

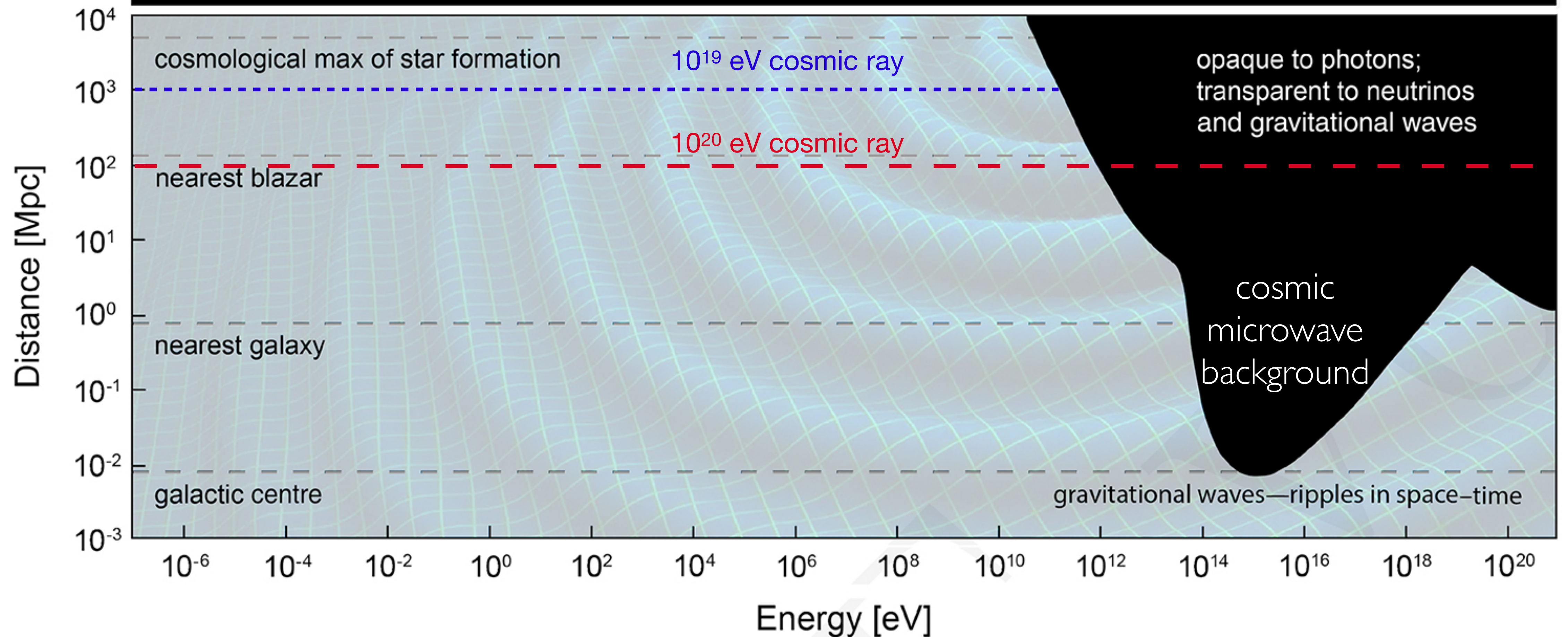
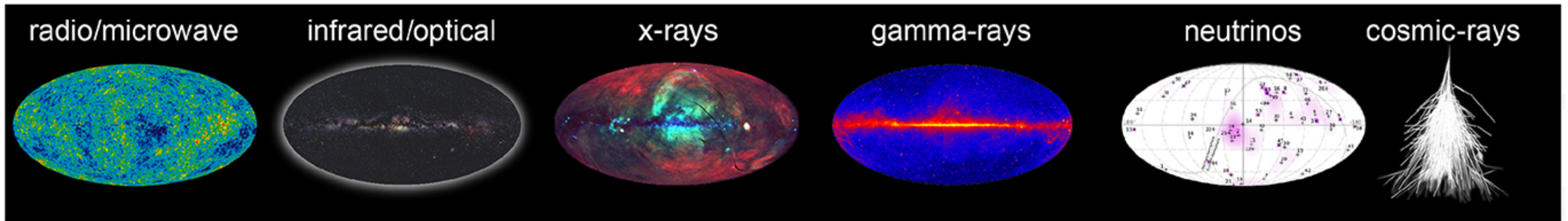
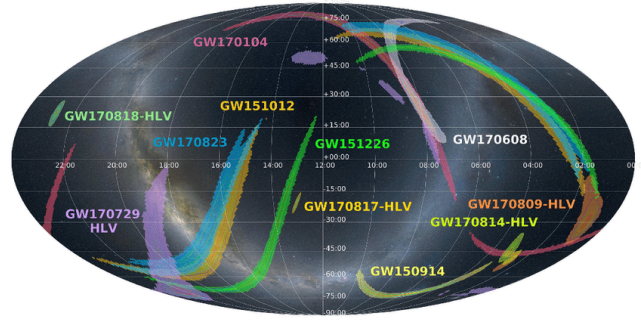


Multimessenger diagnostics of hadronic acceleration from PeV to EeV

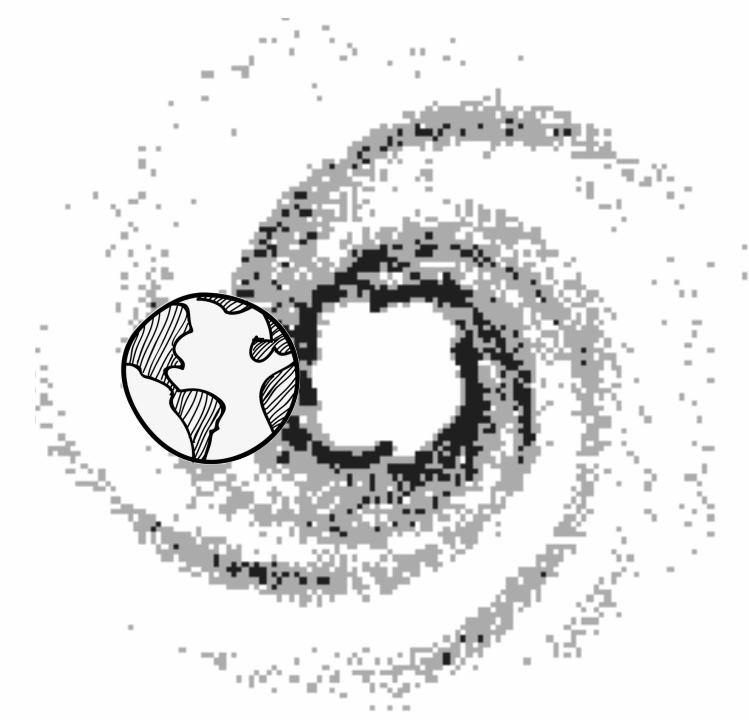
Foteini Oikonomou

High-energy messengers

gravitational waves



High-energy messengers



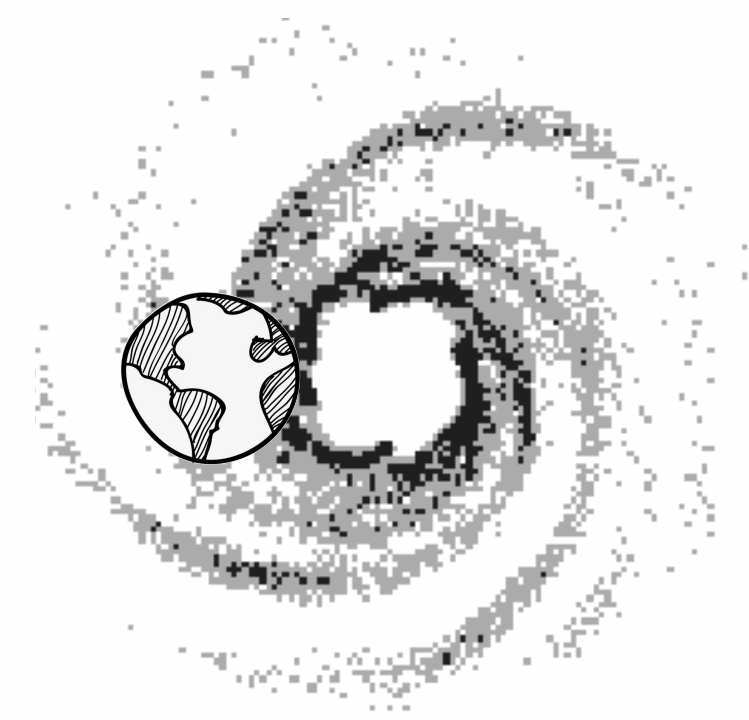
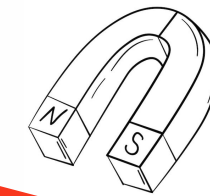
High-energy messengers



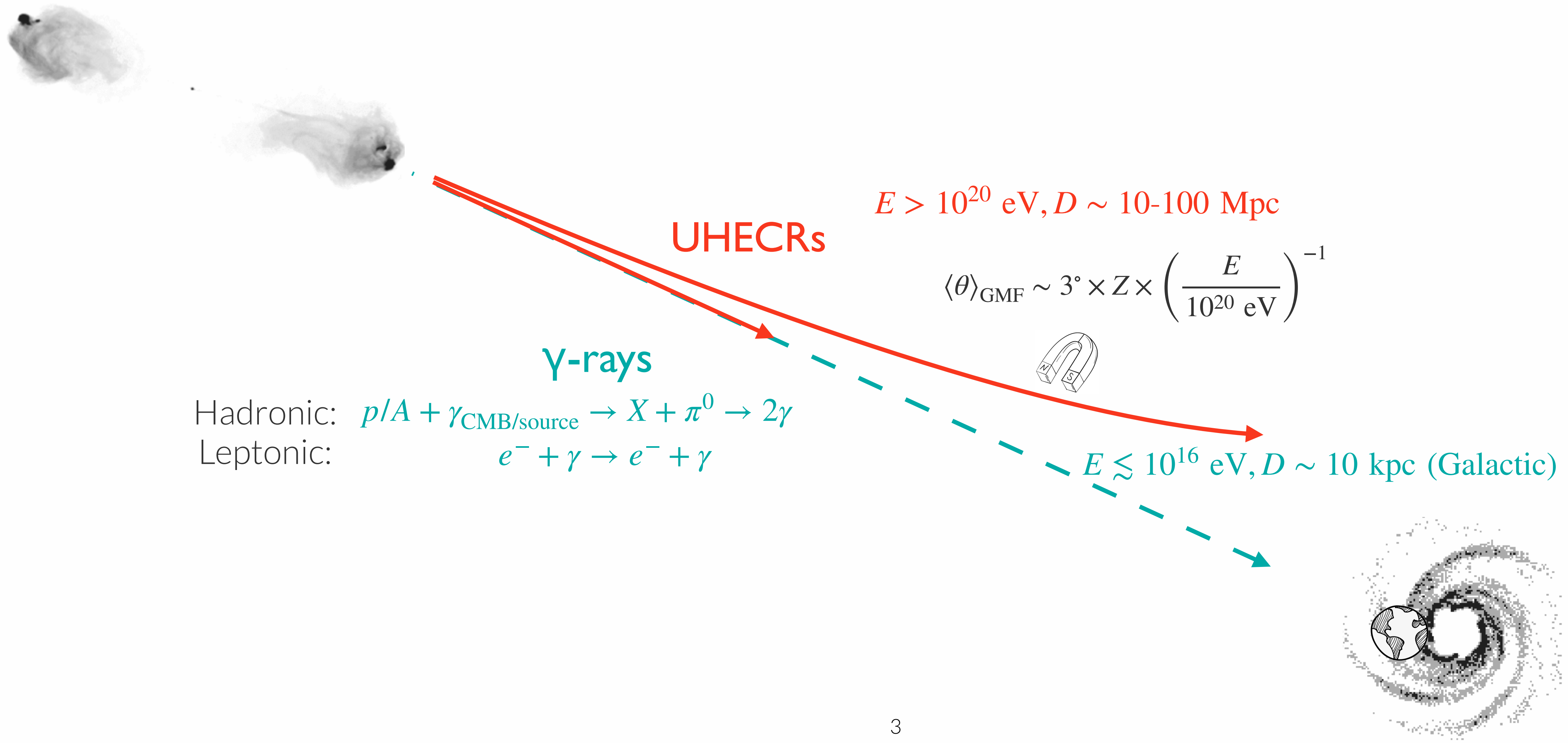
UHECRs

$E > 10^{20}$ eV, $D \sim 10\text{-}100$ Mpc

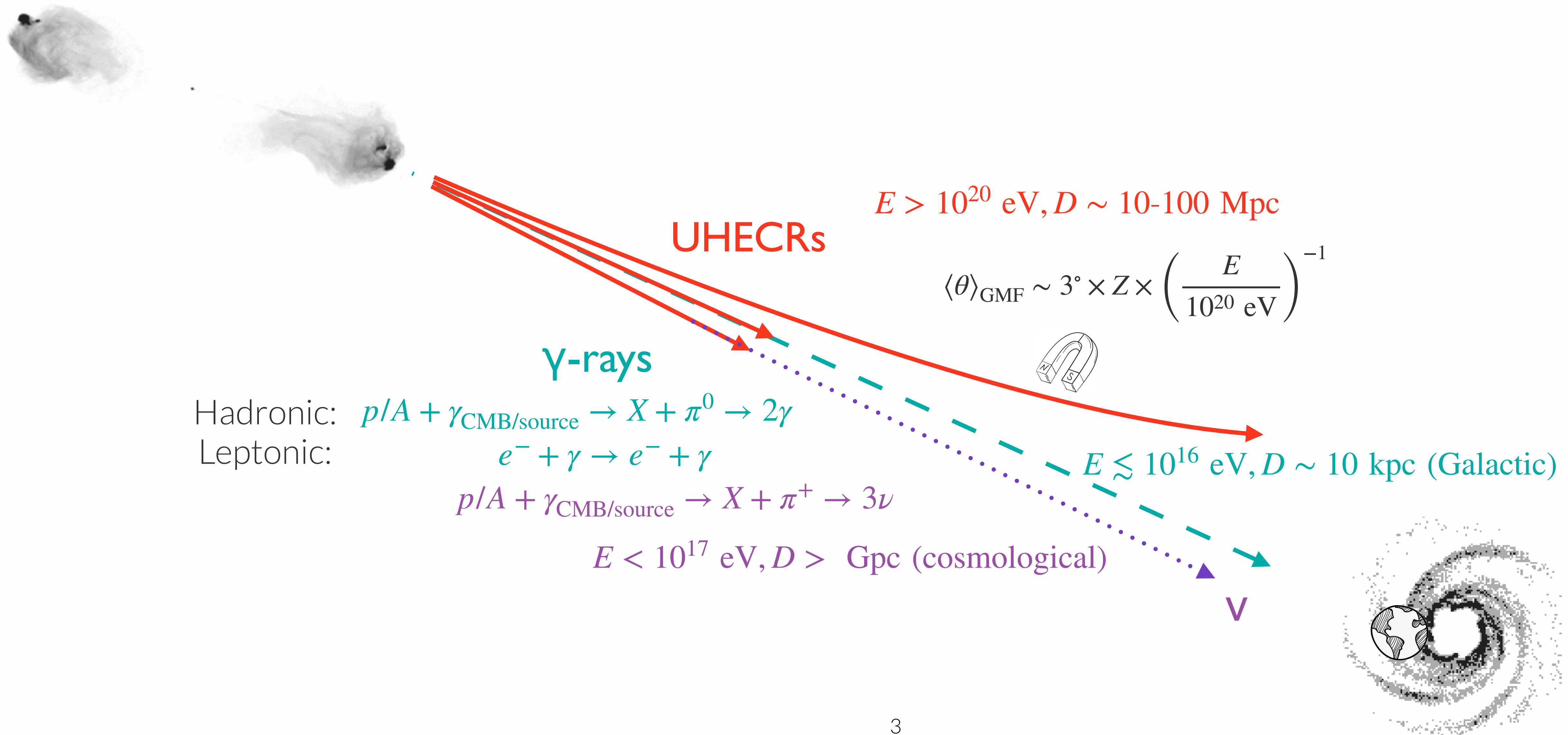
$$\langle \theta \rangle_{\text{GMF}} \sim 3^\circ \times Z \times \left(\frac{E}{10^{20} \text{ eV}} \right)^{-1}$$



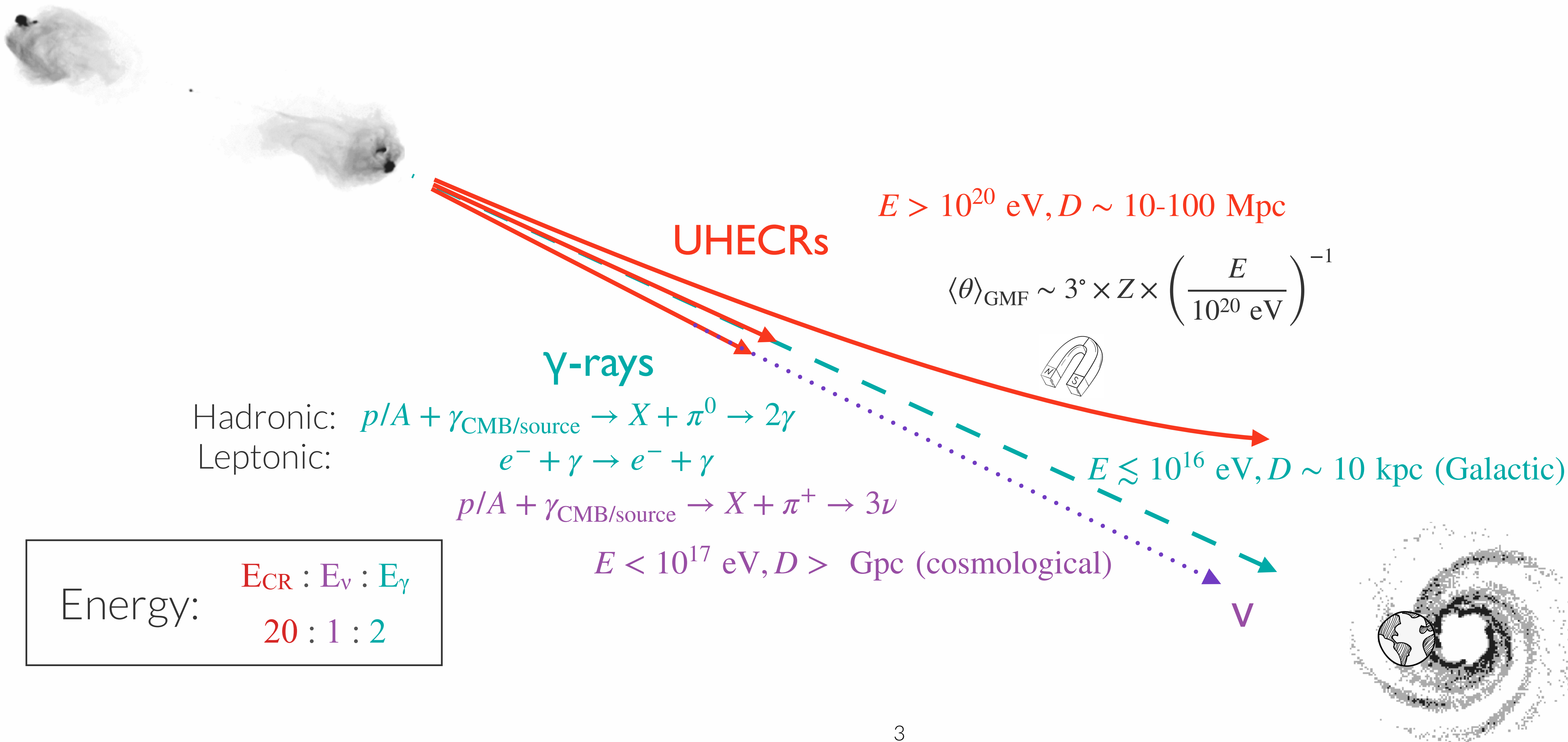
High-energy messengers



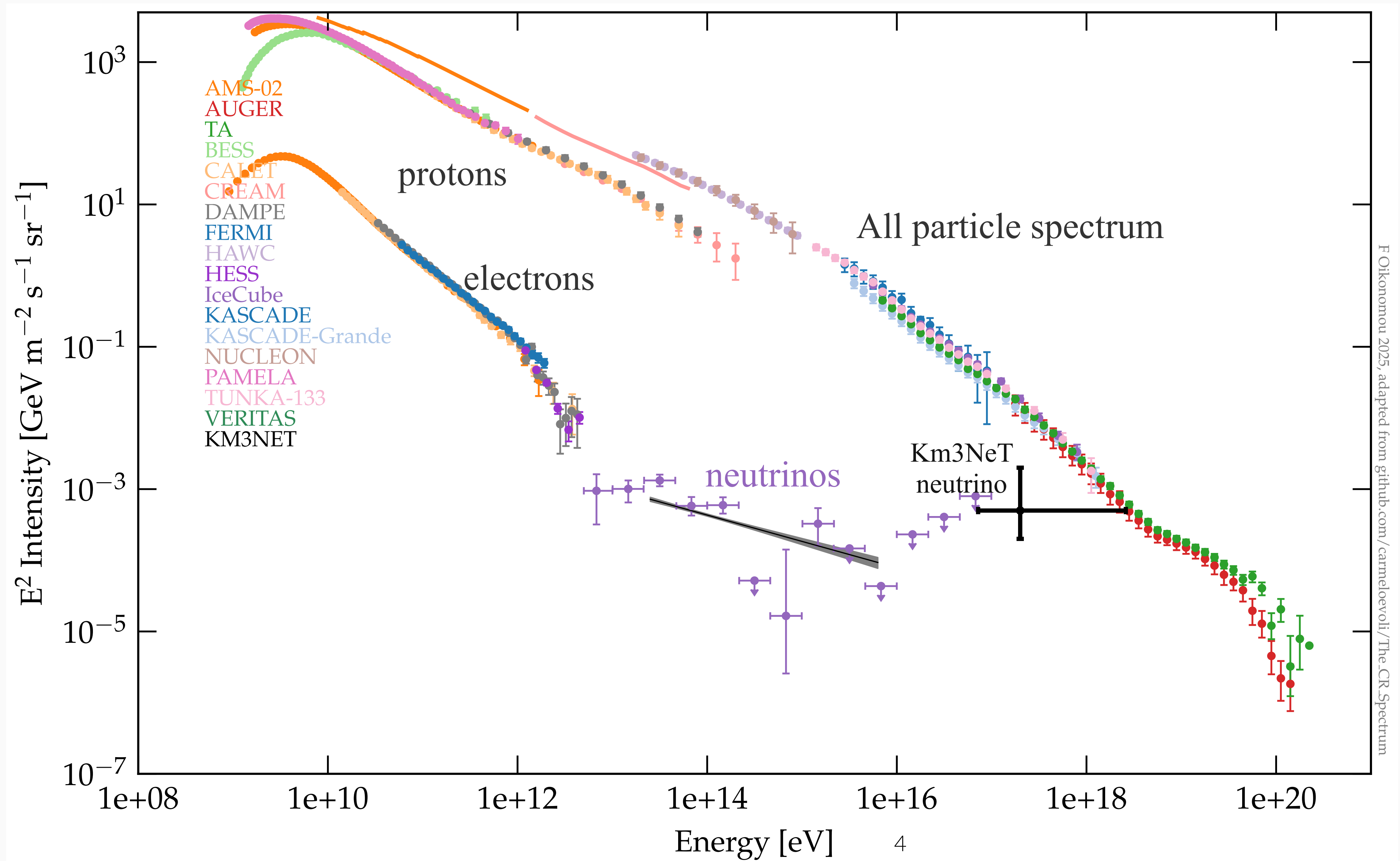
High-energy messengers



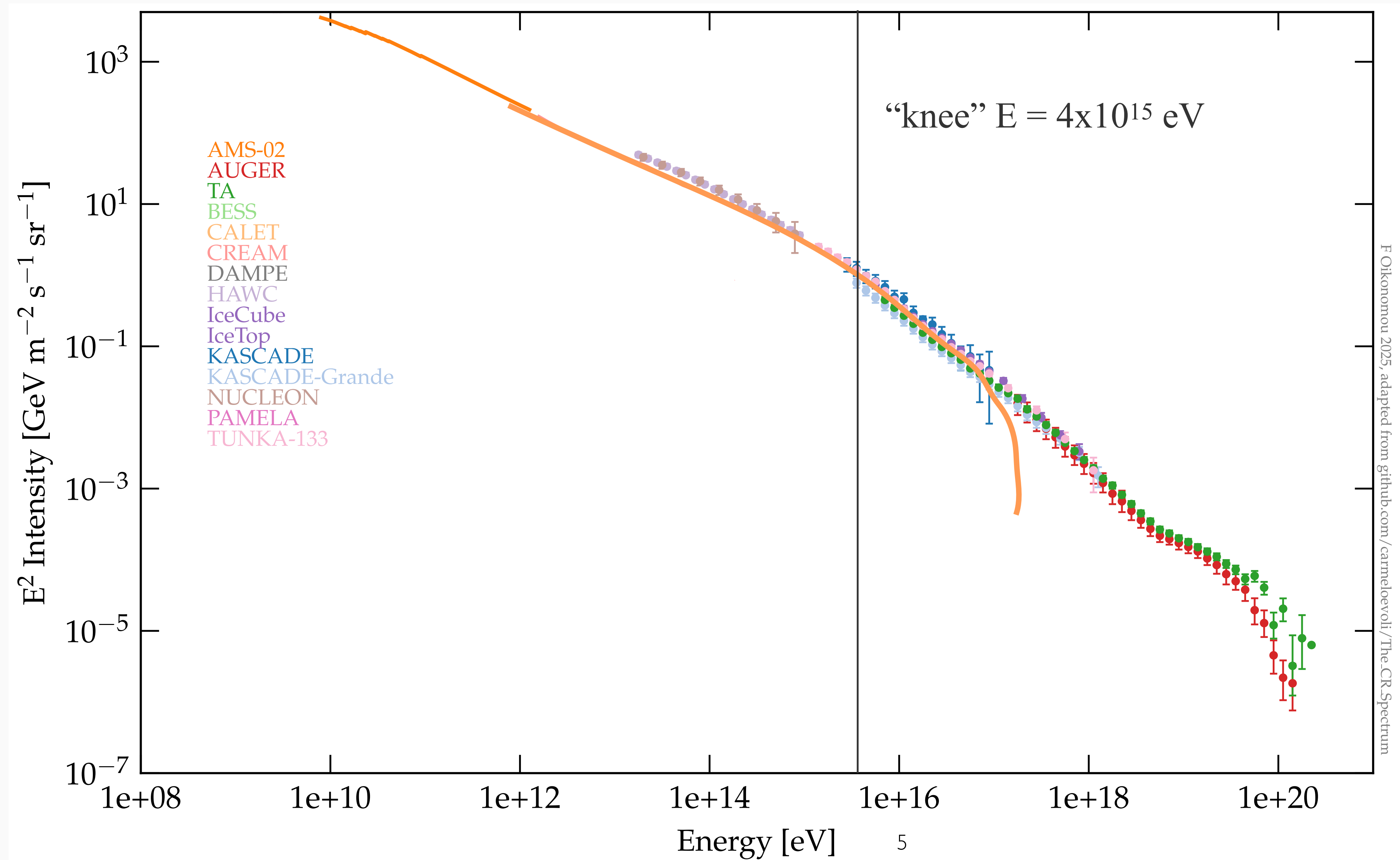
High-energy messengers



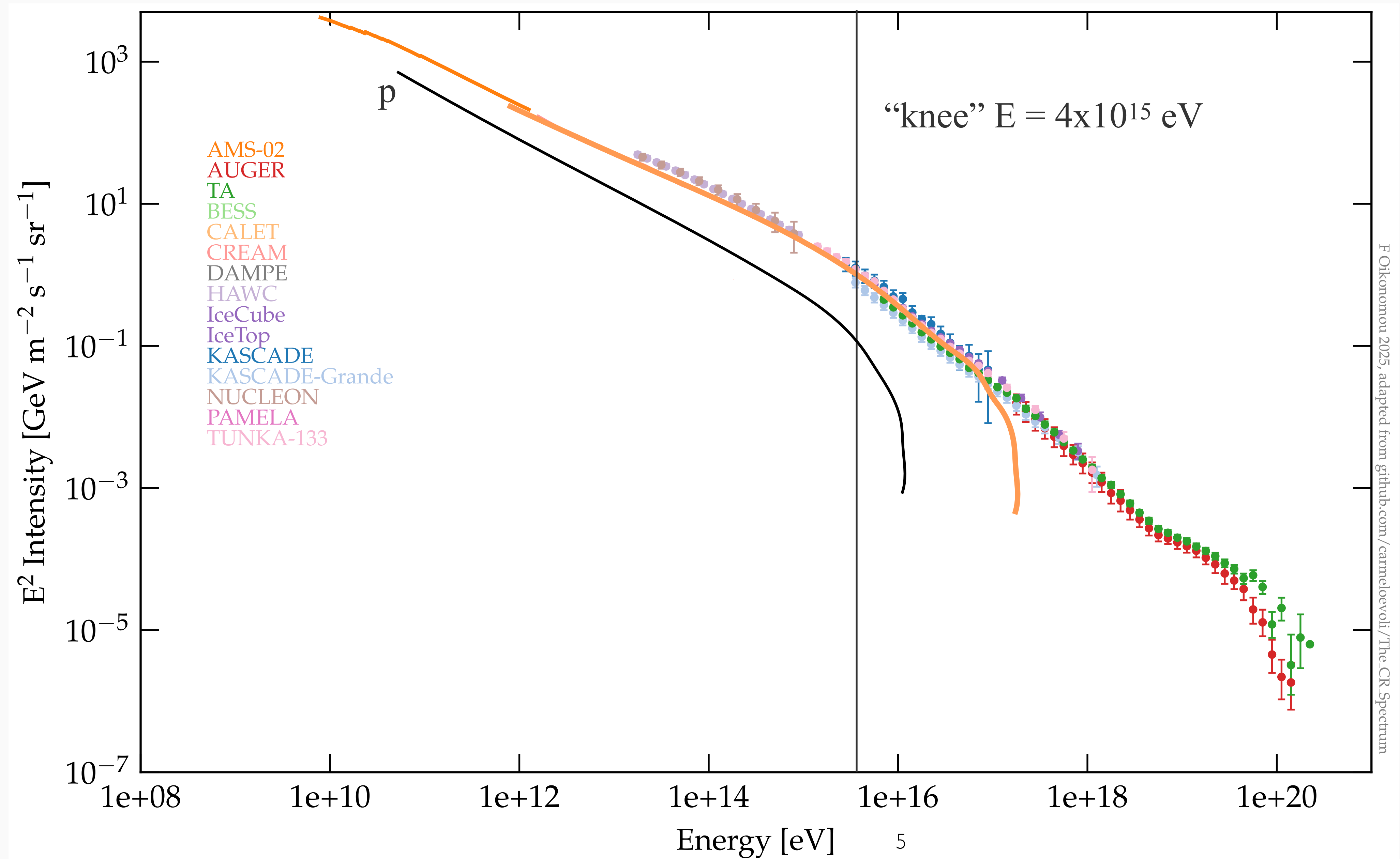
Diffuse Particle Spectrum



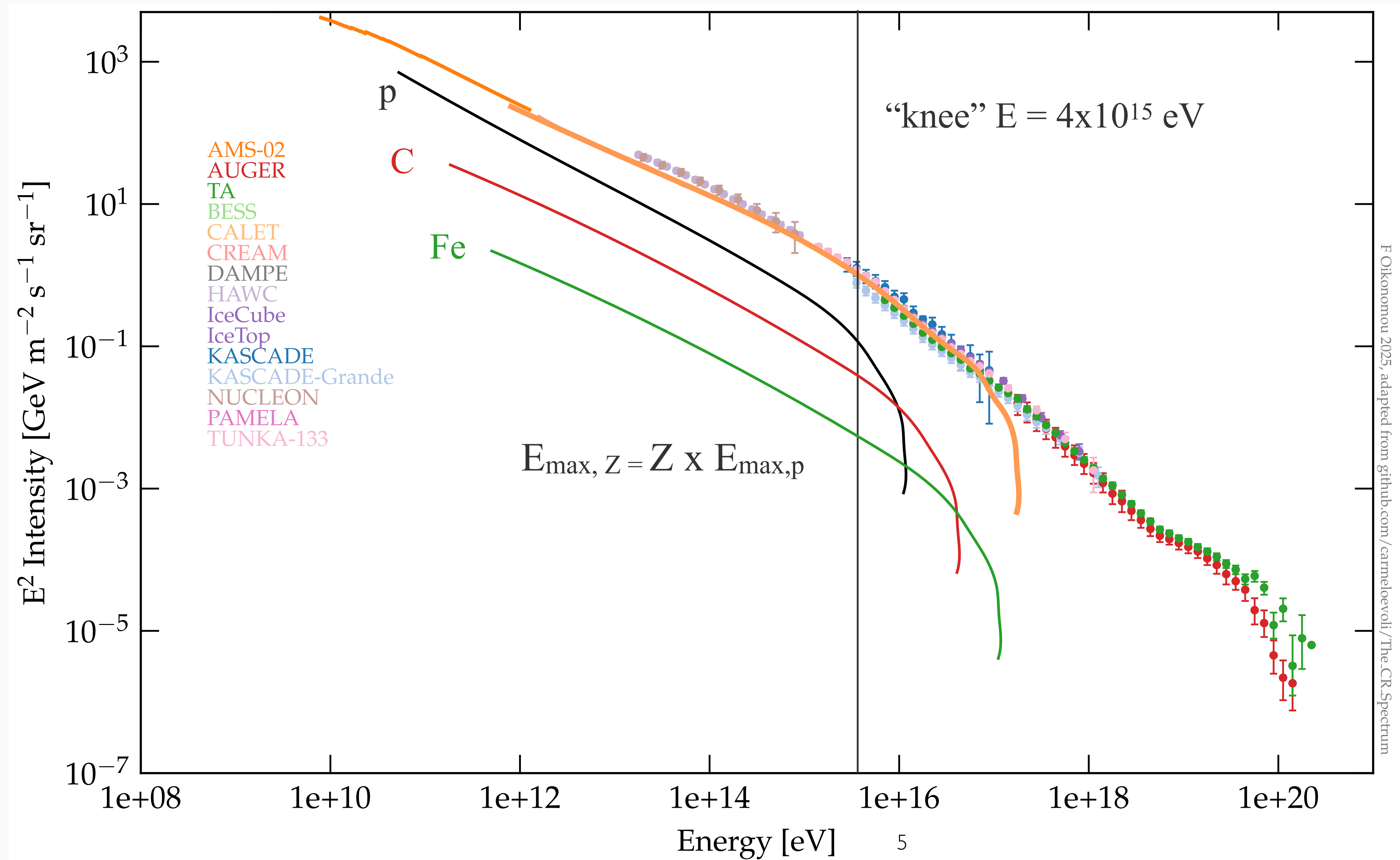
Galactic Cosmic Rays



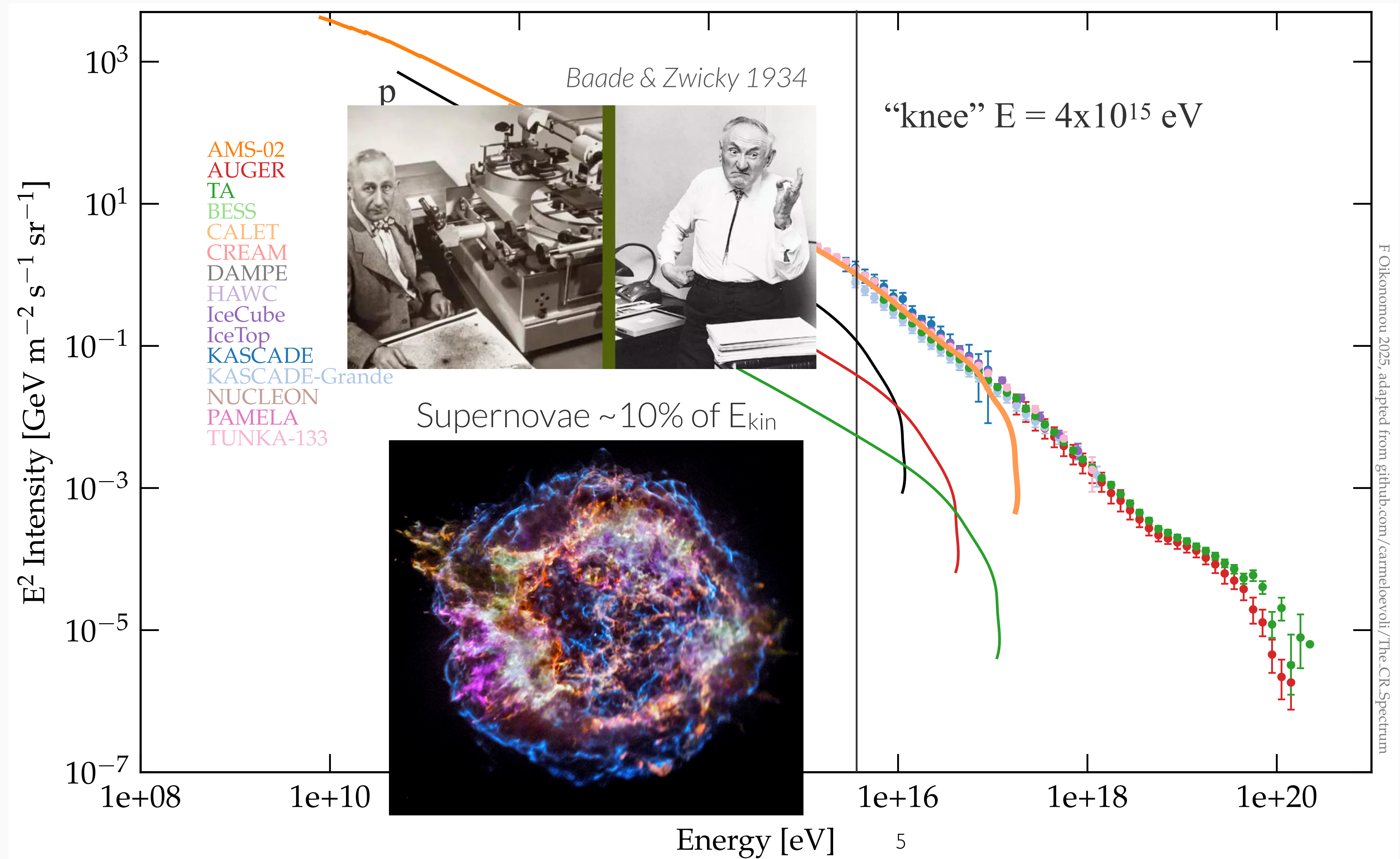
Galactic Cosmic Rays



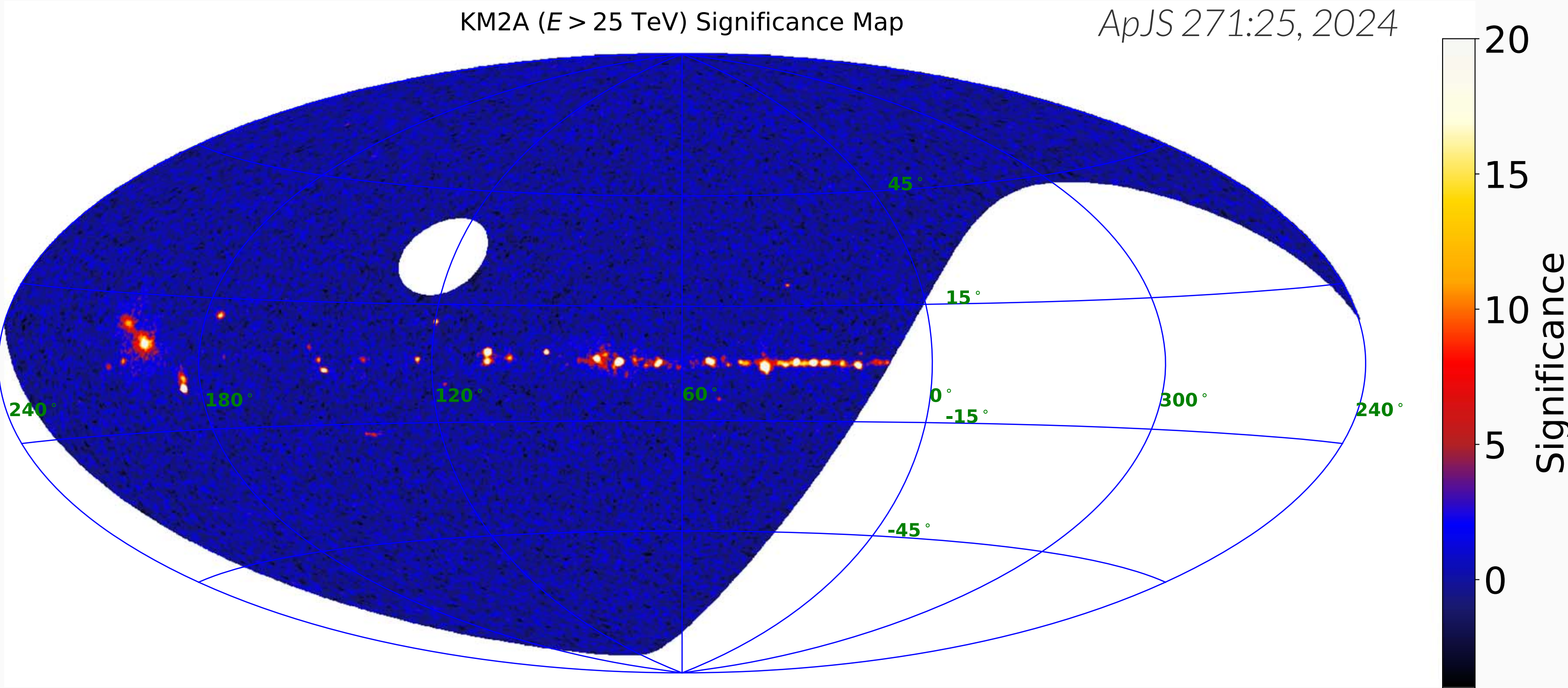
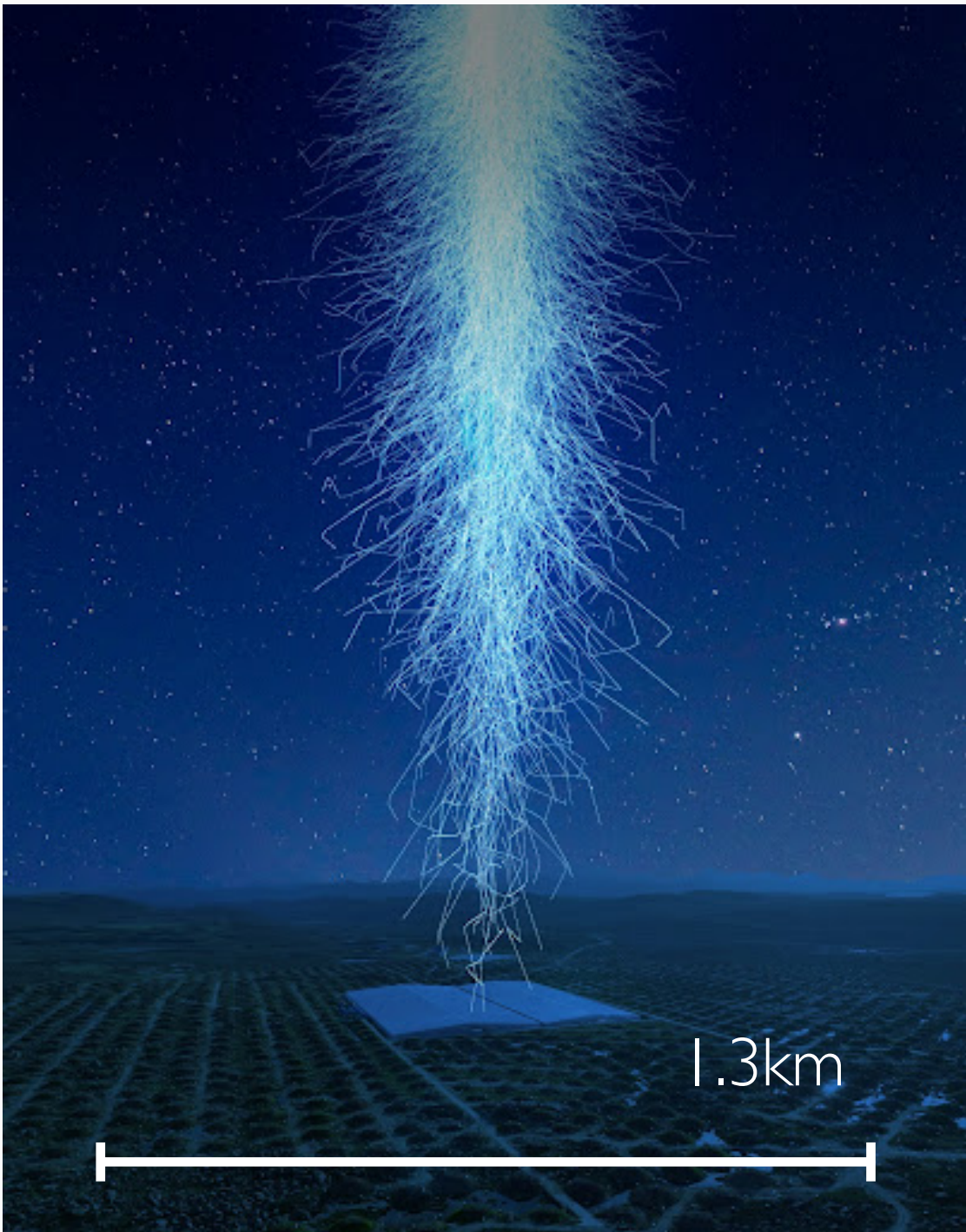
Galactic Cosmic Rays



Galactic Cosmic Rays



Learning from Galactic gamma-rays: 1st LHAASO Catalog

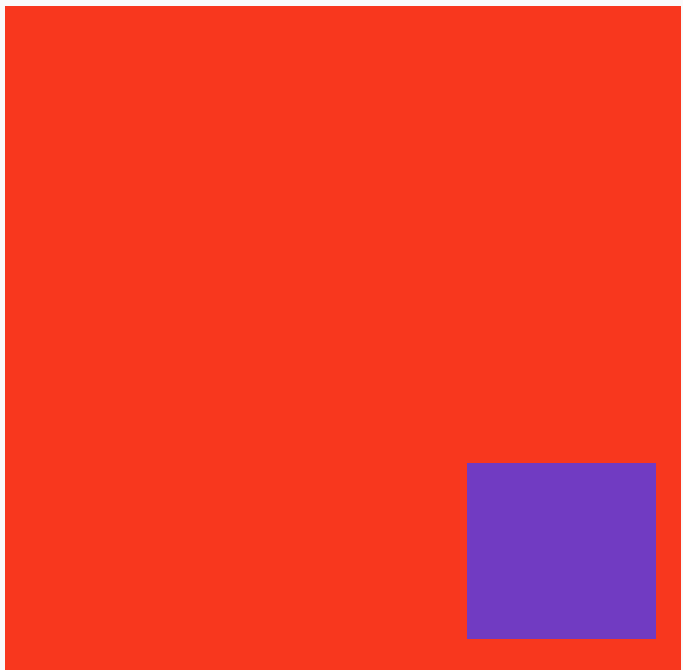


Hadronic

$$\frac{E_{CR}}{E_\gamma} = \frac{10}{1}$$

Leptonic

$$E_e \sim O(E_\gamma)$$



HAWC: 0.1 km² (2015-)
LHAASO $\sim$ 1.0 km² (2021-)

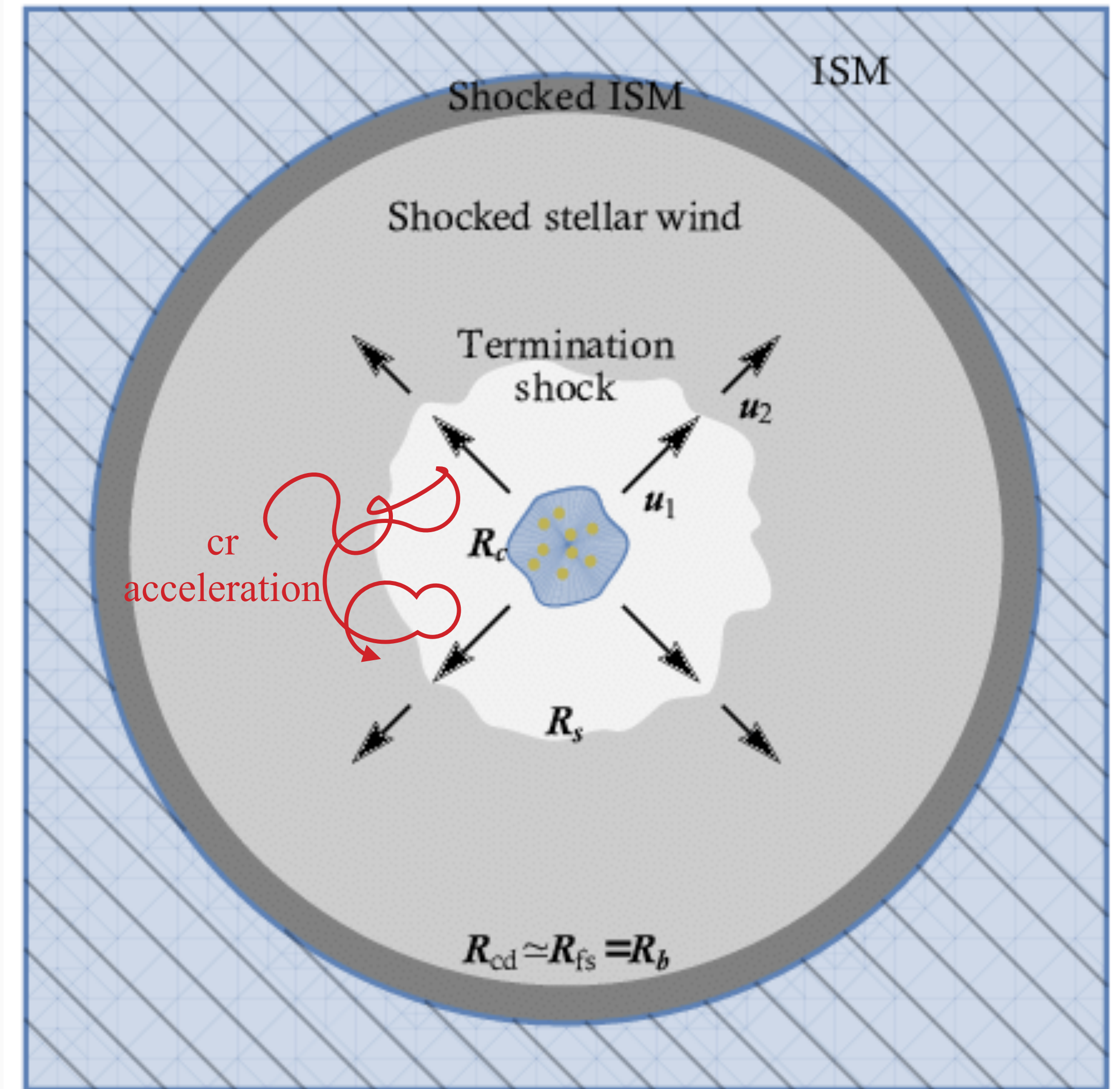
43 Sources with $E_\gamma > 10^{14}$ eV:

- few Supernova remnants (old, $E < 10^{14}$ eV)
- 2 Young Stellar Clusters, 6 Microquasars

Young Stellar Clusters



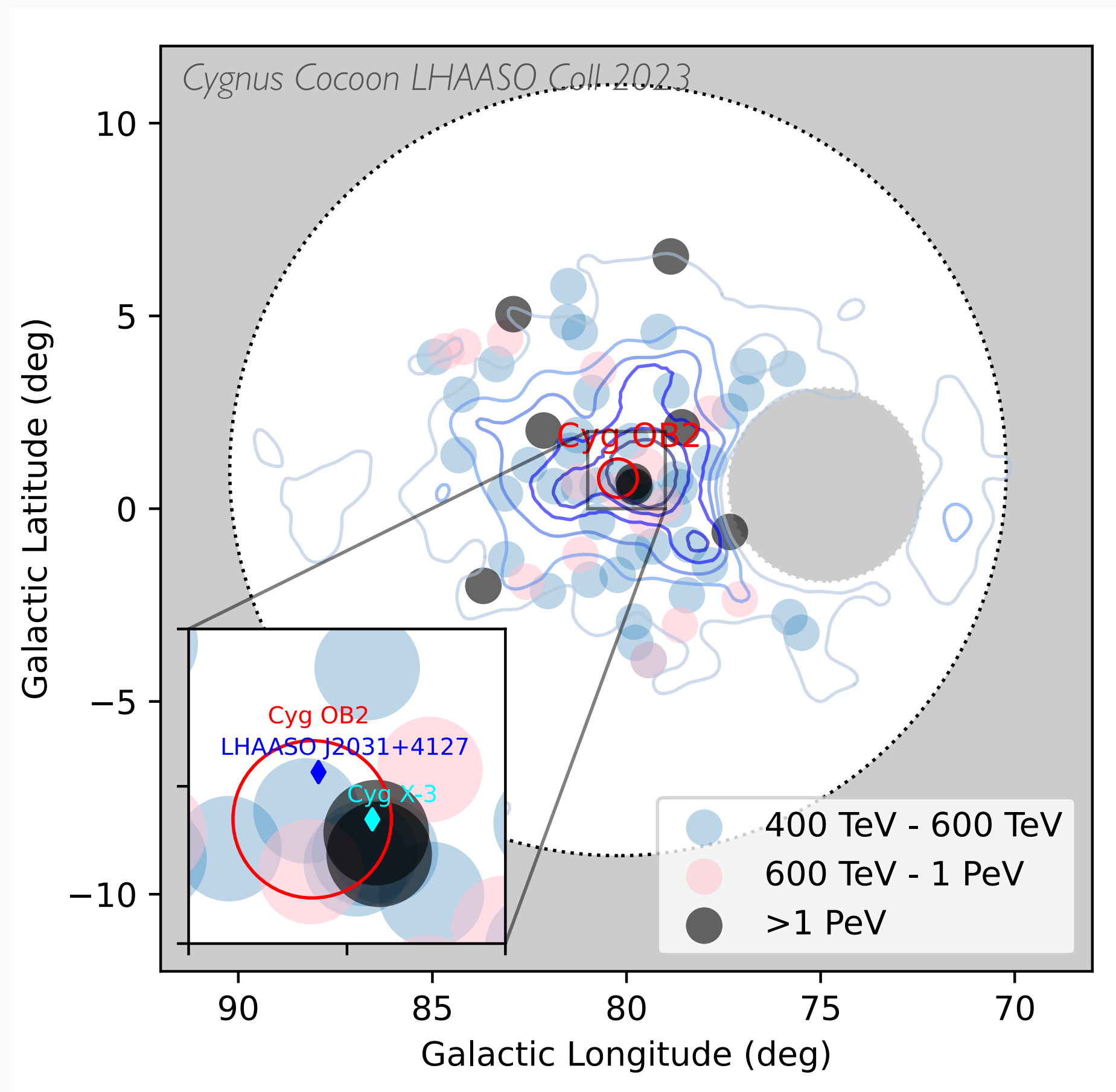
Rosette Nebula (and Open Cluster NGC2244), Waid Observ.



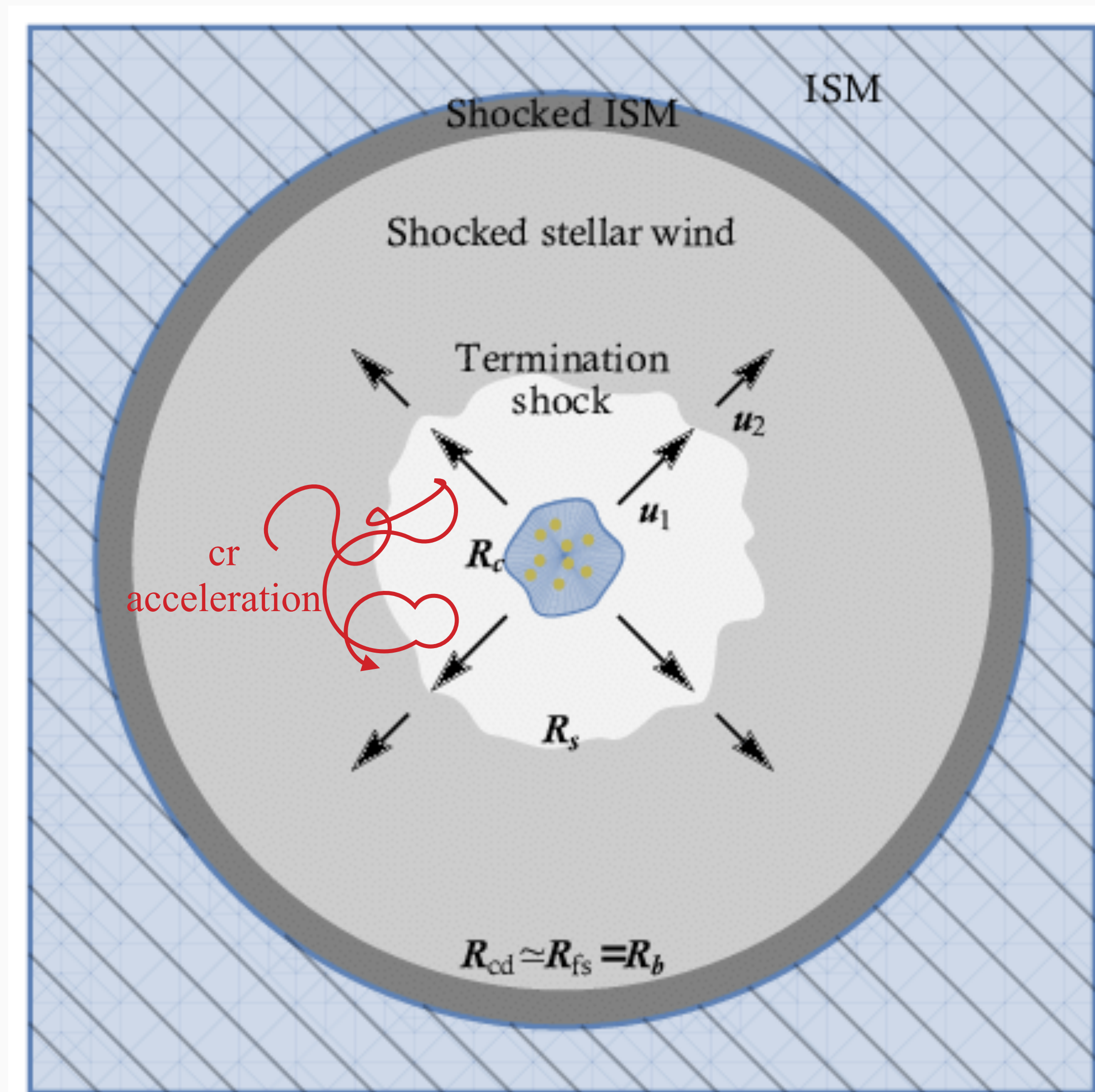
Morlino, Blasi et al, MNRAS 504, 2021, 4

Young Stellar Clusters

Cygnus OB2: 8 photons with $E_\gamma > 10^{15}$ eV in 6° bubble



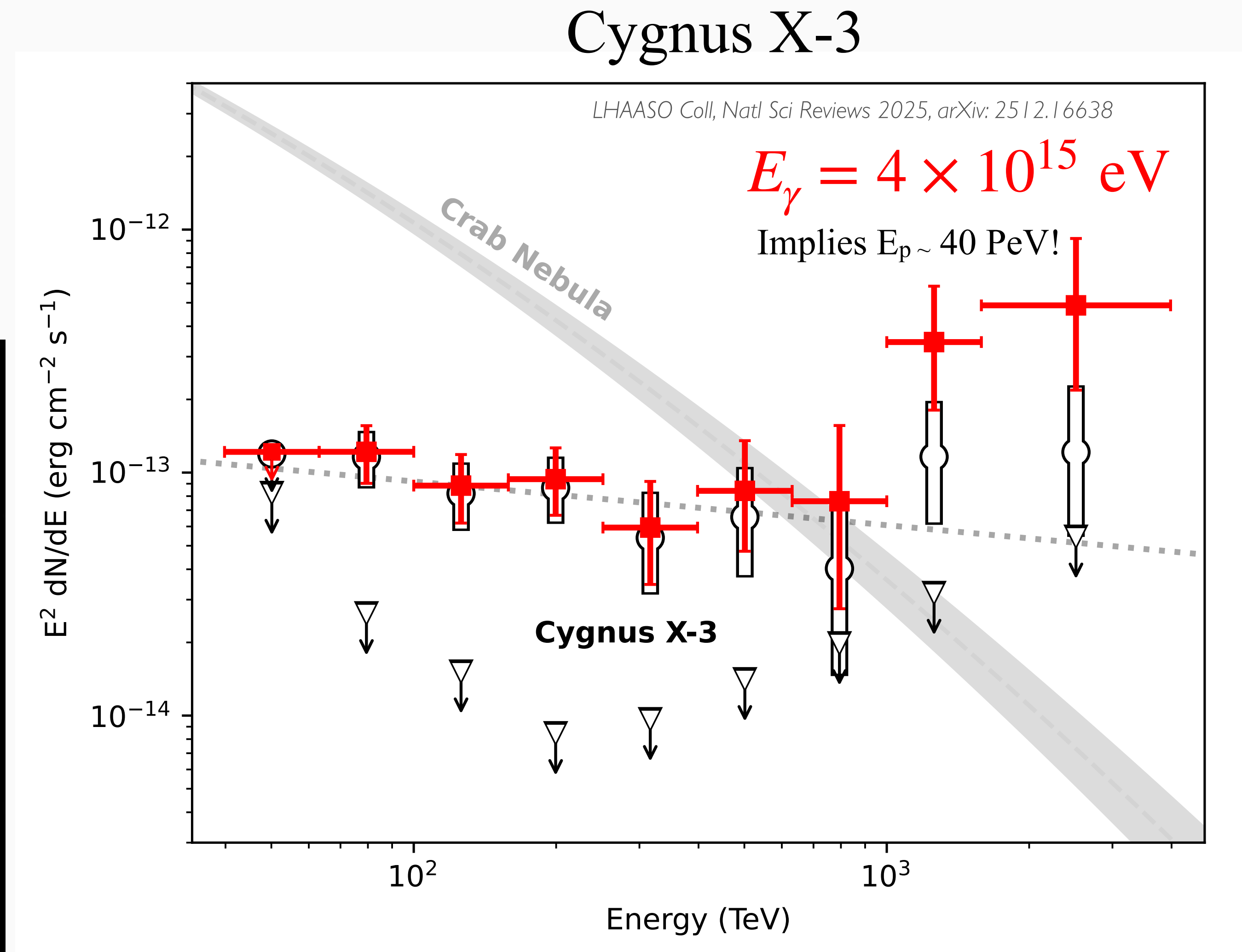
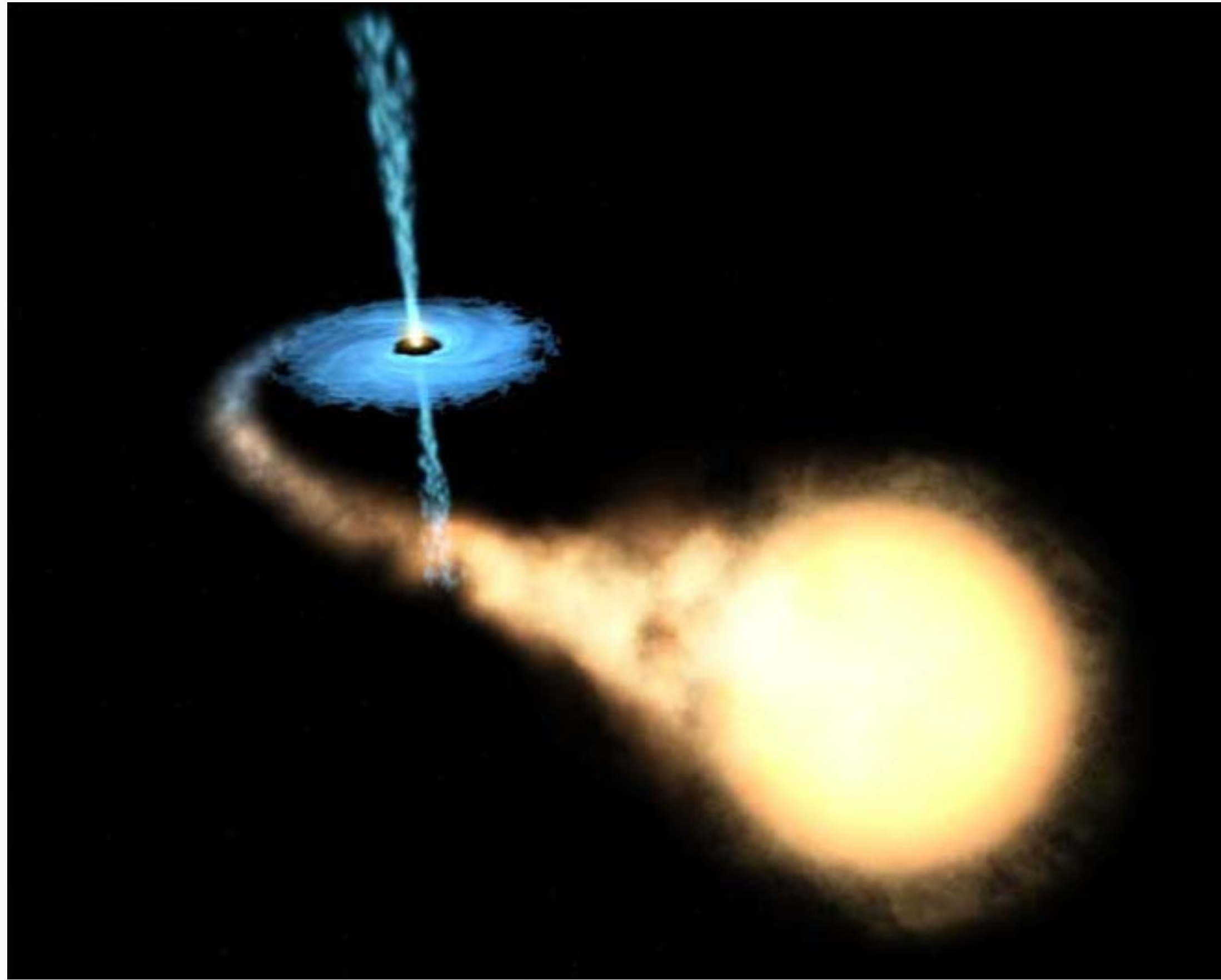
+3 Young Stellar Clusters consistent with HESS GC: $E_\gamma > 4 \times 10^{14}$ eV
 + several more seen with Imaging Atmospheric Cherenkov
 Telescopes and Fermi-LAT



Morlino, Blasi et al, MNRAS 504, 2021, 4

Microquasars

6/12 detected with LHAASO at $E_\gamma \geq 10^{14}$ eV

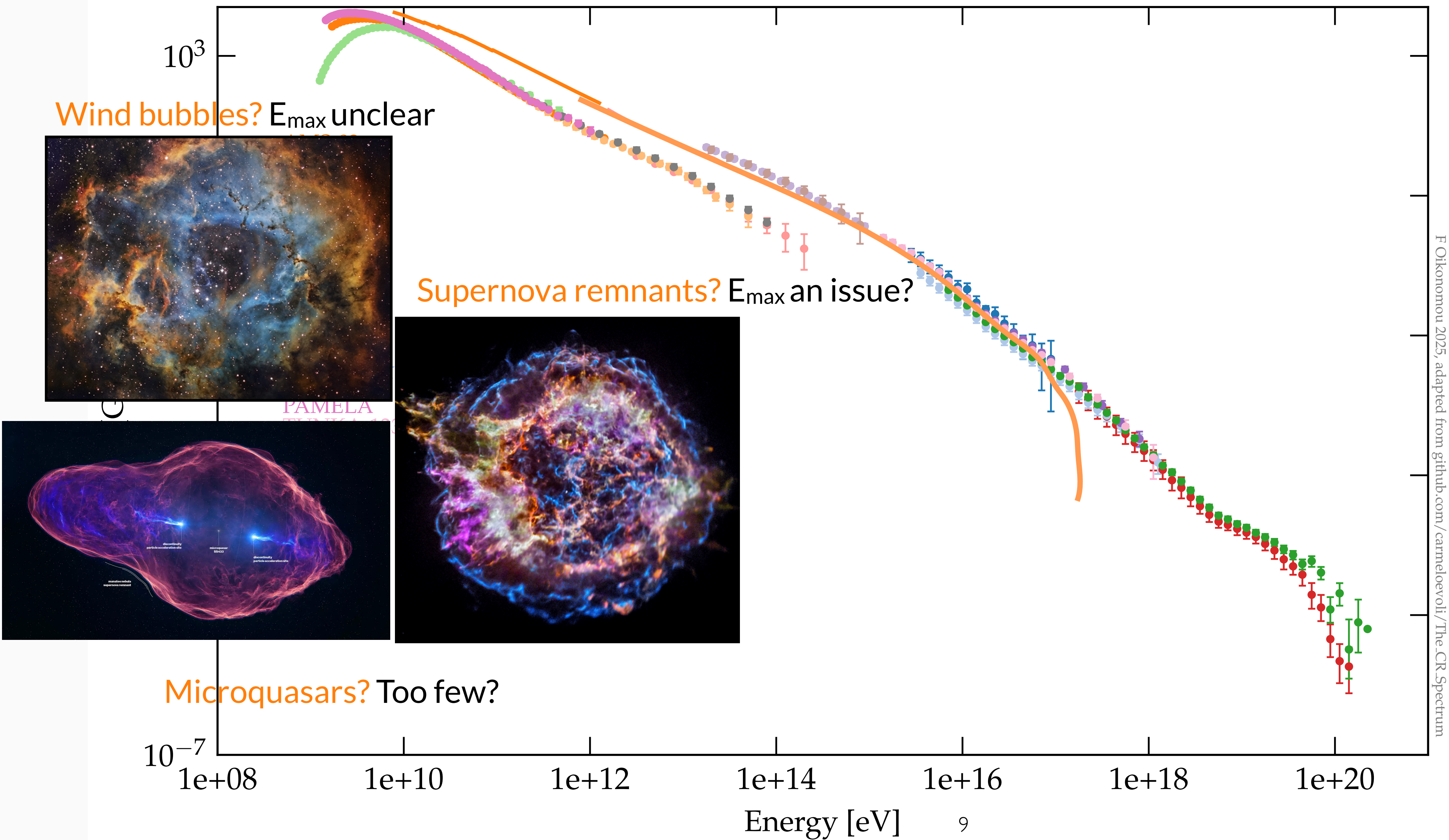


Transient and compact (jet)

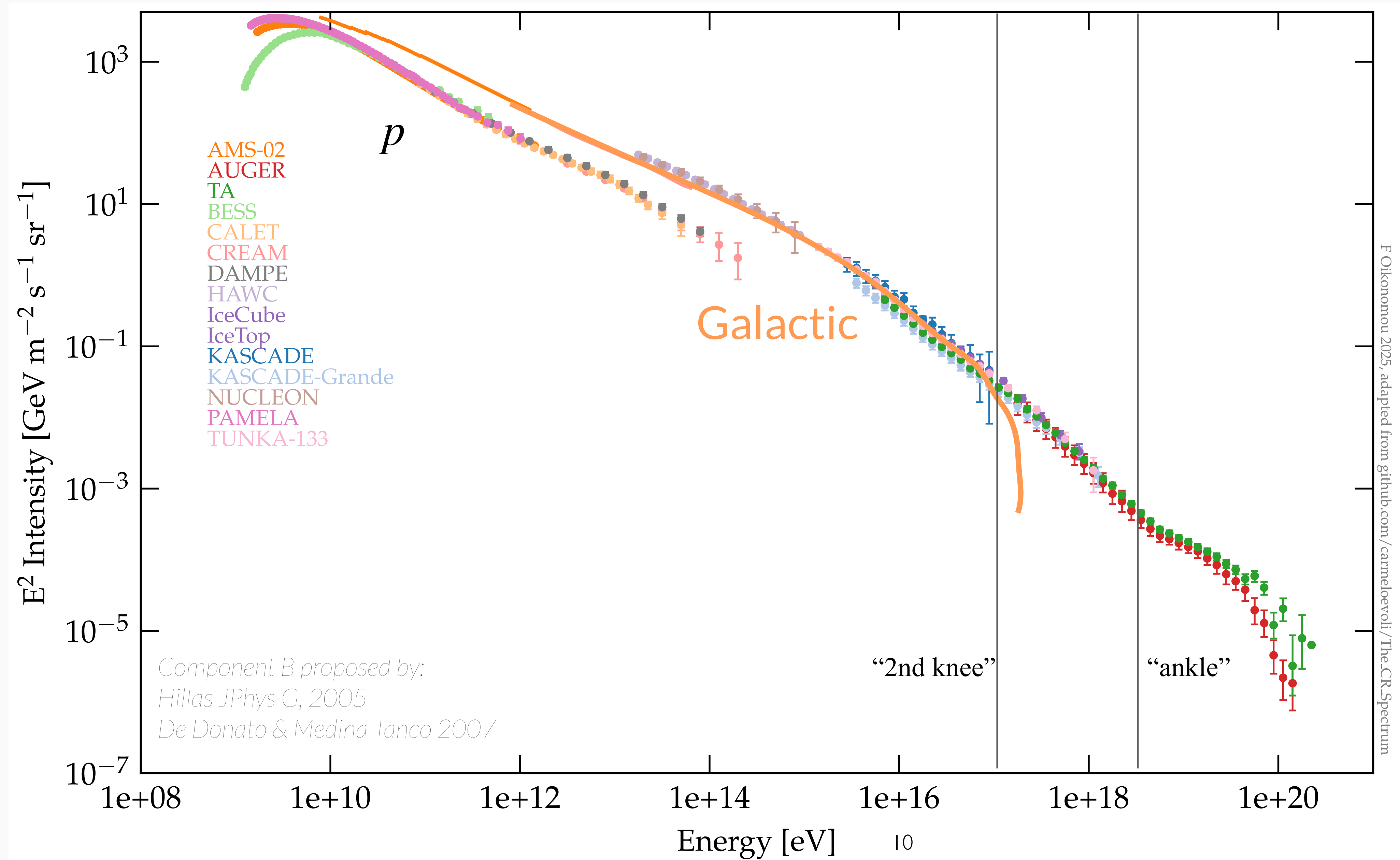
Orbital modulation ~ 5 h (3σ for LHAASO)

Must be hadronic if orbital modulation is real

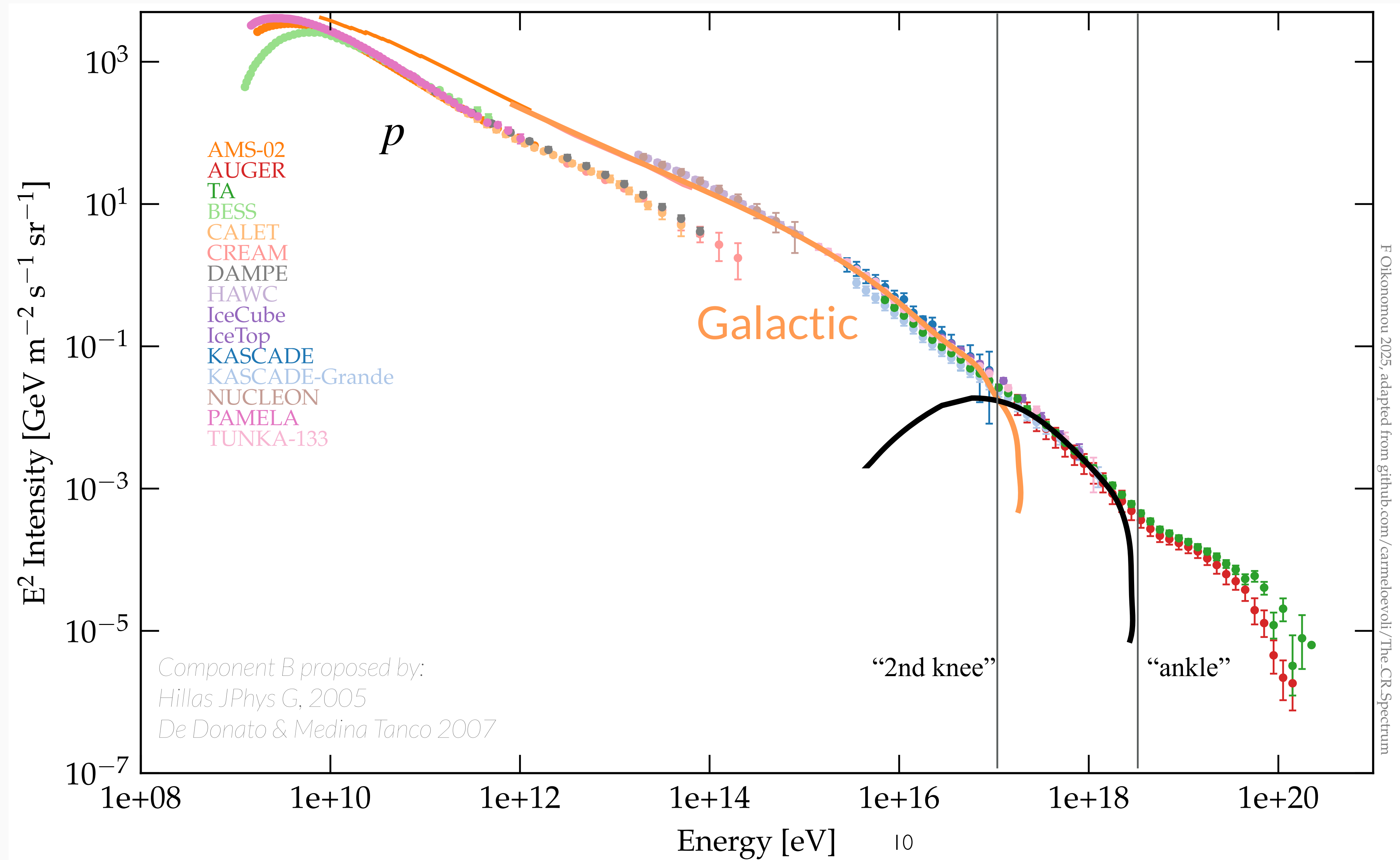
Galactic cosmic rays



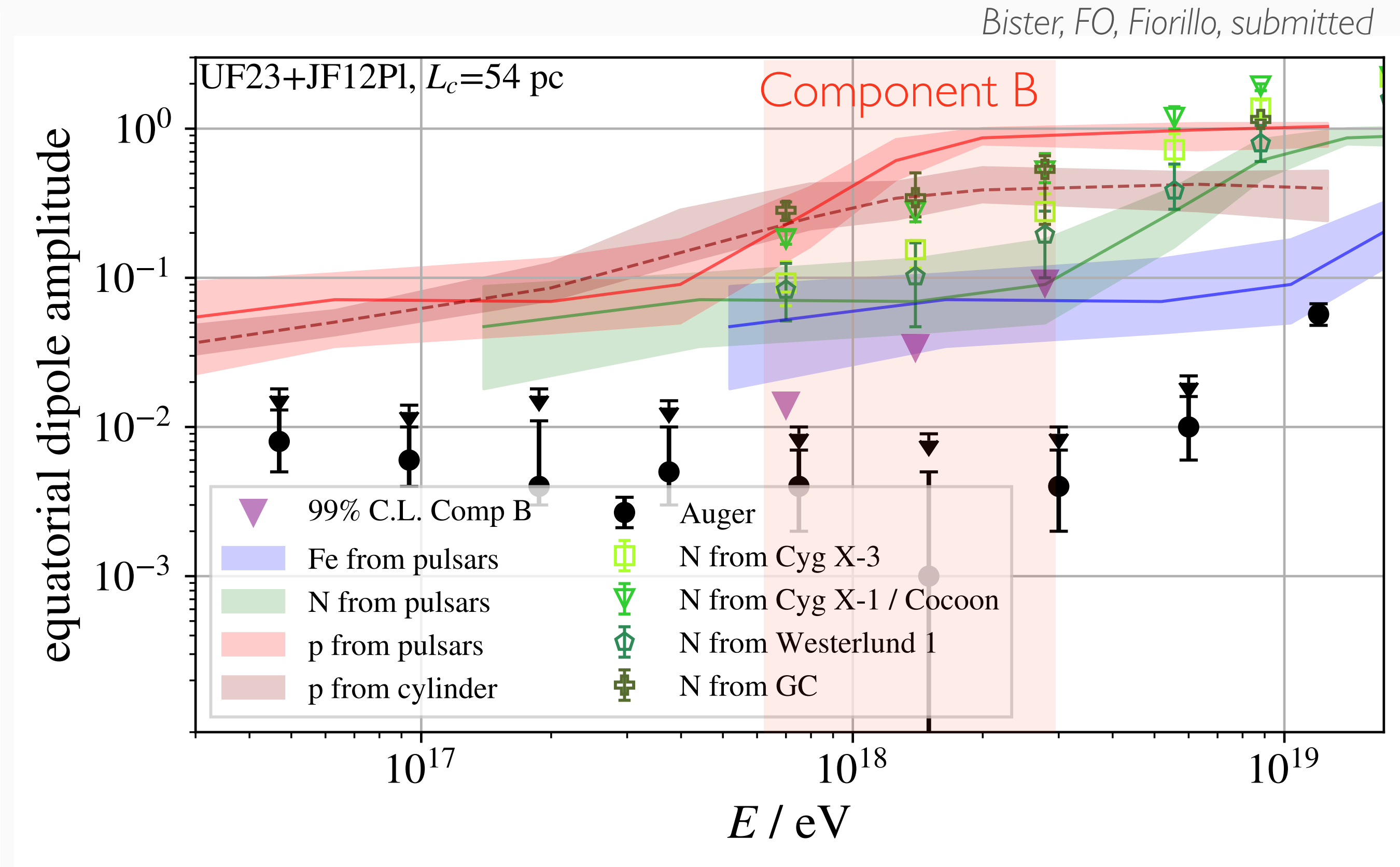
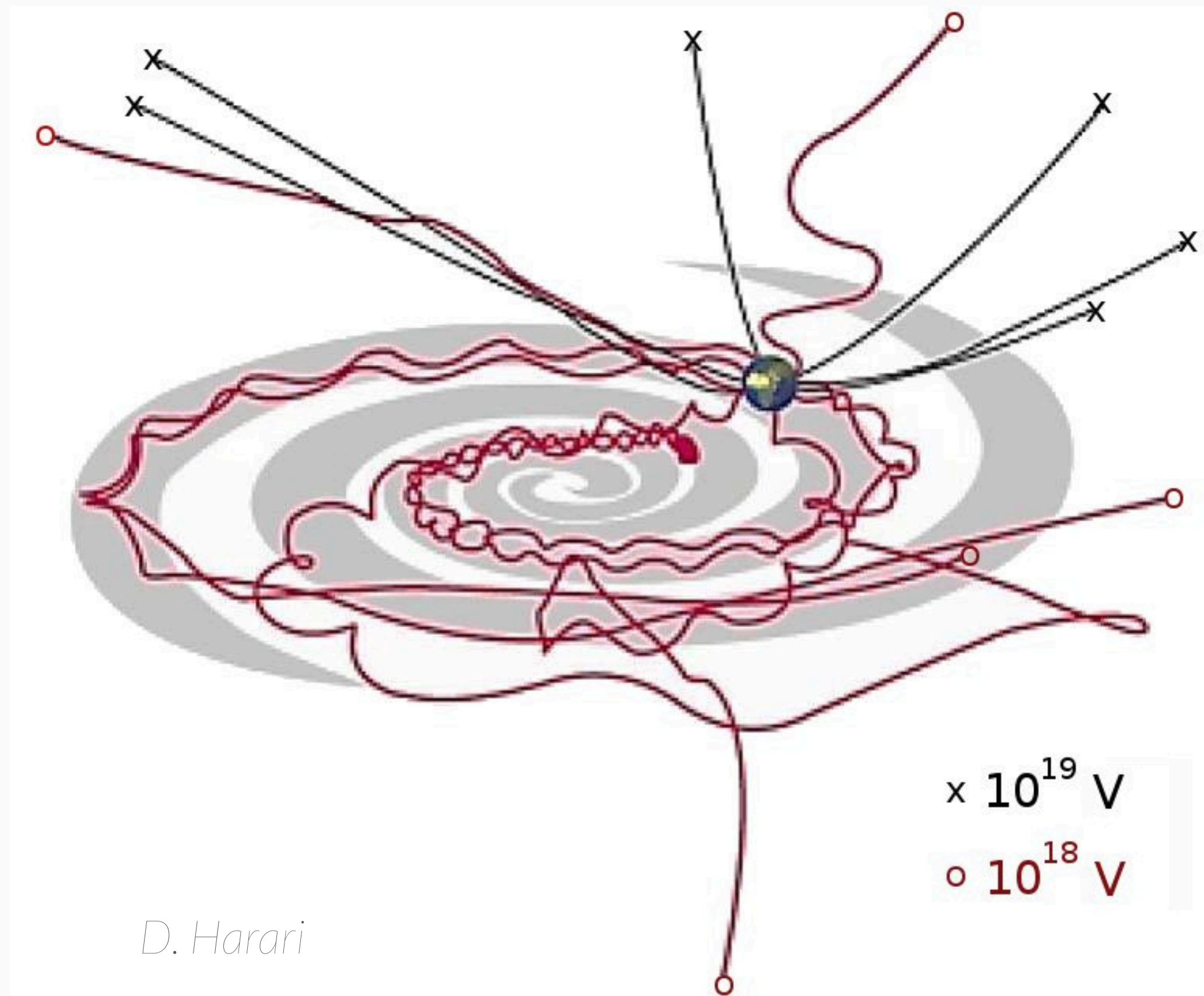
Component B



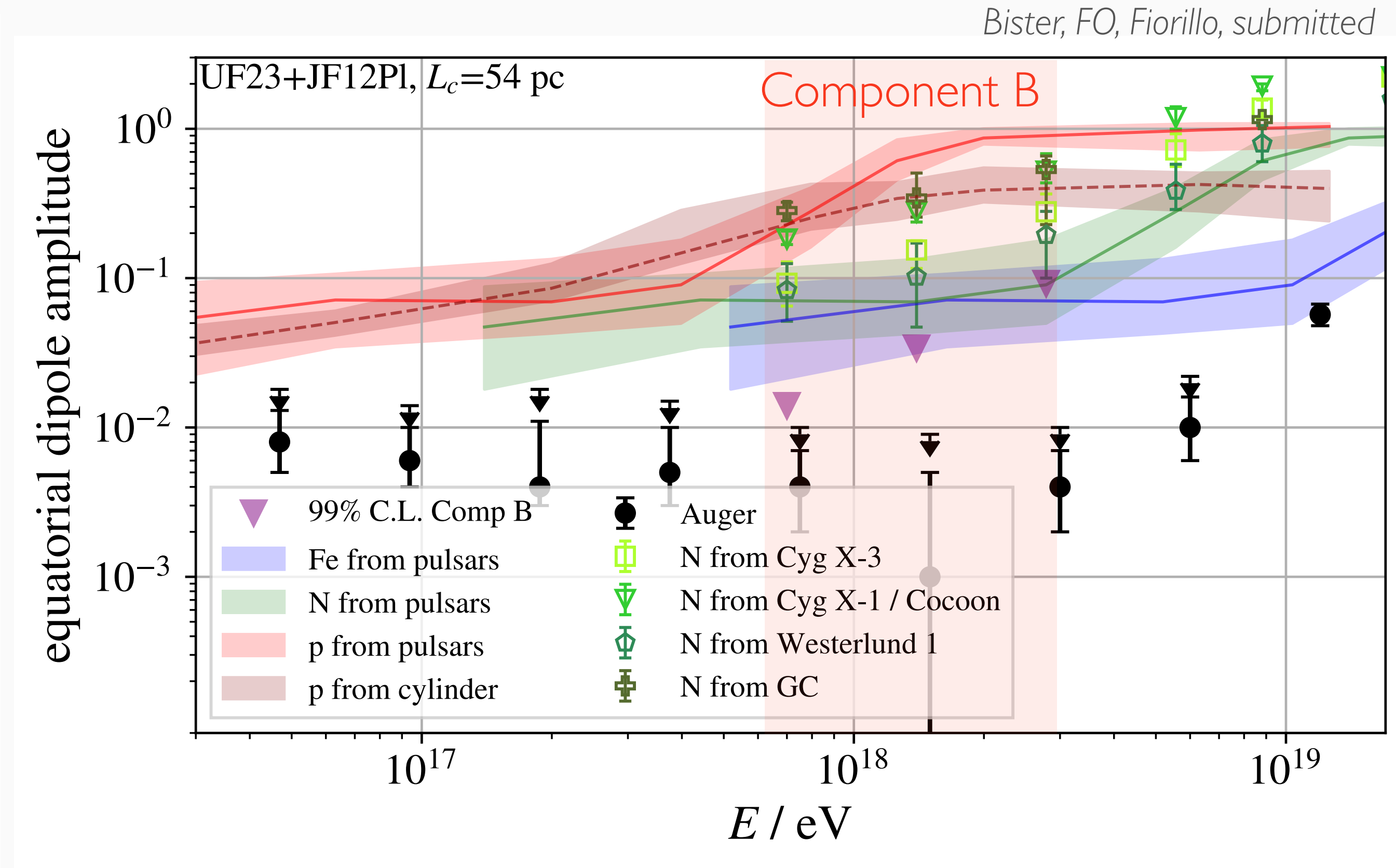
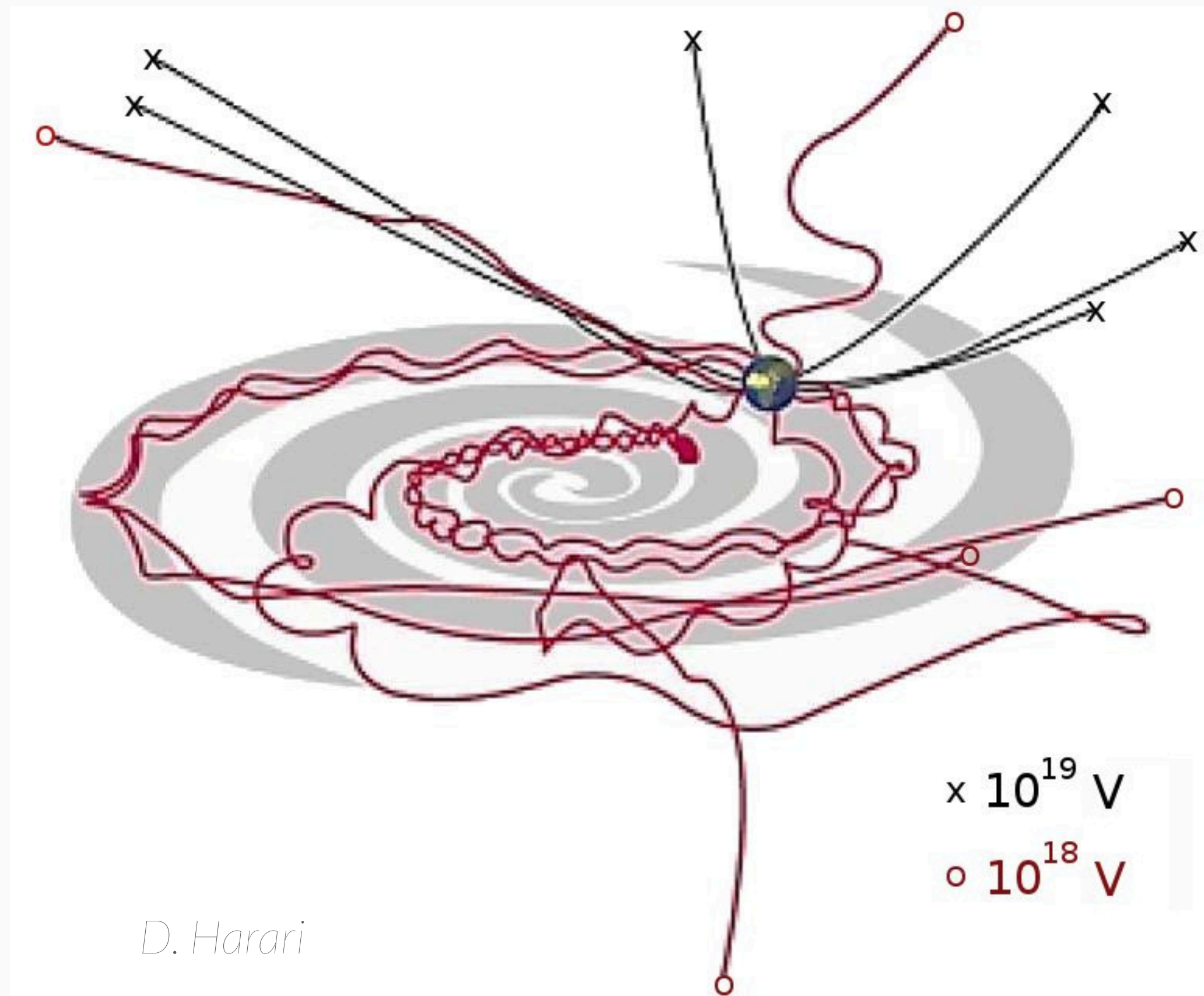
Component B



Origin of Component B: Extragalactic?

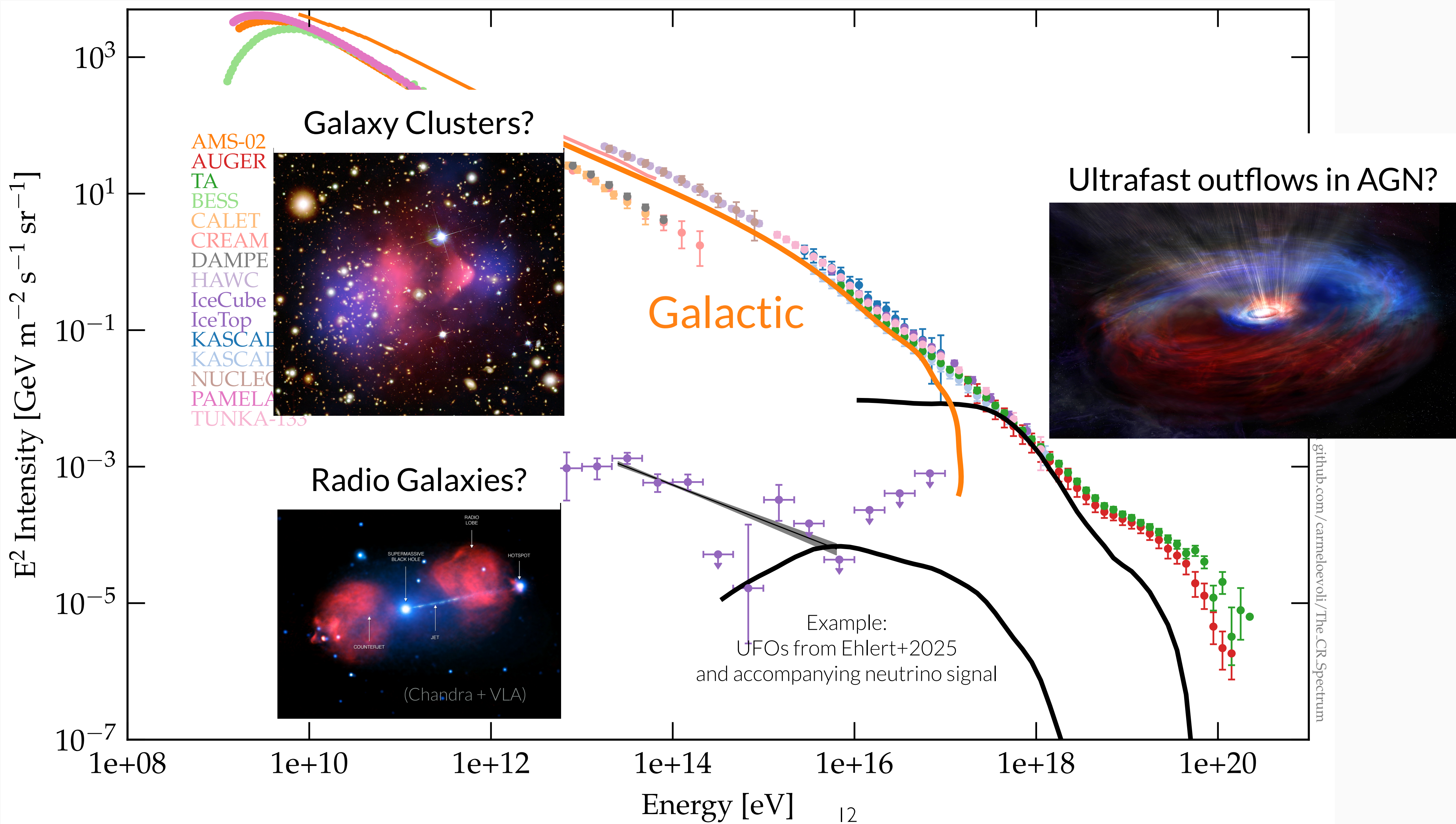


Origin of Component B: Extragalactic?

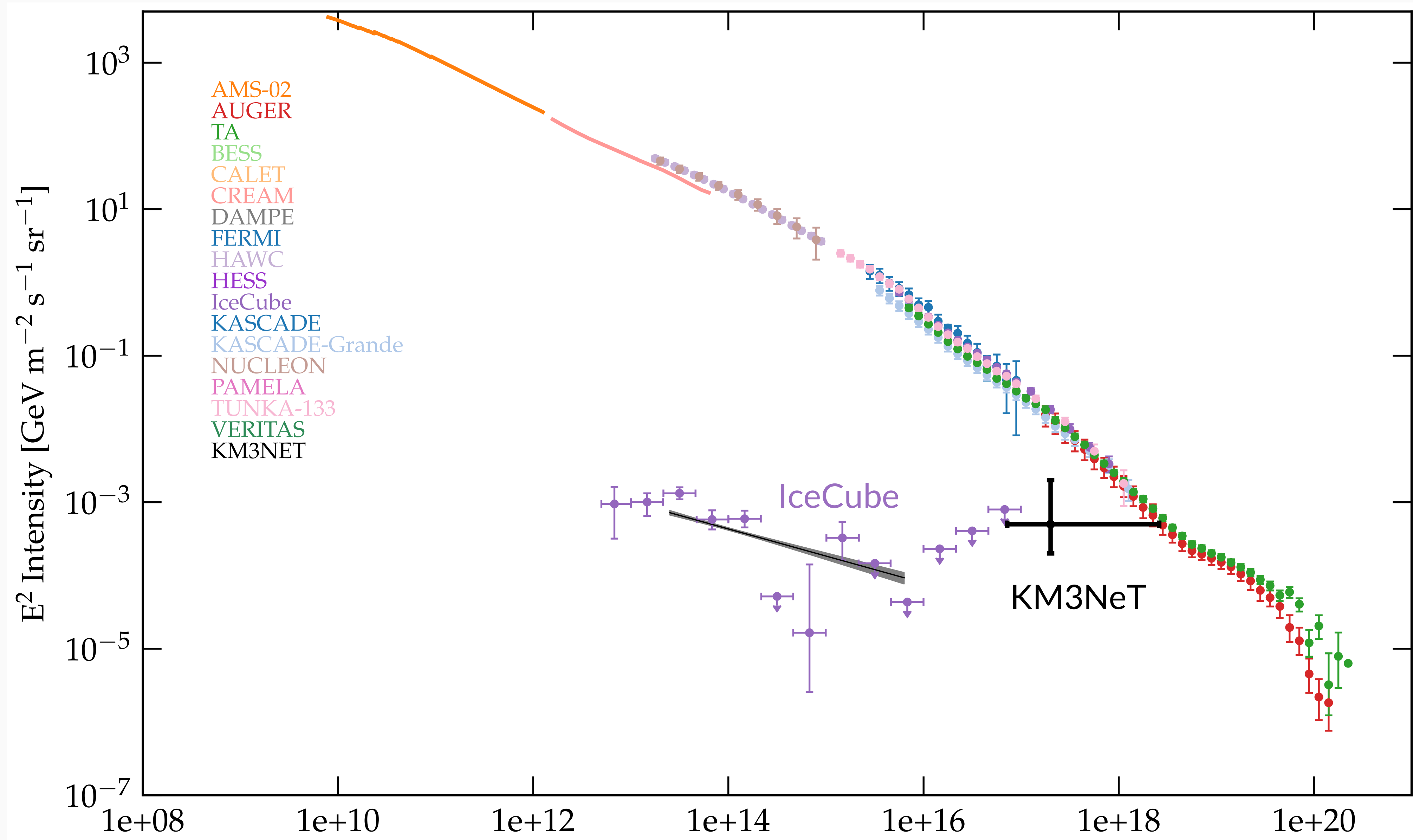


Conclusion: Component B Extragalactic

Origin of Component B?

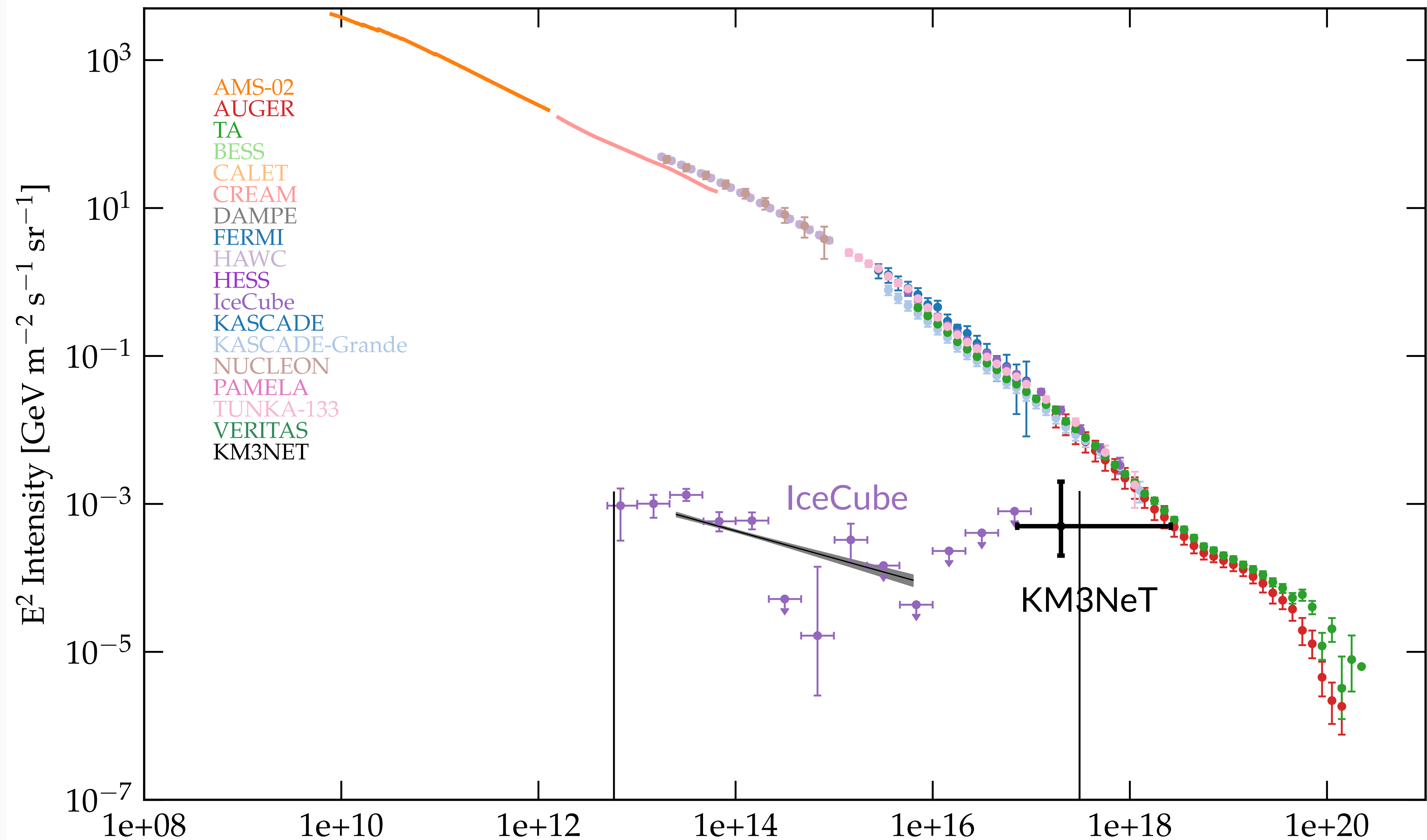


Neutrinos



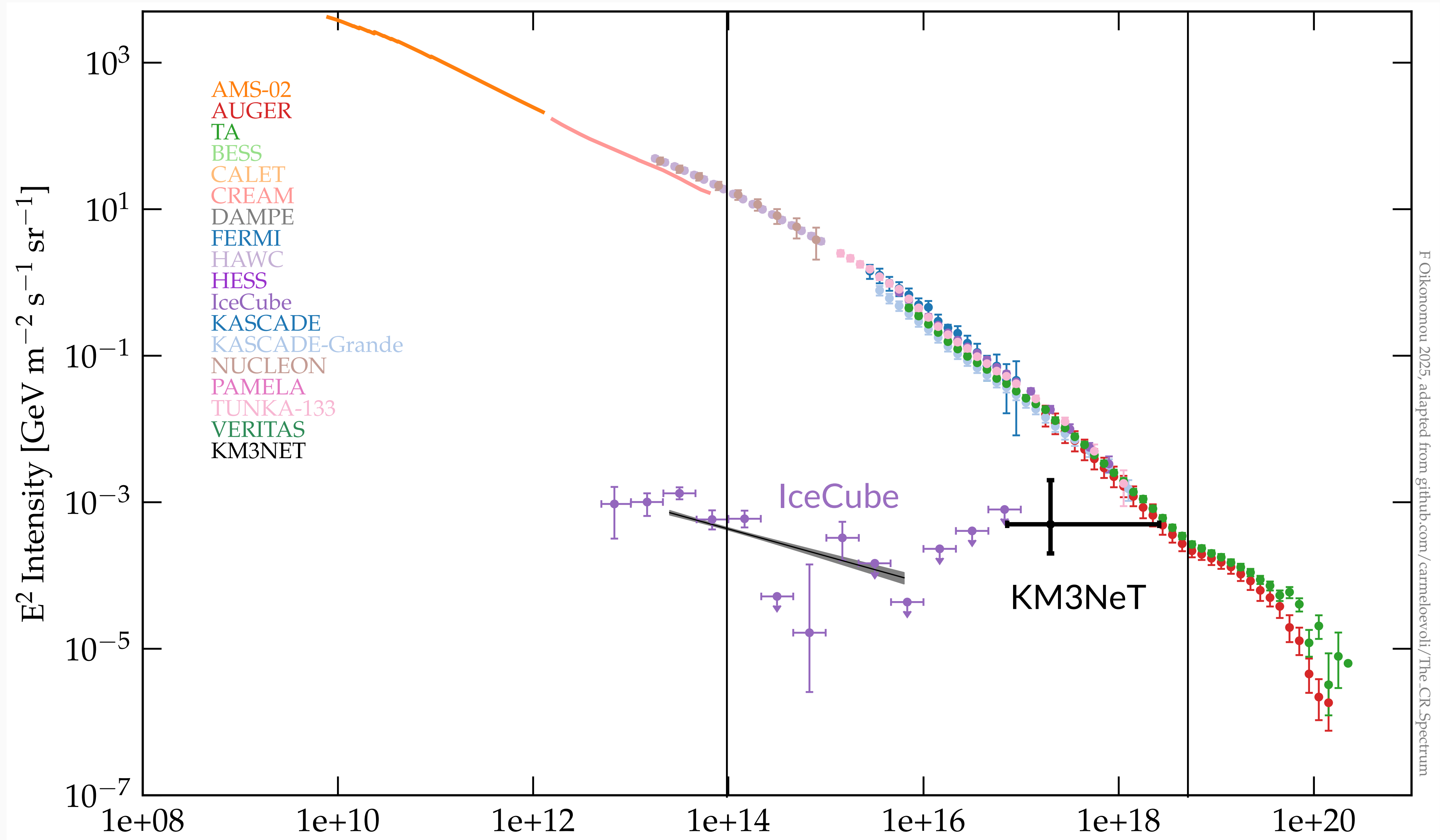
F Oikonomou 2025, adapted from github.com/carmeloevoli/The_CR_Spectrum

Neutrinos



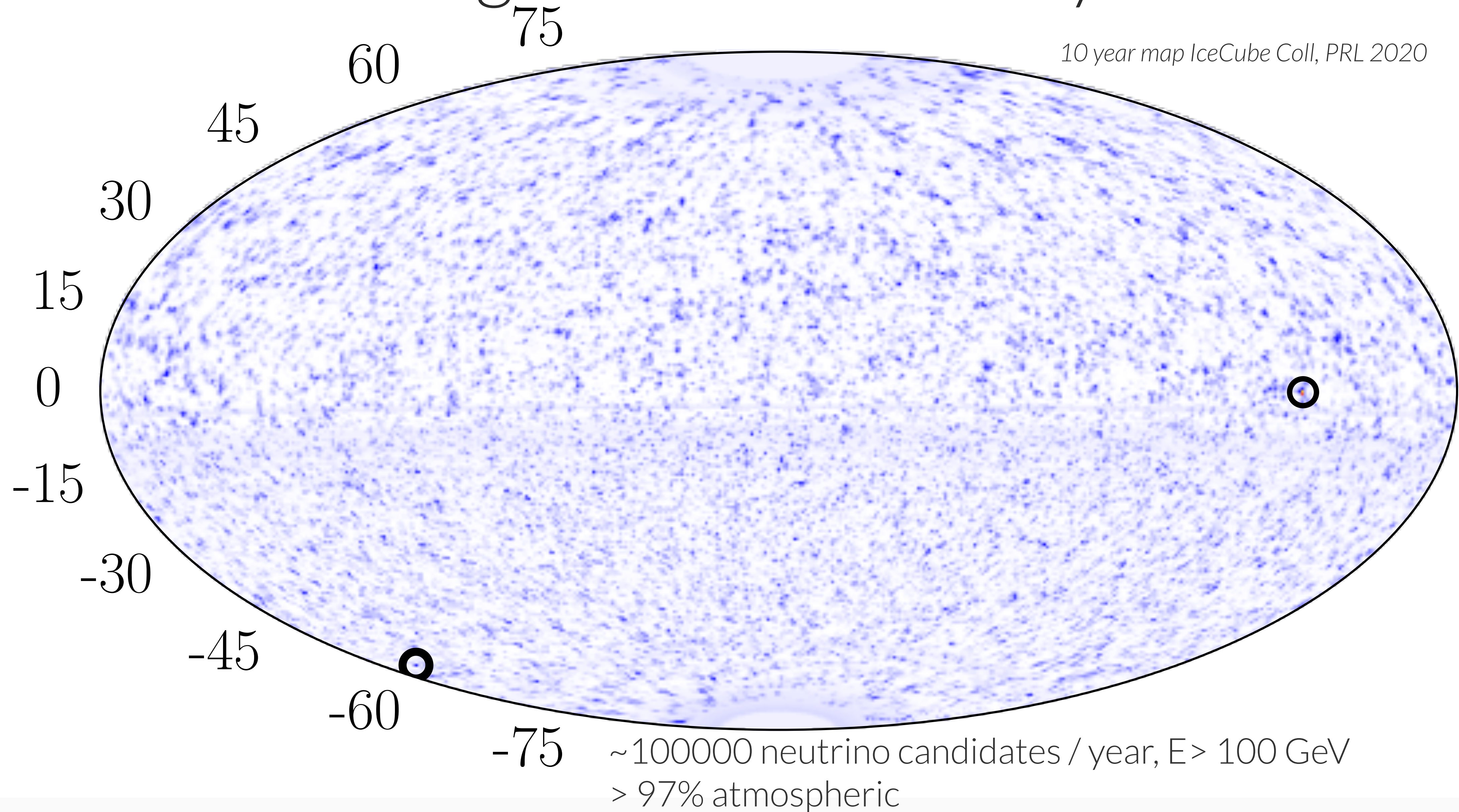
F Oikonomou 2025, adapted from github.com/carmeloevoli/The_CR_Spectrum

Neutrinos

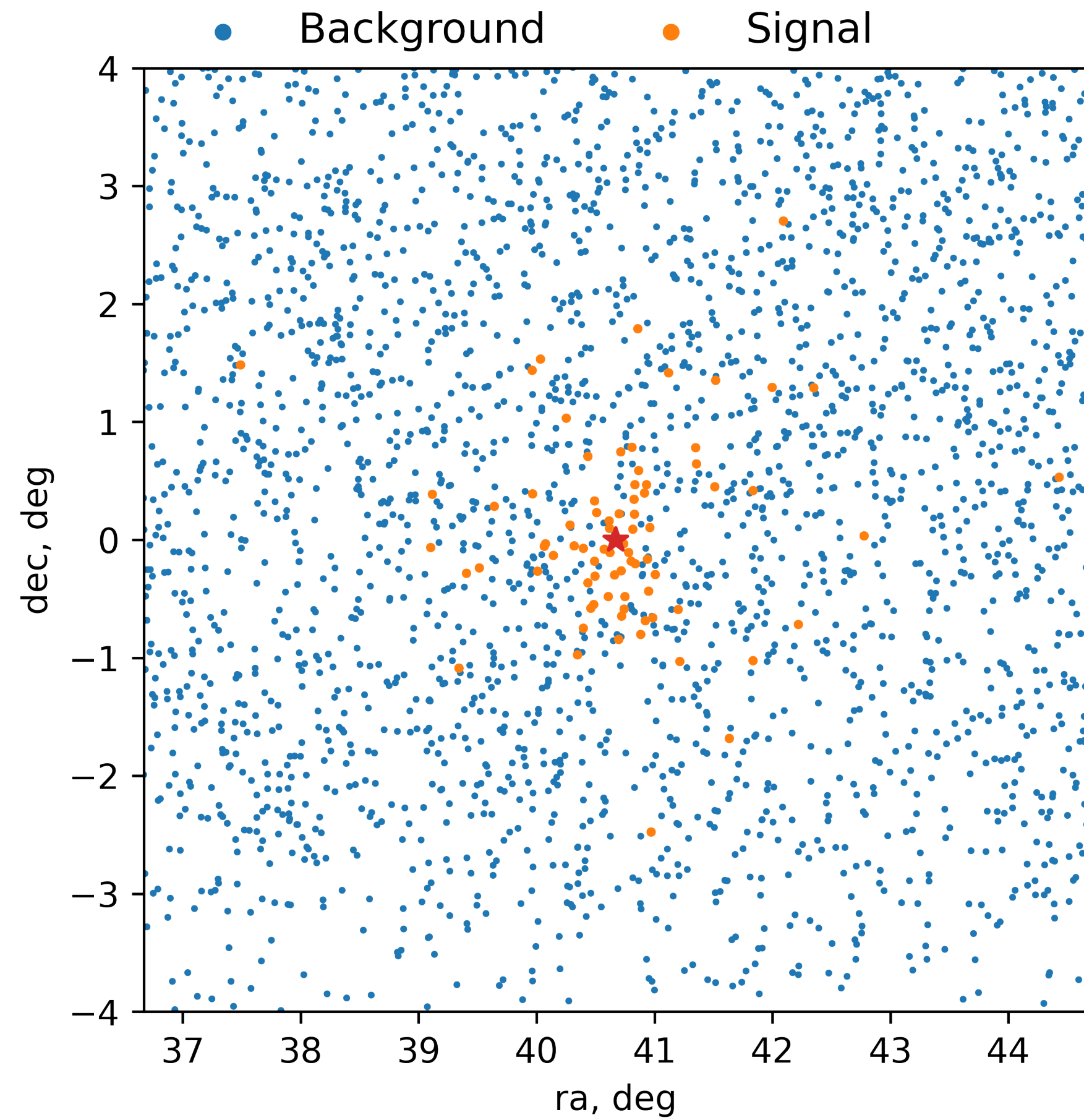


F Oikonomou 2025, adapted from github.com/carmeloiovoli/The_CR_Spectrum

Neutrinos: Looking for a needle in a haystack



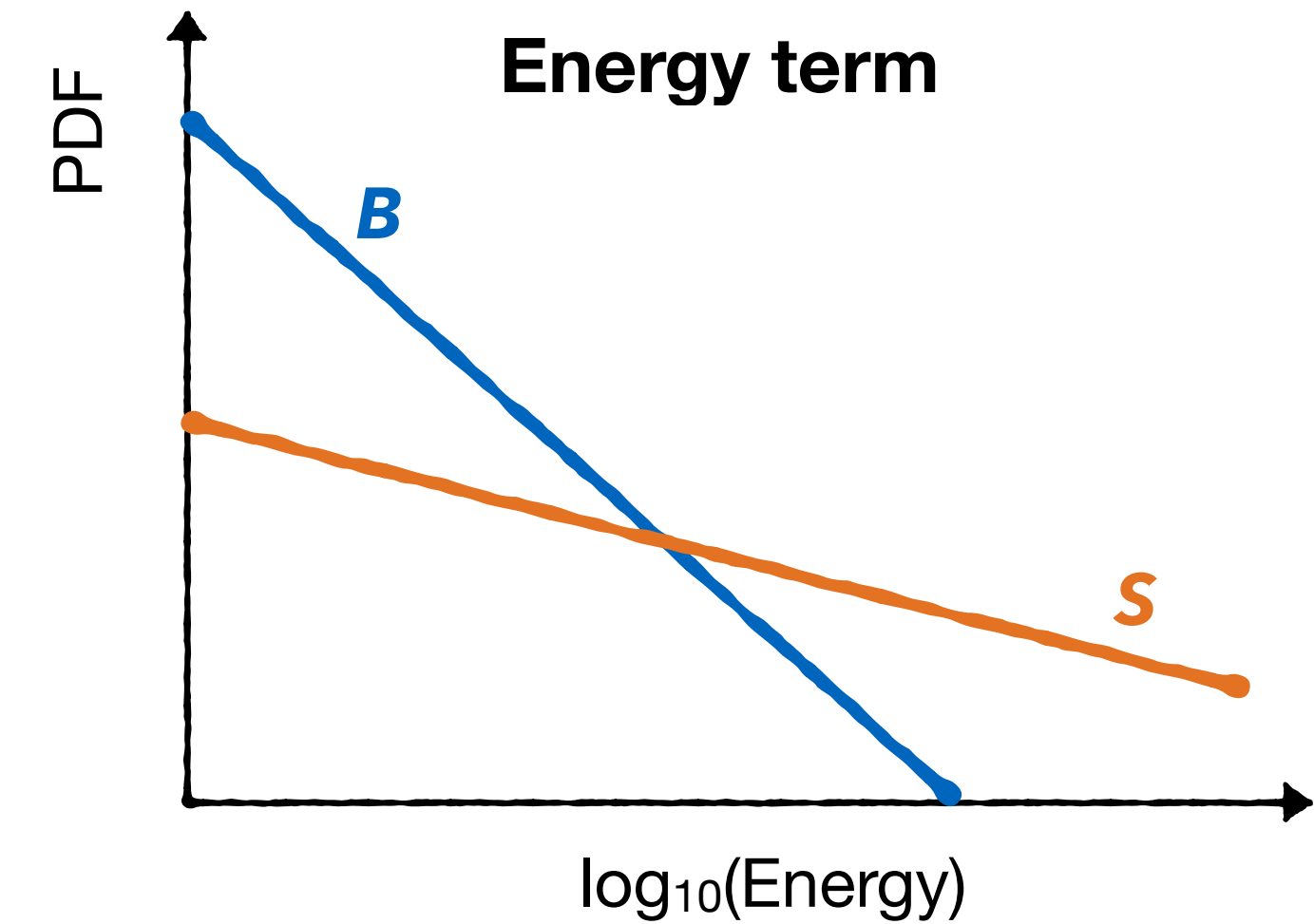
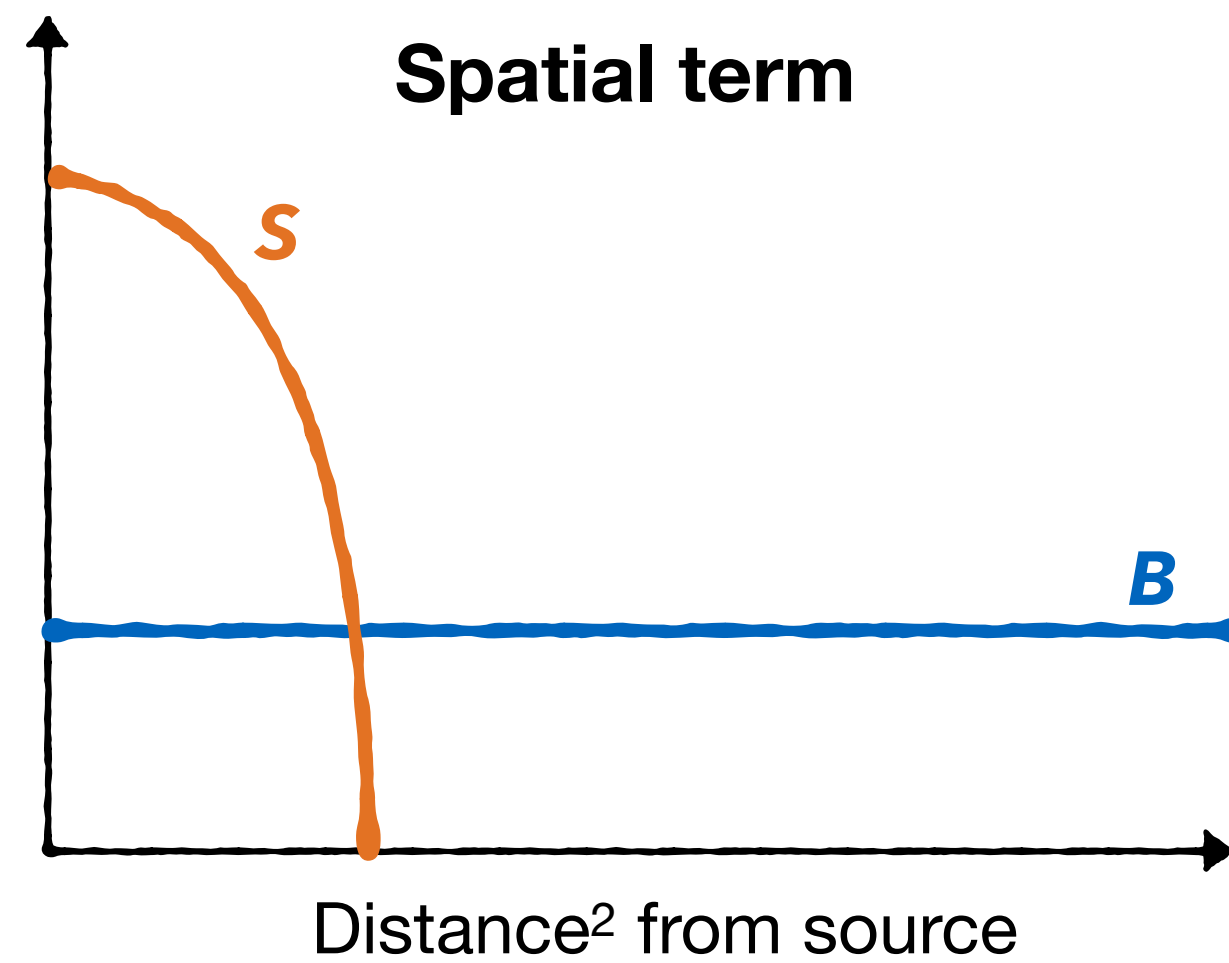
Likelihood stacking analyses



The unbinned likelihood approach:

$$\mathcal{L} = \prod_i^N \left[\frac{n_s}{N} \boxed{S_i} + \left(1 - \frac{n_s}{N} \right) \cdot \boxed{B_i} \right]$$

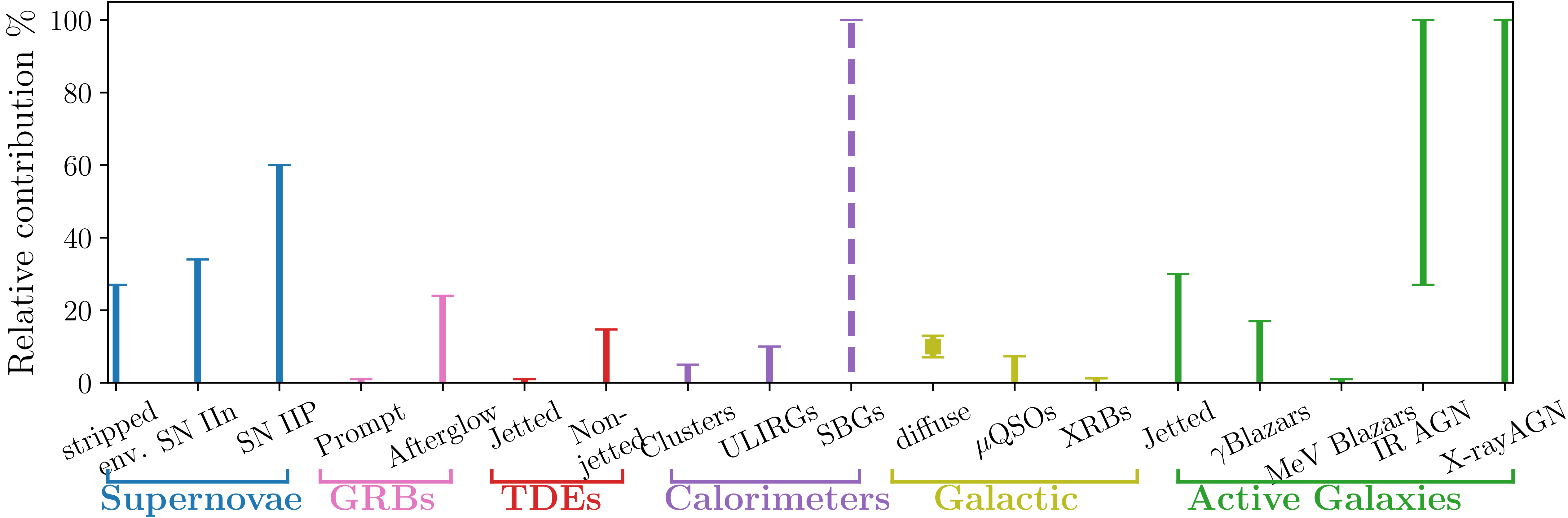
Arrows from the boxed S_i and B_i terms point to the 'Spatial term' and 'Energy term' plots respectively.



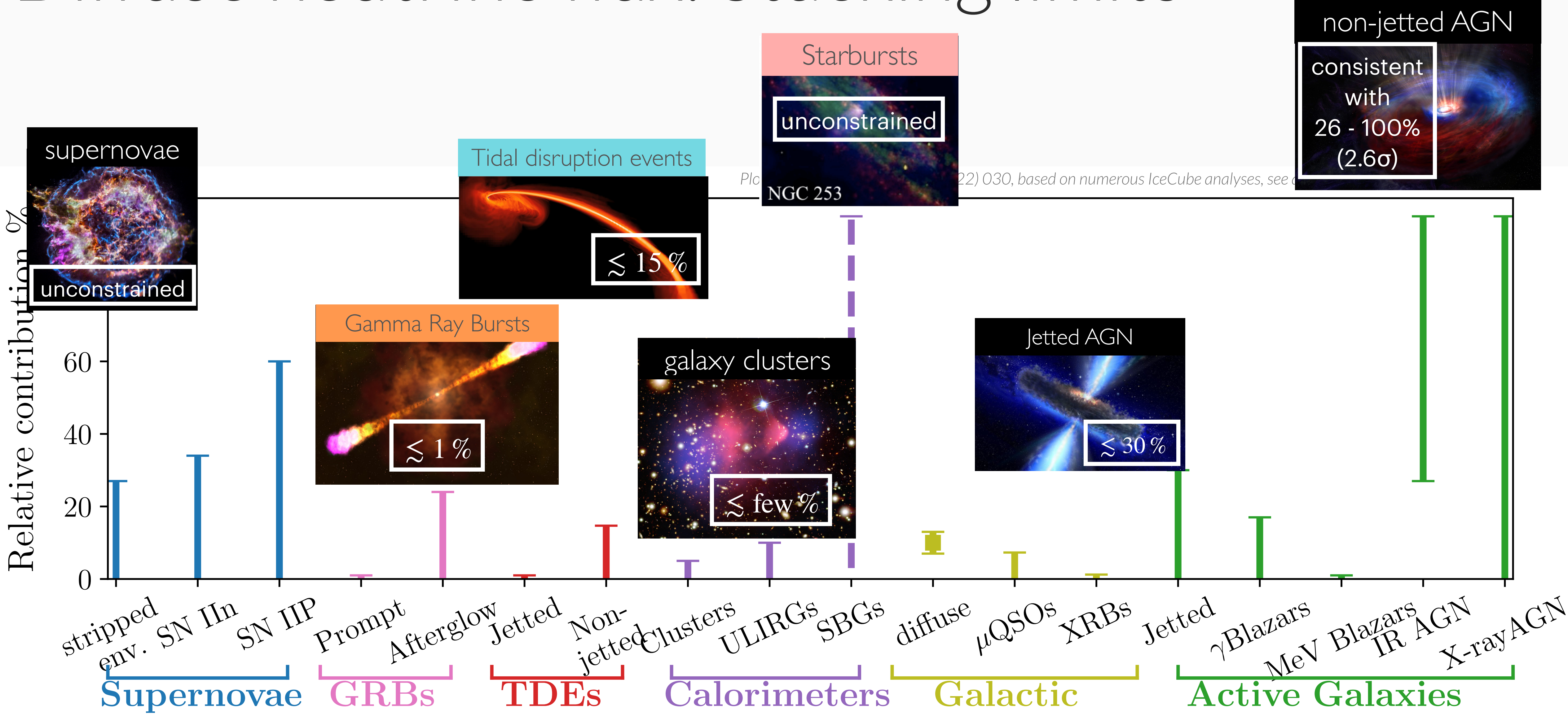
Tomas Kontrimas | TeVPA 2024 | 26th of August, 2024 | Chicago, US

Diffuse neutrino flux: Stacking limits

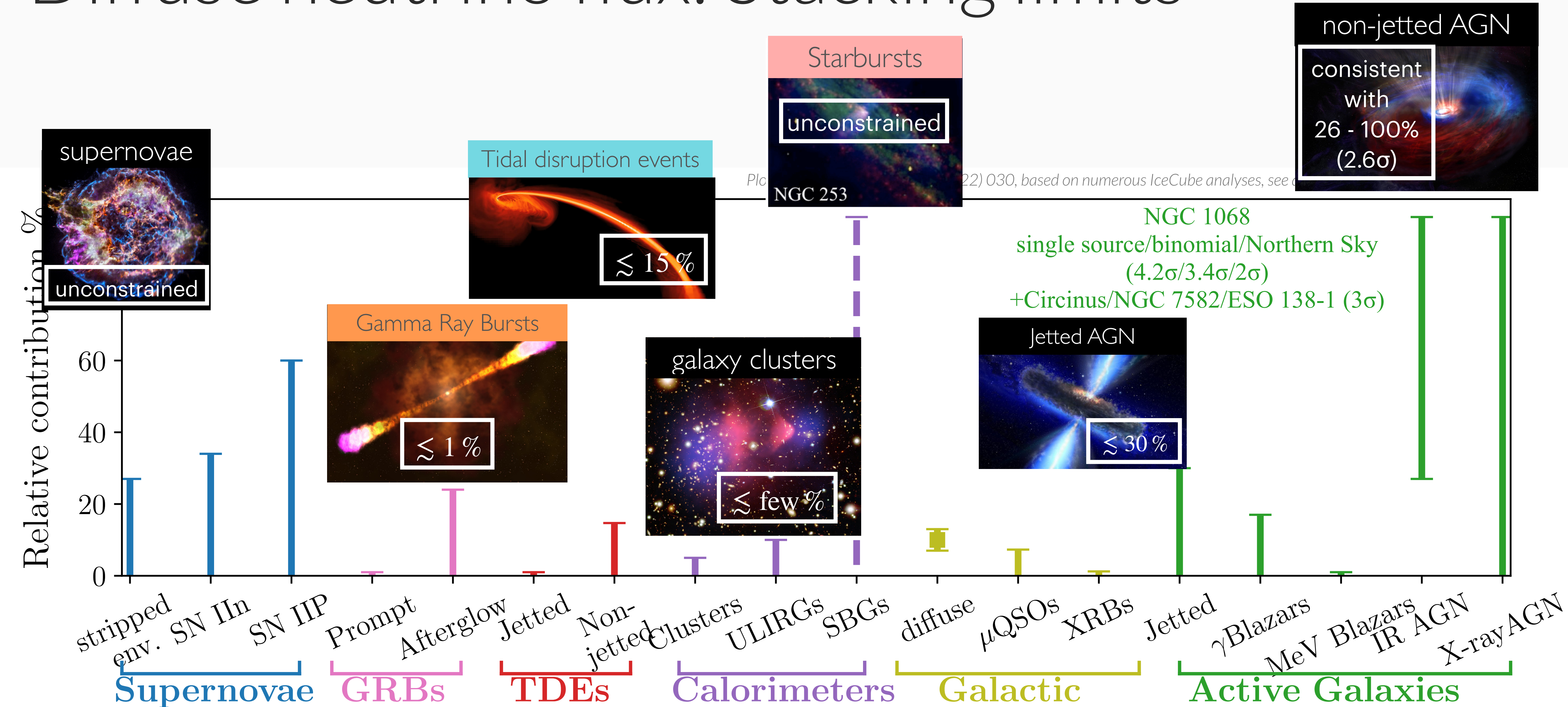
Plot from FO PoS ICRC2021 (2022) 030, based on numerous IceCube analyses, see [arXiv:2201.05623](https://arxiv.org/abs/2201.05623) for references



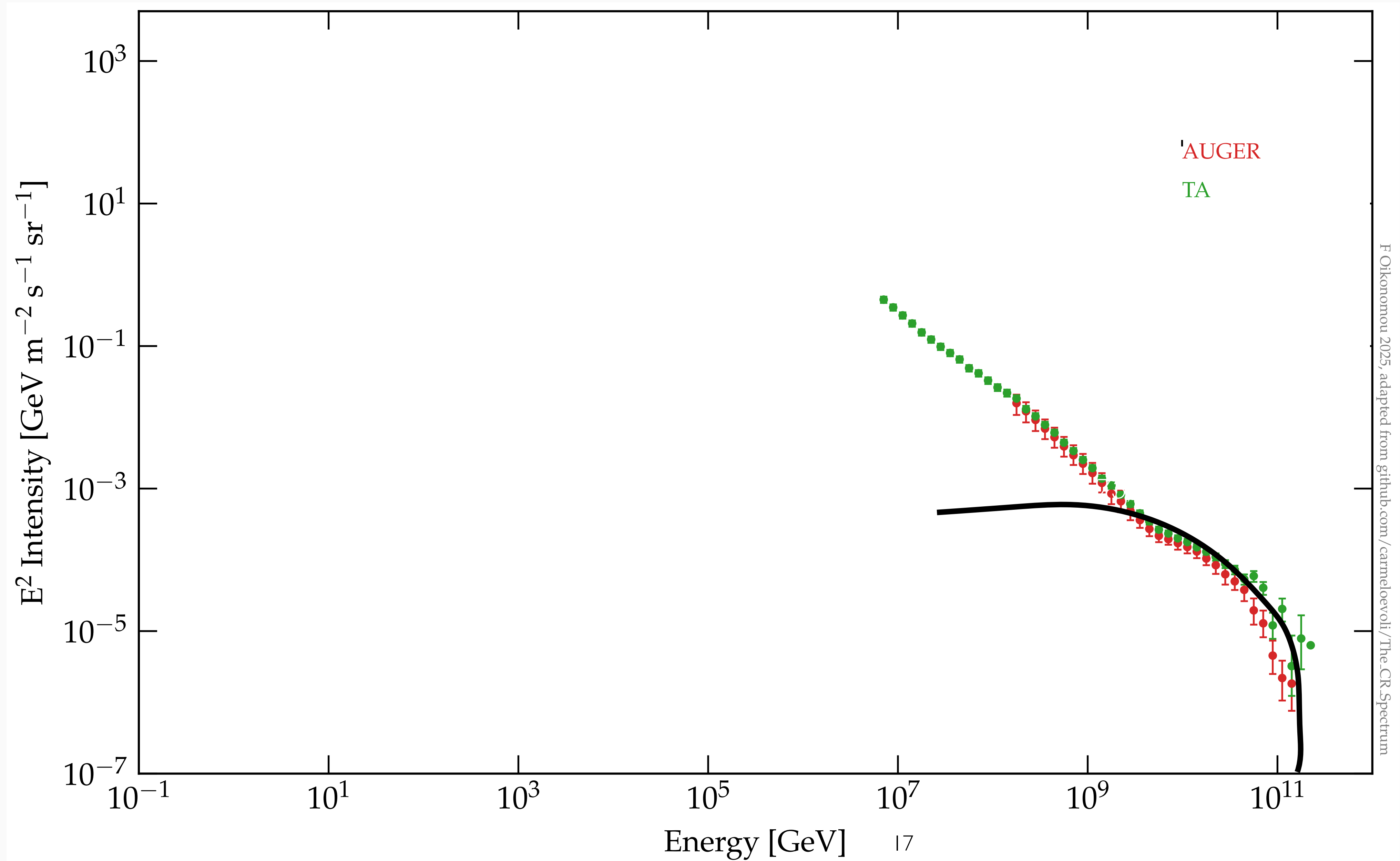
Diffuse neutrino flux: Stacking limits



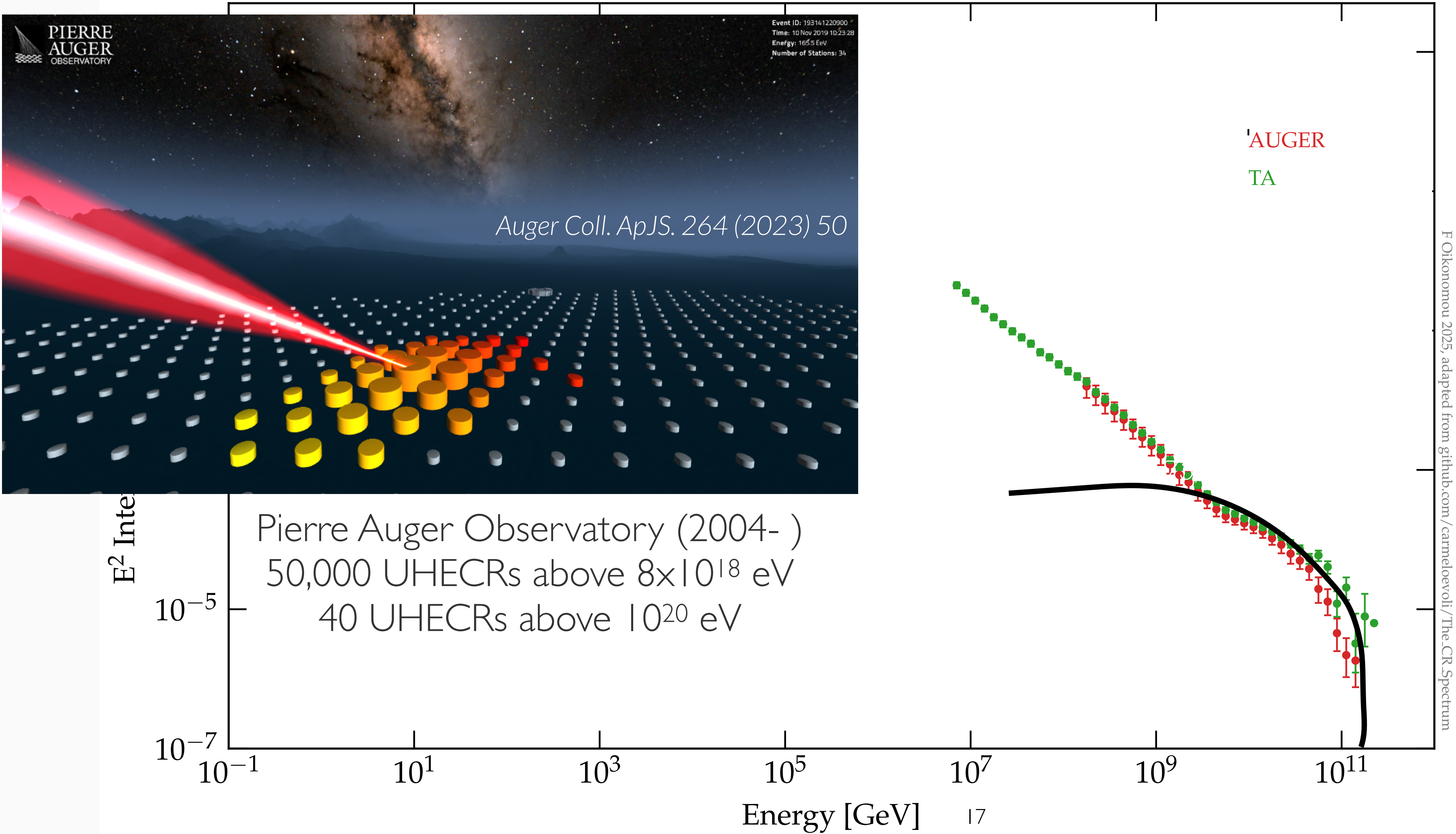
Diffuse neutrino flux: Stacking limits



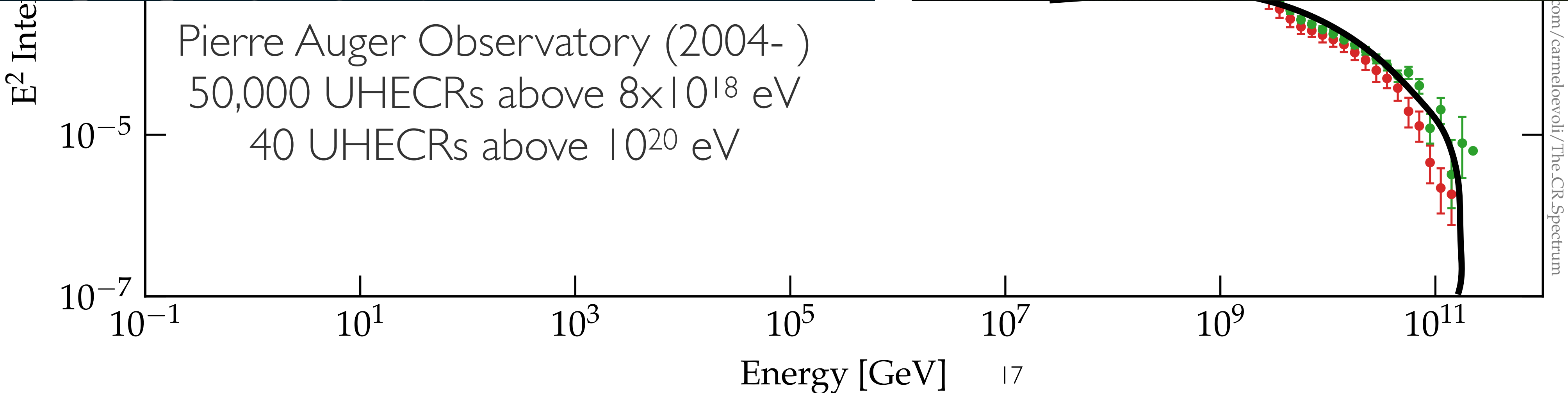
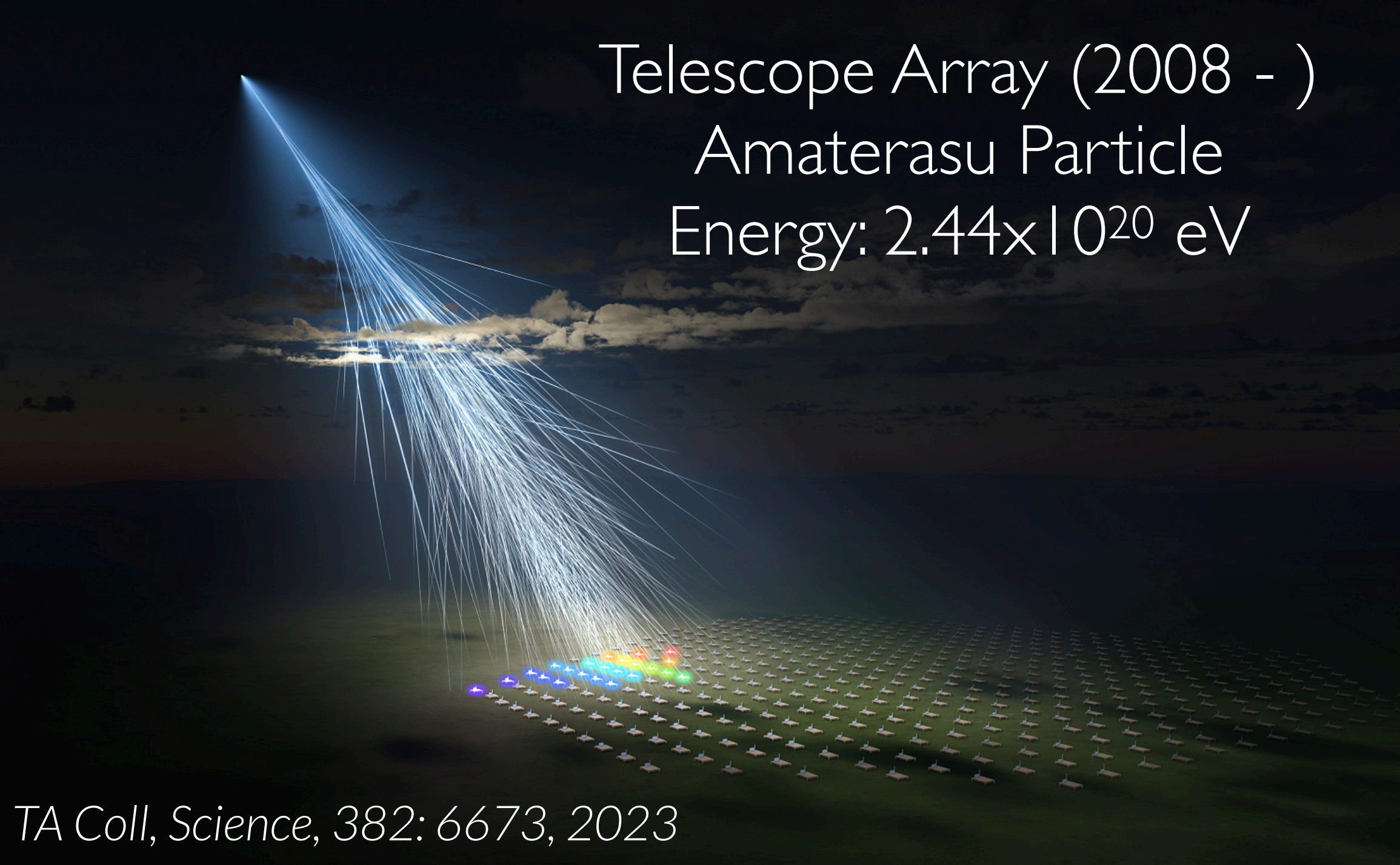
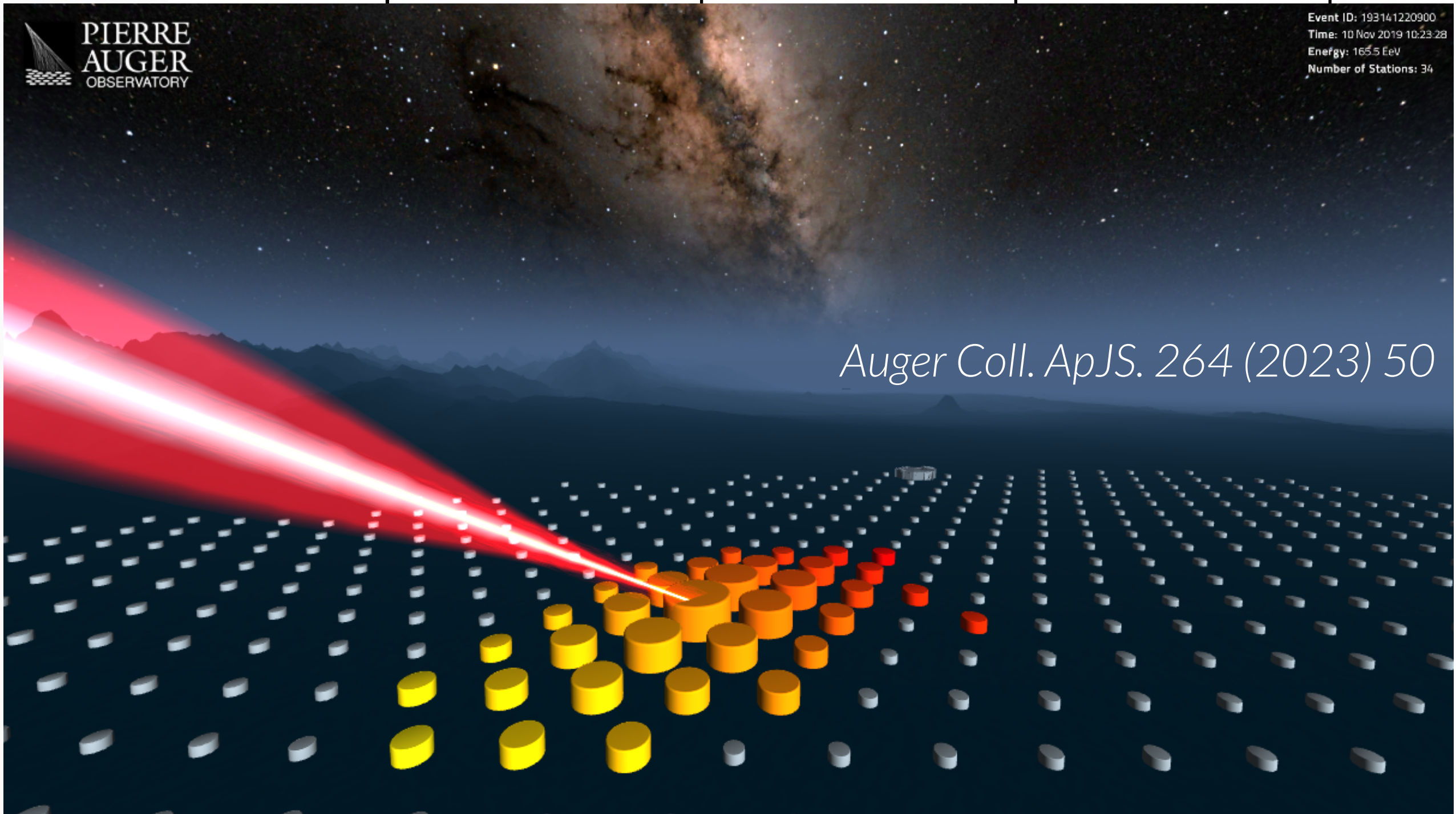
Ultra-high energy cosmic rays



Ultra-high energy cosmic rays

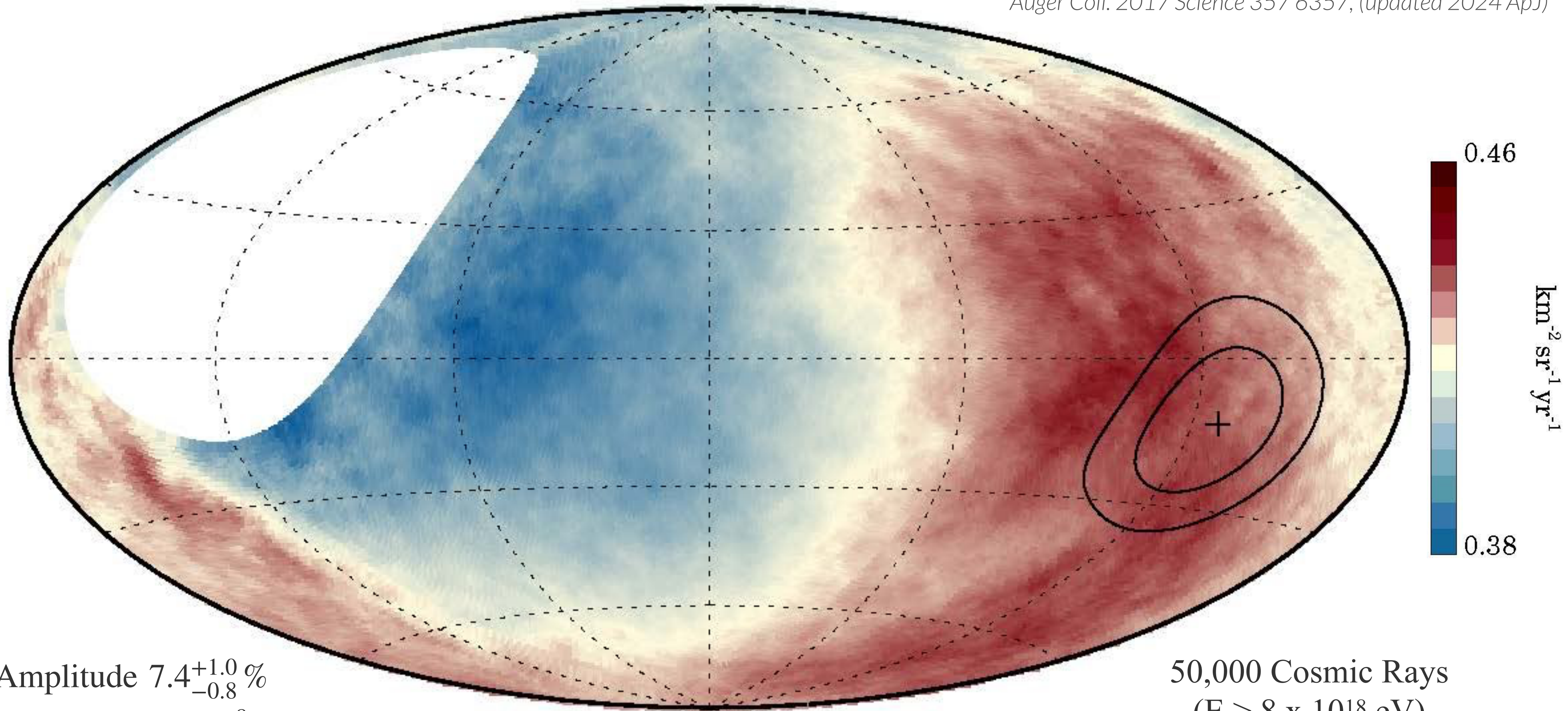


Ultra-high energy cosmic rays



Arrival directions

Auger Coll. 2017 Science 357 6357, (updated 2024 ApJ)

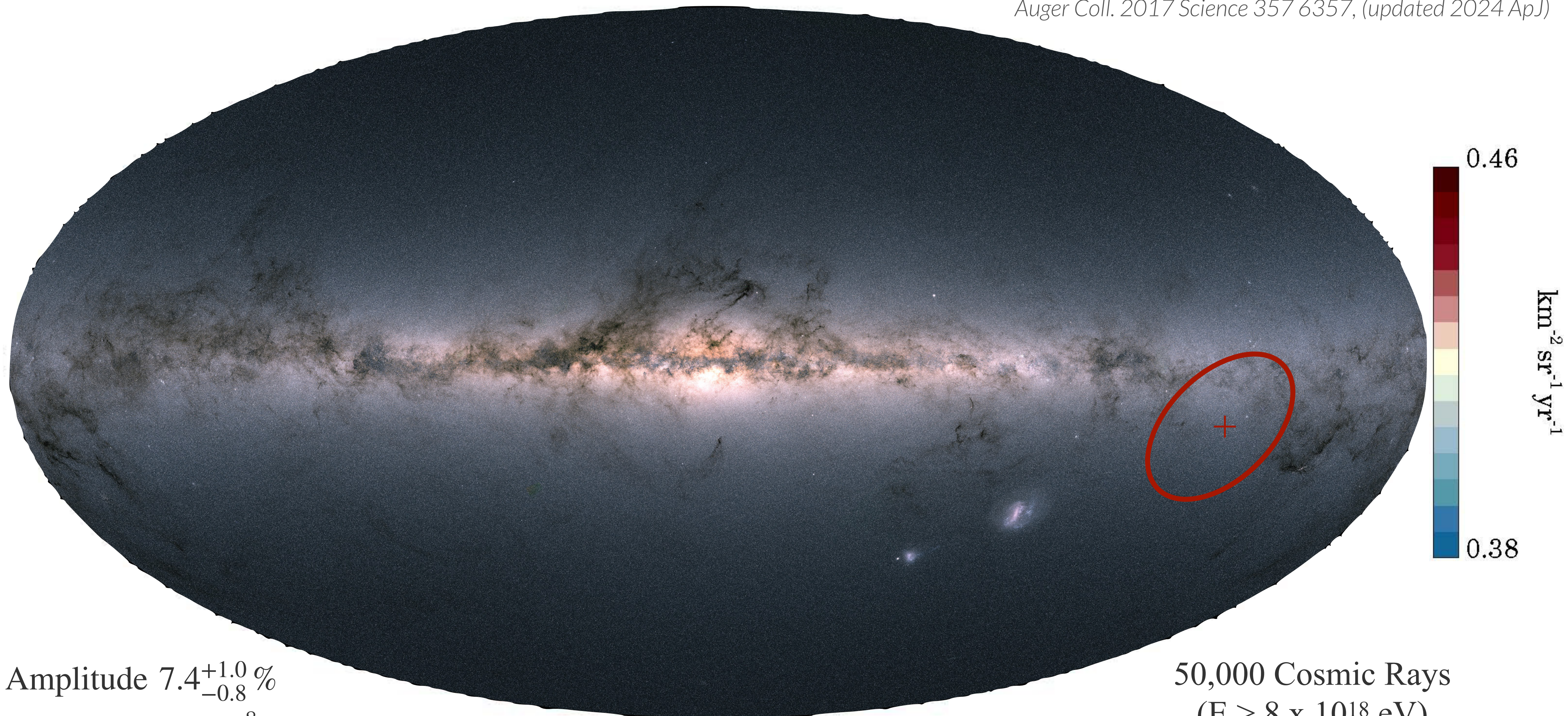


Amplitude $7.4^{+1.0}_{-0.8} \%$
p-val : 2.6×10^{-8} (6.8σ)

50,000 Cosmic Rays
($E > 8 \times 10^{18}$ eV)

Arrival directions

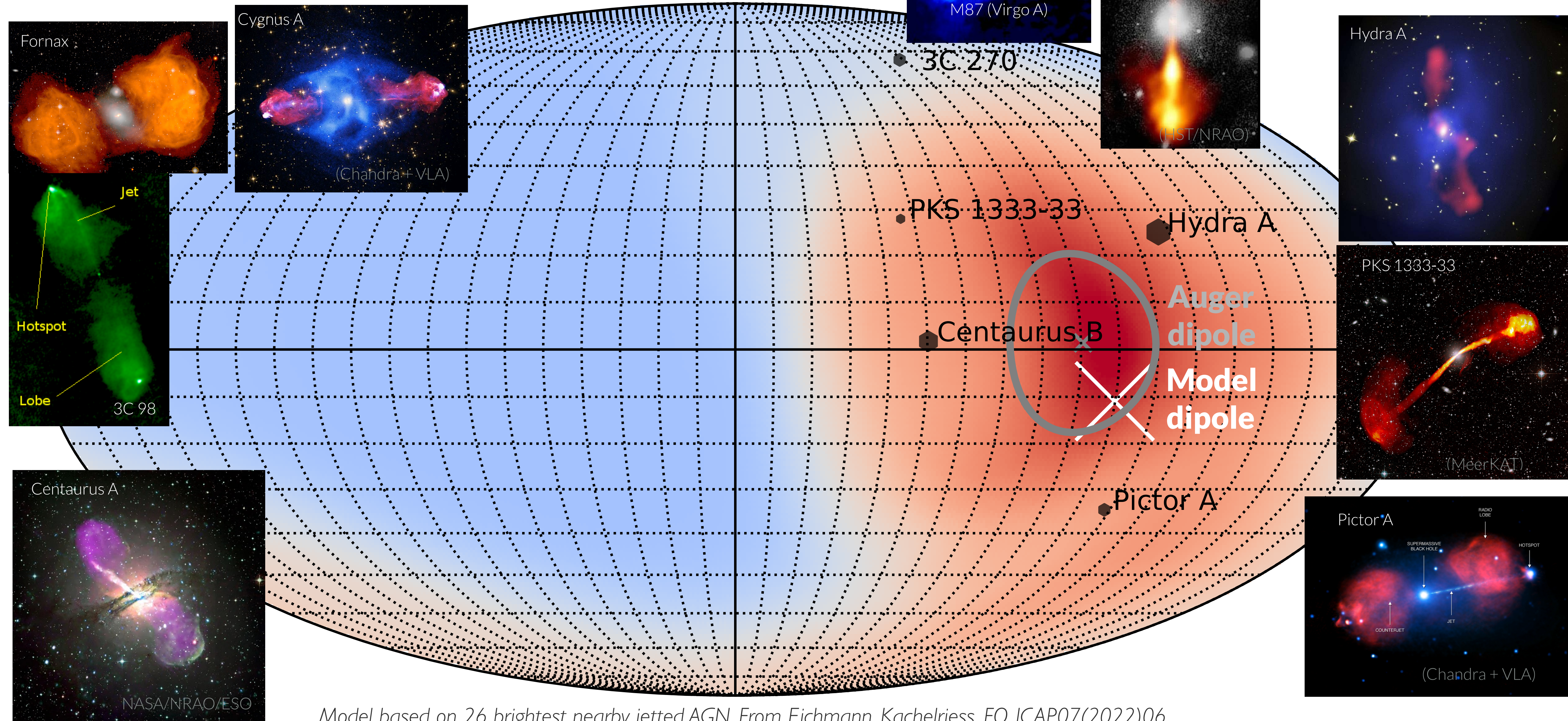
Auger Coll. 2017 Science 357 6357, (updated 2024 ApJ)



Amplitude $7.4^{+1.0}_{-0.8} \%$
p-val : 2.6×10^{-8} (6.8σ)

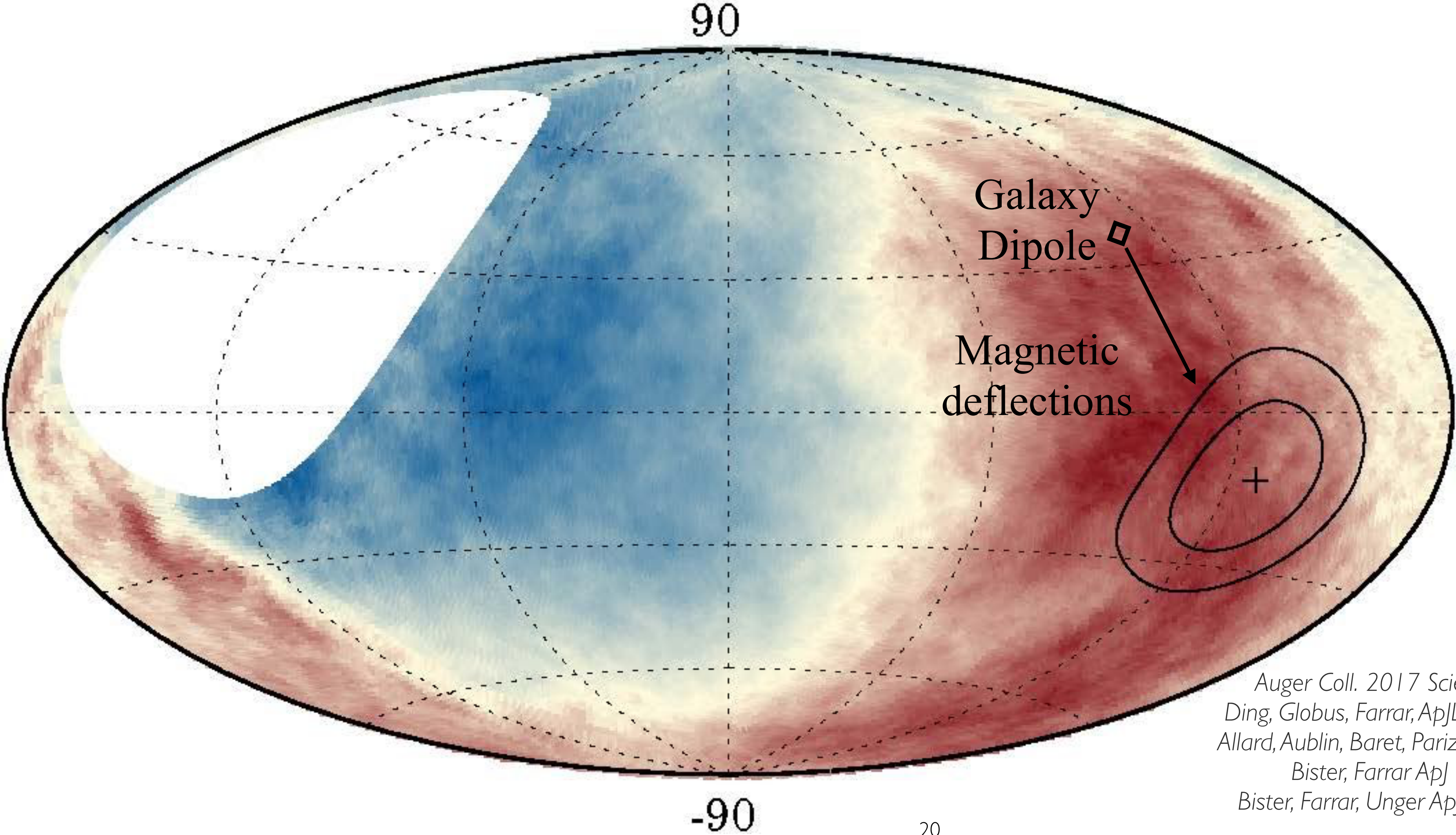
50,000 Cosmic Rays
($E > 8 \times 10^{18} \text{ eV}$)

Arrival directions



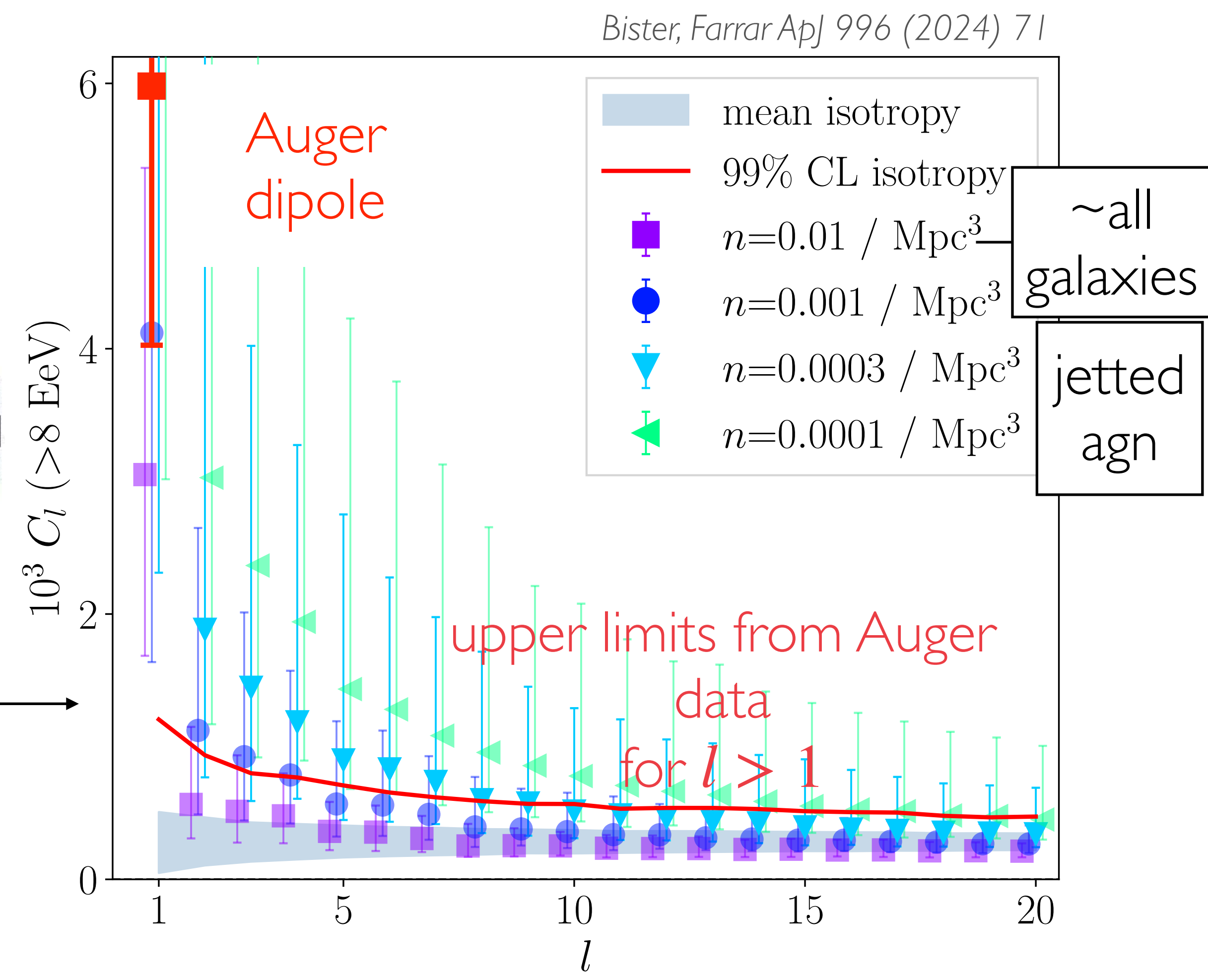
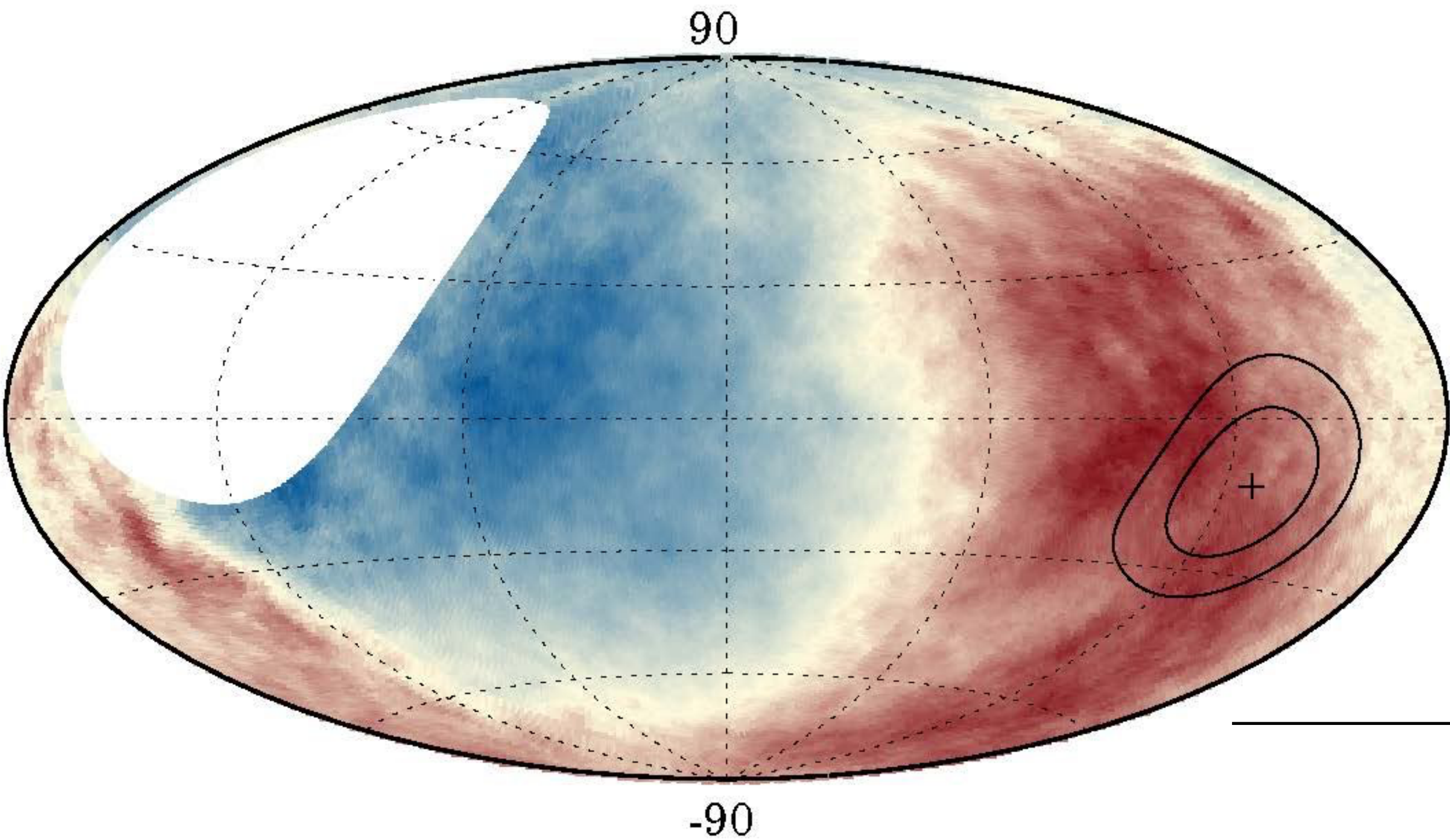
Model based on 26 brightest nearby jetted AGN. From Eichmann, Kachelriess, FO, JCAP07(2022)06
see also Harari et al 2016, Mollerach et al 2019, Mollerach & Roulet 2022, Bister (arXiv:2509.06594)

Arrival directions

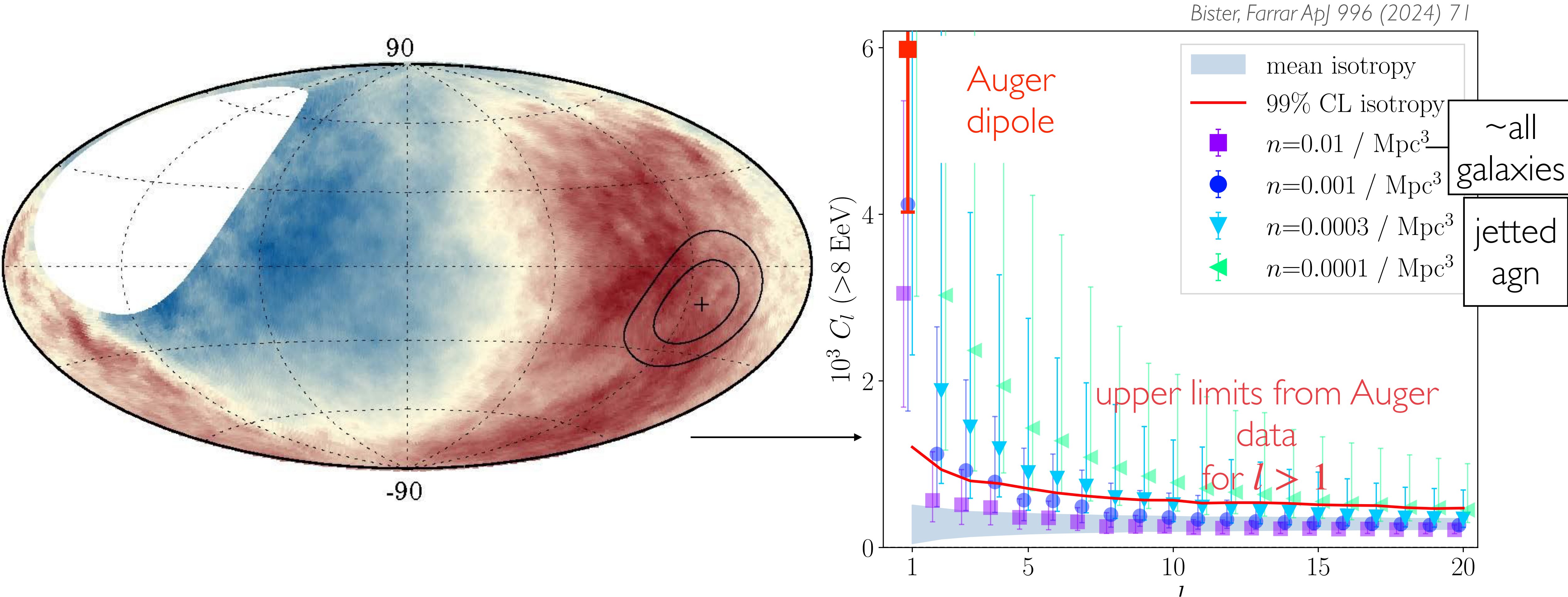


Auger Coll. 2017 Science 357 6357
Ding, Globus, Farrar, ApJL 913 (2021) 1
Allard, Aublin, Baret, Parizot, A&A (2022)
Bister, Farrar ApJ 996 (2024) 71
Bister, Farrar, Unger ApJ 975 (2024) 1

Arrival directions

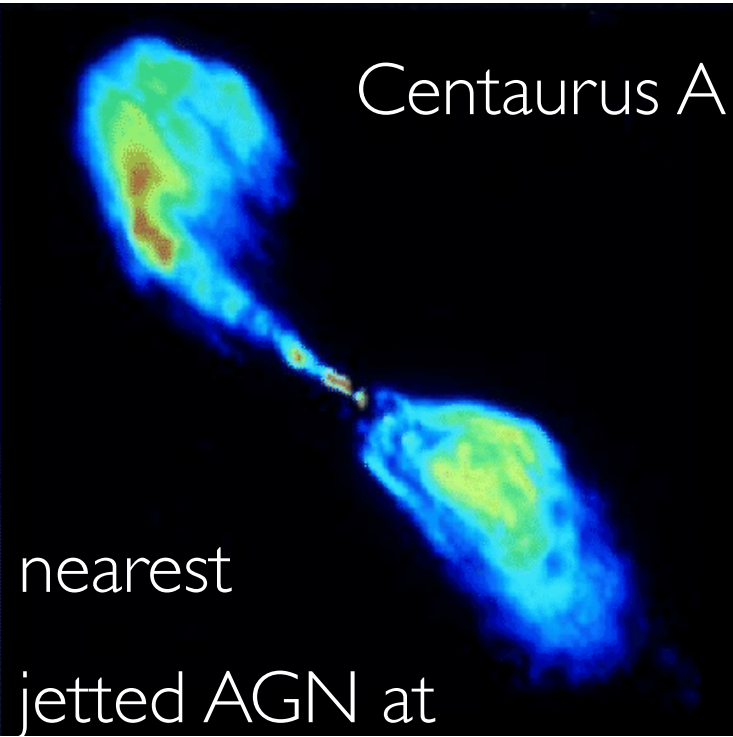
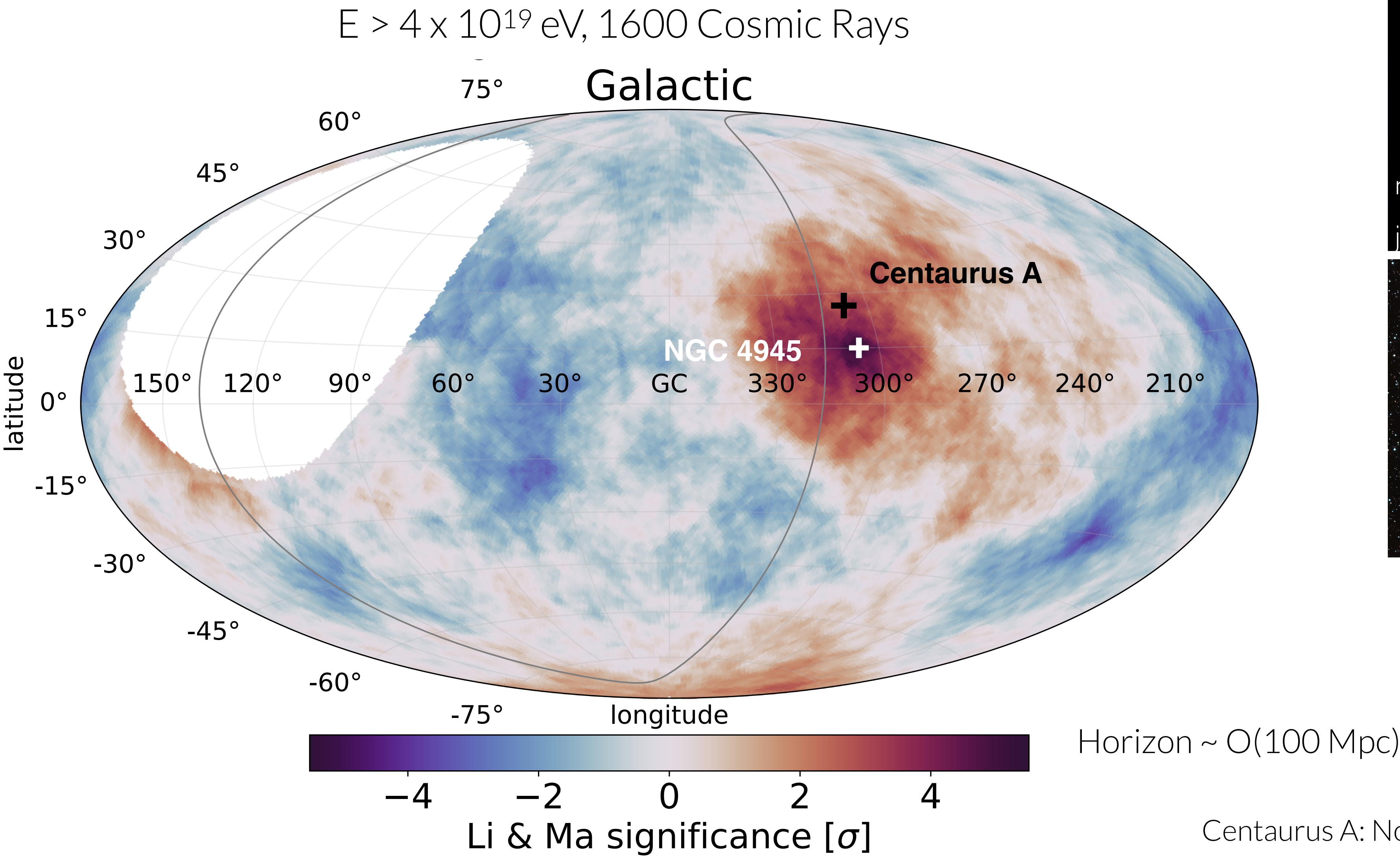


Arrival directions



Conclusion #1: UHECR sources are numerous

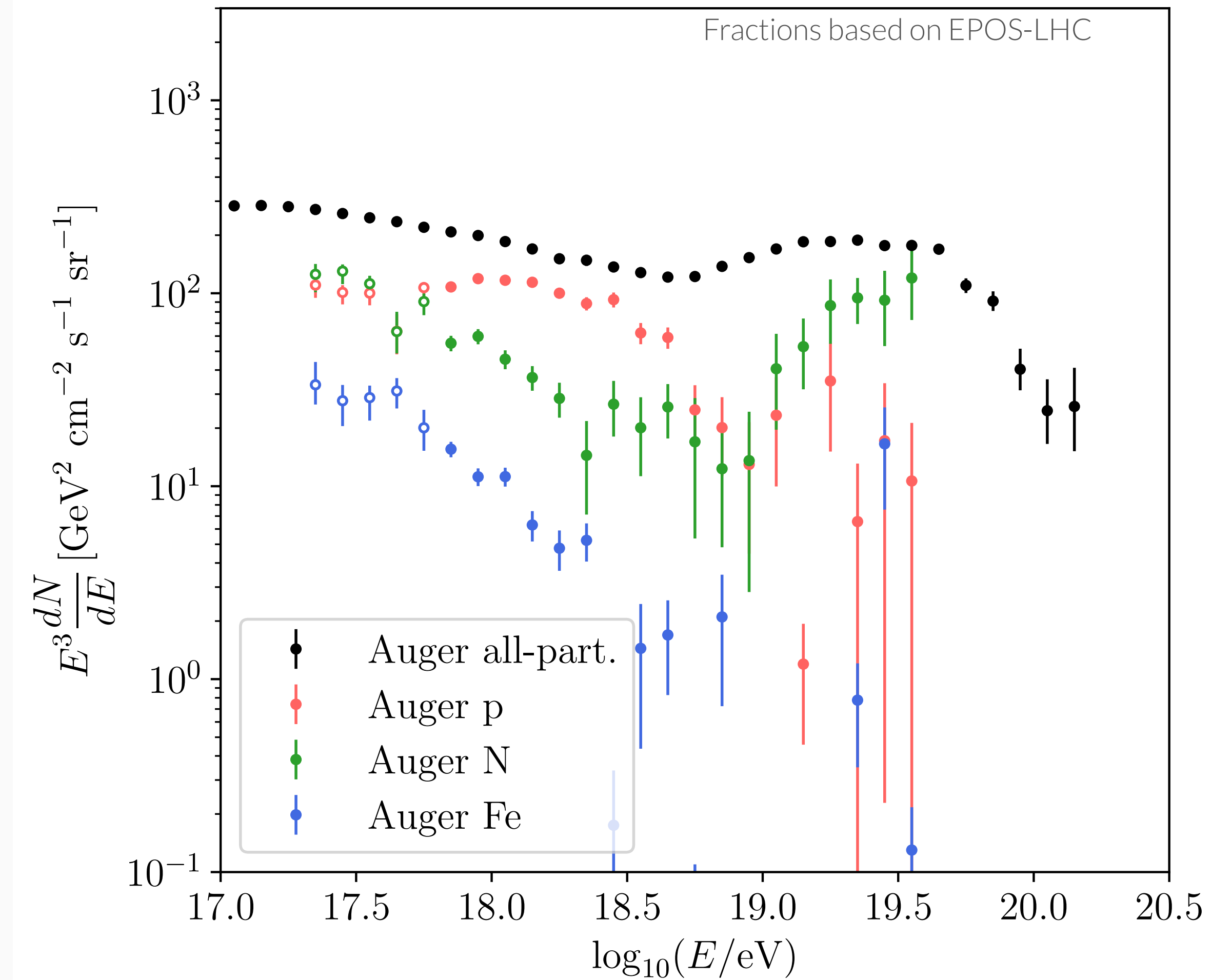
Arrival directions above 4×10^{19} eV



Centaurus A: Nobs = 215, Nexp=152
angular radius: 27deg
post-trial significance: 3.9σ

Spectrum and Composition Observables

Auger Measurements

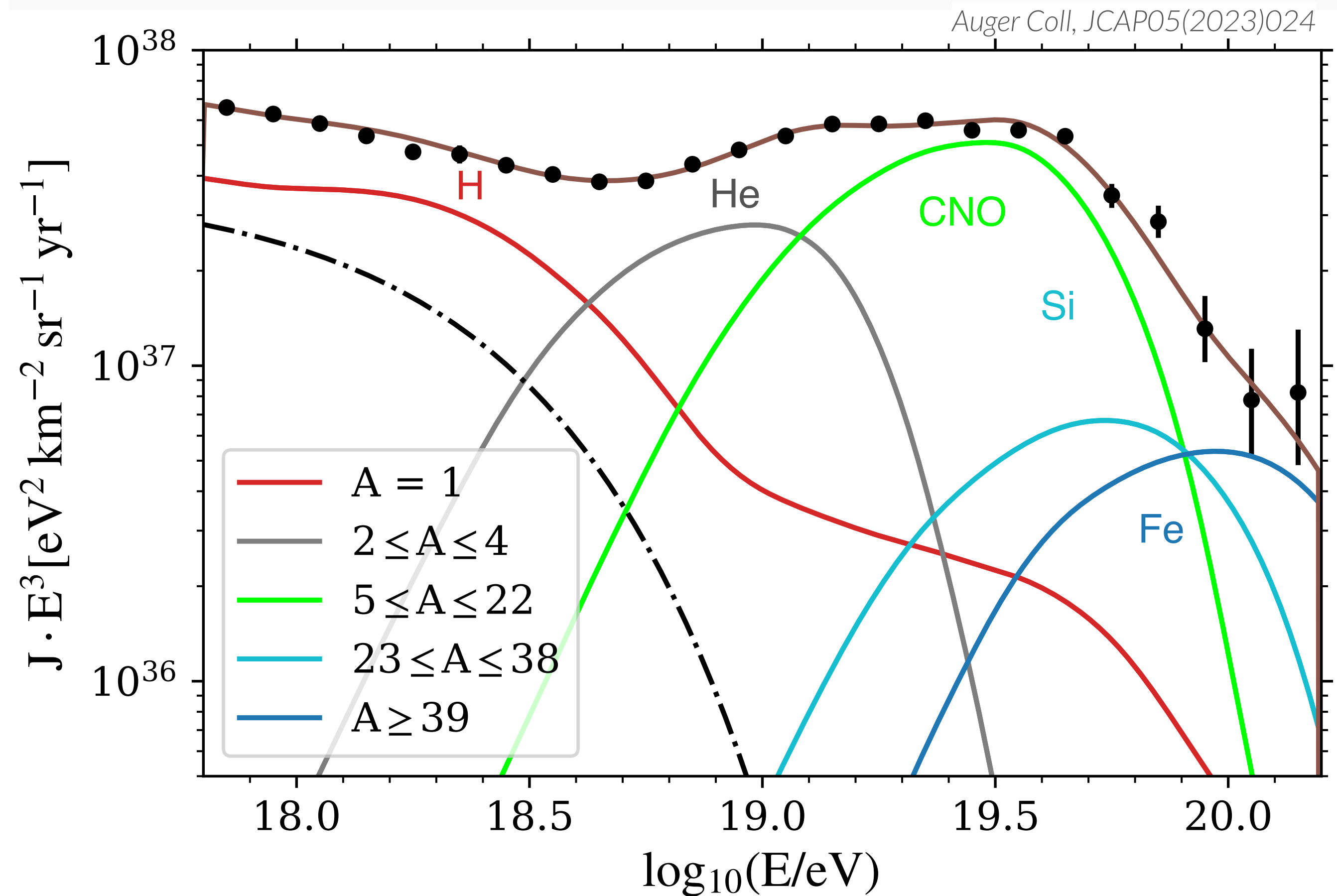


Auger Coll, PRL, 125, 121106, 2020

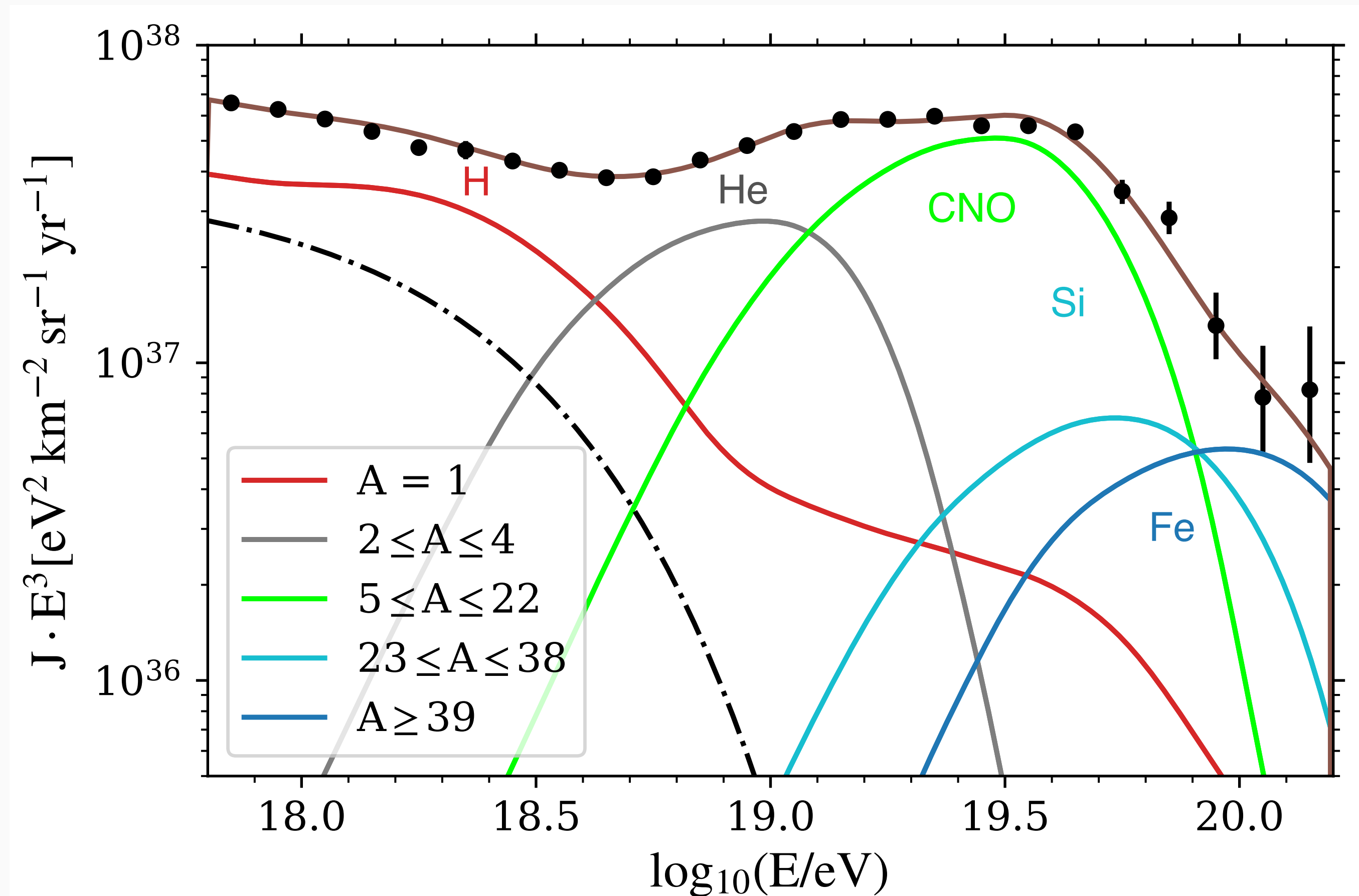
Tkachenko for Auger Coll, PoS(ICRC2023)438

Auger Coll, PRL, 134, 021001, 2024

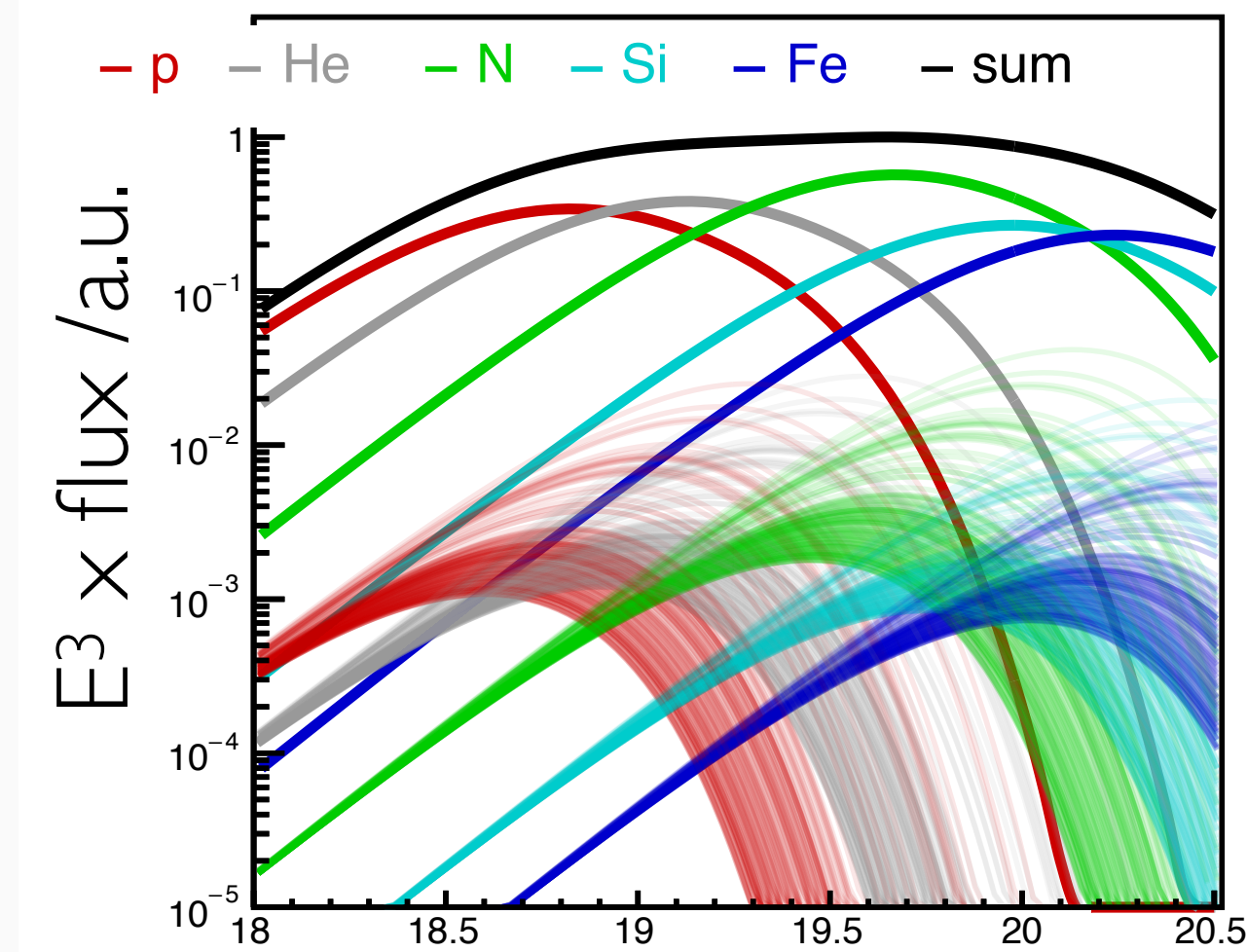
Example Fit



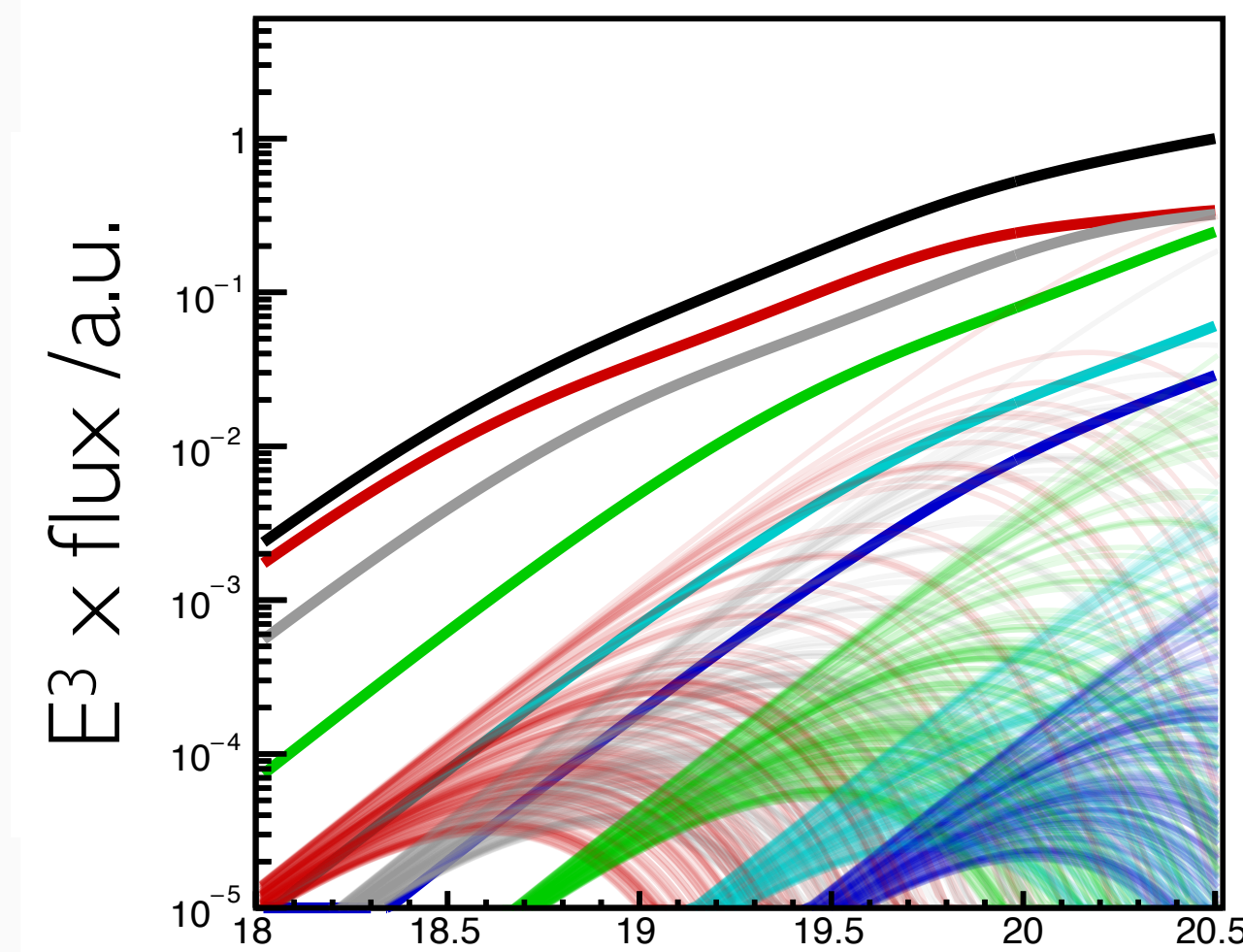
From identical sources to a population



D. Ehlert, FO, M. Unger, PRD 107 (2023) 10



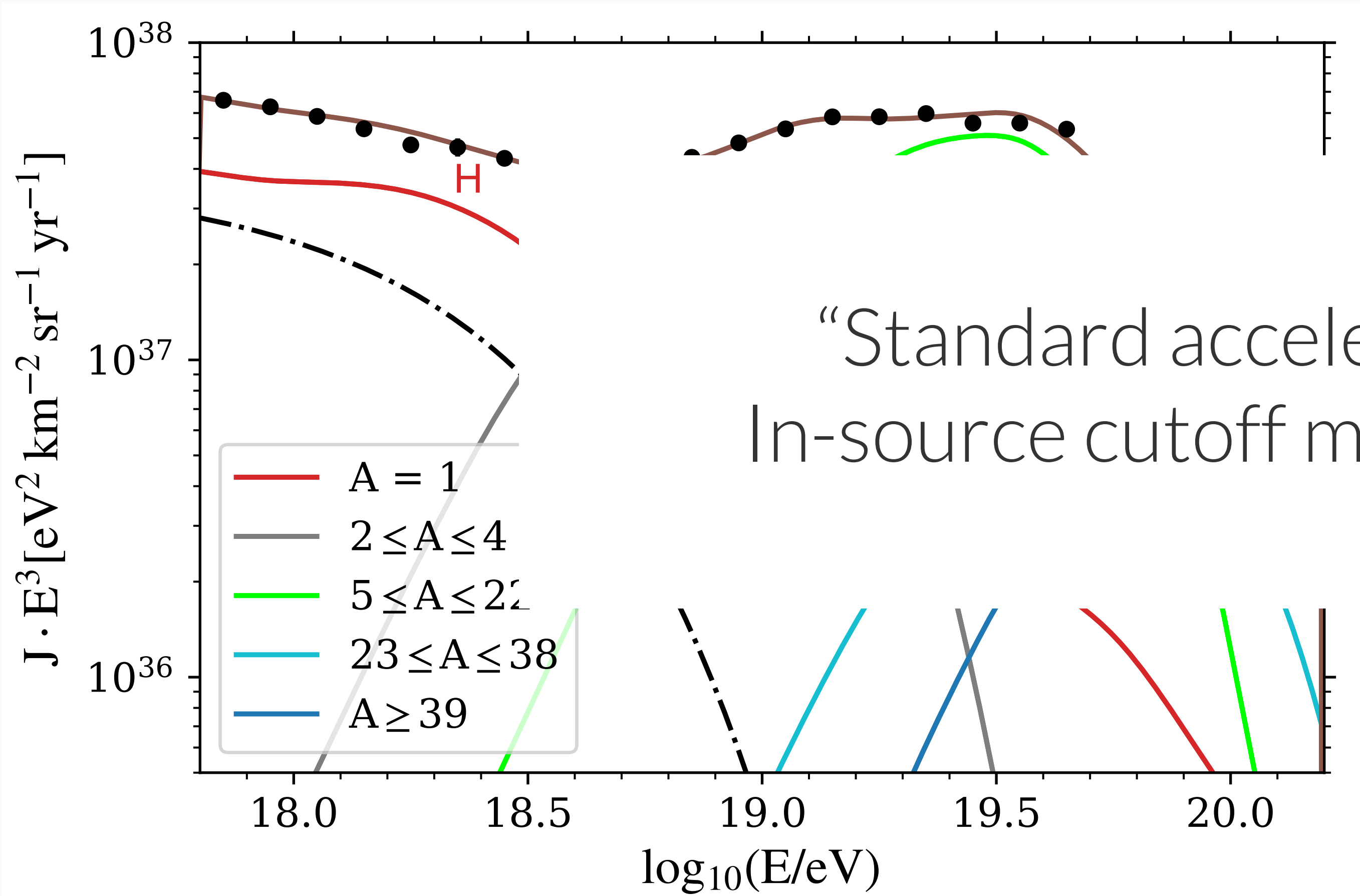
Near-identical sources



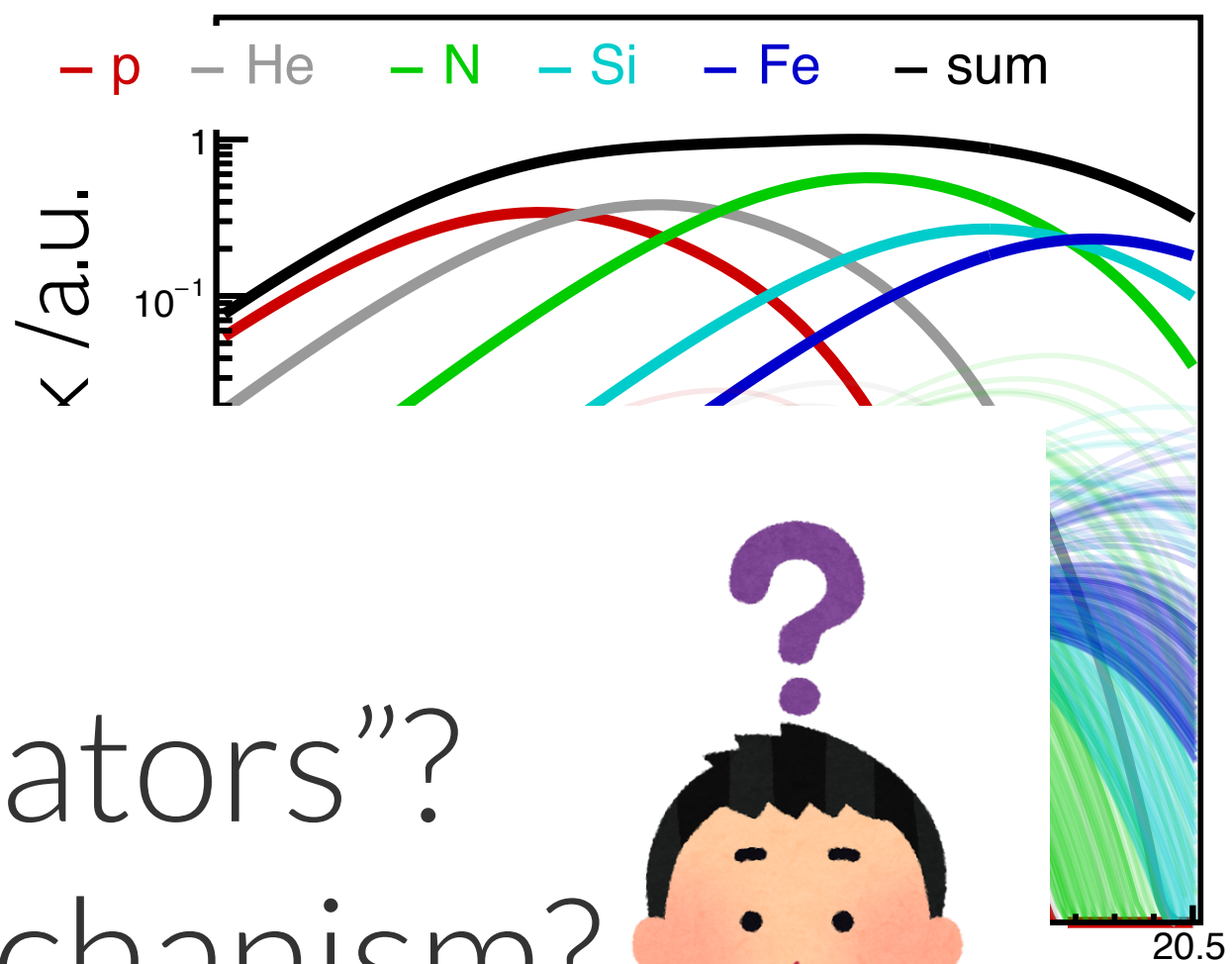
Non-identical sources

From identical sources to a population

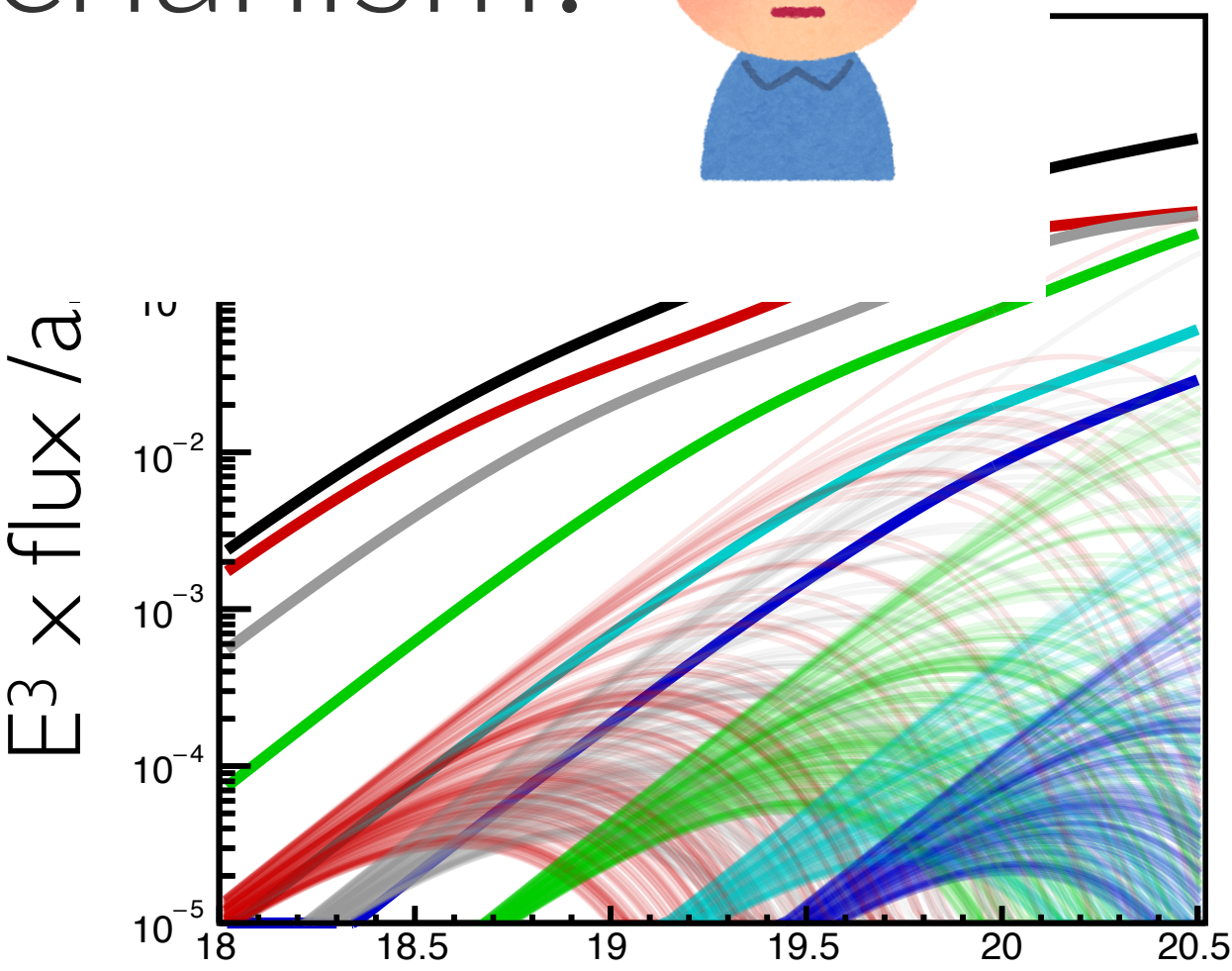
D. Ehlert, FO, M. Unger, PRD 107 (2023) 10



“Standard accelerators”?
In-source cutoff mechanism?



Near-identical sources



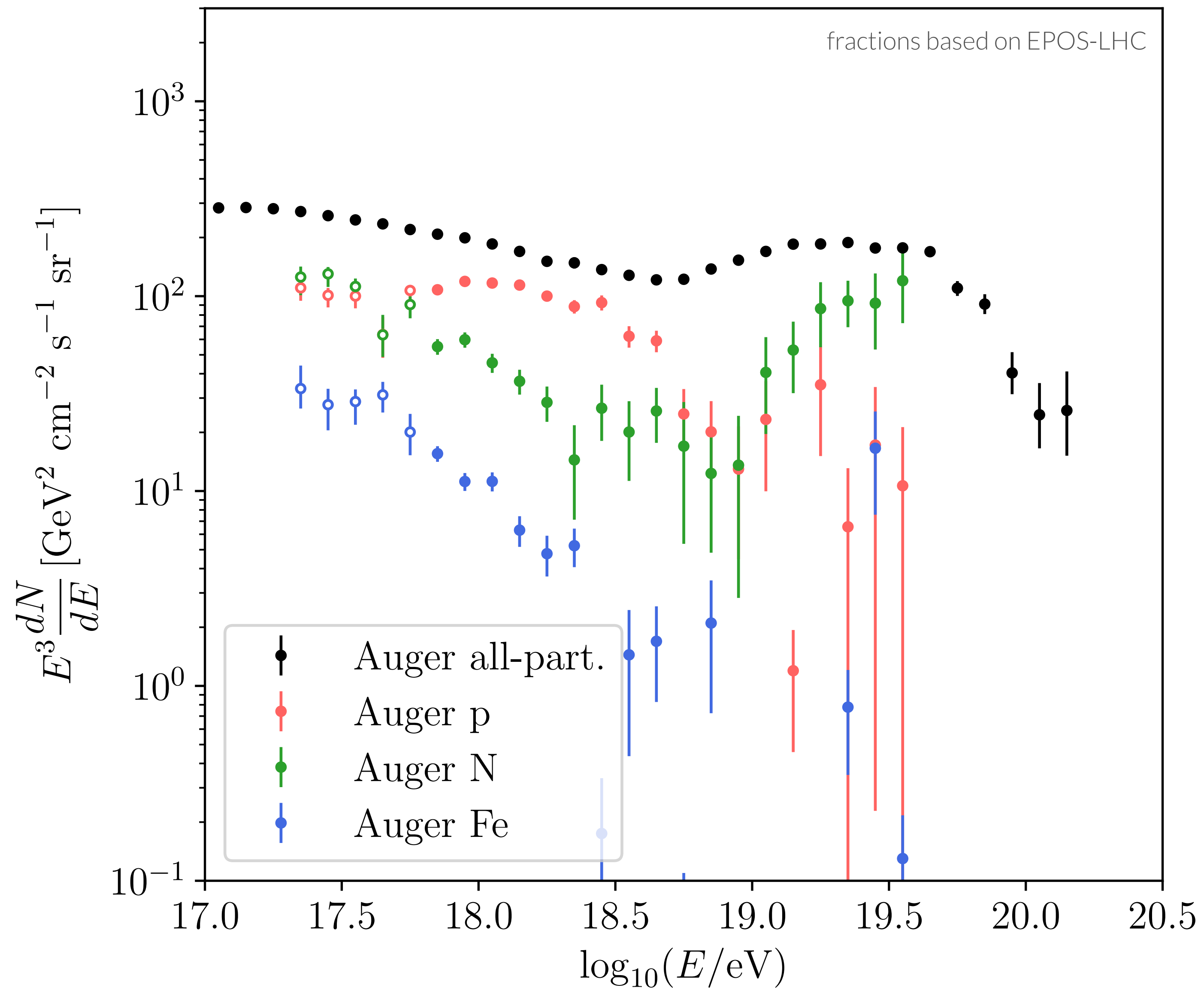
Non-identical sources

UHECR composition

Auger Coll, PRL, 125, 121106, 2020

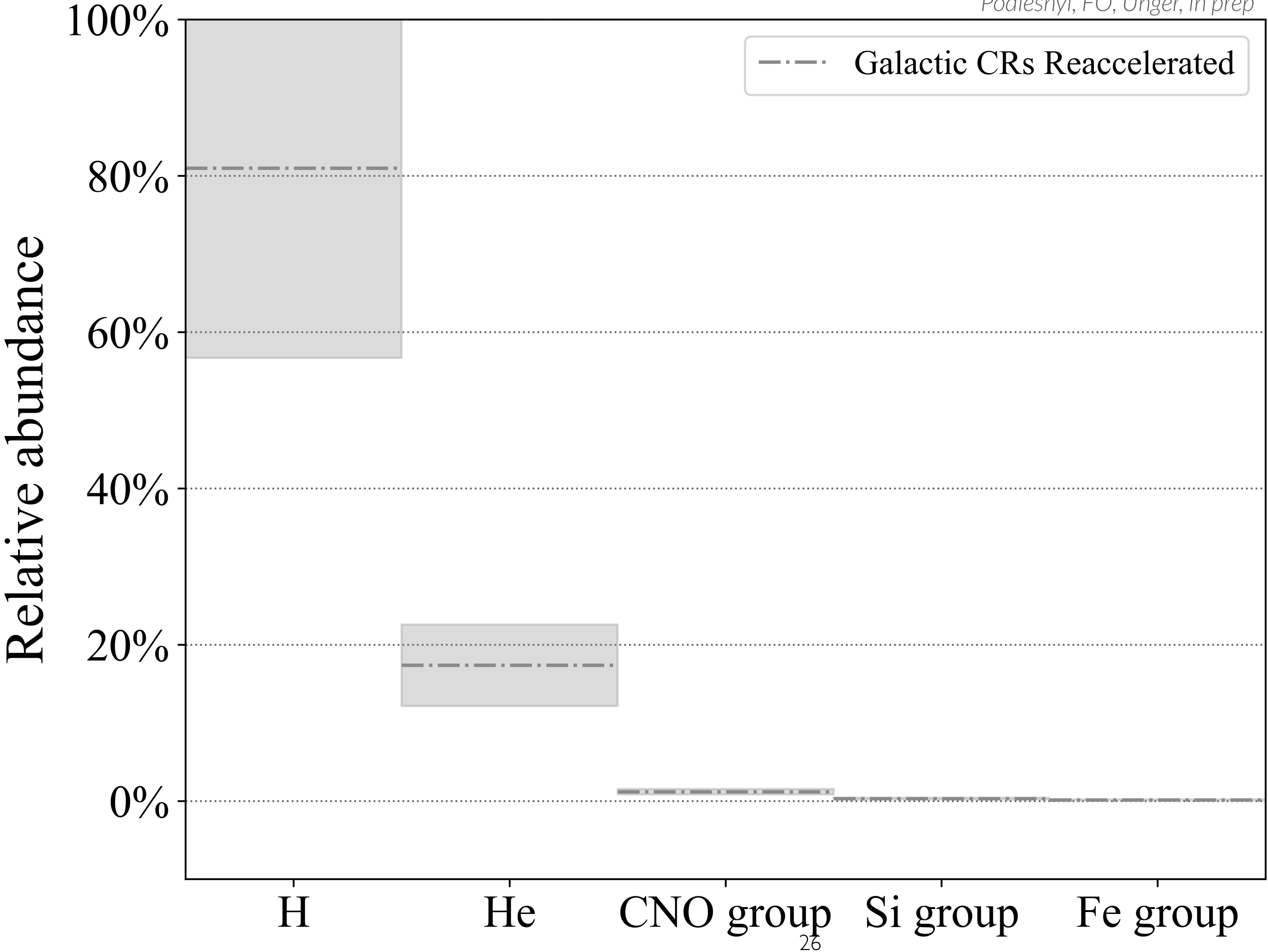
Tkachenko for Auger Coll, PoS(ICRC2023)438

Auger Coll, PRL, 134, 021001, 2024



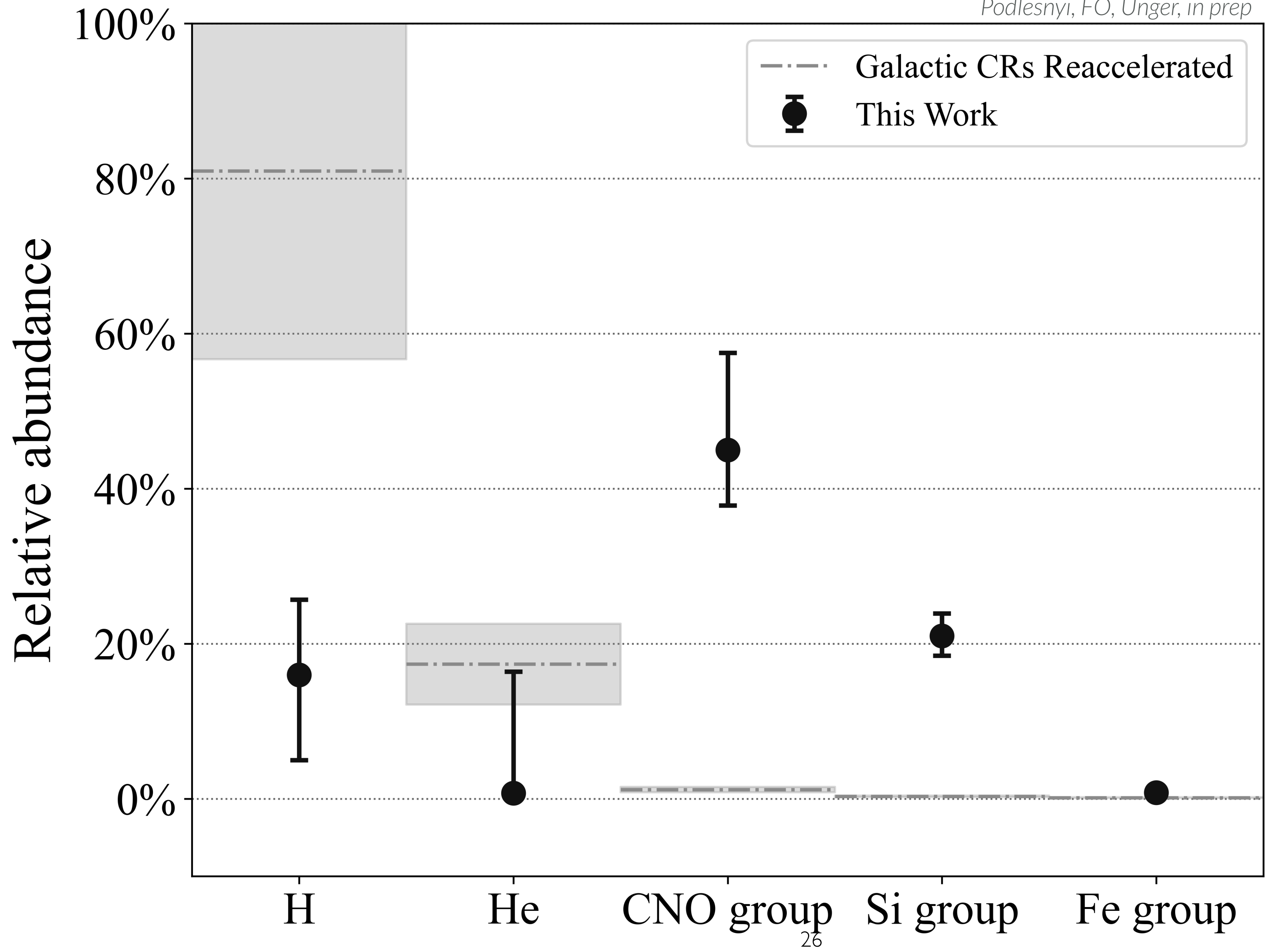
A Curious Composition

Podlesnyi, FO, Unger, in prep



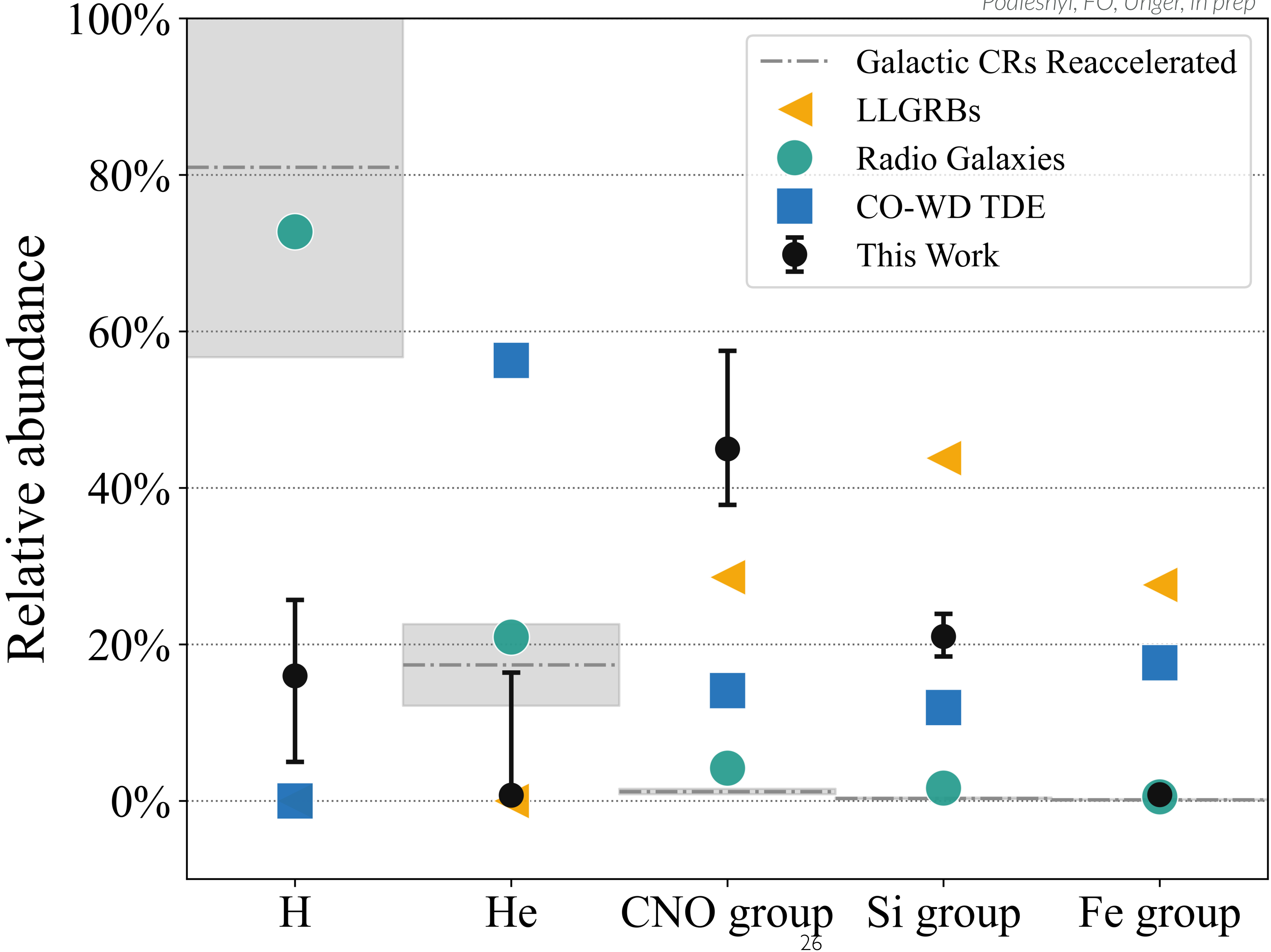
A Curious Composition

Podlesnyi, FO, Unger, in prep



A Curious Composition

Podlesnyi, FO, Unger, in prep

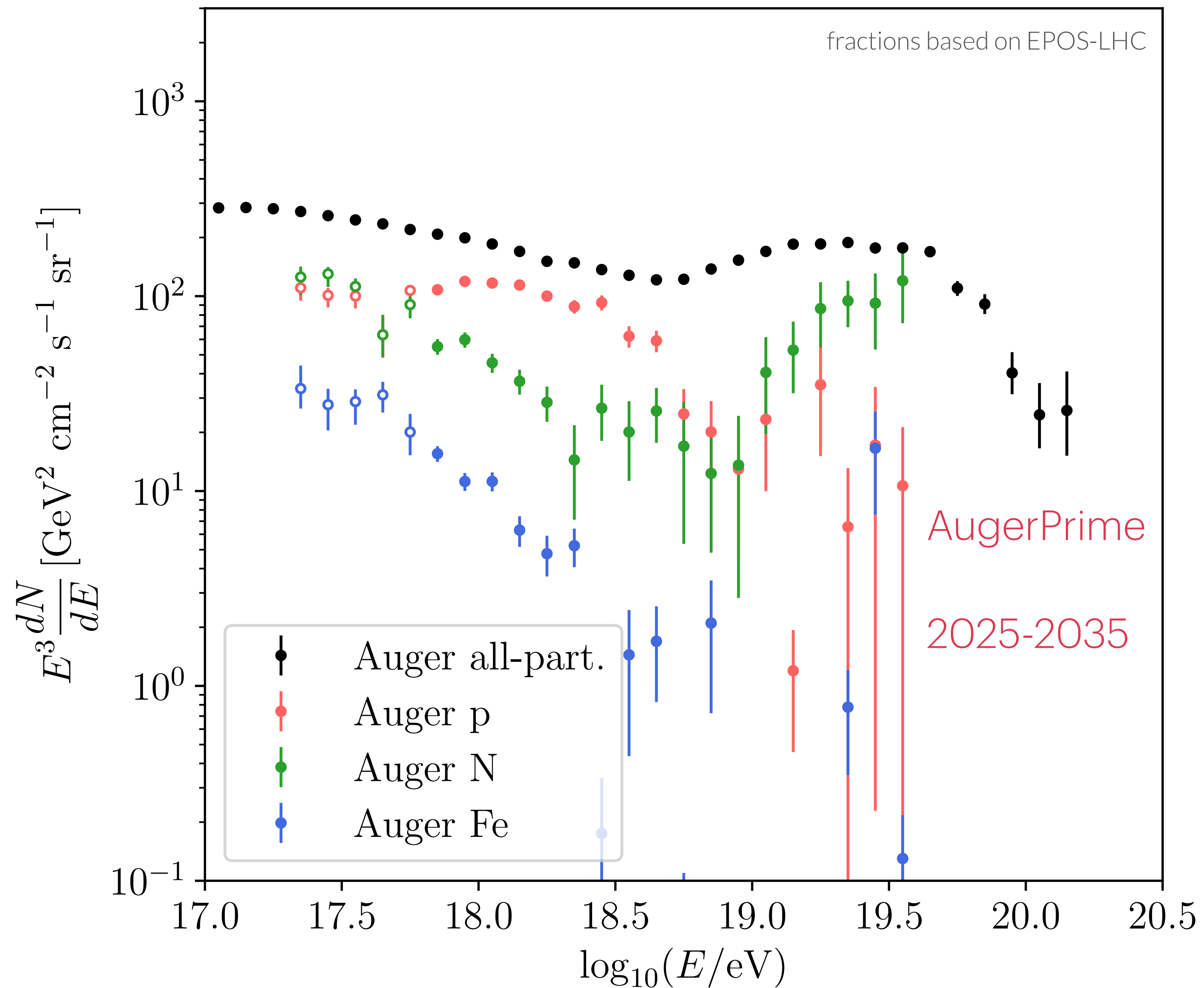


UHECR composition

Auger Coll, PRL, 125, 121106, 2020

Tkachenko for Auger Coll, PoS(ICRC2023)438

Auger Coll, PRL, 134, 021001, 2024



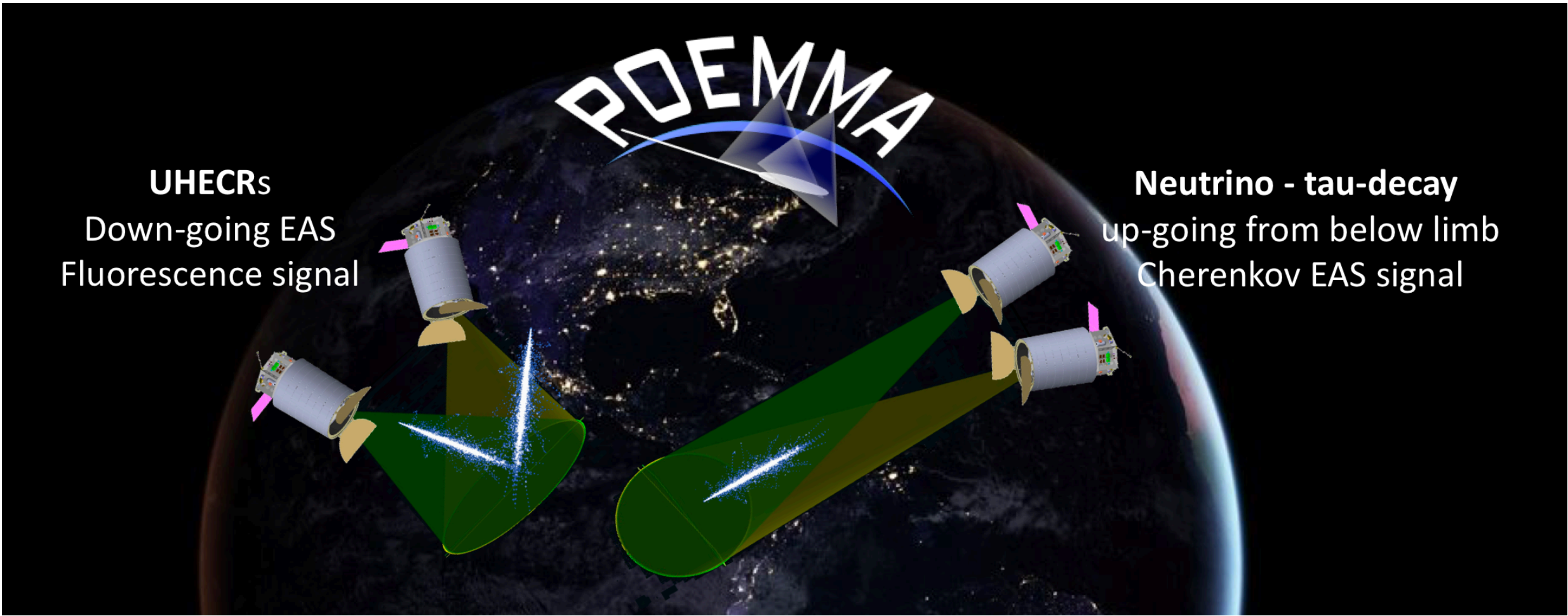
The future

GROUND BASED

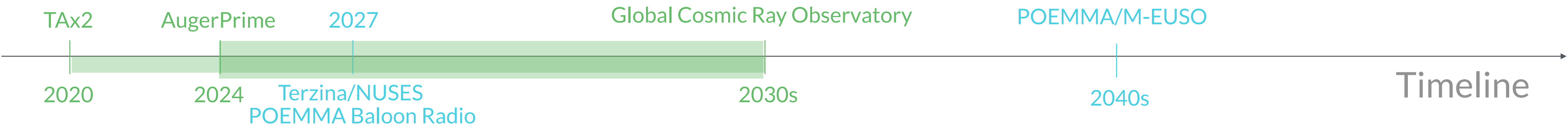


Strawman design <https://arxiv.org/abs/2502.05657>

SPACE BASED



<https://arxiv.org/abs/2012.07945>



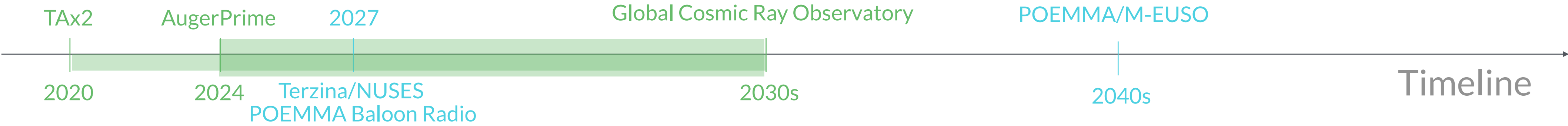
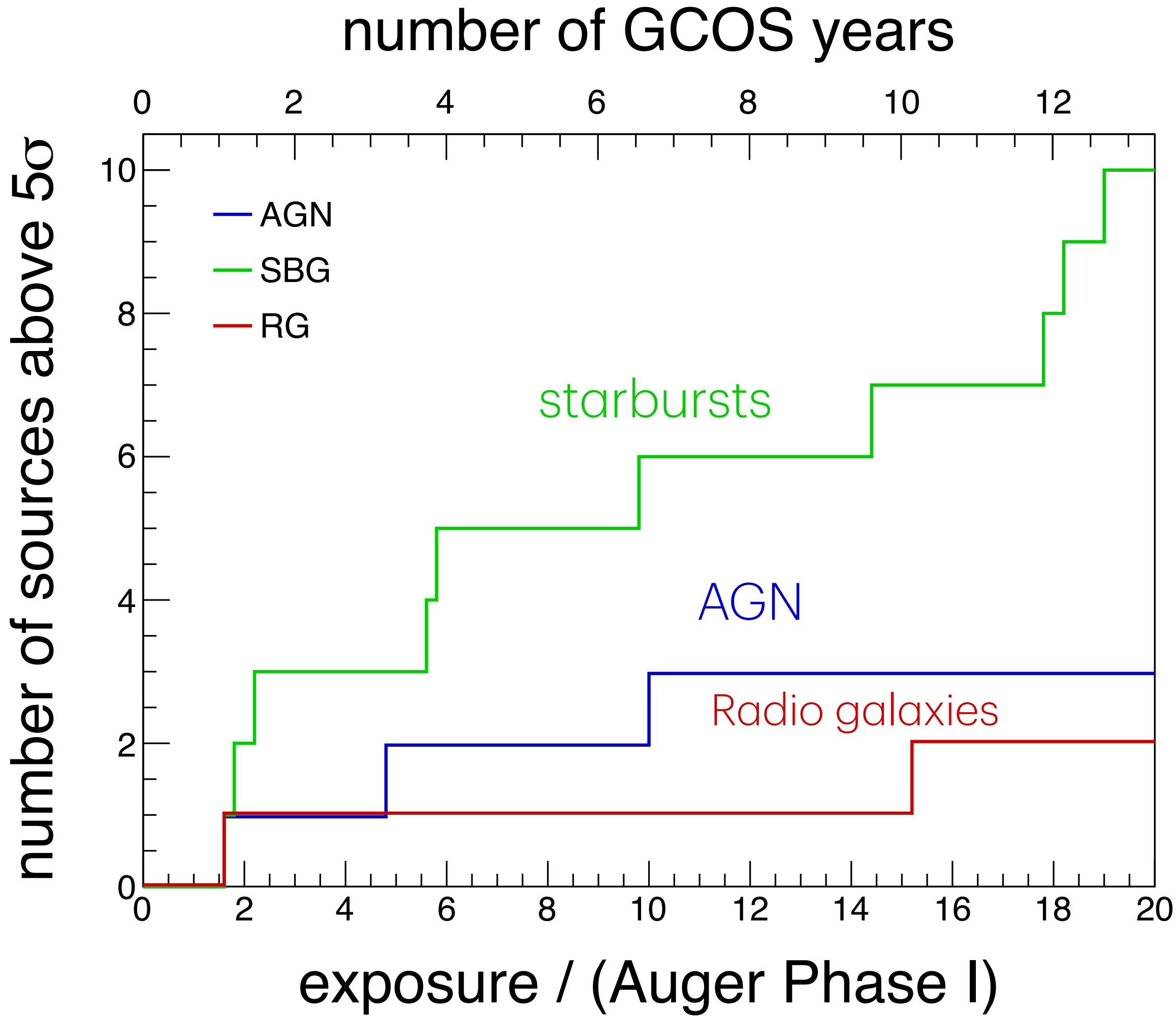
The future

GROUND BASED



Strawman design <https://arxiv.org/abs/2502.05657>

number of sources above 5σ



Summary

Galactic cosmic rays

New insights from γ -rays!

Wind bubbles? Stellar clusters? Microquasars?

Component B

Must be extragalactic

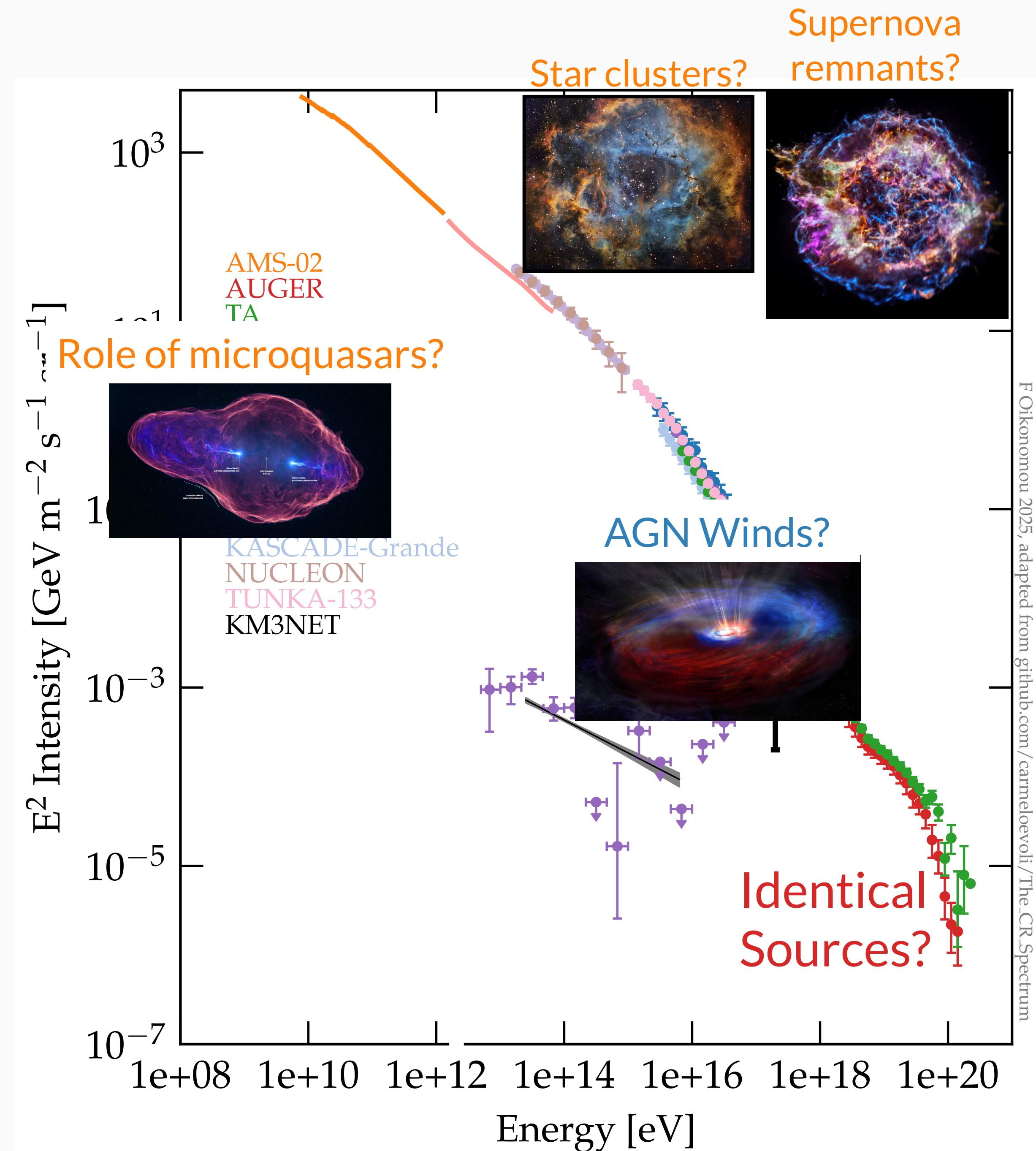
Neutrinos - probes of Extra-galactic Component B

AGN / Supernovae / Starburst Galaxies main options

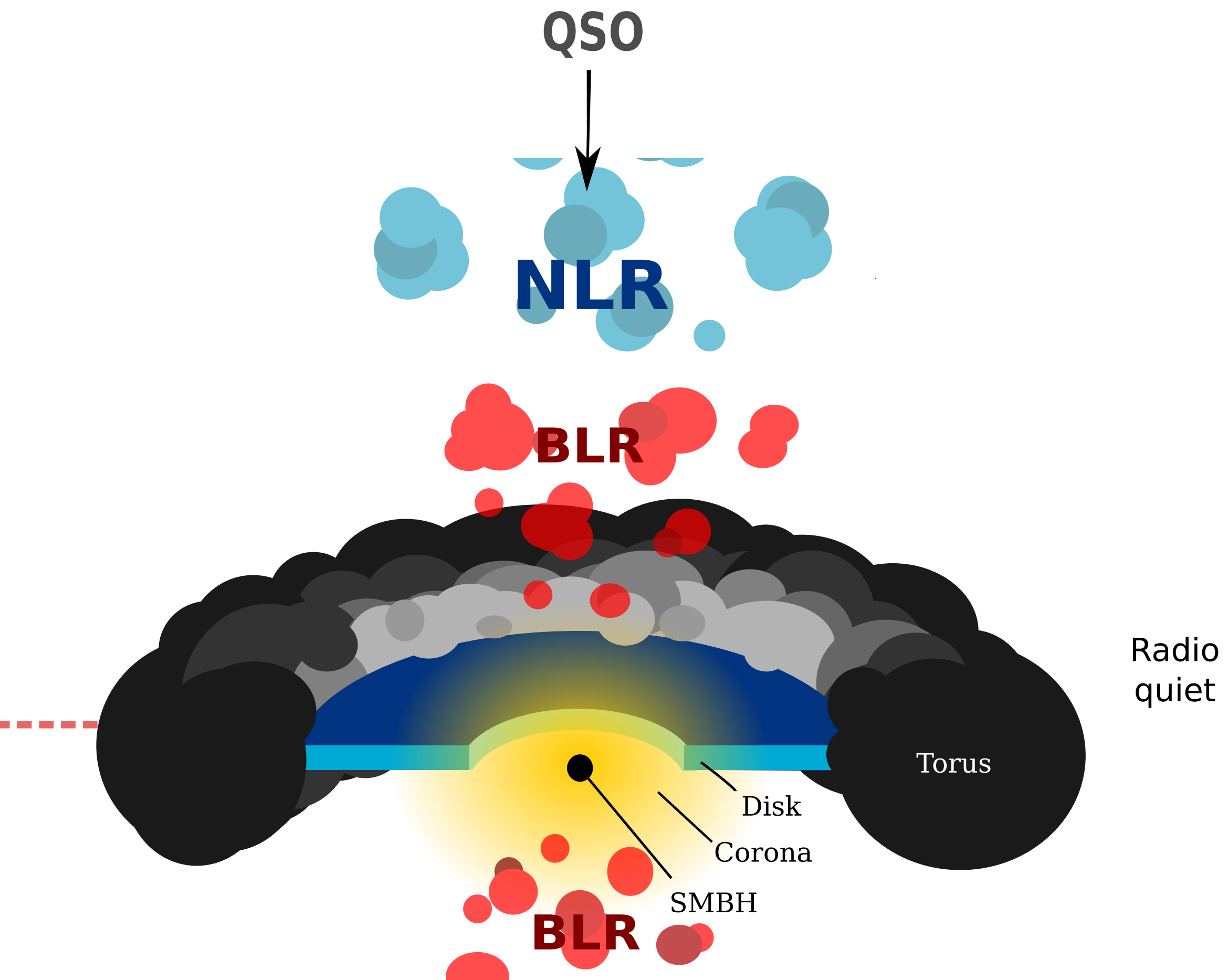
New Puzzles at the highest energies

Sources appear to be numerous but near-identical?

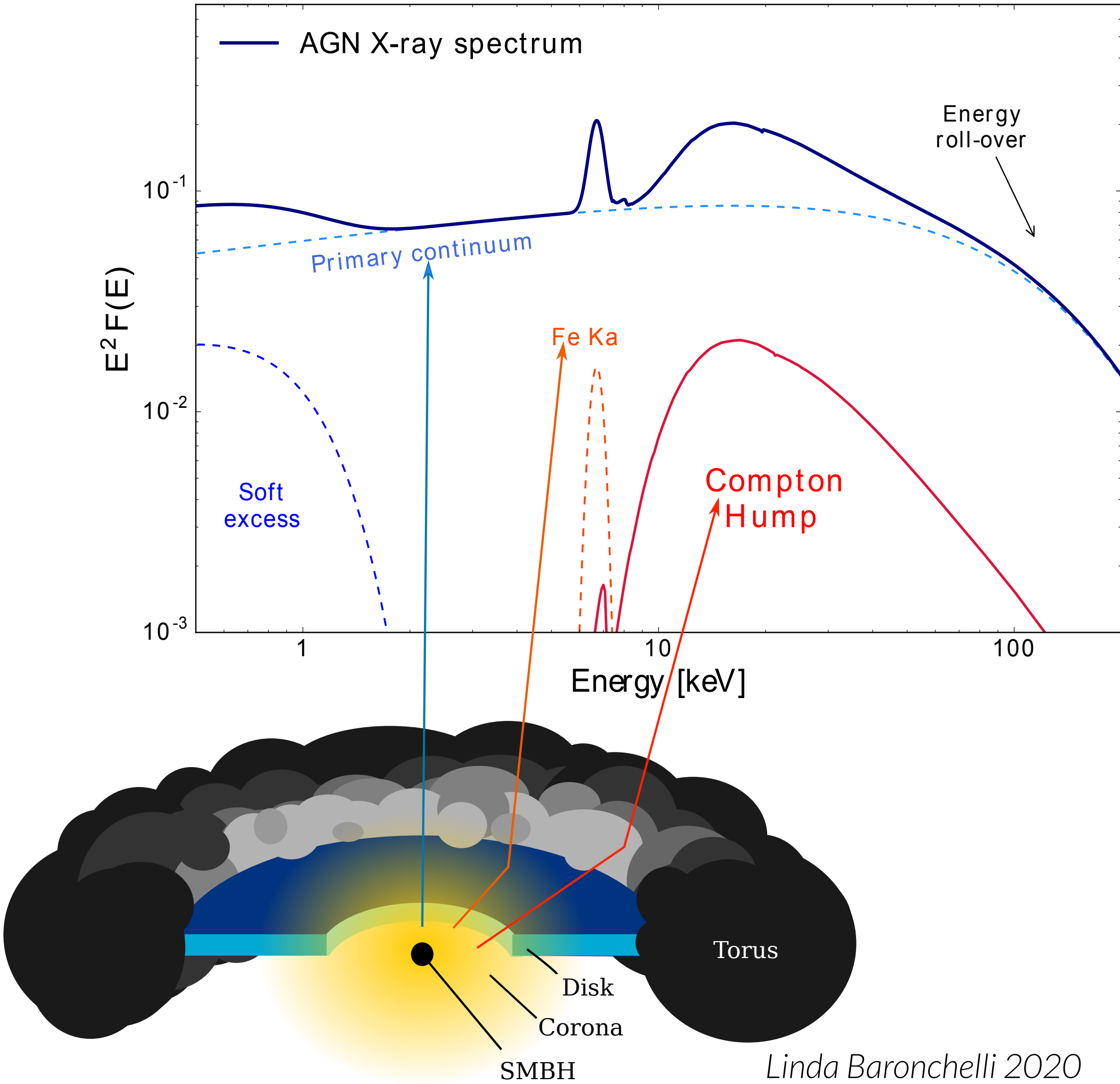
Curious Composition?



Wind bubbles in Active Galactic Nuclei

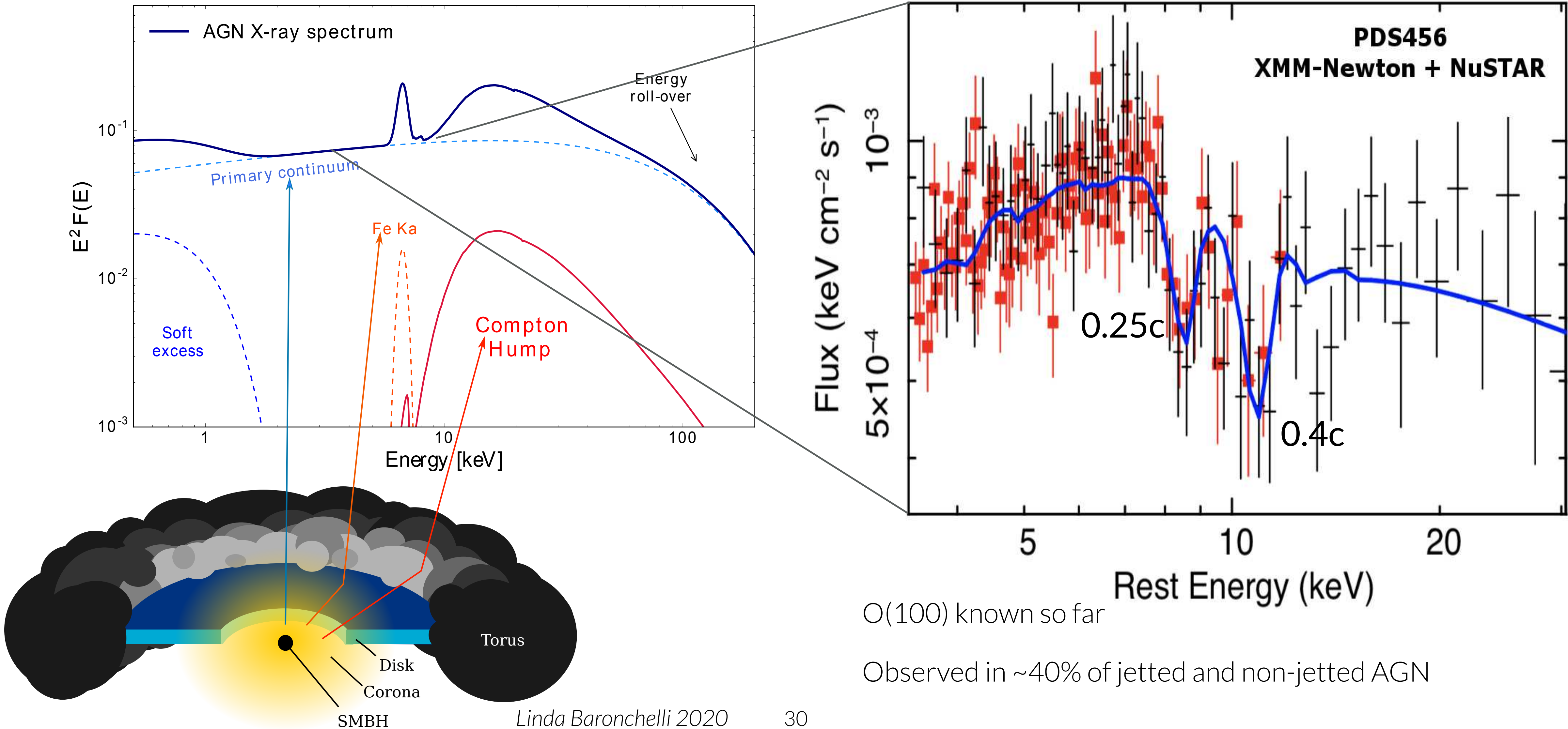


Wind bubbles in Active Galactic Nuclei



Wind bubbles in Active Galactic Nuclei

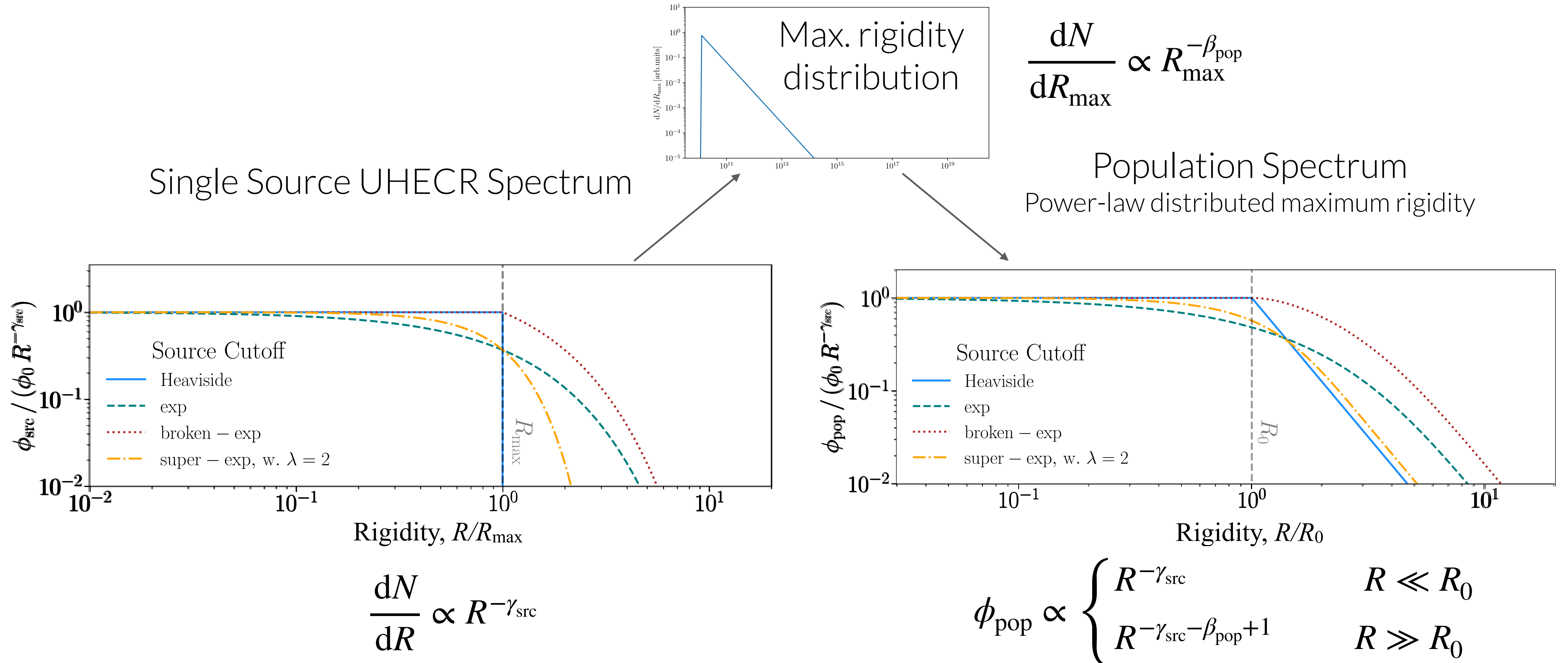
Nardini et al 2015



O(100) known so far

Observed in ~40% of jetted and non-jetted AGN

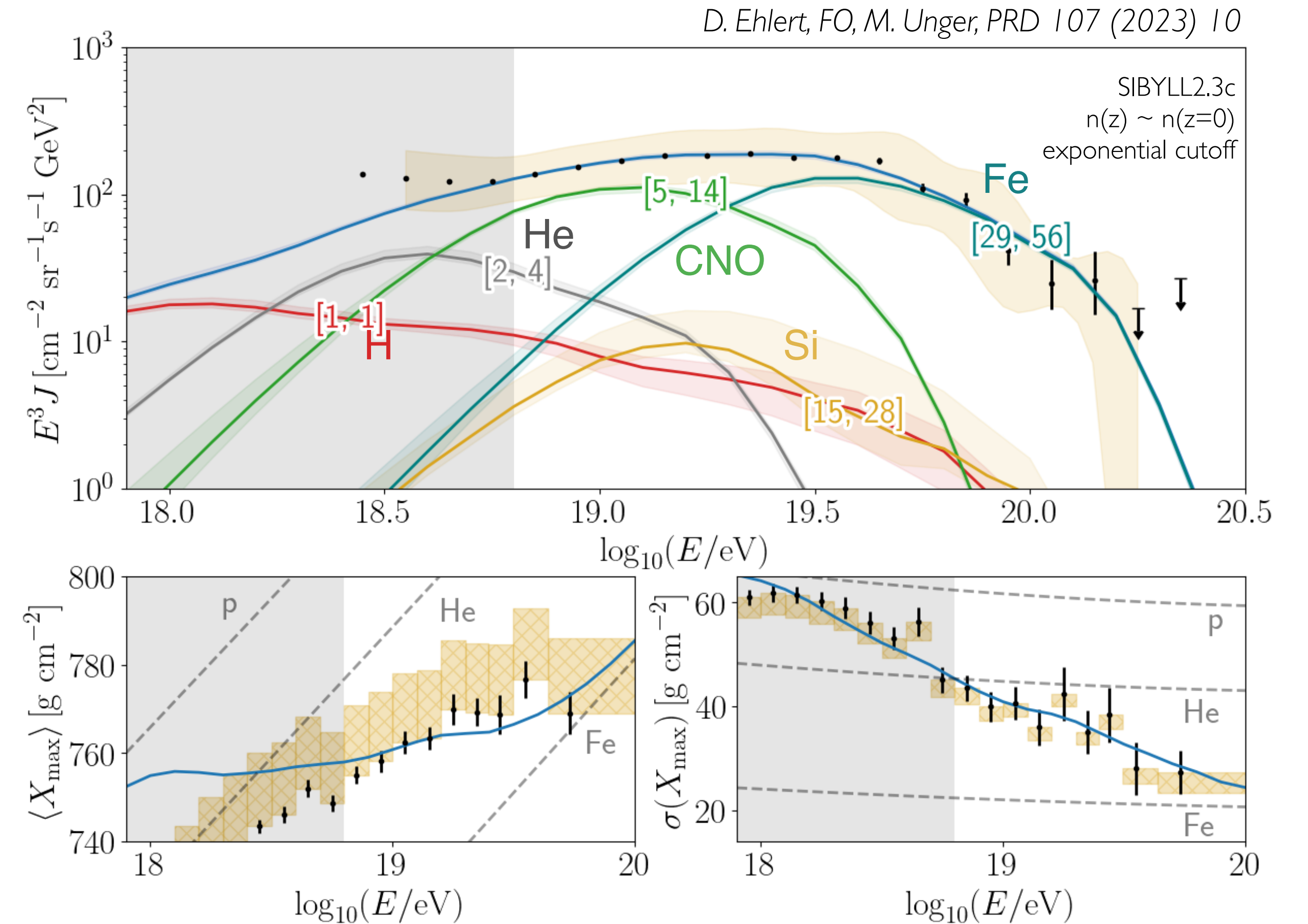
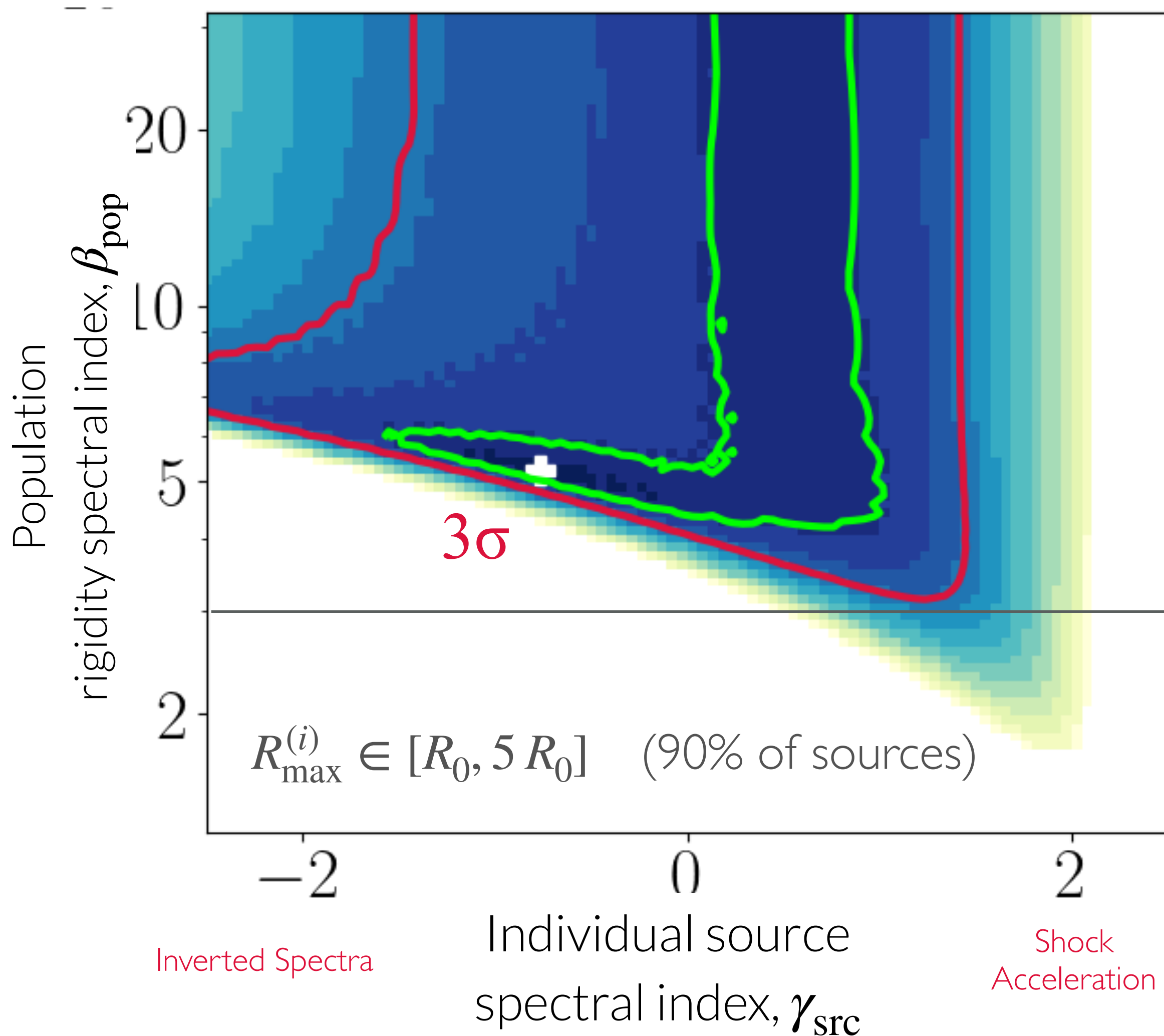
From identical sources to a population



Broken exponential, e.g. Auger Combined Fit (Aab et al 2017)

Super exponential in case of DSA with synchrotron losses with $dN/dR \propto \exp - R^\lambda, \lambda = 2$ e.g. Zirakasvili & Aharonian 2007

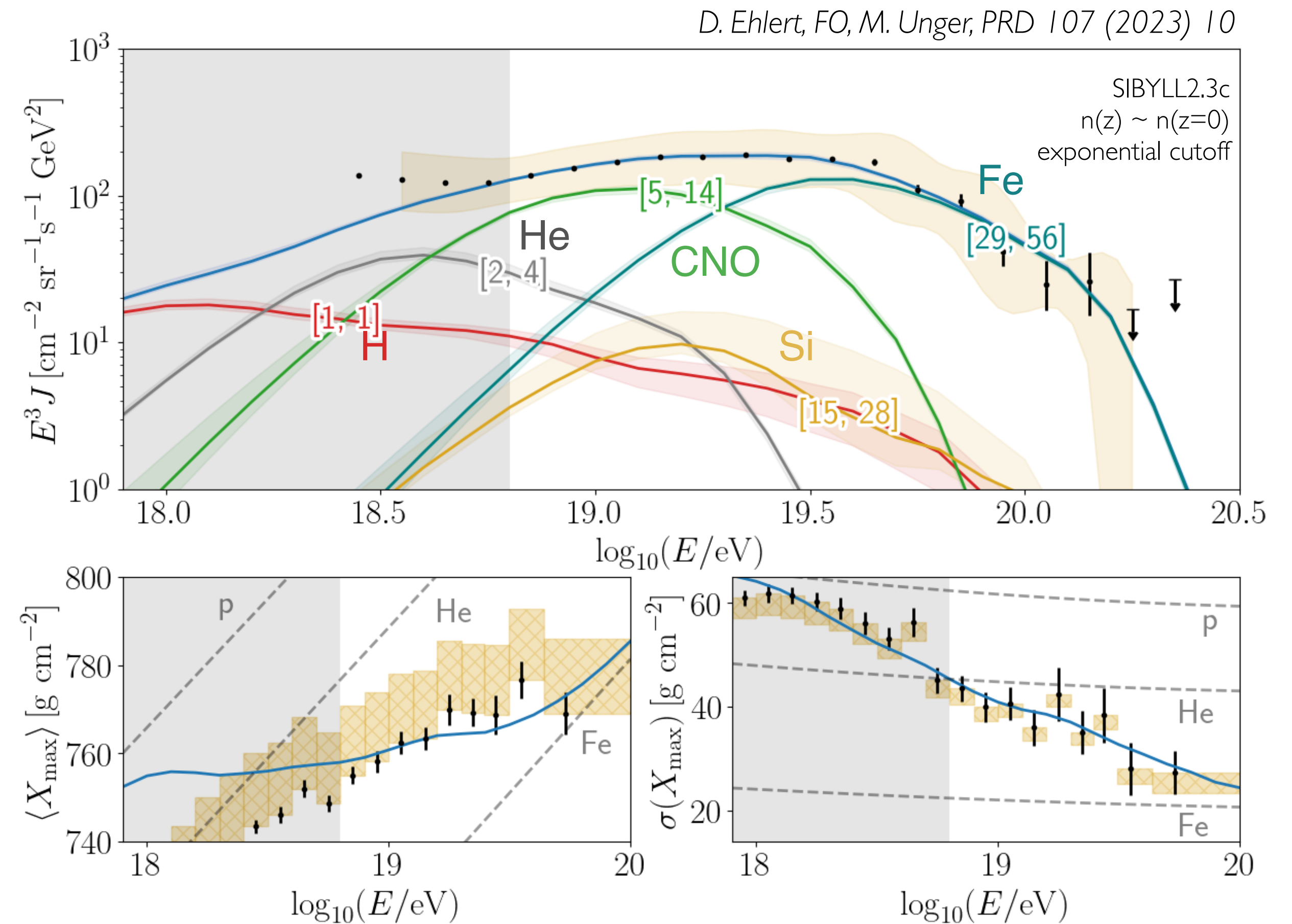
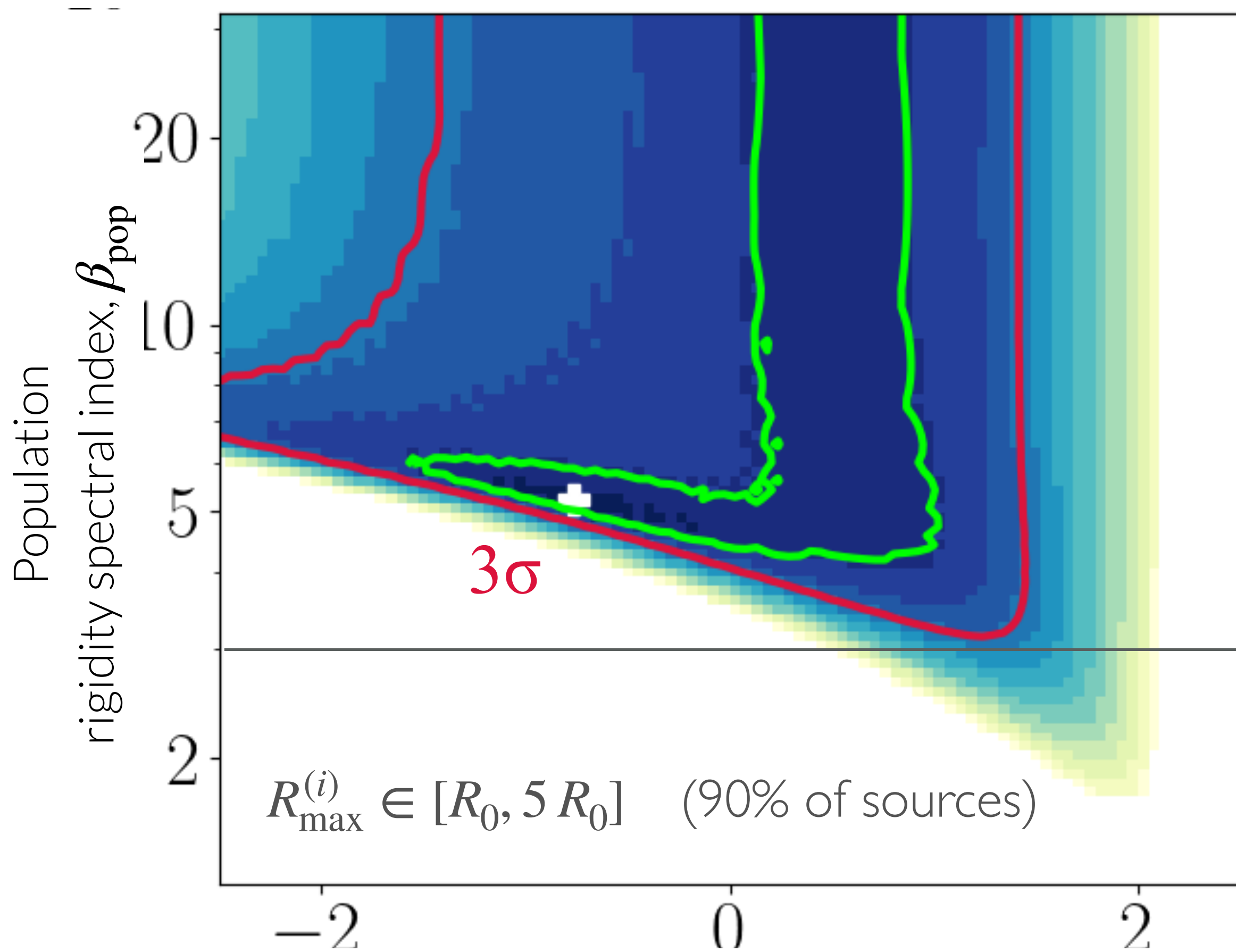
A curious maximum rigidity distribution



$$\frac{dN}{dR} \propto R^{-\gamma_{\text{src}}}$$

$$\frac{dN}{dR_{\text{max}}} \propto R_{\text{max}}^{-\beta_{\text{pop}}}$$

A curious maximum rigidity distribution

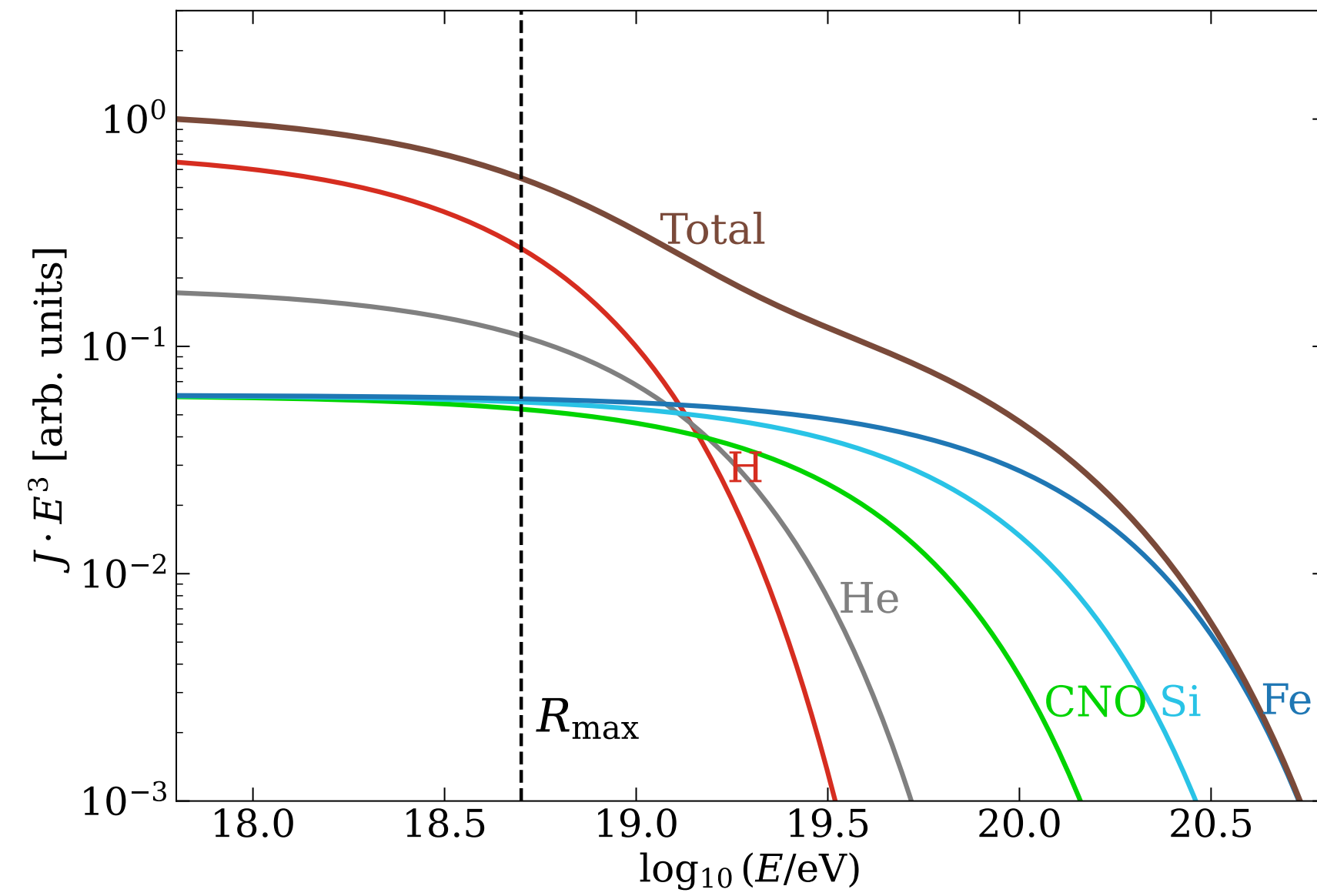


Inv **Conclusion #2:** UHECR sources are few or near-identical E_{max}

spectral index, β_{src}

32 dK dK_{max}

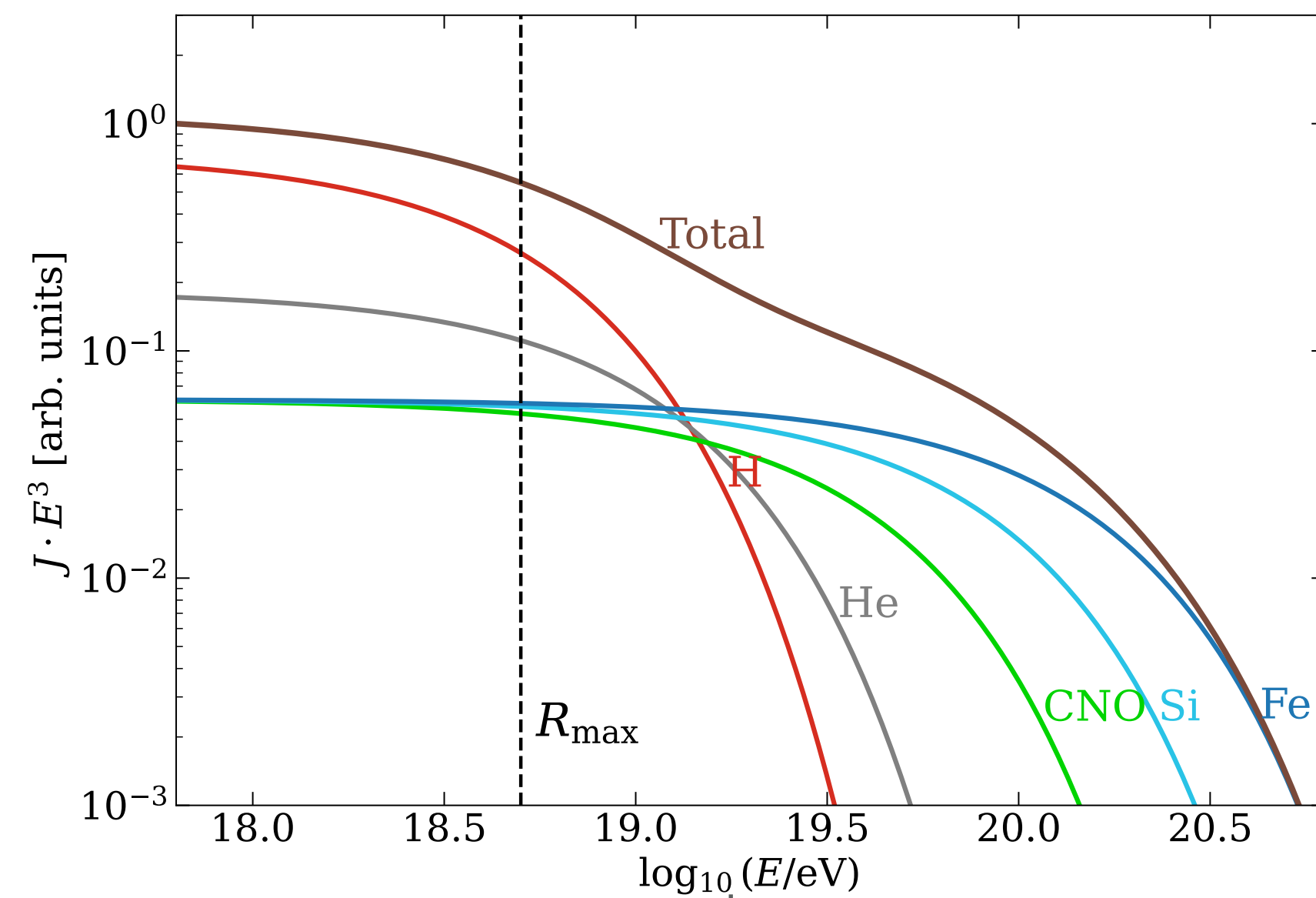
Spectrum and Composition Observables



Each source characterised by:

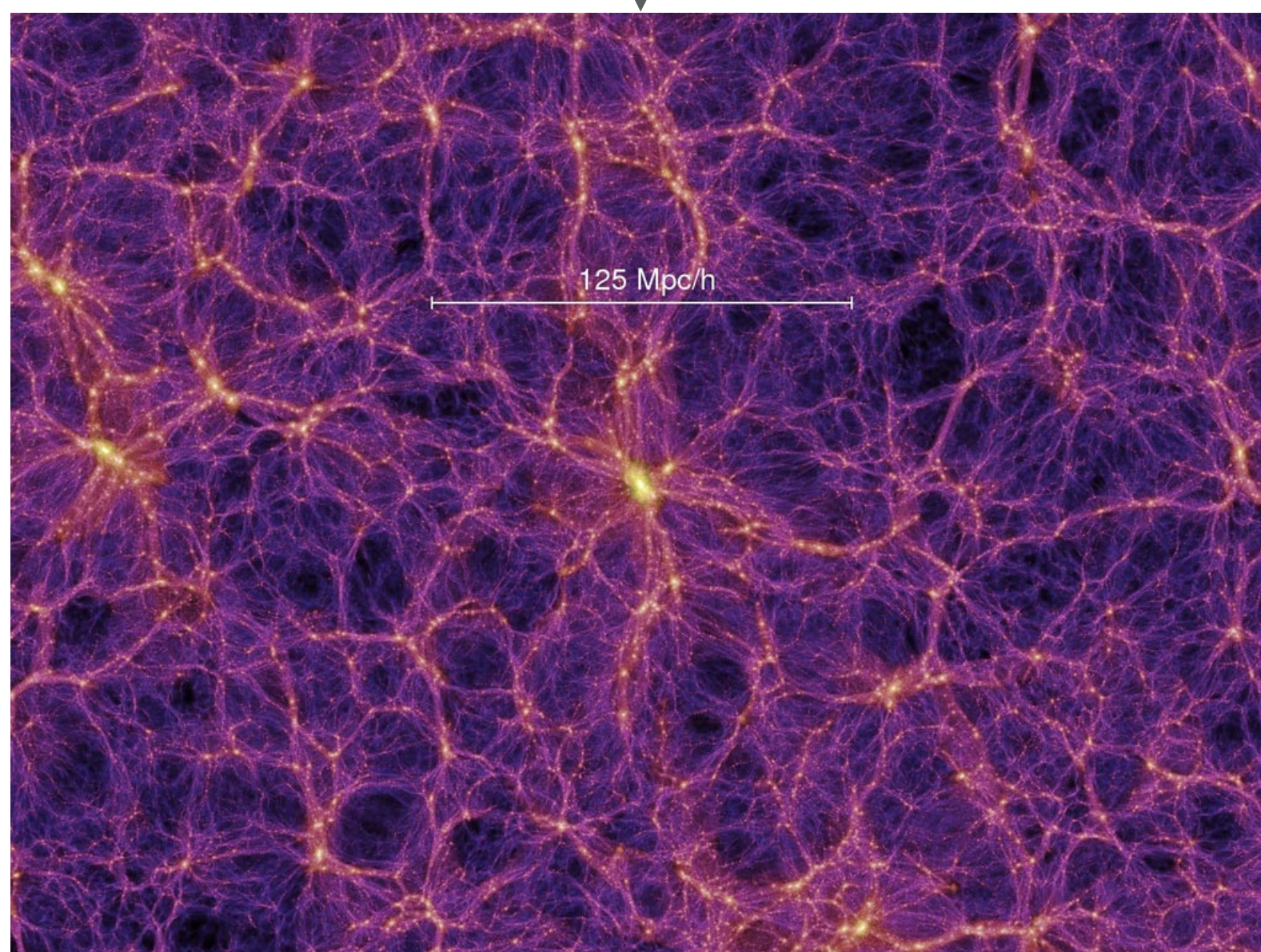
- R_{max}
- Spectral index
- Composition

Spectrum and Composition Observables

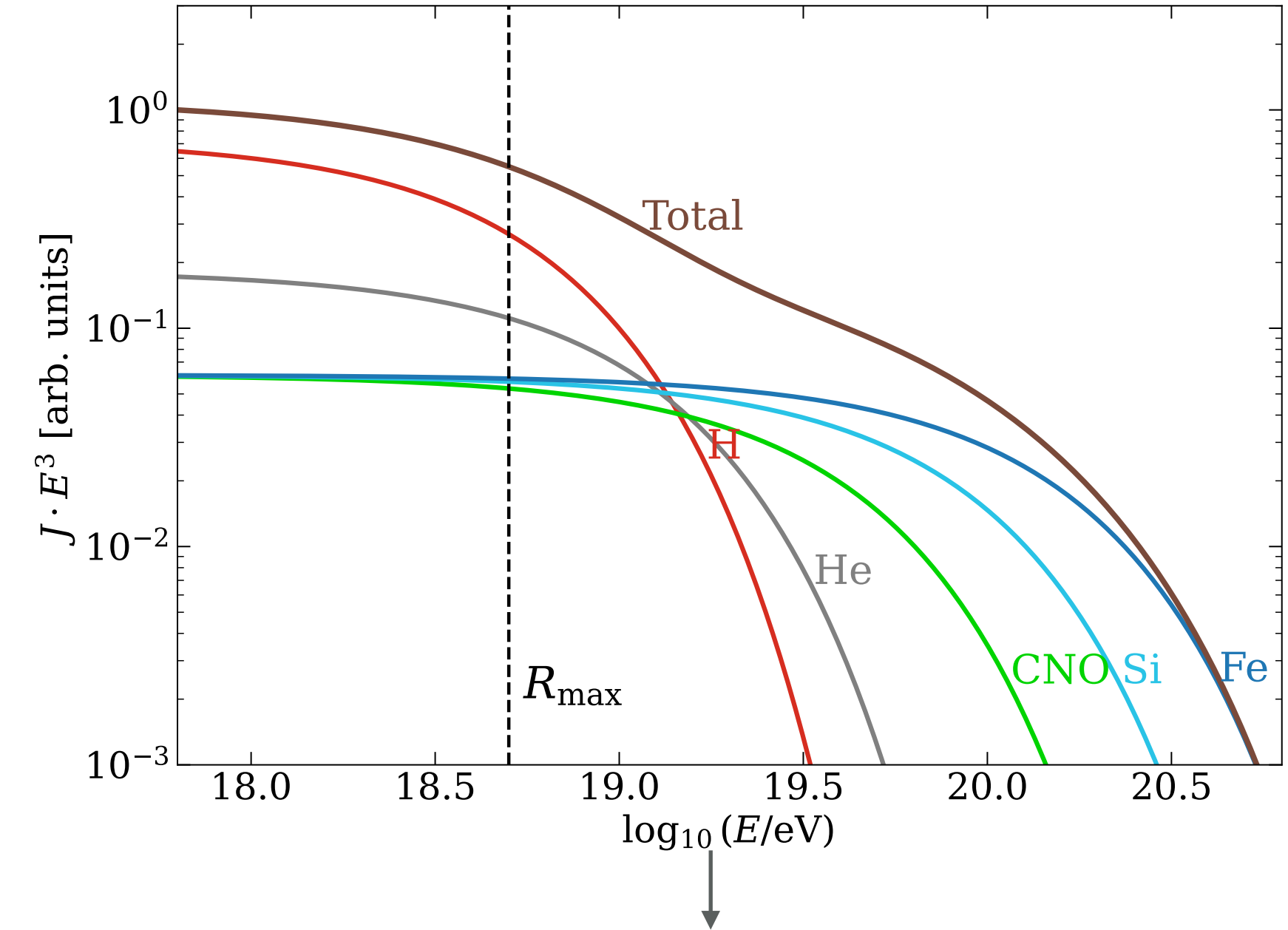


Each source characterised by:

- $R_{\max}$
- Spectral index
- Composition

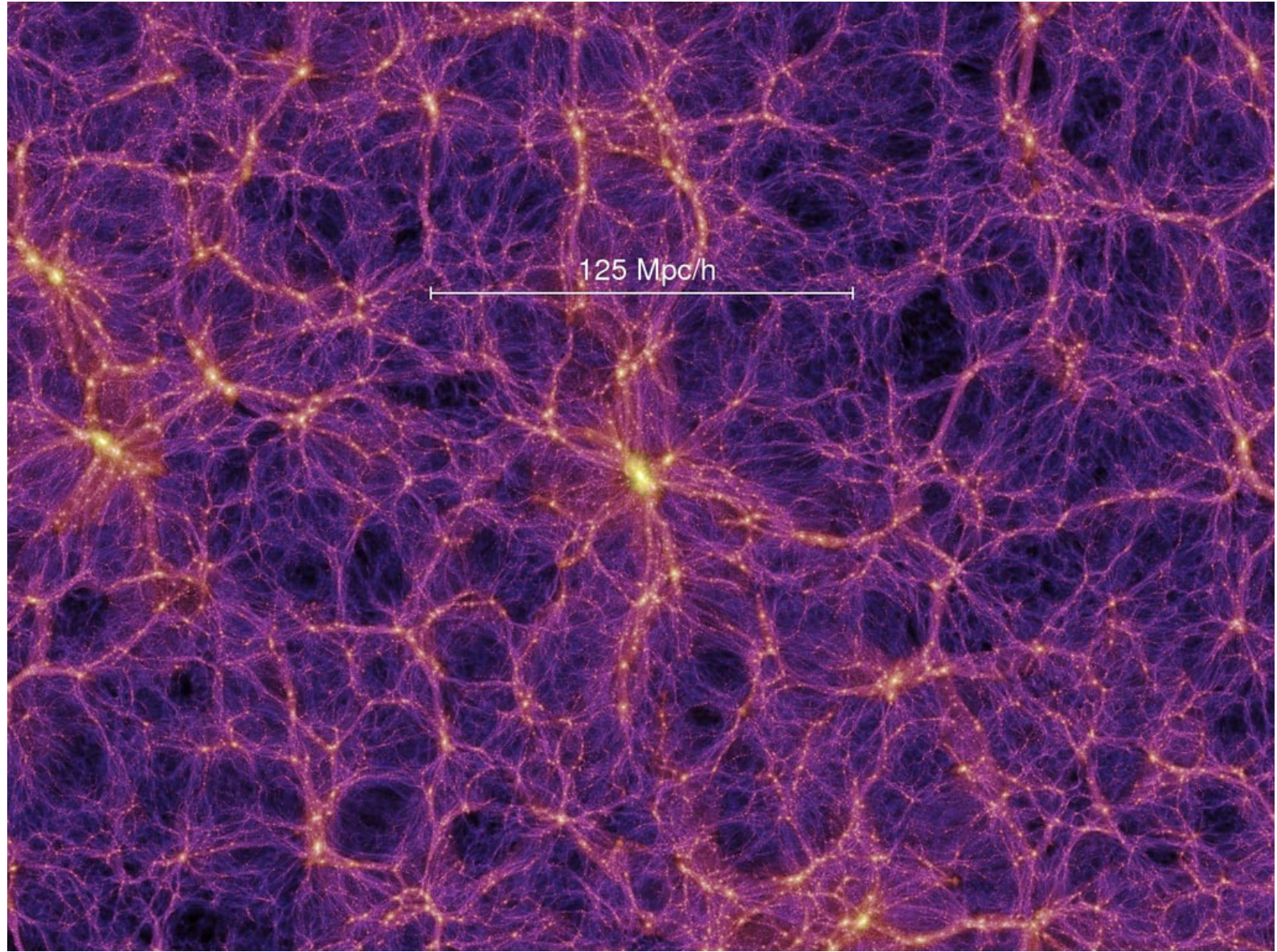


Spectrum and Composition Observables

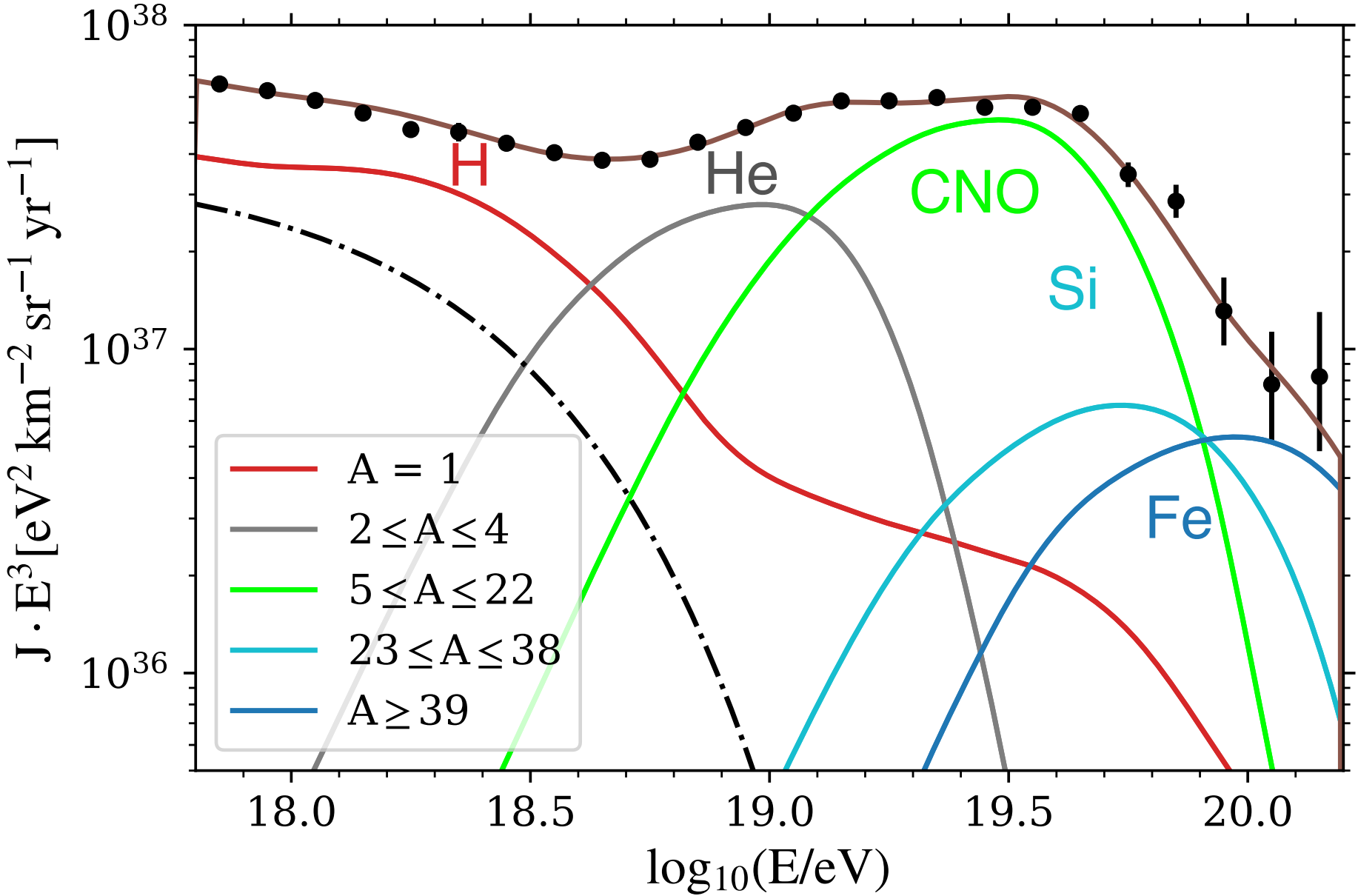


Each source characterised by:

- R_{max}
- Spectral index
- Composition



particle transport



UHECR Composition Systematics

