Recent progress in understanding ultra-high-energy cosmic rays

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PIERRE AUGER OBSERVATORY

(photograph by S. Saffi)

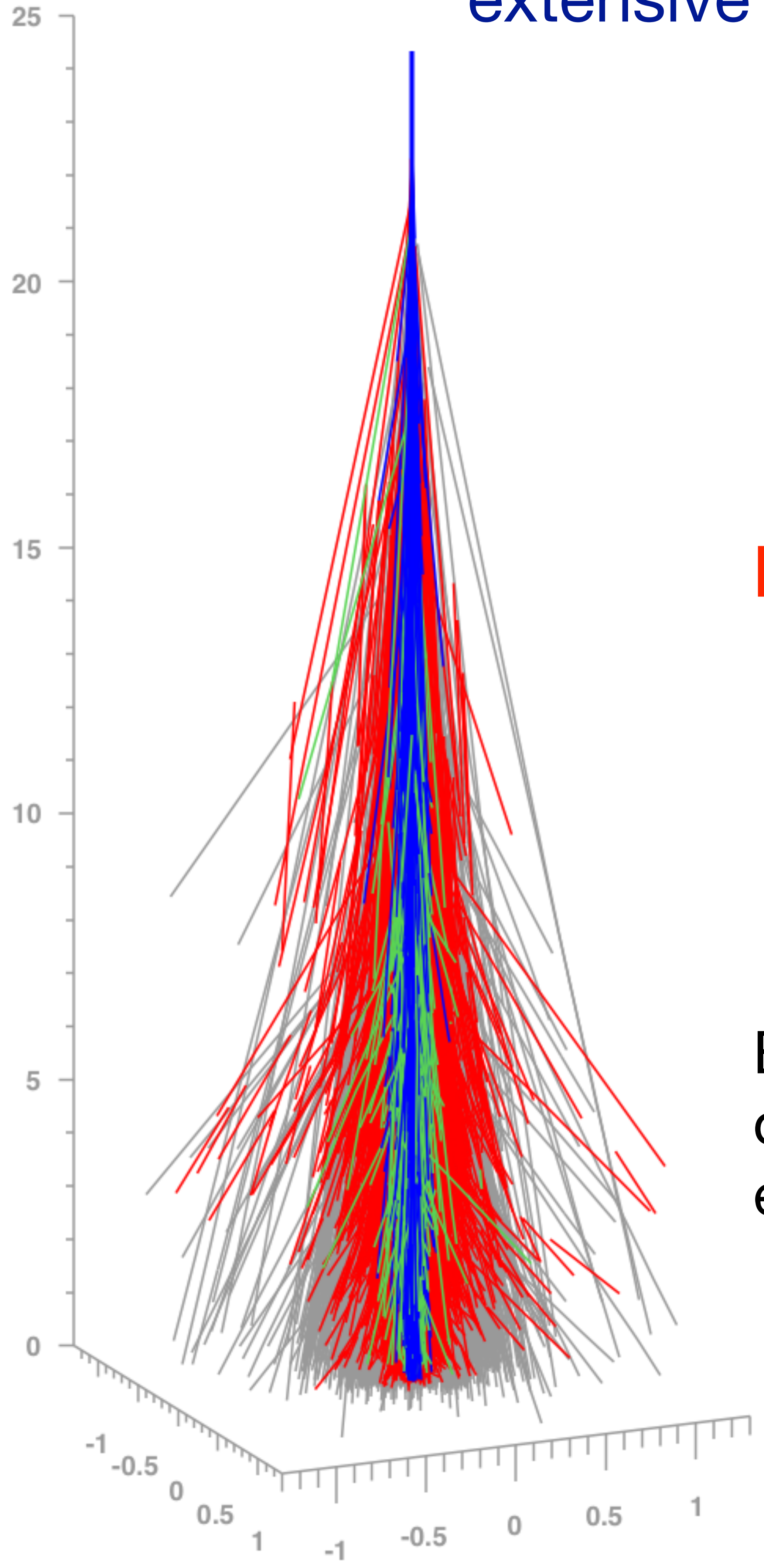
The first cosmic particle of ultra-high energy

VOLUME 10, NUMBER 4 PHYSICAL REVIEW LETTERS 15 FEBRUARY 1963

EVIDENCE FOR A PRIMARY COSMIC-RAY PARTICLE WITH ENERGY 10^{20} eV†

John Linsley
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 10 January 1963)

Cascade of secondary particles:
extensive air shower



E = 10^{20} eV

Energy conservation,
overall energy
estimate robust

Cosmic rays of 10^{20} eV energy exist

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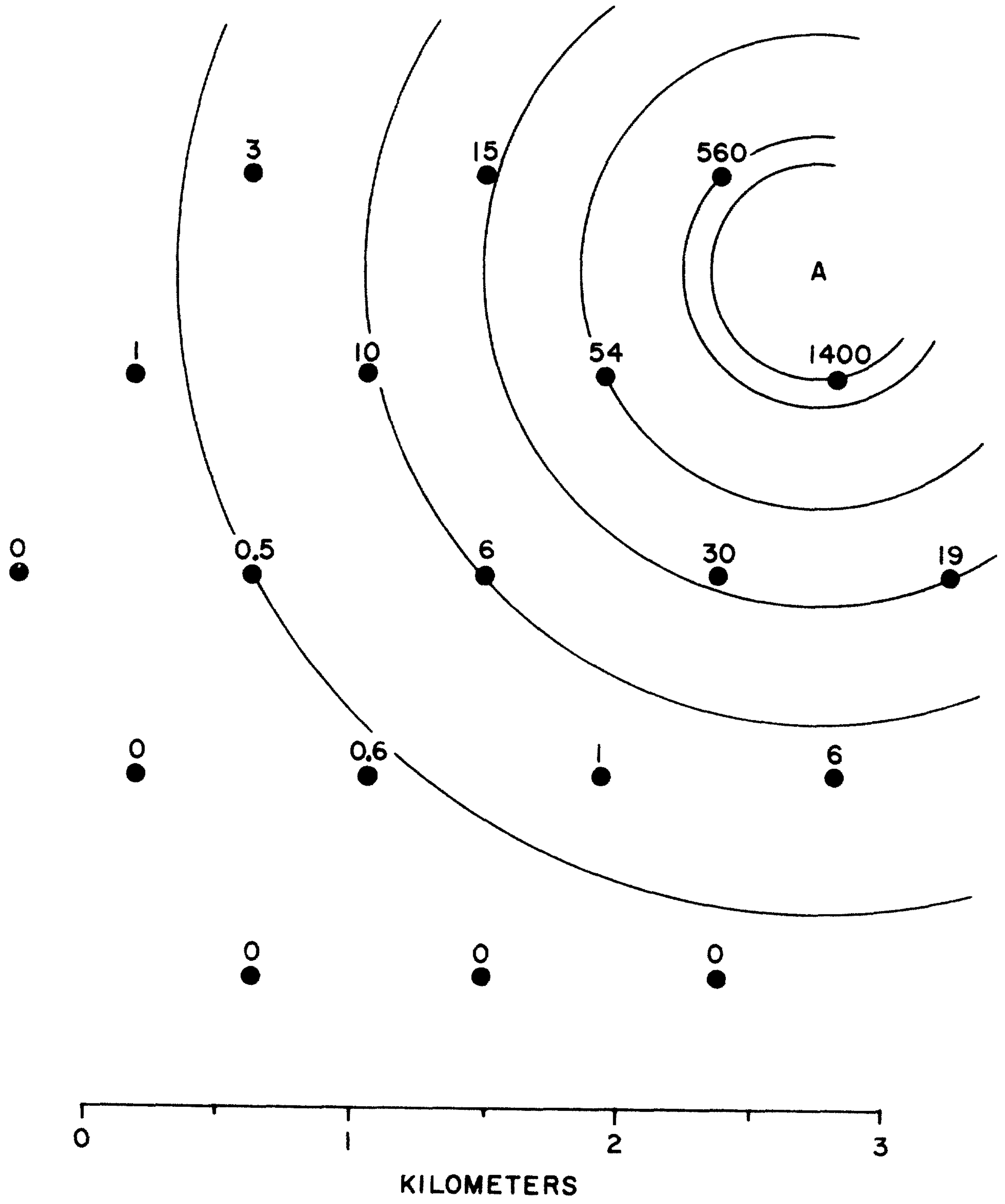
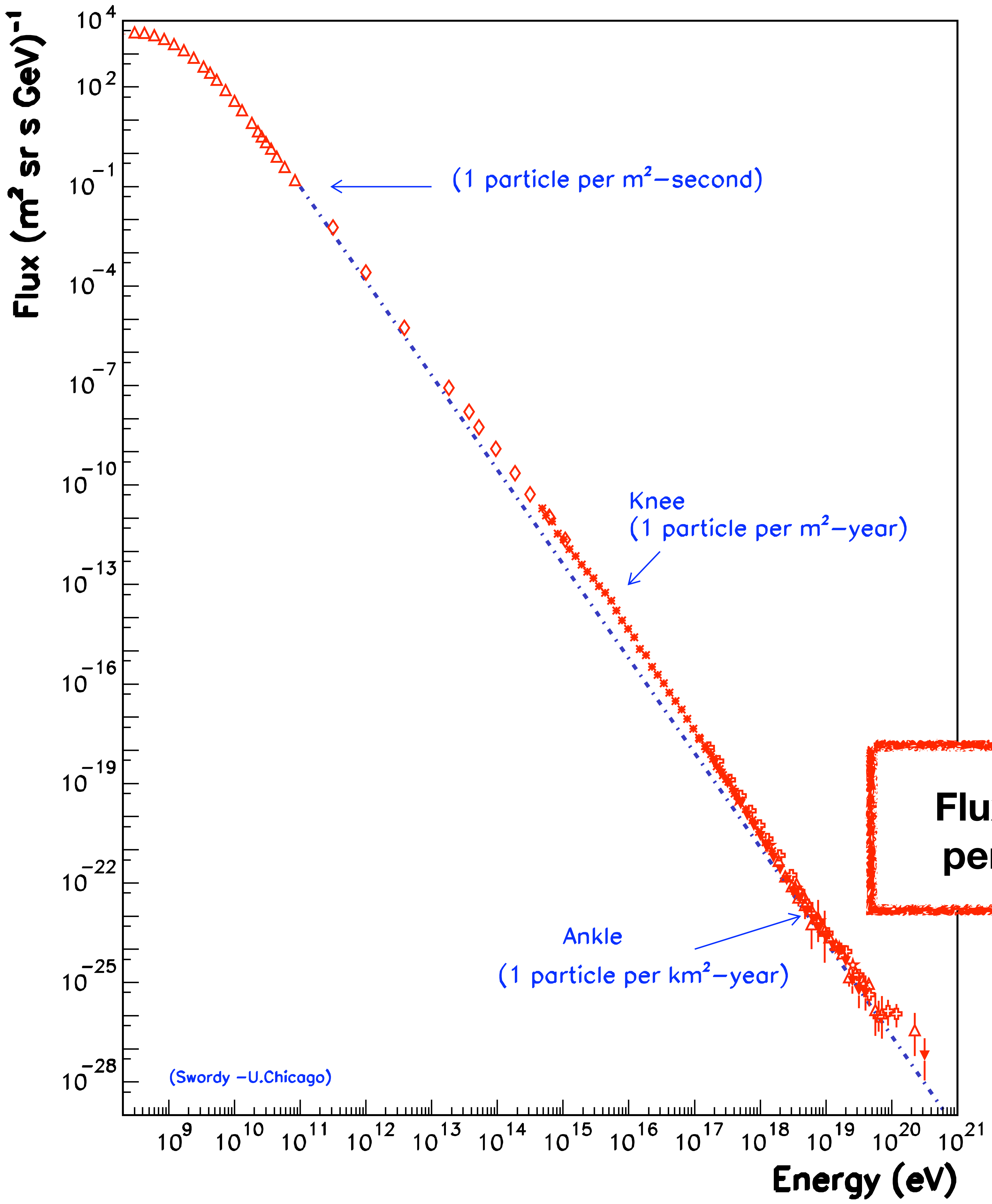
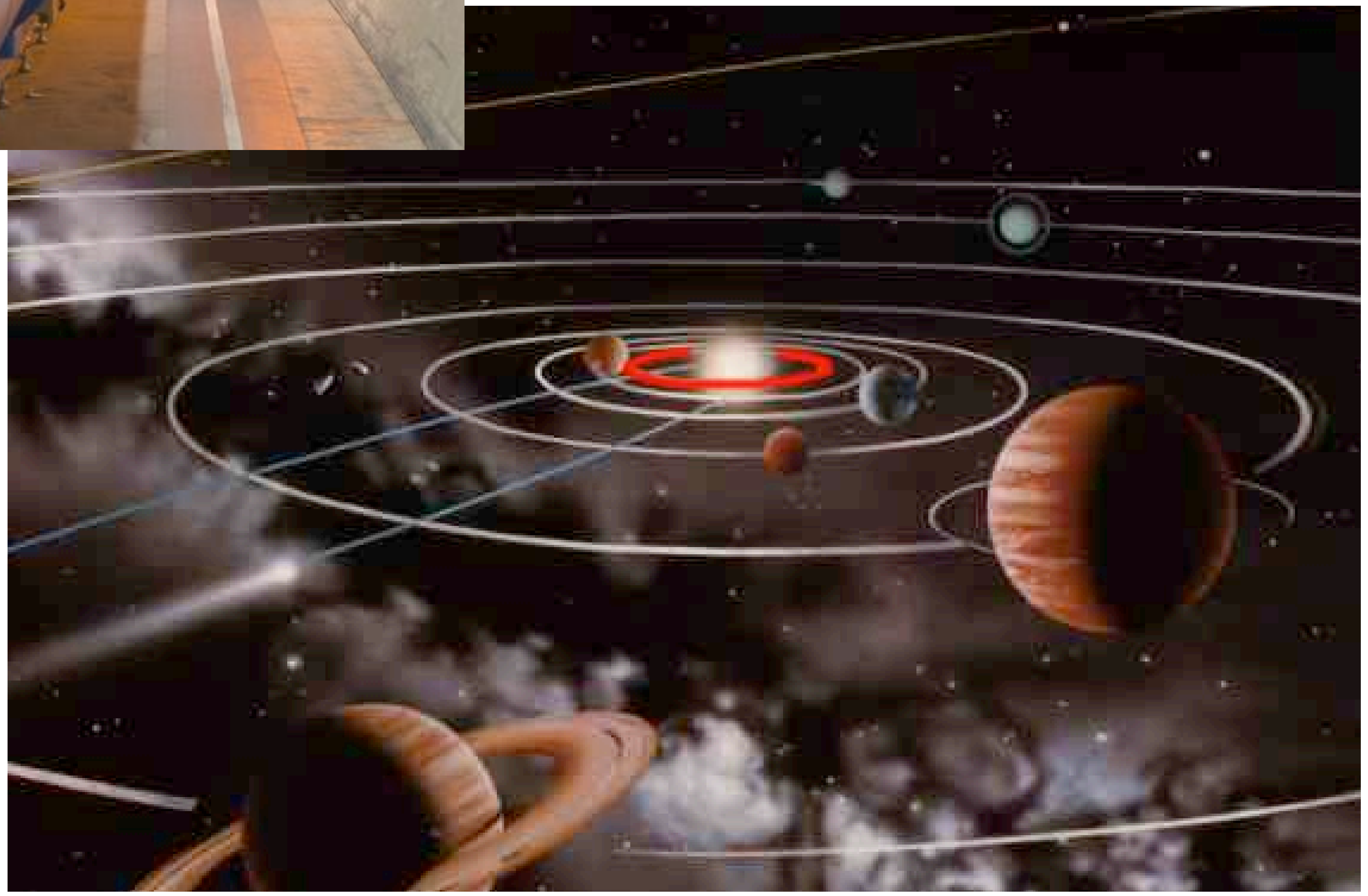


FIG. 1. Plan of the Volcano Ranch array in February 1962. The circles represent 3.3-m^2 scintillation detectors. The numbers near the circles are the shower densities (particles/m^2) registered in this event, No. 2-4834. Point "*A*" is the estimated location of the shower core. The circular contours about that point aid in verifying the core location by inspection.

Energy spectrum of cosmic rays – 10^{20} eV



Large Hadron Collider (LHC), 27 km circumference, superconducting magnets



Flux below 1 particle per km² per century

Gamma factor ~10^{11}

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

Energy loss during propagation in CMB

Proton

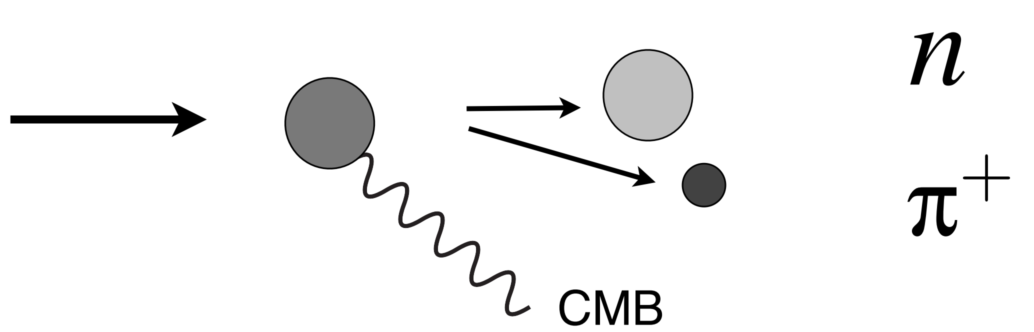


Photo-pion production
(mainly Δ resonance)

Nuclei

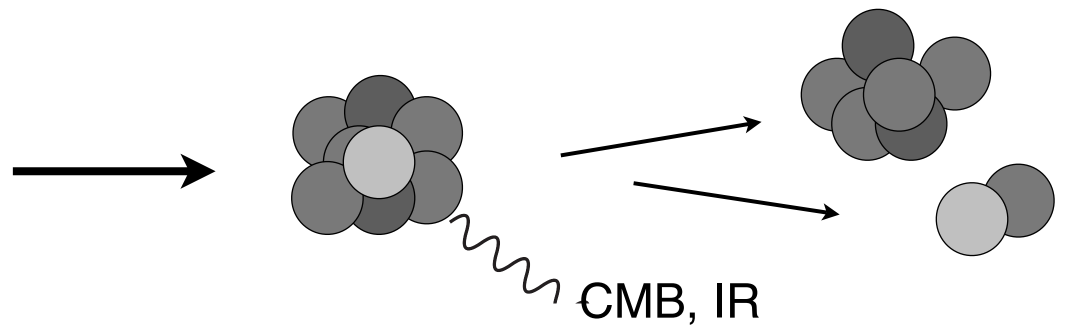
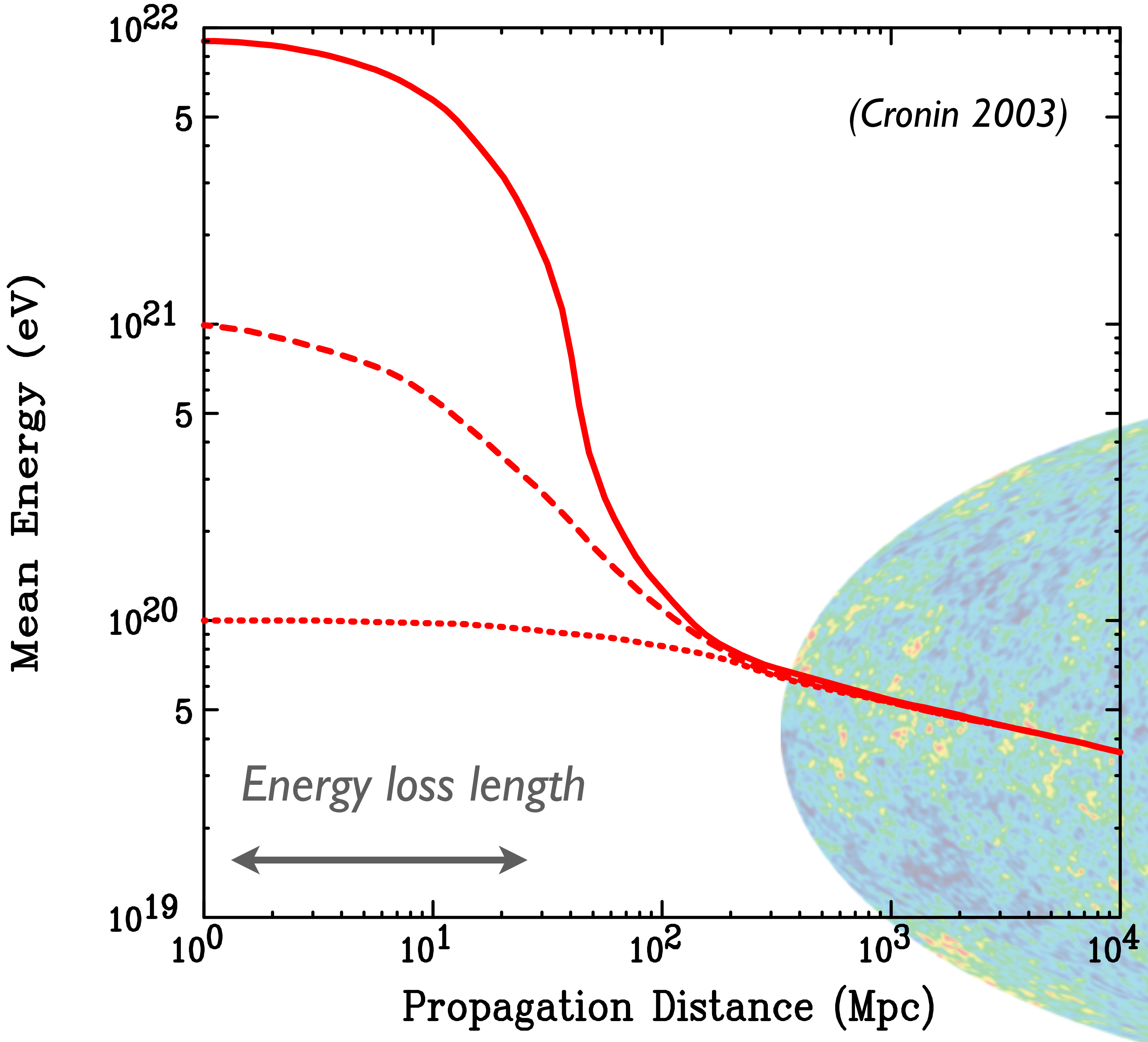
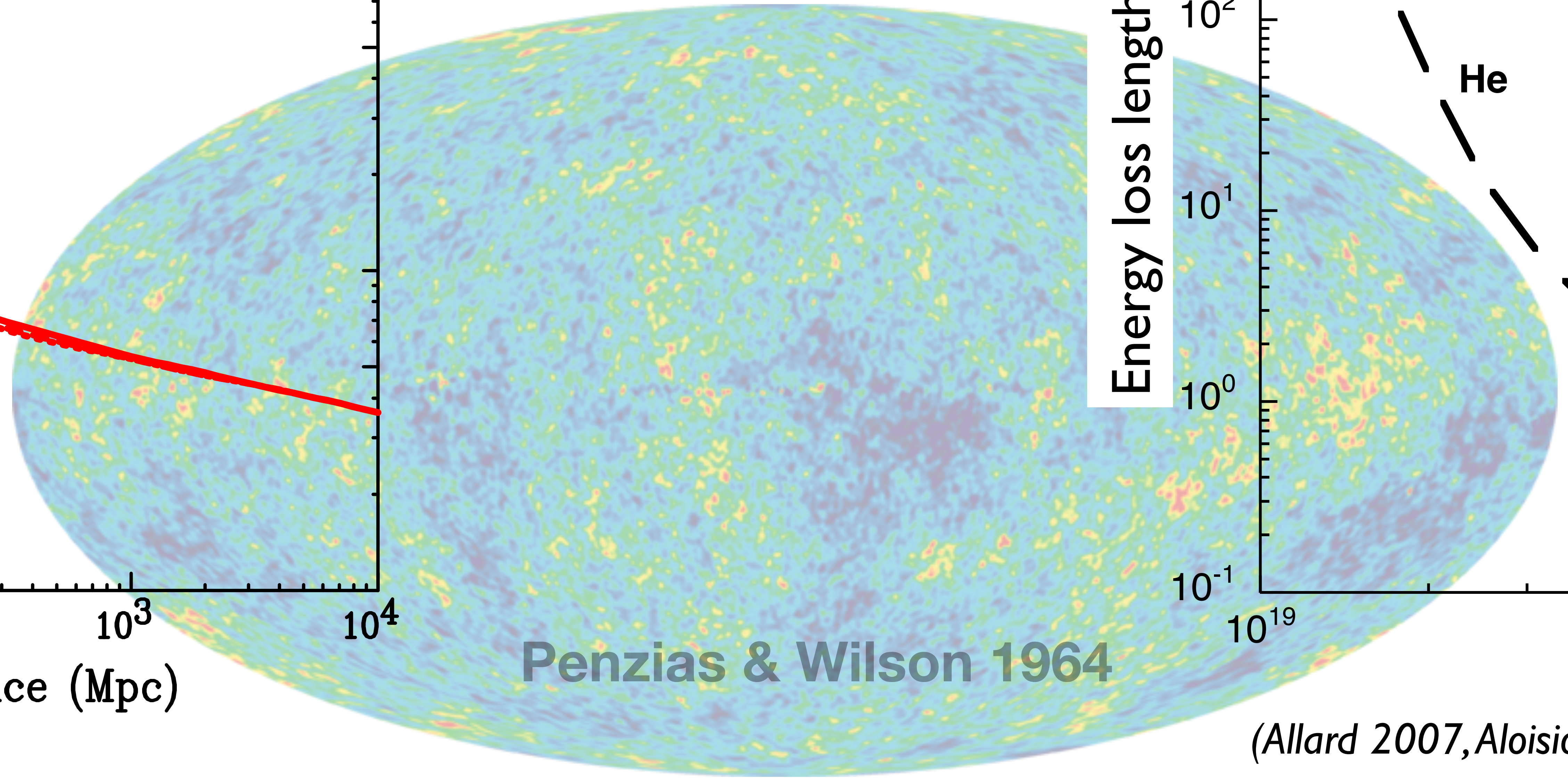
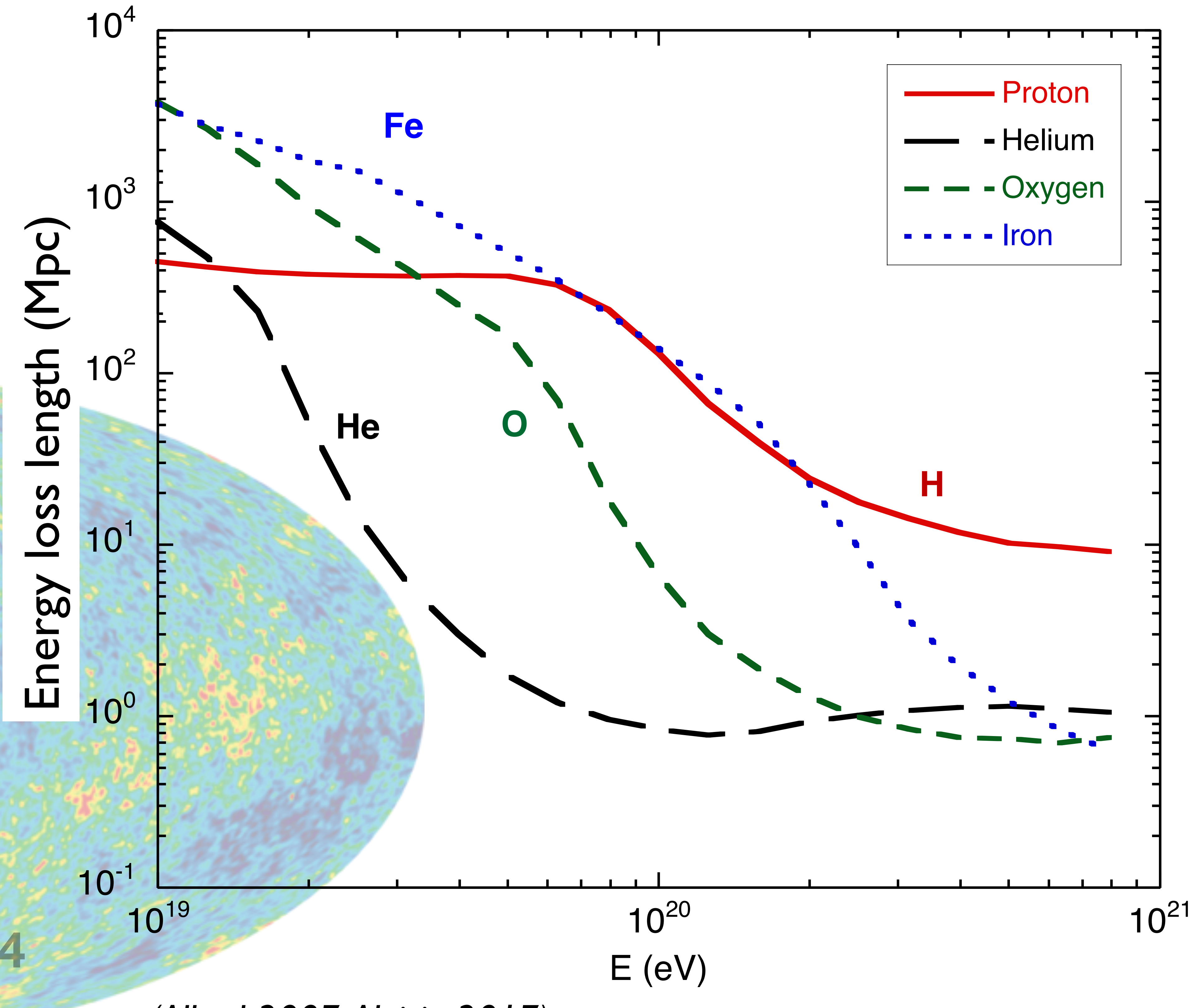


Photo-dissociation
(giant dipole resonance)



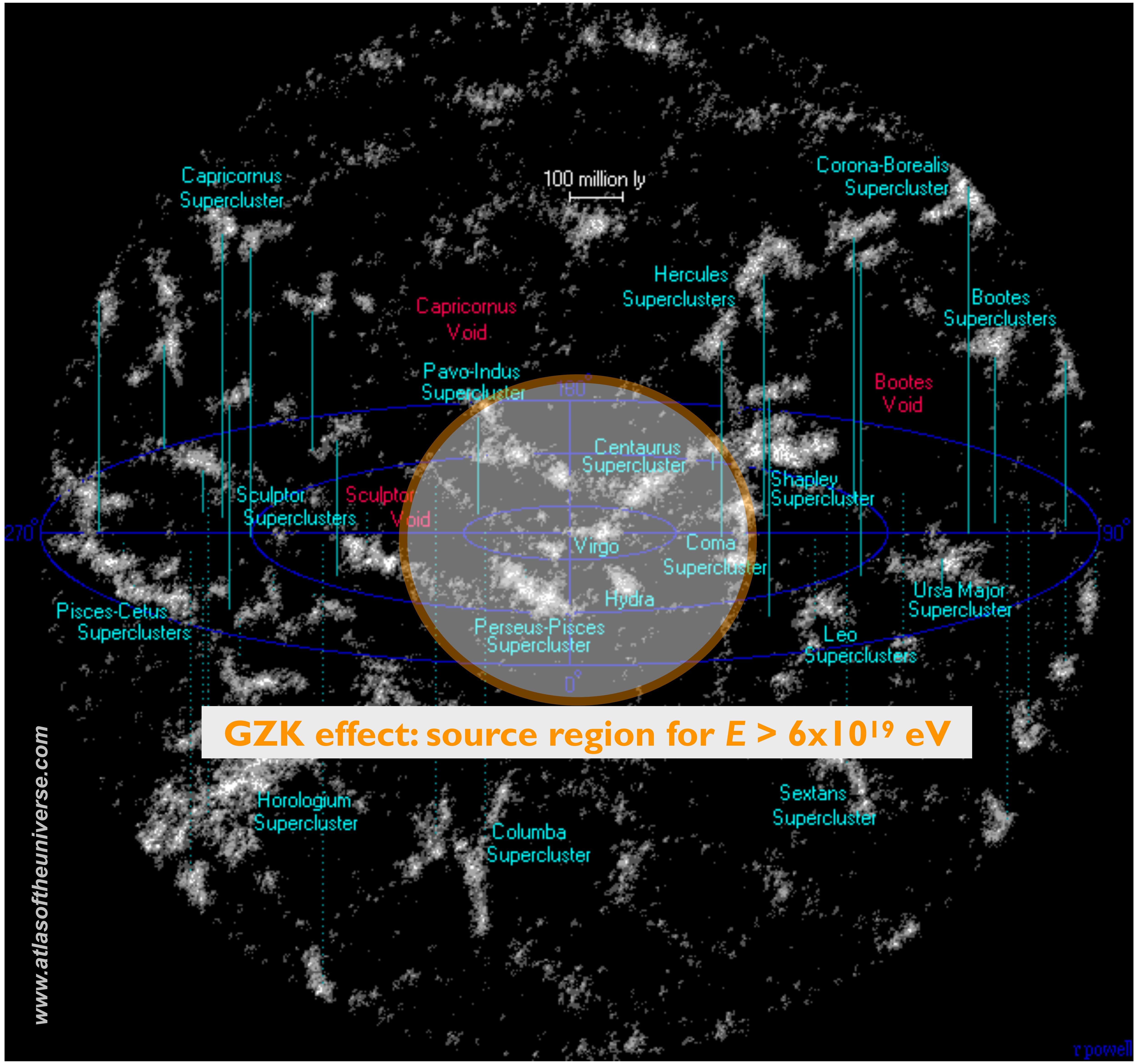
Greisen,
Zatsepin & Kuzmin
(GZK) effect, 1966



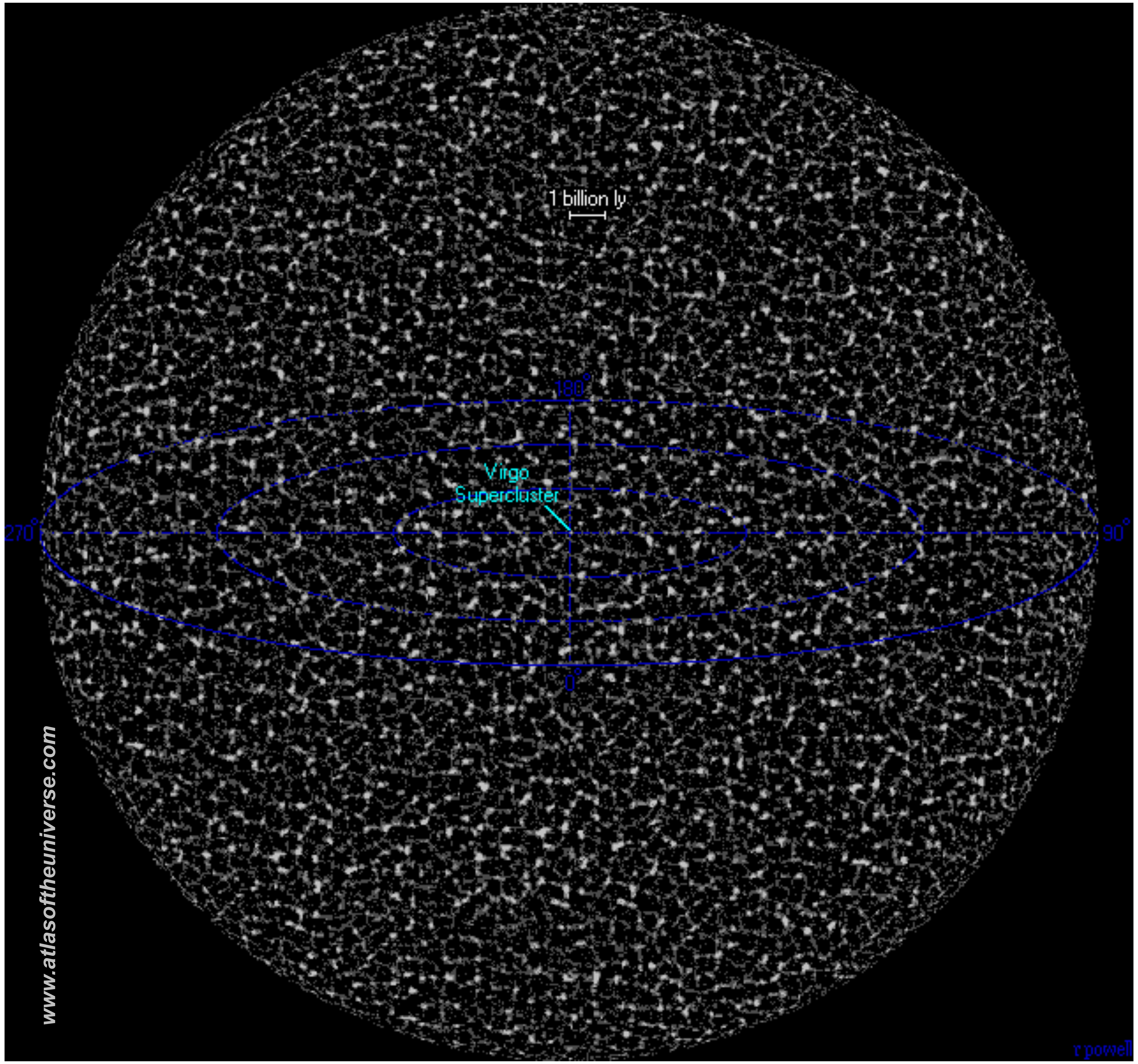


(Allard 2007, Aloisio 2017)

Distance ranges and matter distribution in the Universe



Ultra-high-energy cosmic rays (and also gamma-rays)

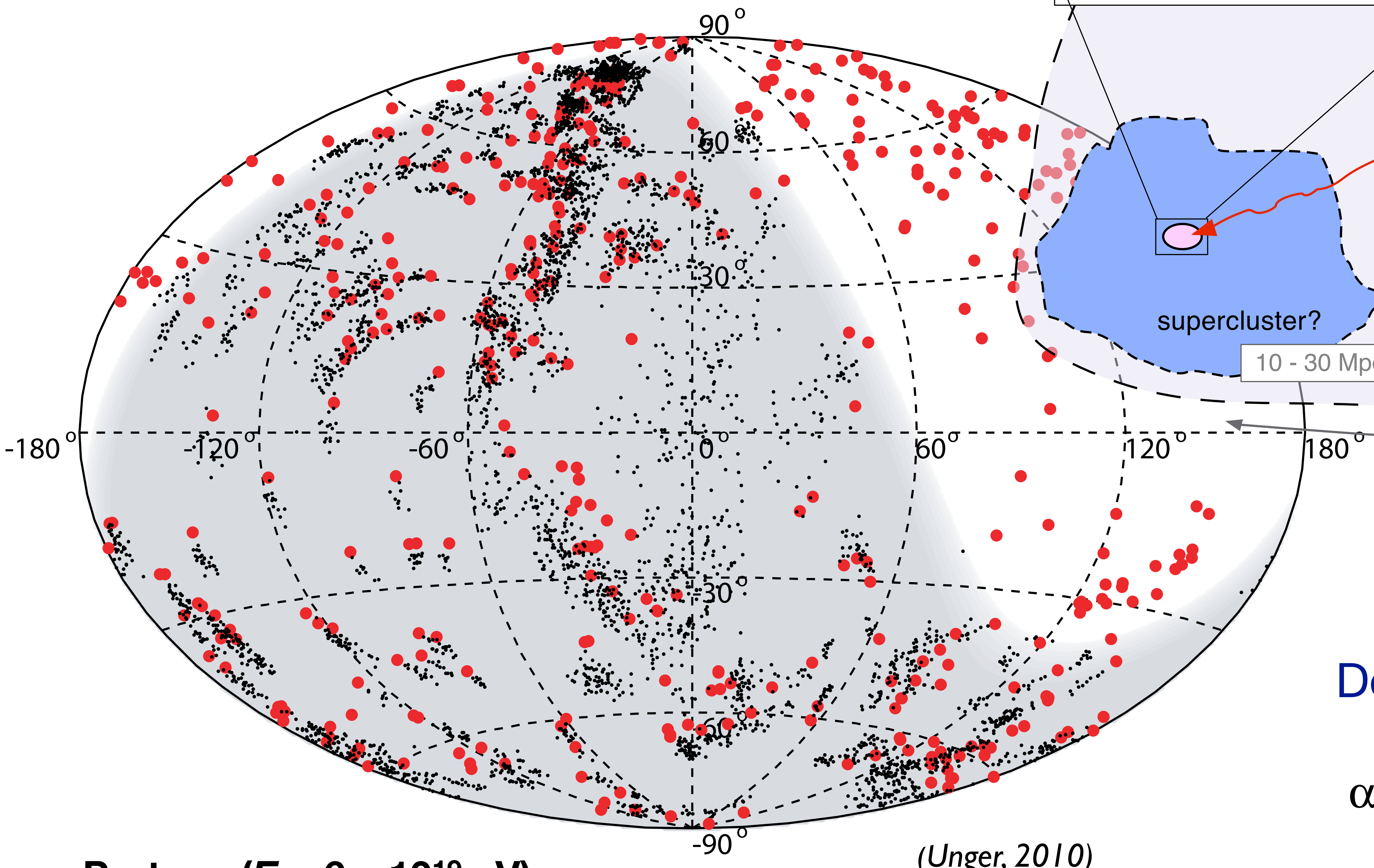


Neutrinos

Angular deflection of ultra-high-energy cosmic rays

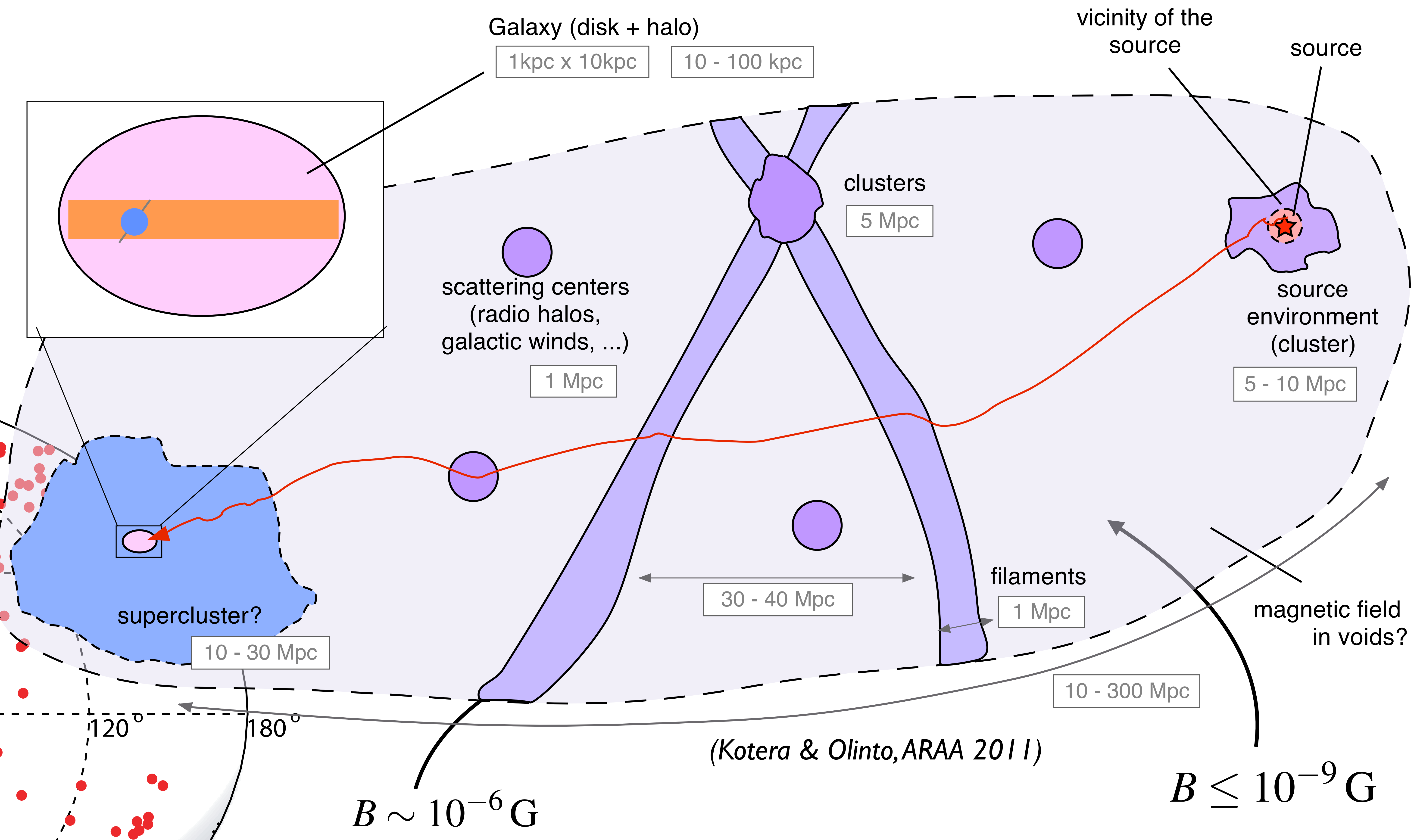
Deflection in Galactic mag. field

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



Protons (E > 6 x 10^{19} eV)

(Unger, 2010)



(Kotera & Olinto, ARAA 2011)

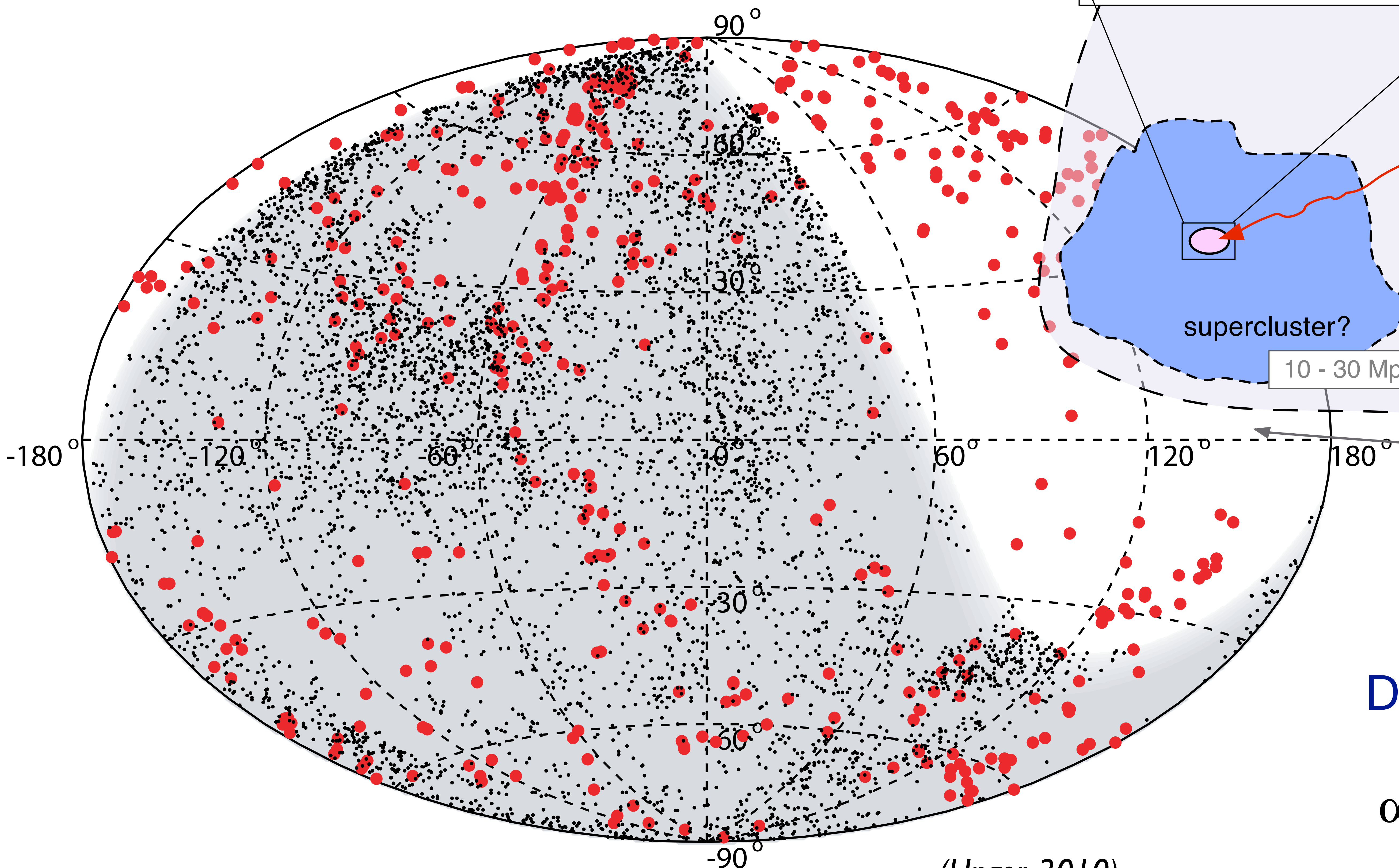
Deflection in extragal. mag. fields

$$\alpha_{\rm rms} \simeq 3.5^\circ \times Z \left(\frac{B}{1\,{\rm nG}}\right) \left(\frac{E}{10^{20}\,{\rm eV}}\right)^{-1} \left(\frac{l_{\rm coh}}{1\,{\rm Mpc}}\right)^{1/2} \left(\frac{D}{100\,{\rm Mpc}}\right)^{1/2}$$

Angular deflection of ultra-high-energy cosmic rays

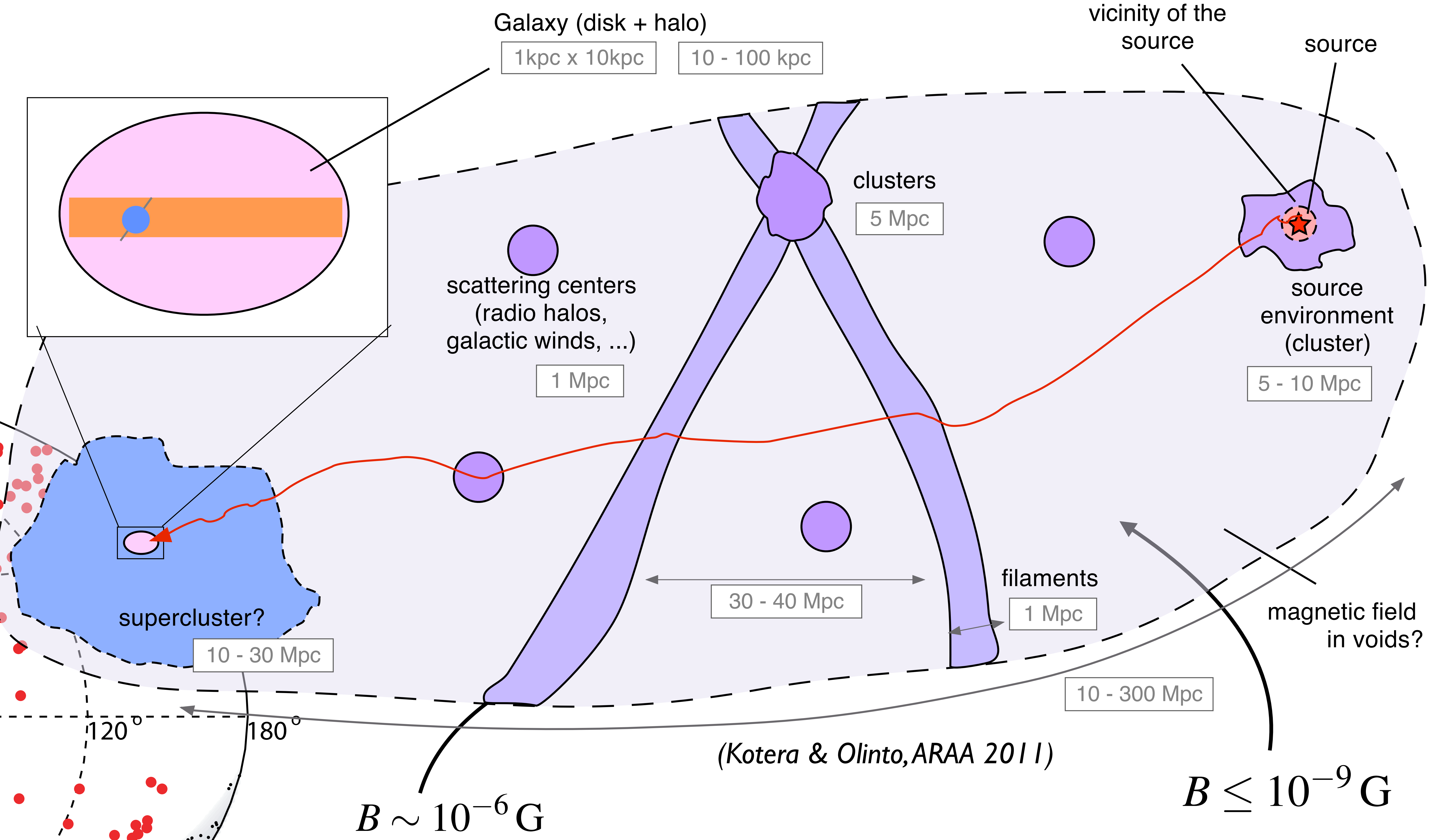
Deflection in Galactic mag. field

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



Carbon (E > 6 x 10^{19} eV)

(Unger, 2010)

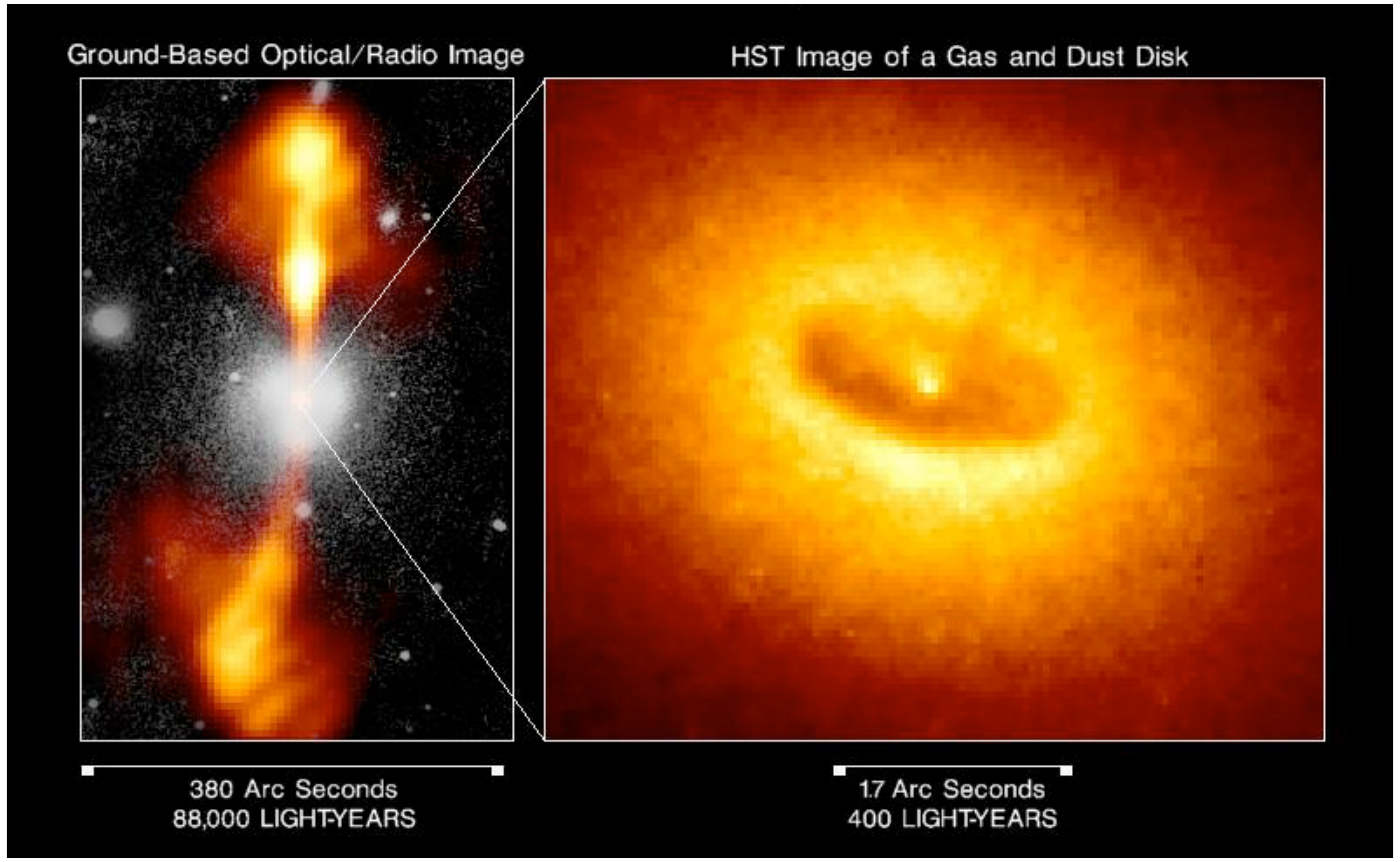


(Kotera & Olinto, ARAA 2011)

Deflection in extragal. mag. fields

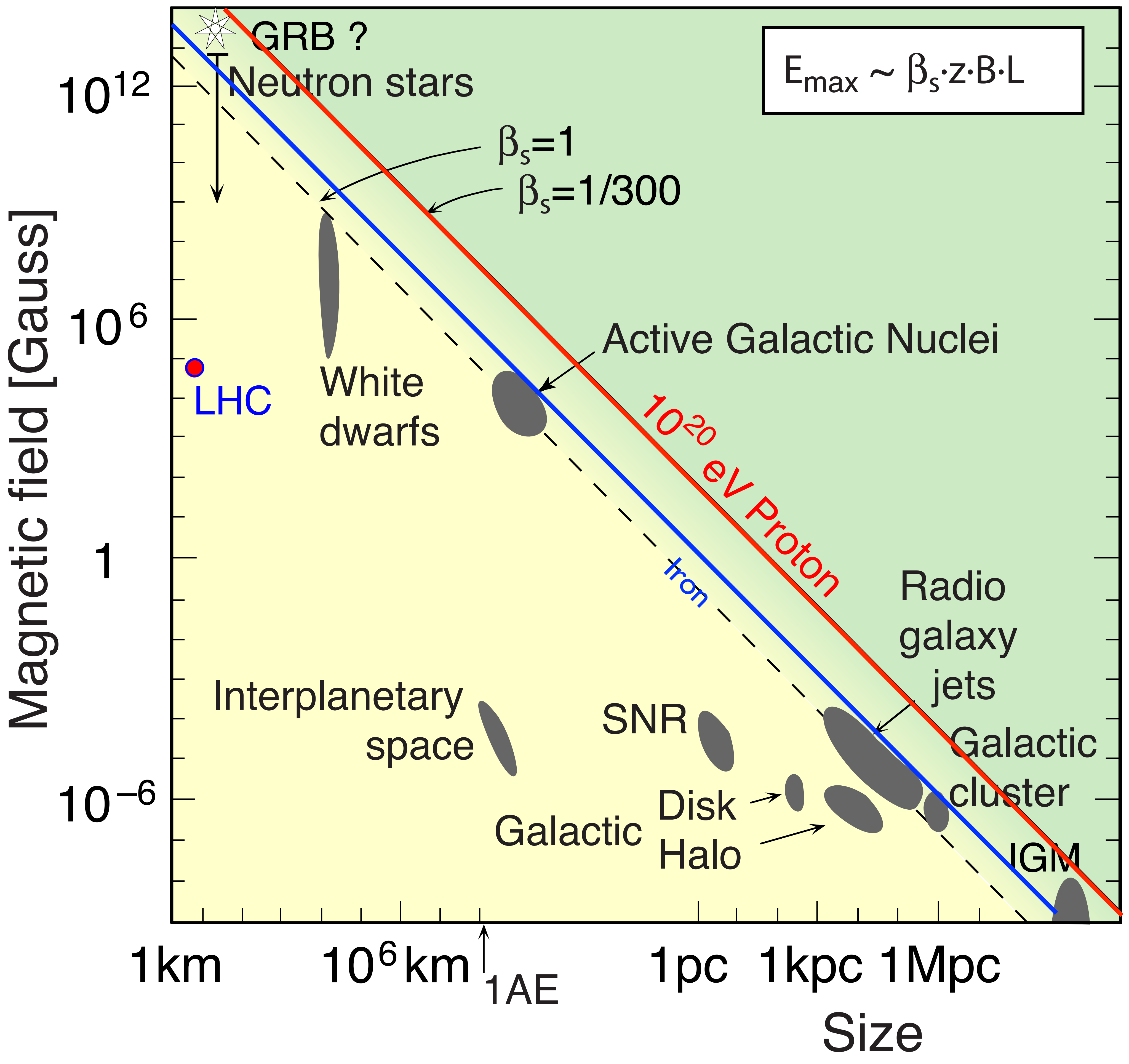
$$\alpha_{\rm rms} \simeq 3.5^\circ \times Z \left(\frac{B}{1\,{\rm nG}}\right)\left(\frac{E}{10^{20}\,{\rm eV}}\right)^{-1}\left(\frac{l_{\rm coh}}{1\,{\rm Mpc}}\right)^{1/2}\left(\frac{D}{100\,{\rm Mpc}}\right)^{1/2}$$

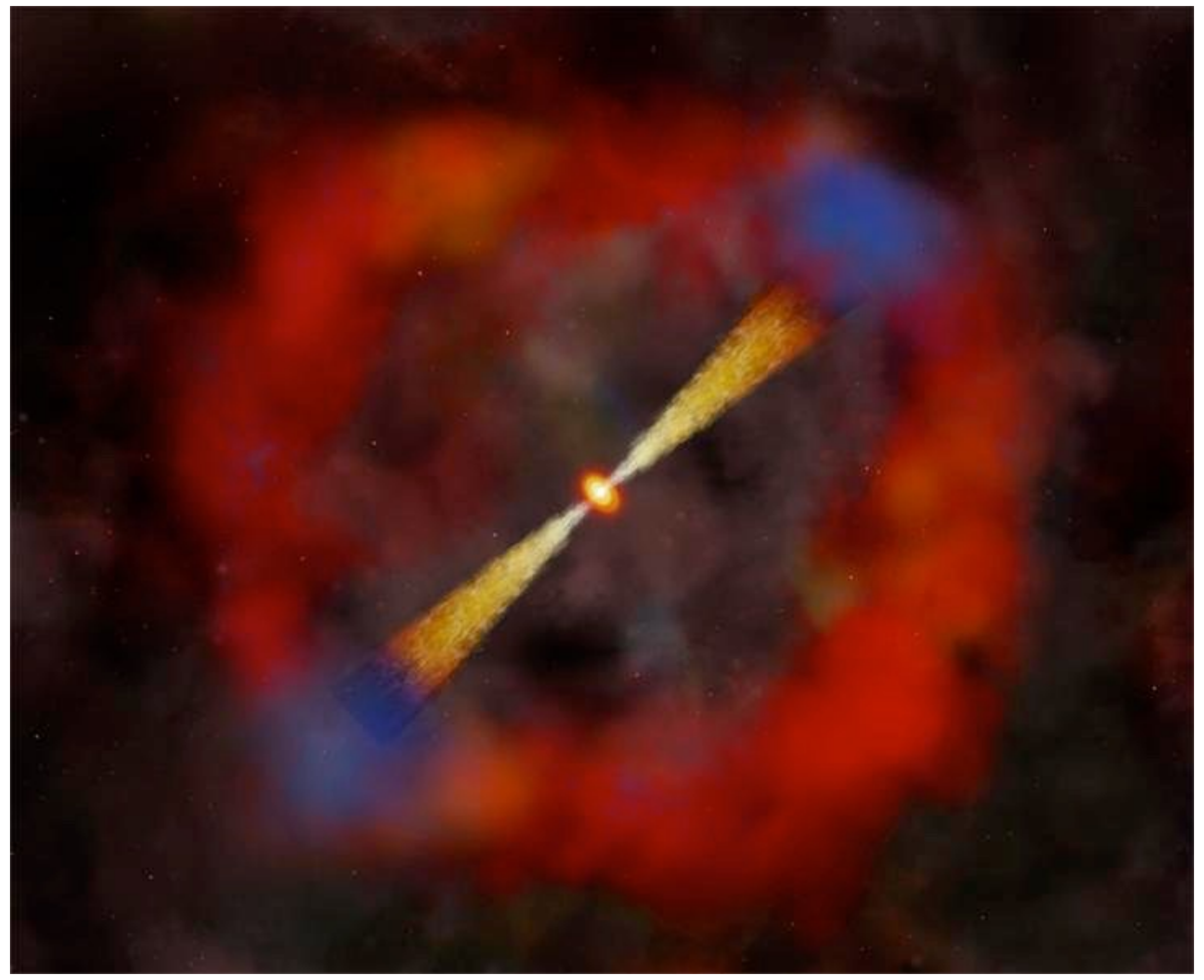
Diffusive shock acceleration



Hillas criterion (1984): $E_{\max} \sim \beta_s Z B R$

Power: $Q(E > 10^{18}\,\mathrm{eV}) \sim 5 \times 10^{45}\ \mathrm{erg/Mpc^3/yr}$





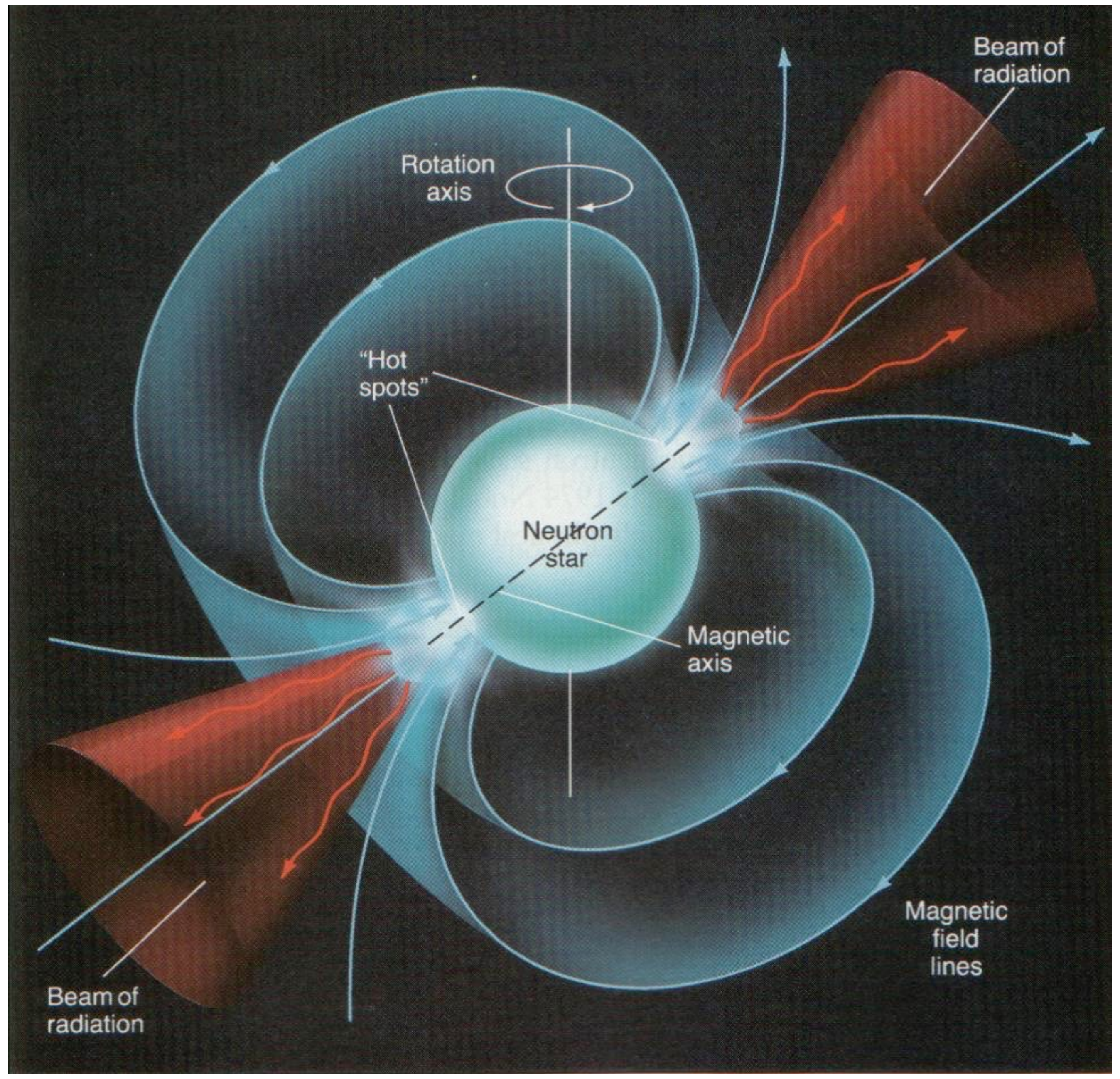
Active Galactic Nuclei (in jets or in radio lobes)

$$\frac{\mathrm{d}N_{\mathrm{inj}}}{\mathrm{d}E} \sim E^{-2}$$

Gamma ray bursts (GRBs)

Alternative source scenarios

Inductive acceleration

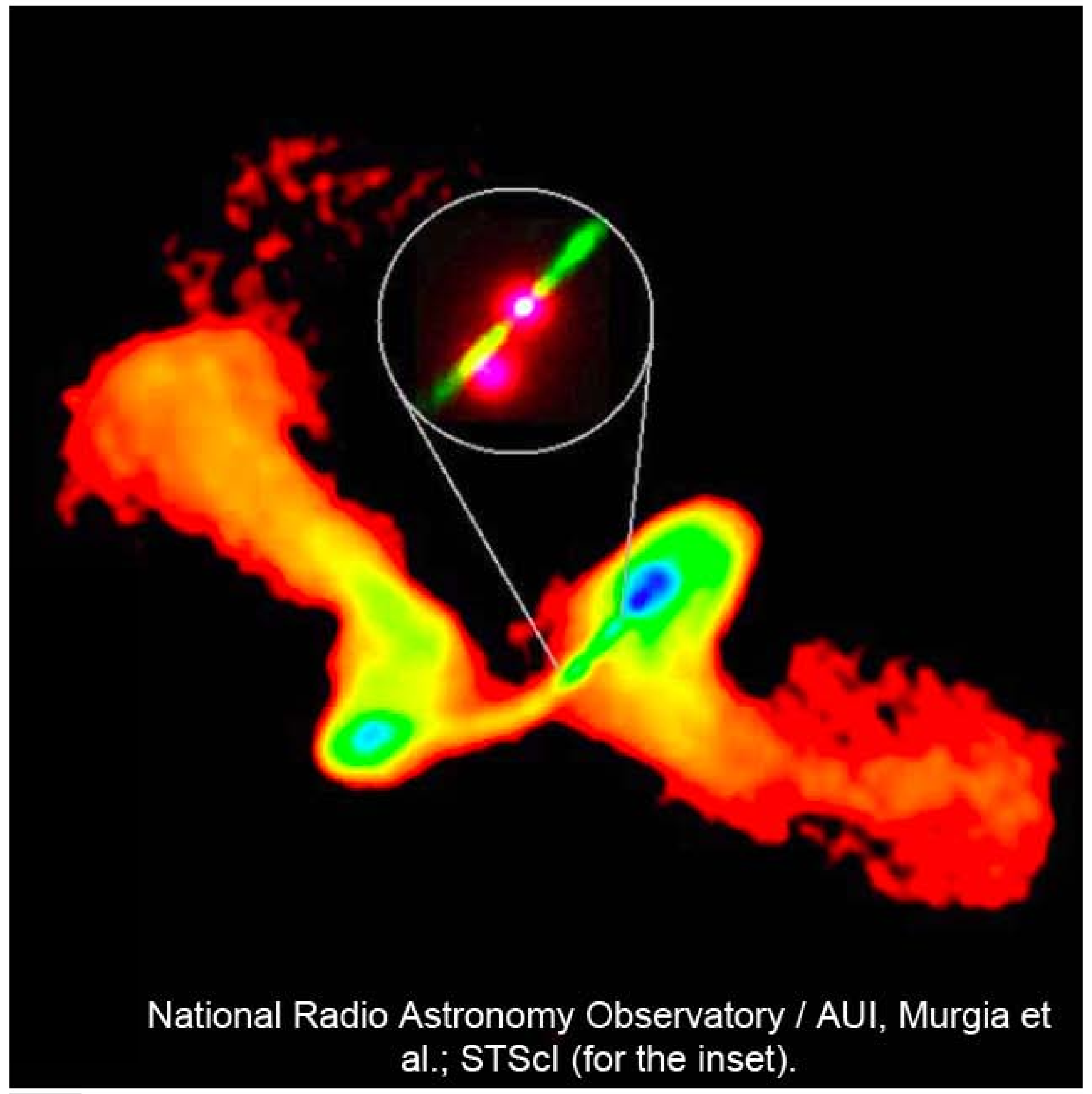


Rapidly spinning neutron stars

$$\frac{\mathrm{d}N_{\rm inj}}{\mathrm{d}E} \sim E^{-1}\left(1+\frac{E}{E_g}\right)^{-1}$$

Wake field acceleration in plasma jets

Single (relativistic) reflection



Spin flip of BH in AGN

Tidal disruption events (TDEs)

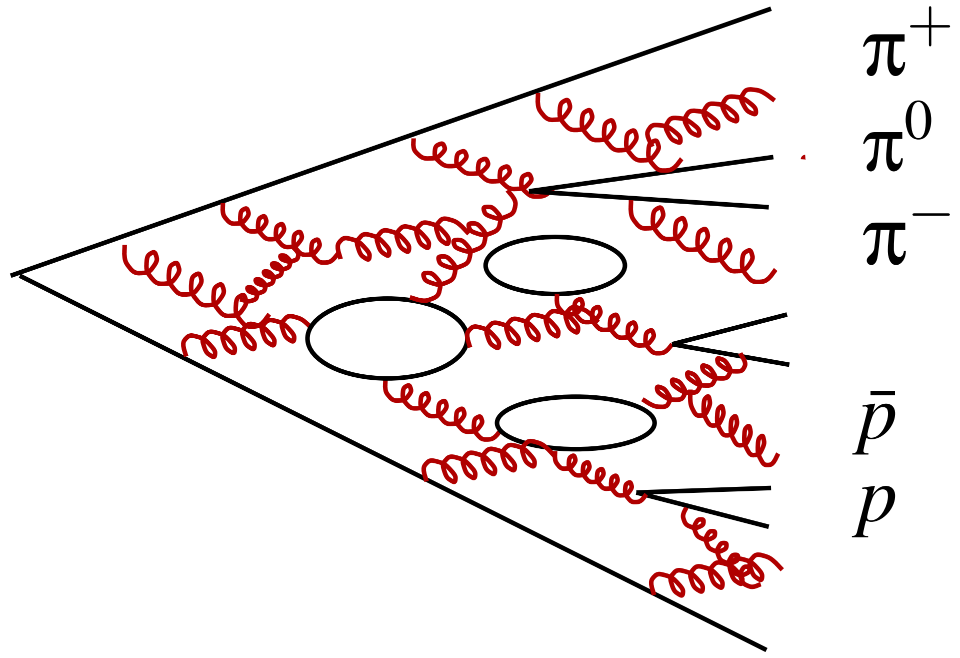
$$E_{\rm max} \sim \Gamma^2 \, E_{\rm inj}$$

New particle physics (top-down scenarios)

X particles from:

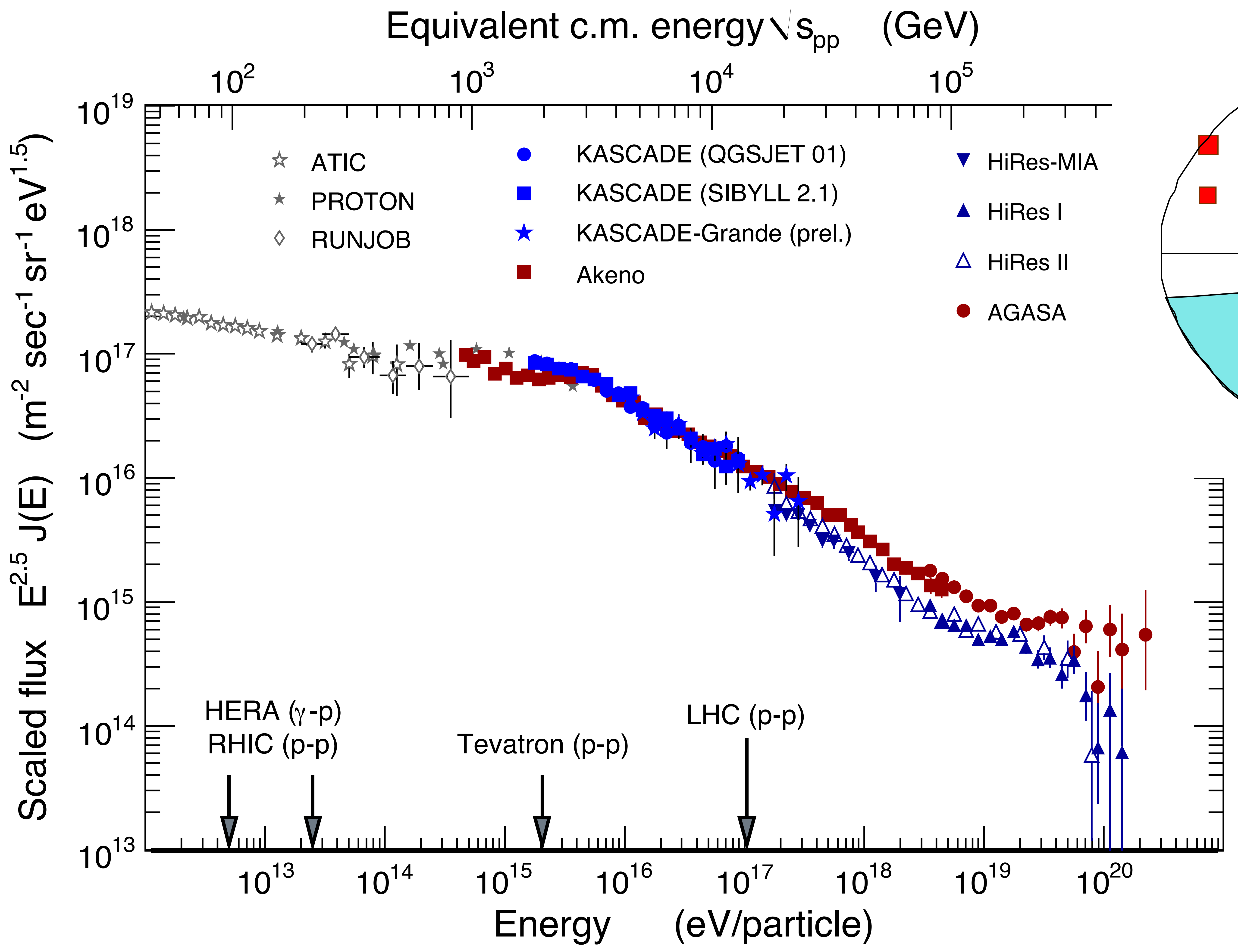
- topological defects
- monopoles
- cosmic strings
- cosmic necklaces
- .....

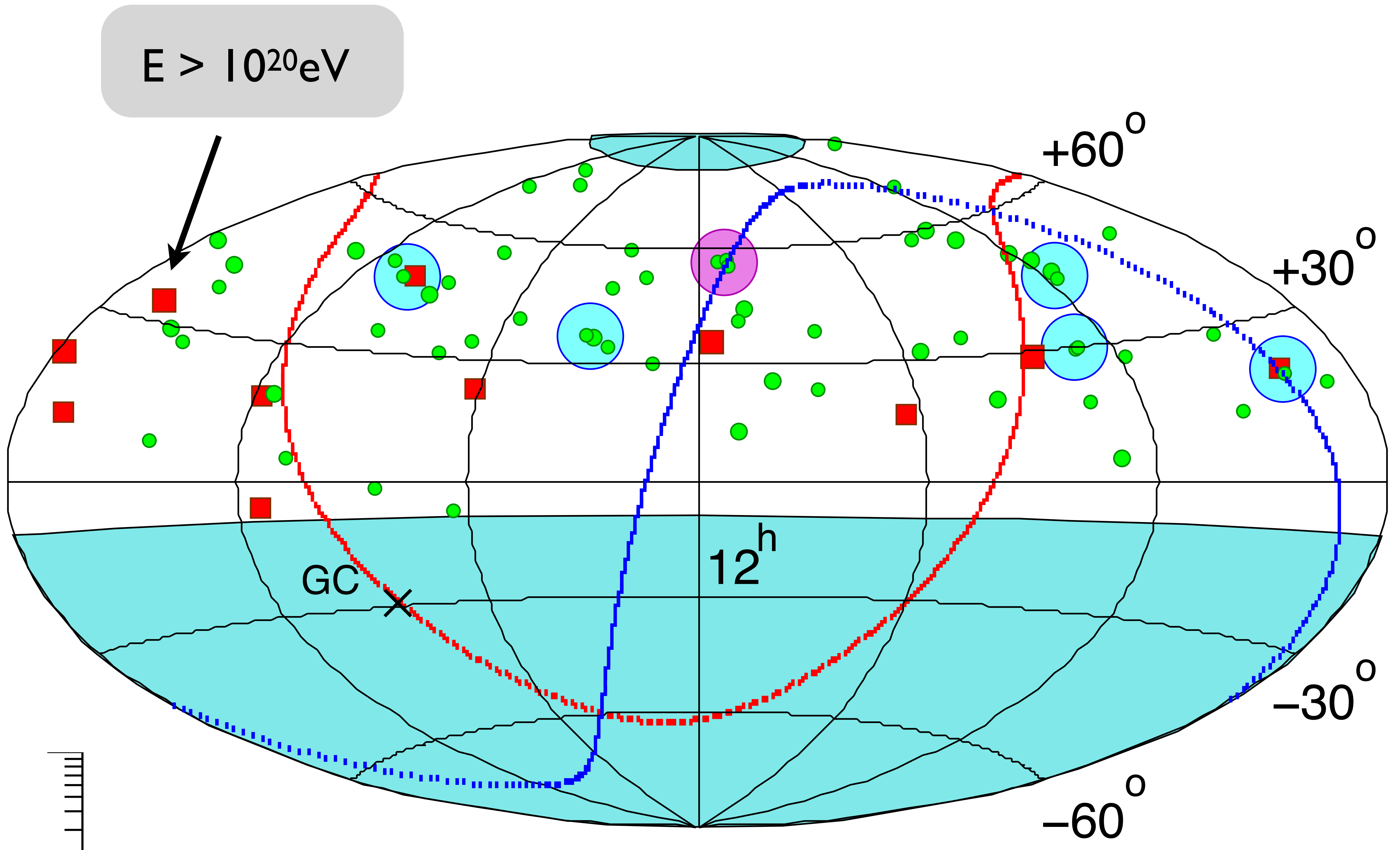
Super-heavy objects from Early Universe that decay slowly (by construction)
$M_X \sim 10^{23}$ - 10^{24} eV



large fluxes of photons and neutrinos

Status of the field 12 years ago (100 km² observatories)





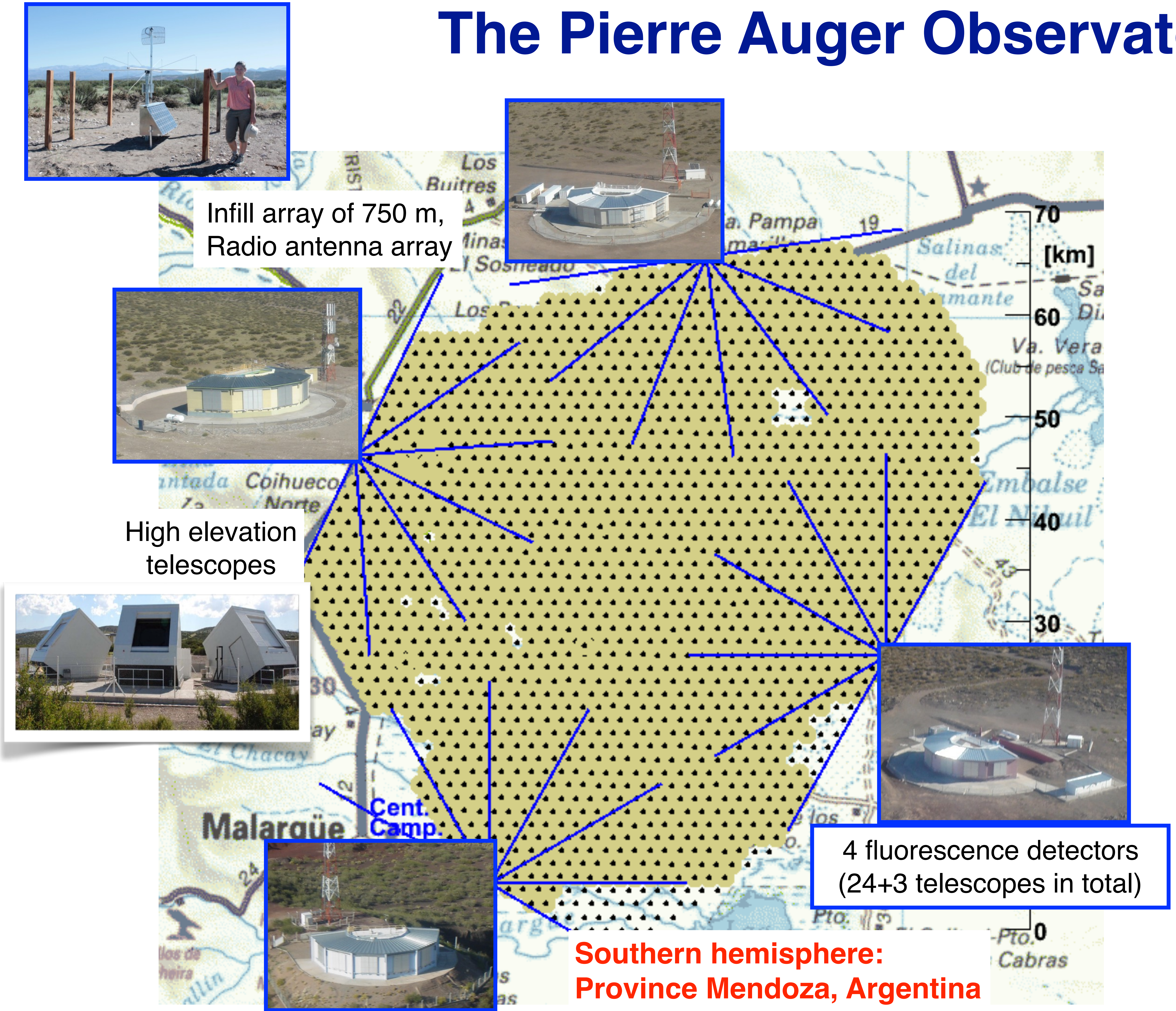
Does the GZK effect exist ?

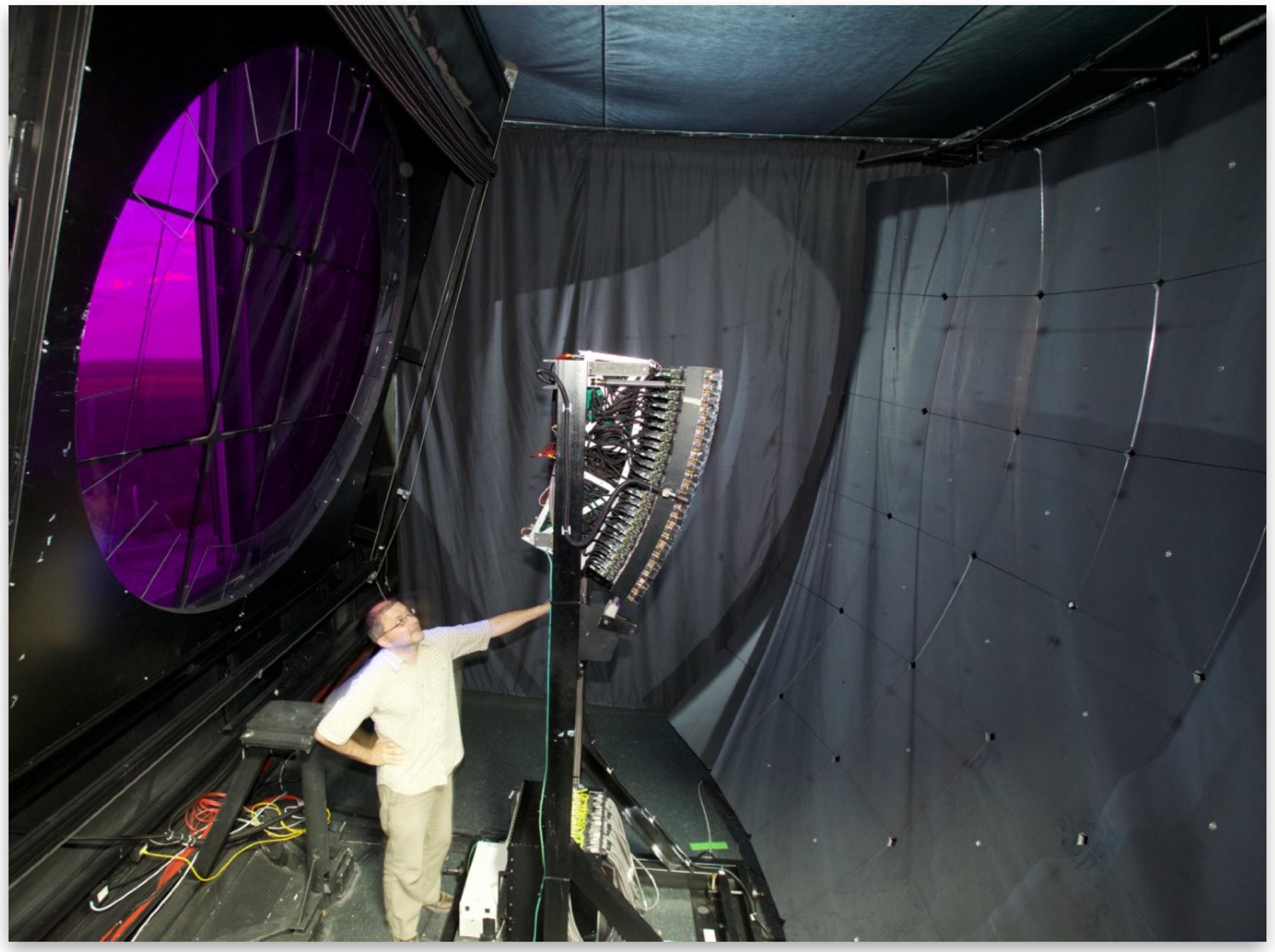
Violation of Lorentz invariance?

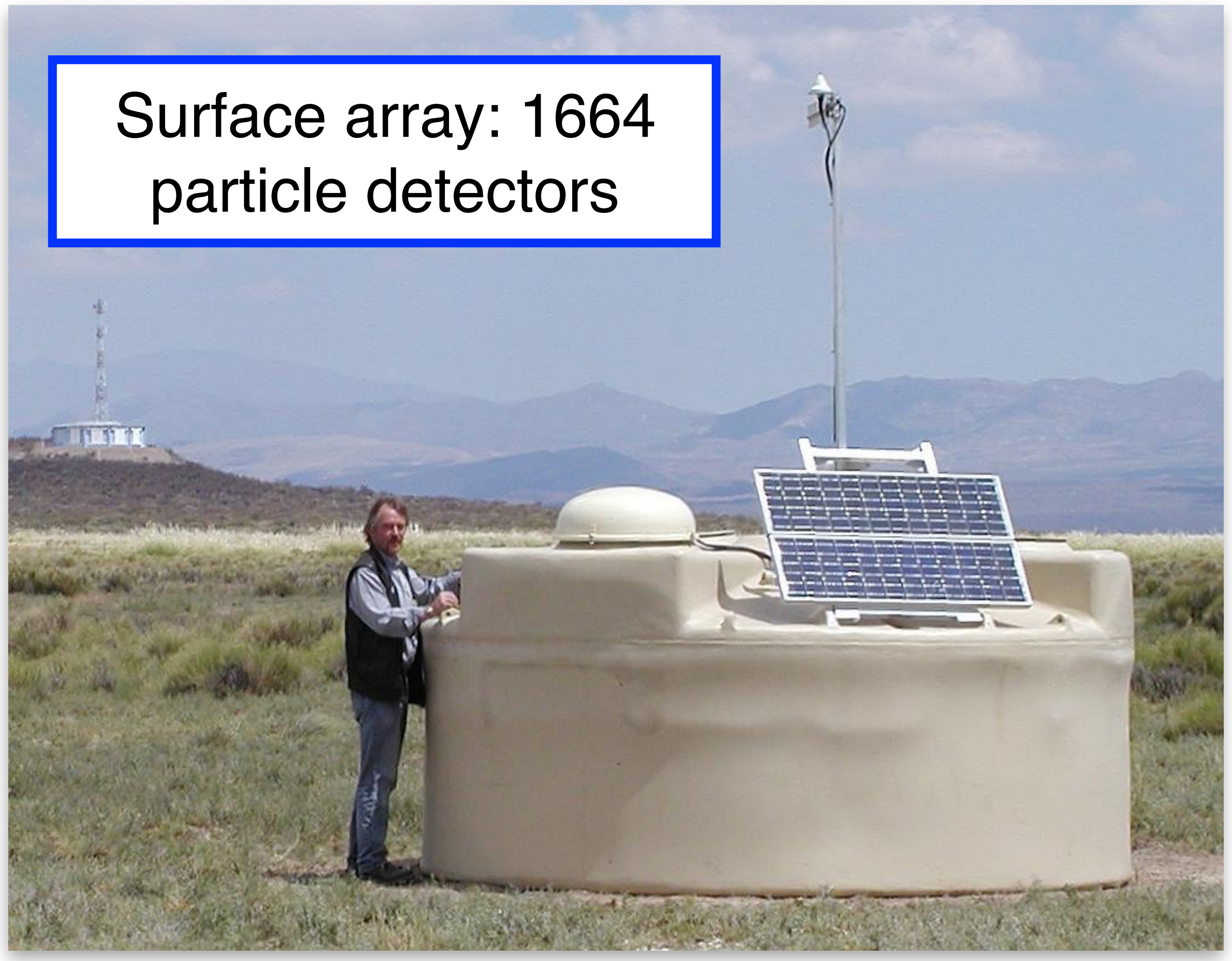
AGASA:
5 doublets, 1 triplet for $\Delta\theta < 2.5°$, $E > 4 \times 10^{19}$eV

HiRes:
no confirmation (different statistics & systematics)

The Pierre Auger Observatory (3000 km²)








1.5 km


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, 700 km²)

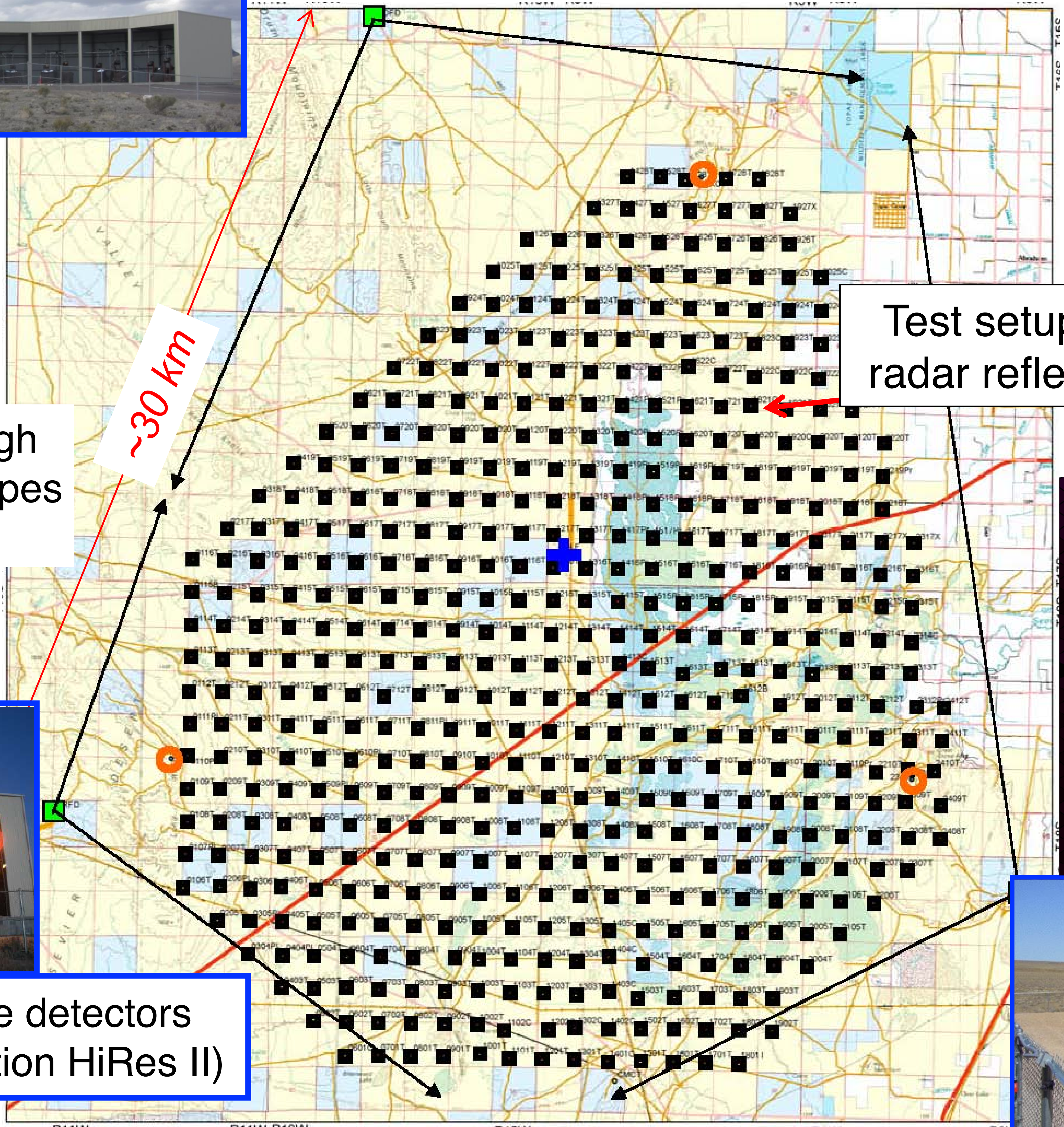
Talk by Abu-Zayyad

Middle Drum: based on HiRes II

TALE (TA low energy extension)

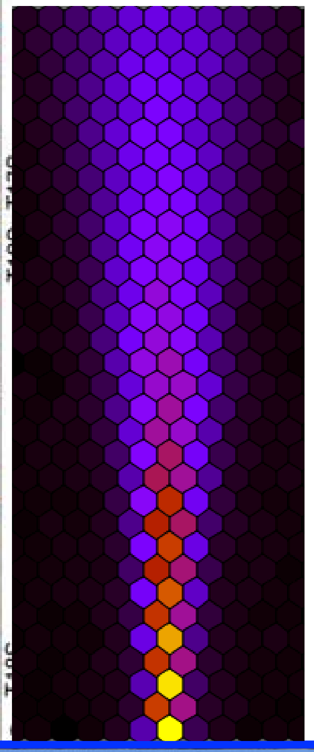
LIDAR
Laser facility

Infill array and high
elevation telescopes

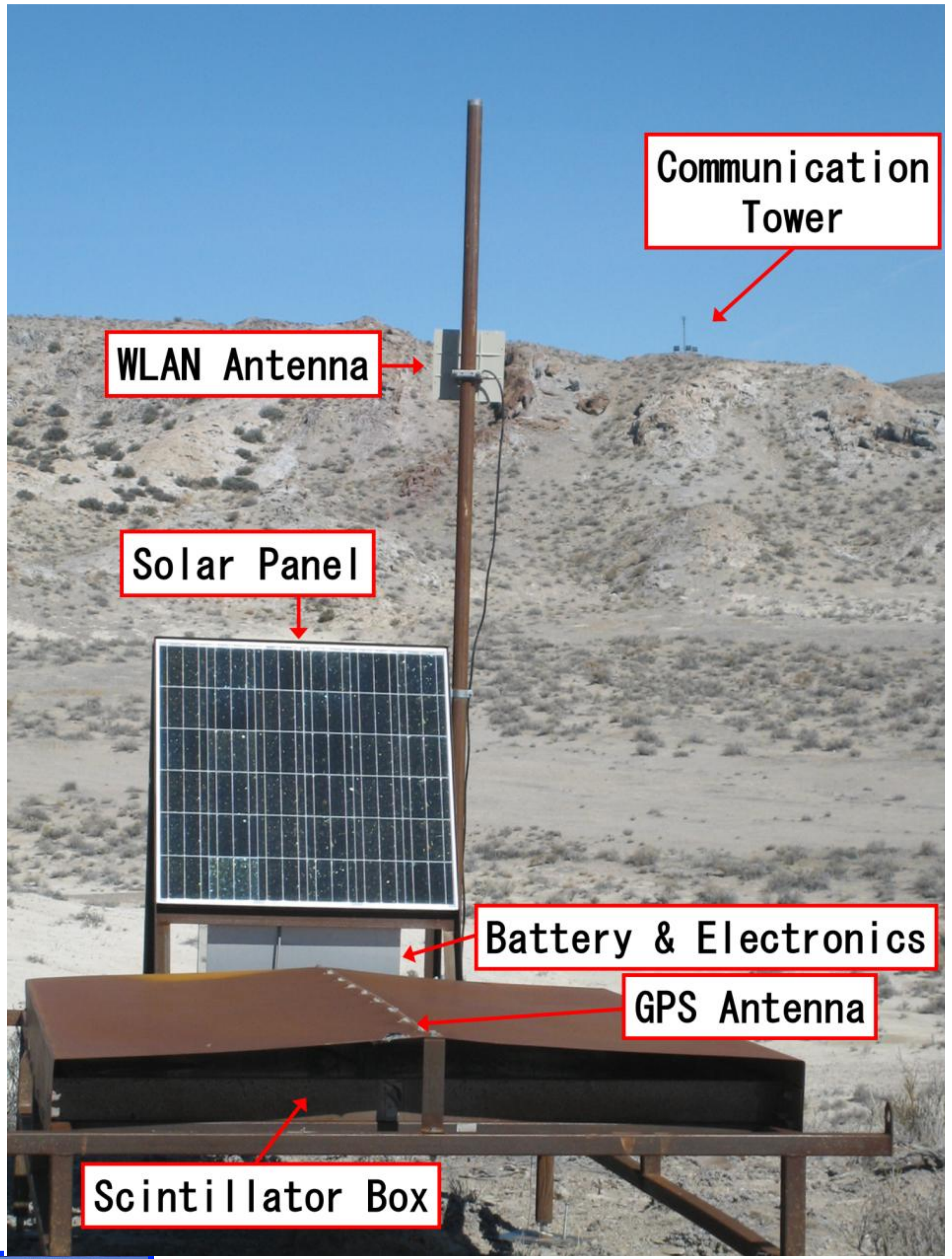


Test setup for
radar reflection

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 km²)

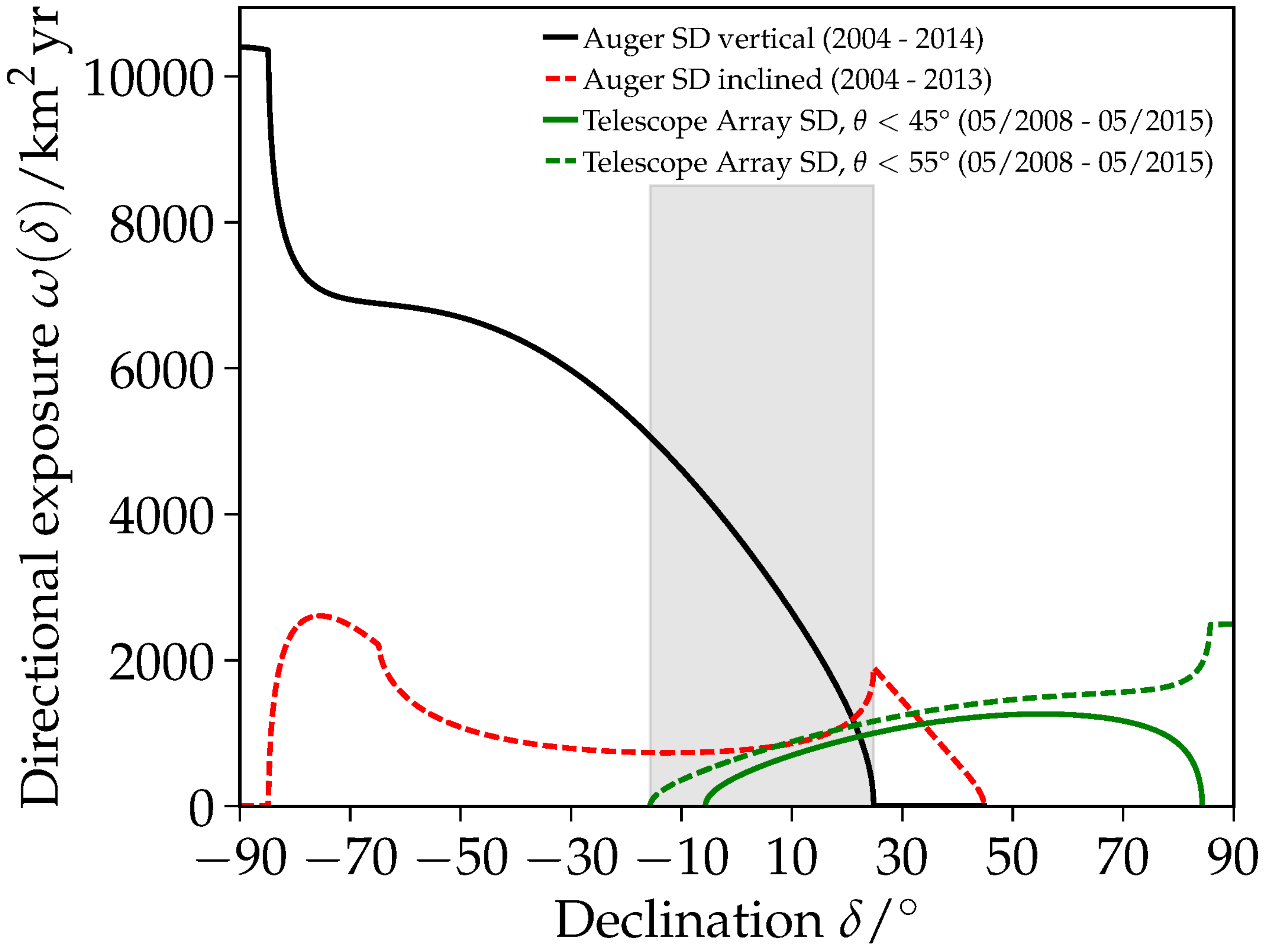
Northern hemisphere: Utah, USA

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

Together full sky coverage

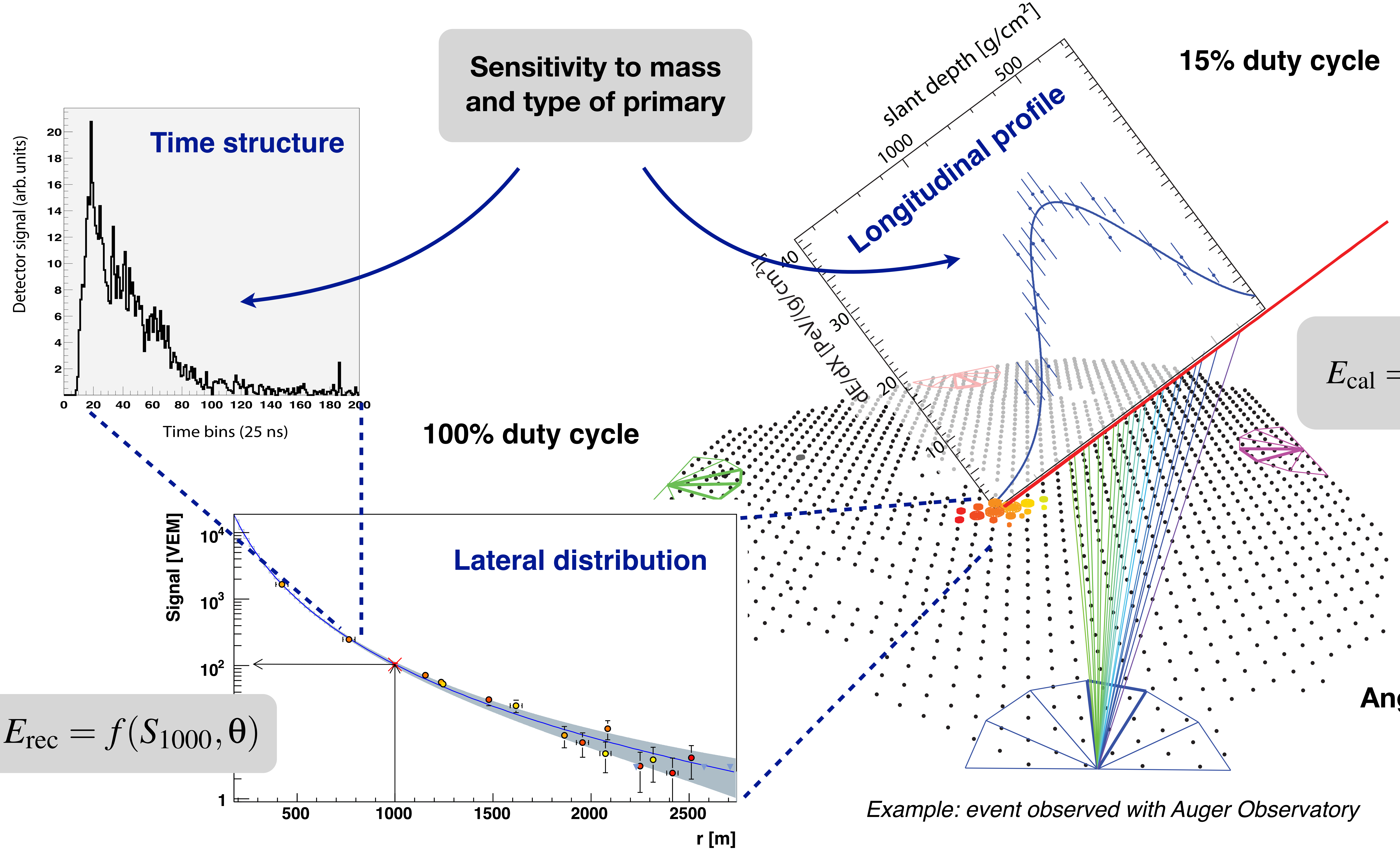


Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km^2
27 fluorescence telescopes

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)

Current state of the art of cosmic ray detection

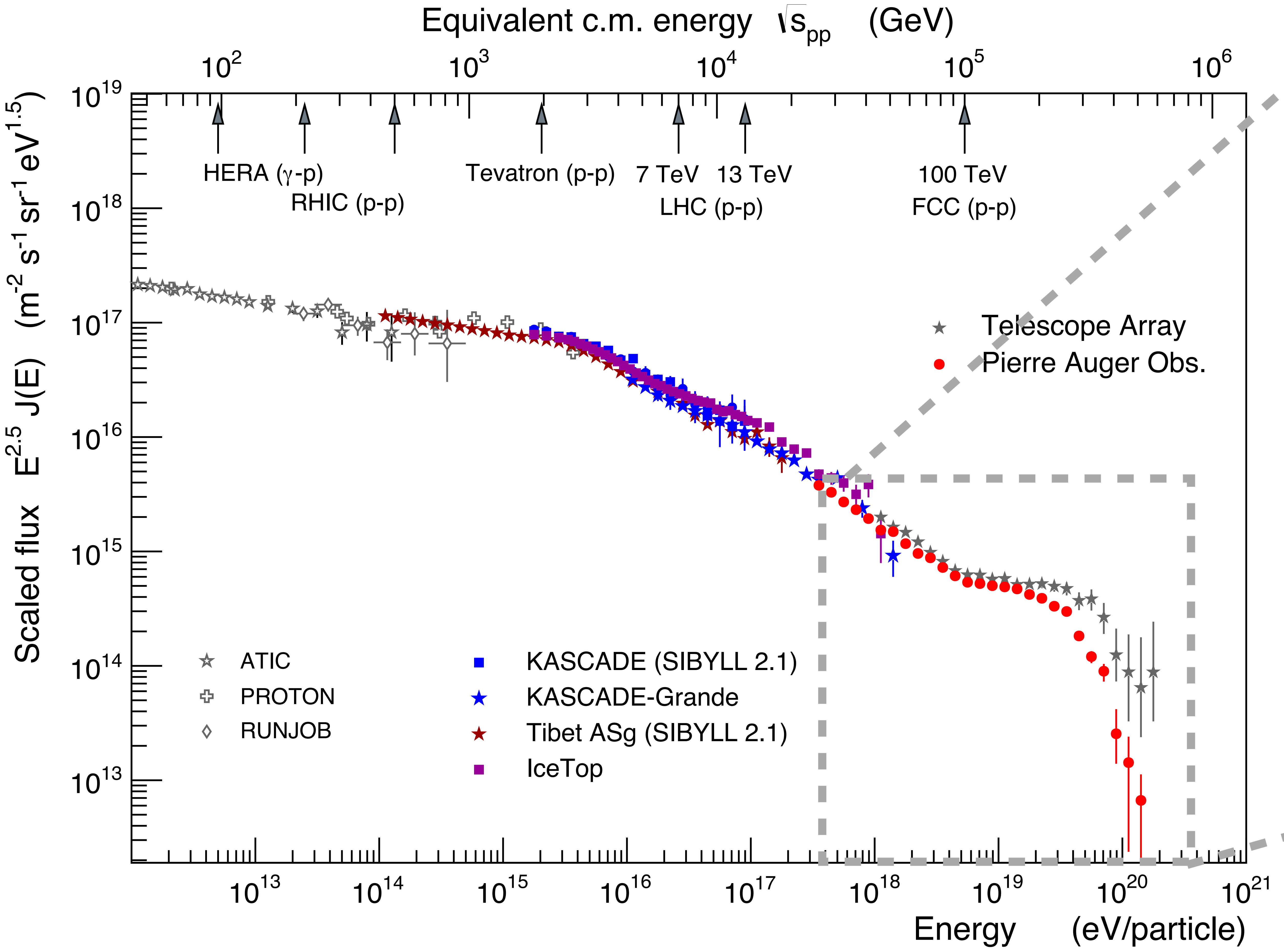


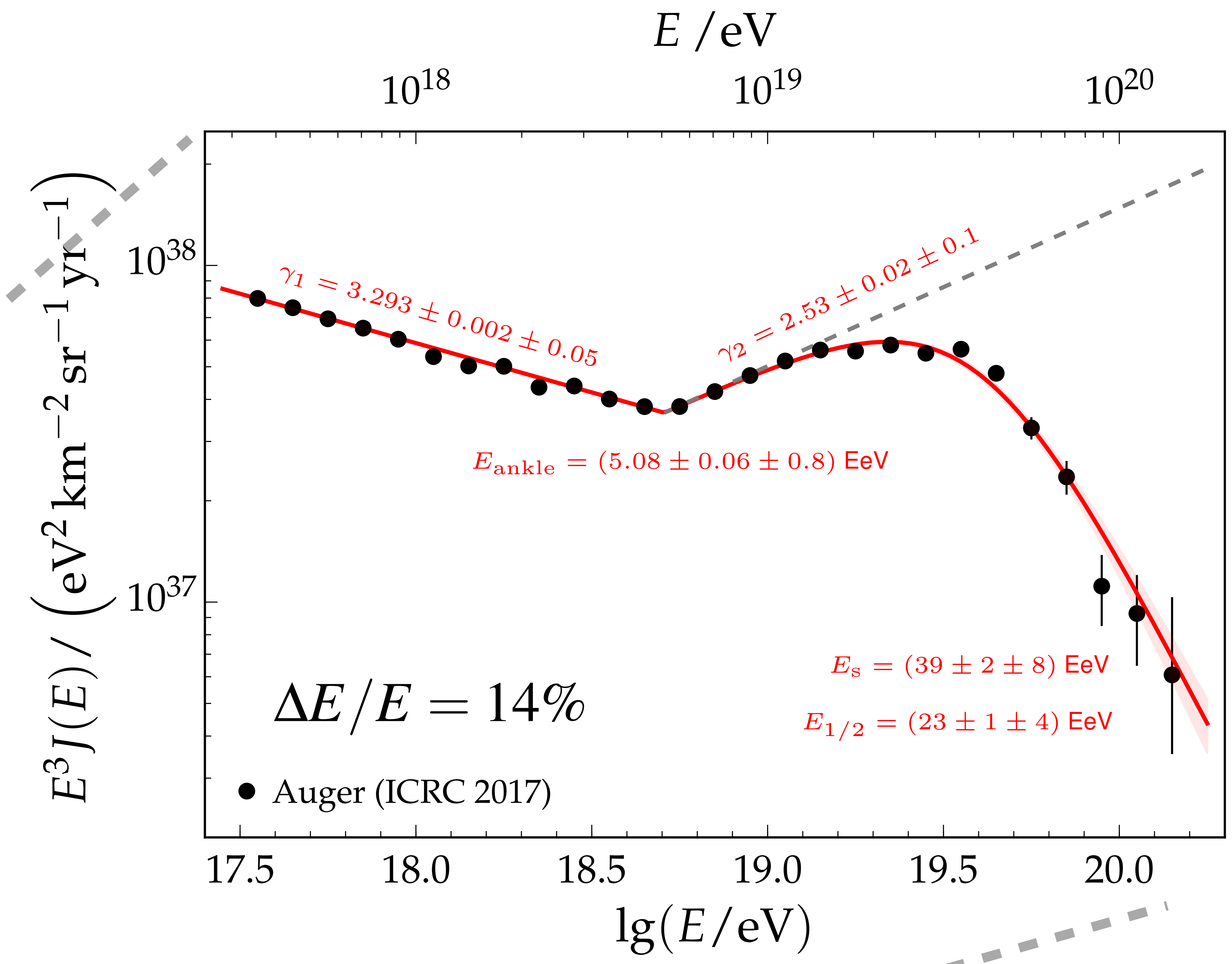
$$E_{\mathrm{rec}} = f(S_{1000}, \theta)$$

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

Example: event observed with Auger Observatory

The flux is strongly suppressed above $E > 10^{19.6}$ eV





Expected 1100 events without suppression, have now 14 events

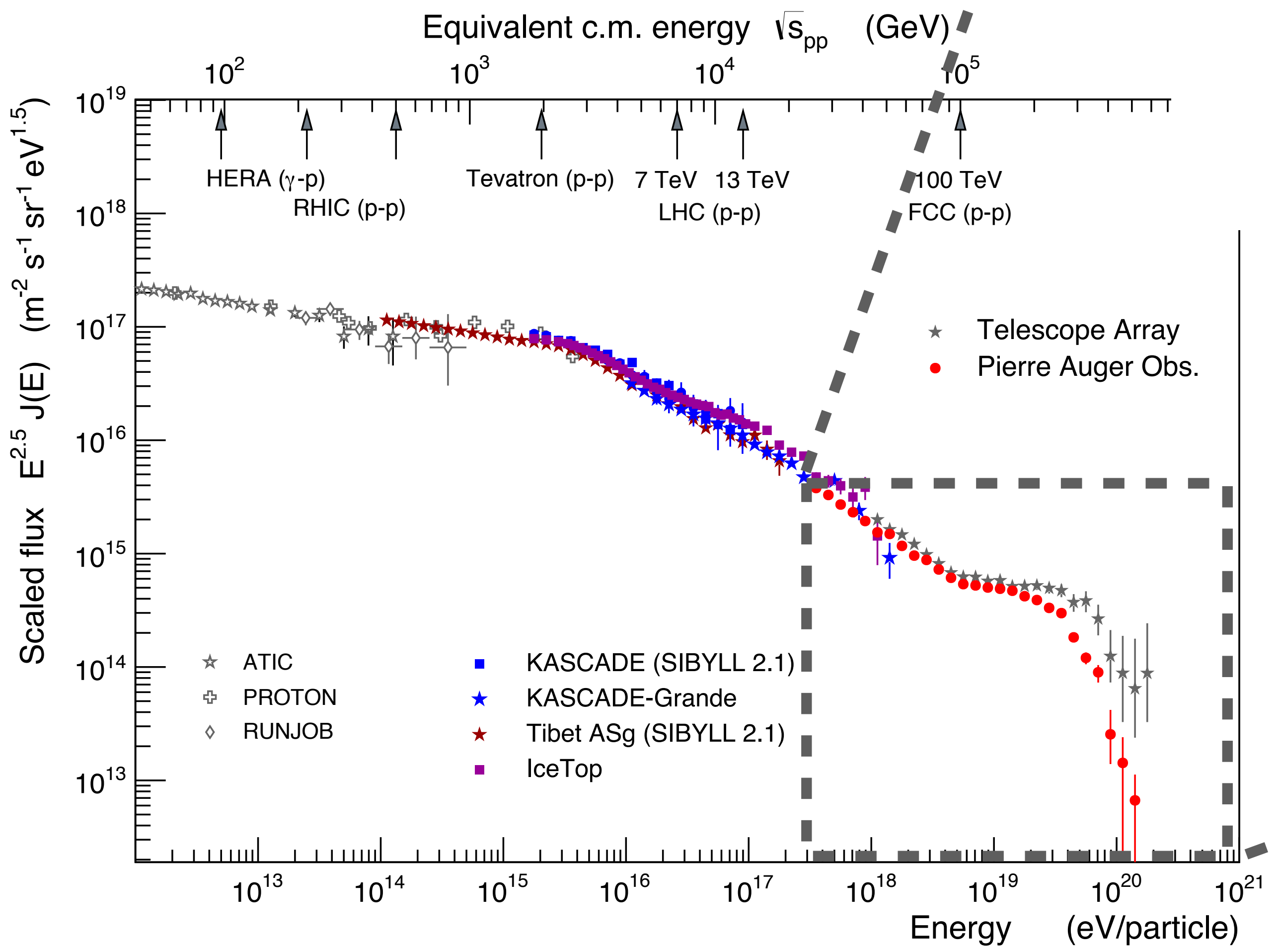
Energy spectrum: comparison with theory predictions

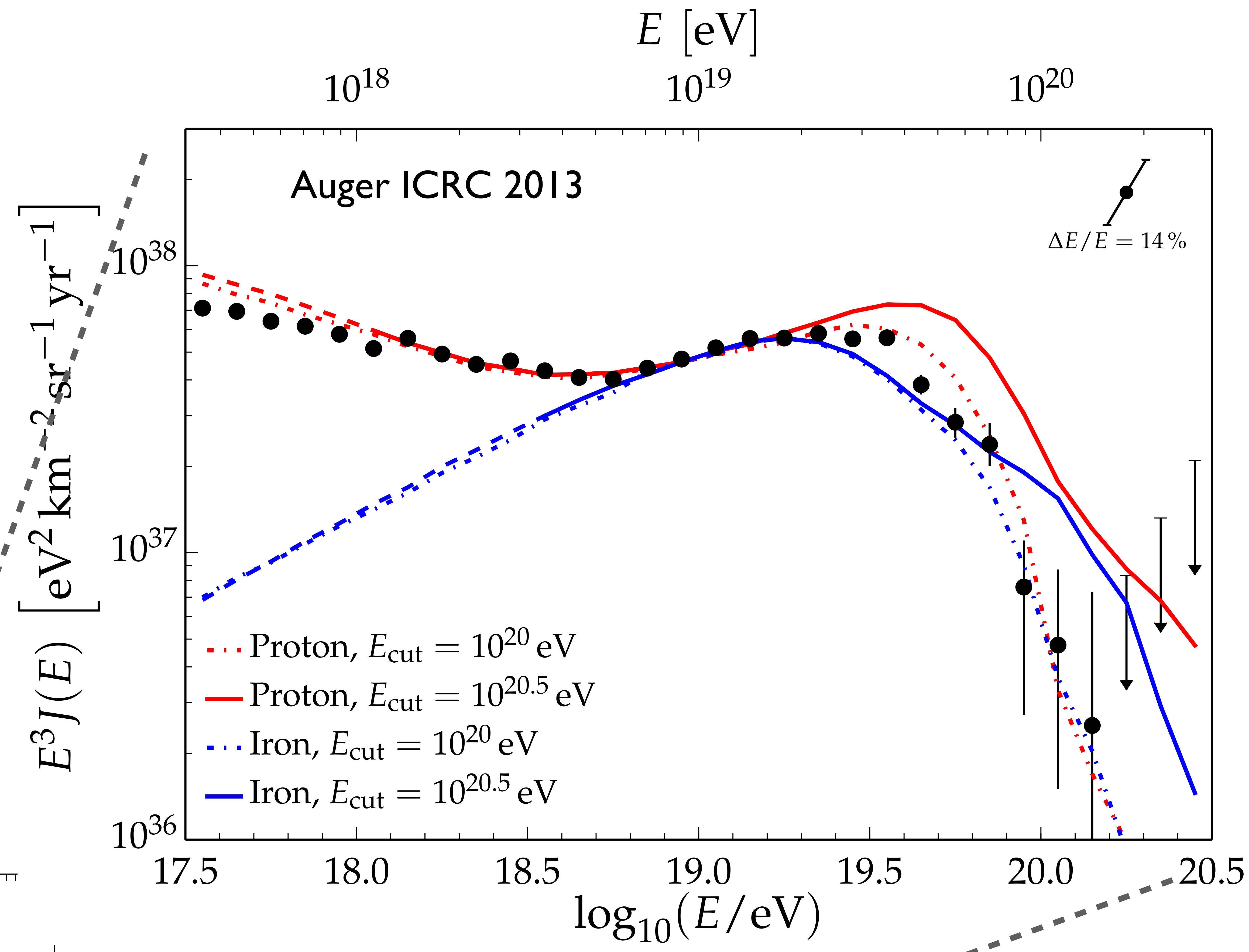
Proton dominated flux

Suppression: delta resonance

Ankle: e^+e^- pair production

(Dip model of Berezinsky et al.)





Greisen-Zatsepin-Kuzmin (GZK) effect

Photo-pion production (mainly Δ resonance)

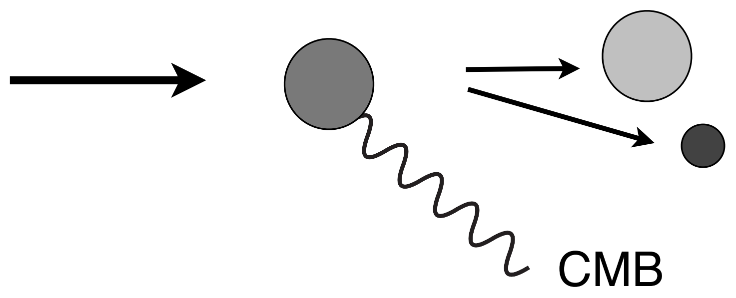
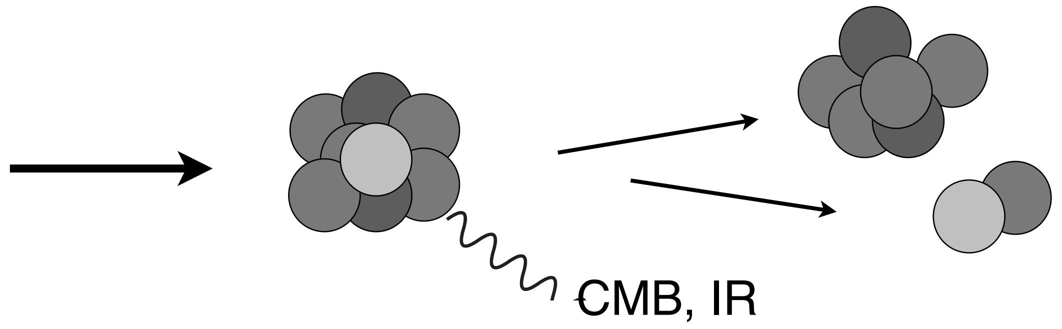


Photo-dissociation (giant dipole resonance)



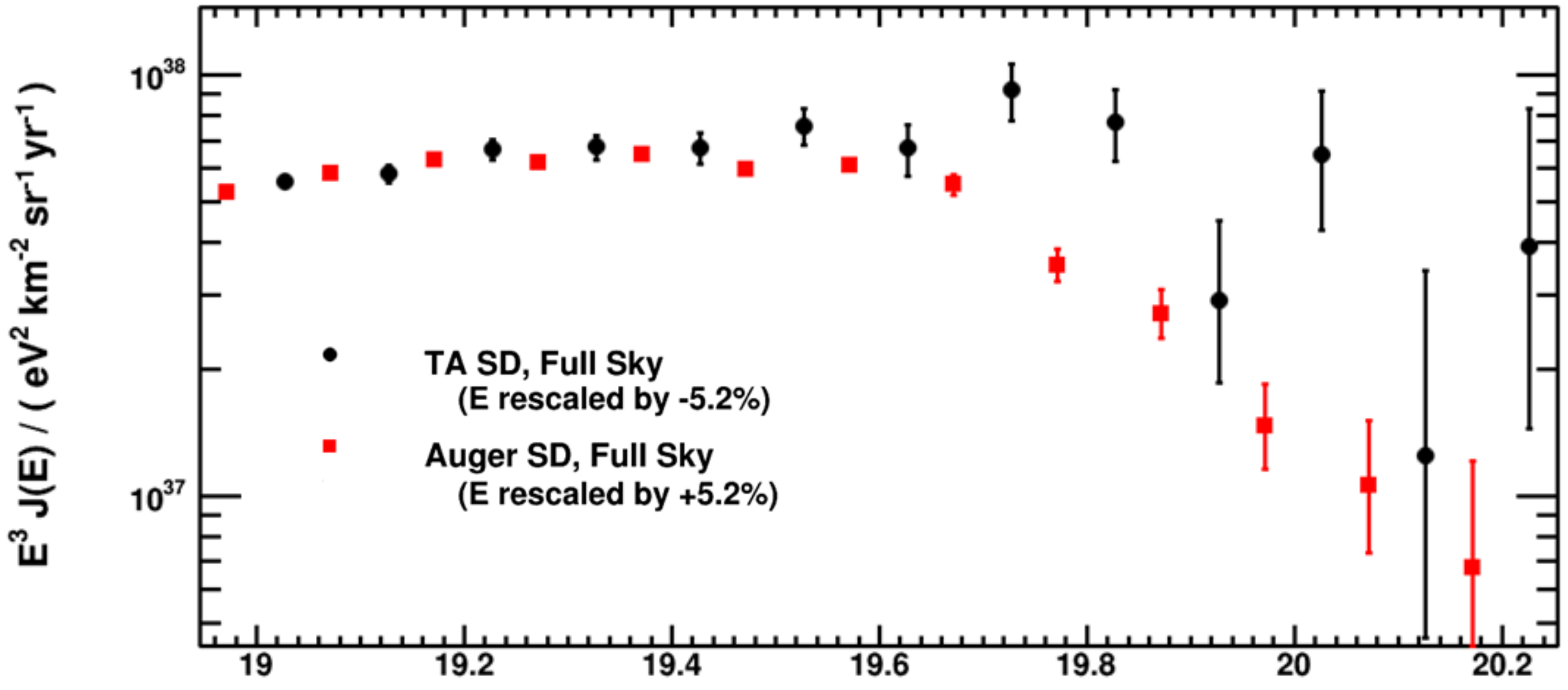
Iron dominated flux

Suppression: giant dipole resonance

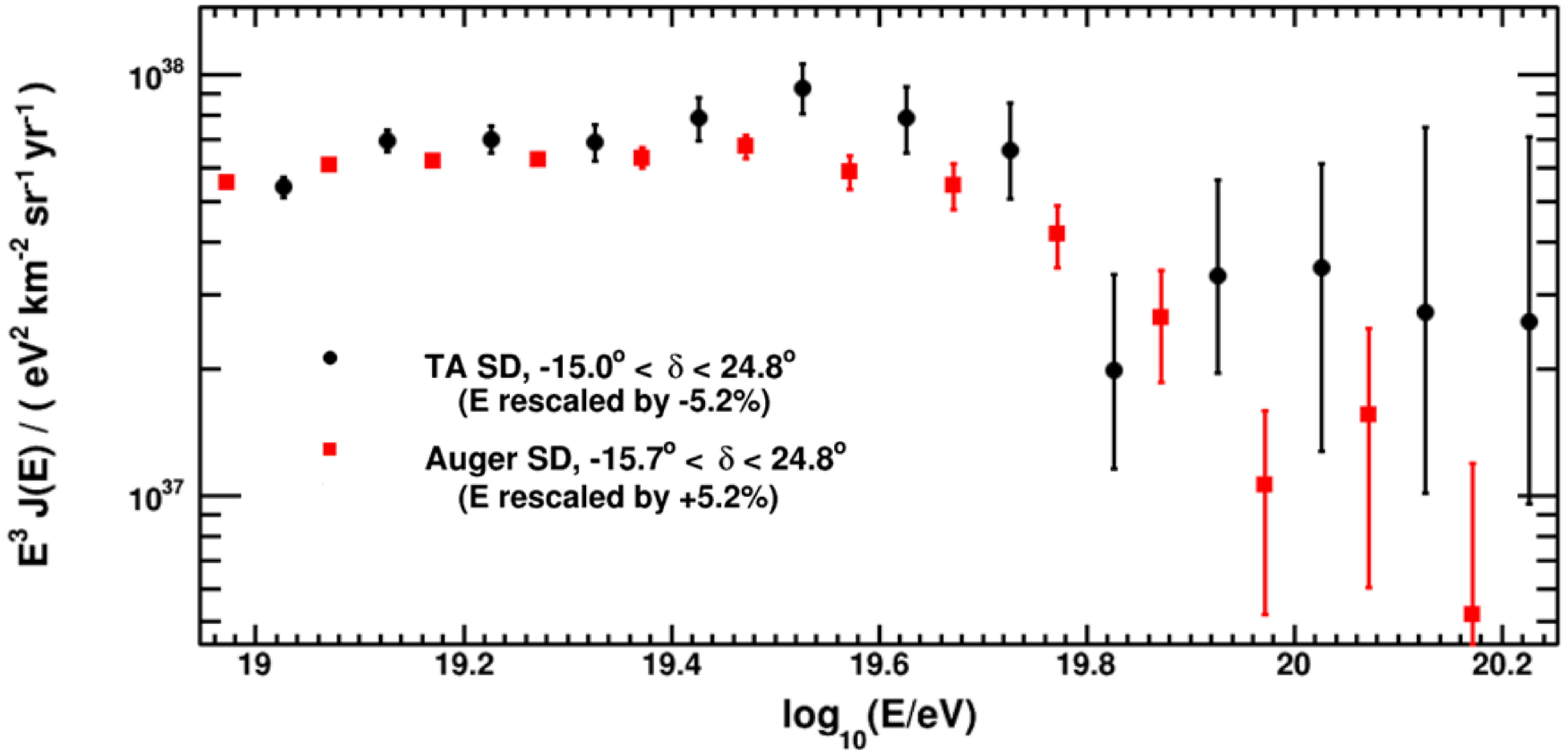
Ankle: transition to galactic sources

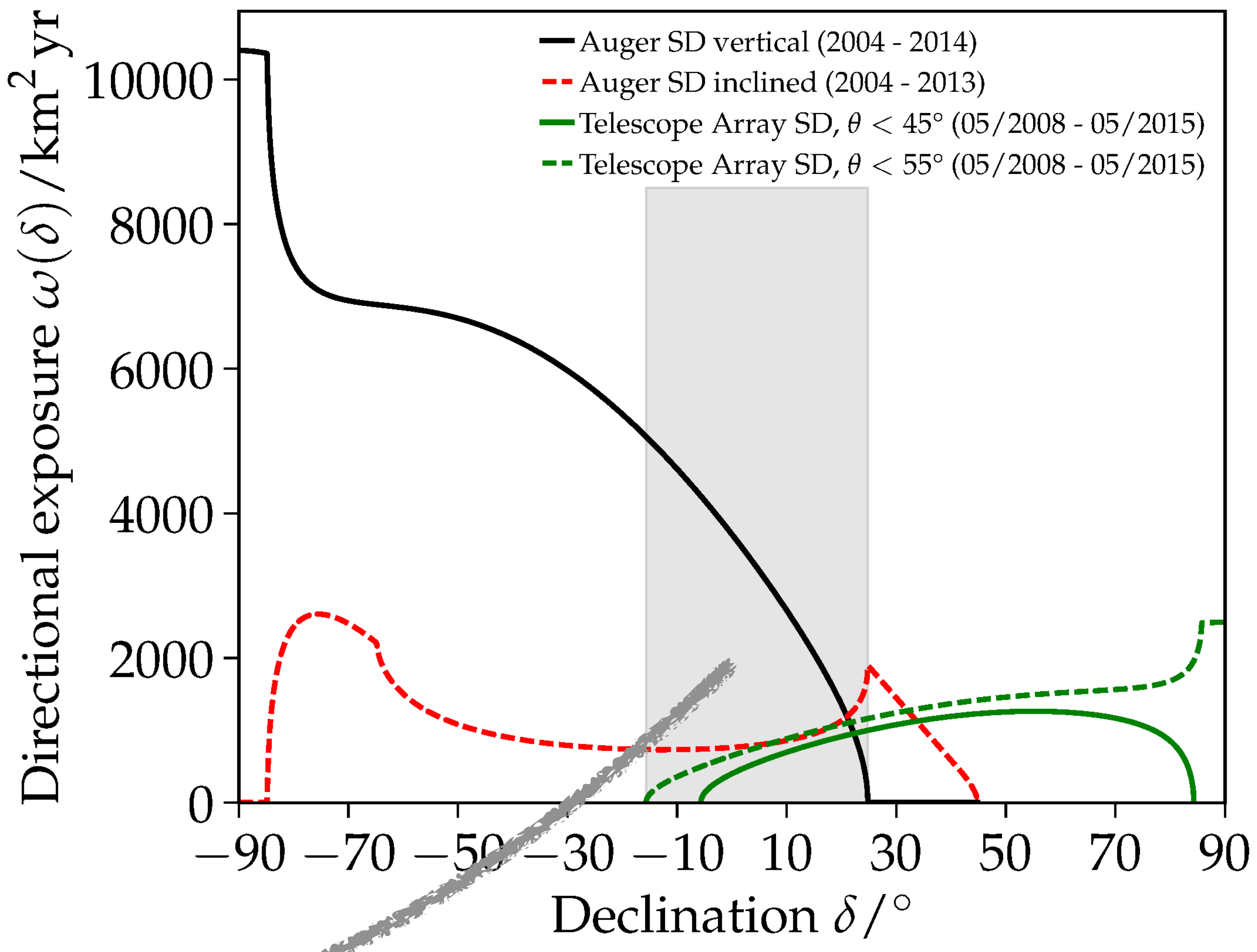
Comparison of energy spectra of Auger and TA

All sky



Common declination band



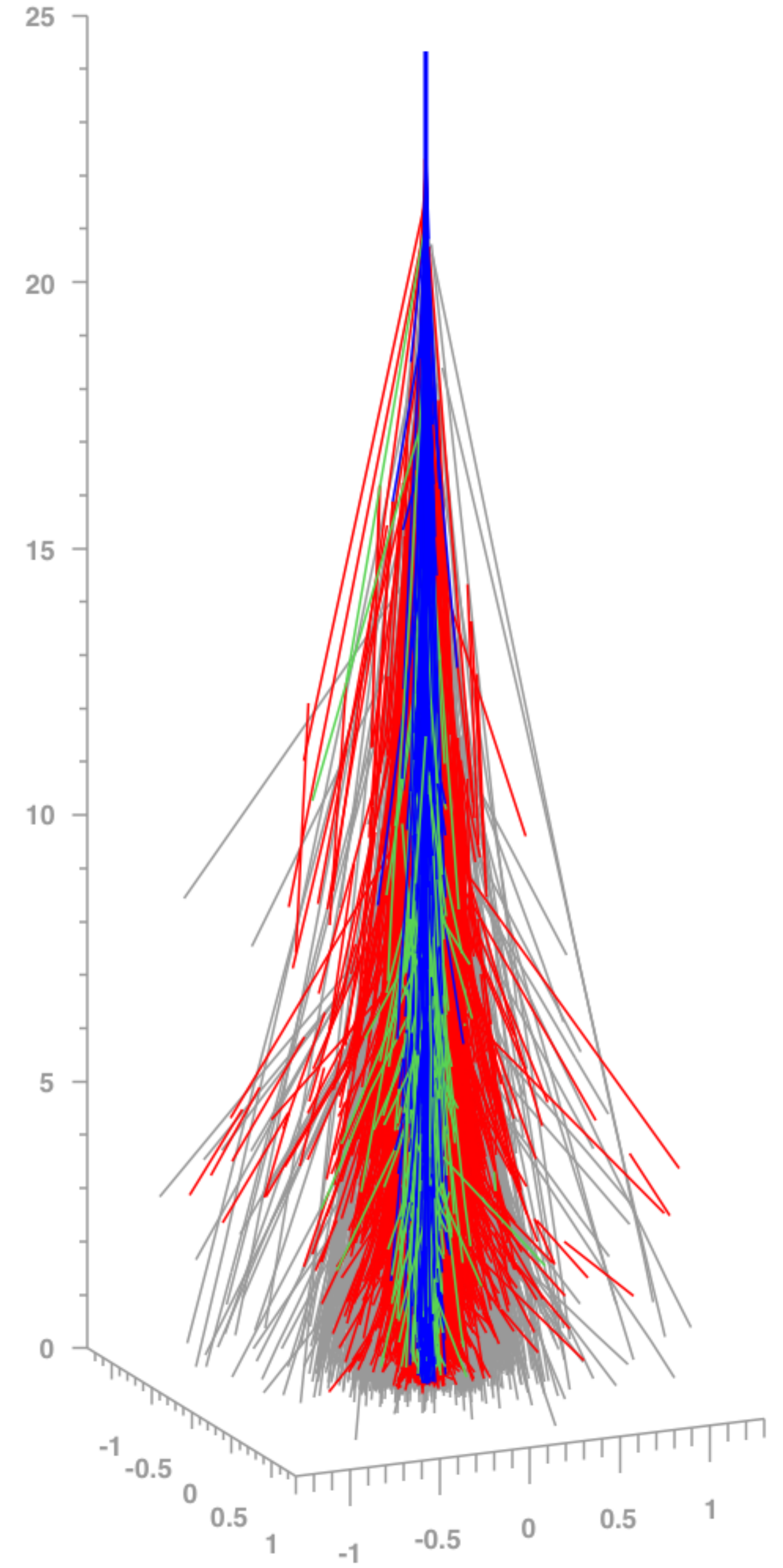


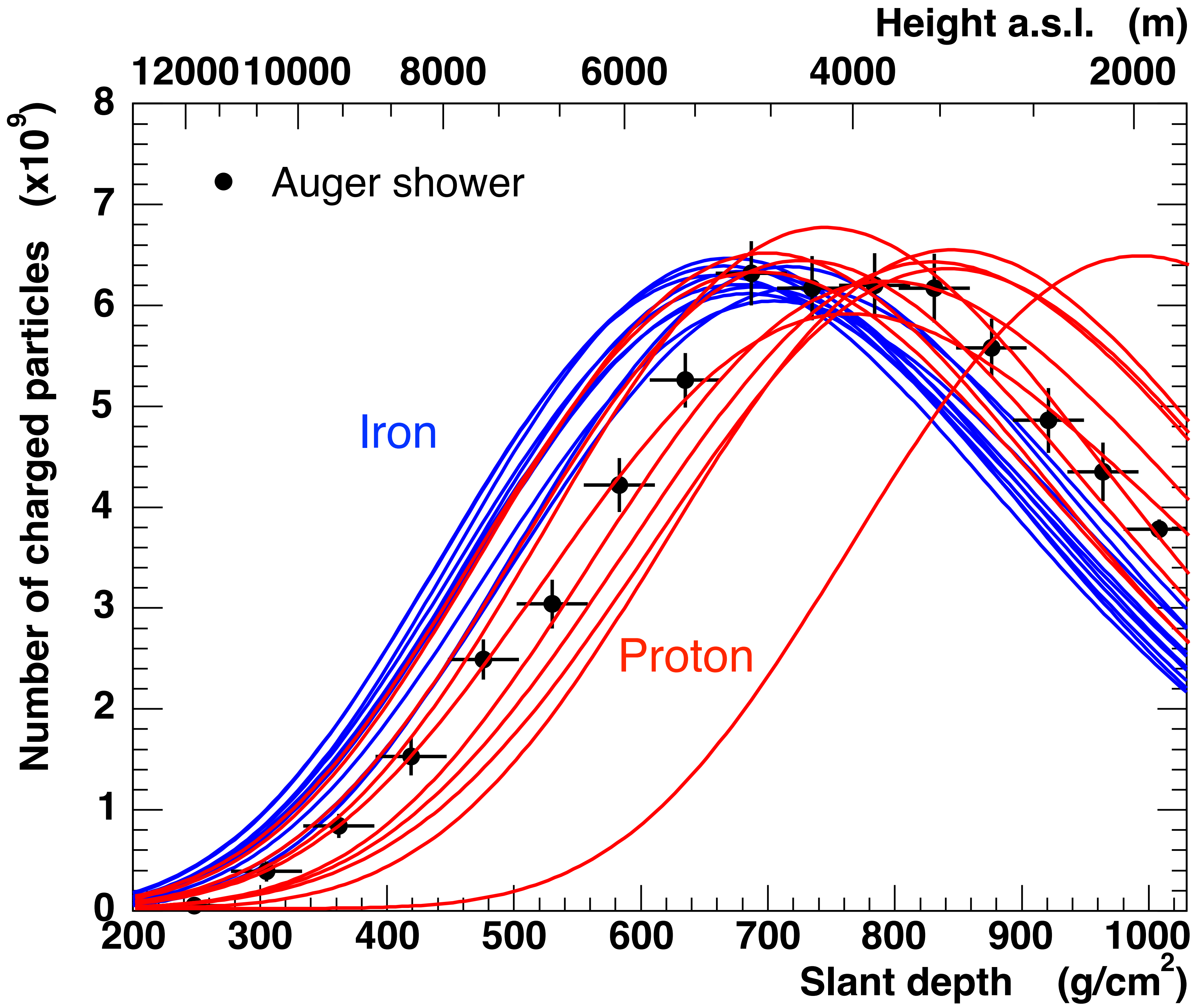
Auger	$\Delta E/E = 14\%$
TA	$\Delta E/E = 21\%$

Better agreement if only common declination band considered – anisotropy, different sources ?

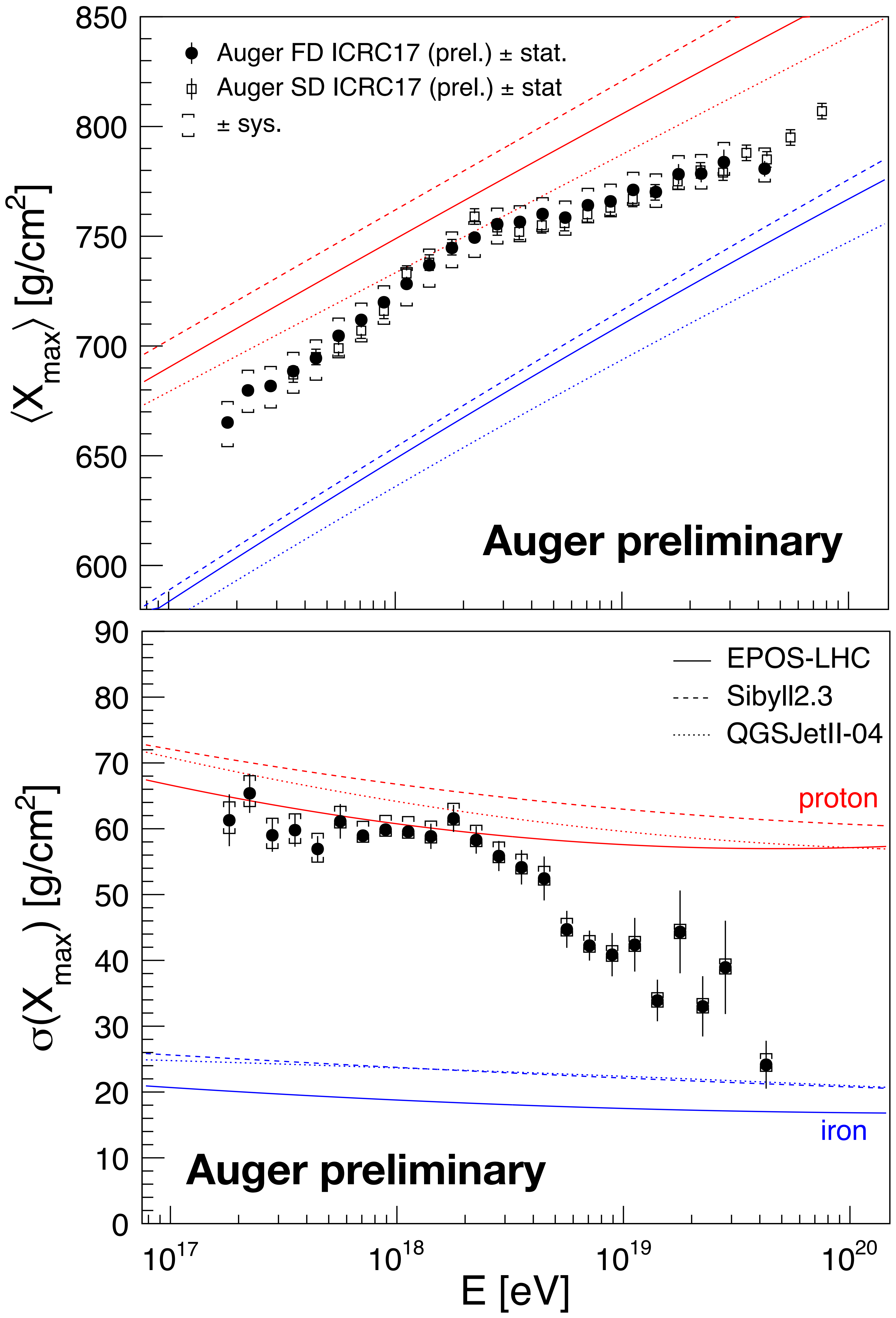
(Auger-TA Spectrum Working Group, TA, arXiv:1801.07820)

Composition from longitudinal shower profile



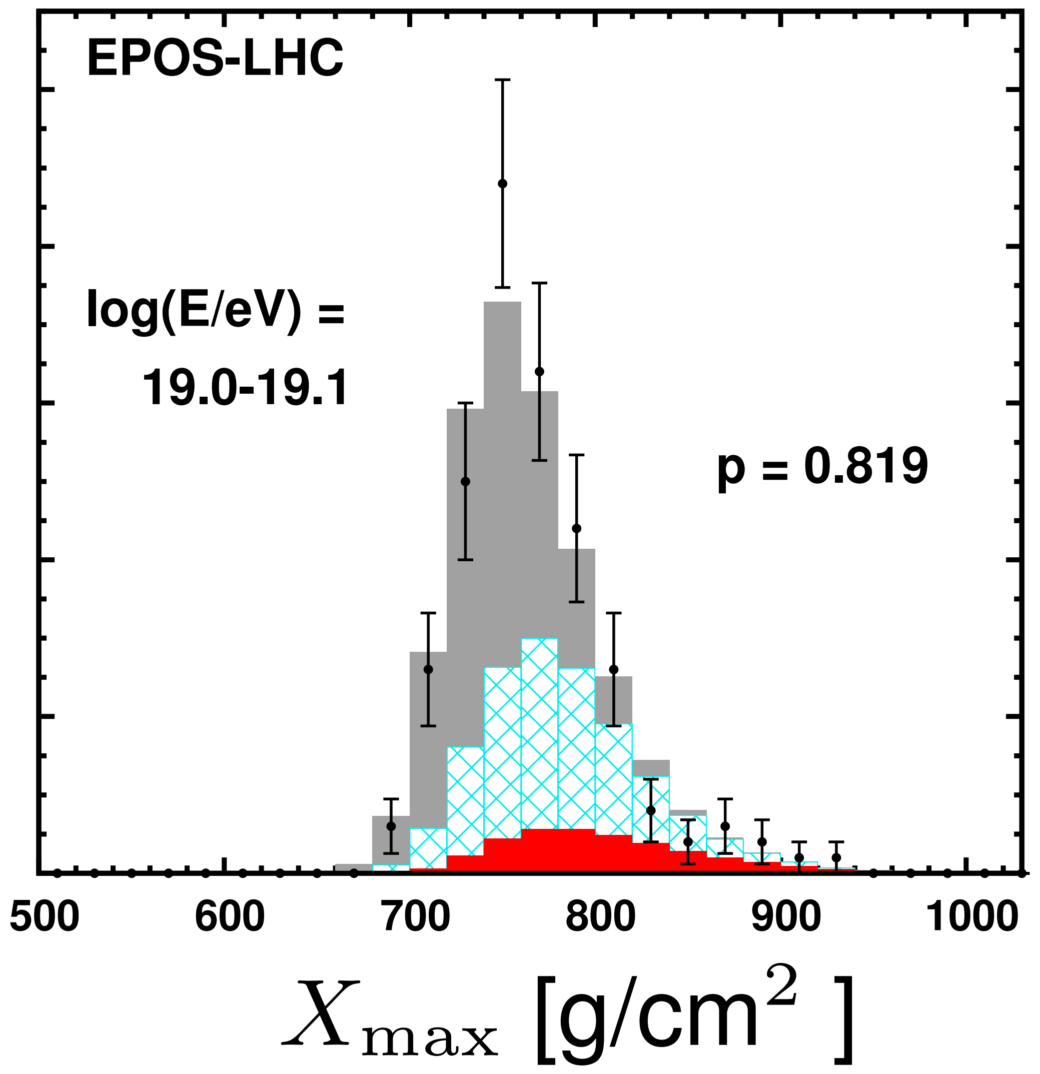


Example: event measured by Auger Collab.



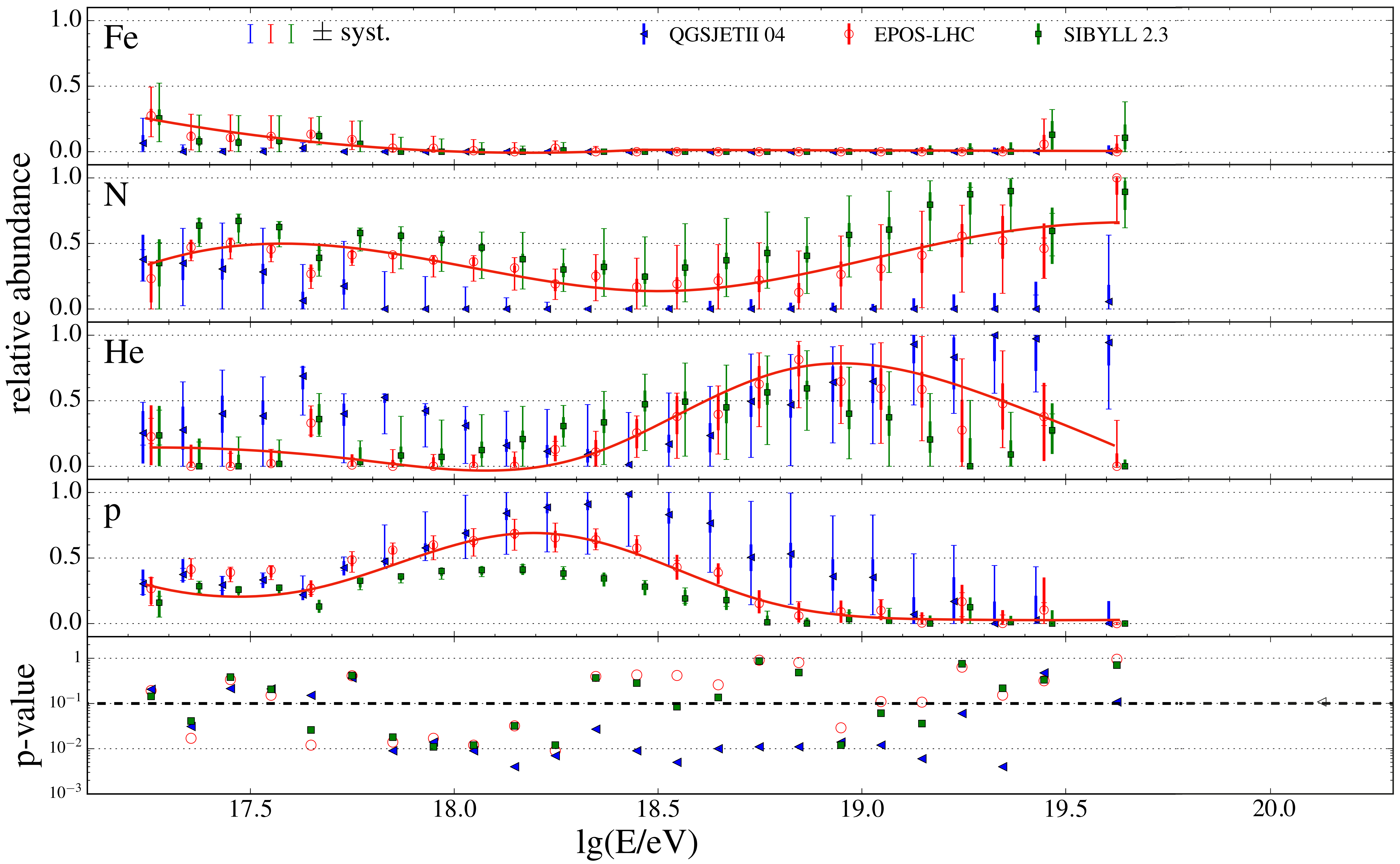
(Auger ICRC2017)

Unexpected change of mass composition (at Earth)



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

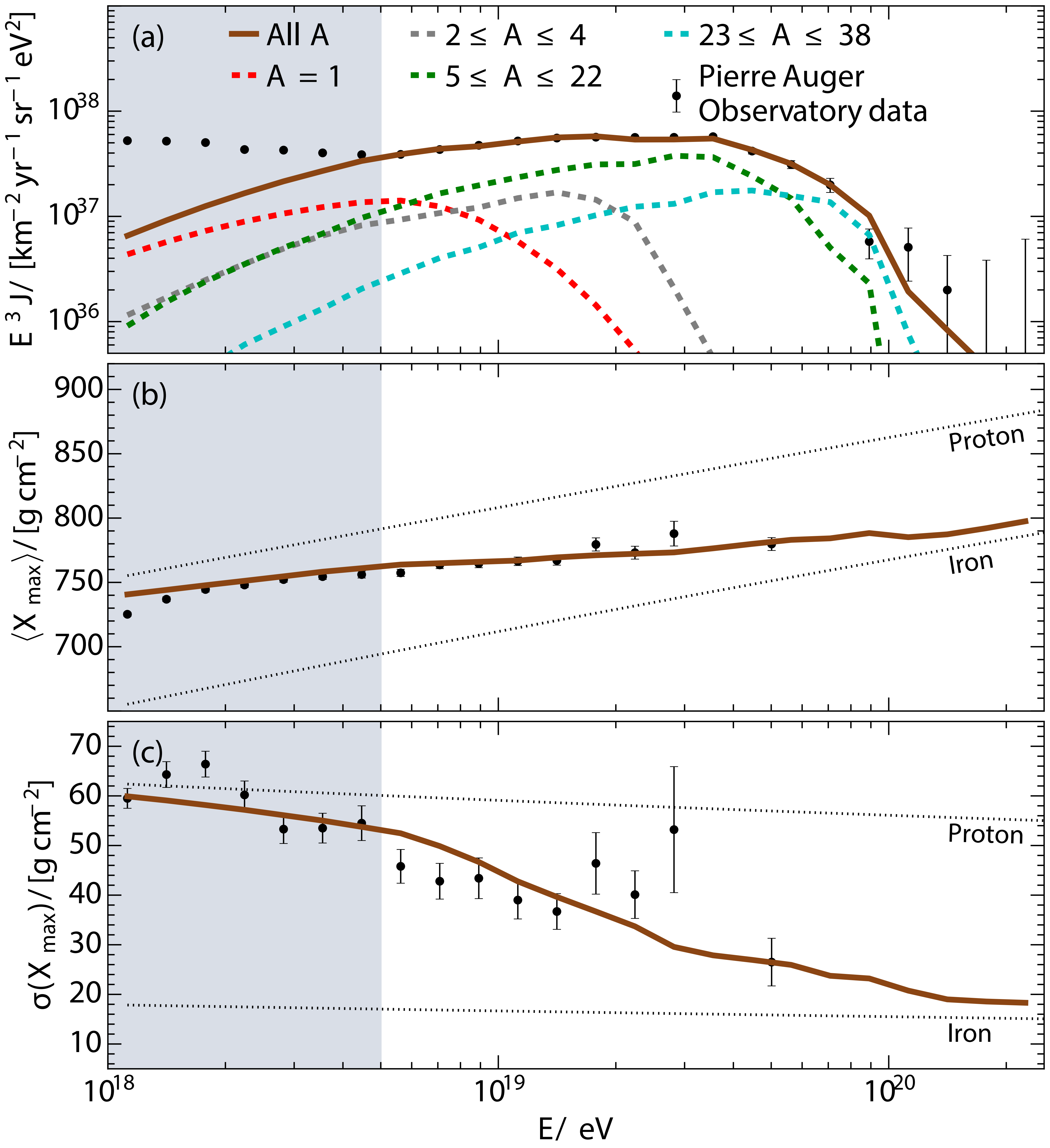
Large proton fraction below ankle

No obvious scaling with rigidity

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

(Bellido ICRC 2017)

Modeling mass composition at sources



(Wittkowski ICRC 2017)

Injection spectrum: $E^{-\gamma}$

Exponential cutoff: $E_{\max} = Z \cdot R_{\max}$

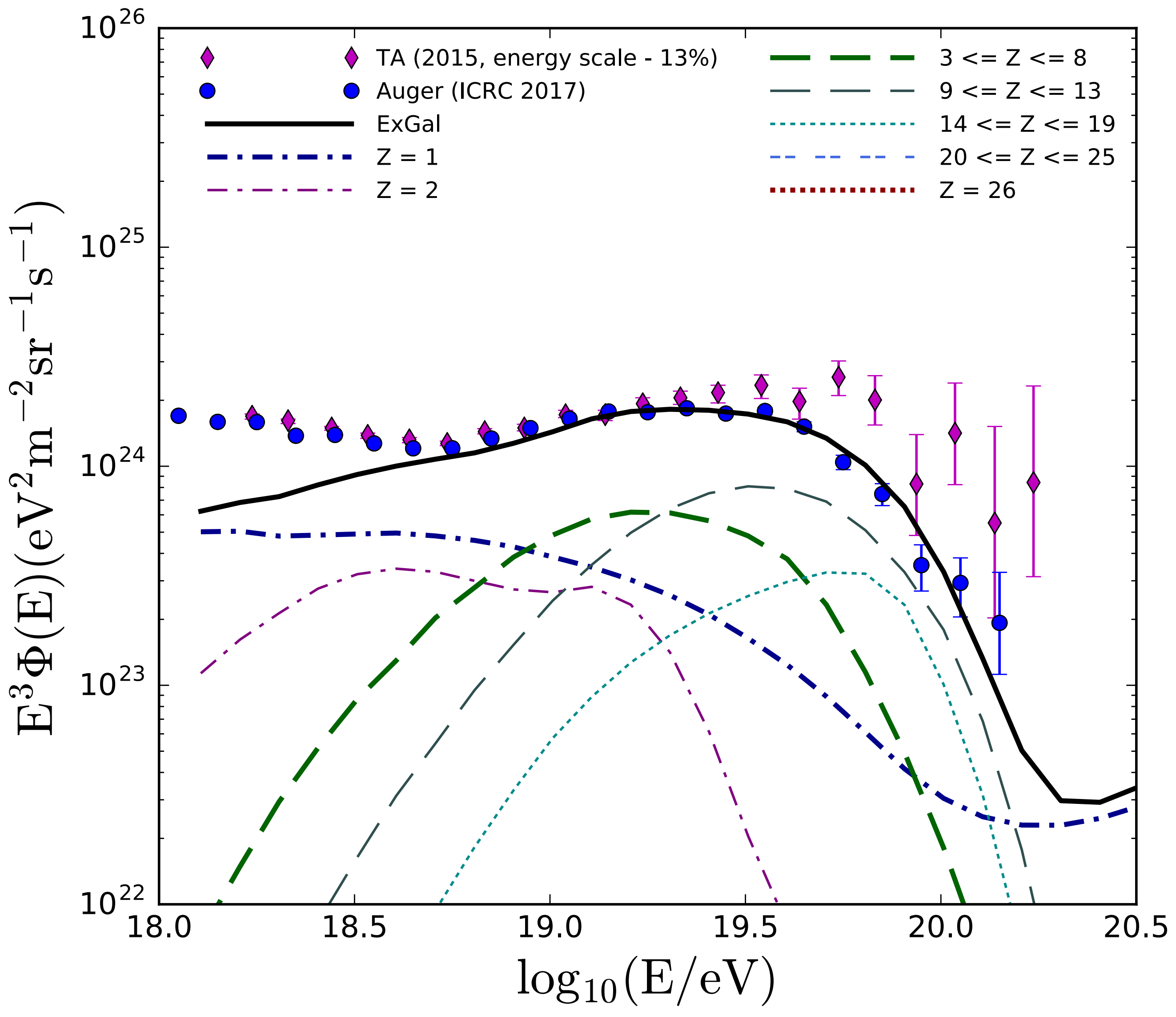
Source properties	4D with EGMF	4D no EGMF	1D no EGMF[1]
γ	1.61	0.61	0.87
$\log_{10}(R_{\mathrm{cut}}/\mathrm{eV})$	18.88	18.48	18.62
f_{H}	3 %	11 %	0 %
f_{He}	2 %	14 %	0 %
f_{N}	74 %	68 %	88 %
f_{Si}	21 %	7 %	12 %
f_{Fe}	0 %	0 %	0 %

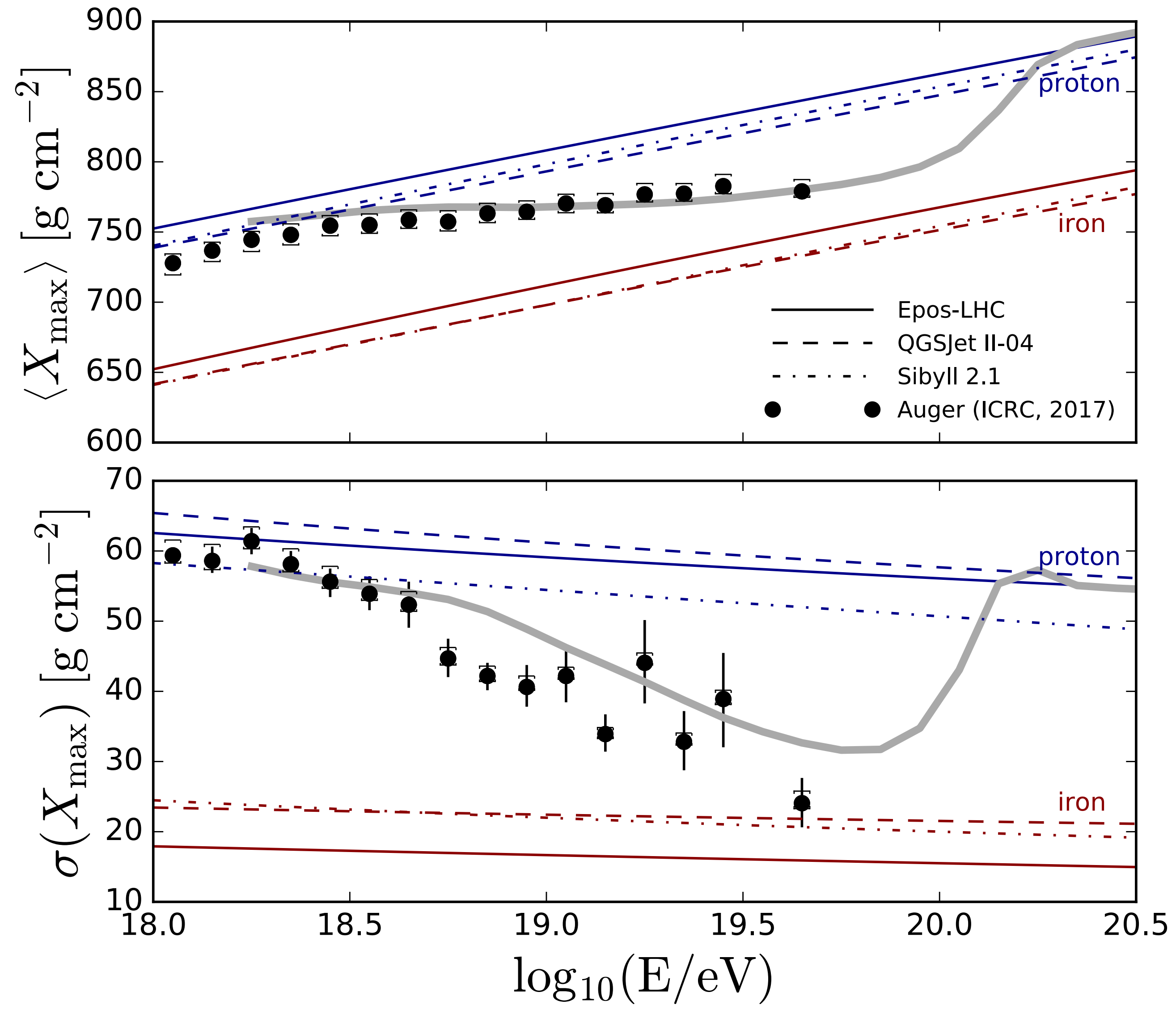
Suppression of flux dominated by maximum injection energy

Very hard index of power law at injection

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

Examples of interpretation of data





Problem 1: injection of mainly heavy elements

Problem 2: ions have to leave source

Problem 3: hard source spectrum

Combination of high- and **low-luminosity GRBs**
(Zhang et al 2018)

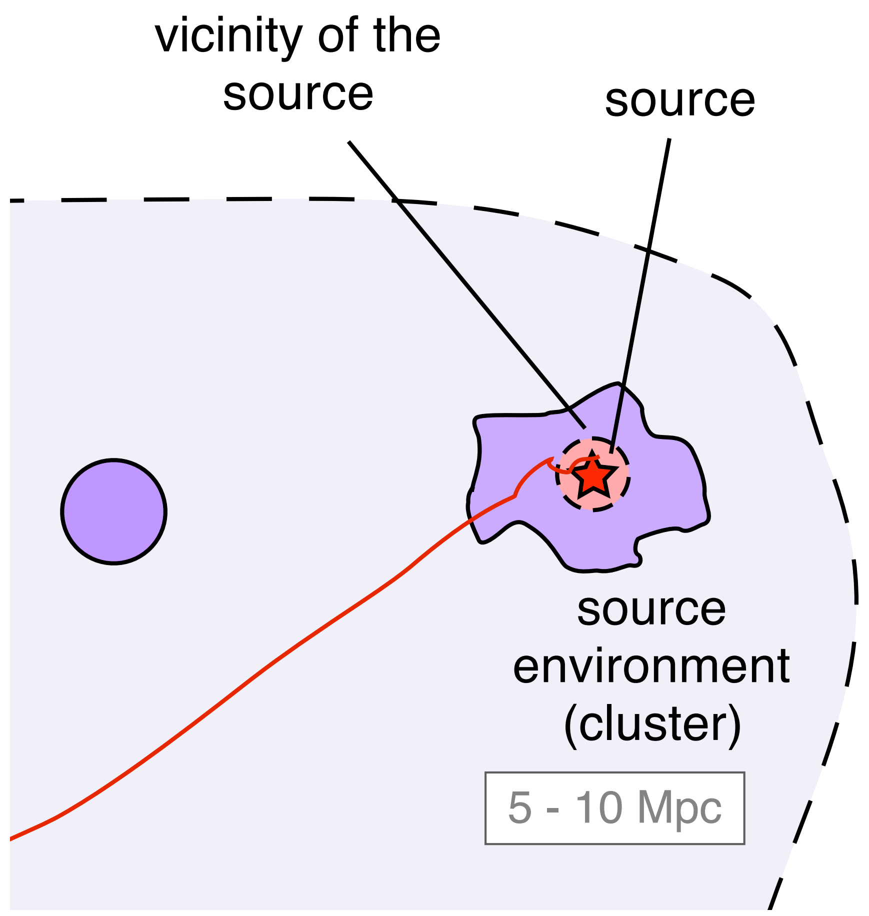
Tidal disruption events (TDEs) of WD or carbon-rich stars
(Farrar, Piran 2009, Pfeffer et al. 2017, Zhang et al 2017)

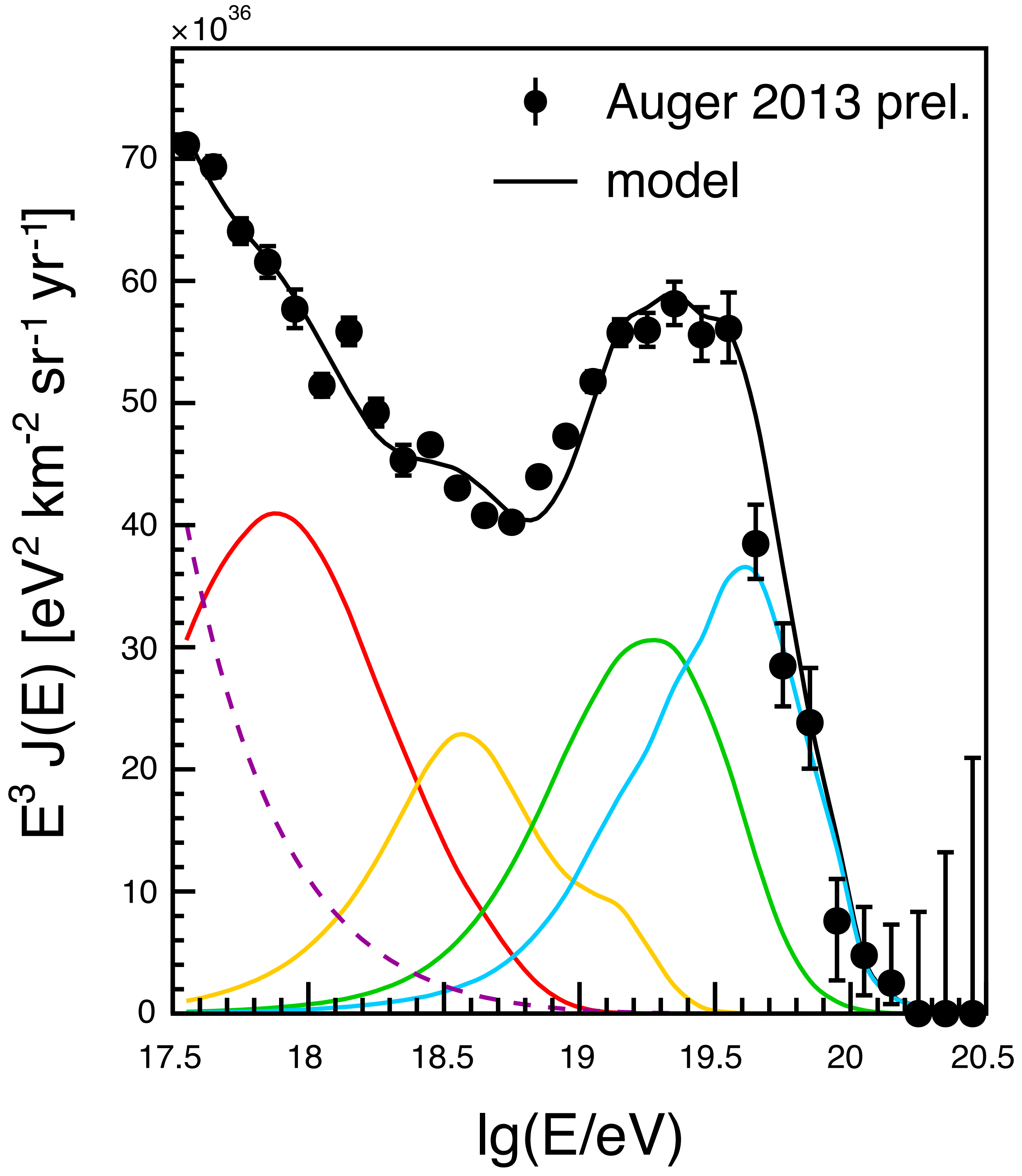
One-shot acceleration in rapidly spinning **neutron stars**
(Arons 2003, Olinto, Kotera, Feng, Kirk …)

Relativistic reflection of existing CR population
(Biermann, Caprioli, Wykes 2012+)

Interplay between **confinement in source** and disintegration of nuclei: hard energy spectra

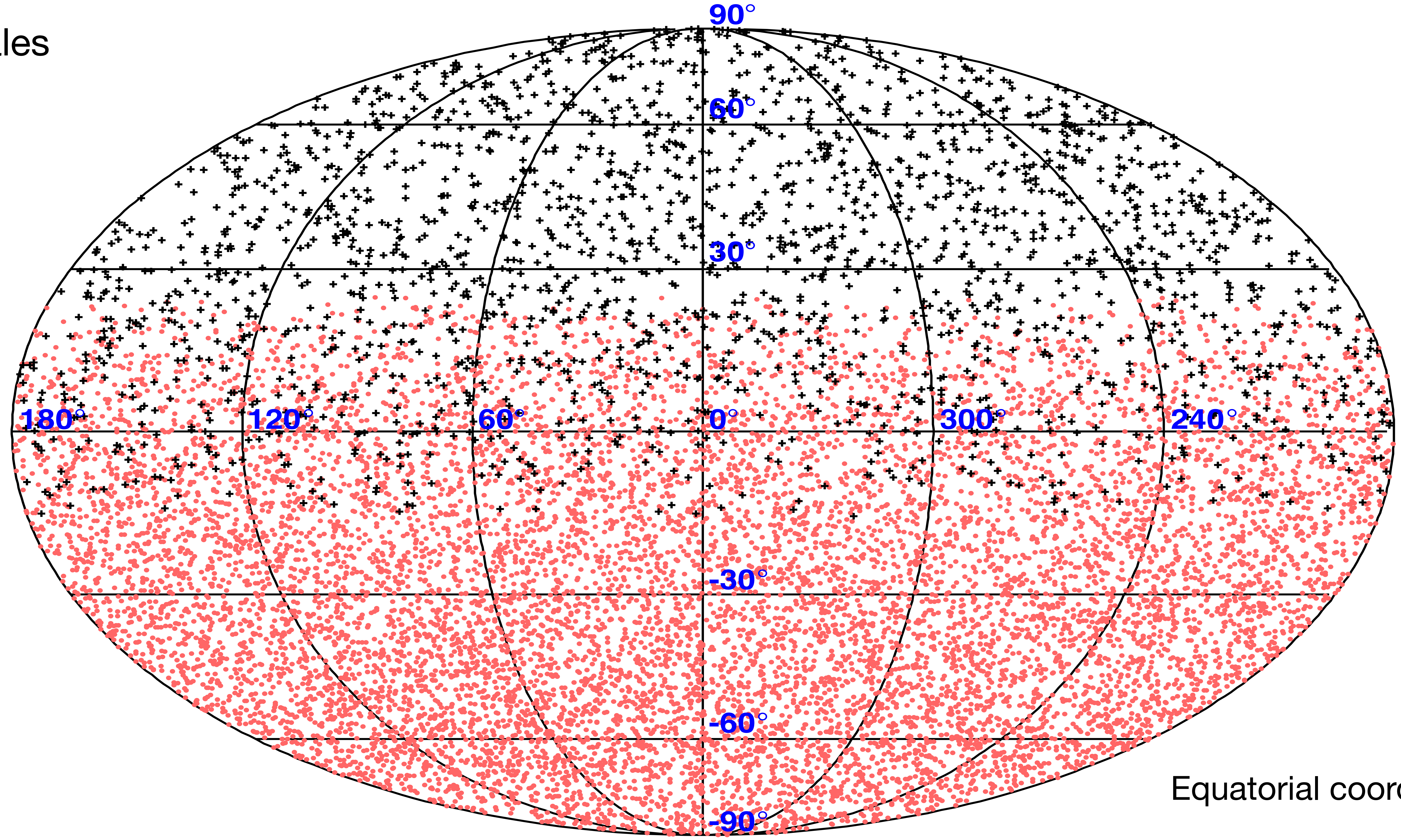
(Aloisio et al. 2014, Taylor et al. 2015, Globus et al. 2015, Unger et al. 2015, Fang & Murase 2017)





Arrival direction distribution at very high energy ($E > 10^{19}$ eV)

Different exposures and energy scales of Auger Observatory and Telescope Array



Equatorial coordinates

After unification of energy scales in overlap region:

In 2014 no significant anisotropy found

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

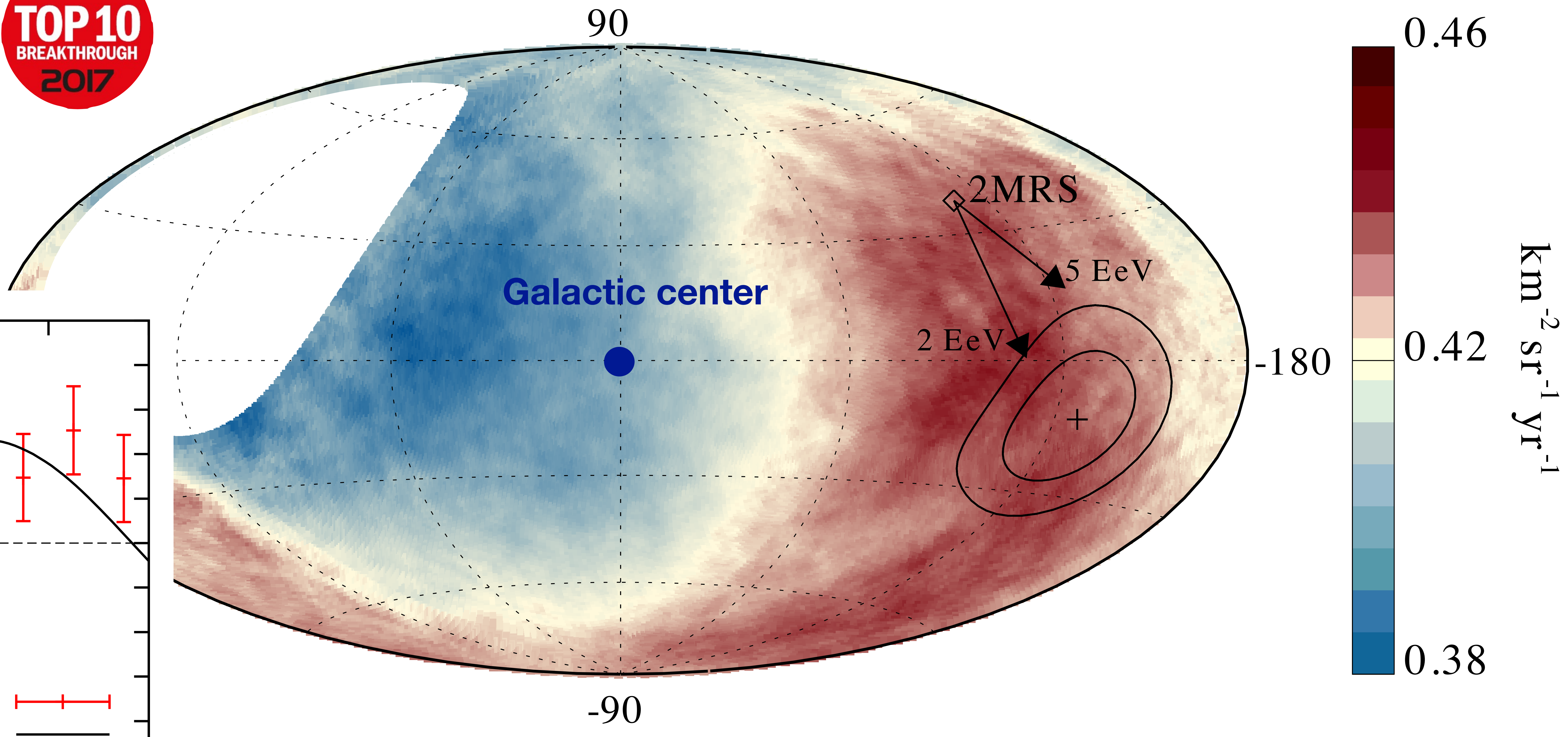
Small but important anisotropy observed at very high energy

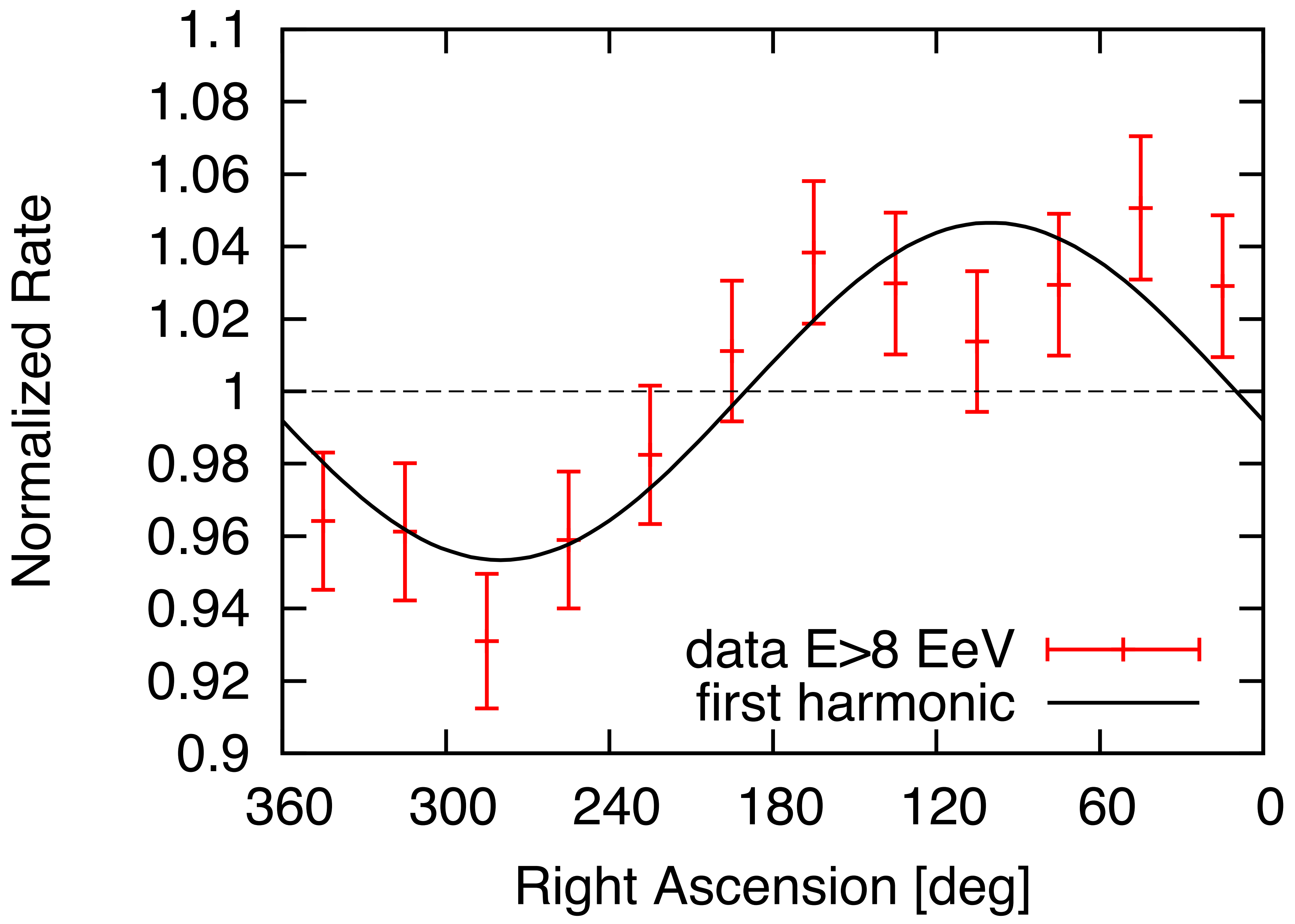
Combination of inclined and vertical events of Auger

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

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

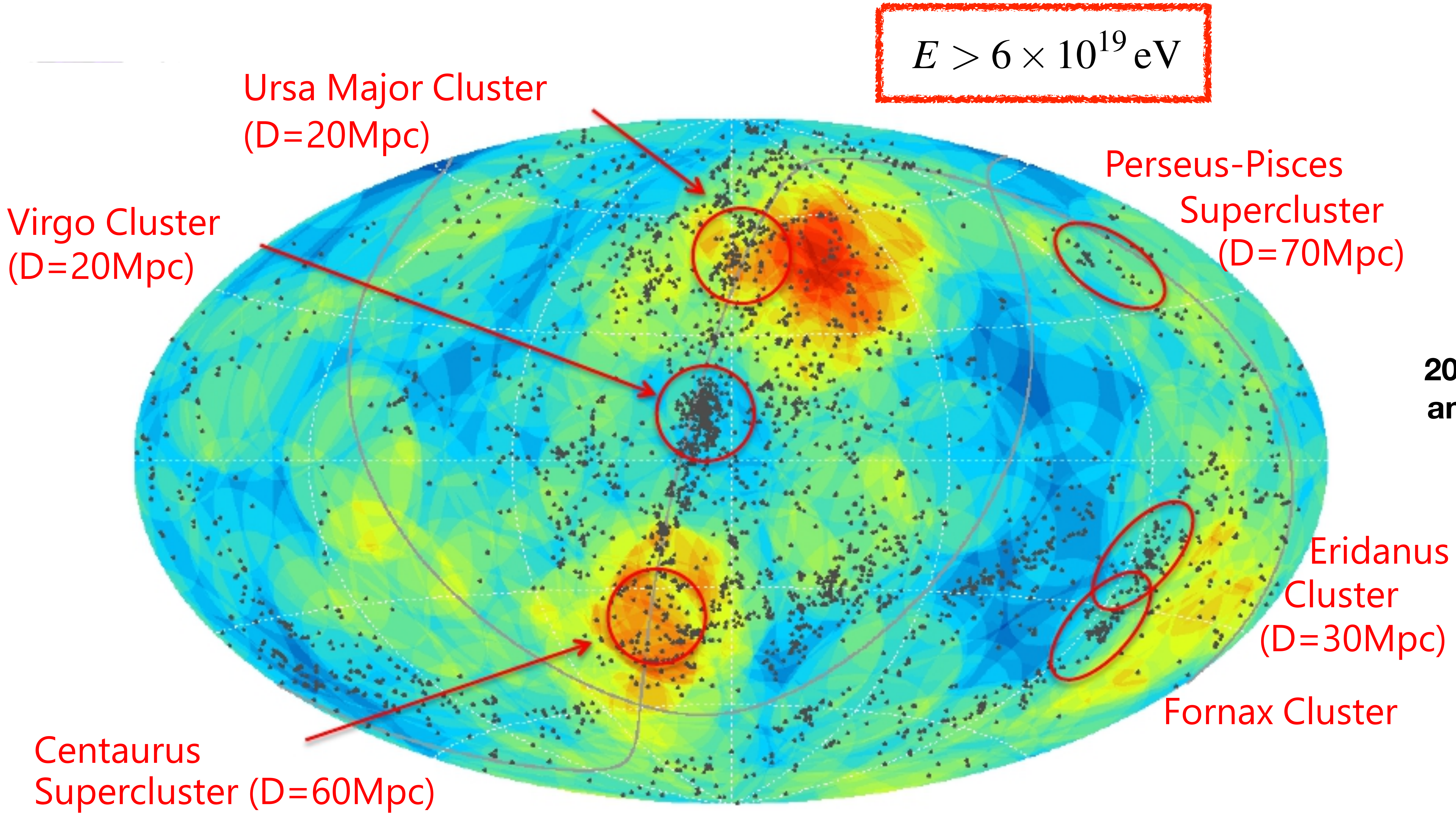
Estimated deflection in galactic mag. field





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

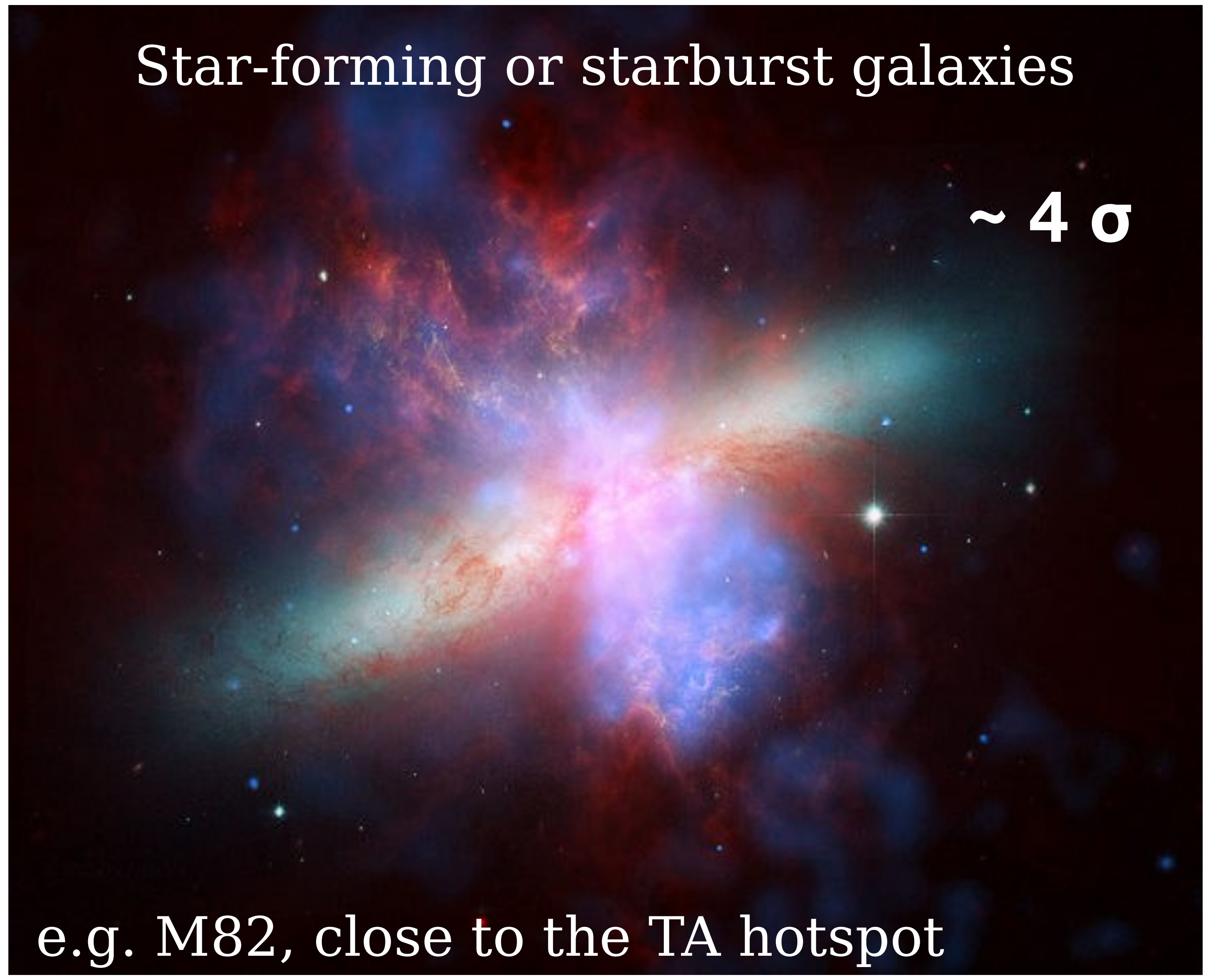
Intermediate-scale anisotropy at highest energies

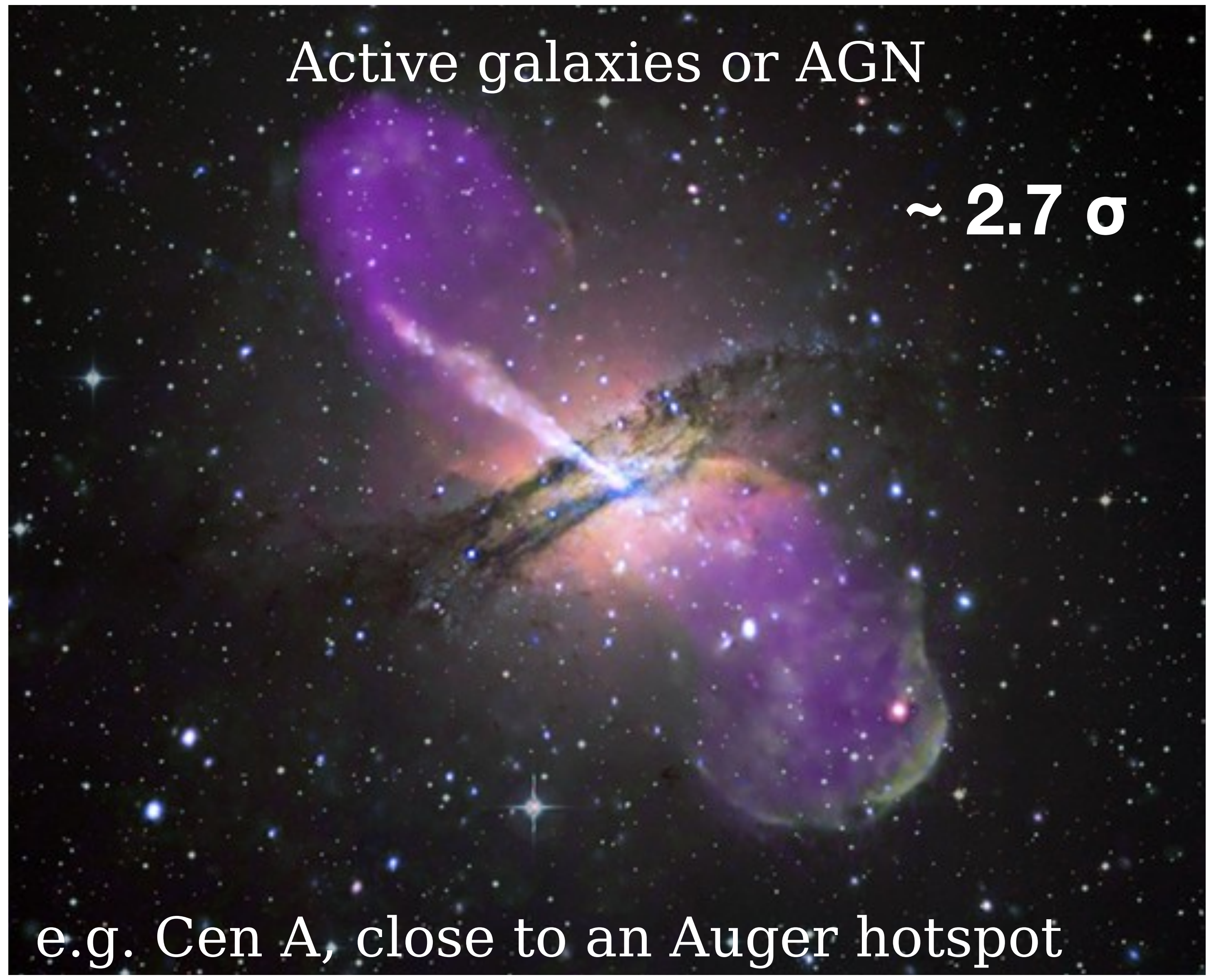


20° smearing in angle assumed

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

Scan: search for correlation with source candidates



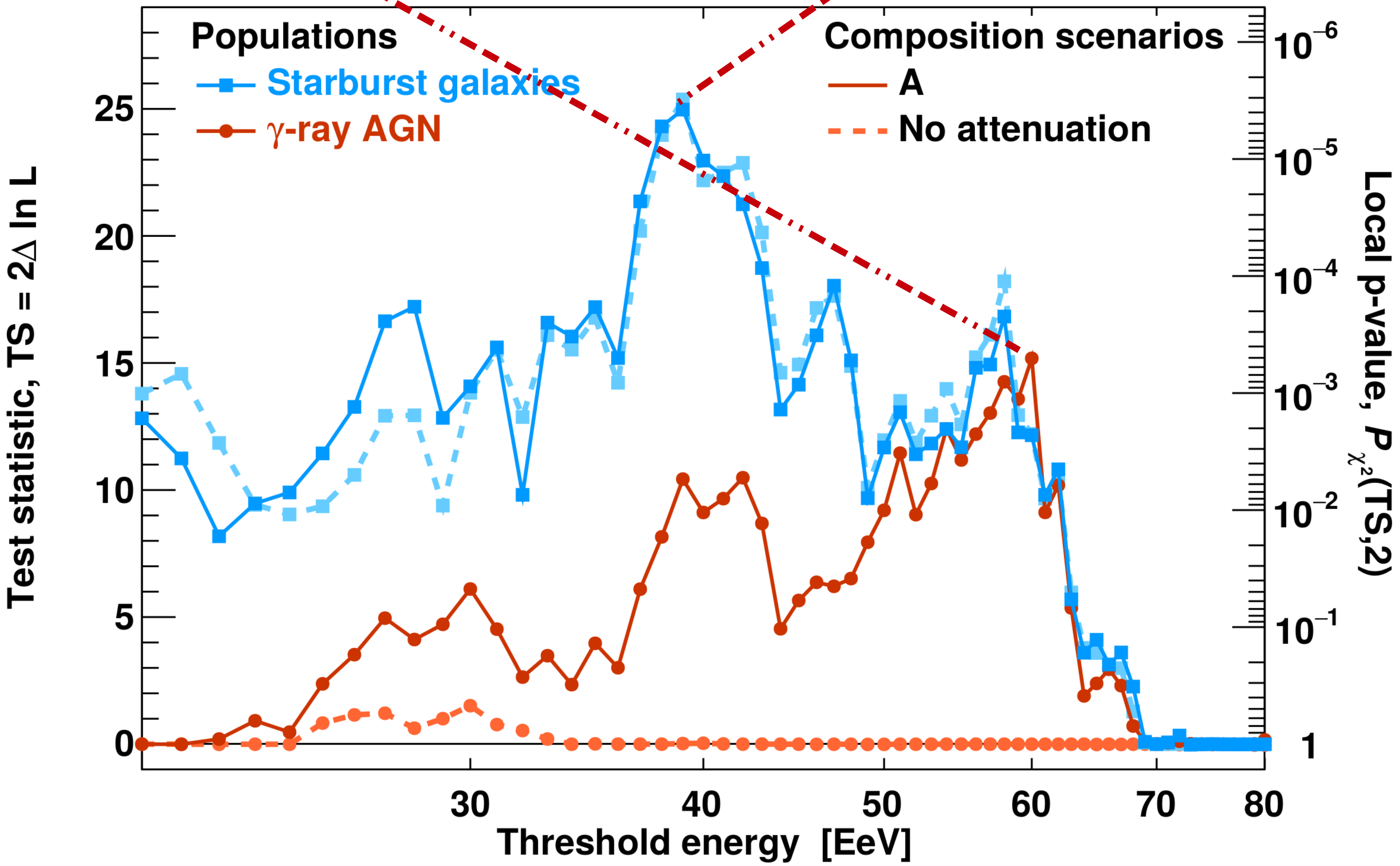


Active galaxies

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

Starforming galaxies

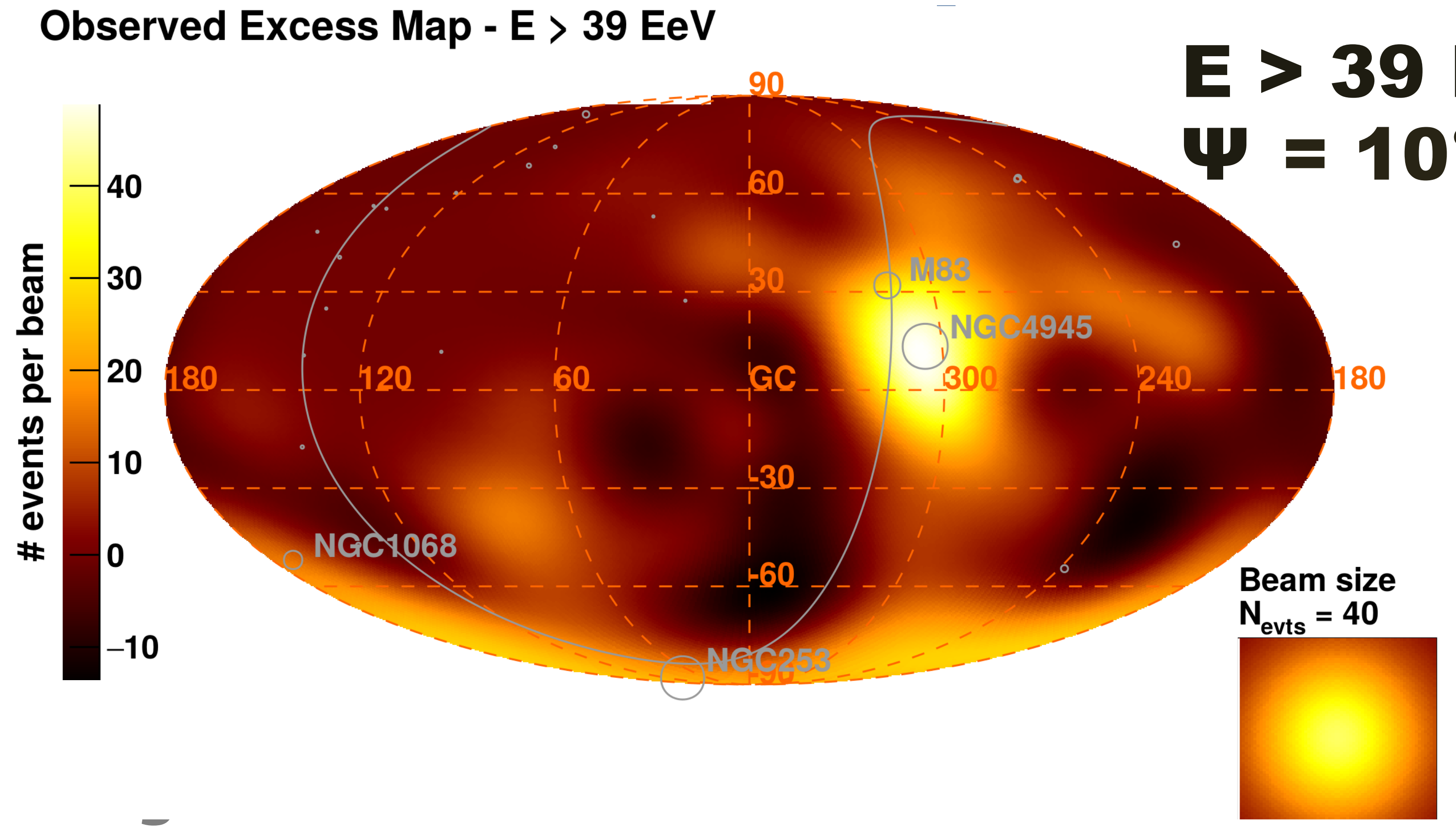
> 39 EeV: N~900 events, TS~25
α=10%, θ=13°
2 free par. + E-scan → 4.0σ



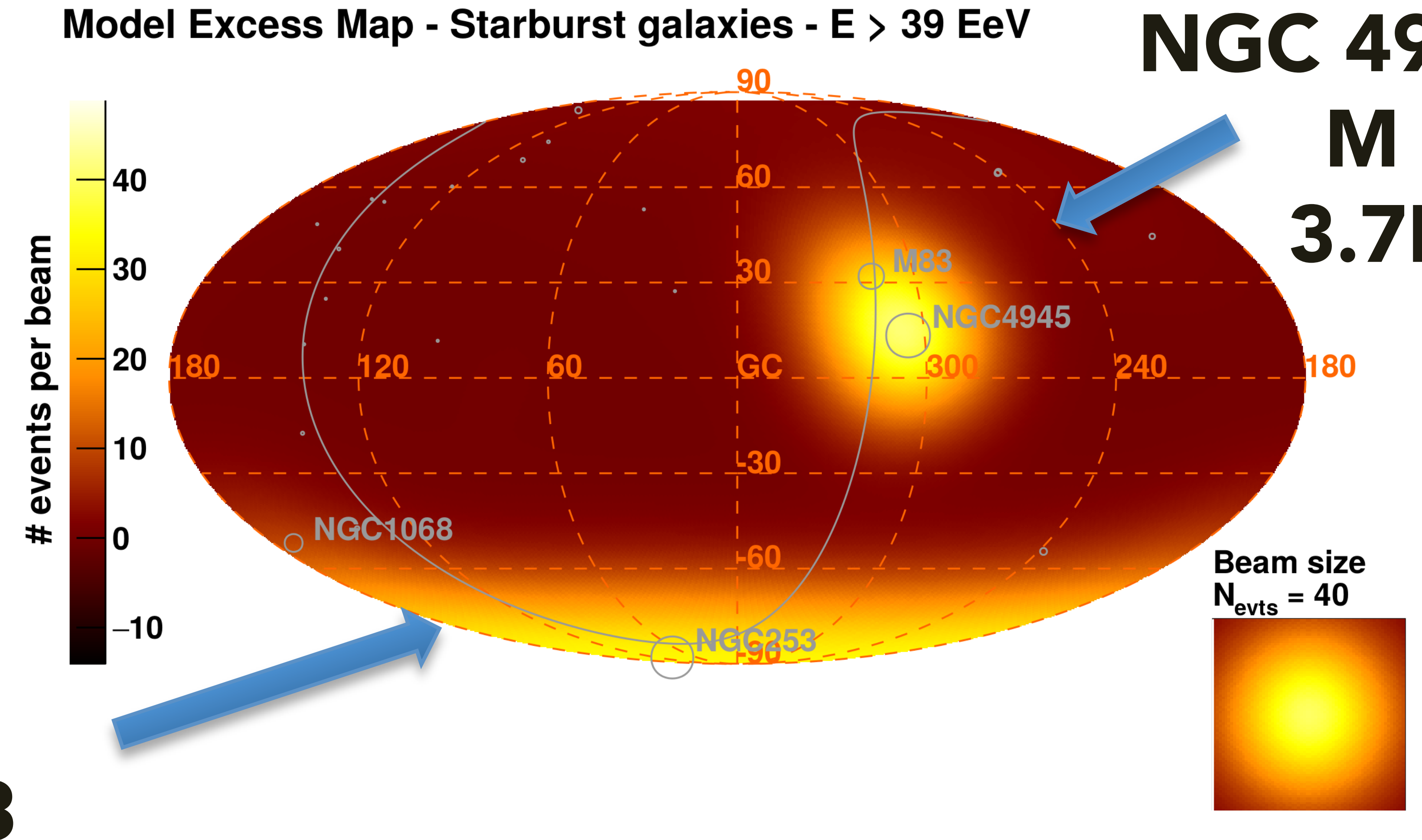
(Auger, ApJL 853, 2018)

Anisotropy – Correlation with catalogs (Auger data)

Starburst galaxies



E > 39 EeV
Ψ = 10°

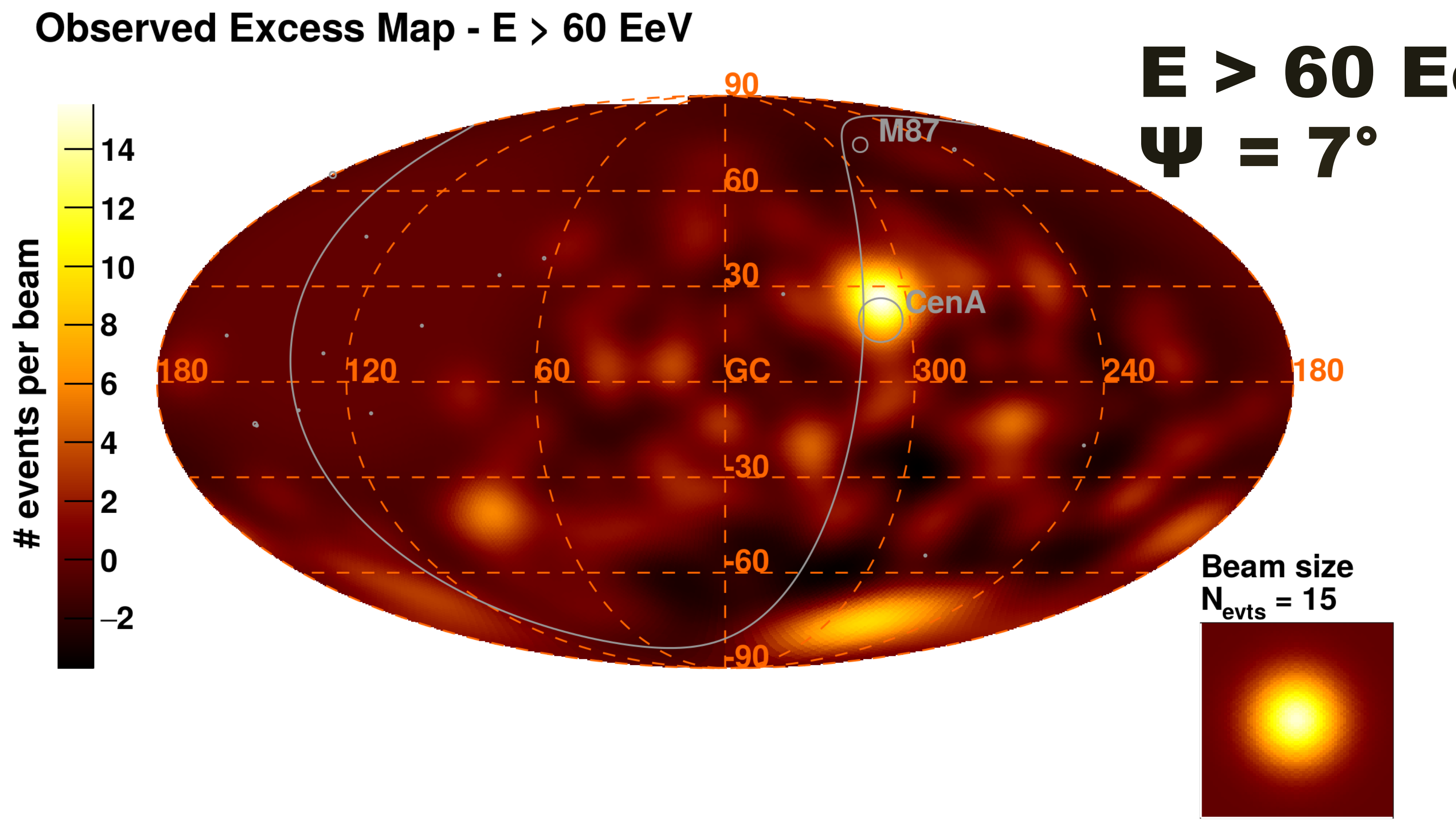


NGC 4945
M 83
3.7Mpc

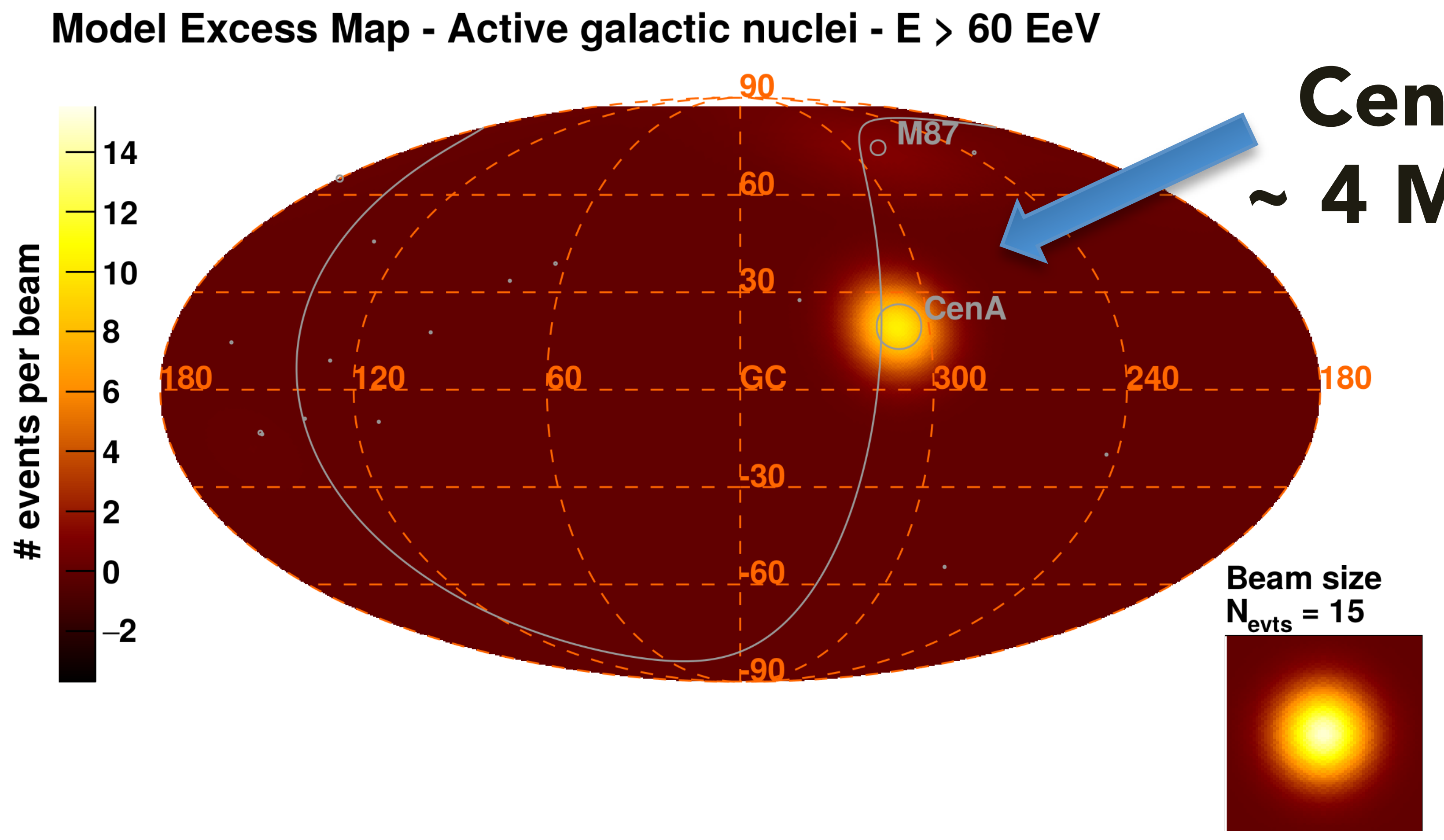
NGC 253
2.5 Mpc

NGC 1068
16.7 Mpc

AGNs



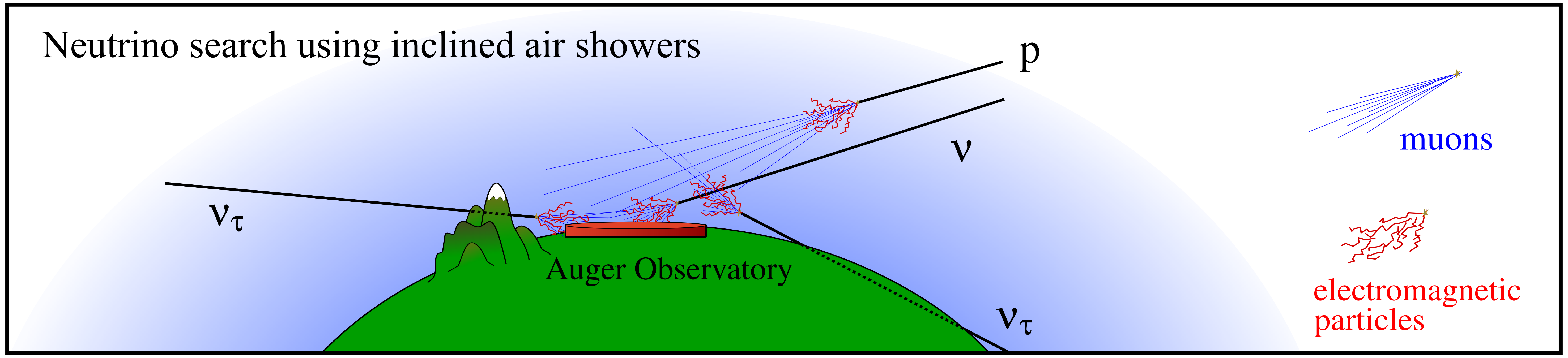
E > 60 EeV
Ψ = 7°



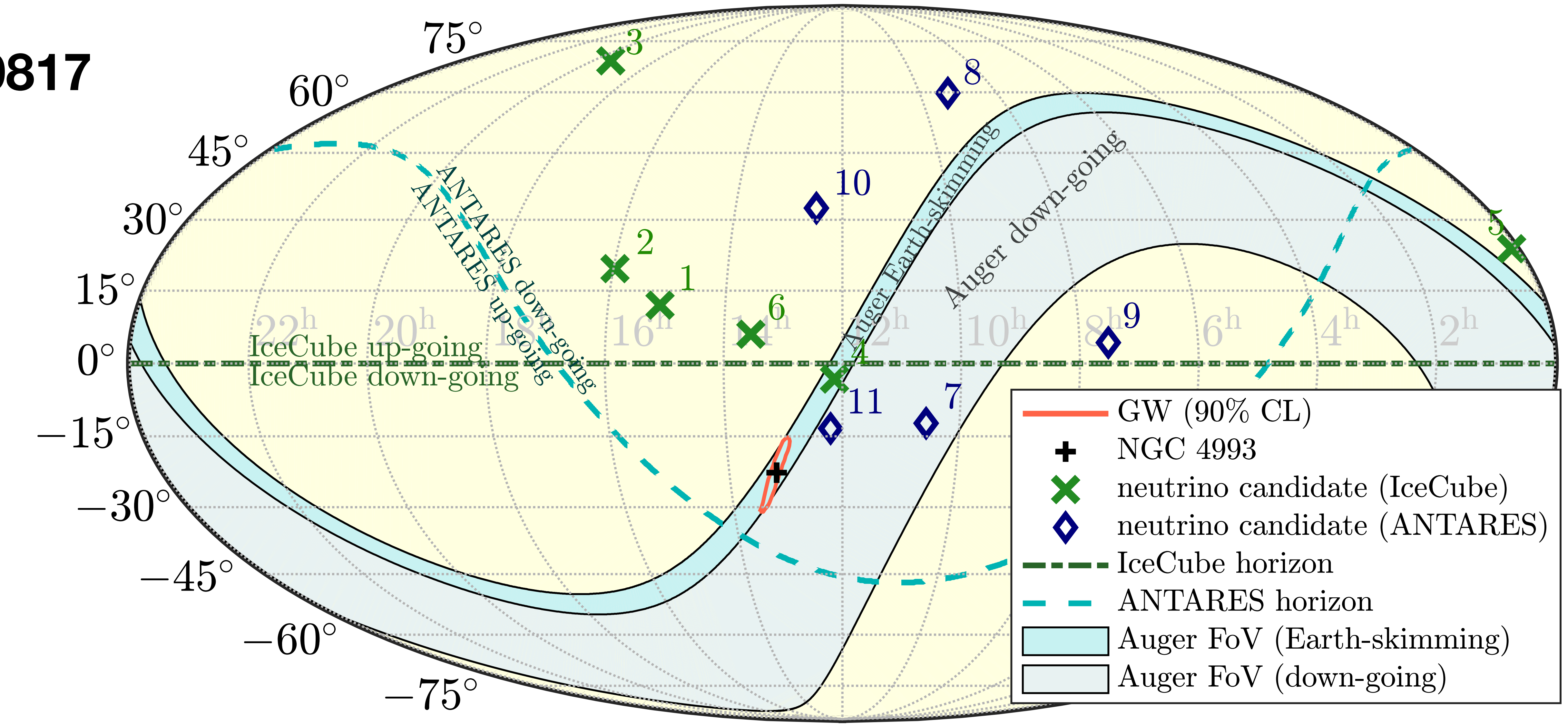
CenA
~ 4 Mpc

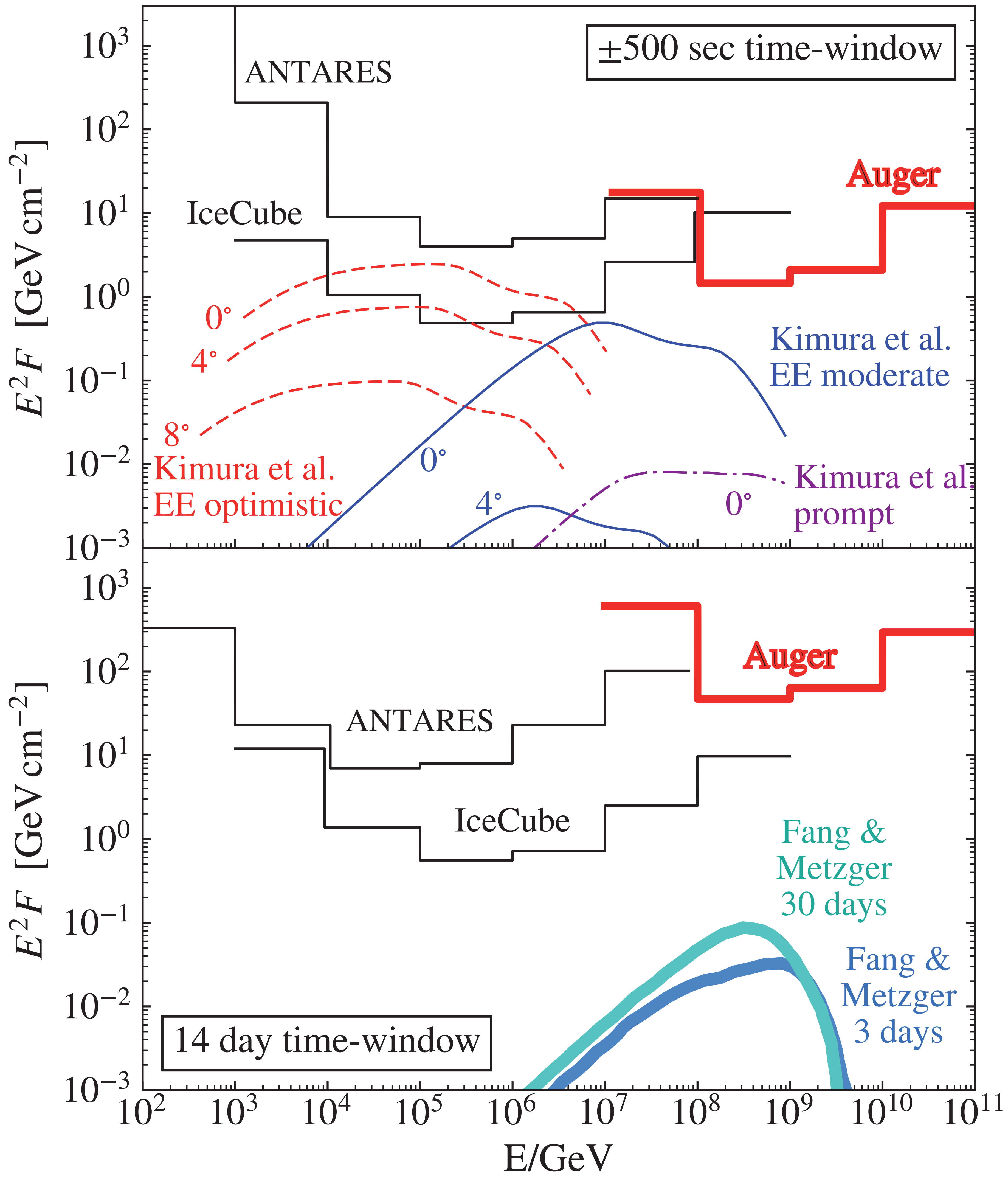
(Giaccari ICRC 2017)

Auger Observatory as multi-messenger detector



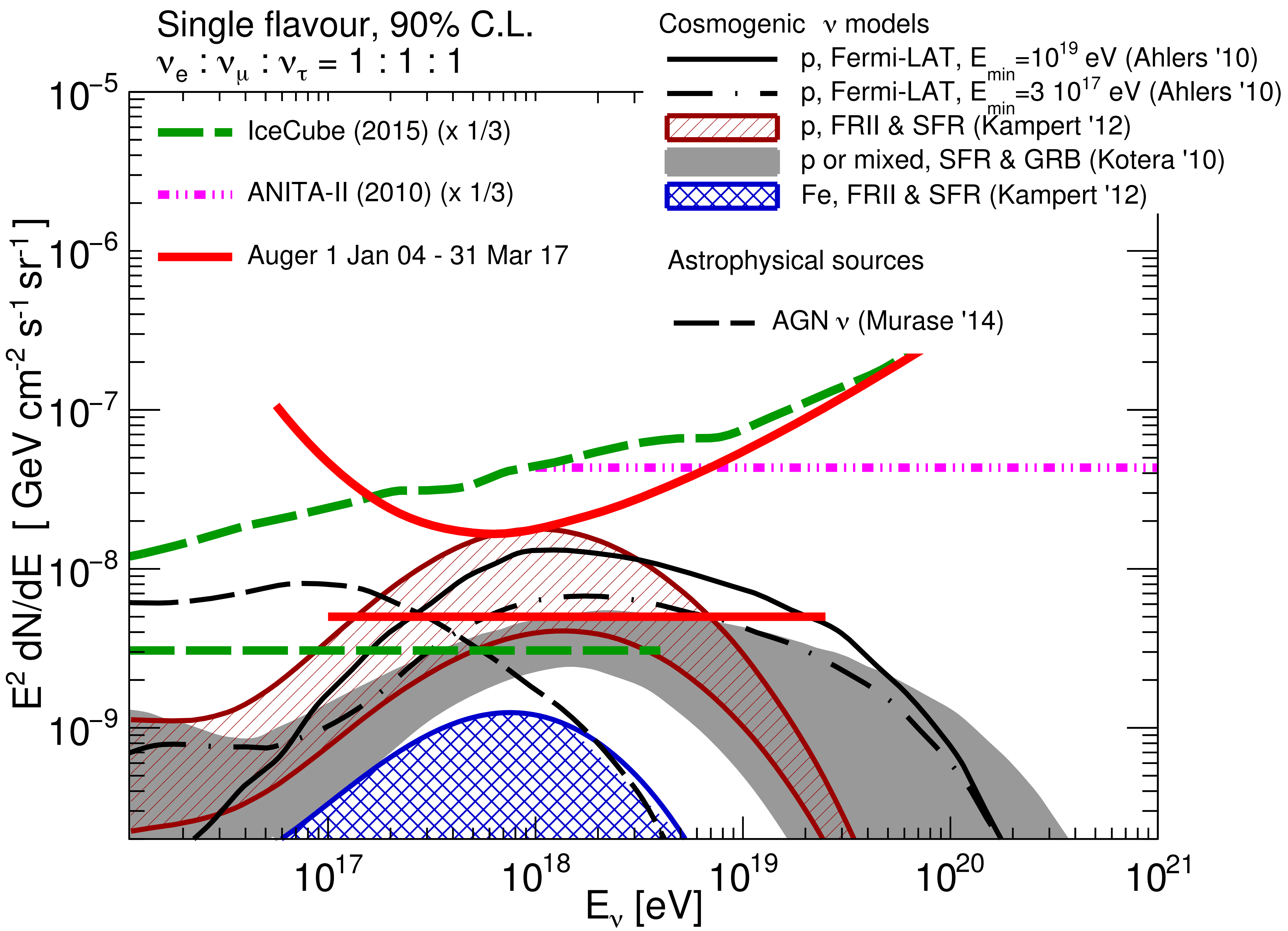
GW170817

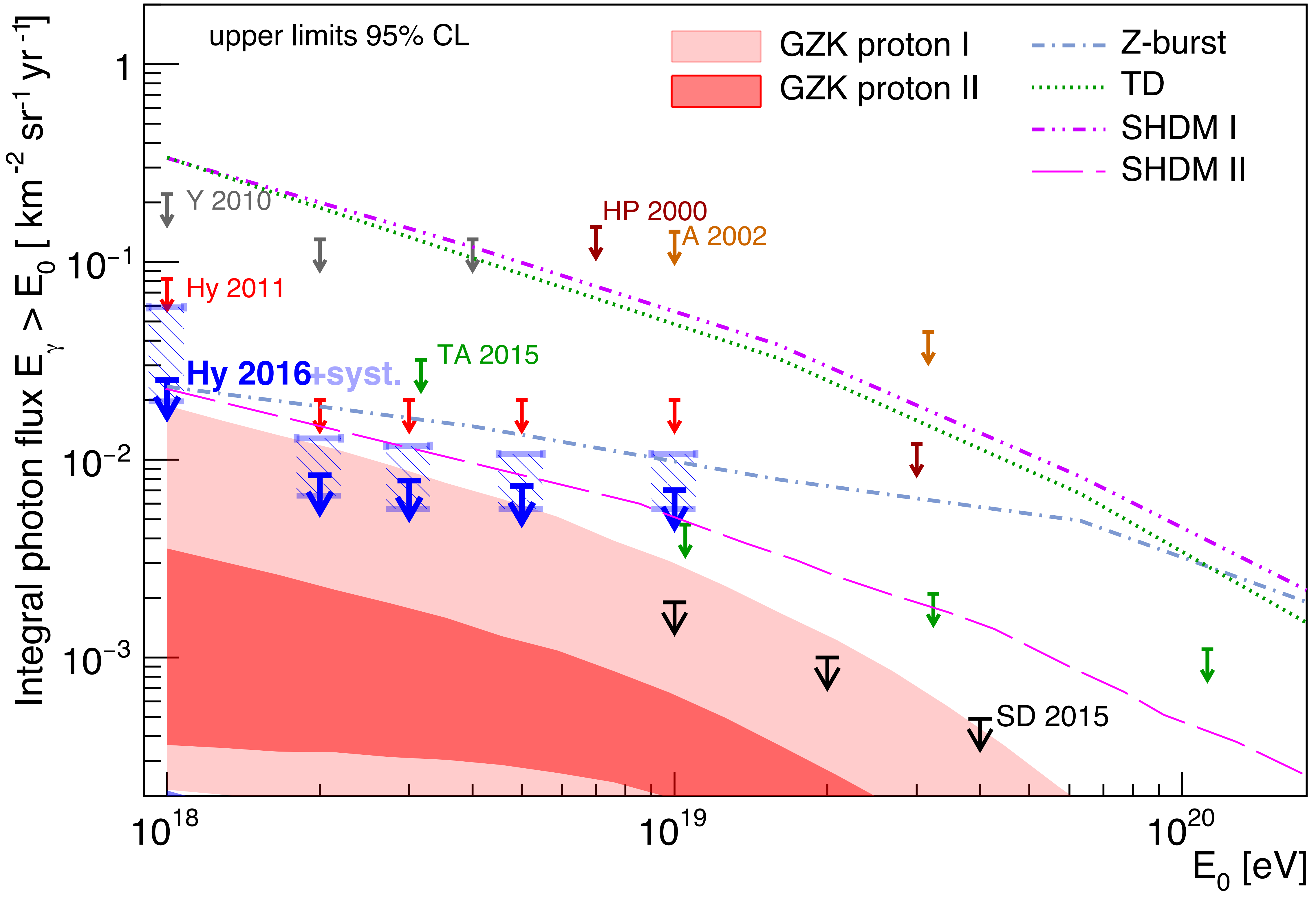




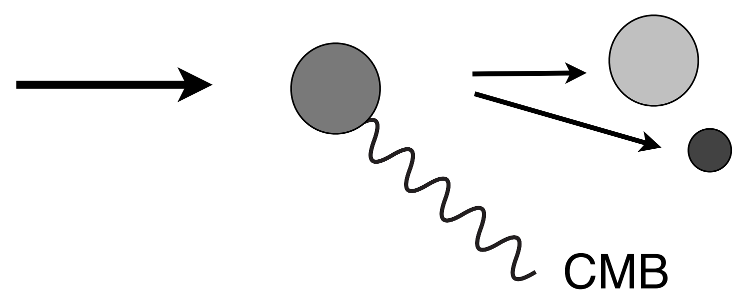
ApJL (2017), special issue (70 collaborations)

Neutrino and photon diffuse flux limits





- **Exotic (top-down) source models strongly disfavored**
- **proton-only model increasingly constrained**



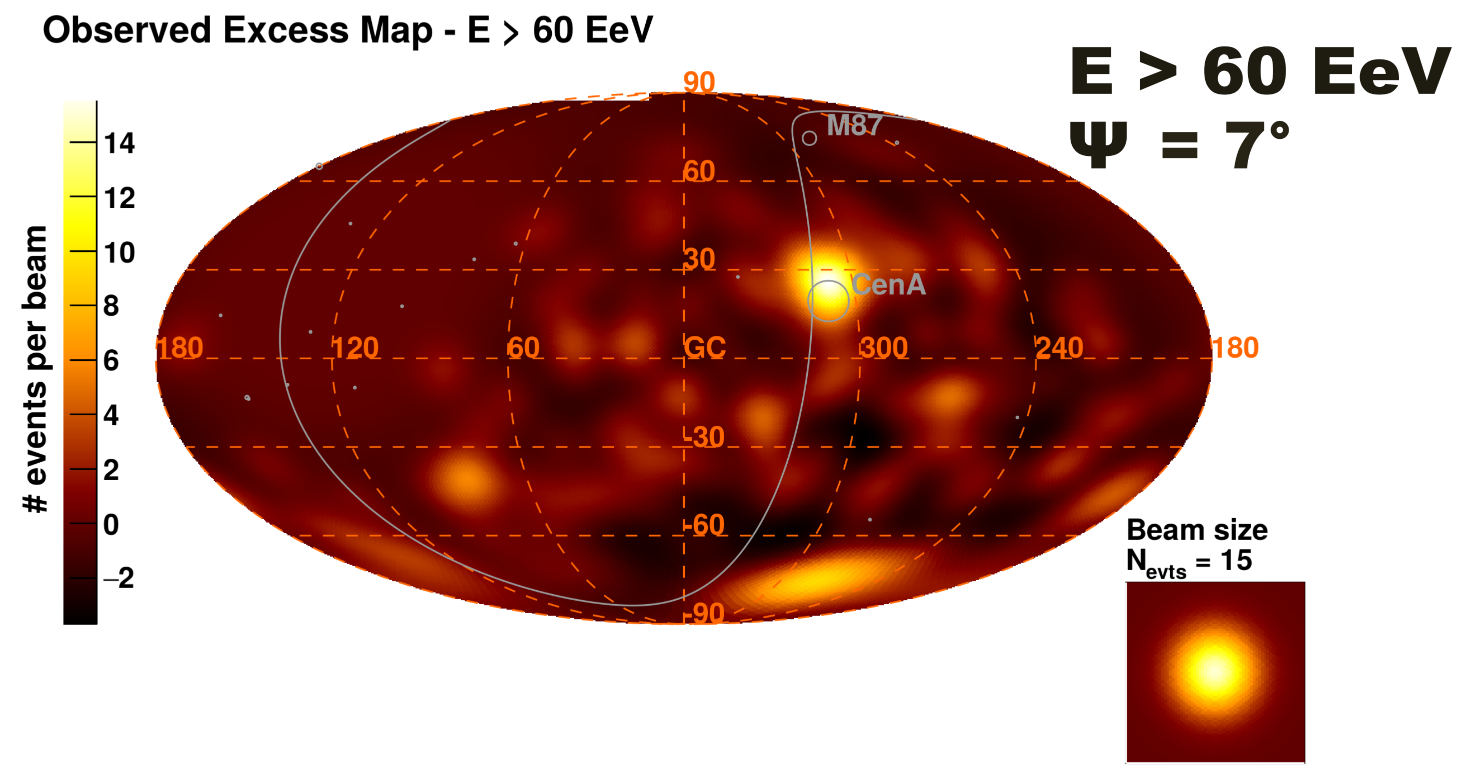
$$\pi^0 \longrightarrow \gamma\,\gamma$$

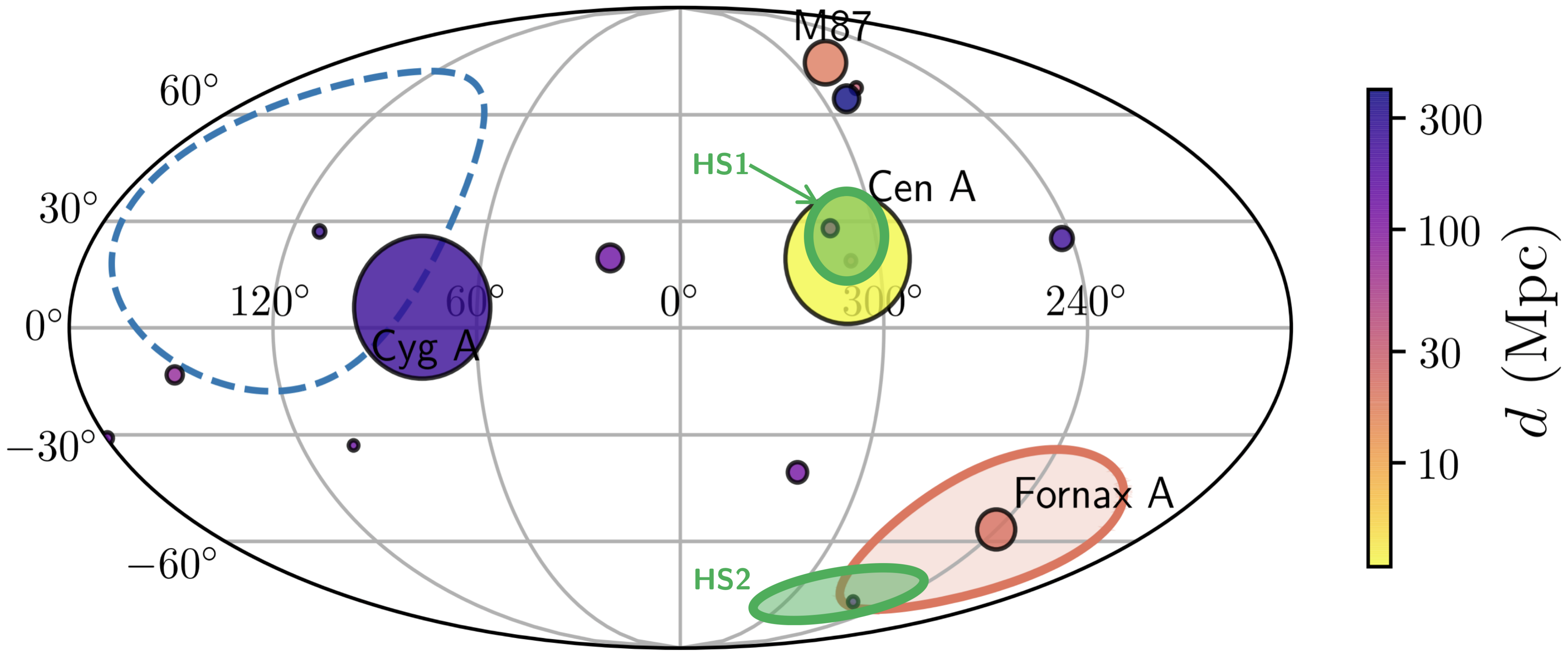
$$\pi^+ \longrightarrow \mu^+\,\nu_\mu \longrightarrow e^+\,\nu_e\,\nu_\mu\,\bar{\nu}_\mu$$

(Zas, Niechciol, Auger 2017)

Conclusions and outlook

- **Complicated and unexpected picture of UHECR emerging**
  (acceleration scenarios, non-trivial changes in mass composition)
- **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**
  (statistics & composition at highest energies will be decisive)
- **Multi-messenger data key for making progress**
  (both for source identification and composition)
- **Mapping of cosmic magnetic fields after source correlation is established**
- **Particle physics and LIV tests**
- **Upgrade of Auger Observatory and TA**



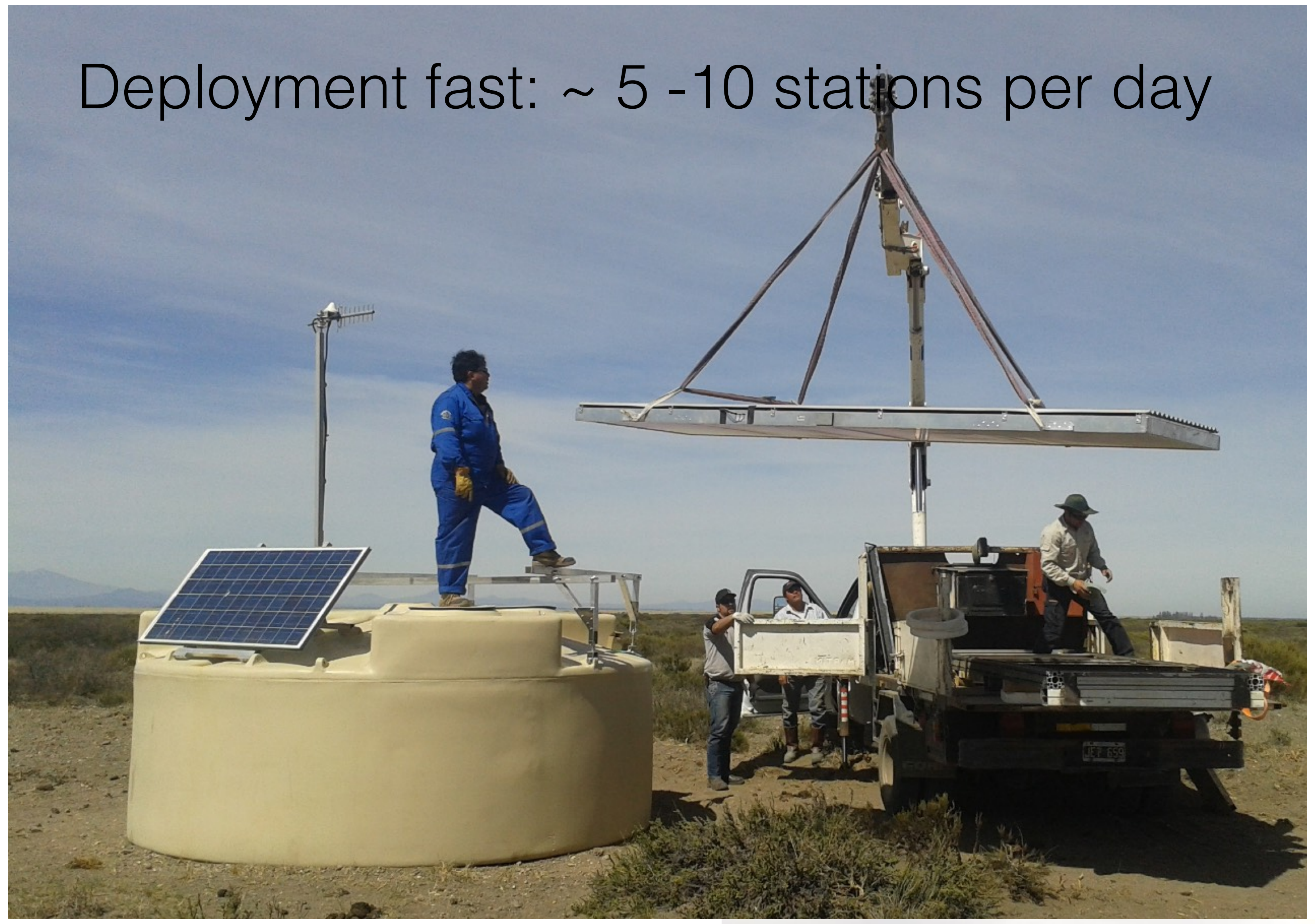


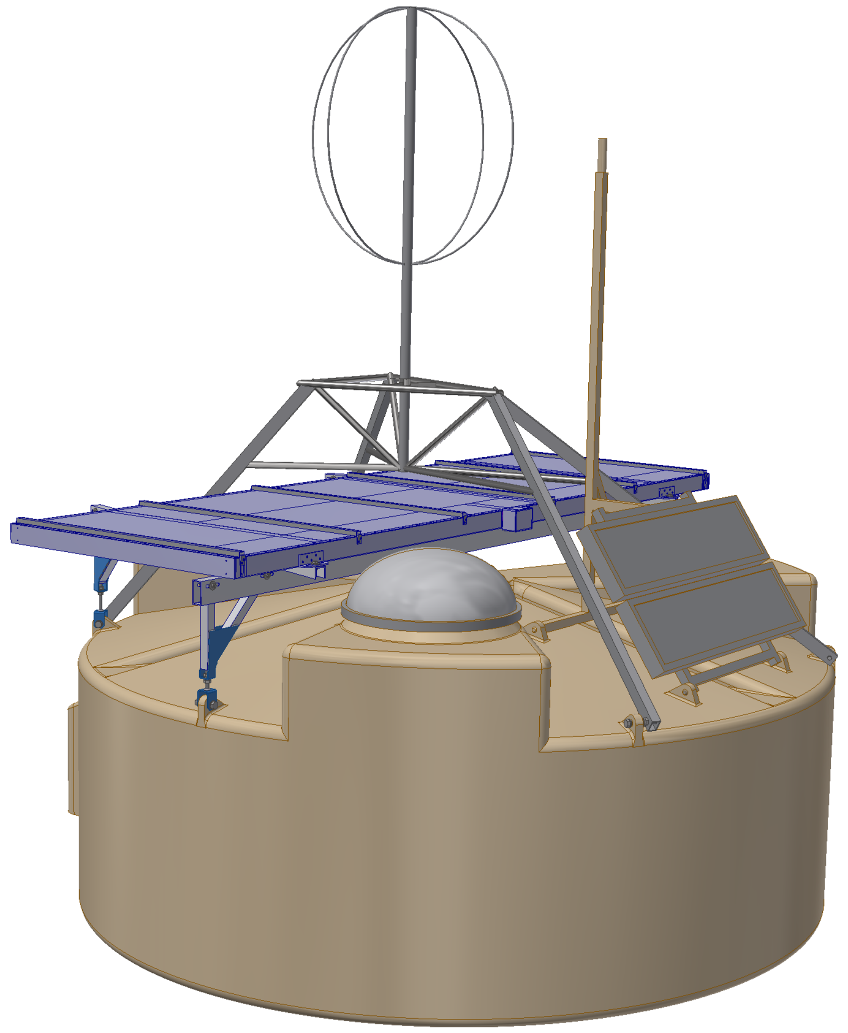
(Matthews, Bell et al. 2018)

Upgrade of Auger Observatory: AugerPrime

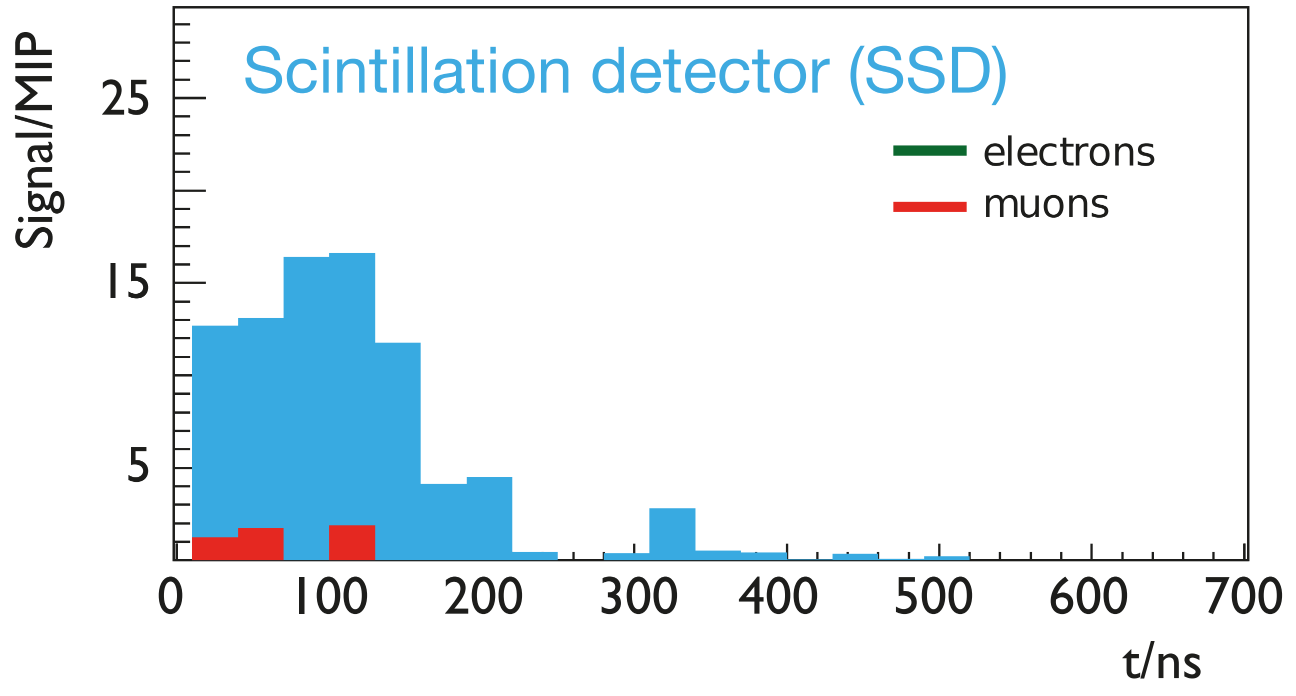
15% duty cycle

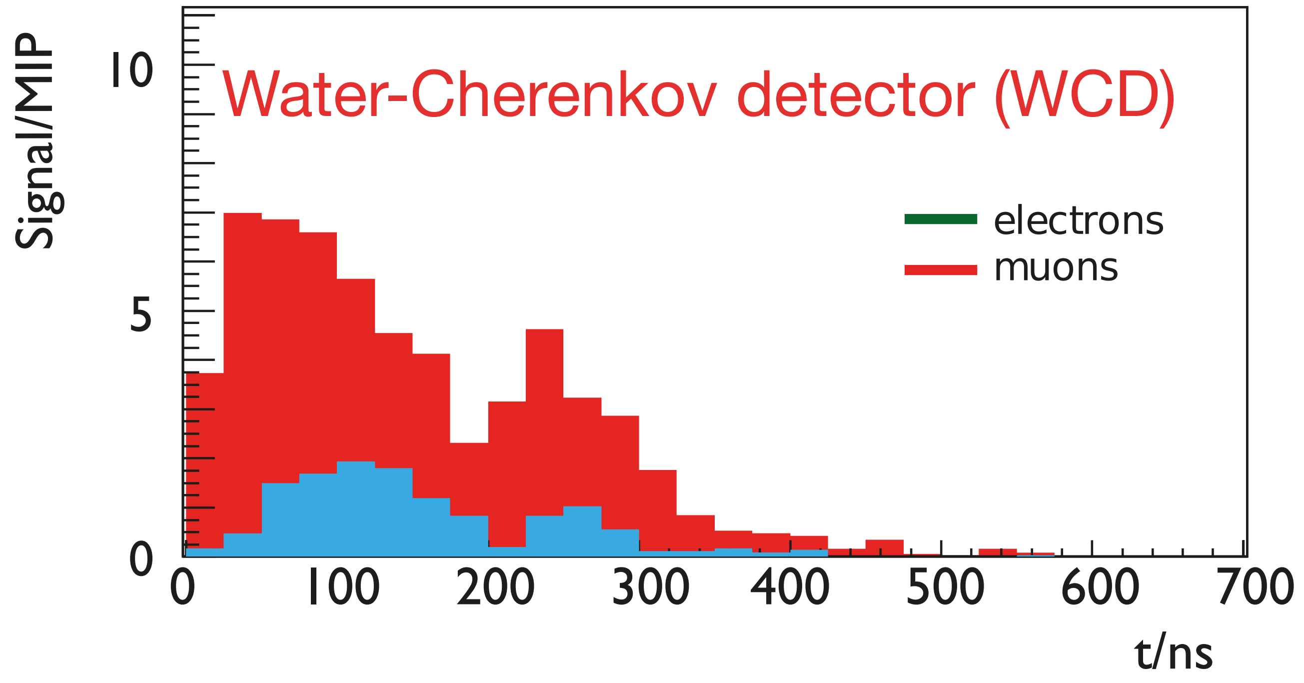
100% duty cycle



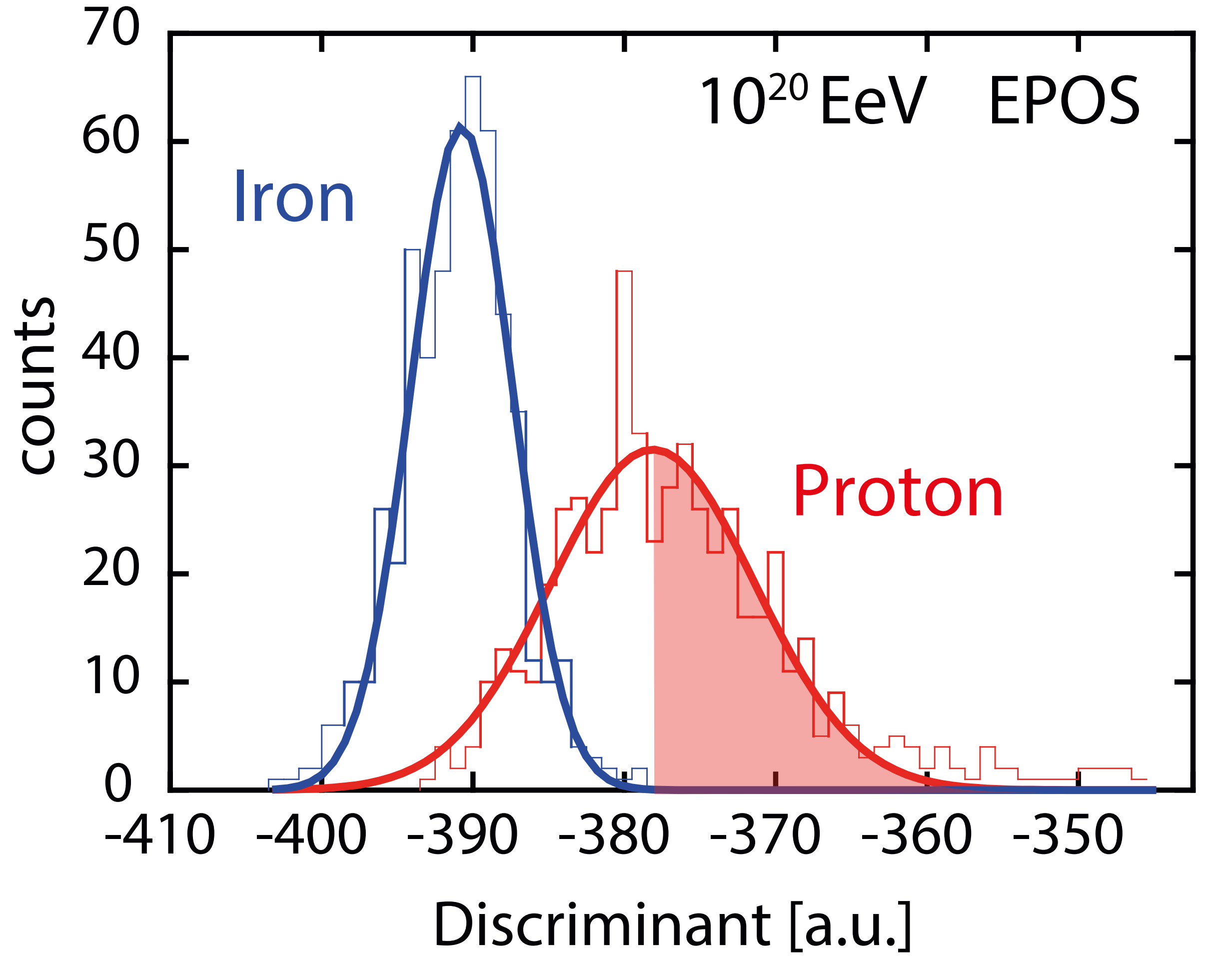


Radio antennas for inclined showers





- **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)

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)

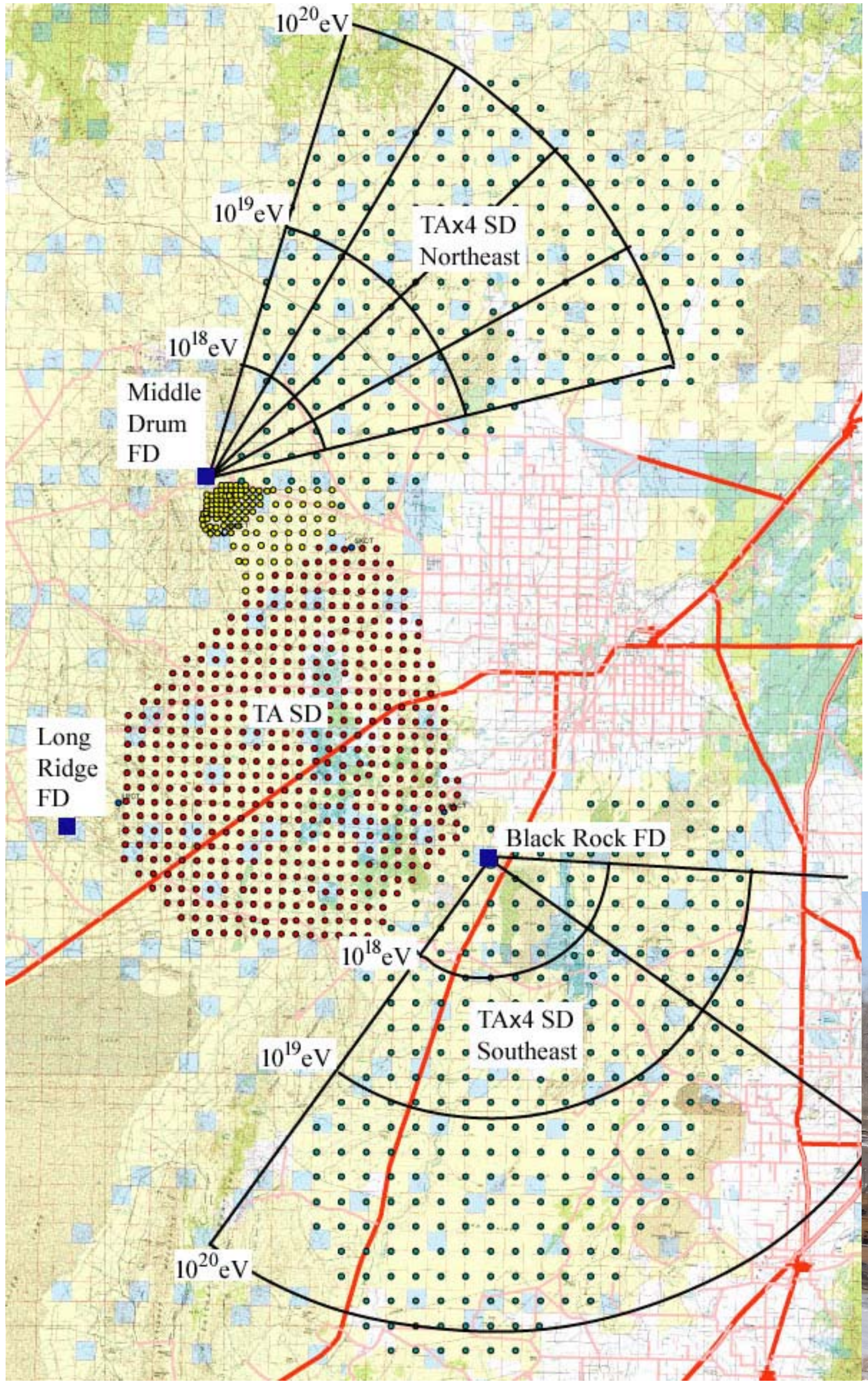
Approved US NSF 2016

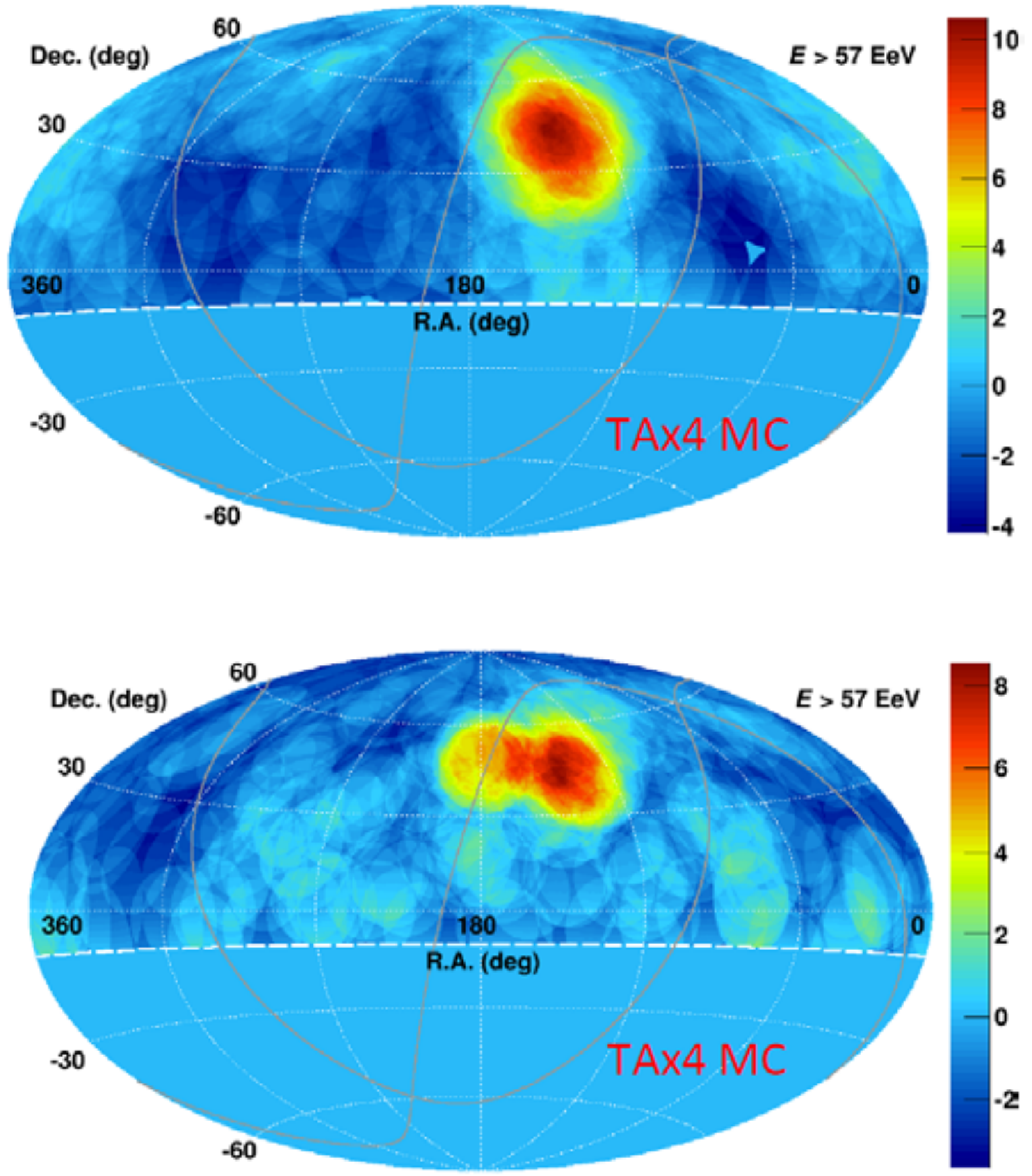
Telescopes/electronics being prepared at Univ. Utah

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





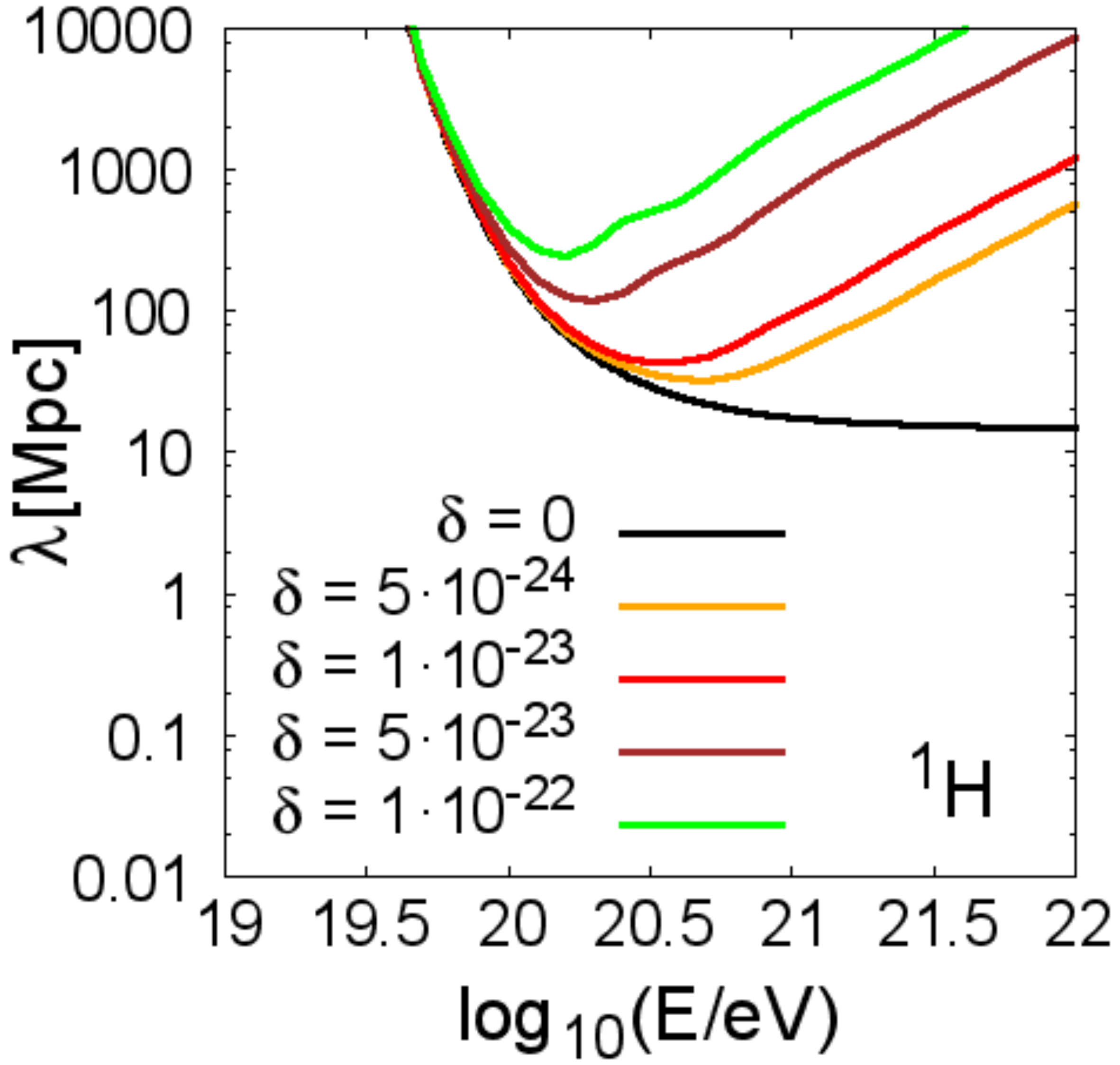
(Kido, Matthews ICRC 2017)

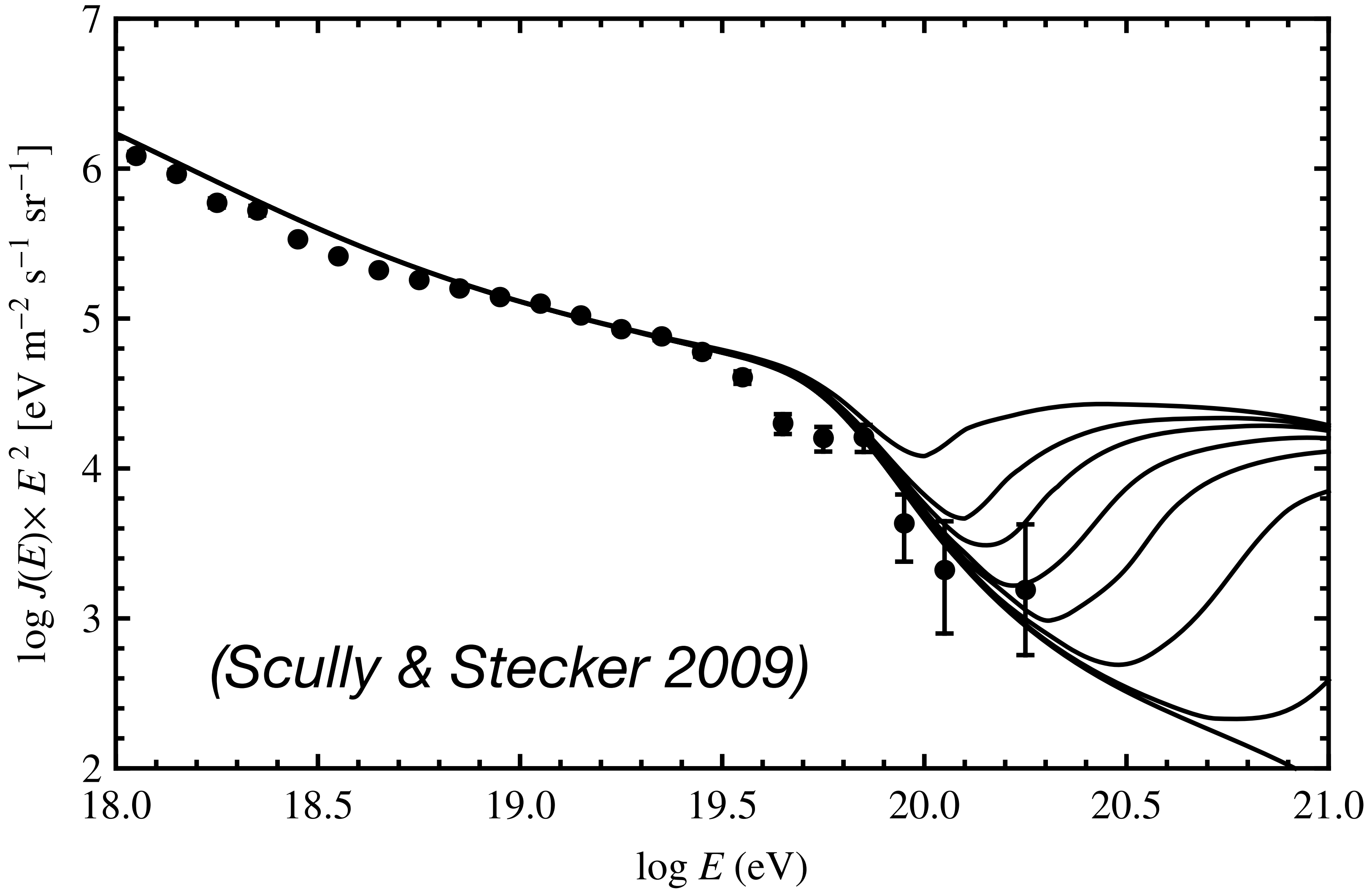
Outlook: Searches for Lorentz invariance violation

$$E_i^2 - p_i^2 = m_i^2 \Rightarrow \mu_i^2(E,p,M_{\rm Pl}) \approx m_i^2 + \sum_{n=0}^{N} \eta_i^{(n)} \frac{E_i^{2+n}}{M_{\rm Pl}^n}$$

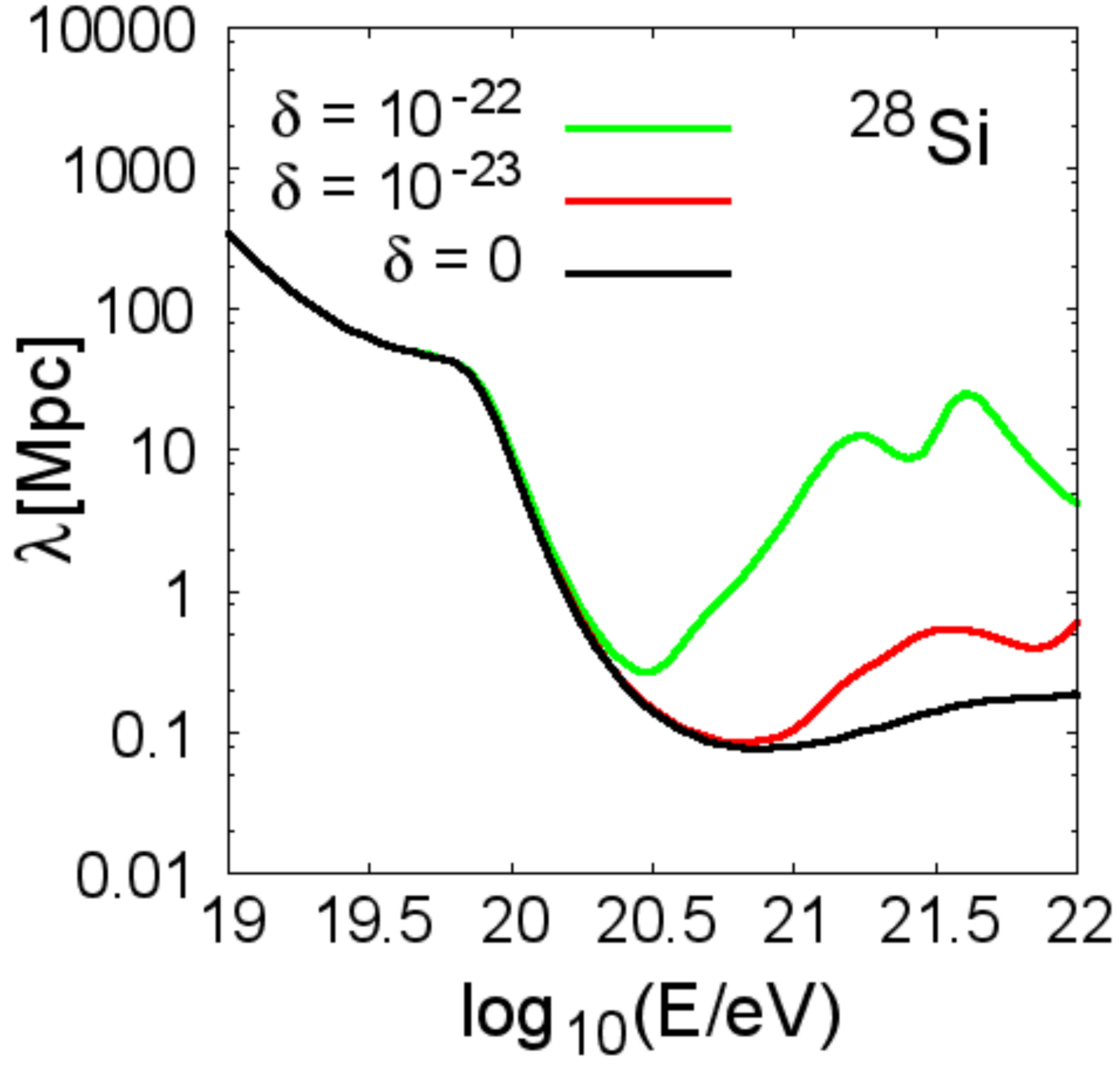
$$\delta_i^{(n)} = \frac{\eta_i^{(n)}}{M_{\rm Pl}^n}$$

(Coleman & Glashow, PRD 59, 1999)





Work in progress



Analysis for protons straightforward,
extension to changing composition adds new degrees of freedom

Further channels for investigation will be exploited

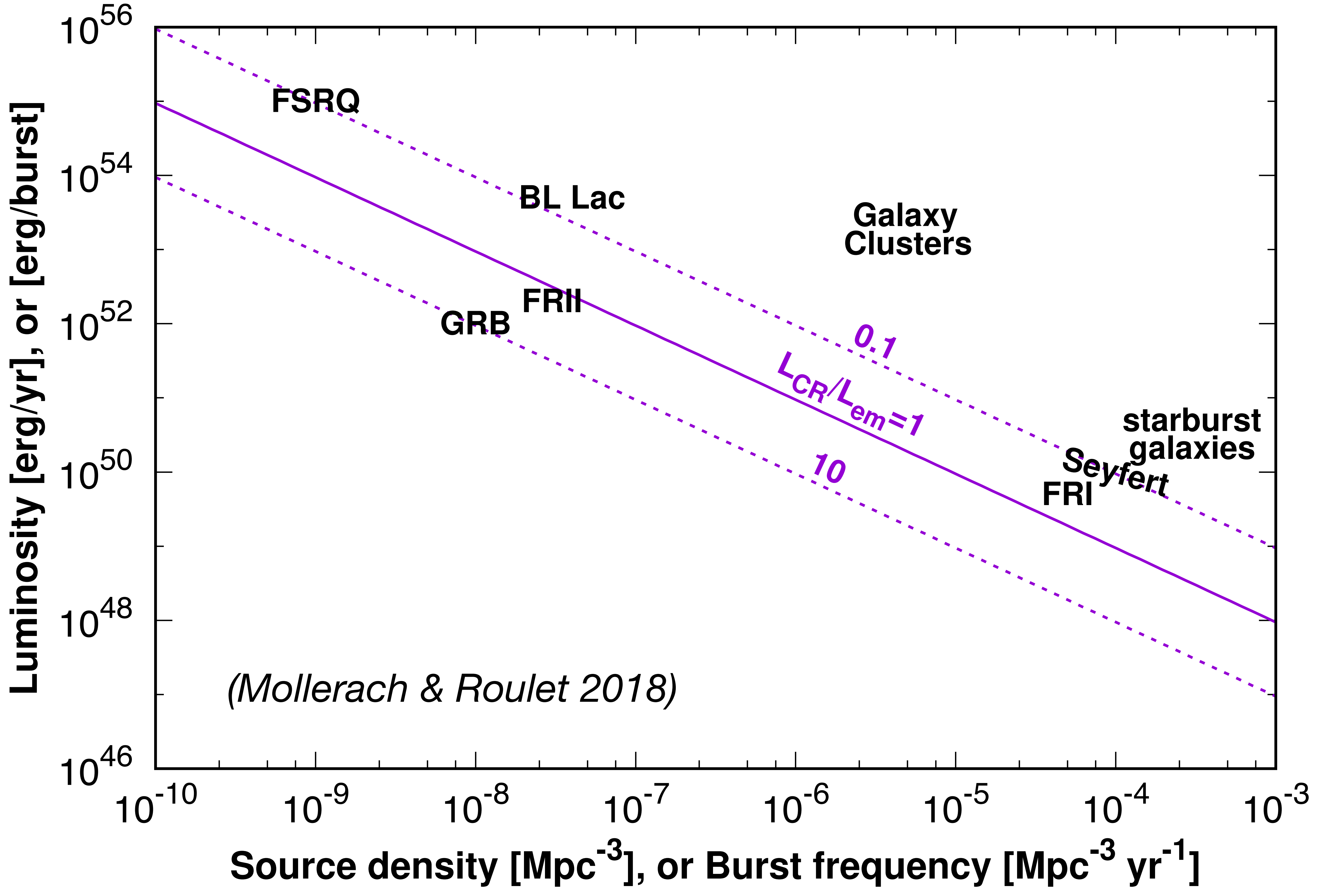
(Boncioli, Auger 2017)

Backup slides

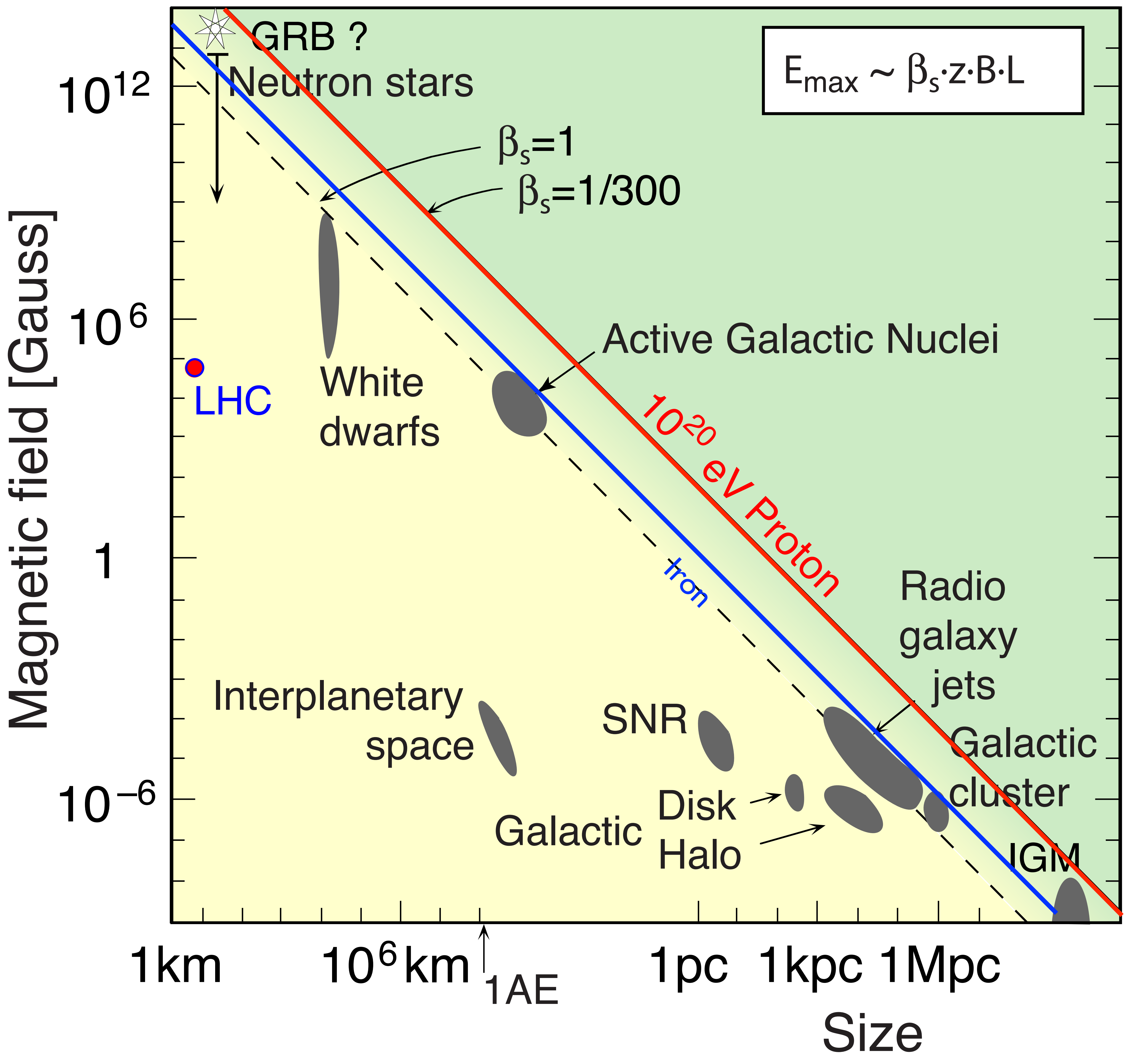
General considerations about sources

Power: $Q(E > 10^{18}\,\mathrm{eV}) \sim 5 \times 10^{45}\ \mathrm{erg/Mpc^3/yr}$

(Gaisser, Waxman… 1998)

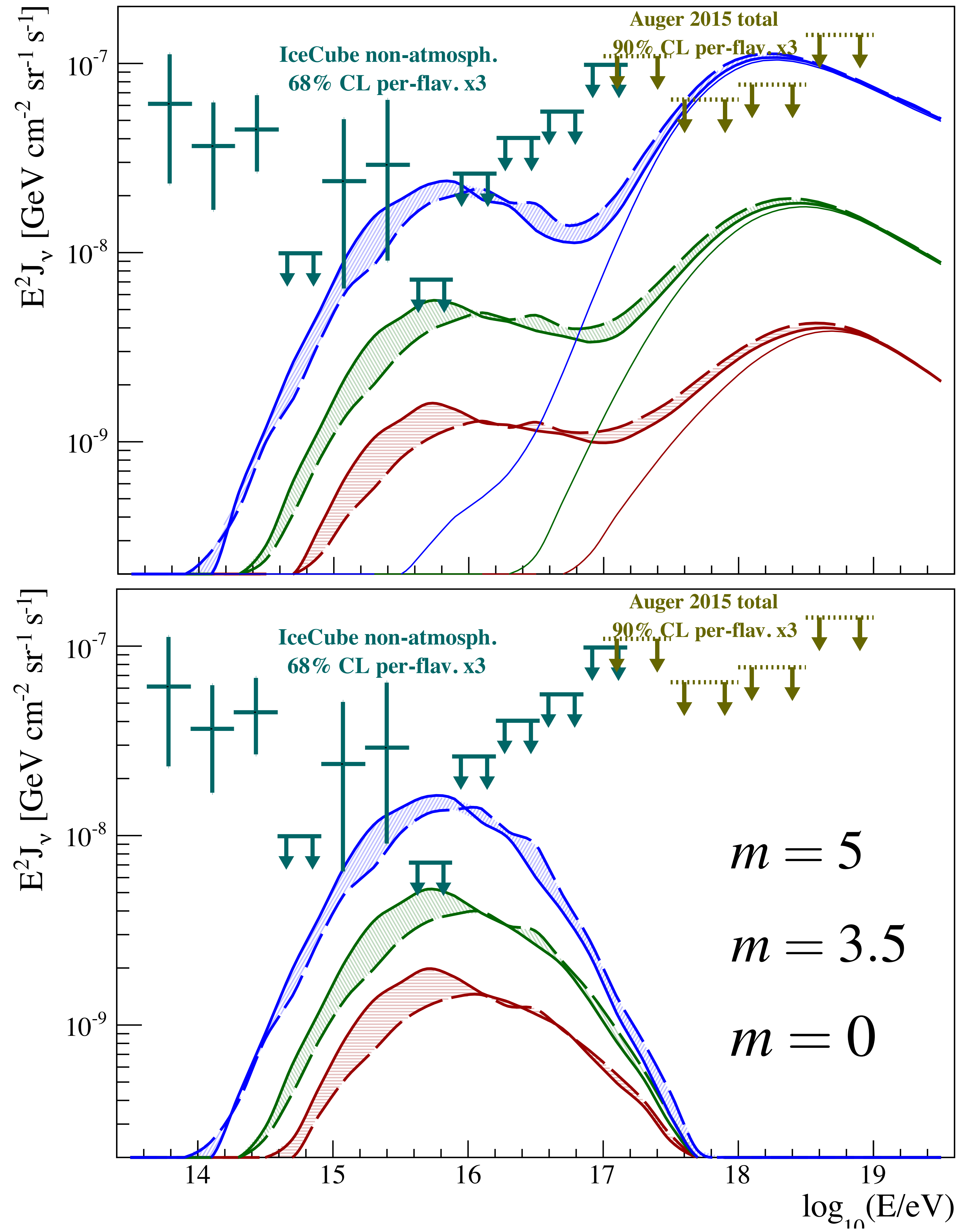


Hillas (1984): $E_{max} \sim \beta_s Z B R$



Neutrino and gamma-ray fluxes

Neutrinos



(Aloisio et al. JCAP 2015) (Ahlers, Heinze et al. 2017)

Complementarity

- Cosmic ray flux local
- Neutrino flux from large distances
- GZK neutrinos probe E > 10^{20} eV

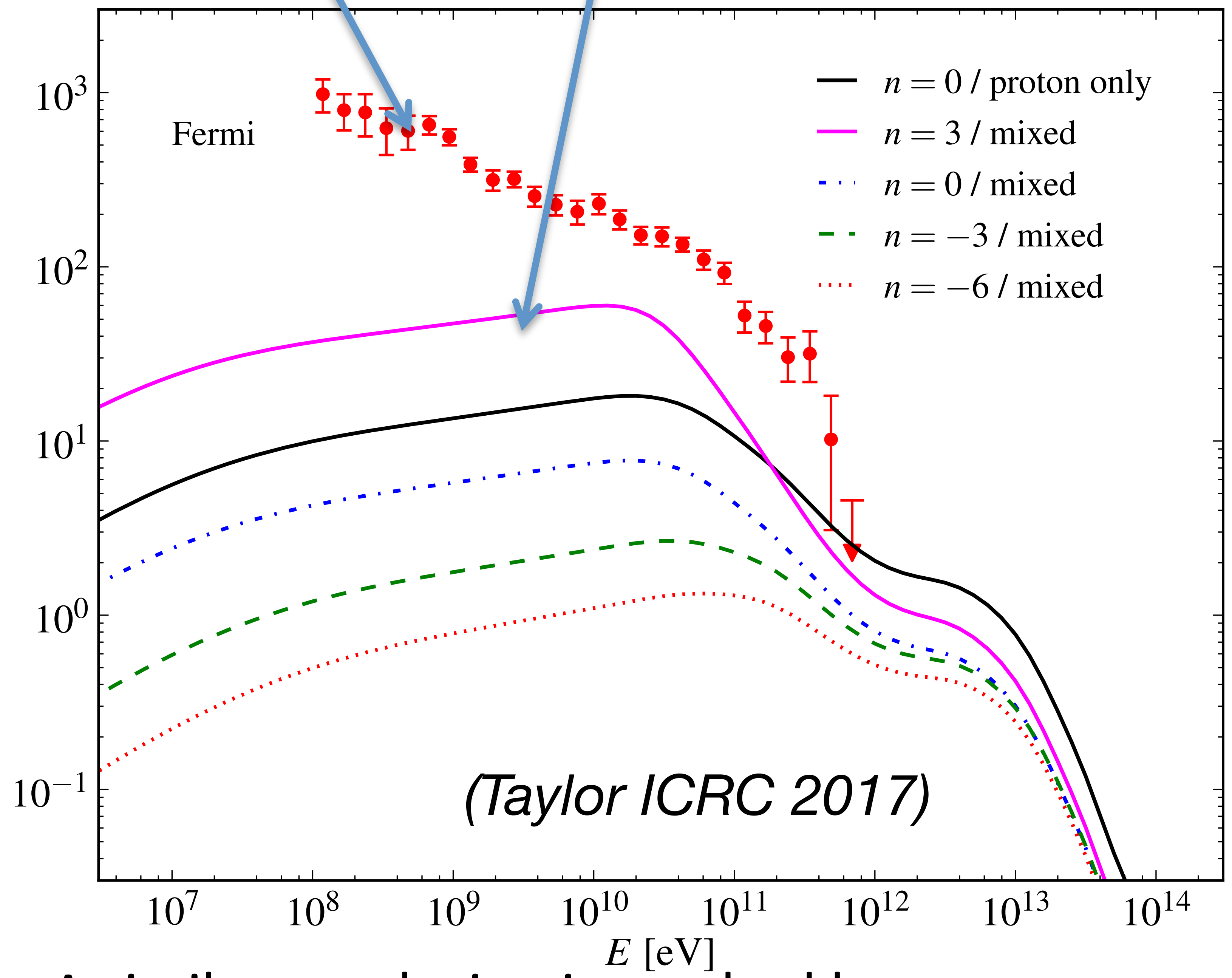
Very low neutrino flux likely

- Nuclei with small GZK losses?
- Negative evolution of sources?
- Local overdensity?

Photons

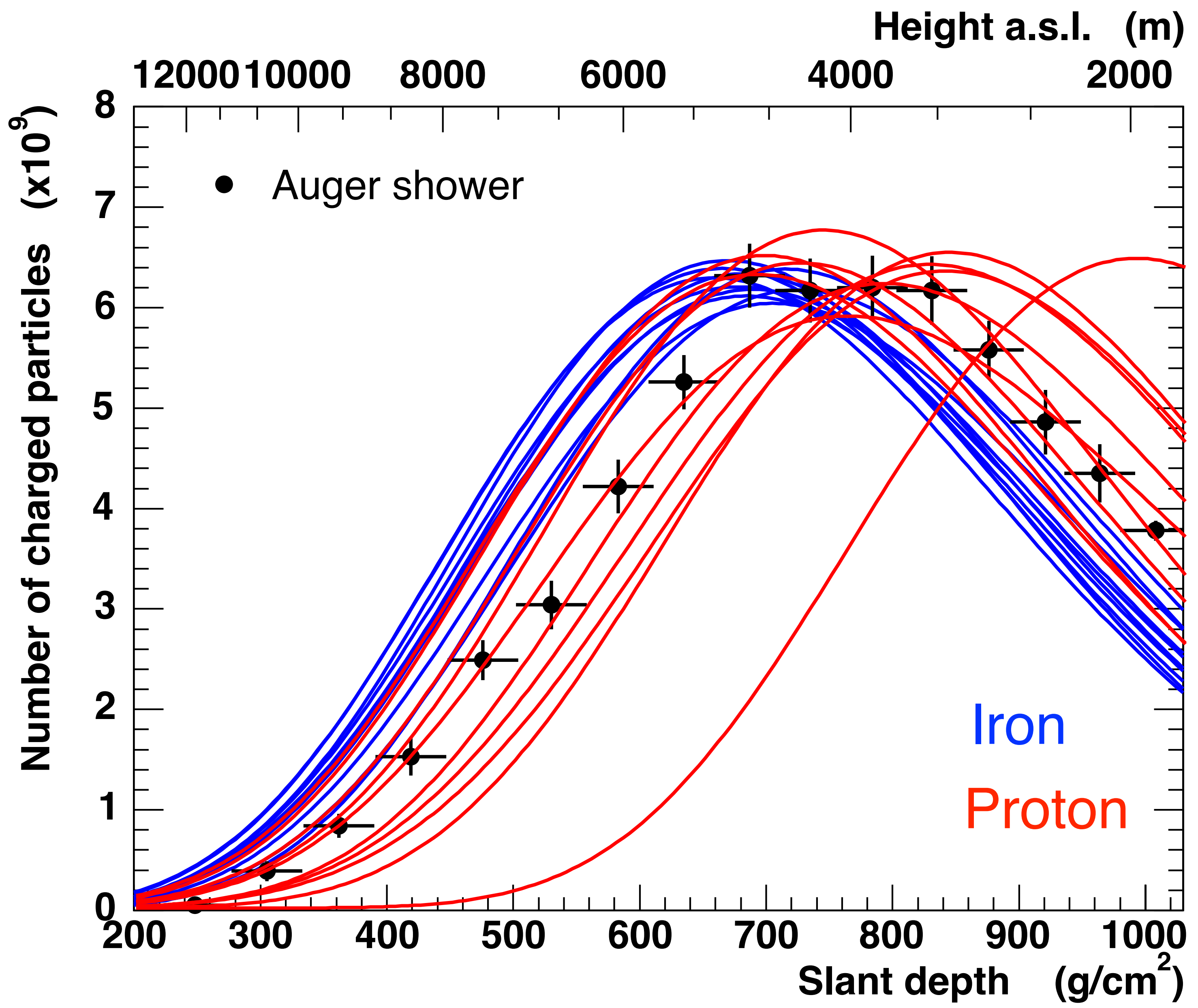
IGRB (EGB with resolved points sources removed)

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

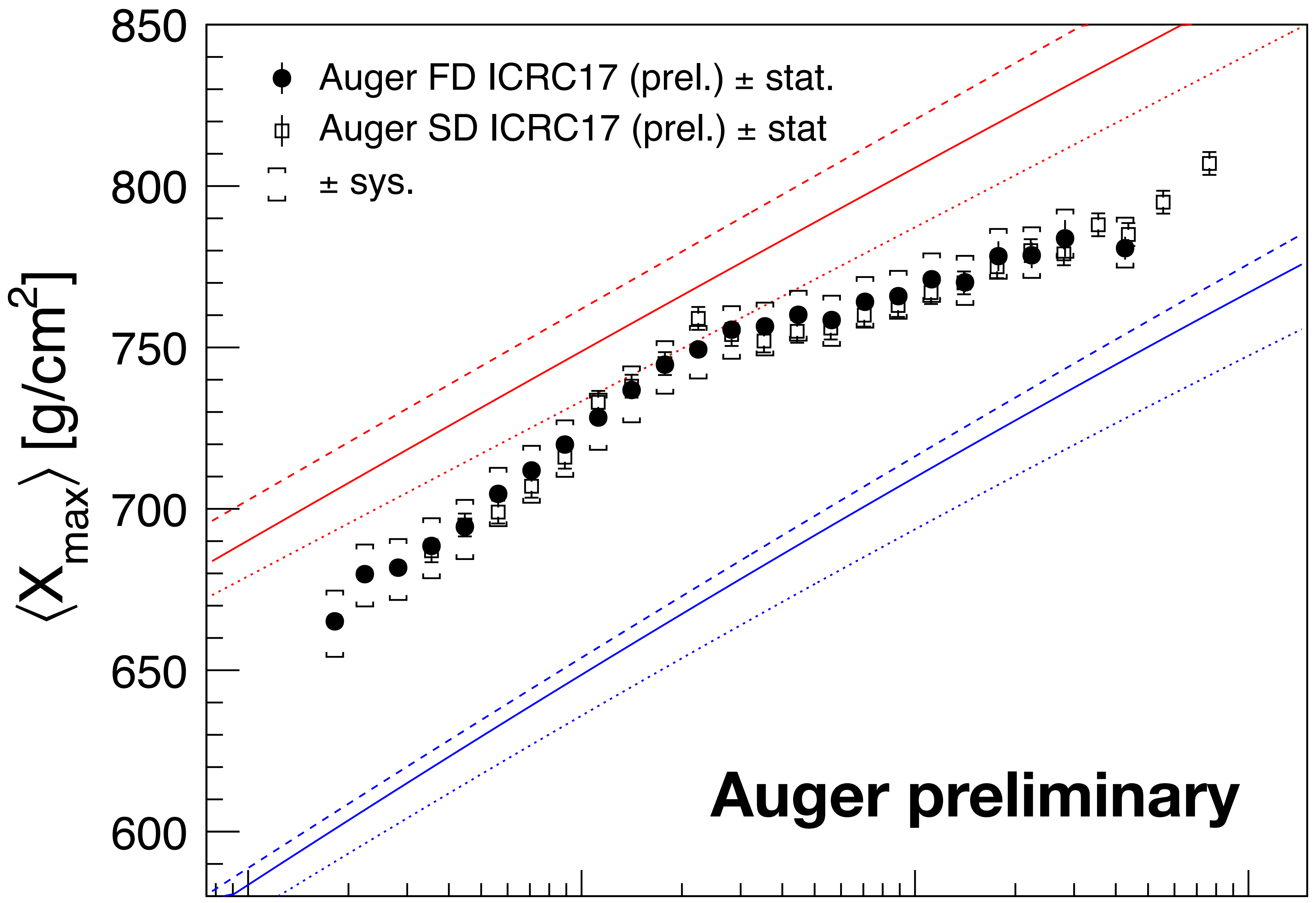


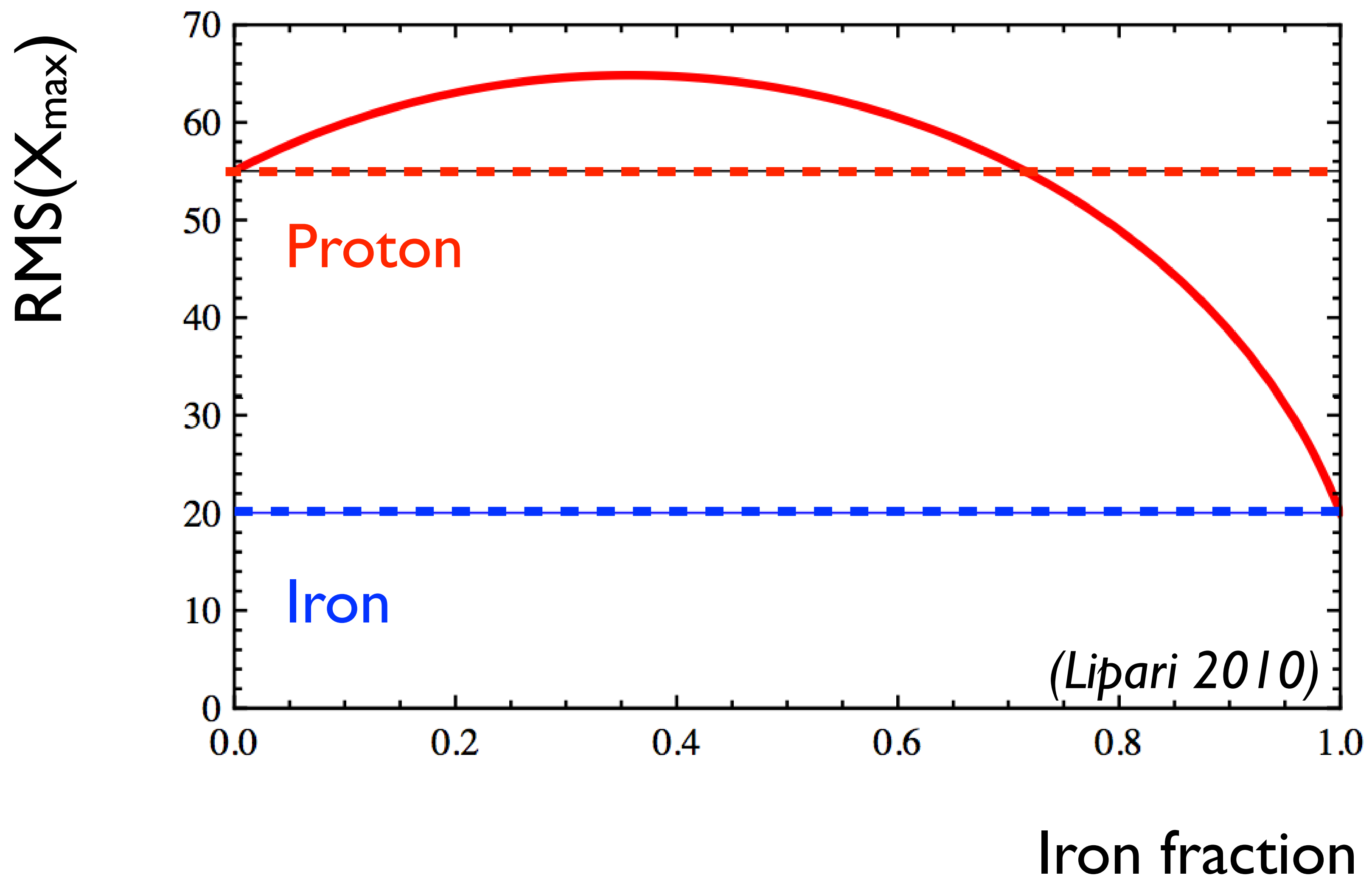
A similar conclusion is reached by **Gavish et al. (2016), 1603.04074**

Mass composition – Depth of shower maximum

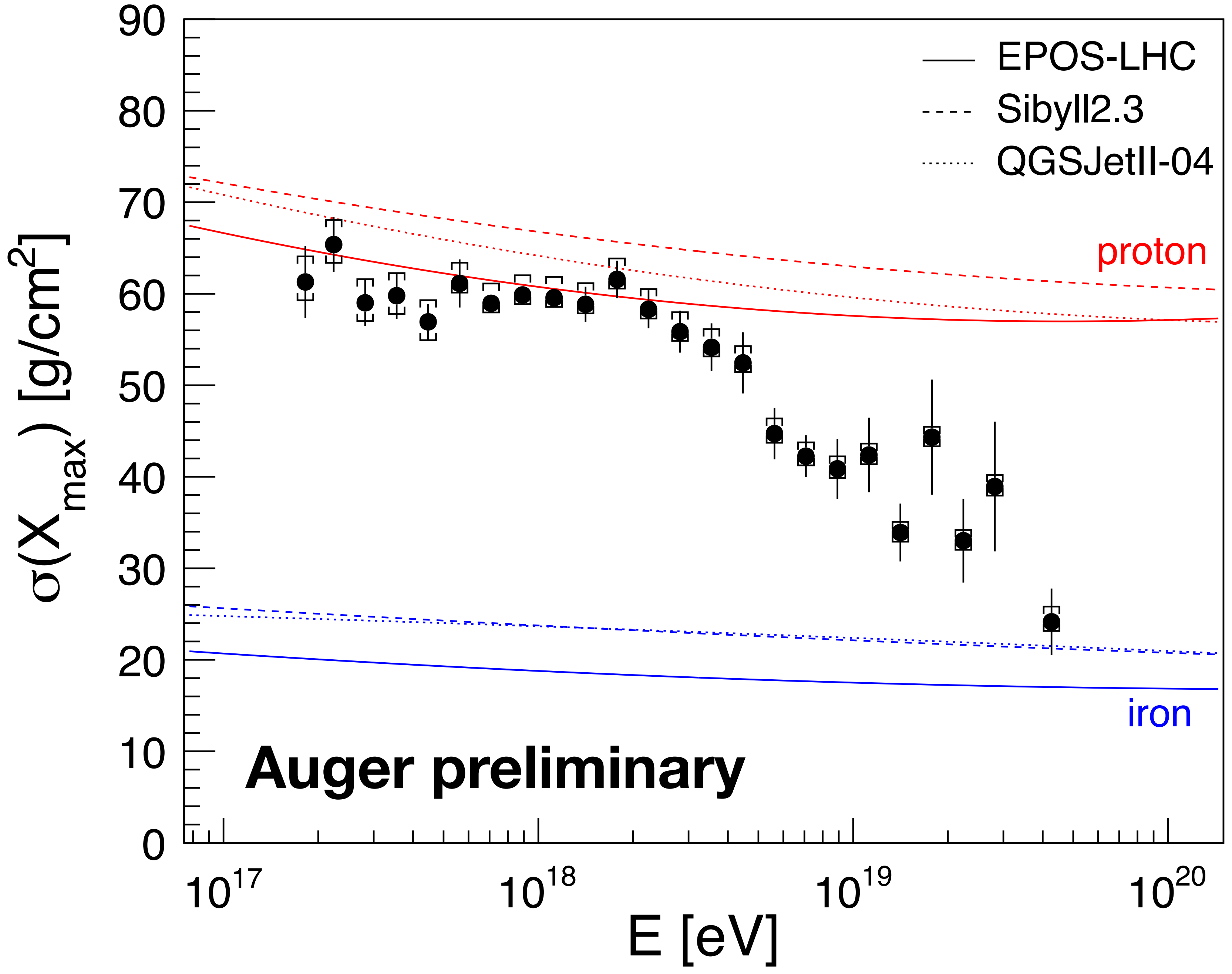


Break in elongation rate just below energy of ankle

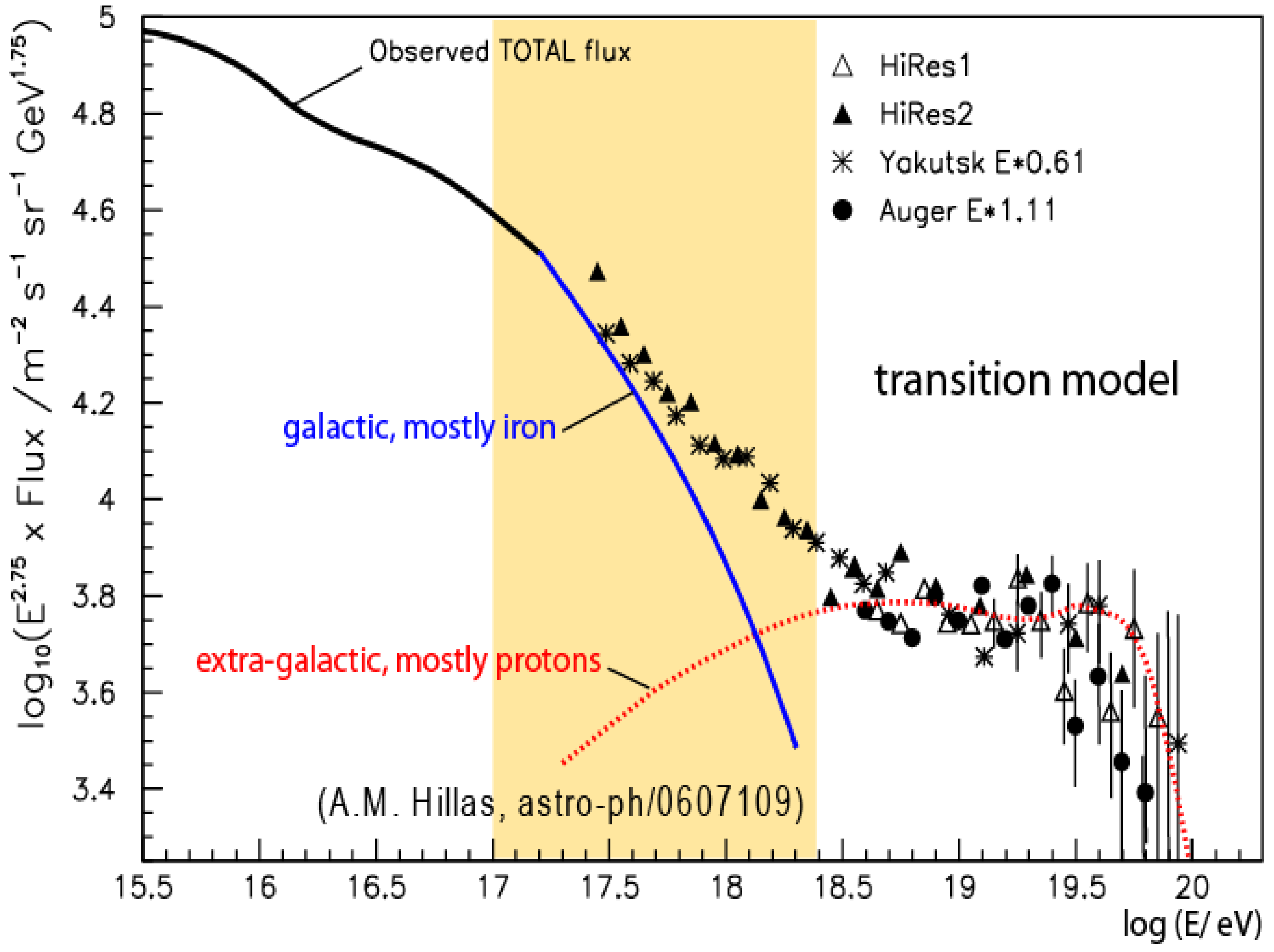




Shower-by-shower fluctuations very small



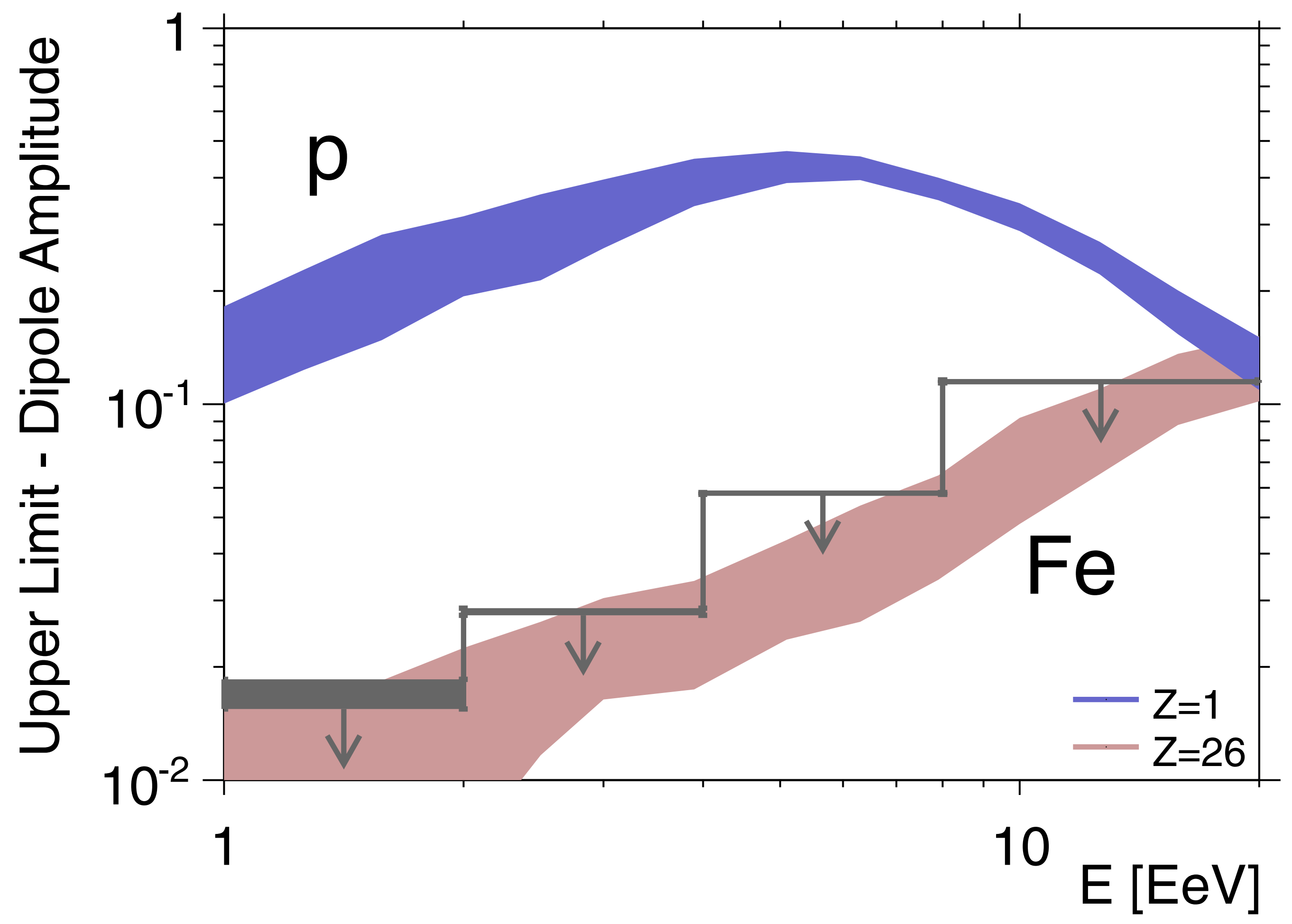
Transition from galactic to extragalactic cosmic rays



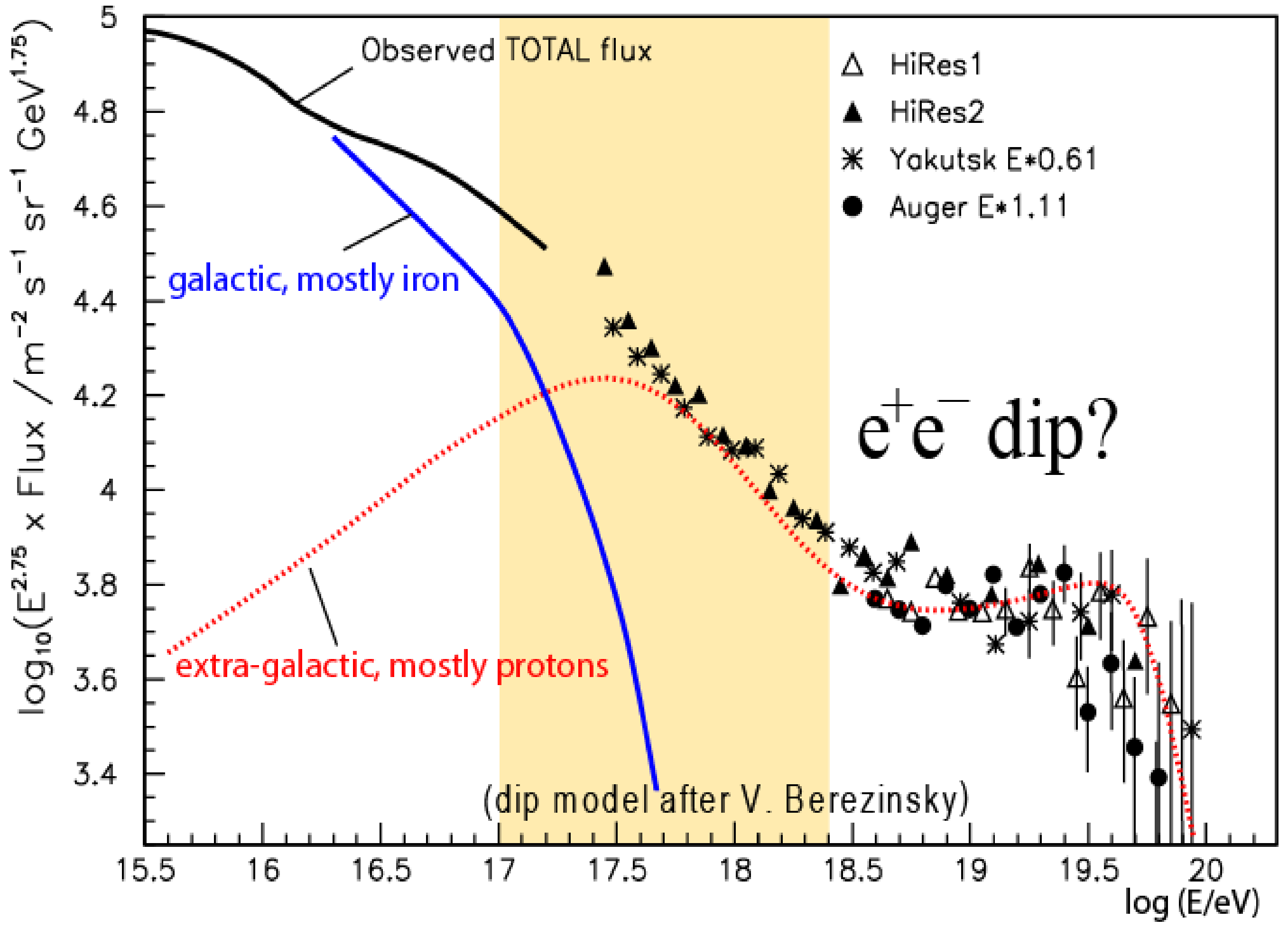
Ankle model:
Hillas, Wolfendale et al.

Transition energy ~10^{18} eV

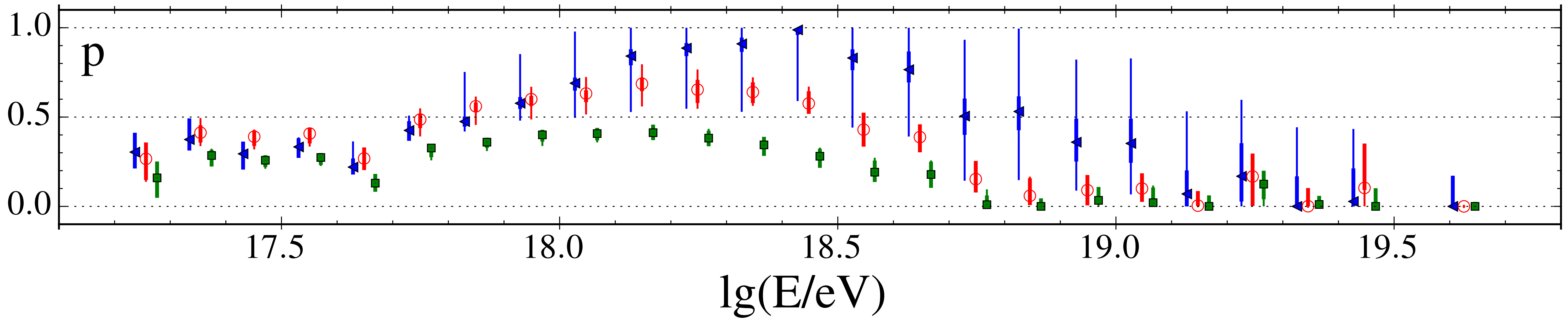
Simulation: Sources in galactic plane



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

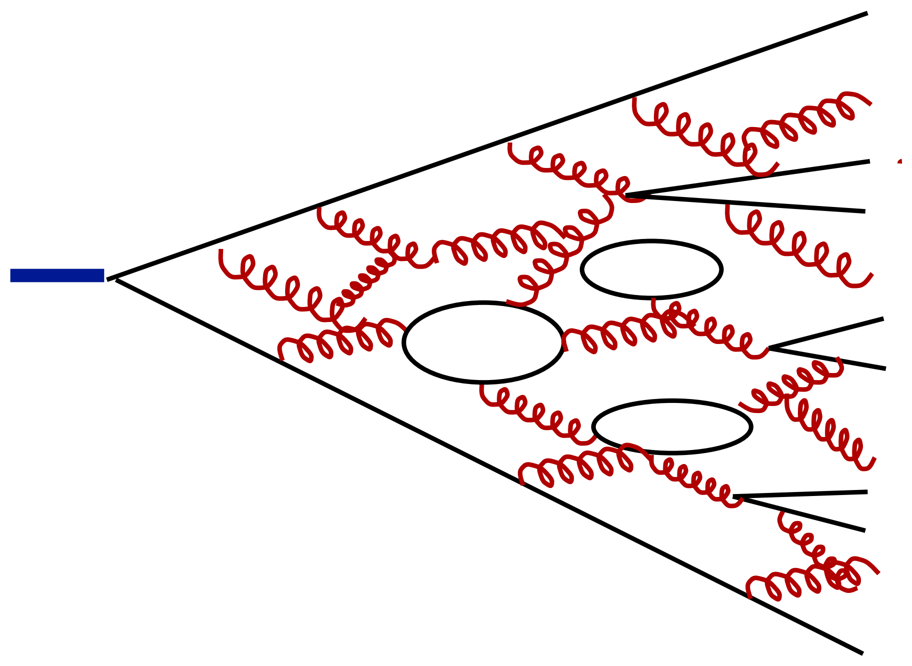


Dip model:
Berezinsky et al.

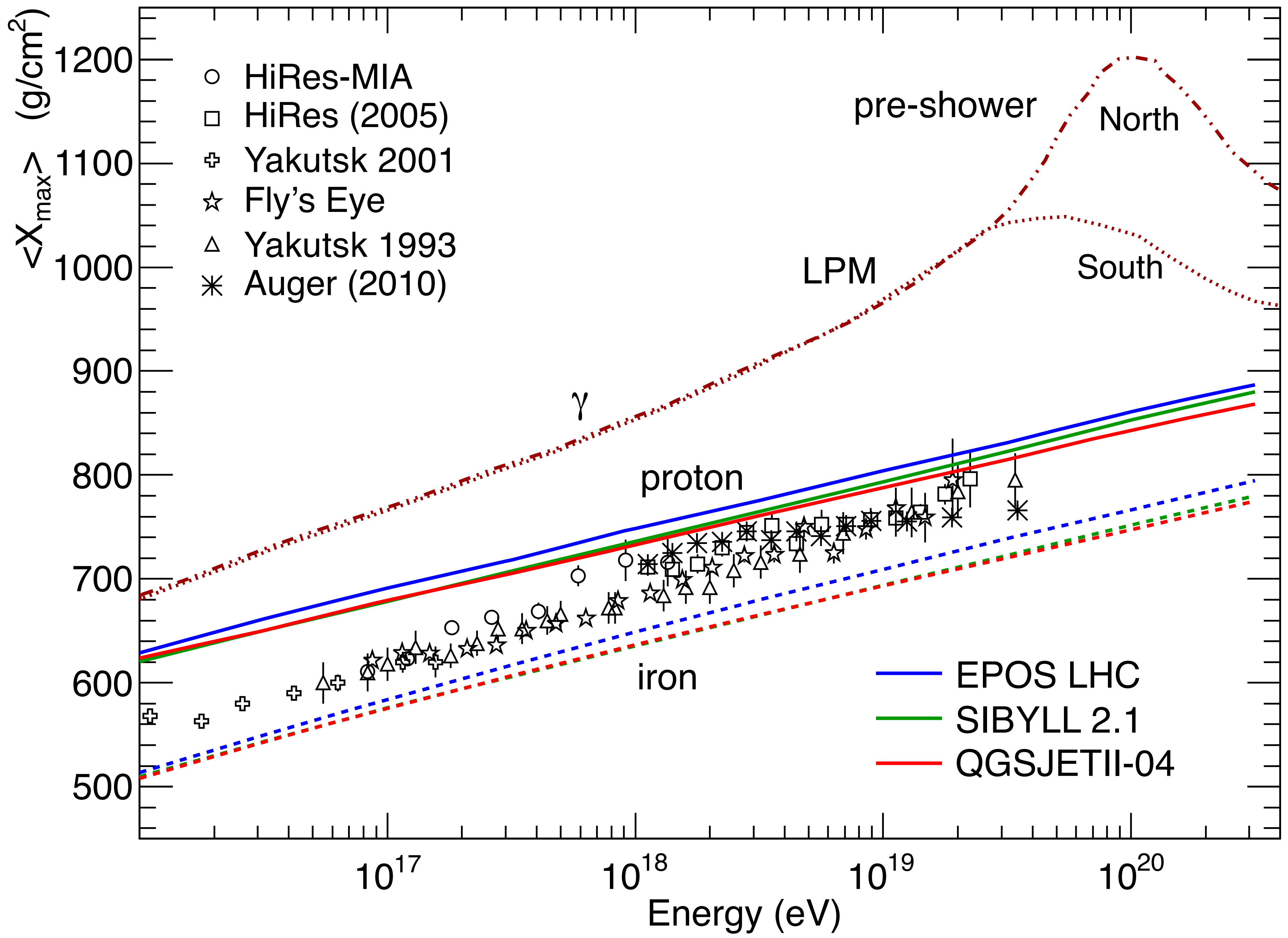


Result 4: Most exotic source models excluded

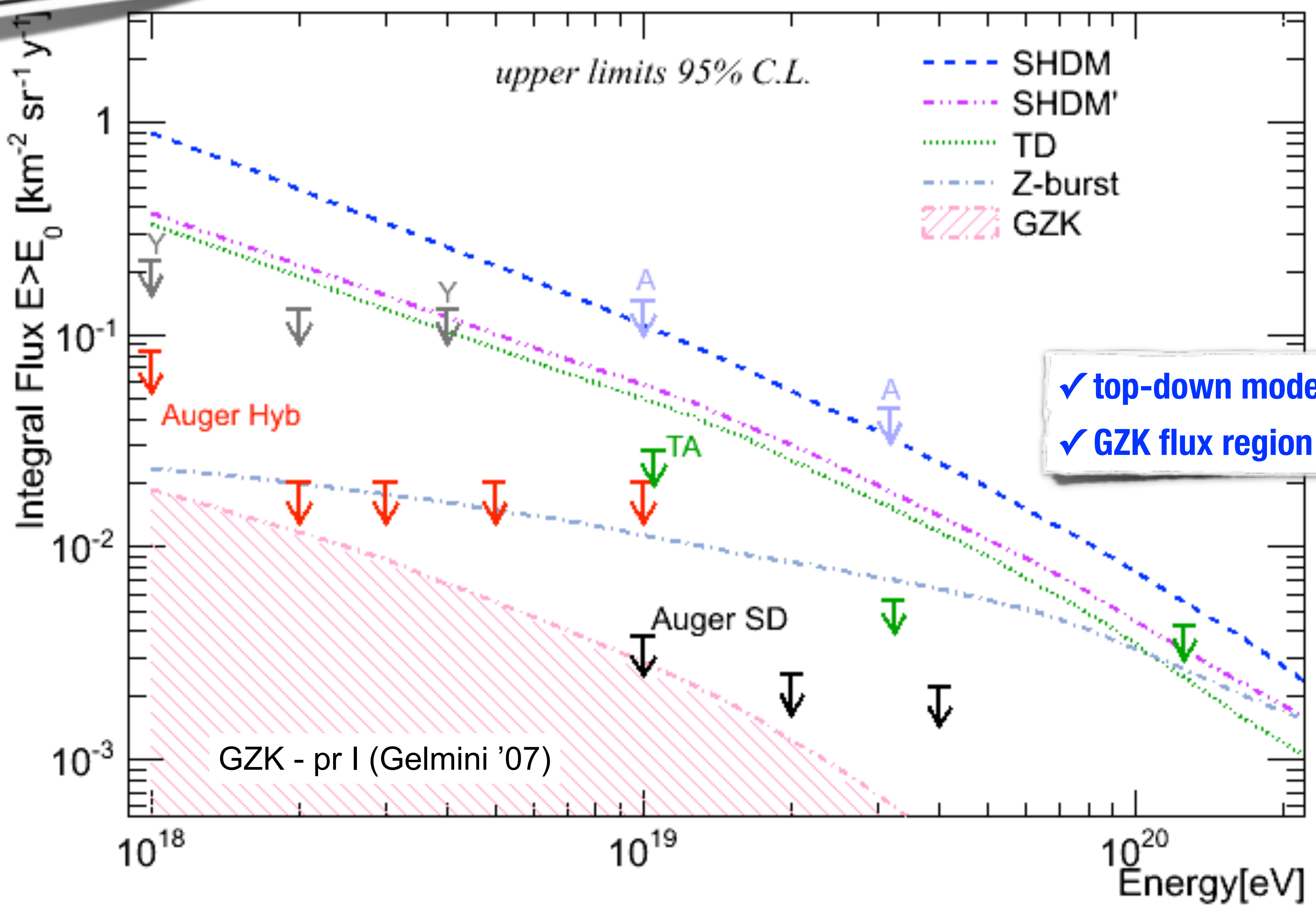
Super-heavy dark matter
Topological defects



large fluxes of photons and neutrinos



No UHE photons identified so far!!

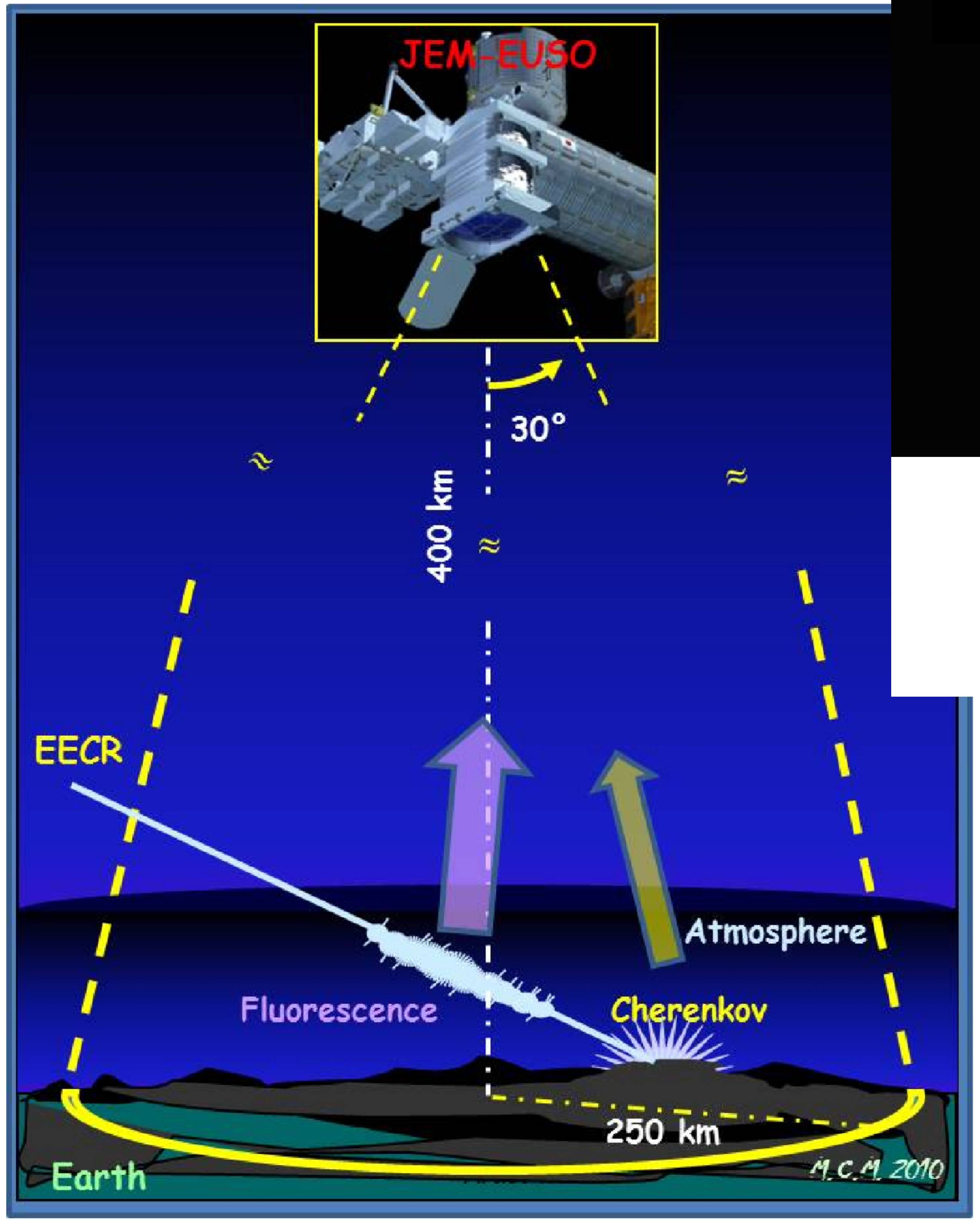


✓ top-down models disfavored
✓ GZK flux region within reach

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

The quest for an instrument of ultimately large aperture

JEM-EUSO (status unclear)

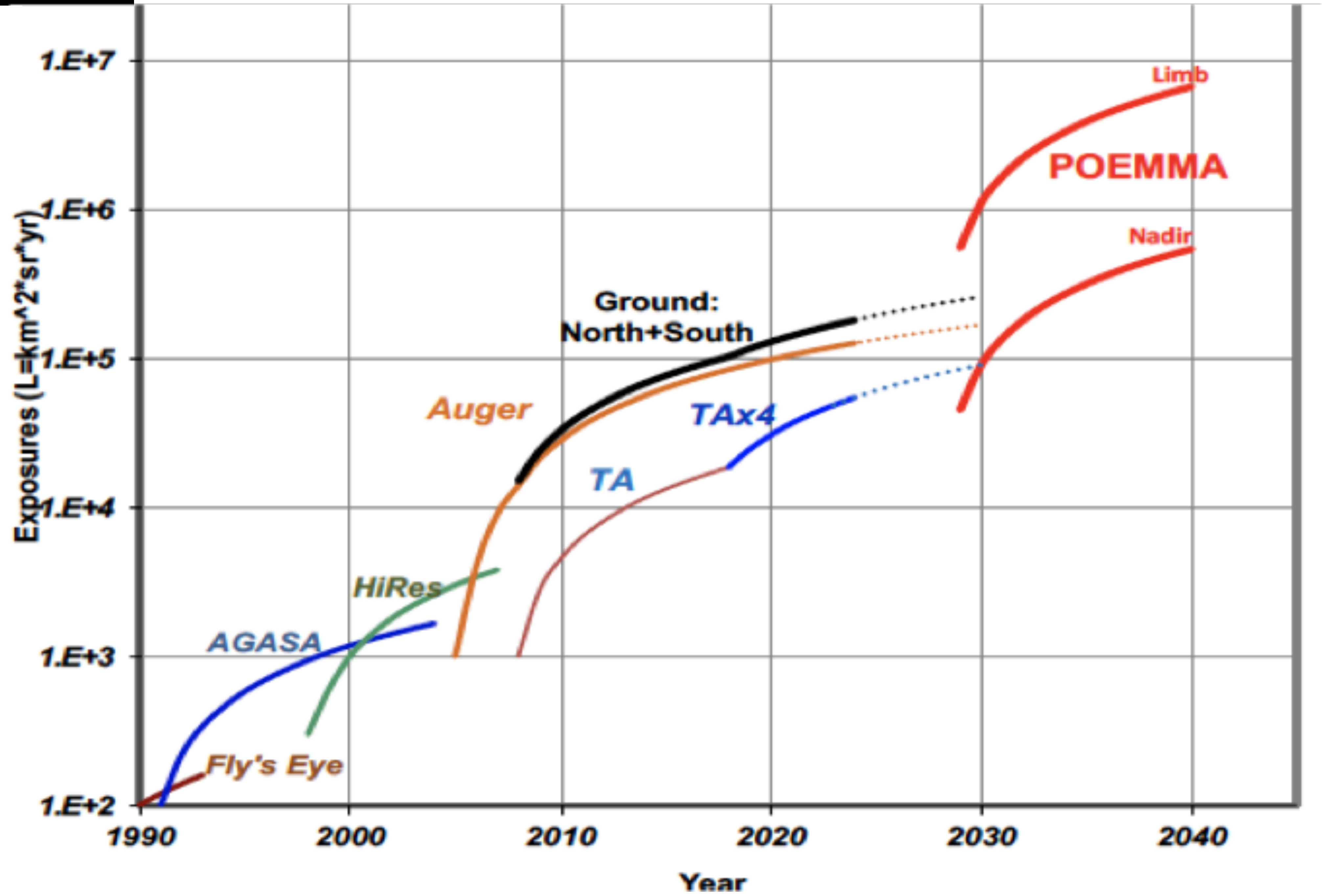


POEMMA:
Probe of Extreme Multi-Messenger Astrophysics UHECRs and Neutrinos

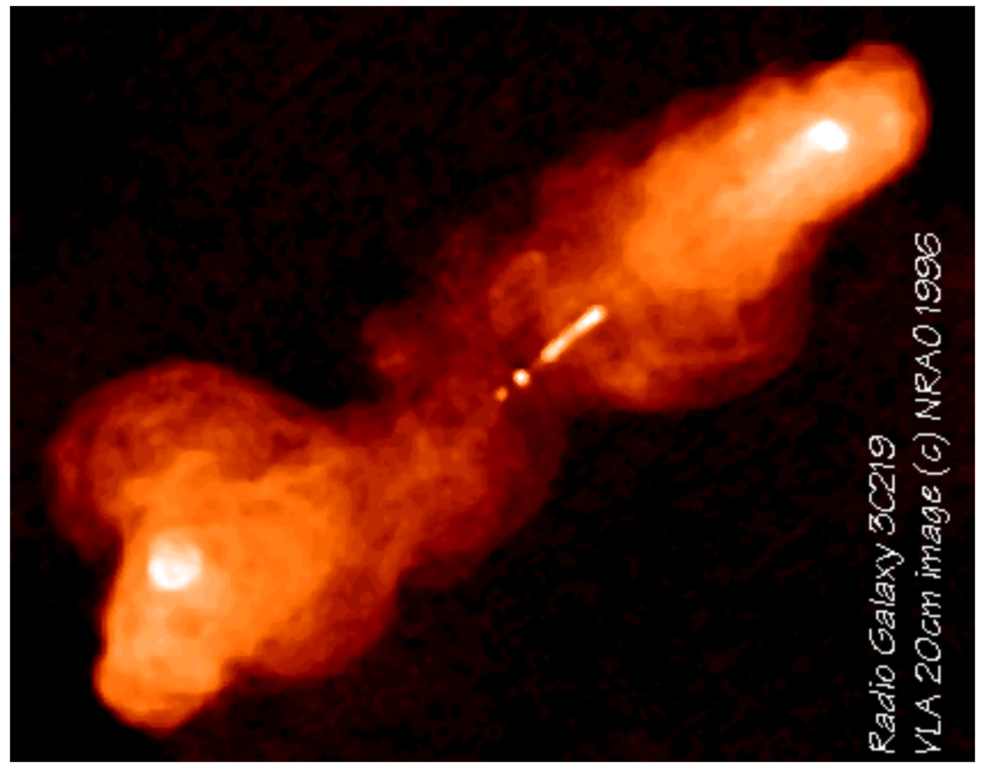
NASA-supported design study

K-EUSO
(Russian Space Agency)

Worldwide distributed hybrid arrays

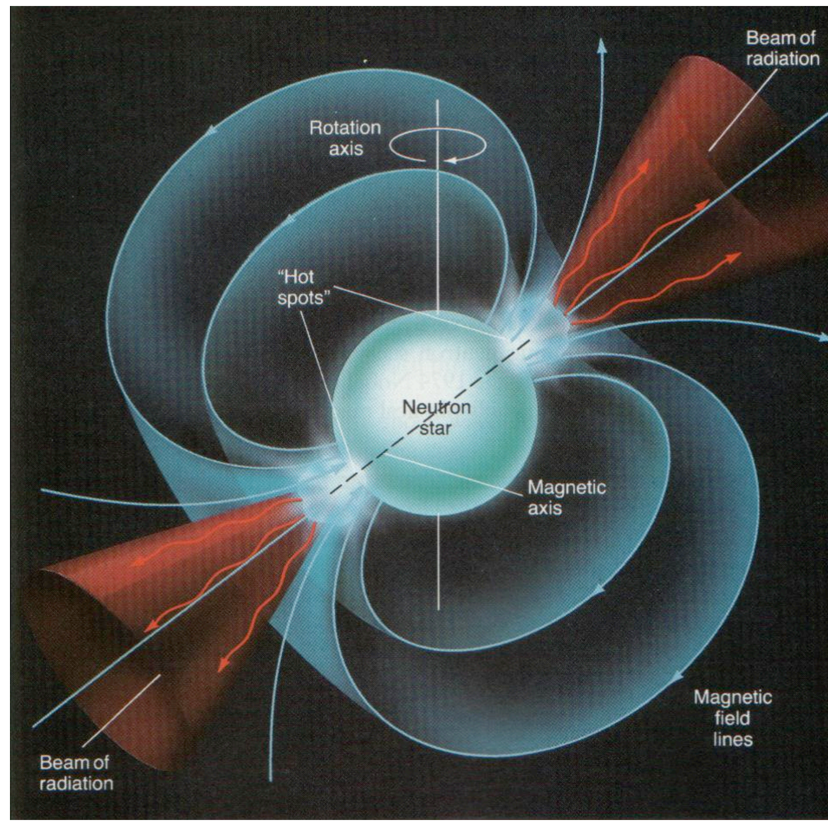


Exotic source and propagation scenarios ?



Active Galactic Nuclei (AGN):
Black Hole of ~10^9 solar masses

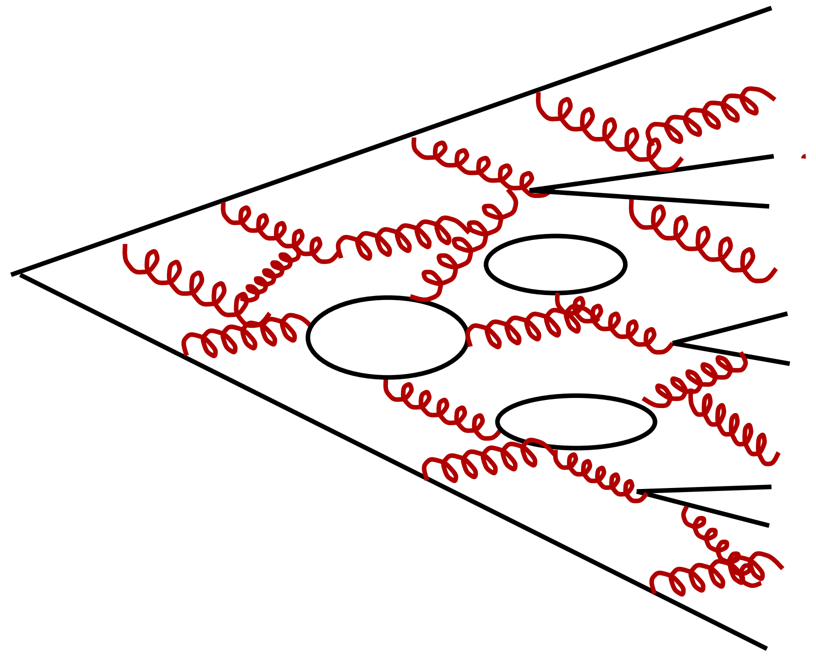
Magnetars:
magnetic field
up to ~10^{15} G



	Process	Distribution	Injection flux
AGNs, GRBs, … (☆)	Diffuse shock acceleration	Cosmological	p … Fe
Young pulsars (☆☆)	EM acceleration	Galaxy & halo	mainly Fe
X particles (☆☆☆)	Decay & particle cascade	(a) Halo (SHDM) (b) Cosmological	ν, γ-rays and p
Z-bursts (☆☆☆☆)	Z^0 decay & particle cascade	Cosmological & clusters	ν, γ-rays and p

X particles from:
- topological defects
- monopoles
- cosmic strings
- cosmic necklaces
- …..

Big Bang:
super-heavy particles,
topological defects:
M_X ~ 10^{23} - 10^{24} eV

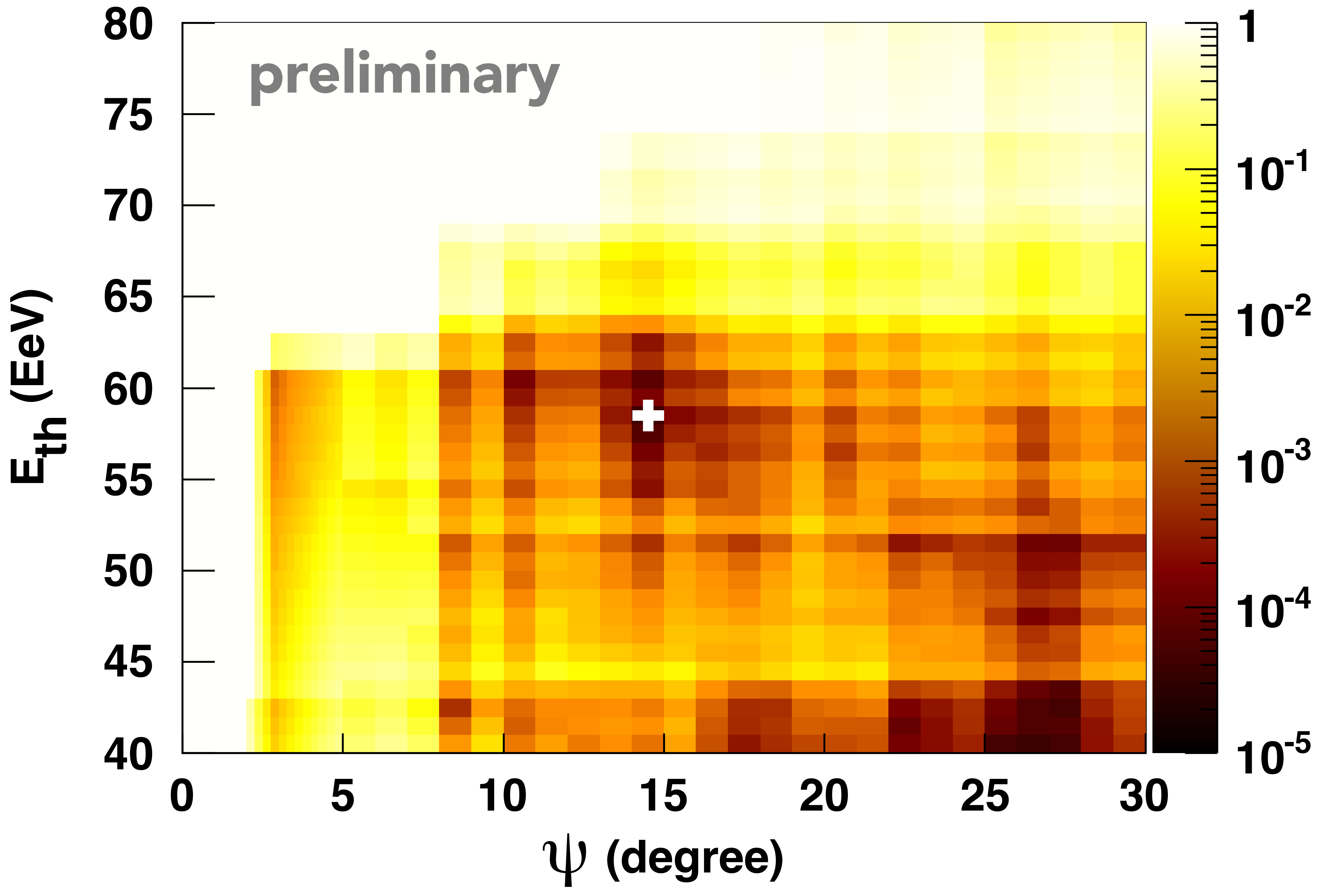


large fluxes of
photons and
neutrinos

(RE, Nijmegen Summer School, 2006)

Intermediate-scale anisotropy – Centaurus A (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, Ψ = 15°

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

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

Post-trial probability

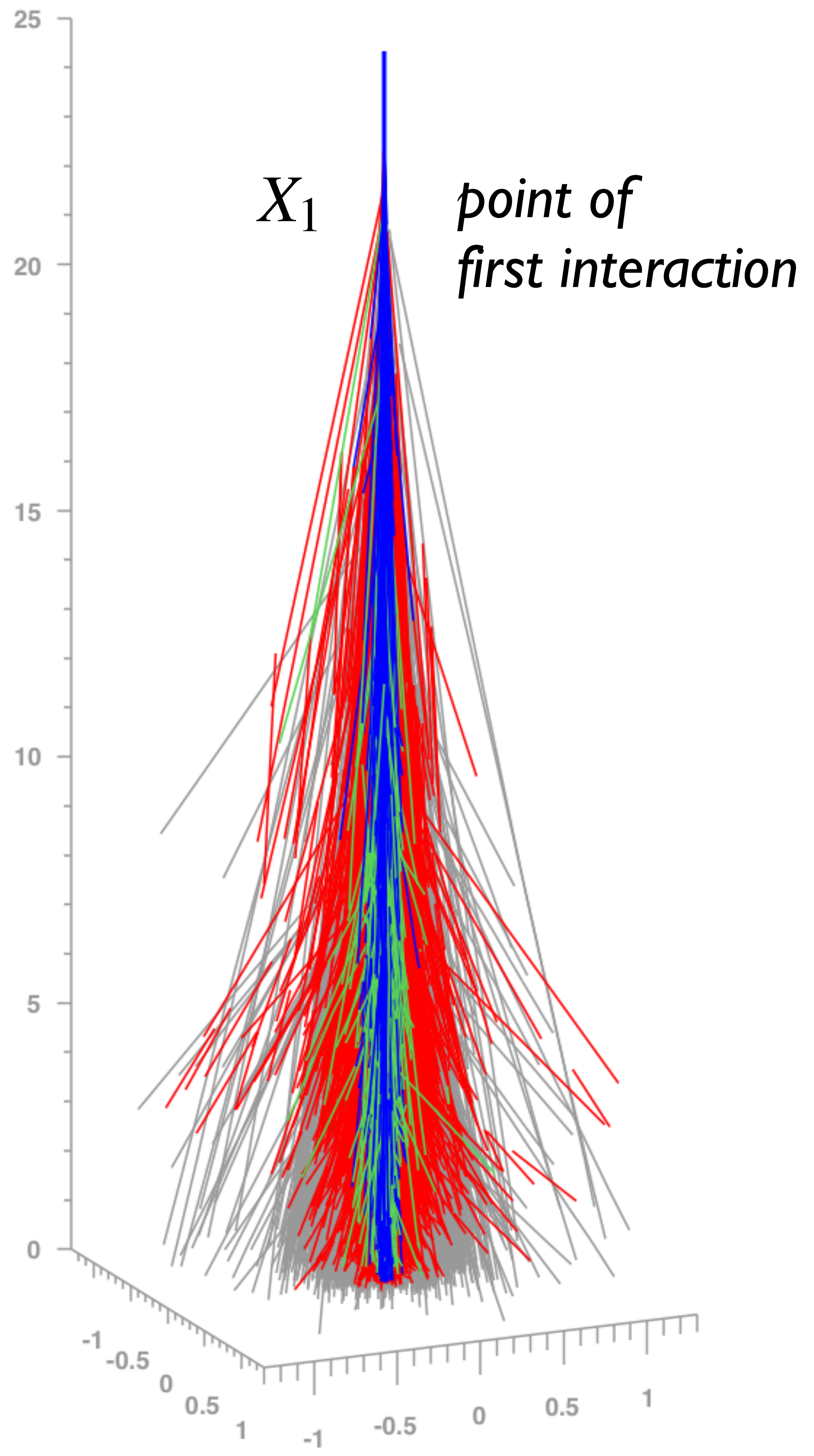
$\sim 1.1 \times 10^{-3}$

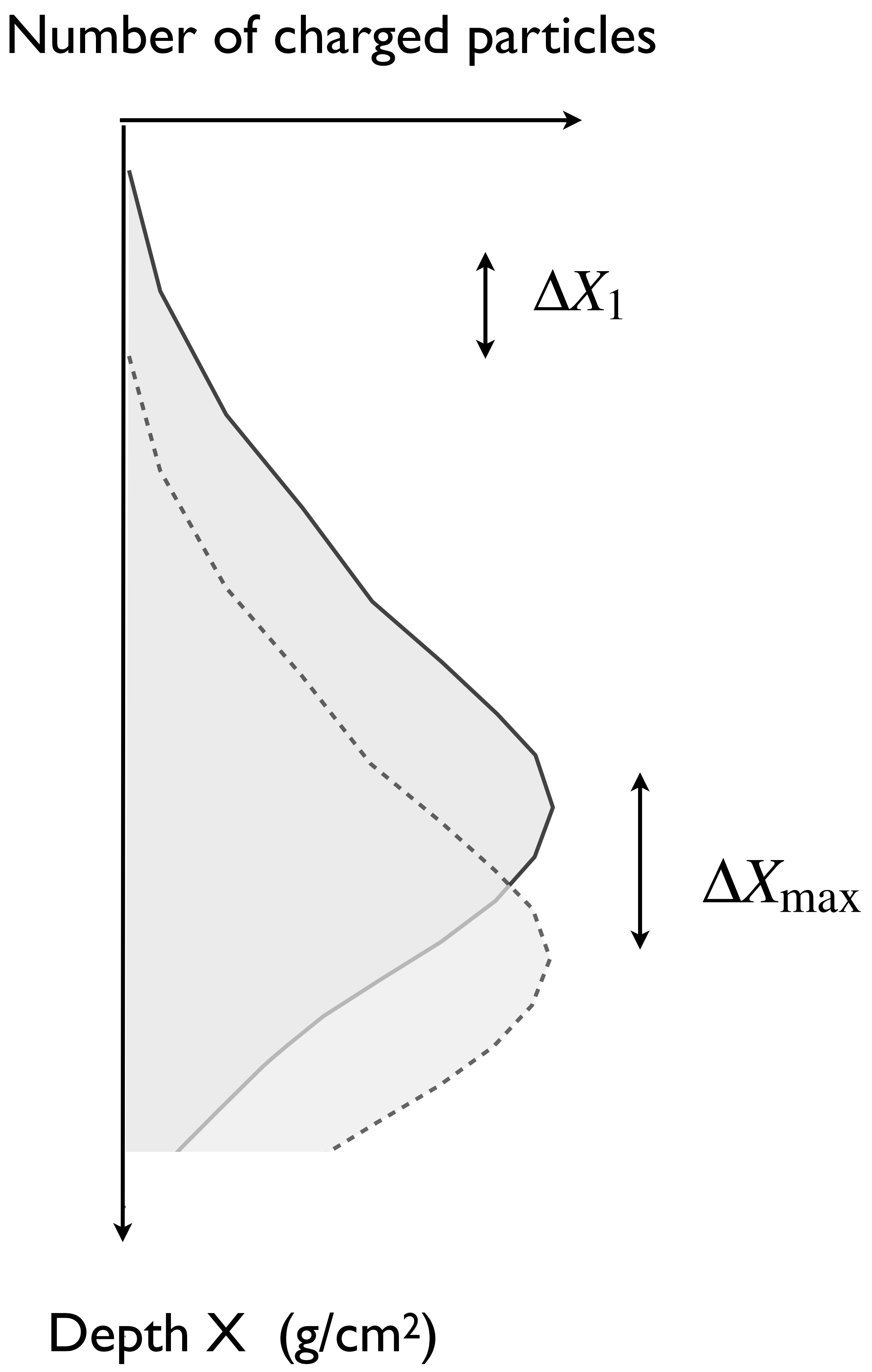
(fraction of isotropic simulations that have a smaller probability under the same scan)

Region of secondary minima above ~40 EeV

(Giaccari ICRC 2017)

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



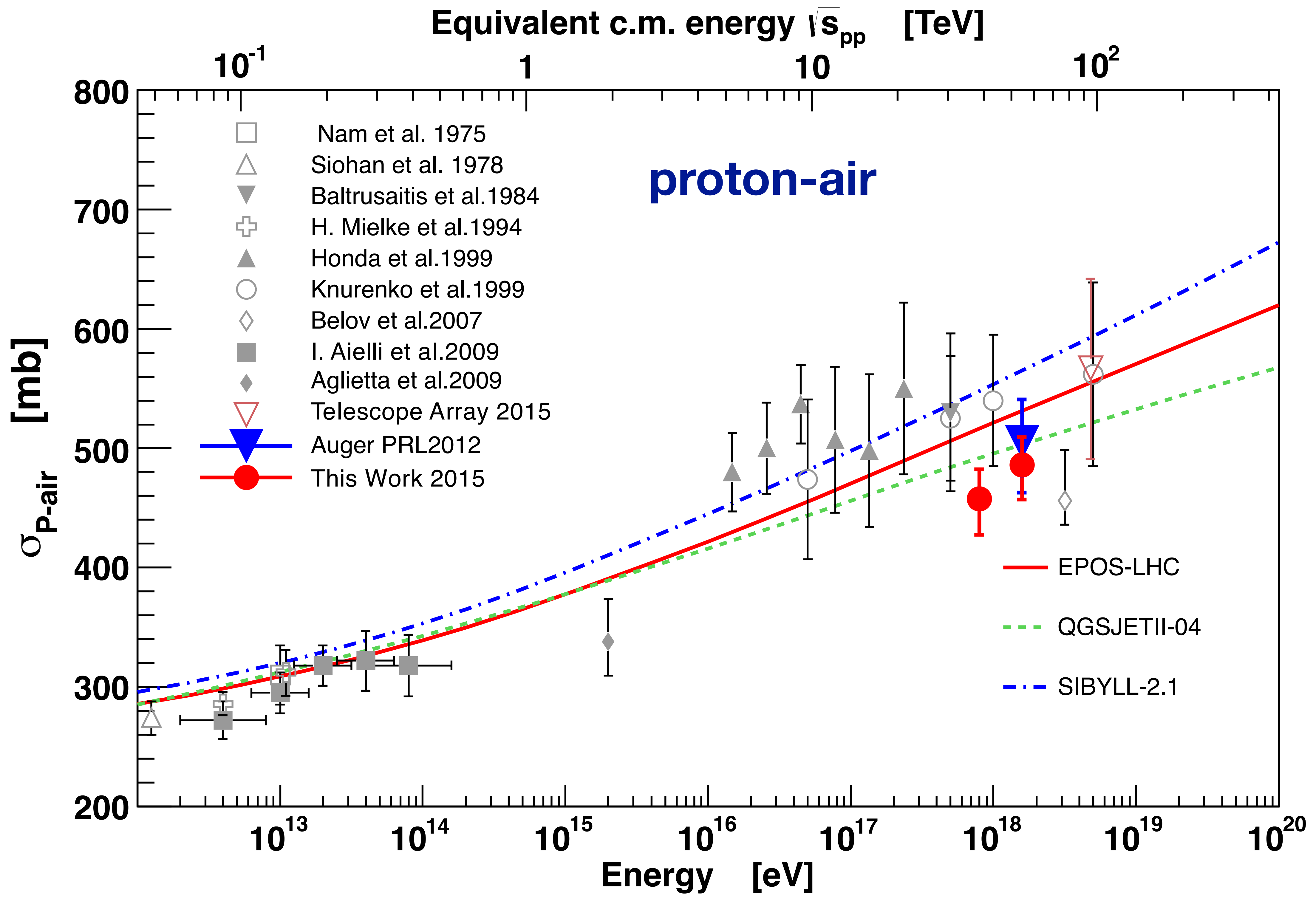


$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

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

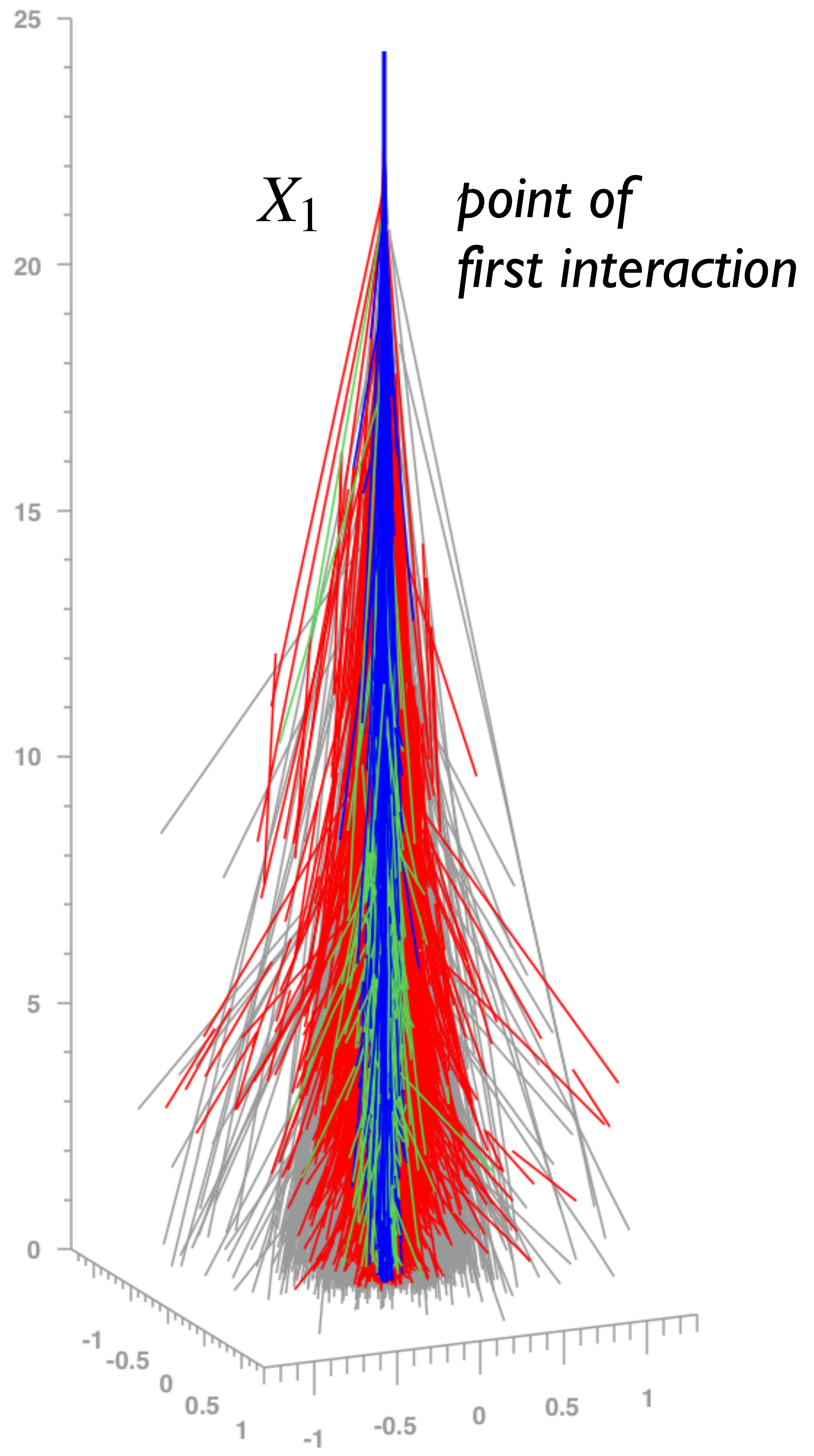
Difficulties

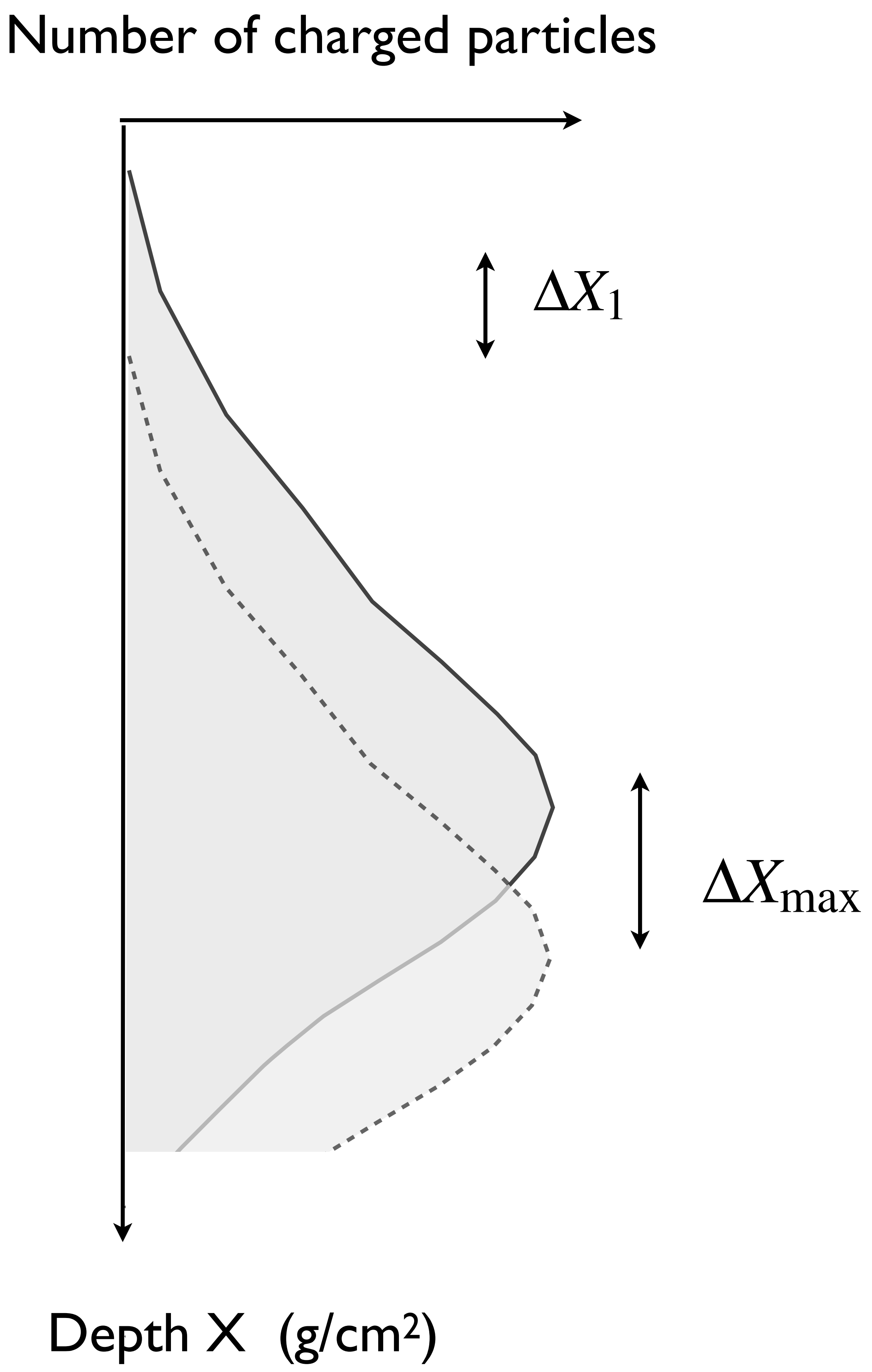
- mass composition
- fluctuations in shower development (model needed for correction)



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

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



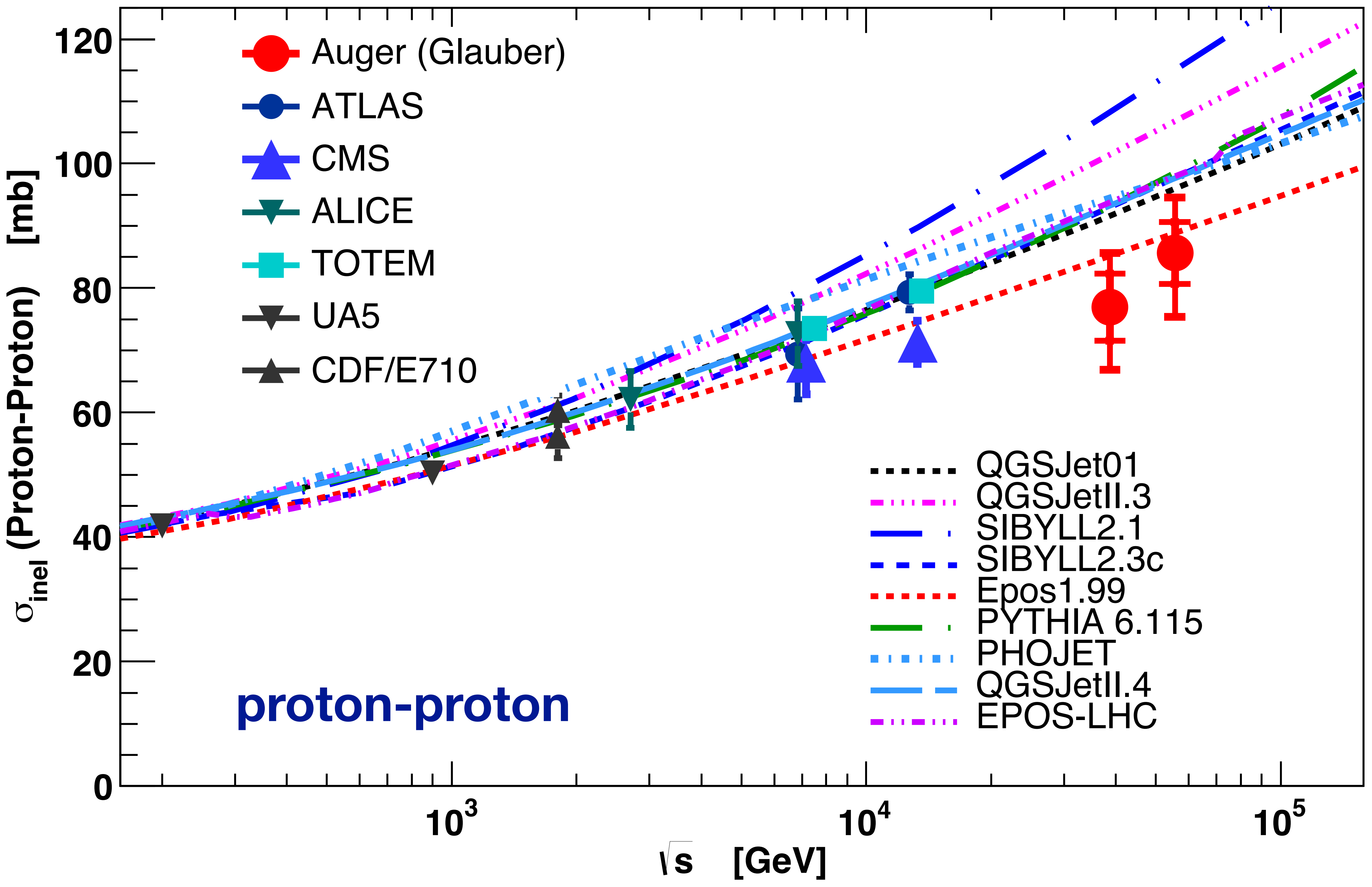


$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

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

Difficulties

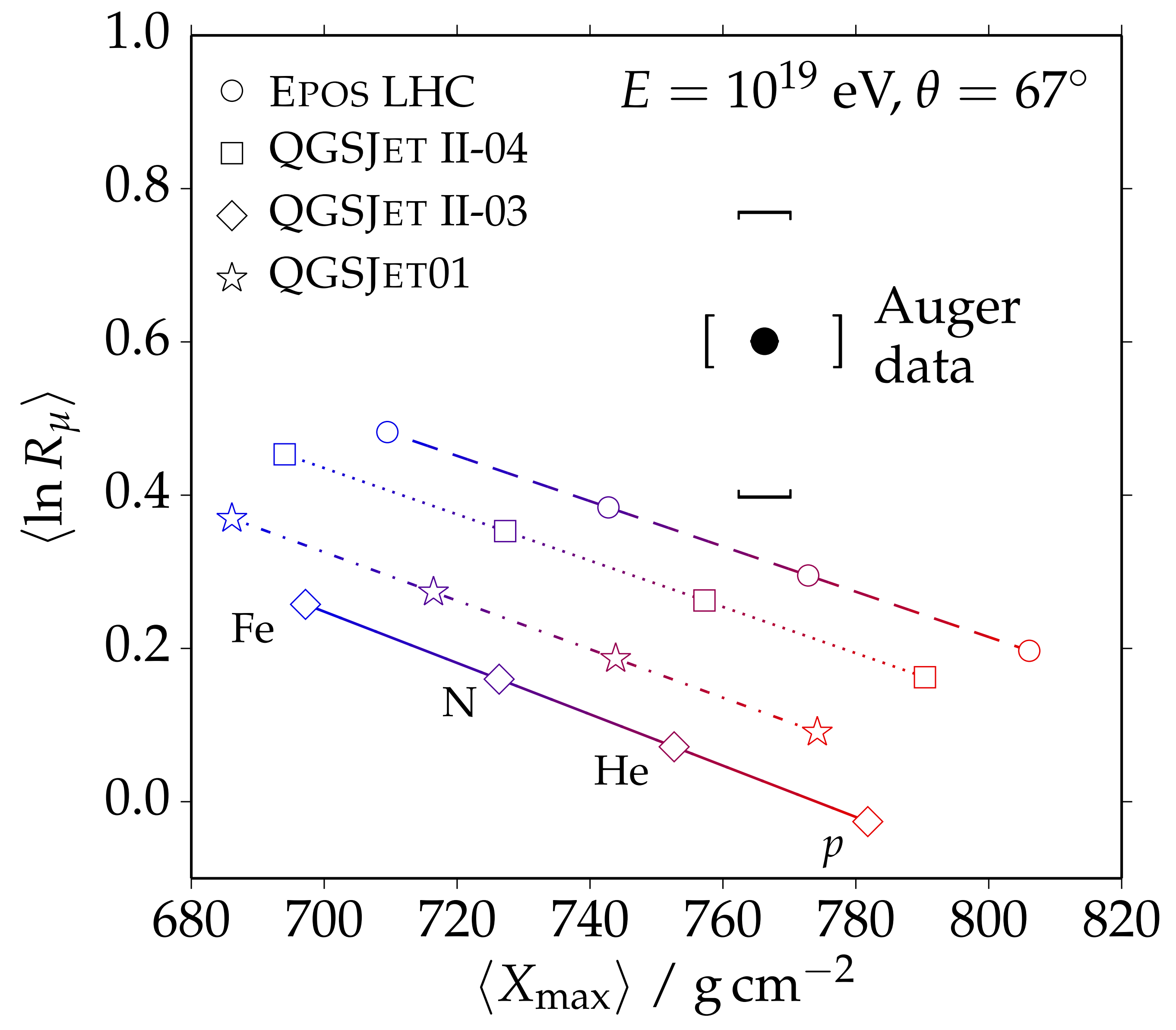
- mass composition
- fluctuations in shower development (model needed for correction)



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

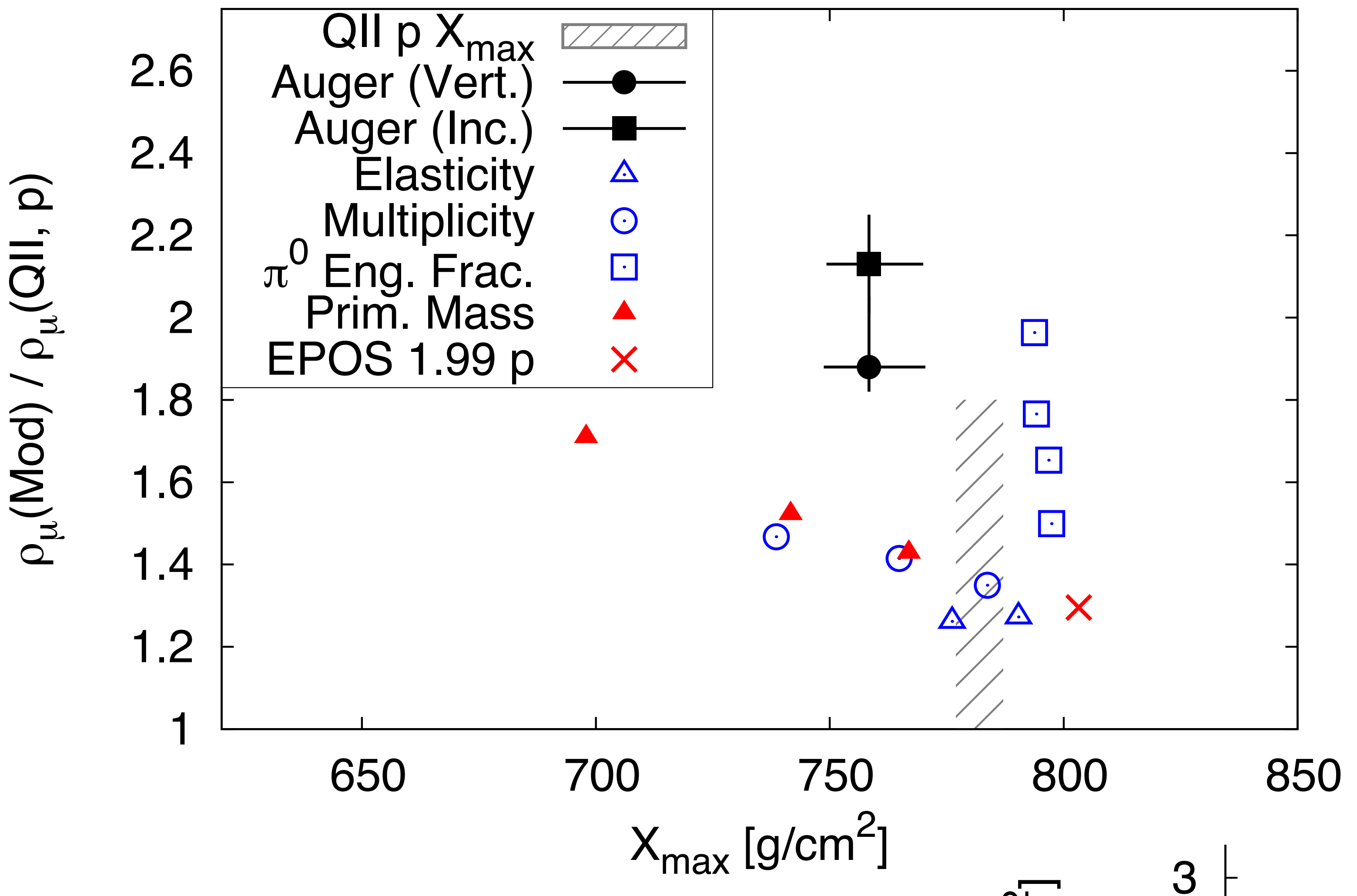
Particle physics with the upgraded Auger Observatory

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)