DESY Particle and Astroparticle Seminar
20, 21. Feb. 2018

UHECRs: Exploring the Universe at the Highest Energies

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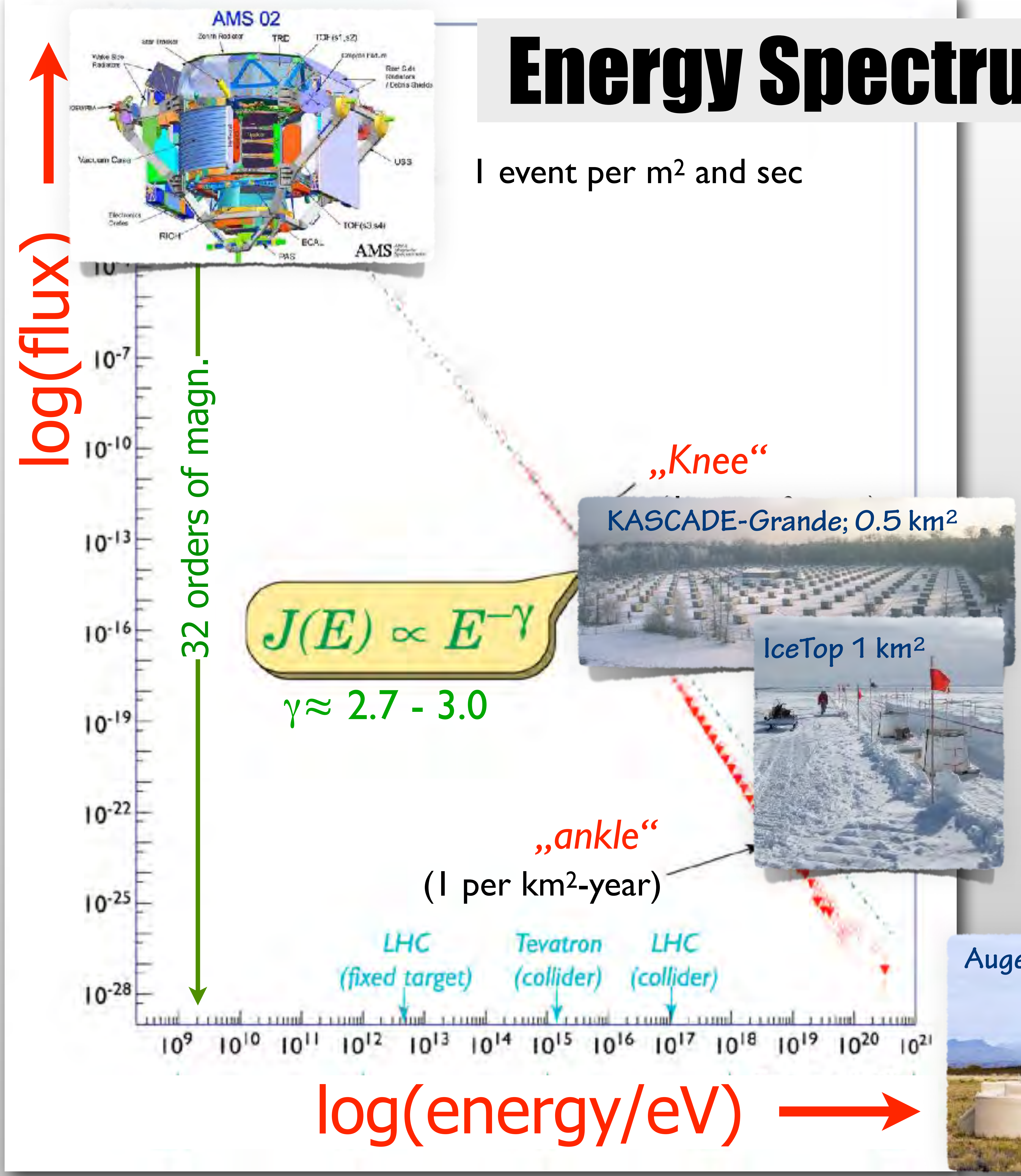
PIERRE AUGER OBSERVATORY

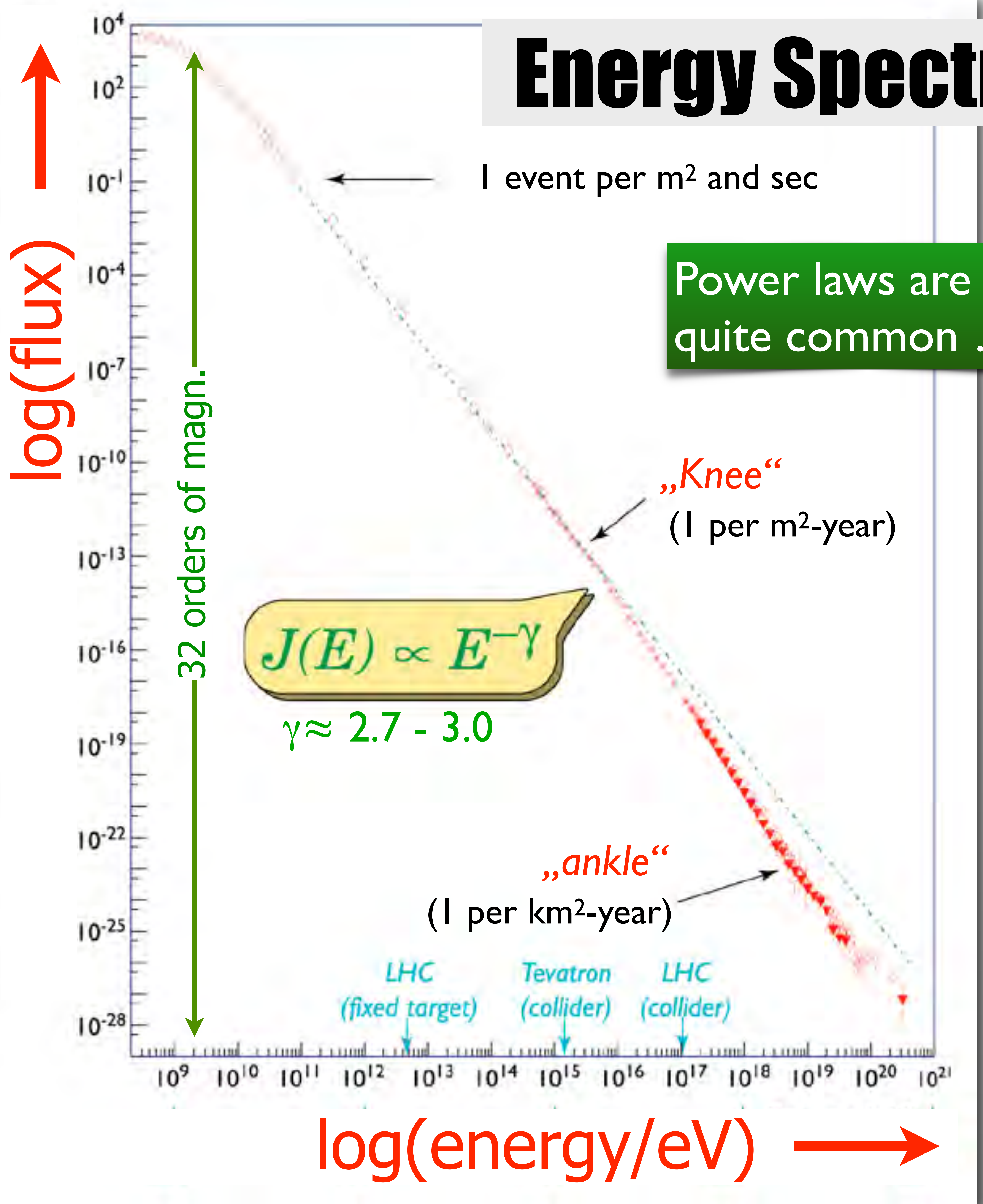
BERGISCHE UNIVERSITÄT WUPPERTAL

Bundesministerium für Bildung und Forschung

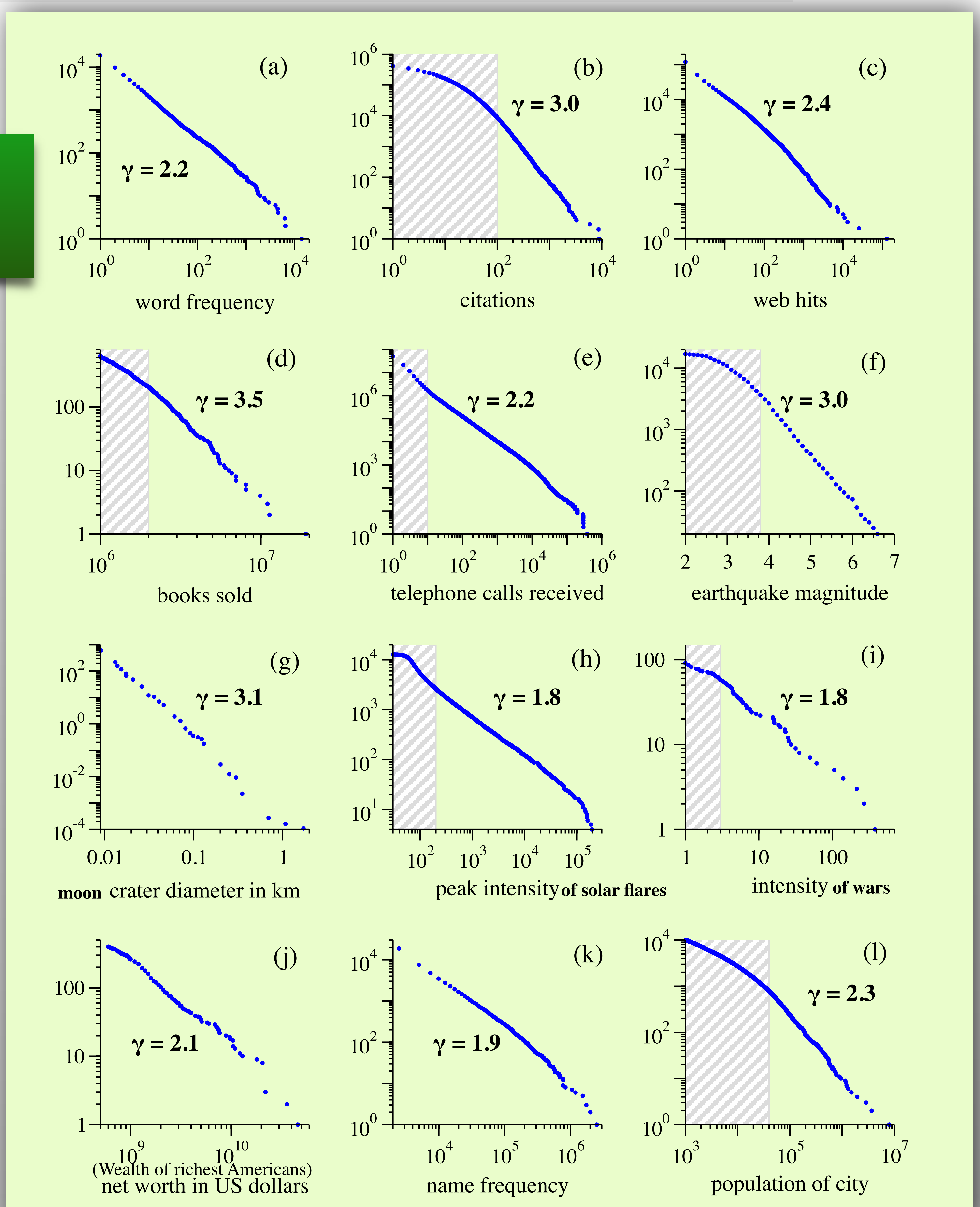
Energy Spectrum of Cosmic Rays



Energy Spectrum of Cosmic Rays

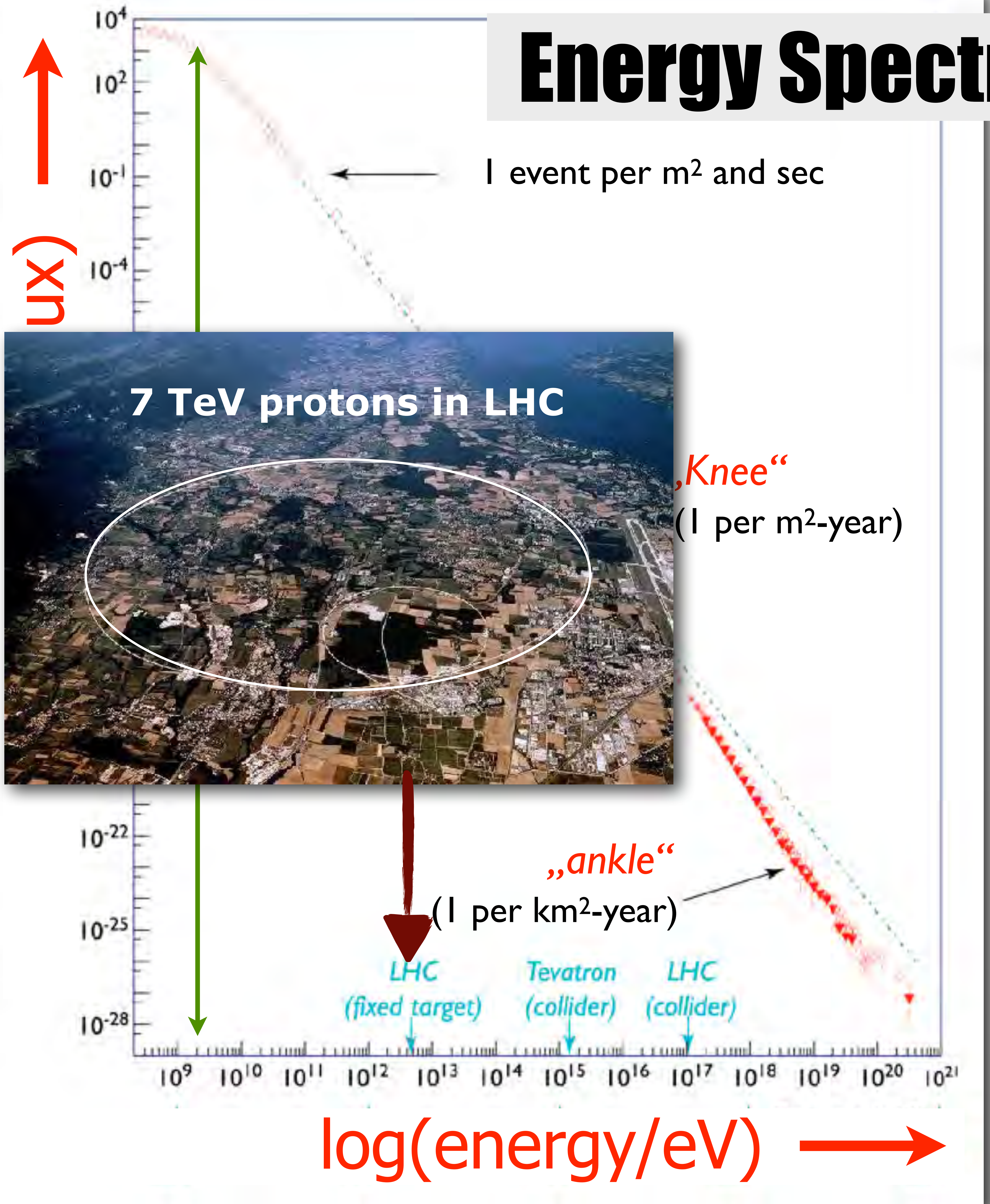


Power laws are quite common ....

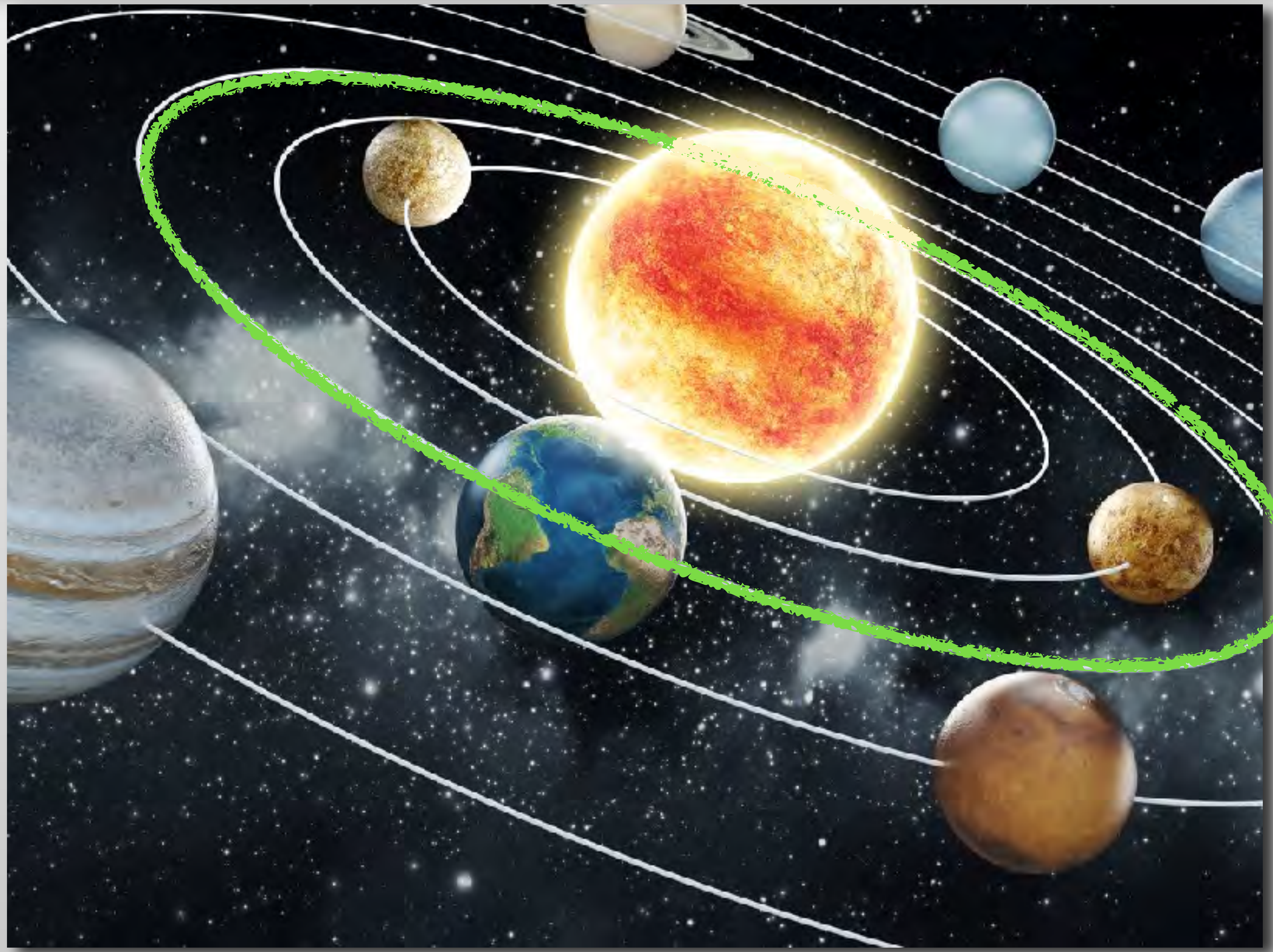


MEJ Newman, Contemp. Phys. 46 (2005) 323

Energy Spectrum of Cosmic Rays



10^{20} eV protons in LHC would require size of Earth's orbit around the Sun



Themes of UHECR Physics

- **Cosmic Particle Acceleration**
  - How and where are cosmic rays accelerated?
  - Does Nature impose any energy limits?
  - How do CRs propagate through space?
  - What is their impact on the environment?
- **Probing Extreme Environments**
  - Processes close to supermassive black holes or GRBs?
  - Processes in relativistic jets, winds and radio-lobes?
  - Exploring cosmic magnetic fields
- **Physics Frontiers – beyond the SM**
  - Lorentz invariance violation; Smoothness of Space-Time
  - Particles beyond SM ?
  - New particle physics at $\sqrt{s}$=150 TeV ?

Putative

Cosmic Particle Accelerators

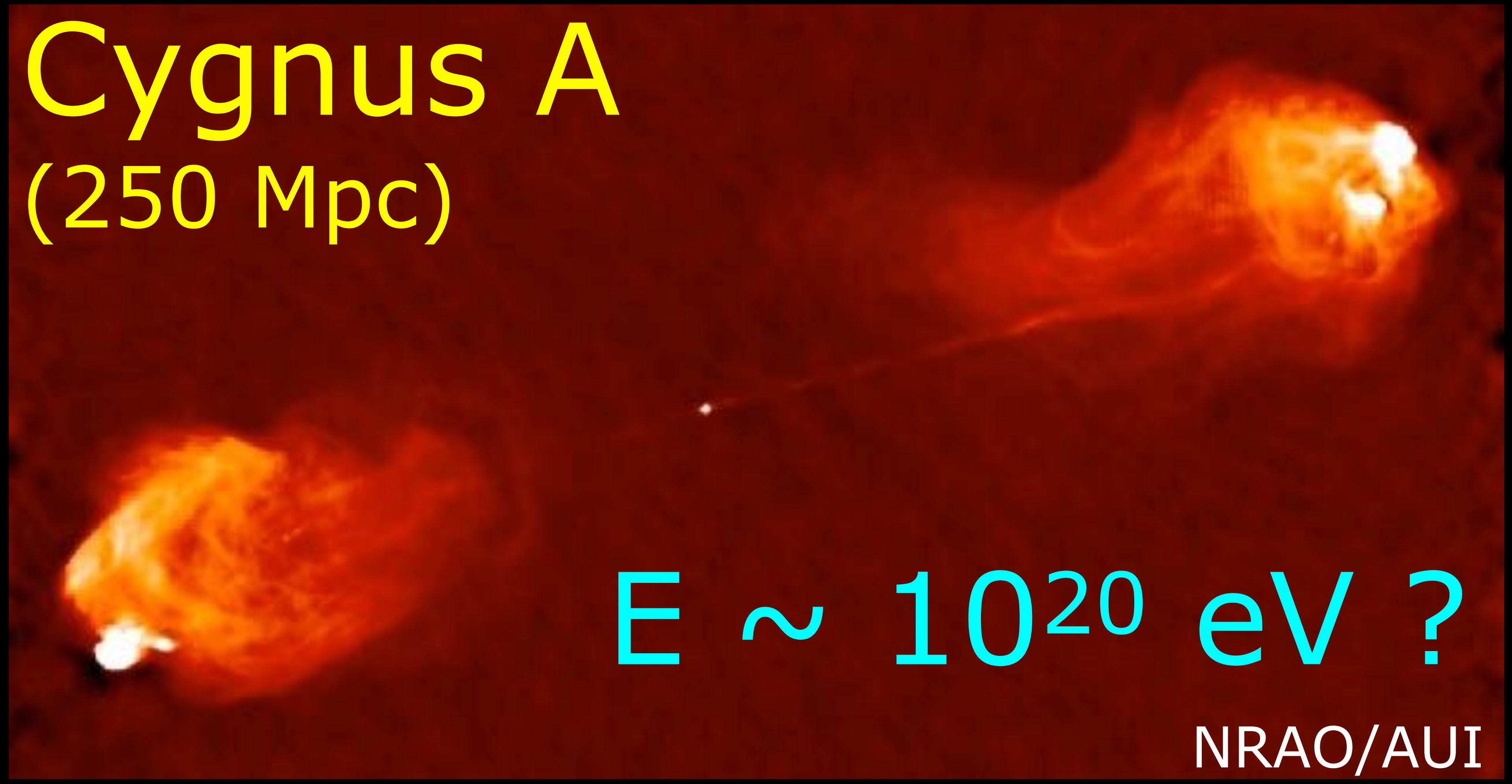
Supernova Remnants

SNR509
(50 kpc)

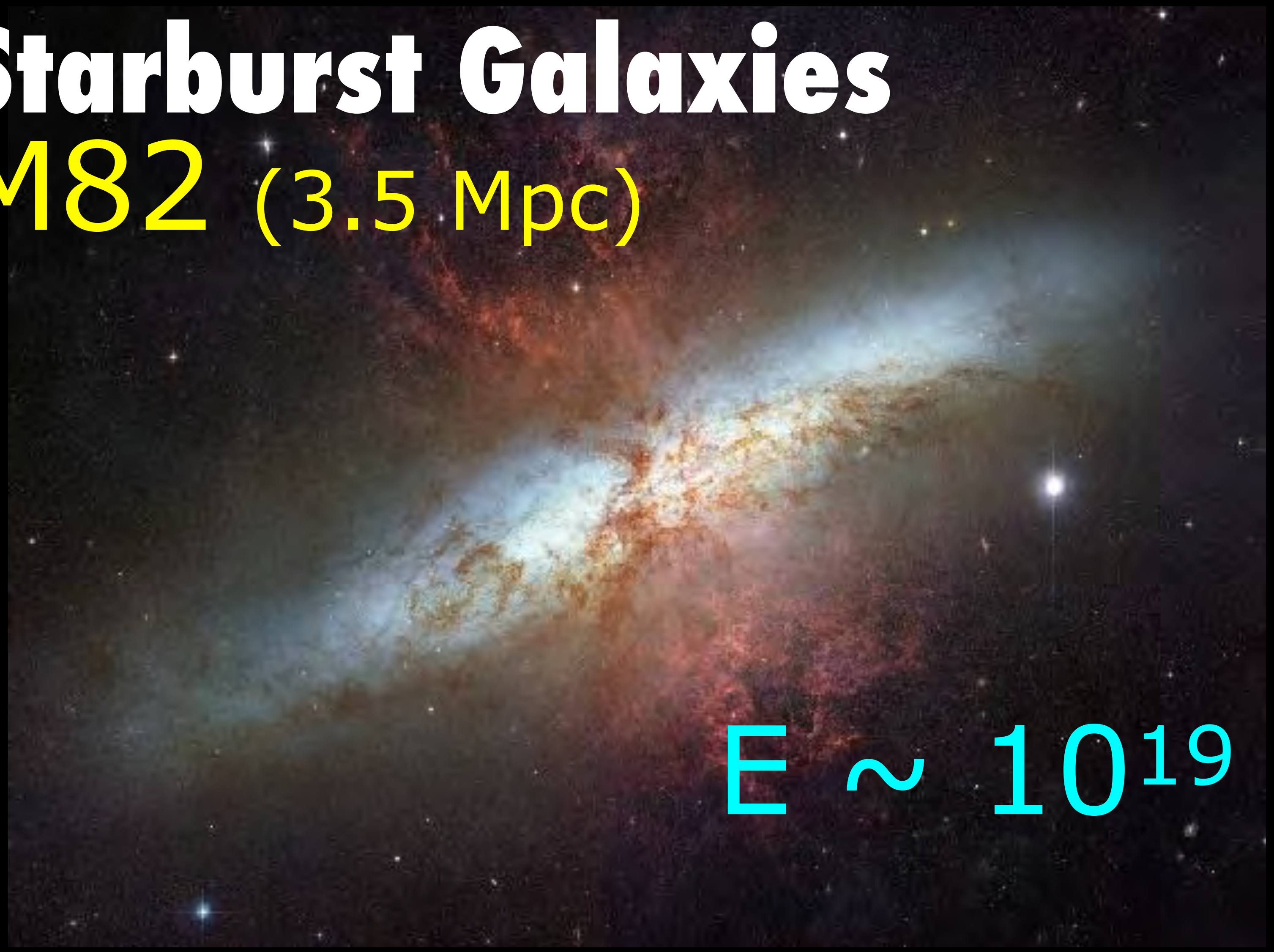
$E < 10^{15}$ eV

particle acceleration at shock waves

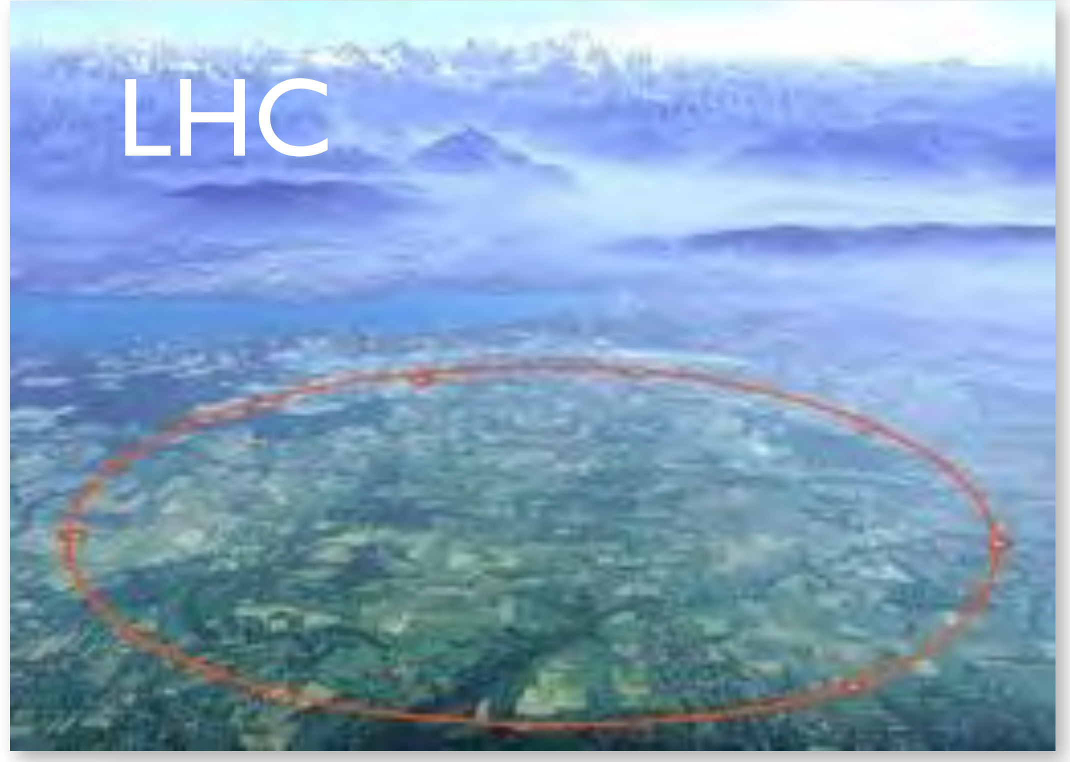
AGN and their Jets/Lobes

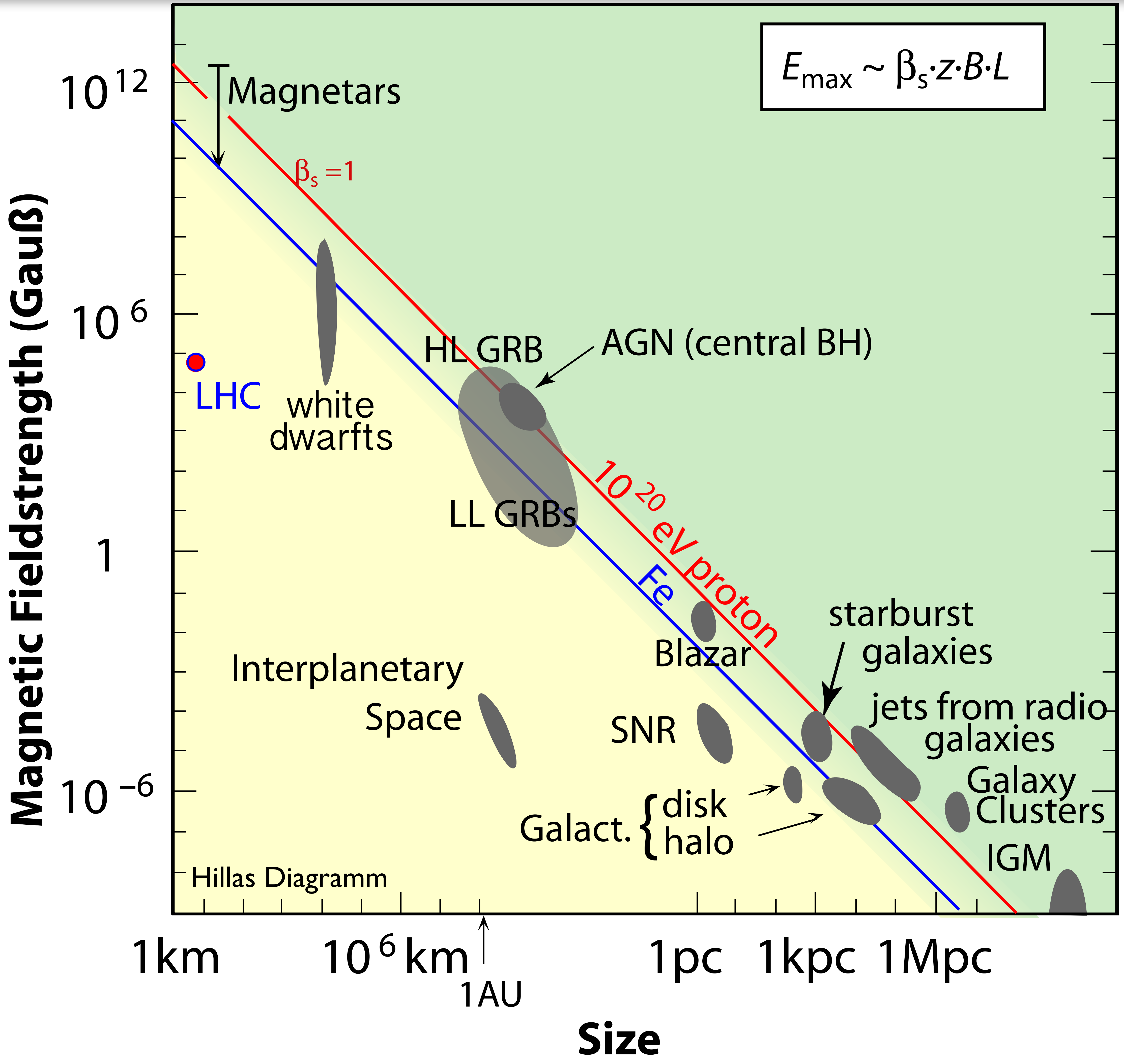


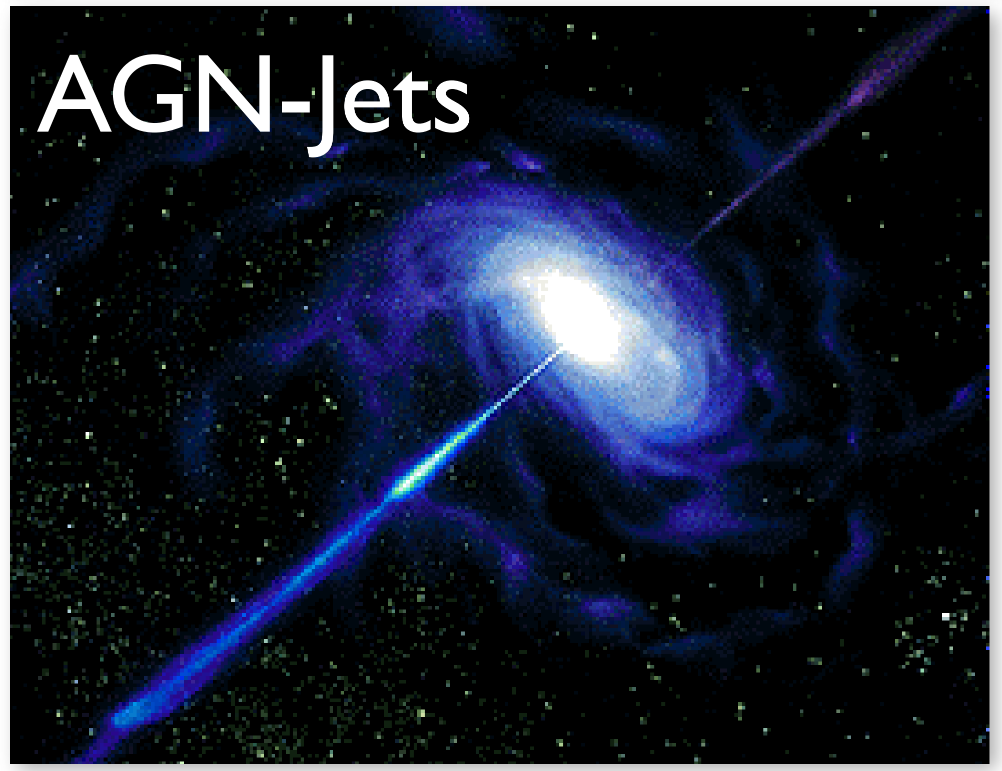
Starburst Galaxies



Requirement: B × Size ≳ 1 Gauss × 1 parsec



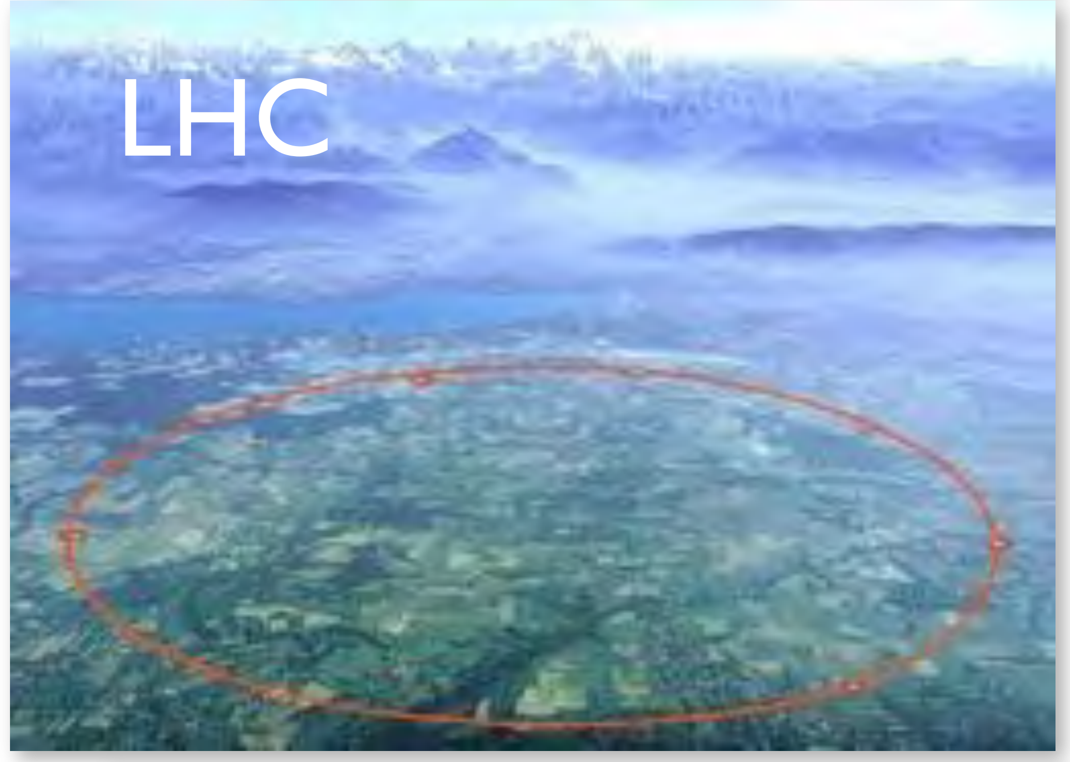


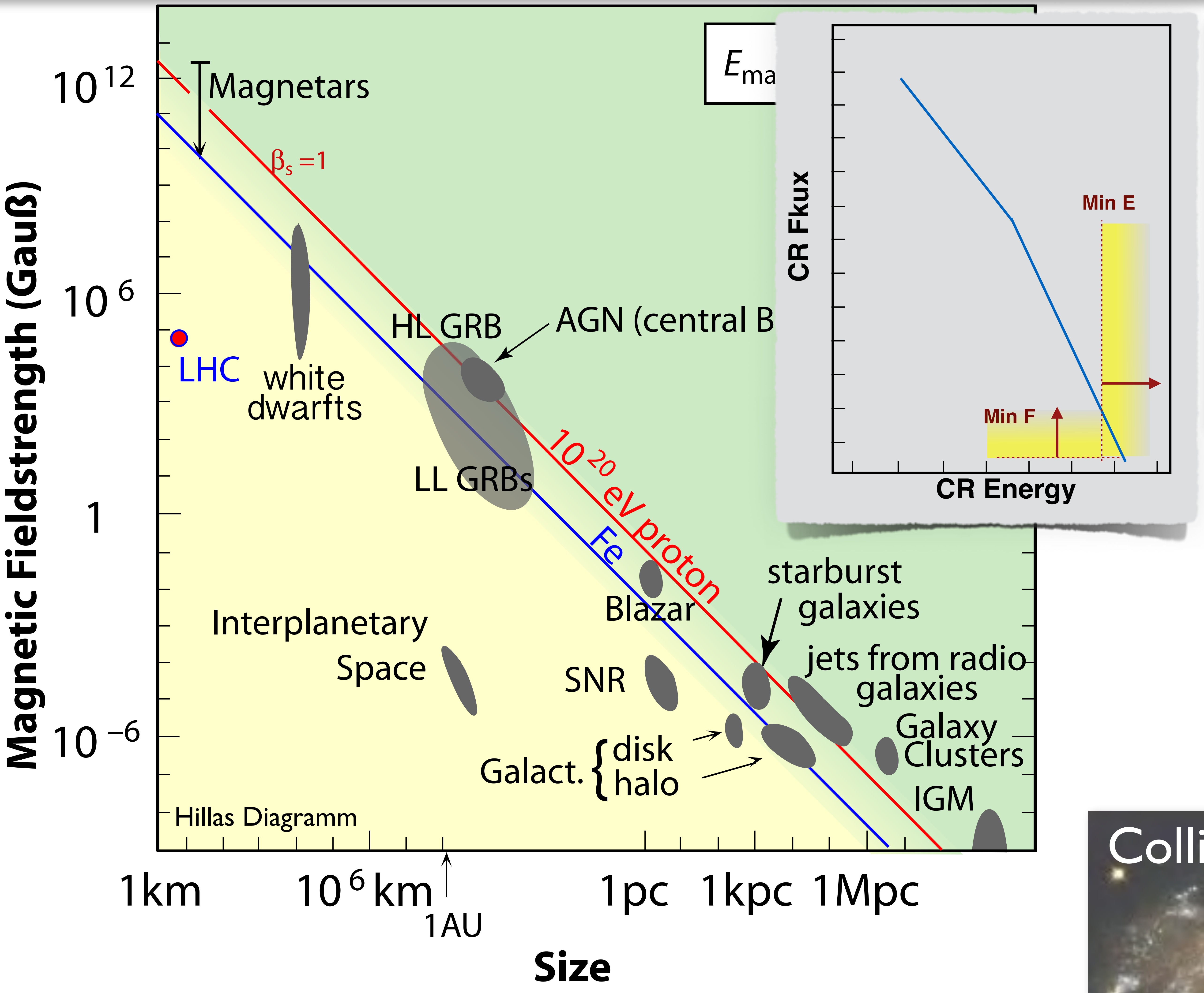


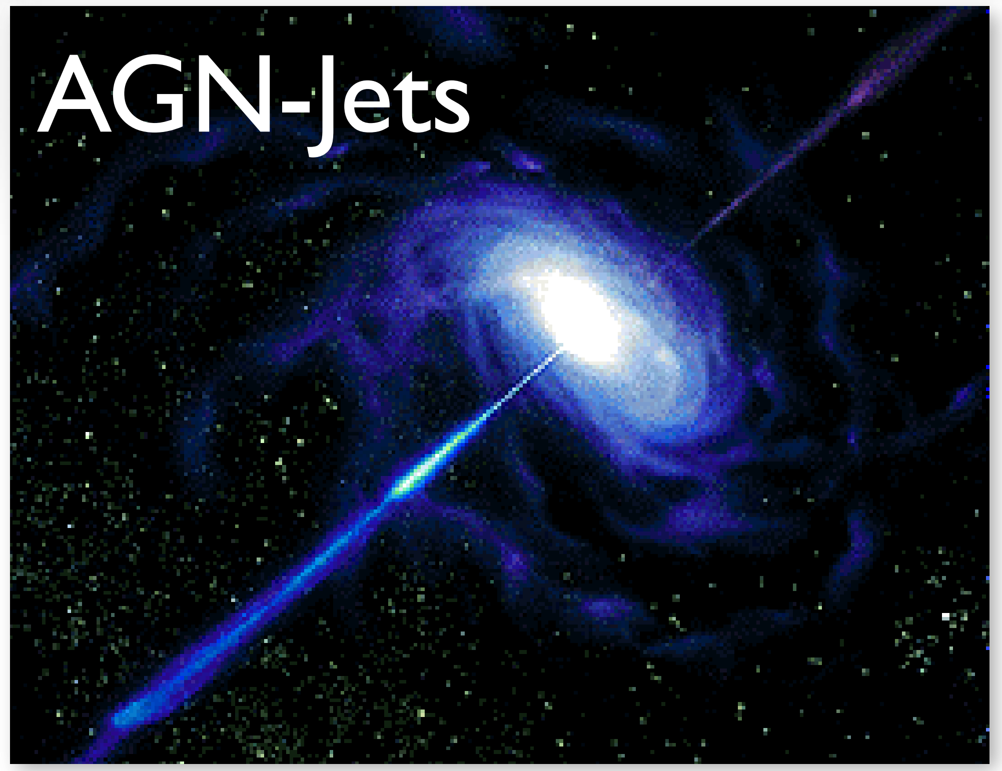
Realistic constraints more severe

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

Requirement: B × Size ≳ 1 Gauss × 1 parsec







Realistic constraints more severe

- small acceleration efficiency
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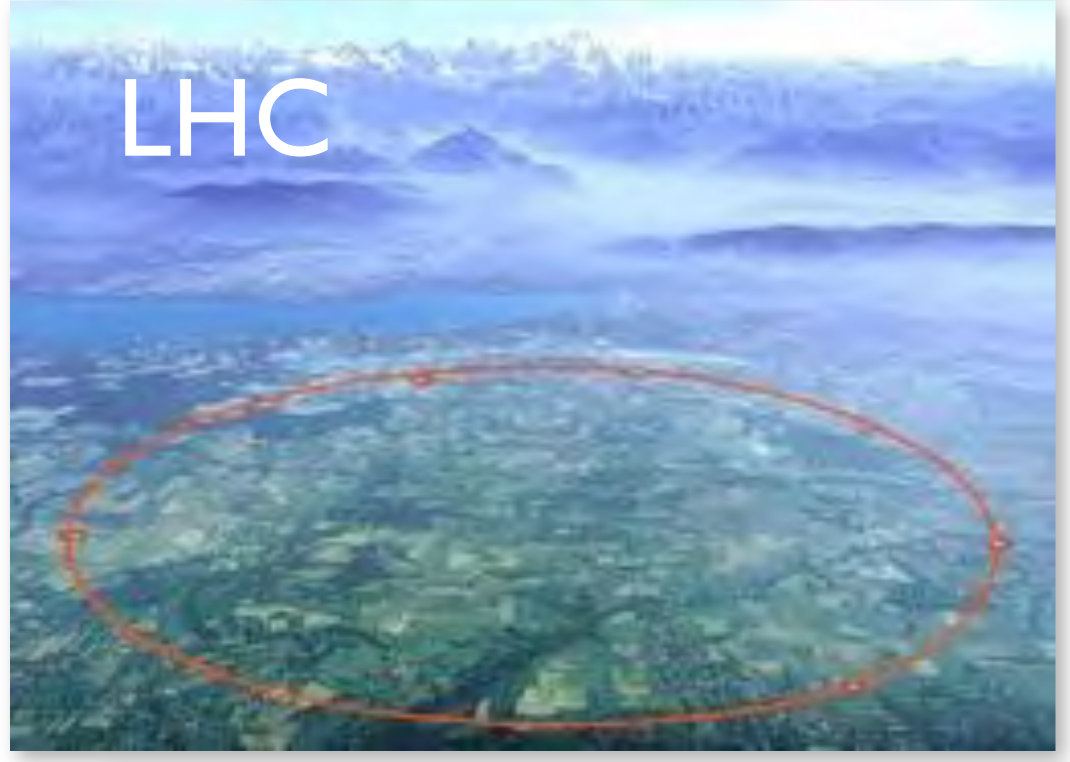
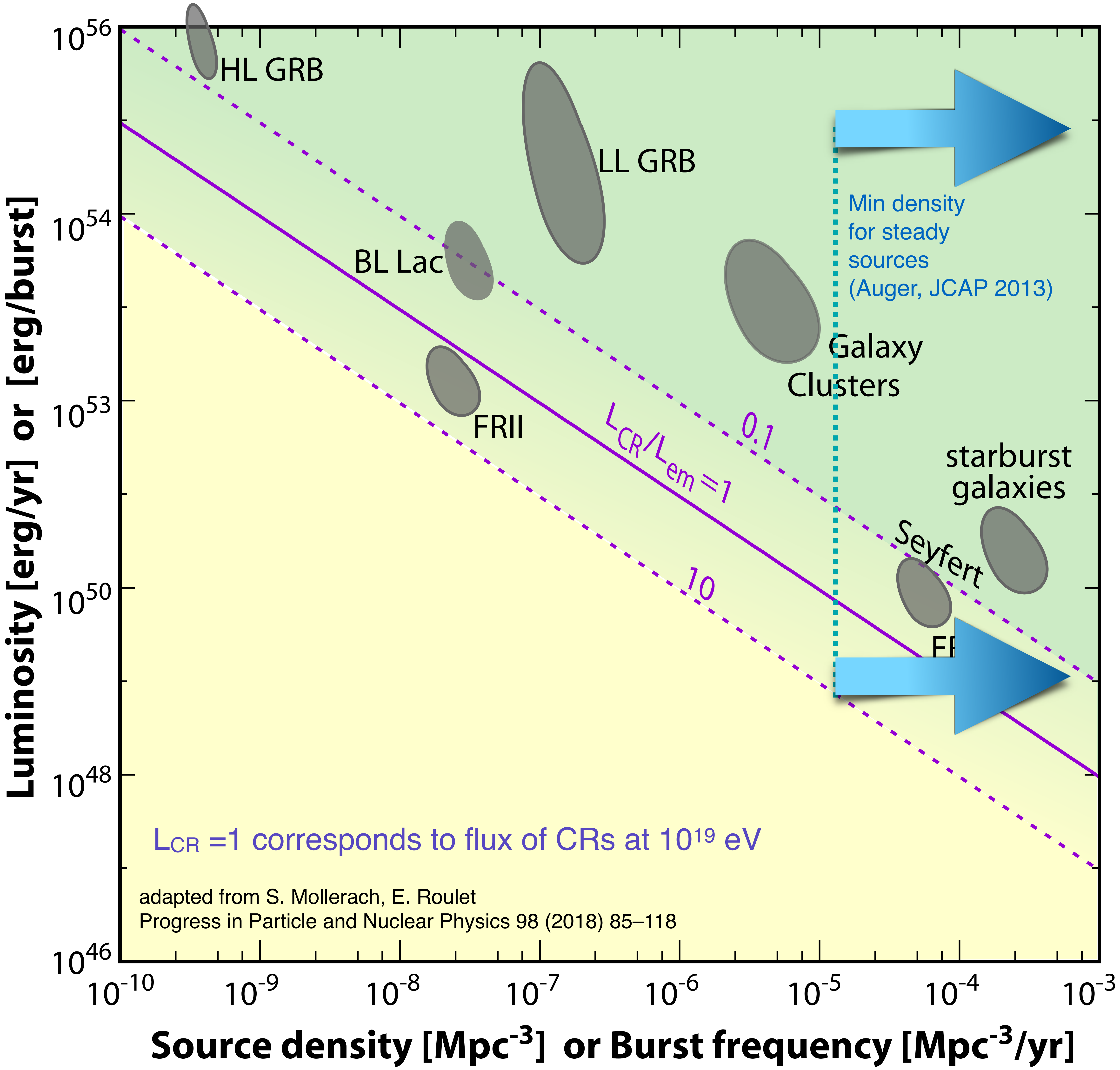
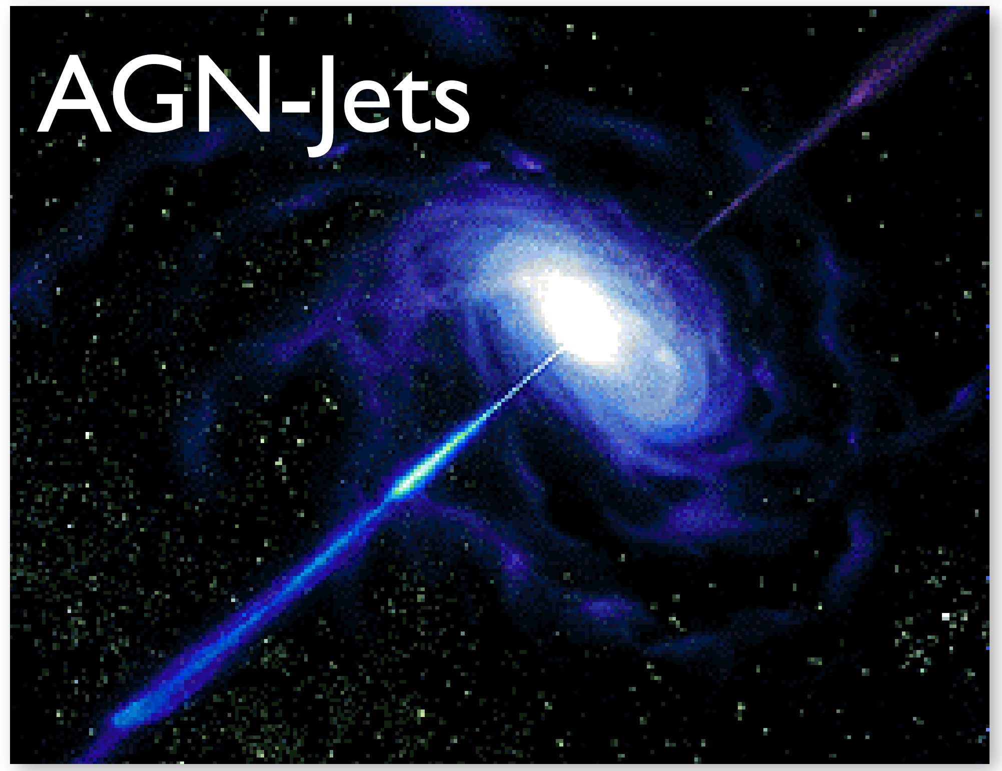
- interactions in source region

Source Luminosity vs Source Density

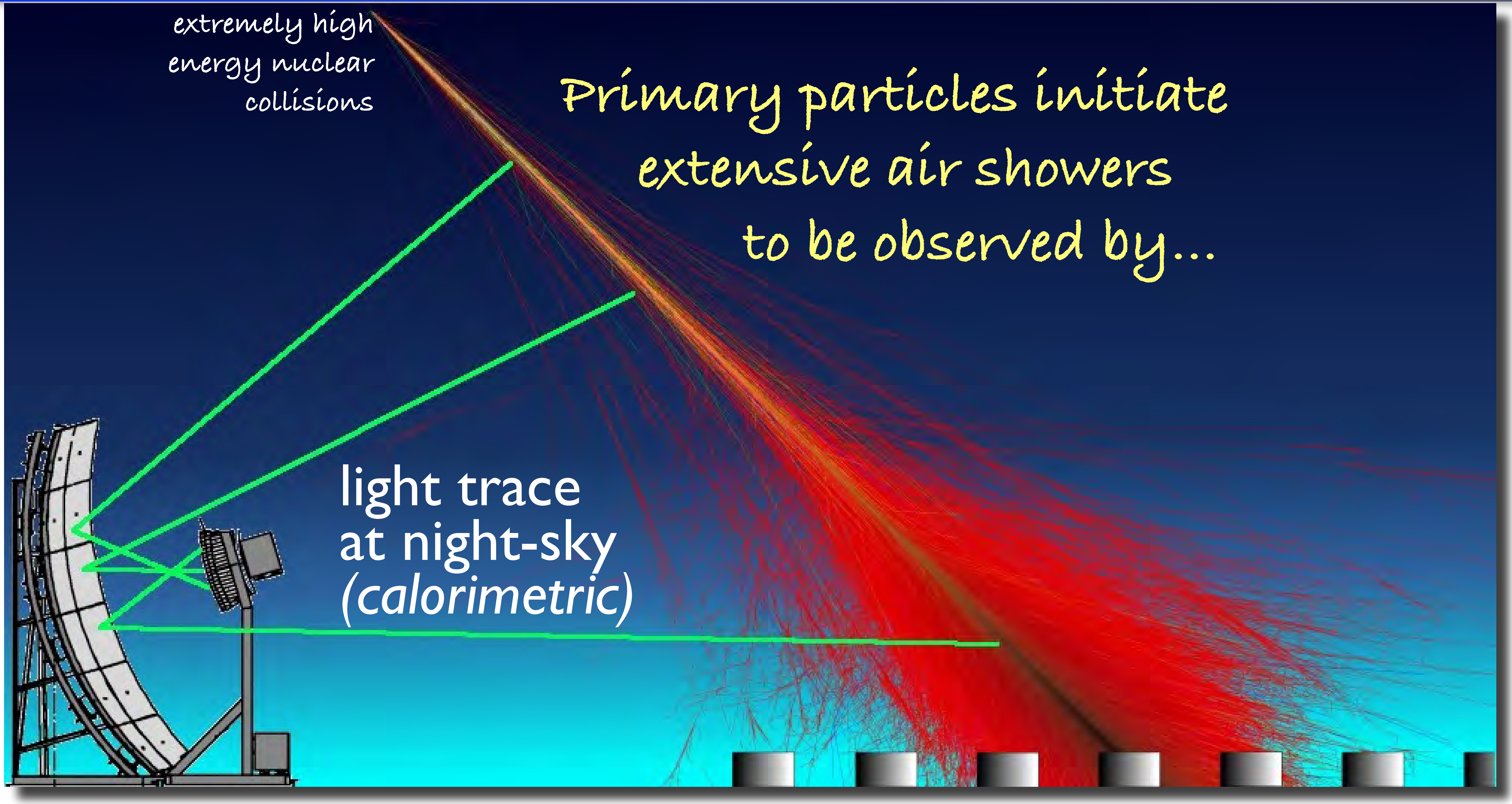






UHECR Observations

Observation of UHECR



Fluorescence light

Particle-density and
-composition at ground

Also:
Detection of Radio- & Microwave-Signals

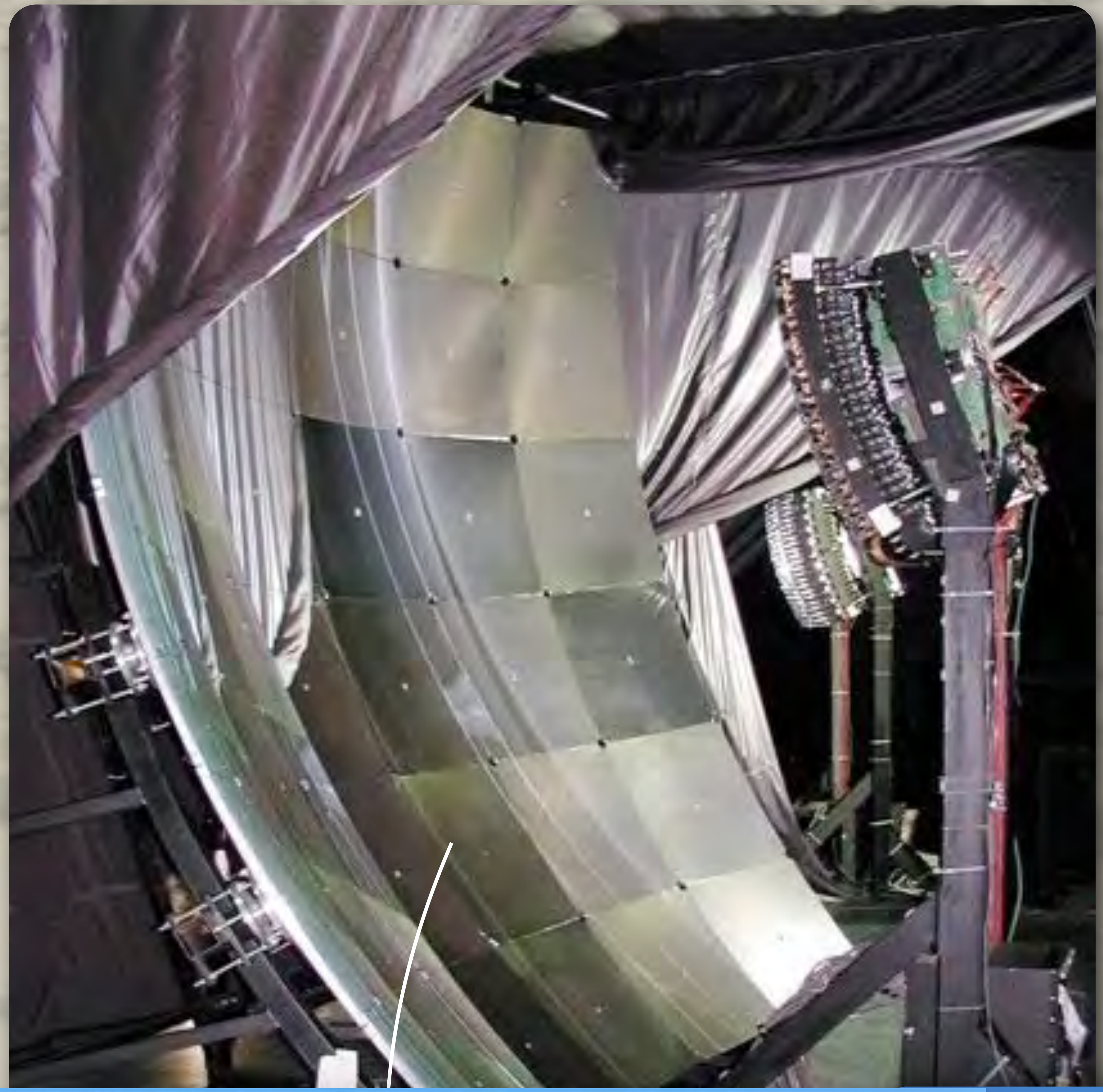
Pierre Auger Observatory

1660 detector stations on 1.5 km grid

27 fluores. telescopes at periphery

153 radio antennas over 17 km^2

Auger Hybrid Observatory



3000 km² area, Argentina
27 fluorescence telescopes plus
153 Radio Antennas

...1660 Water Cherenkov tanks

Event Example in Auger Observatory

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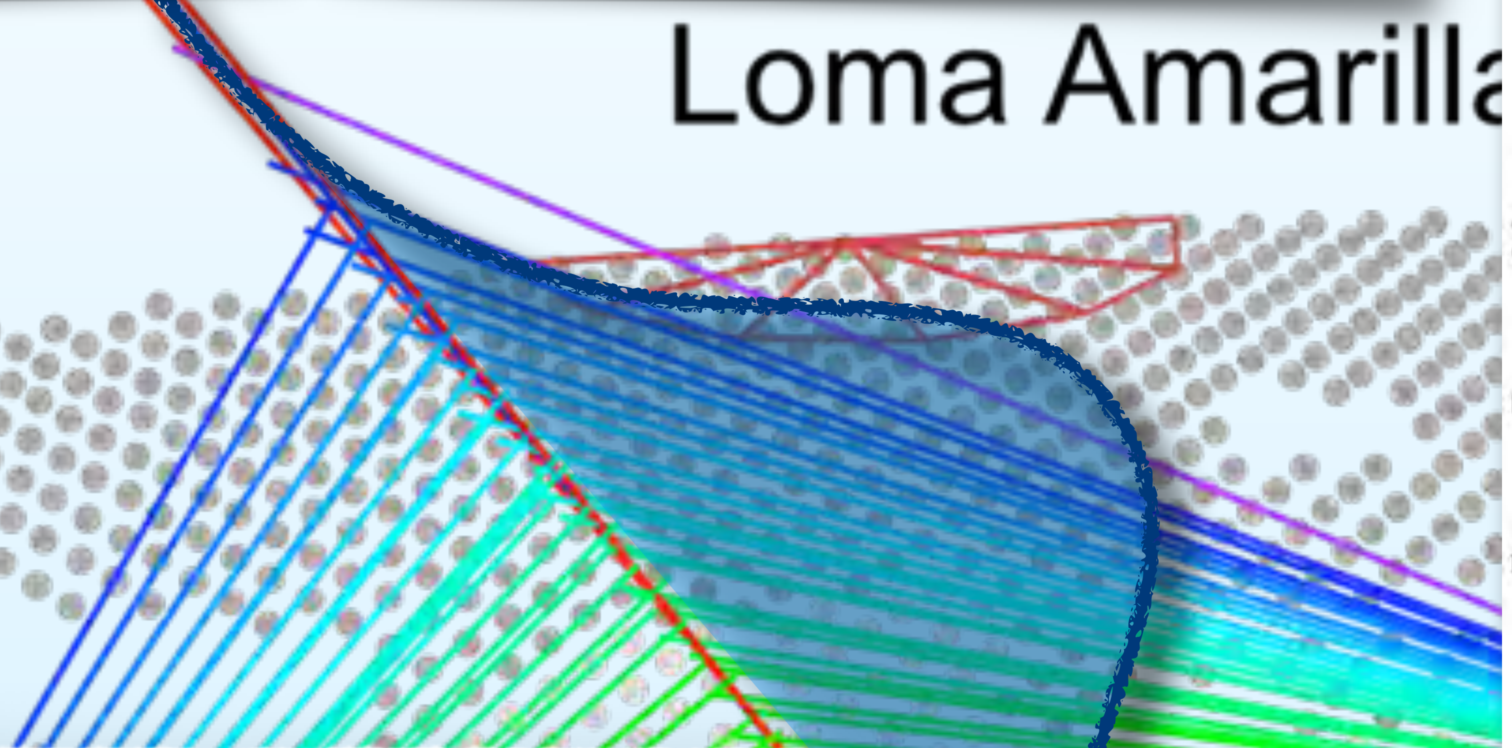
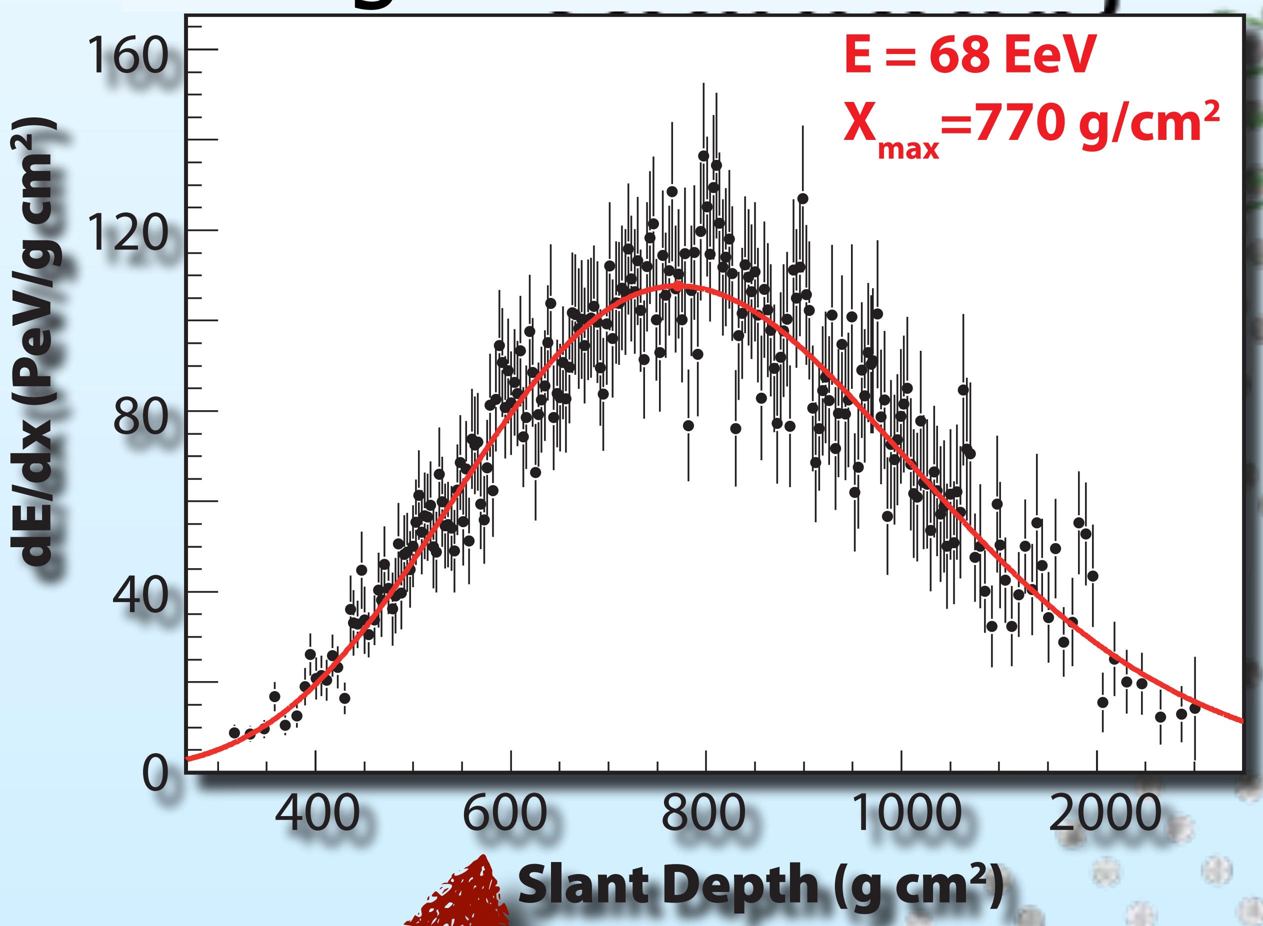
Energy calibration based on experimental data (including invisible energy correction)

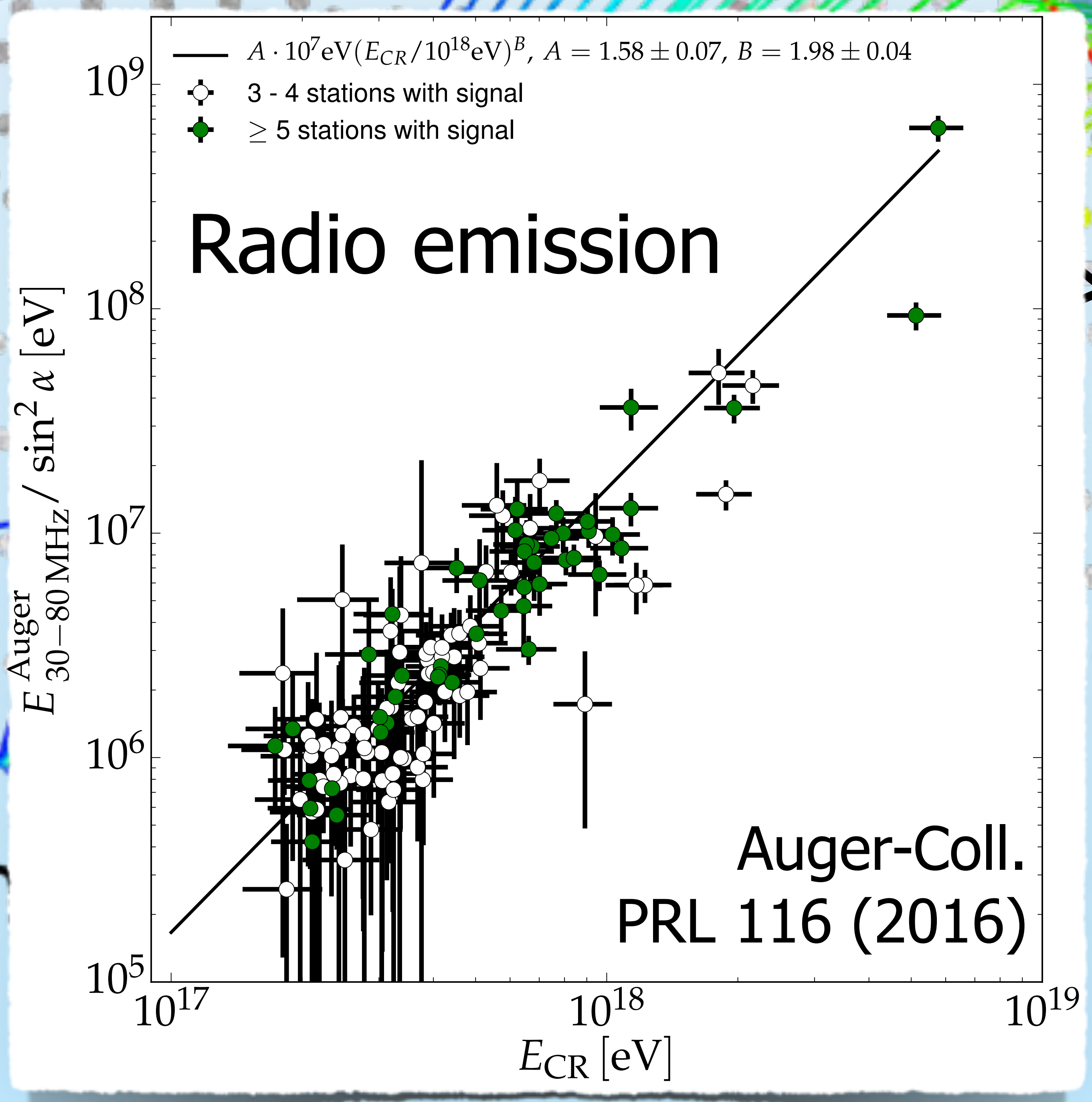


calorimetric meas.

Longitudinal Profile

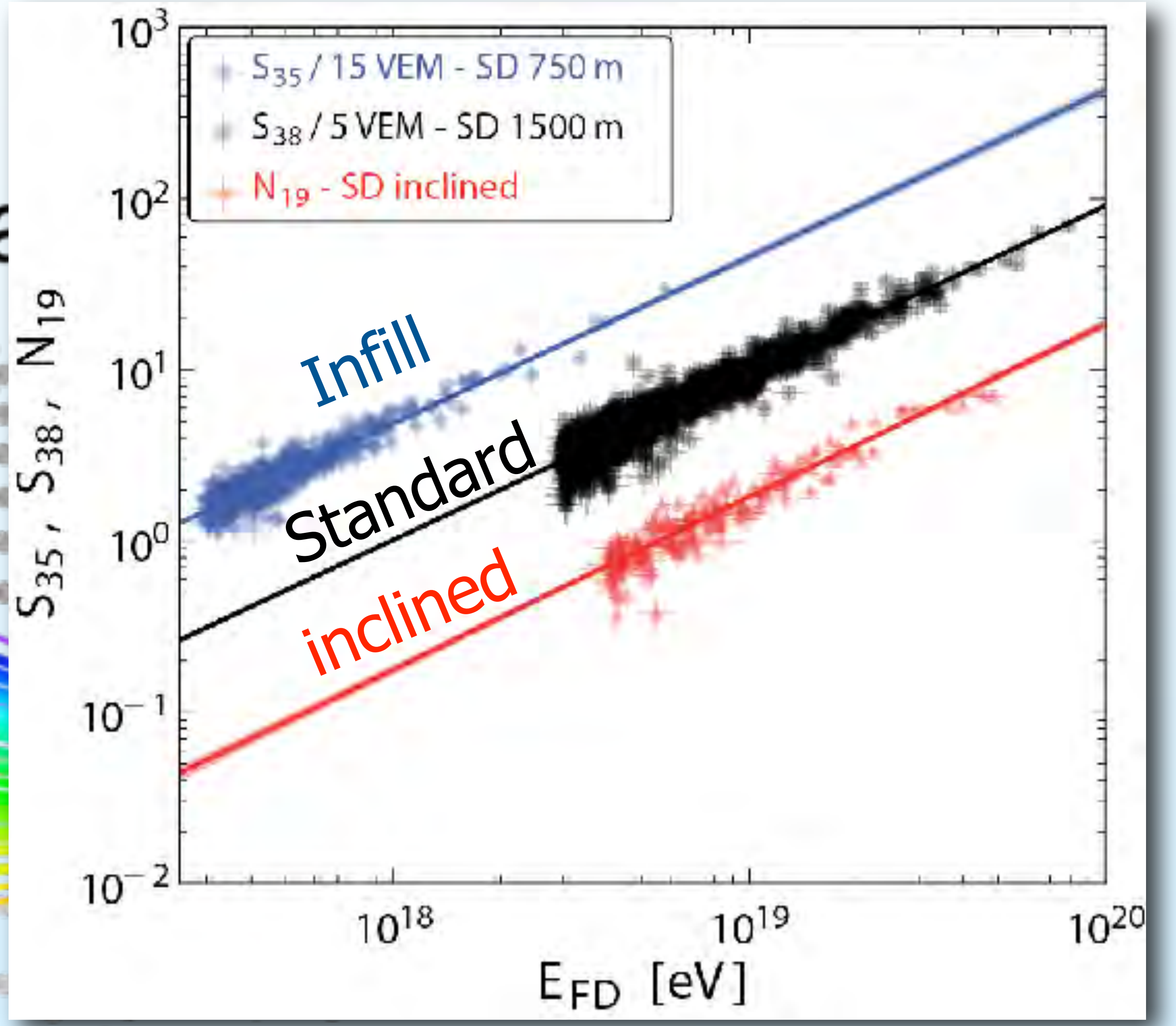


Radio emission

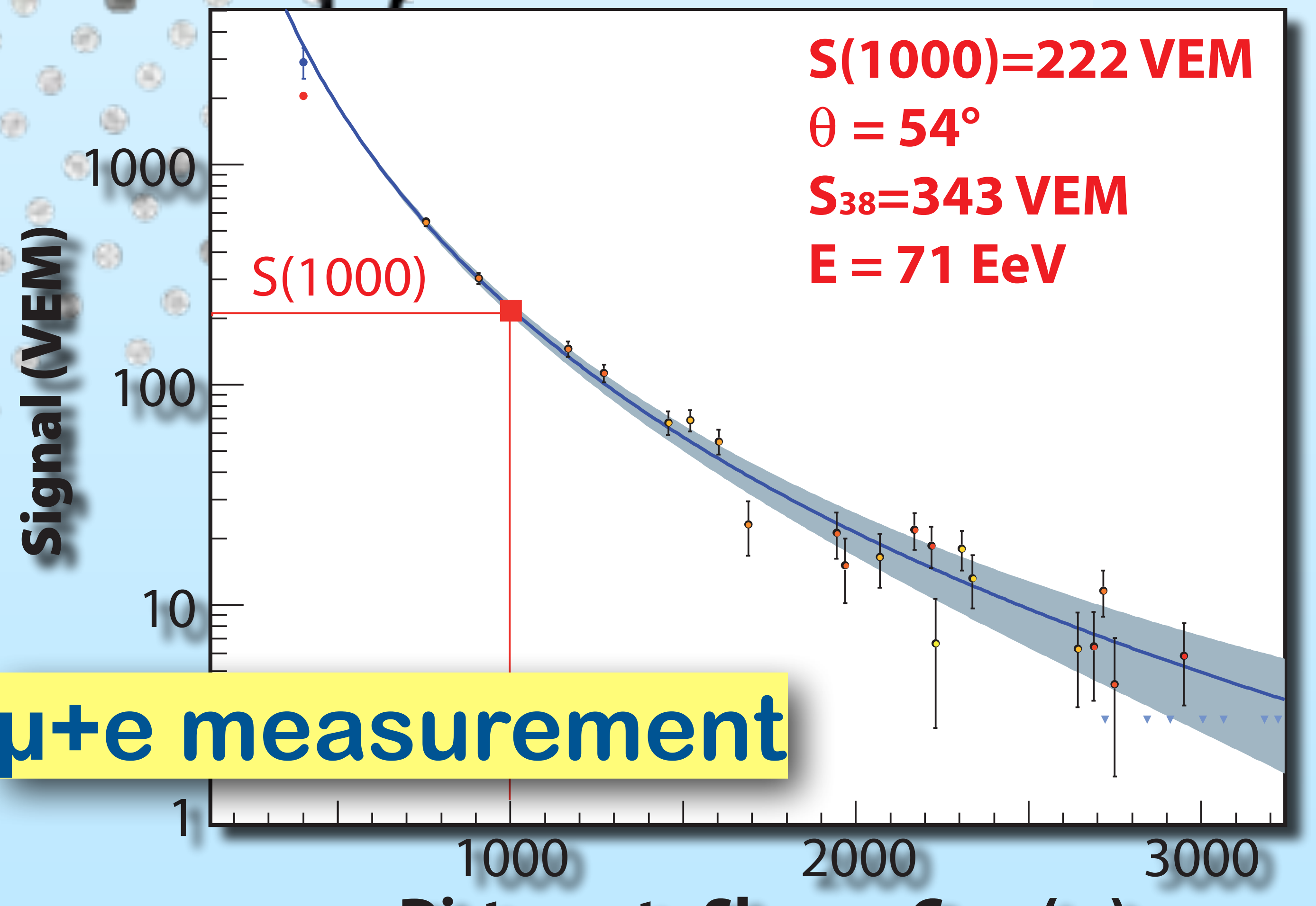


Auger-Coll. PRL 116 (2016)

Cross Correlation



Lateral Profile



μ+e measurement

Pierre Auger Collaboration

~450 Collaborators; 92 Institutions, 18 Countries:

- Argentina
- Australia
- Brazil
- Czech Republic
- France
- Germany (Aachen, Bonn, Hamburg, KIT, Siegen, Wuppertal)
- Italy
- Mexico
- Netherlands
- Poland
- Portugal
- Romania
- Slovenia
- Spain
- UK
- USA

Colombia, Belgium — Associated

Peru, Bolivia — EoI

New members are welcome!

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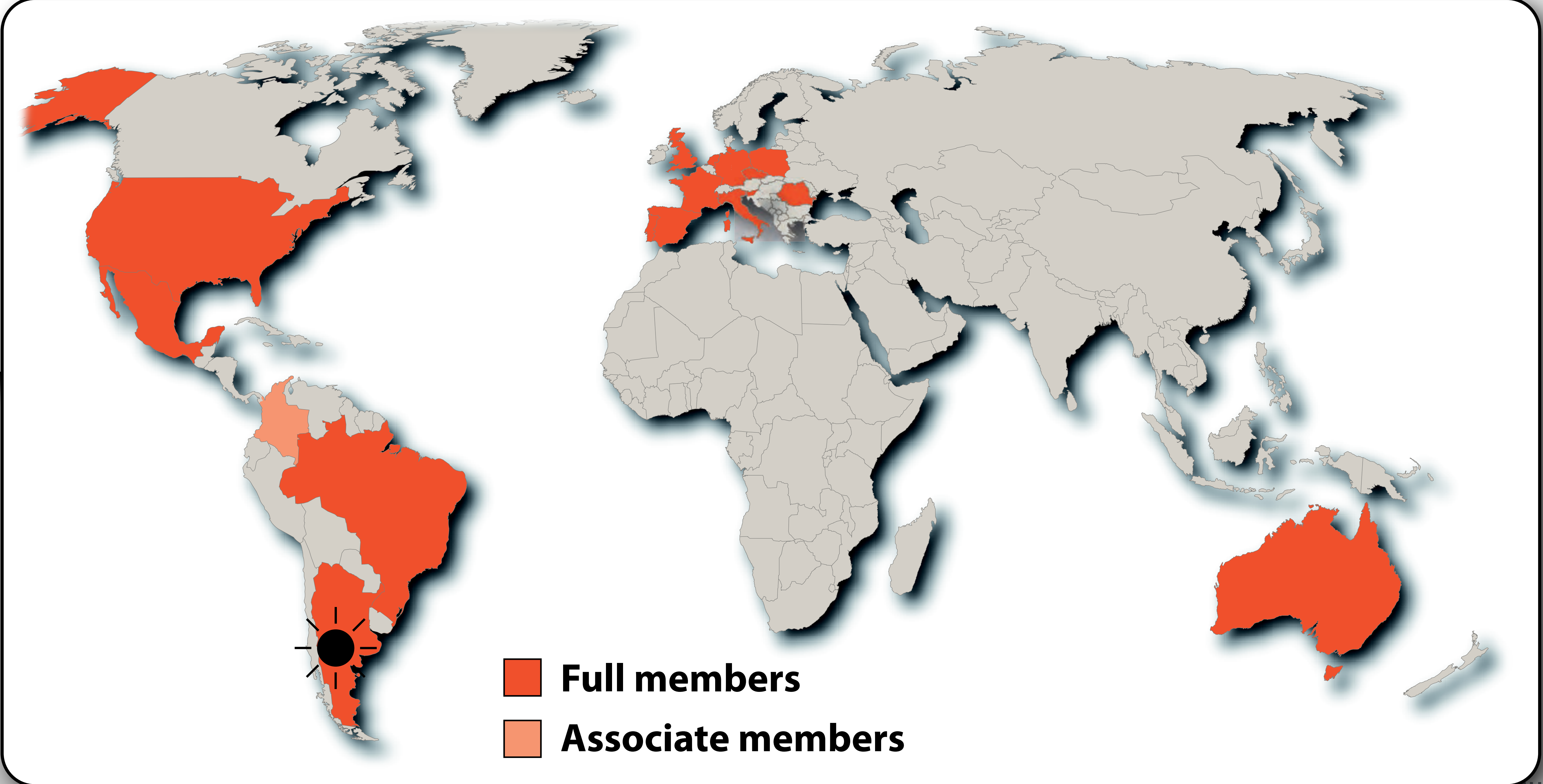
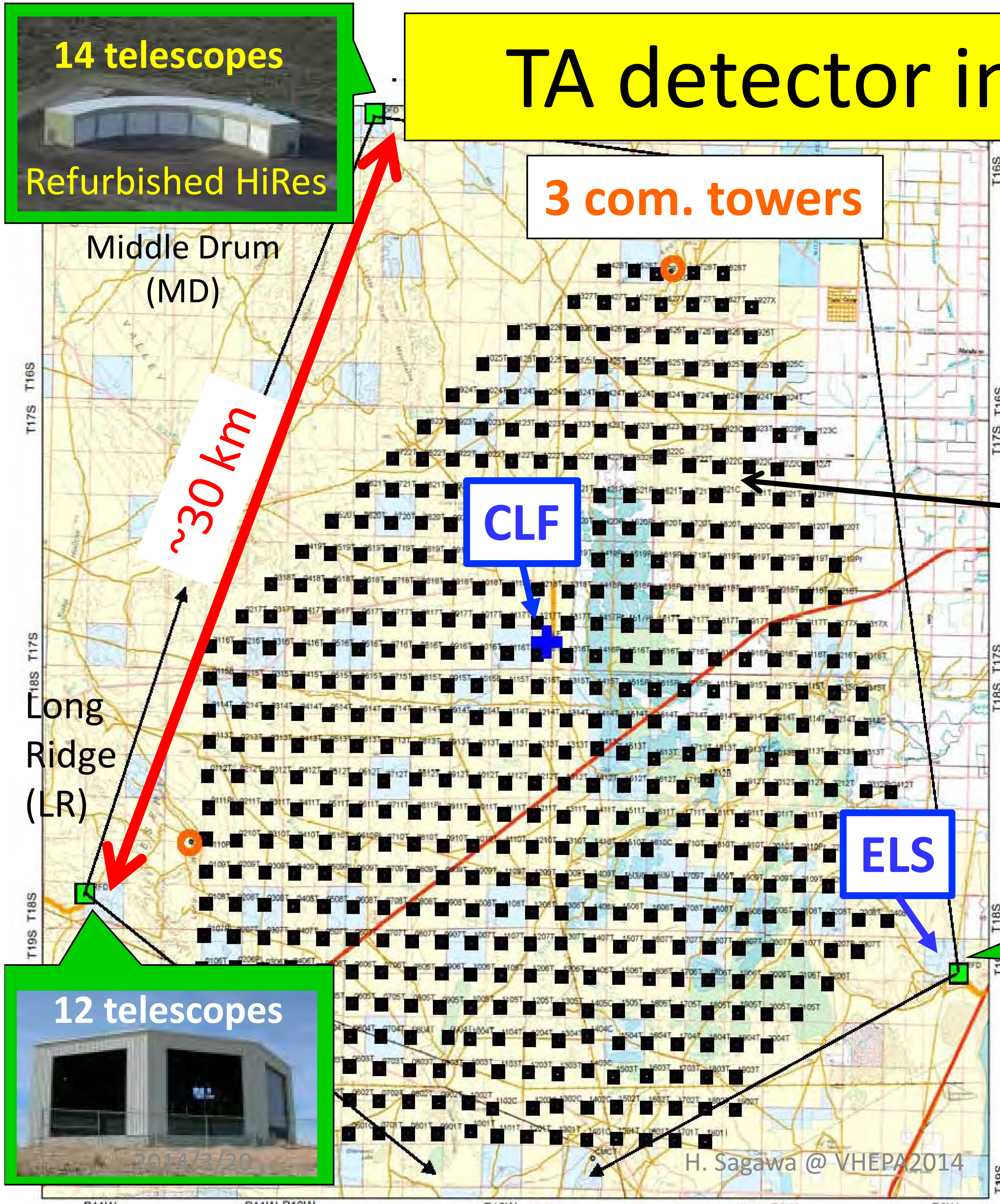


TA detector in Utah

39.3°N, 112.9°W
~1400 m a.s.l.



Surface Detector (SD)

507 plastic scintillator SDs

1.2 km spacing

~700 km²

to be upgraded to 2800 km² with coarser spacing

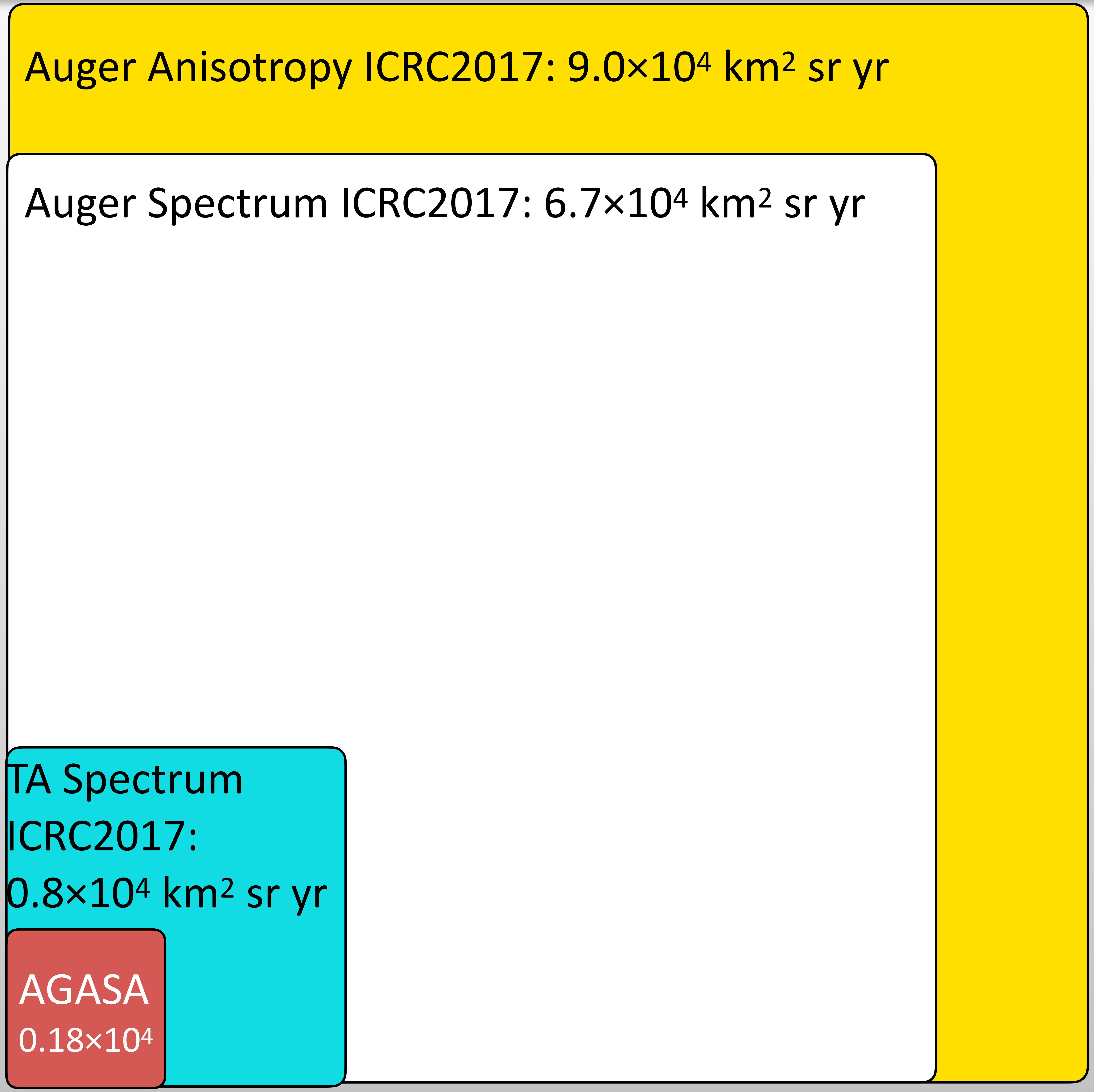
Fluorescence Detector(FD)

3 stations

38 telescopes

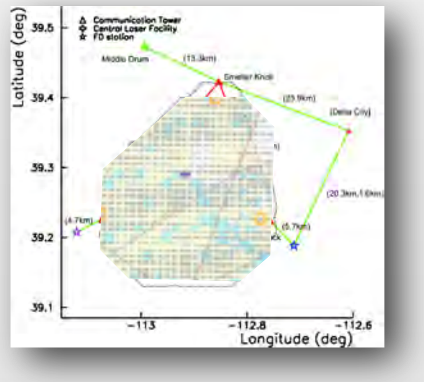
FD and SD: fully operational since 2008/May 4

UHE Exposure in Comparison

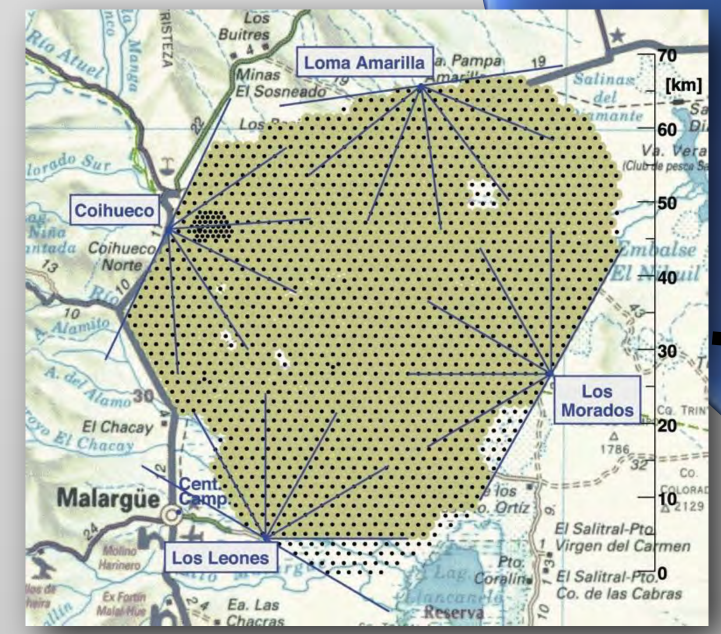


Combined Auger and TA cover full sky

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

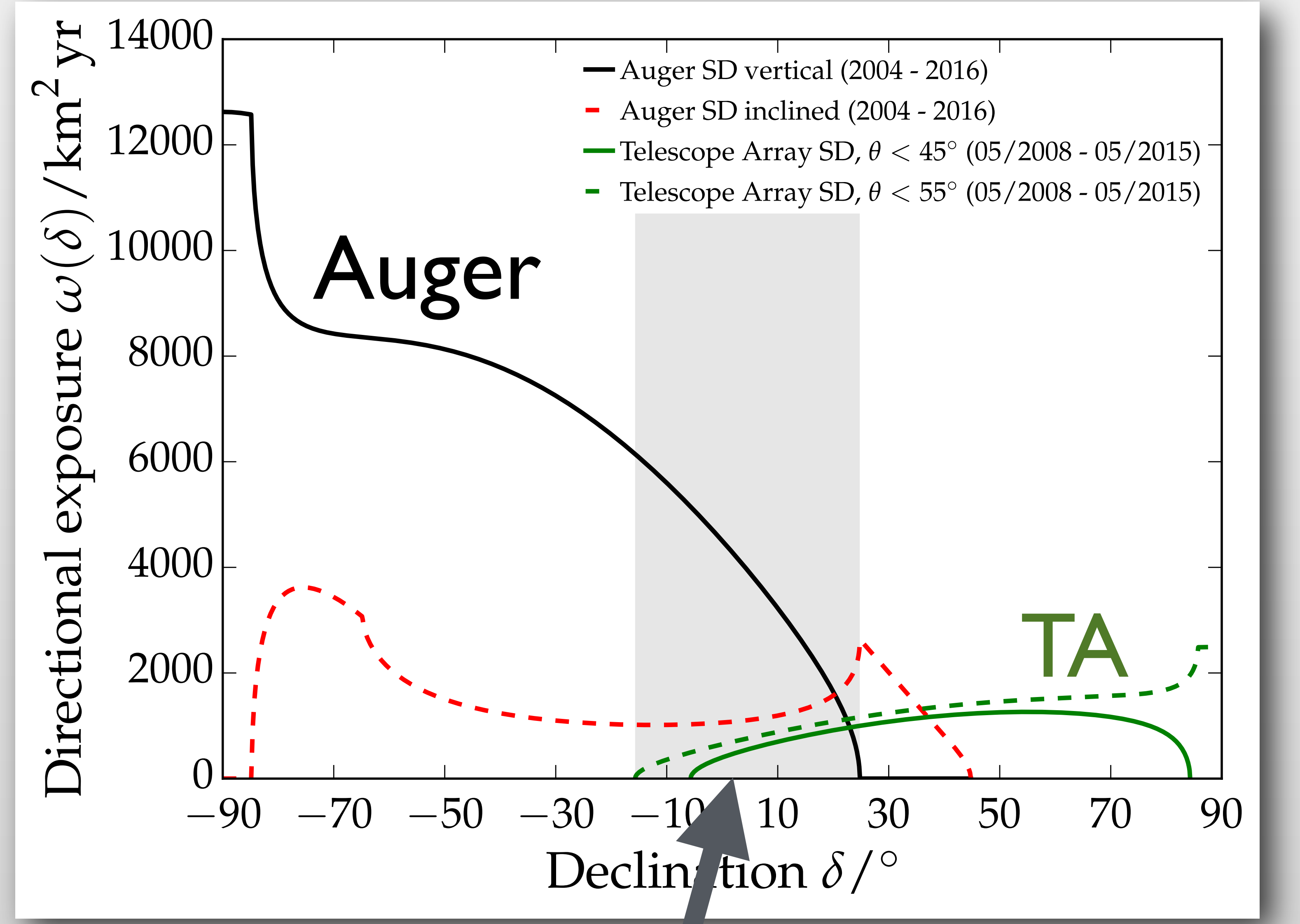


same scale



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

Auger: started 01/2004
TA: started 05/2008

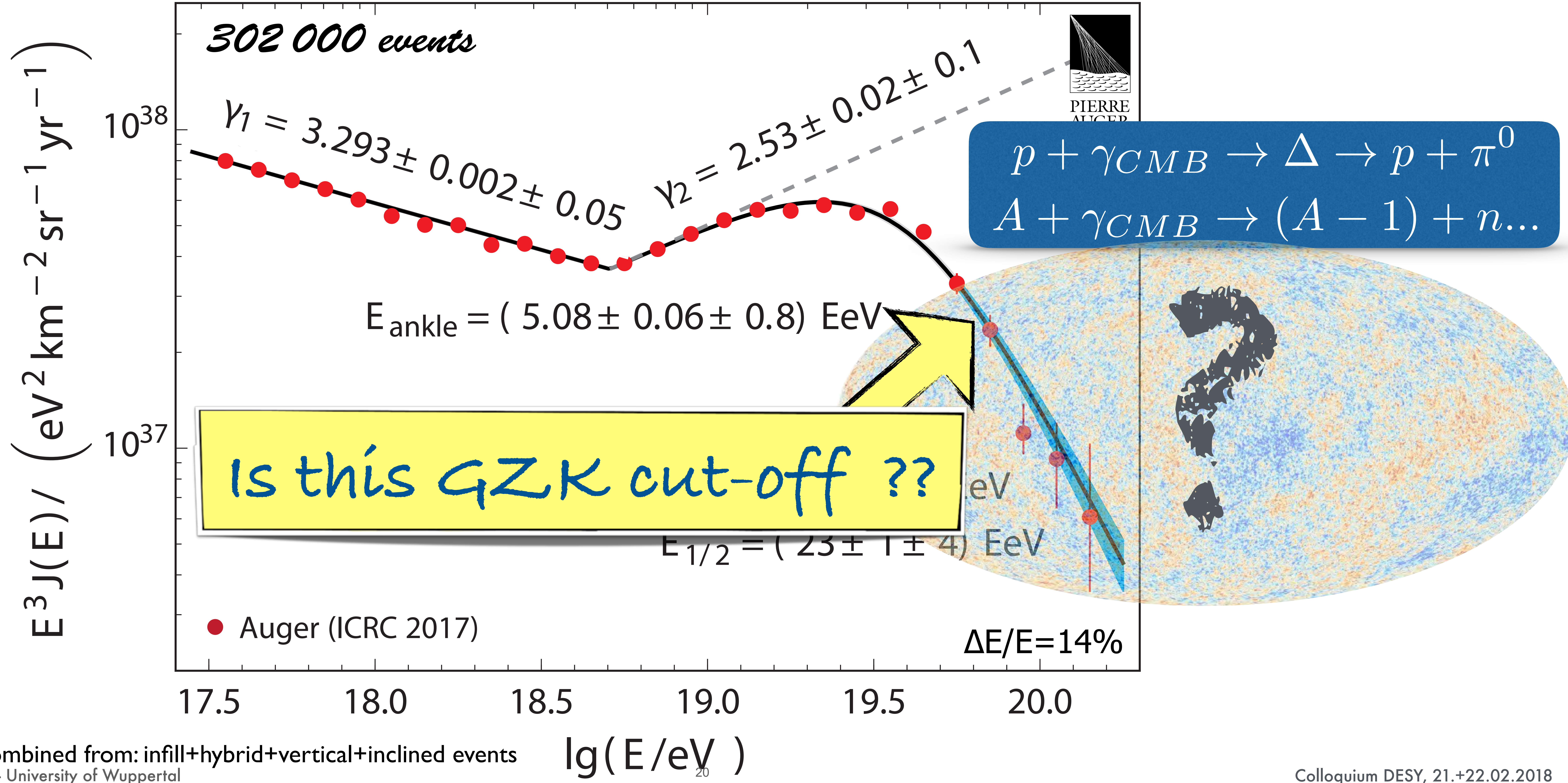


Auger and TA can see the same sky

UHECR
Energy Spectrum

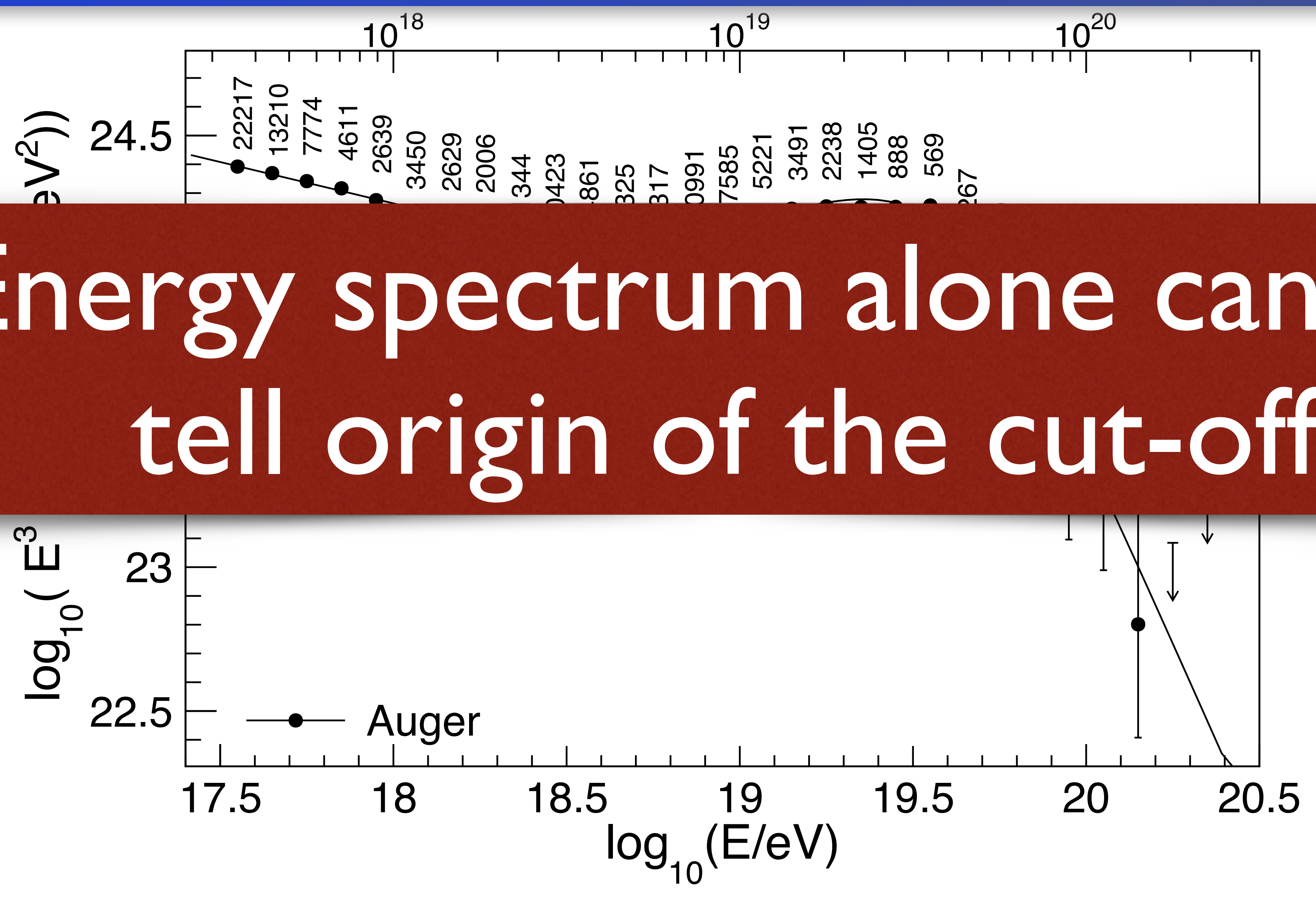
End of the CR-Spectrum (0°-80°)

arXiv:1708.06592
Update from: PRL 101, 061101 (2008), Physics Letters B 685 (2010) 239



combined from: infill+hybrid+vertical+inclined events

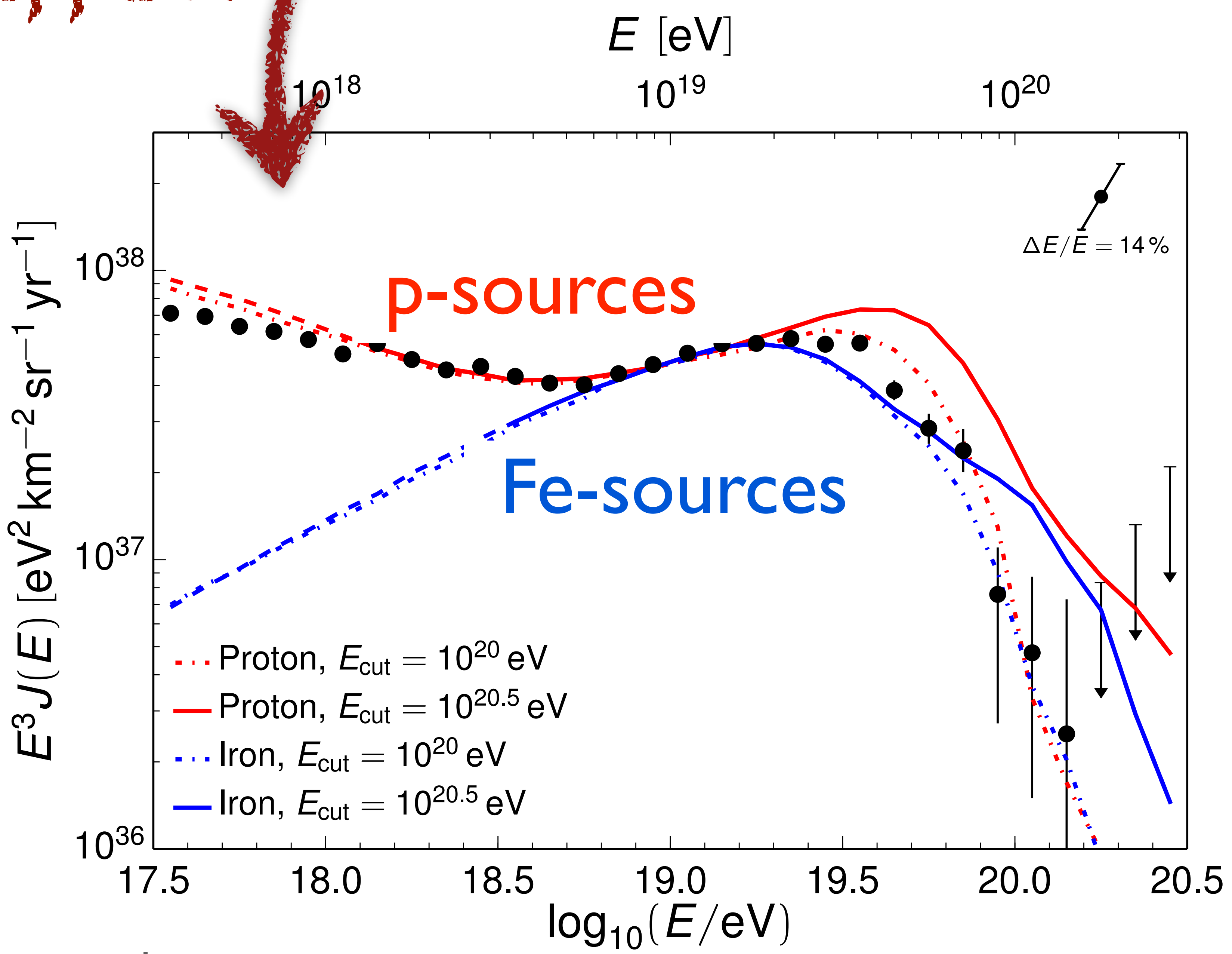
GZK-Effect or Exhausted Sources?



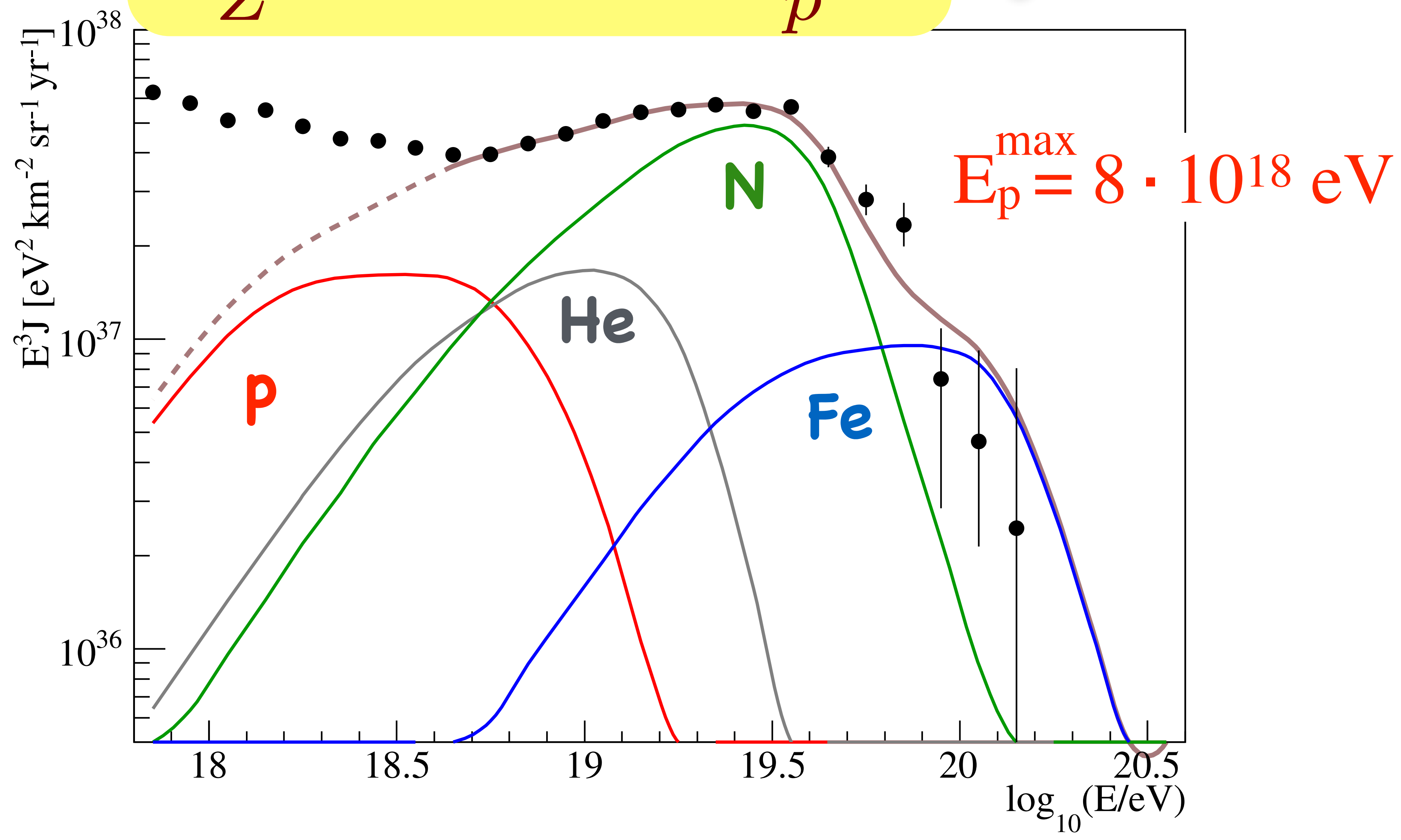
Energy spectrum alone cannot tell origin of the cut-off

GZK-effect

exhausted sources

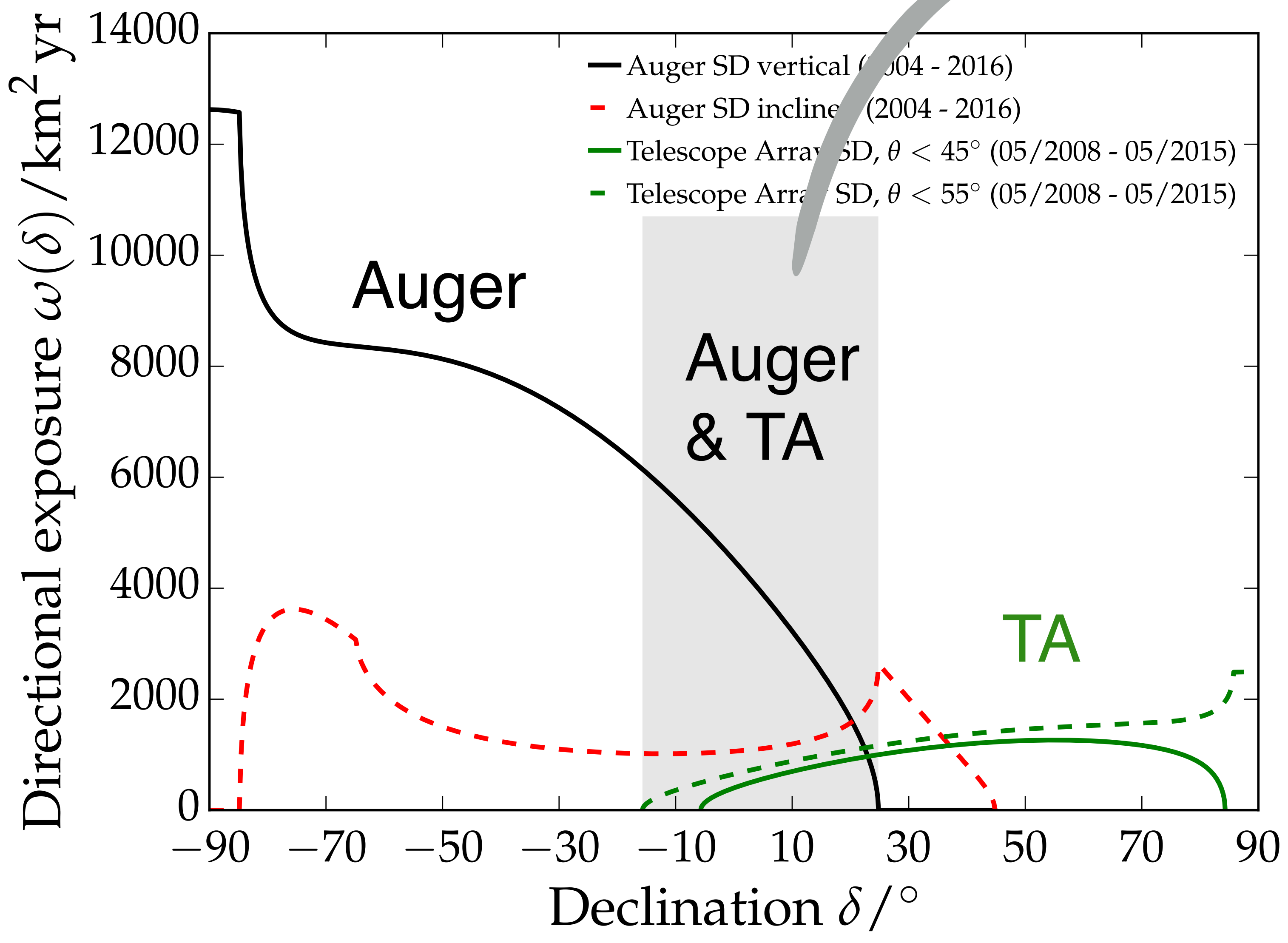


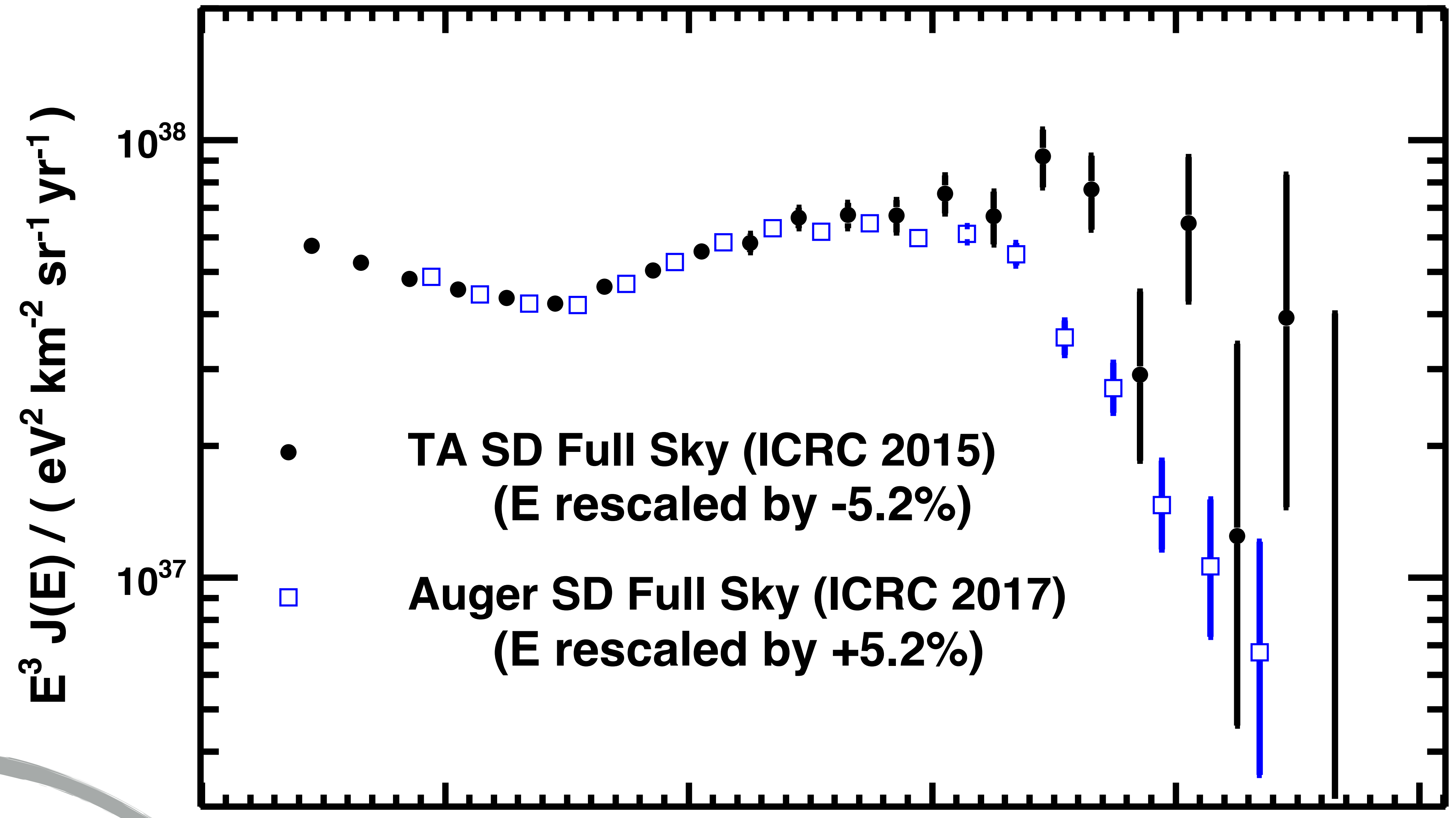
$$E_Z^{max} \propto Z \times E_p^{max}$$



Energy Spectra : Comparison Auger & TA

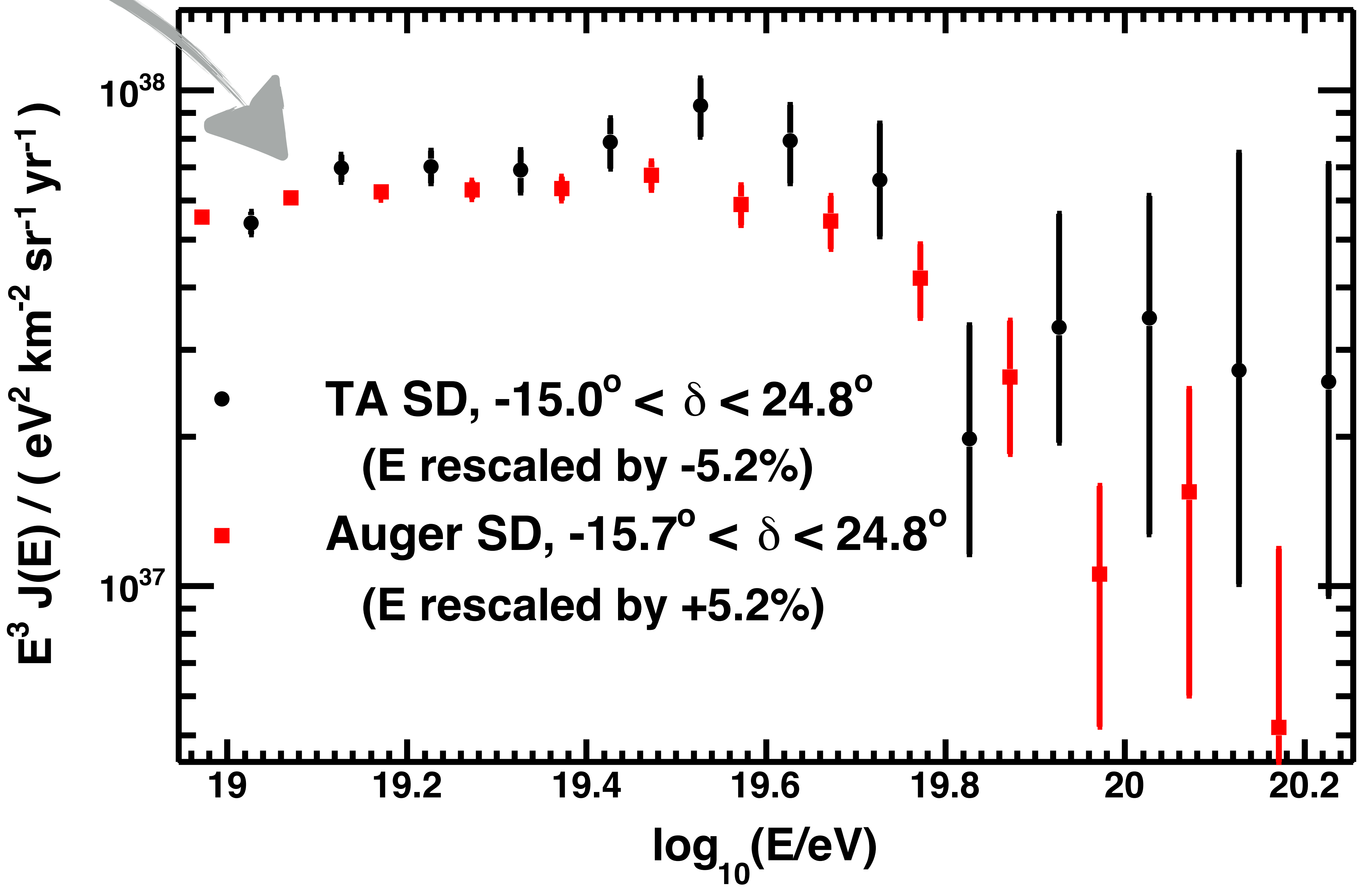
Auger-TA Working Group
@ ICRC2017





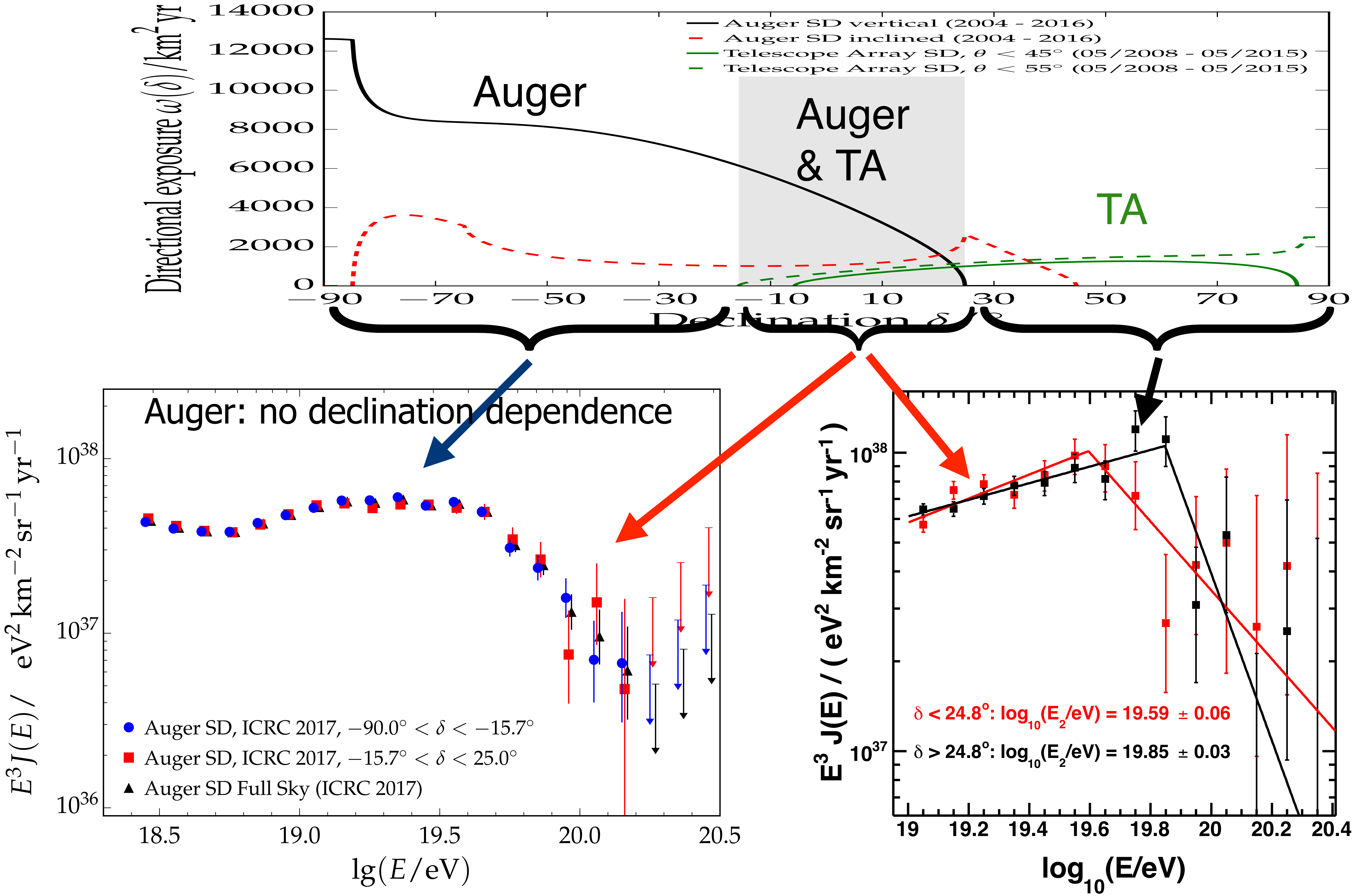
Each in their full sky

Instrumental or astrophysical effect?



Joint declination band

Energy Spectrum in Declination Bands



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TA-collaboration;
arXiv:1801.07820 → 3.5σ

Globus et al, arXiv:1707.01177
→ would yield much larger anisotropies than observed

Need

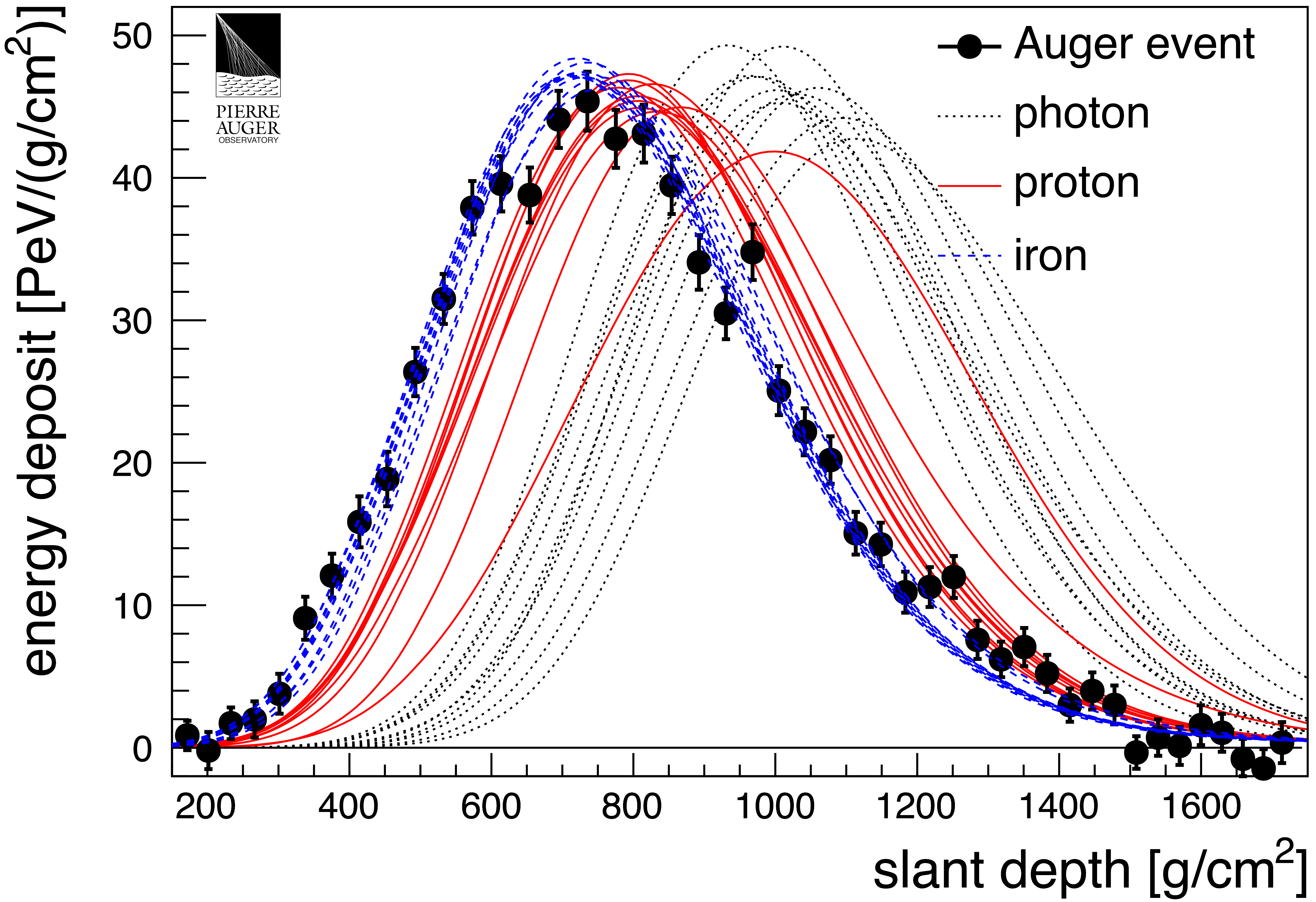
Mass Composition

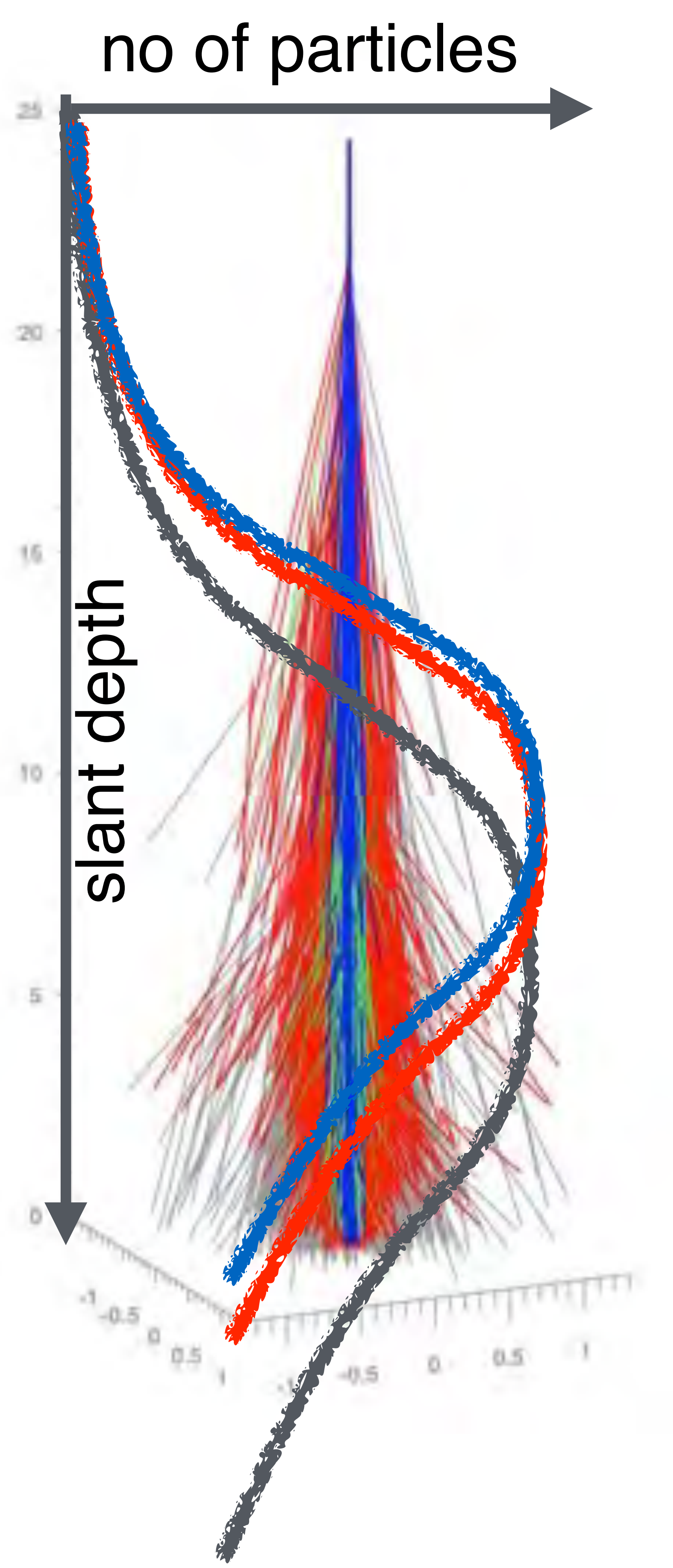
to disentangle GZK-suppression
from maximum energy scenario

Longitudinal Shower Development ➙ Primary Mass

KHK, Unger, APP 35 (2012)
EPOS 1.99 Simulations

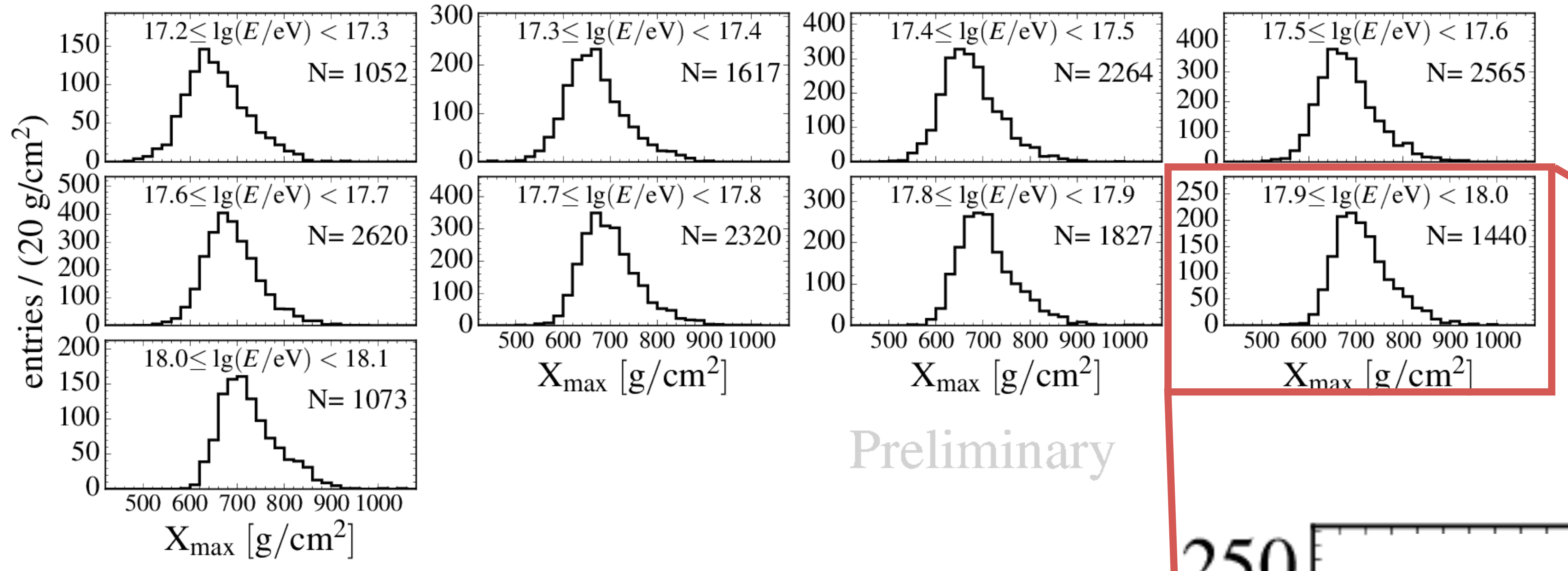
Example of a $3 \cdot 10^{19}$ eV EAS event in FD

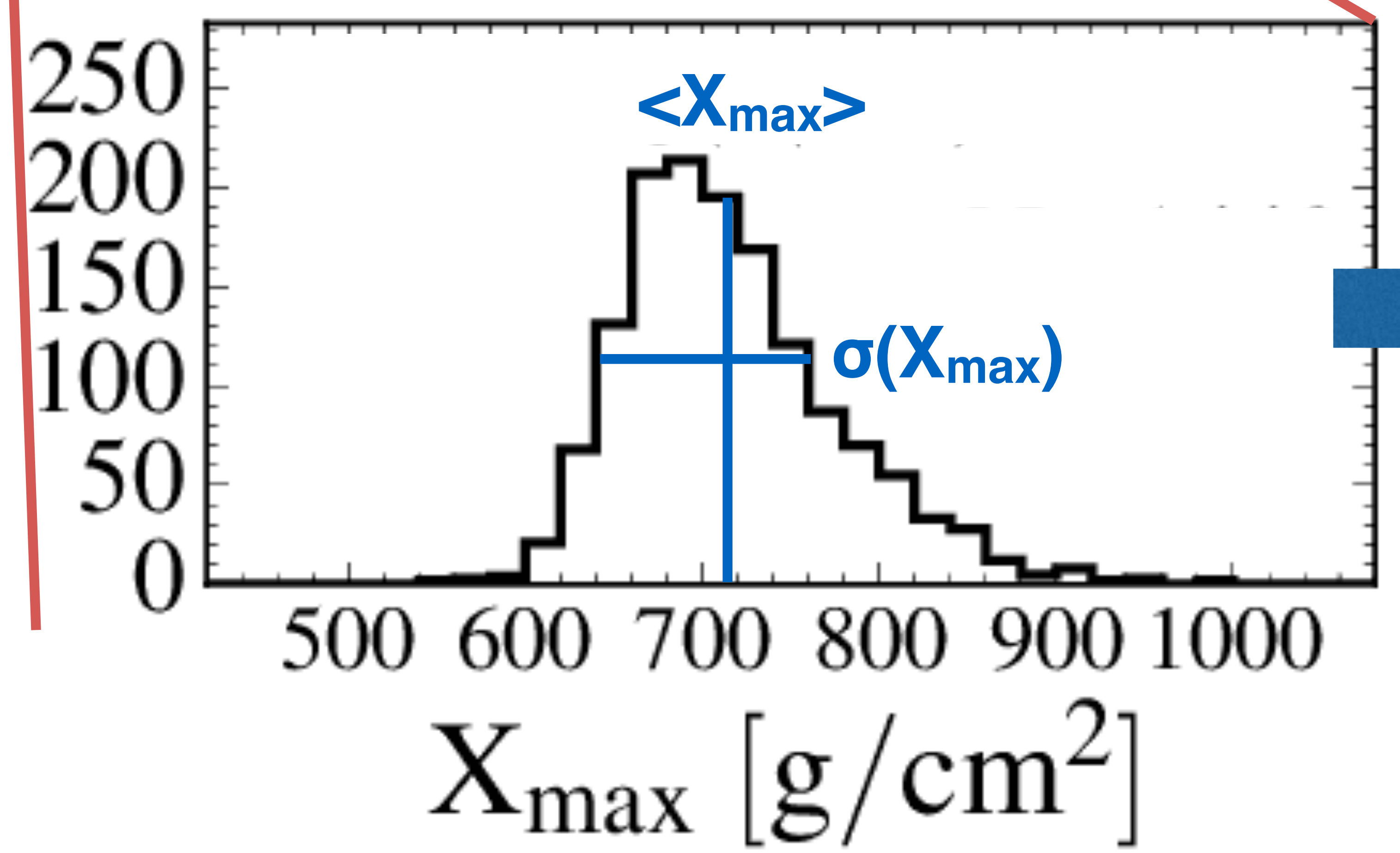


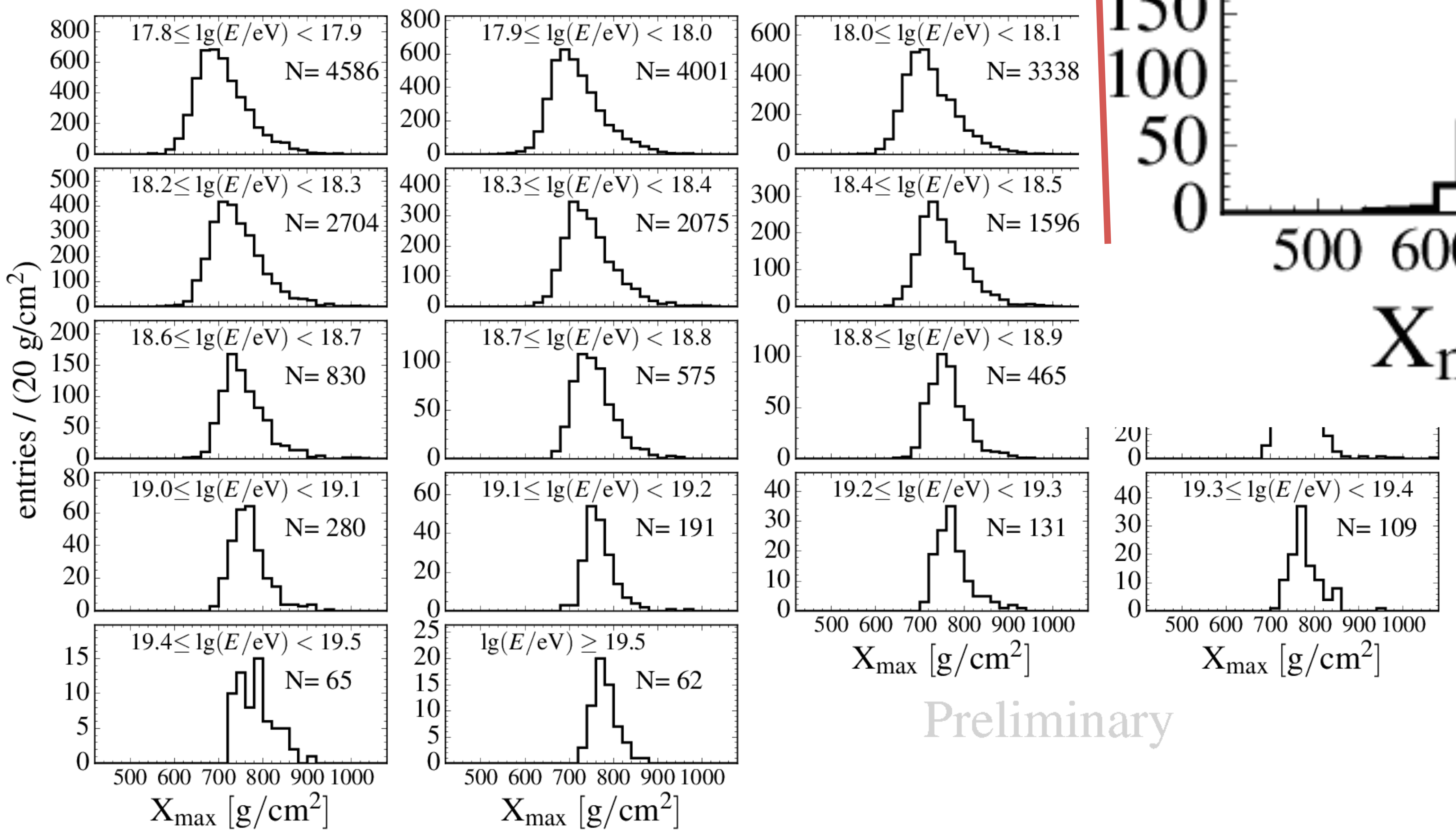


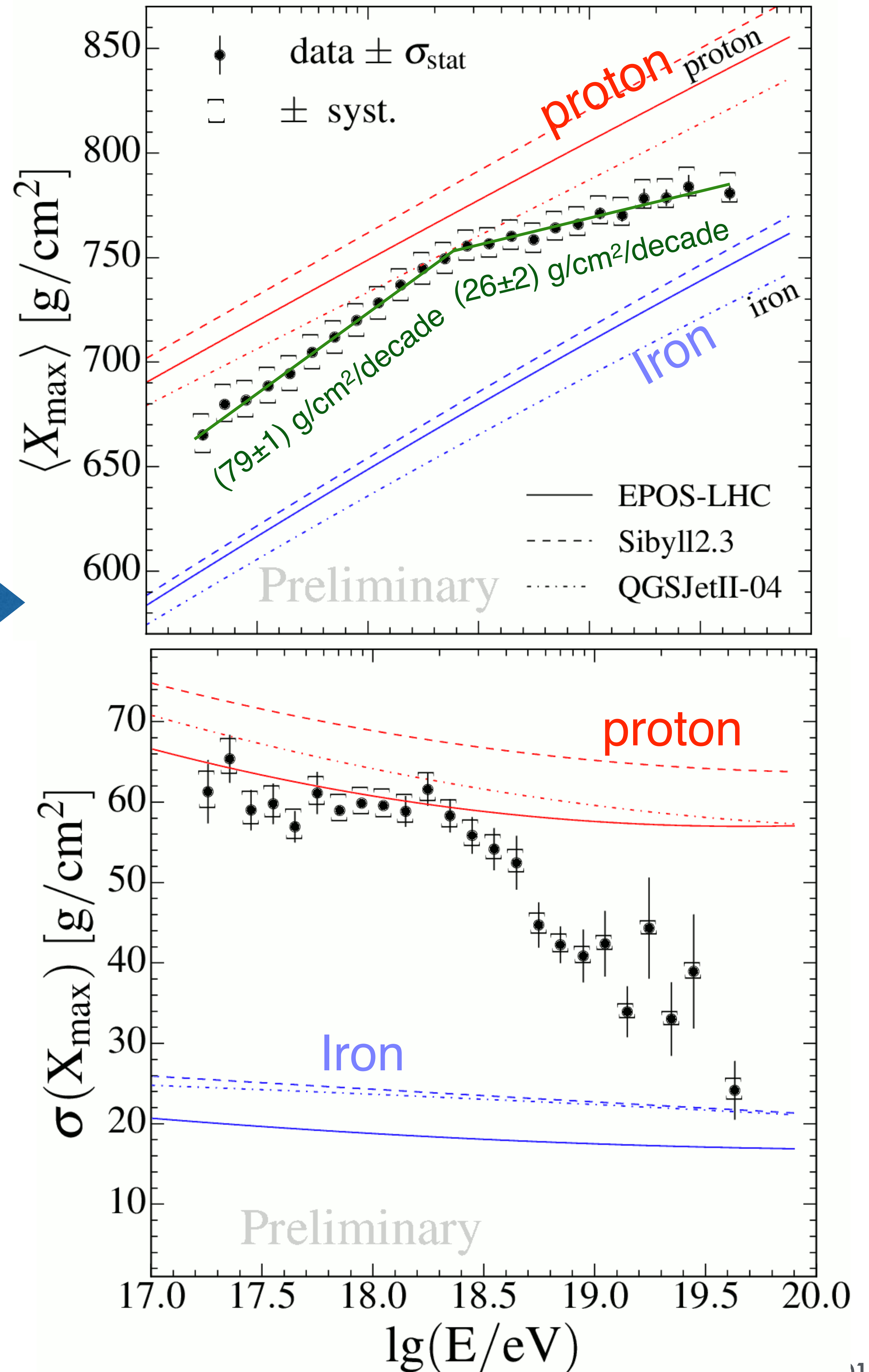
X_{max} Distributions

Bellido (Auger)
@ ICRC2017

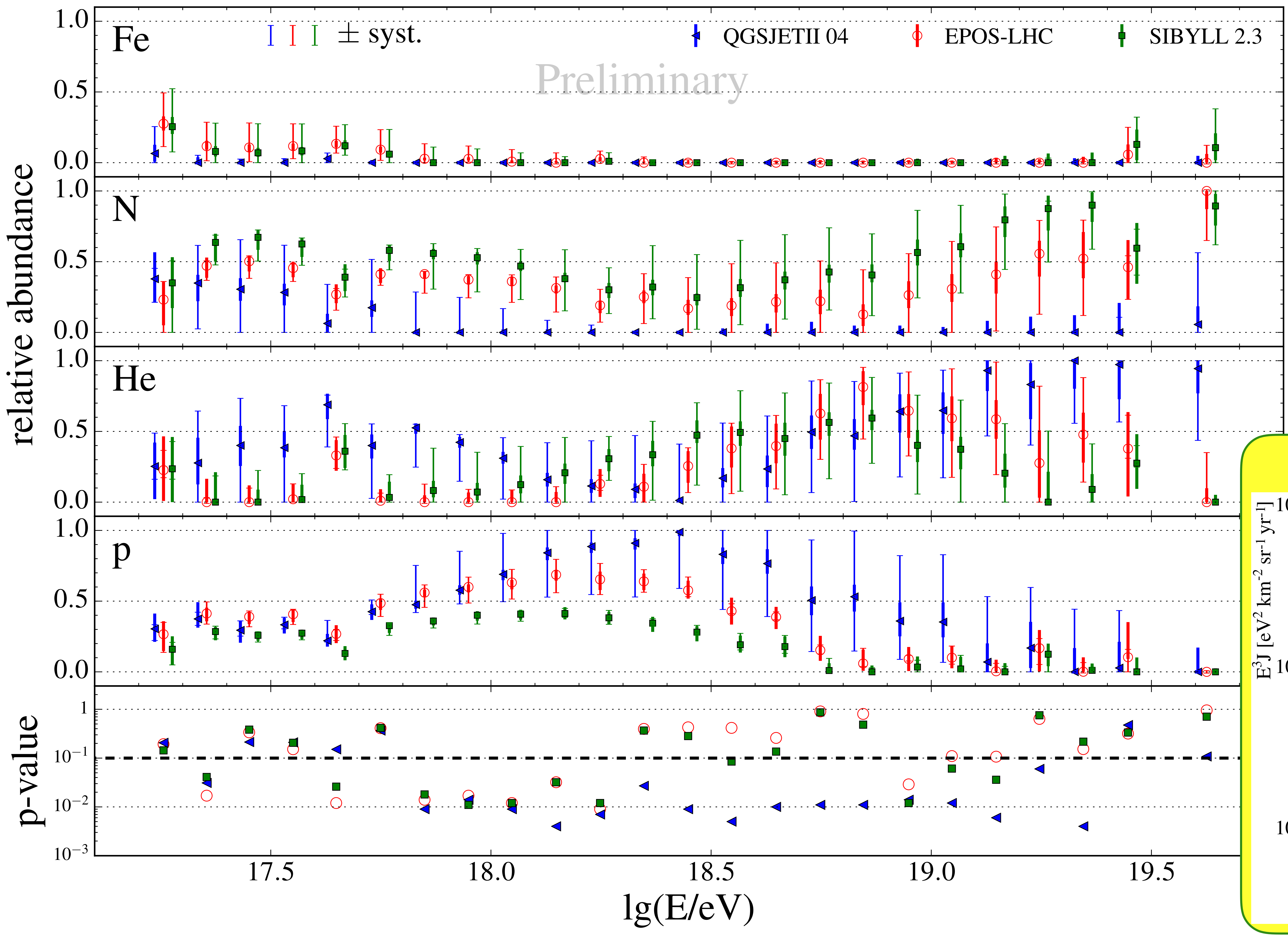








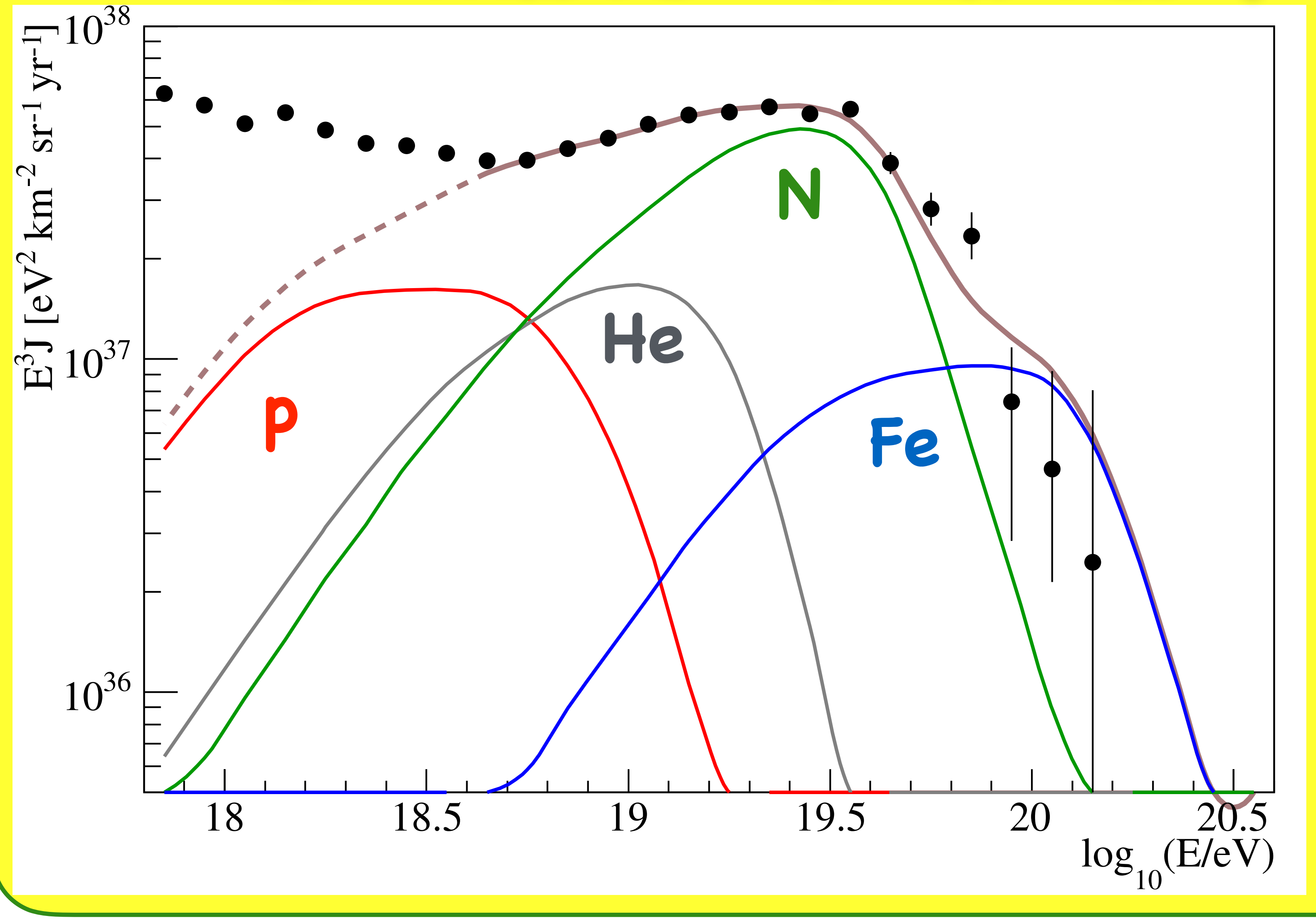
Mass Fractions



Bellido (Auger)
@ ICRC2017

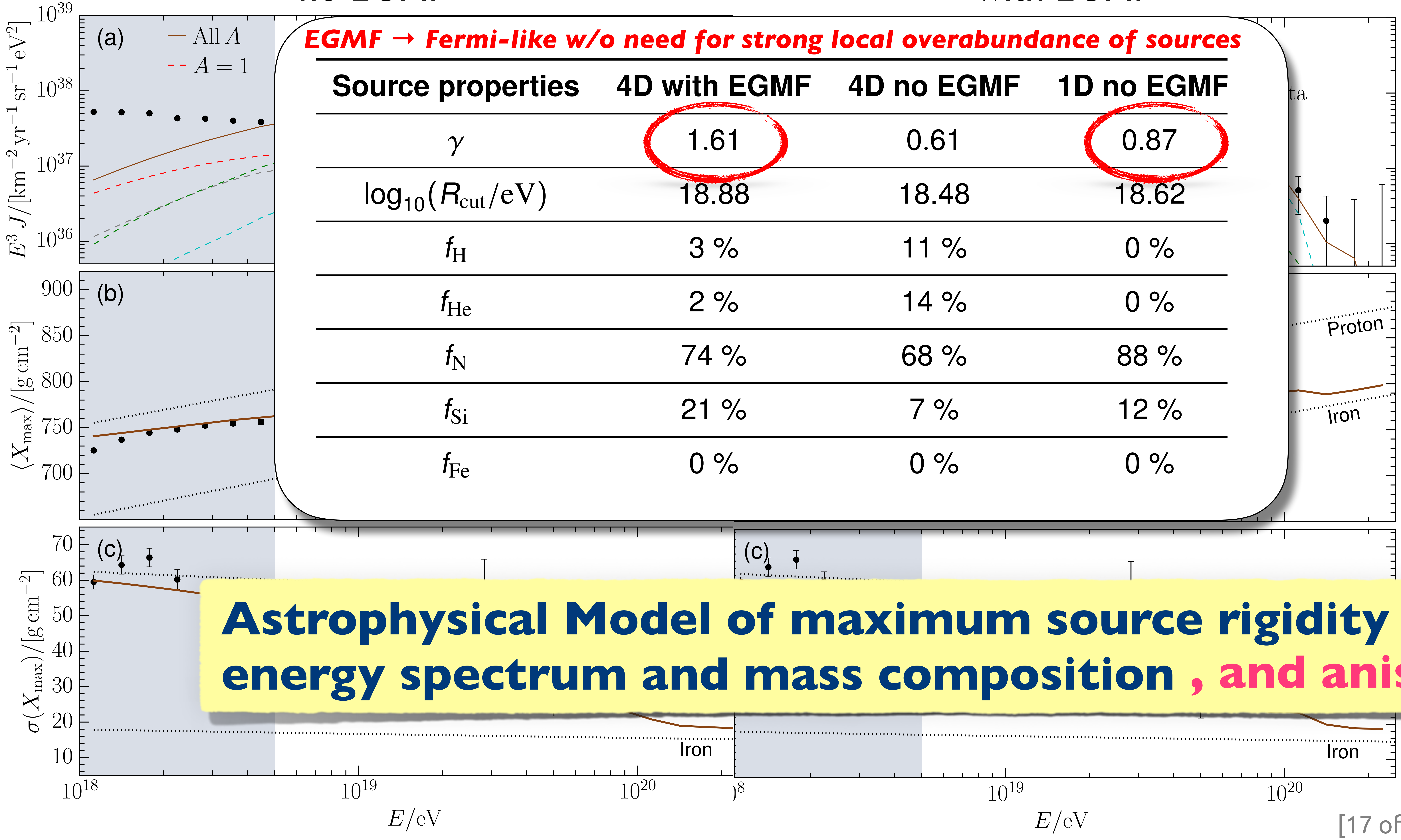
remember....

exhausted sources ?



Combined Fit of E-Spectr. and X_{max} Distr.

no EGMF — with EGMF



EGMF → Fermi-like w/o need for strong local overabundance of sources

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

rigidity-dependent cutoff at source: $E_{max} = R_{cut} \times Z$,

power law injection $E^{-\gamma}$,

mass fractions f_A.

propagation with CRPropa 3,

Gilmore12 EBL,

Dolag12 LSS

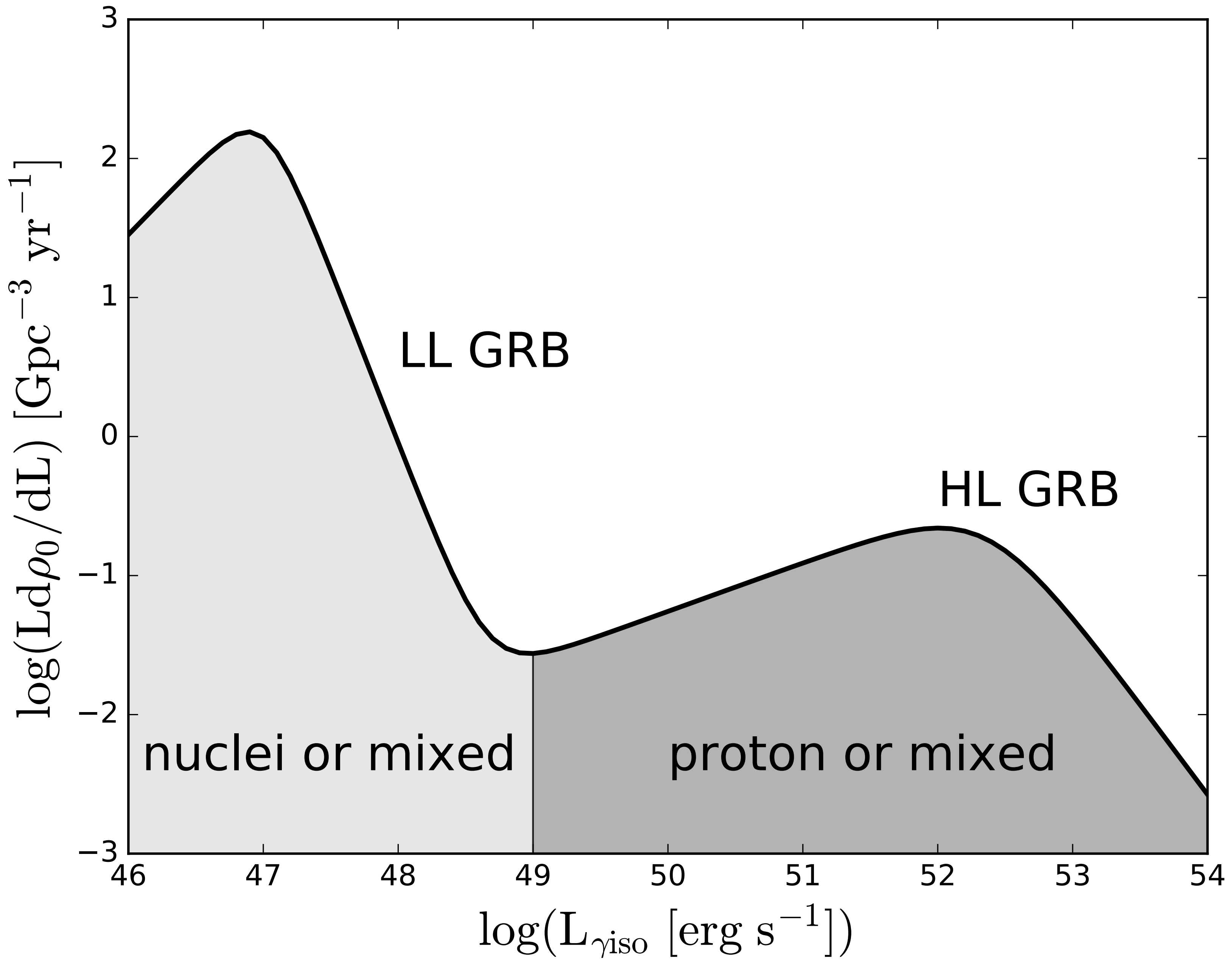
Astrophysical Model of maximum source rigidity describes energy spectrum and mass composition , and anisotropy!

Wittkowski (Auger) @ ICRC2017

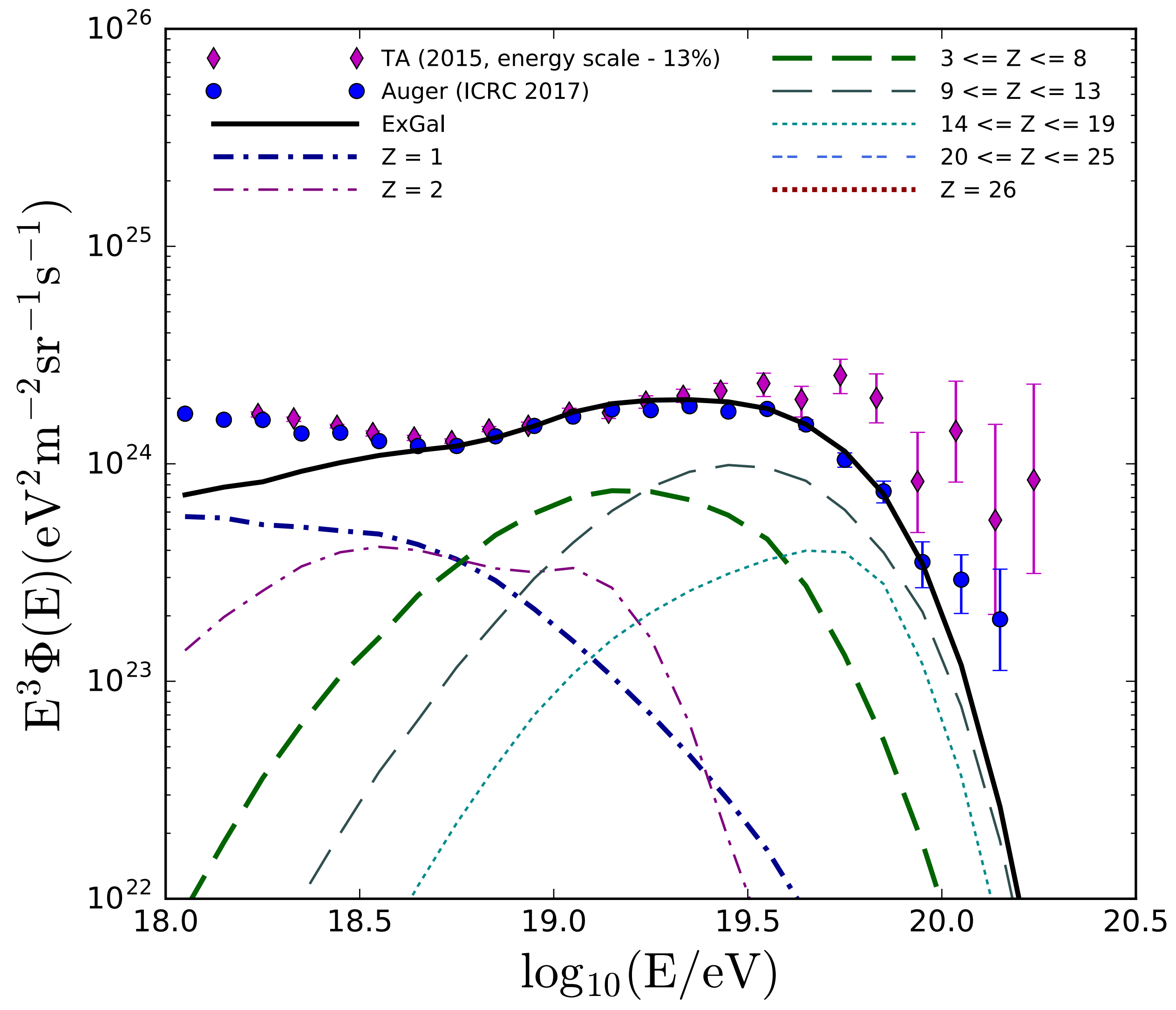
Models with specific source classes: LL/HL-GRBs

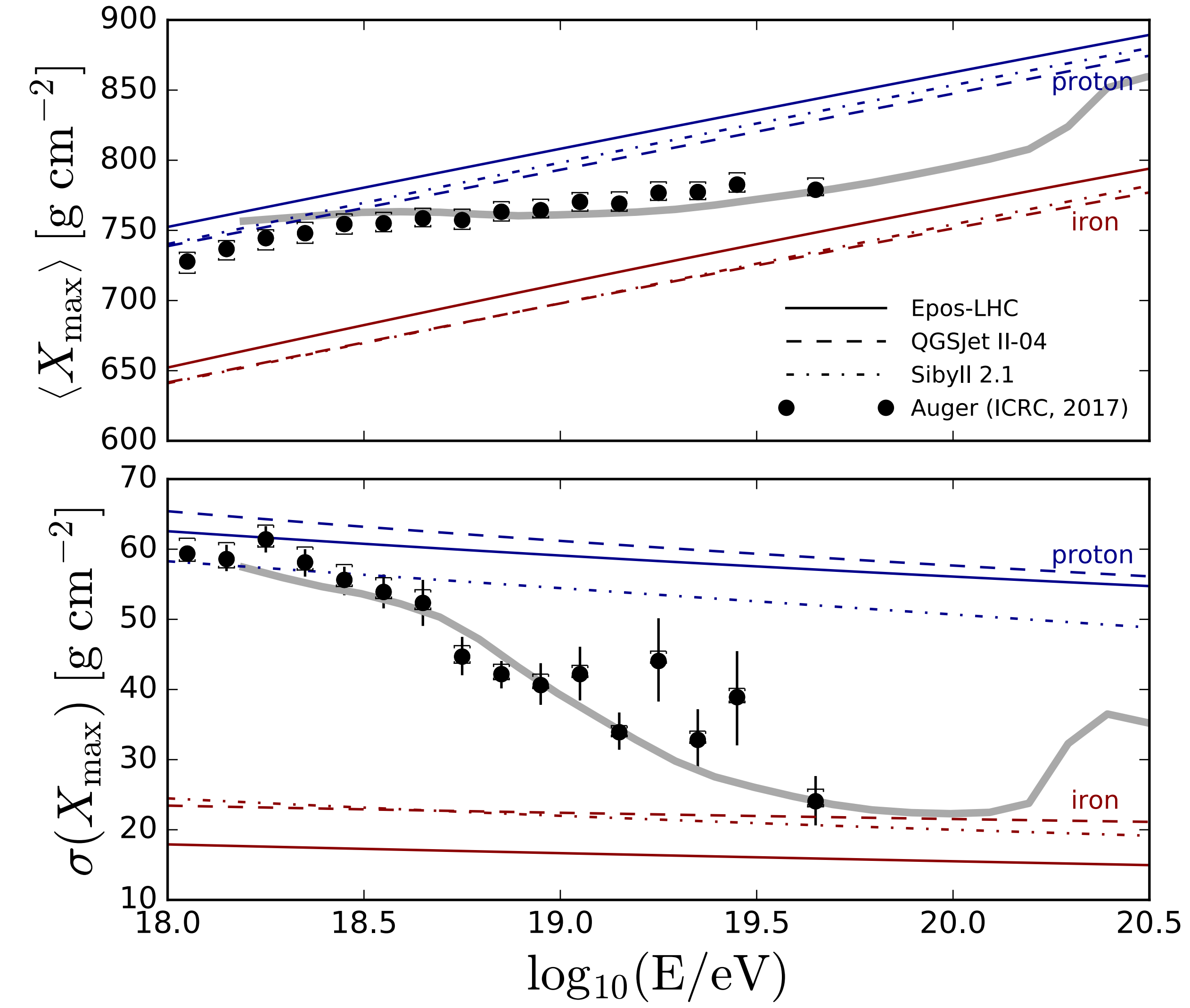
Zhang, Murase, et al.,
arXiv:1712.09984

Low and High Luminosity GRBs
as sources of UHECR

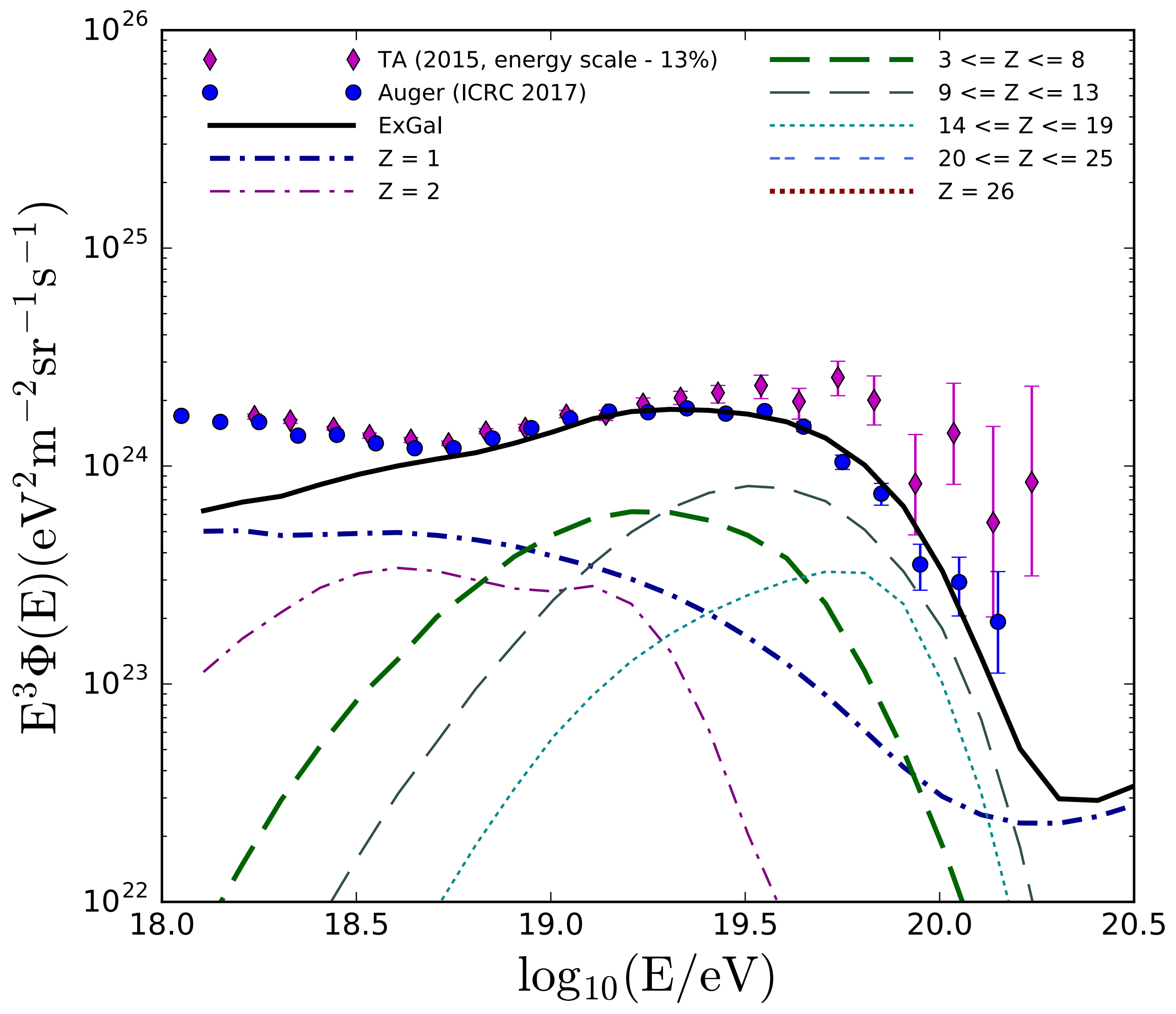


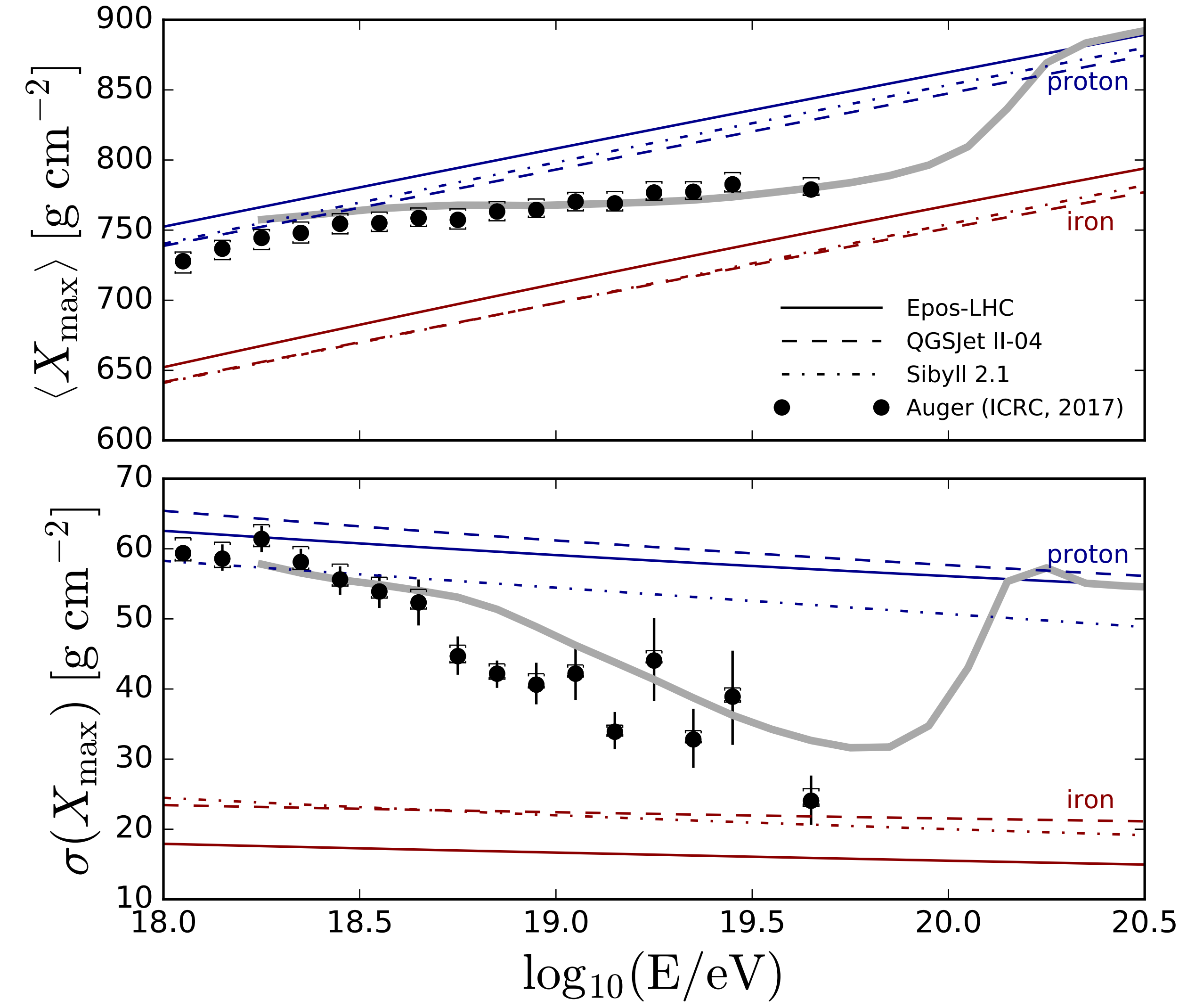
LL GRBs with Si-rich progenitor





LL GRBs + HL GRBs





Auger data and all these models suggest seeing exhausting sources

⇒ Strongly Suppressed Cosmogenic Neutrino Fluxes

Recall:

- If flux suppression above $5 \cdot 10^{19}$ eV is due to GZK-effect: expect cosmogenic neutrinos & photons

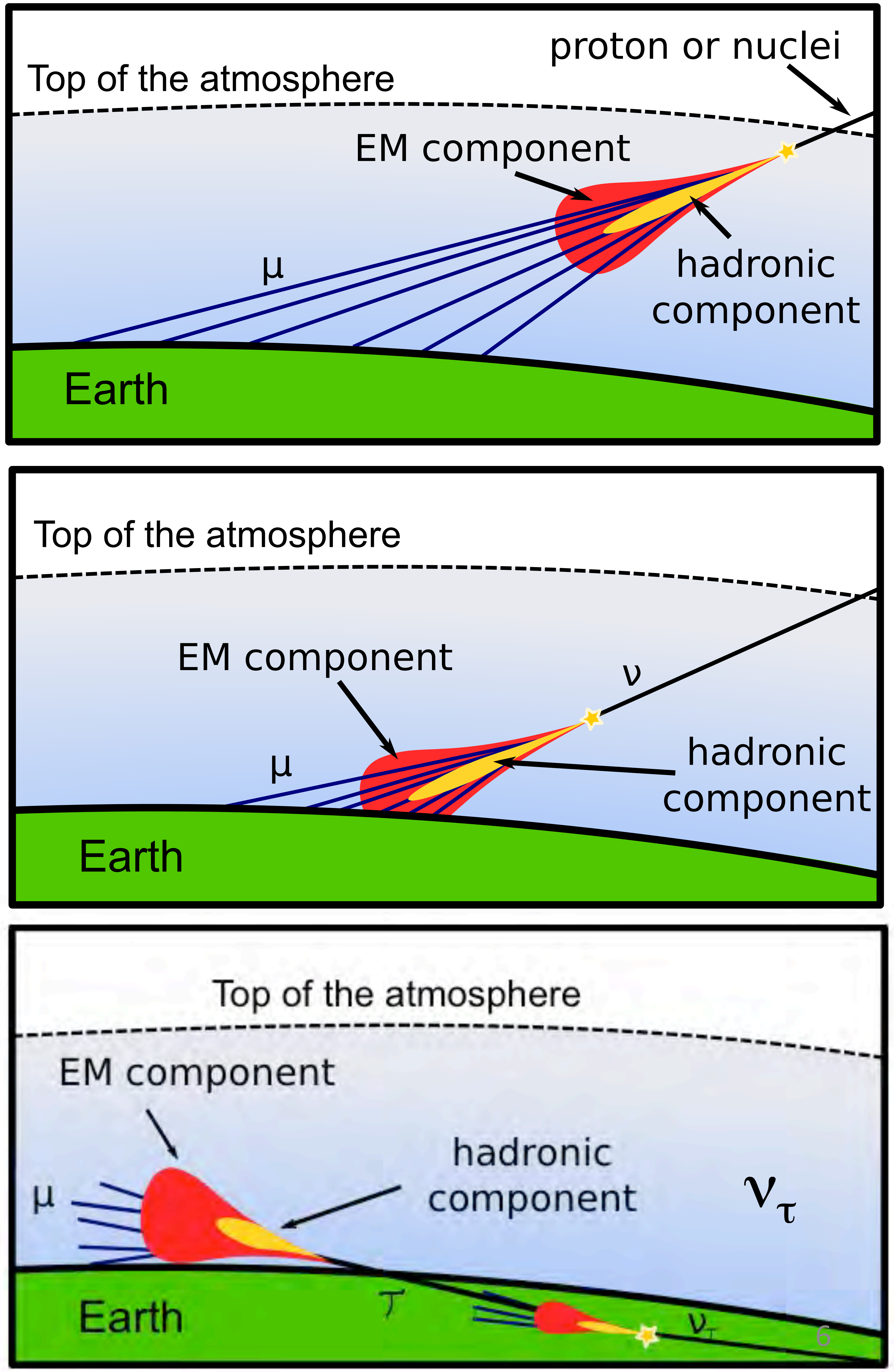
$$p + \gamma_{CMB} \rightarrow \Delta \rightarrow p + \pi^0 \rightarrow \gamma$$
$$\rightarrow n + \pi^+ \rightarrow \nu$$

smoking gun...

- If due to source exhaustion: neutrinos & photons strongly suppressed

Search for EeV Neutrinos in inclined showers

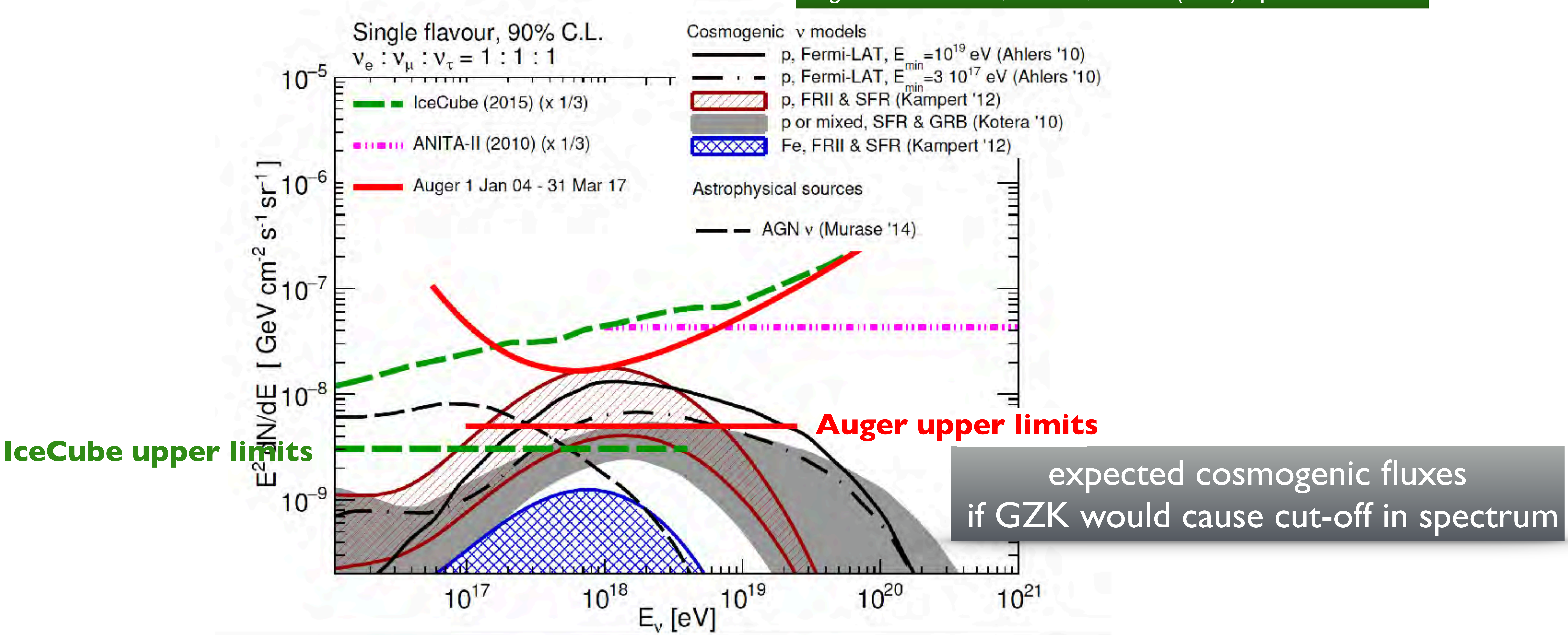
- Protons & nuclei initiate showers high in the atmosphere.
  - Shower front at ground:
    - mainly composed of muons
    - electromagnetic component absorbed in atmosphere.
- Neutrinos can initiate “deep” showers close to ground.
  - Shower front at ground: electromagnetic + muonic components



Searching for neutrinos ⇒ searching for inclined showers with electromagnetic component

EeV Neutrino Limits challenge GZK

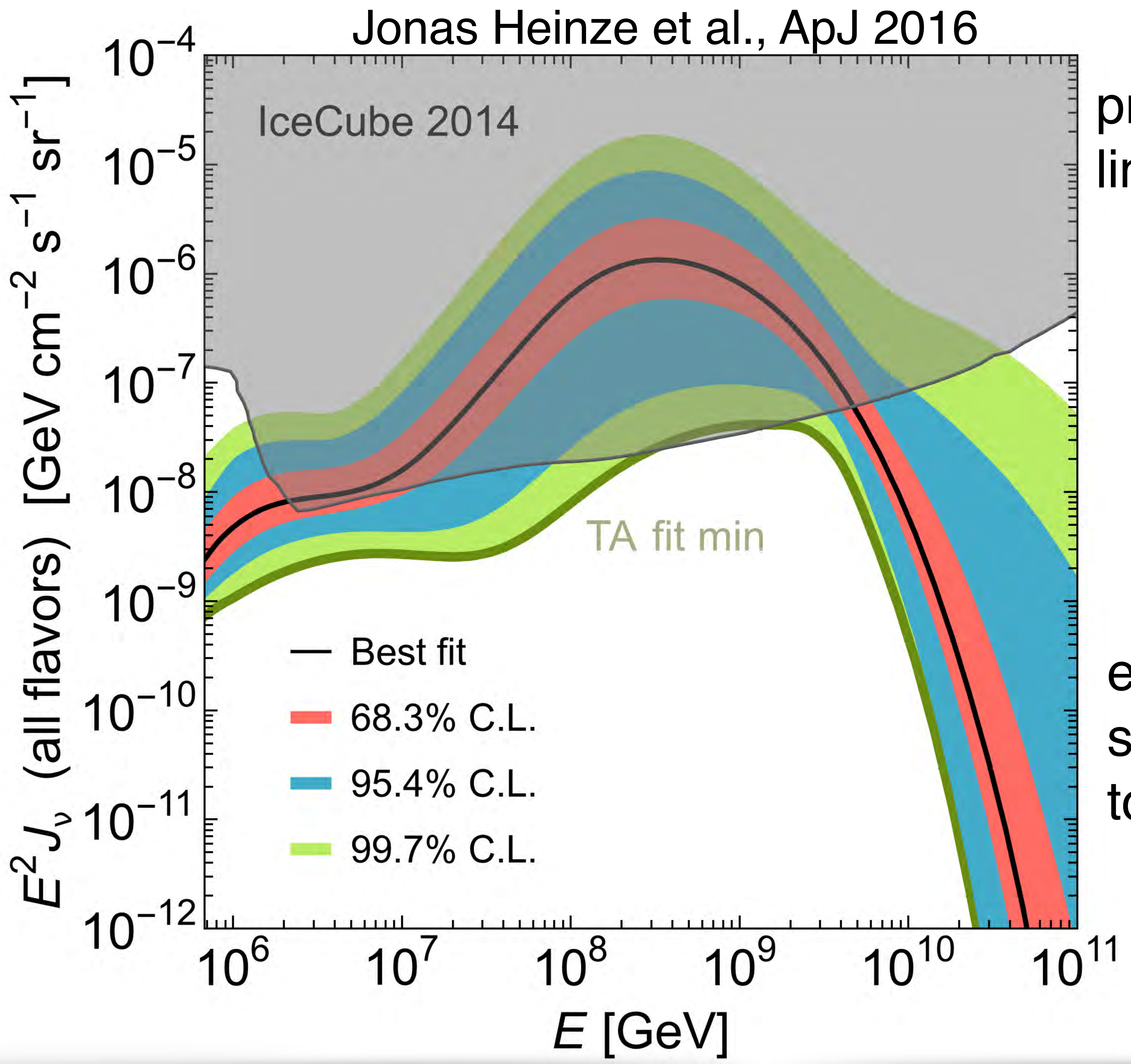
Auger Collaboration, PRD 91, 092008 (2015); update ICRC2017



Would have expected to see 1-7 GZK neutrinos (for different models), have seen none

Neutrino upper limits start to constrain cosmogenic neutrino fluxes of p-sources

EeV Neutrino Limits challenge GZK

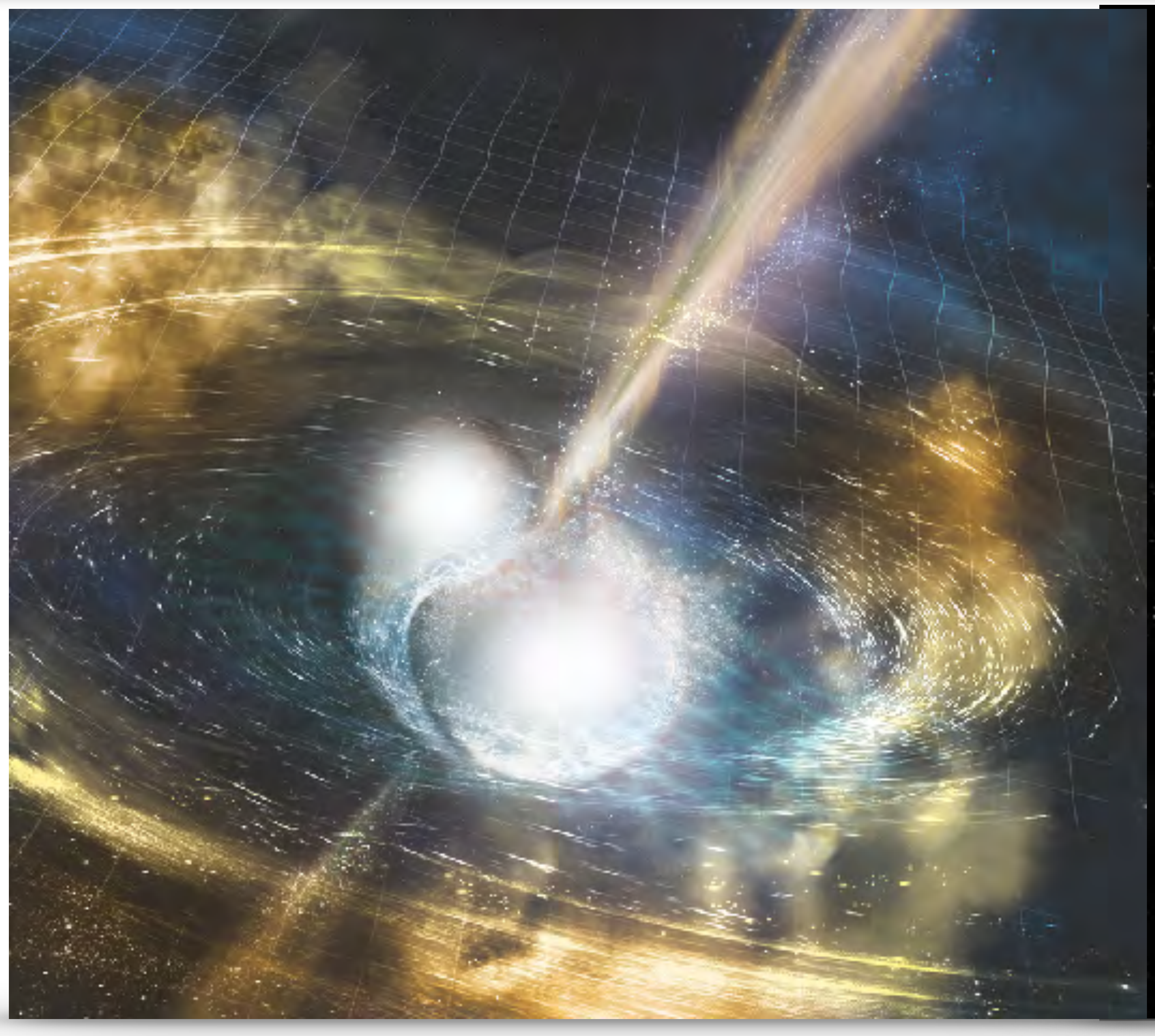


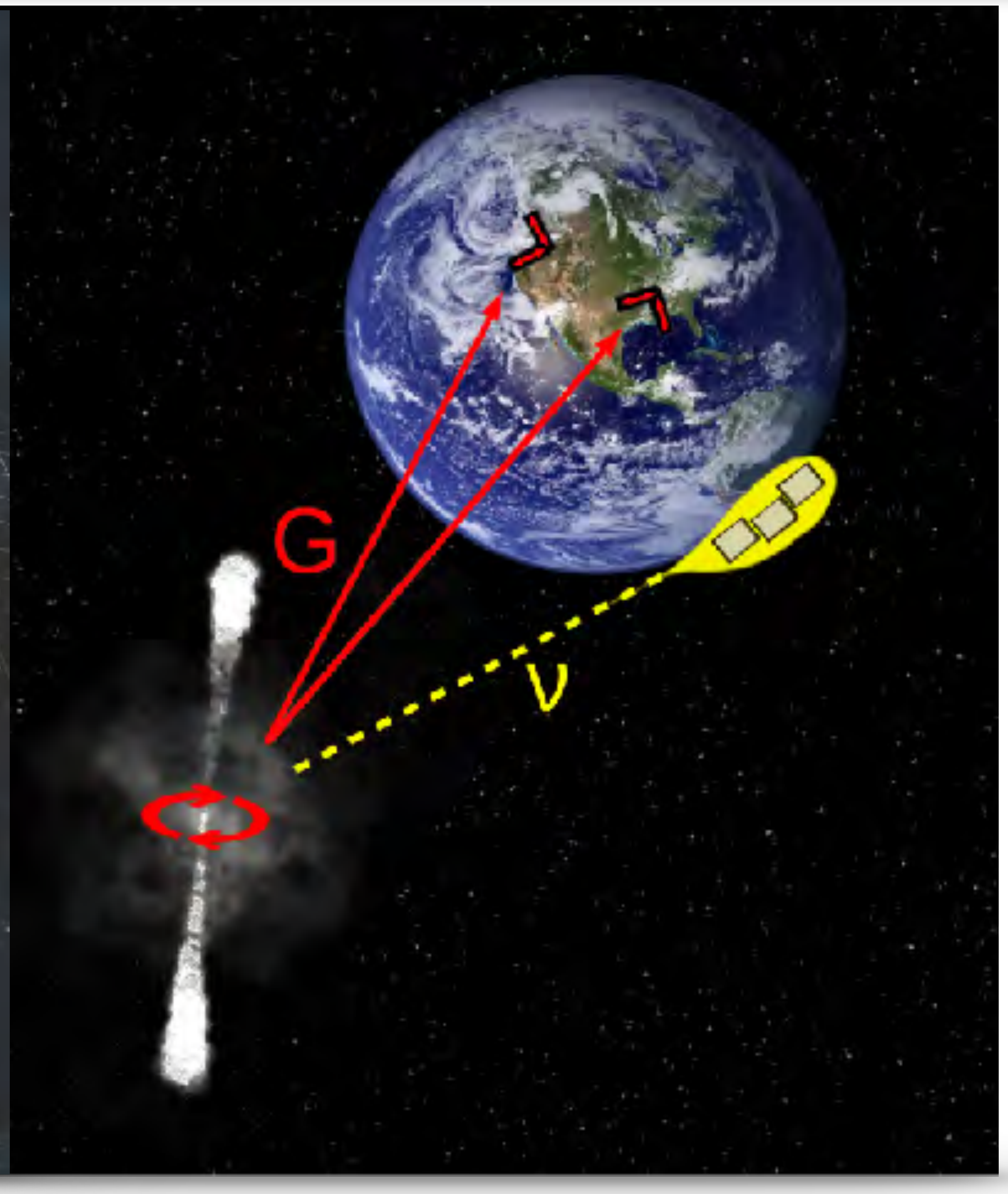
preliminary exclusion limits from IceCube

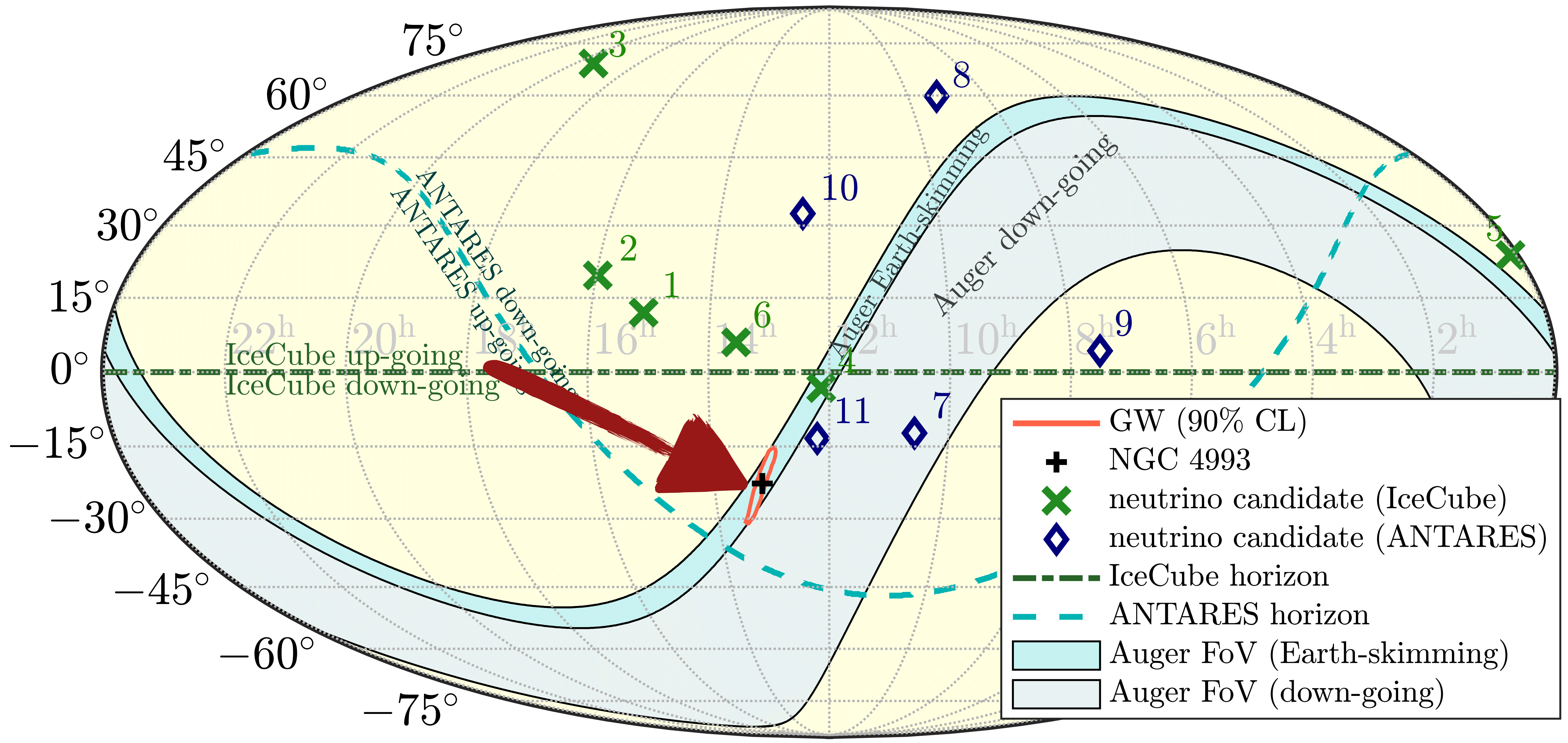
expected ν-fluxes if flux suppression of TA is due to GZK-effect

Pure proton with GZK suppression challenged by upper limits to neutrino fluxes

Neutrino Upper Limits for GW170817







The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20
https://doi.org/10.3847/2041-8213/aa91c9

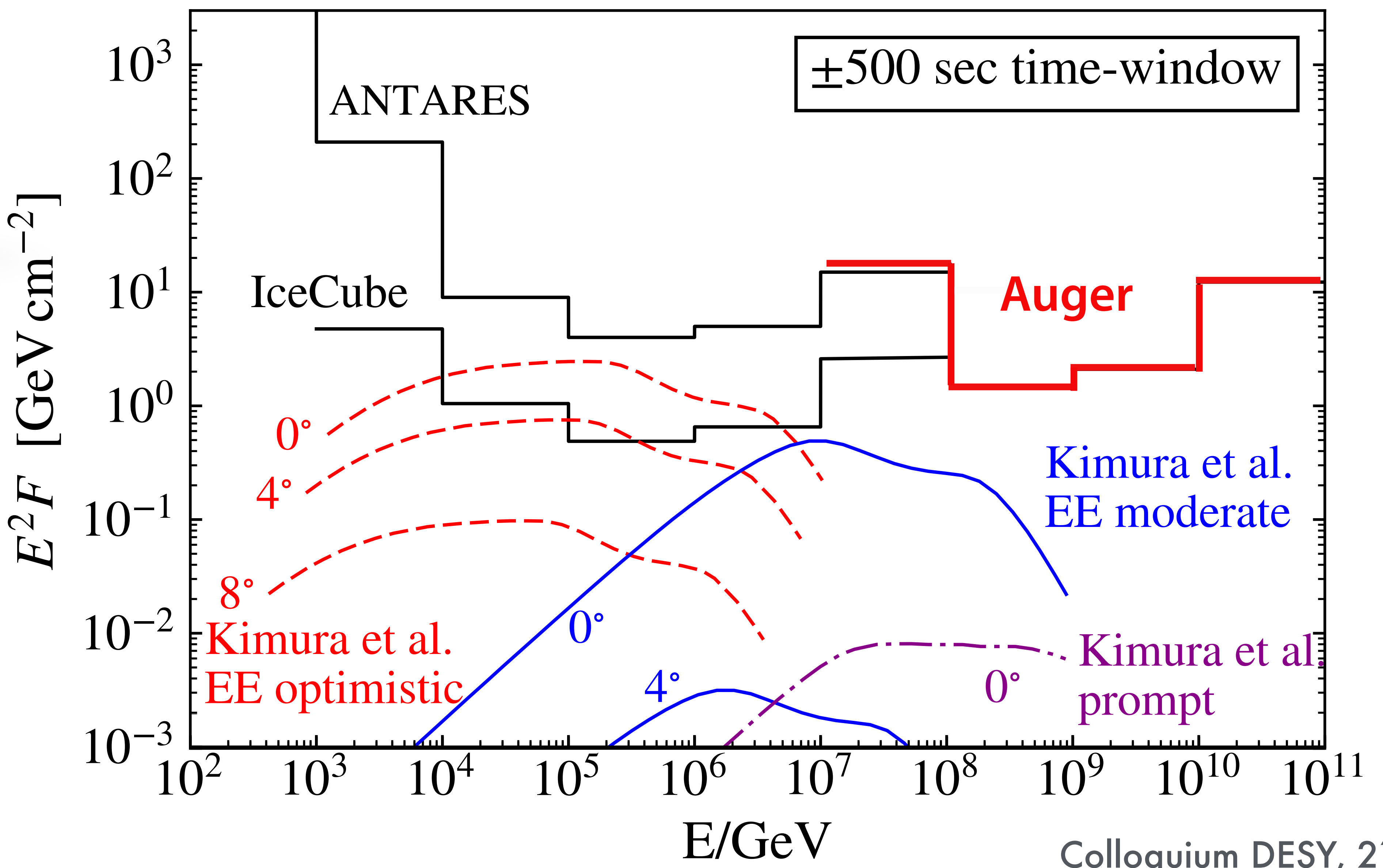
CrossMark

Multi-messenger Observations of a Binary Neutron Star Merger

Scientific Breakthrough of 2017:
Birth of Multimessenger Astronomy

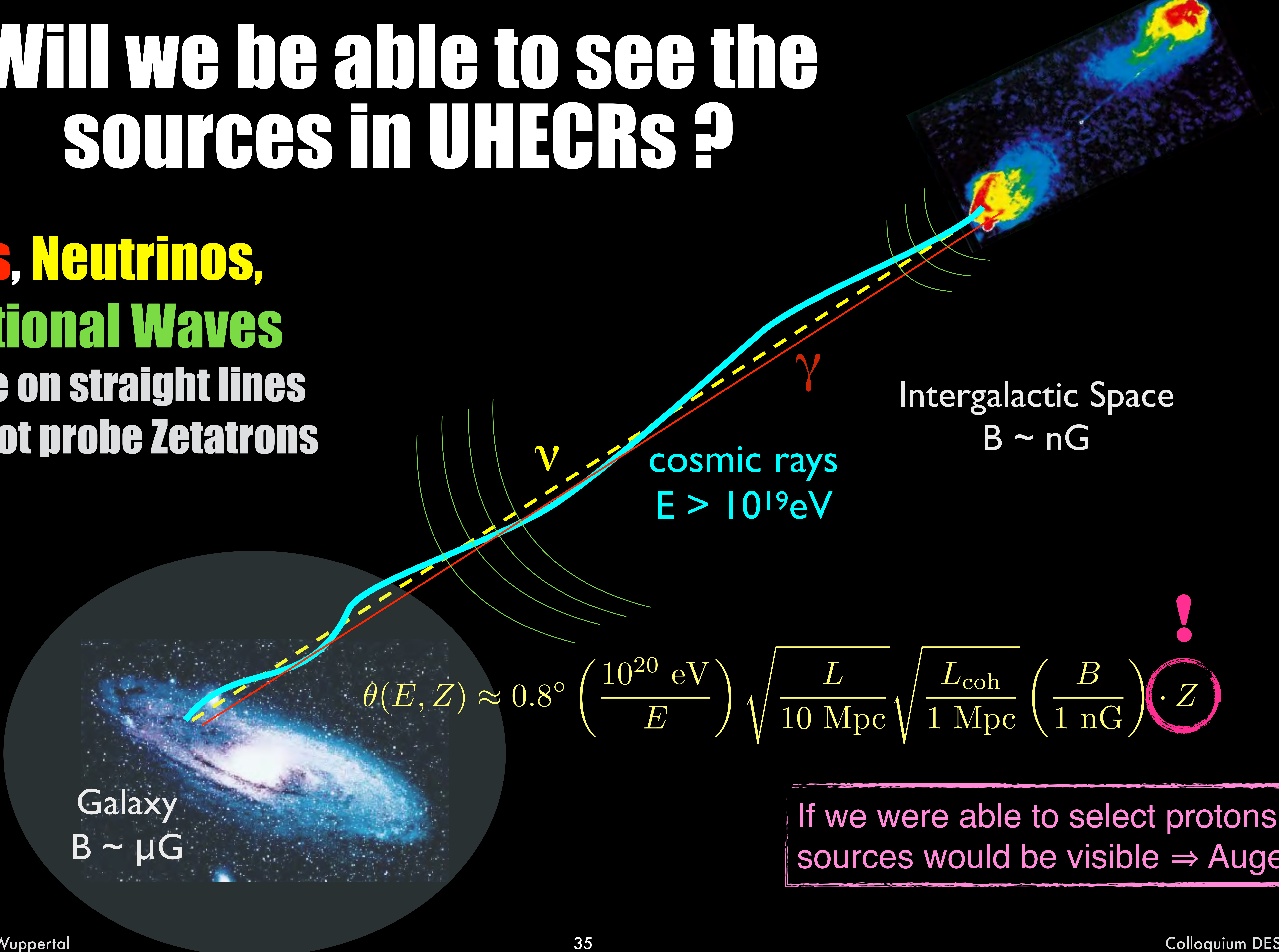
LIGO, ANTARES, IceCube, Auger,
The Astrophys. J. Lett. 850 (2017) L35

GW170817 Neutrino limits (fluence per flavor: $\nu_x + \bar{\nu}_x$)



Will we be able to see the sources in UHECRs ?

Photons, Neutrinos, Gravitational Waves
propagate on straight lines but may not probe Zetatrons



$$\theta(E,Z) \approx 0.8^\circ \left(\frac{10^{20}\ \mathrm{eV}}{E}\right)\sqrt{\frac{L}{10\ \mathrm{Mpc}}}\sqrt{\frac{L_{\mathrm{coh}}}{1\ \mathrm{Mpc}}}\left(\frac{B}{1\ \mathrm{nG}}\right)\cdot Z$$

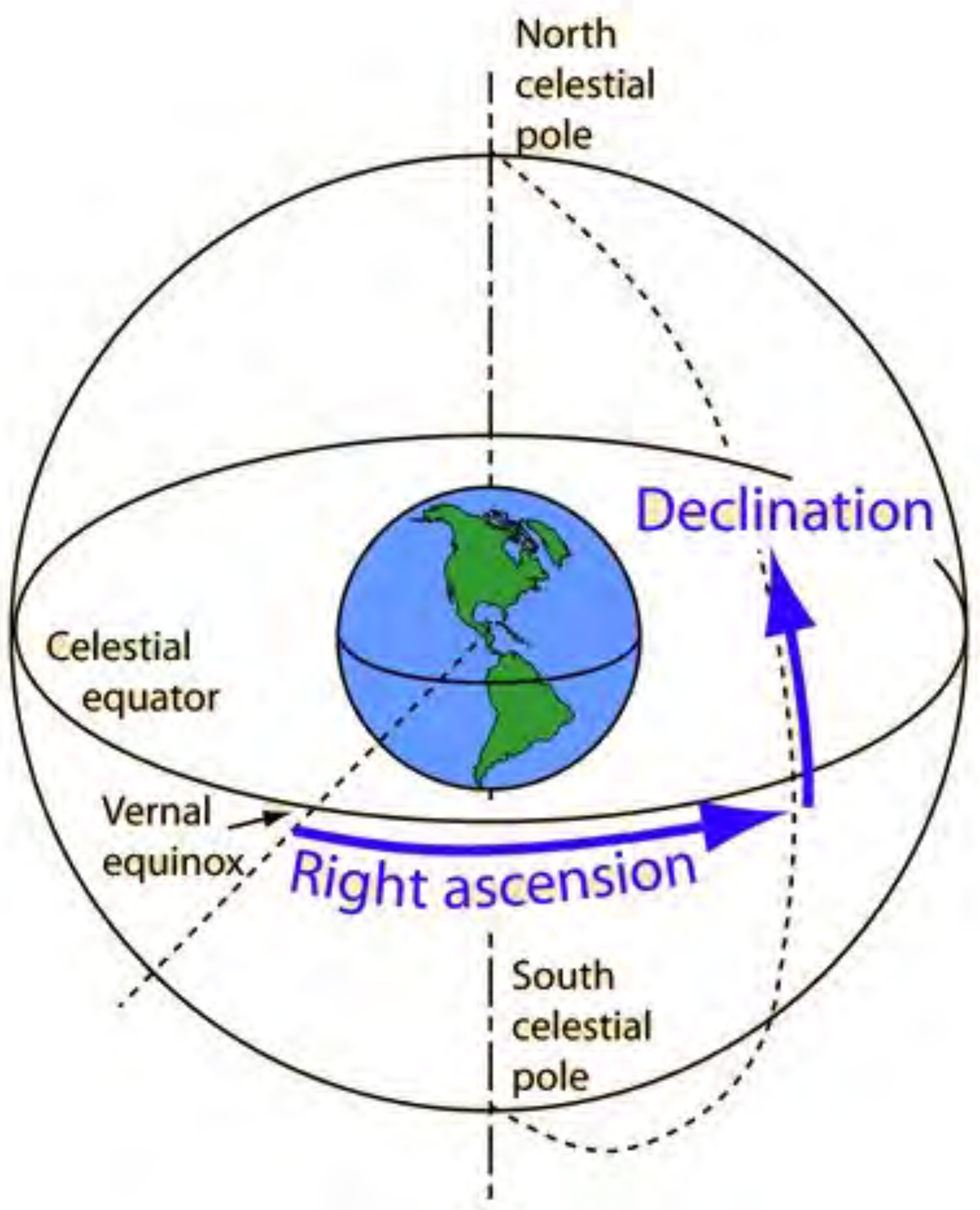
If we were able to select protons, sources would be visible ⇒ AugerPrime

Rayleigh Analysis in Right Ascension α

Fourier coefficients: $a_\alpha = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \cos\alpha_i \; ; \; b_\alpha = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \sin\alpha_i \; ; \; \mathcal{N} = \sum_{i=1}^{N} w_i$

weights w_i account for small variations in coverage and tilt of the array

Auger Collaboration, Science 357 (2017) 1266

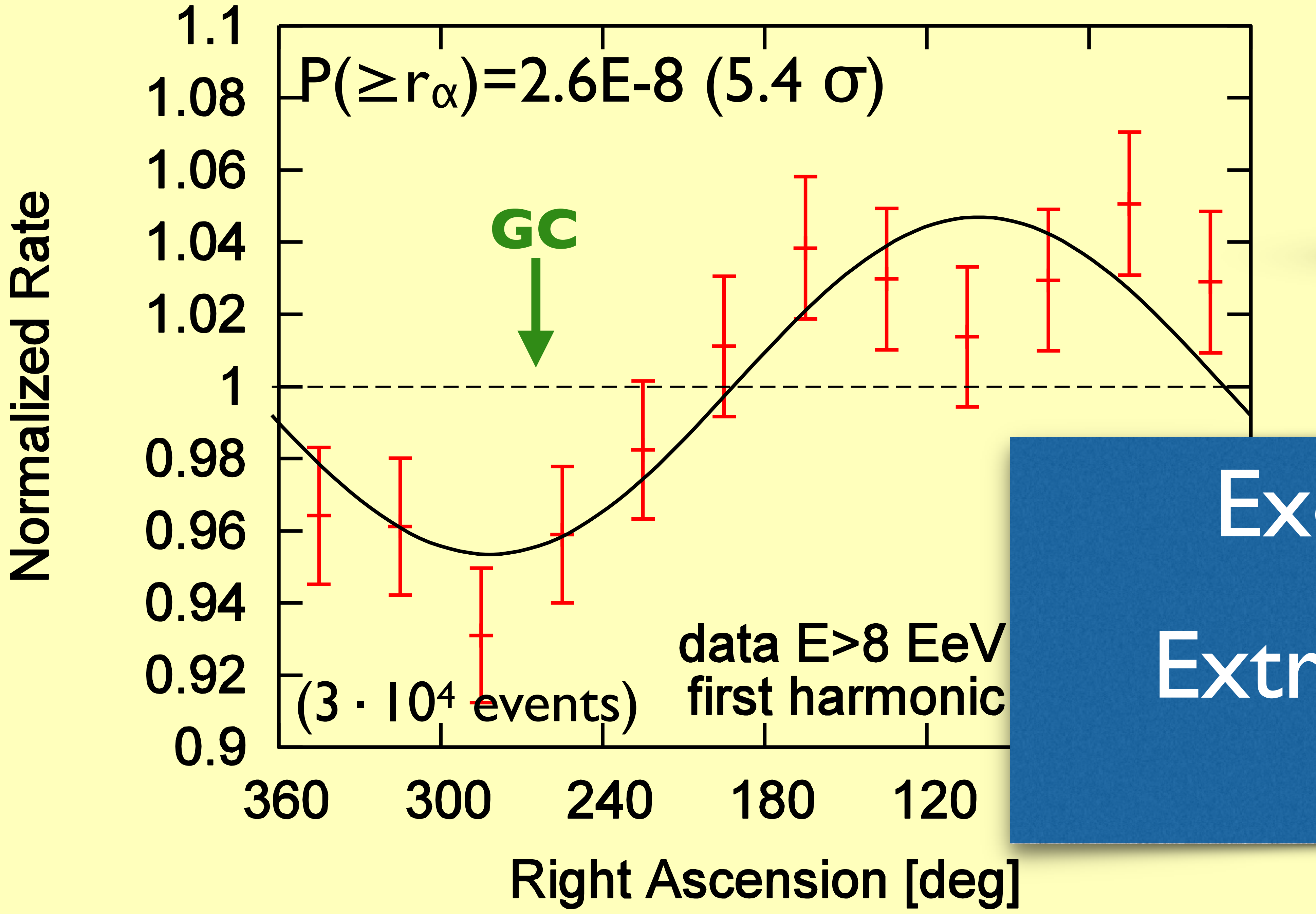


Data compatible with isotropy for 4 ≤ E ≤ 8 EeV

E > 8 EeV

$r_\alpha = \sqrt{a_\alpha^2 + b_\alpha^2}$ amplitude $r_\alpha = 0.047 \pm 0.007$

$\tan\varphi_\alpha = \frac{b_\alpha}{a_\alpha}$ phase $\varphi_\alpha = 100° \pm 10°$



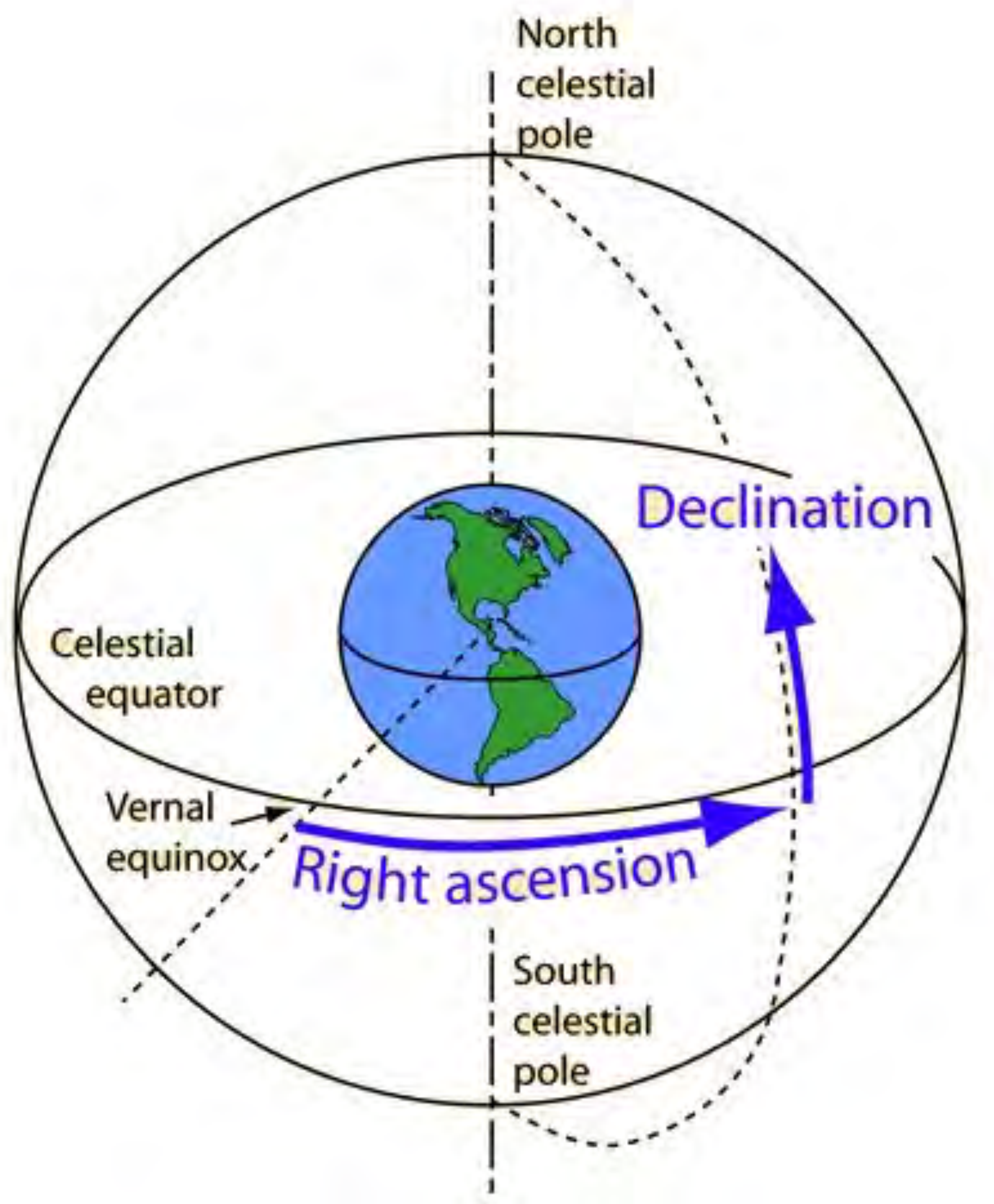
Excess direction ⇒

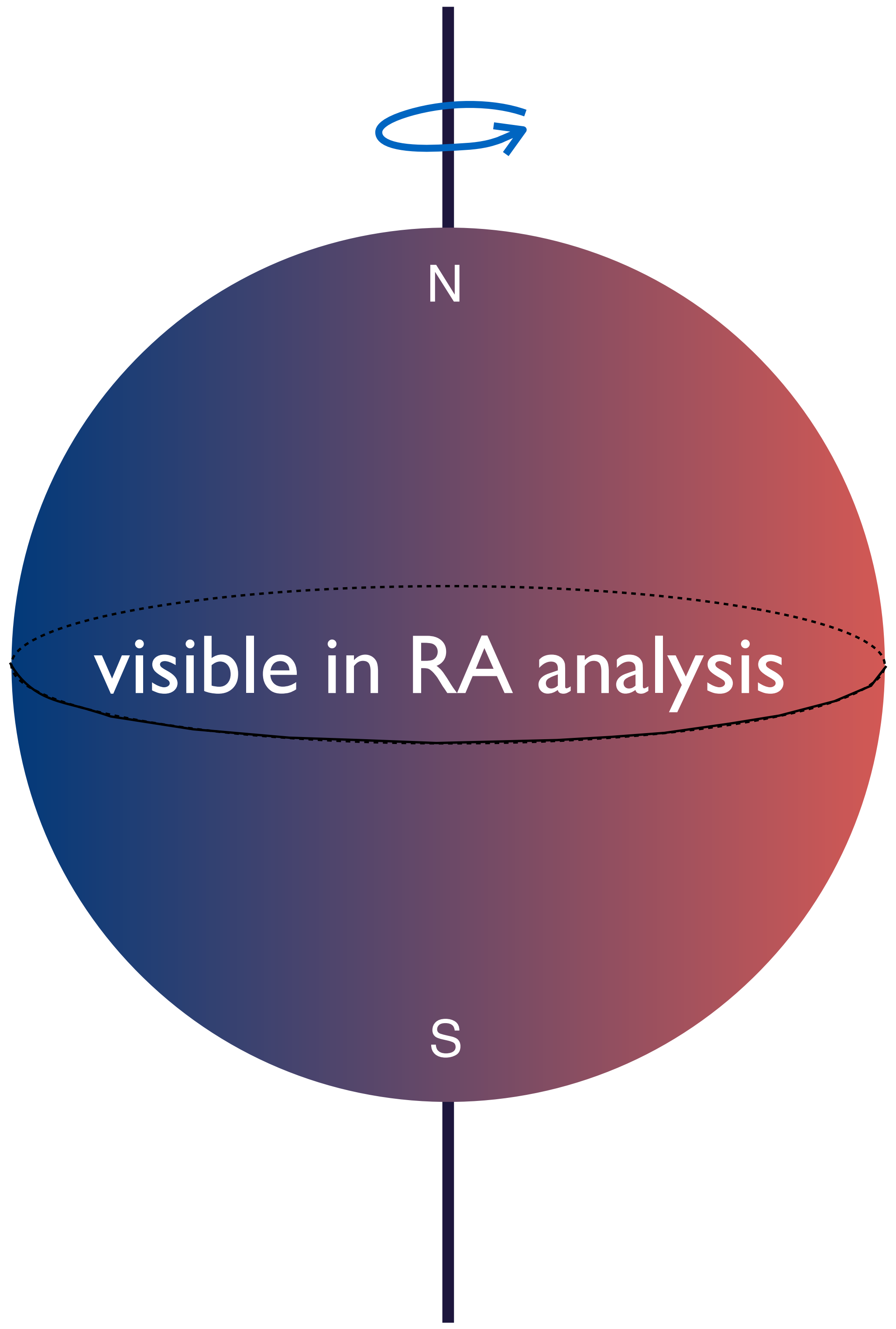
Extragalactic Origin of UHECR

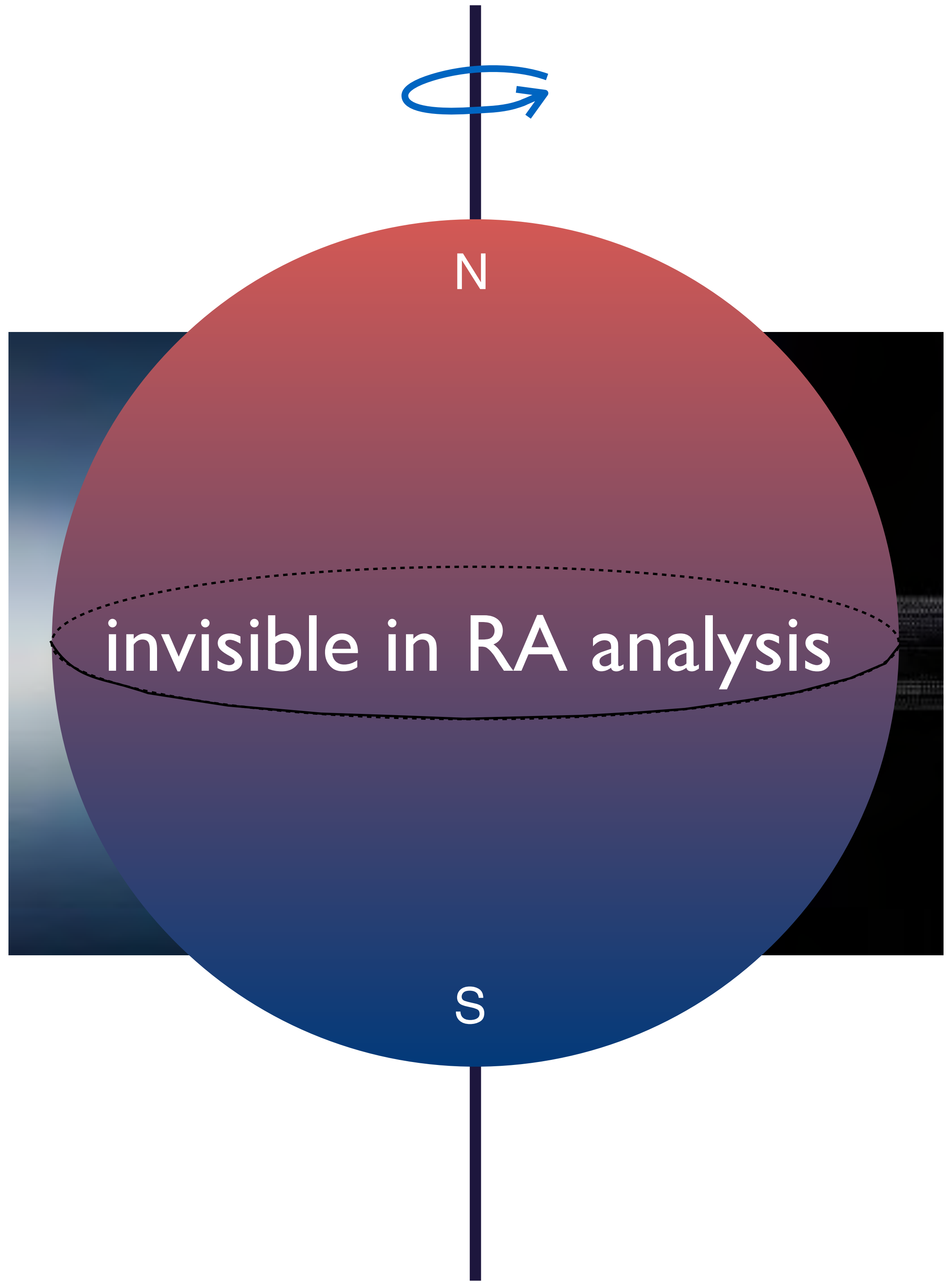
Reconstruction of 3-dim Dipole

Fourier coefficients: $$a_\alpha = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \cos\alpha_i \;\; ; \;\; b_\alpha = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \sin\alpha_i \;\; ; \;\; \mathcal{N} = \sum_{i=1}^{N} w_i$$

weights w_i account for small variations in coverage and tilt of the array



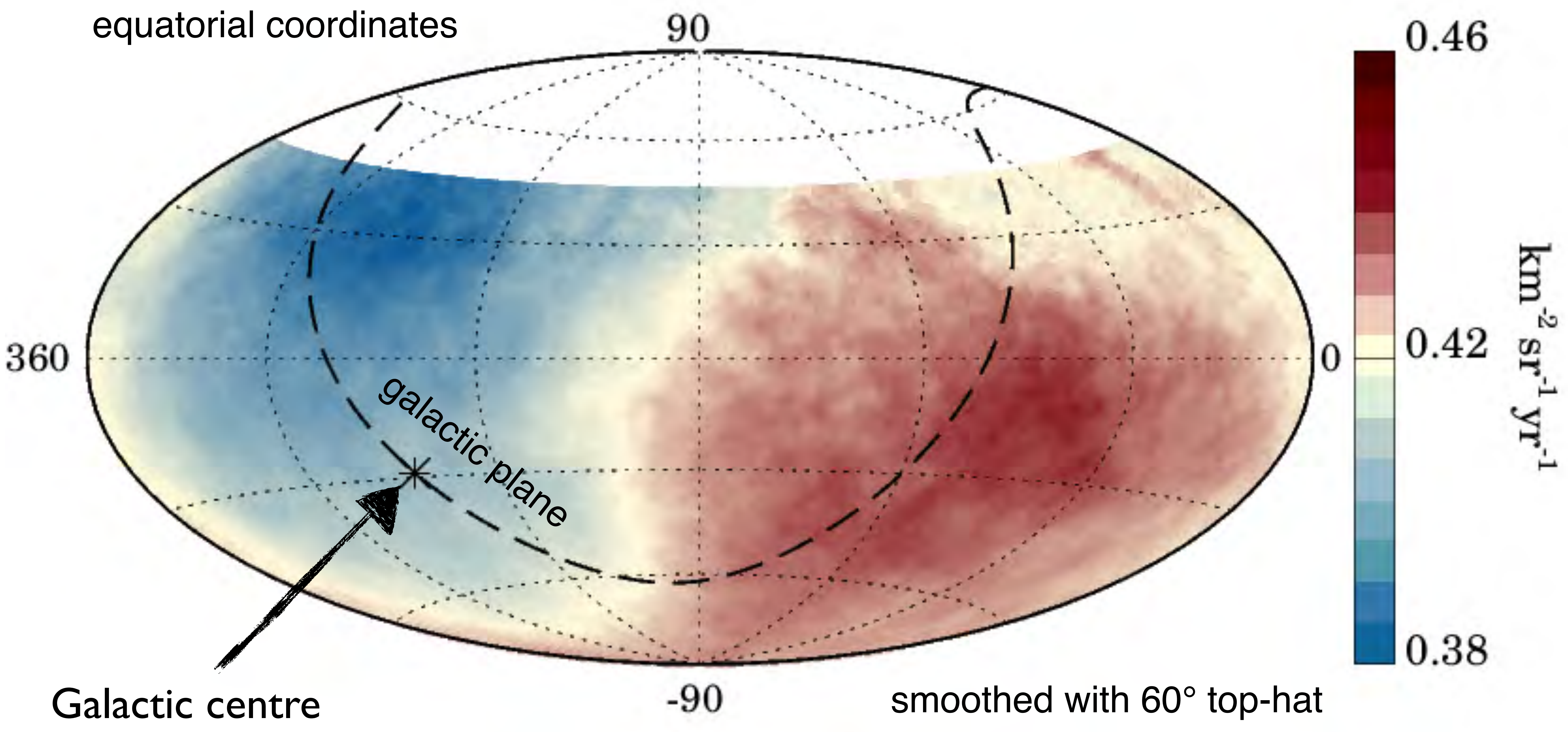




➠ combine harmonic analysis in RA with harmonic in North-South

Flux Map above 8 EeV

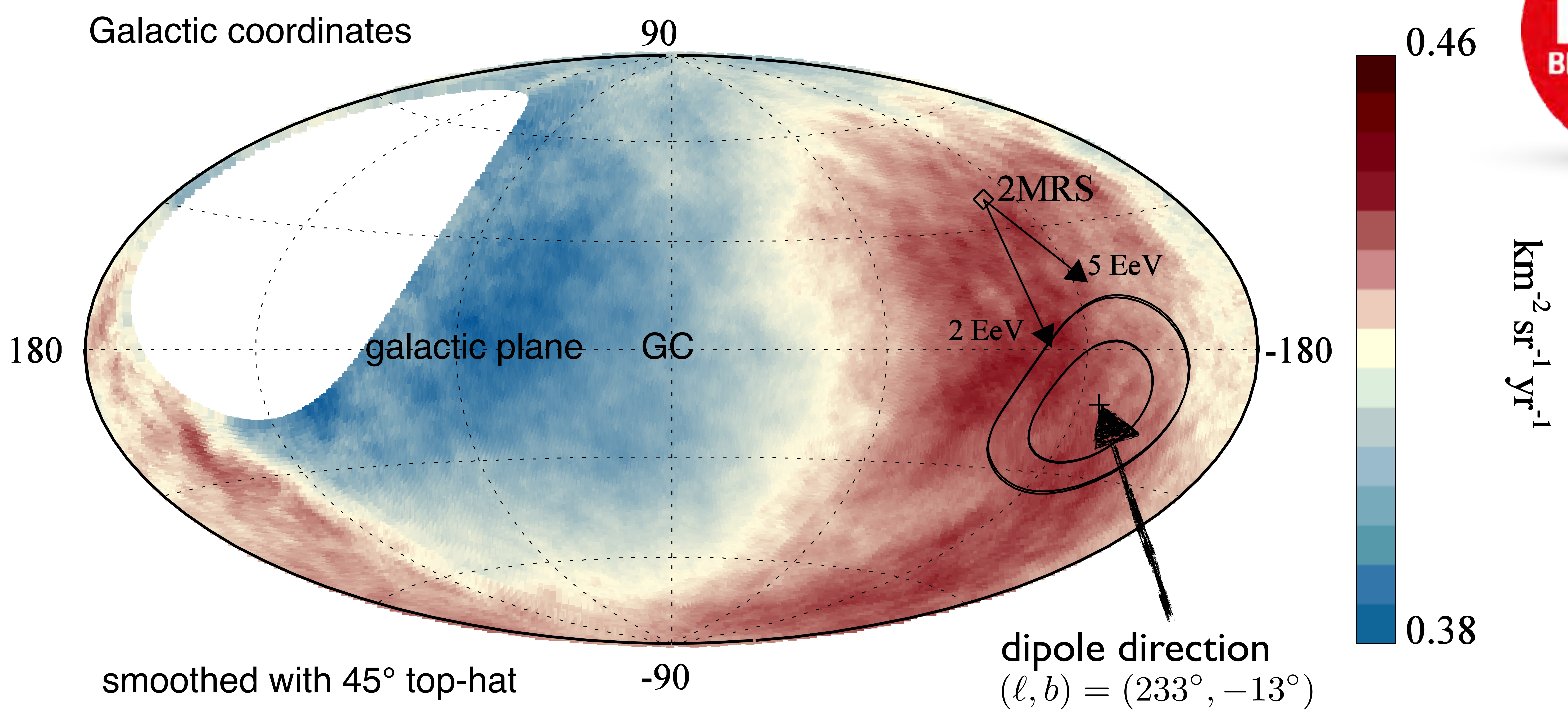
Auger Collaboration, Science 357 (2017) 1266



$$\mathcal{A} = 6.5^{+1.3}_{-0.9}\,\% \;\; ; \;\; \alpha_d = (100 \pm 10)^\circ \;\; ; \;\; \delta_d = (-24^{+12}_{-13})^\circ$$

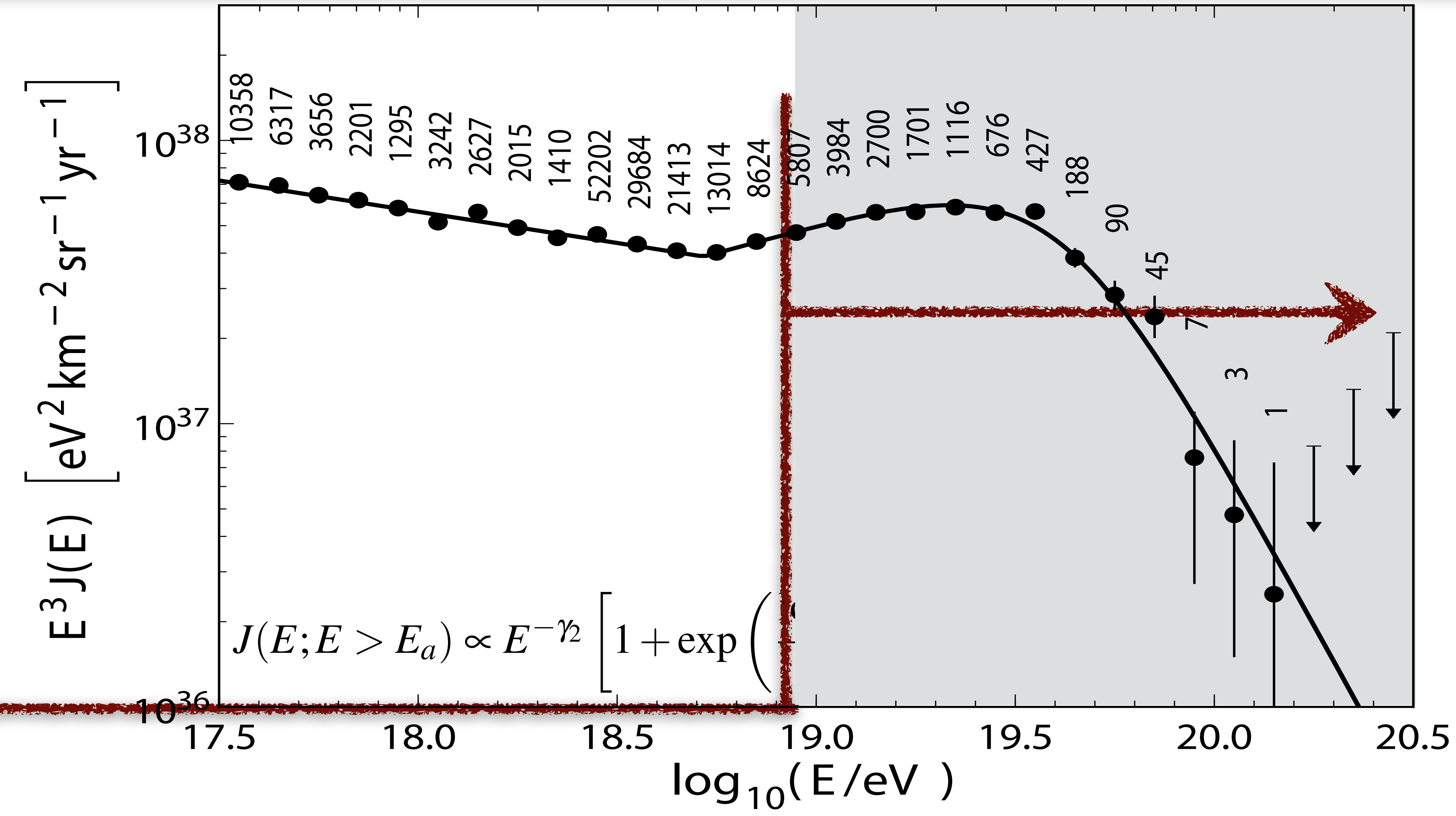
Flux Map above 8 EeV

Auger Collaboration, Science 357 (2017) 1266

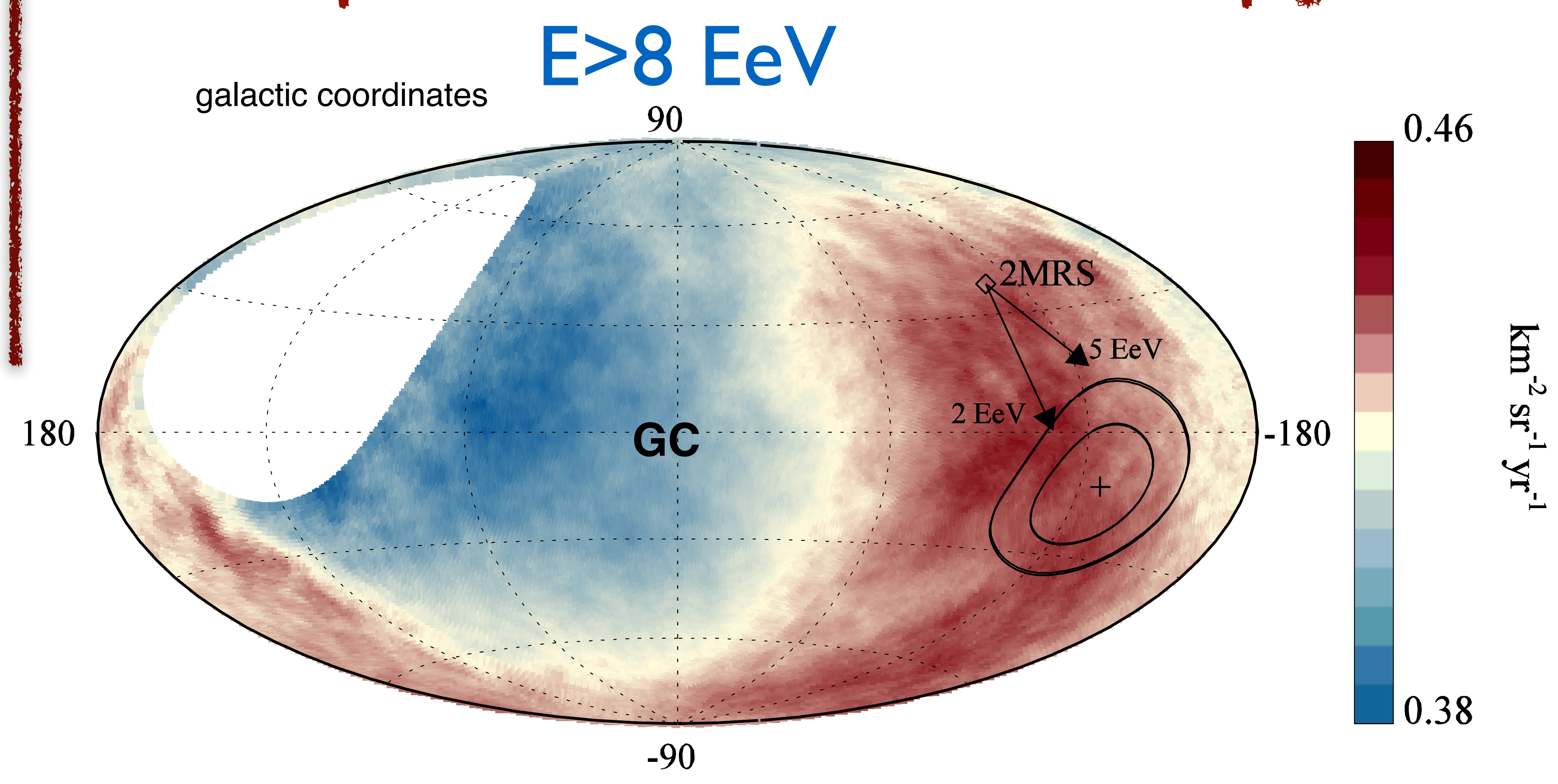


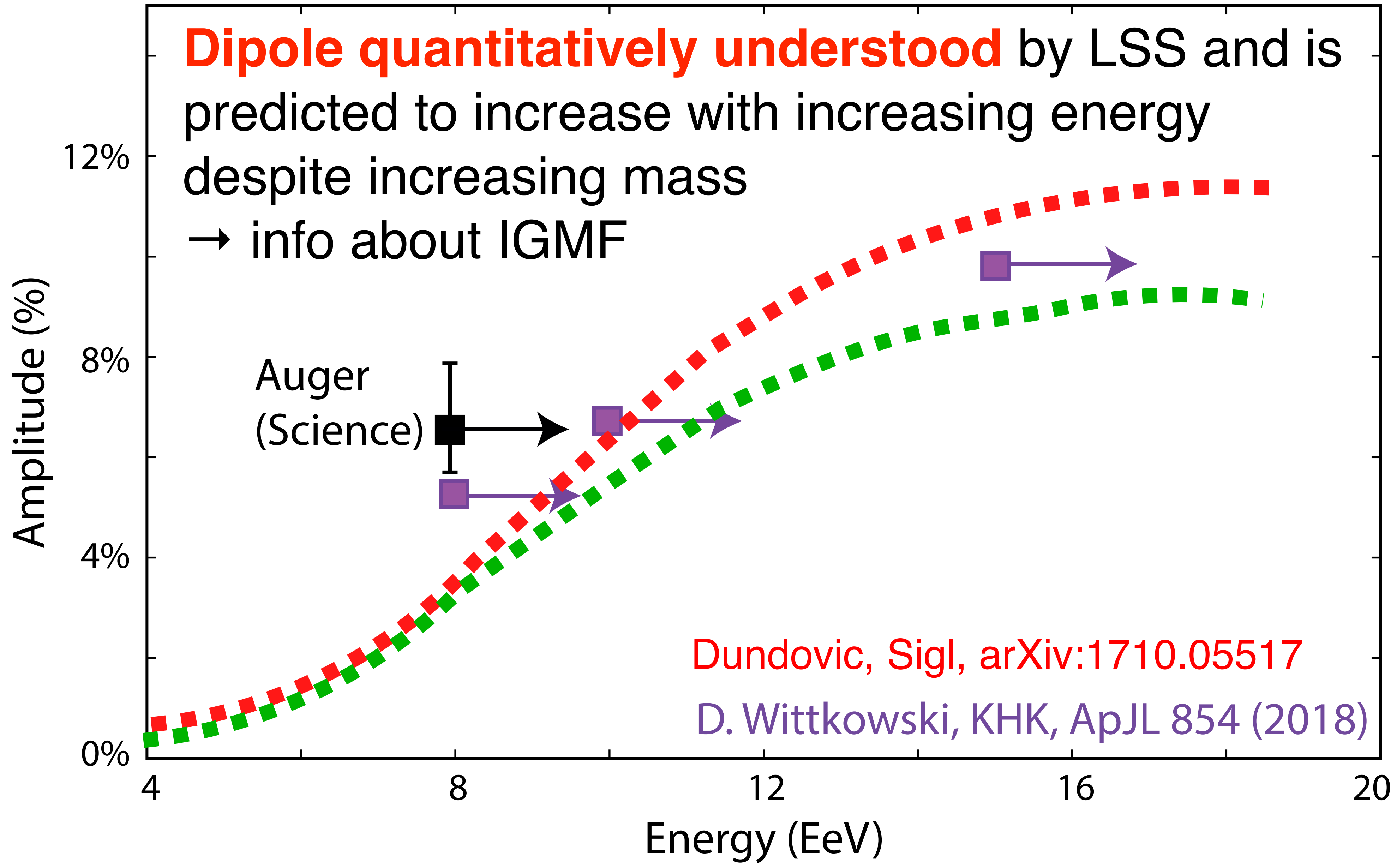
Extragalactic origin of UHECR confirmed

Detection of UHECR Anisotropies

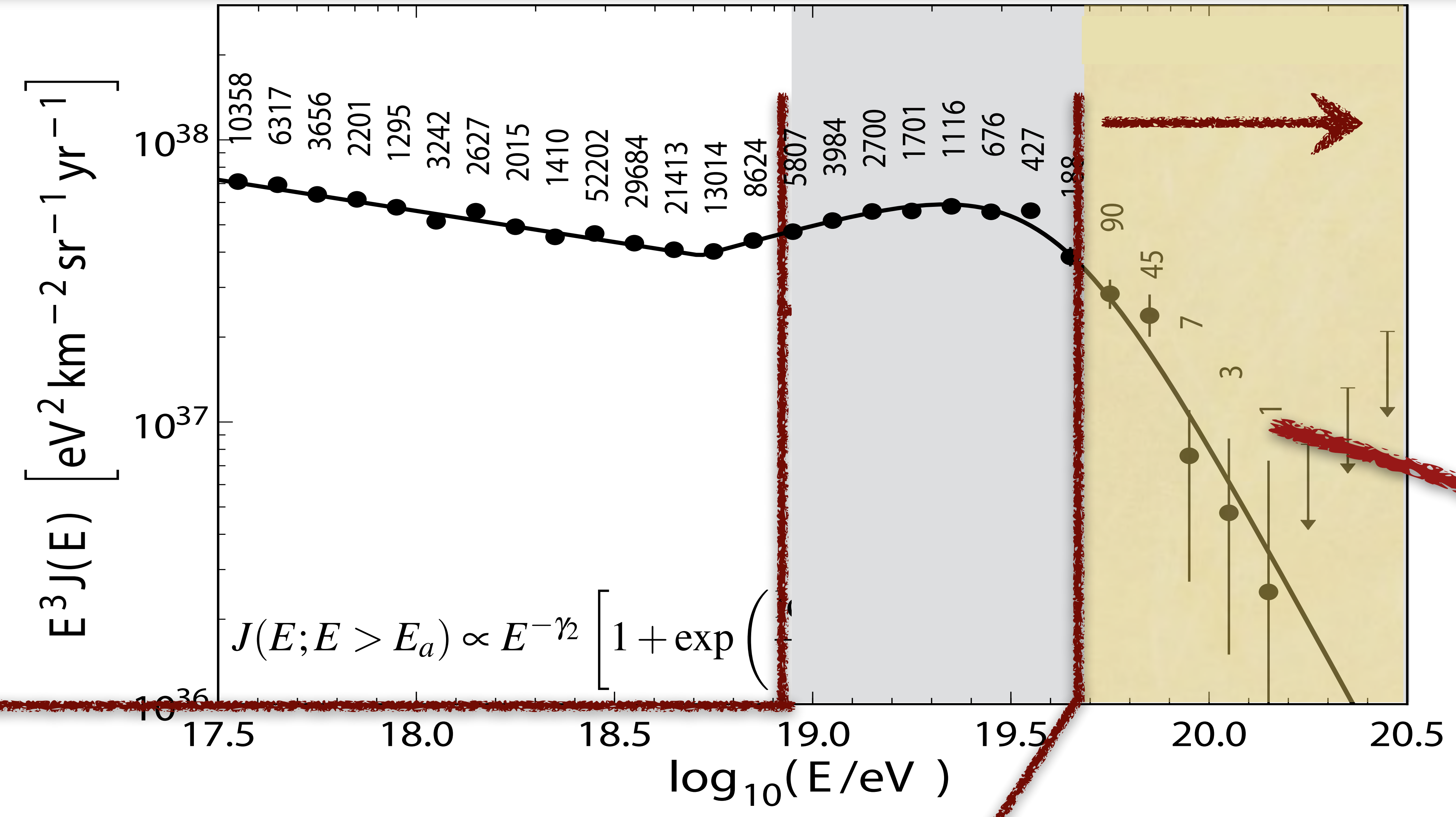


dipole like anisotropy



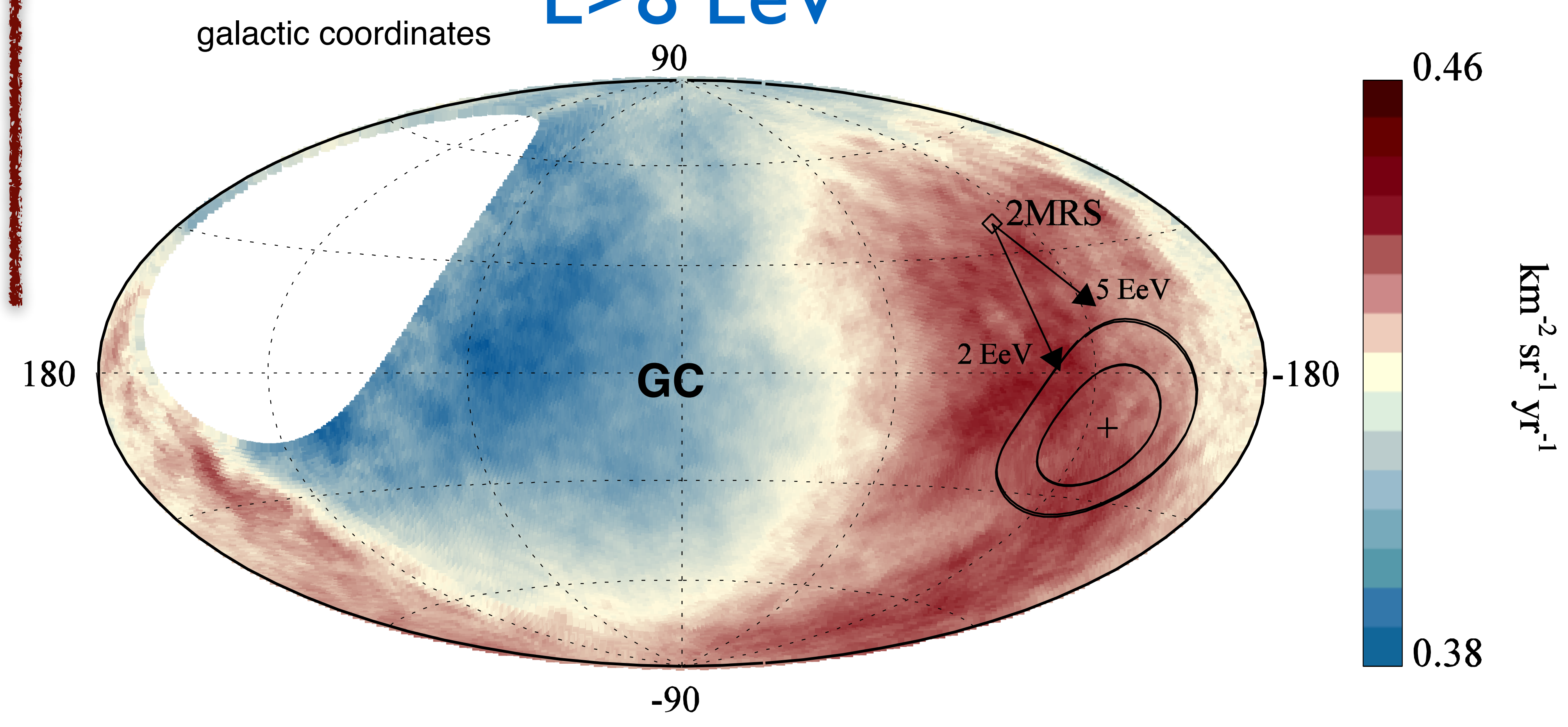


Detection of UHECR Anisotropies



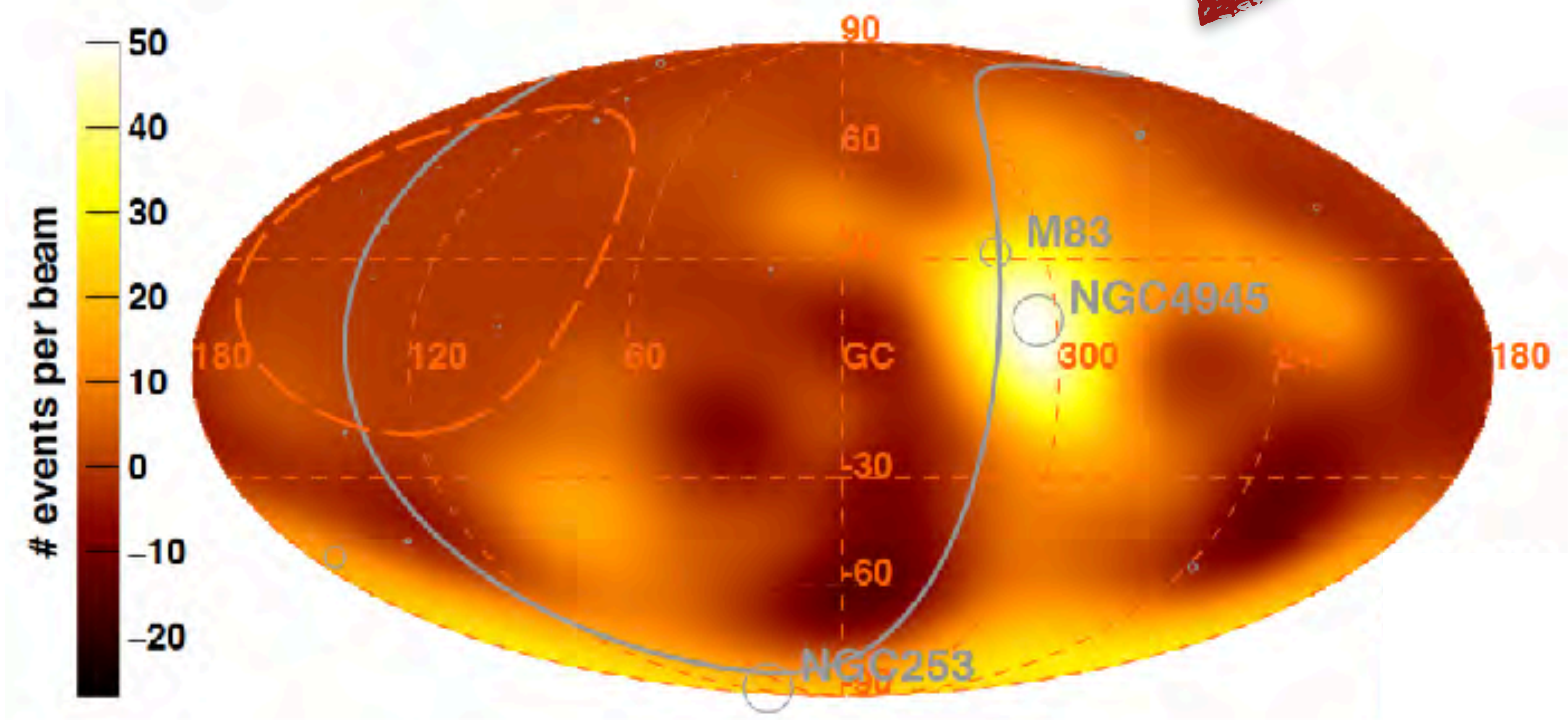
dipole like anisotropy

E>8 EeV



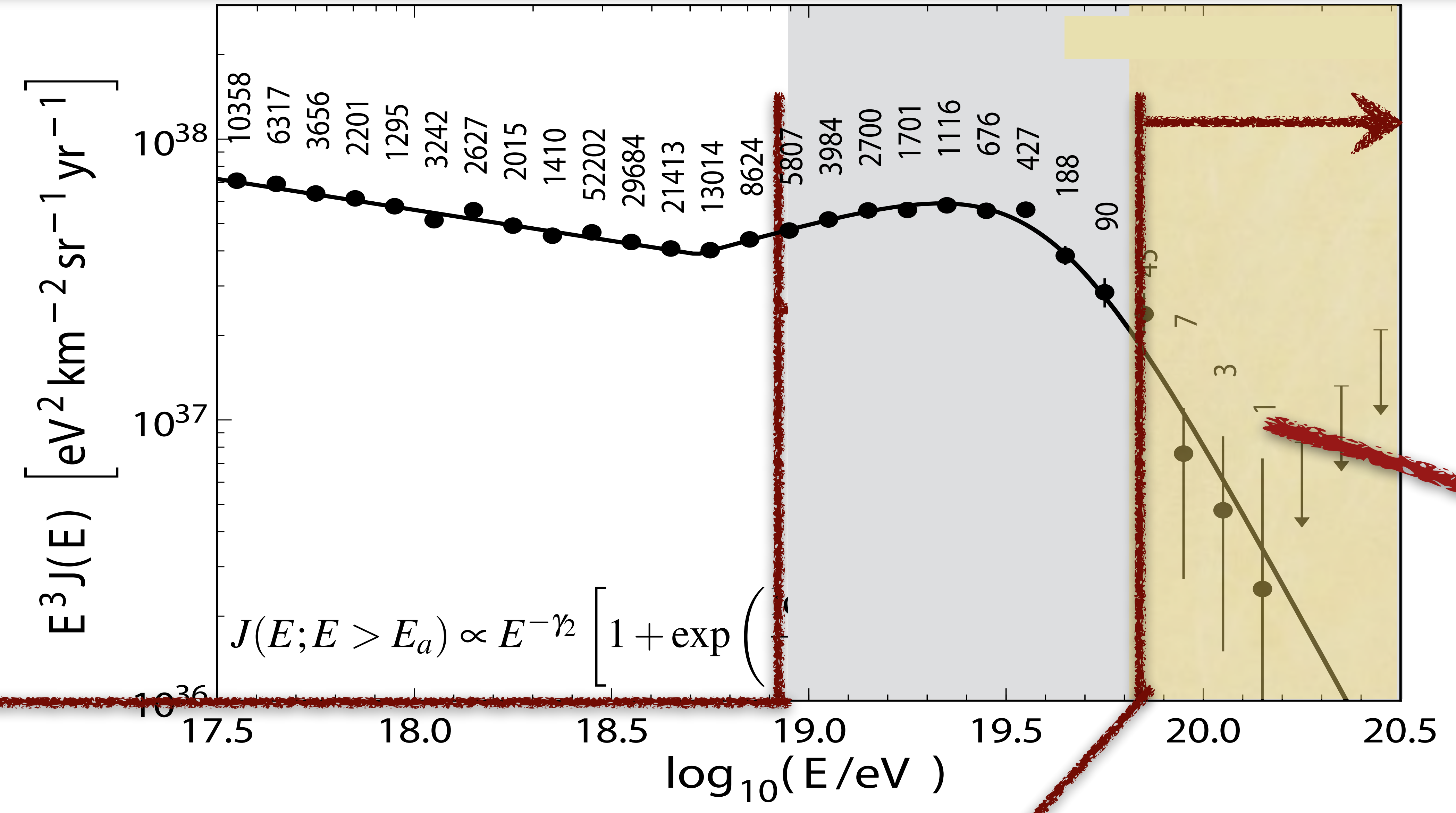
more structures

E>39 EeV



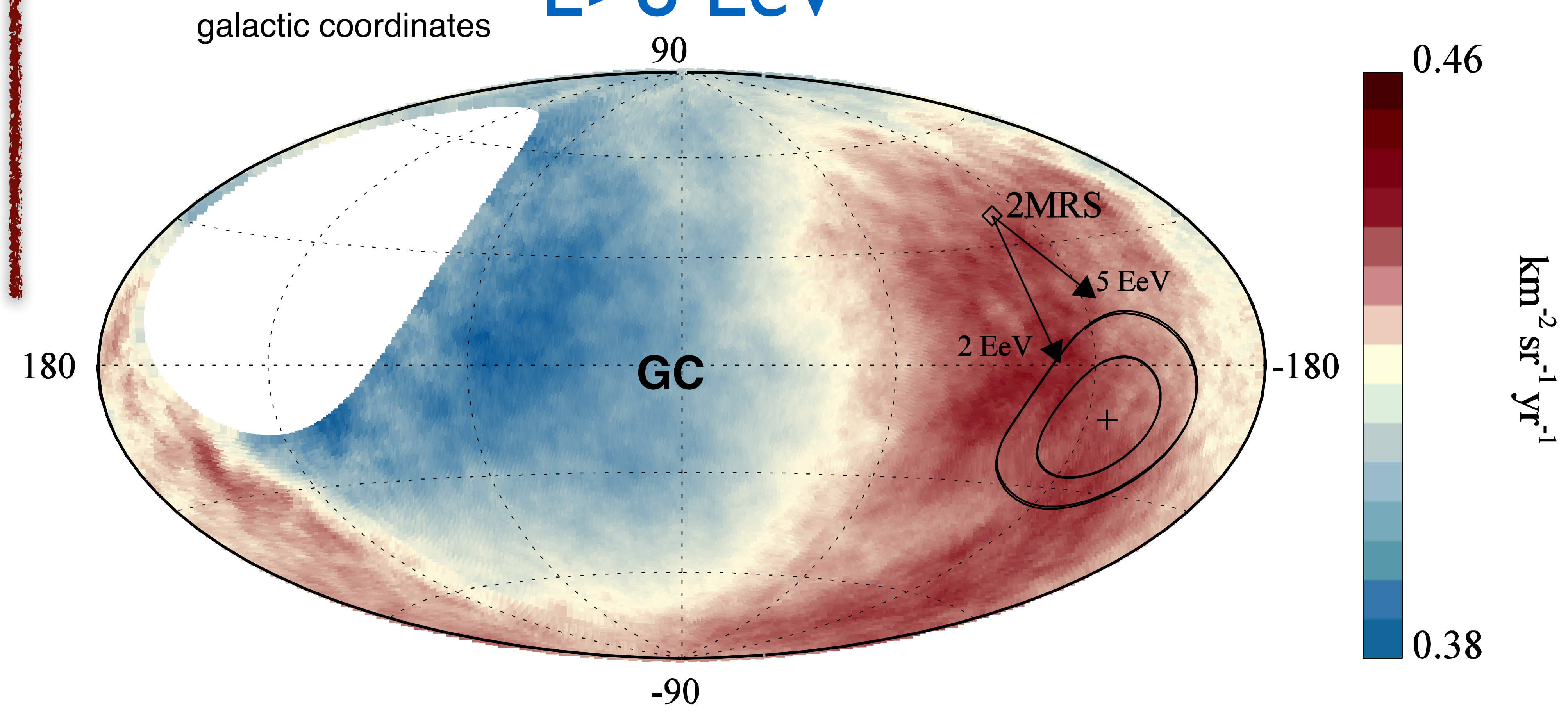
Auger: ApJL 853:L29 (2018)

Detection of UHECR Anisotropies



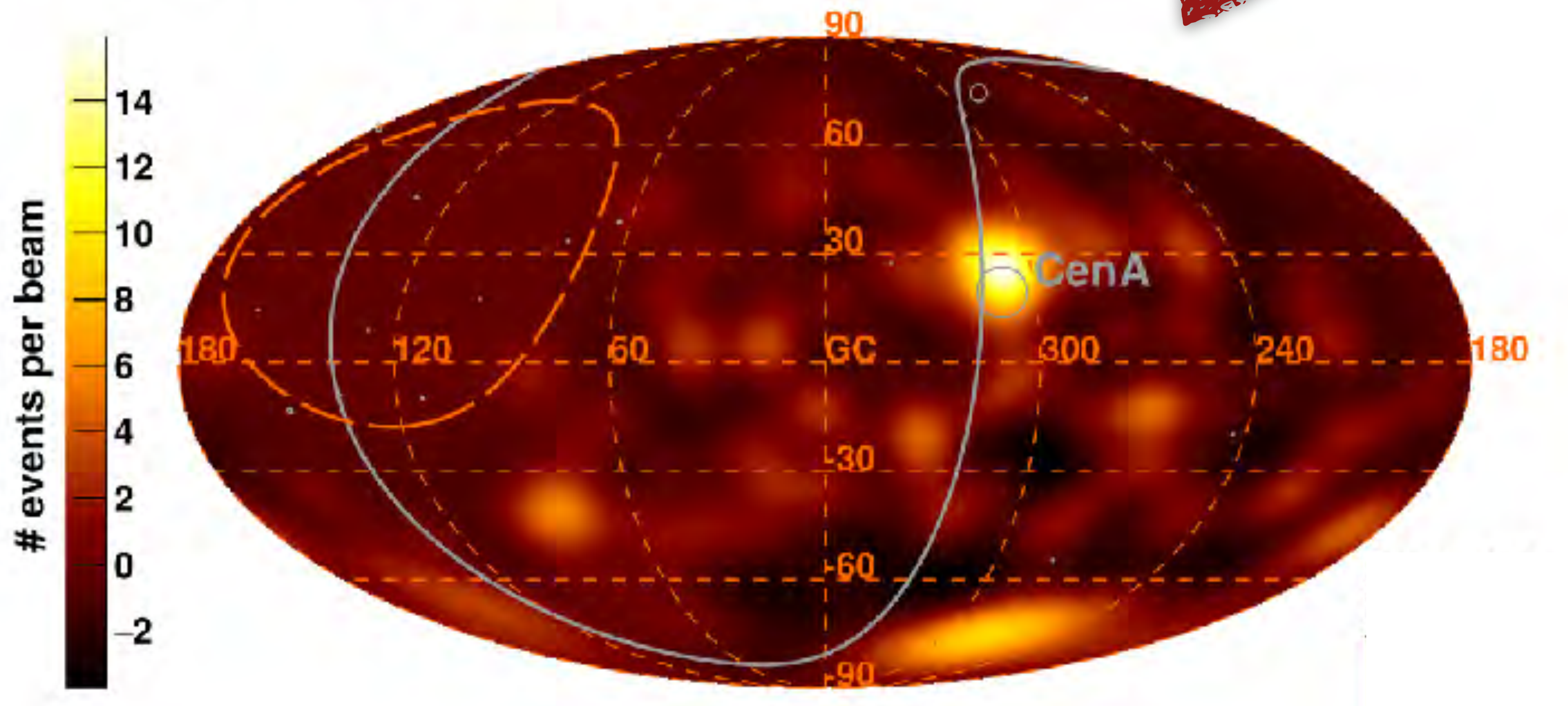
dipole like anisotropy

E>8 EeV



even more structures

E>60 EeV

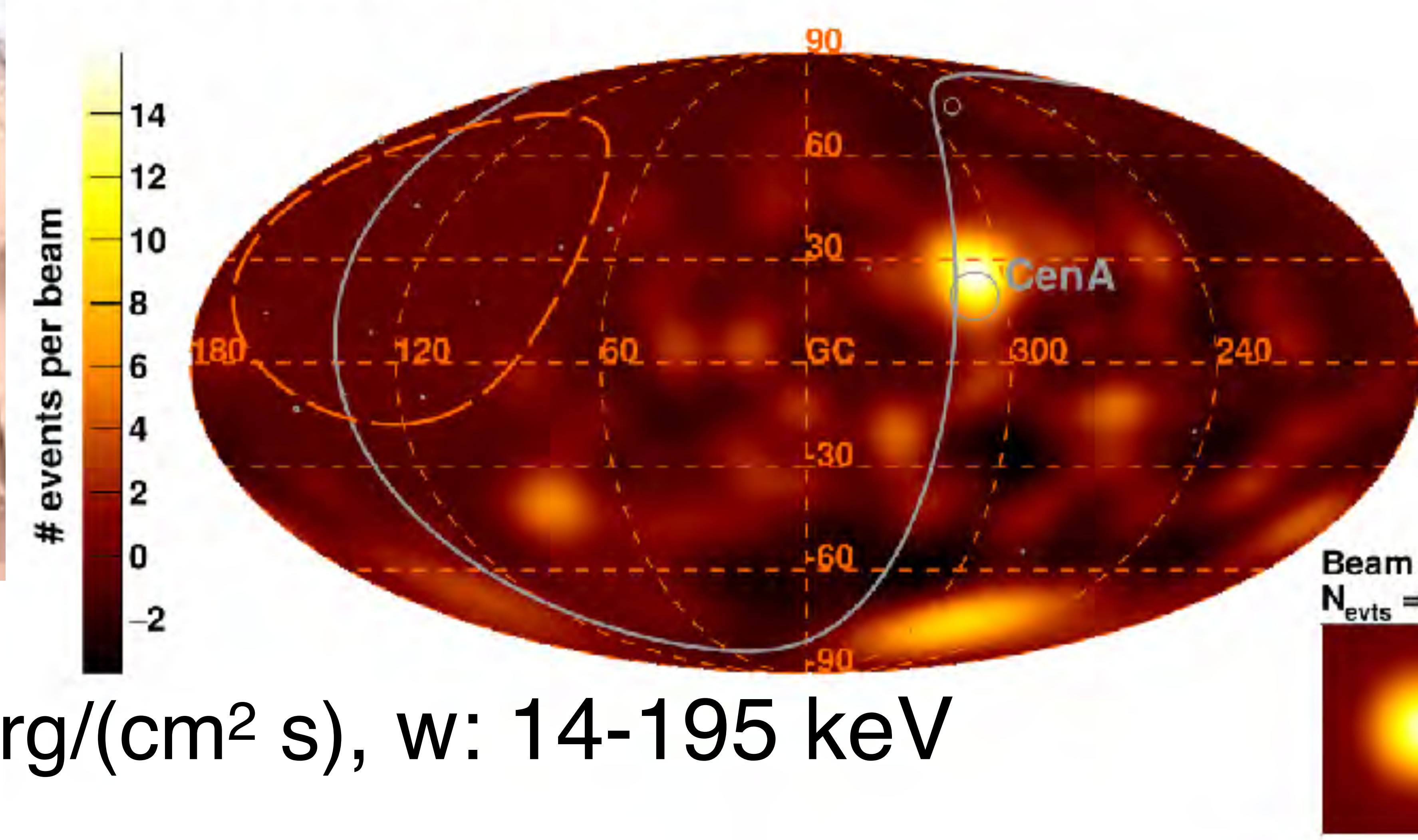


Auger: ApJL 853:L29 (2018)

The Usual UHECR Source Suspects

Swift-BAT 2MRS SGB γAGN ~~VCV~~

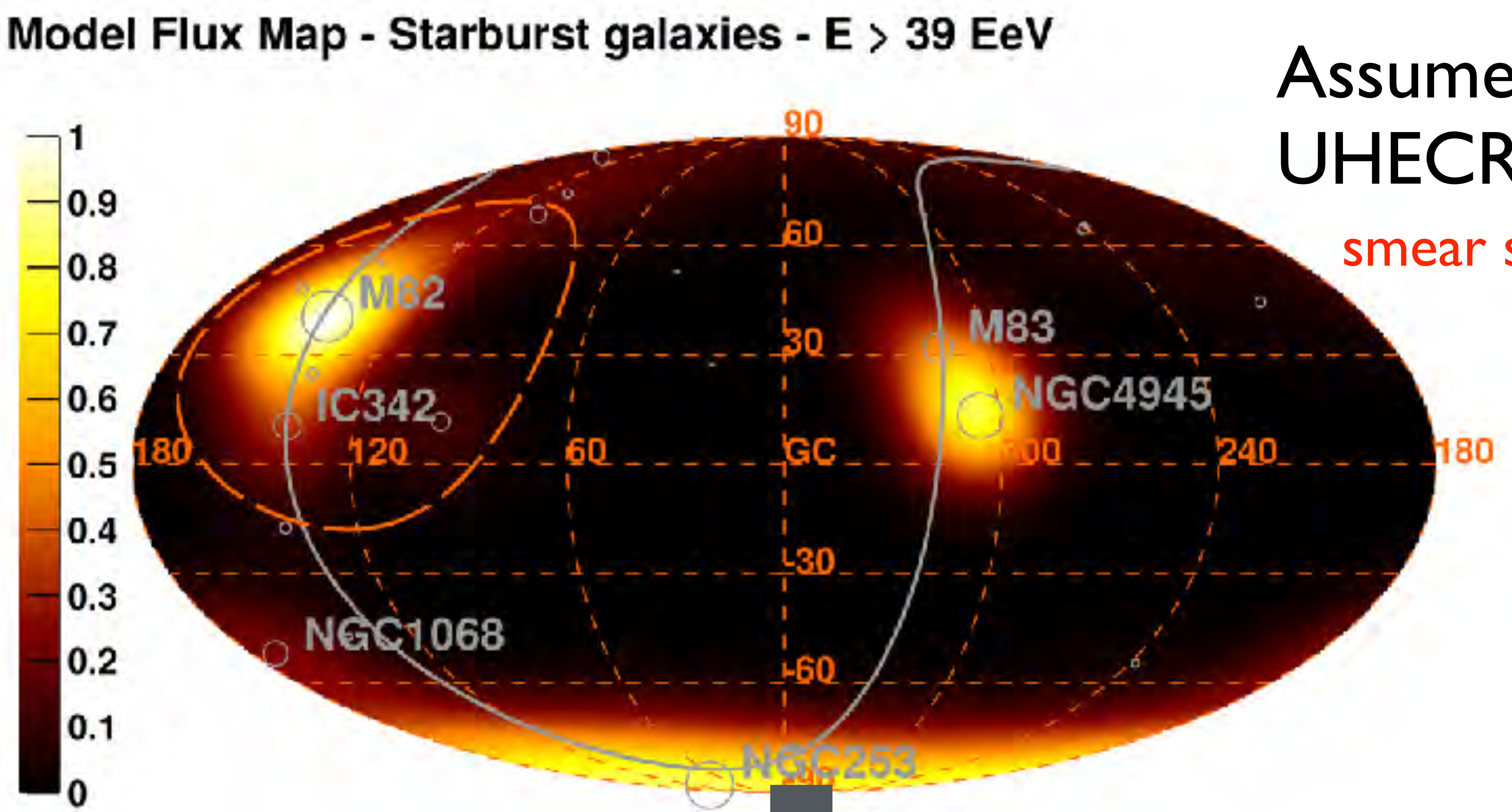
Adapted from M. Unger



- Swift-BAT X-ray-selected galaxies, D < 250 Mpc, $\Phi > 1{:}3\times10^{-11}$ erg/(cm² s), w: 14-195 keV
- 2MRS IR-selected galaxies, D > 1 Mpc, w: K-band
- SBG: 23 nearby starburst galaxies, $\Phi > 0.3$ Jy, w: radio at 1.4 GHz
- γAGN: 17 2FHL blazars and radio galaxies, D < 250 Mpc, w: γ-ray 50 GeV - 2 TeV

Understanding the UHECR Sky

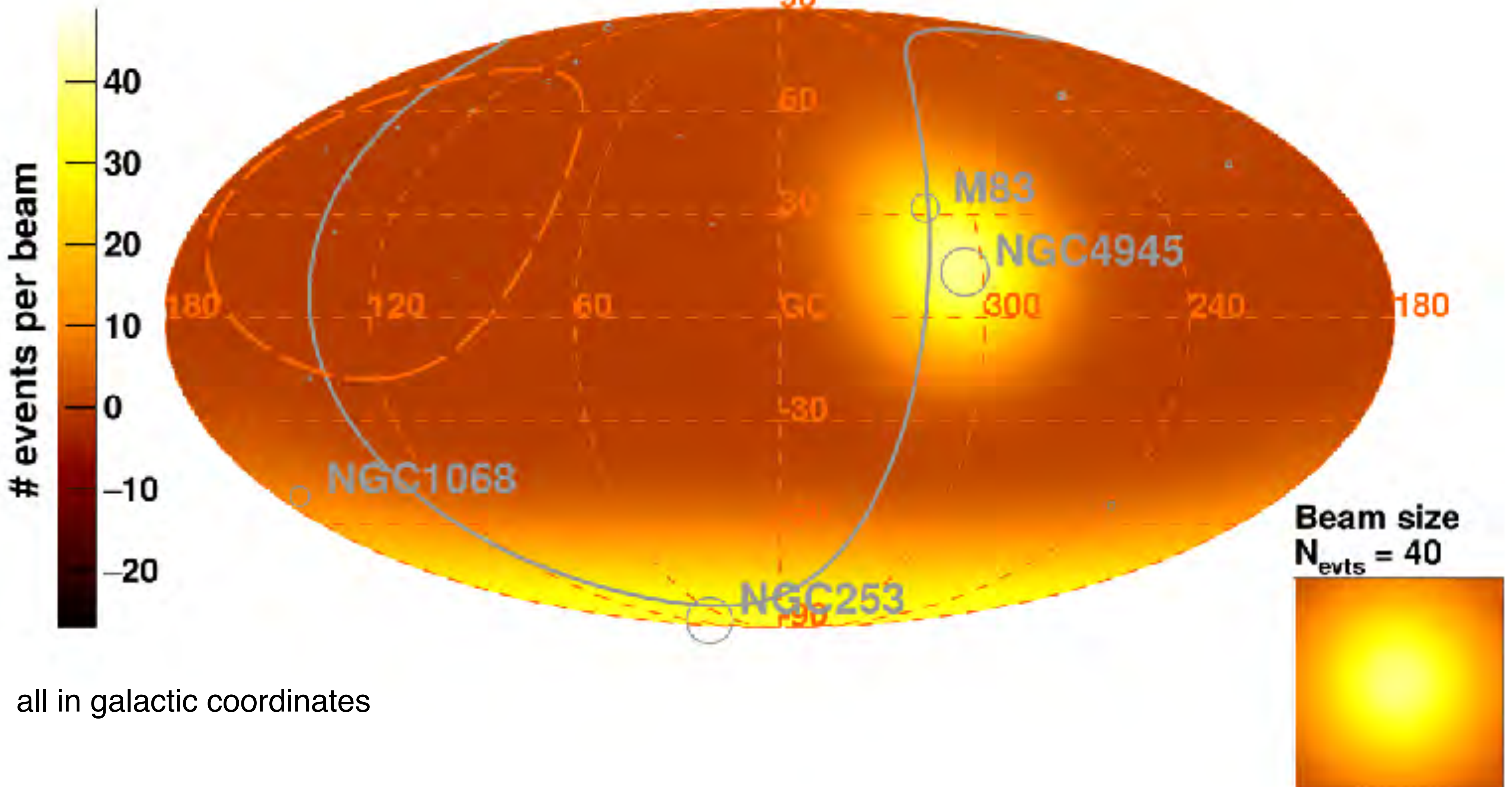
Starburst Galaxy Model



Assume, starburst galaxies produce UHECR with $L_{UHECR} \sim L_{\gamma}$ @ 1.4 GHz

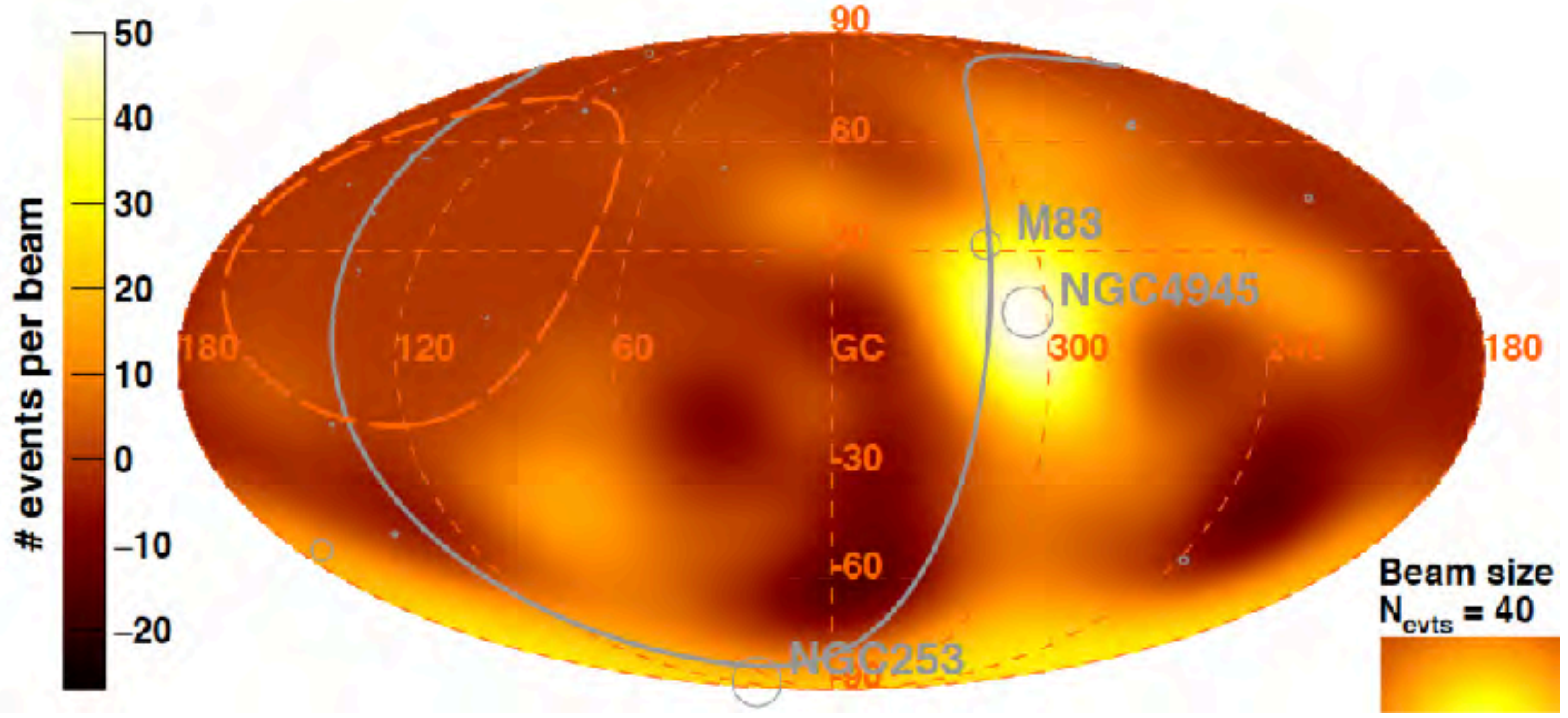
smear sources to account for B-field deflections

Add isotropic background (allow background sources a/o larger deflections by heavy primaries), such that model map…



…maximises degree of correlation with observed UHECR sky

Auger data map at E>39 EeV



Sources assumed to emit UHECR spectrum and composition according to results from combined fit.
Propagation effects (attenuation) fully accounted for.

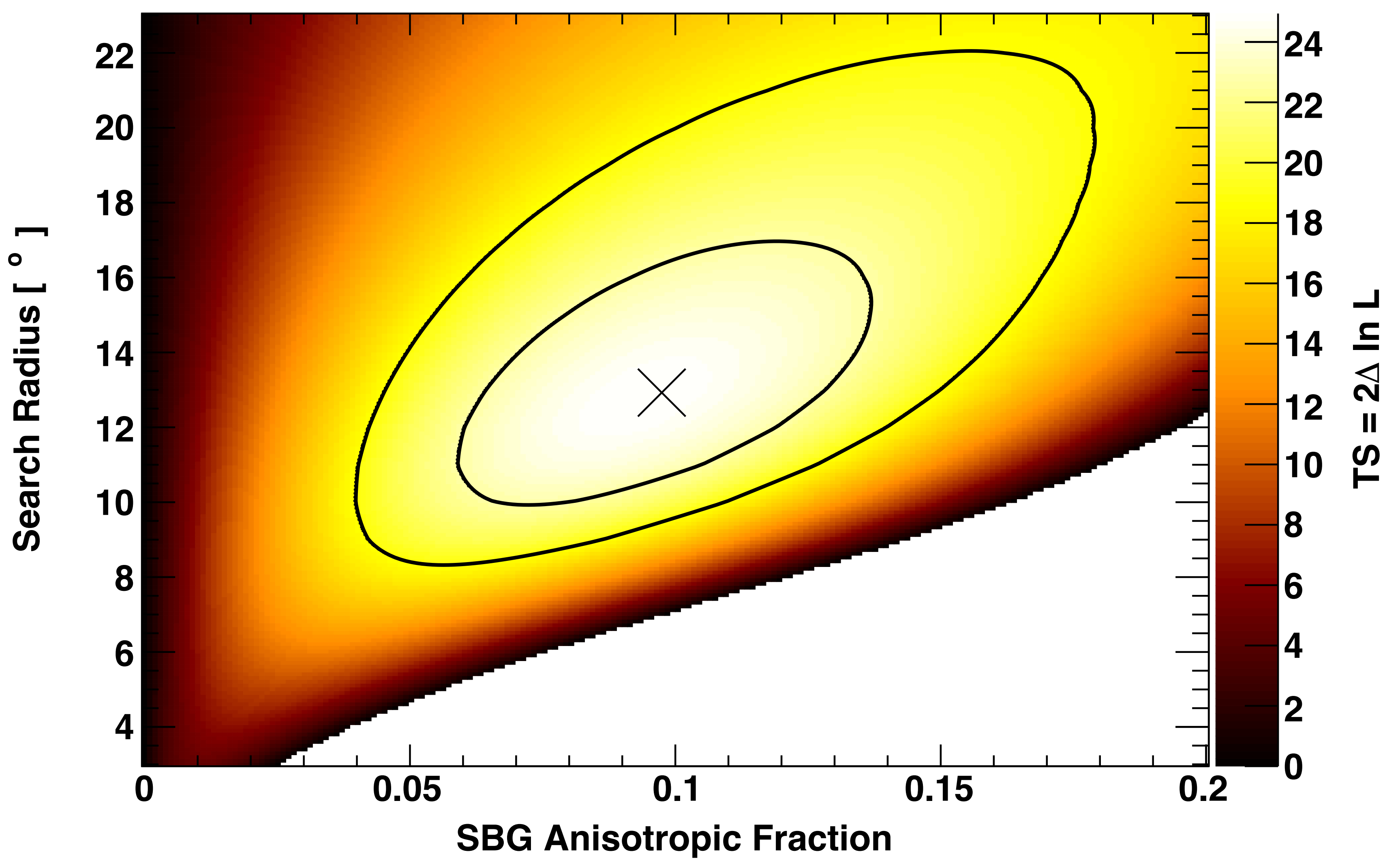
Auger: ApJL 853:L29 (2018)

all in galactic coordinates

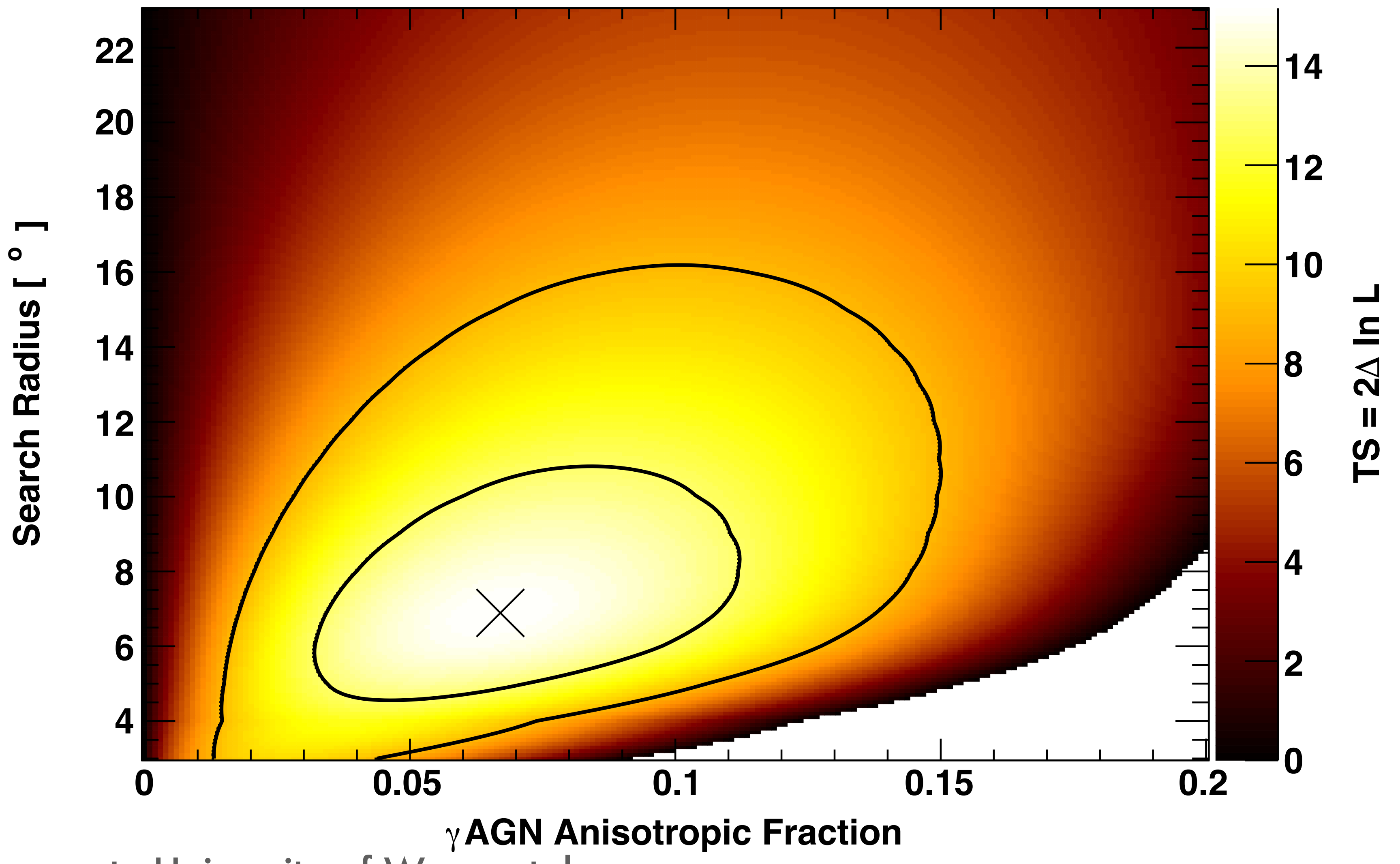
Test Statistics & 2D-Profiles

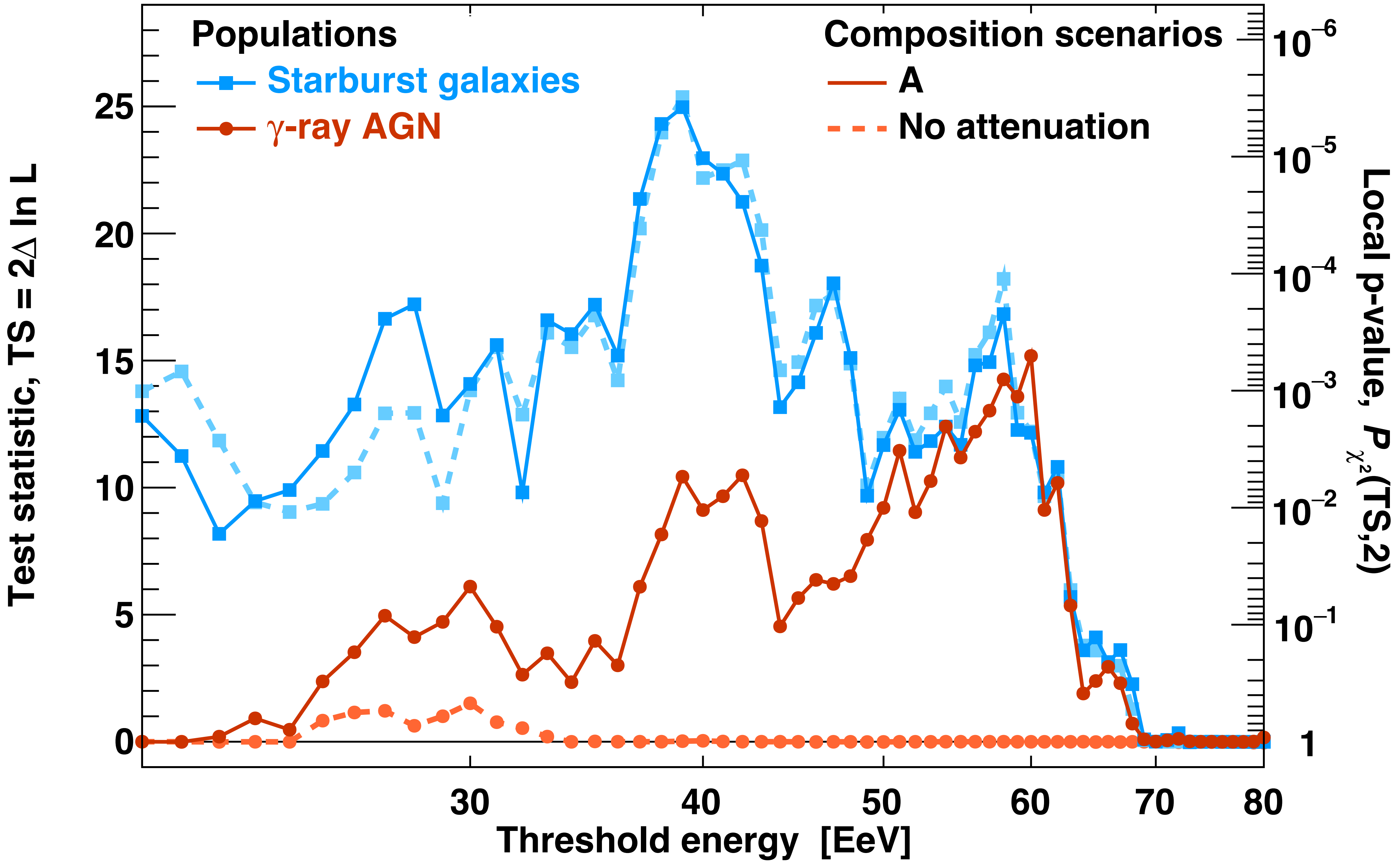
Two free parameters:
smearing angle, anisotropic fraction

Starburst galaxies - E > 39 EeV



Active galactic nuclei - E > 60 EeV





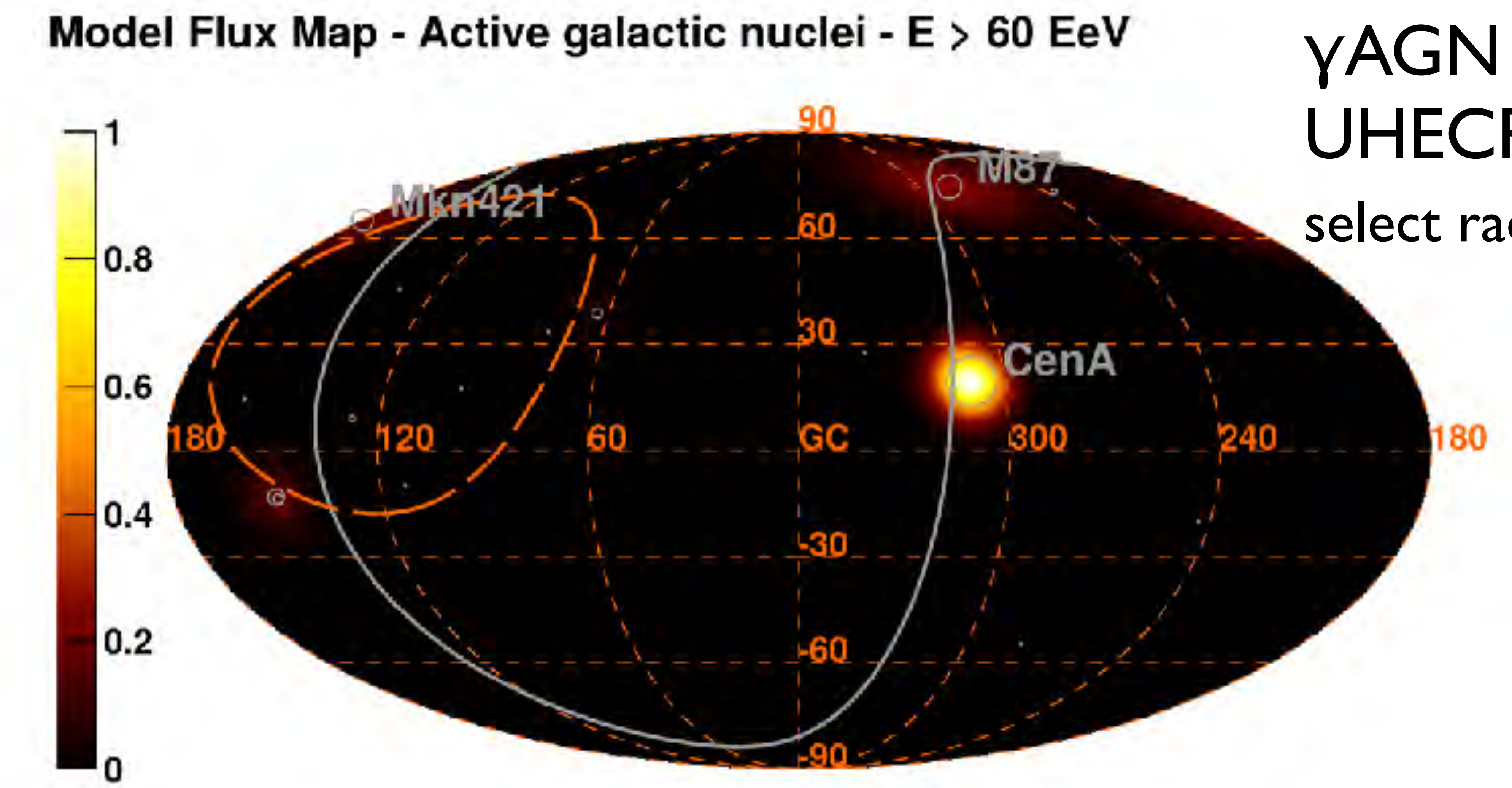
Result: SBG-model fits data better than isotropy at 4σ

Result: γAGN-model fits data better than isotropy at 2.7σ

Auger: ApJL 853:L29 (2018)

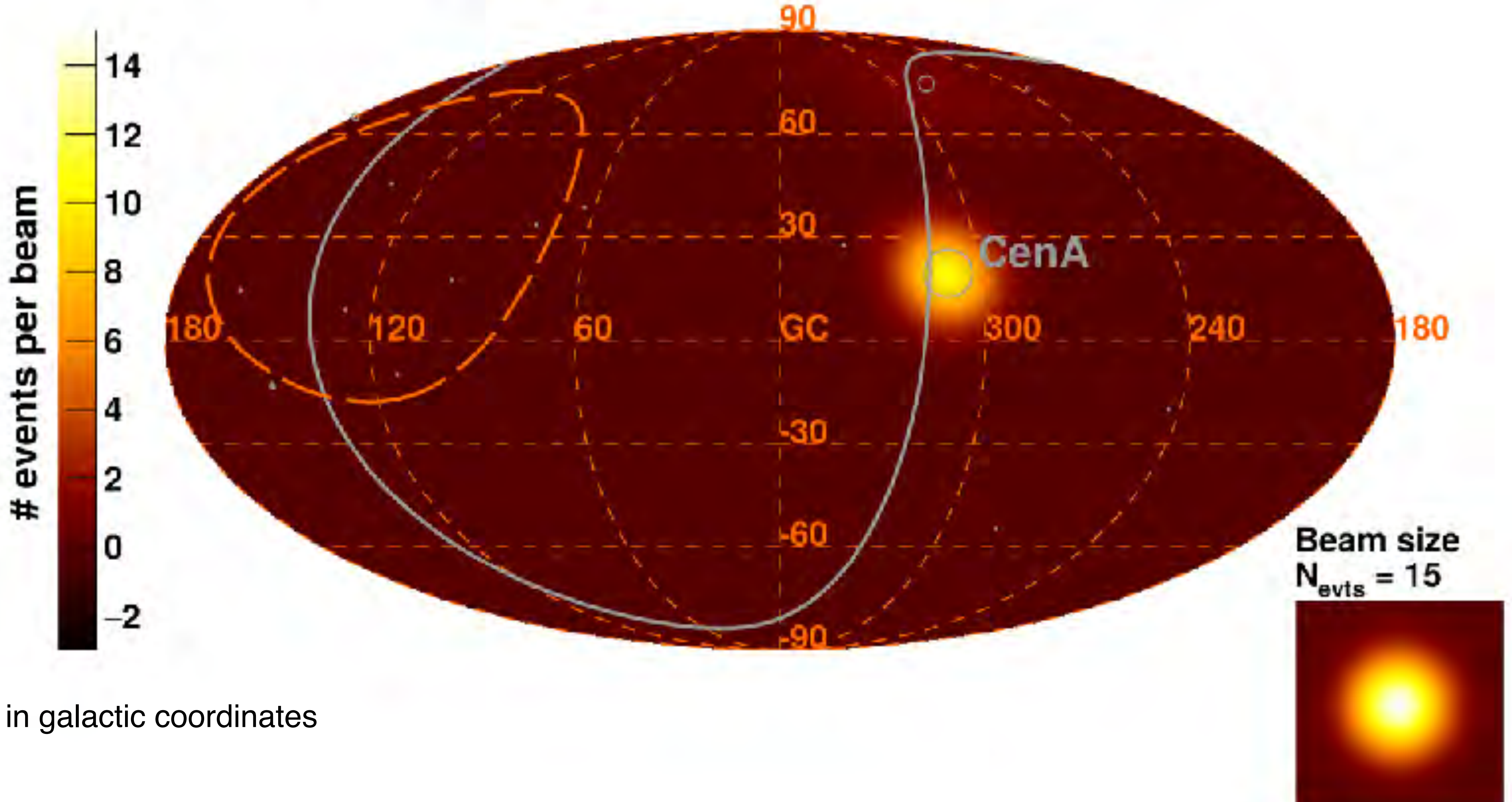
Understanding the UHECR Sky

γAGN Model



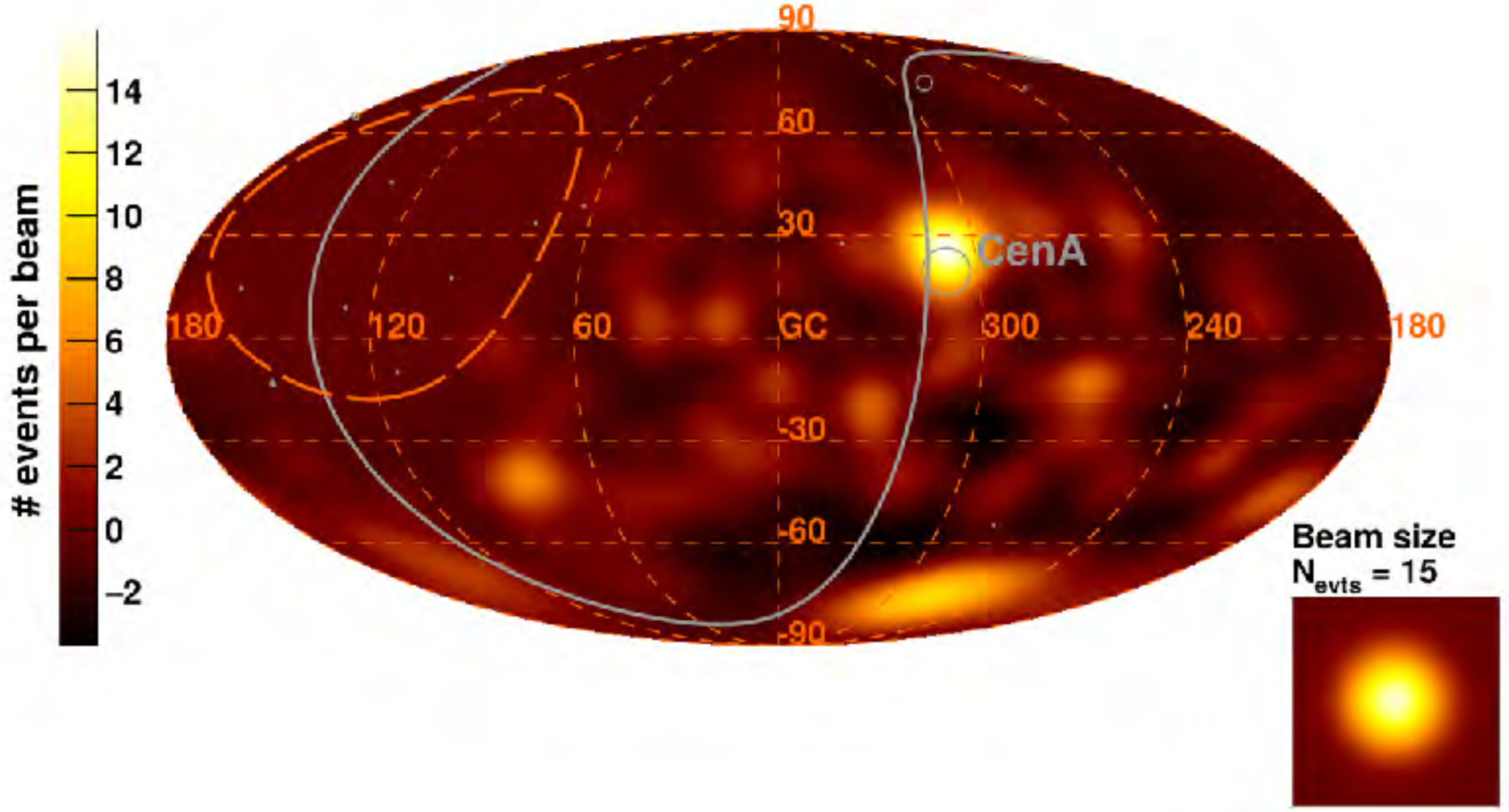
γAGN sky assuming
UHECR with $L_{UHECR} \sim L_\gamma$
select radio loud AGN within 250 Mpc

isotropic background added…



all in galactic coordinates

UHECR data map @ E> 60 EeV

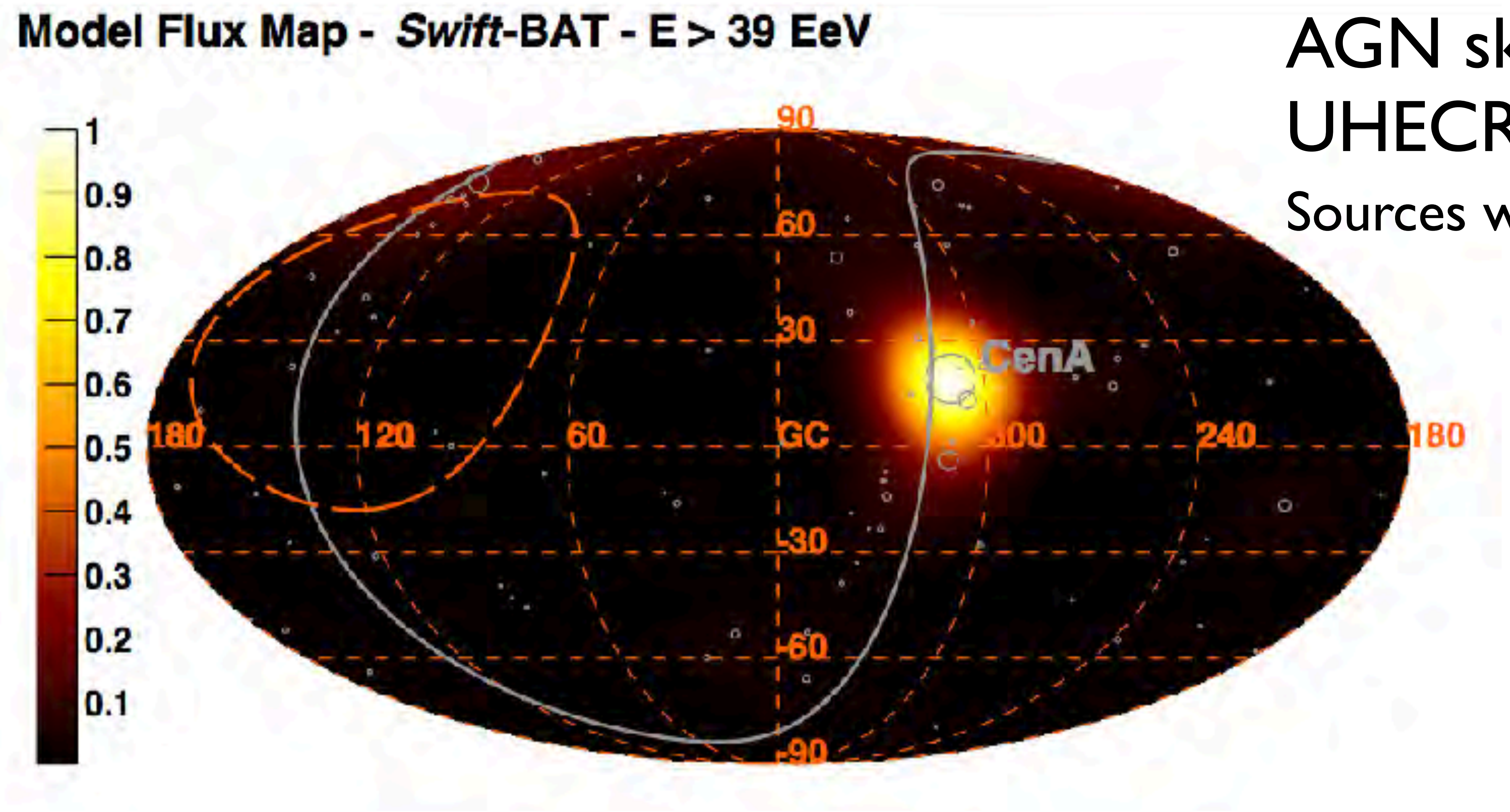


Result: γAGN-model fits data better than isotropy at 2.7σ

Auger: ApJL 853:L29 (2018)

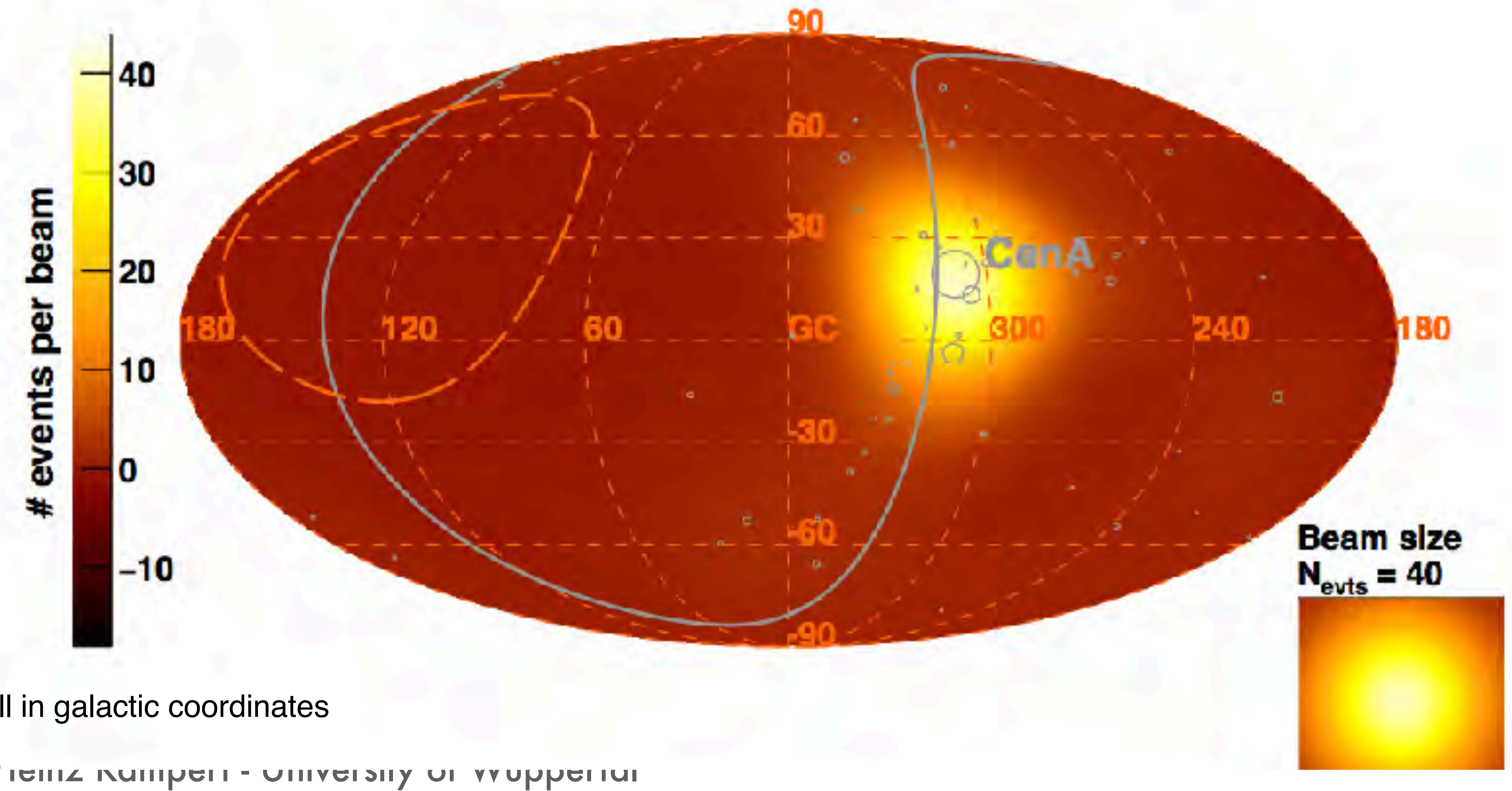
Understanding the UHECR Sky

Swift-BAT Model

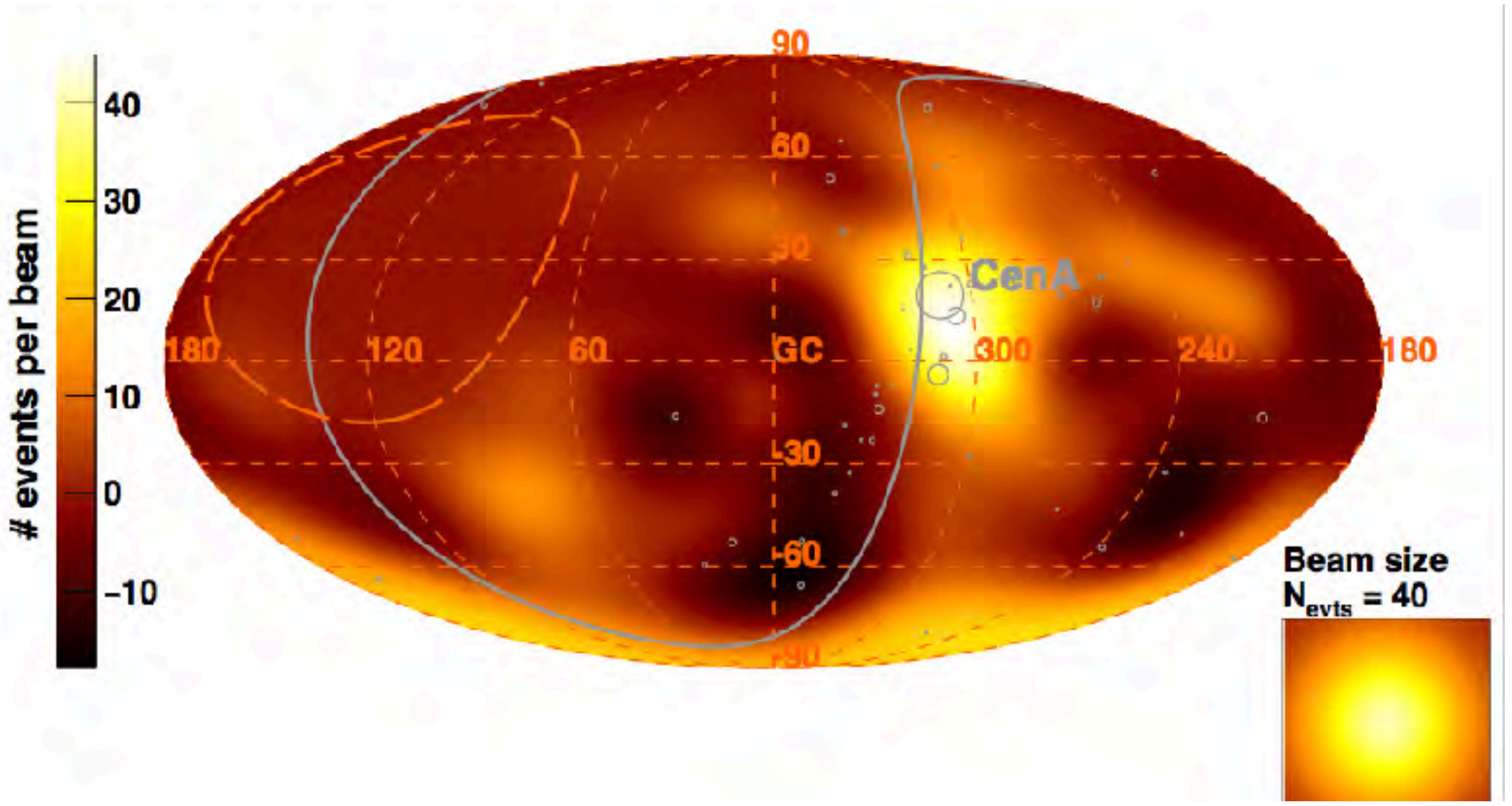


AGN sky assuming
UHECR with $L_{UHECR} \sim L_\gamma$
Sources with $F > 13.4 \times 10^{-12}$ erg/cm²/s within 250 Mpc

isotropic background added…



UHECR data map @ E> 39 EeV



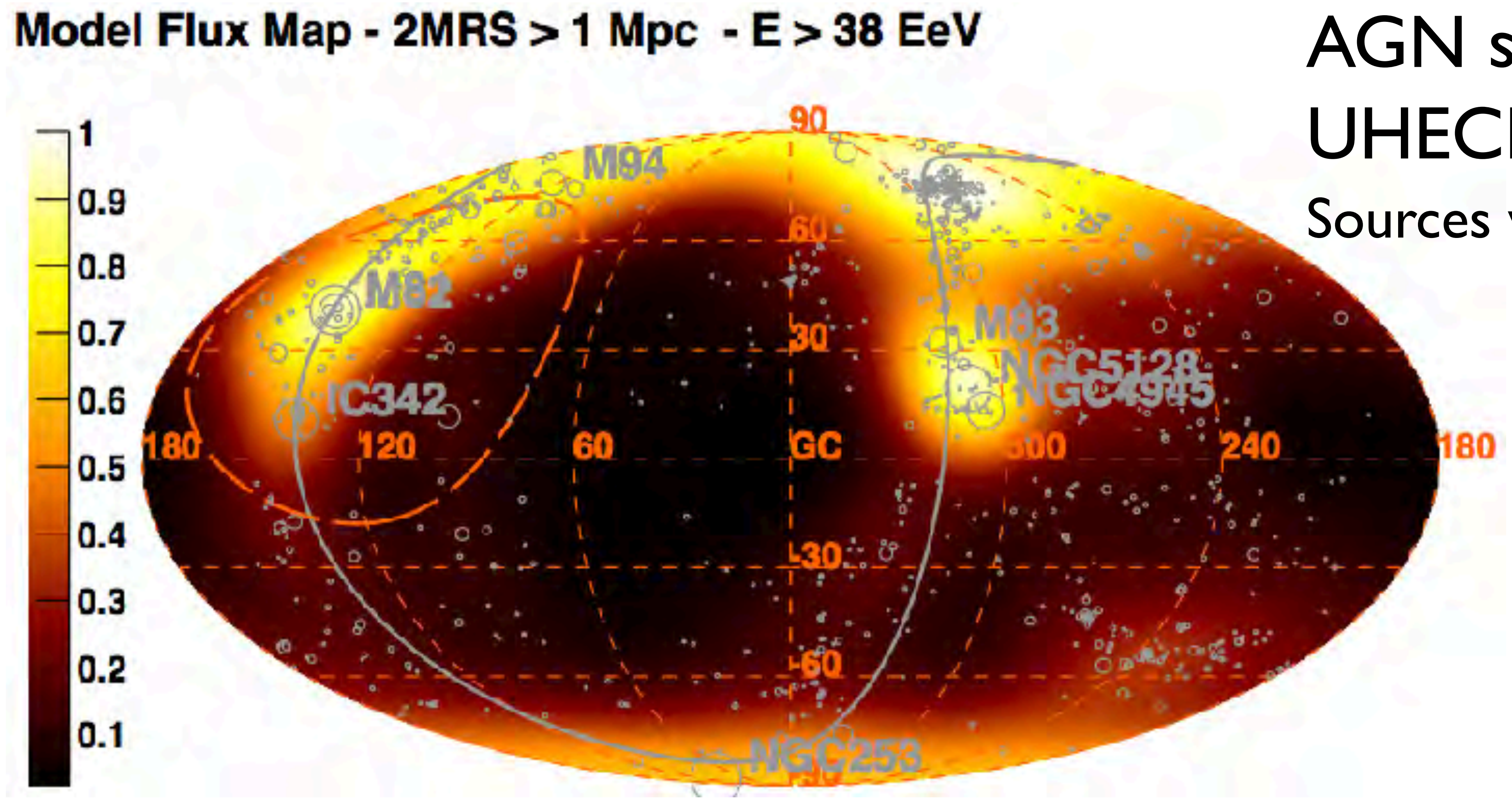
Result: Swif-BAT model fits data better than isotropy at 3.2σ

Auger: ApJL 853:L29 (2018)

all in galactic coordinates

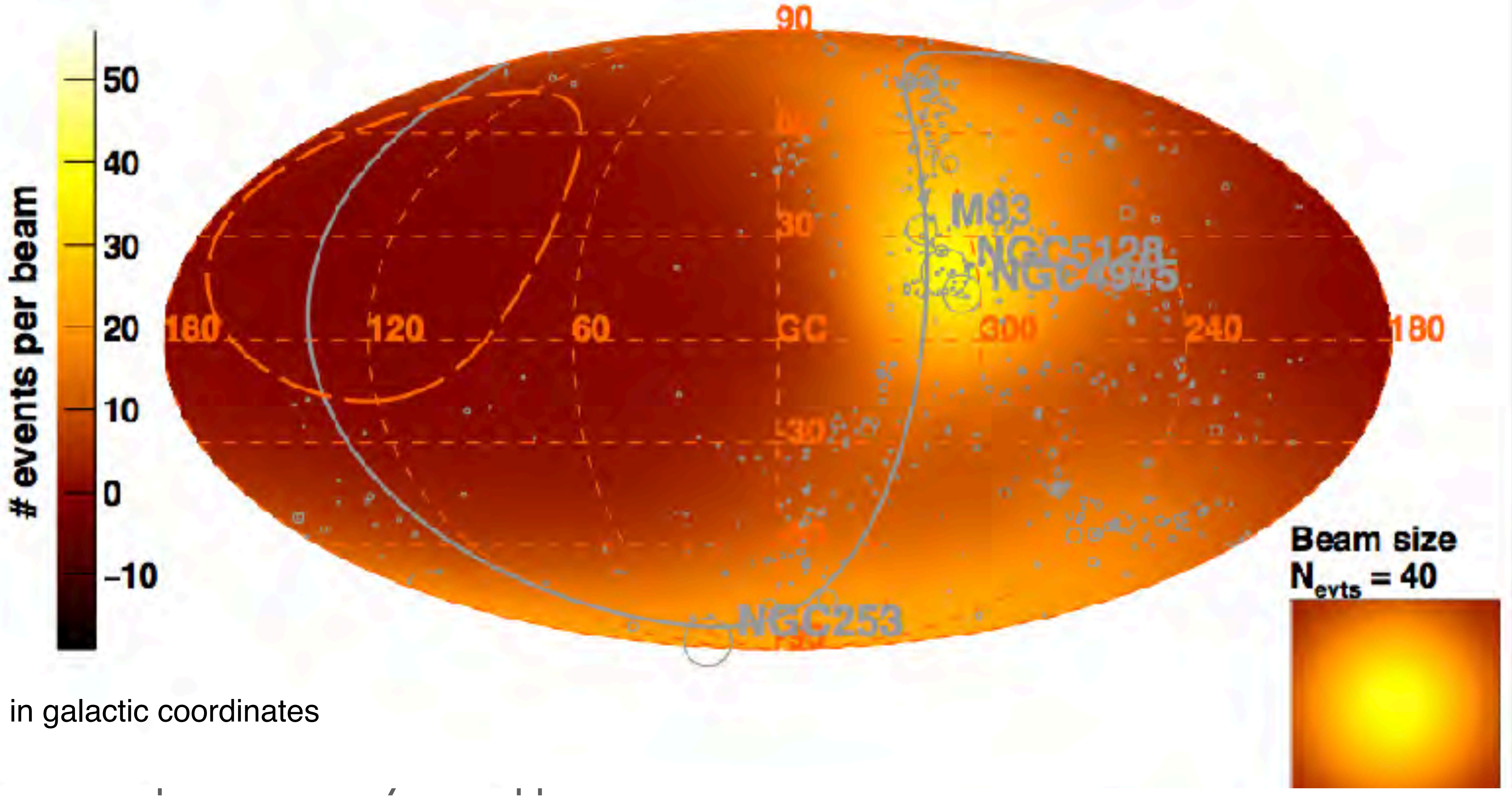
Understanding the UHECR Sky

2MRS Model



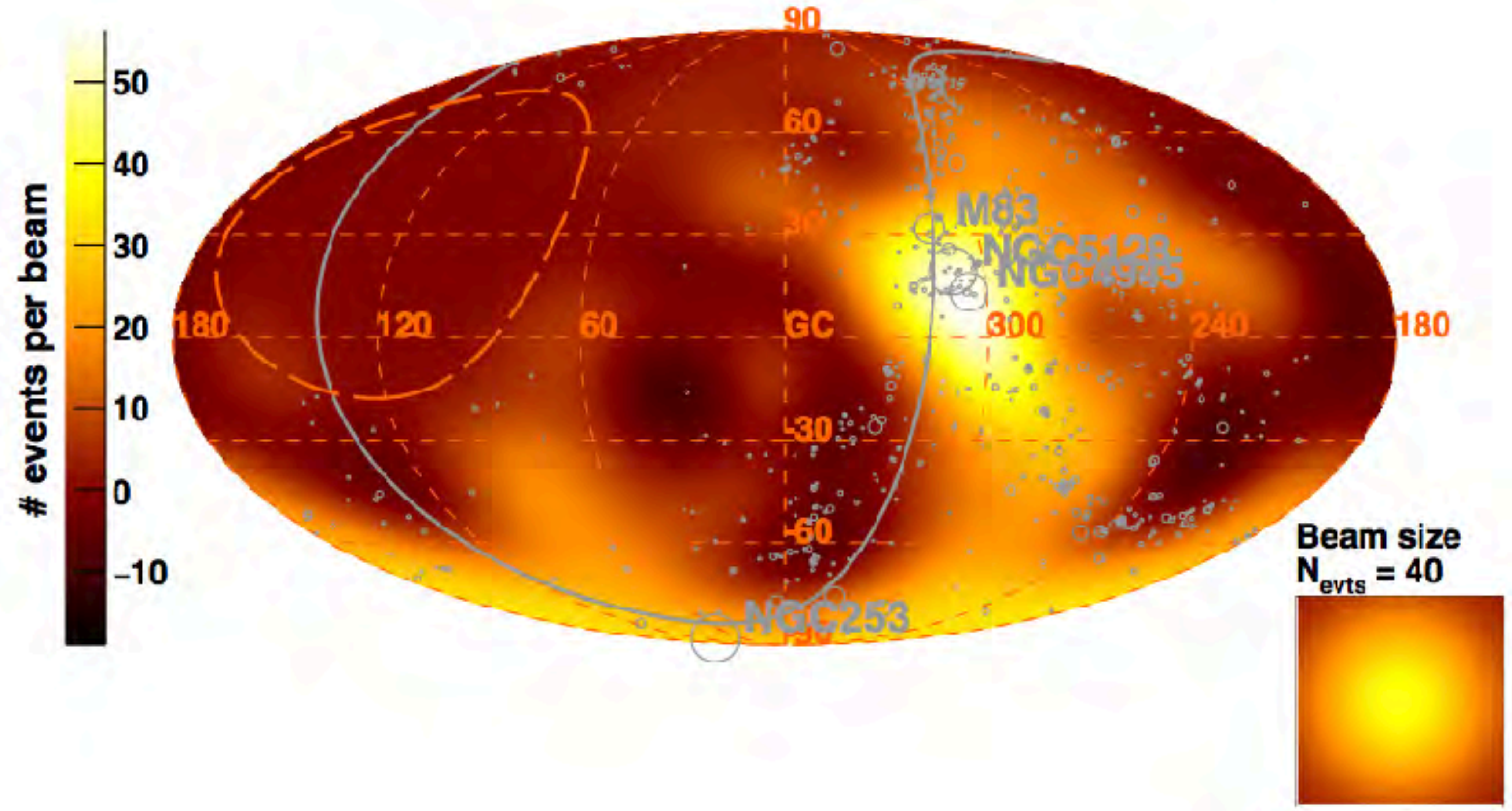
AGN sky assuming
UHECR with $L_{UHECR} \sim L_{K\text{-band}}$
Sources within 250 Mpc, exclude local group

isotropic background added…



all in galactic coordinates

UHECR data map @ E> 38 EeV



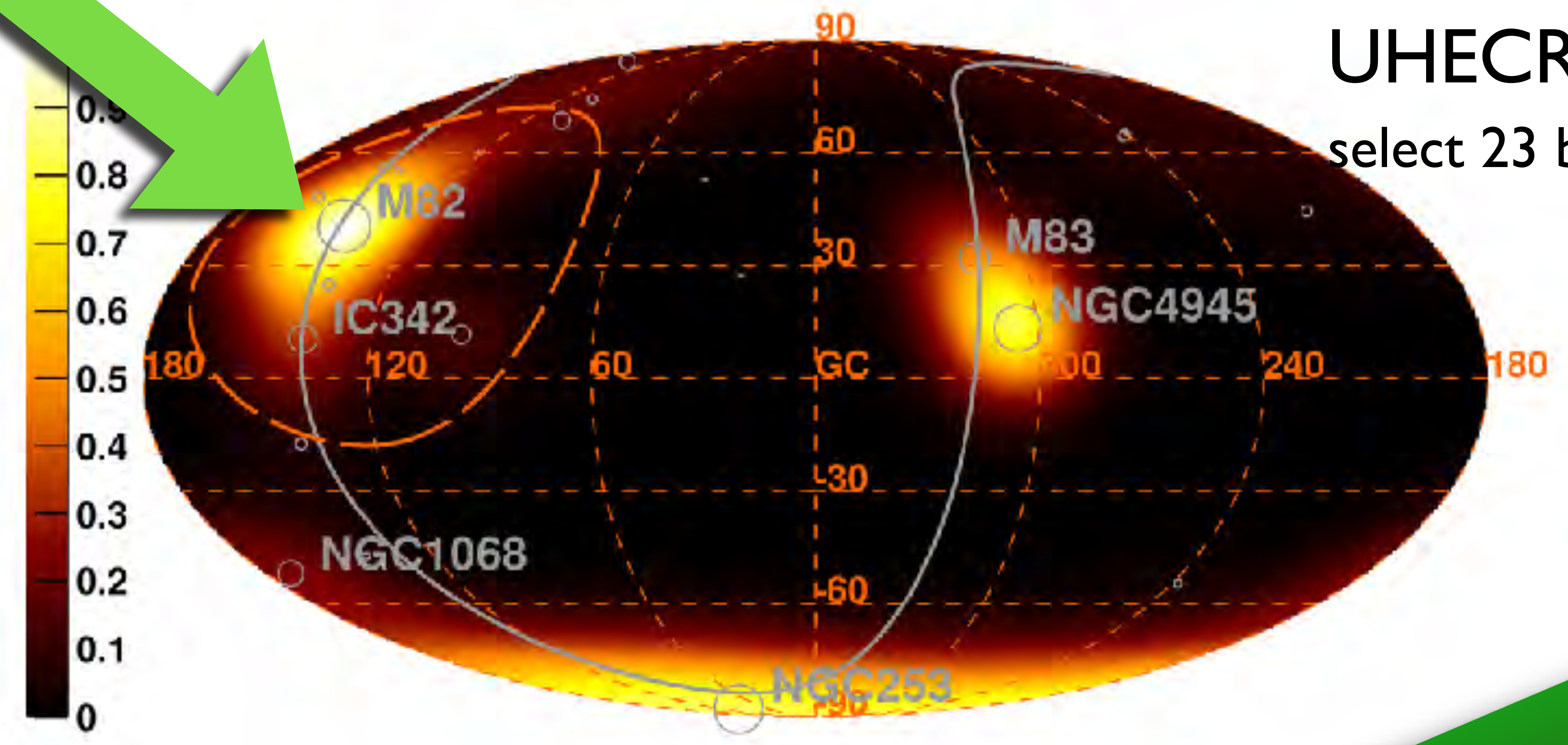
Result: 2MRS-model fits data better than isotropy at 2.7σ

Auger: ApJL 853:L29 (2018)

Understanding the UHECR Sky

Starburst Galaxy Model

Model Flux Map - Starburst galaxies - E > 39 EeV

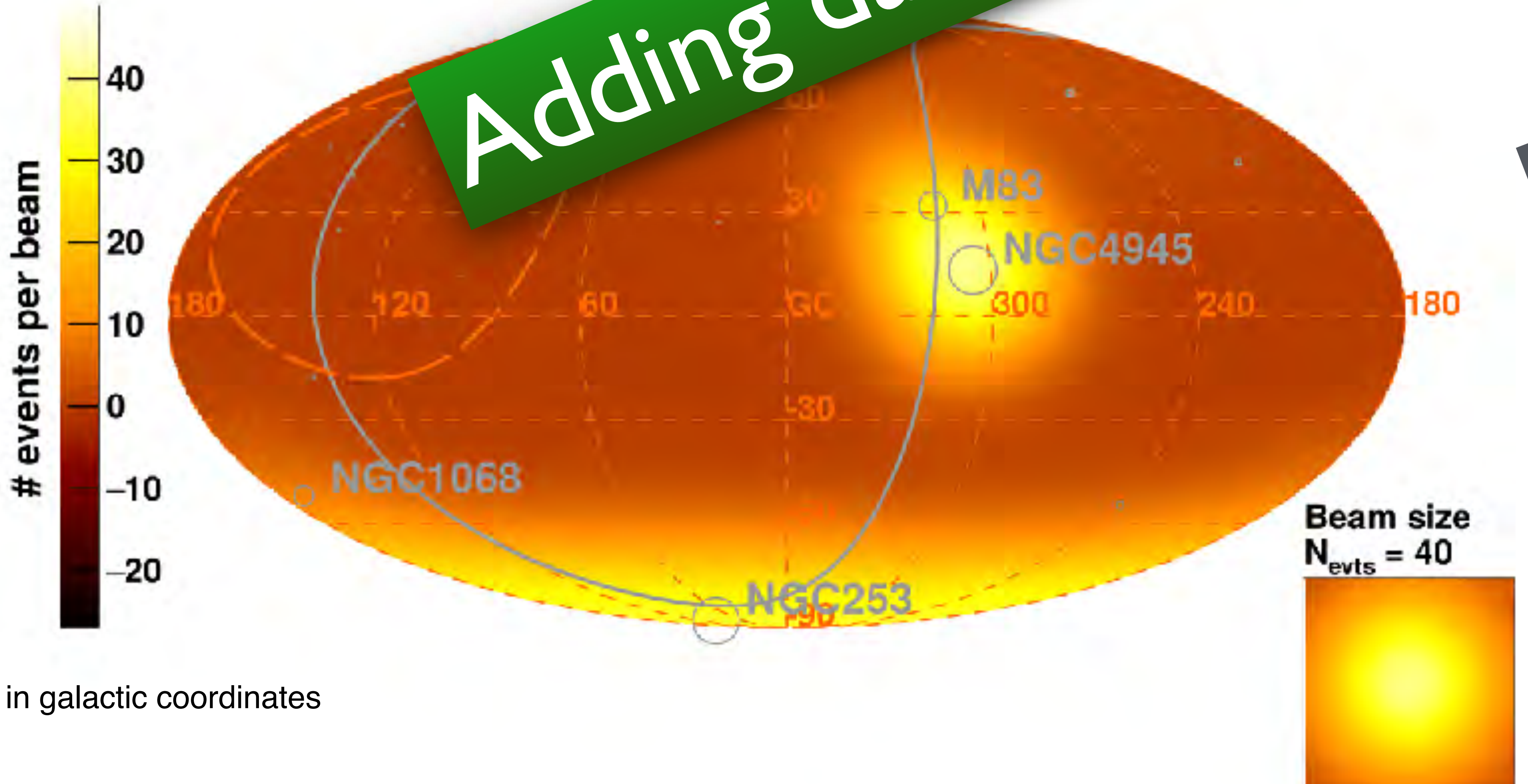


Assume, starburst galaxies produce UHECR with $L_{UHECR} \sim L_{\gamma}$ @ 1.4 GHz

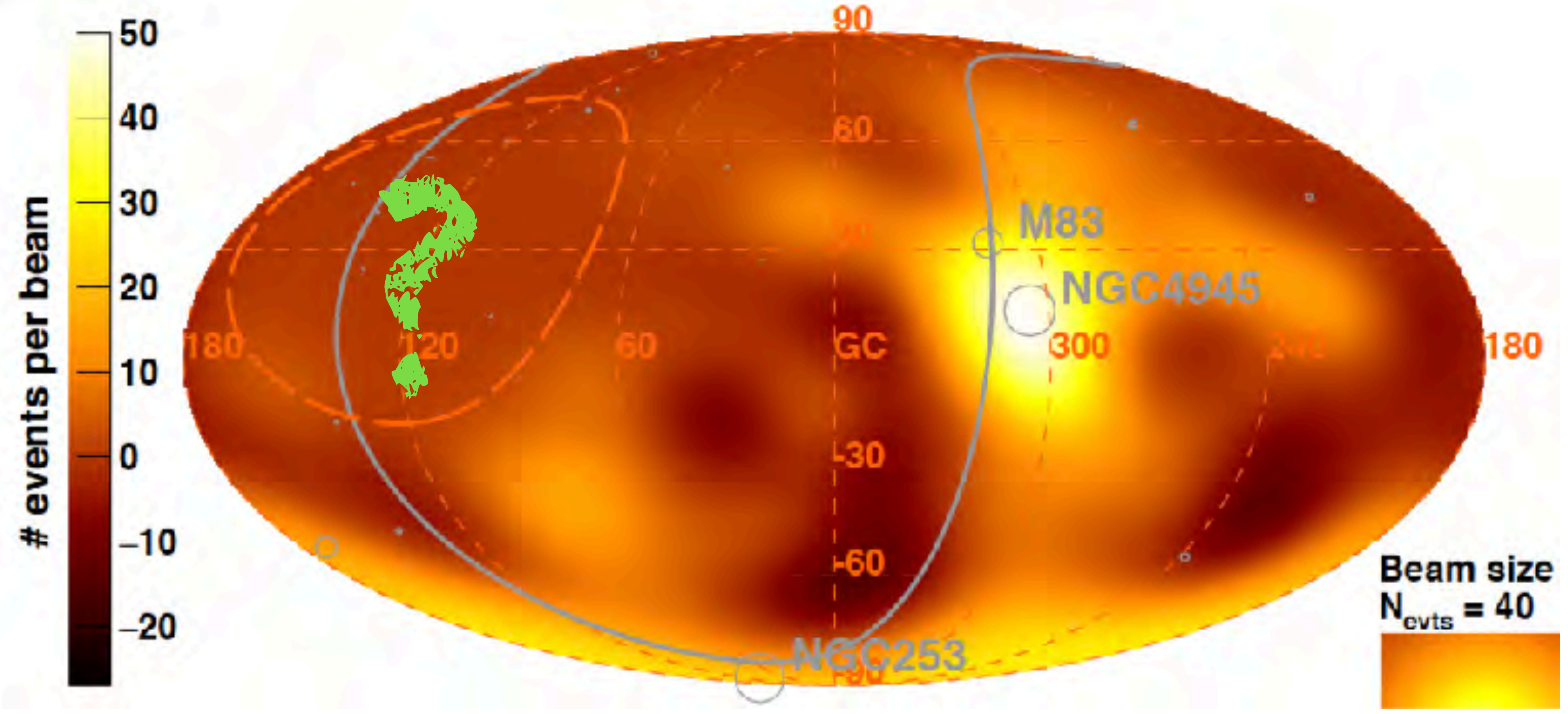
select 23 brightest SBG from Fermi-LAT catalogue and smear s

Adding data from Northern Sky (TA) next logical step

isotropic back… …d…



UHECR data map @ E> 39 EeV

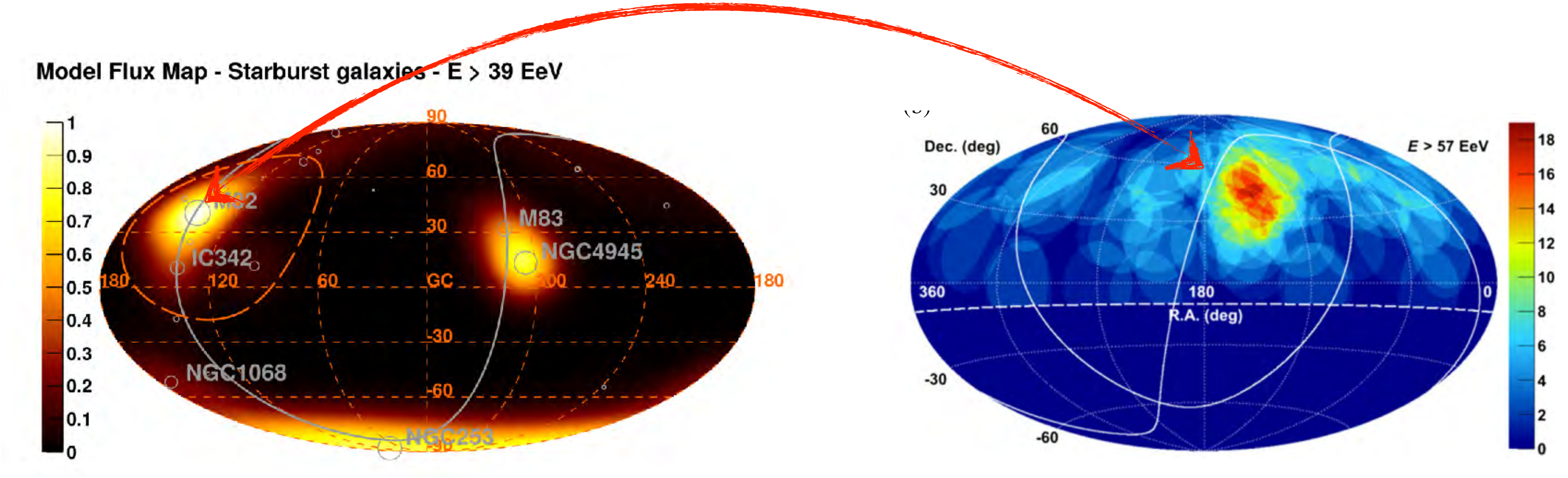


Result: 2MRS-model fits data better than isotropy at 4.0σ

Auger: ApJL 853:L29 (2018)

all in galactic coordinates

TA Hot Spot (M82) may fit into the SBG (2MRS) picture



galactic coordinates **equatorial coordinates**

TA-collaboration, ApJ 790:L21 (2014)

Summary of Results

Spectrum, composition, secondaries

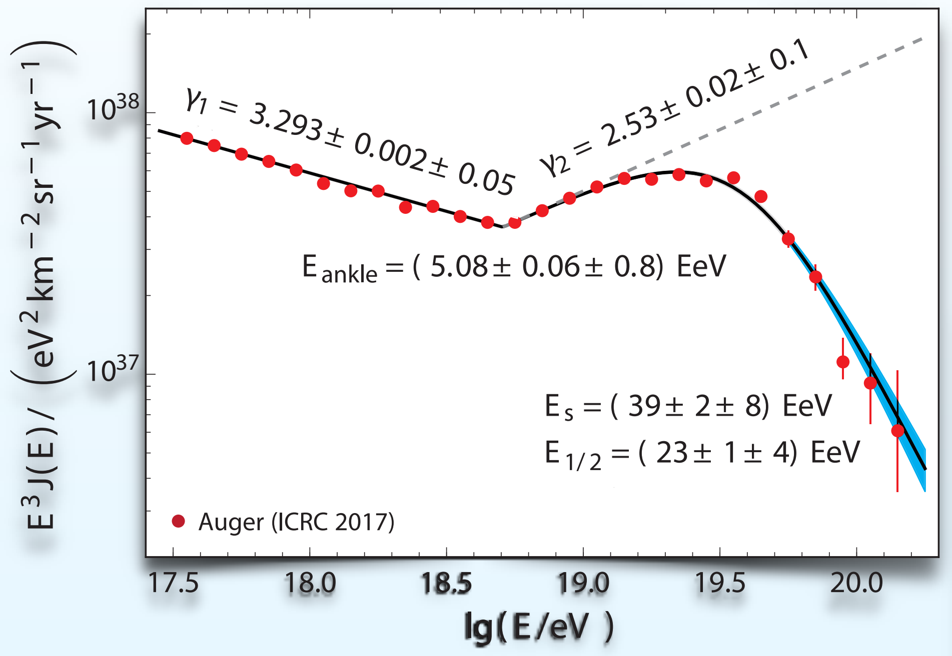
- Strong UHECR flux suppression observed
- Increasingly heavy mass composition observed:
  light at ankle, mixed at UHE
- Proton dominated sources constrained by ν & γ
- Data compatible with rigidity-dependent E_{max}

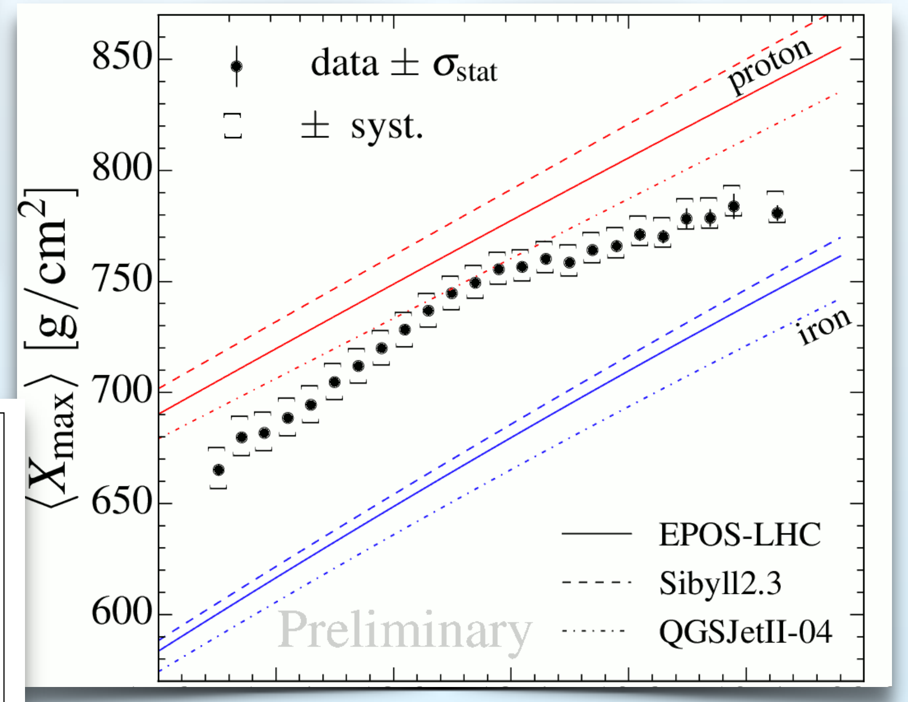
Hadronic Interactions

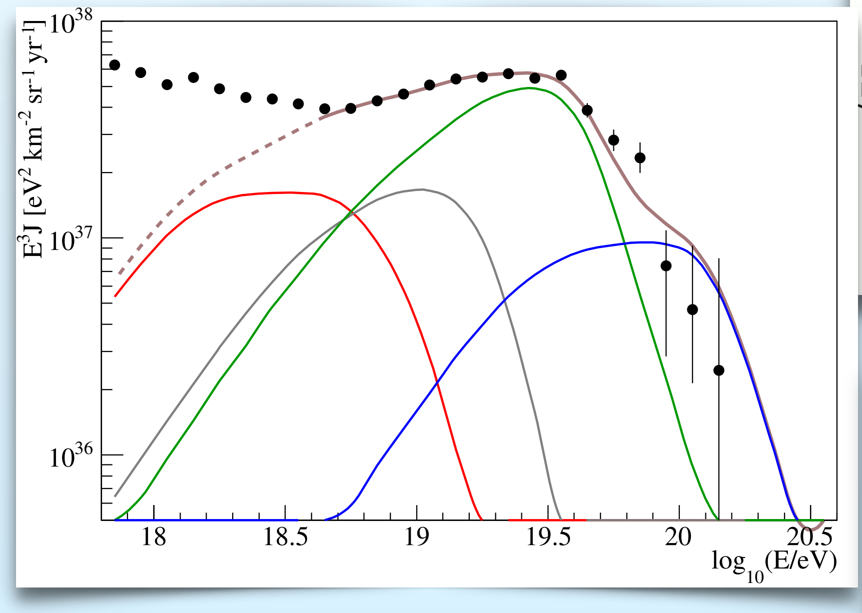
- standard UHE cross sections
- muon deficit in models

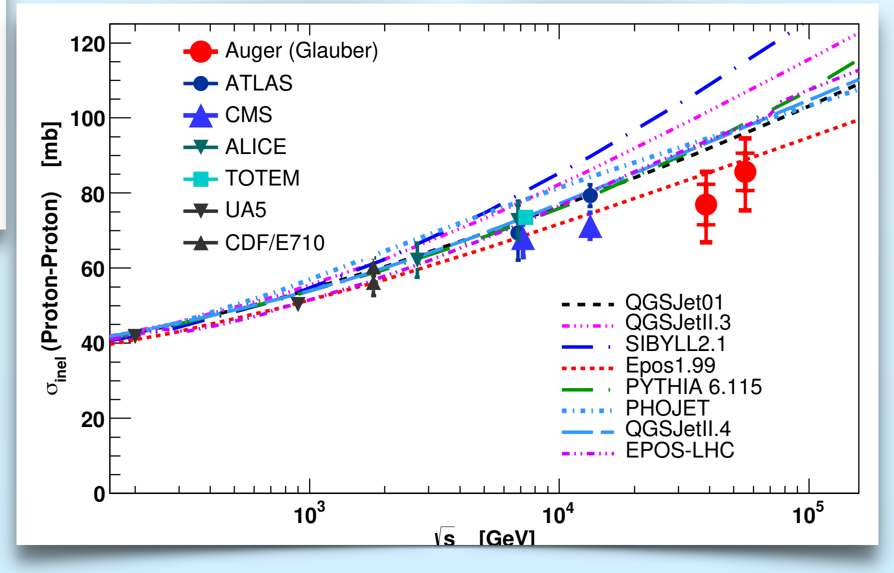
Anisotropies

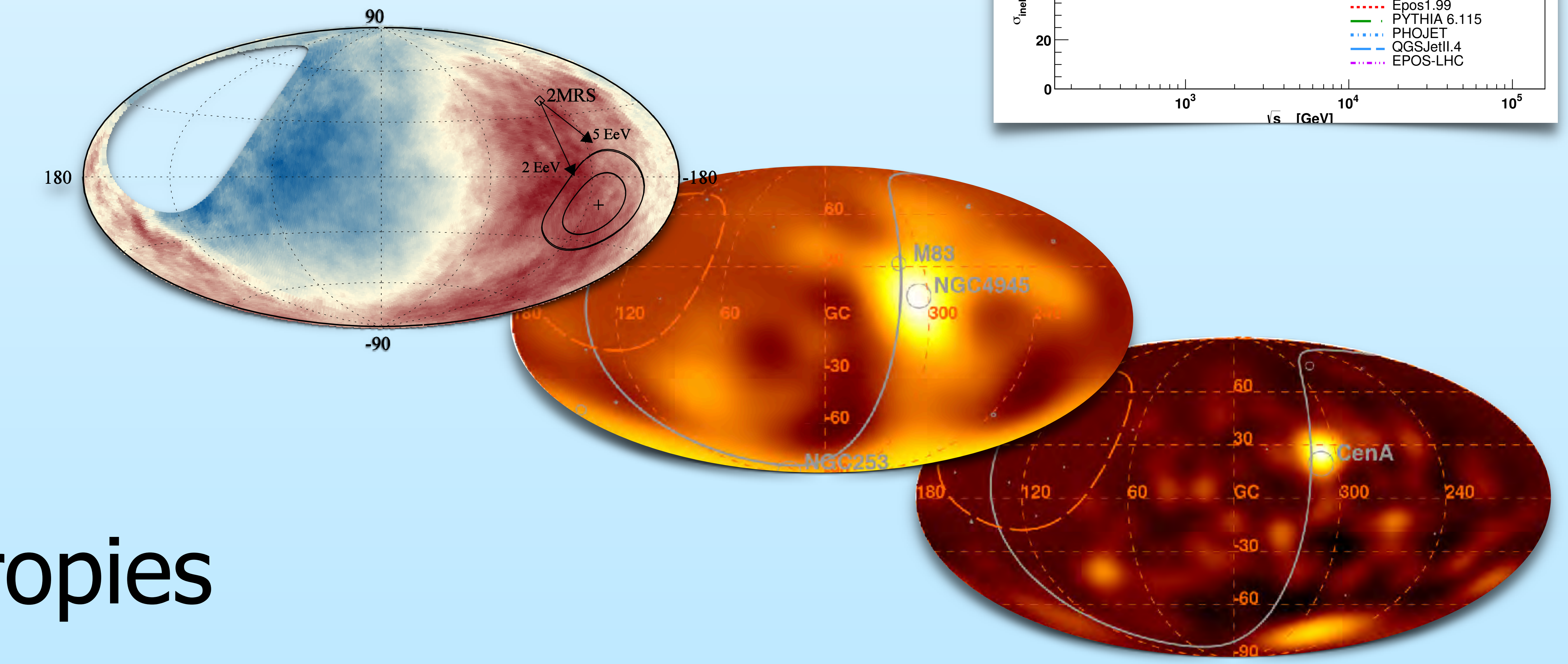
- Observation of dipole like anisotropy
- Indications for intermediate scale anisotropies







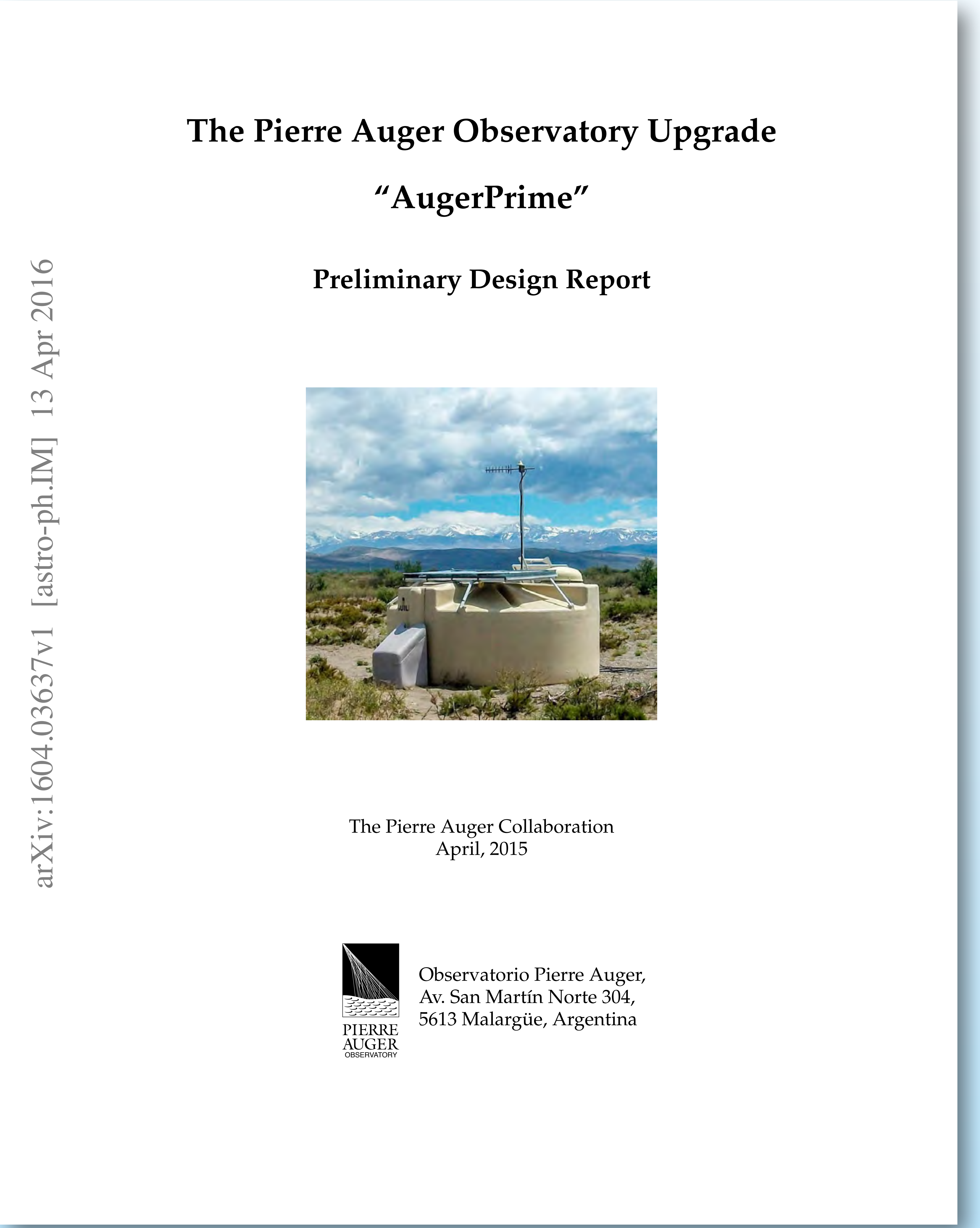




Open Key Questions

- **Origin of the flux suppression ?**
- **Proton fraction at the highest energies ?**
- **Composition enhanced anisotropy**
- **Can we do proton astronomy ?**
- **Hadronic Physics above $\sqrt{s}$ = 140 TeV**

→ **Need large exposure with composition sensitivity !**


arXiv:1604.03637v1 [astro-ph.IM] 13 Apr 2016

The Pierre Auger Observatory Upgrade

"AugerPrime"

Preliminary Design Report

The Pierre Auger Collaboration
April, 2015

PIERRE AUGER OBSERVATORY

Observatorio Pierre Auger,
Av. San Martín Norte 304,
5613 Malargüe, Argentina

AugerPrime

Measure primary mass with 10 times better statistics

- 3.8 m^2 scintillators (SSD) on each 1500 m array stations improve e/μ discr.
- upgrade of station electronics
- additional small PMT to increase dynamic range
- buried muon counters in 750 m array (AMIGA)
- increased FD uptime

Scintillators on top of each Water Cherenkov Tank

(non invasive, fast to install, robust technology, relatively inexpensive)

Time line

- engineering array 09/2016
- construction has started
- deployment to start end 2018
- data taking into 2025

- ☑ do composition enhanced anisotropy
- ☑ p-astronomy: proof of principle
- ☑ particle physics beyond LHC
- ☑ ….

Extremely exciting times
with
great prospects for the near future!

Thank you !