The role of UHECR in Multi-Messenger Physics

during this decade and the next

BERGISCHE UNIVERSITÄT WUPPERTAL

Karl-Heinz Kampert
Bergische Universität Wuppertal

APPEC

AHEAD 2020

The role of UHECR in Multi-Messenger Physics

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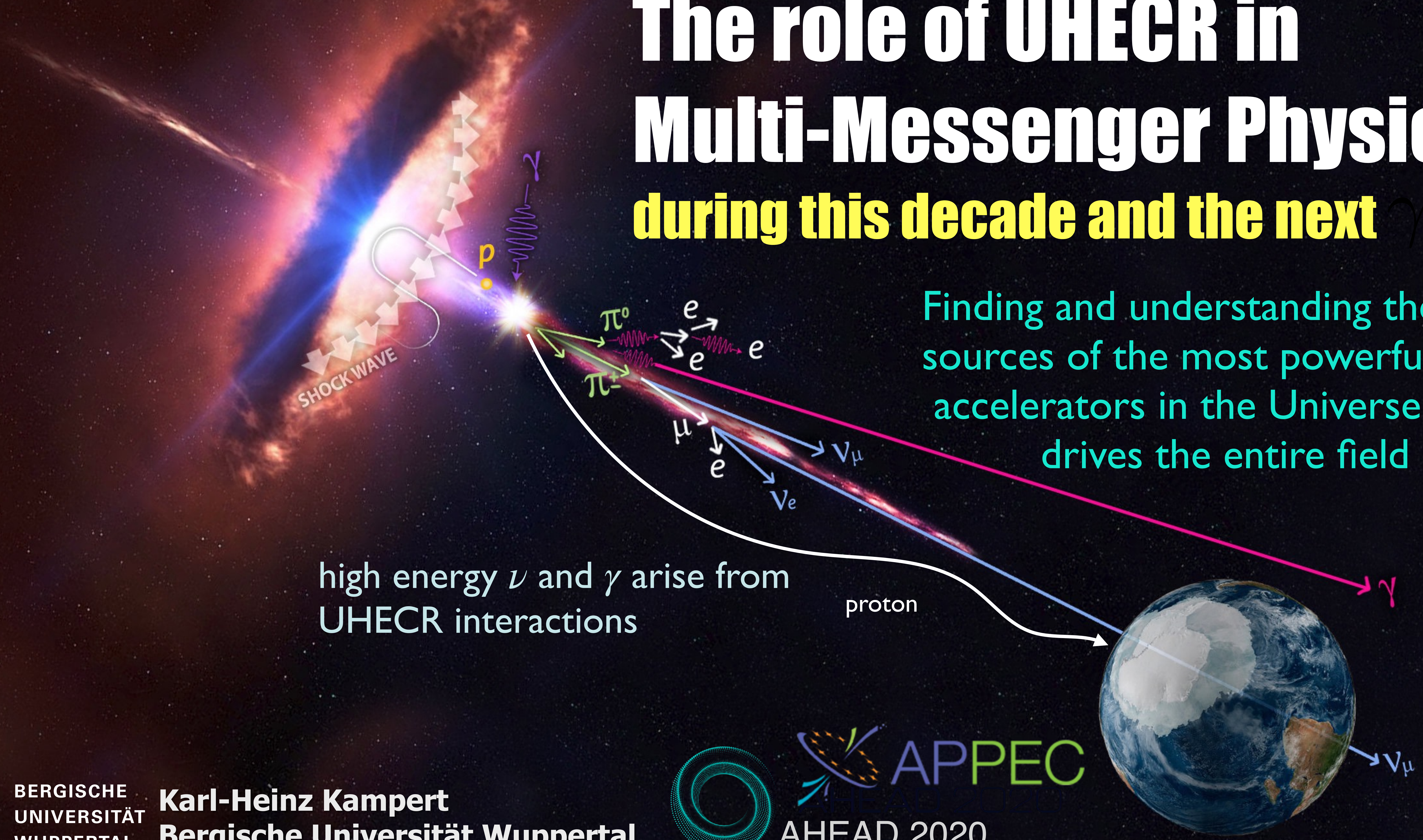
Finding and understanding the sources of the most powerful accelerators in the Universe drives the entire field !



high energy ν and γ arise from UHECR interactions

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direction, time,
energy
direction,
particle type,
energy (time)
CR
ν
direction, time,
waveform
GW
γ
direction, time,
energy


direction, time, energy
direction, particle type, energy (time)
CR
ν
Note, by construction, a CR observatory is in general also a gamma, neutrino, and neutron-observatory
direction, time, waveform
GW
γ
Moreover, MM physics is more than studying transient events (ToOs)
direction, time, energy

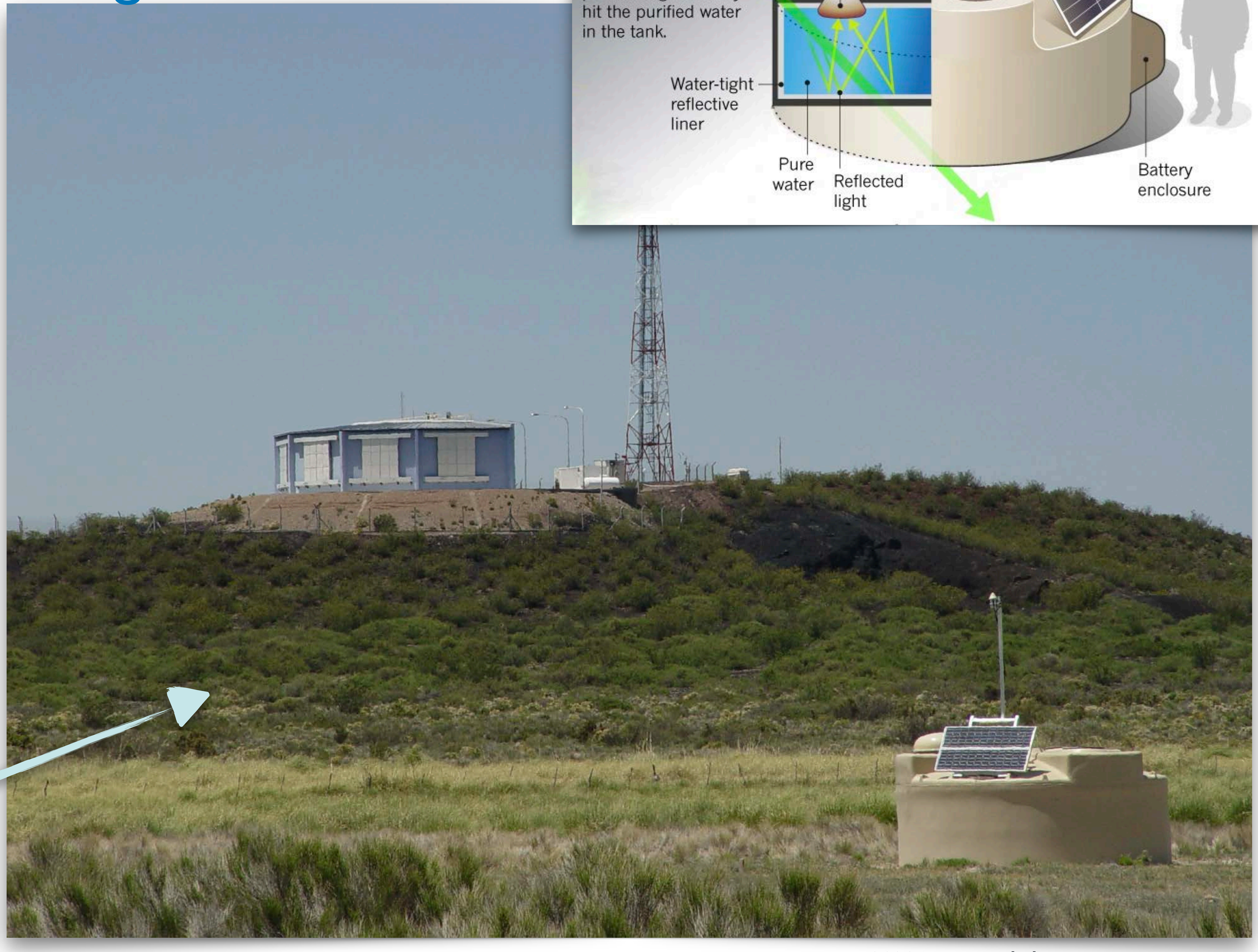
UHECR Observatories

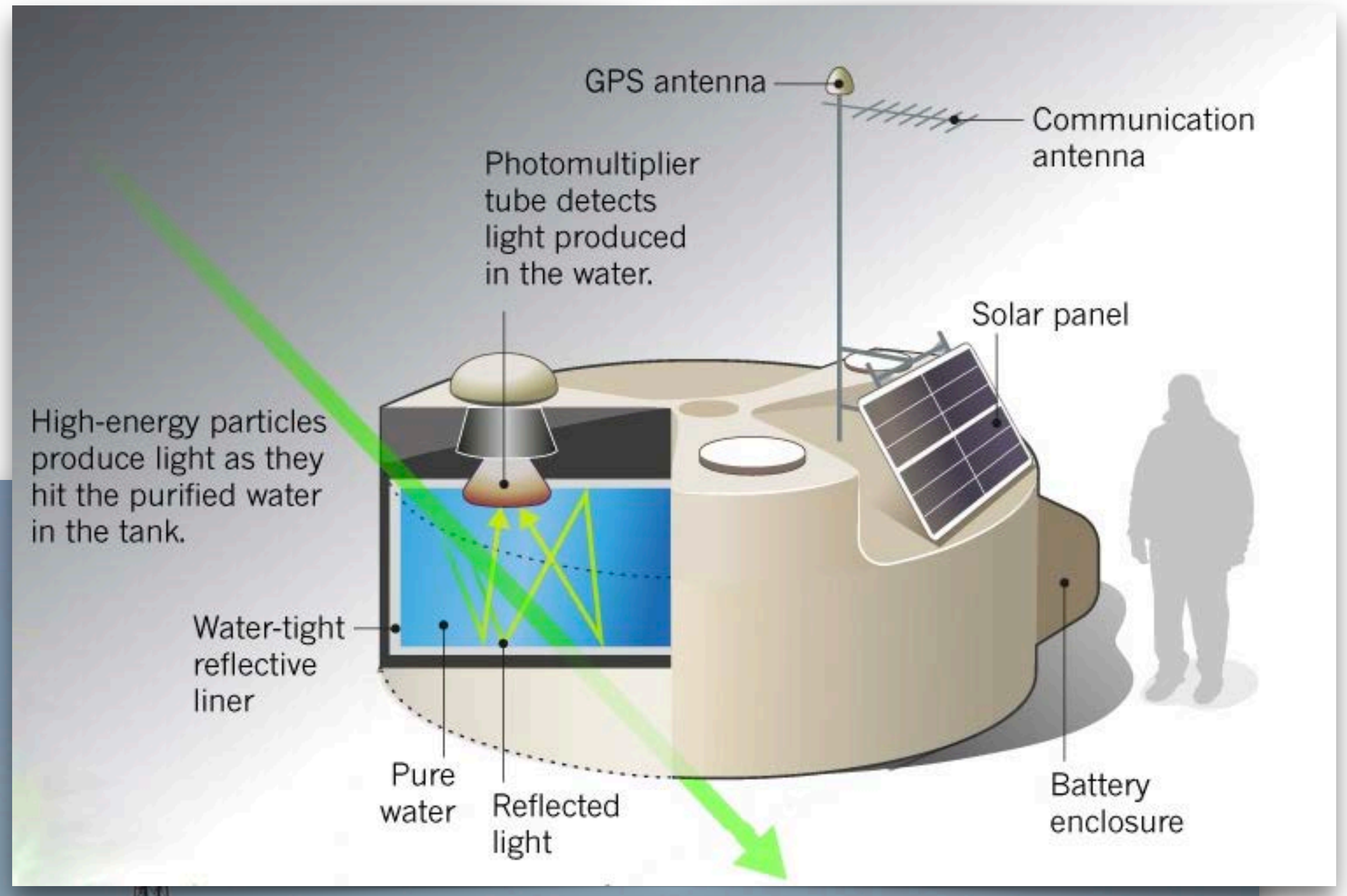
Telescope Array

Utah (USA), 700 km^2

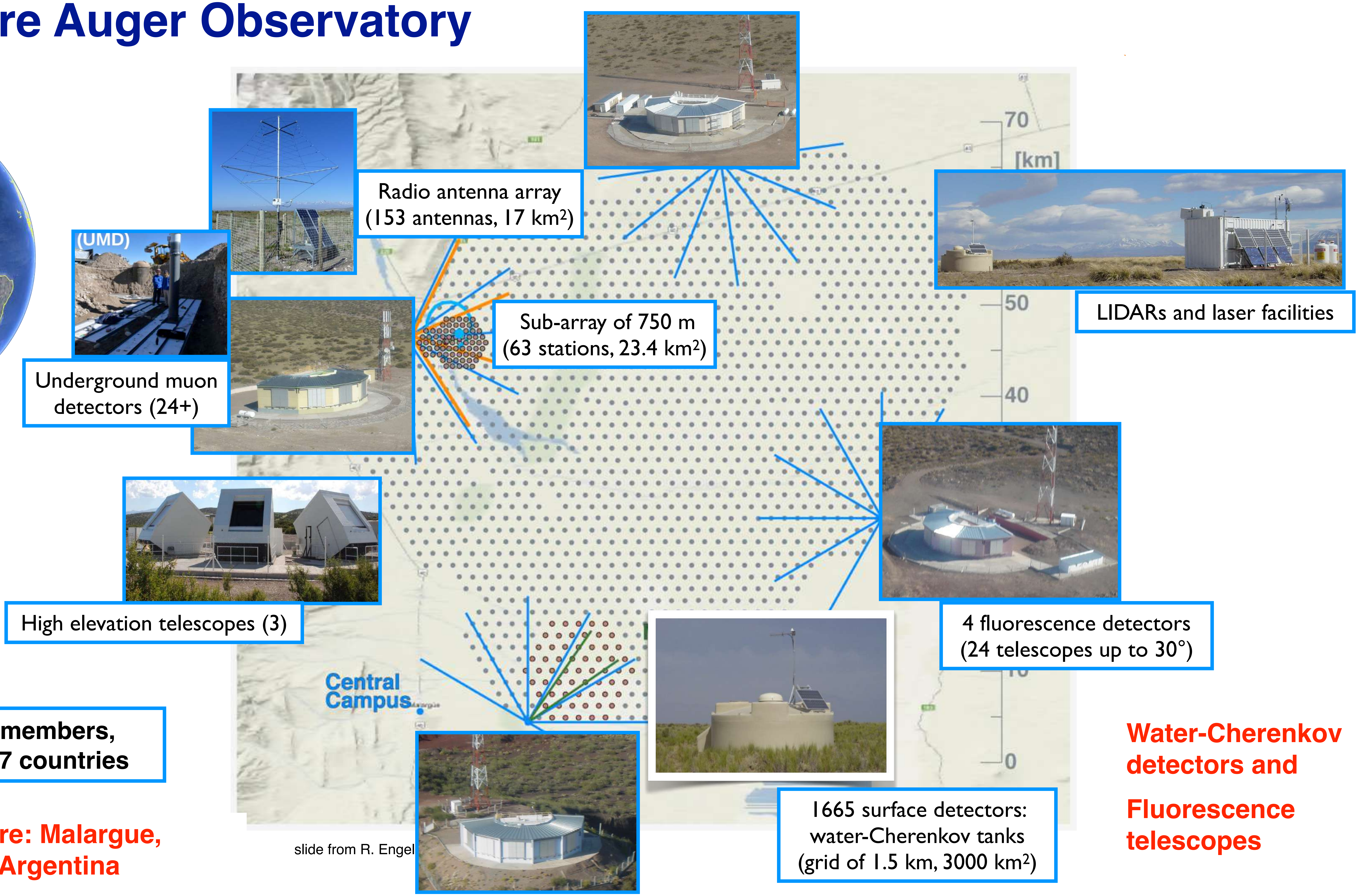
Pierre Auger Observatory

Argentina, 3000 km^2





The Pierre Auger Observatory



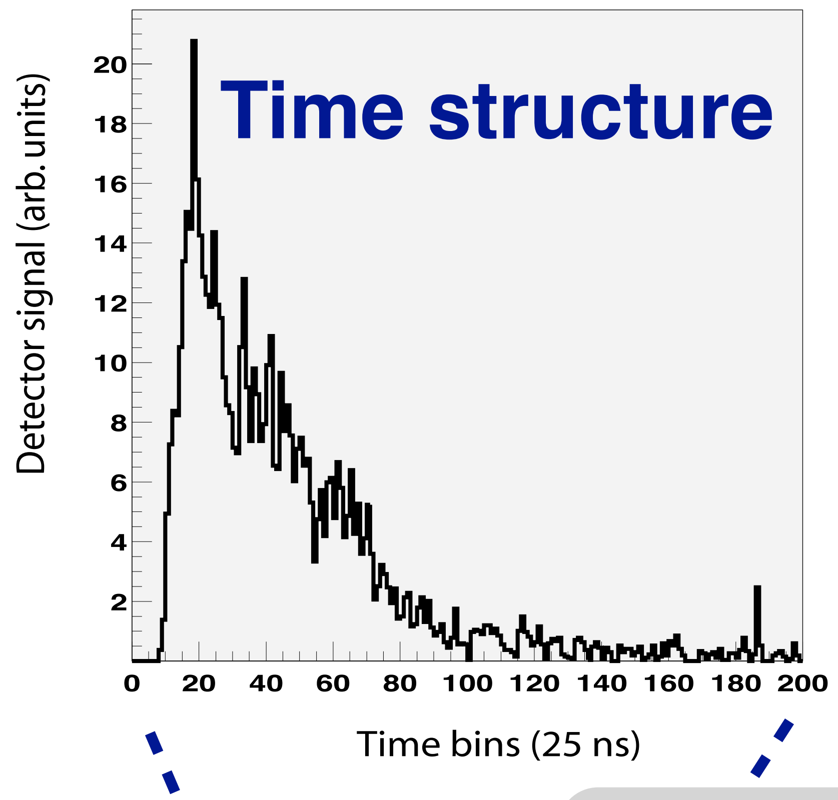
More than 400 members, 98 institutes, 17 countries

Southern hemisphere: Malargue, Province Mendoza, Argentina

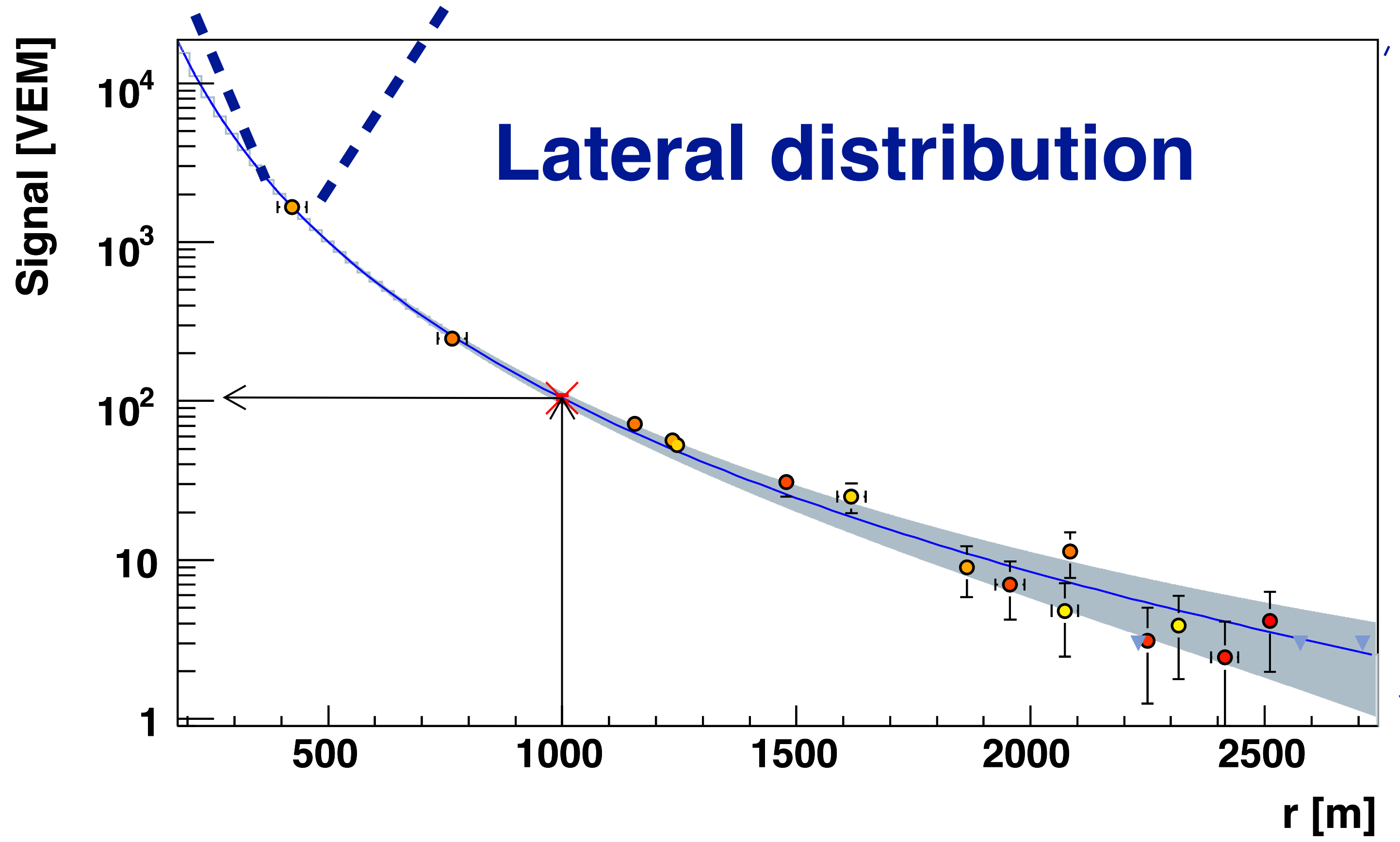
Water-Cherenkov detectors and

Fluorescence telescopes

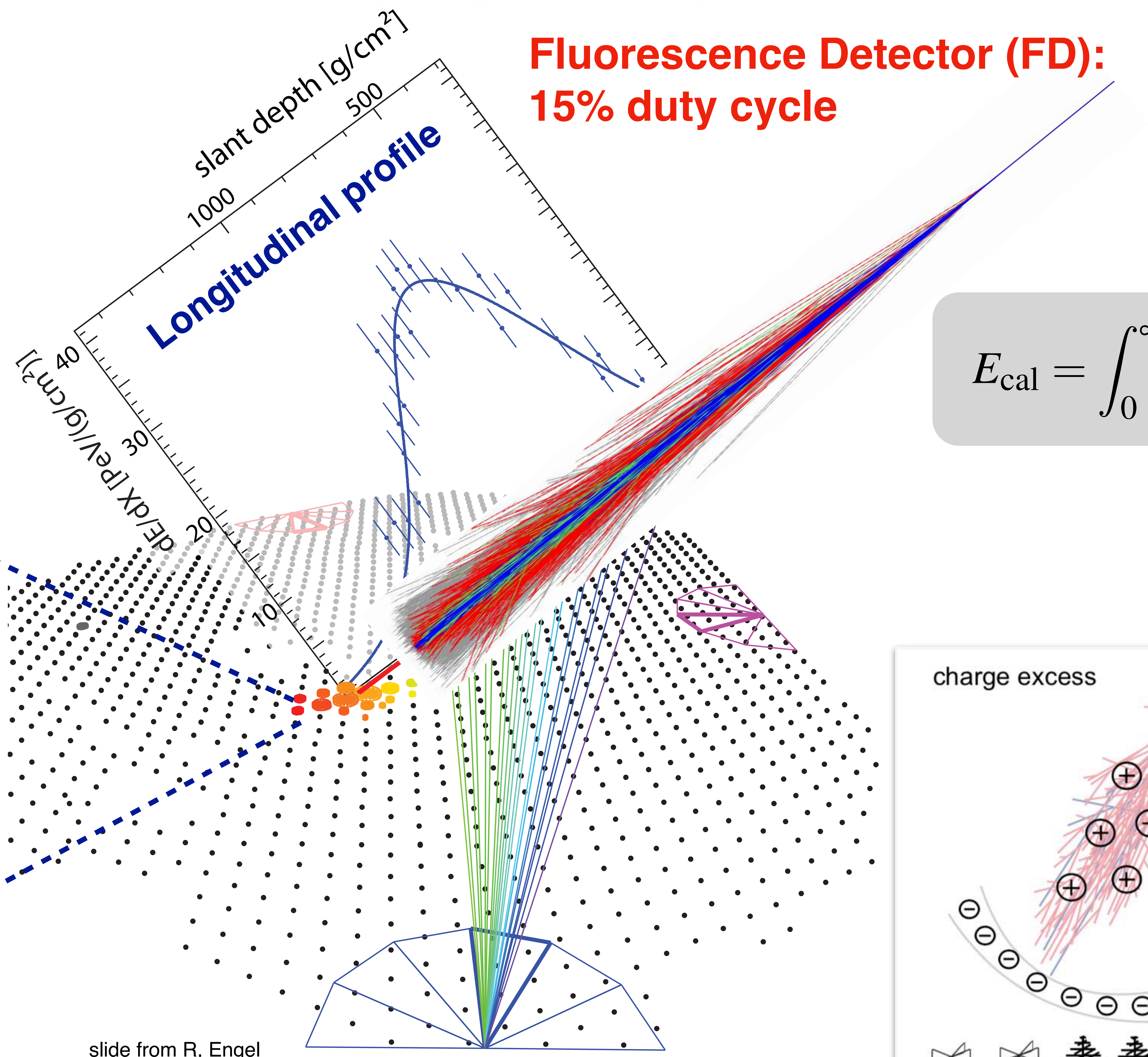
Auger is a Multi-Hybrid Observatory



$$E_{\mathrm{rec}} = f(S_{1000}, \theta)$$



Surface Detector (SD)
100% duty cycle

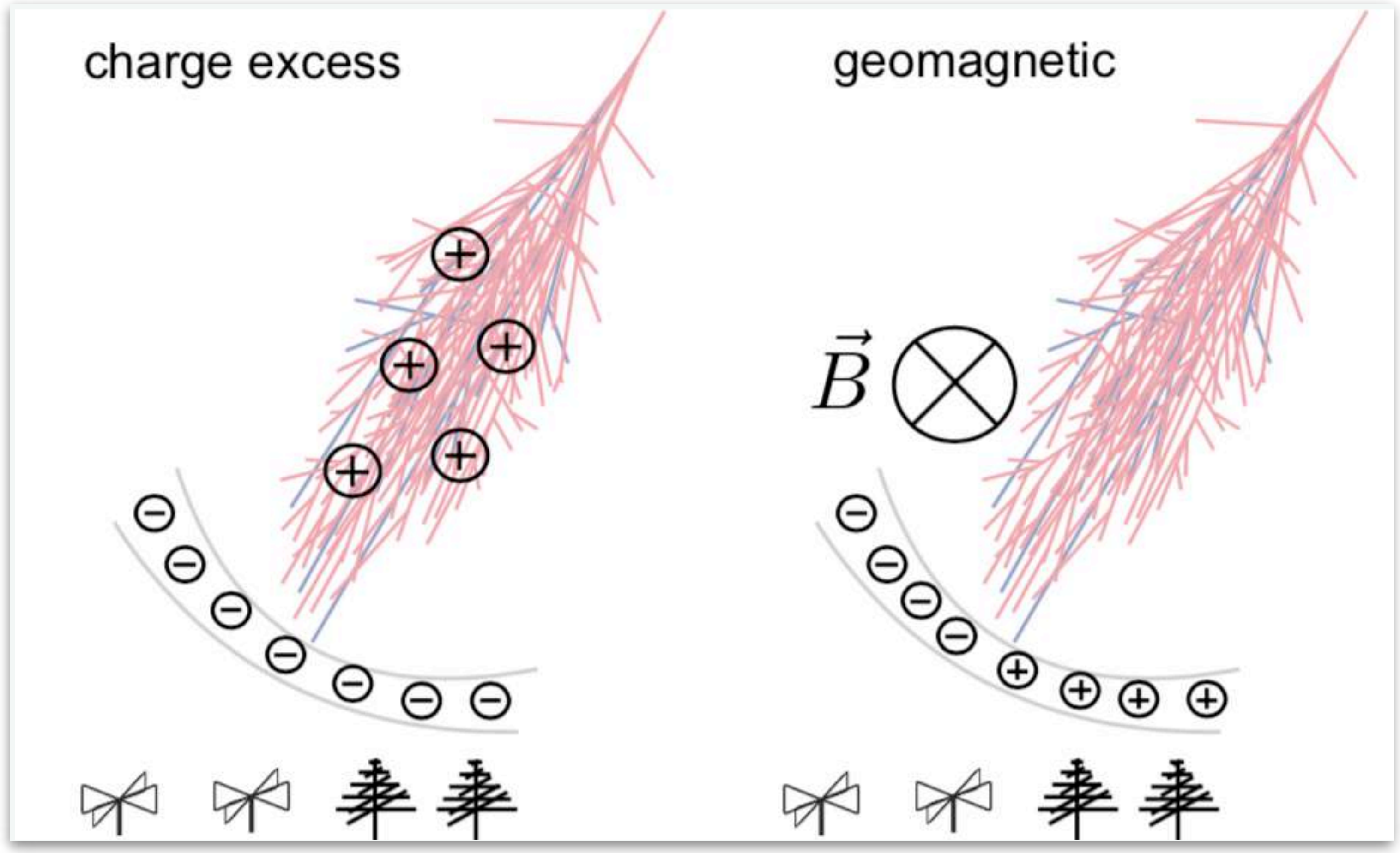


slide from R. Engel

Fluorescence Detector (FD):
15% duty cycle

$$E_{\mathrm{cal}} = \int_0^\infty \left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{\mathrm{obs}} \mathrm{d}X$$

Radio Detector (RD):
100% duty cycle



Auger: A 4π MM Observatory

1️⃣ Neutrons and charged CRs: $\Theta \leq 80°$

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2️⃣ Photons: $30° \leq \Theta \leq 60°$

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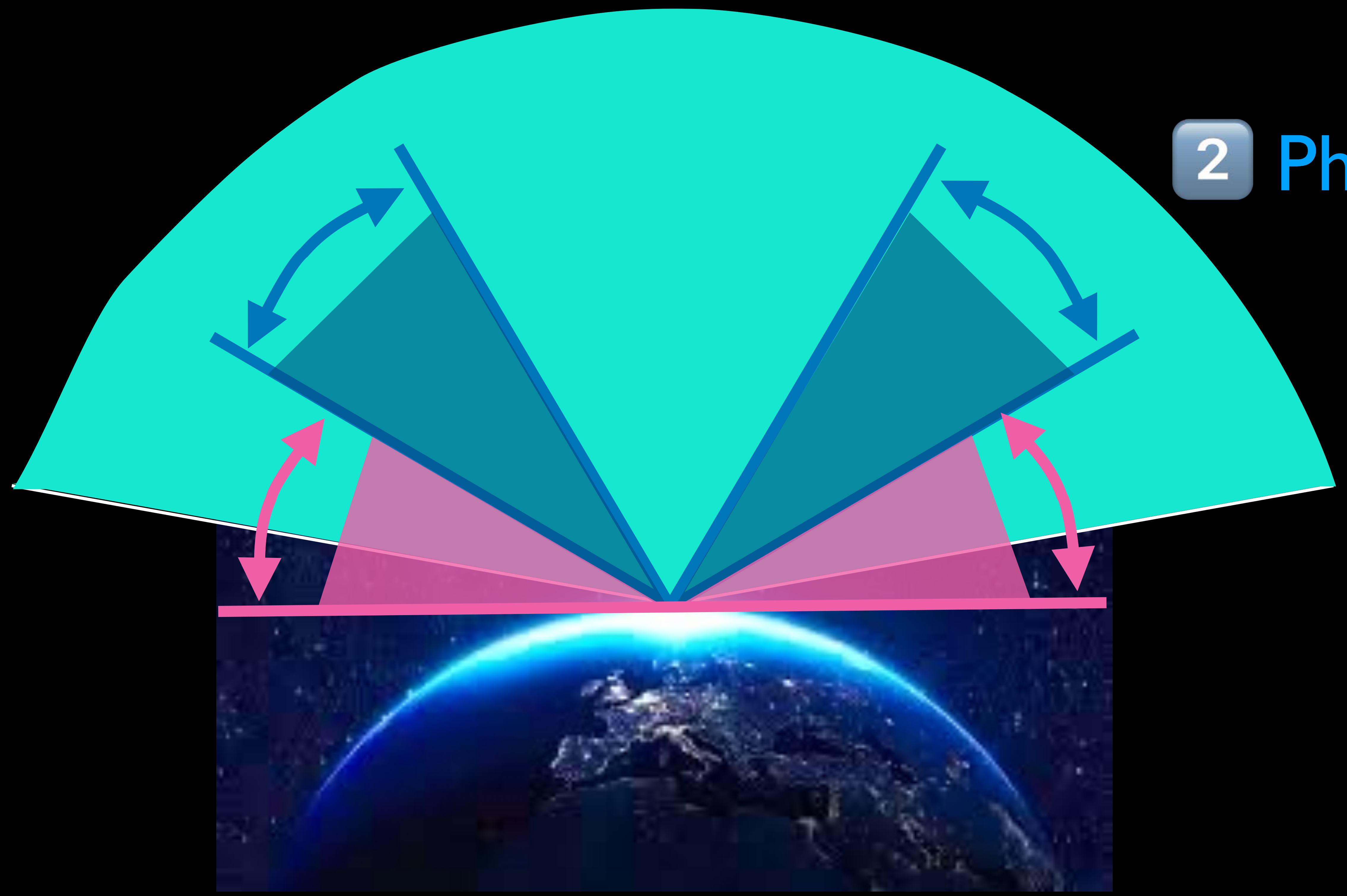
1️⃣ Neutrons and charged CRs: $\Theta \leq 80°$

2️⃣ Photons: $30° \leq \Theta \leq 60°$

3️⃣ Down-Going Neutrinos: $60° \leq \Theta \leq 90°$



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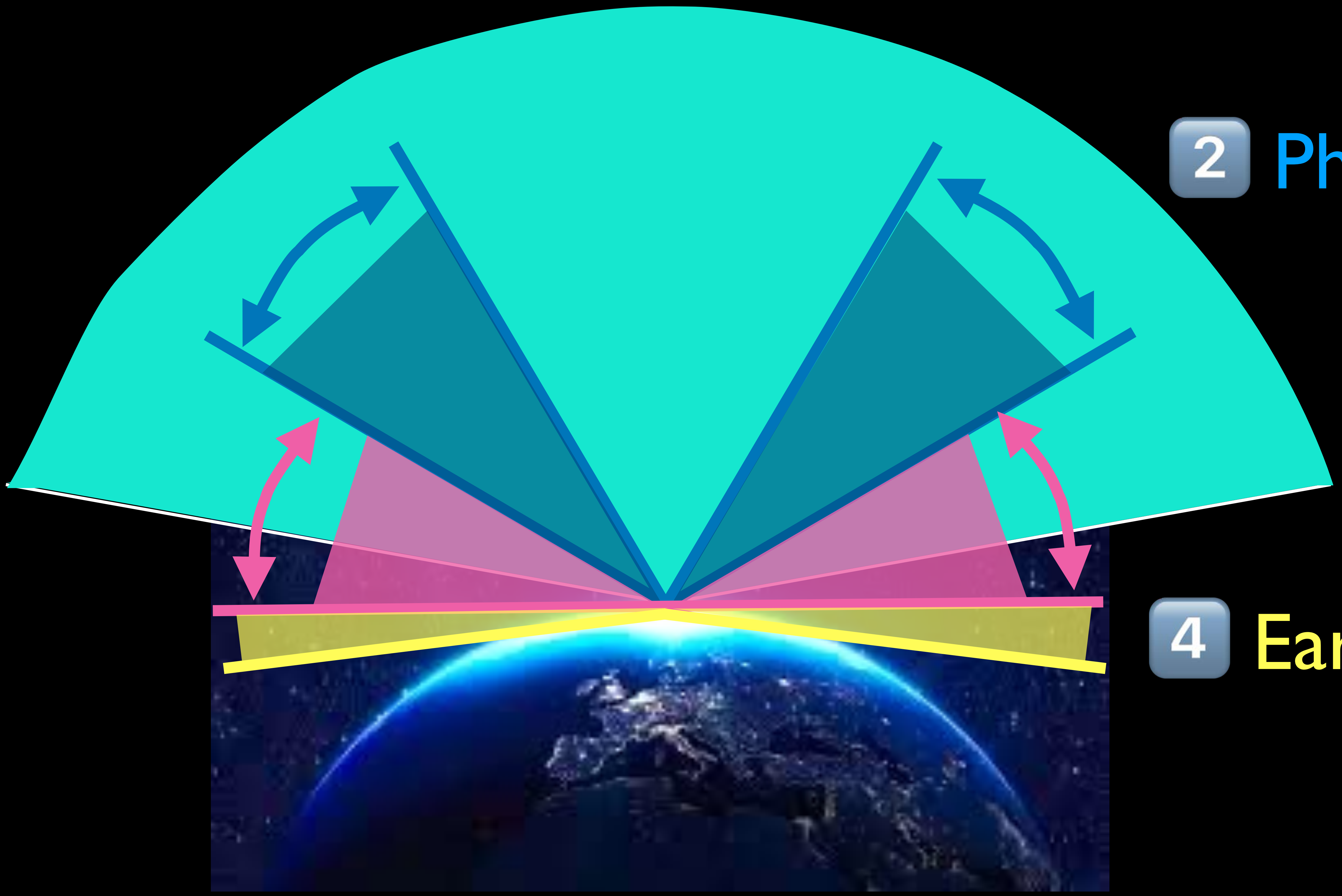


1 Neutrons and charged CRs: $\Theta \leq 80°$

2 Photons: $30° \leq \Theta \leq 60°$

3 Down-Going Neutrinos: $60° \leq \Theta \leq 90°$

4 Earth Skimming Neutrinos: $90° \leq \Theta \leq 95°$

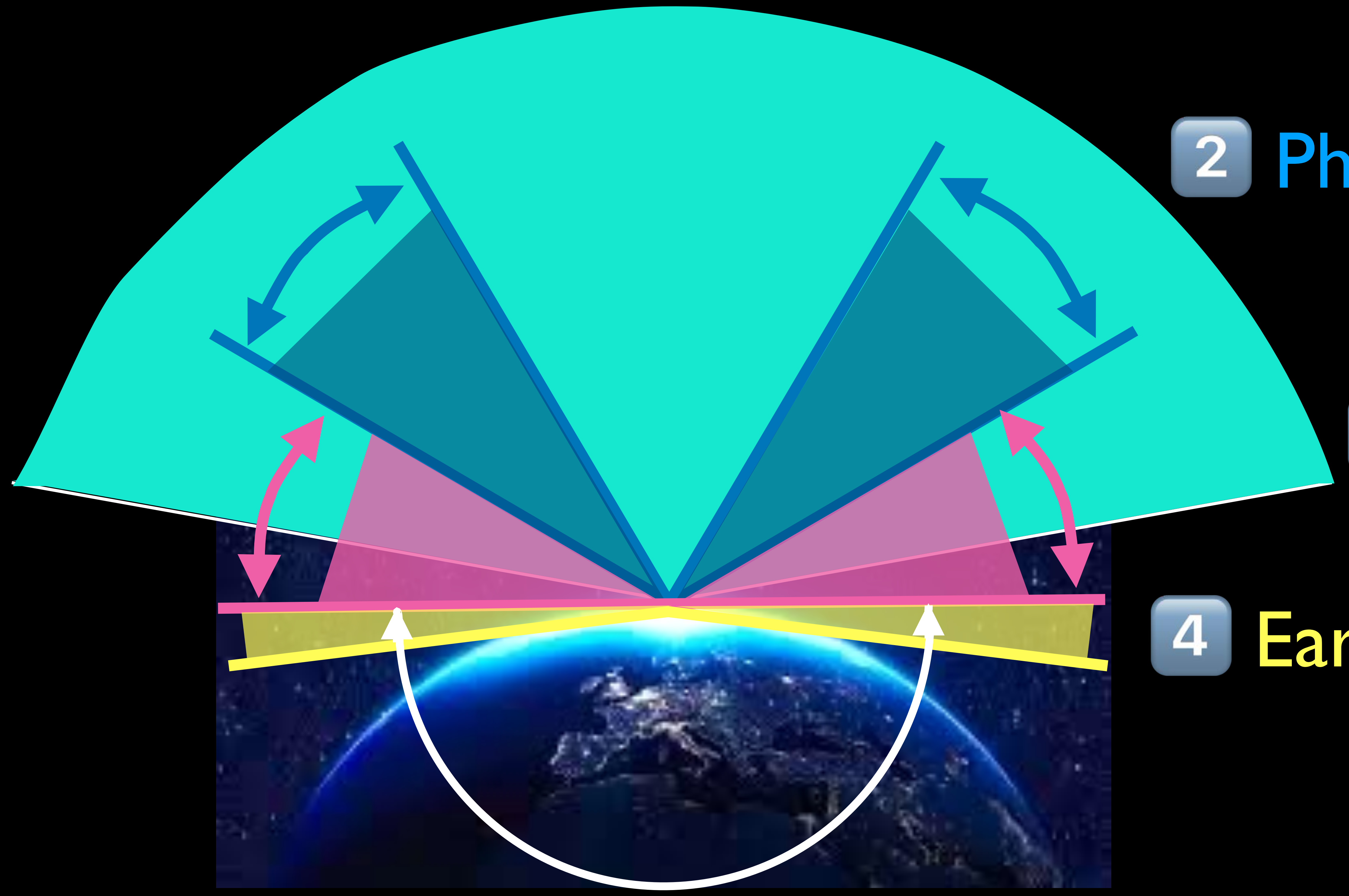
Auger: A 4π MM Observatory

1 Neutrons and charged CRs: Θ ≤ 80°

2 Photons: 30° ≤ Θ ≤ 60°

3 Down-Going Neutrinos: 60° ≤ Θ ≤ 90°

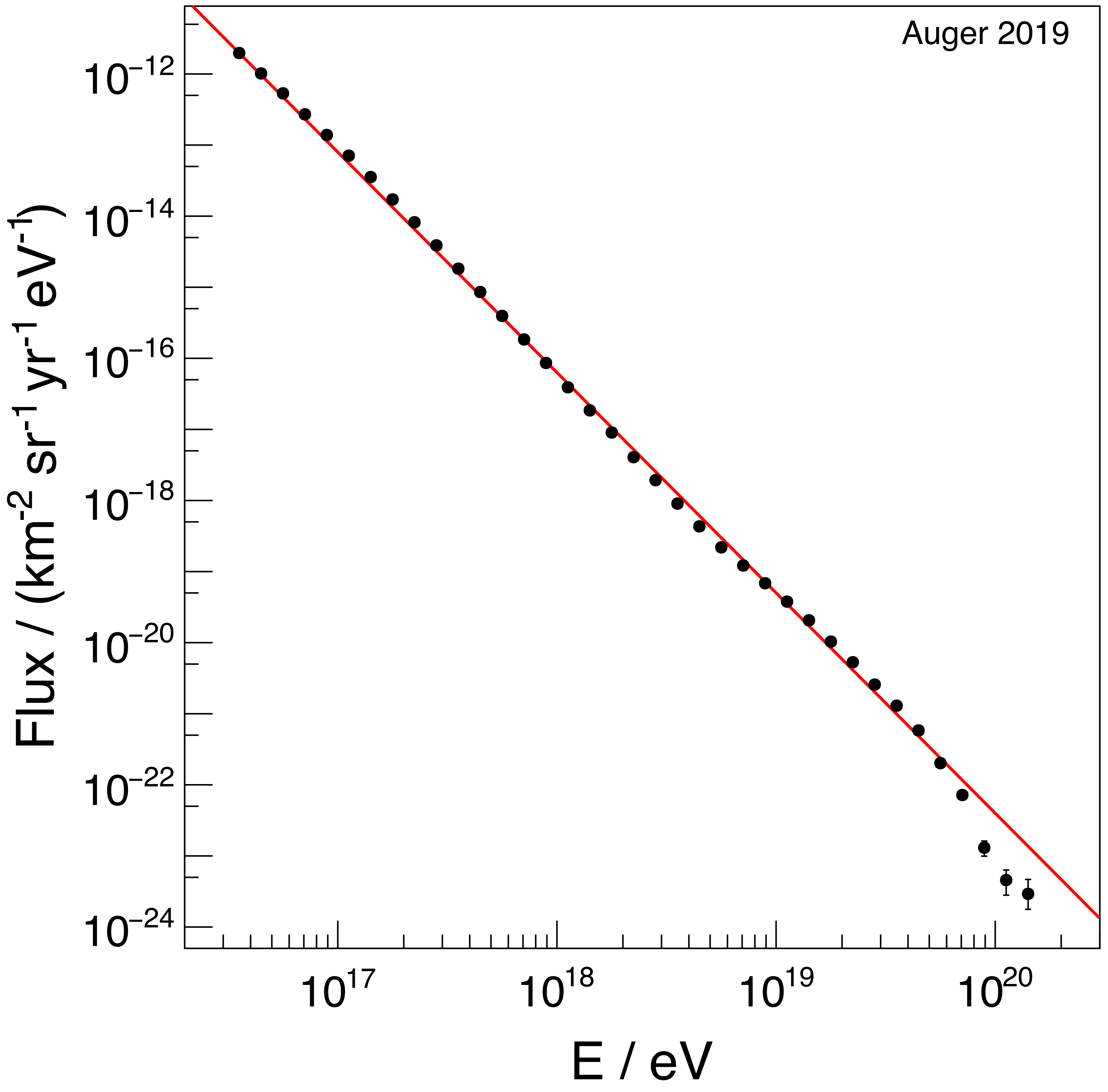
4 Earth Skimming Neutrinos: 90° ≤ Θ ≤ 95°



5 BSM Particles: Θ > 90°

UHECR Energy Spectrum

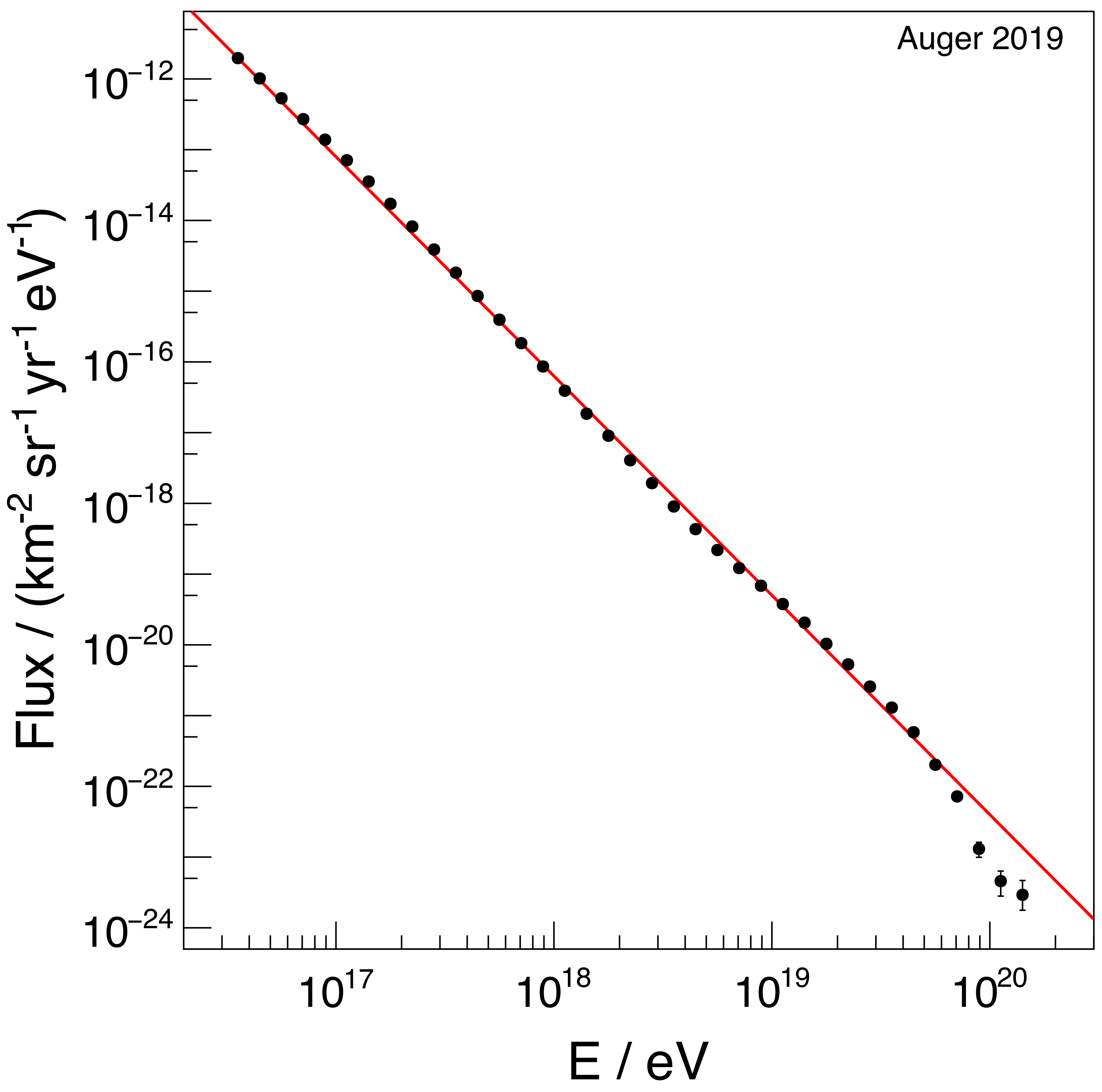
UHECR Energy Spectrum

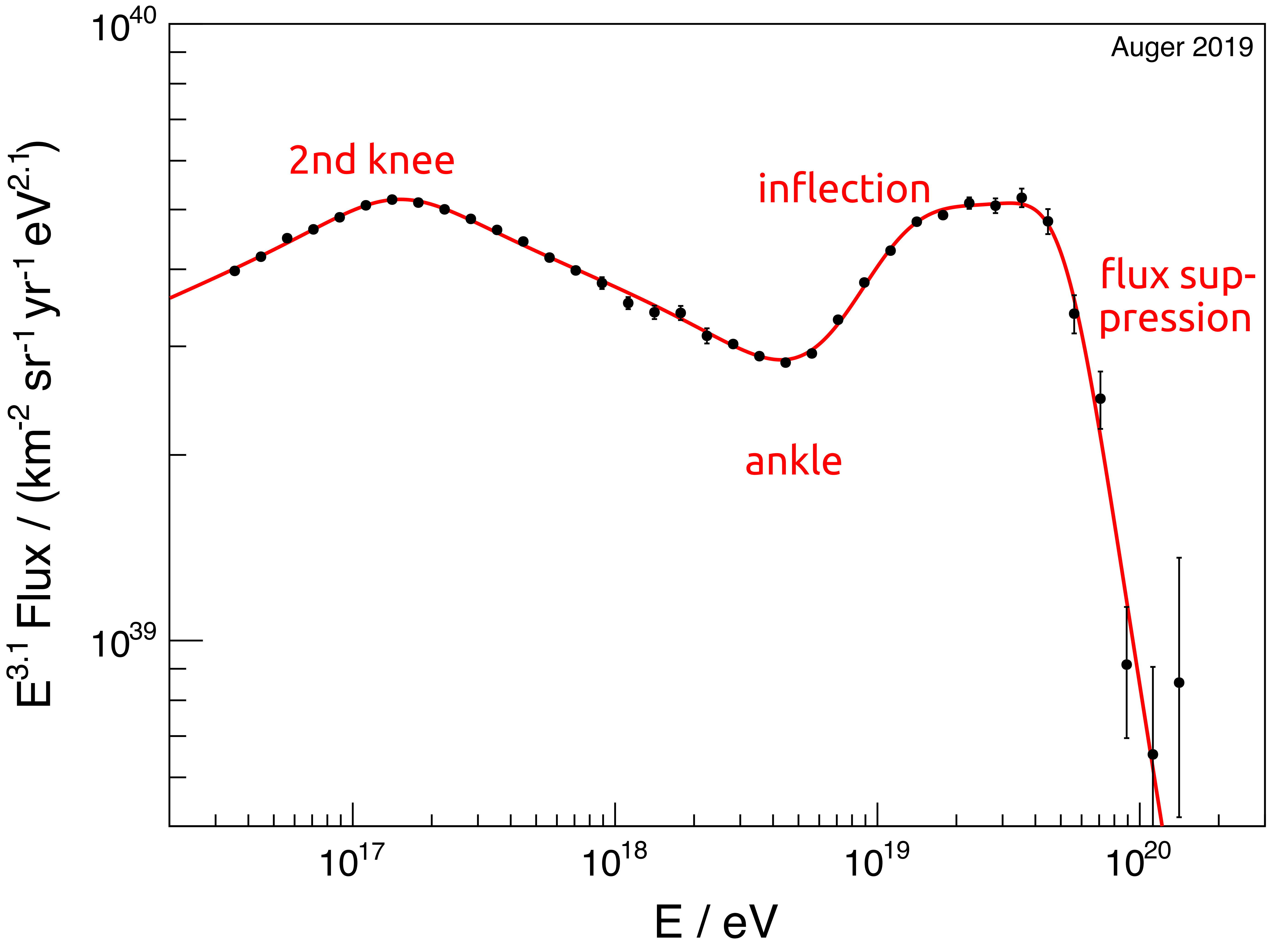


Pierre Auger Coll., PRD 2020, PRL 2020 (twice editor's choice)

Physics See Viewpoint: The Anatomy of Ultrahigh-Energy Cosmic Rays

UHECR Energy Spectrum





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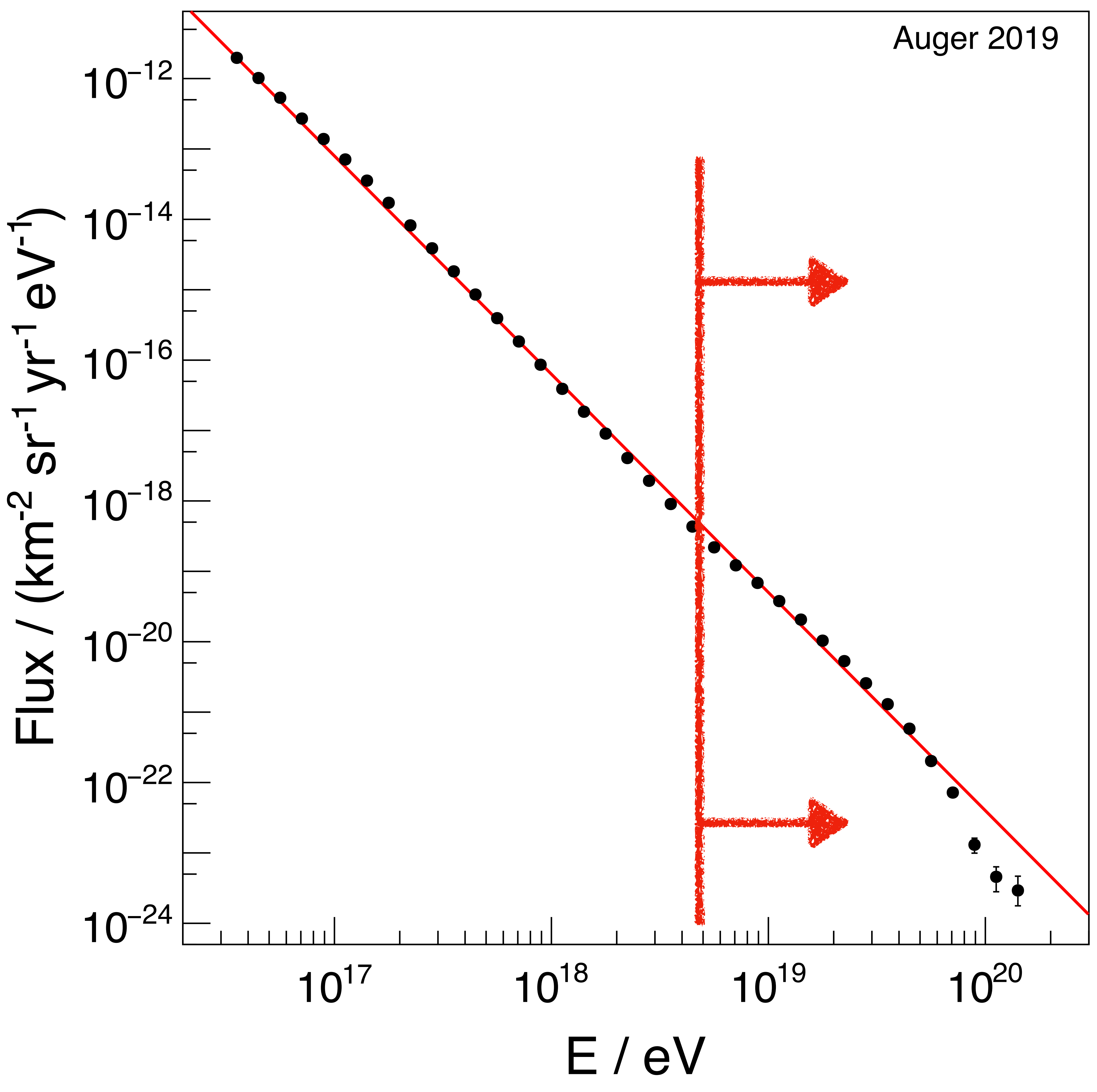
UHECR Luminosity



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Measurement of local CR energy density

$$\varepsilon_{CR} = 4\pi/c \int_{E_{ankle}}^{\infty} E \cdot \mathrm{Flux(E)}\ \mathrm{dE}$$

$$= (5.66 \pm 0.03 \pm 1.40) \cdot 10^{53}\ \mathrm{erg\ Mpc}^{-3}$$

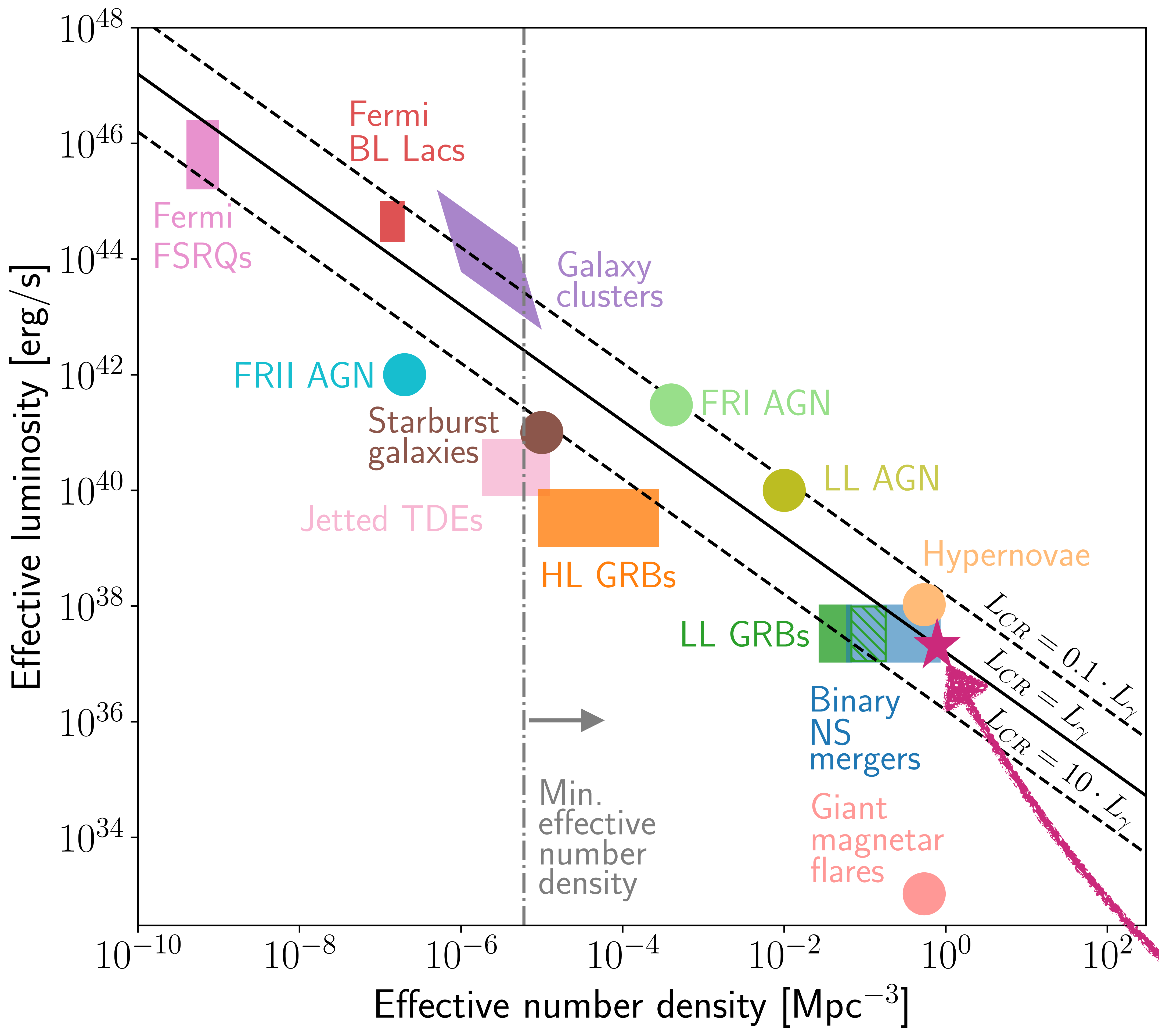
→ source luminosity density

$$\mathscr{L} \sim \varepsilon_{CR}/t_{\rm loss} = 2 \cdot 10^{44}\ \mathrm{erg\ Mpc}^{-3}\ \mathrm{yr}^{-1}$$

Typical energy loss time $t_{\rm loss} \sim 1\,\mathrm{Gpc/c}$ at $E_{\rm ankle} = 5 \cdot 10^{18}\,\mathrm{eV}$

Full calculation with SimpProp: $\mathscr{L} \simeq 6 \cdot 10^{44}\,\mathrm{erg\,Mpc}^{-3}\mathrm{yr}^{-1}$

UHECR Luminosity



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.

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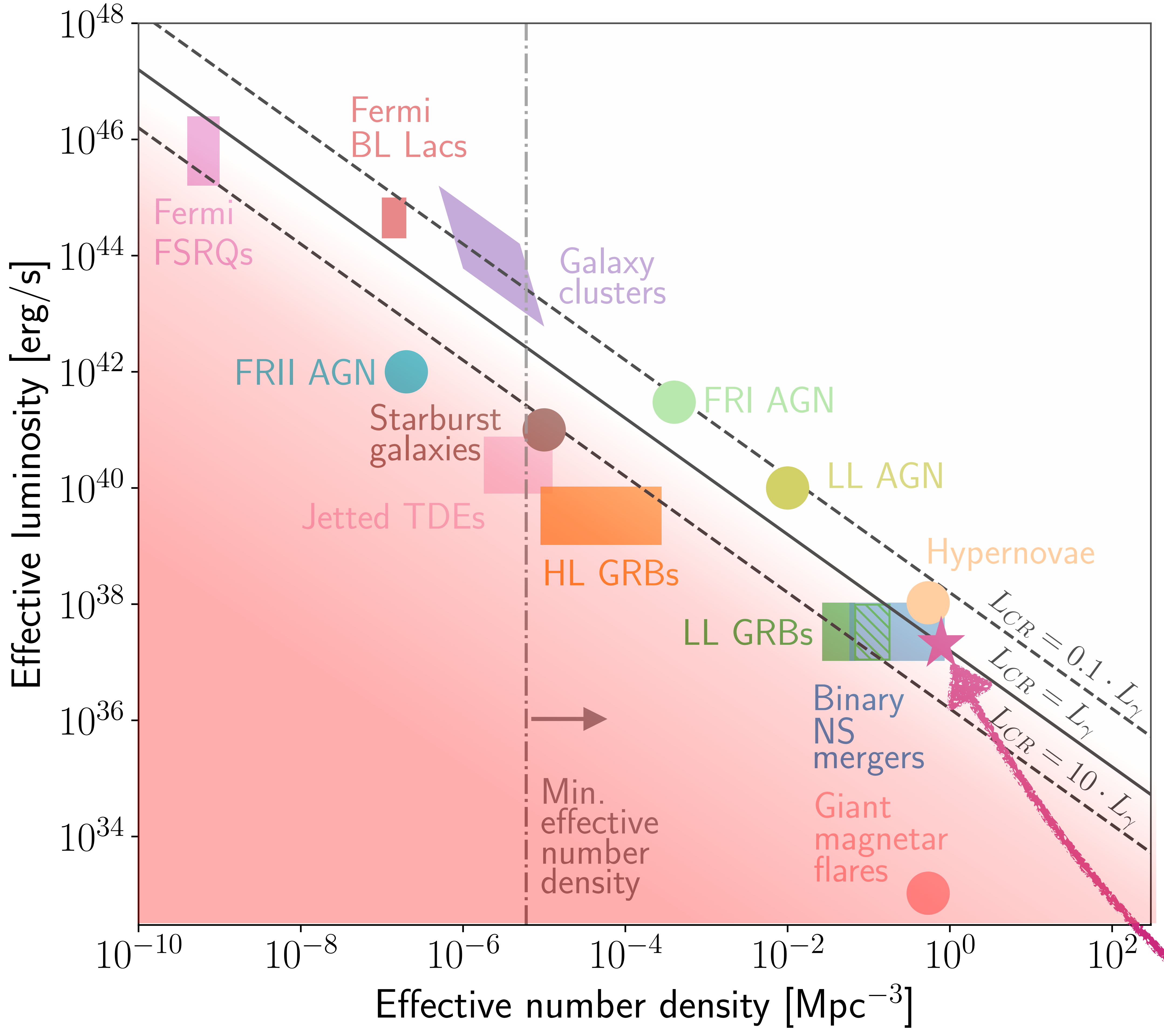

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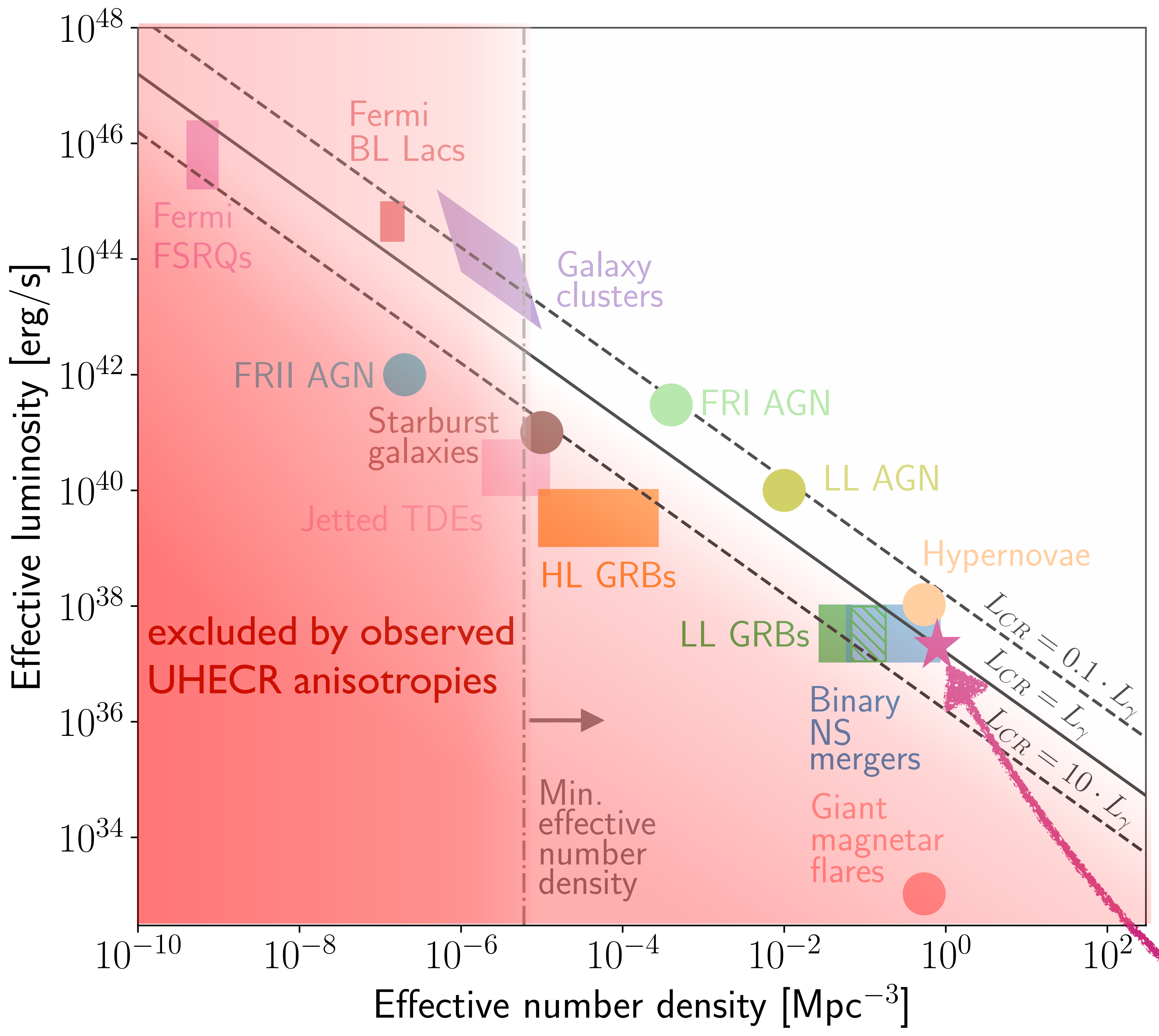

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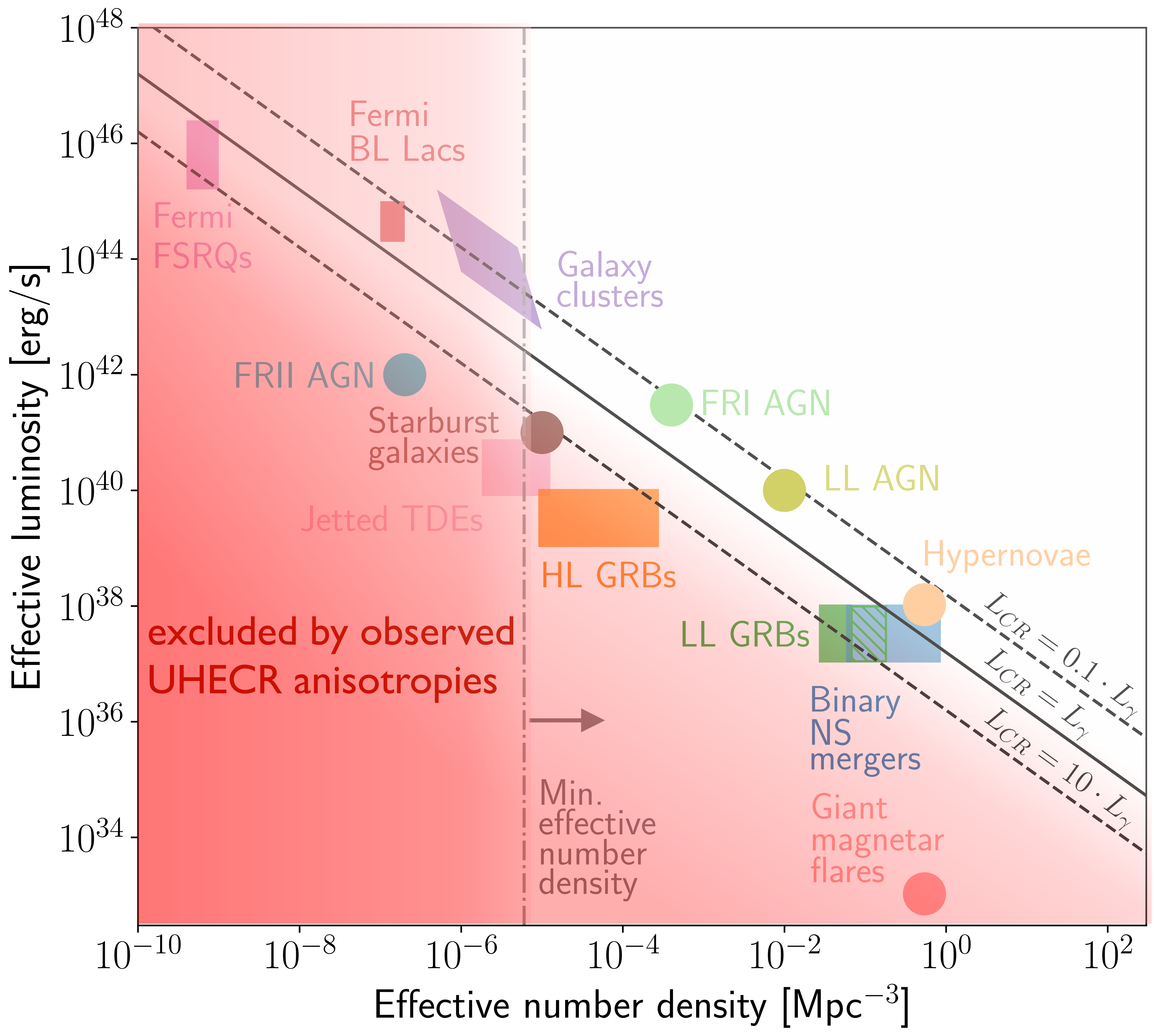
UHECR Luminosity and Acceleration Requirements



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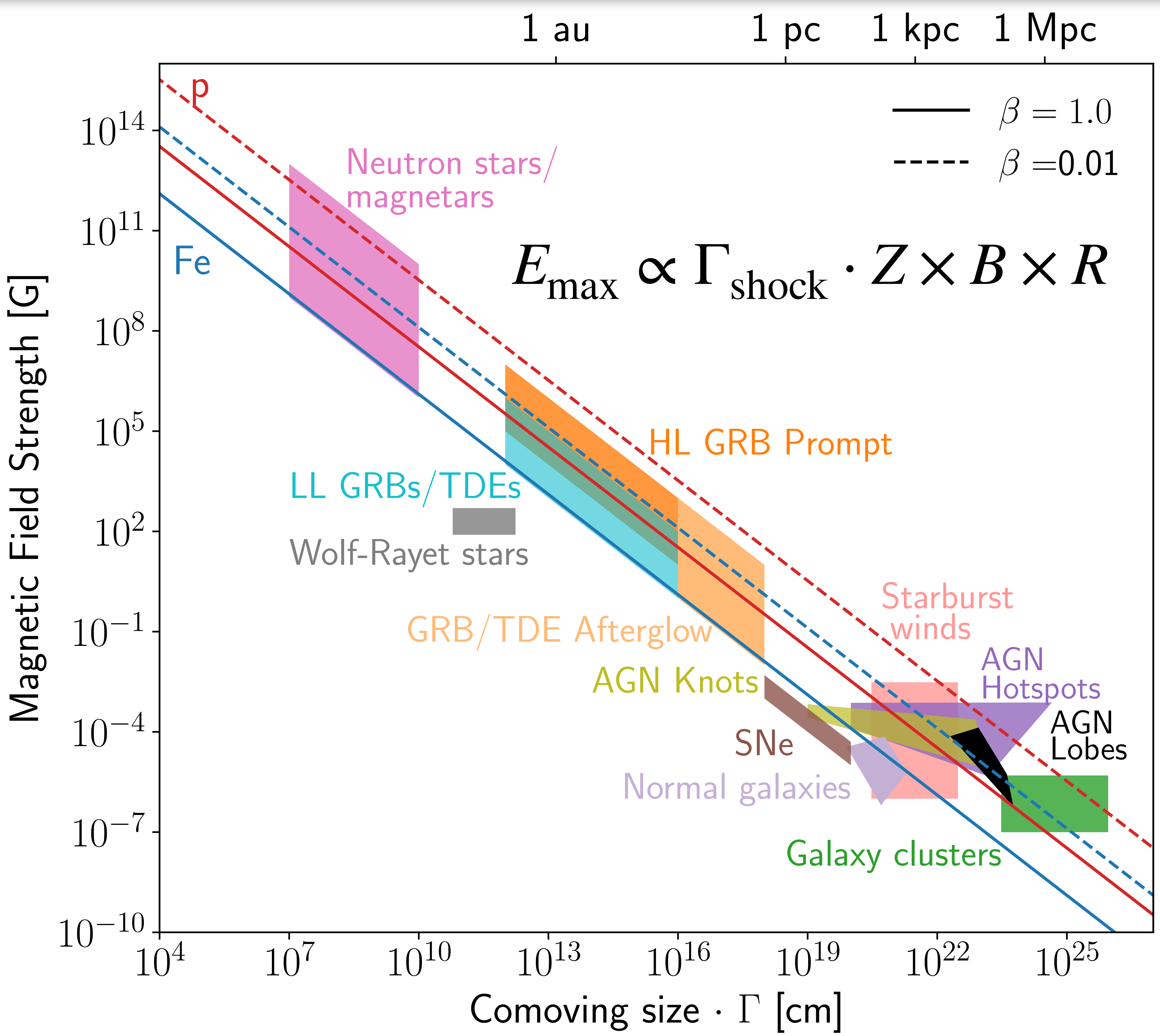

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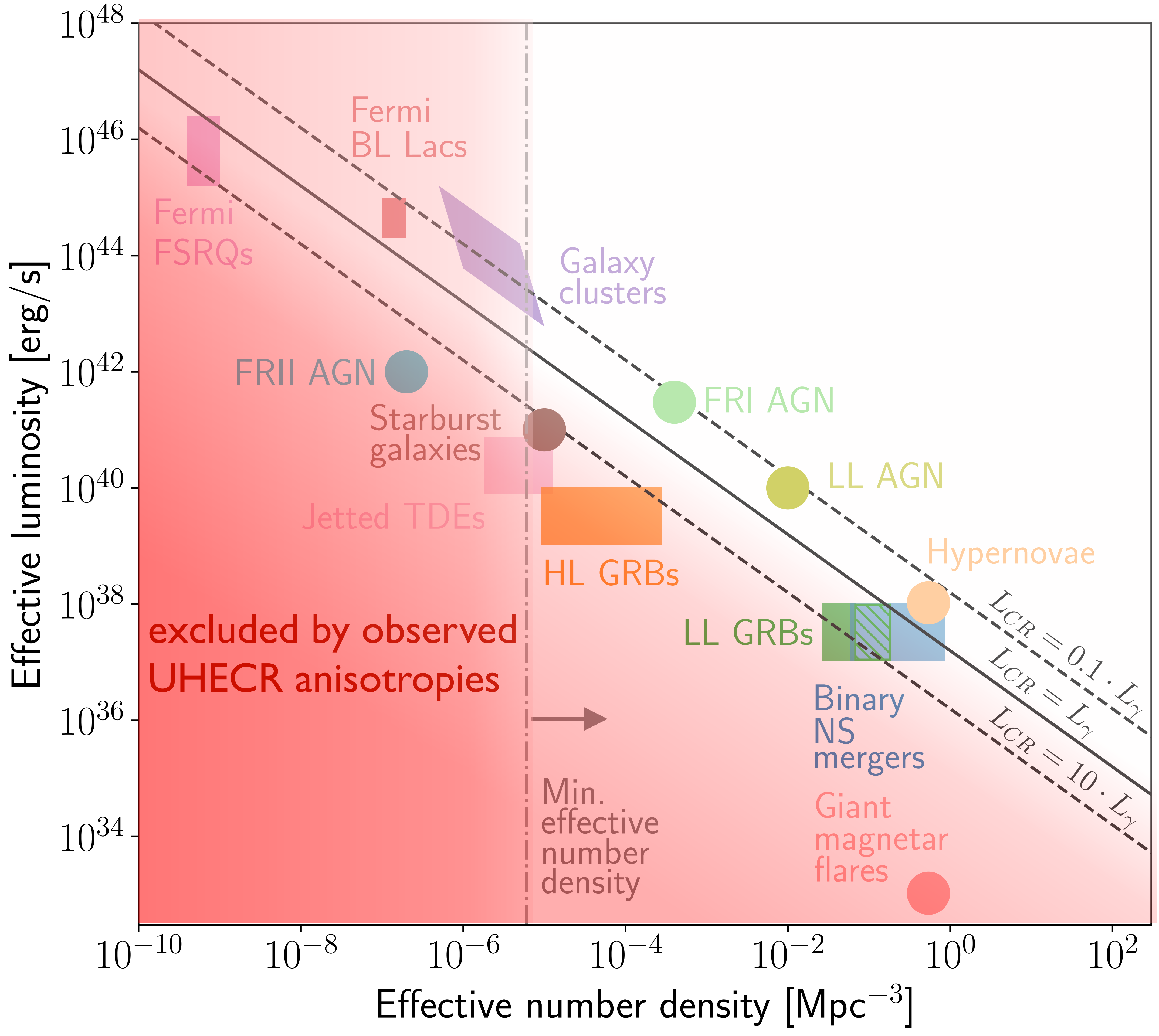

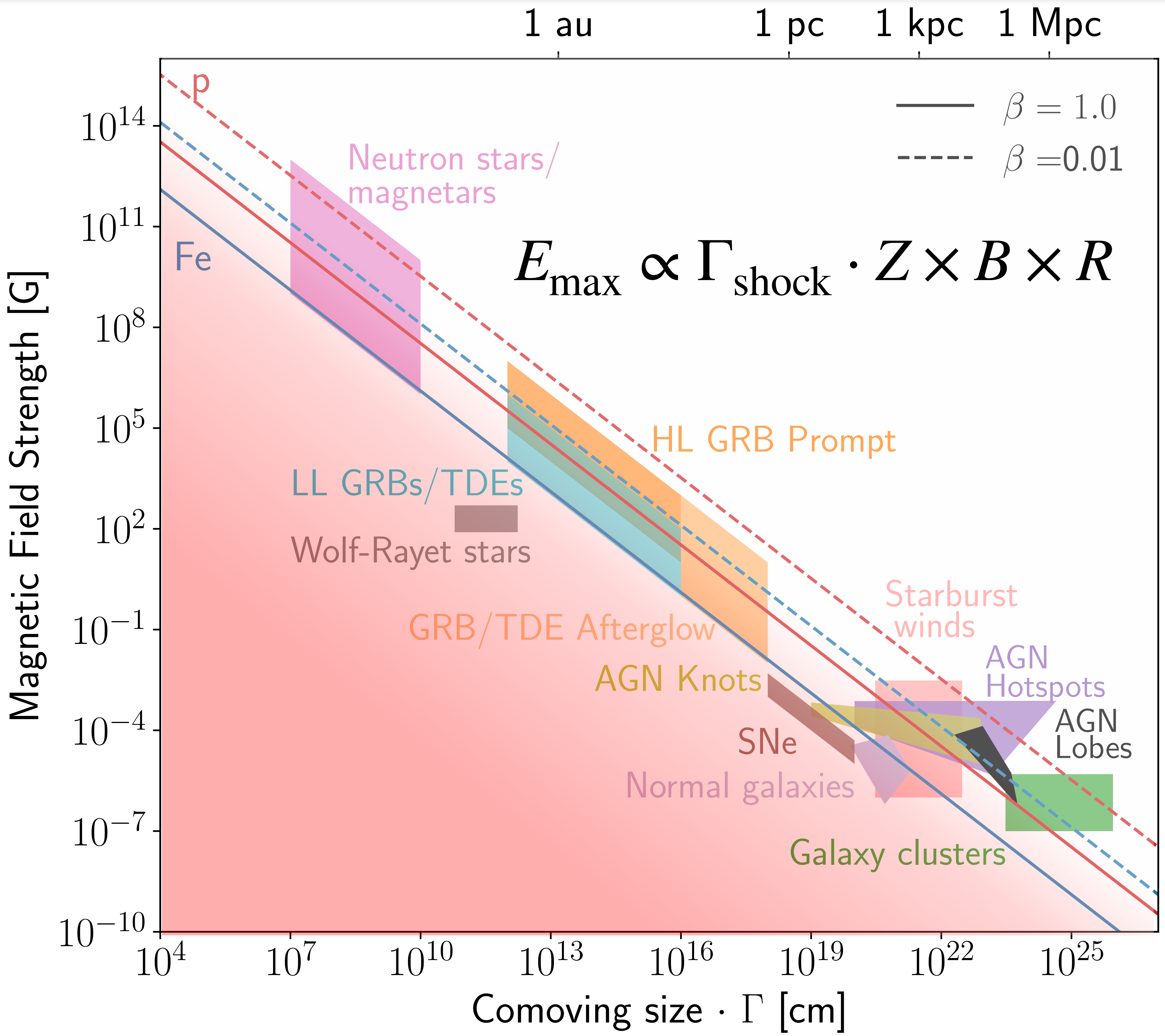

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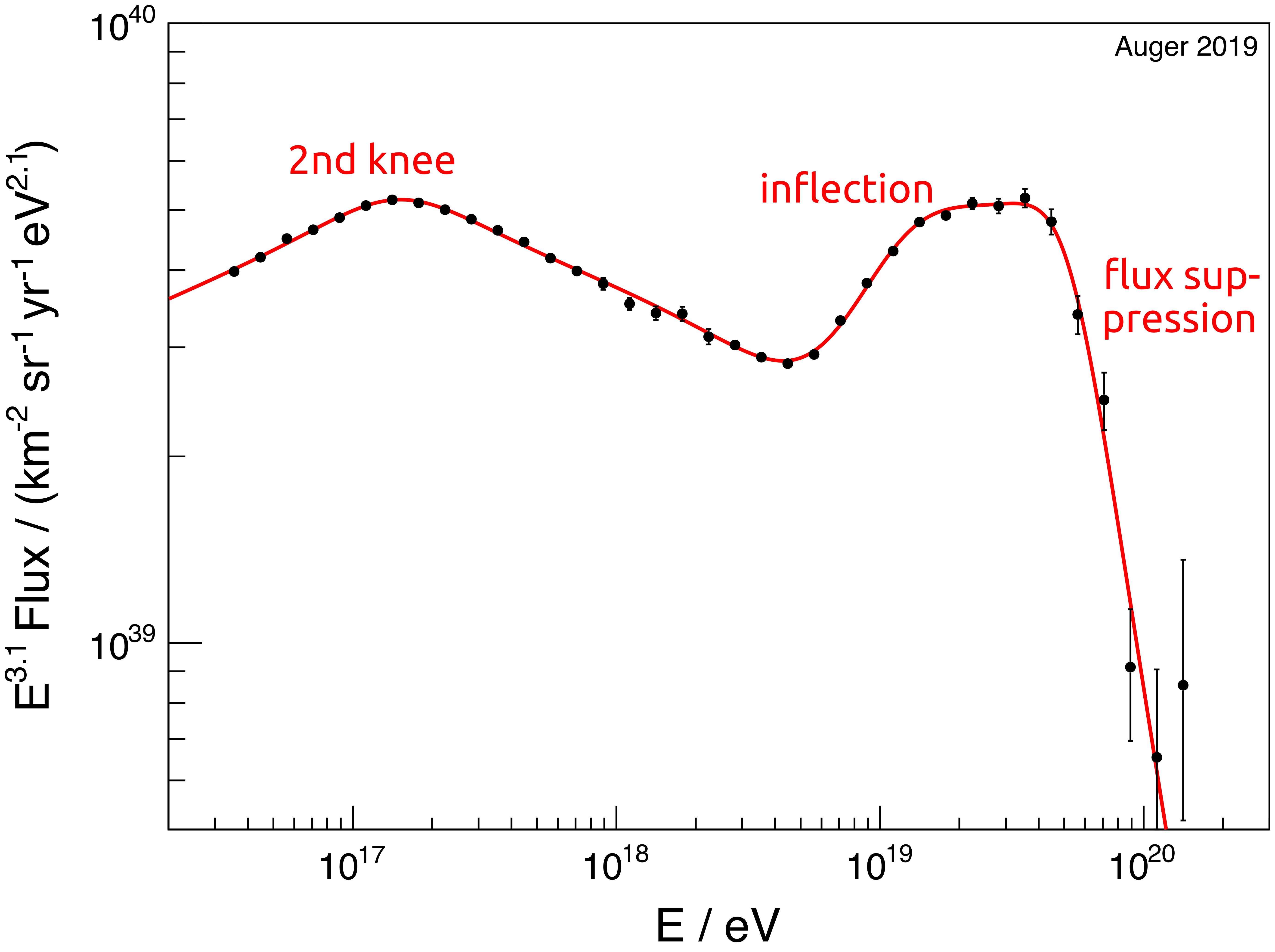
Origin of the cut-off



Physics See Viewpoint: The Anatomy of Ultrahigh-Energy Cosmic Rays

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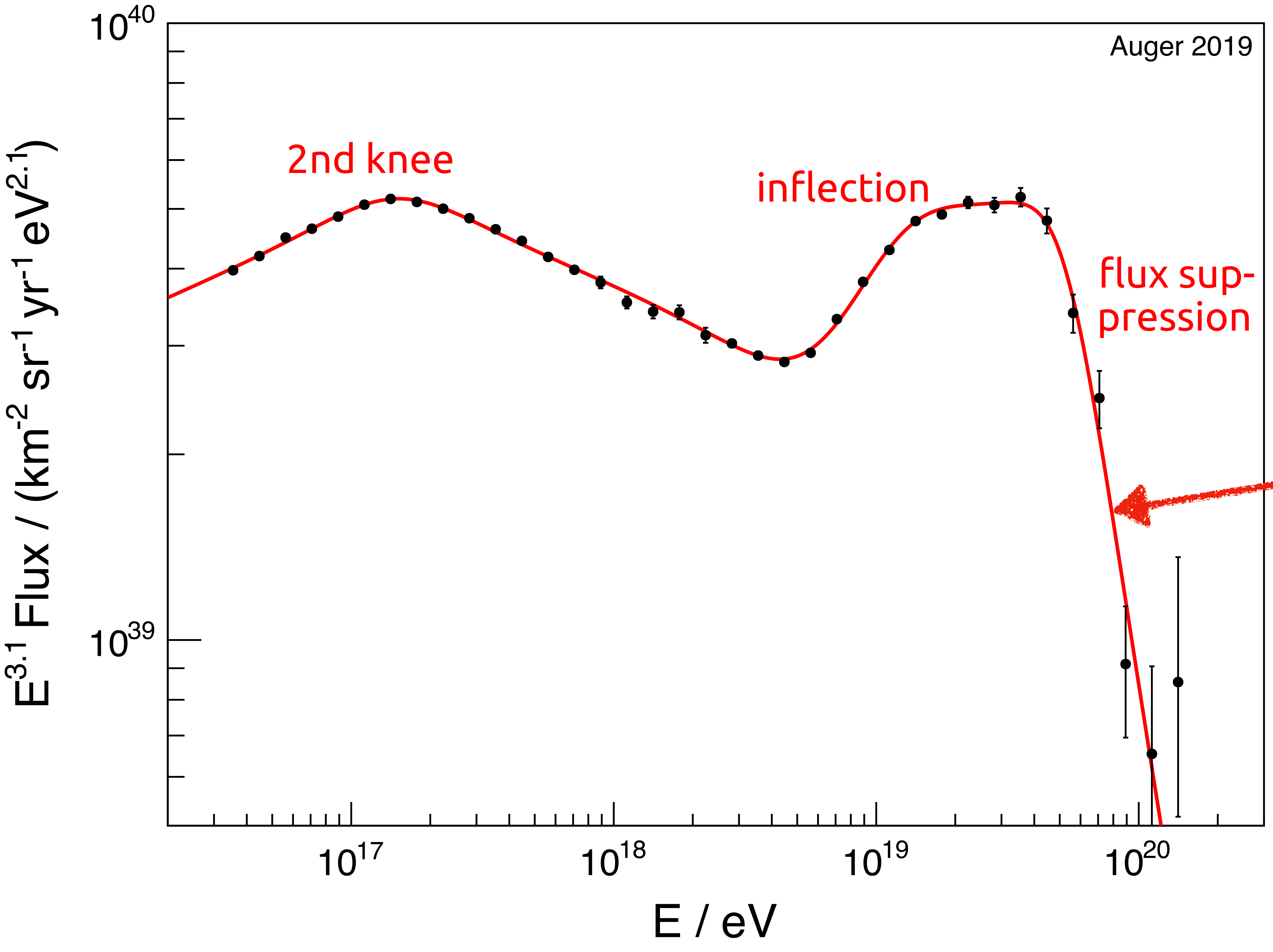

GZK effect ?

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

$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$$
$$\pi^+ \rightarrow \nu_\mu, \nu_e$$

Protons and Nuclei with $E > 6 \cdot 10^{19}$ eV suffer rapid energy losses and produce cosmogenic γ's and ν's

Physics See Viewpoint: The Anatomy of Ultrahigh-Energy Cosmic Rays

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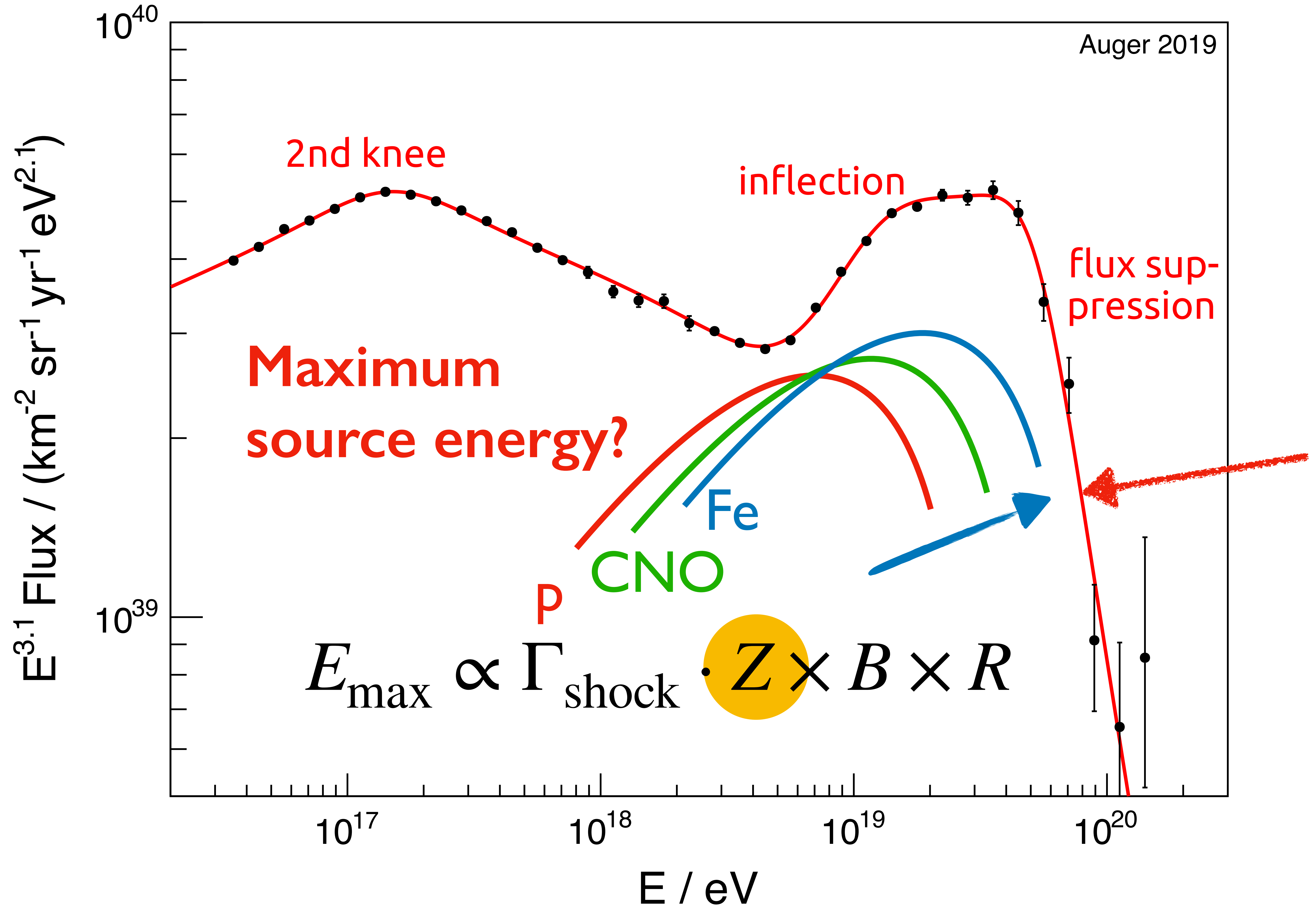

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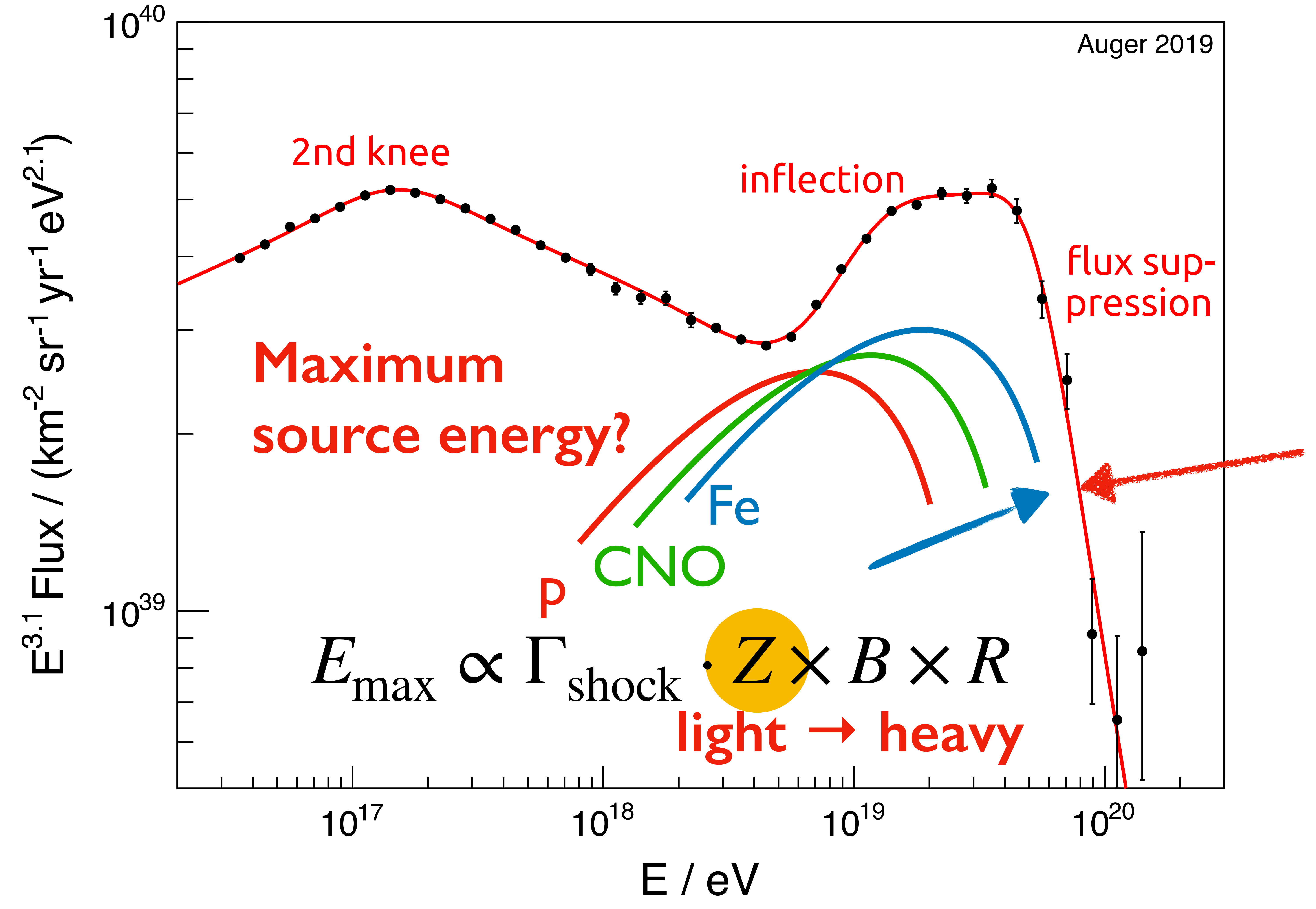

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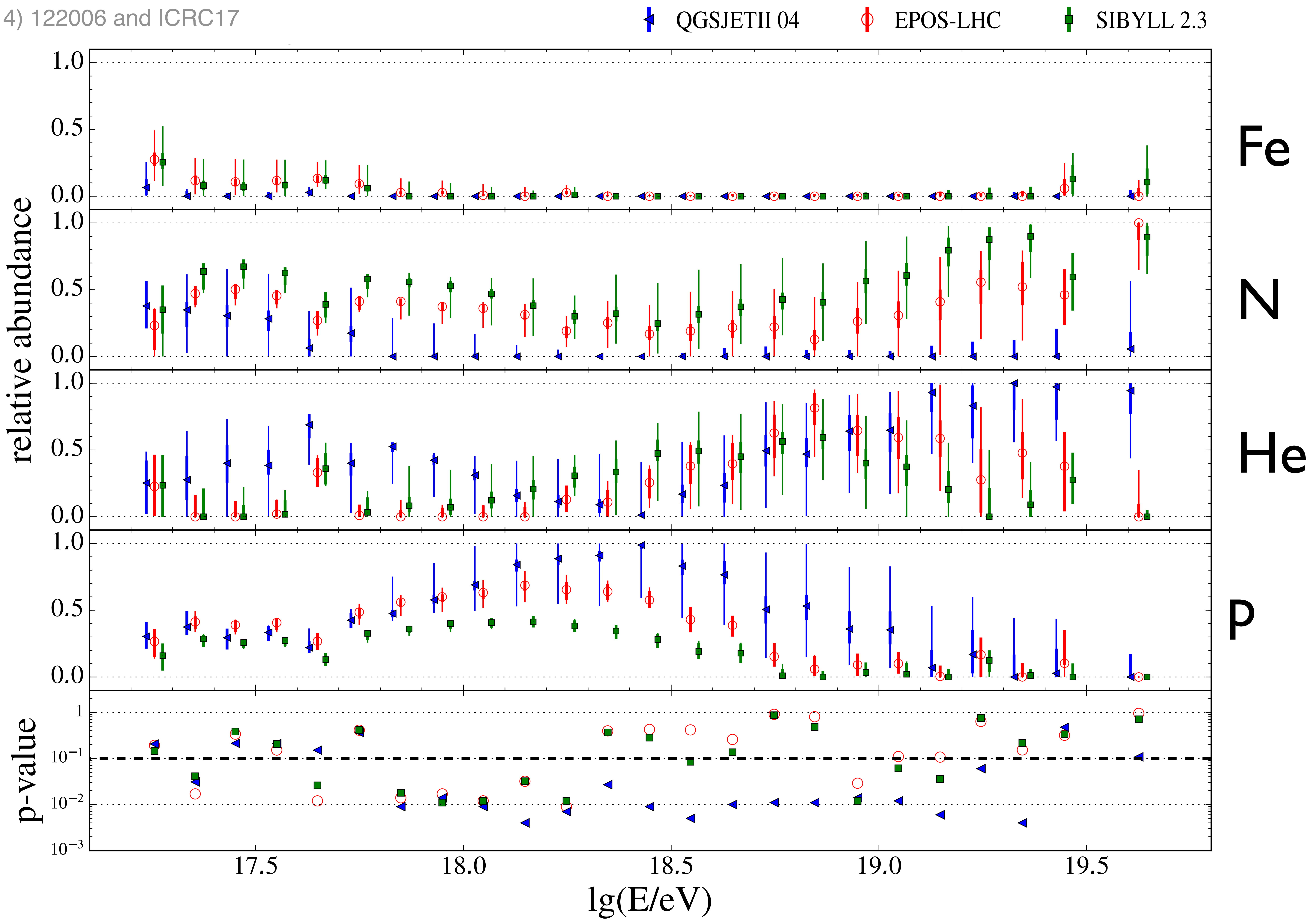
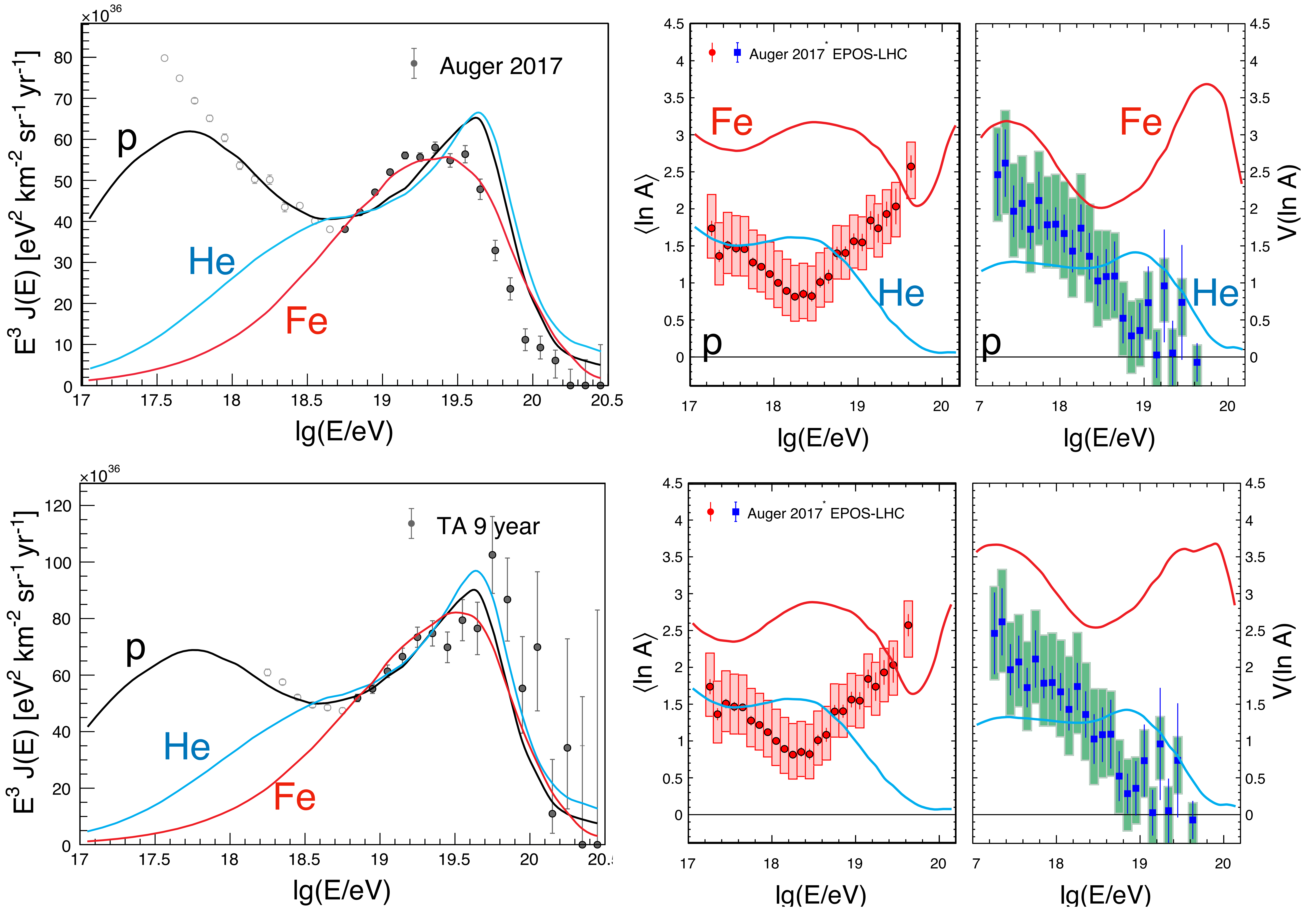
UHECR Mass Composition

Pierre Auger Coll. PRD 90 (2014) 122006 and ICRC17



GZK Flux Suppression ?



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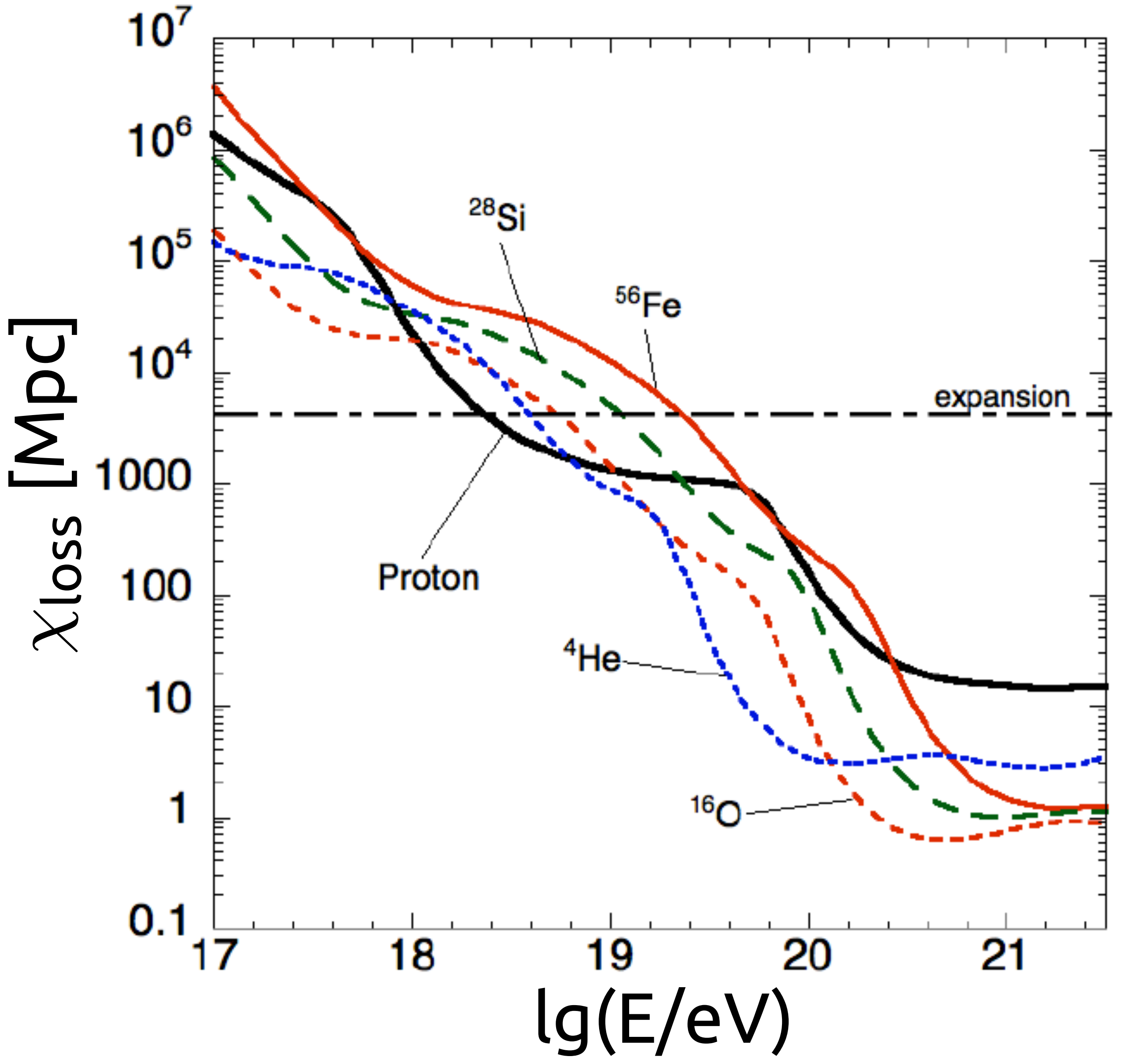
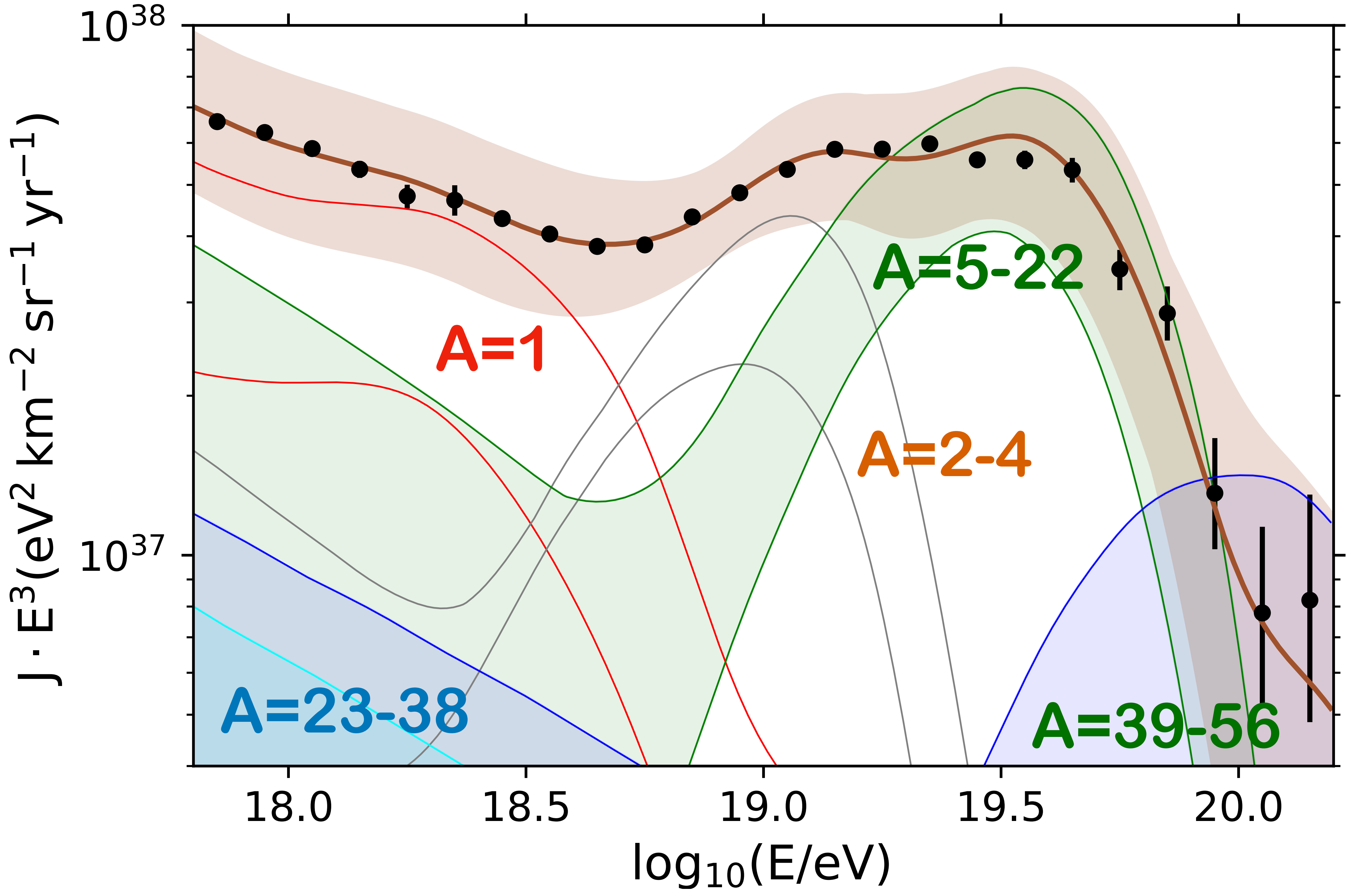
Greisen Zatsepin Kuzmin

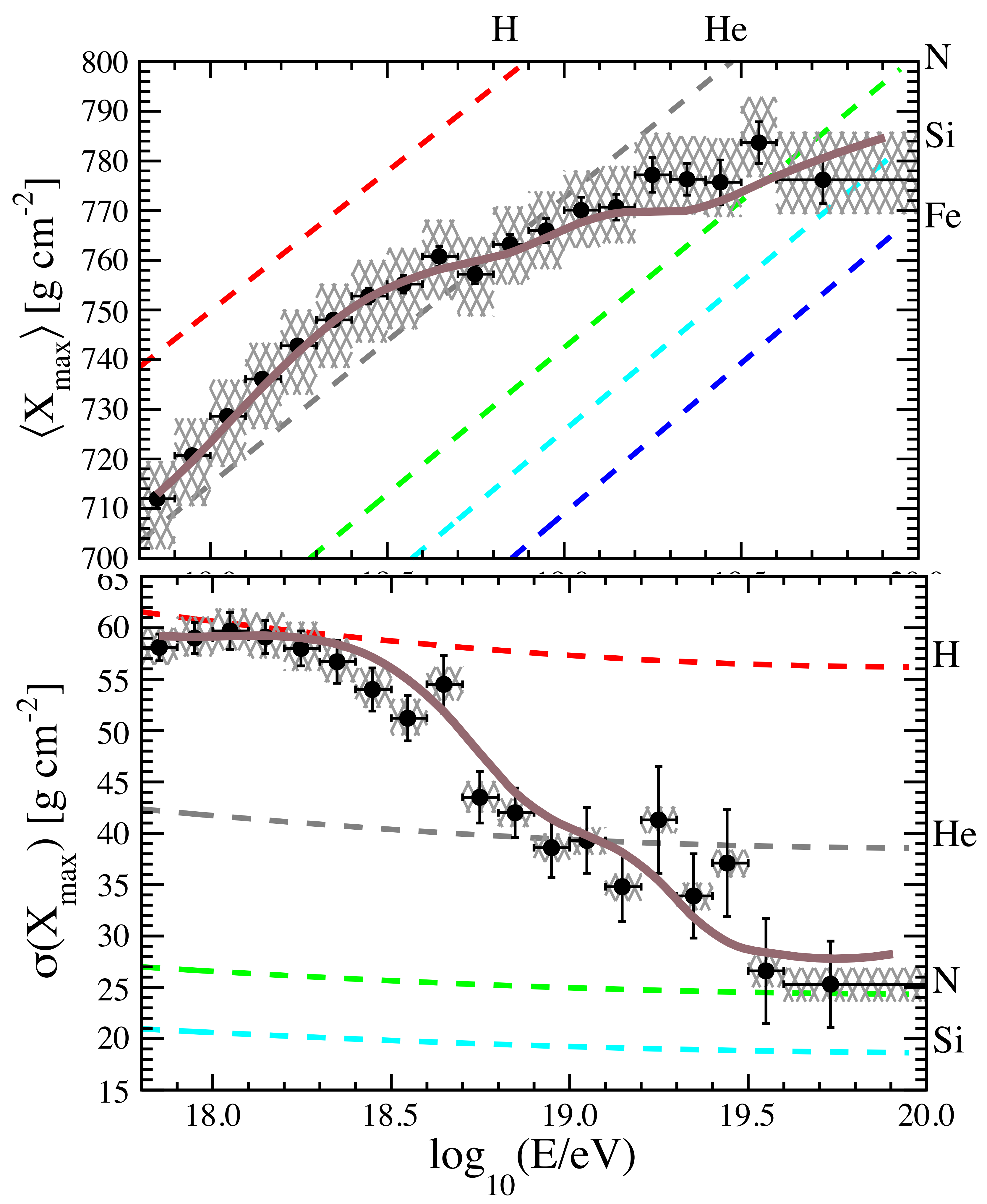


D.Allard Astropart.Phys. **39** (2012) 33

Maximum Rigidity Model describes data well

E. Guido; Auger Collaboration, PoS (ICRC21) 311





Combined fit of all-particle energy spectrum and CR mass composition:

- assuming uniformly distributed identical sources
- and a rigidity dependent cut-off
- and accounting for propagation effects

⇒ Cut-Off appears mostly an effect of sources

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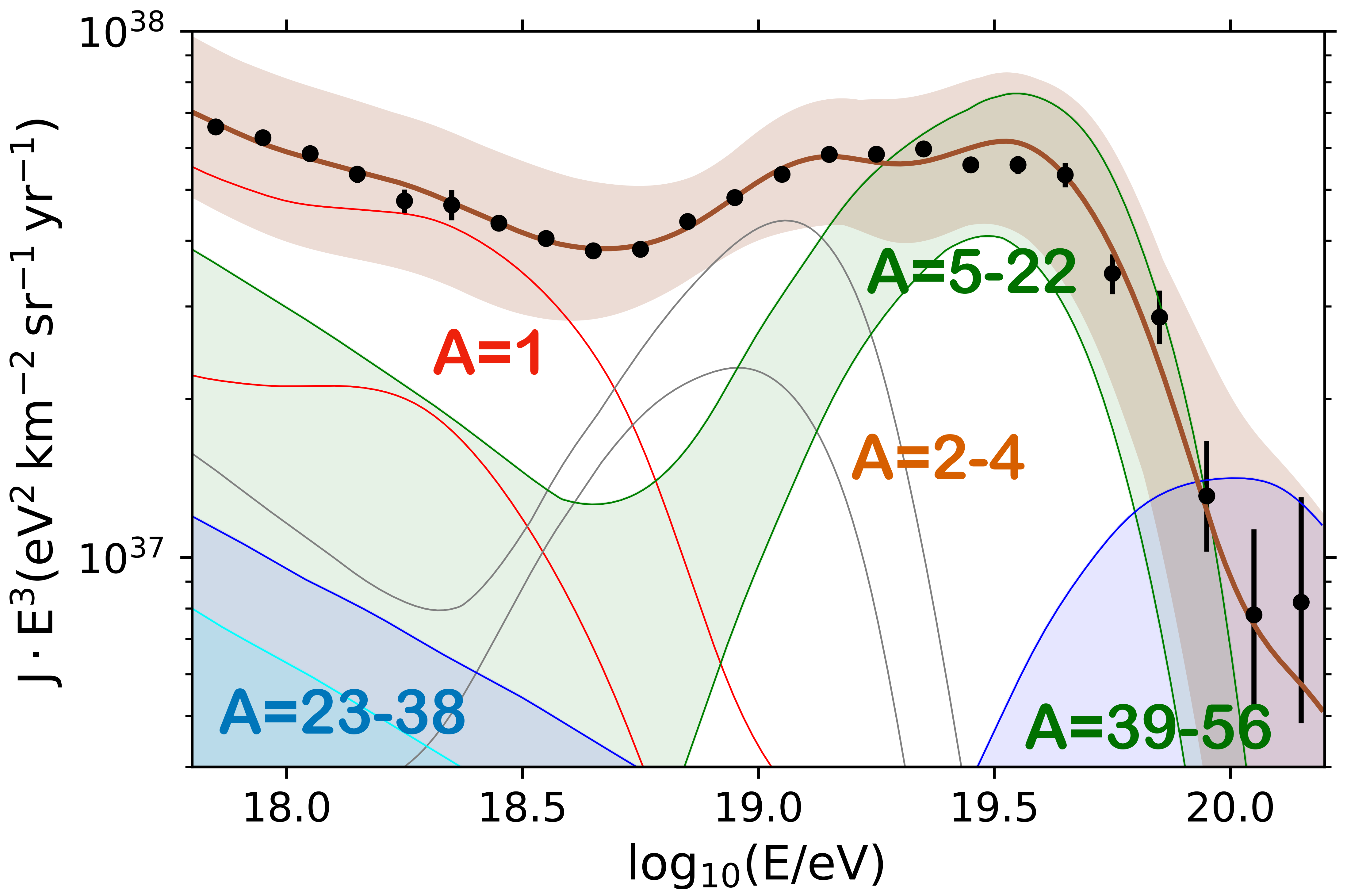

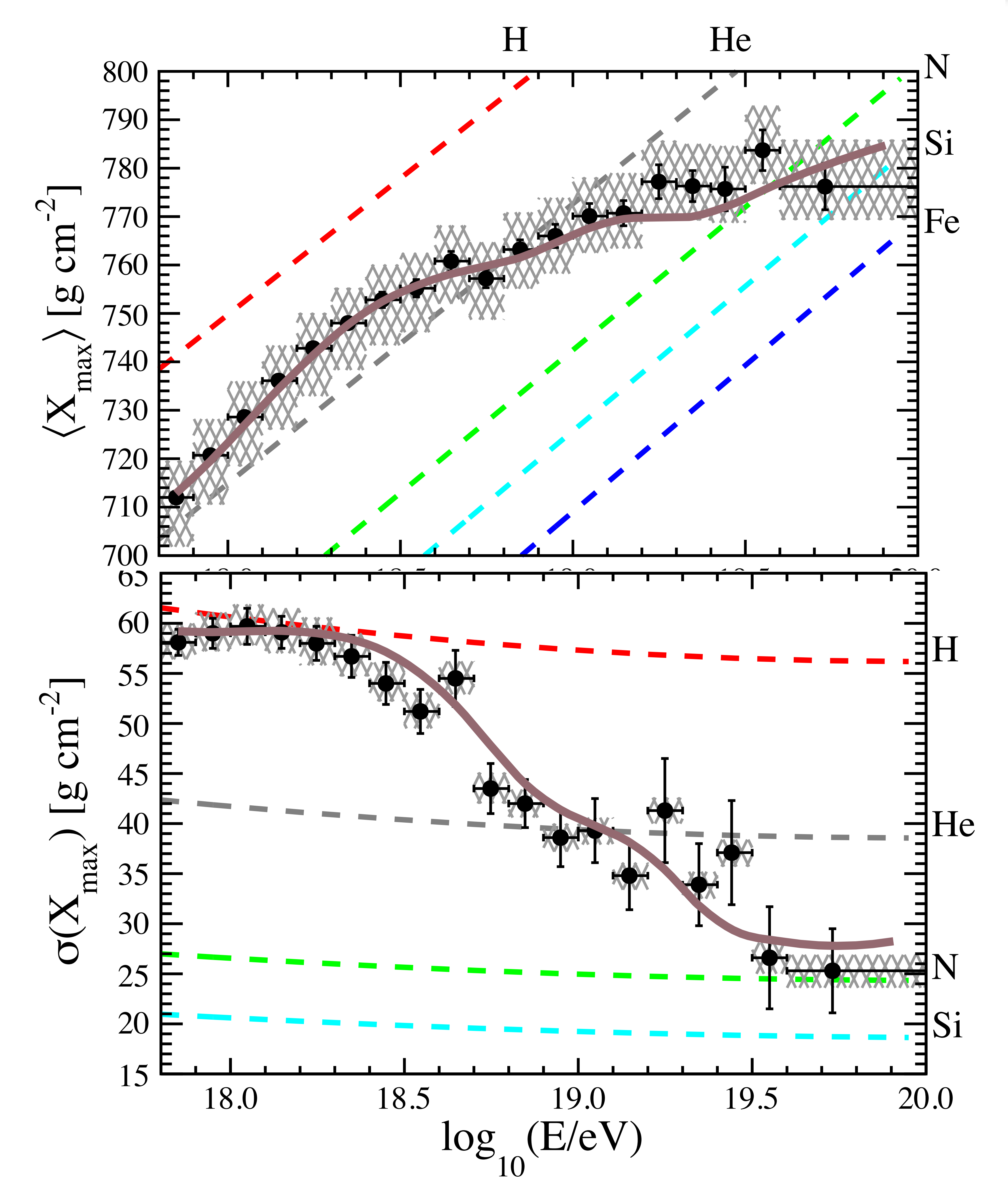

Combined fit of all-particle energy spectrum and CR mass composition:

- assuming uniformly distributed identical sources
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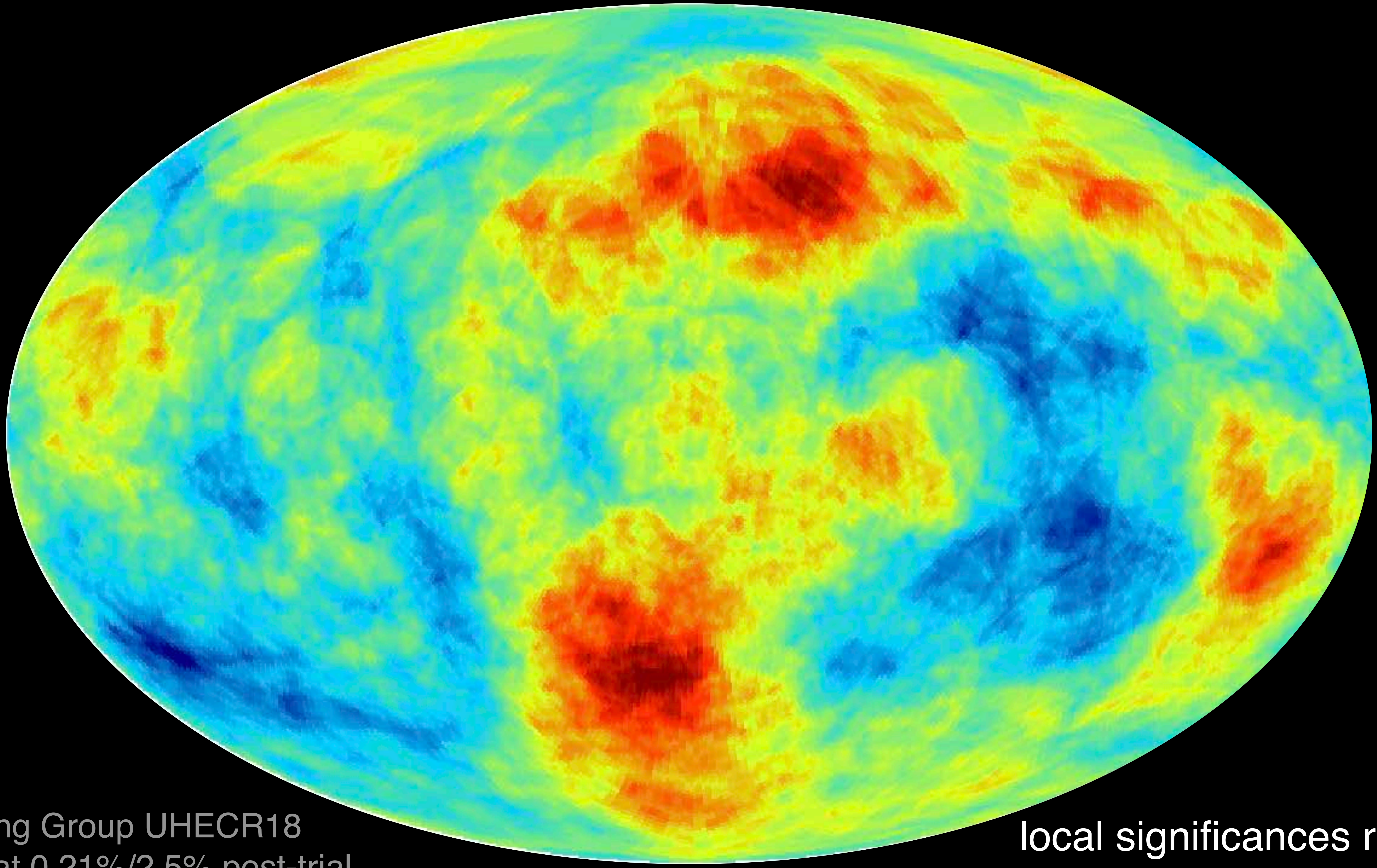
⇒ **Cut-Off appears mostly an effect of sources**

⇒ Two consequences:

1) **Dramatic reduction of cosmogenic ν, γ**
2) **Source hunting more demanding**

UHECR Anisotropies

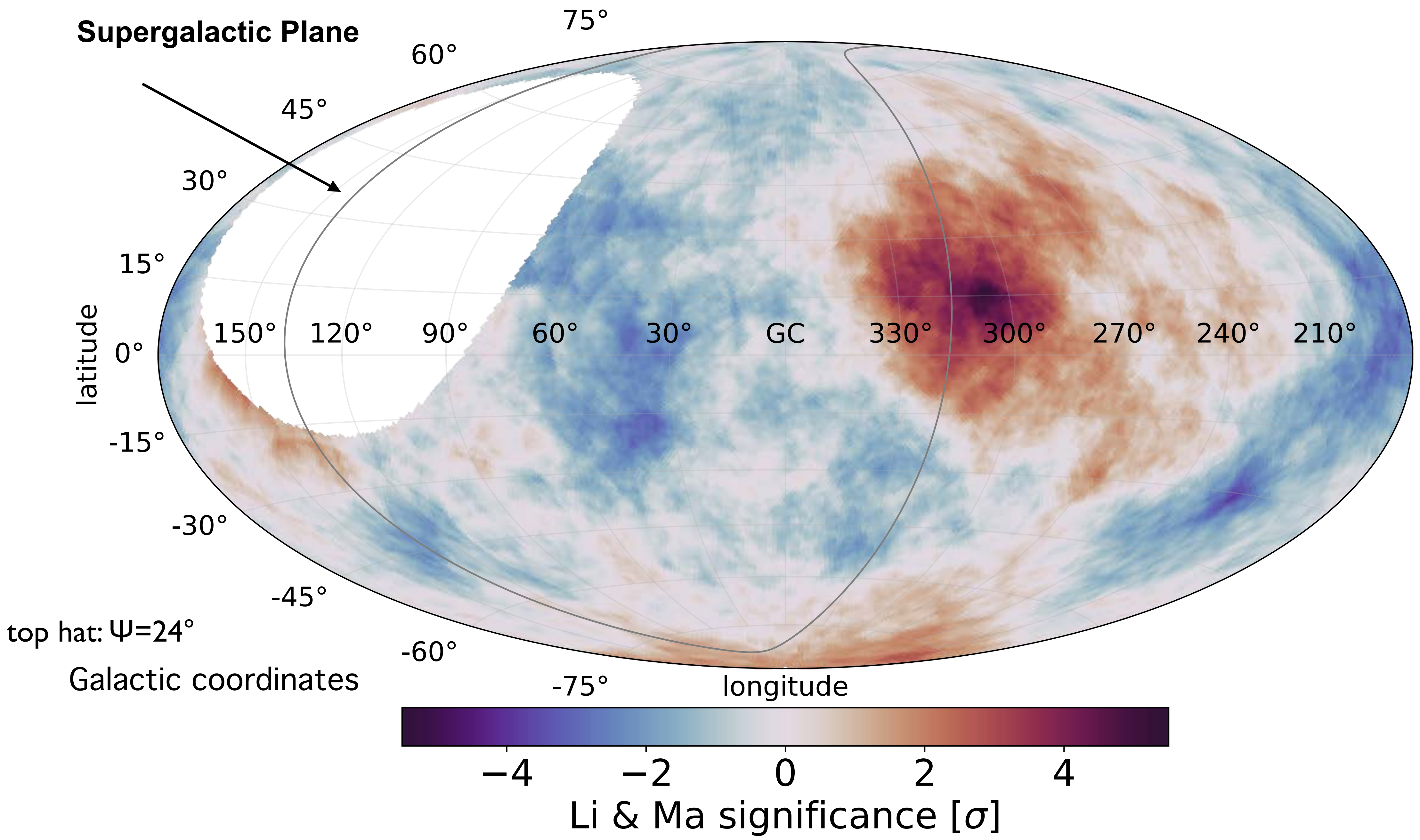


Auger/TA Anisotropy Working Group UHECR18
E > 40/52.3 EeV, 20° top-hat 0.21%/2.5% post-trial

local significances range from +4σ to -σ
Auger/TA Anisotropy Working Group UHECR

Comparing Sky Models (Auger only)

Observed sky E > 41 EeV



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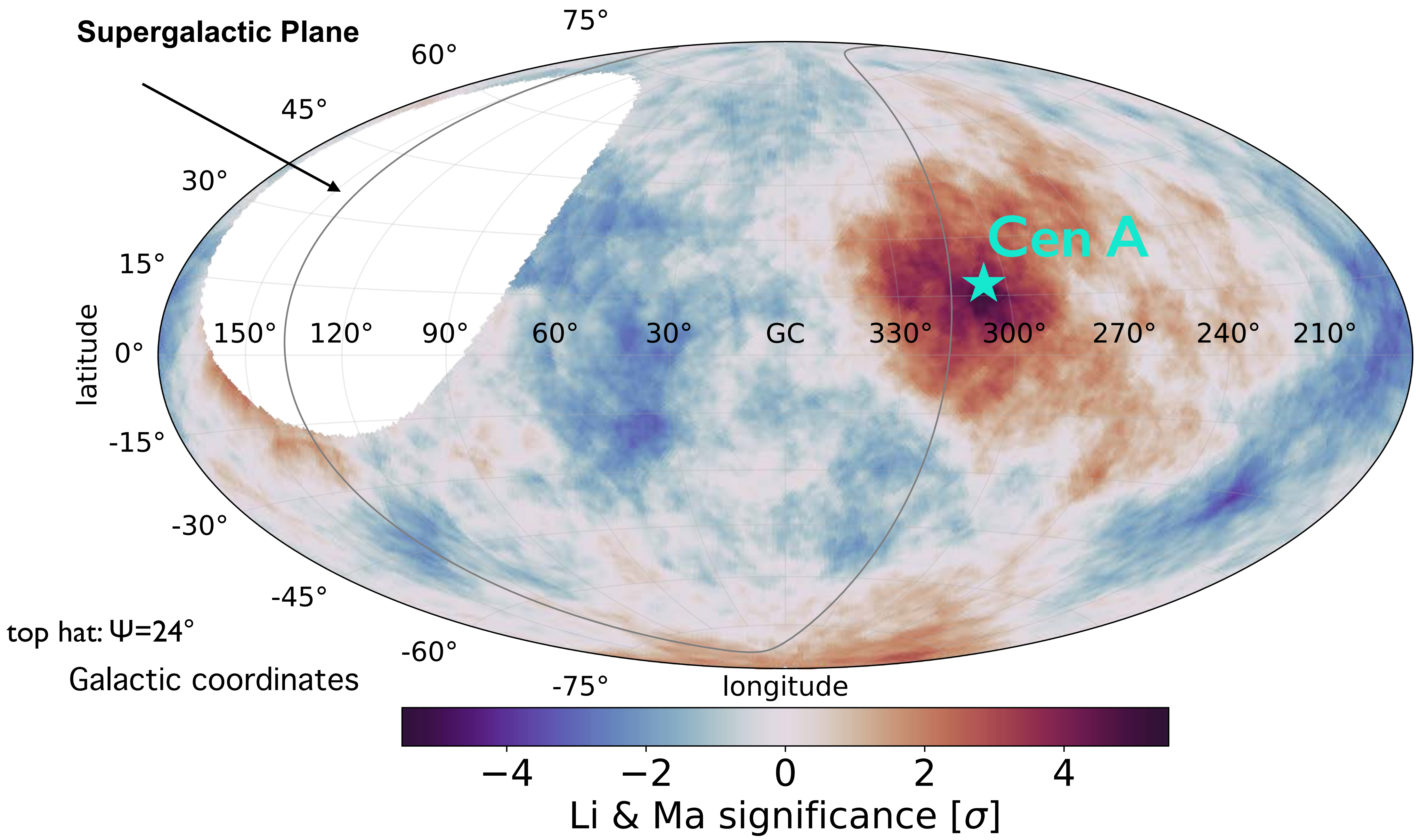

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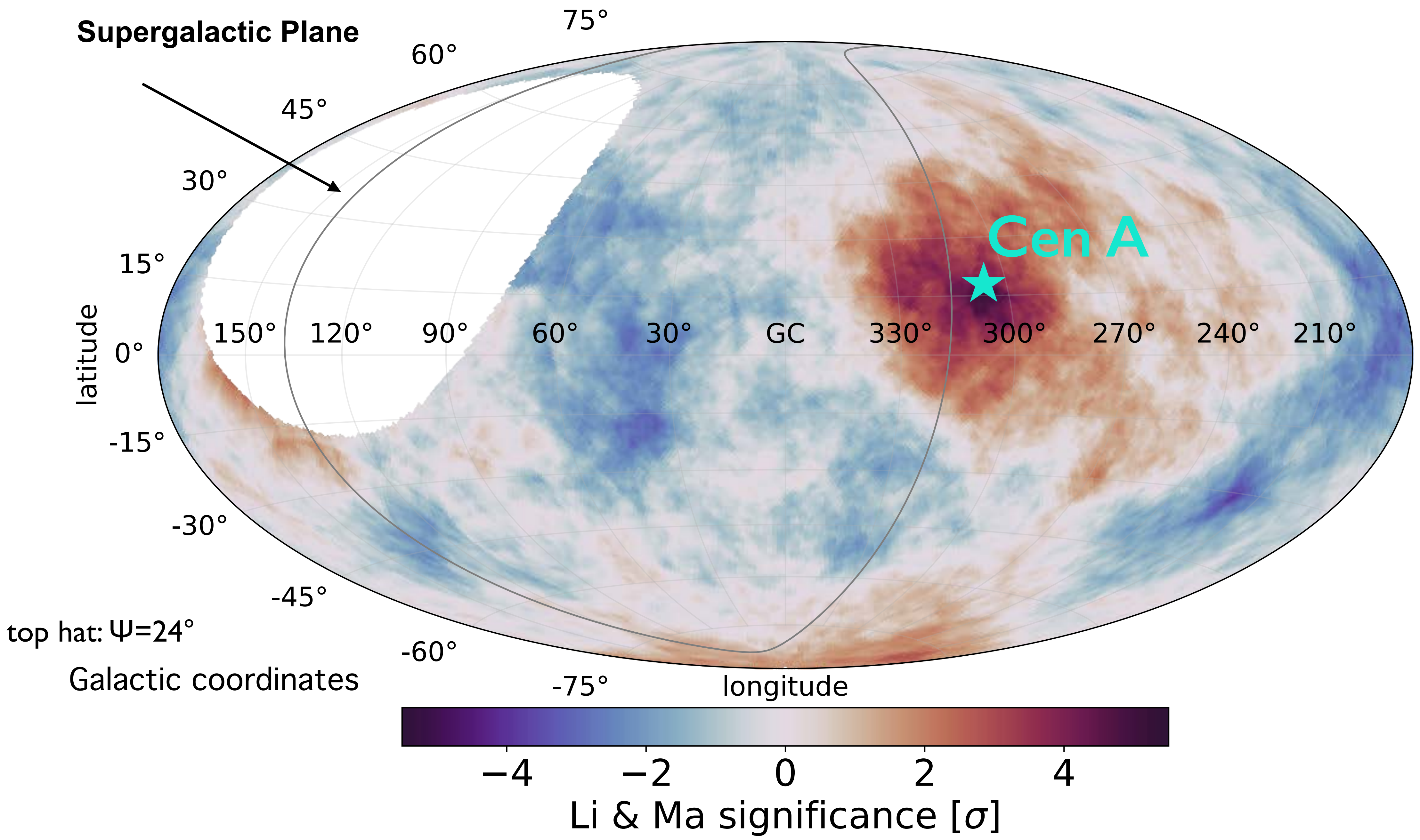

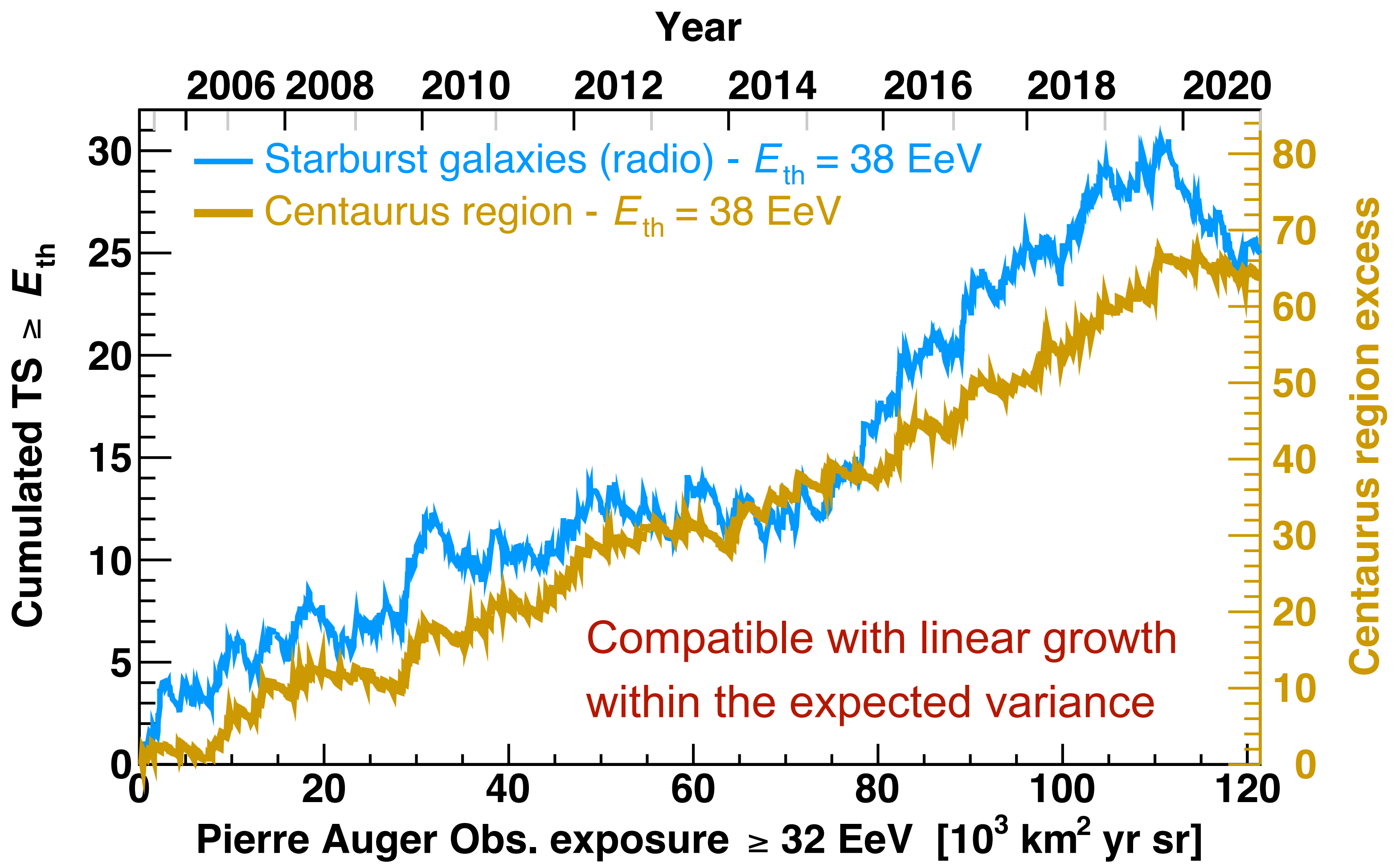

4σ

Comparing Sky Models (Auger only)

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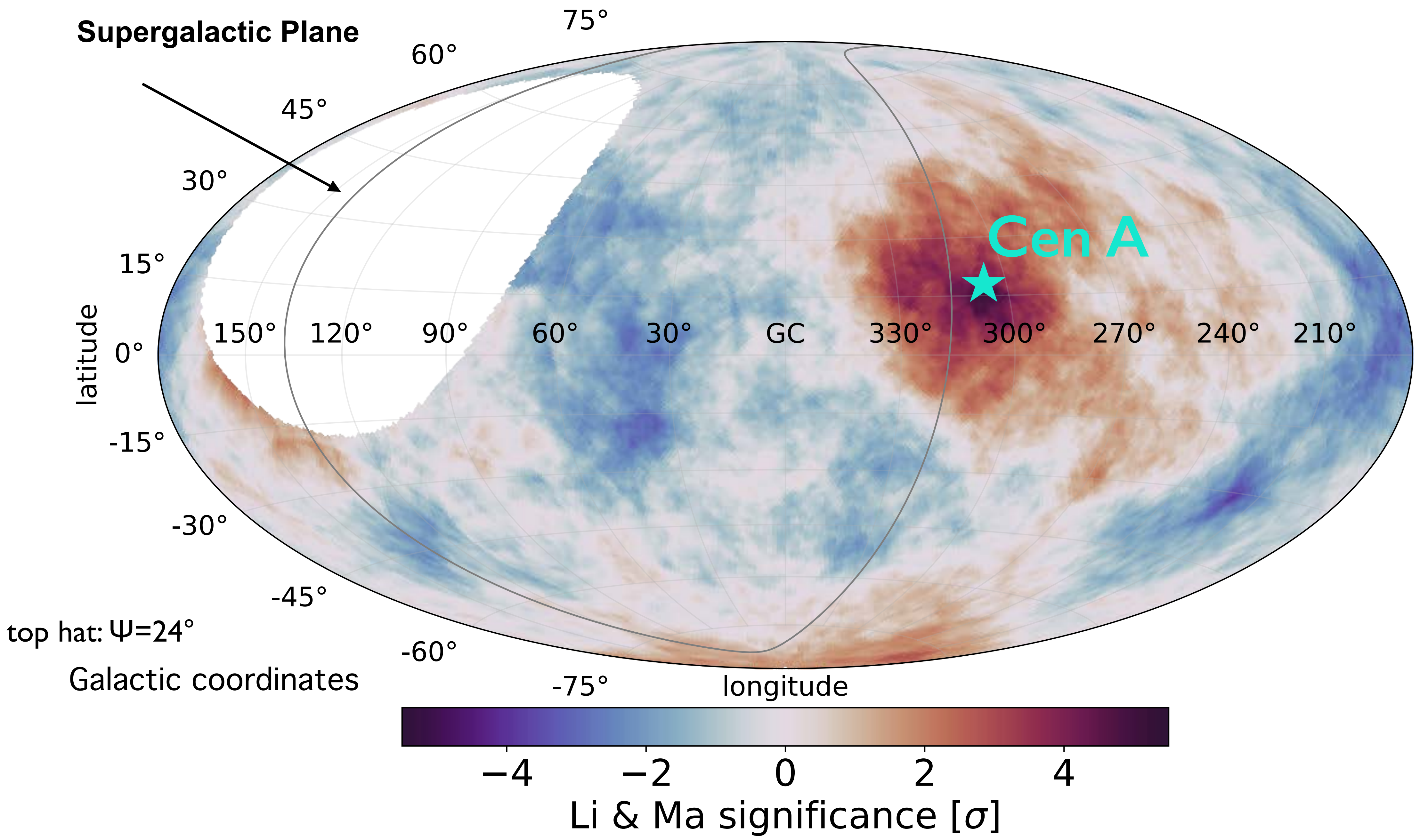
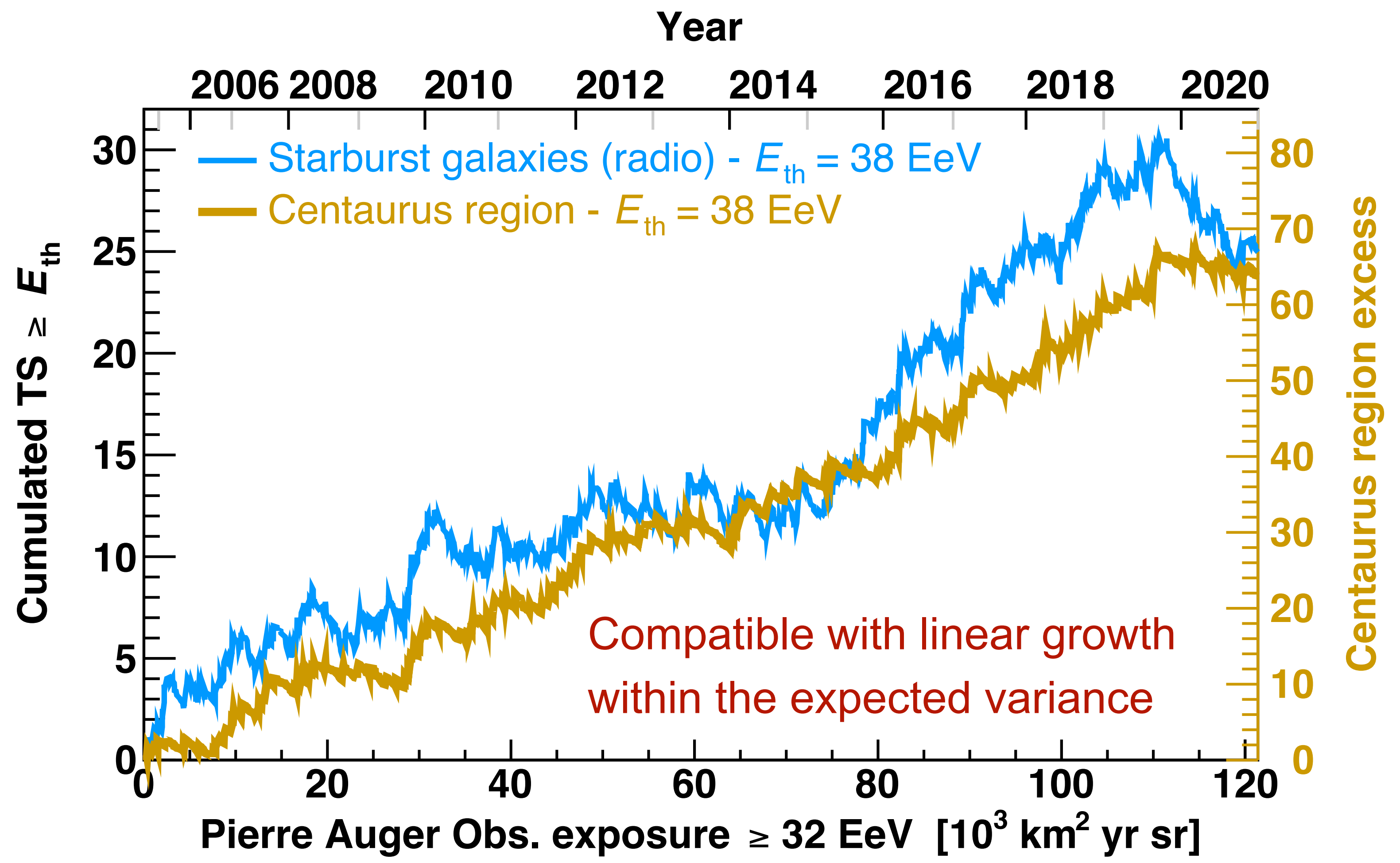
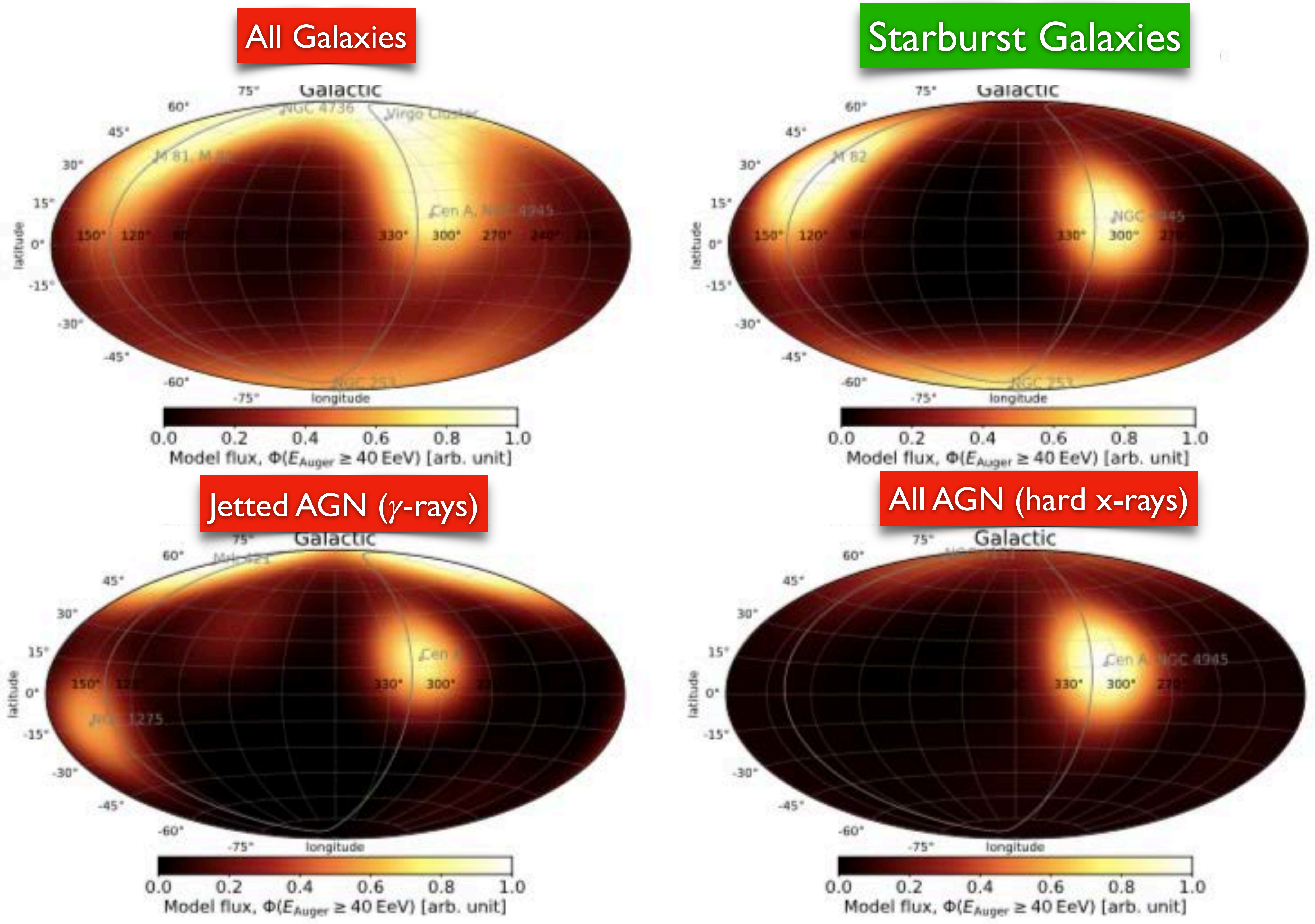




4σ

Best Fit Models E > 40 EeV



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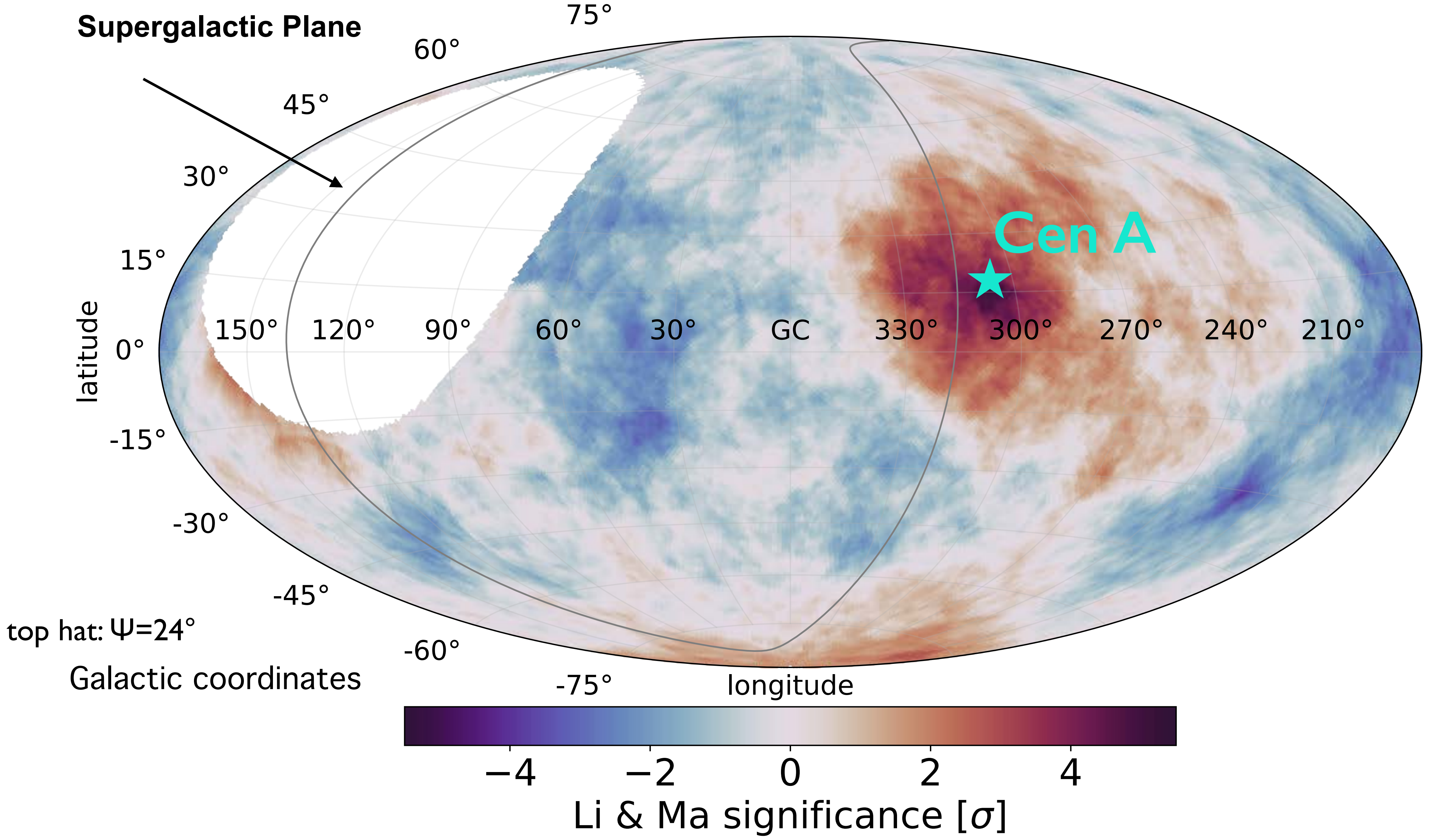
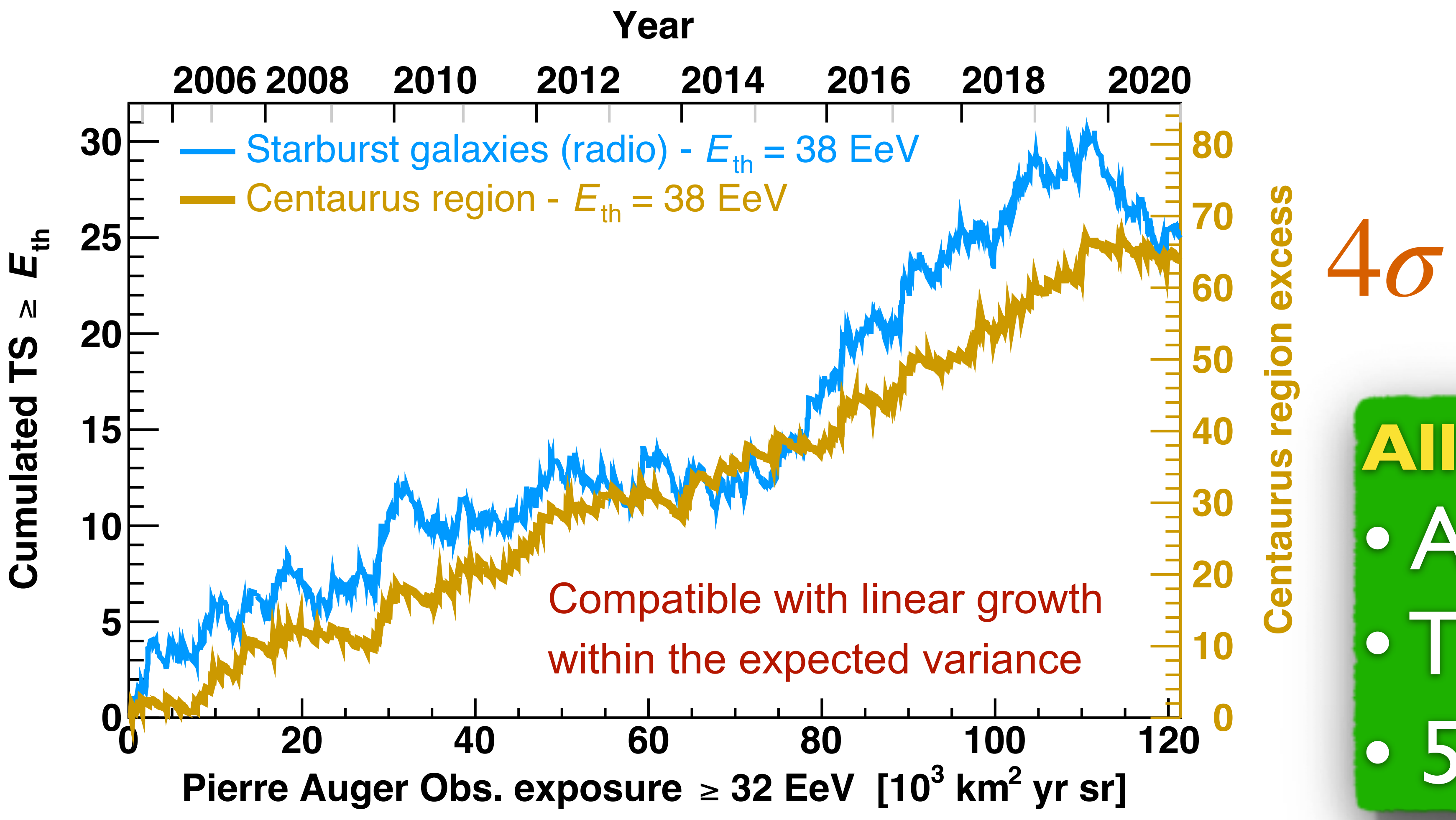
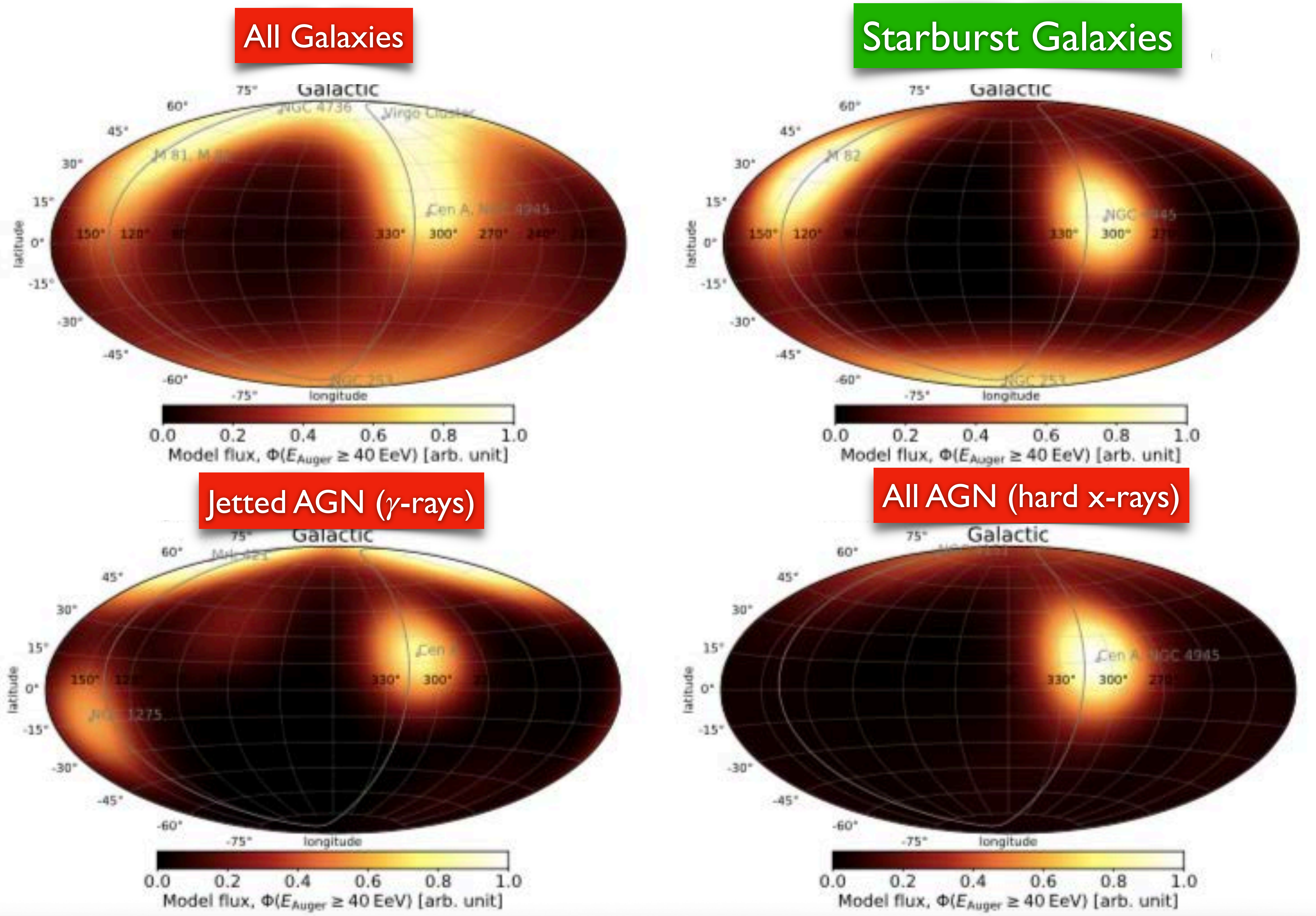




Best Fit Models E > 40 EeV

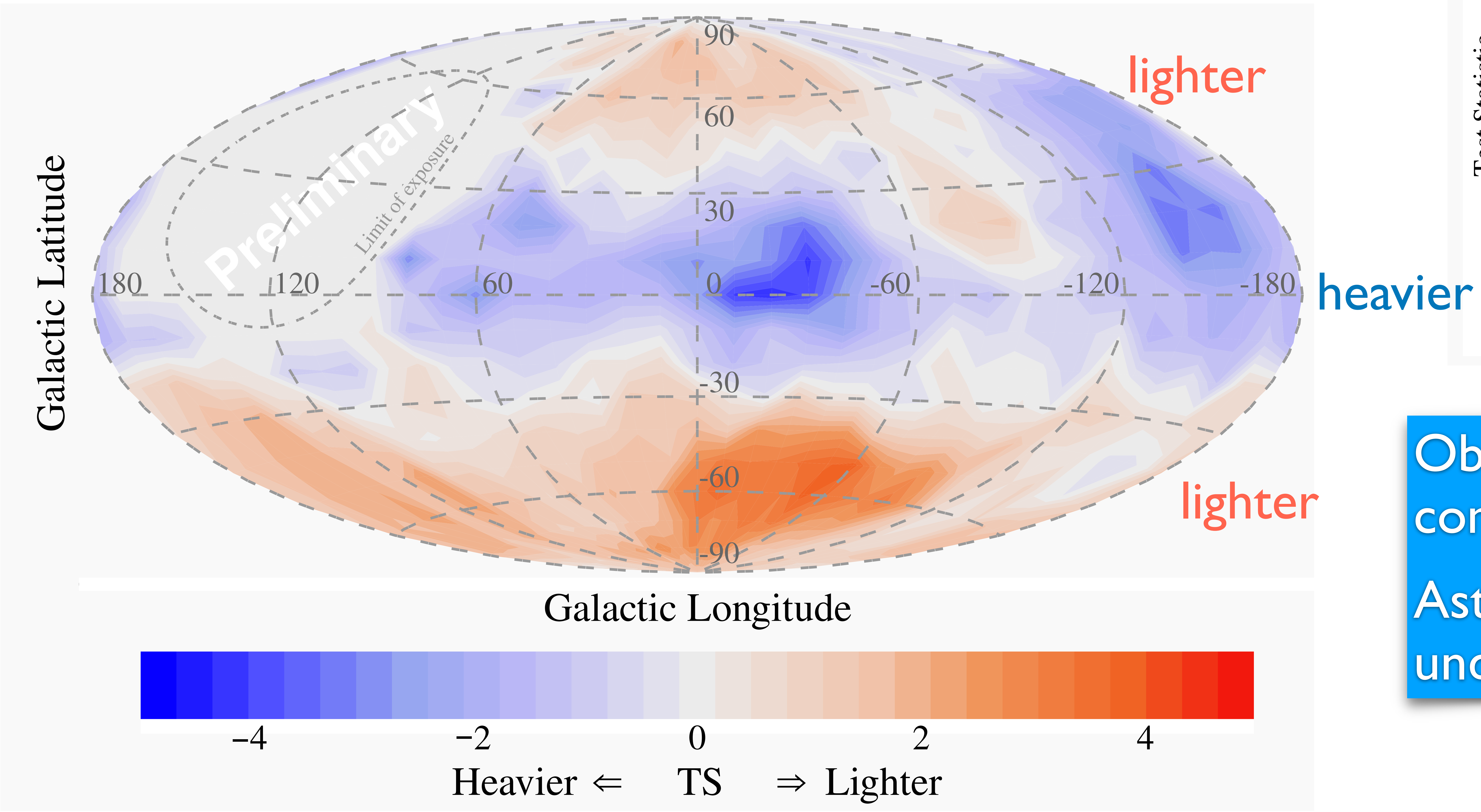


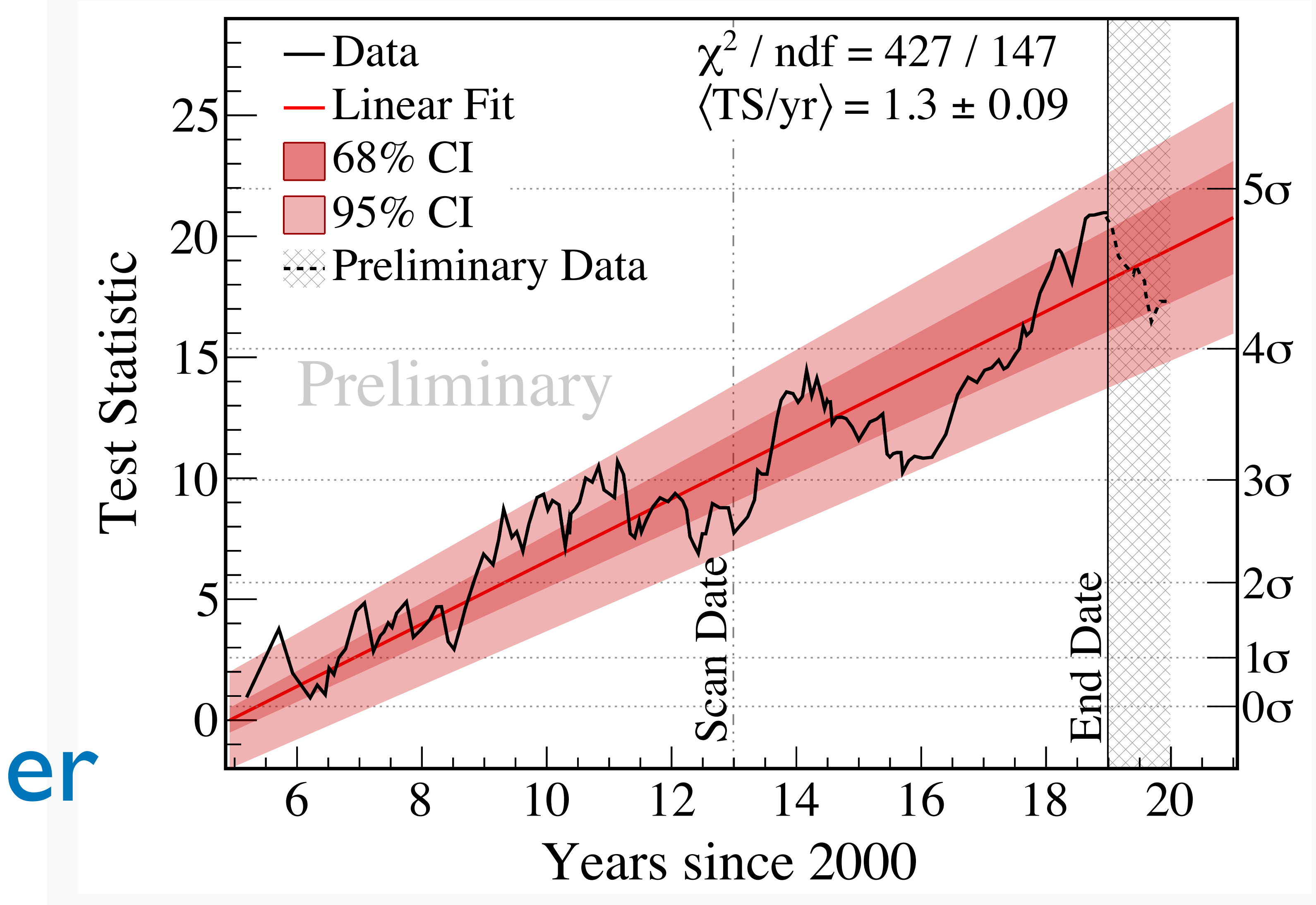
All models account for the measured mass composition and deflections in B-fields

- All source catalogues capture the hotspot in the centaurus region
- The Starburst model adds the excess at the Galactic South Pole (NGC253)
- 5σ deviation expected in 2025±2 yrs

Unexpected Feature: Composition Anisotropy

$E > 5 \cdot 10^{18}$ eV





Observation verifies mixed composition above ankle

Astrophysics origin not yet understood

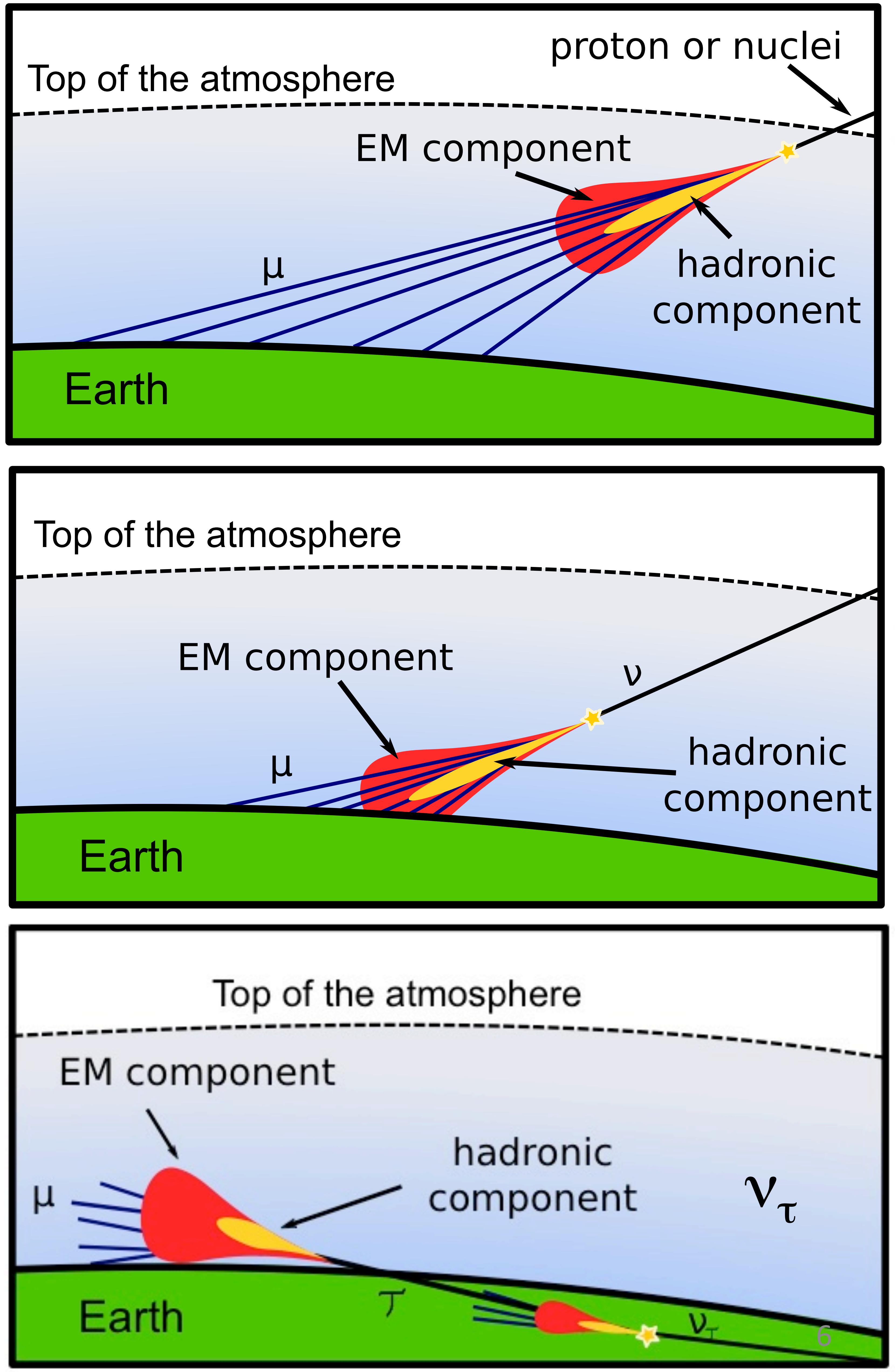
E. Mayotte (Auger-Collaboration), UHECR 20022

Cosmogenic Photons and Neutrinos

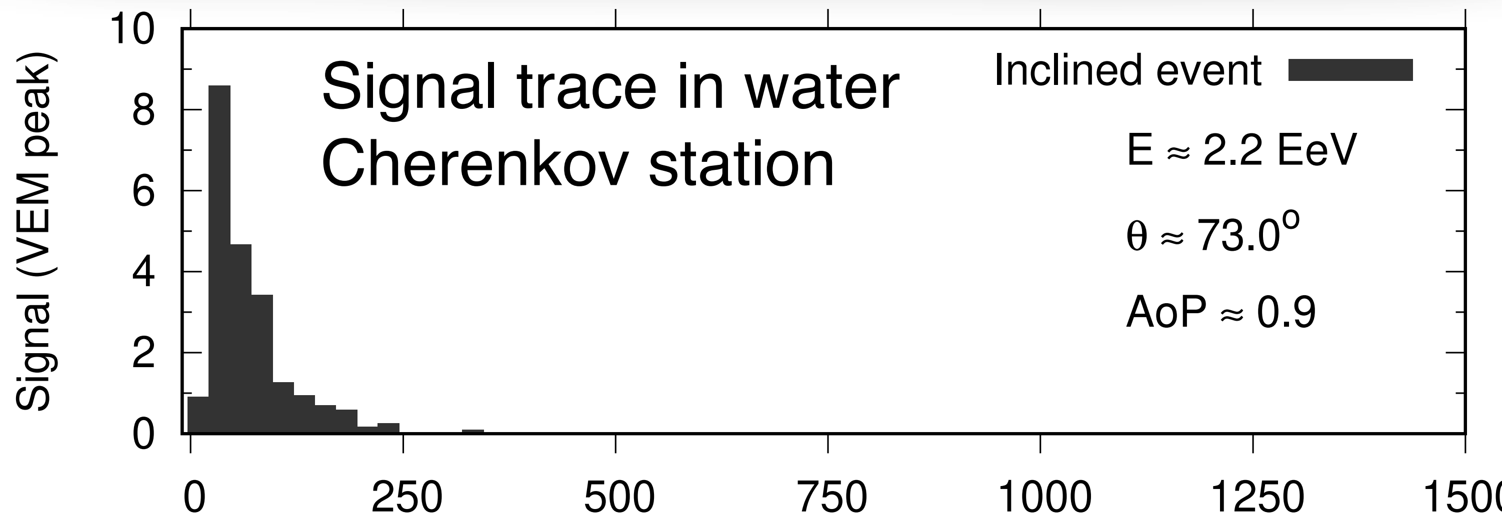
Inclined showers & UHE neutrinos

- 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

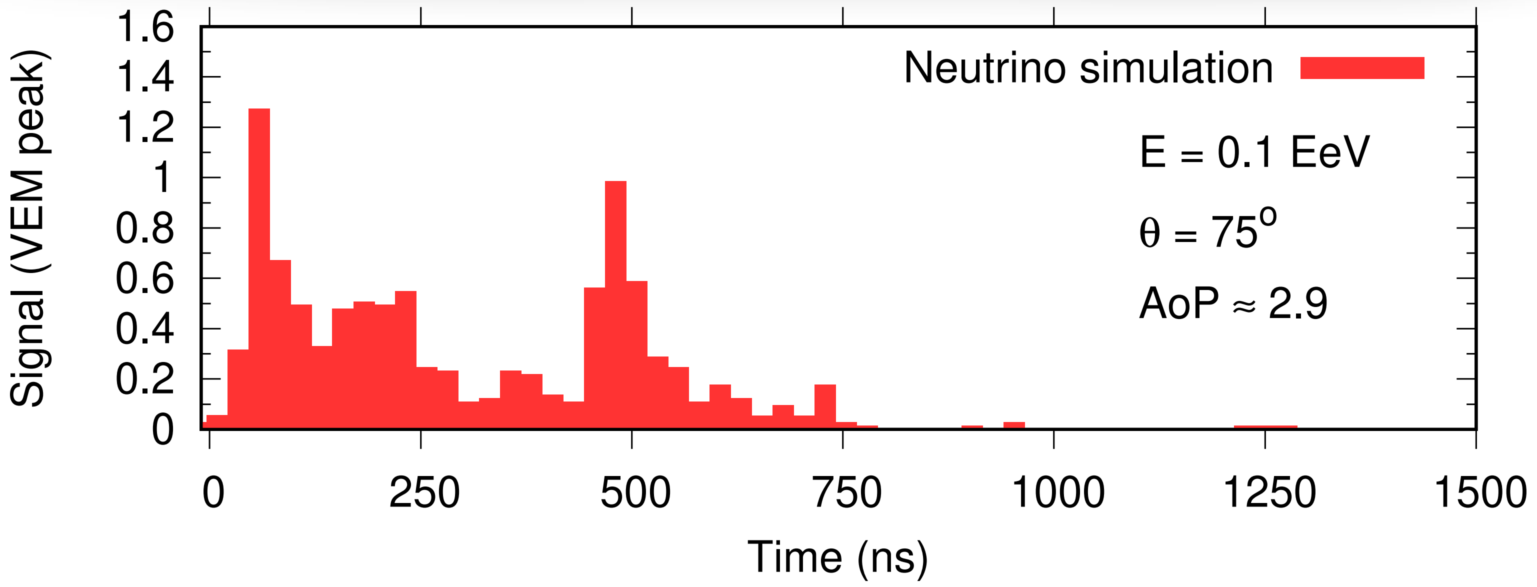
Searching for neutrinos ⇒ searching for inclined showers with electromagnetic component

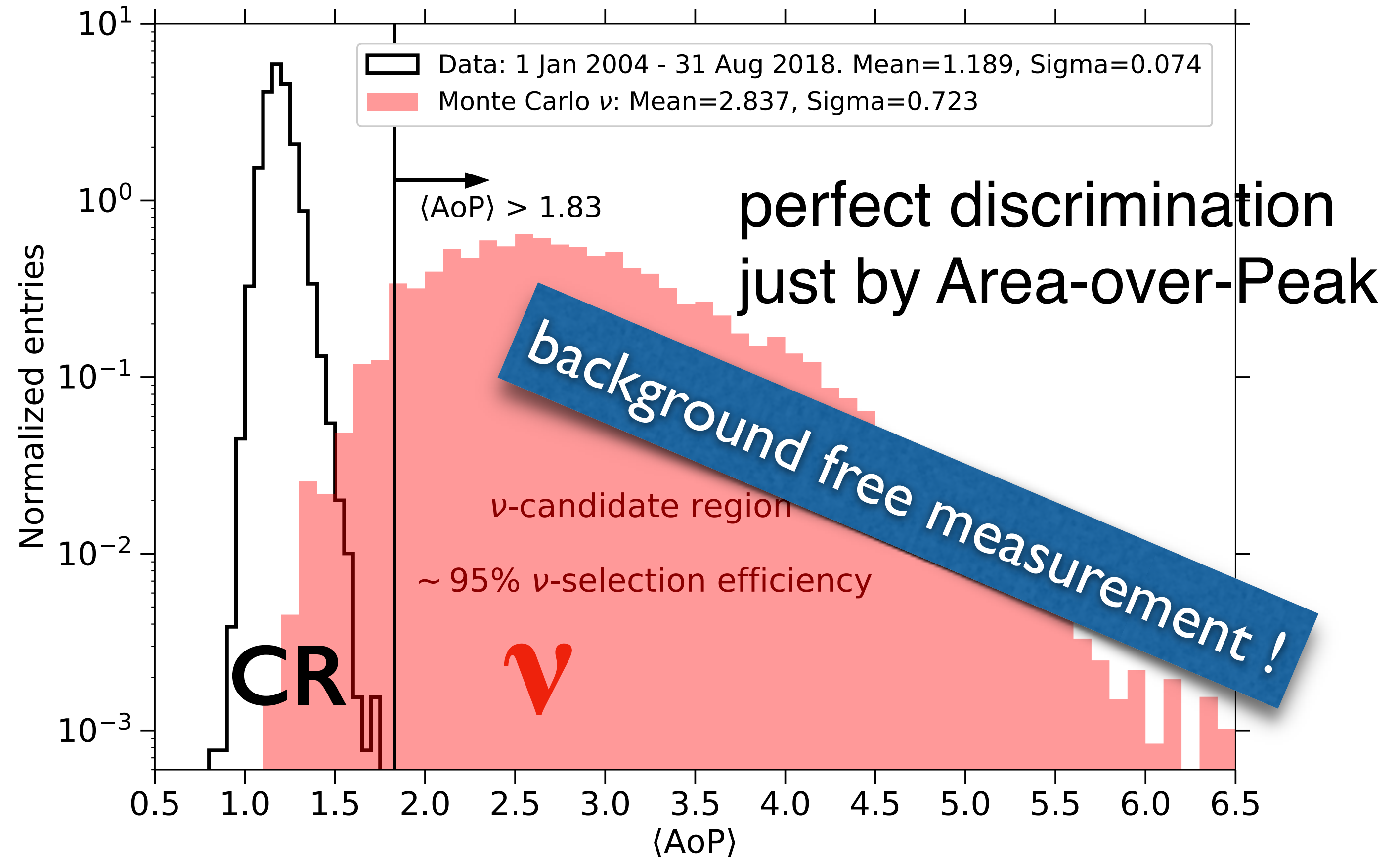


CR → old shower at ground



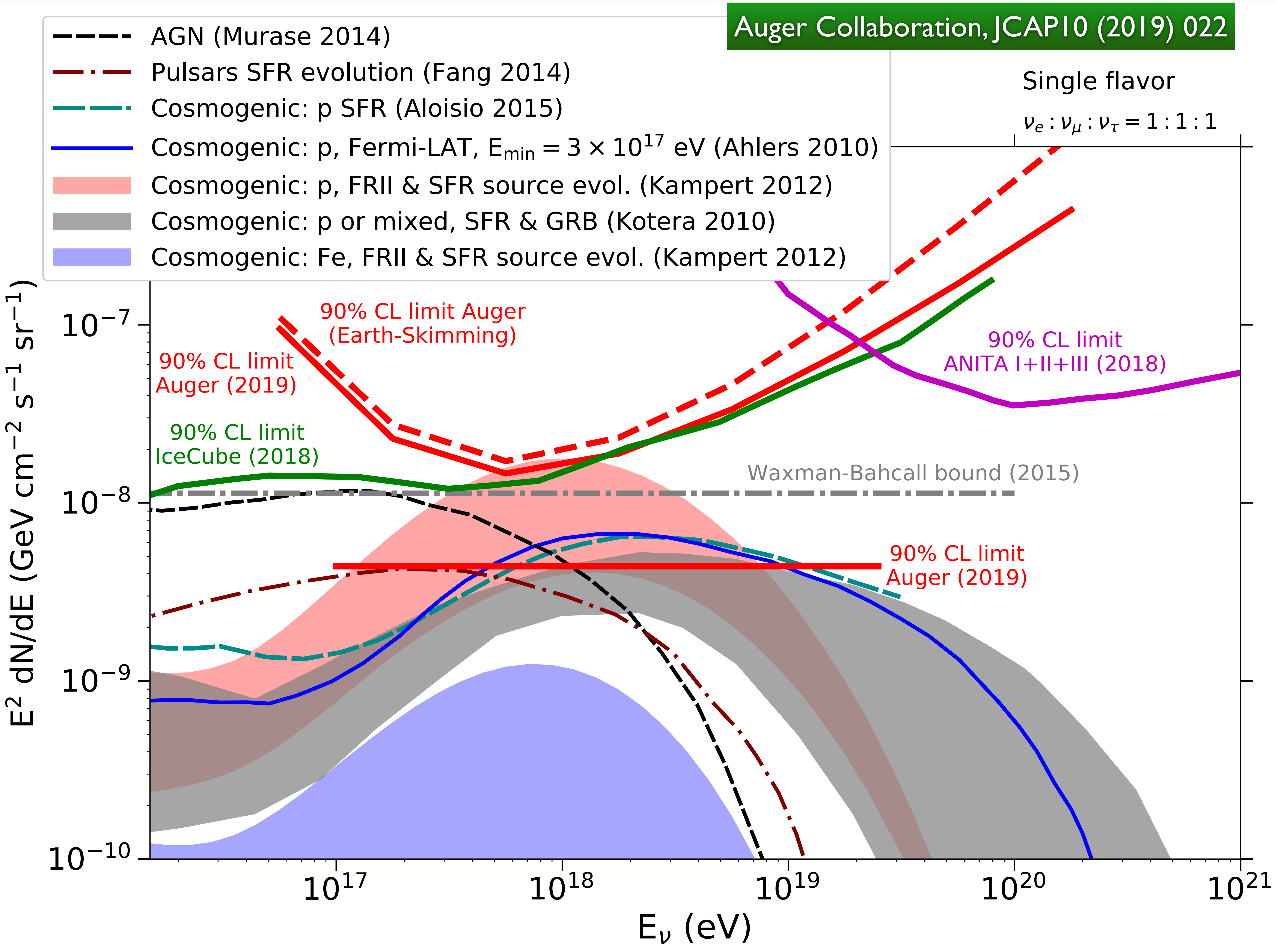
ν → young shower at ground



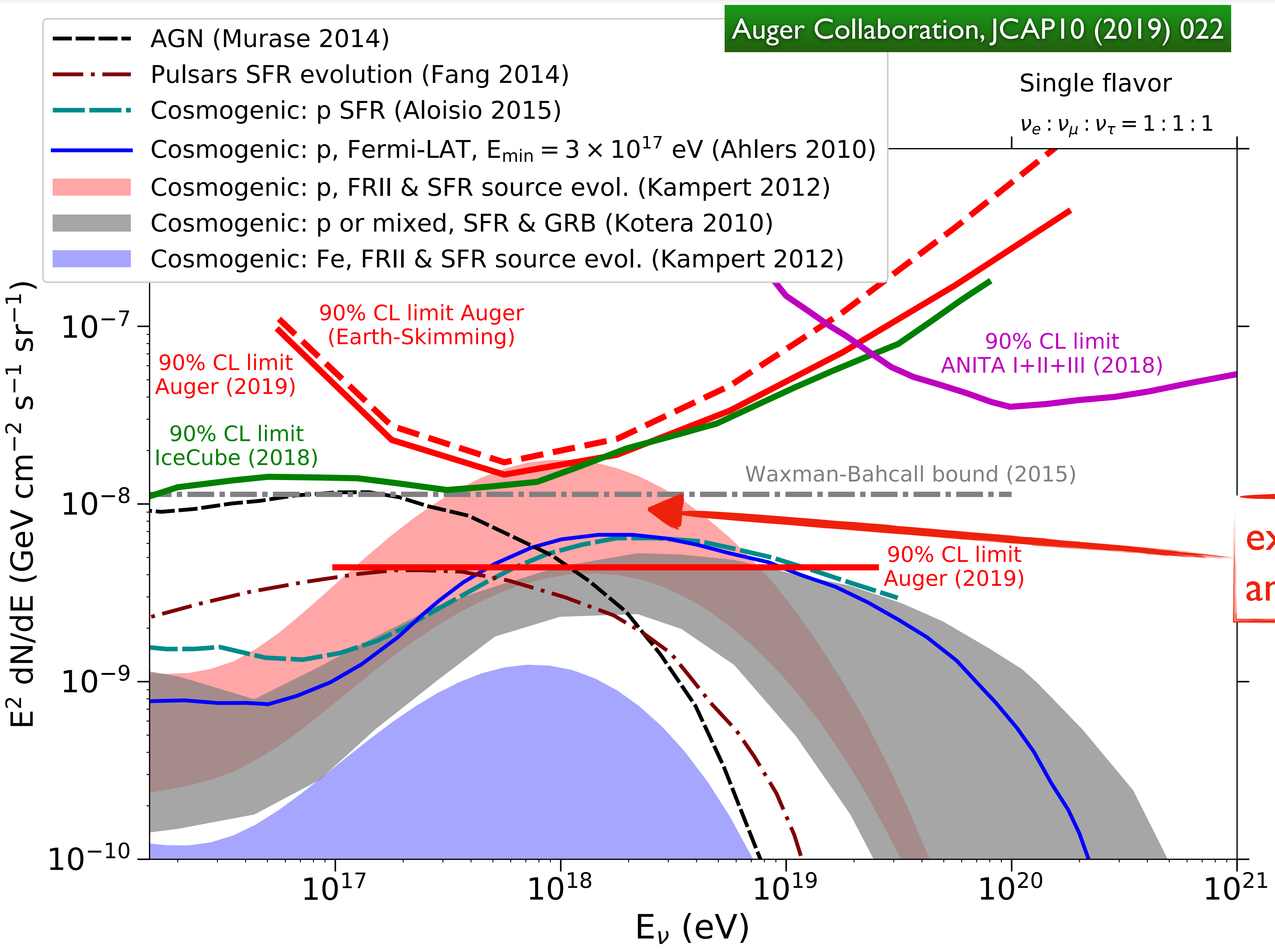


Bounds on cosmogenic neutrino fluxes

Auger Collaboration, JCAP10 (2019) 022



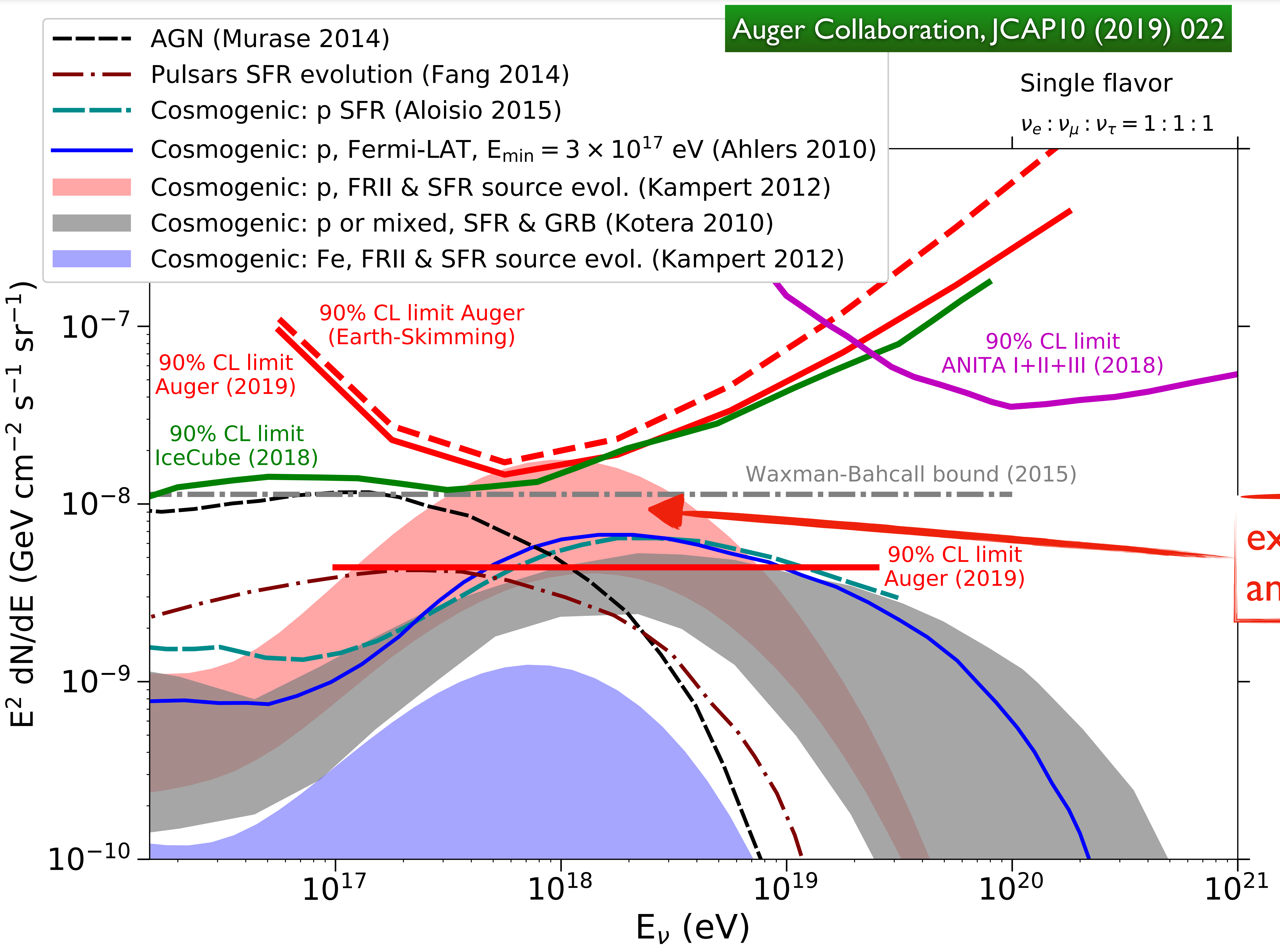
Bounds on cosmogenic neutrino fluxes

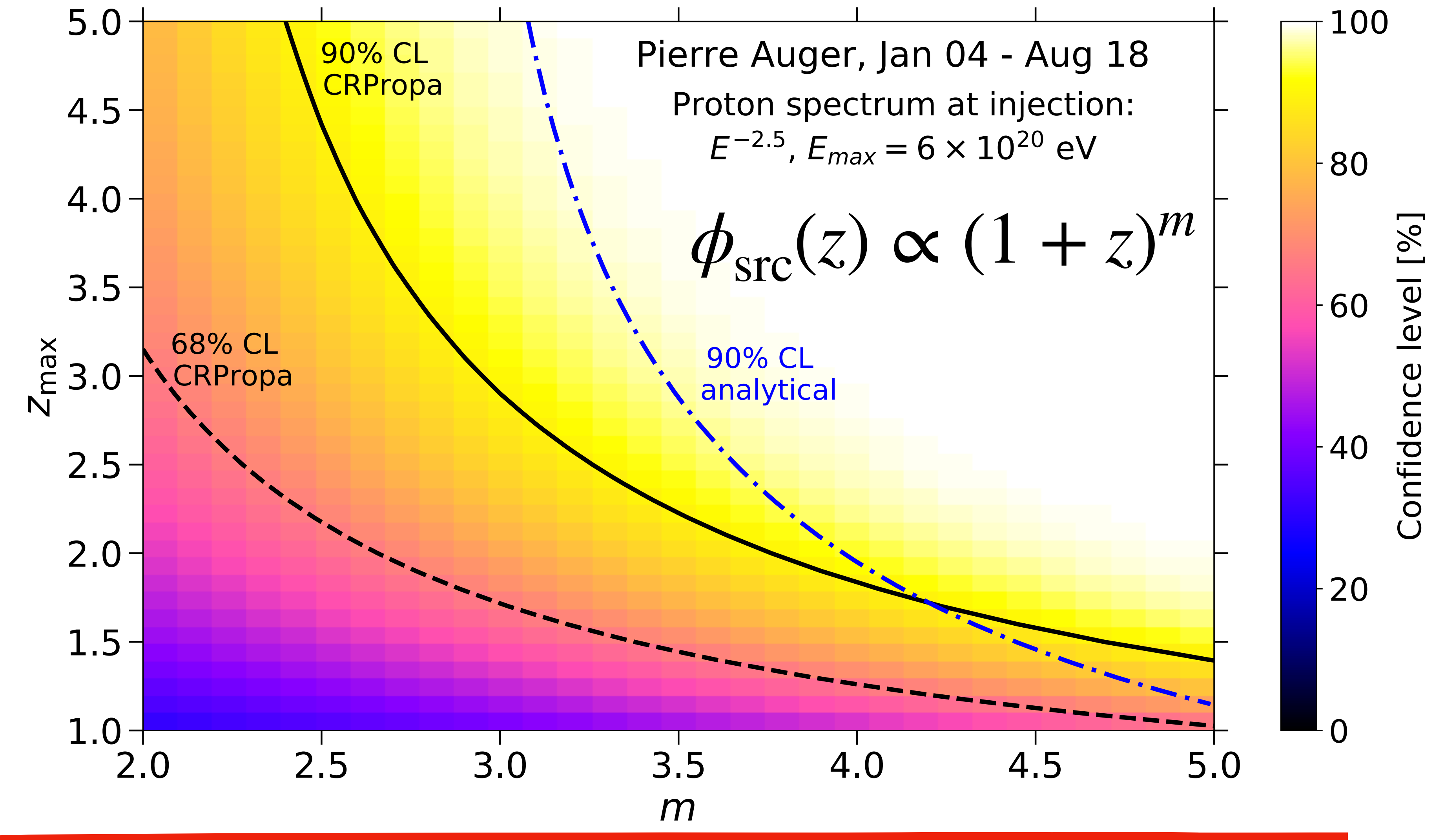


expect up to 6 νs for pure p-composition and spectral cut-off be caused by GZK-effect

Bounds on cosmogenic neutrino fluxes

Auger Collaboration, JCAP10 (2019) 022





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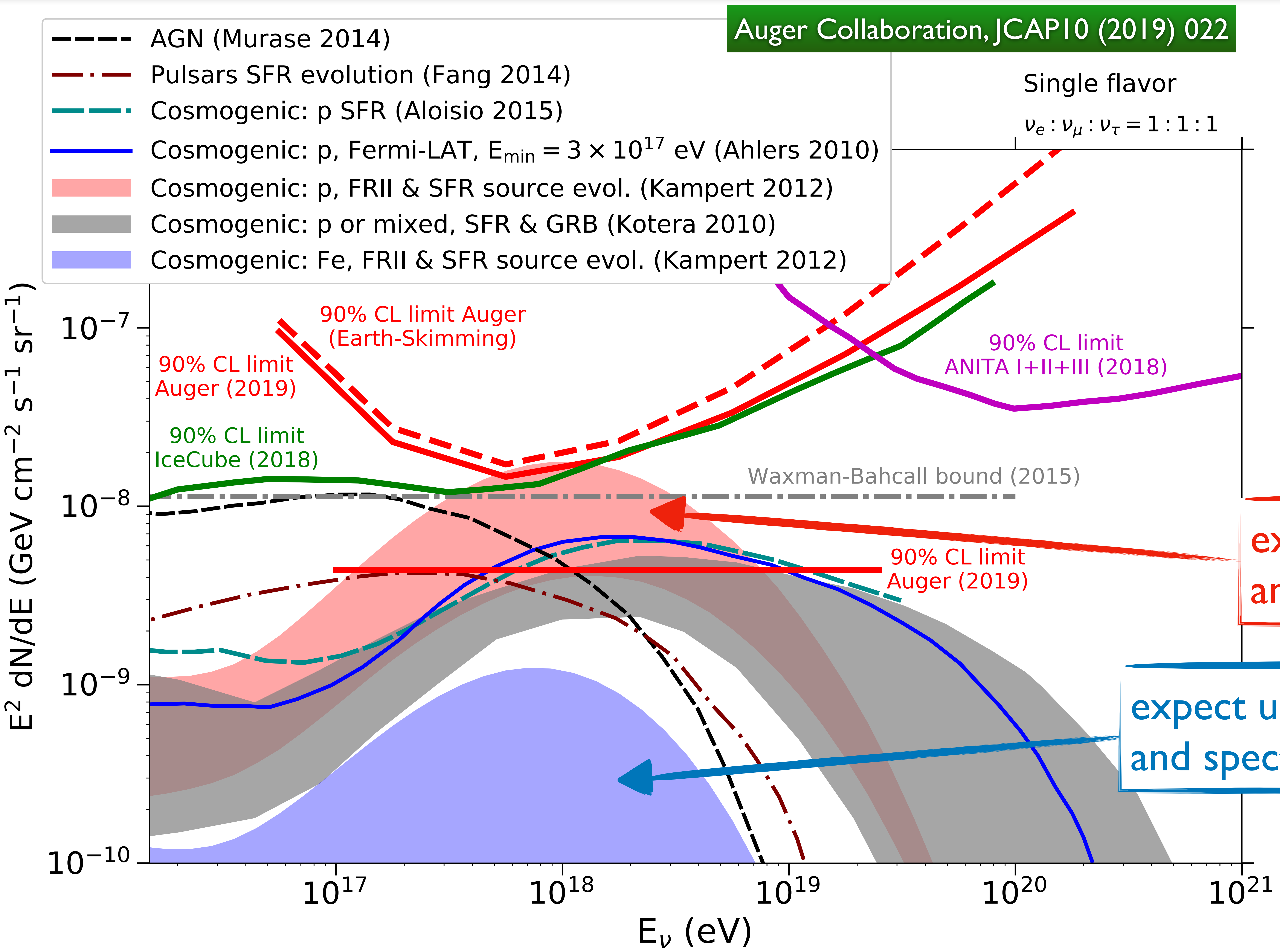
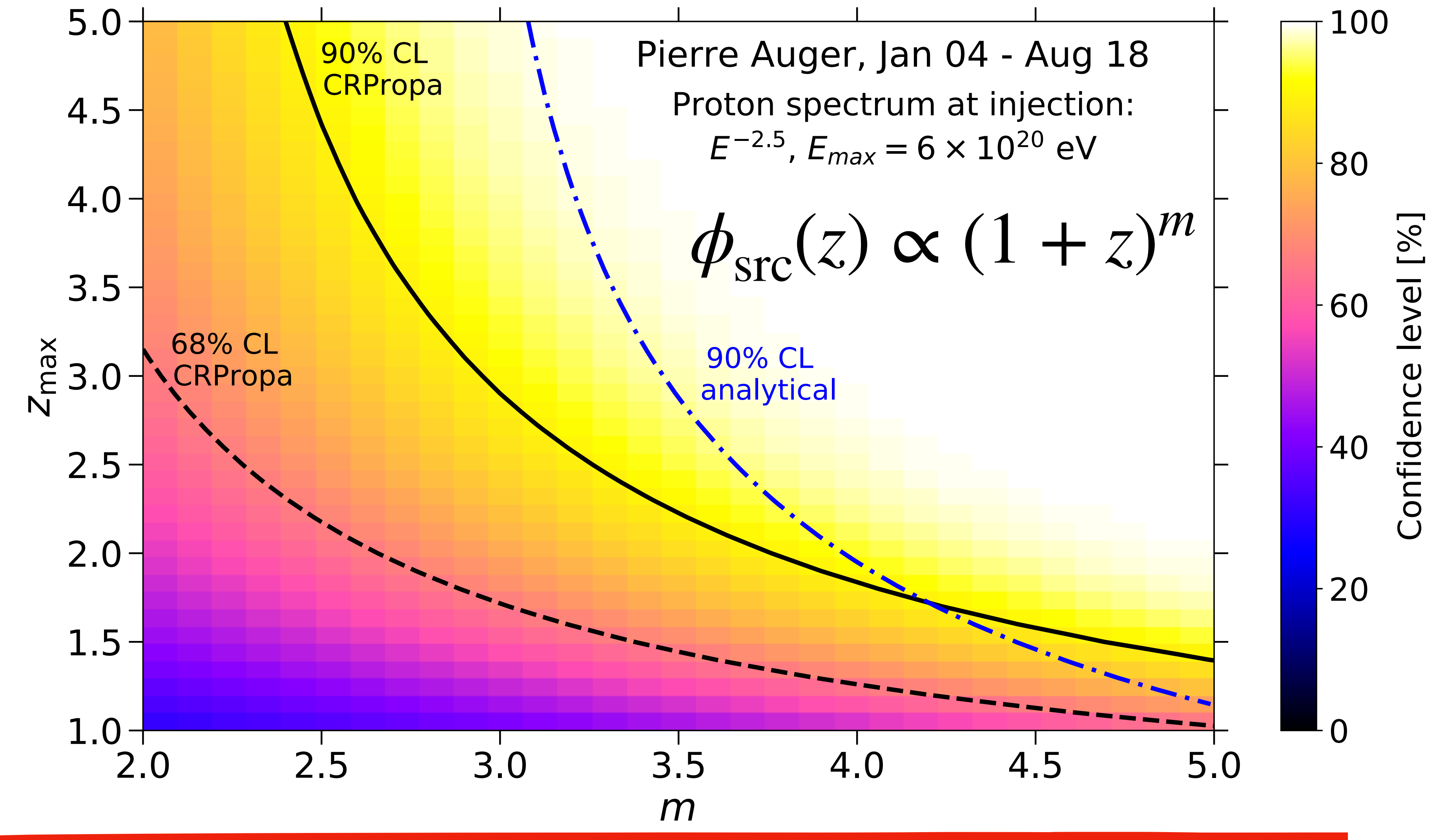
Bounds on cosmogenic neutrino fluxes

Auger Collaboration, JCAP10 (2019) 022



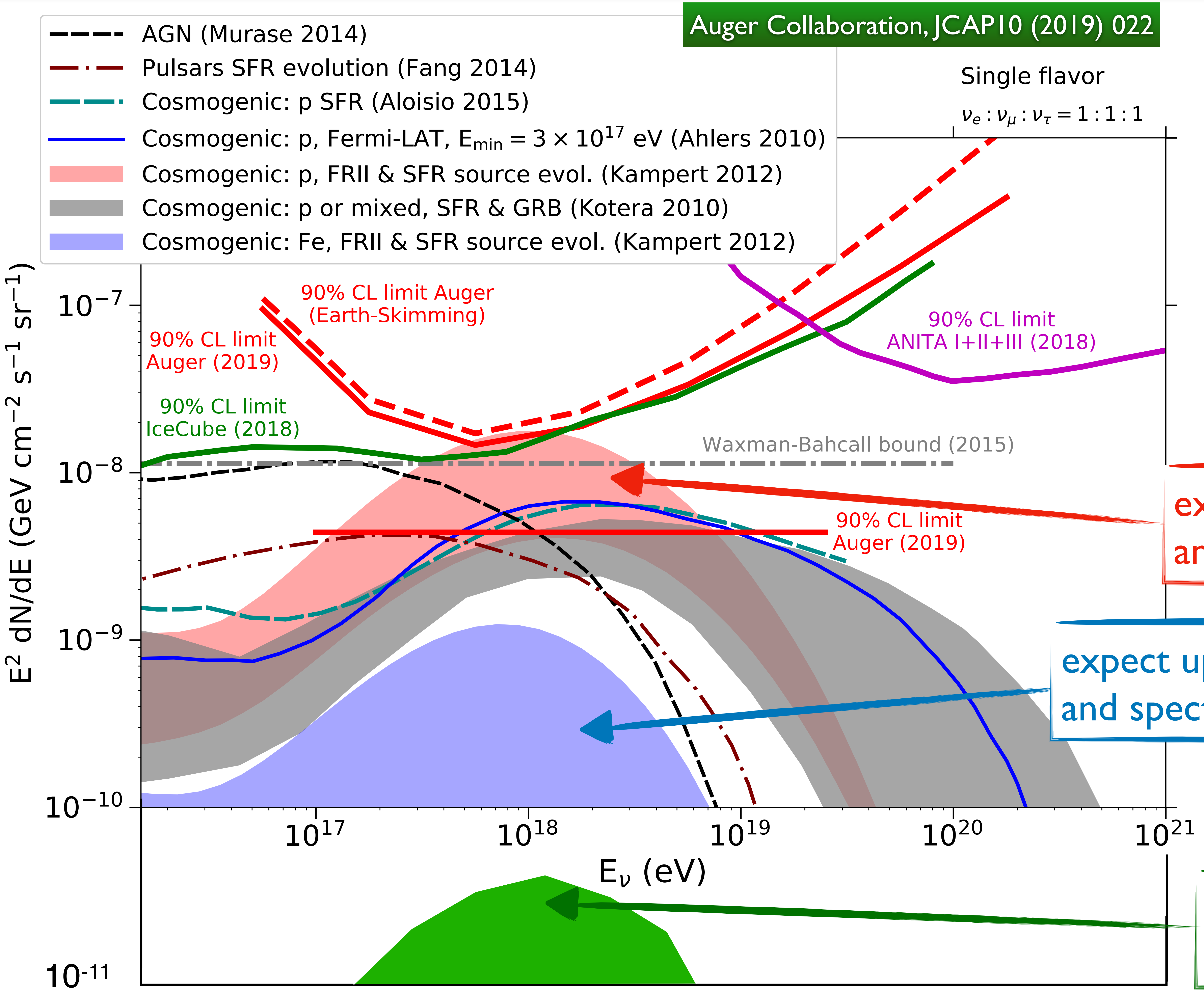


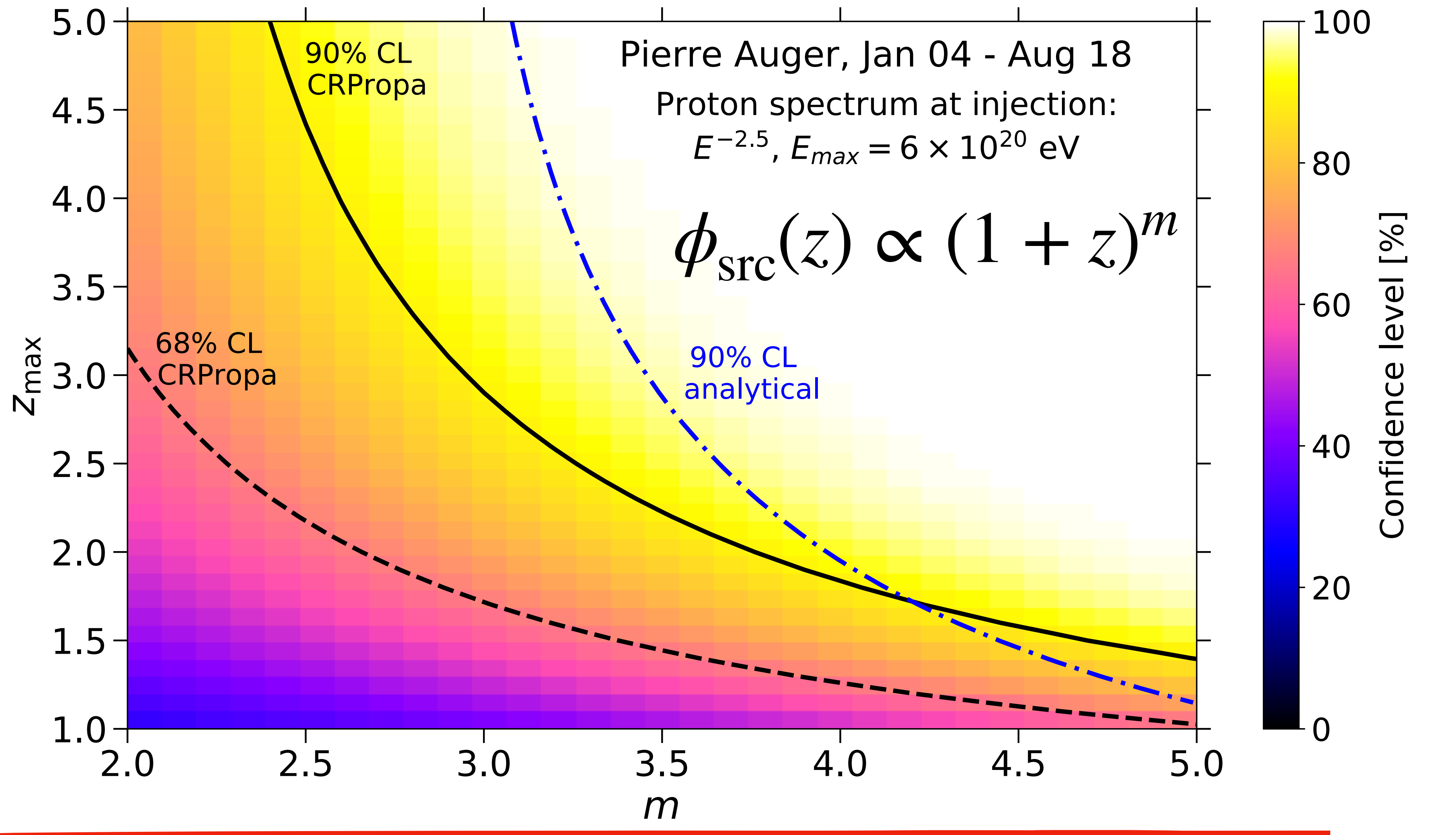
expect up to 6 νs for pure p-composition and spectral cut-off be caused by GZK-effect

expect up to 0.4 νs for pure Fe-composition and spectral cut-off be caused by GZK-effect

Bounds on cosmogenic neutrino fluxes

Auger Collaboration, JCAP10 (2019) 022





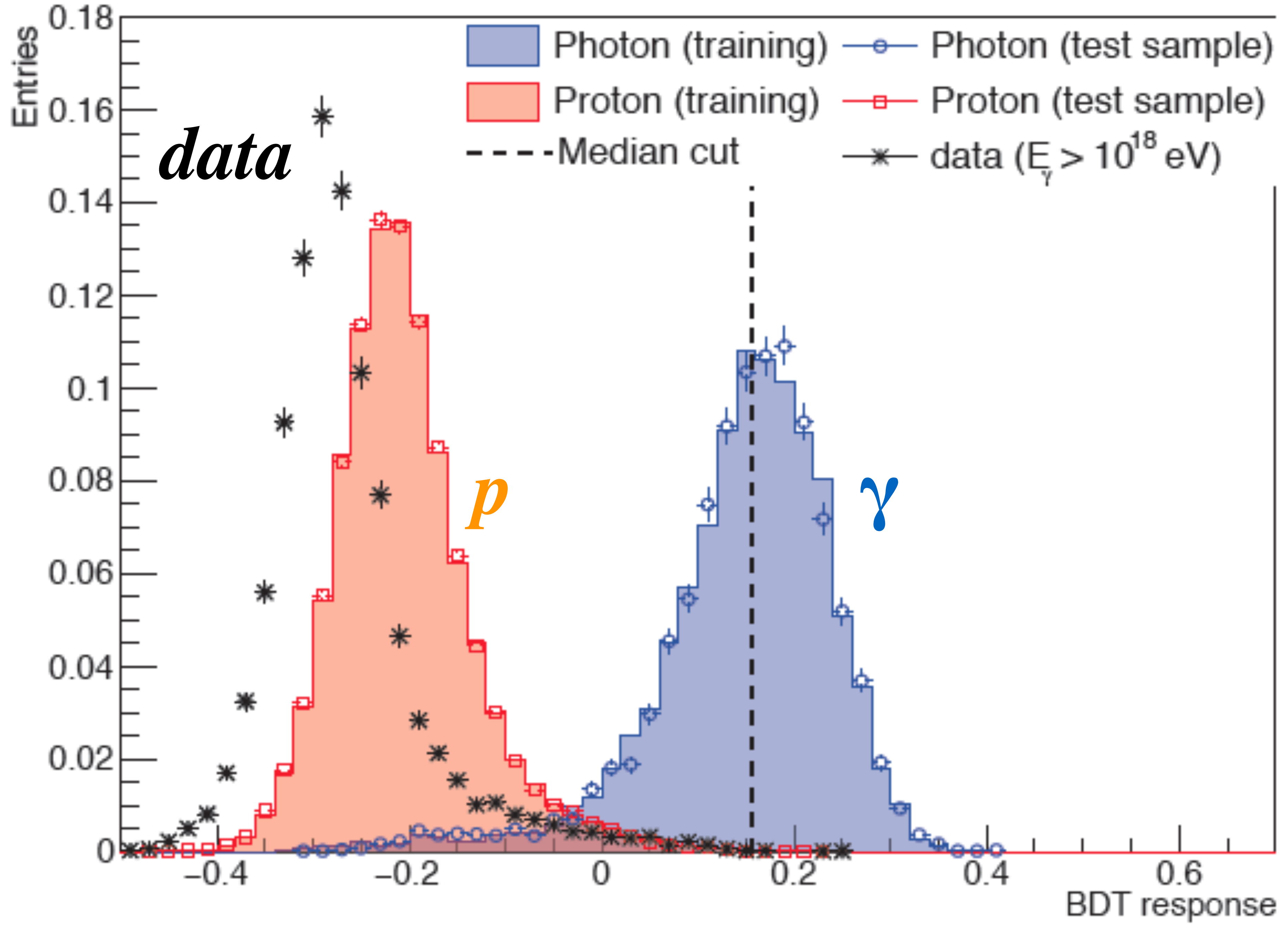
expect up to 6 νs for pure p-composition and spectral cut-off be caused by GZK-effect

expect up to 0.4 νs for pure Fe-composition and spectral cut-off be caused by GZK-effect

expect up to ~0.001 νs in Auger (& IceCube) for maximum source energy scenario

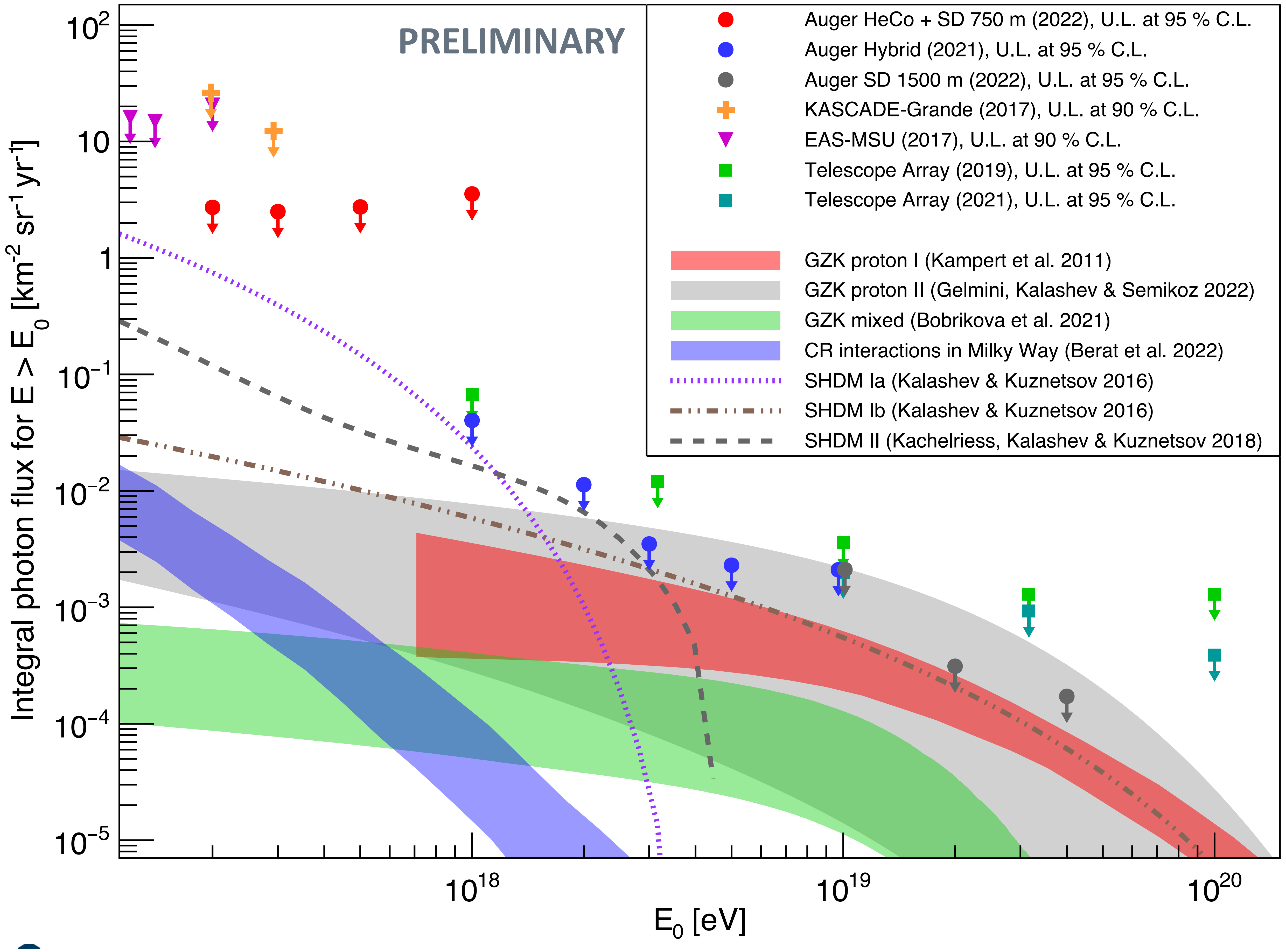
EeV Photon Limits challenge protons suffering GZK-losses

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



Auger Collaboration, JCAP04 (2017) 009

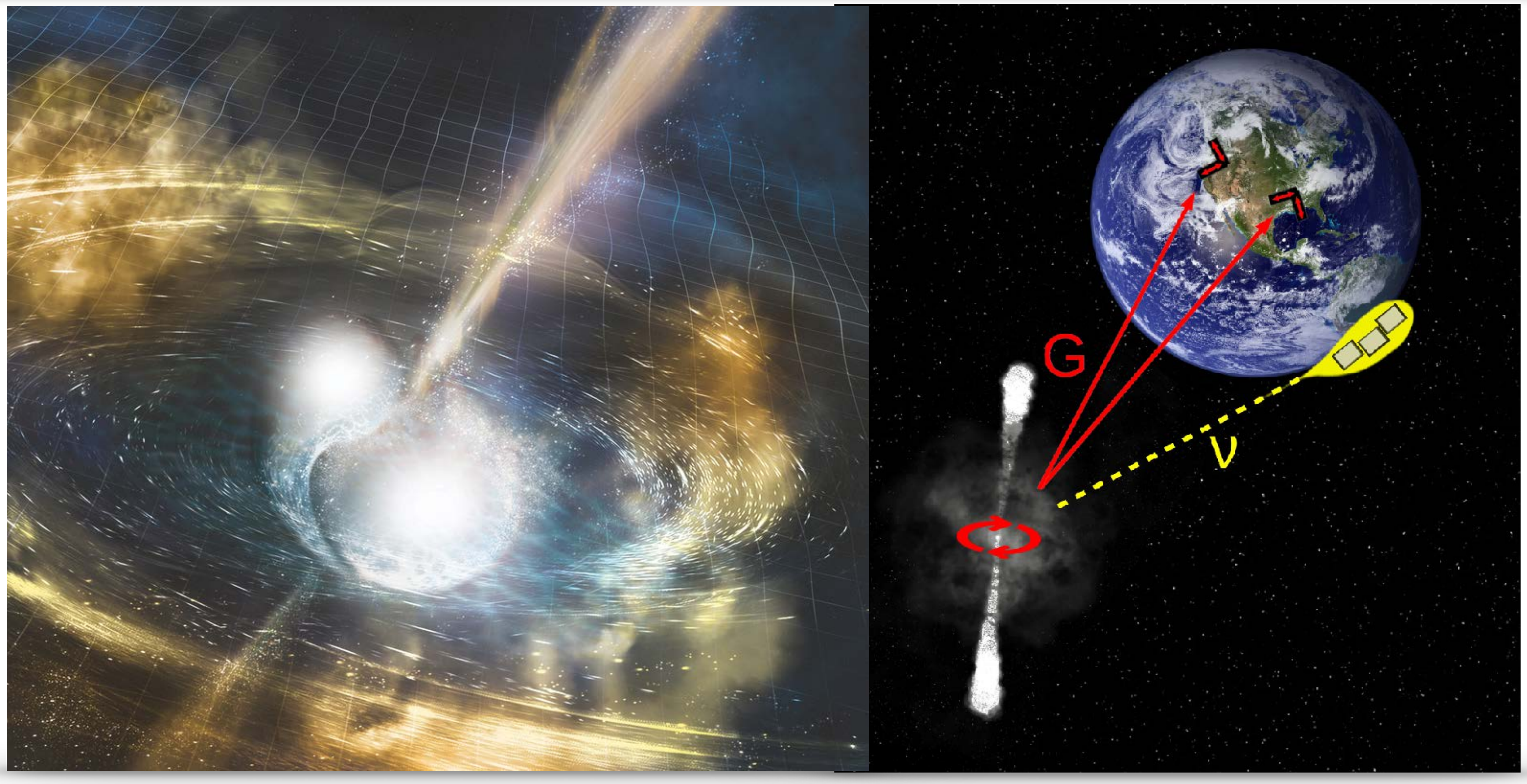
M. Niechciol (Auger collaboration), UHECR2022

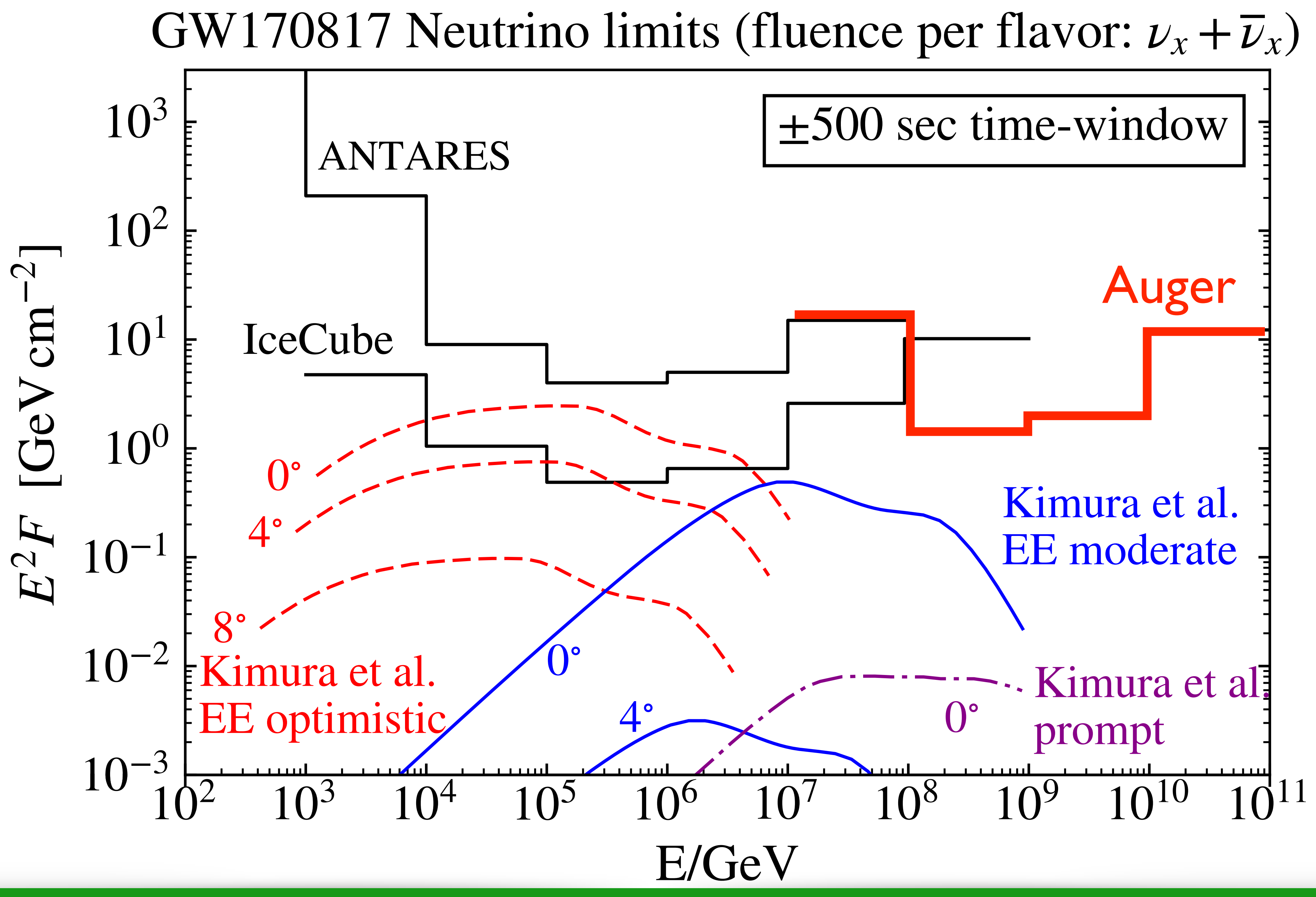


Similarly, photon upper limits start to constrain cosmogenic photon fluxes of p-sources and SHDM models

Follow-Up Observations

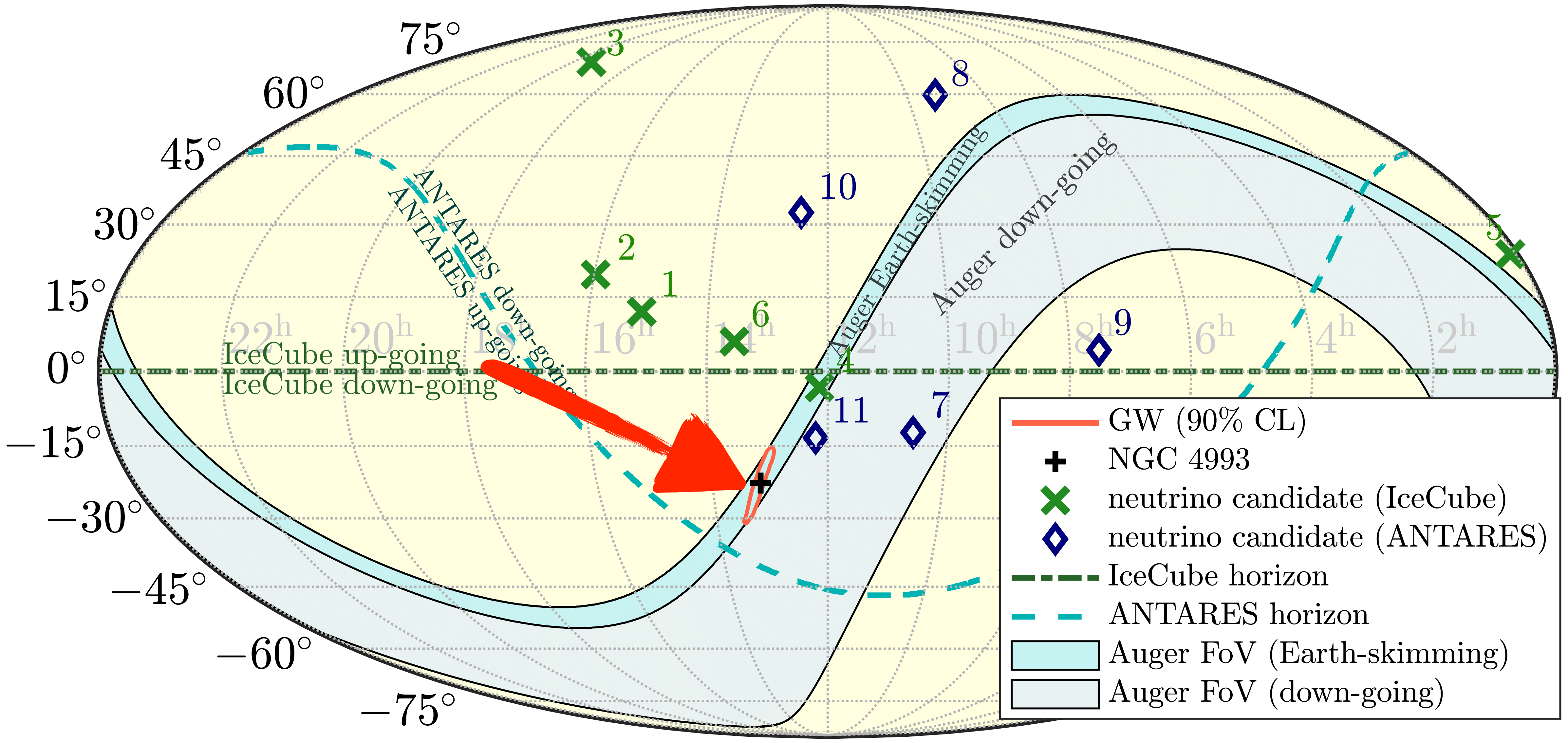
Neutrino Upper Limits for GW170817





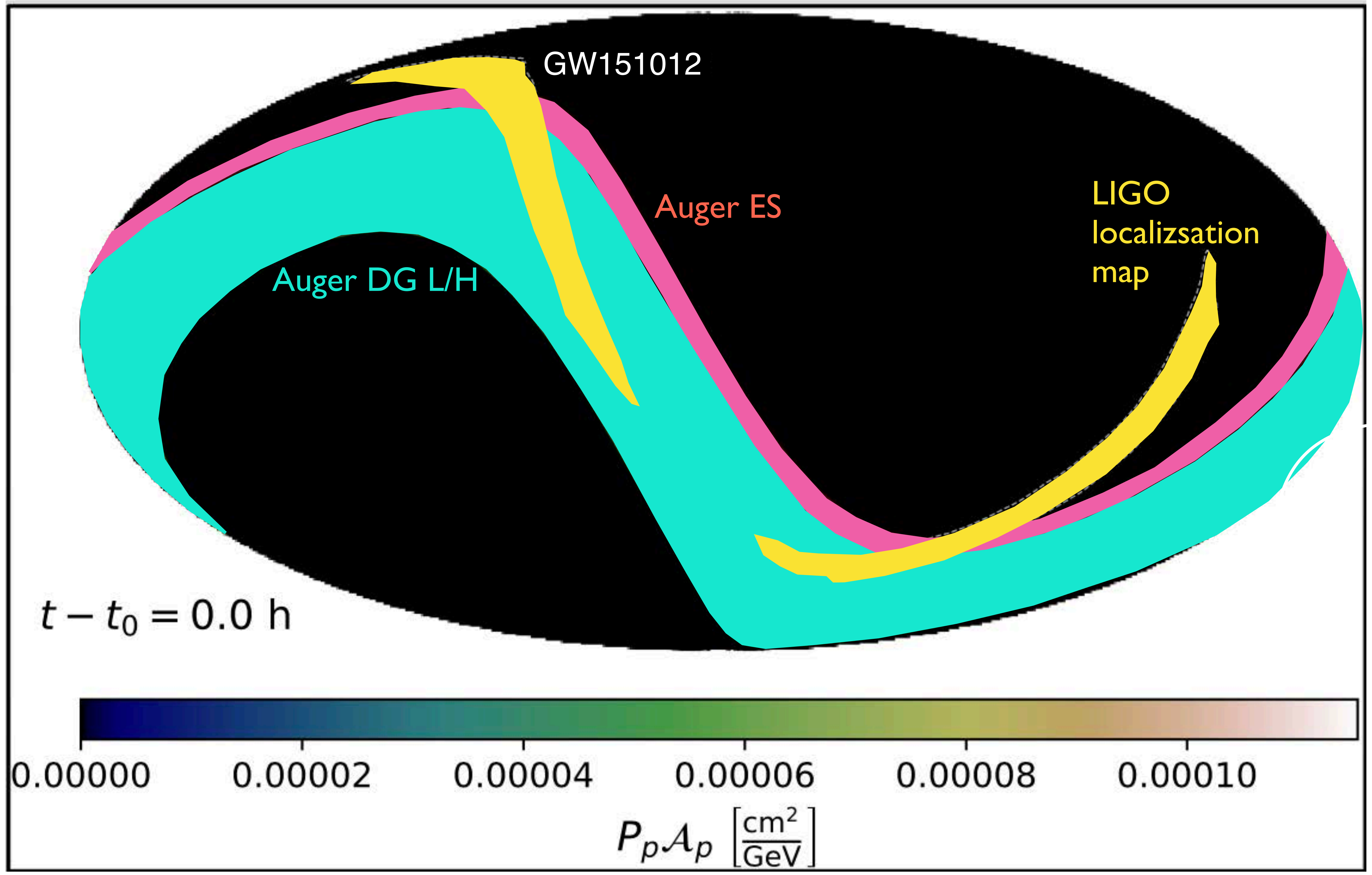
Absence of Neutrino consistent with SGRB viewed at >20° angle

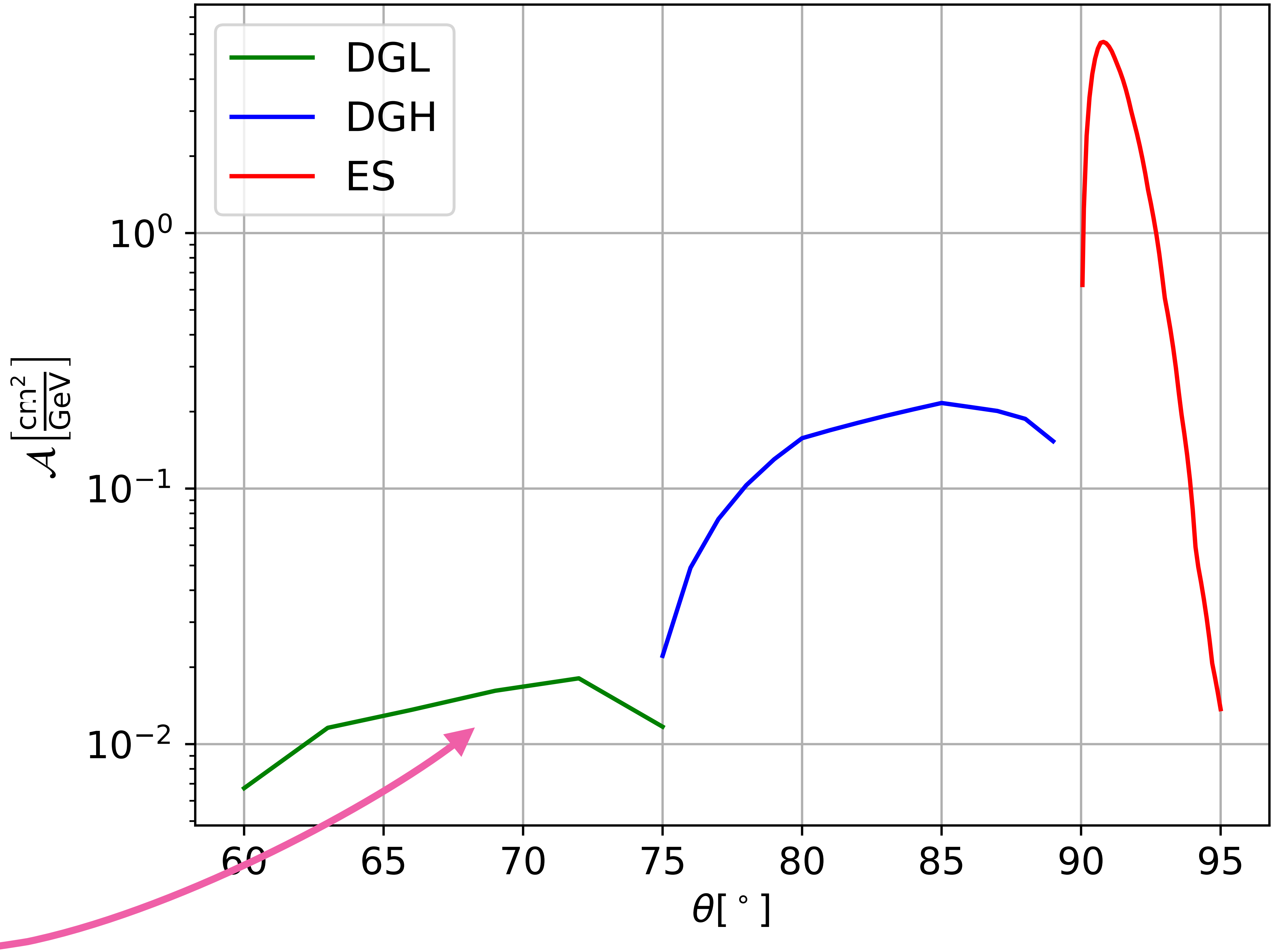
May have seen neutrinos if jet were pointing towards us



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

Combining BBH Mergers





solid angle integration

effective area

$$N_{\nu,i} = L_i \, \Delta t \sum_s \frac{\sum_p P_{p,s} \mathscr{A}_{p,s,i}}{d_s^2}$$

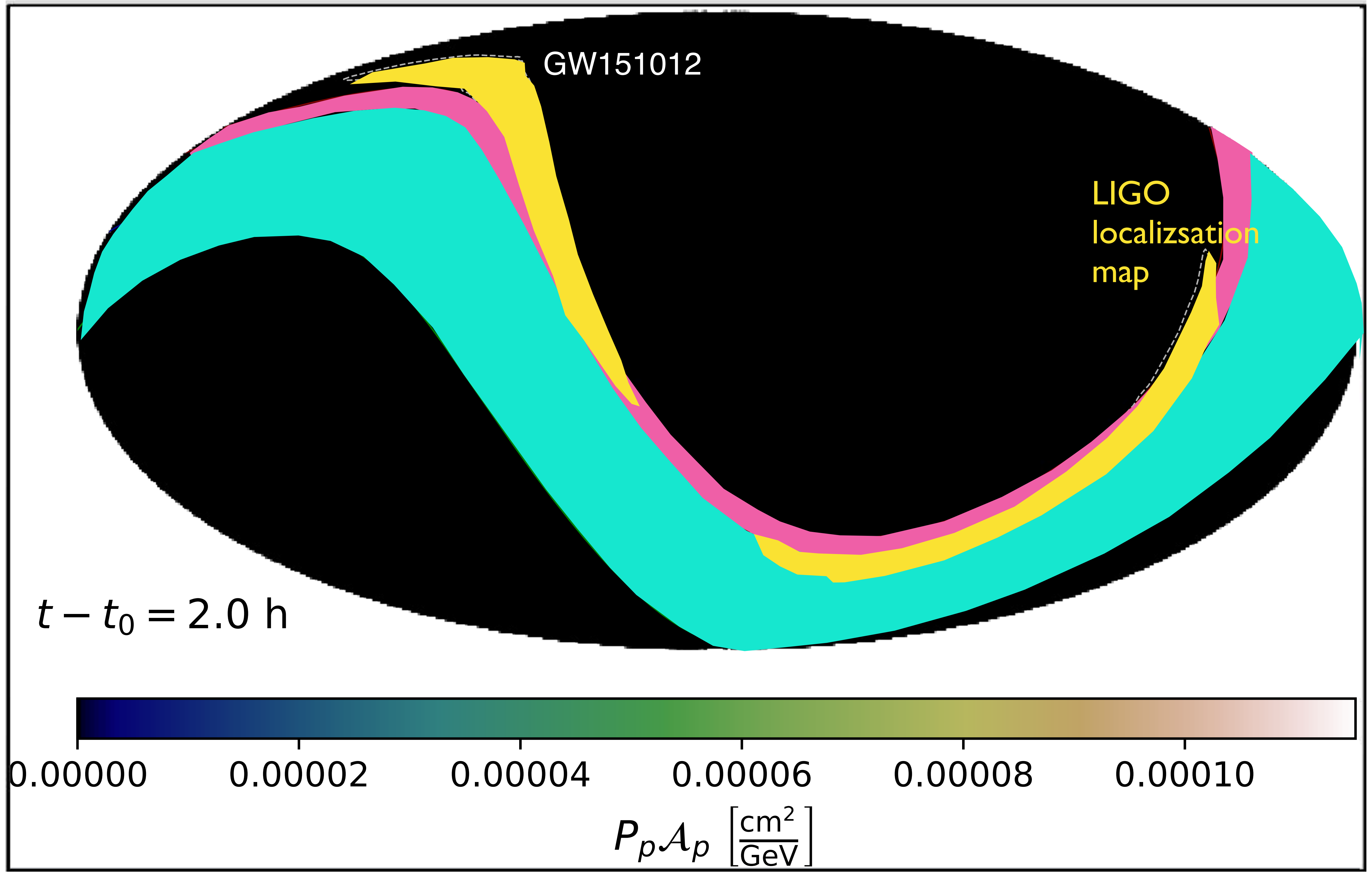
sum over all sources

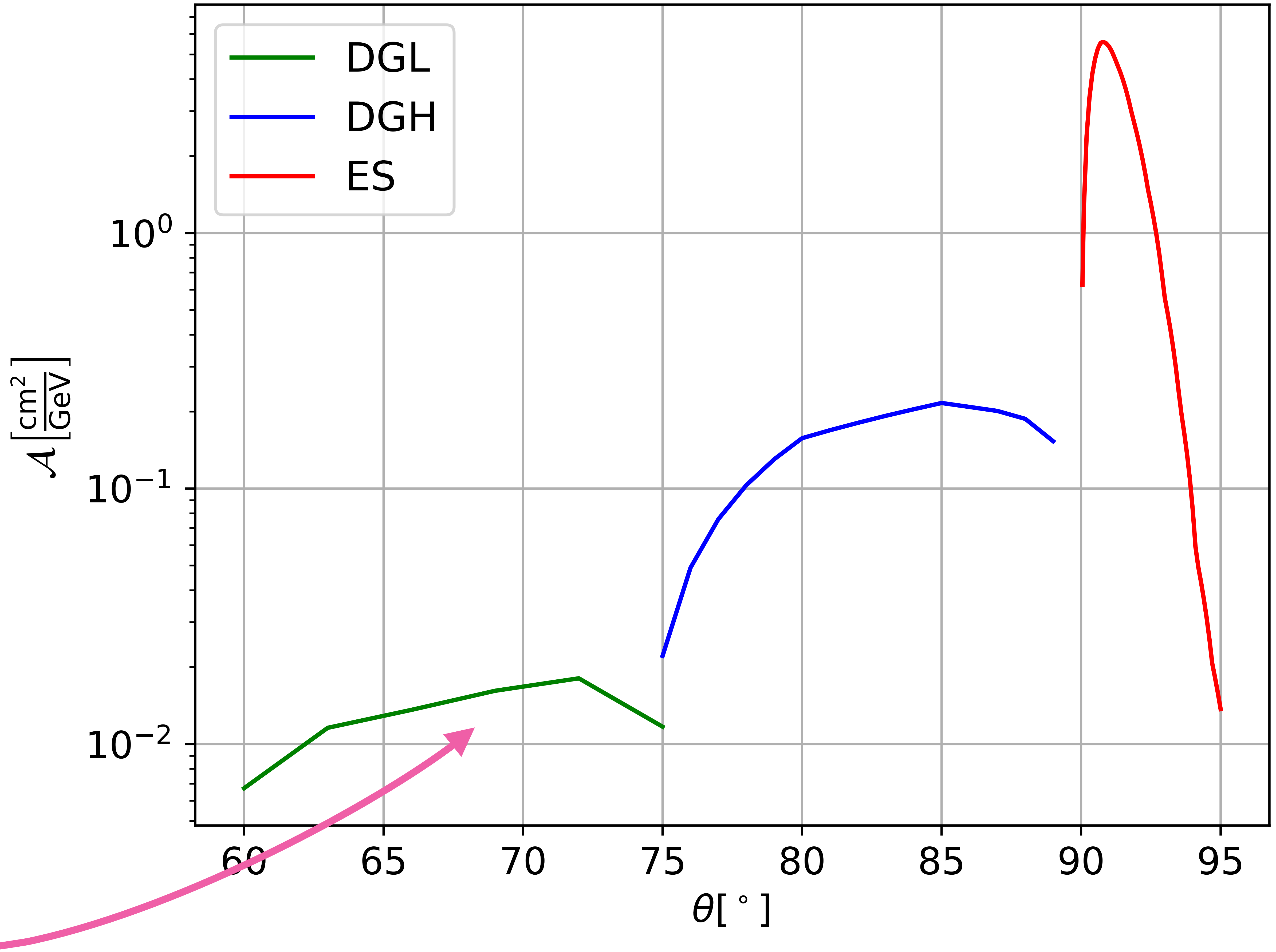
luminosity distance of source

Number of expected neutrinos per source proportional to weighted overlap area integrated over time time

L_i: Neutrino luminosity (to be constrained)

Combining BBH Mergers





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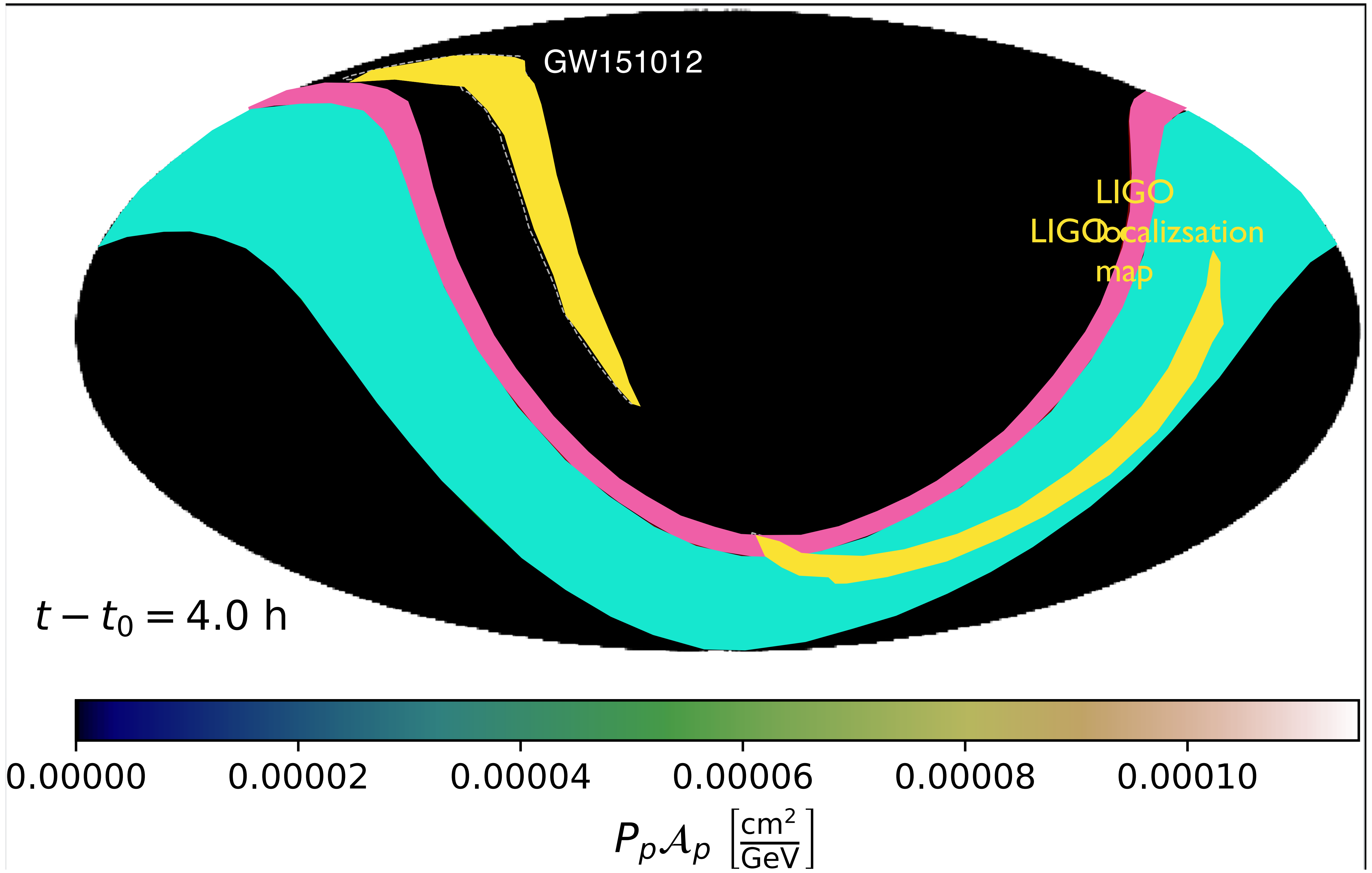
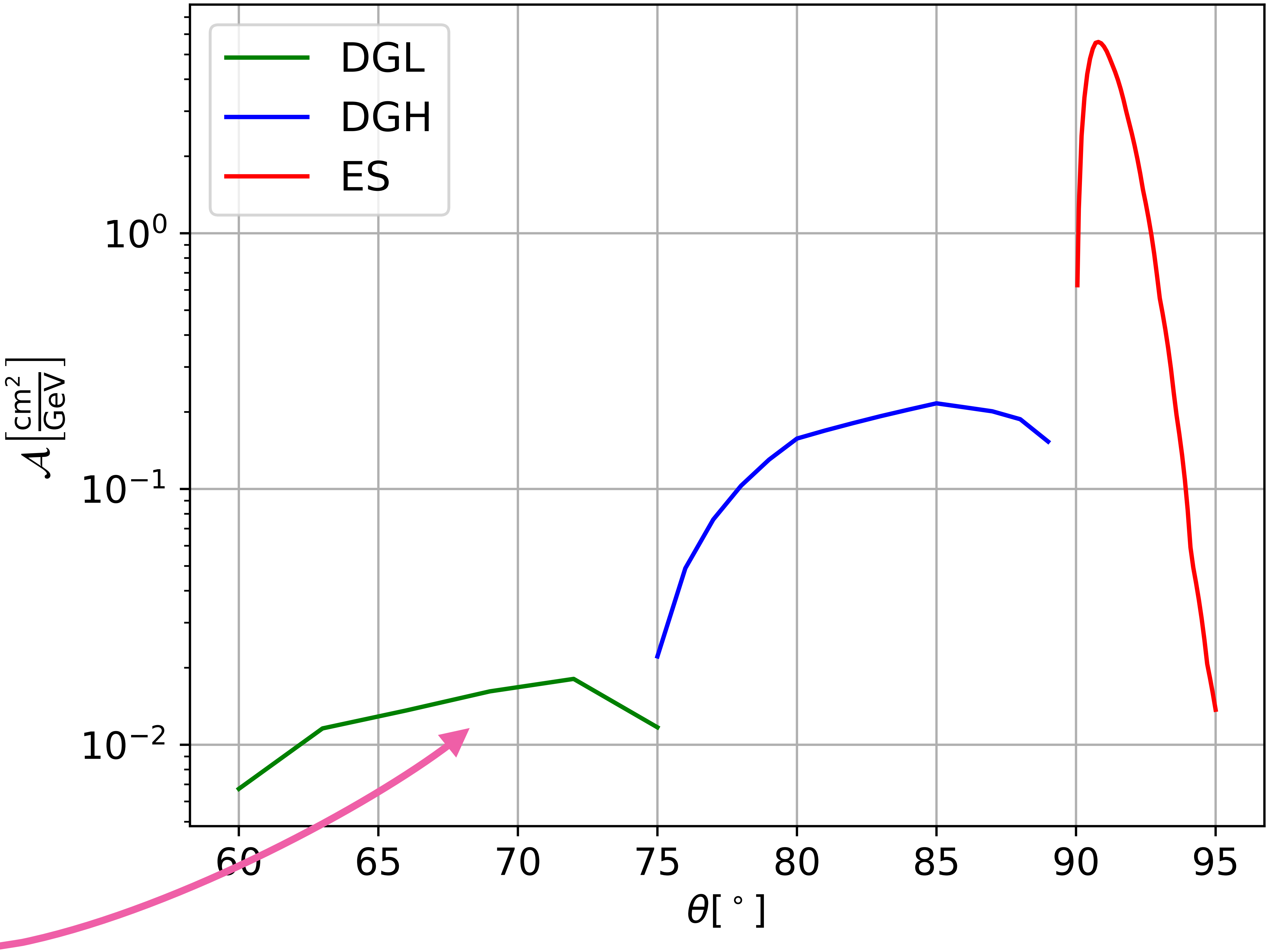




solid angle integration

effective area

$$N_{\nu,i} = L_i \, \Delta t \sum_s \frac{\sum_p P_{p,s} \mathscr{A}_{p,s,i}}{d_s^2}$$

sum over all sources

luminosity distance of source

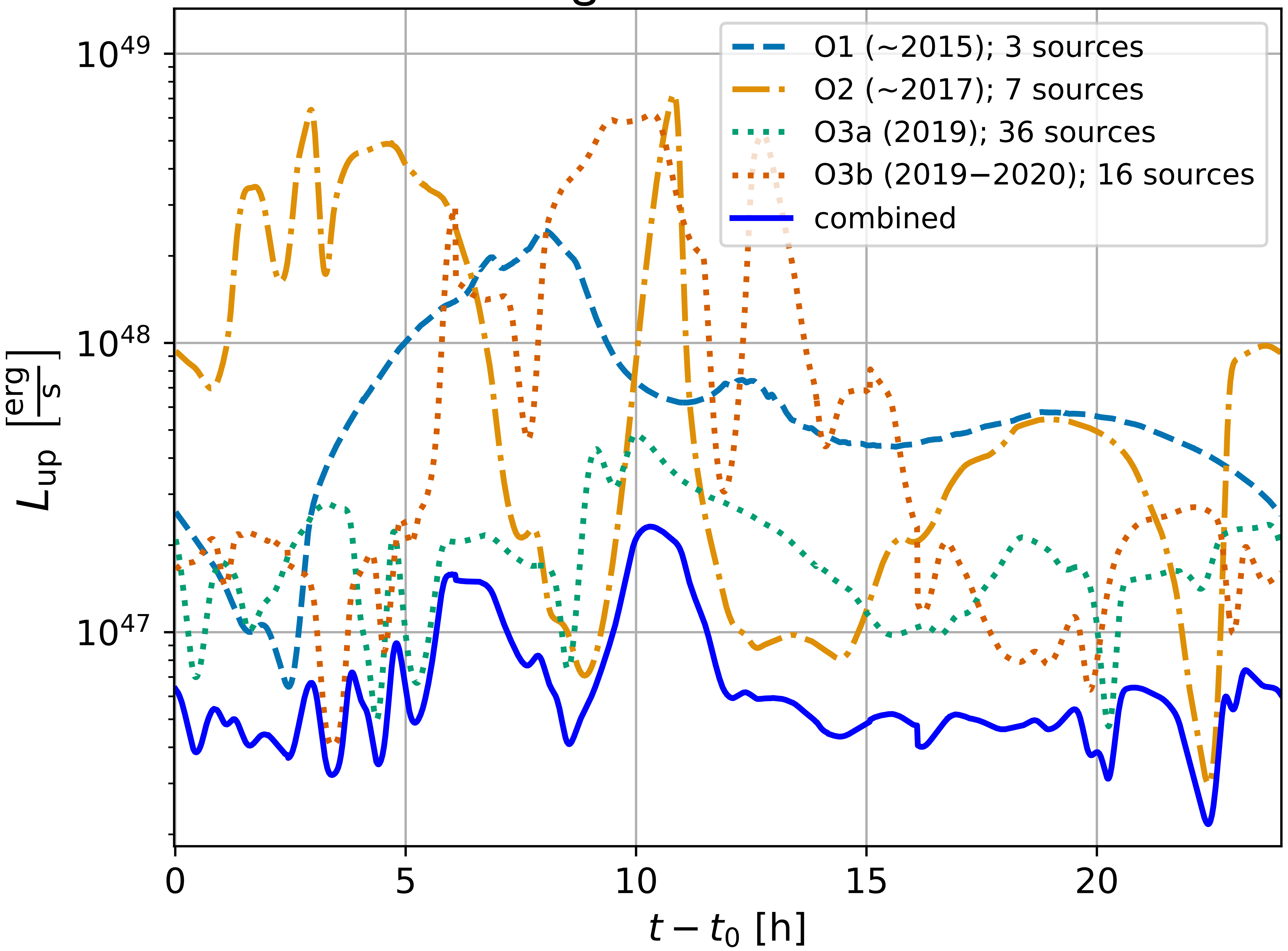
Number of expected neutrinos per source proportional to weighted overlap area integrated over time time

L_i: Neutrino luminosity (to be constrained)

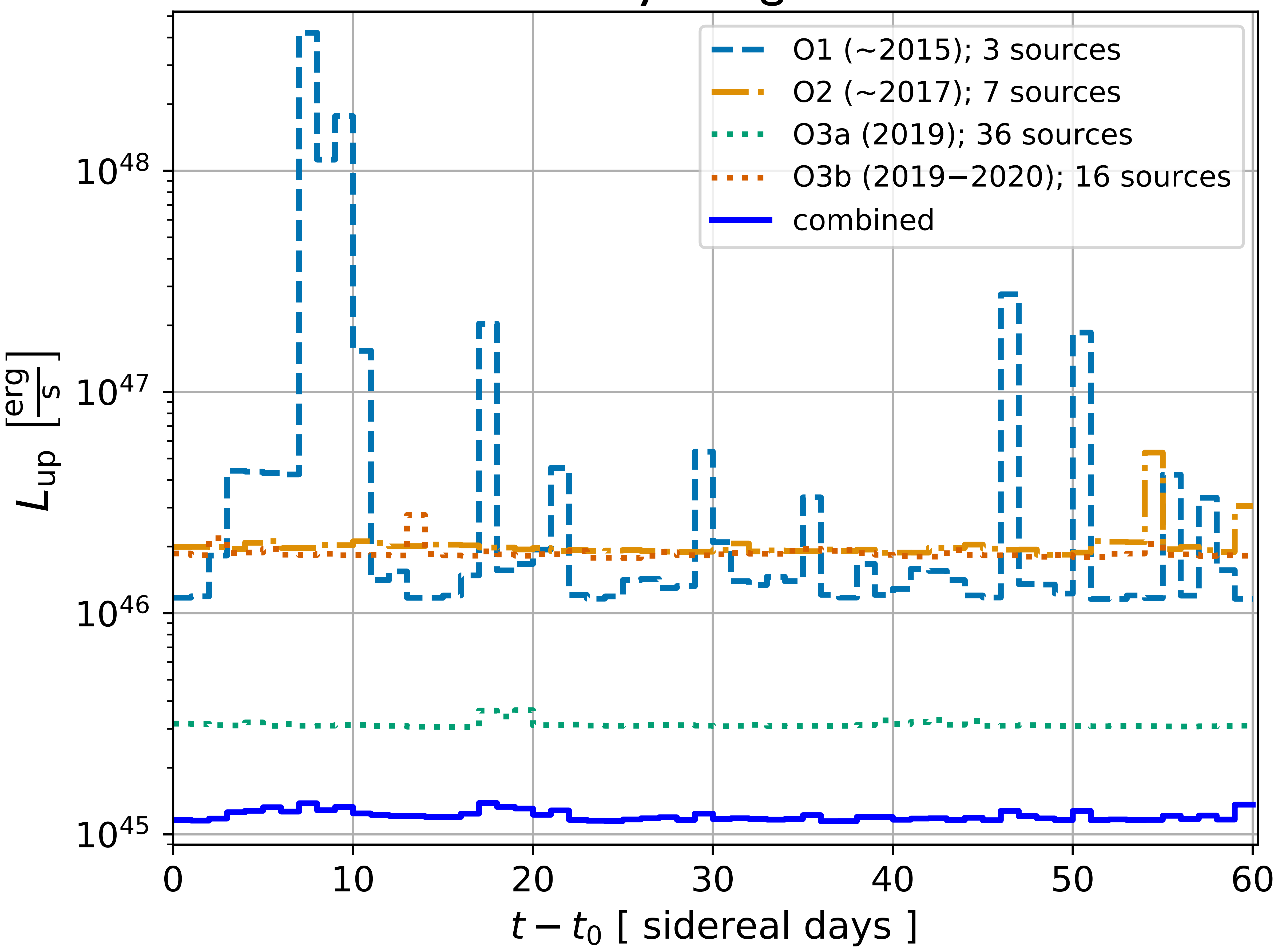
Isotropic Neutrino Luminosity Bound from BBHs

M. Schimp; Auger Collaboration, PoS (ICRC2021) 968

24 hrs stacking limit from 62 GW events



60 day integration



Neutrino emission energy limit $\sim M_{\odot}c^2/300$ as compared to $\sim M_{\odot}c^2$ radiated GW energy assuming isotropic emission and E_{ν}^{-2} flux

Alerts & MM-network

- Excellent sensitivity to photons and neutrinos in the EeV range
- **The Pierre Auger Observatory actively participates in the joint international effort within the framework of multi-messenger astrophysics**
  - Automatic GW follow-up routine in place
  - Sending and receiving alerts to/from Global Coordinate Network (GCN)
  - SD Data stream sent to the AMON and Deeper Wider Faster (DWF)

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

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 Steps

Snowmass Whitepaper

- UHECR whitepaper prepared for U.S. Snowmass survey which is about *particle physics* in the next decade(s)
  - WP covers particle and astrophysics aspects of UHECR
  - almost 100 authors + 200+ endorsers
  - 283 pages (with front- and back-matter)
  - to be published in Astroparticle Physics
- Input from the community via workshops and via topical conveners
- WP makes general recommendations and outlines a plan for experiments over the next decades
  - caveat: Snowmass targets U.S. funding agencies and particle physics community

see references in WP for material shown here:

https://arxiv.org/pdf/2205.05845

Ultra-High-Energy Cosmic Rays

The Intersection of the Cosmic and Energy Frontiers

CONVENERS

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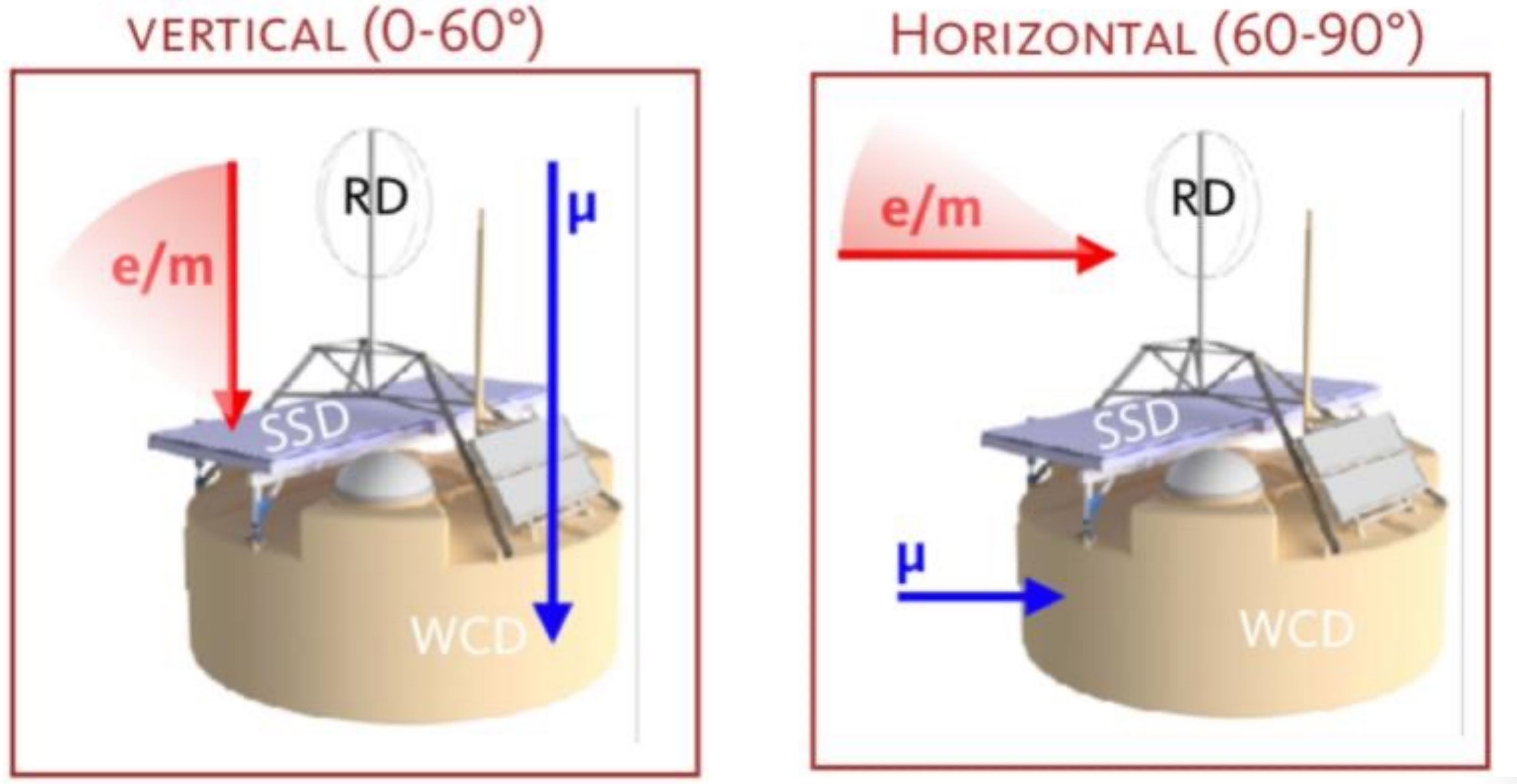
Ongoing …

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



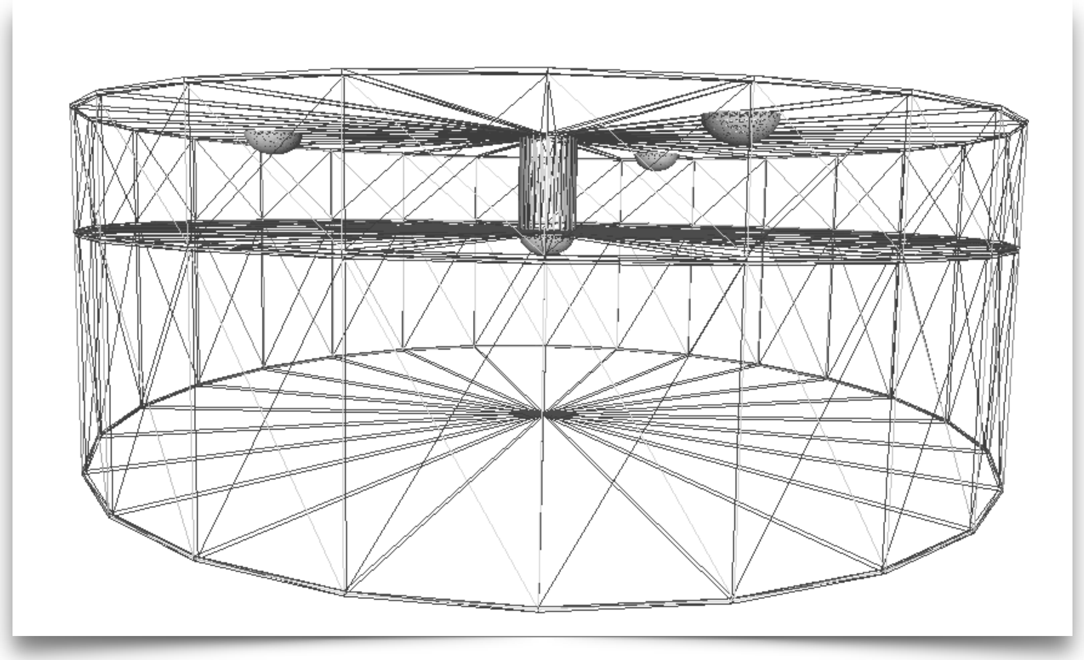
Next...: Global Cosmic ray ObServatory (GCOS)

Distributed UHECR Observatory covering > 60,000 km^2

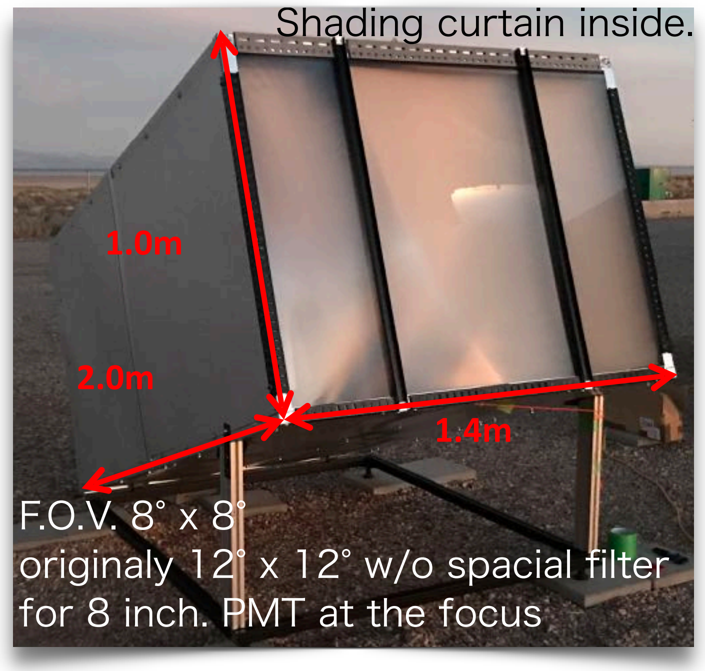
Several highly attended workshops were conducted for conceptual design, targeted at

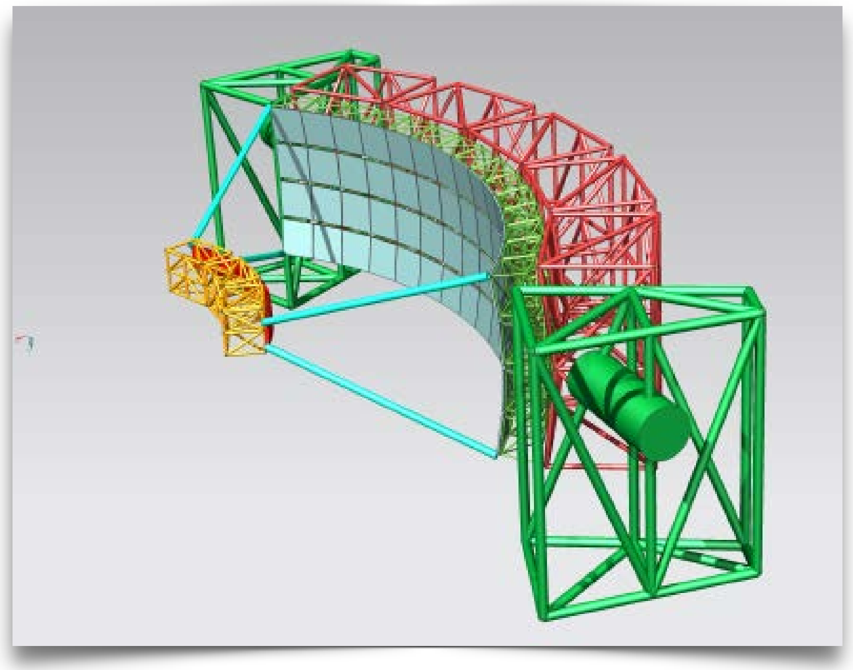
- full efficiency at 10 EeV
- energy resolution <10%, muon resolution <10%
- Xmax better than 30 g/cm^2
- angular resolution ~1°
- strong MM capabilities with photons and neutrinos

⇒ source correlations at 5σ within one year of operation



segmented Water Cherenkov Detectors

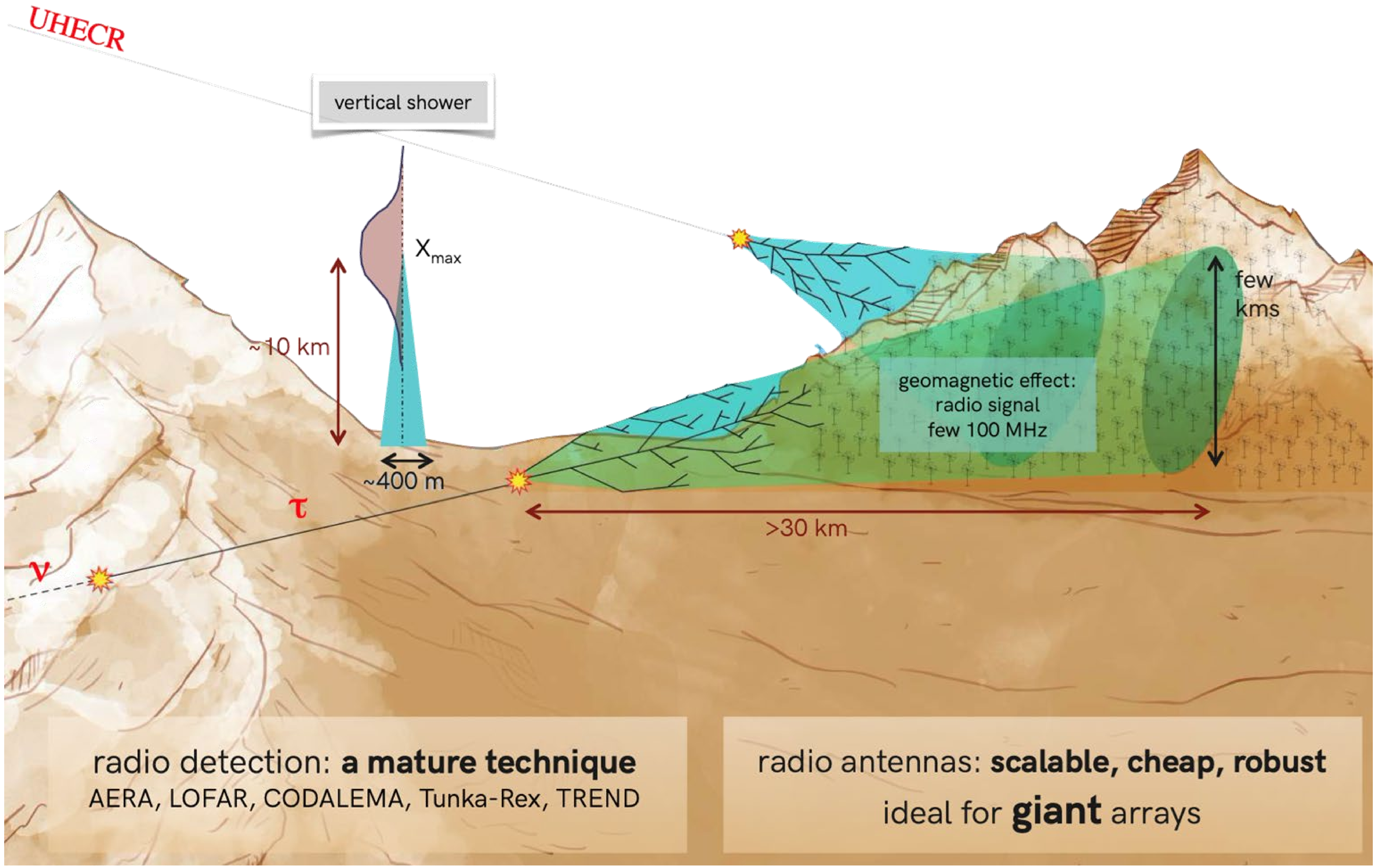




concepts for simplified fluorescence telescopes

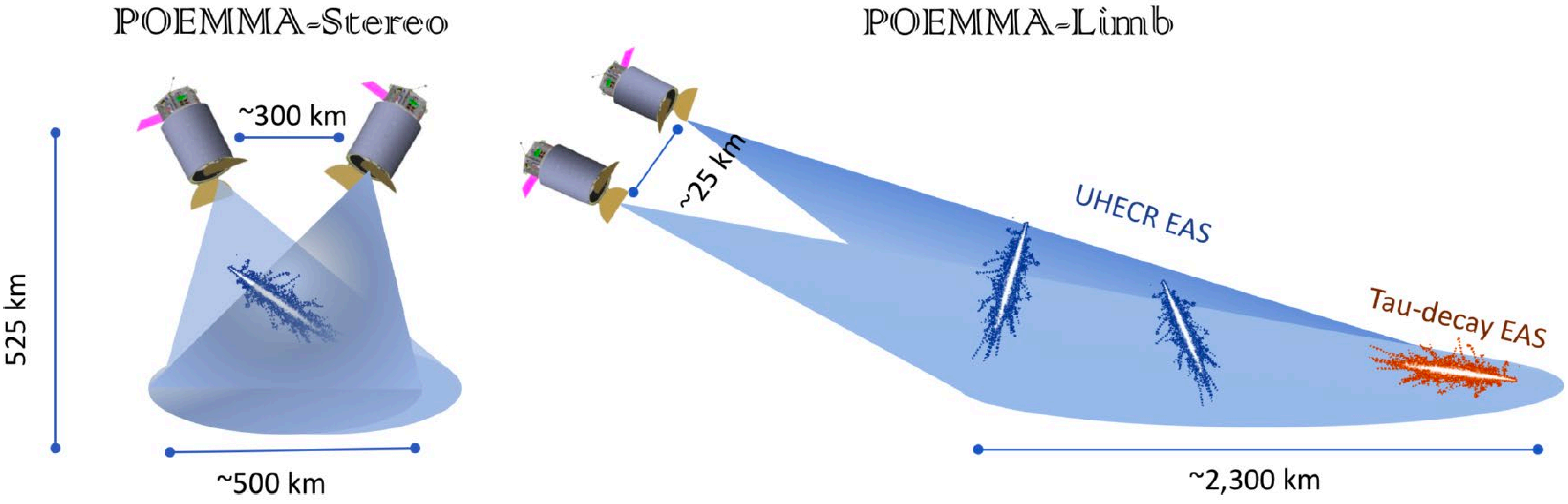
GRAND: Giant Radio Array for Neutrino Detection

- 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



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, …



UHECRs in next two decades

- Auger and TA upgrades will lead the field for the next 10 years
- 4 main experiments identified for the decade afterwards that complement each other
  - 3 of them designed also (mainly) as neutrino observatories: IceCube-Gen2, GRAND, POEMMA
  - GCOS (Global Cosmic Ray Observatory) will be designed to deliver event-by-event rigidity for UHECR

Experiment	Feature	Cosmic Ray Science*	Timeline
Pierre Auger Observatory	Hybrid array: fluorescence, surface e/μ + radio, 3000 km^2	Hadronic interactions, search for BSM, UHECR source populations, $\sigma_{\text{p-Air}}$	AugerPrime upgrade
Telescope Array (TA)	Hybrid array: fluorescence, surface scintillators, up to 3000 km^2	UHECR source populations proton-air cross section ($\sigma_{\text{p-Air}}$)	TAx4 upgrade
IceCube / IceCube-Gen2	Hybrid array: surface + deep, up to 6 km^2	Hadronic interactions, prompt decays, Galactic to extragalactic transition	Upgrade + surface enhancement; IceCube-Gen2 deployment; IceCube-Gen2 operation
GRAND	Radio array for inclined events, up to 200,000 km^2	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	GRANDProto 300; GRAND 10k; GRAND 200k multiple sites, step by step
POEMMA	Space fluorescence and Cherenkov detector	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	JEM-EUSO program; POEMMA
GCOS	Hybrid array with X_{max} + e/μ over 40,000 km^2	UHECR sources via event-by-event rigidity, forward particle physics, search for BSM, $\sigma_{\text{p-Air}}$	GCOS R&D + first site; GCOS further sites
			2025 2030 2035 2040

*All experiments contribute to multi-messenger astrophysics also by searches for UHE neutrinos and photons; several experiments (IceCube, GRAND, POEMMA) have astrophysical neutrinos as primary science case.

https://arxiv.org/pdf/2205.05845

RI related Questions

- **TNA**
  UHECR do continuous all-sky observations → no observer programs needed

- **Data Management**
  - open data already implemented
  - tools and sample scripts for analysis are provided
  - … allow reproducing published results
  - open source software, heavily used by community
  - distributed computing facilities for joint simulations, using also GPUs

- **Tools**
  - alert tools: do exist but would profit from standardisation, both sending & receiving
  - regular workshops for training young scientists

- **Societal Impact**
  - geophysics data are 100% public, including tools
  - carbon footprint: observatories mostly run on solar power
  - visitors centres and regular citizen science programs

- UHECR DATA FULL OF SURPRISES
- DRIVE EXTREME UNIVERSE
- ESSENTIAL IN MM STUDIES
- FUTURE BEING PLANNED

Deflections: JF12 vs JF22a

R = 20 EV