Recent progress in understanding ultra-high-energy cosmic rays

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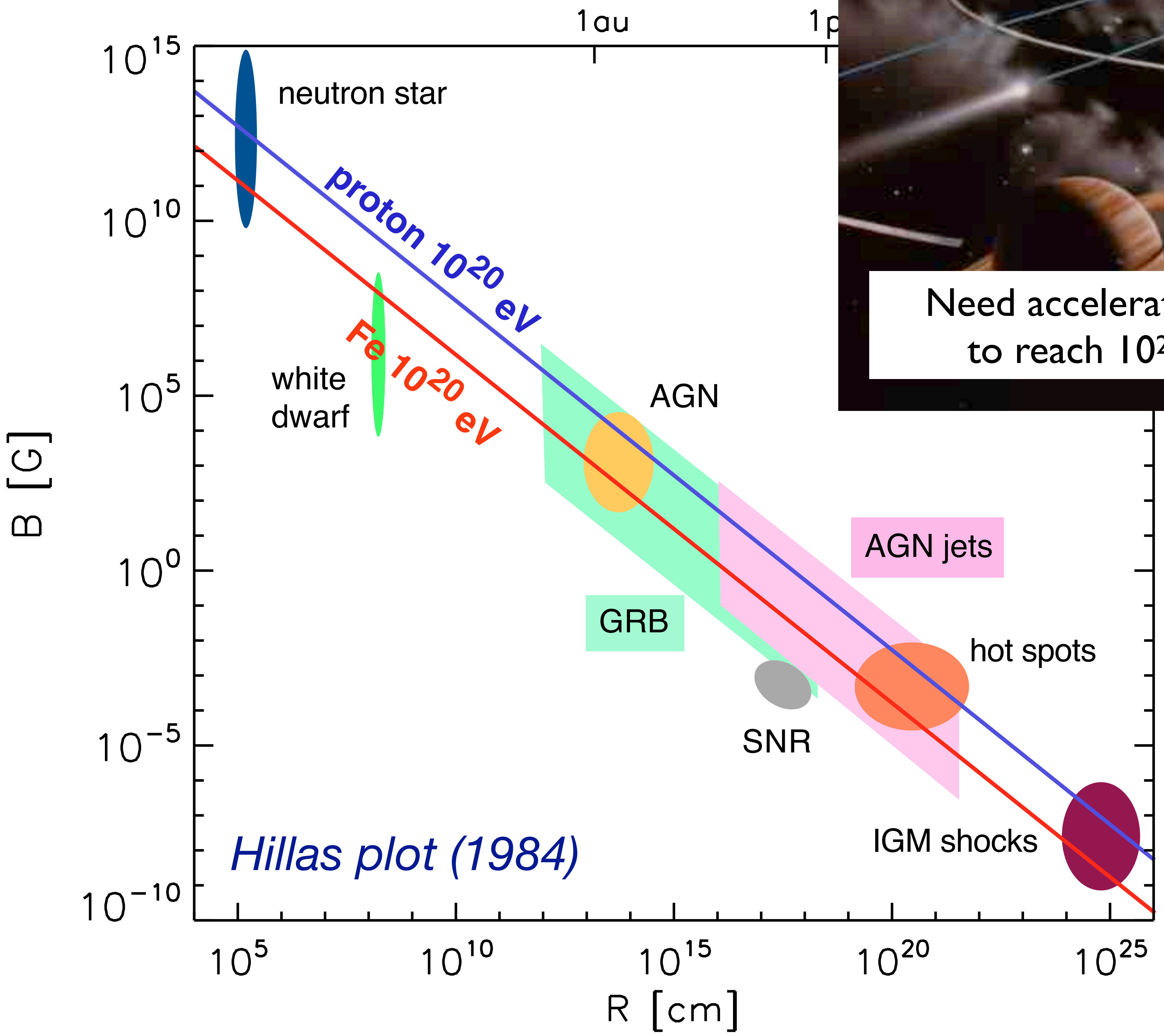
PIERRE
AUGER
OBSERVATORY

Physics of ultra-high-energy cosmic rays (UHECRs)

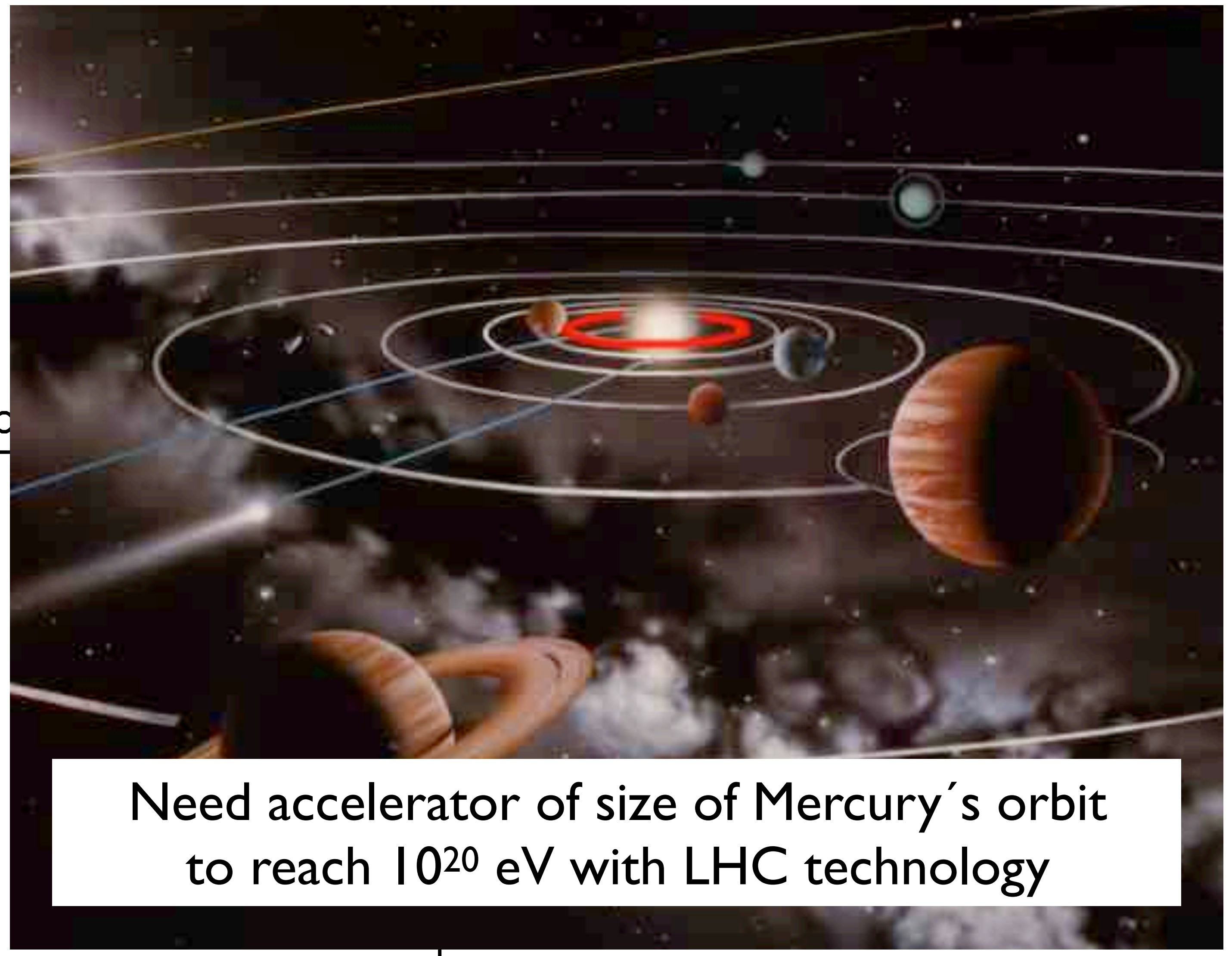
Sources of UHECR and astrophysics

$$E_{\max} \sim \beta_s Z B R$$



Hillas plot (1984)

(Kotera & Olinto, ARAA 2011)



Need accelerator of size of Mercury´s orbit to reach 10^{20} eV with LHC technology

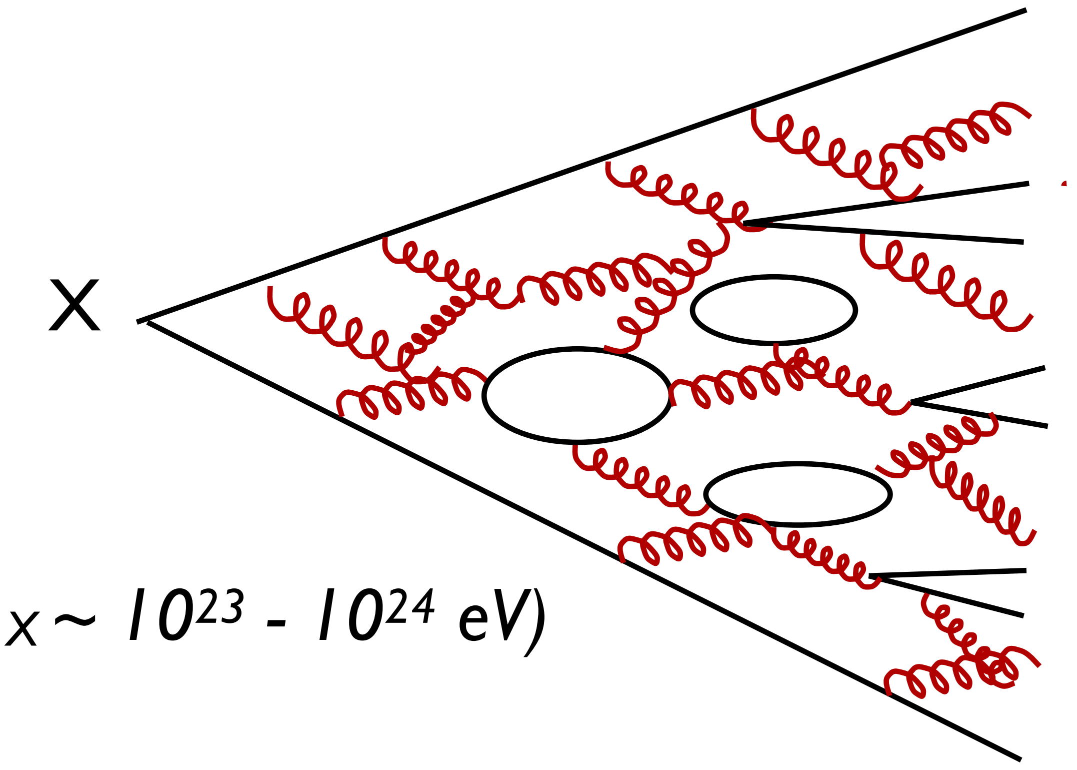
(Unger, 2006)

Propagation of UHECR (including mag. fields)

Particle physics beyond the reach of colliders

X particles from:

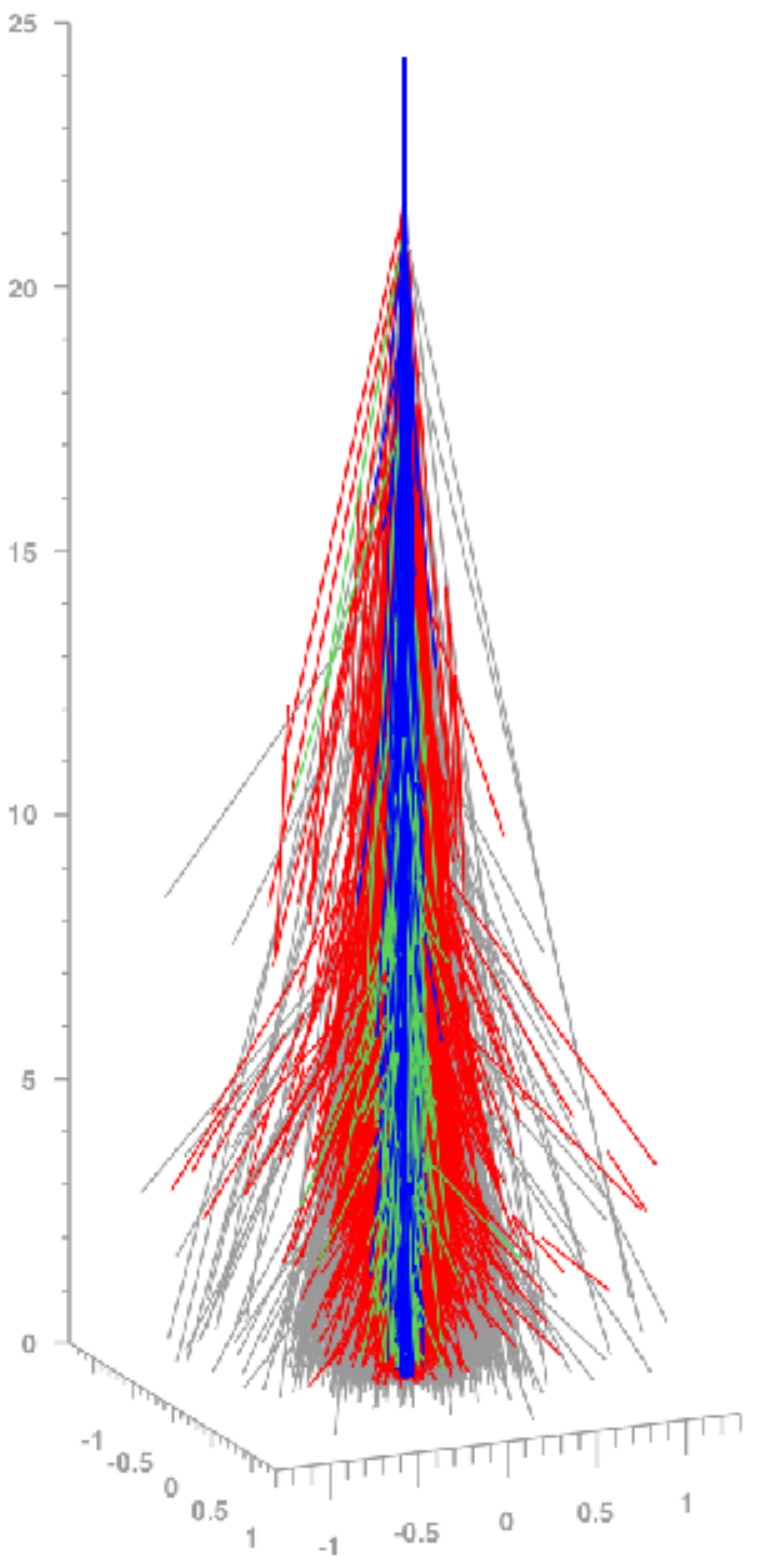
- topological defects
- monopoles
- cosmic strings
- cosmic necklaces
- .....



($M_X \sim 10^{23}$ - 10^{24} eV)

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

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



Space-time properties (LIV)

UHECRs – how to get them to Earth

Proton

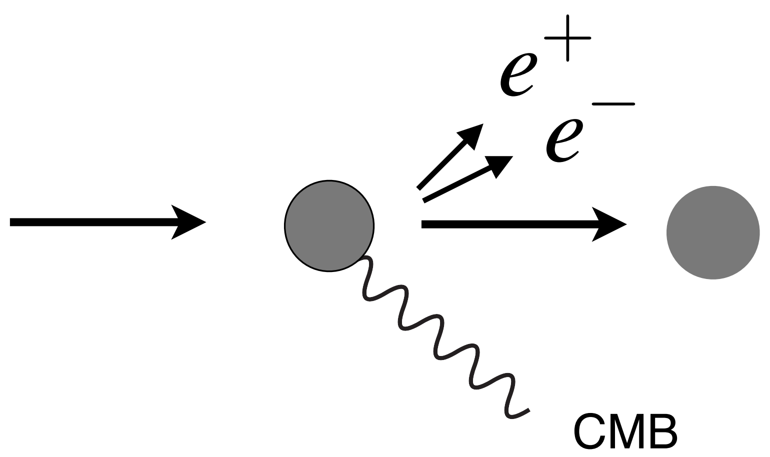
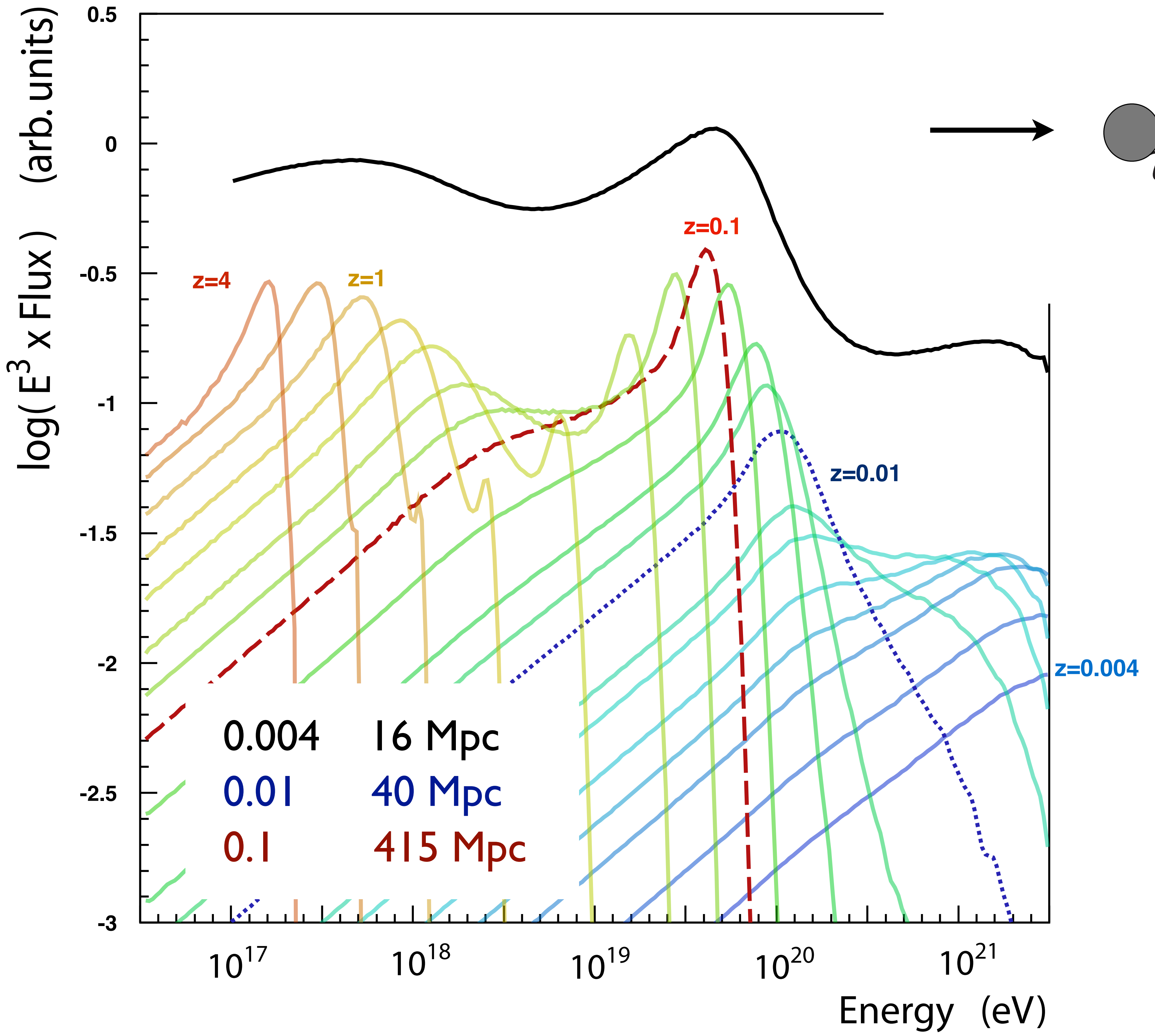
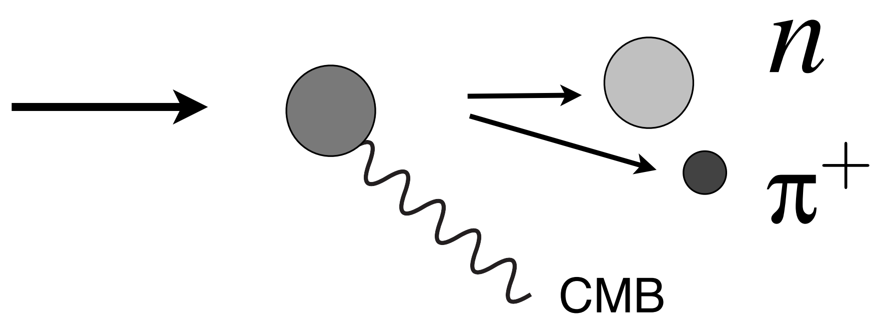


Photo-pion production
(mainly Δ resonance)





(Bergmann et al., PLB 2006)

Iron

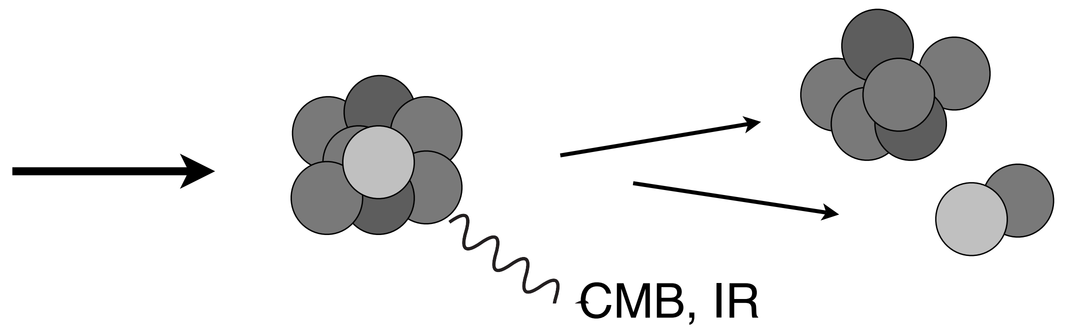
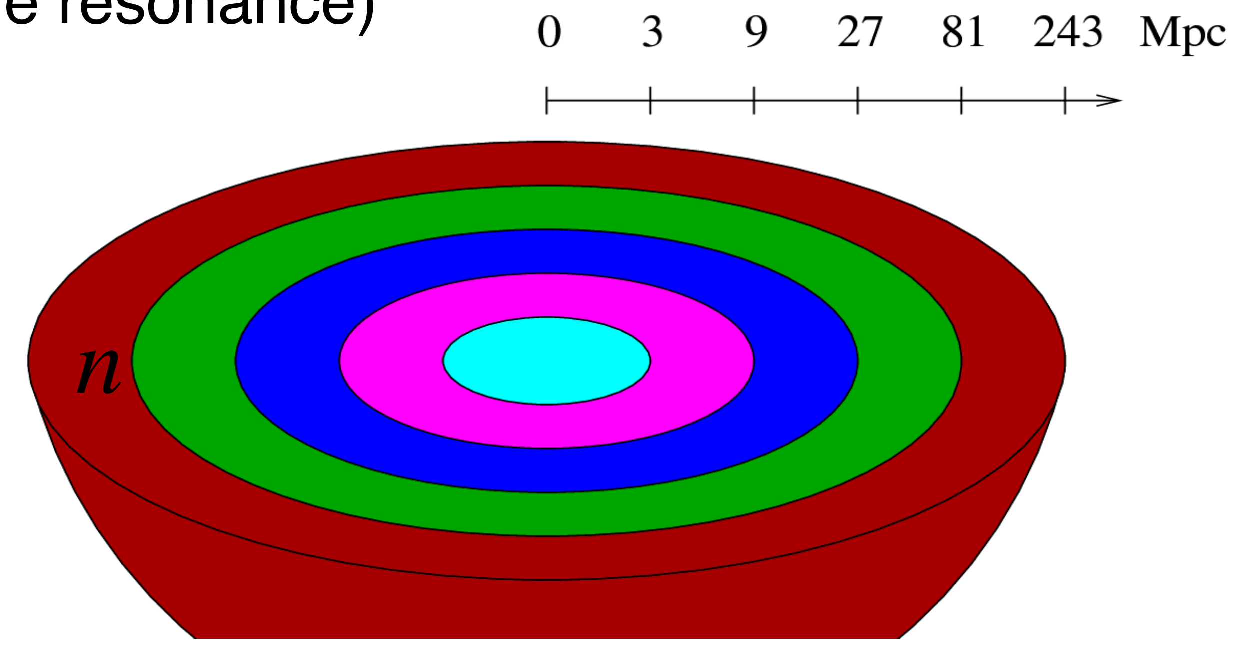
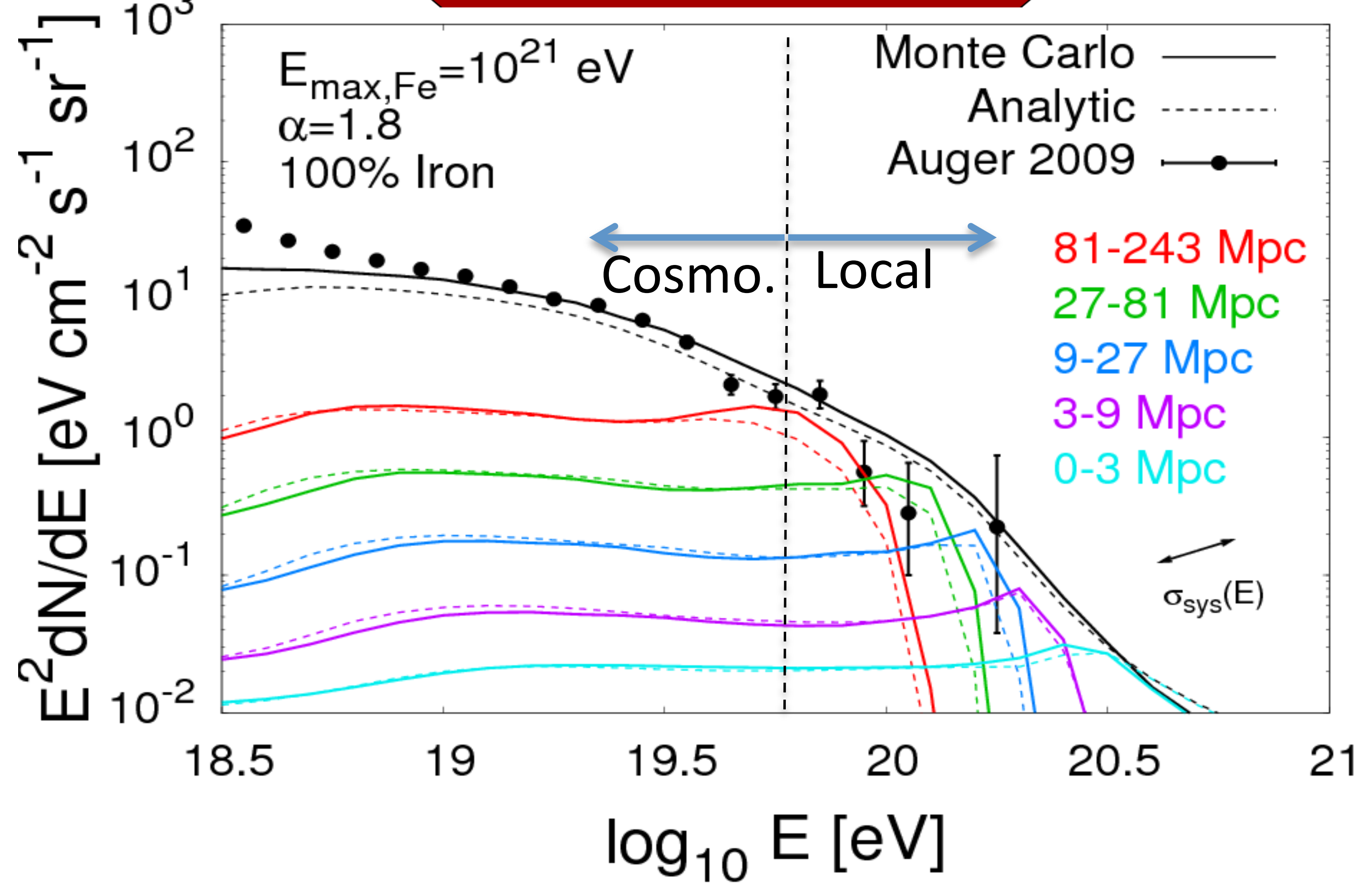


Photo-dissociation
(giant dipole resonance)

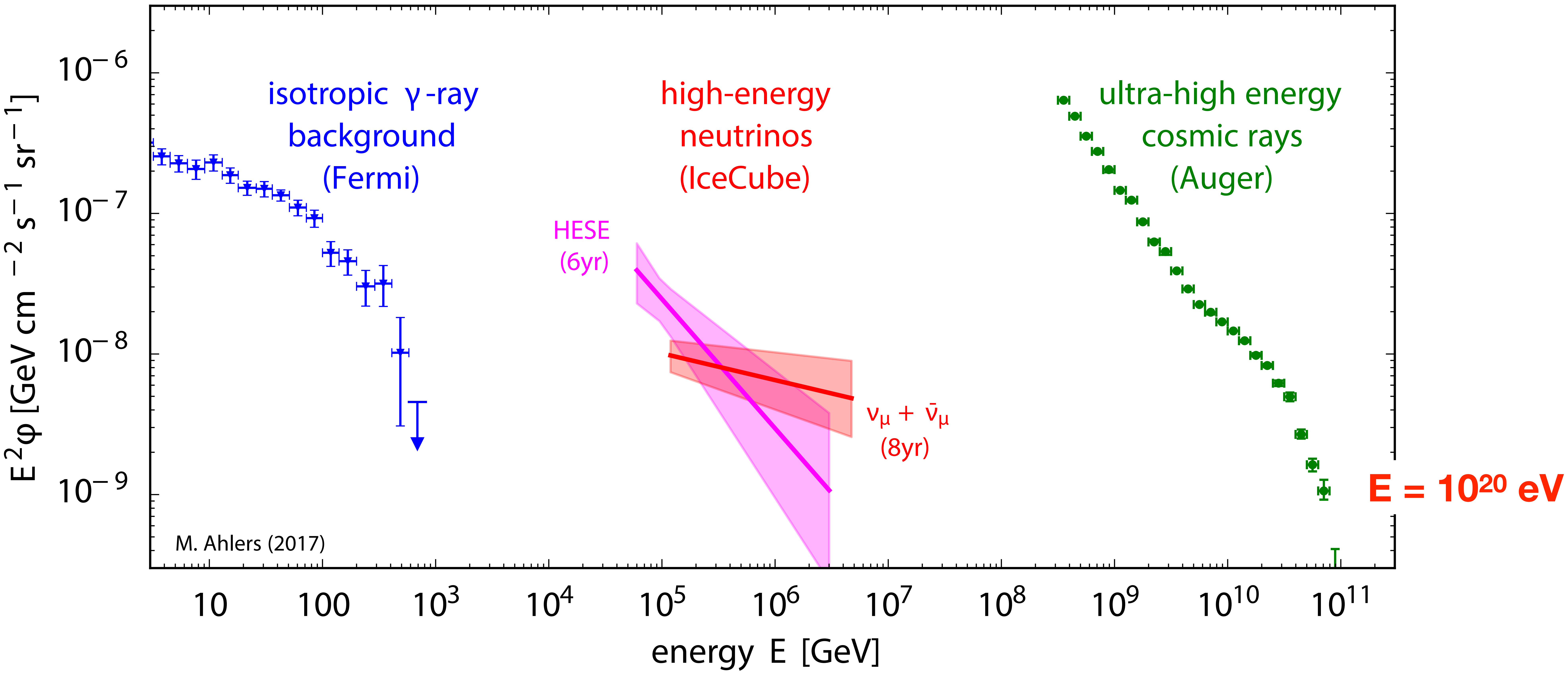




Greisen-Zatsepin-Kuzmin (GZK) effect, 1966

(Hooper, Taylor et al., PRD 2008)

Global picture – energy density & multi-messenger physics



Particle flux multiplied by E^2

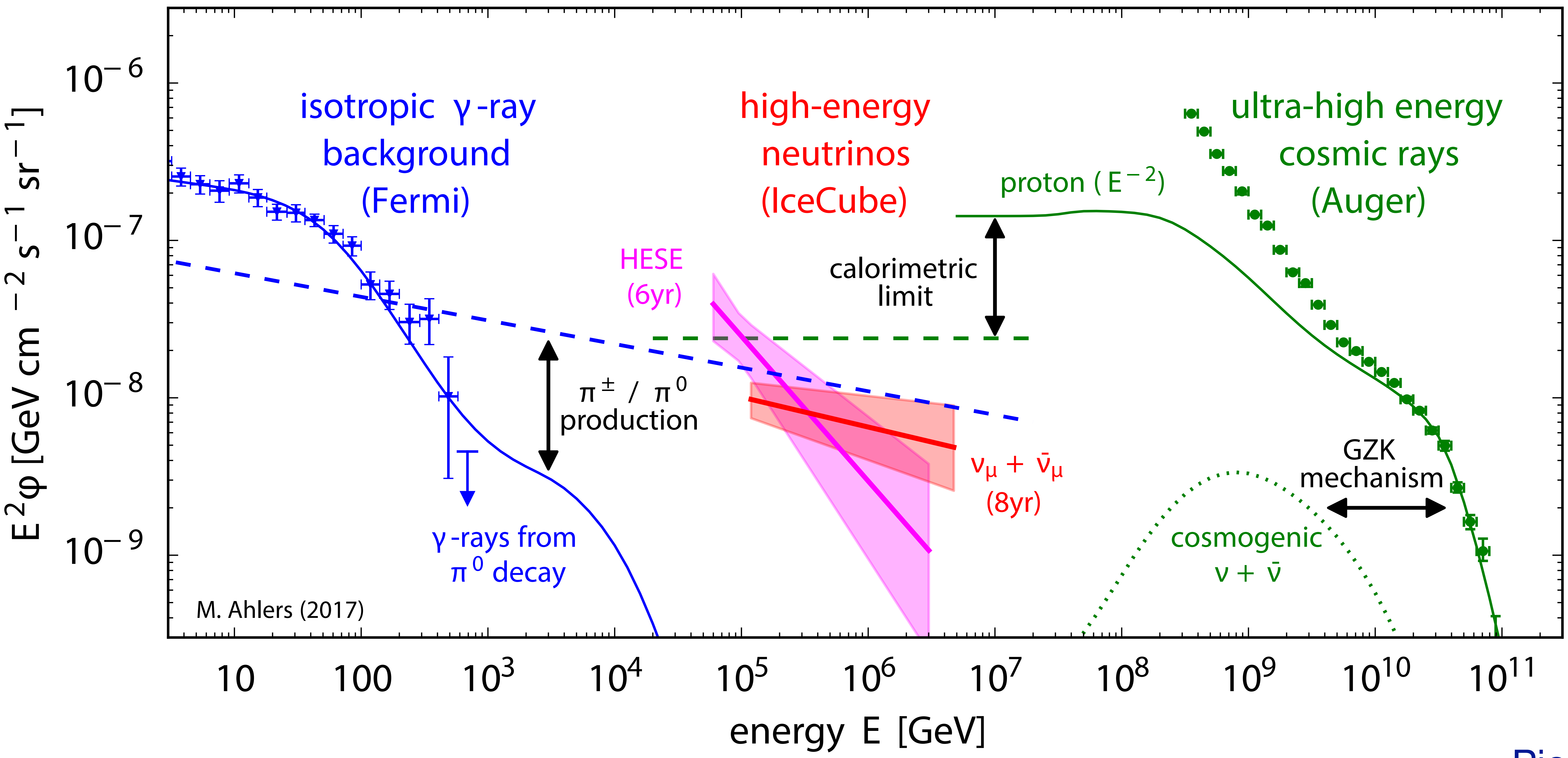
$$E^2 \frac{dN}{dE} = E \frac{dN}{d\ln E}$$

Energy density per decade

$$\rho_{\text{decade}} = \int_{\text{decade}} E \frac{dN}{d\ln E} \, d\ln E$$

Energy density per decade similar in all three messenger particles

The multi-messenger view at highest energies



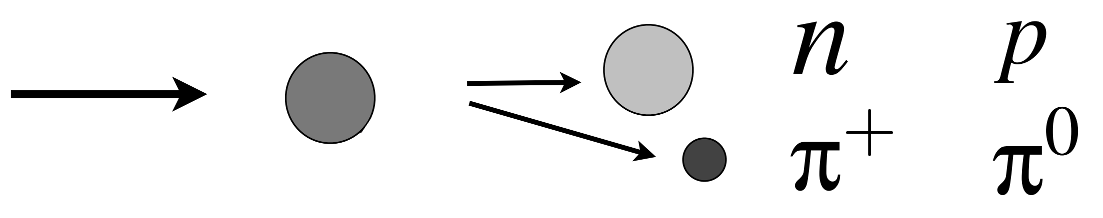
Interplay of

interaction in source

vs.

escape from source

Pion production on any target



$$\pi^0 \longrightarrow \gamma\,\gamma$$

$$\pi^+ \longrightarrow \mu^+\,\nu_\mu \longrightarrow e^+\,\nu_e\,\nu_\mu\,\bar{\nu}_\mu$$

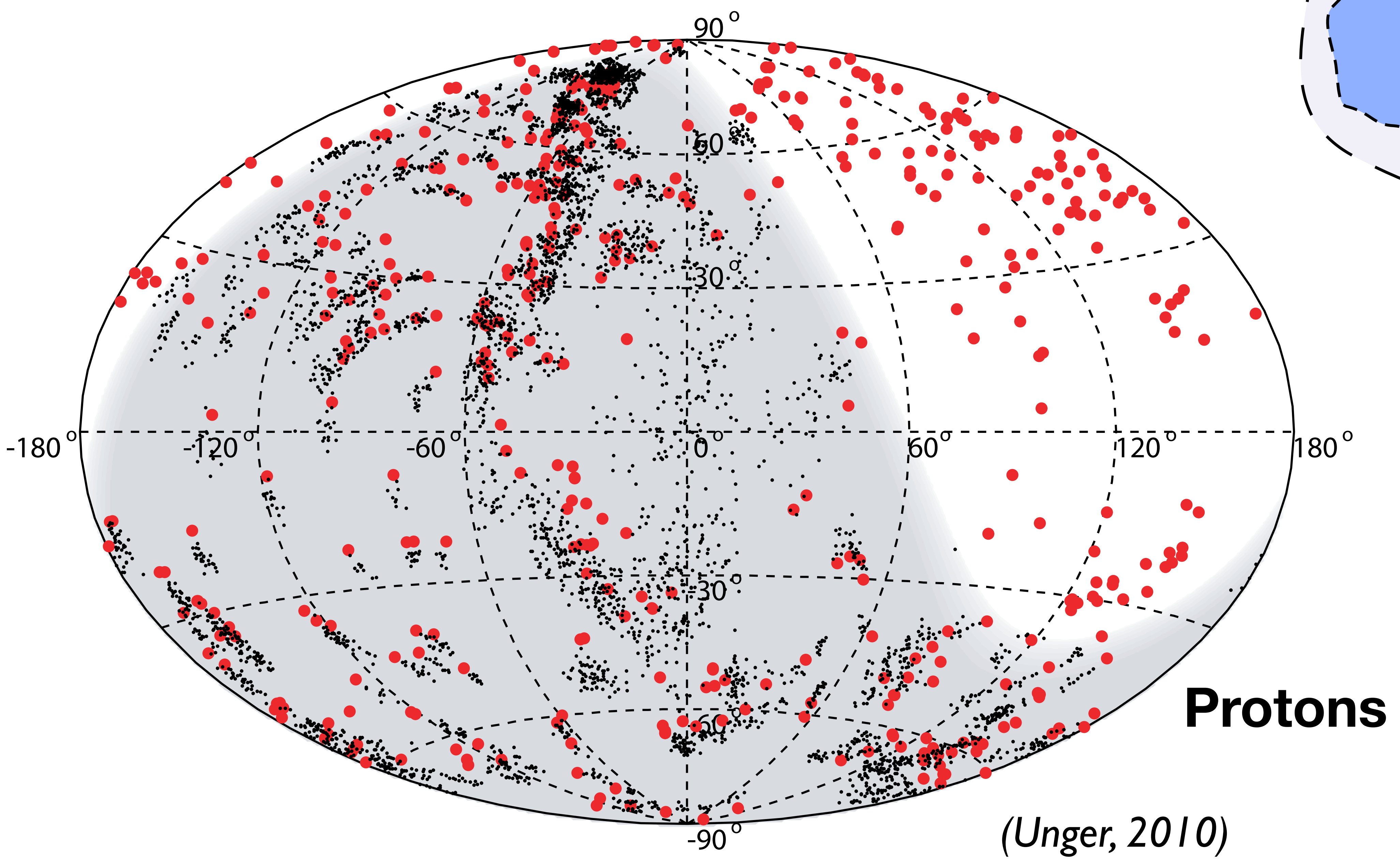
$$\boxed{\nu_\mu : \nu_e \sim 2 : 1}$$

(neutrino + antineutrino flavor)

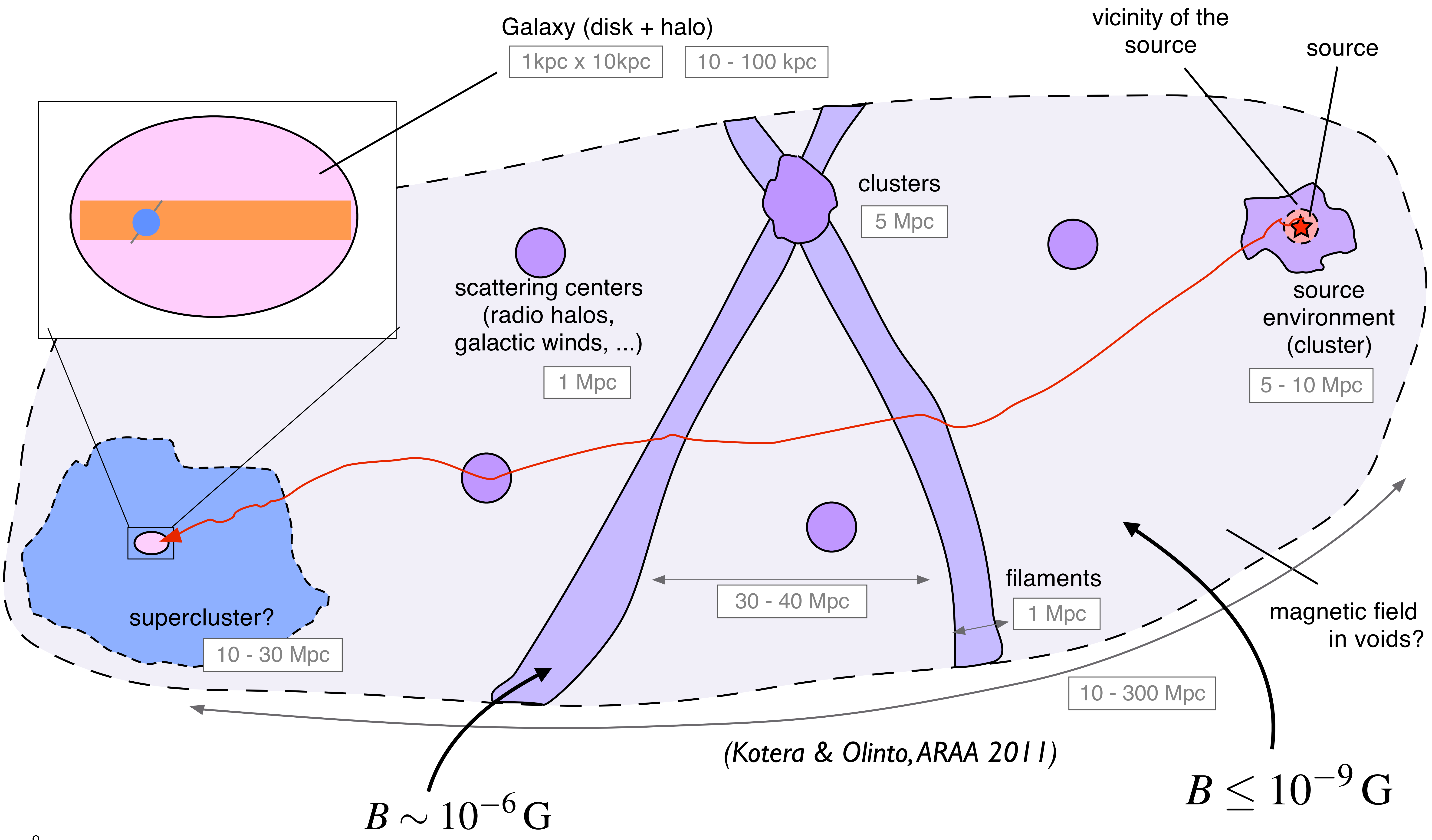
Question 3: What are the sources of ultra-high-energy cosmic rays ?

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)

Question 3: What are the sources of ultra-high-energy cosmic rays ?

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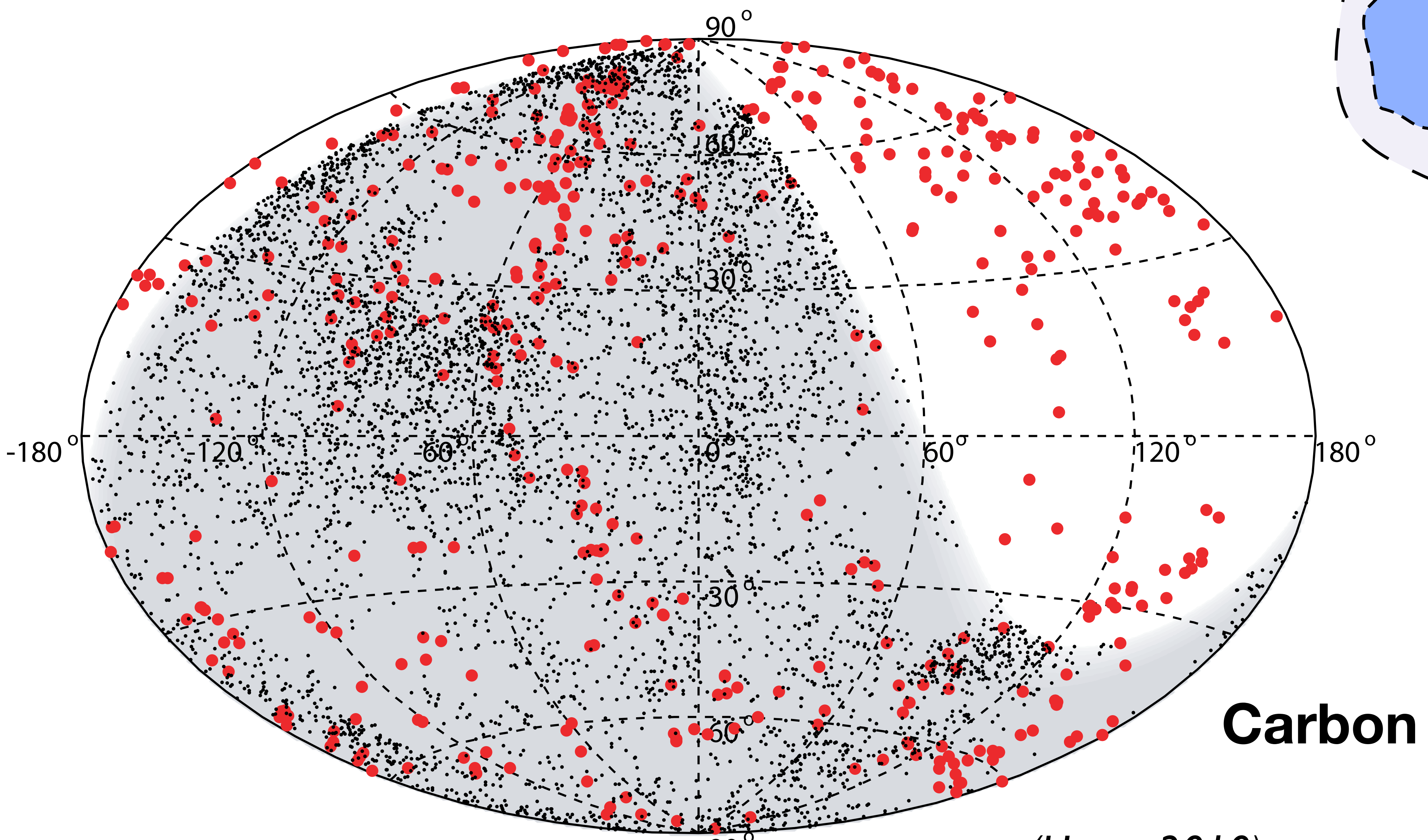

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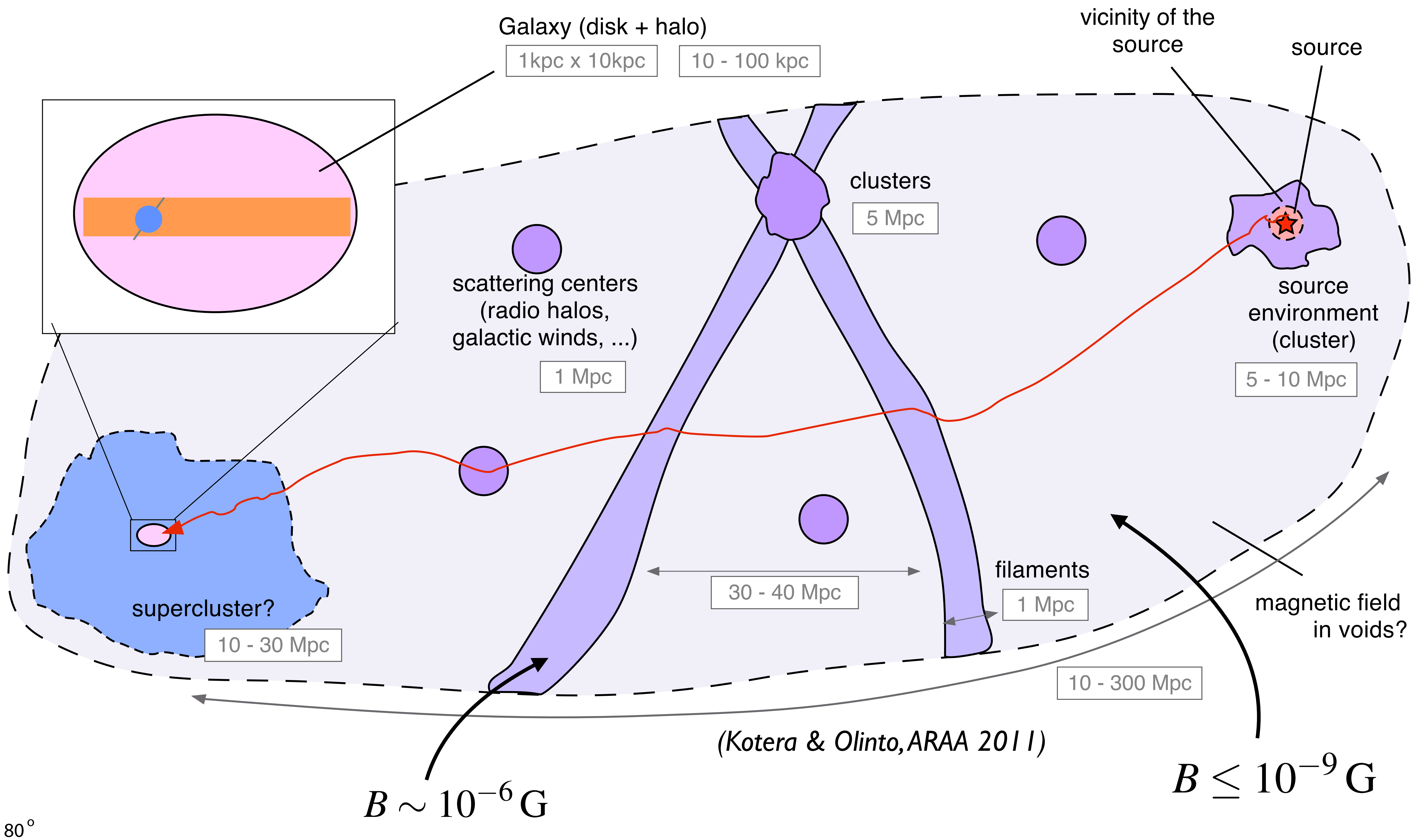
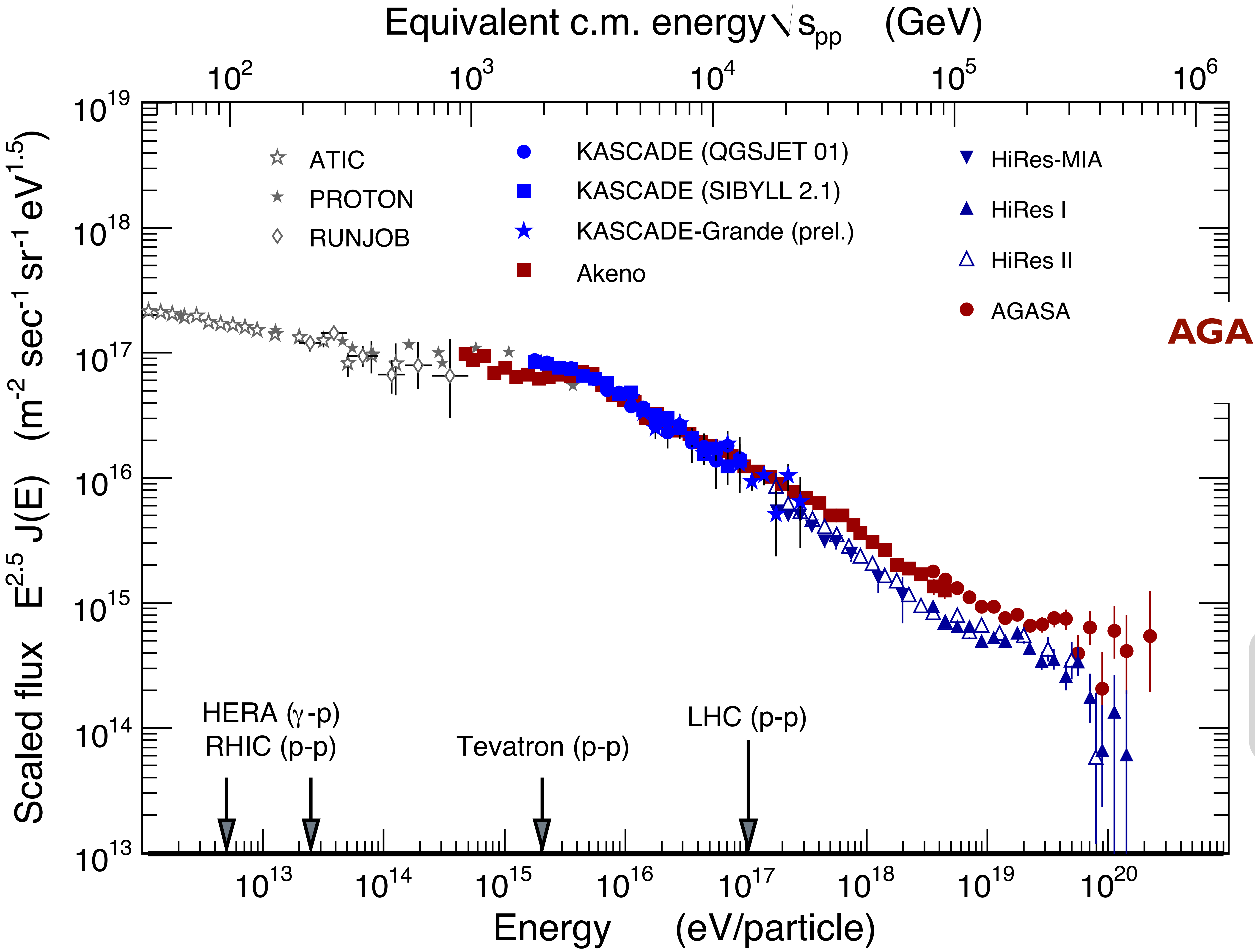


(Kotera & Olinto, ARAA 2011)

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

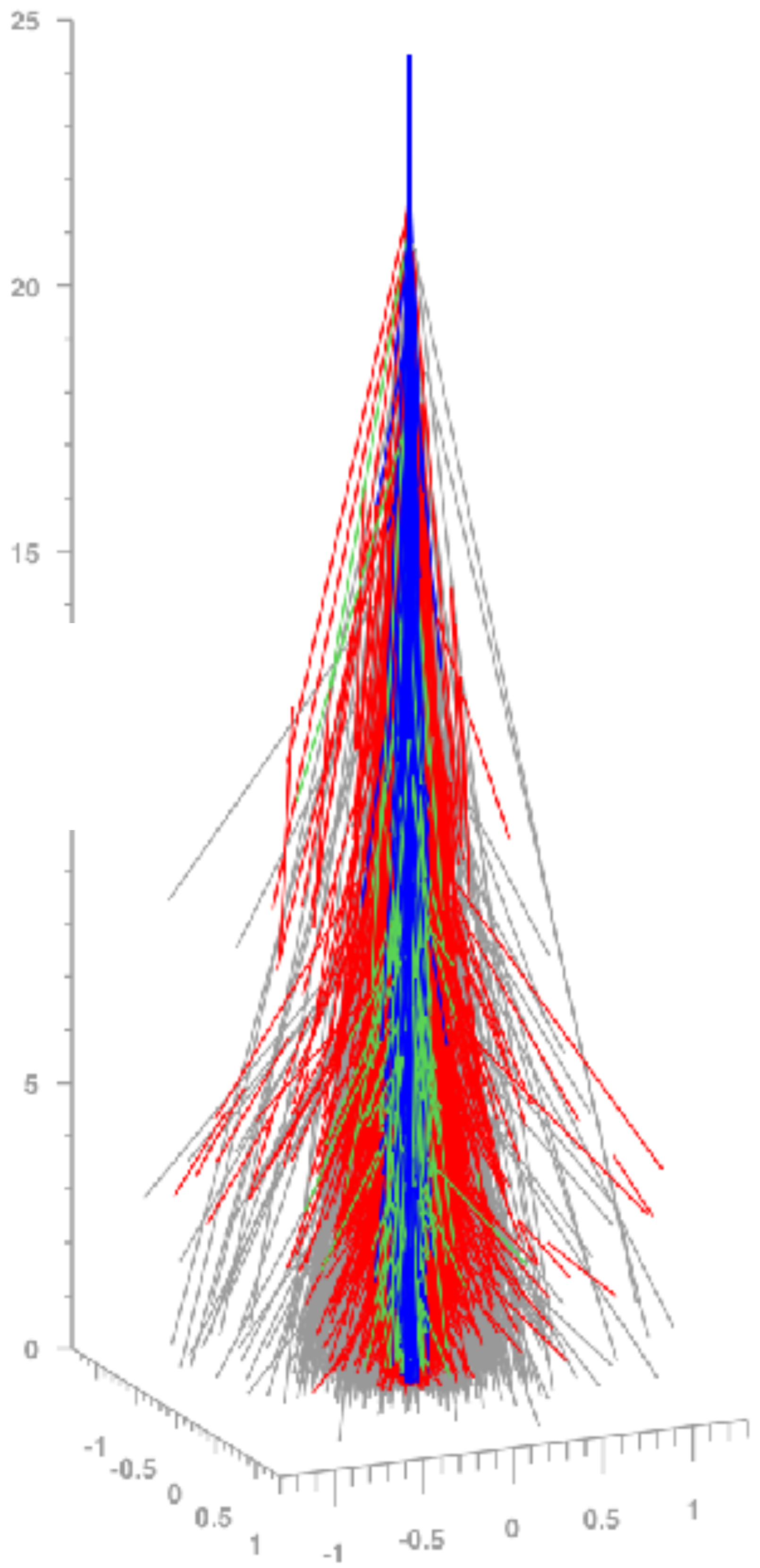
Multi-messenger signals (gamma-rays and neutrinos)

Status of the field 12 years ago – particle flux



AGASA: particles at ground
(scintillator array)

Does GZK suppression exist ?



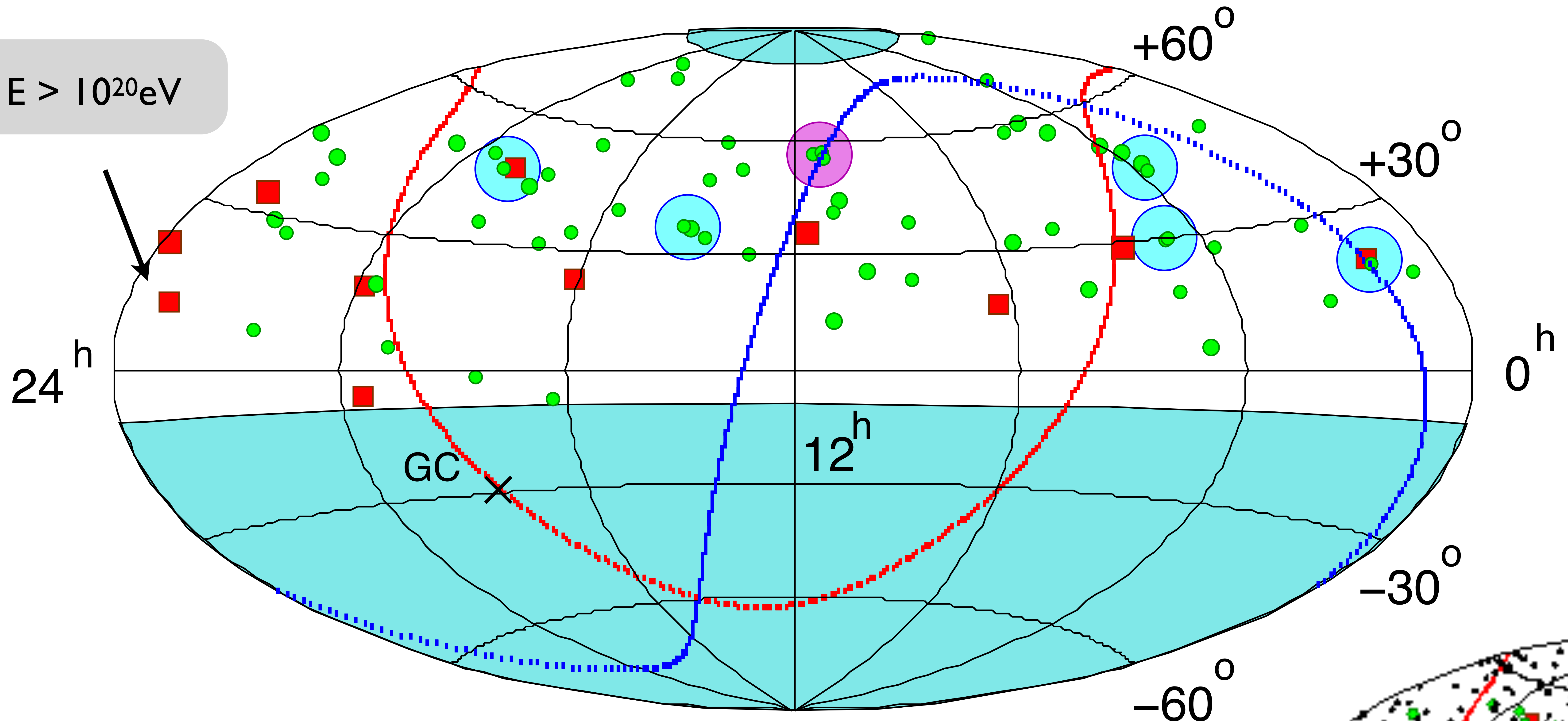
HiRes Fly´s Eye: longitudinal shower profile
(fluorescence telescopes)

- **Flux data contradictory**
- **Composition: protons ?**
- **Apparent isotropy**

(RE, Nijmegen Summer School, 2006)

Status of the field 12 years ago – arrival direction distribution

E > 10^{20}eV

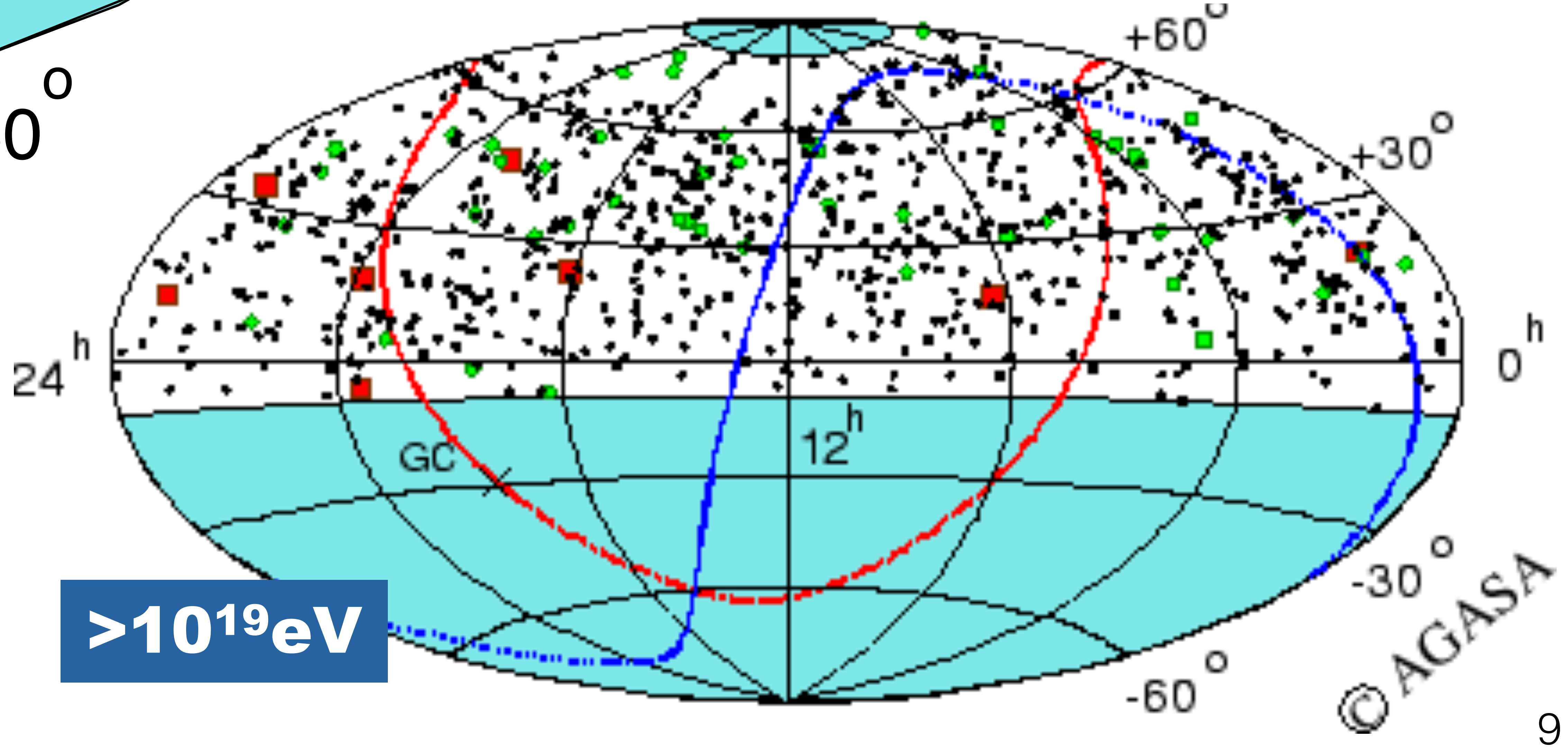


AGASA:

5 doublets, 1 triplet for
$\Delta\theta < 2.5°$, E > 4×10^{19}eV

HiRes:

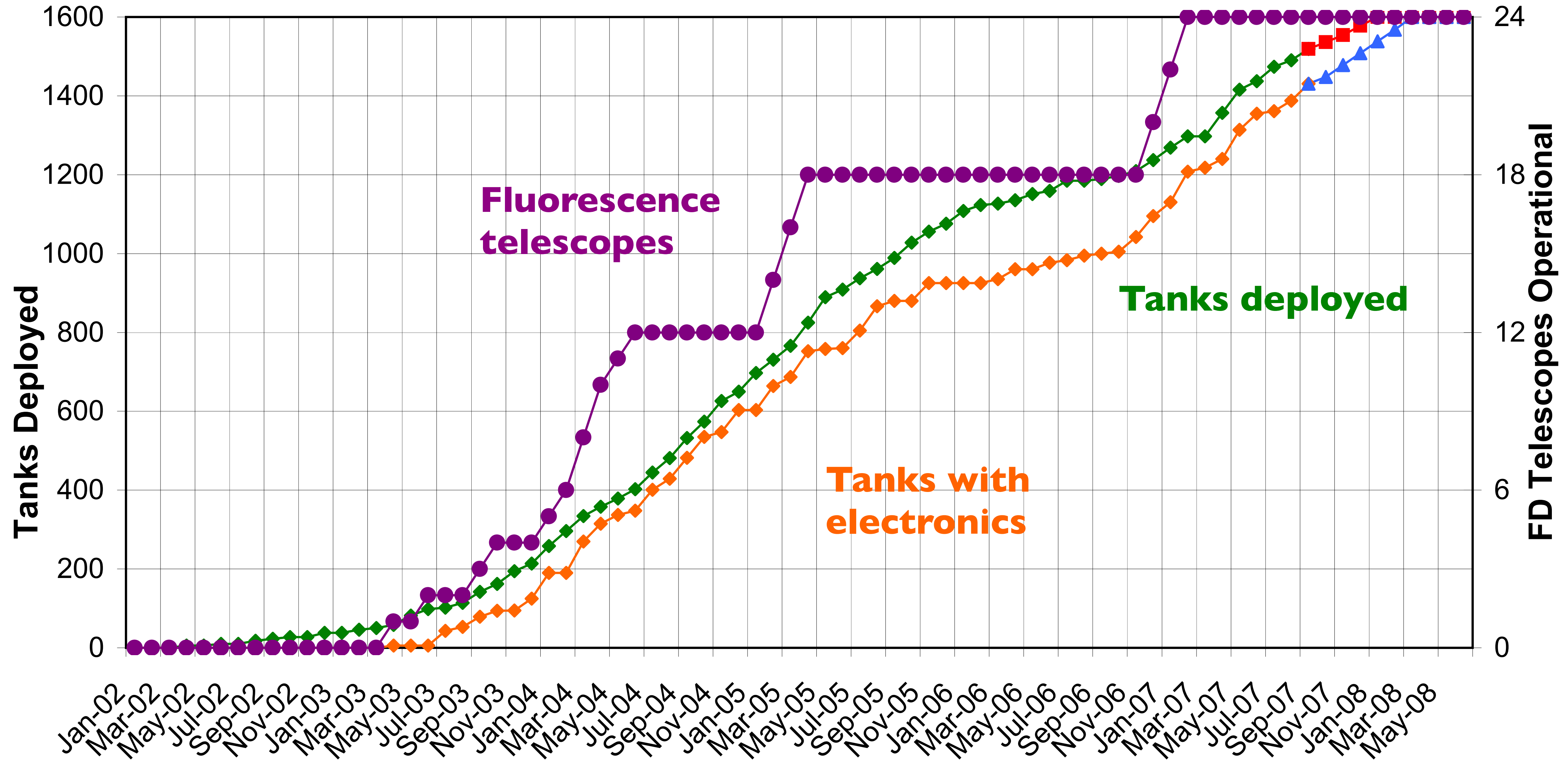
no confirmation (different
statistics & systematics)



(RE, Nijmegen Summer School, 2006)

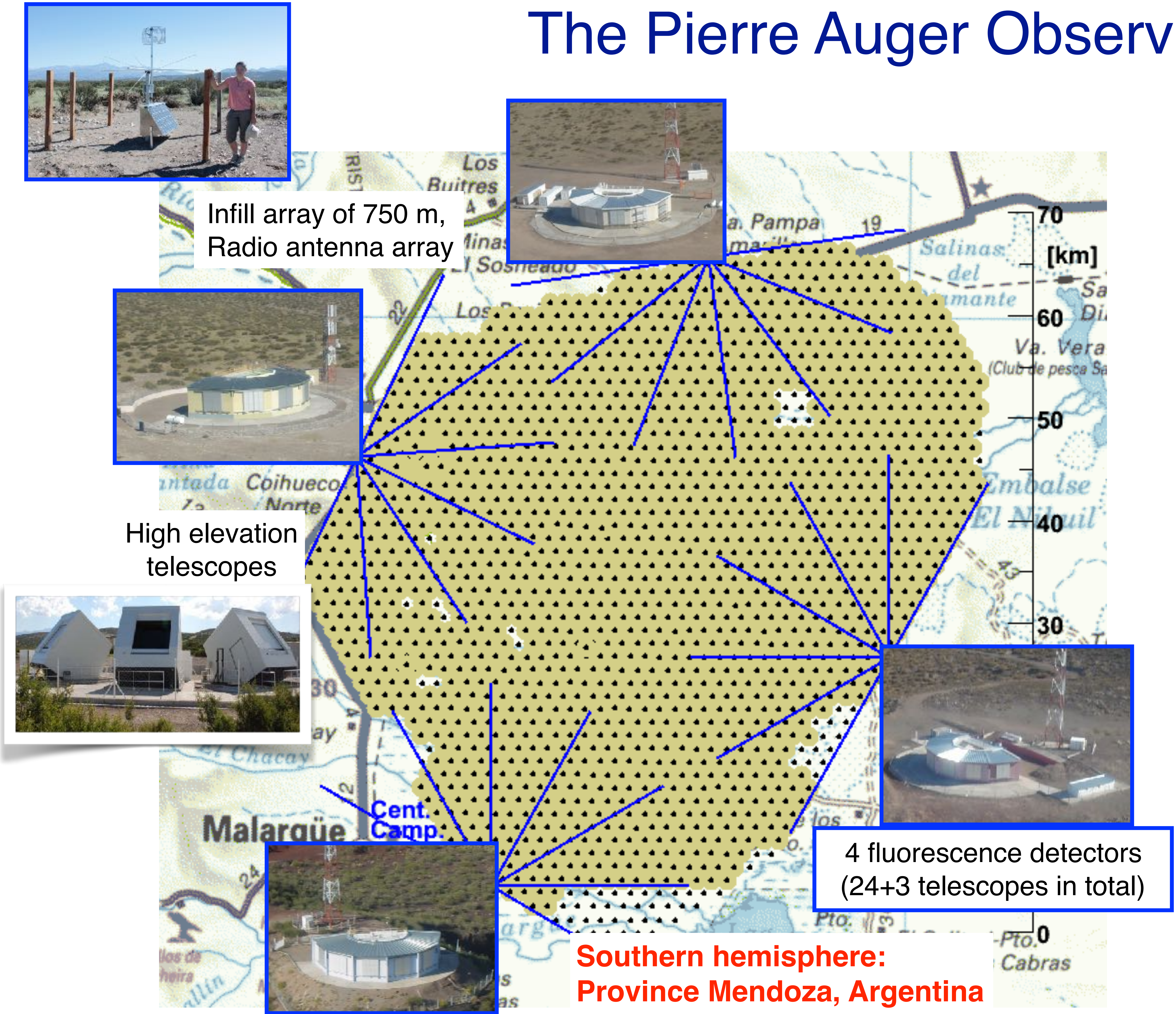
Building and operating a big observatory …

MAGIC, H.E.S.S., IceCube, Auger – similar time scales




“Last Friday, June 13th, at 13:00 hs, the "last" surface detector (the one with signatures from the whole Collaboration) was filled with water. It was put to work immediately afterwards.”

The Pierre Auger Observatory

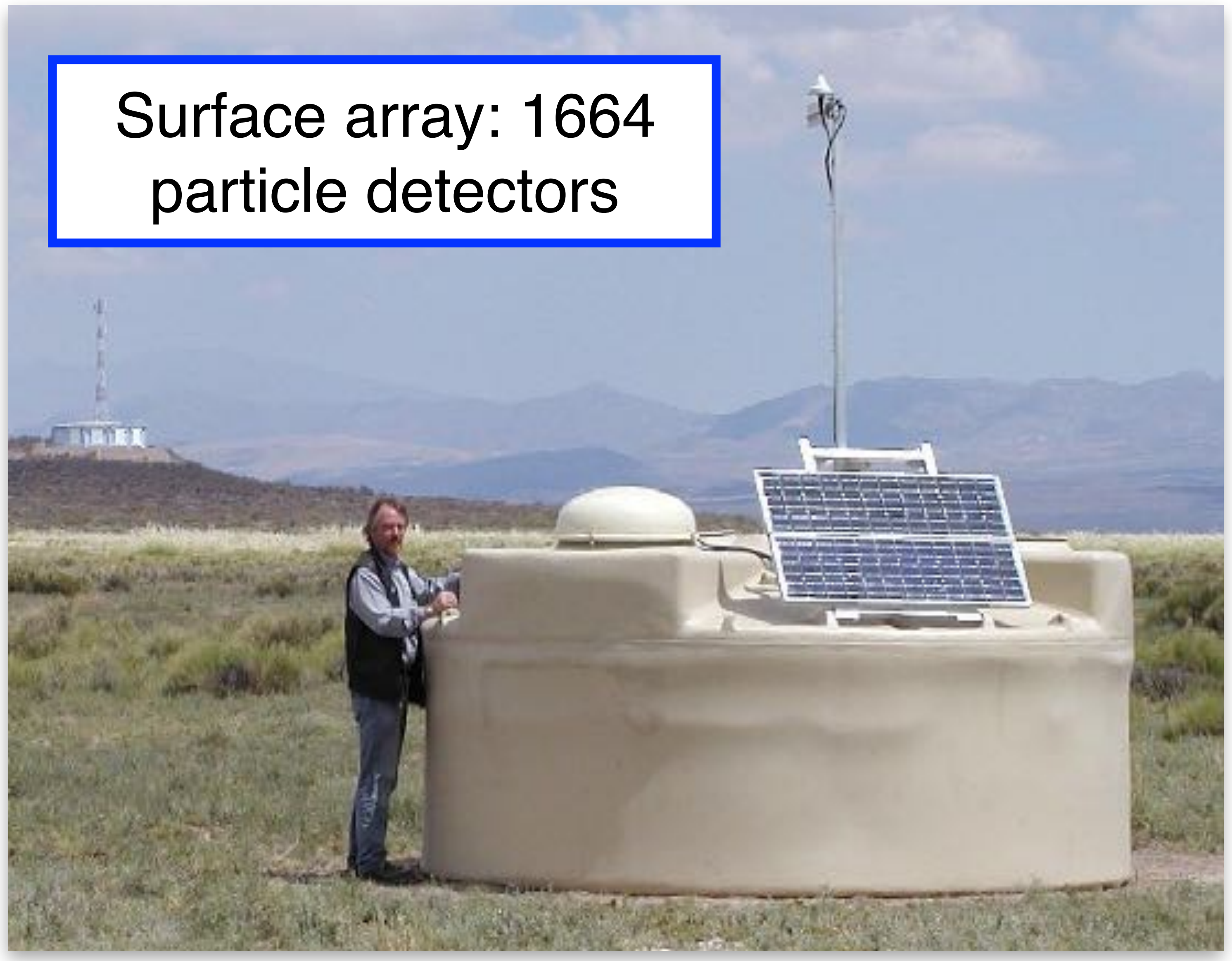


Infill array of 750 m,
Radio antenna array

High elevation telescopes

4 fluorescence detectors
(24+3 telescopes in total)

Southern hemisphere:
Province Mendoza, Argentina



Surface array: 1664 particle detectors

Fluorescence telescopes

Particle detectors
10 m² area, 1.20 m high
12 tons of water

PMT camera with
440 pixels, 1.5° FoV
per pixel, 10 MHz

UV transmitting
filter, corrector
lens, safety curtain

3.4 m segmented mirror
(aluminum alloy, glass)

Telescope Array (TA)

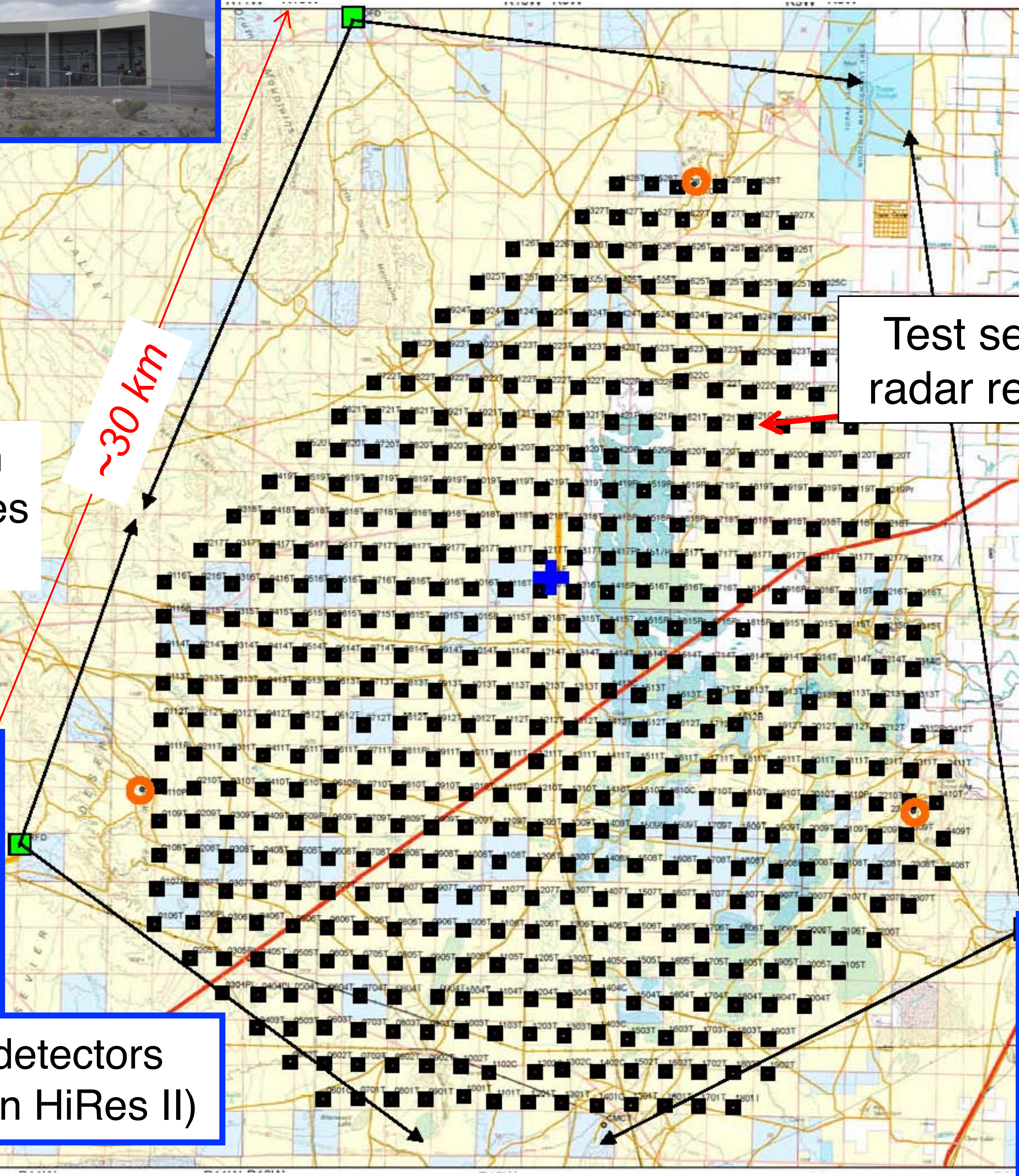
Talk by Abu-Zayyad

Middle Drum: based on HiRes II

TALE (TA low energy extension)

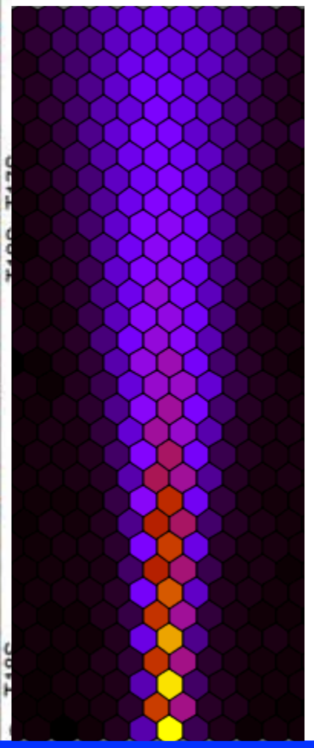
LIDAR
Laser facility

Infill array and high
elevation telescopes

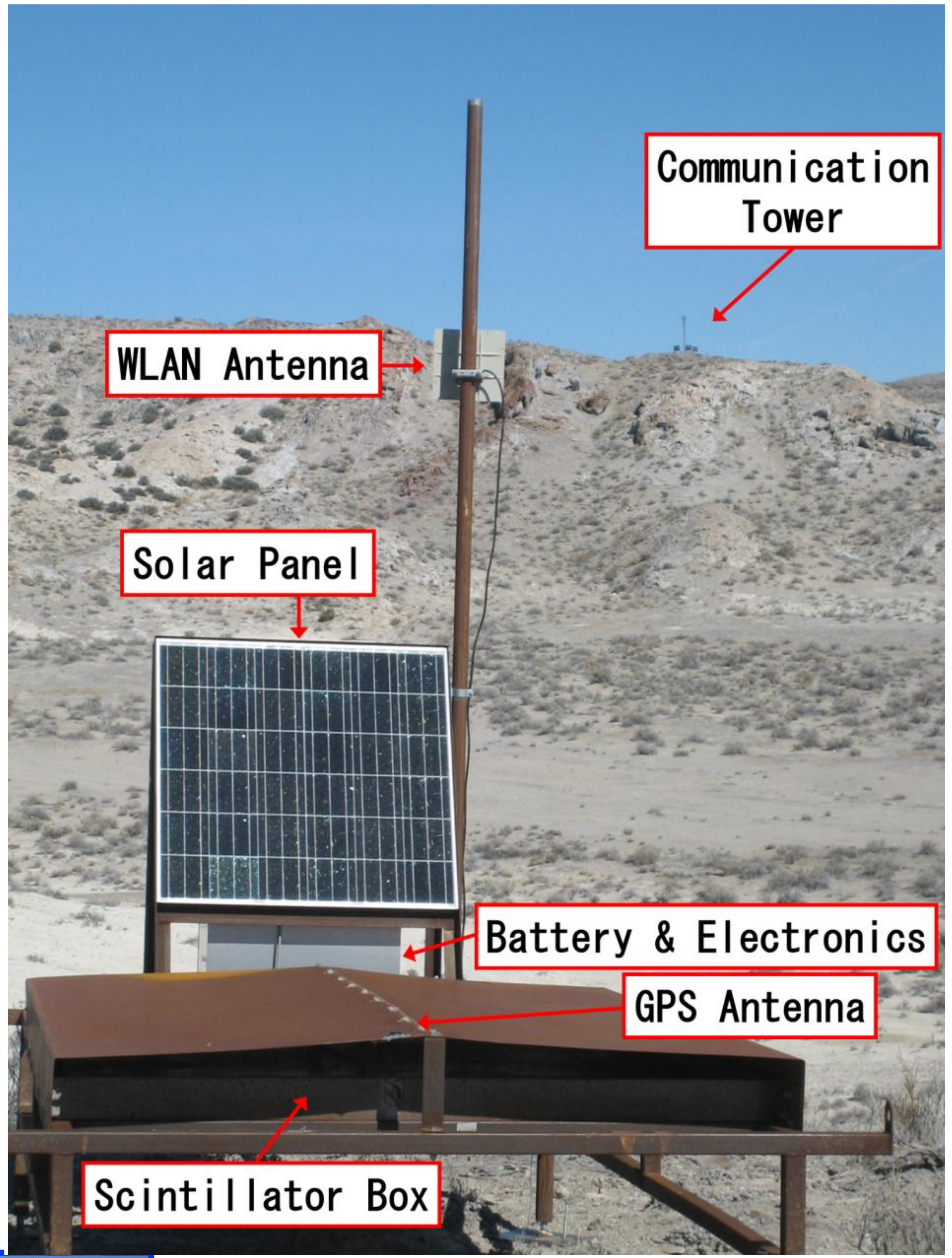


Test setup for
radar reflection

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



Electron light
source (ELS):
~40 MeV



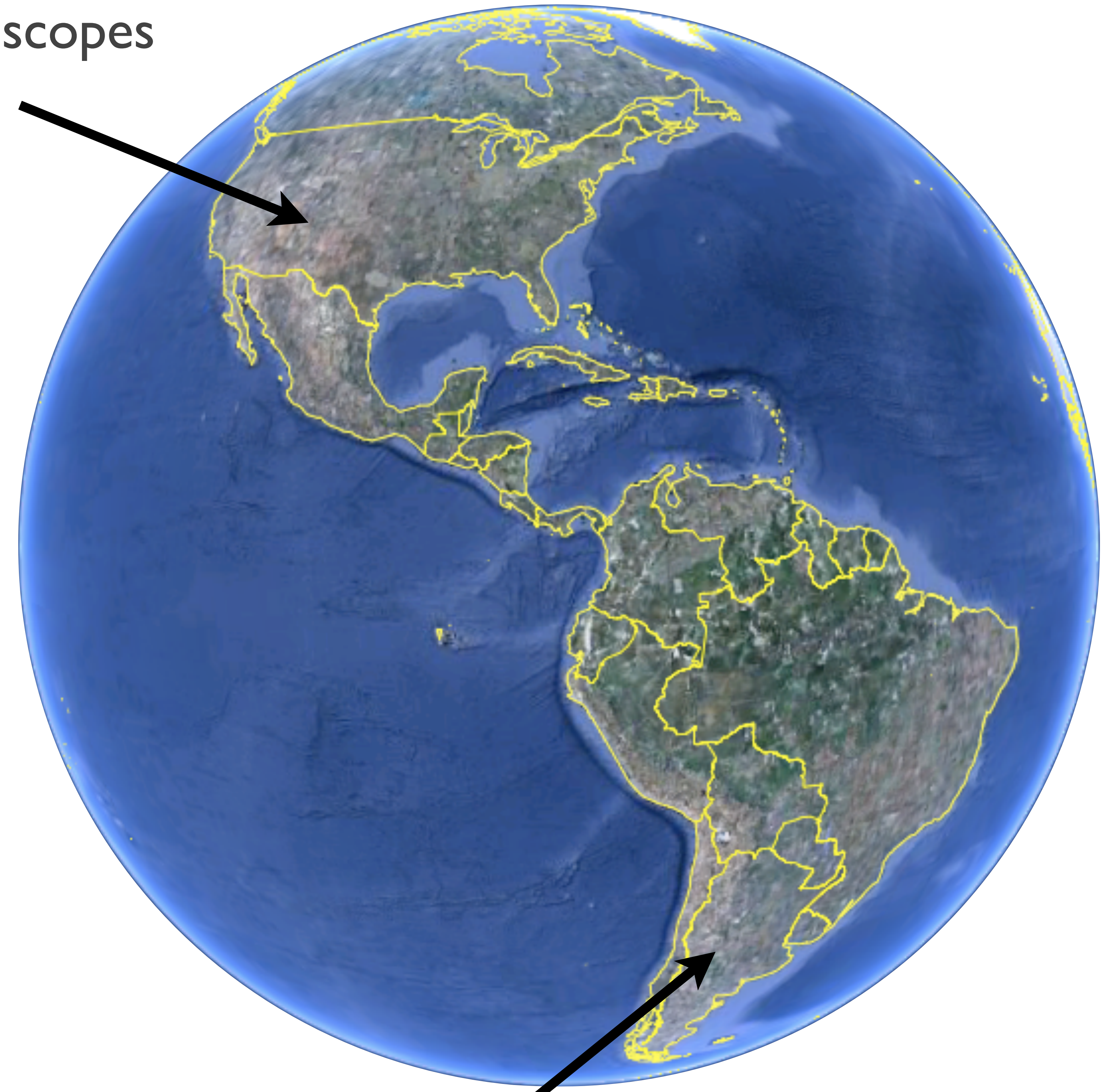
507 surface detectors:
double-layer scintillators
(grid of 1.2 km, 680 km^2)

Northern hemisphere: Utah, USA

Pierre Auger Observatory and Telescope Array

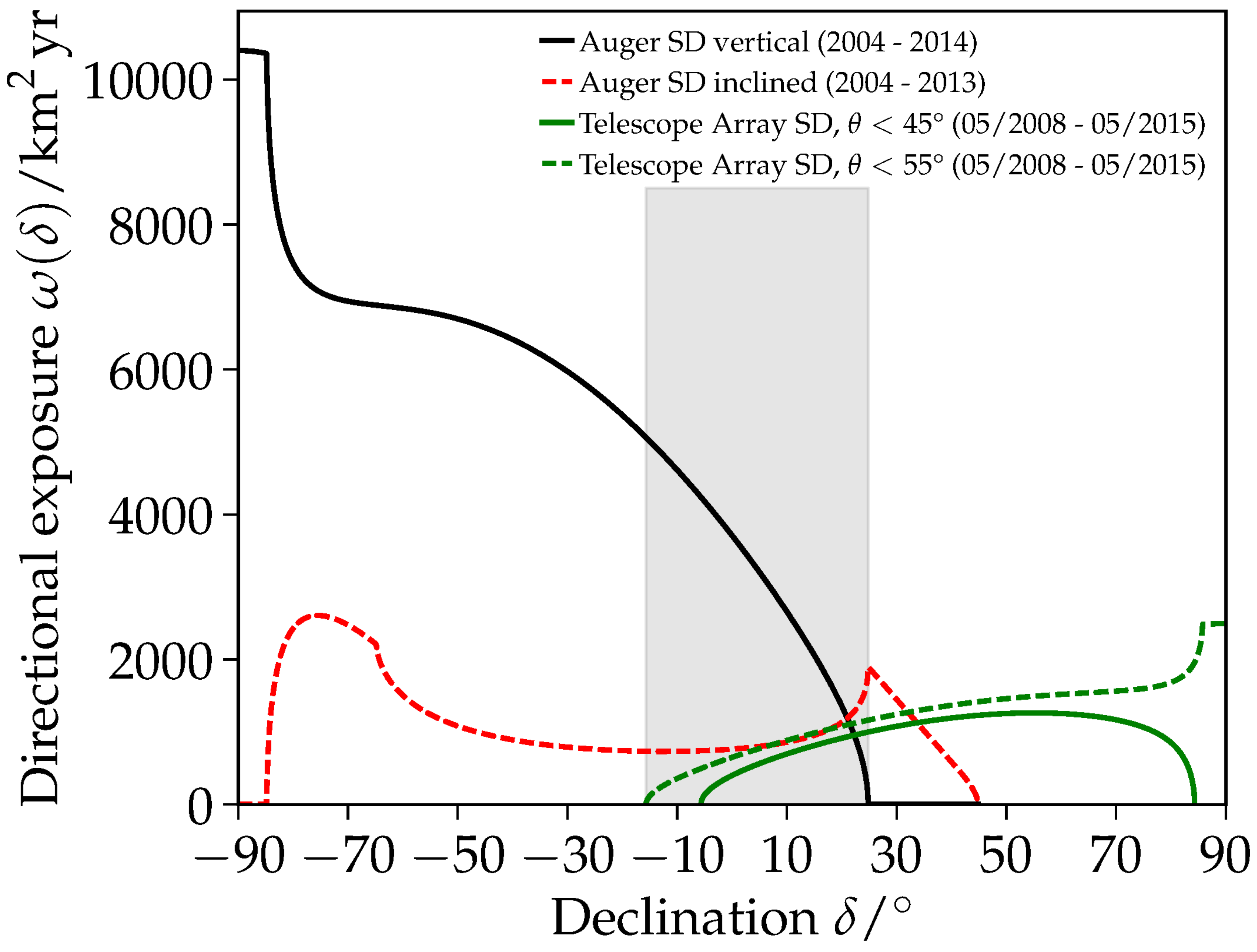
Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km^2
36 fluorescence telescopes

HiRes I (mono) ~ 5 x 10^3 km^2 sr yr @ 10^{20} eV
AGASA: 1.6 x 10^3 km^2 sr yr



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

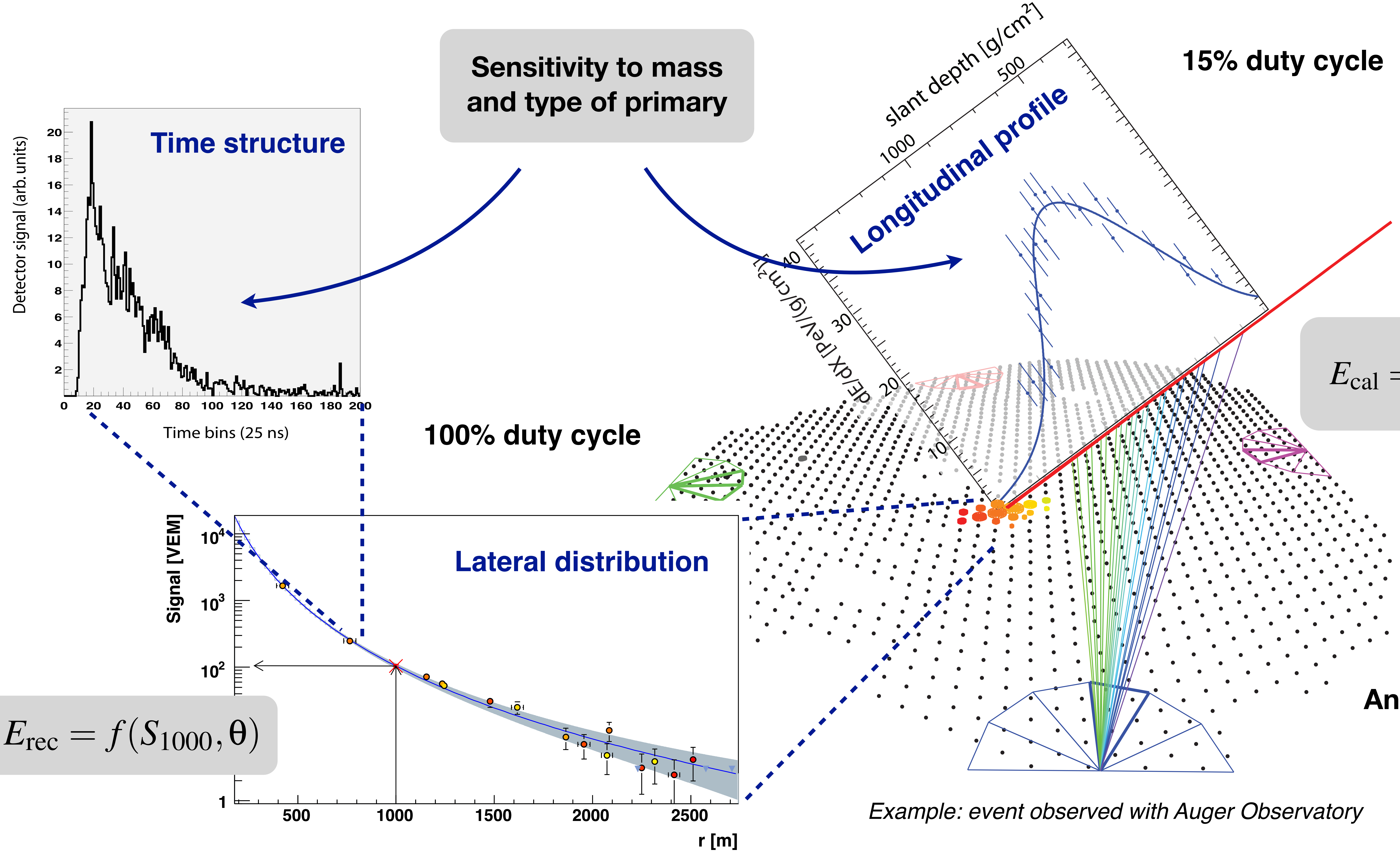
Together full sky coverage



Auger:
6.7 x 10^4 km^2 sr yr (spectrum)
9 x 10^4 km^2 sr yr (anisotropy)

TA:
8.1 x 10^3 km^2 sr yr (spectrum)
8.6 x 10^3 km^2 sr yr (anisotropy)

UHECRs: How to detect them



Sensitivity to mass and type of primary

100% duty cycle

15% duty cycle

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

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

Angular resolution
~ 1.5° – 0.5°

Example: event observed with Auger Observatory

HL 1: The flux is strongly suppressed for E > $10^{19.6}$ eV

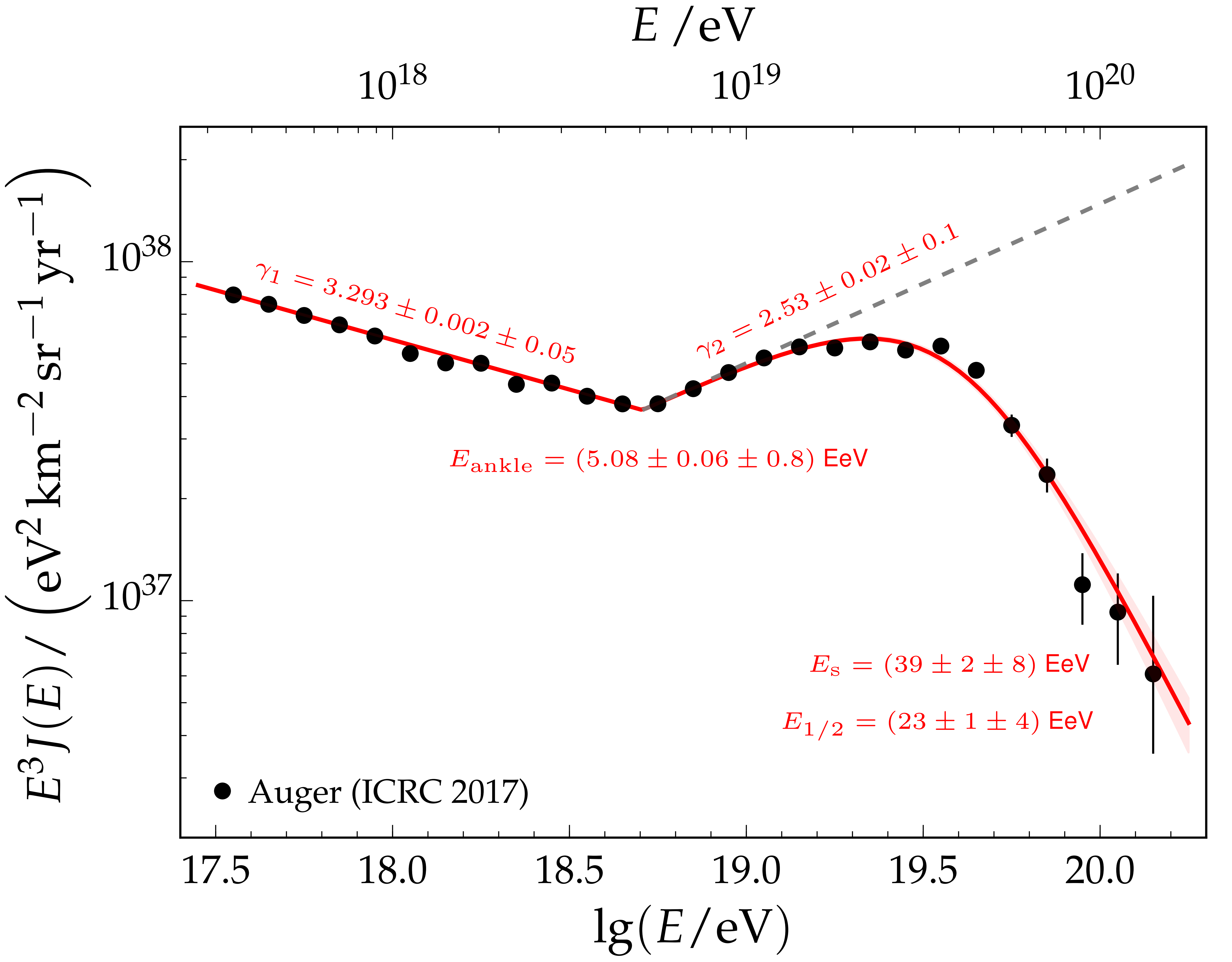
Events per year
(based on AGASA spectrum)

	SD only	SD + ≥1 FD
> 6 x 10^{17} eV	0	45000
> 10^{18} eV	0	30000
> 3 x 10^{18} eV	15000	4700
> 10^{19} eV	5150	515
> 2 x 10^{19} eV	1590	159
> 5 x 10^{19} eV	490	49
> 10^{20} eV	103	10
> 2 x 10^{20} eV	32	3
> 5 x 10^{20} eV	10	1

FD *2 tanks with 4 VEM and
10% duty cycle
SD *5 tanks with each 4 VEM

zenith angle >60°: + 50%

(RE, Nijmegen Summer School, 2004)



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

Expected 1100, have now 14 events

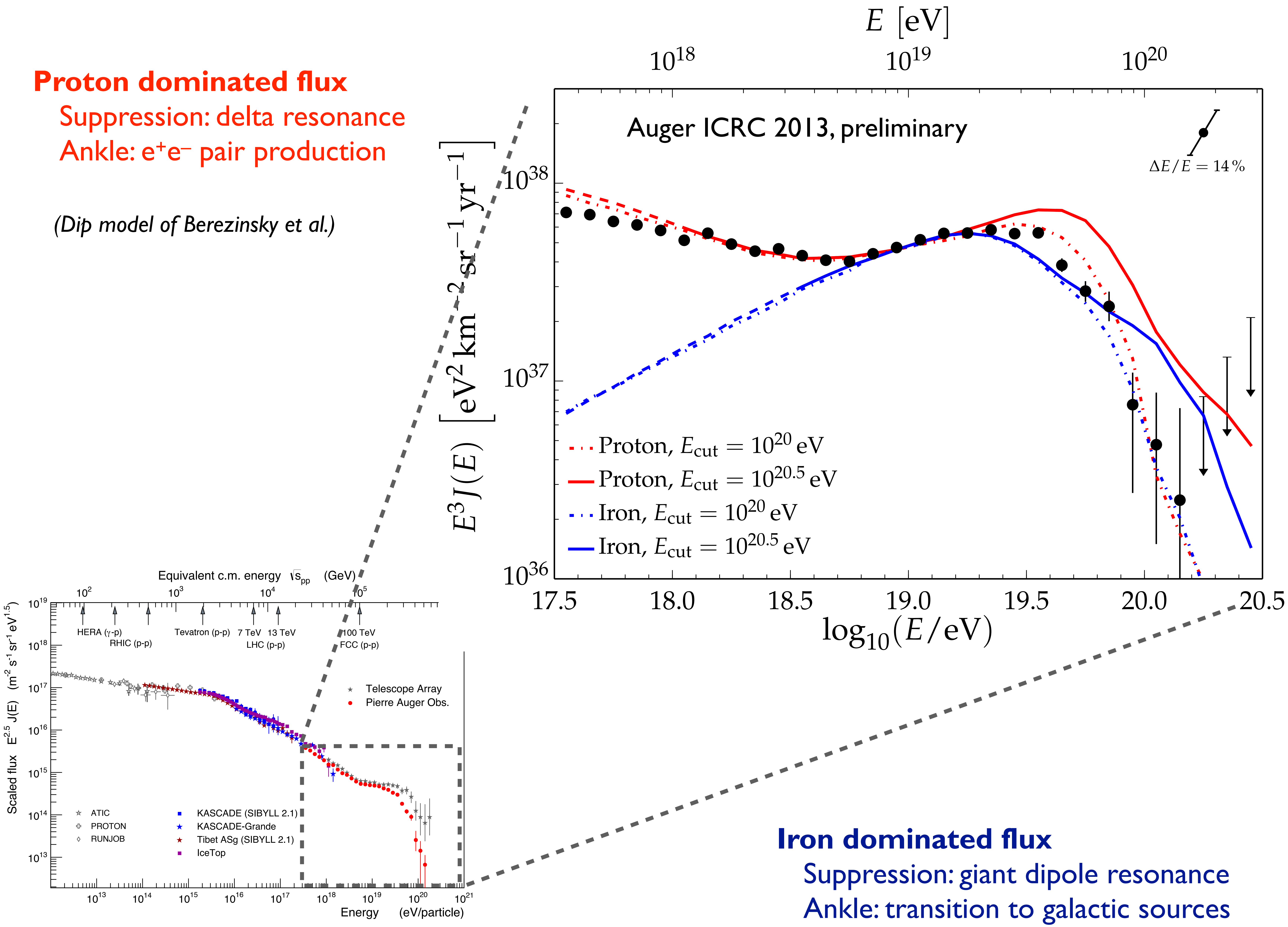
Energy spectrum: comparison with theory predictions

Proton dominated flux

Suppression: delta resonance

Ankle: e⁺e⁻ pair production

(Dip model of Berezinsky et al.)



Iron dominated flux

Suppression: giant dipole resonance

Ankle: transition to galactic sources

Greisen-Zatsepin-Kuzmin (GZK) effect

Photo-pion production
(mainly Δ resonance)

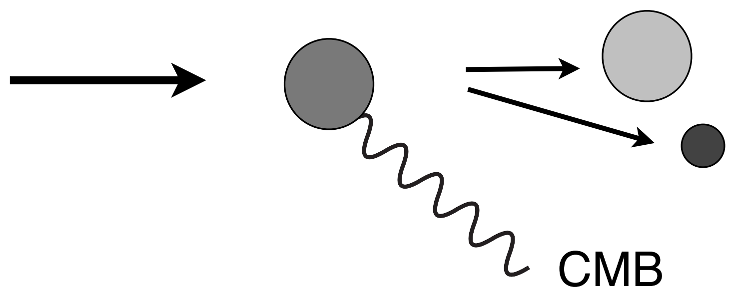
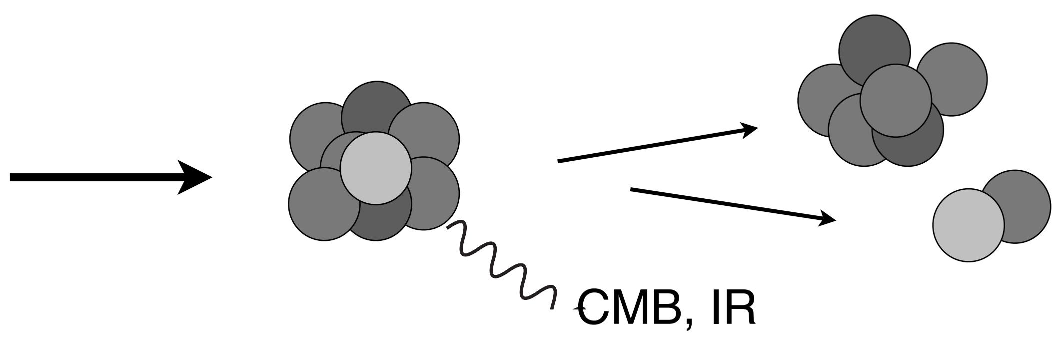
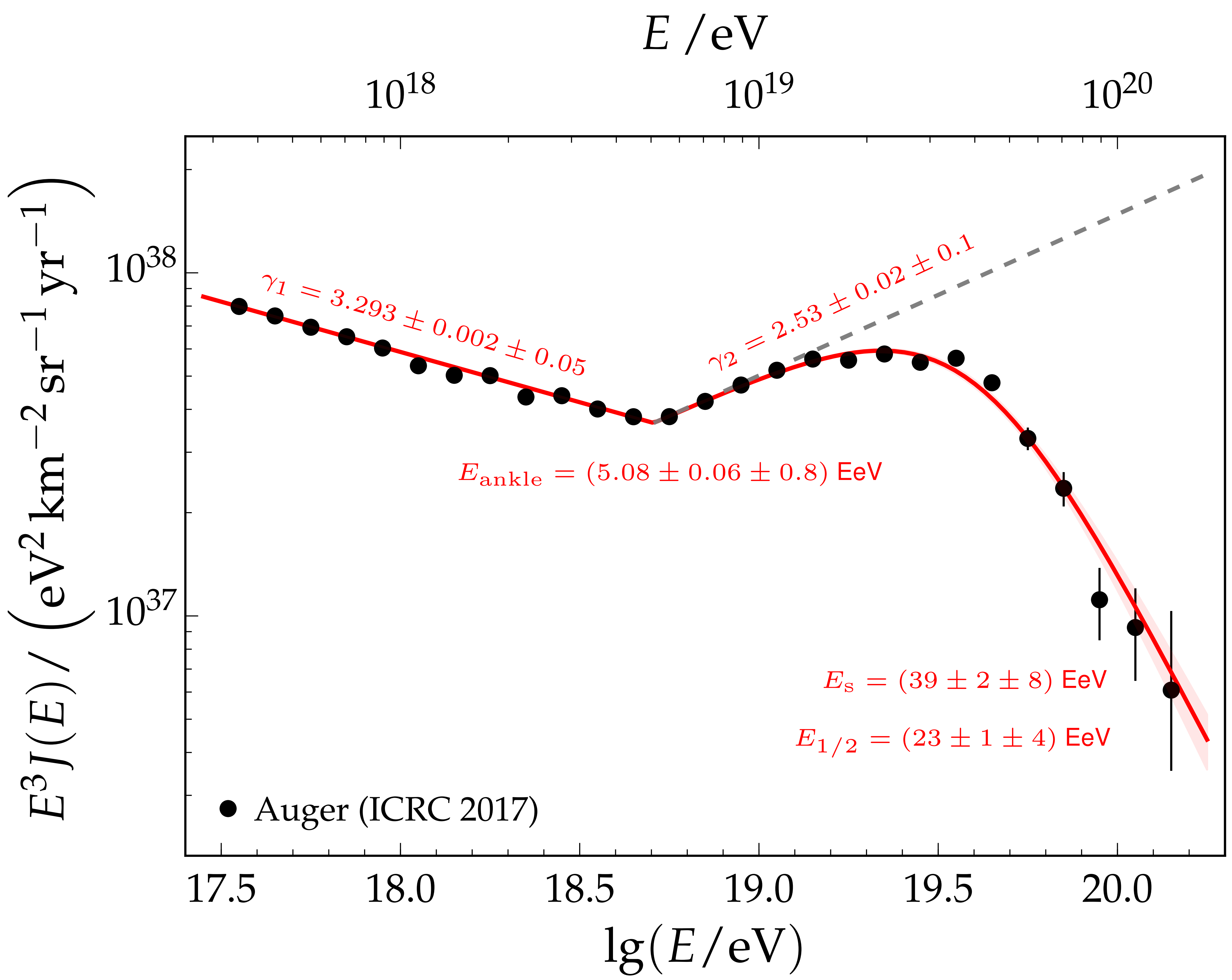


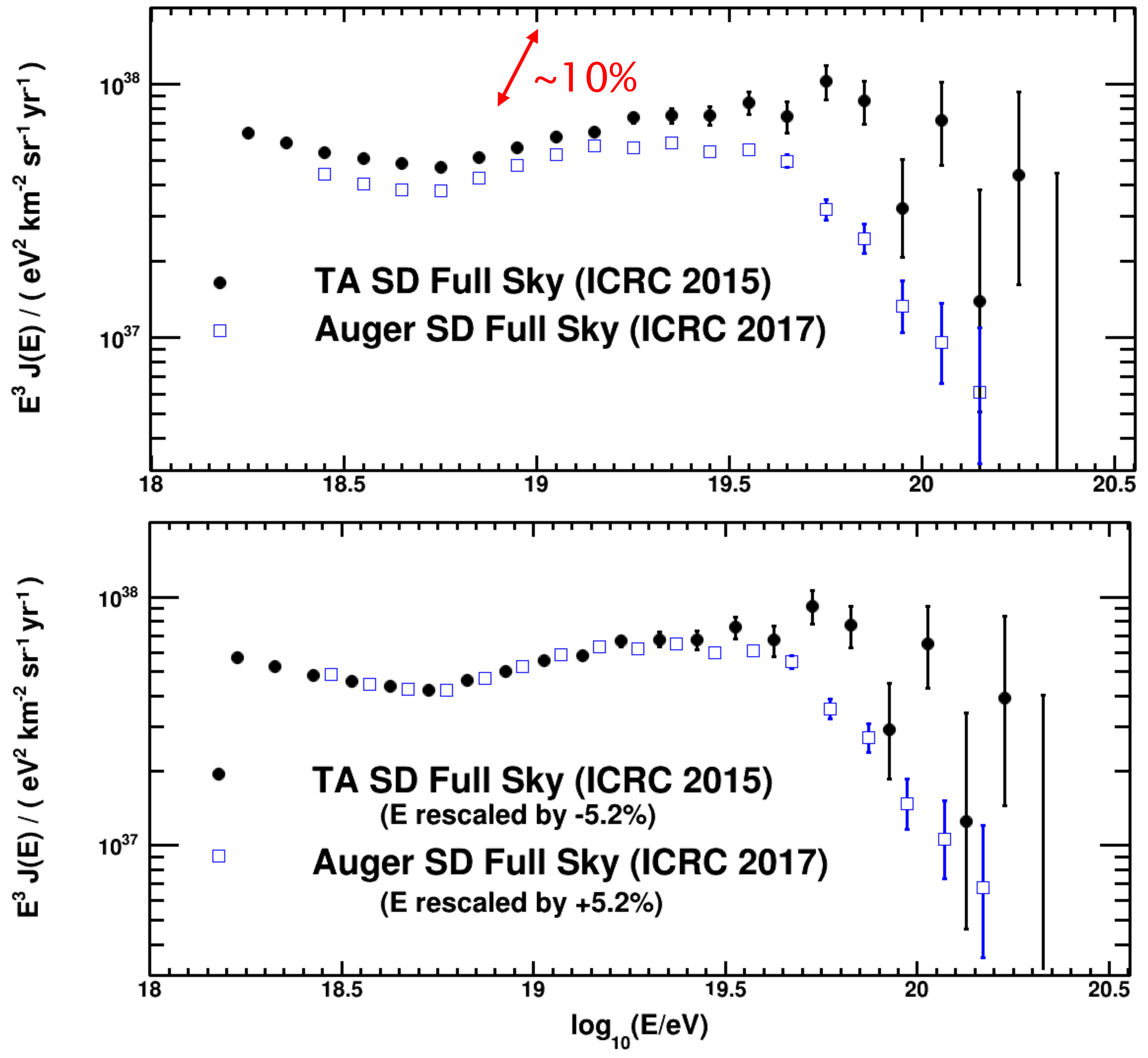
Photo-dissociation
(giant dipole resonance)



Directional dependence of flux (energy spectrum) ?



(Auger-TA Spectrum Working Group)



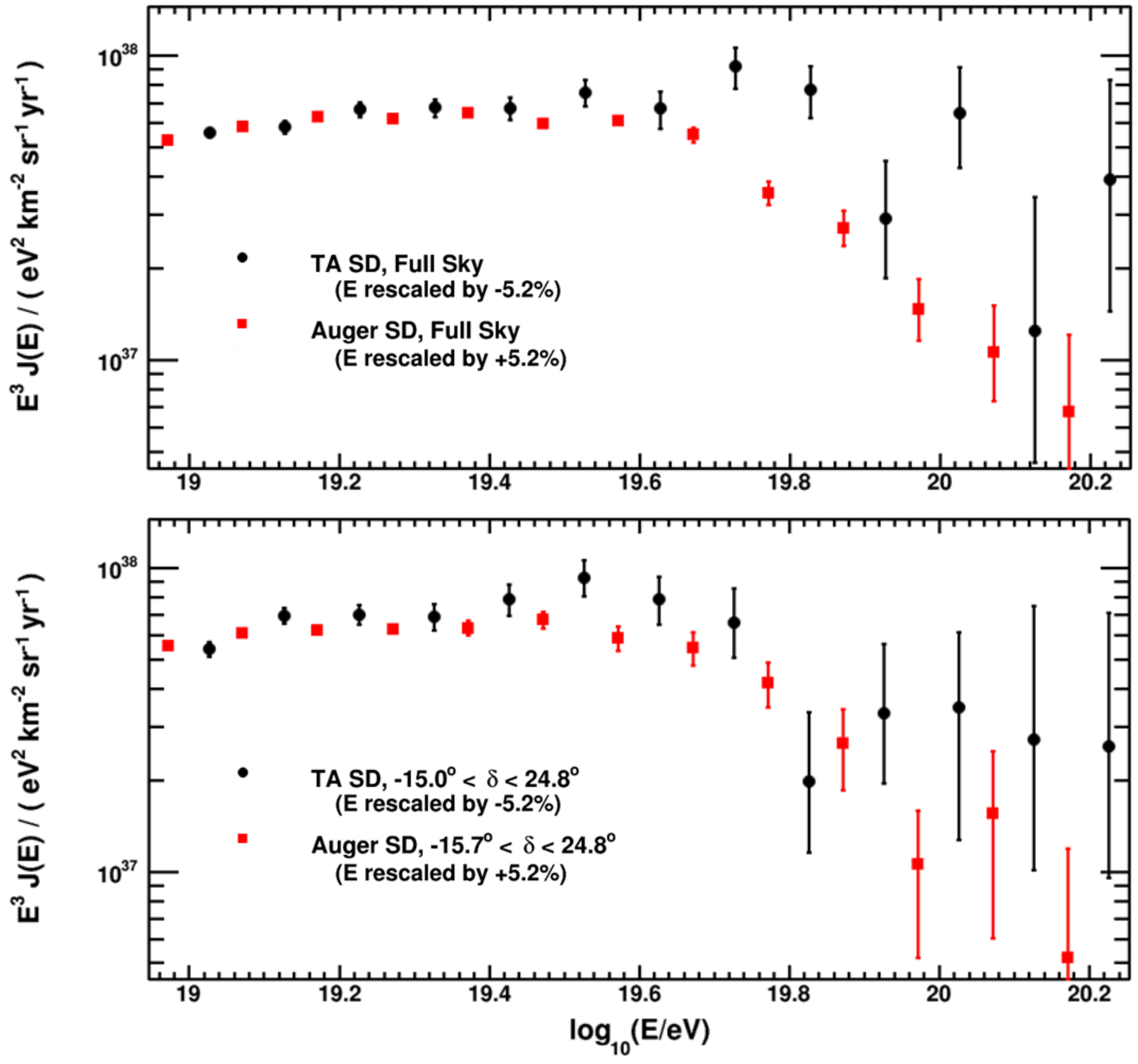
Sys. uncertainty
of energy scale

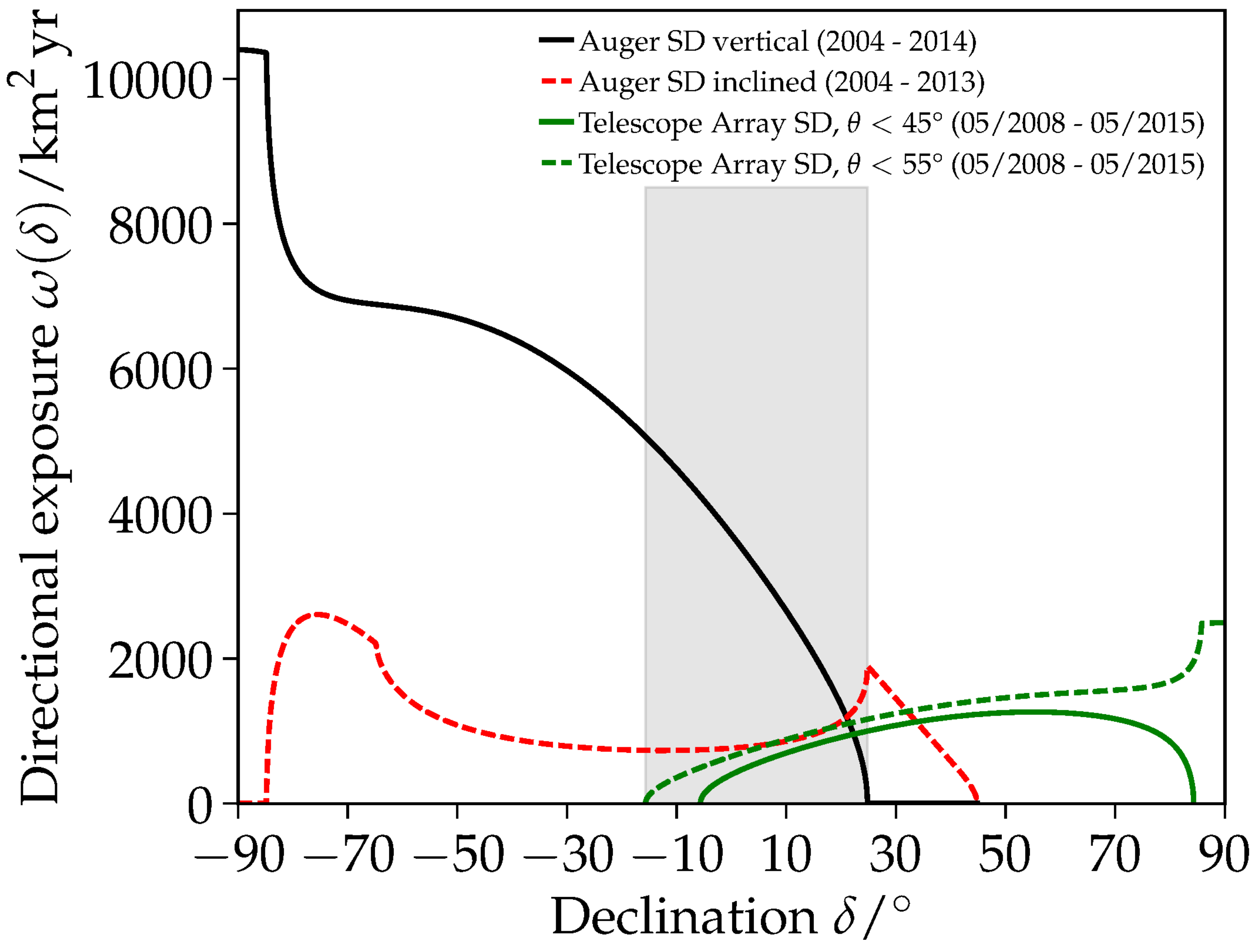
Auger	$\Delta E/E = 14\%$
TA	$\Delta E/E = 21\%$

Are the energy spectra consistent with each other?

All sky

Common declination band

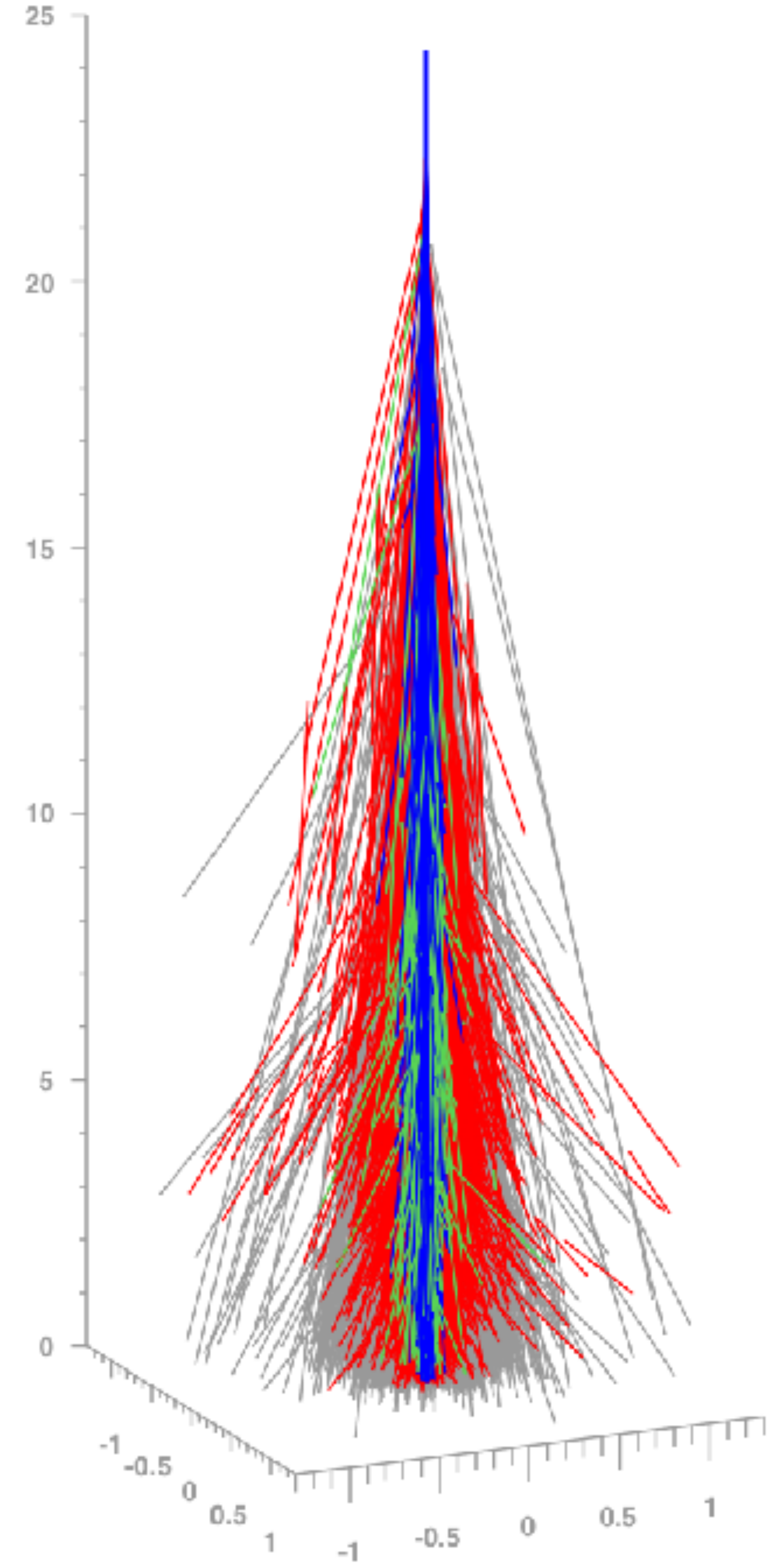


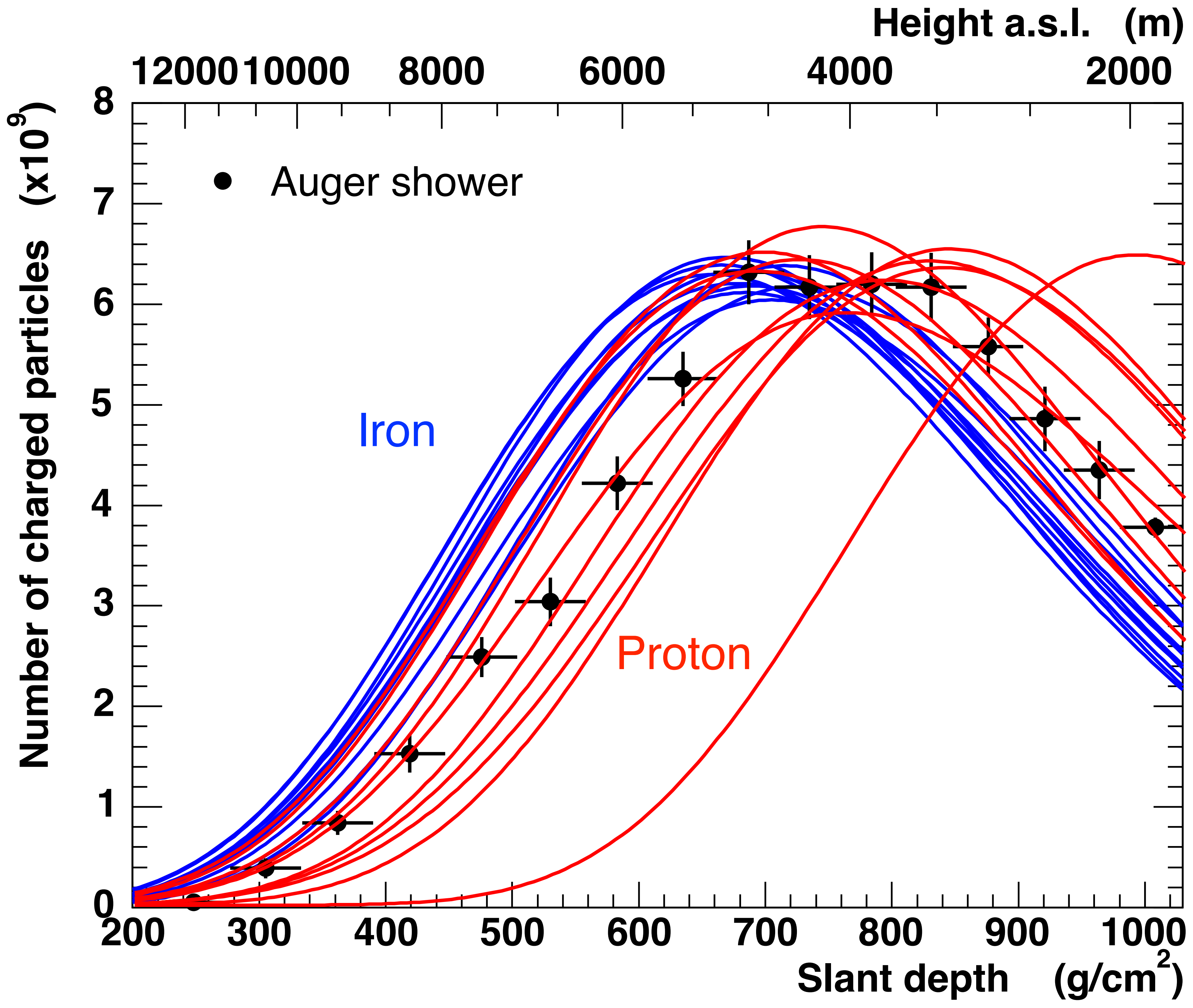


(Auger-TA Spectrum Working Group, TA, arXiv:1801.07820)

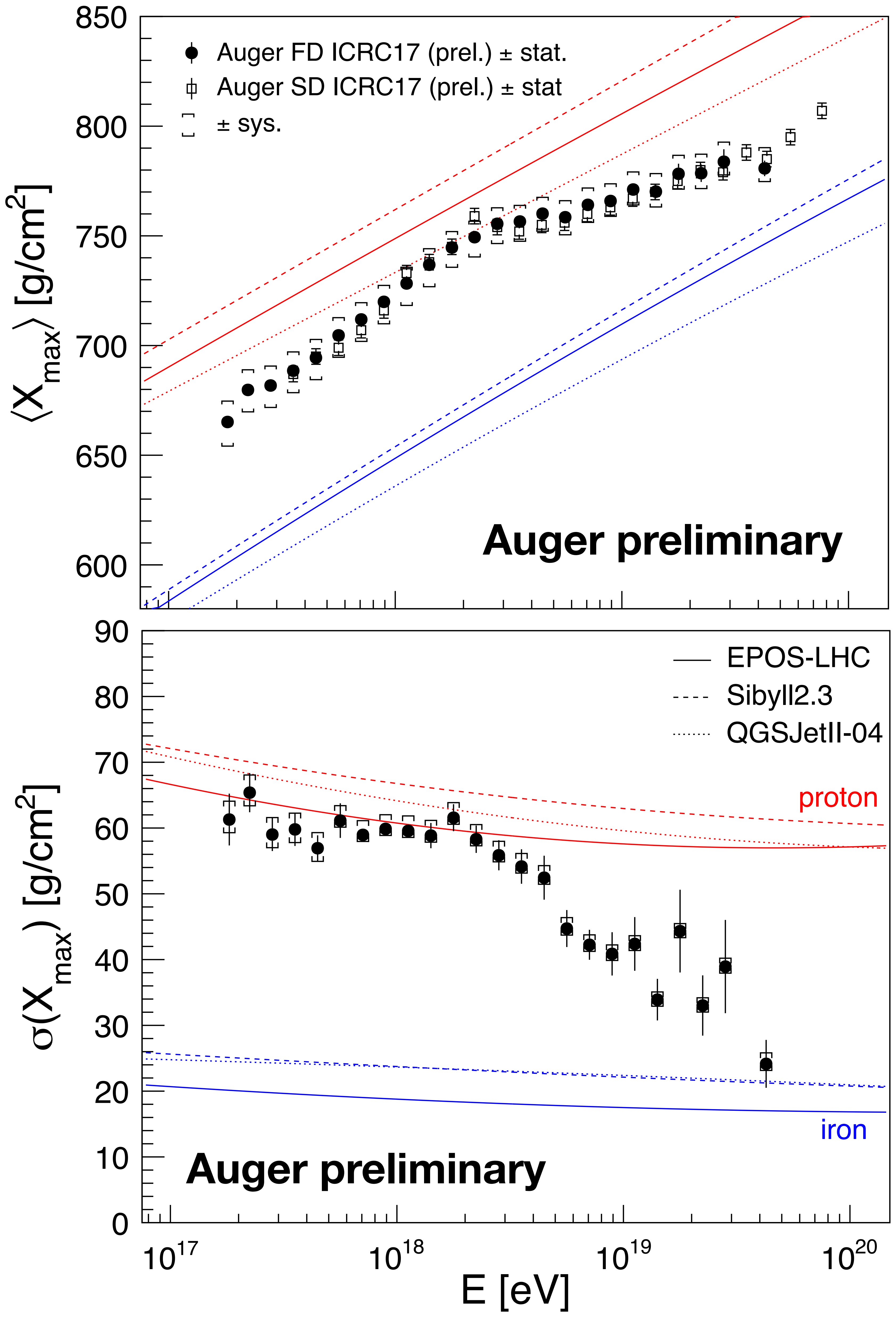
Better agreement if only common declination band considered – anisotropy ?

Composition from longitudinal shower profile





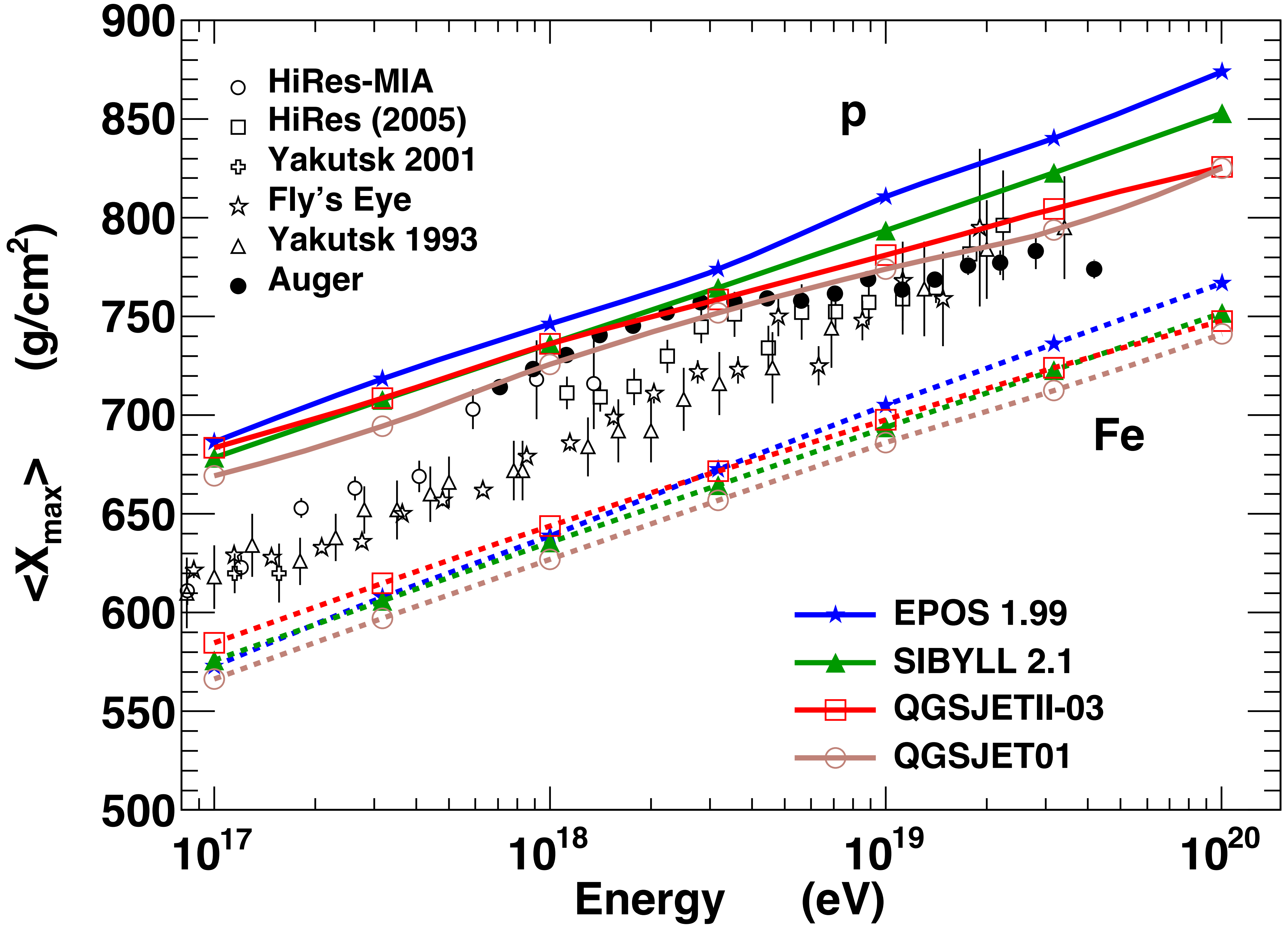
Example: event measured by Auger Collab.



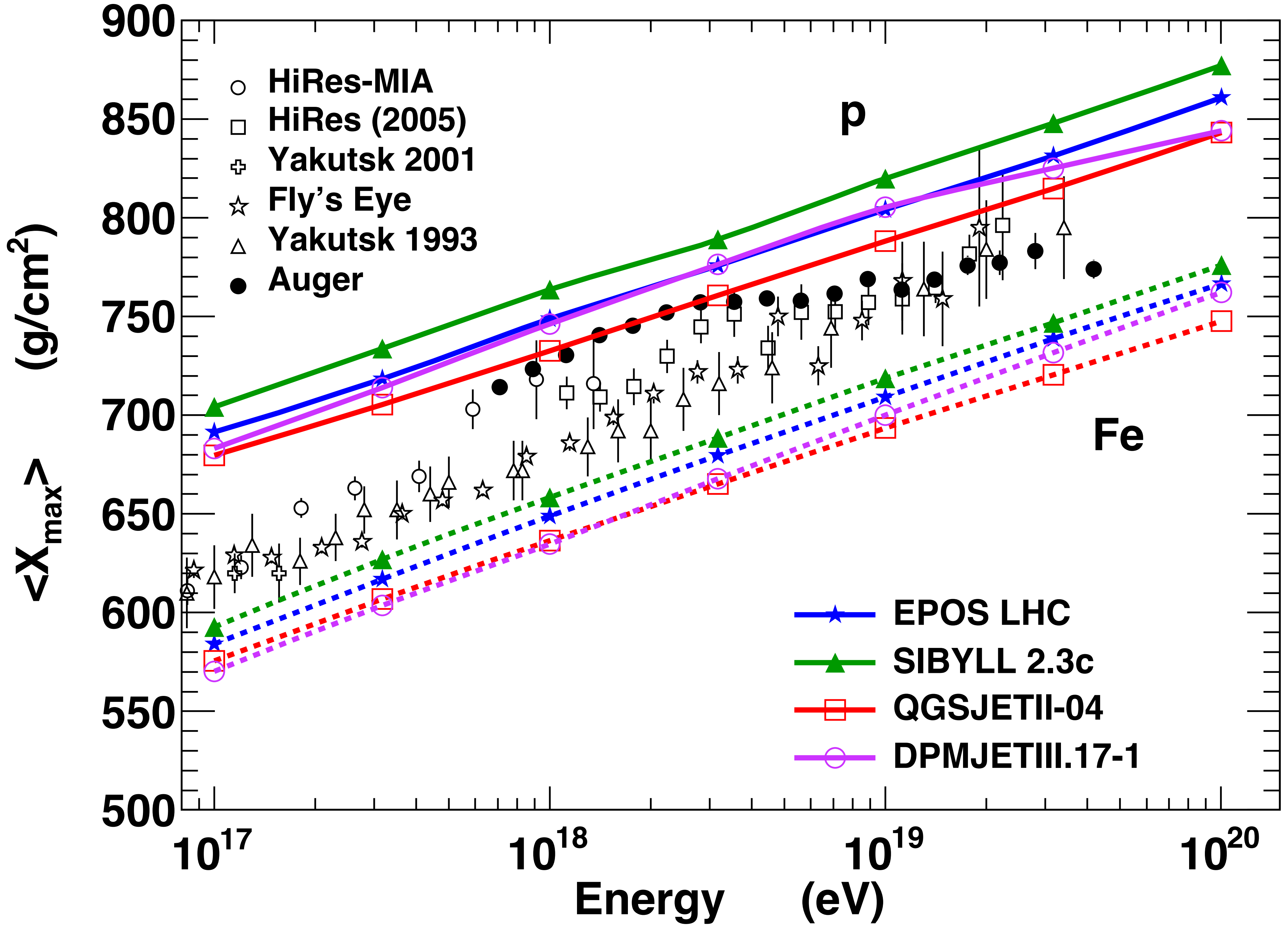
(Auger ICRC2017)

Change of model predictions thanks to LHC data

pre-LHC models



post-LHC models



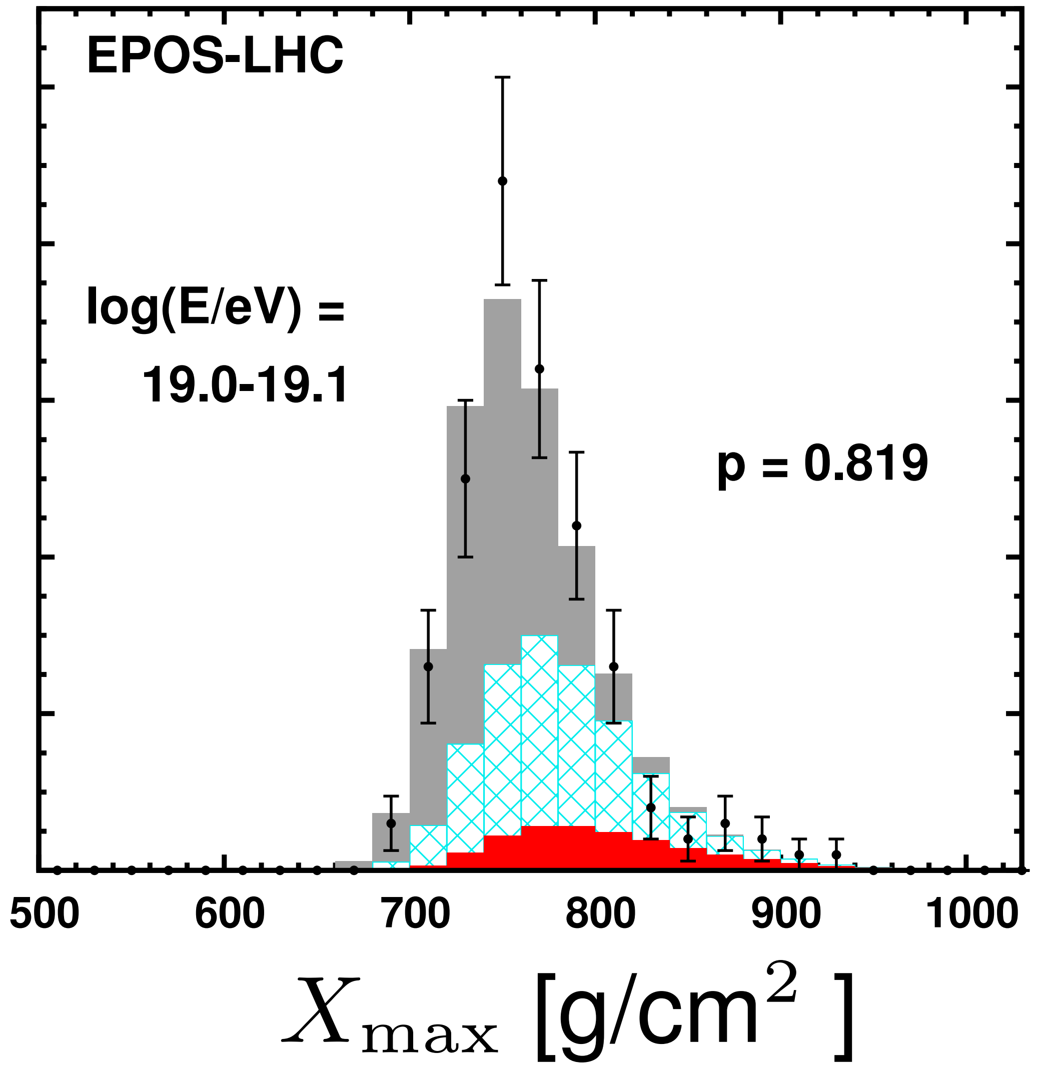
(Pierog, ICRC 2017)

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

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

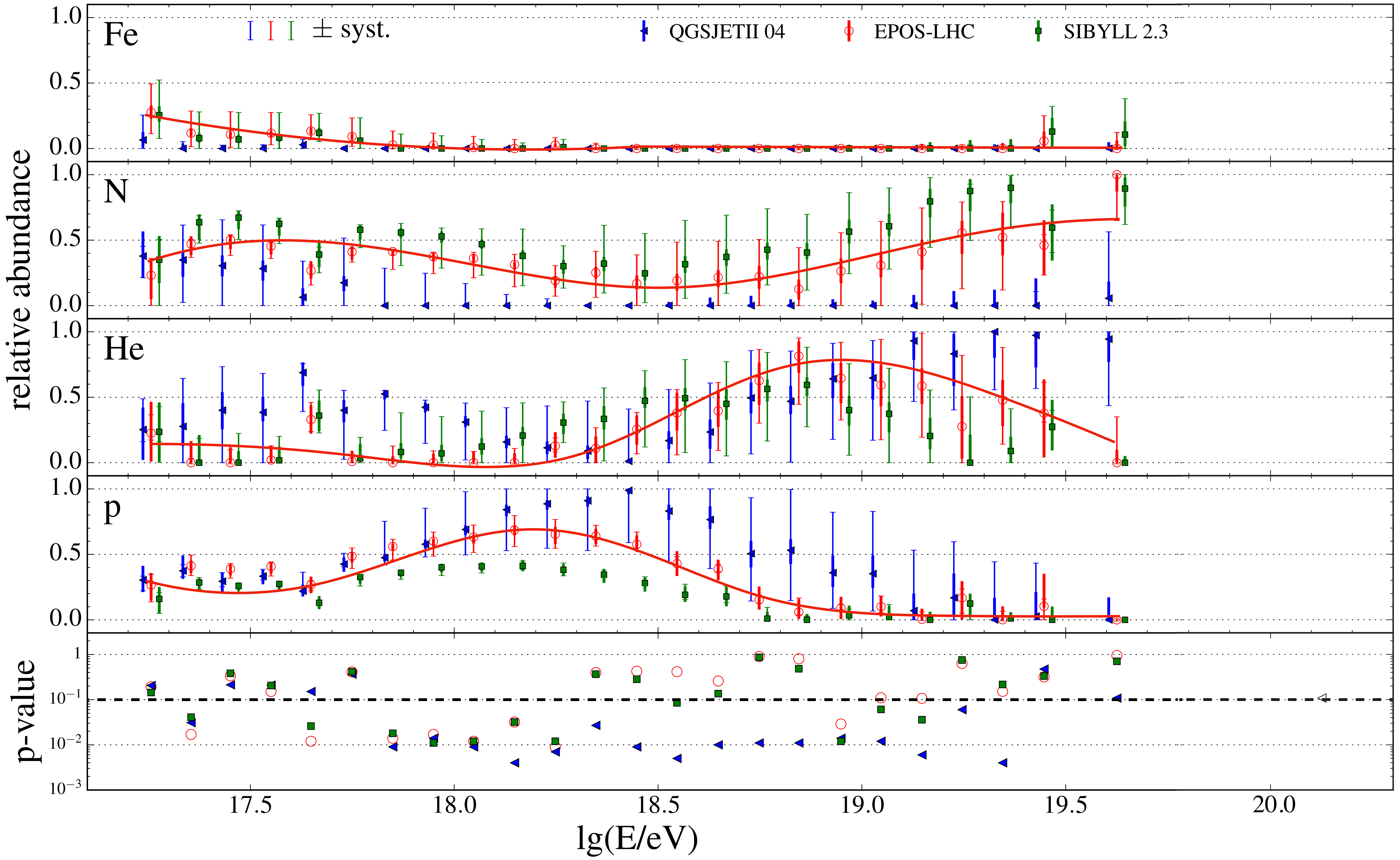
LHC-tuned models should be used for data interpretation

HL 2: Unexpected change of mass composition



p He N Fe

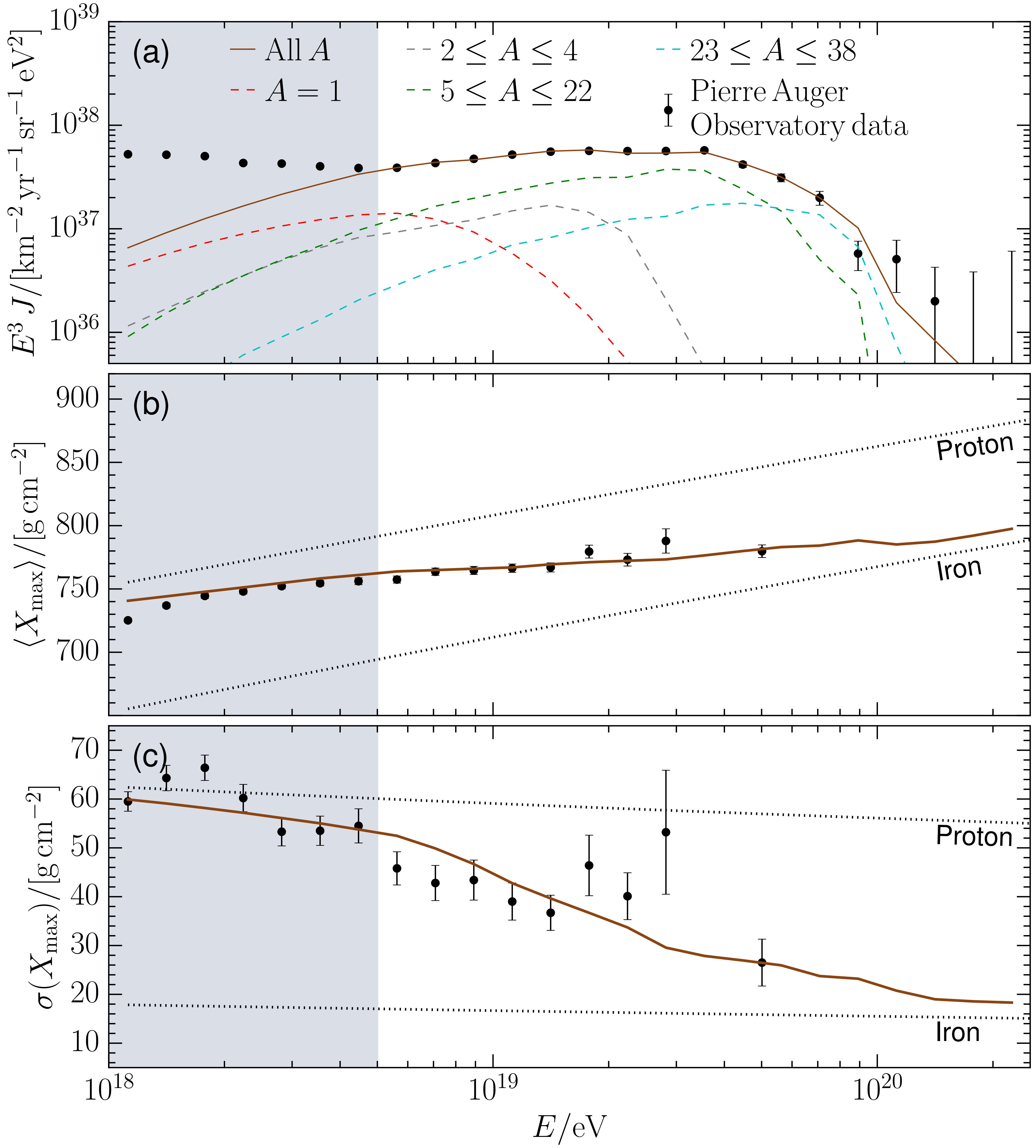
Composition based on fluorescence telescope data (15% duty cycle)



- 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

(Bellido ICRC 2017)

Mass composition at sources (model dependent)



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
$\log_{10}(R_{\mathrm{cut}}/\mathrm{eV})$	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 %

Suppression of flux dominated by maximum injection energy

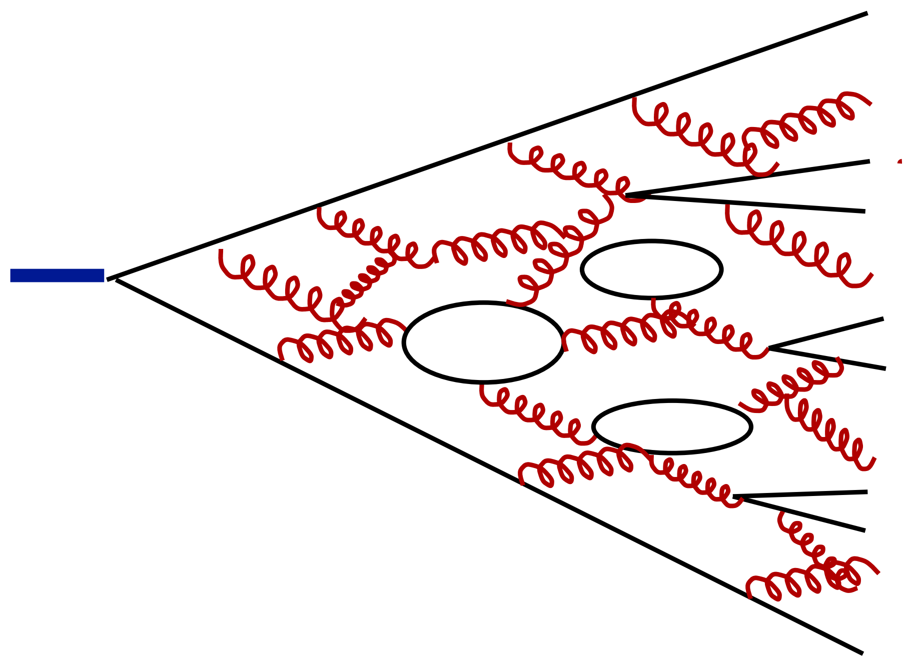
Very hard index of power law at injection

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

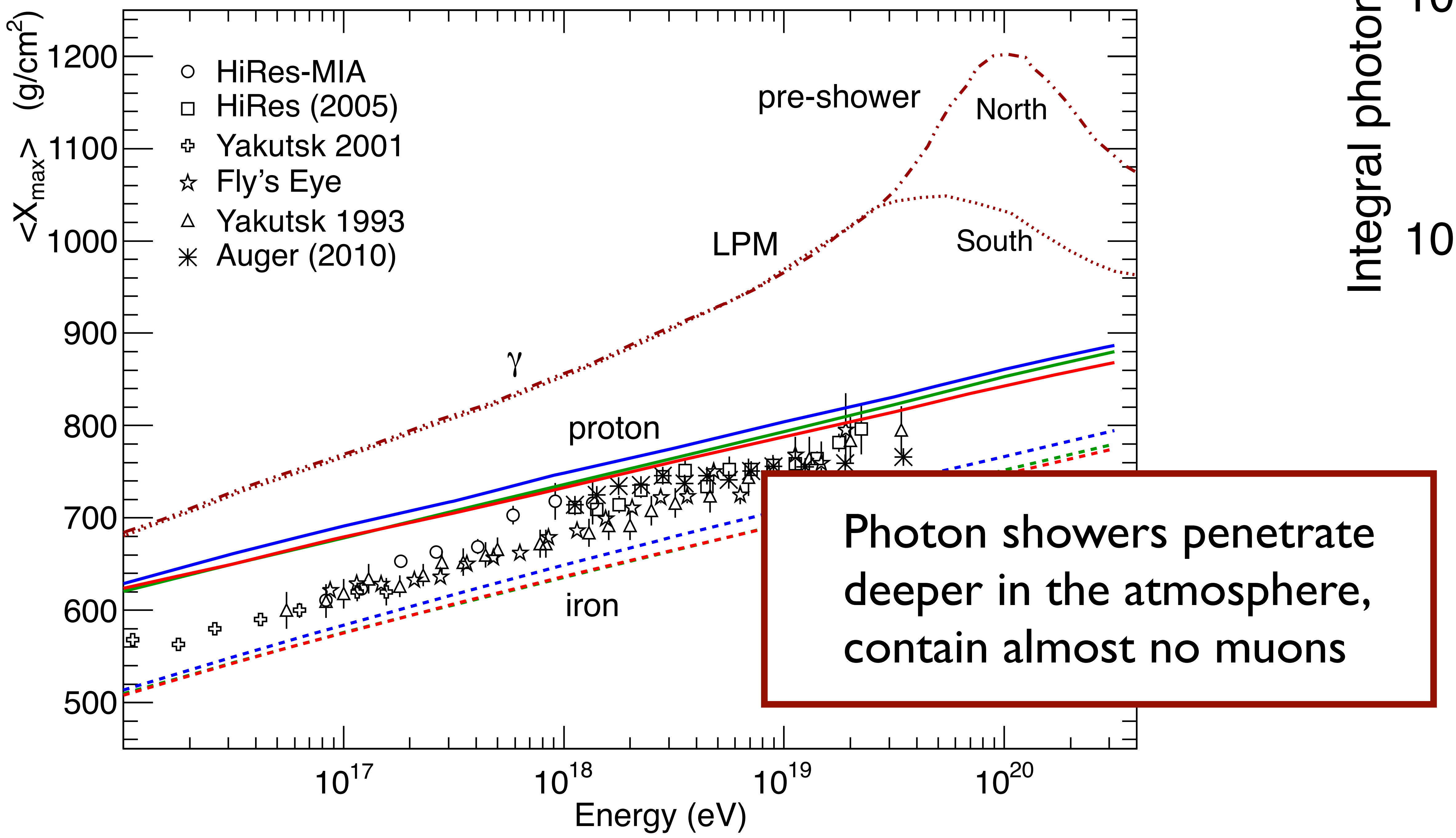
(Wittkowski ICRC 2017)

HL 3: The UHE photon and neutrino fluxes are very small

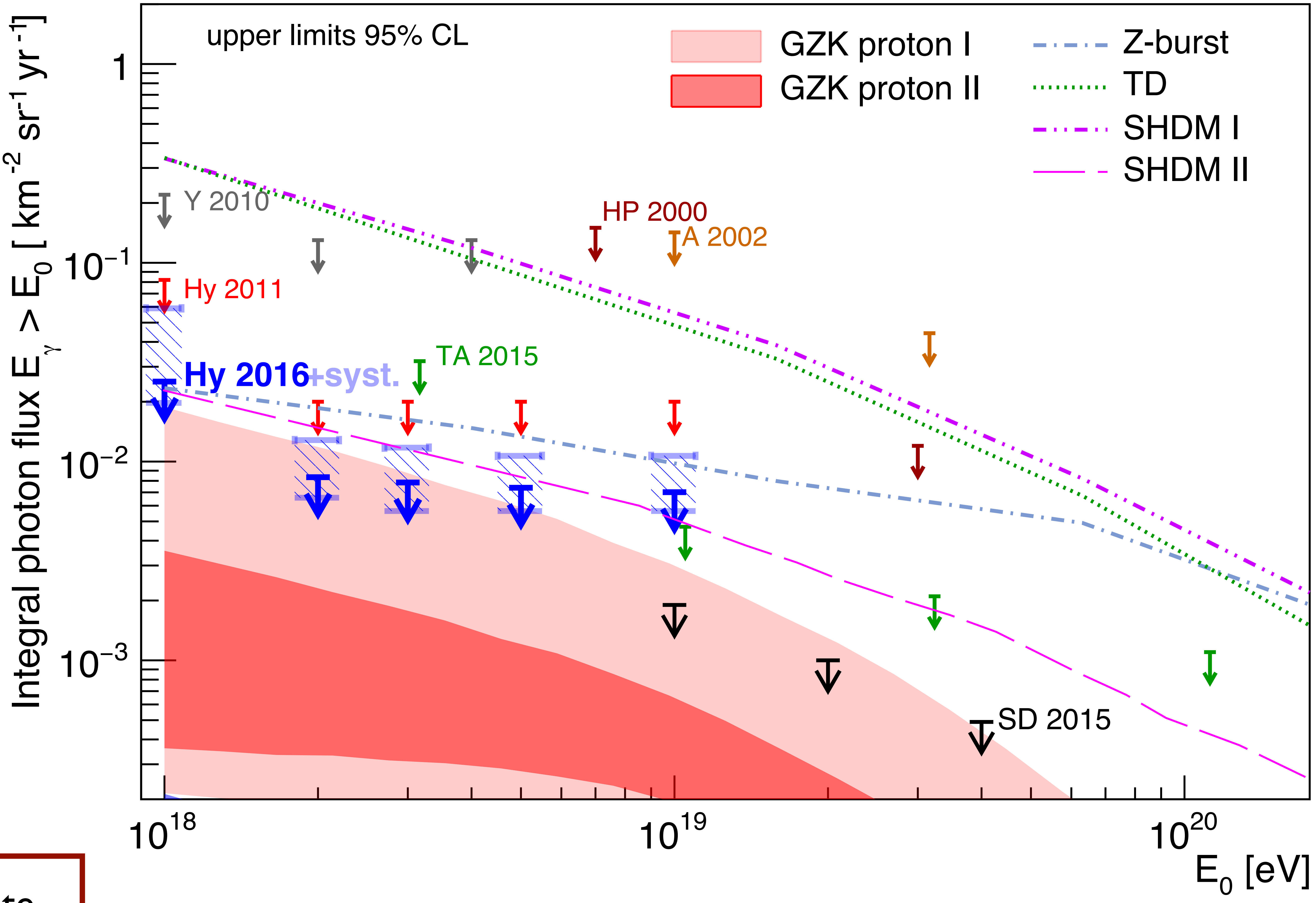
Super-heavy dark matter
Topological defects



large fluxes of photons and neutrinos



Photon showers penetrate deeper in the atmosphere, contain almost no muons

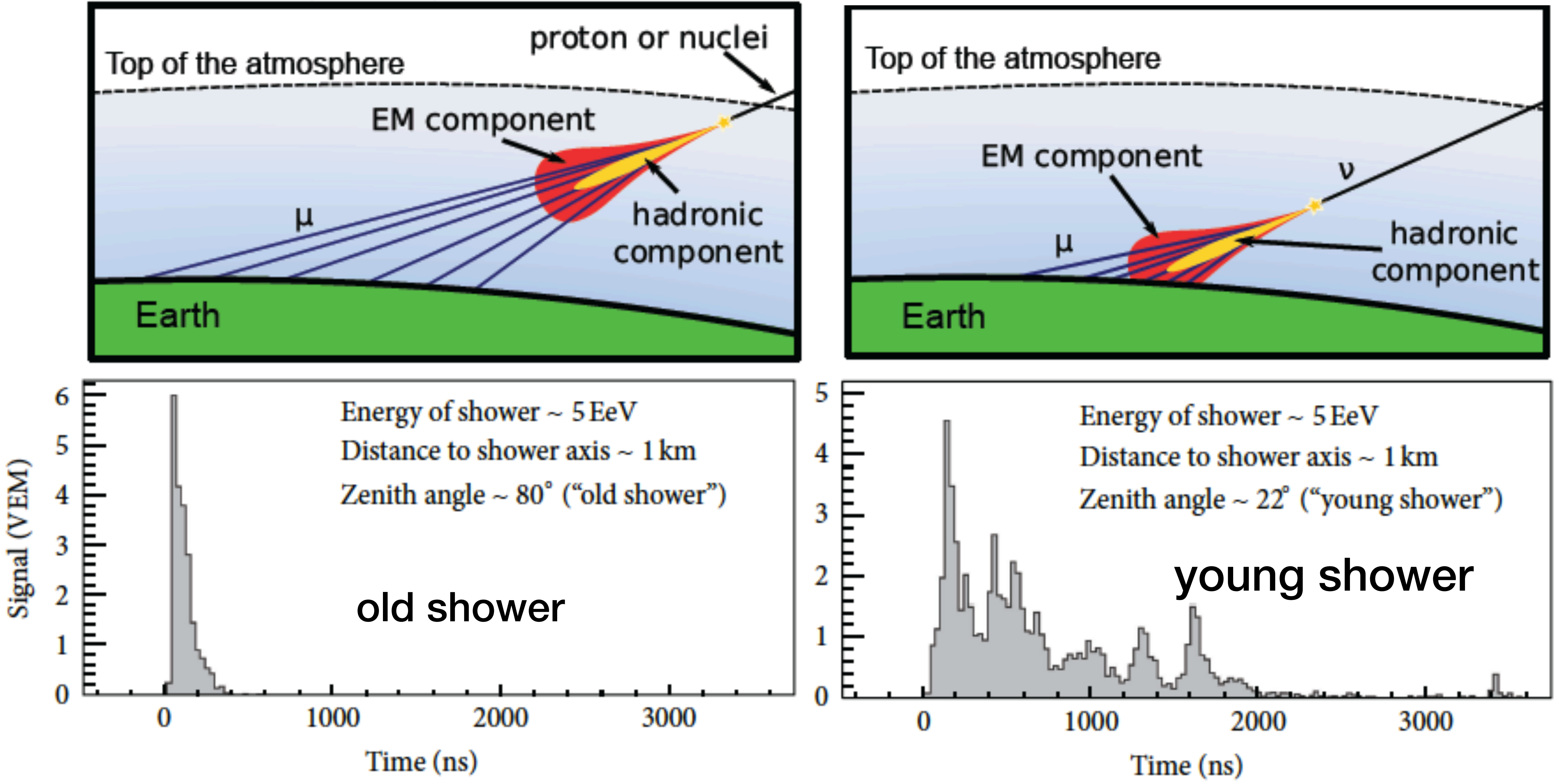


Exotic (to-down) source models strongly disfavored

(Niechciol, Auger ICRC 2017)

Neutrino detection with the Auger Observatory

- down-going



all ν flavor

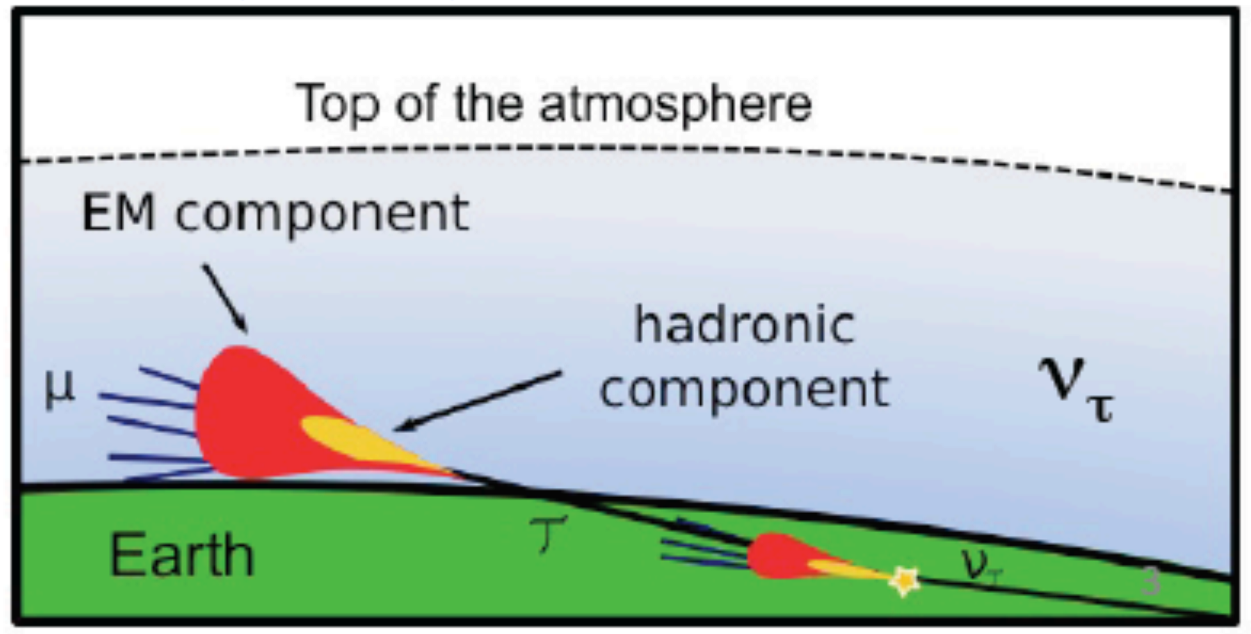
Low zenith (65º,75º)

contrib. to total evt rate: **23%**

High zenith (75º,90º):

contrib. to total evt rate: 4%

- up-going (Earth-Skimming)

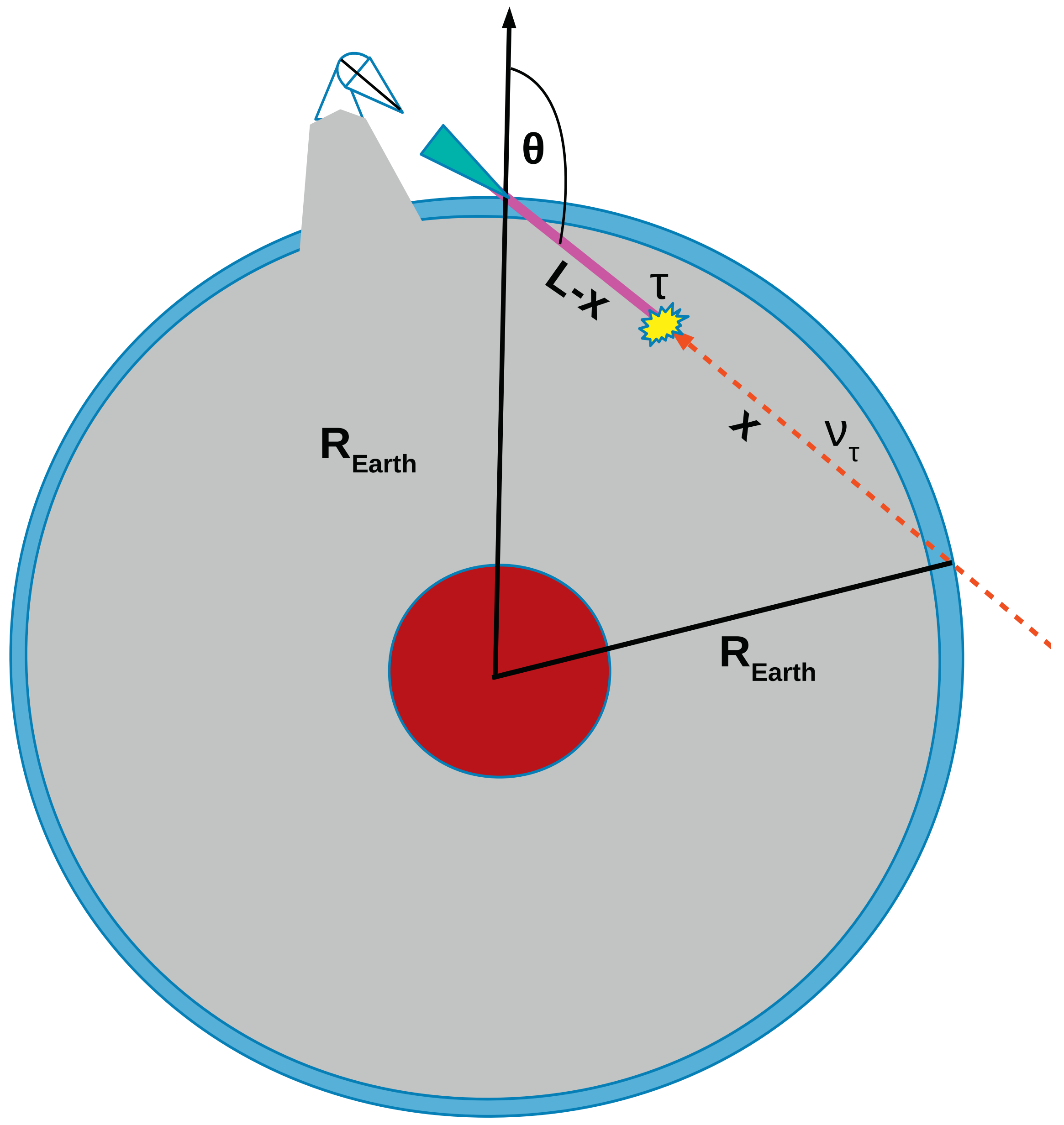


ν_τ flavor

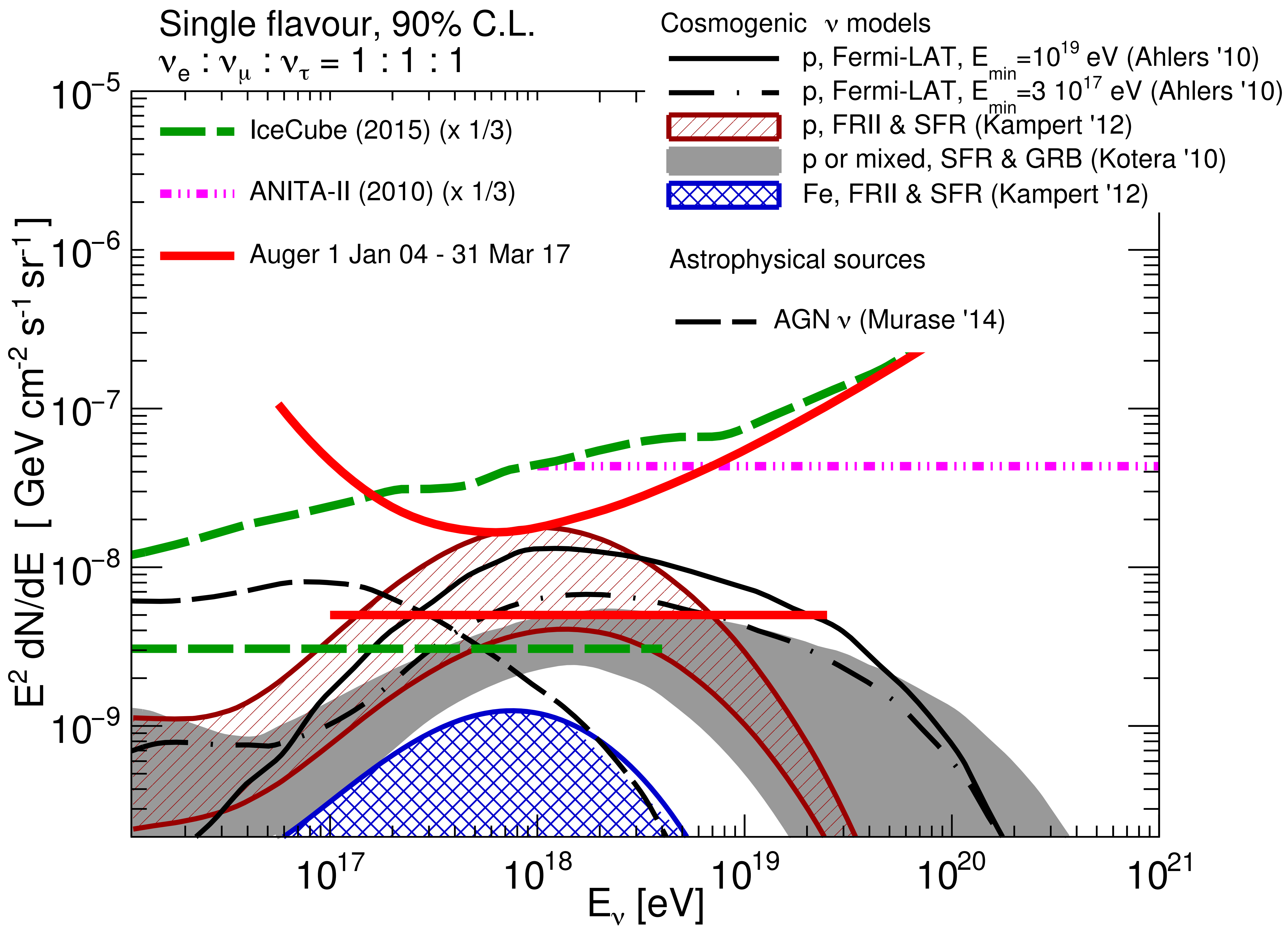
Earth-Skimming (90º, 95º)

contrib. to total evt rate **73%**

MAGIC (APP 102, 2018)

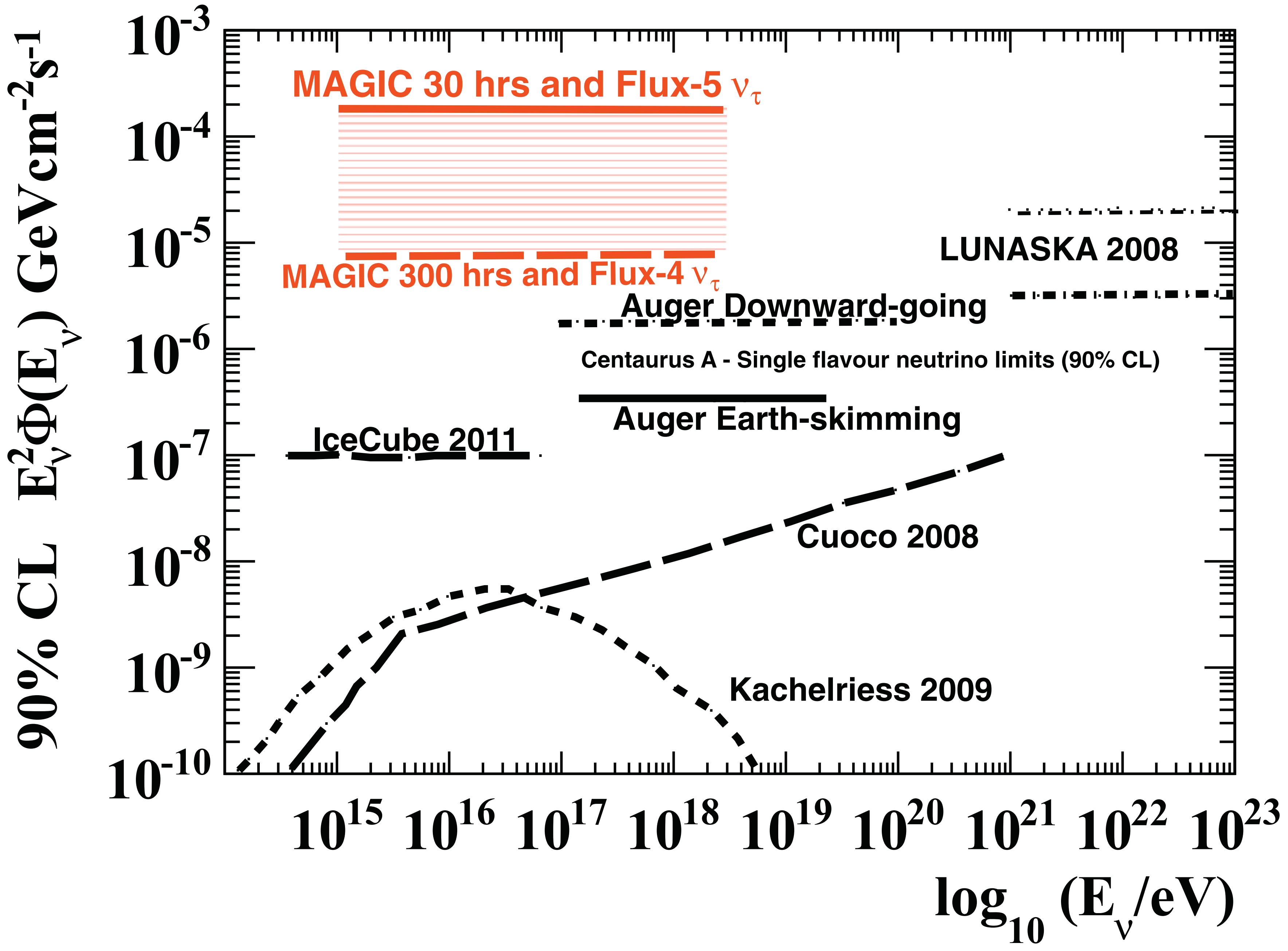


HL 4: The Auger Observatory is a good neutrino detector



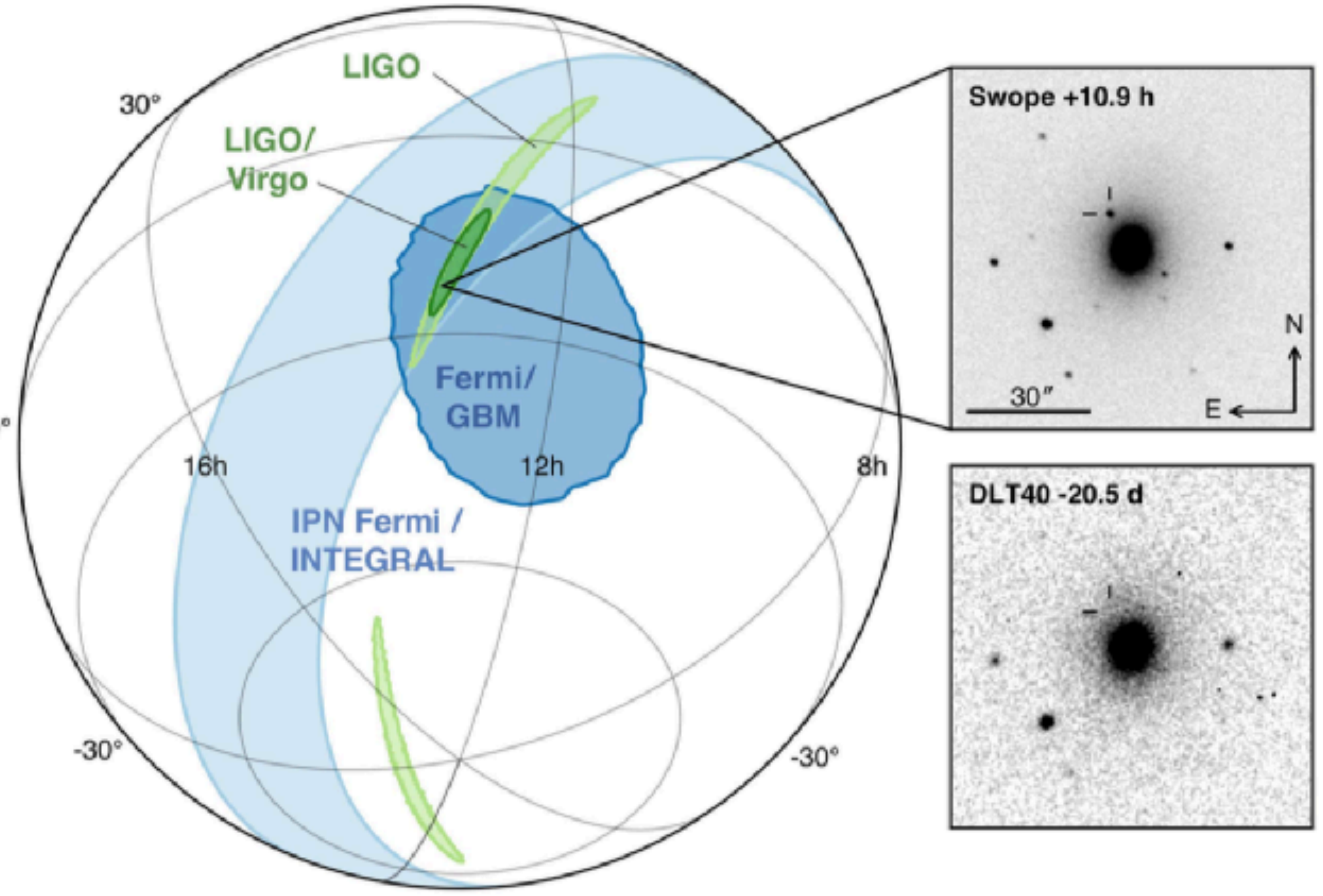
Diffuse flux limits

MAGIC limit

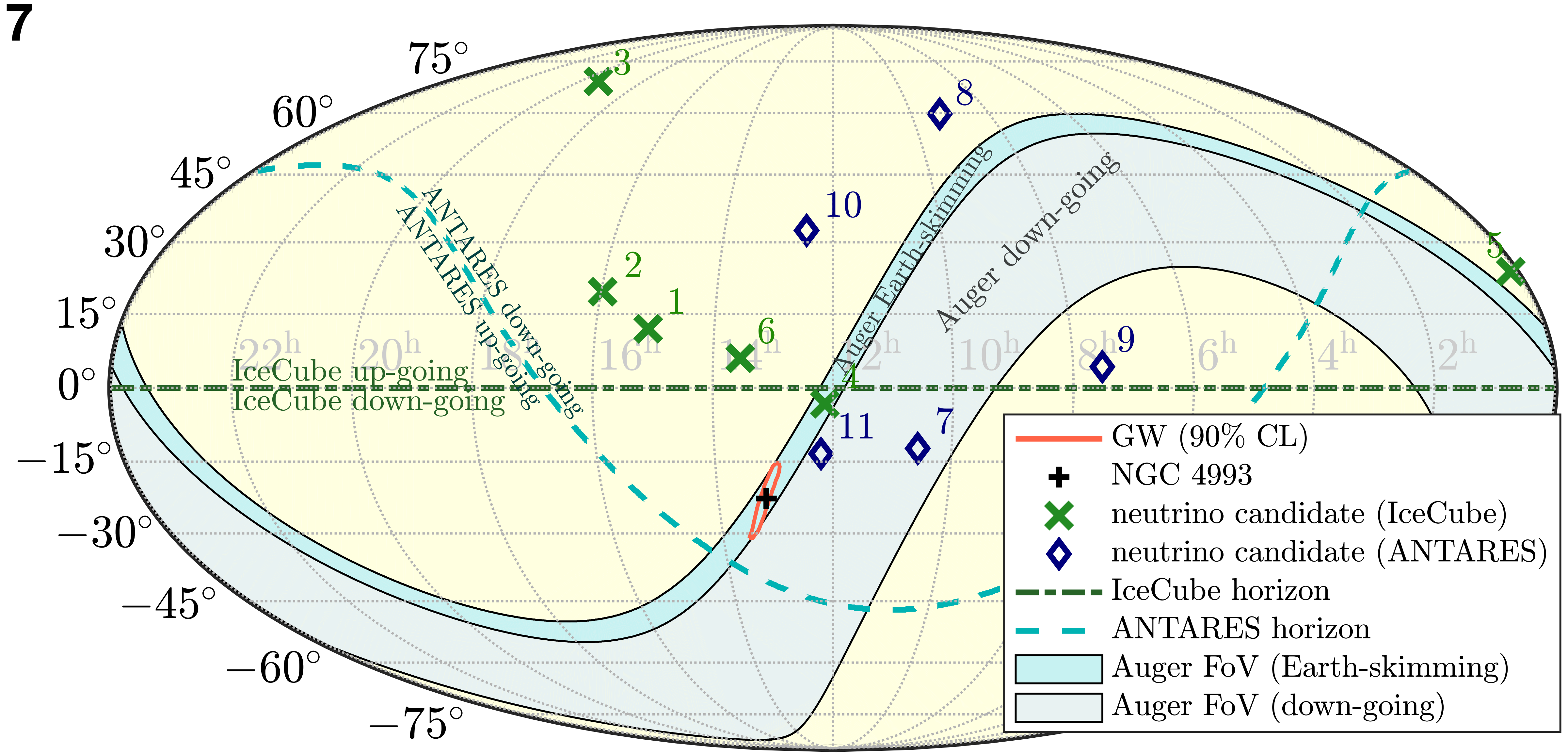


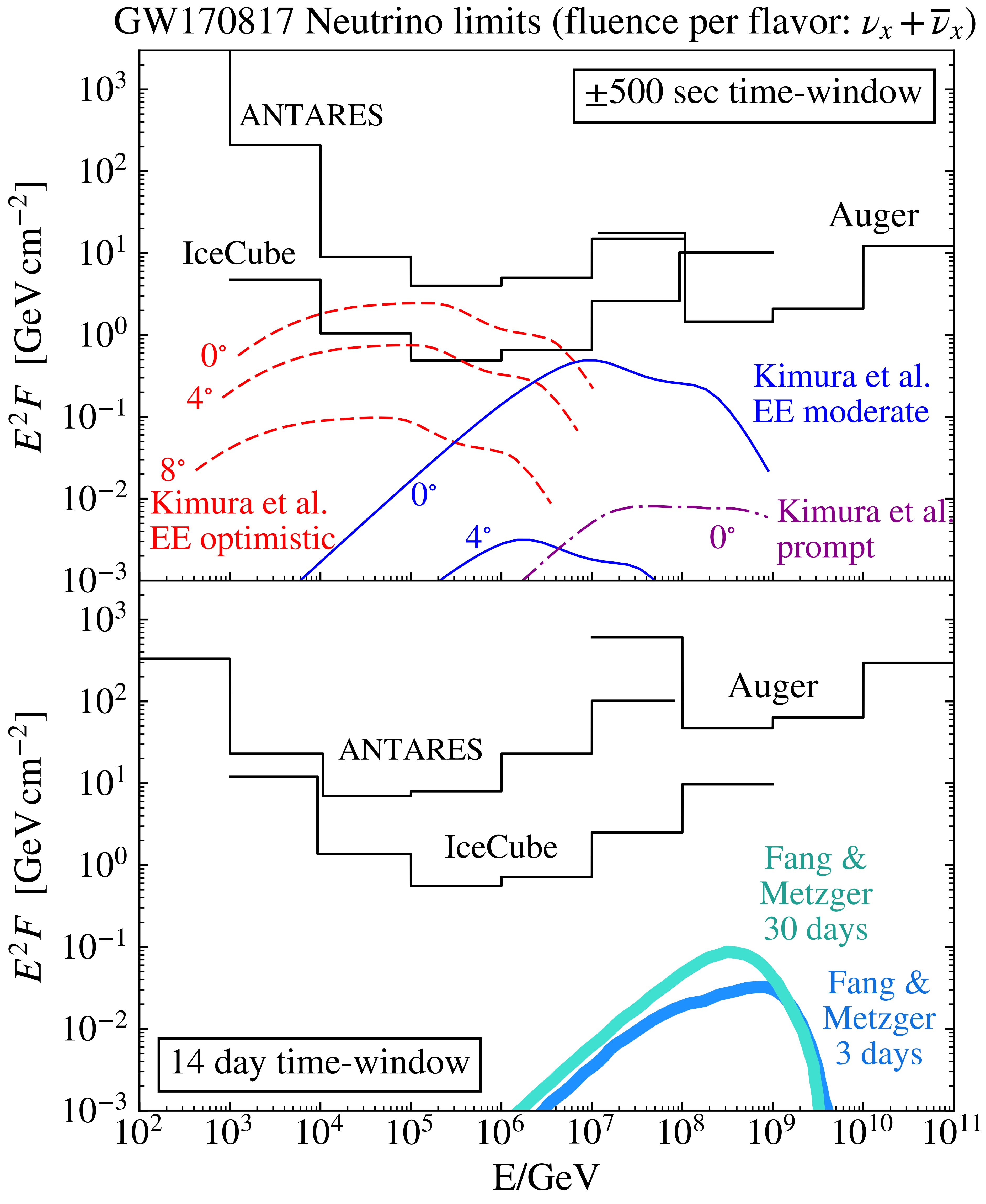
(Zas, ICRC 2017)

Auger Observatory as multi-messenger detector



GW170817





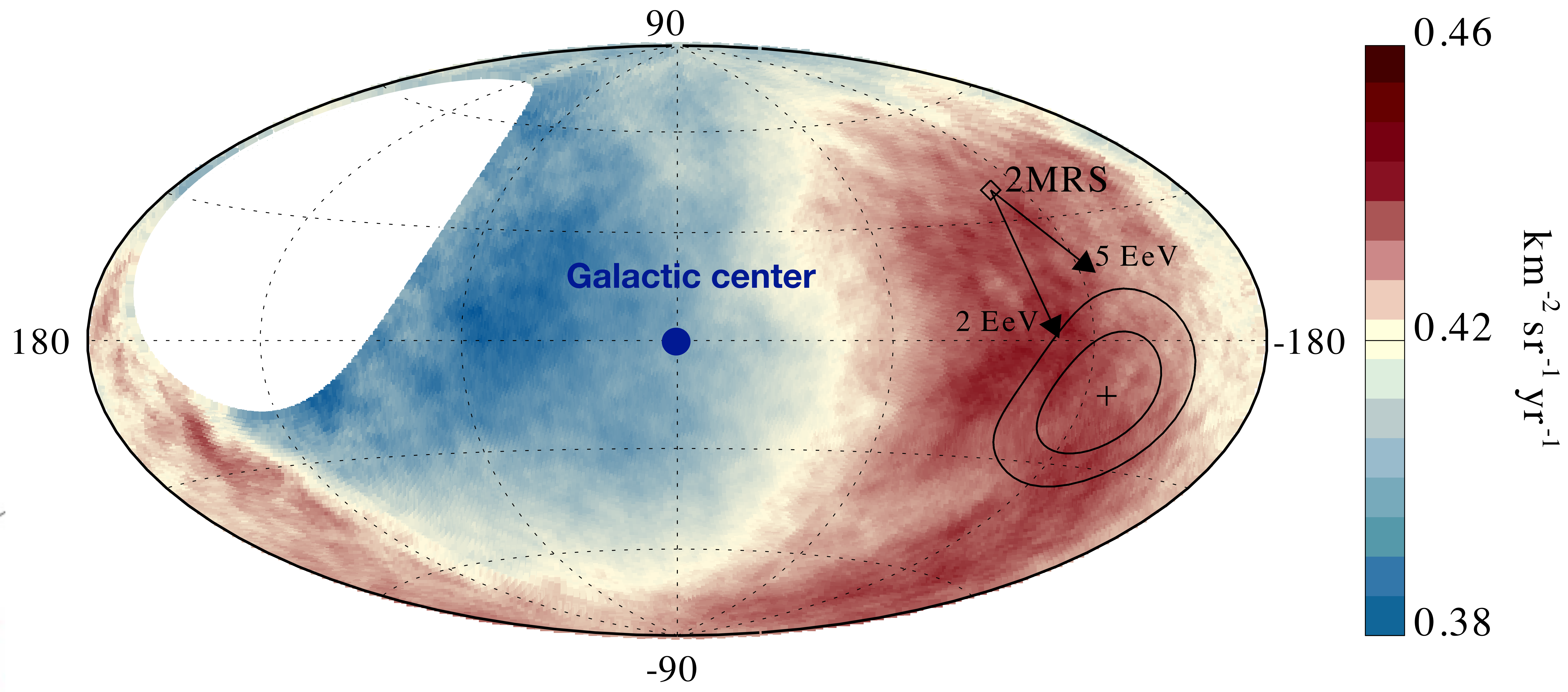
ApJL (2017), special issue (70 collaborations)

HL 5: Very small anisotropy observed at very high energy

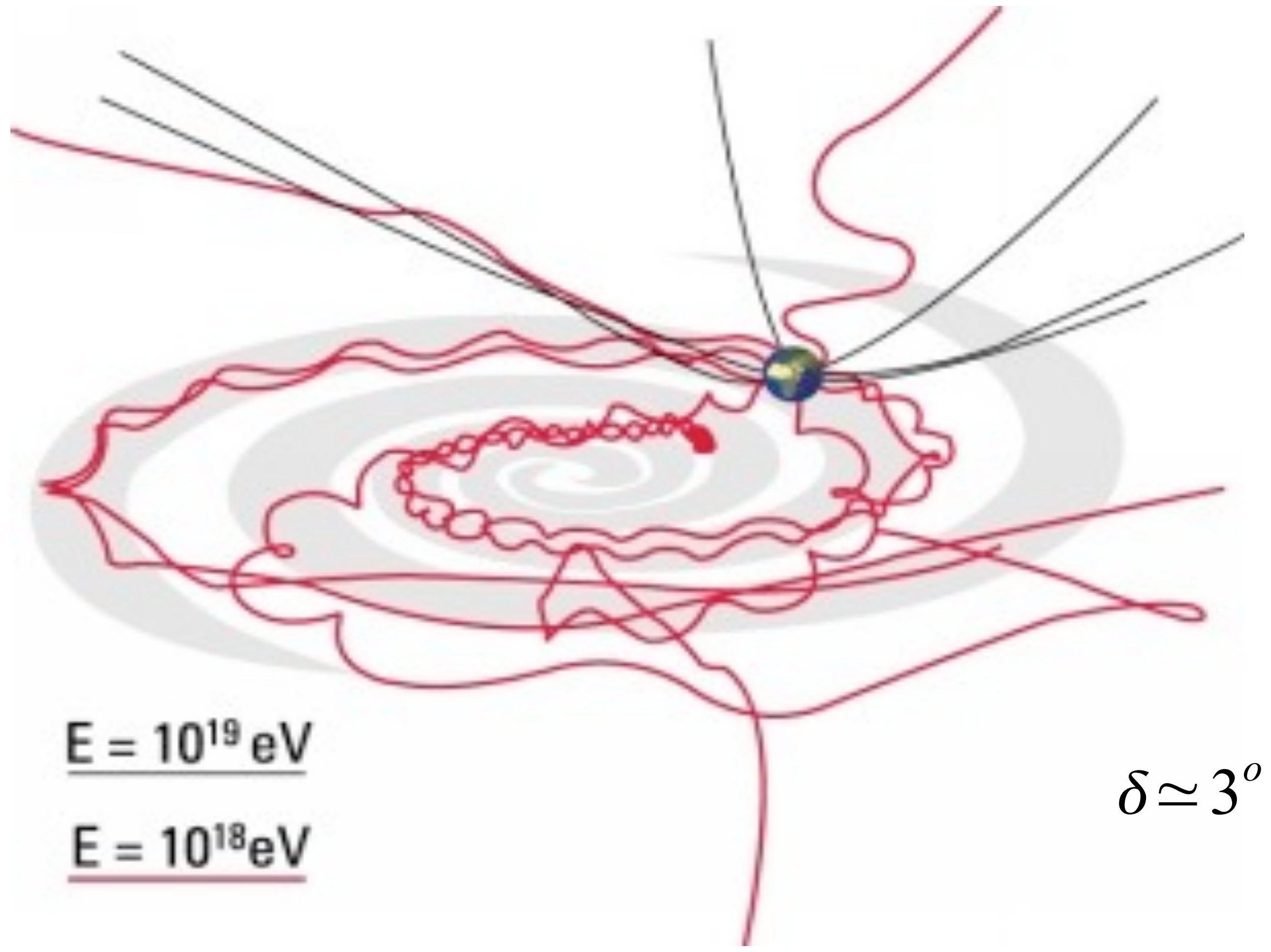
6.5% dipole at 5.2 sigma
Science 357 (2017) 1266

physicsworld
TOP 10
BREAKTHROUGH
2017

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



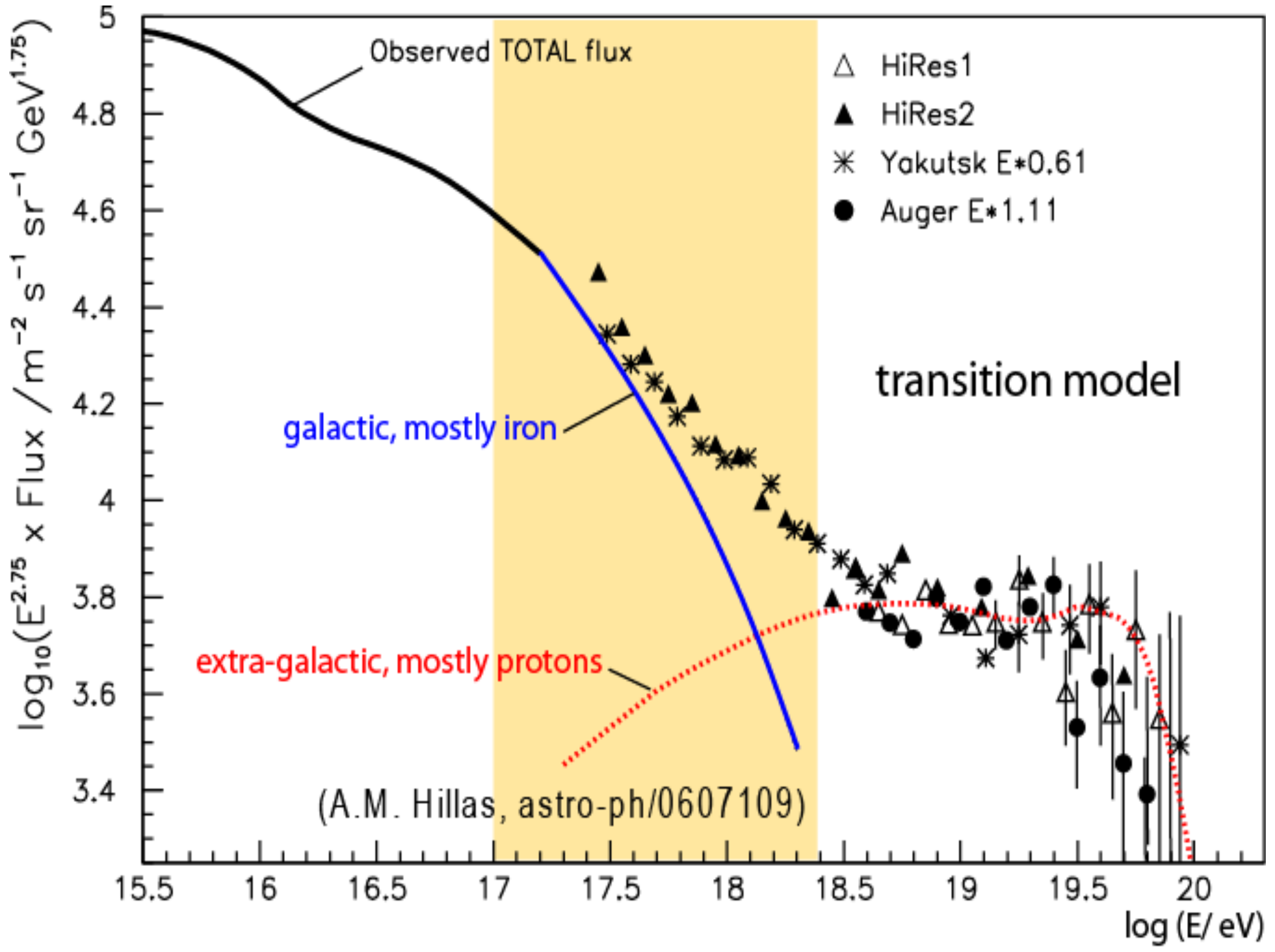
Estimated deflection in galactic mag. field



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

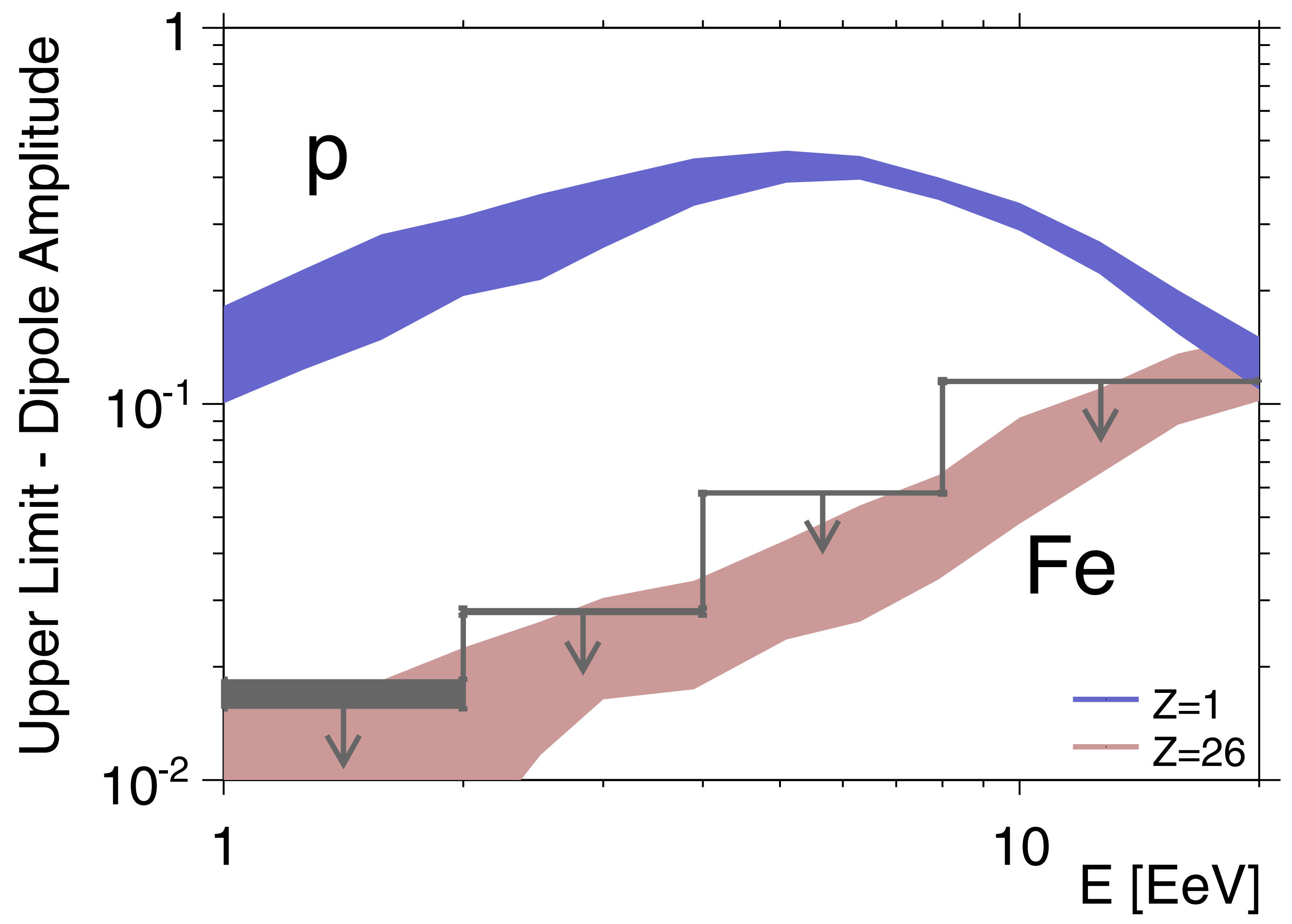
Arrival directions follow mass distribution of near-by galaxies: extragalactic origin of sources

Transition from galactic to extragalactic cosmic rays



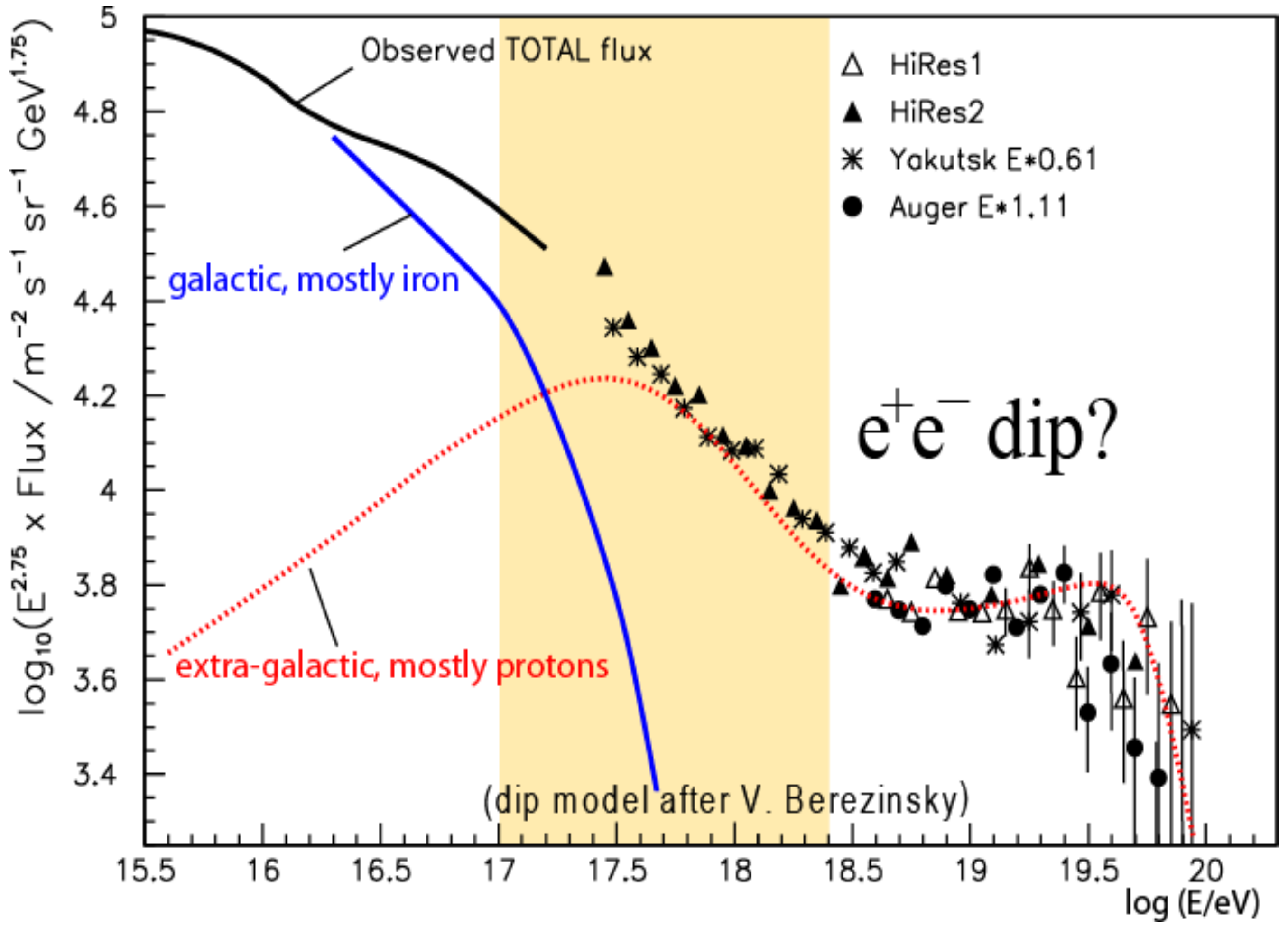
Ankle model:
Hillas, Wolfendale et al.

Simulation: Sources in galactic plane

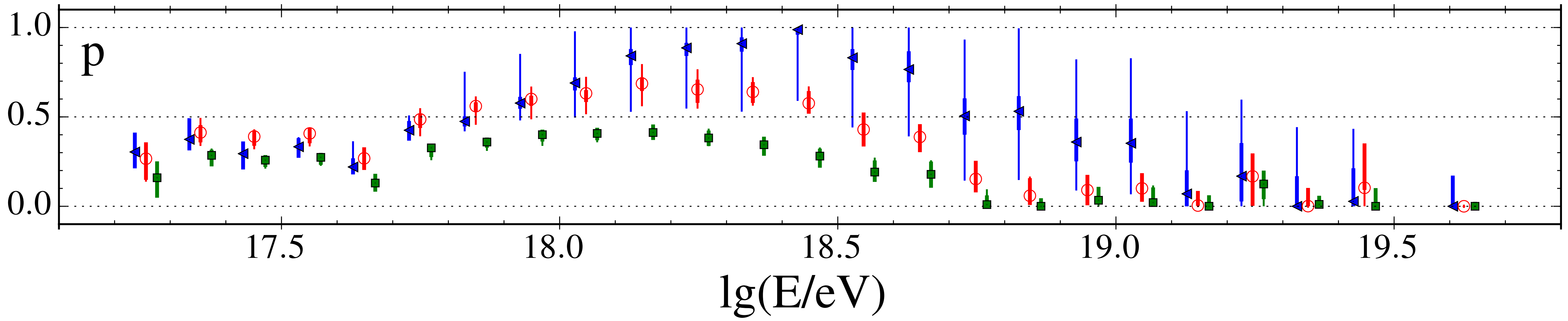


(Auger, ApJ 203, 2012,
Giacinti et al. JCAP 2012, 2015)

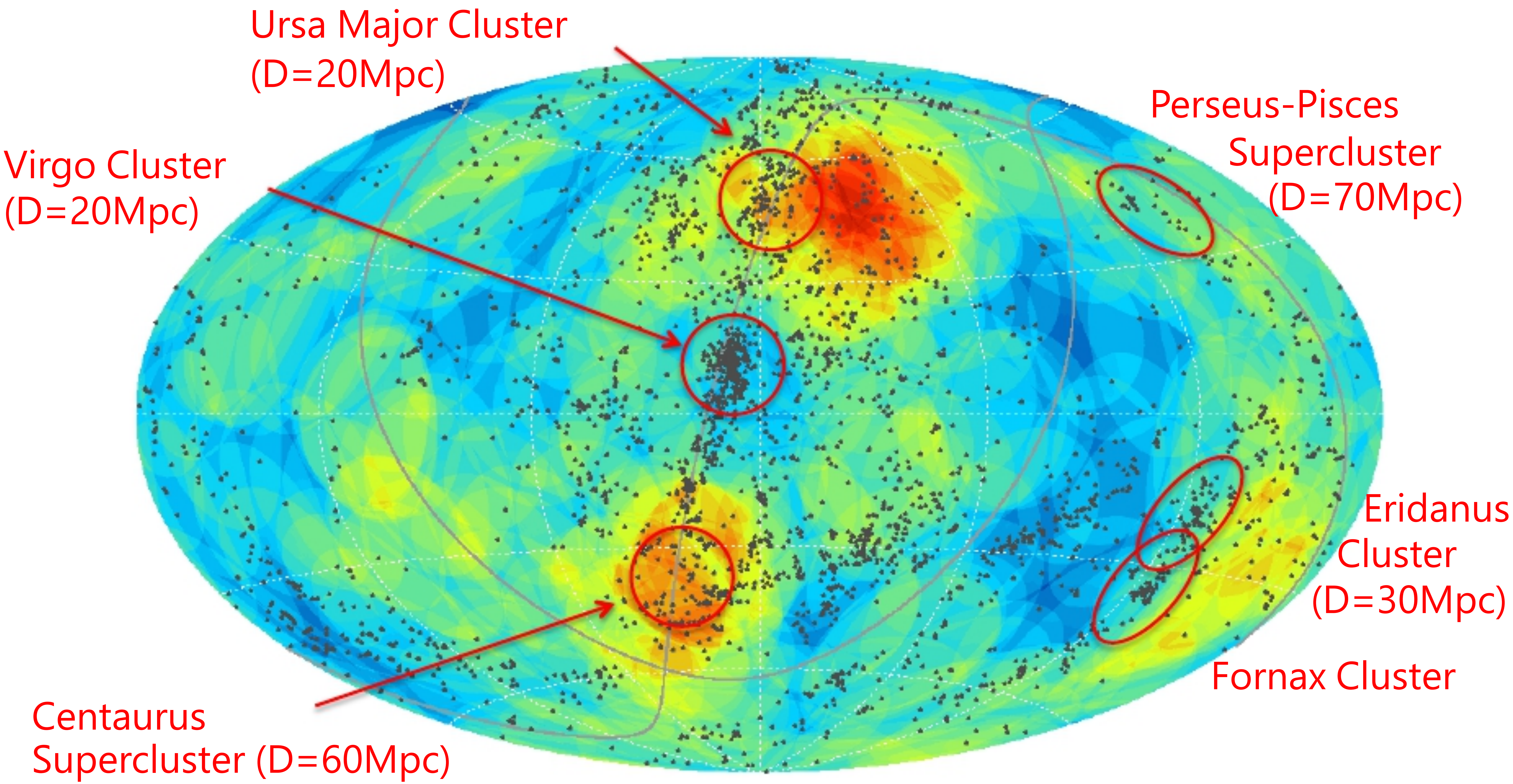
Transition energy ~10^{18} eV



Dip model:
Berezinsky et al.



HL 6: Intermediate-scale anisotropy at highest energies



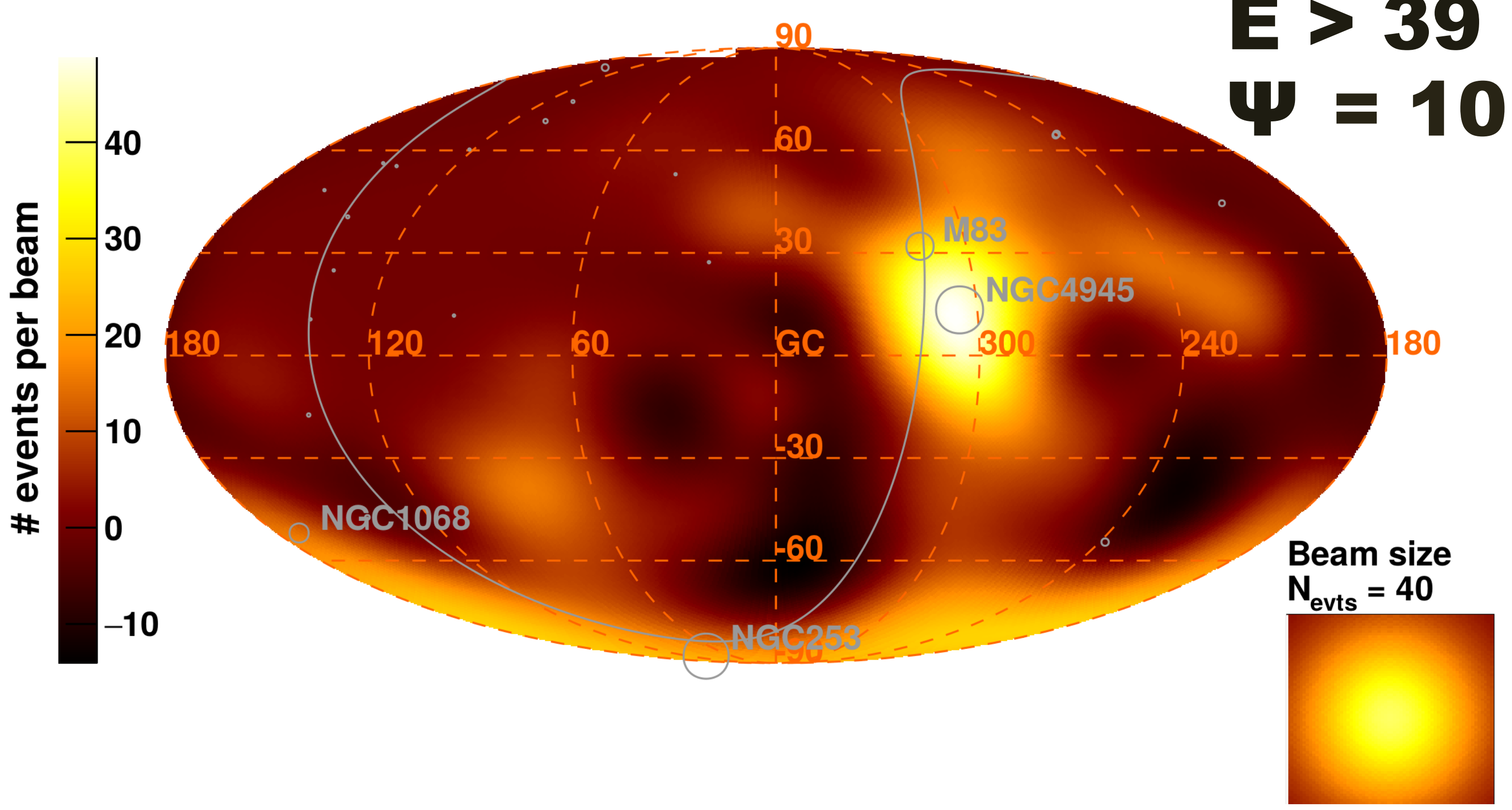
Huchra, et al, ApJ, (2012)

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

Anisotropy – Correlation with catalogs (Auger data)

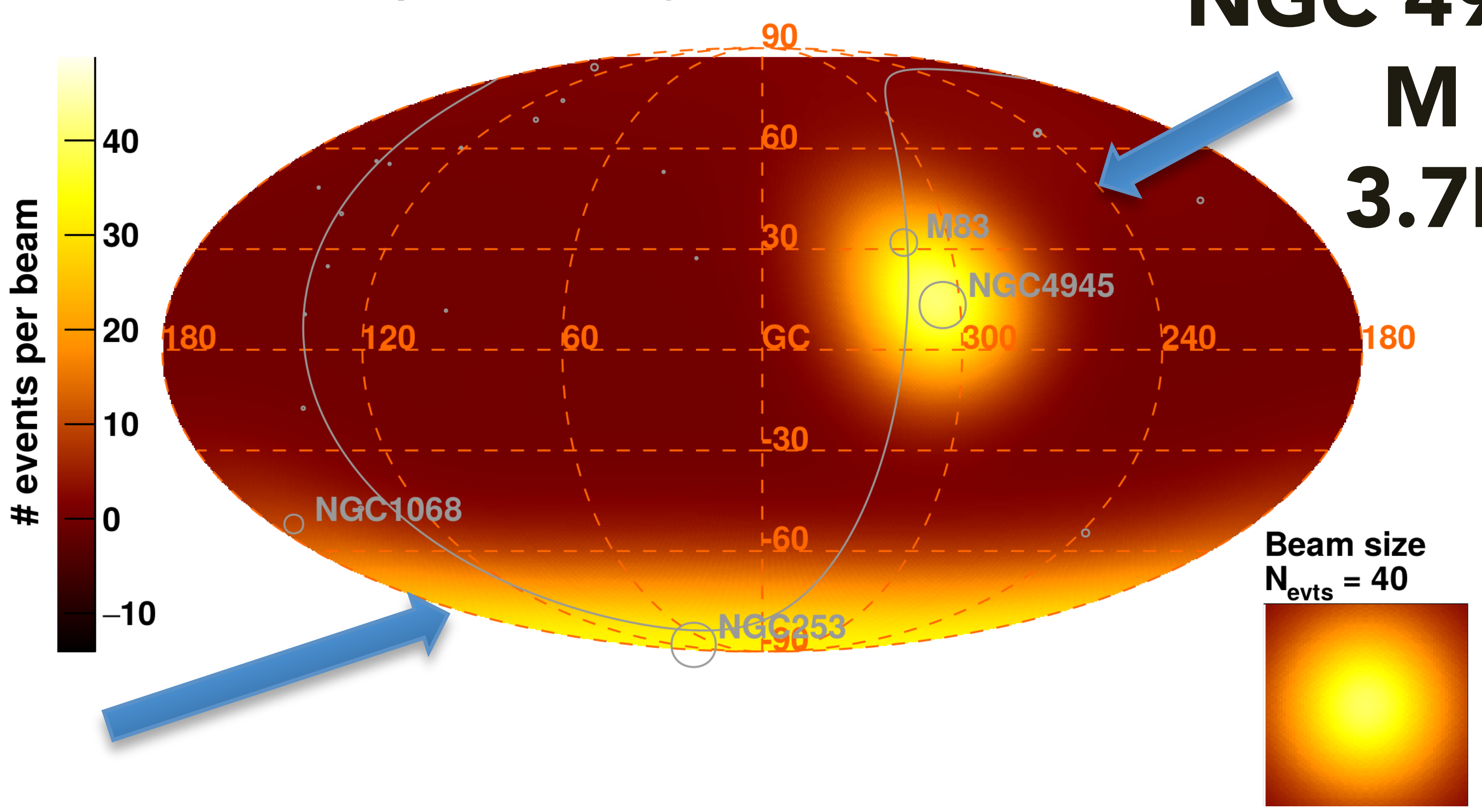
Starburst galaxies

Observed Excess Map - E > 39 EeV



E > 39 EeV
Ψ = 10°

Model Excess Map - Starburst galaxies - E > 39 EeV



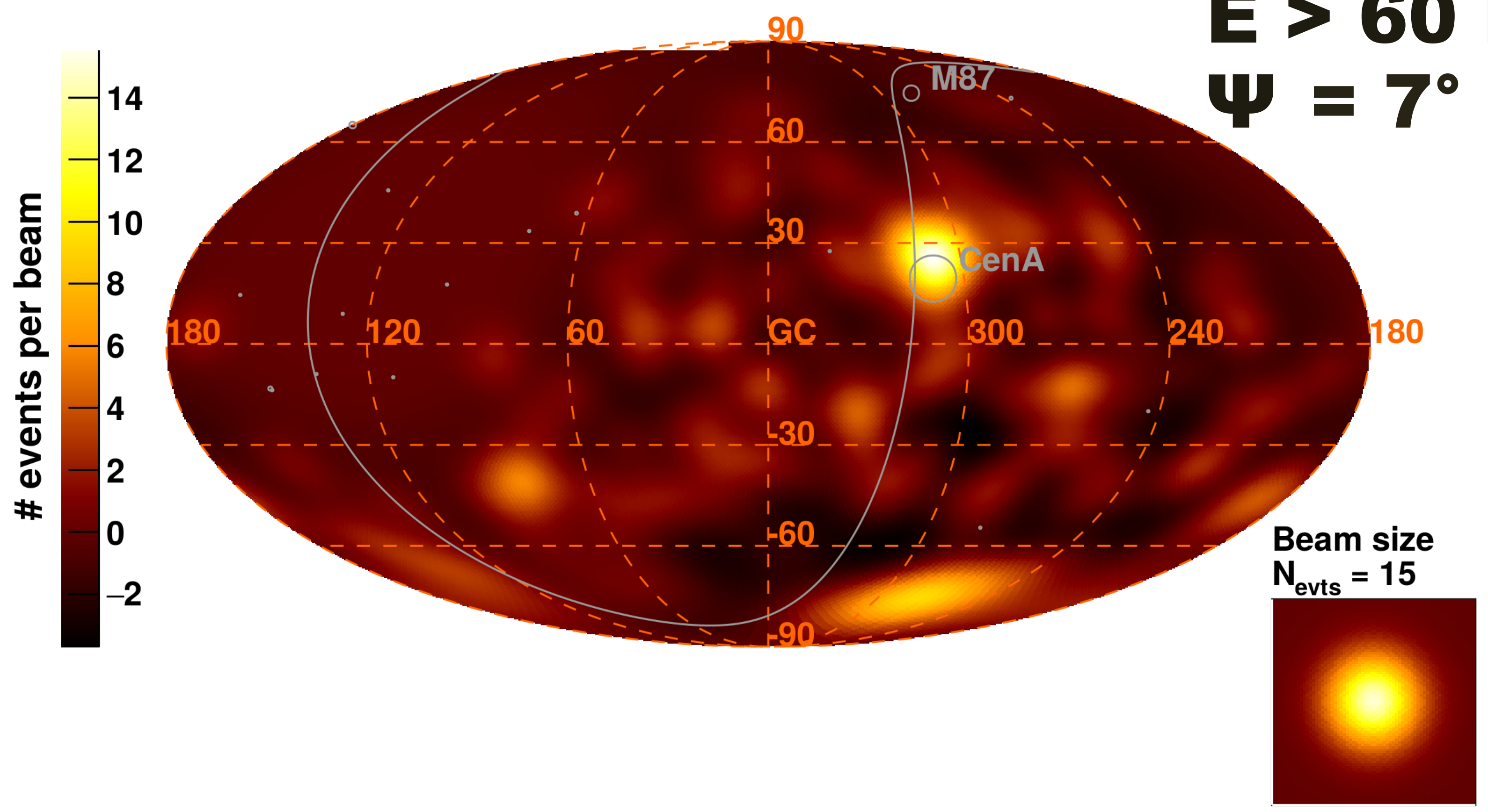
NGC 4945
M 83
3.7Mpc

NGC 253
2.5 Mpc

NGC 1068
16.7 Mpc

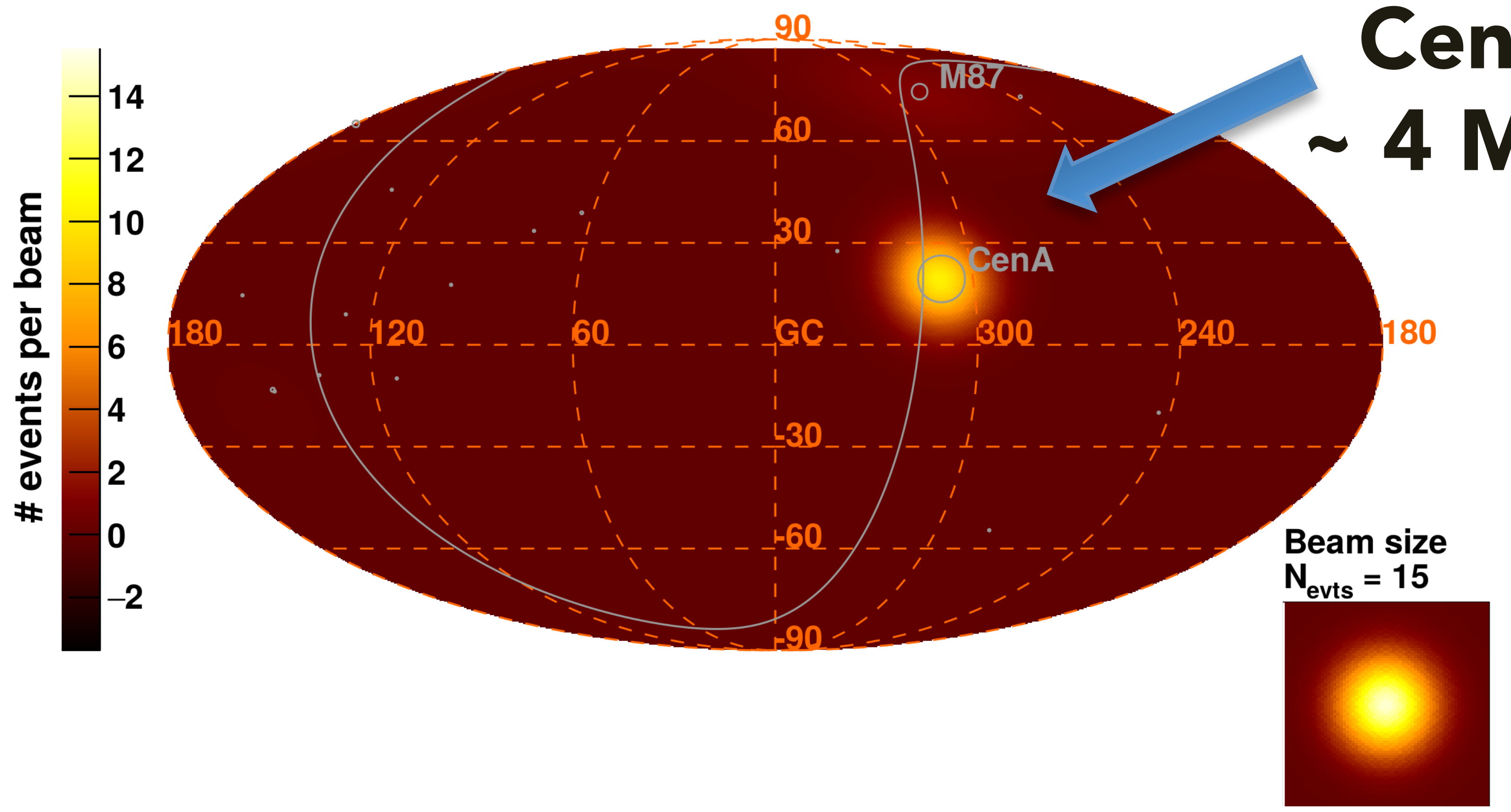
AGNs

Observed Excess Map - E > 60 EeV



E > 60 EeV
Ψ = 7°

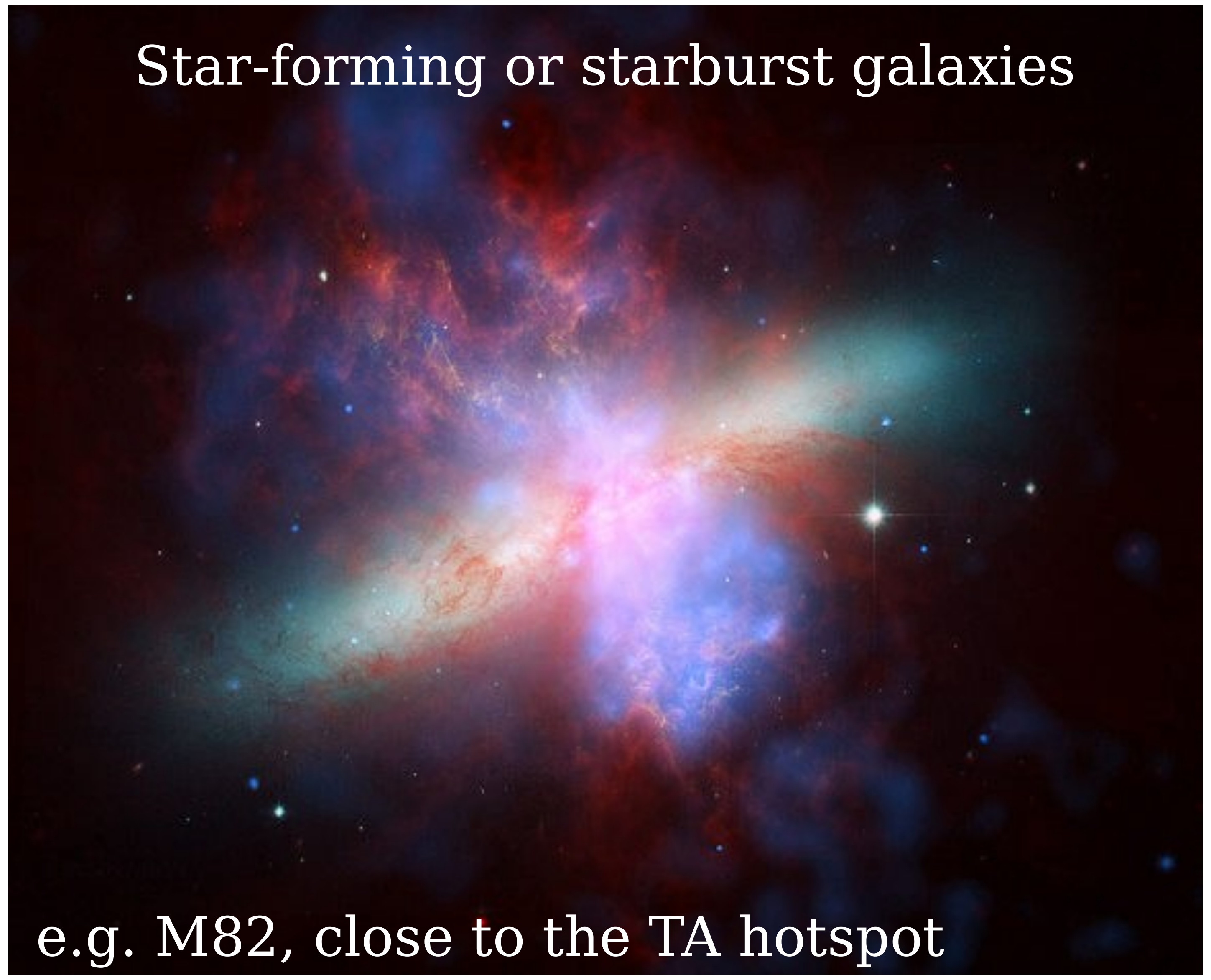
Model Excess Map - Active galactic nuclei - E > 60 EeV



CenA
~ 4 Mpc

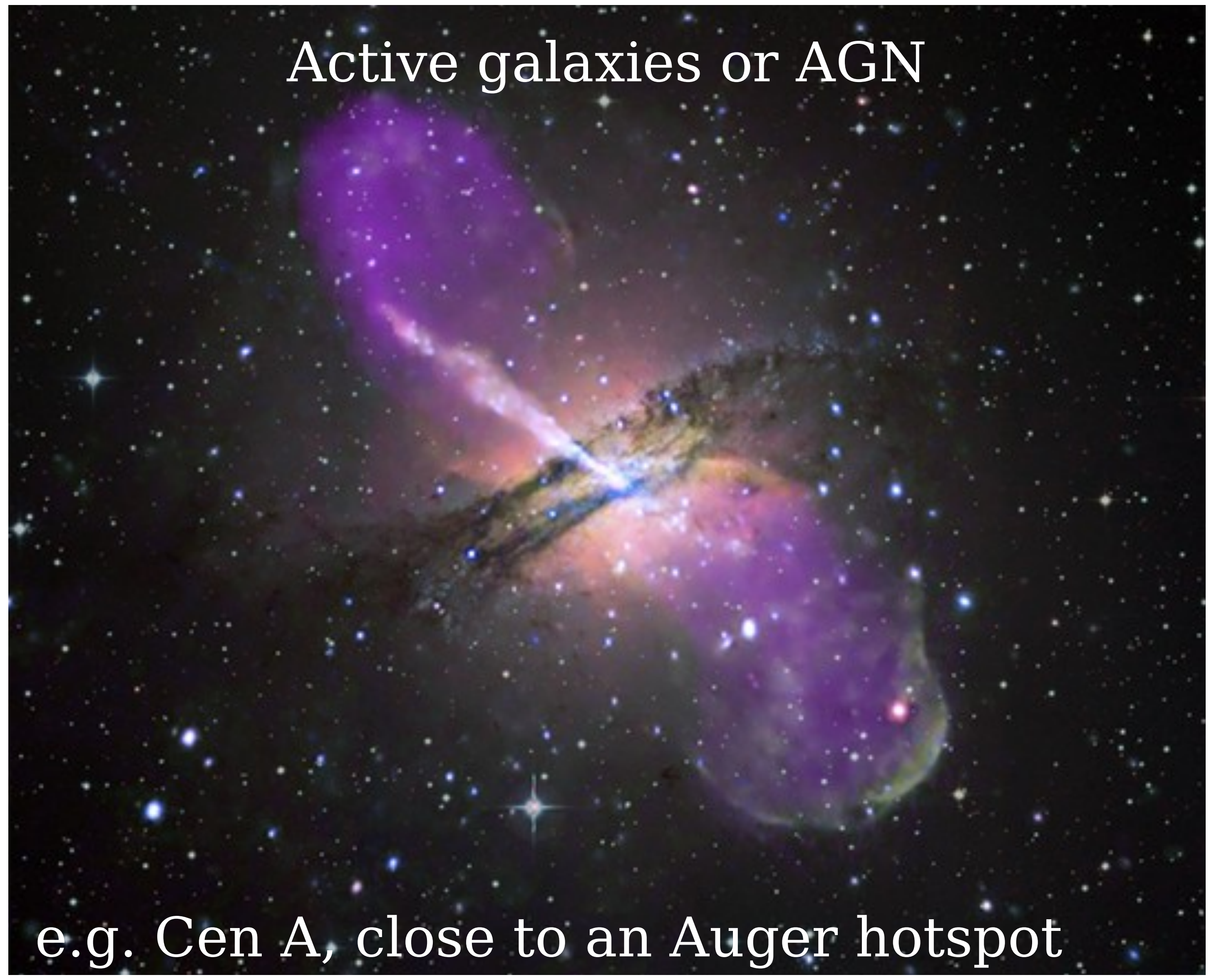
(Giaccari ICRC 2017)

Hints for sources or source regions?



Star-forming or starburst galaxies

e.g. M82, close to the TA hotspot



Active galaxies or AGN

e.g. Cen A, close to an Auger hotspot

~ 4 σ

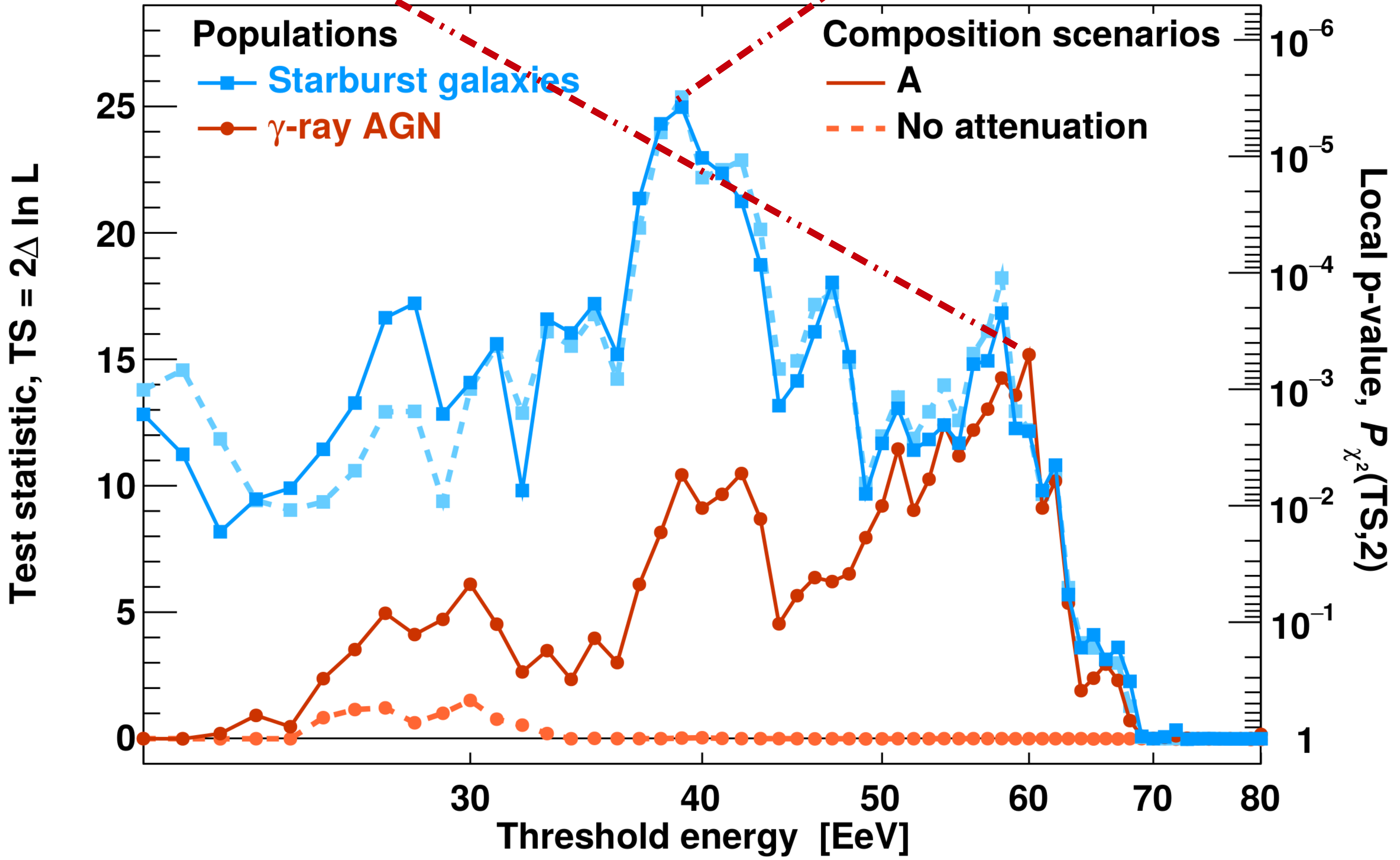
~ 3 σ

Active galaxies

> 60 EeV: N~180 events, TS=15
α=7%, θ=7°
2 free par. + E-scan → 2.7σ

Starforming galaxies

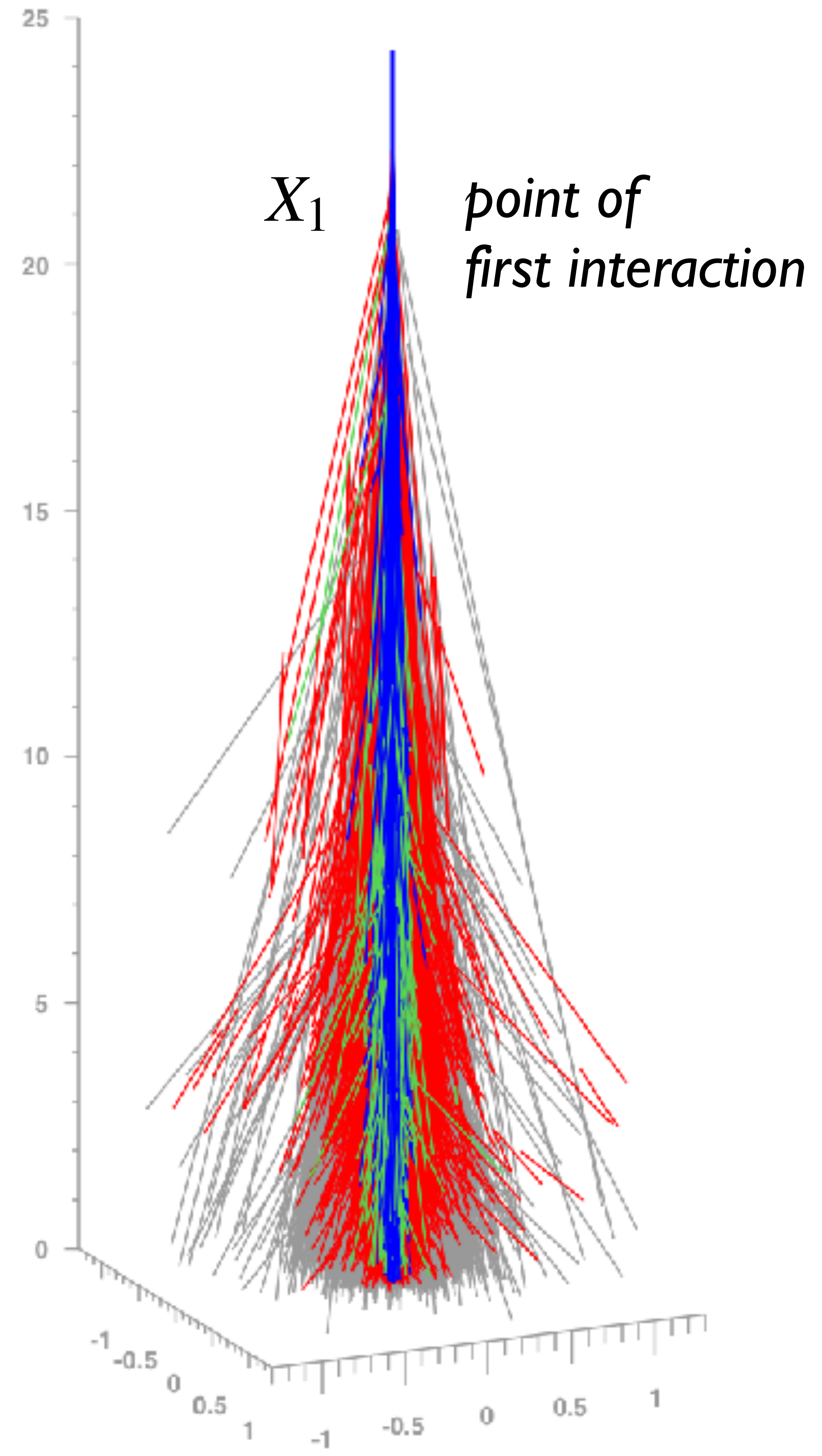
> 39 EeV: N~900 events, TS~25
α=10%, θ=13°
2 free par. + E-scan → 4.0σ

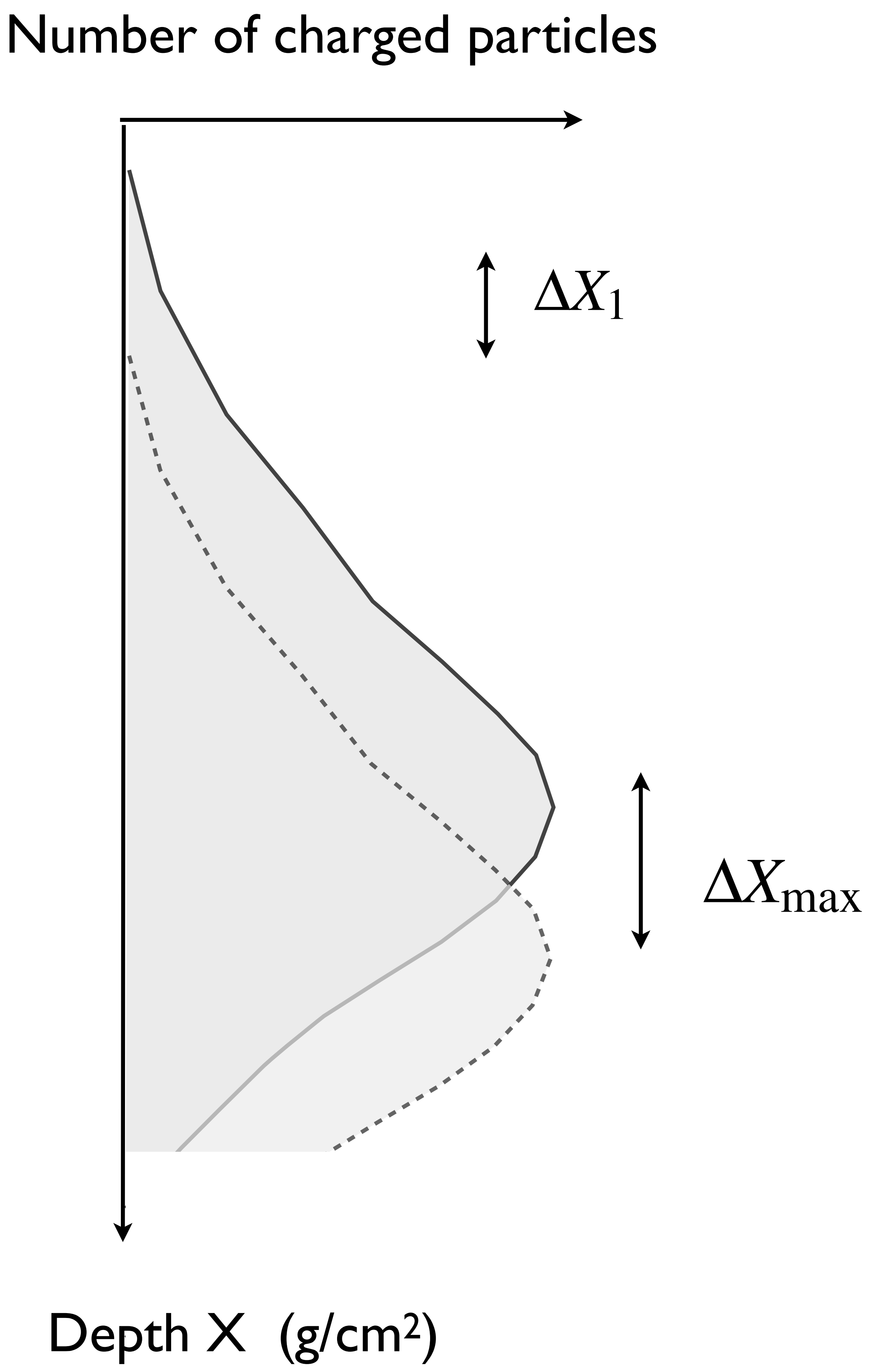


Jonathan Biteau | MIAPP | **Page 11/14**

(Auger, ApJL 853, 2018)

HL 7: Proton-proton interactions “normal” up to 50 TeV c.m.s.



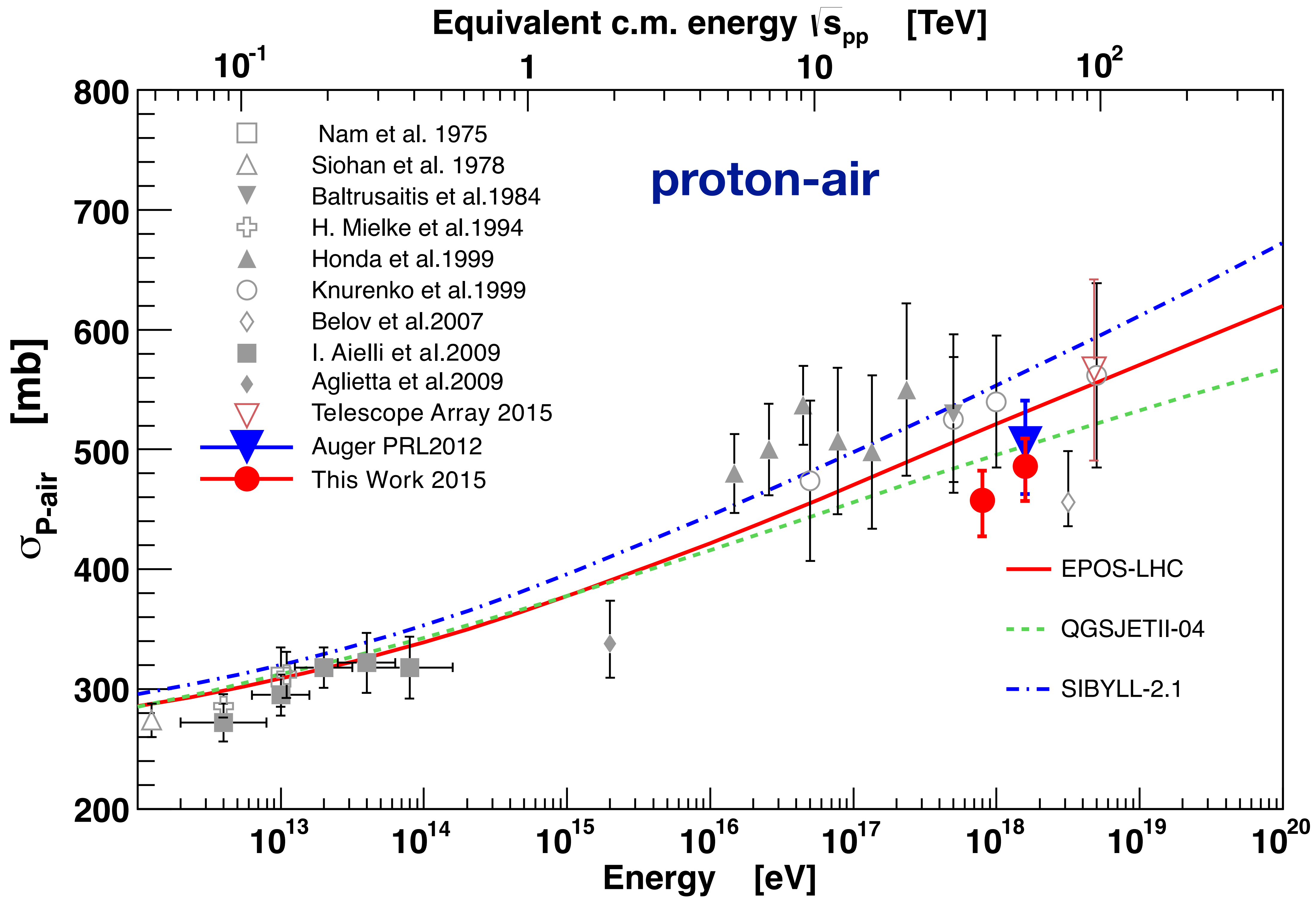


$$\frac{\mathrm{d}P}{\mathrm{d}X_1} = \frac{1}{\lambda_{\mathrm{int}}} e^{-X_1/\lambda_{\mathrm{int}}}$$

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

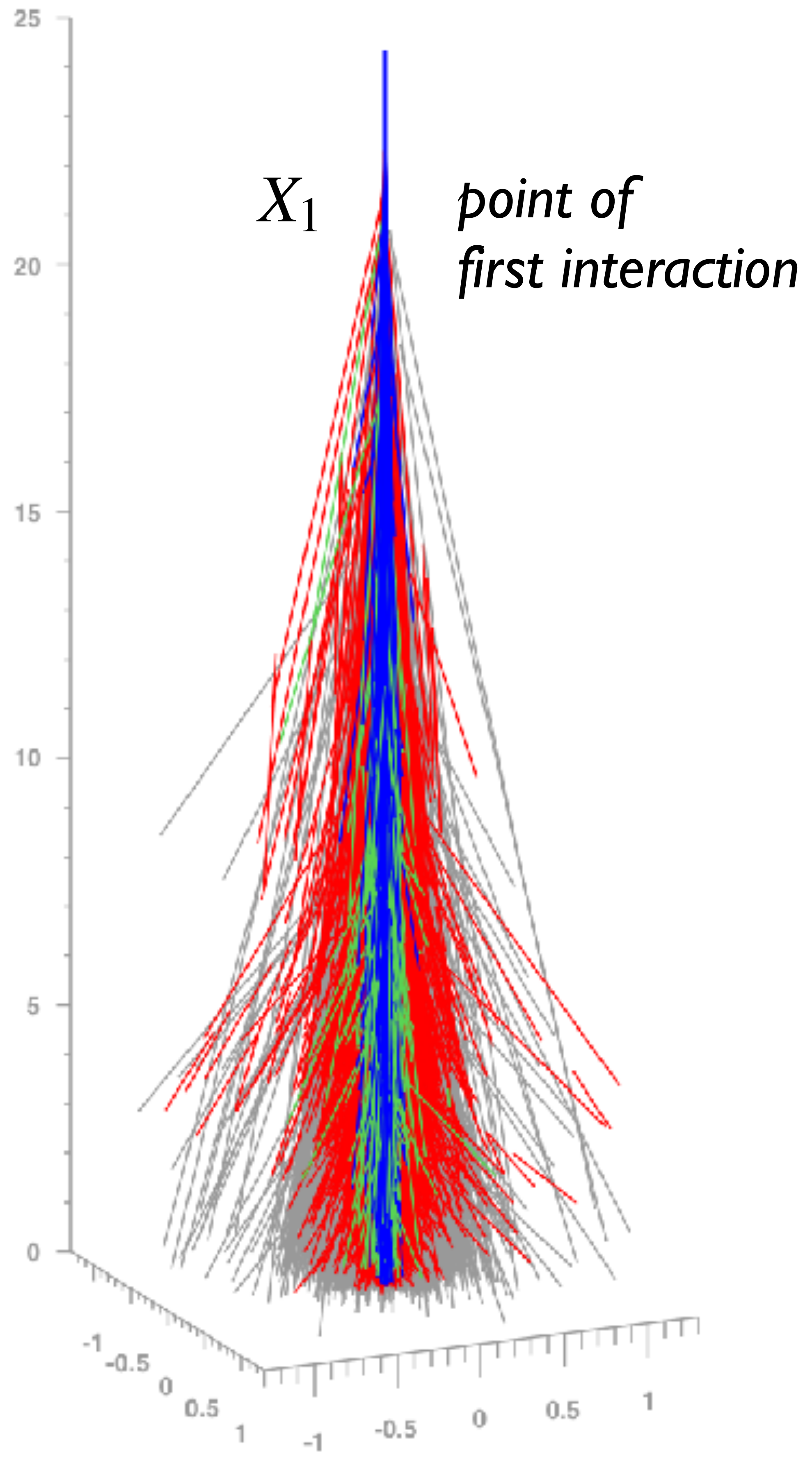
Difficulties

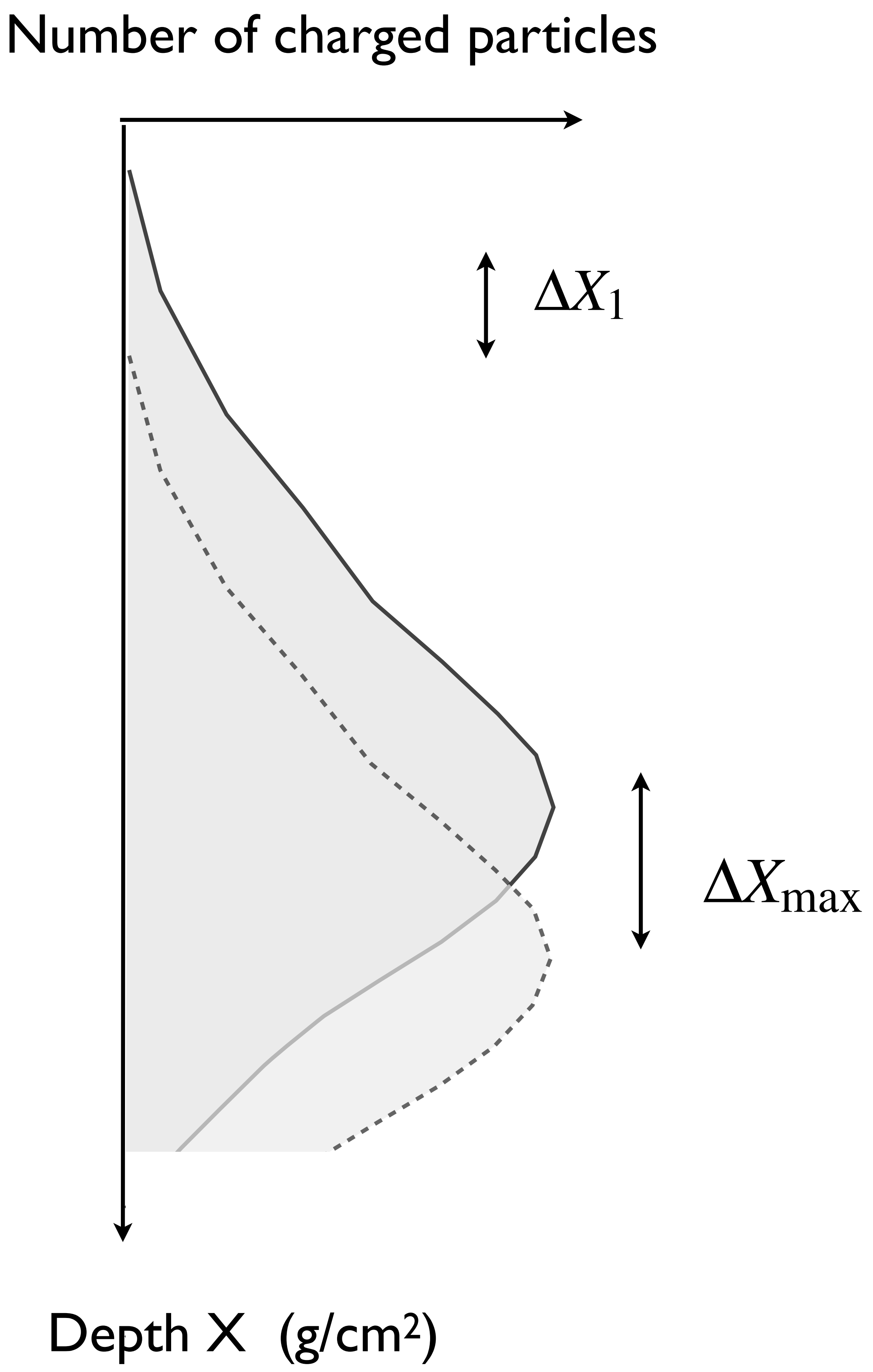
- mass composition
- fluctuations in shower development (model needed for correction)



(Auger PRL 109, 2012; Telescope Array PRD 92, 2015)

HL 7: Proton-proton interactions “normal” up to 50 TeV c.m.s.



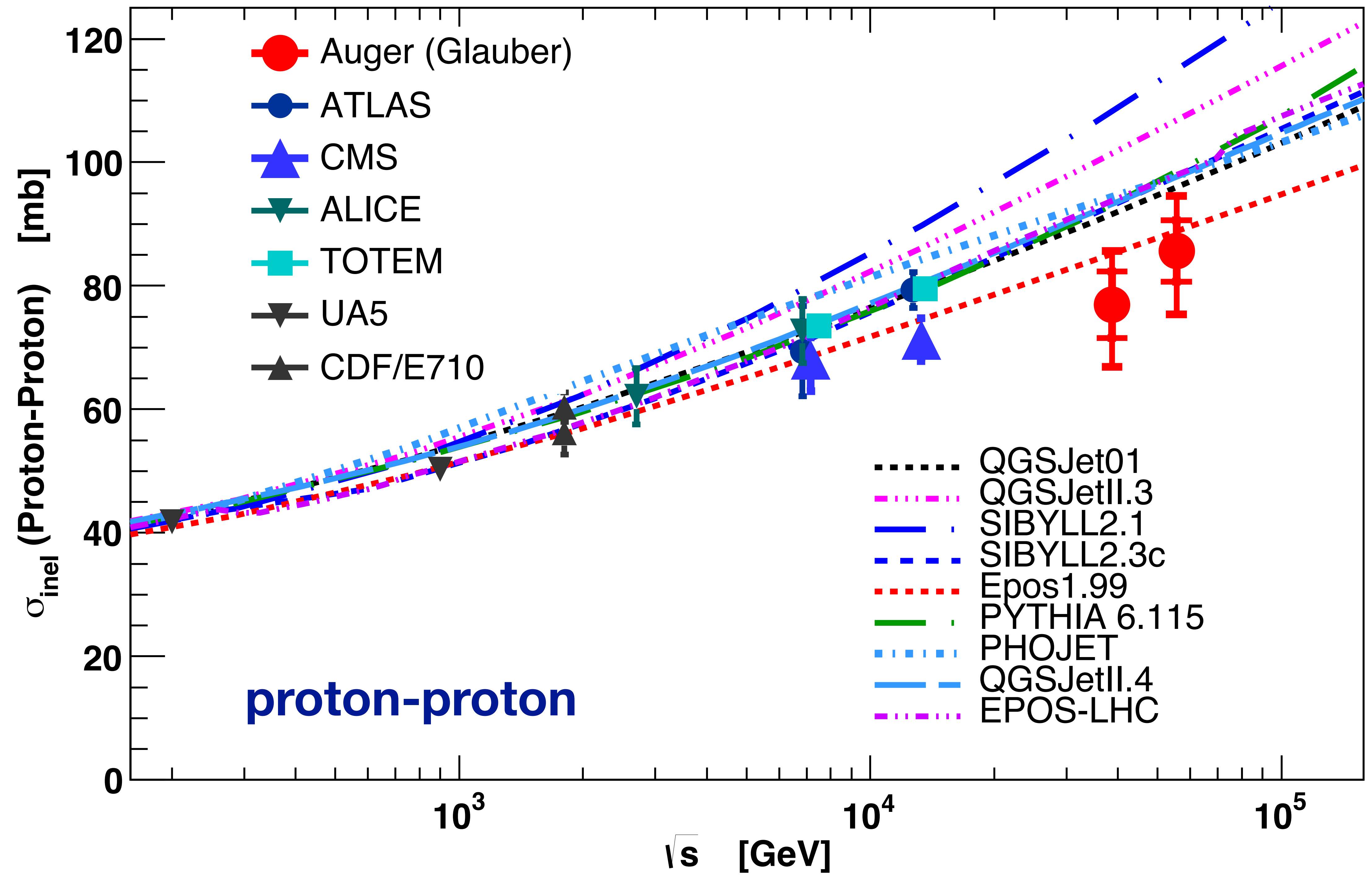


$$\frac{dP}{dX_1} = \frac{1}{\lambda_{\rm int}} e^{-X_1/\lambda_{\rm int}}$$

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

Difficulties

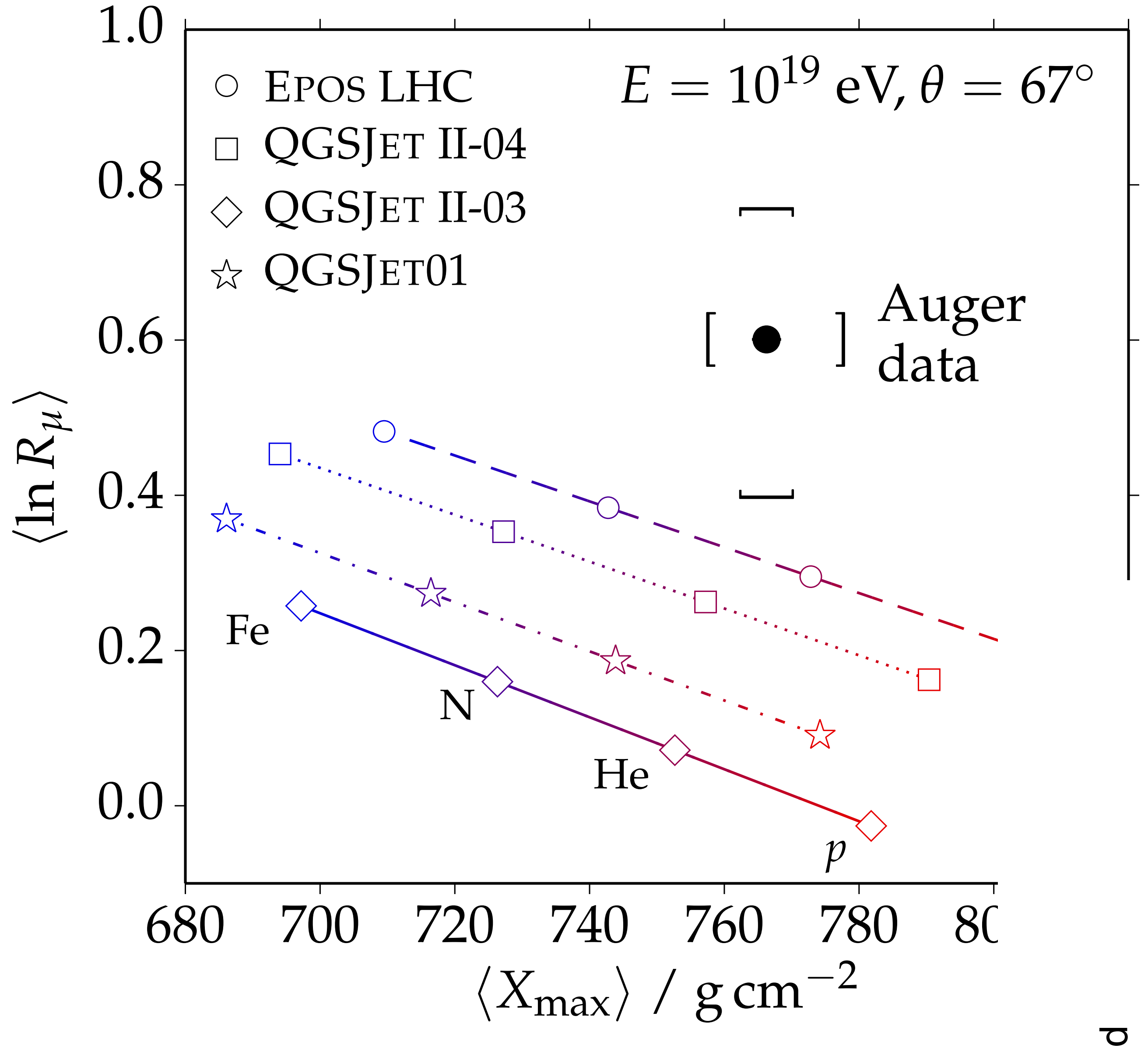
- mass composition
- fluctuations in shower development (model needed for correction)



(Auger PRL 109, 2012; Telescope Array PRD 92, 2015)

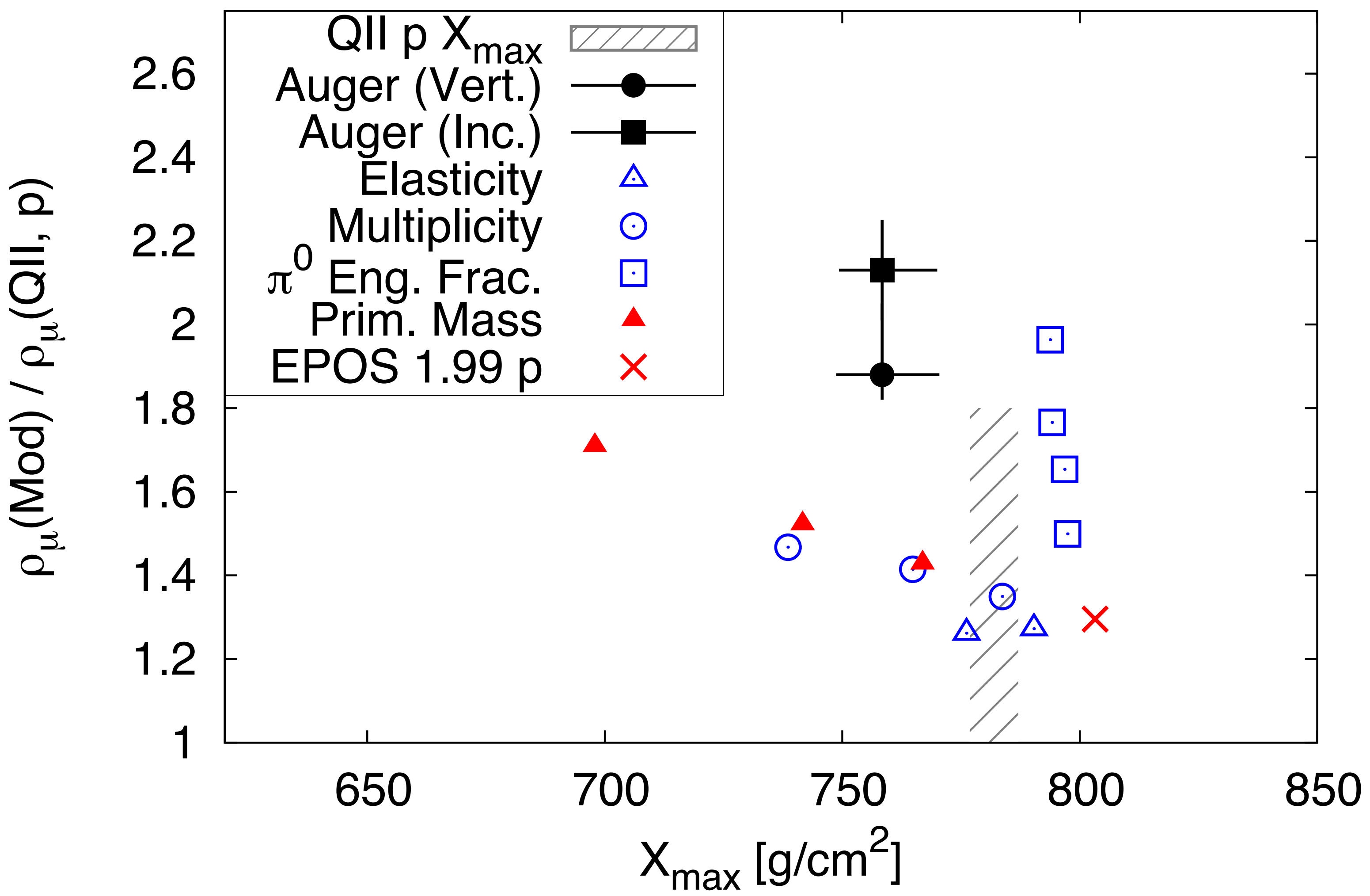
HL 8: Muon discrepancy in air showers & particle physics

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

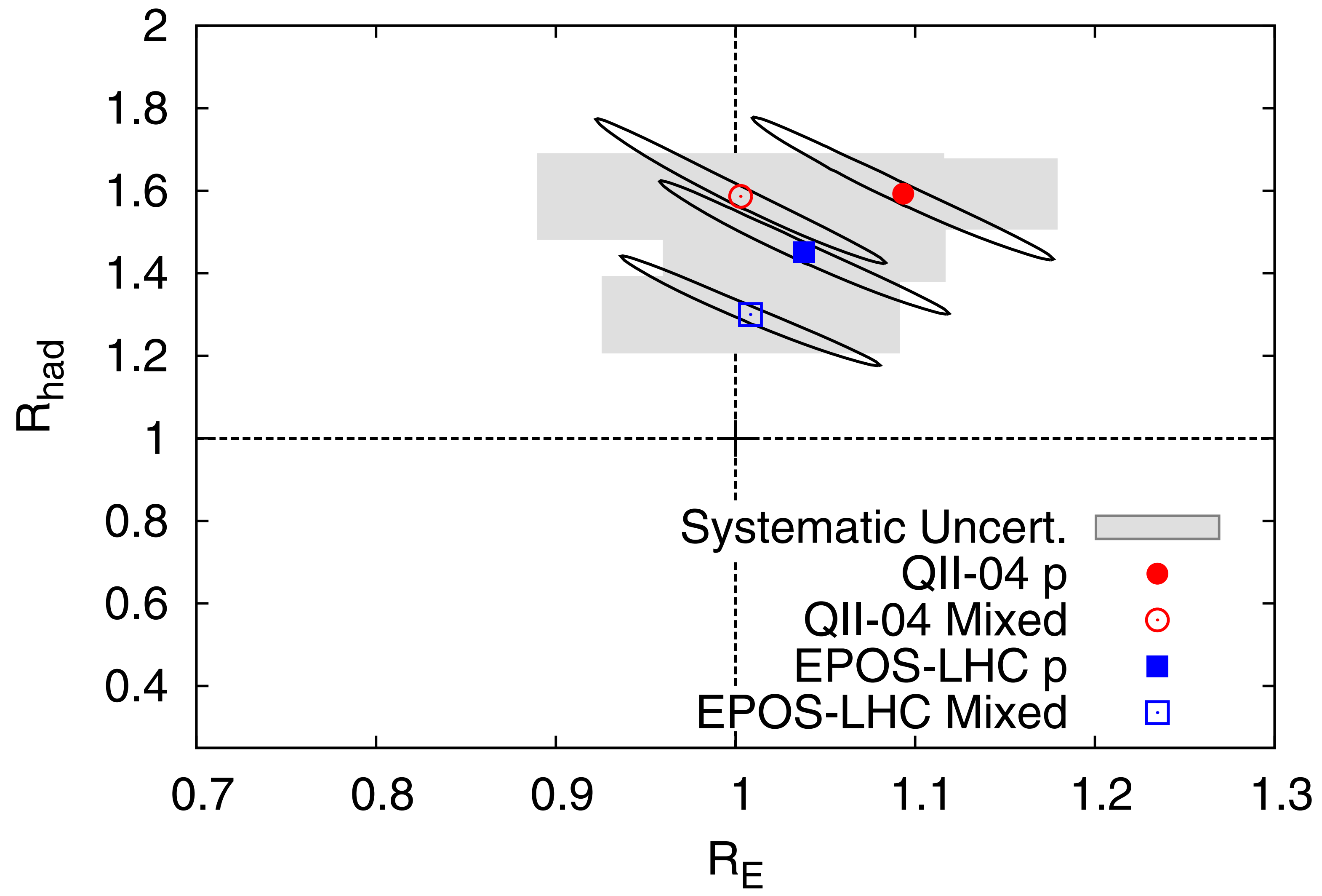


(Auger, PRD 91, 2015)

Example of power of muon measurement

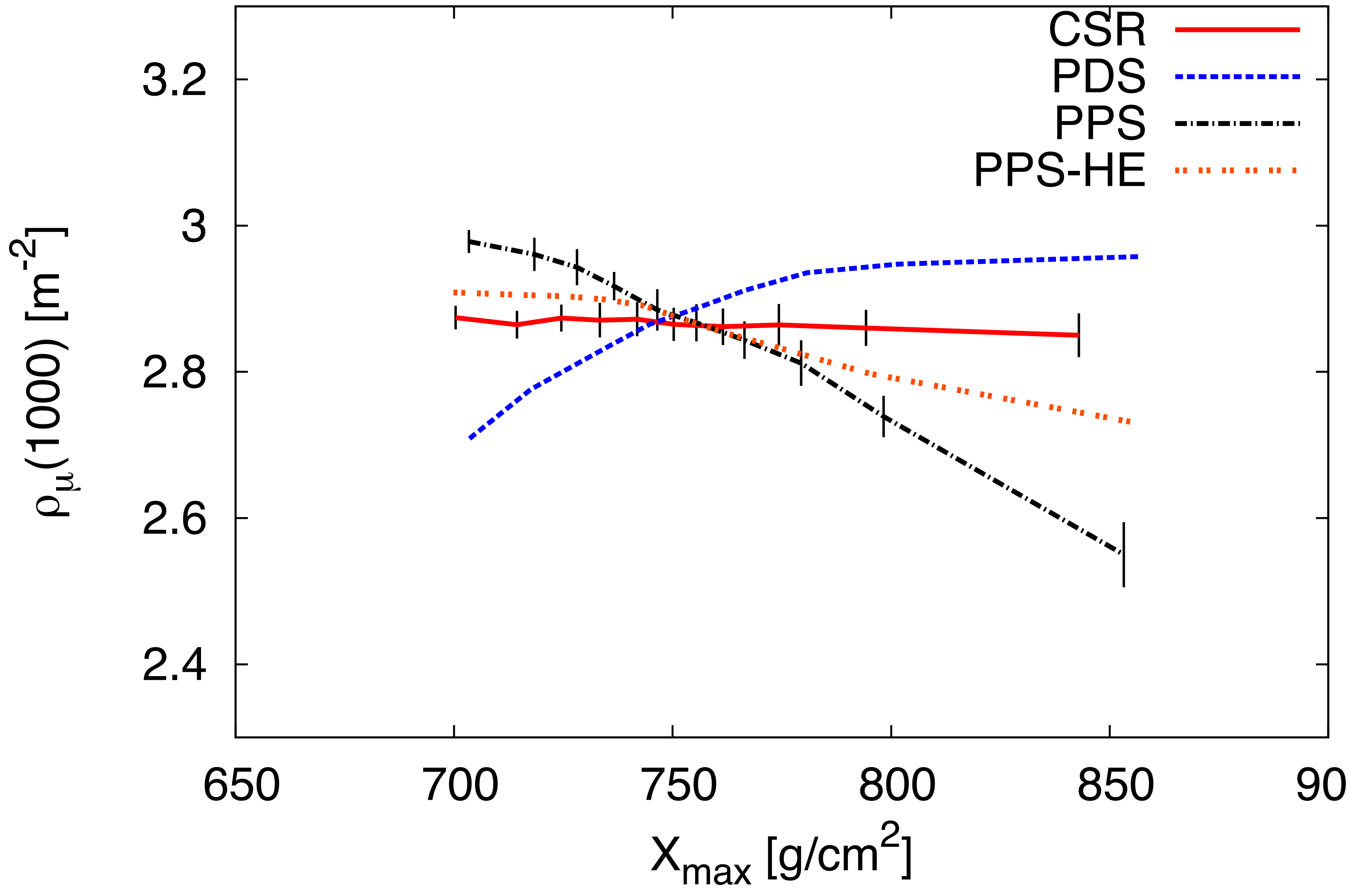


(Auger, PRL 117, 2016)

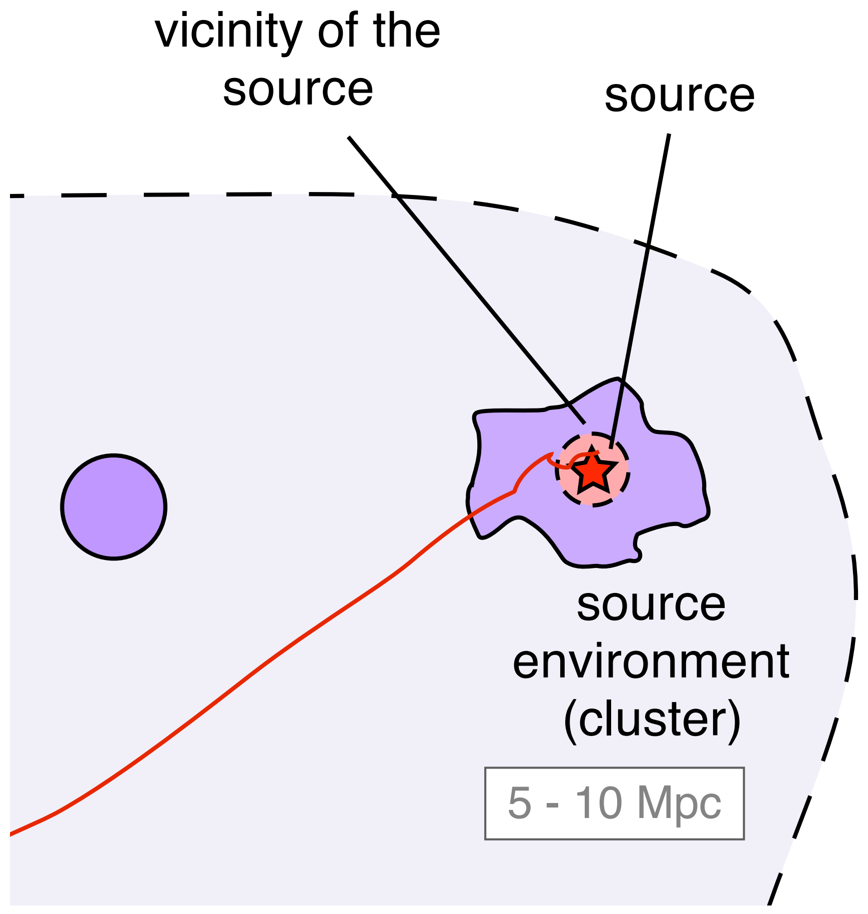


Correlations between X_{max} and muon density

(Allen & Farrar, 1307.7131)



Conclusions and outlook



- **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)

- **We seem to start seeing an anisotropic sky**
  (composition at highest energies matters)

- **Multi-messenger data key for making progress**

- **Further progress in modeling hadronic interactions required for reliable composition studies**
  (LHC data for p-nuclei needed)

- **Upgrade of Auger Observatory and TA**

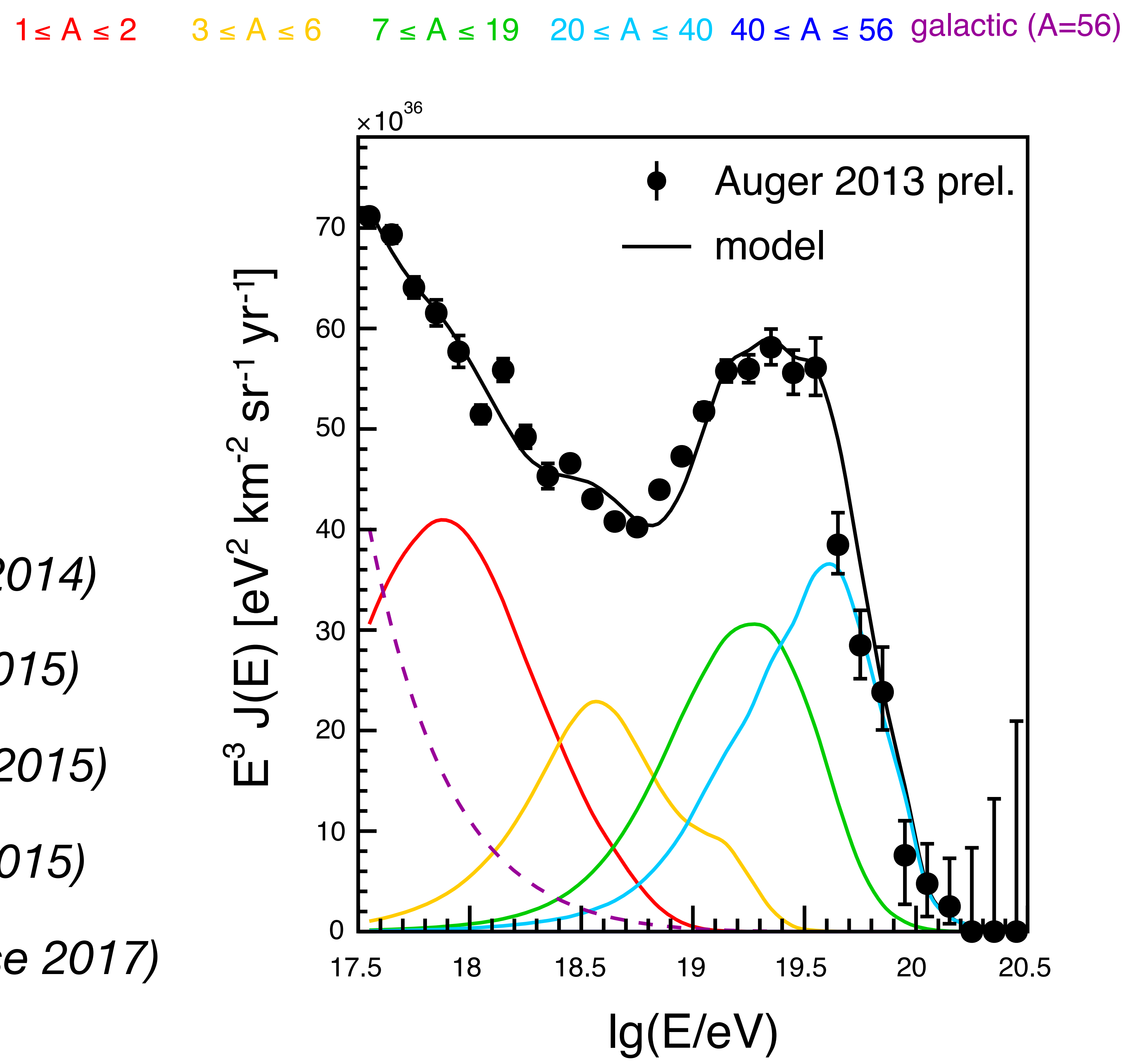
(Aloisio et al. 2014)

(Taylor et al. 2015)

(Globus et al. 2015)

(Unger et al. 2015)

(Fang & Murase 2017)

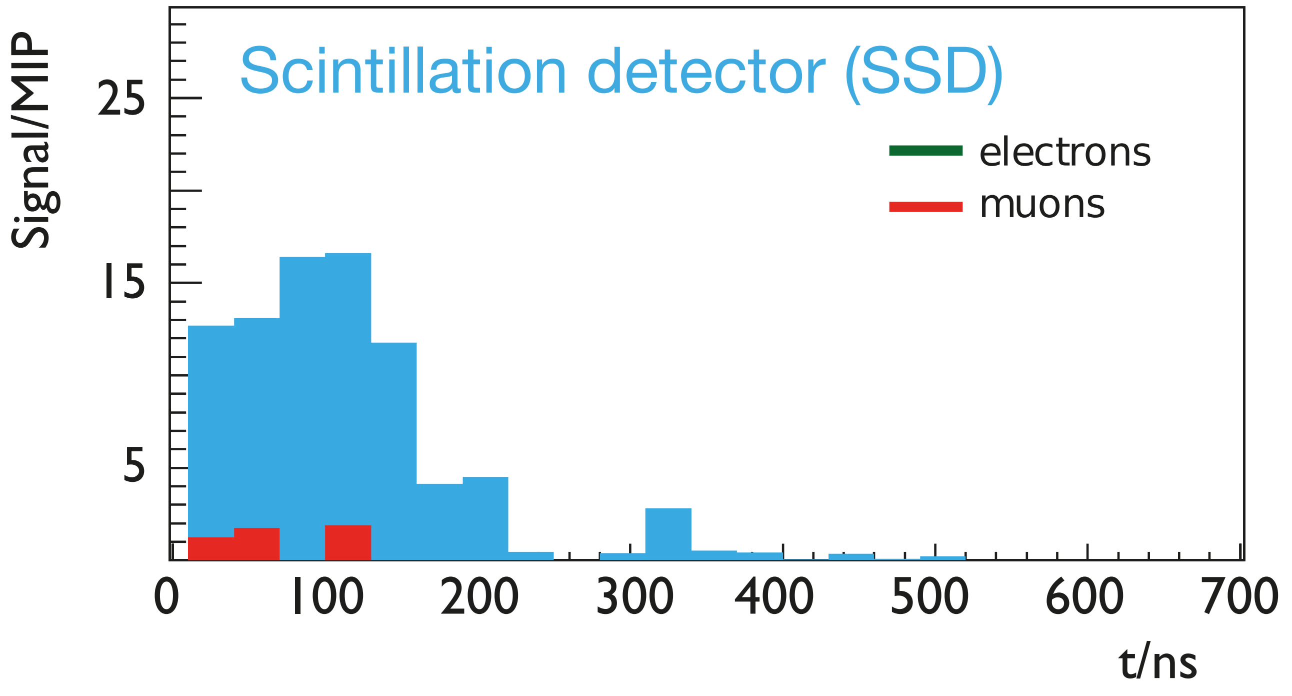


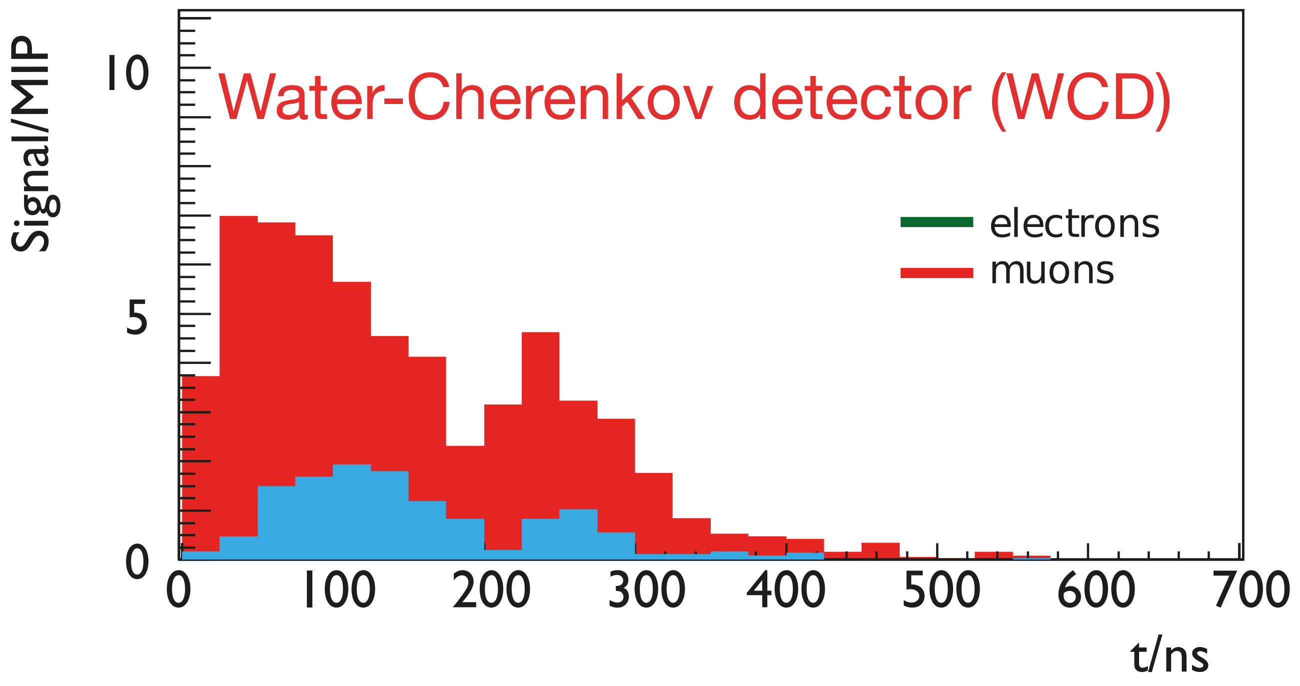
Upgrade of Auger Observatory: AugerPrime

15% duty cycle

100% duty cycle

Deployment fast: ~ 5 -10 stations per day

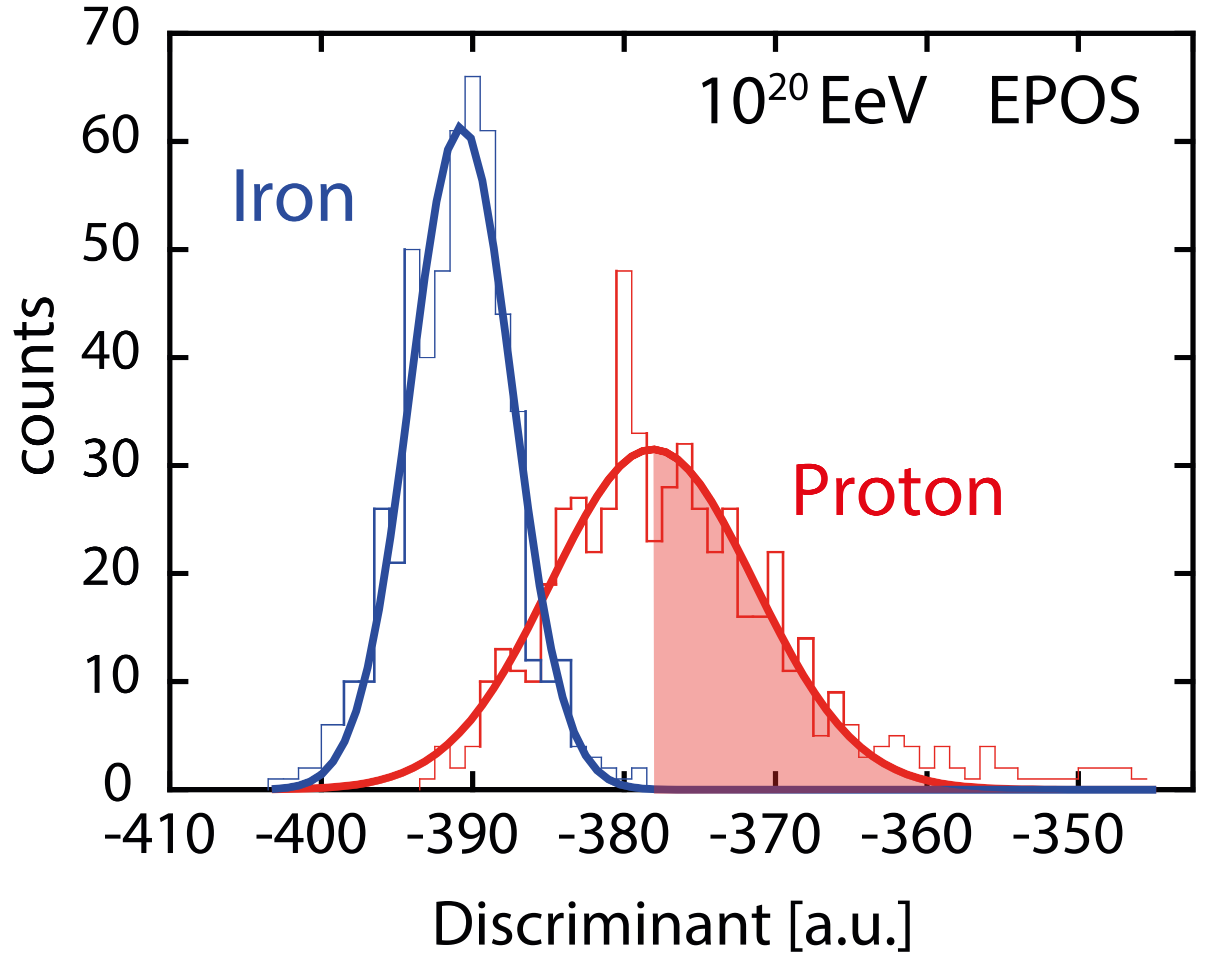




- **Scintillators (3.8 m^2) on top of each array detector**
- **Composition measurement up to 10^{20} eV**
- **Composition selected anisotropy**
- **Particle physics with air showers**

(AugerPrime design report 1604.03637)

2016-09-15: first station in field



Production and shipping of upgrade detectors in full swing

Karlsruhe
(standard loading)

Lecce (top loading)

Production sites

Aachen and KIT (Germany)
Grenoble (France)
Krakow (Poland)
Nijmegen (Netherlands)
Lecce (Italy)

First container: 25 Apr 2018 in Malargue

TAx4 Project

TA SD (~3000 km^2): 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)

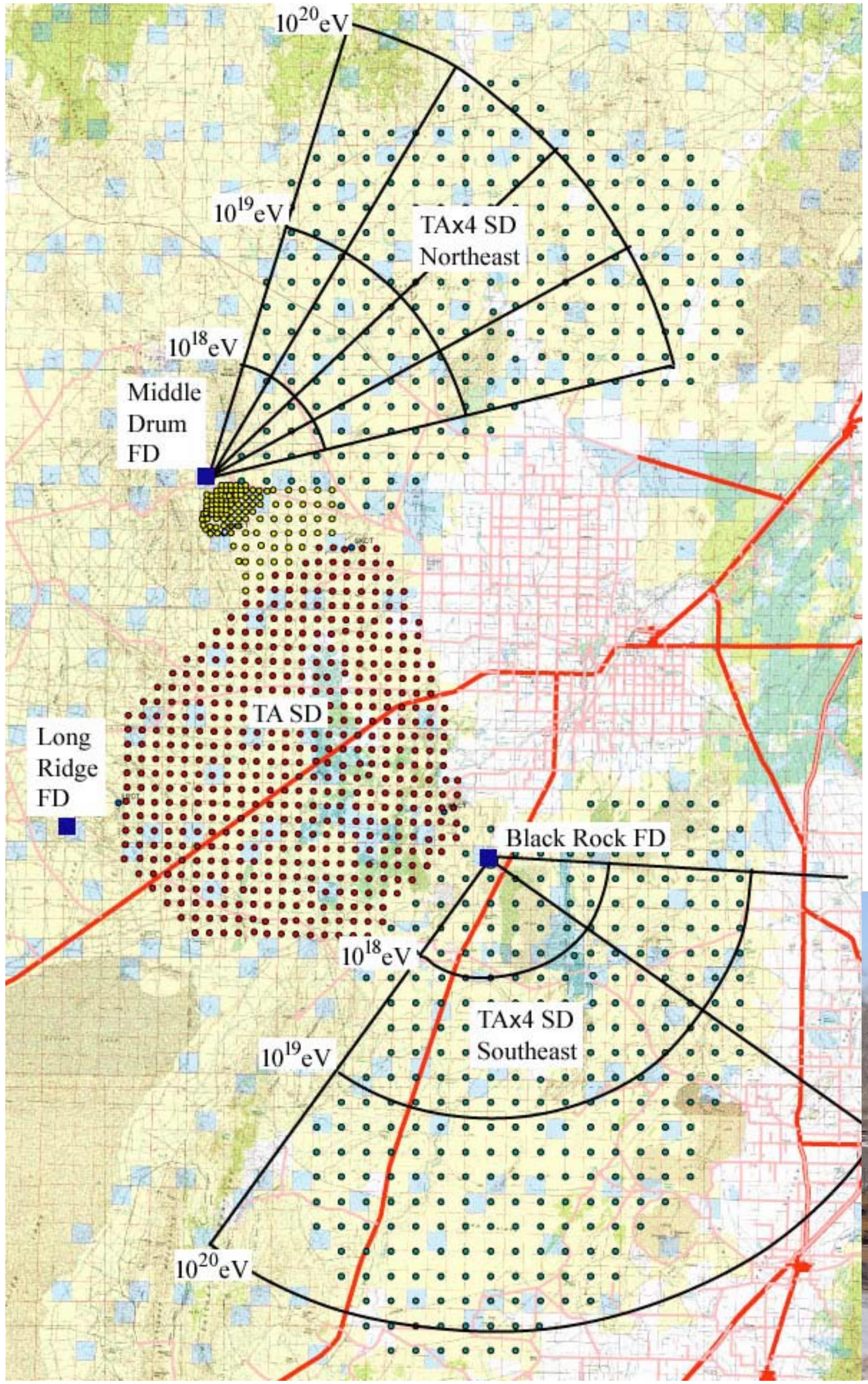
Approved US NSF 2016

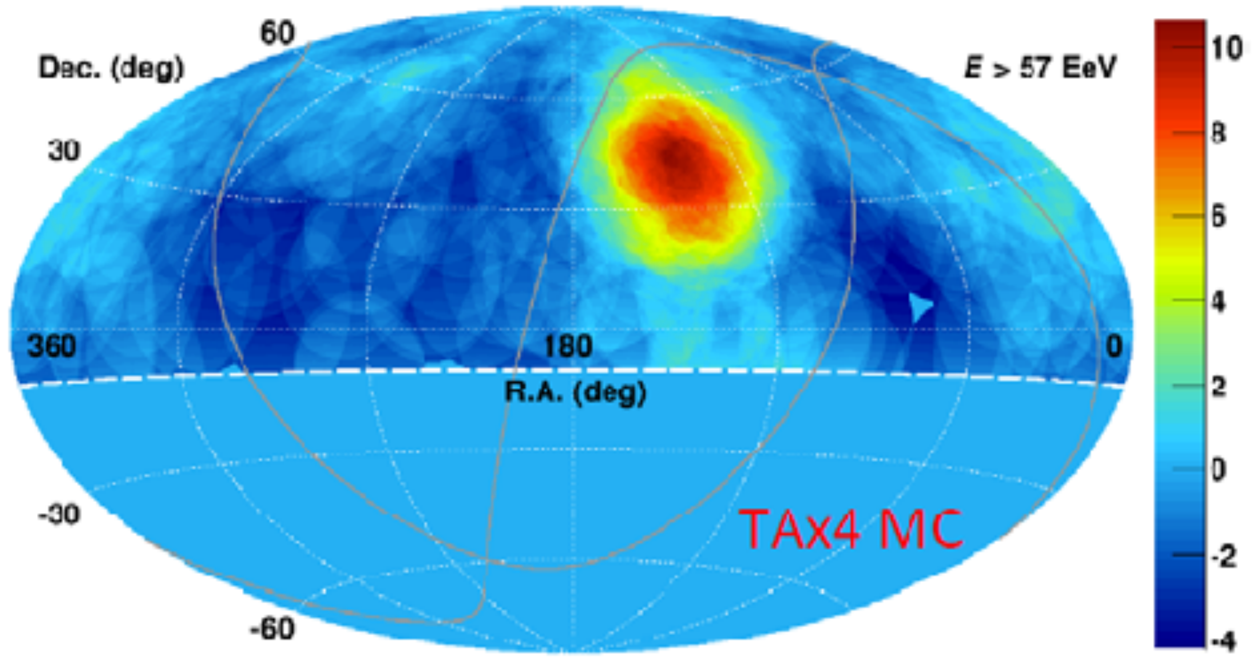
Telescopes/electronics being prepared at Univ. Utah

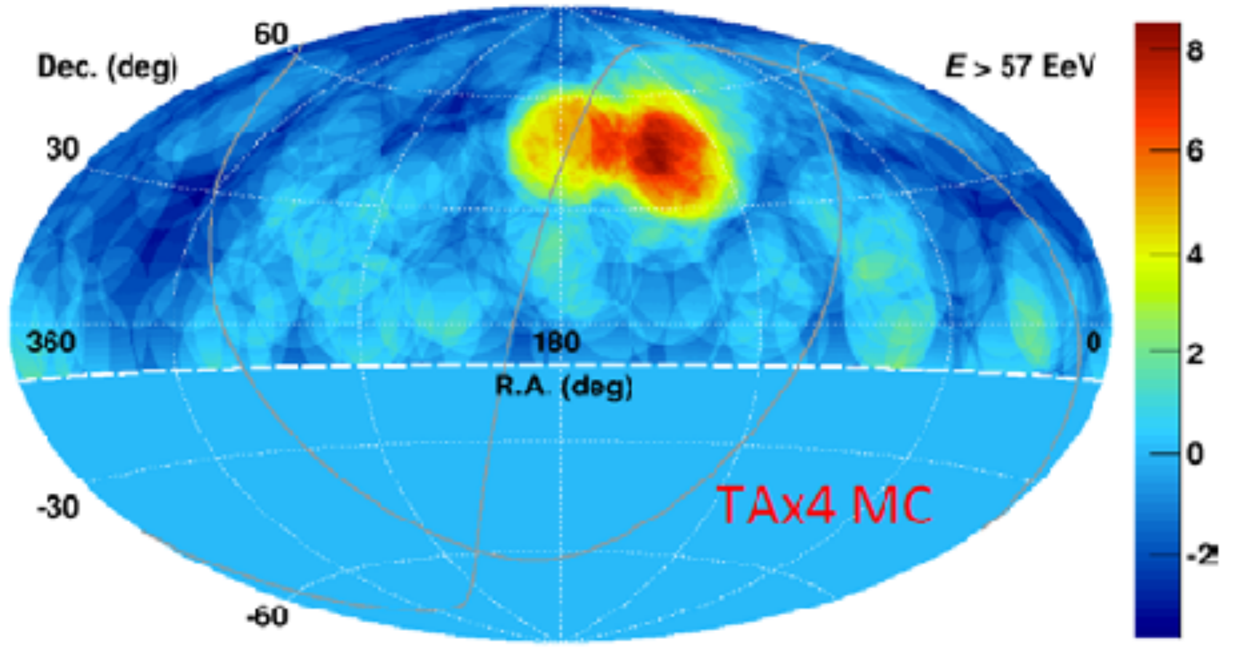
Site construction underway at the northern station.

Get 19 TA-equiv years of SD data by 2020

Get 16.3 (current) TA years of hybrid data







(Kido, Matthews ICRC 2017)