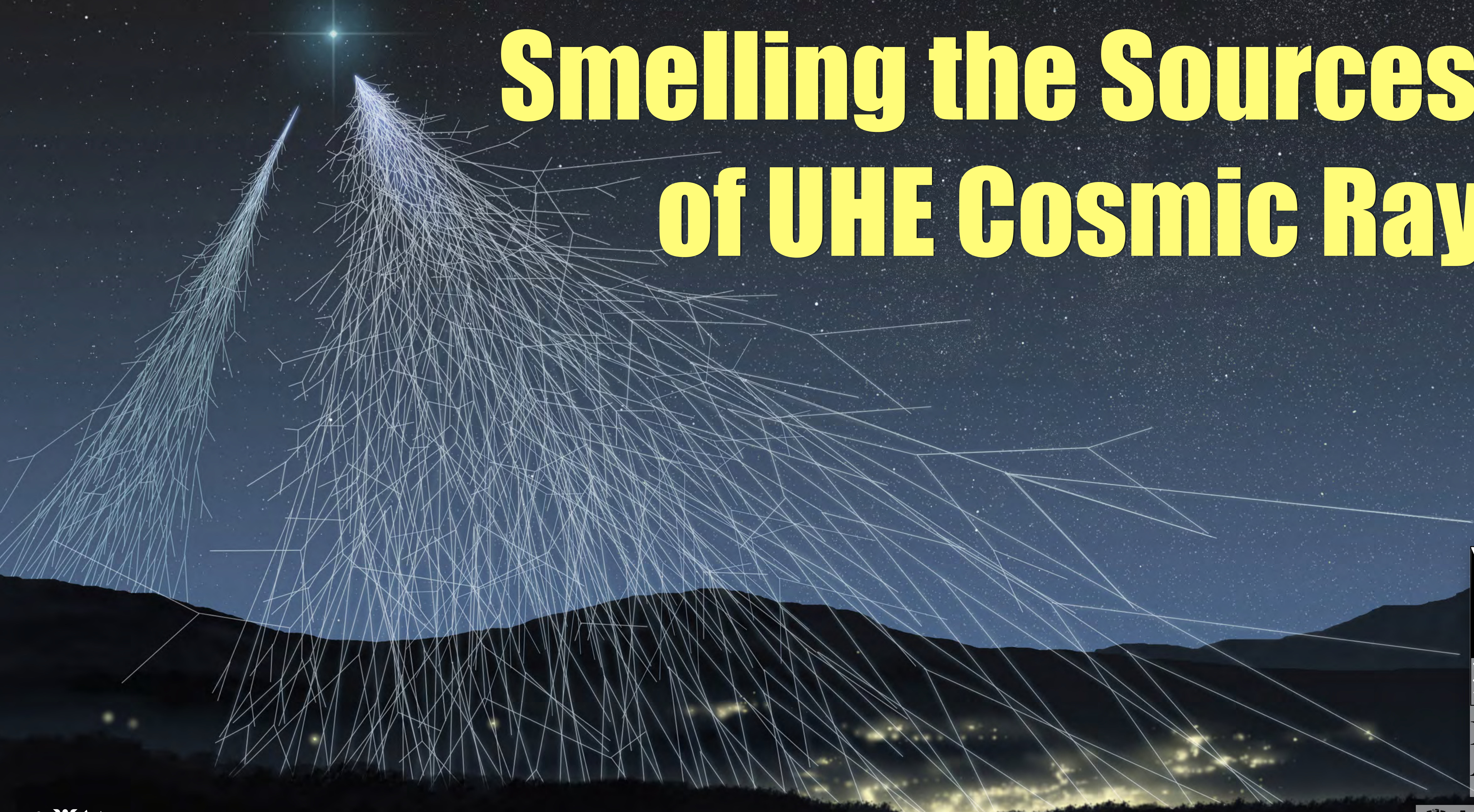
Smelling the Sources of UHE Cosmic Rays



PIERRE AUGER
OBSERVATORY

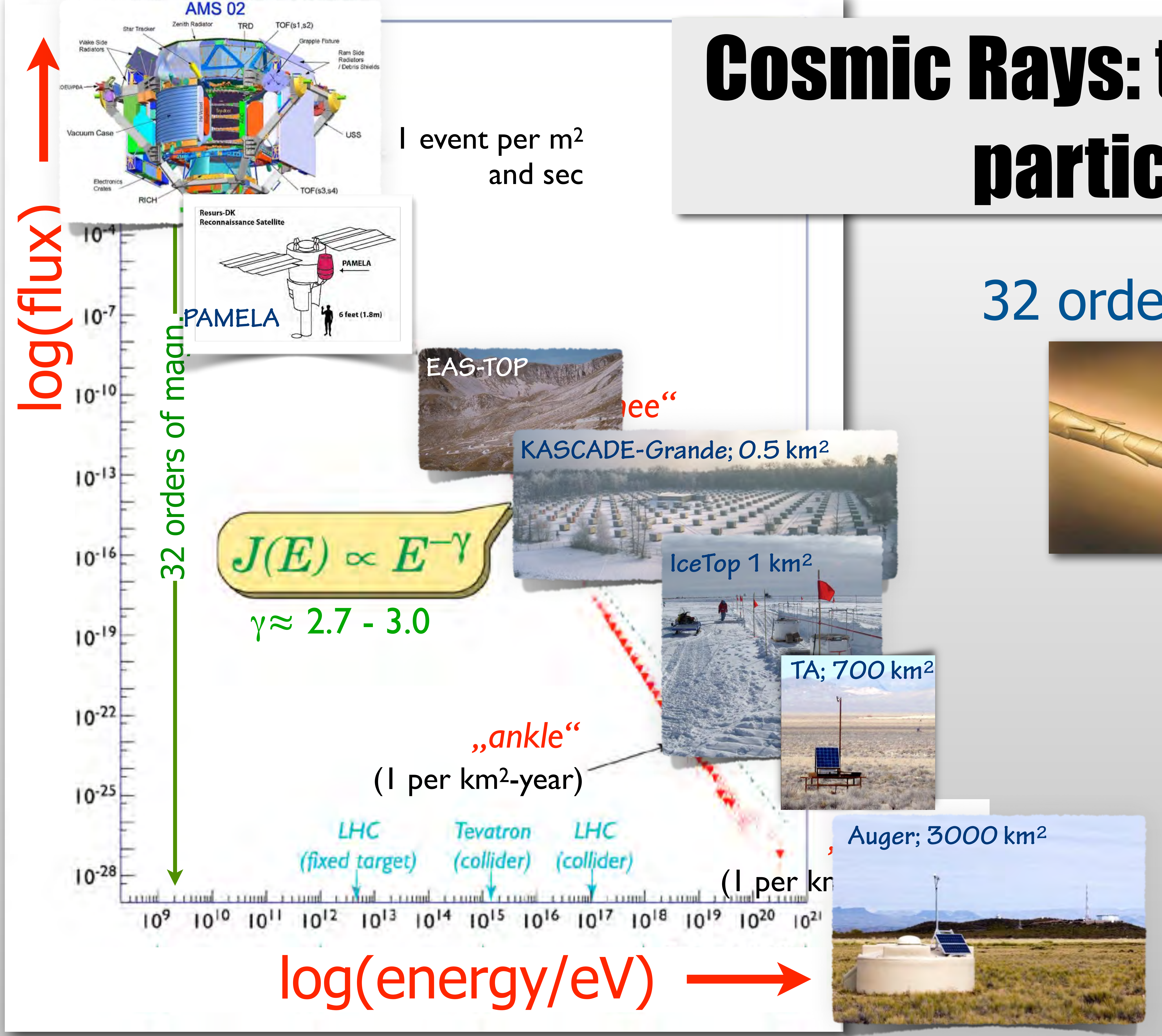
BERGISCHE
UNIVERSITÄT
WUPPERTAL

Karl-Heinz Kampert
Bergische Universität Wuppertal

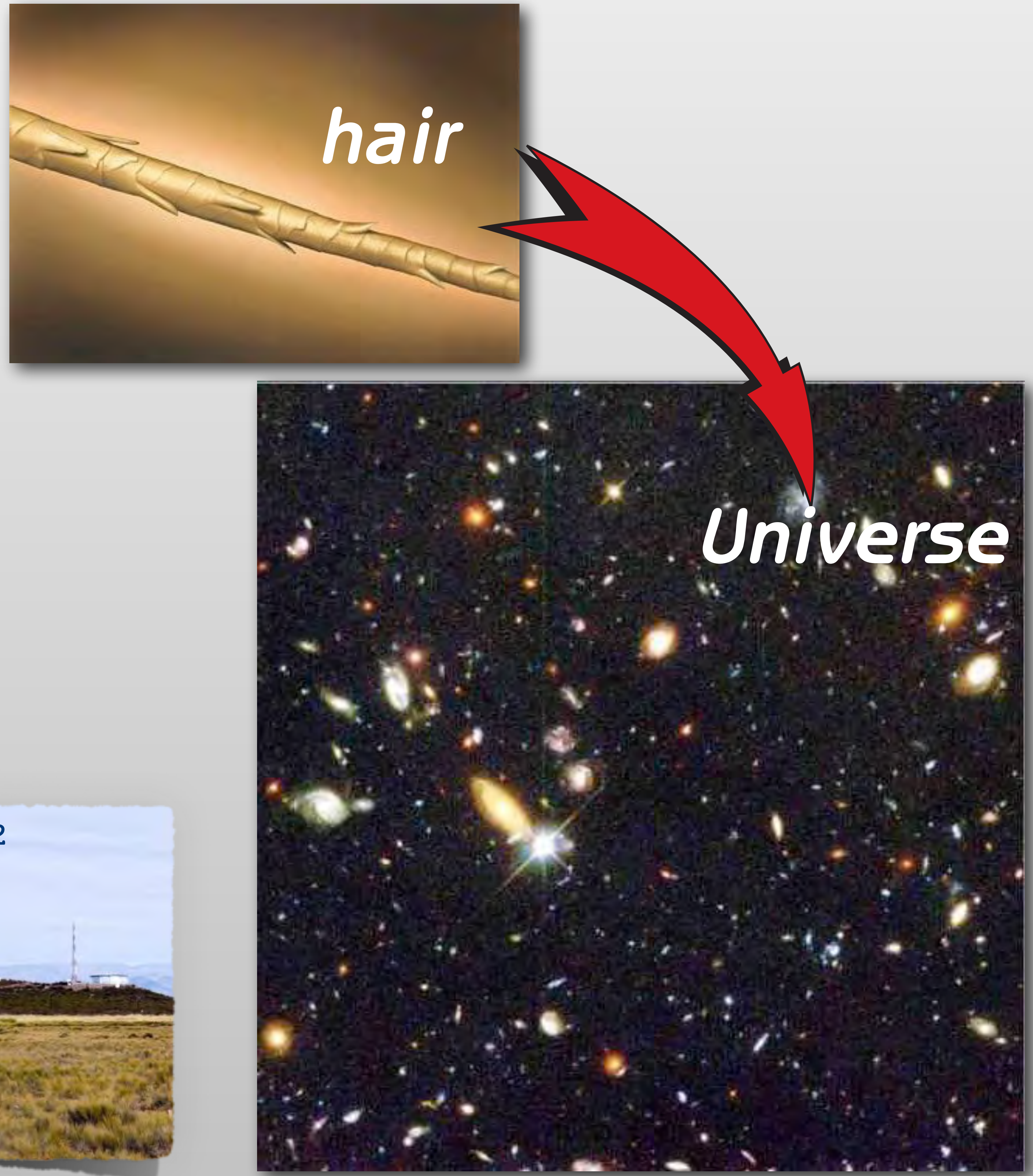
Astroparticle Colloquium
GSSI 19.02.2020

Bundesministerium
für Bildung
und Forschung

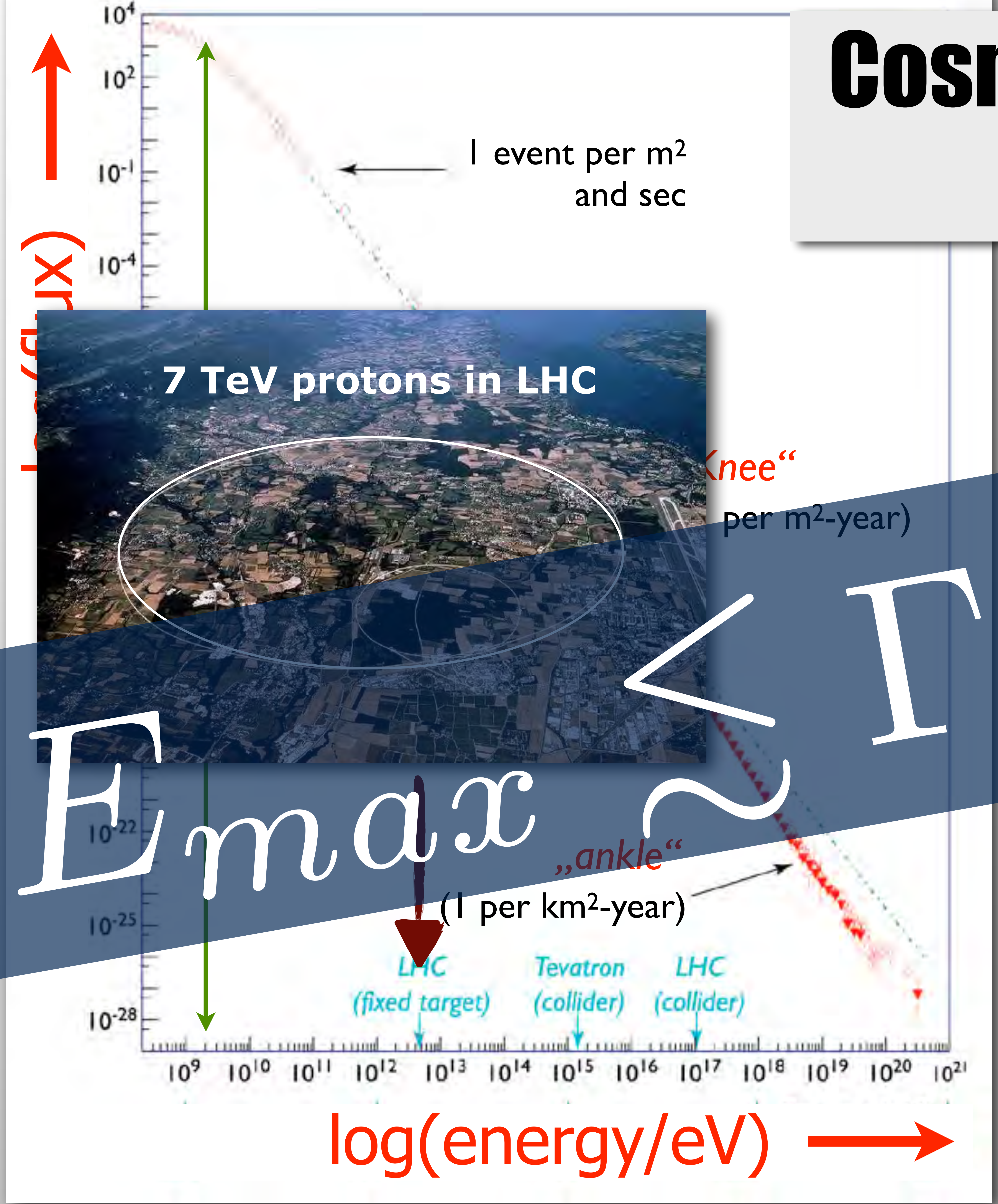
Cosmic Rays: the most energetic particles in the Universe



32 orders of magnitude:



Cosmic Rays: the most energetic particles in the Universe



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

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

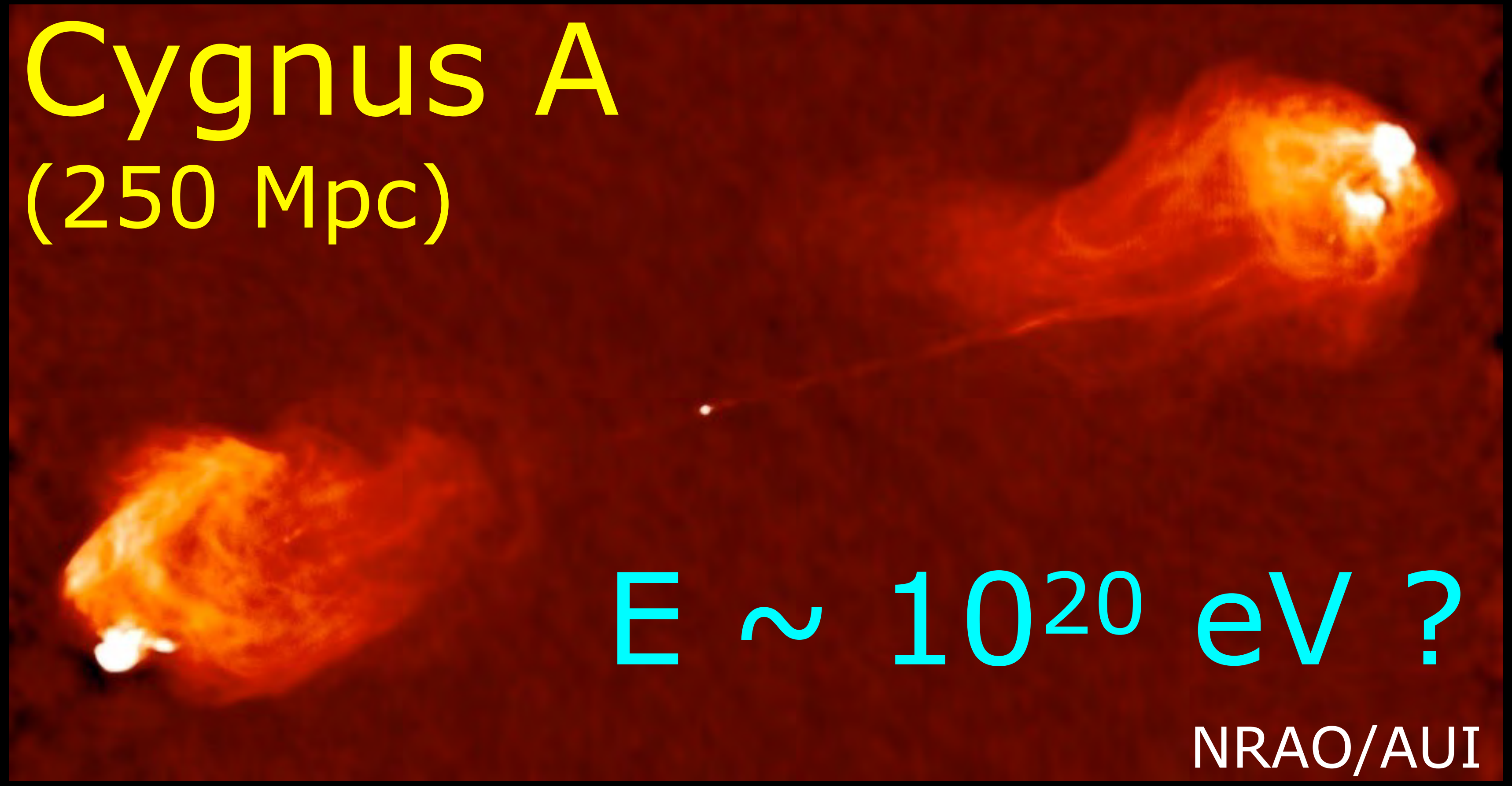
SNR509
(50 kpc)

$E < 10^{15}$ eV

X-ray (Chandra) + optical (Hubble)

particle acceleration at shock waves

AGN and their Jets/Lobes

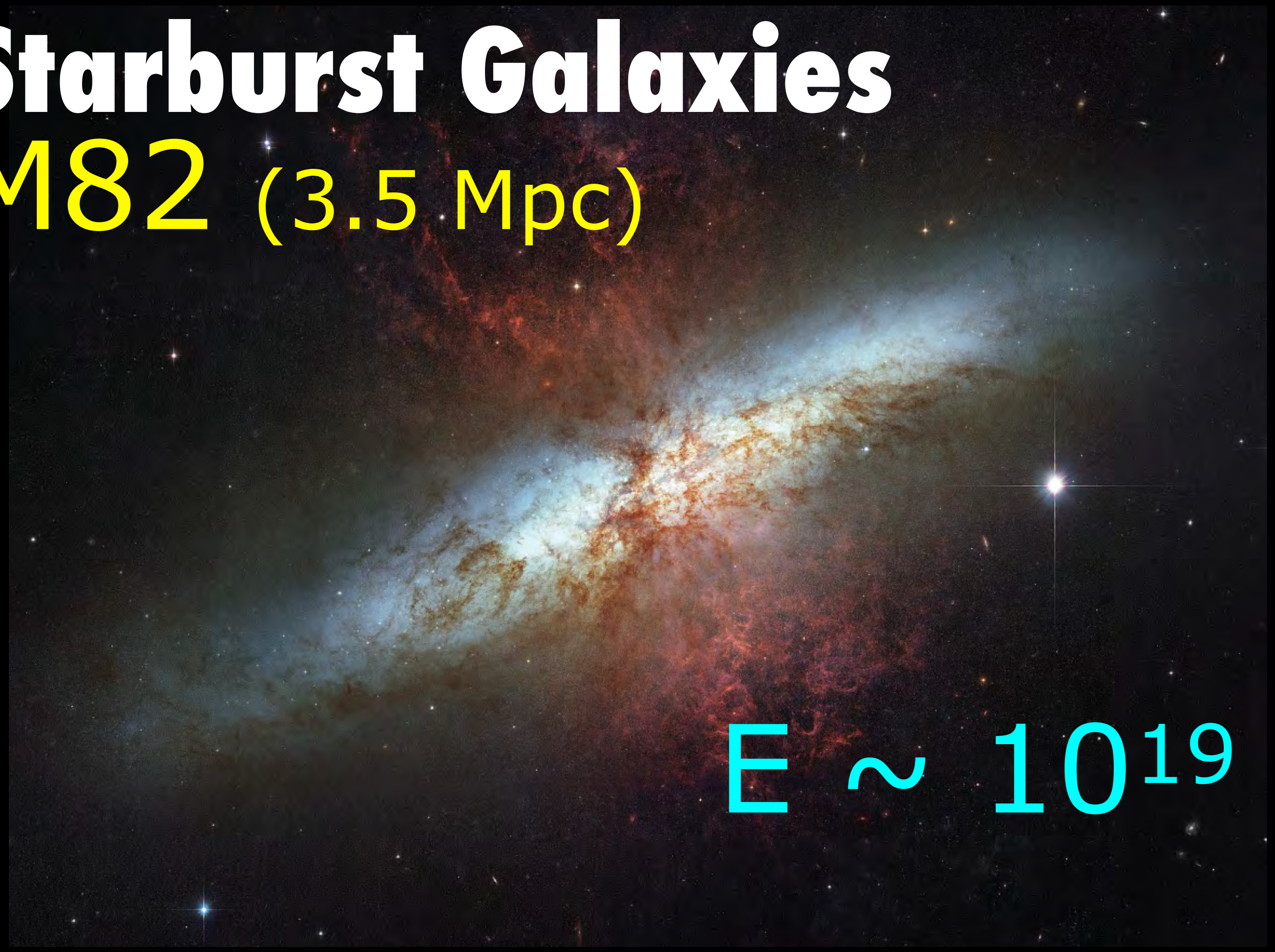


Cygnus A
(250 Mpc)

$E \sim 10^{20}$ eV ?

NRAO/AUI

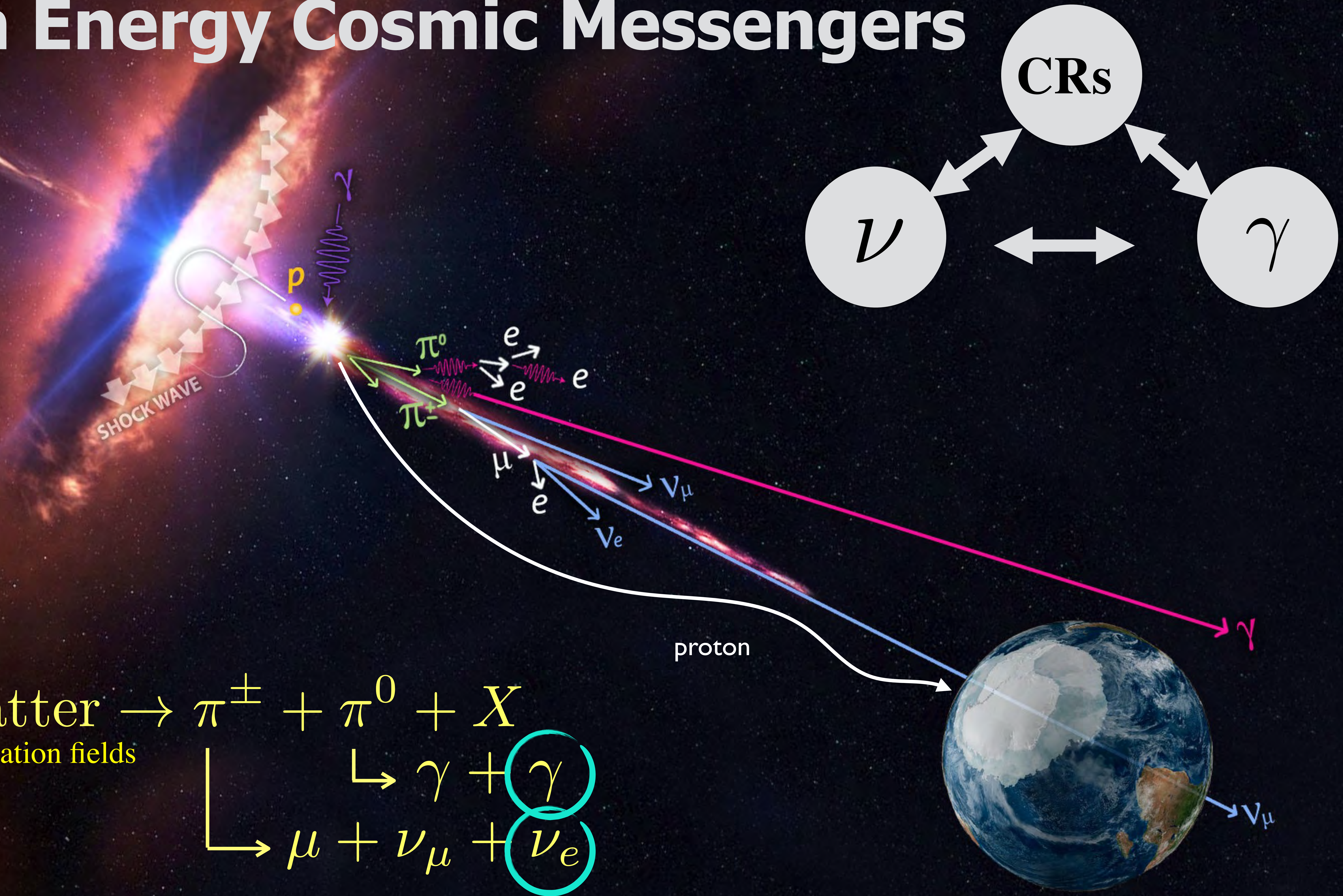
Starburst Galaxies



M82 (3.5 Mpc)

$E \sim 10^{19}$ eV ?

The High Energy Cosmic Messengers

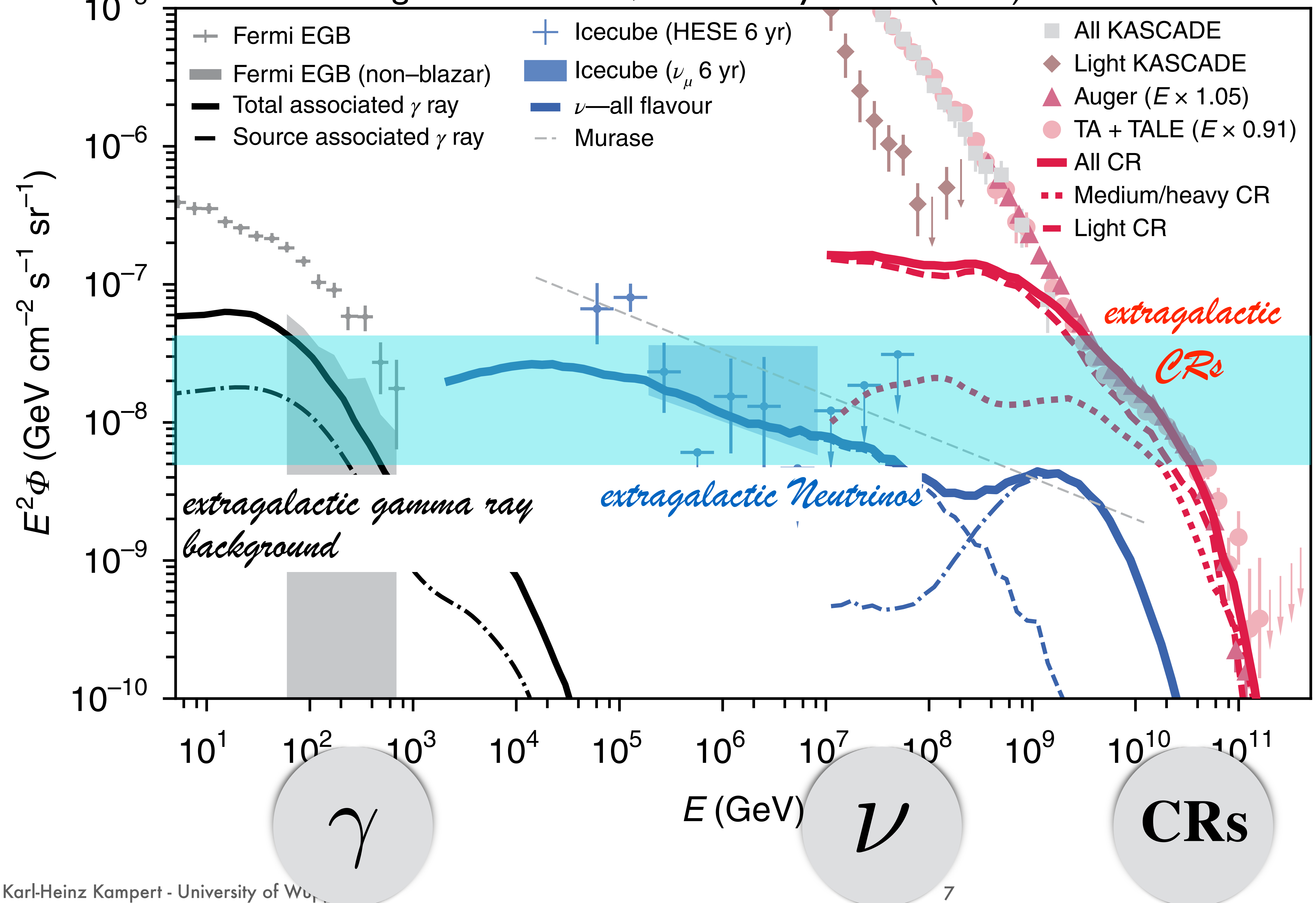


$$p_{CR} + \underset{\text{a/o radiation fields}}{\text{matter}} \rightarrow \pi^{\pm} + \pi^{0} + X$$

$$\hookrightarrow \gamma + \gamma$$

$$\hookrightarrow \mu + \nu_{\mu} + \nu_{e}$$

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

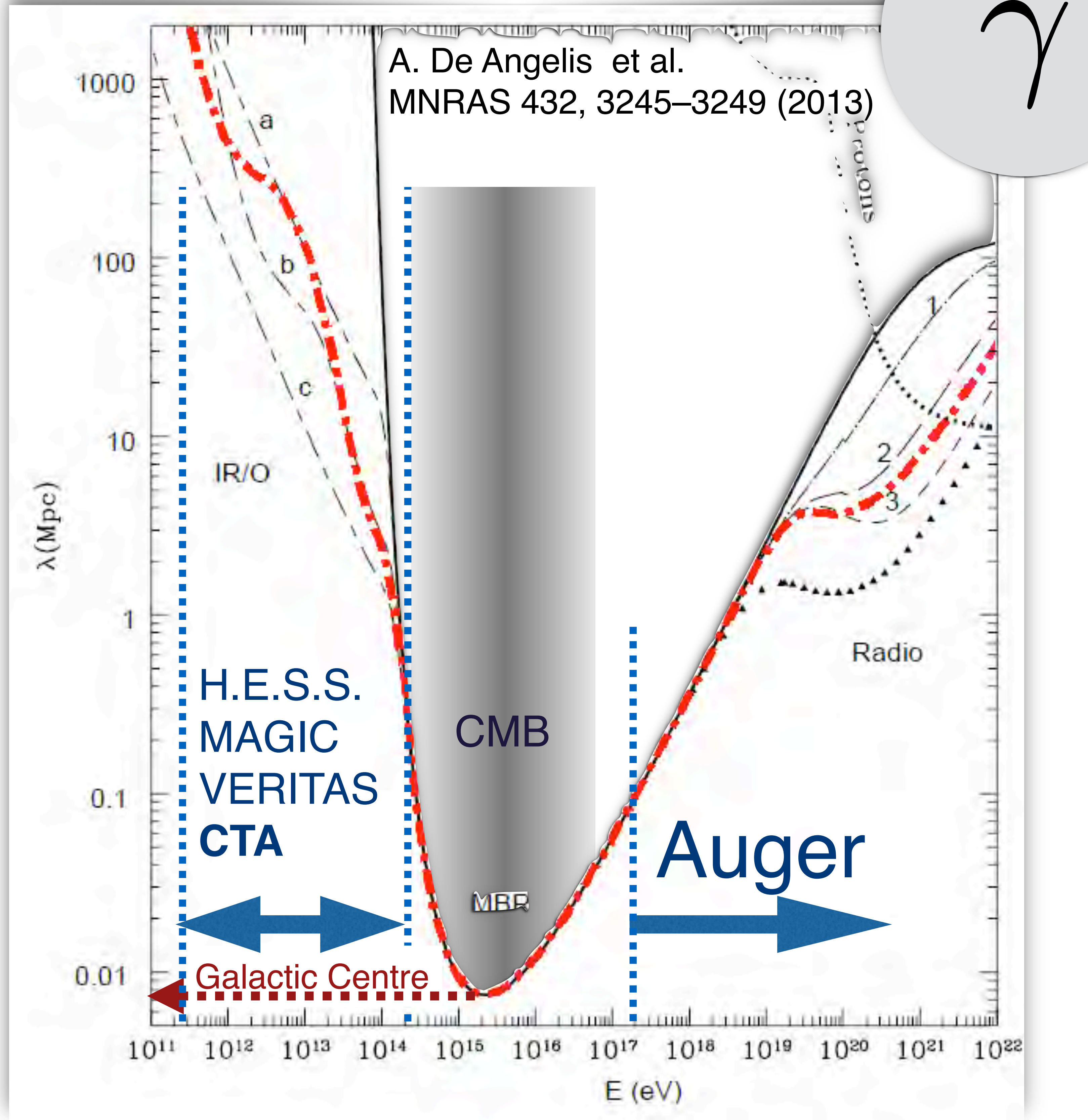
→ energy generation rates per decade in E are the same

Suggests again a common / related origin

No „Best“ Messenger

γ-ray horizon

γ

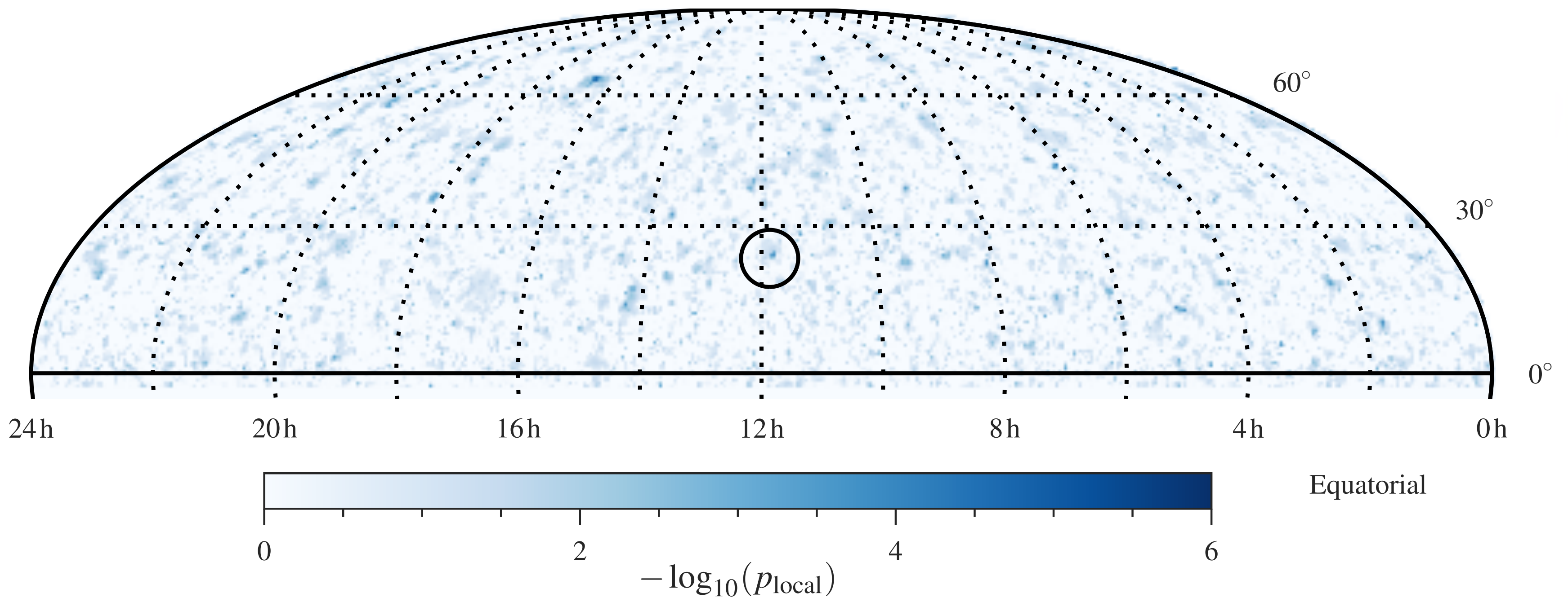

A. De Angelis et al.
MNRAS 432, 3245–3249 (2013)

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

HE-Neutrino Sky

ν

IceCube, EPJ 2019 (arXiv:1811.07979)



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

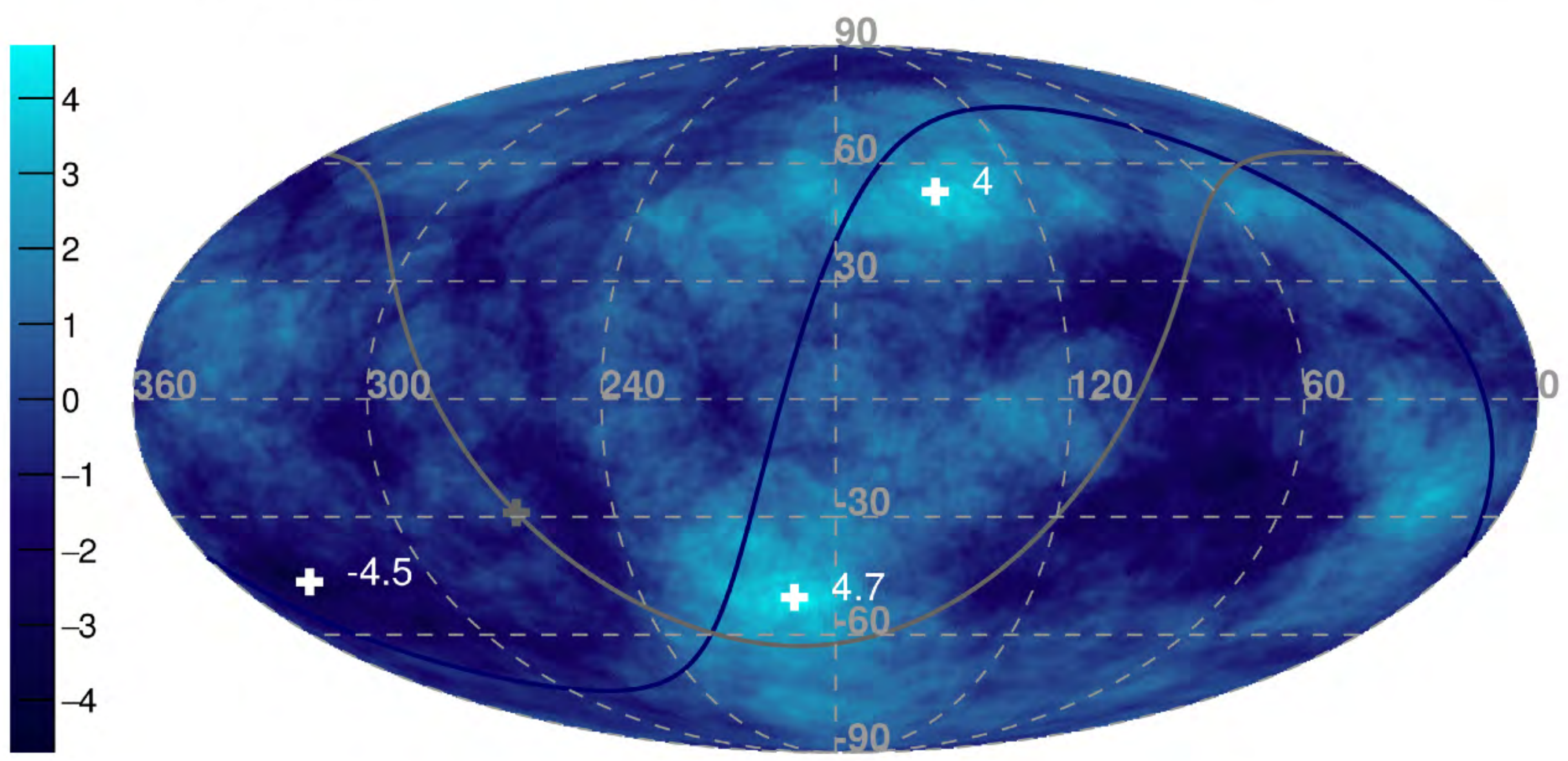
UHECR Sky

above 40 EeV

CRs

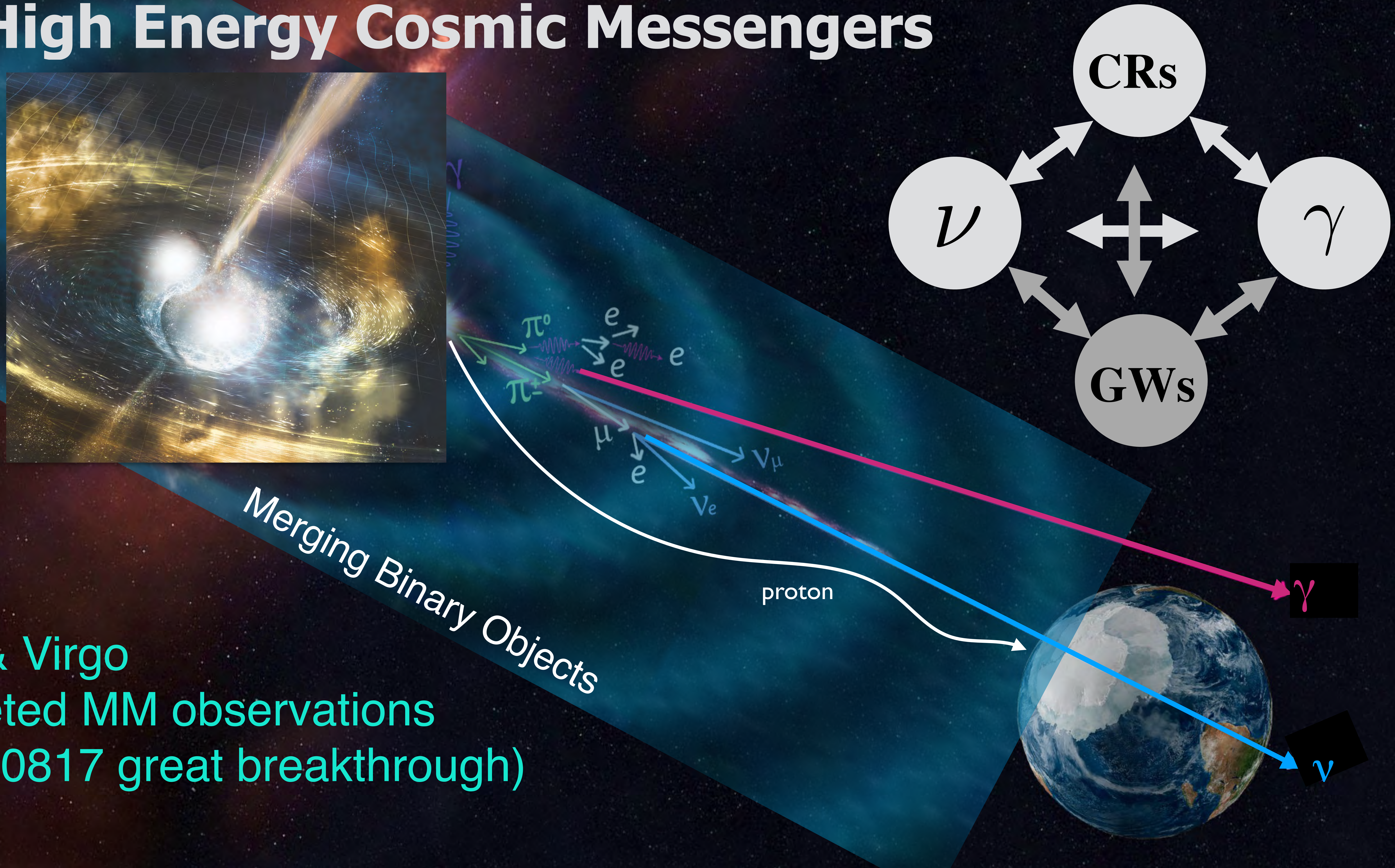
Auger & TA Working Group at ICRC 2019

Local σ($E_{\rm Auger/TA}$ > **40/53.2 EeV**) - Equatorial coordinates - **R = 20°**



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

The High Energy Cosmic Messengers

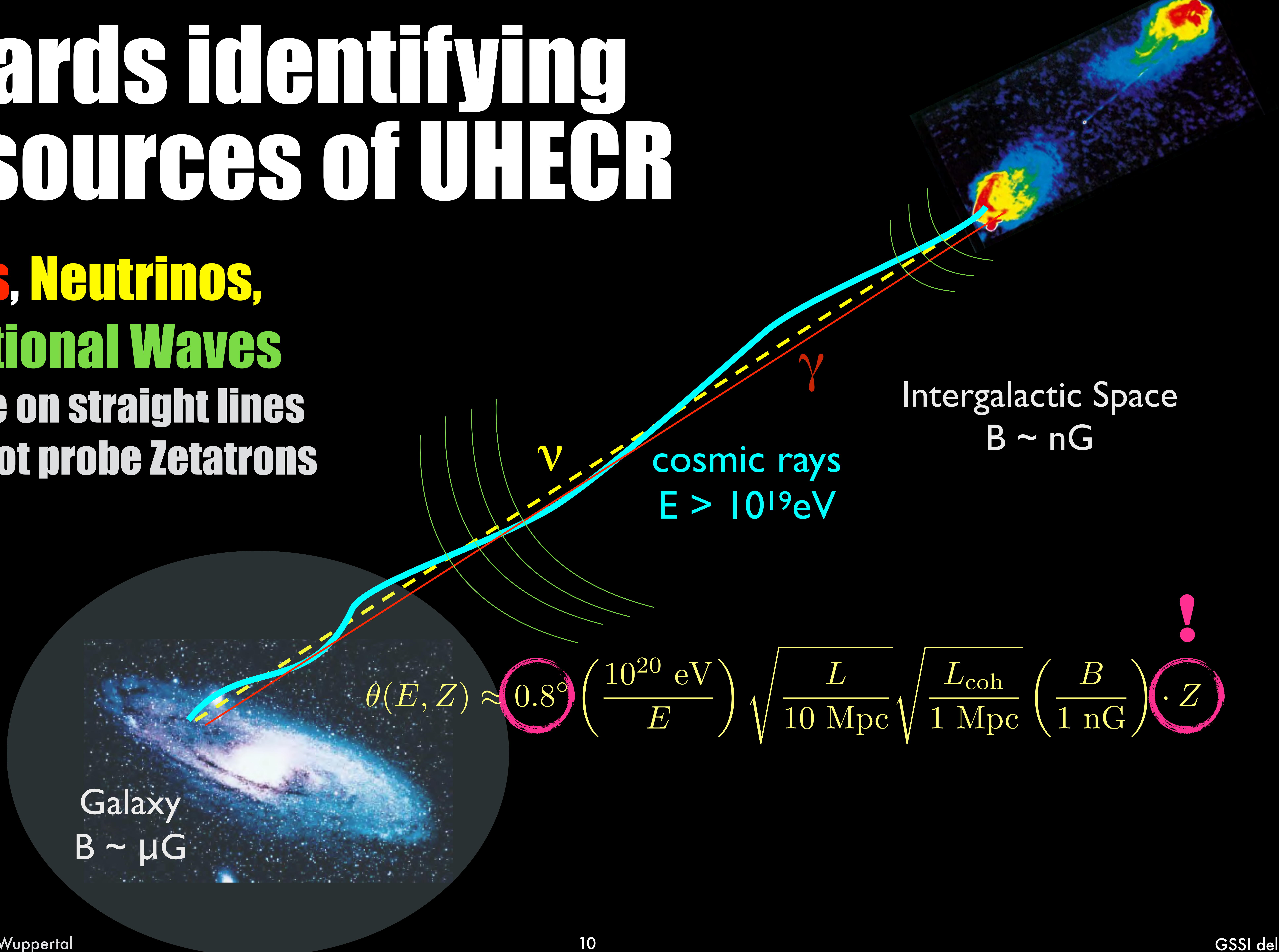


LIGO & Virgo
completed MM observations
(GW170817 great breakthrough)

Towards identifying the sources of UHECR

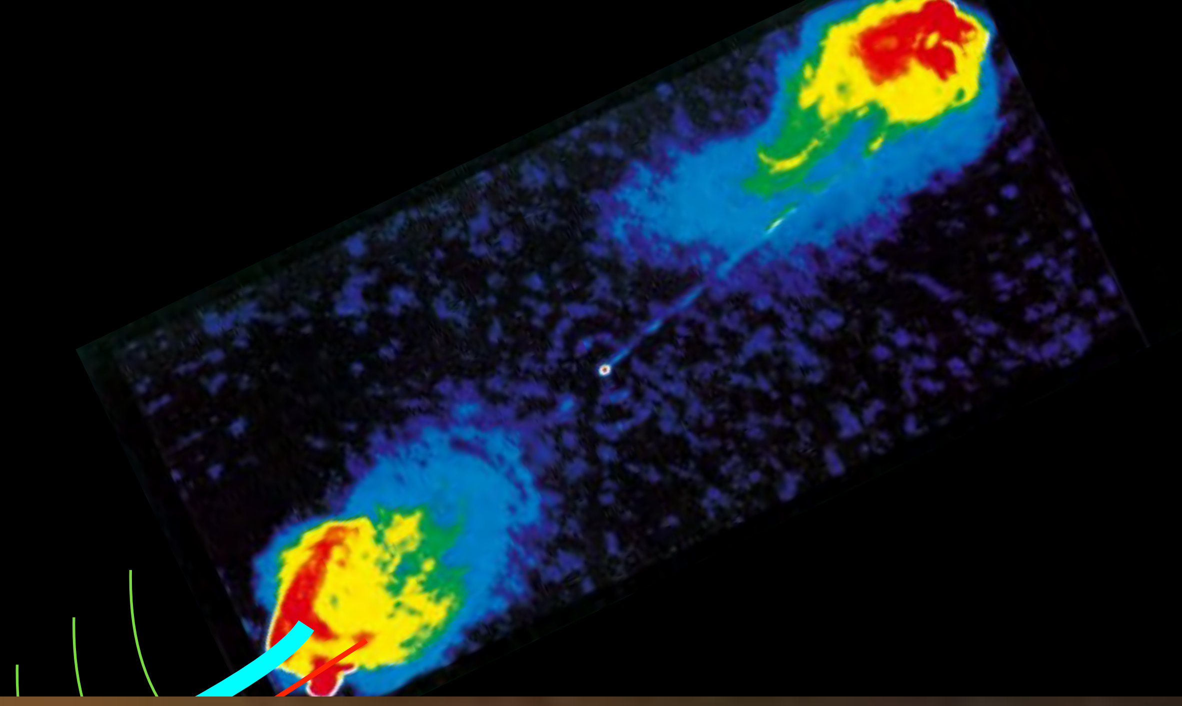
Photons, Neutrinos, Gravitational Waves

propagate on straight lines but may not probe Zetatrons



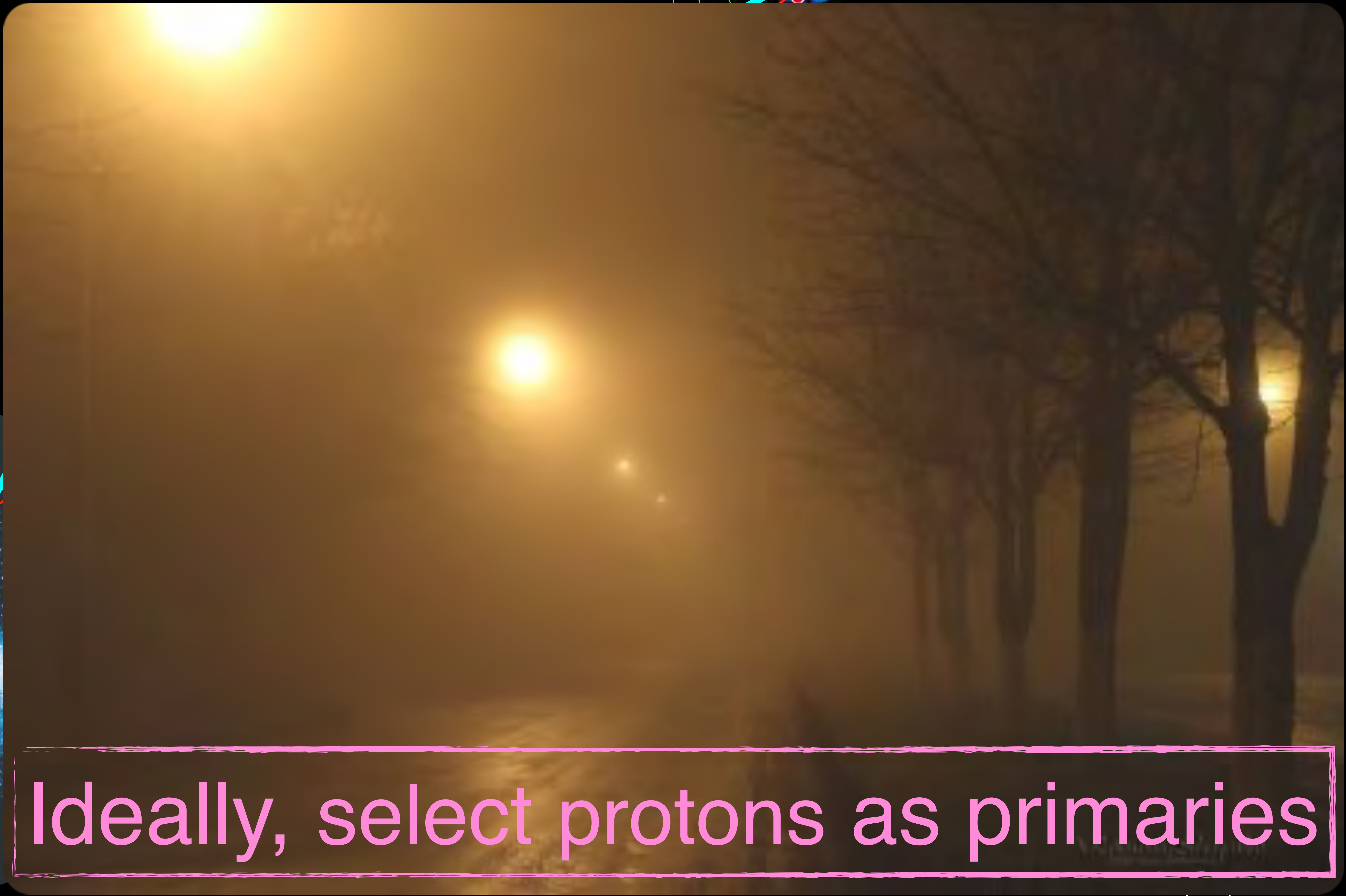
$$\theta(E,Z) \approx \boxed{0.8^\circ} \left(\frac{10^{20}\ \mathrm{eV}}{E}\right) \sqrt{\frac{L}{10\ \mathrm{Mpc}}} \sqrt{\frac{L_\mathrm{coh}}{1\ \mathrm{Mpc}}} \left(\frac{B}{1\ \mathrm{nG}}\right) \overset{!}{\boxed{\cdot Z}}$$

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

extremely high
energy nuclear
collisions

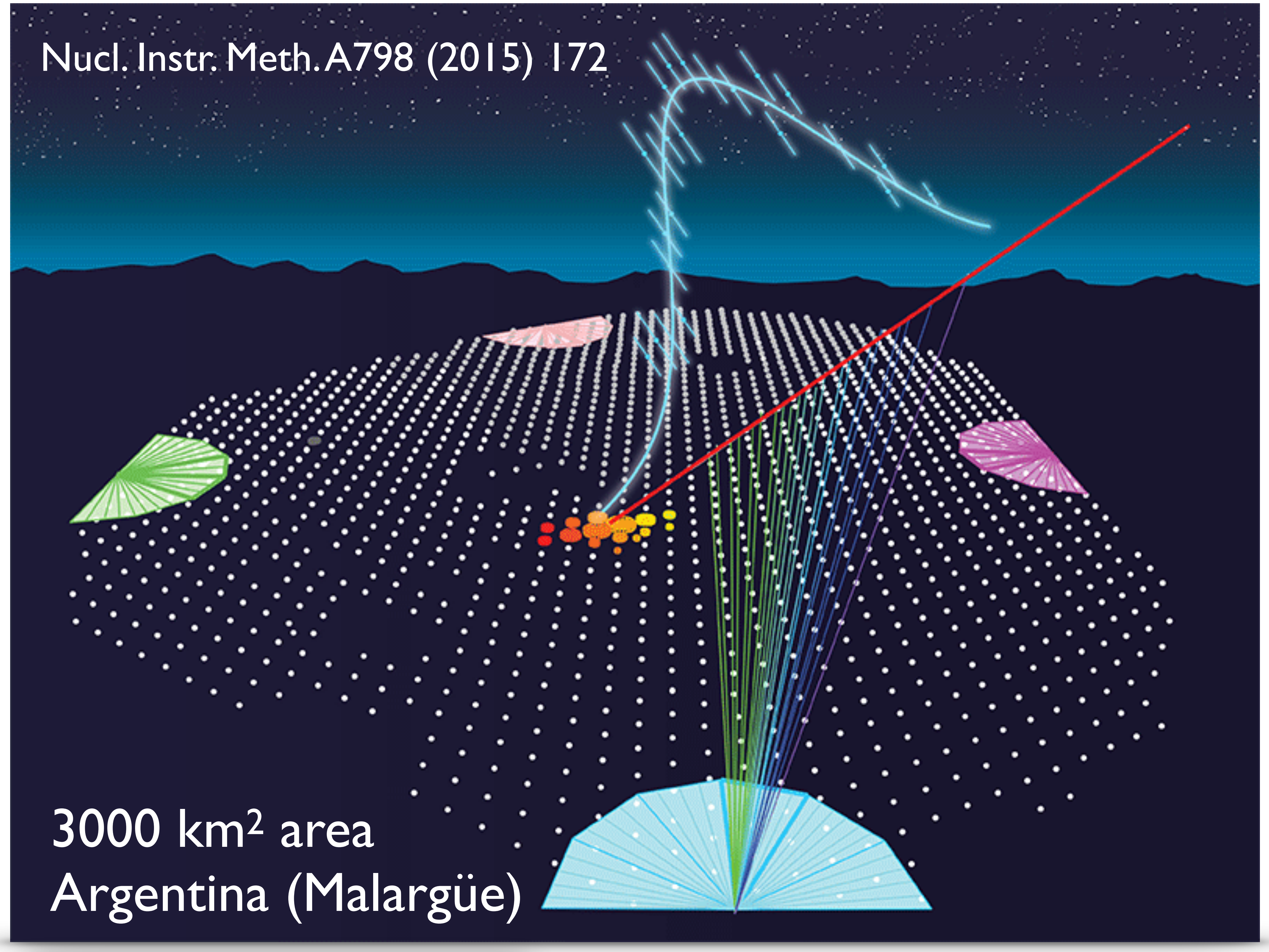
Primary particles initiate
an extensive air shower

light trace
at night-sky
(calorimetric)

Fluorescence Light

Particle & Radio Footprint at Ground

Multi Hybrid Detection of UHECR: Auger Observatory

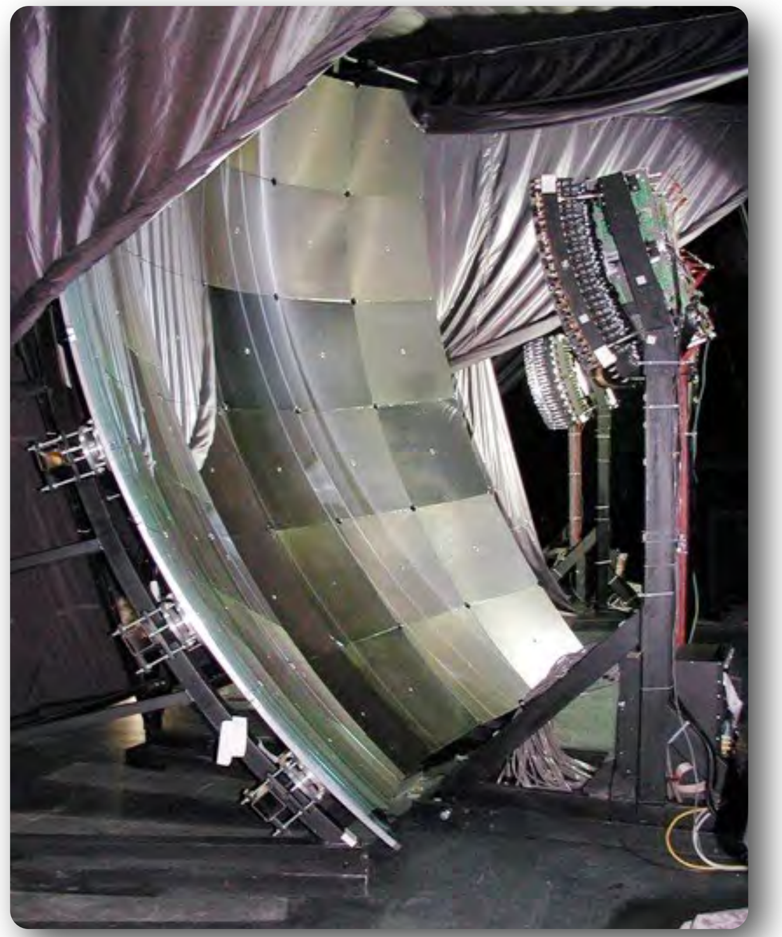


Nucl. Instr. Meth. A798 (2015) 172

$3000\ km^2$ area
Argentina (Malargüe)

- 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**
- $18\ km^2$ area
- 100% duty cycle

Central campus with visitors center

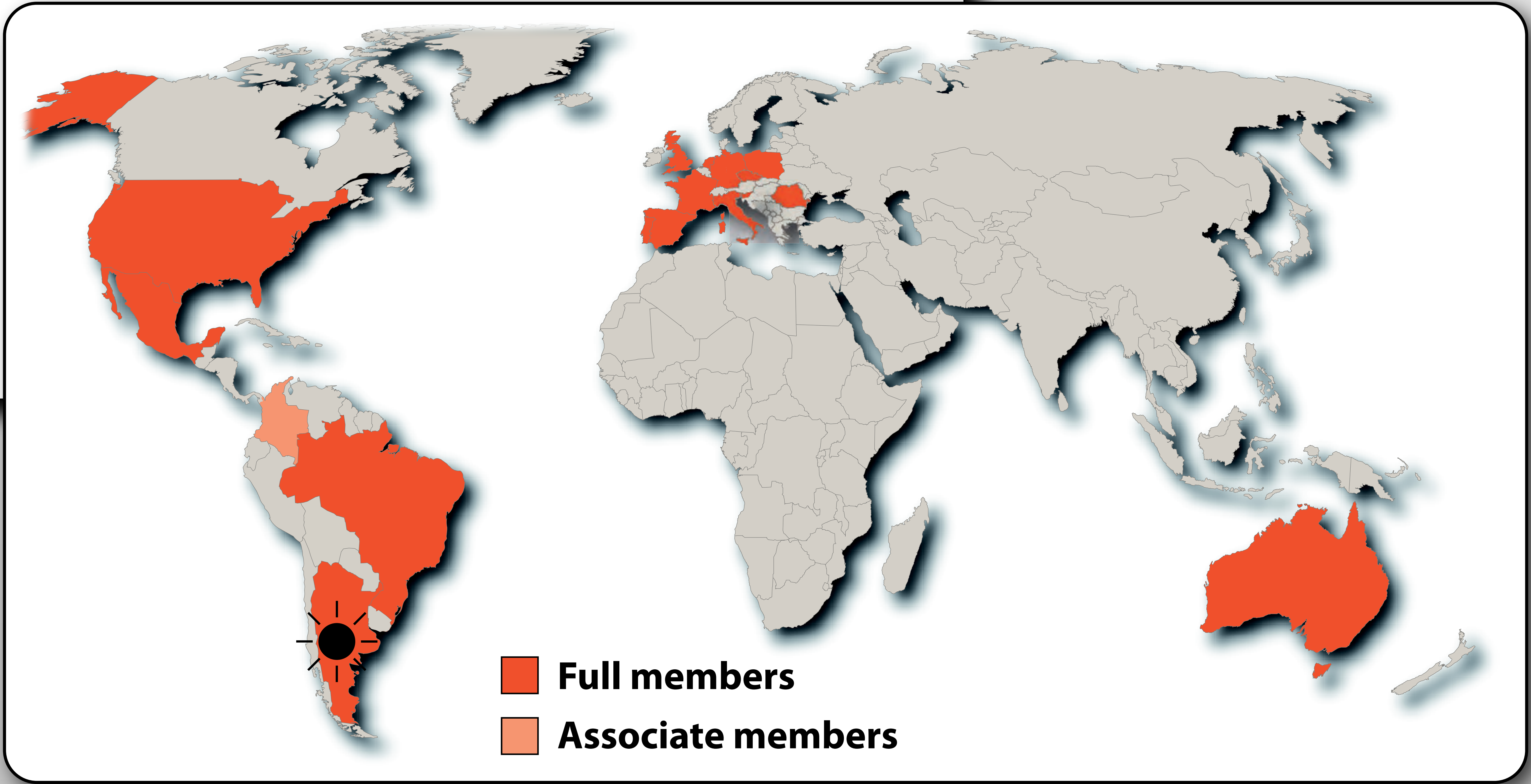
Pierre Auger Collaboration

~450 Collaborators; 92 Institutions, 17 Countries:

- **Argentina**
- **Australia**
- **Belgium**
- **Brazil**
- **Czech Republic**
- **France**
- **Germany**
- **Italy**
- **Mexico**
- **Netherlands**
- **Poland**
- **Portugal**
- **Romania**
- **Slovenia**
- **Spain**
- **UK**
- **USA**
- **Colombia**
- **Peru** (associated)

L'Aquila
Catania
Lecce
Milano
Naples
Rome
Torino

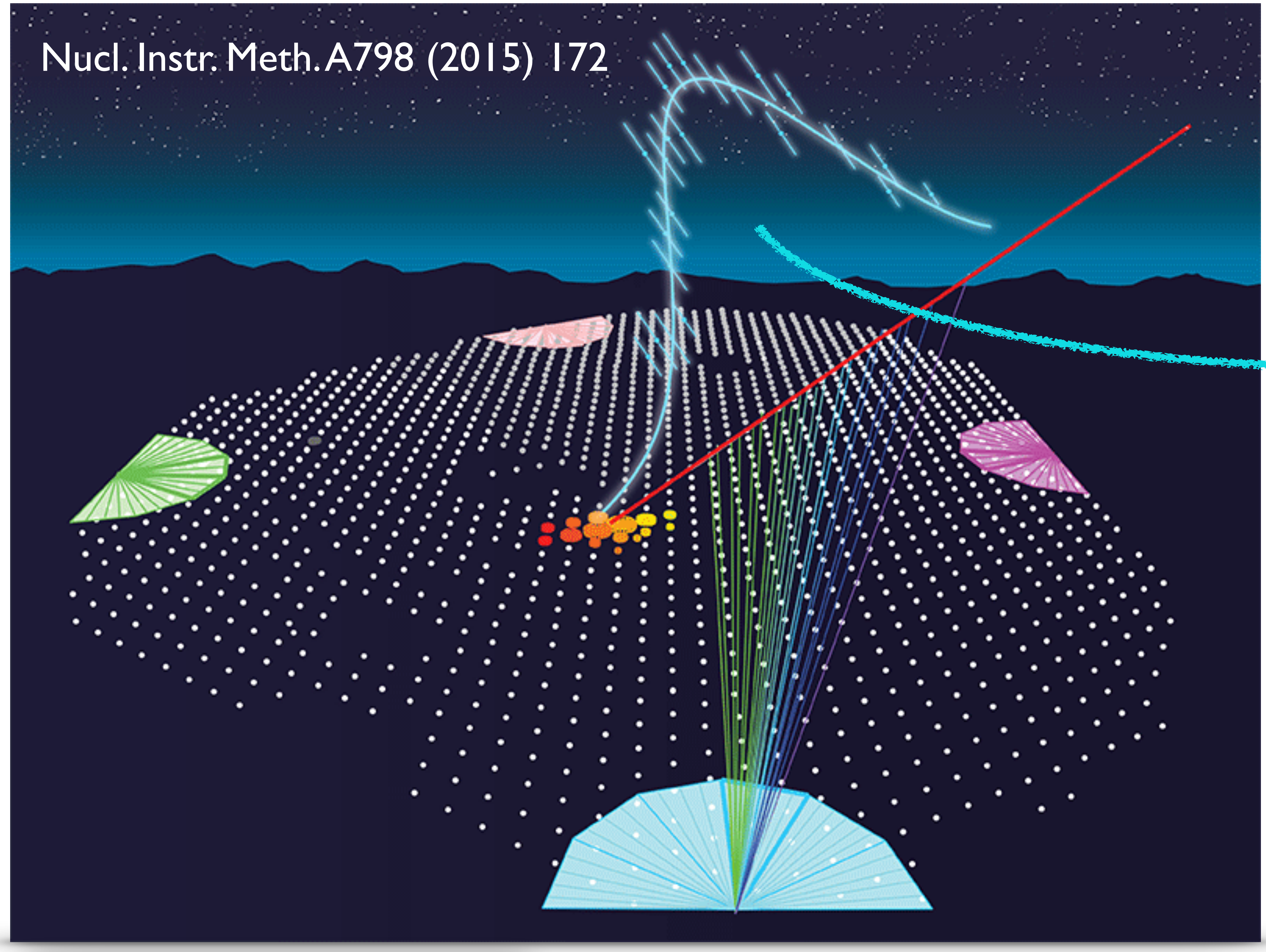
PIERRE
AUGER
OBSERVATORY



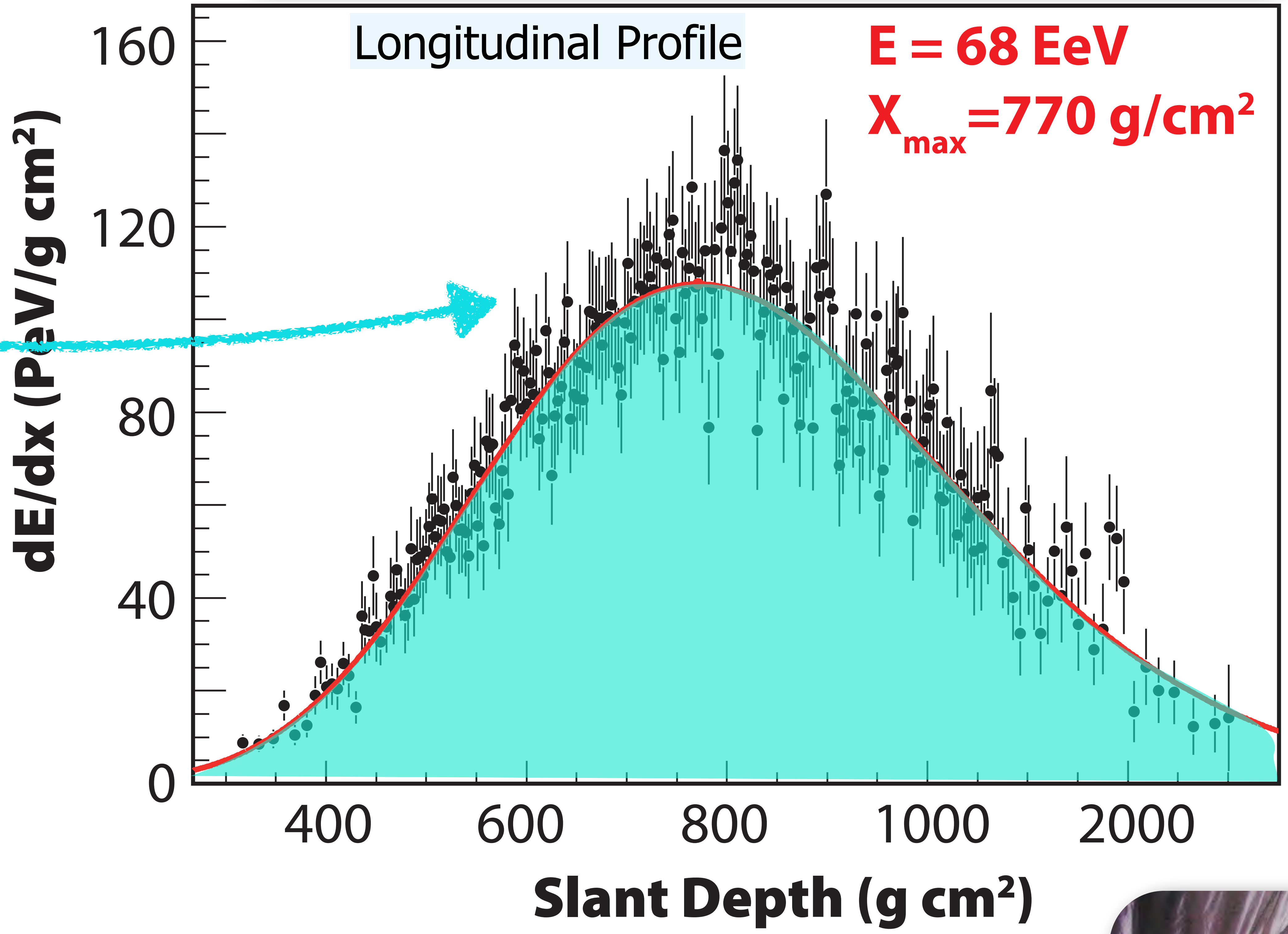
A quadruple event

4 Telescopes + 20 km2 Footprint

Calibrating the Primary Energy


Nucl. Instr. Meth. A798 (2015) 172

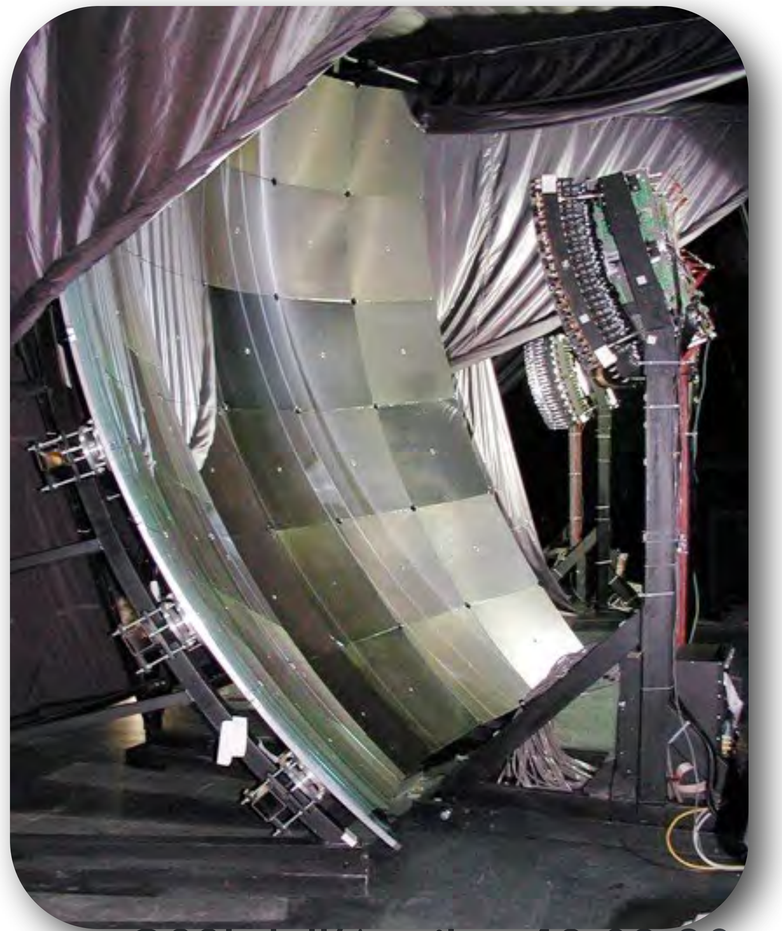
absolute E-scale from light intensity



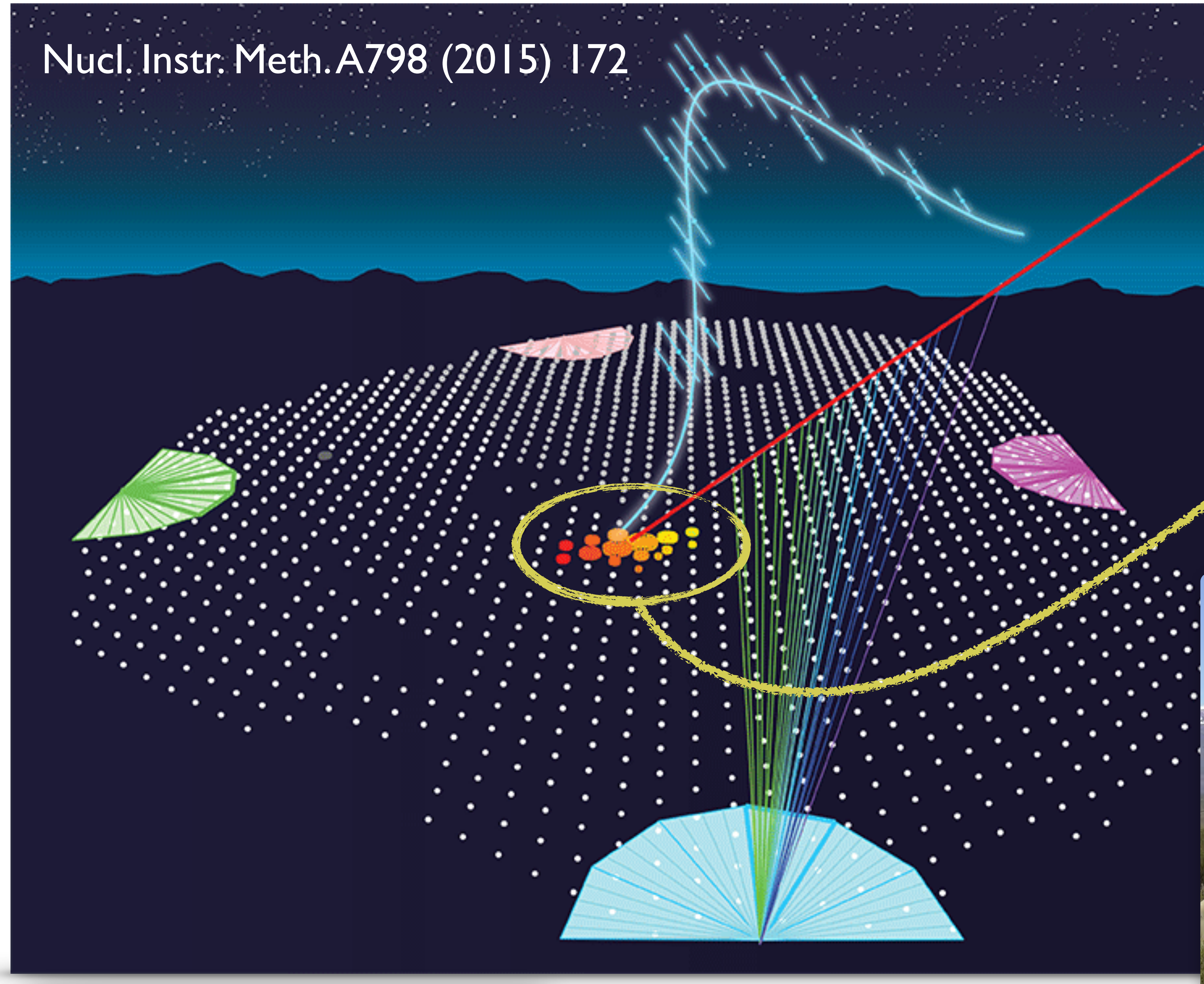
$$E_{cr} = \int \varepsilon_\gamma \frac{dN_\gamma}{dx} dx = \int \frac{dE}{dx} dx$$

fluorescence yield

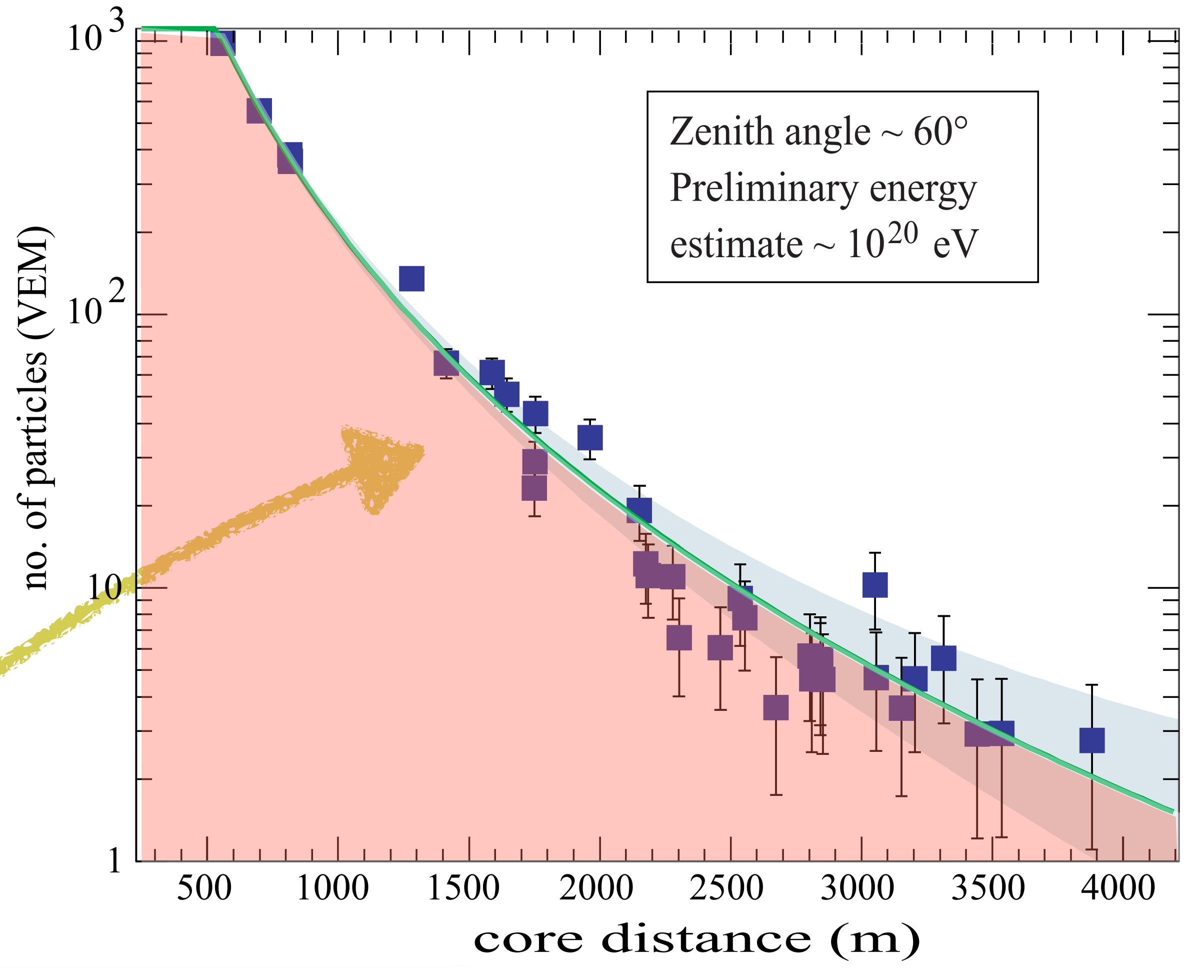

Central campus with visitors center



Calibrating the Primary Energy



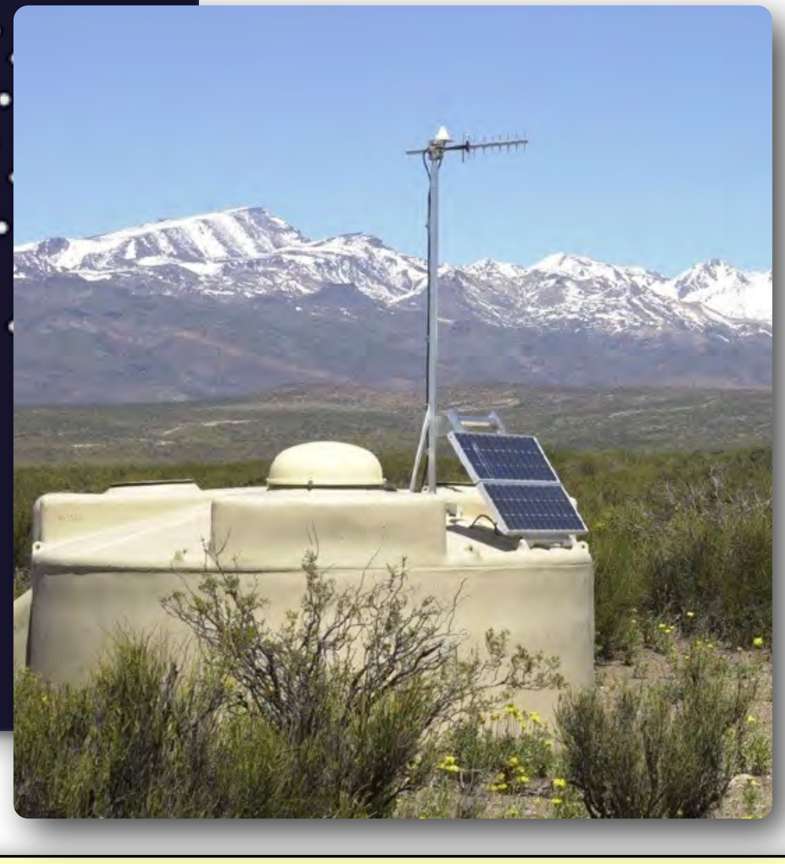
Nucl. Instr. Meth. A798 (2015) 172

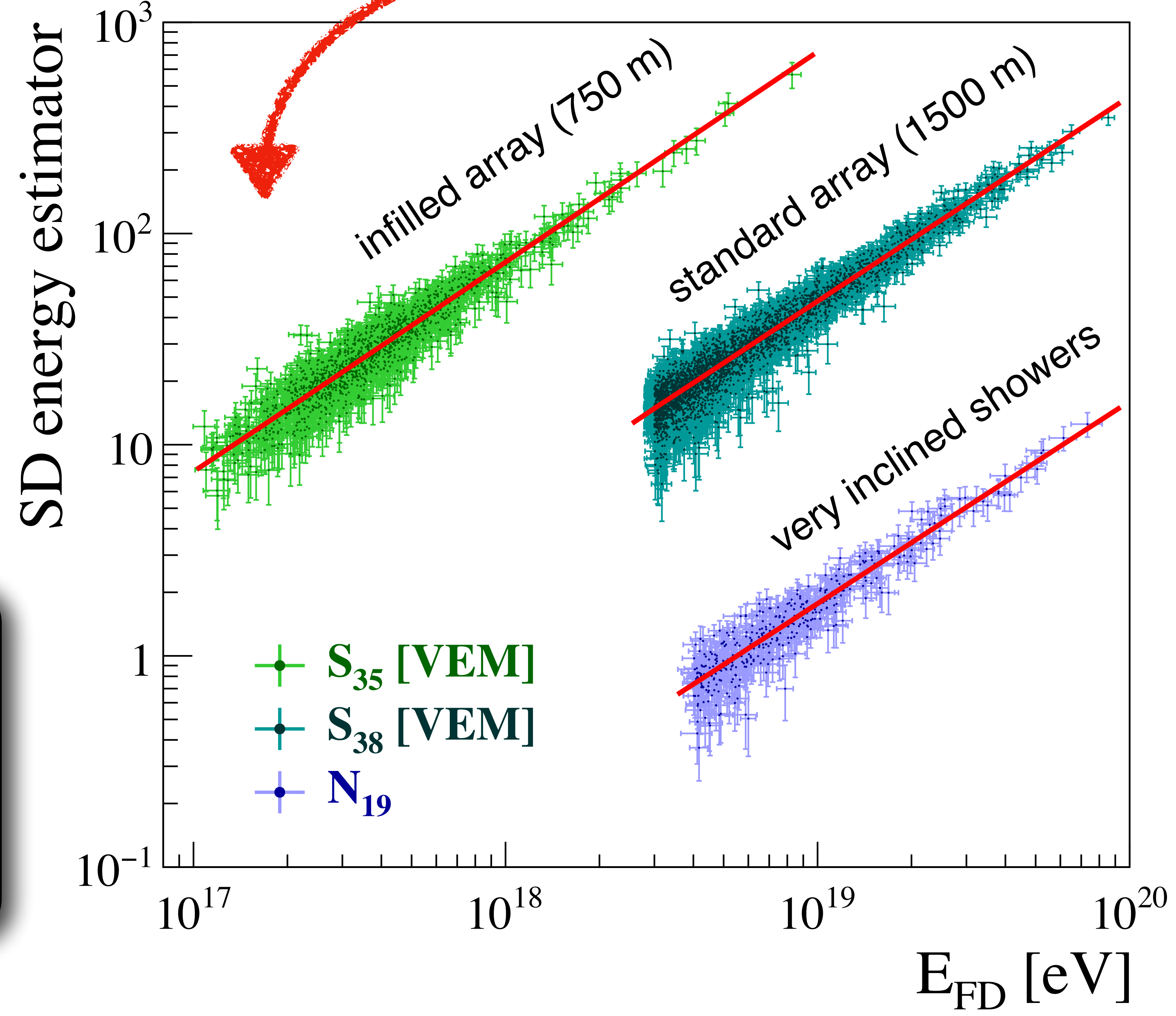


Fit of particle density as a fct of distance from shower core → ρ(r)

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

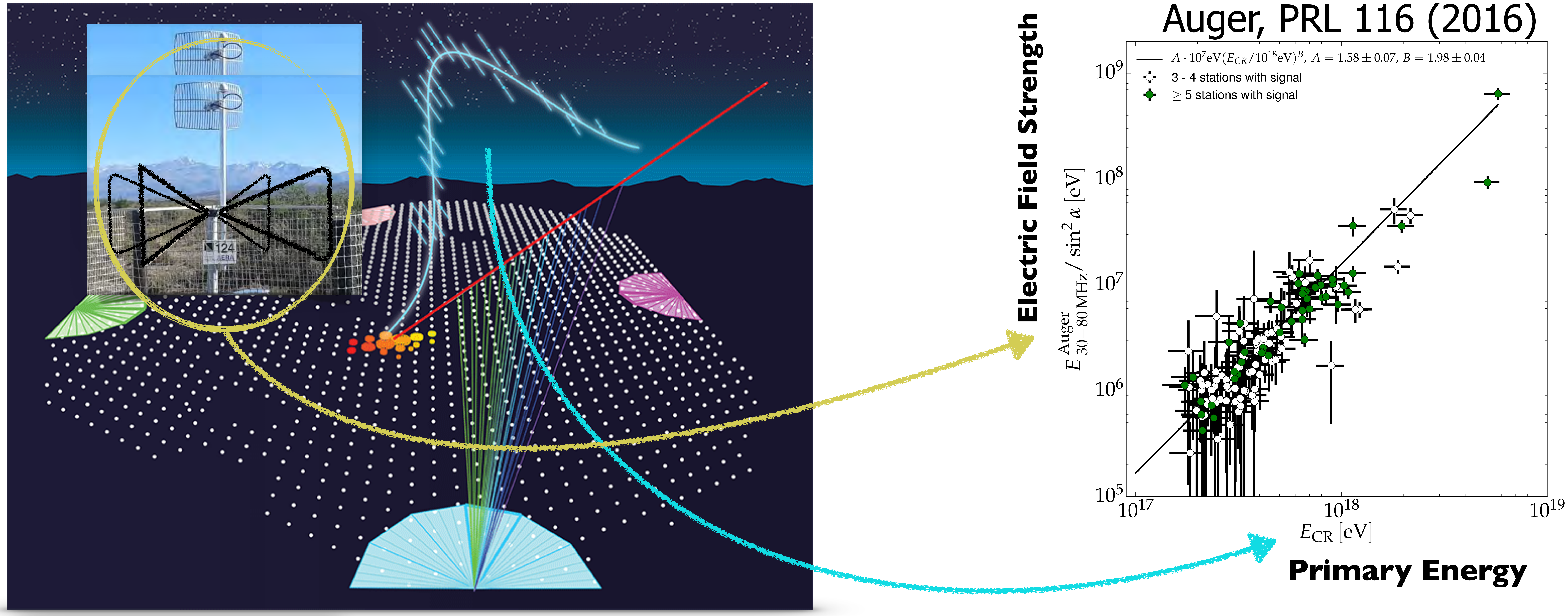
Normalise S_{tot} to specific zenith angle → S_{38}, etc





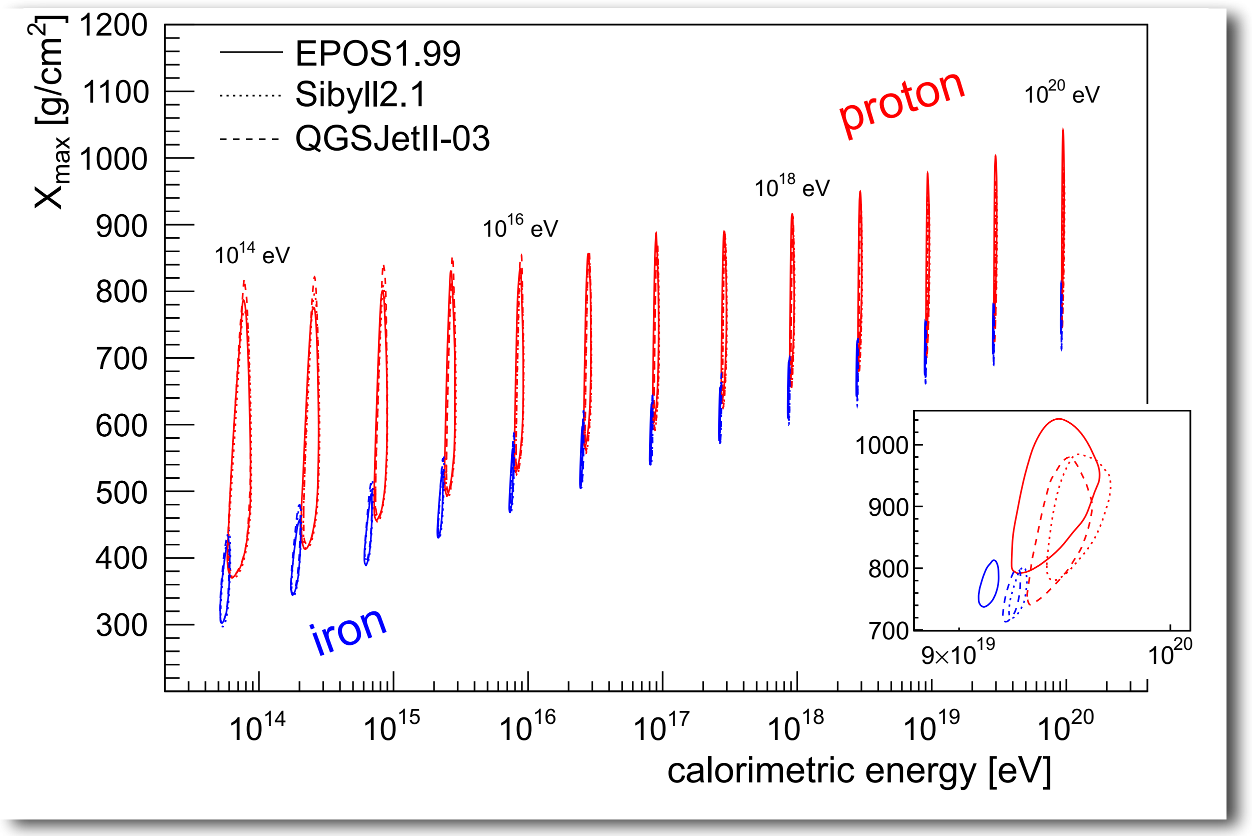
Note, this way the surface detector array is calibrated by the fluorescence telescopes, based on lab measurements!

Calibrating the Primary Energy


Auger, PRL 116 (2016)

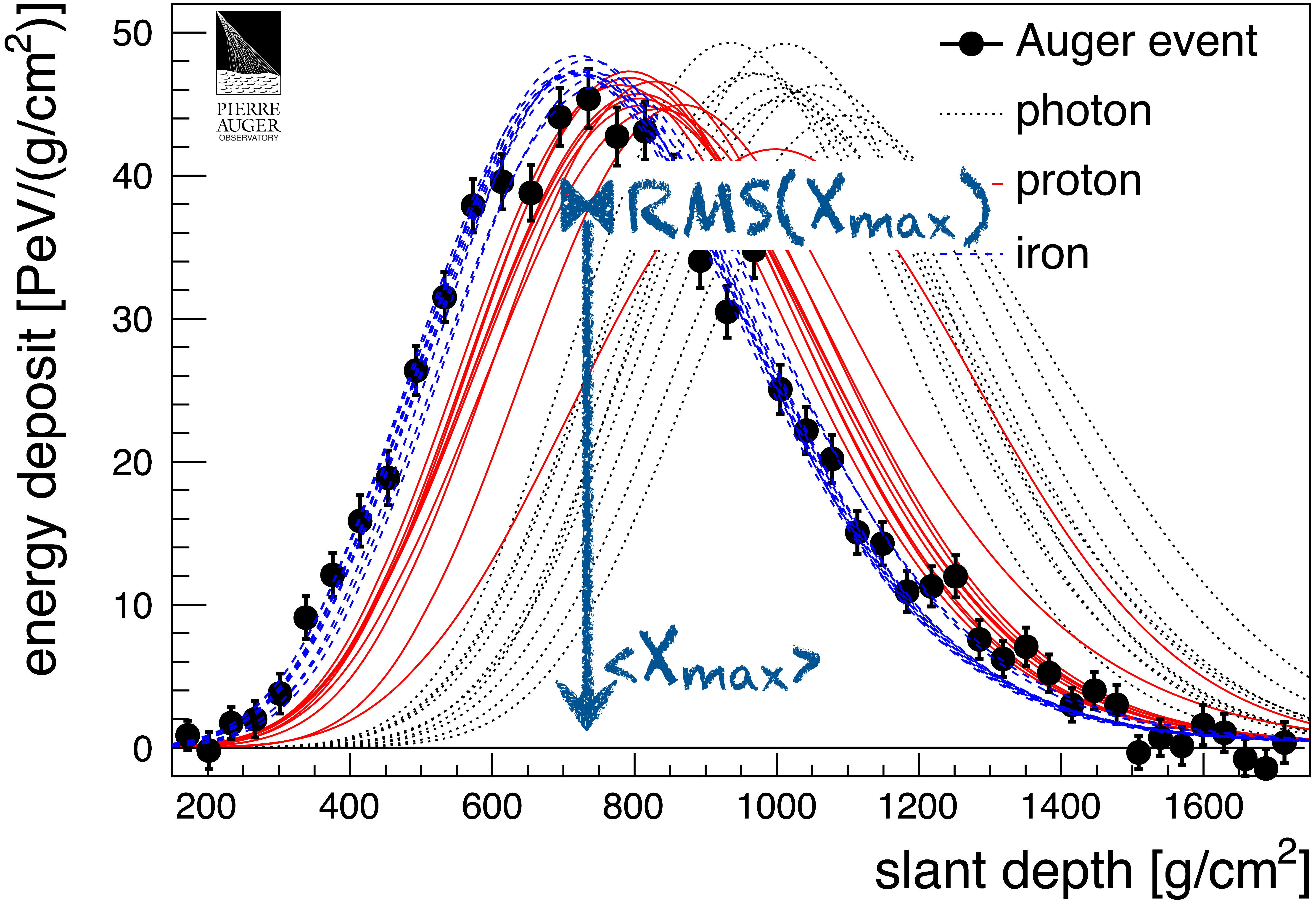
Absolute calibration of radio signal:
18 MeV energy radiated in radio signal @ 1 EeV

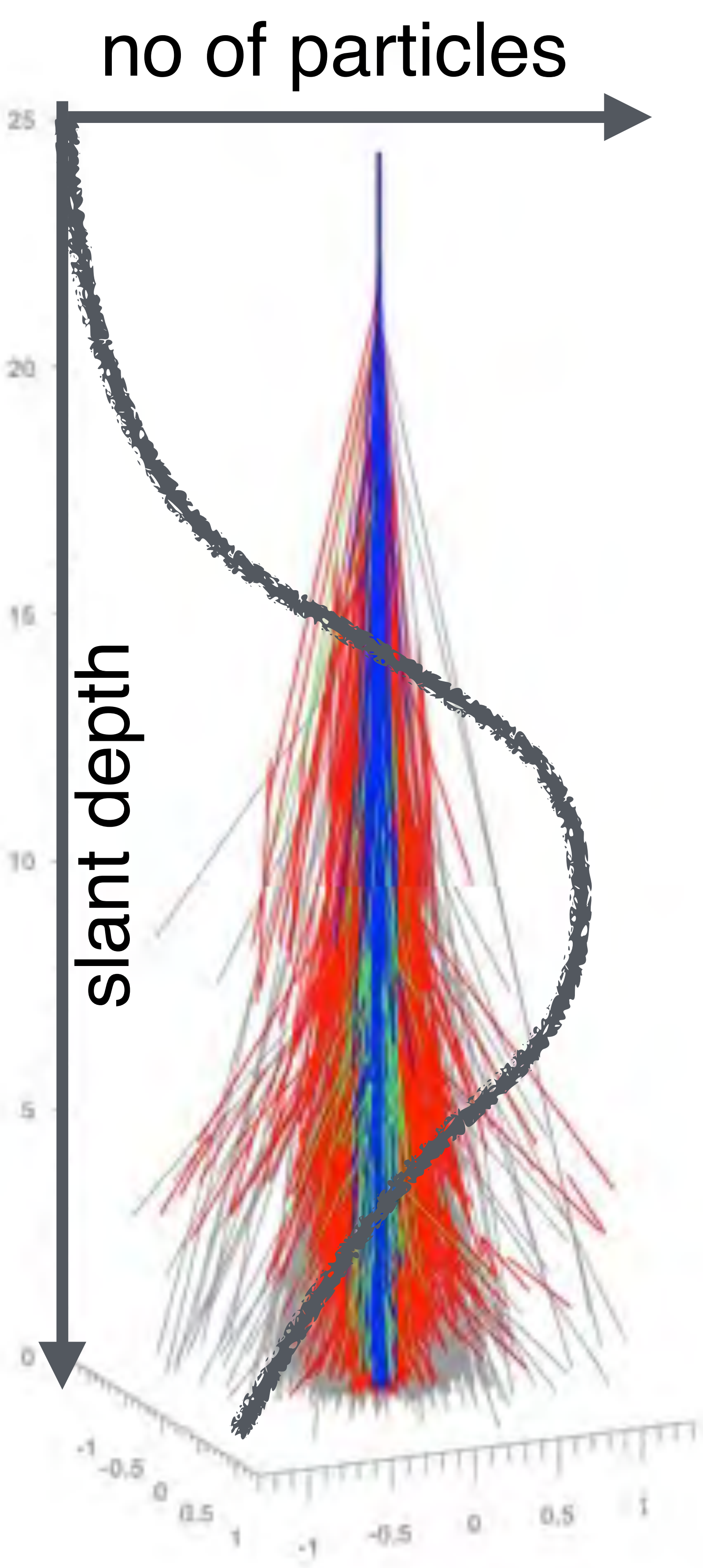
Longitudinal Shower Development → Primary Mass



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

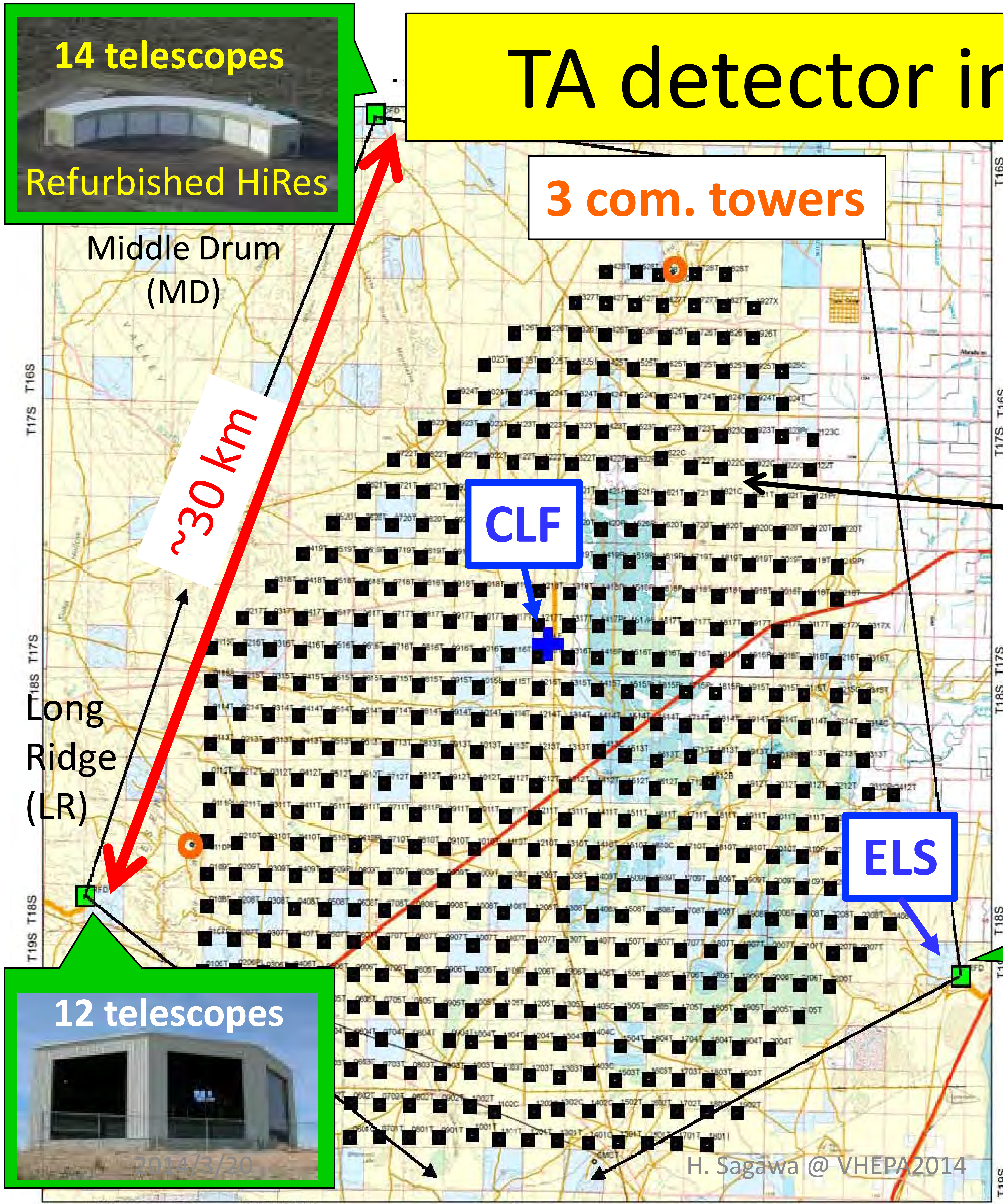
Example of a $3 \cdot 10^{19}$ eV EAS event in FD





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 km^2

Fluorescence Detector(FD)

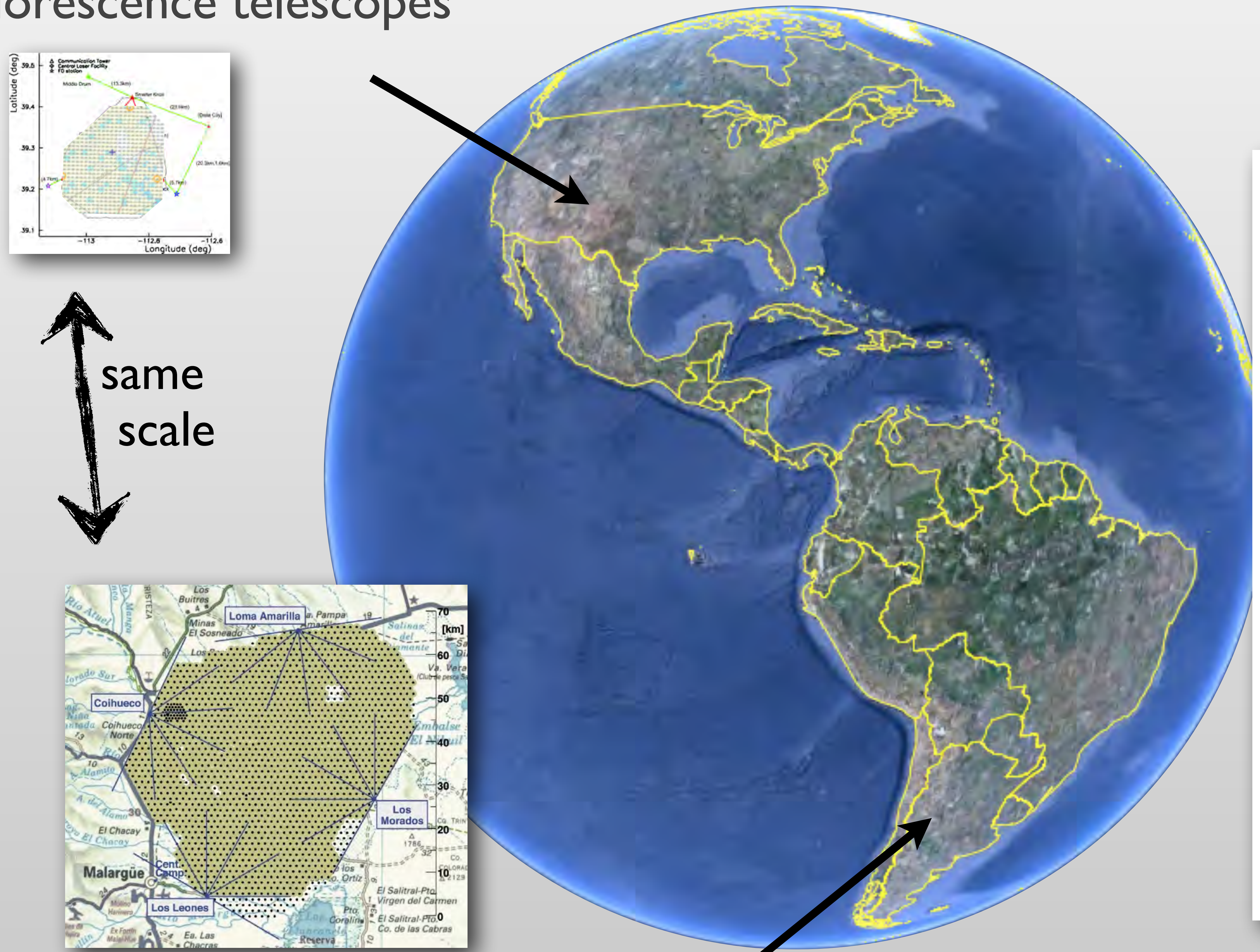
3 stations

38 telescopes

FD and SD: fully operational since 2008/May

Auger and TA

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

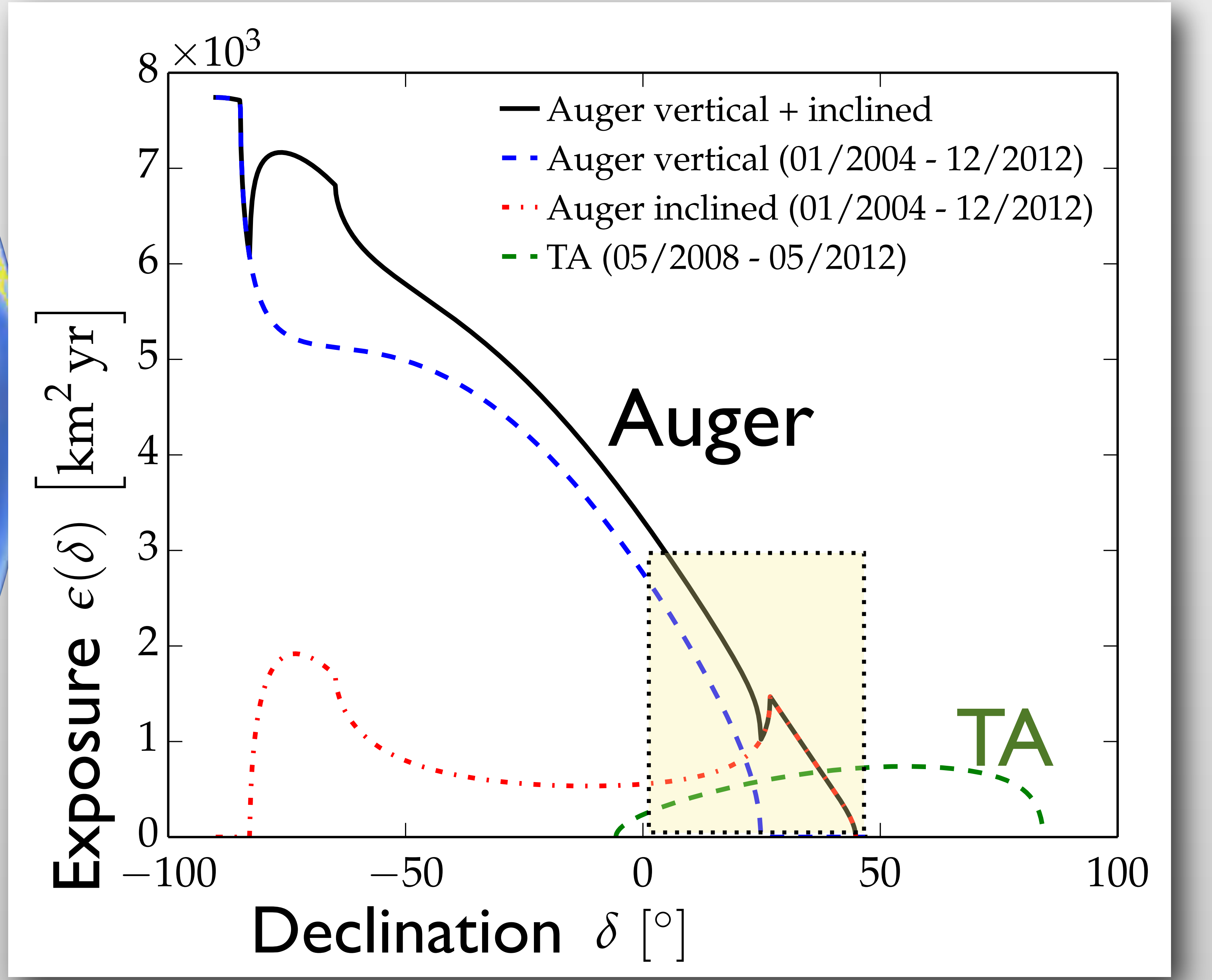


same scale

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

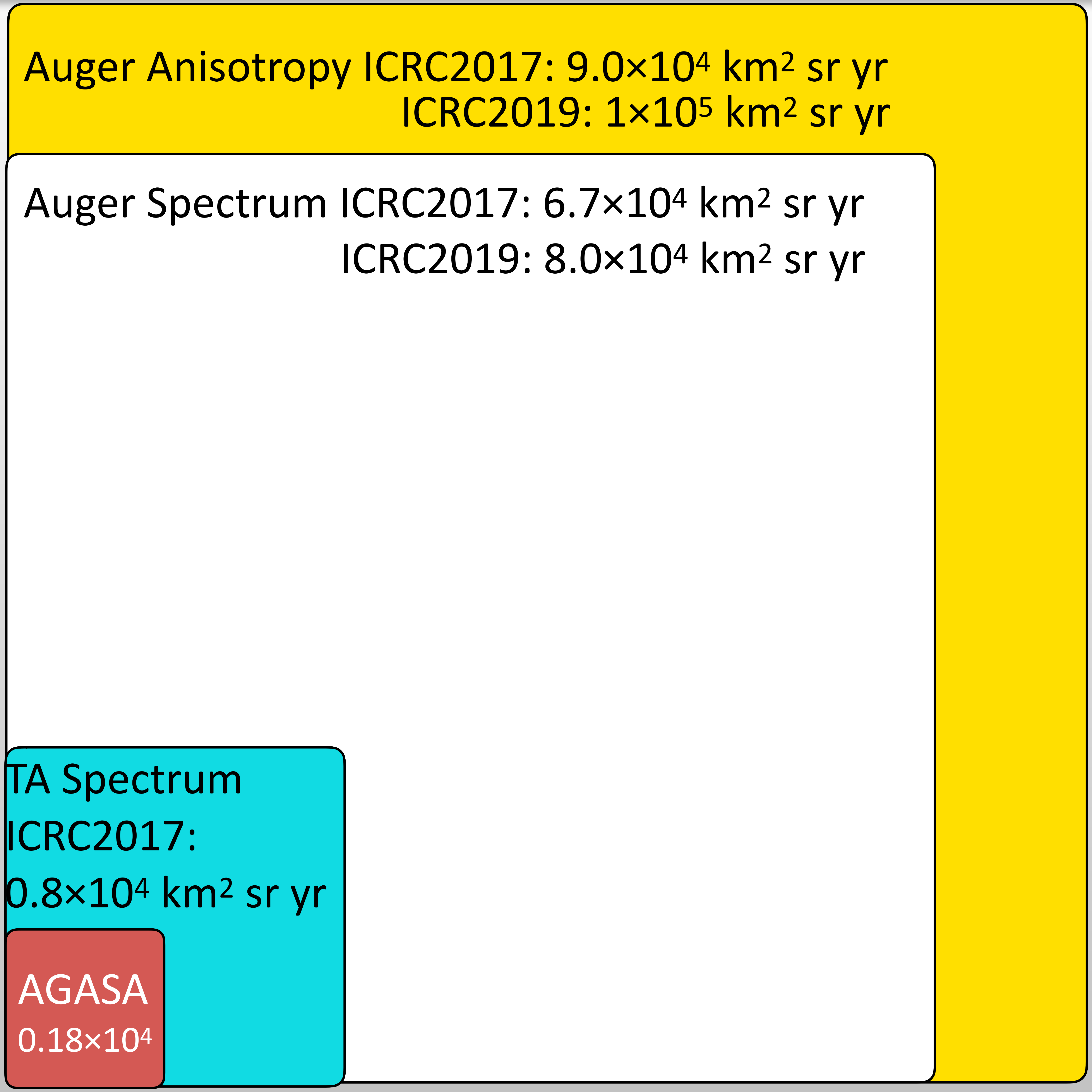
Auger and TA can see the same sky

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



Auger exposure ~8 times that of TA

UHE Exposure in Comparison



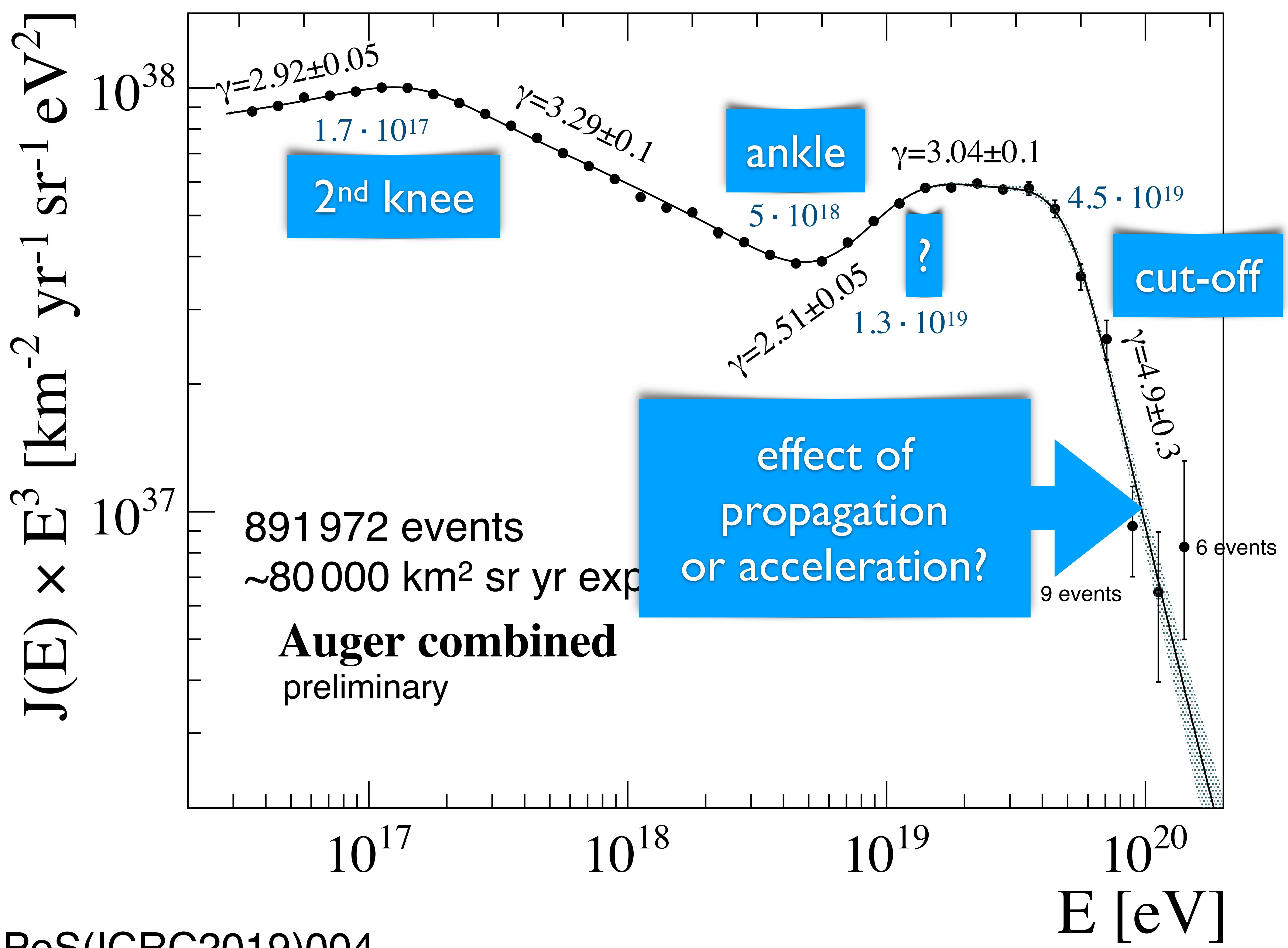
Auger Anisotropy ICRC2017: 9.0×10^4 km^2 sr yr
ICRC2019: 1×10^5 km^2 sr yr

Auger Spectrum ICRC2017: 6.7×10^4 km^2 sr yr
ICRC2019: 8.0×10^4 km^2 sr yr

TA Spectrum
ICRC2017:
0.8×10^4 km^2 sr yr

AGASA
0.18×10^4

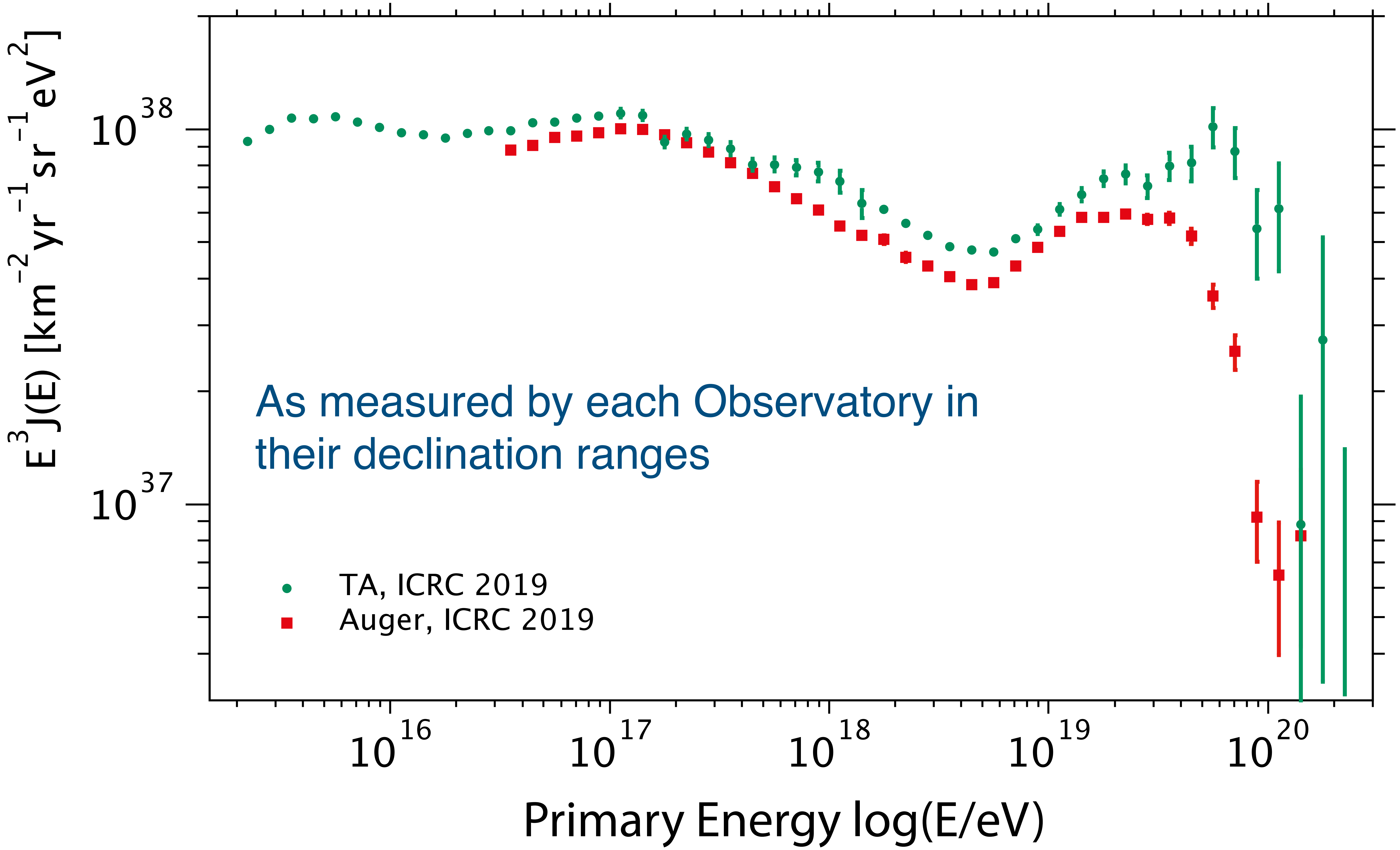
Auger UHECR Energy Spectrum



A. Castellina et al, PoS(ICRC2019)004

Journal papers on arXiv, soon

Comparison of Auger and TA spectra

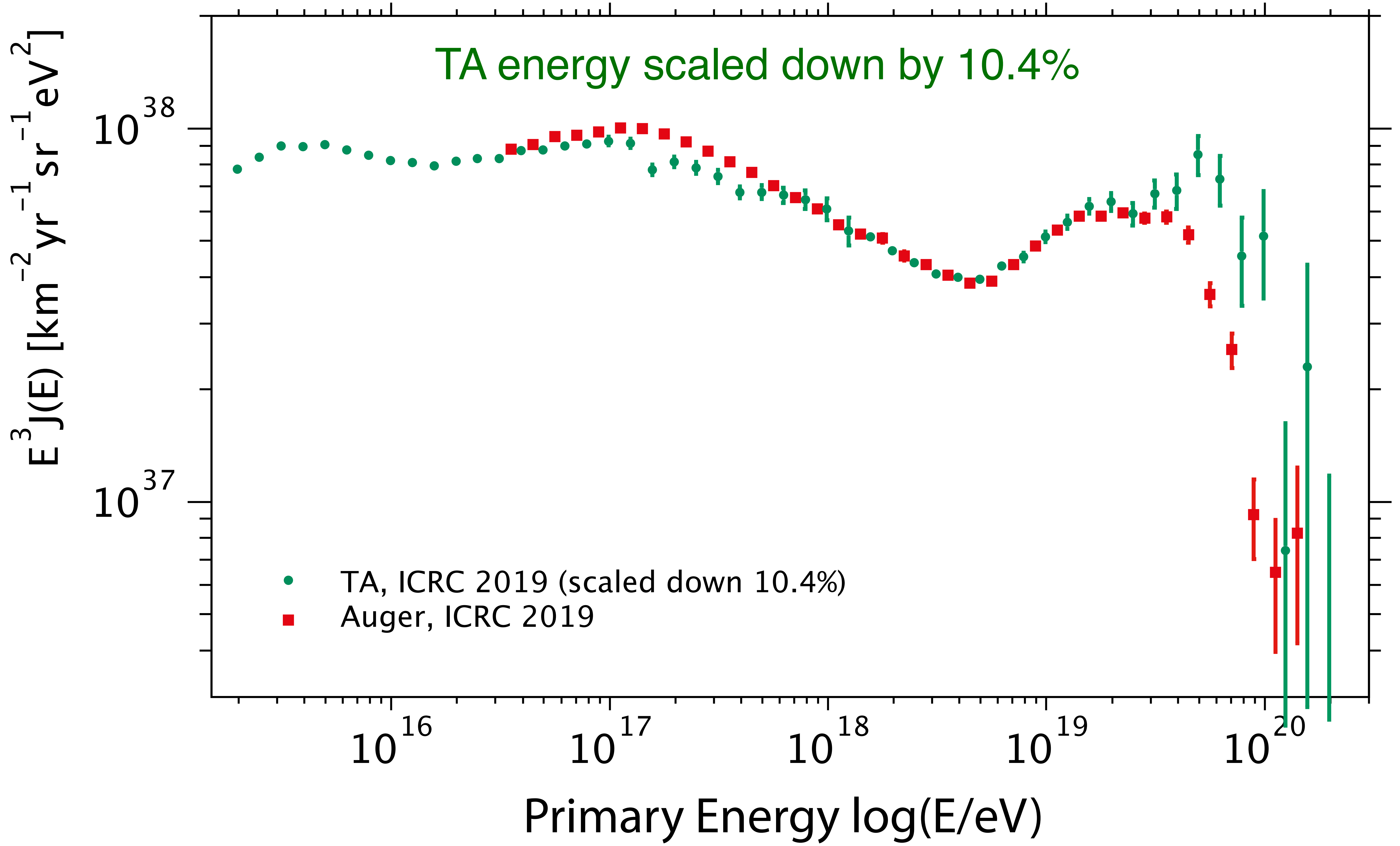


As measured by each Observatory in their declination ranges

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

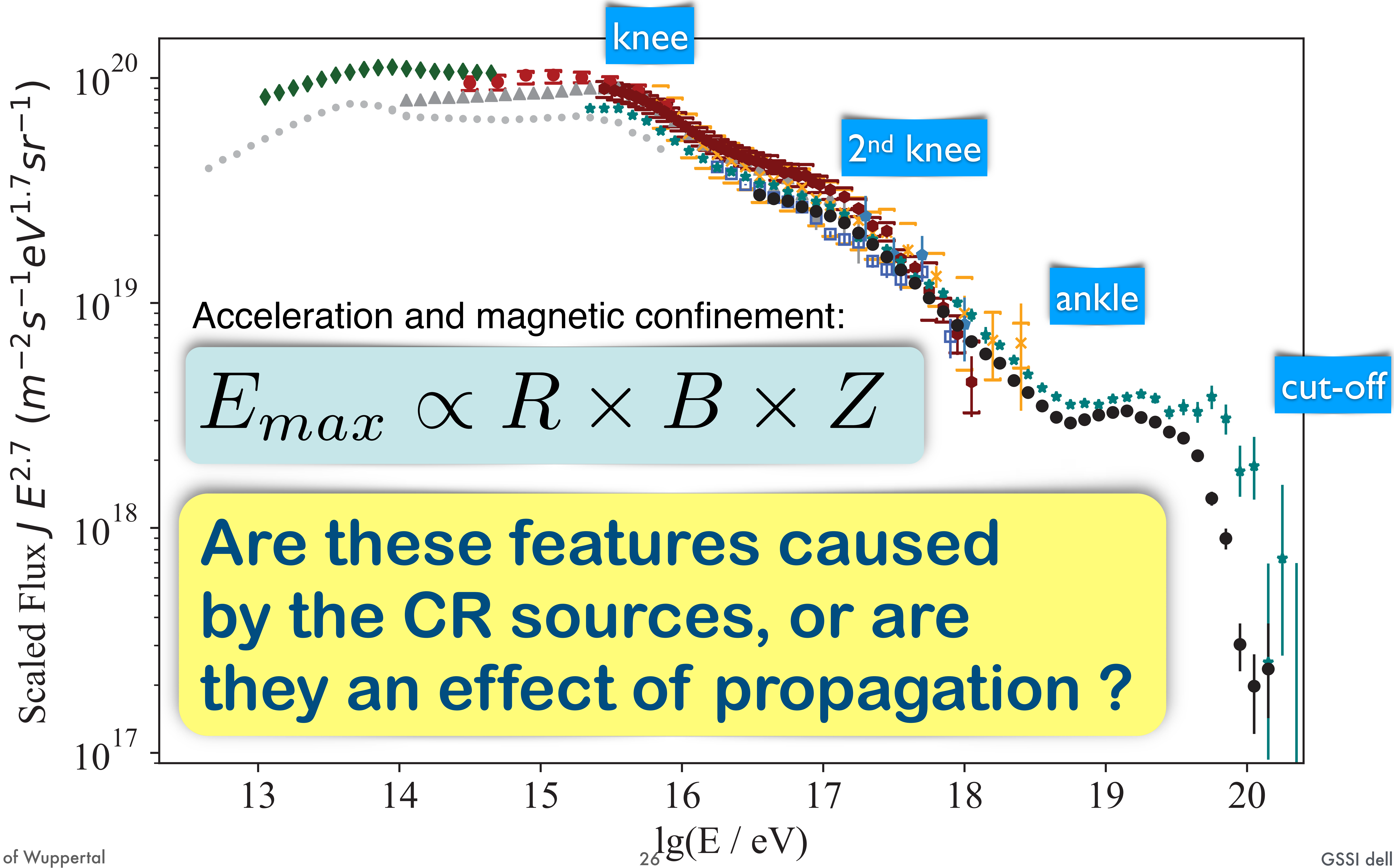
Comparison of Auger and TA spectra



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

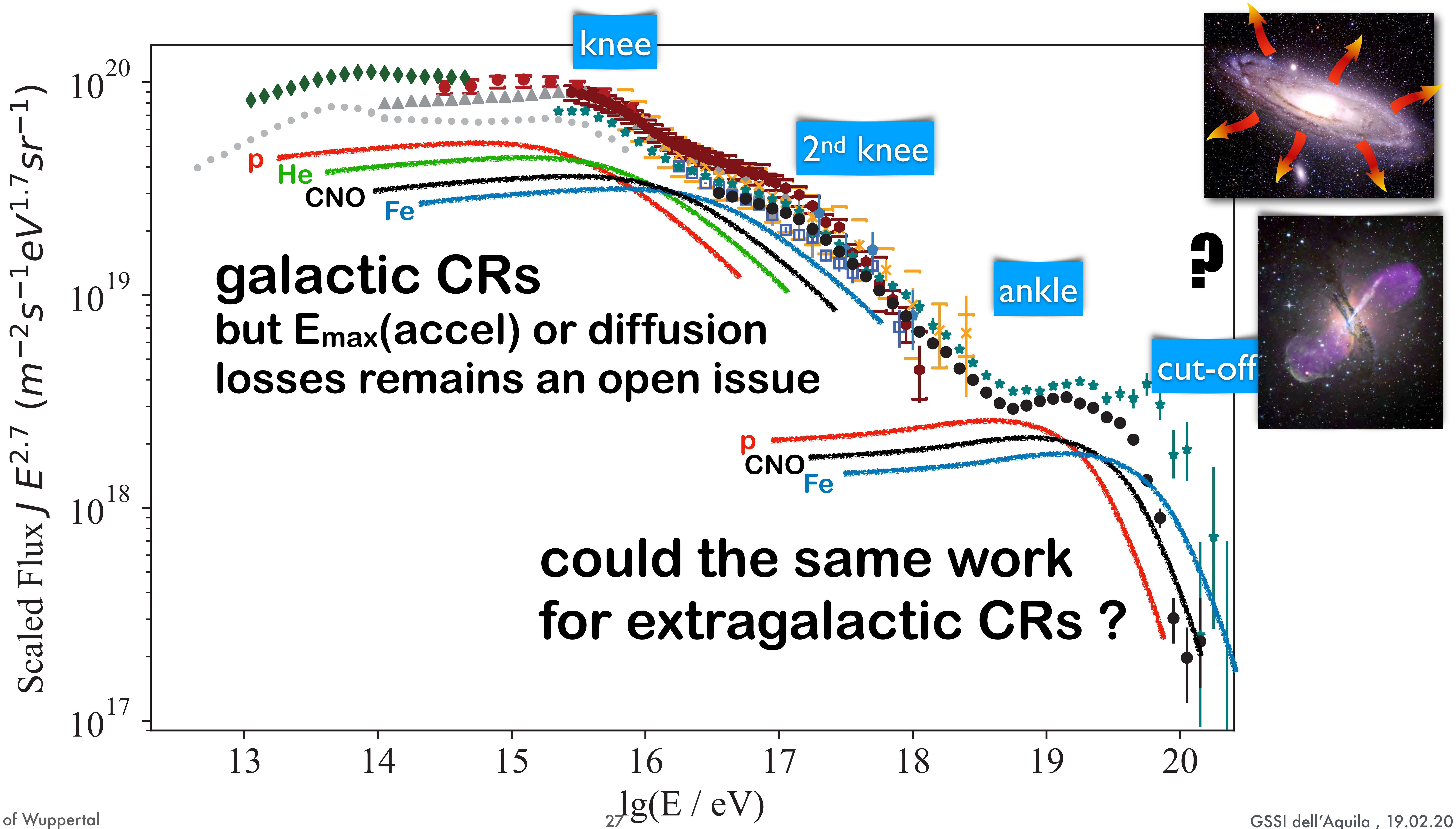


Acceleration and magnetic confinement:

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

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

Features of the CR spectrum

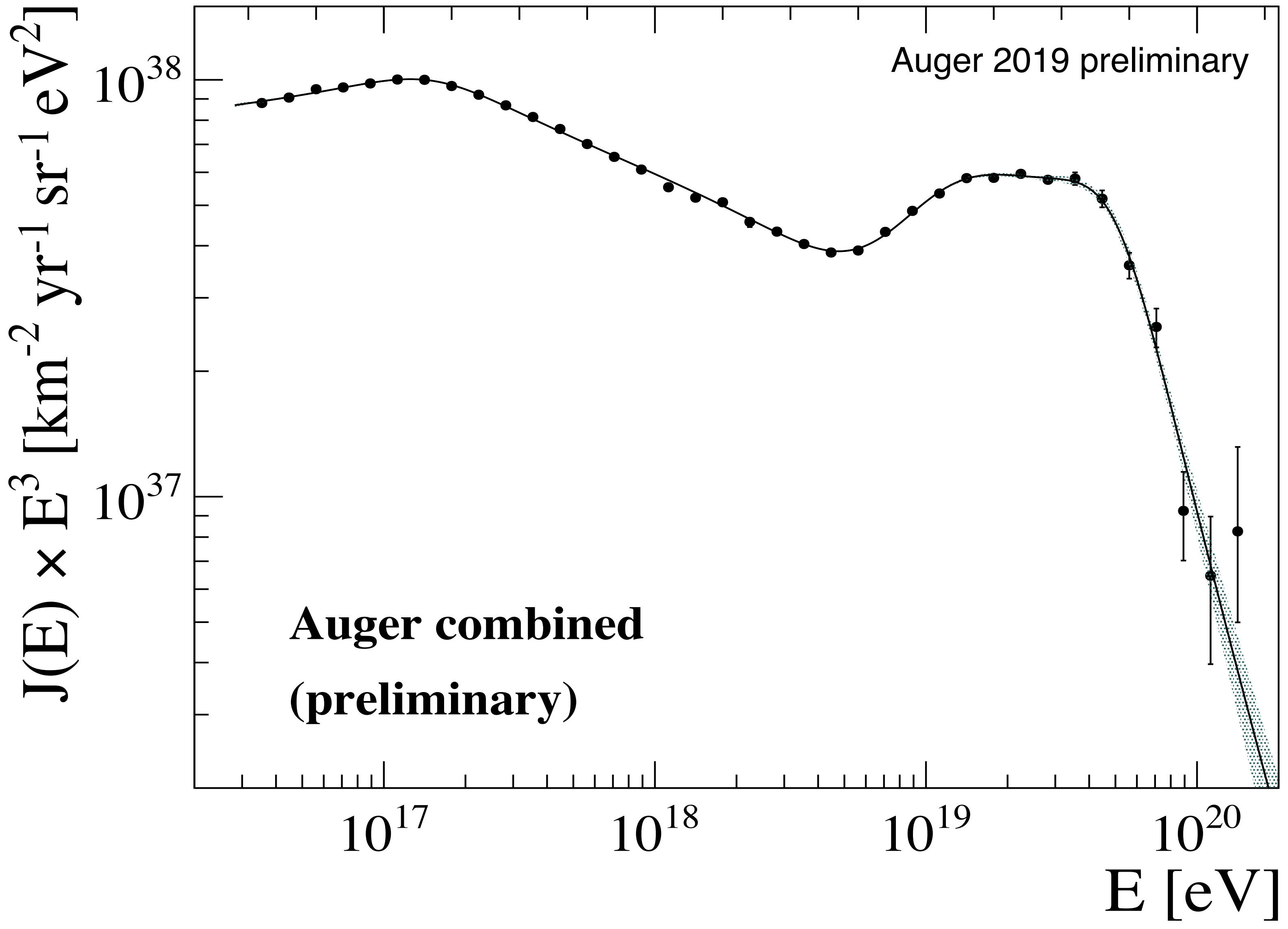


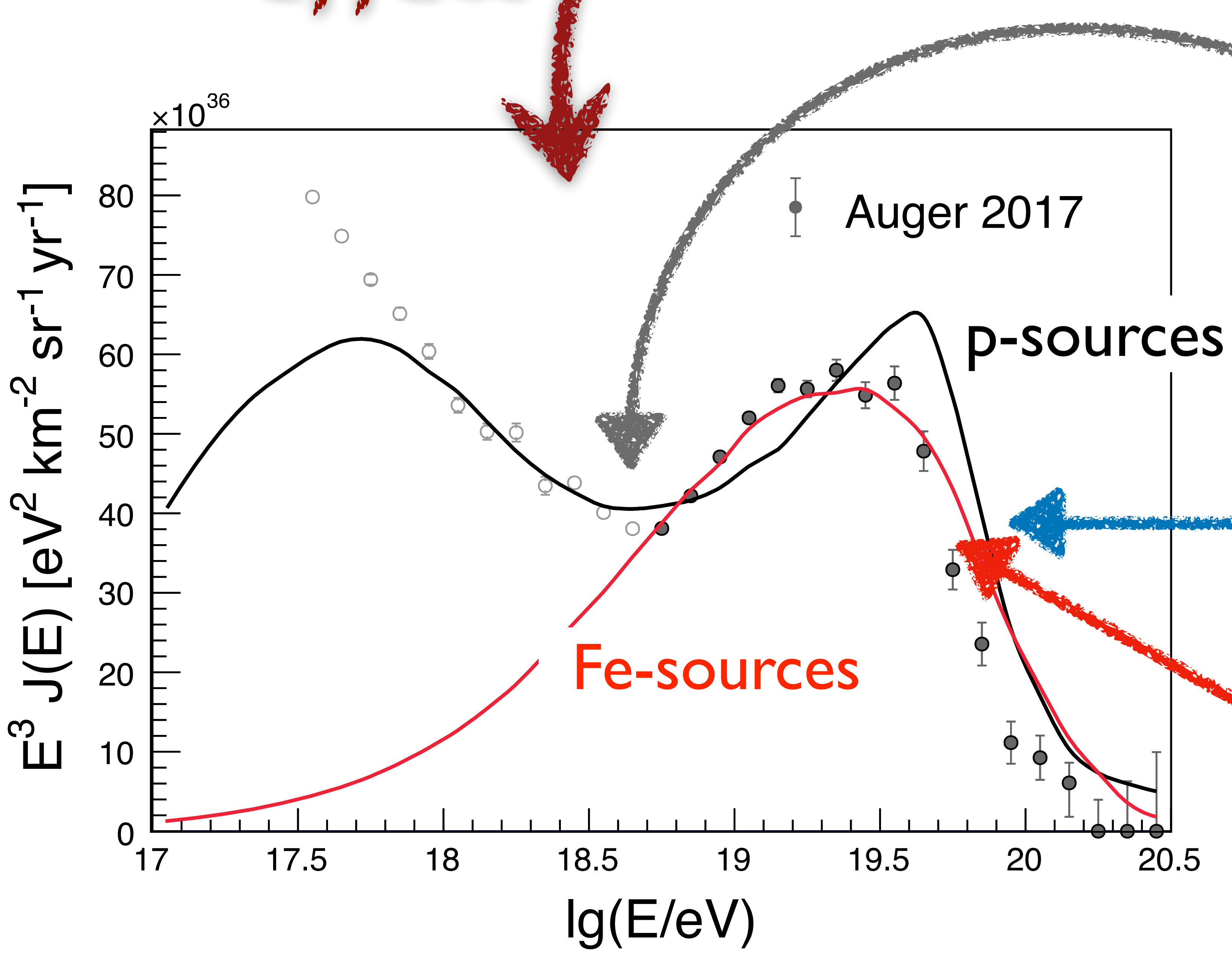
galactic CRs

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

could the same work for extragalactic CRs ?

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

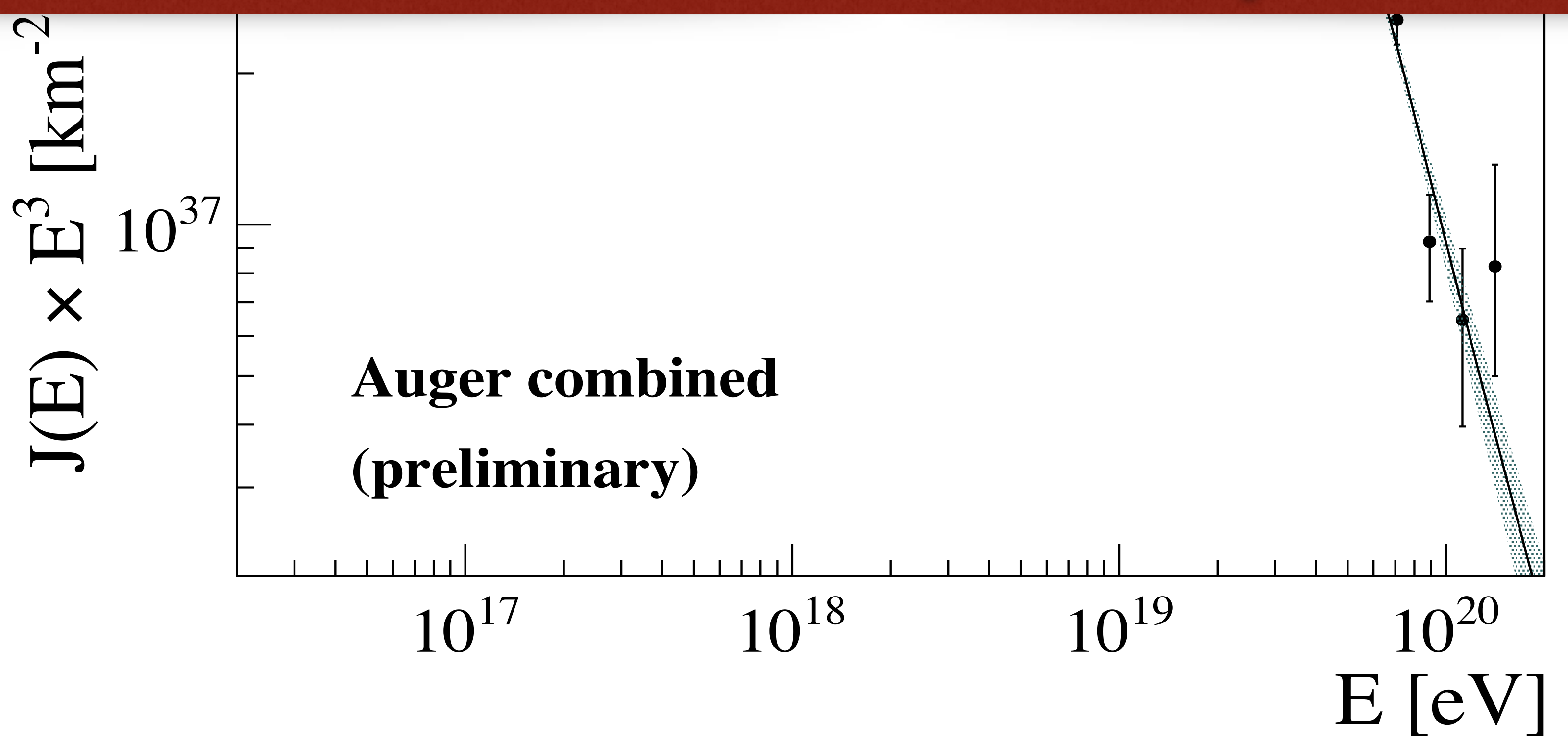
$p\gamma \rightarrow \Delta \rightarrow p+\pi$

Fe+γ → „Cr“ + p + n

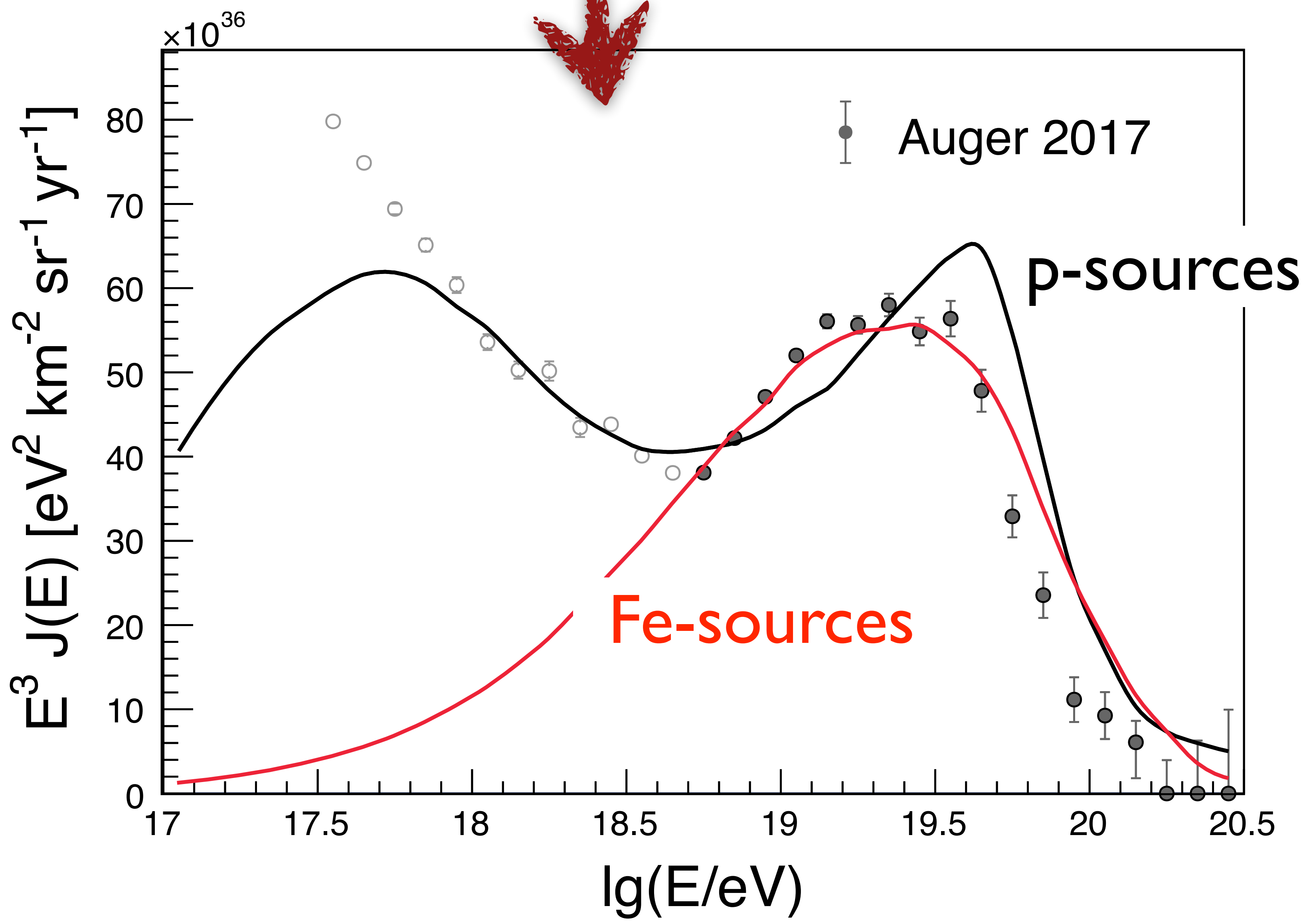
Greisen, Zatsepin & Kuzmin (GZK), 1966

GZK-effect or Sources running at their RxB limits?

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

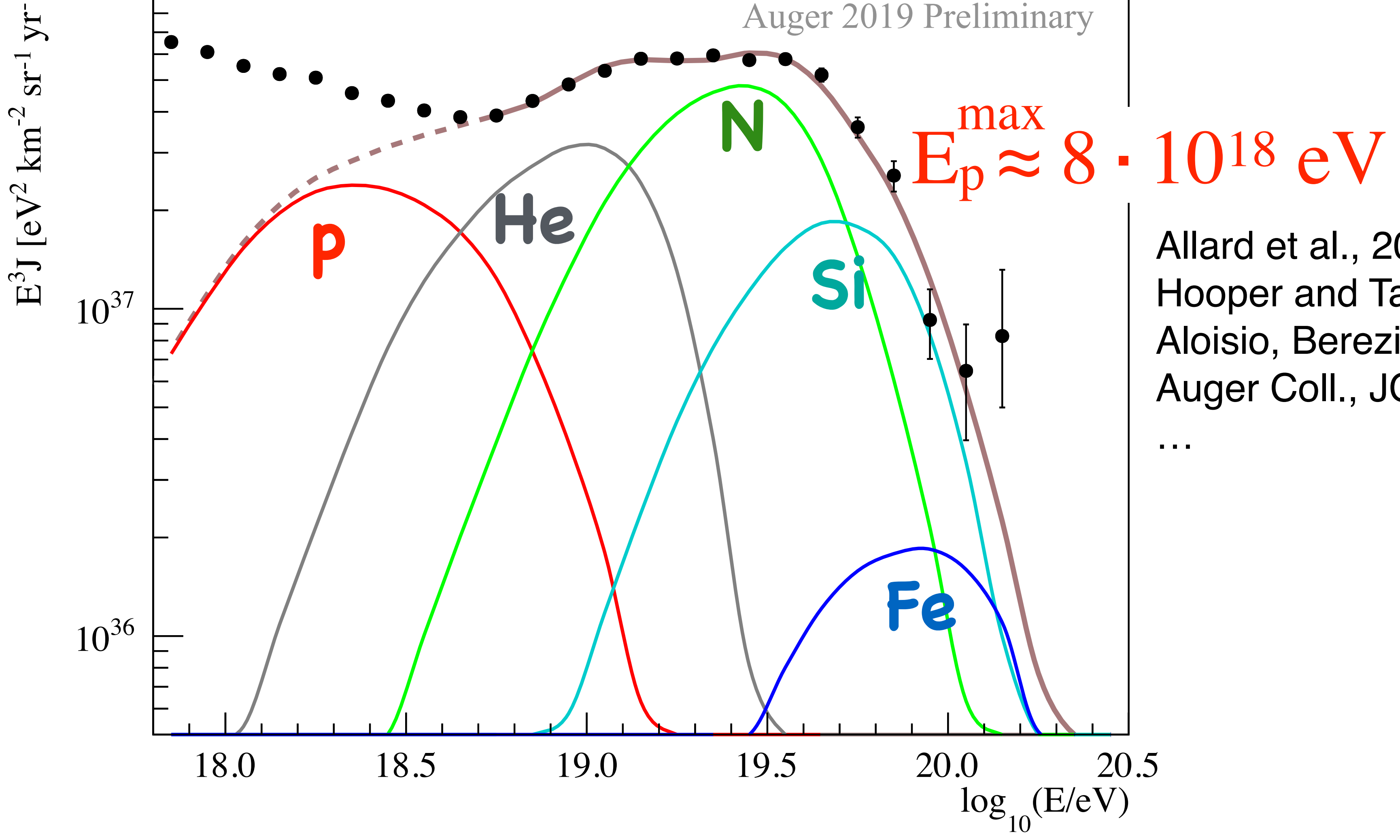


GZK-
effect



Emax of
sources

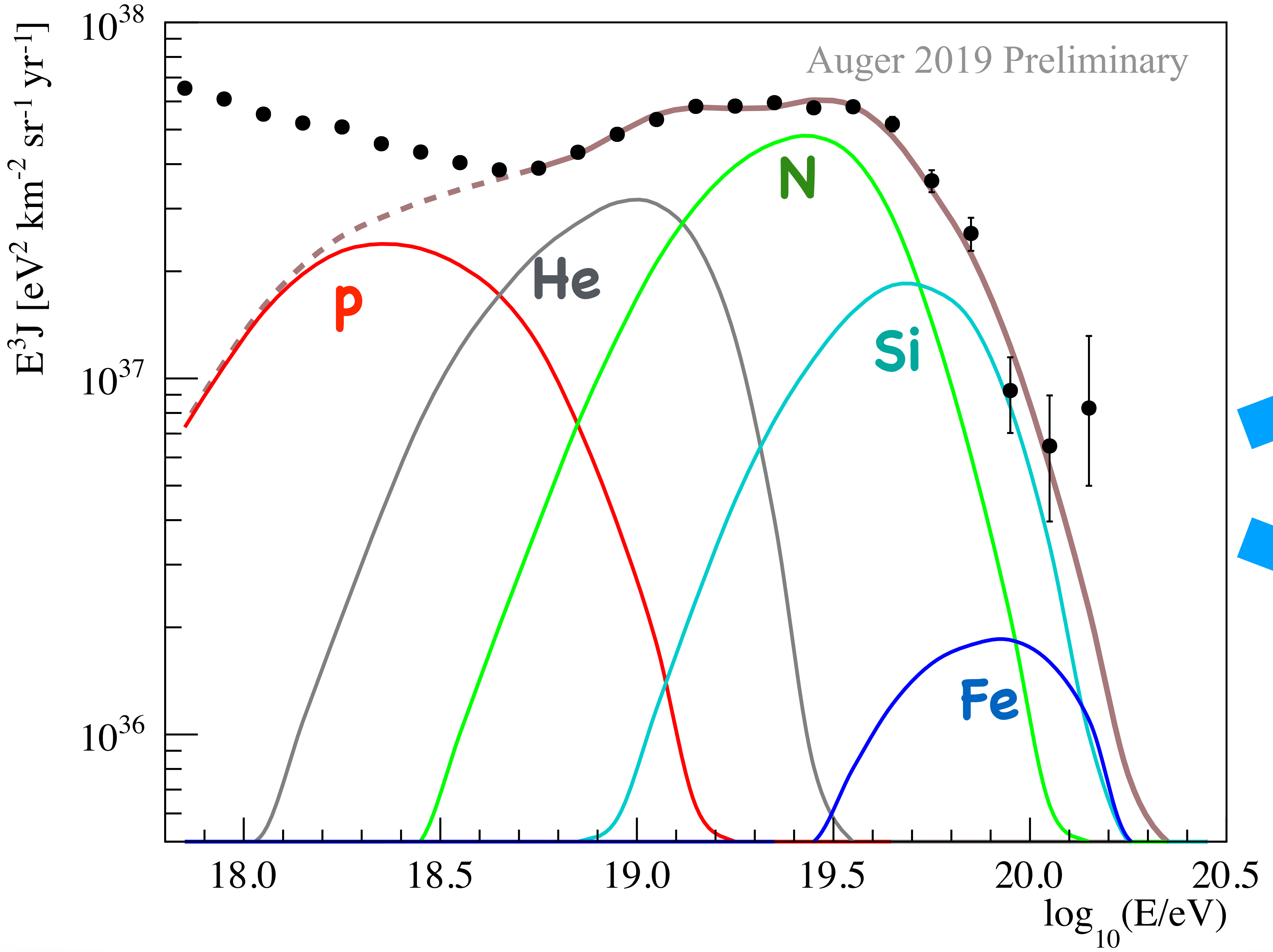
$$E_Z^{\max} \propto Z \times E_p^{\max}$$

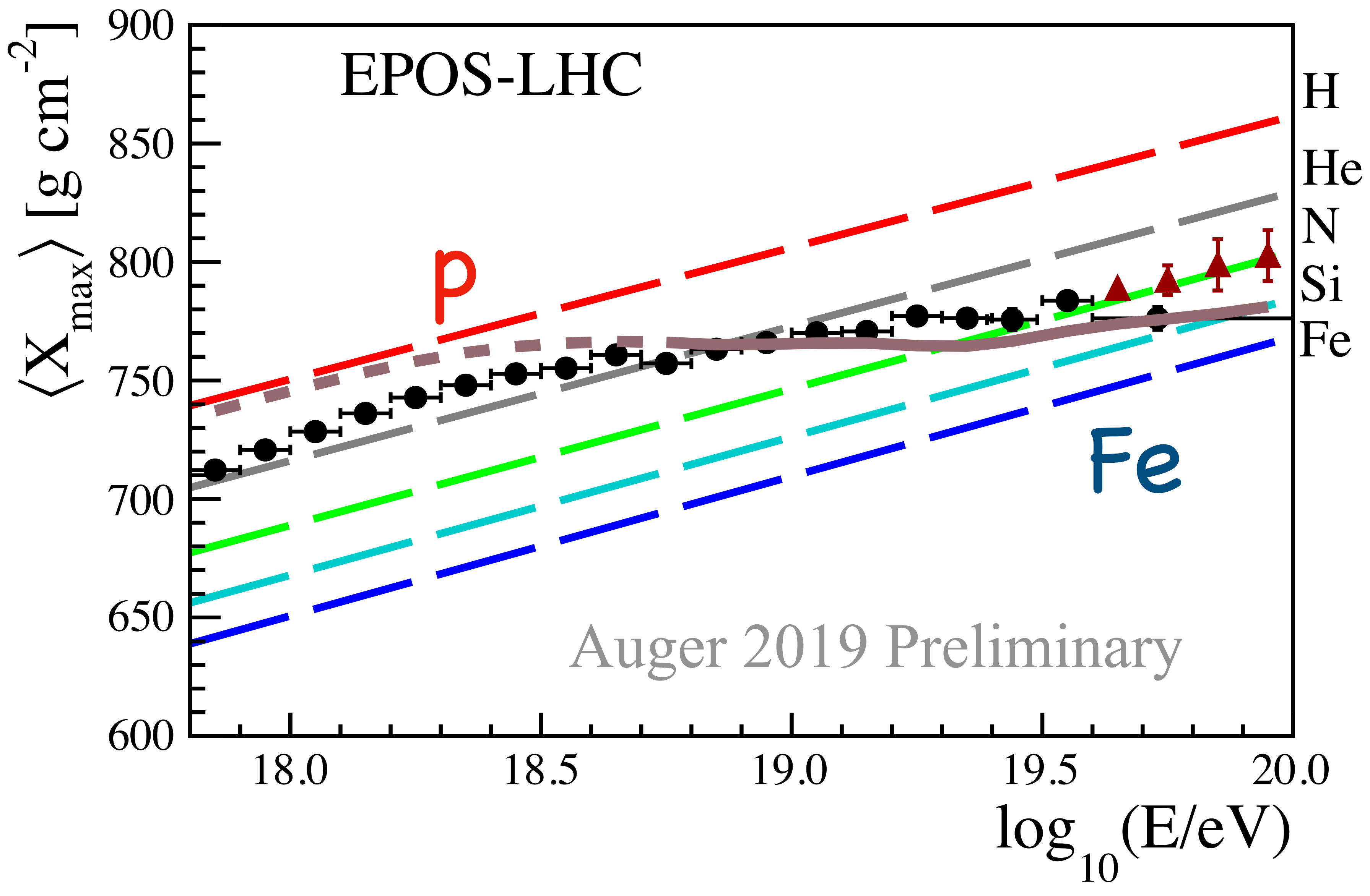


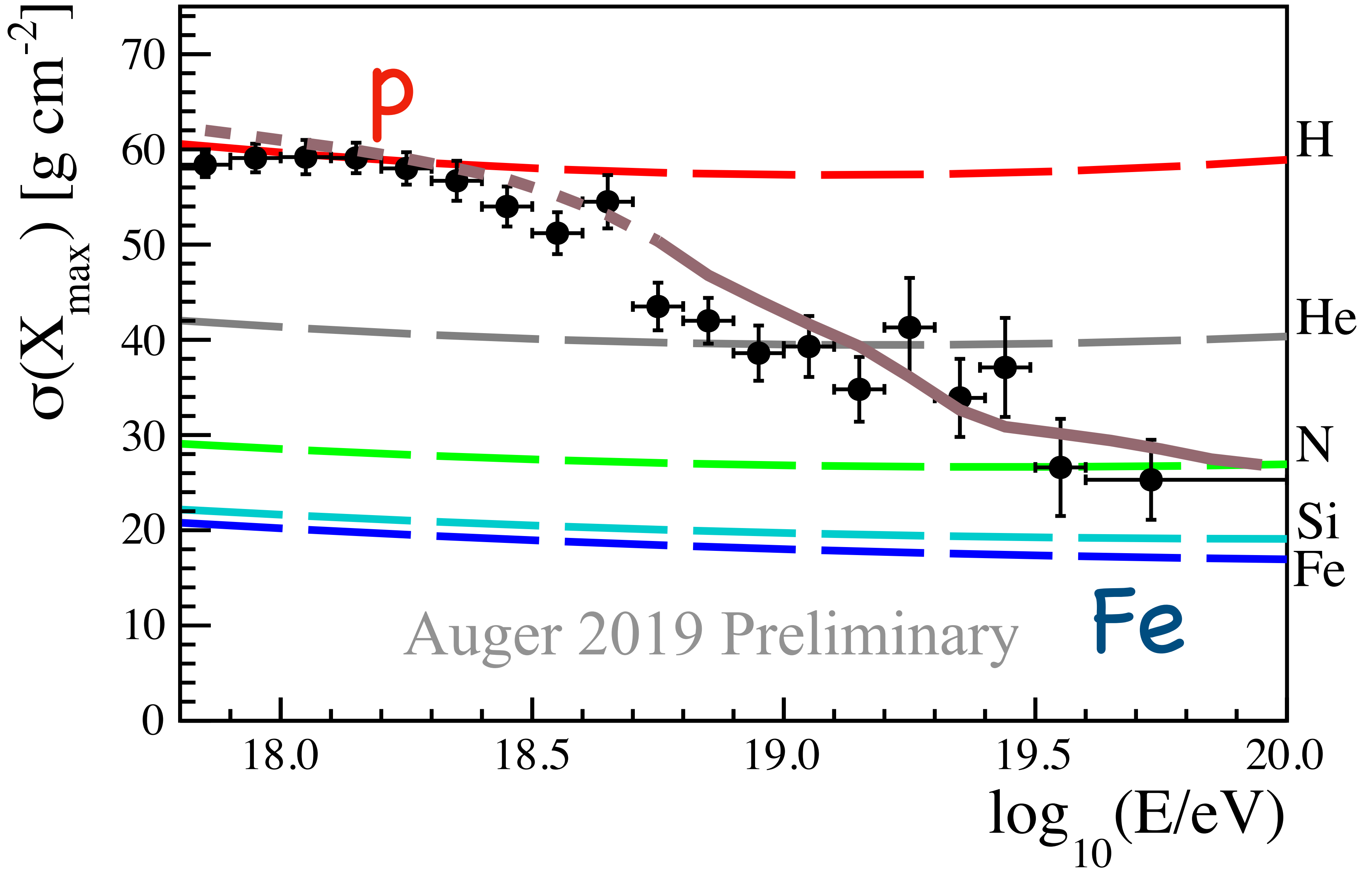
Allard et al., 2008
Hooper and Taylor, Astropart. Phys. 2010
Aloisio, Berezinky, Blasi, JCAP 2014
Auger Coll., JCAP 2017
…

Model of Max. Source Energy describes Composition

Castellina et al, PoS(ICRC2019)004

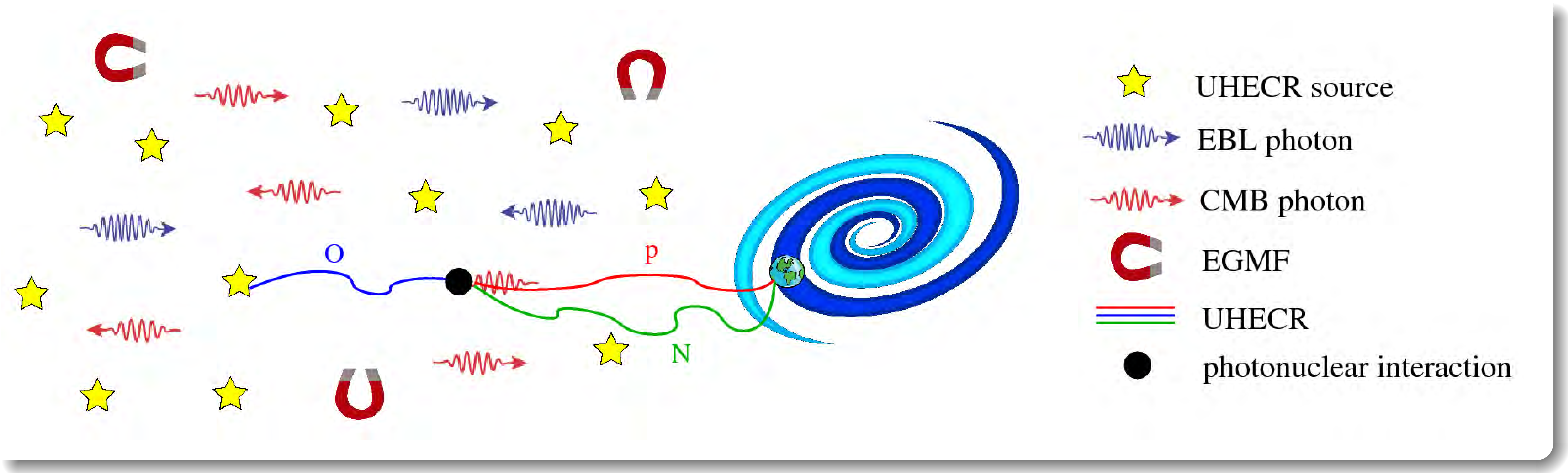






Auger data suggest cut-off to be dominated by E_{max} of sources

Combined Fit of E-spec, X_{max}, $\sigma(X_{max})$



minimal astrophysical model

Pierre Auger Coll., JCAP 1704 (2017) no.04, 038

- $E_{\text{max}} = R_{\text{cut}}\, Z$
- power law injection $E^{-\gamma}$
- five mass groups: p, He, N, Si, Fe
- source evolution $(1+z)^m$
- 1D propagation with CRPropa3
- Gilmore+12 EBL photon field

extended model

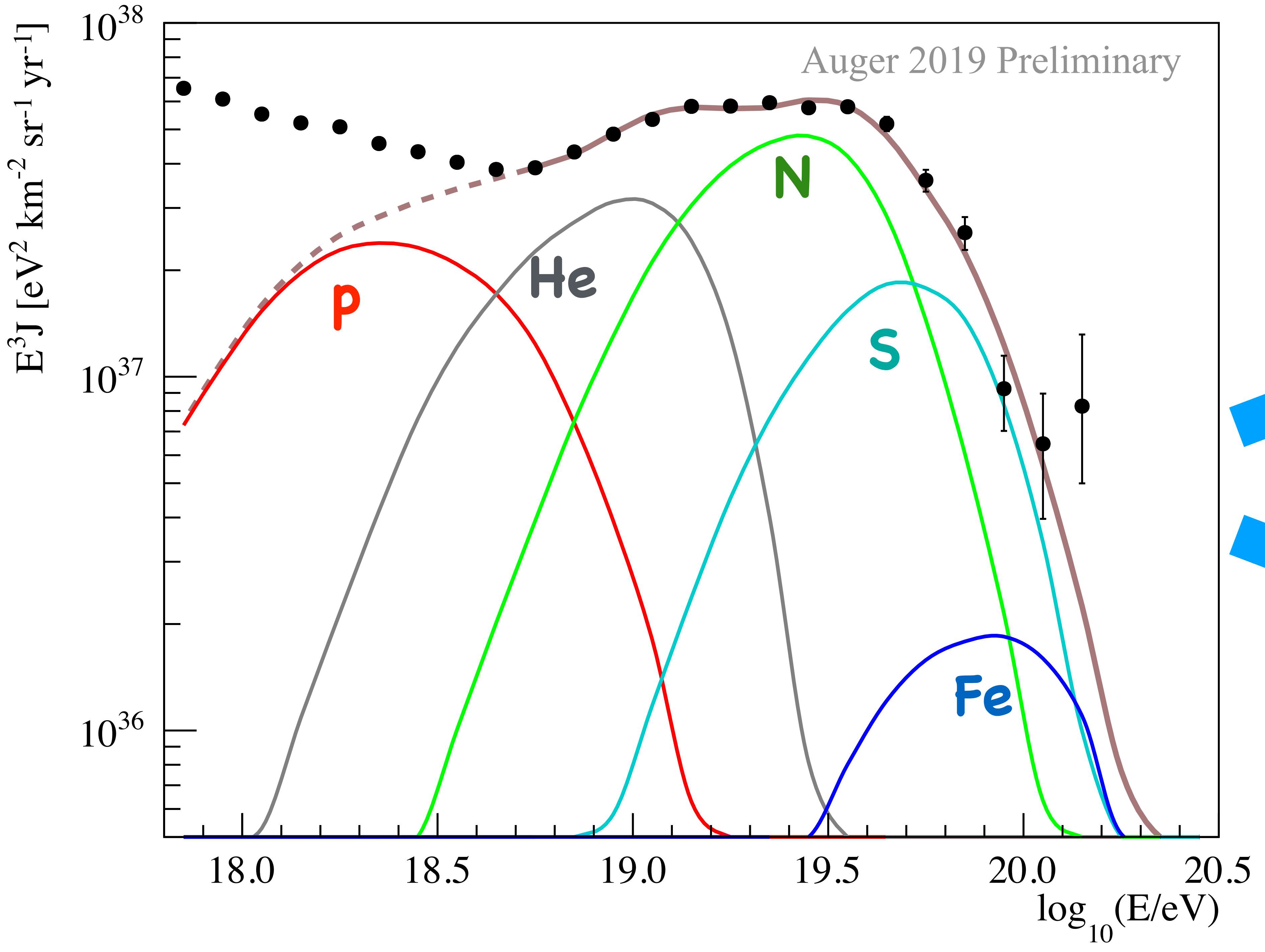
D. Wittkowski for the Pierre Auger Coll., ICRC15

- local large scale structure (Dolag+12)
- extragalactic magnetic field (Sigl+03)
- 4D propagation with CRPropa3

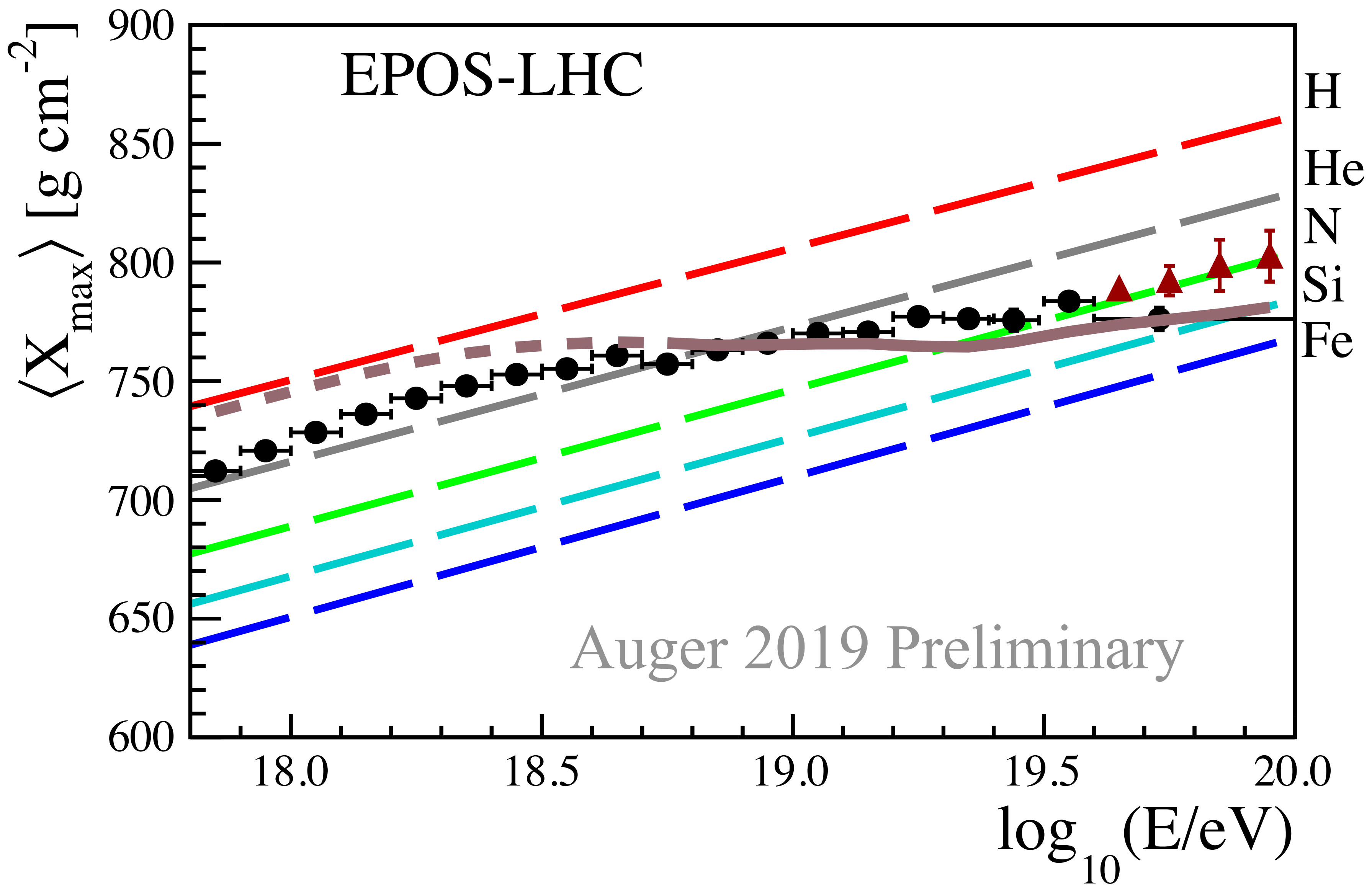
slide adapted from M. Unger

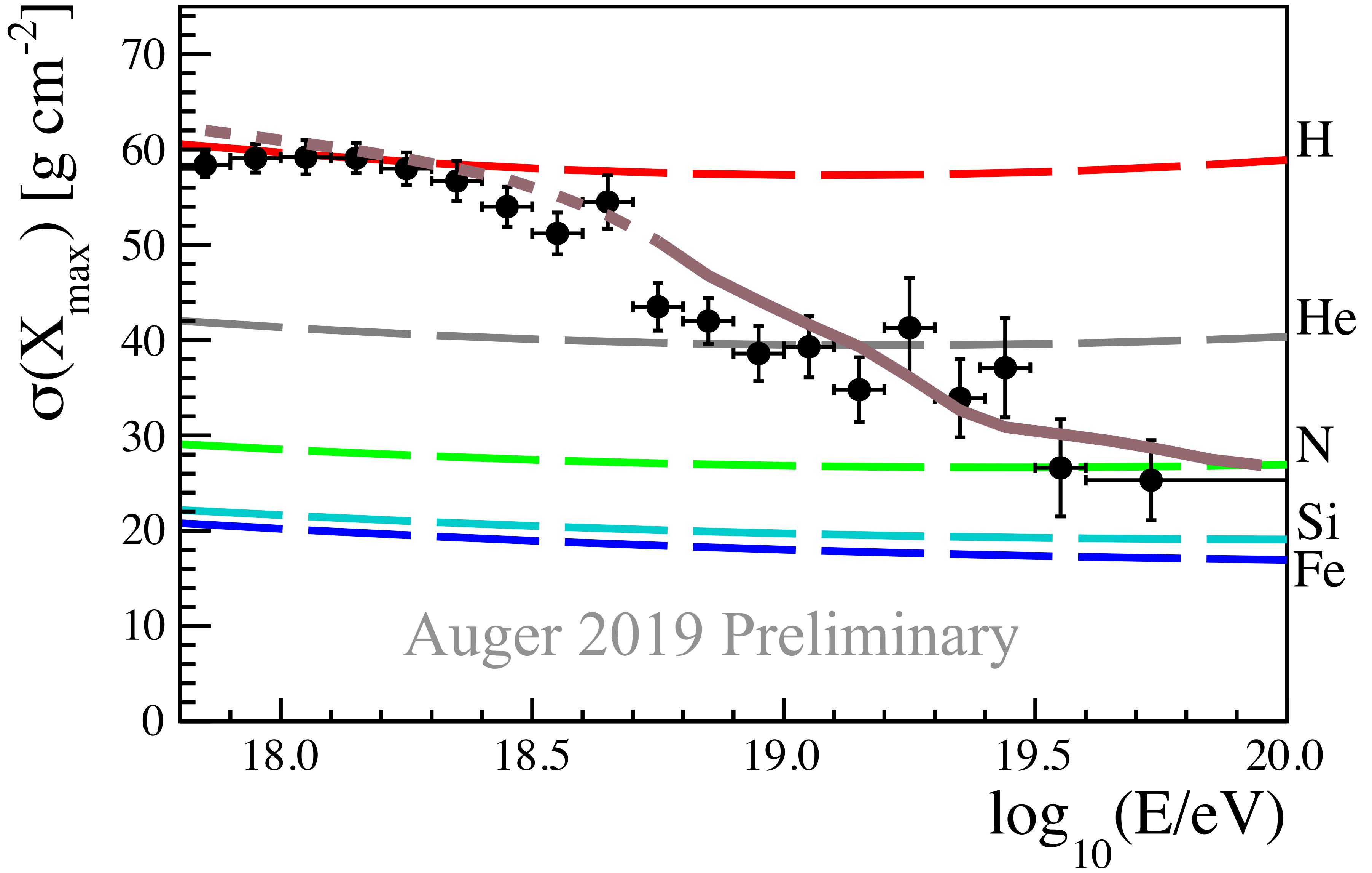
Model of Max. Source Energy describes Composition

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



Castellina et al, PoS(ICRC2019)004





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

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

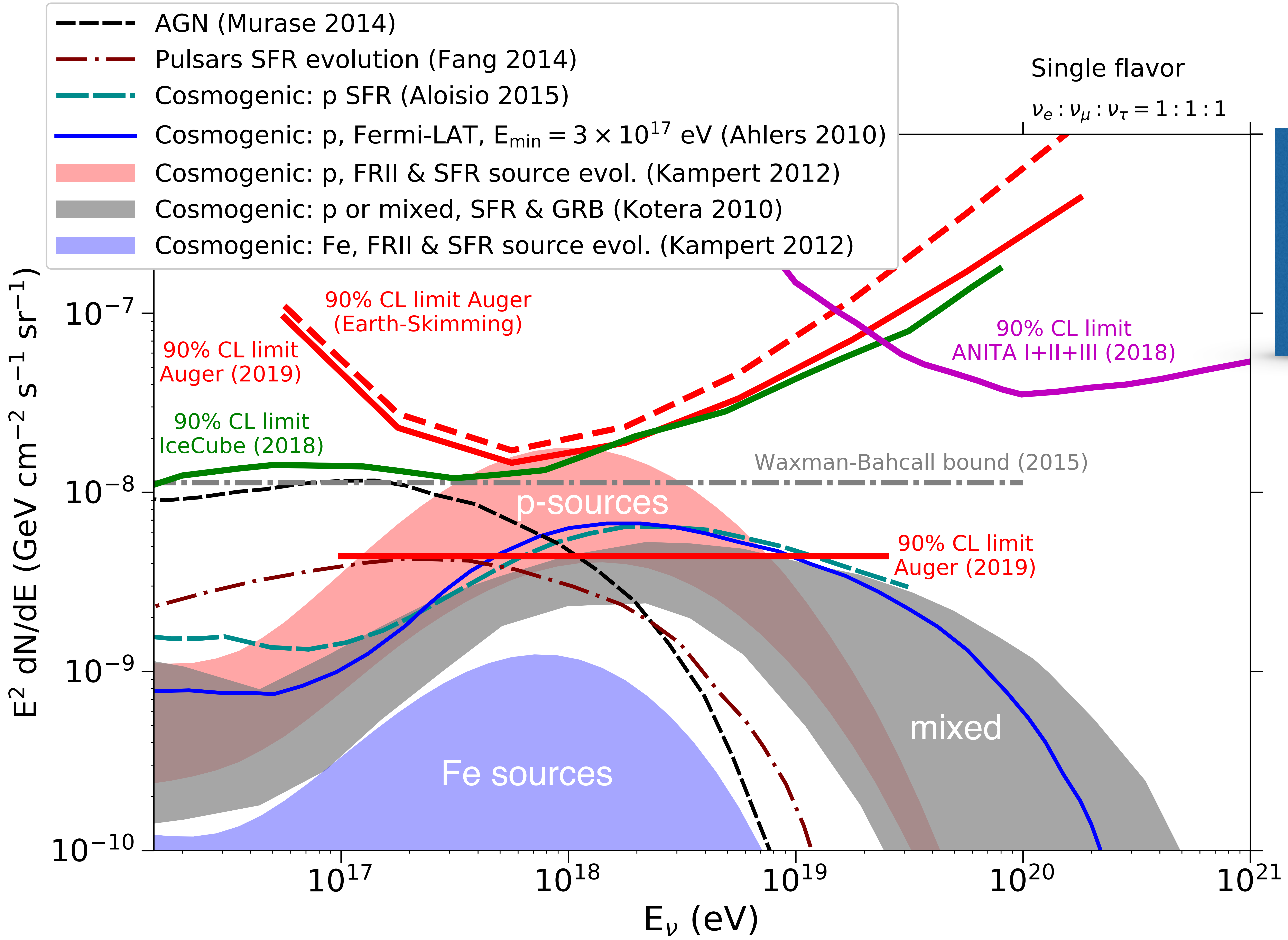
$$\rightarrow E_p \simeq 6 \cdot 10^{19}\,\mathrm{eV}$$

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

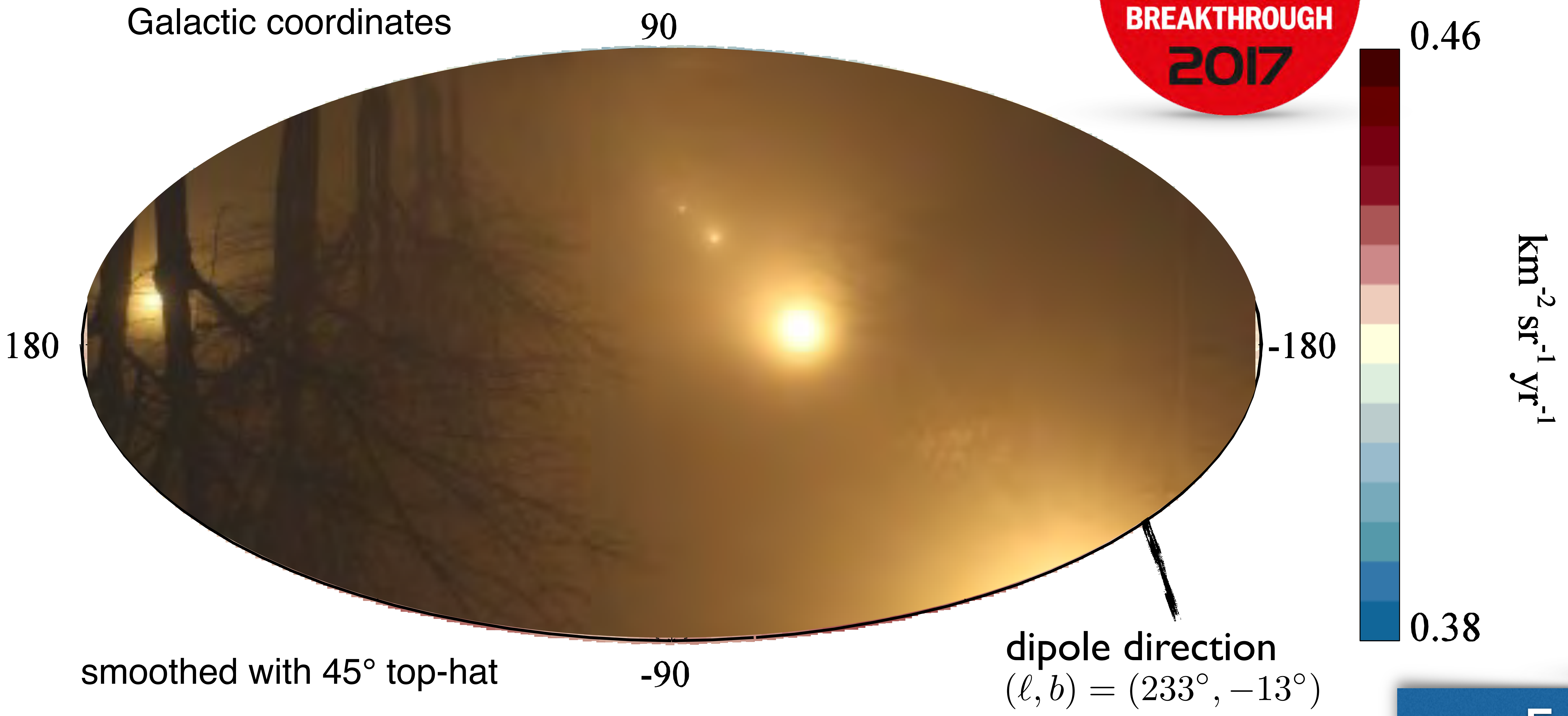
Resulting Intermediate Mass Composition challenges source hunting!

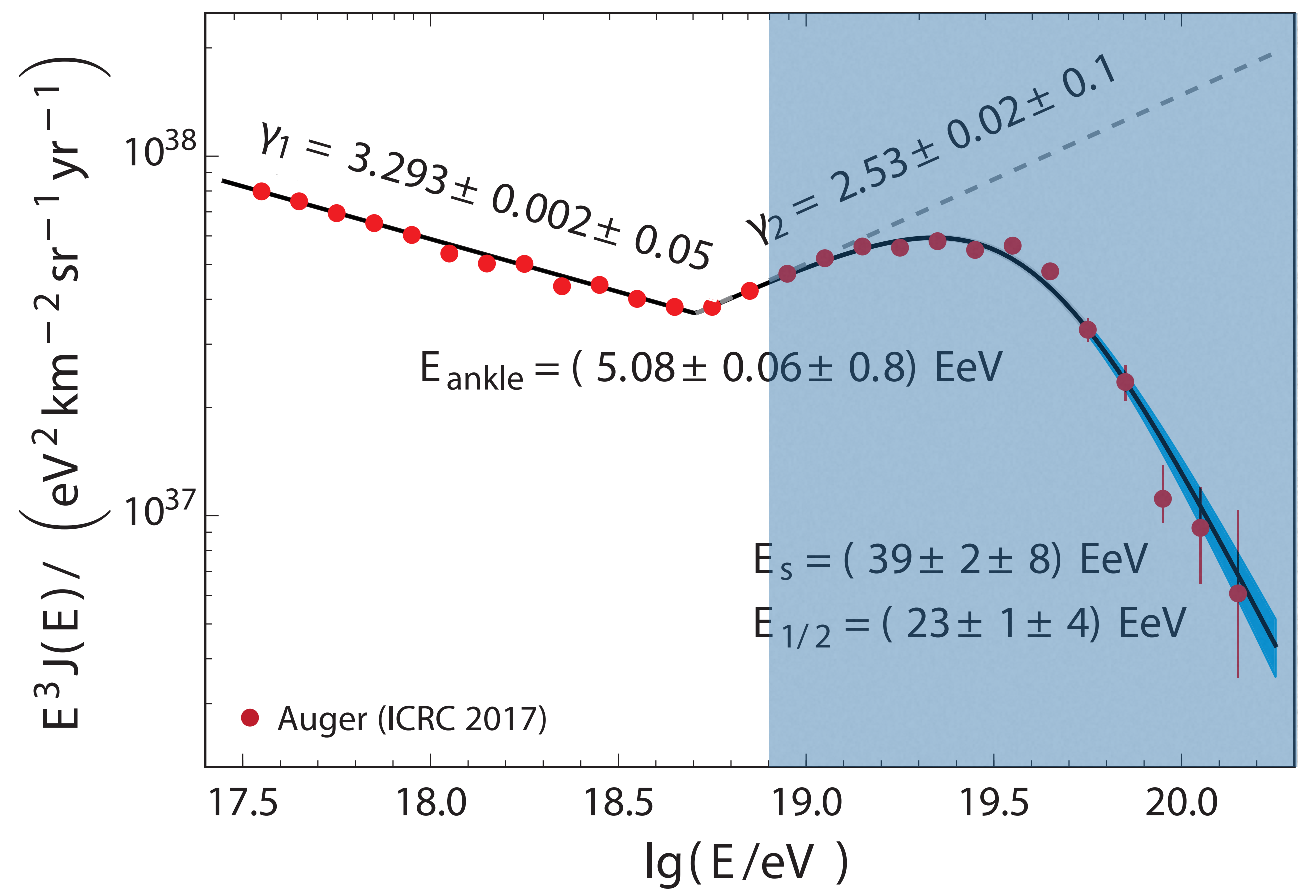
sitting in the fog

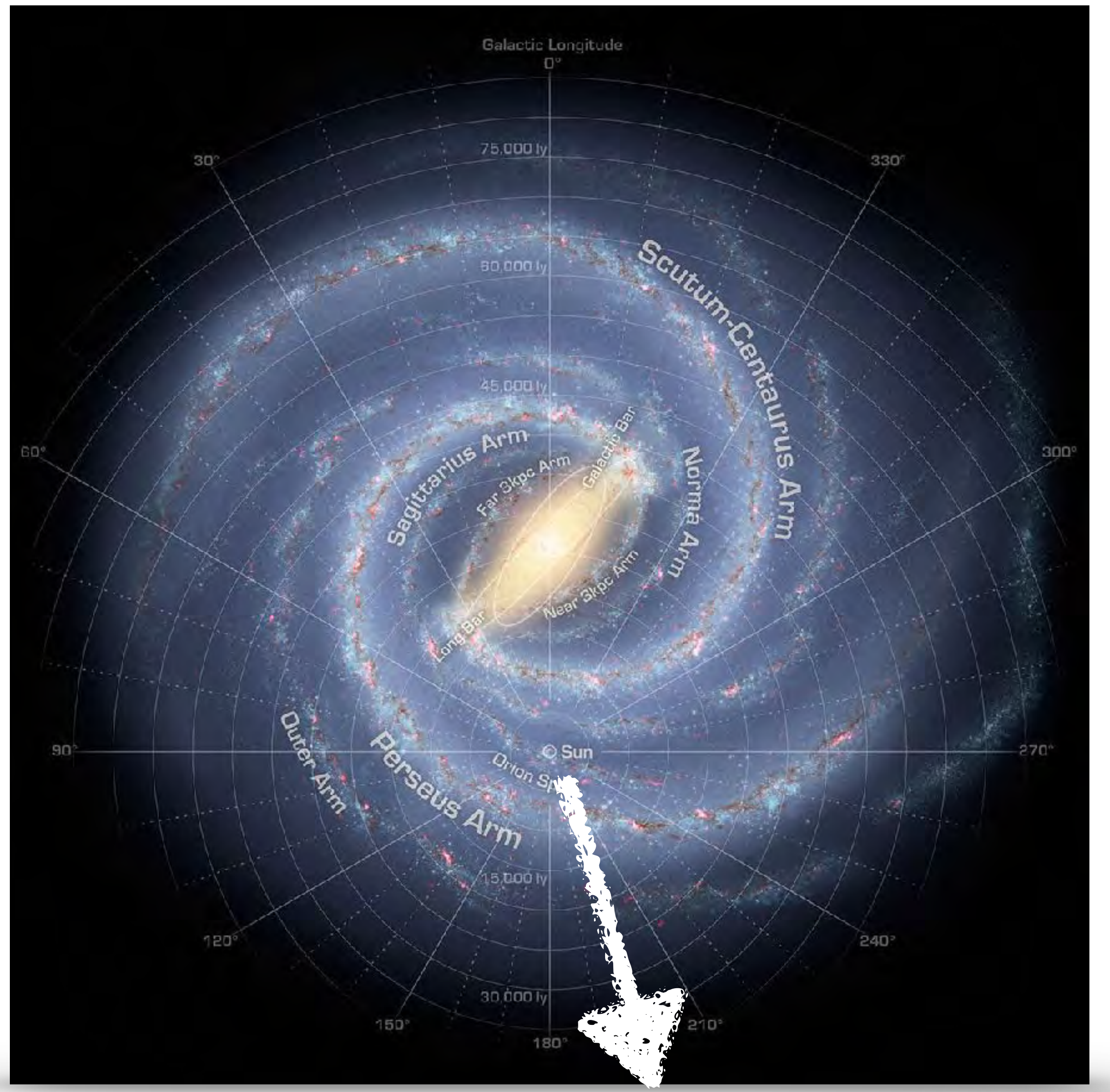
Flux Map above 8 EeV

Auger Collaboration, Science 357 (2017) 1266

physicsworld
TOP 10
BREAKTHROUGH
2017







First harmonic in right ascension:

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

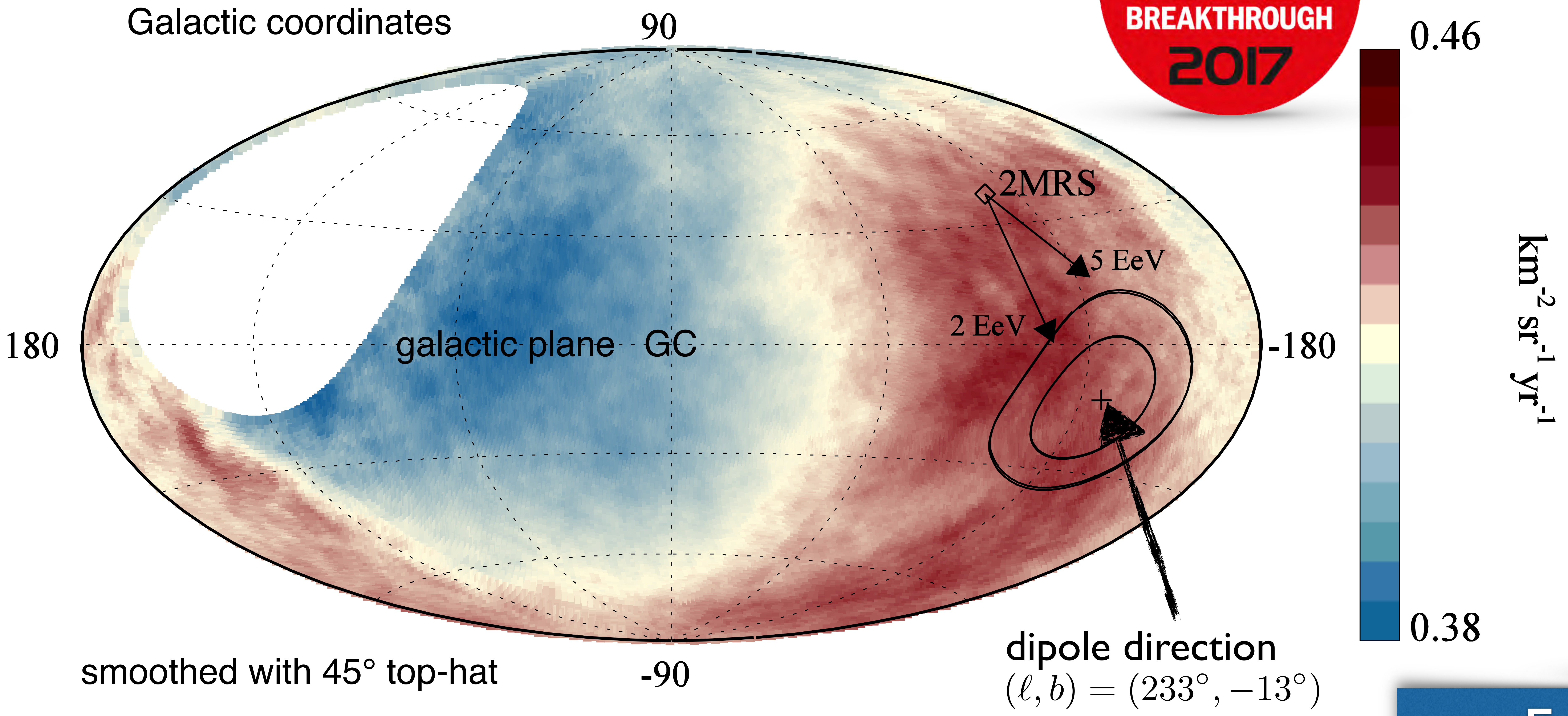
Excess direction ⇒

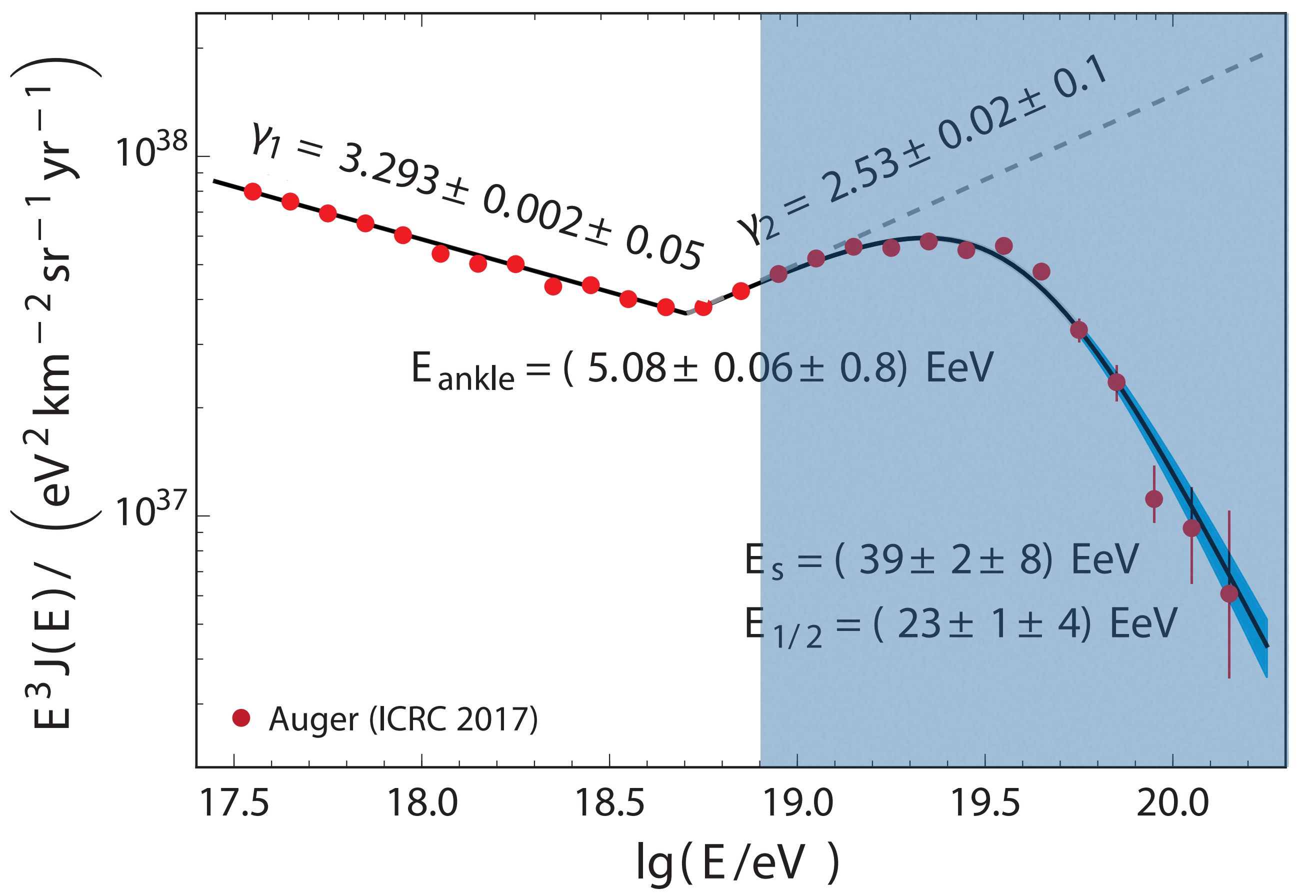
Extragalactic Origin of UHECR

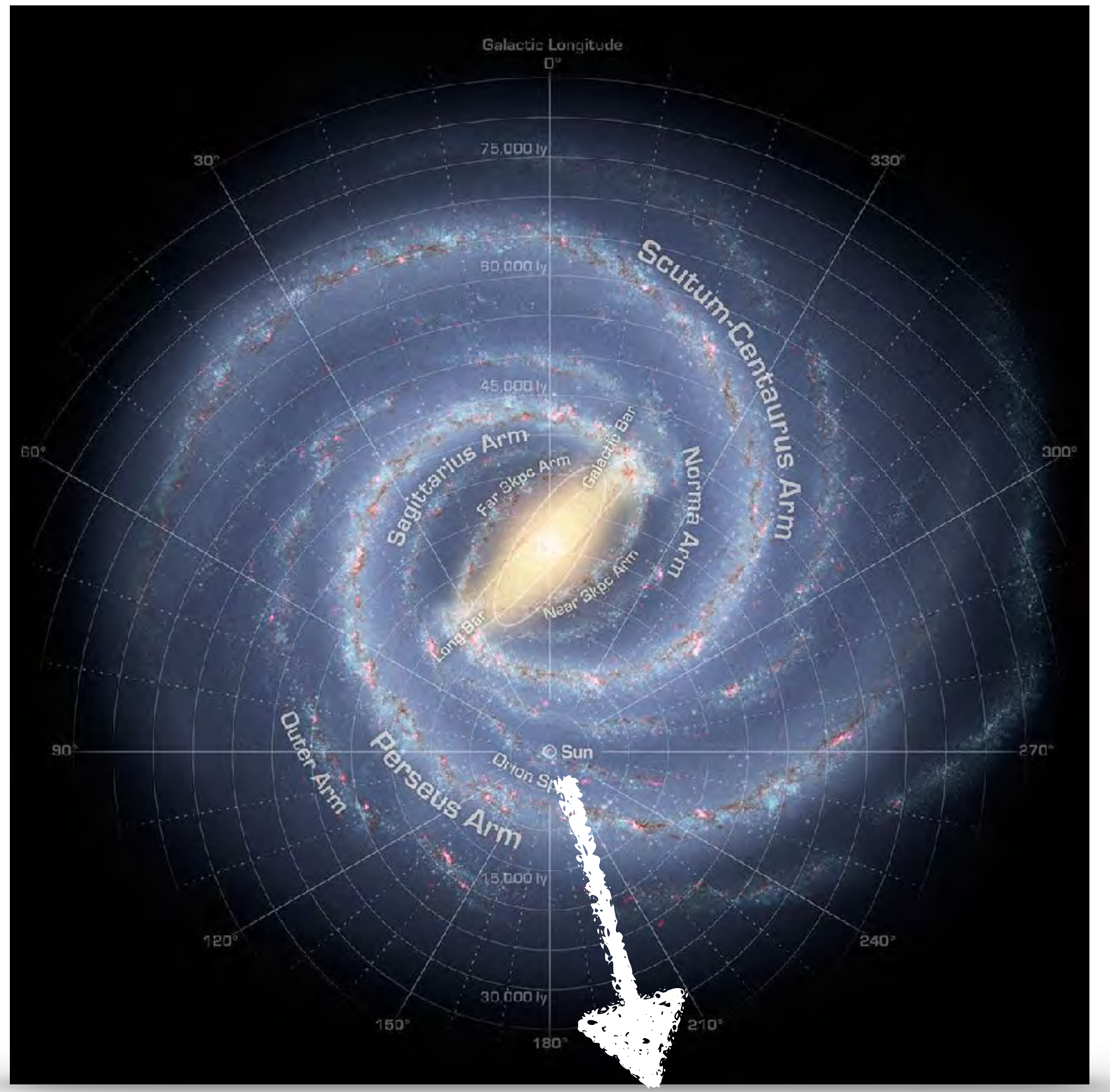
Flux Map above 8 EeV

Auger Collaboration, Science 357 (2017) 1266

physicsworld
TOP 10
BREAKTHROUGH
2017







Excess direction ⇒

Extragalactic Origin of UHECR

First harmonic in right ascension:

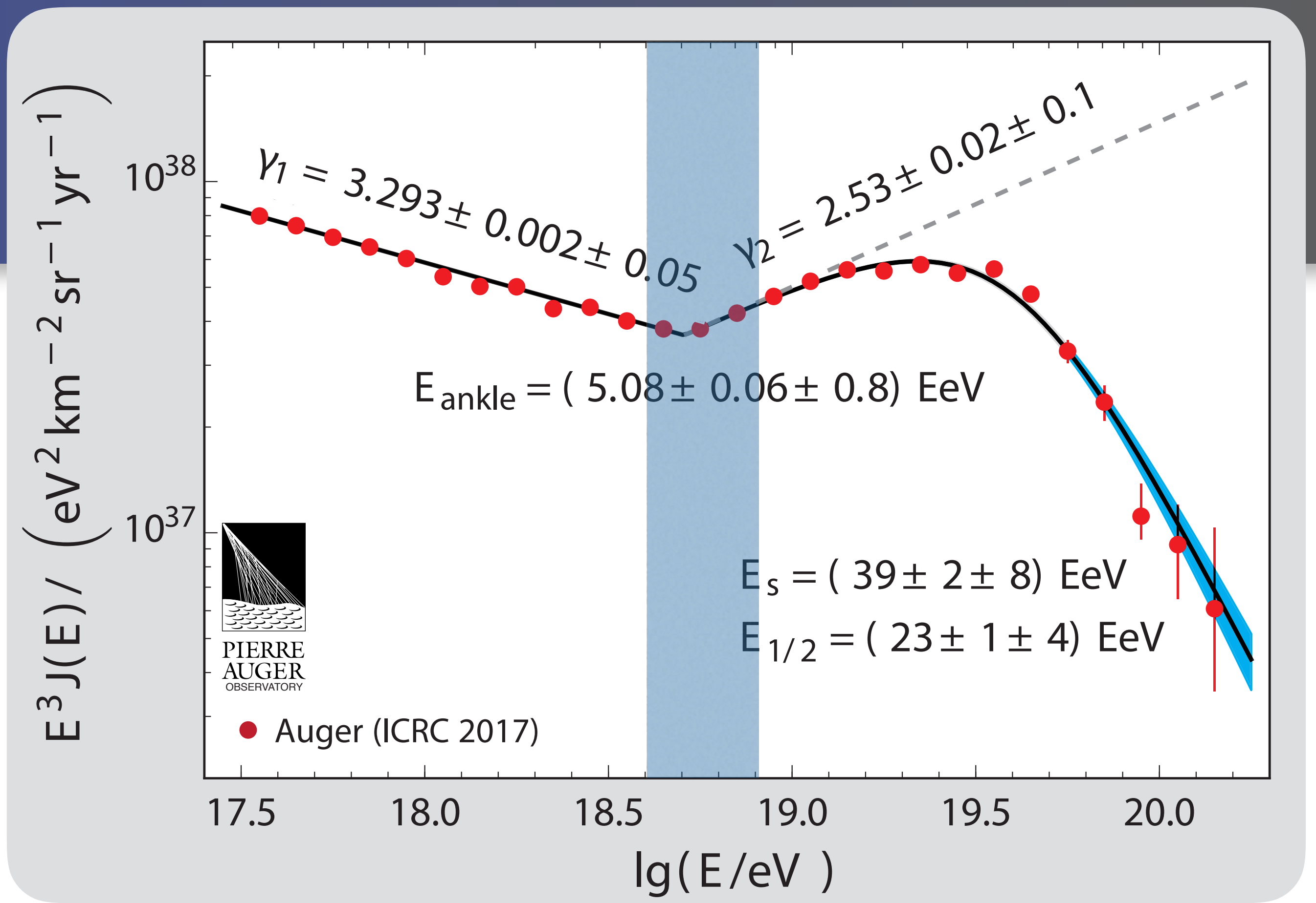
$$\mathcal{A} = 6.5^{+1.3}_{-0.9}\,\% \ ; \ \alpha_d = (100 \pm 10)^\circ \ ; \ \delta_d = (-24^{+12}_{-13})^\circ$$

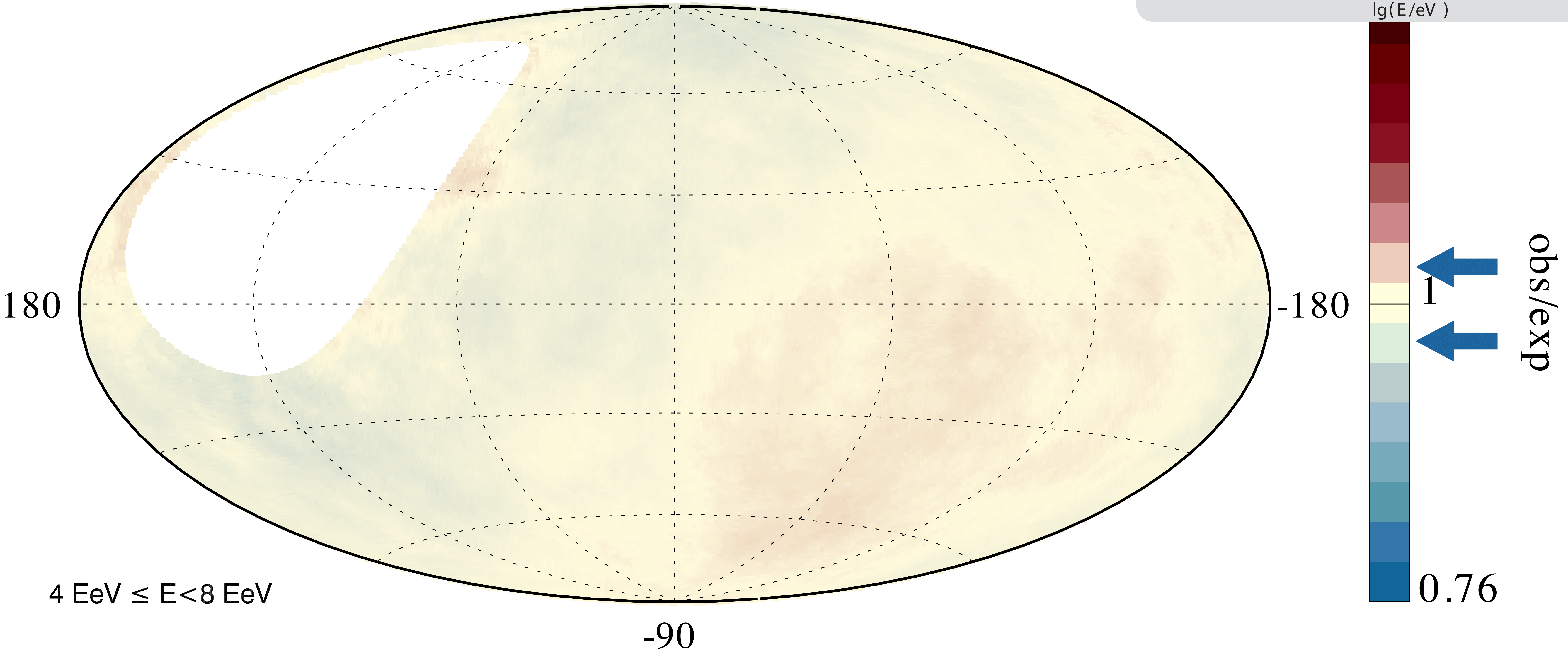
Evolution with Energy: 4-8 EeV

Auger Collaboration, ApJ 868 (2018) 1

map smoothed with 45° top-hat
Galactic coordinates

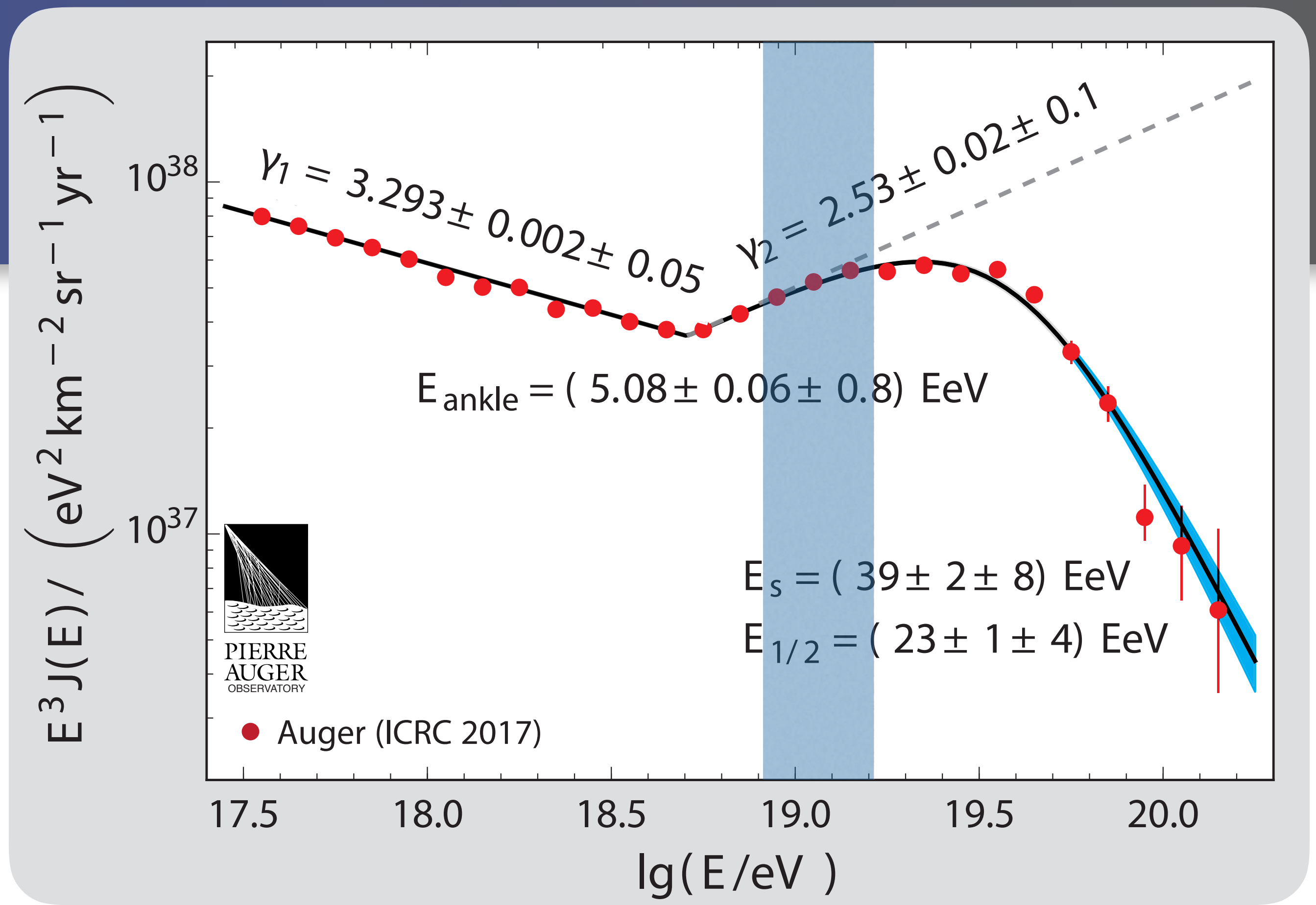
all maps with identical color scale





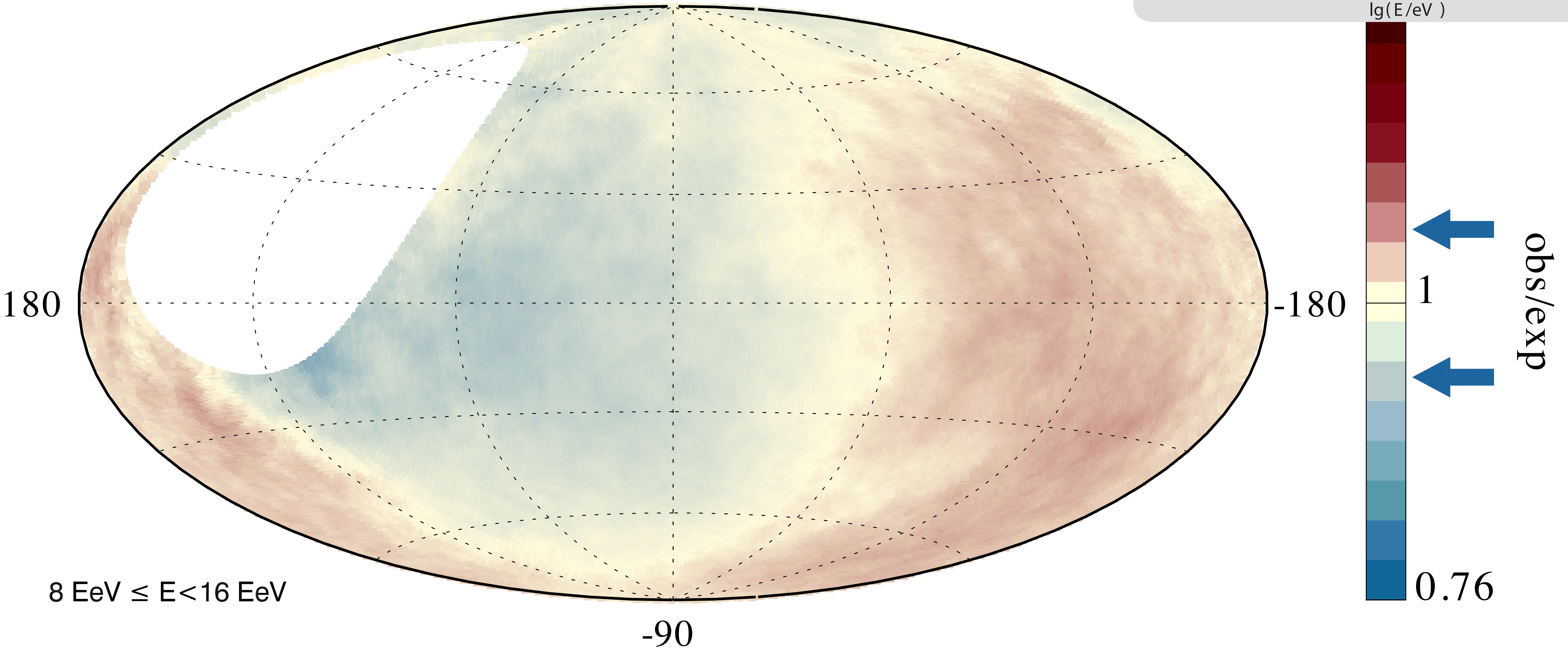
Evolution with Energy: 8-16 EeV

Auger Collaboration, ApJ 868 (2018) 1



map smoothed with 45° top-hat
Galactic coordinates

all maps with identical color scale

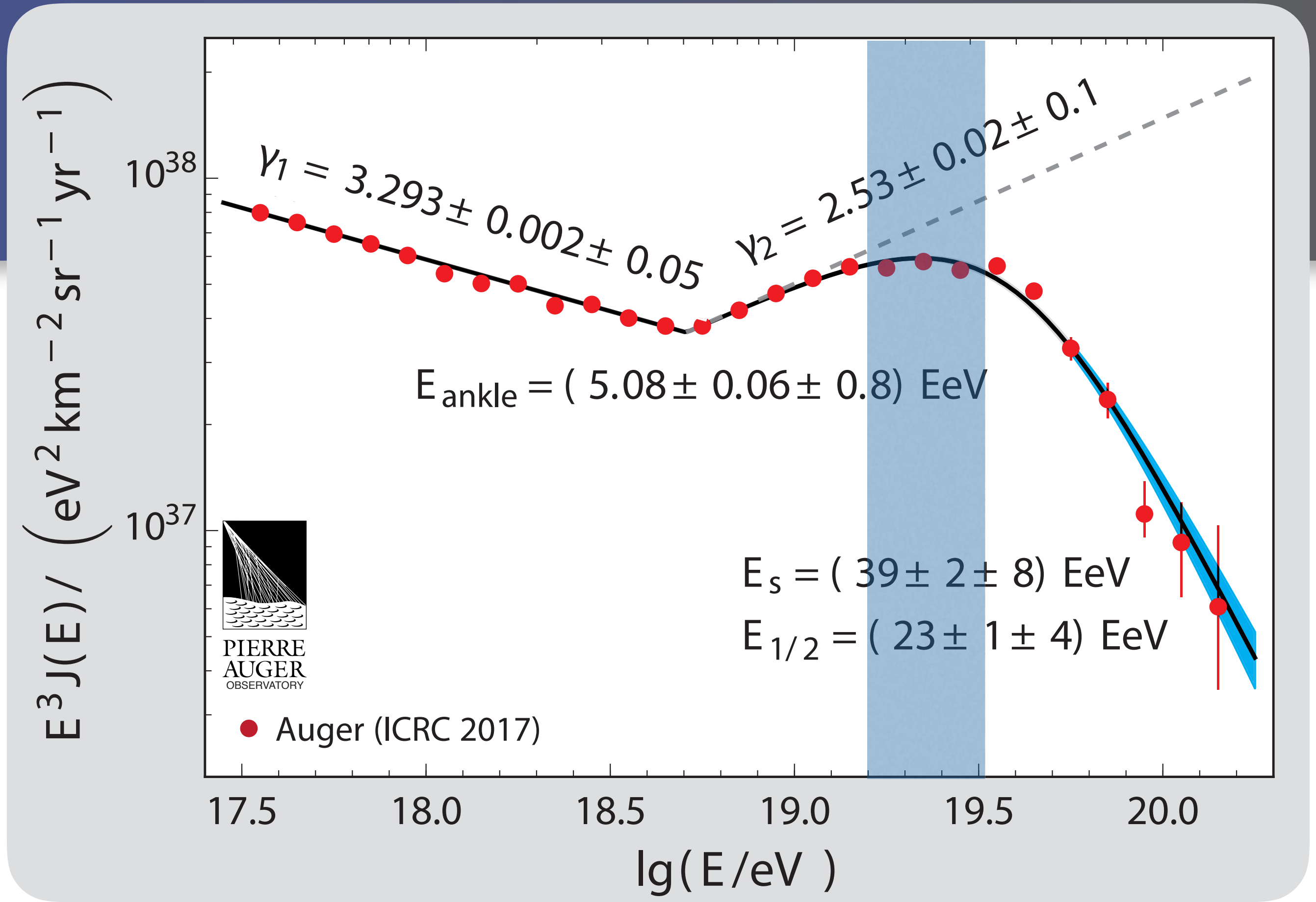


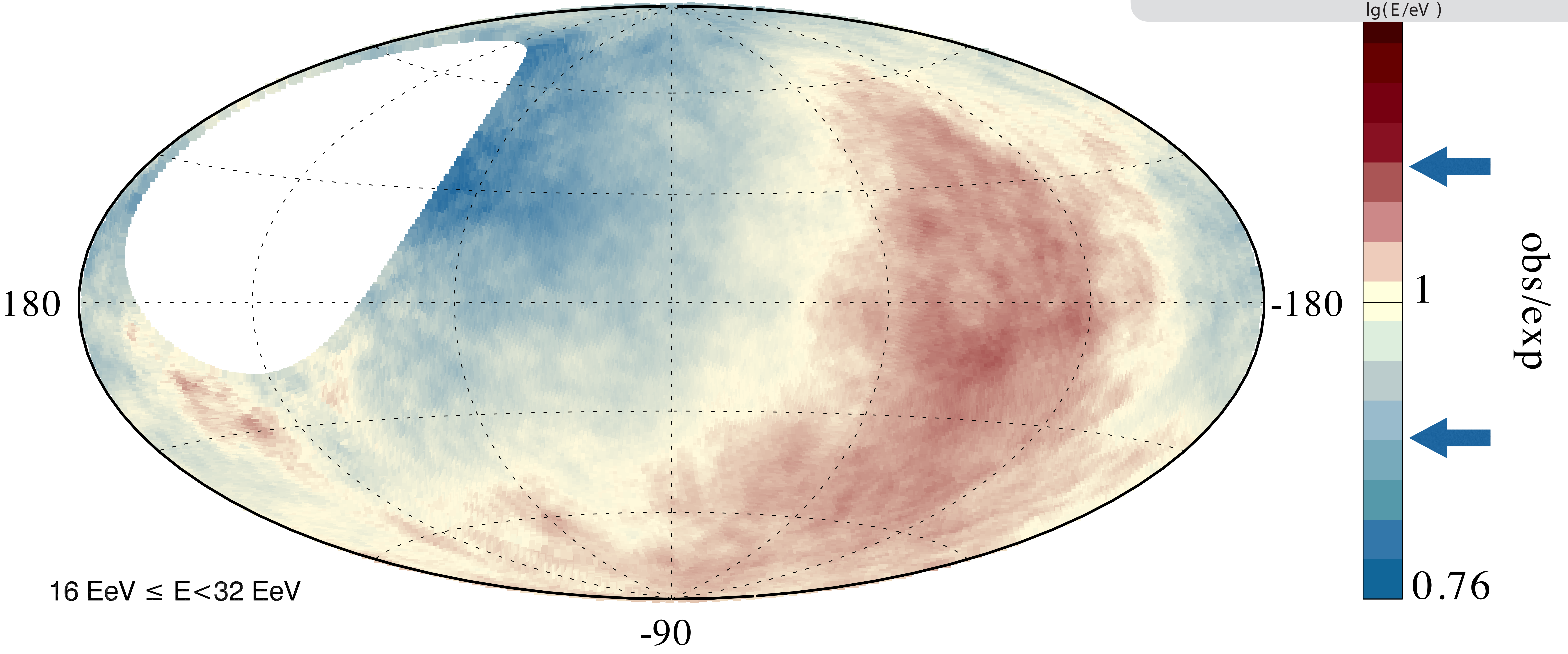
Evolution with Energy: 16-32 EeV

Auger Collaboration, ApJ 868 (2018) 1

map smoothed with 45° top-hat
Galactic coordinates

all maps with identical color scale



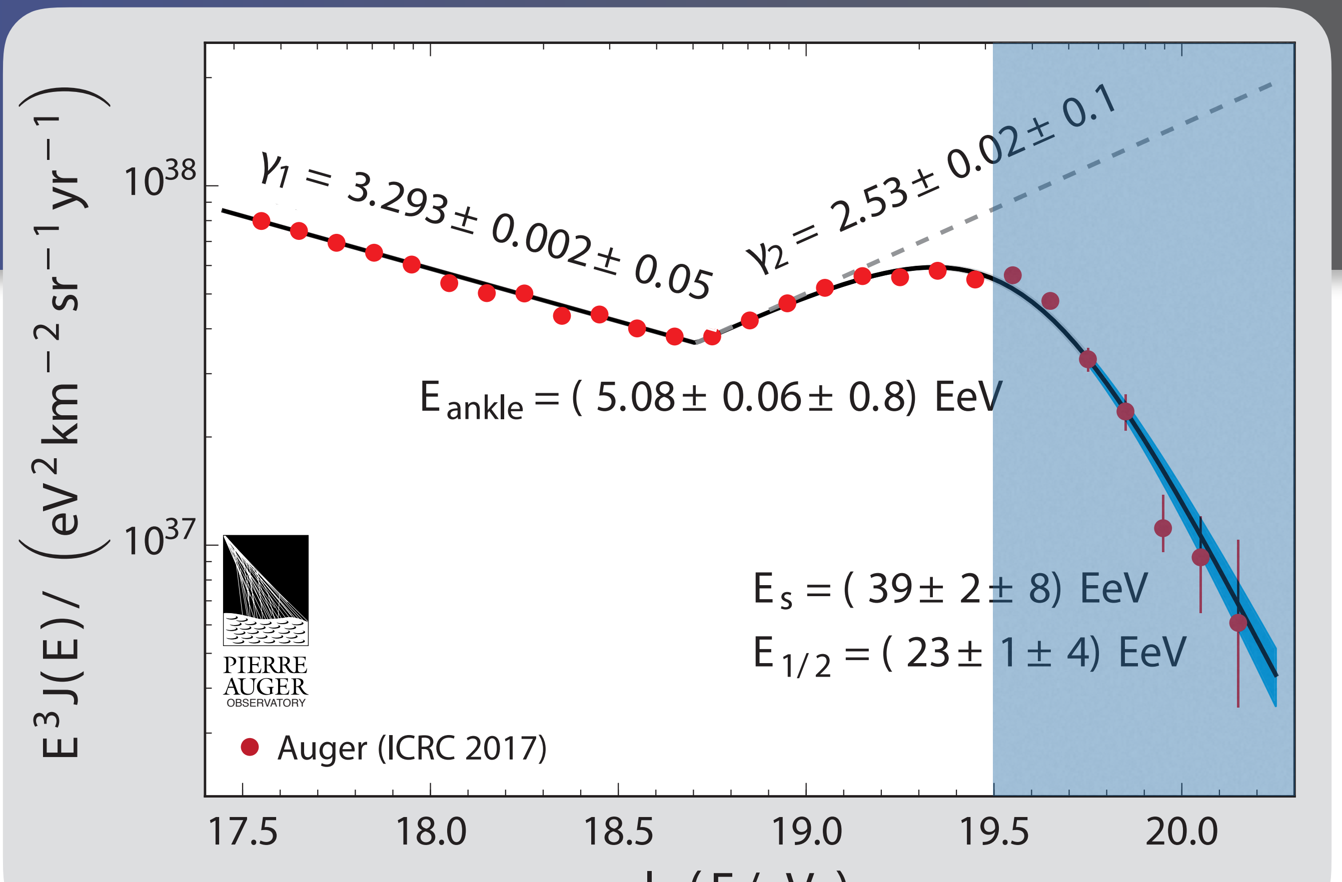


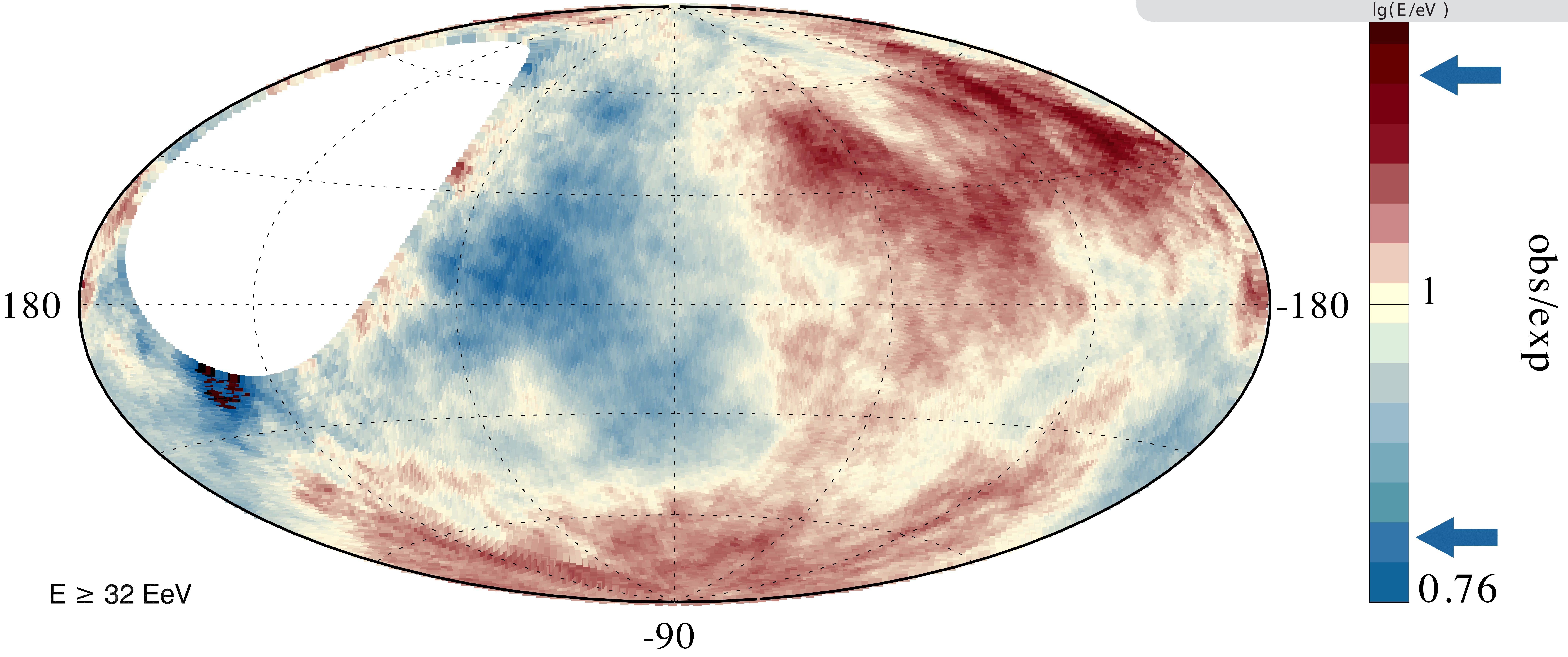
Evolution with Energy: >32 EeV

Auger Collaboration, ApJ 868 (2018) 1

map smoothed with 45° top-hat
Galactic coordinates

all maps with identical color scale



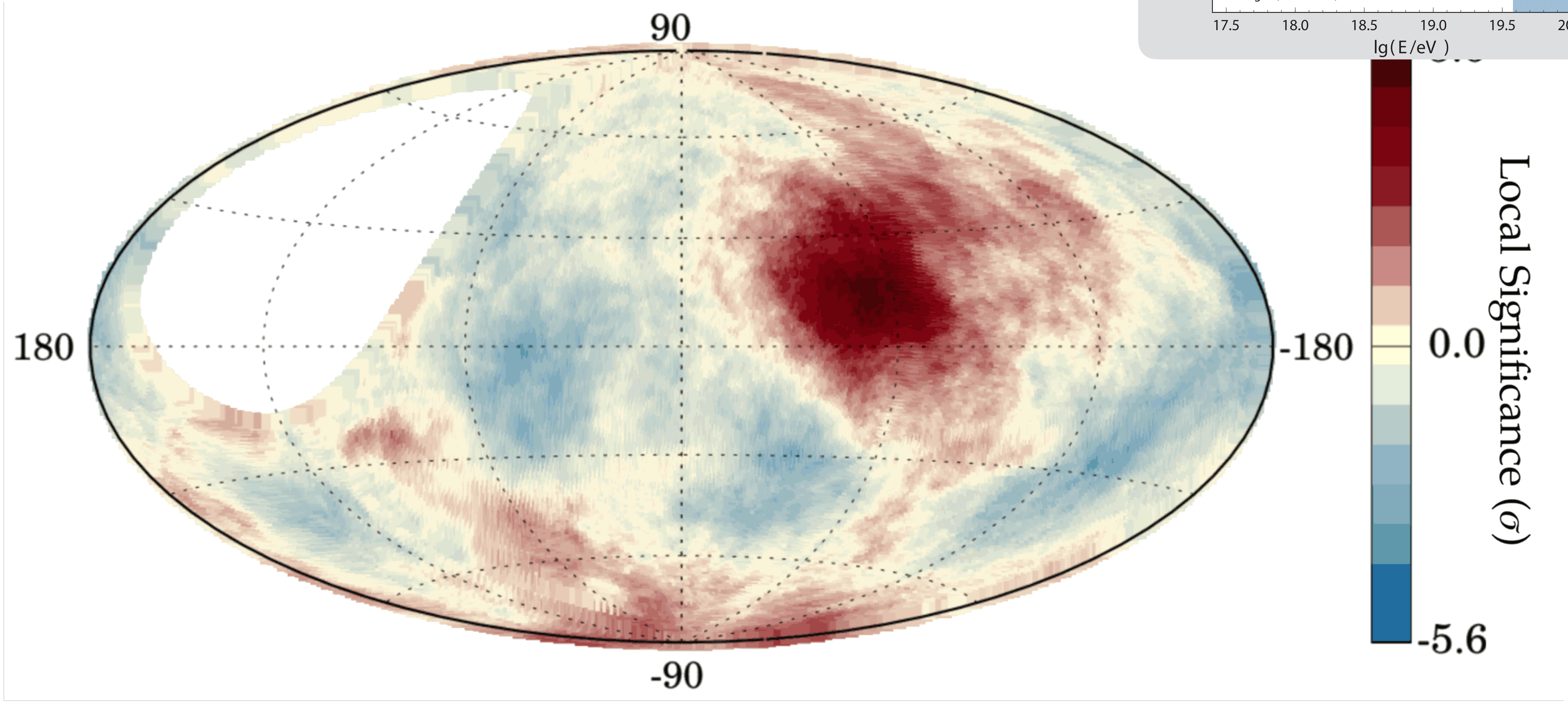


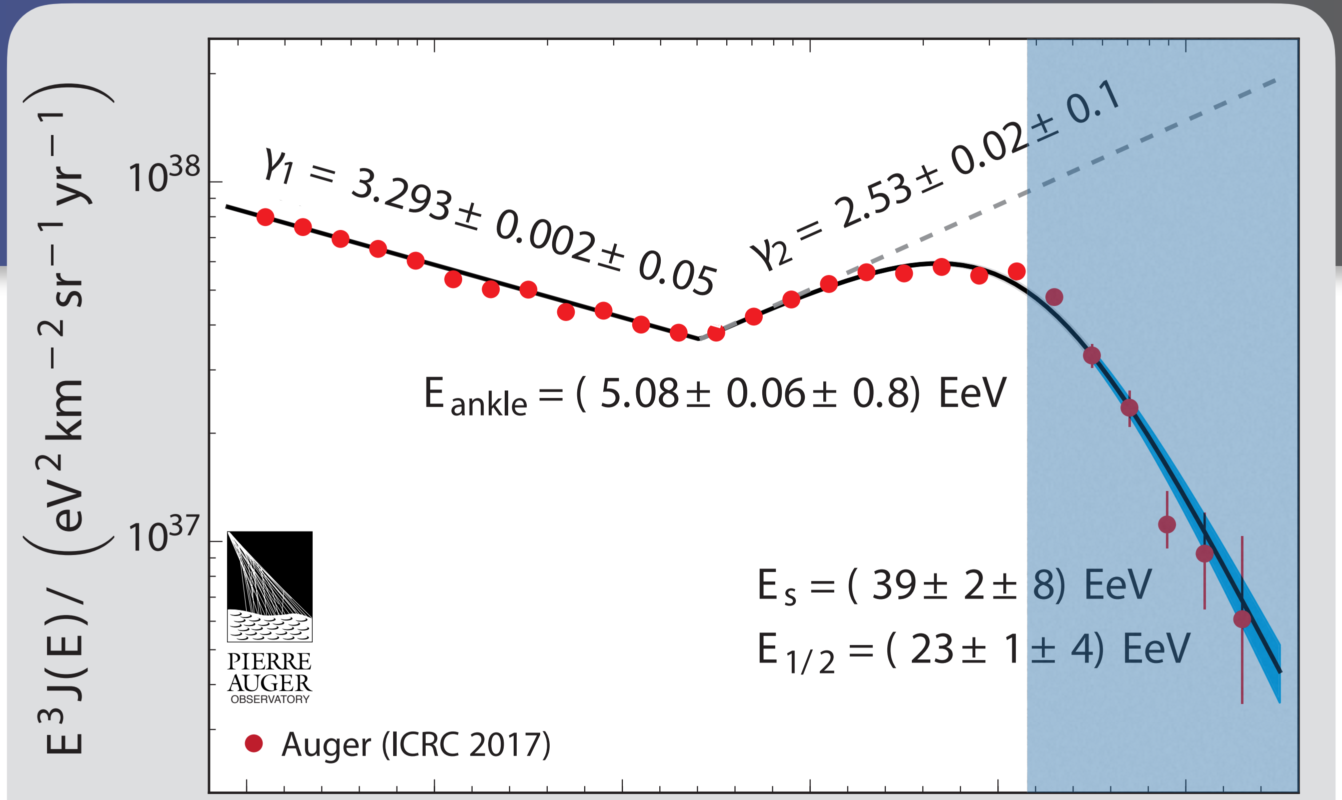
Evolution with Energy: >38 EeV

Auger Collaboration, PoS(ICRC2019)206

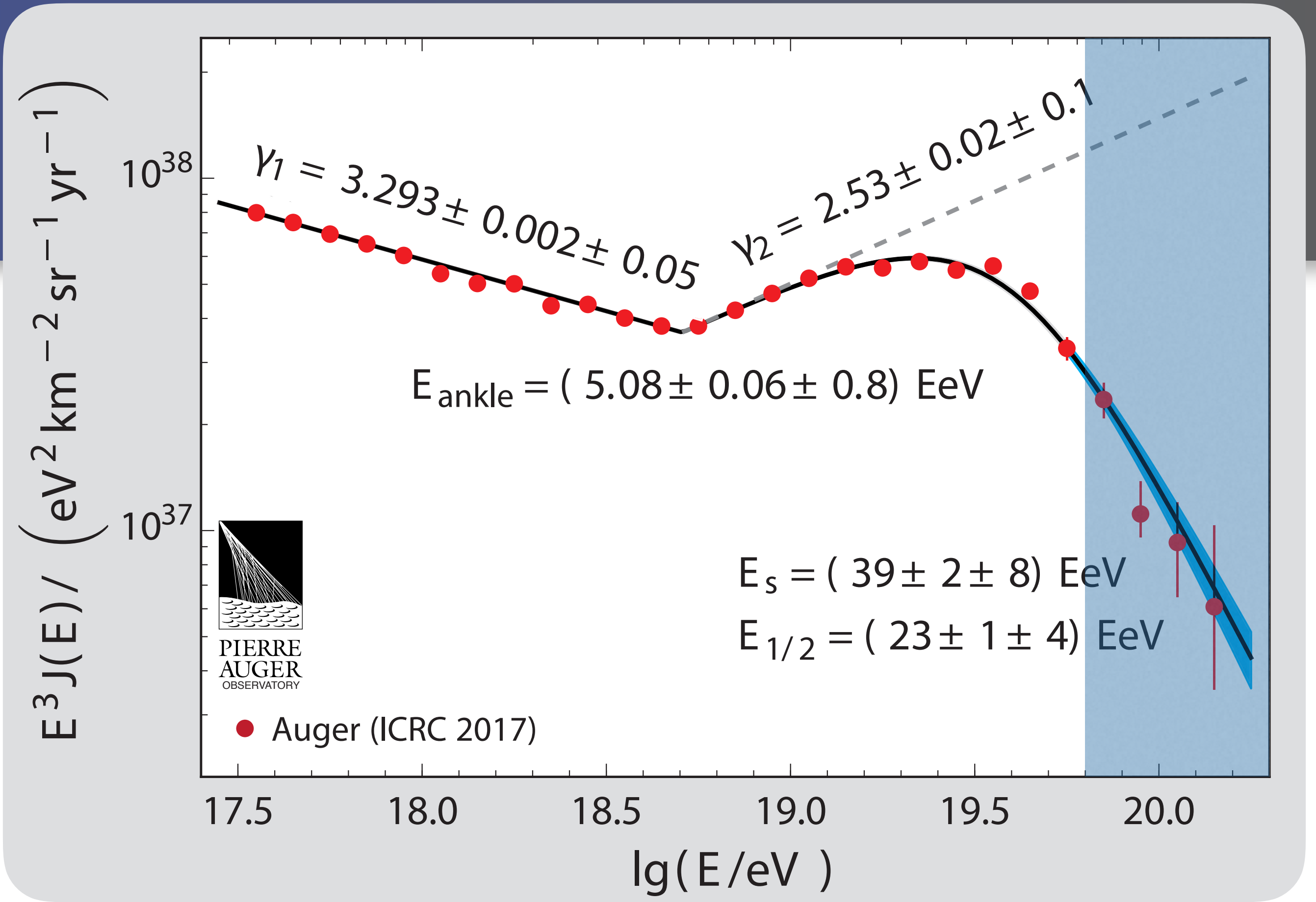
map smoothed with 27° top-hat
Galactic coordinates

significance map



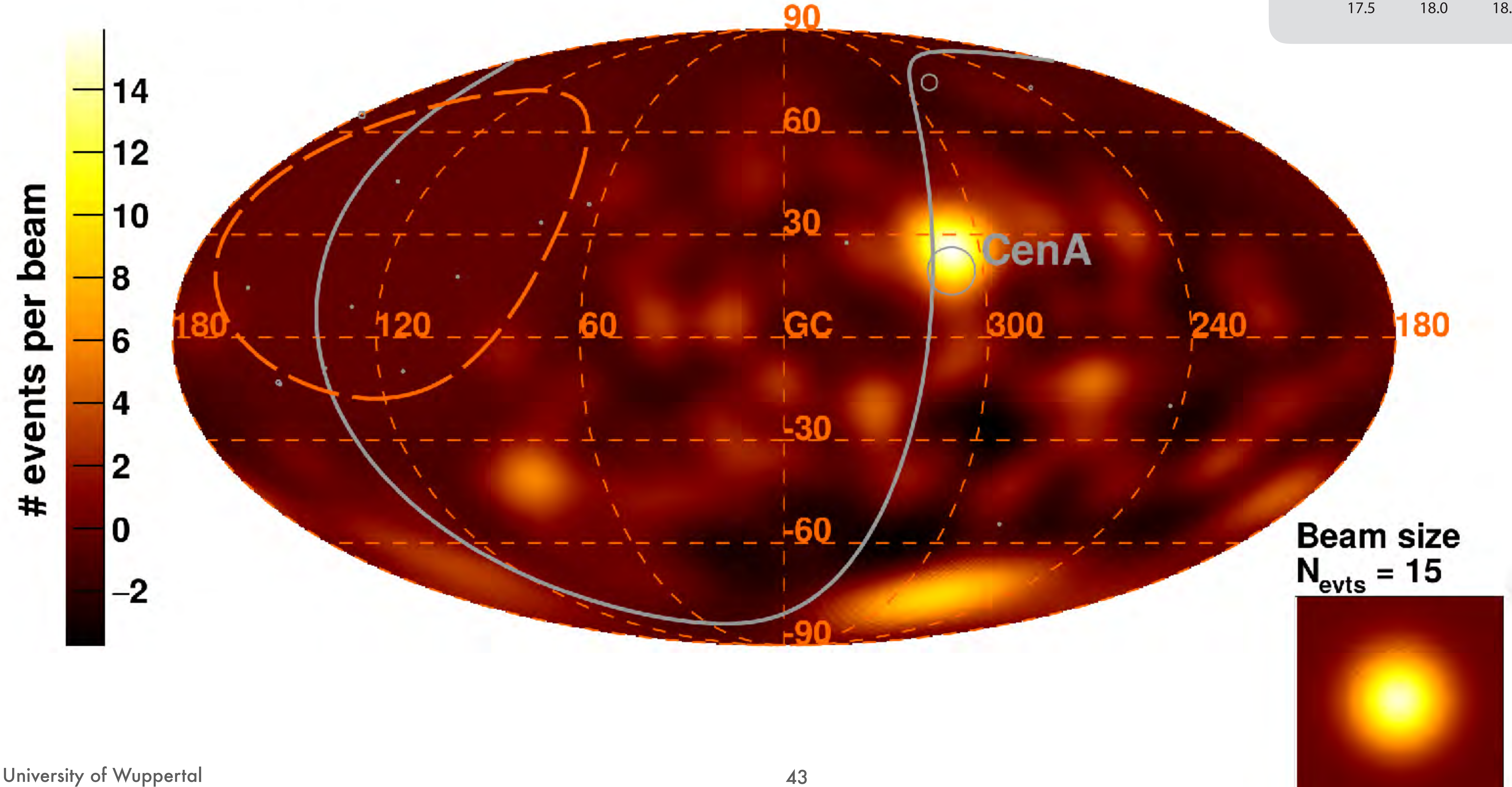


Evolution with Energy: >60 EeV



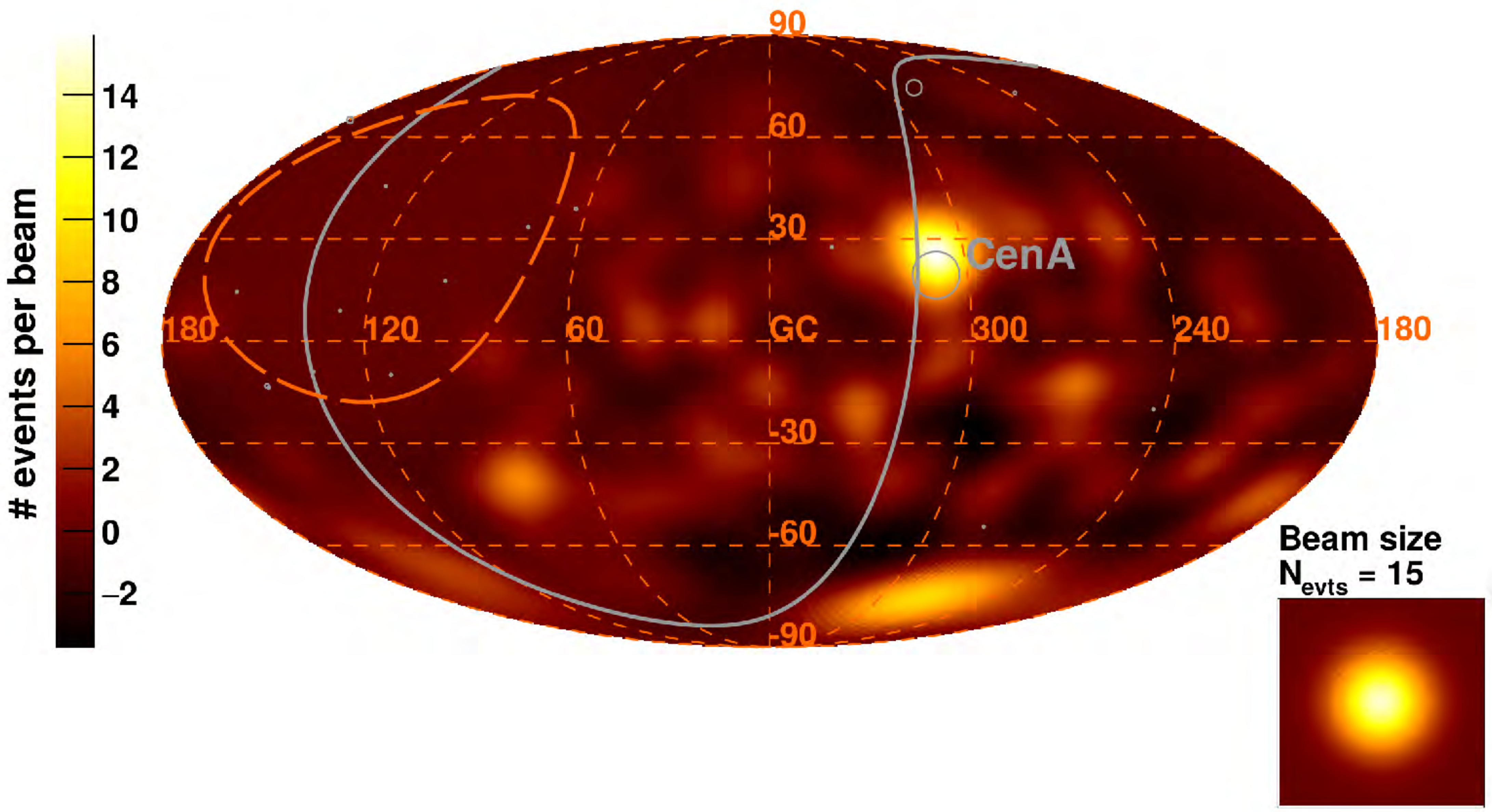
Auger: ApJL 853:L29 (2018)

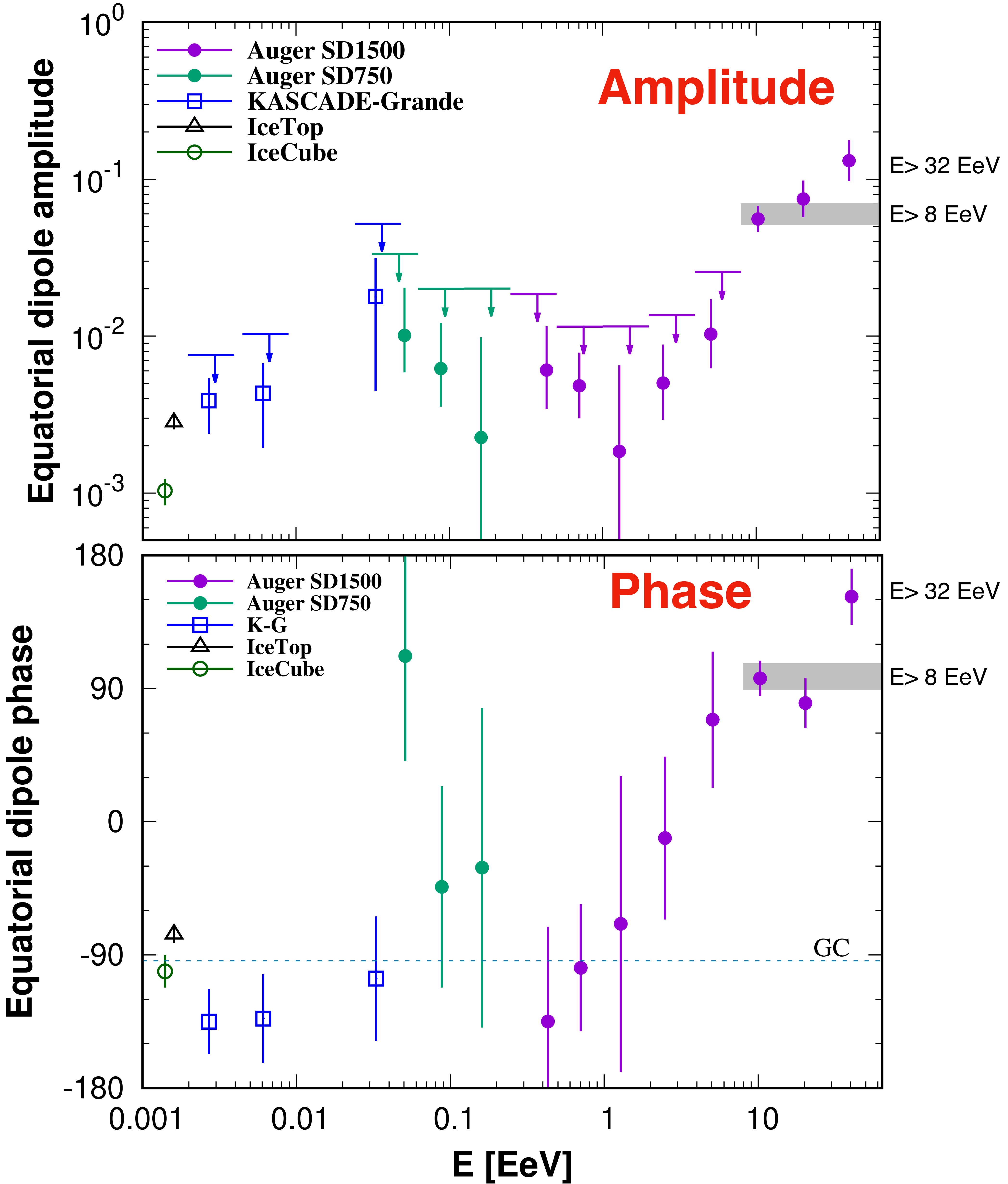
map smoothed with 7° top-hat
Galactic coordinates



Anisotropies expressed as Equatorial Dipole

Auger Collaboration, ApJ in press, arXiv:2002.06172

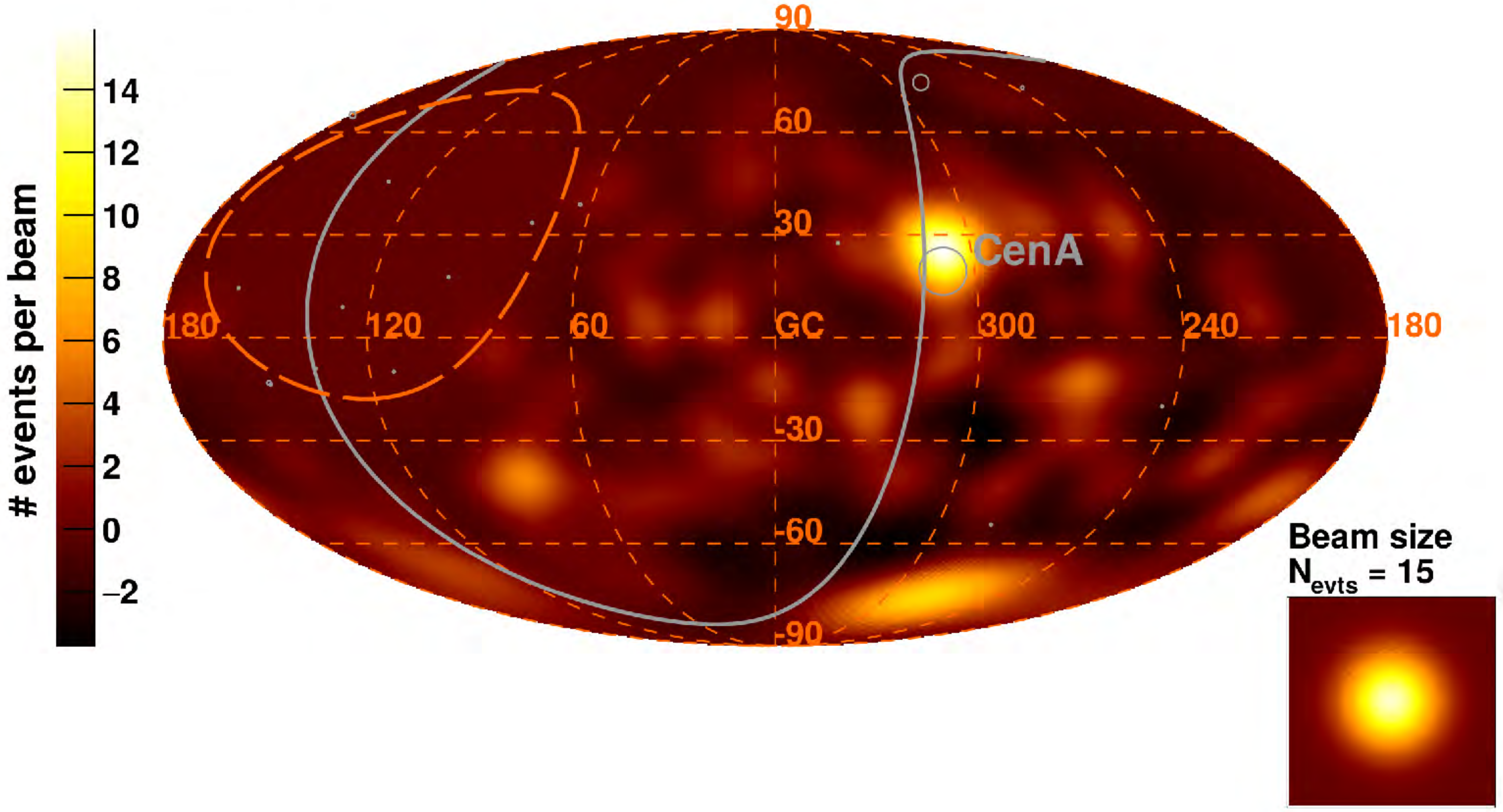


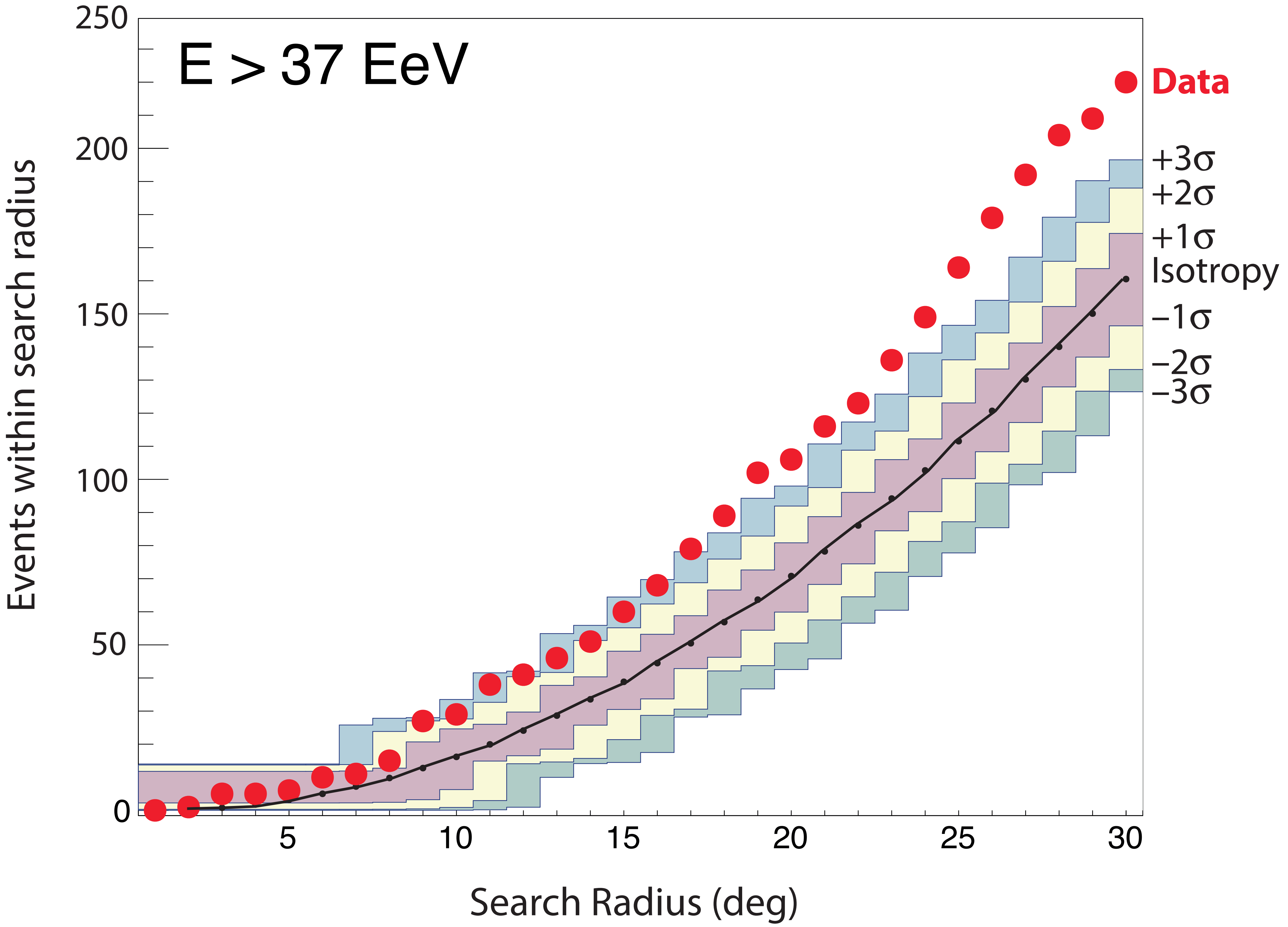


Progressive evolution of amplitude as a fct of energy
Phase changes from GC to Anticenter

Centaurus A: A source of UHECR?

Auger Collaboration, PoS(ICRC2019)206





Cen A suggestive, but more structure than a single source

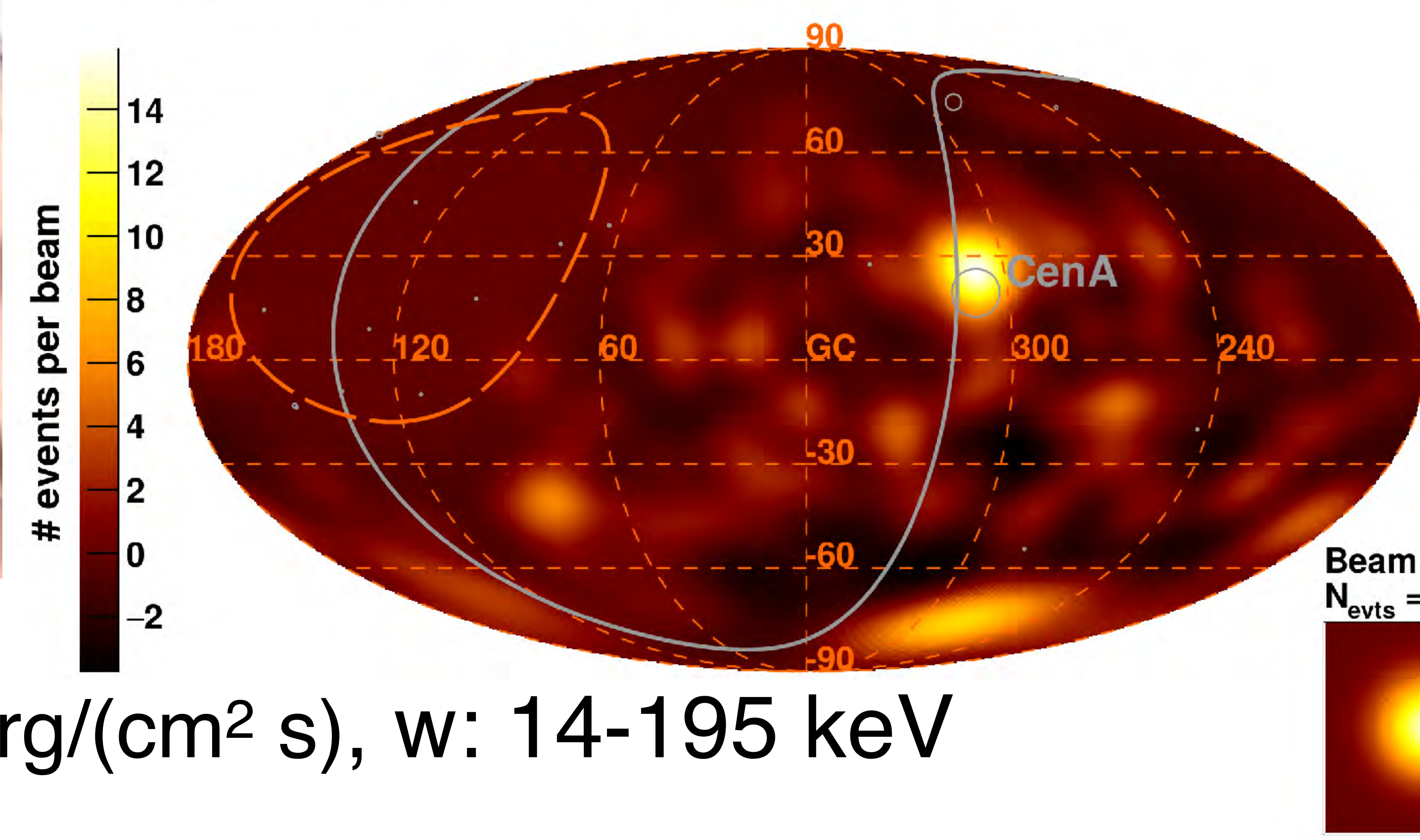
Most significant excess at 28° and 2° offset from Cen A: 203 observed
141 expected → local sign. 5.1σ

⇒ post trial significance: 3.9σ

The Usual UHECR Source Suspects

Swift-BAT **2MRS** **SGB** **γAGN** **~~VCV~~**

Adapted from
M. Unger

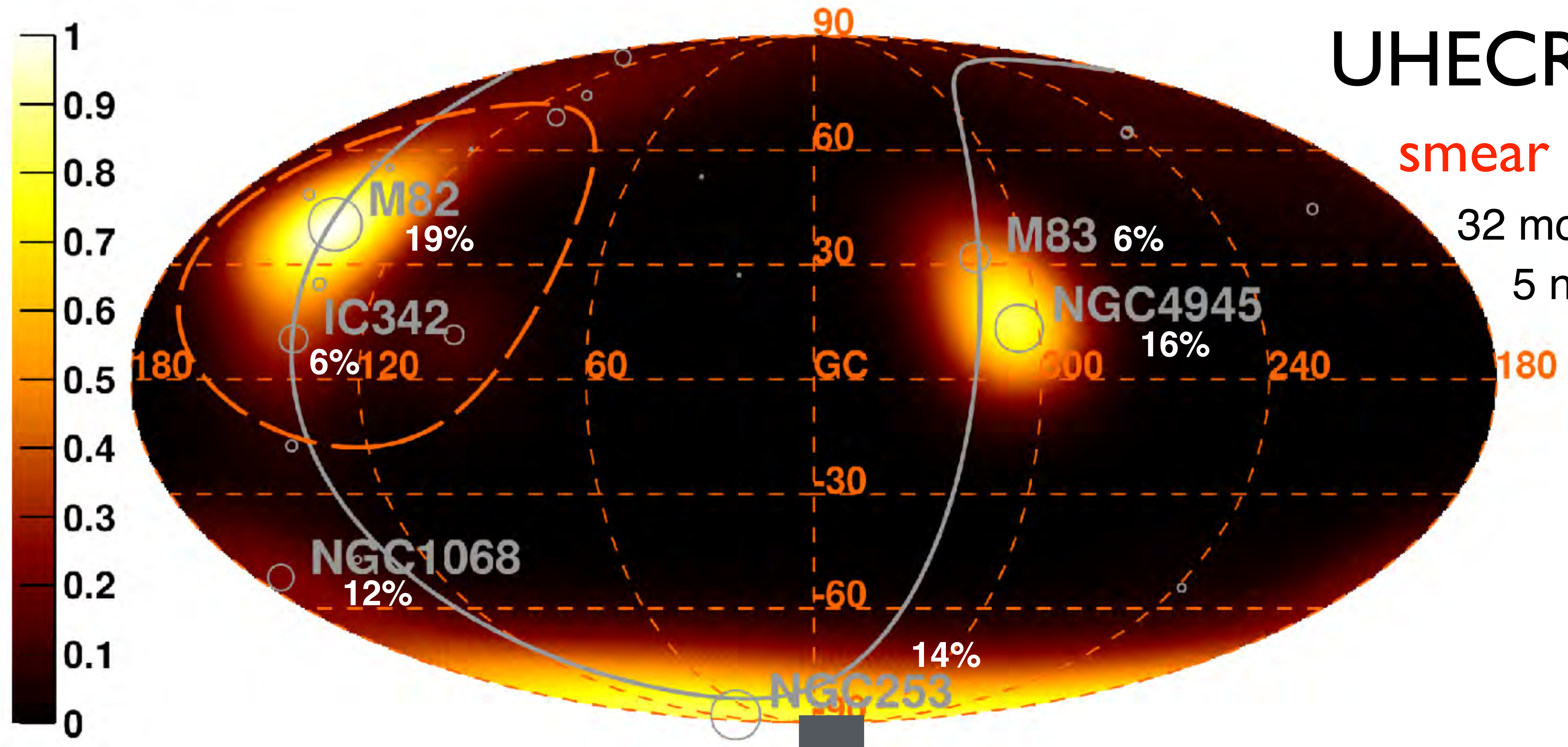


- Swift-BAT X-ray-selected galaxies, D < 250 Mpc, Φ > 1:3×10^{-11} erg/(cm² s), w: 14-195 keV
- 2MRS IR-selected galaxies, D > 1 Mpc, w: K-band
- SBG: 23 nearby starburst galaxies, Φ > 0.3 Jy, w: radio at 1.4 GHz
- γAGN: 17 3FHL blazars and radio galaxies, D < 250 Mpc, w: γ-ray 10 GeV - 1 TeV

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

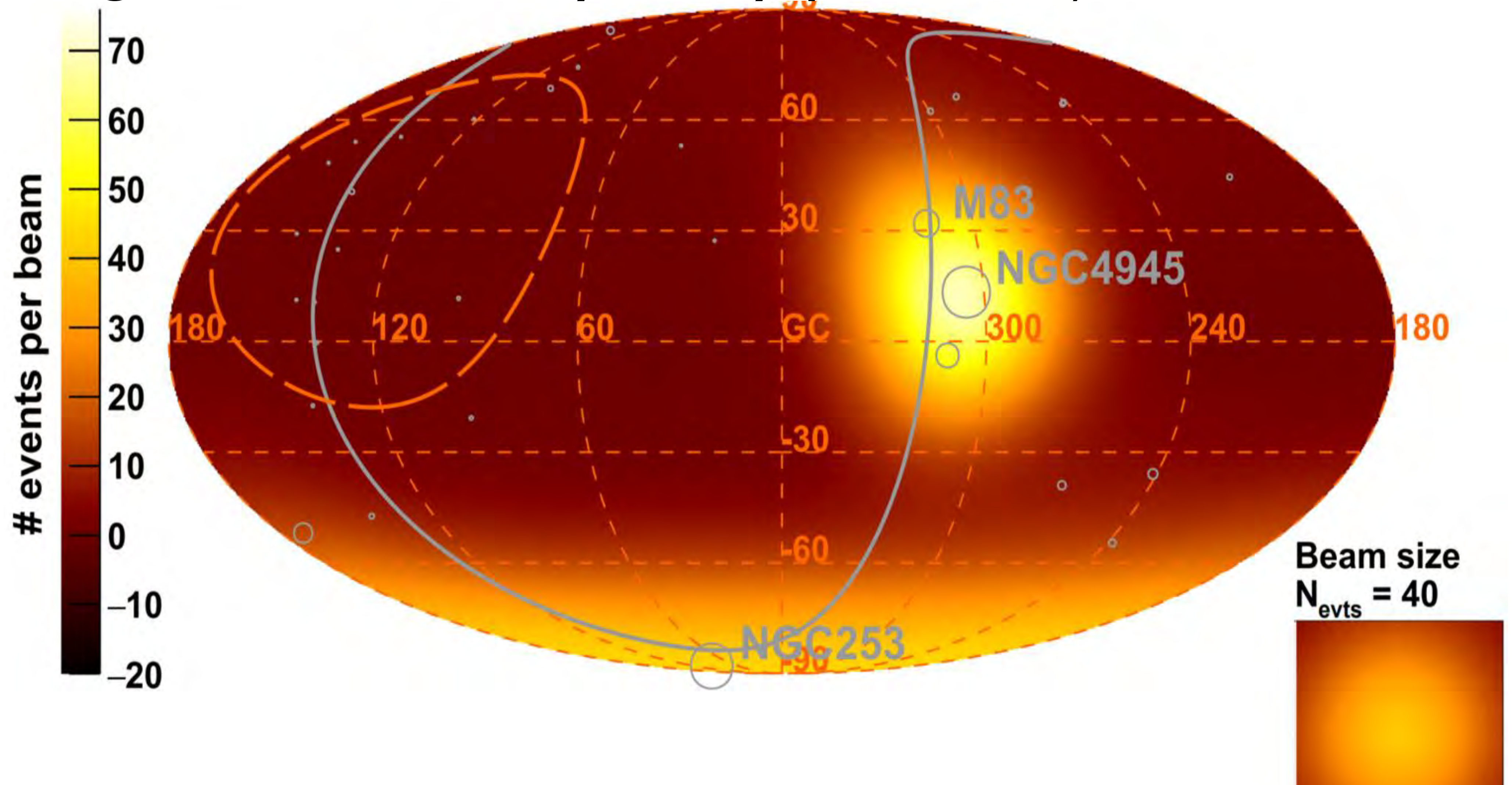
Assume, starburst galaxies produce UHECR with $L_{UHECR} \sim L_{\gamma}$ @ 1.4 GHz

smear sources to account for B-field deflections

32 most bright sources included

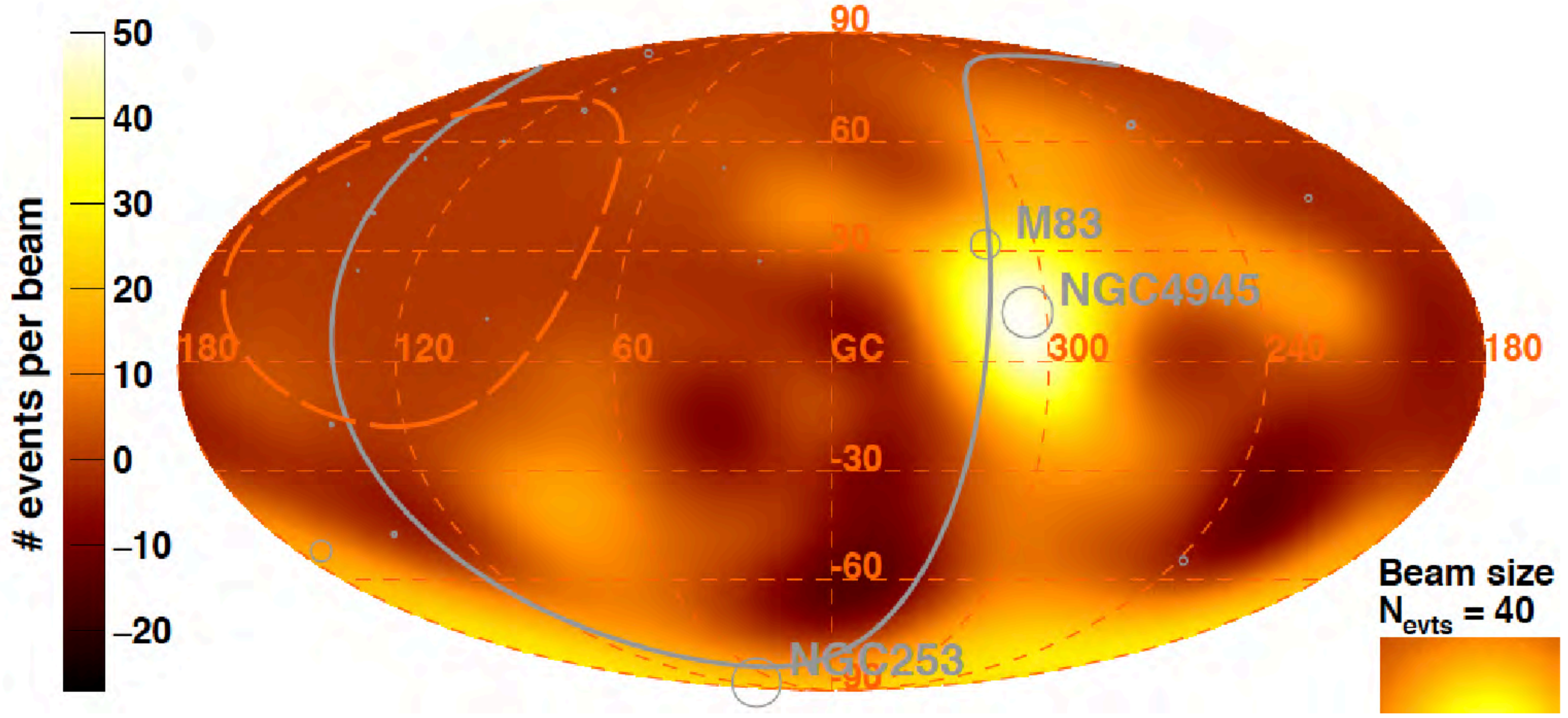
5 named sources contribute 75% of total flux

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

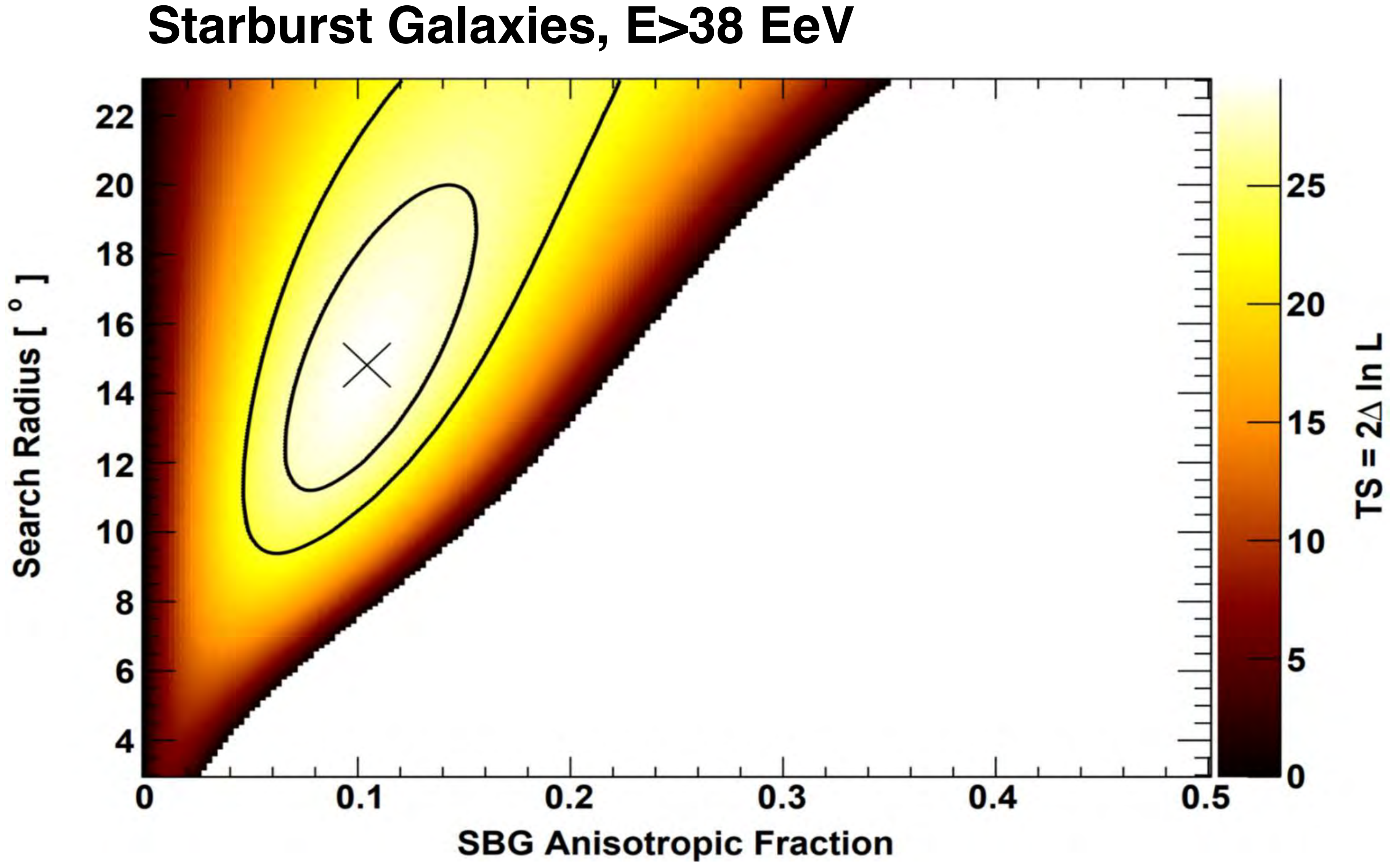


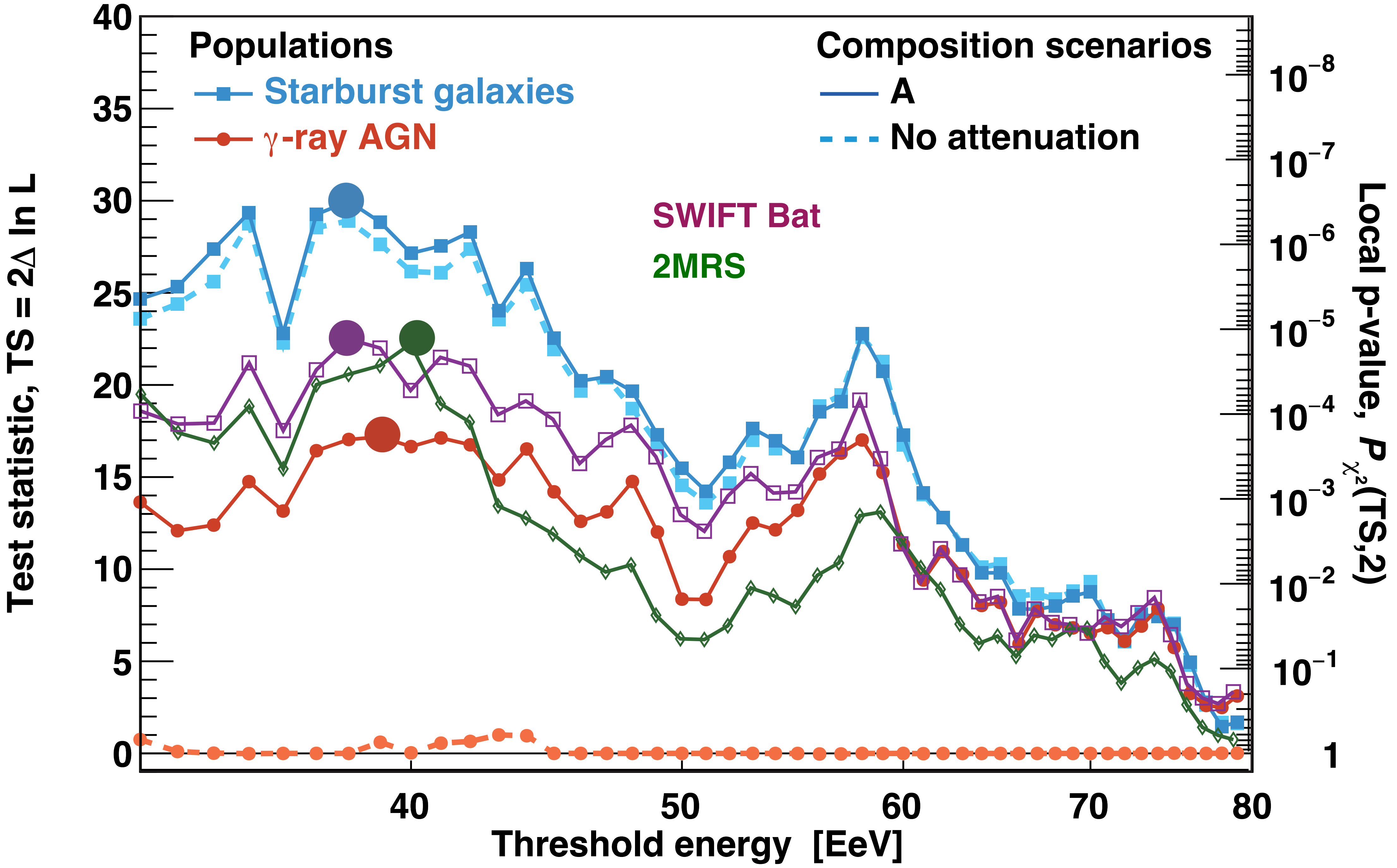
Sources assumed to emit UHECR spectrum and composition according to results from combined fit.
Propagation effects (attenuation) fully accounted for.

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	$15^{+5\circ}_{-4}$	$11^{+5}_{-4}\%$	29.5	4.5 σ
γ-AGNs	39 EeV	$14^{+6\circ}_{-4}$	$6^{+4}_{-3}\%$	17.8	3.1 σ
Swift-Bat	38 EeV	$15^{+6\circ}_{-4}$	$8^{+4}_{-3}\%$	22.2	3.7 σ
2MRS	40 EeV	$15^{+7\circ}_{-4}$	$19^{+10}_{-7}\%$	22.0	3.7 σ

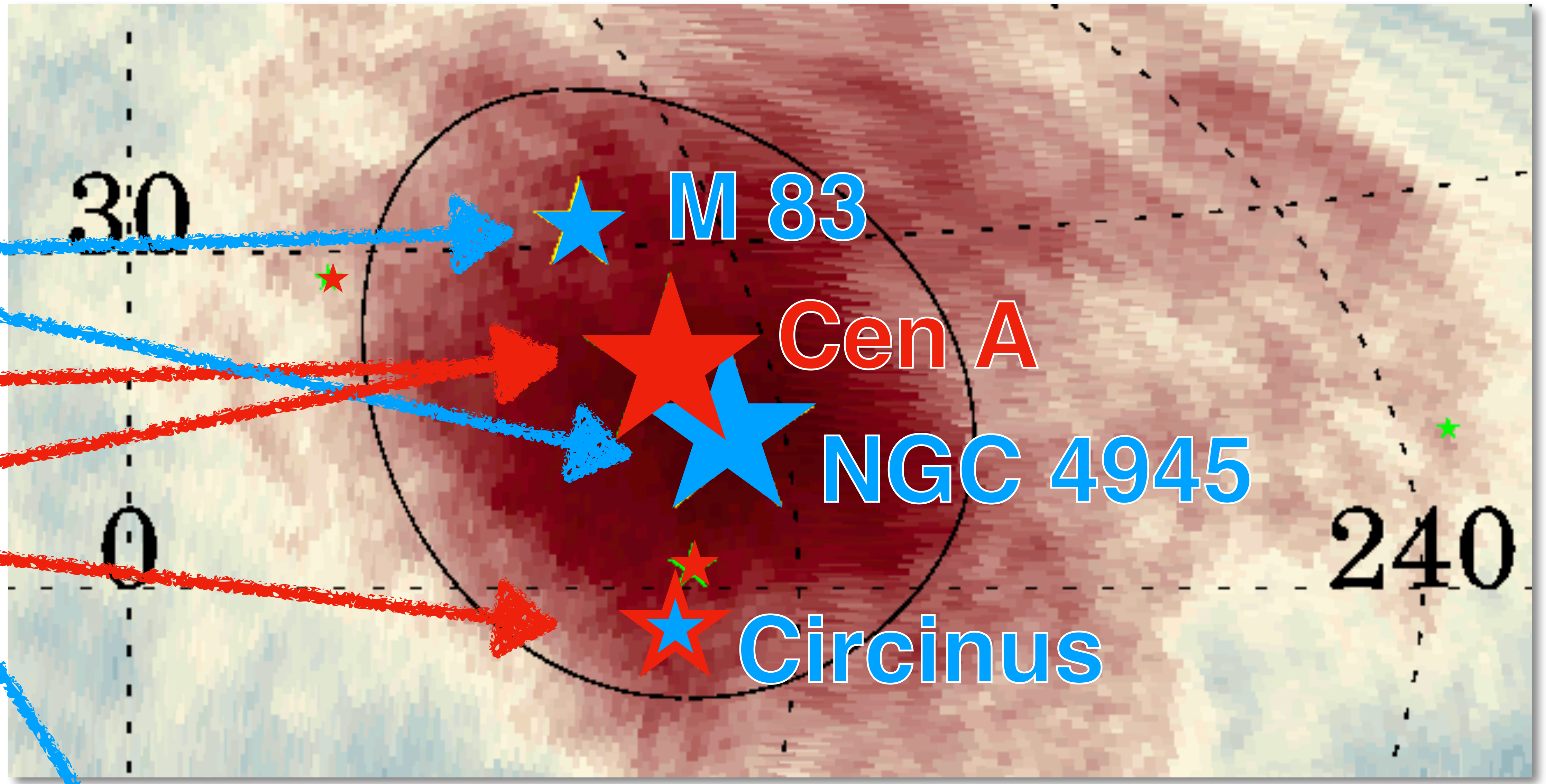
Result: SBG-model fits data better than isotropy at 4.5σ

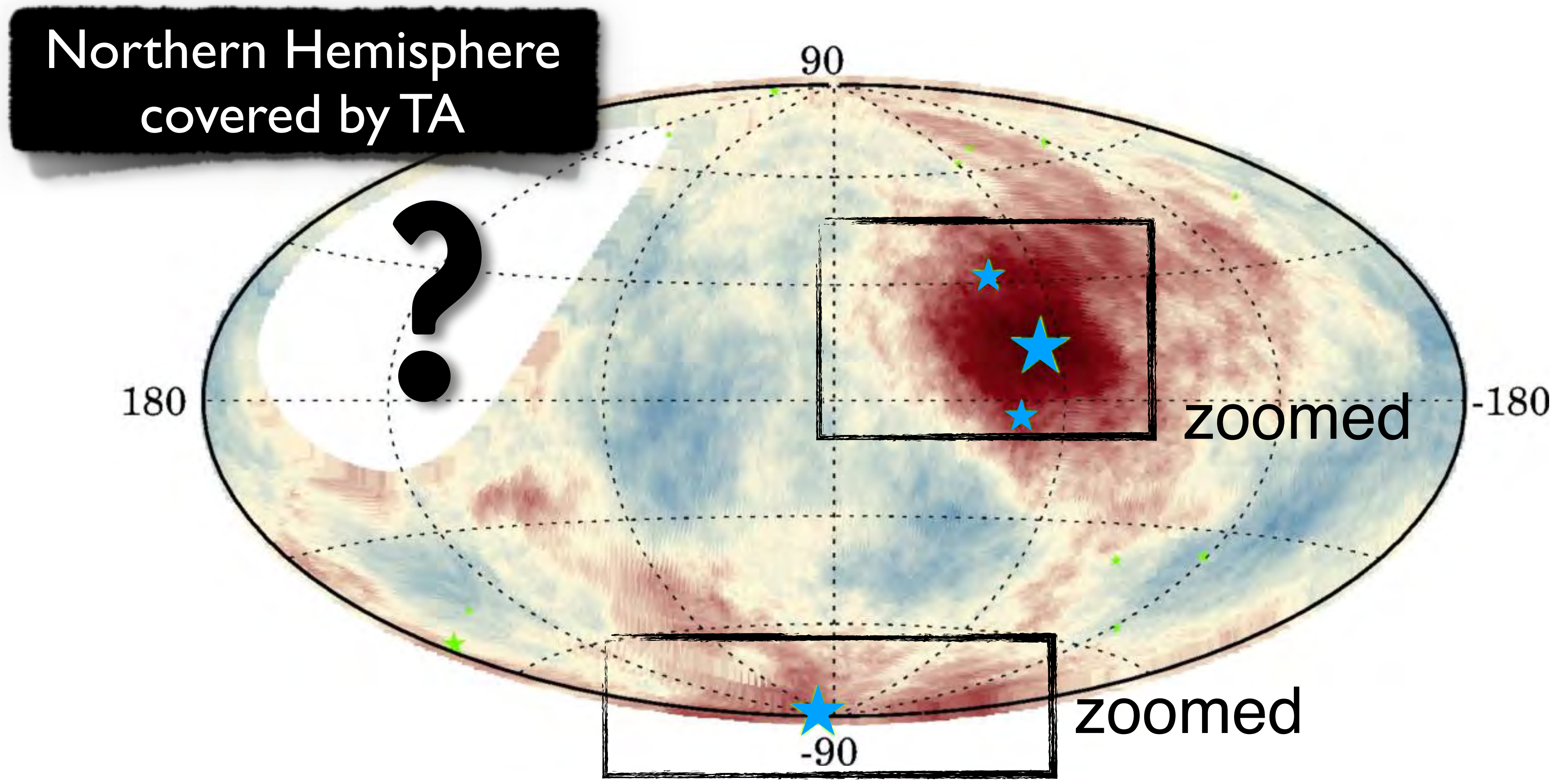
Interesting connection to diffuse neutrinos
→ E. Peretti, P. Blasi et al, arXiv:1911.06163

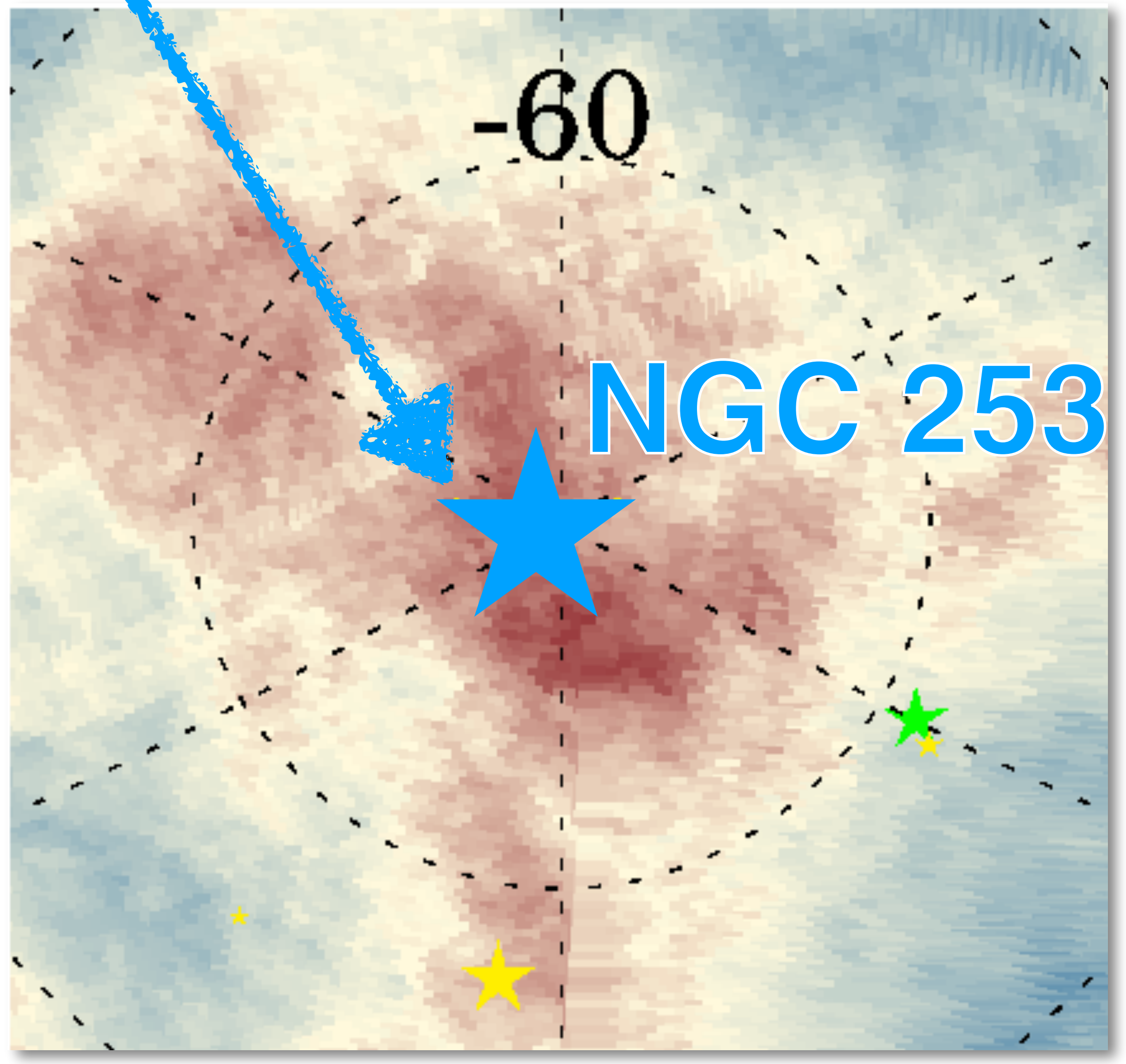
Auger: ApJL 853:L29 (2018), updated in PoS(ICRC2019)206

Many Candidate Sources in Excess Region

Catalog	E_{th}	θ	f_{aniso}	TS	Post-trial
Starburst	38 EeV	15^{+5}_{-4}°	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




Northern Hemisphere covered by TA



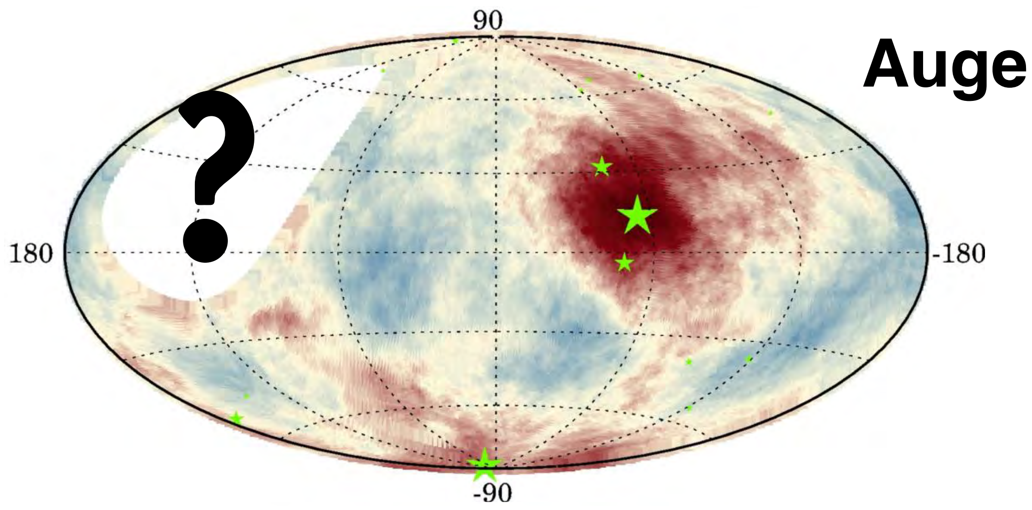
South Galactic Pole region well described by SBG model

no excess expected in γ-AGN

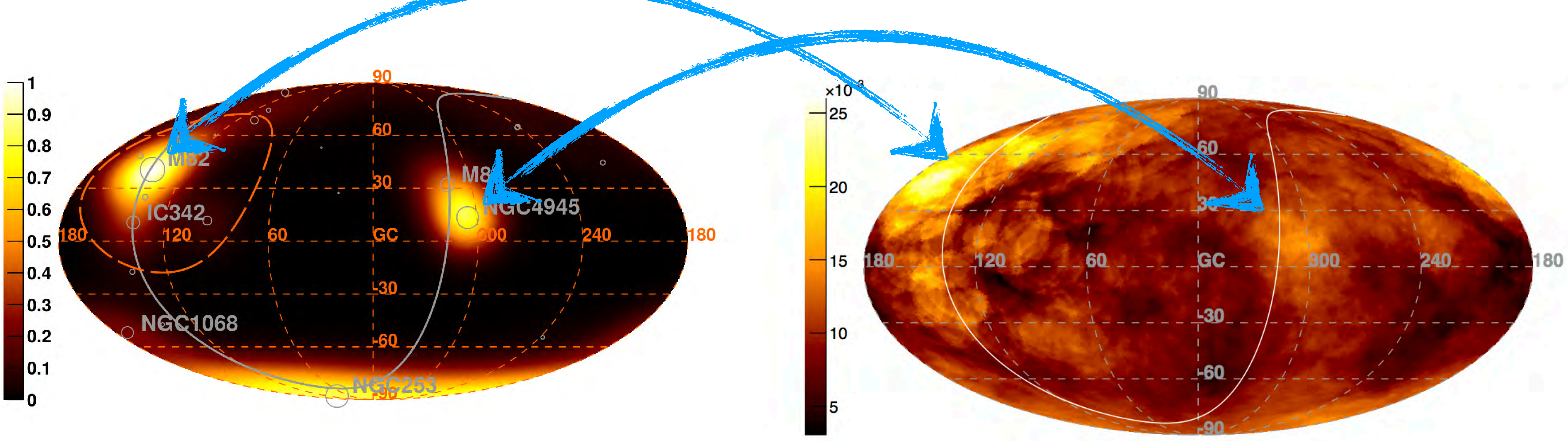
Auger: ApJL 853:L29 (2018), updated in PoS(ICRC2019)206

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

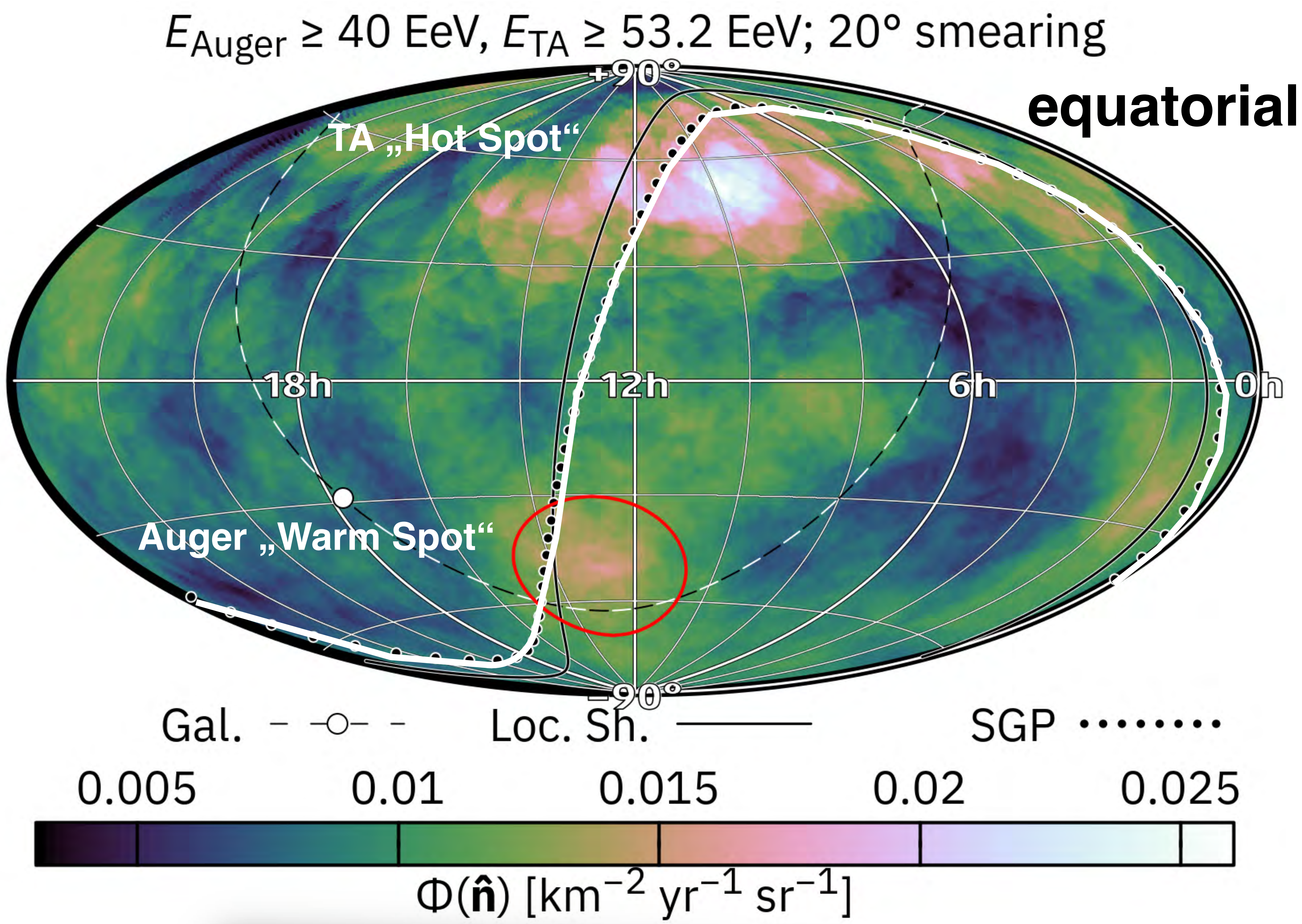
Auger+TA UHECR sky map

galactic coordinates

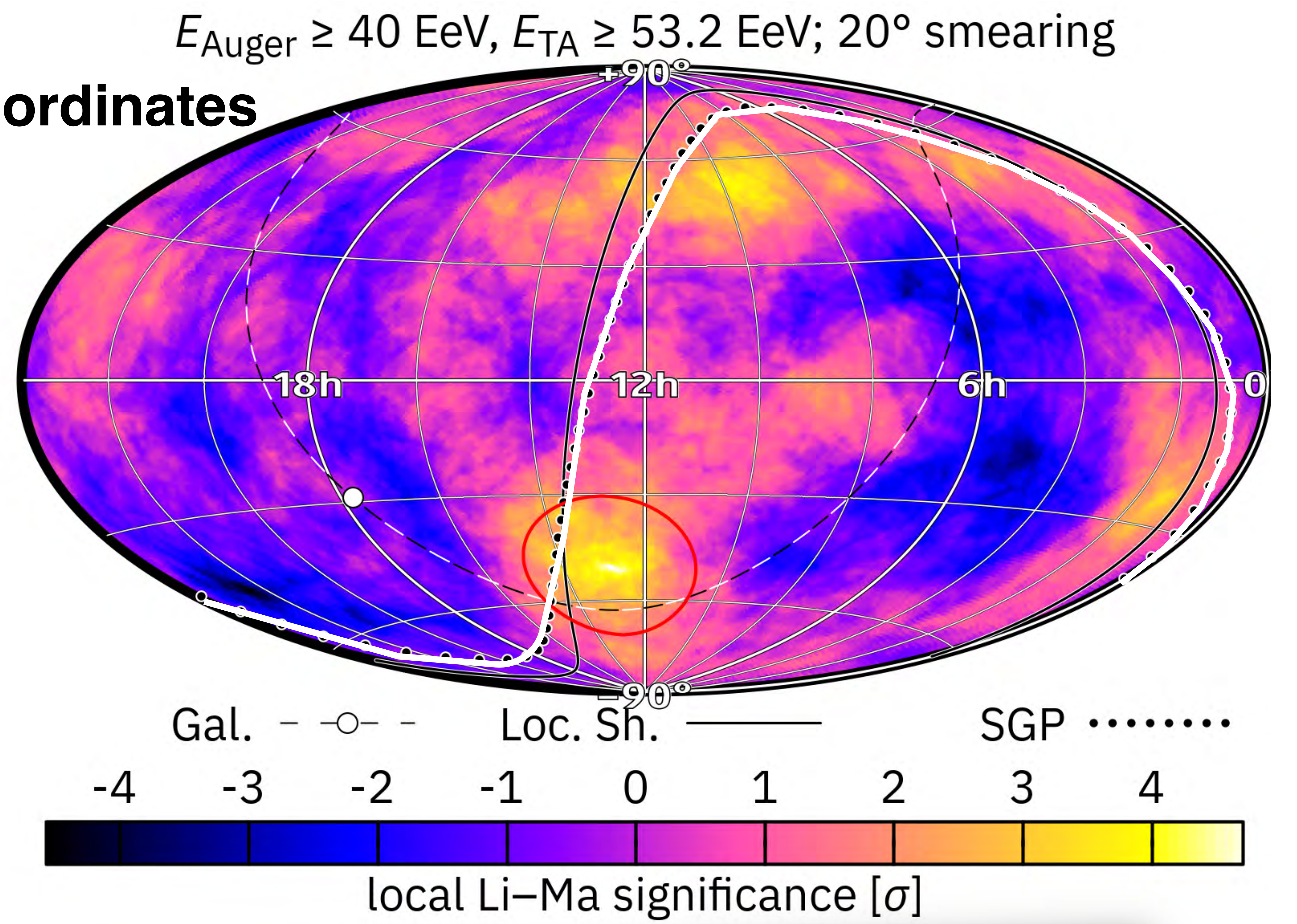
joint full-sky analysis in progress …

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

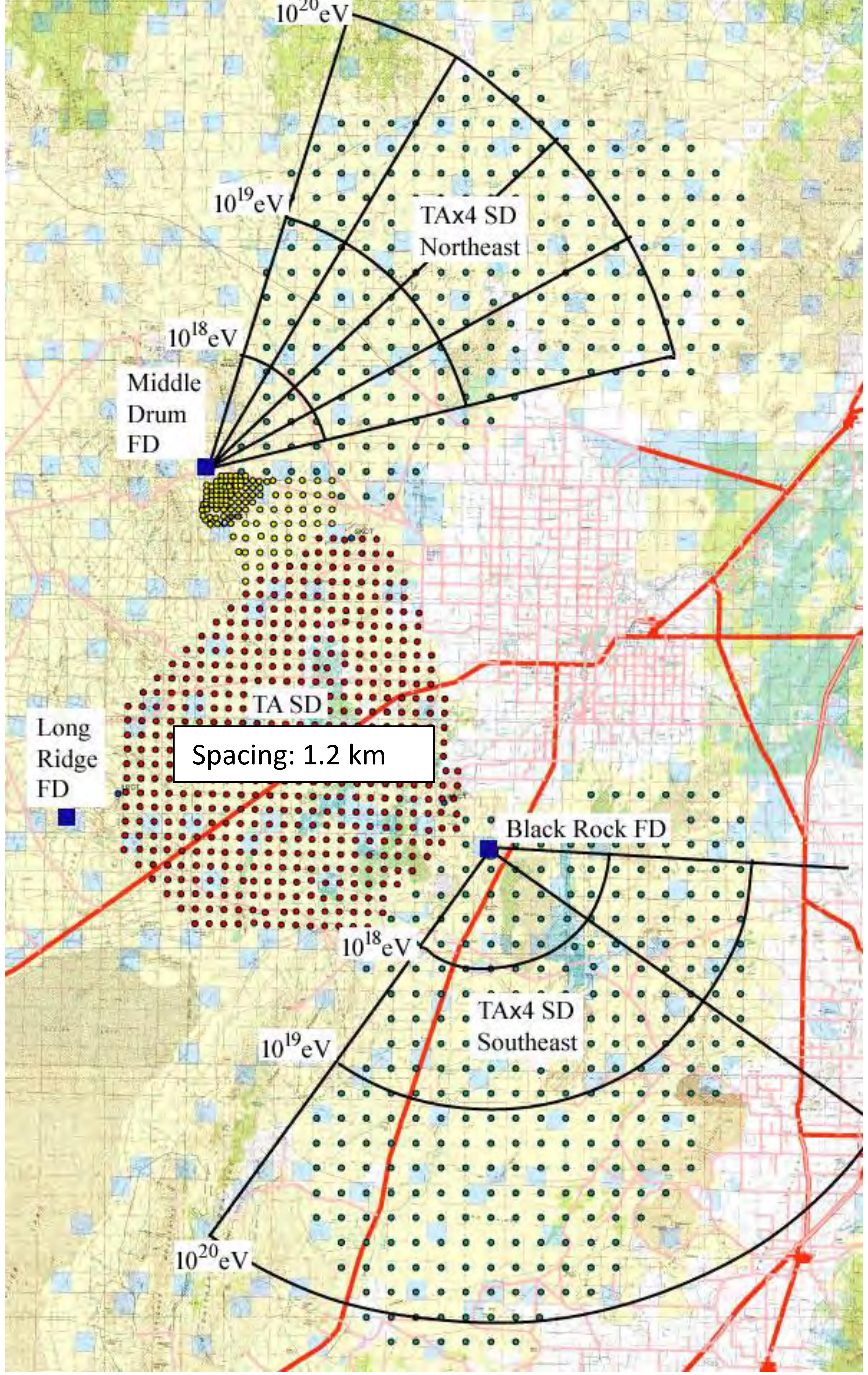
NEXT LOGICAL STEPS

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

currently very busy with deployment

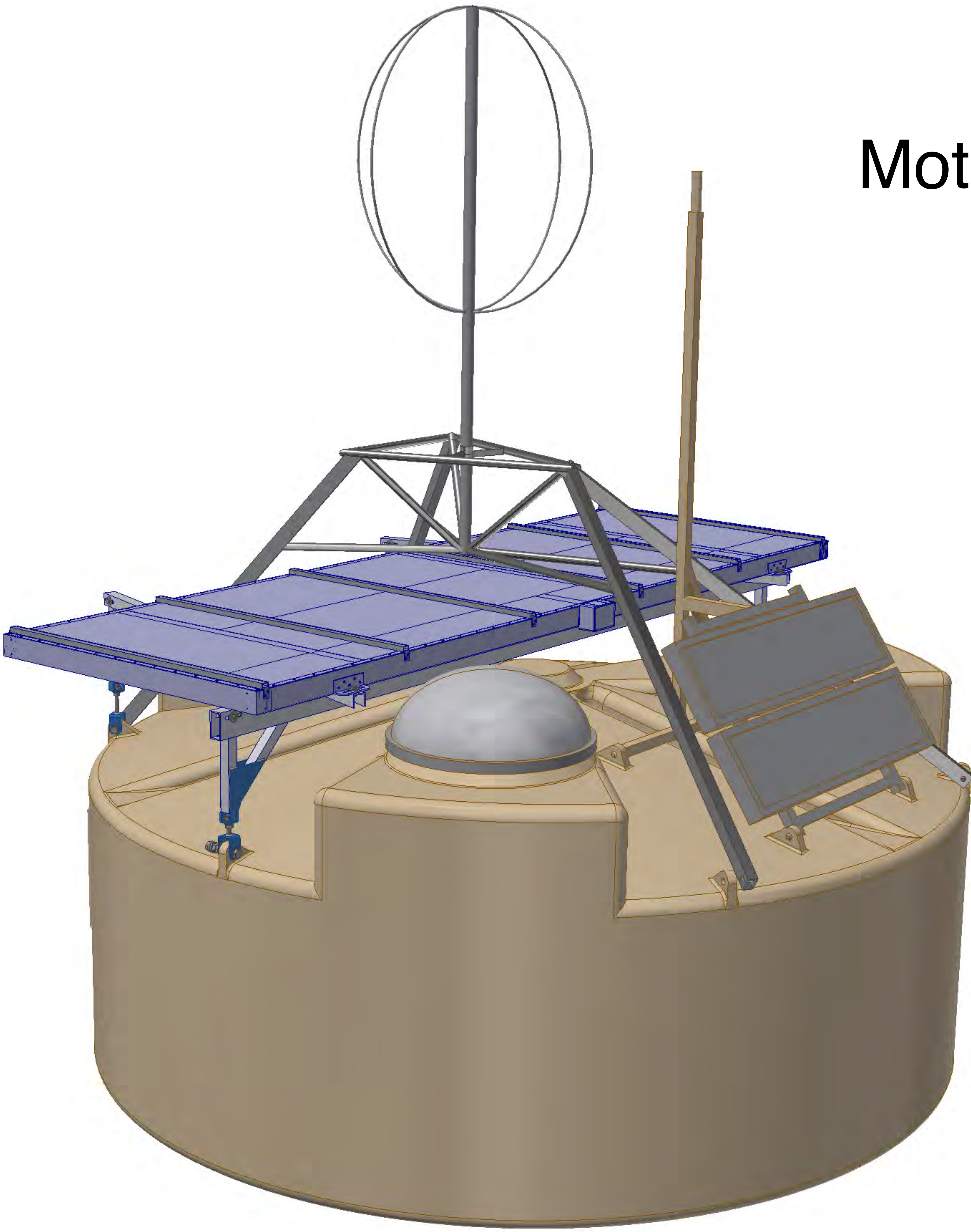
- 3.8 m^2 scintillators (SSD) on each 1500 m array stations improve e/μ discr.
- upgrade of station electronics
- additional small PMT to increase dynamic range
- buried muon counters in 750 m array (AMIGA)
- increased FD uptime

get rid of the fog…

Scintillators on top of each Water Cherenkov Tank

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

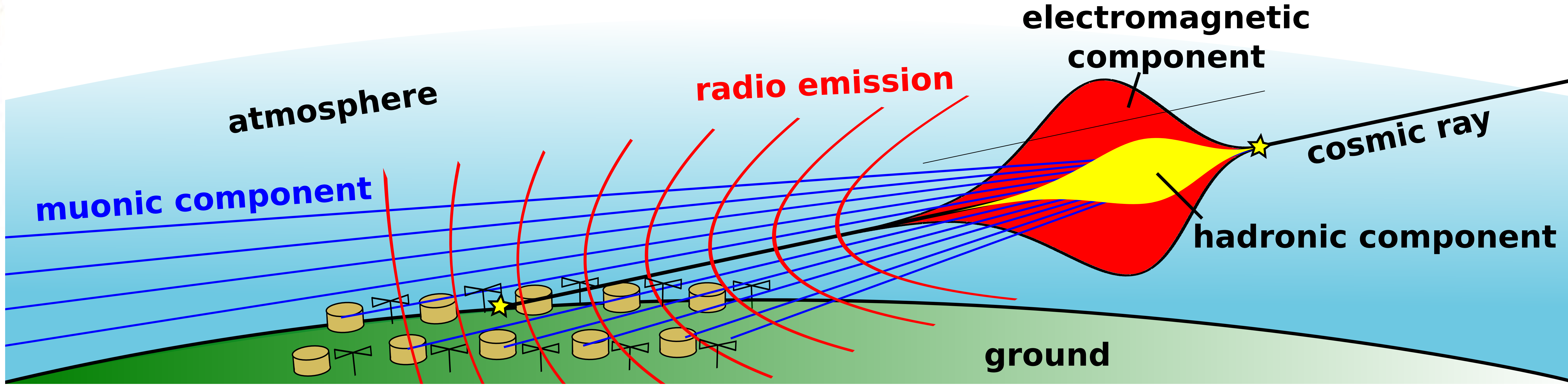
Radio added to each station



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

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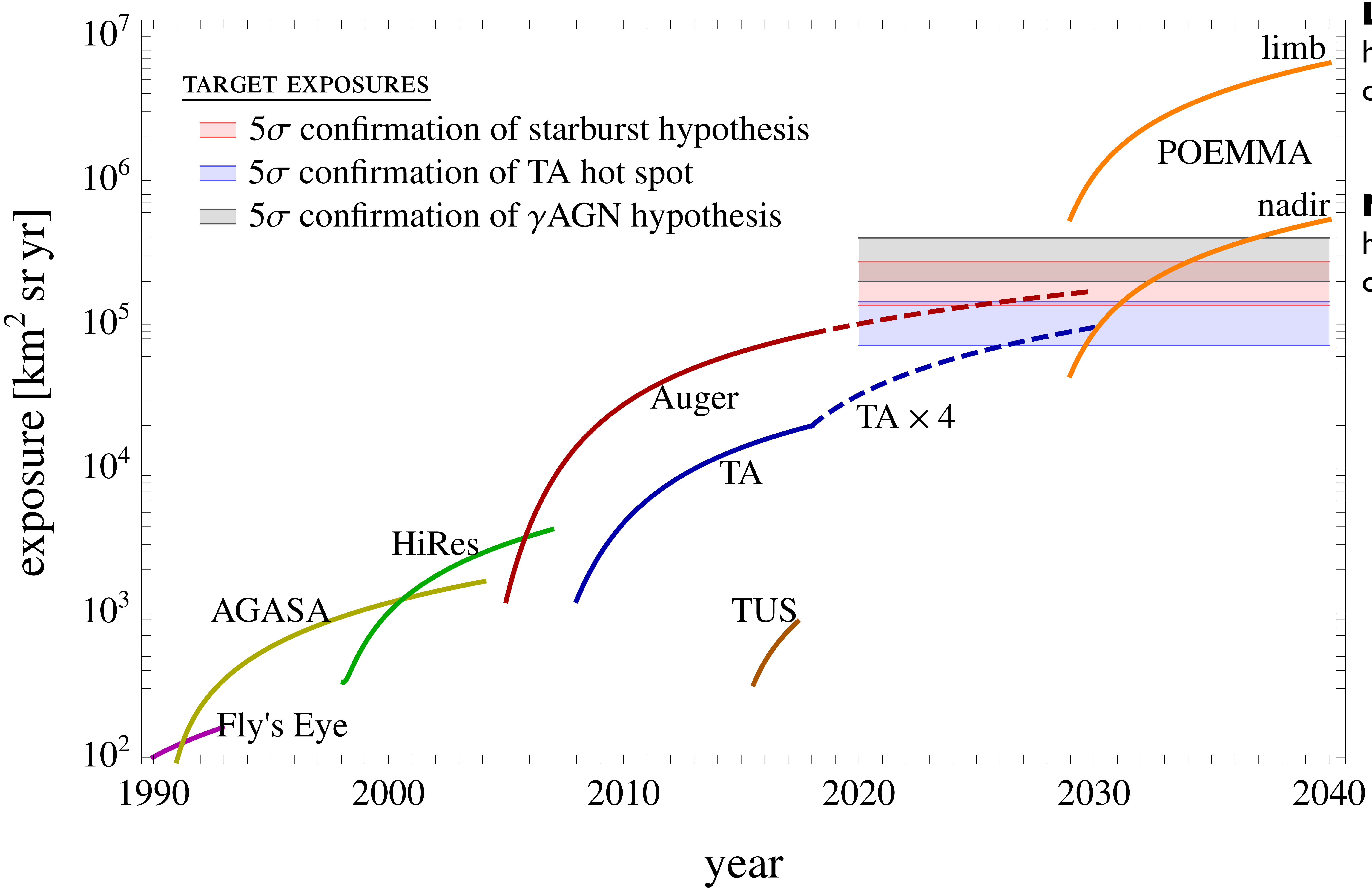
Looking beyond Auger and TA



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 even enhanced by composition
- Verify proton component at highest energies in MM approach
- Long term goal: Study spectrum and composition of *individual* UHECR sources

Thanks for your attention!

Sources most contributing to the likelihood analysis

Starburst Galaxies

Src	l	b	excess-weight
NGC4945	305.27	13.34	100.0%
NGC253	97.36	-87.97	77.7%
M83	314.58	31.97	27.7%
Circinus	311.33	-3.81	22.4%
NGC1068	172.10	-51.93	14.8%
NGC1808	241.21	-35.90	3.8%
NGC1672	268.78	-38.99	2.8%
NGC4631	142.81	84.22	2.2%
NGC1365	237.96	-54.60	2.1%
NGC4666	299.54	62.37	1.3%
M61	284.37	66.28	1.3%
NGC3627	241.96	64.42	1.3%
NGC2903	208.71	44.54	1.2%
M51	104.85	68.56	1.1%
NGC660	141.61	-47.35	1.1%
NGC3628	240.85	64.78	1.1%

γ-emitting AGNs

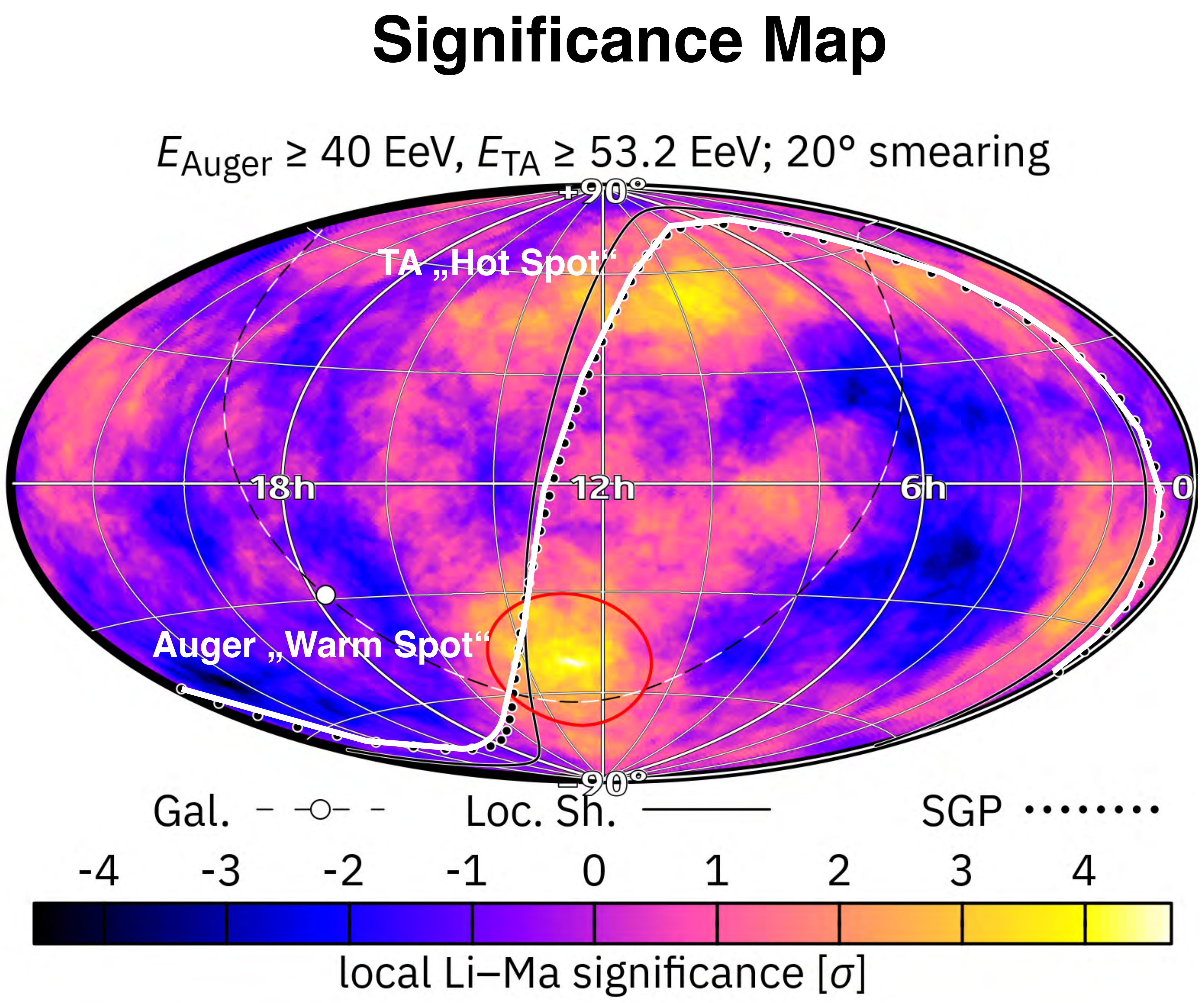
Src	l	b	excess-weight
CenA	309.52	19.42	100.0%
Mkn421	179.83	65.03	22.6%
NGC1275	150.58	-13.26	14.2%
FornaxA	240.16	-56.69	11.0%
M87	283.78	74.49	11.0%
CenB	309.72	1.73	7.3%
Mkn501	63.60	38.86	5.7%
APLibrae	340.68	27.58	2.3%
PMNJ0816-1311	234.80	12.12	1.6%

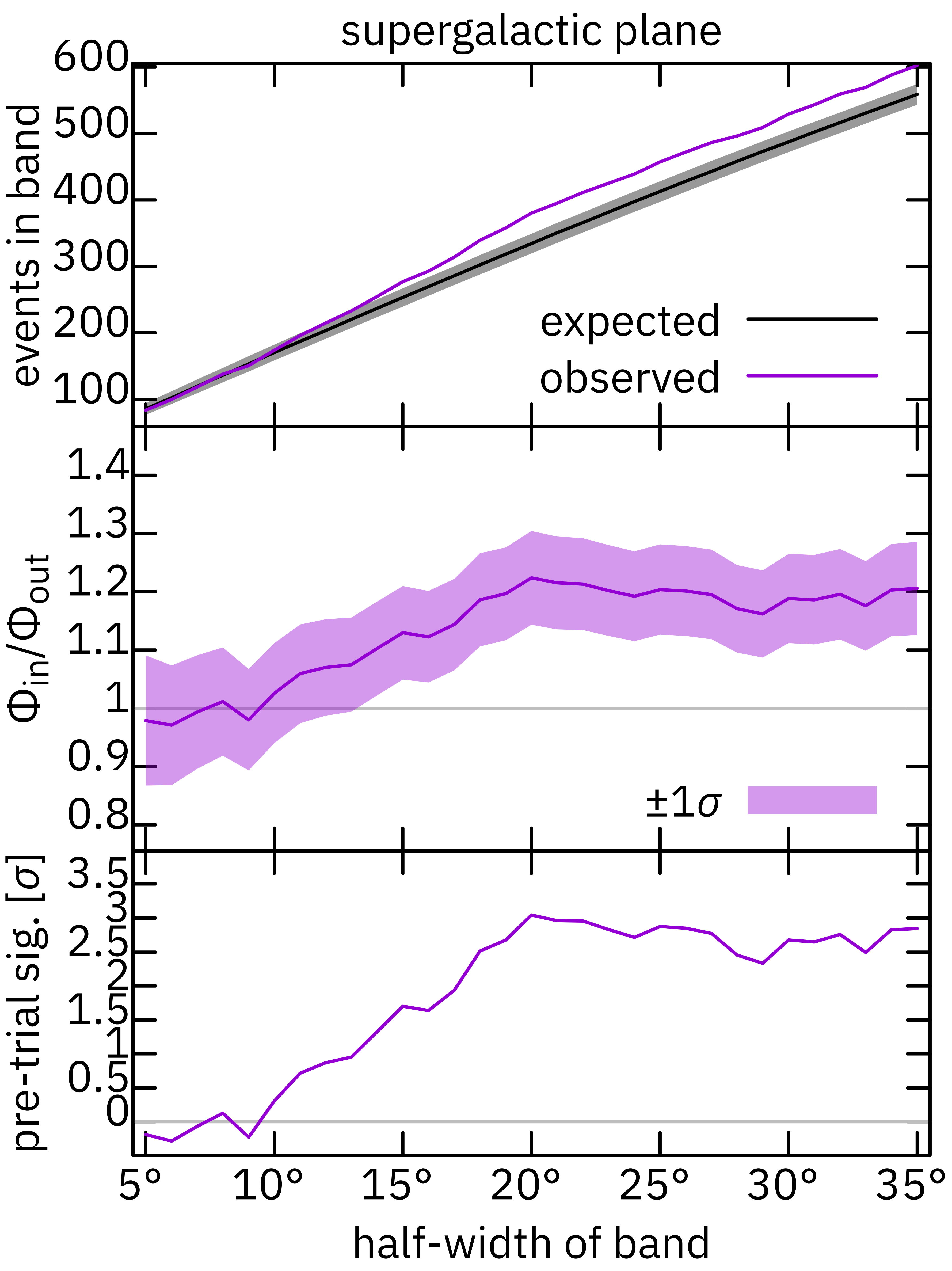
Swift-BAT

Src	l	b	excess-weight
CenA	309.52	19.42	100.0%
Circinus	311.33	-3.81	18.0%
NGC4945	305.27	13.34	12.9%
NGC2110	212.93	-16.55	3.8%
NGC6300	328.49	-14.05	3.3%
NGC5506	339.15	53.81	3.2%
MCG-05-23-016	262.74	17.23	3.0%
NGC7172	15.13	-53.07	2.5%
NGC3783	287.46	22.95	2.5%
NGC4507	299.64	22.86	2.1%
IC4329A	317.50	30.92	2.1%
NGC4388	279.12	74.34	2.1%
NGC7582	348.08	-65.70	1.9%
NGC4151	155.08	75.06	1.8%
ESO103-035	329.78	-23.18	1.4%
NGC1365	237.96	-54.60	1.4%
NGC6814	29.35	-16.01	1.3%
4U1344-60	309.77	1.51	1.3%
NGC3081	259.02	25.03	1.2%
NGC7314	27.14	-59.74	1.1%
NGC3227	216.99	55.45	1.1%
NGC3281	273.01	19.78	1.1%
NGC5728	337.32	38.10	1.1%
MCG-06-30-015	313.29	27.68	1.0%

From Lorenzo Caccianga @ ICRC2019

Correlation with QGP ?

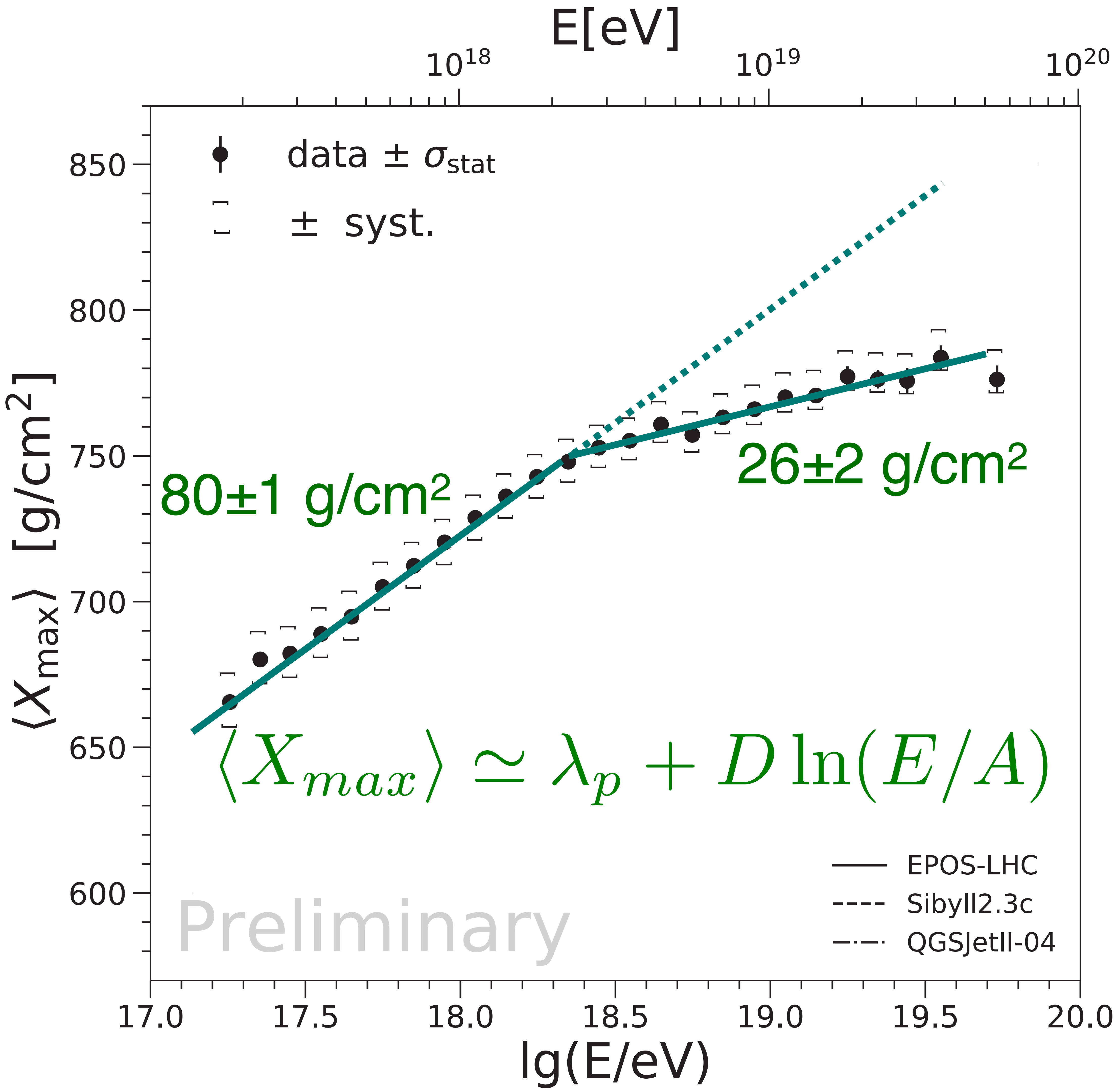




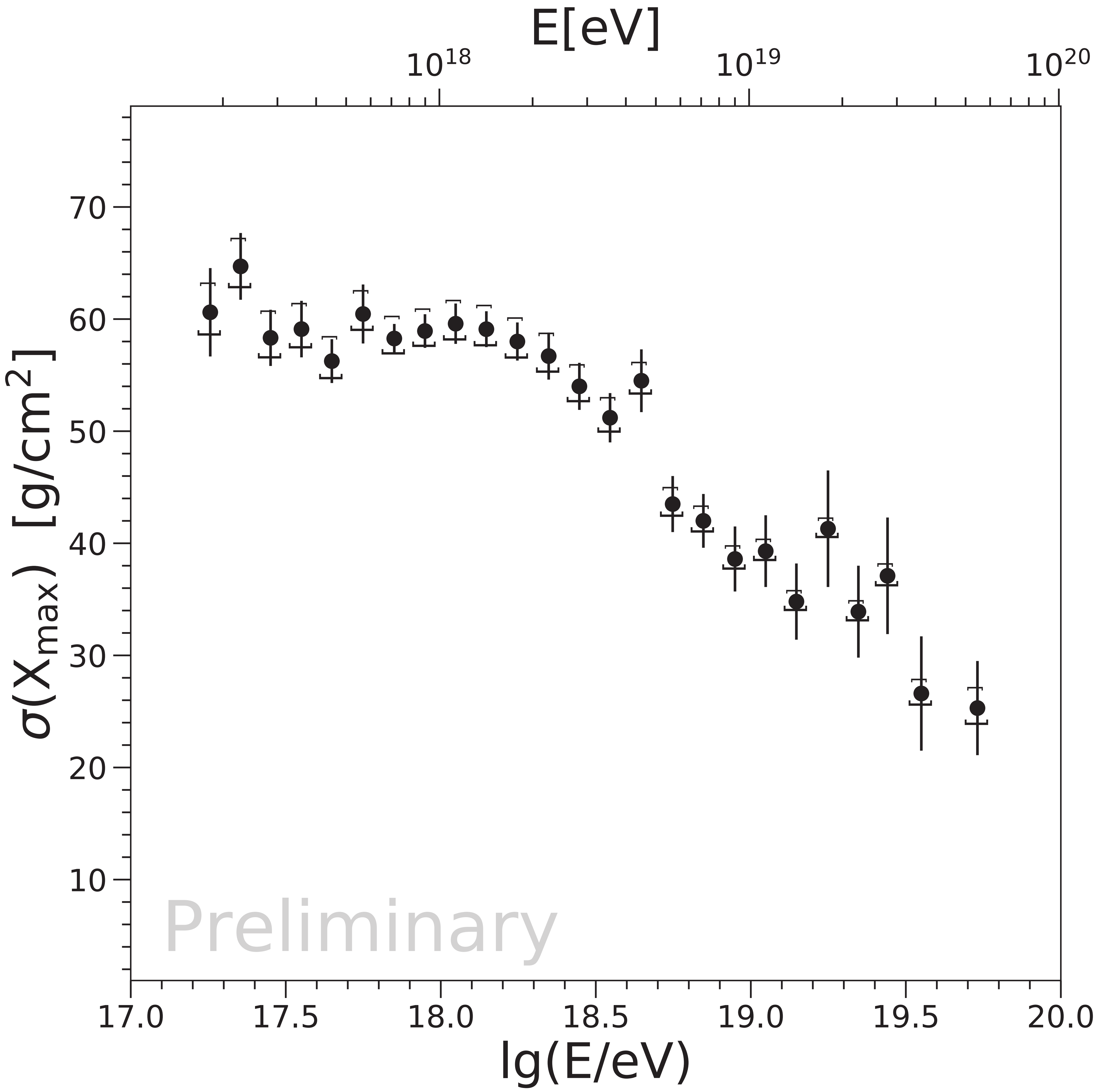
3σ: 380 events within 20°, 335±15 expected

$<X_{max}>$ and RMS(X_{max})

Auger @ ICRC2019: arXiv:1909.09073



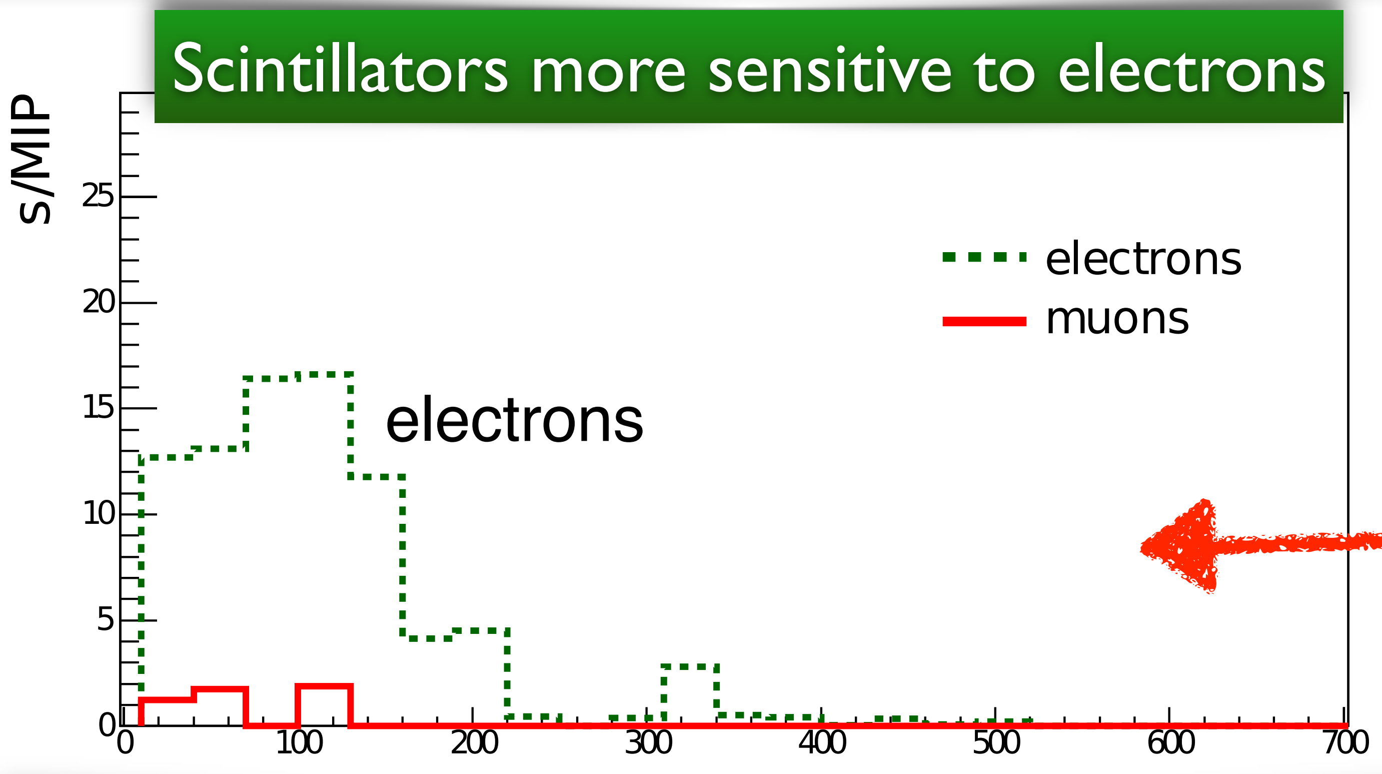
$$\langle X_{max} \rangle \simeq \lambda_p + D\ln(E/A)$$



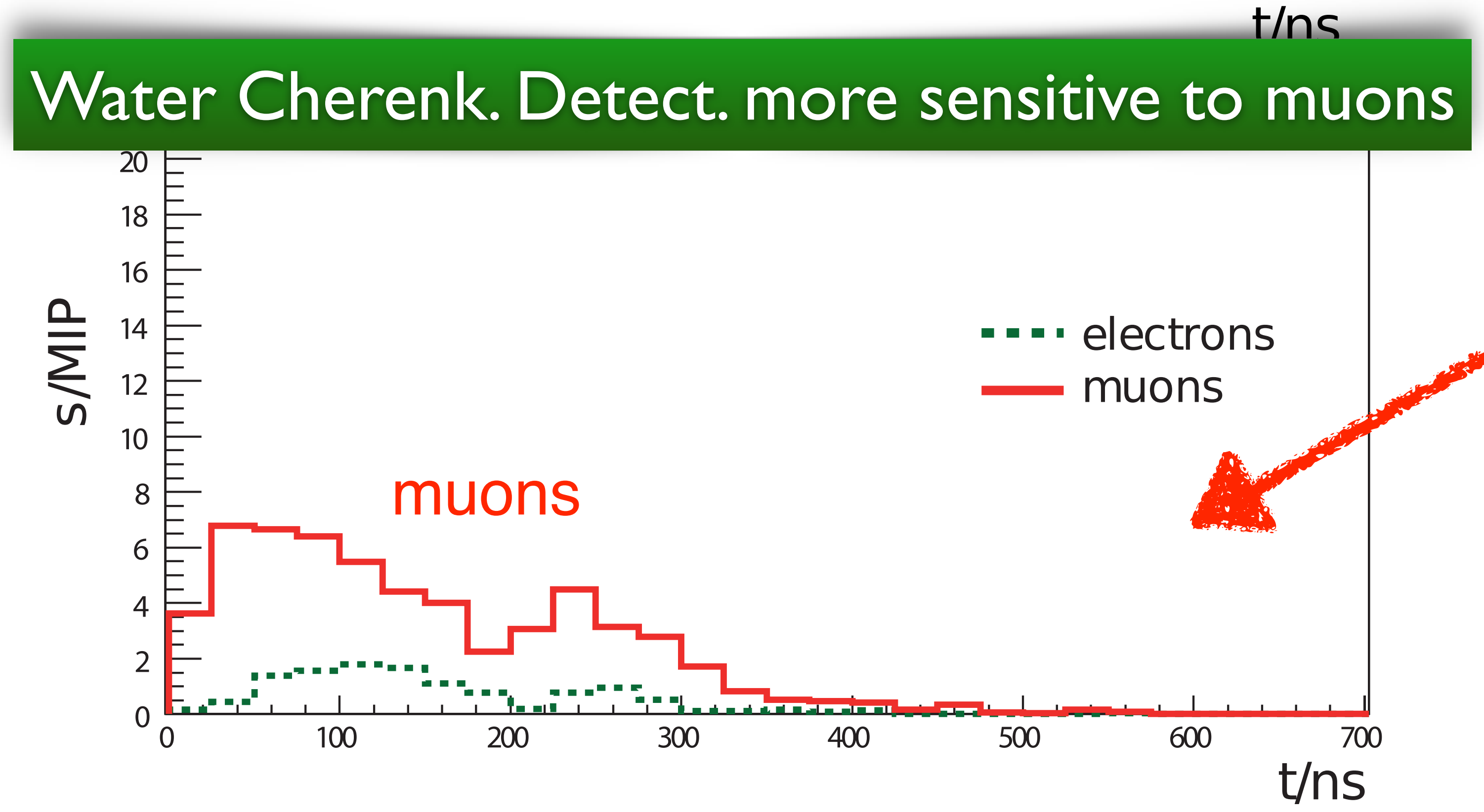
Technical Realisation

100% duty cycle

15% duty cycle



Scintillators more sensitive to electrons



Water Cherenk. Detect. more sensitive to muons

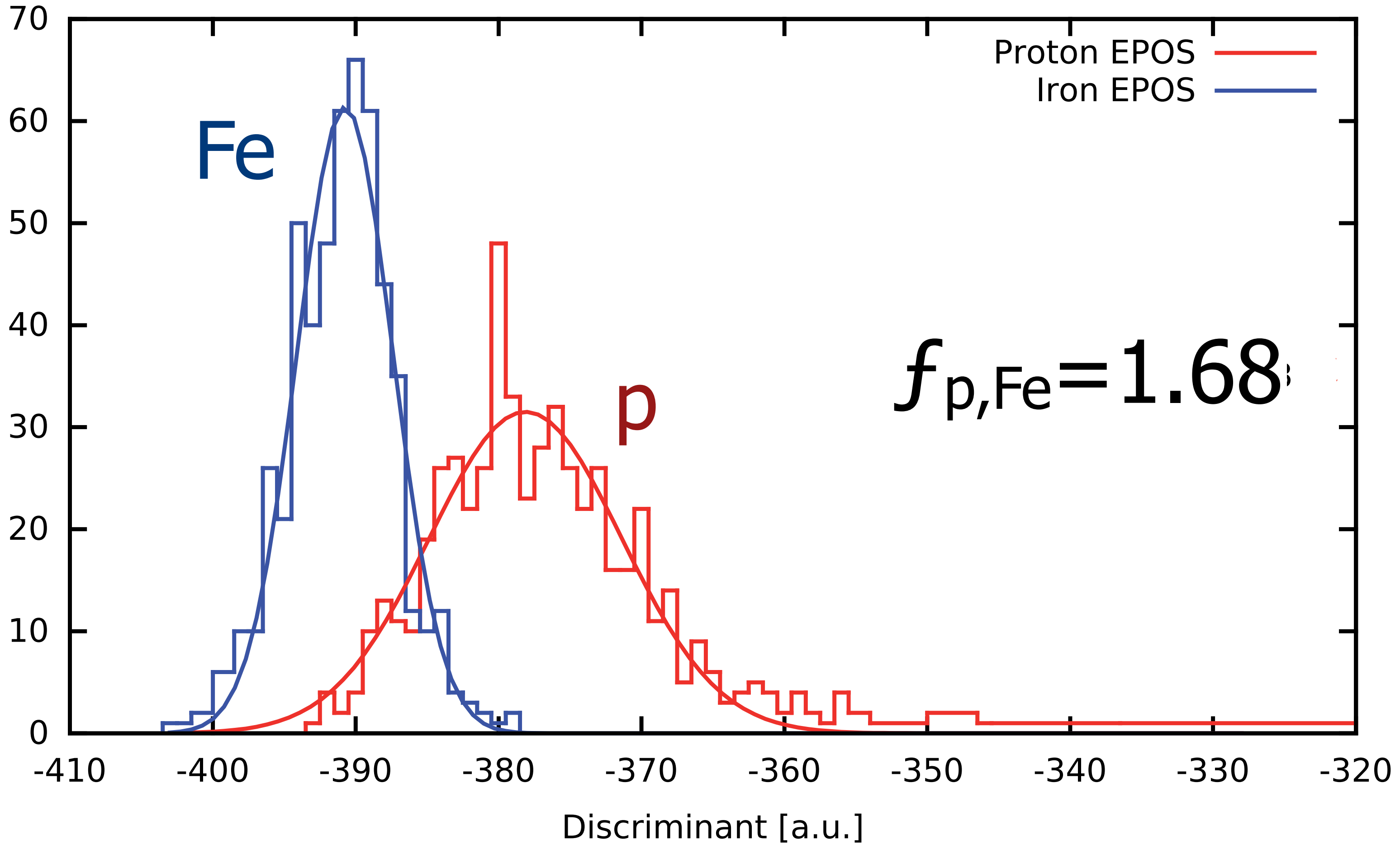
figure of merit:

$$f_{p,Fe} = \frac{|\langle S_{Fe}\rangle - \langle S_p\rangle|}{\sqrt{\sigma(S_{Fe})^2 + \sigma(S_p)^2}}$$

Linear system of equations:

$$\begin{pmatrix} S_{top} \\ S_{bot} \end{pmatrix} = \begin{pmatrix} a_{em} & a_\mu \\ 1 - a_{em} & 1 - a_\mu \end{pmatrix} \begin{pmatrix} S_{em} \\ S_\mu \end{pmatrix}$$

$$\Rightarrow \begin{pmatrix} S_{em} \\ S_\mu \end{pmatrix} = \begin{pmatrix} a_{em} & a_\mu \\ 1 - a_{em} & 1 - a_\mu \end{pmatrix}^{-1} \begin{pmatrix} S_{top} \\ S_{bot} \end{pmatrix}$$



Looking more ahead to the Future