High Energy Cosmic Ray and Multi-Messenger Astrophysics

XXXIV International School
“Francesco Romano”
on Nuclear, Subnuclear and Astroparticle Physics

Lecture 2: Diving into the UHECR science

PIERRE AUGER OBSERVATORY

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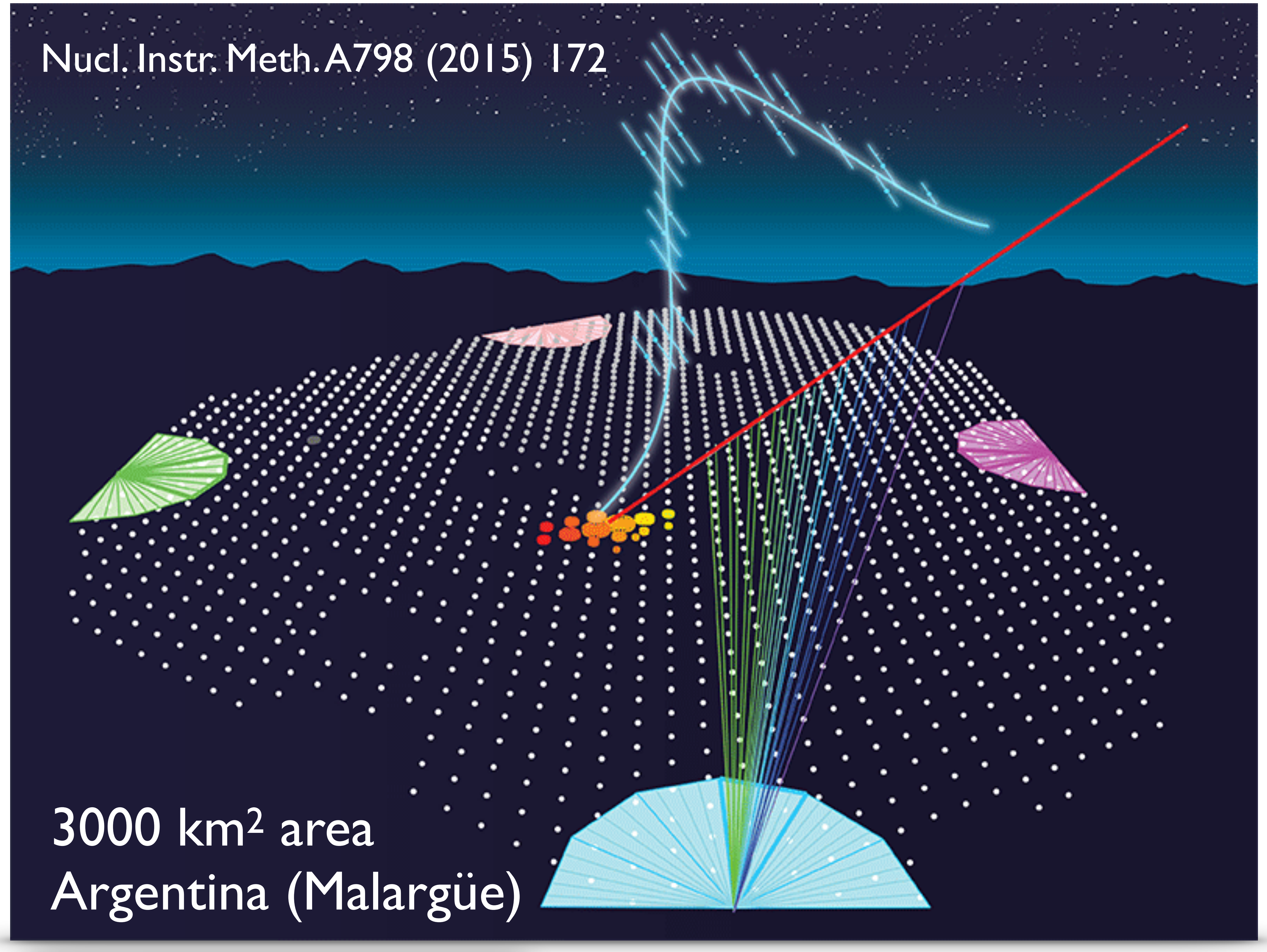
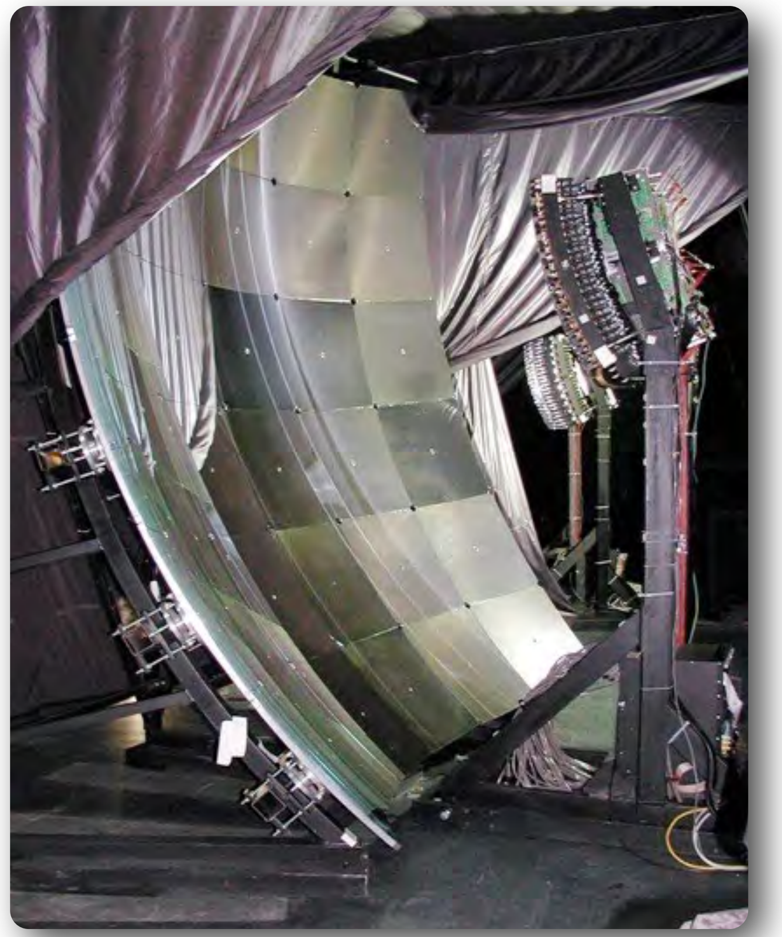
SFB1491
Bundesministerium für Bildung und Forschung

Monopoli (Bari) - Italy
2023 Sept. 17th - 24th

Hybrid Detection of UHECR: Pierre Auger Observatory



- 1400 m altitude
- 35° S, 69° W

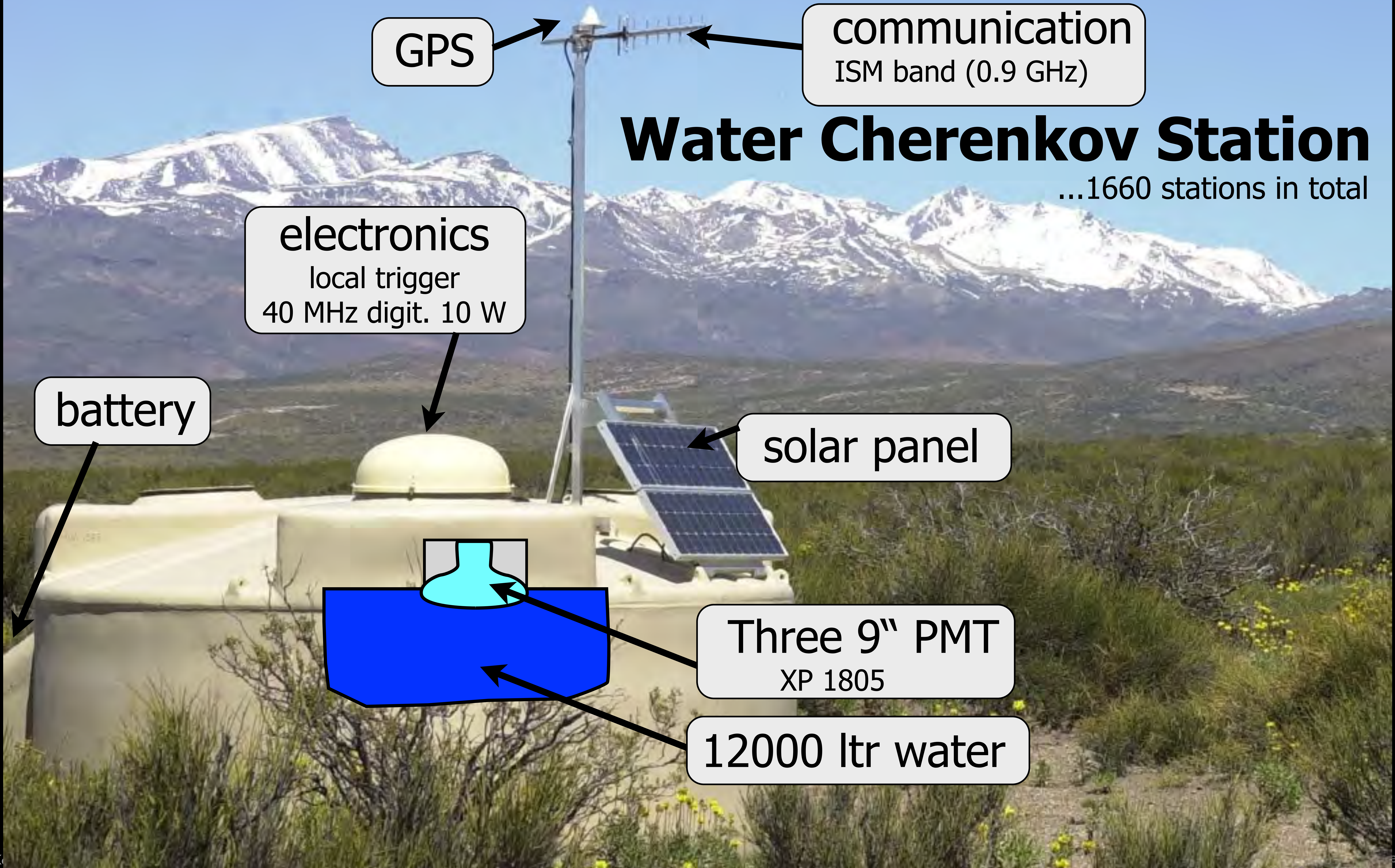


- 27 Telescopes to measure light trace of EAS in atmosphere
- integrated light intensity → CR energy
- 13% duty cycle

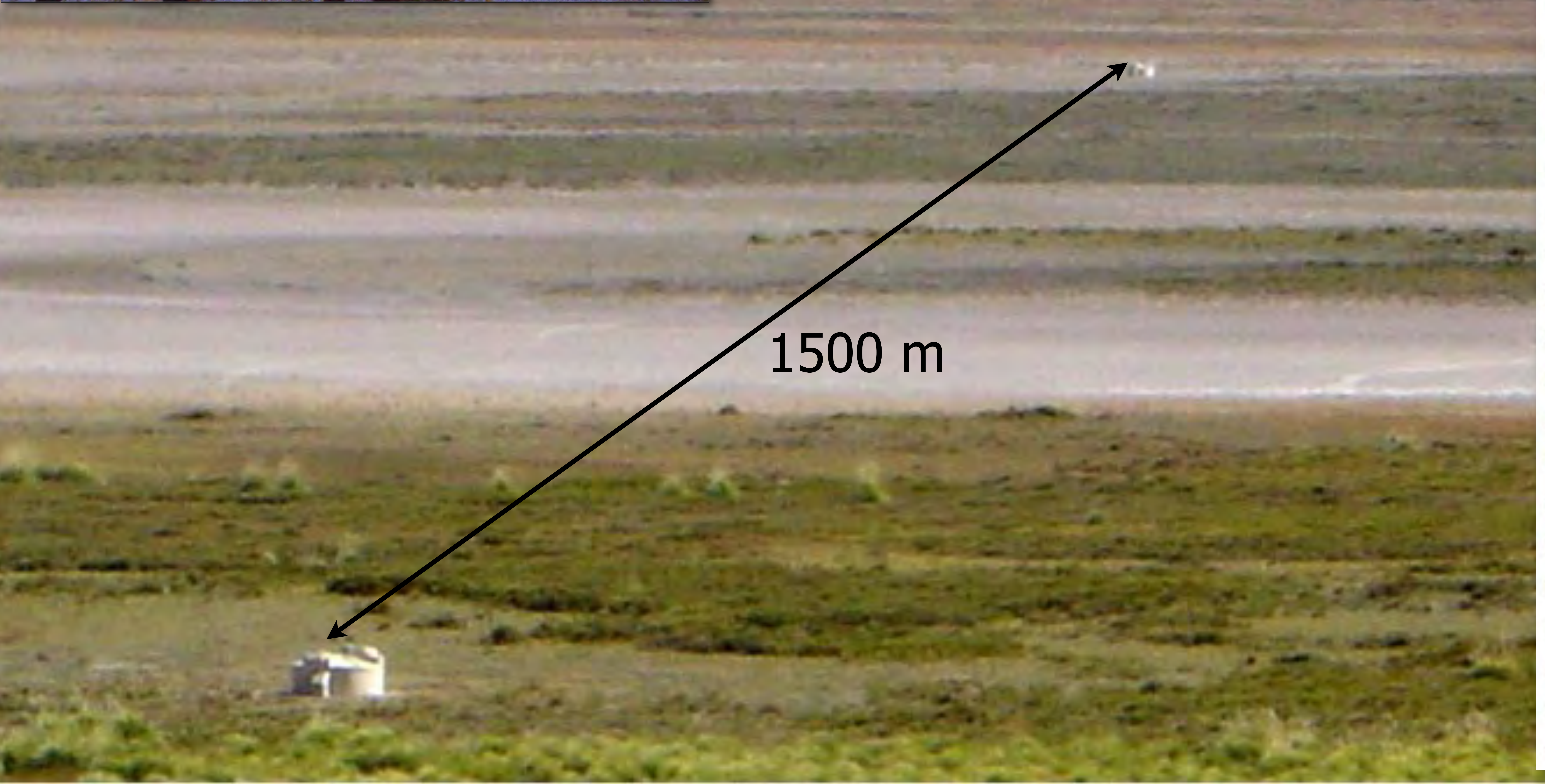
- 1660 Water Cherenkov detectors on 1.5 km grid to measure footprint of particles at ground
- 100% duty cycle
- cross calibrated with FD-telescopes with hybrid events

- 153 radio antennas for em-radiated energy
- 18 km^2 area
- 100% duty cycle

Central campus with visitors center


GPS
communication
ISM band (0.9 GHz)
Water Cherenkov Station
...1660 stations in total
electronics
local trigger
40 MHz digit. 10 W
battery
solar panel
Three 9" PMT
XP 1805
12000 ltr water

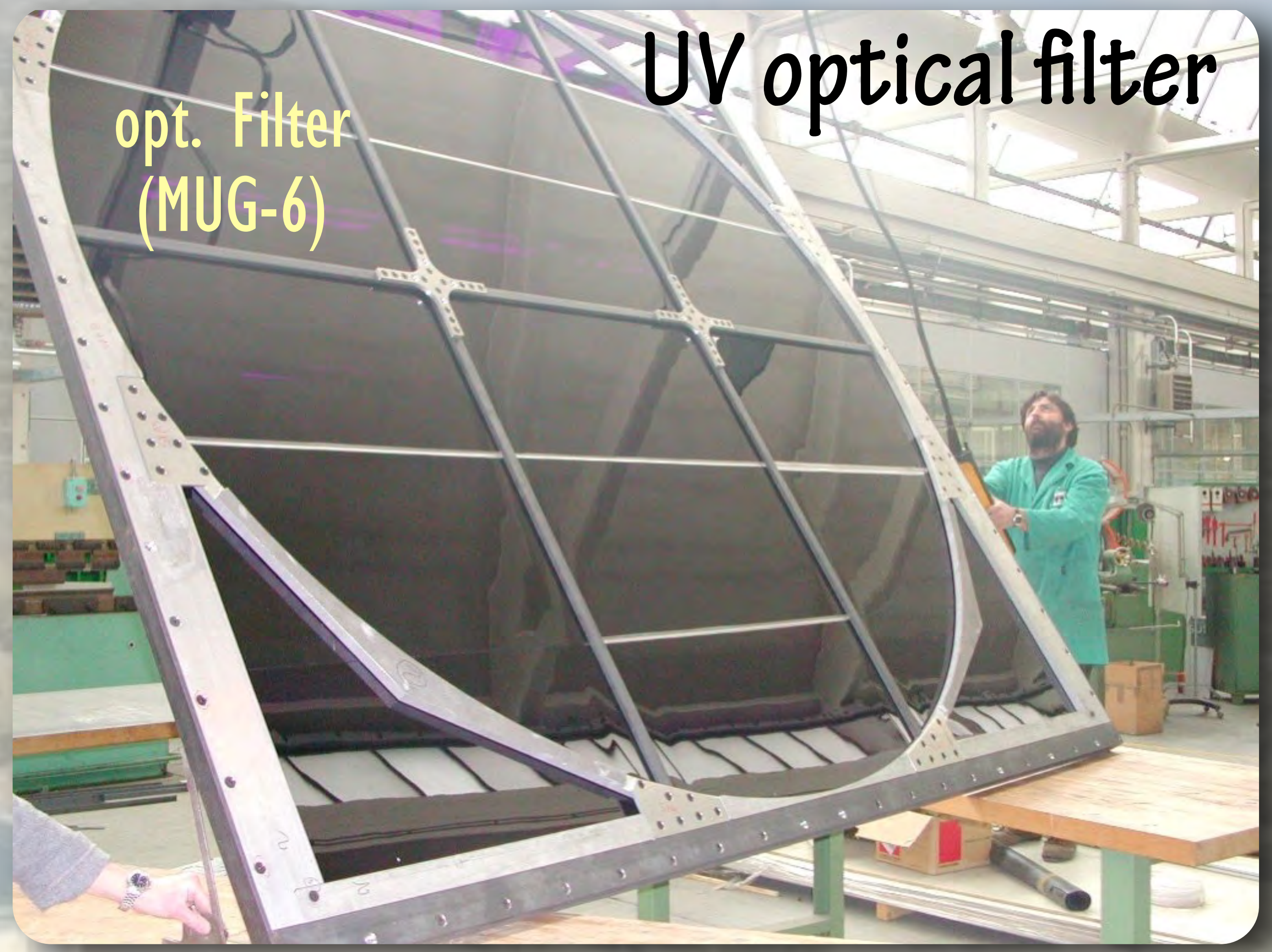
Counting detector stations

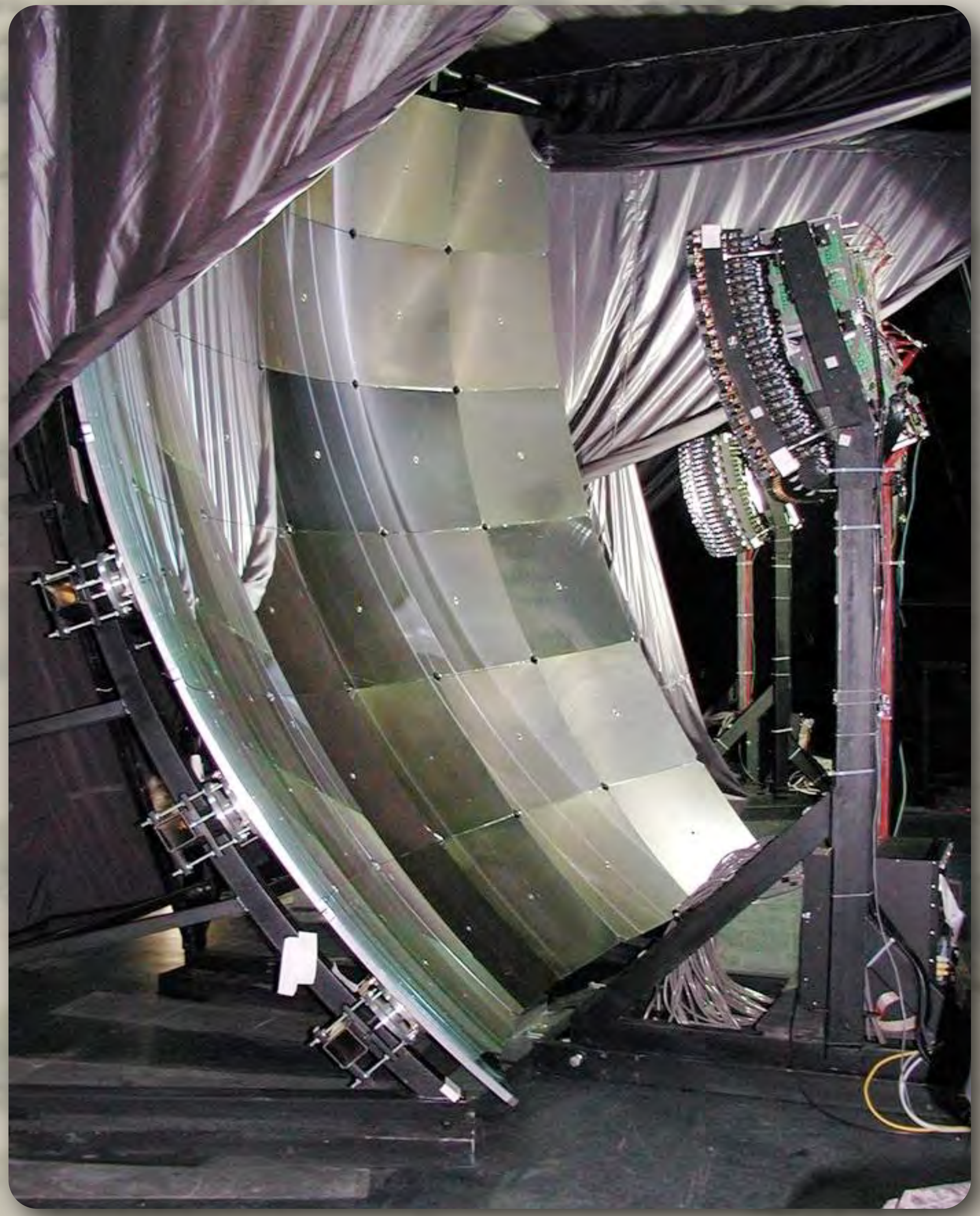


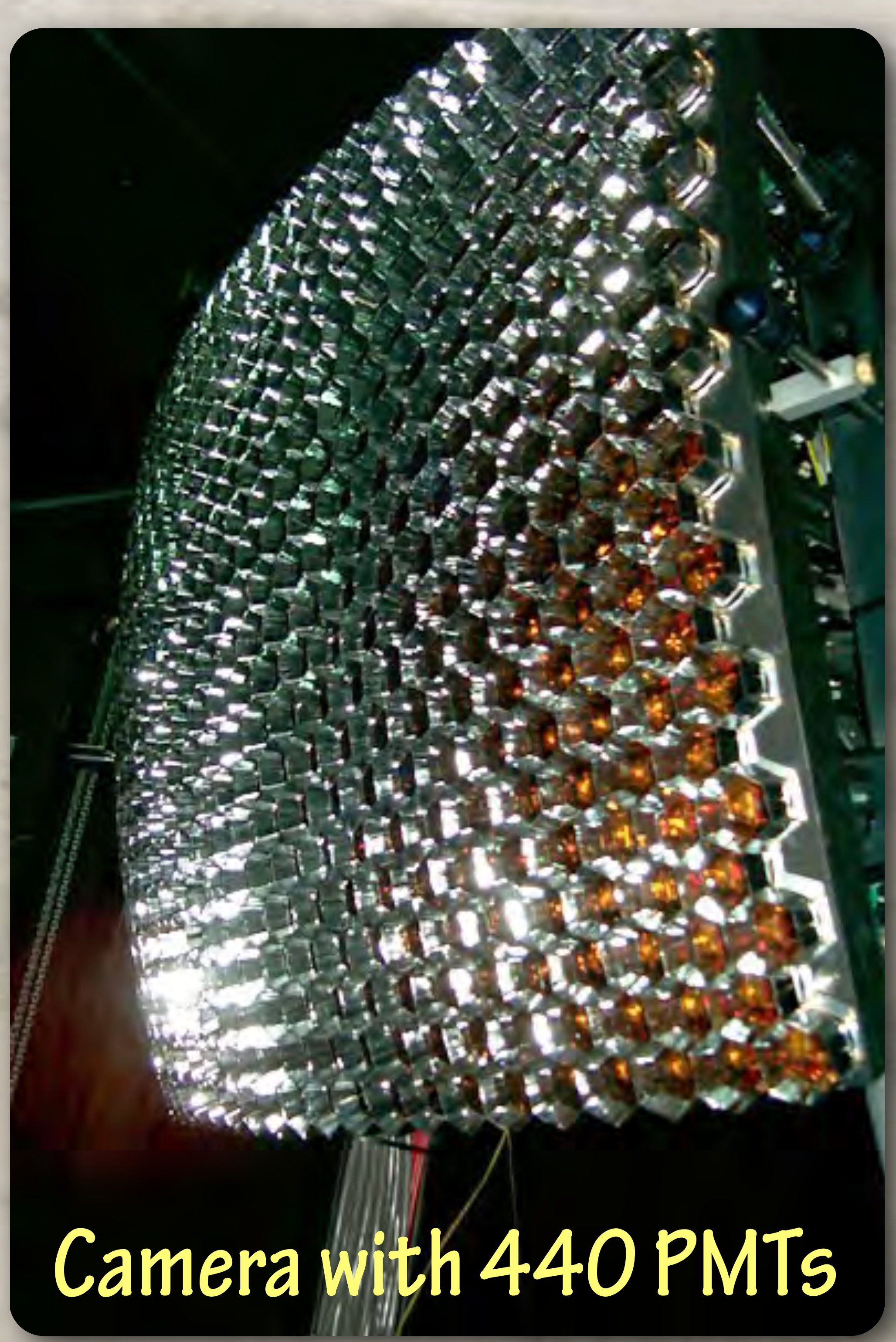
Official stamp

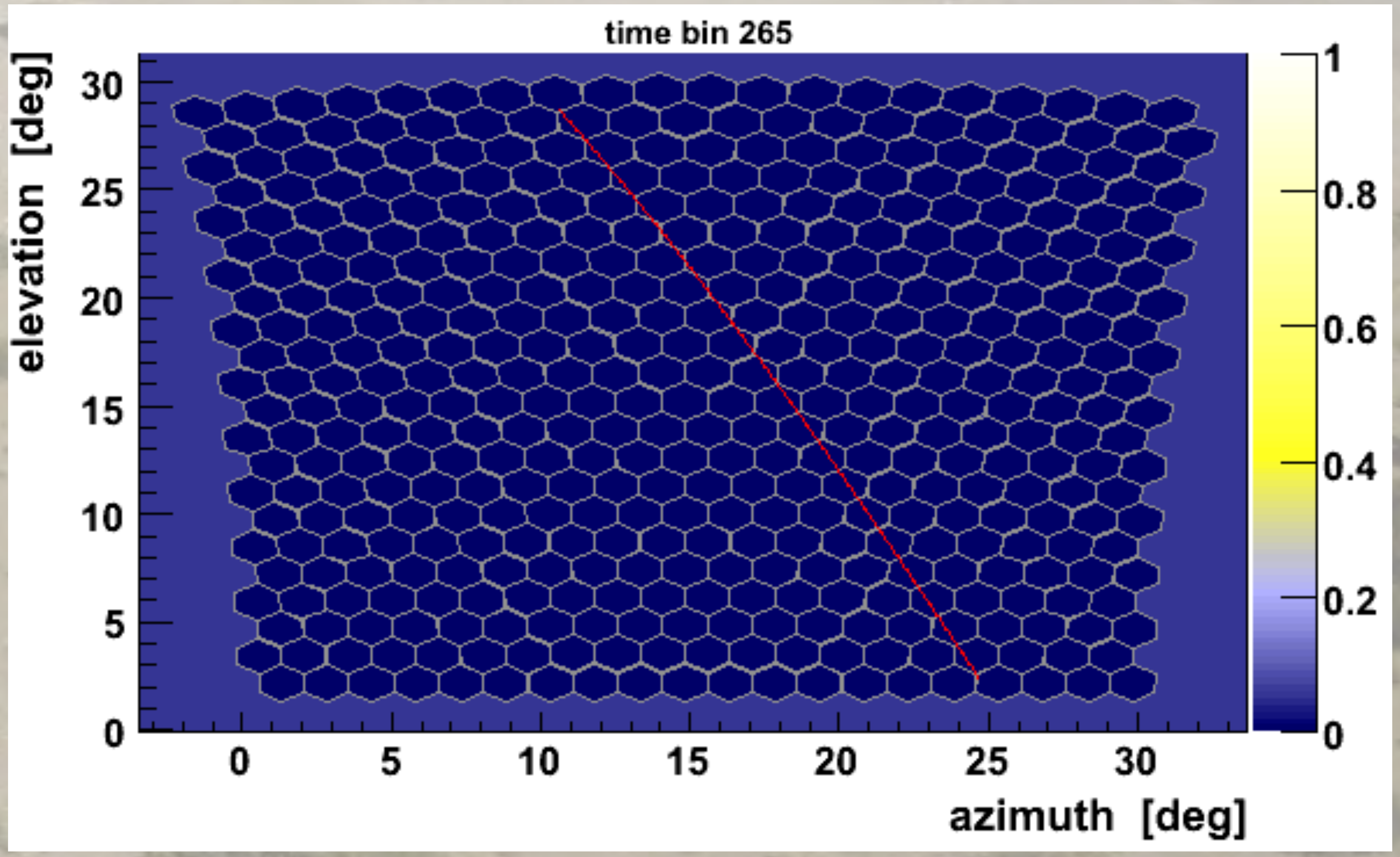
Light Spot as seen by Camera

24 telescopes (6 per site)
12 m² mirrors, Schmidt optics
30°x30° deg field of view
440 PMTs/camera
10 MHz FADC readout



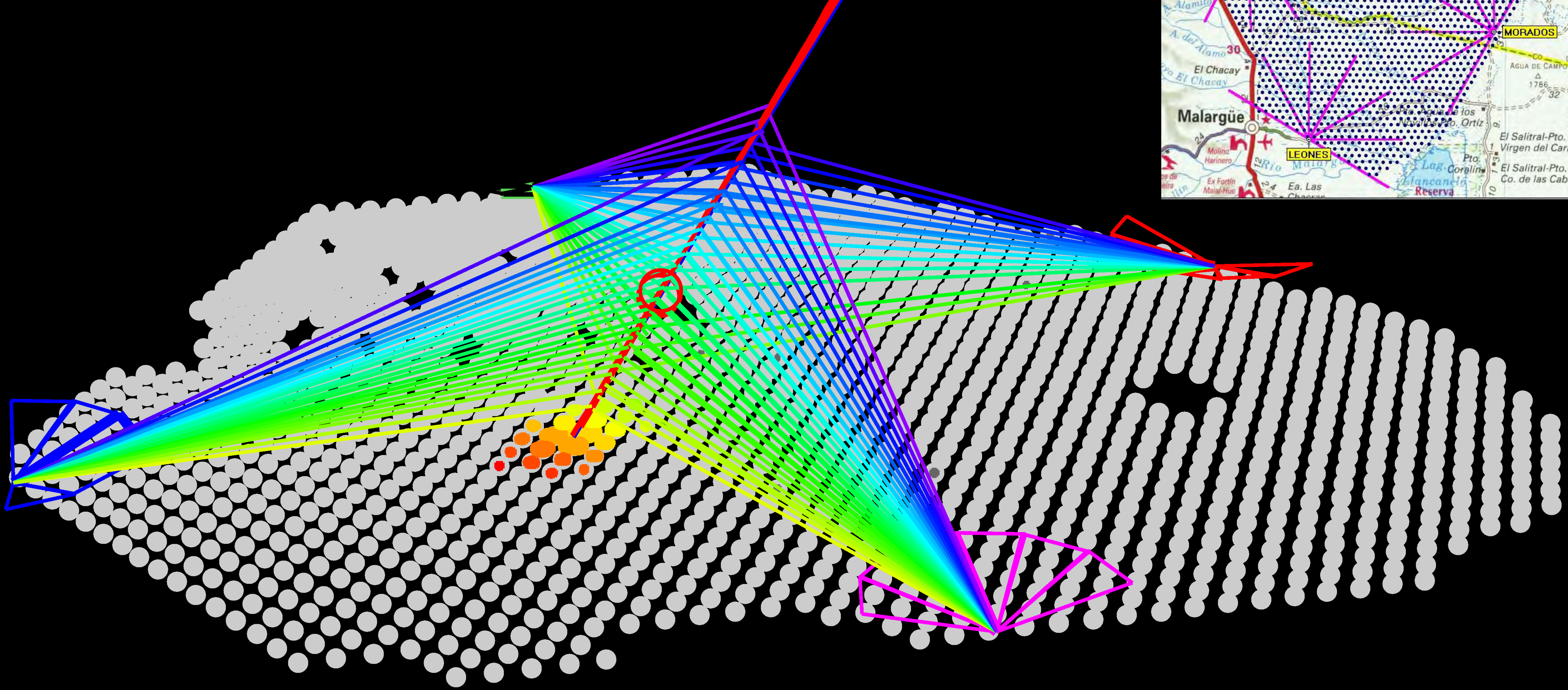


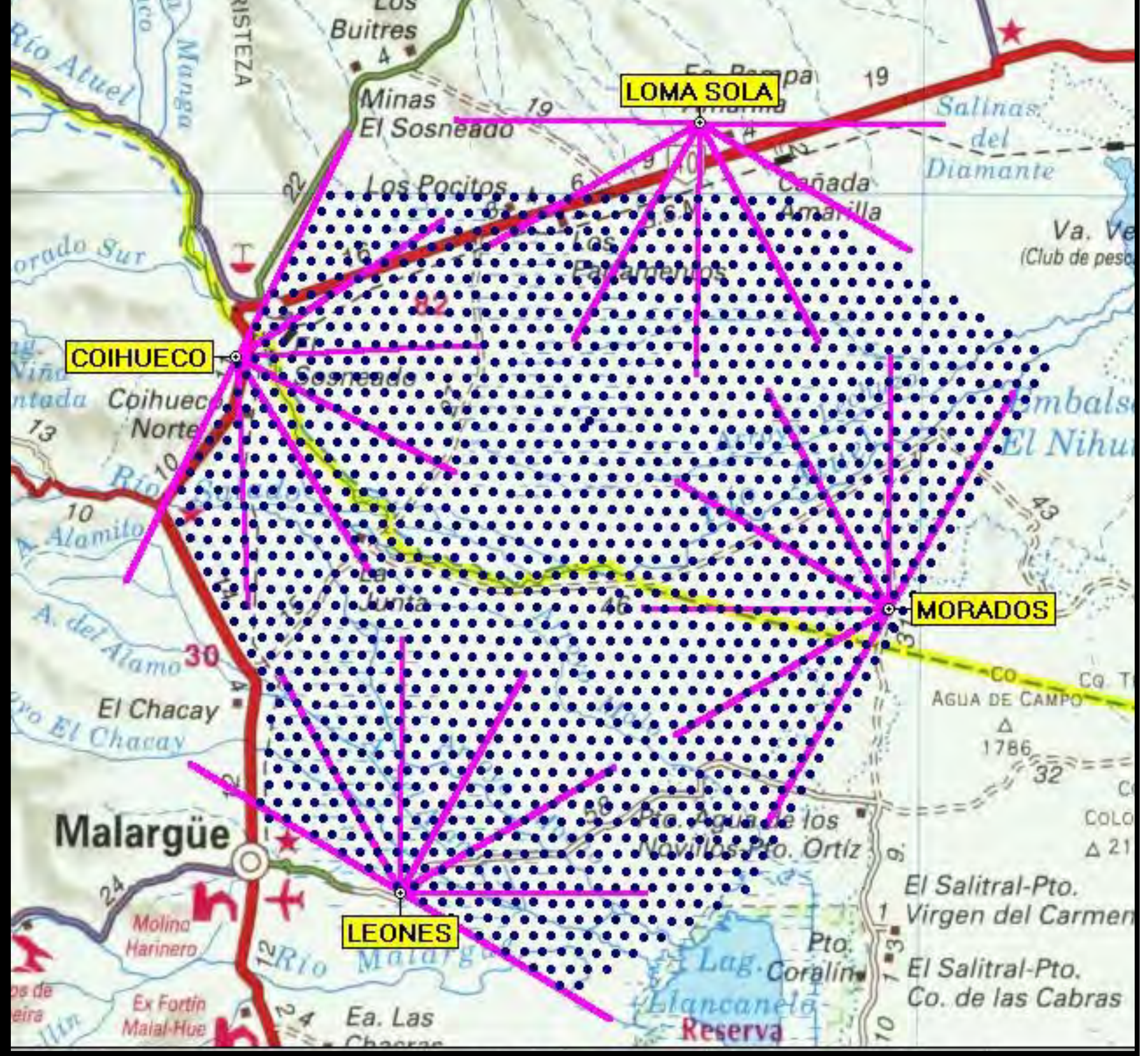




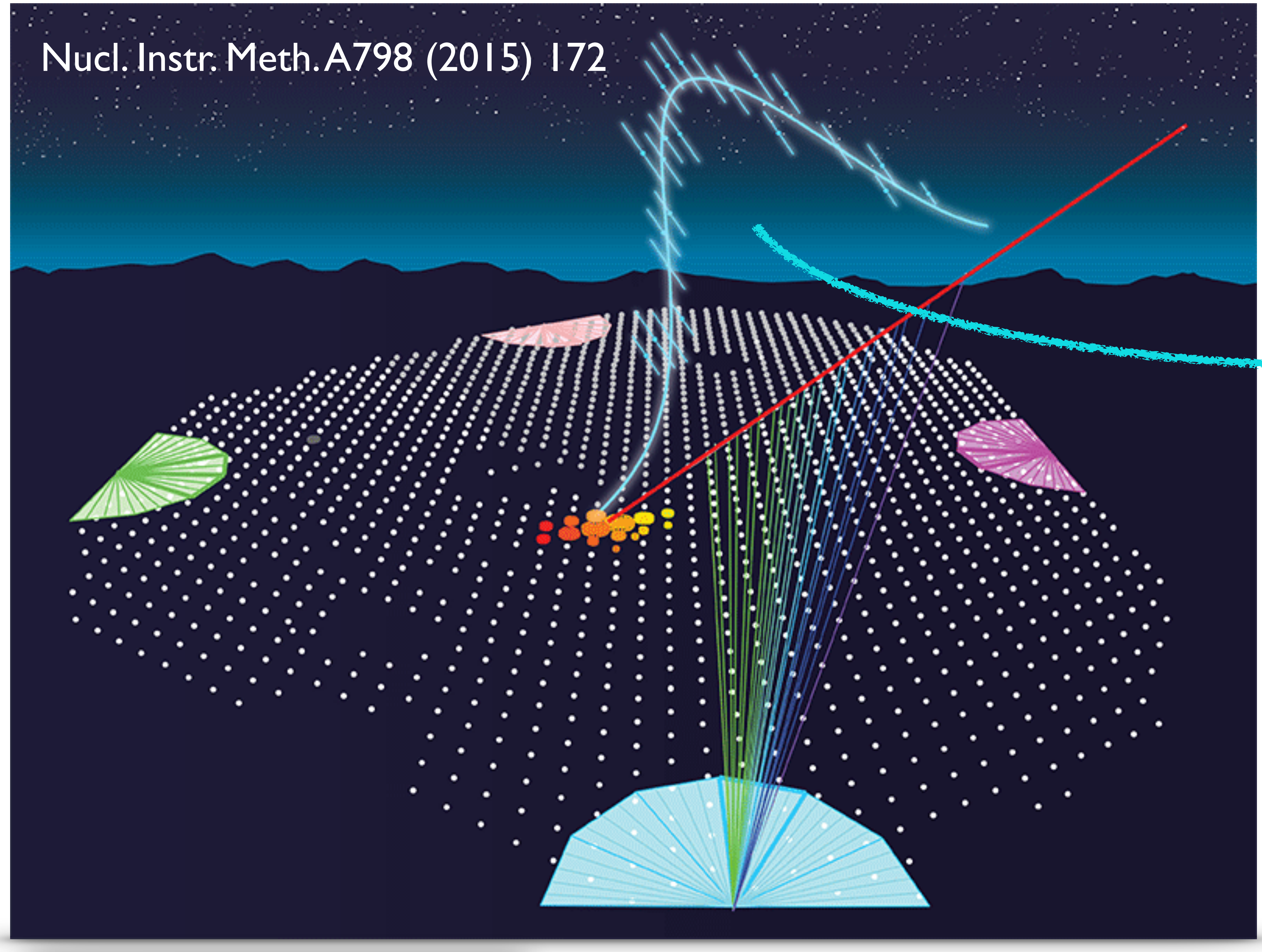
A quadruple event

4 Telescopes + 20 km2 Footprint

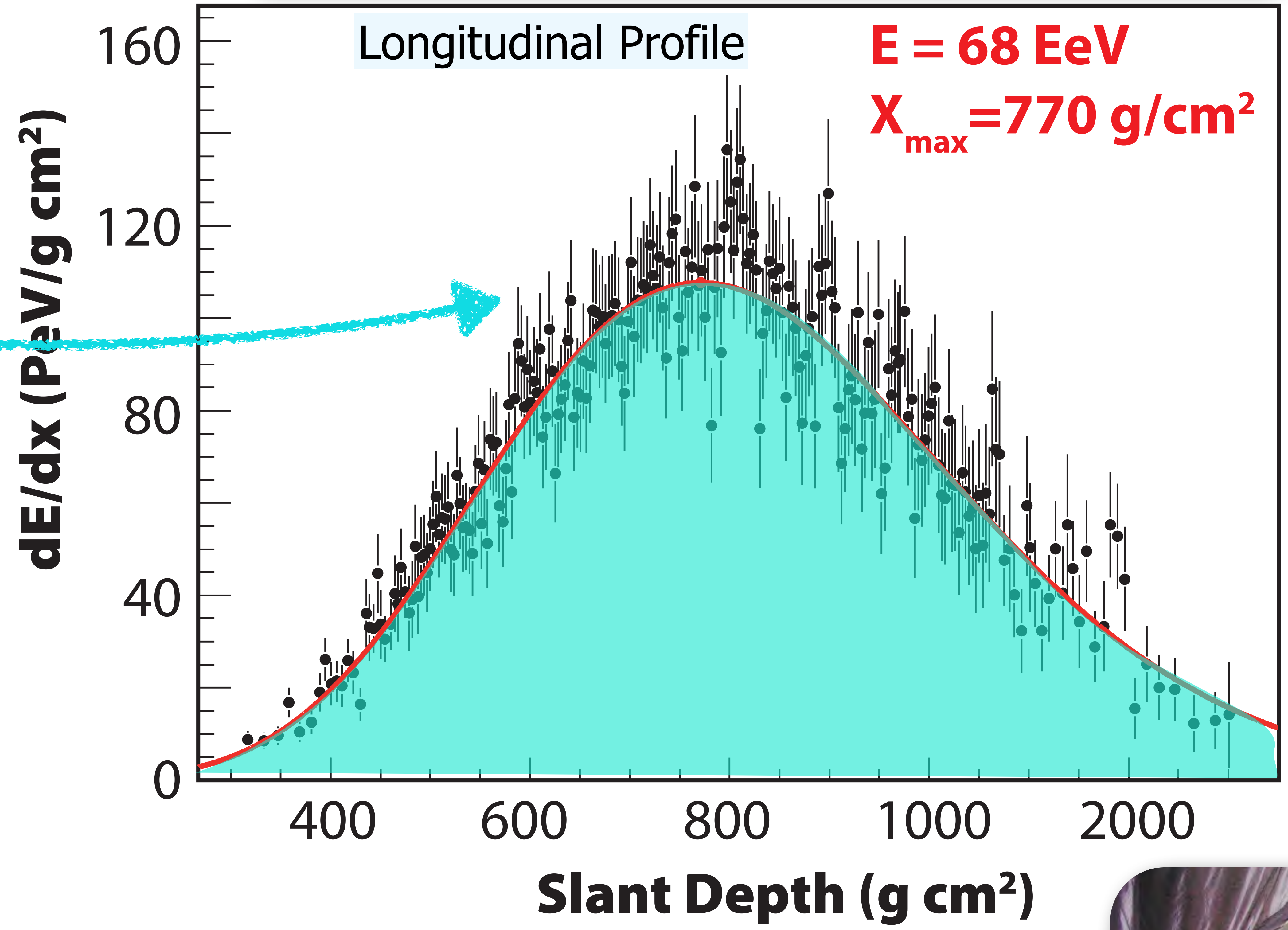




Calibrating the Primary Energy

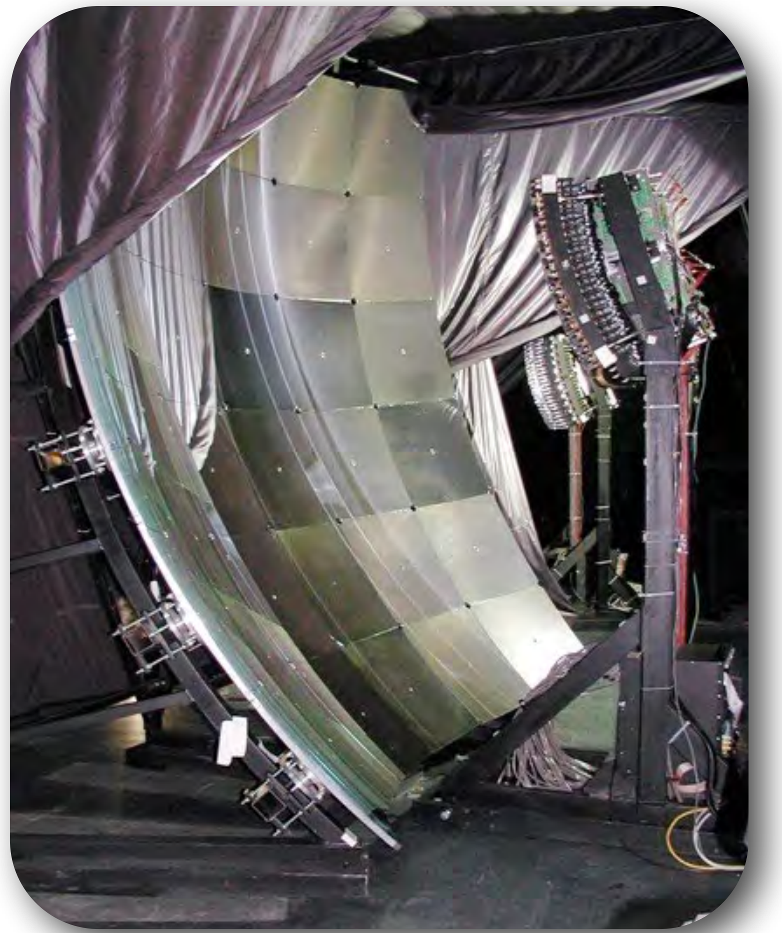


absolute E-scale from light intensity

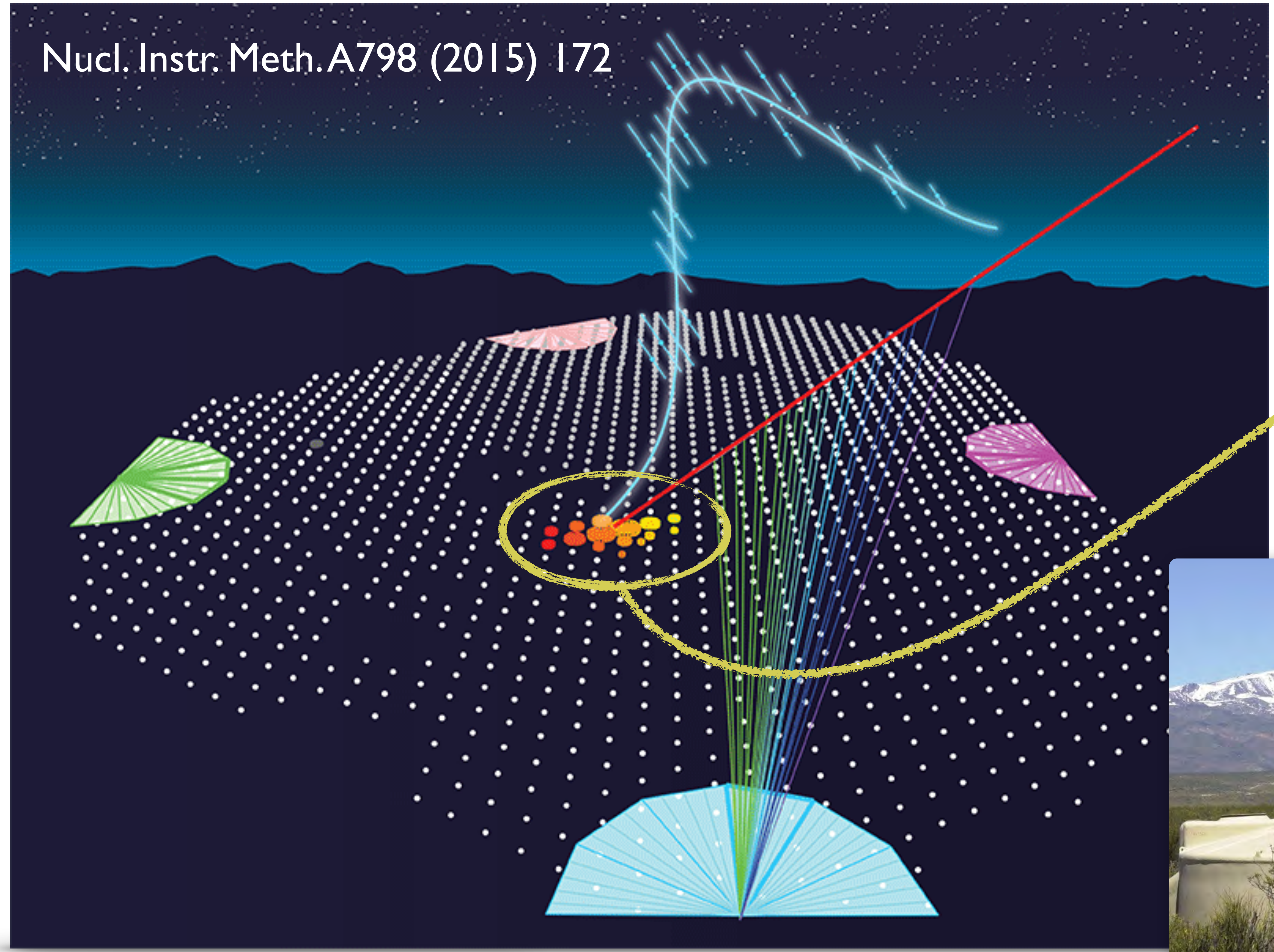


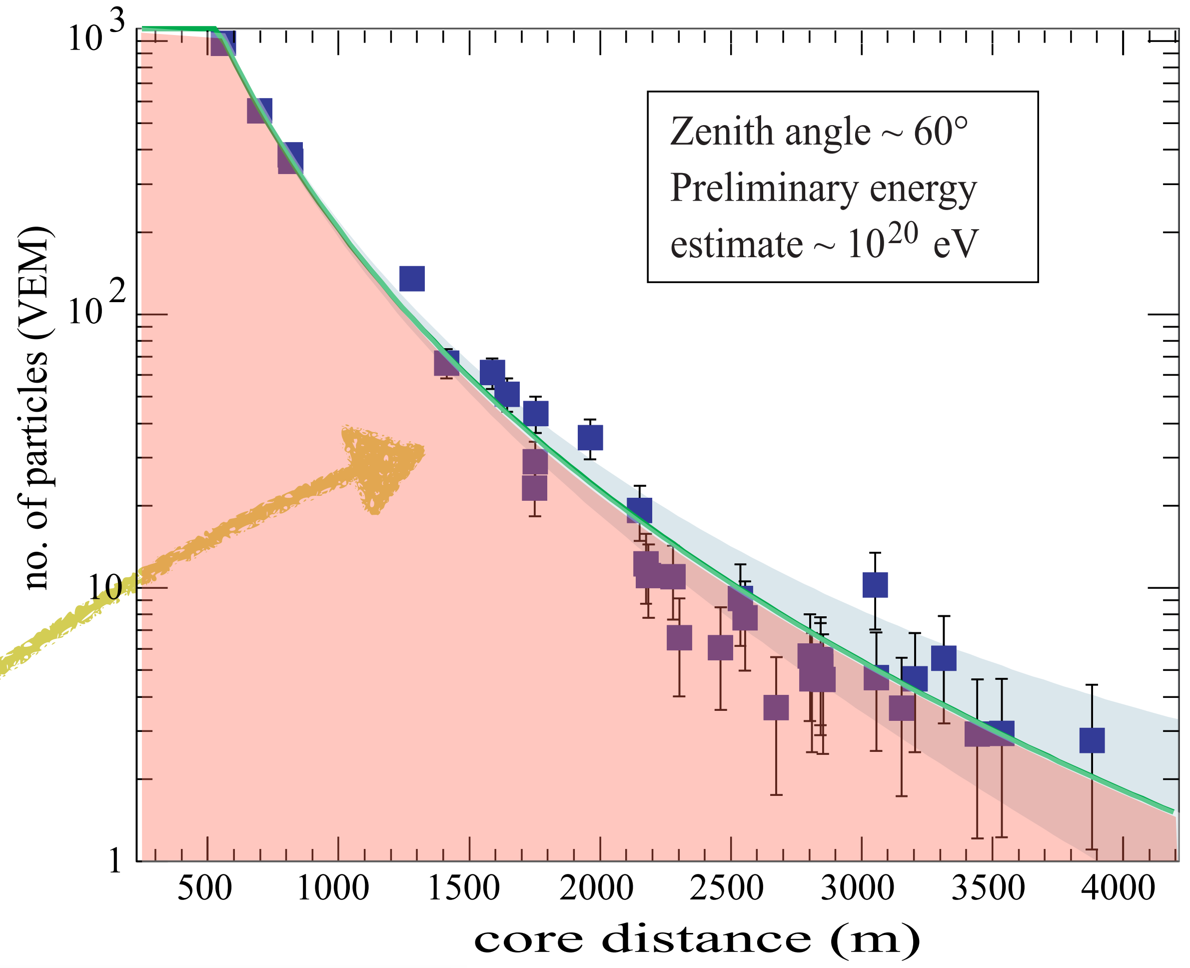
$$E_{cr} = \int \varepsilon_\gamma \frac{dN_\gamma}{dx} dx = \int \frac{dE}{dx} dx$$

fluorescence yield



Calibrating the Primary Energy

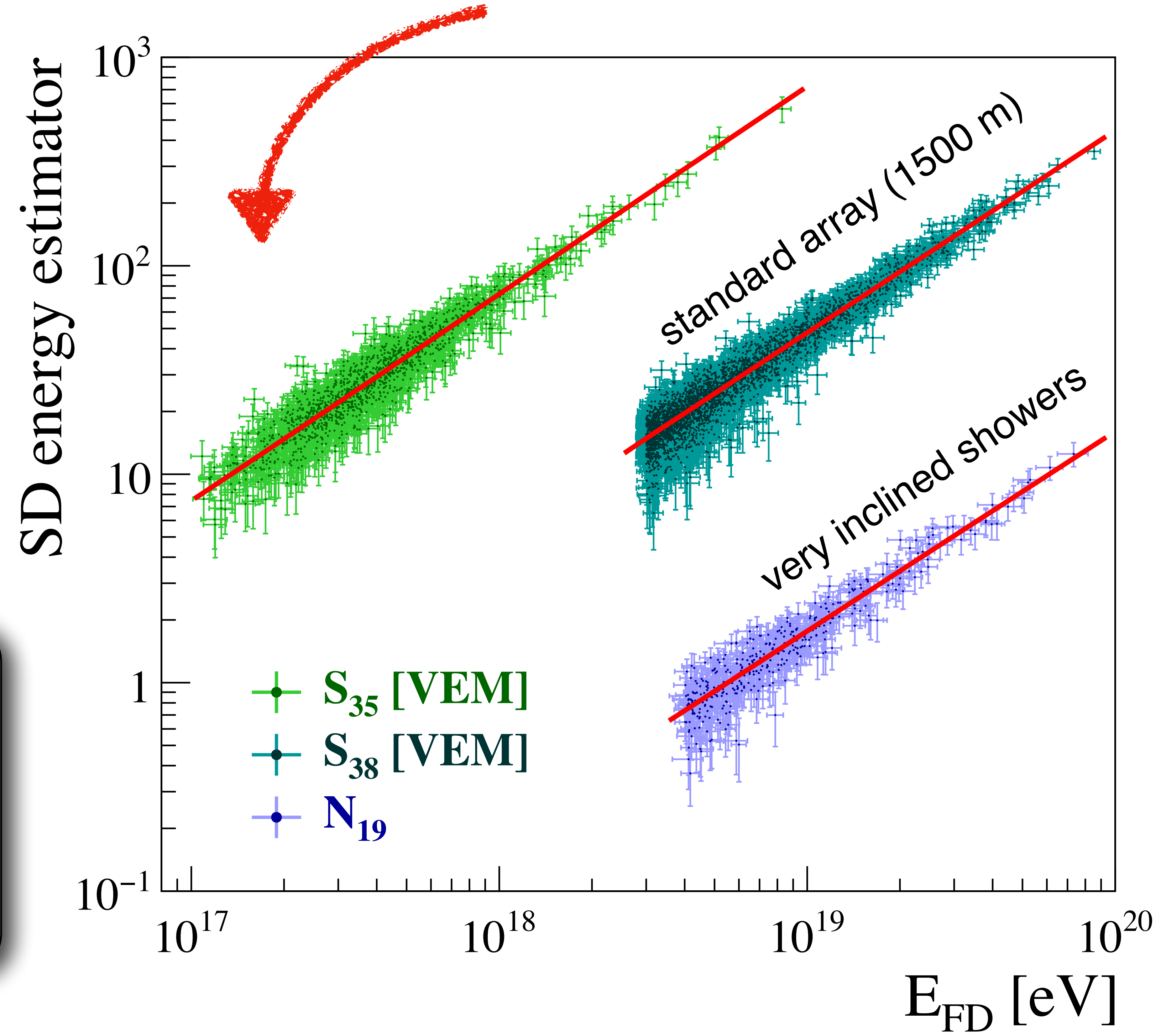




Fit of particle density as a fct of distance from shower core → ρ(r)

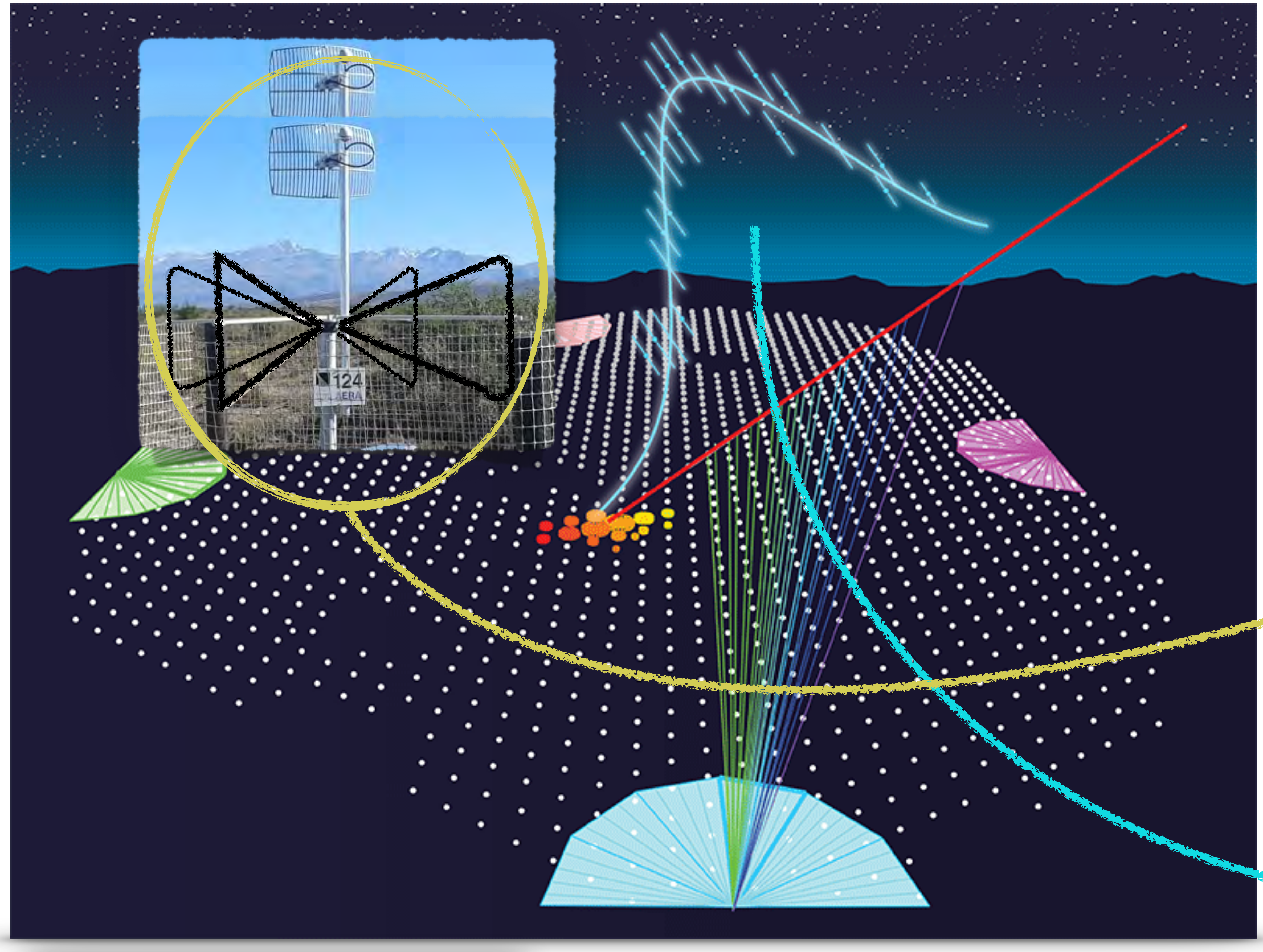
$$S_{tot} = \int 2\pi r \rho(r) dr$$

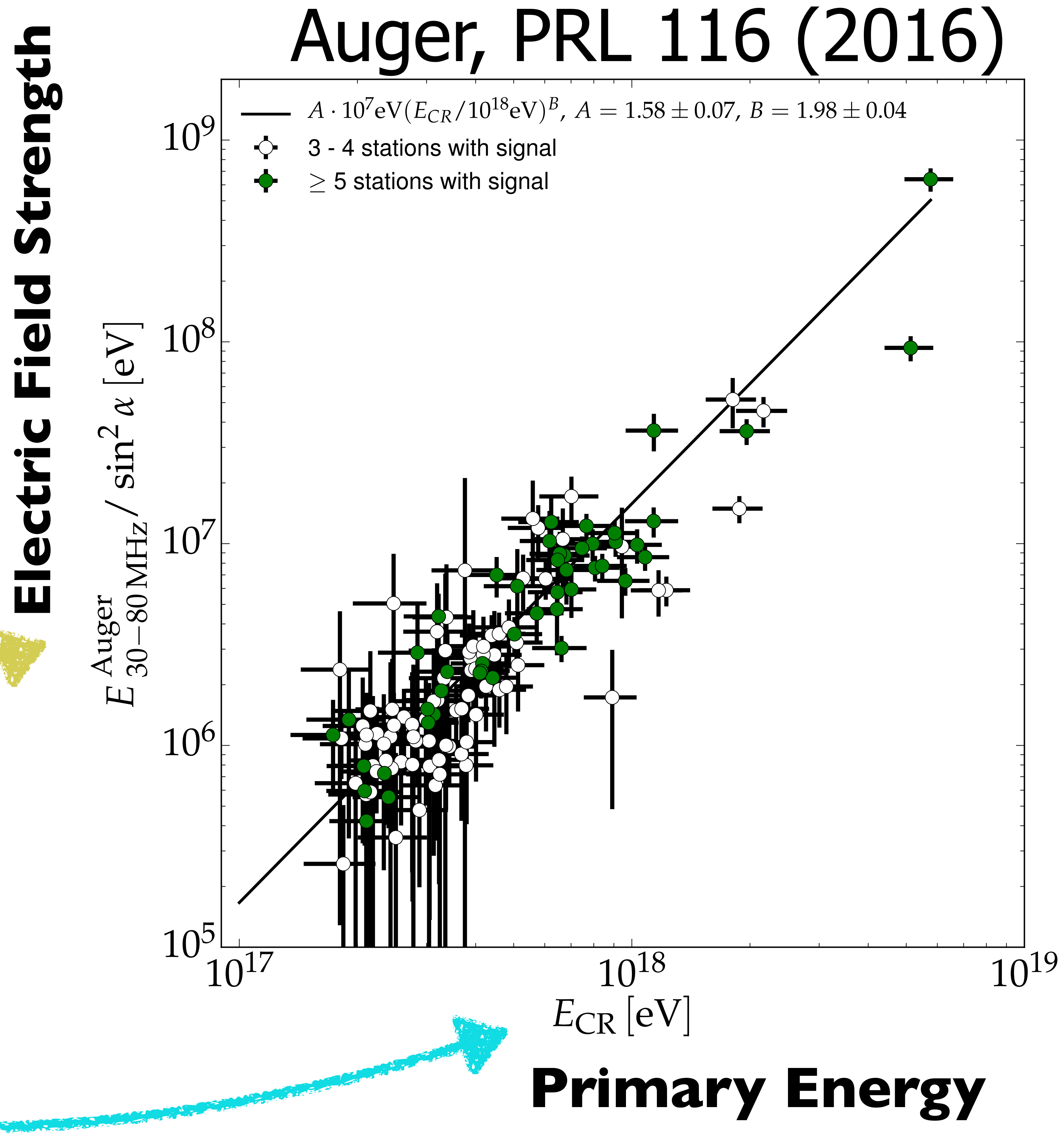
Normalise S_{tot} to specific zenith angle → S_{38}, etc



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

Calibrating the Primary Energy

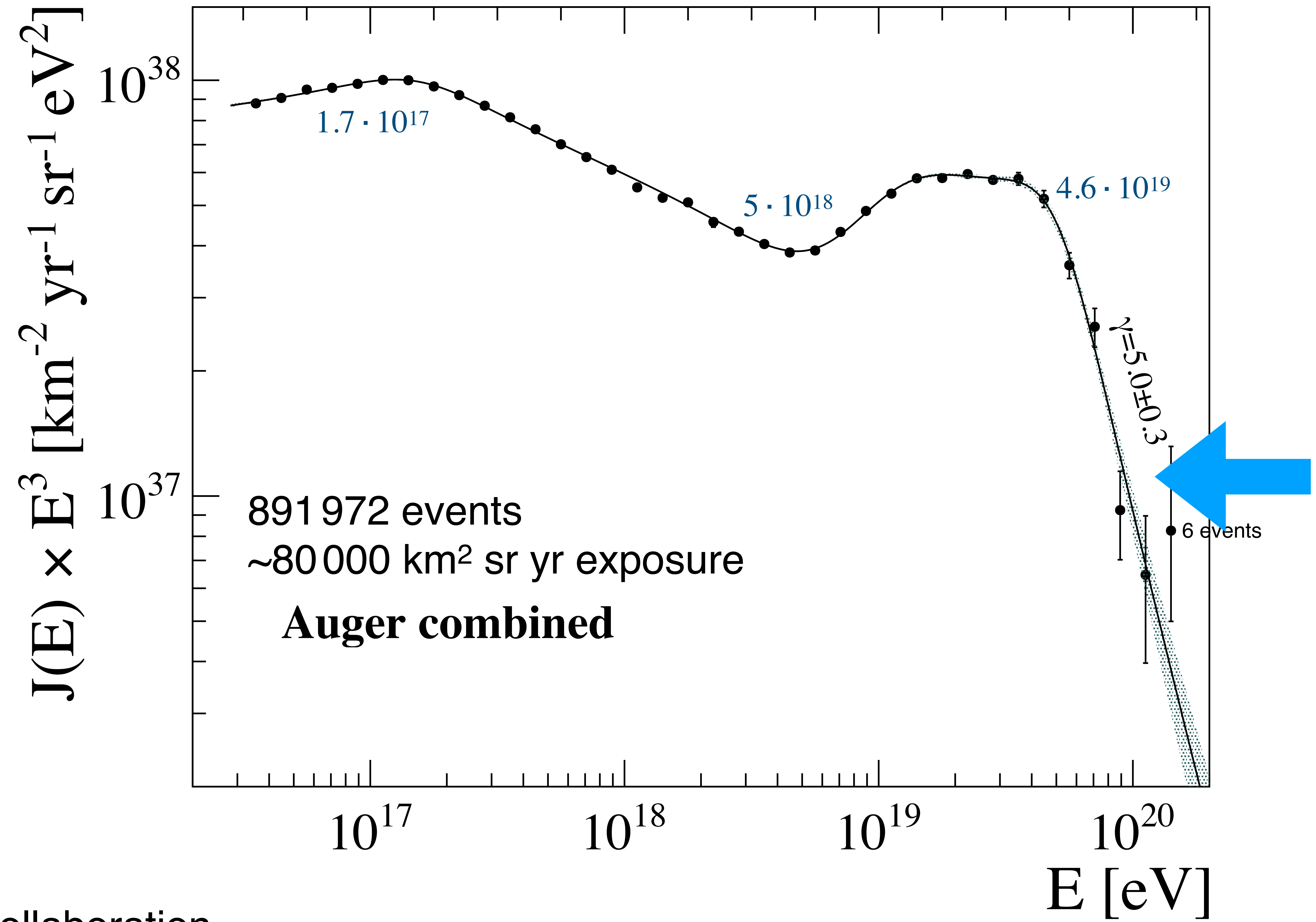




Absolute calibration of radio signal:

18 MeV energy radiated in radio signal @ 1 EeV

The End of the CR Energy Spectrum



Is this the maximum energy of cosmic accelerators or the famous GZK effect?

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

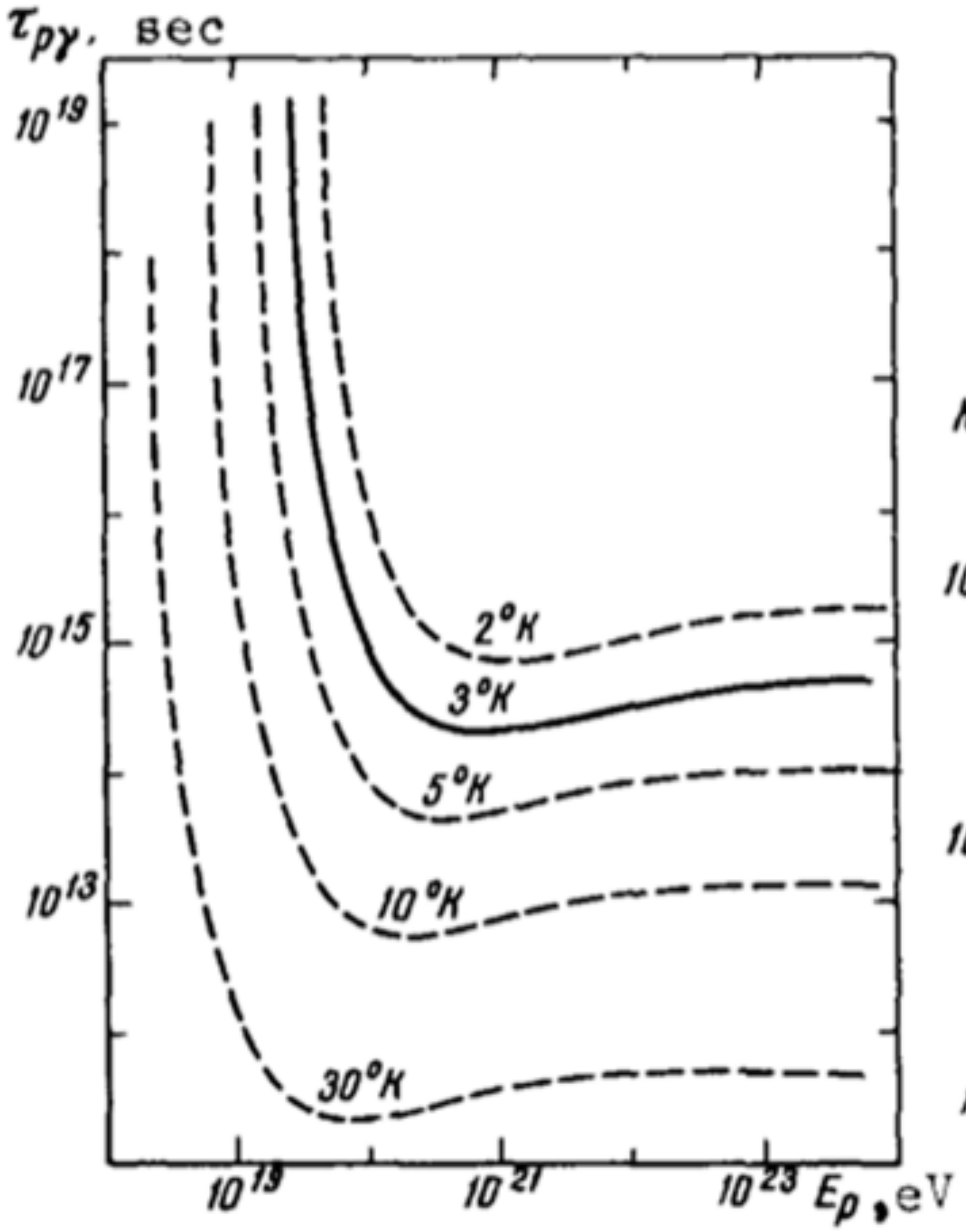
1966: „End to the CR Spectrum ?"

Volume 16, Number 17 PHYSICAL REVIEW LETTERS 25 April 1966

END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

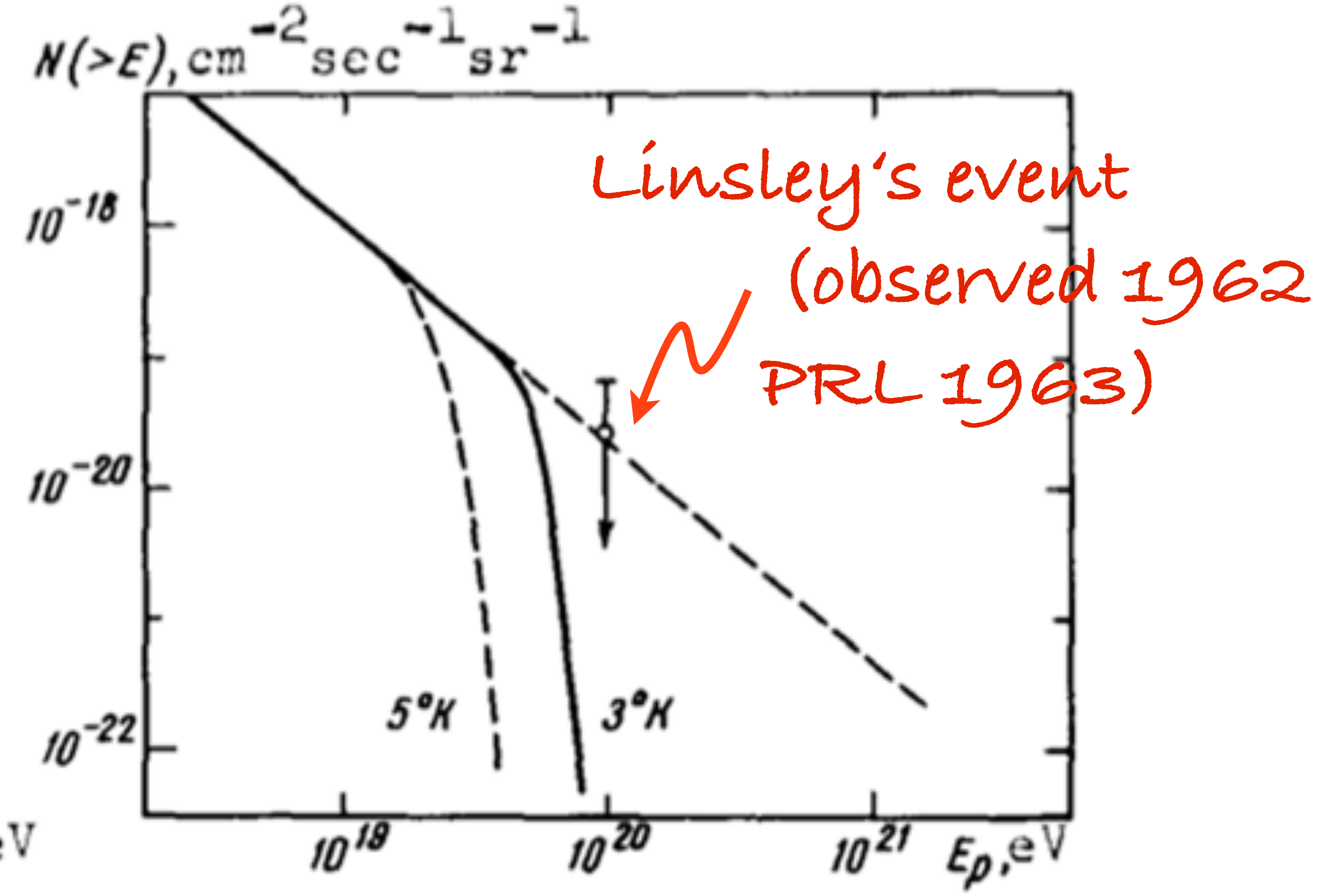
Cornell University, Ithaca, New York
(Received 1 April 1966)



Greisen,
Zatsepin & Kuz'min

UPPER LIMIT OF THE SPECTRUM OF COSMIC RAYS

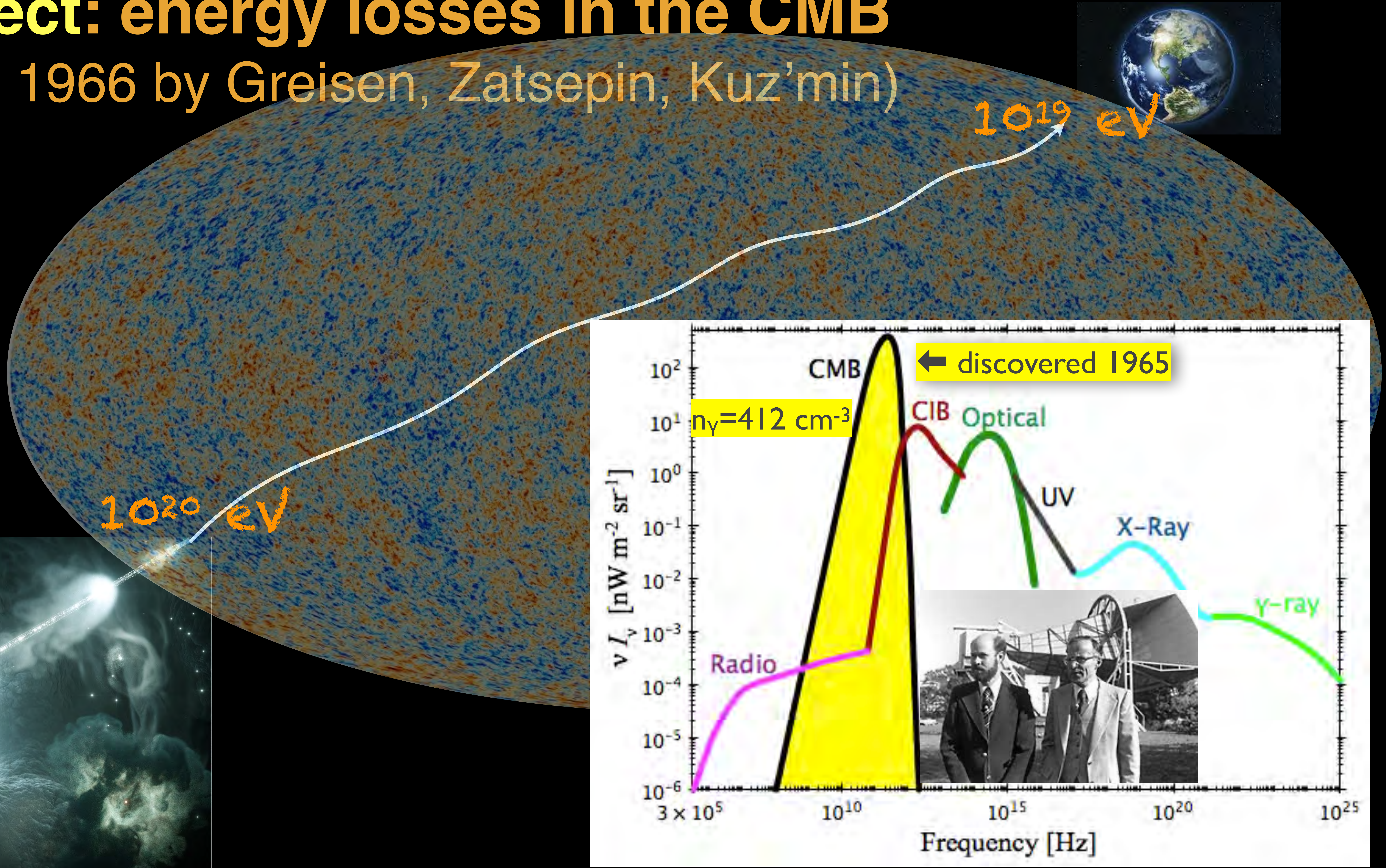
G. T. Zatsepin and V. A. Kuz'min
P. N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 26 May 1966
ZhETF Pis'ma 4, No. 3, 114-117, 1 August 1966



John Linsley @ Volcano Ranch

GZK-effect: energy losses in the CMB

(predicted 1966 by Greisen, Zatsepin, Kuz'min)



Picture: DESY,
Science Communication Lab

GZK-effect: energy losses in the CMB

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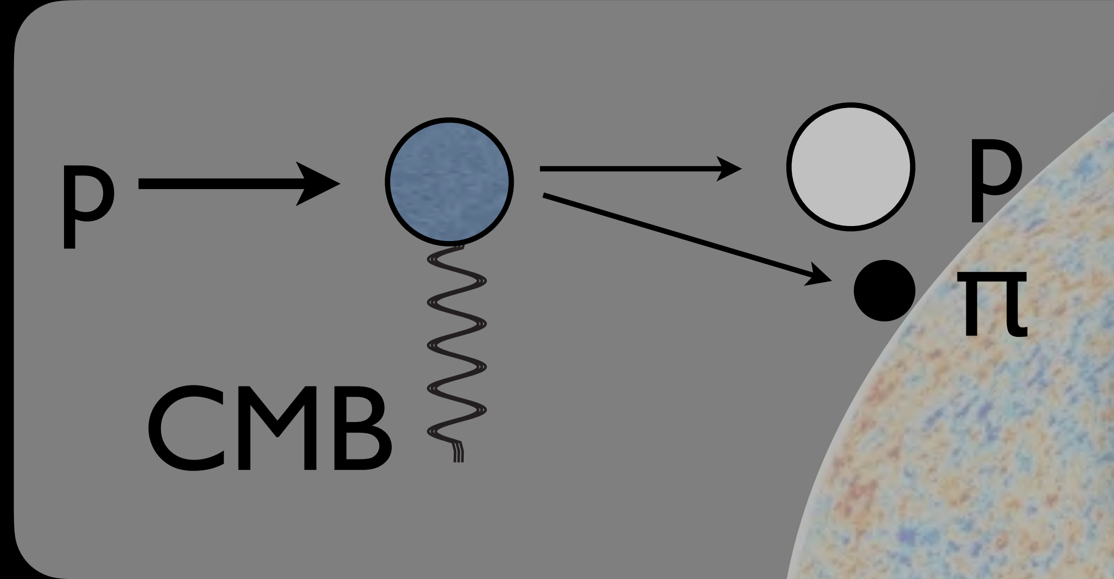


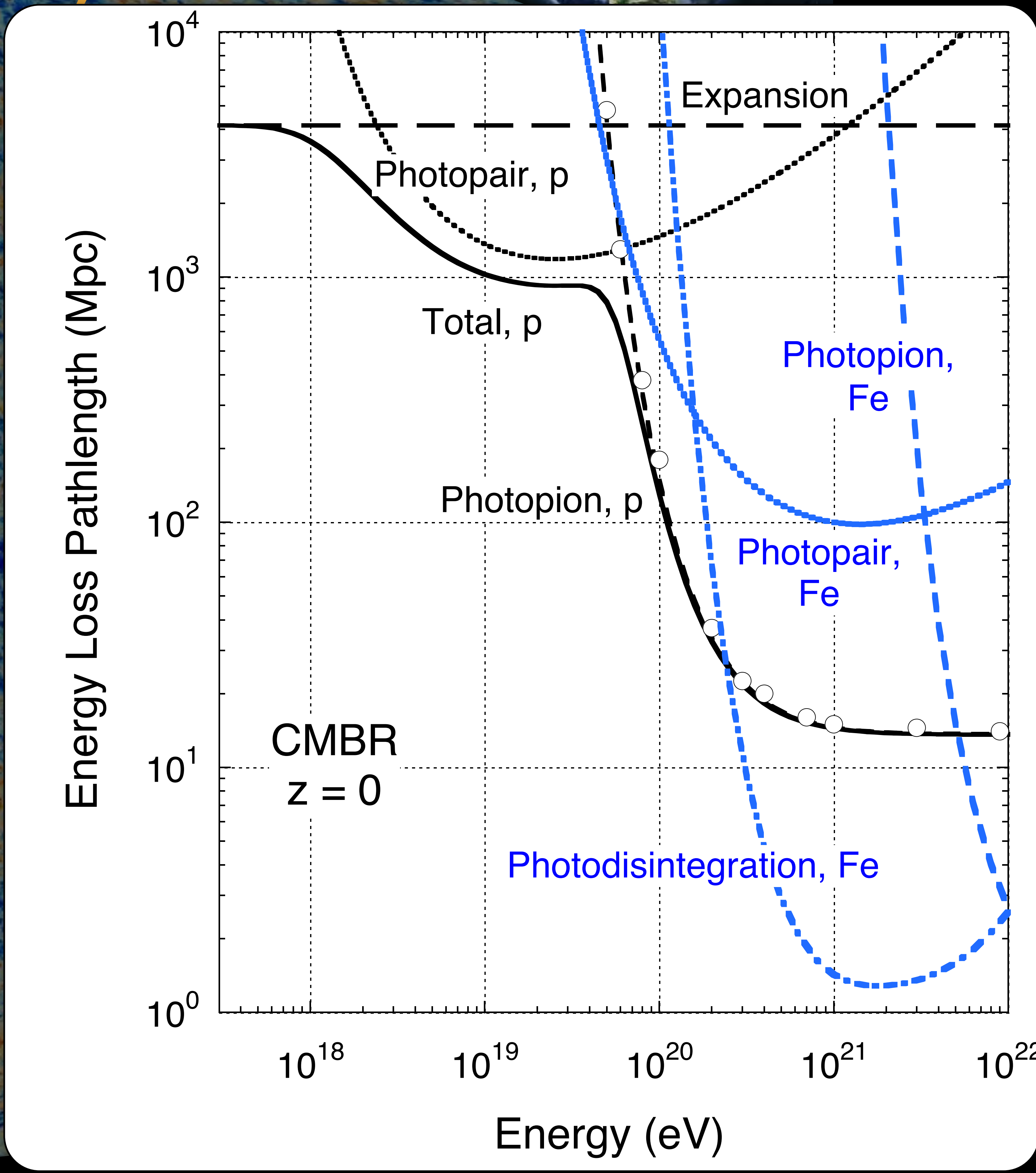
photo-pion production

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

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

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

$$\lambda_{eff} = \left(\int n(\epsilon) \cdot \sigma_{\gamma p}(\epsilon) d\epsilon\right)^{-1} \approx 8\ \text{Mpc}$$

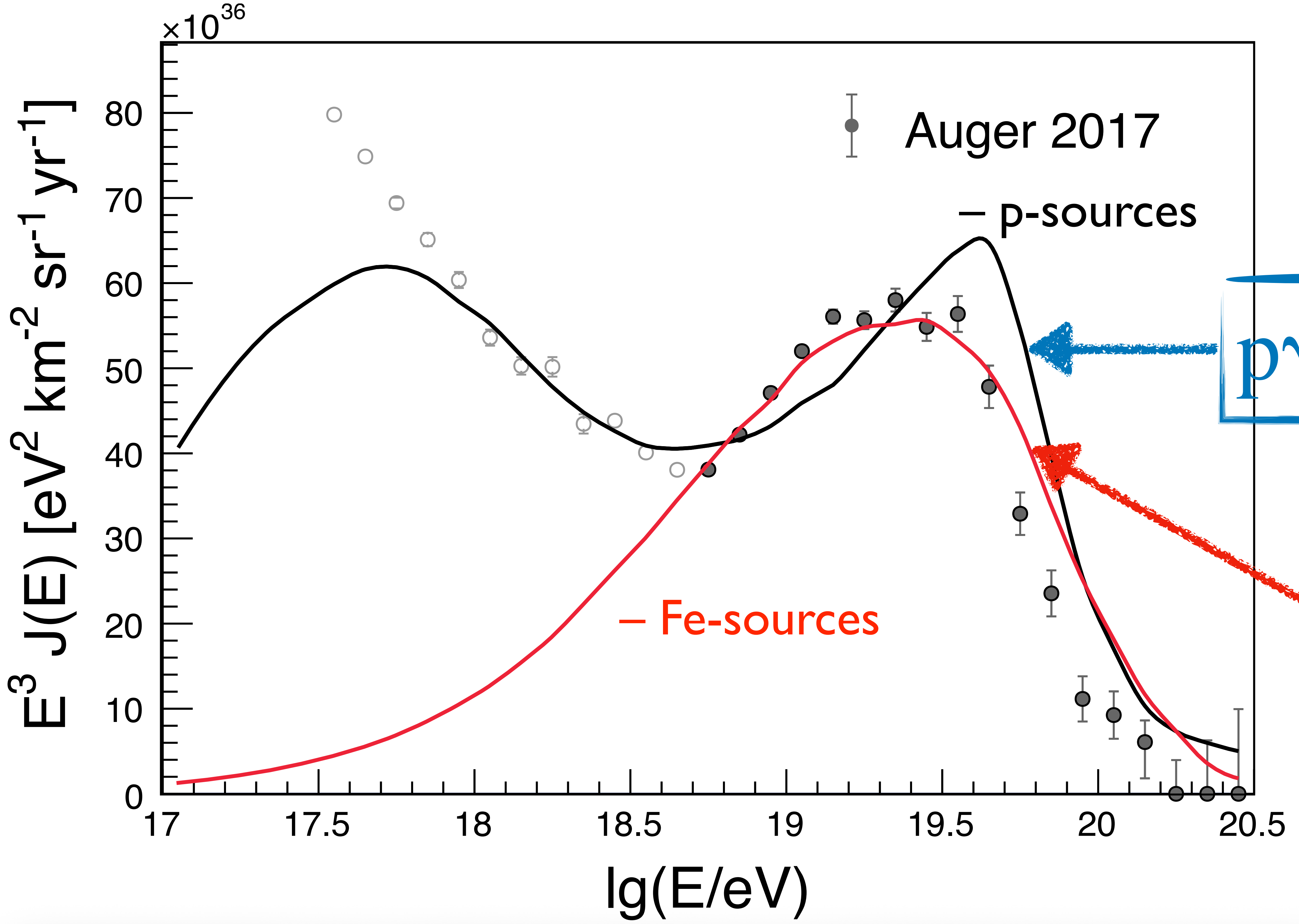


Picture: DESY,
Science Communication Lab

Nuclei suffer photo disintegration:

$$A + \gamma_{CMB} \rightarrow (A-1) + n \ldots$$

Simulation of GZK-effect



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

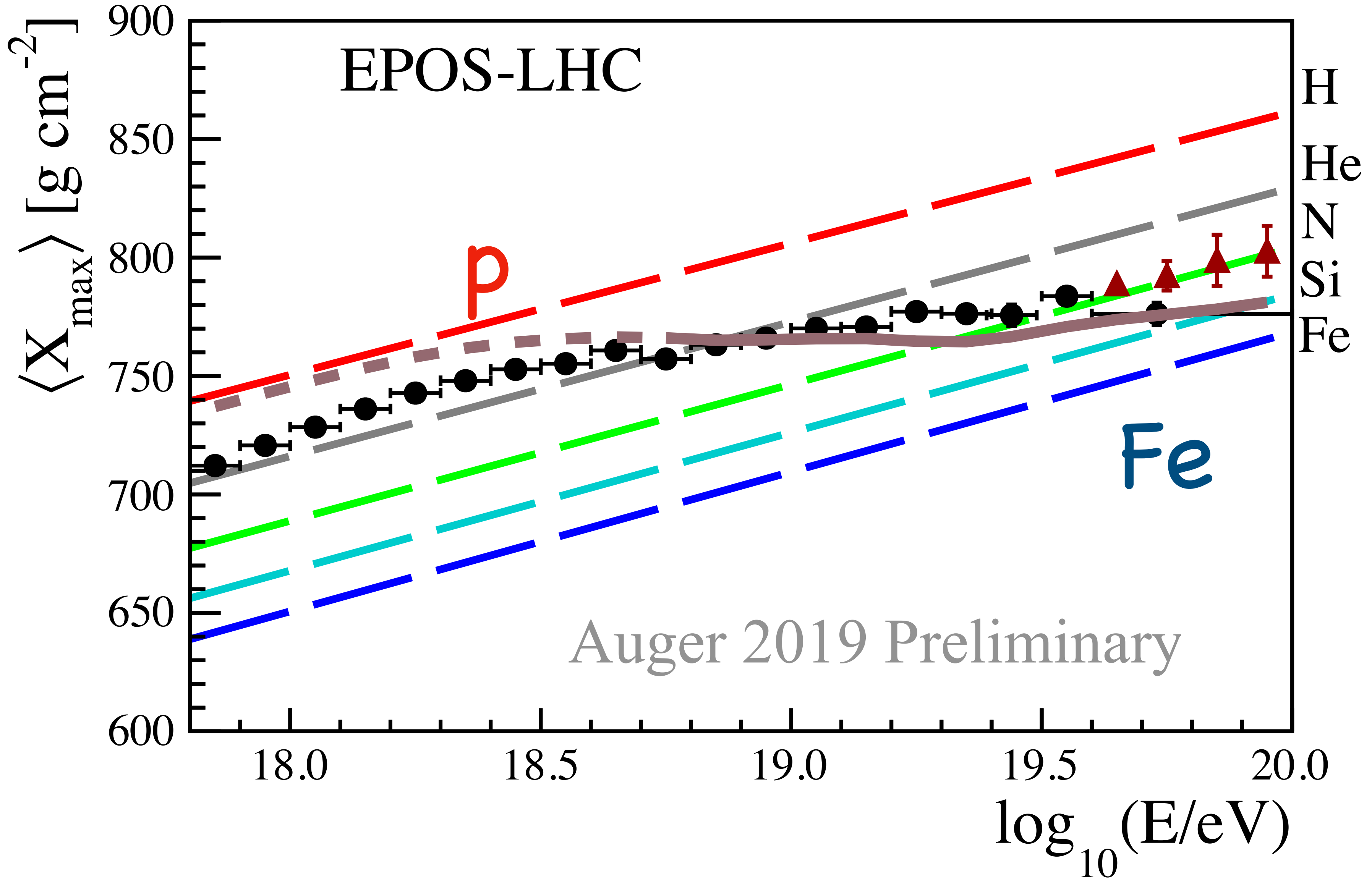
$Fe+\gamma \rightarrow$ „Cr“ $+ p + n$

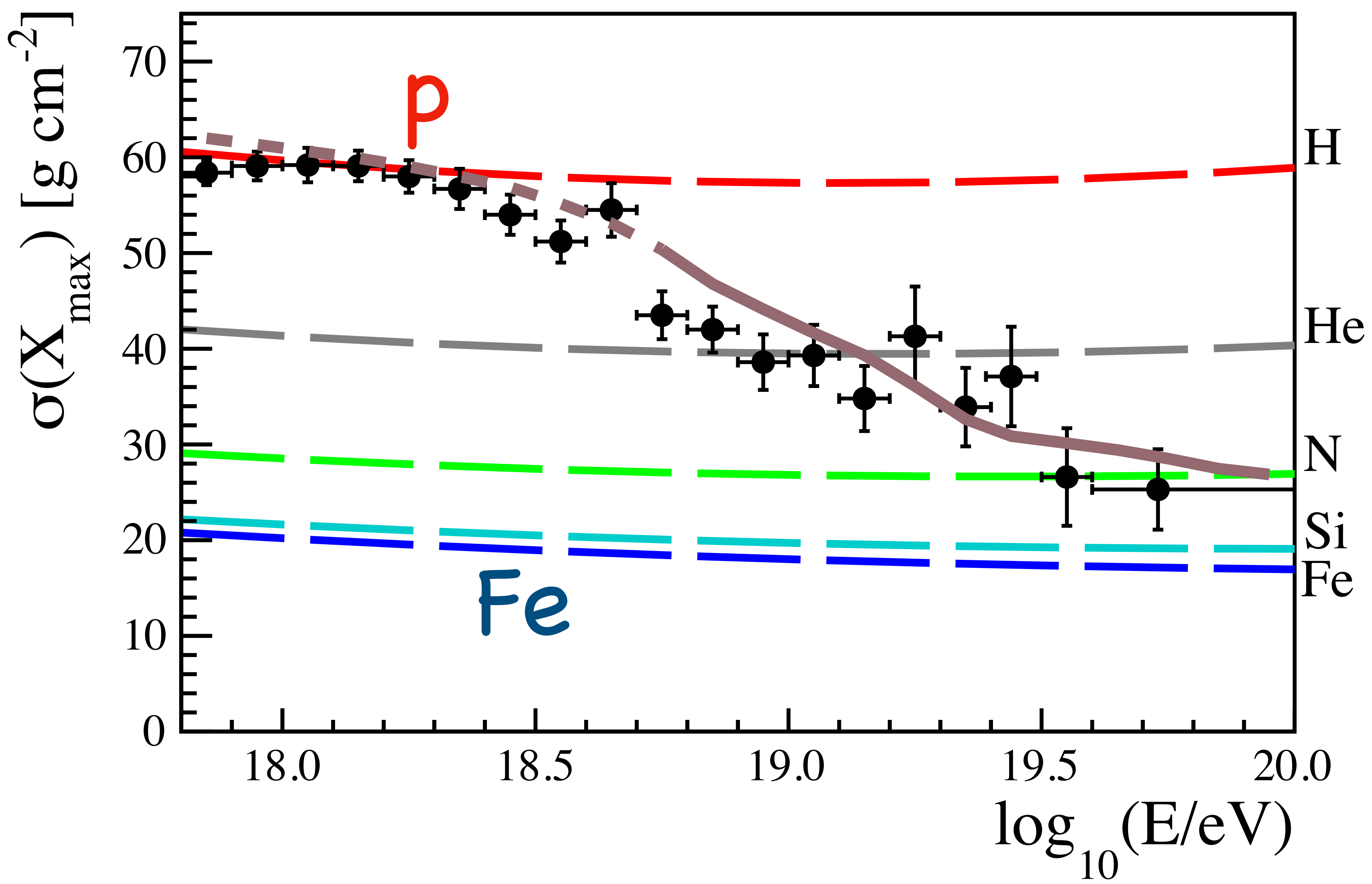
The cut-off shape is reasonably well described

However, …
the composition is neither protons nor Fe

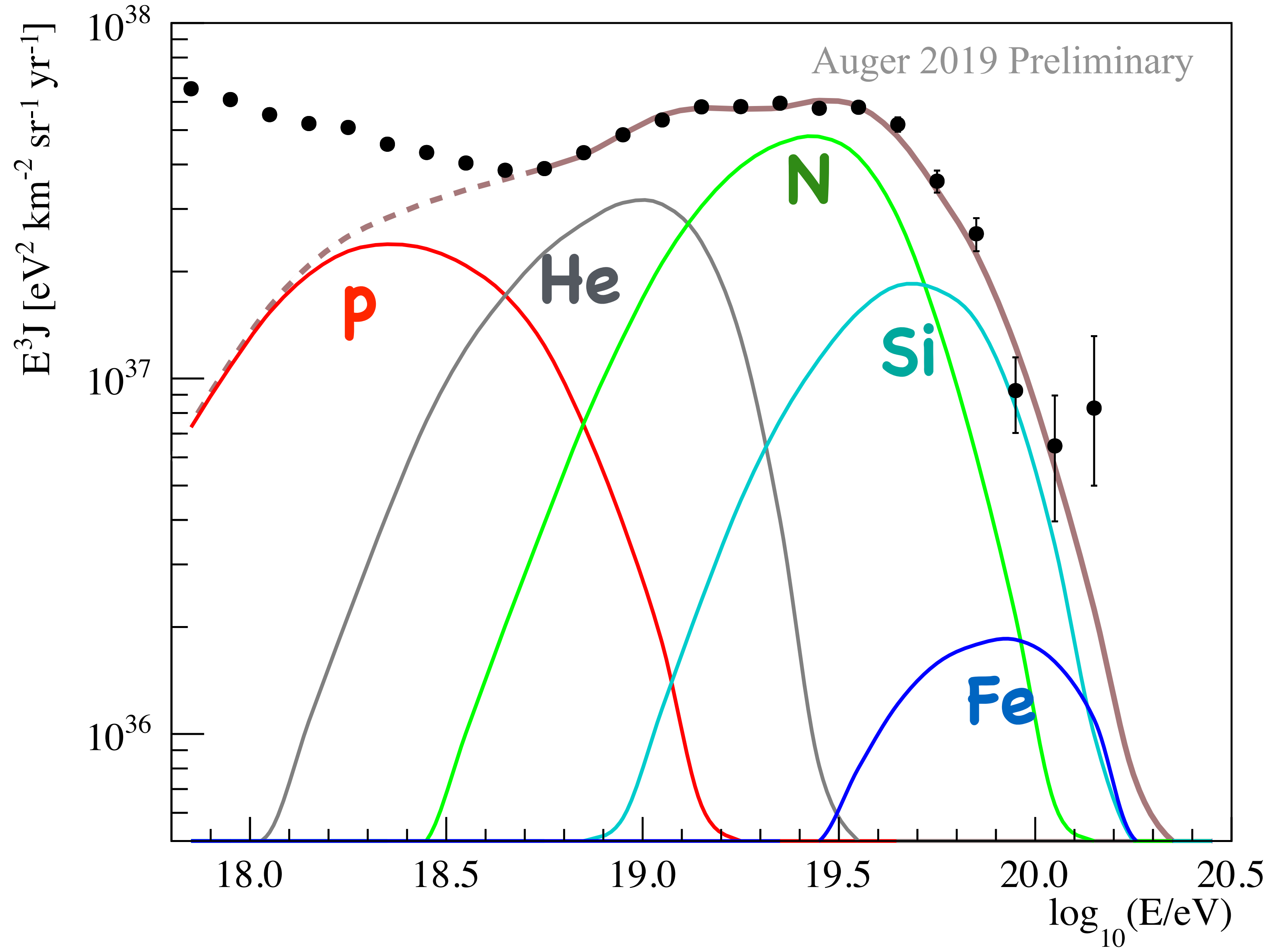
Increasingly Heavy Composition

Auger Coll., PoS(ICRC2019)004





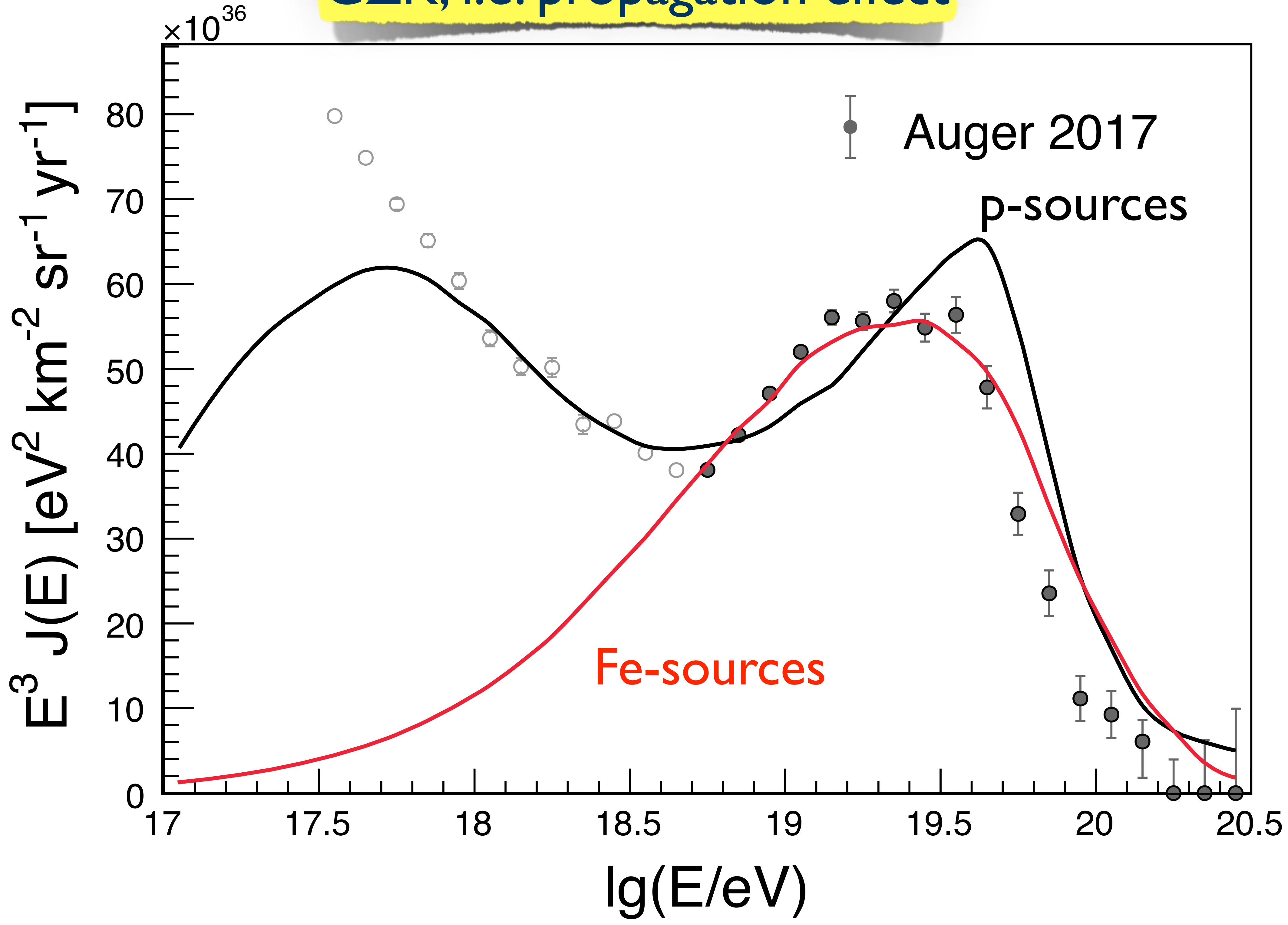
$$E_{max,CR} \propto Z_{CR} \cdot (R \times B)_{source}$$



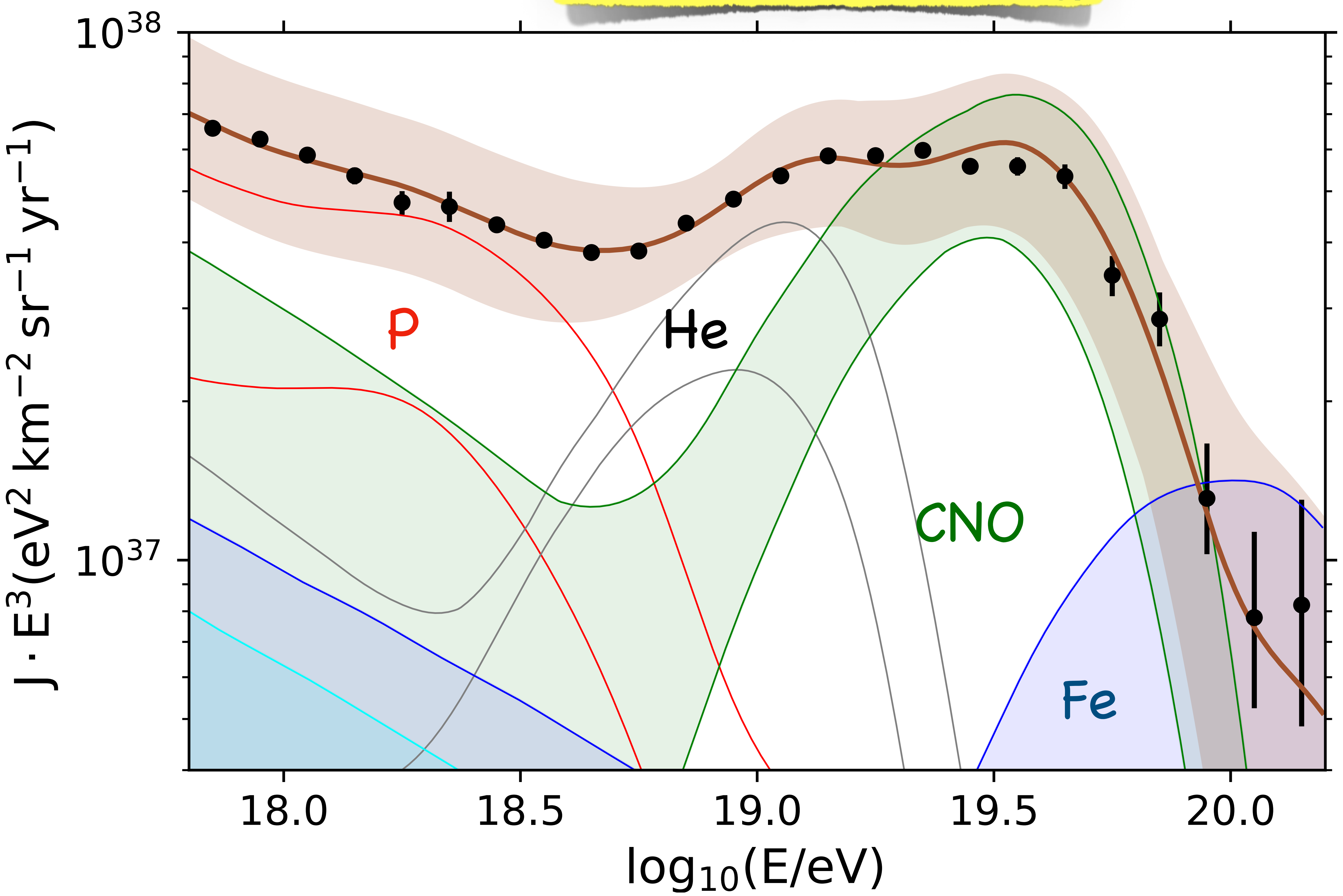
Perfect fit to the data, but implies that we see the maximum source rigidity

GZK effect or Maximum Source energy ?

GZK, i.e. propagation effect

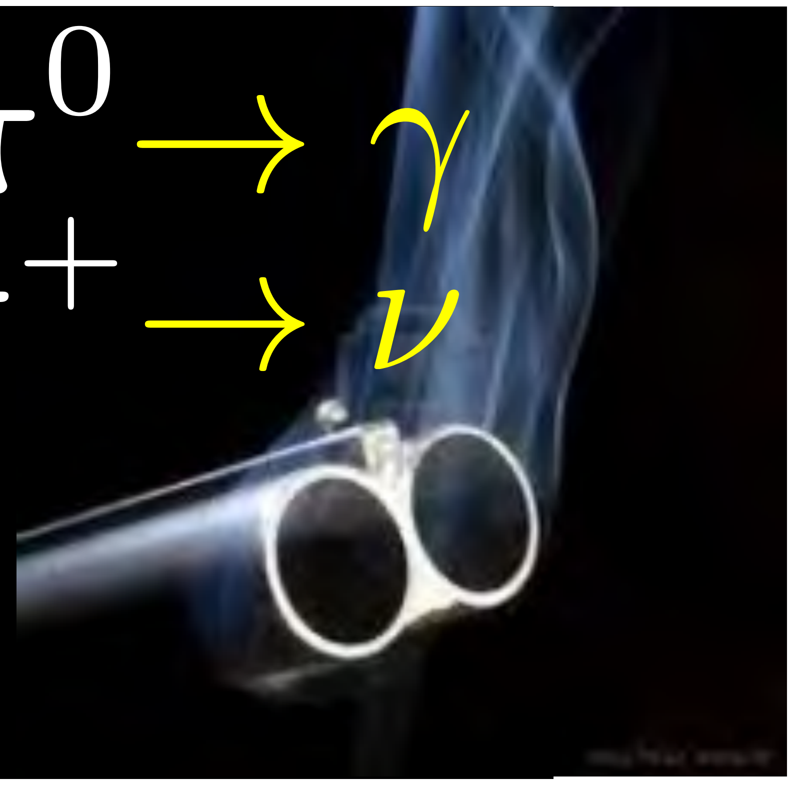


Maximum source energy



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

smoking gun…

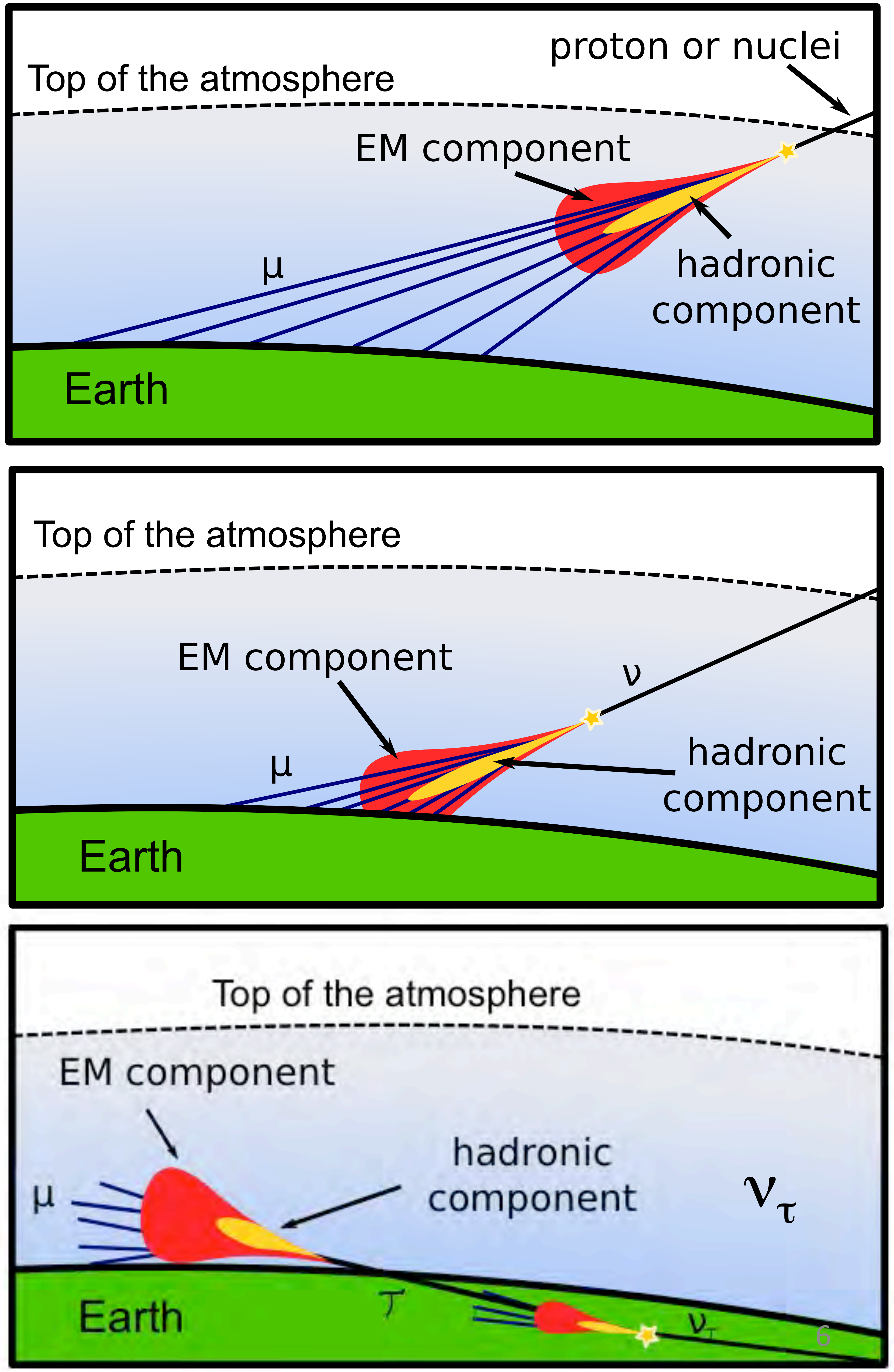


This realisation will make astronomy more difficult (note CR deflections ~ Z)

EeV Neutrinos detectable in inclined air 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



hadronic induced shower at large zenith angles
→ no em-component („old" shower)

neutrino induced shower at large zenith angles
→ normal em-component („young" shower)

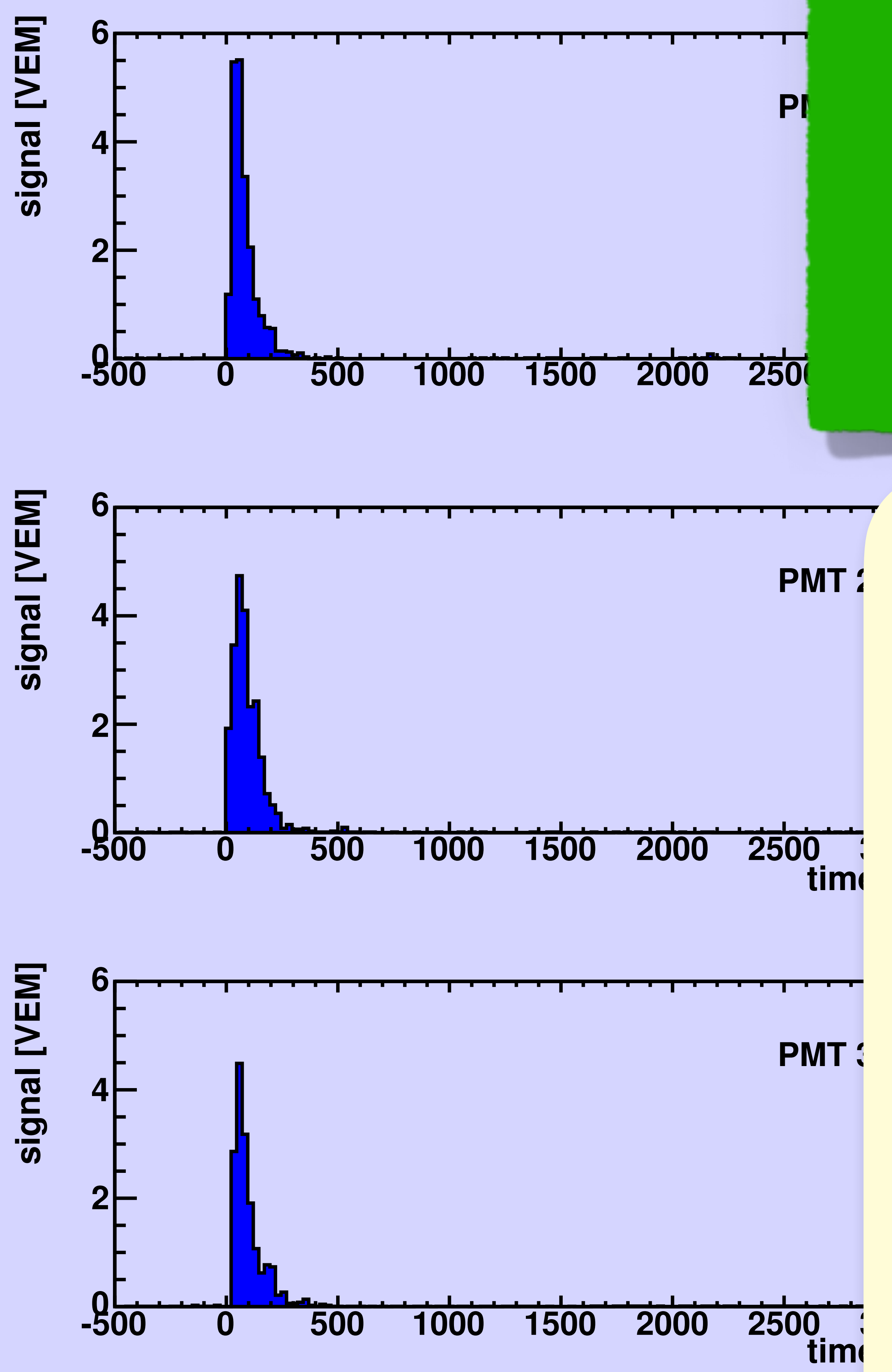
tau-neutrino in Earth skimming event produces up-going young shower

Identifying νs in surface detector data

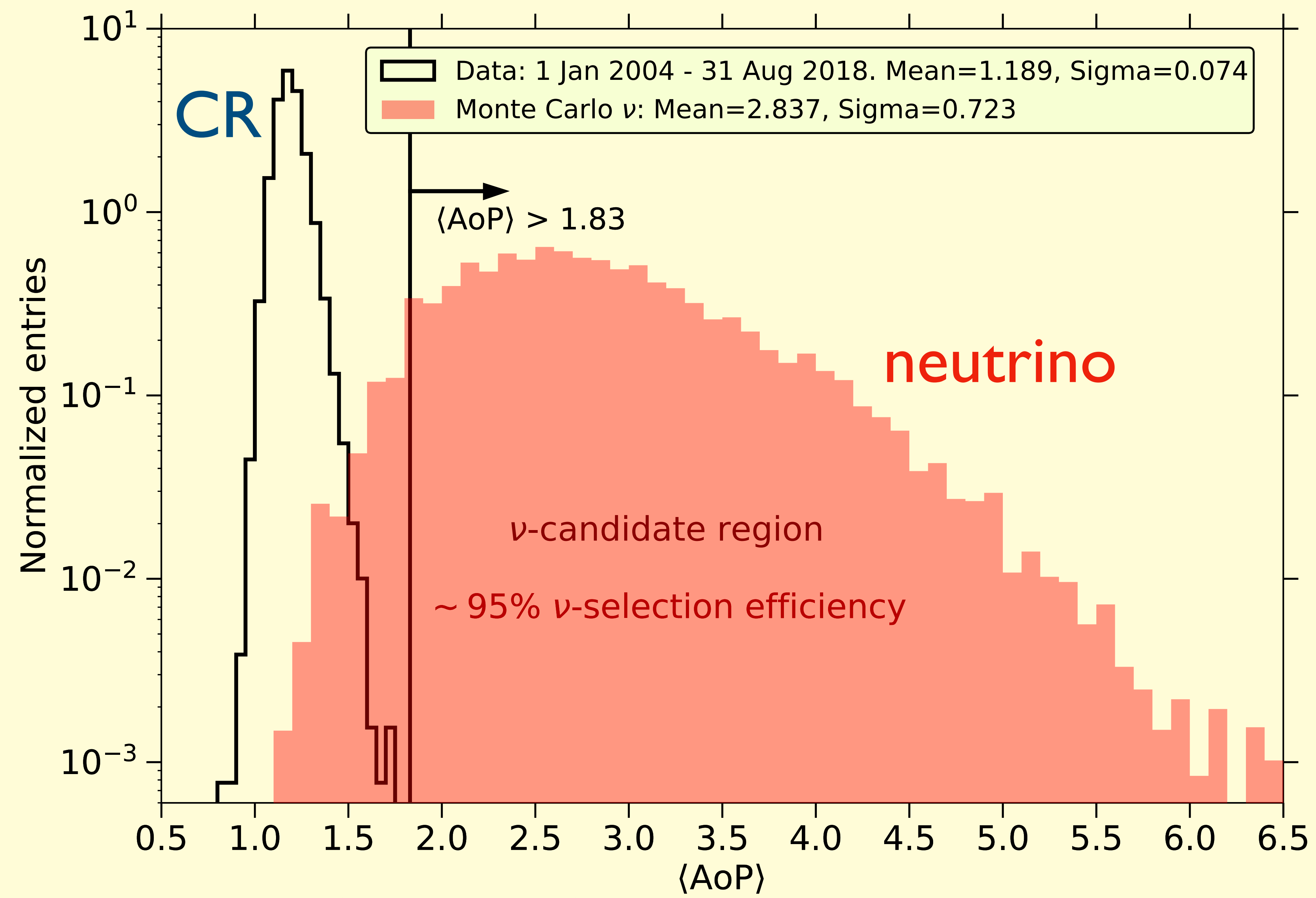
„old" shower

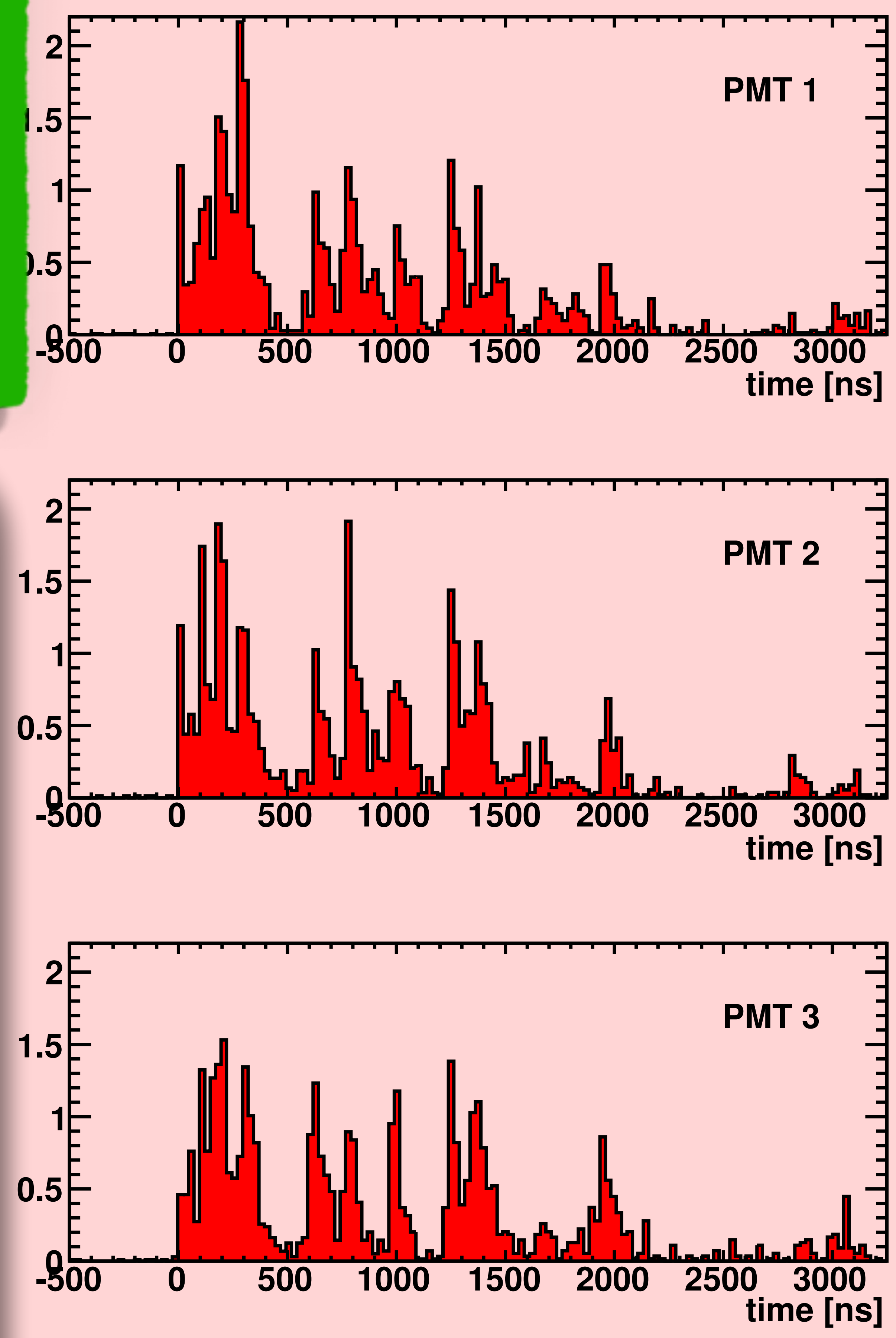
„young" shower

Muonic shower front: narrow signals



Area over Peak by itself provides already a very powerful discrimination





EM shower front: broad signals

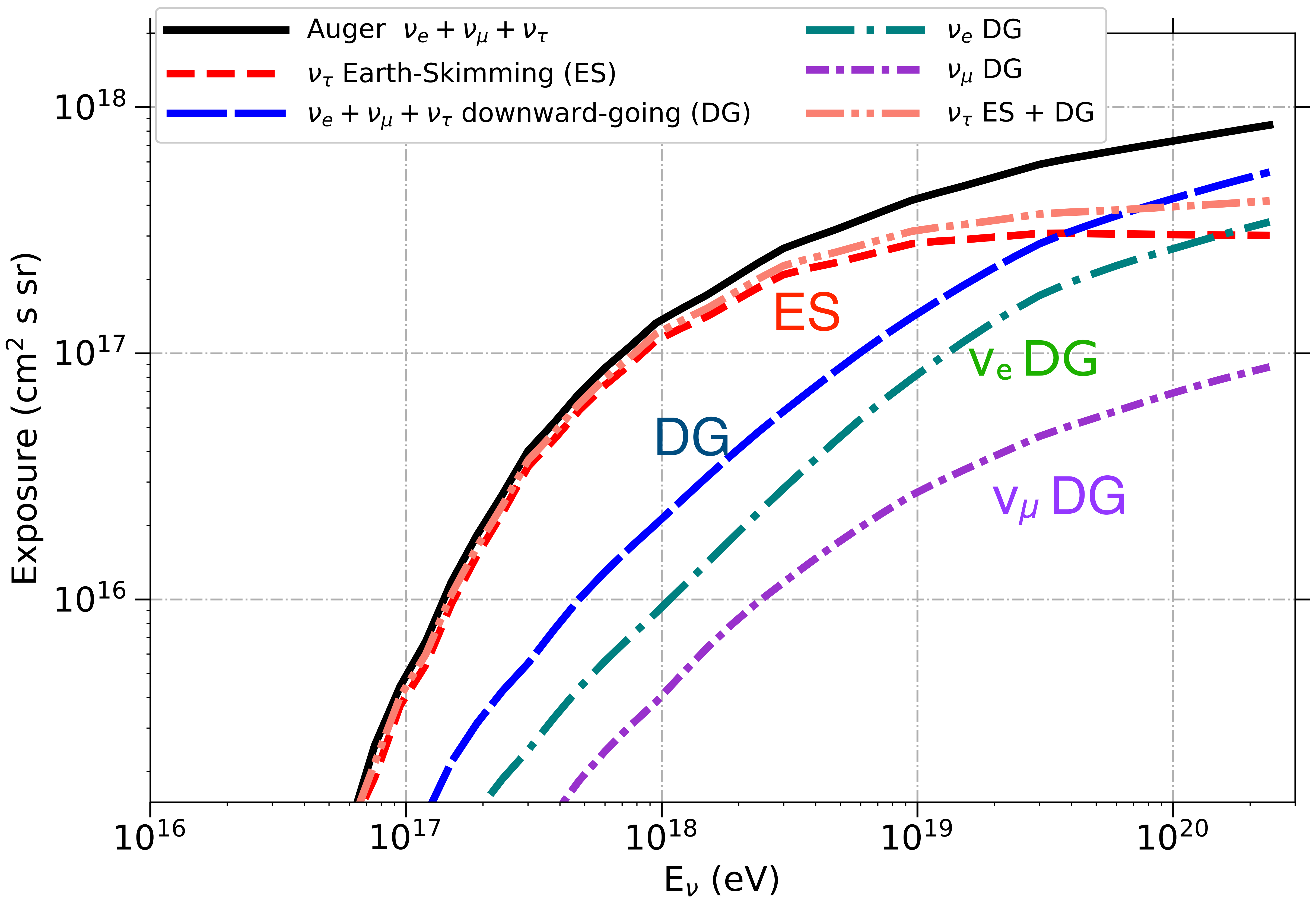
5 EeV, distance to shower axis ~1km
zenith angle ~80°

Area over Peak of signal traces (AoP)

5 EeV, distance to shower axis ~1km
zenith angle ~22°

Exposure

To translate a non-observation into upper flux limits, you need to know the acceptance (sensitivity) of your experiment and the observation (exposure) time



Earth-Skimming ν_τ dominates exposure

(loss at higher energies due to τ decays high in the atmosphere)

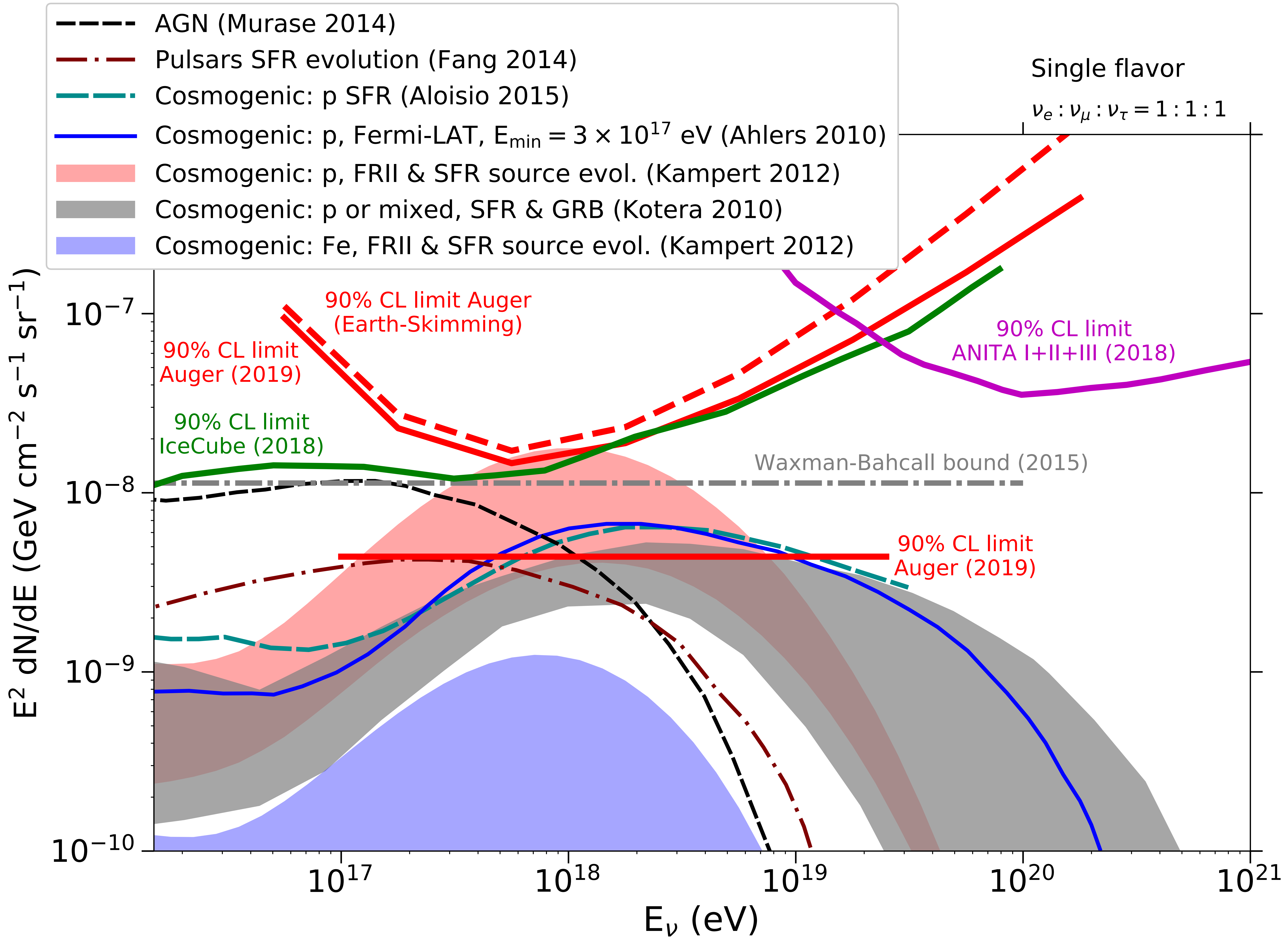
Relative contribution to expected event rate:

Earth Skimming: ~84%
Down Going (75°-90°): ~ 14%
Down Going (60°-75°): ~ 2%

Source of systematic	Combined uncertainty band
Simulations	~ +4%, -3%
ν cross section & τ E-loss	~ +34%, -28%
Topography	~ +15%, 0%
Total	~ +37%, -28%

Bounds on a diffuse Flux of EeV Neutrinos

Auger Collaboration, JCAP10 (2019) 022

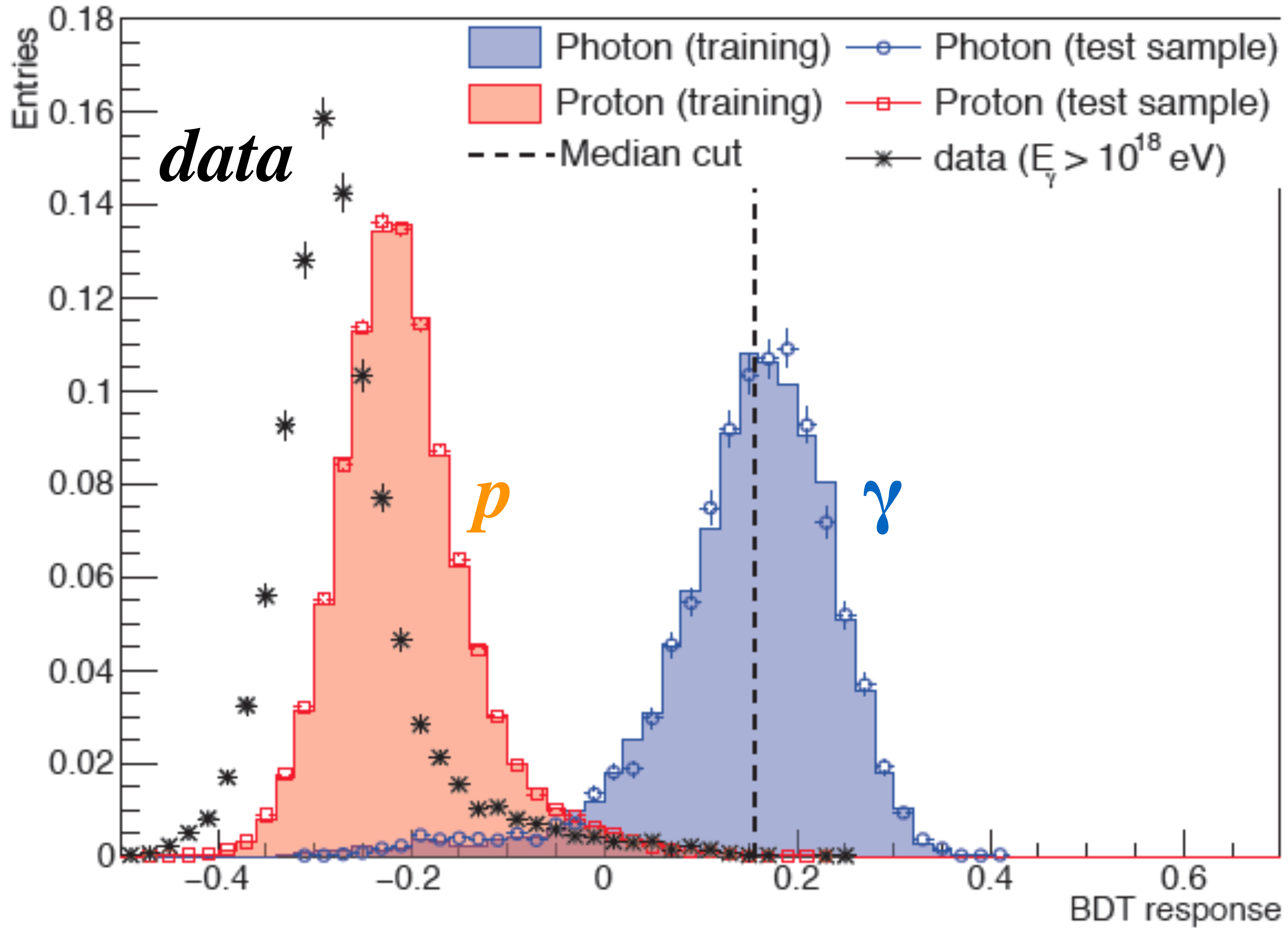


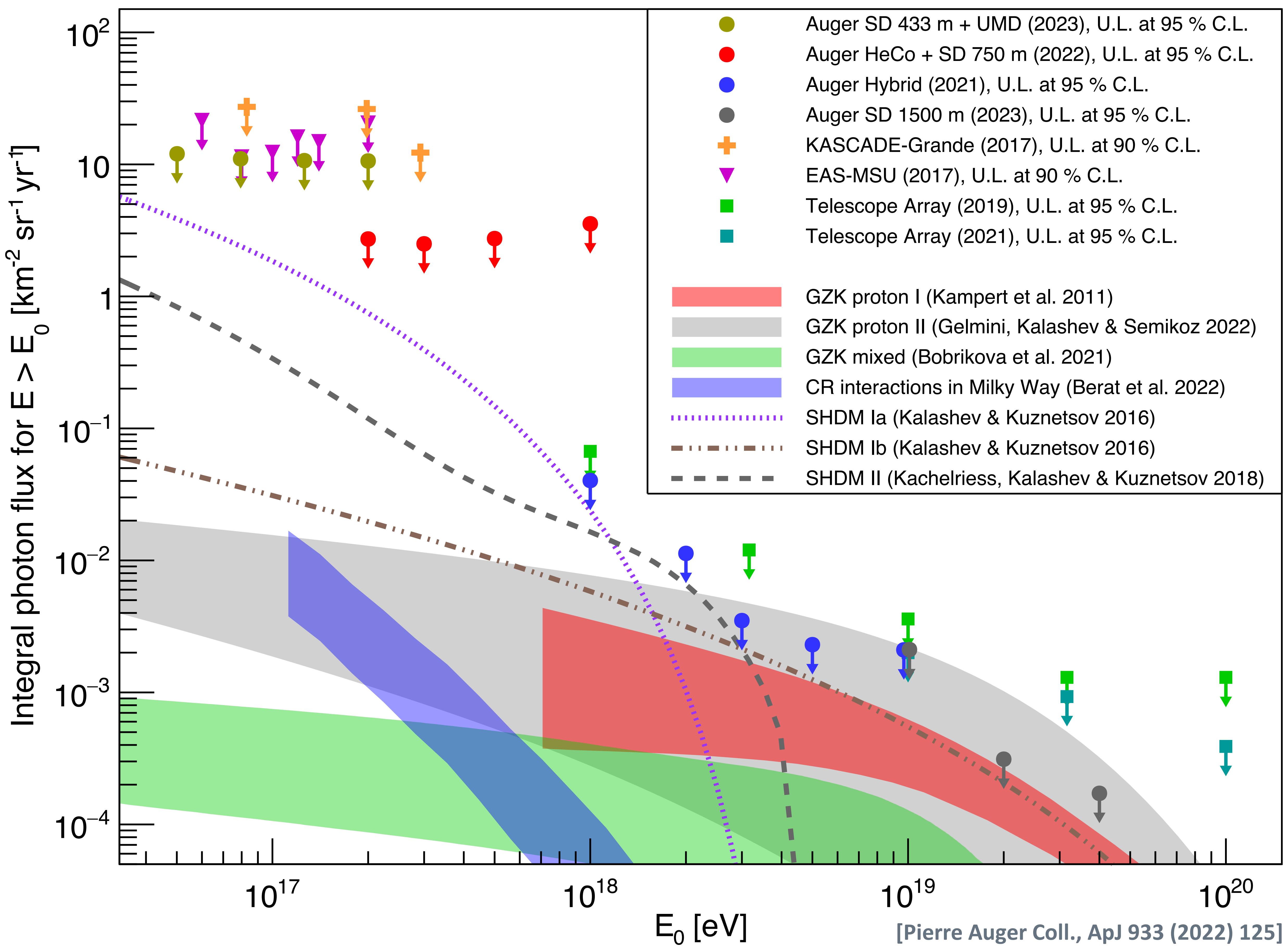
GZK effect should have given us 2-10 neutrinos
Observed: None

Bounds on a diffuse Flux of EeV Photons

Auger Collaboration, JCAP04 (2017) 009, M. Niechciol ICRC2023

Photons can be identified by deep X_{max} and low muon number

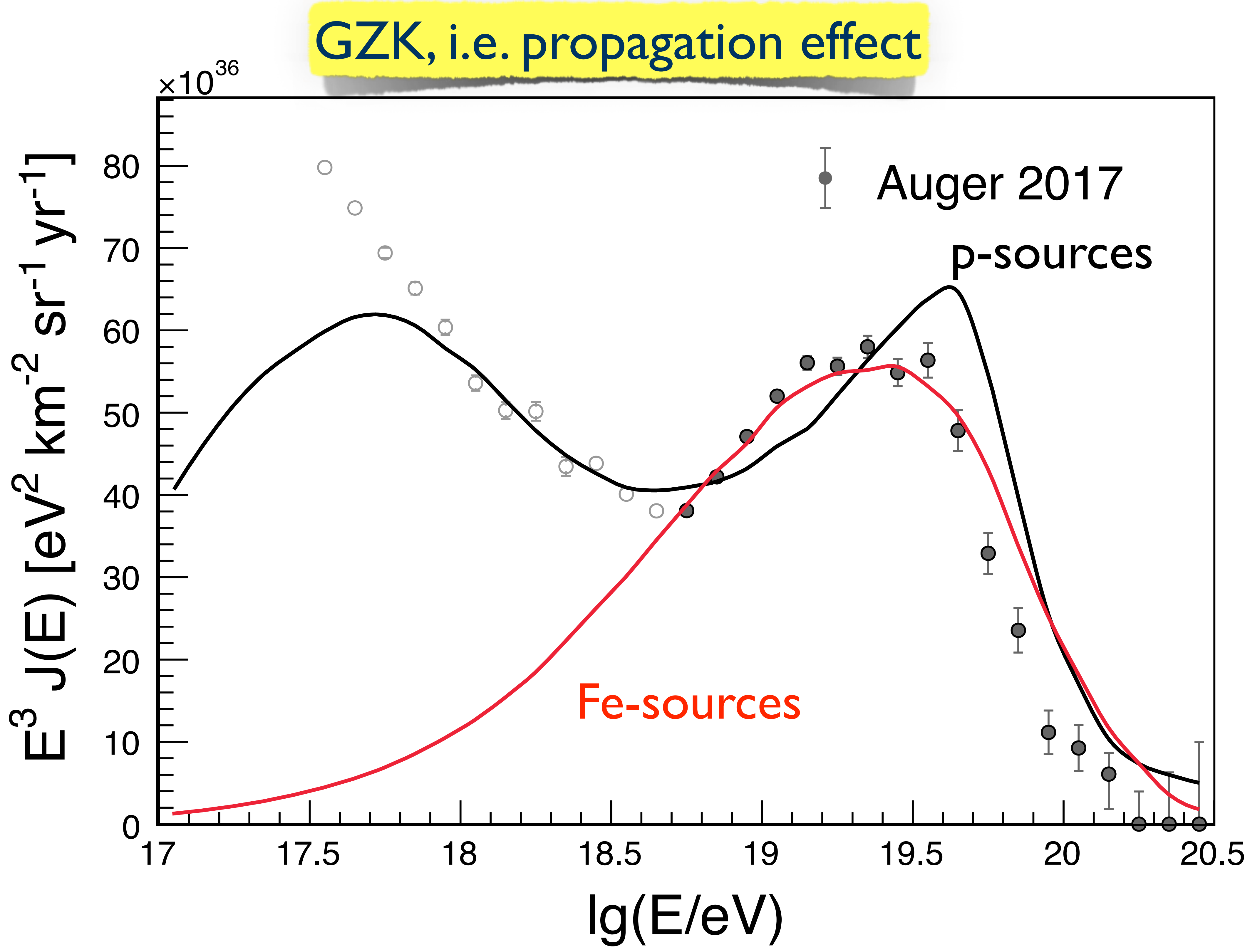


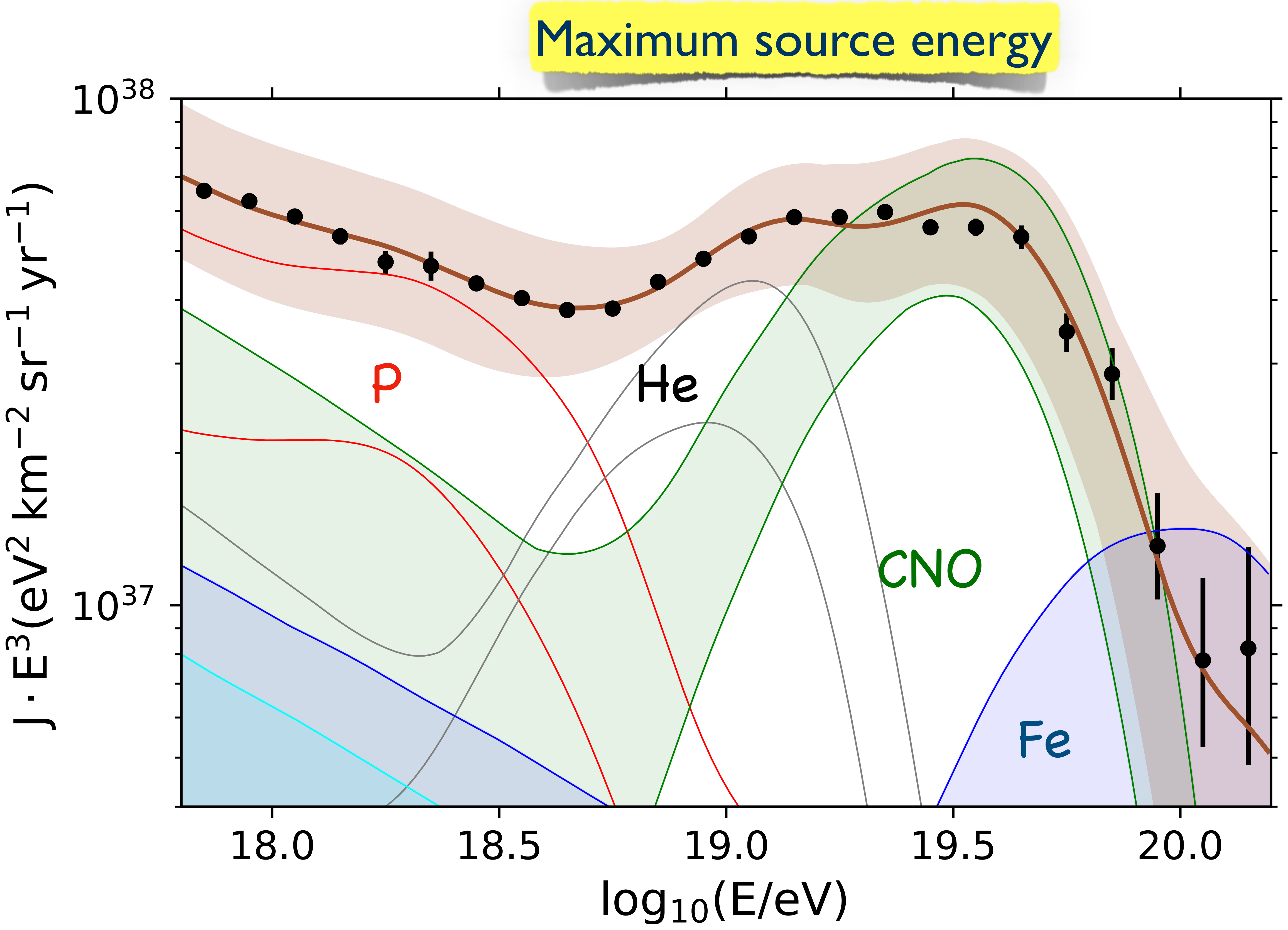


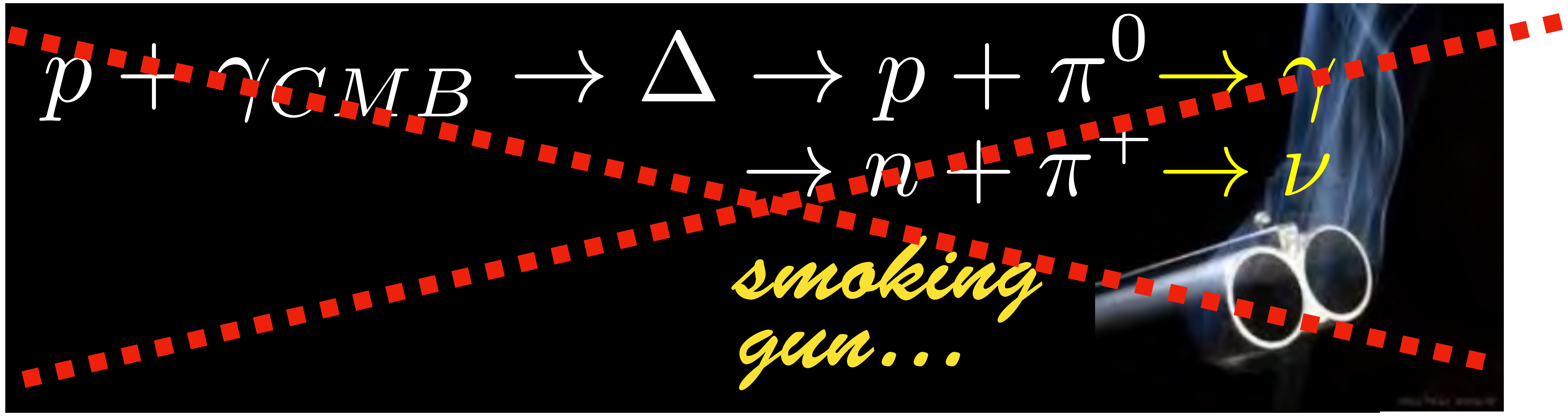
[Pierre Auger Coll., ApJ 933 (2022) 125]

Similarly, photon upper limits start to constrain cosmogenic photon fluxes of p-sources

GZK effect or Maximum Source energy ?



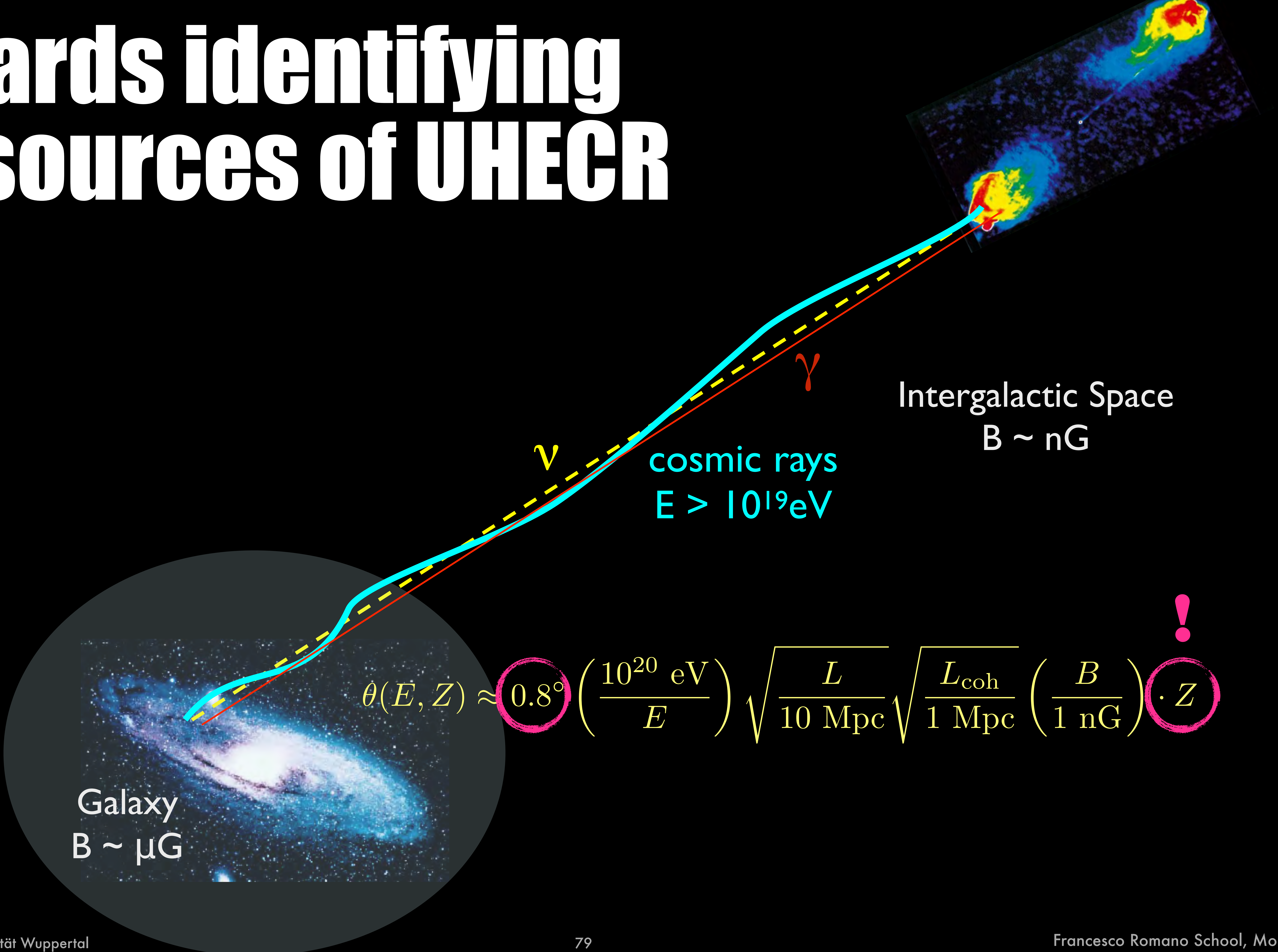




This realisation will make astronomy more difficult (note CR deflections ~ Z)

Anisotropies

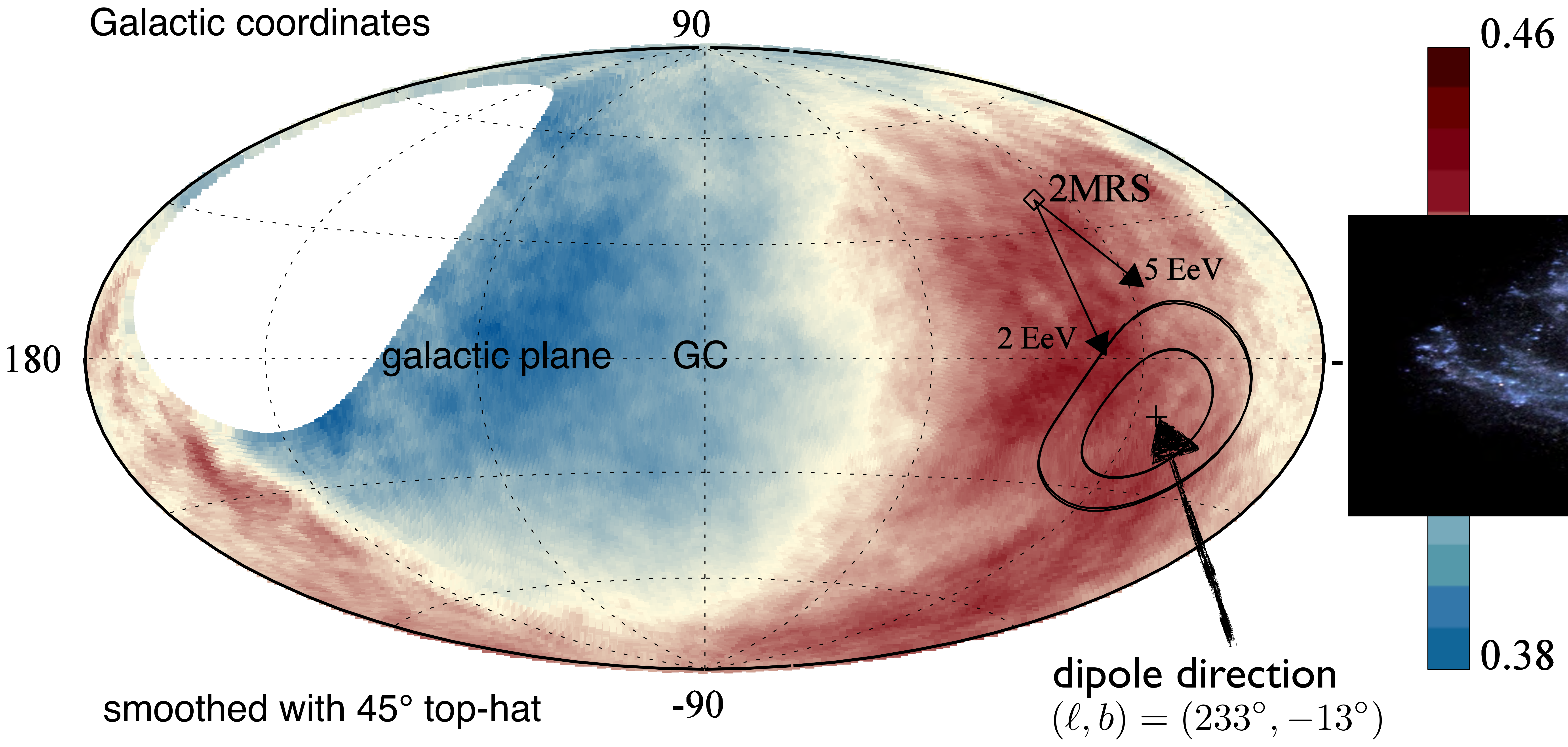
Towards identifying the sources of UHECR



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

Flux Map above 8 EeV

Auger Collaboration, Science 357 (2017) 1266

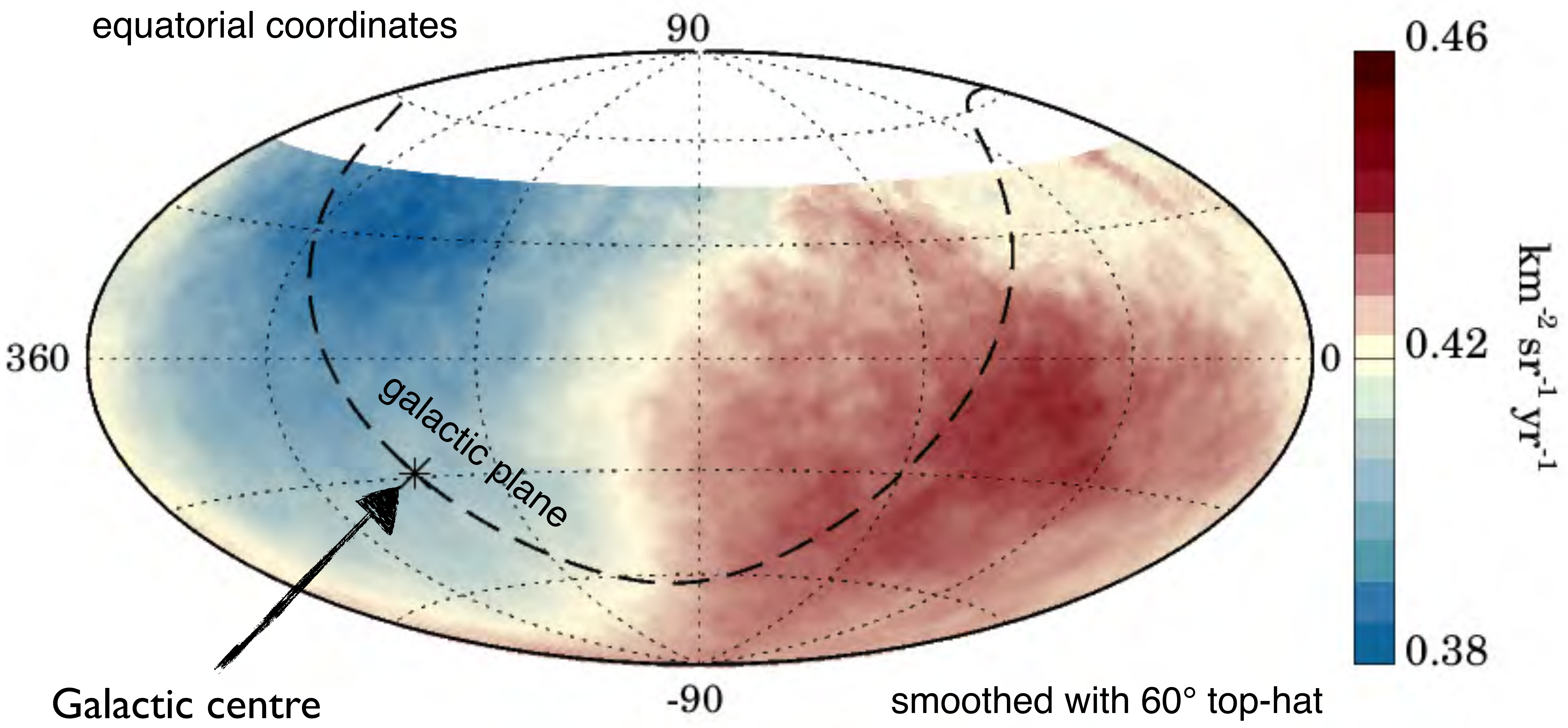


Flux excess from directions from outside Milky Way

Extragalactic origin of UHECR confirmed

Flux Map above 8 EeV

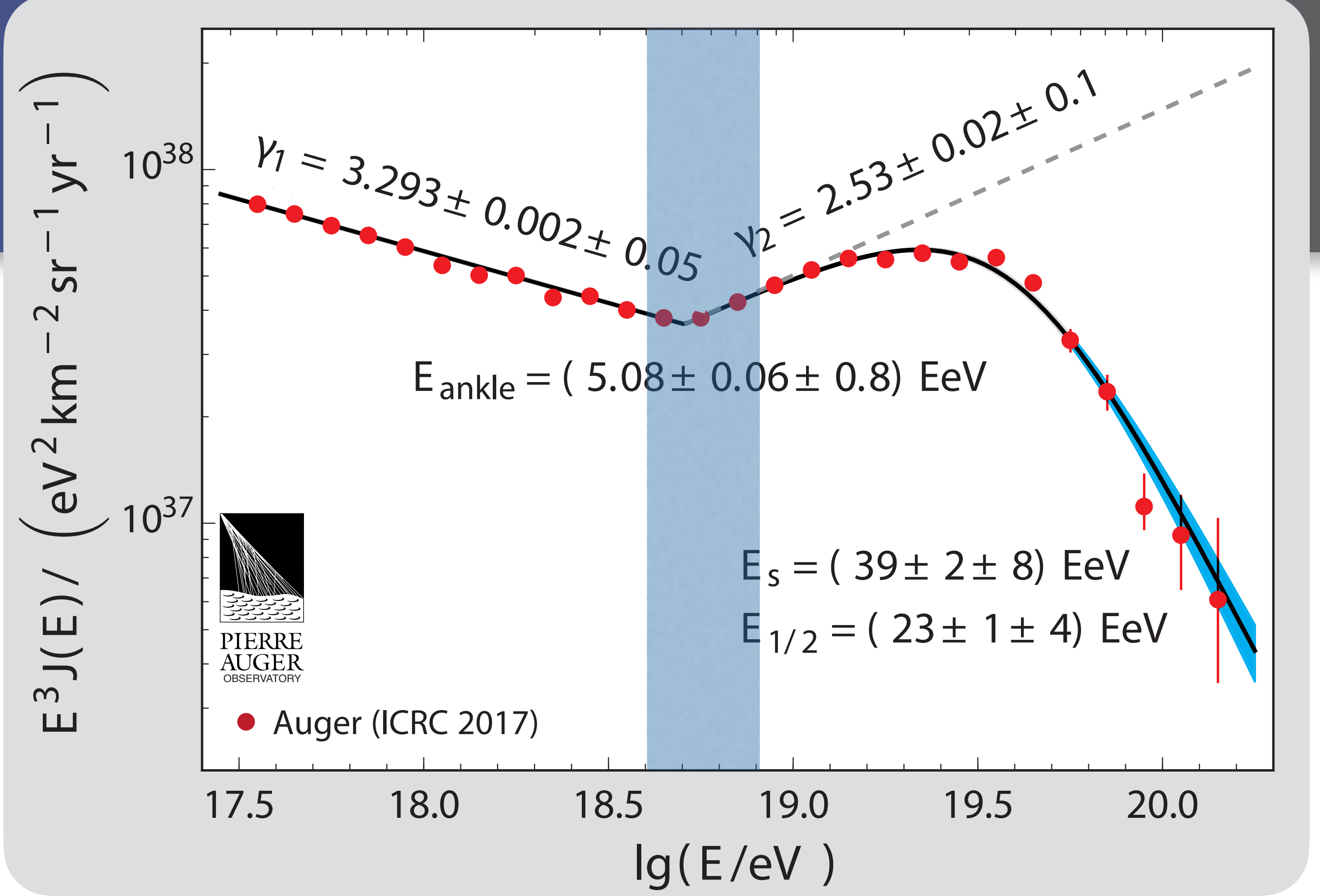
Auger Collaboration, Science 357 (2017) 1266



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

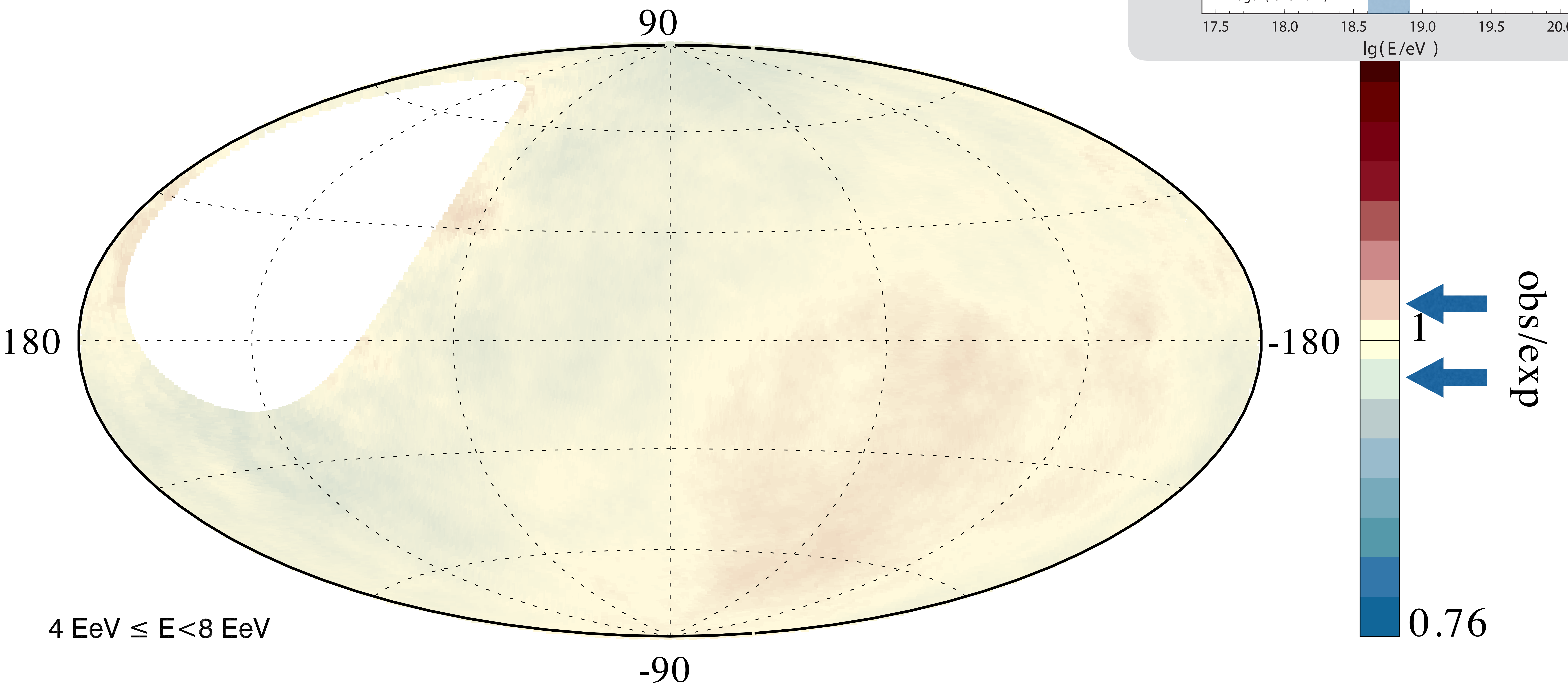
Evolution with Energy: 4-8 EeV

Auger Collaboration, ApJ 868 (2018) 1



map smoothed with 45° top-hat
Galactic coordinates

all maps with identical color scale



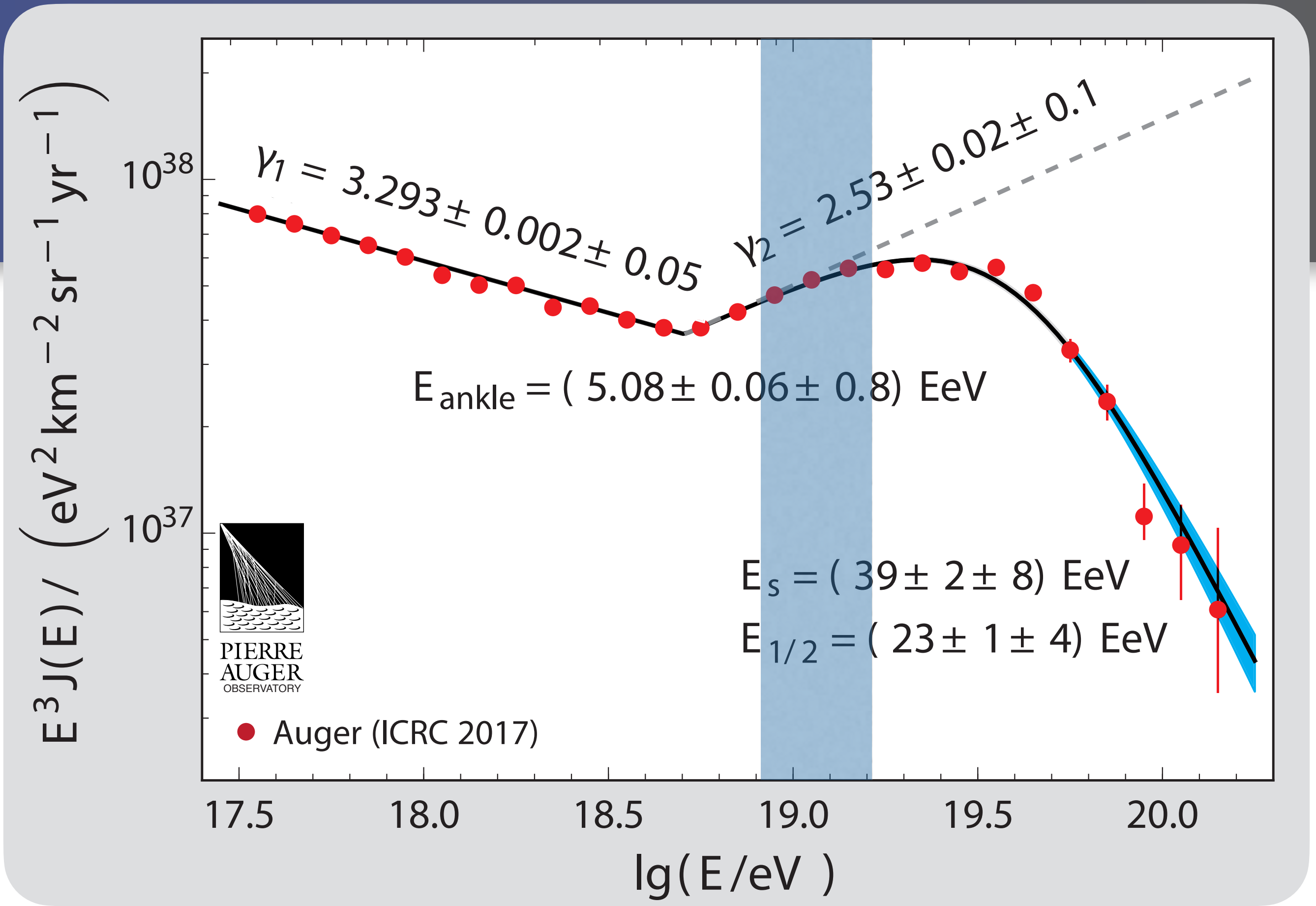
4 EeV ≤ E<8 EeV

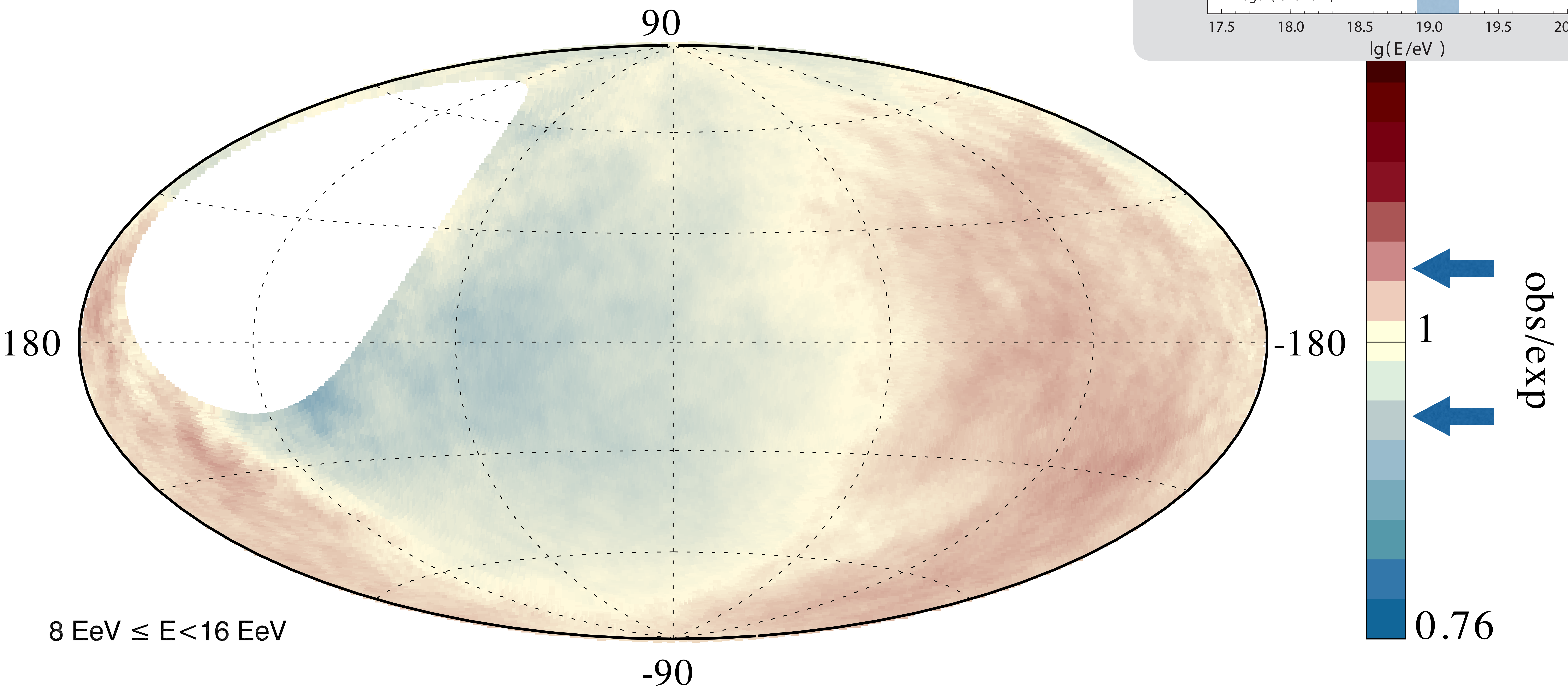
Evolution with Energy: 8-16 EeV

Auger Collaboration, ApJ 868 (2018) 1

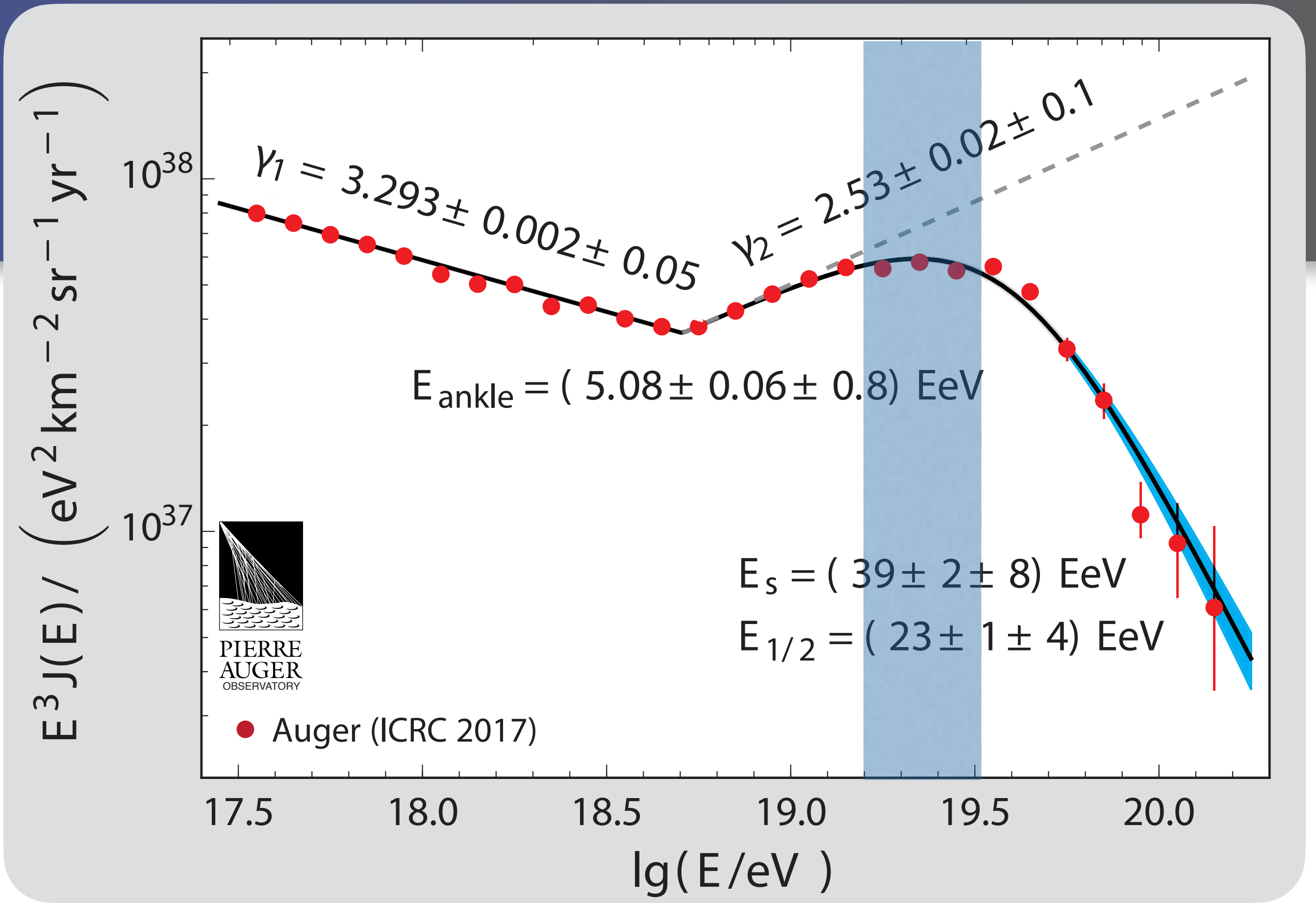
map smoothed with 45° top-hat
Galactic coordinates

all maps with identical color scale





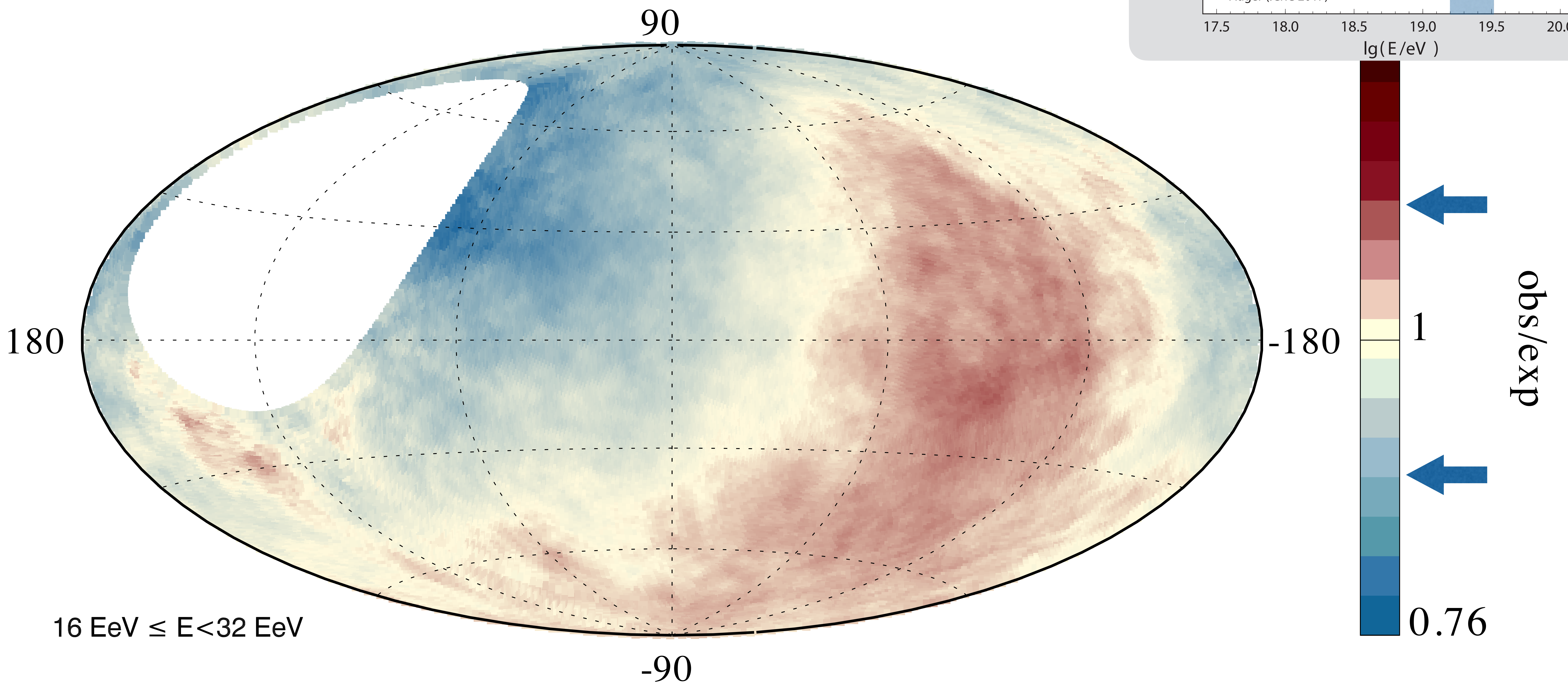
Evolution with Energy: 16-32 EeV



Auger Collaboration, ApJ 868 (2018) 1

map smoothed with 45° top-hat
Galactic coordinates

all maps with identical color scale

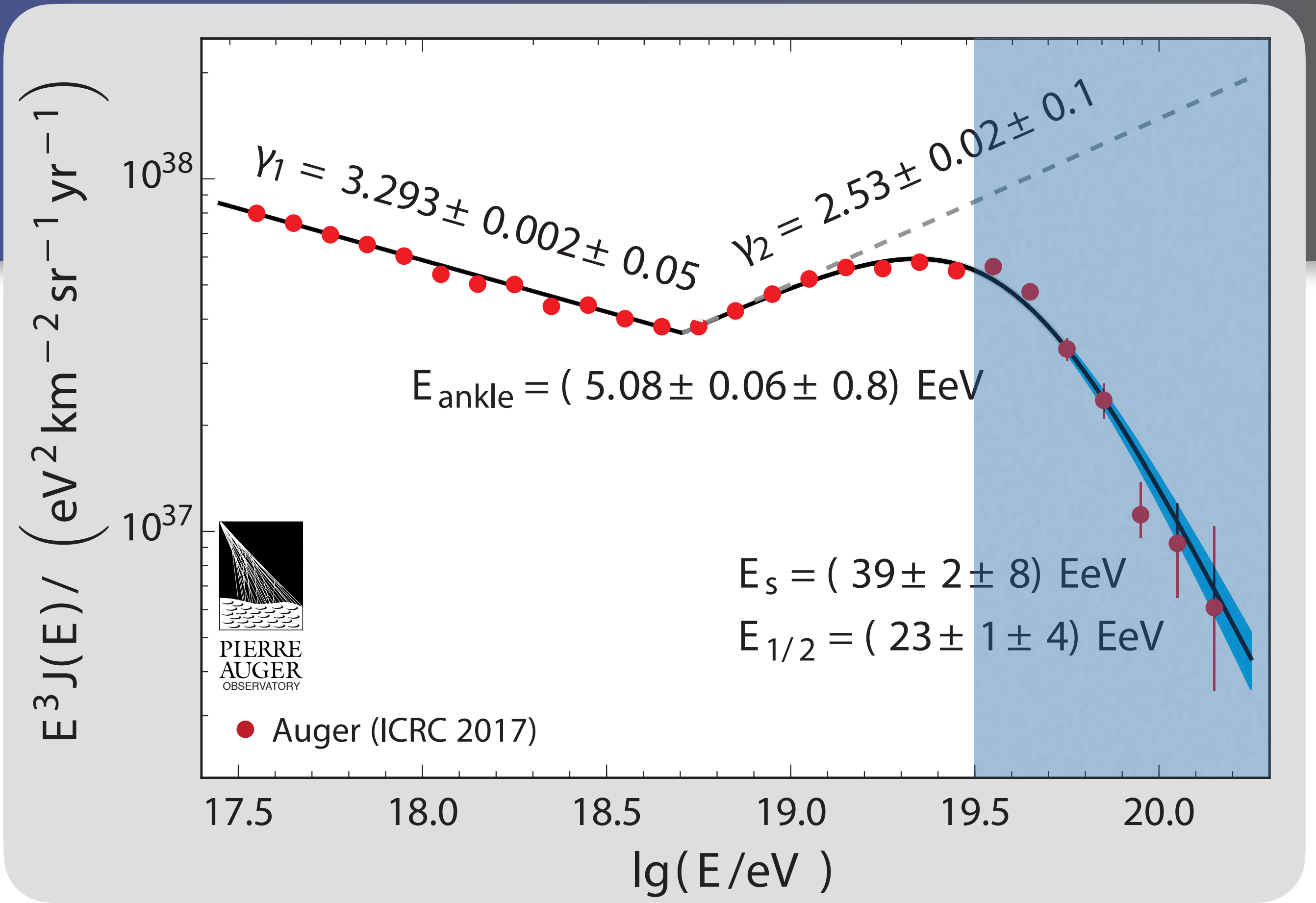


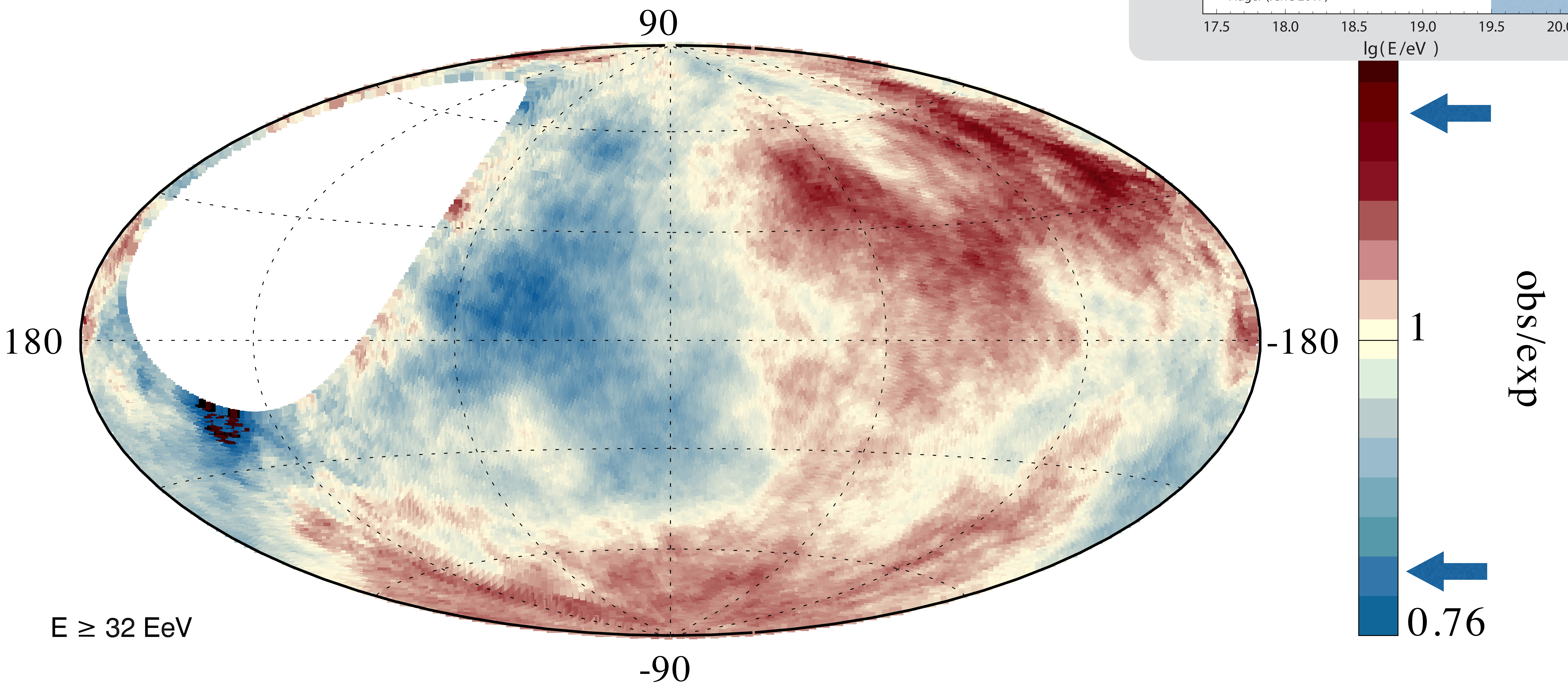
Evolution with Energy: >32 EeV

Auger Collaboration, ApJ 868 (2018) 1

map smoothed with 45° top-hat
Galactic coordinates

all maps with identical color scale

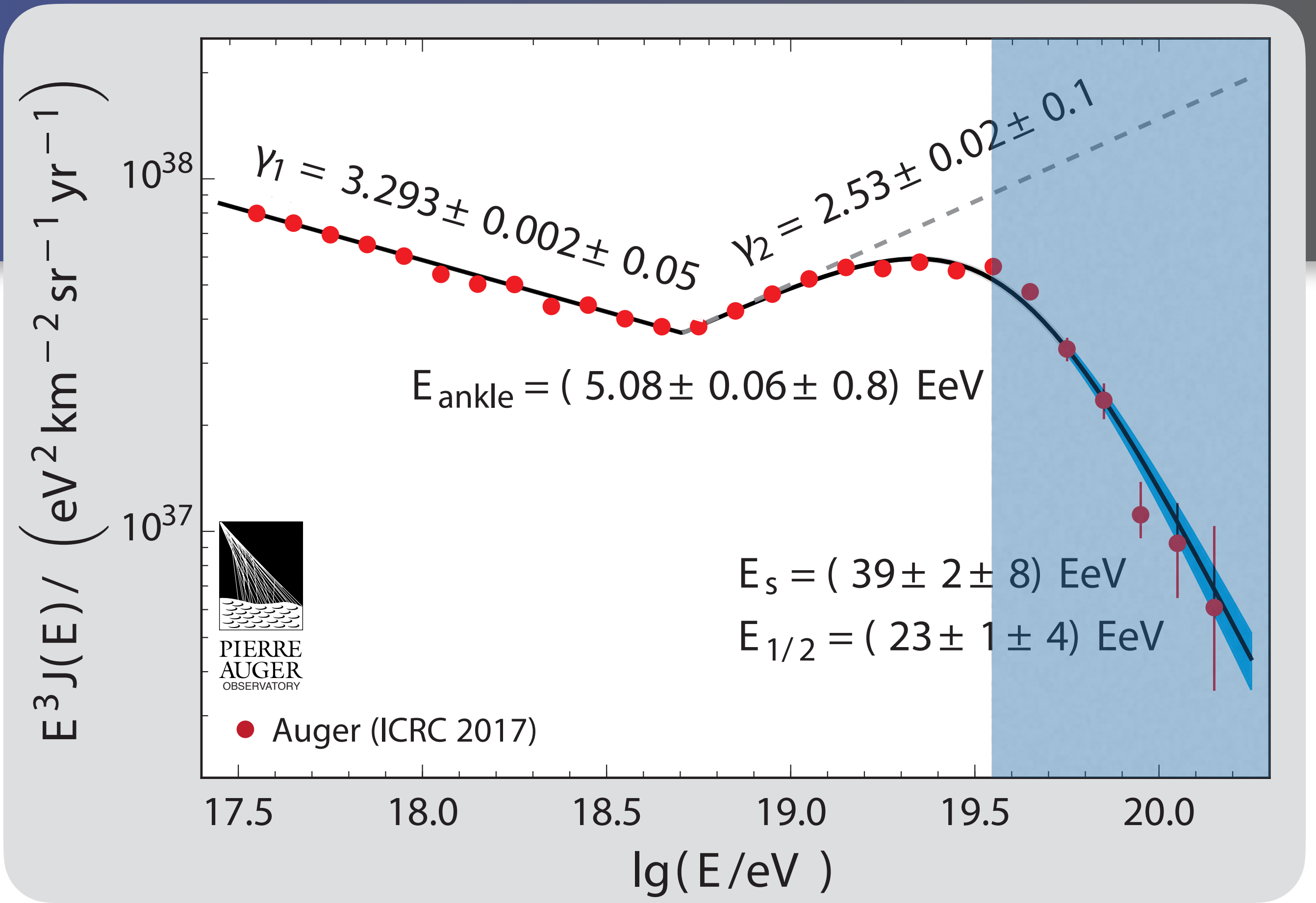


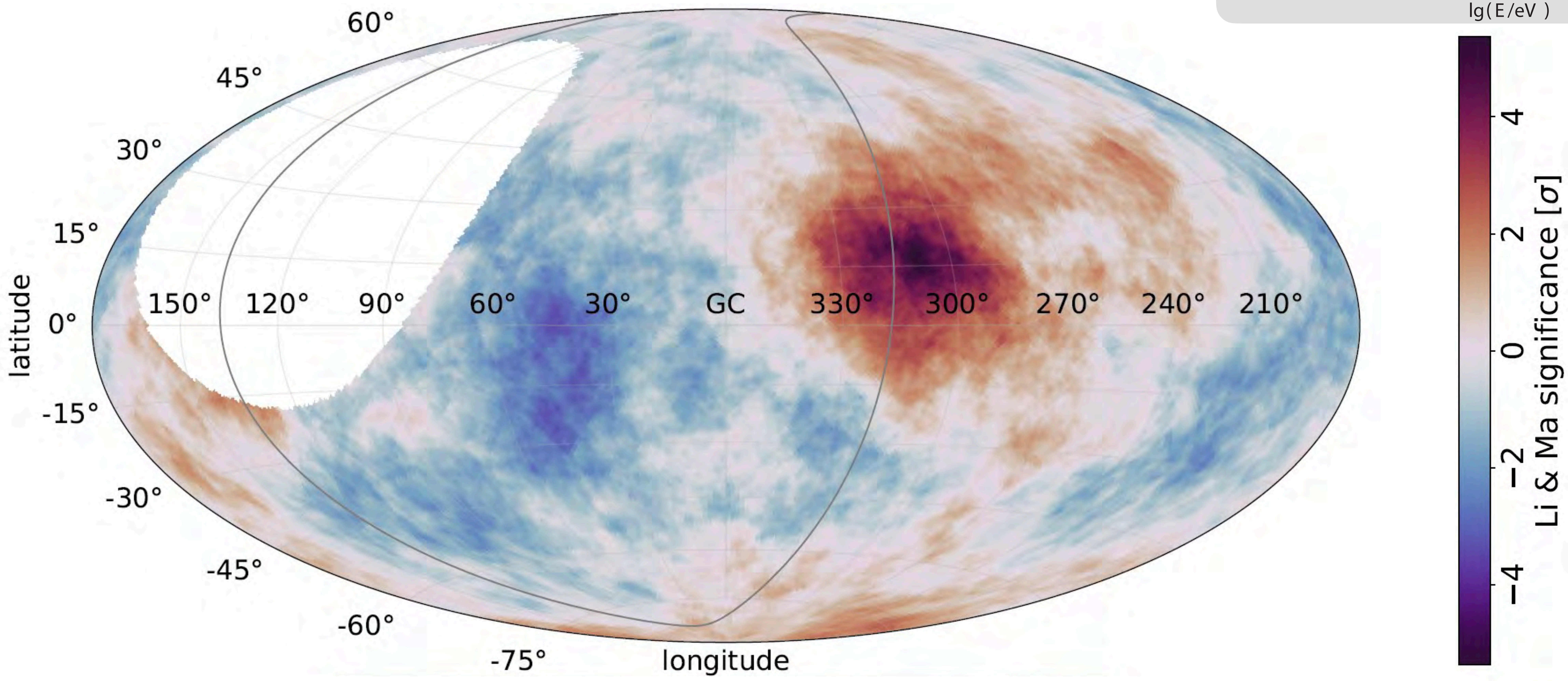


Evolution with Energy: >38 EeV

Auger Collaboration, G. Golup (ICRC 2023)

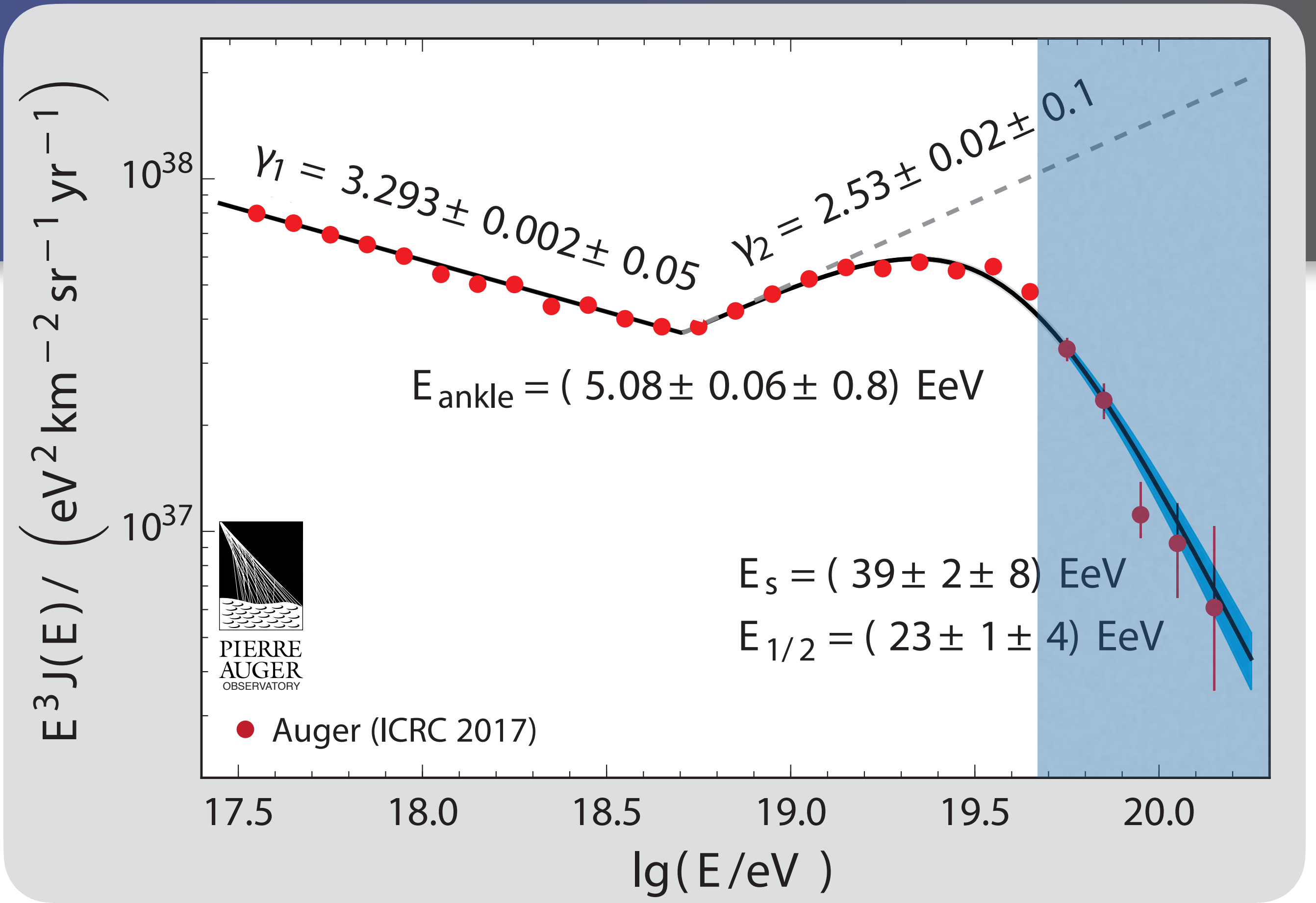
map smoothed with 27° top-hat
Galactic coordinates



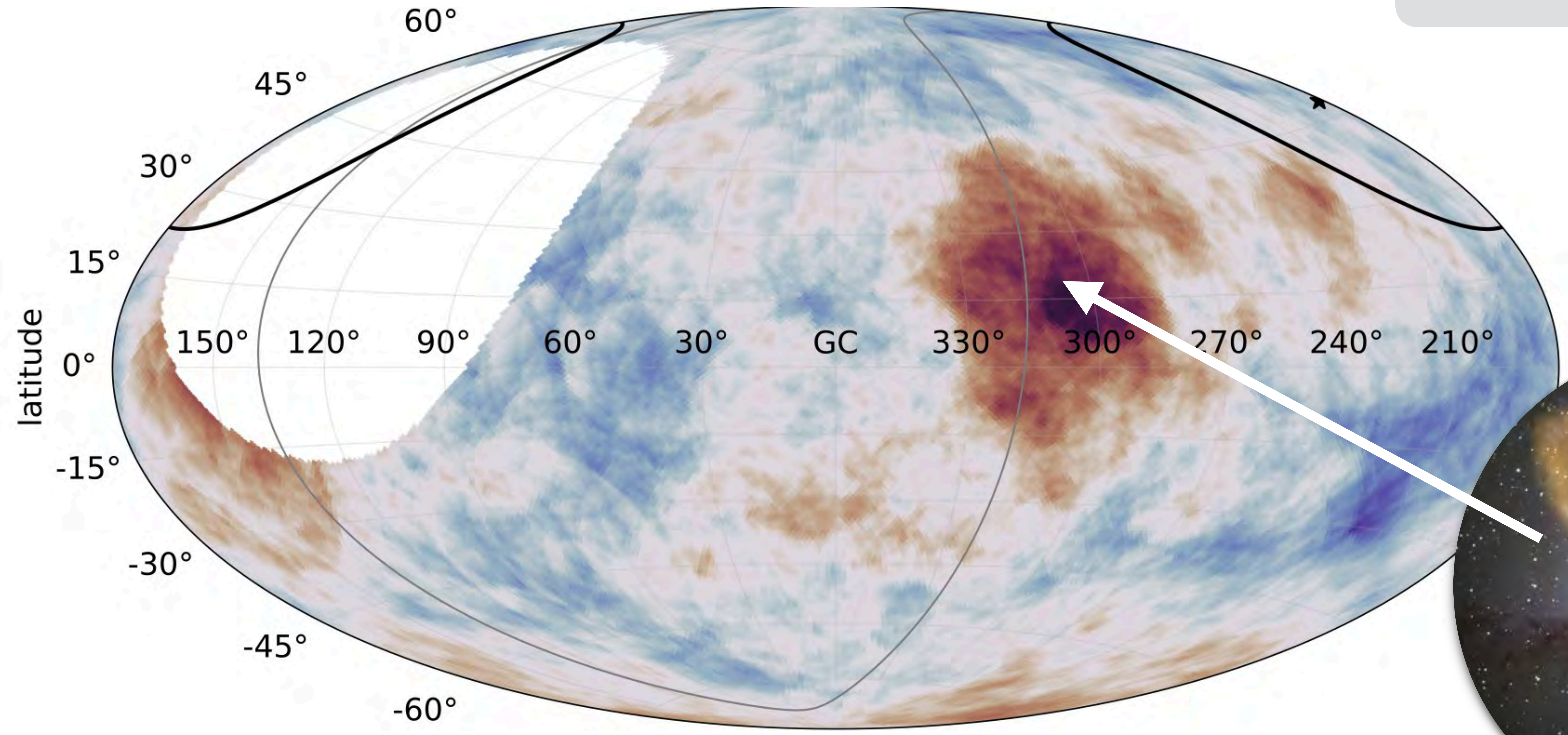


Evolution with Energy: >45 EeV

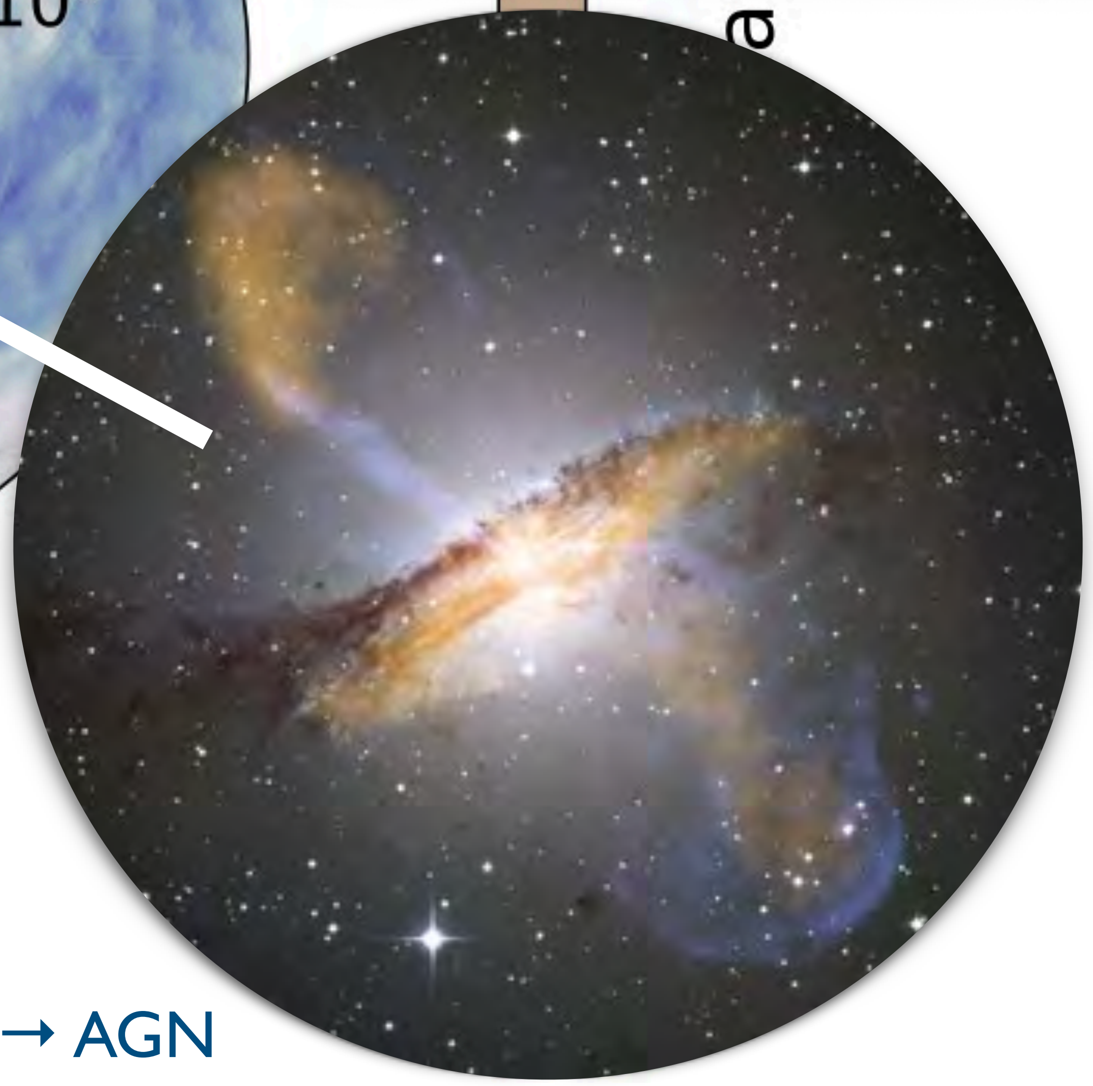
Auger Collaboration, G. Golup (ICRC 2023)



map smoothed with 25° top-hat
Galactic coordinates

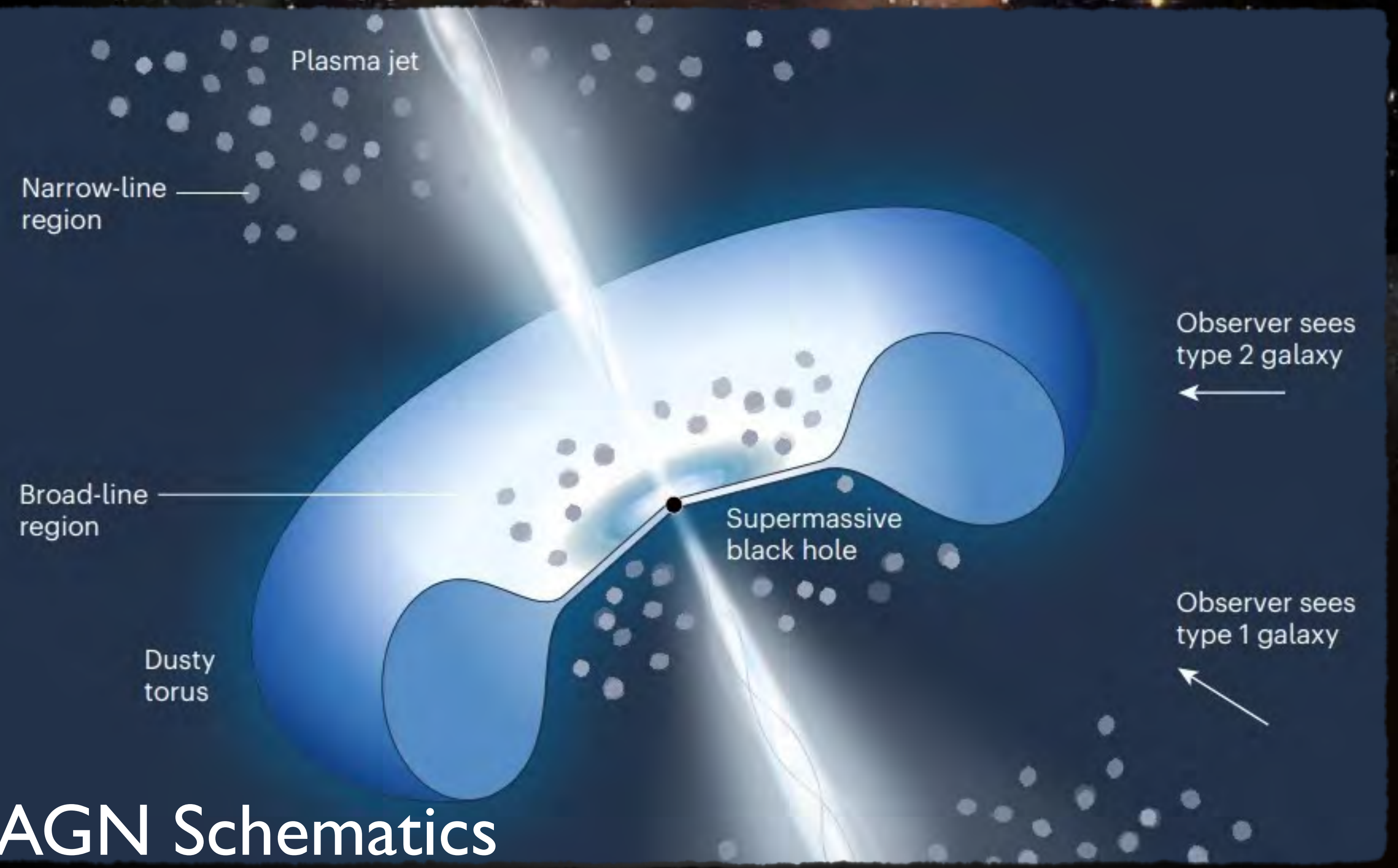


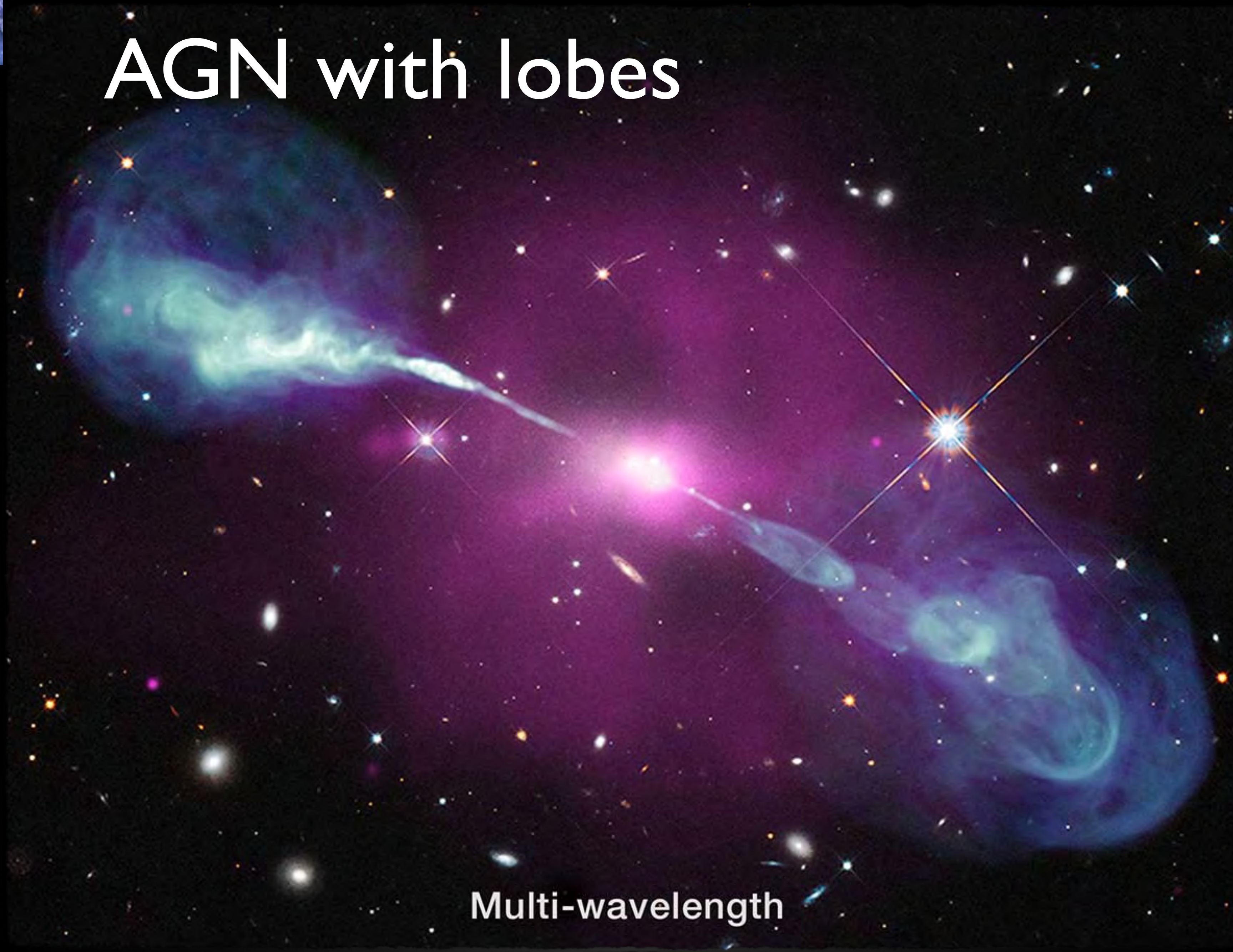
Directional correlation with Centaurus A at >4σ



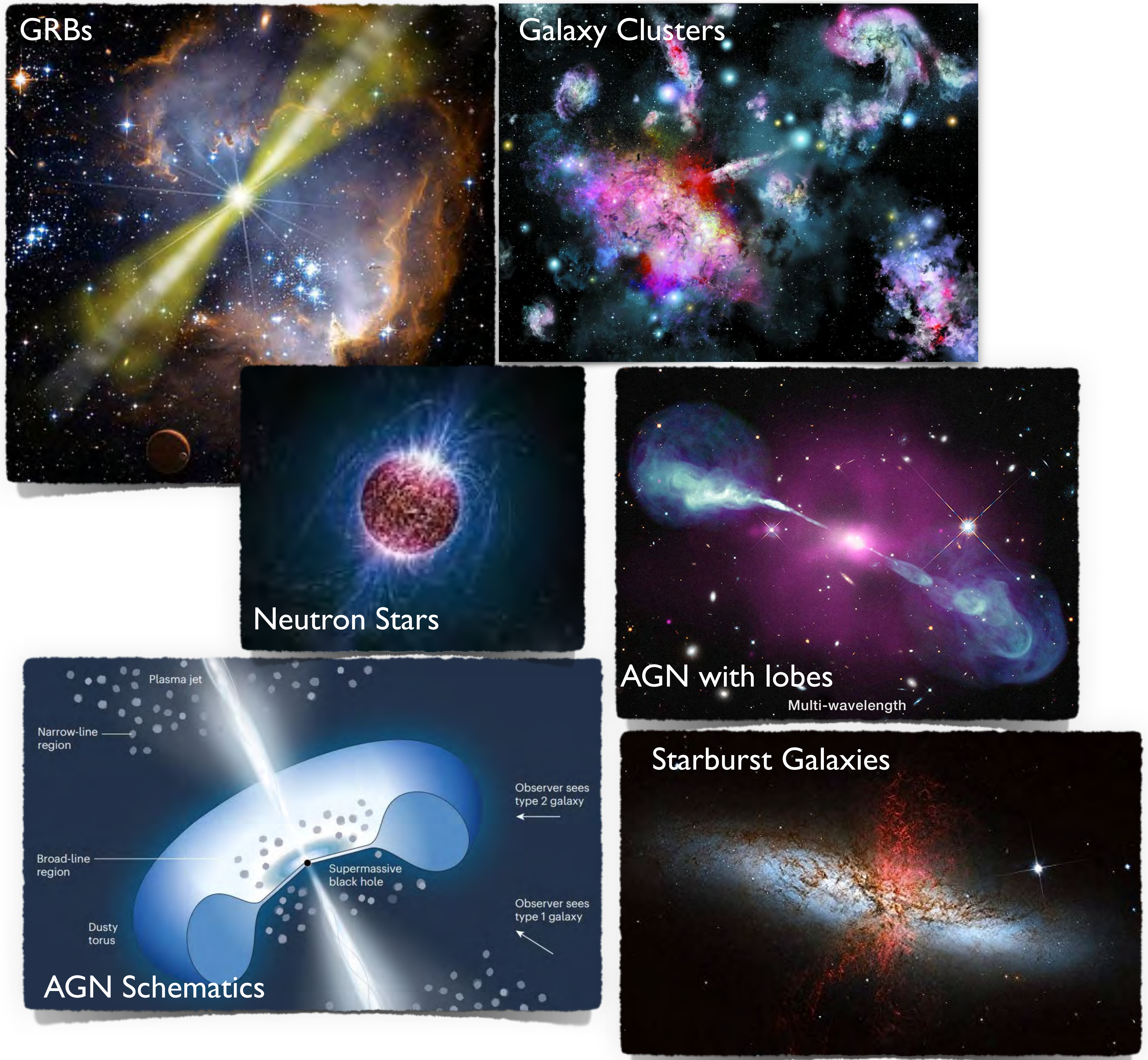
Active core → AGN
also considered as Starburst Galaxy

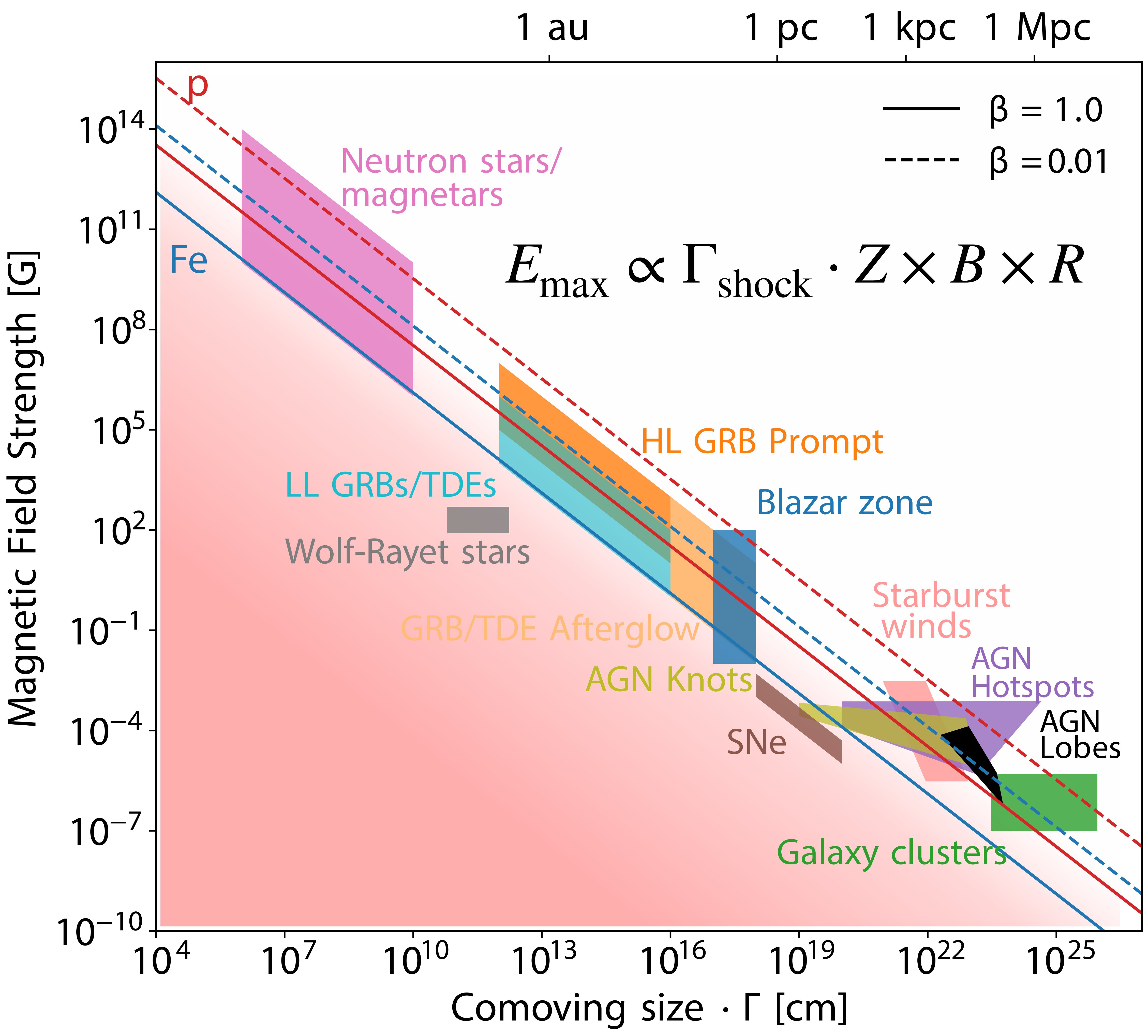
UHECR Source Candidates: The usual Suspects...





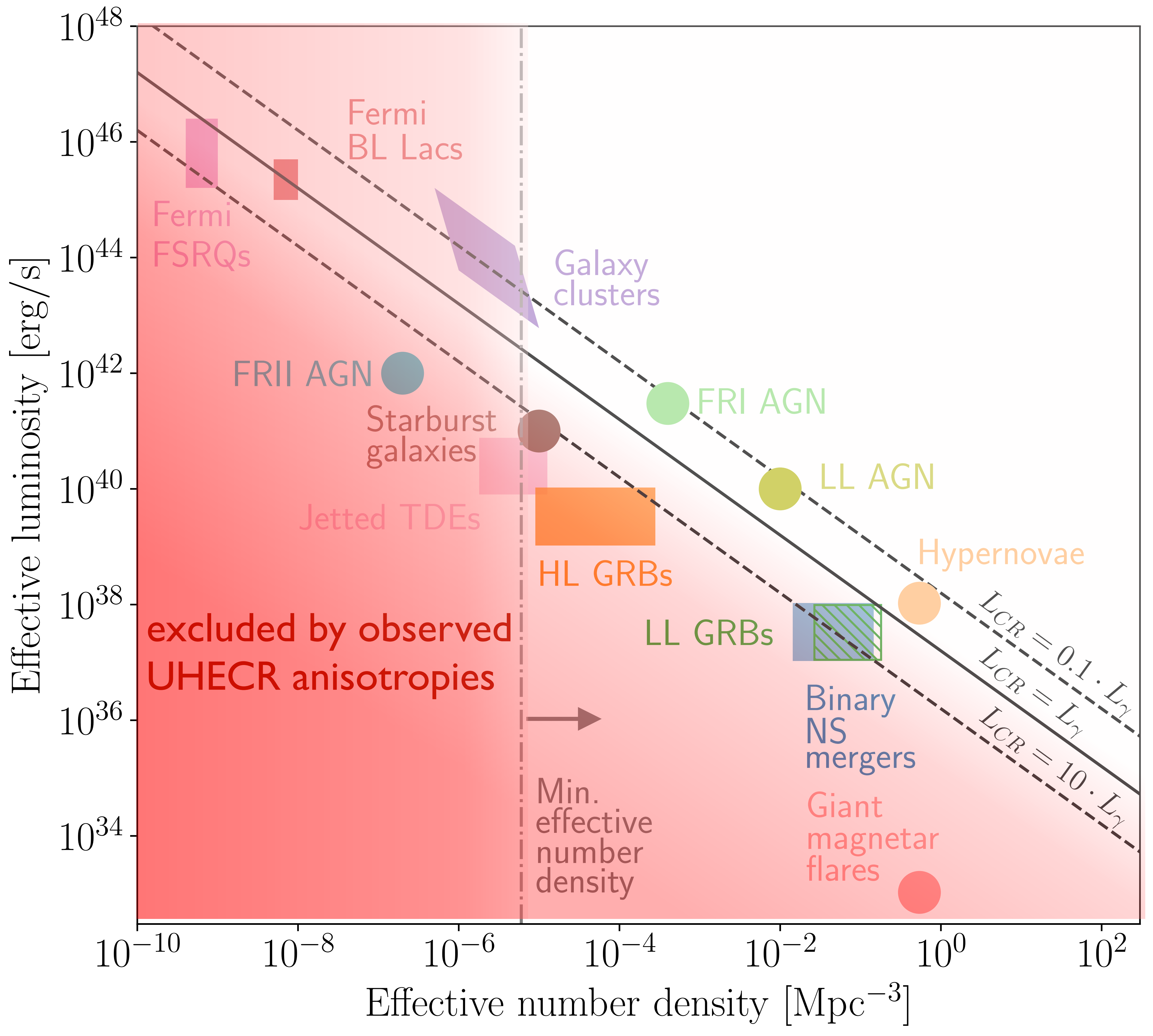
Hillas Plot: B vs Size of Accelerators



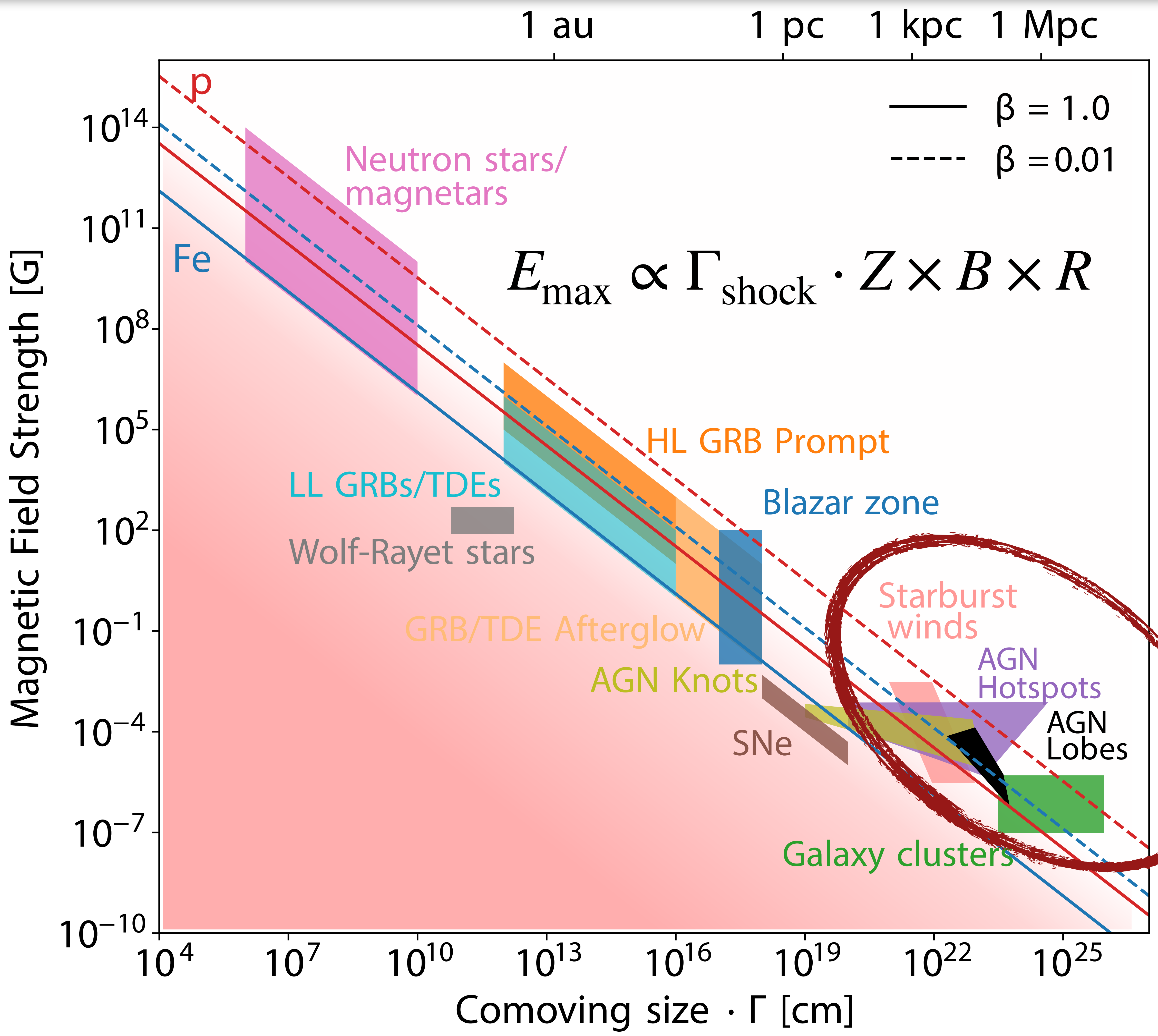


MIAPP review, Front.Astron.Space Sci. 6 (2019) 23

UHECR Luminosity and Acceleration Requirements



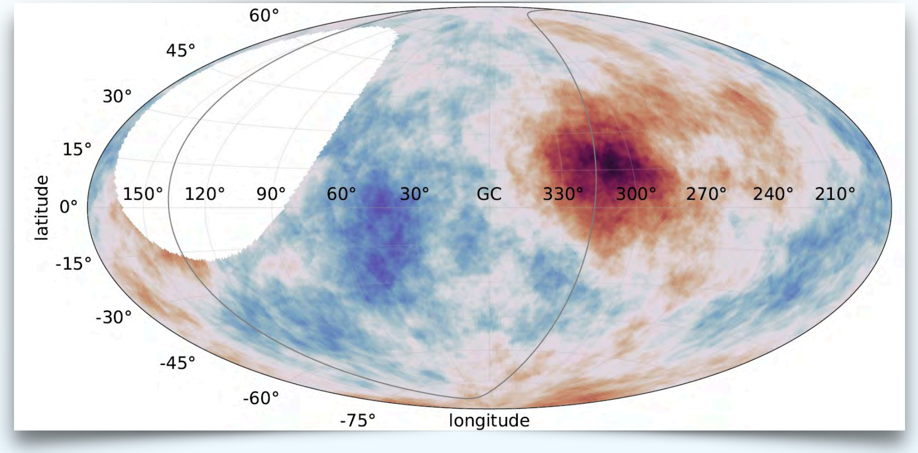
MIAPP review, Front.Astron.Space Sci. 6 (2019) 23

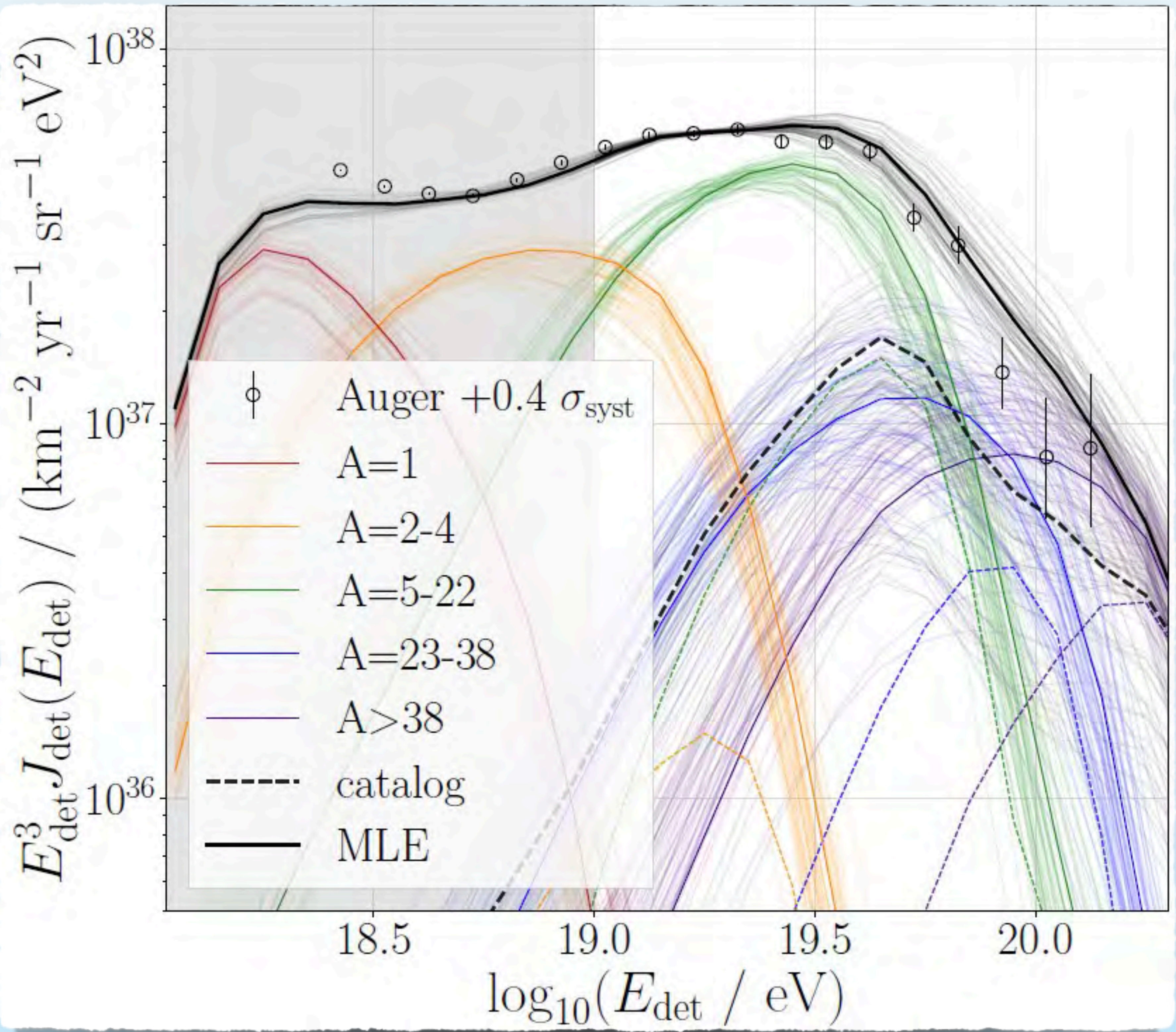


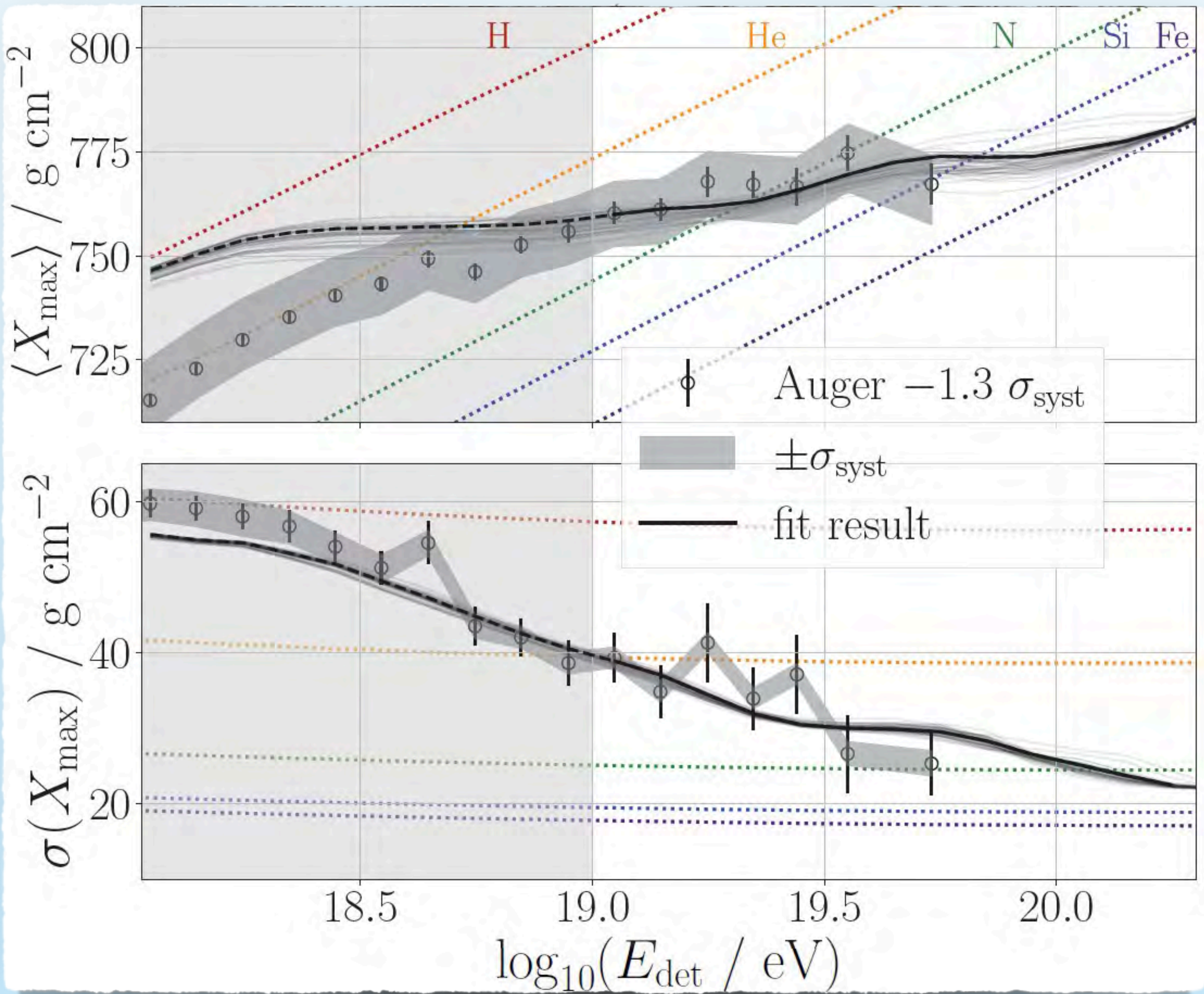
Note: plot applies both for steady and transient sources, when assuming a characteristic time spread of $\tau = 3 \cdot 10^5$ yr.

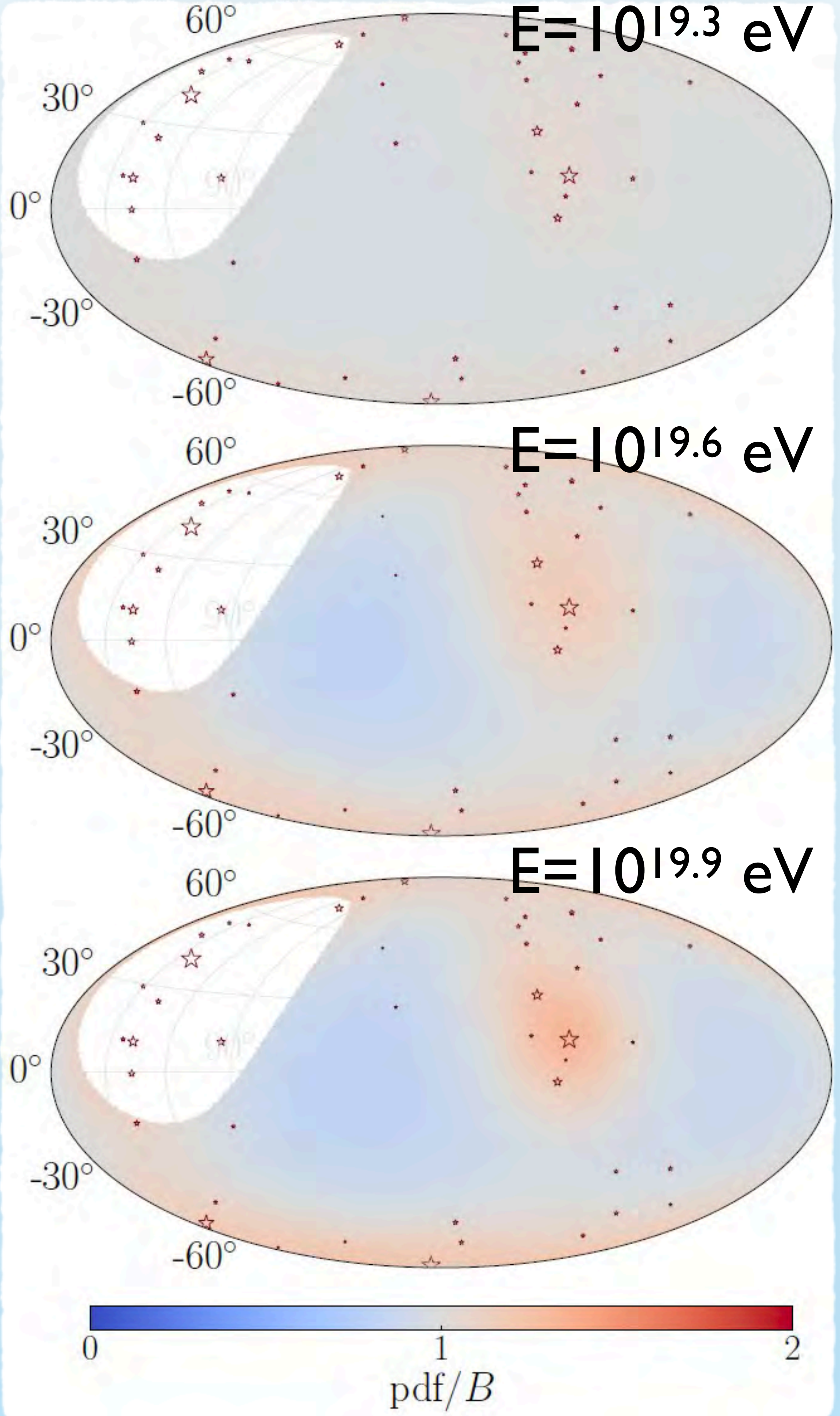
Towards understanding the Universe at its highest energies

Idea:
- investigate possibility of SBGs / ɣ-AGNs / Cen A as sources of over-densities
- build one coherent model for injection → propagation → detection
- describe arrival directions + spectrum + composition data at the same time









Result of likelihood fit to measured E-spectrum, Composition, and Sky-Map when taking a catalog of all Starburst Galaxies (SBG)

Terese Bister, ICRC2023

Towards understanding the Universe at its highest energies

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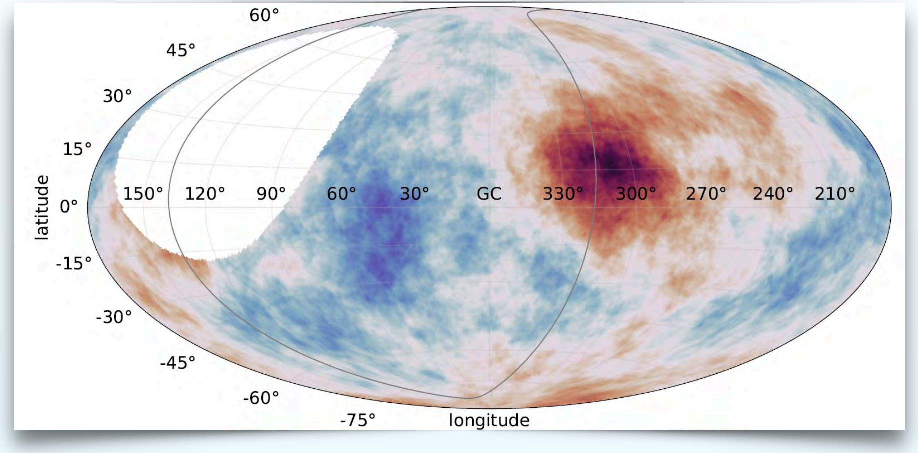
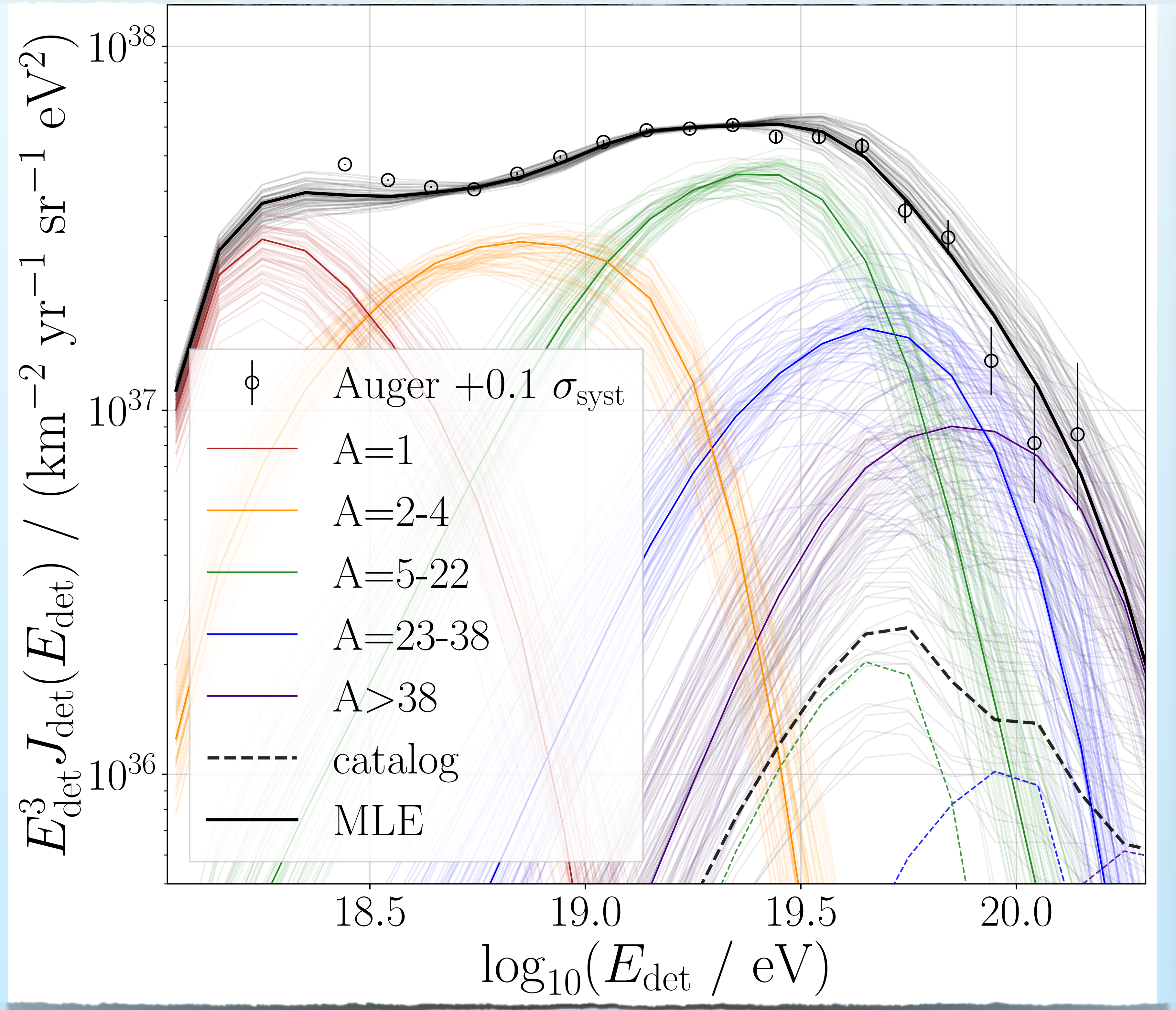
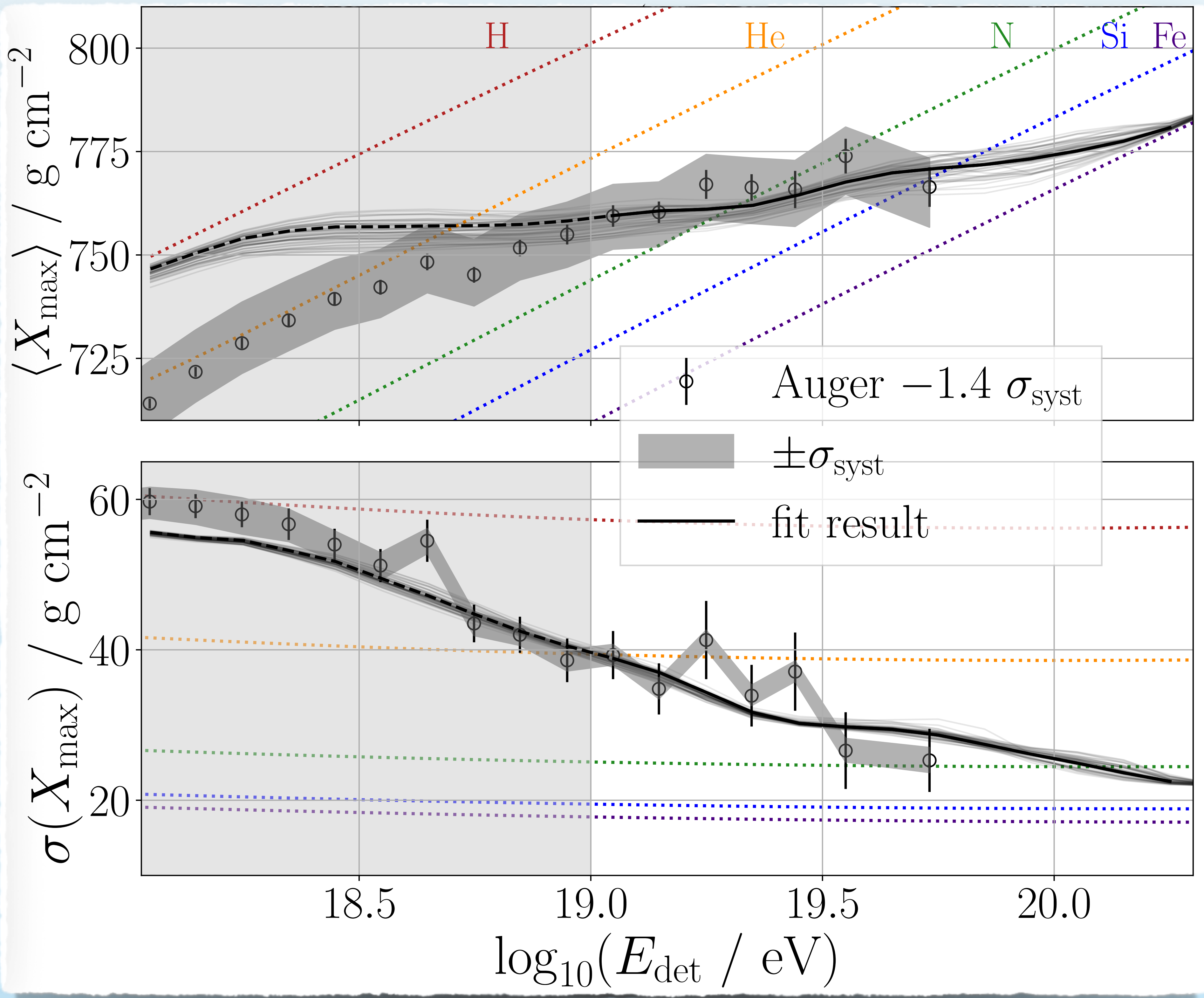
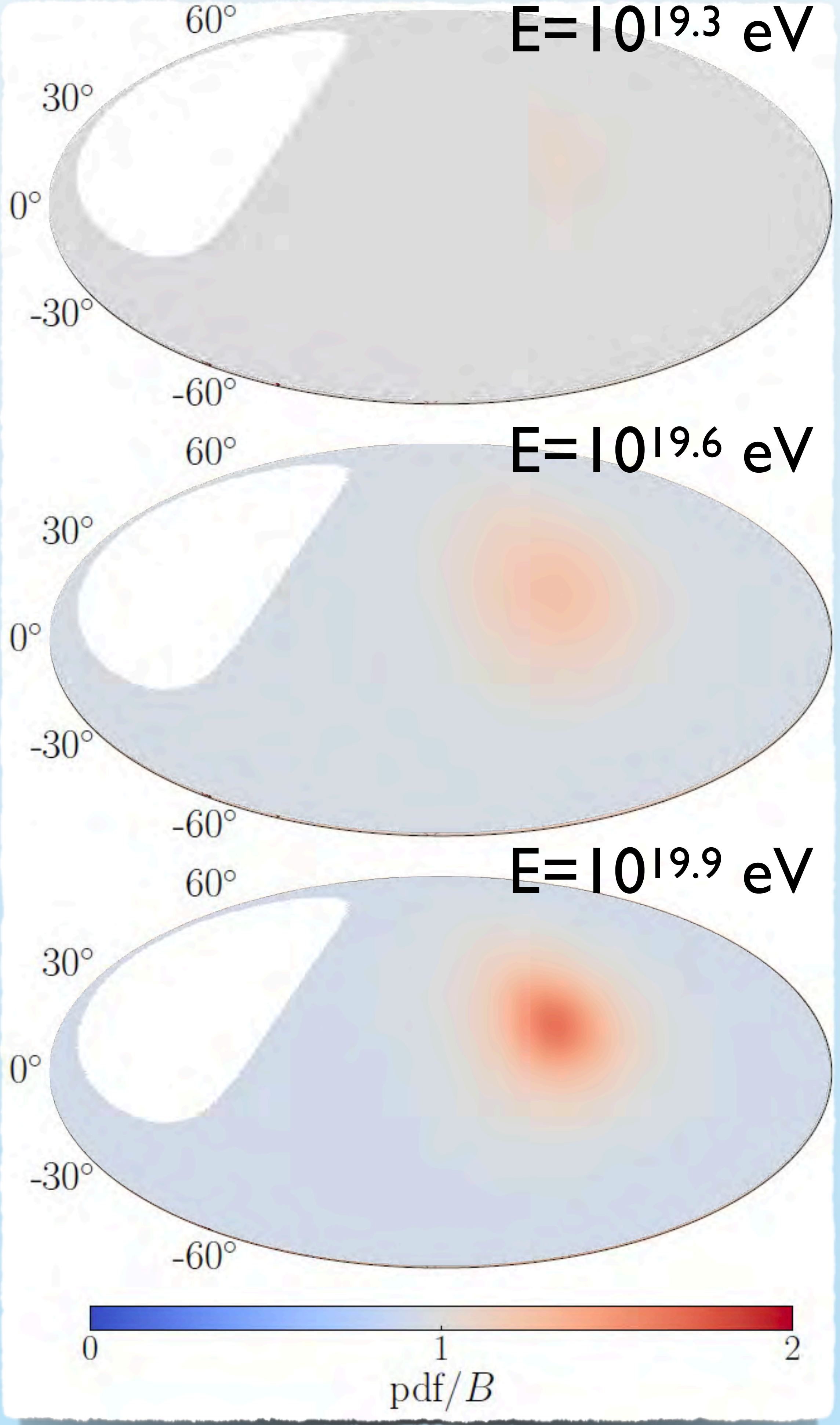








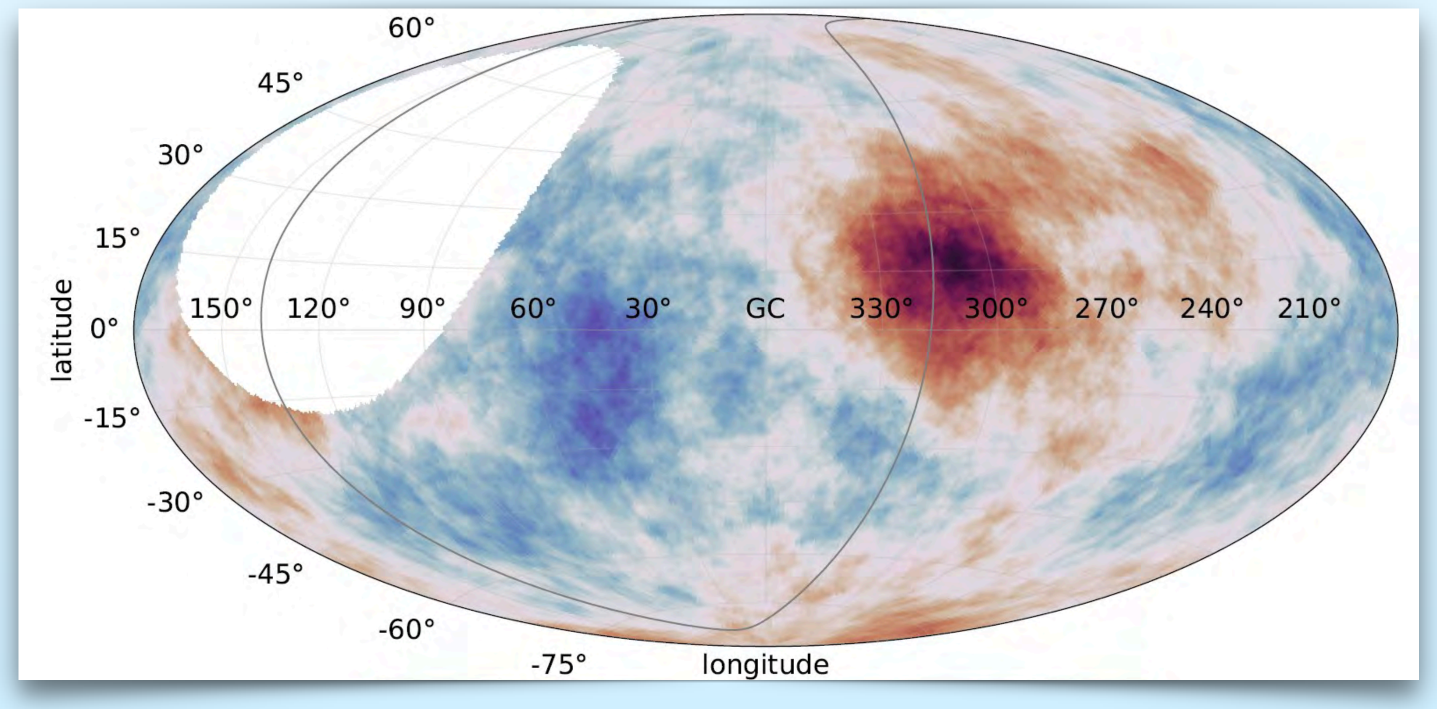
Result of likelihood fit to measured E-spectrum, Composition, and Sky-Map when taking a Cen A model (σ=3.4)

Terese Bister, ICRC2023

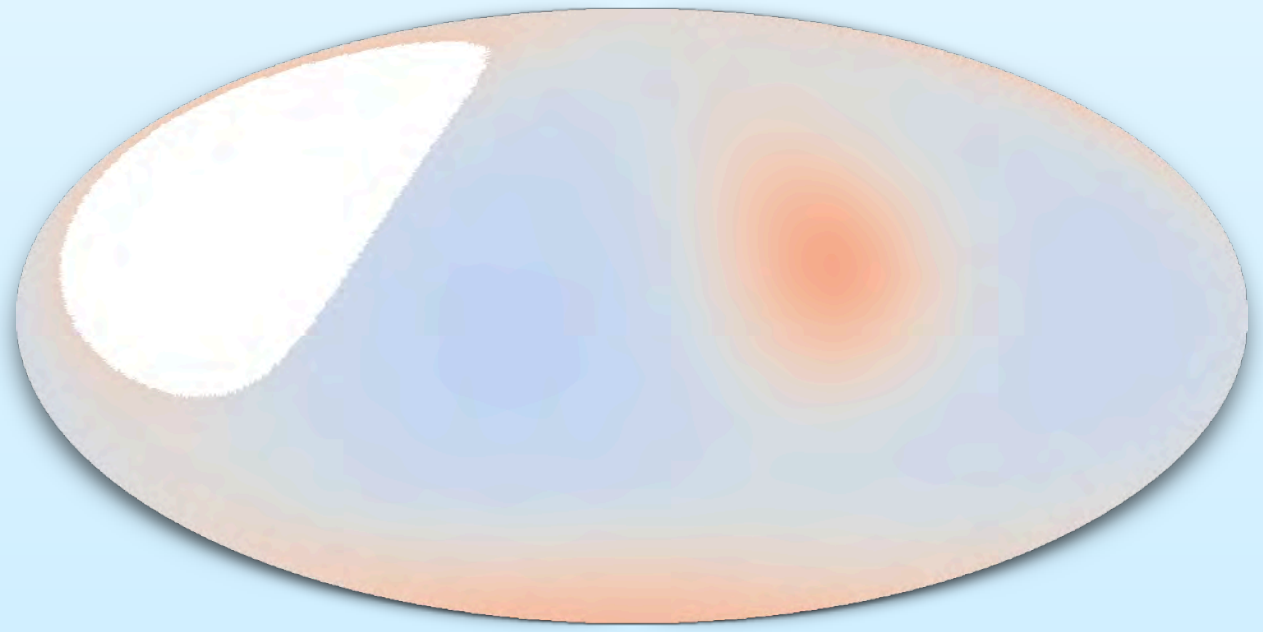
Towards understanding the Universe at its highest energies

Conclusion:

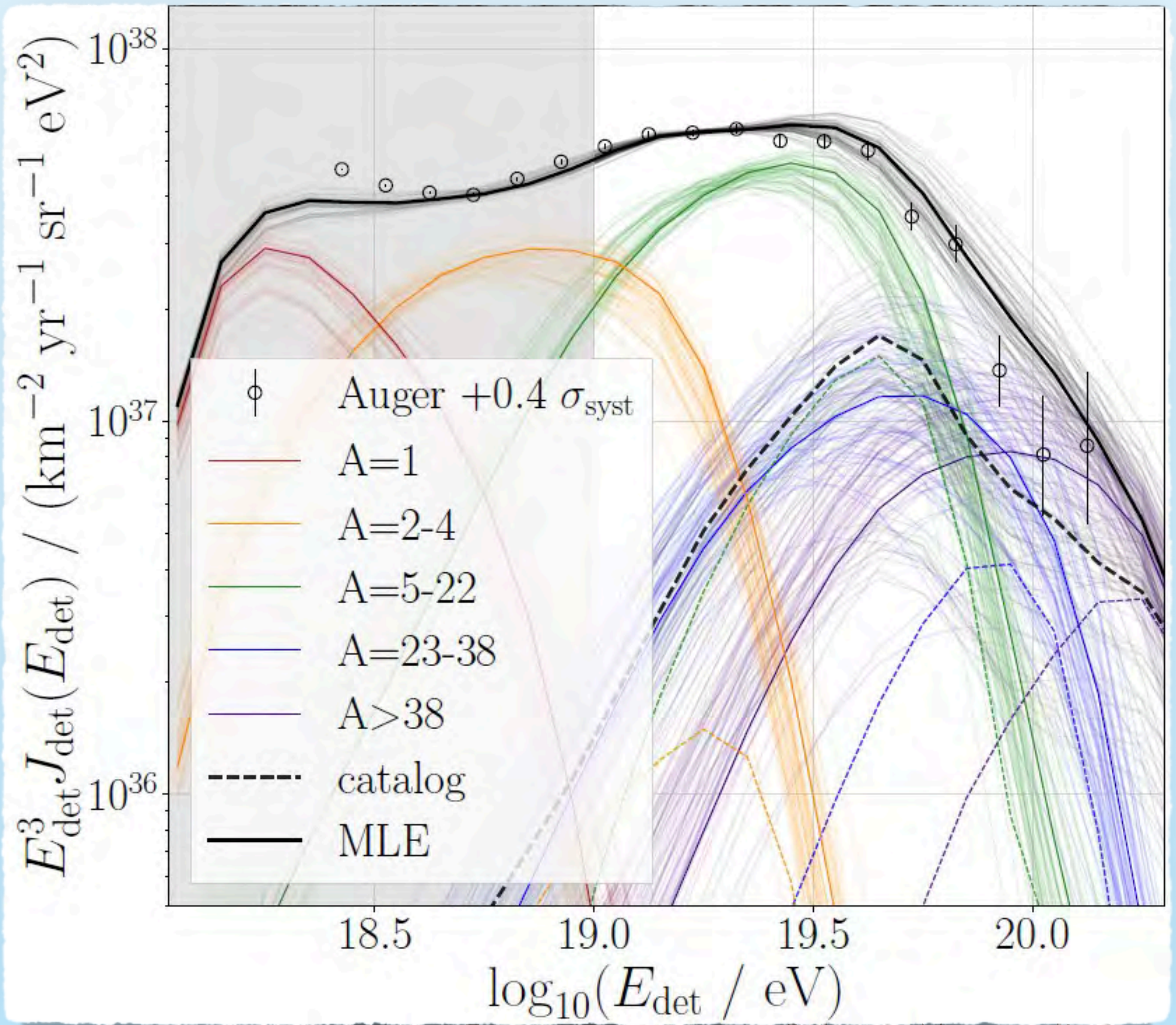
- The combined description of arrival directions + spectrum + composition works best with Starburst Galaxies (signal fraction ~20% at E=40 EeV) significance against isotropic sky: 4.5σ
- Blurring found at ~20°at a rigidity of 10 EV
- Maximum source rigidity: $R=10^{18.8}$ V



Data



expected sky from SBG with composition and energy spectrum from data



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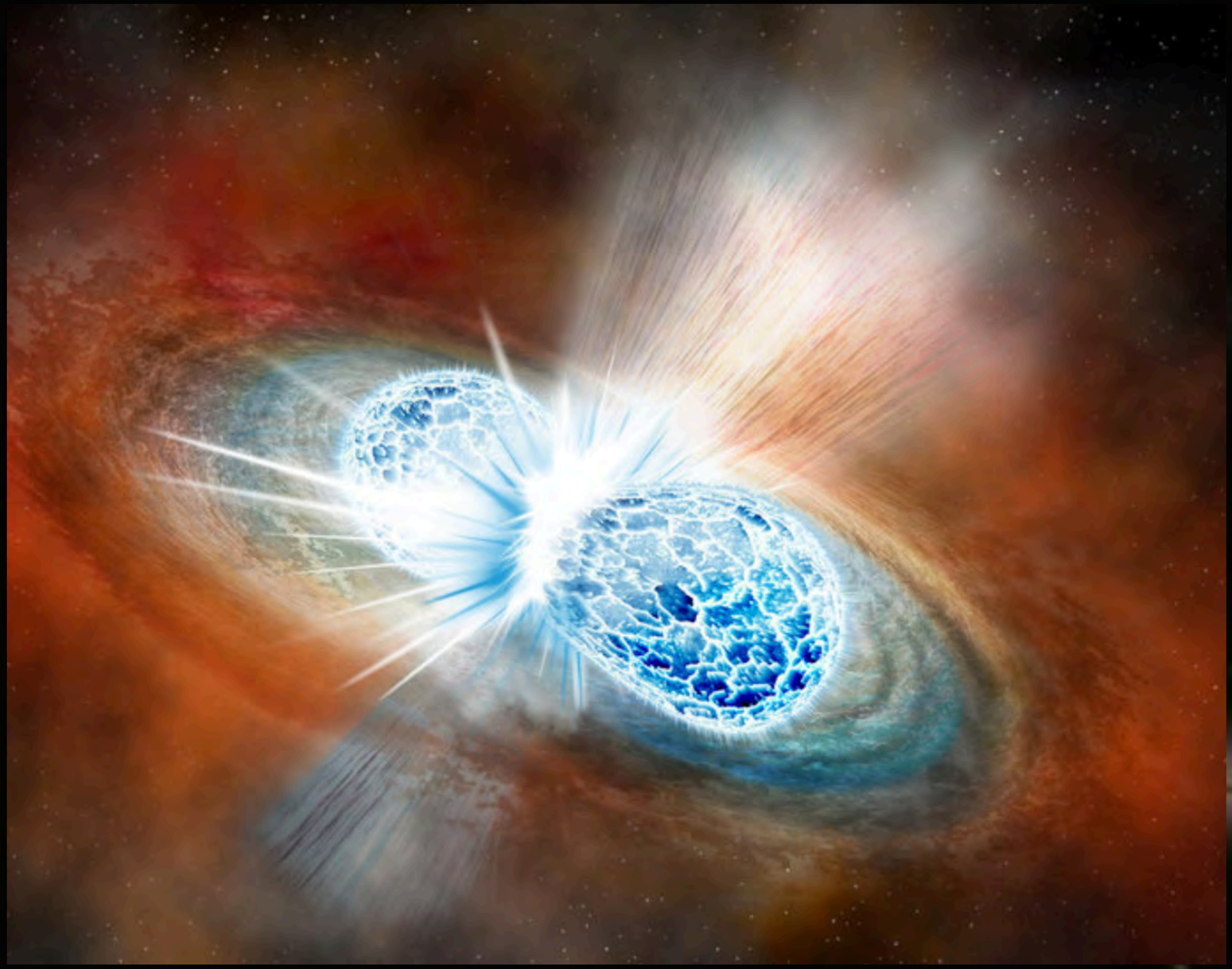
9) **Multi-Messenger: Some examples**

8) Related non-CR opportunities

9) UHECR future: challenges and prospects

2017: Big Bang of Multimessenger Astrophysics



Scientific Breakthrough of 2017

Neutron Star Merger GW 170817

observed also in broad range of
electromagnetic radiation
with strong bounds on
HE neutrino emission

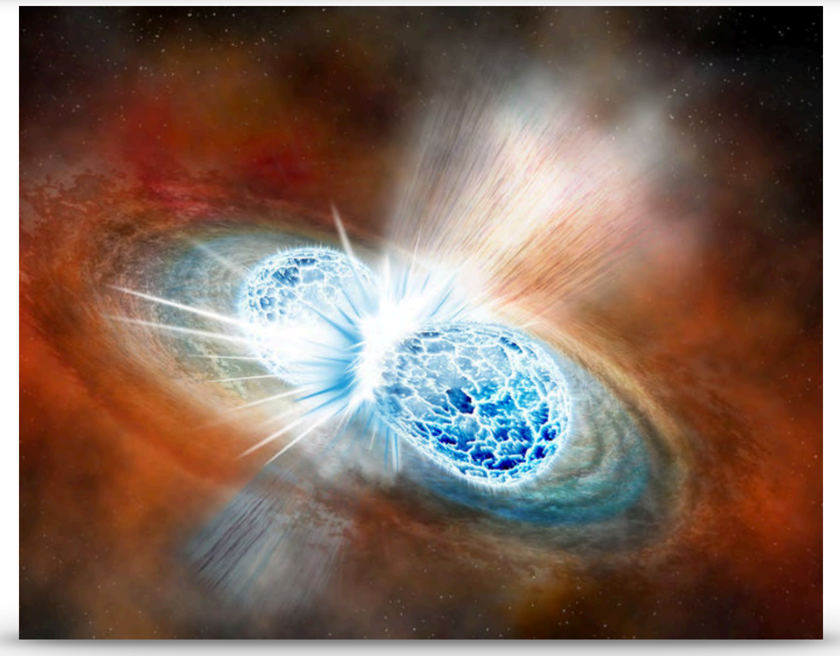
Joint publication by > 3000 authors (LHC scale)

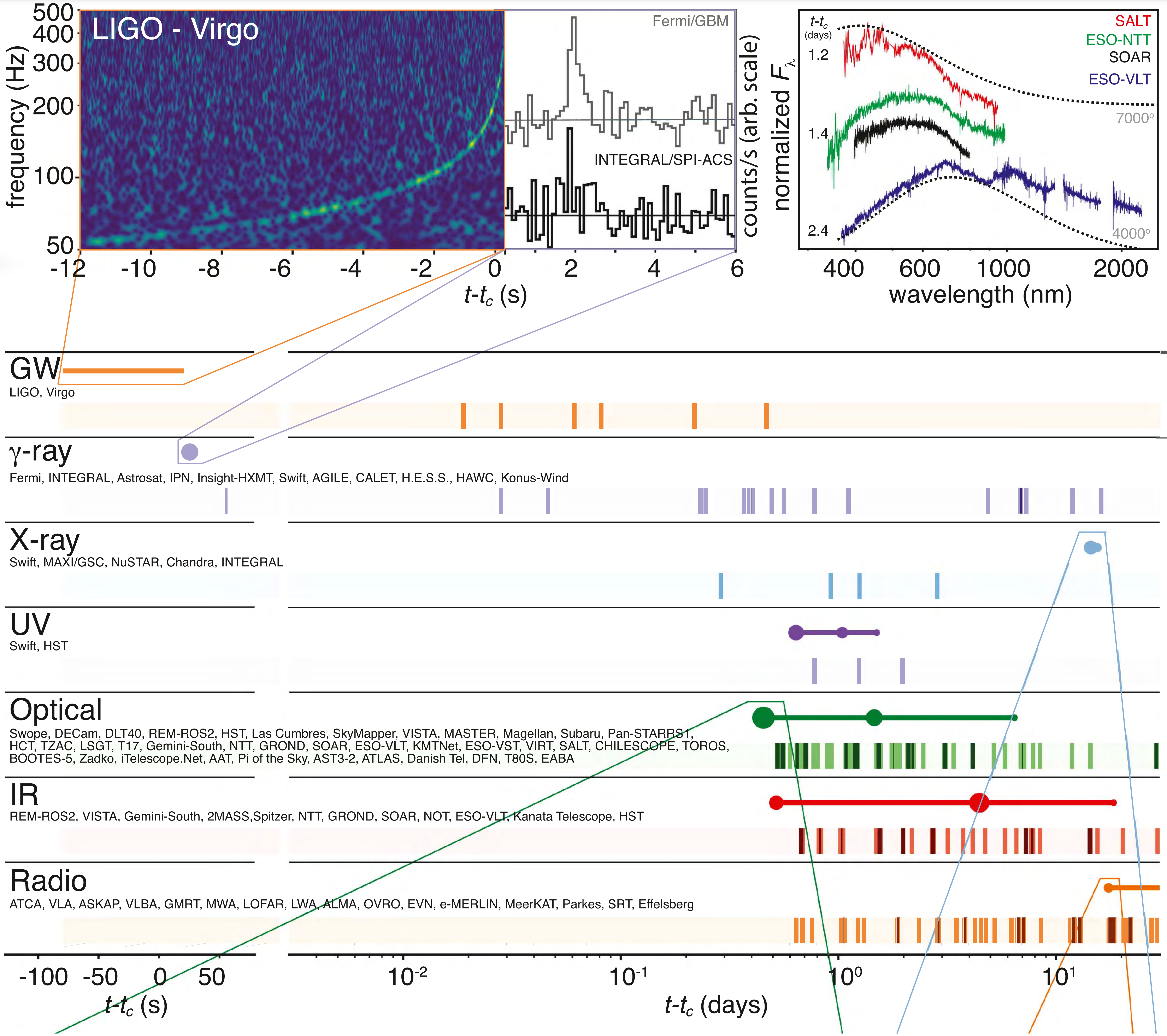
The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

Multi-messenger Observations of a Binary Neutron Star Merger

This was a very lucky event...!

GW170817: Time Sequence





lasted 100 s !

1.7 s after GWs

still after weeks

m_1 = (1.36 - 2.26) $M_\odot$

m_2 = (0.86 - 1.36) $M_\odot$

Host galaxy: NGC 4993

distance: 40 Mpc

optical brightness after one day $10^8\ L_\odot$ → kilonova powered by radioactive decays

13:08 UTC LIGO sent a a BNS alert that occurred <2 s before GRB from same direction

Fermi-GBM sent an automated alert of an unspectacular GRB at 12:41 UTC

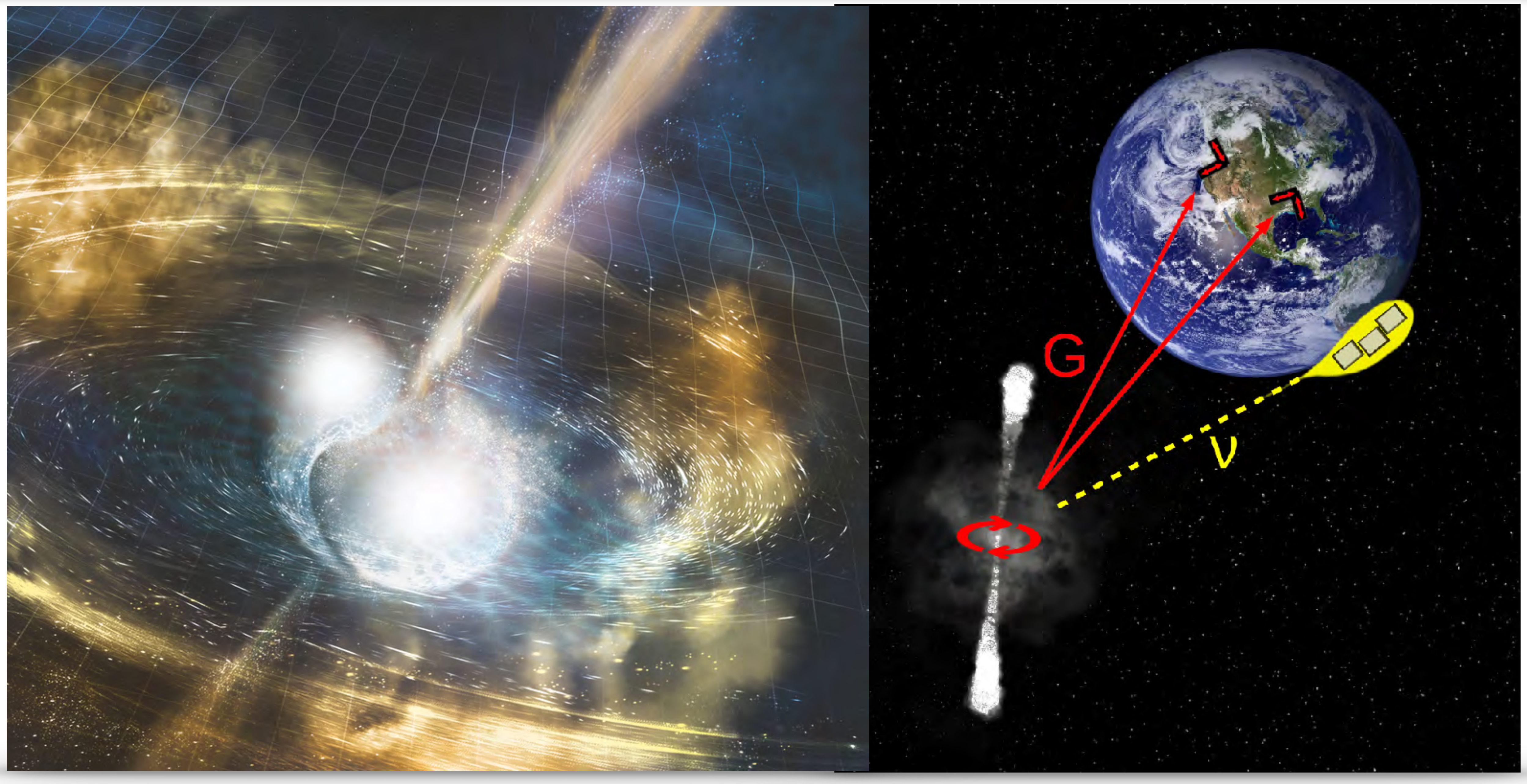
excessive campaign during next days and weeks

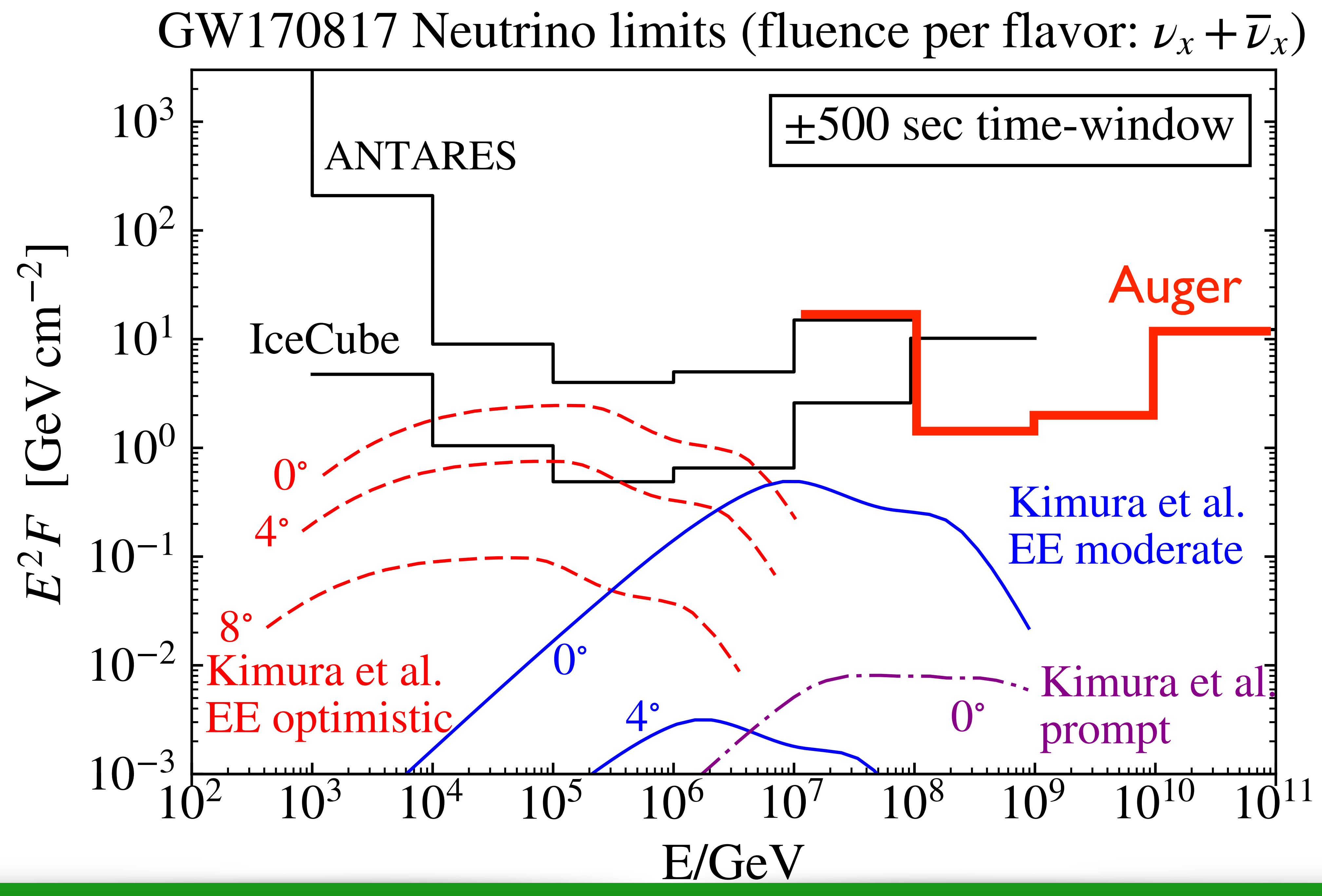
GW170817: Physics across multiple aspects/fields

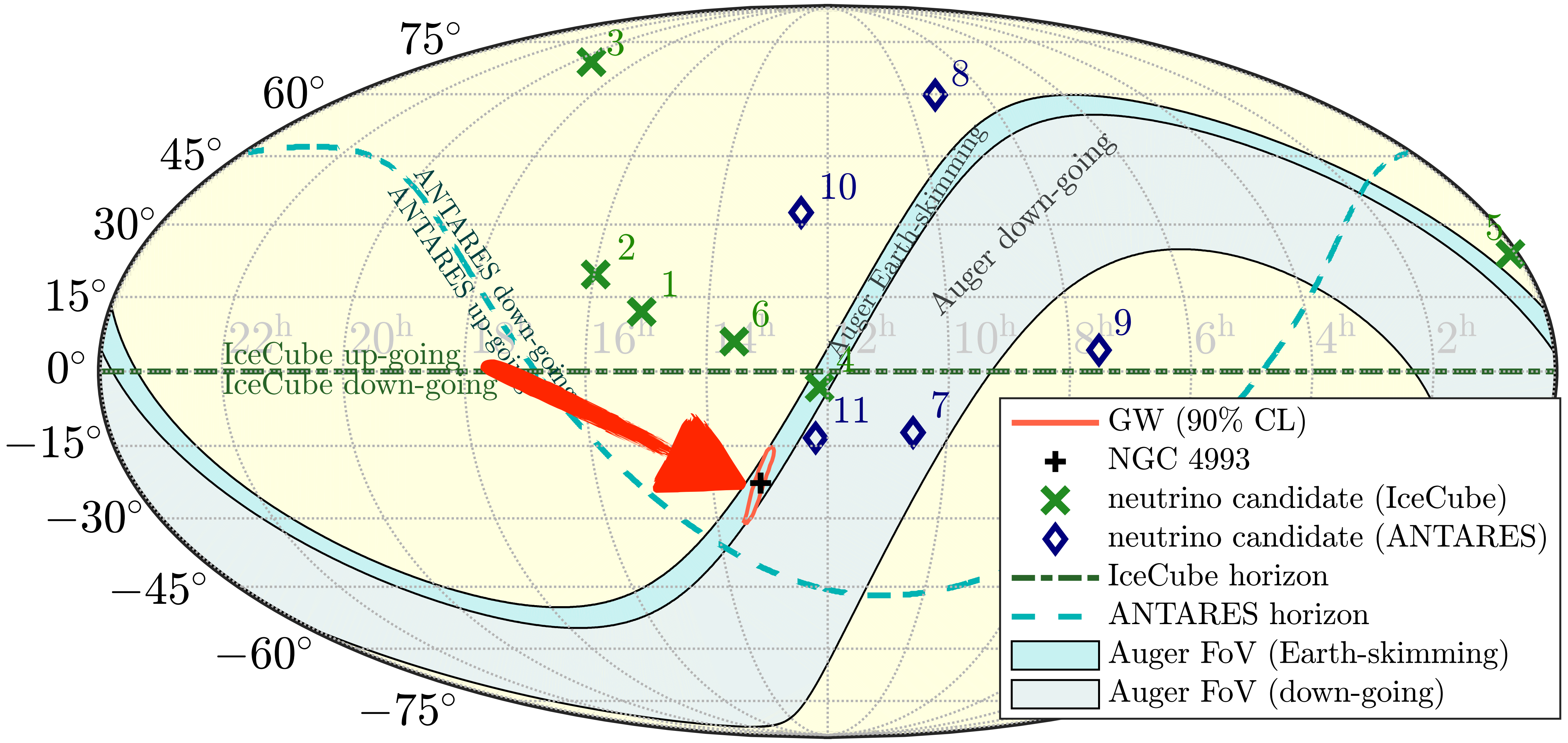
- **General Relativity**: gravitational waves
- **Cosmology**: independent Hubble constant determination
- **Astronomy**: Follow ups, multiwavelength
- **Astrophysics**: Compact objects, Neutron stars
- **Nuclear Physics**: r-process, equation of state
- **Particle Physics**: Neutrino oscillations
- **Astroparticle Physics**: Particle acceleration, UHE counterparts

Unique Event
→ Brought together different communities

Neutrino Upper Limits for GW170817







Absence of Neutrino consistent with sGRB viewed at >20° angle

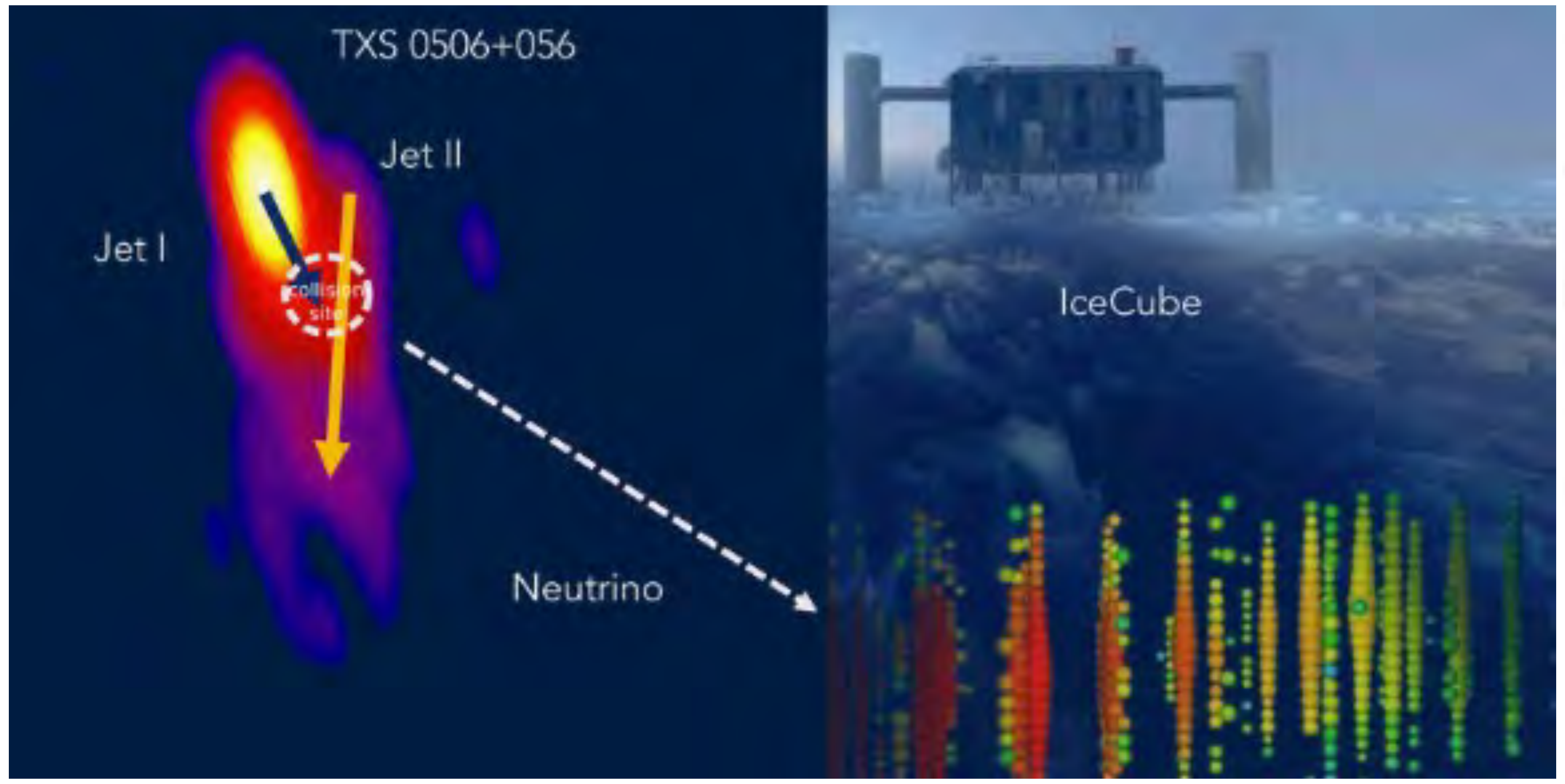
May have seen neutrinos if jet were pointing towards us

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

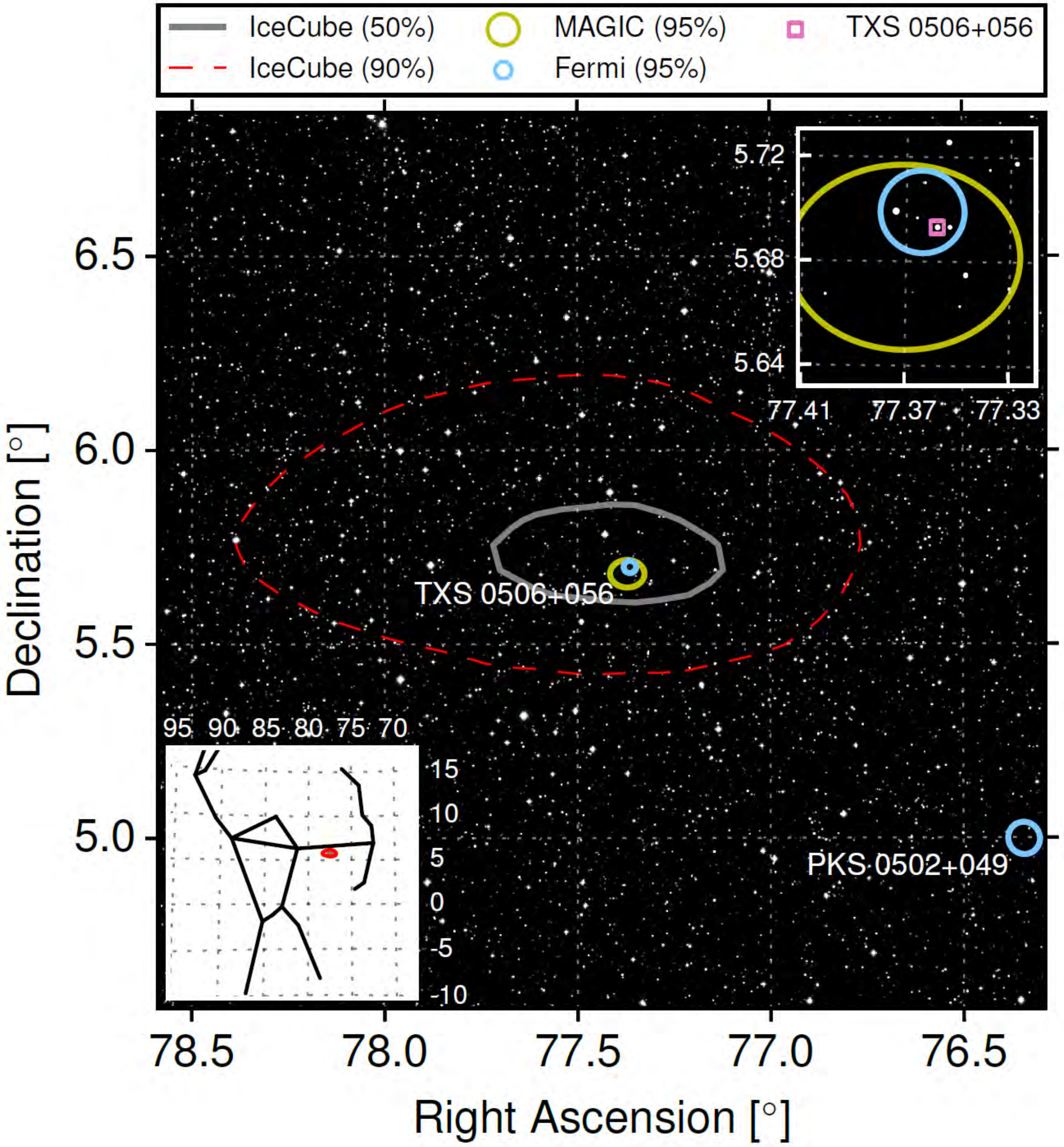
High energy neutrino from direction of TXS 0506-056

On Sept. 22, 2017 a 290 TeV neutrino from the direction of TXS 0506-056 was observed by IceCube

→ routinely an alert was sent to the Global Coordinate Network (GCN)

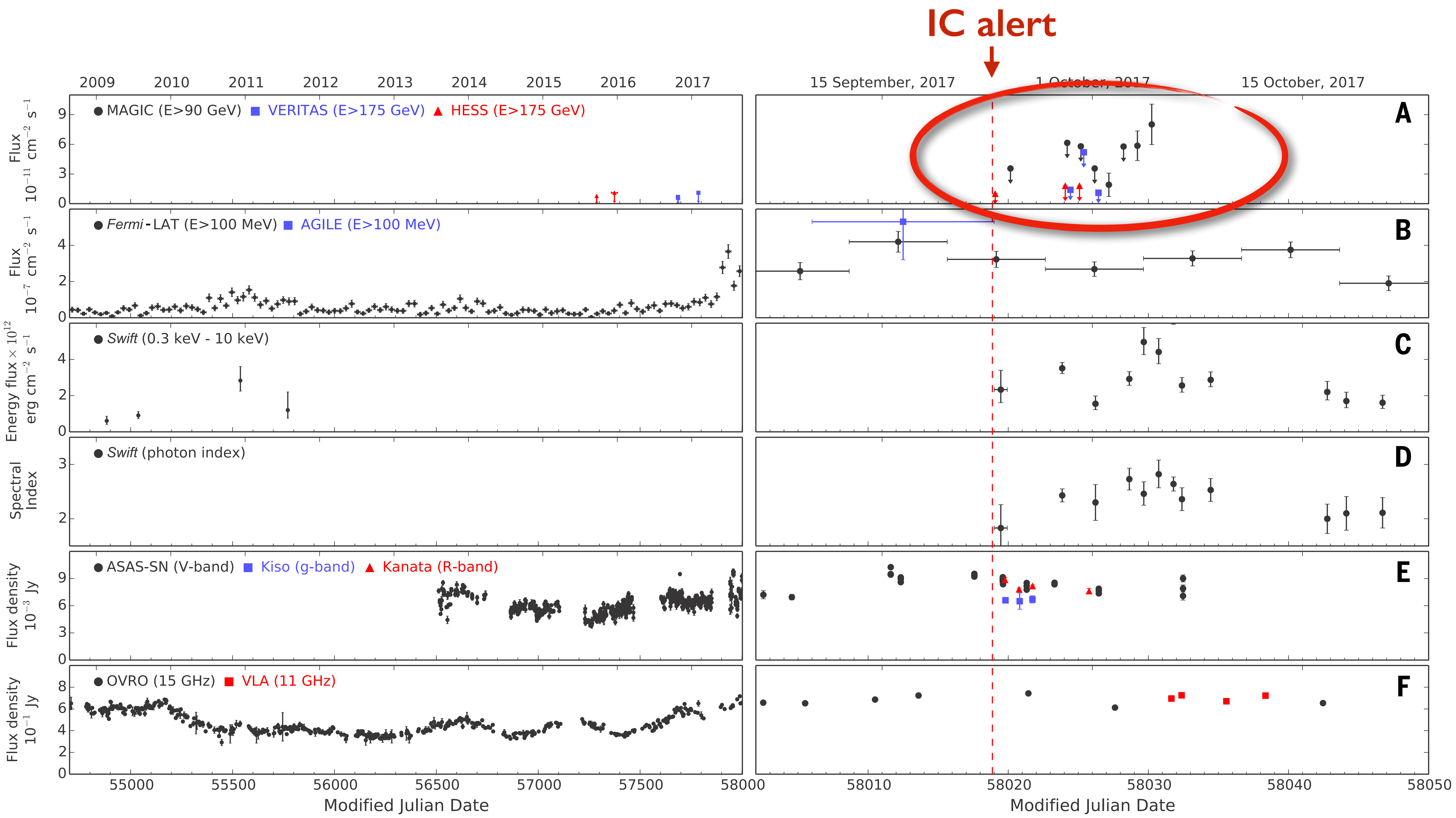


Science 361, 146 (2018)



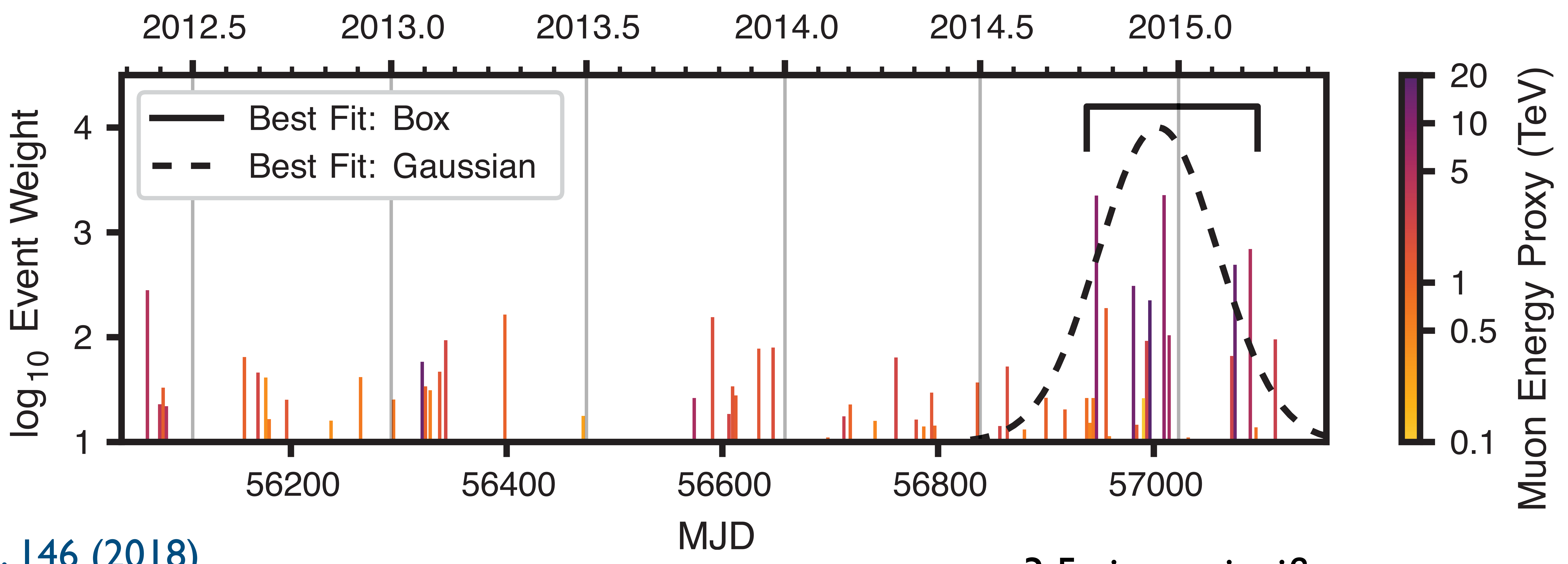
TXS 0506-056 in flaring state

The MAGIC telescope was pointed there and found the blazer entering a flaring state with E_γ > 90 GeV



TXS 0506-056 Neutrino Flare ?

IceCube then checked archives and found some neutrino excess (flare?) from TXS 0506-56 in 2015



Science 361, 146 (2018)

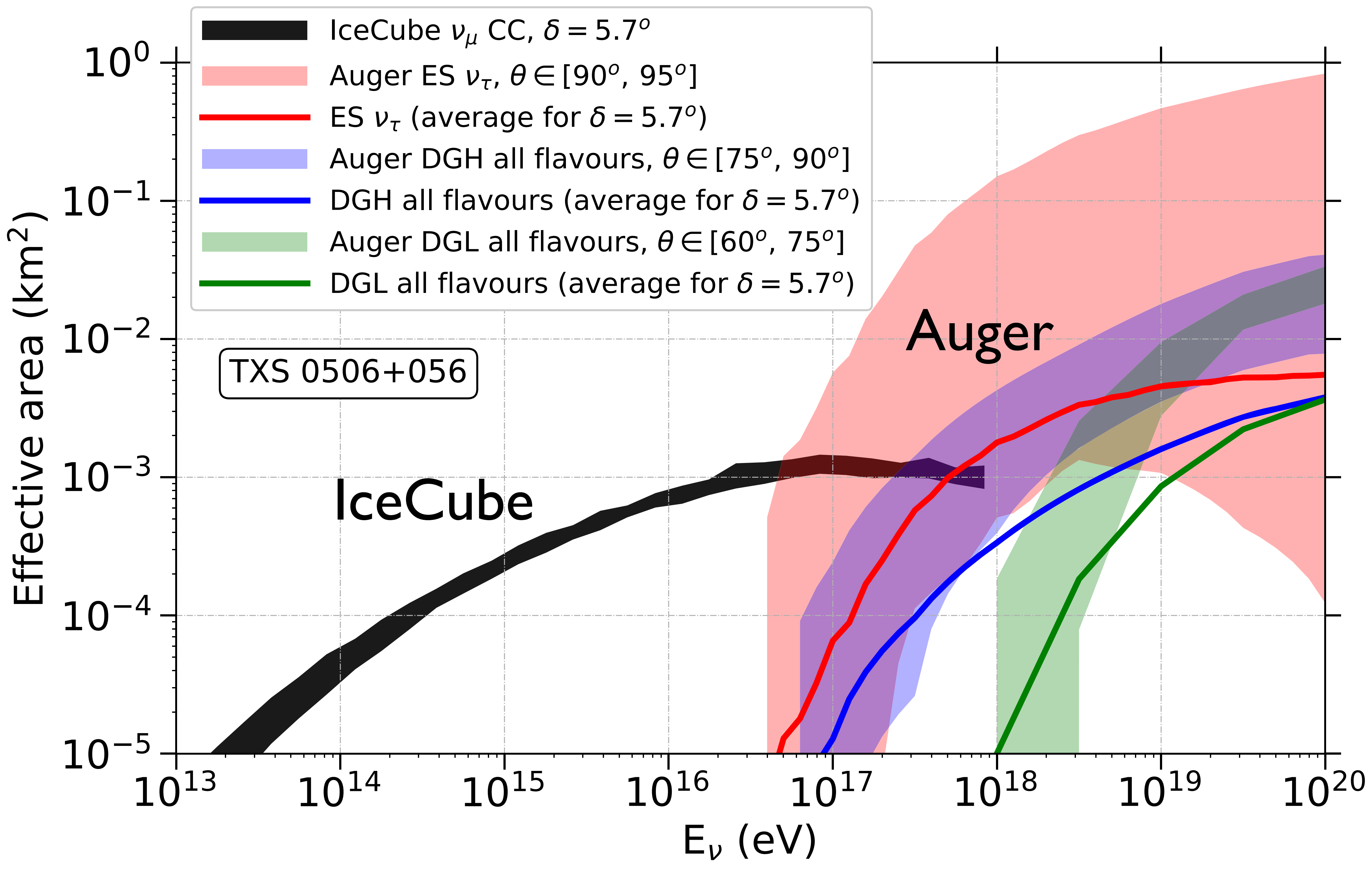
3.5 sigma significance

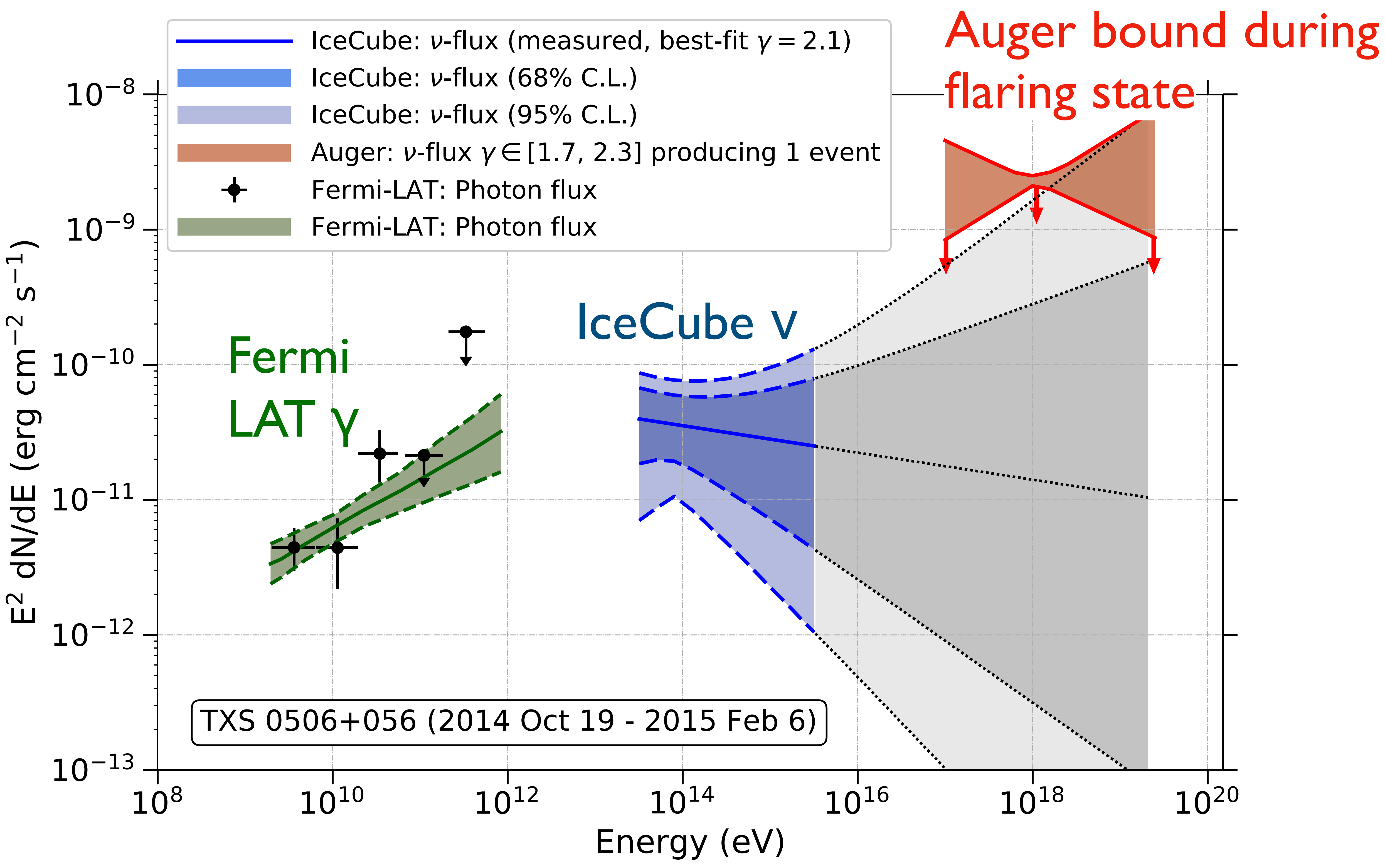
These are two ‚independent' 3.5σ observations
⇒ is TXS 0506-56 a neutrino source?

Search for nu's from TXS 0506+56 with Auger

TXS 0506-056 visibility on daily basis in ES channel of Auger for < 1 hrs but in an unfavourable direction

effective area in comparison to IceCube





Auger Collaboration, ApJ 902 (2020) 105

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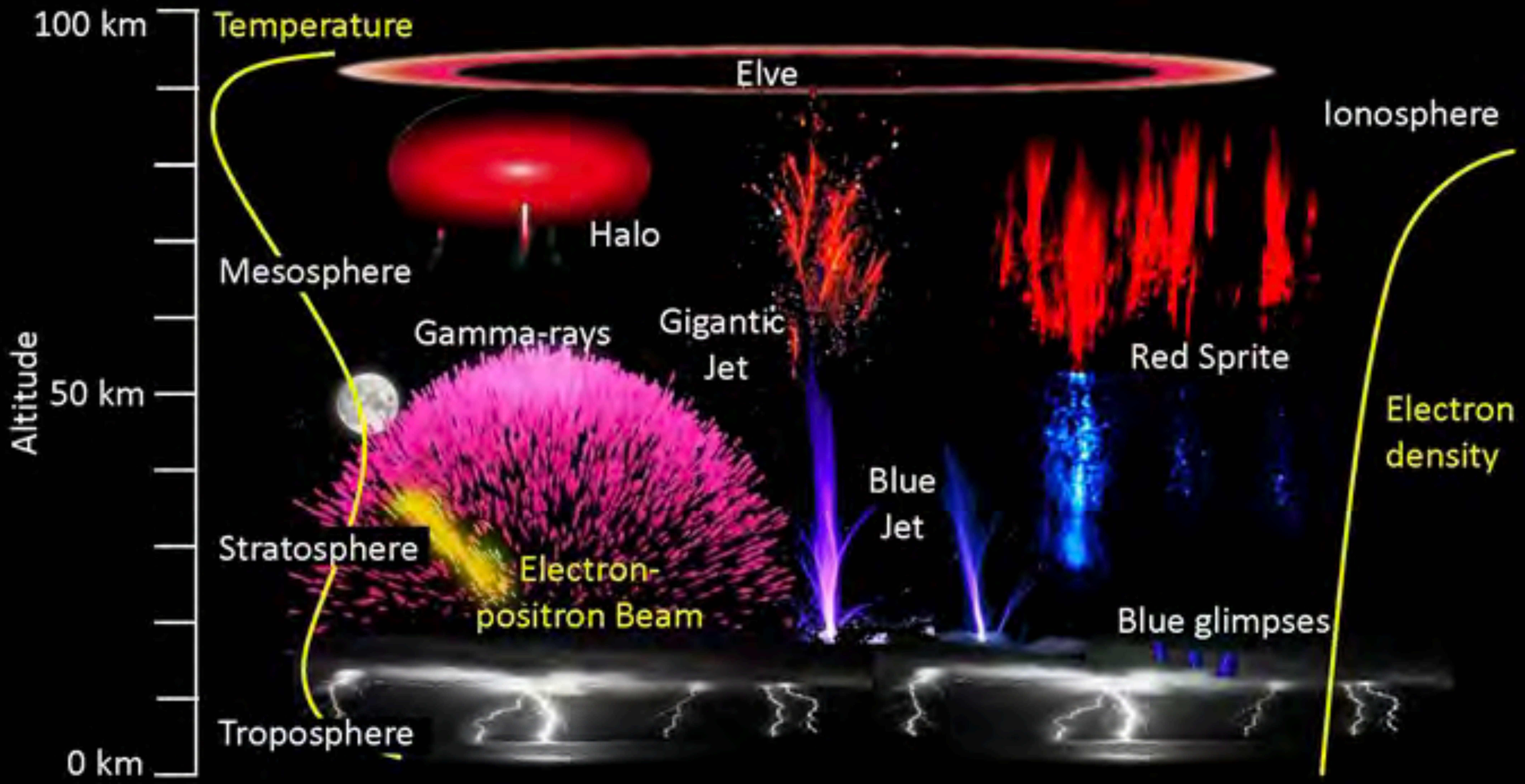
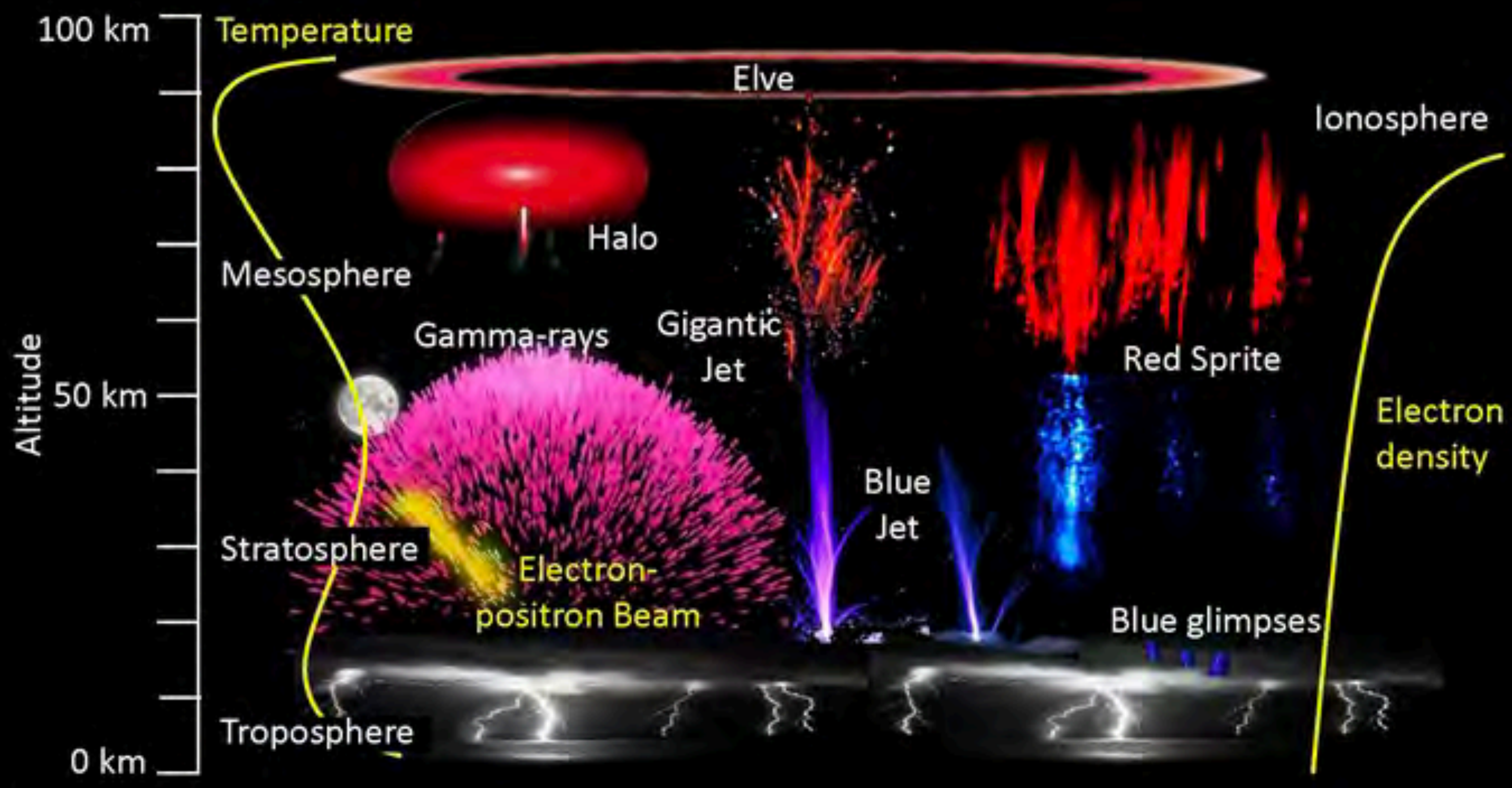
Observation of Elves and Terrestrial Gamma-Ray Flashes

Auger Collaboration, Earth and Space Sciences 7 (2020) 1

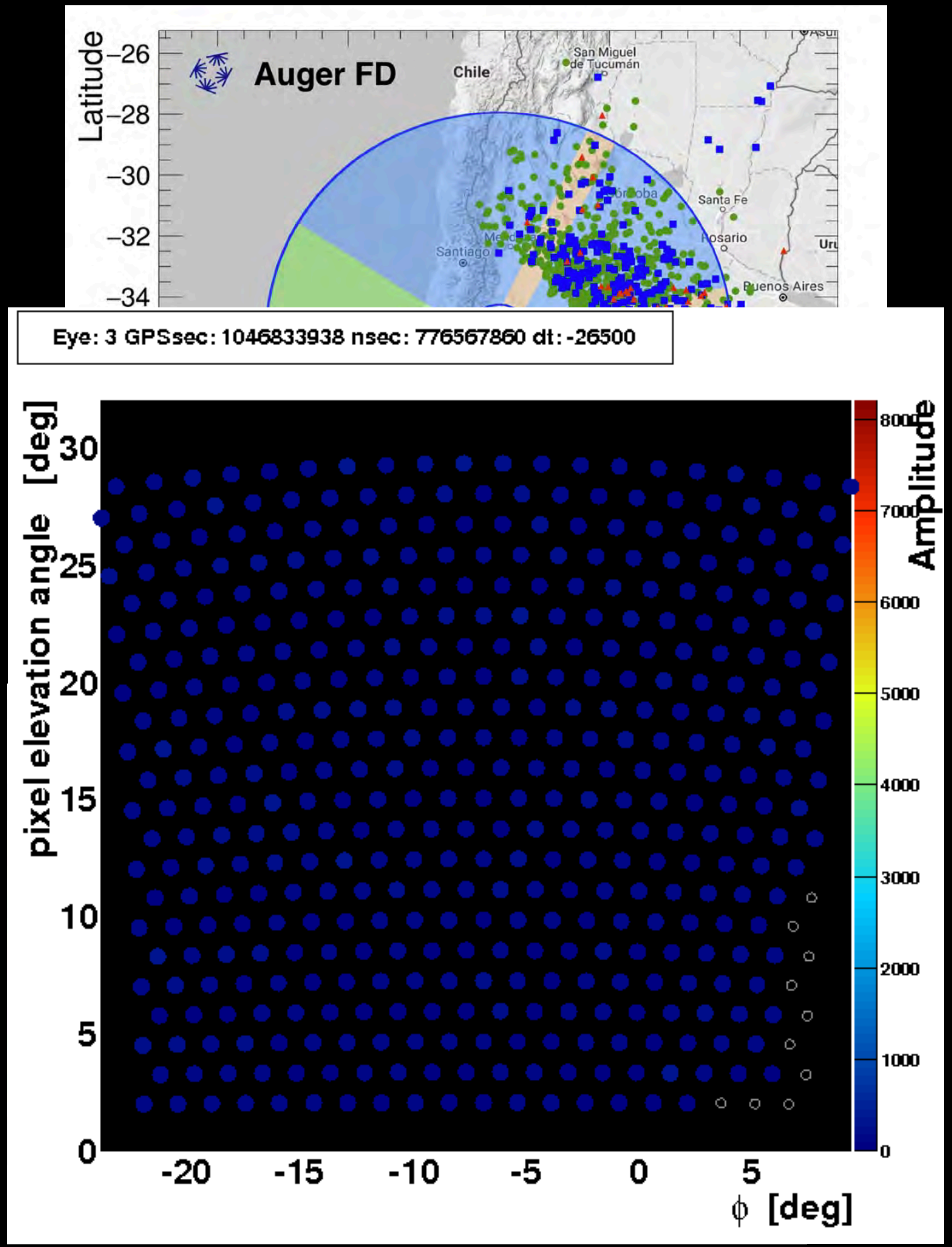


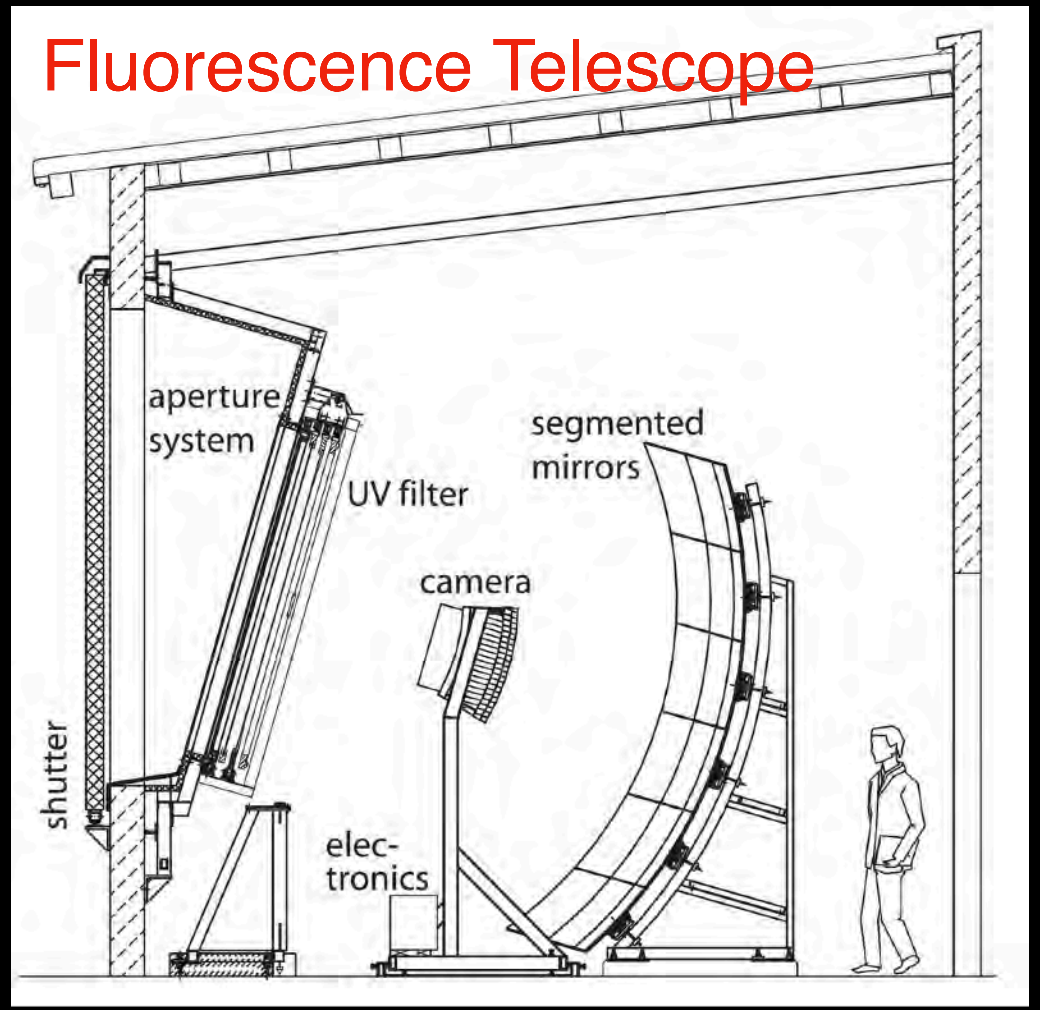
Observation of Elves and Terrestrial Gamma-Ray Flashes

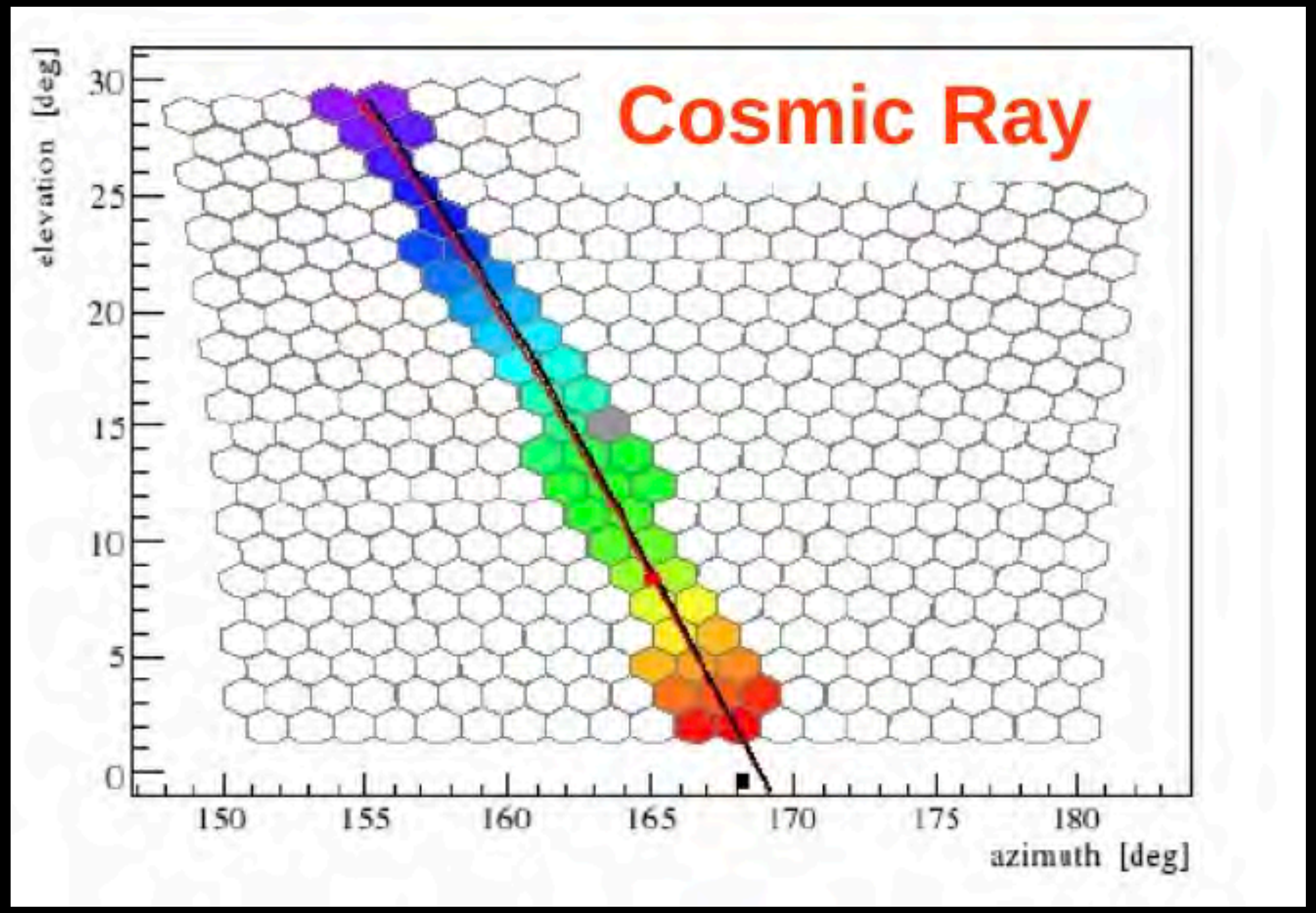
Auger Collaboration, Earth and Space Sciences 7 (2020) 1



Elves seen in 800 km distance, near BsAs







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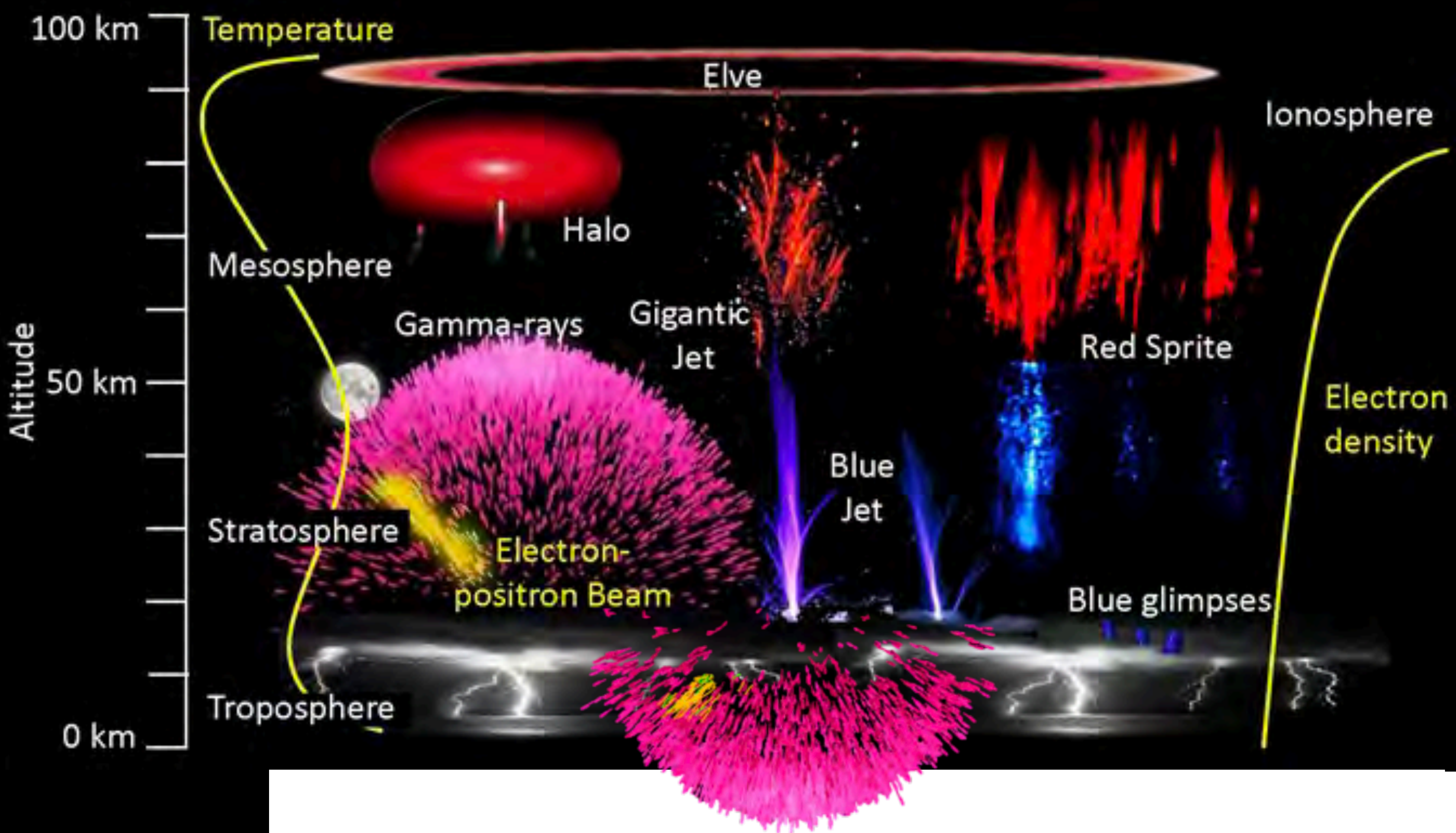
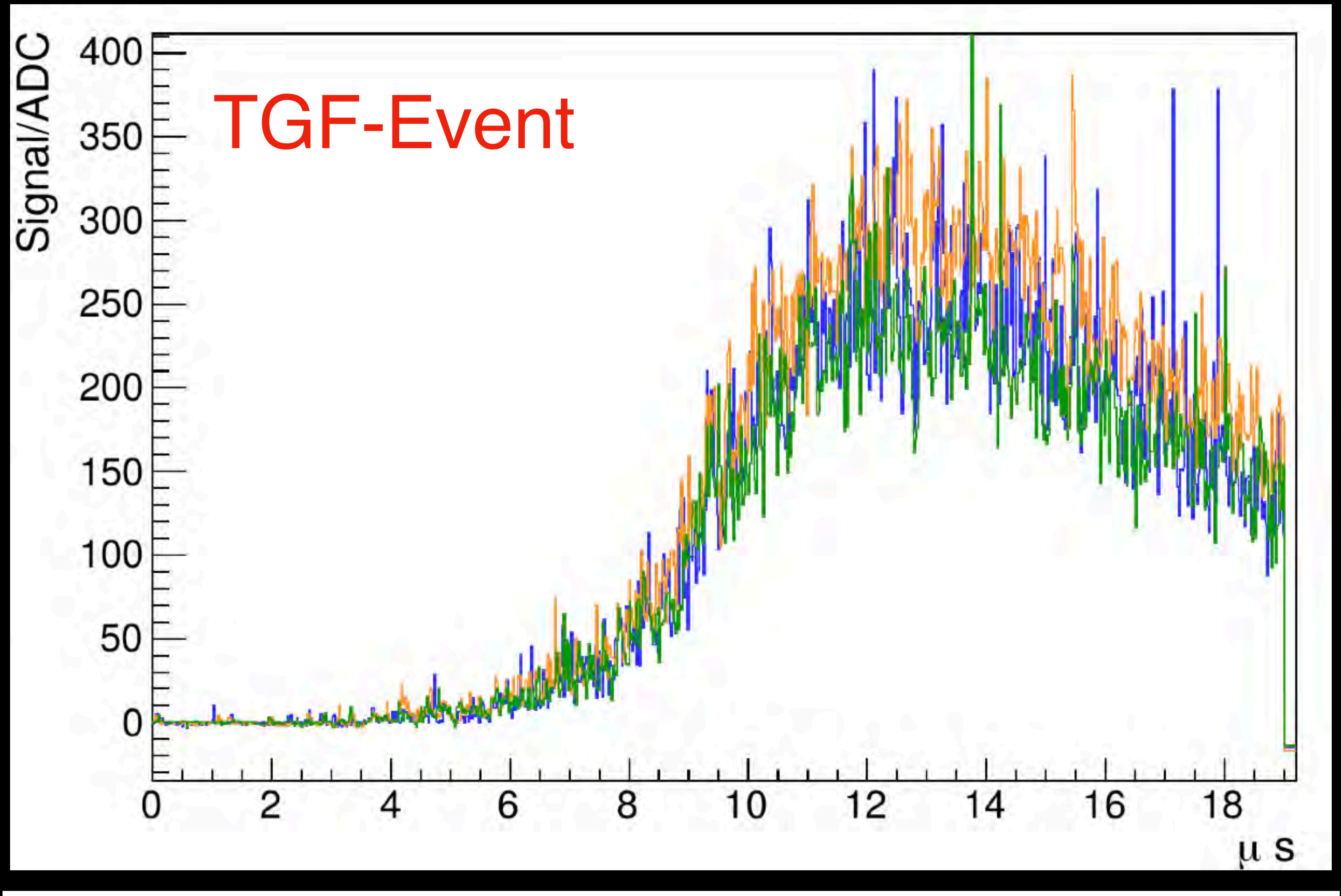
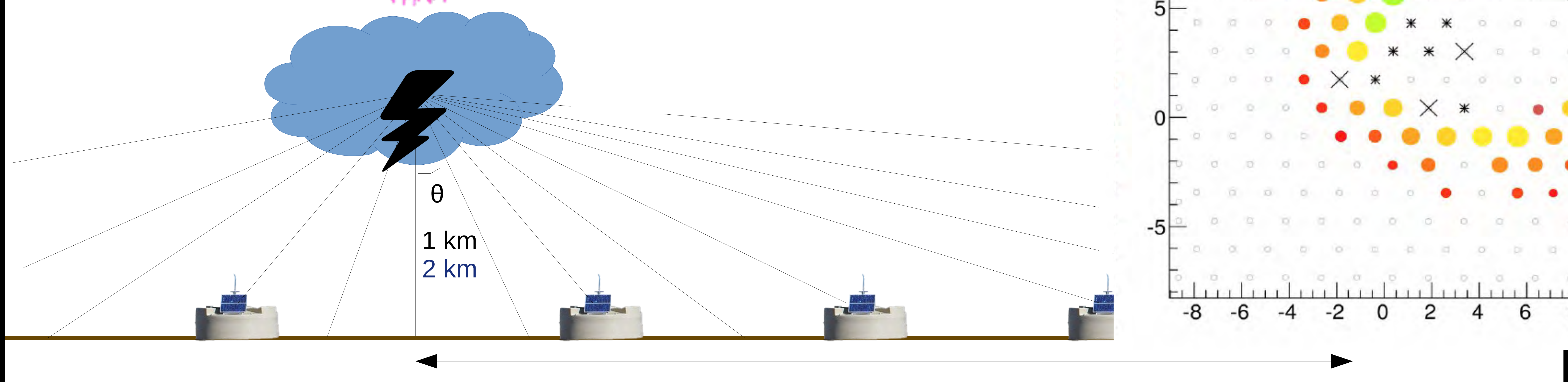
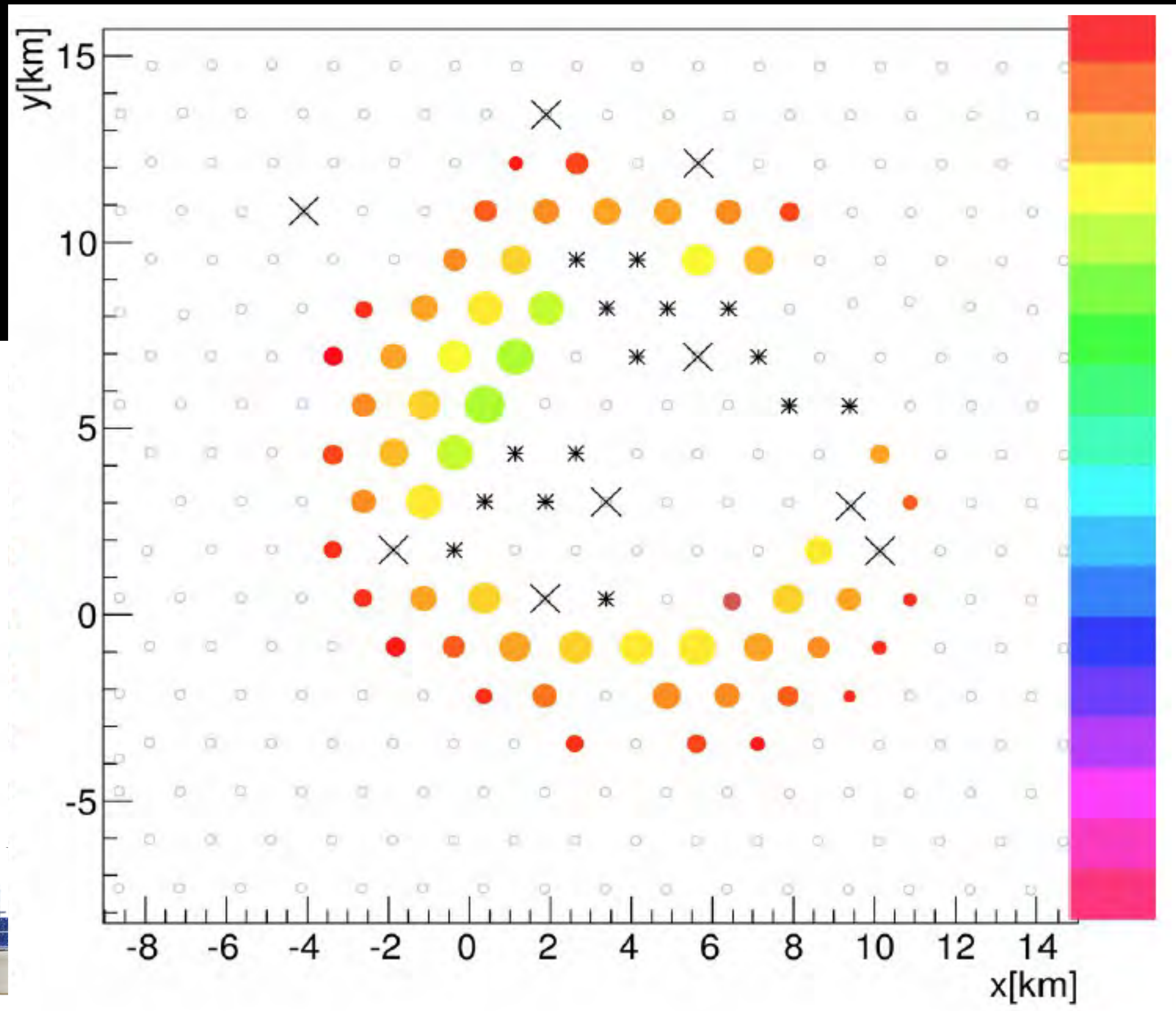
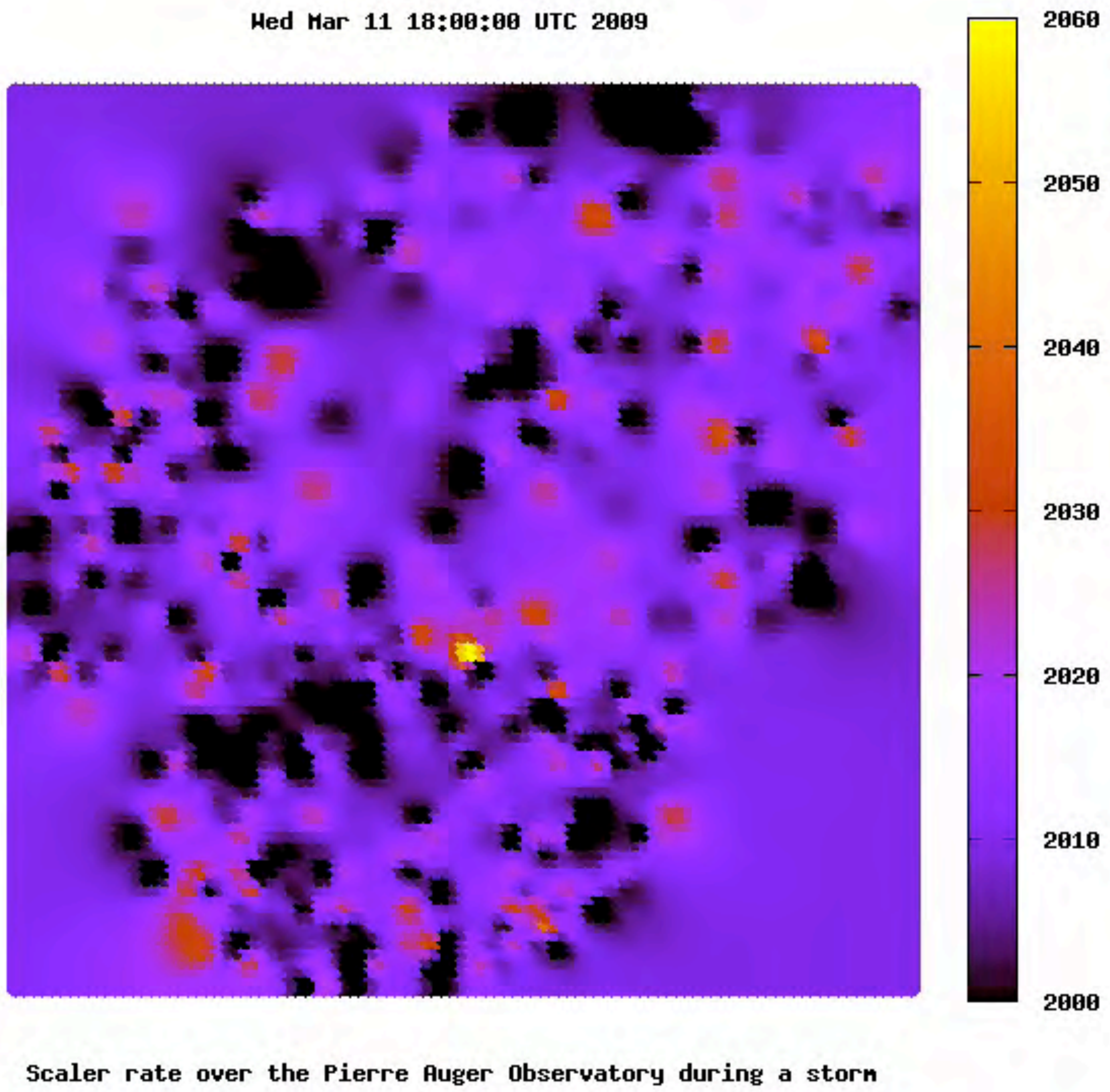




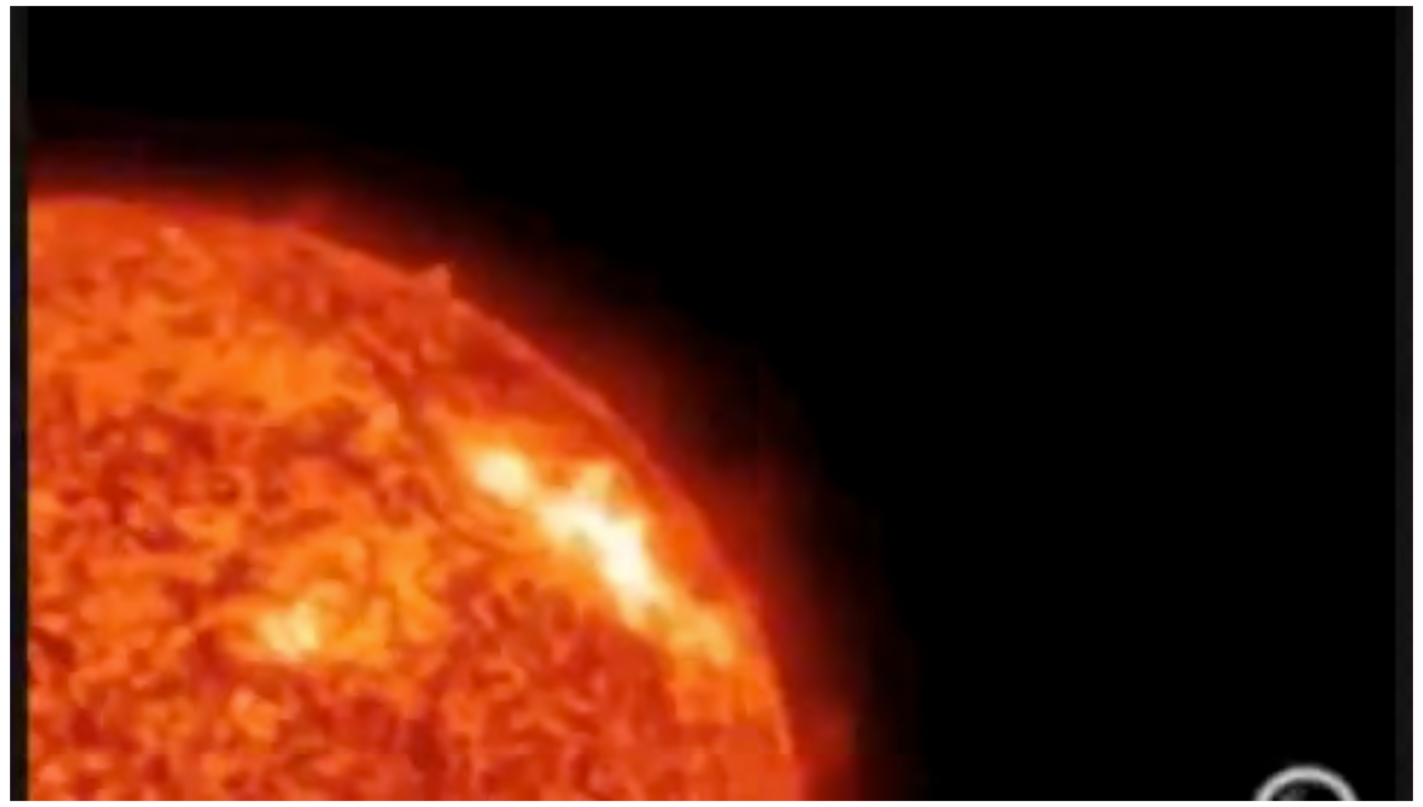




Electromagnetic Storm in the Pampa



Counting rates of the 1600 Water Cherenkov Stations during 7 hrs in March 2009 (1 min averages)



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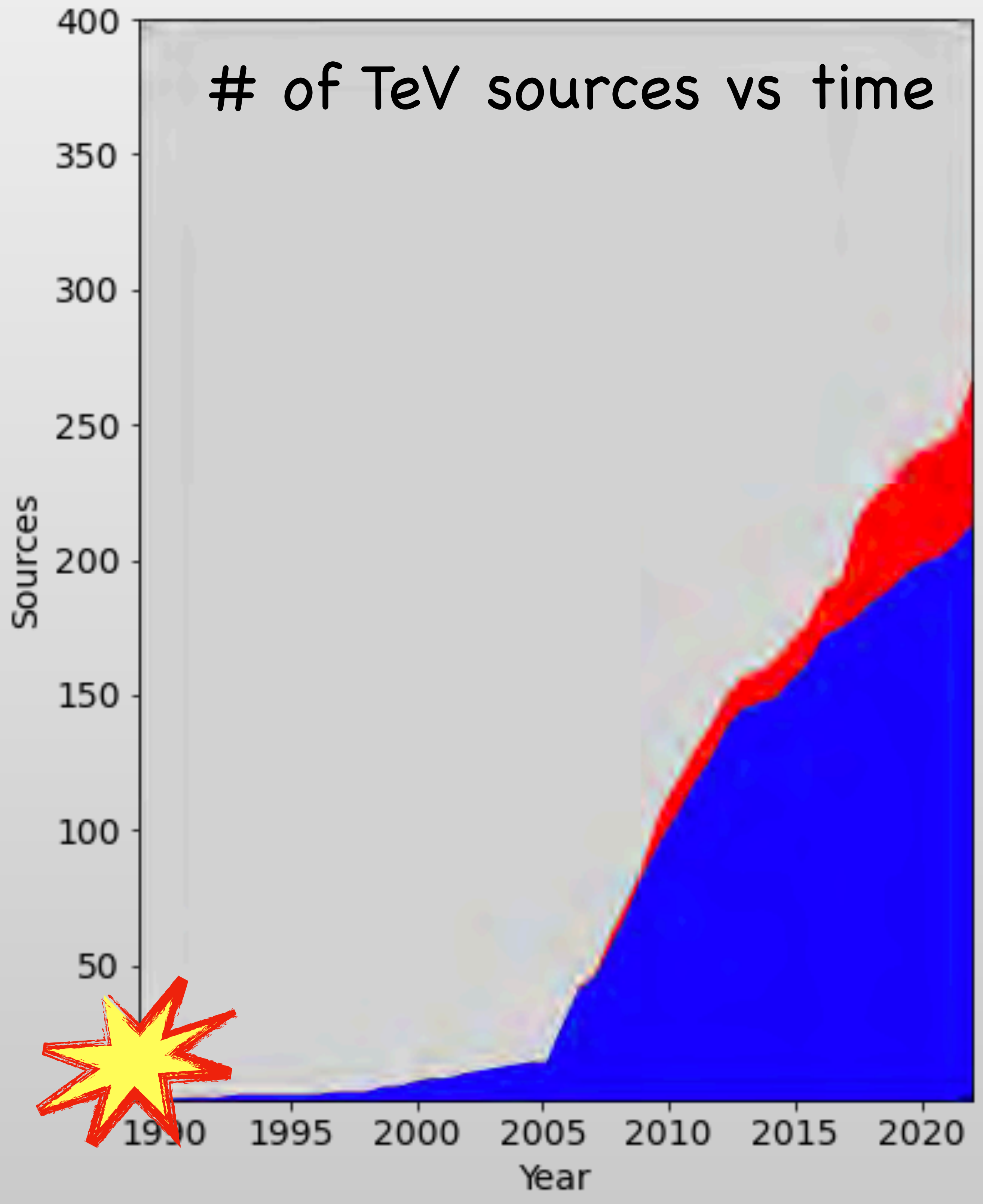
8) Related non-CR opportunities
9) Conclusions, future challenges and prospects

Resumé: What did we learn…

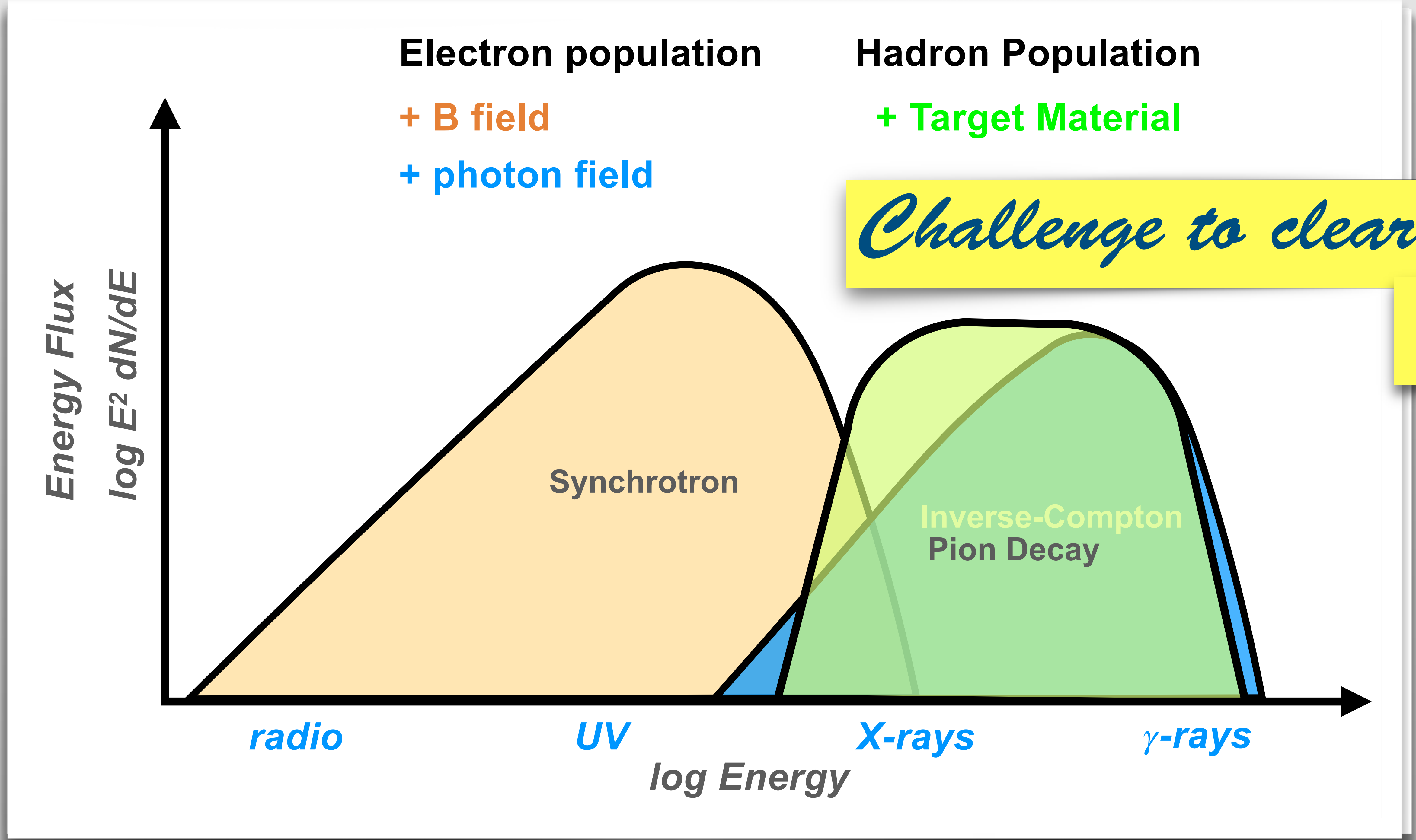
The last 15 years have been a series of important discoveries

this list is very subjective and selective…



1989 discovery of Crab Nebula

Several new types of sources,
good understanding of physics and source environments
However, holy grail „hadronic sources“ still open…



Challenge to clearly identify pion decay over IC

Resumé: What did we learn…

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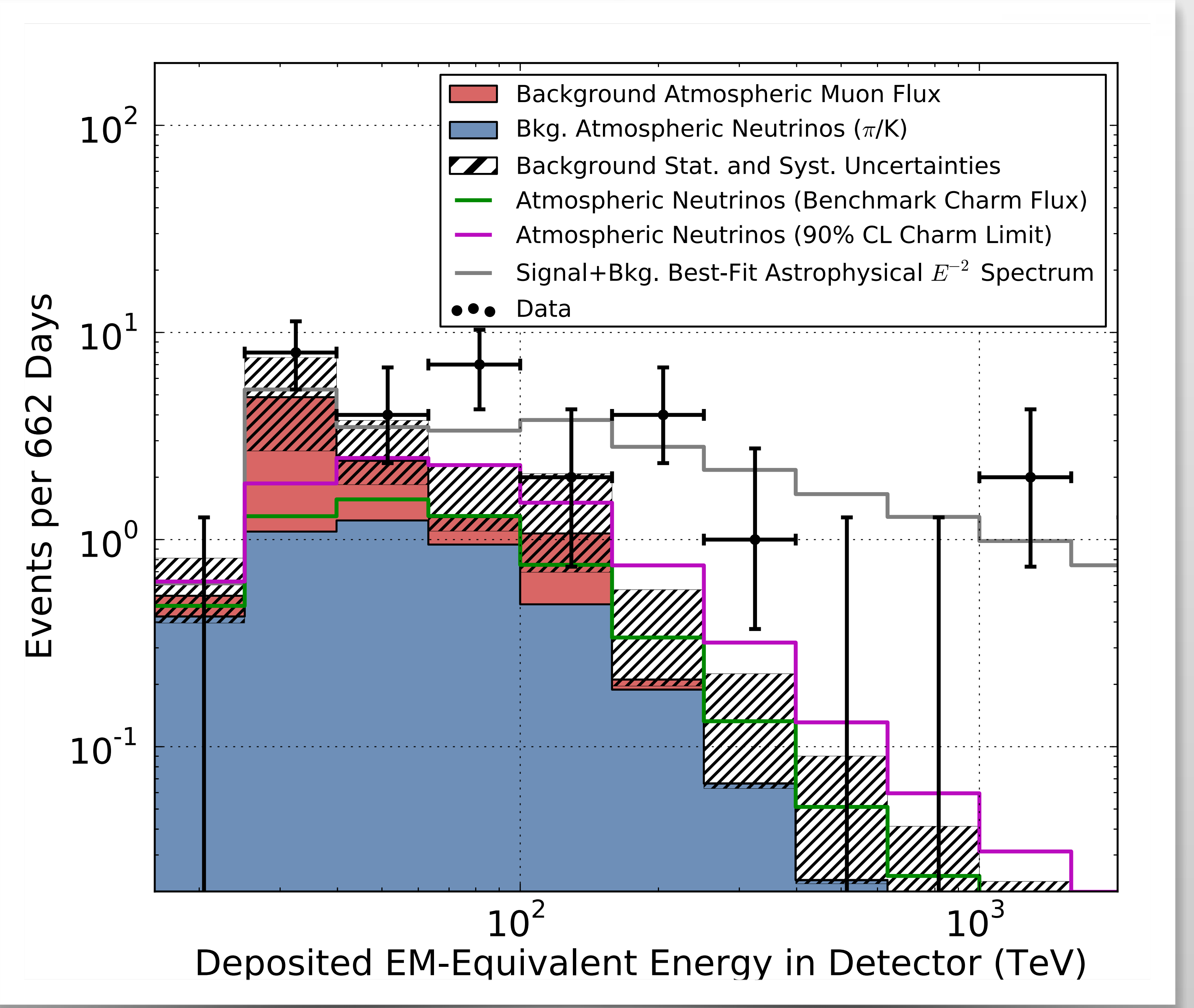
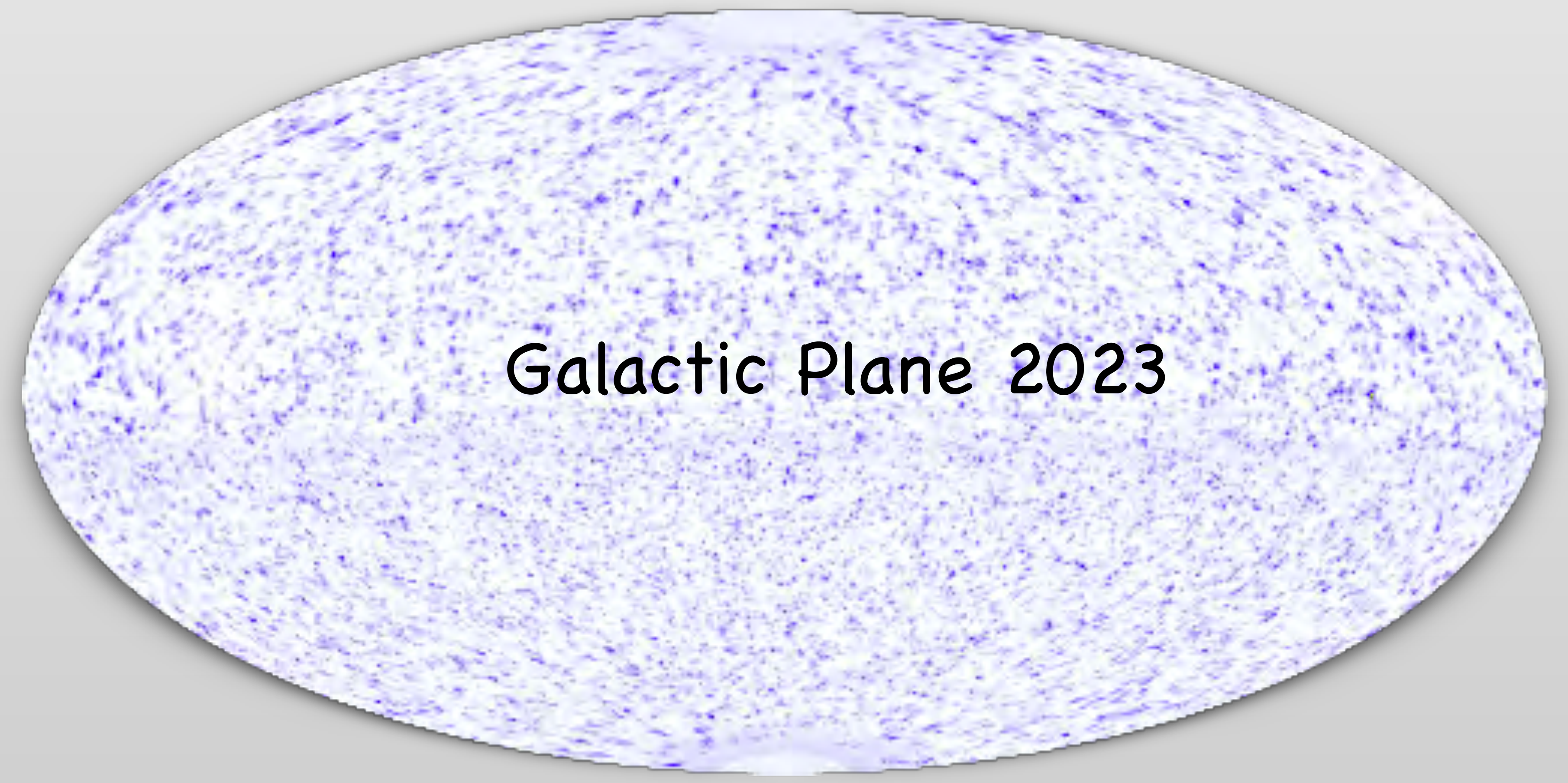
2012: First detection of astrophysical neutrinos, IceCube, Science 342 (2013)



Neutrino Sky 2020



Several 3.5σ indications of bursting point sources

steady sources more difficult because of huge horizon

⇒ Need more data

Resumé: What did we learn...

The last 15 years have been a series of important discoveries

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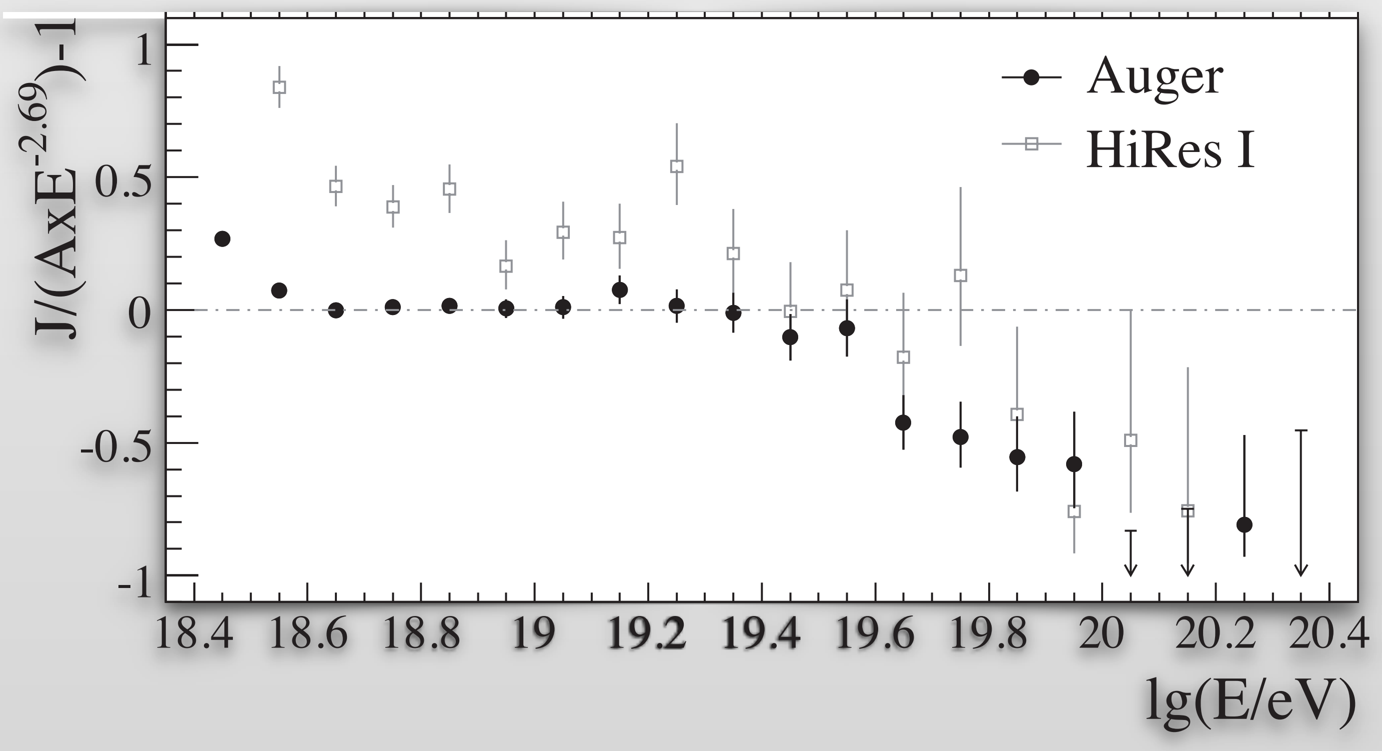
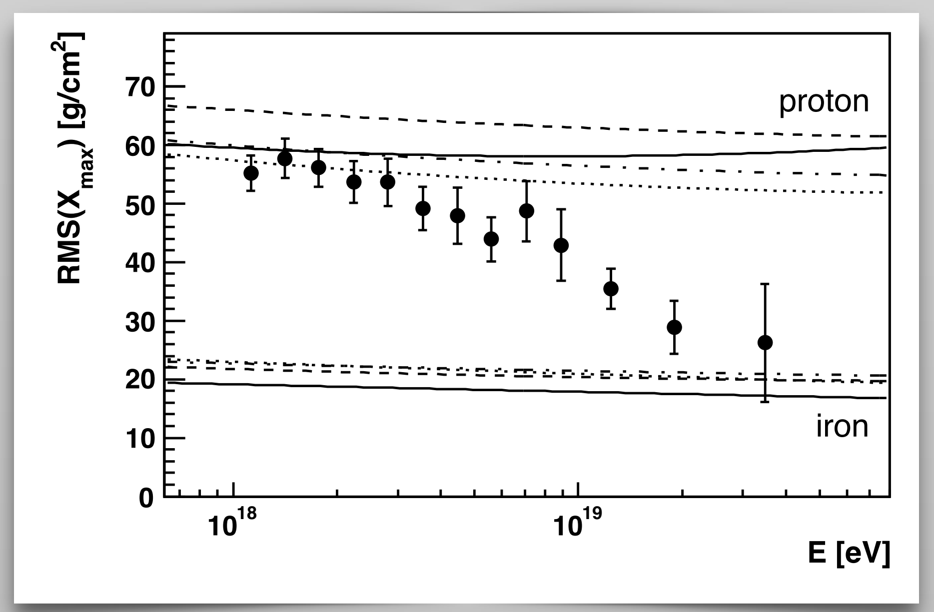
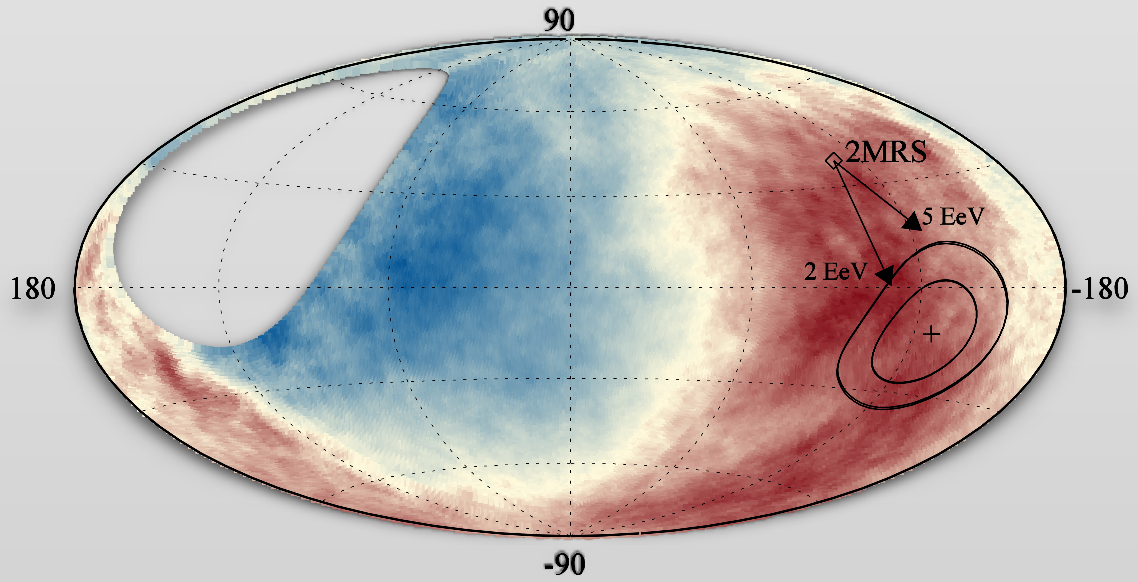
2008: First detection of Flux suppression
by Auger and HiRes
PRL 101 (2008)



2010: Increasing Mass composition
PRL 104 (2010)



2017: Establishing extragalactic
UHECR
Science 357 (2017)



Waiting for 5σ source detection, yet (only 4.5σ's so far)

⇒ challenge:
proton-astronomy

Pierre Auger: Open Data & Open Source

- 10% cosmic ray data
- 100% atmospheric data
- Close to raw data and higher level reconstruction
- Surface and Fluorescence Detectors
- JSON and summary CSV files
- Python code for data analysis

https://opendata.auger.org
doi 10.5281/zenodo.4487613

Try out your own ideas!

Offline reconstruction framework is open source

Datasets
the released datasets and their complementary data

Visualize
an online look at the released pseudo raw cosmic-ray data

Analyze
example analysis codes in online python notebooks to run on the datasets

Outreach
a page dedicated to the general public

NEXT ONGOING STEPS

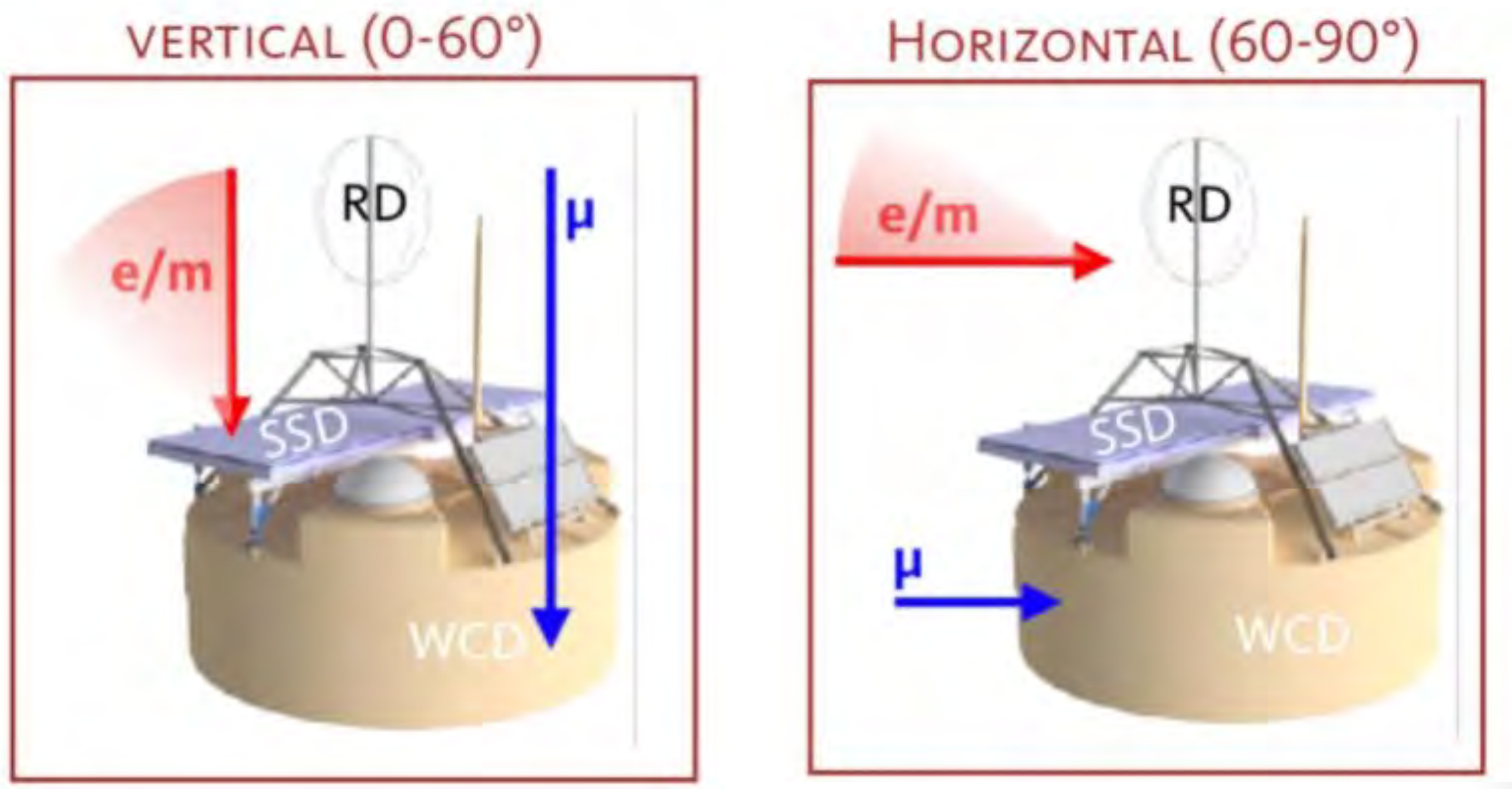
UHECR: Ongoing …

Telescope Array now upgraded to TA*4 (start operation 2024)

→ increasing size from 700 km^2 to 2800 km^2 (focussed to higher energies)

Auger upgraded to AugerPrime (start operation 2023)

→ enhance composition capabilities to allow „proton astronomy“ and enhance particle physics capabilities



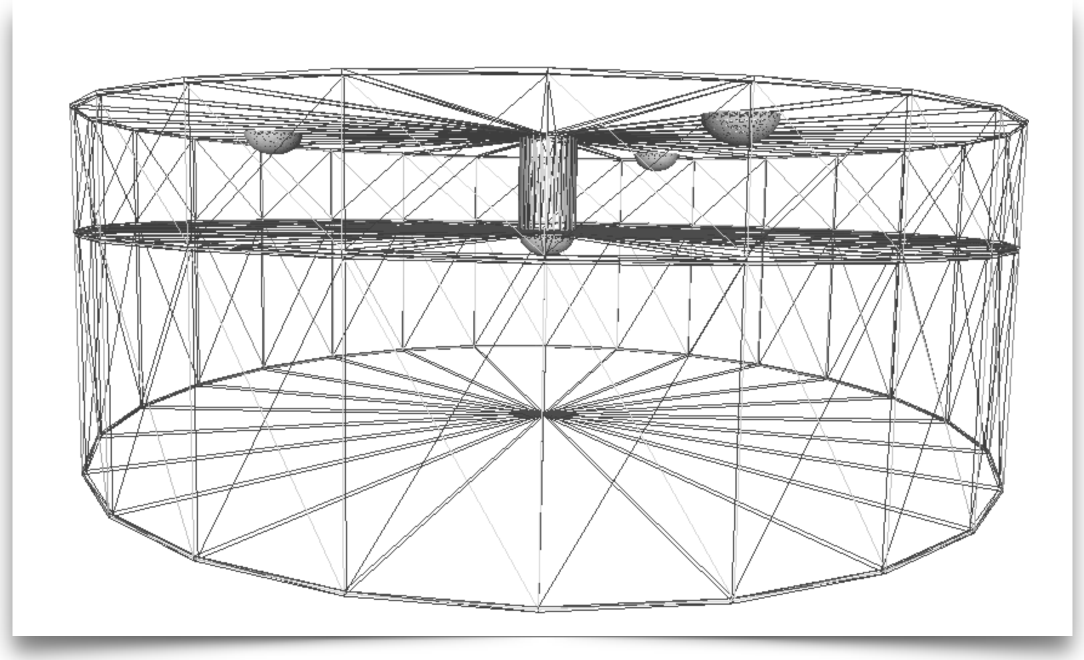
Next...: Global Cosmic ray ObServatory (GCOS)

Distributed UHECR Observatory covering > 60,000 km^2

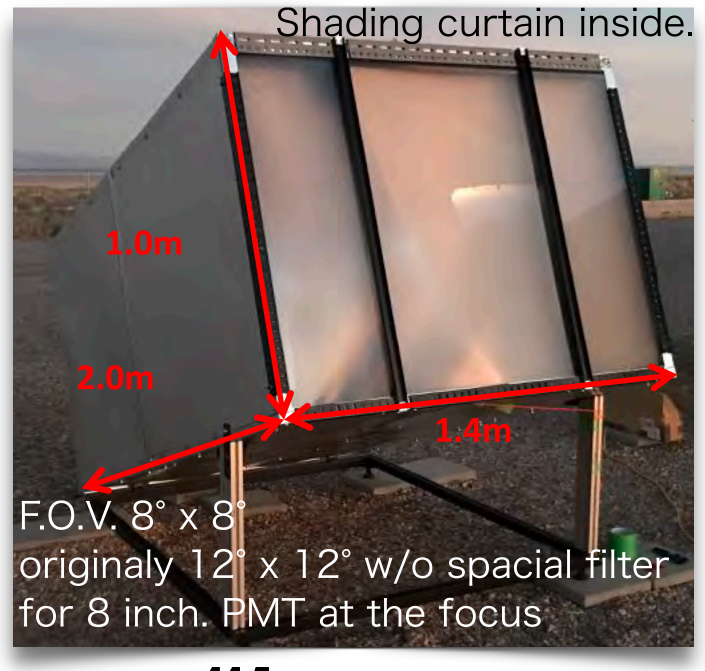
Several highly attended workshops were conducted for conceptual design, targeted at

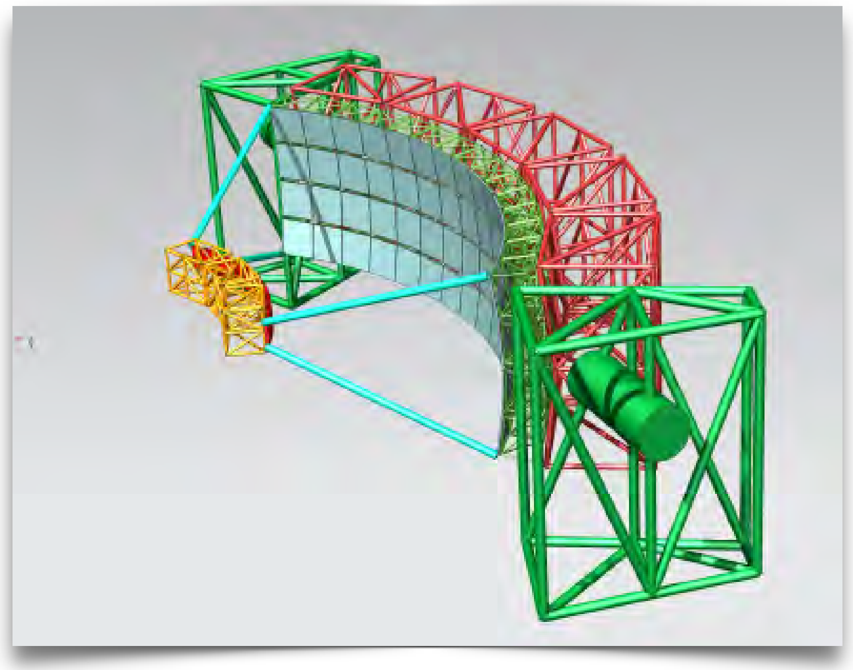
- full efficiency at 10 EeV
- energy resolution <10%, muon resolution <10%
- Xmax better than 30 g/cm^2
- angular resolution ~1°
- strong MM capabilities with photons and neutrinos

⇒ source correlations at 5σ within one year of operation



segmented Water Cherenkov Detectors

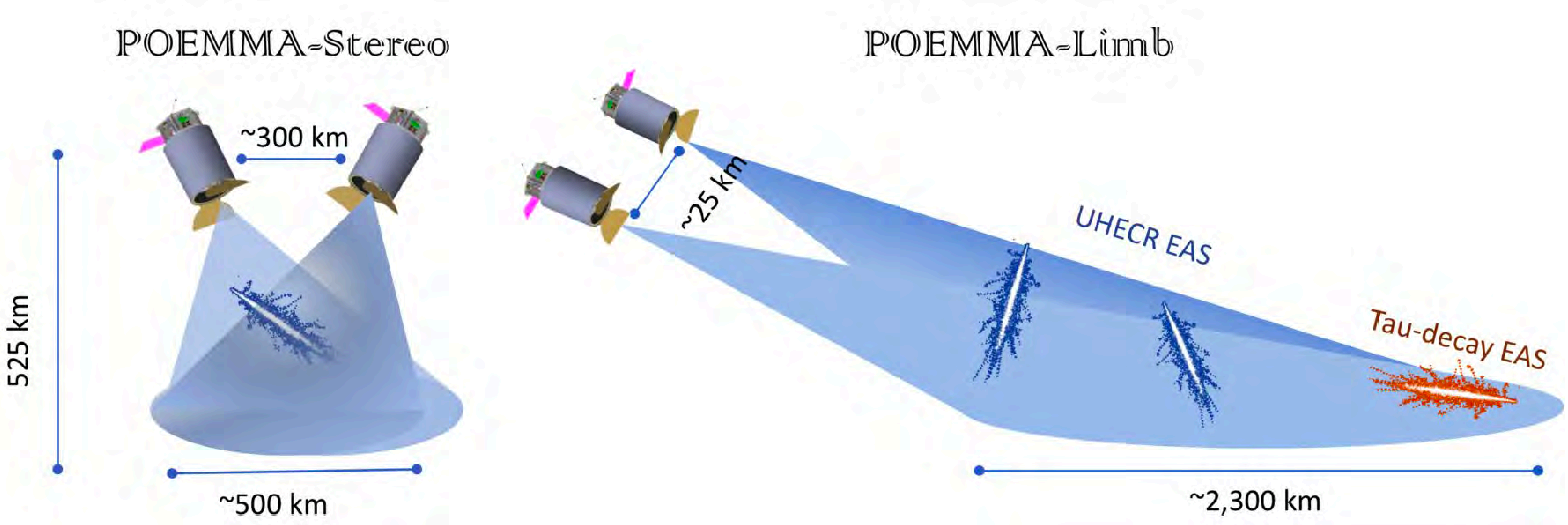




concepts for simplified fluorescence telescopes

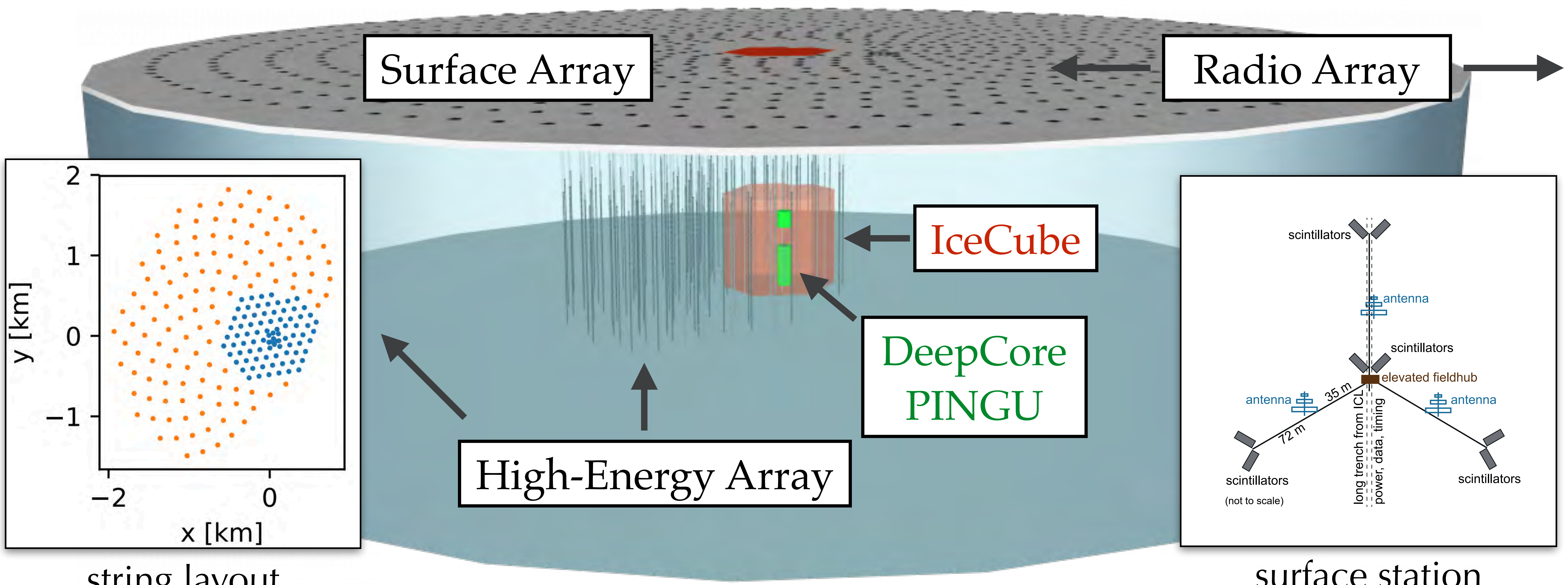
POEMMA: Stereo Fluorescence Obs. from Space

- Two science cases: UHECR and neutrinos, both with full sky coverage
- Good X_{max} and ok energy resolution (→ mediocre rigidity resolution) and very high aperture
- Complementary to GRAND in many aspects: technology, space vs. ground, …



Neutrinos: IceCube-Gen2

- **Multi-component facility** (low- and high-energy & multi-messenger)
- **In-ice optical Cherenkov array** with 120 strings and 240m spacing
- **Surface array** (scintillators & radio antennas) for PeV-EeV CRs & veto
- **Askaryan radio array** for >10PeV neutrino detection



string layout

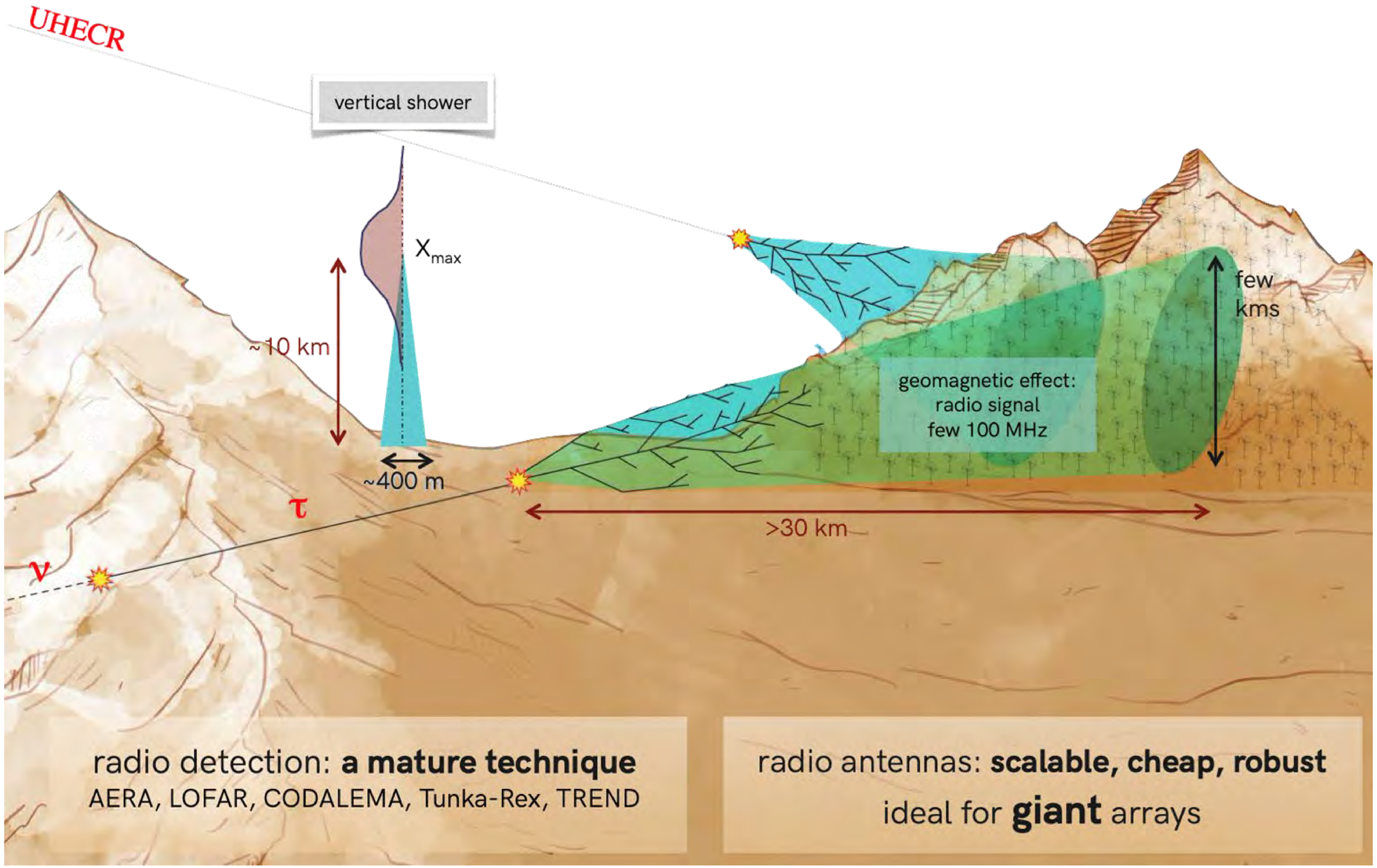
surface station

[IceCube-Gen2 *White Paper*, arXiv:2008.04323]

Markus Ahlers

GRAND: Giant Radio Array for Neutrino Detection

- UHECR as important second science case next to neutrinos
- various sites worldwide
  - main ones in China
- 200,000 km^2 total
  - inclined showers only
  - **aperture of 100,000 km^2 sr**
- Possibly X_{max} measurement in addition to energy, but no muon detection at most sites
  - mediocre mass resolution
- strengths is the high statistics
- common sites with GCOS possible, but different requirements on accuracy



TeV Gammas:

cta cherenkov telescope array


CTA ARRAY SITES
CTA North
ORM La Palma, Spain
CTA South
ESO, Chile

EXCITING TIMES AHEAD OF YOU