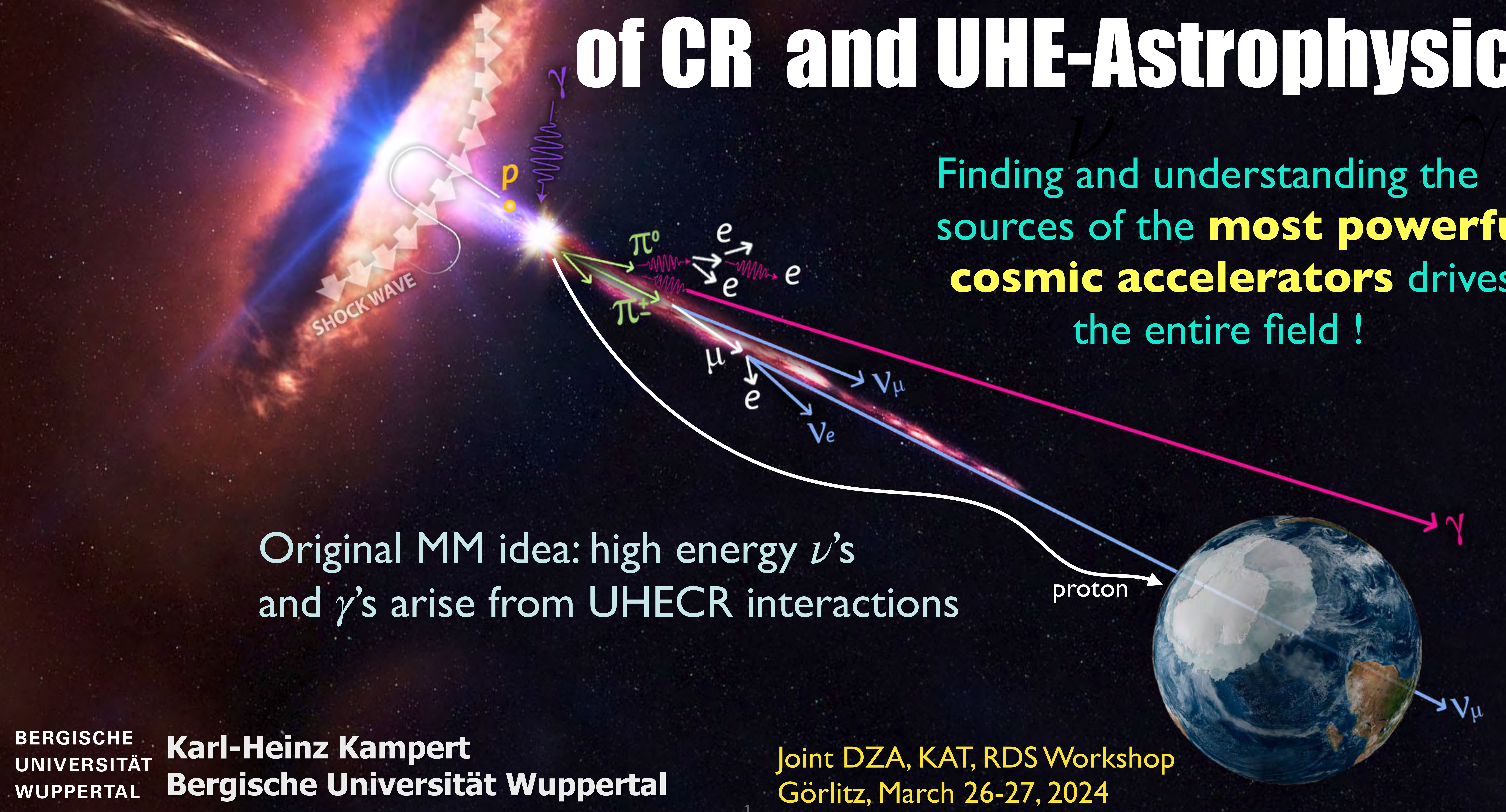
Multi-Messenger Aspects of CR and UHE-Astrophysics



Finding and understanding the sources of the **most powerful cosmic accelerators** drives the entire field !

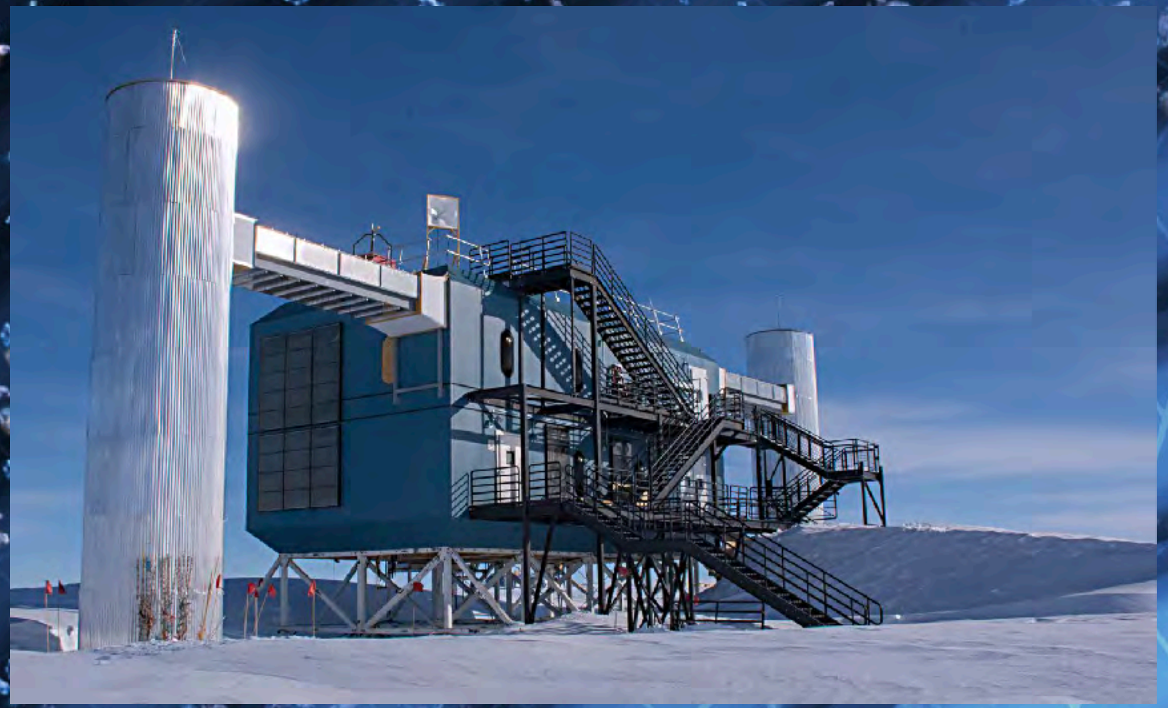
Original MM idea: high energy ν's and γ's arise from UHECR interactions

BERGISCHE
UNIVERSITÄT
WUPPERTAL

Karl-Heinz Kampert
Bergische Universität Wuppertal

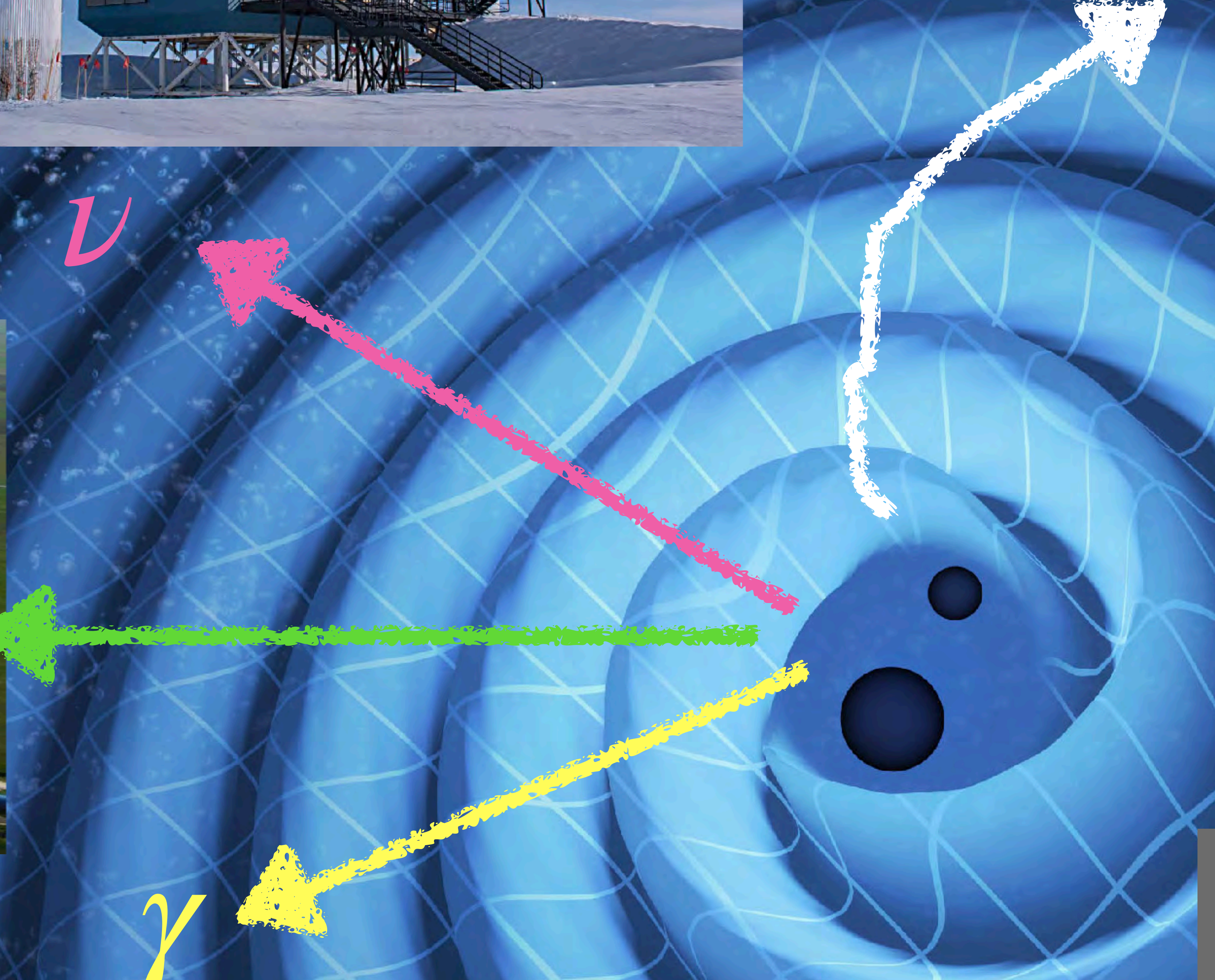
Joint DZA, KAT, RDS Workshop
Görlitz, March 26-27, 2024

direction, time,
energy



direction, (time),
particle type,
energy

Note, CRs delayed wrt GW, γ, ν



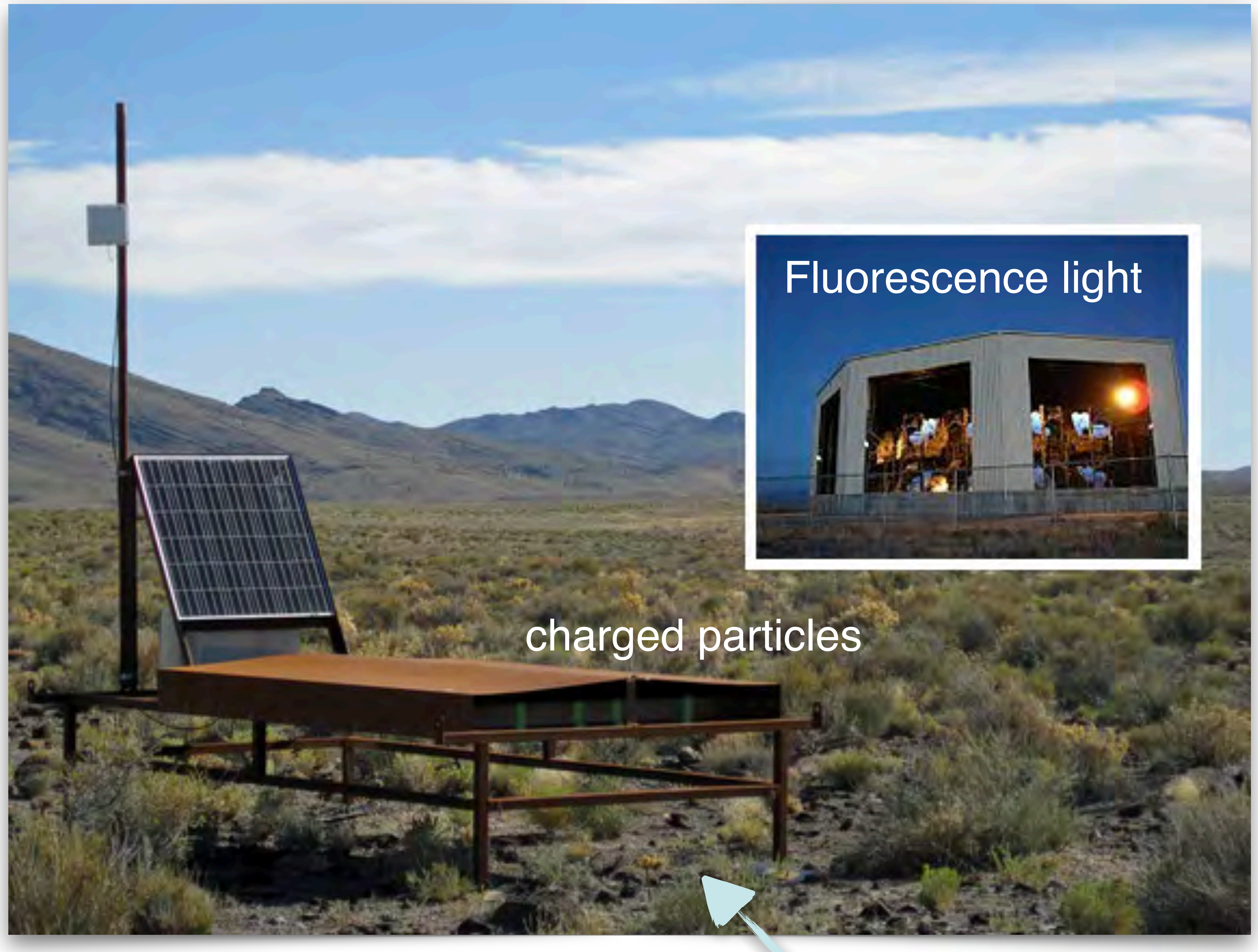
direction, time,
waveform

By construction, a CR observatory is in general also a gamma, neutrino, and neutron-observatory

direction, time,
energy

Moreover, MM physics is more than MWL and more than studying transient events (ToOs)

UHECR Hybrid Multi-Particle Observatories



Telescope Array

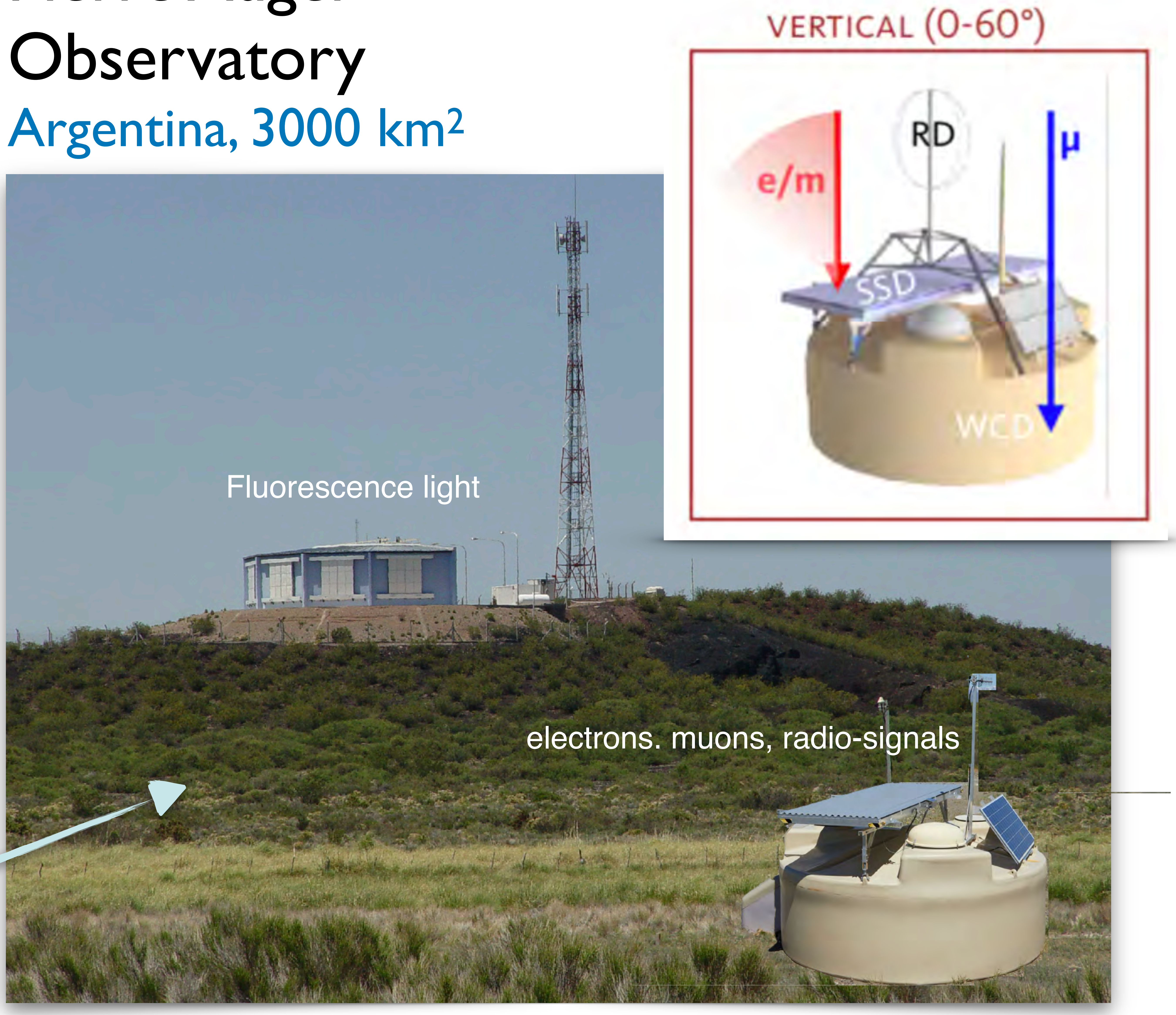
Utah (USA), 700 km^2

to be extended to 2800 km^2

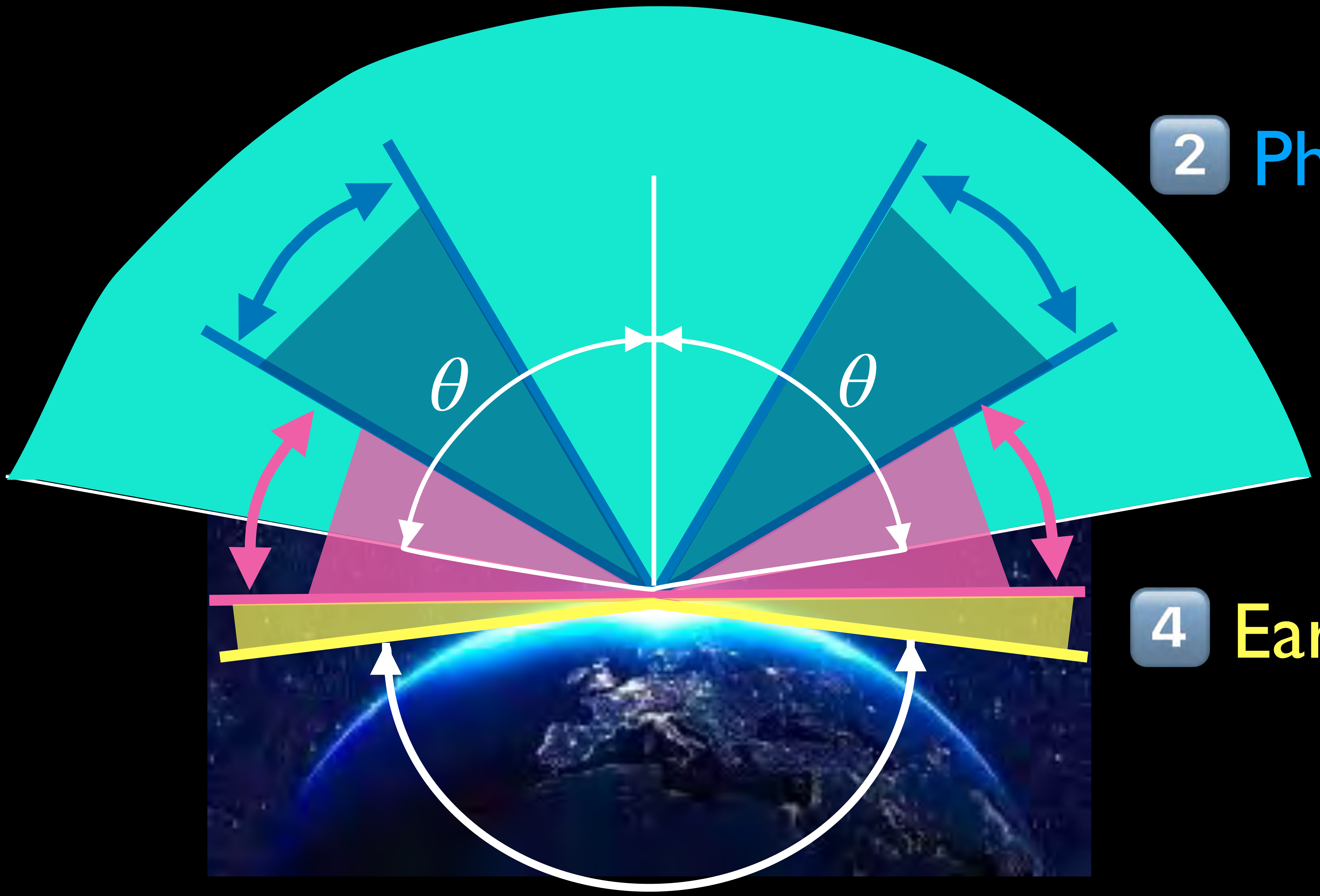
Pierre Auger Observatory

Argentina, 3000 km^2

just upgraded to AugerPrime



Auger: A 4π MM Observatory



1️⃣ Neutrons and charged CRs: Θ ≤ 80°

2️⃣ Photons: 30° ≤ Θ ≤ 60°

zenith range to be extended

3️⃣ Down-Going Neutrinos: 60° ≤ Θ ≤ 90°

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

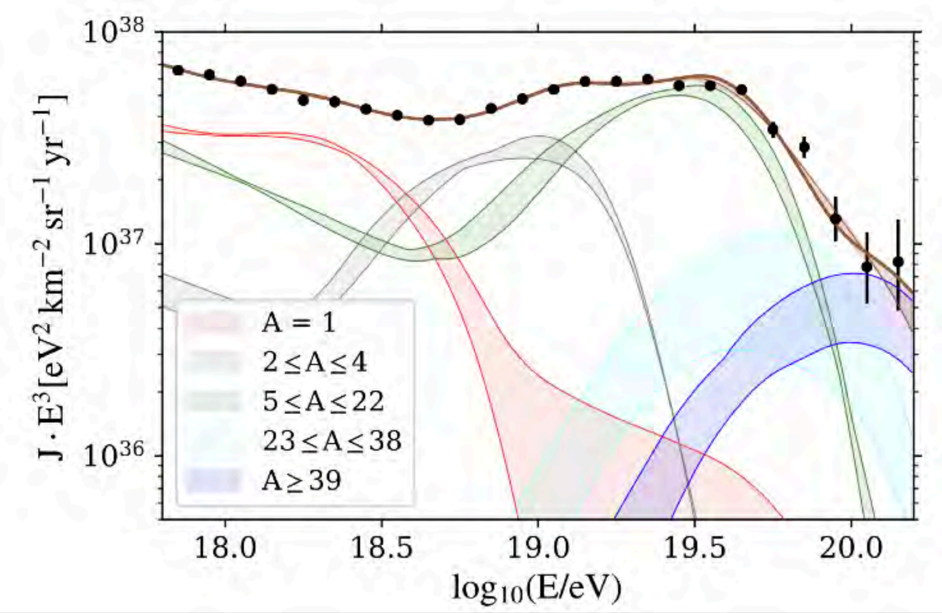
extremely sensitive to EeV neutrinos

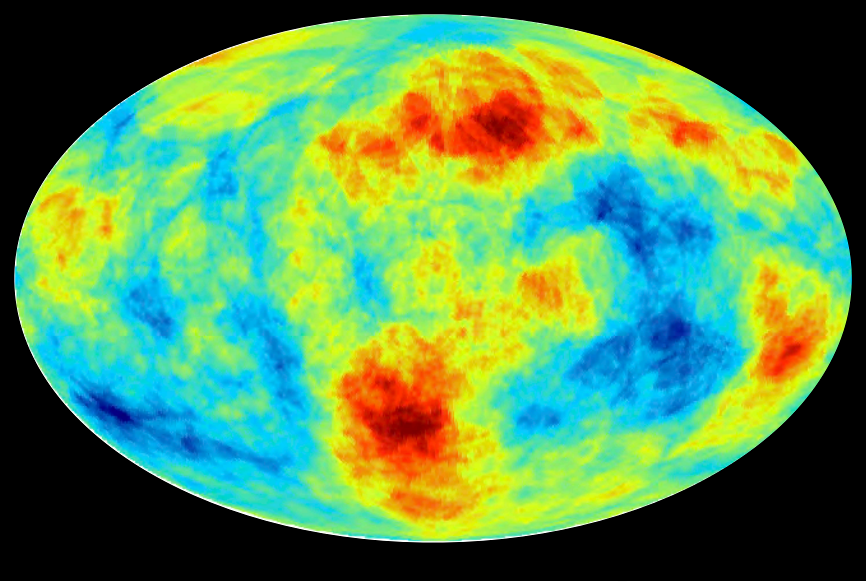
5️⃣ BSM Particles: Θ > 95°

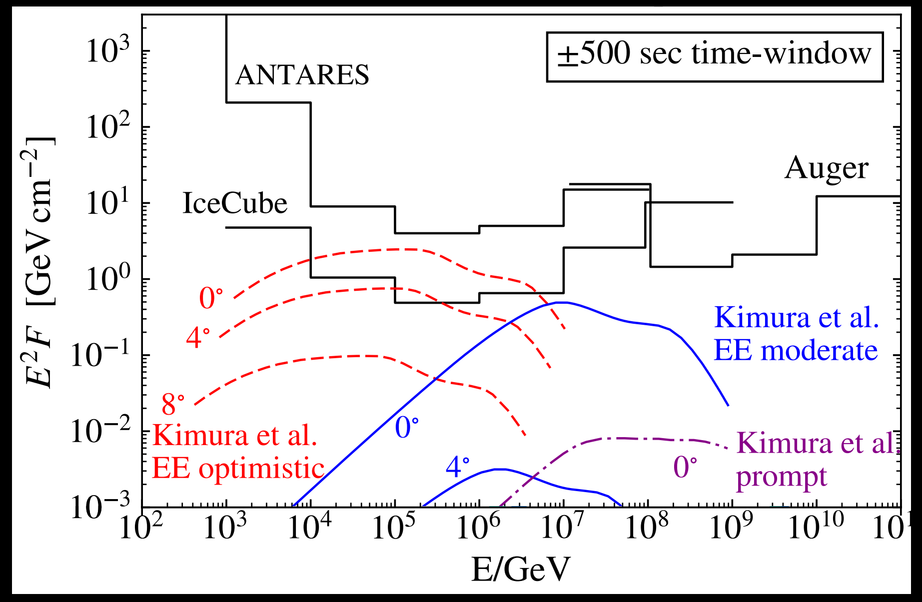
What do CRs and UHECR observatories contribute to MM physics ?

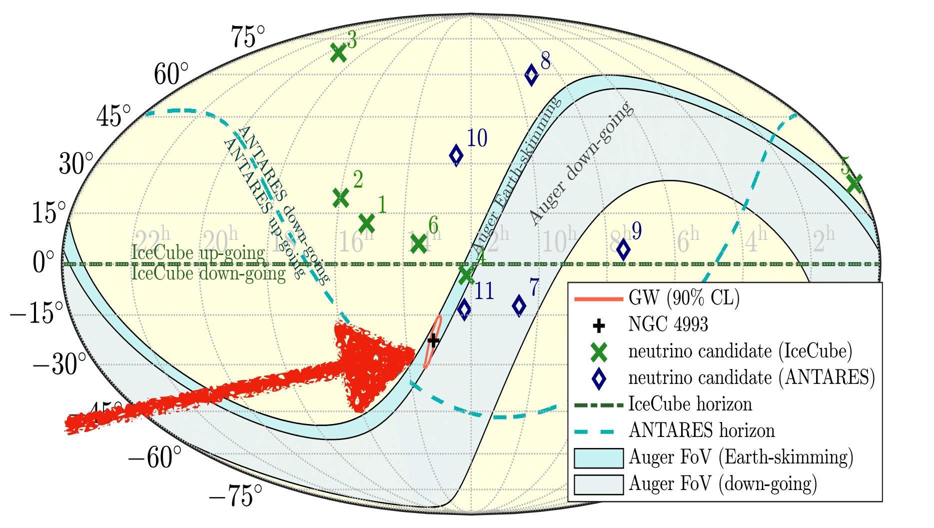
What do CRs and UHECR observatories contribute to MM physics ?

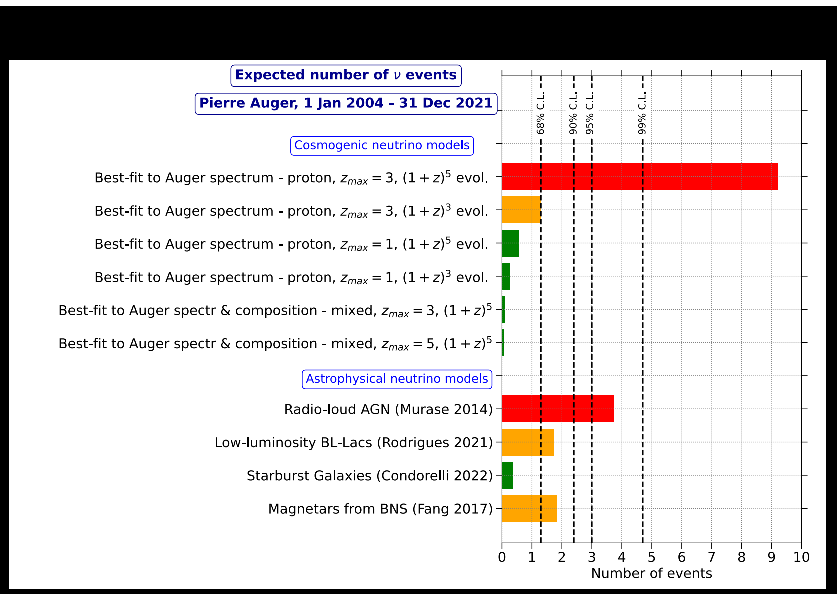
- Constraining EHE (10^{20} eV) source properties:
  - a) source luminosity × volume density
  - b) maximum rigidity
  - c) chemical environment
- Constraining EHE source classes by anisotropies
- Robust input to flux calculations of cosmogenic neutrinos and photons
- Unprecedented sensitivity to EHE neutrinos and photons by UHECR observatories
  - → partner in transient follow-up searches
- Constraining redshift evolution of UHECR sources
- Start to constrain galactic and extragalactic B-fields
- Constrain bursting source scenarios
- …

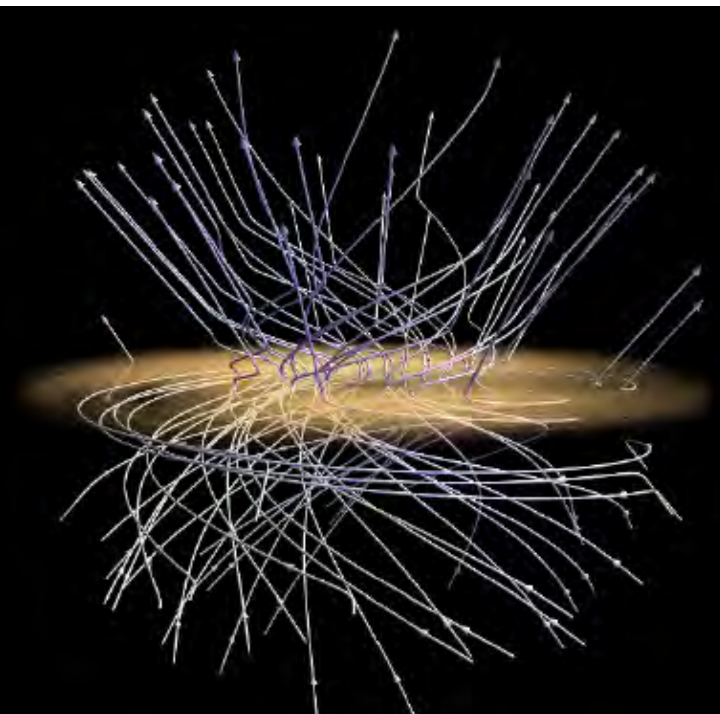




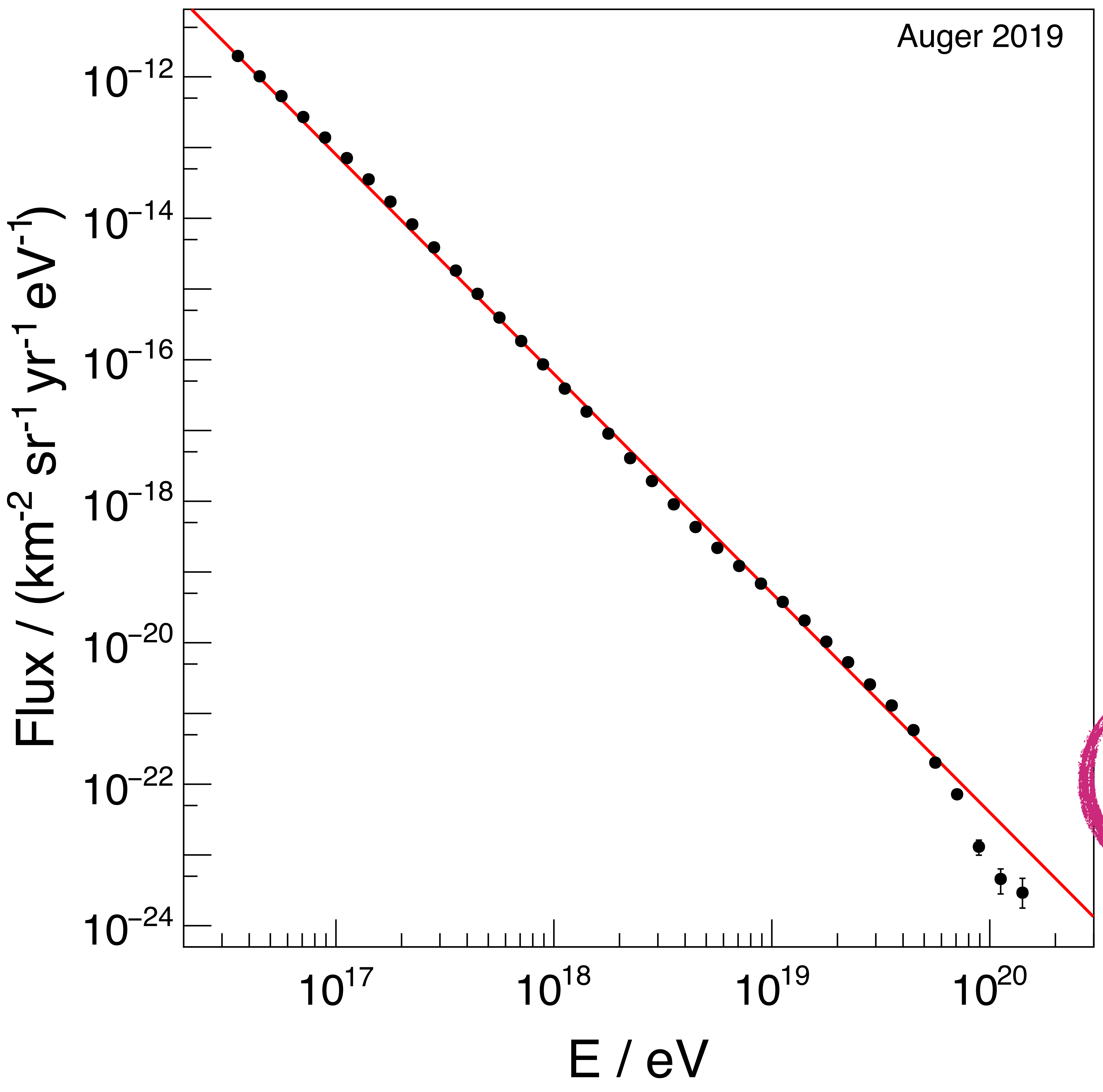


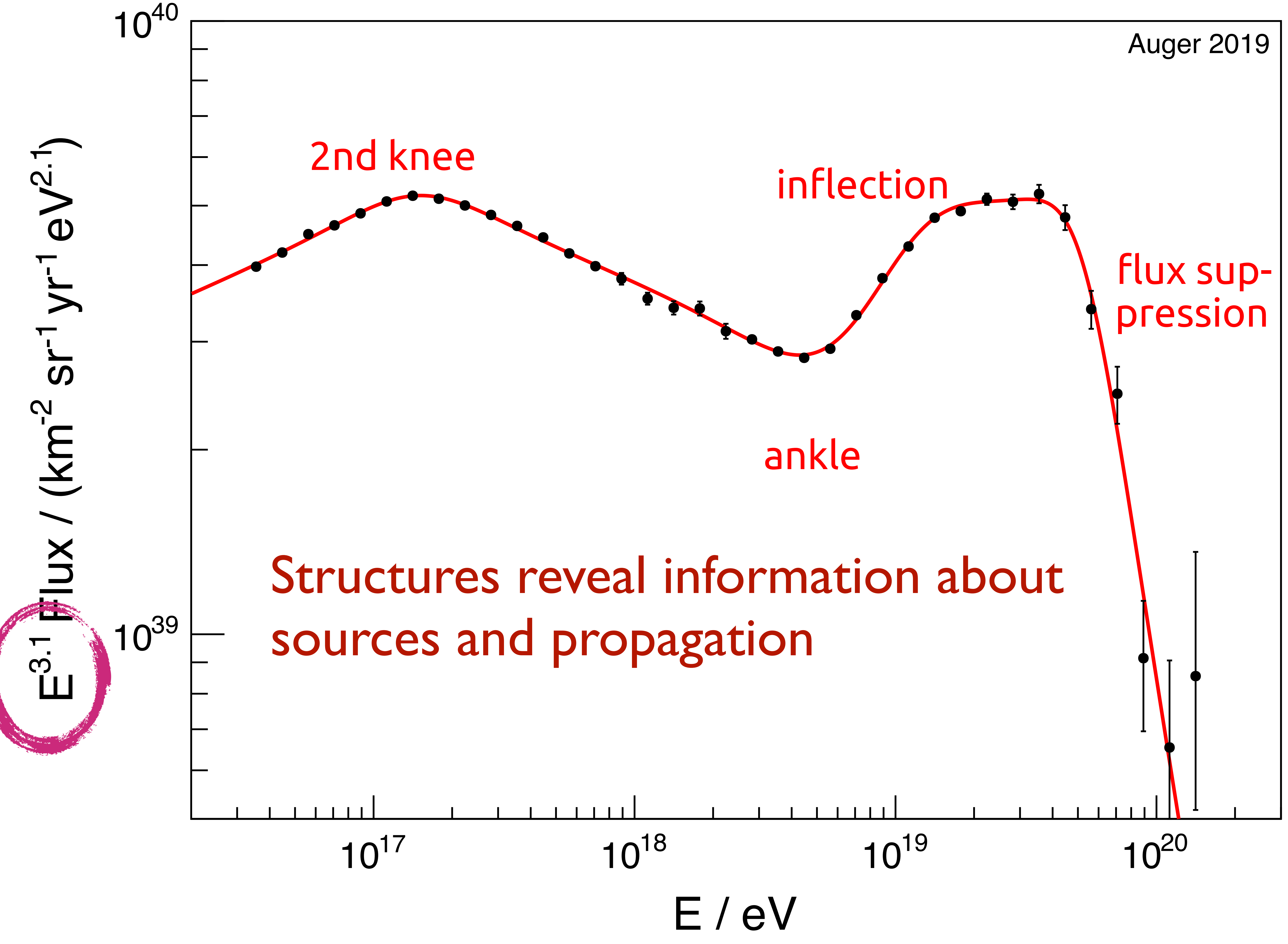






UHECR Energy Spectrum



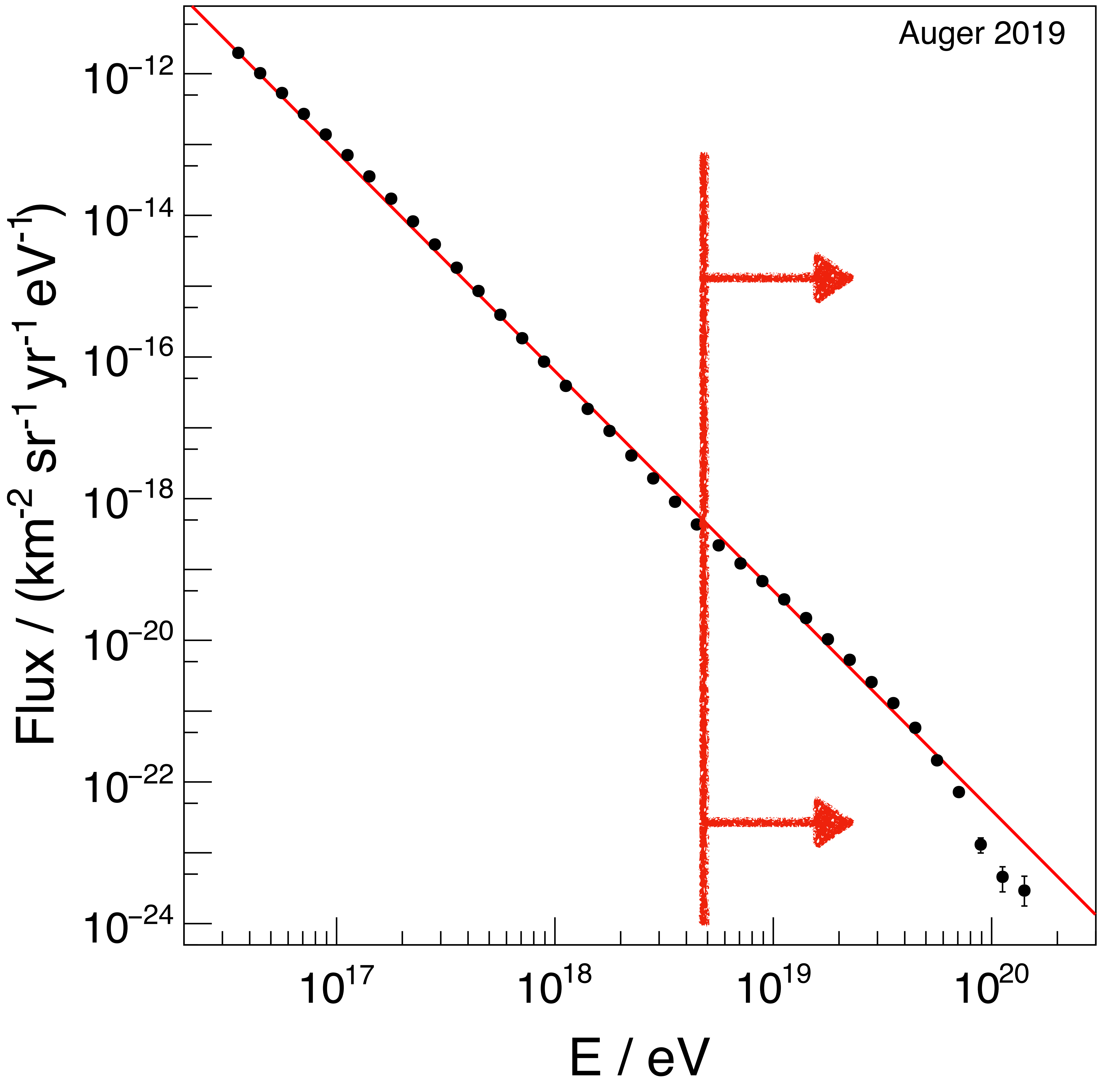


Structures reveal information about sources and propagation

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

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

UHECR Luminosity



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

Measurement of local CR energy density

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

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

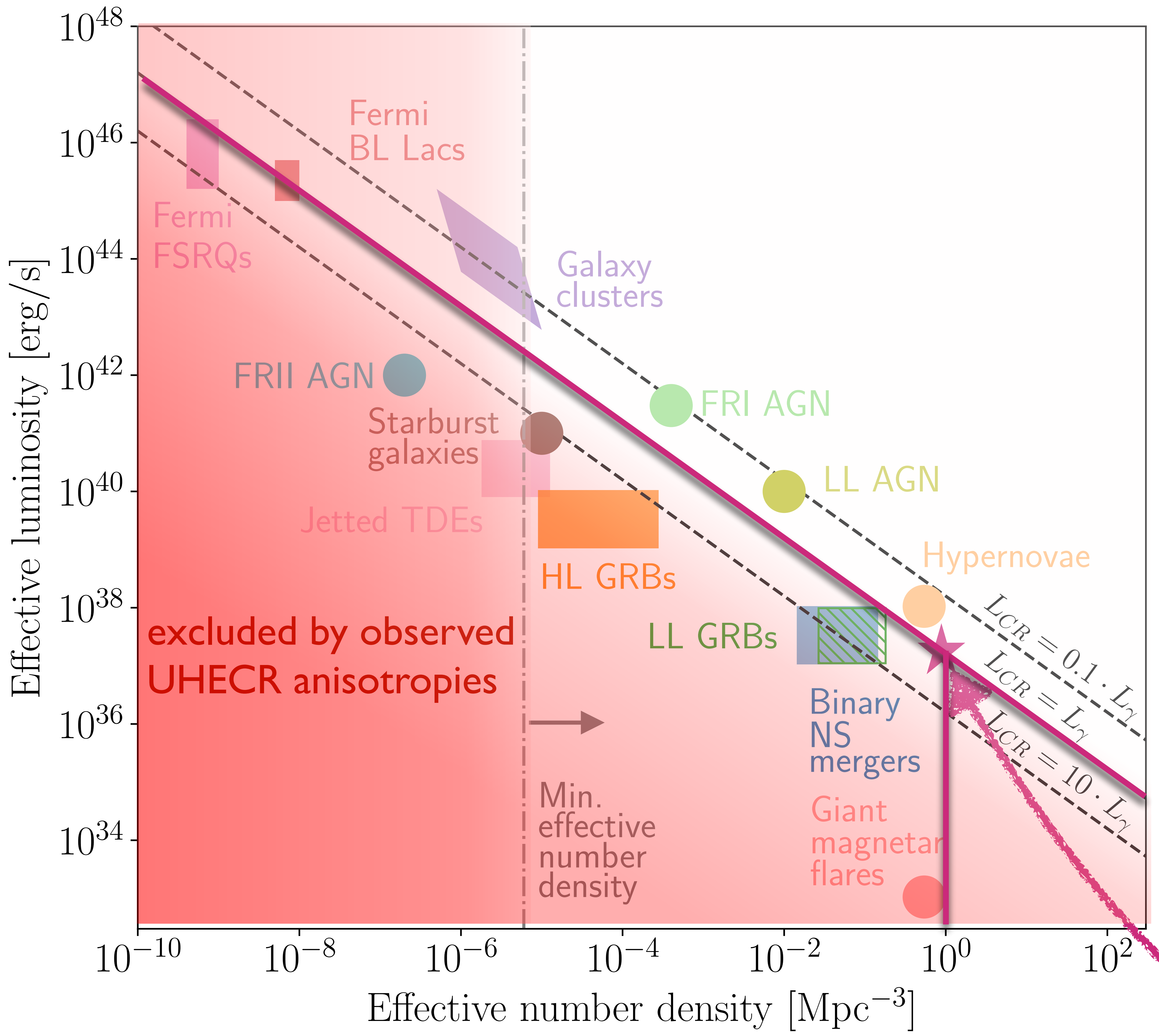
→ source luminosity density

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

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

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

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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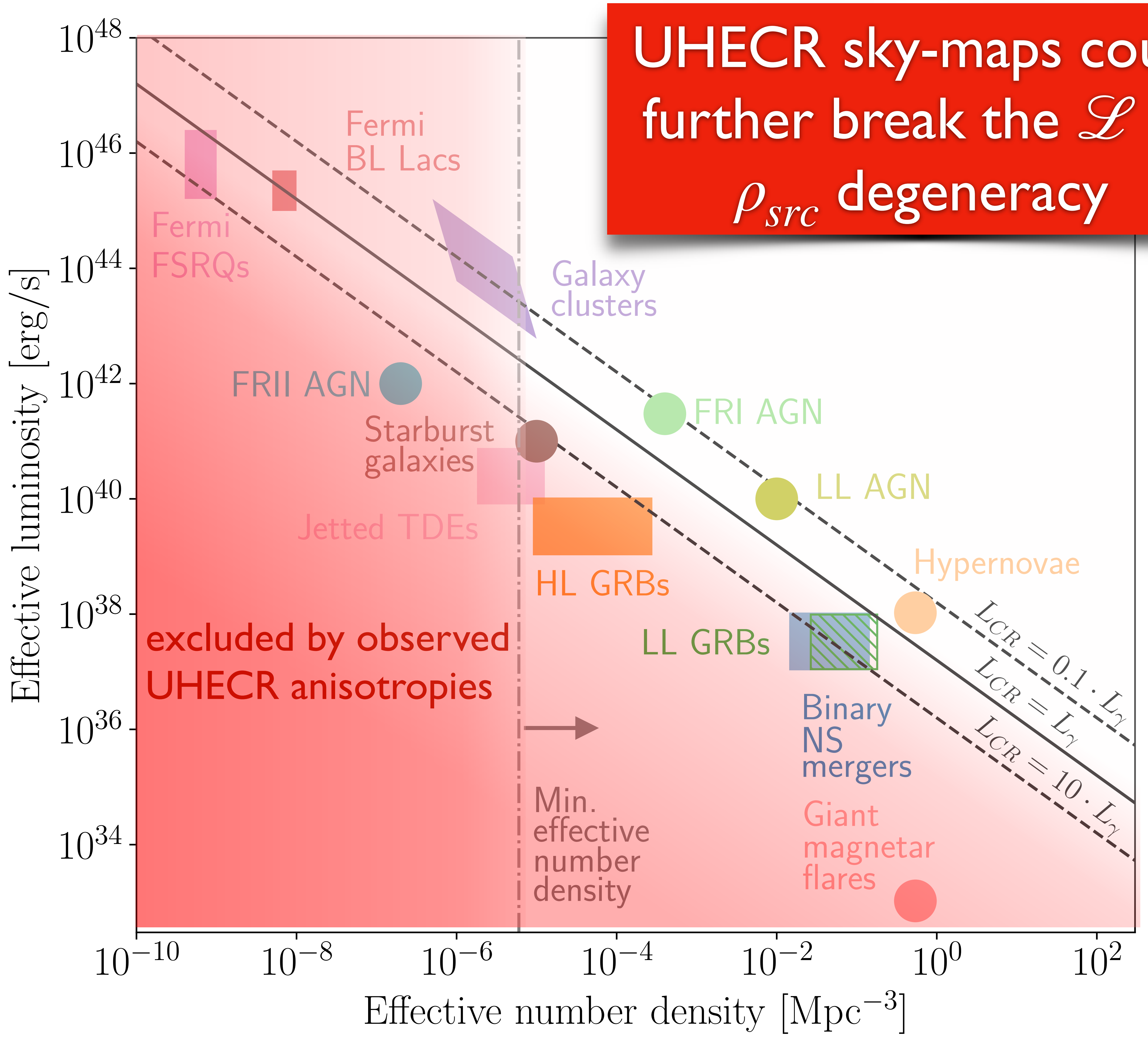
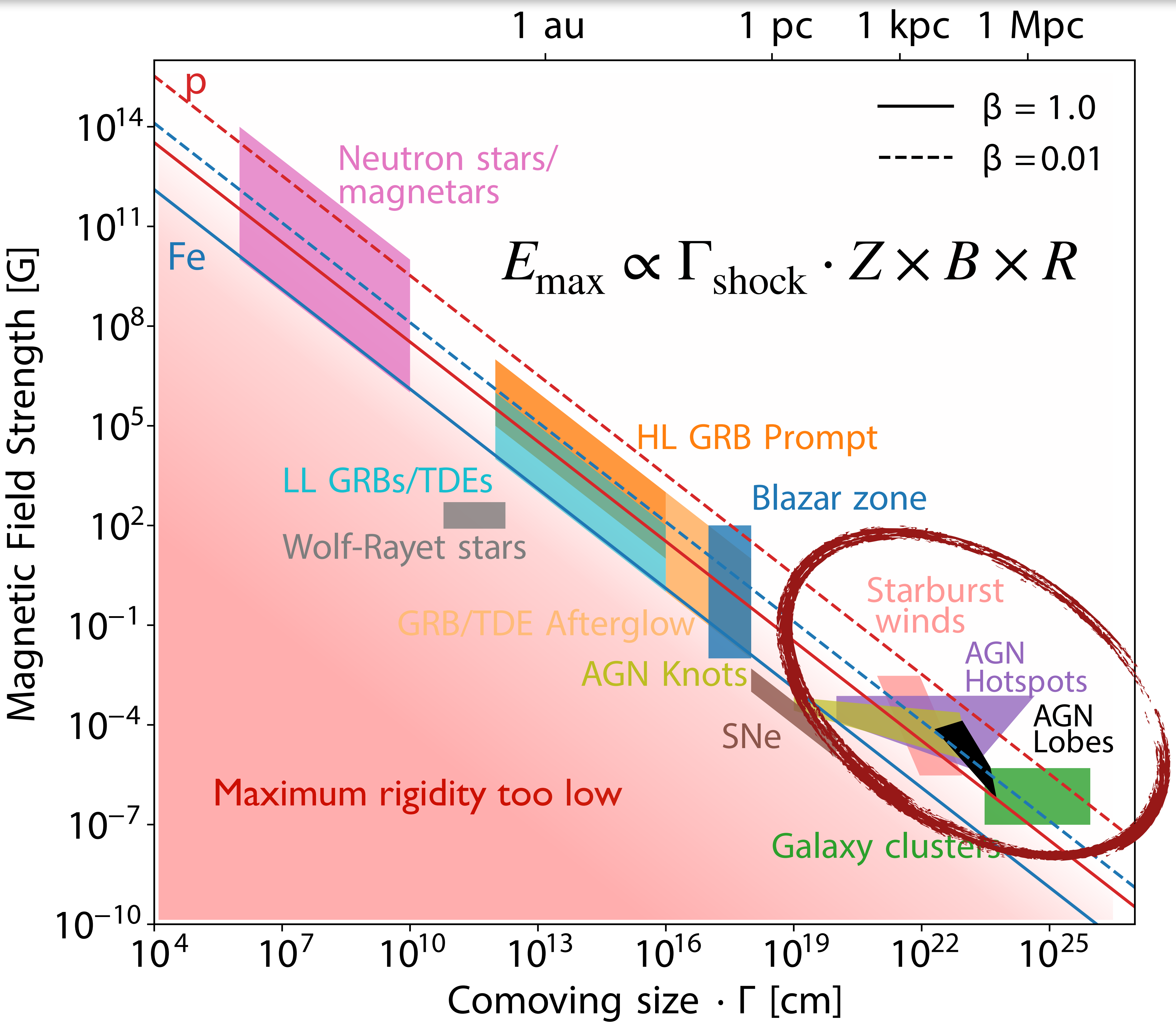
UHECR Luminosity and Acceleration Requirements



UHECR sky-maps could further break the $\mathscr{L}$ vs ρ_{src} degeneracy

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

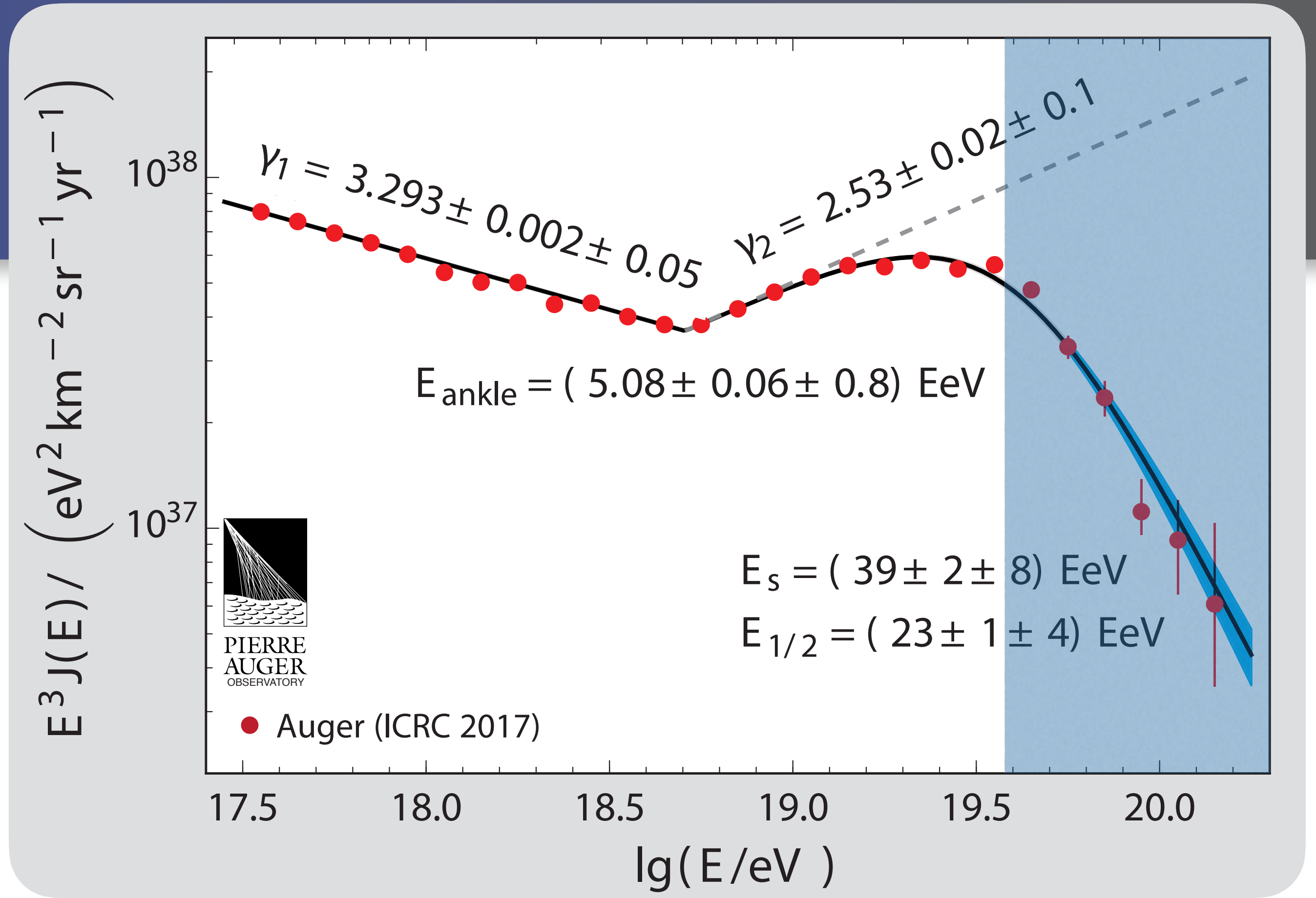


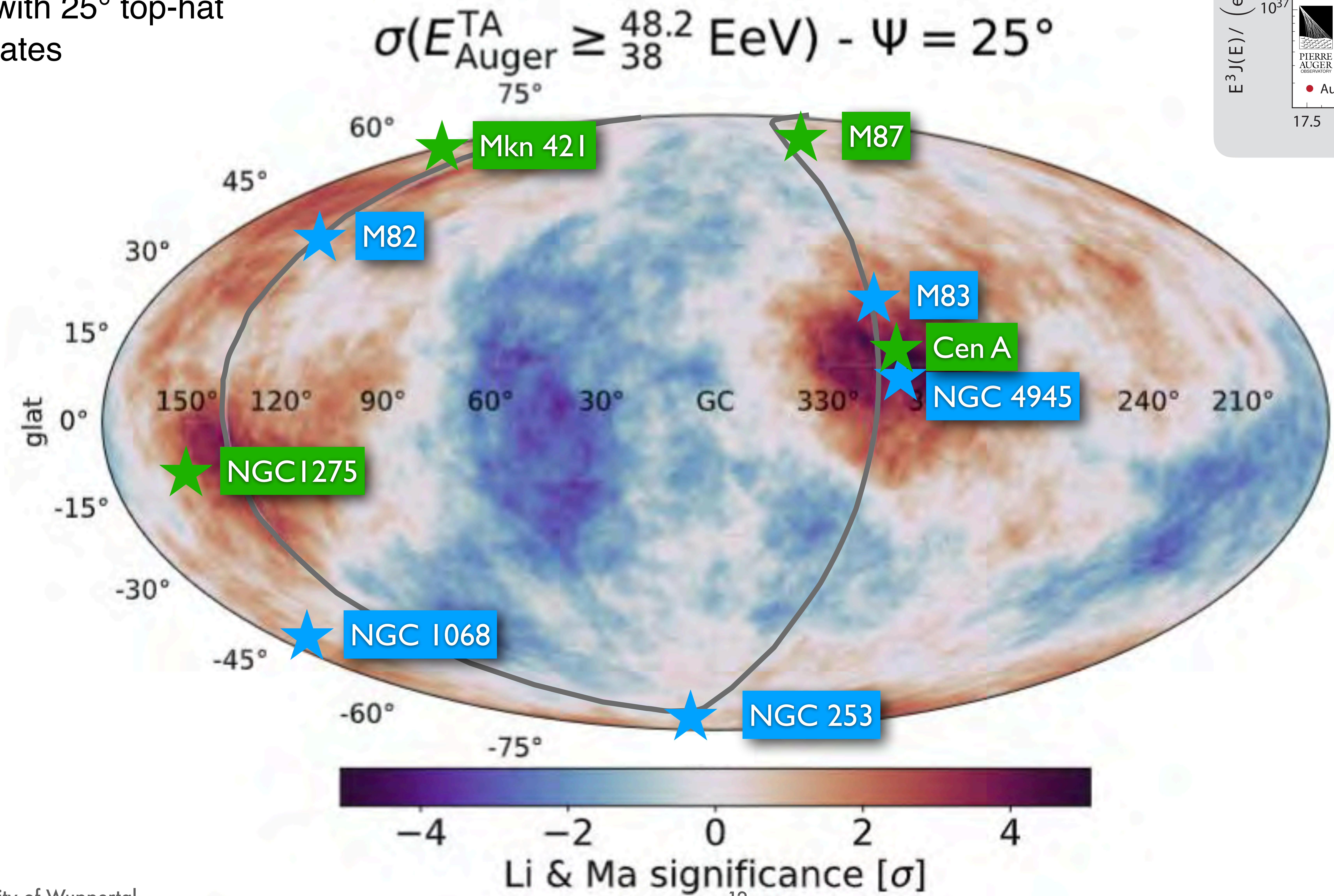
Note: plot applies both for steady and transient sources, when assuming a characteristic time spread of $\tau = 3 \cdot 10^5$ yr.

Auger combined with TA: > 38 EeV

Auger Collaboration, PoS(ICRC2023)544

map smoothed with 25° top-hat
Galactic coordinates





★ γ AGN

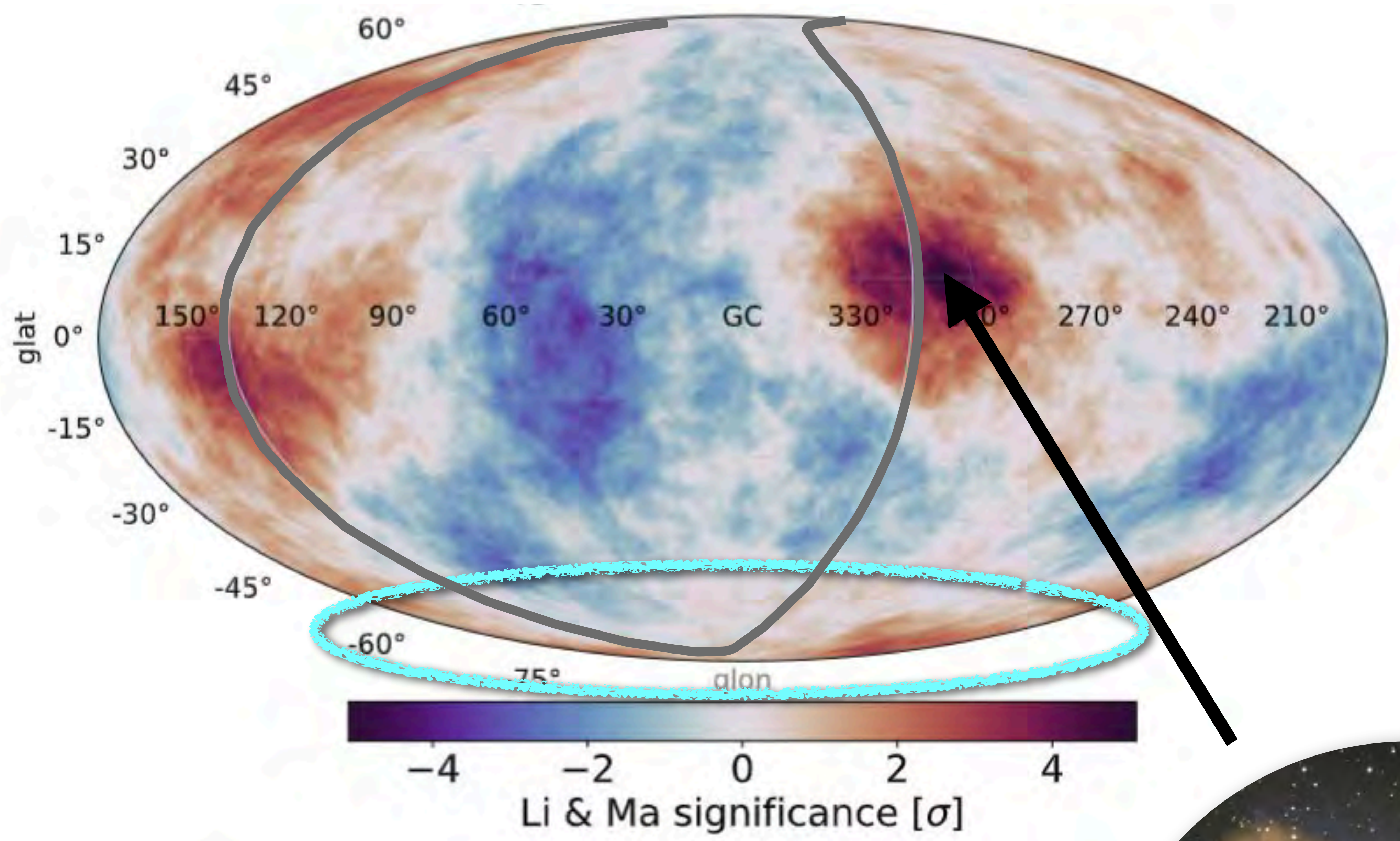
★ SBGs

— SuperGalactic Plane

Testing Correlation with Catalogues

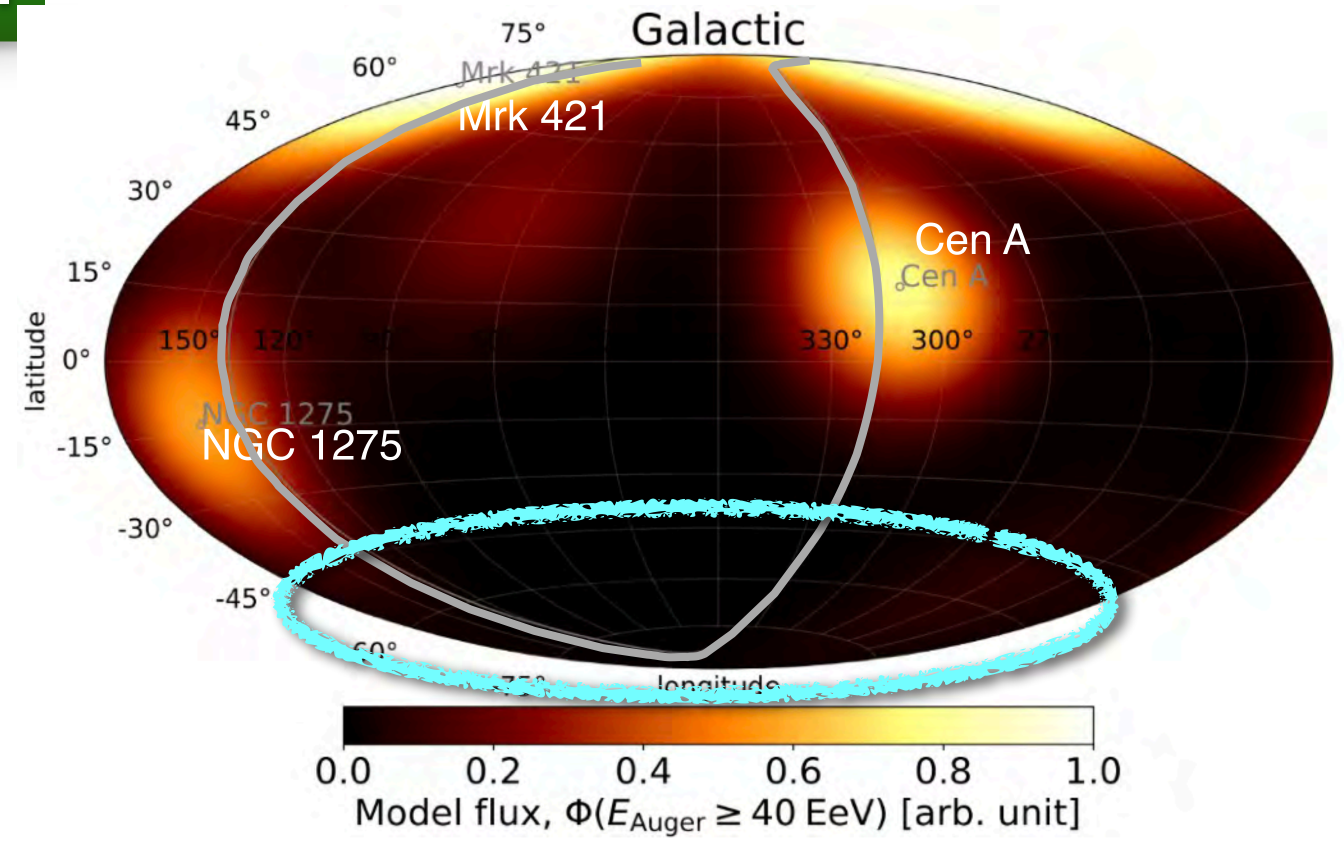
Auger Collaboration, ApJ 935 (2022), PoS(ICRC2023)352, 521

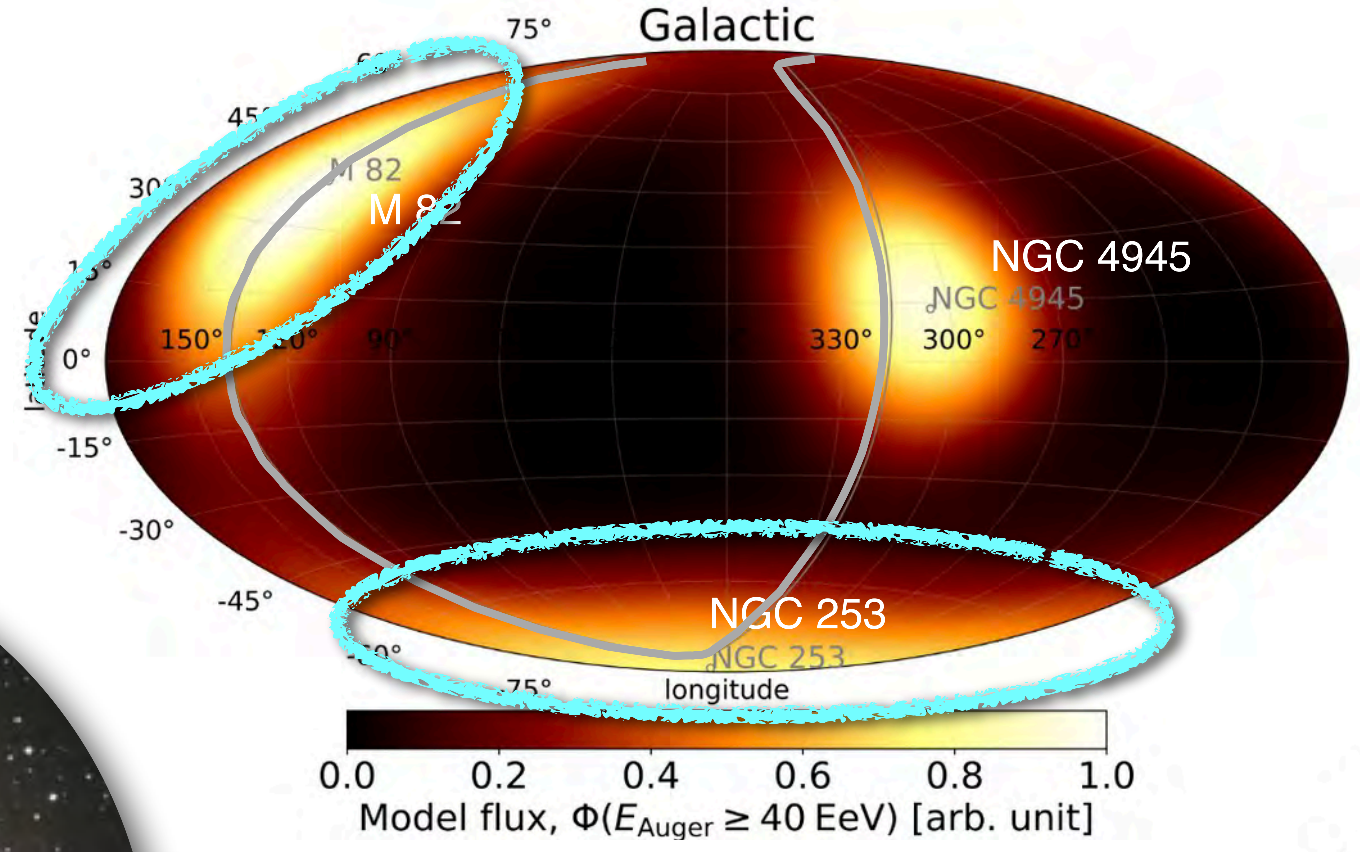
map smoothed with 25° top-hat
Galactic coordinates



Correlation
with Cen A: 4.0σ

5σ discovery level expected ≲2025





relative CR luminosities scaled by γ-ray luminosity;

scan of E_{th}, Ψ, sign. fraction

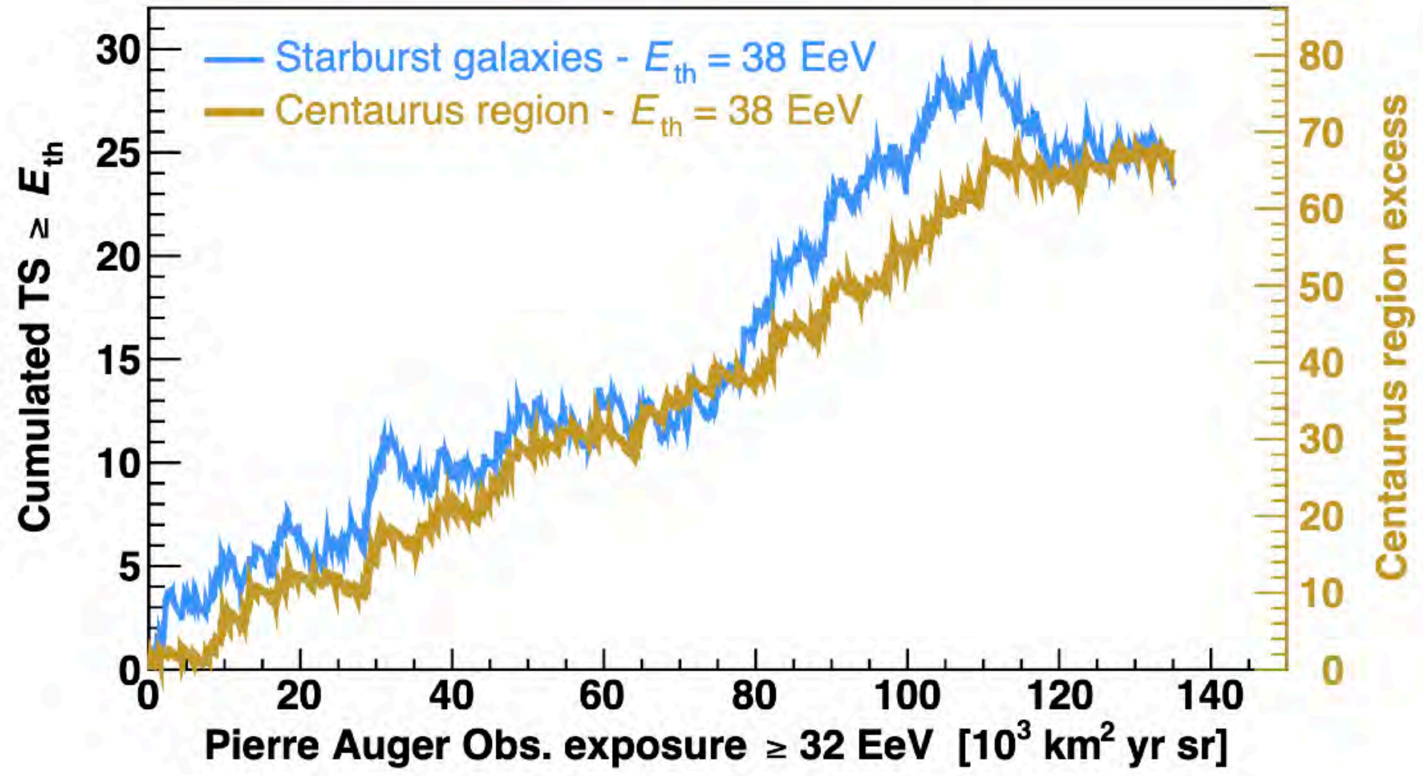
γ-AGN : 3.3 σ

E_{th} = 38 EeV, Ψ=23°, α=6%

SGB : 4.6 σ (incl. TA)

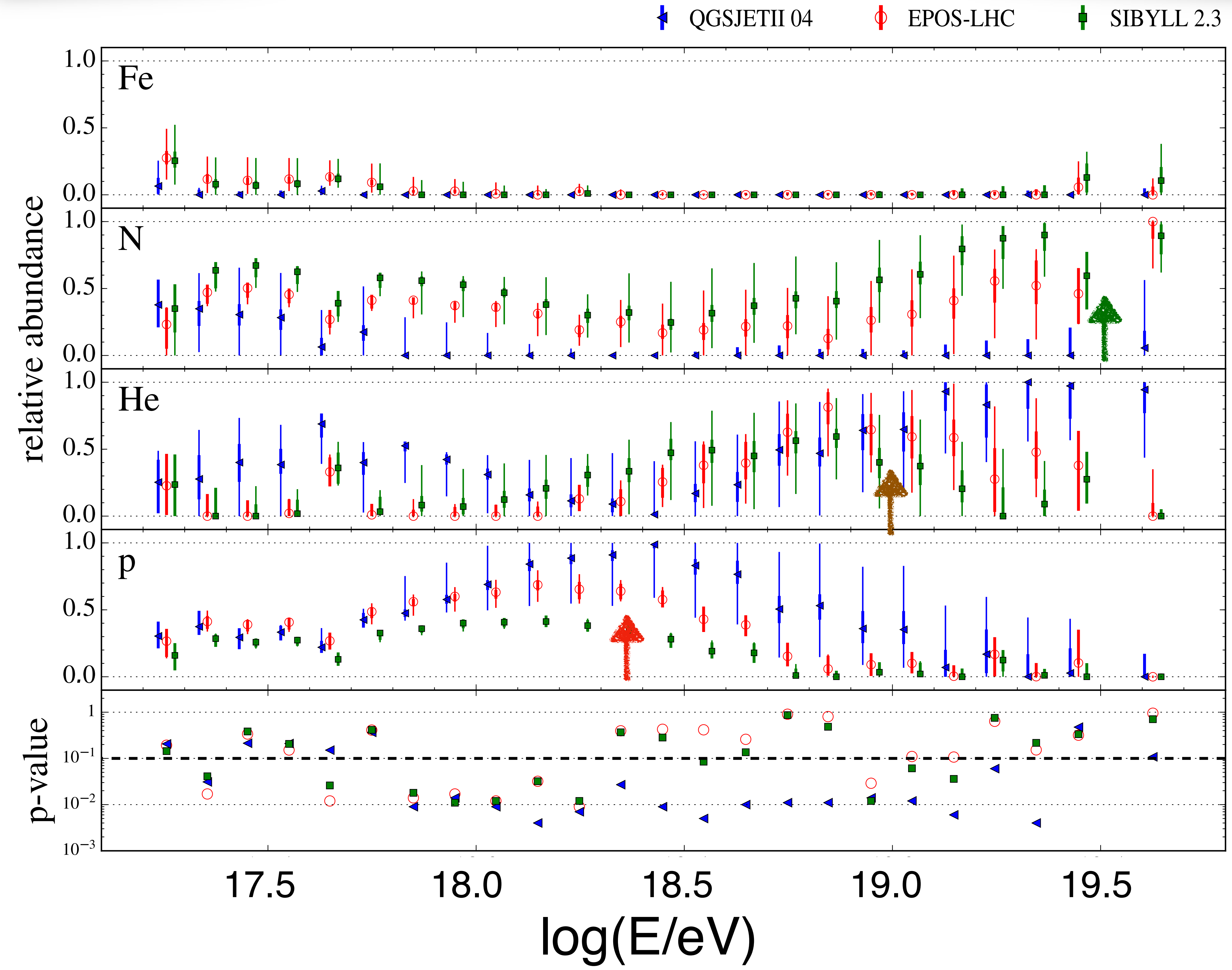
E_{th} = 38 EeV, Ψ=25°, α=9%

need also isotropic bkg → these sources contribute only 10-20% of CR flux!

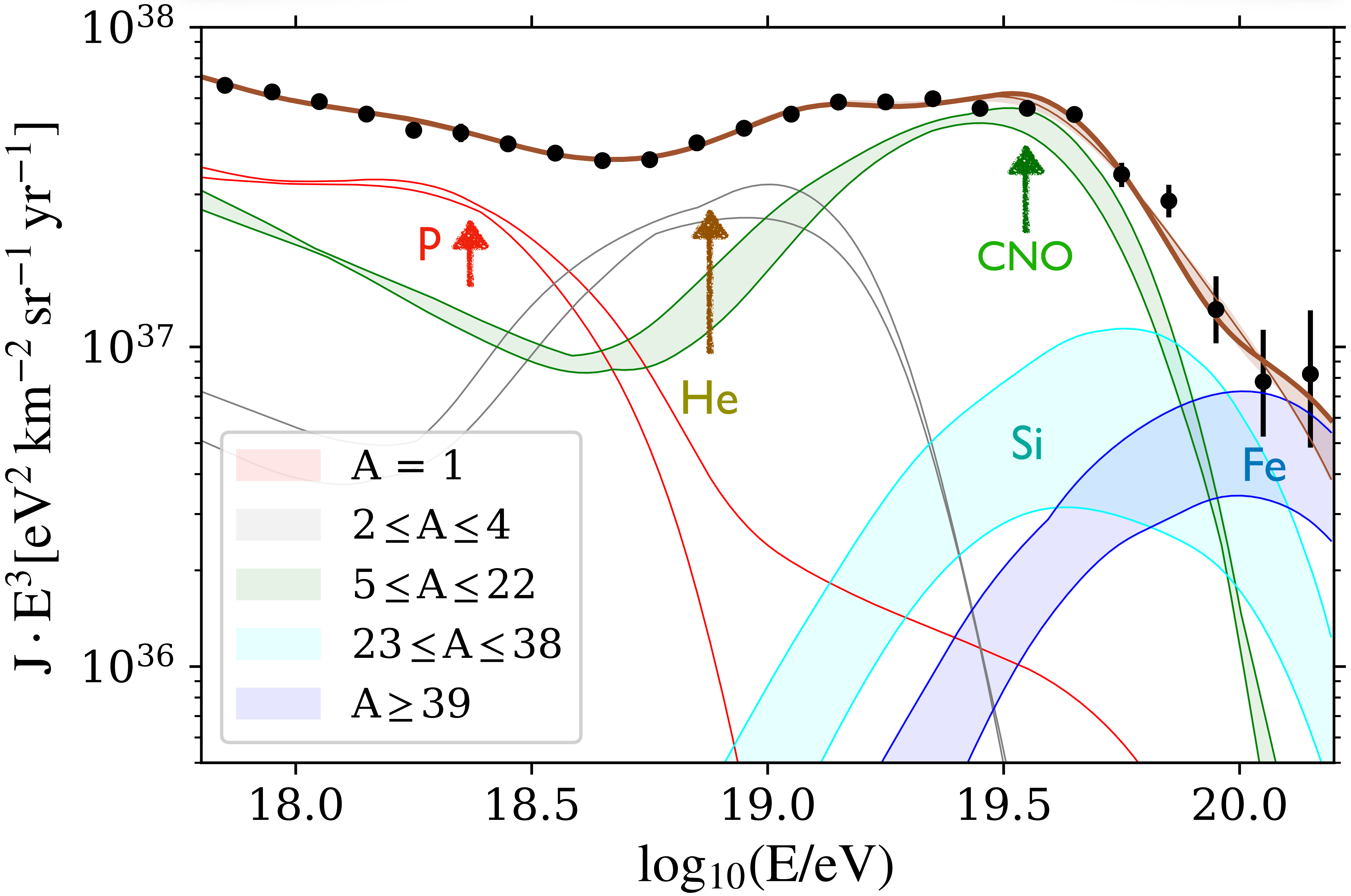


CR Energy Spectrum and Mass Composition

CR mass fractions from longitudinal shower development: X_{max}, $\sigma(X_{max})$, PRD 2014



Combined fit of E, X_{max}, $\sigma(X_{max})$; JCAP 05 (2023)
note, nearly mono elemental compositions !



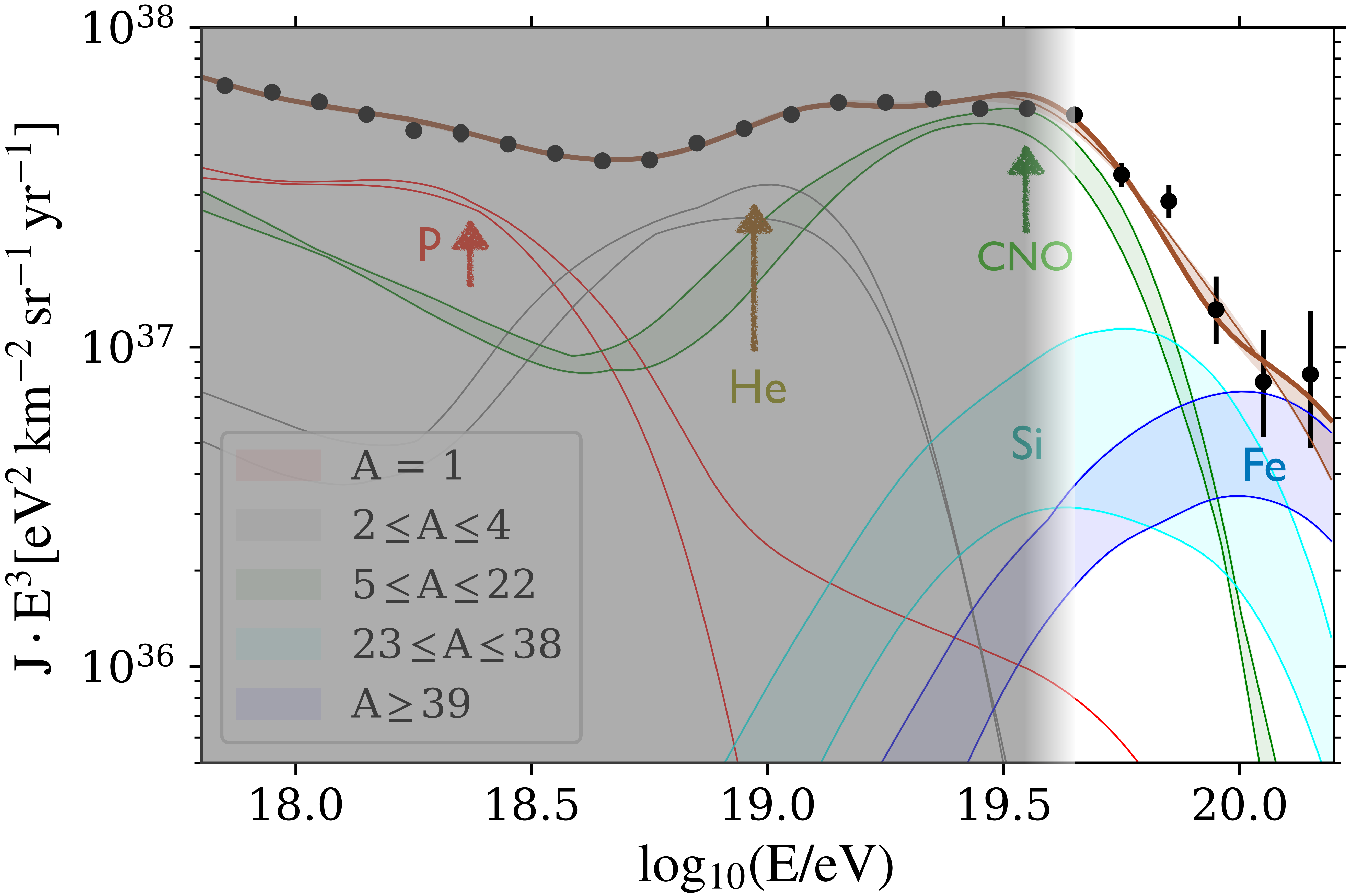
Derived source parameters: $\mathscr{L} \simeq 5.1 \cdot 10^{44}\,\mathrm{erg\,Mpc^{-3}yr^{-1}}$

$\log(R_{max}) = 18.15$ V

⇒ end of CR spectrum rather a source than a propagation effect !

very hard nuclear spectra escaping from sources (assuming steady EG sources)

GZK-Effect



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

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

Energy threshold $E_p \sim 6 \cdot 10^{19}$ eV

Almost no protons above GZK threshold → strong reduction of cosmogenic ν's and γ's

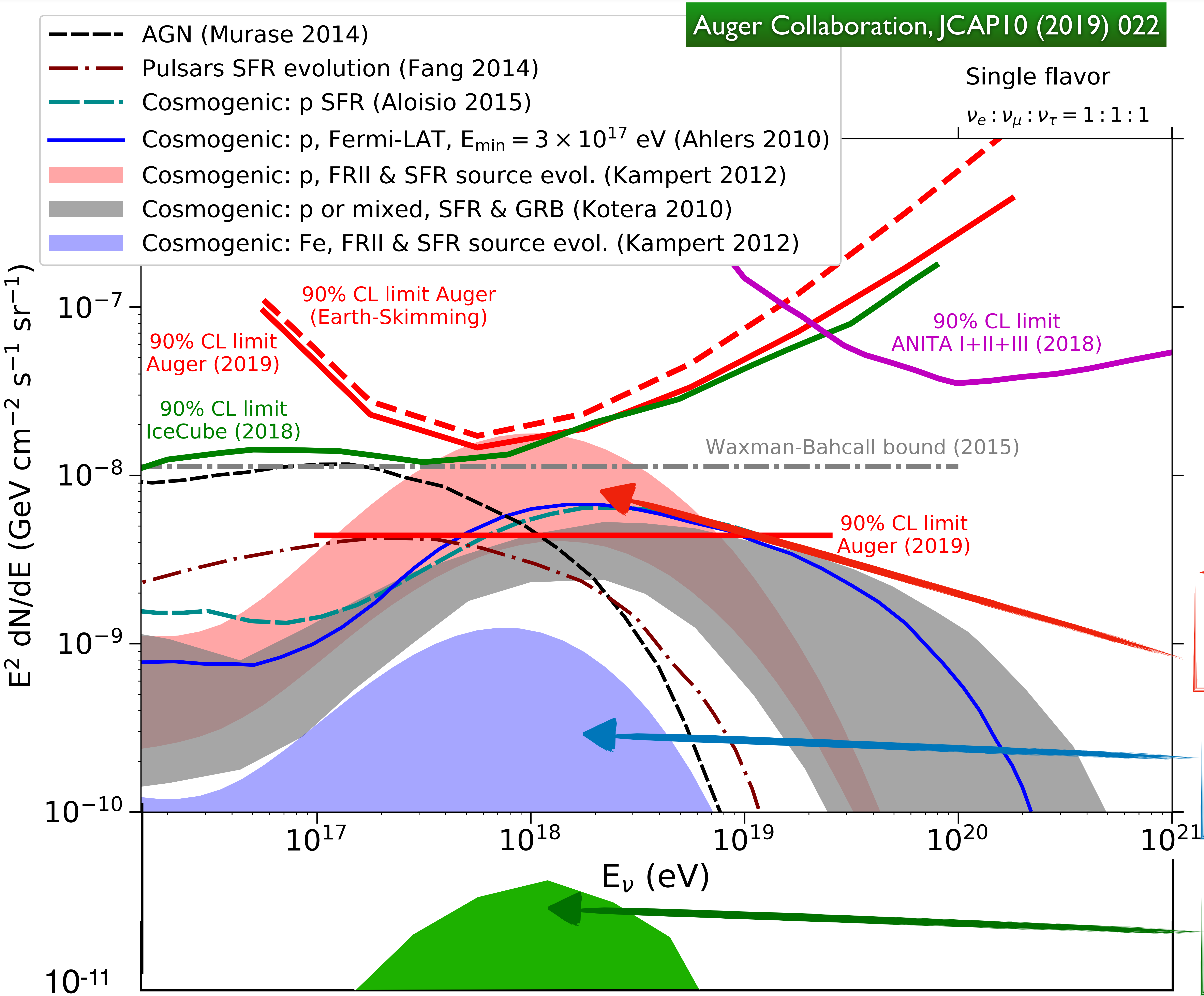
Nuclei suffer photo disintegration

$$A + \gamma_{CMB} \rightarrow (A-1) + p, n \rightarrow \nu_e; E_\nu \lesssim E_A / A$$

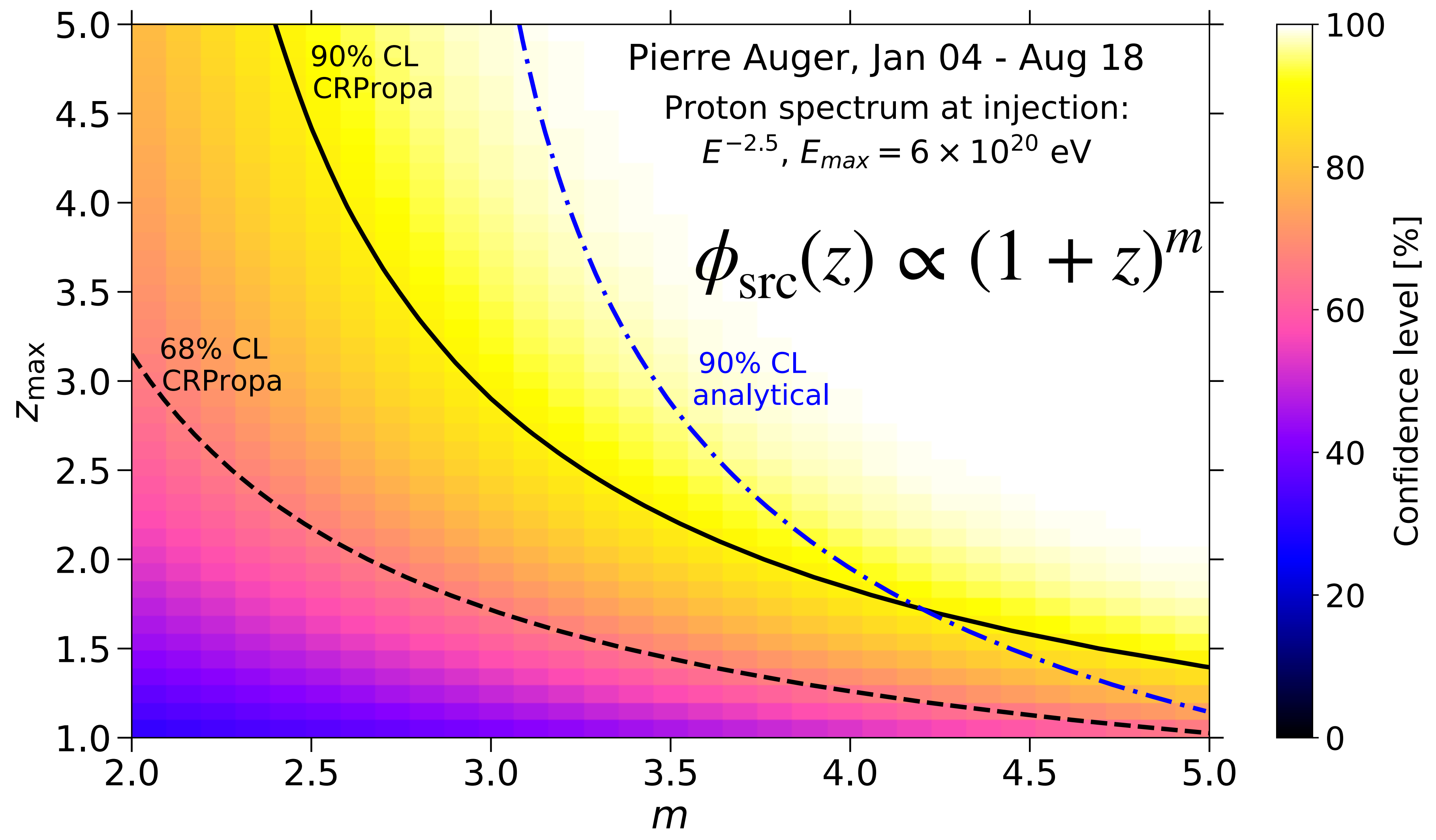
at $E_A \lessapprox 5 \cdot 10^{19}$ eV

⇒ cosmogenic fluxes down by orders of magnitude

Bounds on cosmogenic neutrino fluxes



Auger Collaboration, JCAP10 (2019) 022



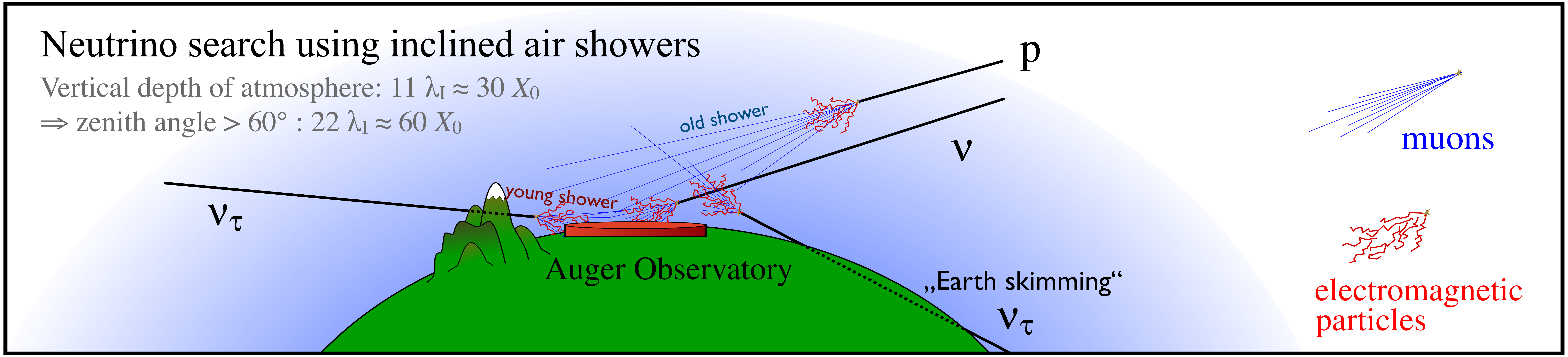
cosmological evolution of sources could be constrained up to f_p=0.1

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

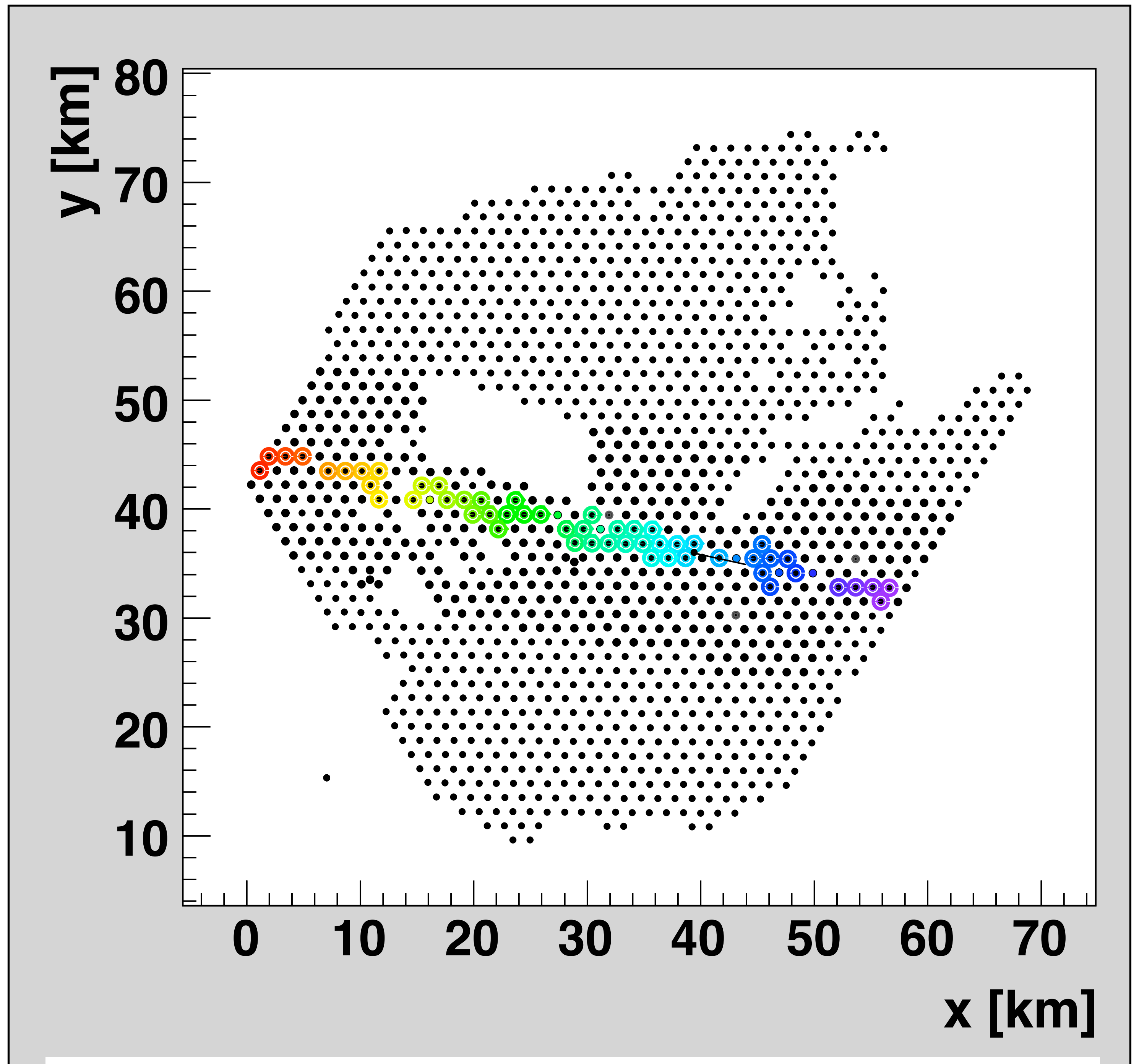
Neutrinos in Air Shower Experiments



Neutrino search using inclined air showers

Vertical depth of atmosphere: $11\ \lambda_I \approx 30\ X_0$

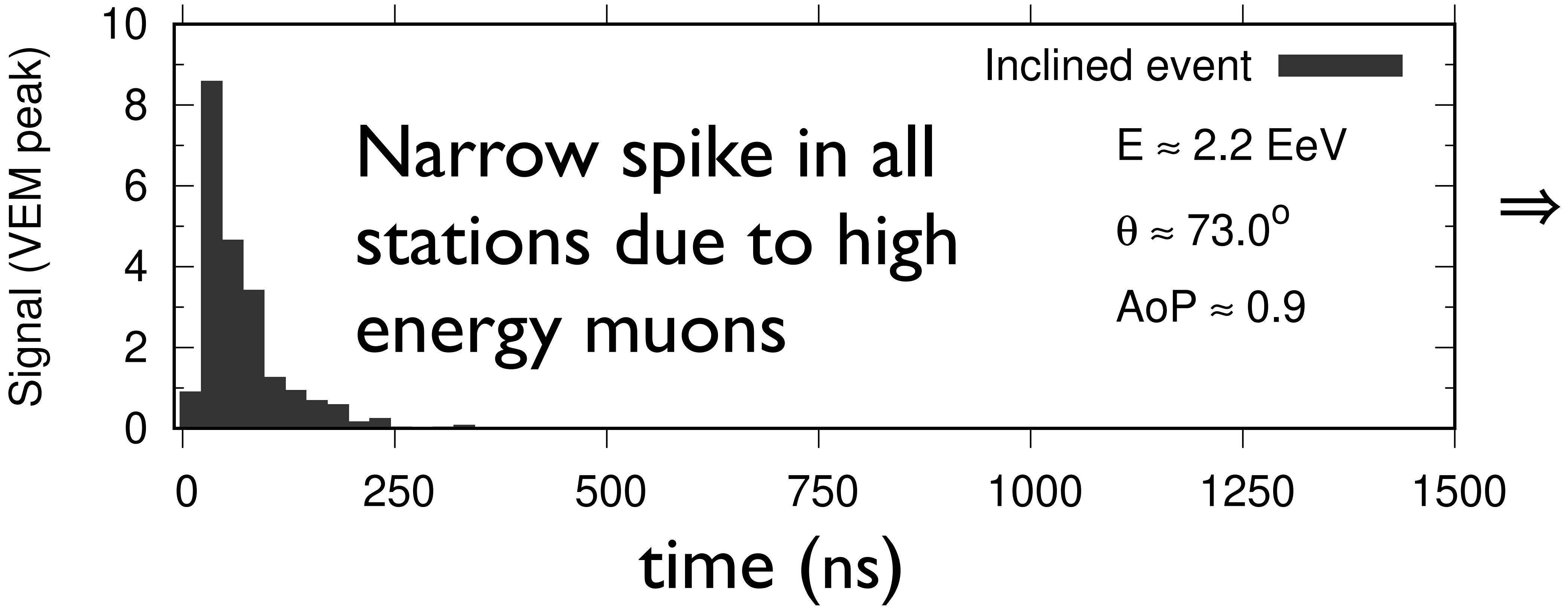
$\Rightarrow$ zenith angle > 60° : $22\ \lambda_I \approx 60\ X_0$



Event 3618809 (25 June 2007): 59 stations,

Example of a very horizontal shower in Auger, extending over ~60 km!

Time traces in Water Cherenkov stations



Narrow spike in all stations due to high energy muons

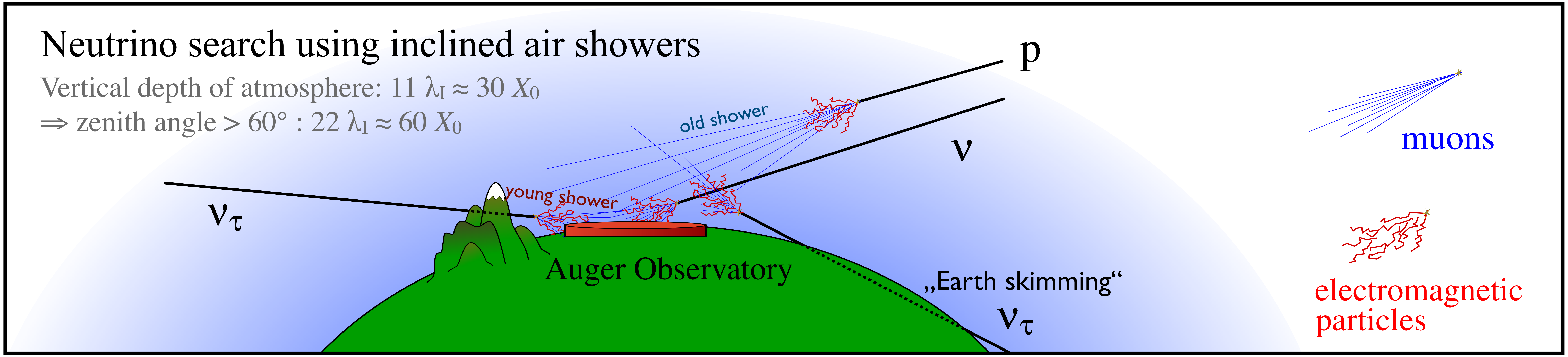
$\Rightarrow$ ordinary hadronic origin, no neutrino

Neutrinos in Air Shower Experiments

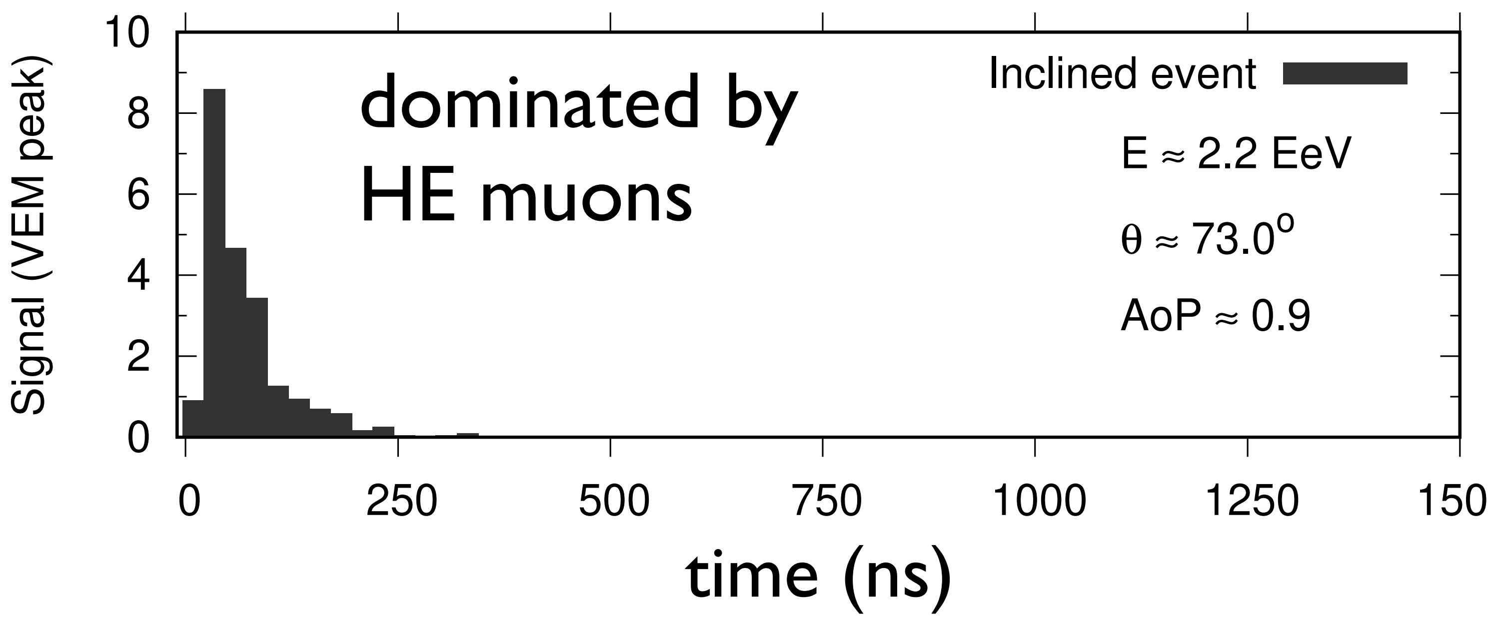
Neutrino search using inclined air showers

Vertical depth of atmosphere: 11 $\lambda_I \approx 30\ X_0$

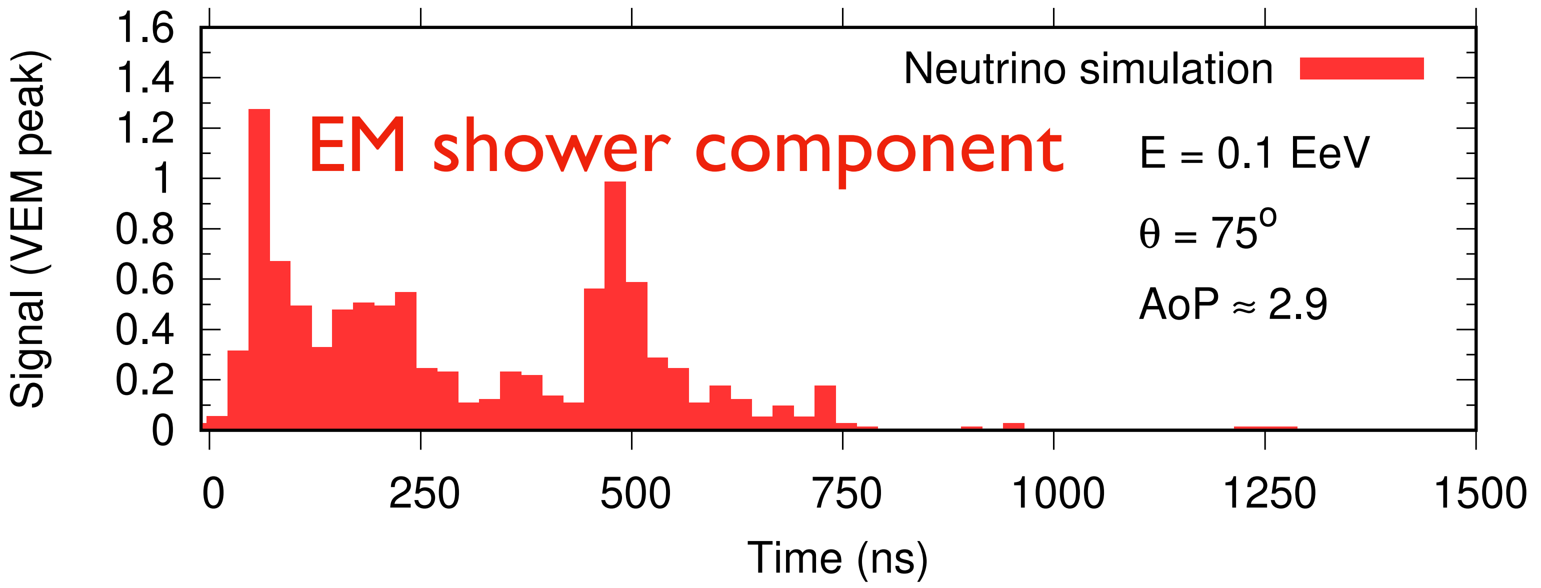
$\Rightarrow$ zenith angle > 60° : 22 $\lambda_I \approx 60\ X_0$



CR → old shower at ground

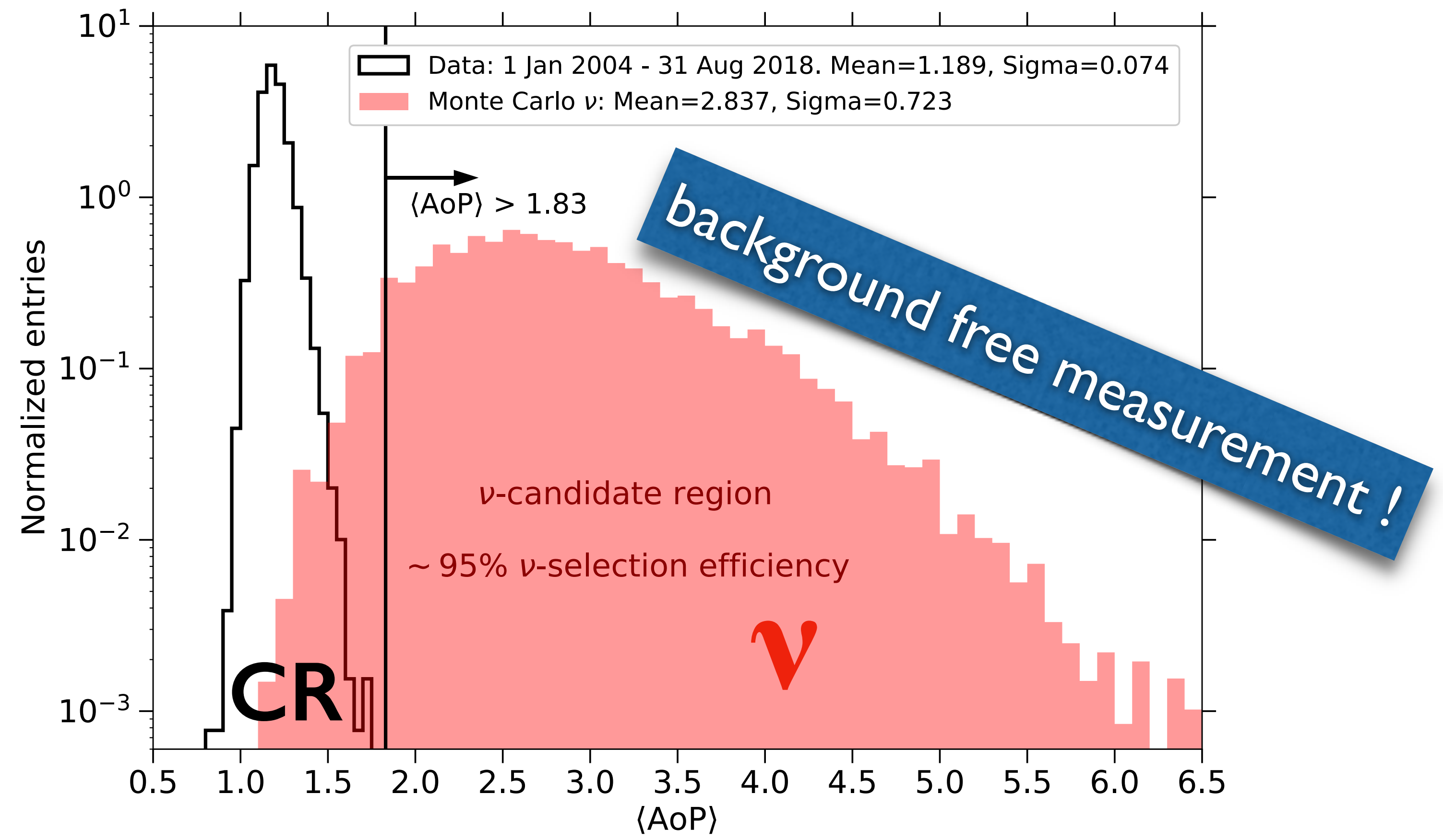


ν → young shower at ground



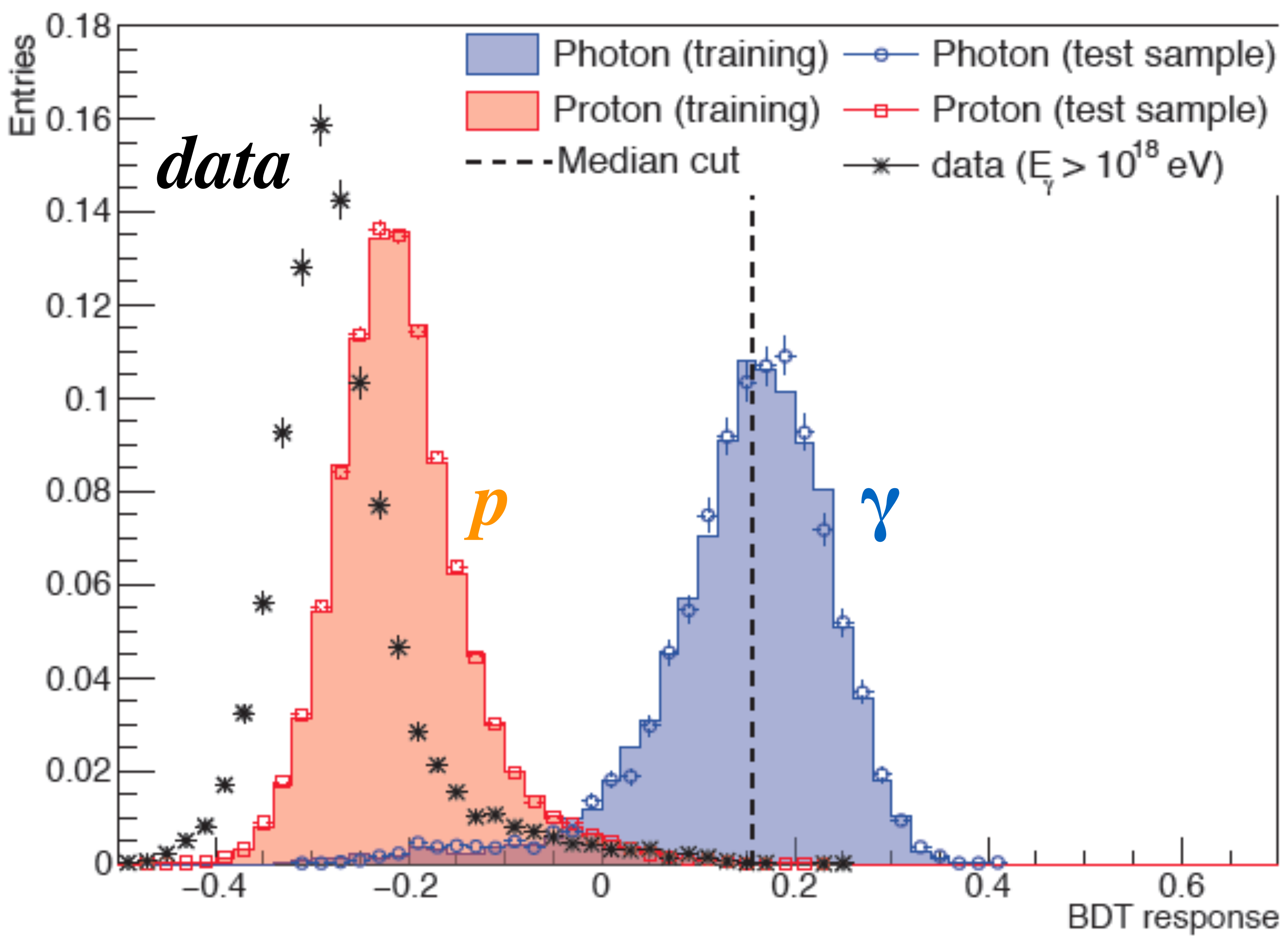
Typical signal traces in water Cherenkov stations

perfect discrimination just by Area-over-Peak

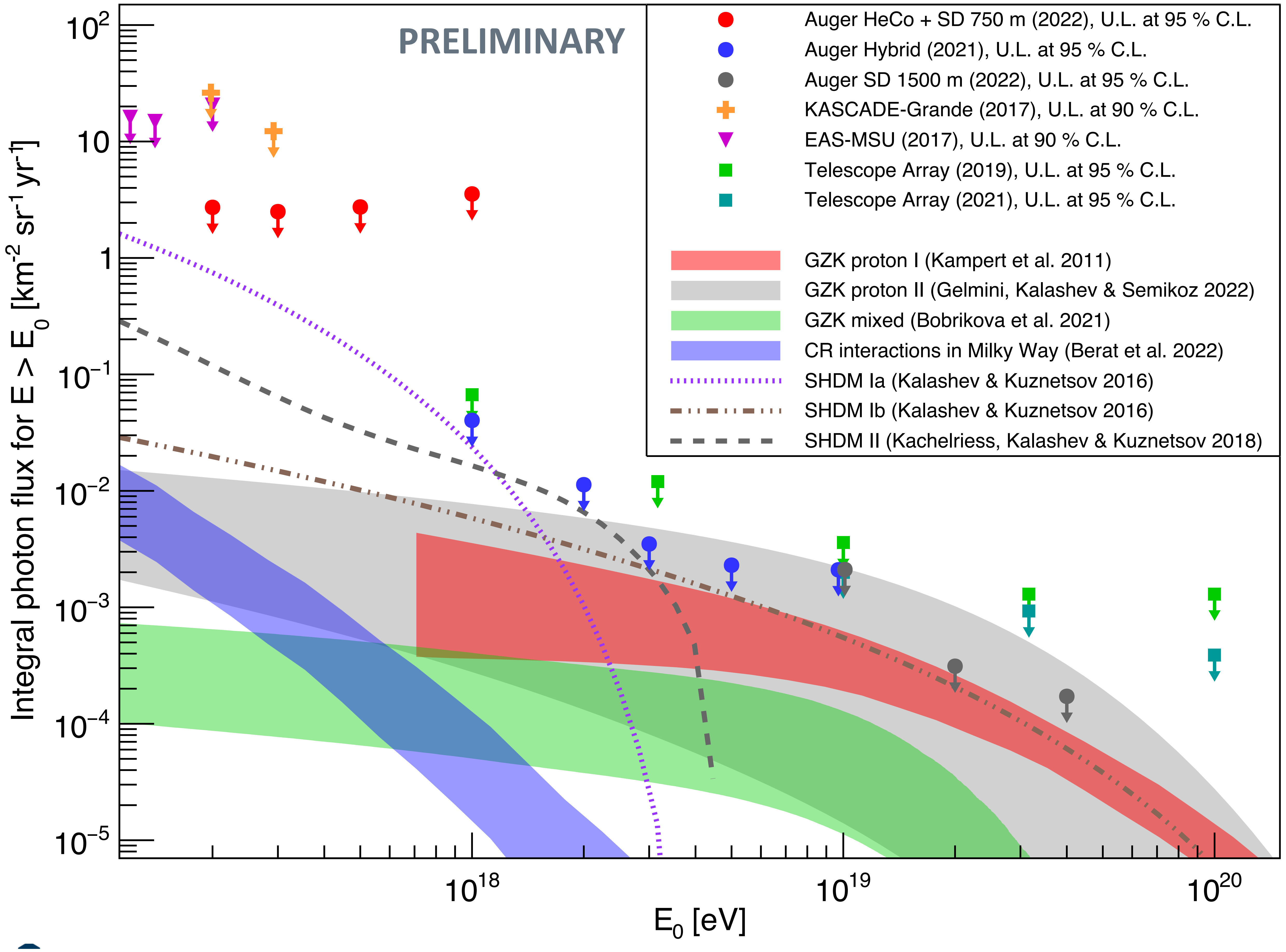


EeV **Photon Limits** challenge protons suffering GZK-losses

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

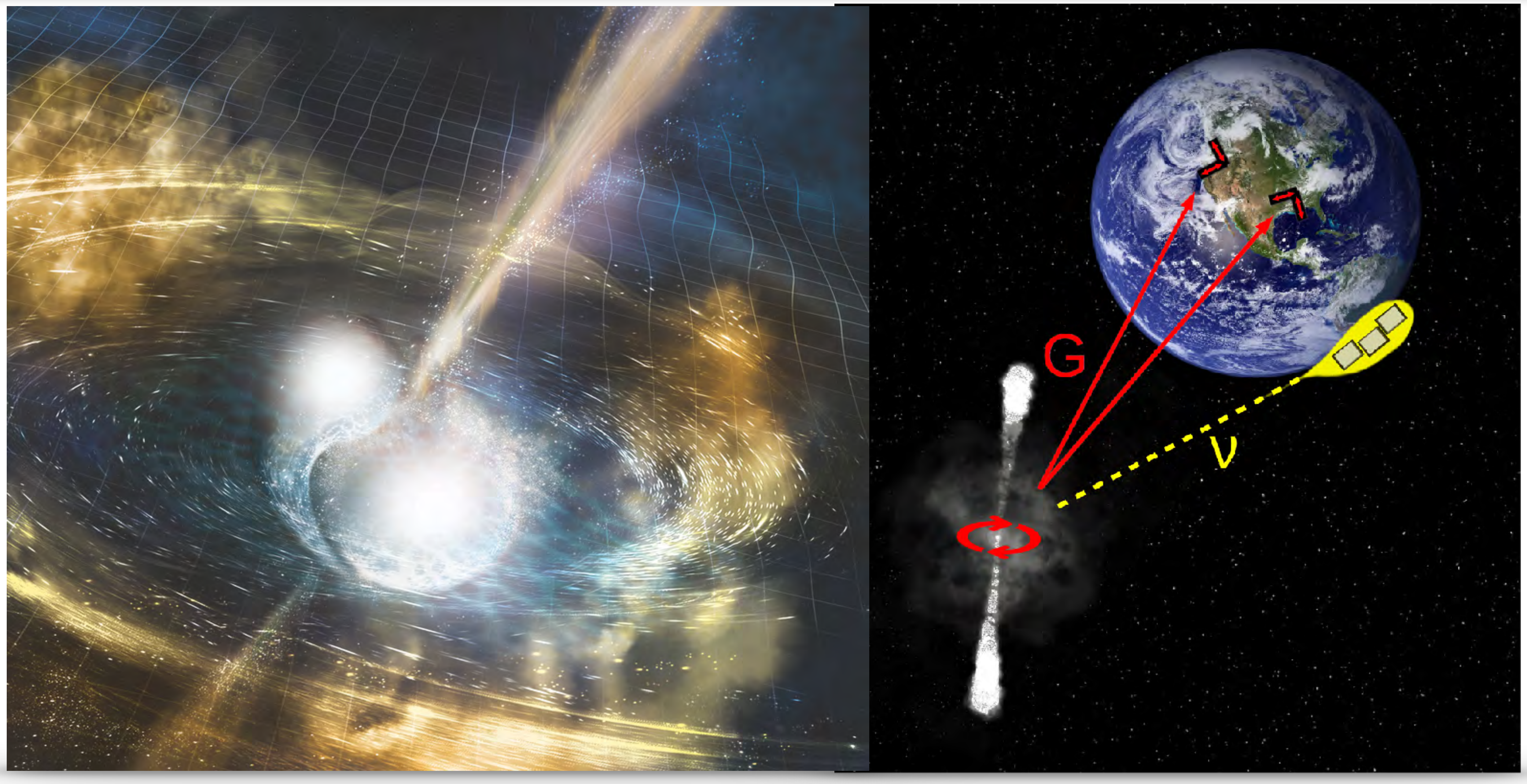


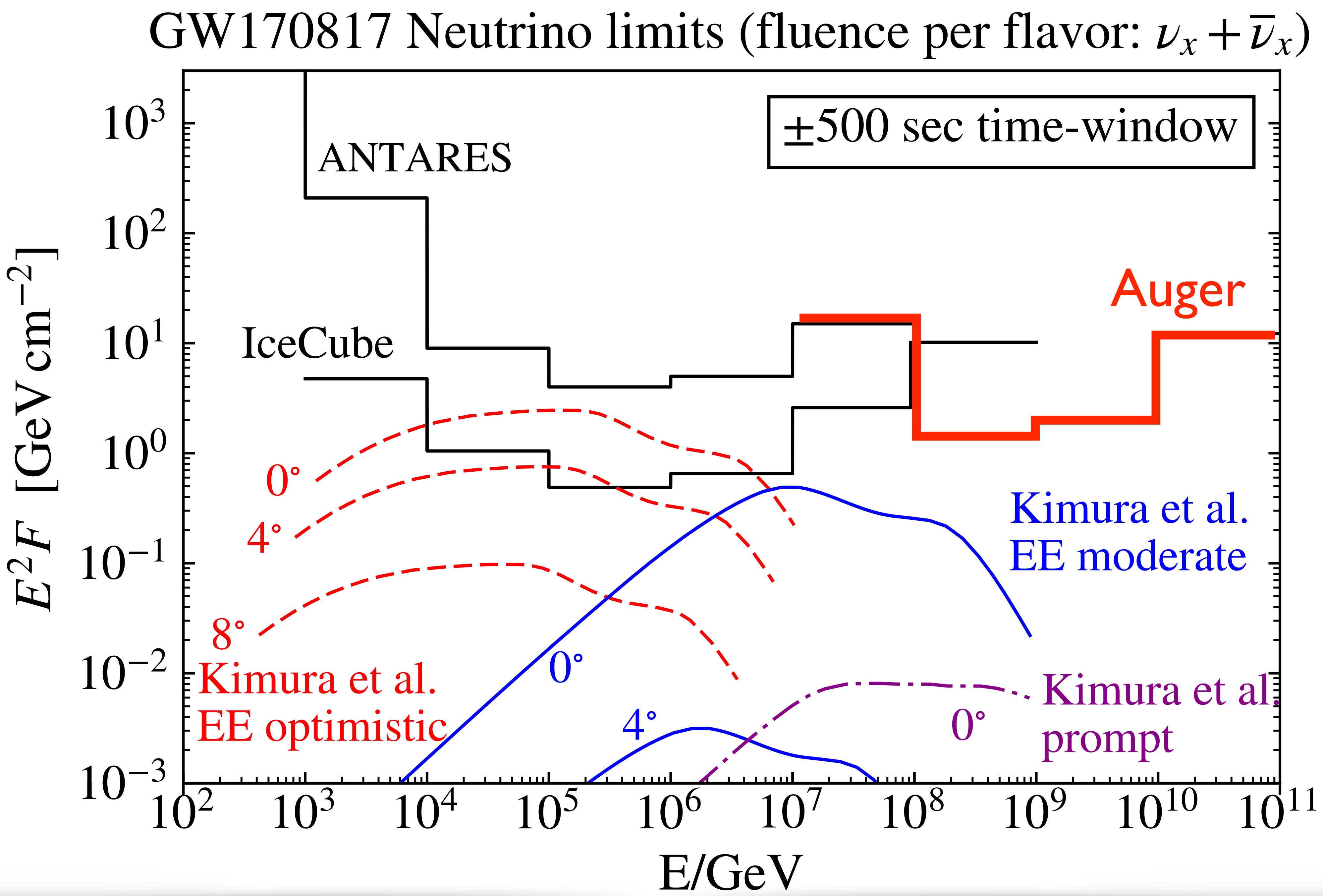
Auger Collaboration, JCAP04 (2017) 009; Universe (2022) 8, 579; JCAP05 (2023) 021

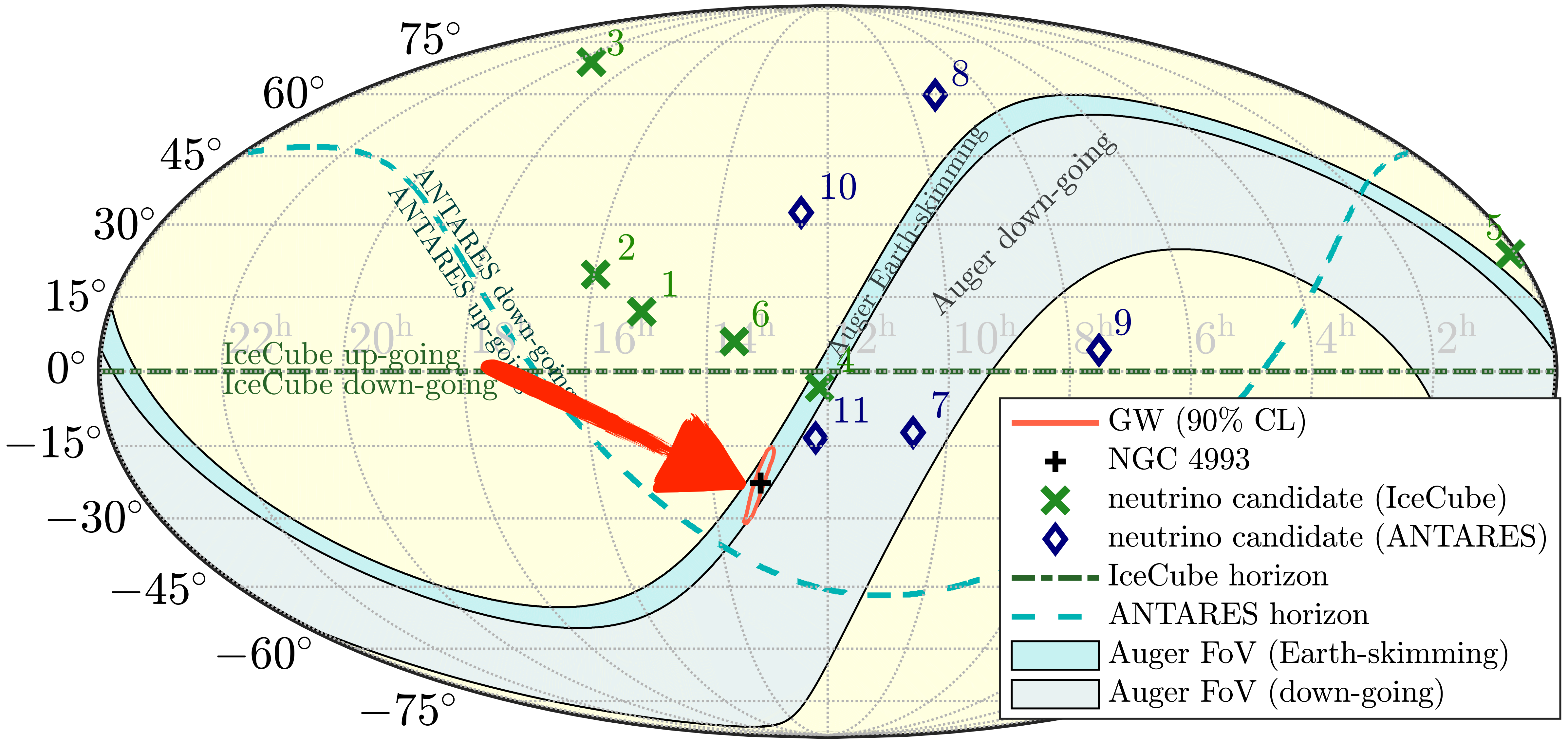


Similarly, photon upper limits start to constrain cosmogenic photon fluxes of p-sources and SHDM models

Neutrino Upper Limits for GW170817







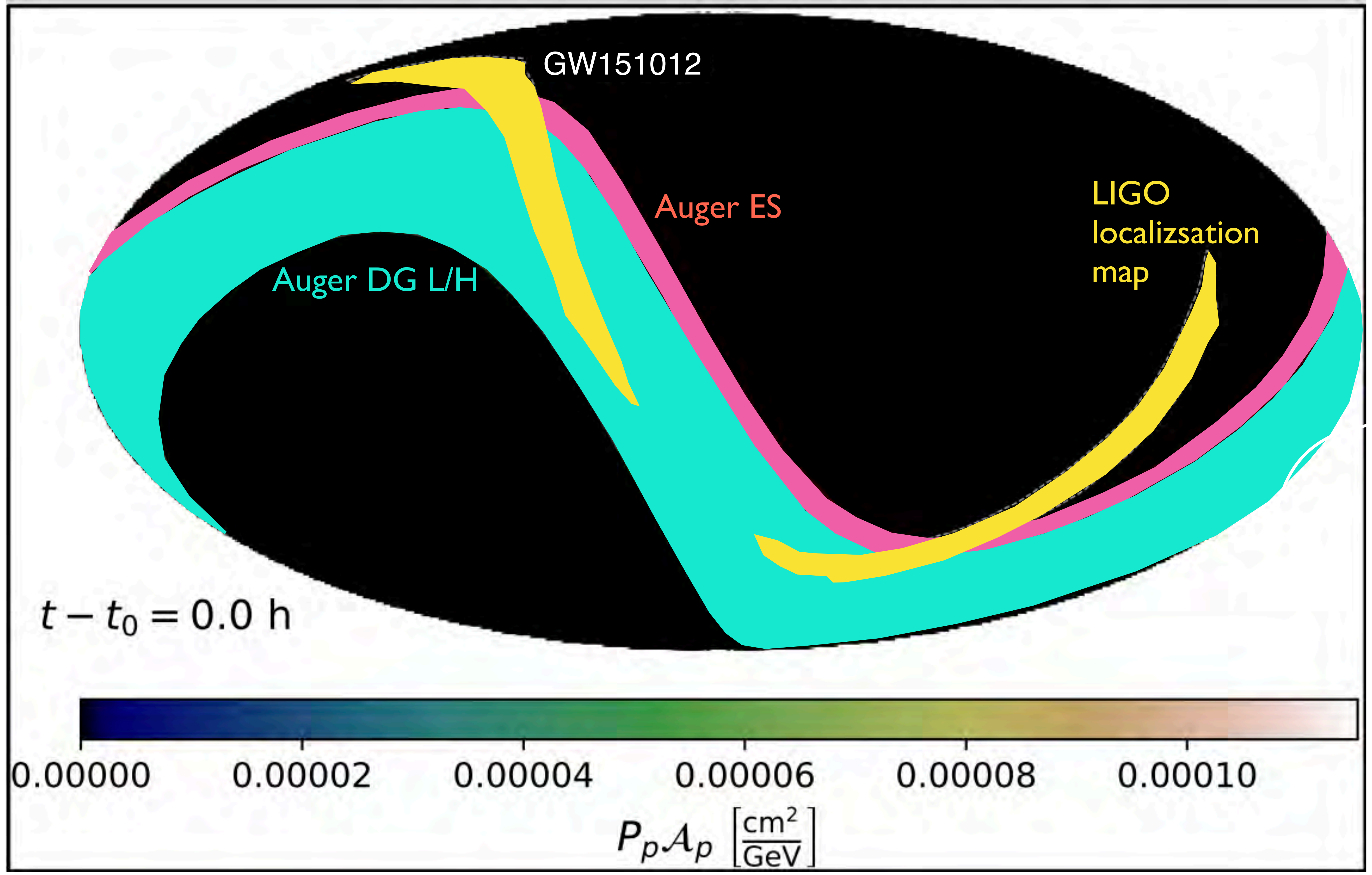
Absence of neutrinos consistent with SGRB viewed at >20° angle

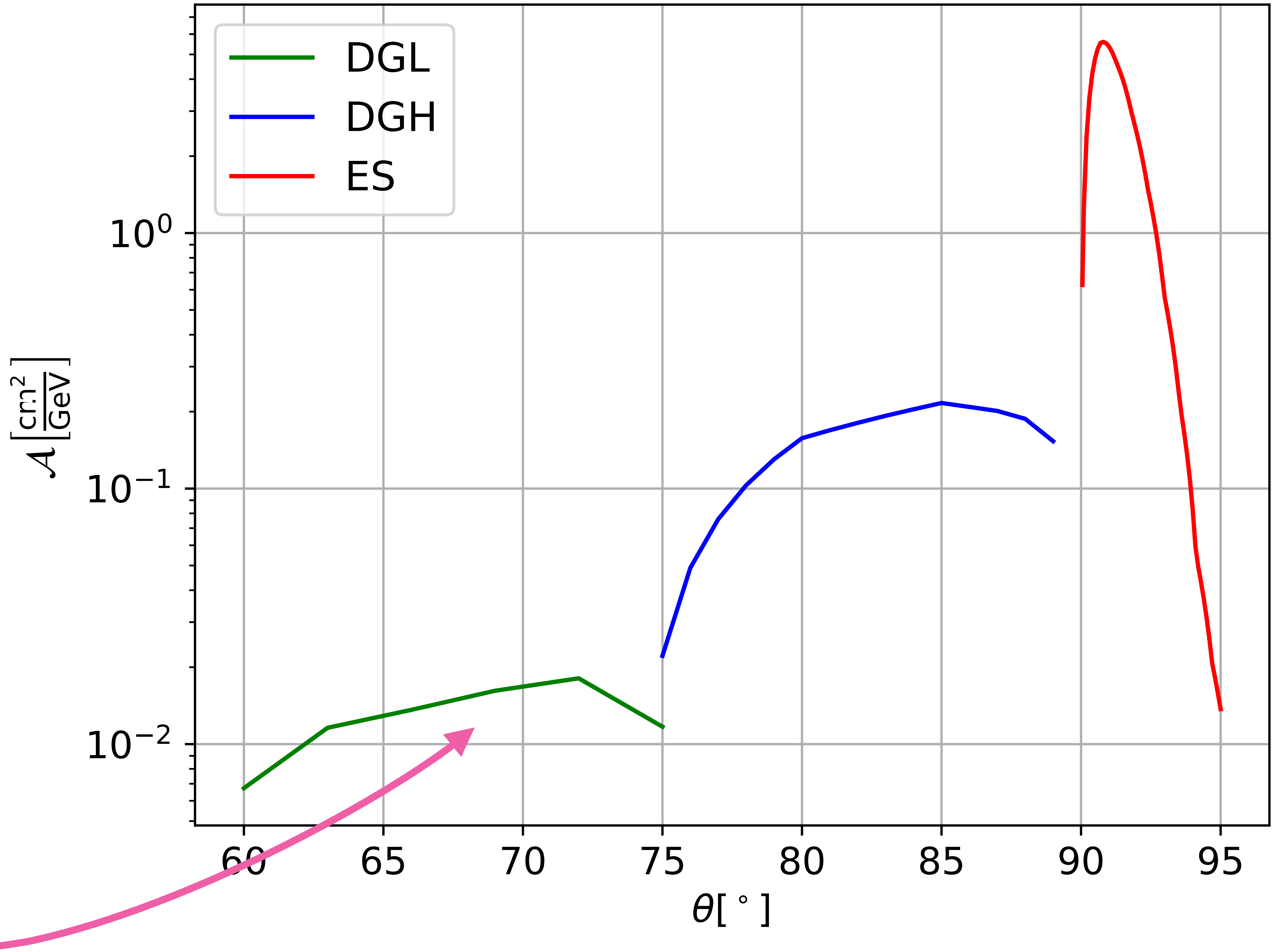
May have seen neutrinos if jet were pointing towards us

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

see also Samaya's talk

Combining BBH Mergers





solid angle integration

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

effective area

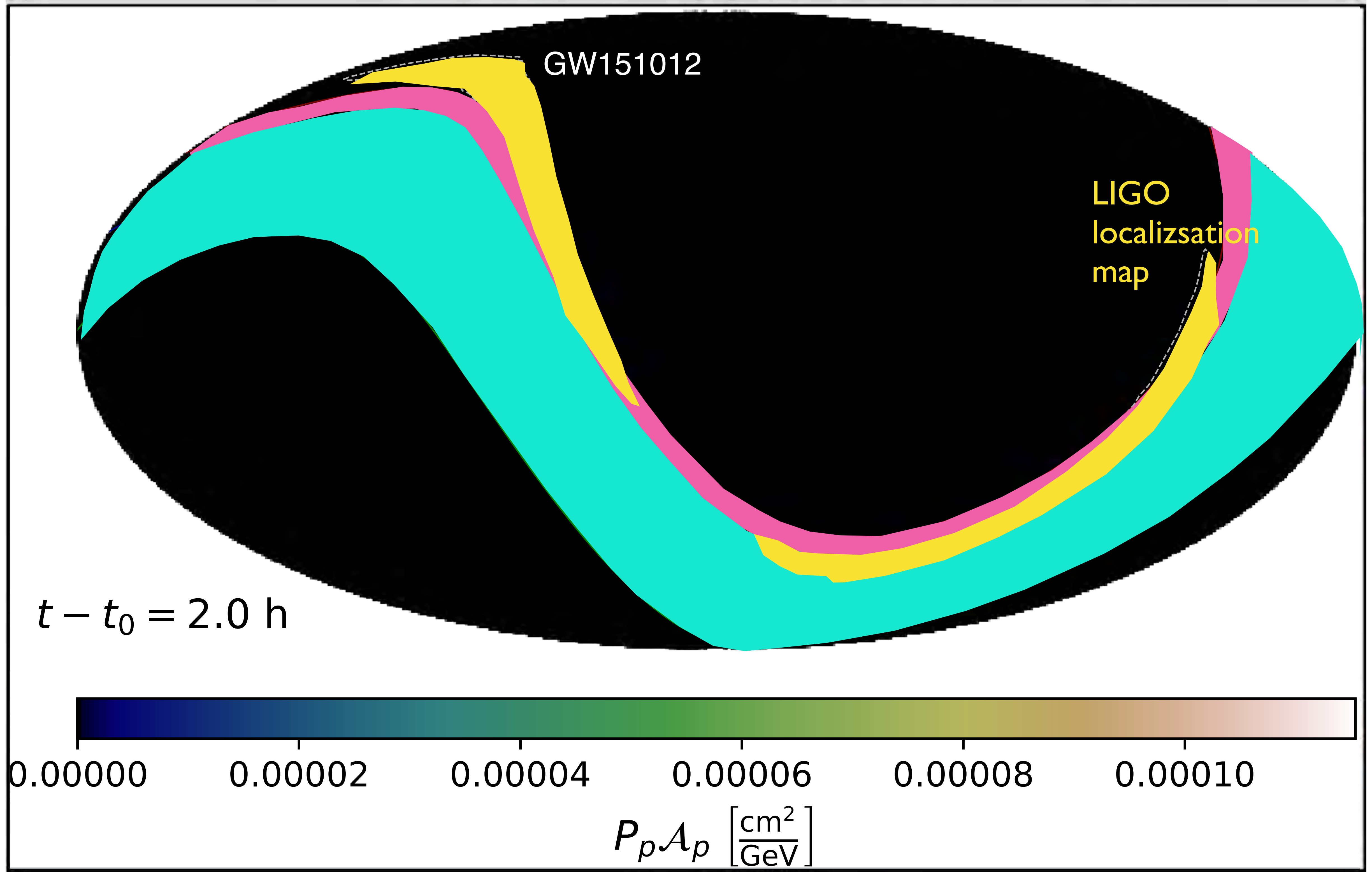
sum over all sources

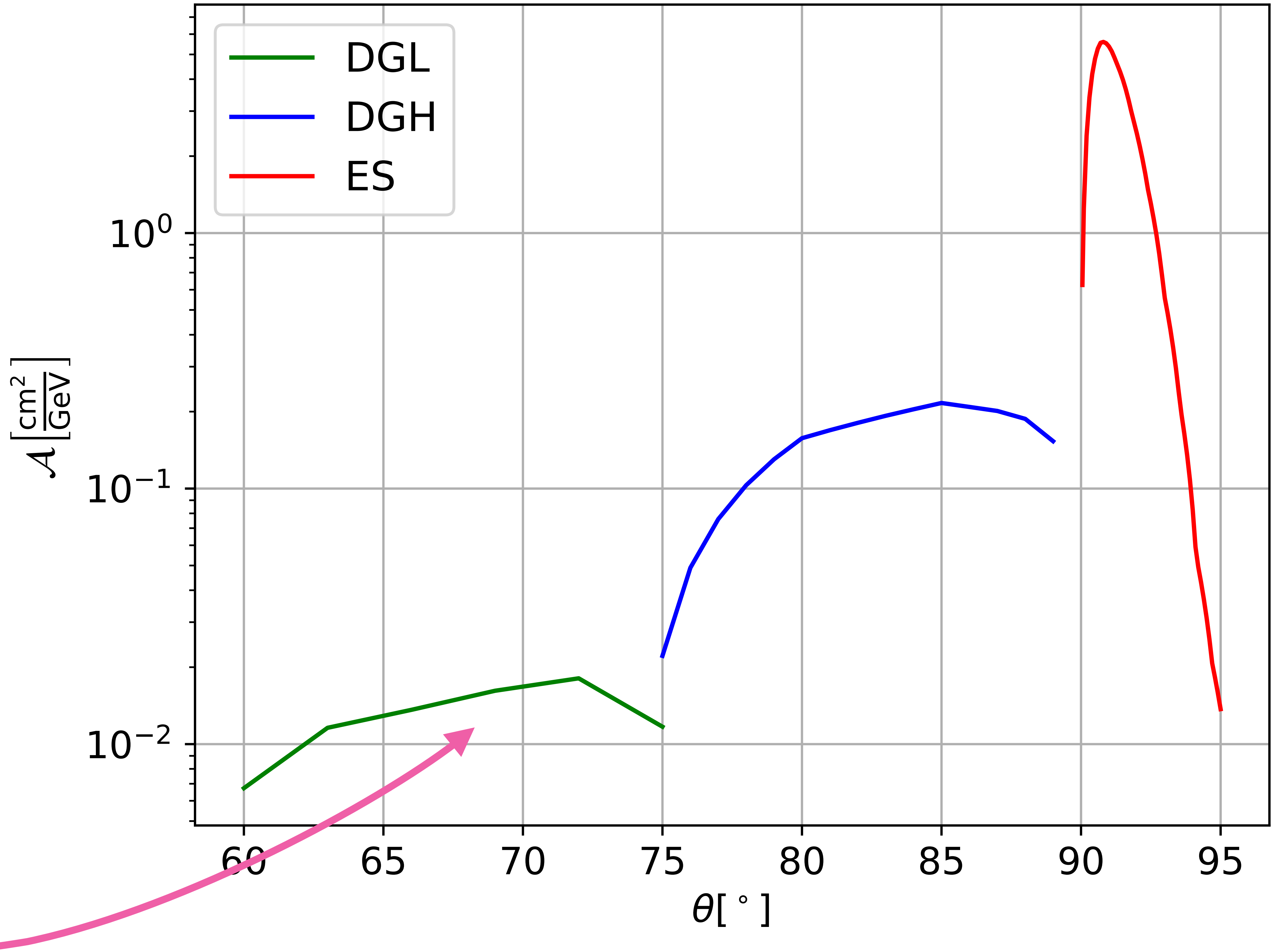
luminosity distance of source

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





solid angle integration

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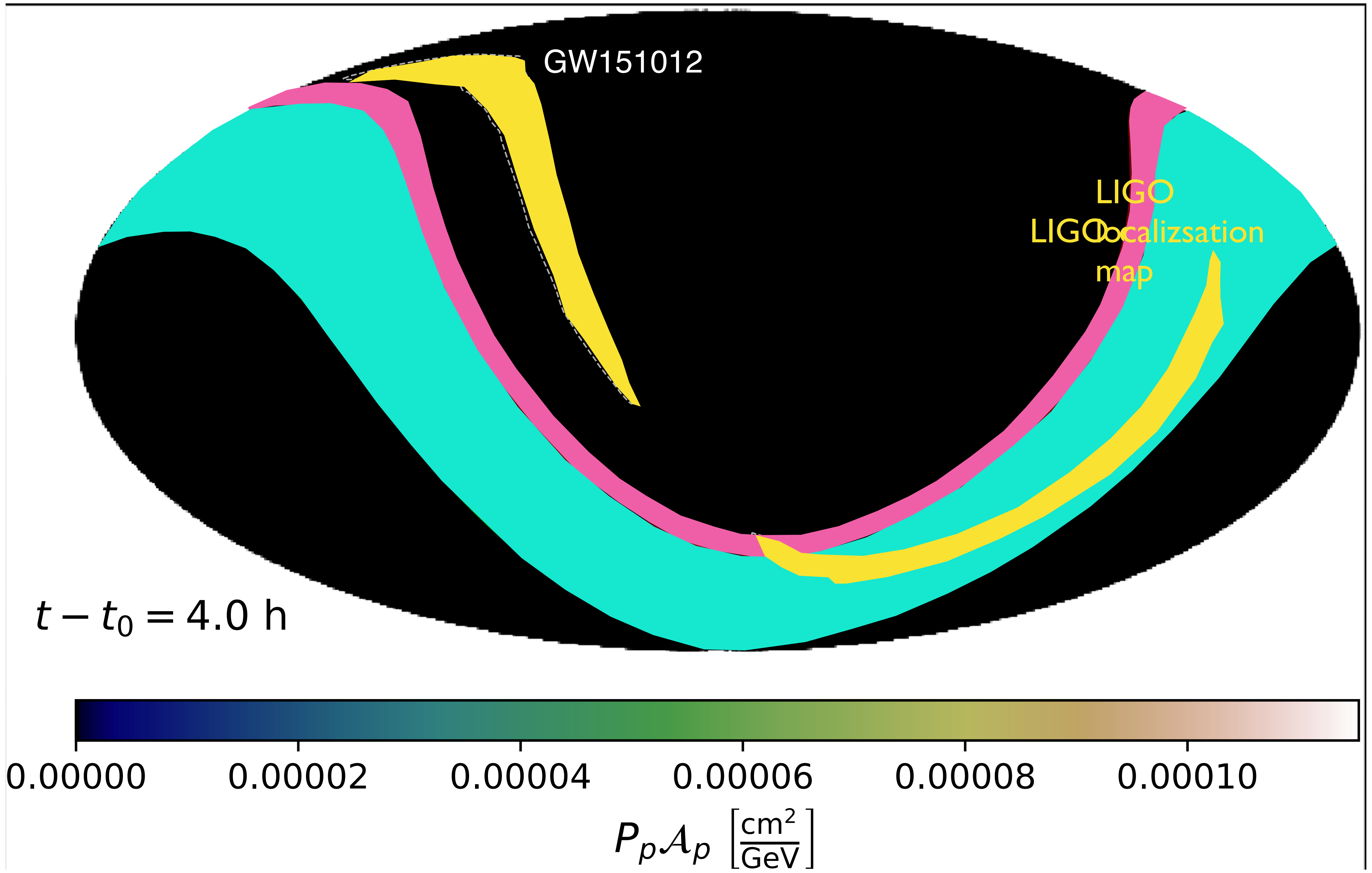

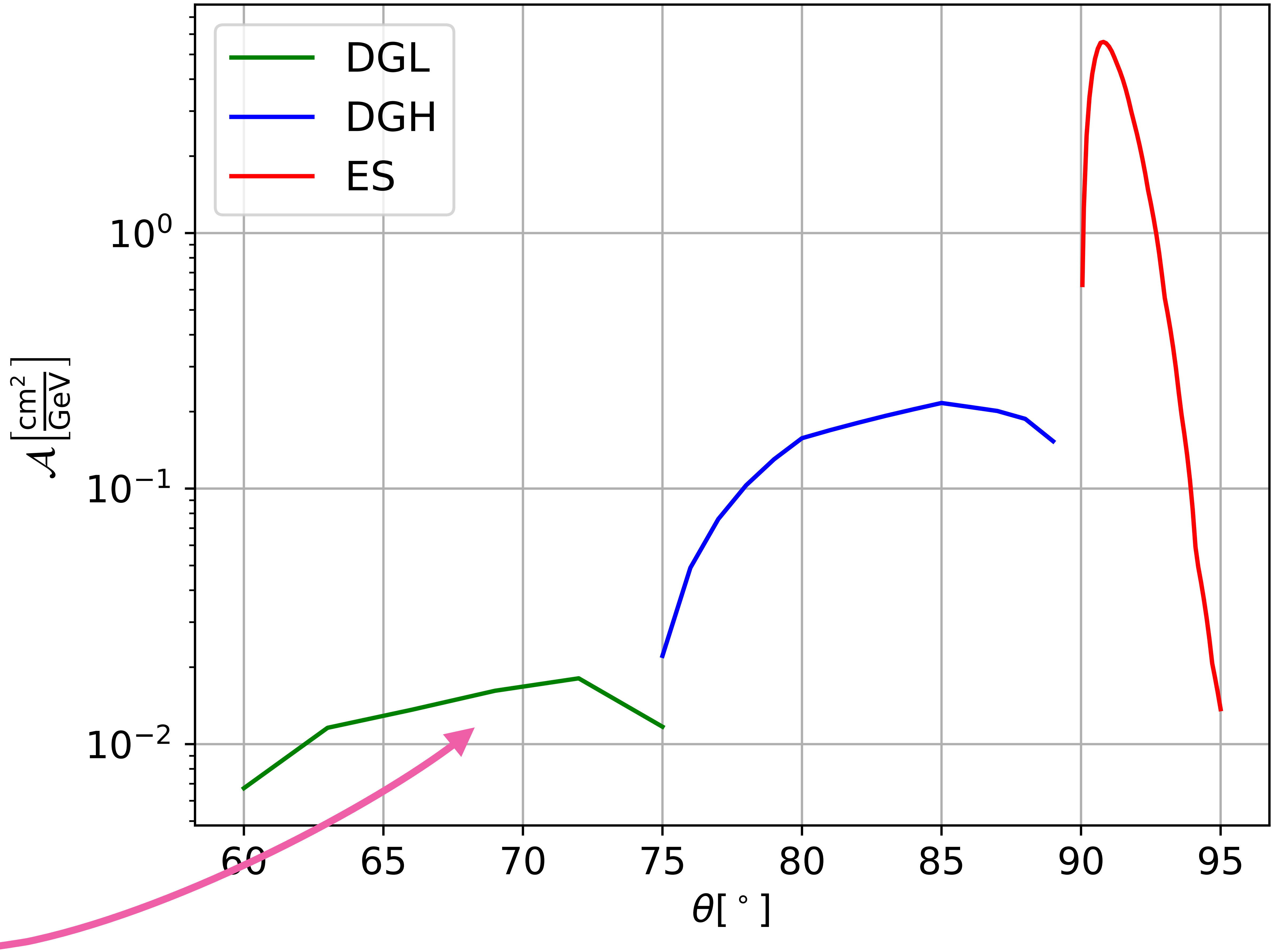

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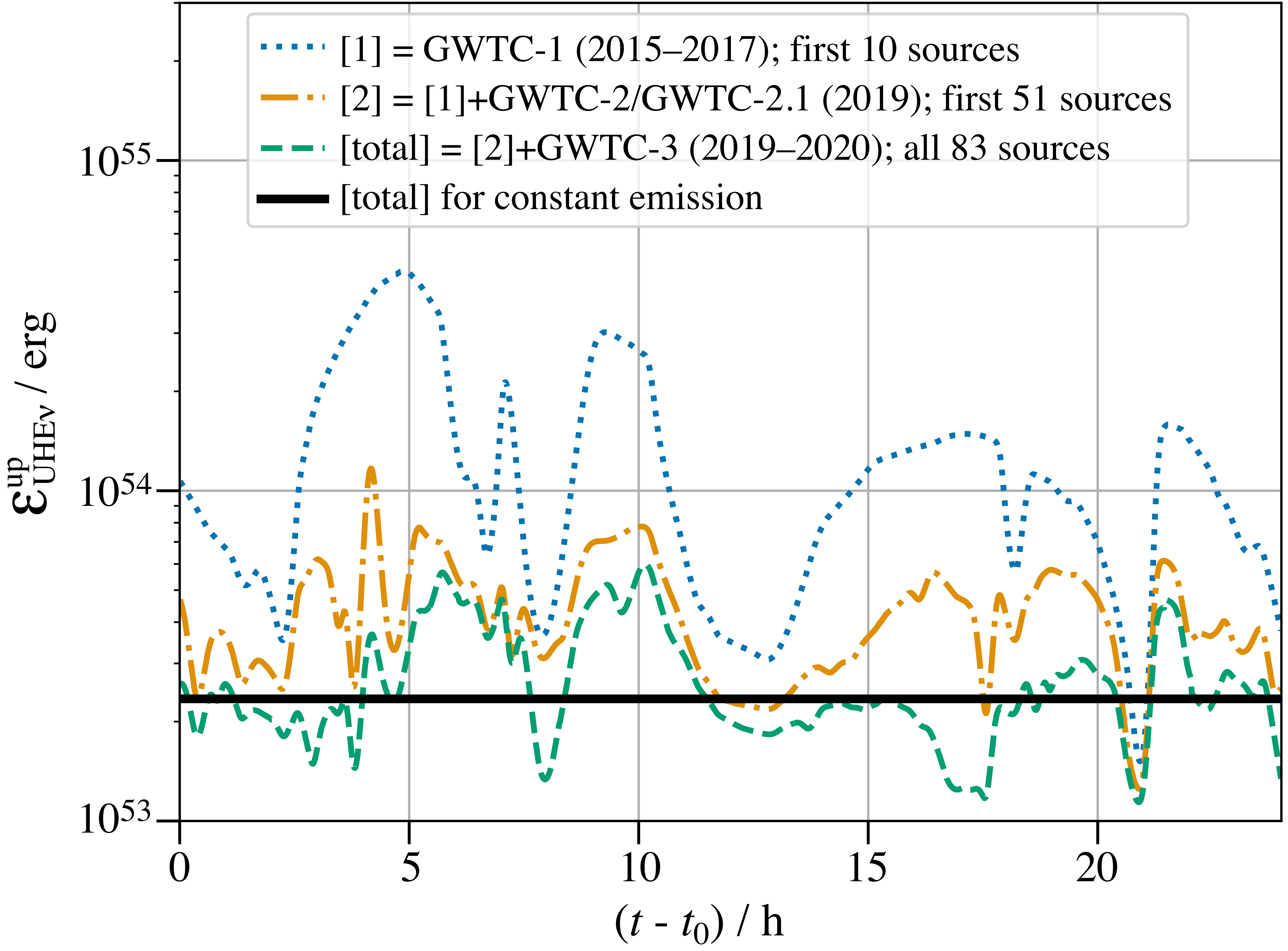
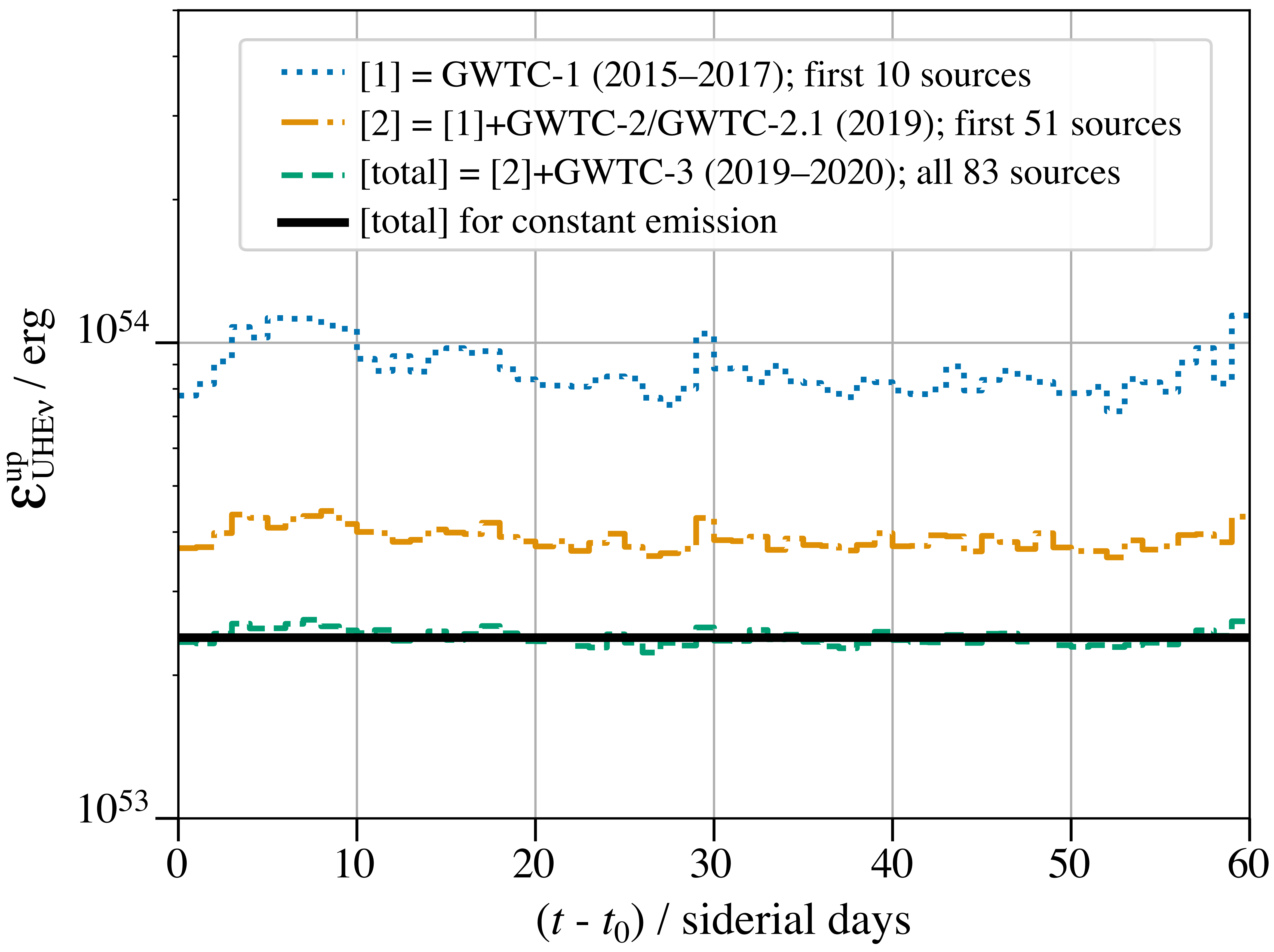
Isotropic Neutrino Luminosity Bound from BBHs

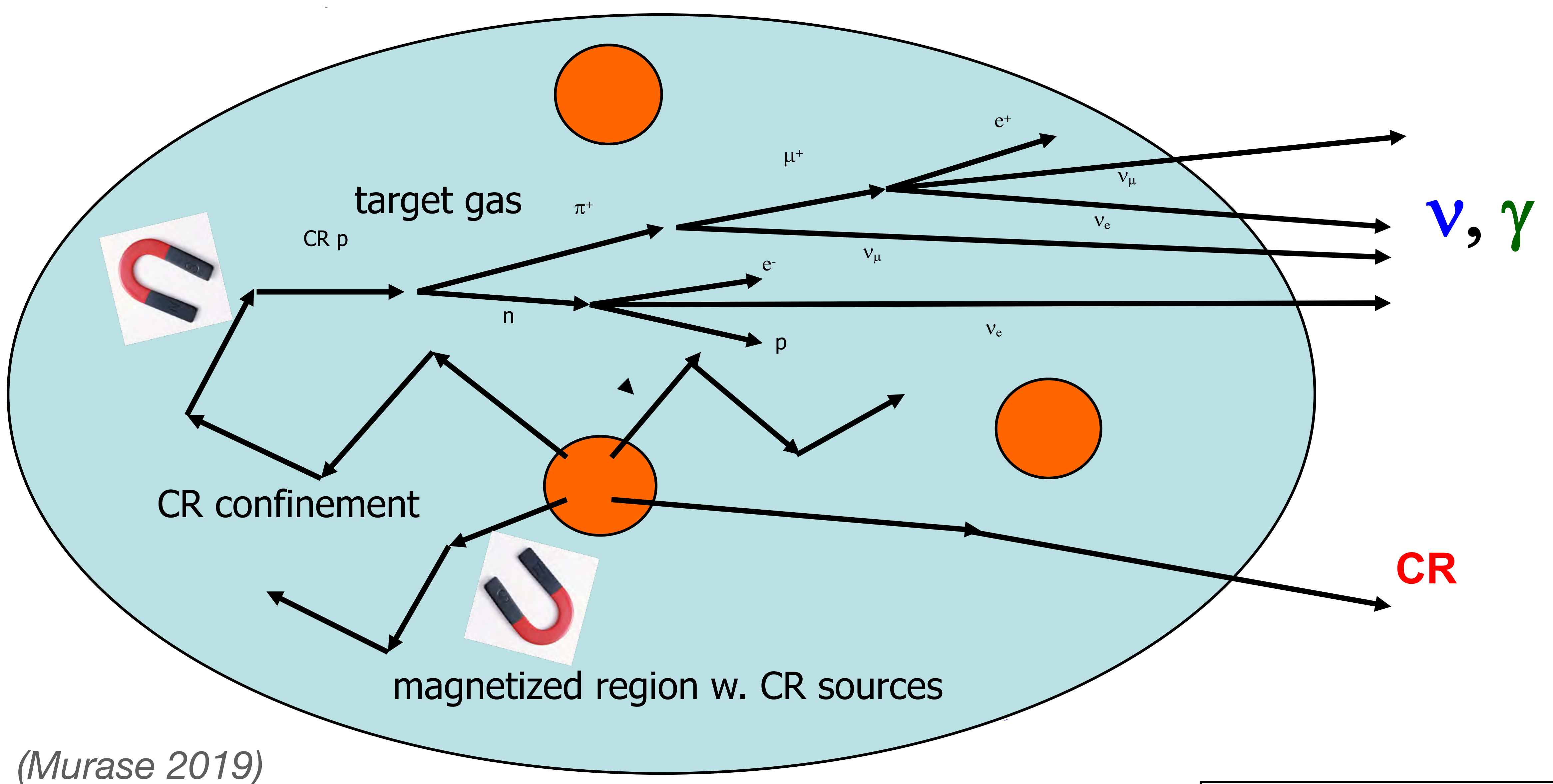
M. Schimp; Auger Collaboration, PoS (ICRC2021) 968, subm. to ApJ 2024


90% CL upper limit of energy emitted in ν's within 24 hrs


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

Source models and challenges



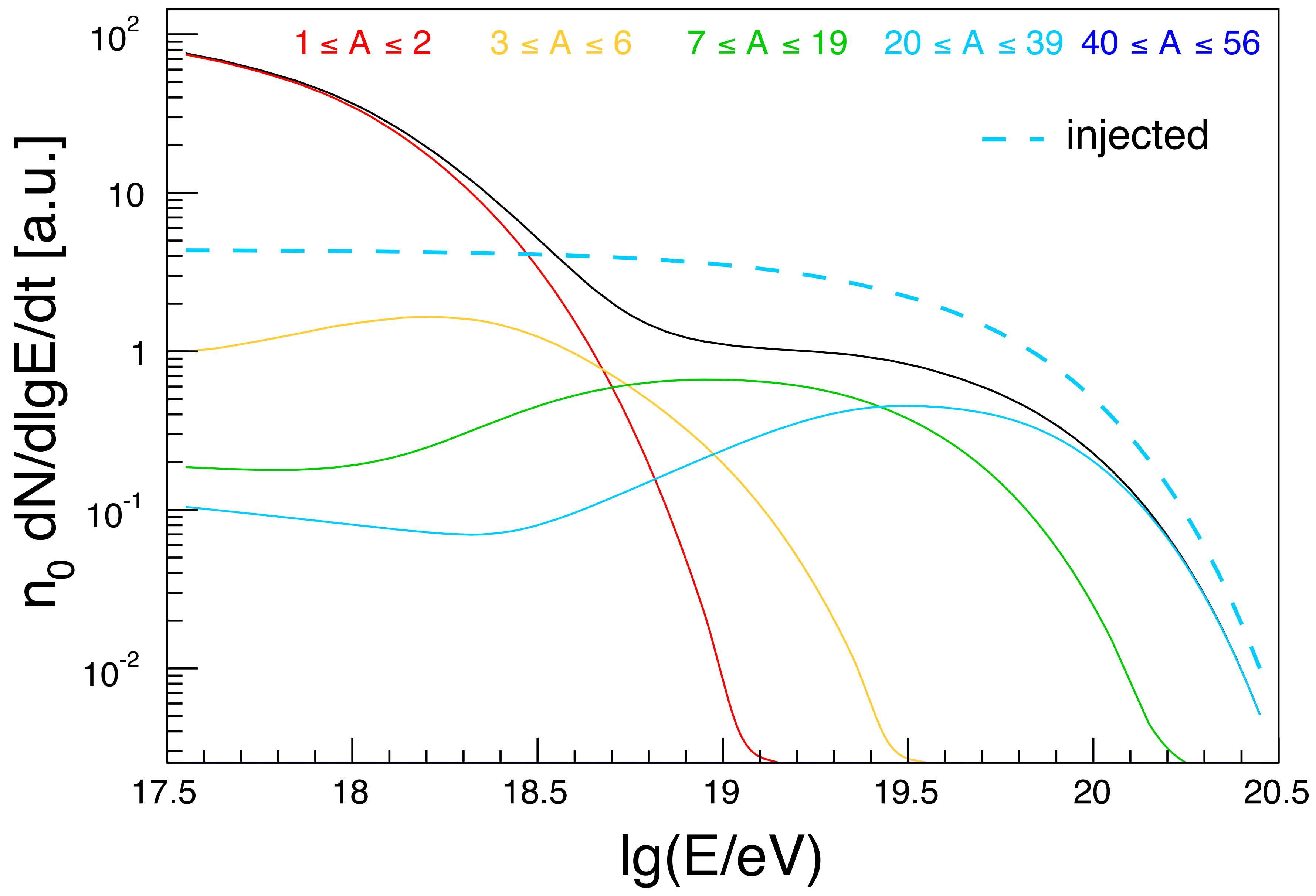
(Murase 2019)

Problem 1: injection of mainly heavy elements
Problem 2: ions have to leave source
Problem 3: hard source spectrum
Problem 4: source population diversity
Problem 5: large degree of isotropy
Problem 6: it may be bursting sources

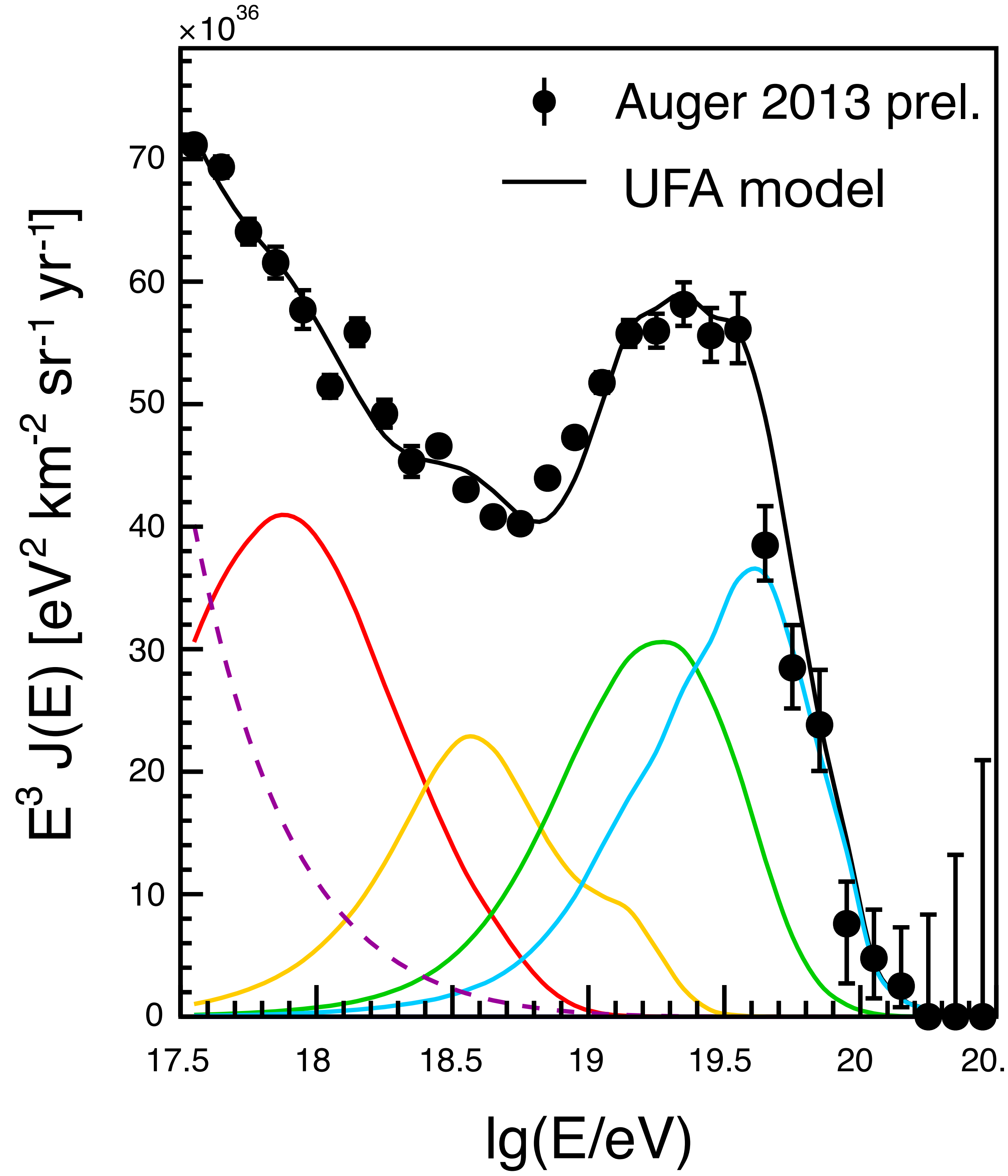
$$\frac{dN_{\mathrm{ini}}}{dE} \sim E^{-1}$$

Nuclear disintegration in source region (scaling with mass *A*)

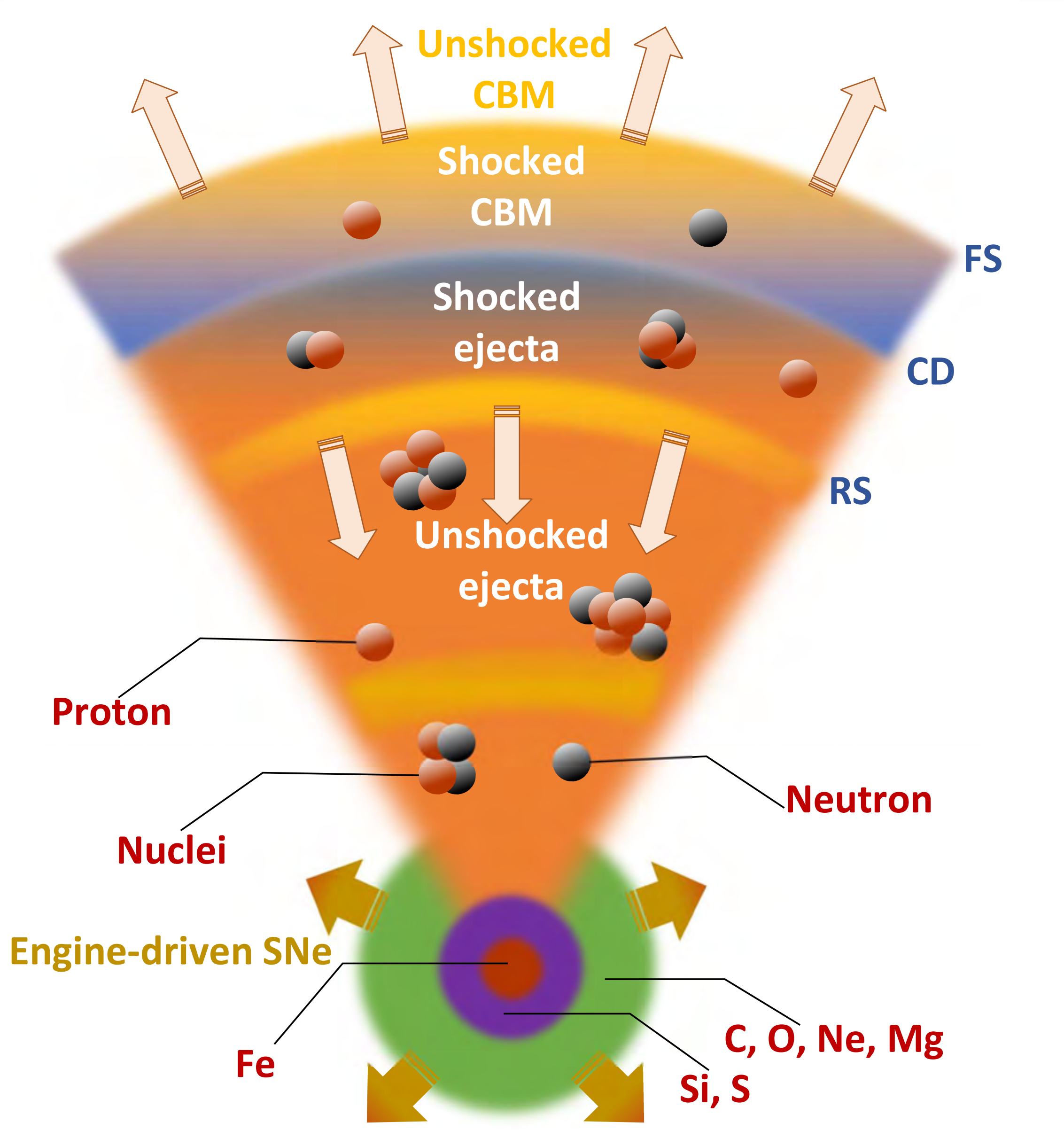
(Globus et al. 2015, Unger et al. 2015, Fang & Murase 2017)

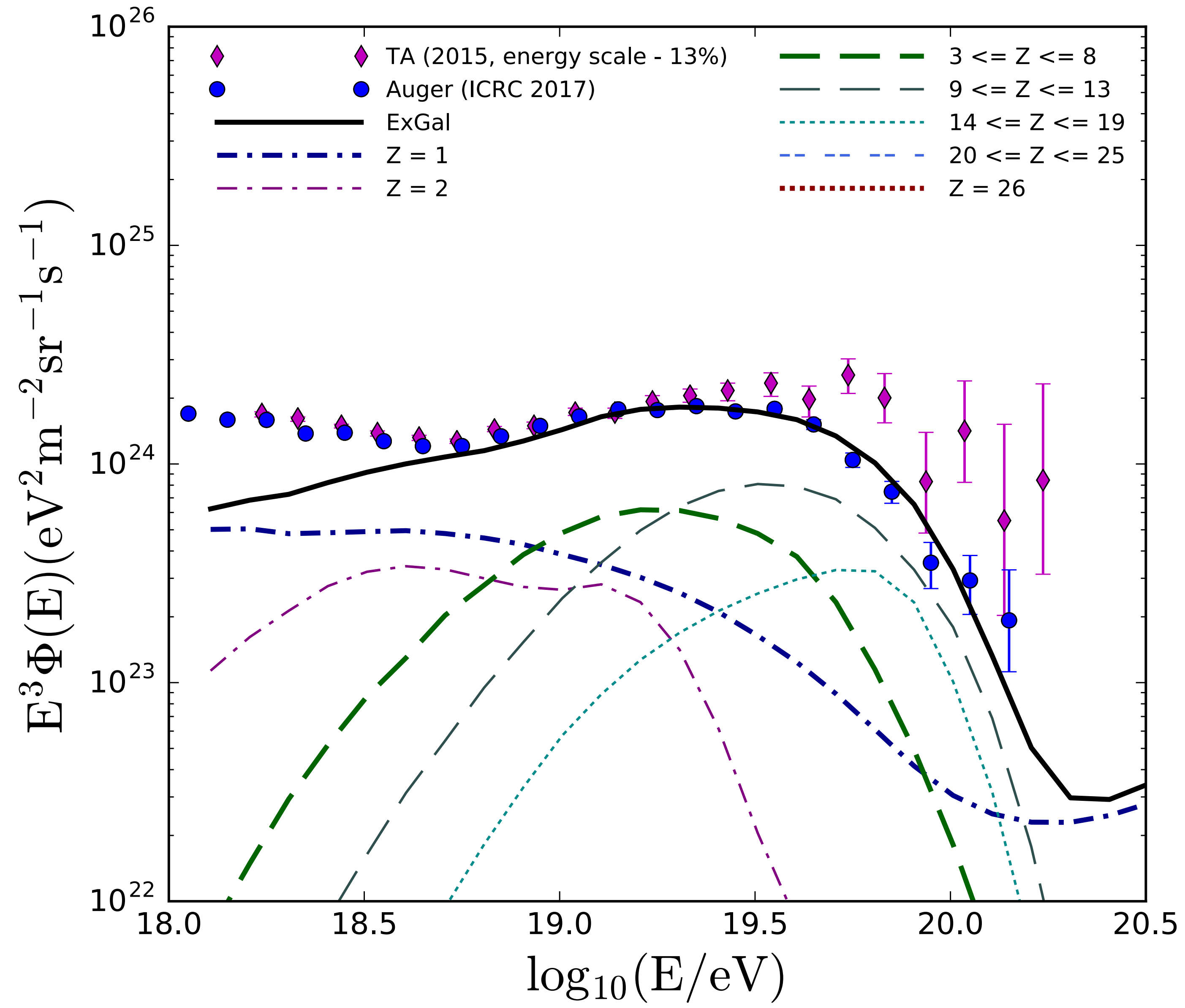


(Unger, Farrar, Anchordoqui, PRD 92, 2015)



New generation of complex model scenarios





Interplay between **confinement in source** and disintegration of nuclei: hard energy spectra

(Aloisio et al. 2014, Taylor et al. 2015, Globus et al. 2015, Unger et al. 2015, Fang & Murase 2017)

Reverse shock scenario in **low-luminosity long GRBs**

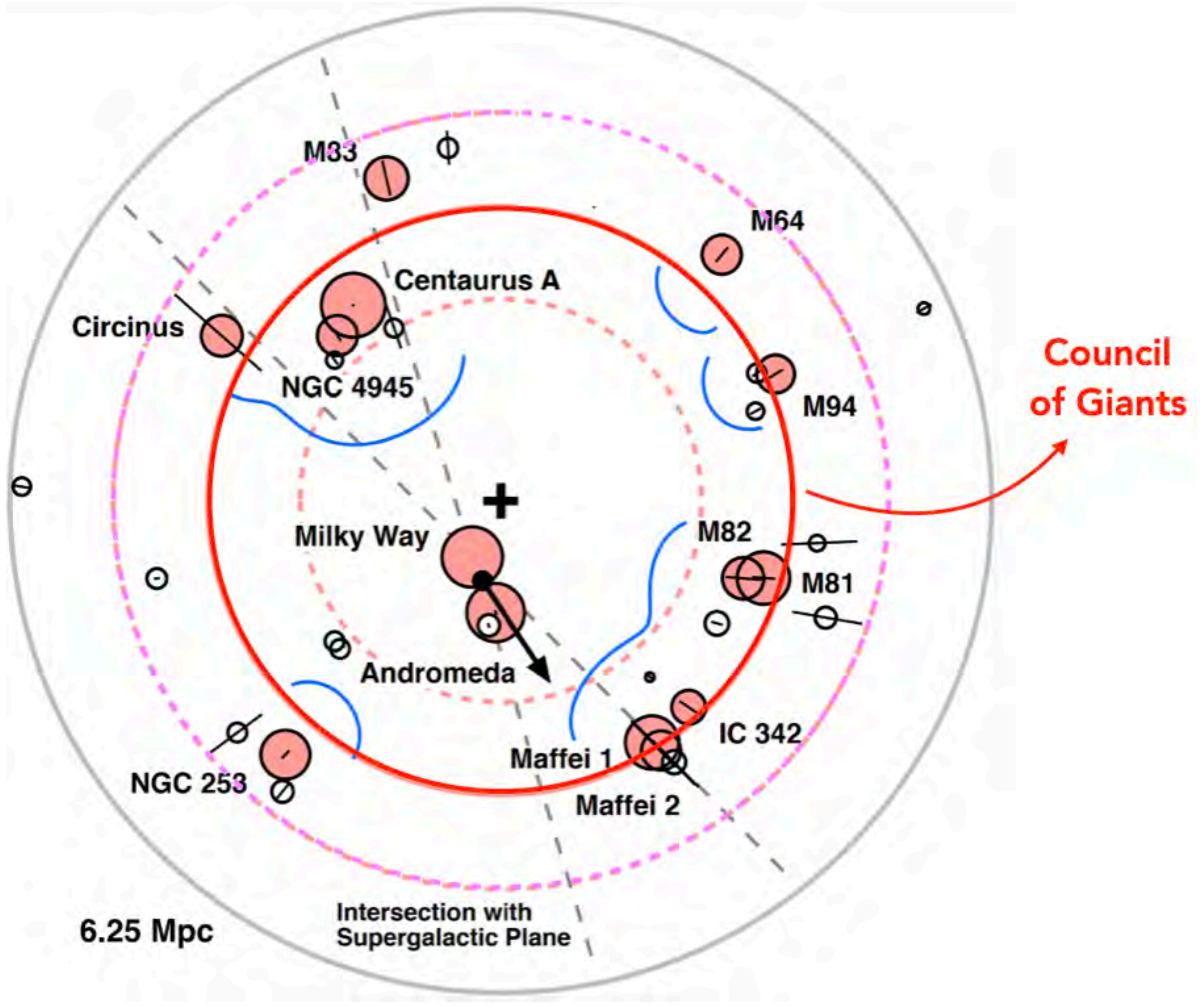
(Zhang, Murase et al 2019+)

Tidal disruption events (TDEs) of WD or carbon-rich stars

(Farrar, Piran 2009, Pfeffer et al. 2017, Zhang et al 2017)

One-shot acceleration in rapidly spinning **neutron stars**

(Arons 2003, Olinto, Kotera, Feng, Kirk …)



Cen-A burst & **deflection on Council of Giants**, solving isotropy and source diversity problem

(Taylor et al. 2023)

Relativistic reflection of existing CR population

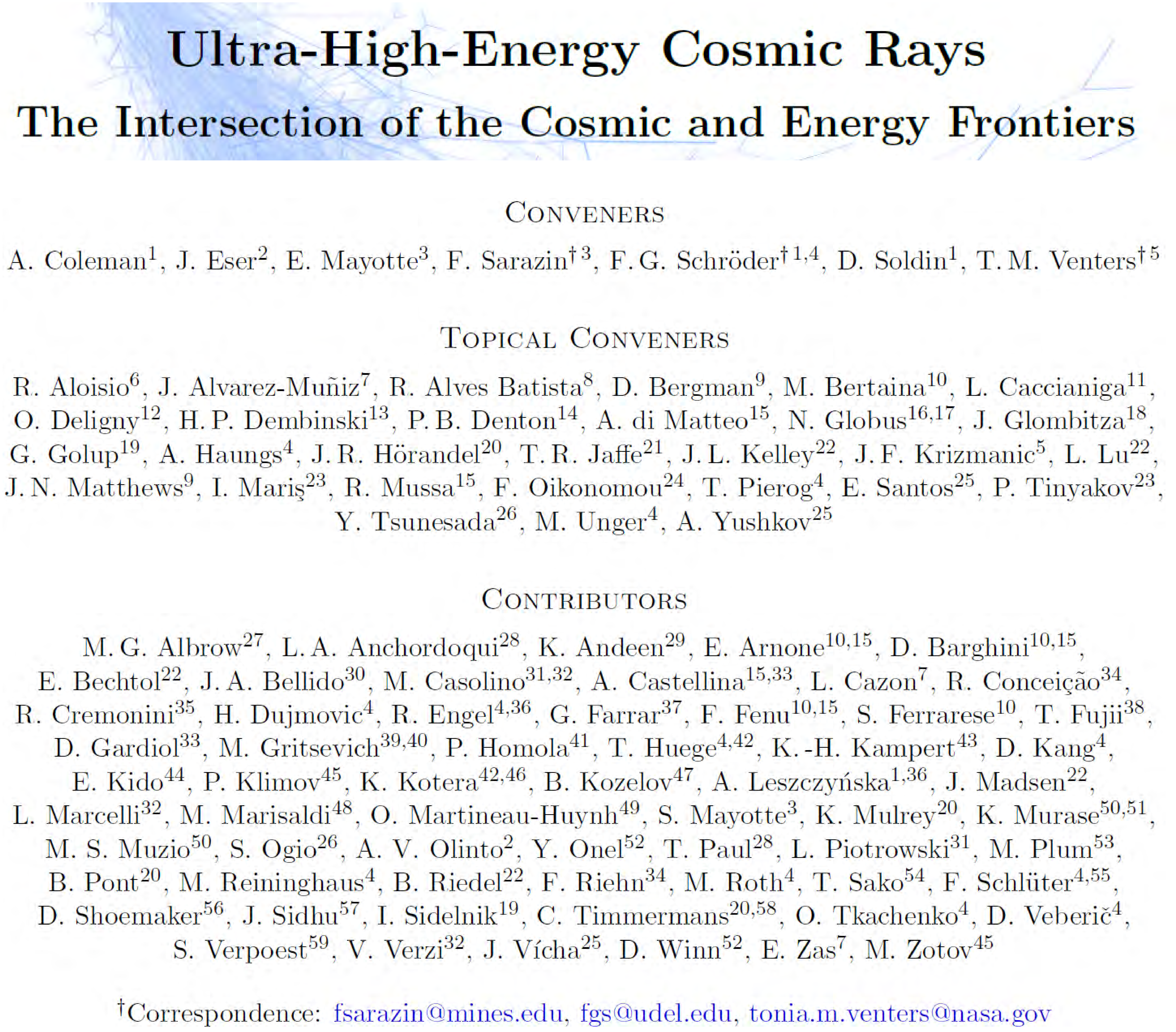
(Biermann, Caprioli, Wykes, 2012+, Blandford 2023)

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

A. Coleman[1], J. Eser[2], E. Mayotte[3], F. Sarazin†[3], F. G. Schröder†[1,4], D. Soldin[1], T. M. Venters†[5]

TOPICAL CONVENERS

R. Aloisio[6], J. Alvarez-Muñiz[7], R. Alves Batista[8], D. Bergman[9], M. Bertaina[10], L. Caccianiga[11], O. Deligny[12], H. P. Dembinski[13], P. B. Denton[14], A. di Matteo[15], N. Globus[16,17], J. Glombitza[18], G. Golup[19], A. Haungs[4], J. R. Hörandel[20], T. R. Jaffe[21], J. L. Kelley[22], J. F. Krizmanic[5], L. Lu[22], J. N. Matthews[9], I. Mariş[23], R. Mussa[15], F. Oikonomou[24], T. Pierog[4], E. Santos[25], P. Tinyakov[23], Y. Tsunesada[26], M. Unger[4], A. Yushkov[25]

CONTRIBUTORS

M. G. Albrow[27], L. A. Anchordoqui[28], K. Andeen[29], E. Arnone[10,15], D. Barghini[10,15], E. Bechtol[22], J. A. Bellido[30], M. Casolino[31,32], A. Castellina[15,33], L. Cazon[7], R. Conceição[34], R. Cremonini[35], H. Dujmovic[4], R. Engel[4,36], G. Farrar[37], F. Fenu[10,15], S. Ferrarese[10], T. Fujii[38], D. Gardiol[33], M. Gritsevich[39,40], P. Homola[41], T. Huege[4,42], K.-H. Kampert[43], D. Kang[4], E. Kido[44], P. Klimov[45], K. Kotera[42,46], B. Kozelov[47], A. Leszczyńska[1,36], J. Madsen[22], L. Marcelli[32], M. Marisaldi[48], O. Martineau-Huynh[49], S. Mayotte[3], K. Mulrey[20], K. Murase[50,51], M. S. Muzio[50], S. Ogio[26], A. V. Olinto[2], Y. Onel[52], T. Paul[28], L. Piotrowski[31], M. Plum[53], B. Pont[20], M. Reininghaus[4], B. Riedel[22], F. Riehn[34], M. Roth[4], T. Sako[54], F. Schlüter[4,55], D. Shoemaker[56], J. Sidhu[57], I. Sidelnik[19], C. Timmermans[20,58], O. Tkachenko[4], D. Veberič[4], S. Verpoest[59], V. Verzi[32], J. Vícha[25], D. Winn[52], E. Zas[7], M. Zotov[45]

†Correspondence: fsarazin@mines.edu, fgs@udel.edu, tonia.m.venters@nasa.gov

Summary and Conclusions

- **10^{20} eV regime accessible only by cosmic rays**

- **UHECRs provide important input to Multi-Messenger physics**
  e.g. EHE neutrinos and photons, source composition, interactions within sources, burst rates,…

- **… and benefit from several other observations**
  incl. B-fields, neutrinos, photons, GWs…

- UHECR observatories **Partner in follow-up observations**
  ACME within Europe, AMON in USA

- **Multi-Messenger Astrophysics of key importance to understand EHE Universe**