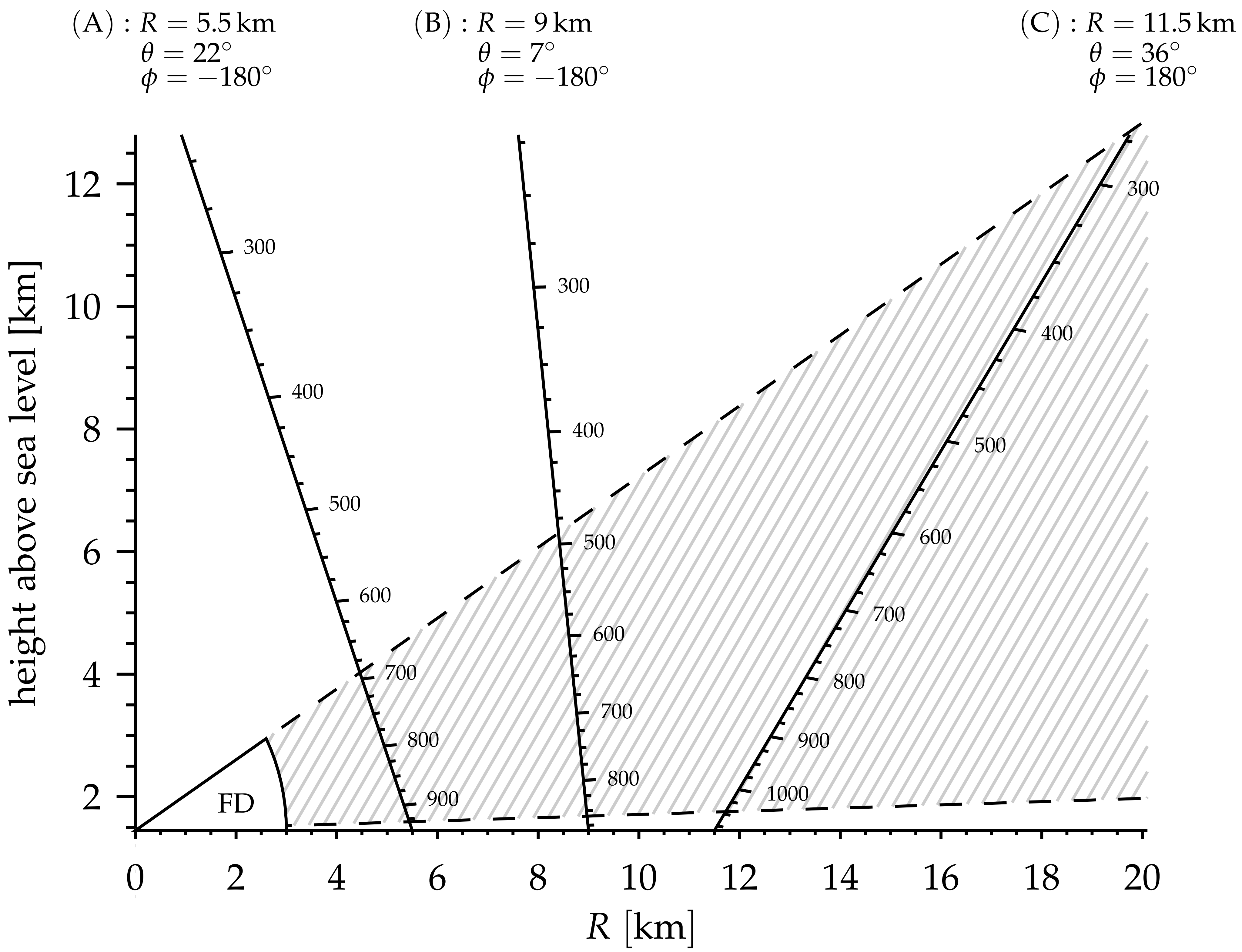
Data cover only range up to $10^{19.5}$ eV

Comparison with TA results

(TA composition summary, Hanlon, ICRC 2017)



Data cannot be compared directly due to different FoV treatment



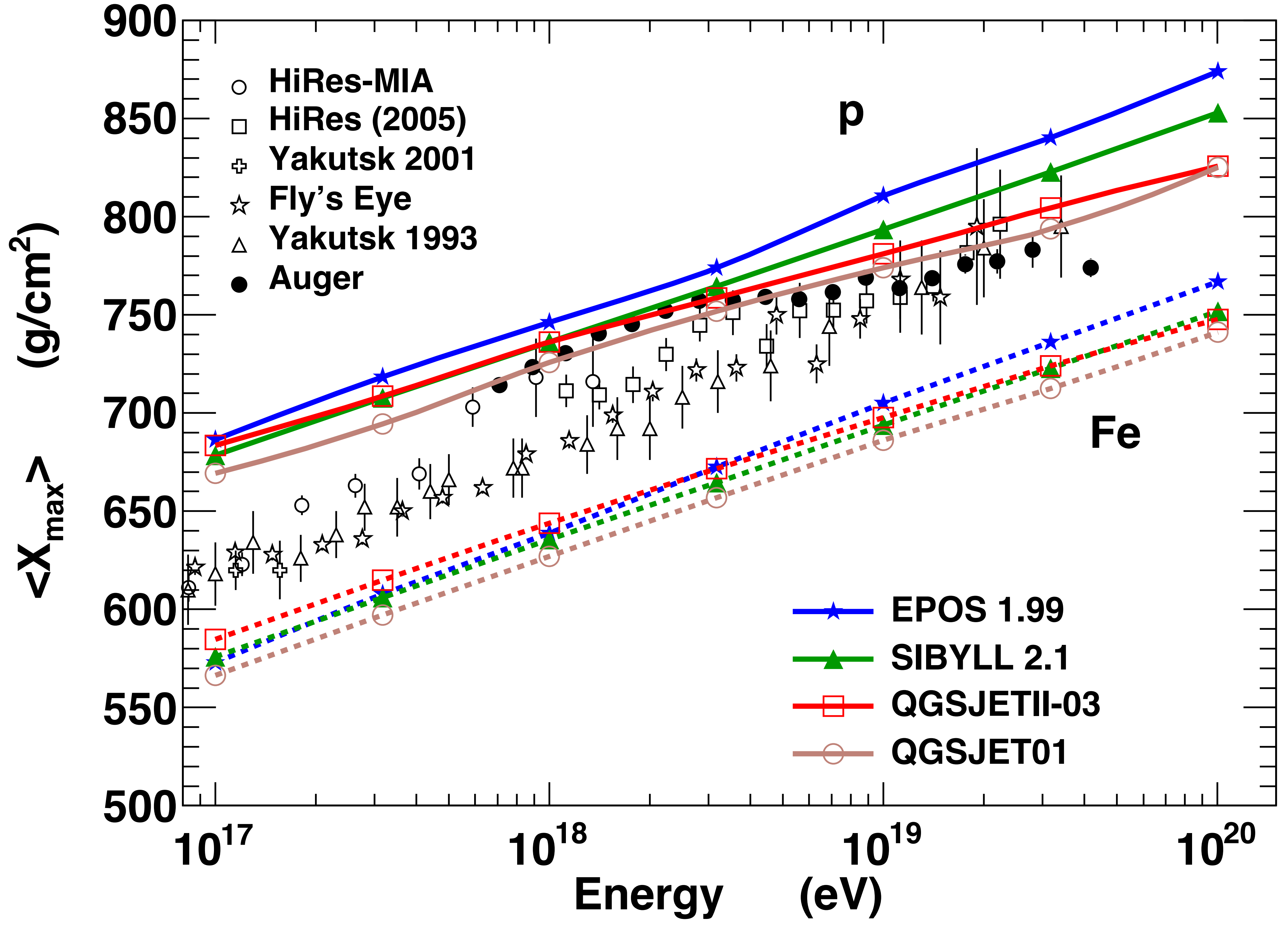
Auger: only shower geometries for which all X_{max} values visible

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

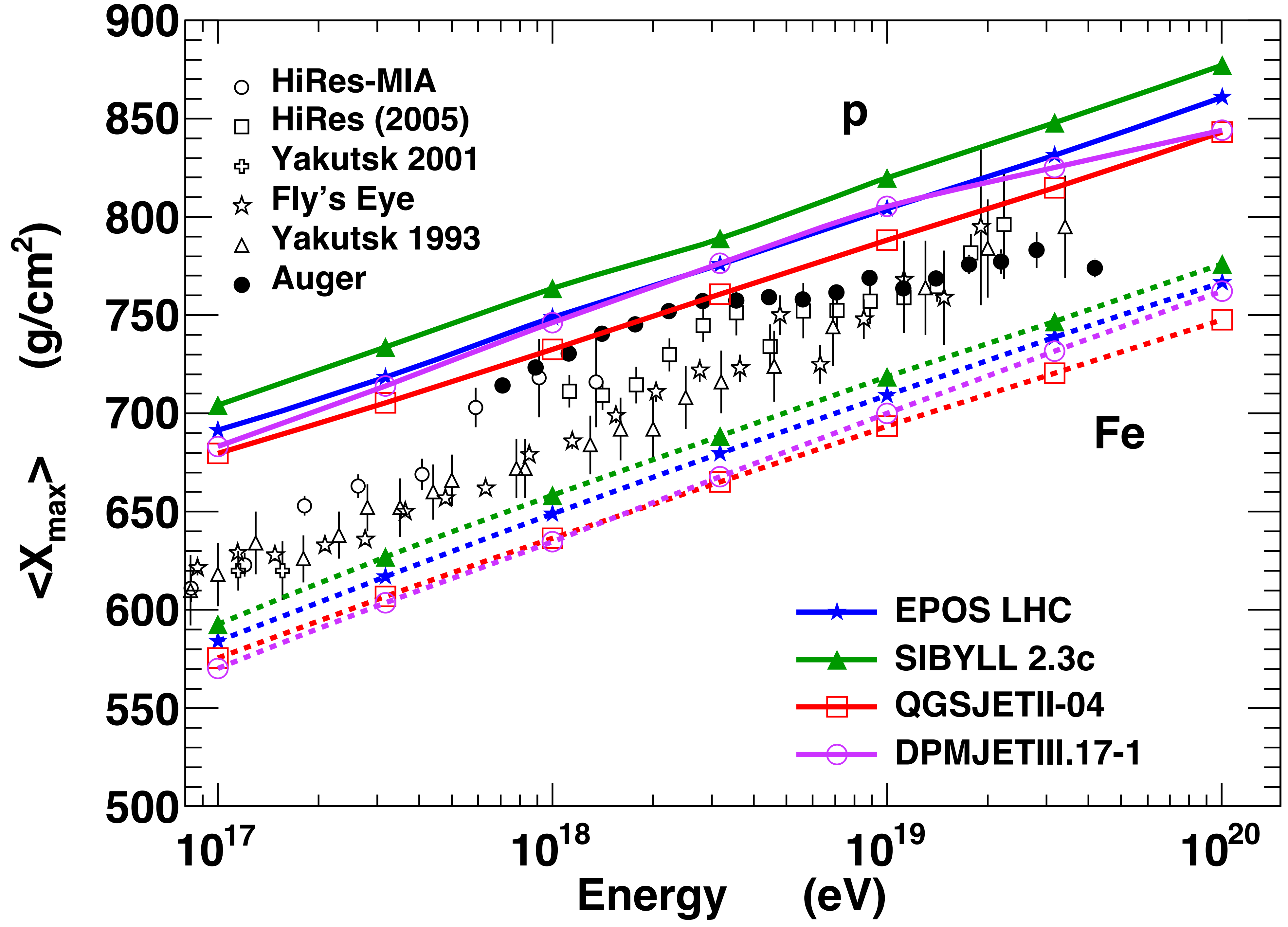
Auger-TA Working Group: data of the two experiments in agreement within the exp. uncertainties ($E < 10^{19}$ eV)

Change of model predictions thanks to LHC data

pre-LHC models



post-LHC models



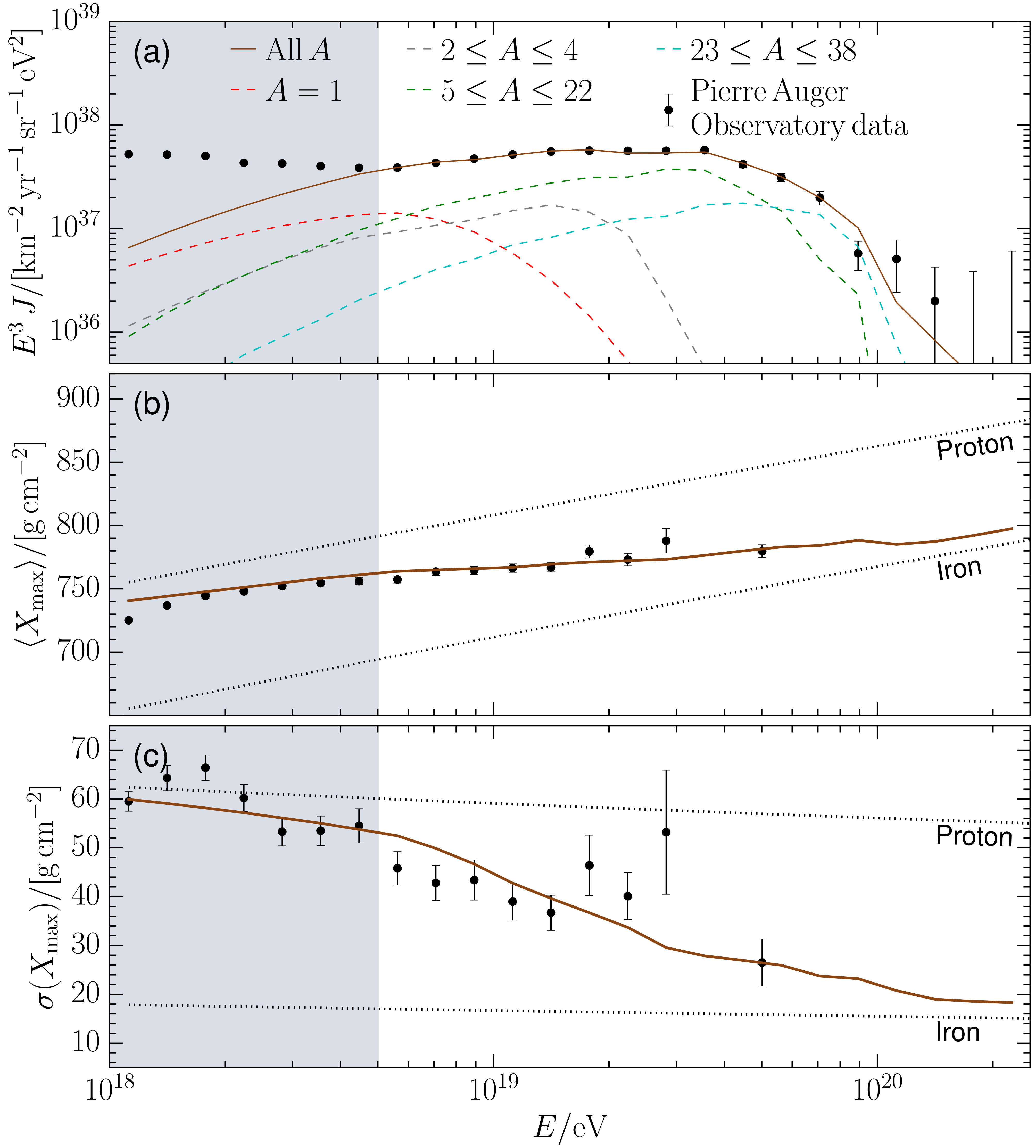
(Pierog, ICRC 2017)

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

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

LHC-tuned models should be used for data interpretation

Mass composition at sources (model dependent)



(Wittkowski ICRC 2017)

Rigidity-dependent injection spectra with exp. suppression

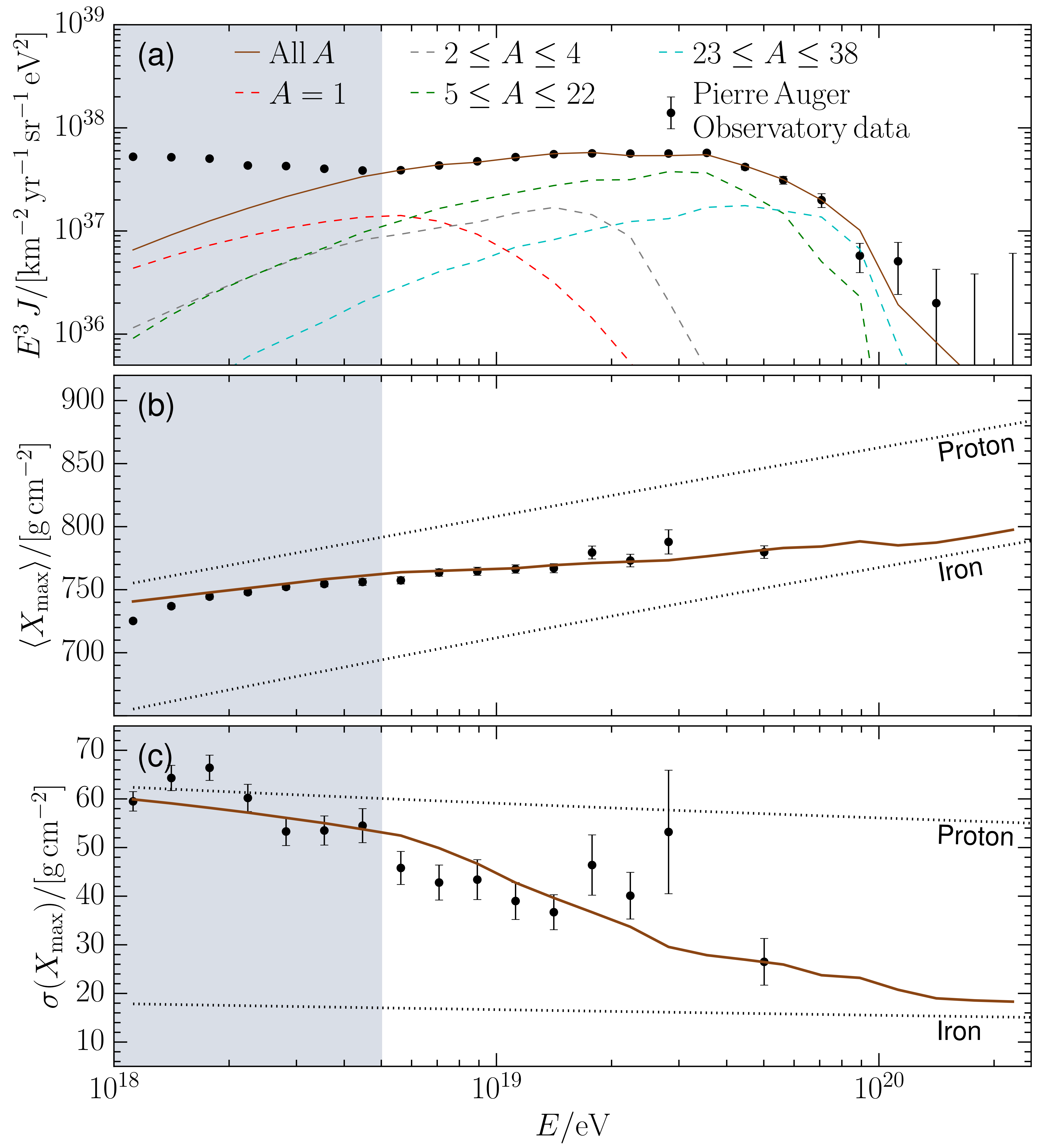
$$\frac{dN}{dE} = J_0 \sum_\alpha f_\alpha E_0^{-\gamma} \begin{cases} 1 & \text{for} \quad E_0/Z_\alpha < R_{\text{cut}}\,, \\ \exp\left(1 - \frac{E_0}{Z_\alpha R_{\text{cut}}}\right) & \text{for} \quad E_0/Z_\alpha \ge R_{\text{cut}} \end{cases}$$

Results for different model scenarios (CRpropa), m=0

Source properties	4D with EGMF	4D no EGMF	1D no EGMF[1]
γ	1.61	0.61	0.87
$\log_{10}(R_{\text{cut}}/\text{eV})$	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)]

Mass composition at sources (model dependent)



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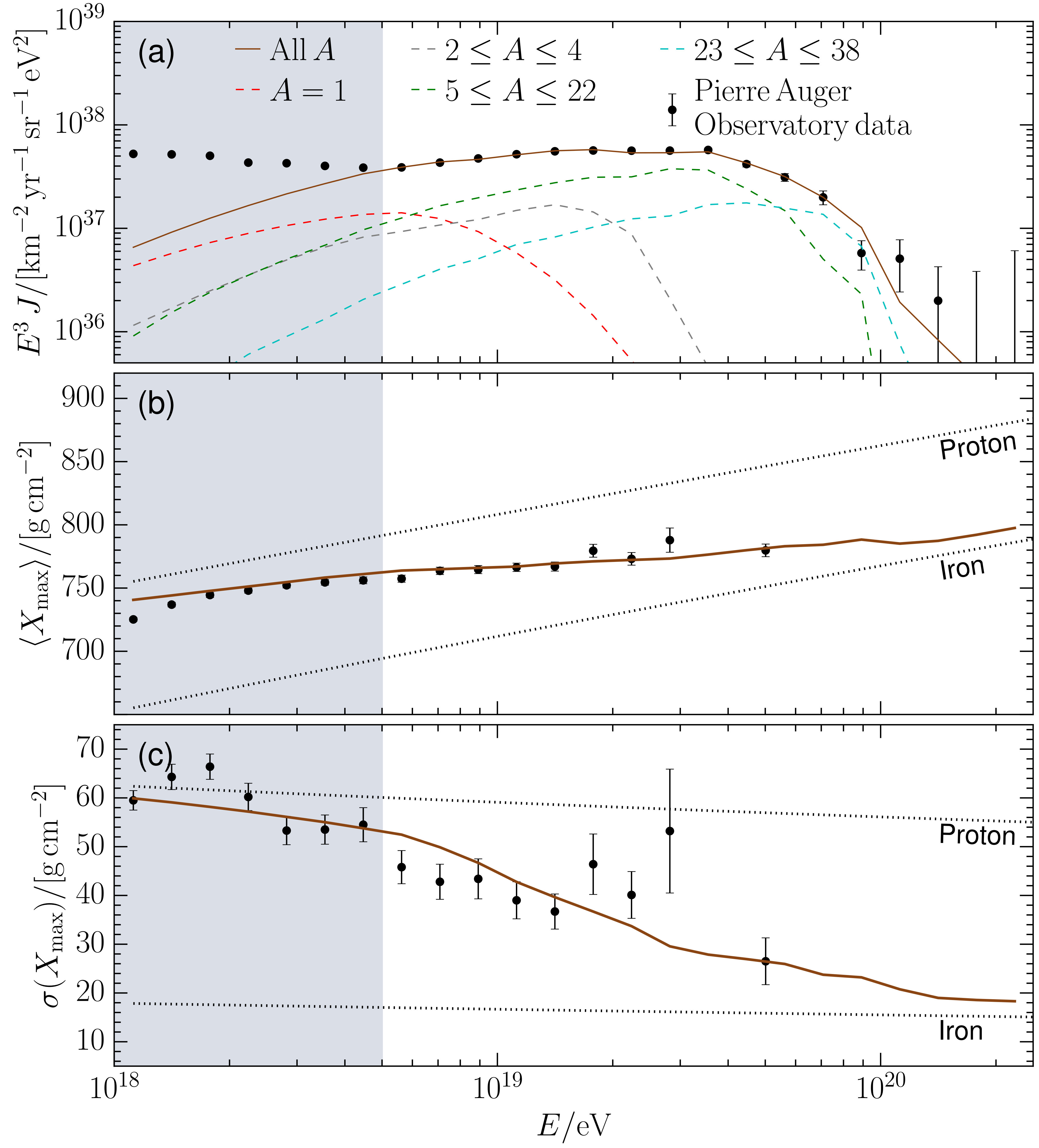
Suppression of flux dominated by maximum injection energy

$$E_{cut} = Z\, R_{cut} \approx 7 \times 10^{18.6}\,\mathrm{eV} = 3 \times 10^{19}\,\mathrm{eV}$$

(Si about two times higher)

Mass composition at sources (model dependent)



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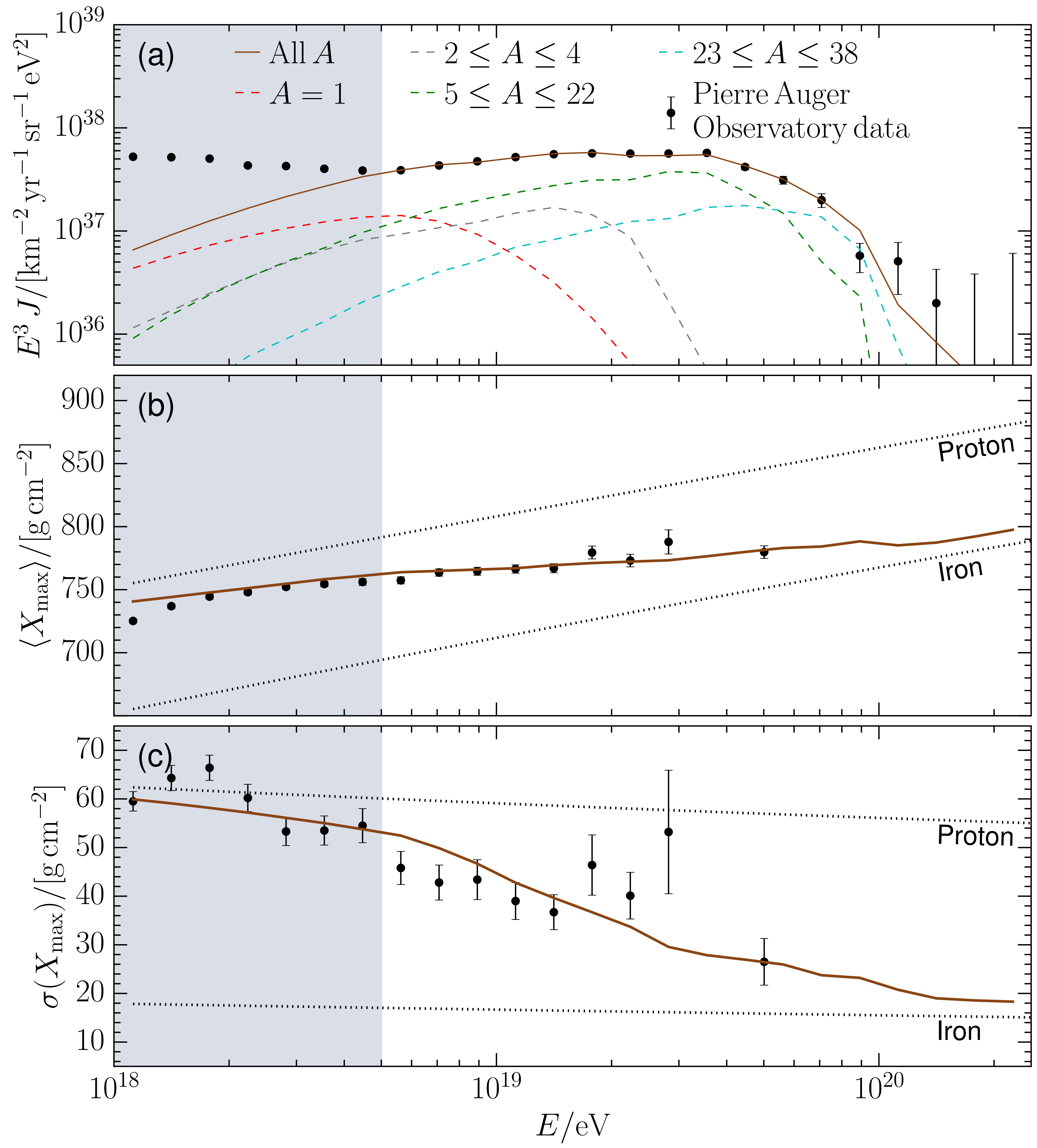
Suppression of flux dominated by maximum injection energy

Very hard index of power law at injection

(Wittkowski ICRC 2017)

Mass composition at sources (model dependent)



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f_N	74 %	68 %	88 %
f_{Si}	21 %	7 %	12 %
f_{Fe}	0 %	0 %	0 %

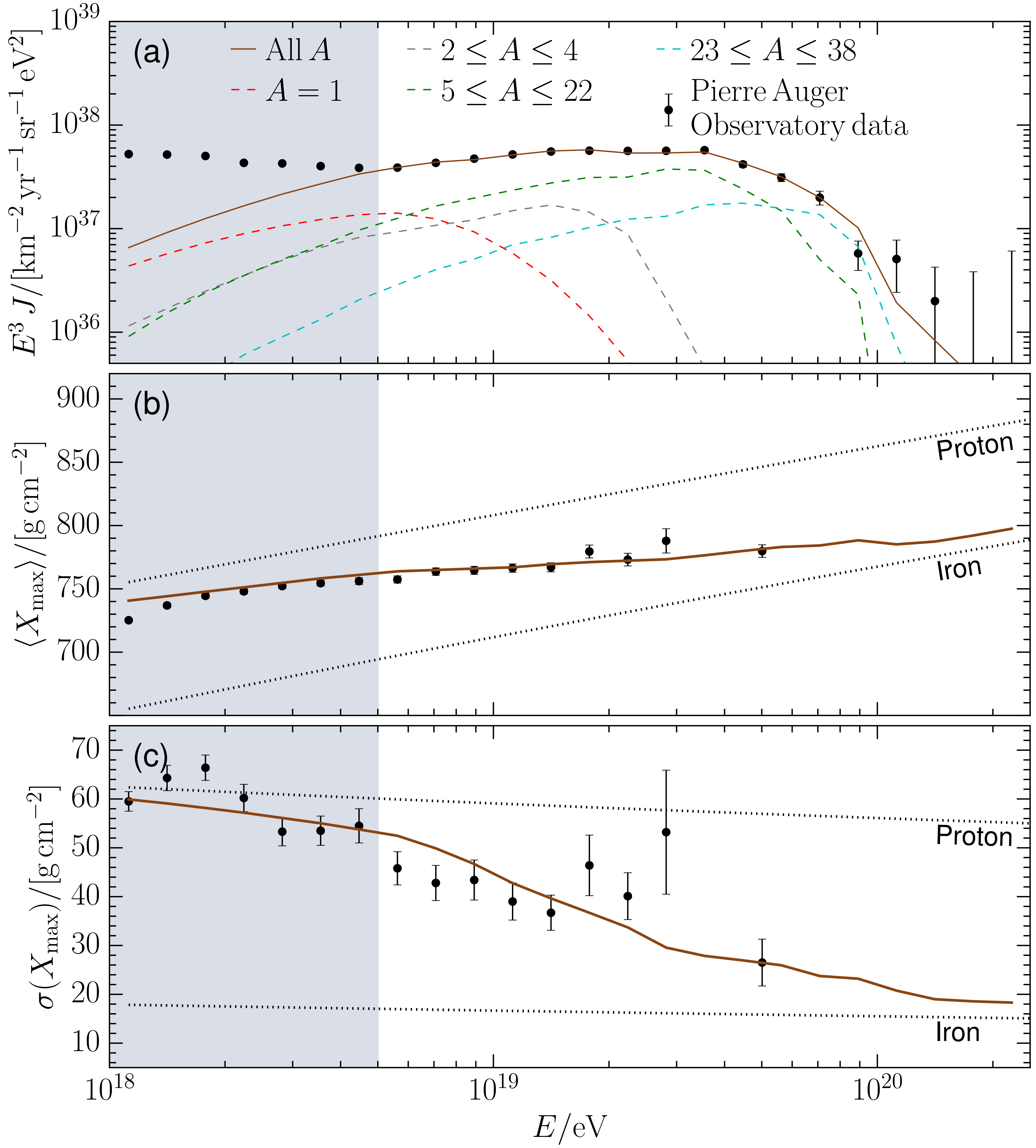
Suppression of flux dominated by maximum injection energy

Very hard index of power law at injection

Mainly primaries of the CNO and Si group injected, no Fe, very little p, p produced by spallation

(Wittkowski ICRC 2017)

Mass composition at sources (model dependent)

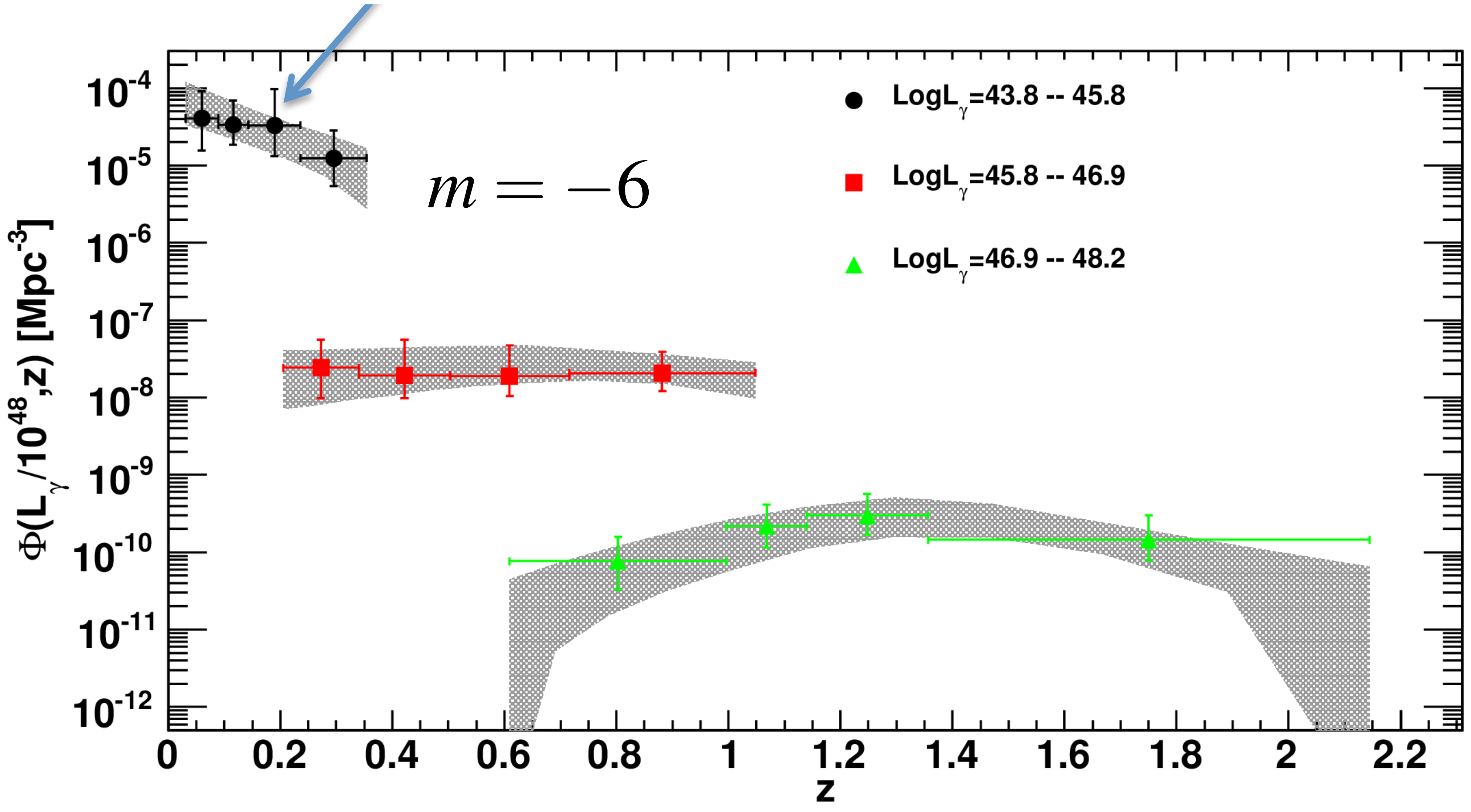


(Wittkowski ICRC 2017)

Source evolution parameter	γ	$\log_{10}(R_{\mathrm{cut}}/\mathrm{eV})$	$D_{\min}{}^2$
$m = 3$	1.20	18.70	184
$m = 0$	1.61	18.88	192
$m = -3$	1.78	18.77	199
$m = -6$	1.95	18.77	202
$m = -9$	2.05	18.78	203

(Taylor, ICRC 2017)

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



Ajello et al. (2014), 1310.0006

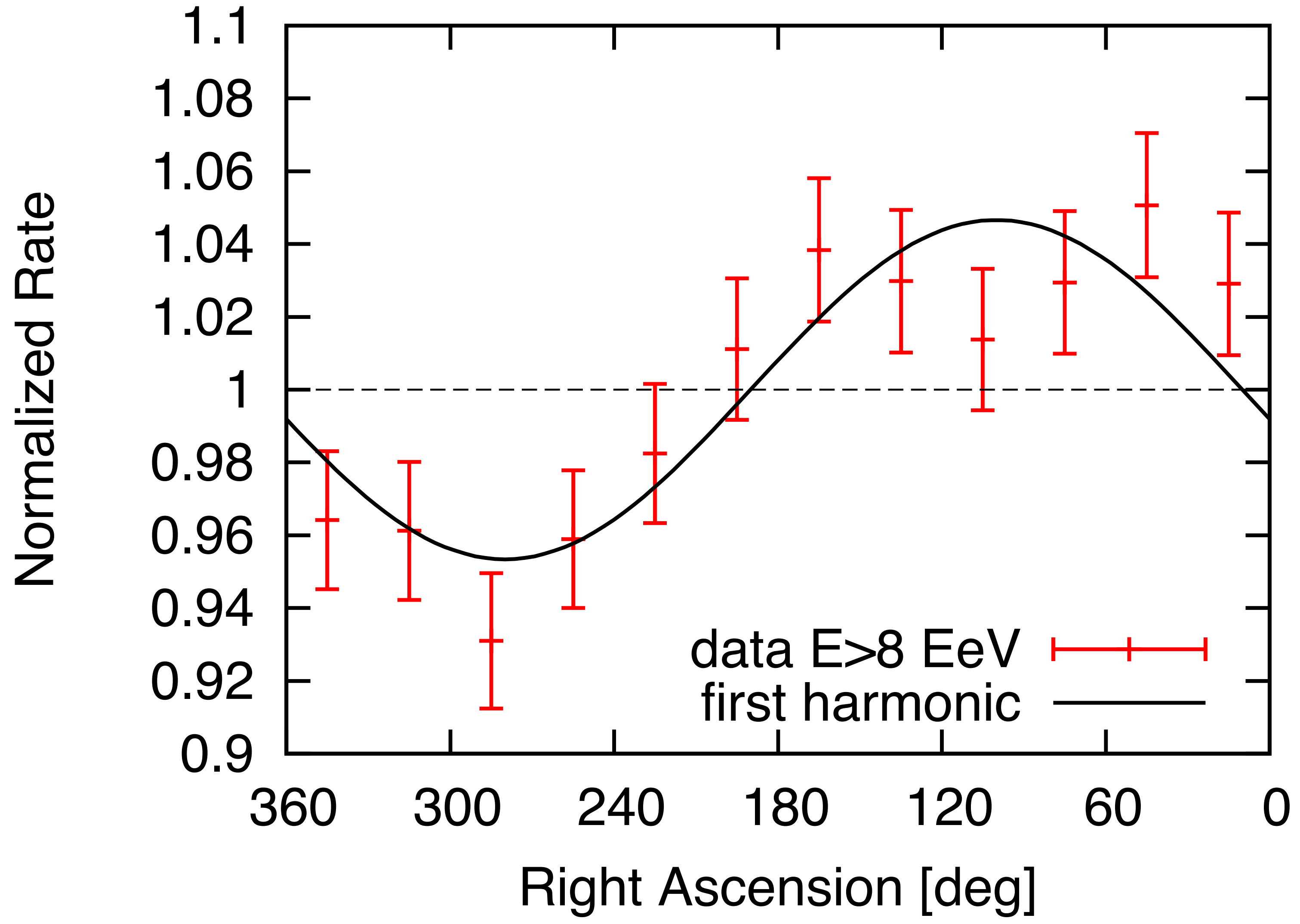
Large-scale anisotropy (Auger data)

Combination of vertical and inclined showers

Harmonic analysis in right ascension α

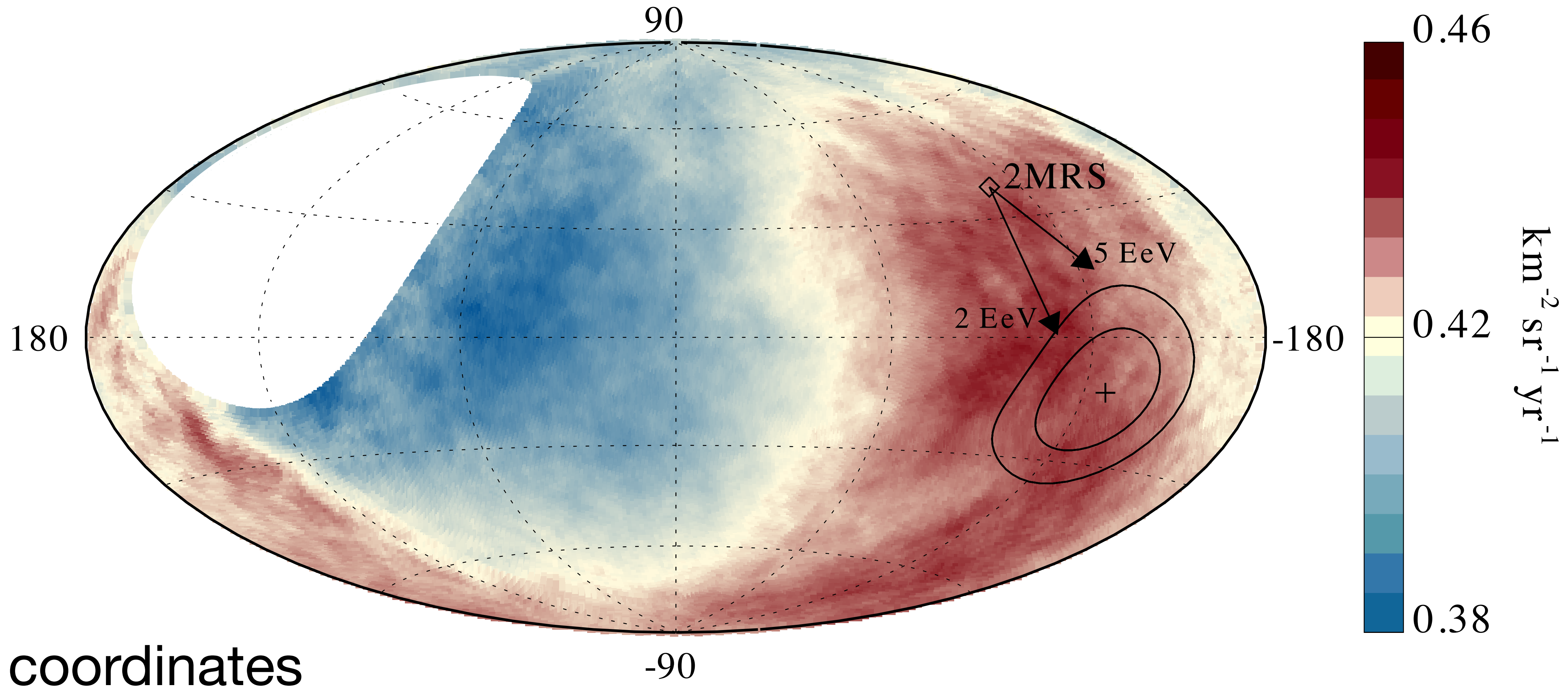
E [EeV]	events	amplitude r	phase [deg.]	$P(\geq r)$
4-8	81701	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
> 8	32187	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

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 $(\alpha, \delta) = (100°, -24°)$ $\quad (l, b) = (233°, -13°)$



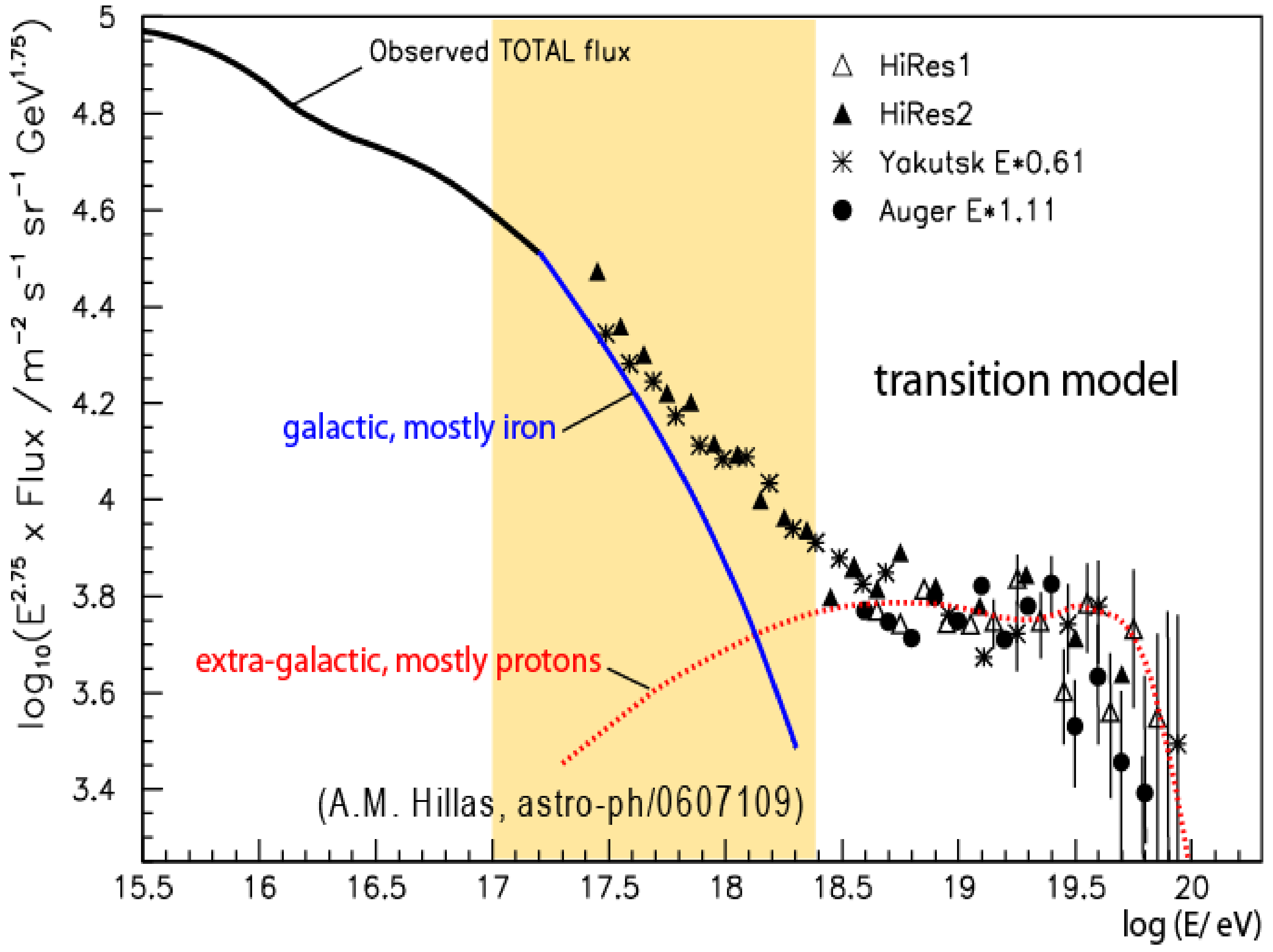
gal. coordinates

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

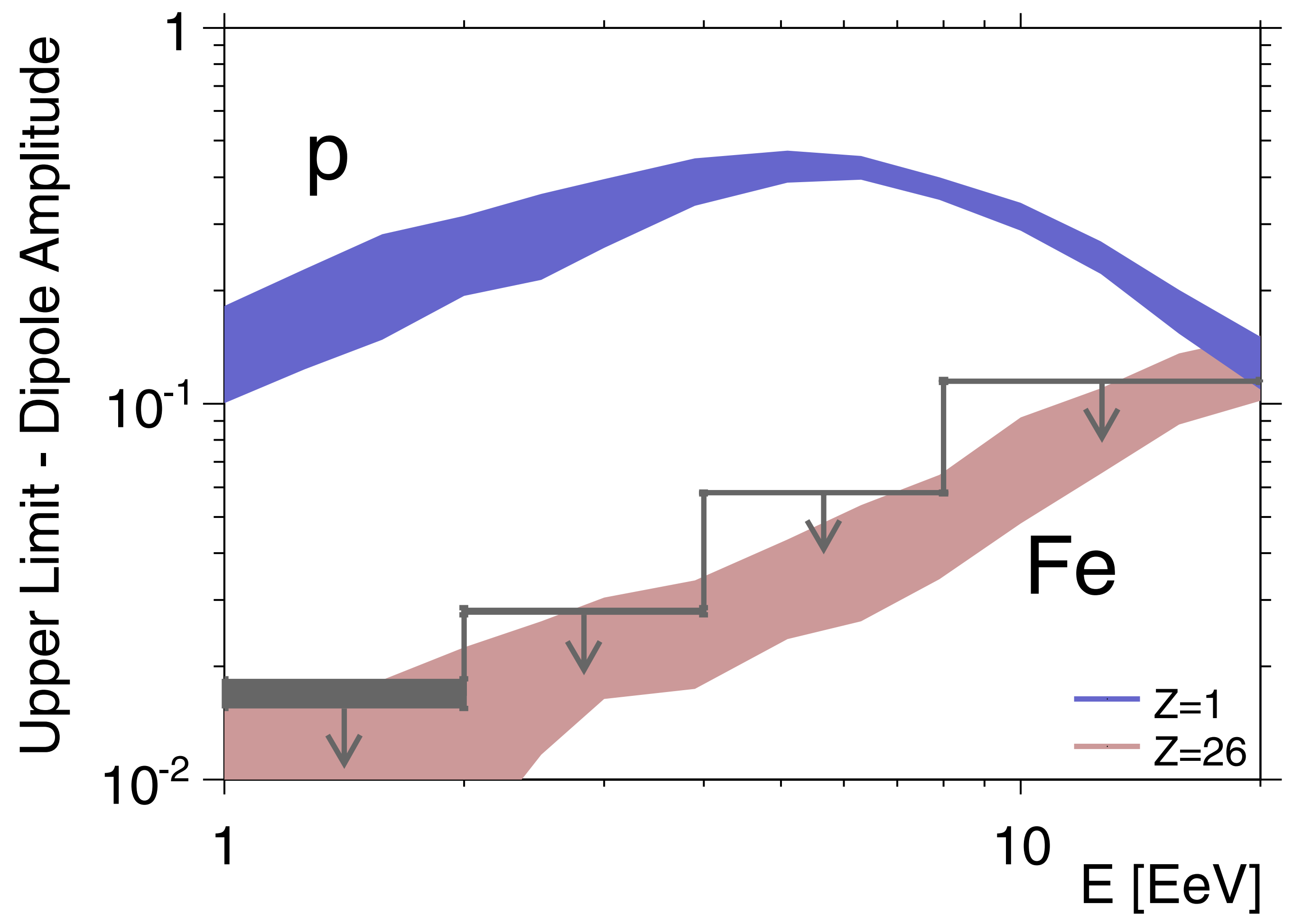
Strong indication for extragalactic origin

Transition from galactic to extragalactic cosmic rays



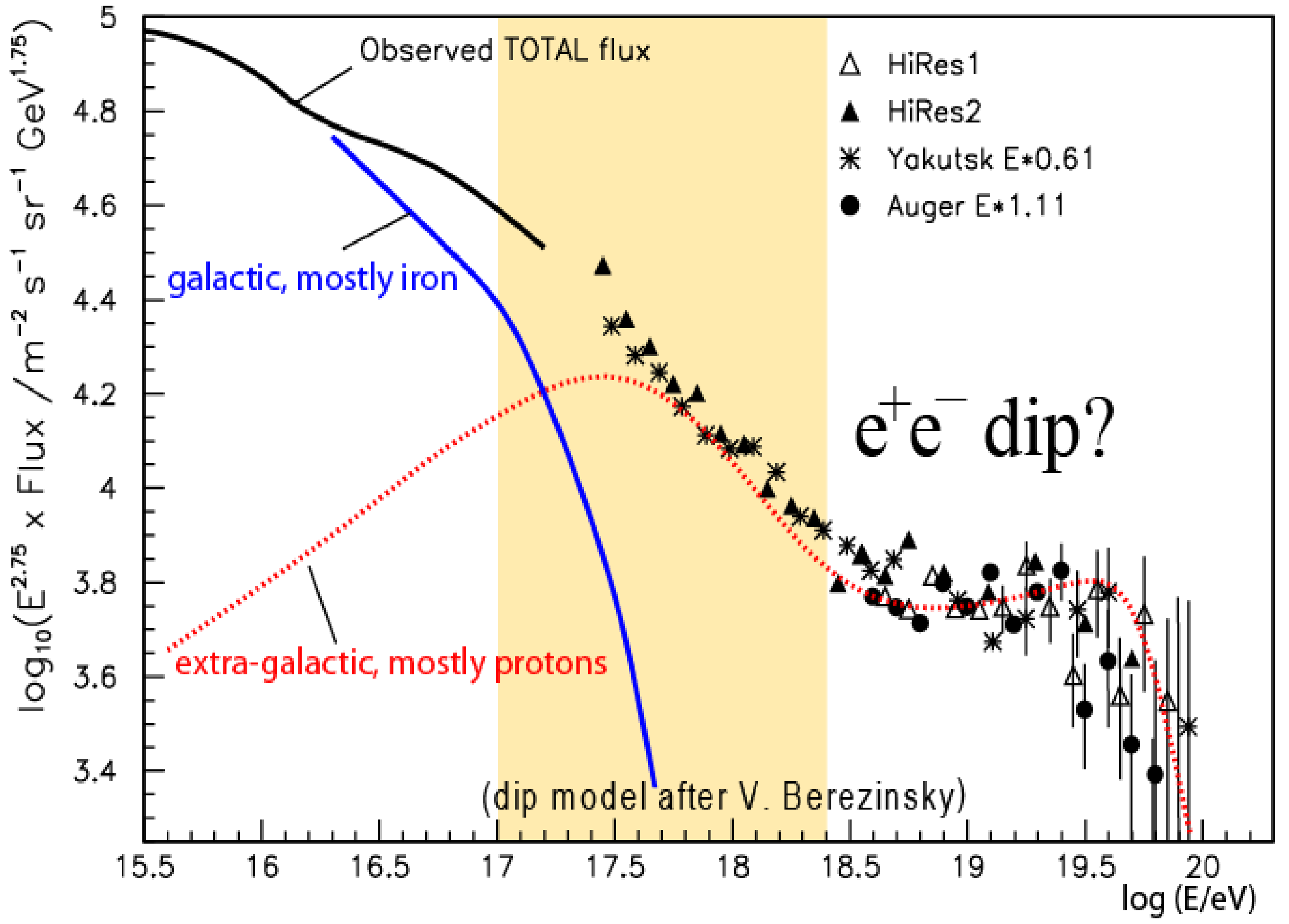
Ankle model:
Hillas, Wolfendale et al.

Simulation: Sources in galactic plane

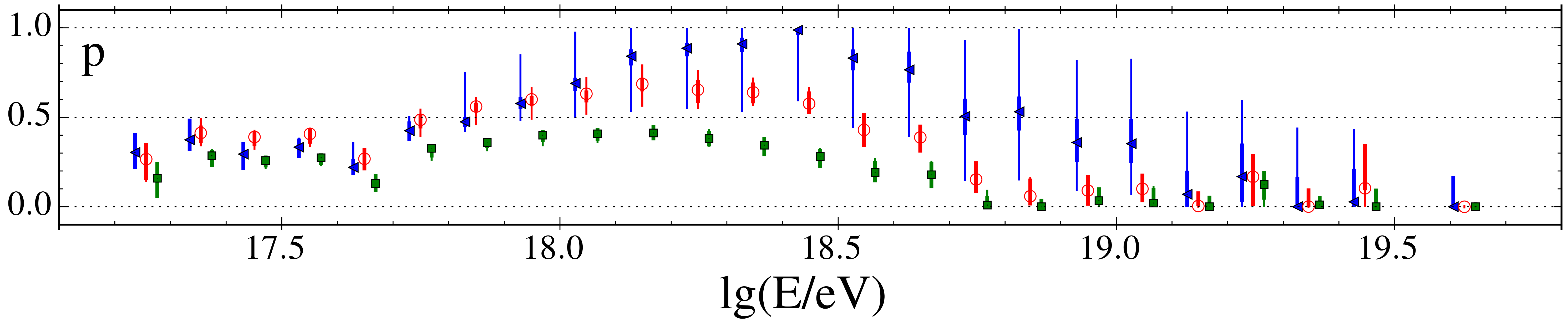


(Auger, ApJ 203, 2012,
Giacinti et al. JCAP 2012, 2015)

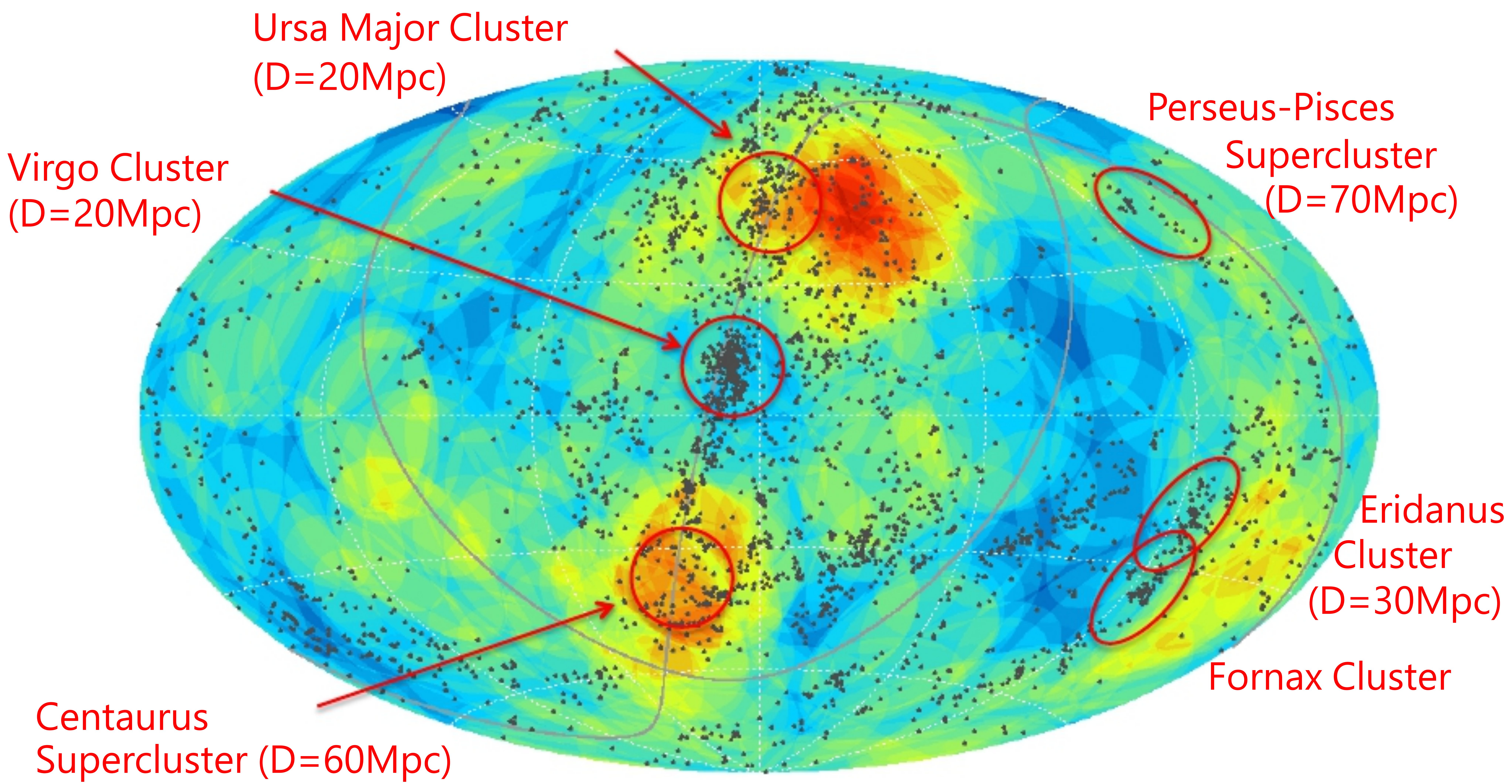
Transition energy ~10^{18} eV



Dip model:
Berezinsky et al.



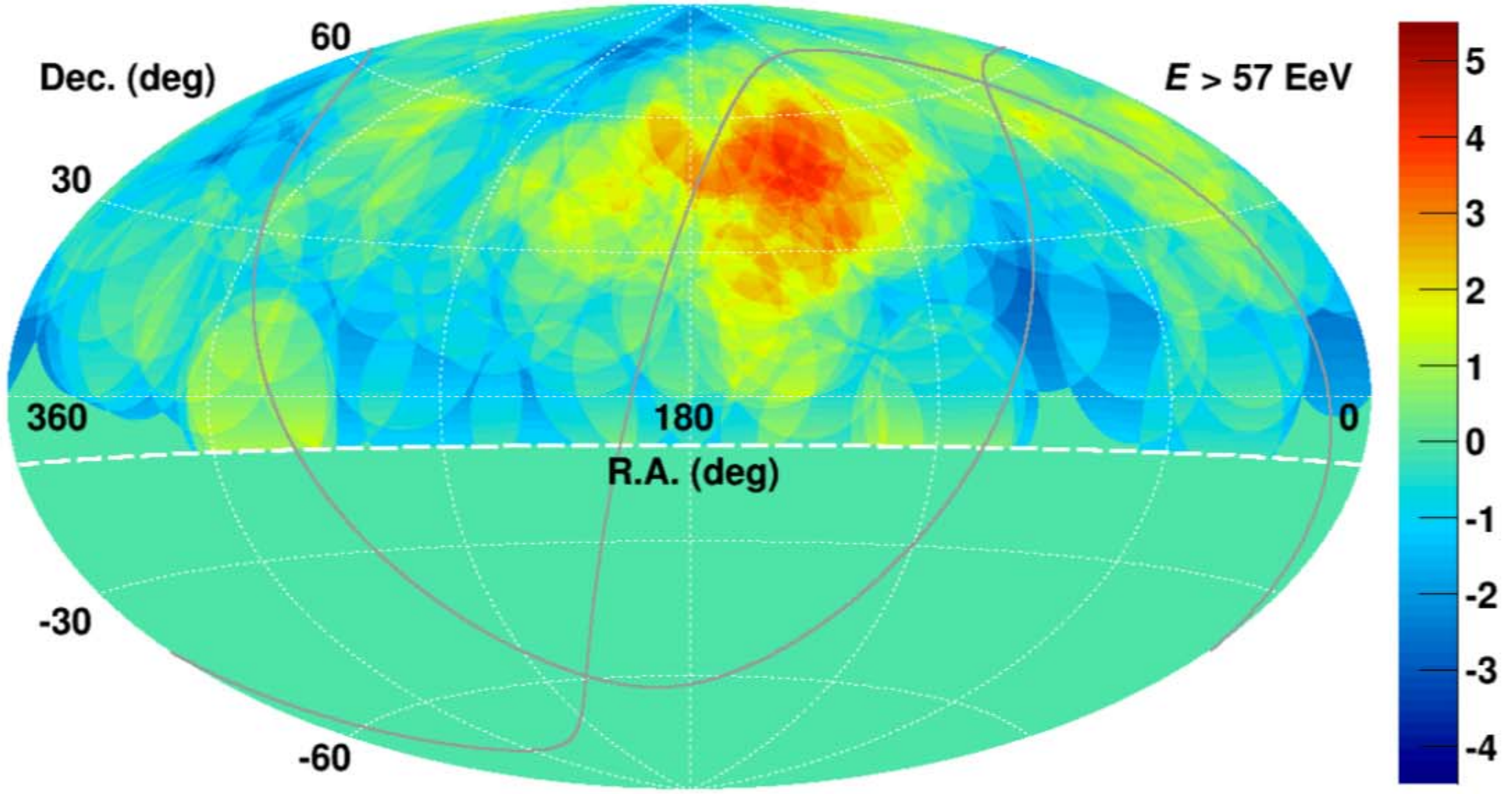
Intermediate-scale anisotropy

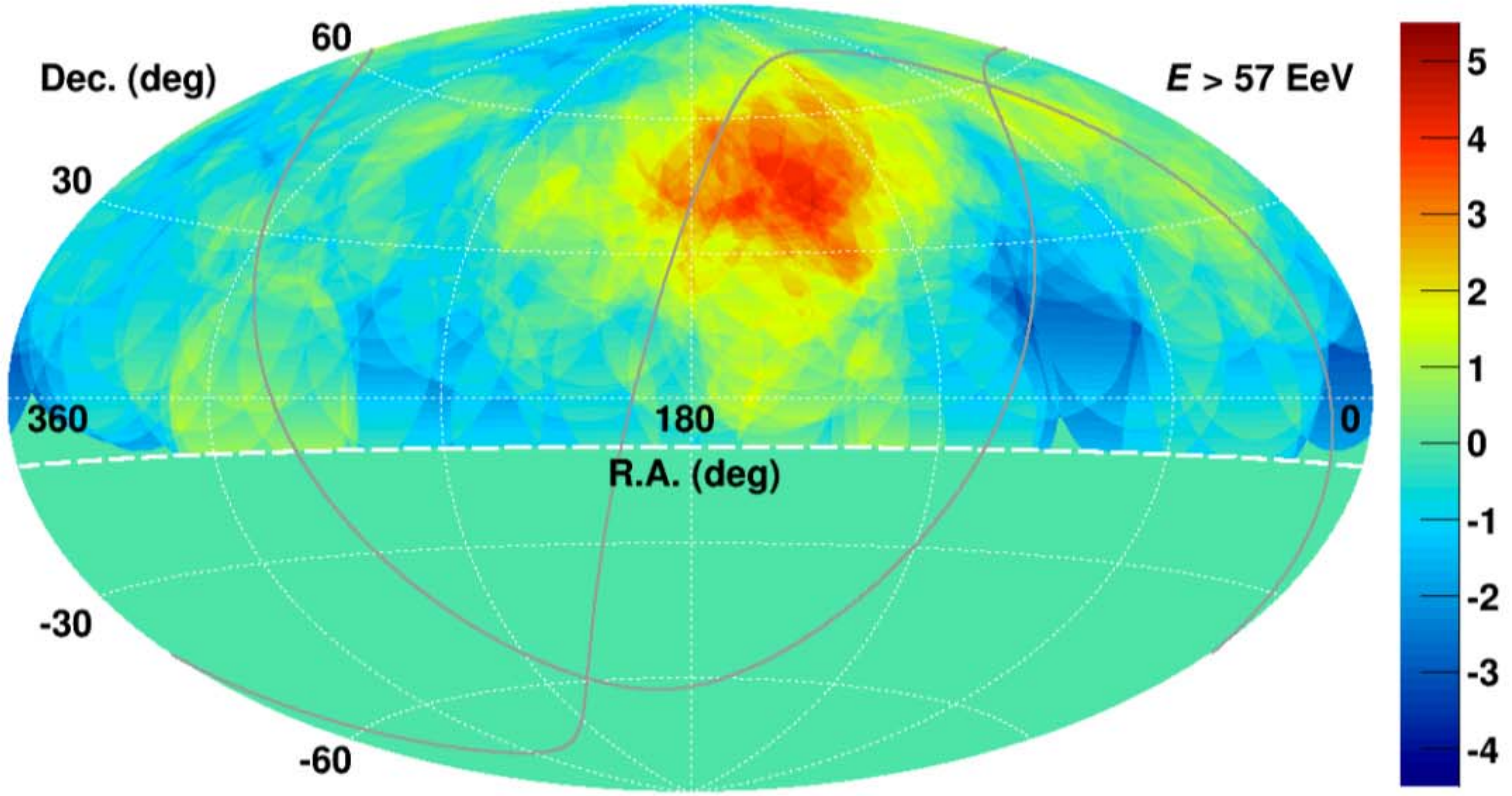


Huchra, et al, ApJ, (2012)

Dots : 2MASS catalog Heliocentric velocity <3000 km/s (D<~45MpC)

Intermediate-scale anisotropy – Hot spot (TA data)





With original 20° oversampling, spot looks larger…. Thus, scan over 15°, 20°, 25°, 30°, & 35°

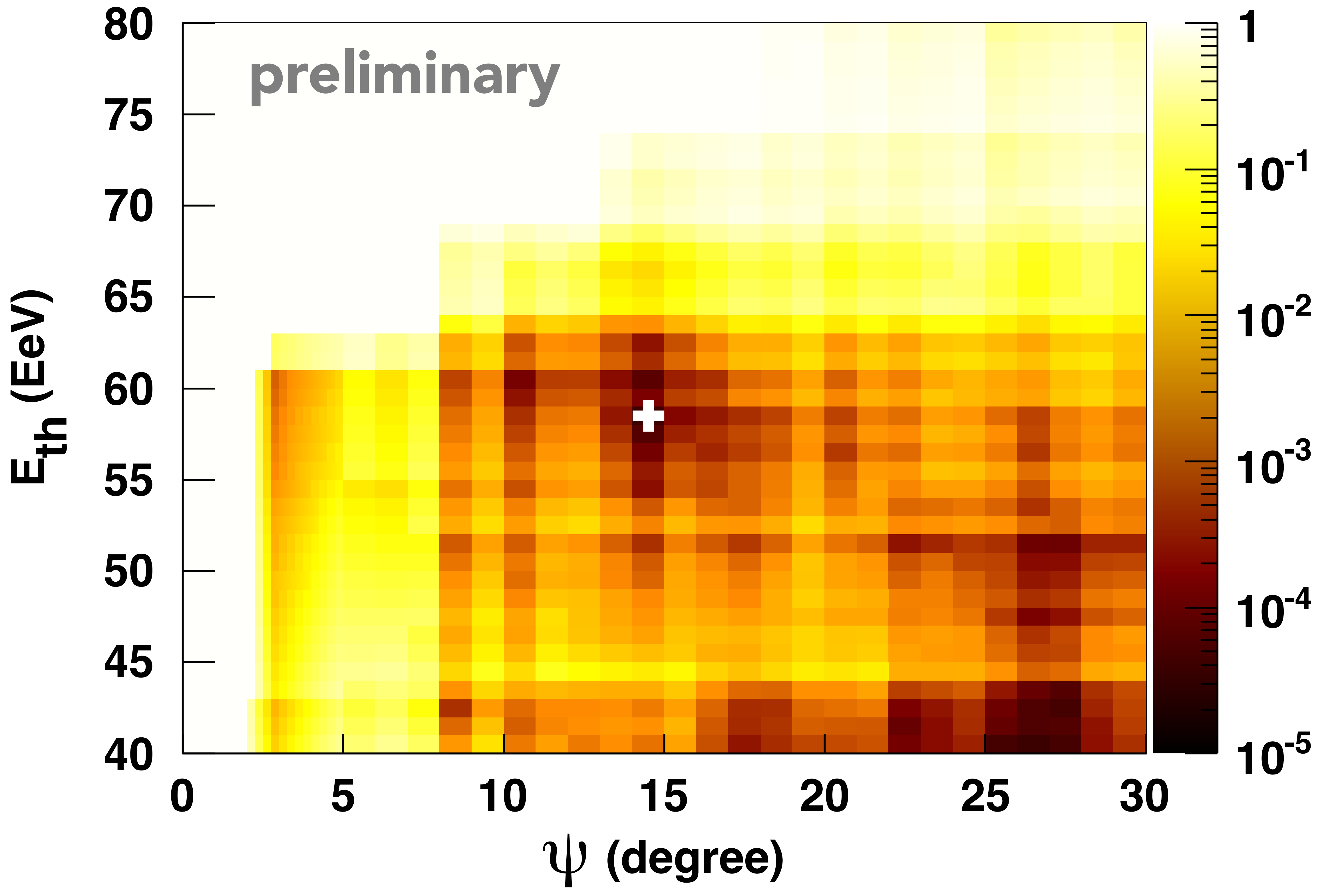
With 25° oversampling, significance maximum 3σ

Binsize	15		20		25		30		35	
	Local	Global	Local	Global	Local	Global	Local	Global	Local	Global
Year 5	5.12	3.14	5.43	3.55	5.16	3.19	4.82	2.73	4.33	2.05
Year 7	4.92	2.84	5.37	3.44	5.65	3.80	5.37	3.44	5.03	2.99
Year 9	4.42	2.06	4.72	2.50	5.06	2.96	5.01	2.91	4.66	2.41

(Matthews, ICRC 2017)

Intermediate-scale anisotropy – Warm spot (Auger data)

✓ 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



Largest excess

$E_{th} = 58$ EeV, $\Psi = 15°$

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

$P \sim 1.1 \times 10^{-5}$

Post-trial probability

$\sim 1.1 \times 10^{-3}$

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

Region of secondary minima above ~40 EeV

(Giaccari ICRC 2017)

Anisotropy – Correlation with catalogs (Auger data)

Active Galactic Nuclei

- 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

γ-ray detected AGNs

f_{ani} = 7%, Ψ = 7°

TS = 15.2 → *p-value* 5.1×10^{-4}

Post-trial probability

3×10^{-3} (~ 2.7 σ)

Star-forming or 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

Starburst Galaxies

f_{ani} = 10%, Ψ = 13°

TS = 24.9 → *p-value* 3.8×10^{-6}

Post-trial probability

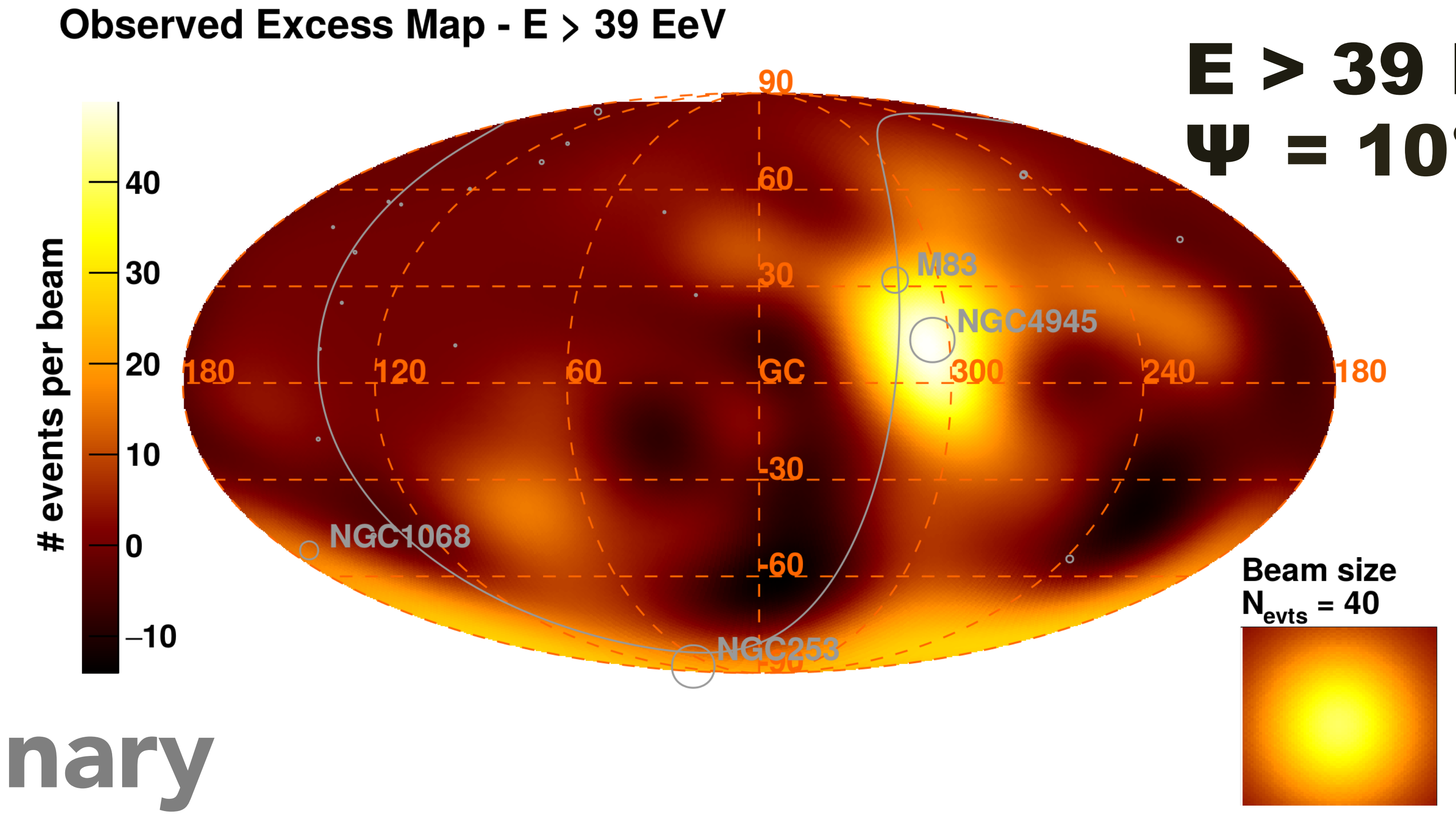
4×10^{-5} (~ 3.9 σ)

Assumption UHECRs flux proportional to non thermal photon flux

(Giaccari ICRC 2017)

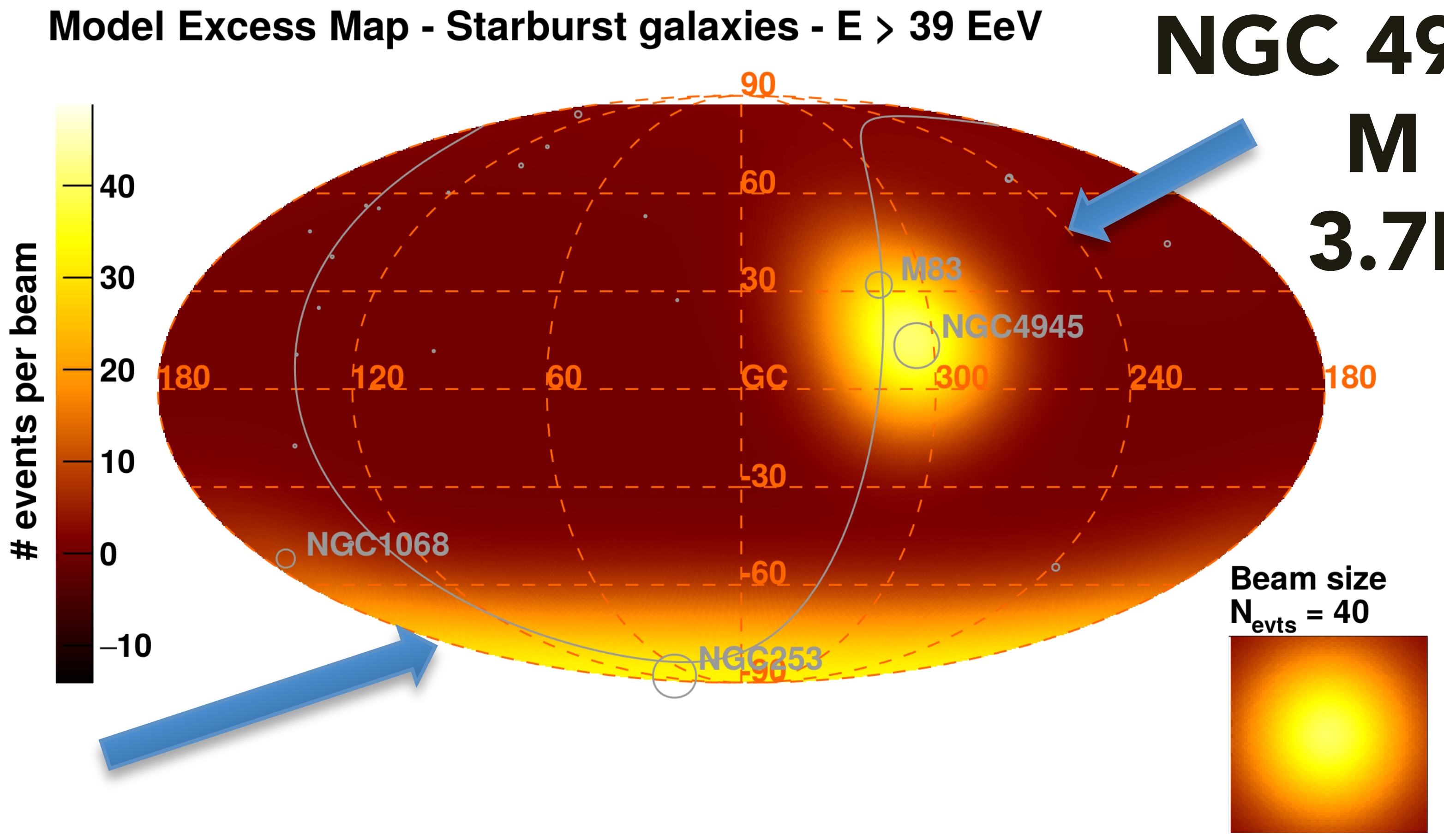
Anisotropy – Correlation with catalogs (Auger data)

Starburst galaxies



E > 39 EeV
Ψ = 10°

preliminary

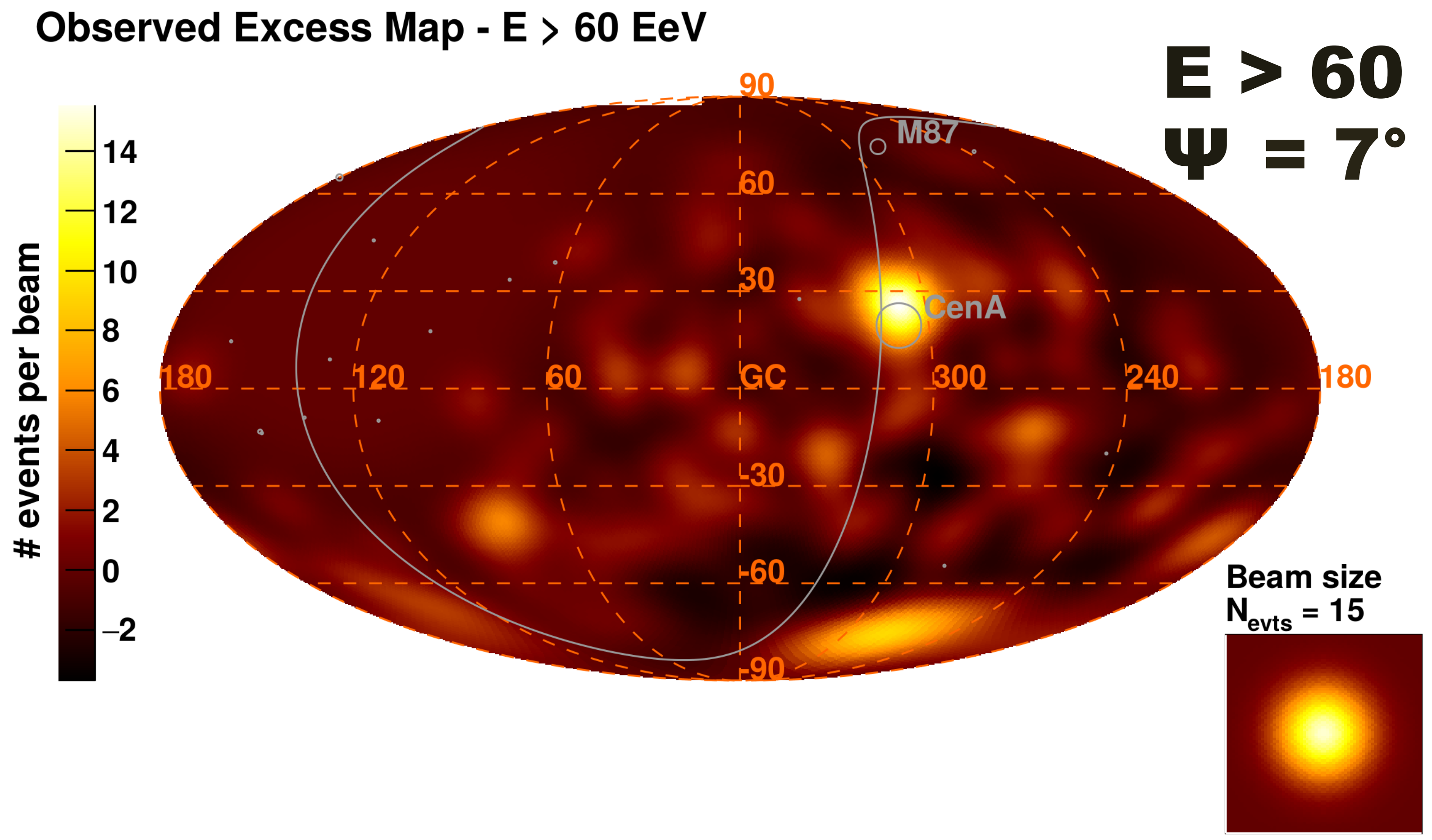


NGC 4945
M 83
3.7Mpc

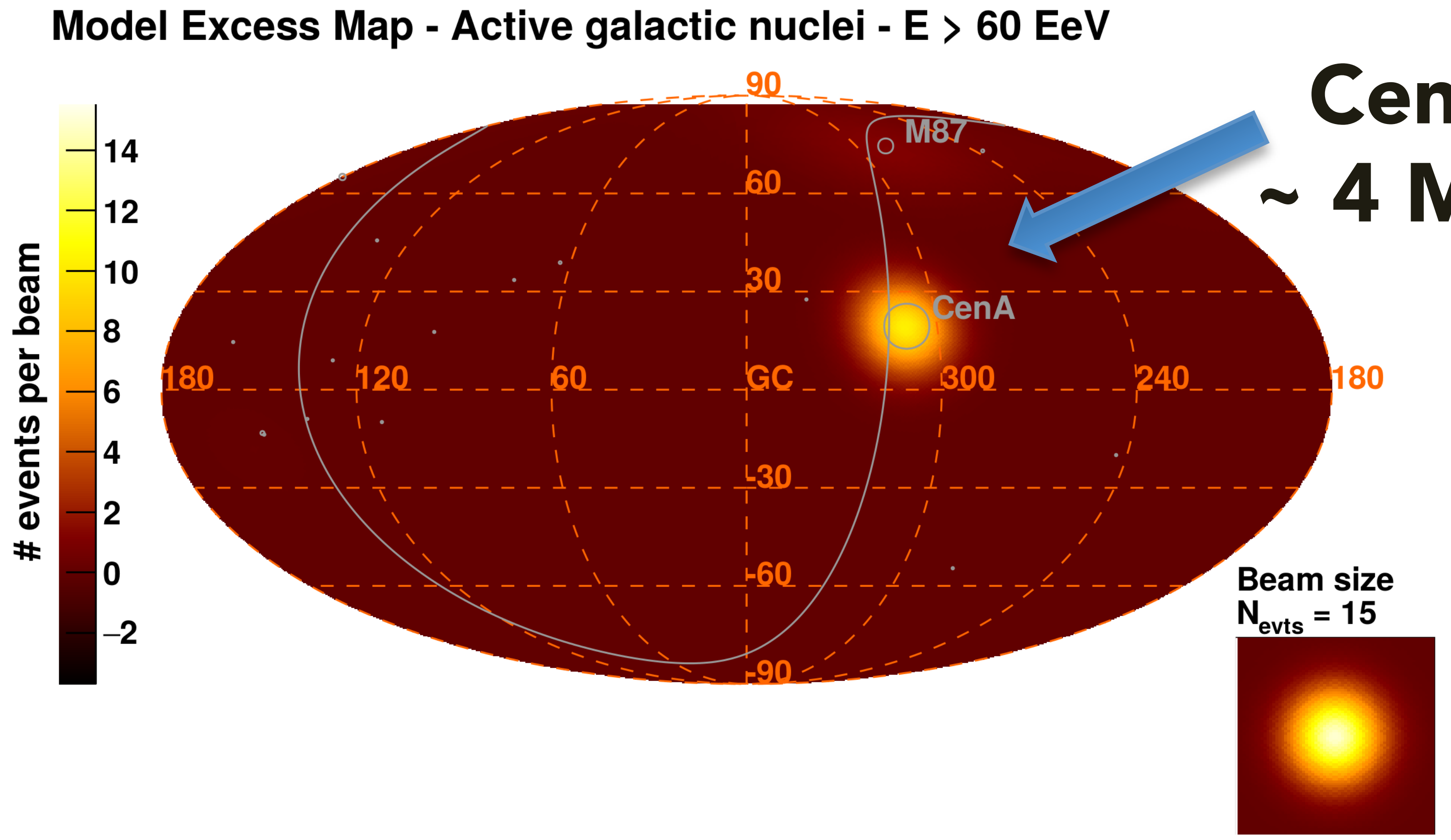
NGC 253
2.5 Mpc

NGC 1068
16.7 Mpc

AGNs



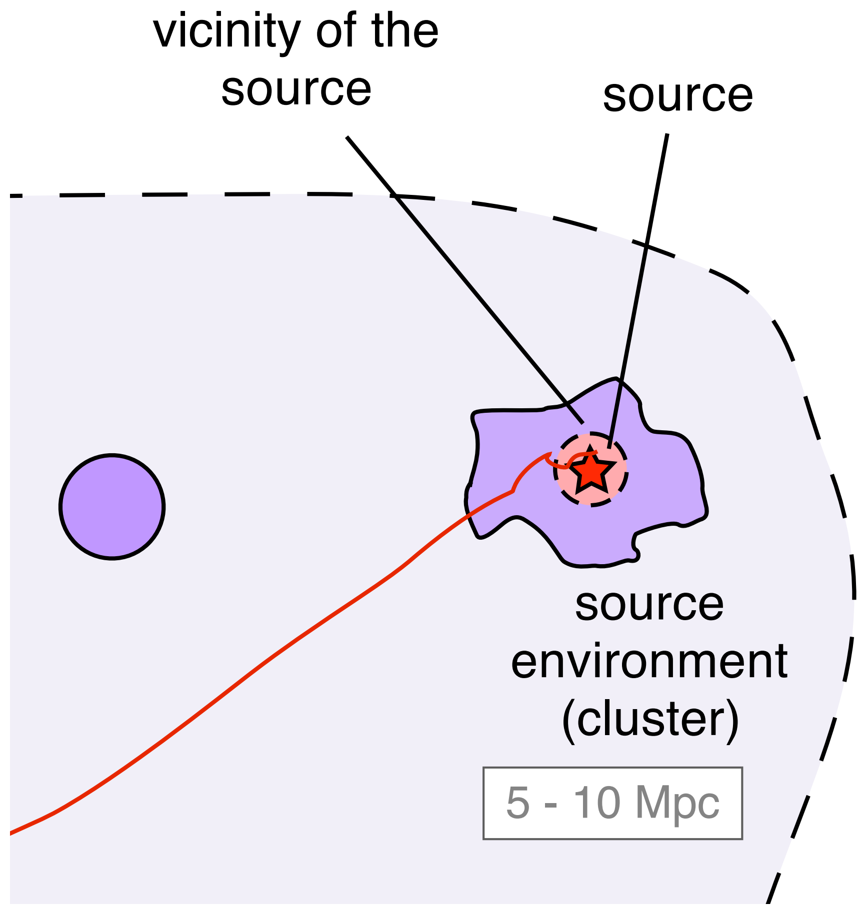
E > 60 EeV
Ψ = 7°



CenA
~ 4 Mpc

(Giaccari ICRC 2017)

Some comments



- **Complicated and unexpected picture of UHECR emerging**
  (More composition and anisotropy data needed)
- **Source models have to be more sophisticated than simple power laws**
  (environment+escape, local large-scale structure, different sources)
- **Multi-messenger data crucial for model building**
- **Further progress in modeling hadronic interactions required for reliable composition studies**
- **Auger and TA:**
  - independent analyses
  - joint working groups
  - very productive interaction

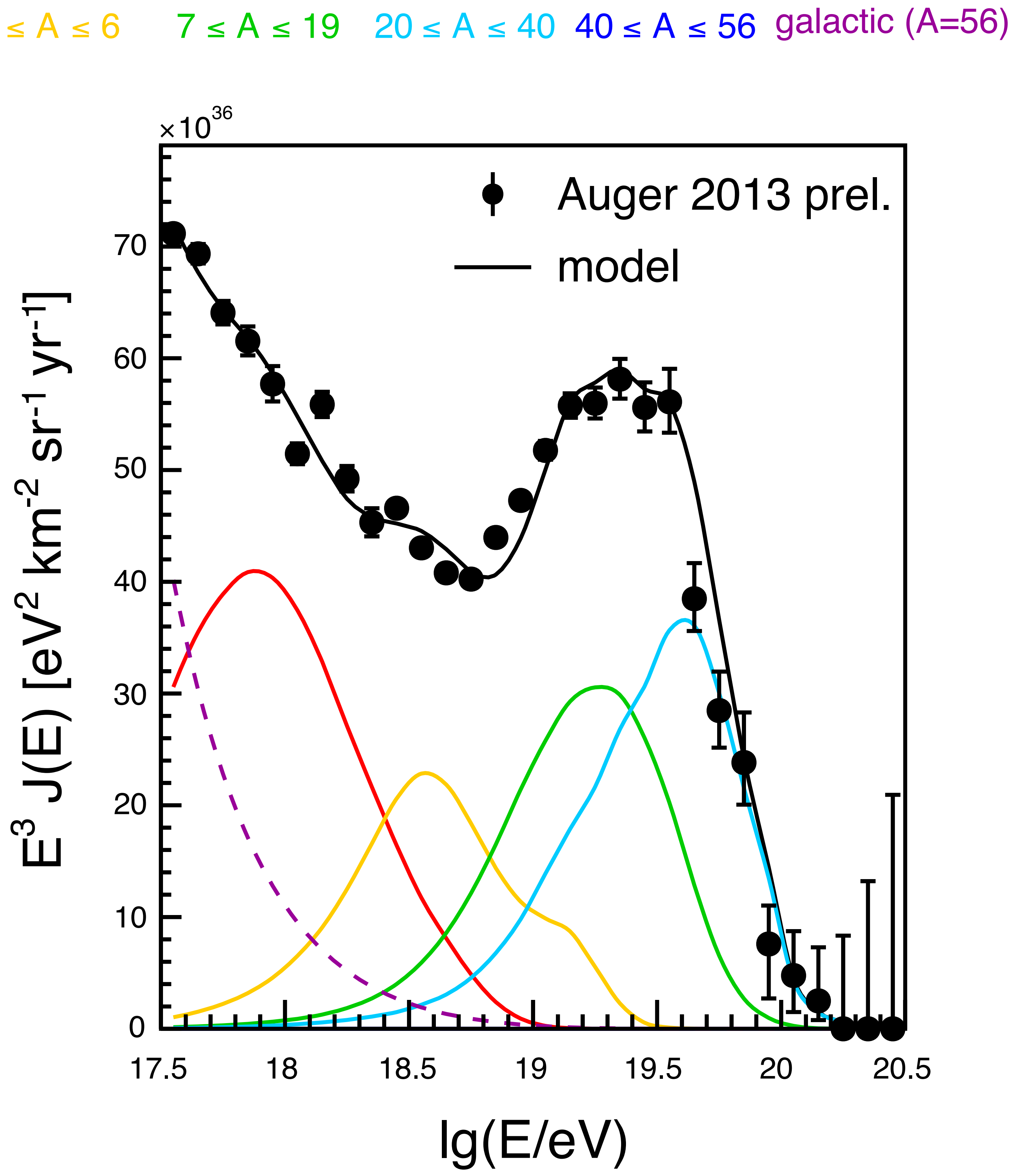
(Aloisio et al. 2014)

(Taylor et al. 2015)

(Globus et al. 2015)

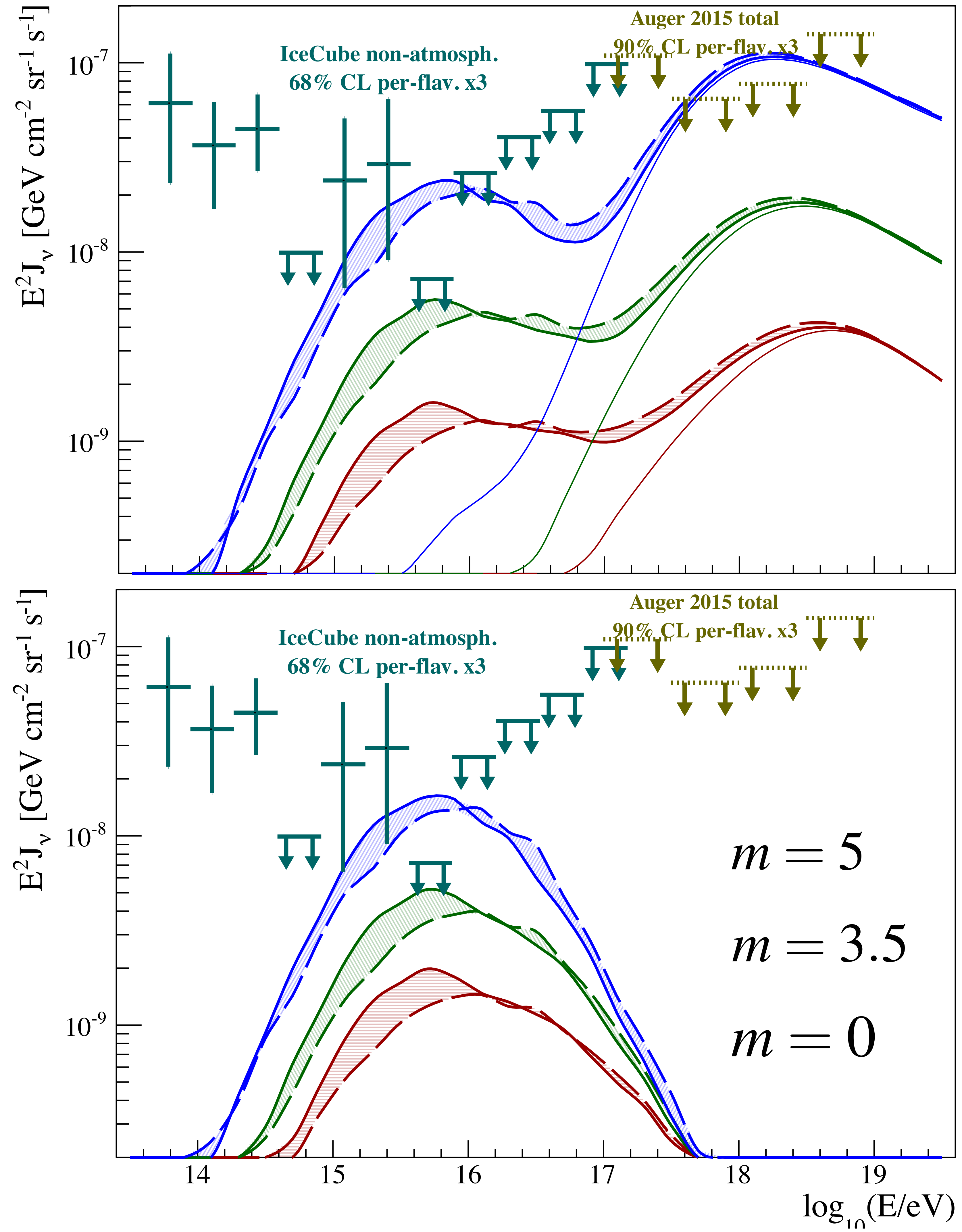
(Unger et al. 2015)

(Fang & Murase 2017)



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?

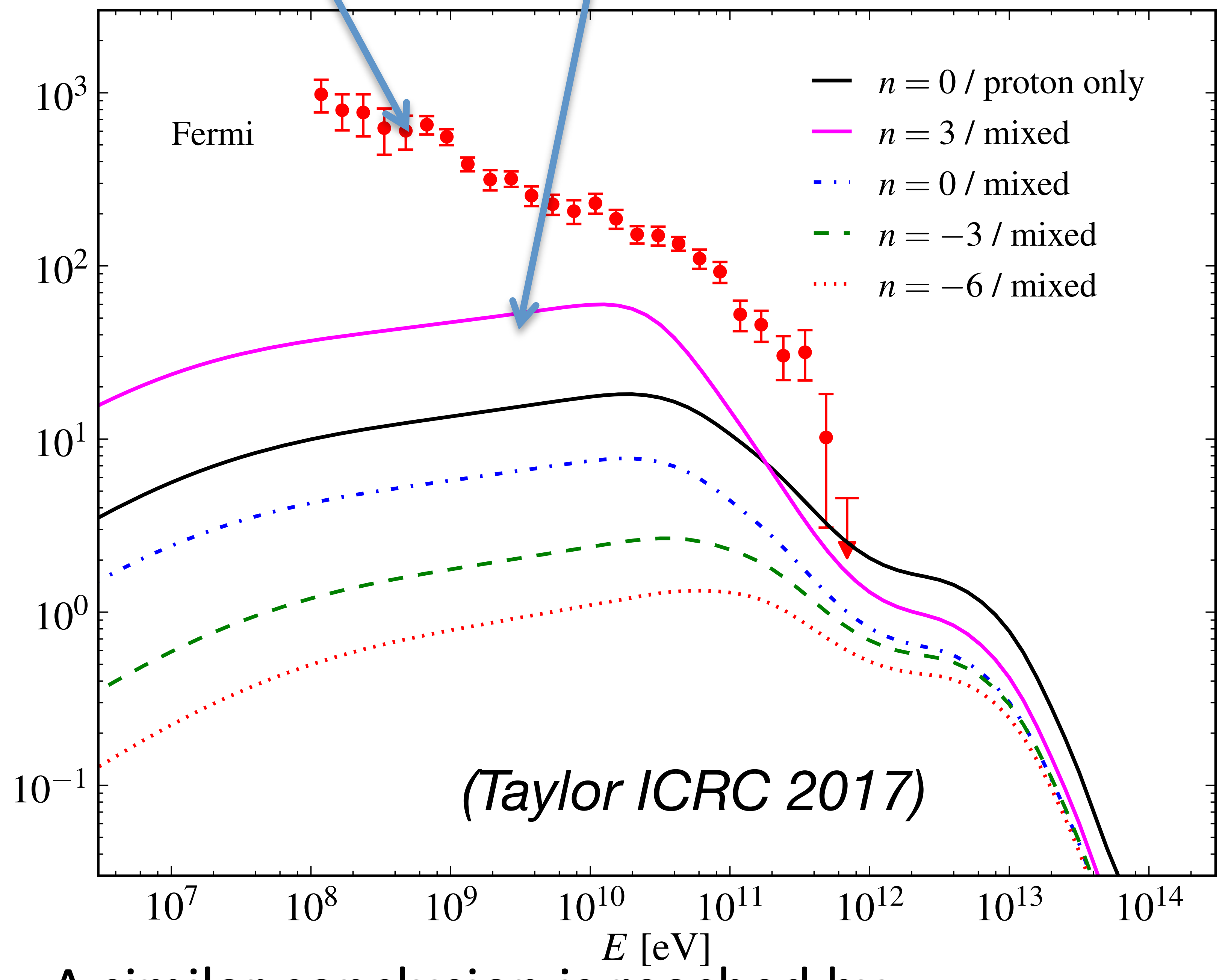
Negative evolution of sources?

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**

TAx4 Project

TA SD (~3000 km²): Quadruple area

Approved in Japan 2015

500 scintillator SDs

2.08 km spacing

3 yrs construction, first 173 SDs have arrived in Utah for final assembly, next 77 SD to be prepared at Akeno Obs. (U.Tokyo) 2017-08 and shipped to Utah

2 FD stations (12 HiRes Telescopes)

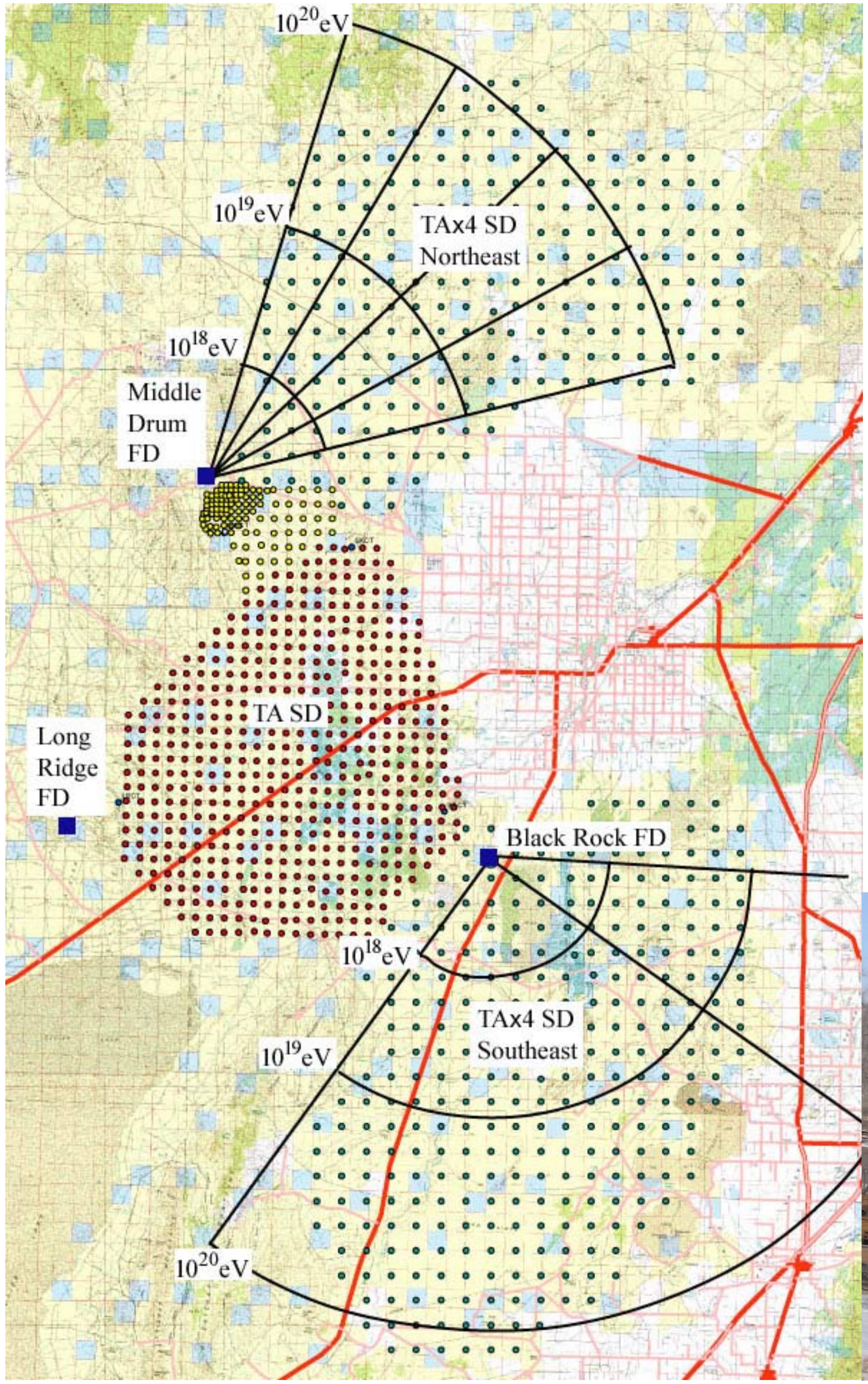
Approved US NSF 2016

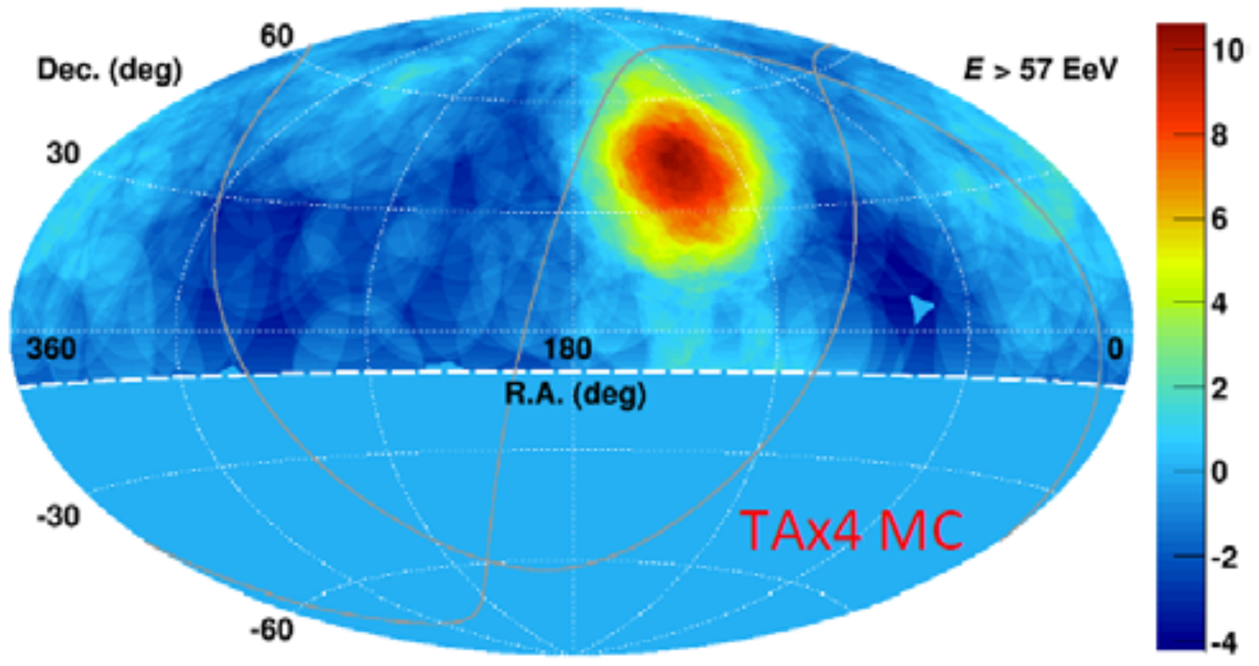
Telescopes/electronics being prepared at Univ. Utah

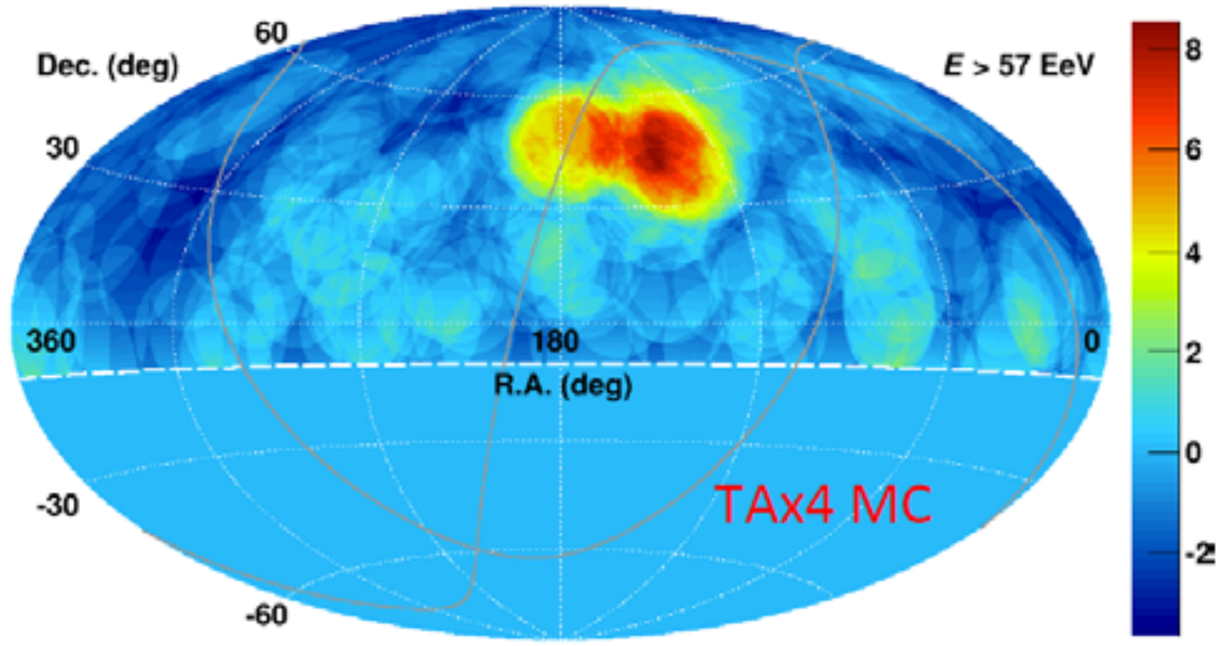
Site construction underway at the northern station.

Get 19 TA-equiv years of SD data by 2020

Get 16.3 (current) TA years of hybrid data







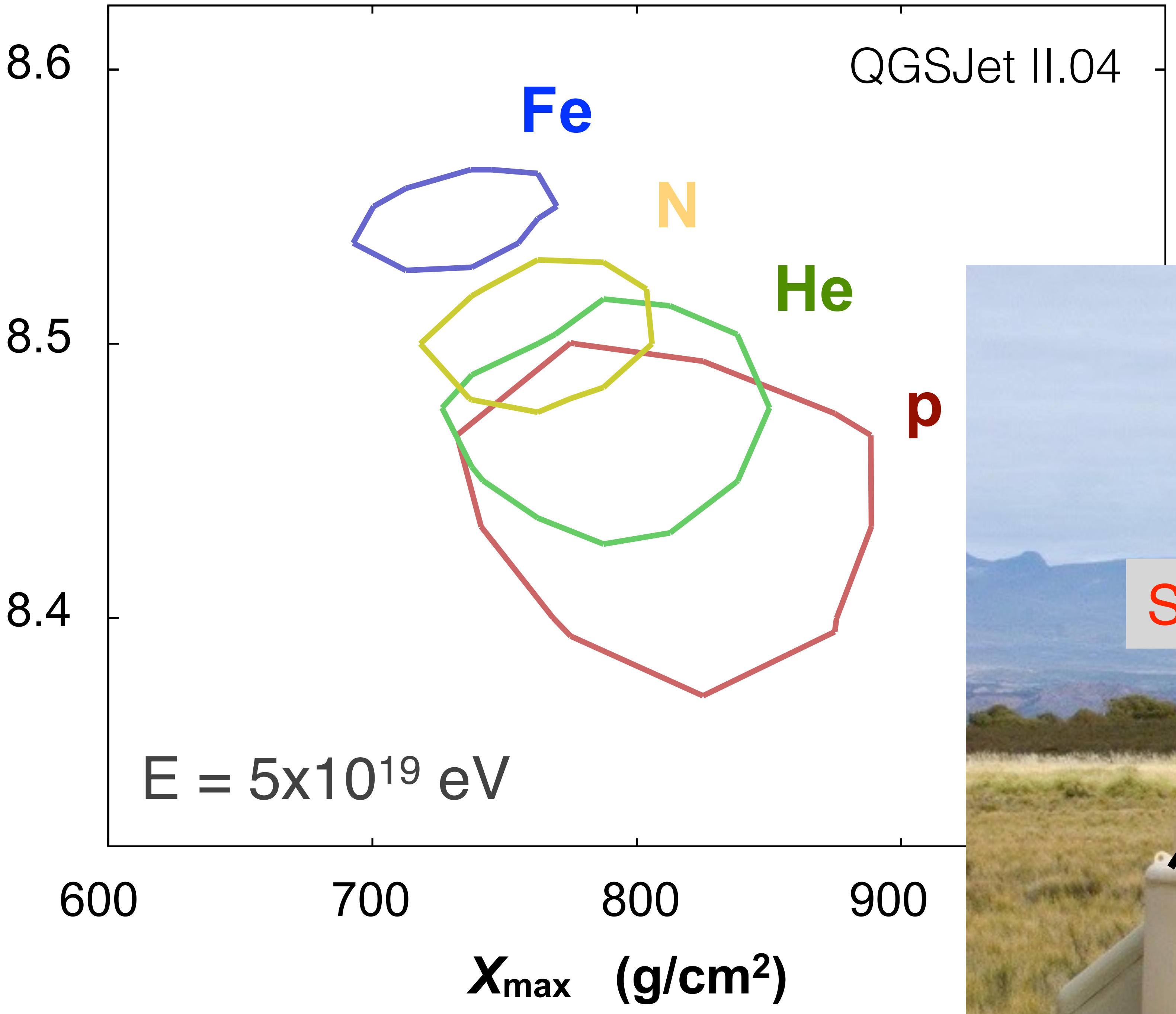
(Kido, Matthews ICRC 2017)

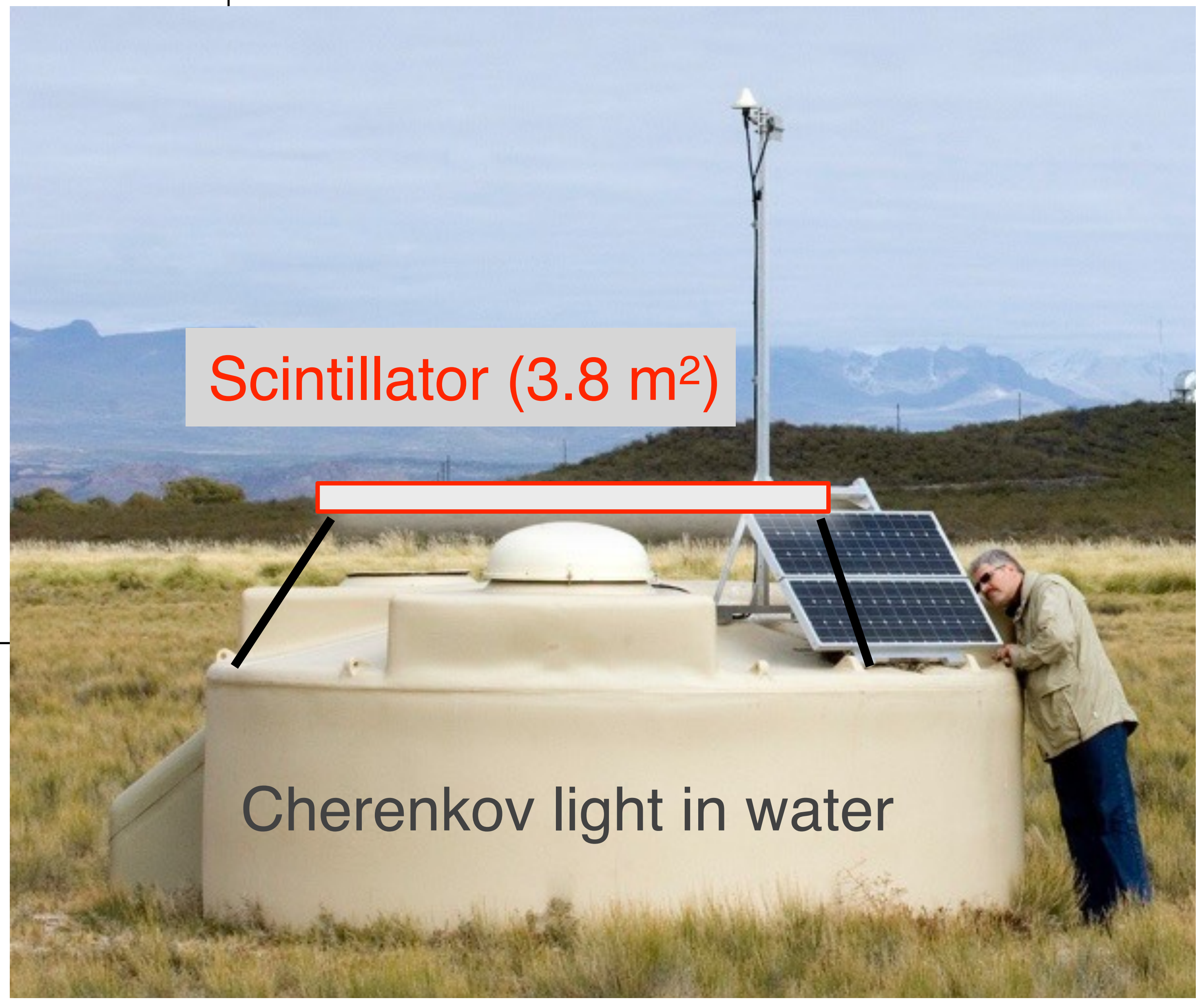
Upgrade of Auger Observatory: AugerPrime

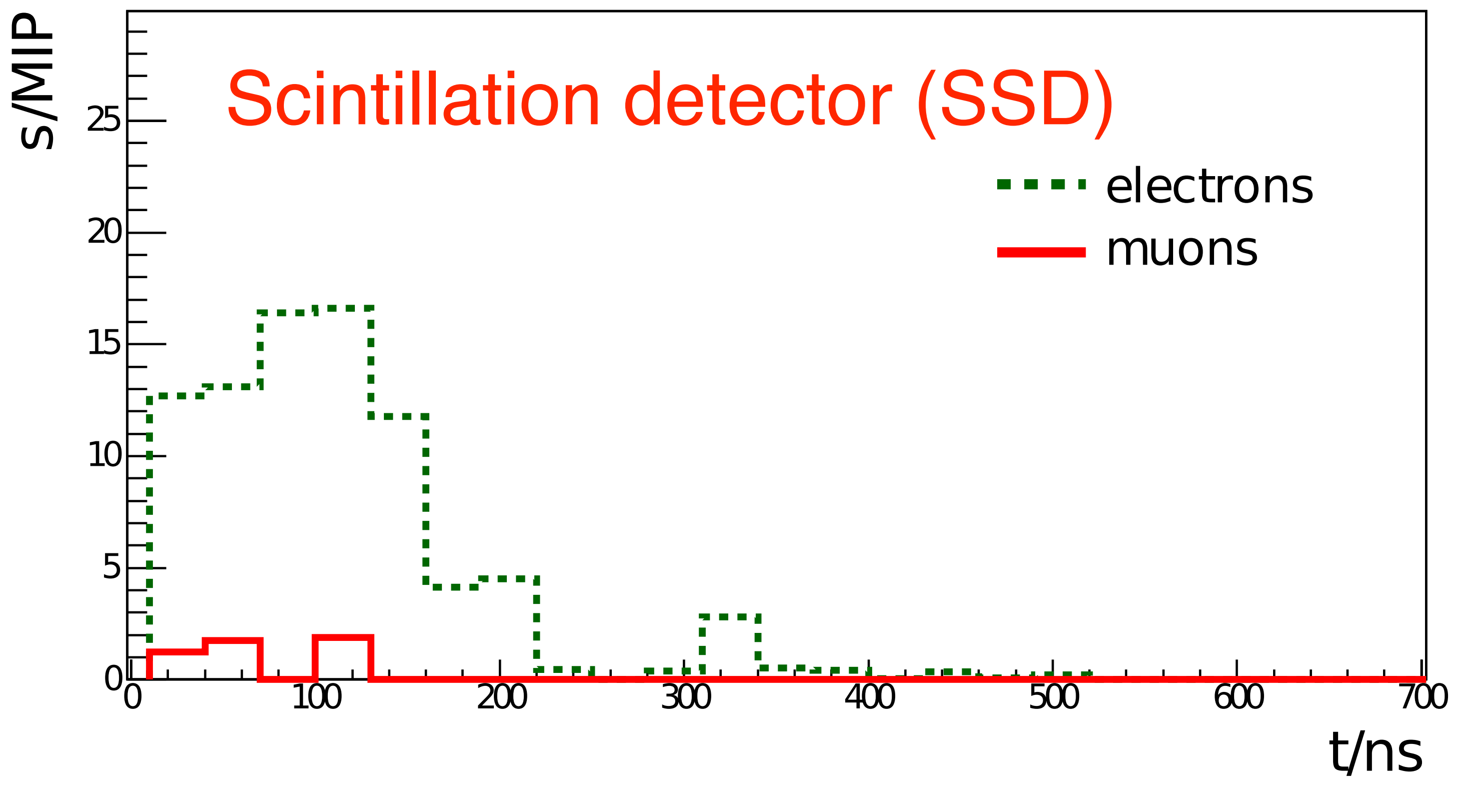
100% duty cycle

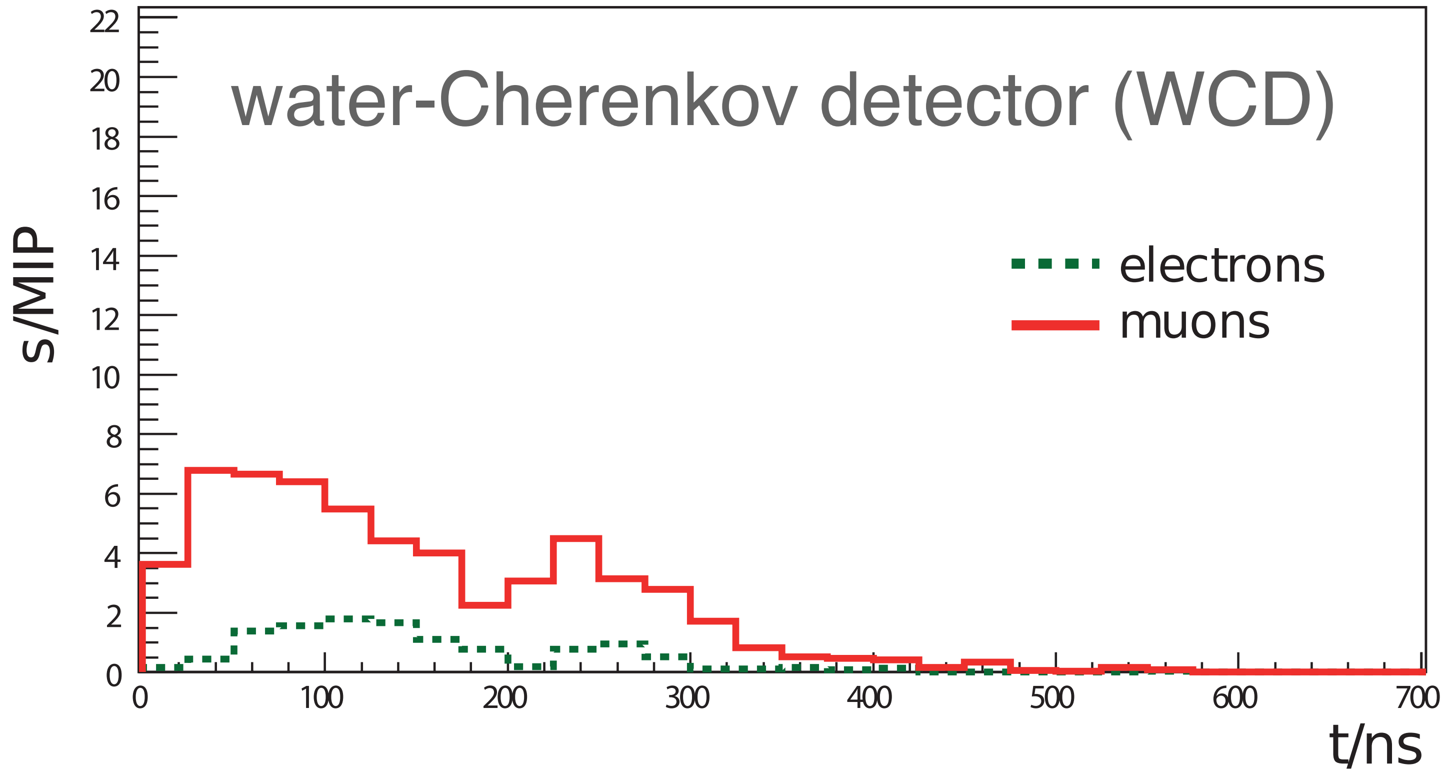
15% duty cycle

Complementarity of particle response used to discriminate em. and muonic components









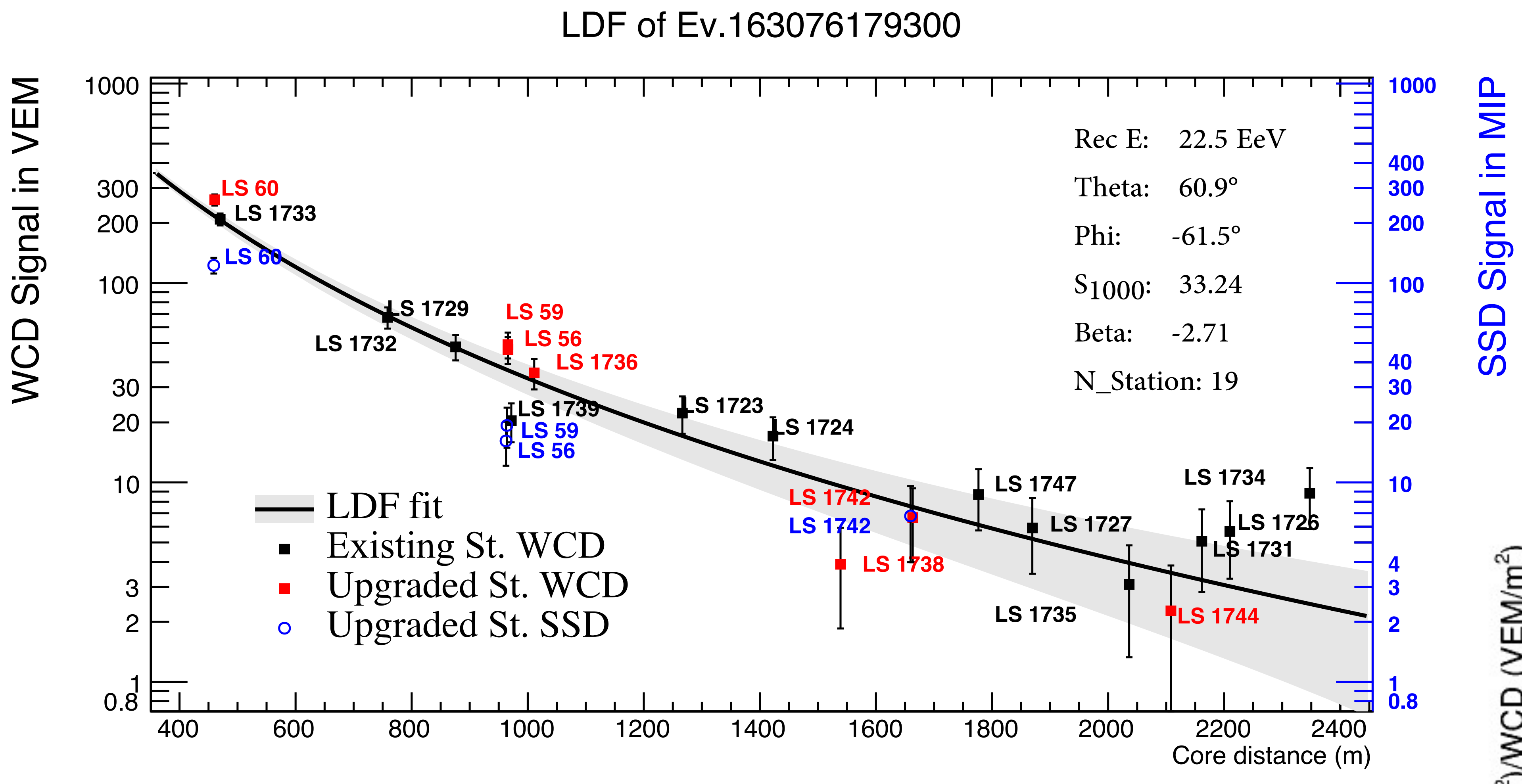
$$S_{\mu,\mathrm{WCD}} = a\, S_{\mathrm{WCD}} + b\, S_{\mathrm{SSD}}$$
$$S_{\mathrm{em,WCD}} = c\, S_{\mathrm{WCD}} + d\, S_{\mathrm{SSD}}$$

(Martello, ICRC 2017)

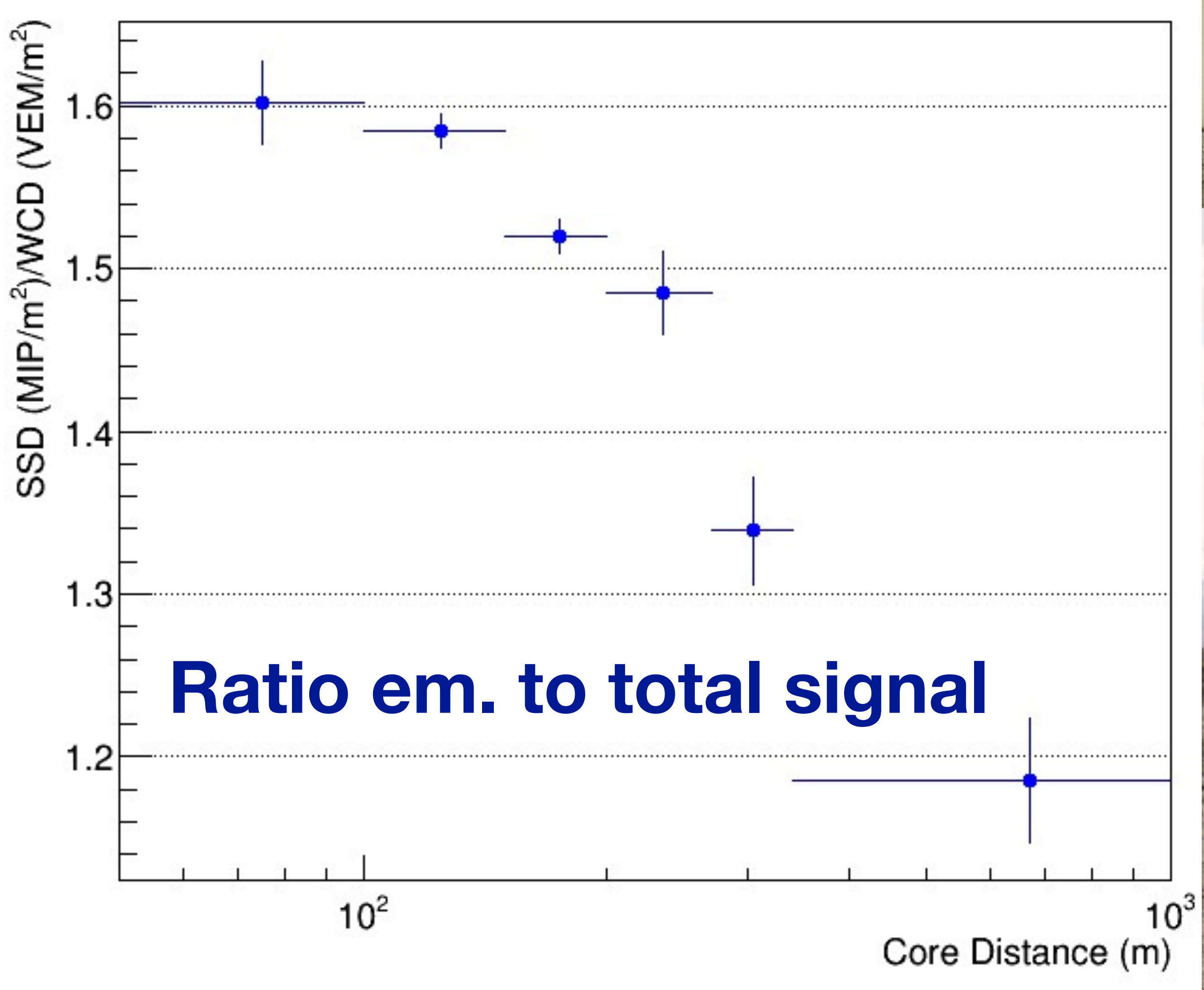
(AugerPrime design report 1604.03637)

Status and plans for AugerPrime

Engineering Array: 12 stations



Deployment fast: ~ 5 -10 stations per day



2016-09-15: first station in field

2016: engineering array

2018-19: deployment

2019-25: data taking (40,000 km^2 sr yr)

Composition measurement at 10^{20} eV

Composition selected anisotropy studies

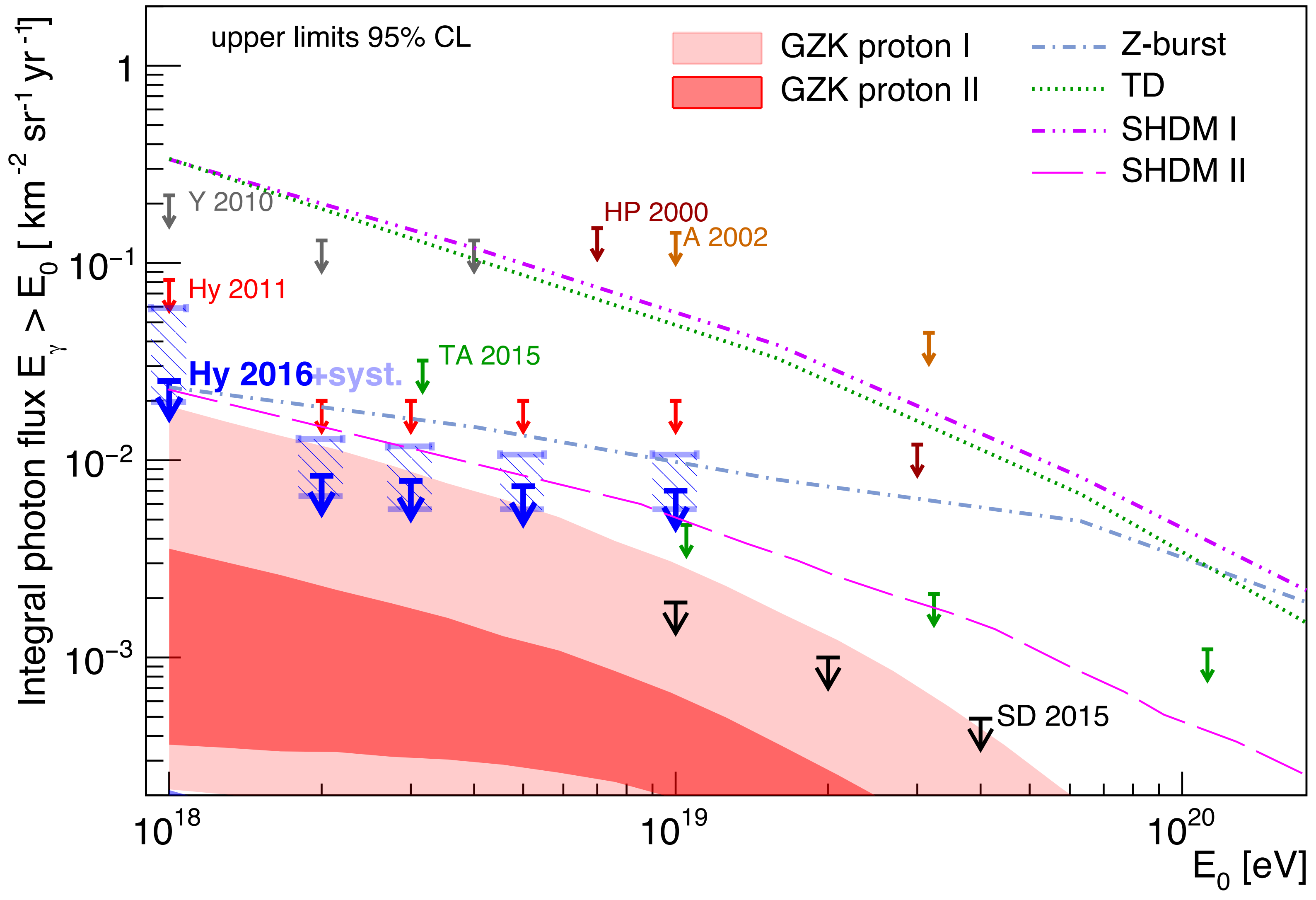
Particle physics with air showers

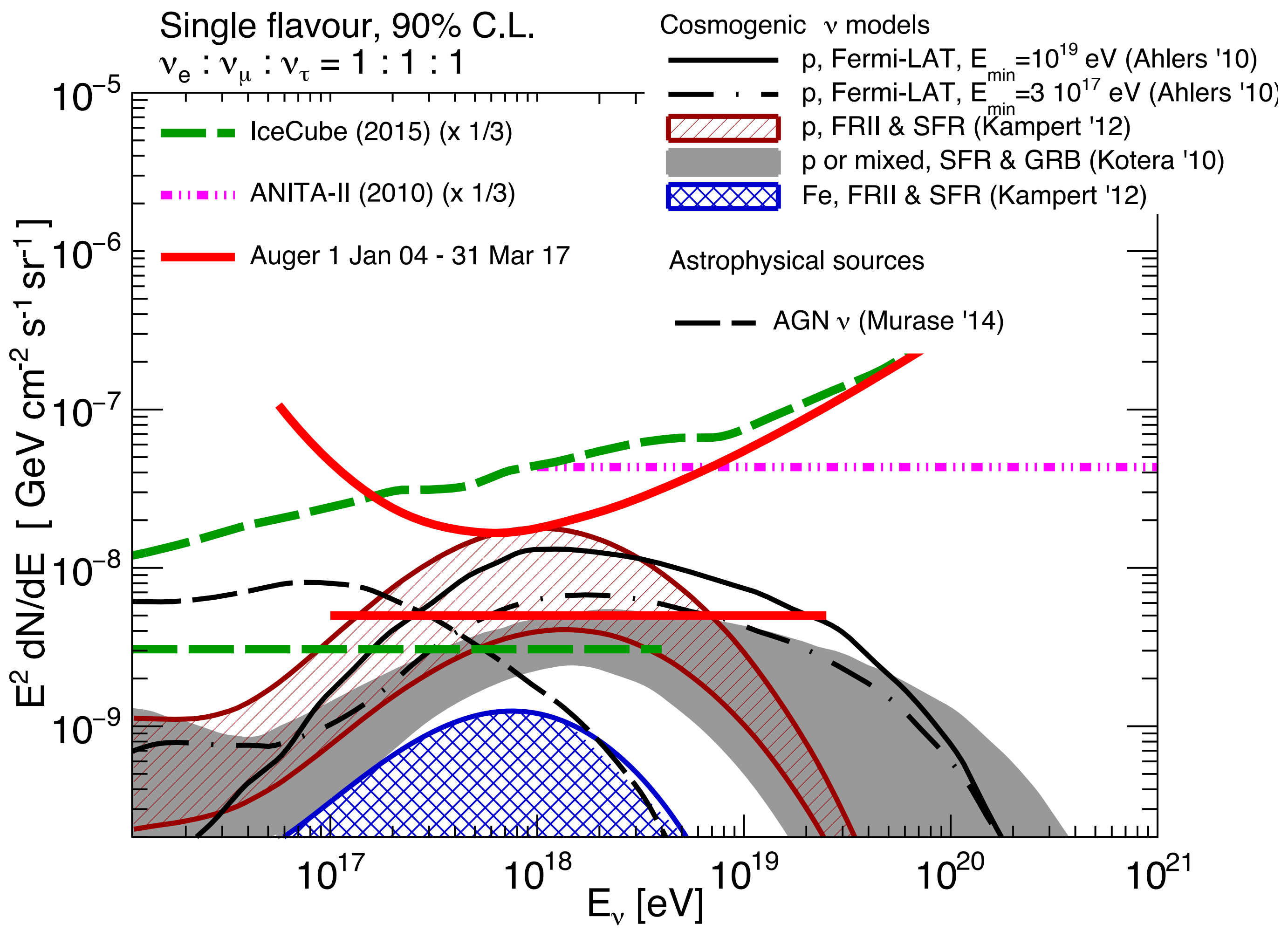
Backup slides

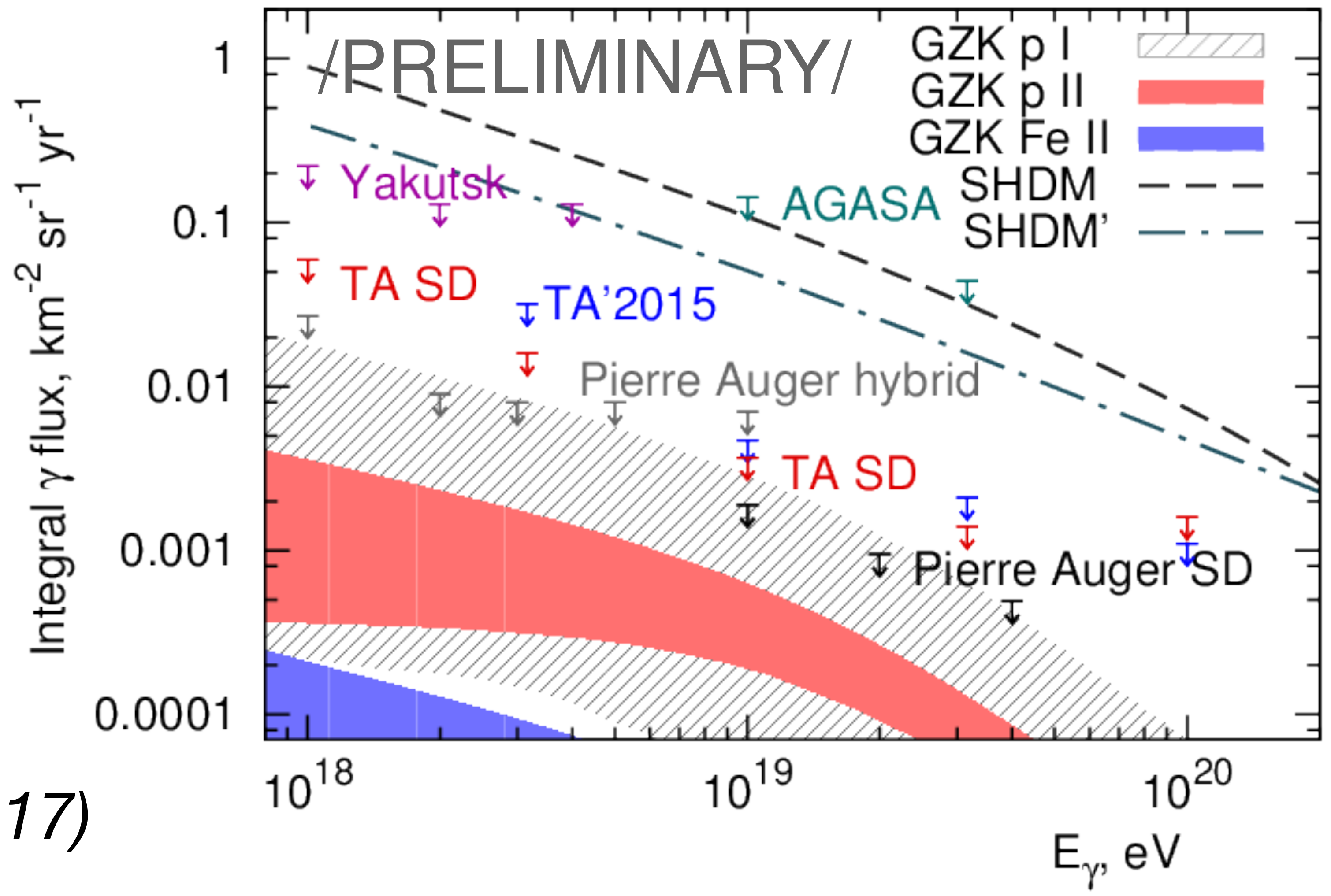
Photon and neutrino limits at ultra-high energy

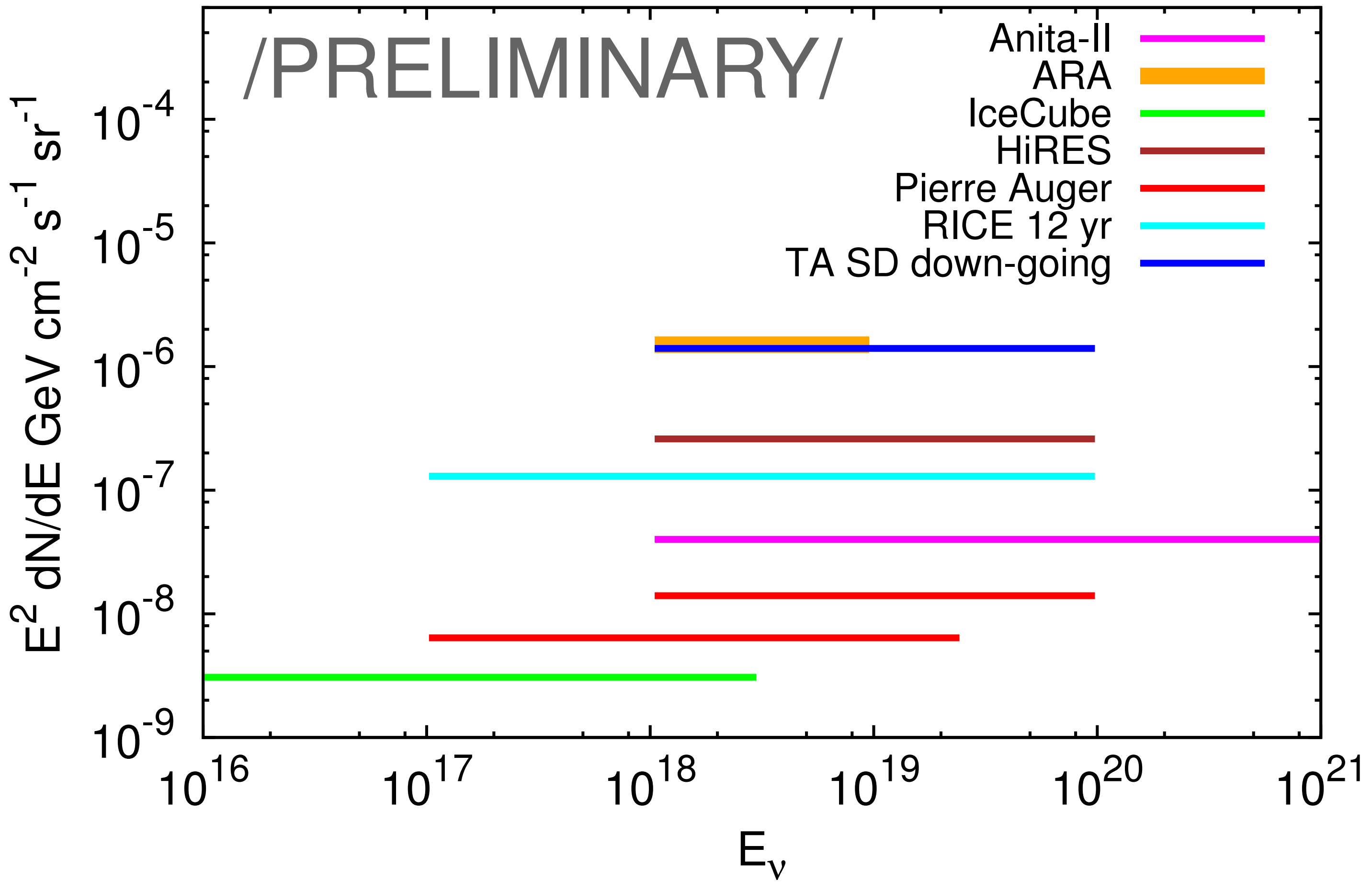
$$p + \gamma_{\mathrm{CMB}} \rightarrow p + \pi^0 \searrow \gamma\gamma$$

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









(Niechciol, Auger ICRC 2017)

(Rubtsov, TA ICRC 2017, Zas, Auger, ICRC 2017)

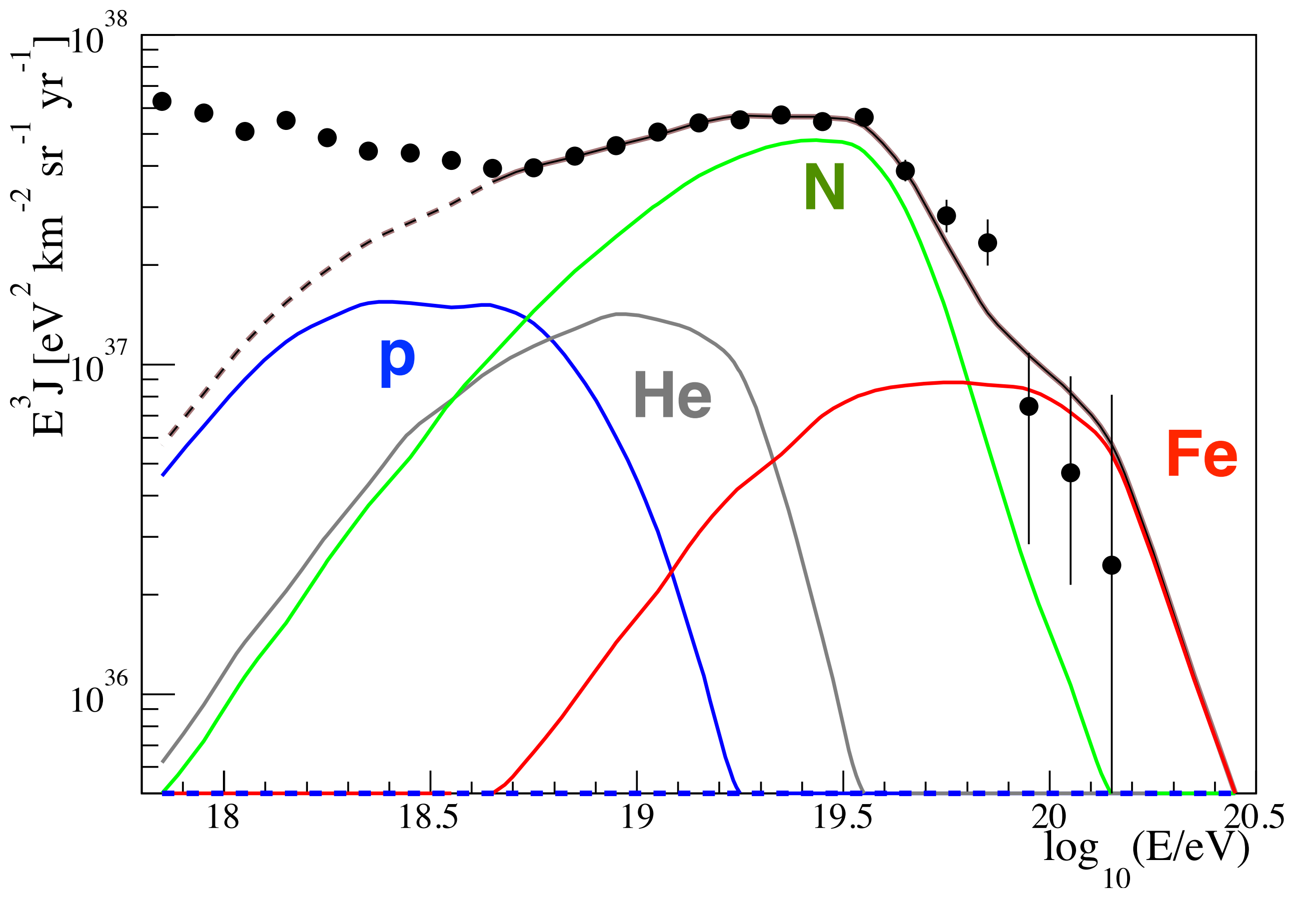
Physics reach: mass sensitivity & discrimination of scenarios

Illustration with two benchmark scenarios

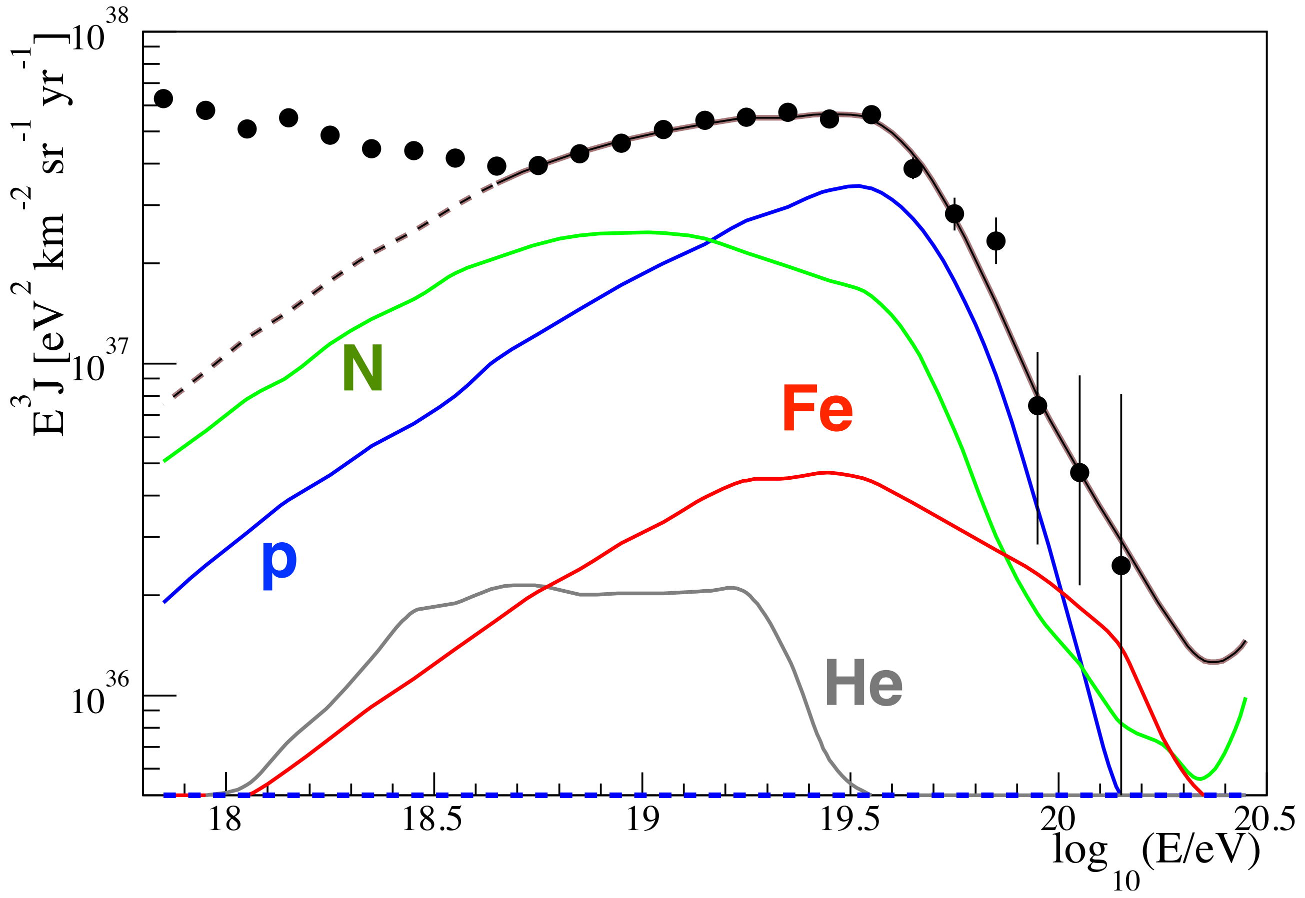
(note: these are not physics models)

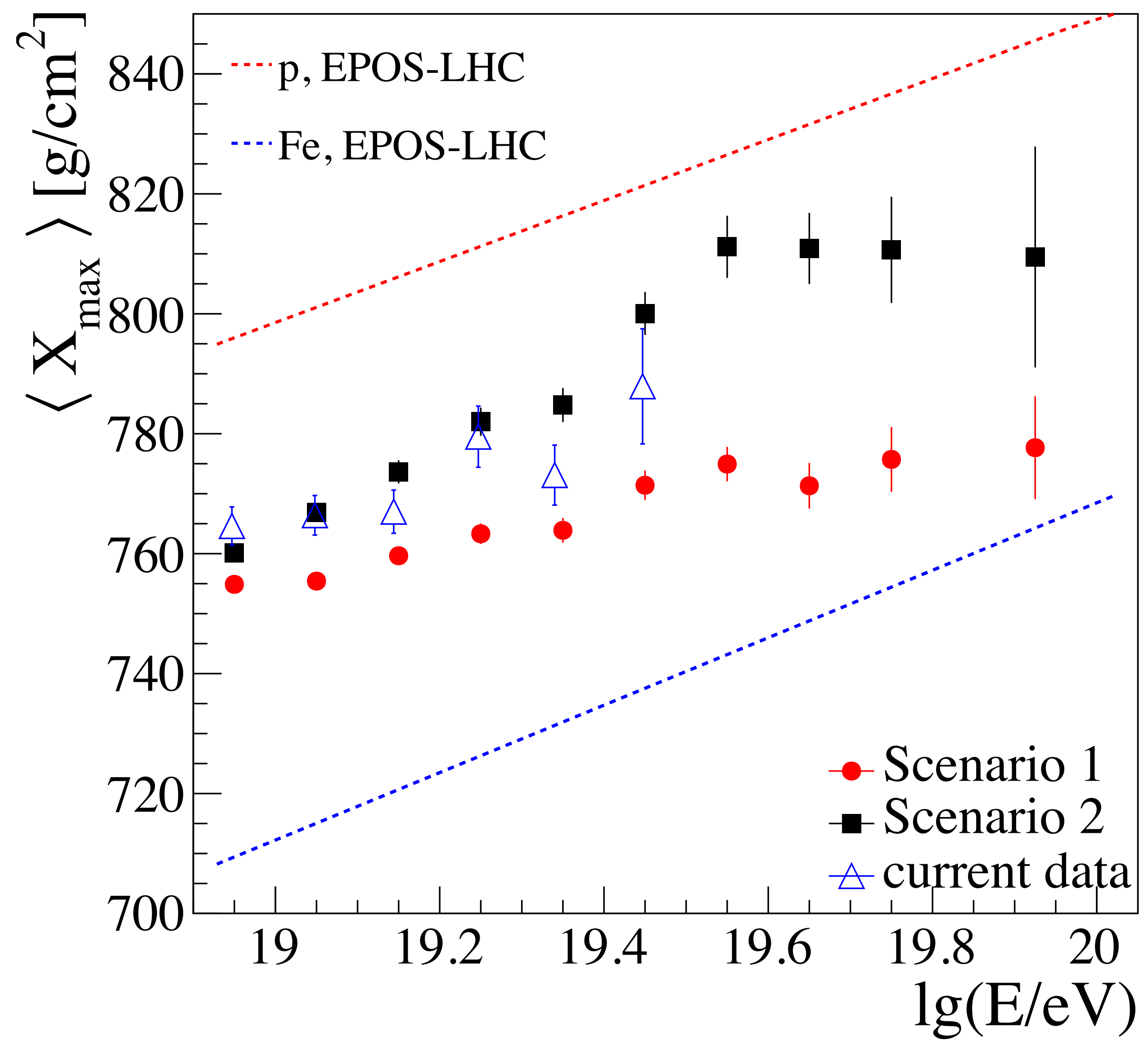
(AugerPrime 1604.03637)

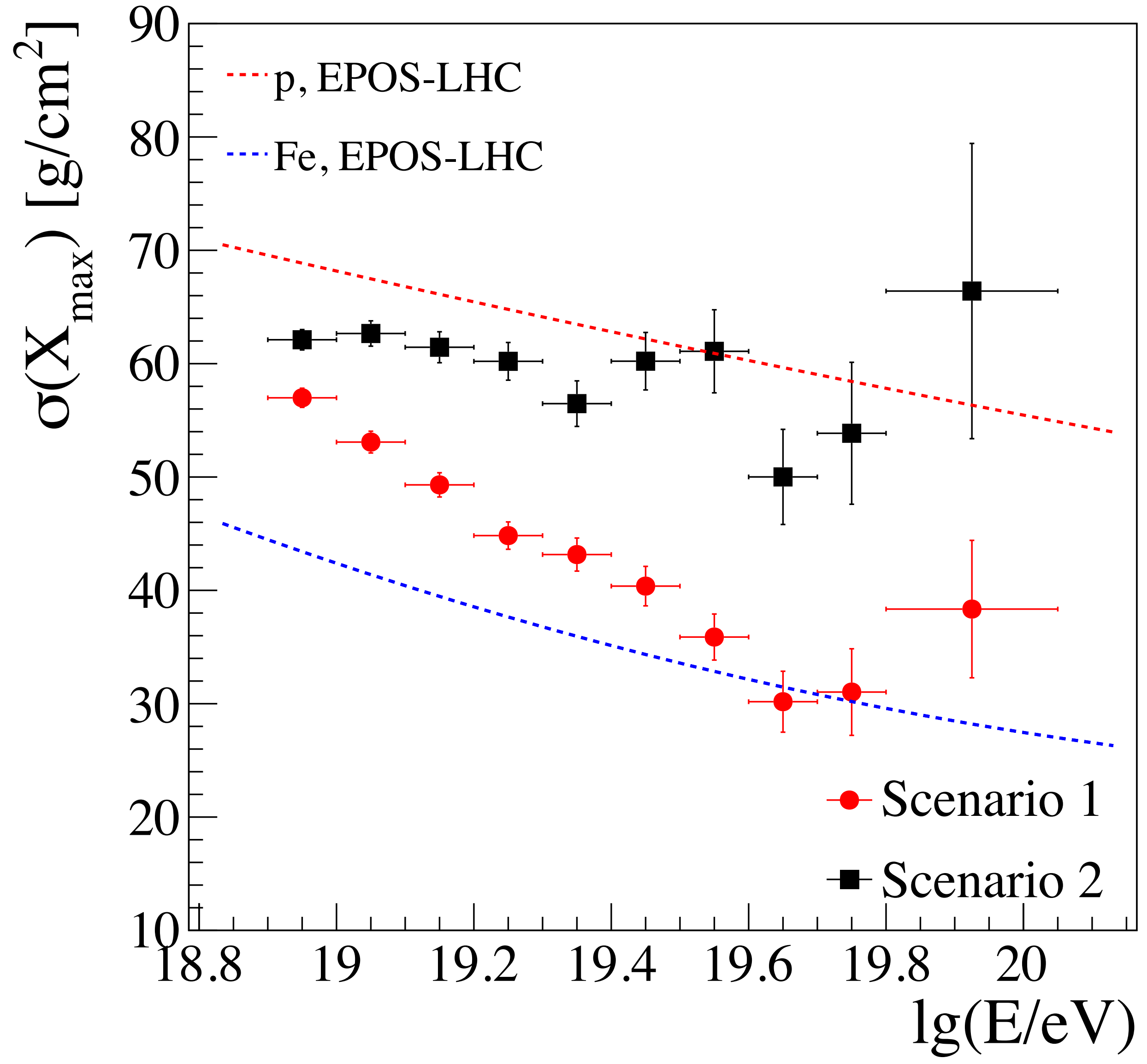
Scenario 1: maximum rigidity model

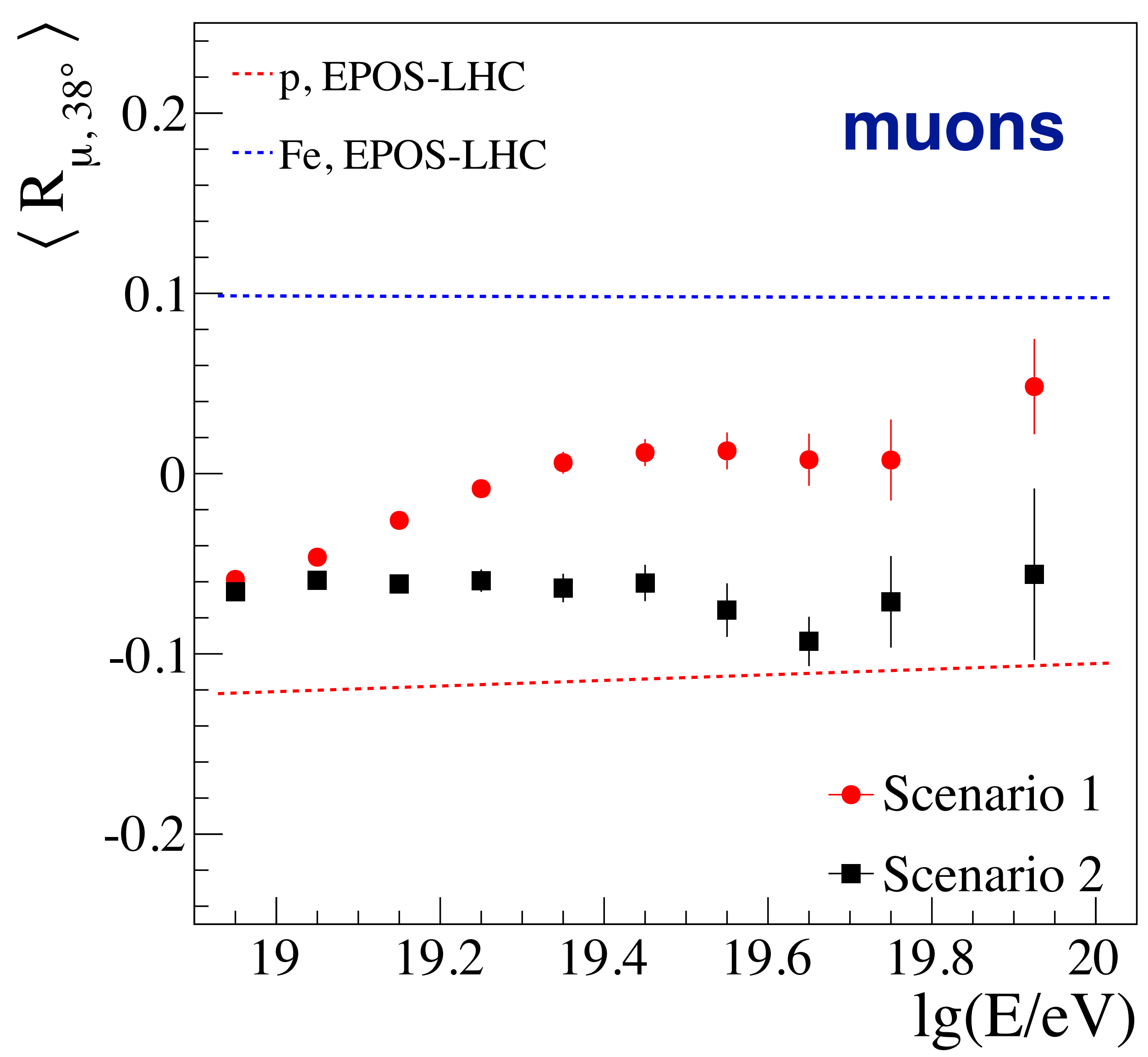


Scenario 2: photo-disintegration model



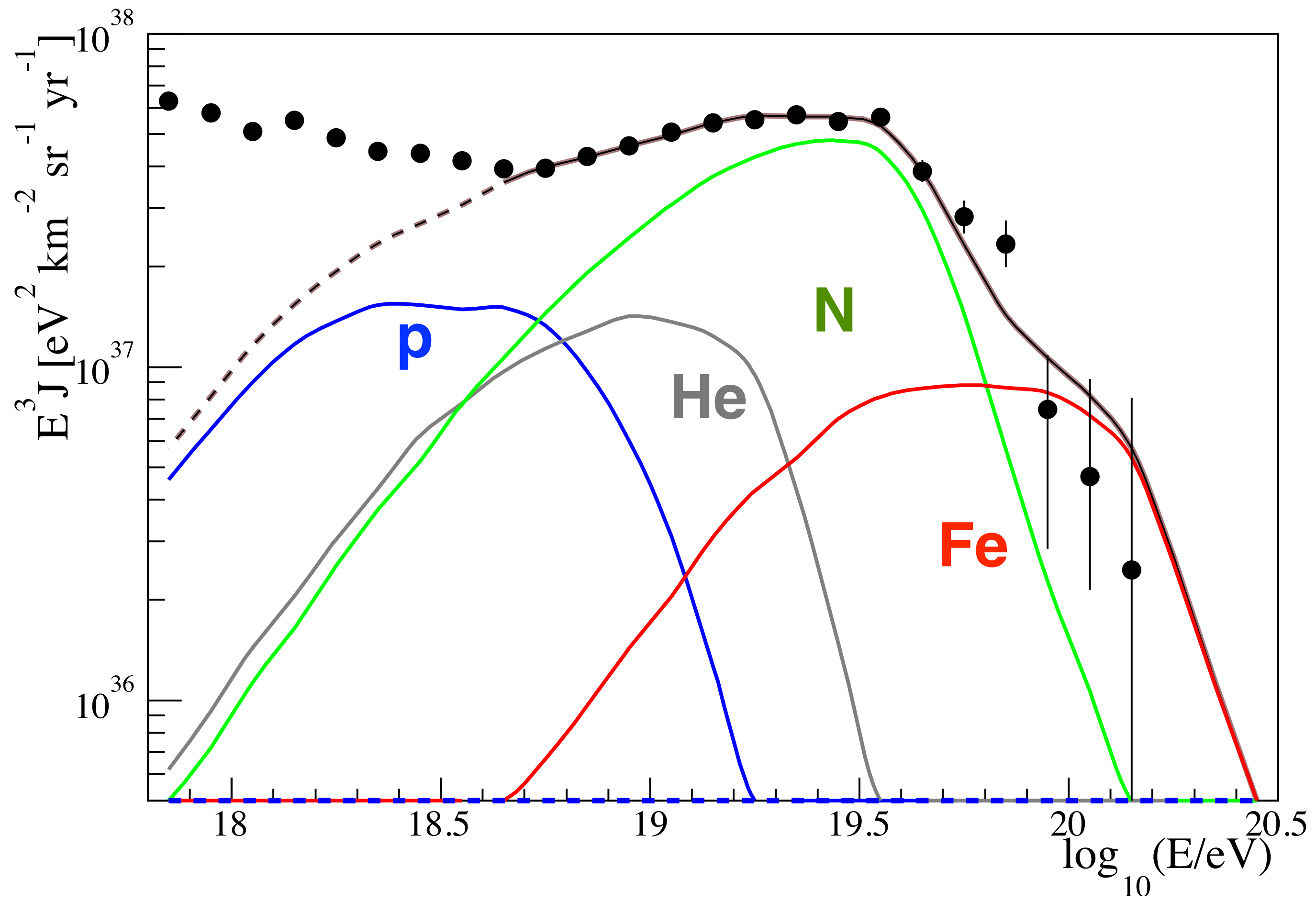






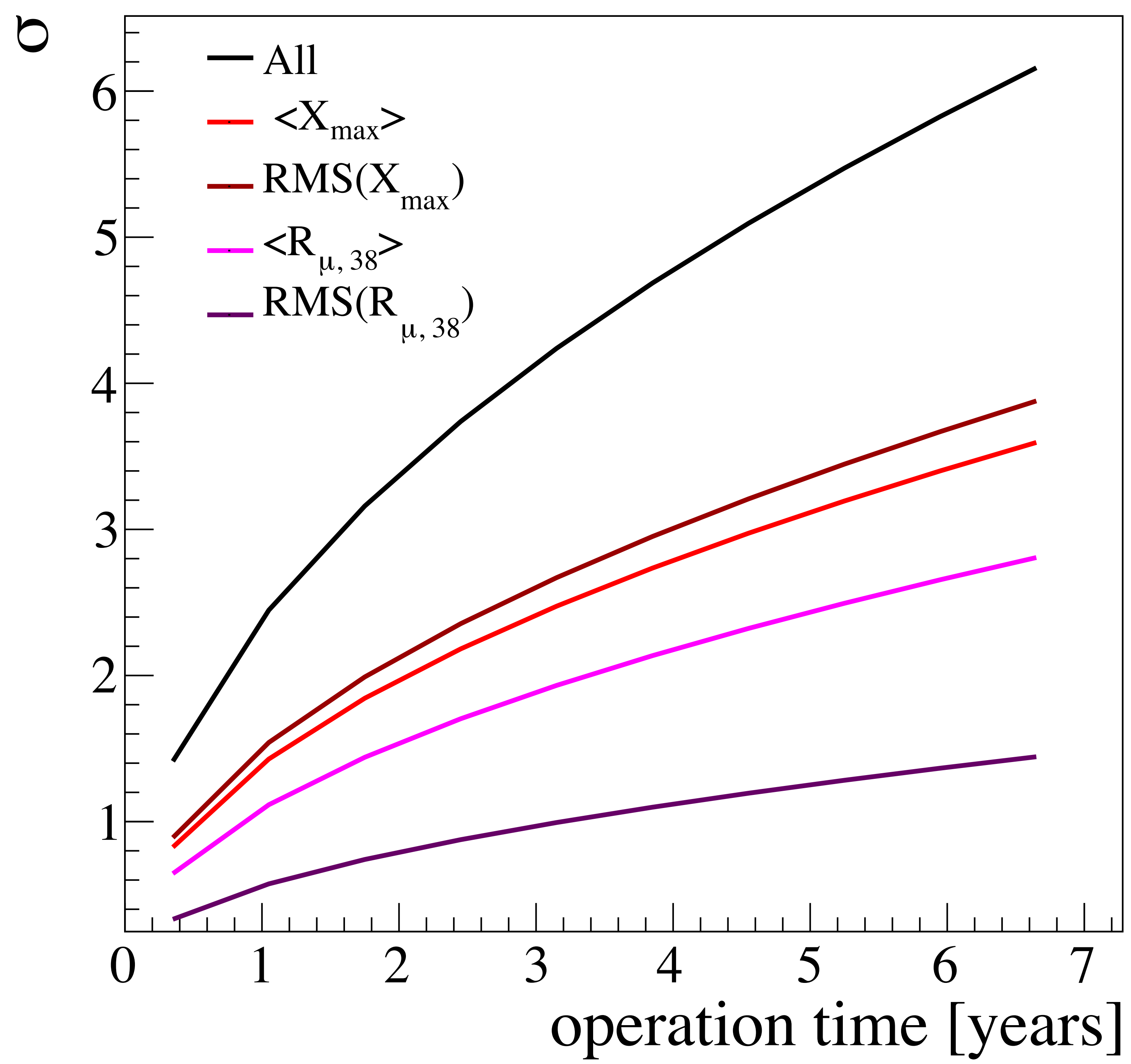
Physics reach: detection of 10% proton contribution

Reference: maximum rigidity model



- Standard scenario 1 (no protons at high energy)
- Scenario 1 with 10% protons added

Significance of distinguishing scenarios with and without 10% protons



(ideal case for knowing proton predictions without uncertainty due to had. int. models)

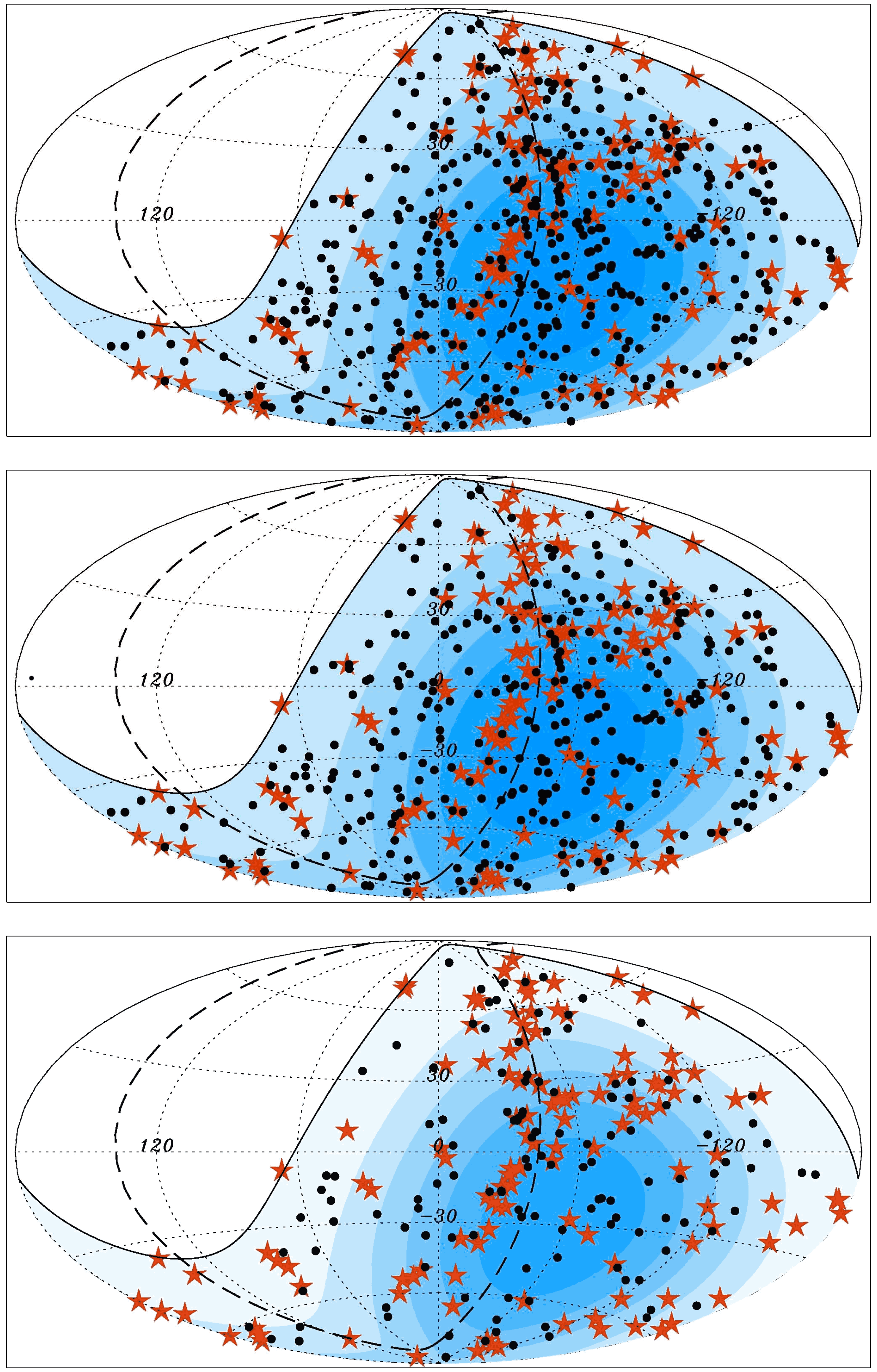
(AugerPrime 1604.03637)

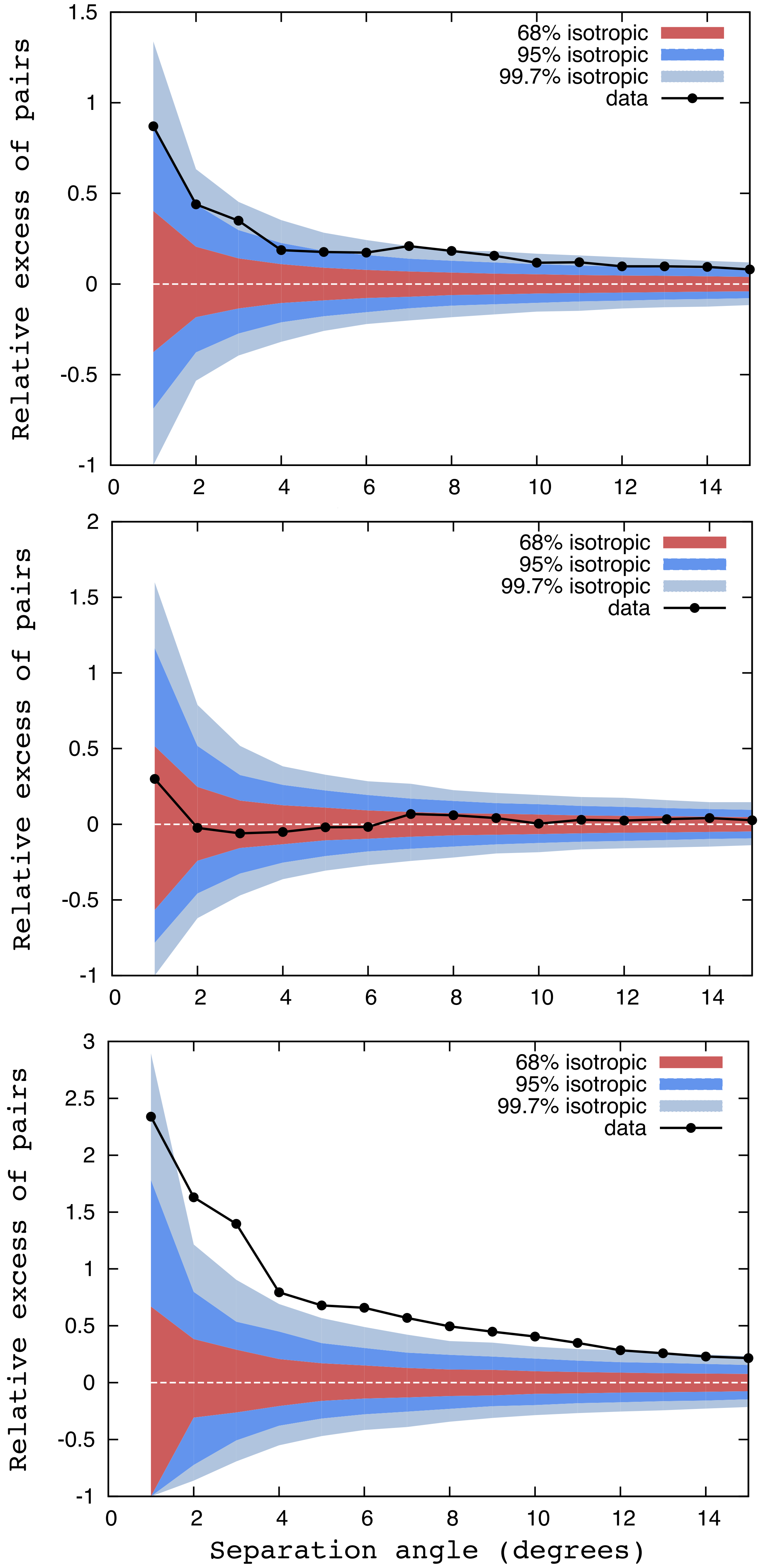
Physics reach: composition-enhanced anisotropy

Modified Auger data set
(E > 4×10^{19} eV, 454 events,
ApJ 804 (2015)15)

X_{max} assignment according to maximum rigidity scenario

10% protons added, half of which from within 3° of AGNs





all 454 events

proton depleted data set (326)

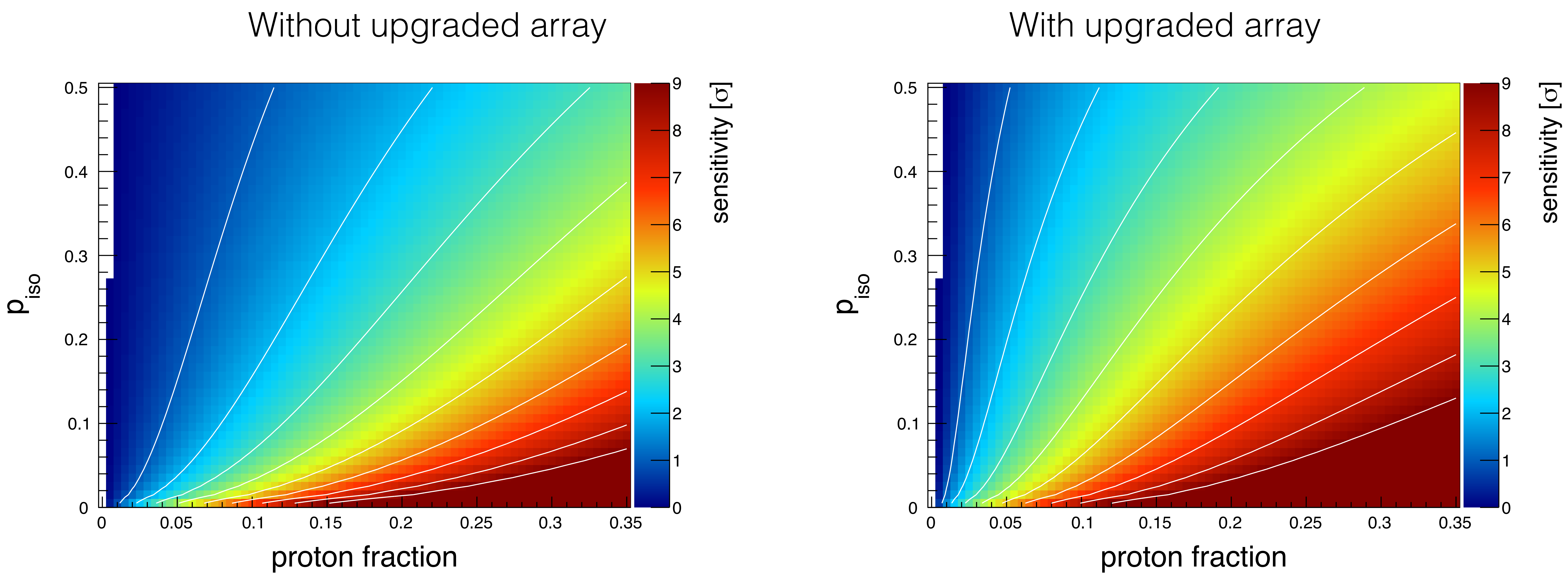
proton enhanced data set (128)

(AugerPrime 1604.03637)

Physics reach: generic composition-enhanced anisotropy

Generic source correlation study: 75% of the protons in the data correlate with sources, sources+correlation radius cover p_{iso} of sky (folded with exposure)

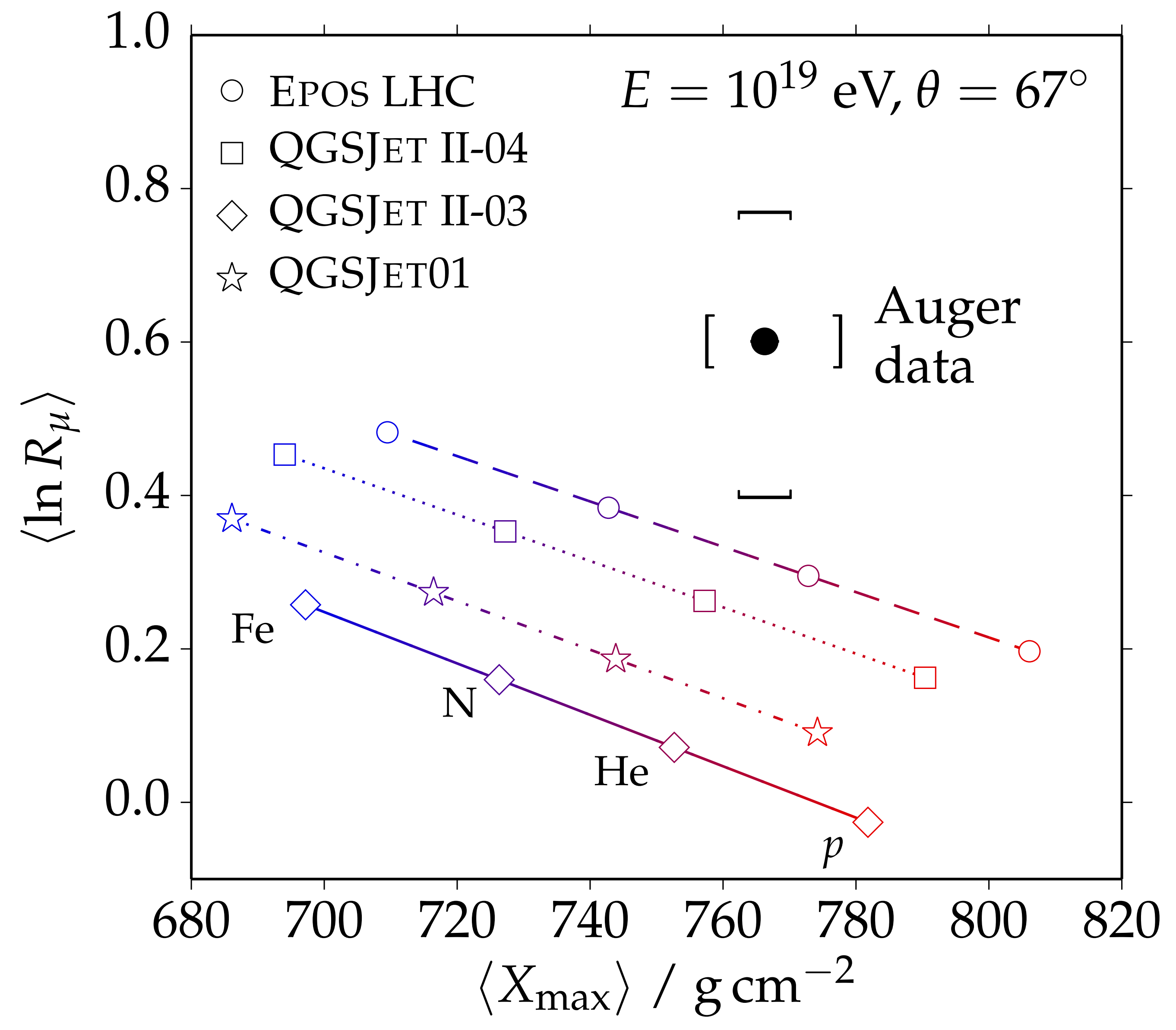
Merit factor of 1.5 for discrimination light/heavy assumed



(AugerPrime 1604.03637)

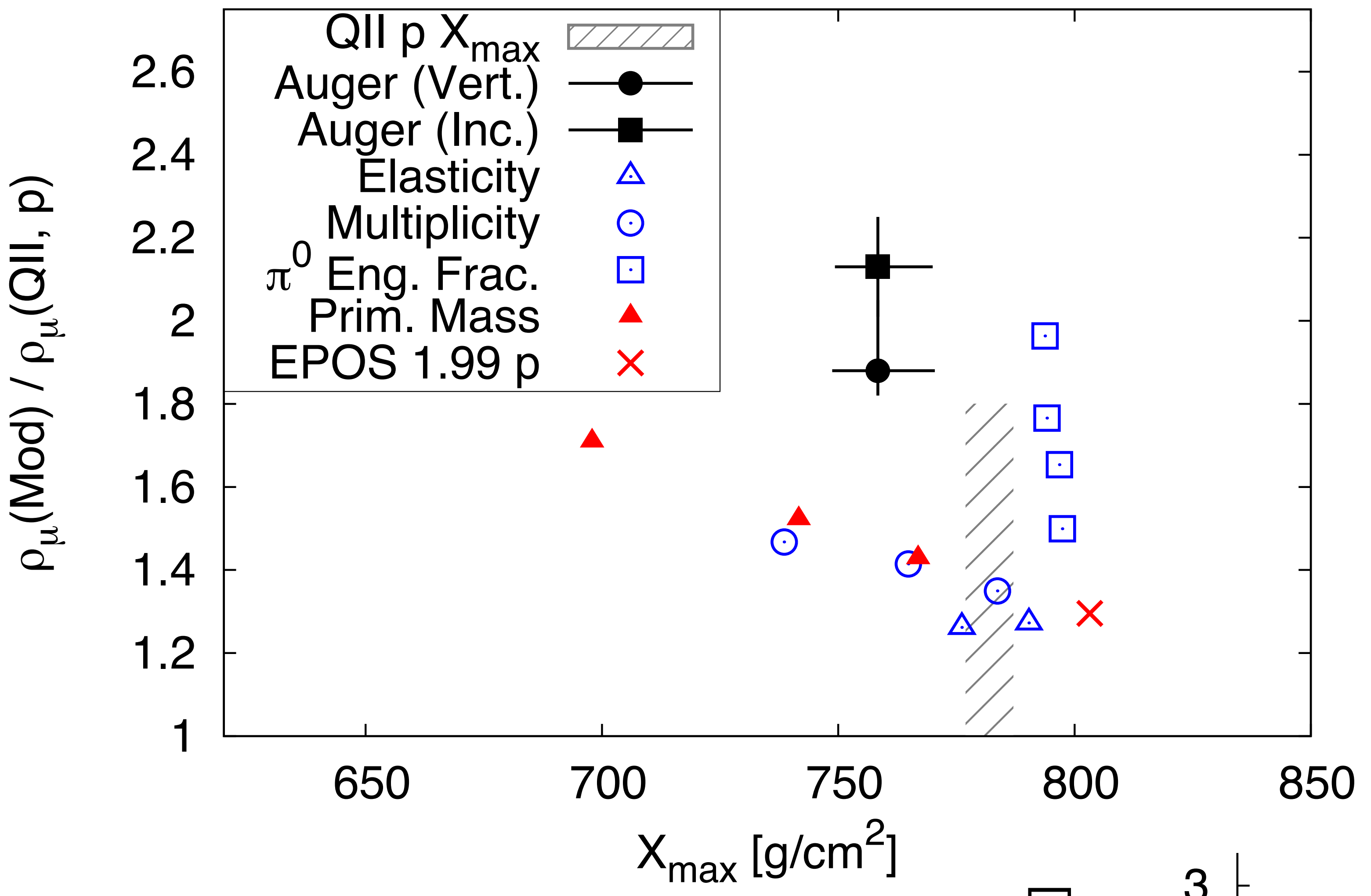
Particle physics with the upgraded Auger Observatory

Results on muon number of showers still not understood, important effect missing in models?



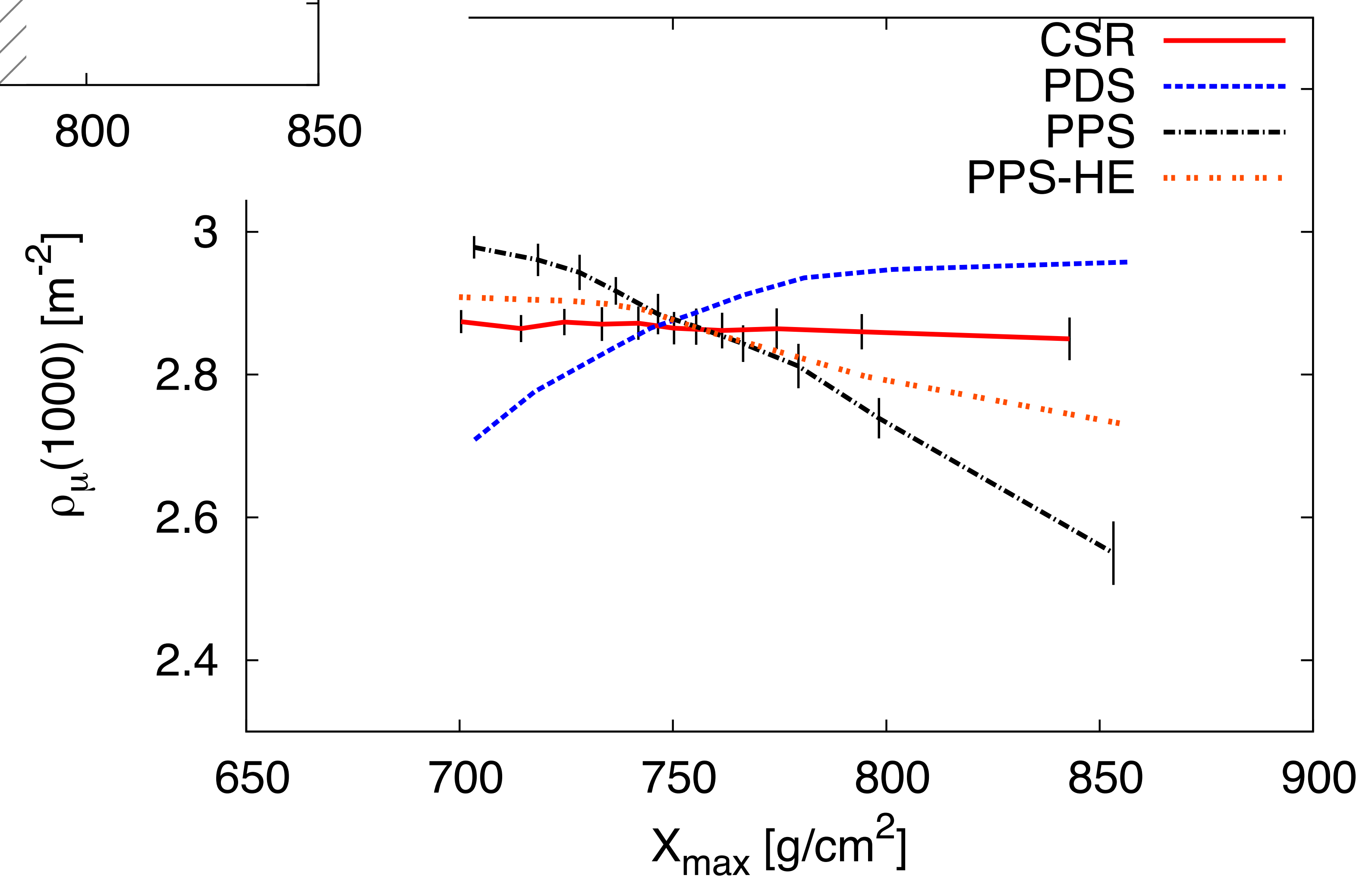
(Auger Collab. Phys. Rev. D91, 2015 & ICRC 2015)

Example of power of upgraded detectors



Correlations between X_{max} and muon density

(Allen & Farrar, 1307.7131)



Overview of AugerPrime: items needed to make things work

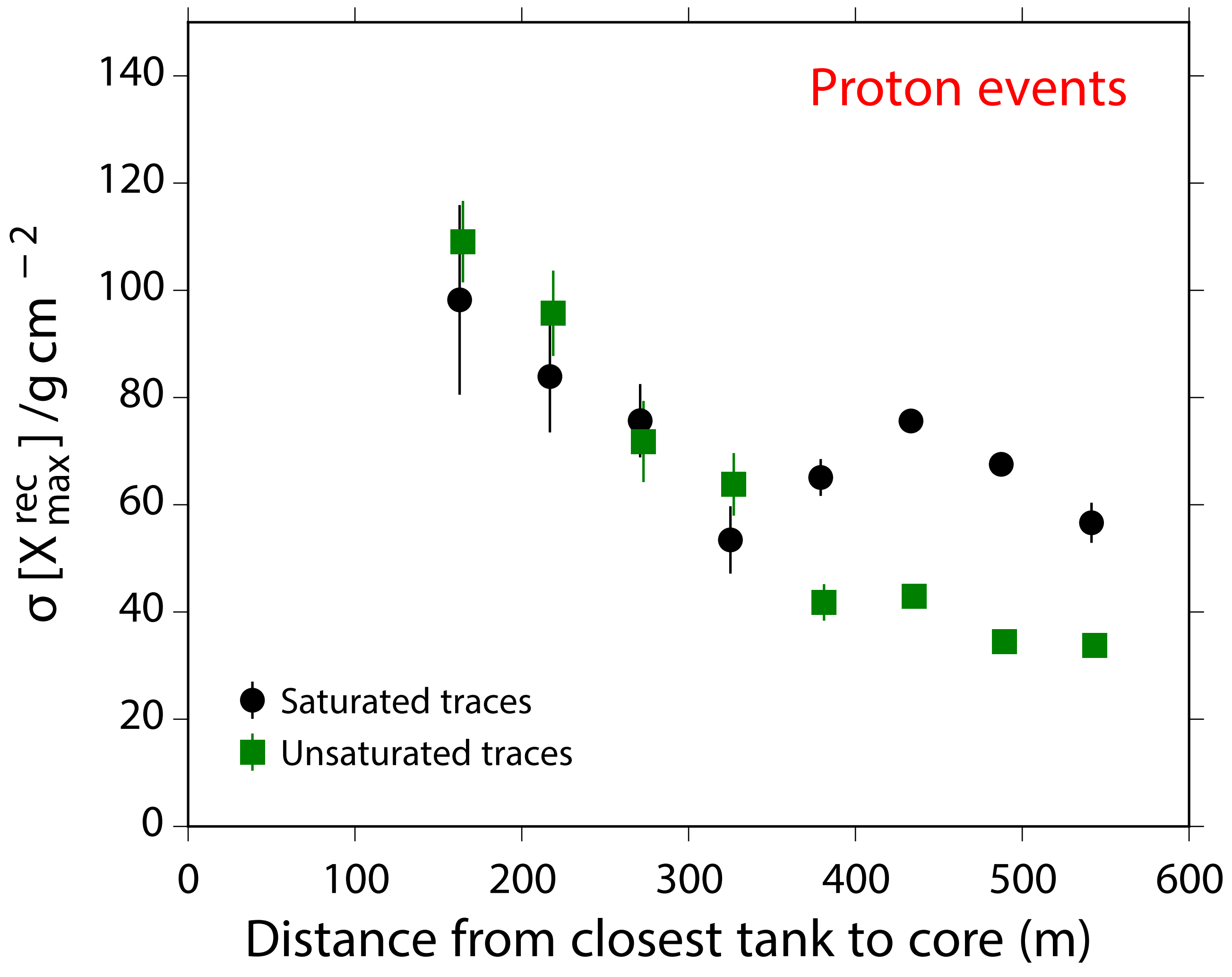
1. Installation of 1700 **scintillation detectors** (3.8 m^2, 1cm thick)

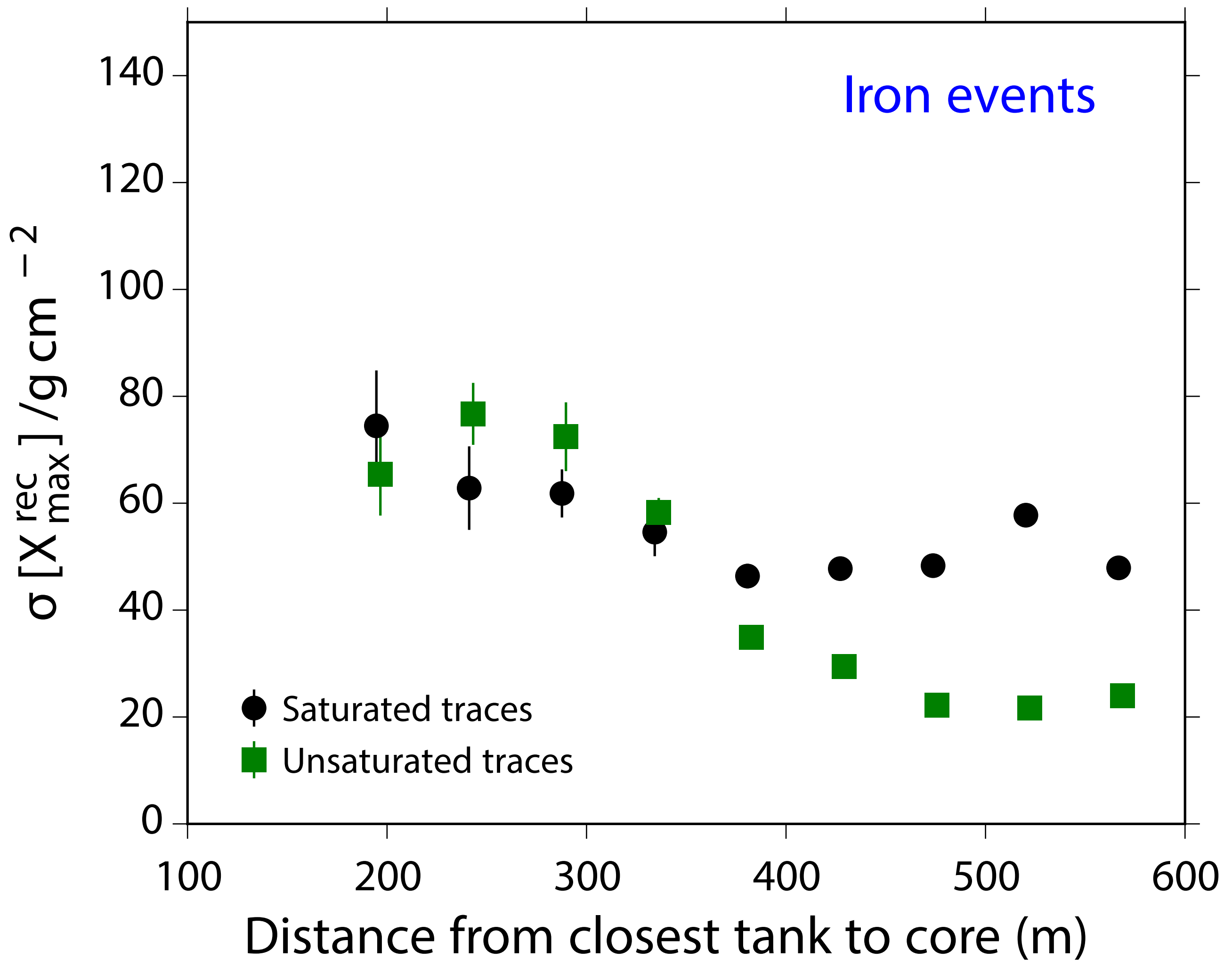
2. Installation of **new electronics** (additional channels, 40 MHz -> 120 MHz, better GPS timing)

3. Installation of **small PMT** in water-Cherenkov detectors for increasing dynamic range: typical lateral distance of saturation reduced from ~500 m (E > $10^{19.5}$ eV) to 300 m

4. Cross checks of upgraded detectors with **direct muon detectors** shielded by 2.3 m of soil (AMIGA, 750 m spacing, 61 detectors of 30 m^2, 23.4 km^2)

5. **Increase of FD exposure** by ~50% (lowering HV of PMTs)





(AugerPrime 1604.03637)