Cosmic Rays at the Highest Energies

Lecture 05/12
In Modern Astro- and Astroparticle Physics
04.12.2020

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BERGISCHE UNIVERSITÄT WUPPERTAL

PIERRE AUGER OBSERVATORY

Bundesministerium für Bildung und Forschung

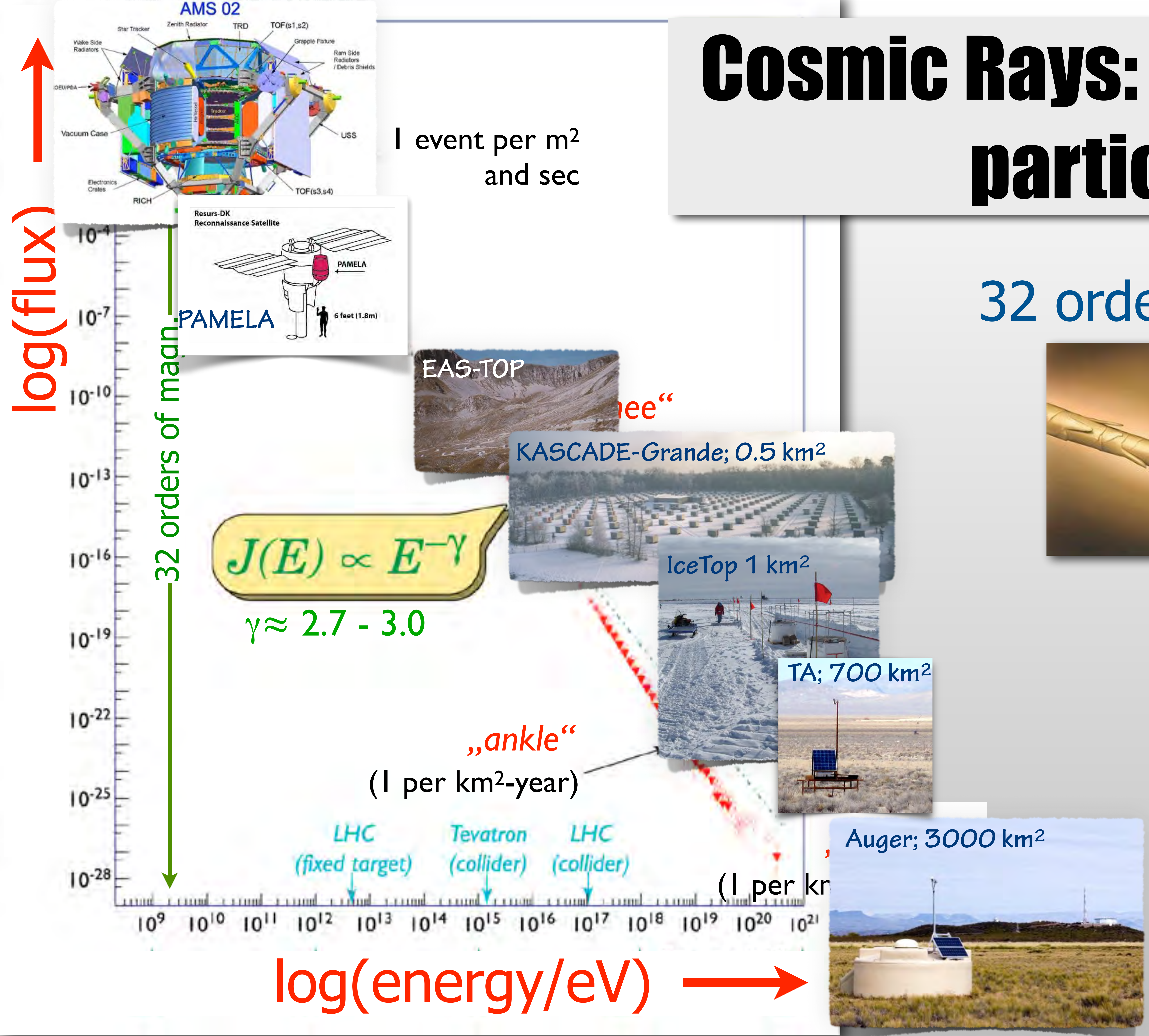
Topics of Lecture Series 2020/2021

06.11.: Dominik Elsässer „Current Generation of ground-based VHE Gamma-Ray Telescopes"
13.11.: Tim Ruhe "The IceCube Neutrino Observatory"
20.11.: Anna Pollmann „Beyond Standard Model Physics with IceCube"
27.11.: Julia Tjus „Understanding Multimessenger Signatures with Cosmic-Ray Propagation and Interaction in Astrophysical Plasmas"

04.12.: Karl-Heinz Kampert „Cosmic Rays at the Highest Energies"

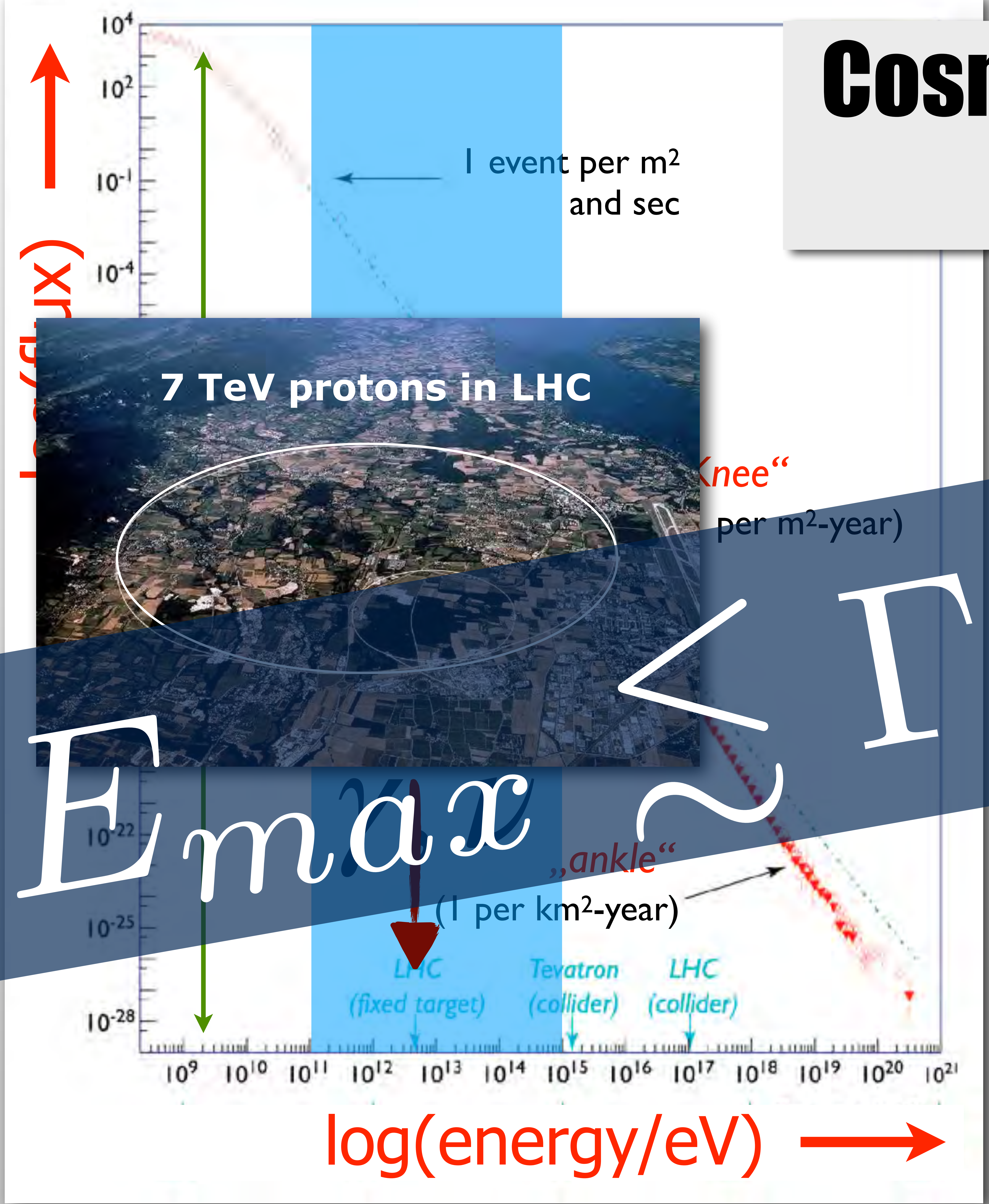
11.12.: Karl Mannheim "Theoretical concepts"
18.12.: Ralf-Jürgen Dettmar "The sky at long wavelengths as seen with LOFAR"
08.01.: Marcus Brüggen "The radio Universe as seen through the Square Kilometre Array and its precursors"
15.01.: Anna Nelles "Radio Detection of Neutrinos and Cosmic Rays"
22.01.: Klaus Helbing „The Mass of the Neutrino and the KATRIN Experiment"
29.01.: Stefan Funk "The Cherenkov Telescope Array"
05.02.: Wolfgang Rhode "Methods and Perspectives for Astroparticle Physics"

Cosmic Rays: the most energetic particles in the Universe



32 orders of magnitude:

Cosmic Rays: the most energetic particles in the Universe



$$E_{max} \sim \Gamma \cdot Z \cdot R \cdot B$$

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

Putative

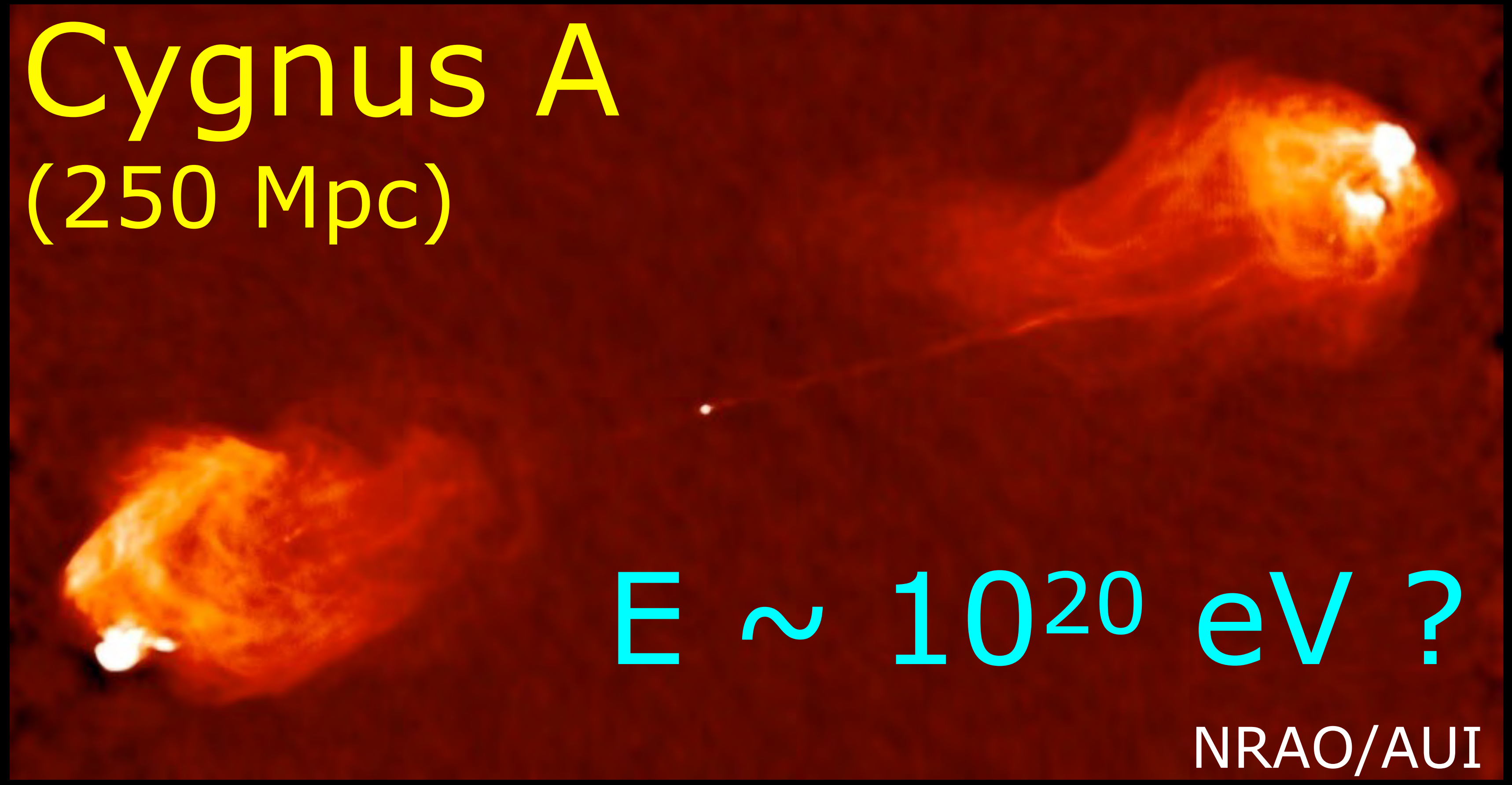
Cosmic Particle Accelerators

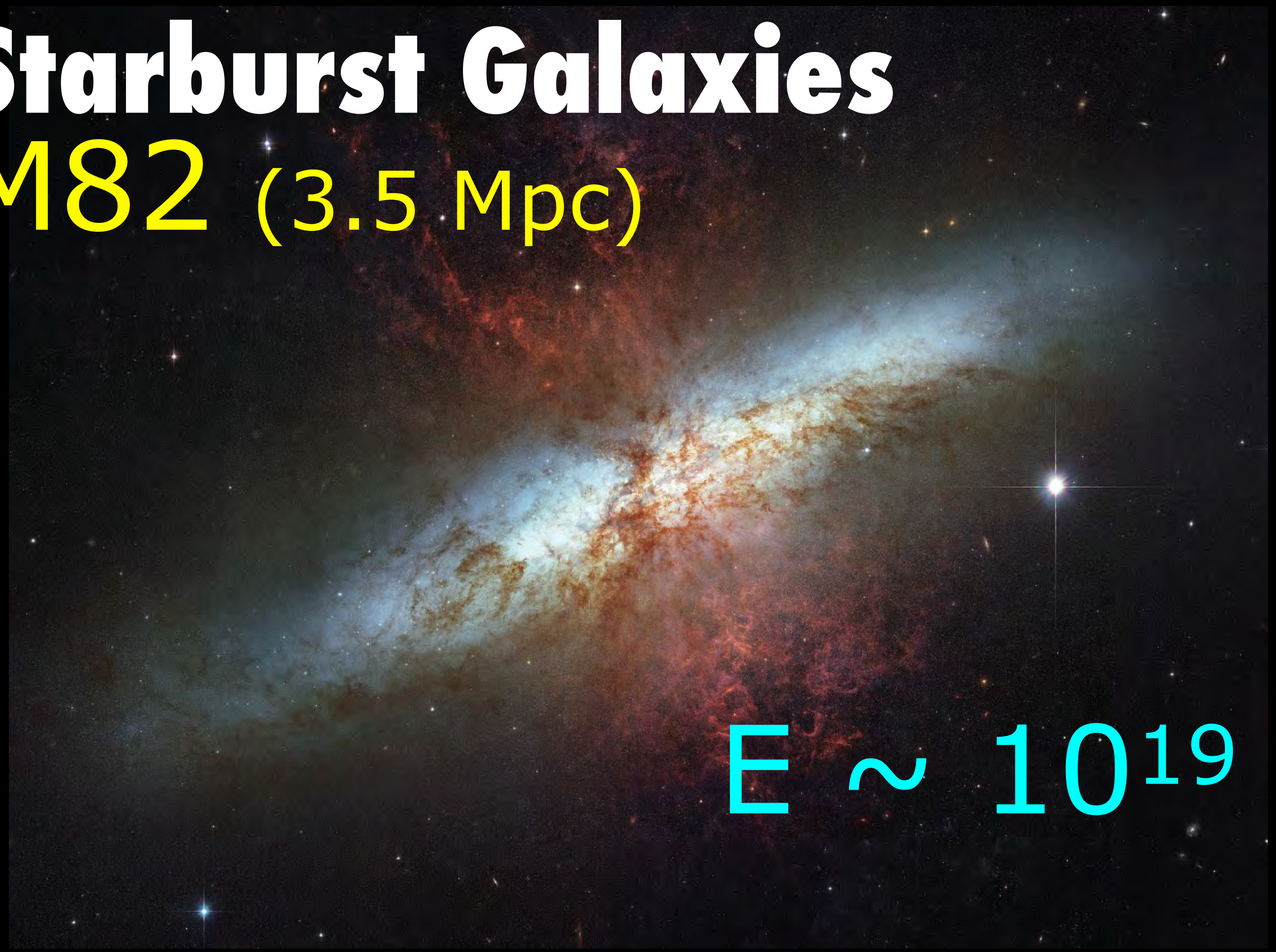
Supernova Remnants

SNR509 (50 kpc) $E < 10^{15}$ eV

particle acceleration at shock waves

AGN and their Jets/Lobes





Themes of UHECR Physics

Cosmic Particle Acceleration

- Where are the most powerful cosmic rays accelerators?
- … and how do they work?
- Does Nature impose any energy limits?
- How do CRs propagate through space?
- What is their impact on the environment? (CR ⇔ B-fields)

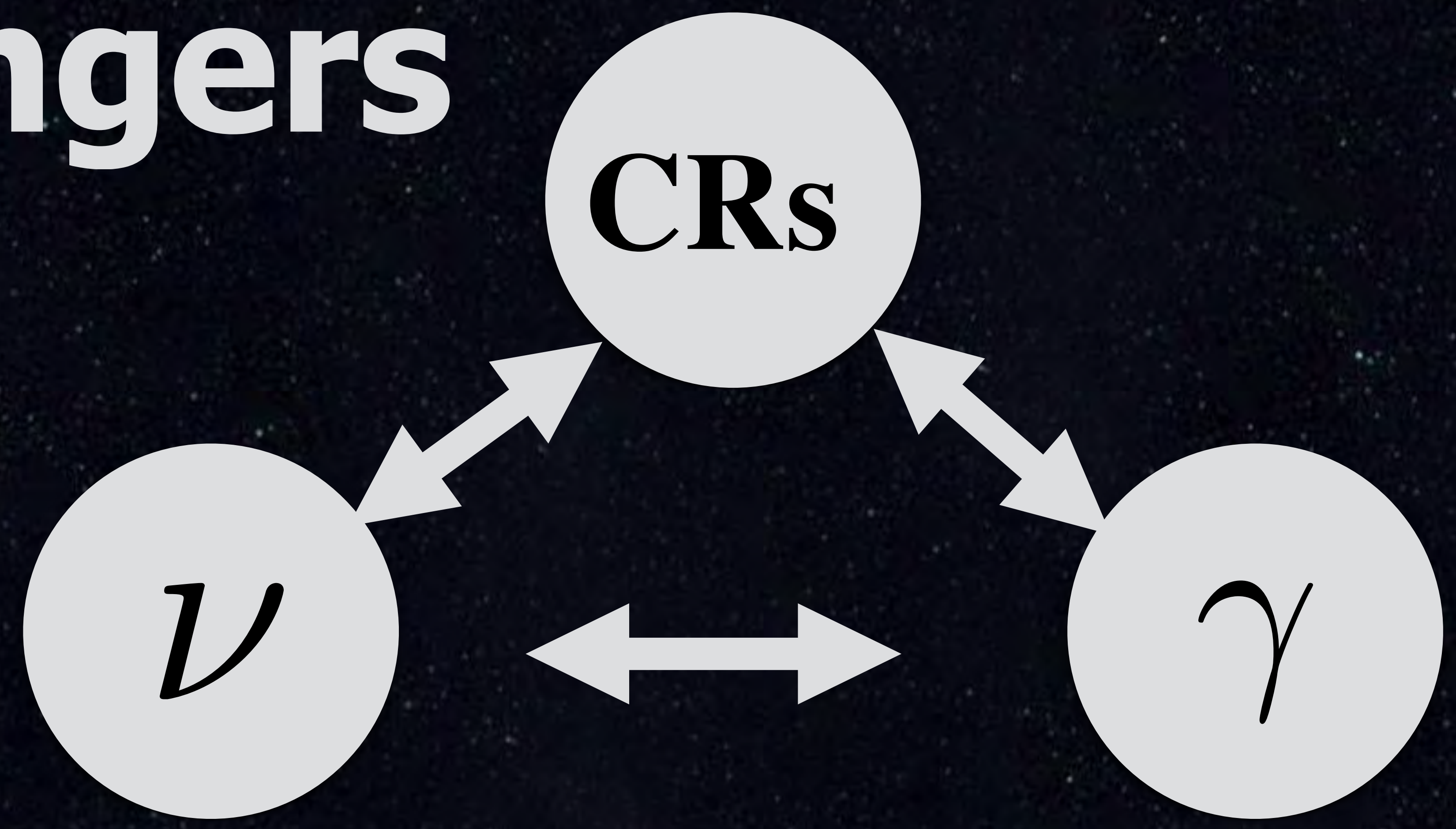
Probing Extreme Environments

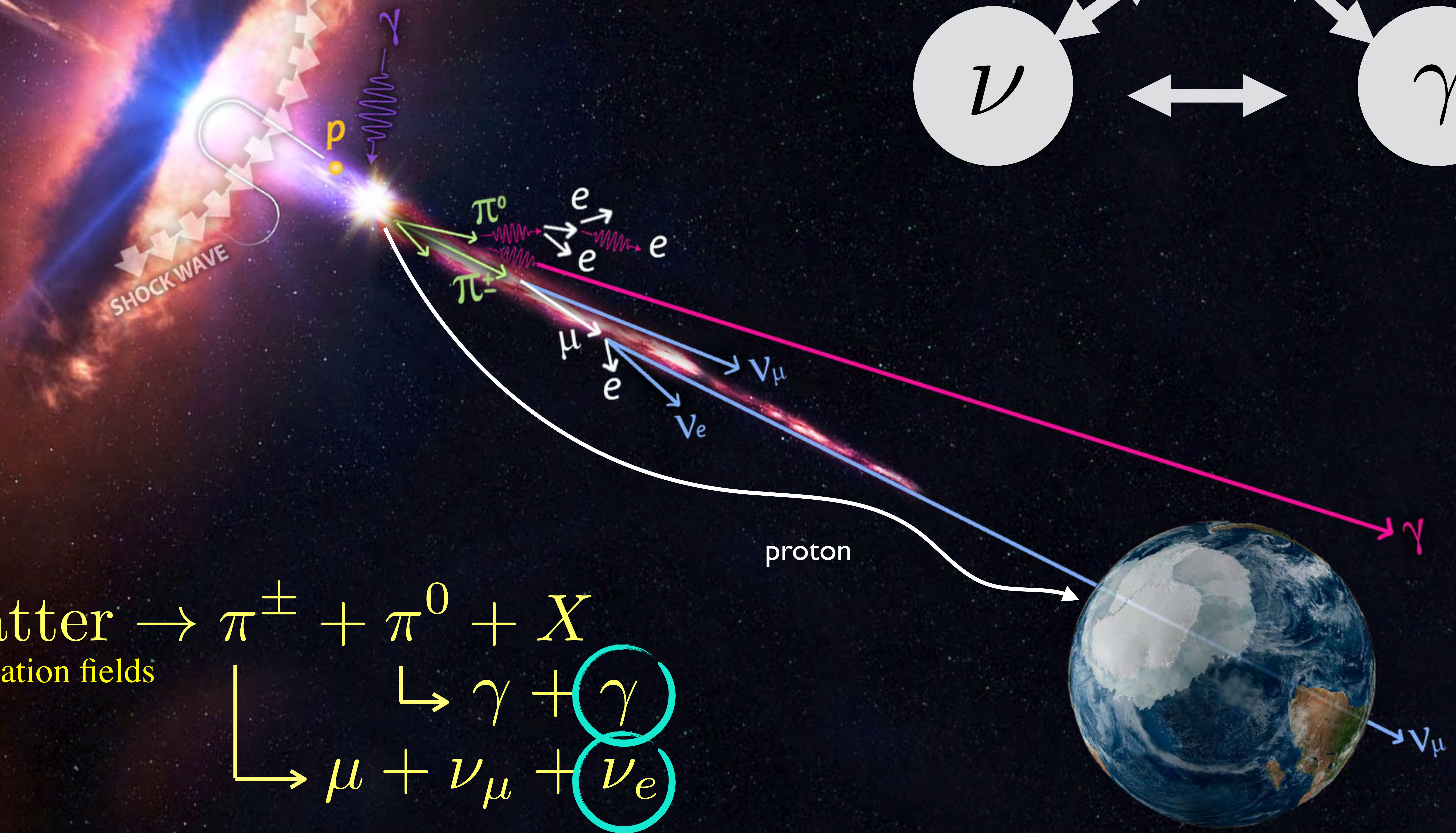
- Processes close to supermassive black holes or GRBs?
- Processes in relativistic jets, winds and radio-lobes?
- Exploring cosmic magnetic fields

Physics Frontiers – beyond the SM

- Lorentz invariance violation; Smoothness of Space-Time
- Particles beyond SM ?
- New particle physics at $\sqrt{s}$=150 TeV ?

The High Energy Cosmic Messengers





$$p_{CR} + \text{matter} \rightarrow \pi^{\pm} + \pi^{0} + X$$

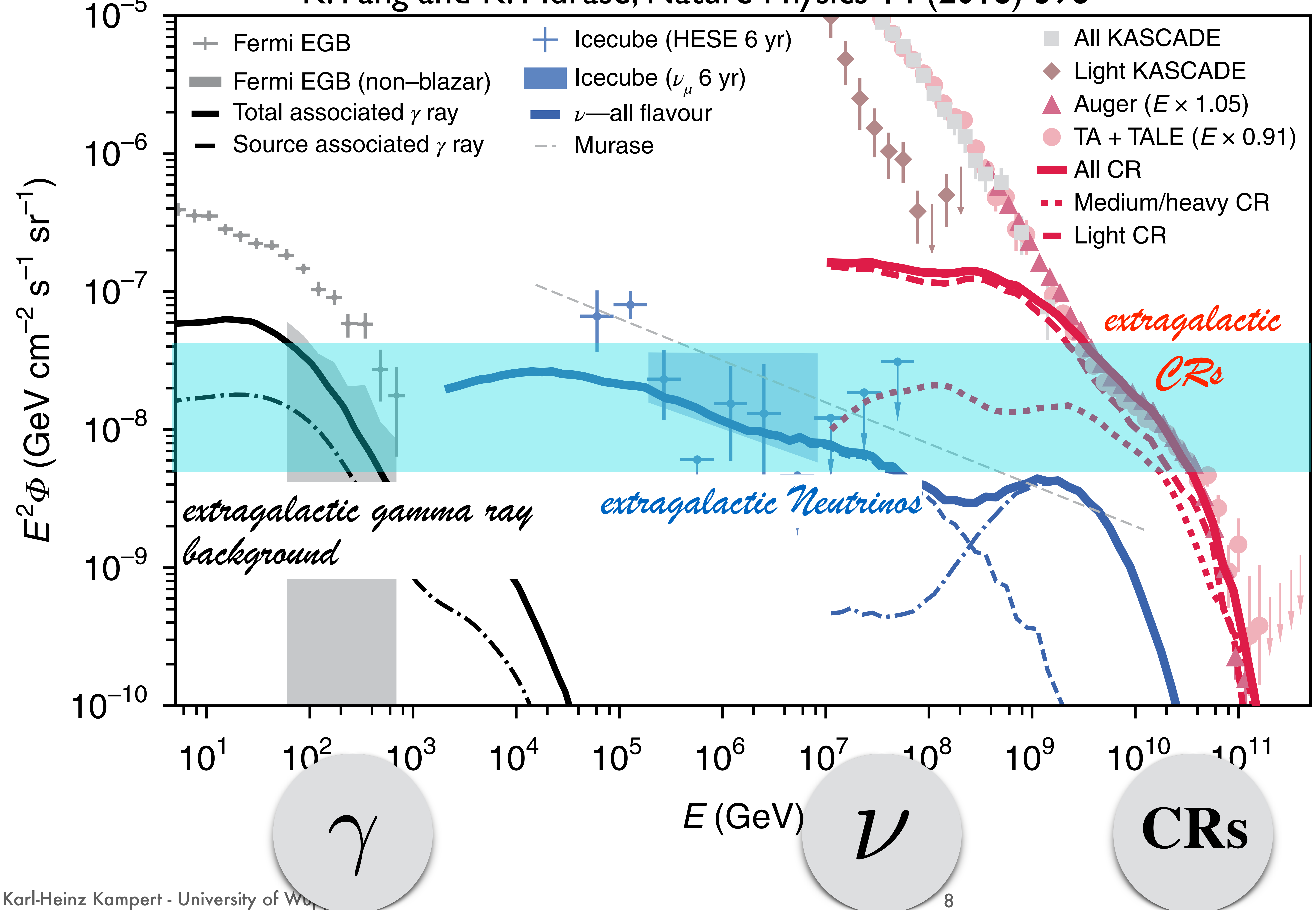
a/o radiation fields

$$\pi^{0} \rightarrow \gamma + \gamma$$

$$\pi^{\pm} \rightarrow \mu + \nu_{\mu} + \nu_{e}$$

Cosmic Coincidence or Grand Unified Picture ?

K. Fang and K. Murase, Nature Physics 14 (2018) 396



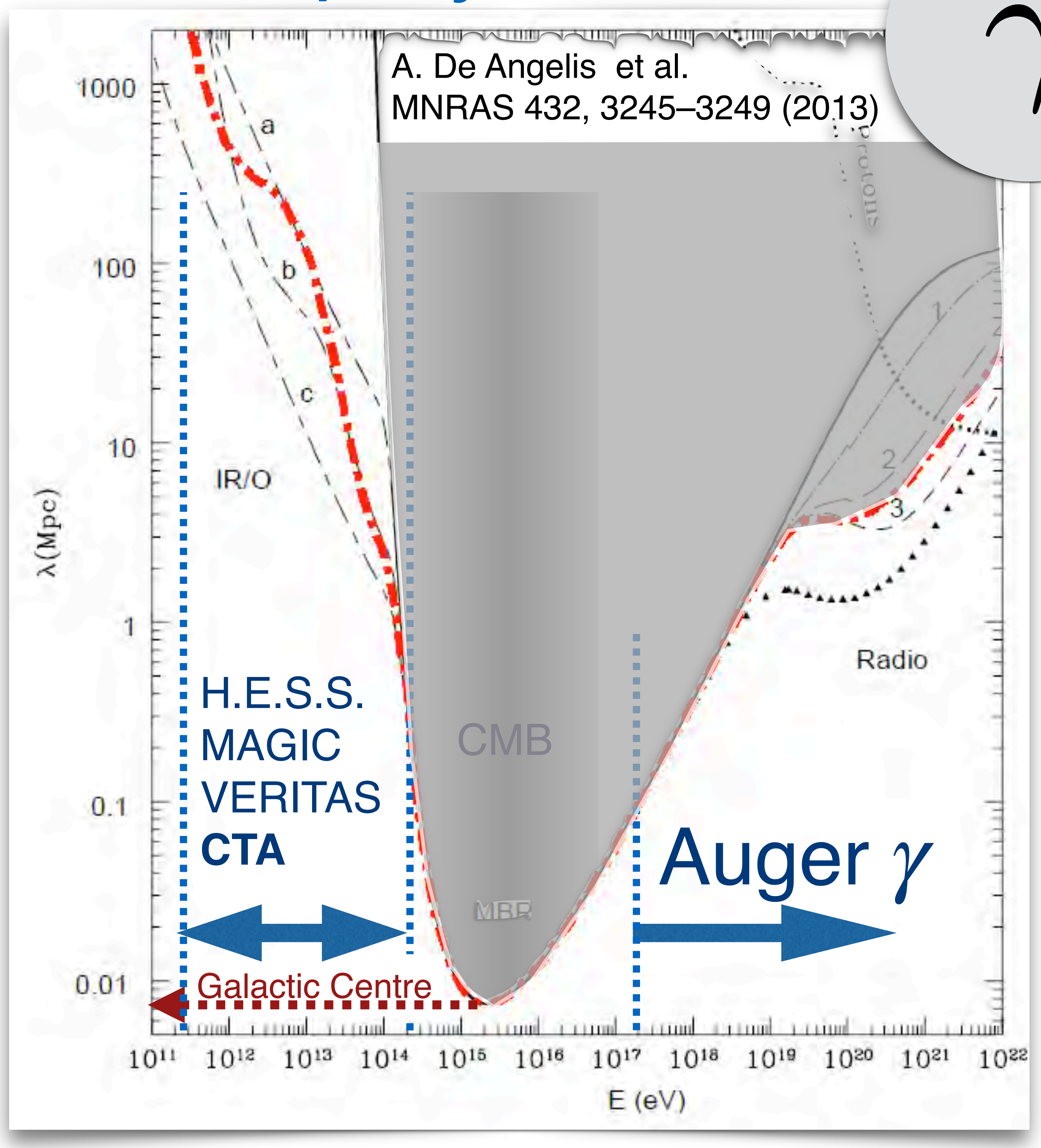
10 orders of magnitude in energy, but $E^2 \cdot \Phi$ is about the same

→ energy generation rates per decade in E are the same

Suggests again a common / related origin

No „Best" Messenger

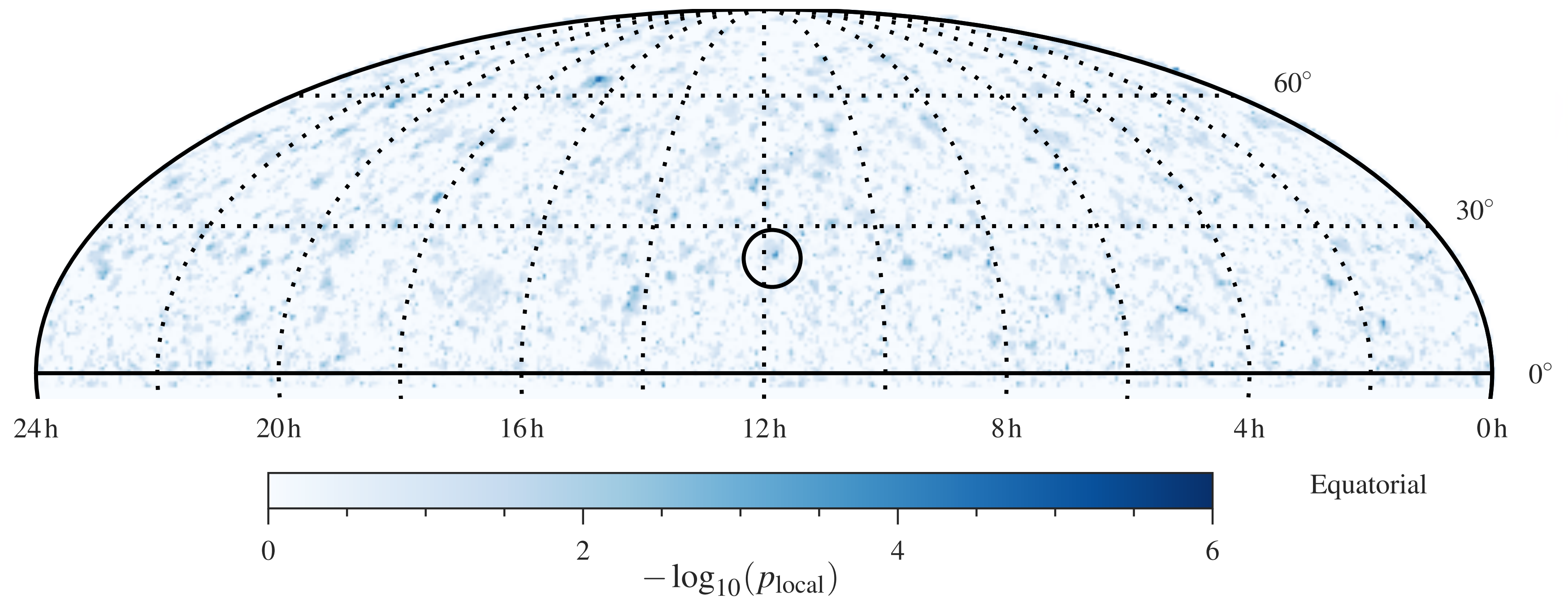
γ-ray horizon



- ⊕ straight lines
- ⊕ unexplored at >10^{17} eV
- ⊖ UHE Horizon < 10 Mpc
- ⊖ no clean probe of hadron acceleration

HE-Neutrino Sky

IceCube, EPJ 2019 (arXiv:1811.07979)

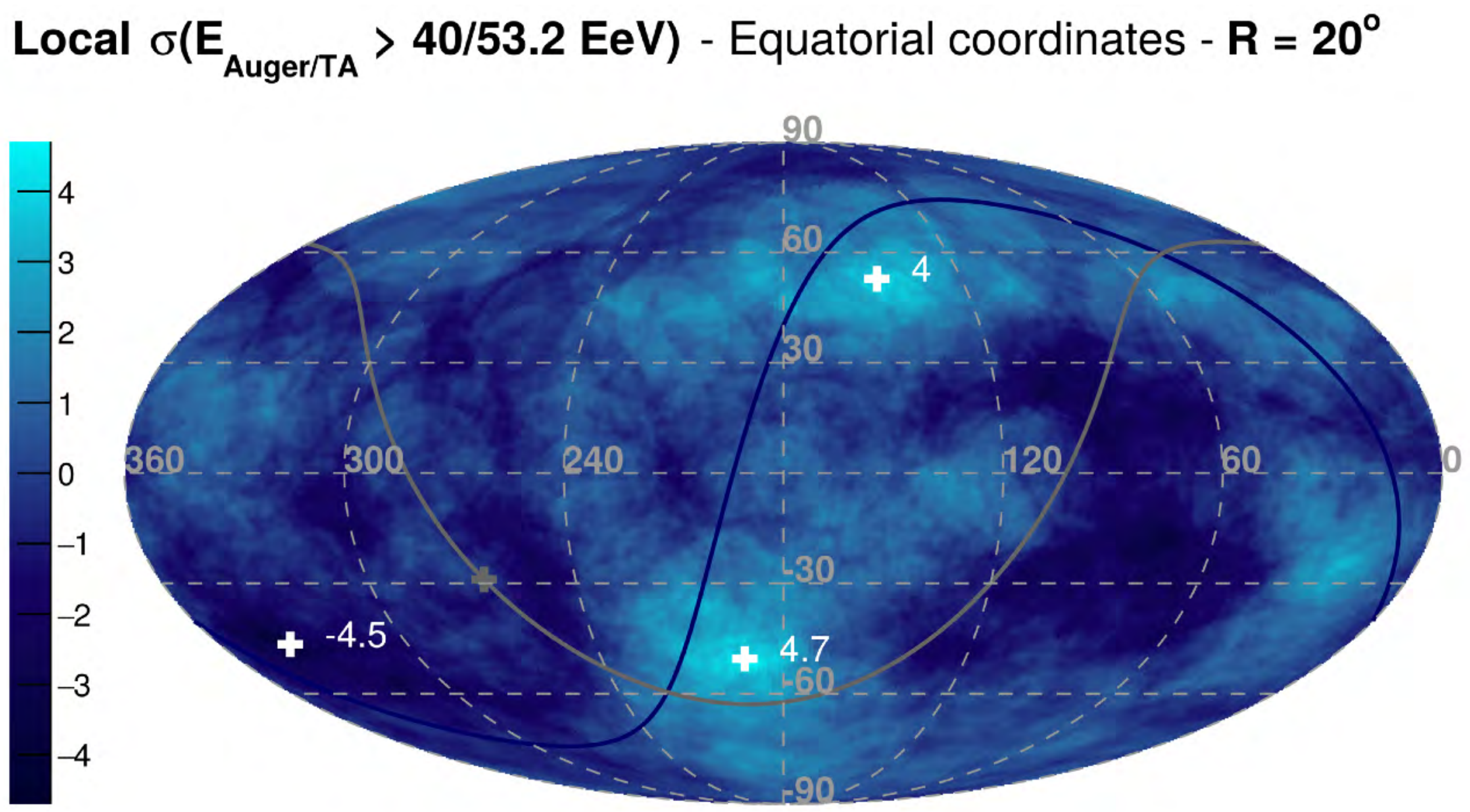


- ⊕ straight lines
- ⊕ clean hadronic probe
- ⊖ Horizon = Hubble ⇒ isotropic
- ⊖ (non bursting) point sources difficult

UHECR Sky

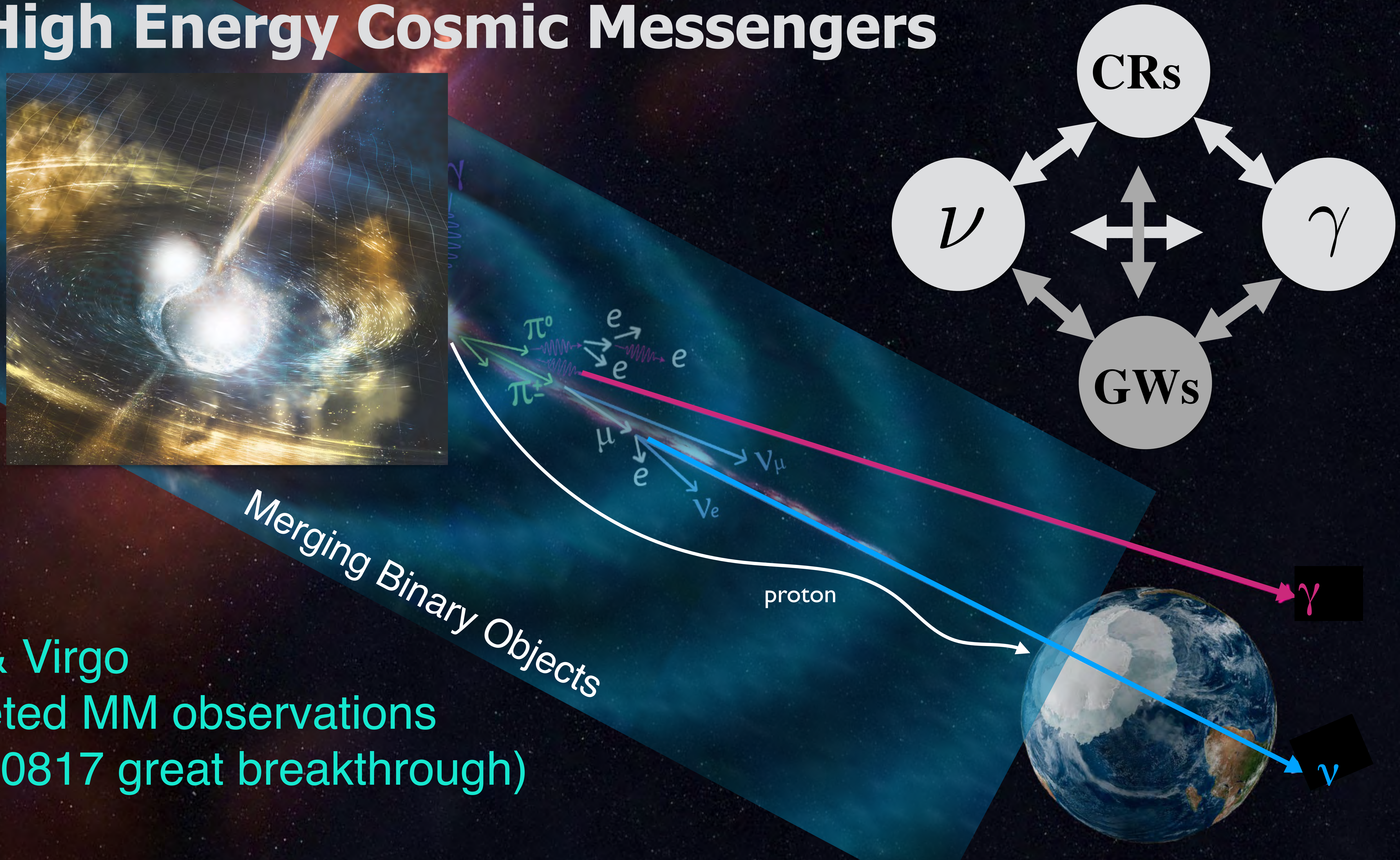
above 40 EeV

Auger & TA Working Group at ICRC 2019



- ⊕ the only direct probe
- ⊕ probes extreme accelerator
- ⊕ chemical composition
- ⊕/⊖ Horizon some 100 Mpc
- ⊖ deflection in magnetic fields

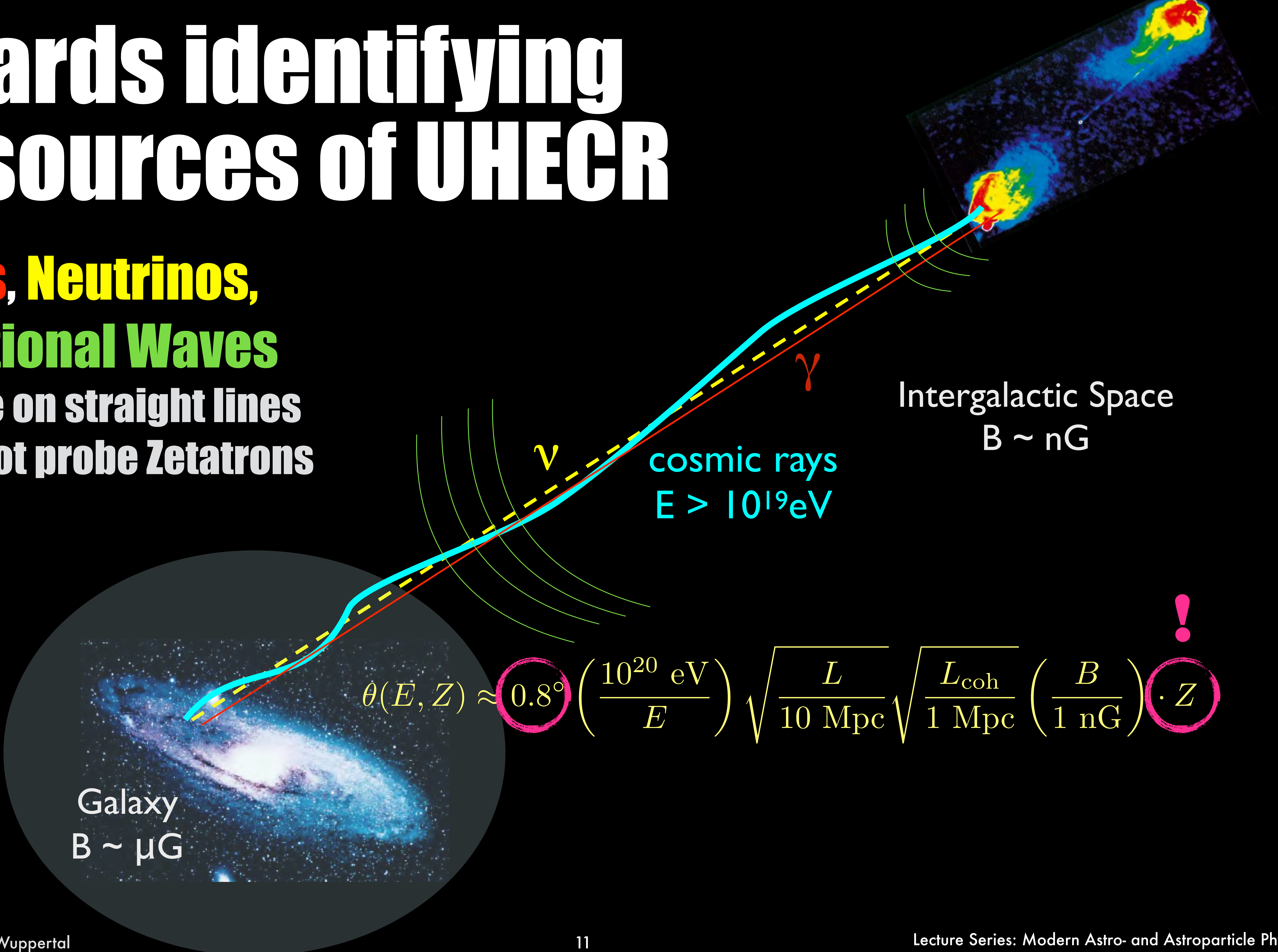
The High Energy Cosmic Messengers



LIGO & Virgo
completed MM observations
(GW170817 great breakthrough)

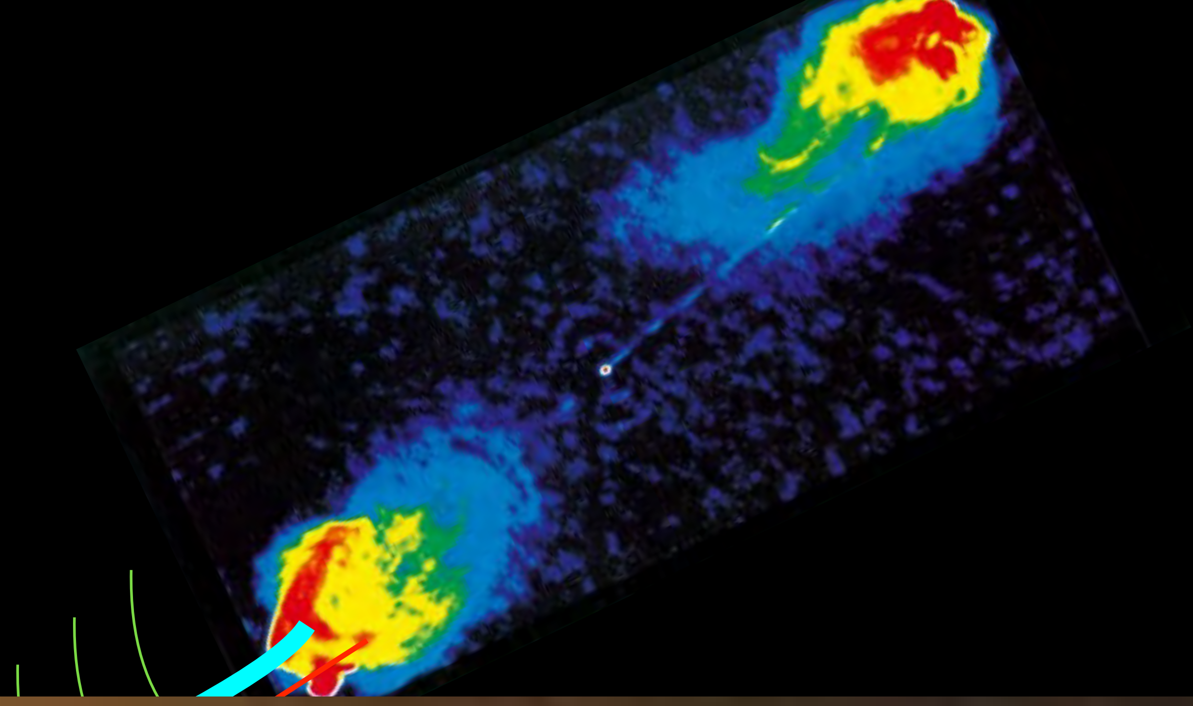
Towards identifying the sources of UHECR

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

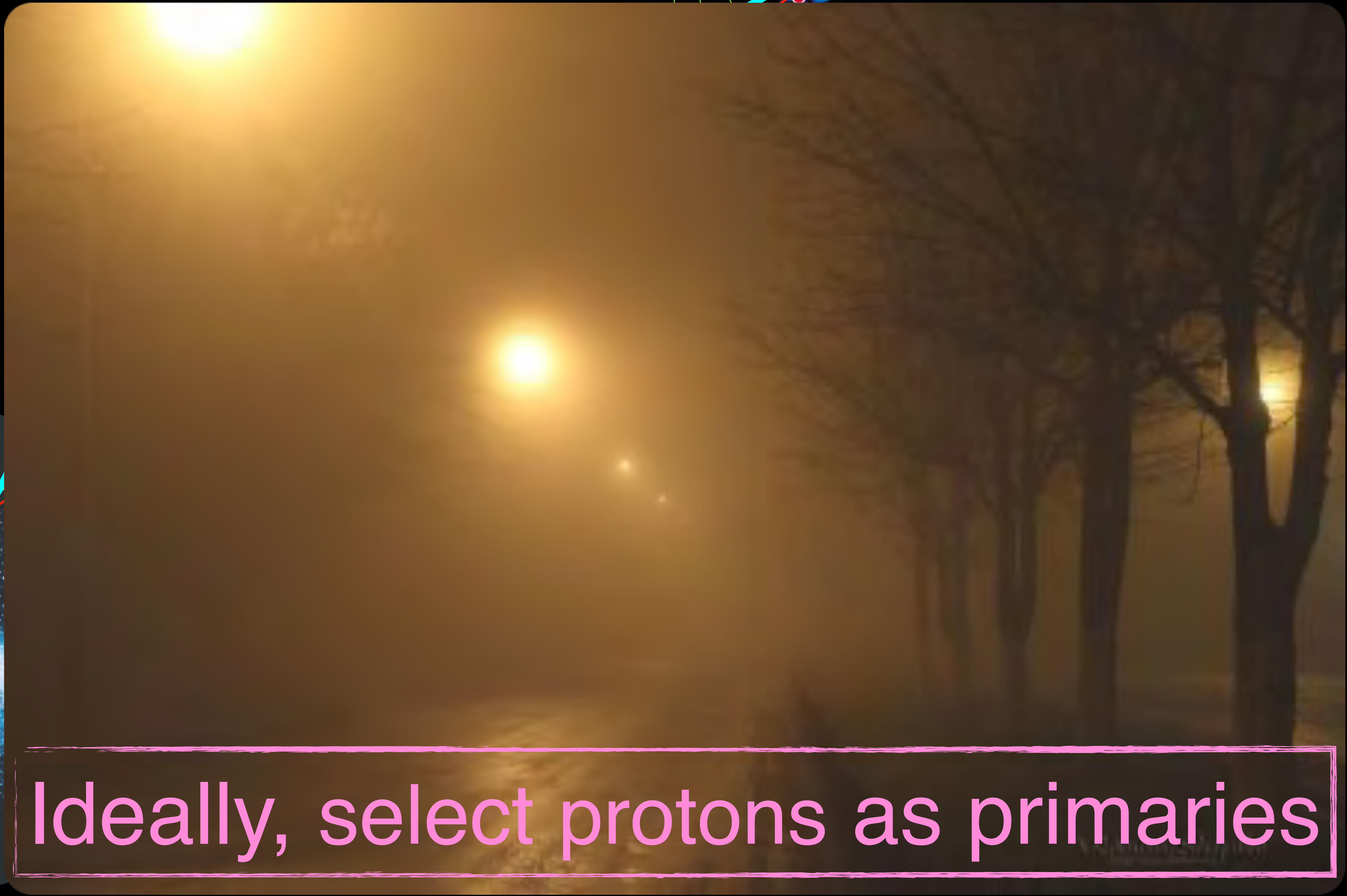


$$\theta(E,Z) \approx 0.8^{\circ} \left(\frac{10^{20}\ \mathrm{eV}}{E}\right) \sqrt{\frac{L}{10\ \mathrm{Mpc}}} \sqrt{\frac{L_{\mathrm{coh}}}{1\ \mathrm{Mpc}}} \left(\frac{B}{1\ \mathrm{nG}}\right) \cdot Z$$

Towards identifying the sources of UHECR



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



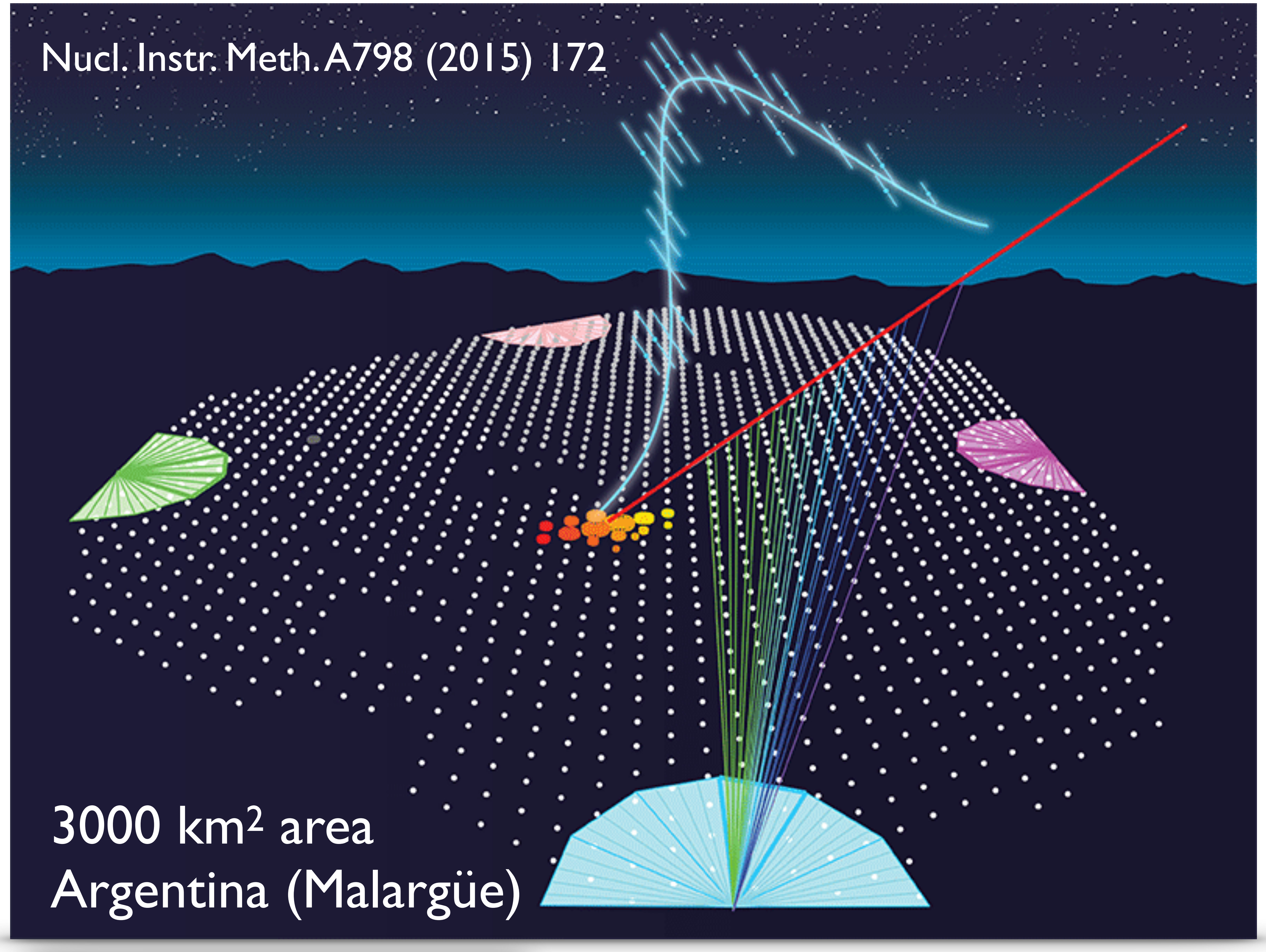
Ideally, select protons as primaries

Multi Hybrid Detection of EAS

Fluorescence Light

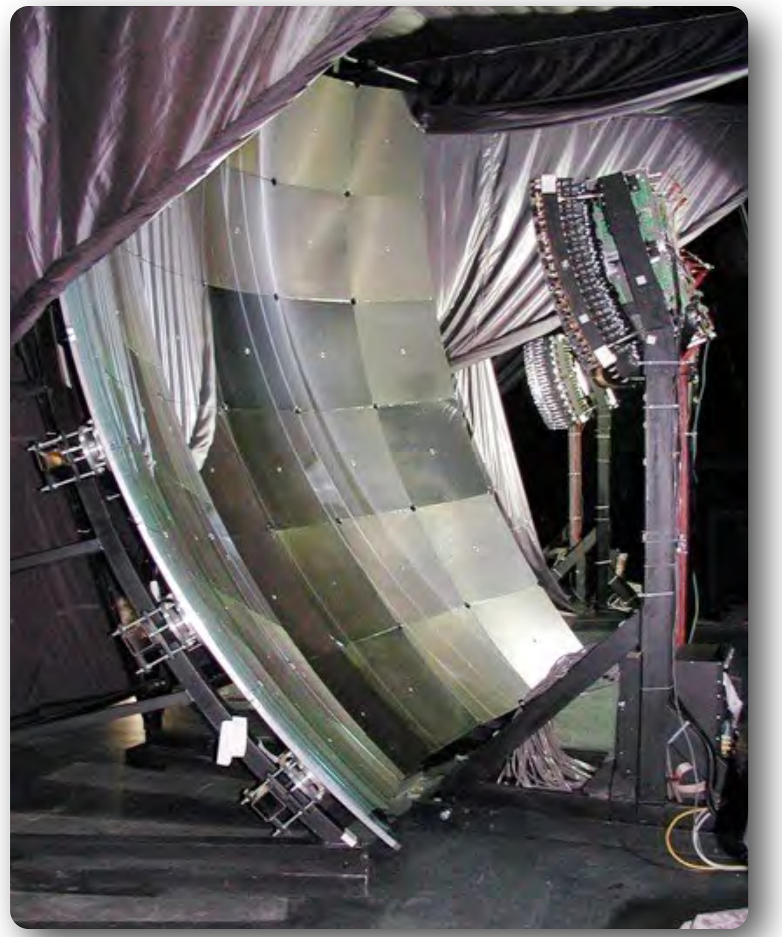
Particle & Radio Footprint at Ground

Multi Hybrid Detection of UHECR: Auger Observatory



- 1400 m altitude
- 35° S, 69° W

❶



- 27 Telescopes to measure **light trace of EAS** in atmosphere
- integrated light intensity → CR energy
- 13% duty cycle

❷

- 1660 Water Cherenkov detectors on 1.5 km grid to measure footprint of **particles at ground**
- 100% duty cycle
- cross calibrated with FD-telescopes with hybrid events

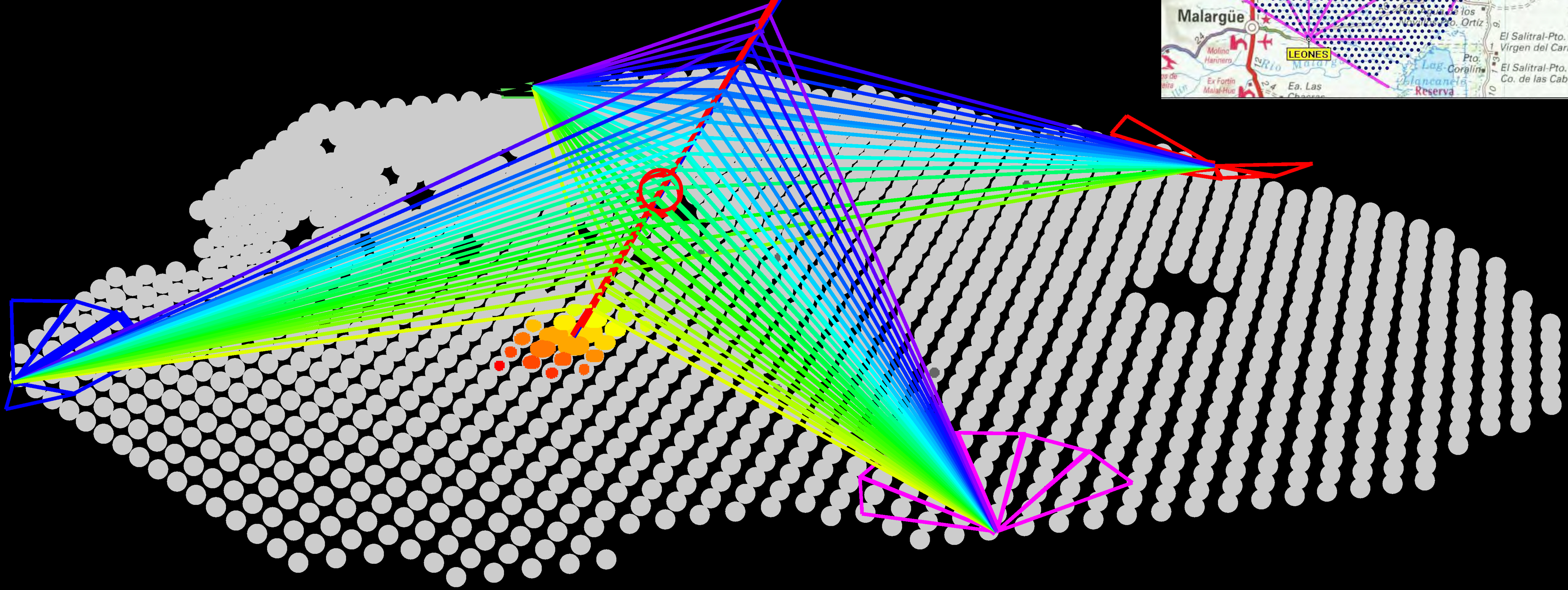
❸

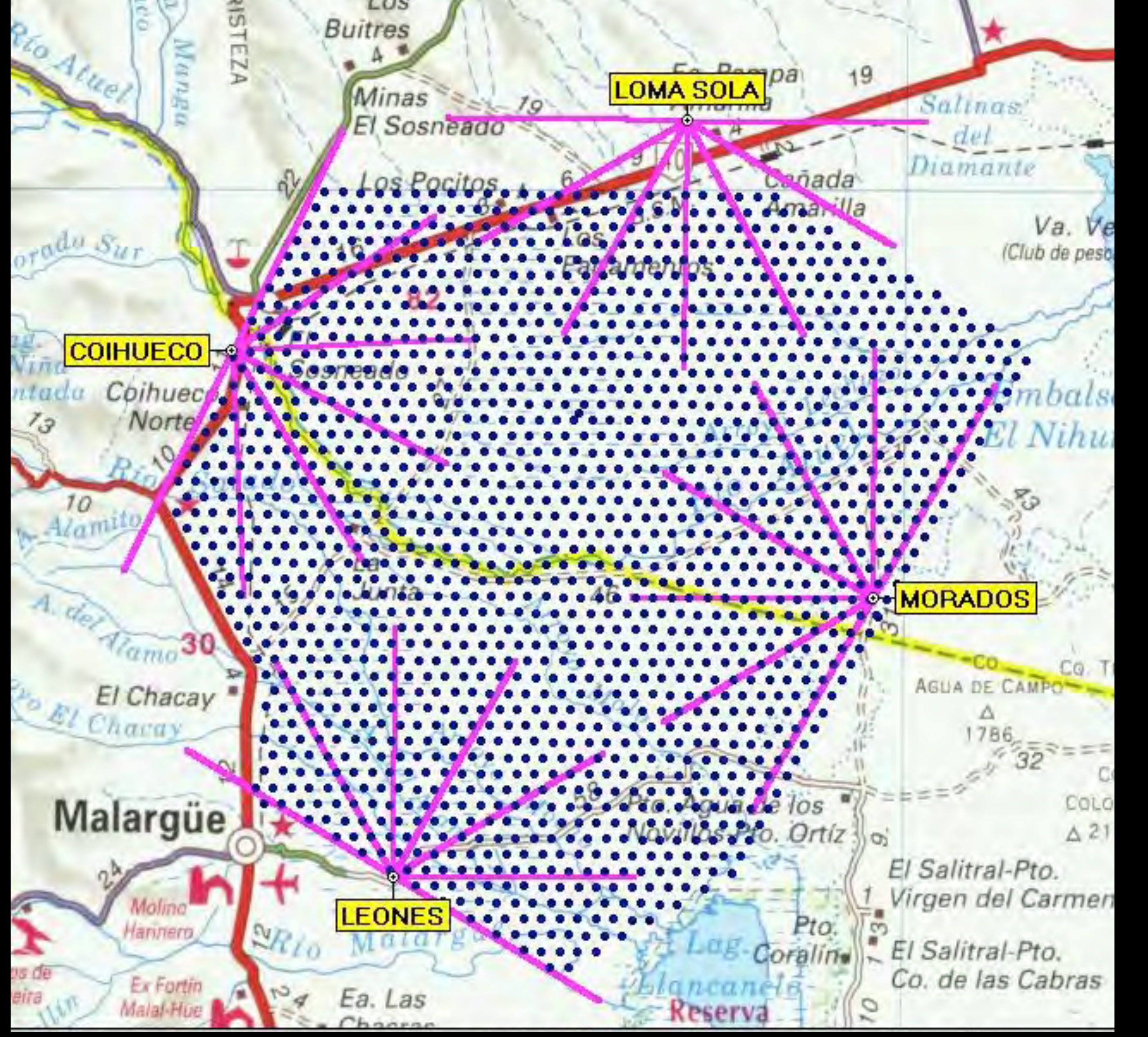
- 153 radio antennas for **em-radiated energy**
- 18 km² area
- 100% duty cycle

Central campus with visitors center

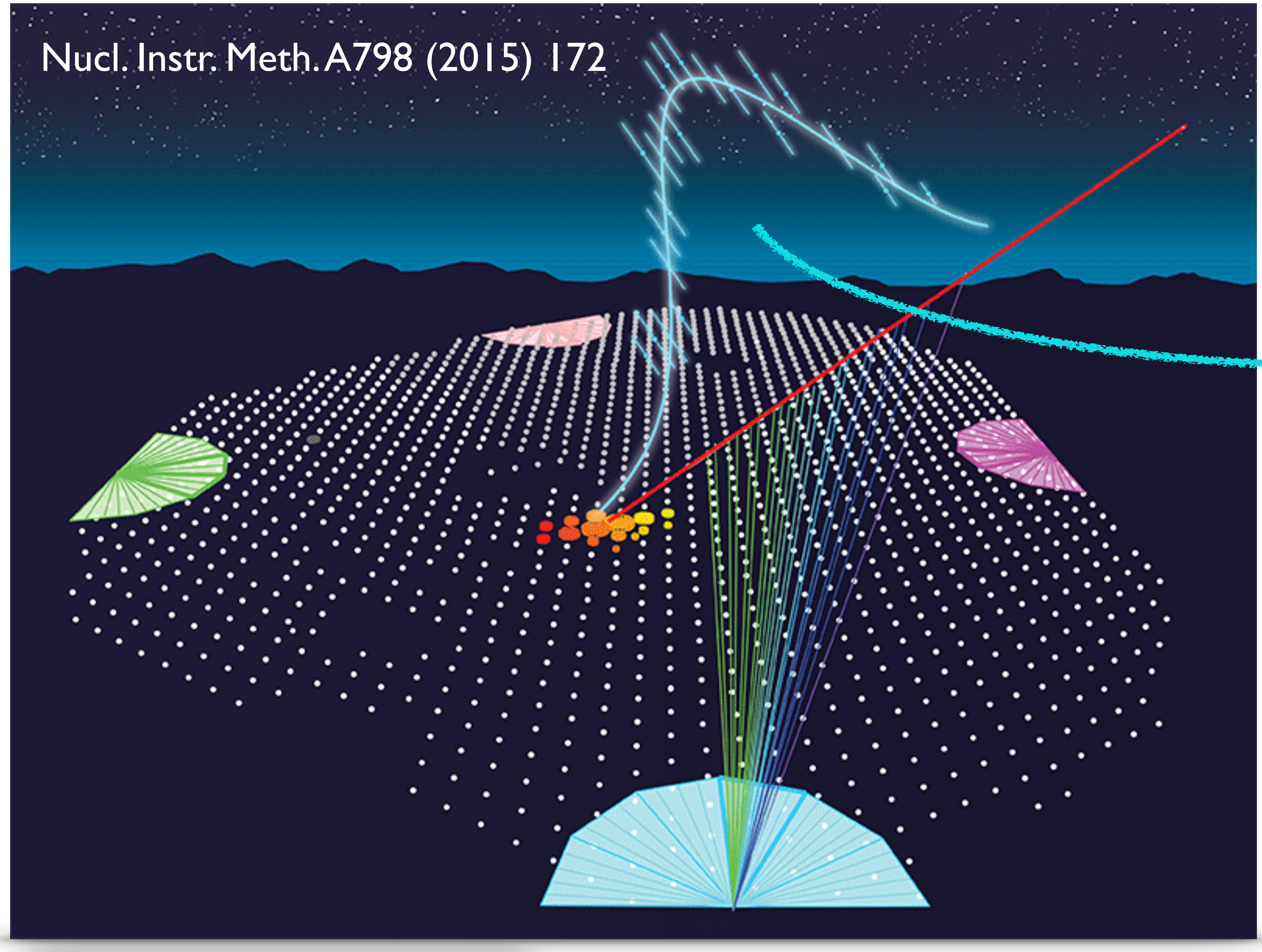
A quadruple event

4 Telescopes + 20 km2 Footprint

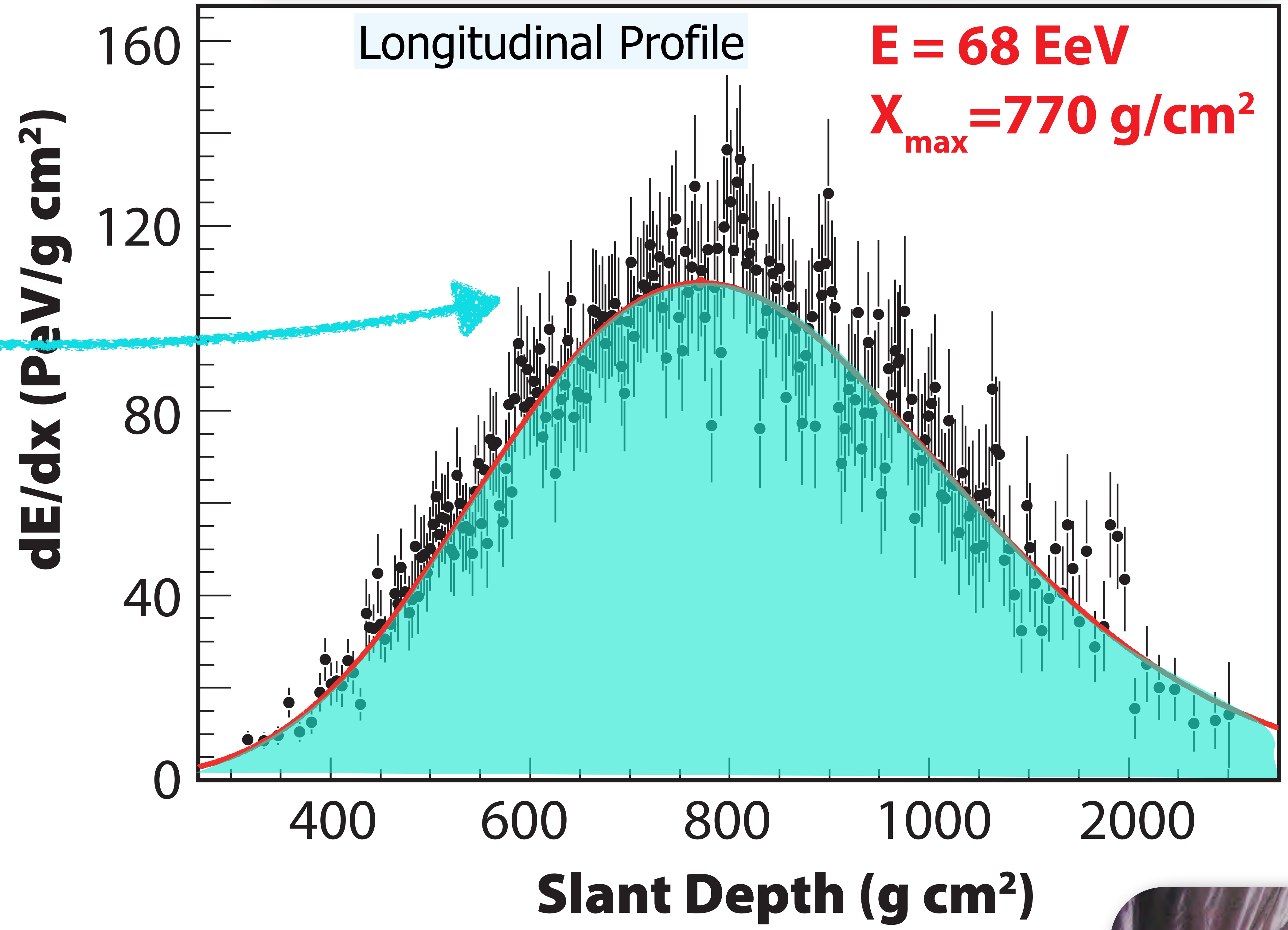




Calibrating the Primary Energy



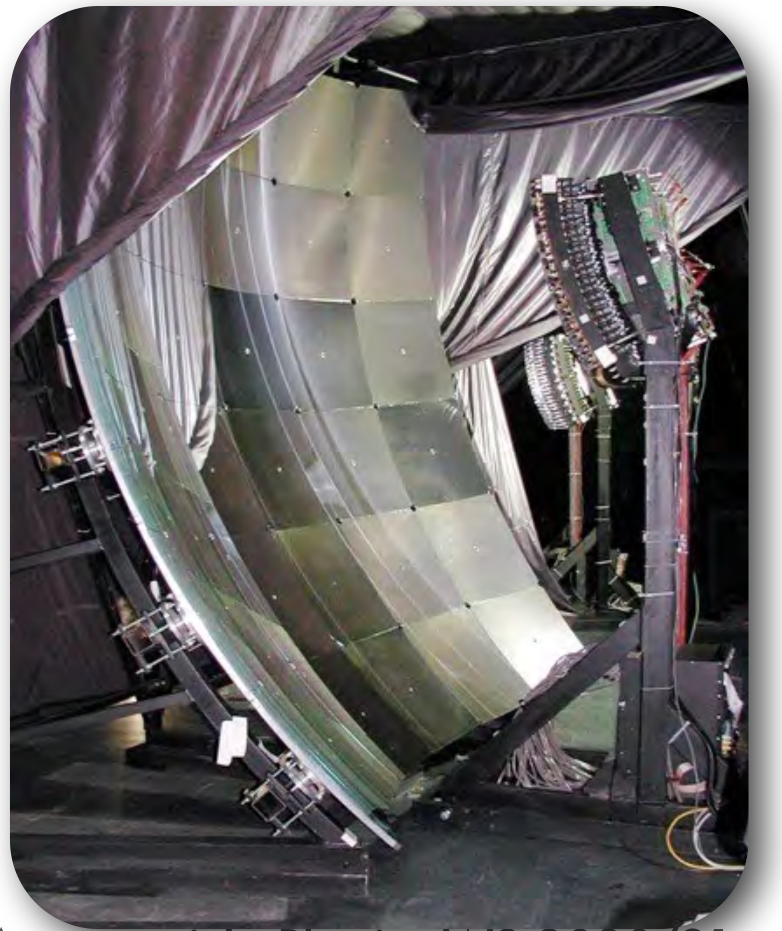
absolute E-scale from light intensity



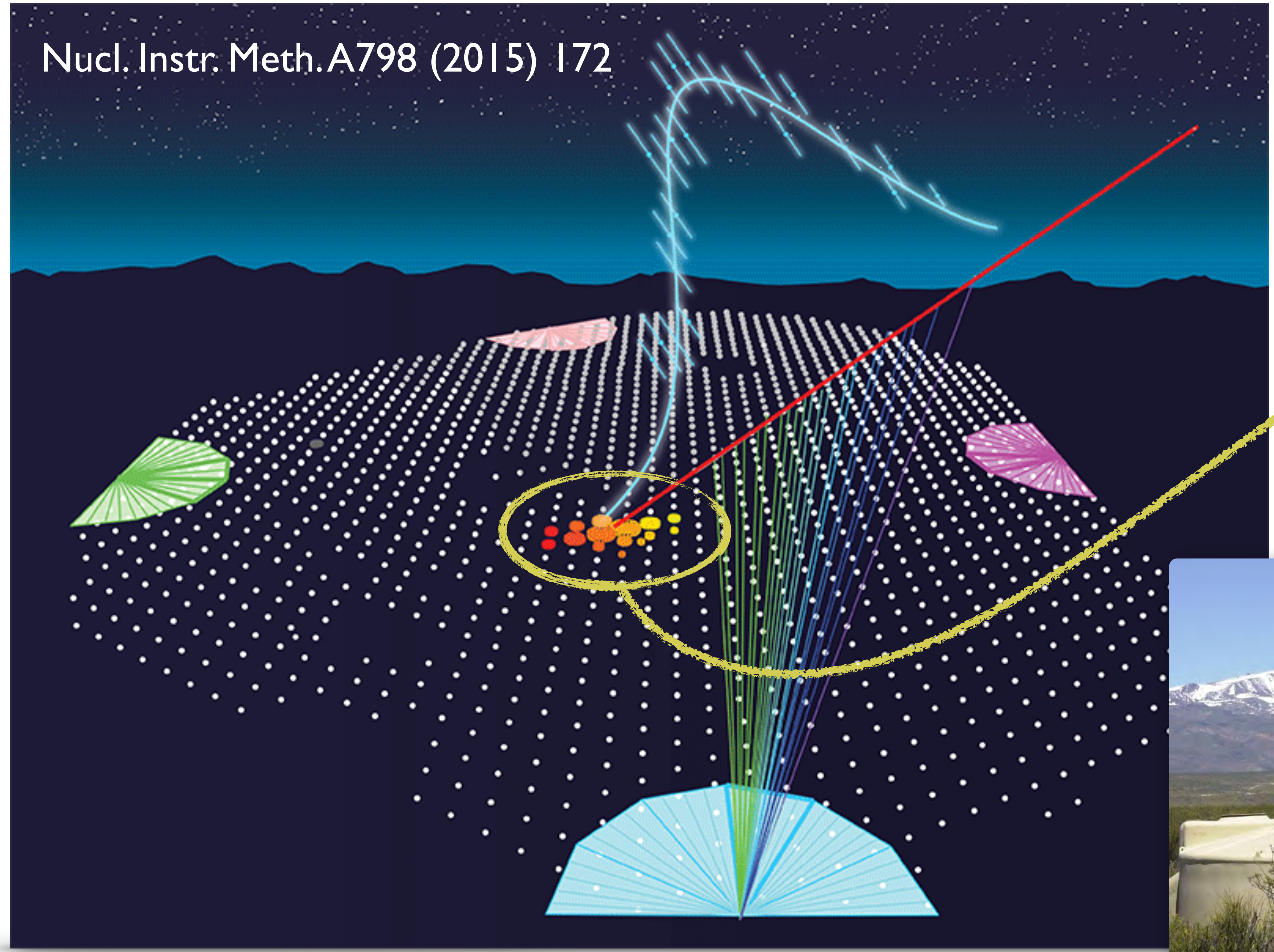
$$E_{cr} = \int \varepsilon_\gamma \frac{dN_\gamma}{dx} dx = \int \frac{dE}{dx} dx$$

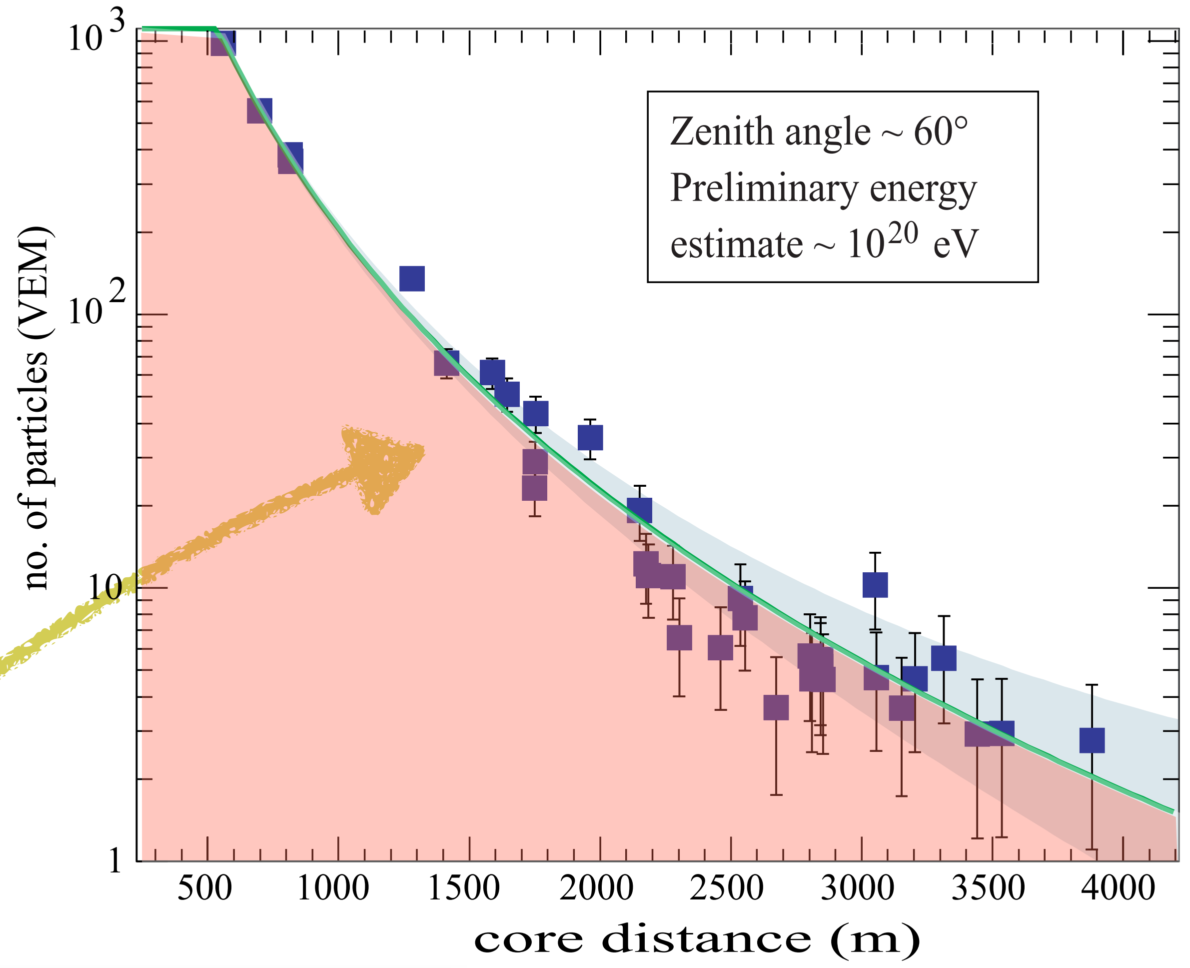
fluorescence yield

Central campus with visitors center



Calibrating the Primary Energy

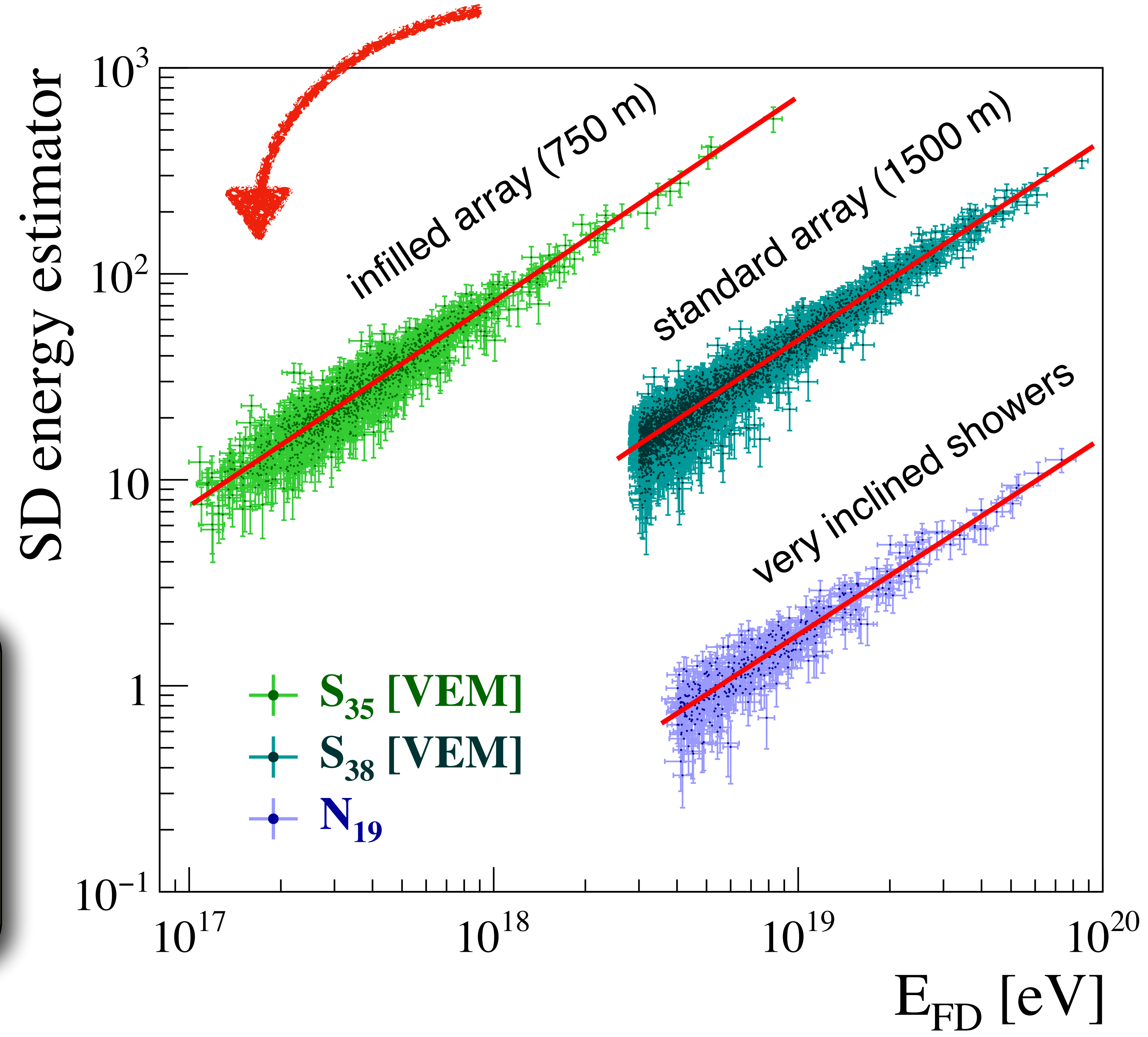




Fit of particle density as a fct of distance from shower core → ρ(r)

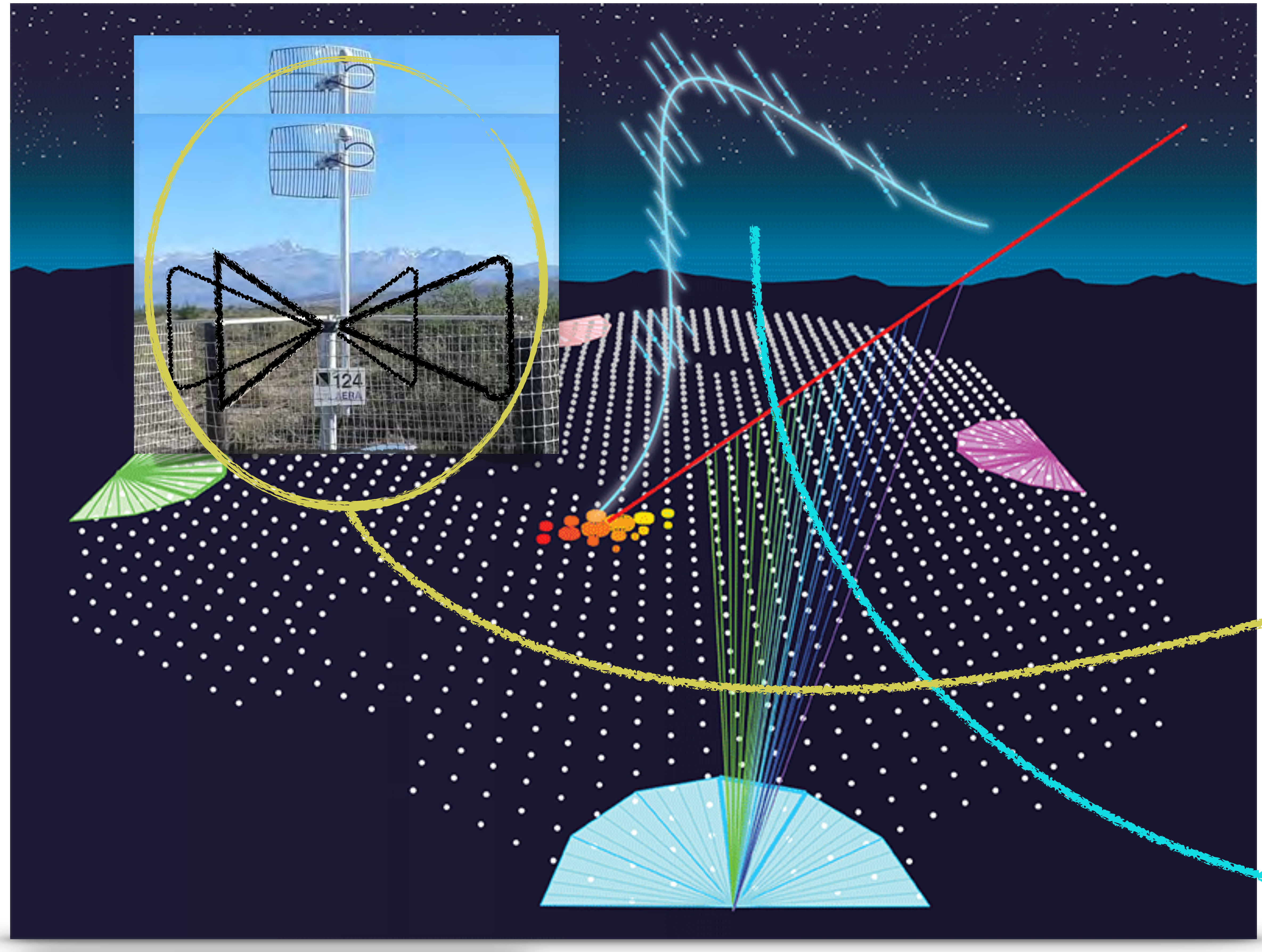
$$S_{tot} = \int 2\pi r \rho(r) dr$$

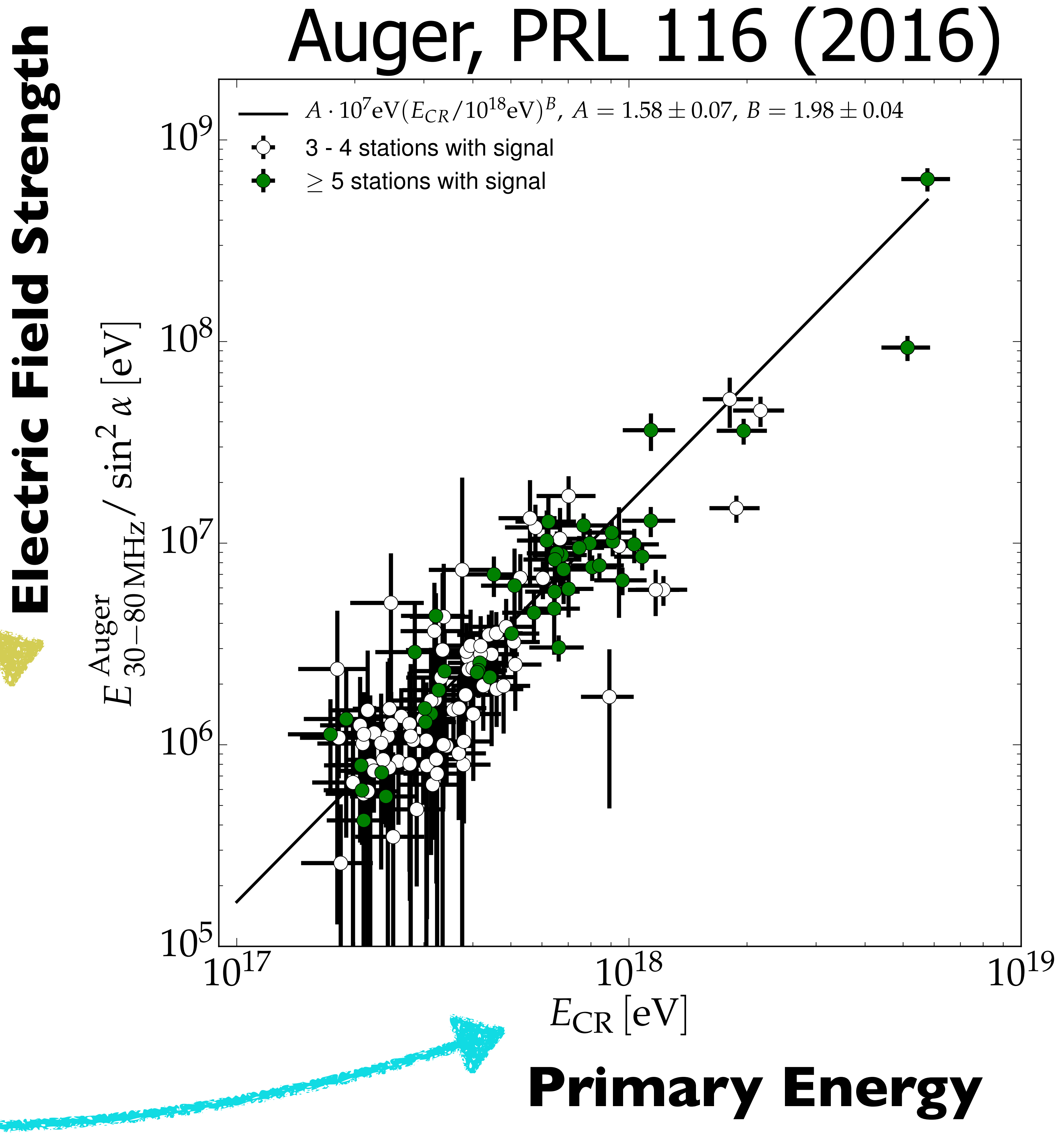
Normalise S_{tot} to specific zenith angle → S_{38}, etc



Note, this way the surface detector array is calibrated by the fluorescence telescopes, based on lab measurements!

Calibrating the Primary Energy

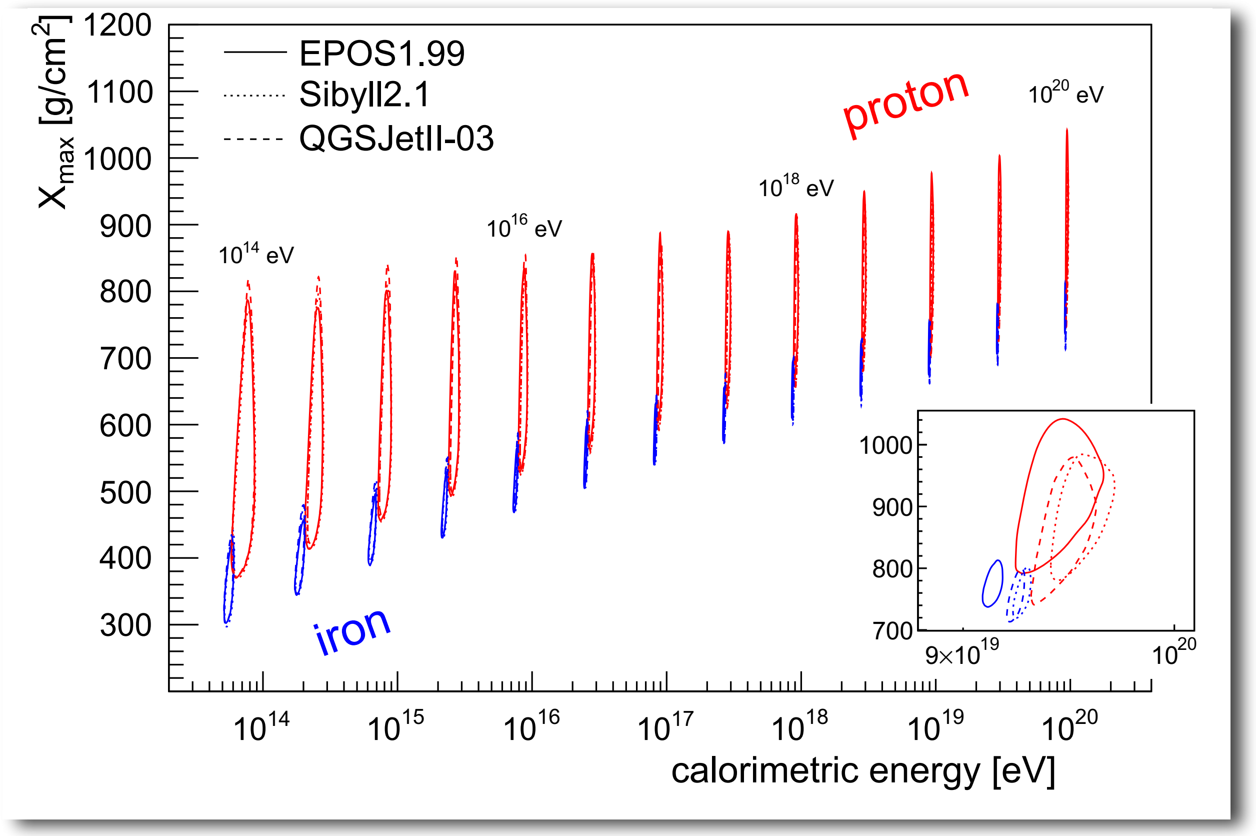




Absolute calibration of radio signal:
18 MeV energy radiated in radio signal @ 1 EeV

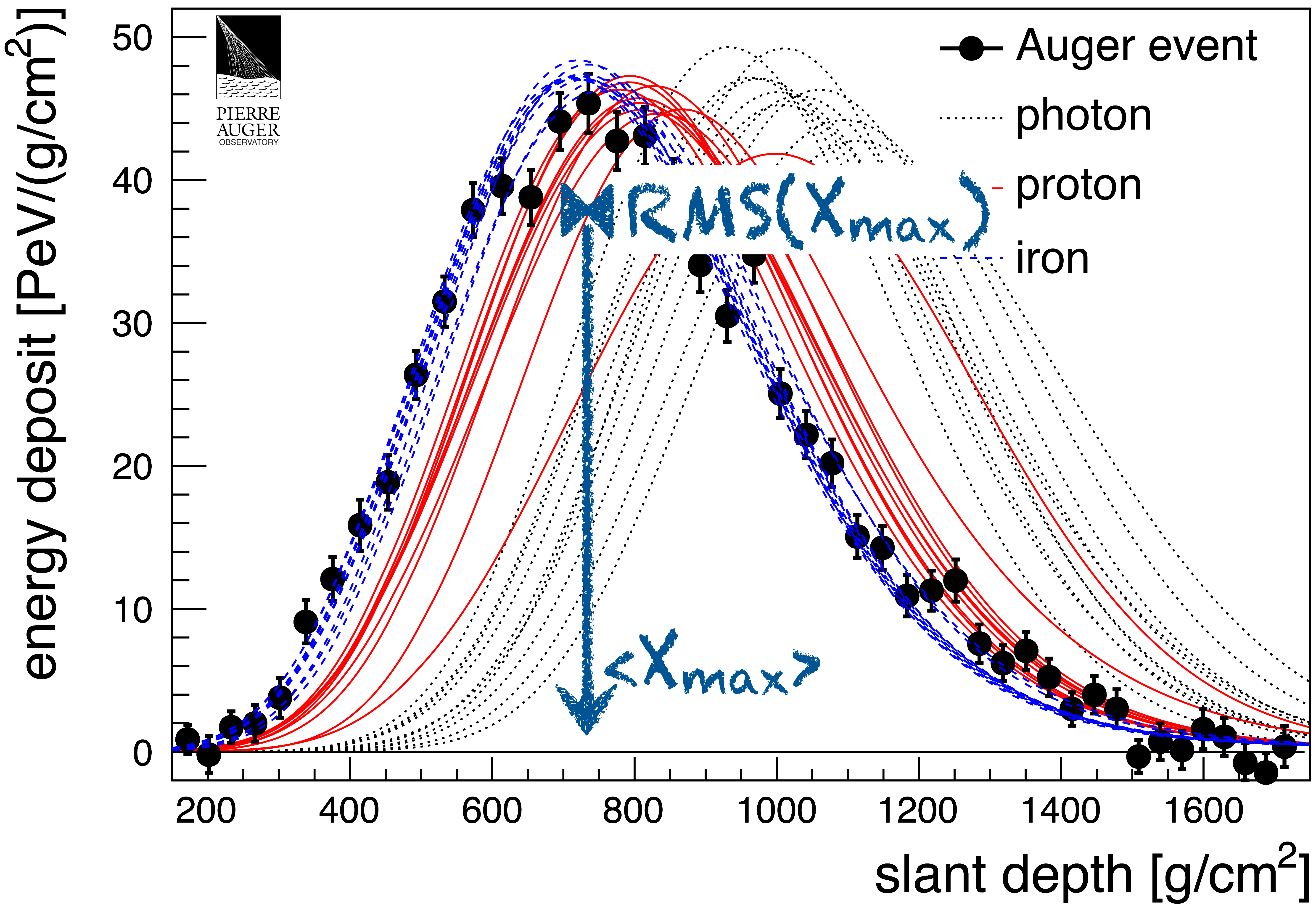
⇒ dedicated Lecture by Anna Nelles 15.01.2021

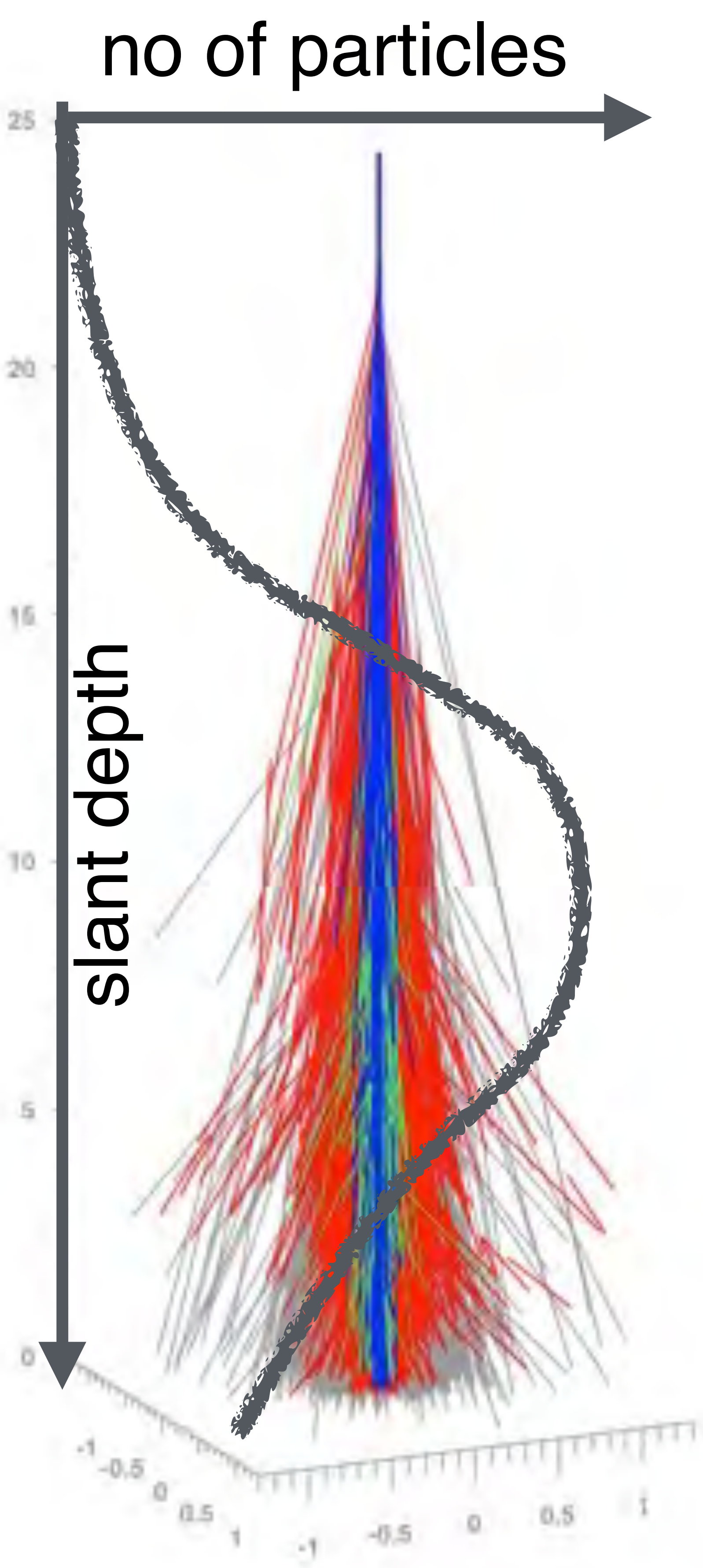
Longitudinal Shower Development → Primary Mass



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

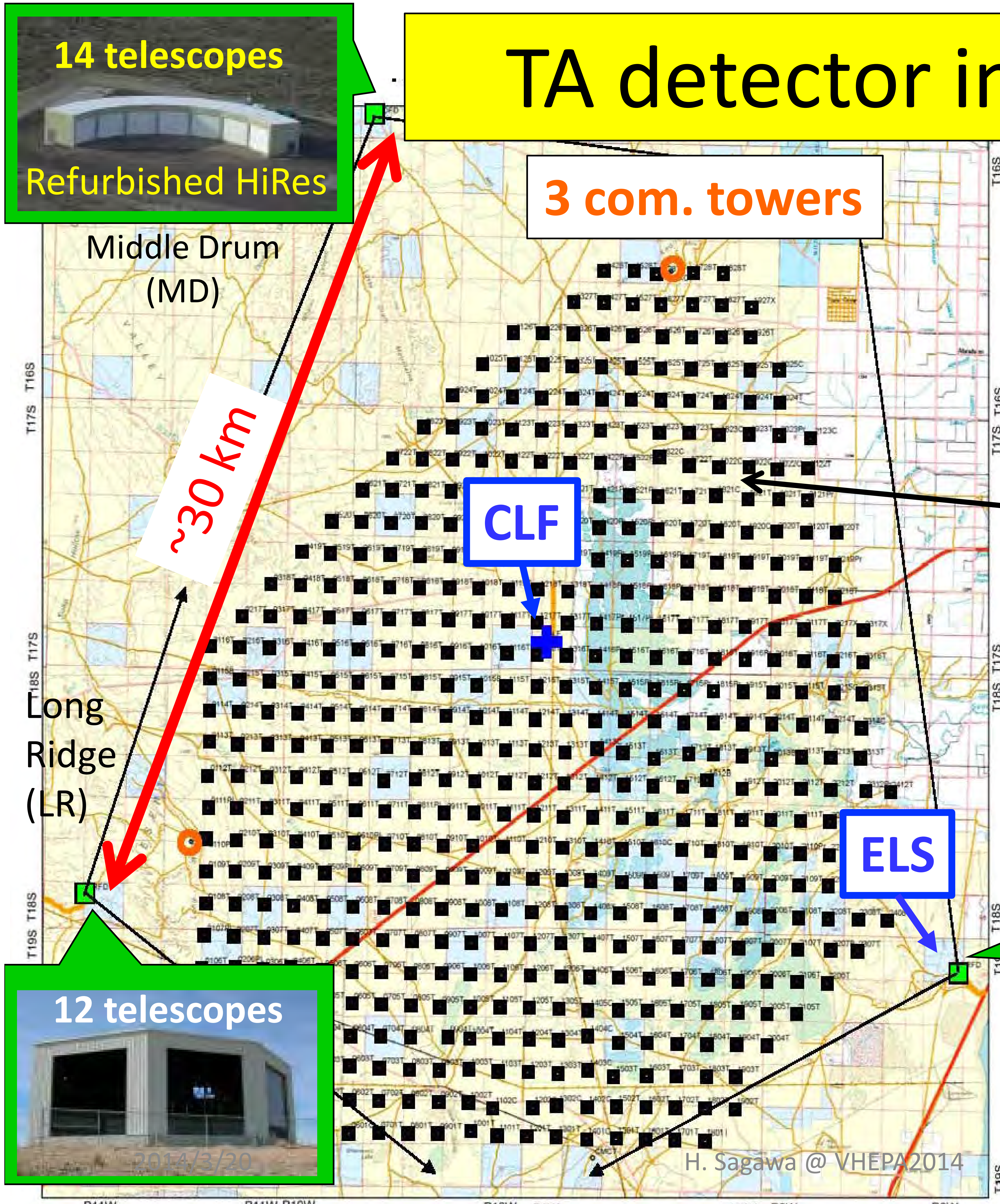
Example of a $3 \cdot 10^{19}$ eV EAS event in FD





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

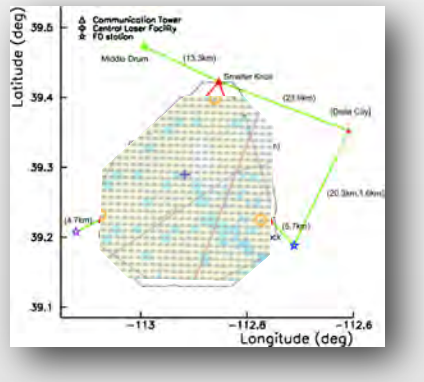
Fluorescence Detector(FD)

3 stations
38 telescopes

FD and SD: fully operational since 2008/May 4

Auger and TA

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

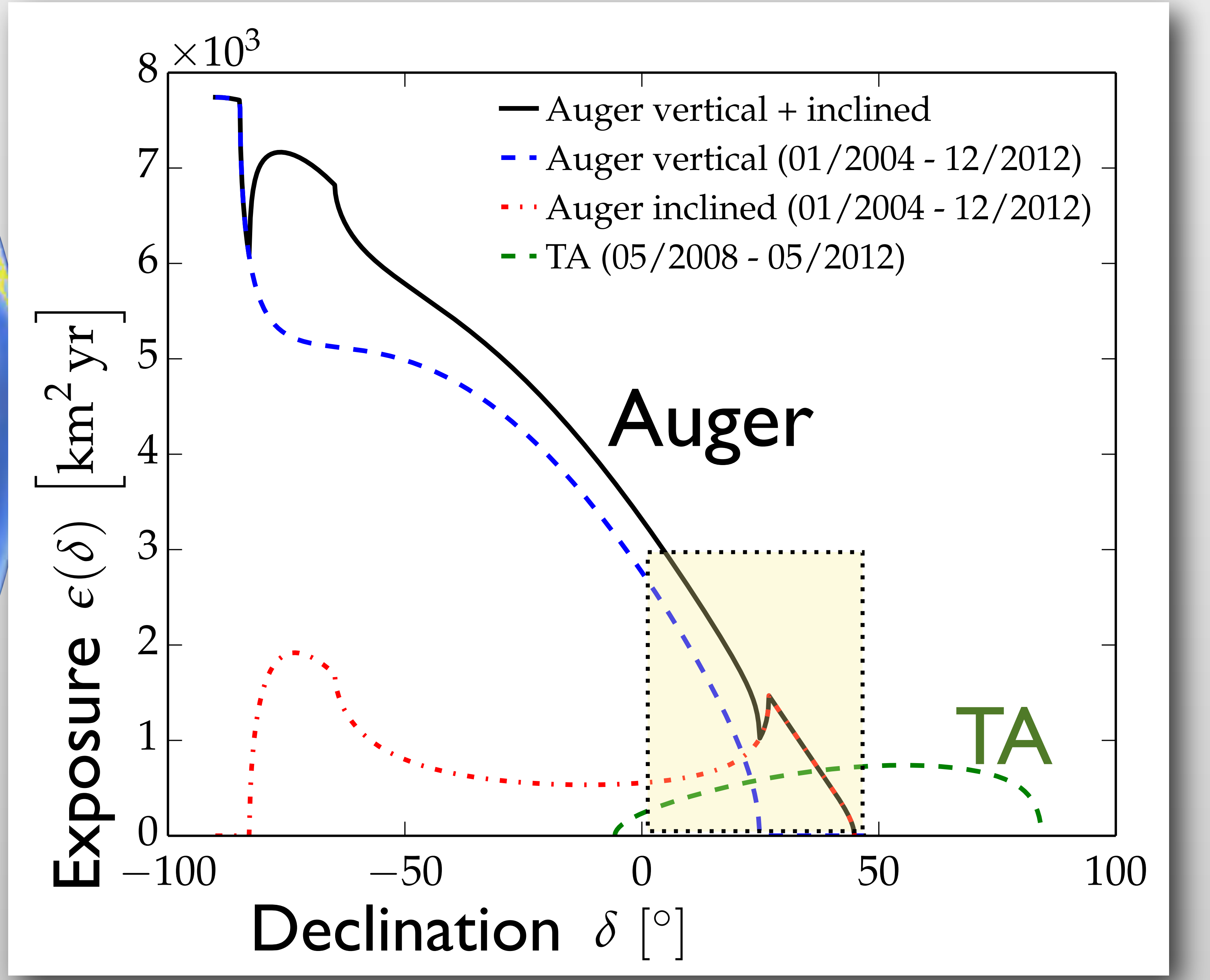


same scale

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

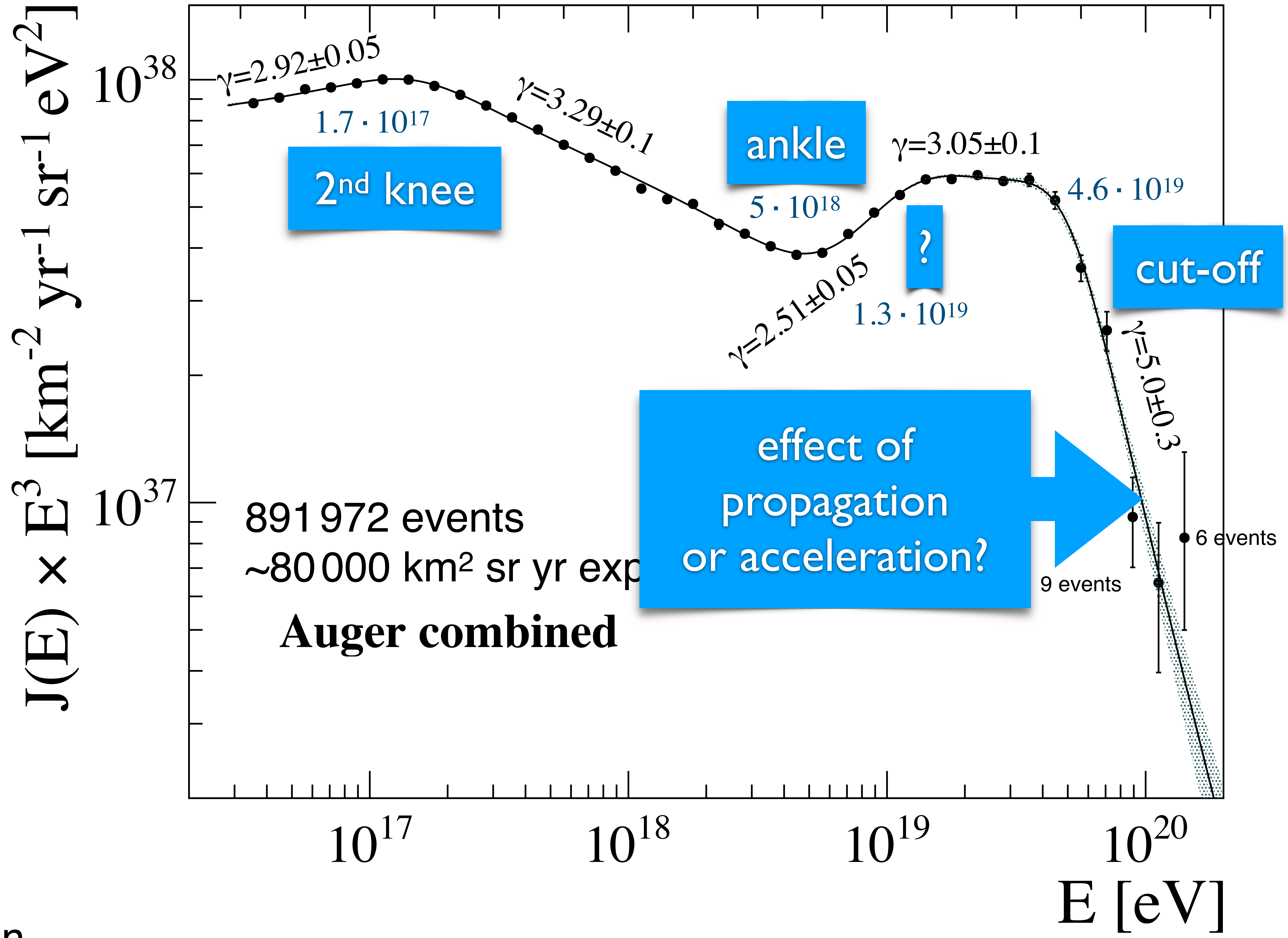
Auger and TA can see the same sky

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



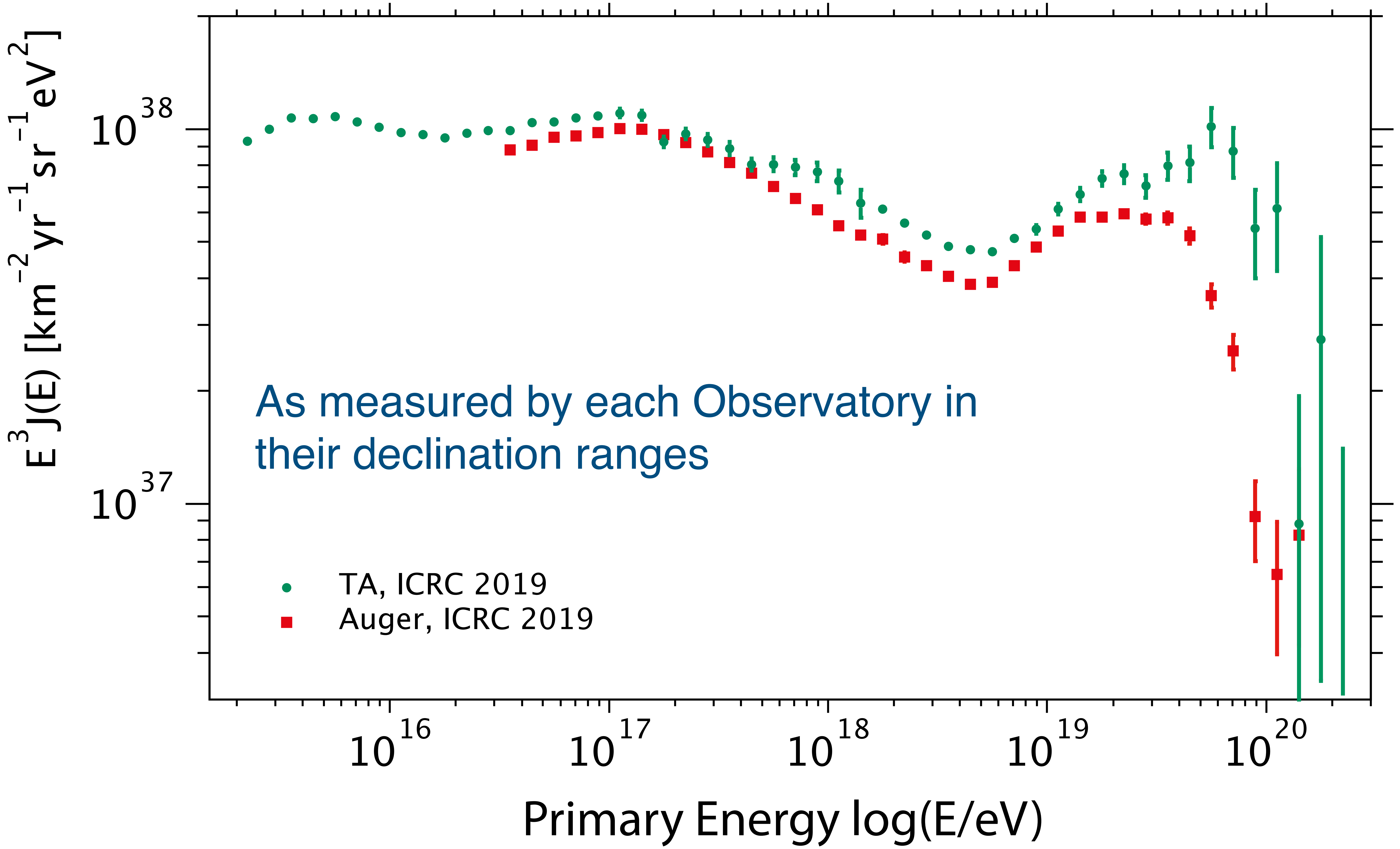
Auger exposure ~8 times that of TA

Auger UHECR Energy Spectrum



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

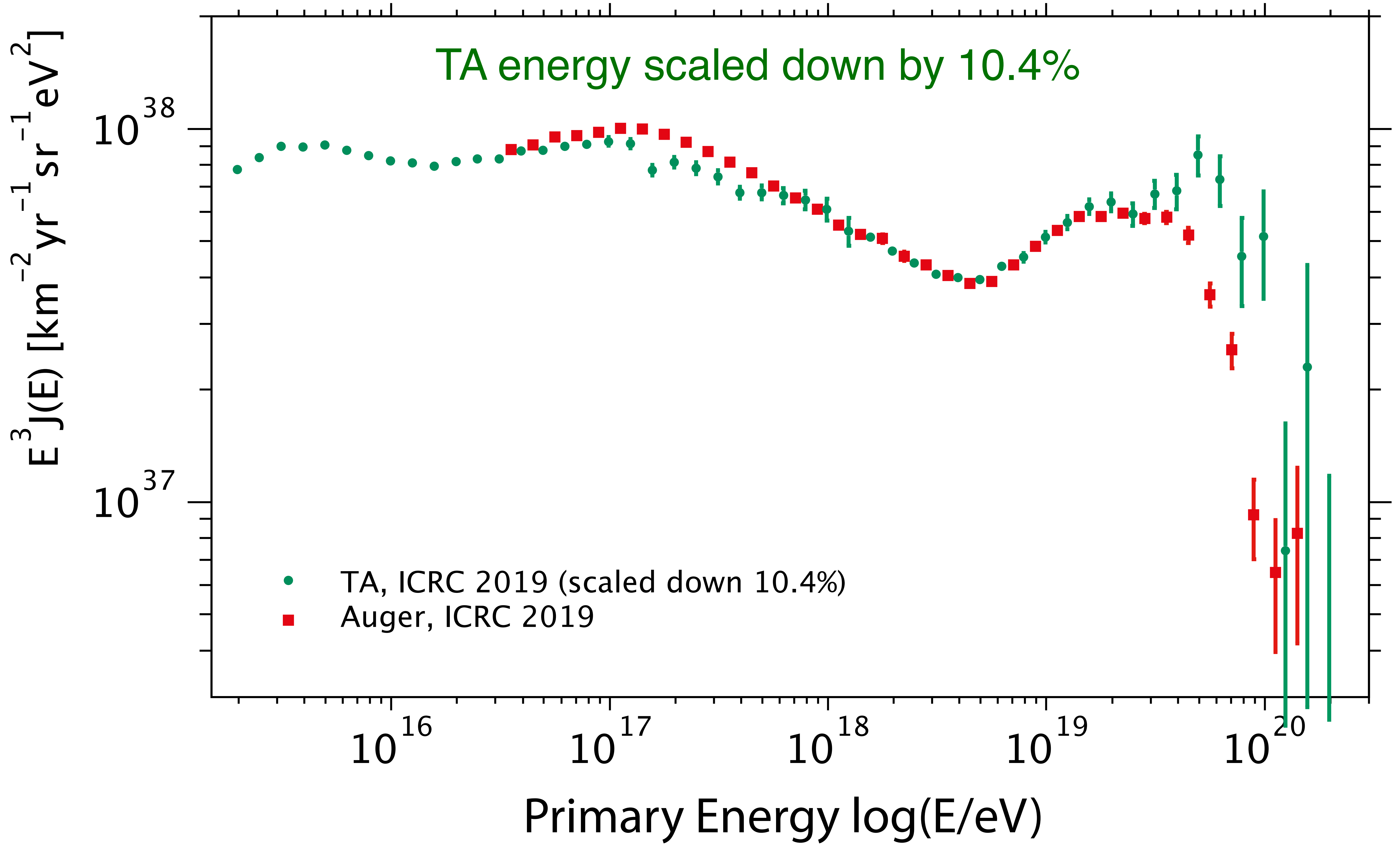
Comparison of Auger and TA spectra



Energy shift of +5.2% (Auger) and –5.2% TA makes them to agree up to the spectral cut-off

Auger-TA working group, PoS(ICRC2019)235

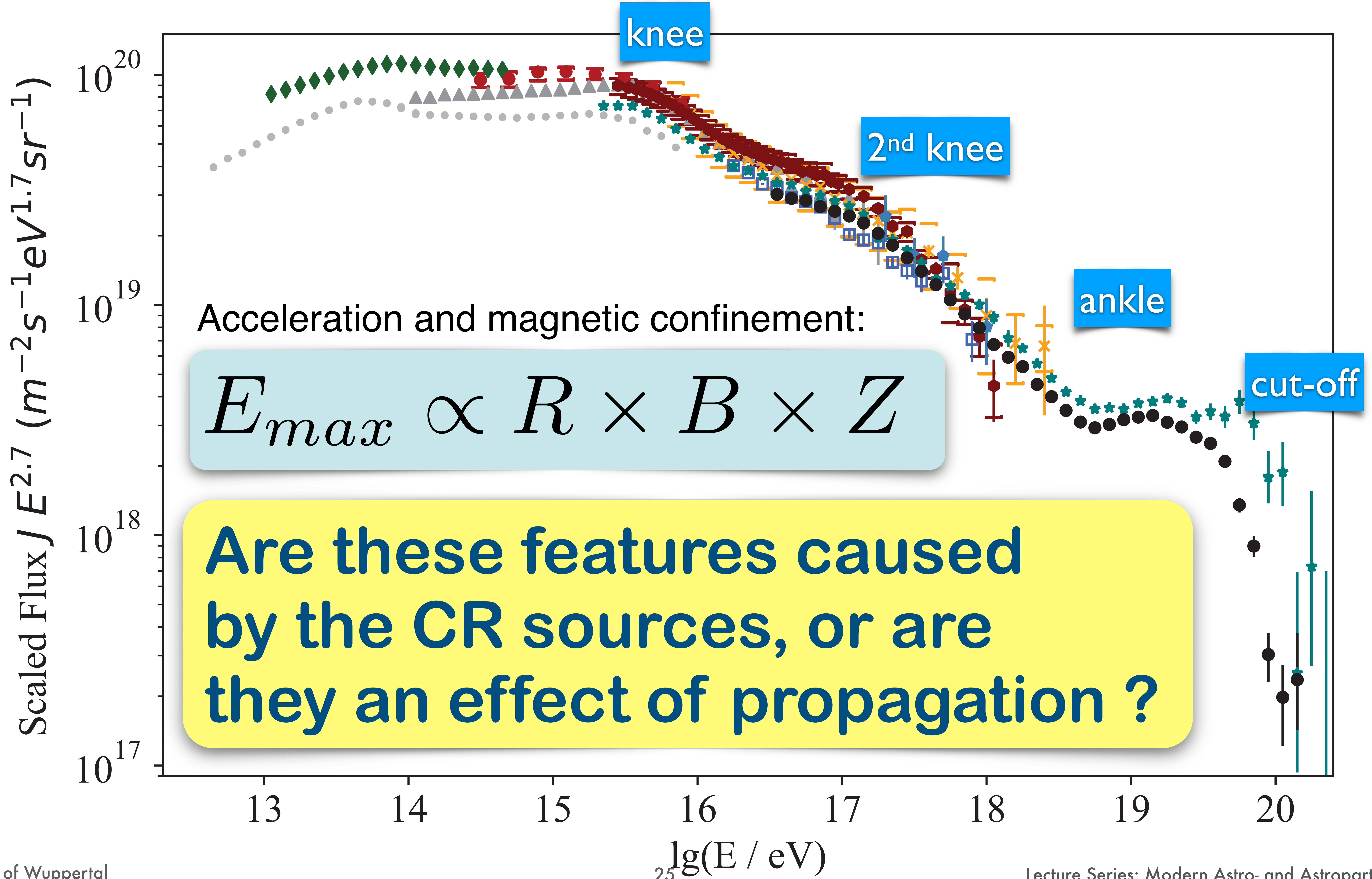
Comparison of Auger and TA spectra



Energy shift of +5.2% (Auger) and –5.2% TA makes them to agree up to the spectral cut-off

Auger-TA working group, PoS(ICRC2019)234

Features of the CR spectrum

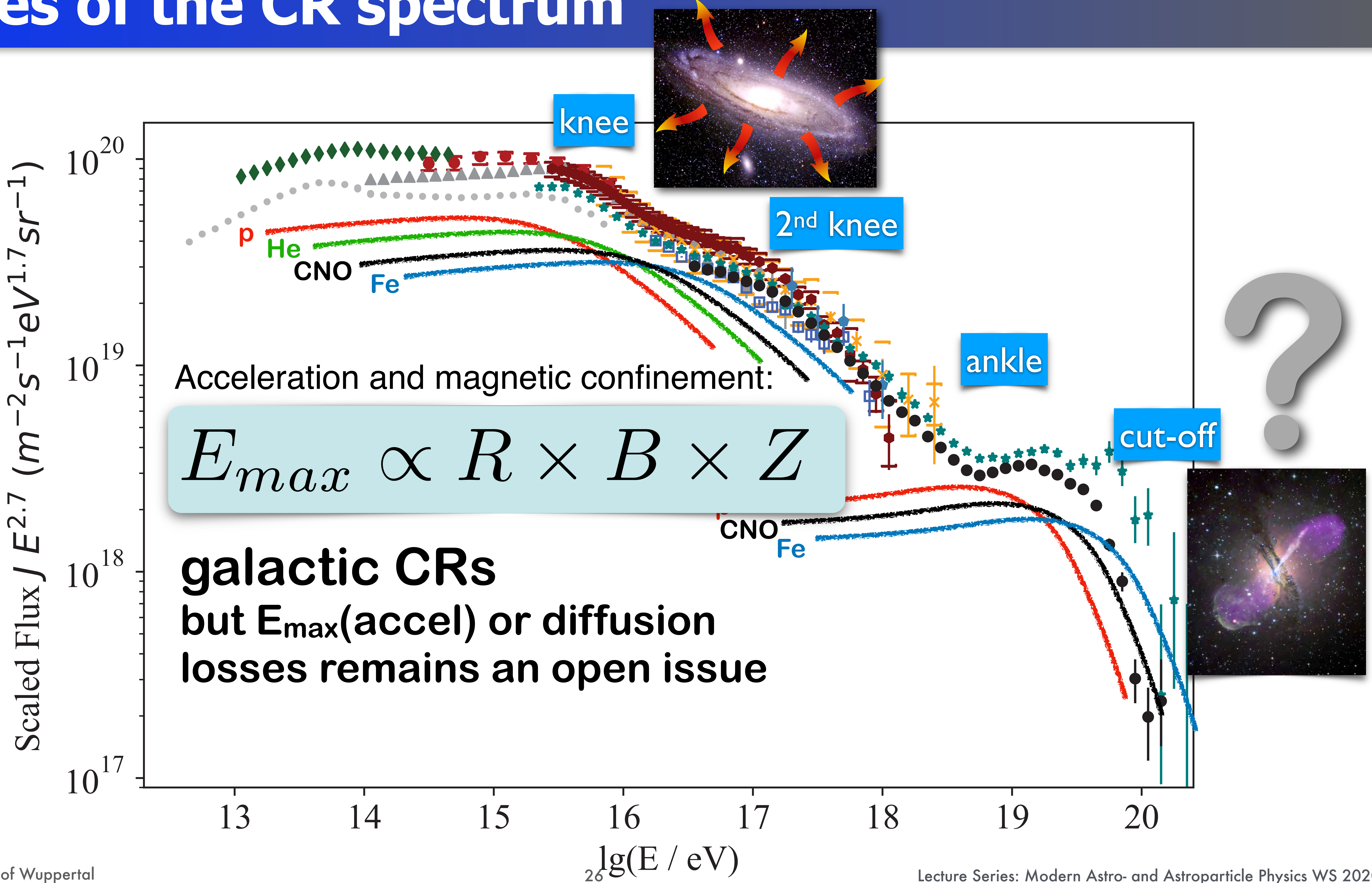


Acceleration and magnetic confinement:

$$E_{max} \propto R \times B \times Z$$

Are these features caused by the CR sources, or are they an effect of propagation ?

Features of the CR spectrum



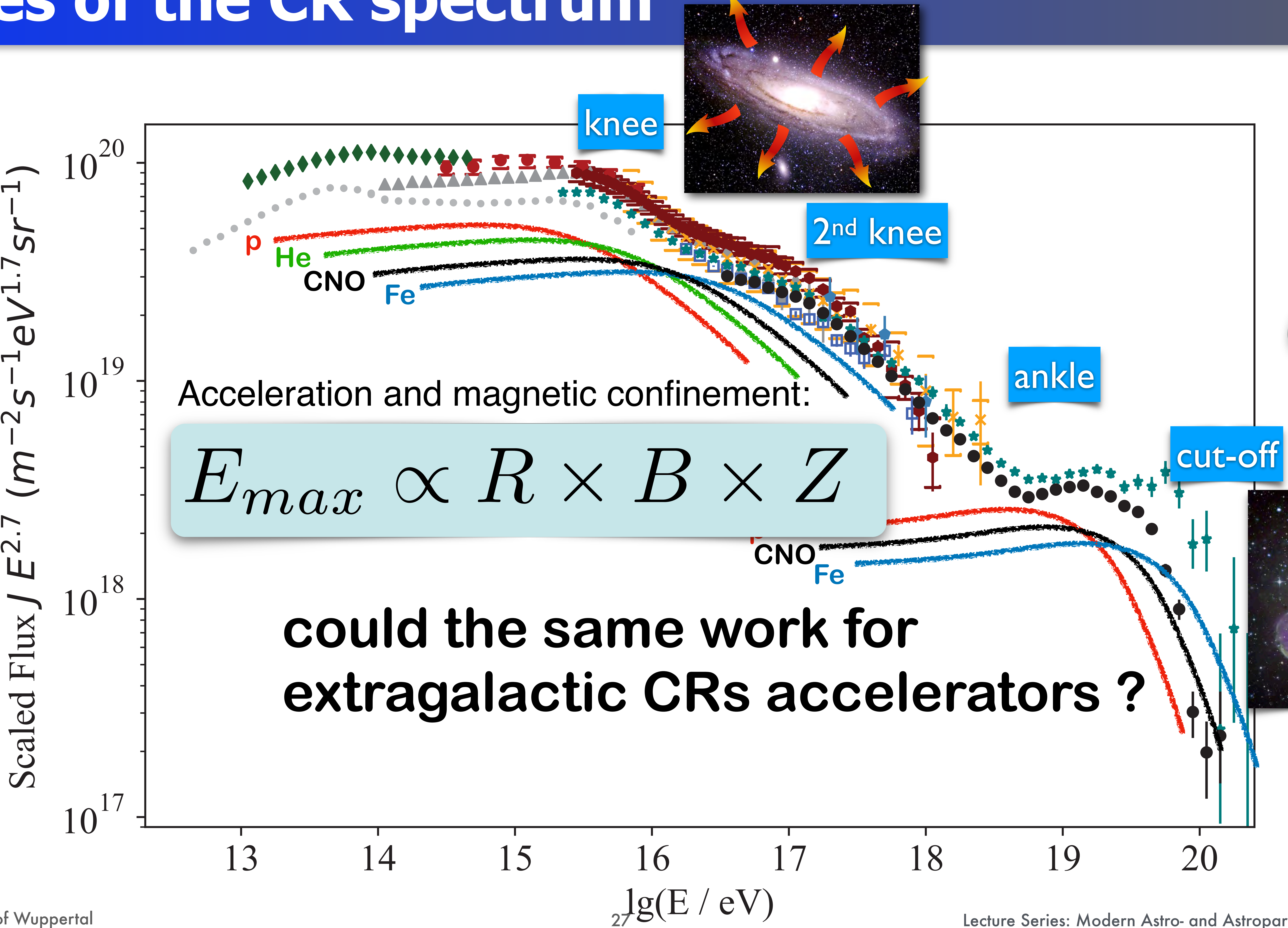
Acceleration and magnetic confinement:

$$E_{max} \propto R \times B \times Z$$

galactic CRs

but E_{max}(accel) or diffusion losses remains an open issue

Features of the CR spectrum

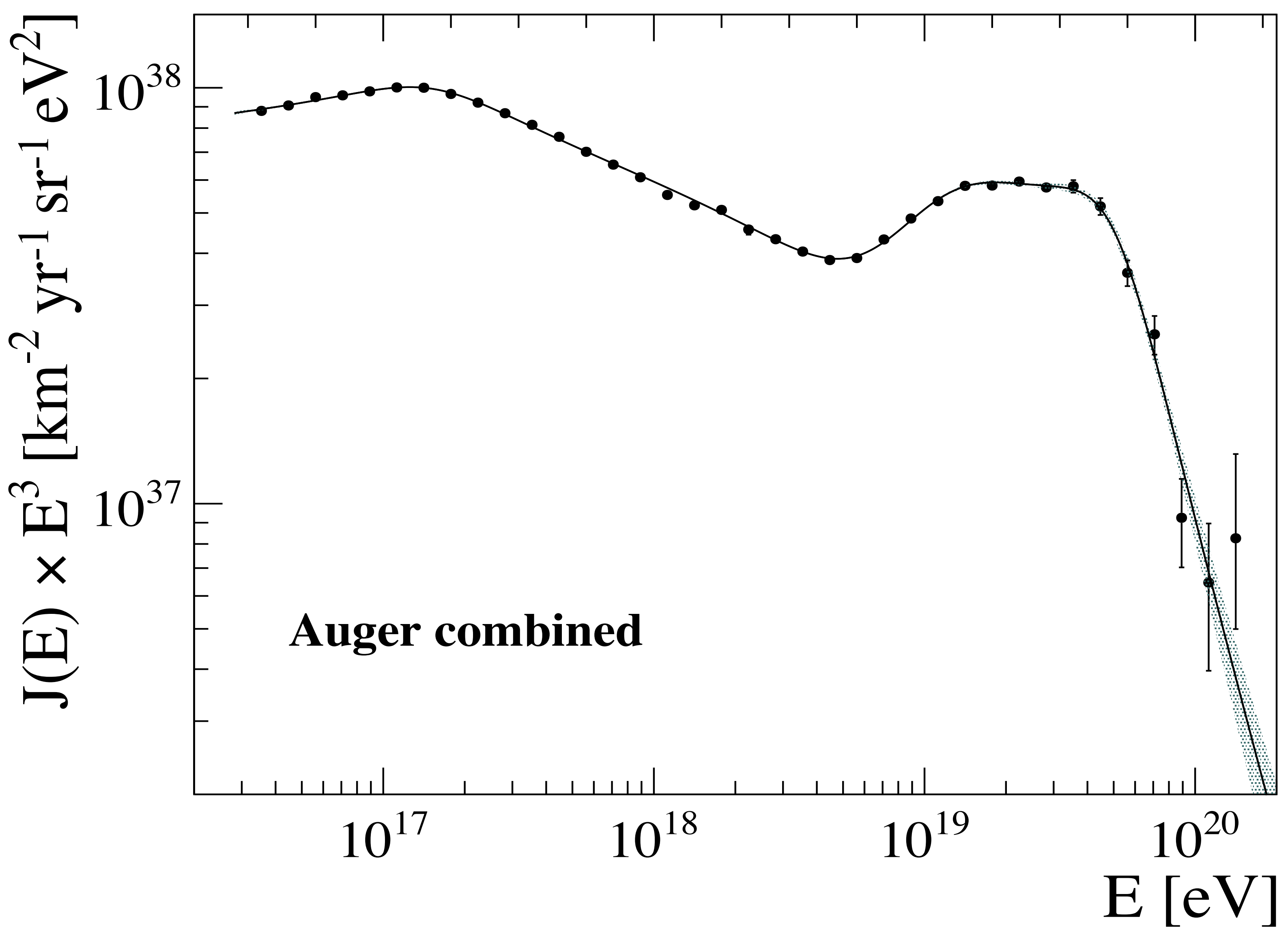


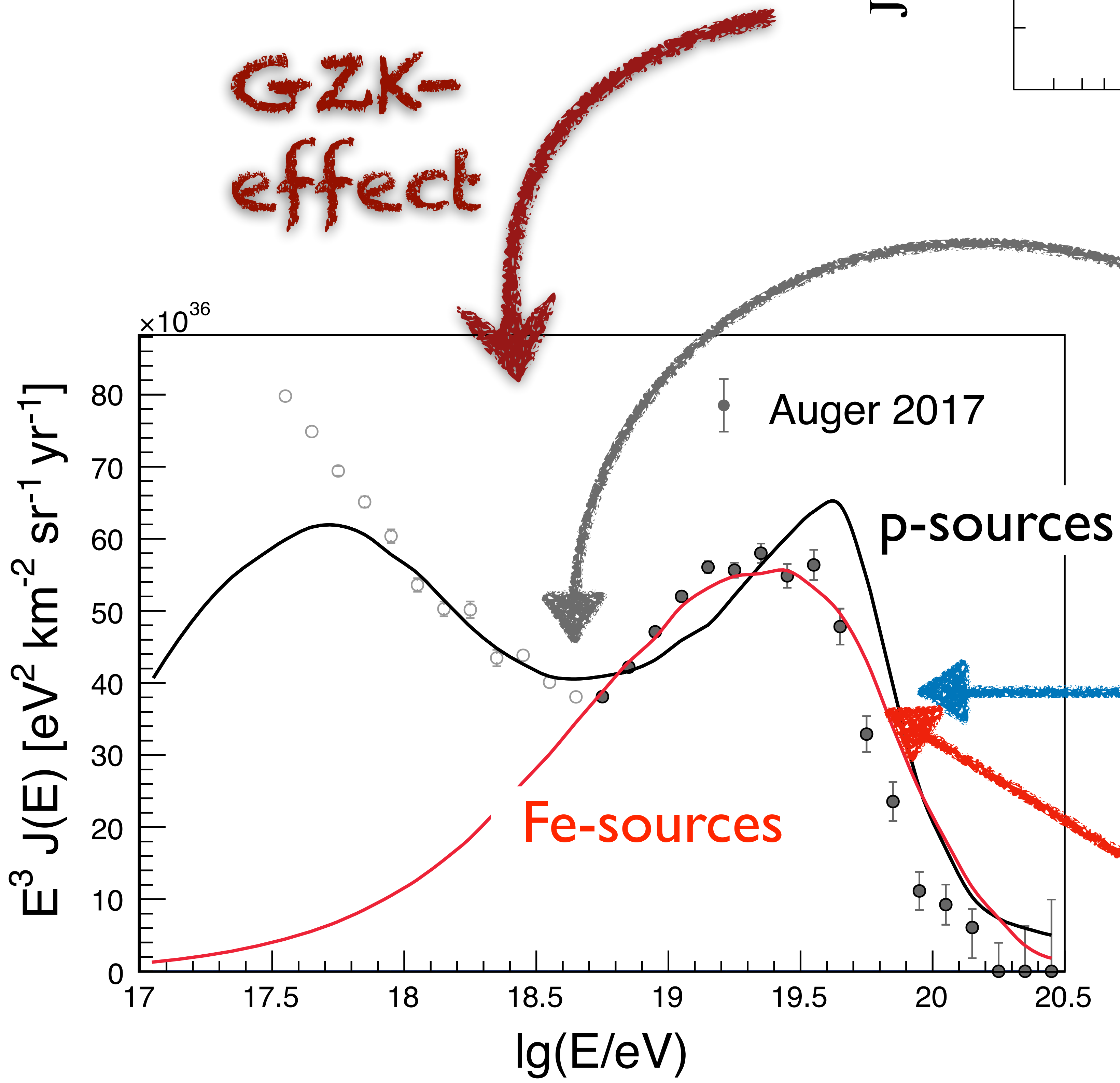
Acceleration and magnetic confinement:

$$E_{max} \propto R \times B \times Z$$

could the same work for extragalactic CRs accelerators ?

GZK-effect, i.e. propagation effect ?





Why is there a „dip“ for propagated protons ?

$p\gamma \rightarrow e^+e^- + p$ first pointed out by V. Berezinsky et al., 2005

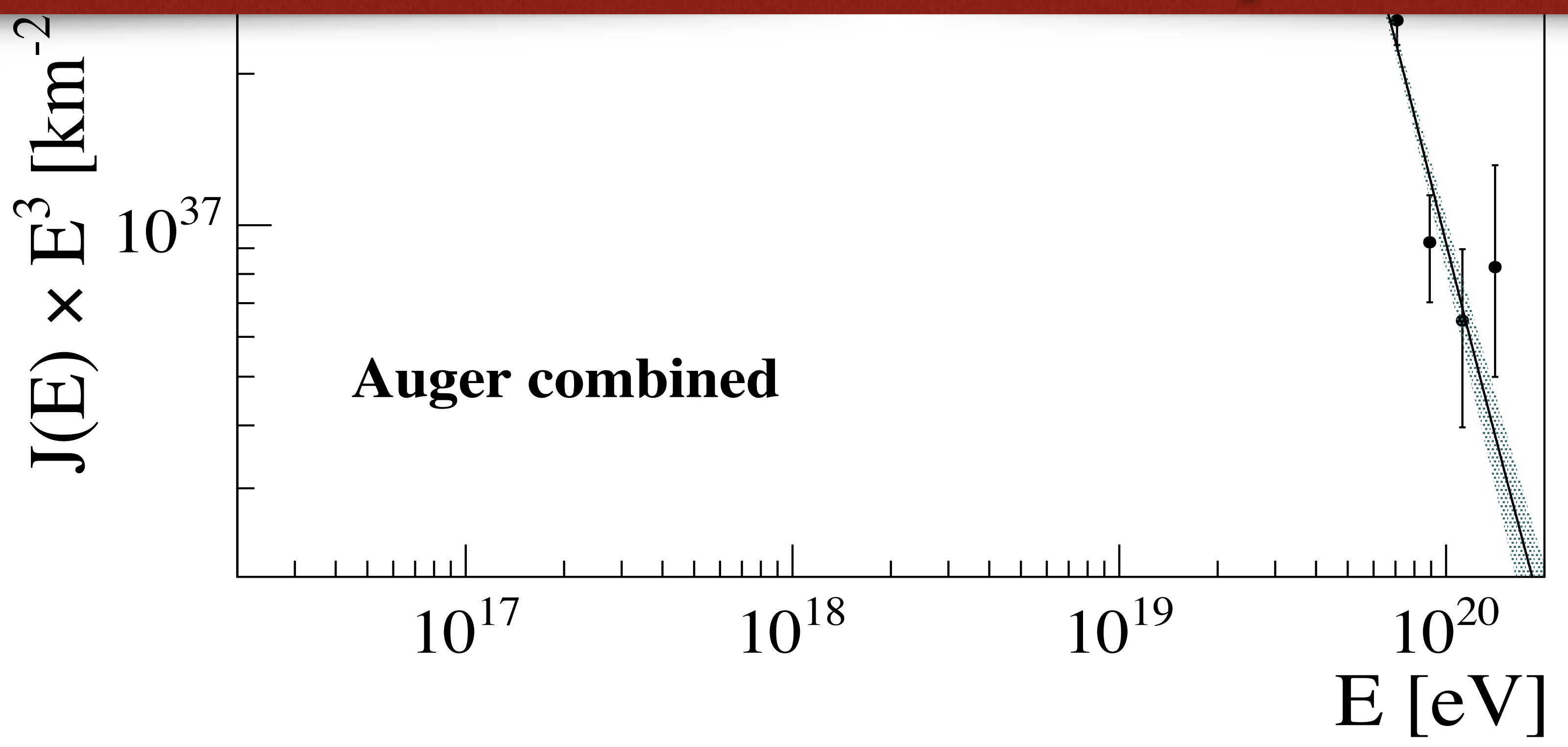
$p\gamma \rightarrow \Delta \rightarrow p+\pi$

$Fe+\gamma \rightarrow$ „Cr“ $+ p + n$

Greisen, Zatsepin & Kuzmin (GZK), 1966

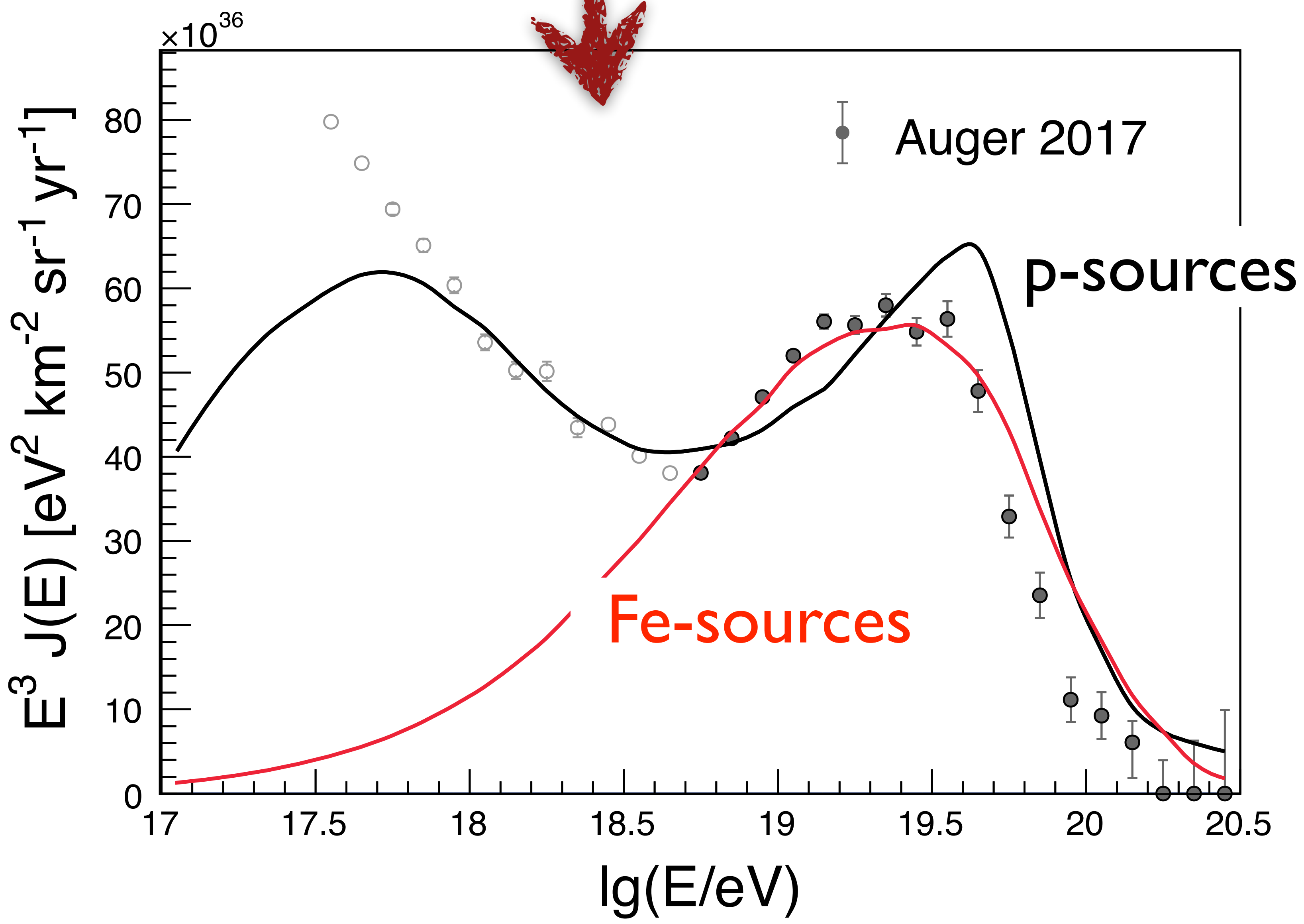
GZK-effect or Sources running at their RxB limits?

Energy spectrum alone cannot tell about origin of the cut-off, need mass composition in addition

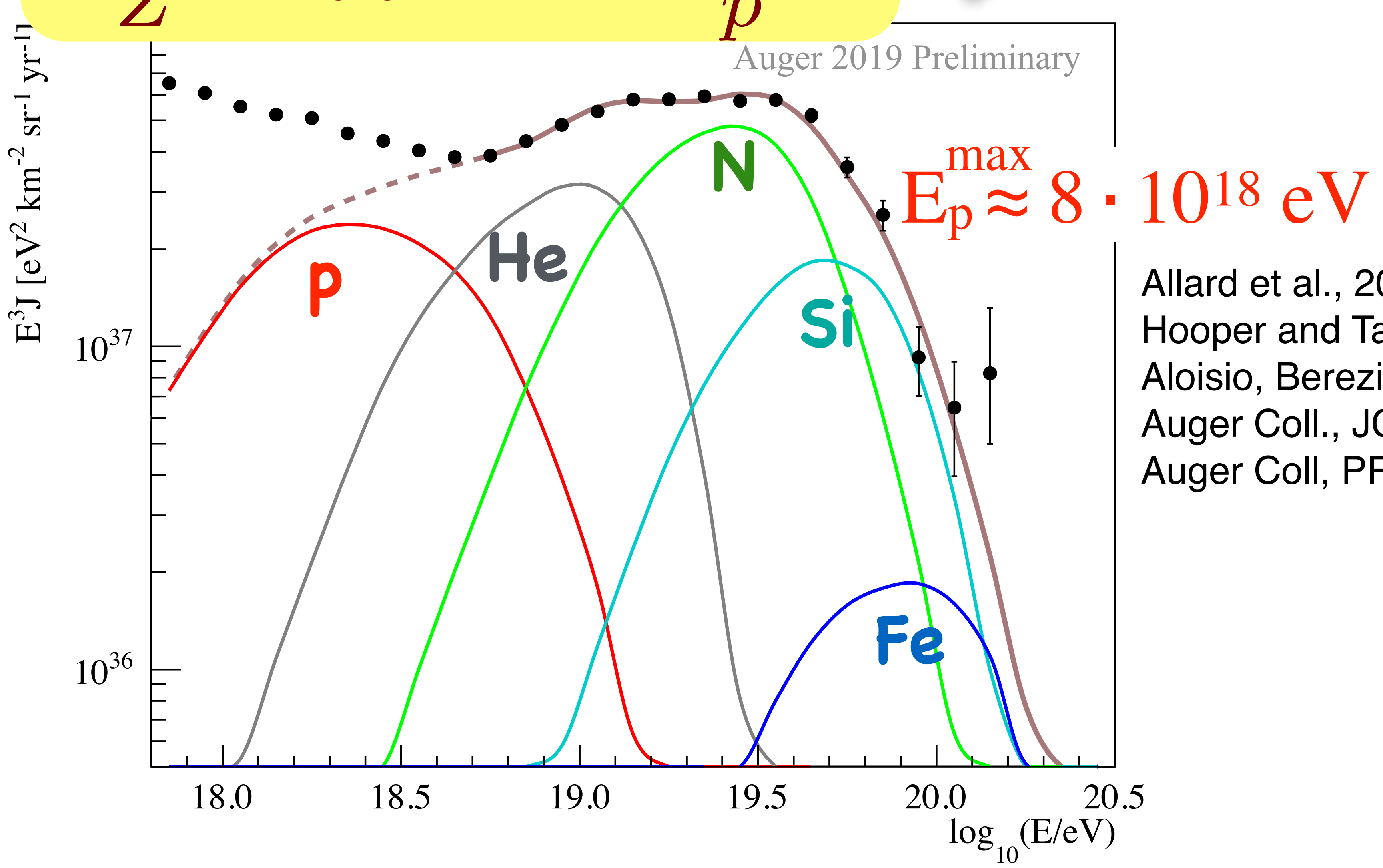


GZK-effect

Emax of sources



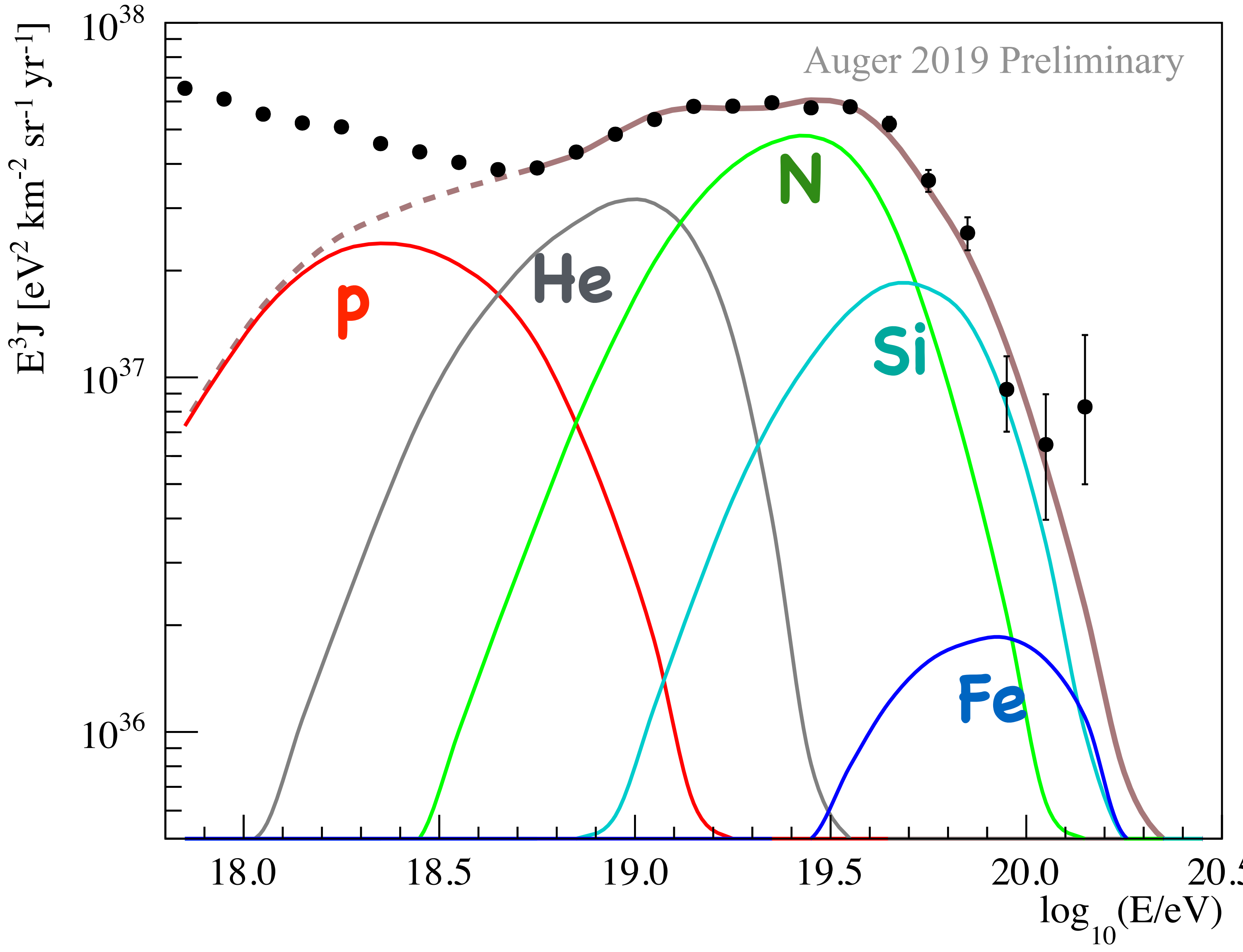
$$E_Z^{max} \propto Z \times E_p^{max}$$

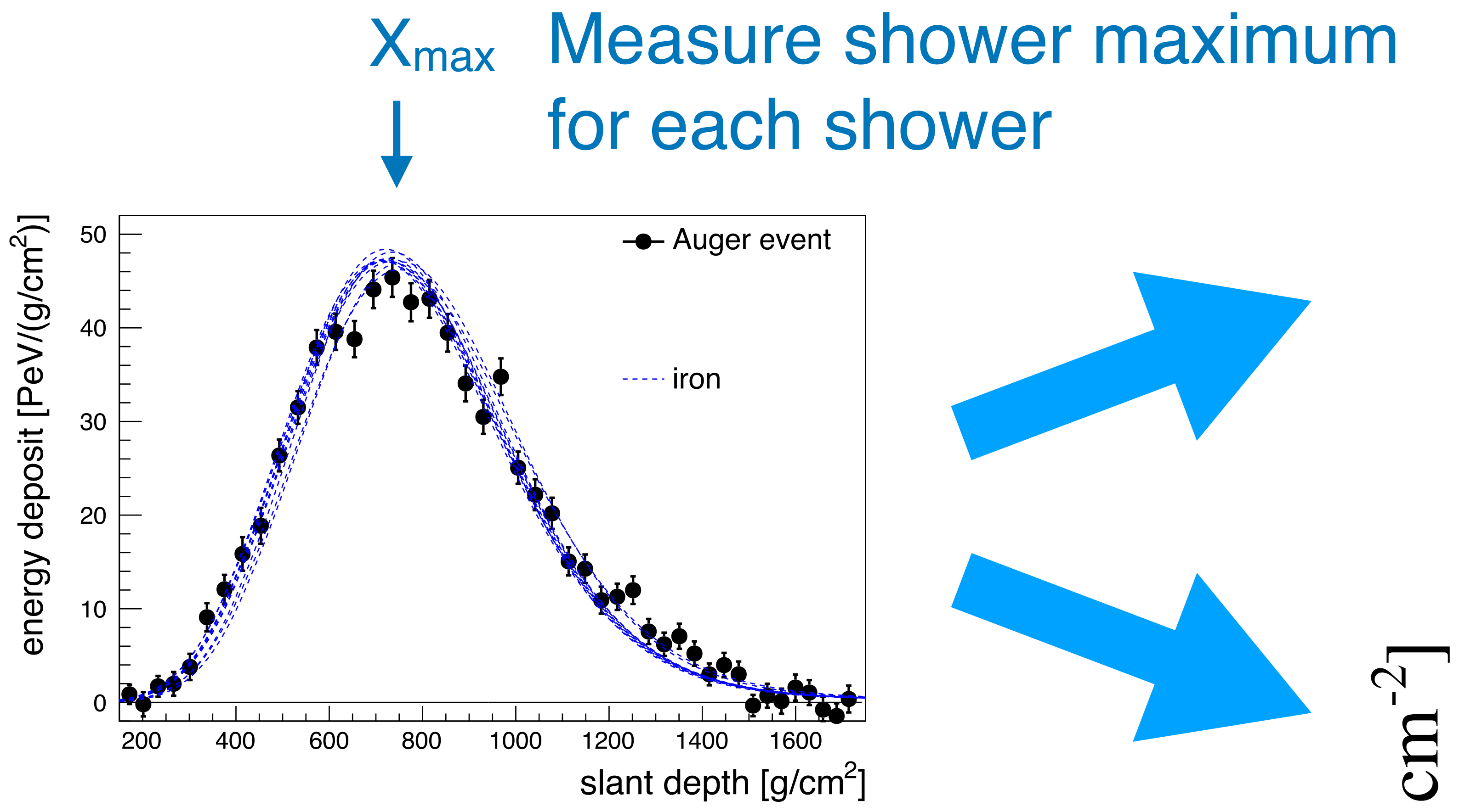


Allard et al., 2008
Hooper and Taylor, Astropart. Phys. 2010
Aloisio, Berezinky, Blasi, JCAP 2014
Auger Coll., JCAP 2017
Auger Coll, PRL 2020

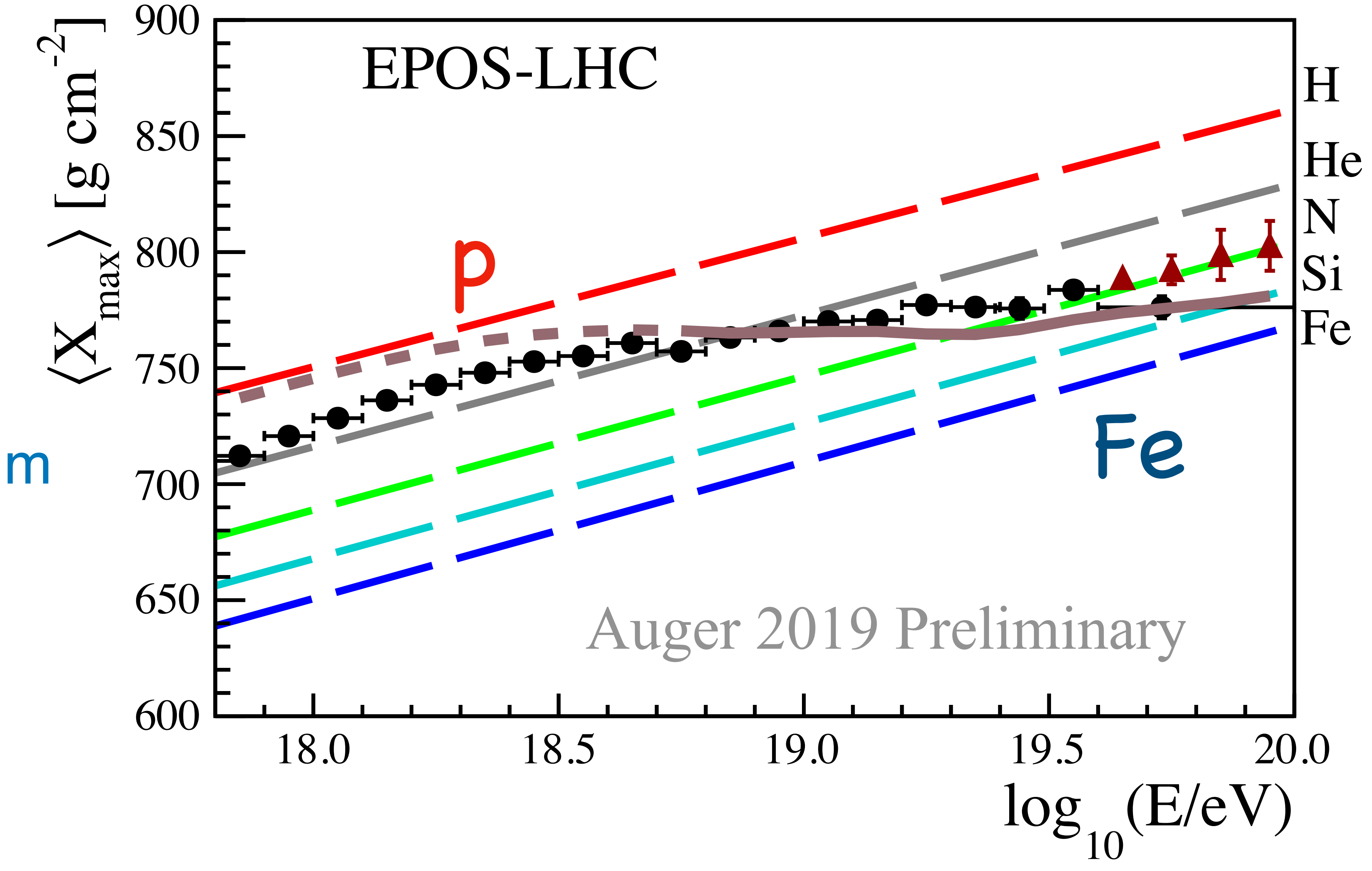
Model of Max. Source Energy describes Composition

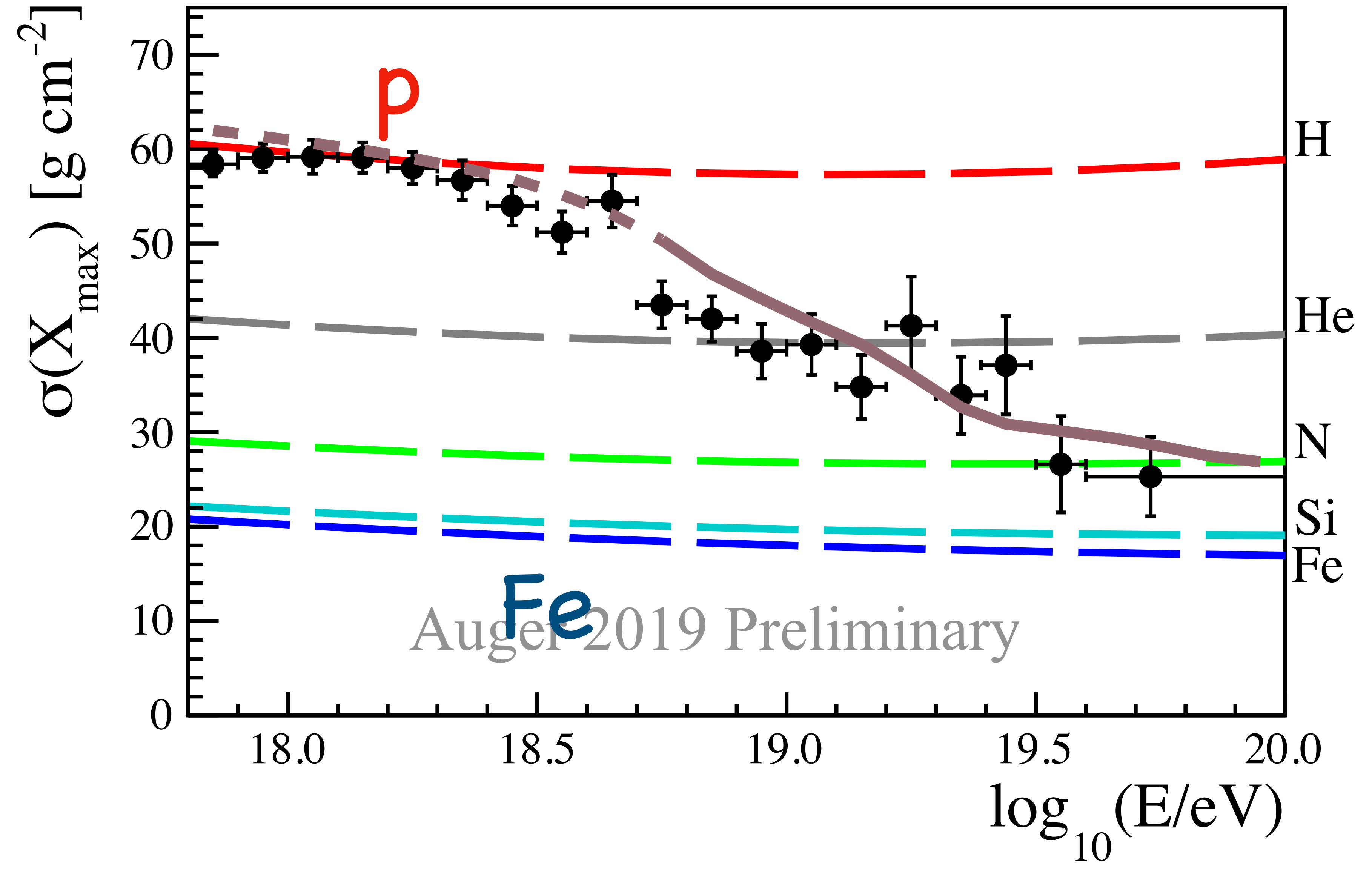
Can we verify this interpretation of the cut-off independently ?





Auger Coll., PoS(ICRC2019)004

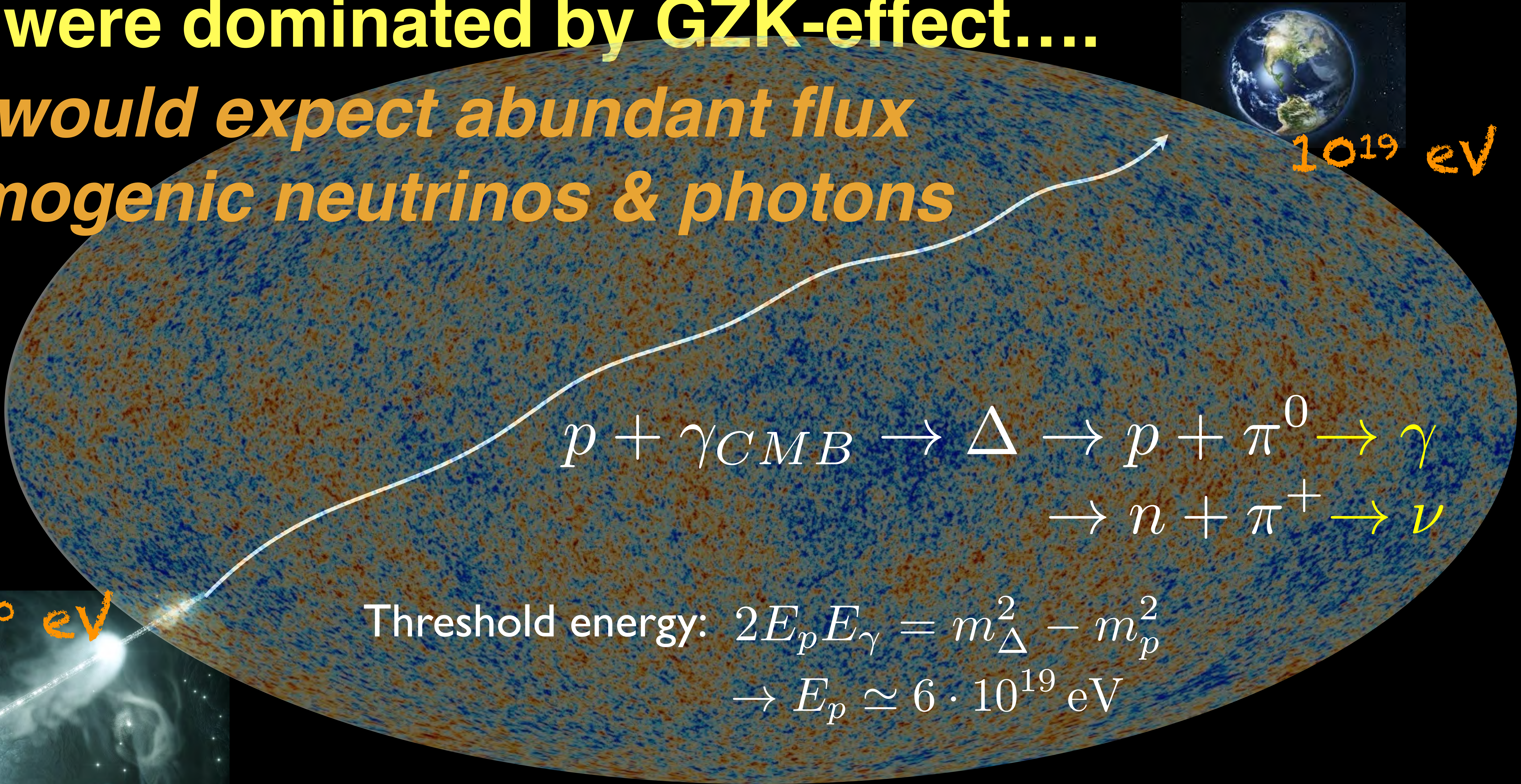




Auger data suggest cut-off to be dominated by E_{max} of sources

If cut-off were dominated by GZK-effect….

… one would expect abundant flux of cosmogenic neutrinos & photons



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

Threshold energy: $2E_pE_\gamma = m_\Delta^2 - m_p^2$

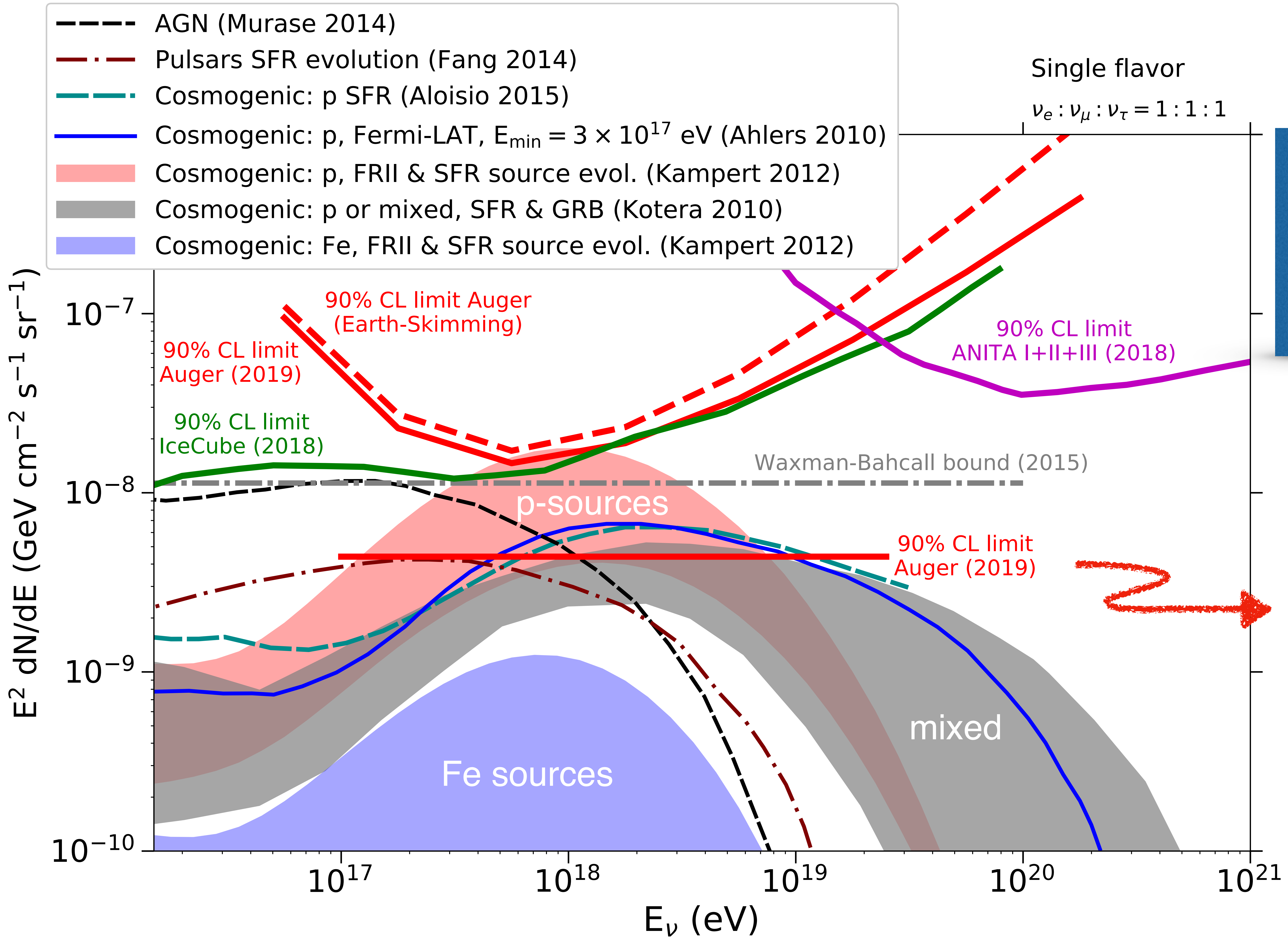
$$\rightarrow E_p \simeq 6 \cdot 10^{19}\,\mathrm{eV}$$

Picture: DESY,
Science Communication Lab

First proposed by Berezinsky and Zatsepin, Phys. Lett. B28 (1969) 423

EeV Neutrino Limits challenge protons suffering GZK-losses

Auger Collaboration, JCAP10 (2019) 022



GZK effect should have given us 1-7 neutrinos
Observed: None

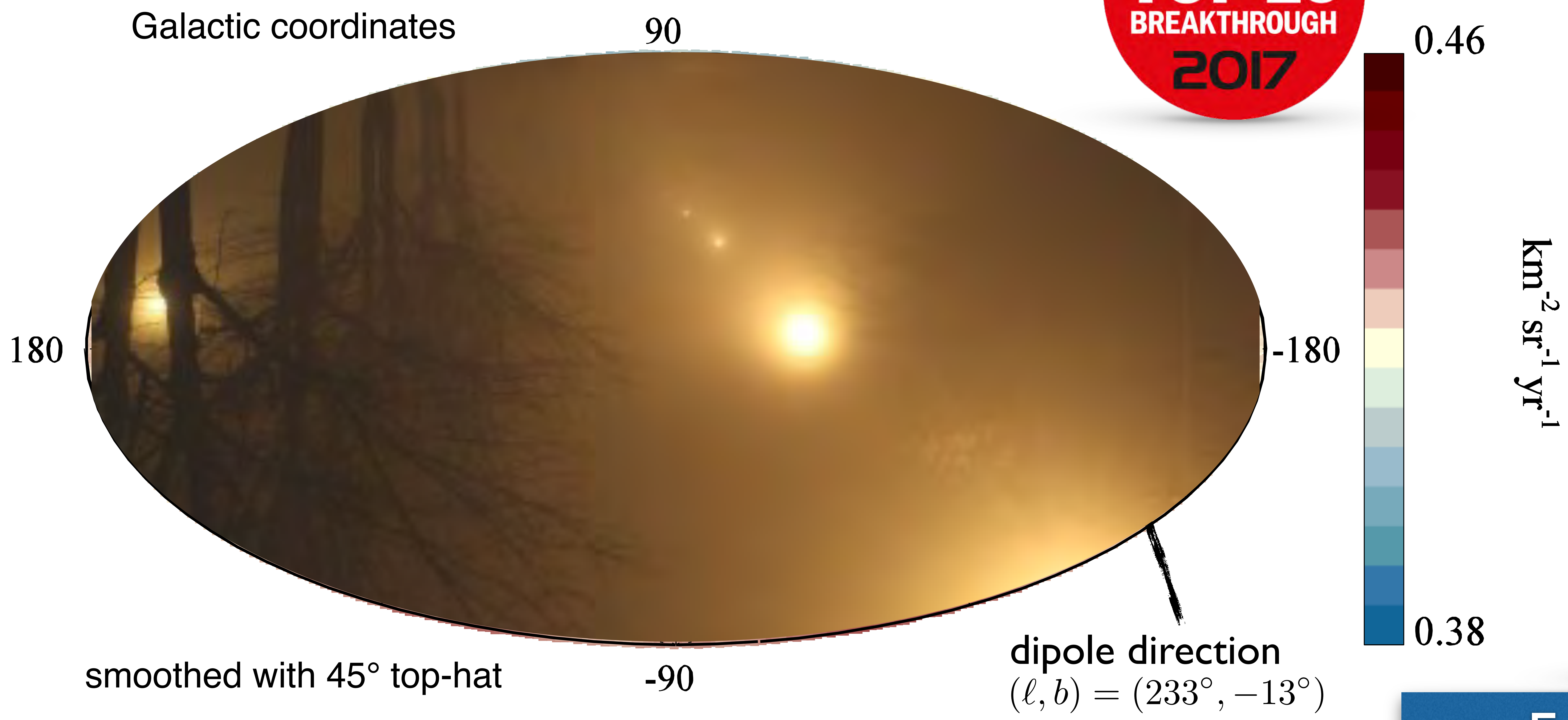
fraction of protons estimated to < 20% at E>50 EeV for m≥3.8 and z_{max}=5

All data from Auger suggest seeing sources reaching their maximum energy rather than protons suffering energy losses in CMB

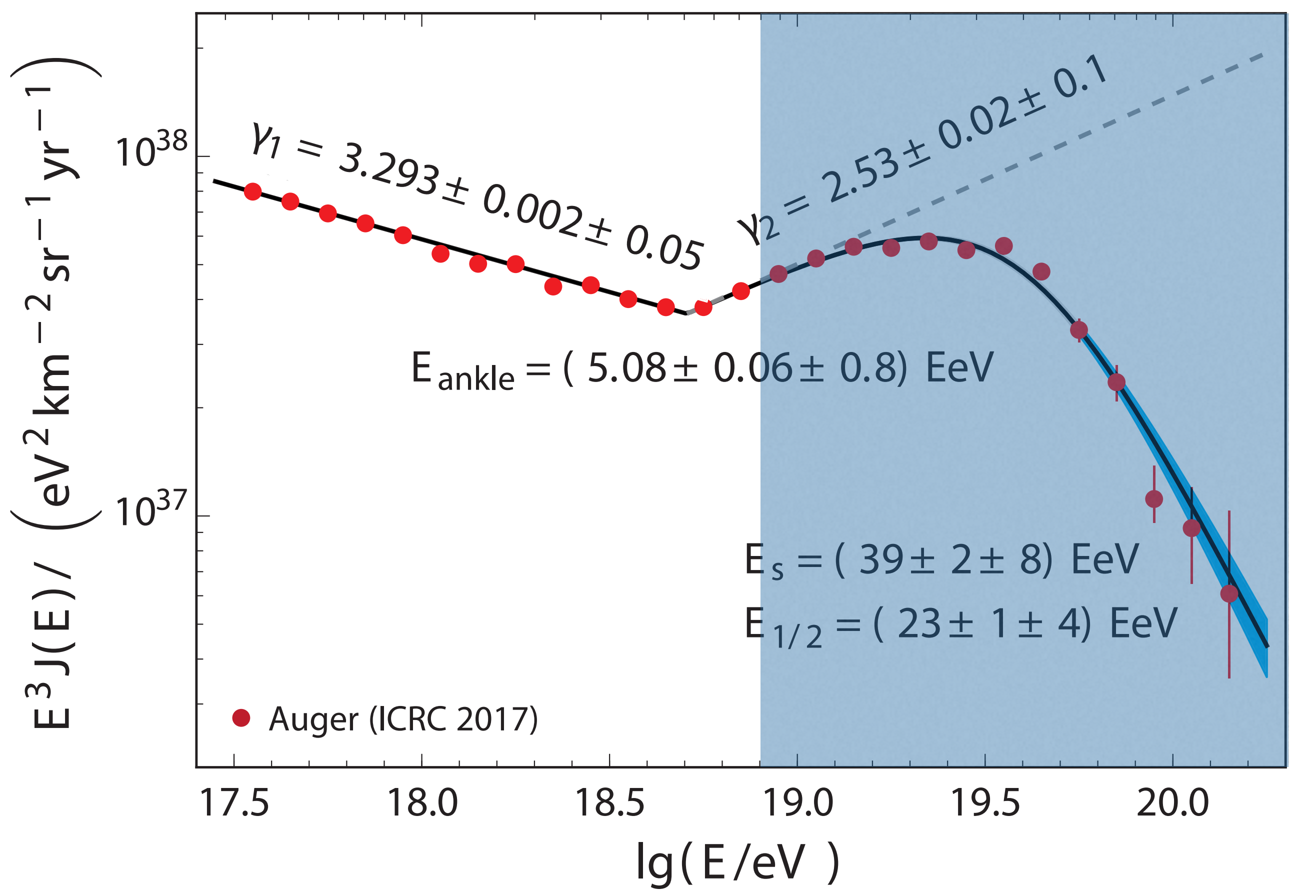
Resulting Intermediate Mass Composition challenges source hunting!

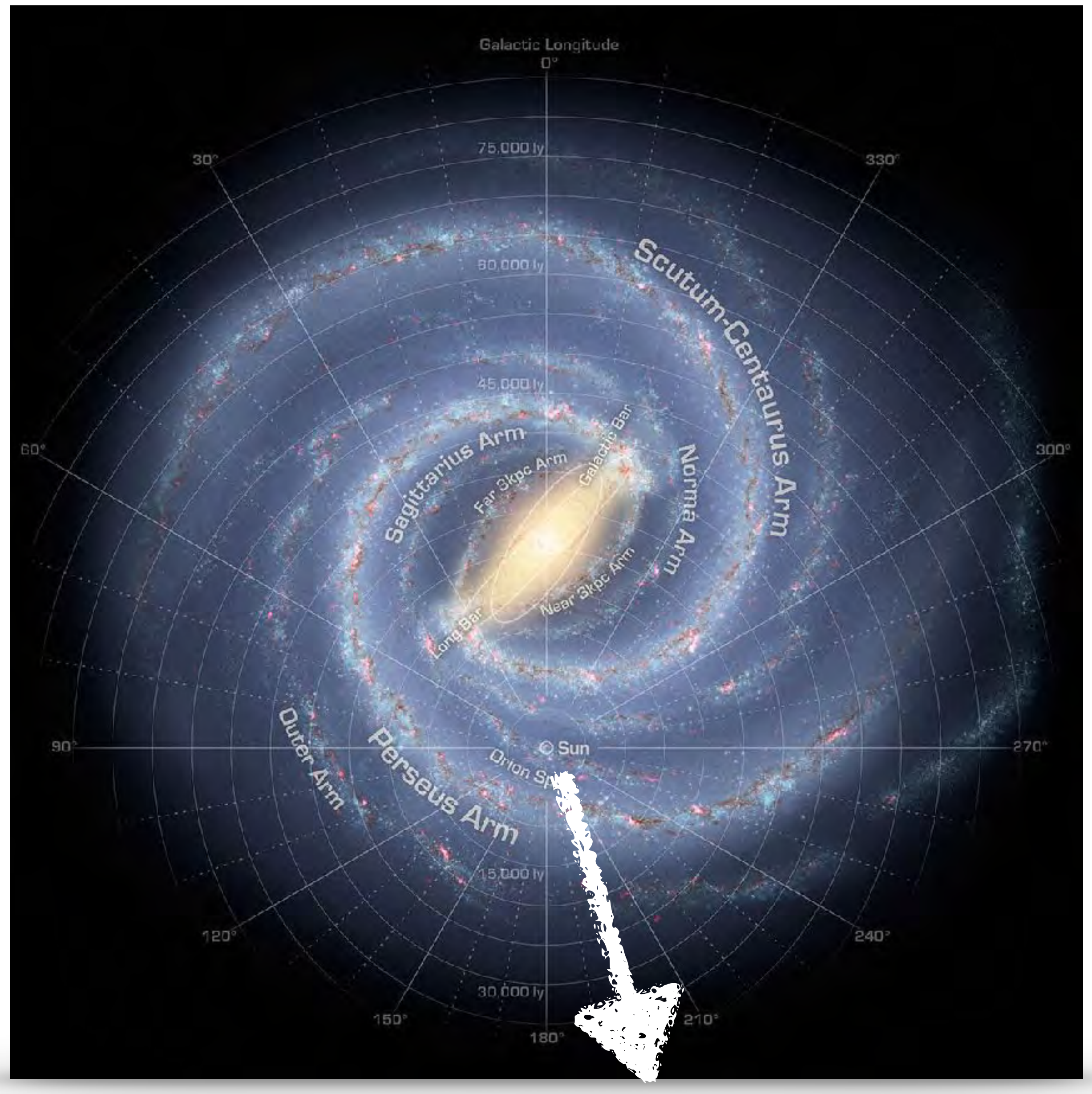
Flux Map above 8 EeV

Auger Collaboration, Science 357 (2017) 1266



physicsworld TOP 10 BREAKTHROUGH 2017





Excess direction ⇒

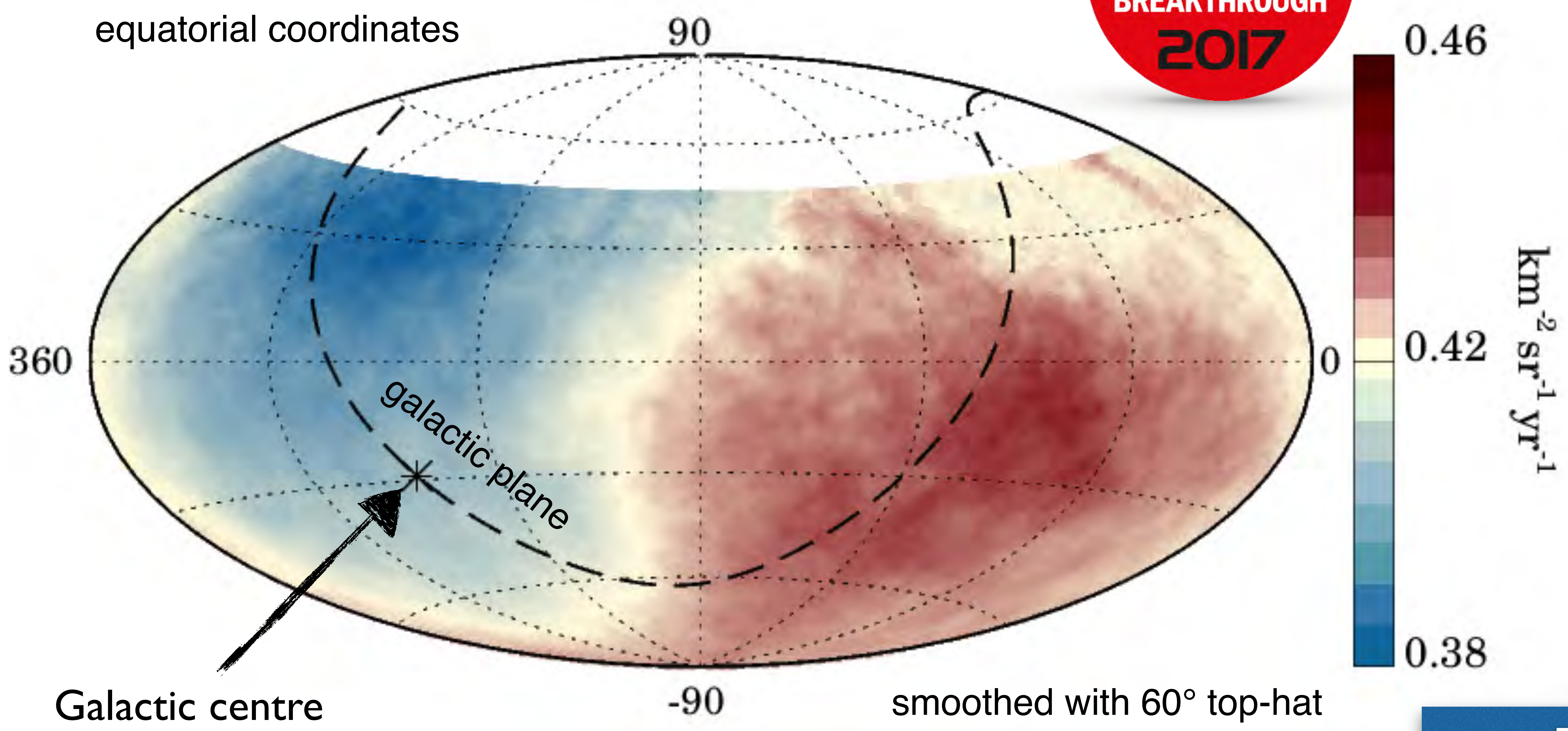
Extragalactic Origin of UHECR

First harmonic in right ascension:

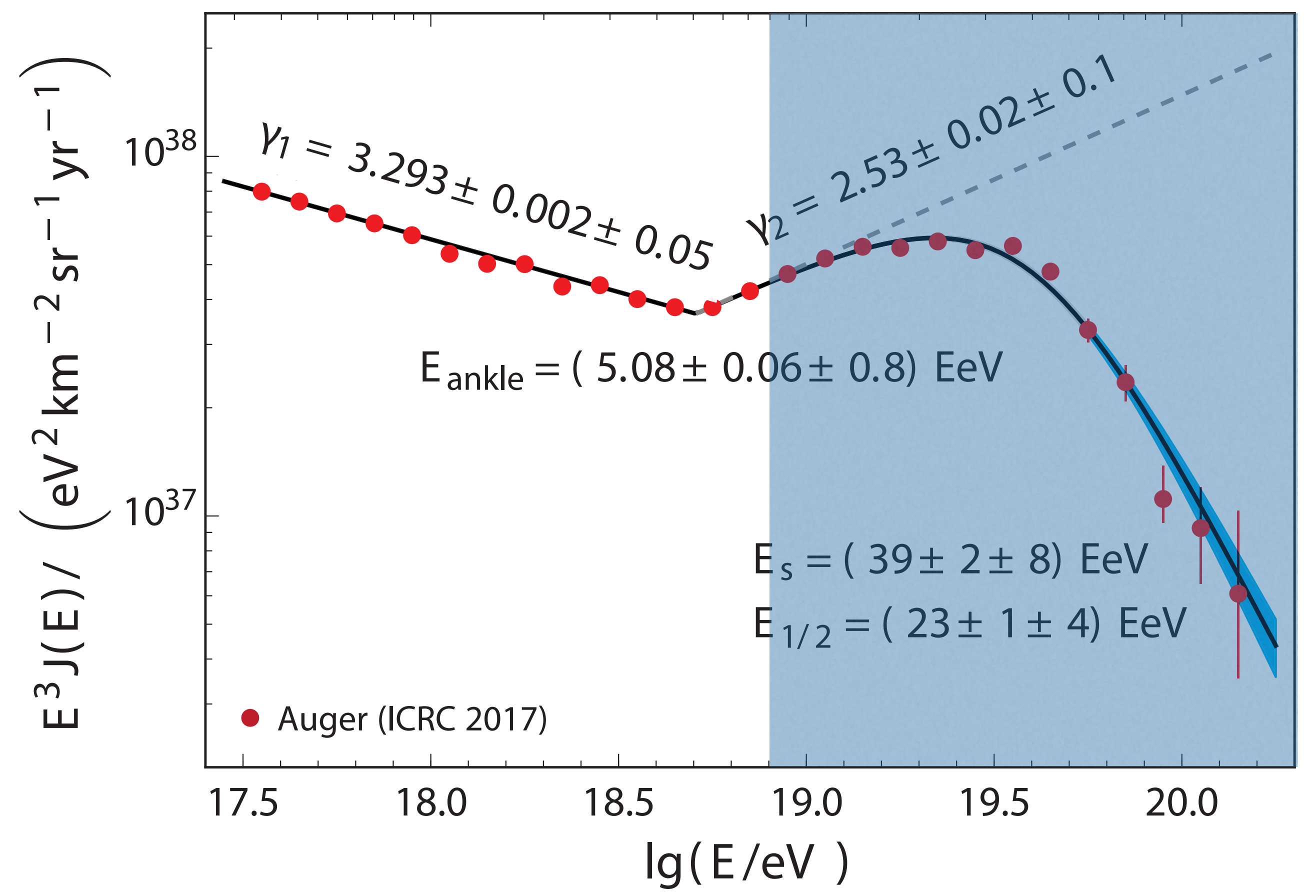
$$\mathcal{A} = 6.5^{+1.3}_{-0.9}\,\% \;\; ; \;\; \alpha_d = (100 \pm 10)^\circ \;\; ; \;\; \delta_d = (-24^{+12}_{-13})^\circ$$

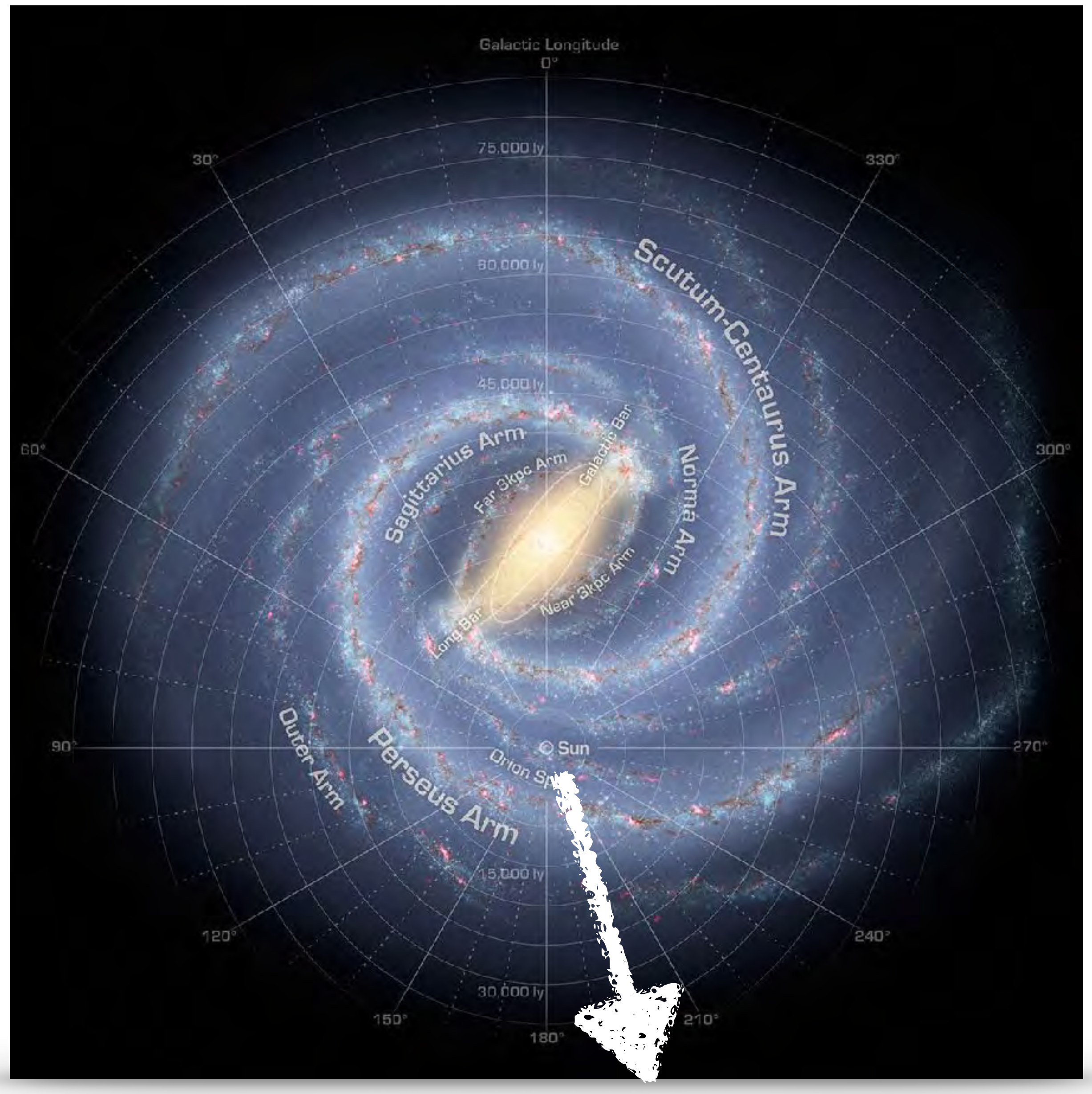
Flux Map above 8 EeV

Auger Collaboration, Science 357 (2017) 1266



physicsworld TOP 10 BREAKTHROUGH 2017



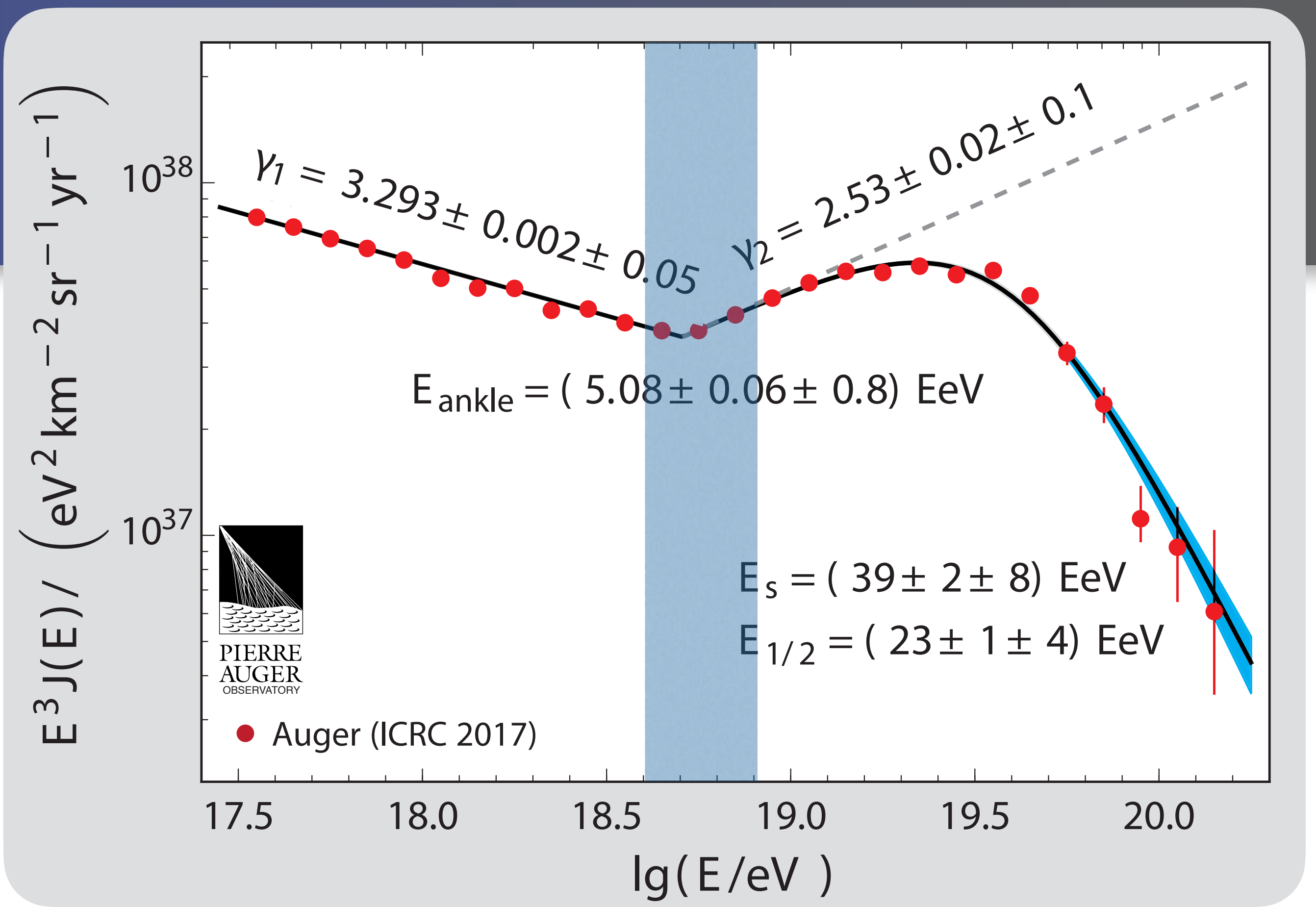


$$\mathcal{A} = 6.5^{+1.3}_{-0.9}\,\% \;\; ; \;\; \alpha_d = (100 \pm 10)^\circ \;\; ; \;\; \delta_d = (-24^{+12}_{-13})^\circ$$

Excess direction ⇒

Extragalactic Origin of UHECR

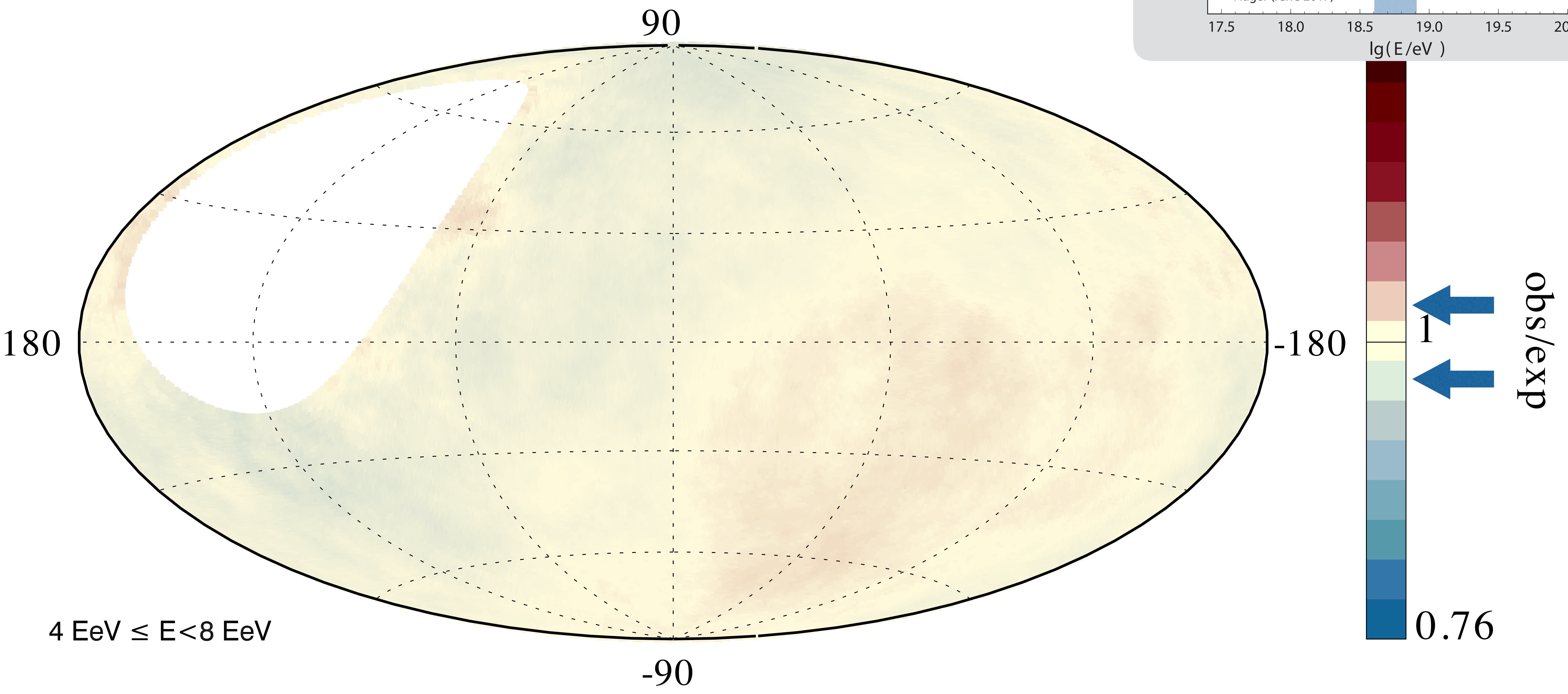
Evolution with Energy: 4-8 EeV



Auger Collaboration, ApJ 868 (2018) 1

map smoothed with 45° top-hat
Galactic coordinates

all maps with identical color scale

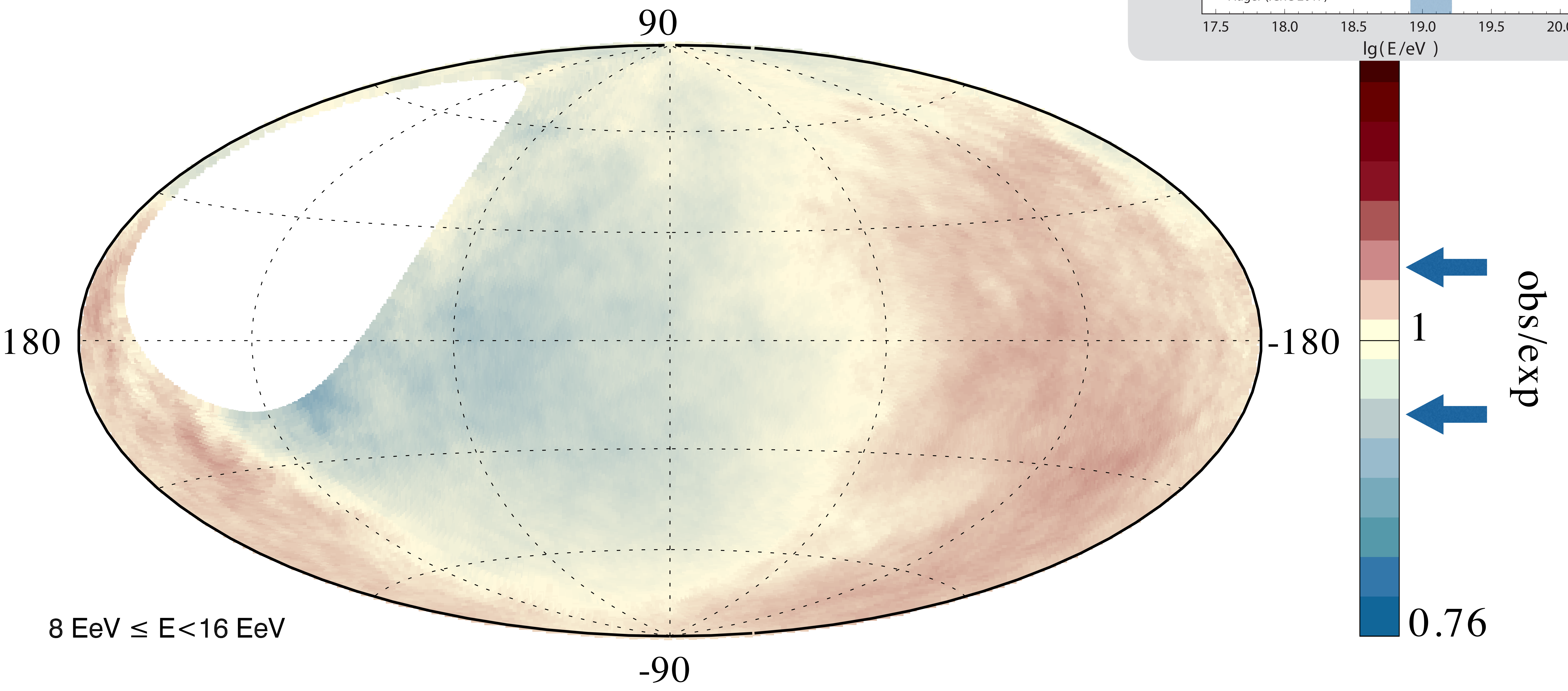


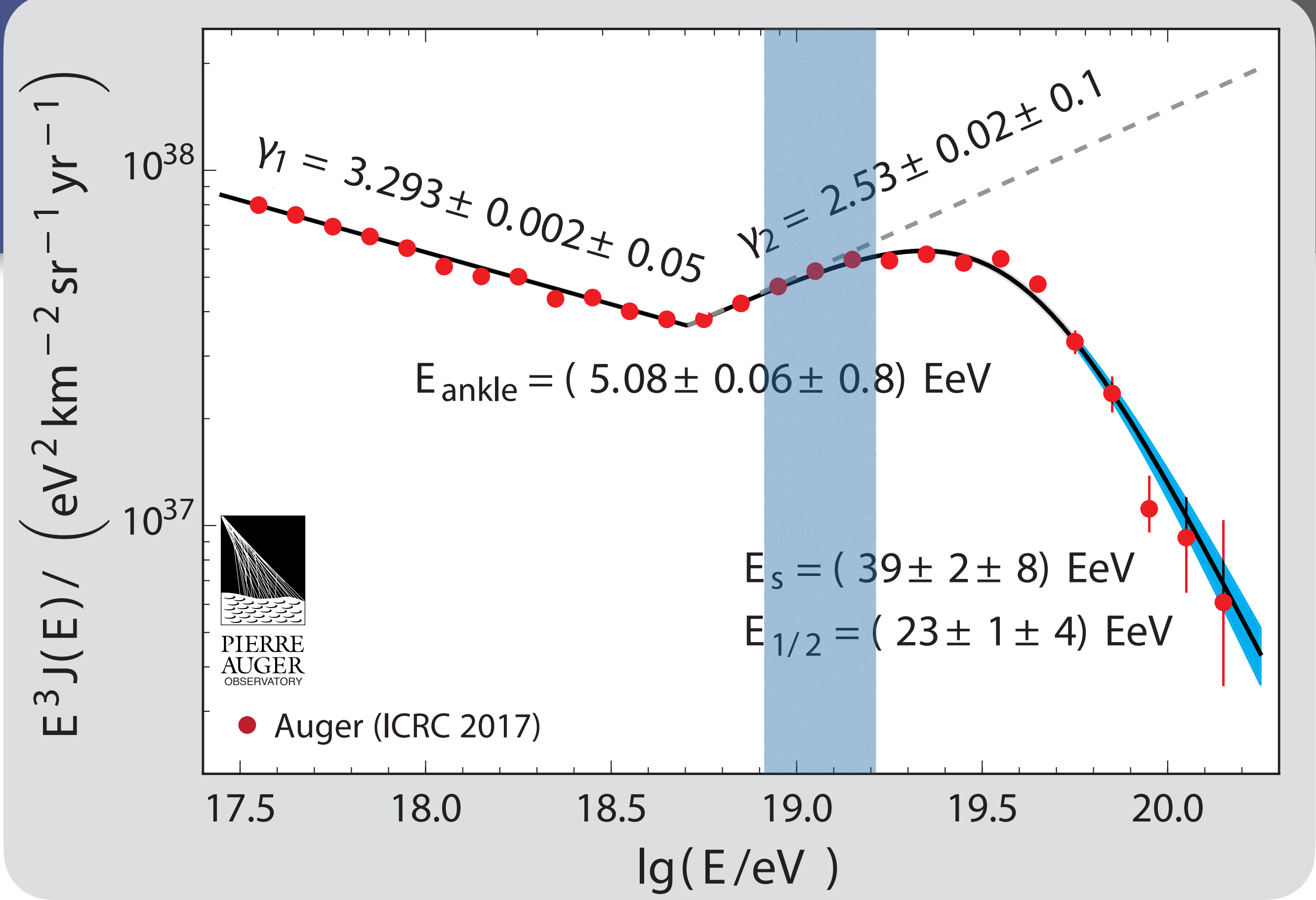
Evolution with Energy: 8-16 EeV

Auger Collaboration, ApJ 868 (2018) 1

map smoothed with 45° top-hat
Galactic coordinates

all maps with identical color scale



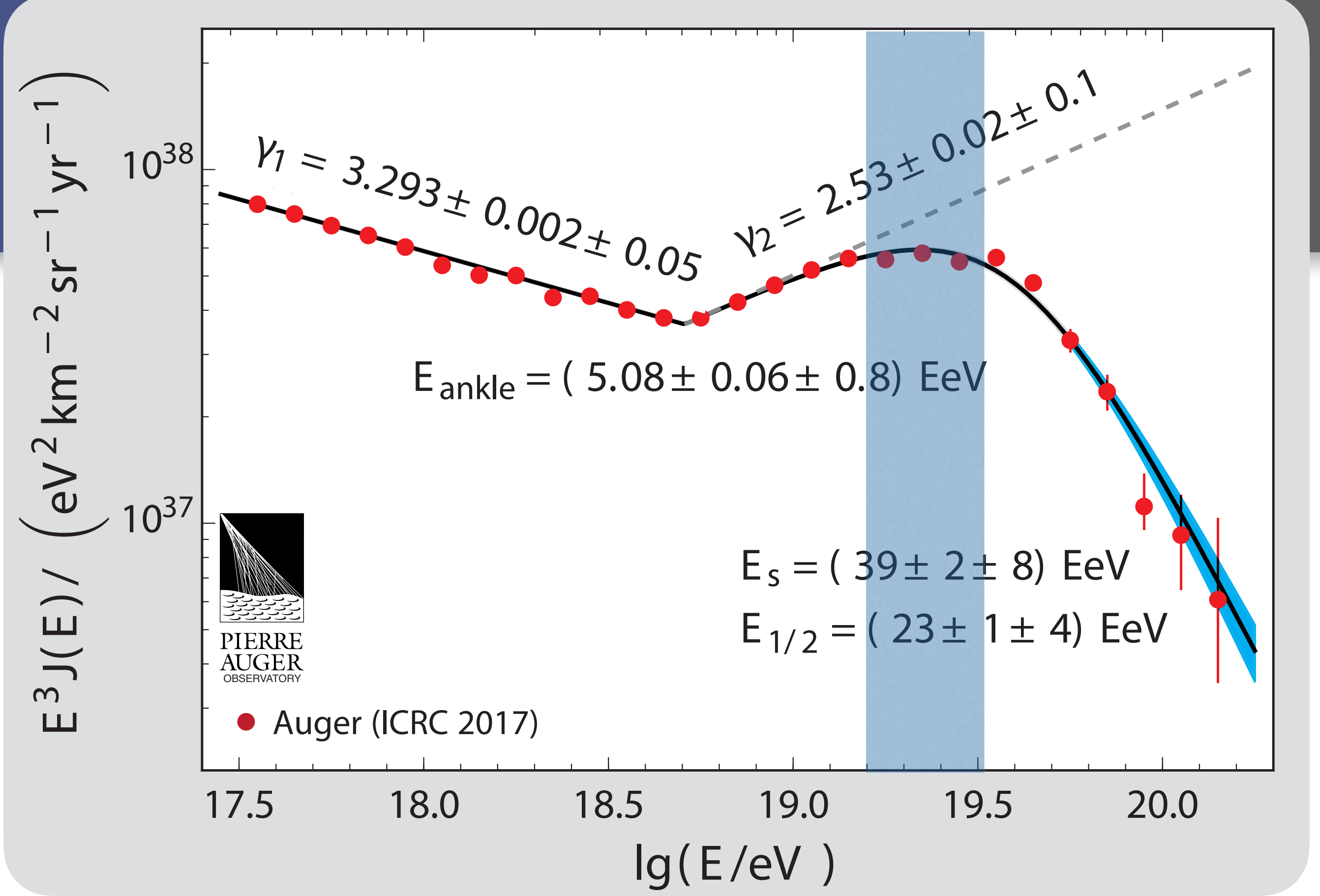


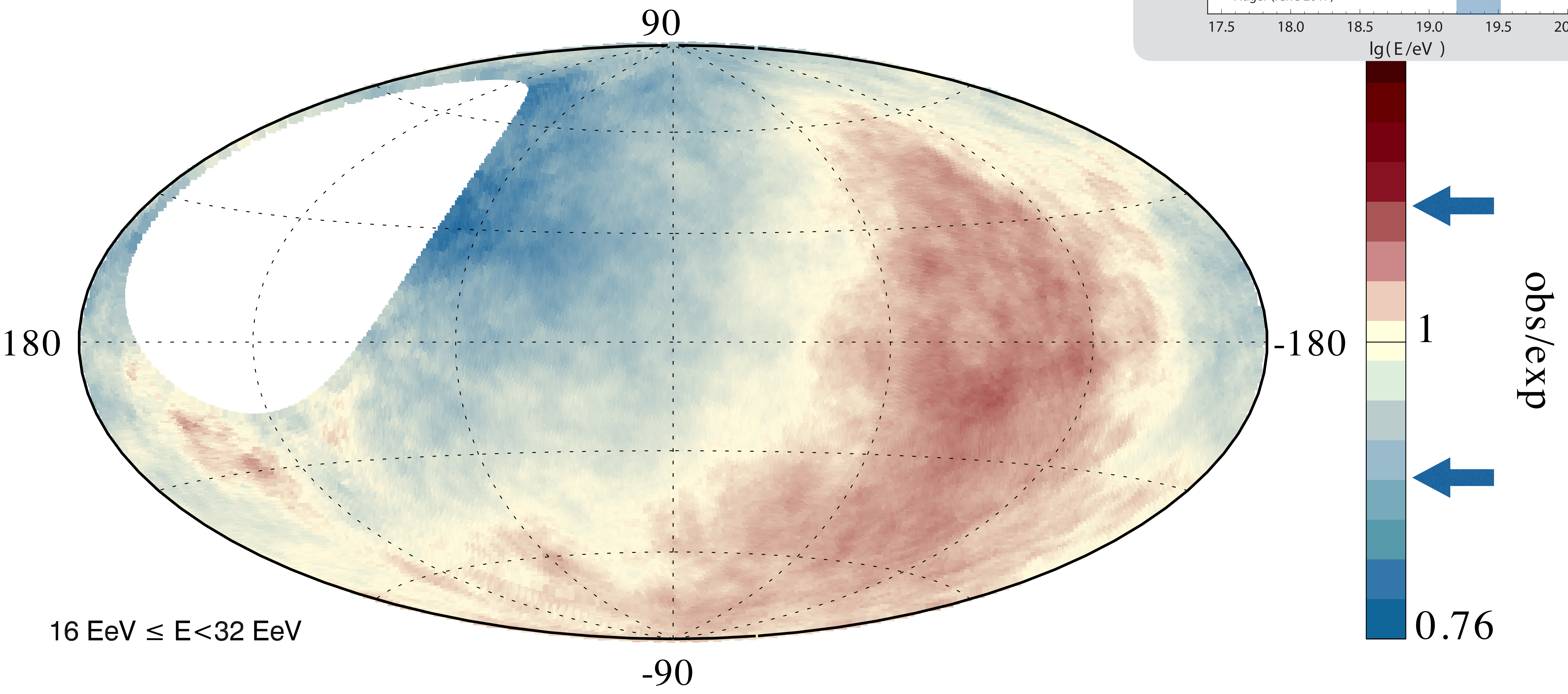
Evolution with Energy: 16-32 EeV

Auger Collaboration, ApJ 868 (2018) 1

map smoothed with 45° top-hat
Galactic coordinates

all maps with identical color scale



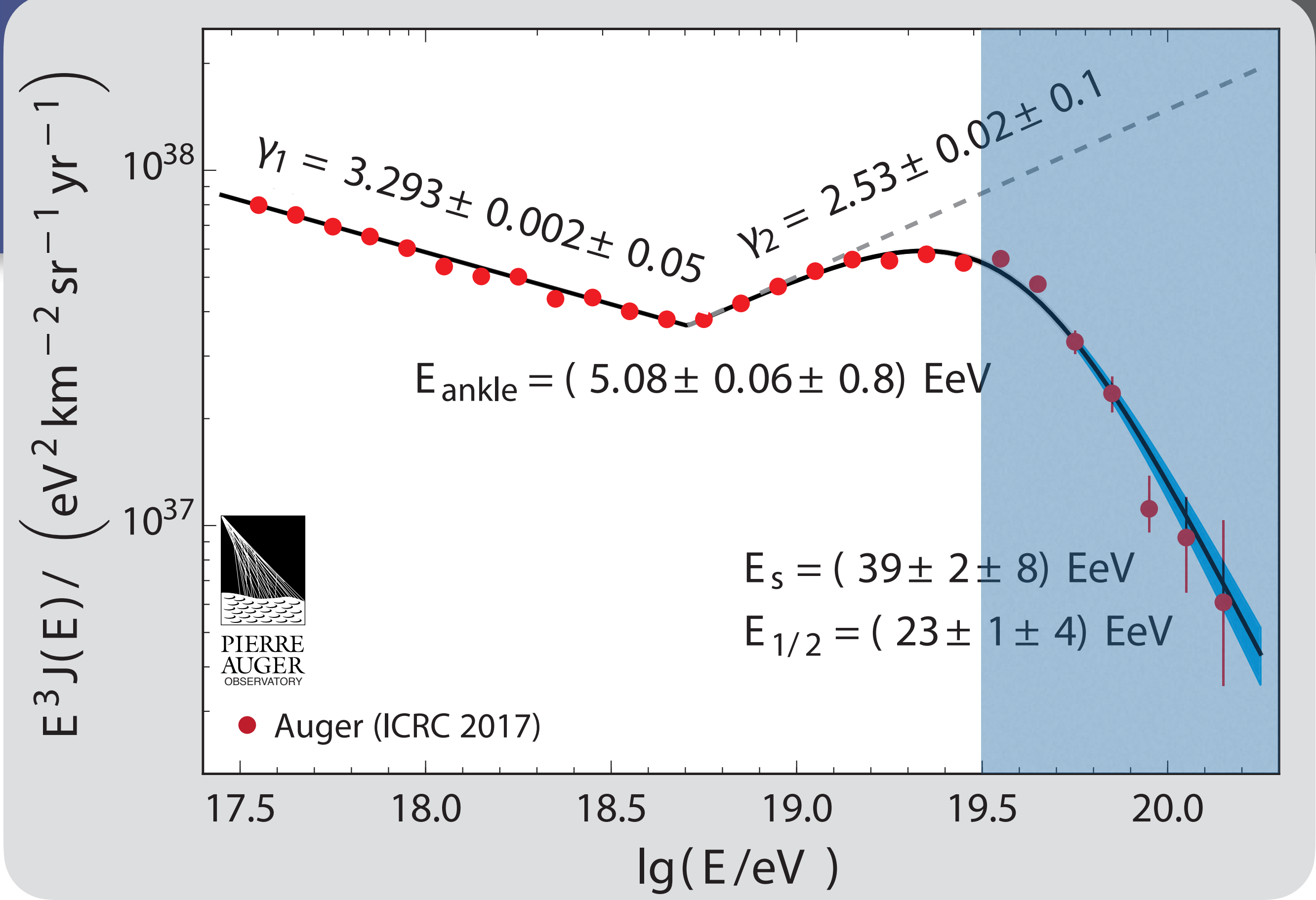


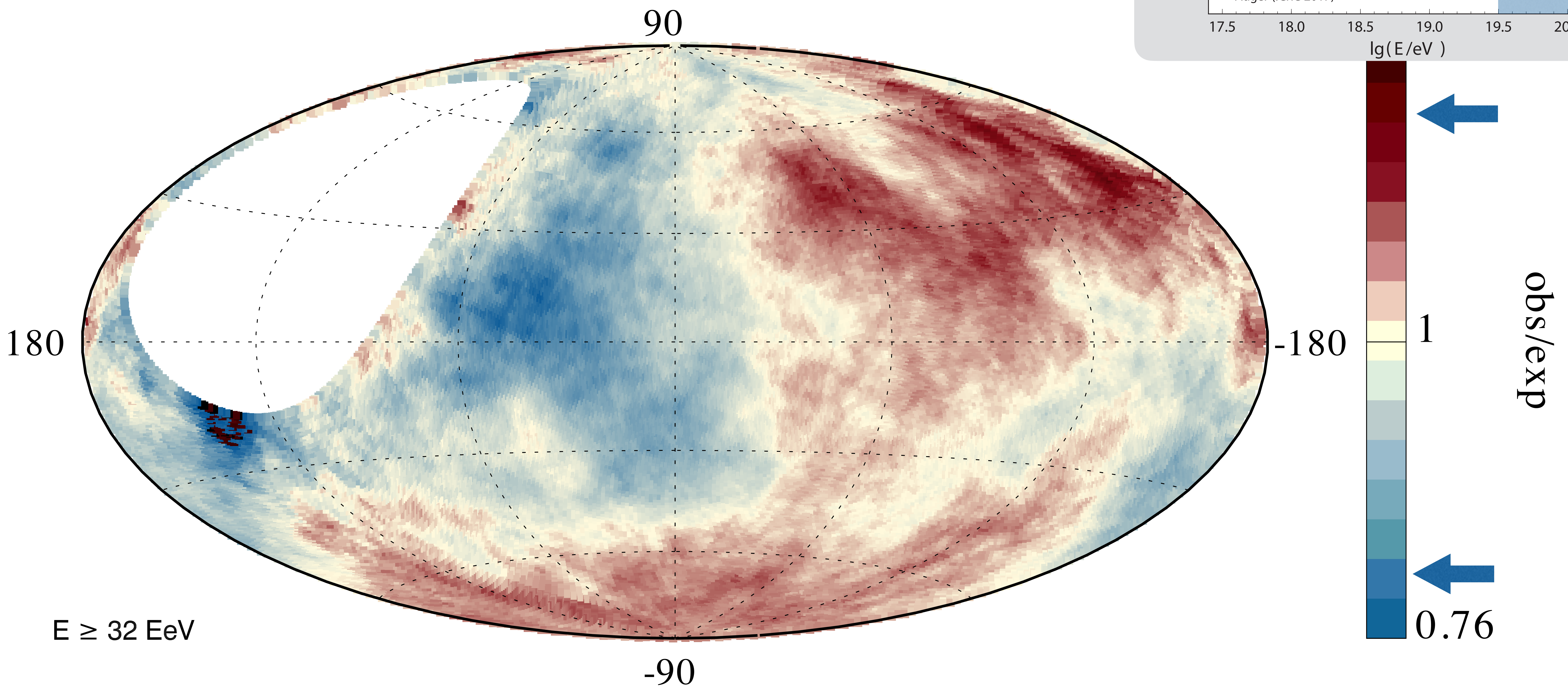
Evolution with Energy: >32 EeV

Auger Collaboration, ApJ 868 (2018) 1

map smoothed with 45° top-hat
Galactic coordinates

all maps with identical color scale



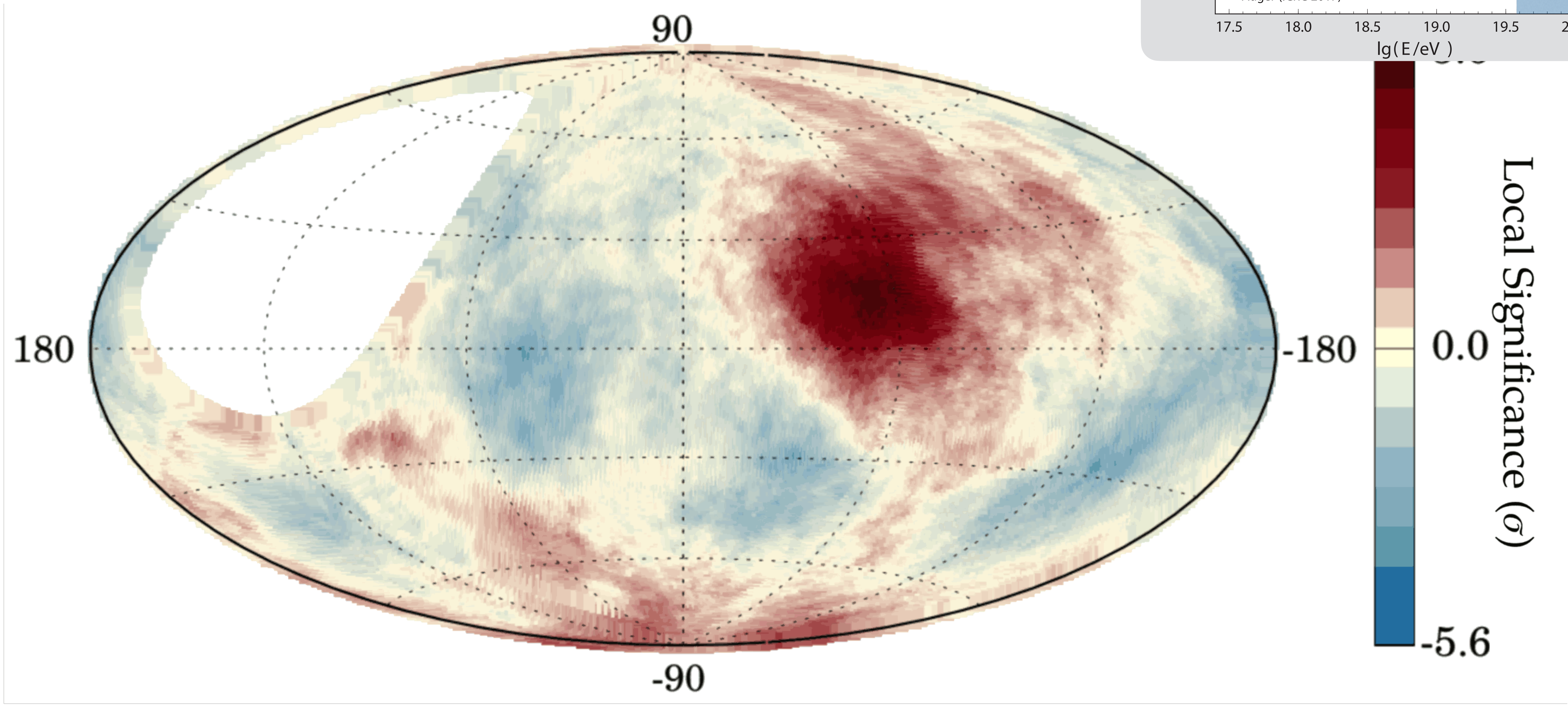


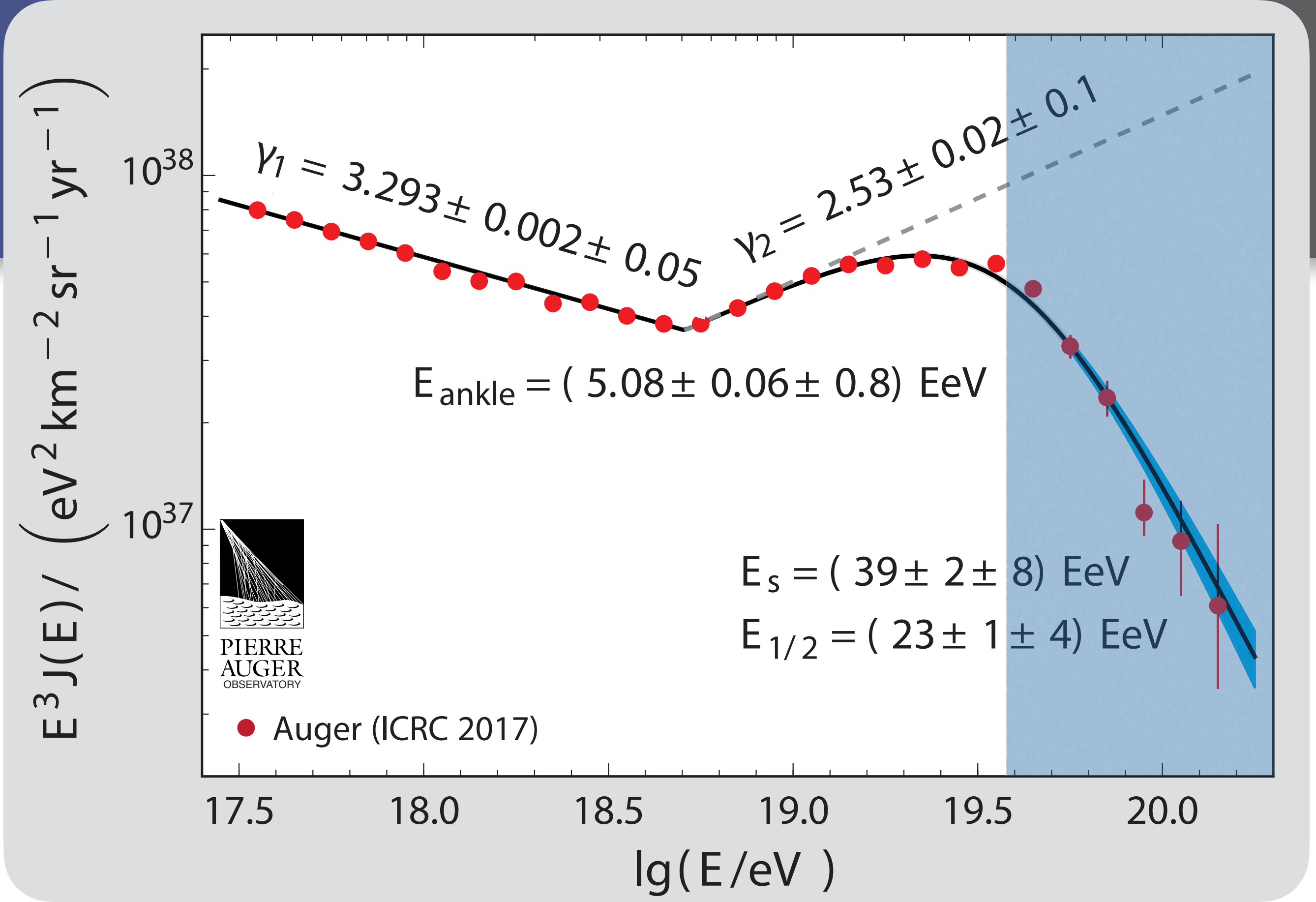
Evolution with Energy: >38 EeV

Auger Collaboration, PoS(ICRC2019)206

map smoothed with 27° top-hat
Galactic coordinates

significance map

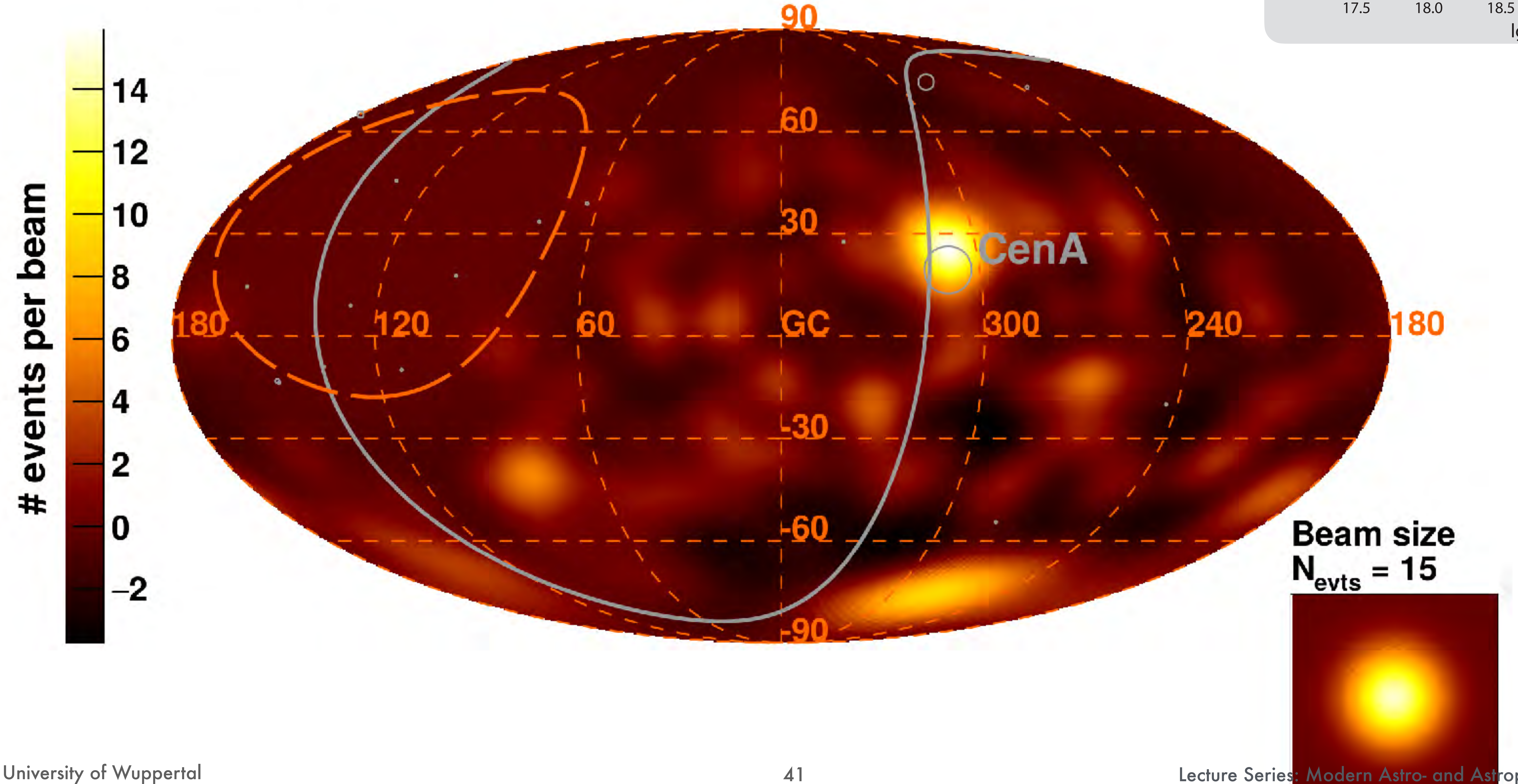


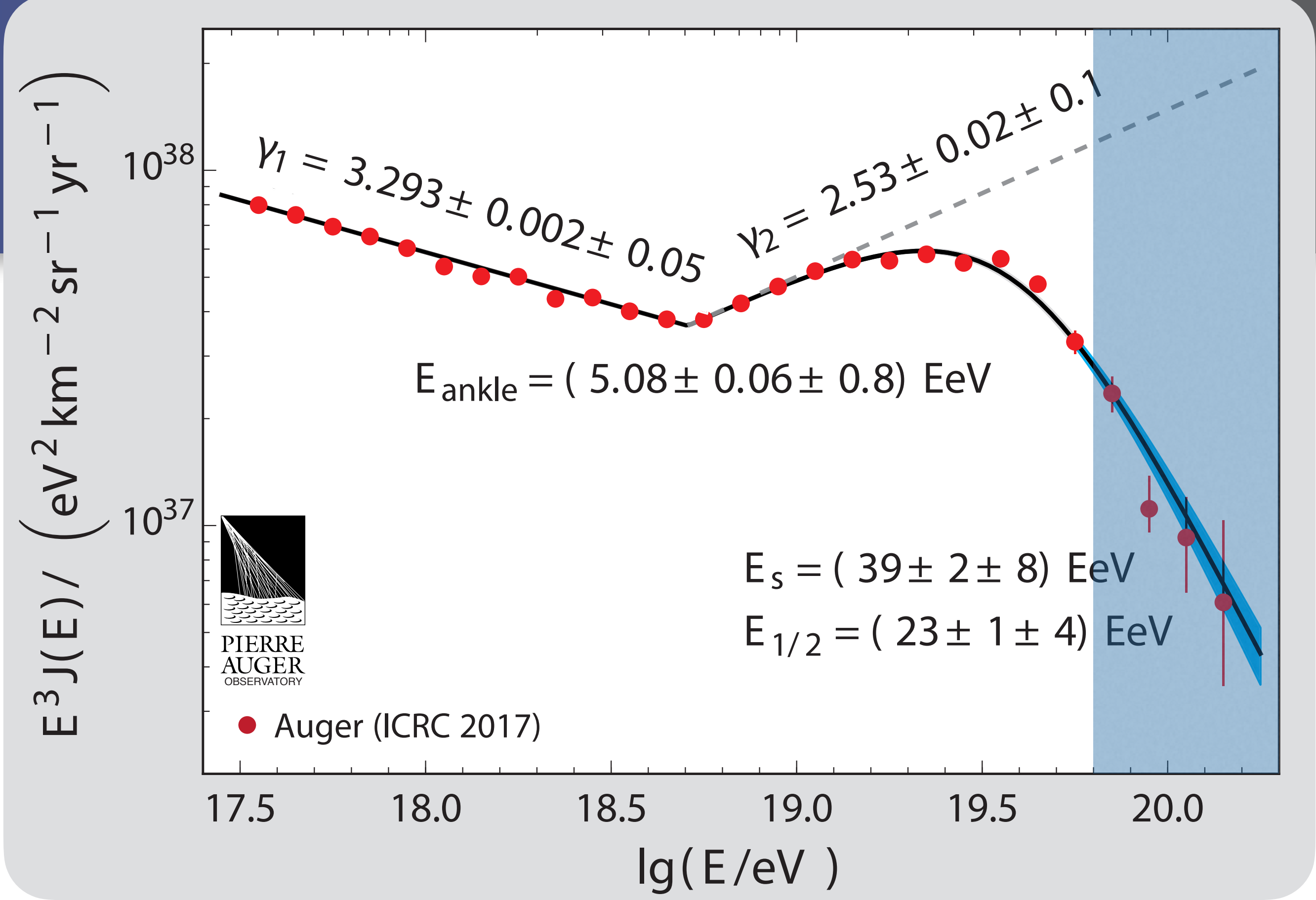


Evolution with Energy: >60 EeV

Auger: ApJL 853:L29 (2018)

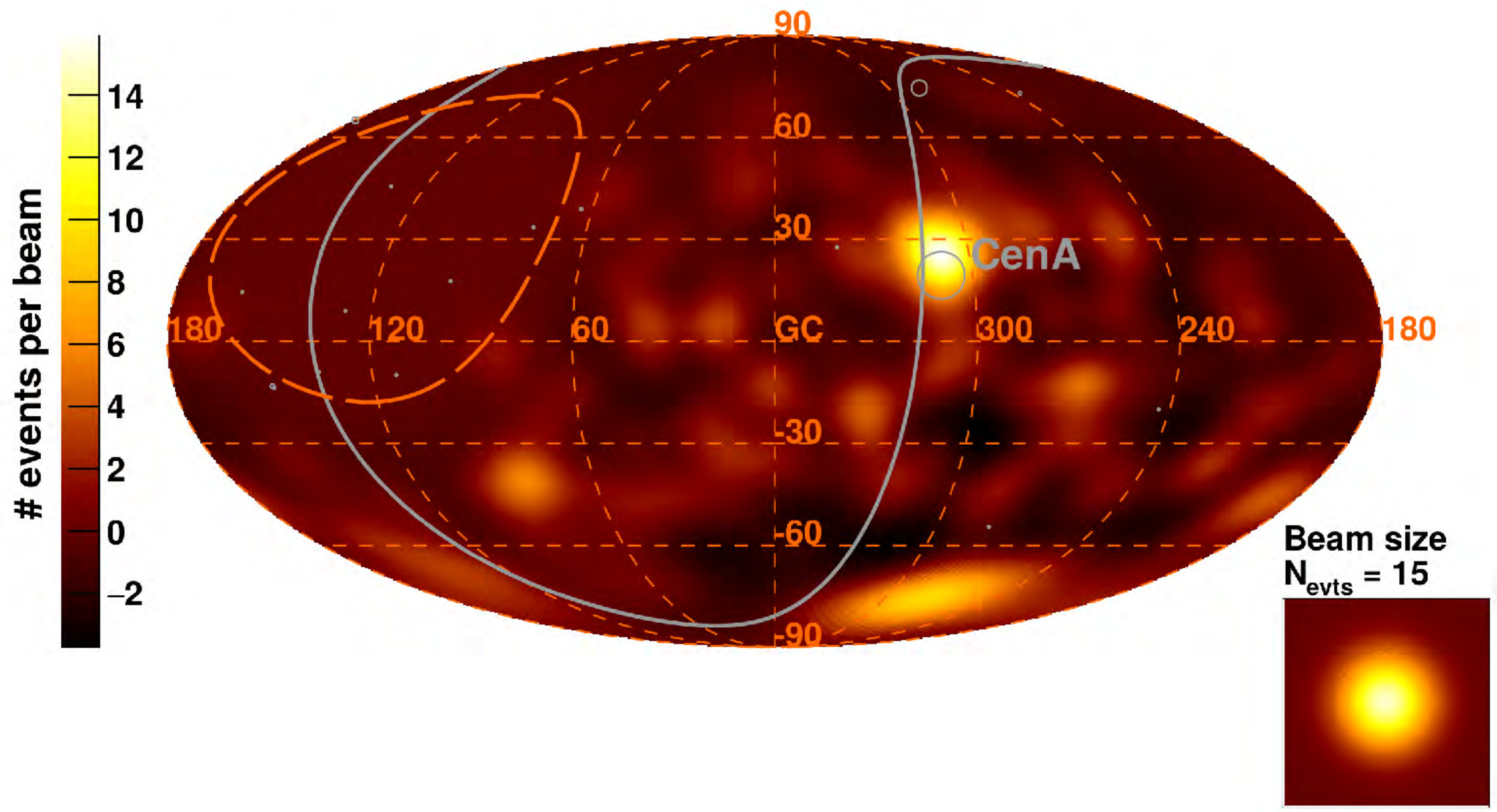
map smoothed with 7° top-hat
Galactic coordinates

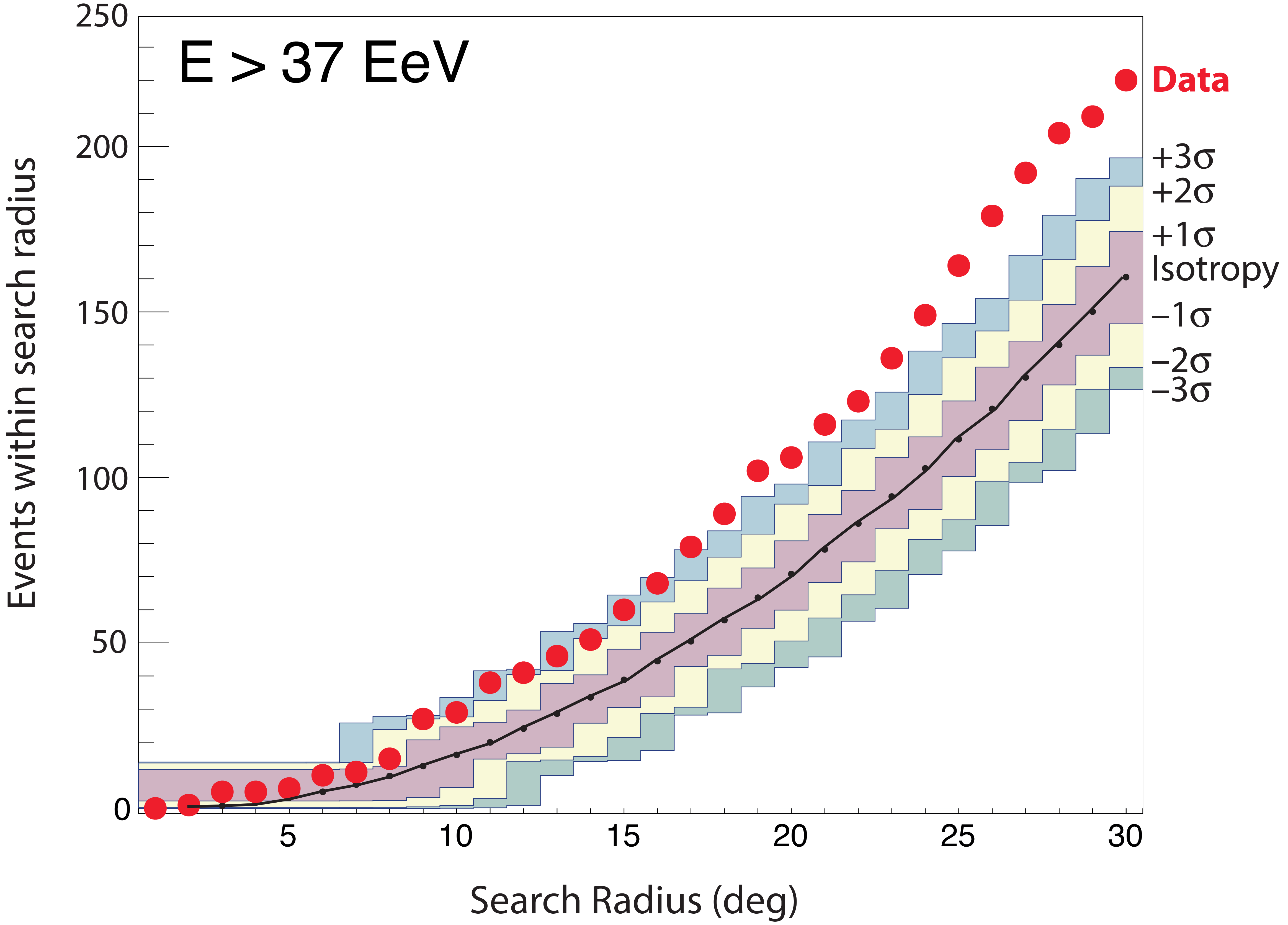




Centaurus A: A source of UHECR?

Auger Collaboration, PoS(ICRC2019)206





Cen A suggestive, but more structure than a single source

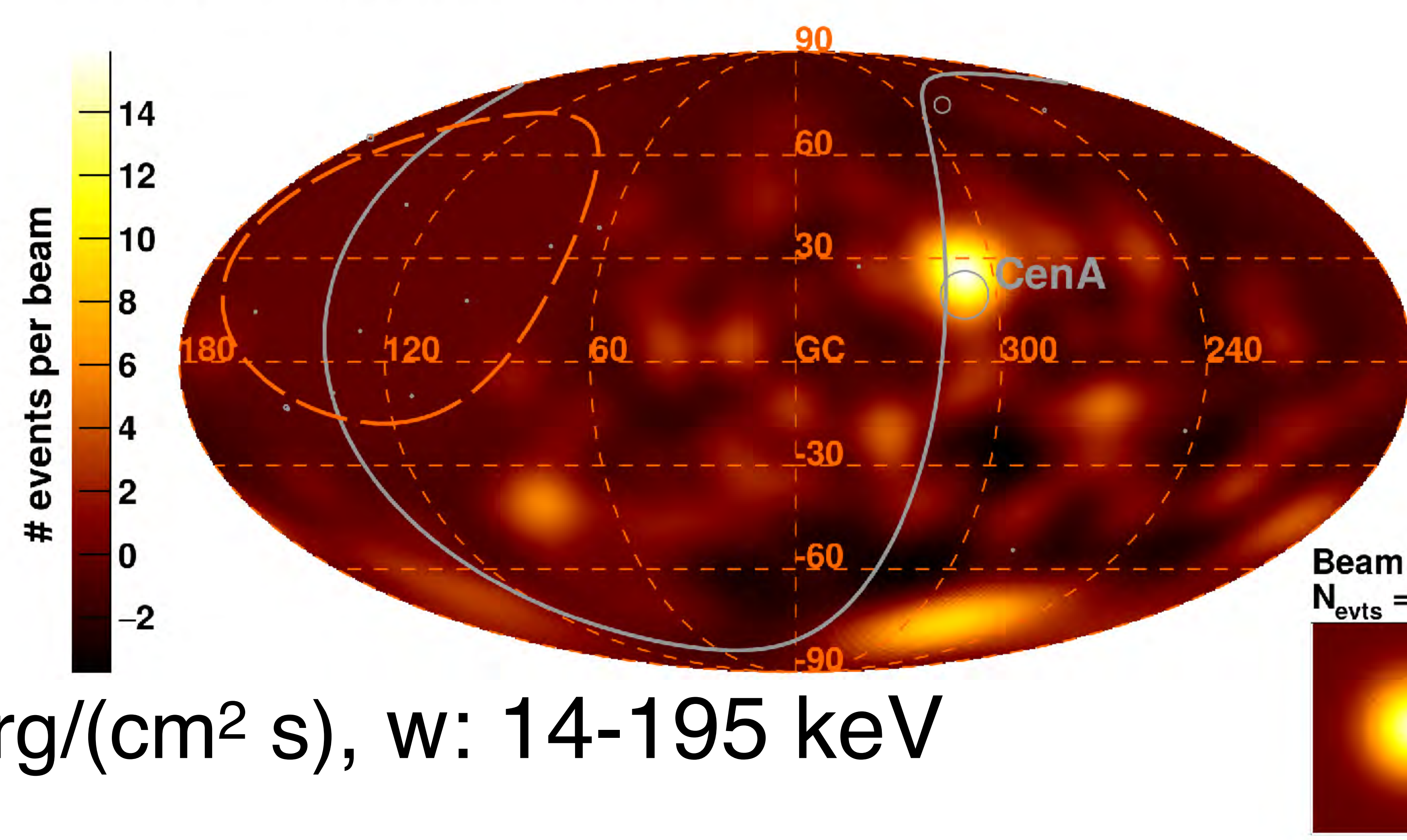
Most significant excess at 28° and 2° offset from Cen A: 203 observed
141 expected → local sign. 5.1σ

⇒ post trial significance: 3.9σ

The Usual UHECR Source Suspects

Swift-BAT 2MRS SGB γAGN ~~VCV~~

Adapted from M. Unger



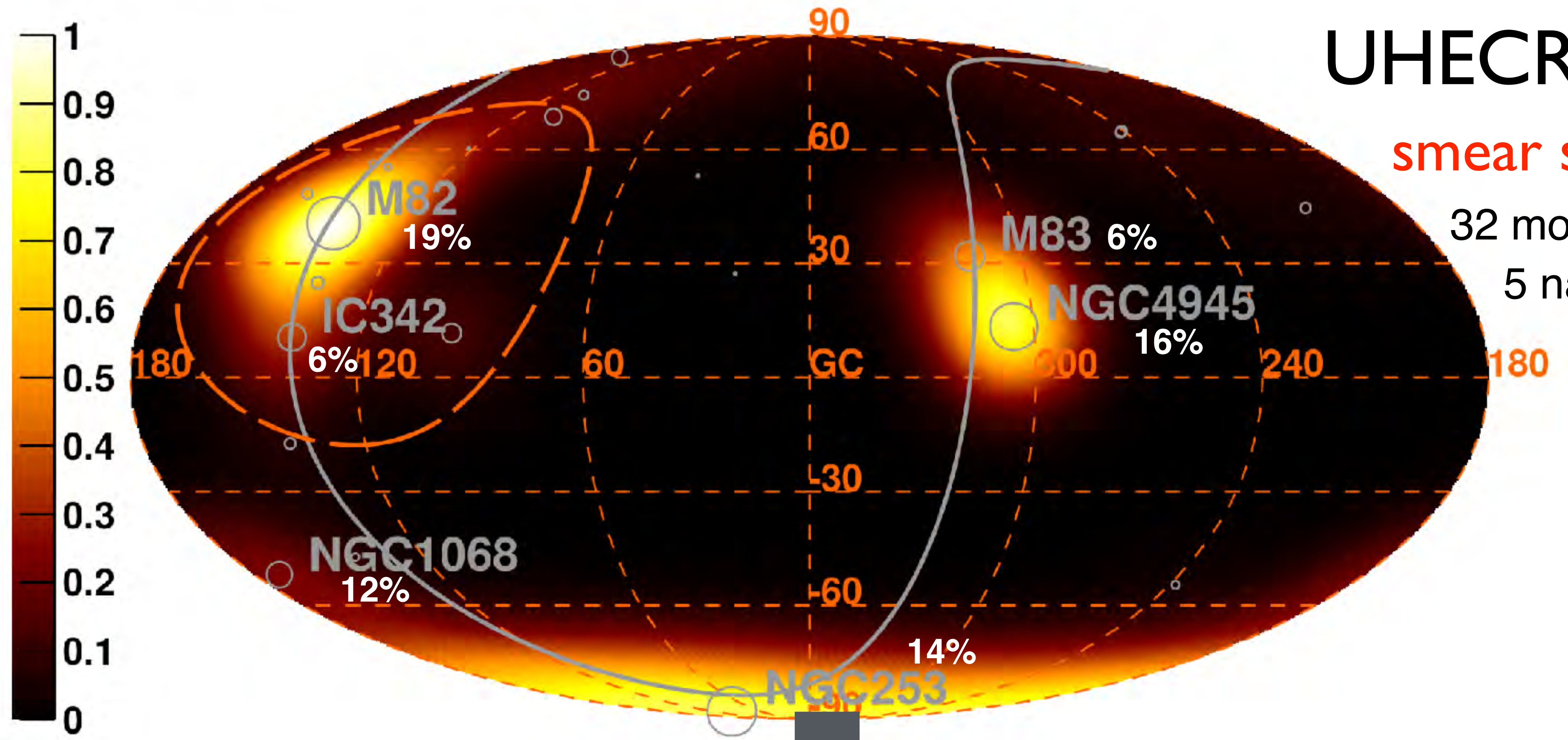
- Swift-BAT X-ray-selected galaxies, D < 250 Mpc, $\Phi > 1{:}3\times10^{-11}$ erg/(cm² s), w: 14-195 keV
- 2MRS IR-selected galaxies, D > 1 Mpc, w: K-band
- SBG: 23 nearby starburst galaxies, $\Phi > 0.3$ Jy, w: radio at 1.4 GHz
- γAGN: 17 3FHL blazars and radio galaxies, D < 250 Mpc, w: γ-ray 10 GeV - 1 TeV

in all cases em-radiation used as proxy for UHECR luminosity

Understanding the UHECR Sky

Starburst Galaxy Model

Model Flux Map - Starburst galaxies E>38 EeV



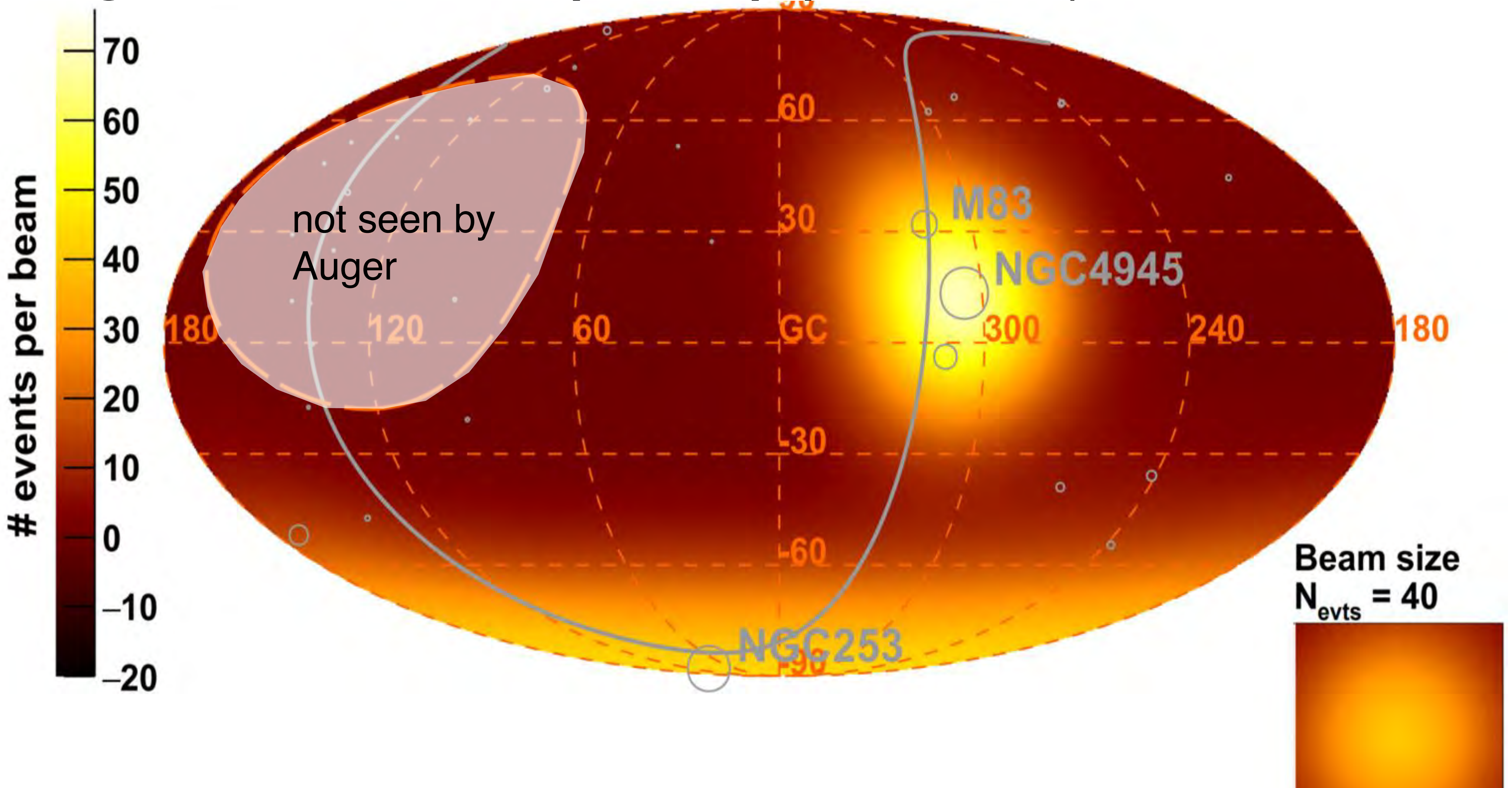
Assume, starburst galaxies produce UHECR with $L_{UHECR} \sim L_{\gamma}$ @ 1.4 GHz

smear sources to account for B-field deflections

32 most bright sources included

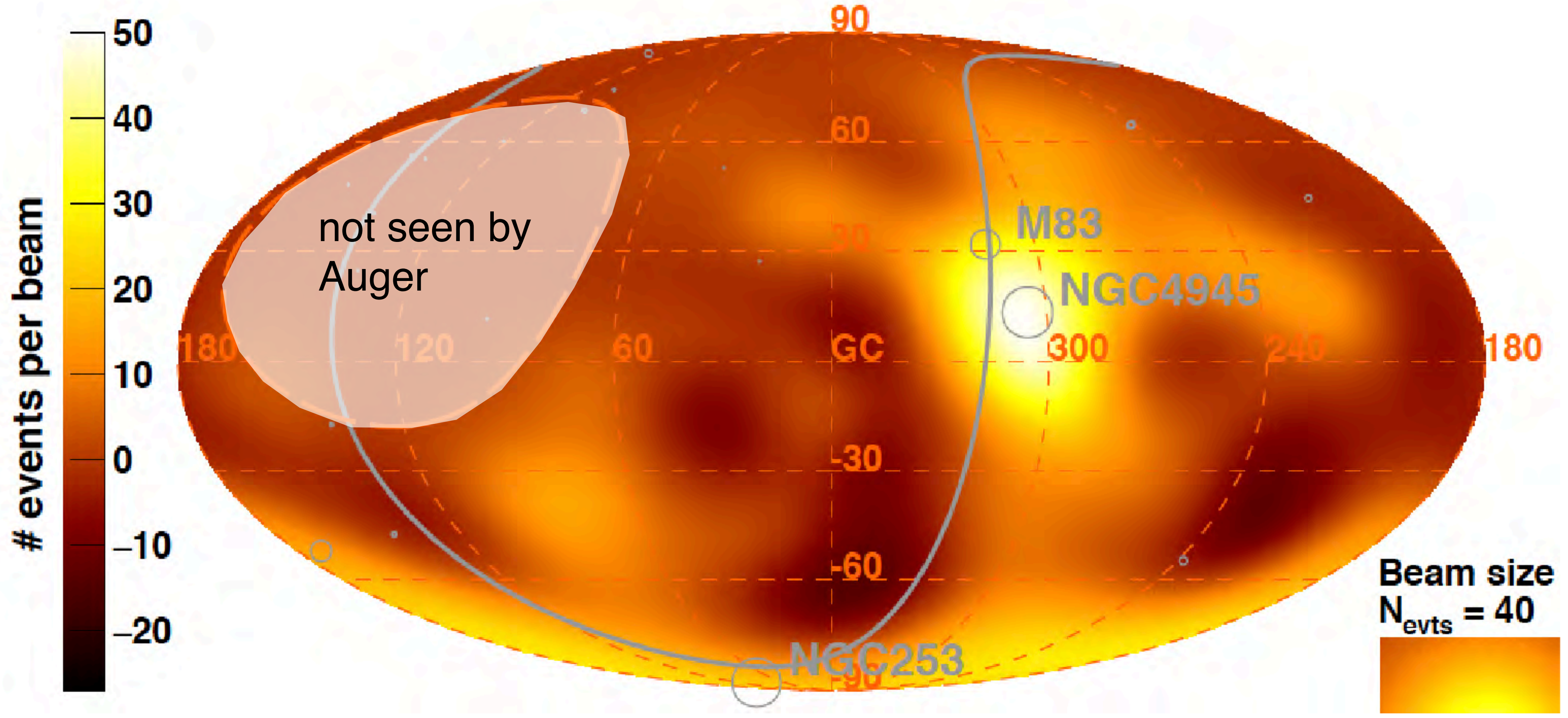
5 named sources contribute 75% of total flux

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>38 EeV

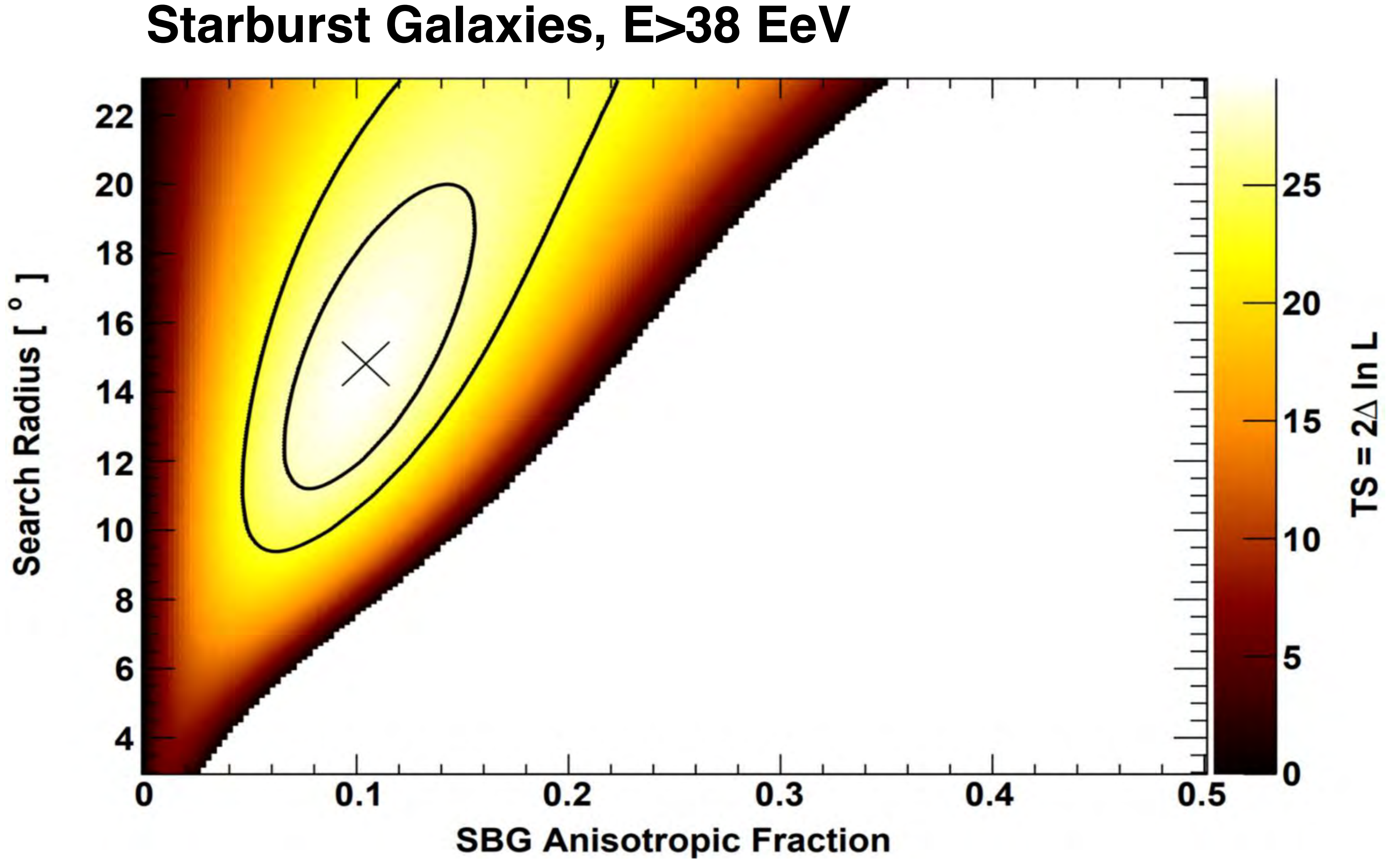


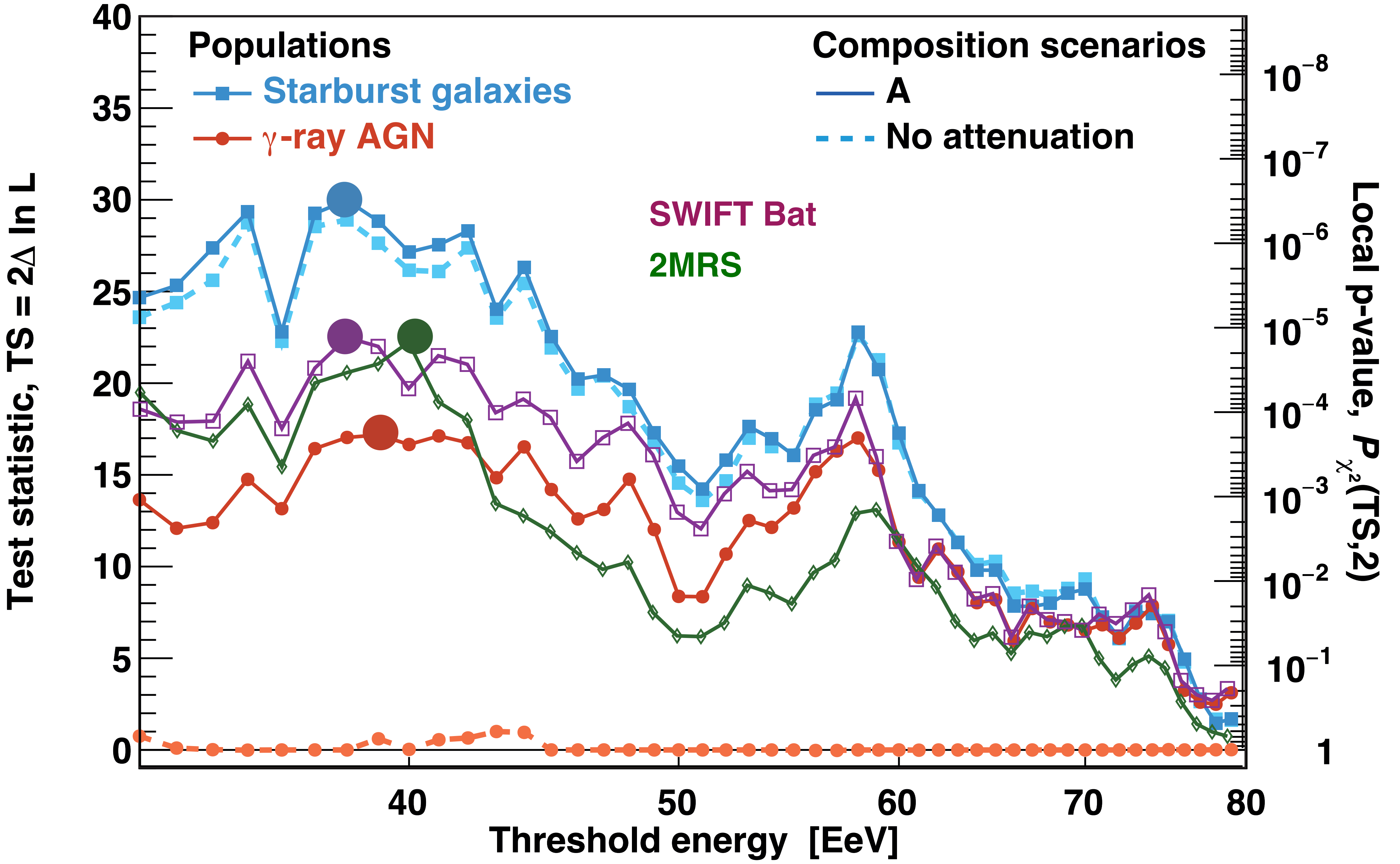
Sources assumed to emit UHECR spectrum and composition according to results from combined fit.
Propagation effects (attenuation) fully accounted for.

Auger: ApJL 853:L29 (2018)

Test Statistic & 2D-Profiles

Two free parameters at each E_{thr}: smearing angle, anisotropic fraction





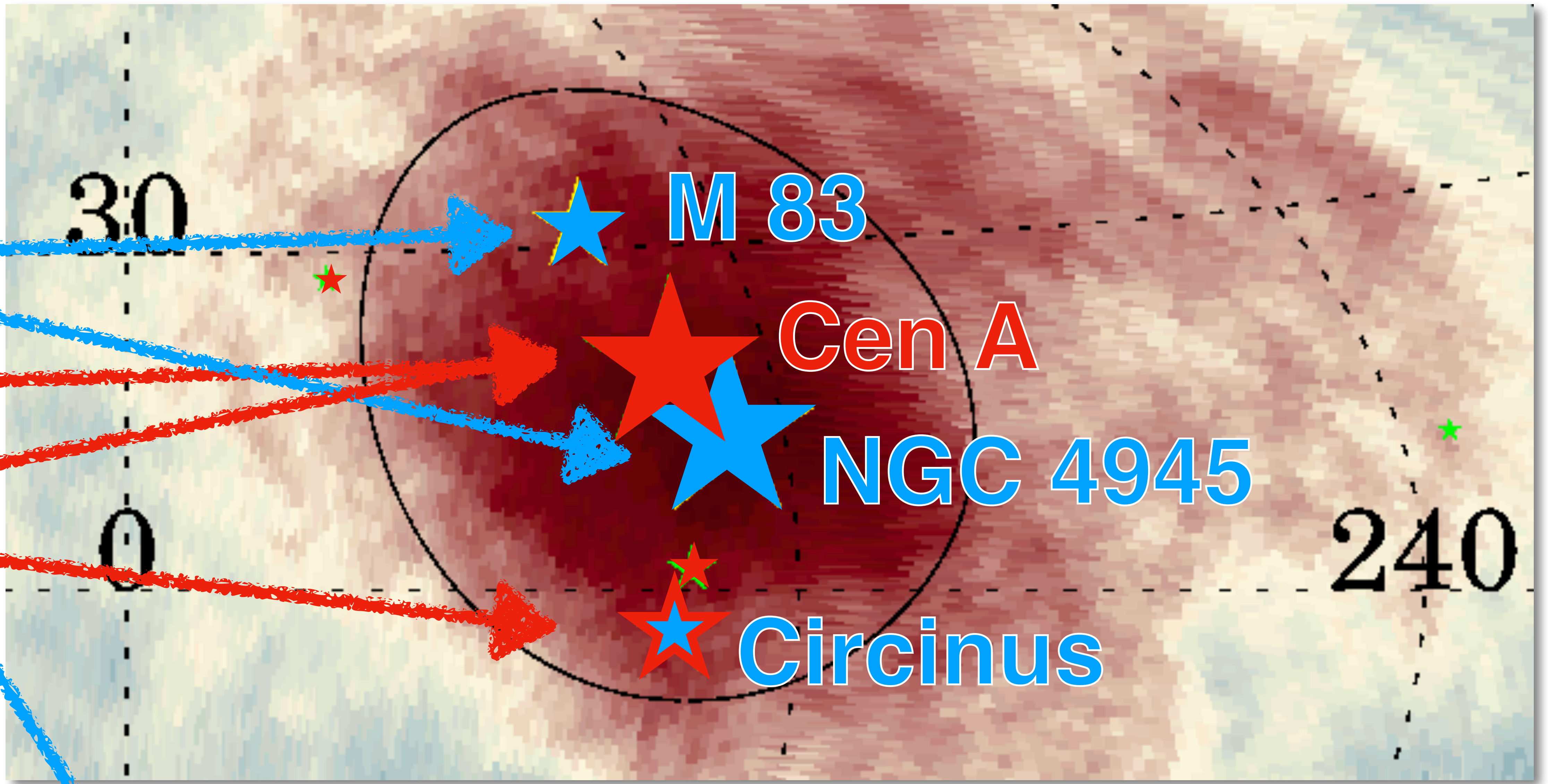
Catalog	E_{th}	θ	f_{aniso}	TS	Post-trial
Starburst	38 EeV	15^{+5}_{-4}°	11^{+5}_{-4}%	29.5	4.5 σ
γ-AGNs	39 EeV	14^{+6}_{-4}°	6^{+4}_{-3}%	17.8	3.1 σ
Swift-Bat	38 EeV	15^{+6}_{-4}°	8^{+4}_{-3}%	22.2	3.7 σ
2MRS	40 EeV	15^{+7}_{-4}°	19^{+10}_{-7}%	22.0	3.7 σ

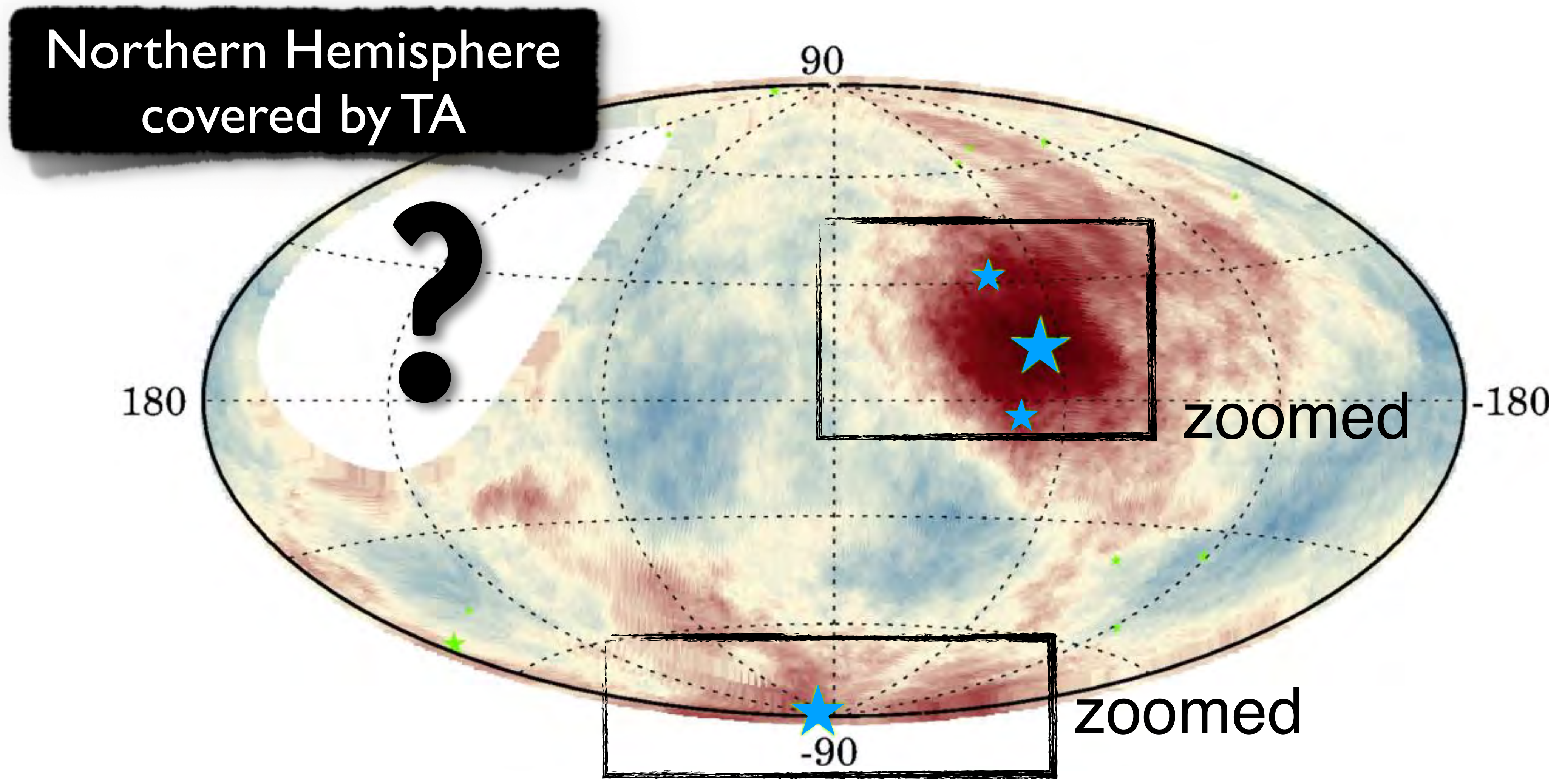
Result: SBG-model fits data better than isotropy at 4.5σ

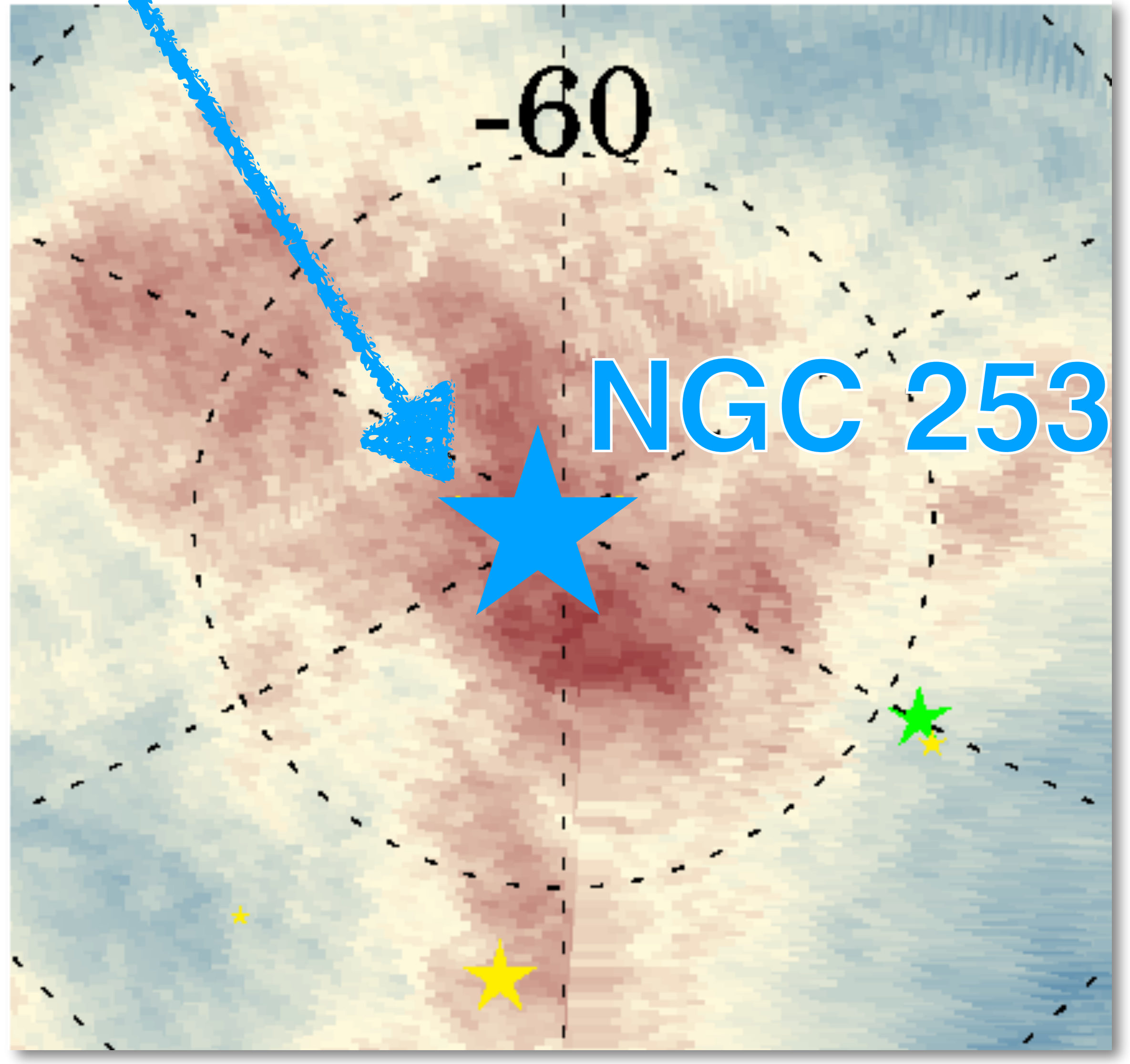
Auger: ApJL 853:L29 (2018), updated in PoS(ICRC2019)206

Many Candidate Sources in Excess Region

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







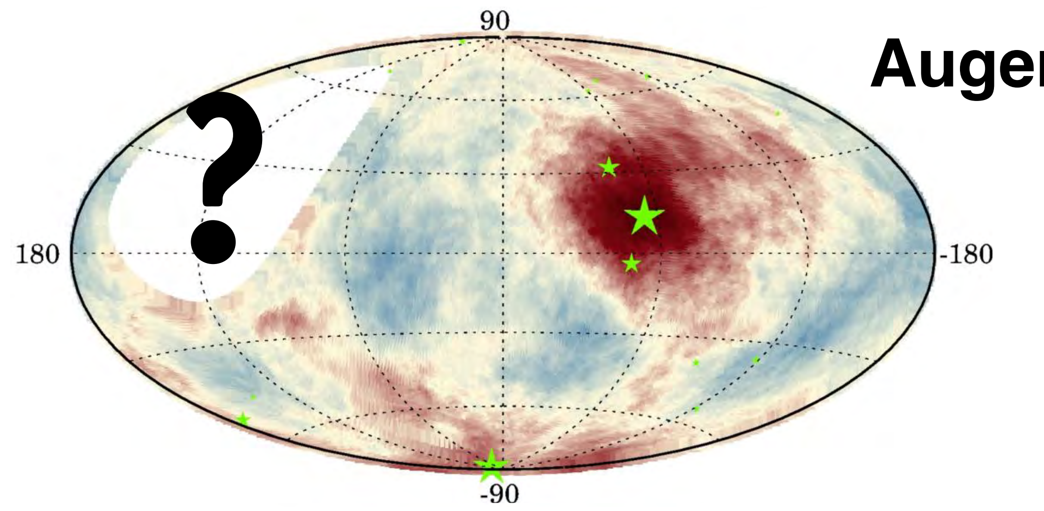
South Galactic Pole region well described by SBG model

no excess expected in γ-AGN

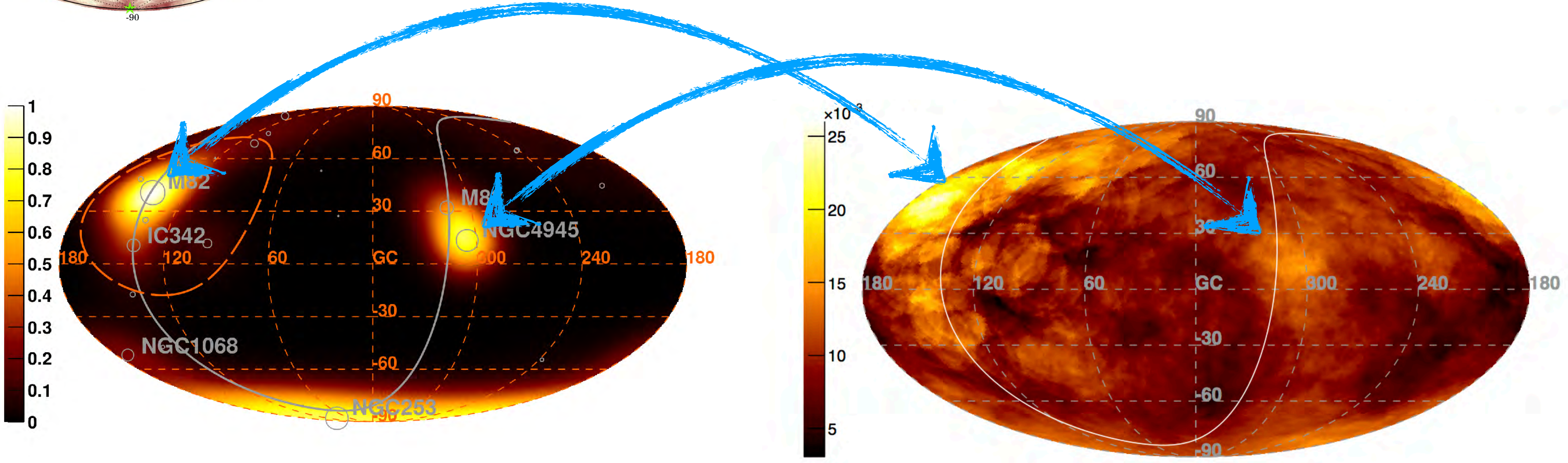
Auger: ApJL 853:L29 (2018), updated in PoS(ICRC2019)206

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

from Auger-TA working group



Auger event map E>38 EeV



SBG model map

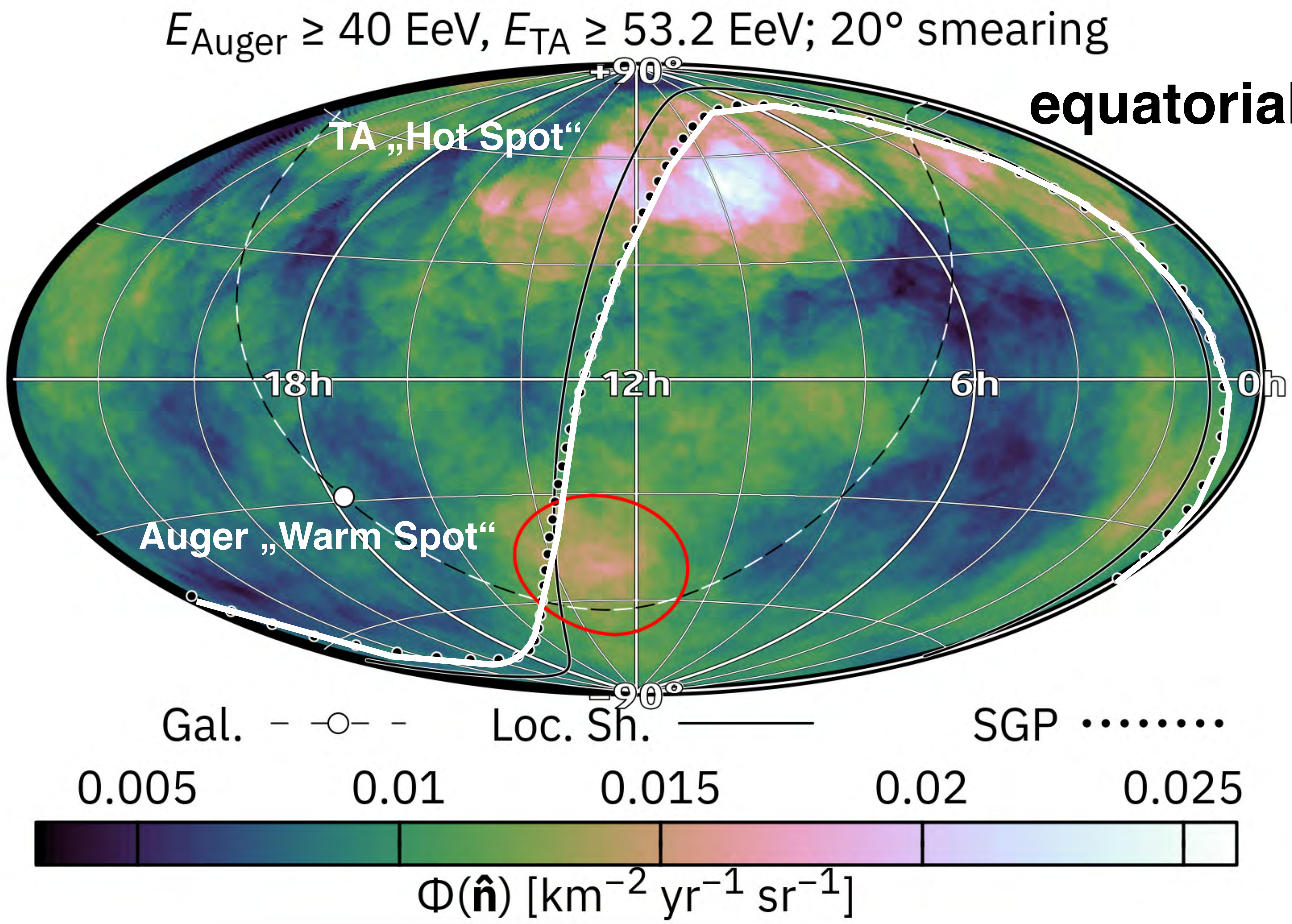
Auger+TA UHECR sky map

galactic coordinates

joint full-sky analysis in progress …

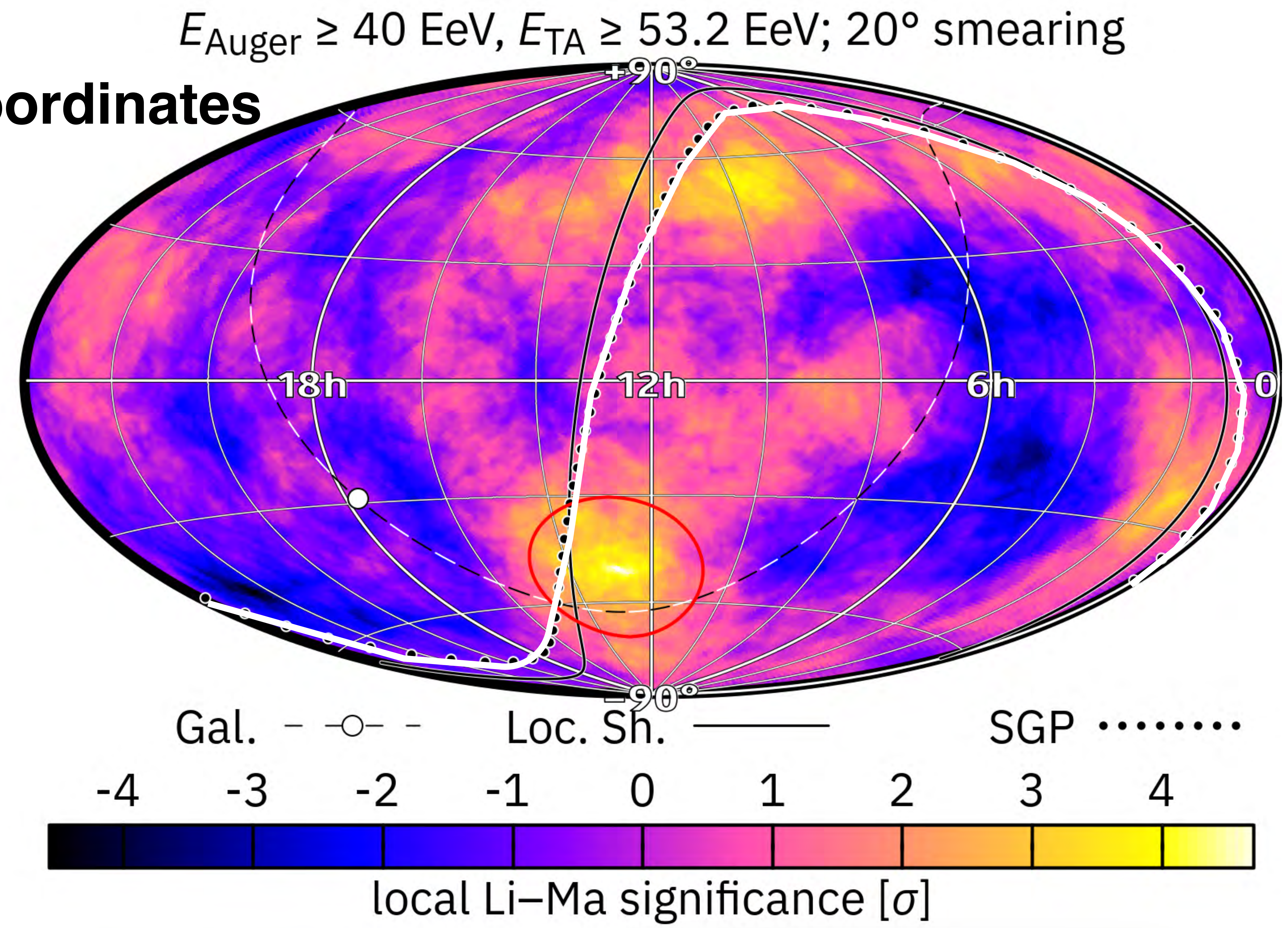
Auger-TA Full Sky Analysis

Flux Map



Significance Map

equatorial coordinates



TA M82 region shows stronger flux excess than Auger Cen A region but Auger Cen A is more significant (4.7σ vs 4.2 σ local sign.)

3σ correlation (within 20°) to SuperGalactic Plane

Auger-TA working group, PoS(ICRC2019)439

more statistics…

*… TA*4*

and even better data…

…AugerPrime

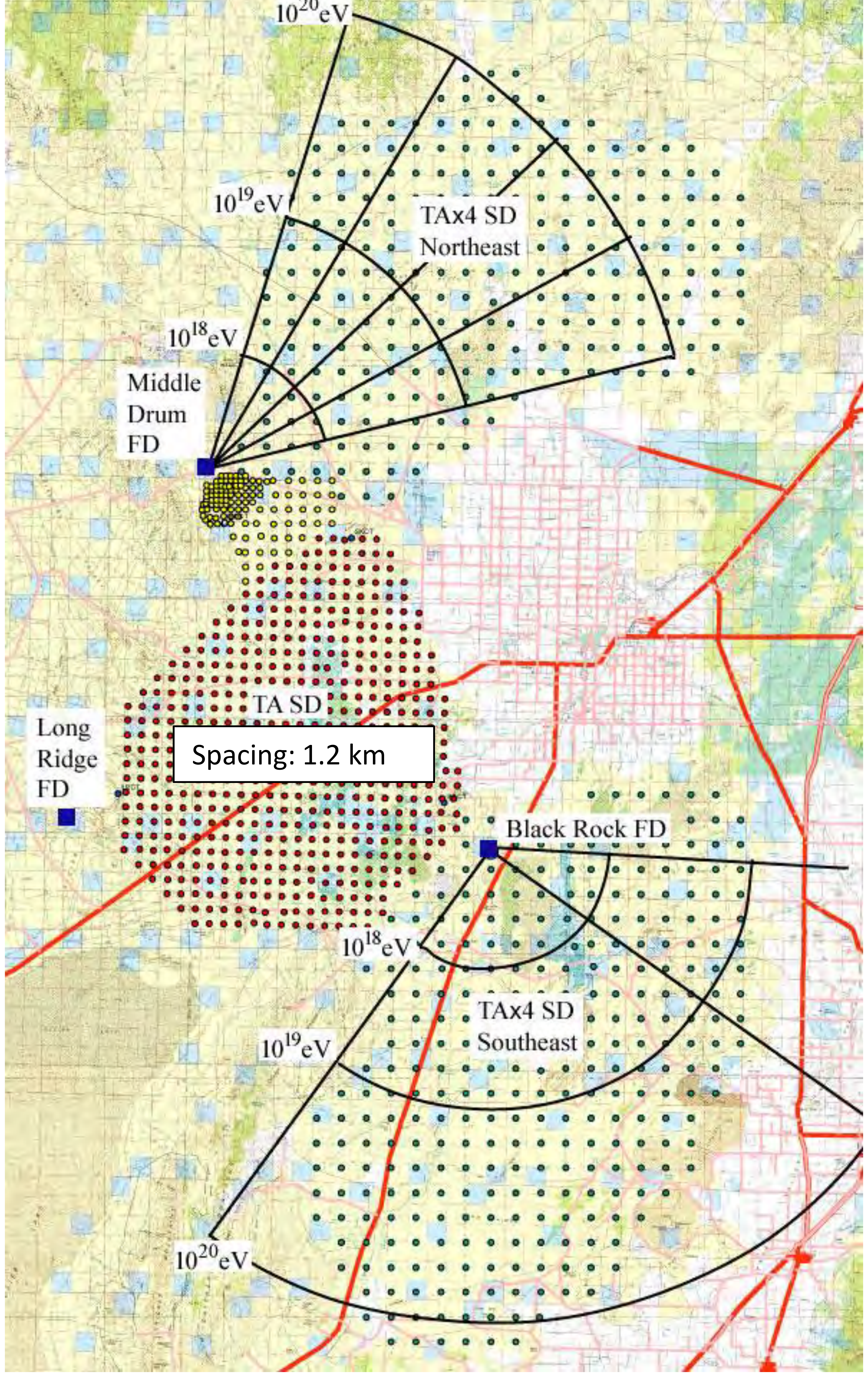
NEXT LOGICAL STEPS

Source hunting best for light primaries → proton enriched astronomy

Need composition information in each shower (not just 10%)

Enhance surface detector array

TA*4



SD: 700 → **2800 km²**

- 500 new SD stations on 2.08 km spacing
- 2 new FD stations
- Optimized for UHECR above cutoff (fully efficient above ~60 EeV)

→ hot spot verification ☜ *prime goal*

GO FOR SIZE

50% of stations already deployed

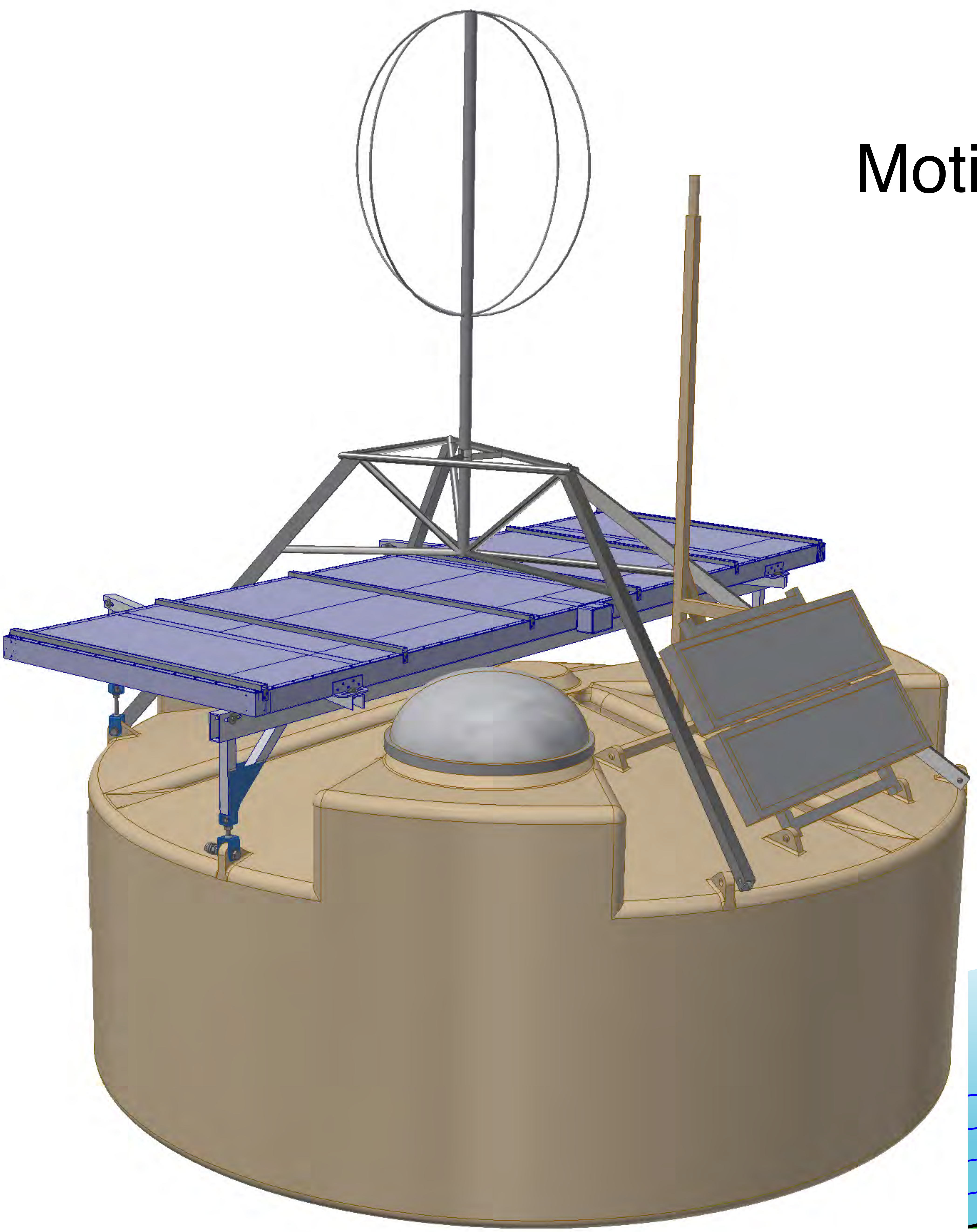
Key Elements of AugerPrime

Measure primary mass with 10 times better statistics

- 3.8 m² 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)

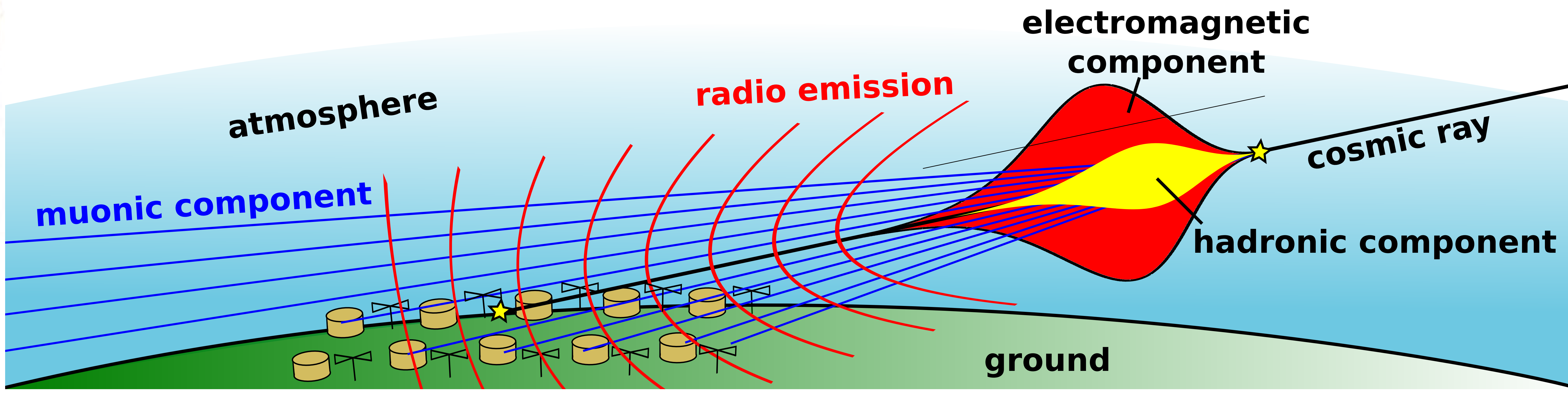


Radio added to each station

Motivation: extend composition enhanced anisotropy studies to inclined showers

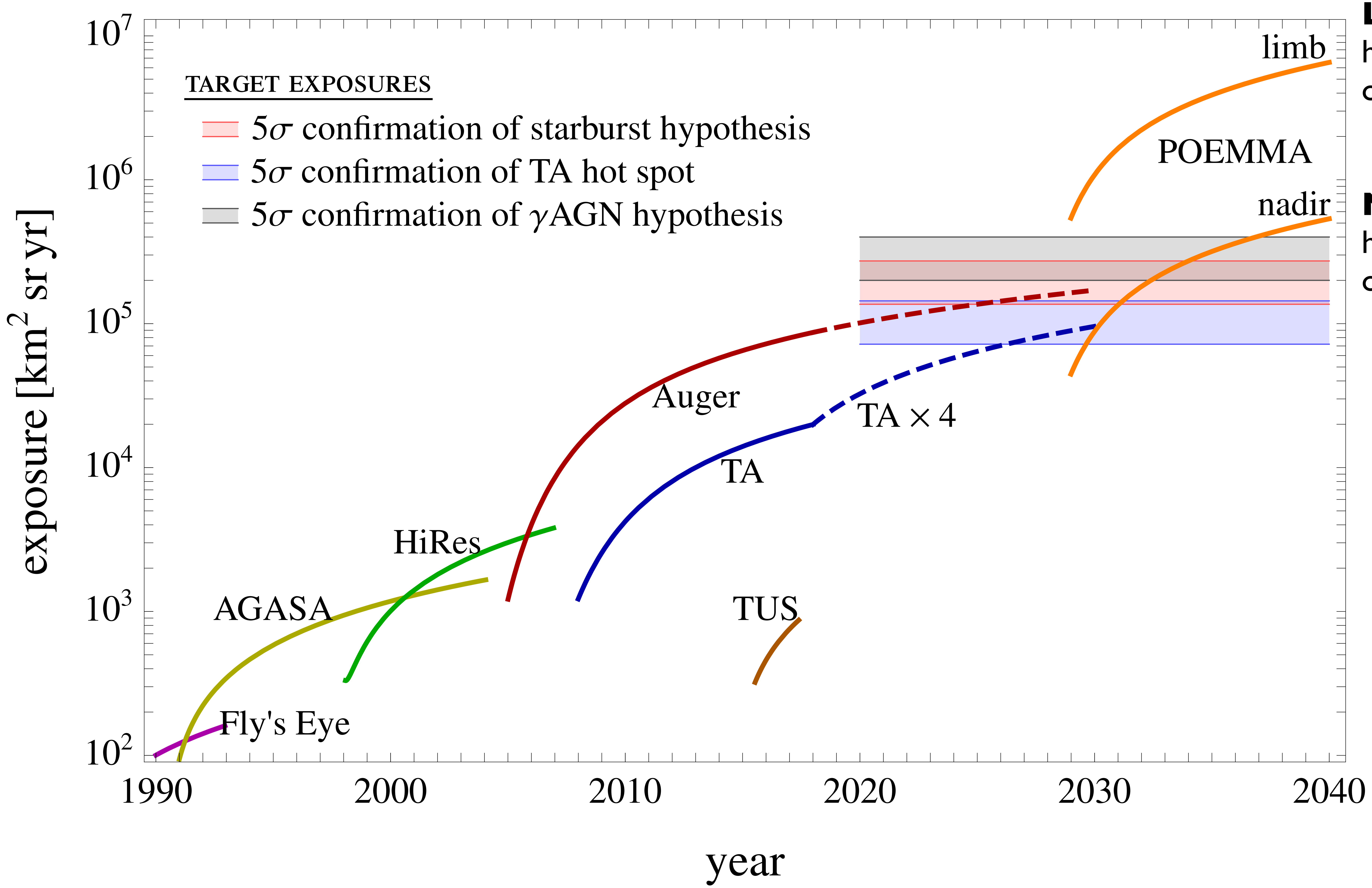
Note: scintillators offer little X-section to inclined showers

radio antennas will see em-part and water Cherenkov detectors will see μ-part of inclined showers




153

Looking beyond Auger and TA



Limb observations:
high-resolution fluorescence, optimised for stereo

Nadir observations:
high-resolution fluorescence, optimised for stereo

Next years will be most exciting!

- UHECR full sky maps with high statistics
- Southern hemisphere with enhanced by composition info
- Verify proton component at highest energies in MM approach
- Long term goal: Study spectrum and composition of *individual* UHECR sources

Thanks for your attention!