# Menu…

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2) Astrophysics and Detection of $E<10^{14}$ eV Galactic CRs (very brief)
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4) Basic concepts and technologies of EAS experiments
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6) **Transition from galactic to extragalactic CRs**
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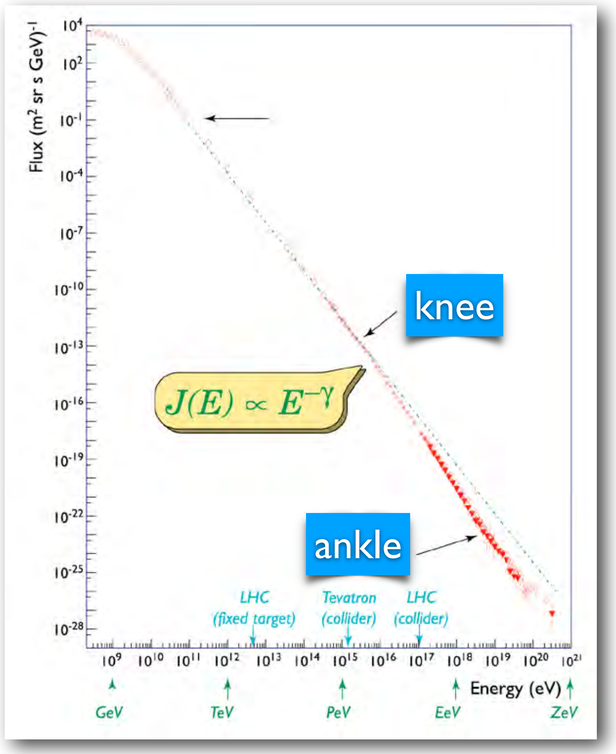
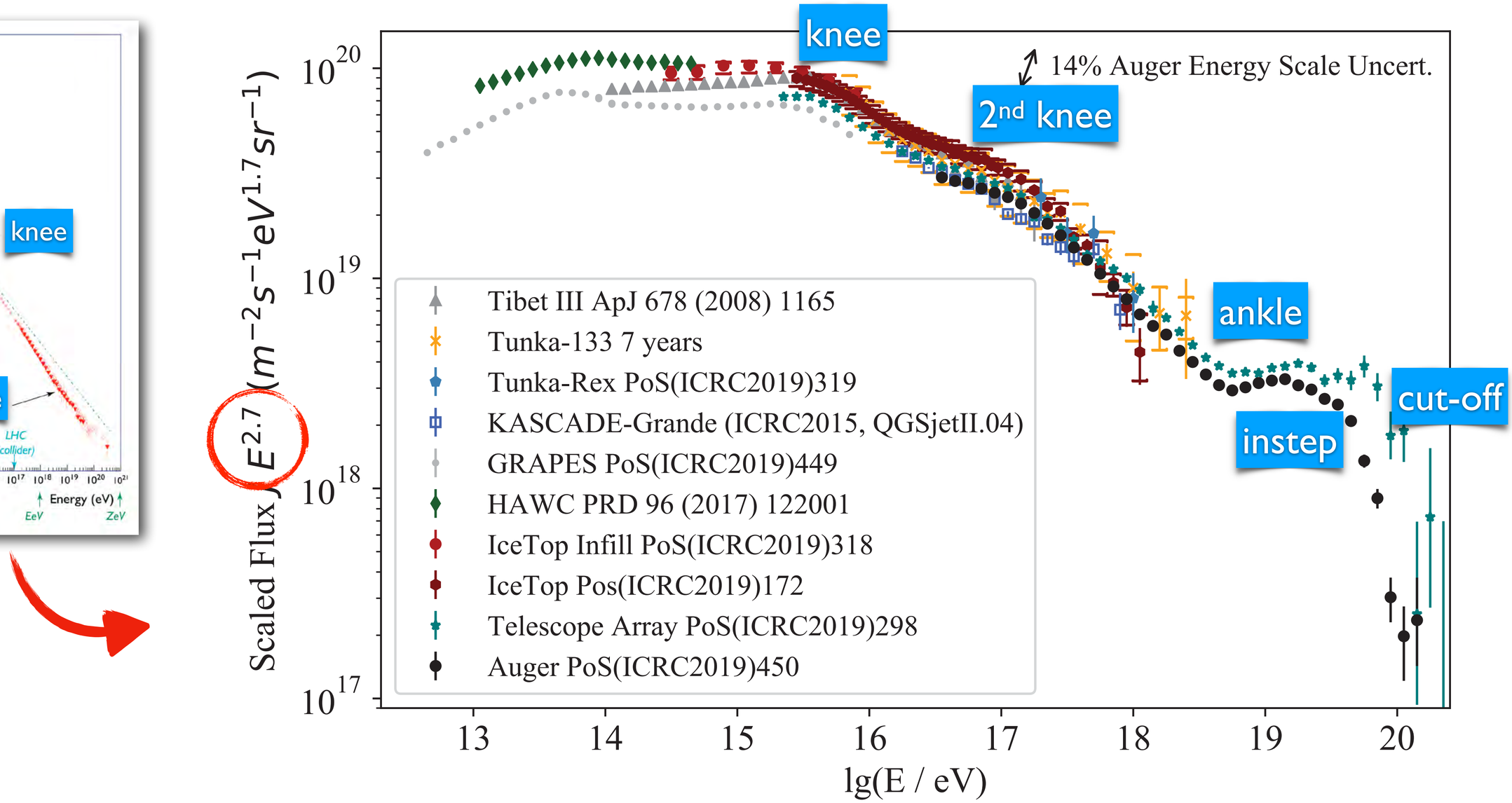
11) Conclusions, future challenges and prospects

# Features of the CR spectrum



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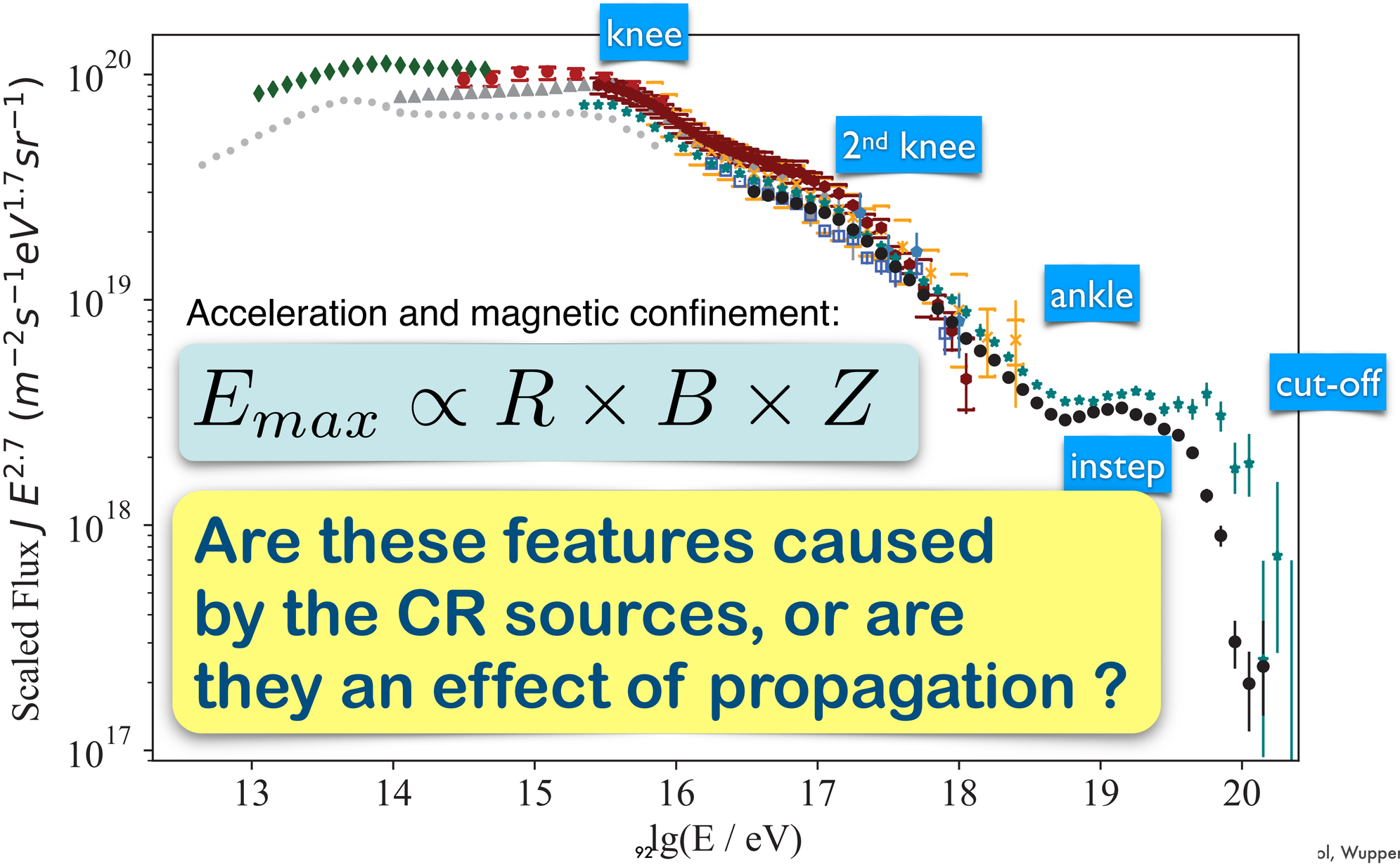


Putative

# Cosmic Particle Accelerators

## Supernova Remnants

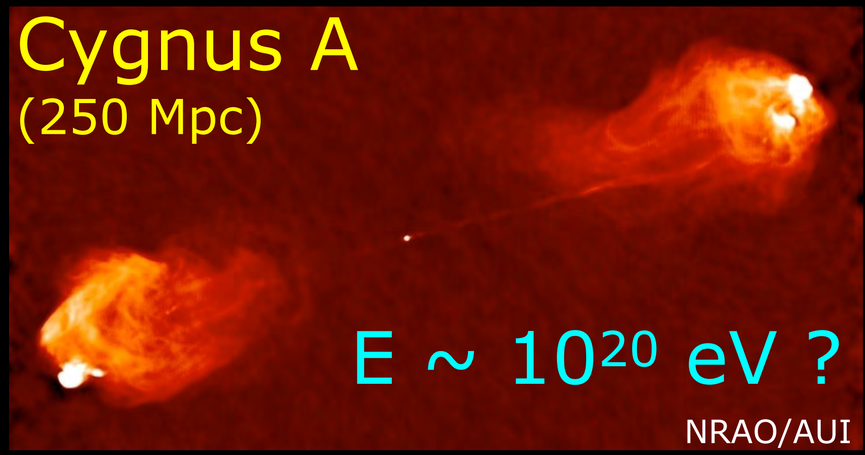
SNR509
(50 kpc)

$E < 10^{16}$ eV

X-ray (Chandra) + optical (Hubble)

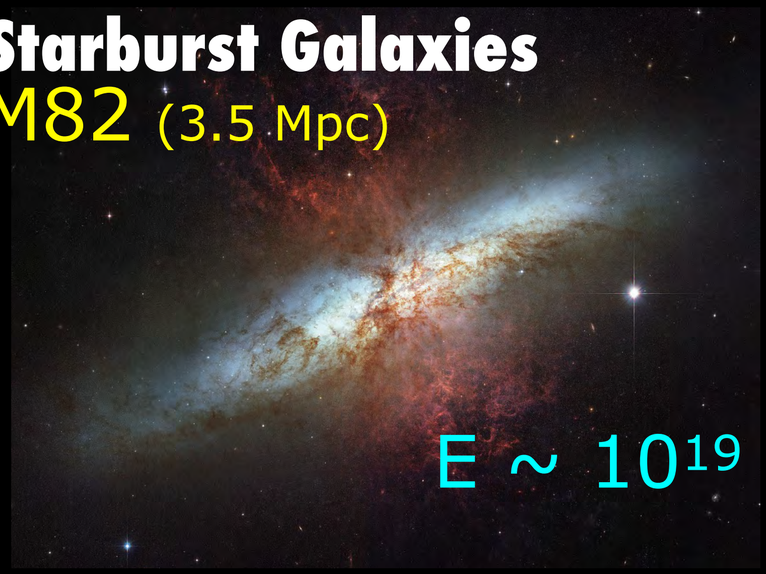
particle acceleration at shock waves

## AGN and their Jets/Lobes

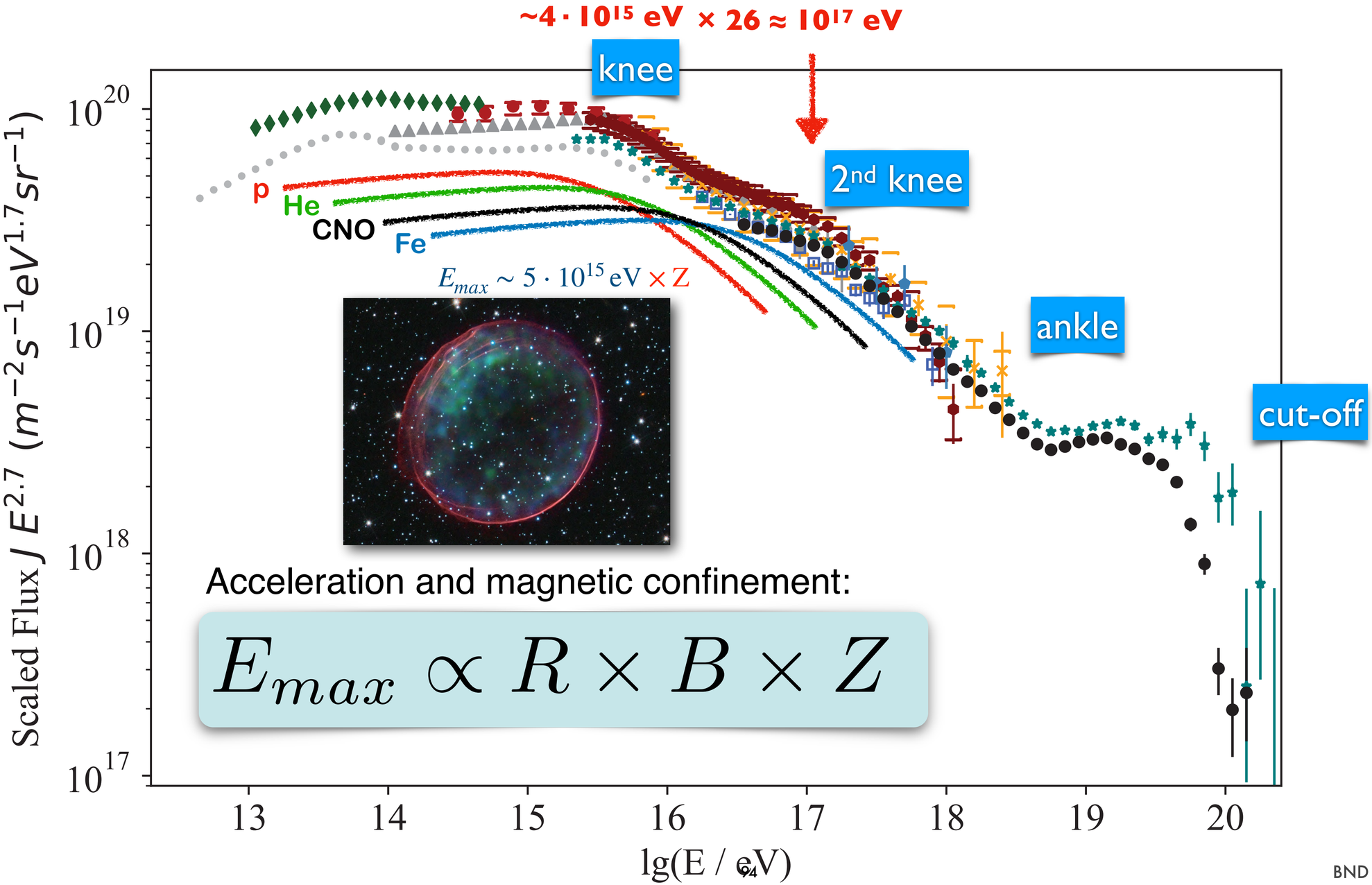



## Starburst Galaxies

M82 (3.5 Mpc)



# Features of the CR spectrum




Acceleration and magnetic confinement:

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

# Features of the CR spectrum

Diffusion losses from Galaxis ?

$E_{\mathrm{PeV}}^{max} \approx R_{\mathrm{pc}} \times B_{\mu\mathrm{G}} \times Z$

$10^{17}$ eV → thickness gal. disk

~4 · 10¹⁵ eV × 26 ≈ 10¹⁷ eV

knee

2nd knee

ankle

cut-off

p

He

CNO

Fe

$10^{20}$

$\mathrm{eV}^{1.7}\mathrm{sr}^{-1}$)

19

17

18

19

20

lg(E / eV)

KASCADE

K.-Grande

p

He+C+Si

Fe

p

He+C+Si

Fe

$\Phi \cdot E^{2.5}$ [$\mathrm{m}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}\,\mathrm{GeV}^{1.5}$]

$10^3$

$10^2$

10

P

Fe

KHK & Unger, APP 2012

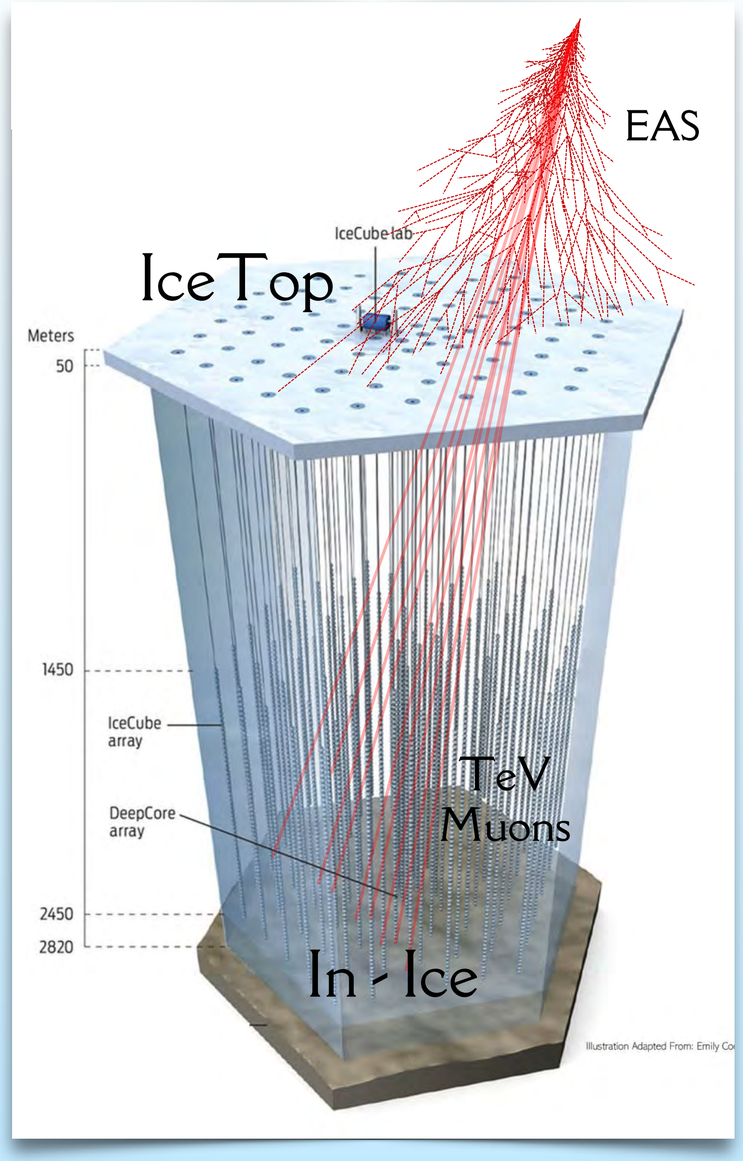
$10^{15}$

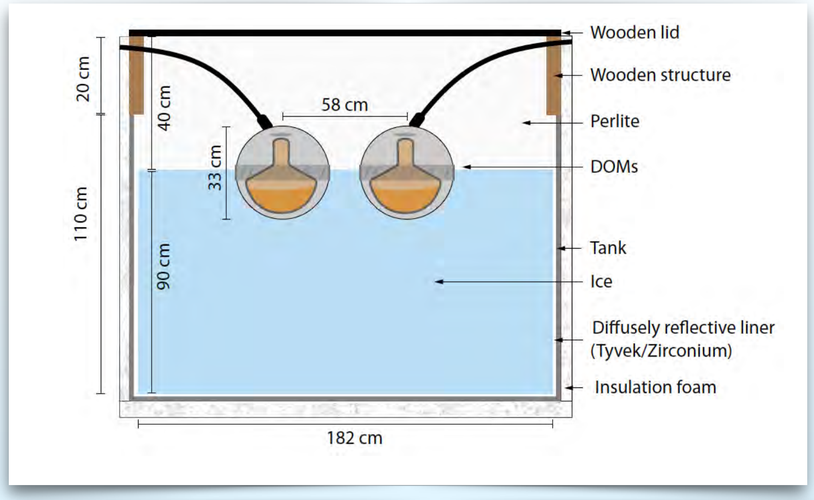
$10^{16}$

$10^{17}$

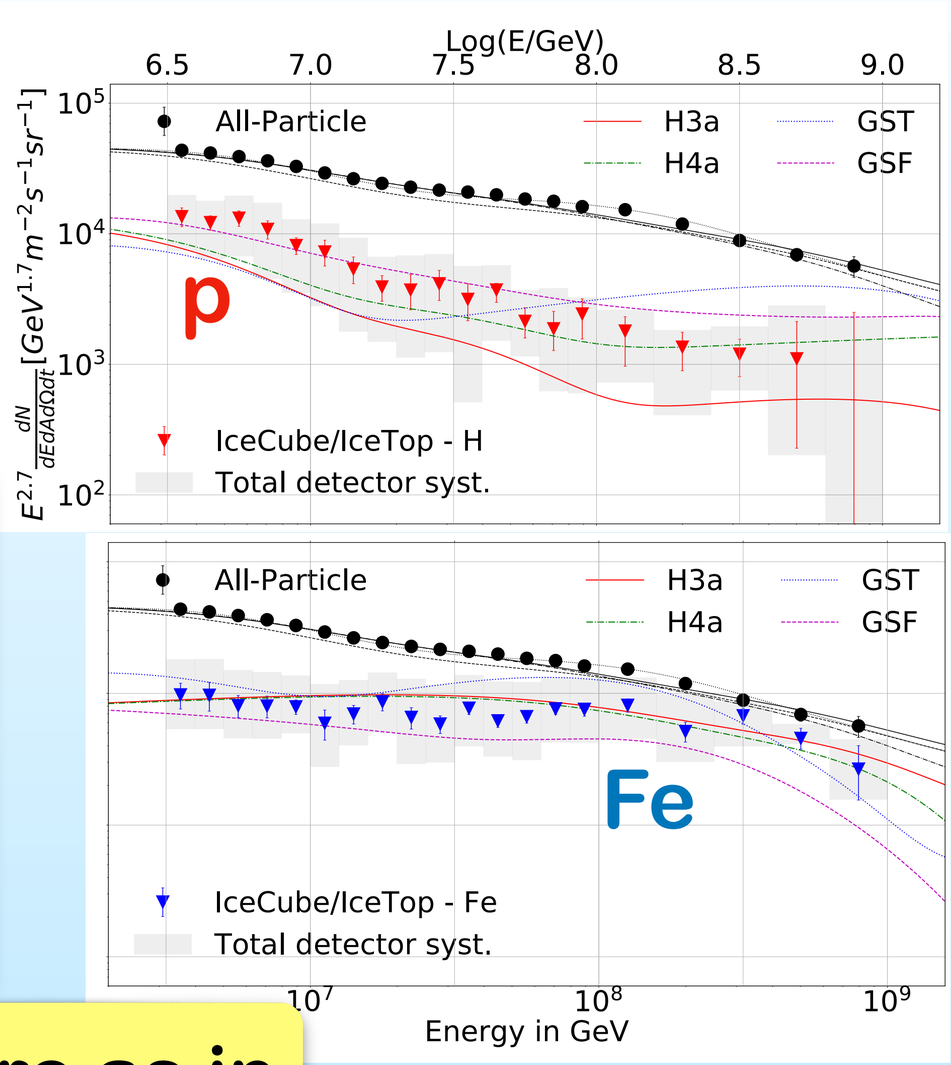
E [eV]

# IceTop at South Pole



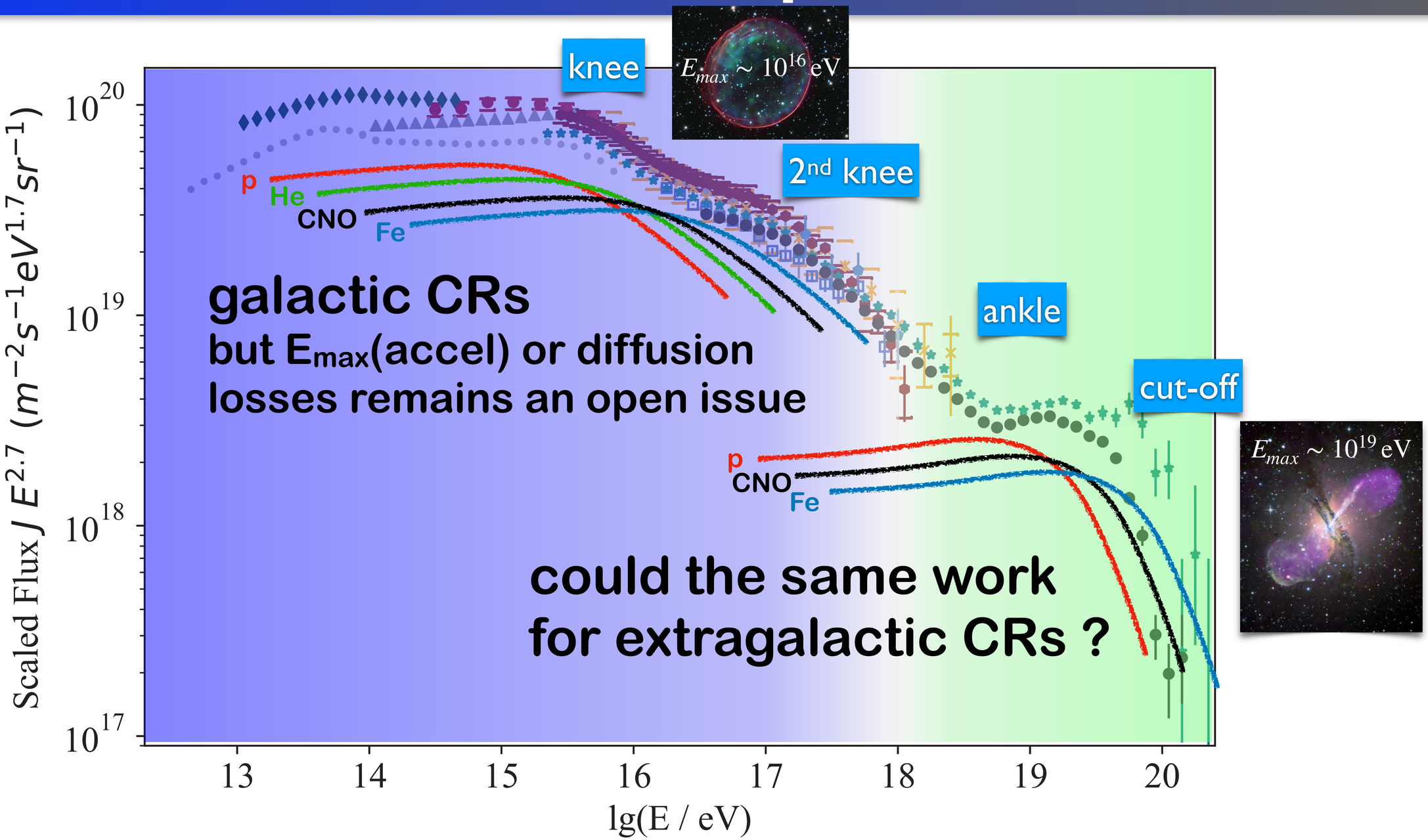





**Same feature as in KASCADE-Grande**

D. Soldin @ ICRC2019

# Features of the CR spectrum



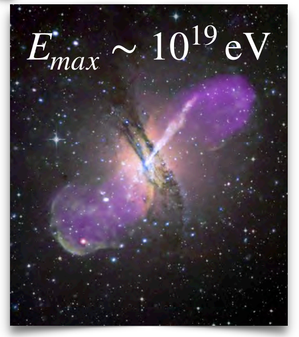
# Features of the CR spectrum

**E-spectrum & Composition suggest the ankle may mark the transition from galactic to extragal. CRs**


2nd knee

ankle

cut-off



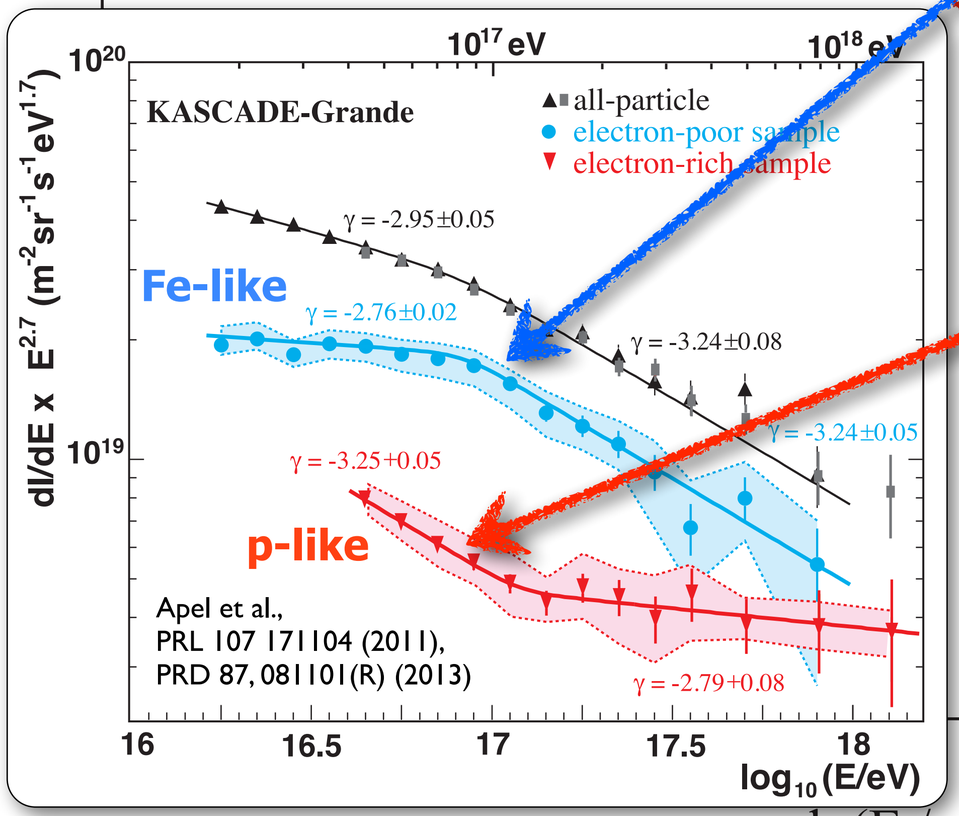

p

CNO

Fe

Scaled Flux $J\,E^{2.7}$ $(m^{-2}s^{-1}eV^{1.7})$

lg(E / eV)



# Further Information from CR anisotropiesus

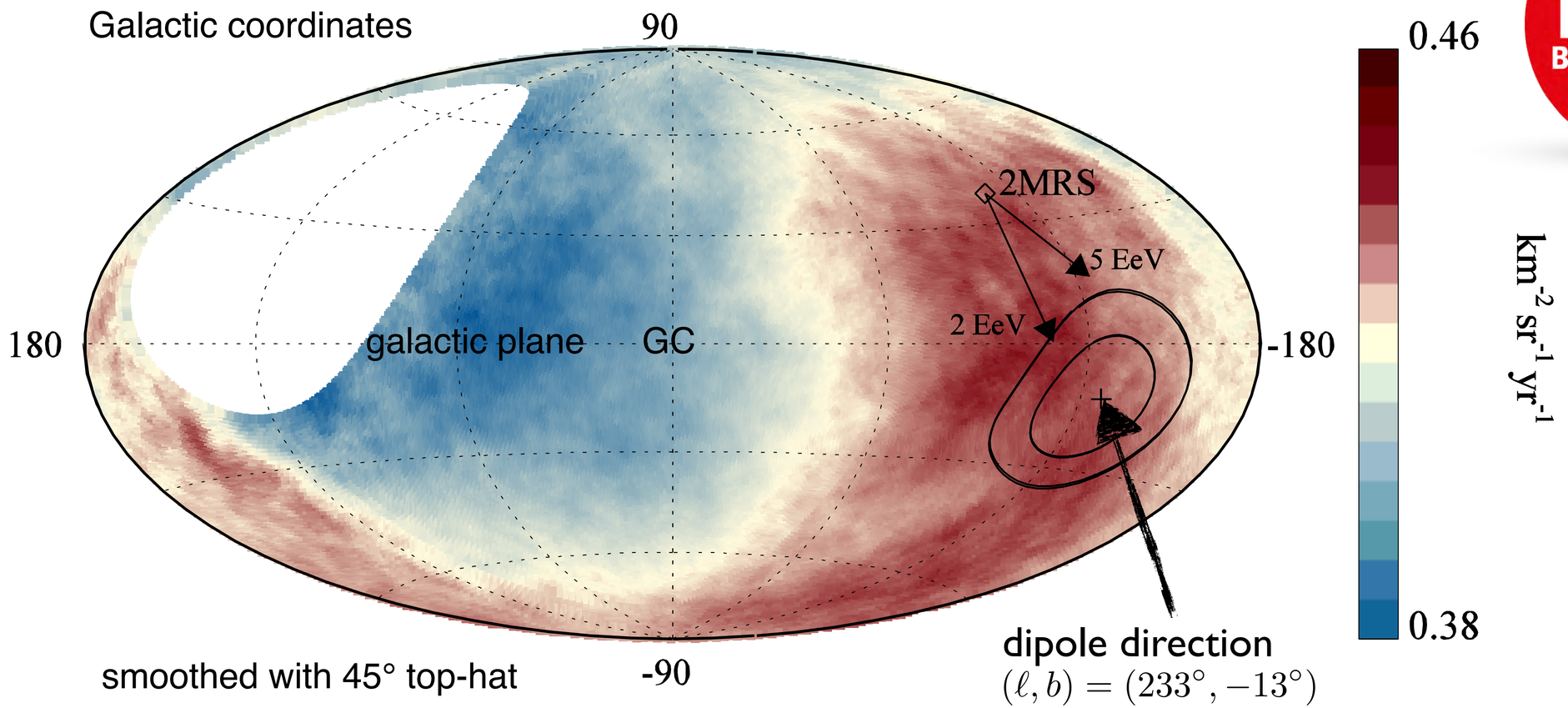

$E > E_{ankle}$ ⇒ more and more ballistic propagation
⇒ source distribution should become visible
⇒ expect directional correlation to galactic plane and possibly excess from galactic center direction

and reduced flux from high galactic latitudes

… this is what we observe!

# Flux Map above 8 EeV

Auger Collaboration, Science 357 (2017) 1266



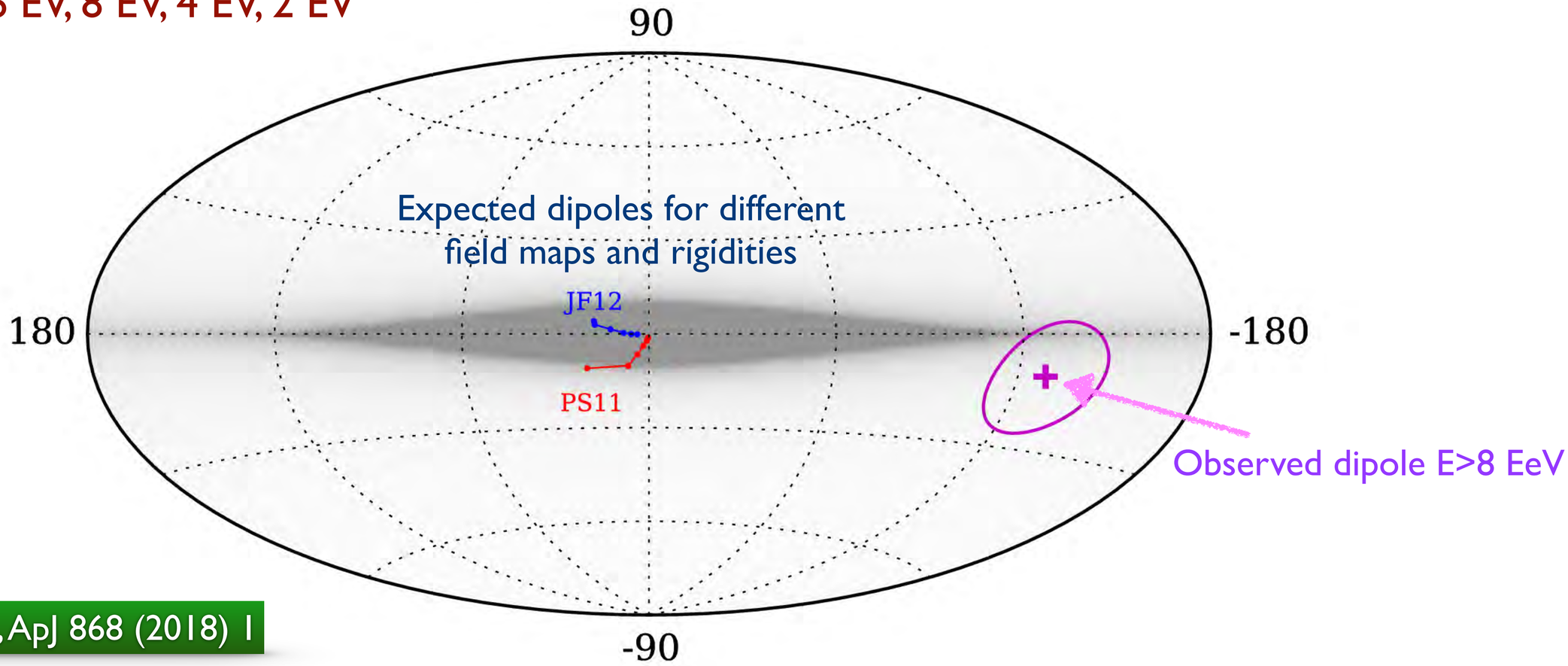

physicsworld TOP 10 BREAKTHROUGH 2017

**Extragalactic origin of UHECR confirmed**

# Expected Dipole from Galactic Sources

Assuming continuous distribution of isotropically emitting sources following luminous Galactic matter (Weber & Boer, Astron. & Astrophys. 509 (2010) 25)

and propagating CRs in two Galactic magnetic field models (JF12, PS11) for rigidities:
64 EV, 32 EV, 16 EV, 8 EV, 4 EV, 2 EV




Auger Collaboration, ApJ 868 (2018) 1

→ observed dipolar modulation at these energies cannot arise from a Galactic CR component

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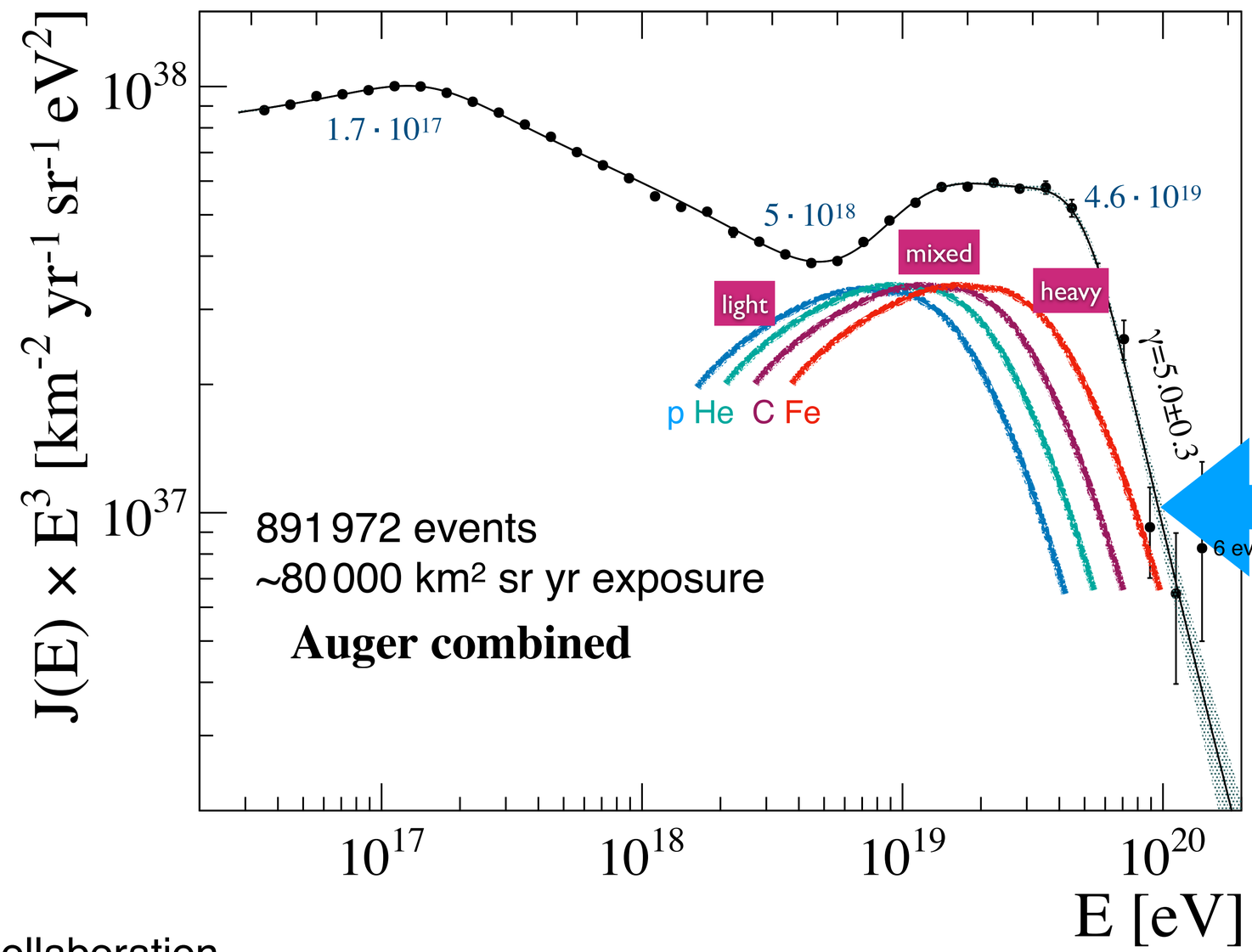
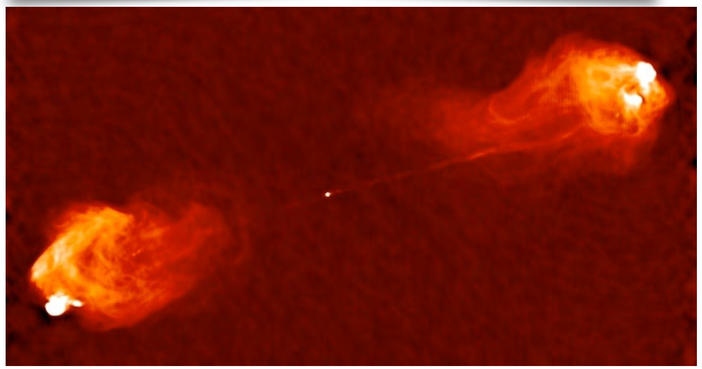
# The End of the CR Energy Spectrum




maximum possible acceleration energy ?



??

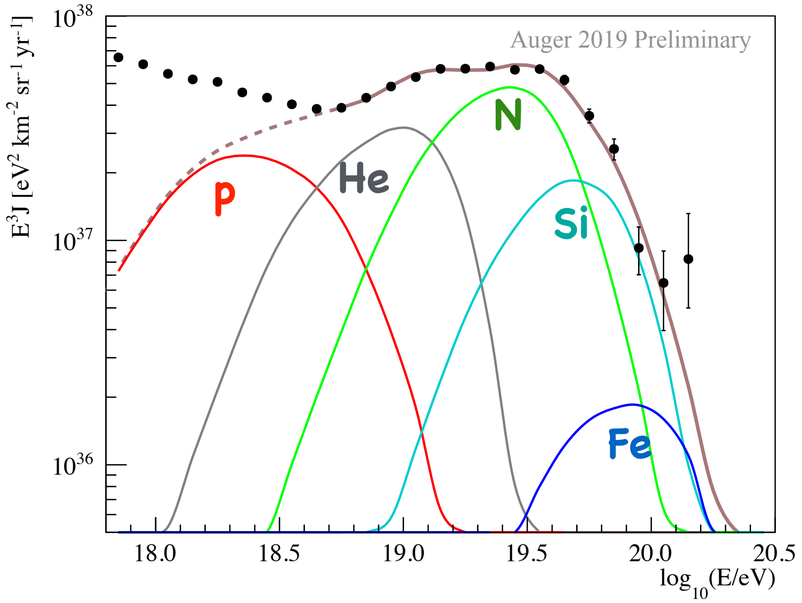
$$E_{max,CR} \propto Z_{CR} \cdot (R \times B)_{source}$$

⇒ expect enrichment of heavy elements towards the end of the spectrum

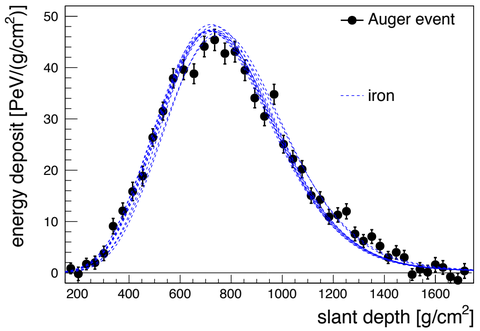
Auger Collaboration
Phys. Rev. Lett. 125, 121106 (2020) & Phys. Rev. D 102, 062005 (2020)

# Increasingly Heavy Composition

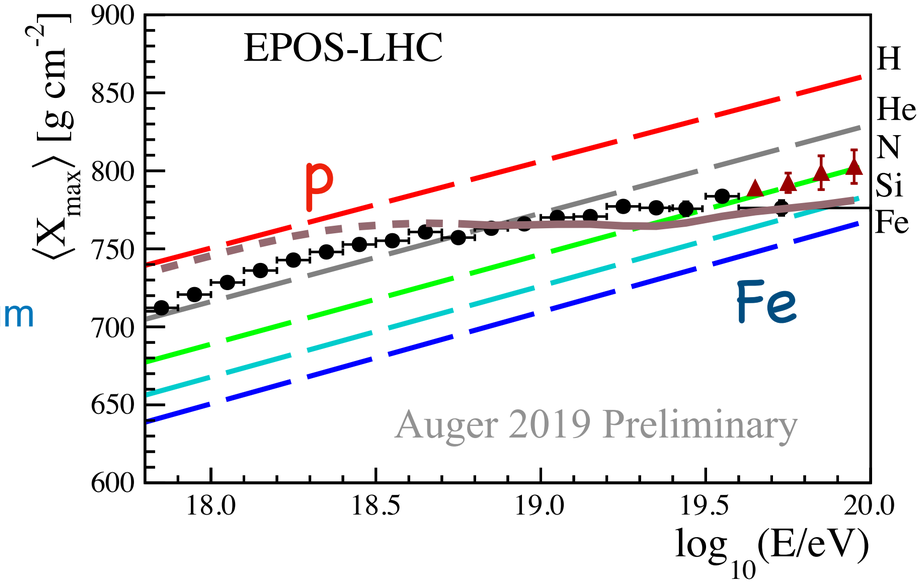
$$E_{max,CR} \propto Z_{CR} \cdot (R \times B)_{source}$$

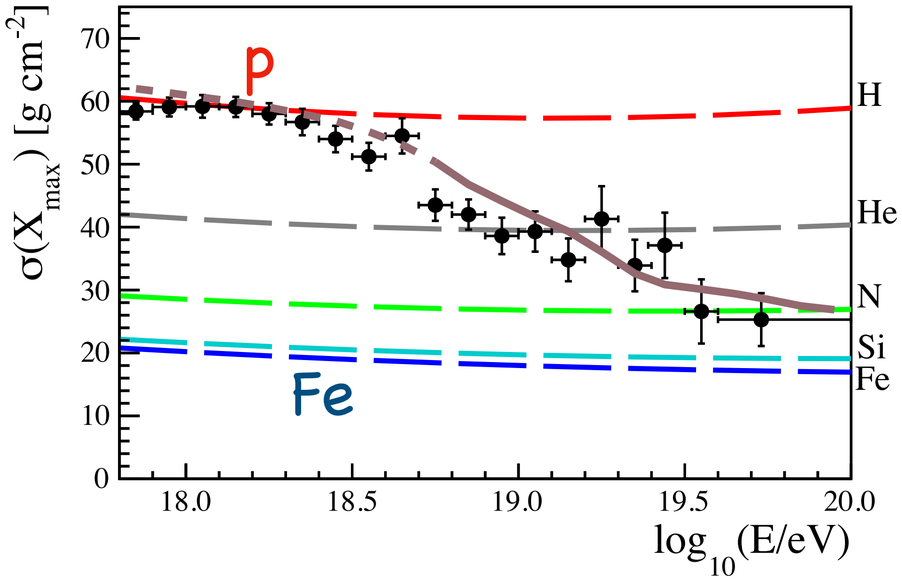



$X_{max}$ Measure shower maximum for each shower




Auger Coll., PoS(ICRC2019)004




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

# Alternative interpretation...

## GZK-effect: energy losses in the CMB

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

$10^{19}$ eV

$10^{20}$ eV

Protons suffer photo pion production:

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

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

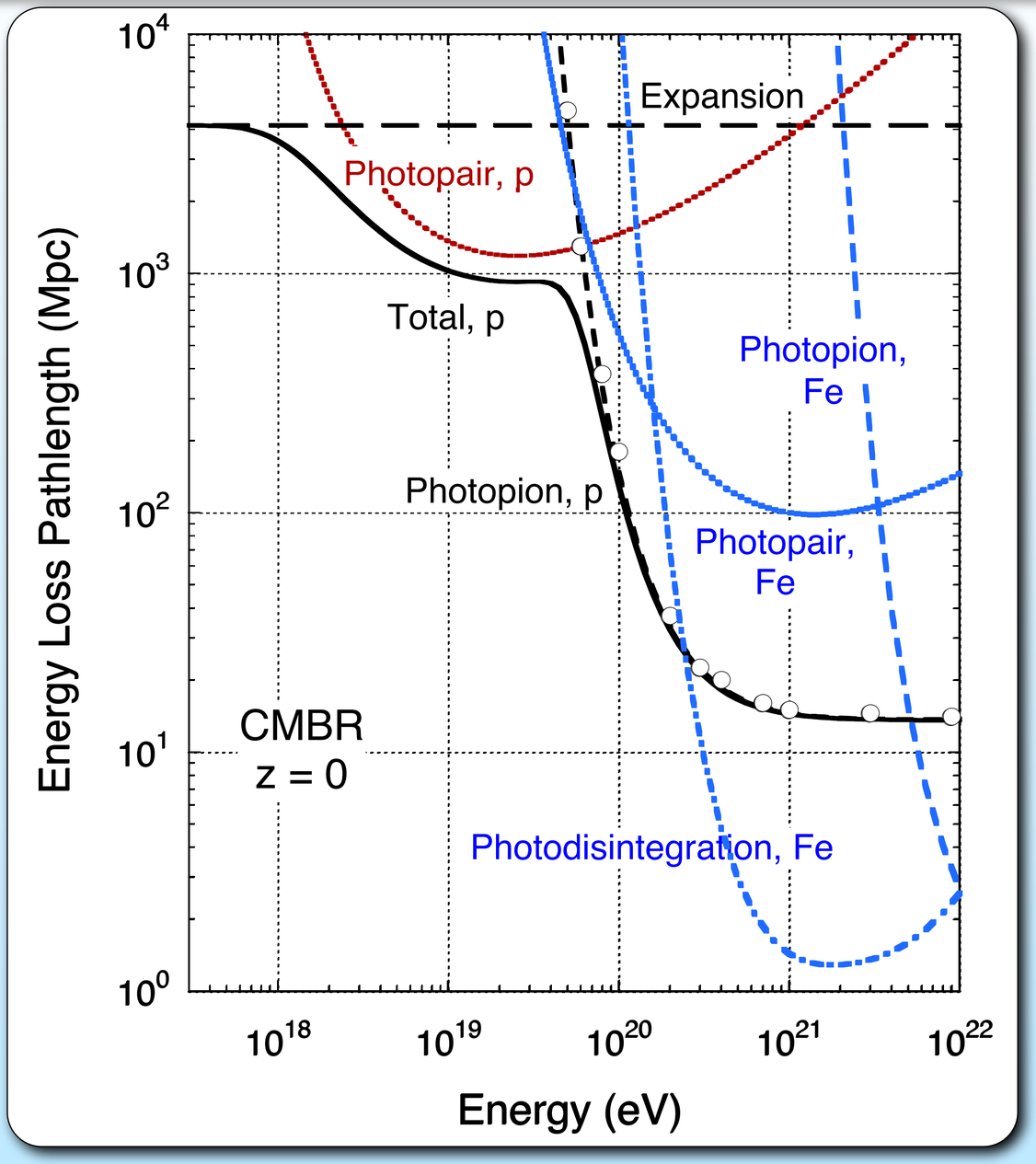
$$\rightarrow E_p \simeq 6 \cdot 10^{19}\,\mathrm{eV}$$

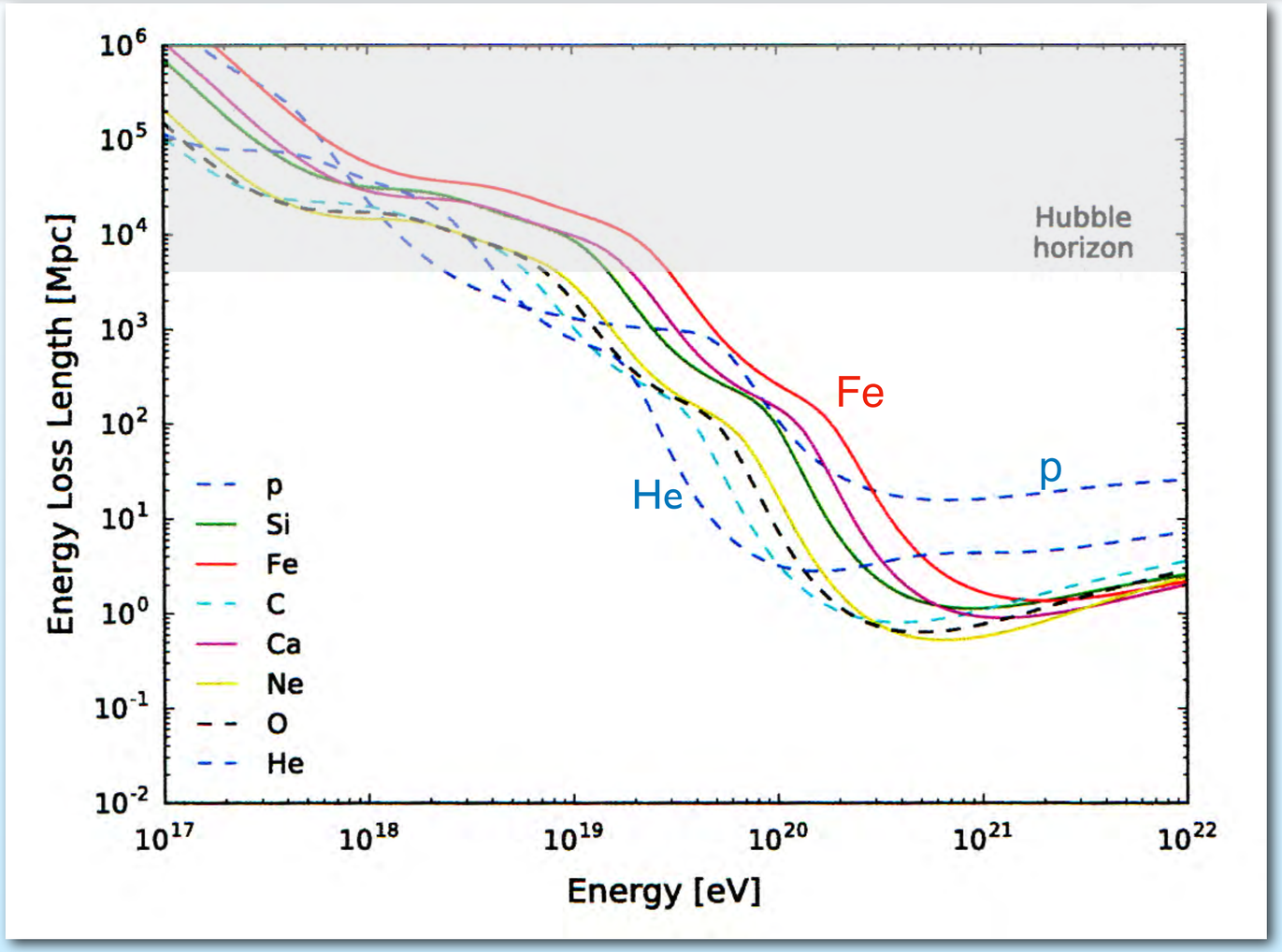
Picture: DESY,
Science Communication Lab

Nuclei suffer photo disintegration:

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

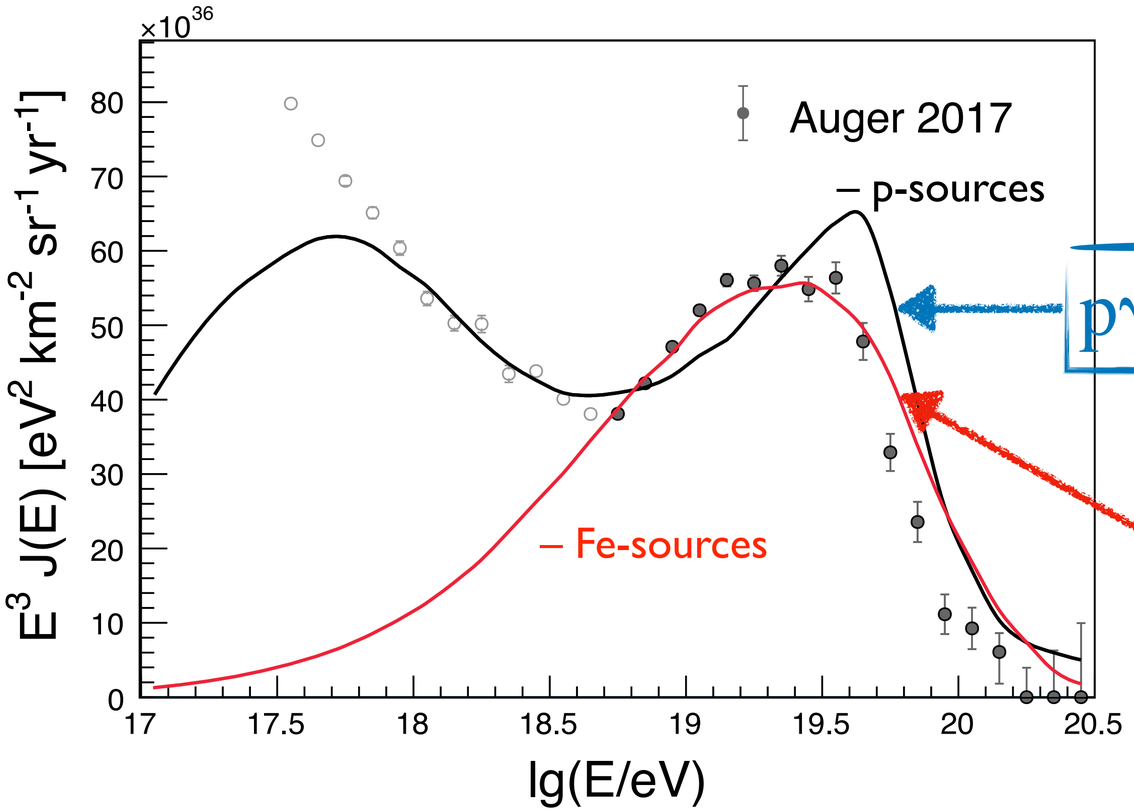
# Energy Loss Length for Nuclei




It's a coincidence of nature that the threshold energies for photo-pion production and photodisintegration are about the same

# Simulation of GZK-effect




$p\gamma \rightarrow \Delta \rightarrow p+\pi$ → „cosmogenic" $\nu + \gamma$

$Fe+\gamma \rightarrow$ „Cr" + p +

*smoking gun…*

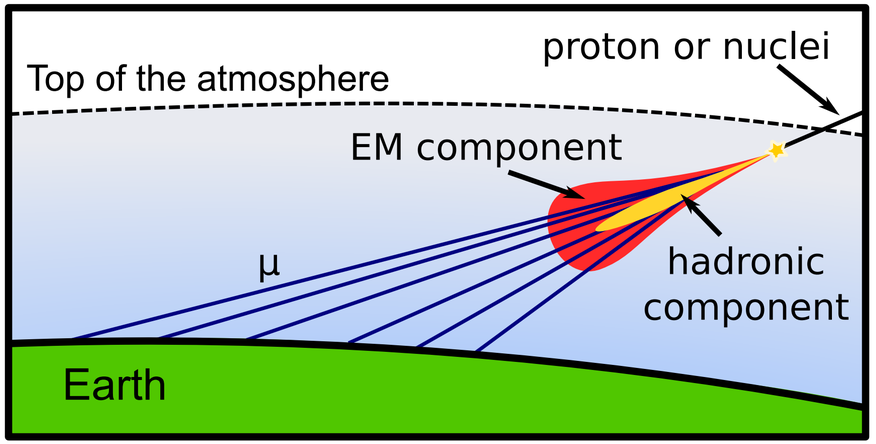
The cut-off shape is reasonably well described,
but the measured composition is neither pure protons nor Fe

Additional information: a) UHECR Anisotropies → Sky more diffuse for high Z CRs
b) GZK effect would produce cosmogenic neutrinos and photons

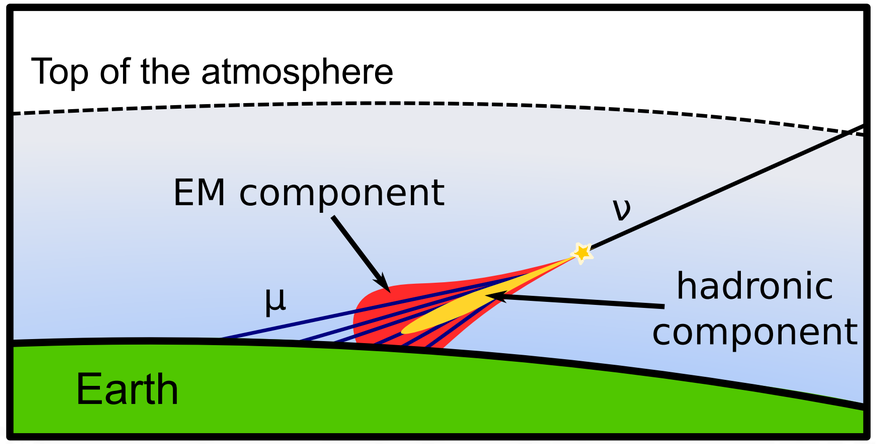
# EeV Neutrinos detectable in inclined air showers

- 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

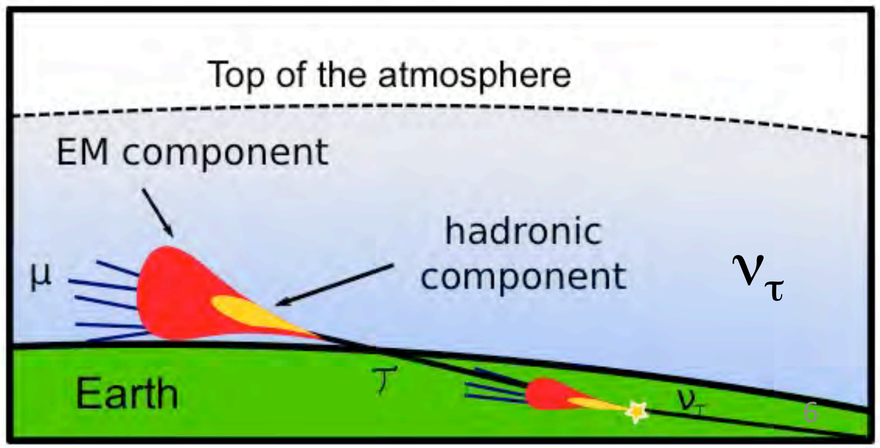
Searching for neutrinos ⇒ searching for inclined showers with electromagnetic component




**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

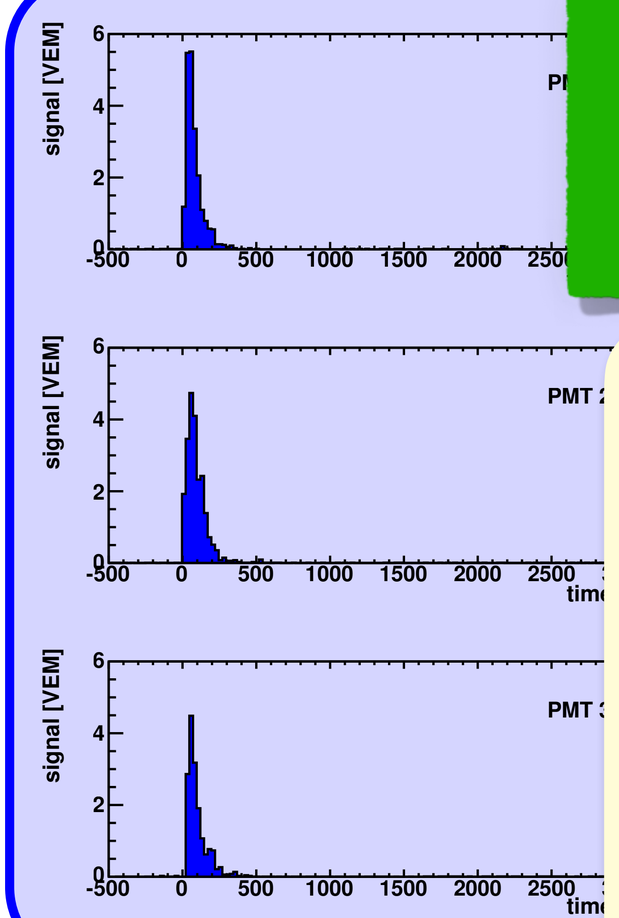
„old“ shower

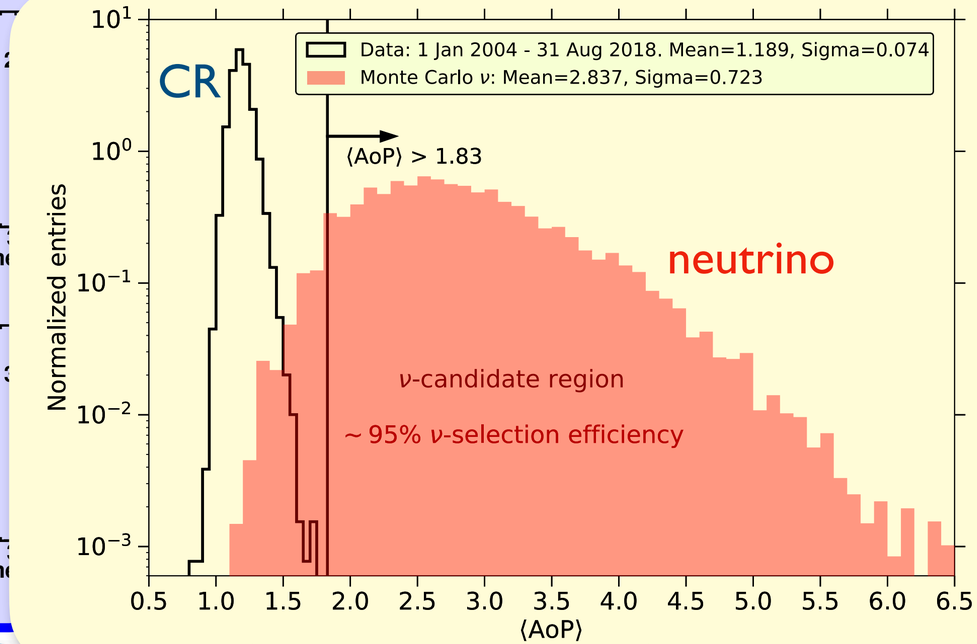
„young“ shower

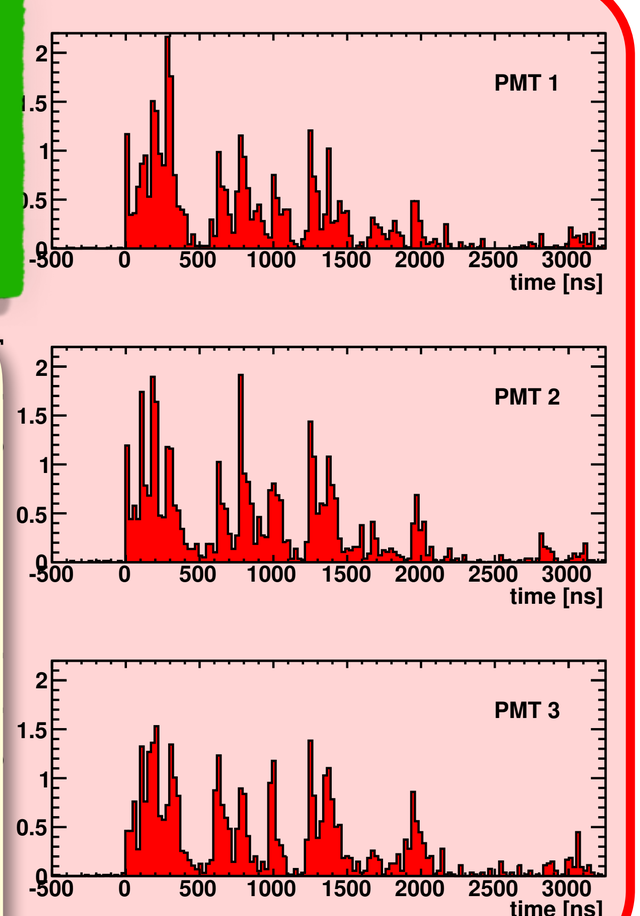
Muonic shower front: narrow signals

EM shower front: broad signals

Area over Peak by itself provides already a very powerful discrimination



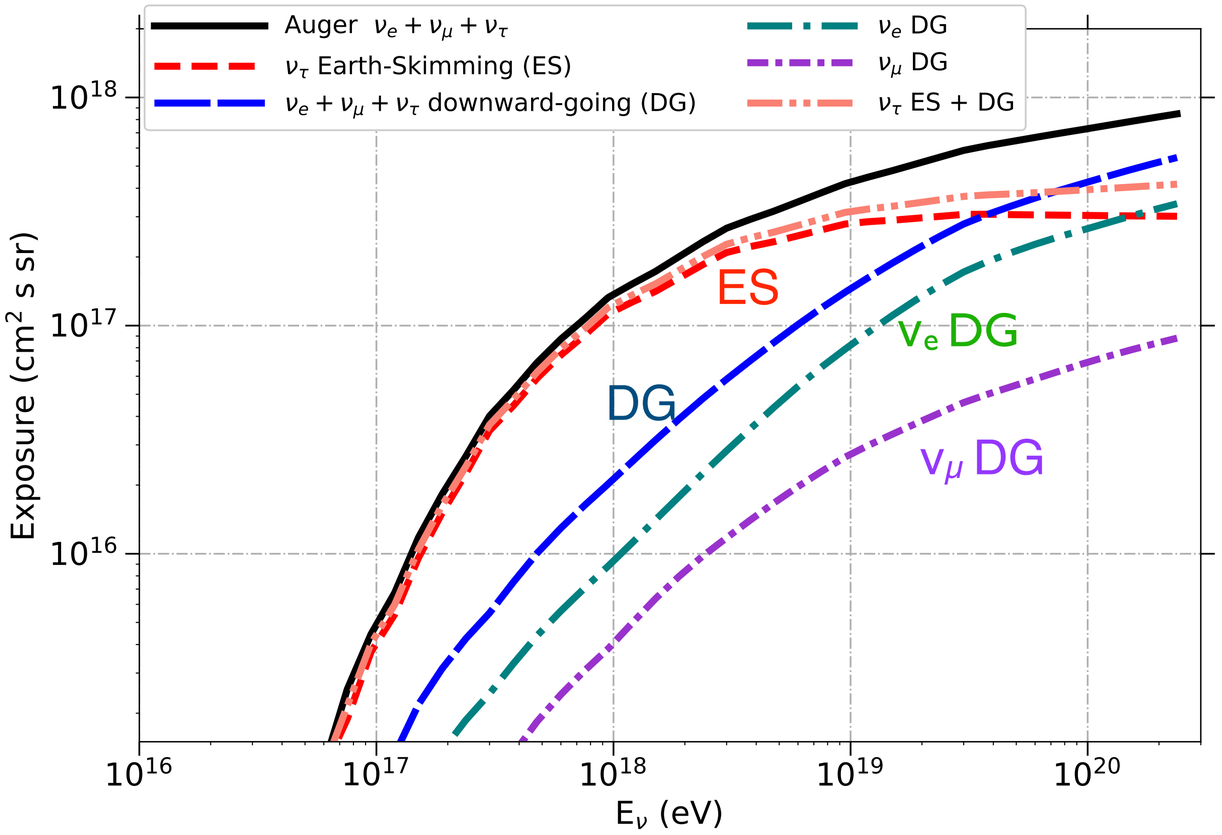

5 EeV, distance to shower axis ~1km
zenith angle ~80°

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 $\nu_\tau$ dominates exposure

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

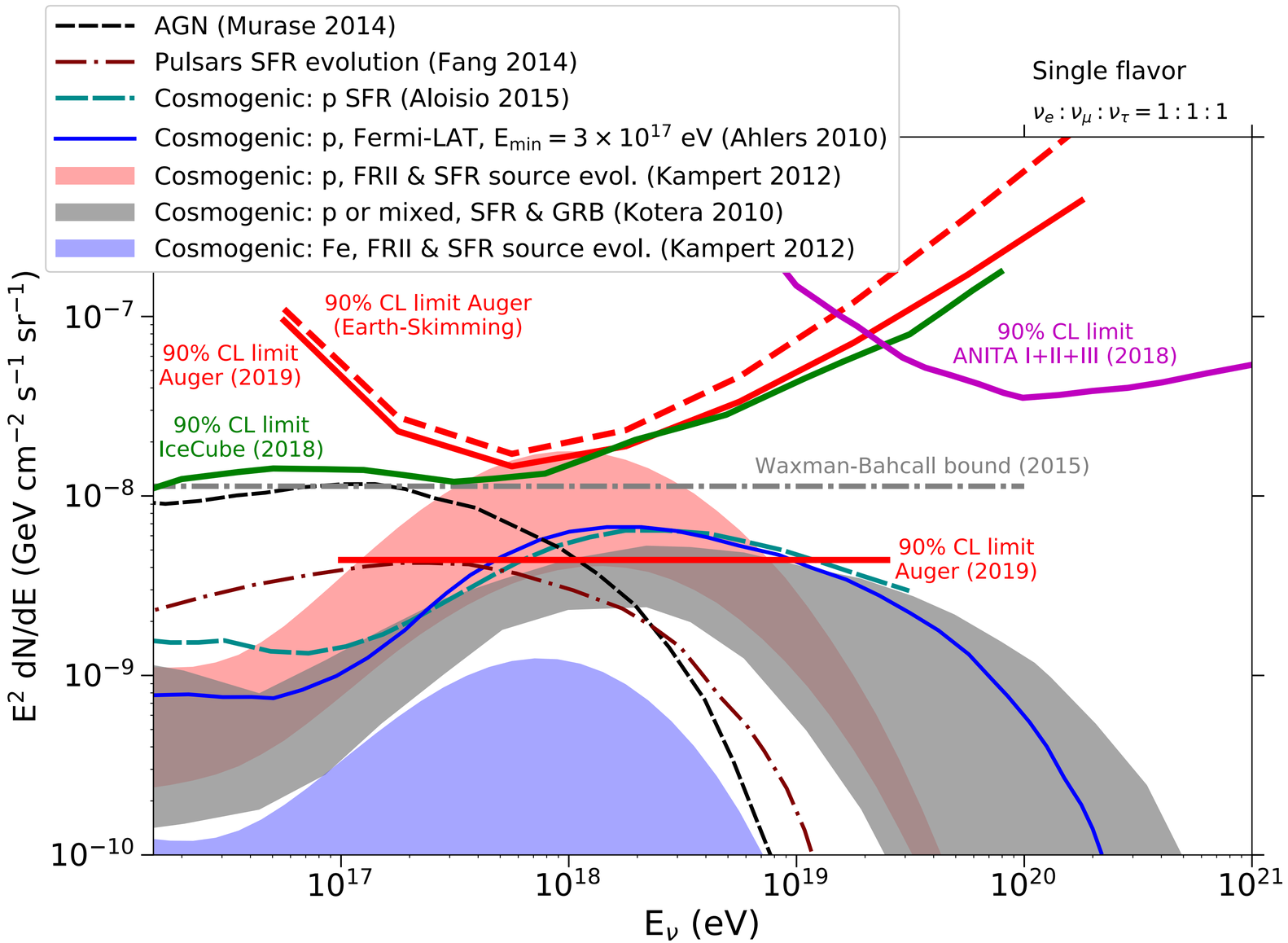
Relative contribution to expected event rate:

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

| Source of systematic | Combined uncertainty band |
|---|---|
| Simulations | $\sim$ +4%, -3% |
| $\nu$ cross section & $\tau$ E-loss | $\sim$ +34%, -28% |
| Topography | $\sim$ +15%, 0% |
| Total | $\sim$ +37%, -28% |

# Bounds on a diffuse Flux of EeV Neutrinos

Auger Collaboration, JCAP10 (2019) 022

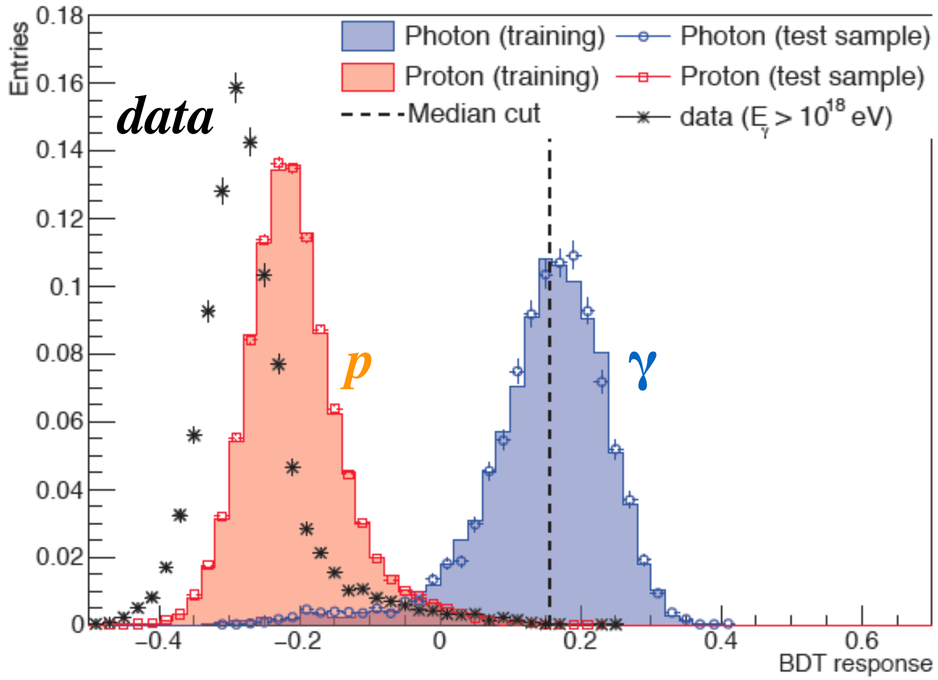


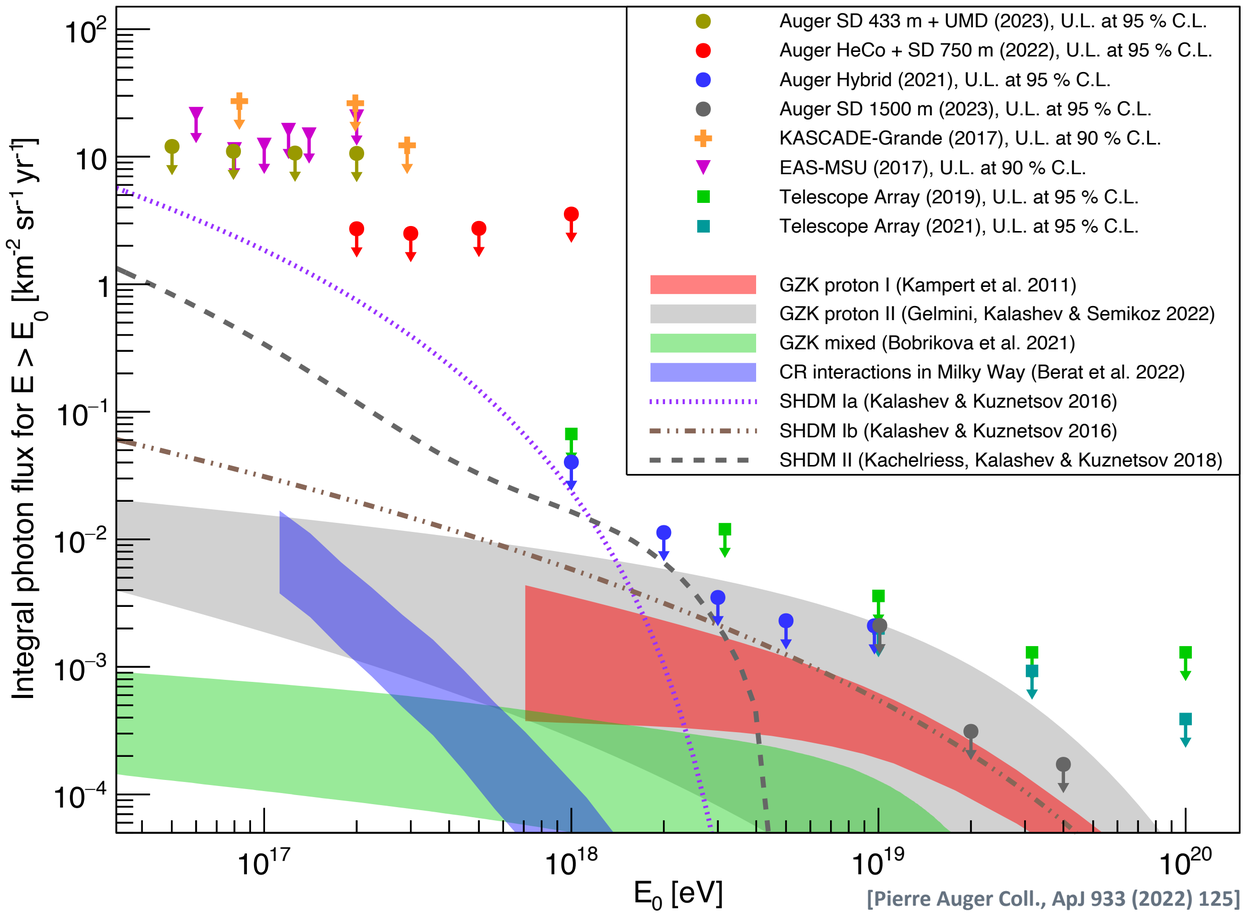

GZK effect should have given us 2-10 neutrinos
Observed: None

# 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



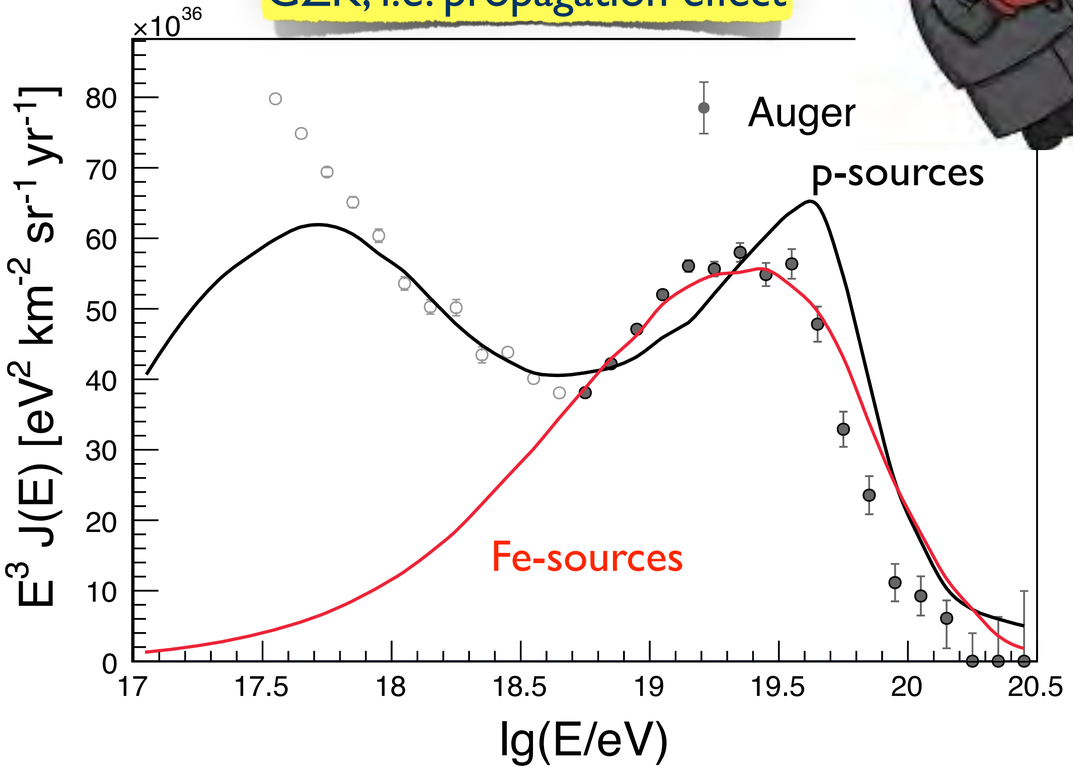

[Pierre Auger Coll., ApJ 933 (2022) 125]

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

# GZK effect or Maximum Source energy ?

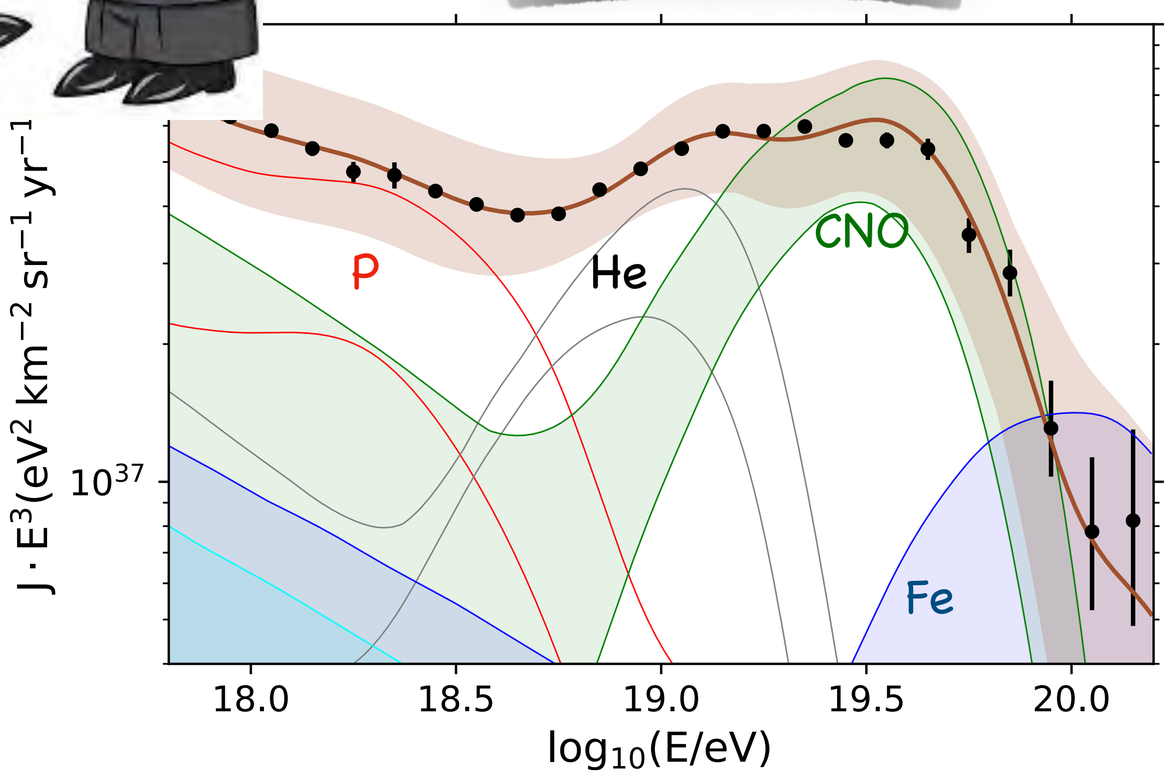

FINAL ROUND: ANISOTROPIES...

GZK, i.e. propagation effect




- poor description of E-spectrum
- disagrees with increasingly heavy mass composition
- in conflict with upper bounds on cosmogenic neutrinos

Maximum source energy




- E-spectrum well described
- Mass composition well described
- do not expect significant fluxes of cosmogenic neutrinos

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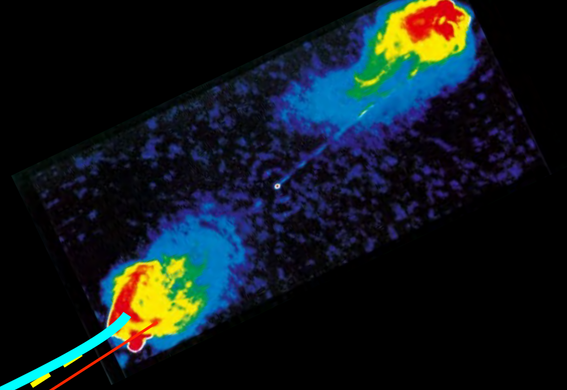
# Towards identifying the sources of UHECR



$\gamma$

Intergalactic Space
B ~ nG

$\nu$

cosmic rays
E > $10^{19}$eV

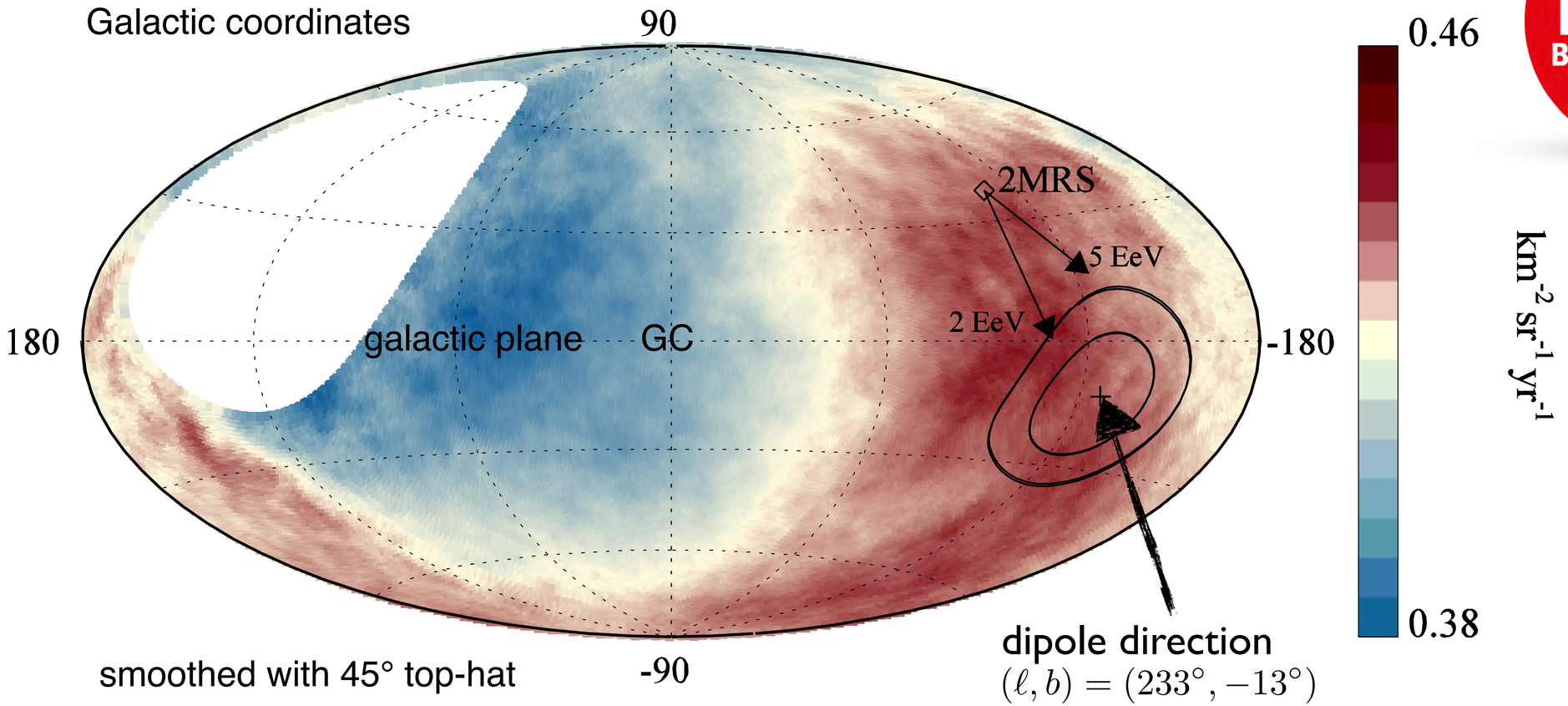
Galaxy
B ~ μG

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

!

# Flux Map above 8 EeV

Auger Collaboration, Science 357 (2017) 1266

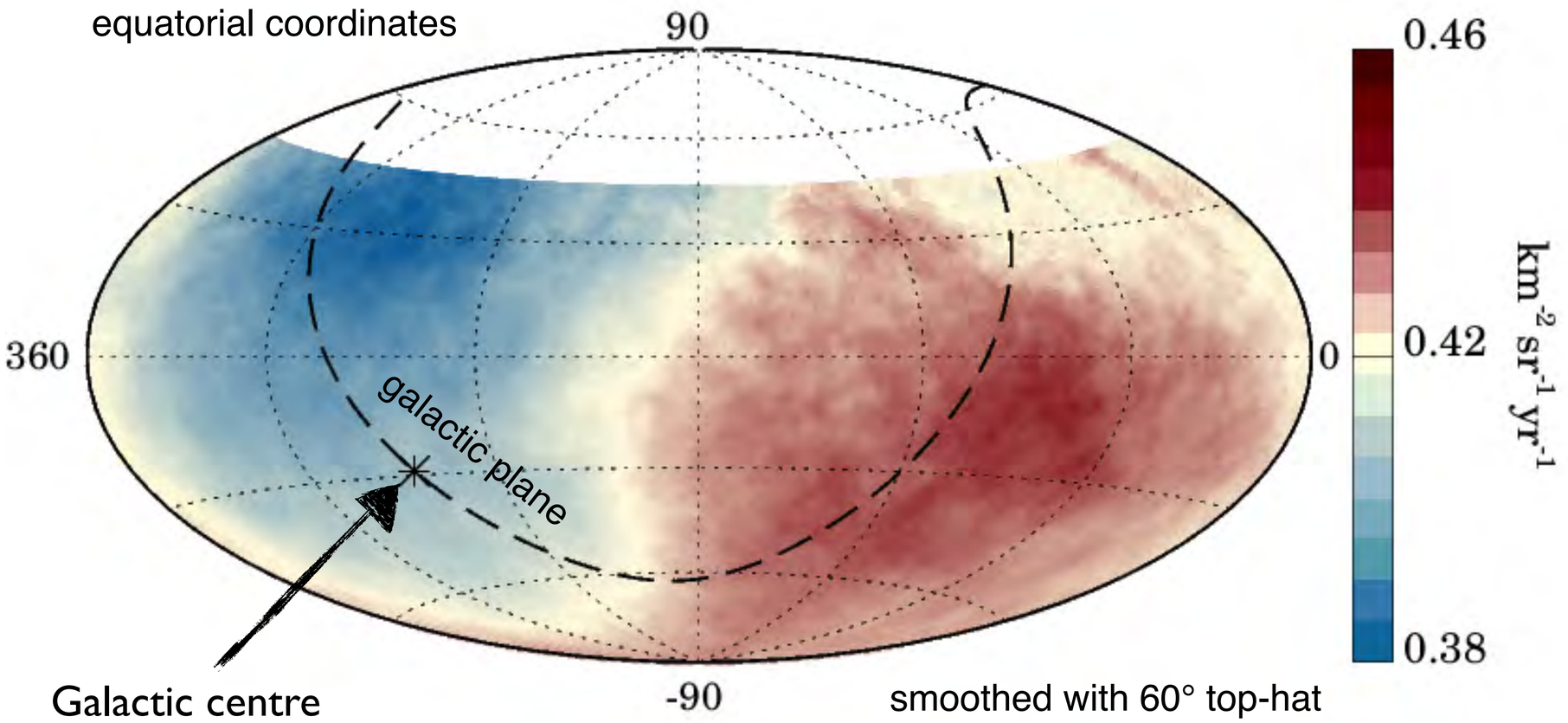



physicsworld TOP 10 BREAKTHROUGH 2017

**Extragalactic origin of UHECR confirmed**

# Flux Map above 8 EeV

Auger Collaboration, Science 357 (2017) 1266



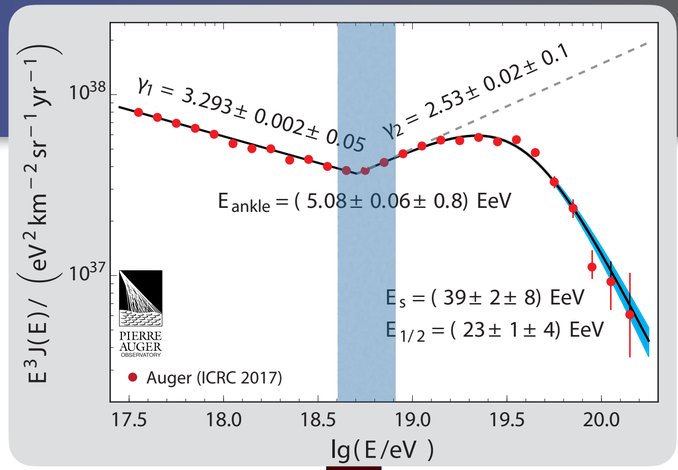

$$\mathcal{A} = 6.5^{+1.3}_{-0.9}\,\% \;\; ; \;\; \alpha_d = (100 \pm 10)^\circ \;\; ; \;\; \delta_d = (-24^{+12}_{-13})^\circ$$

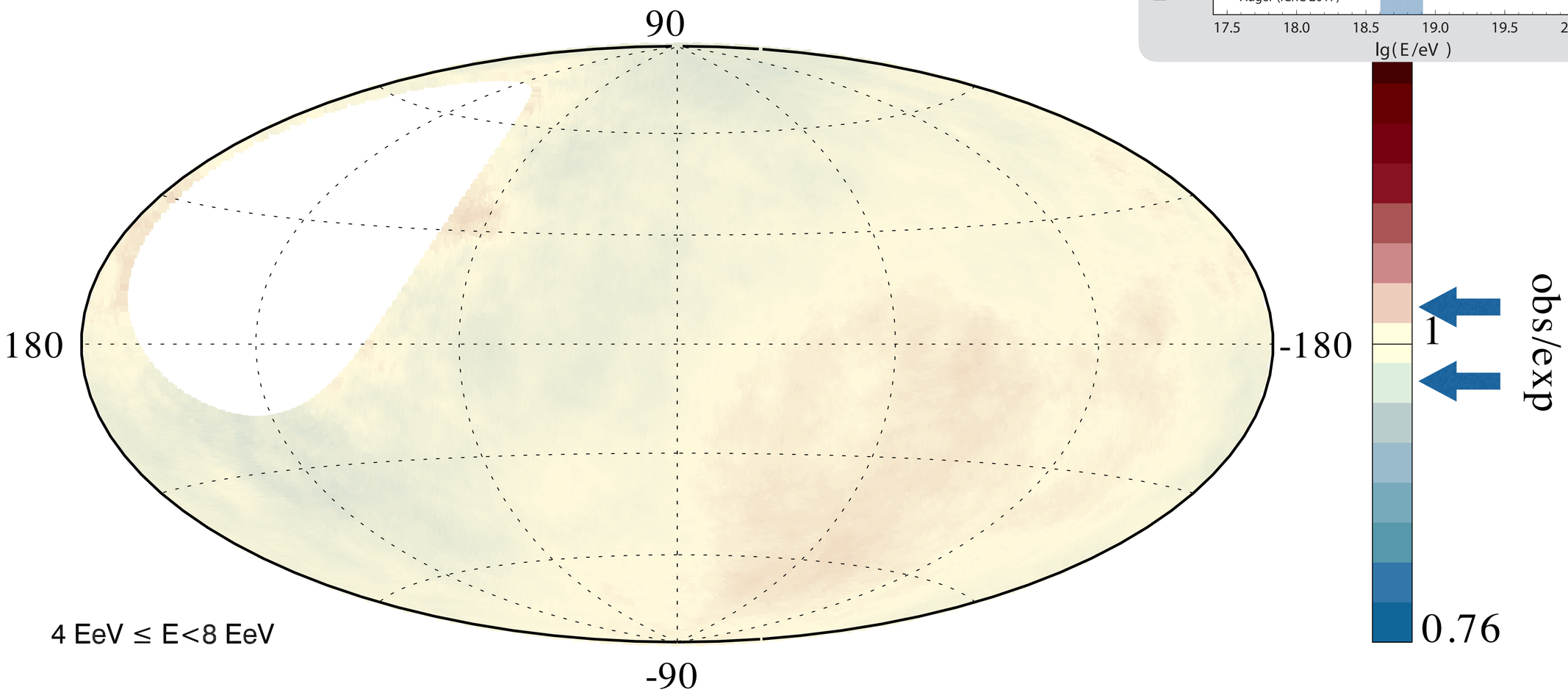
# Evolution with Energy: 4-8 EeV

Auger Collaboration, ApJ 868 (2018) 1

map smoothed with 45° top-hat
Galactic coordinates

all maps with identical color scale



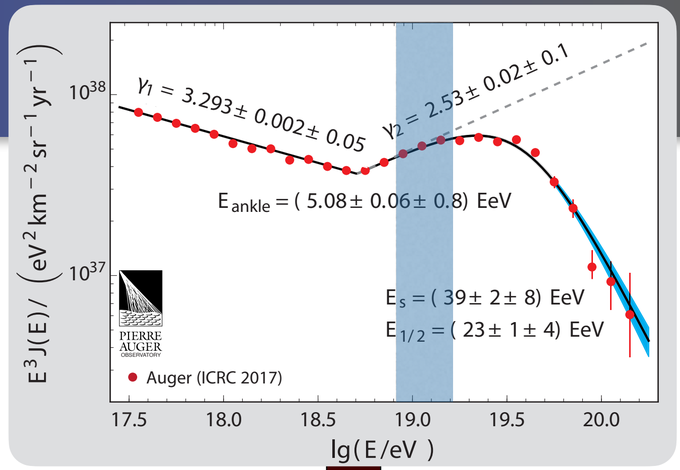



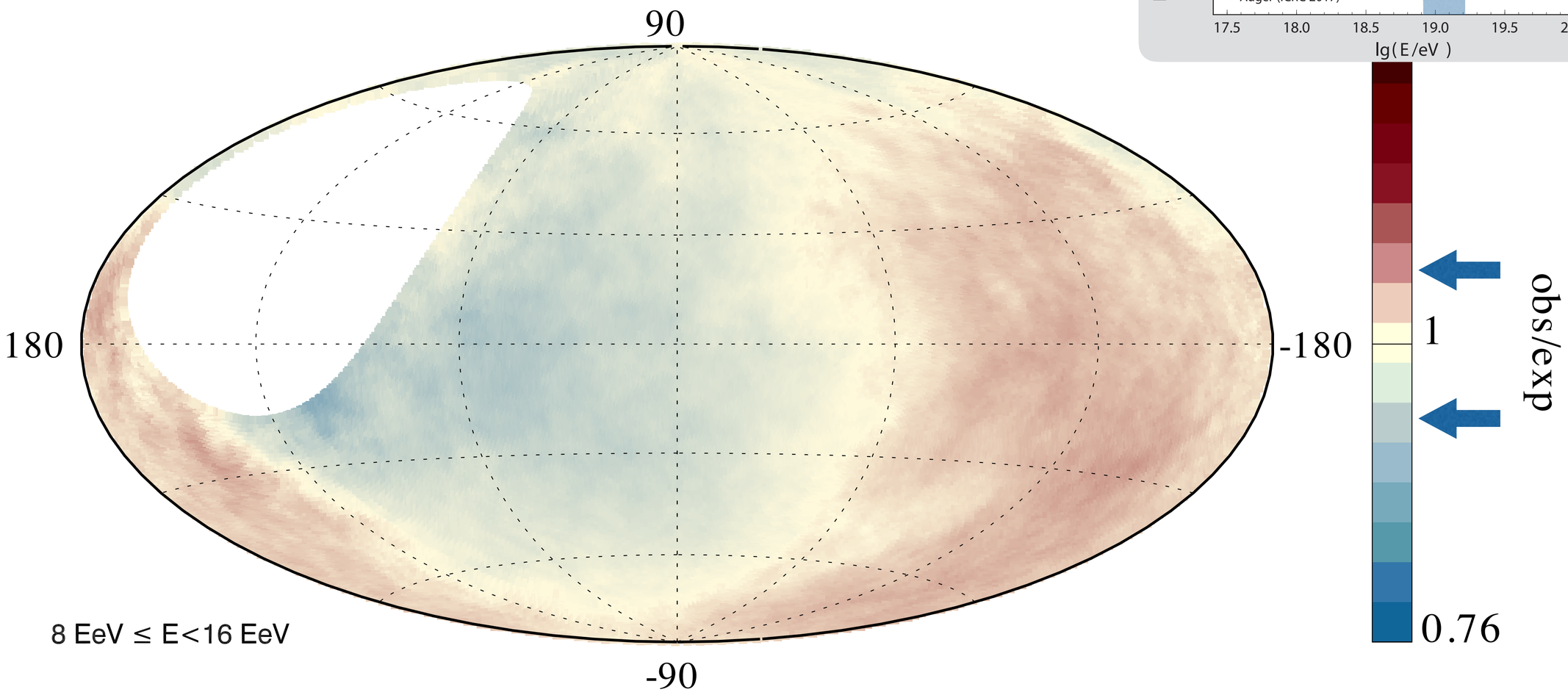
# Evolution with Energy: 8-16 EeV

Auger Collaboration, ApJ 868 (2018) 1

map smoothed with 45° top-hat
Galactic coordinates

all maps with identical color scale



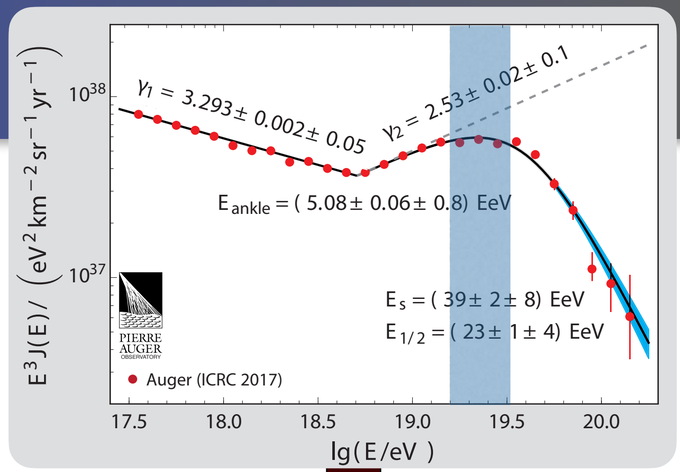



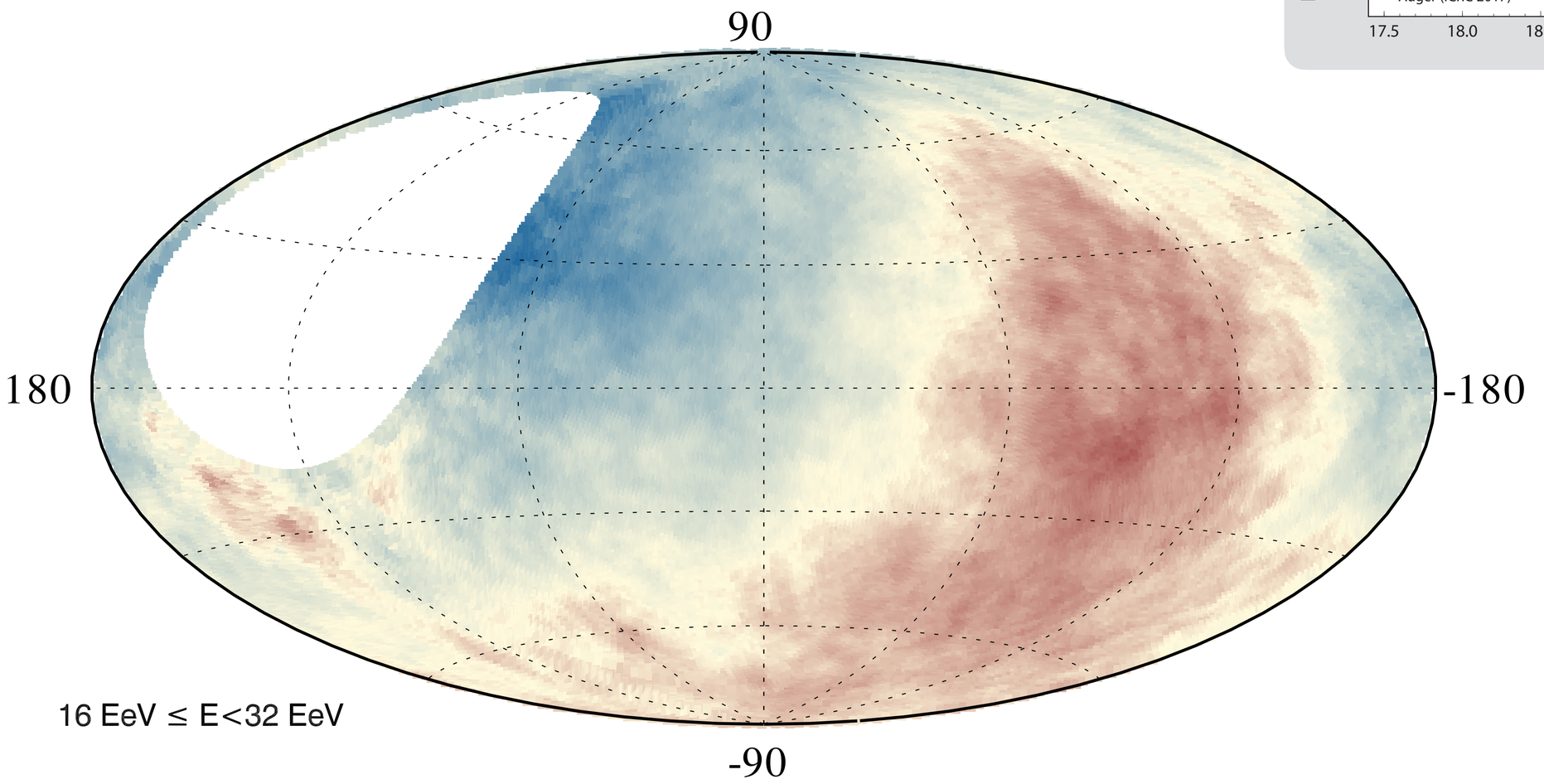
# Evolution with Energy: 16-32 EeV

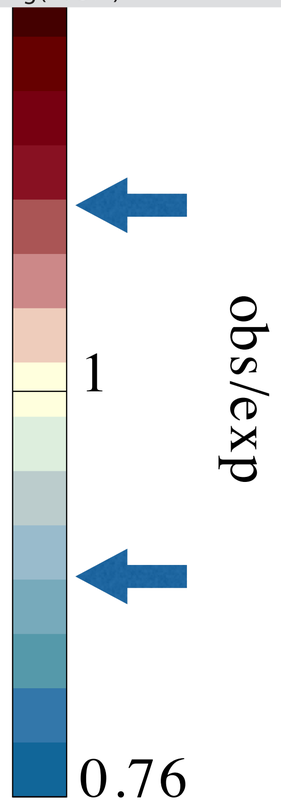
Auger Collaboration, ApJ 868 (2018) 1

map smoothed with 45° top-hat
Galactic coordinates

all maps with identical color scale



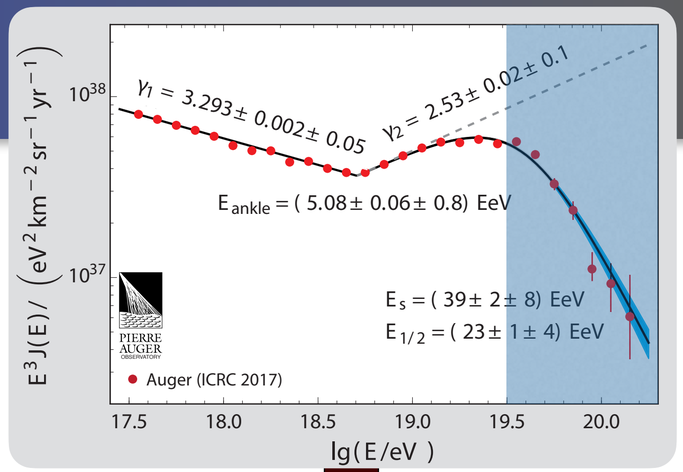



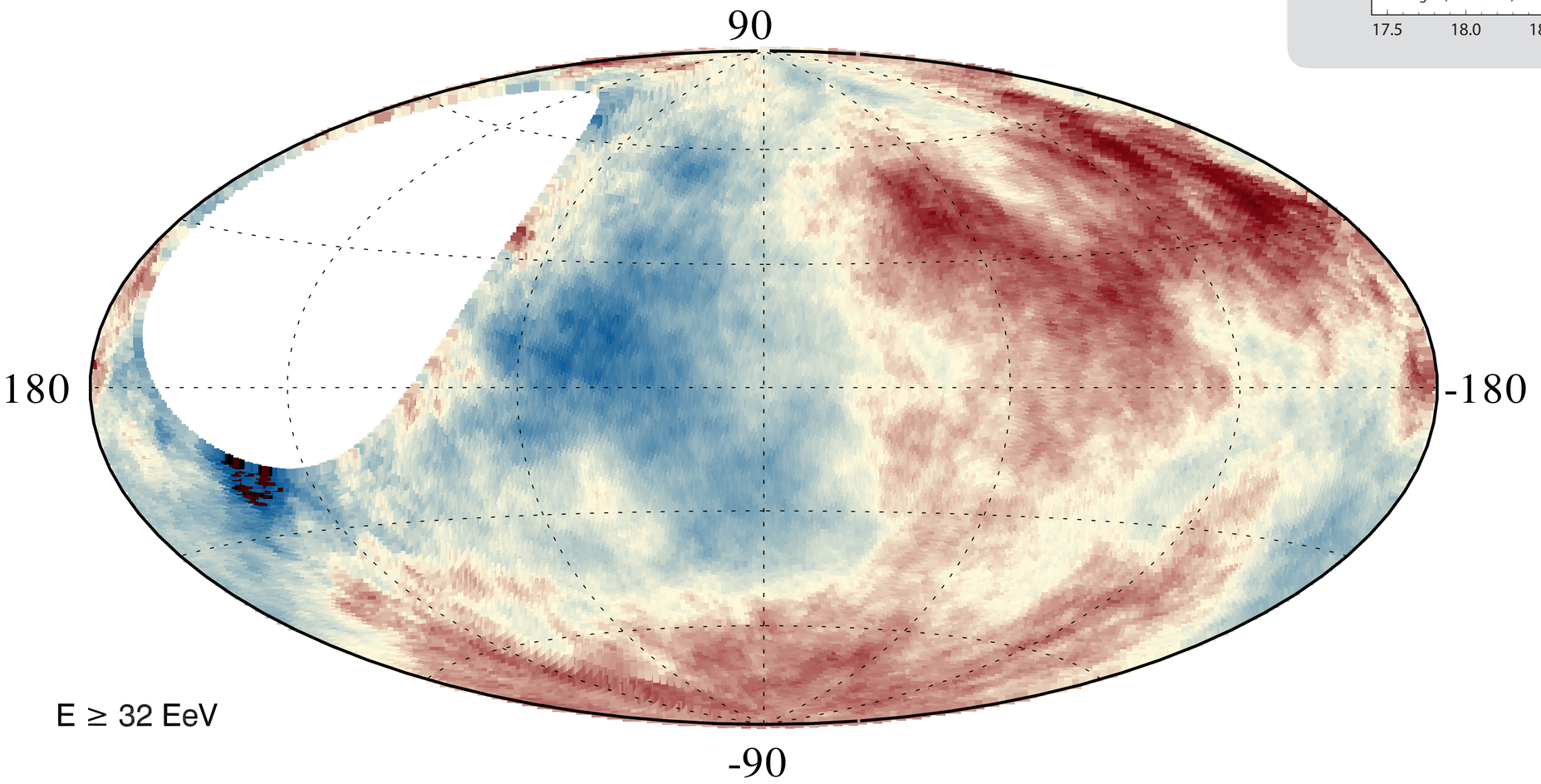
# Evolution with Energy: >32 EeV

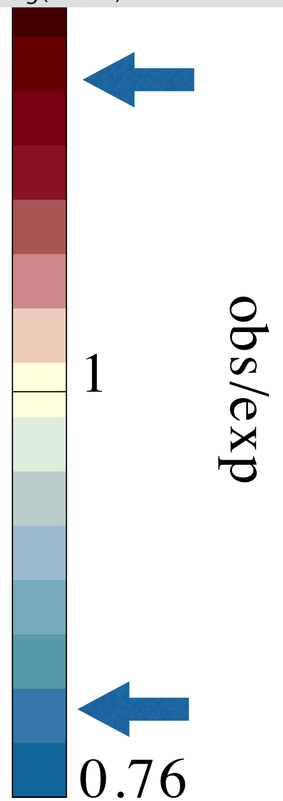
Auger Collaboration, ApJ 868 (2018) 1

map smoothed with 45° top-hat
Galactic coordinates

all maps with identical color scale



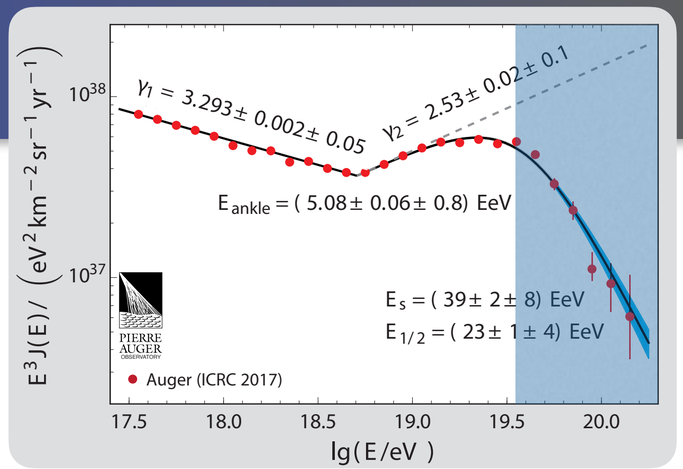



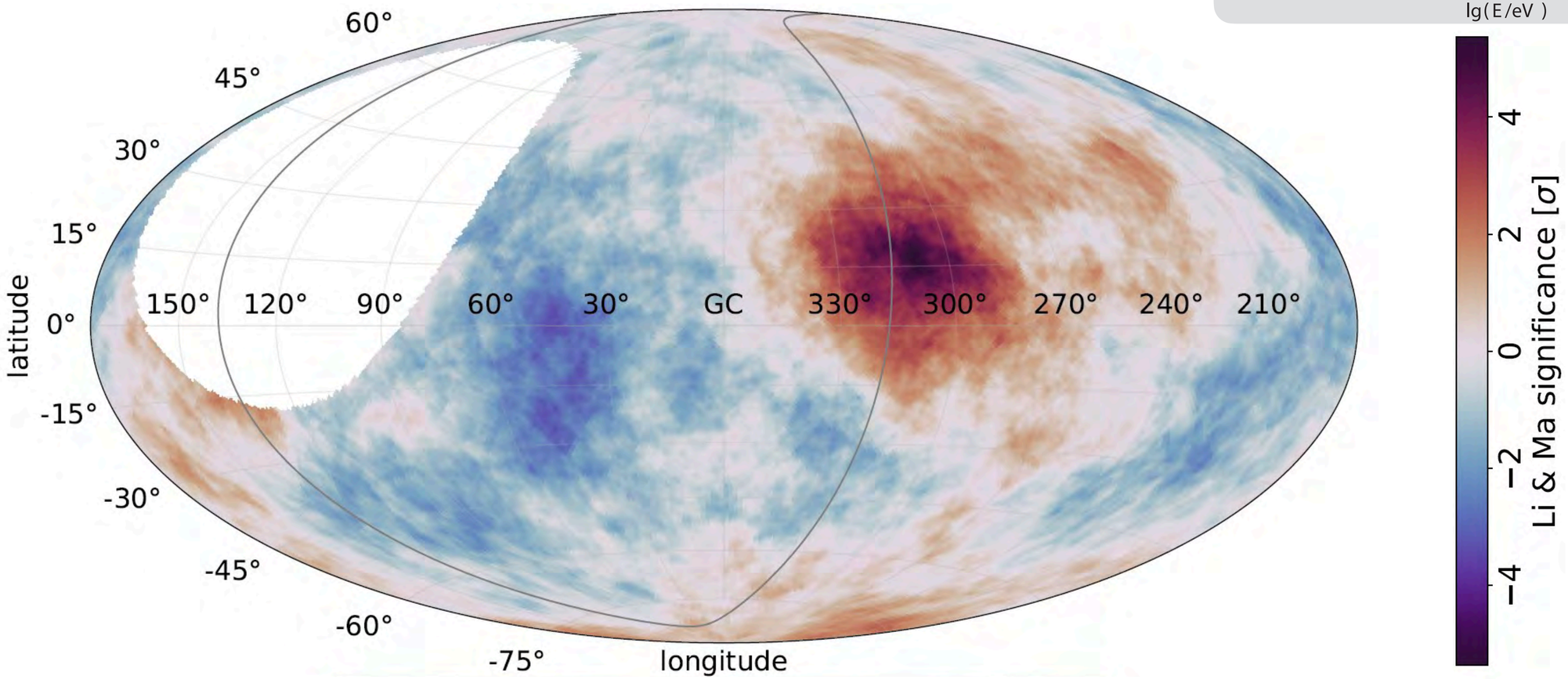



# Evolution with Energy: >38 EeV

Auger Collaboration, G. Golup (ICRC 2023)

map smoothed with 27° top-hat
Galactic coordinates

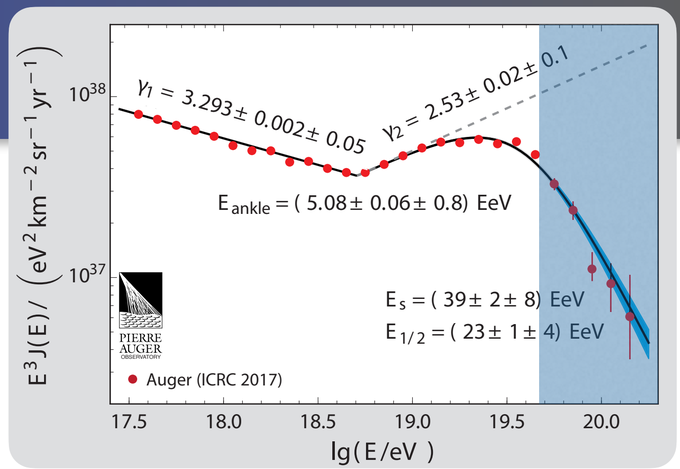


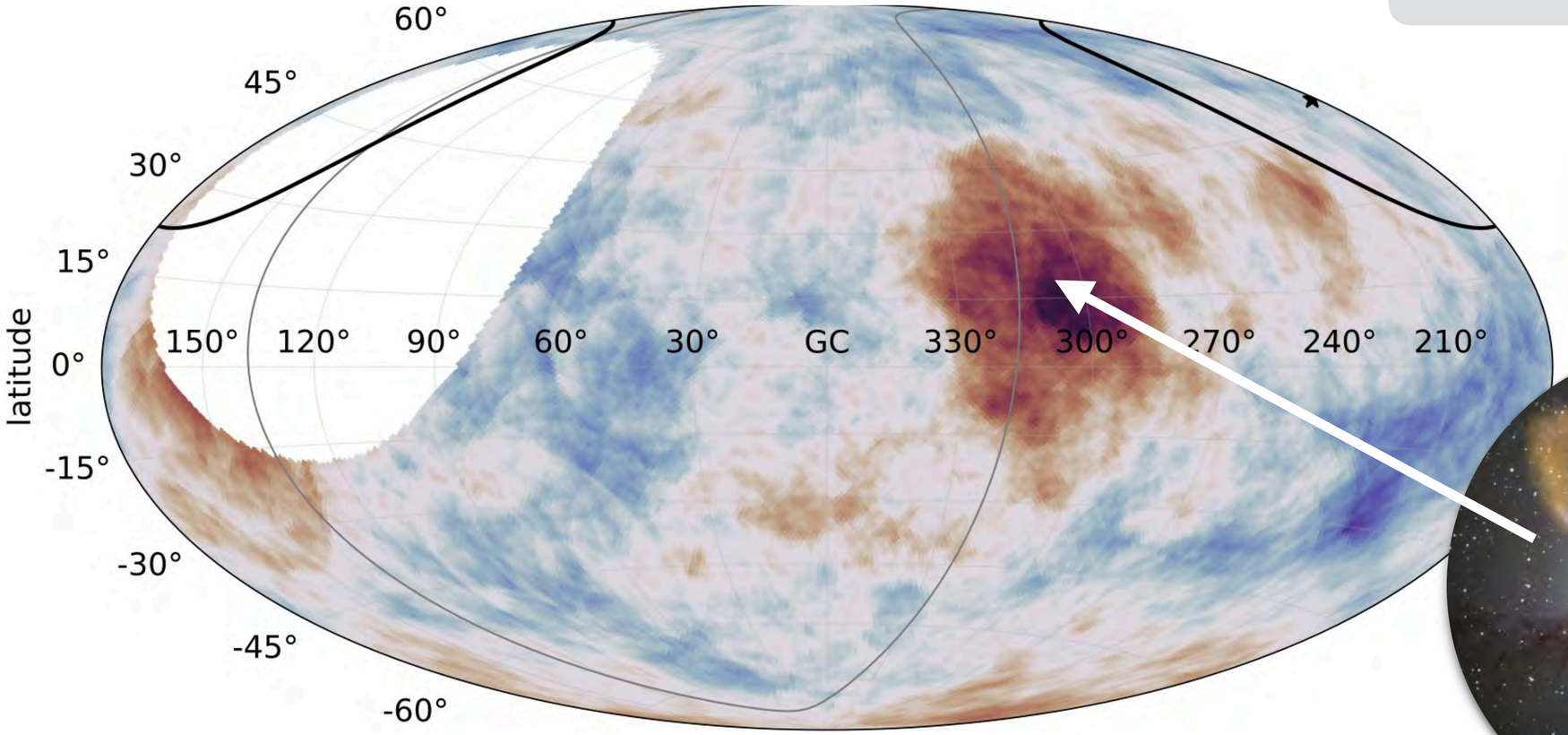



# Evolution with Energy: >45 EeV

Auger Collaboration, G. Golup (ICRC 2023)

map smoothed with 25° top-hat
Galactic coordinates





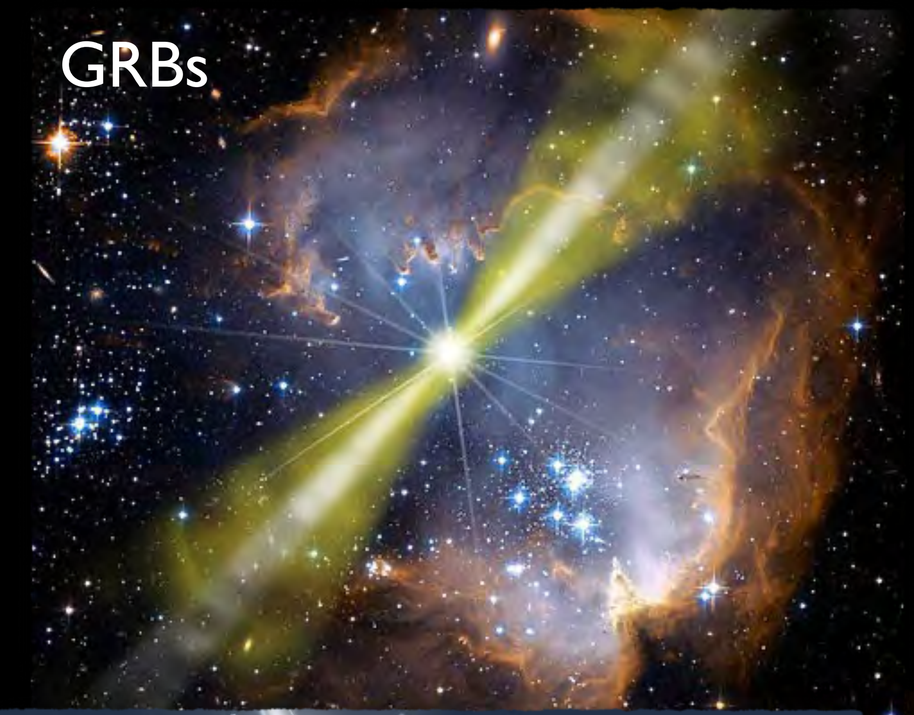
Directional correlation with Centaurus A at 4σ



Active core → AGN
also considered as Starburst Galaxy

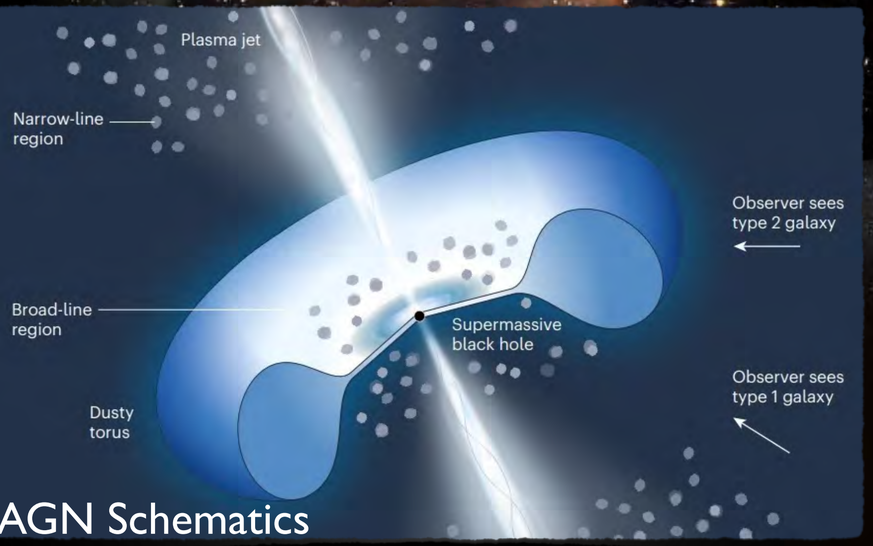
# UHECR Source Candidates: The usual Suspects…

GRBs



Galaxy Clusters

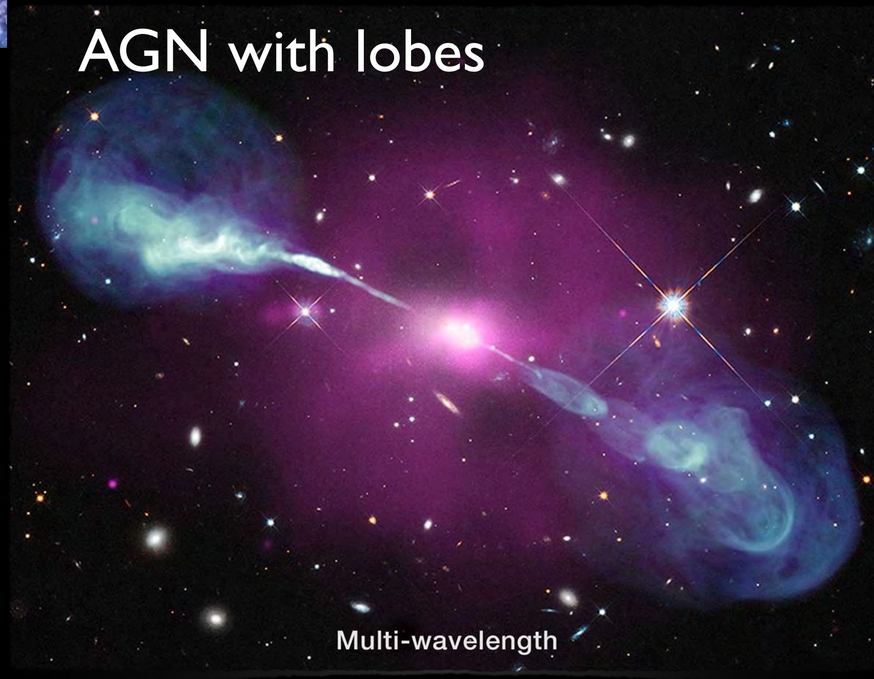
Neutron Stars



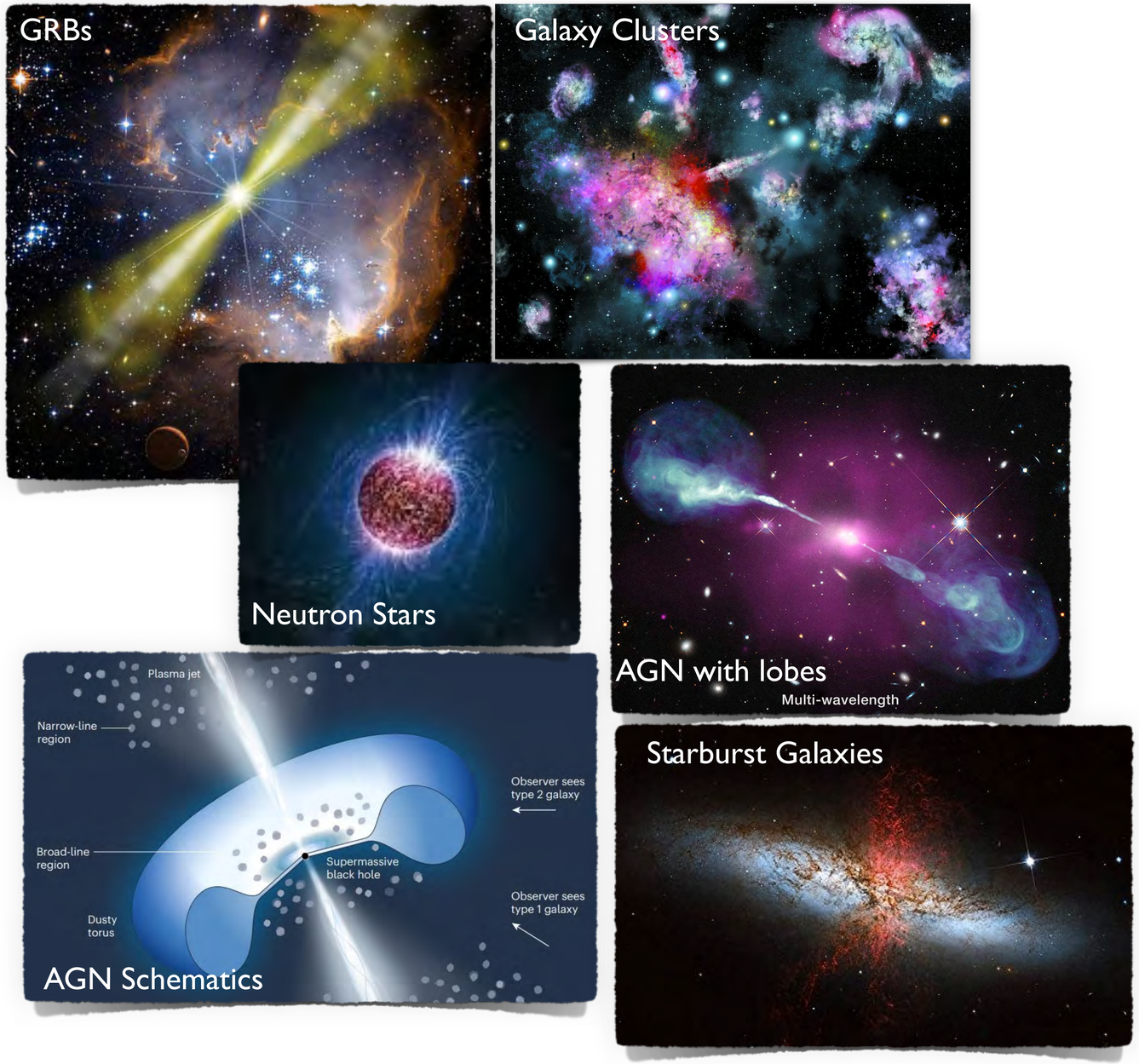

AGN Schematics

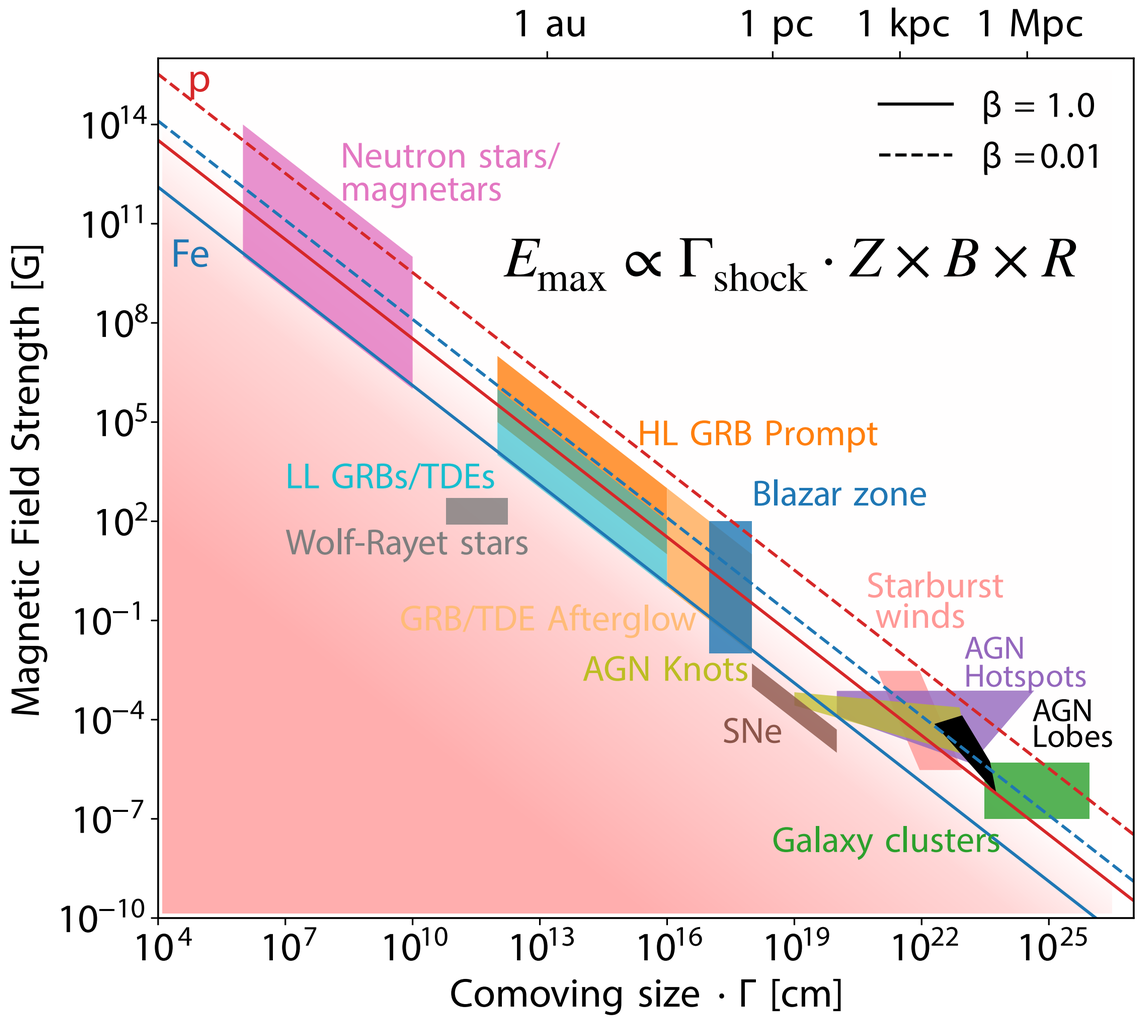
Starburst Galaxies

AGN with lobes



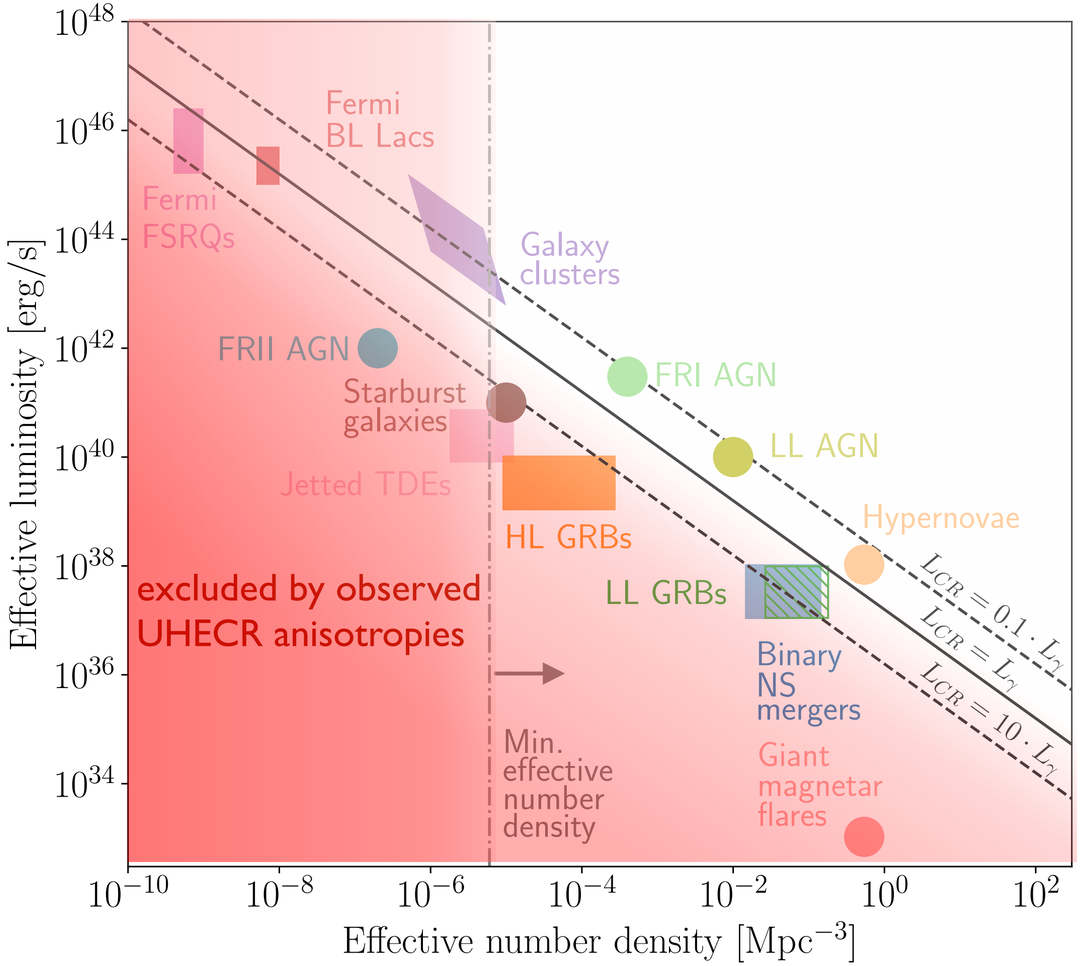
# Hillas Plot: B vs Size of Accelerators



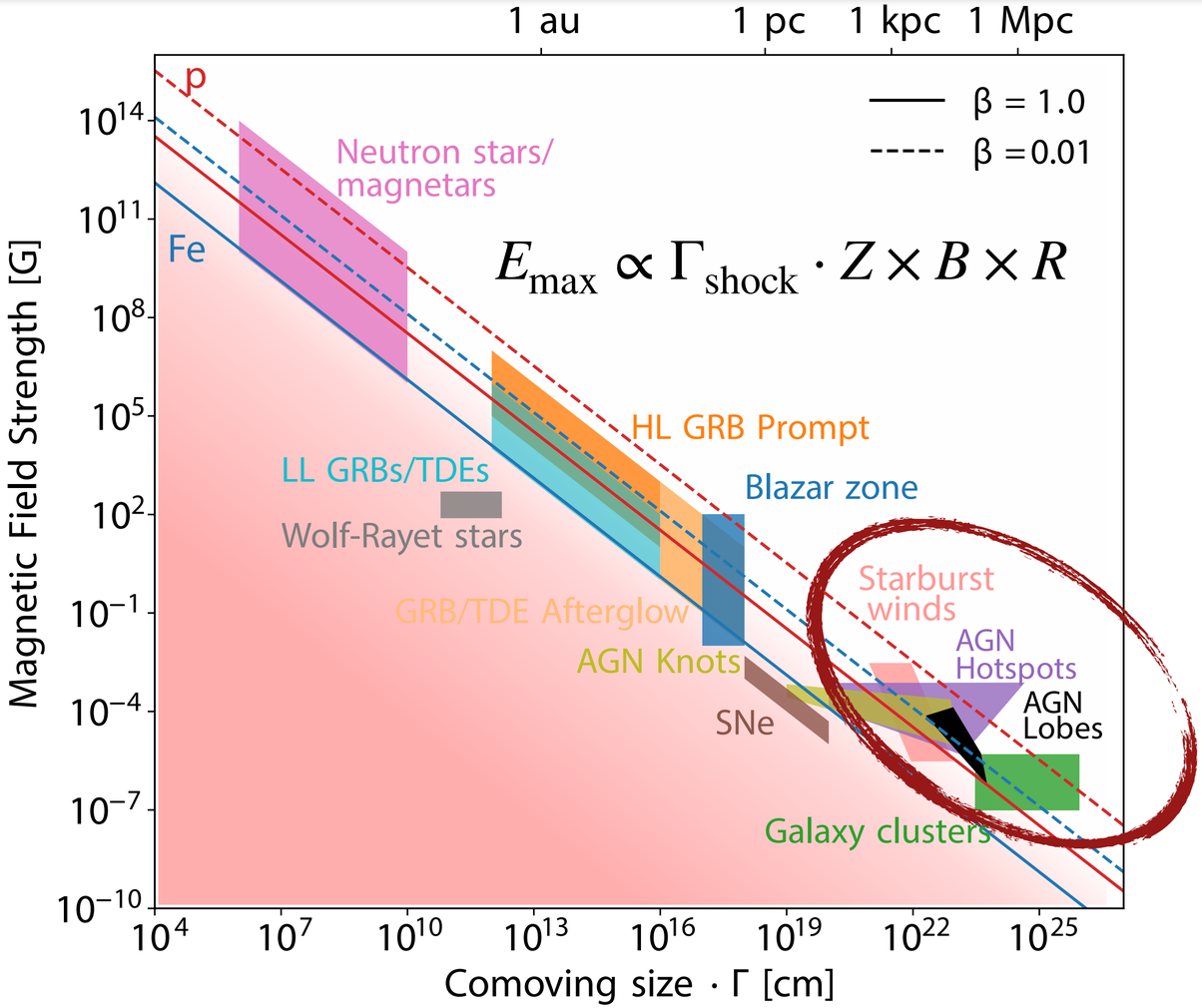




MIAPP review, Front.Astron.Space Sci. 6 (2019) 23

# UHECR Luminosity and Acceleration Requirements



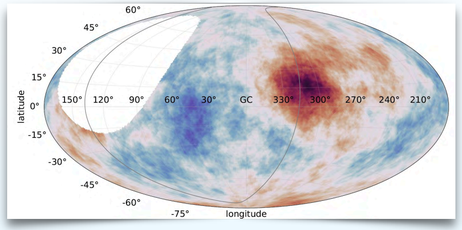

MIAPP review, Front.Astron.Space Sci. 6 (2019) 23

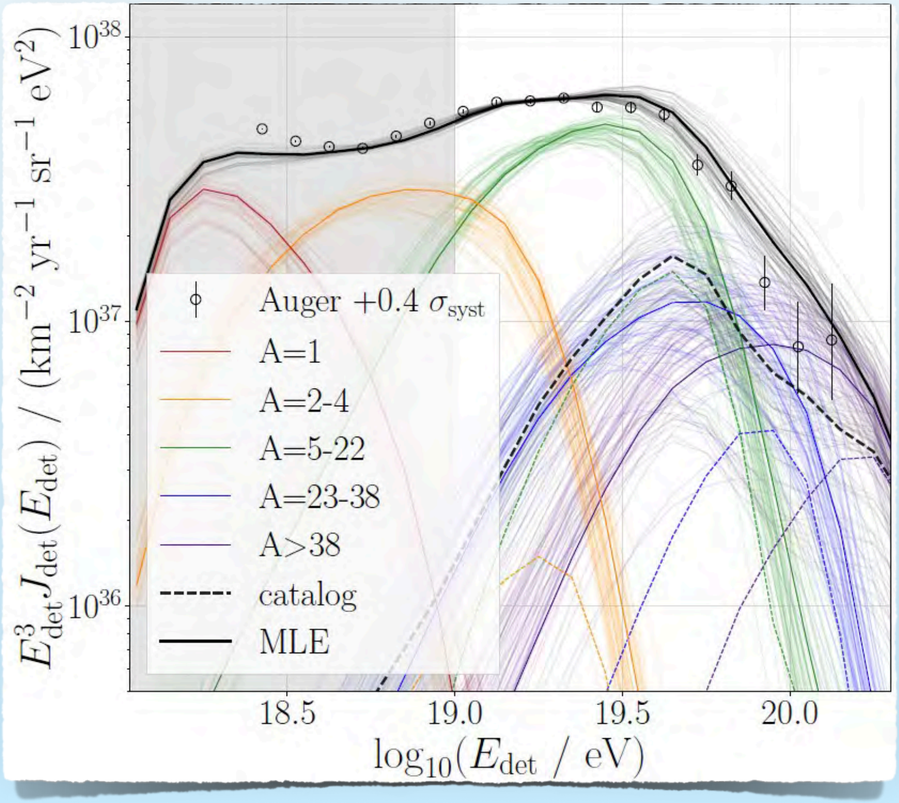


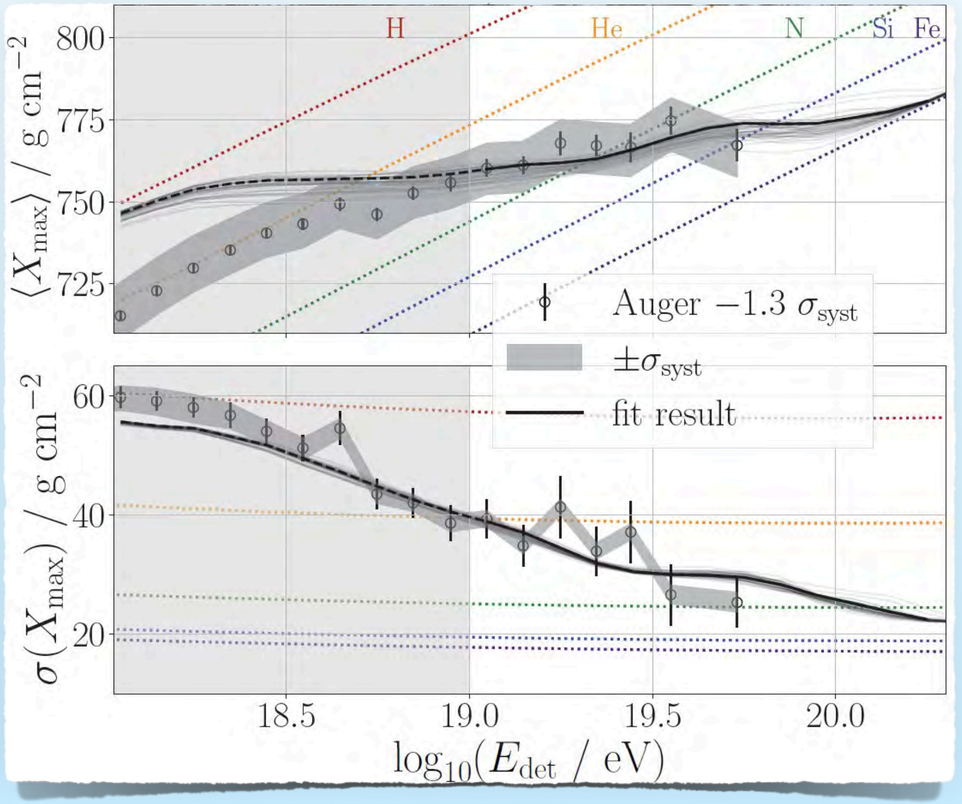

Note: plot applies both for steady and transient sources, when assuming a characteristic time spread of $\tau = 3 \cdot 10^5$ yr.

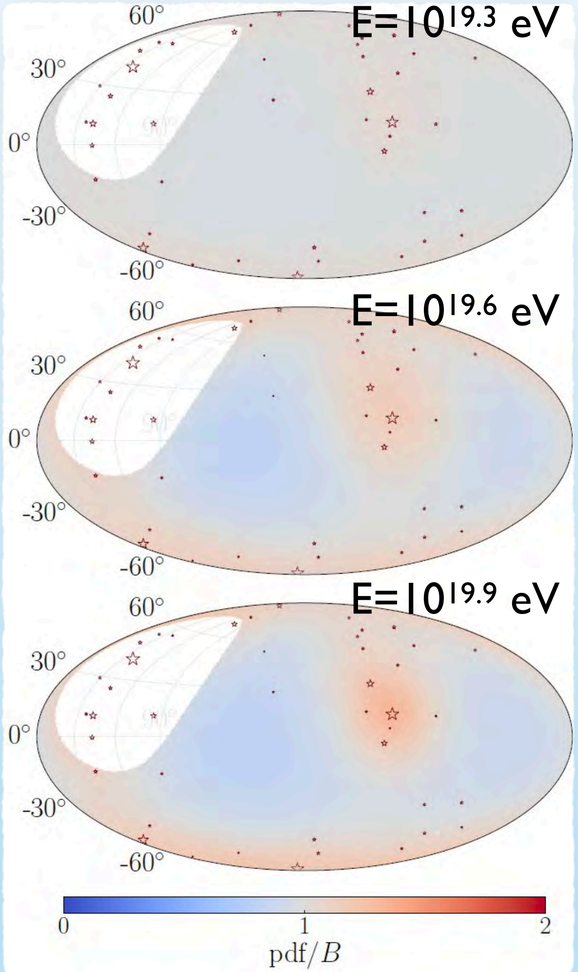
# Towards understanding the Universe at its highest energies

Idea:
- investigate possibility of SBGs / γ-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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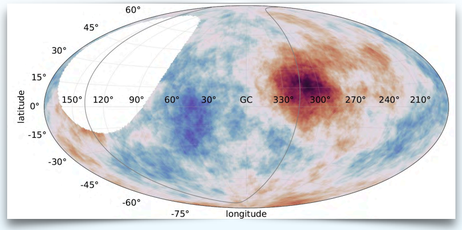
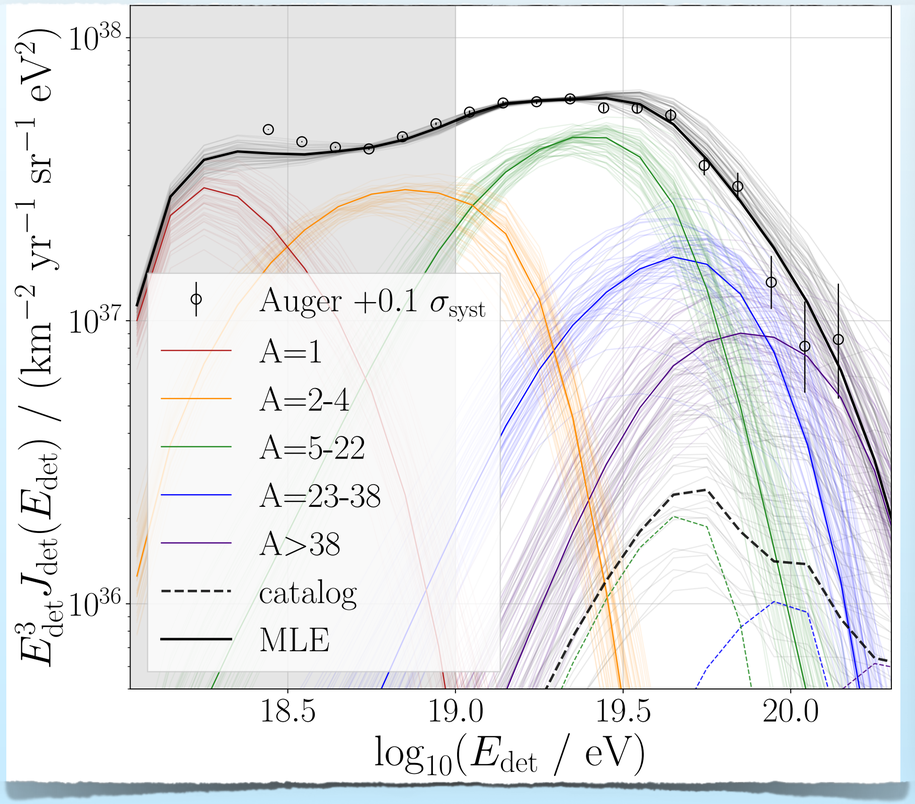
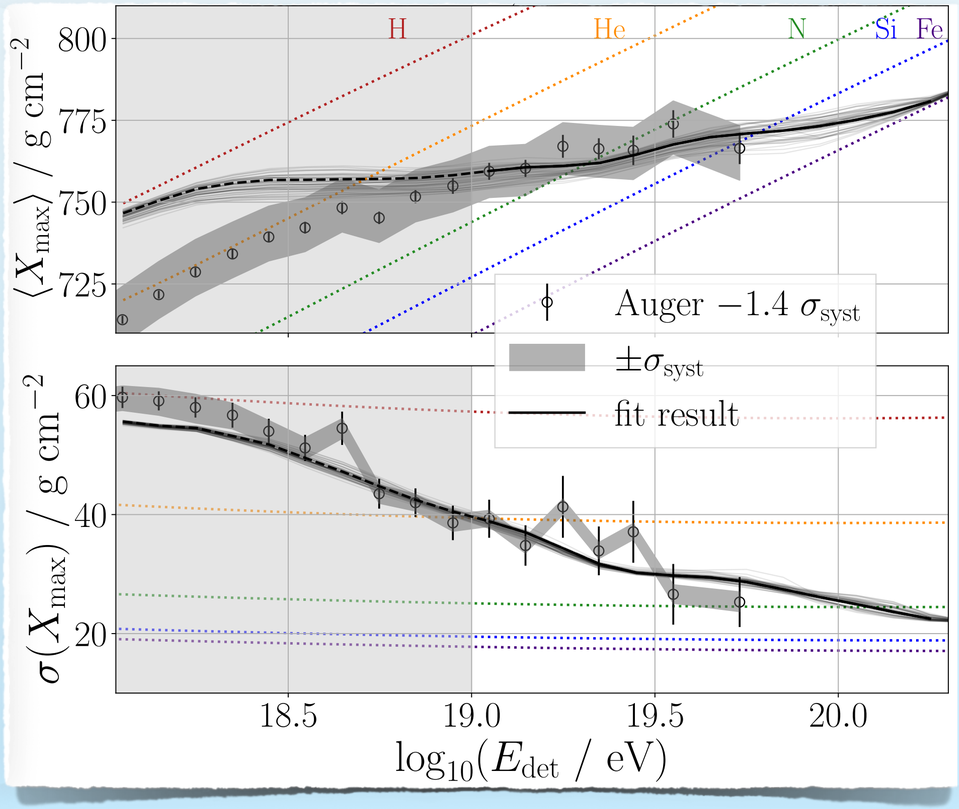
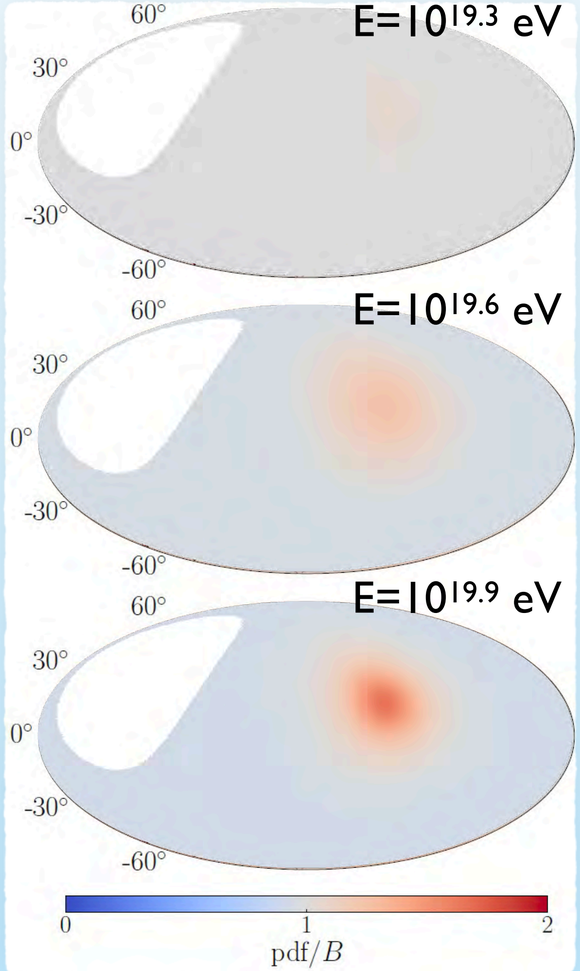


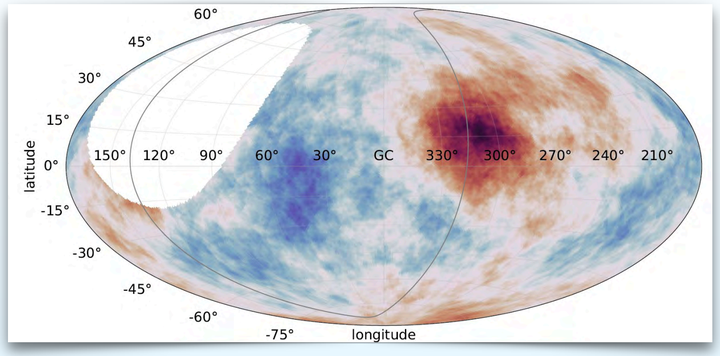

Result of likelihood fit to measured E-spectrum, Composition, and Sky-Map when taking a Cen A model (m=3.4)

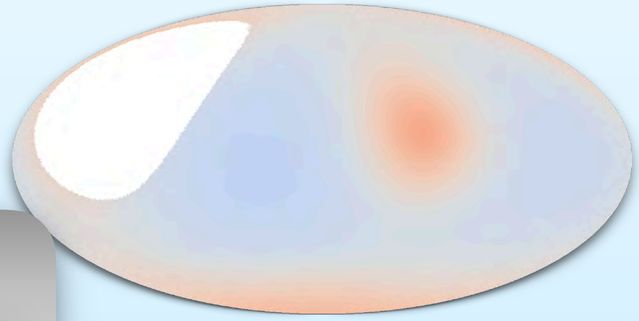
Terese Bister, ICRC2023

# Towards understanding the Universe at its highest energies

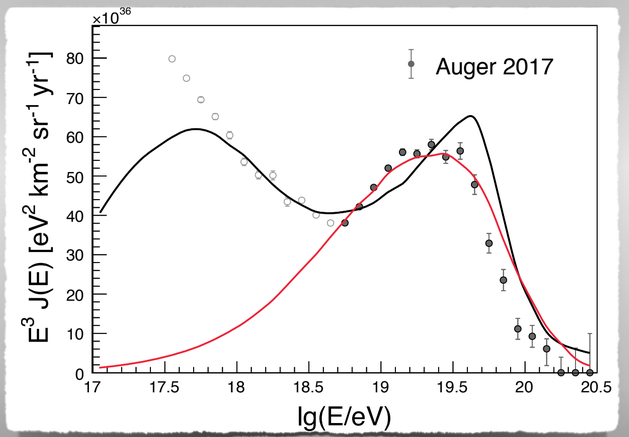
**Conclusion:**

- 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



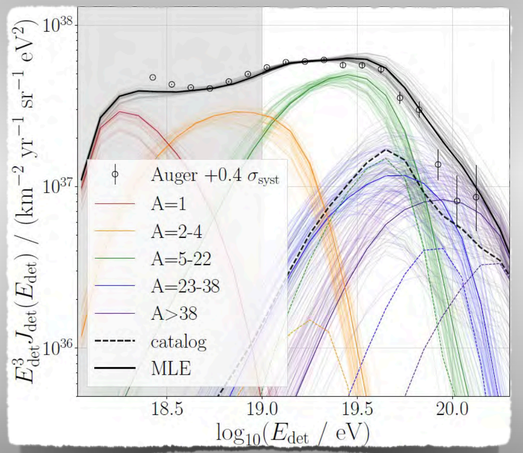



GZK




0:4

$E_{max}$(source)



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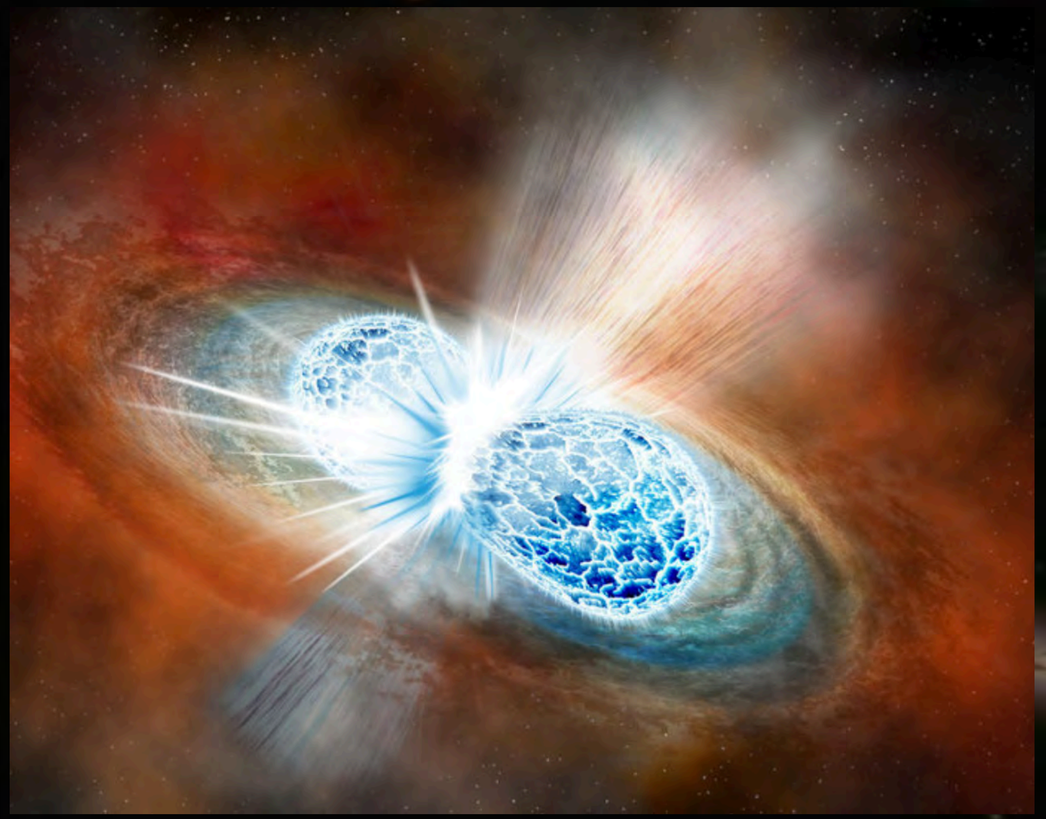
# 2017: Big Bang of Multimessenger Astrophysics



*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)

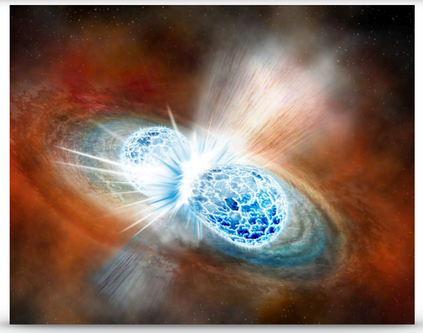
THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

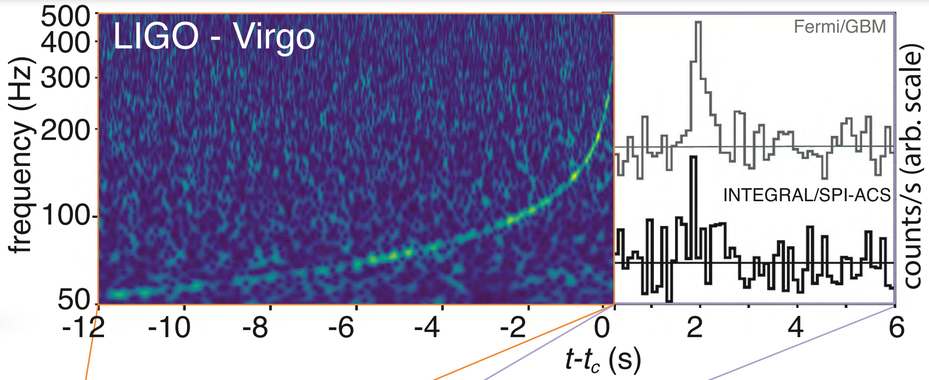
OPEN ACCESS

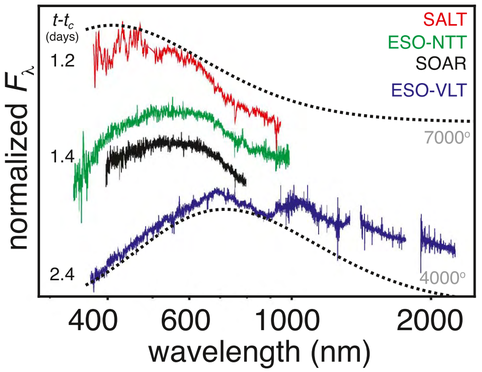
**Multi-messenger Observations of a Binary Neutron Star Merger**

This was a very lucky event...!

# GW170817: Time Sequence






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

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

Host galaxy: NGC 4993

distance: 40 Mpc

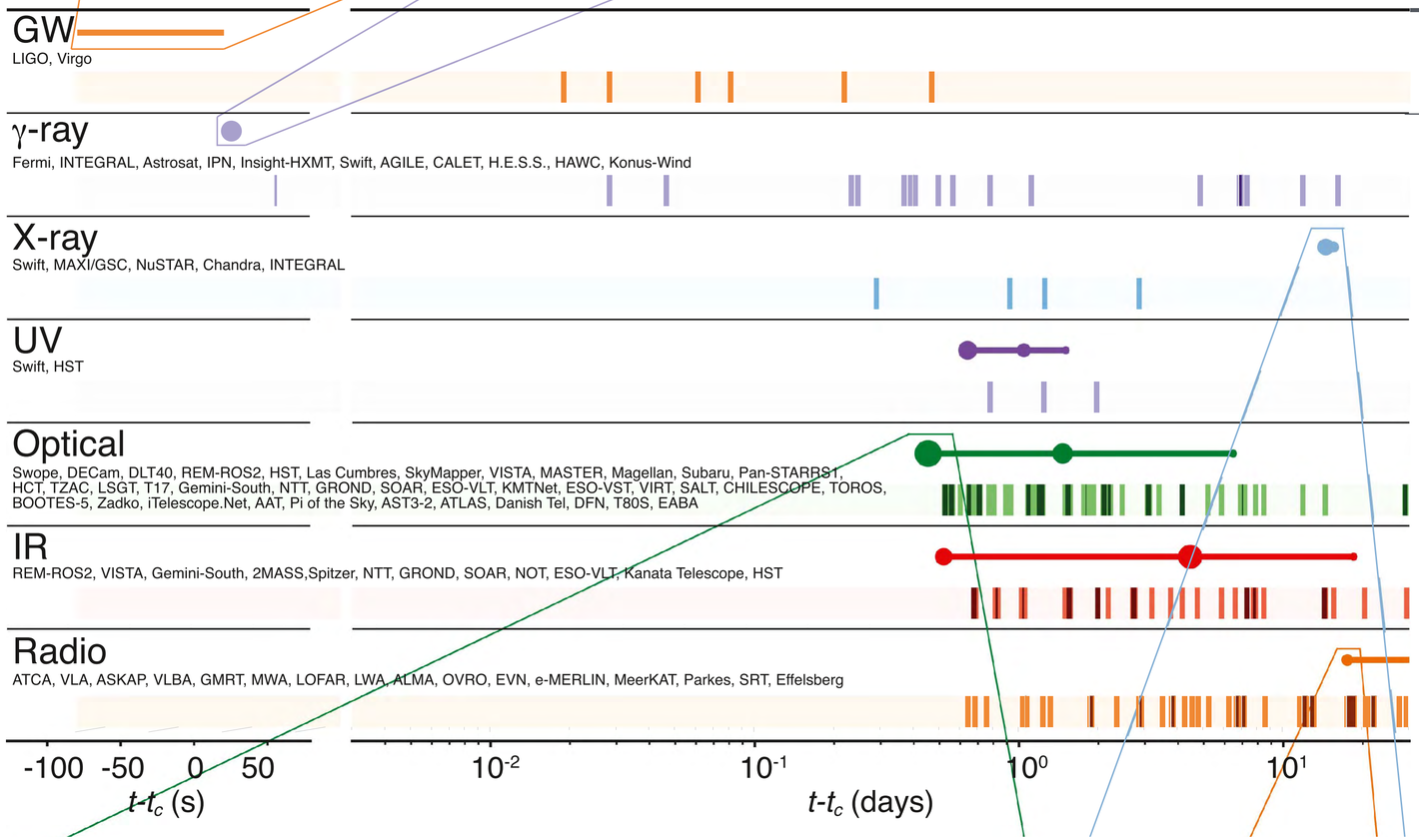
optical brightness after one day

$10^8$ $L_\odot$ → **kilonova** powered by radioactive decays

lasted 100 s !

1.7 s after GWs

still after weeks




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

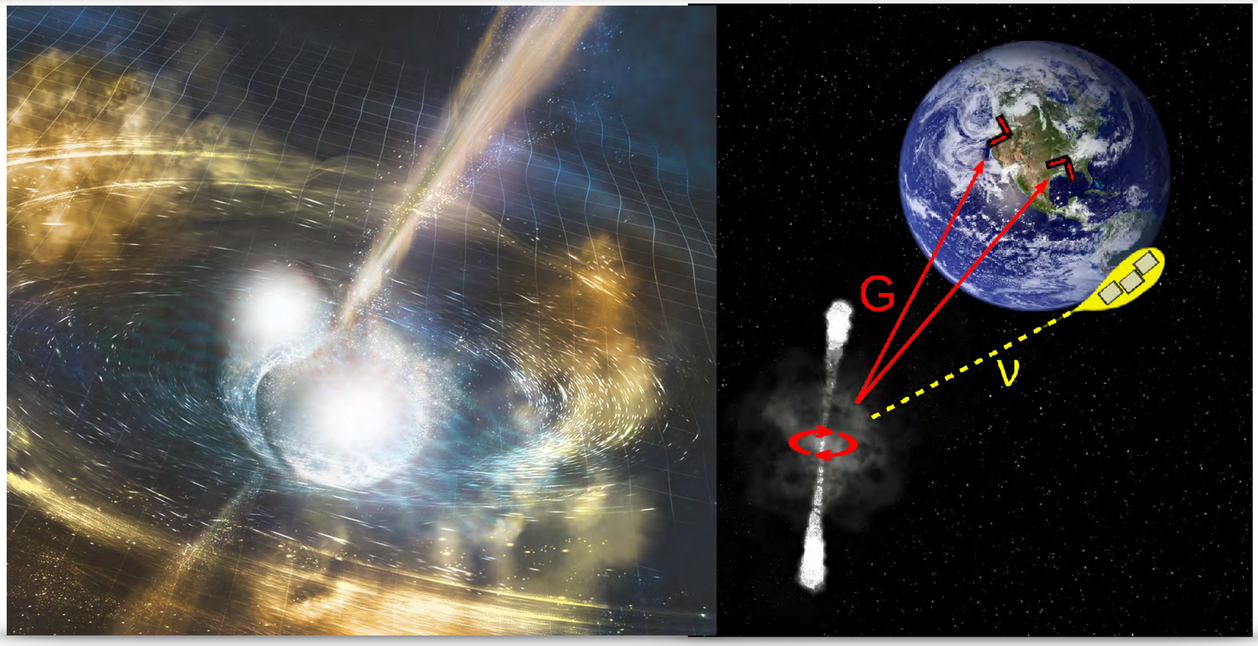
# GW170817: Physics across multiple aspects/fields

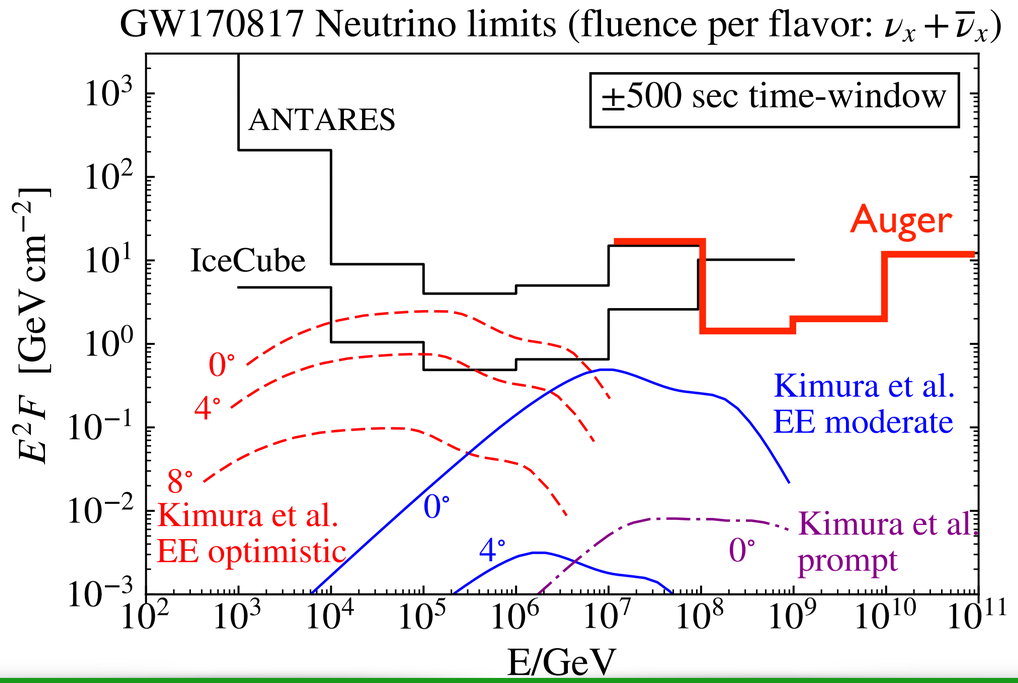
- **General Relativity**: gravitational waves
- **Cosmology**: independent Hubble constant determination
- **Astronomy**: Follow ups, multiwavelength
- **Astrophysics**: Compact objects, Neutron stars
- **Nuclear Physics**: r-process, equation of state
- **Particle Physics**: Neutrino oscillations
-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

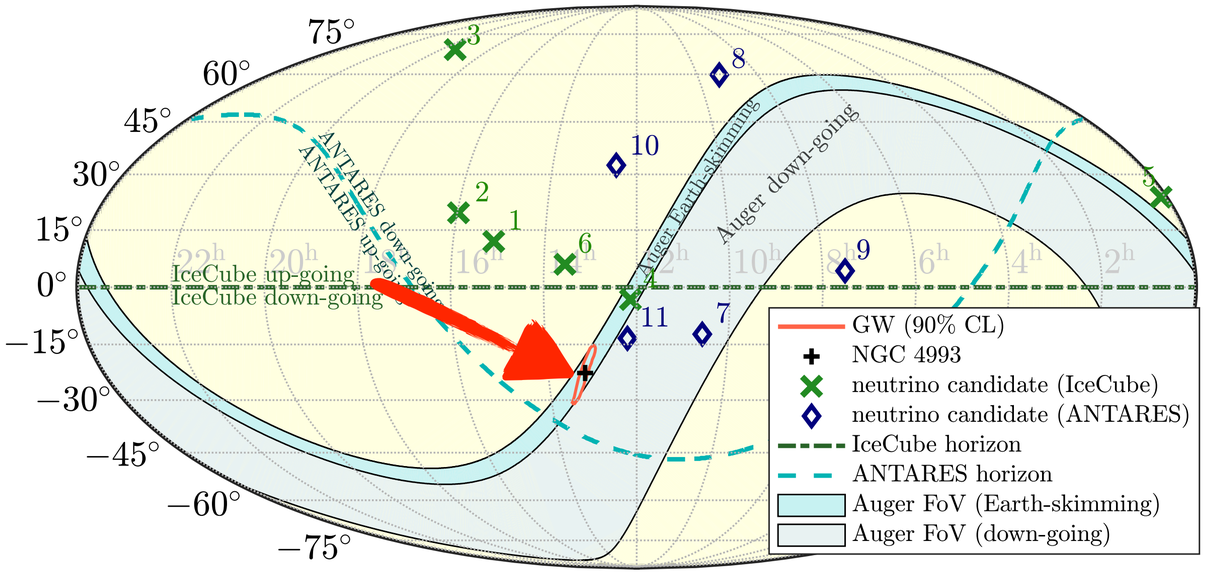
**Unique Event**

**→ Brought together different communities**

# Neutrino Upper Limits for GW170817




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

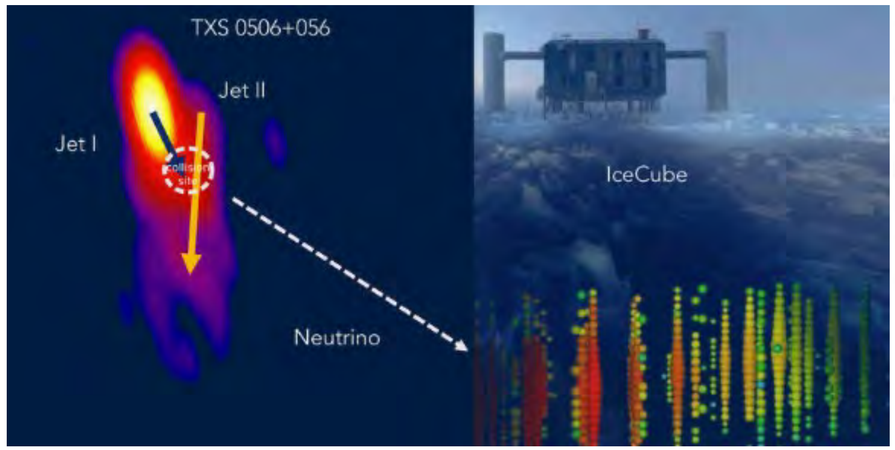
**May have seen neutrinos if jet were pointing towards us**

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

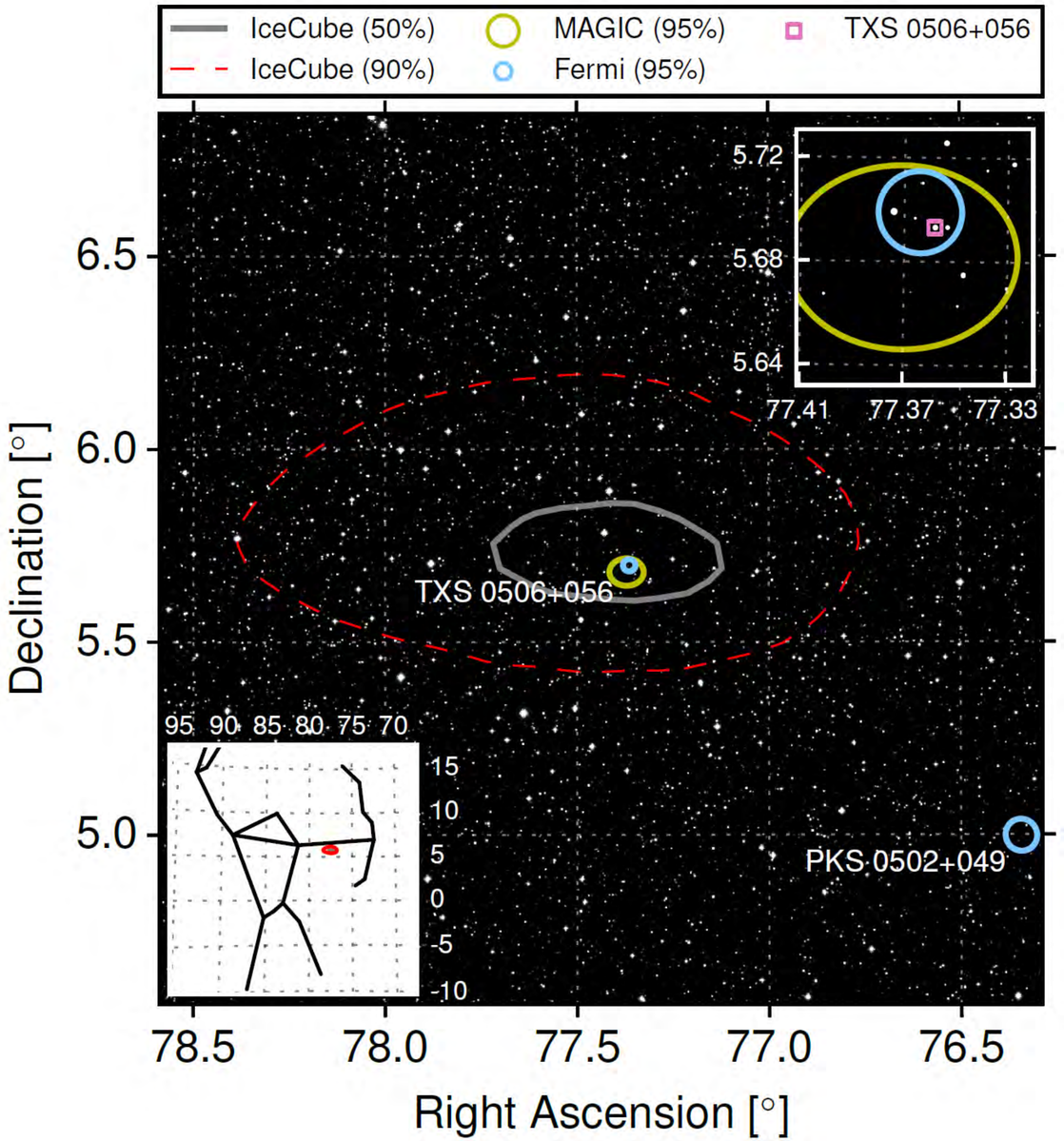
# High energy neutrino from direction of TXS 0506-056

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)

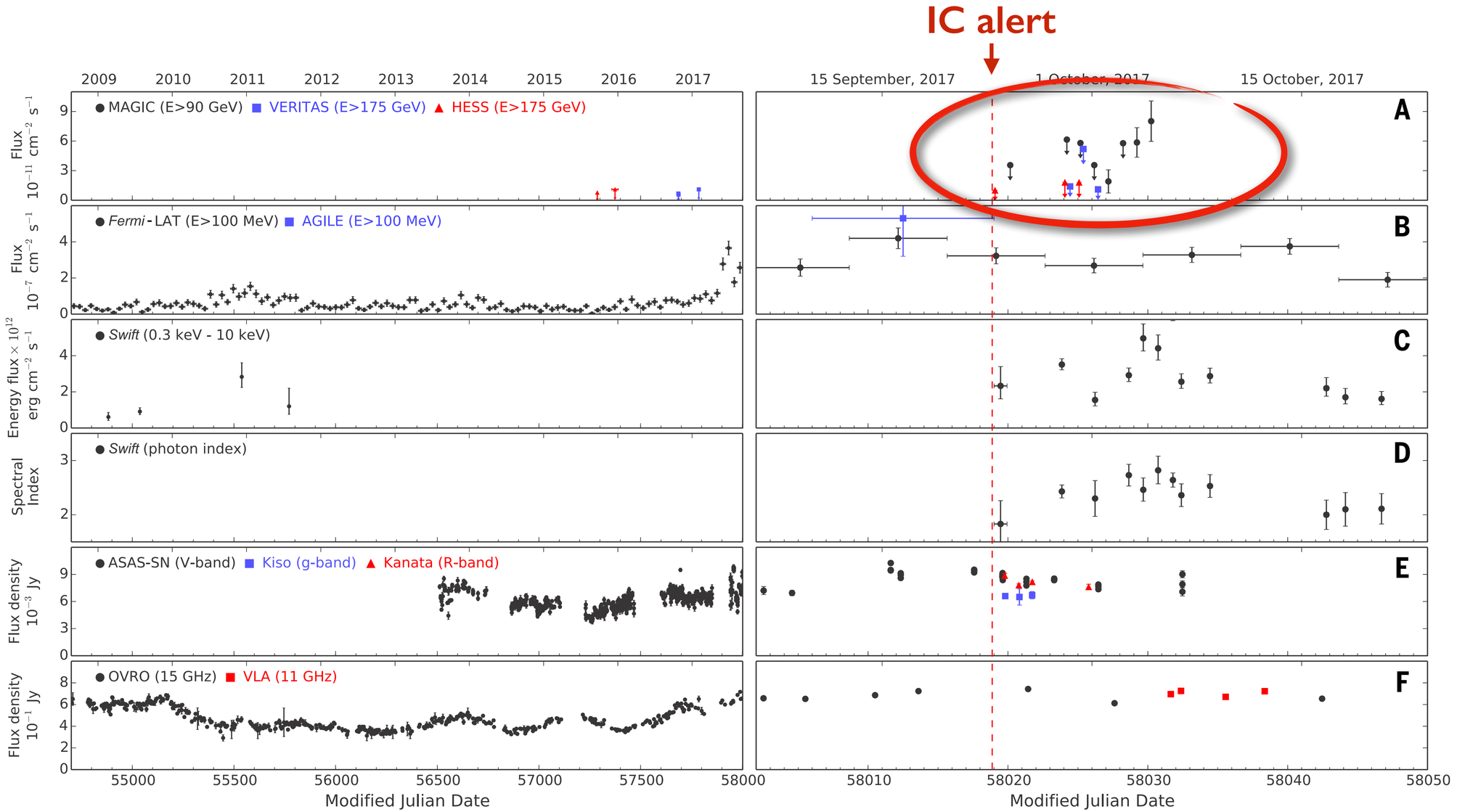



Science 361, 146 (2018)



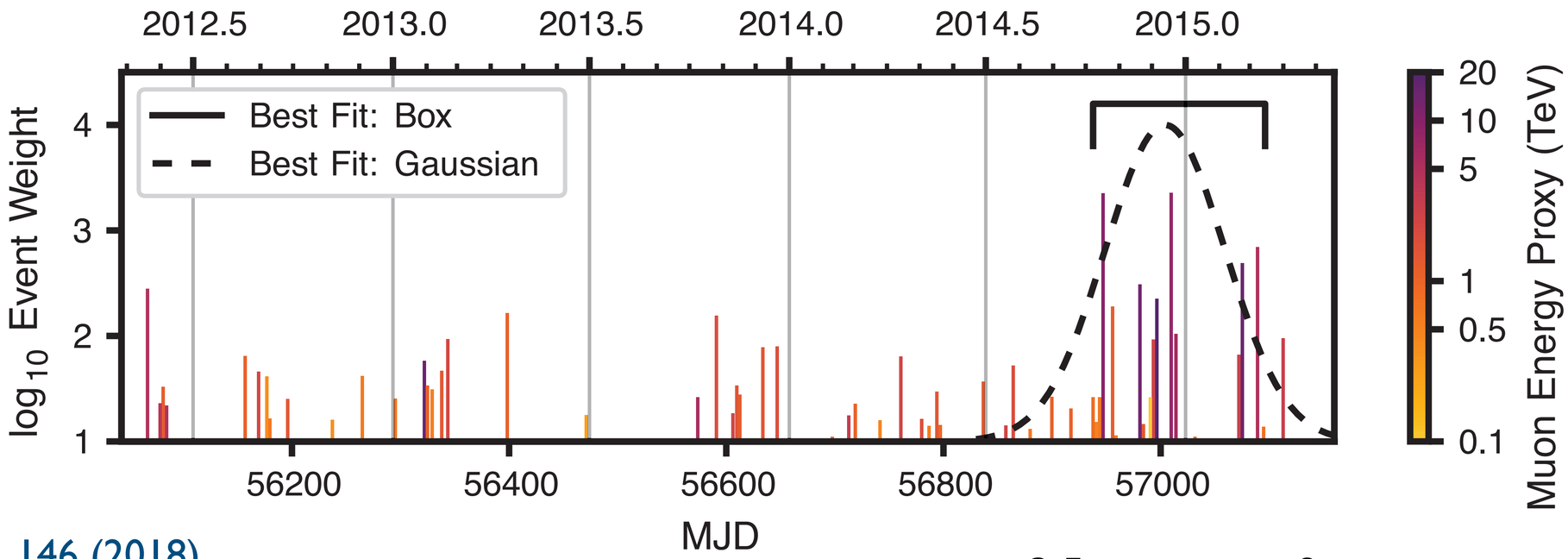
# TXS 0506-056 in flaring state

The MAGIC telescope was pointed there and found the blazer entering a flaring state with $E_\gamma > 90$ 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)

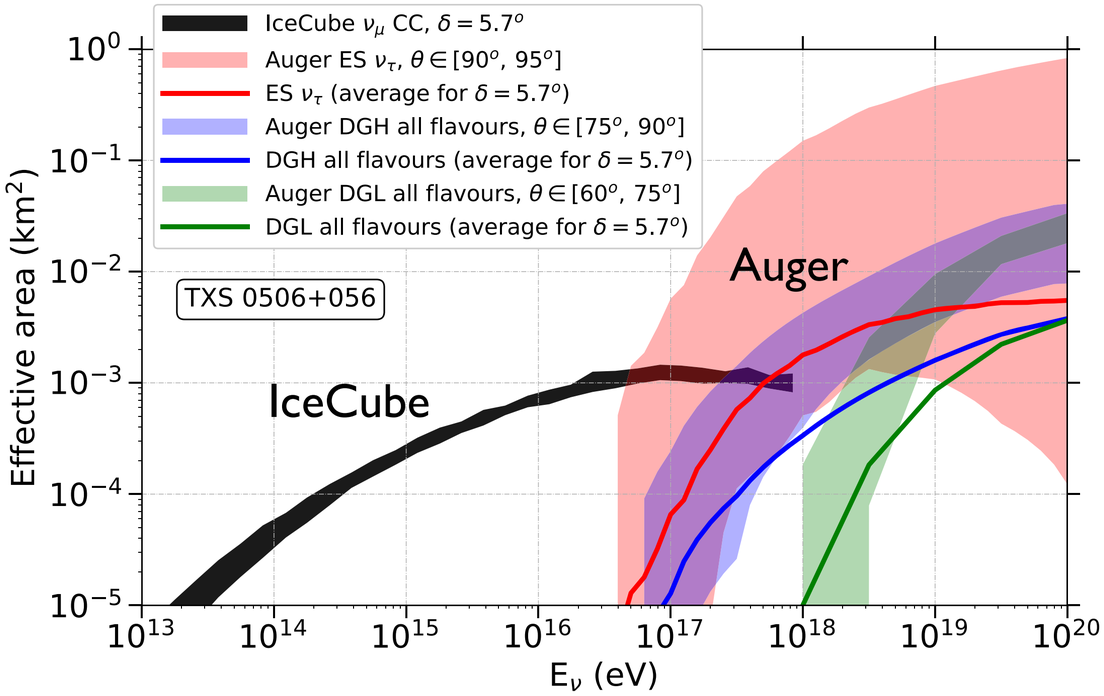
3.5 sigma significance

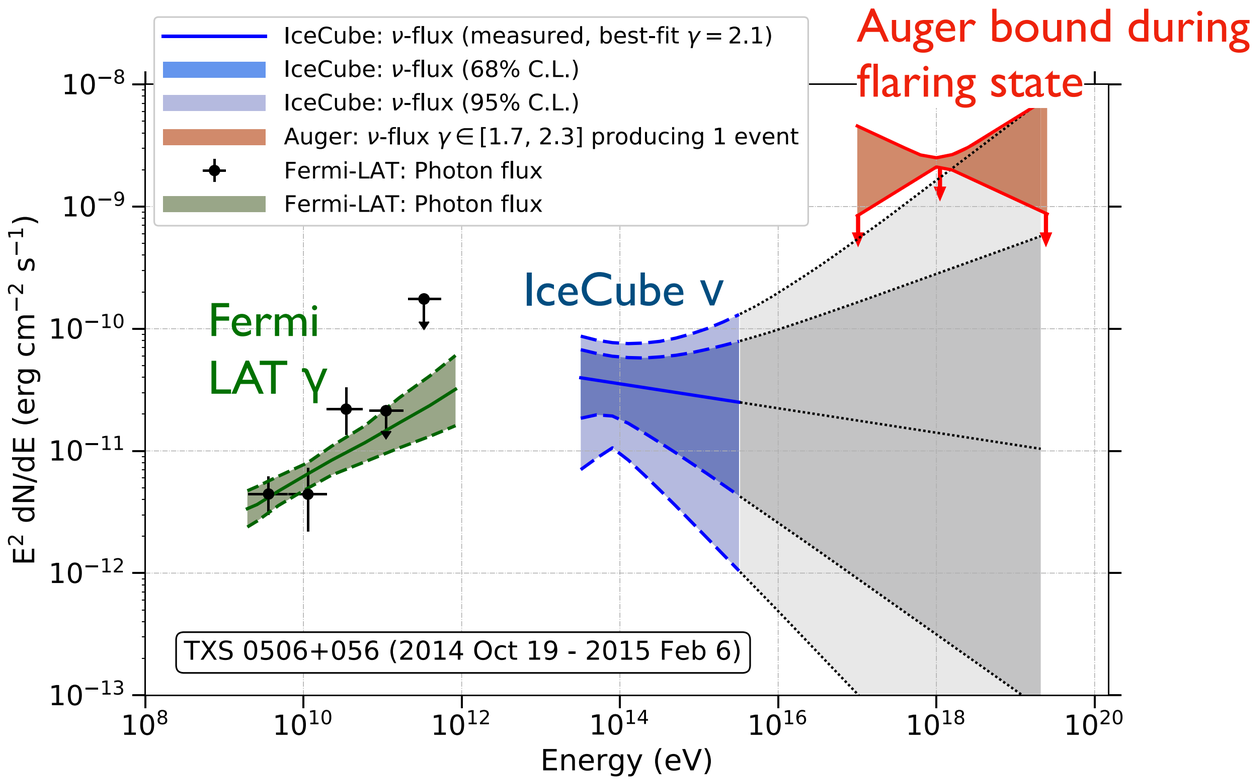
These are two ‚independent' 3.5σ observations
⇒ is TXS 0506-56 a neutrino source?

# 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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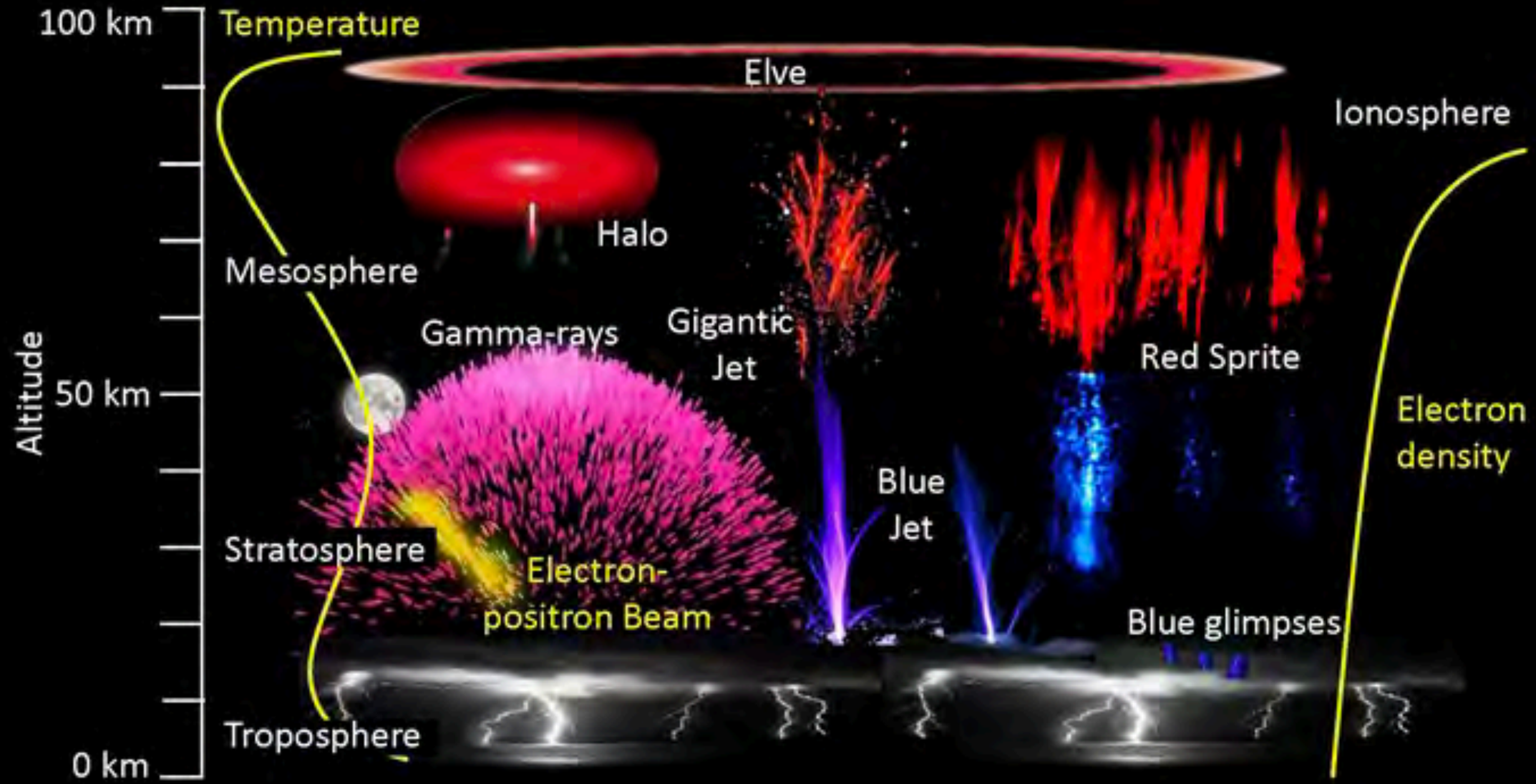
# Observation of Elves and Terrestrial Gamma-Ray Flashes

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



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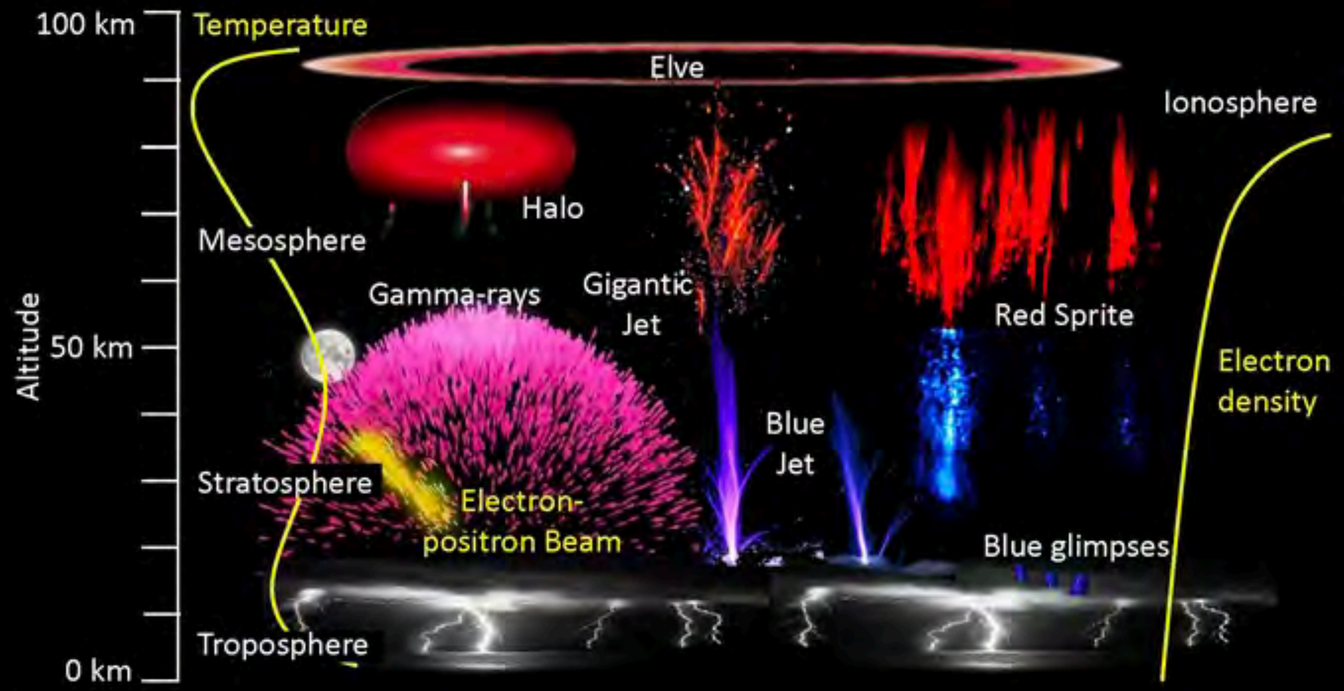
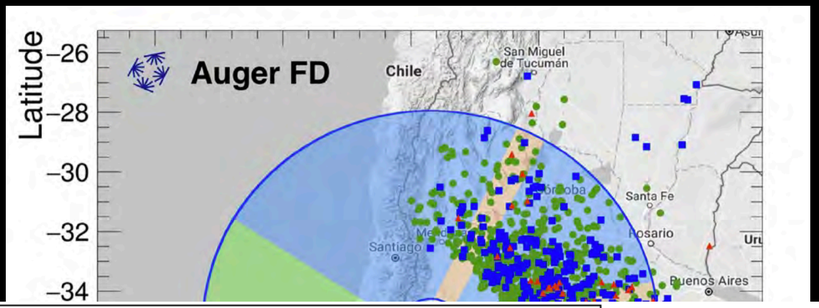
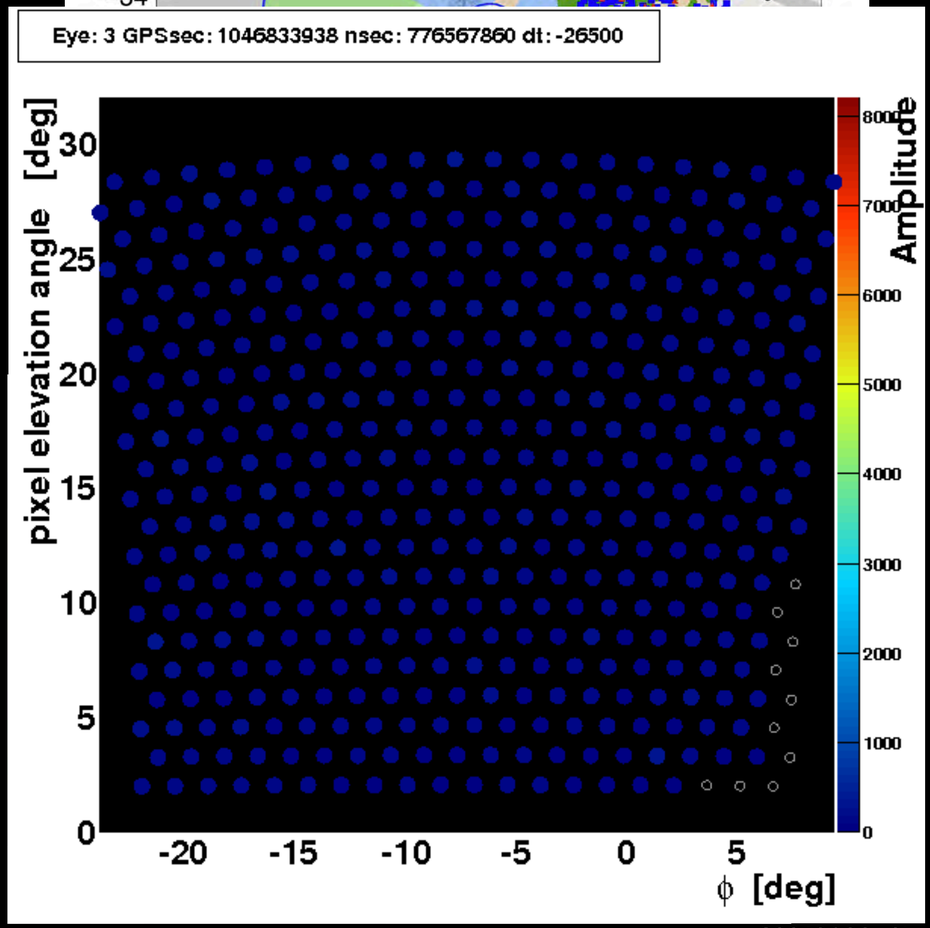
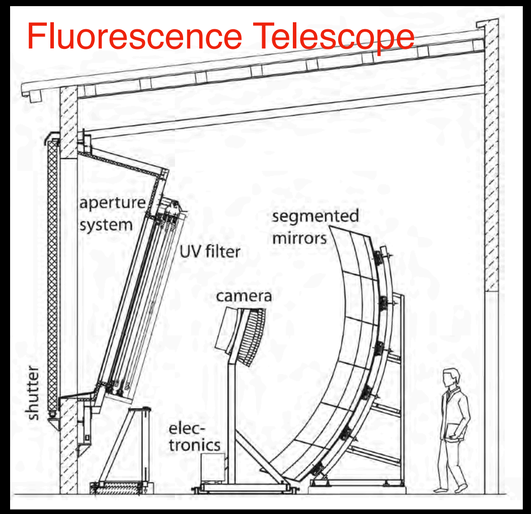
Auger Collaboration, Earth and Space Sciences 7 (2020) 1

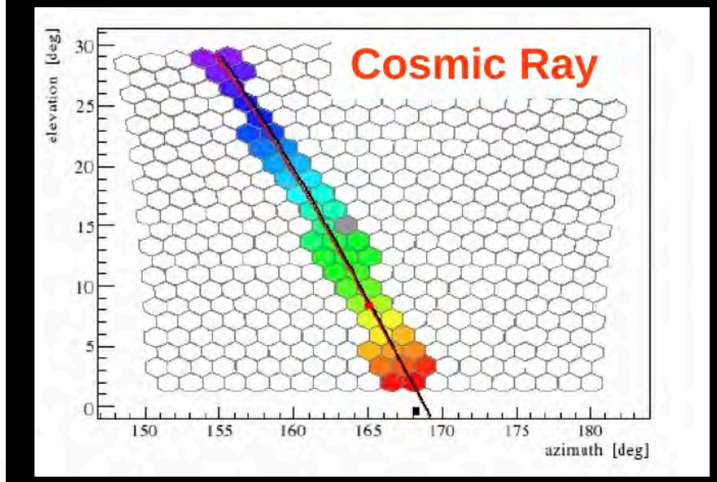



Elves seen in 800 km distance, near BsAs

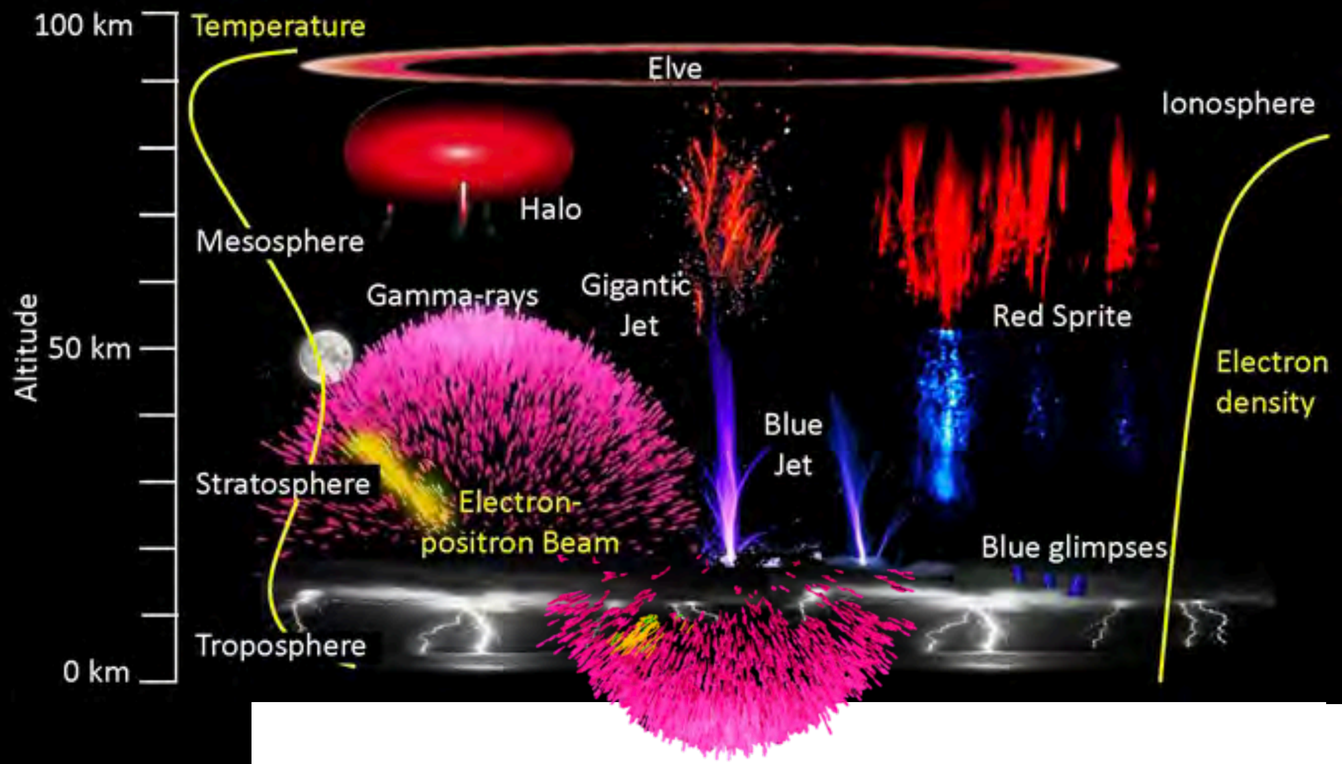


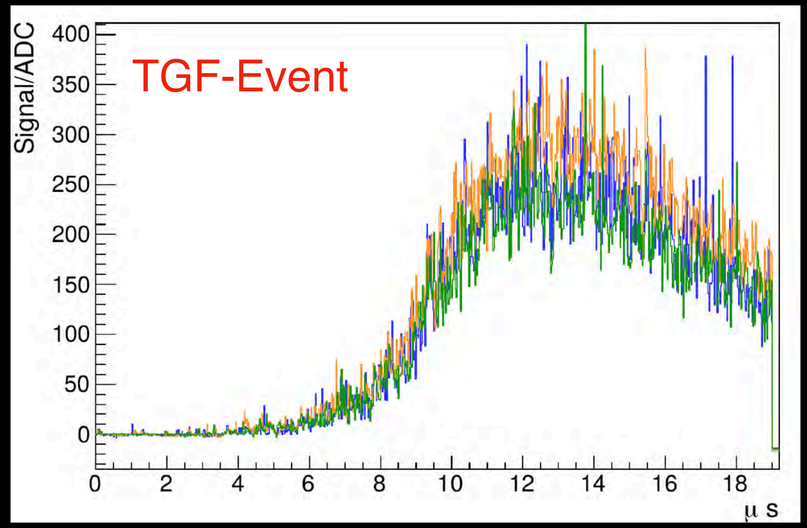



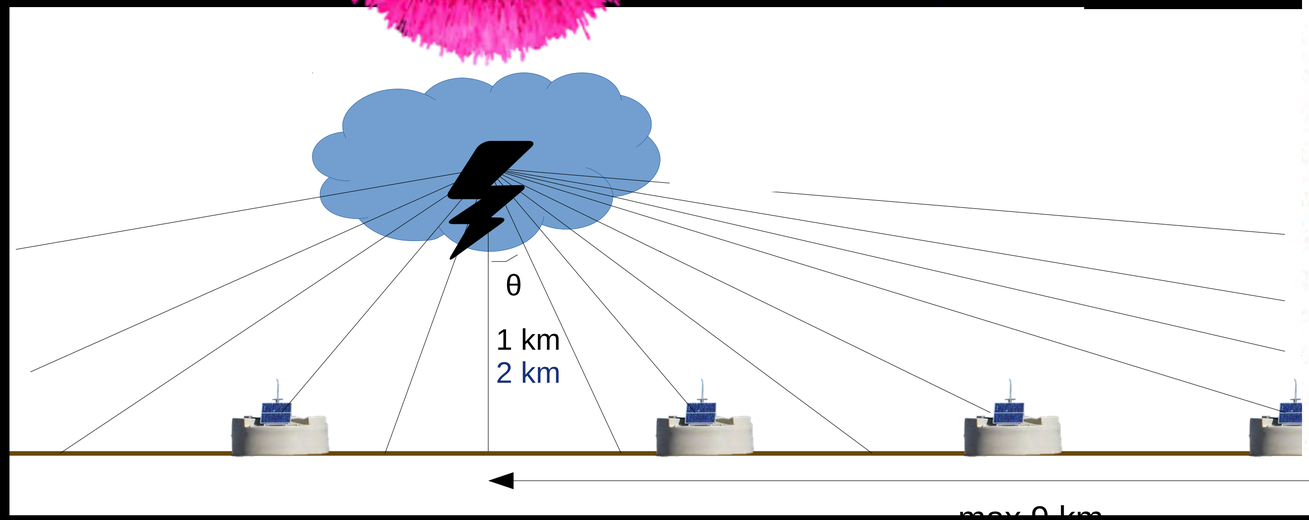



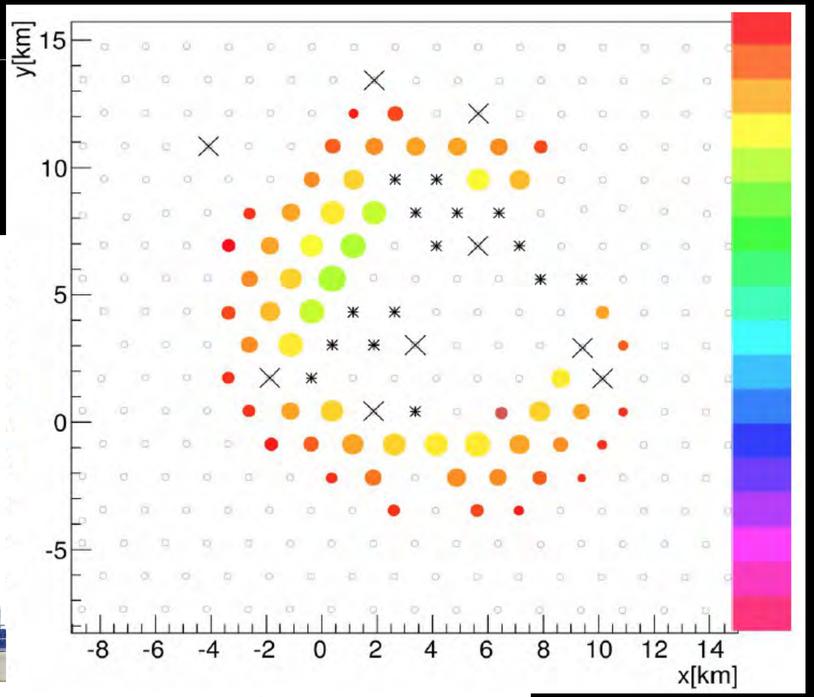



# Observation of Elves and Terrestrial Gamma-Ray Flashes

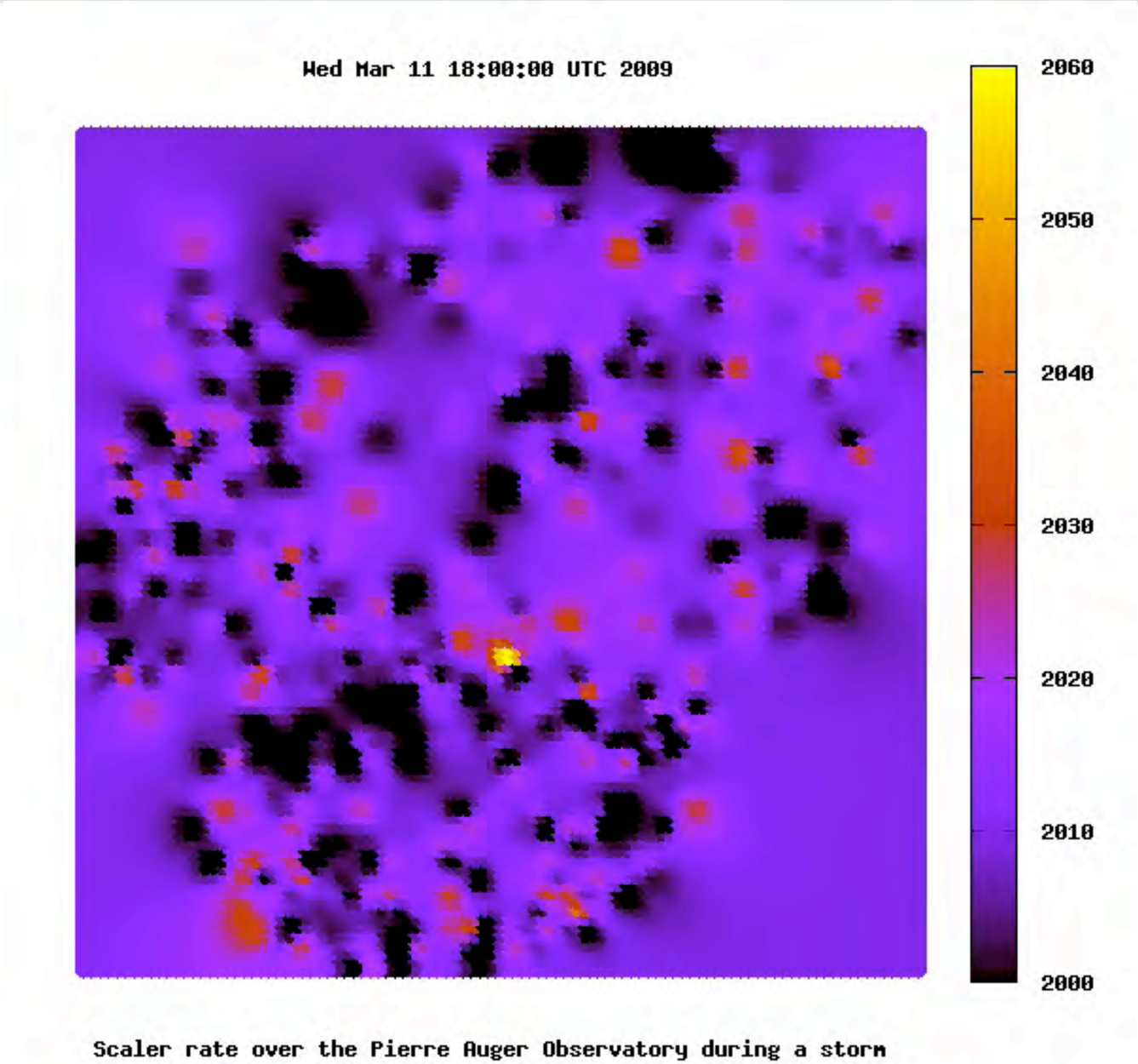


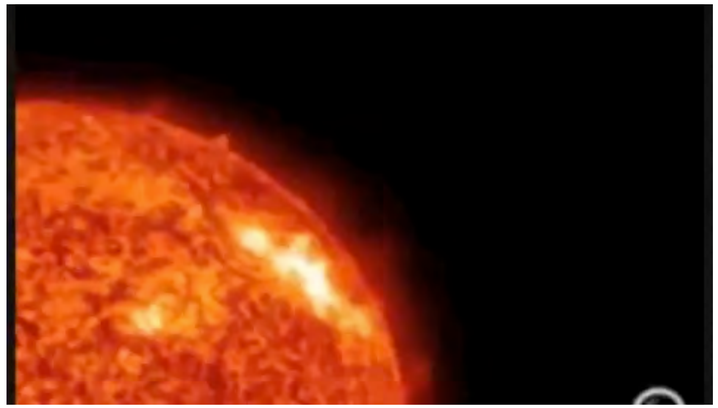



# Electromagnetic Storm in the Pampa




Scaler rate over the Pierre Auger Observatory during a storm

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



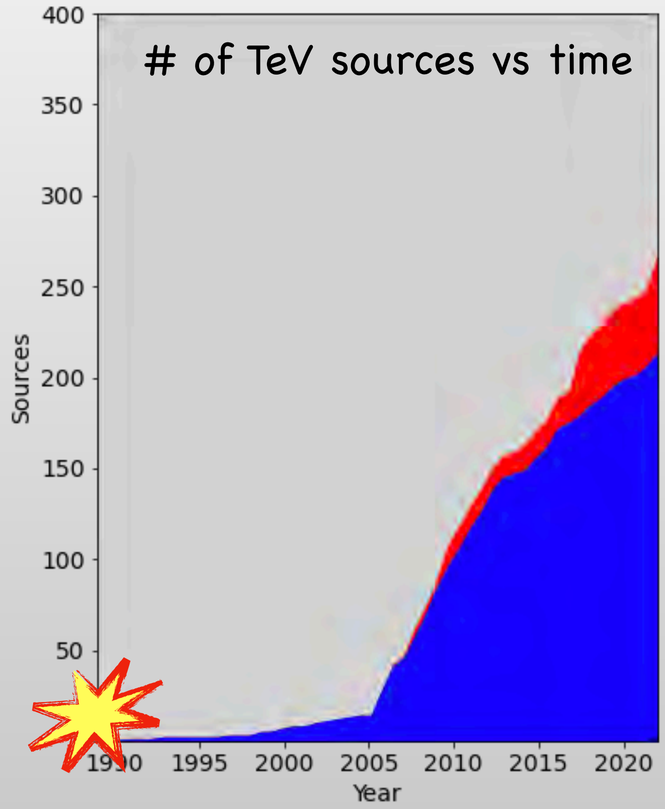
# Menu…

1) The Big Picture: A quick overview
2) Astrophysics and Detection of $E<10^{14}$ eV Galactic CRs (very brief)
3) Detection of $E>10^{14}$ eV: Basic air shower phenomenology
4) Basic concepts and technologies of EAS experiments
5) Little bit of particle physics (hands on exercise)
6) Transition from galactic to extragalactic CRs
7) The end of the CR-spectrum: $E_{max}$ of extragalactic accelerators?
8) Anisotropies: Hunting the UHECR sources
9) Multi-Messenger: Some examples
10) Related non-CR opportunities
11) Conclusions, future challenges and prospects

# Resumé: What did we learn… TEV GAMMA-ASTRONOMY

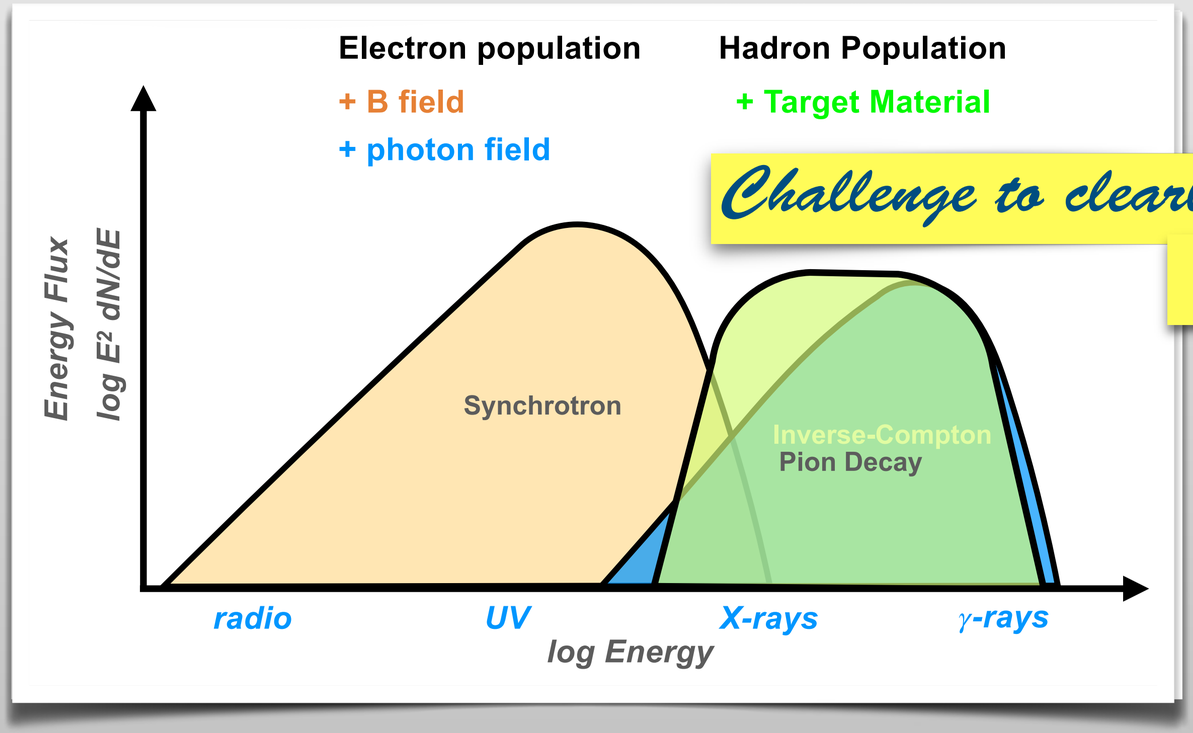
The last 20 years have been a series of important discoveries

*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…



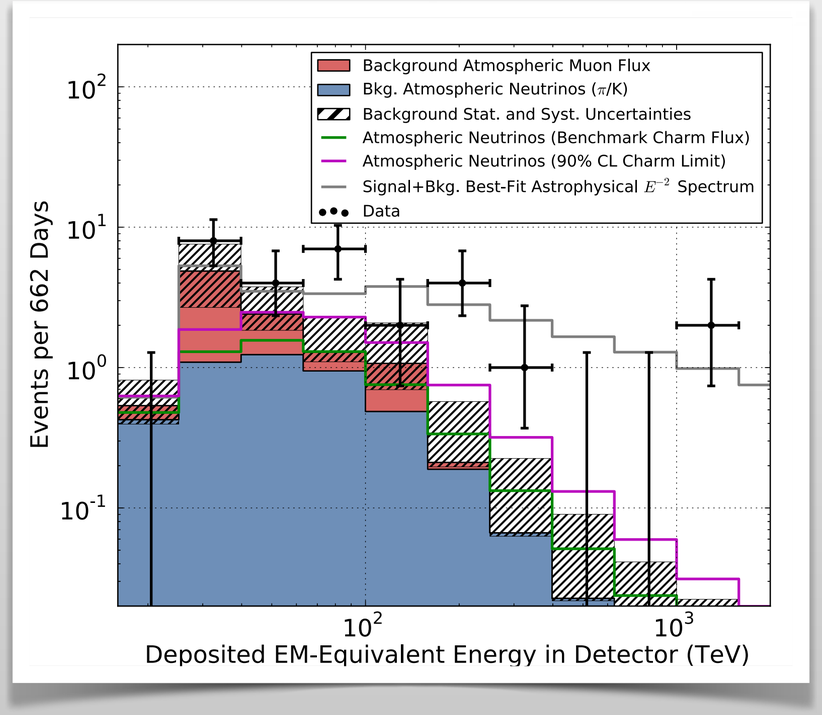

*Challenge to clearly identify pion decay over IC*

# Resumé: What did we learn...

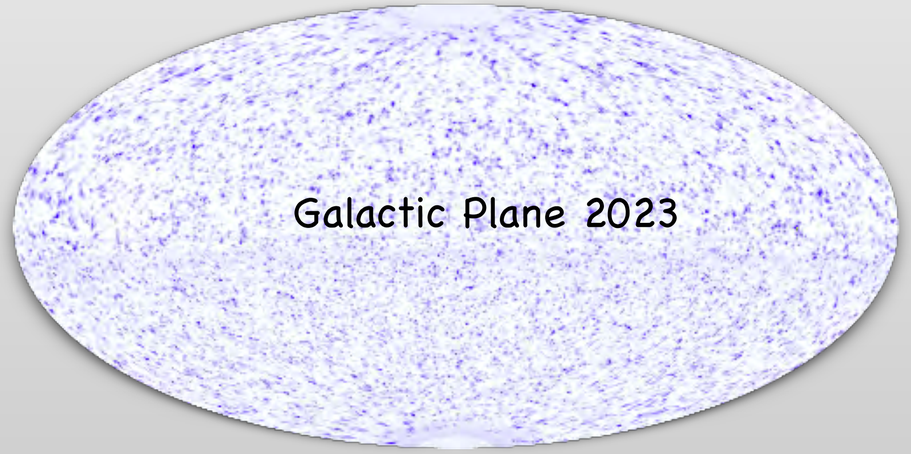
The last 20 years have been a series of important discoveries

*this list is very subjective and selective...*

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

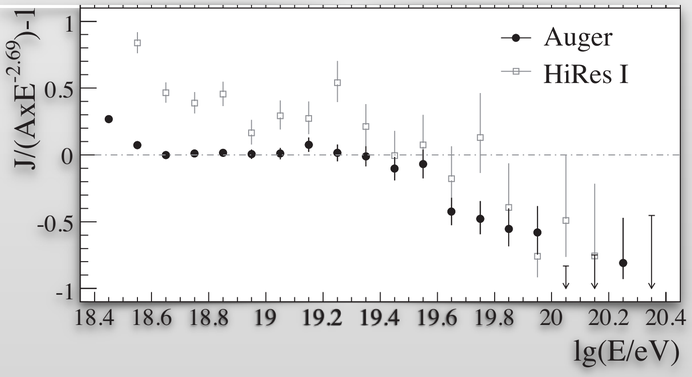
⇒ Need more data

# Resumé: What did we learn... UHE COSMIC RAYS

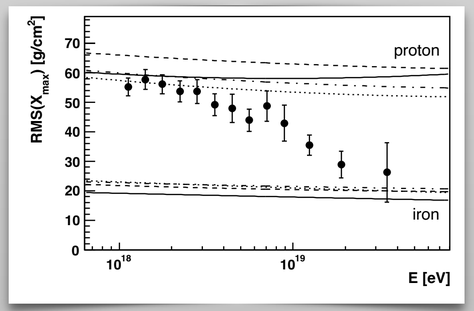
The last 20 years have been a series of important discoveries

*this list is very subjective and selective...*

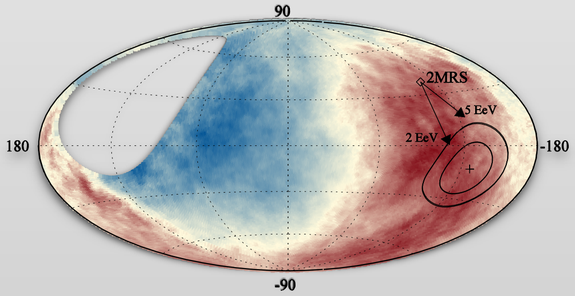
2008: First detection of Flux suppression
by Auger and HiRes
PRL 101 (2008)




2010: Increasing Mass composition
PRL 104 (2010)




2017: Establishing extragalactic
UHECR
Science 357 (2017)

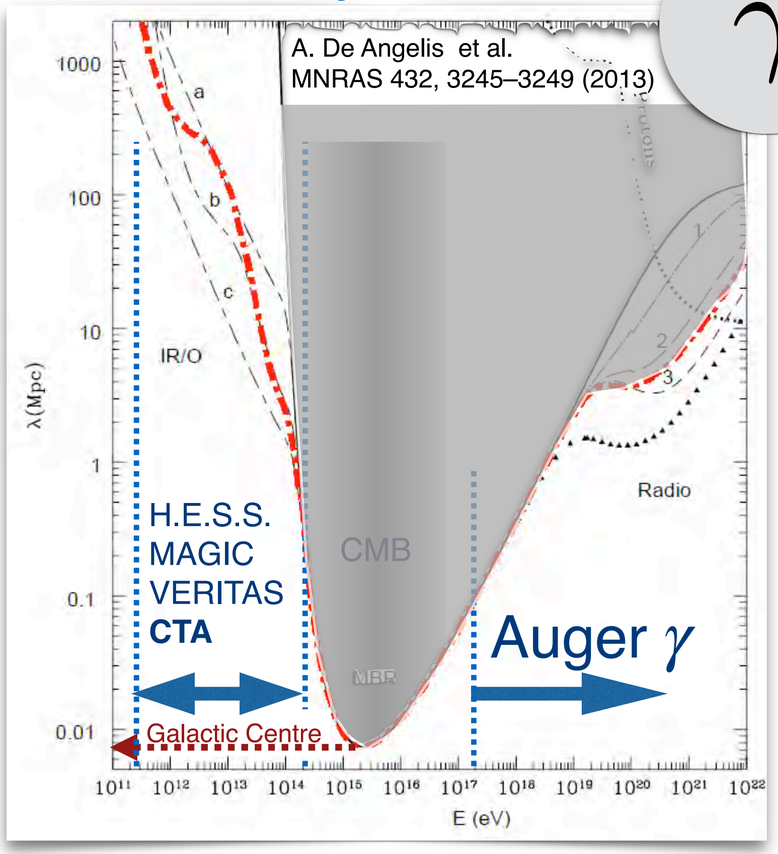



Waiting for 5σ source detection, yet (only 4.5σ's so far)

⇒ challenge:
proton-astronomy

# No „Best“ Messenger

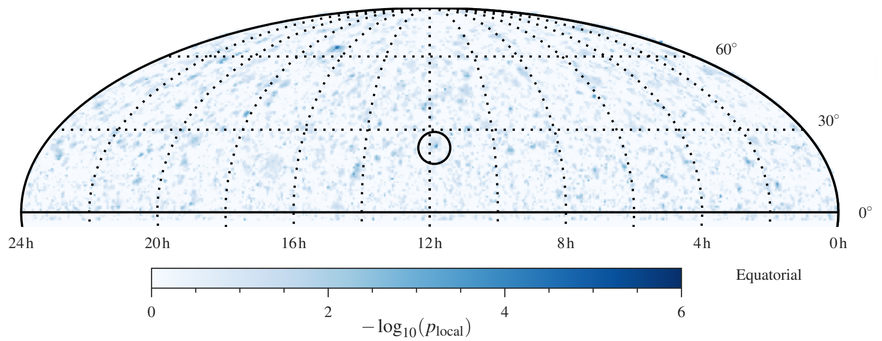
## γ-ray horizon




⊕ 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)

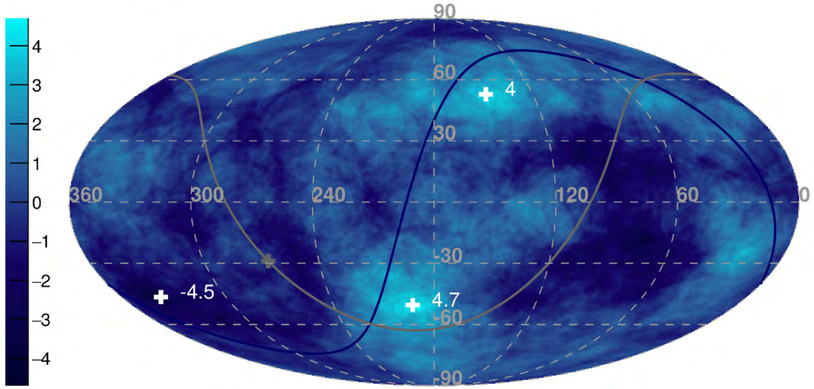



⊕ straight lines
⊕ clean hadronic probe
⊖ Horizon = Hubble ⇒ isotropic
⊖ (non bursting) point sources difficult

## UHECR Sky
above 40 EeV

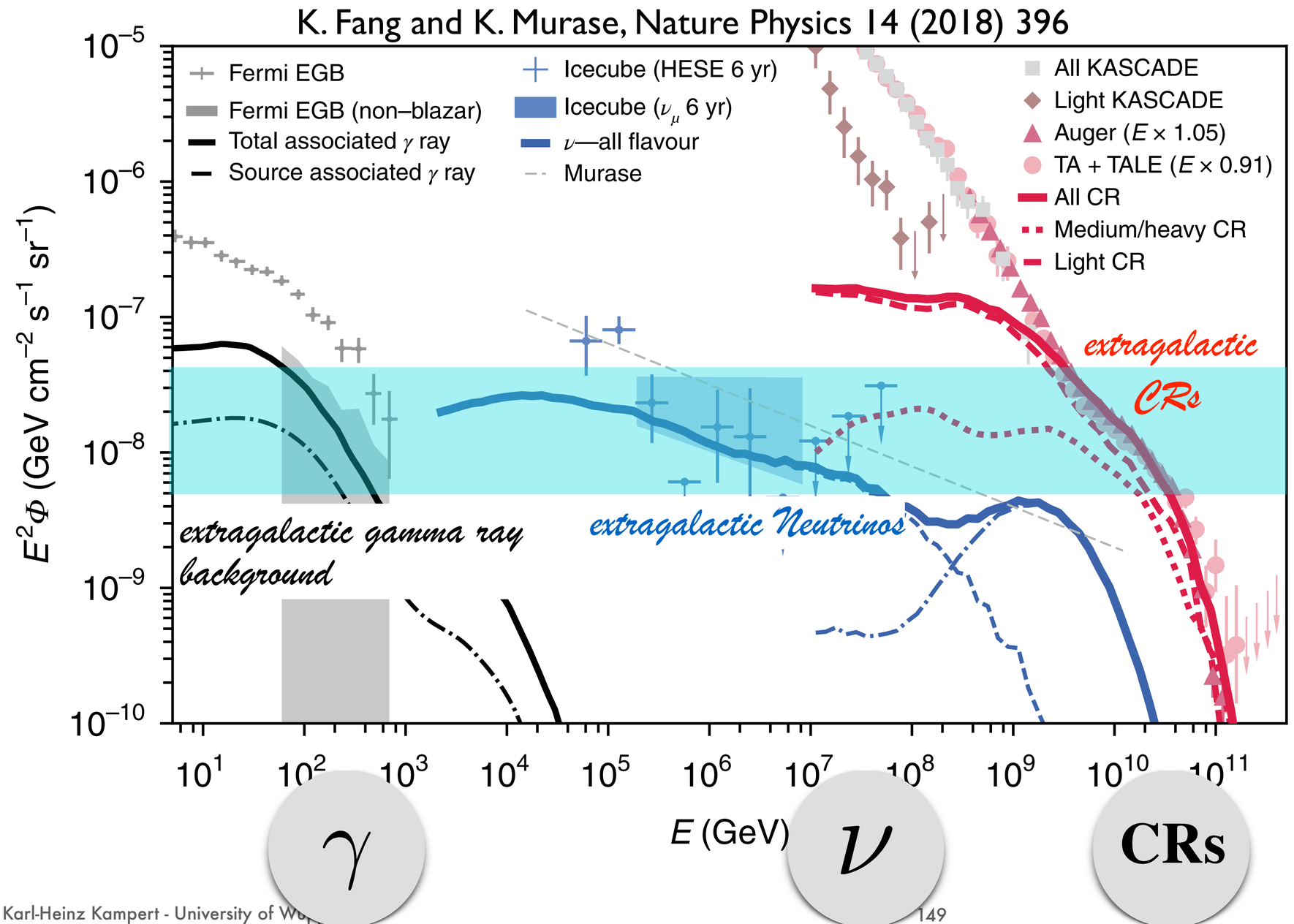
Auger & TA Working Group at ICRC 2019

**Local σ($E_{\text{Auger/TA}}$ > 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

# Cosmic Coincidence or Grand Unified Picture ?

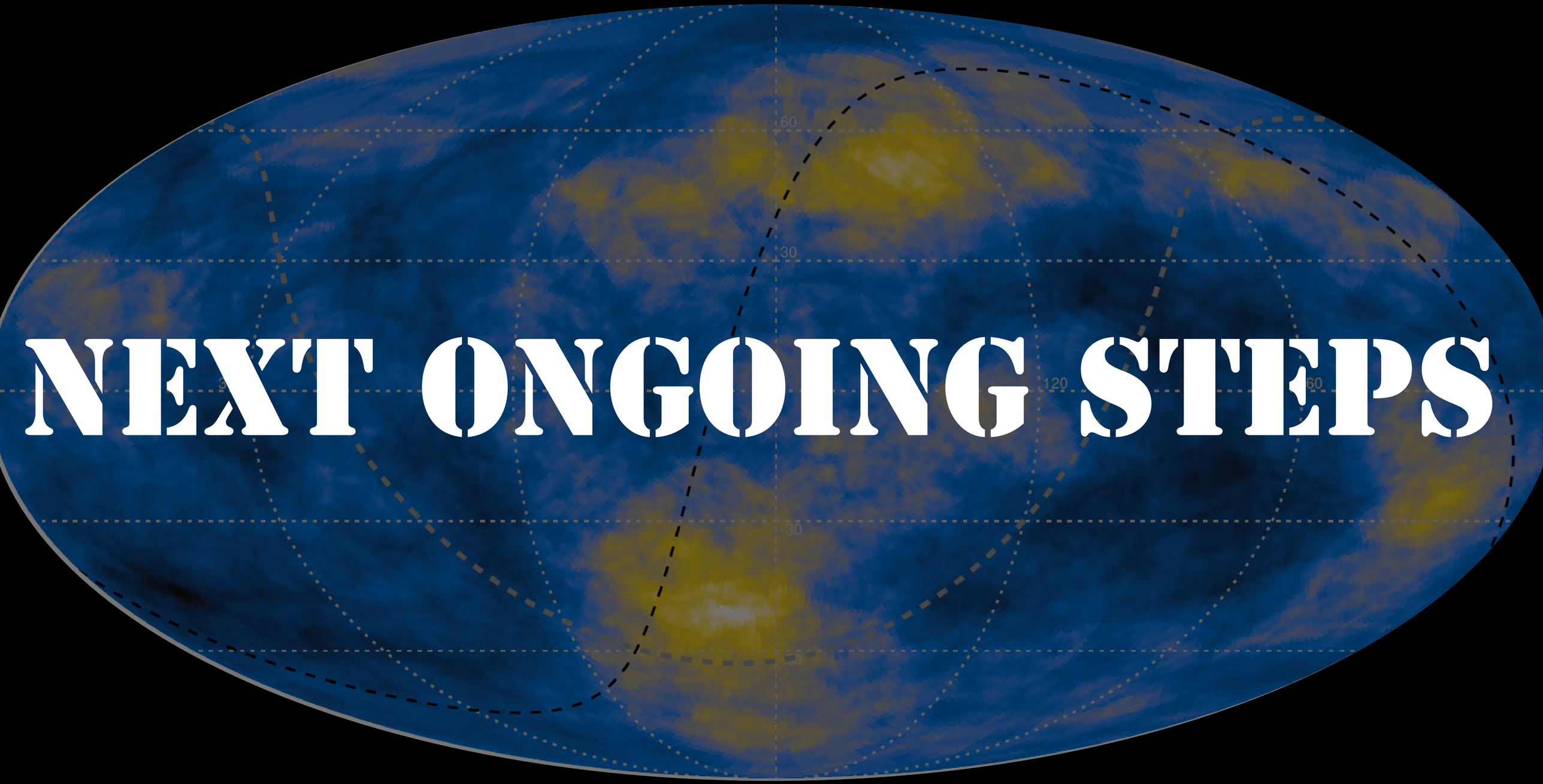



10 orders of magnitude in energy, but

$E^2 \cdot \Phi$ is about the same

→ energy generation rates per decade in E are the same

Suggests again a common / related origin




# NEXT ONGOING STEPS

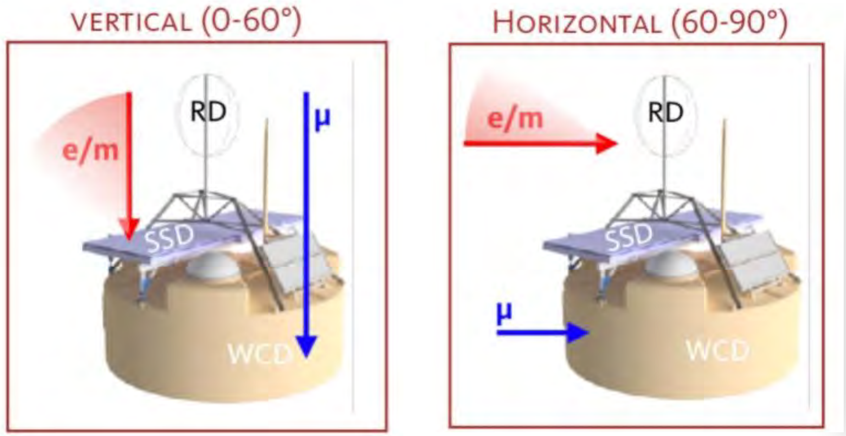
# UHECR: Ongoing ...

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

→ increasing size from 700 km² to 2800 km² (focussed to higher energies)

Auger upgraded to AugerPrime (start operation 2023)

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



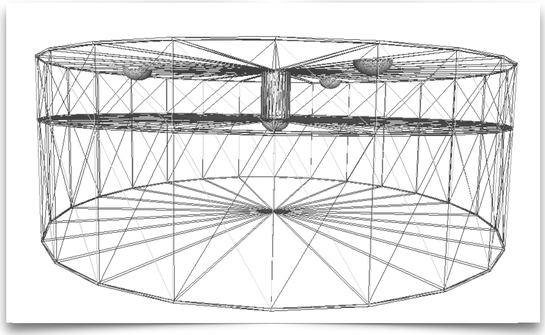

# Next...: Global Cosmic ray ObServatory (GCOS)


Distributed UHECR Observatory covering > 60,000 km$^2$

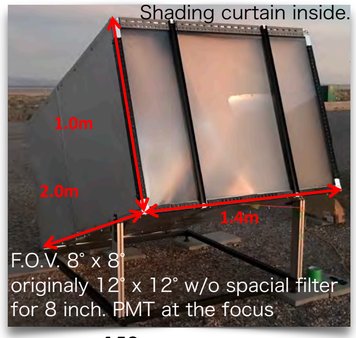
Several highly attended workshops were conducted for conceptual design, targeted at

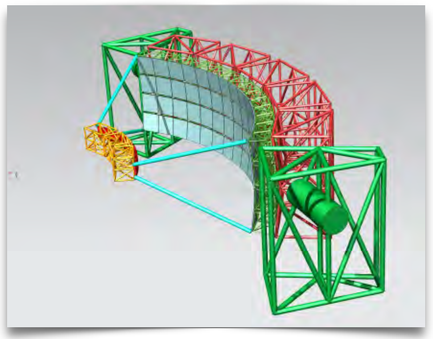
- full efficiency at 10 EeV
- energy resolution <10%, muon resolution <10%
- Xmax better than 30 g/cm$^2$
- angular resolution ~1°
- strong MM capabilities with photons and neutrinos

⇒ source correlations at 5σ within one year of operation



segmented Water Cherenkov Detectors

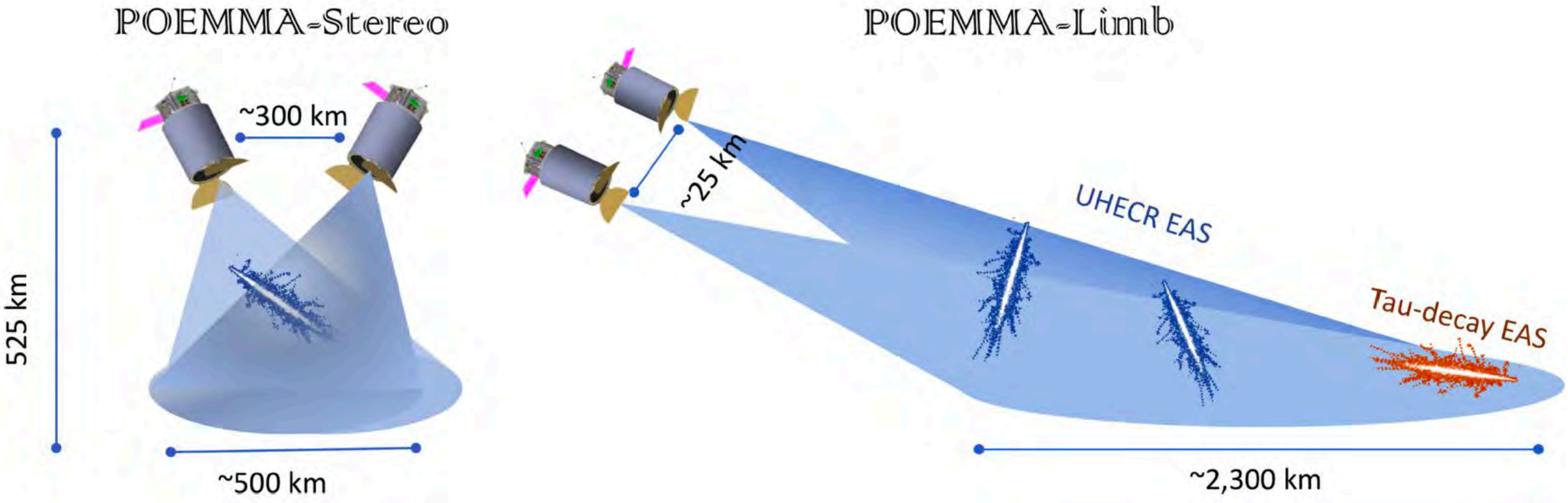


concepts for simplified fluorescence telescopes

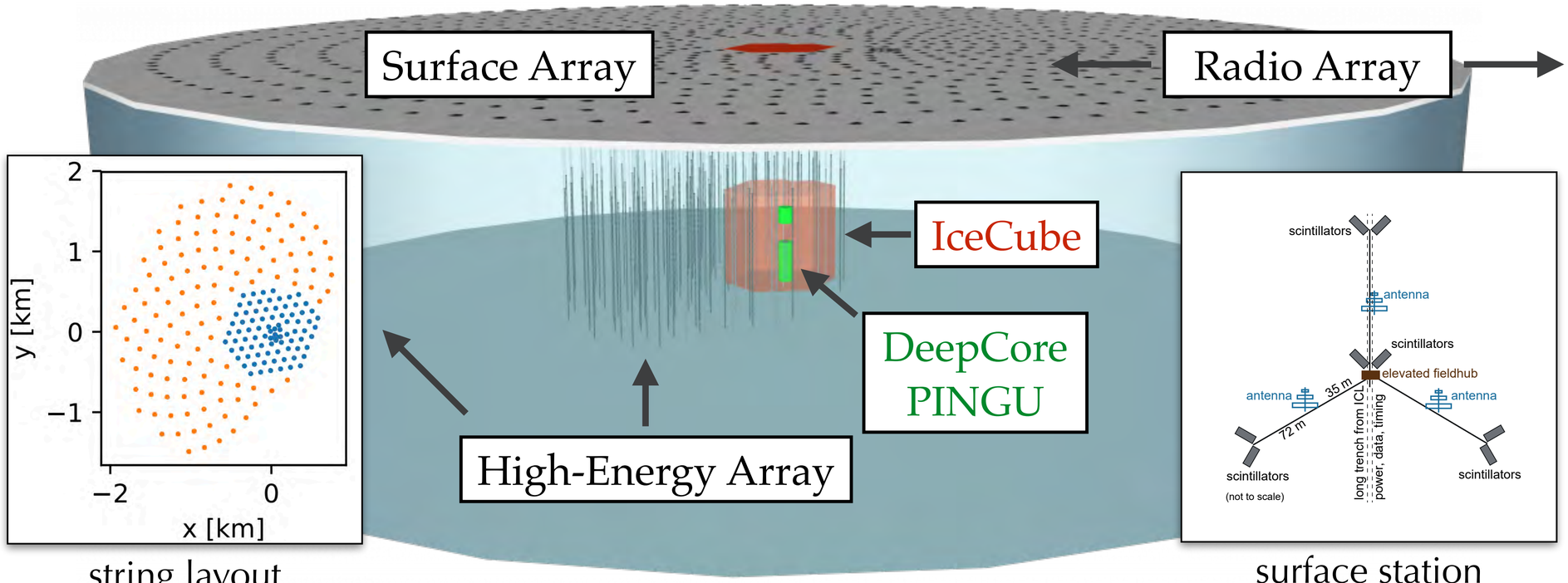
# POEMMA: Stereo Fluorescence Obs. from Space

- 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

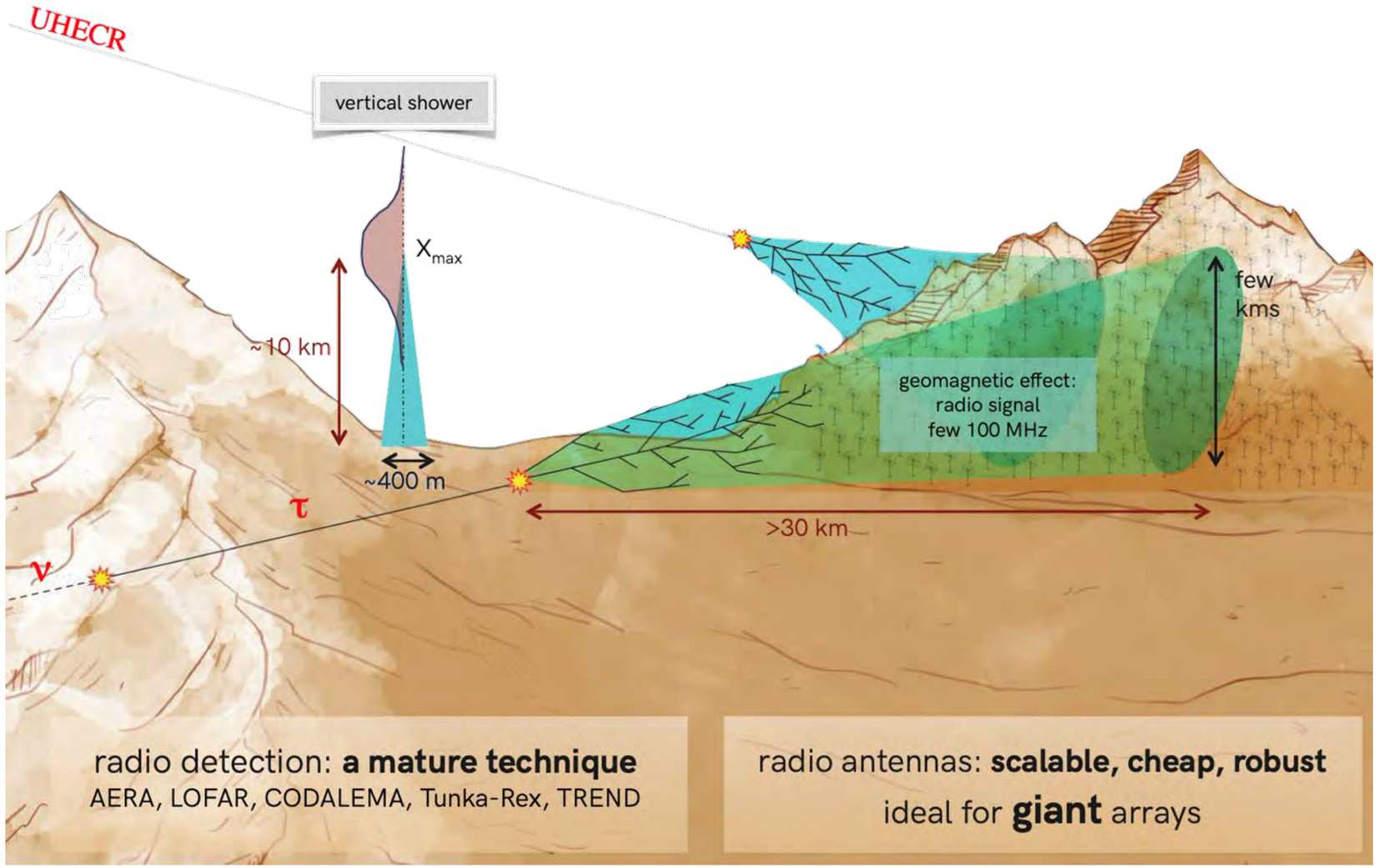
surface station

Markus Ahlers

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

# 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:

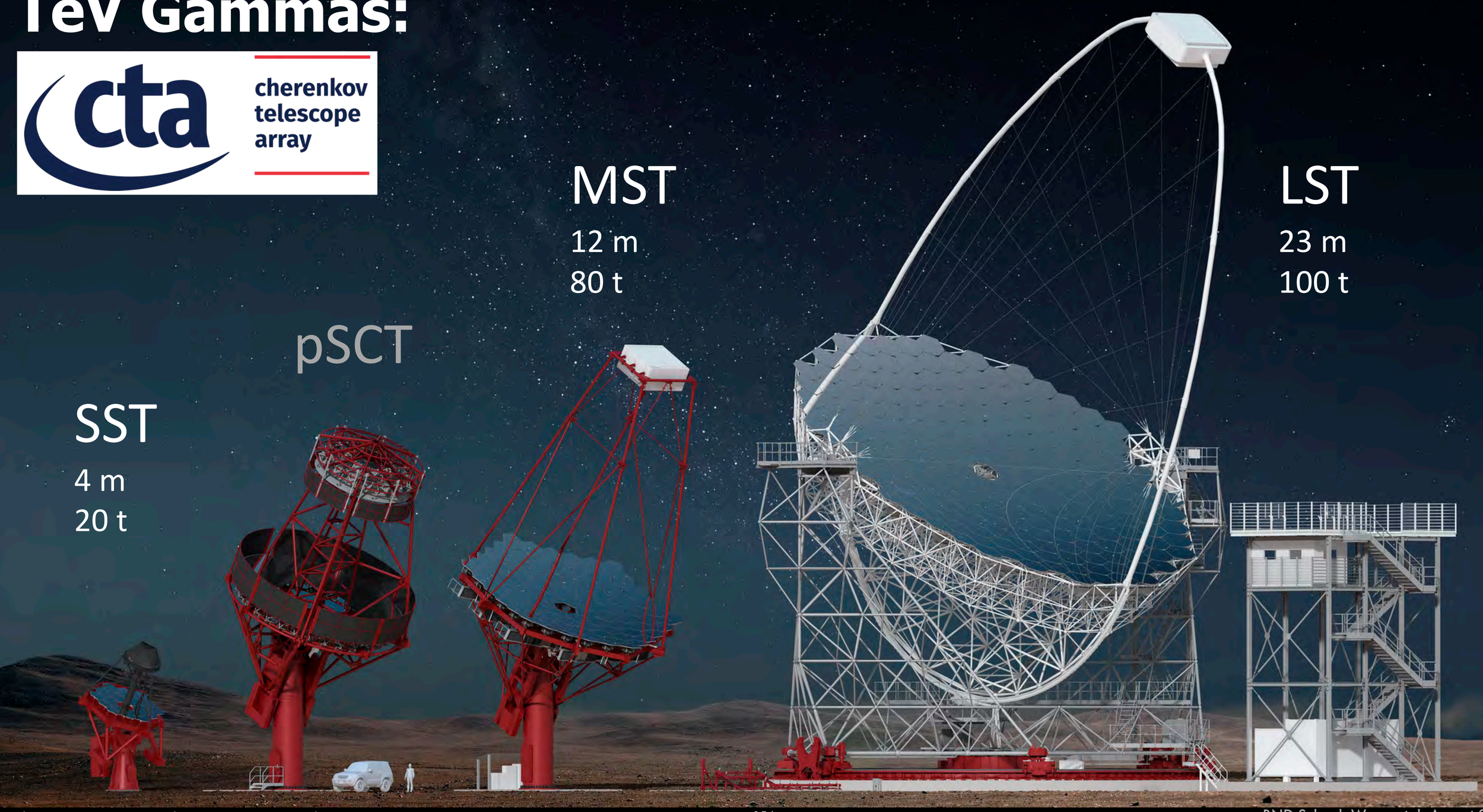
cherenkov telescope array

MST
12 m
80 t

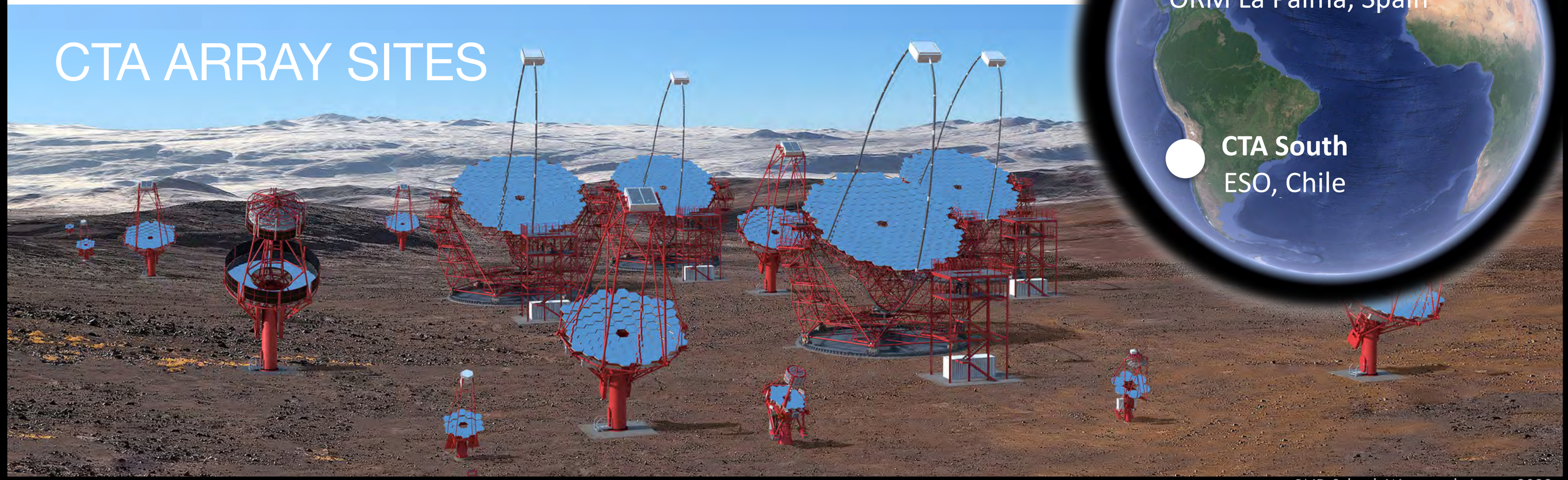
LST
23 m
100 t

pSCT

SST
4 m
20 t

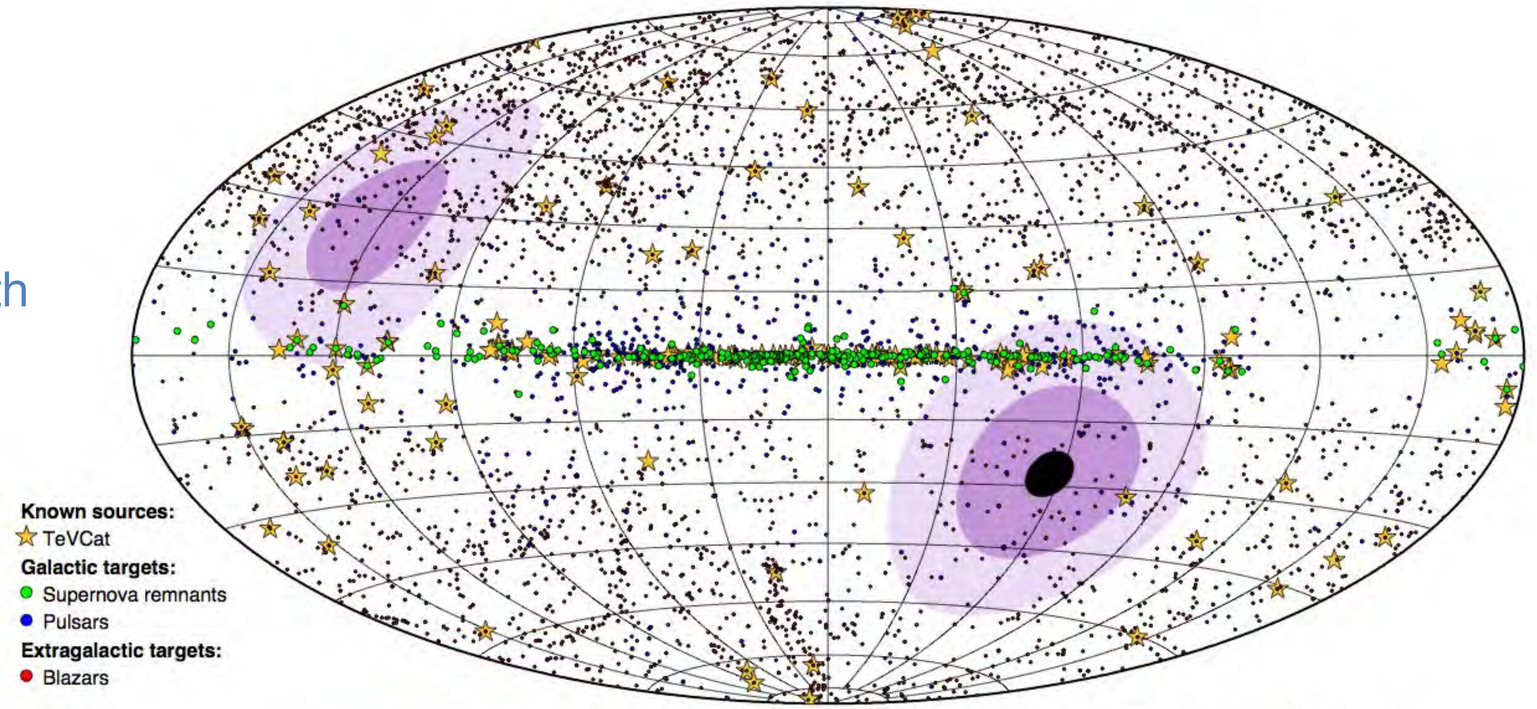


# CTA ARRAY SITES



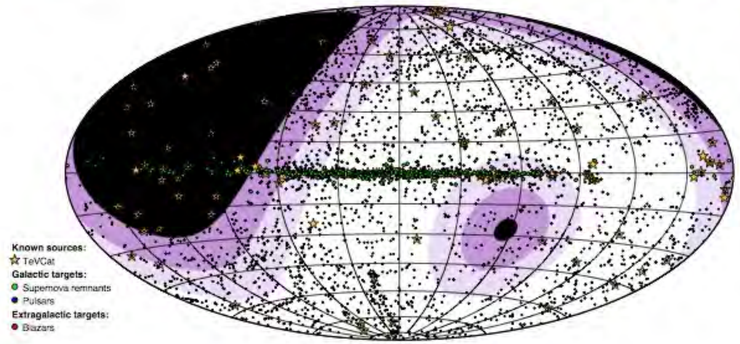
# DESIGN DRIVER: FULL-SKY COVERAGE

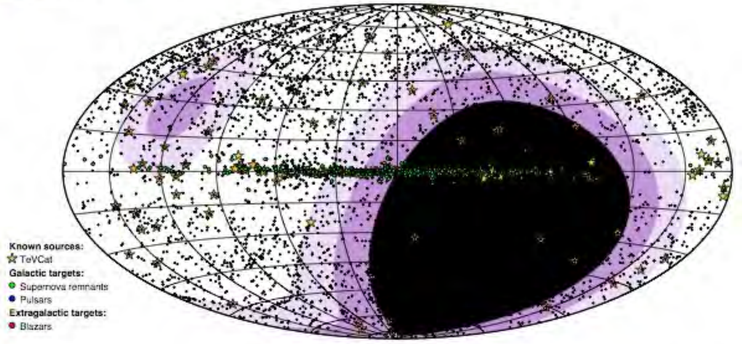
North+South




>60° zenith
45°-60°
30°-45°

South




North

# MORE EXCITING TIMES AHEAD OF YOU