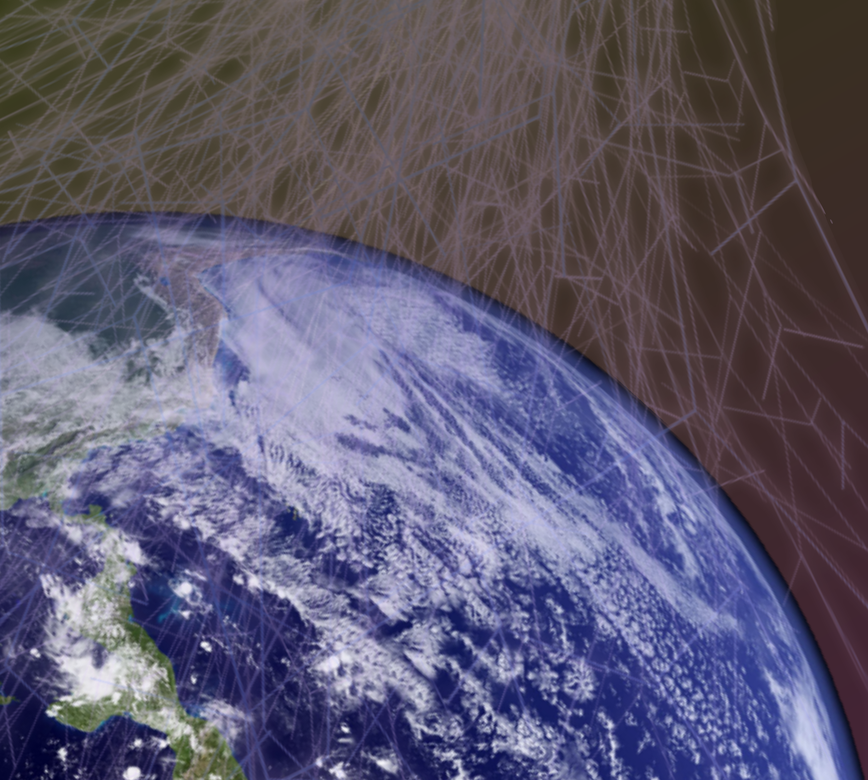
COSMIC-RAY OBSERVATIONS:
latest results and future prospects



Rafael Alves Batista

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Sorbonne Université, Institut d'Astrophysique de Paris (IAP)

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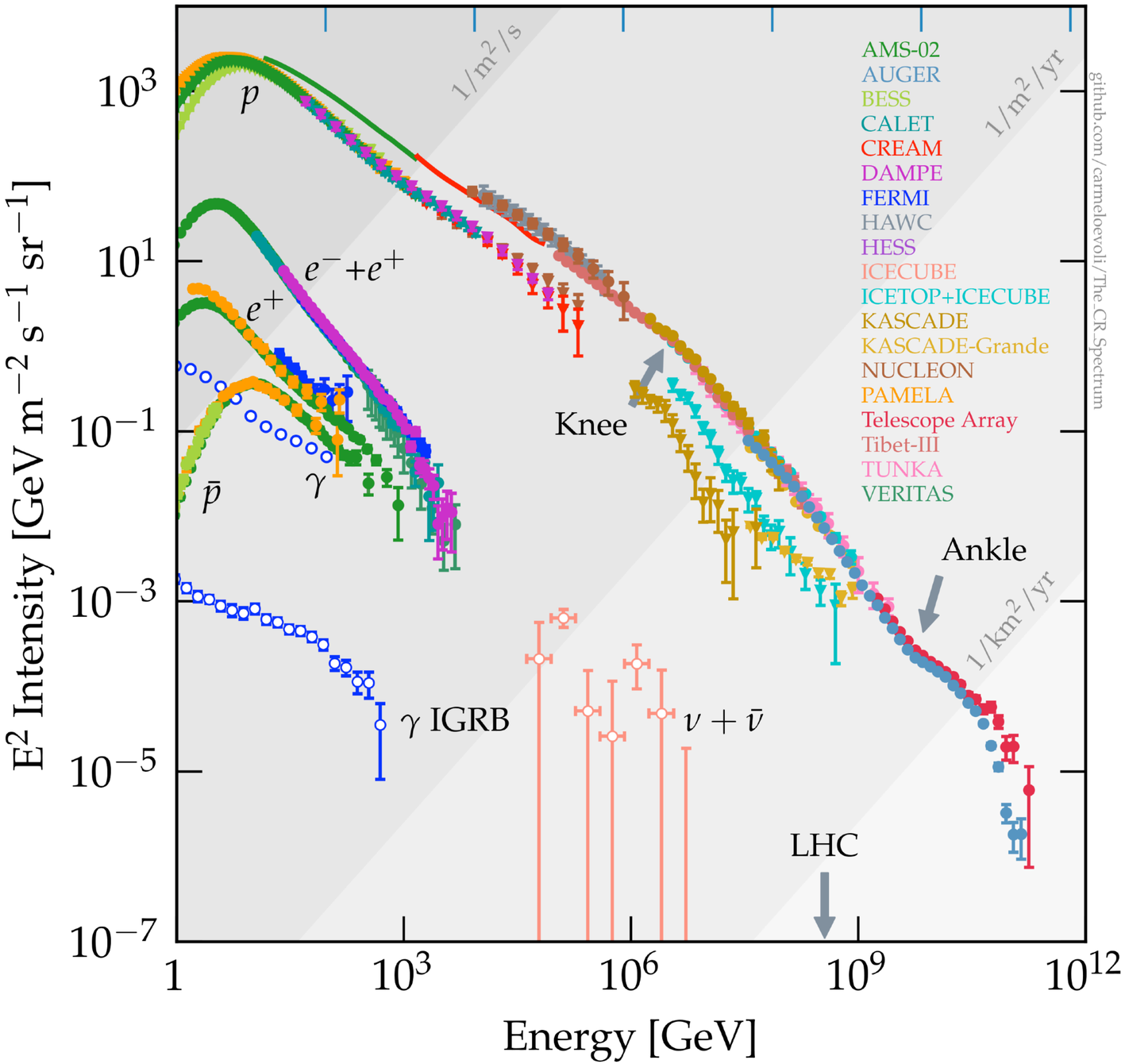
NuPhys 2023: Prospects in Neutrino Physics
London; December 18, 2023

cosmic-ray measurements



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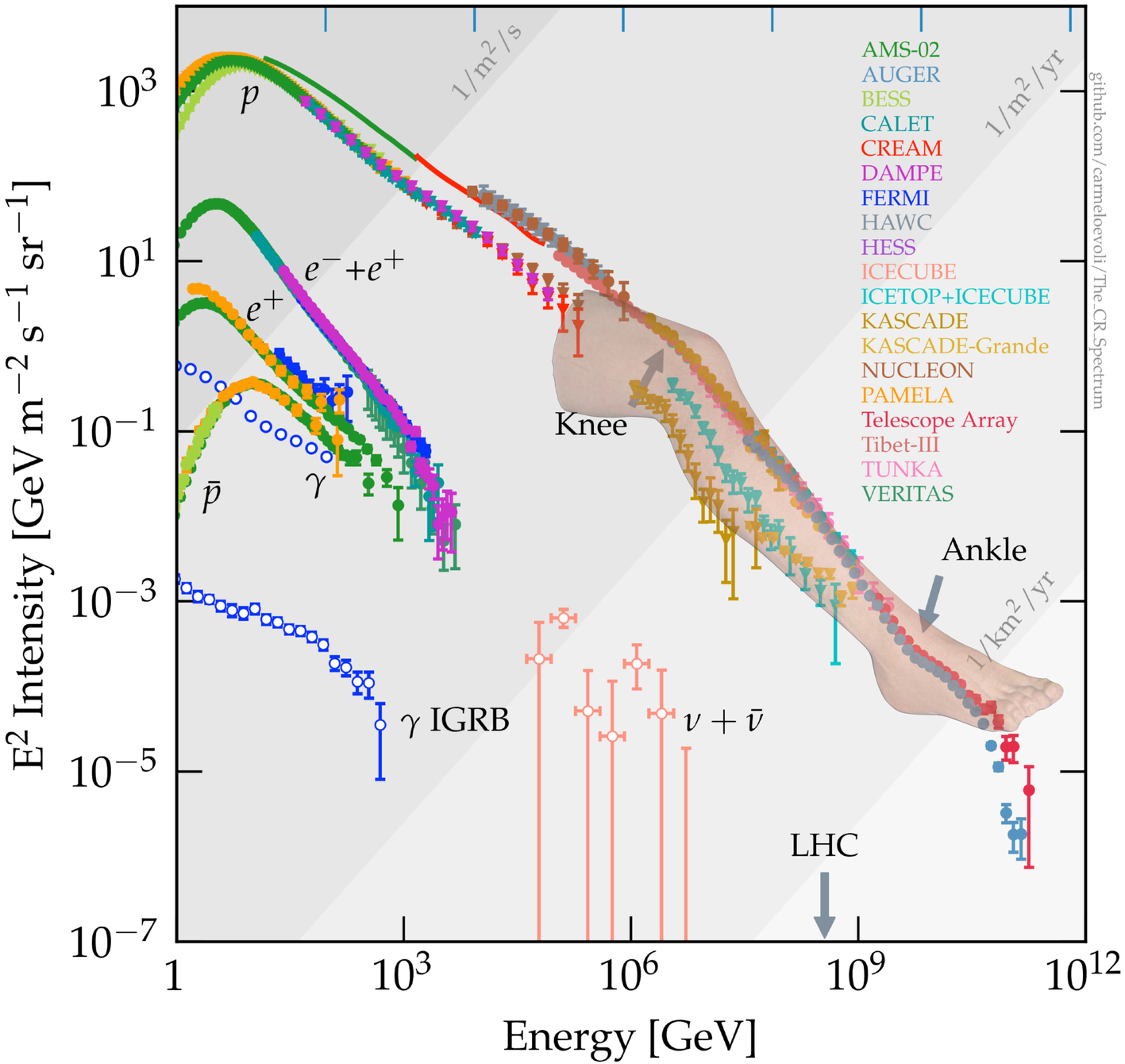

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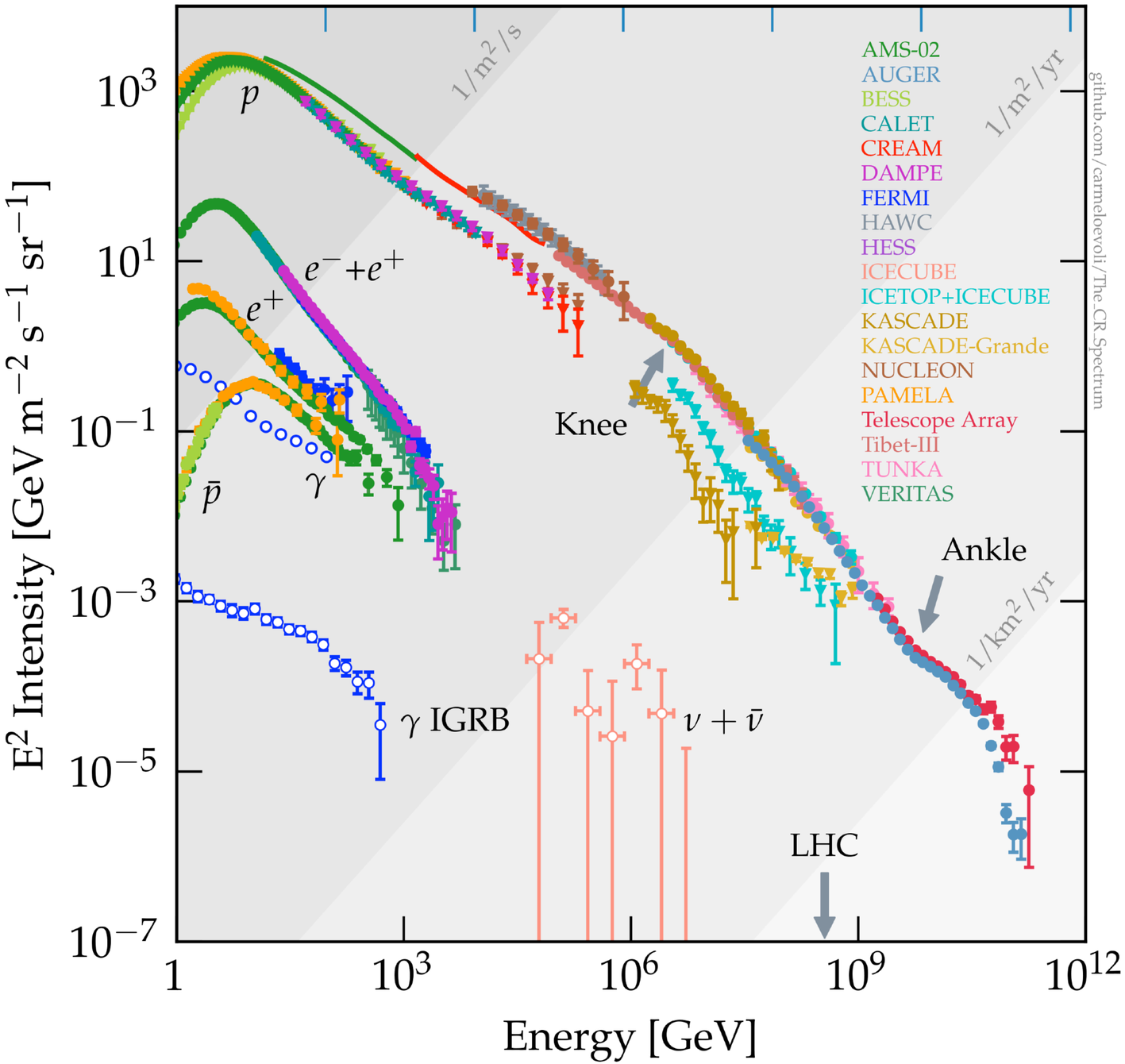

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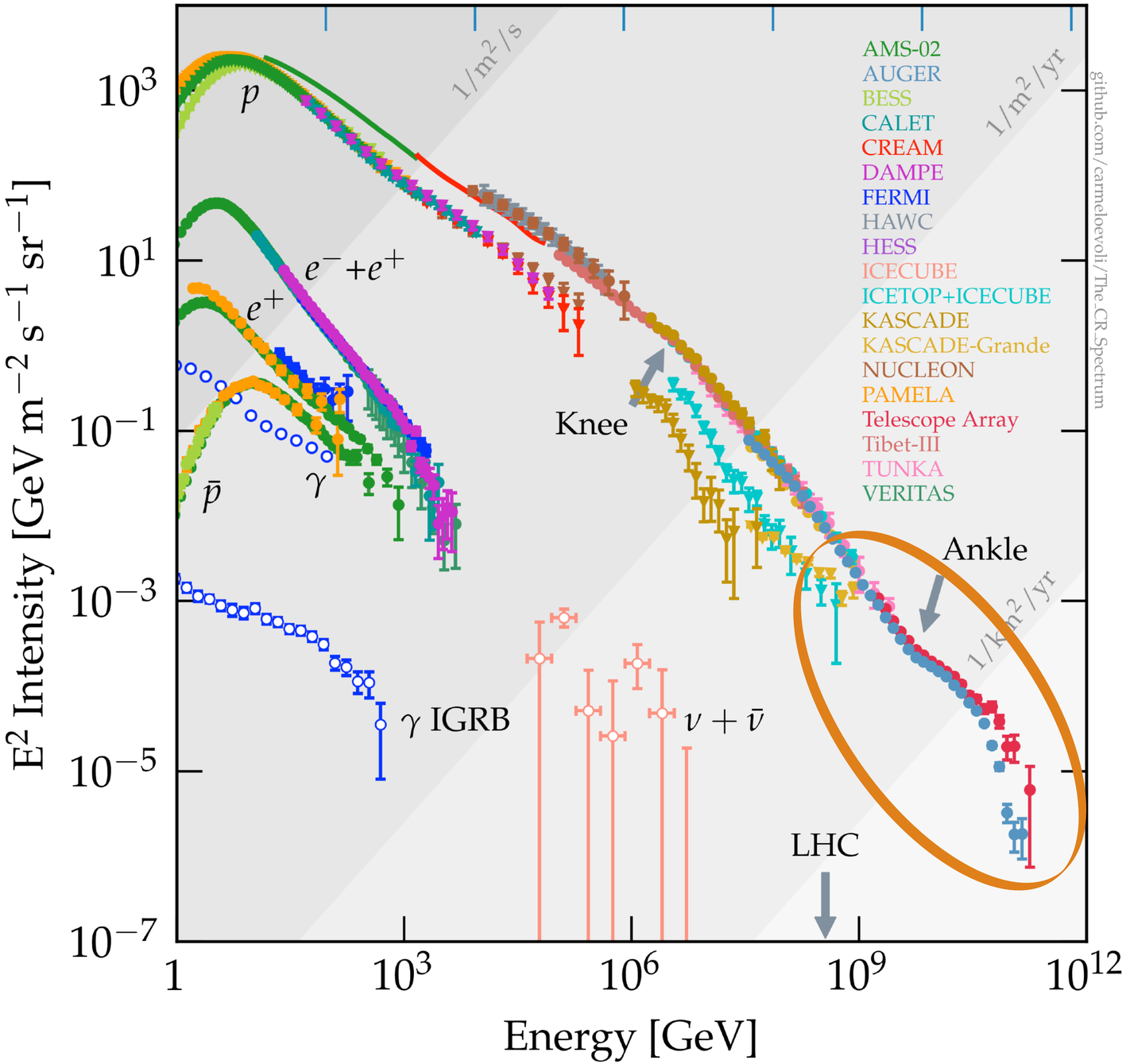

(ultra-)high-energy cosmic messengers. detection principle

fluorescence detector (satellite)

gamma-ray detector (satellite)

atmosphere

fluorescence detectors

radio detectors (antennas)

particle detectors (water-Cherenkov tanks)

Cherenkov telescopes

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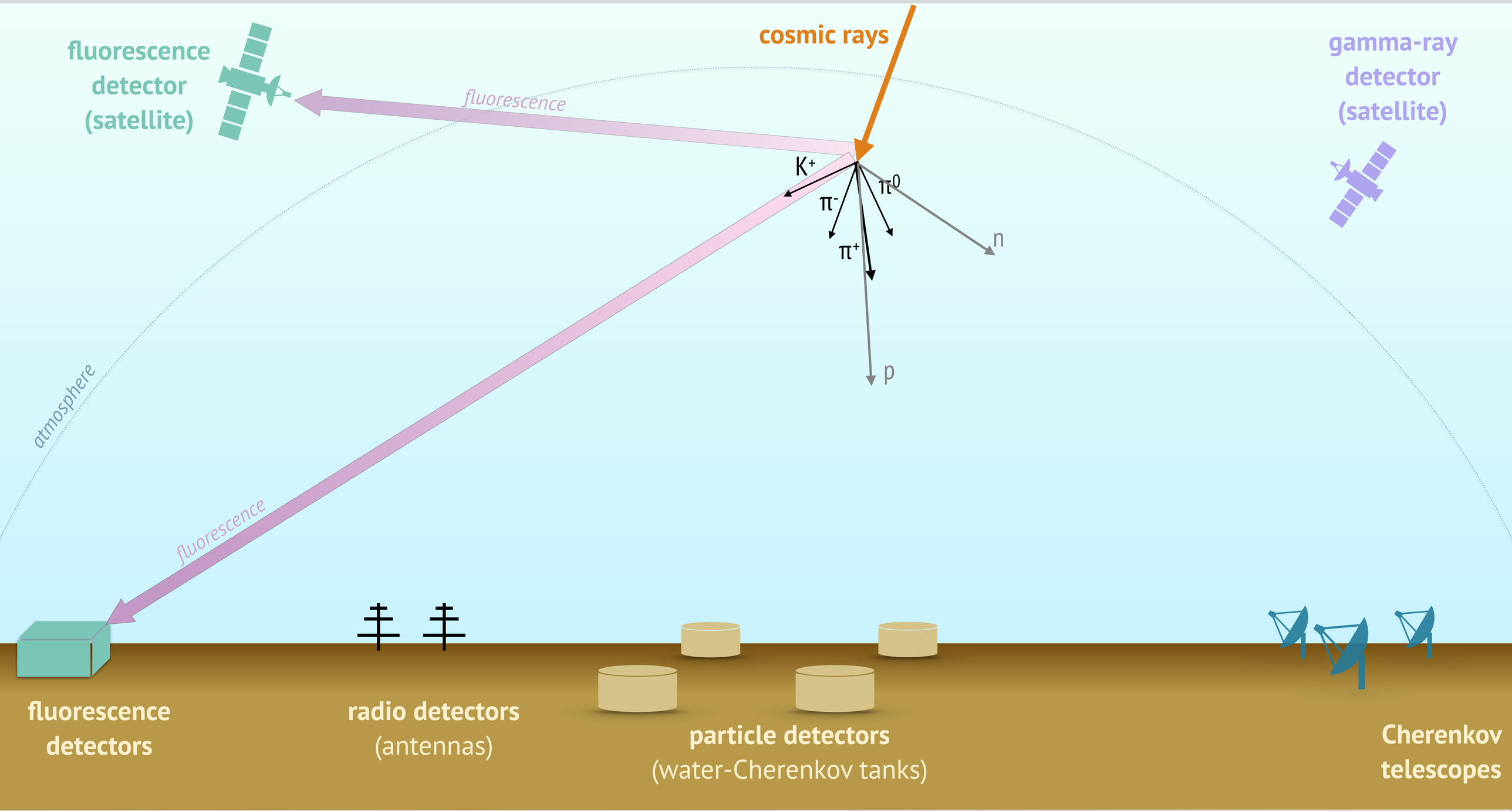

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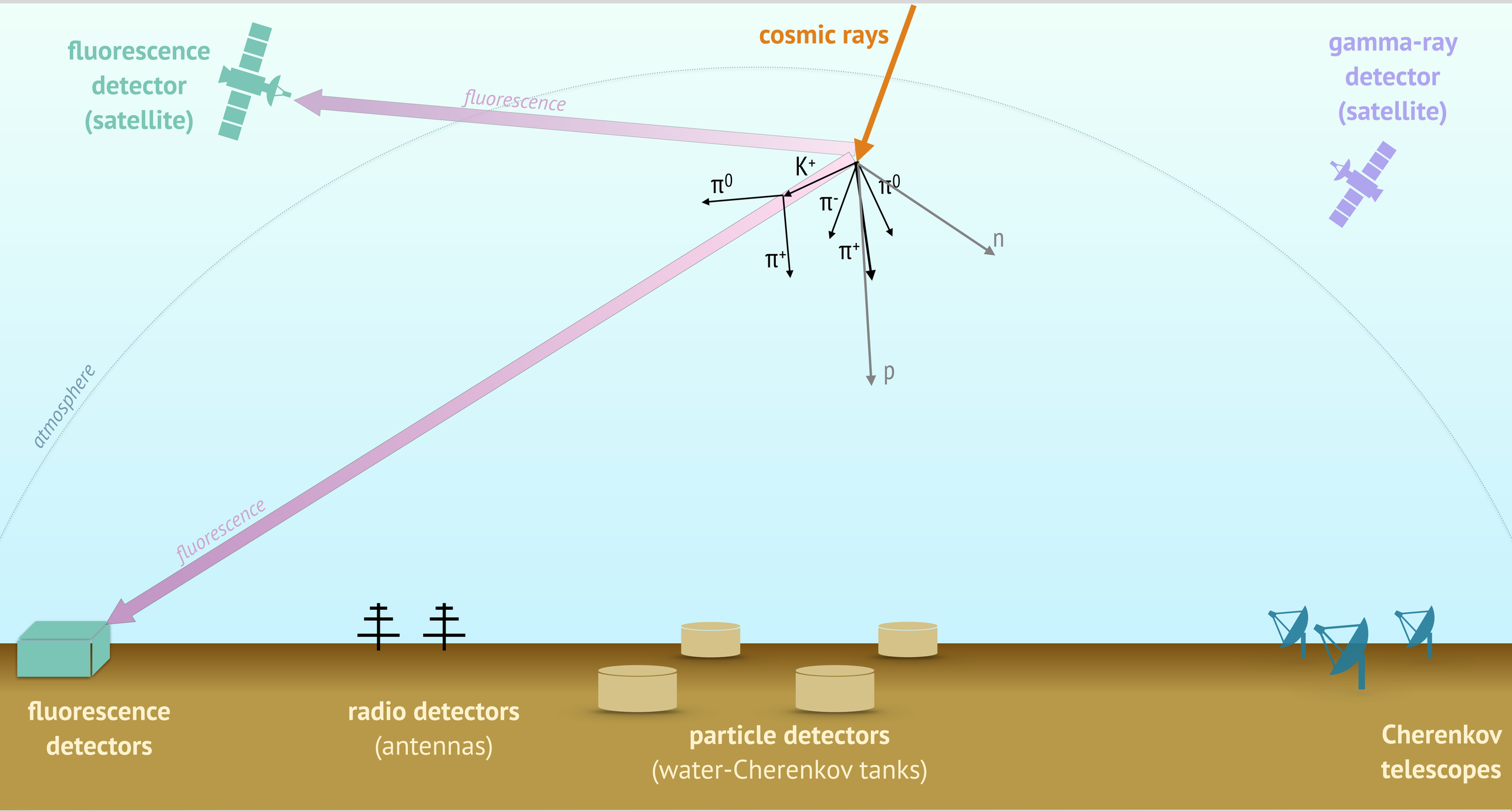

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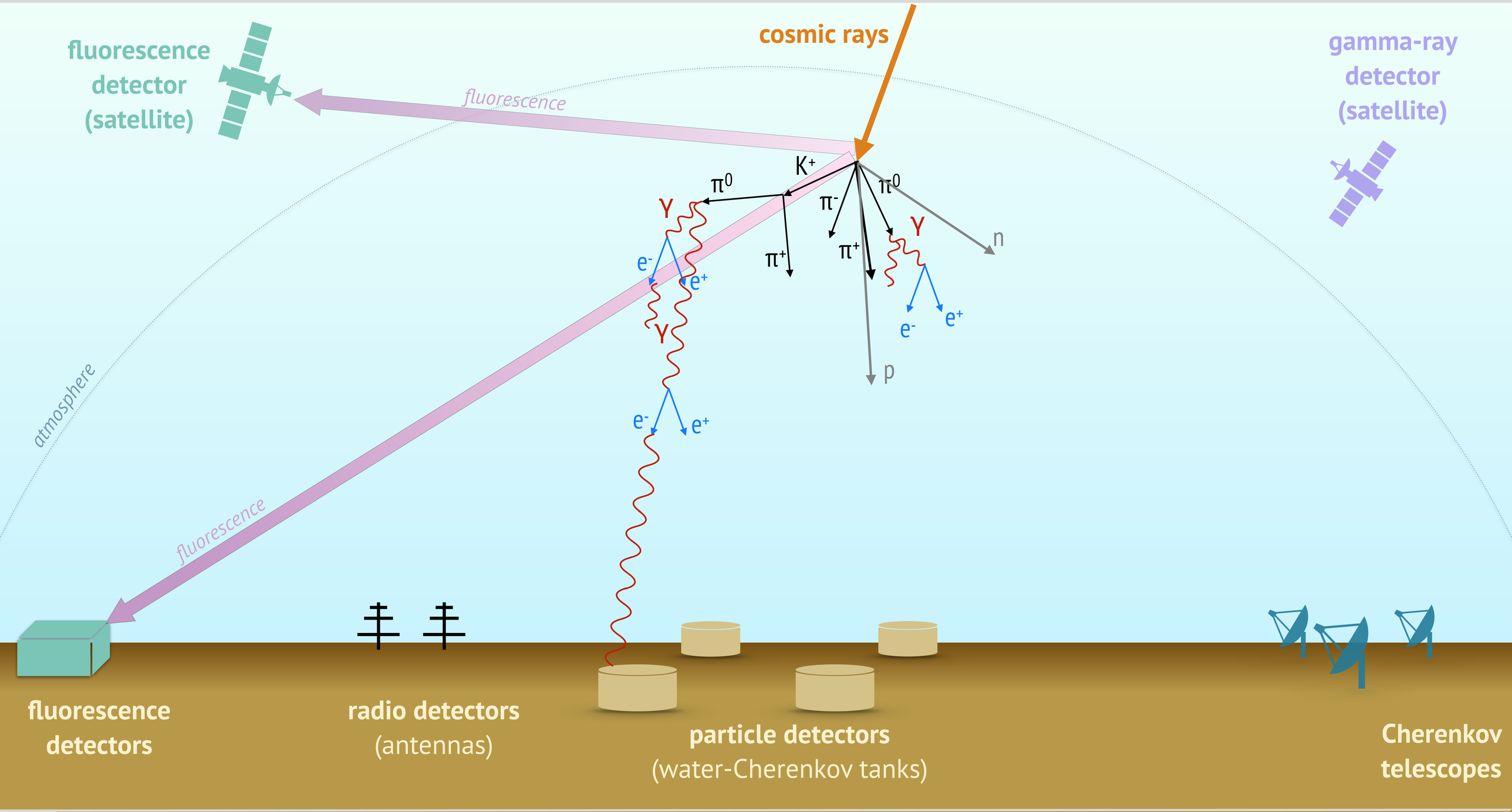

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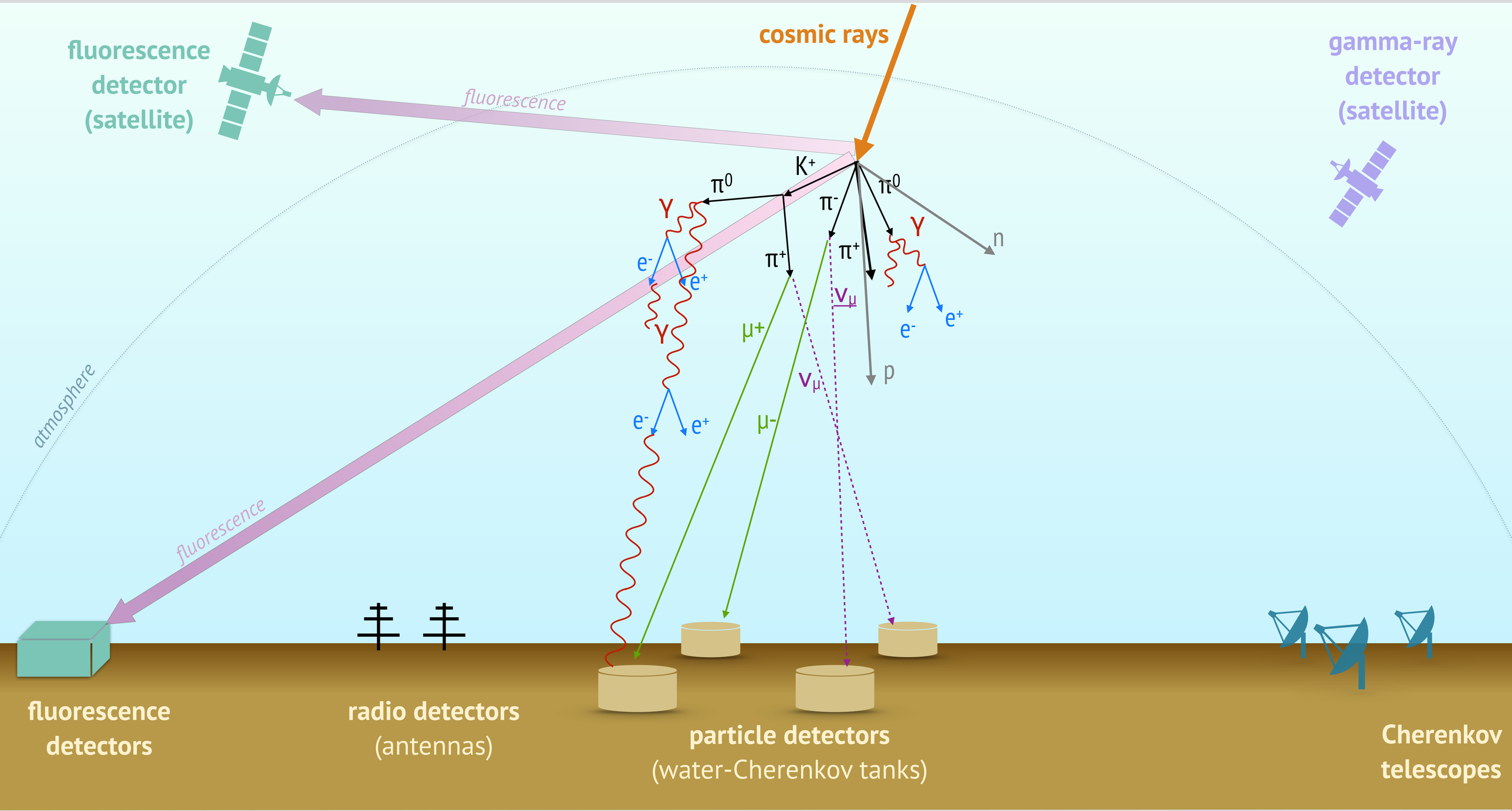

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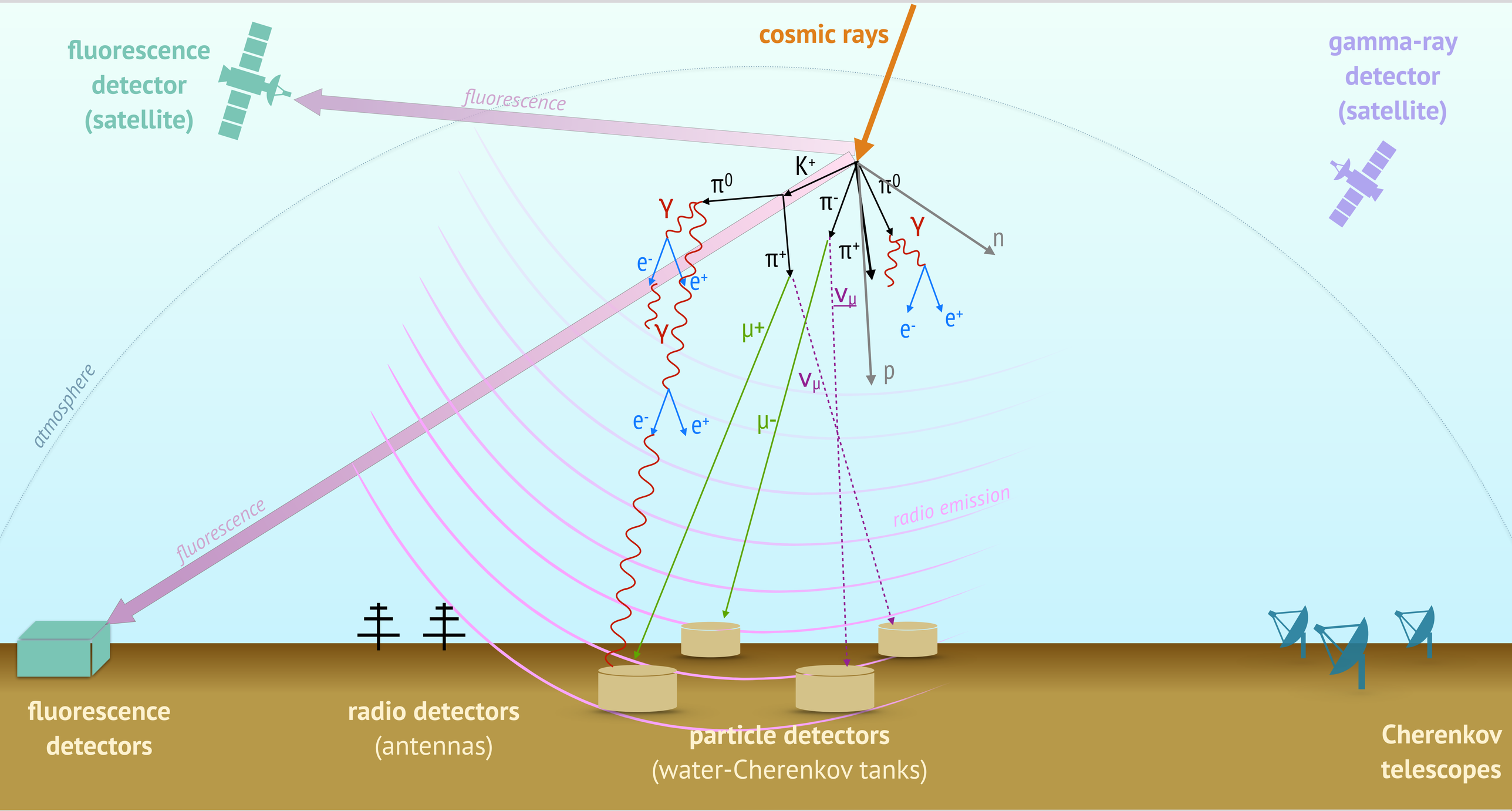

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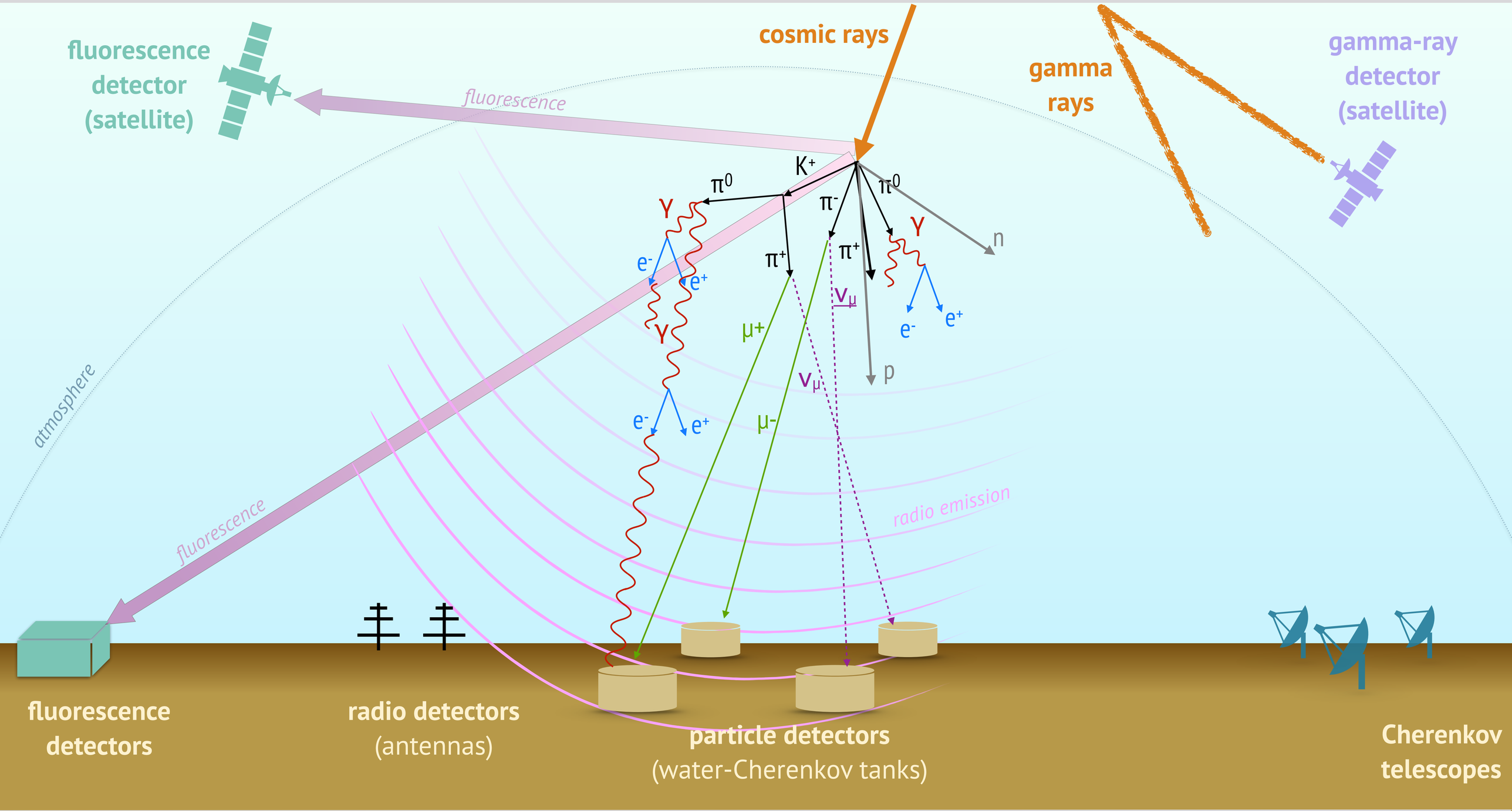

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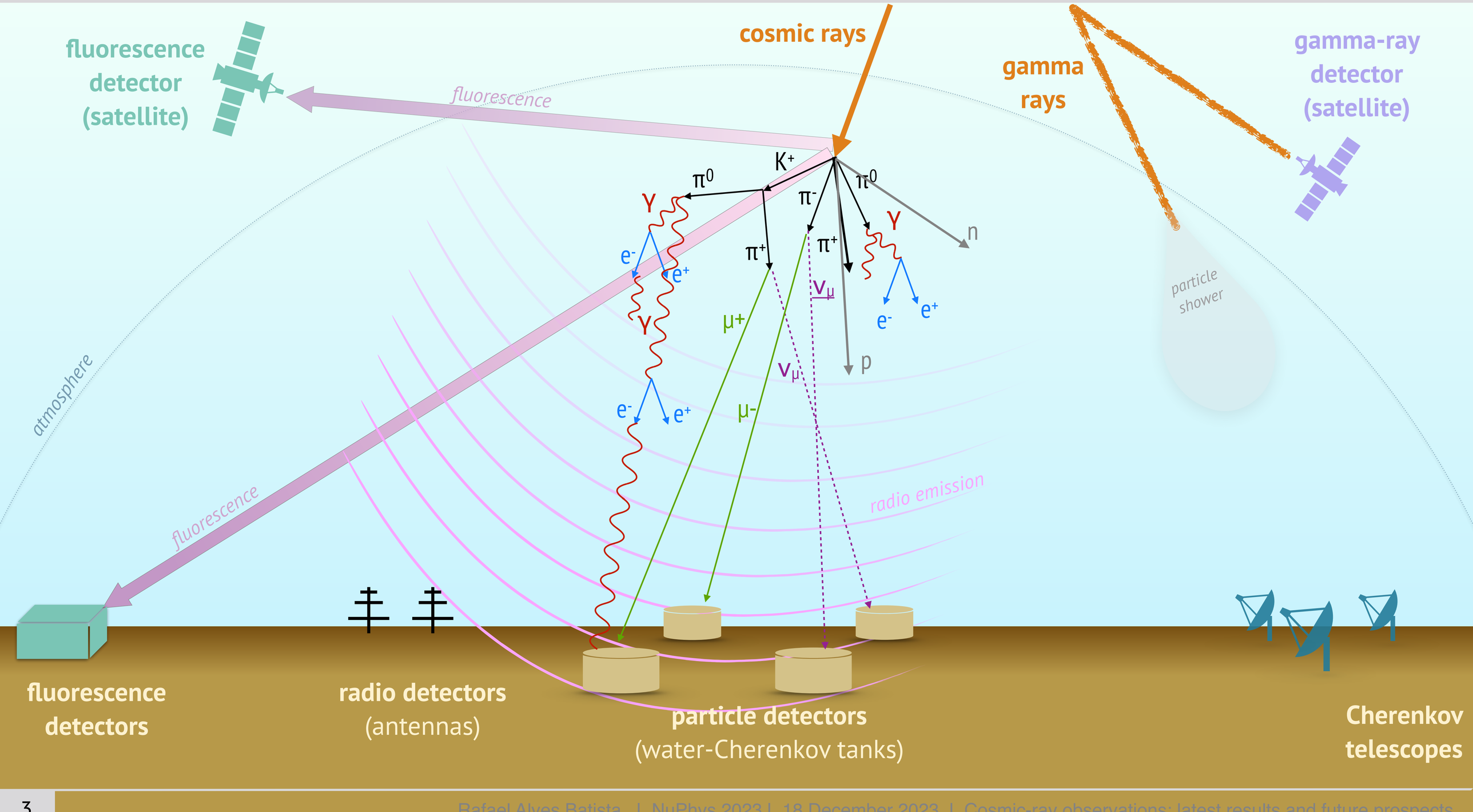

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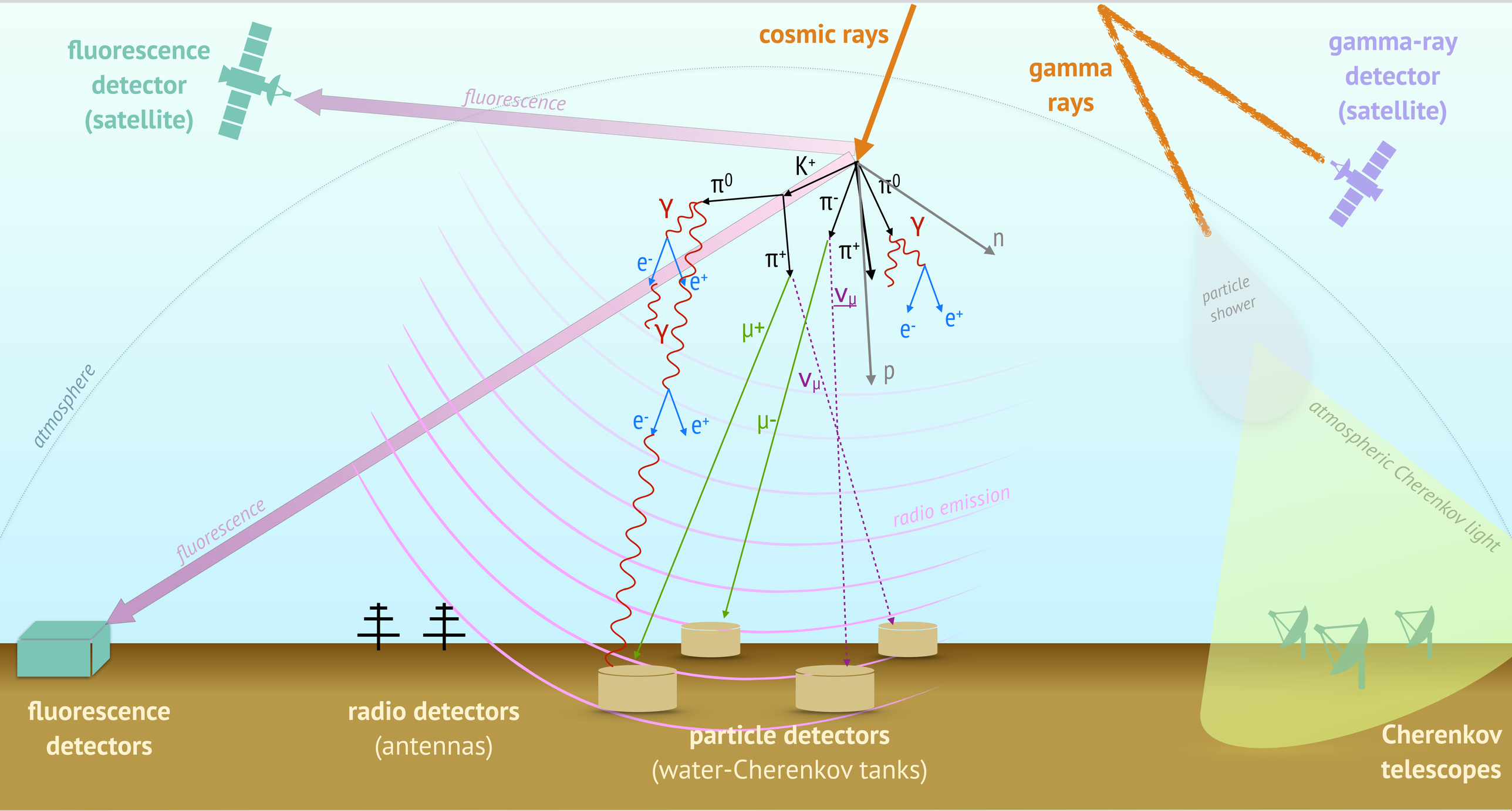

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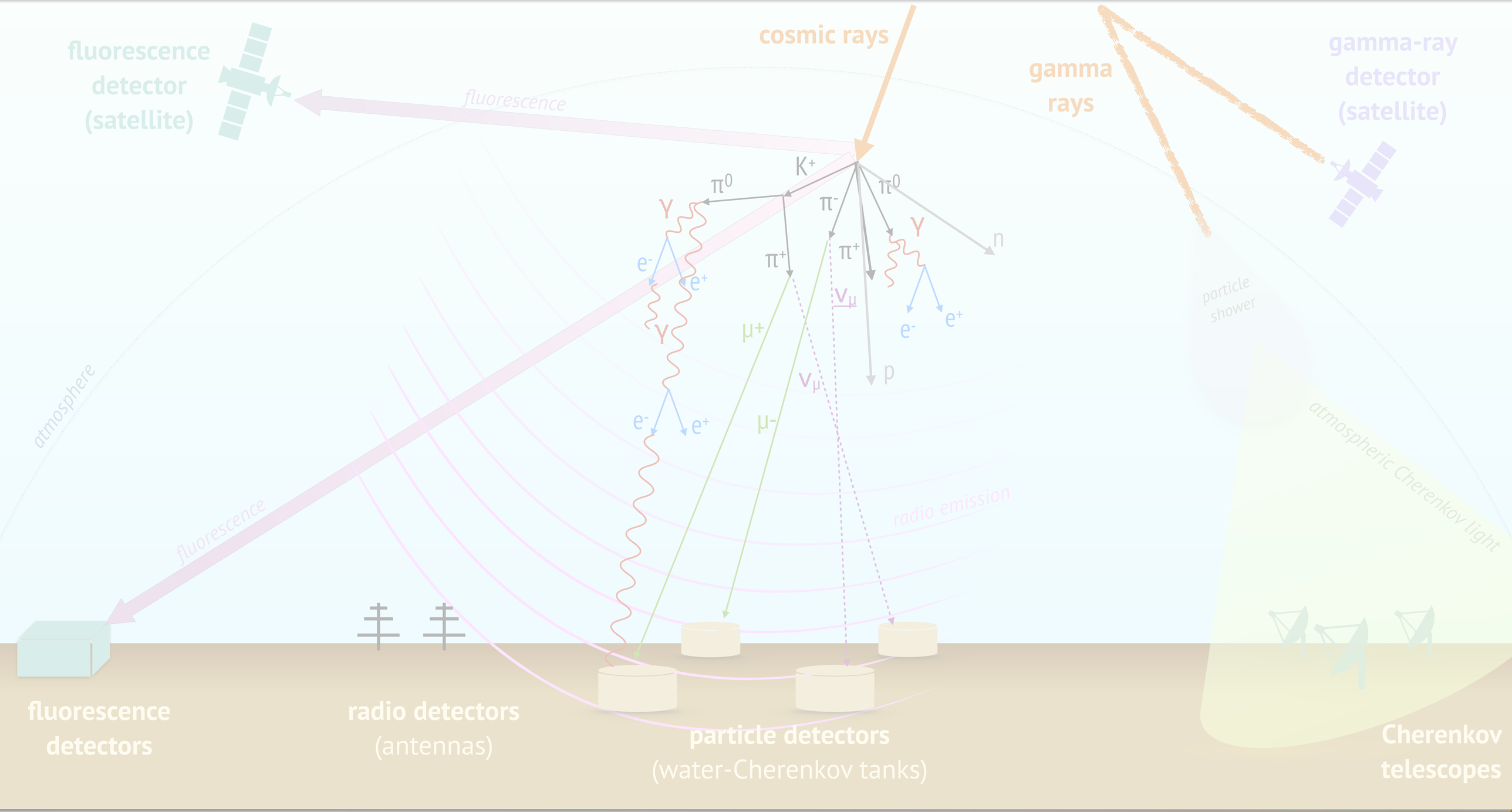

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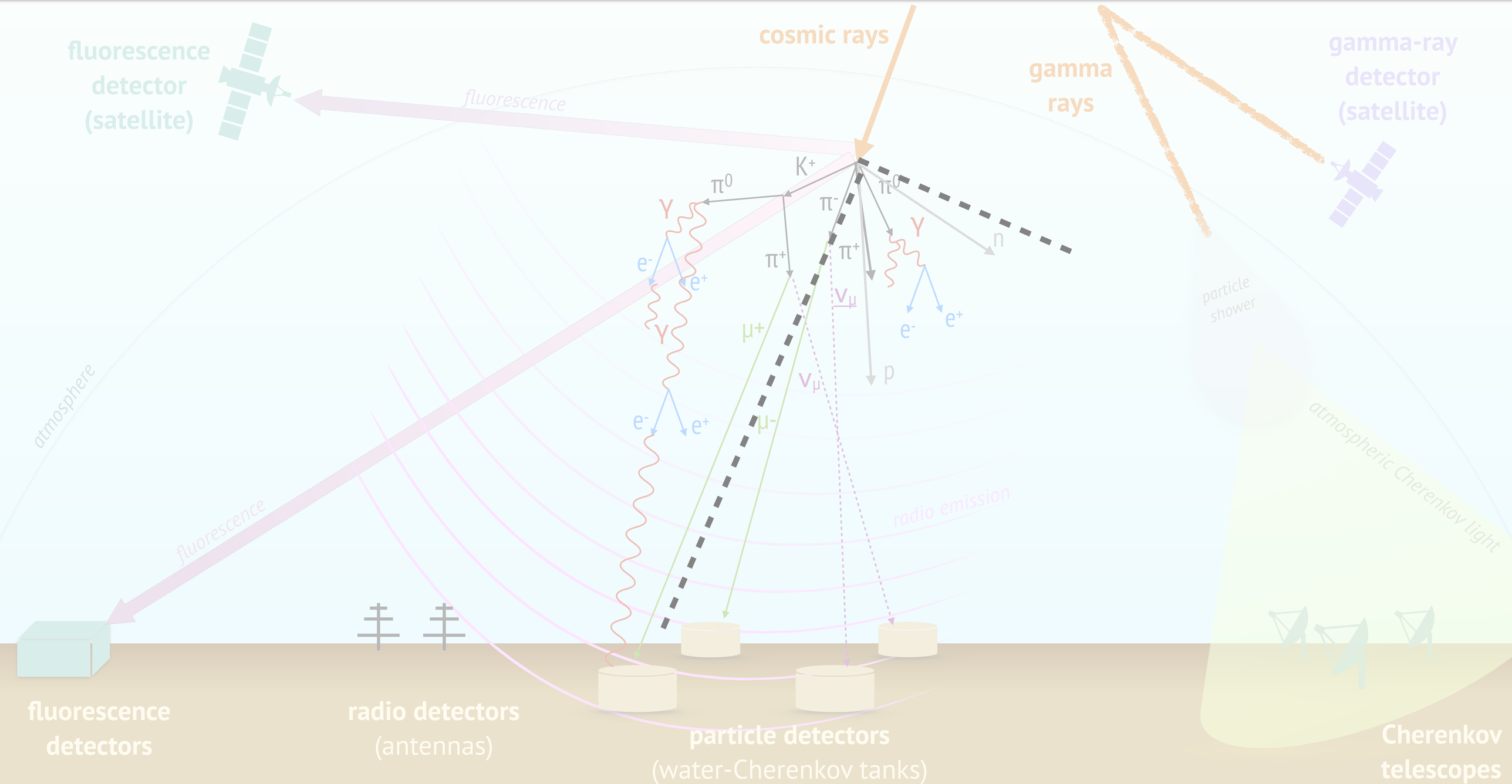

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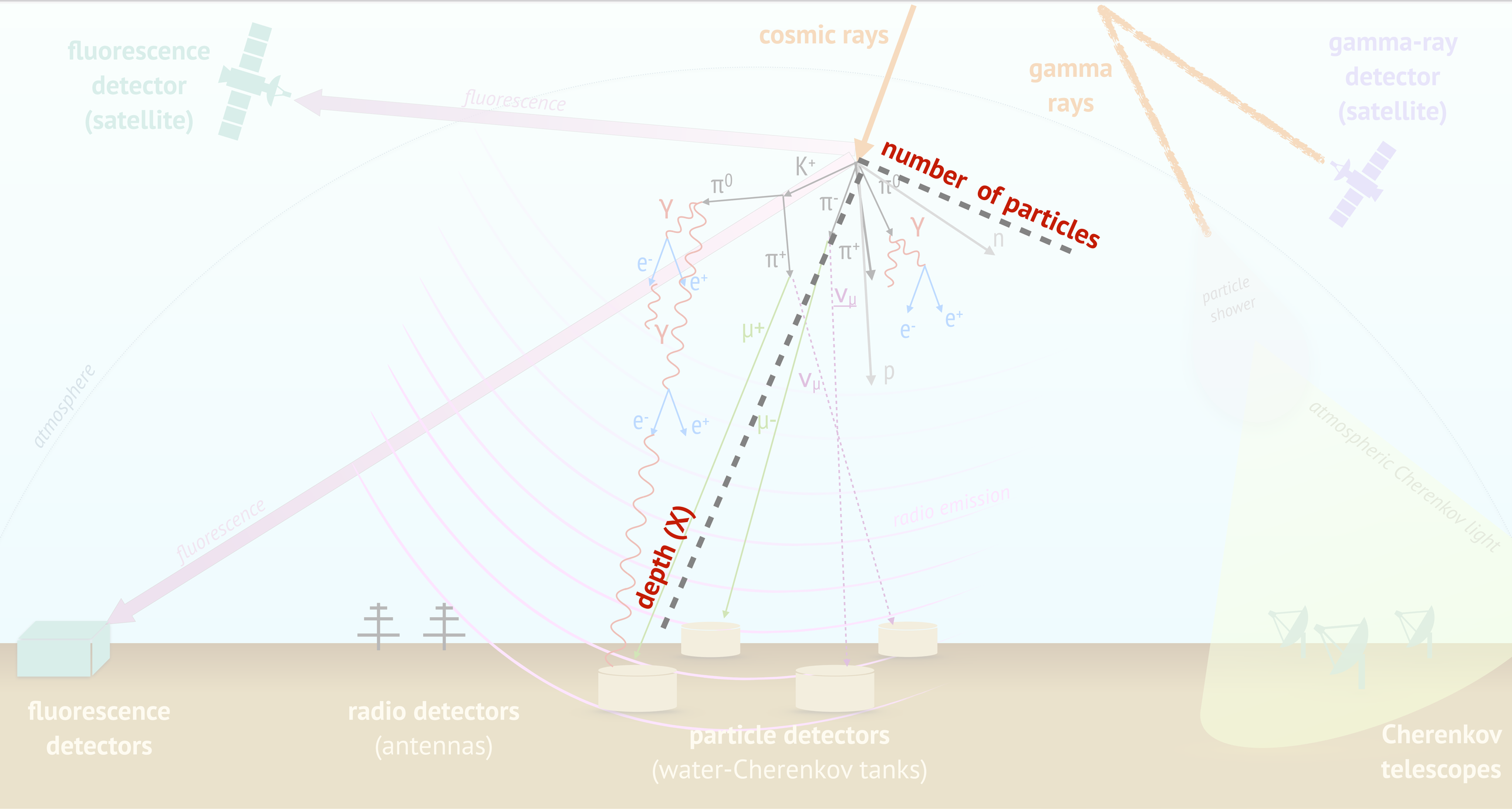

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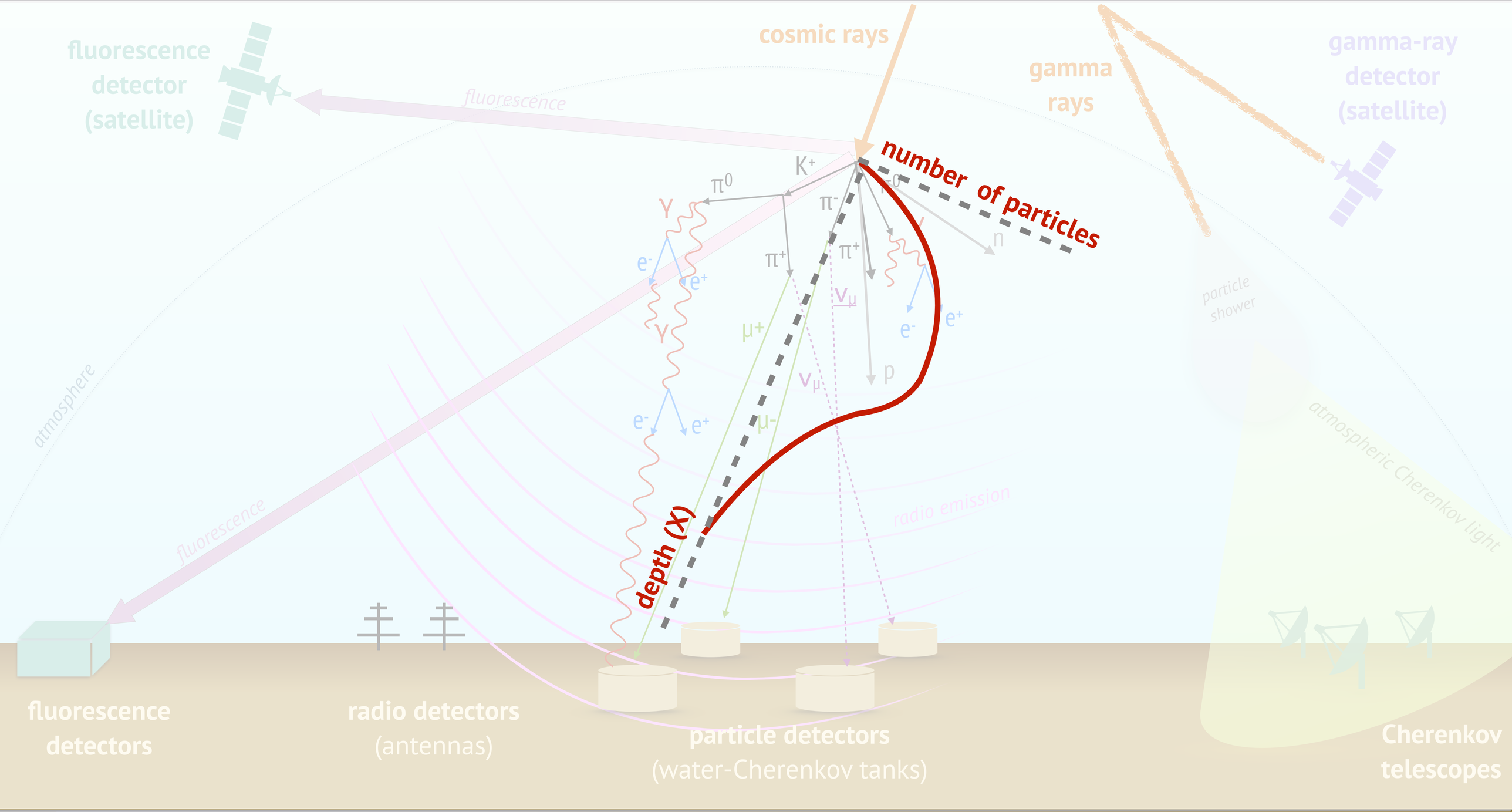

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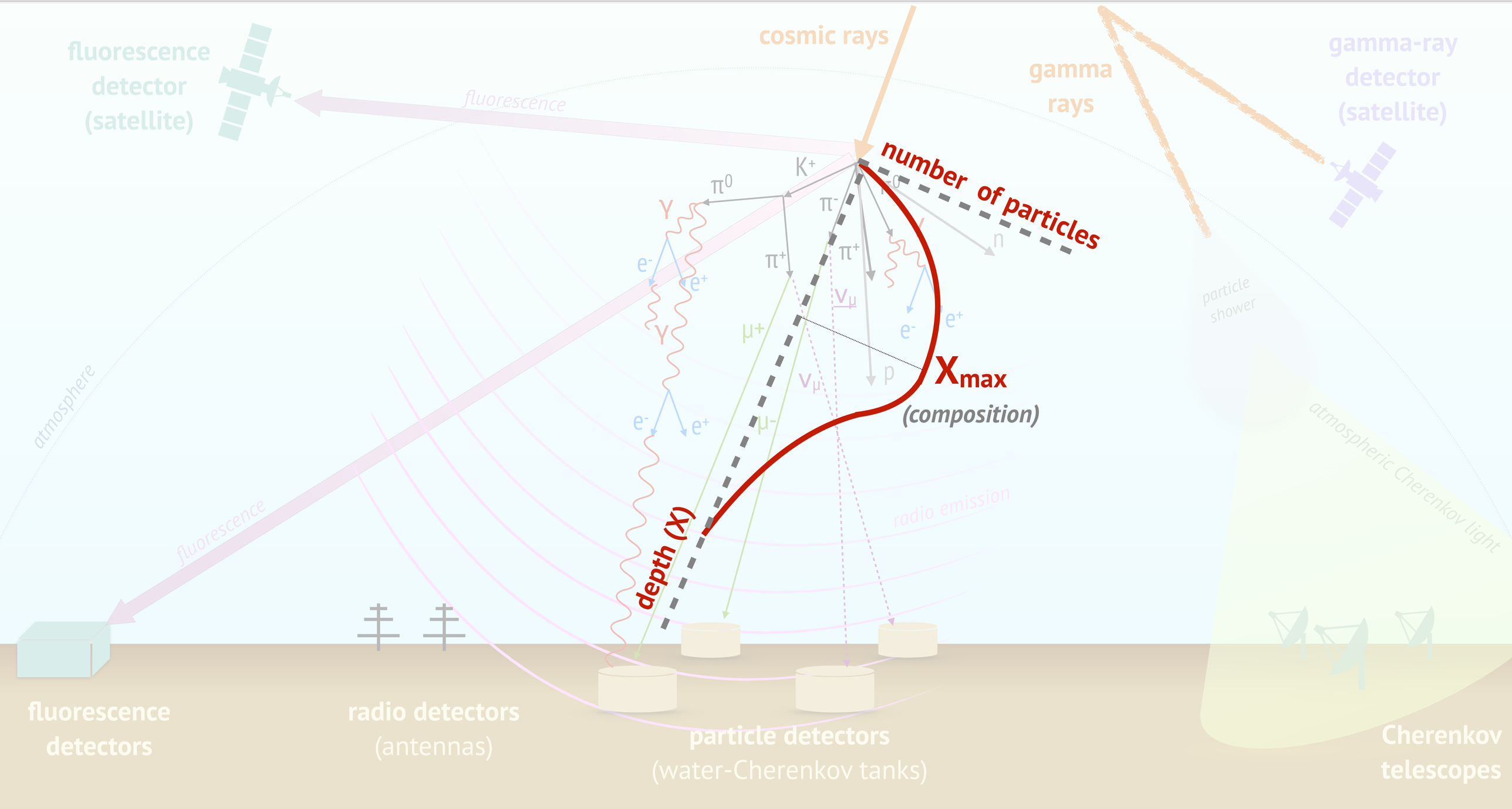

one type of observatory, multiple purposes

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UHE & multimessenger astrophysics

one type of observatory, multiple purposes

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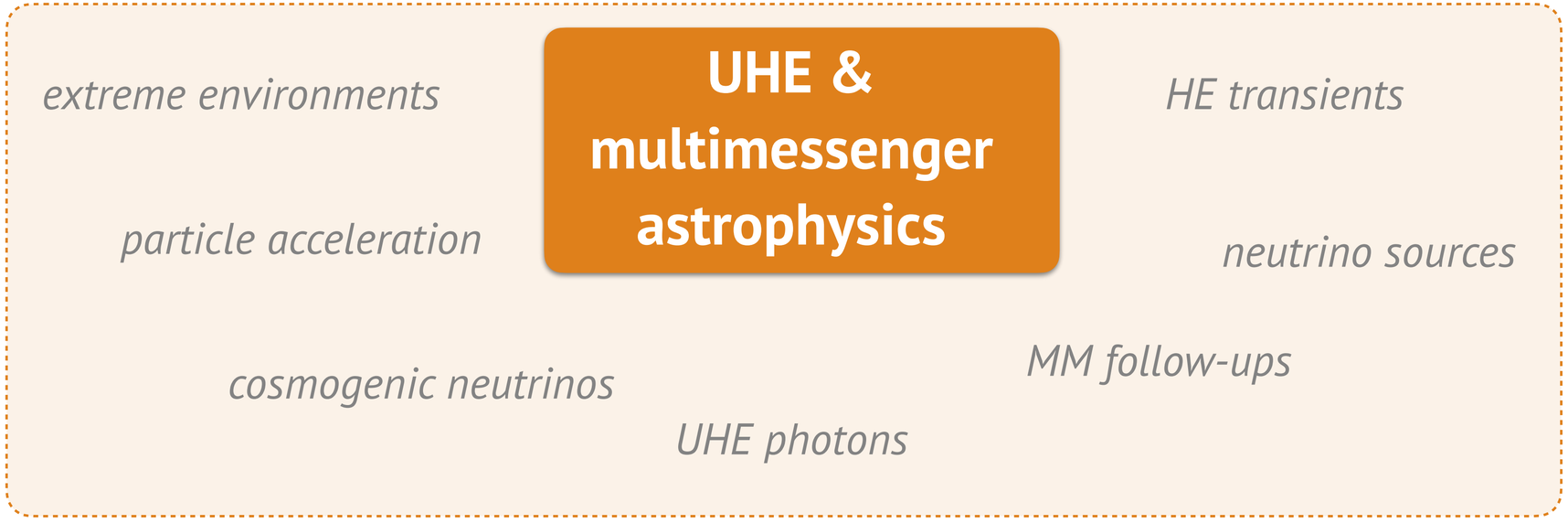

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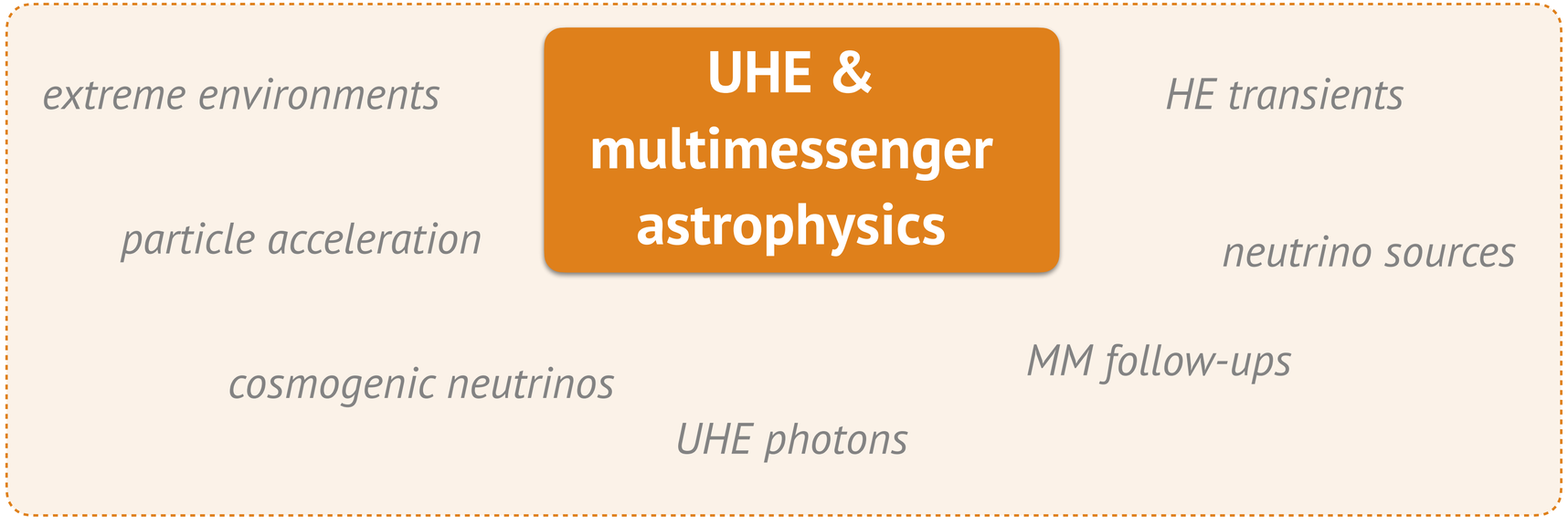

particle physics

one type of observatory, multiple purposes

extreme environments

UHE & multimessenger astrophysics

HE transients

particle acceleration

neutrino sources

MM follow-ups

cosmogenic neutrinos

UHE photons

fundamental physics

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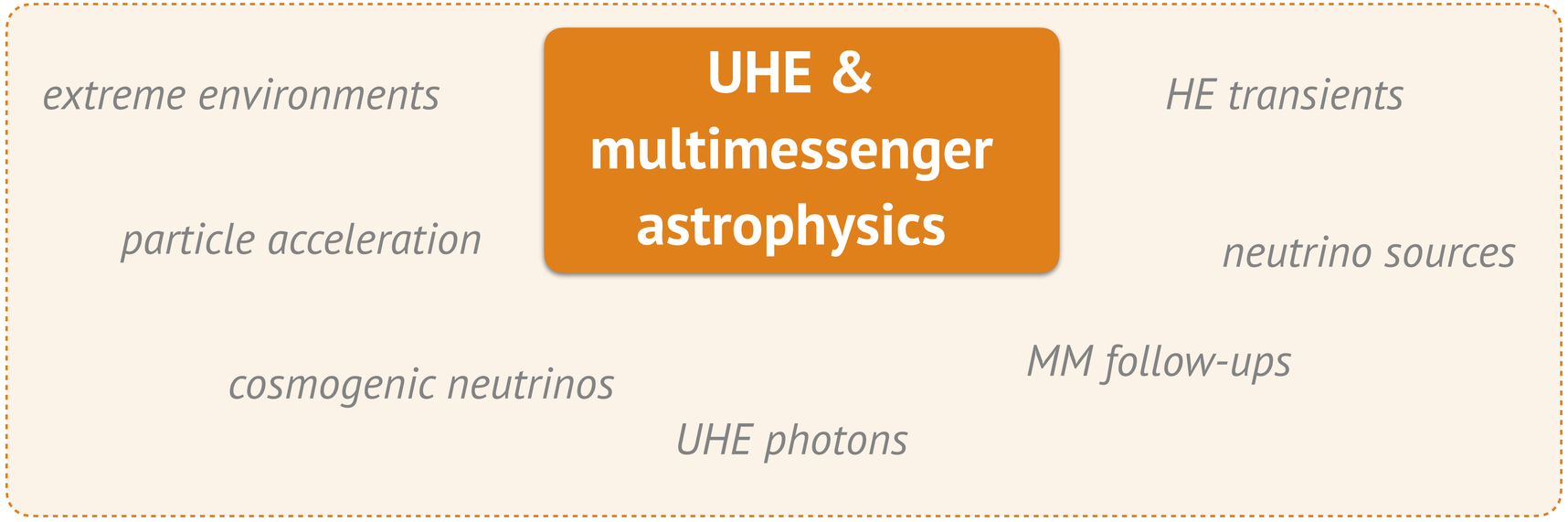

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solar wind

geo & atmospheric physics

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terrestrial gamma-ray flashes

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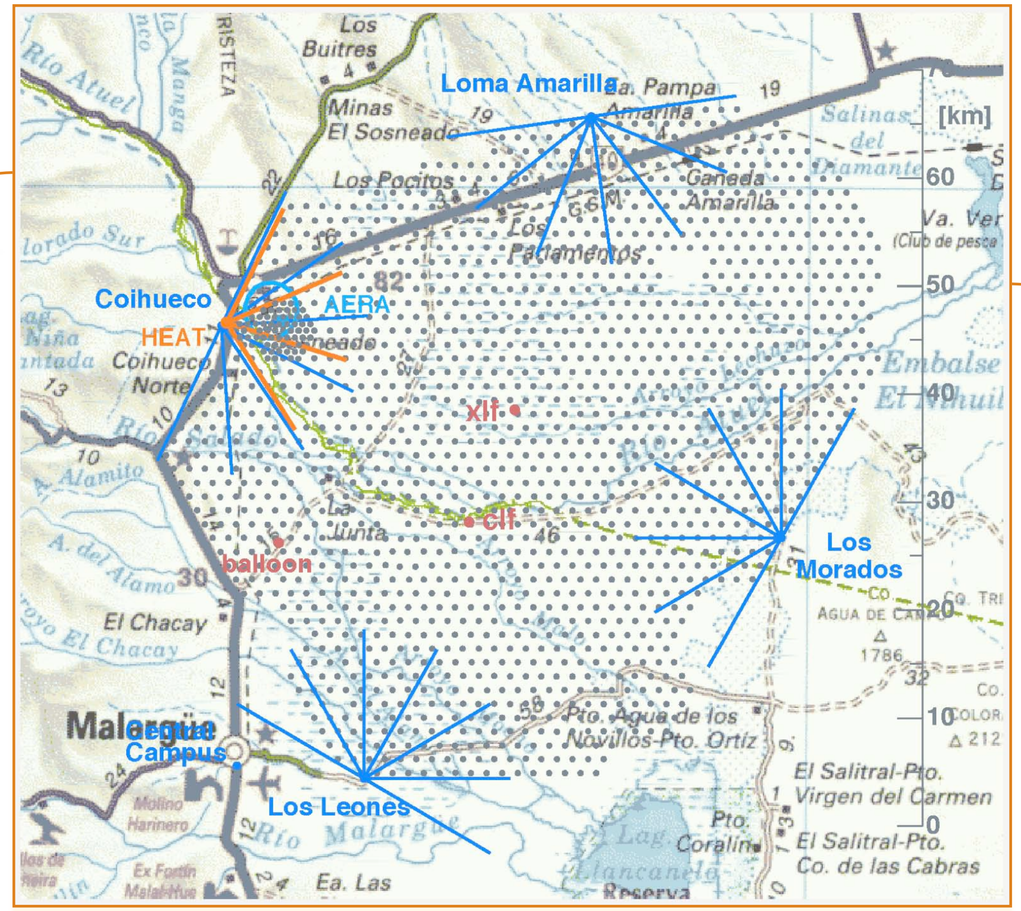
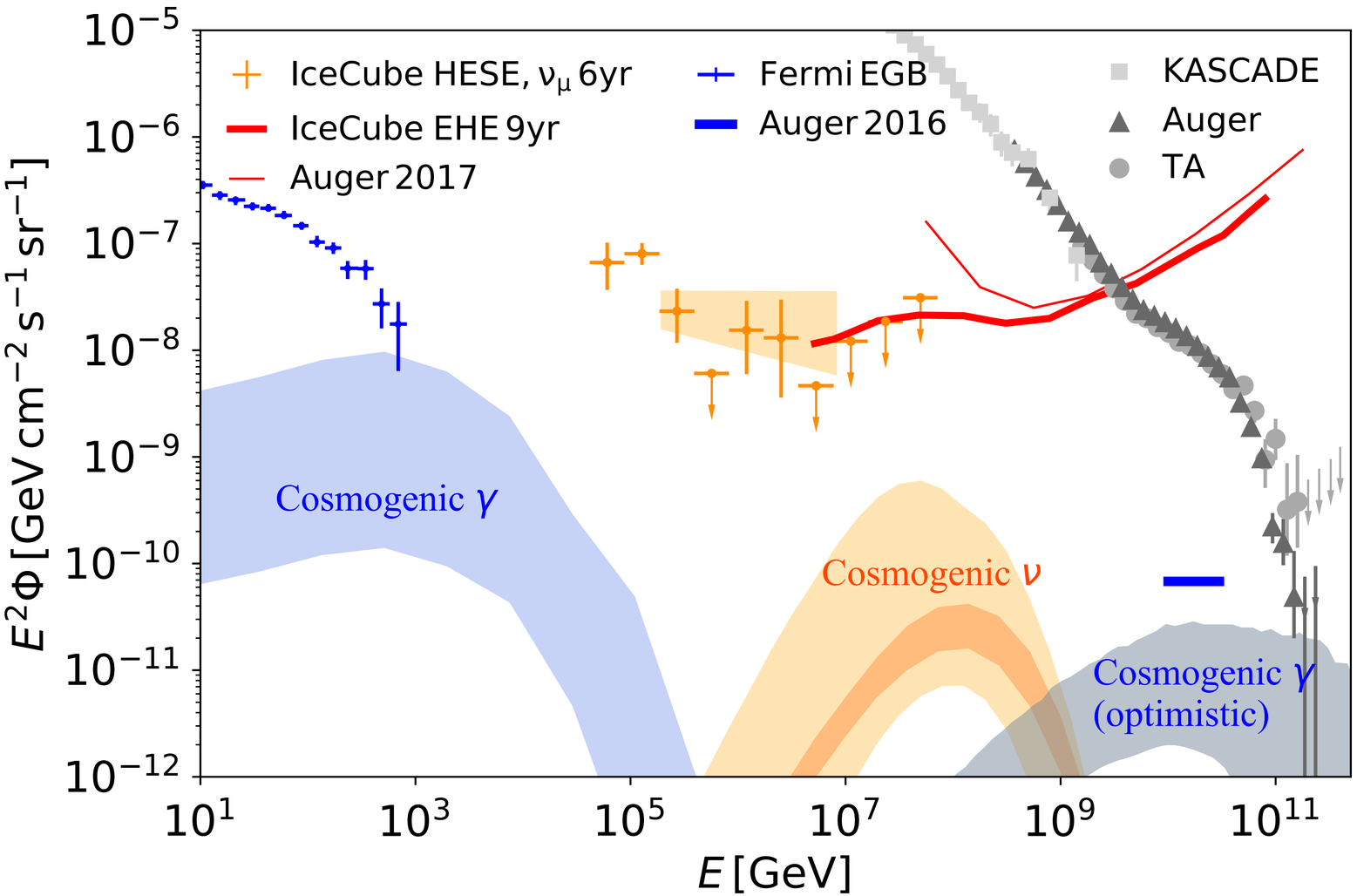
experimental landscape



cosmic rays in the multimessenger context

the high-energy multimessenger landscape

Alves Batista et al. Front. Astron. Space. Sci. 6 (2019) 23. arXiv:1903.06714



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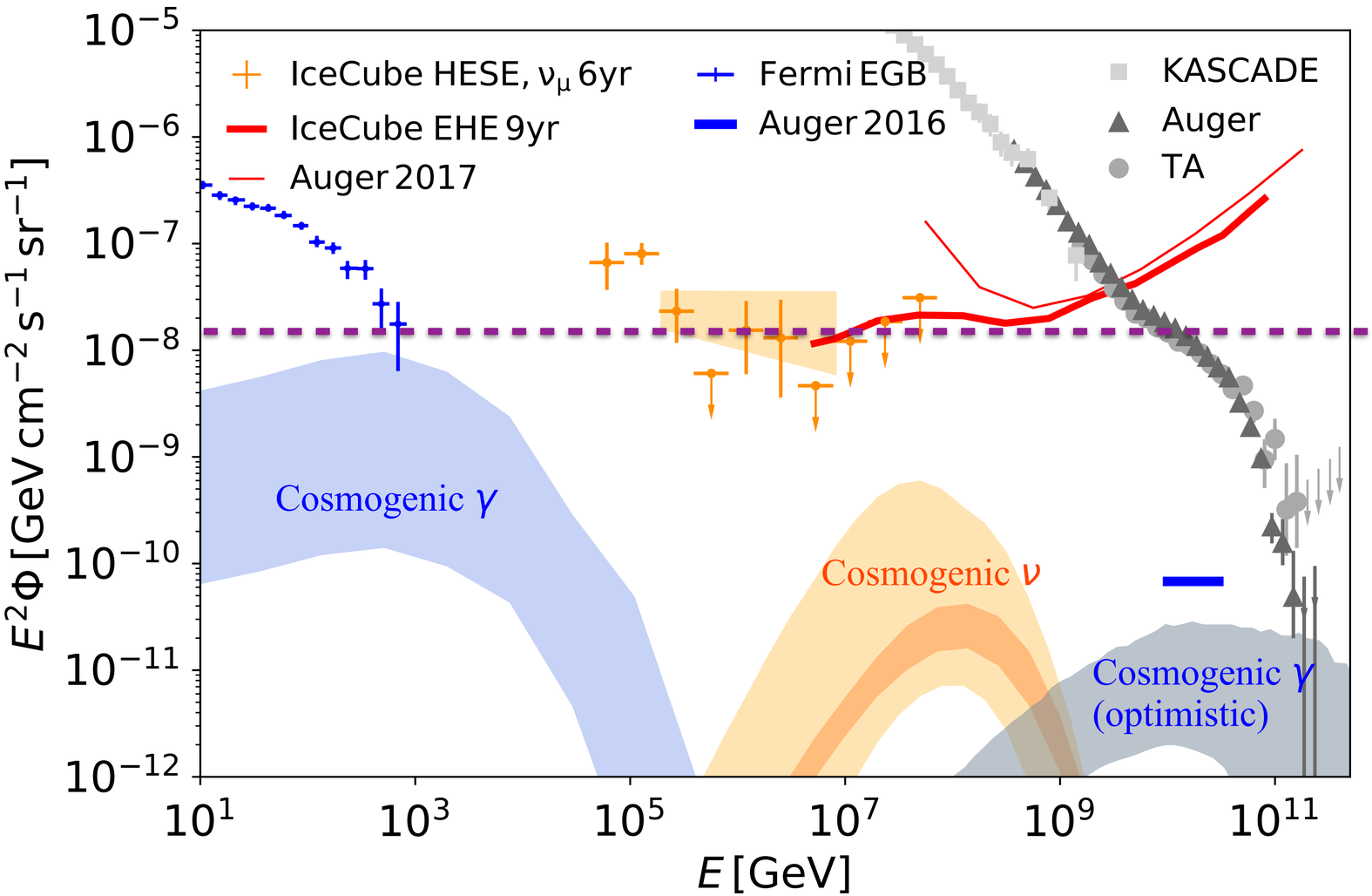

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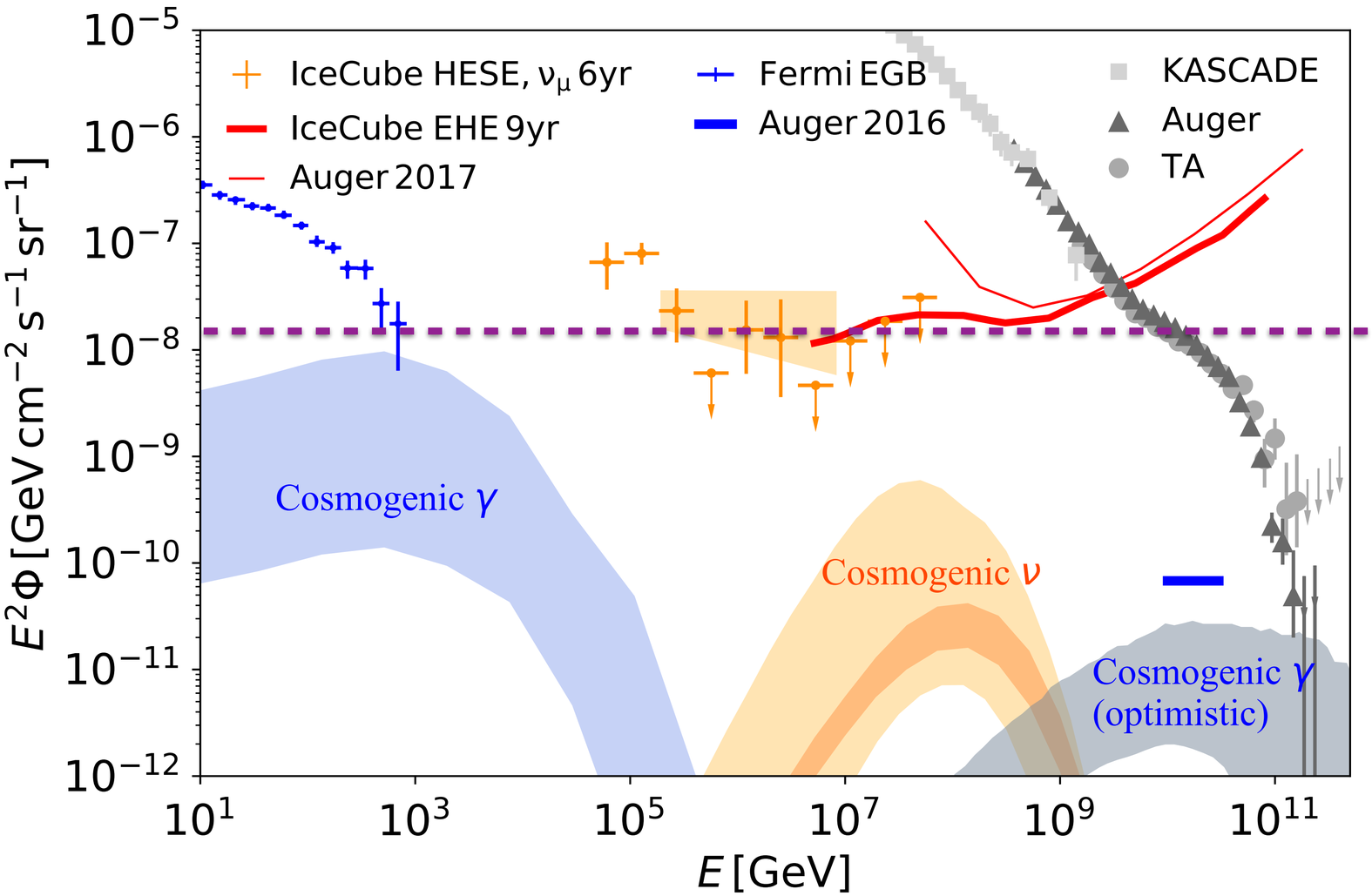

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hypothesis

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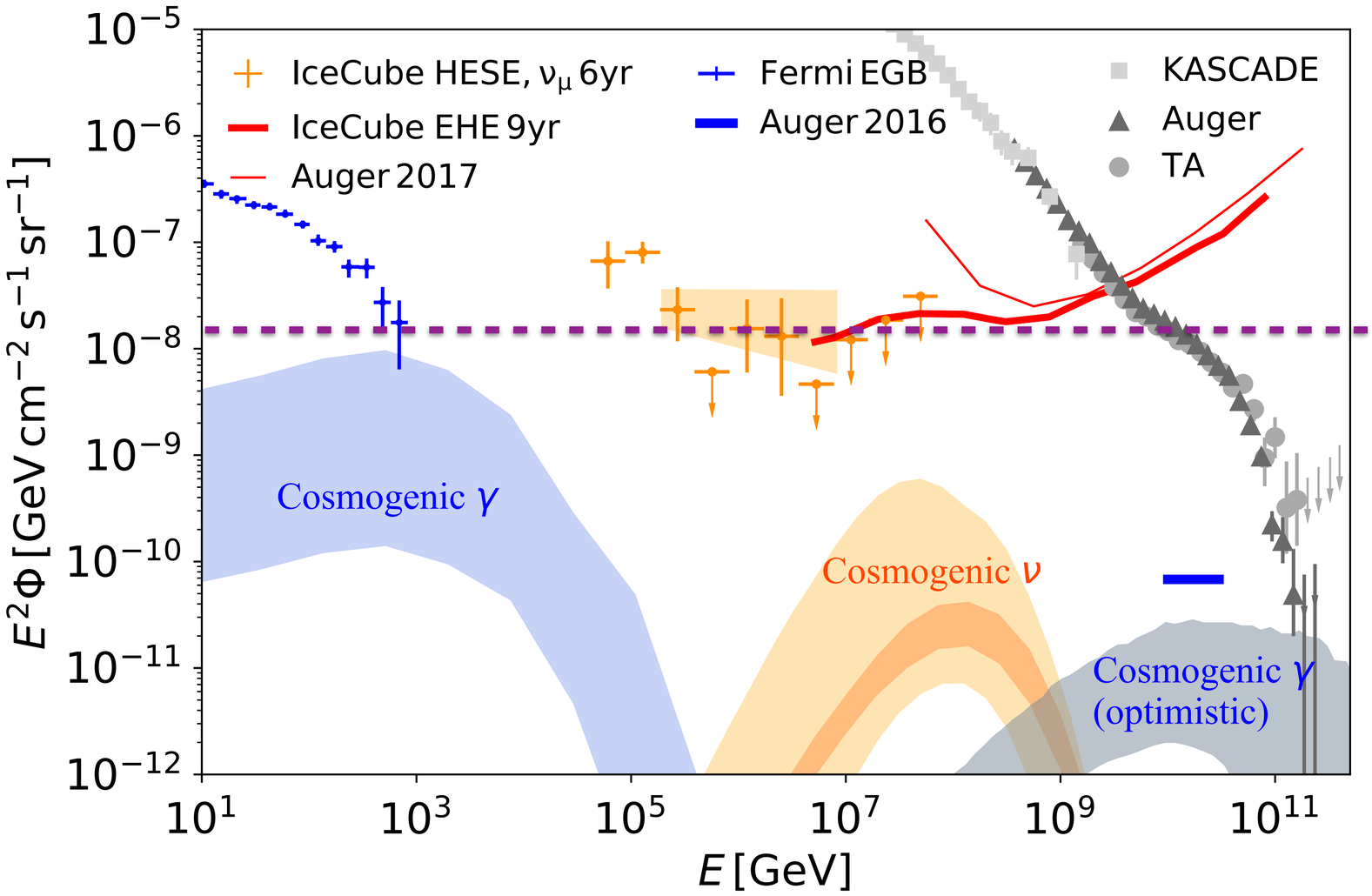

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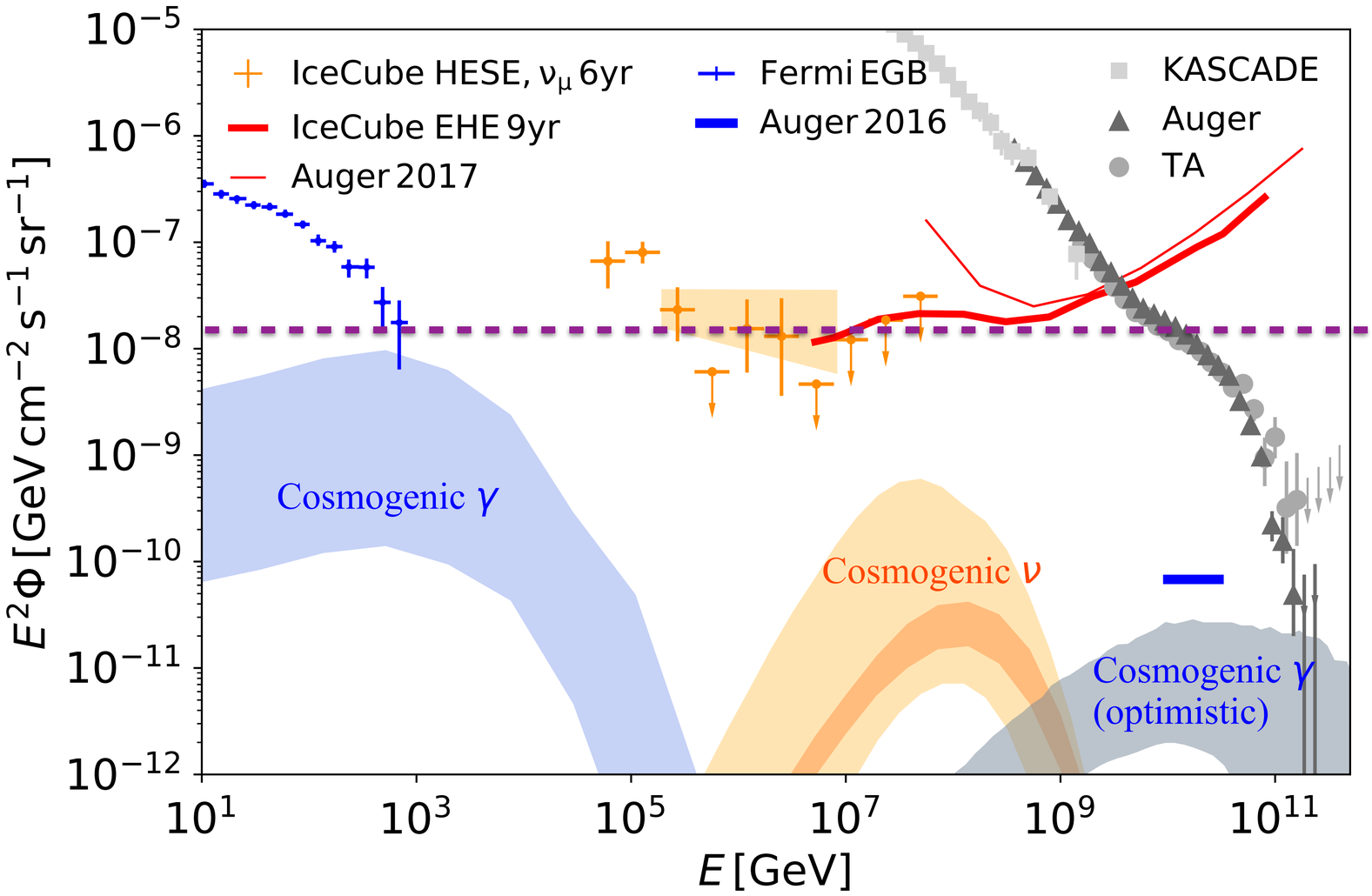

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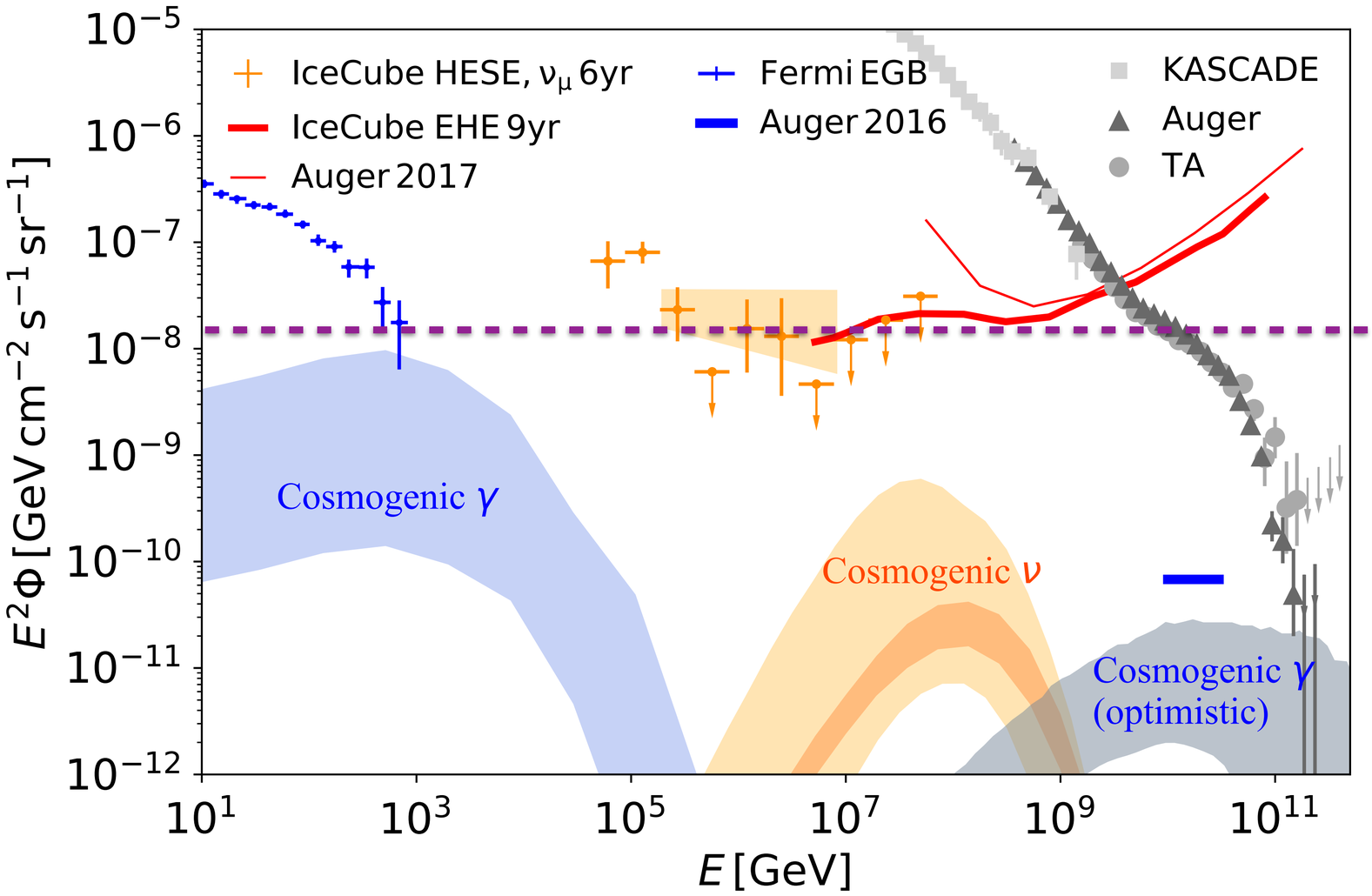

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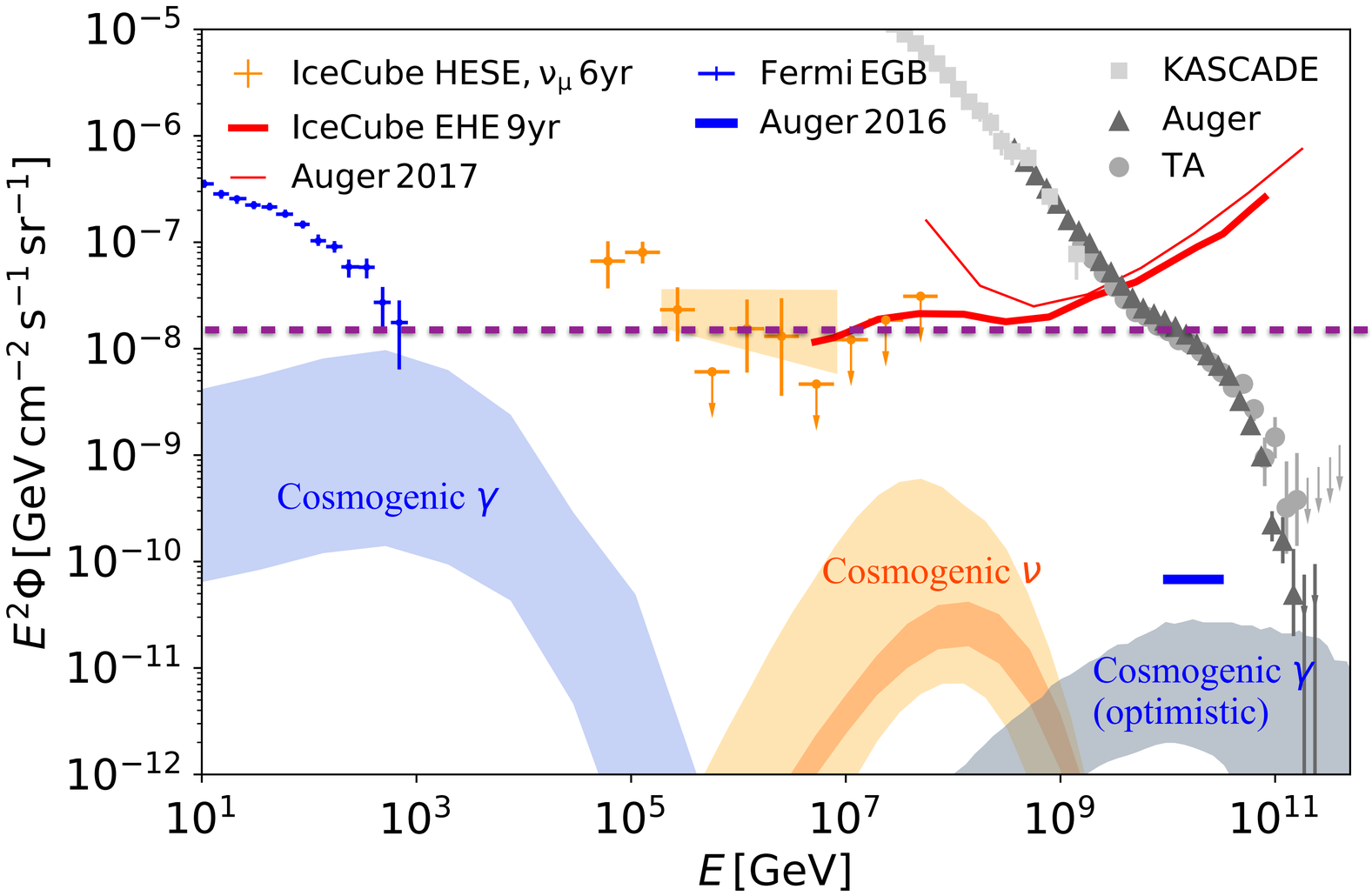

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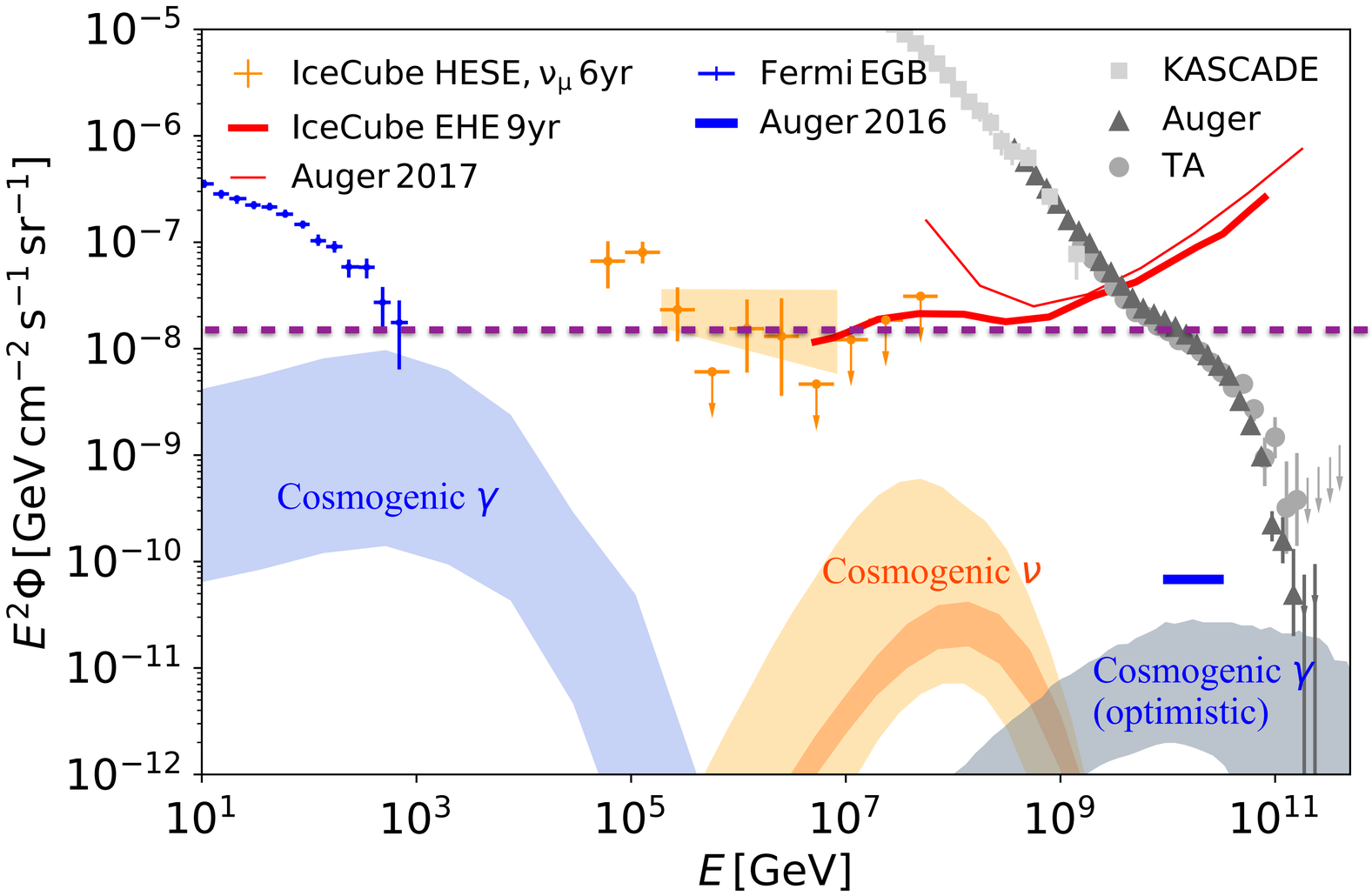

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need to understand how particles are produced and how they propagate

multimessenger picture: sources

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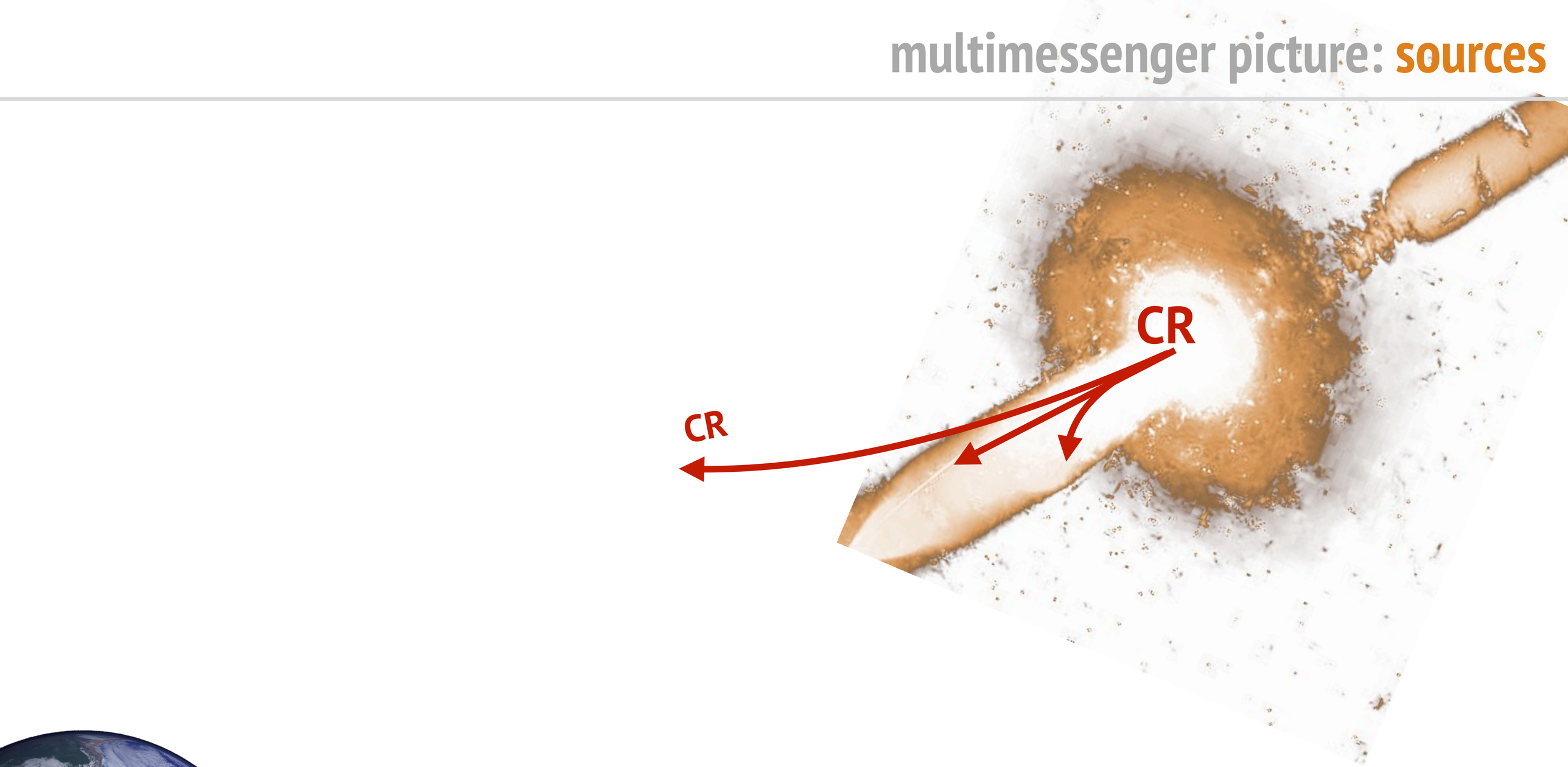

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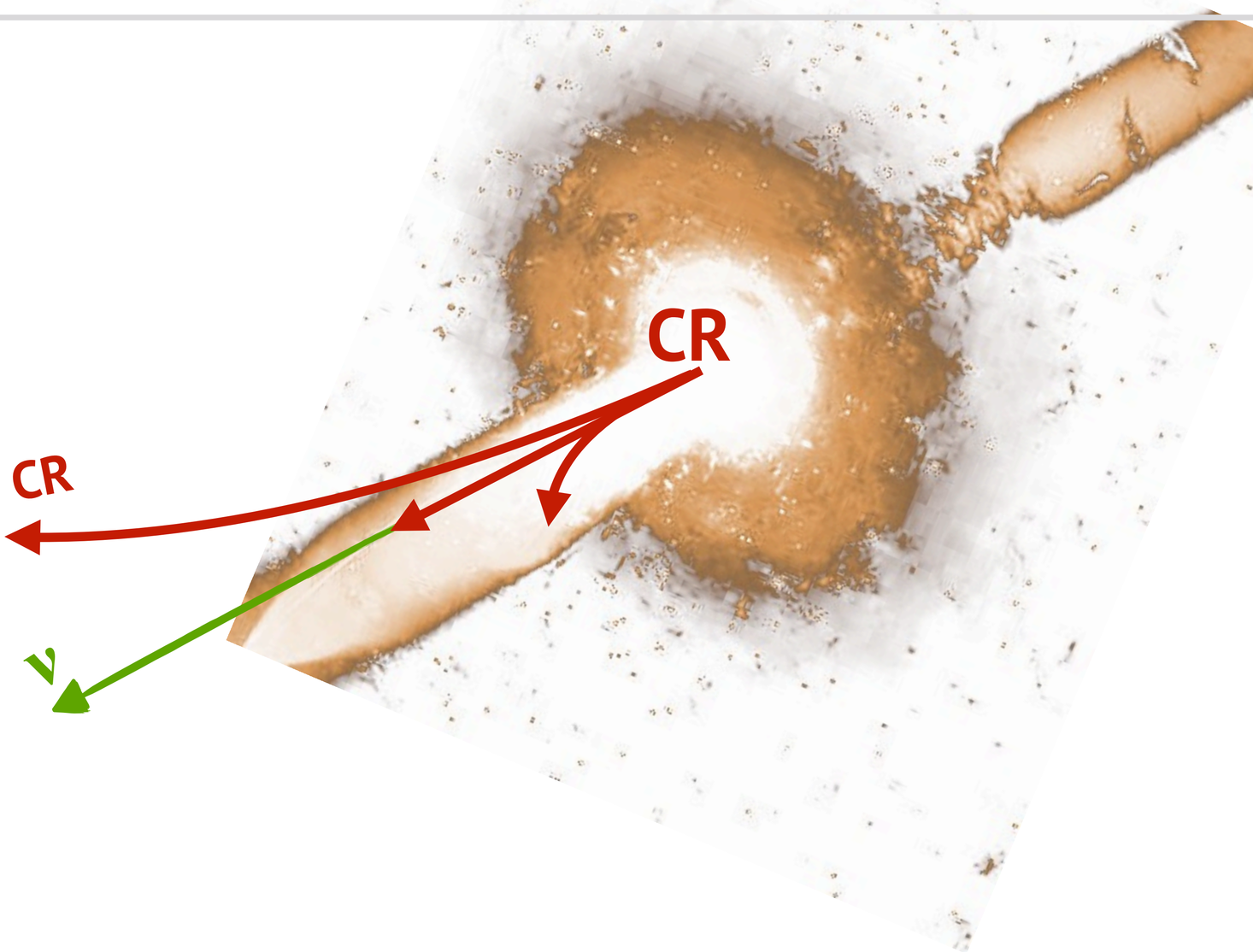

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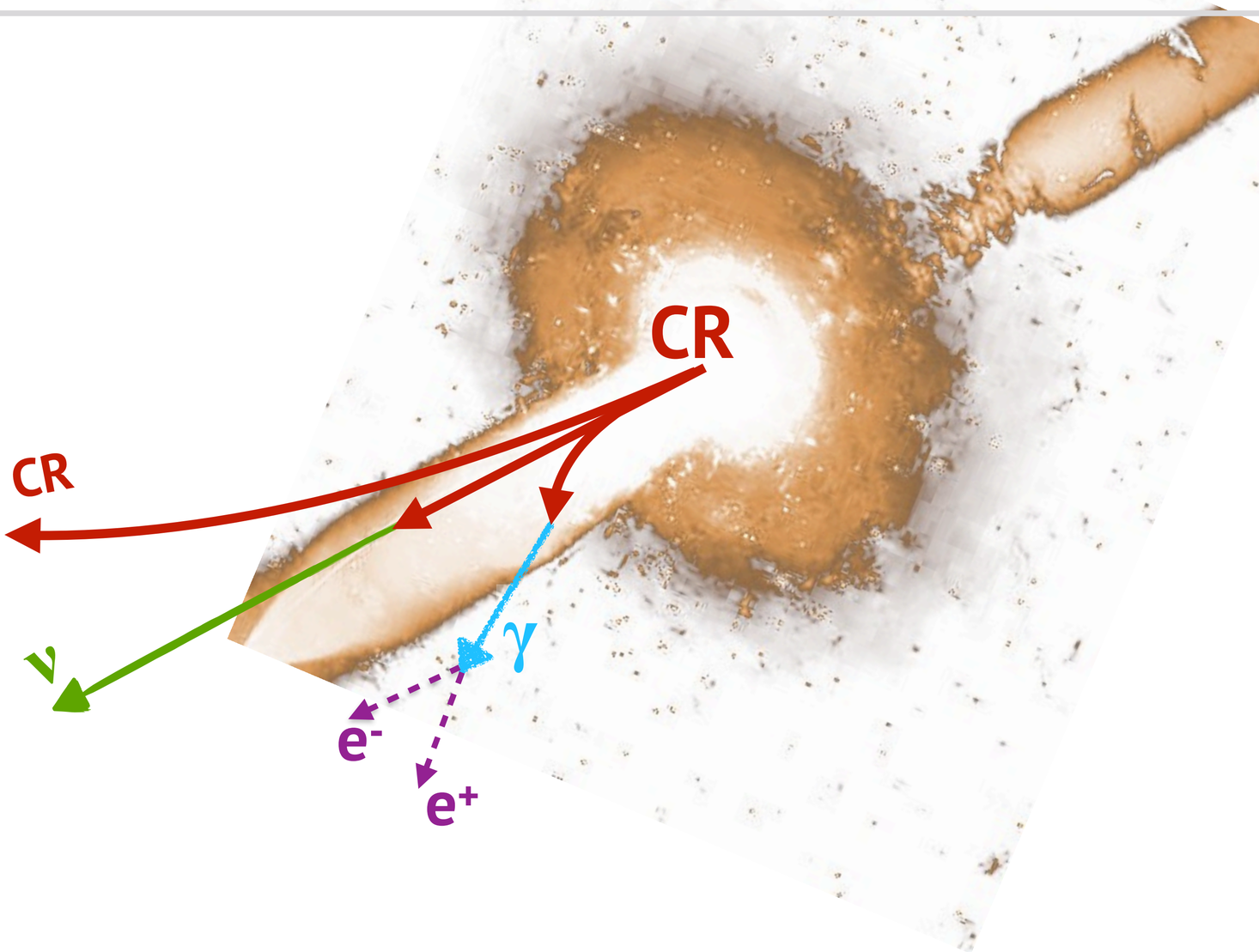

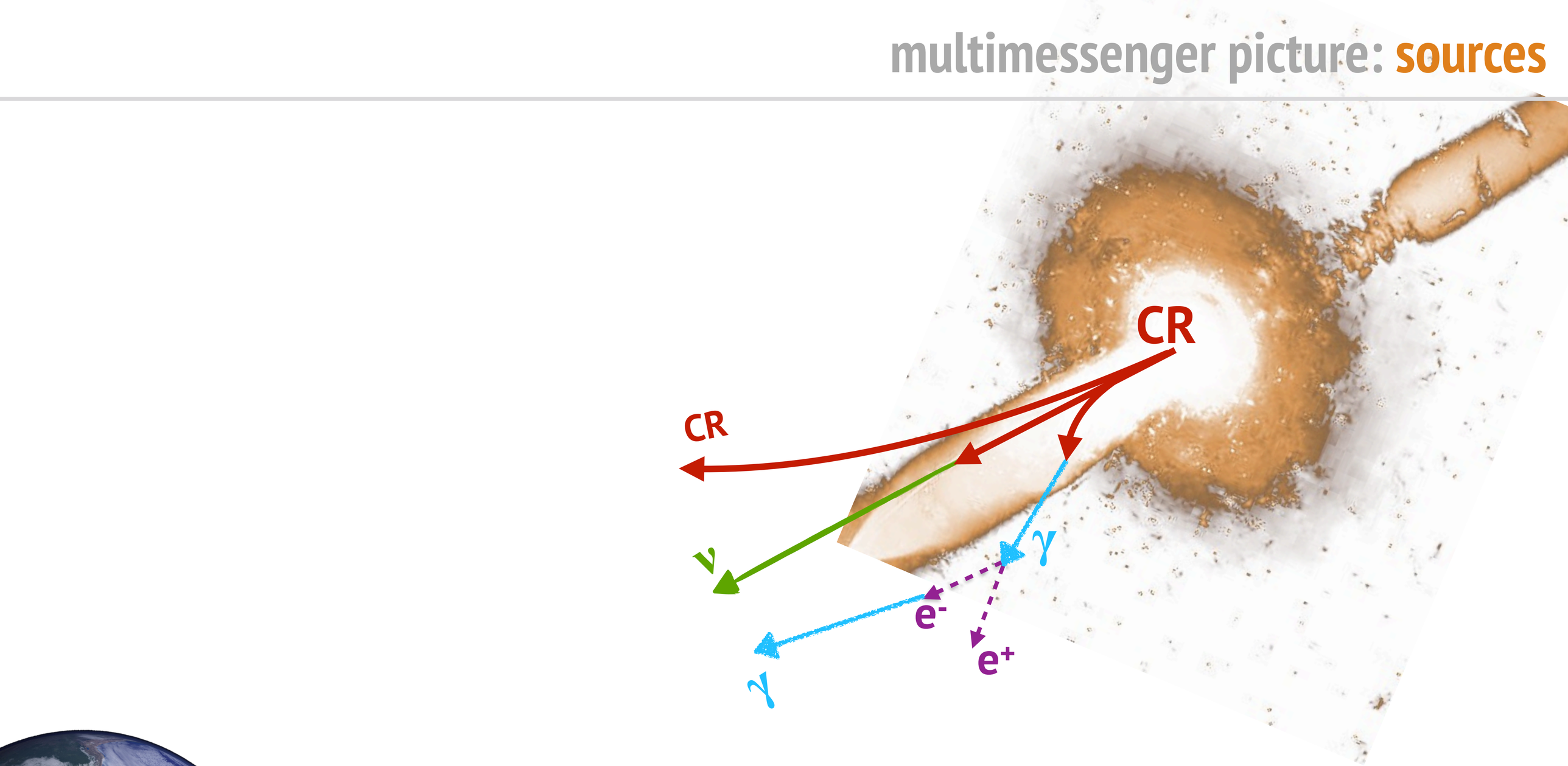
CR
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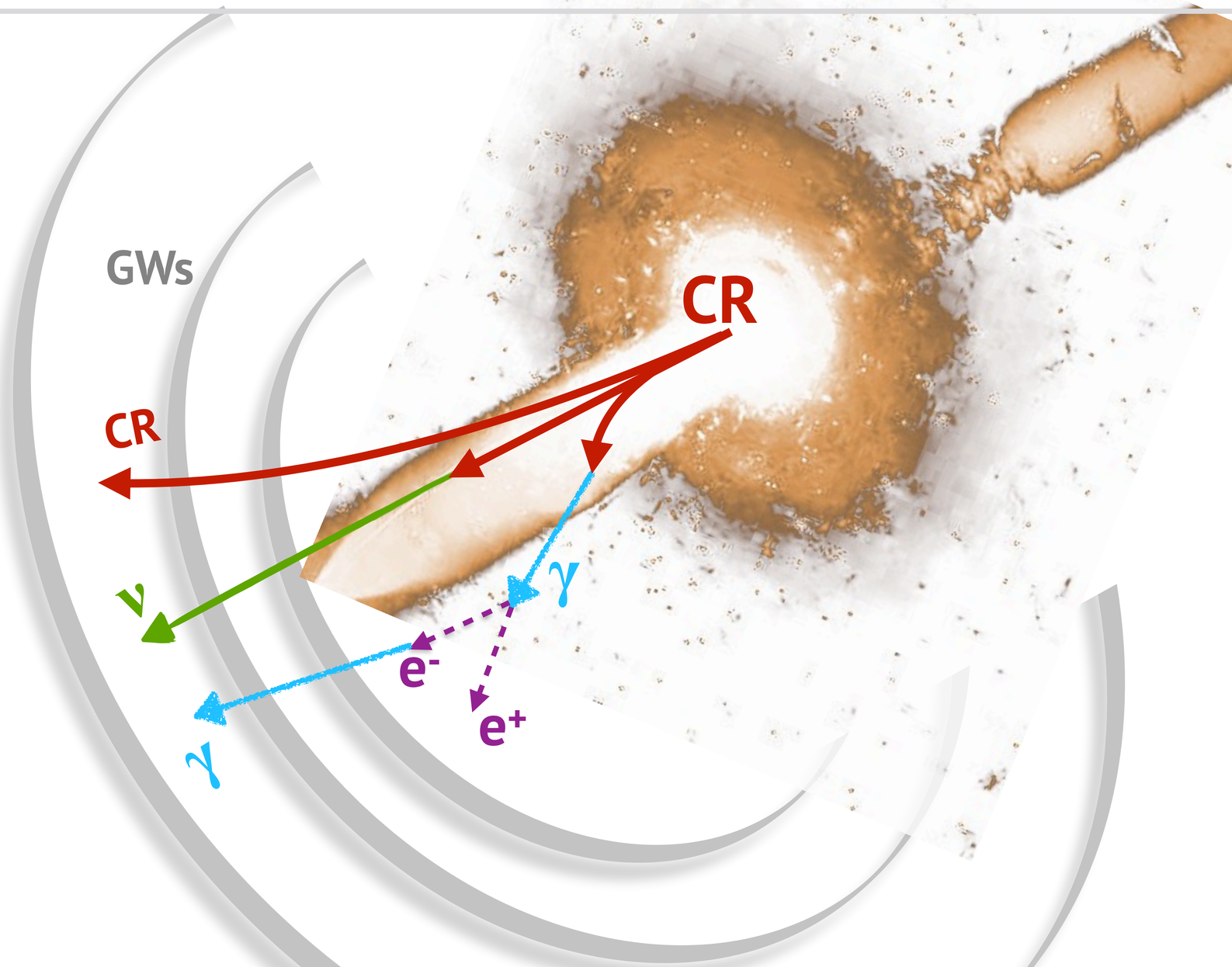
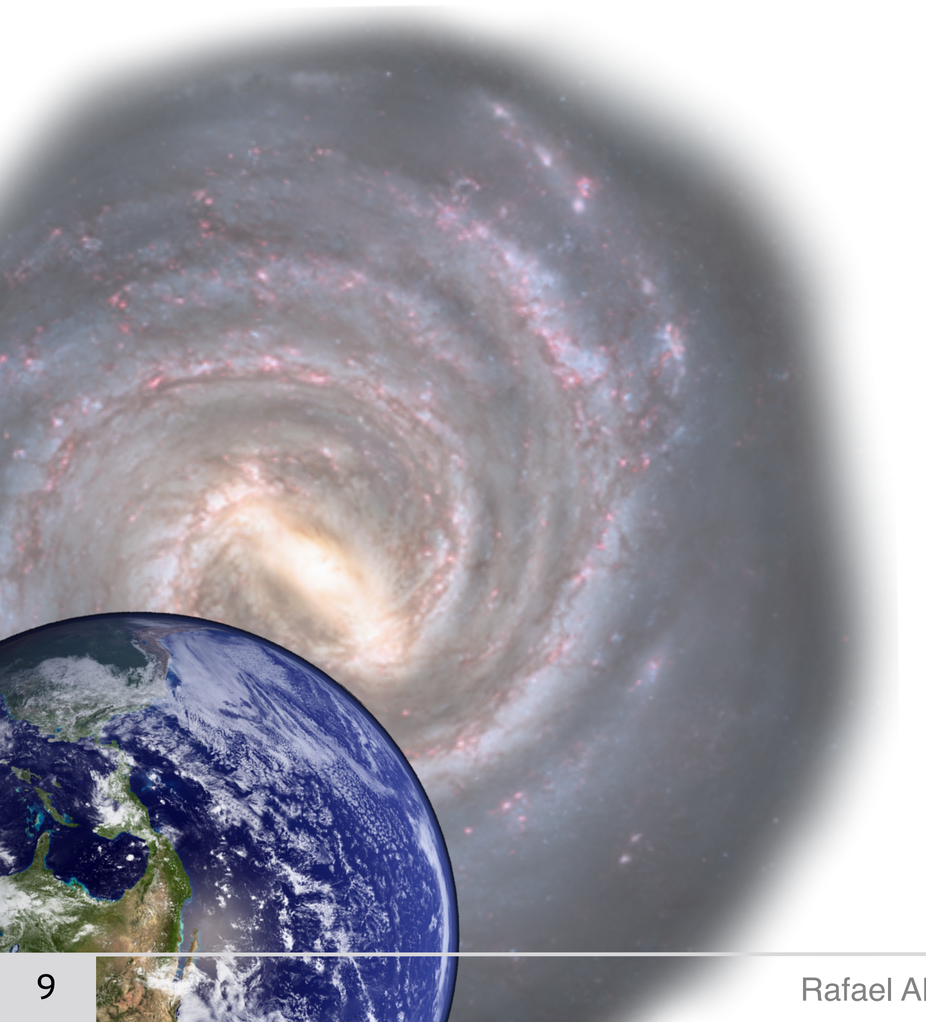


multimessenger propagation picture: cosmic rays and cosmogenic particles



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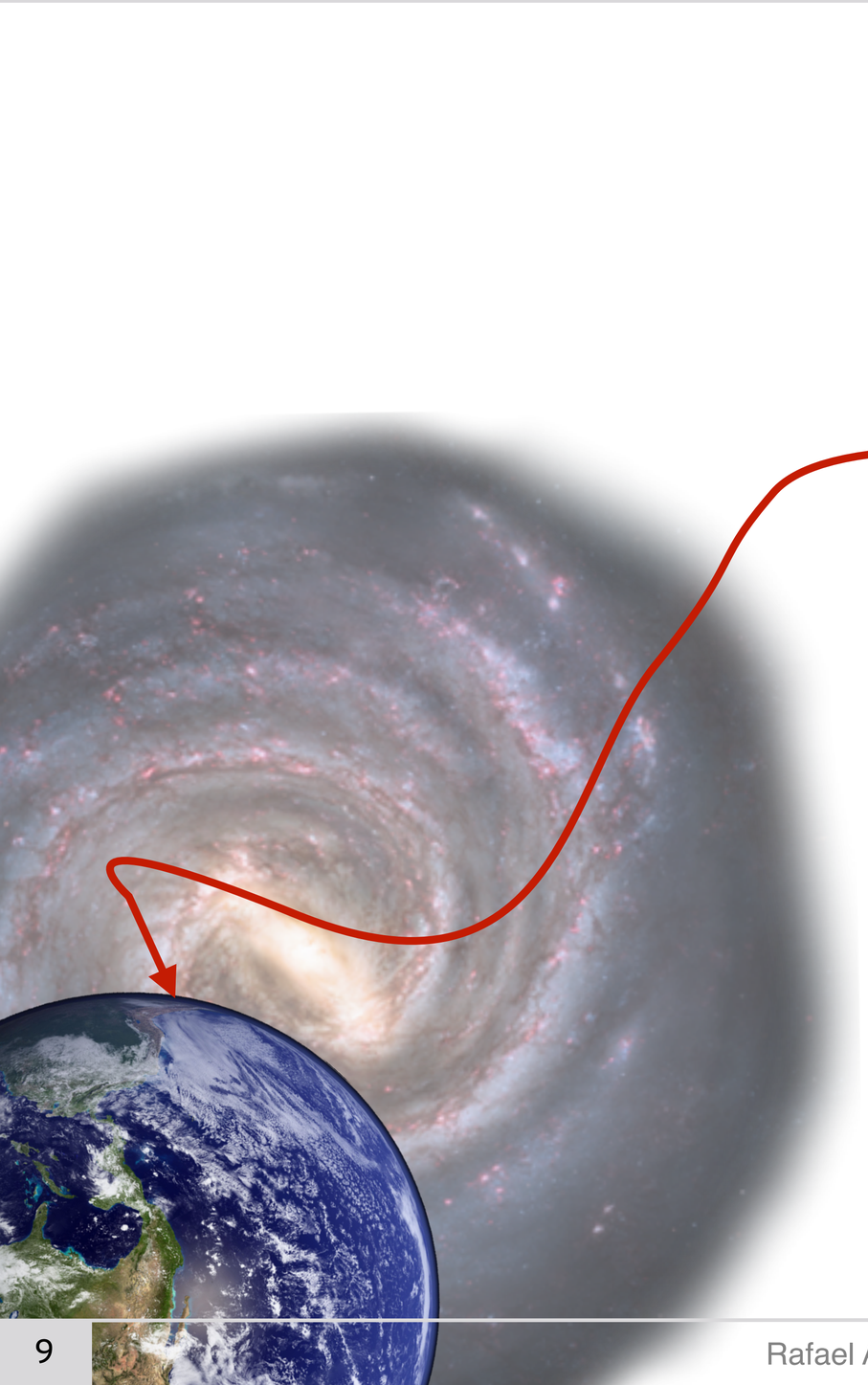

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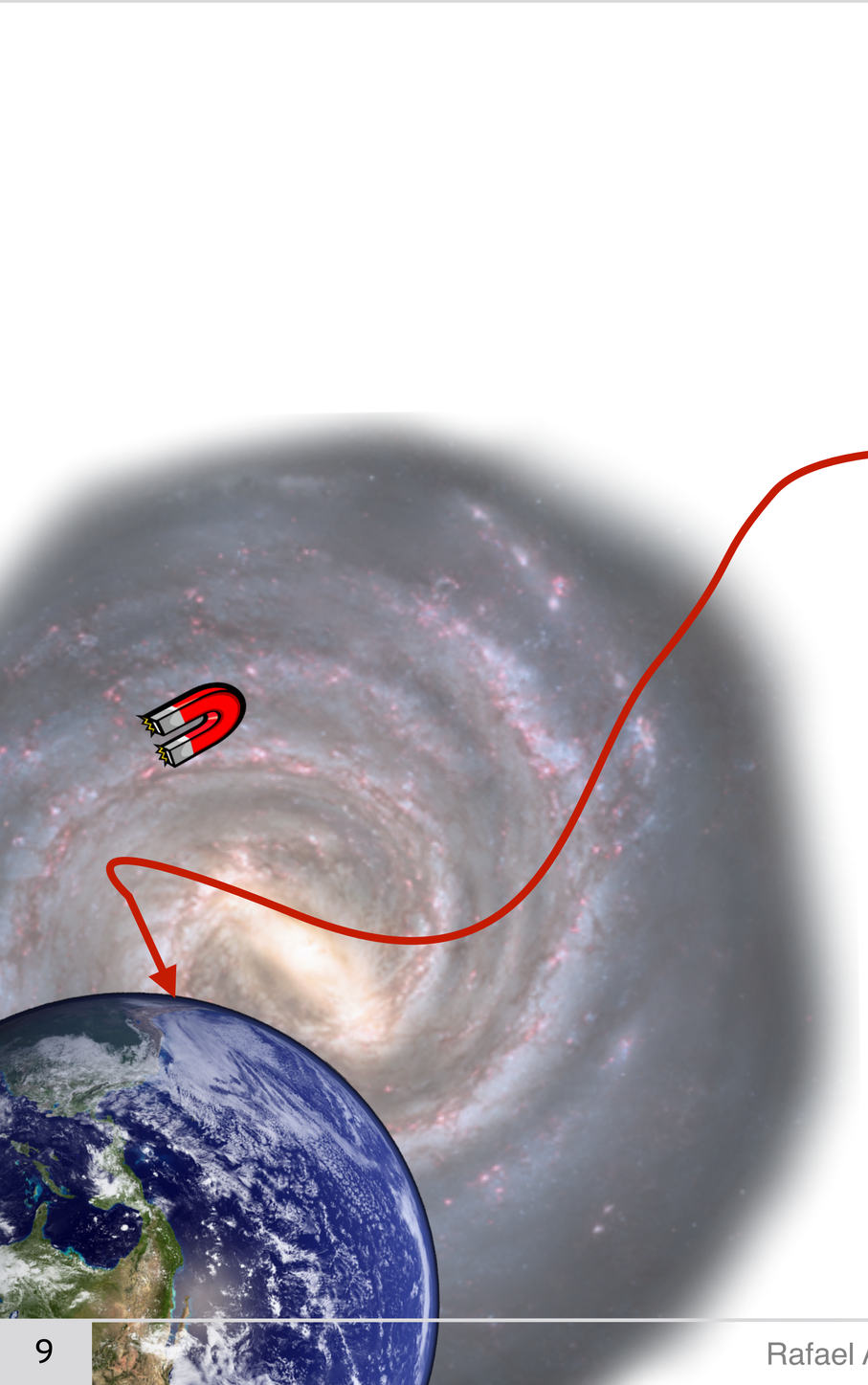

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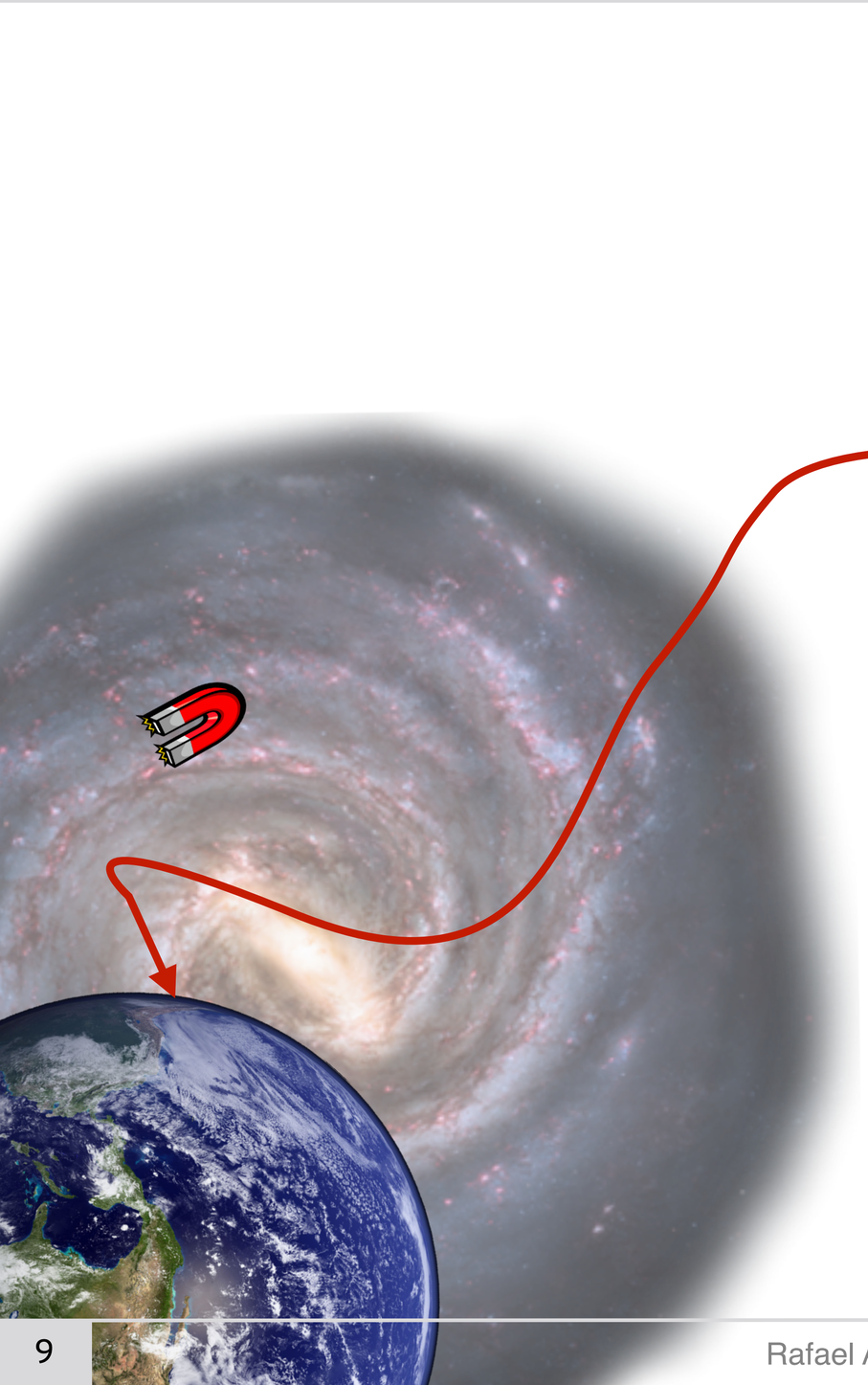
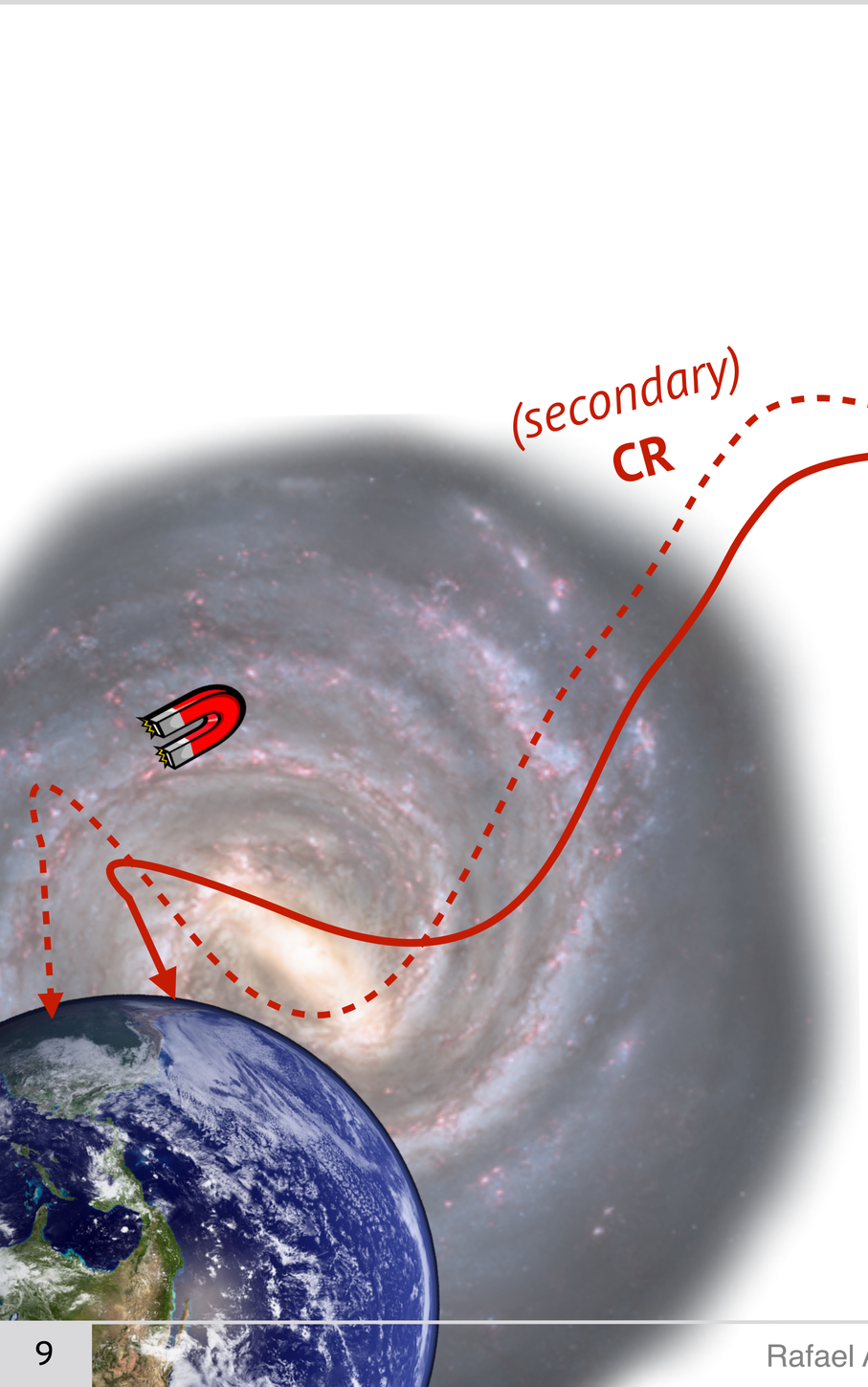


photodisintegration

$$
\begin{aligned}
&{}^{A}_{Z}X + \gamma_{\rm bg} \rightarrow {}^{A-1}_{Z-1}X + p \\
&{}^{A}_{Z}X + \gamma_{\rm bg} \rightarrow {}^{A-1}_{Z}X + n \\
&{}^{A}_{Z}X + \gamma_{\rm bg} \rightarrow {}^{A-4}_{Z-2}X + \alpha \\
&\dots
\end{aligned}
$$

multimessenger propagation picture: cosmic rays and cosmogenic particles



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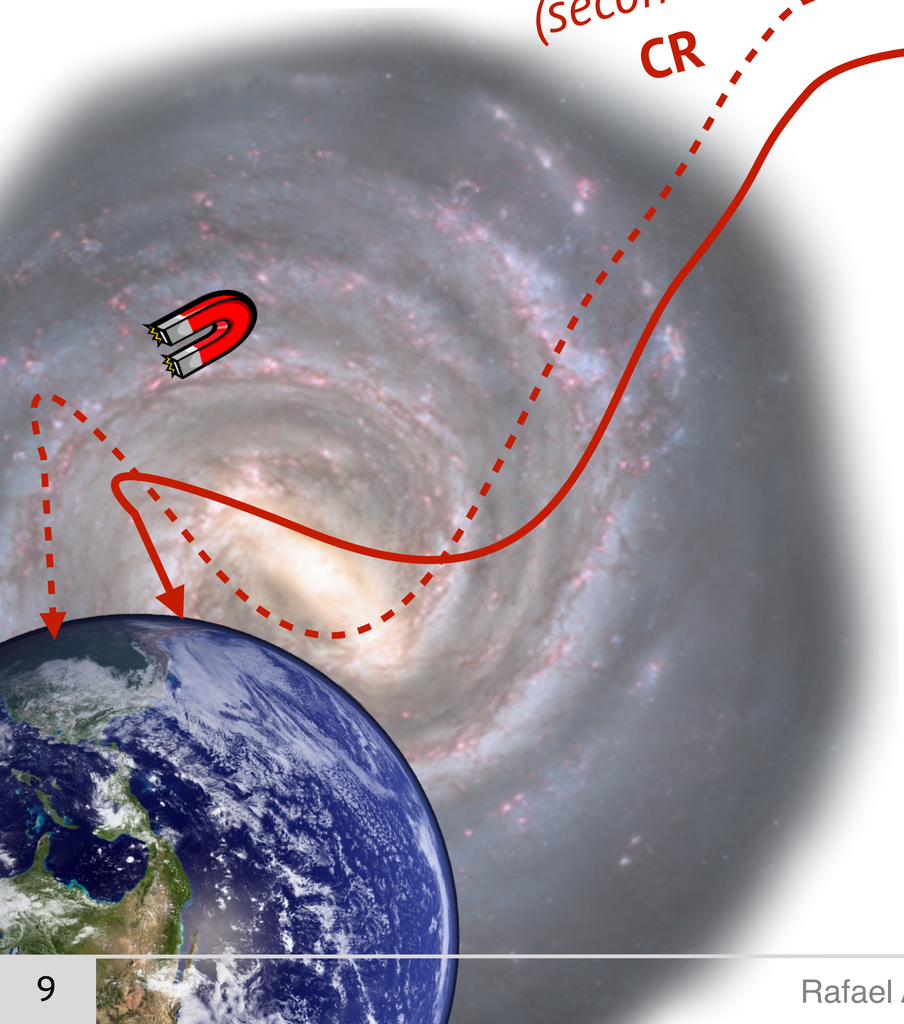
multimessenger propagation picture: cosmic rays and cosmogenic particles

photopion production

$$p + \gamma_{\rm bg} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$



photodisintegration

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multimessenger propagation picture: cosmic rays and cosmogenic particles

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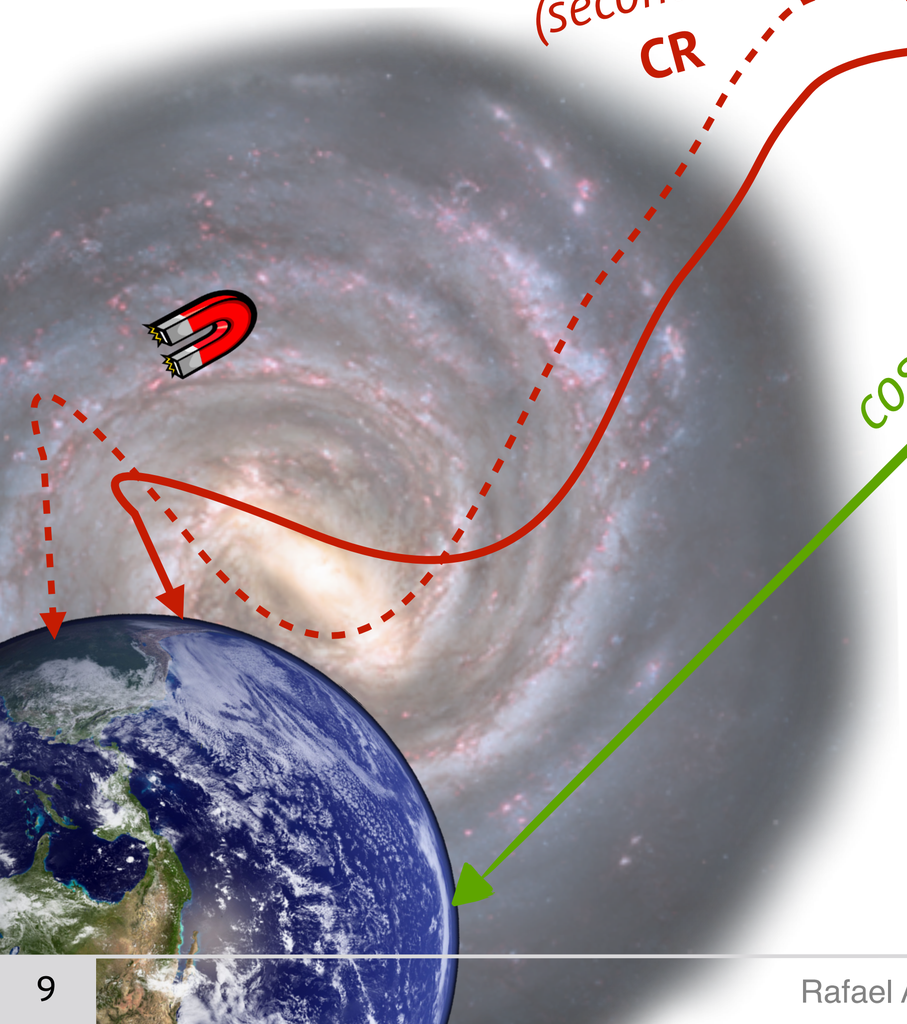
CR

(secondary) CR

cosmogenic ν



photodisintegration

$$^{A}_{Z}X + \gamma_{\rm bg} \rightarrow ^{A-1}_{Z-1}X + p$$

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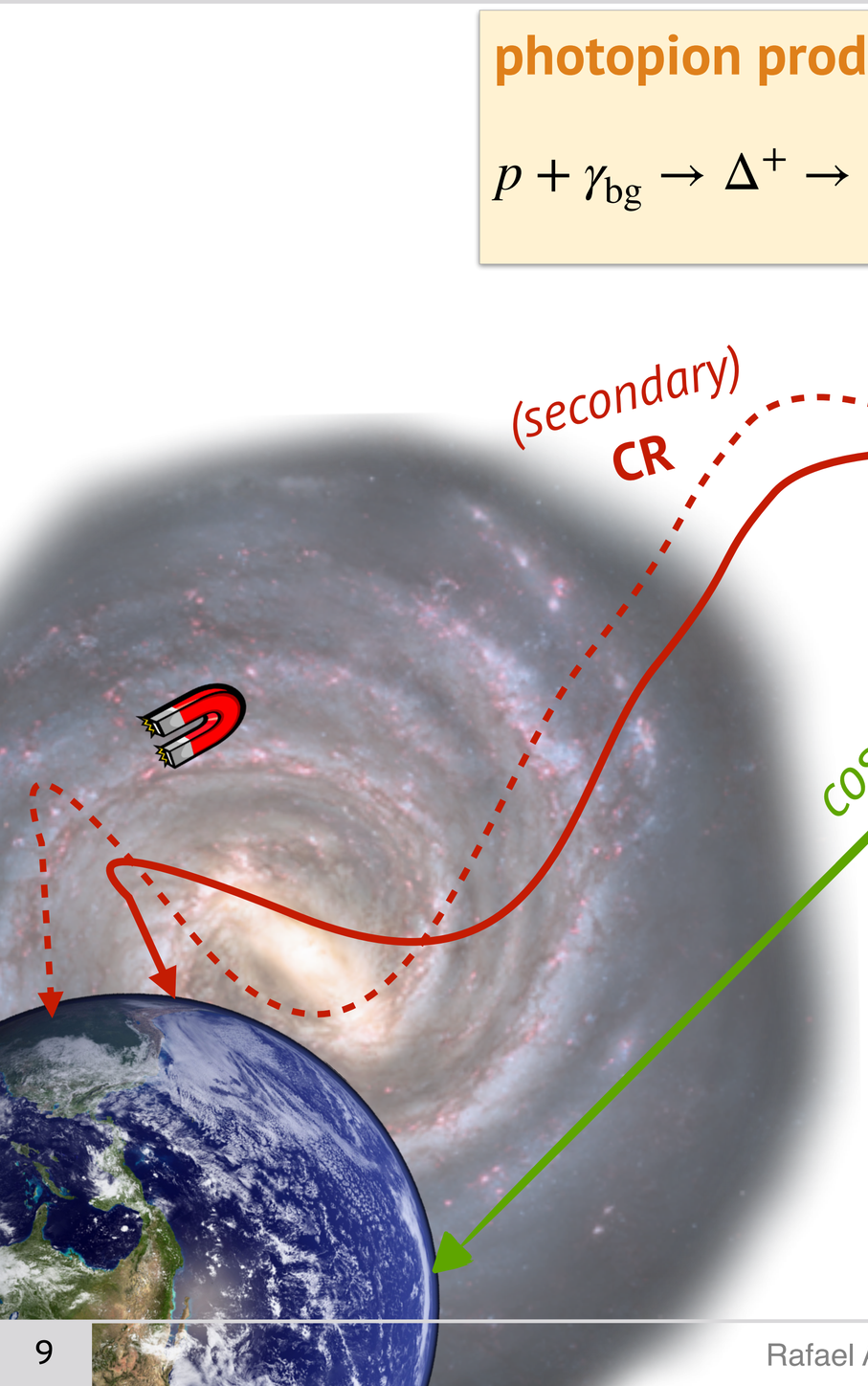

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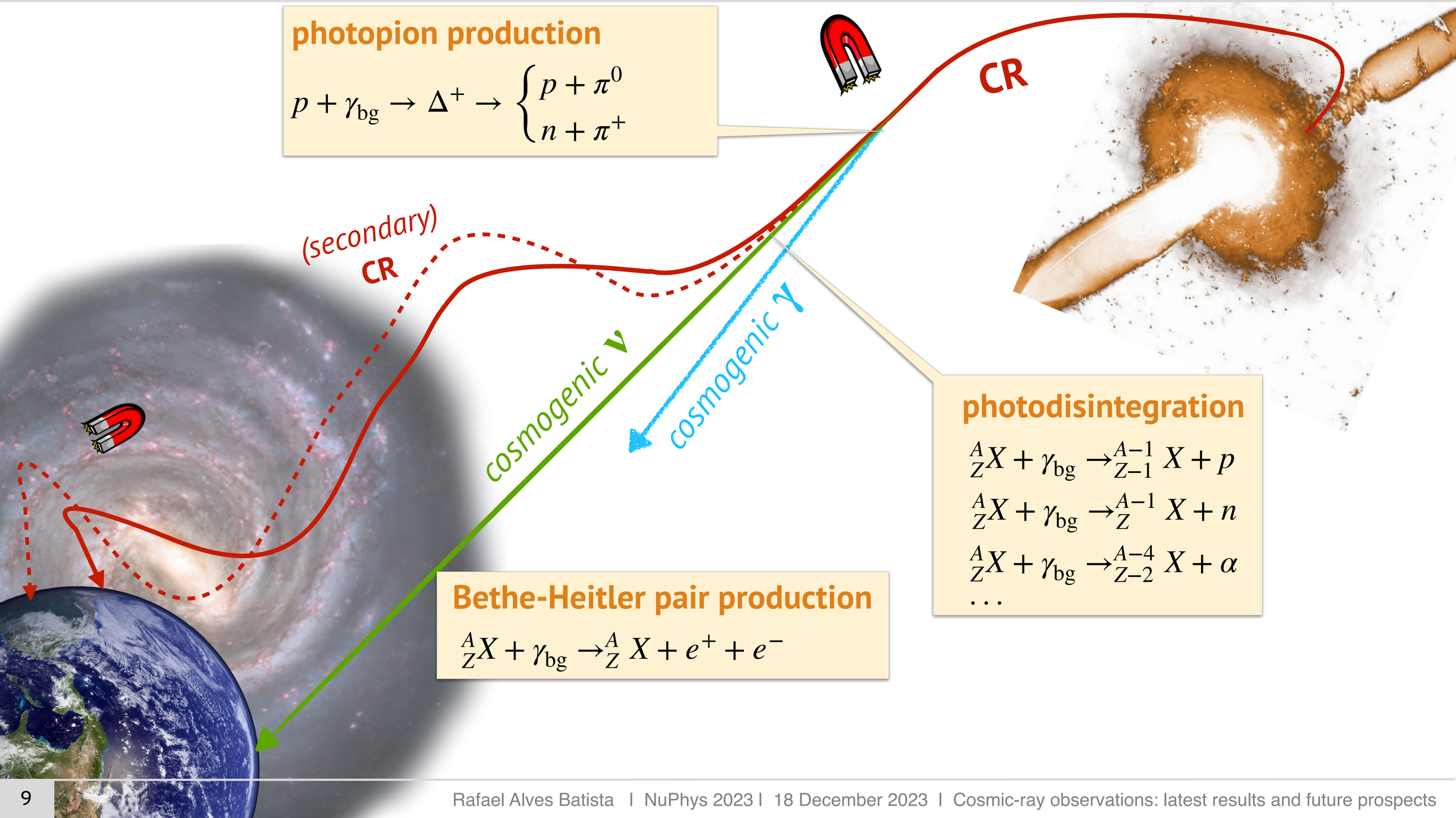
multimessenger propagation picture: cosmic rays and cosmogenic particles

photopion production

$$p + \gamma_{\rm bg} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$



photodisintegration

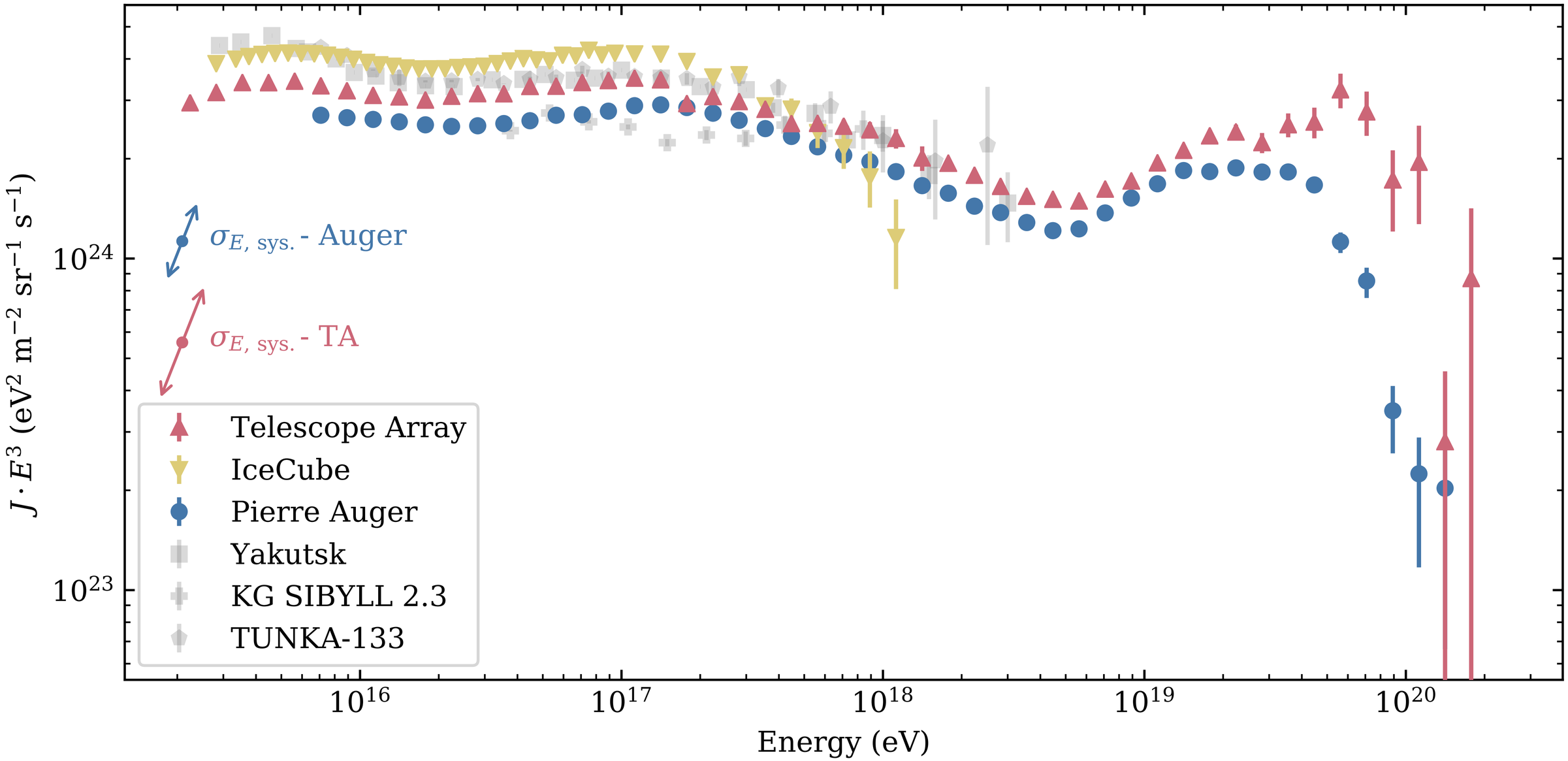
$$^{A}_{Z}X + \gamma_{\rm bg} \rightarrow ^{A-1}_{Z-1}X + p$$
$$^{A}_{Z}X + \gamma_{\rm bg} \rightarrow ^{A-1}_{Z}X + n$$
$$^{A}_{Z}X + \gamma_{\rm bg} \rightarrow ^{A-4}_{Z-2}X + \alpha$$
$$\dots$$

Bethe-Heitler pair production

$$^{A}_{Z}X + \gamma_{\rm bg} \rightarrow ^{A}_{Z}X + e^+ + e^-$$

recent results

Coleman et al. Astroparticle Physics 149 (2023) 102819. arXiv:2205.05845



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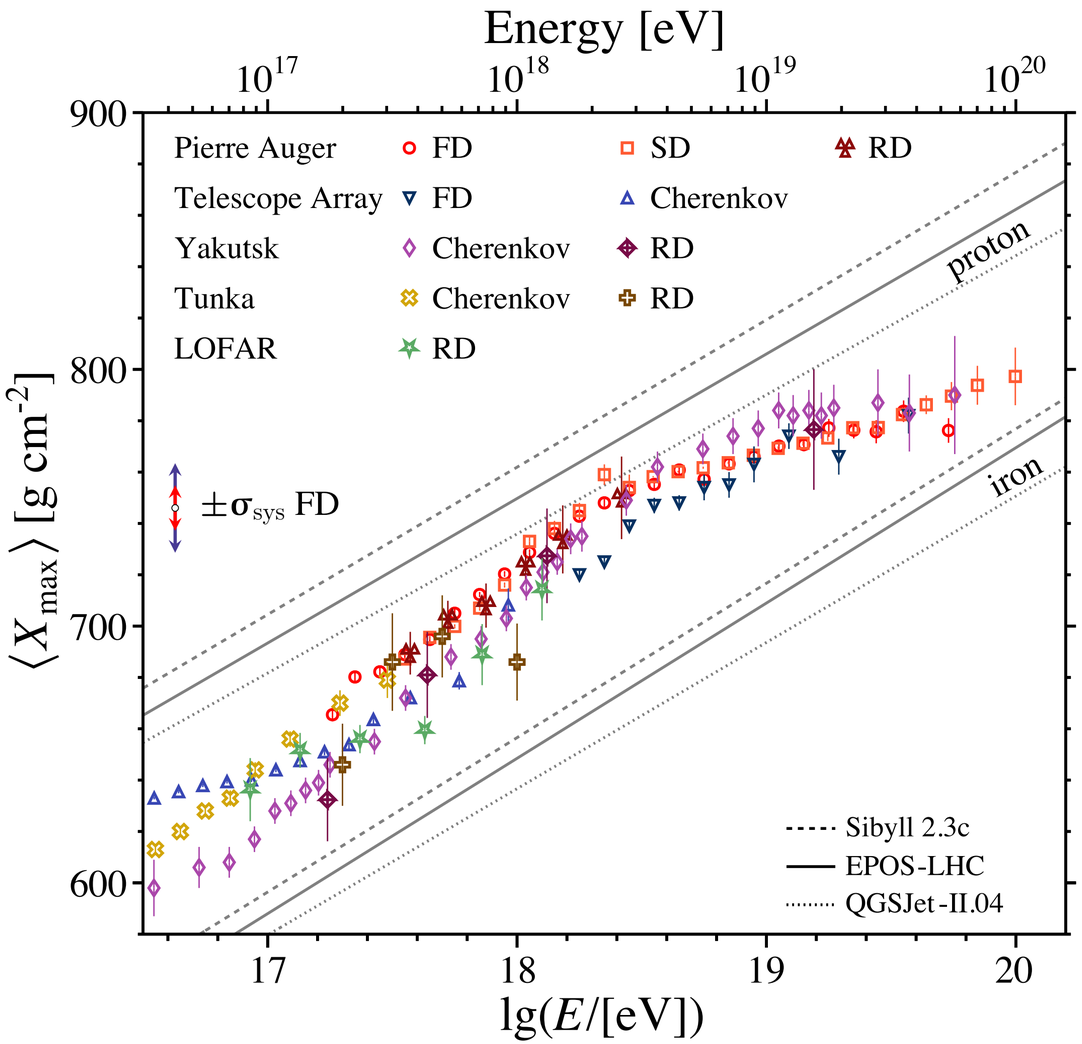
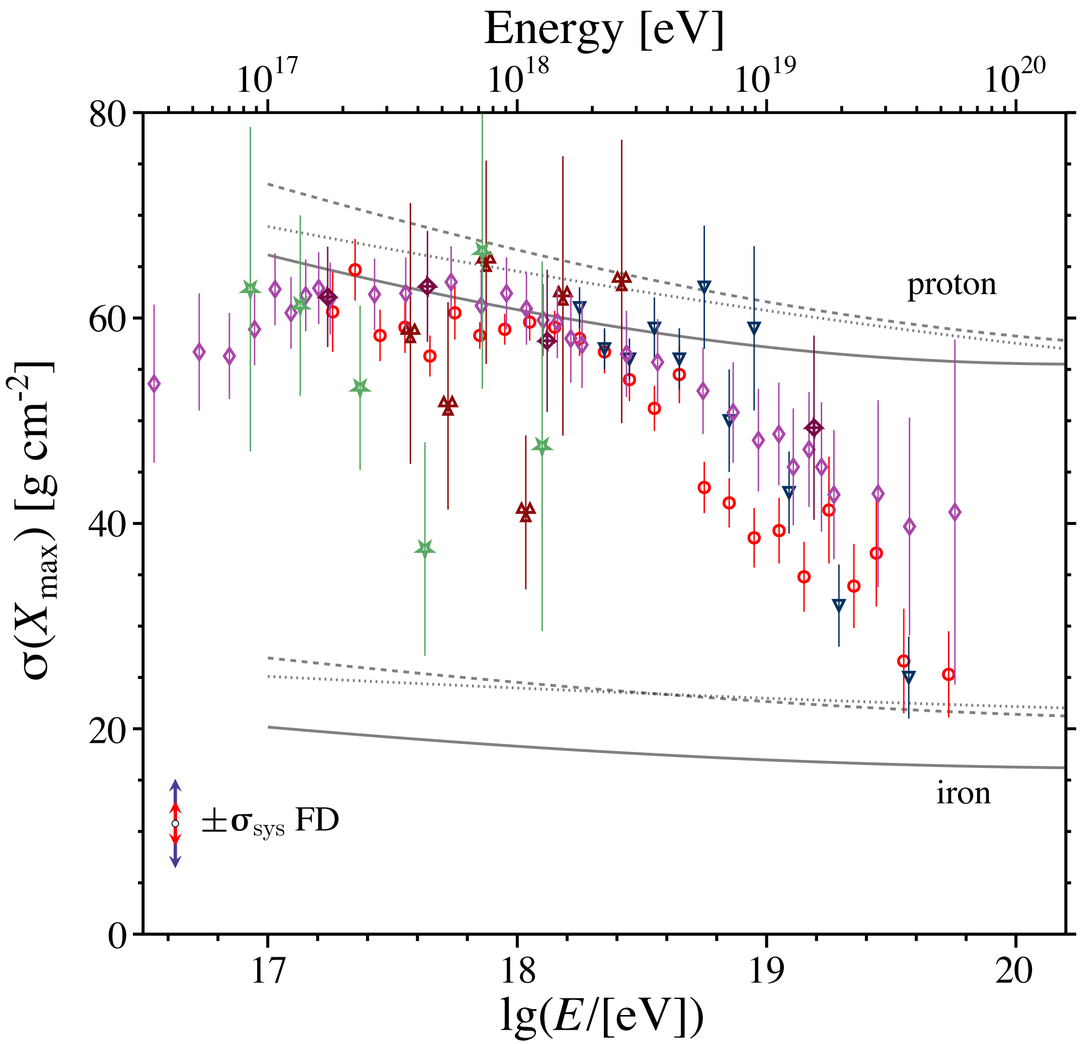
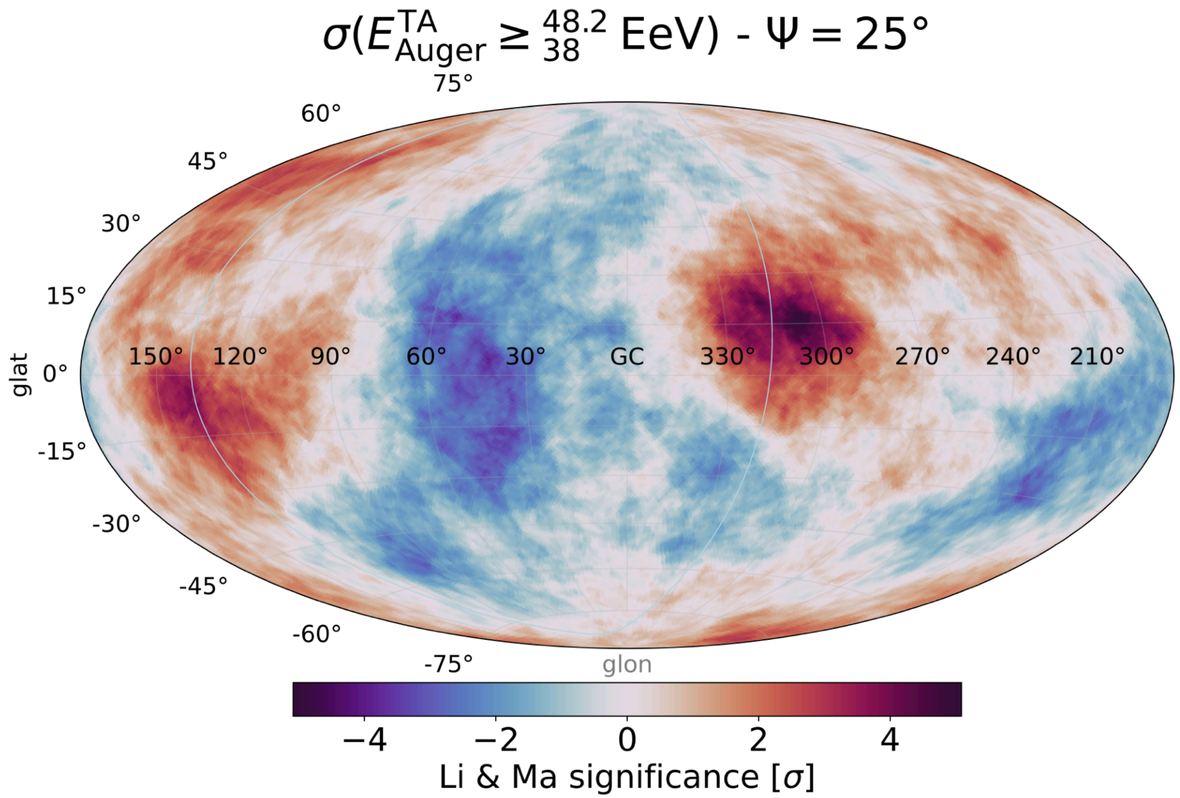




CR measurements. intermediate-scale anisotropies

Pierre Auger Collaboration. ApJ. 938 (2022) 170. arXiv:2206.13492

Caccianiga et al. for the Auger and TA Collaborations. PoS (ICRC2023) 521.



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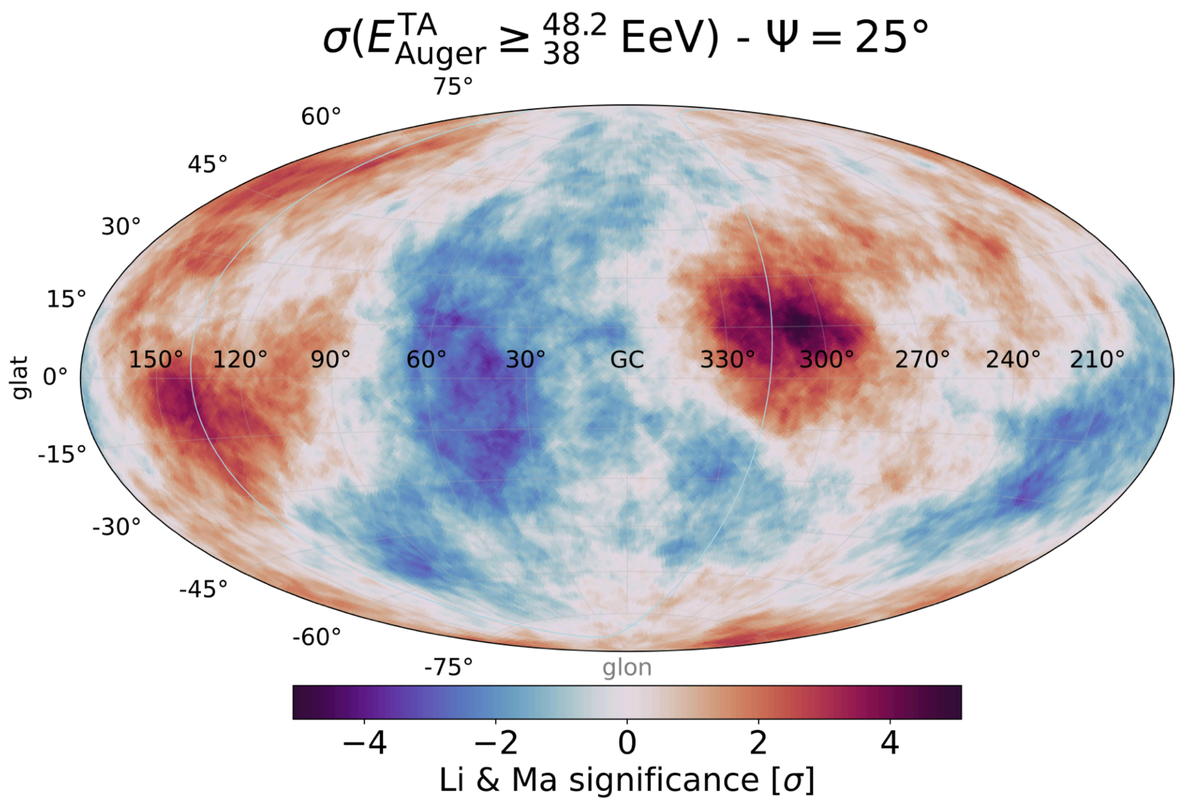

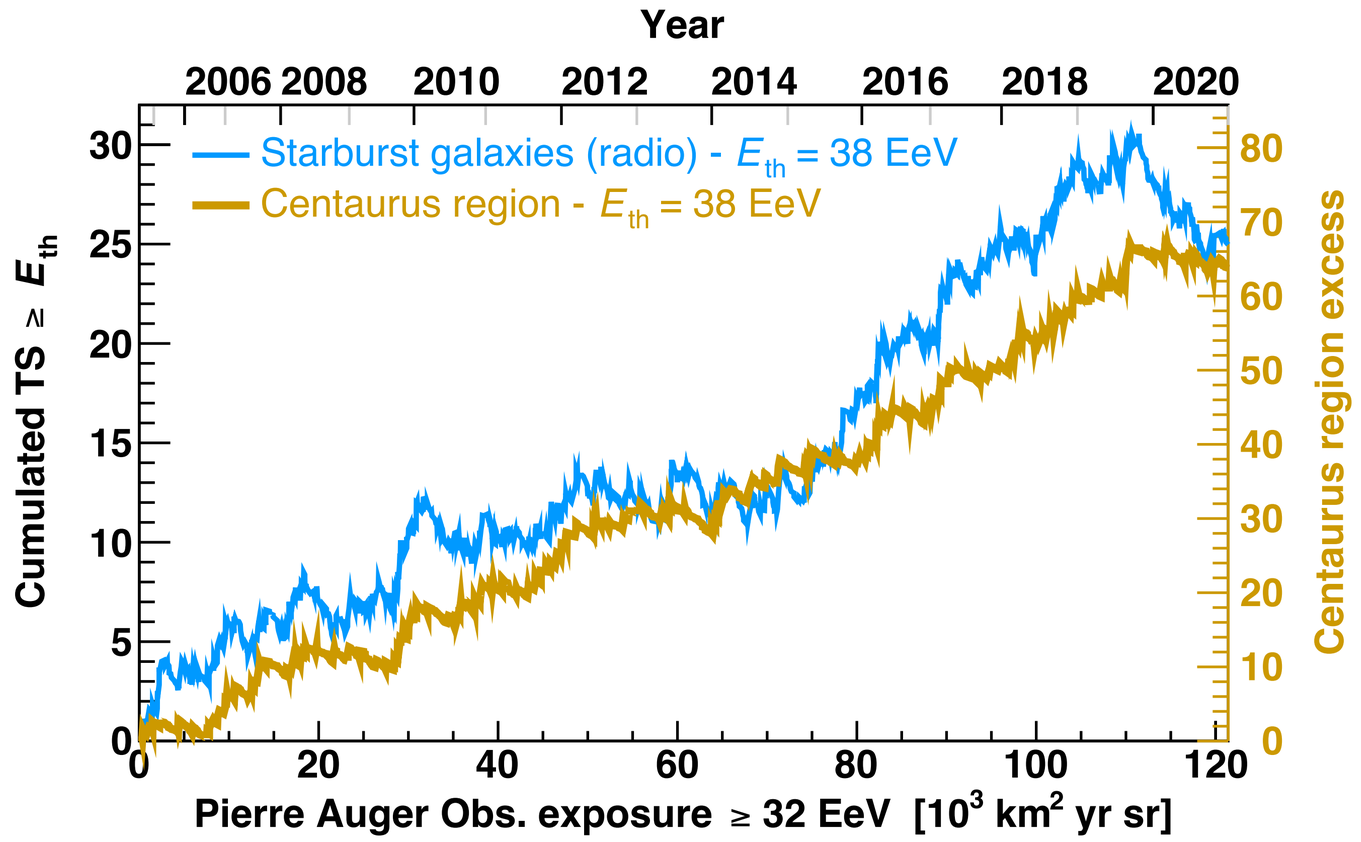

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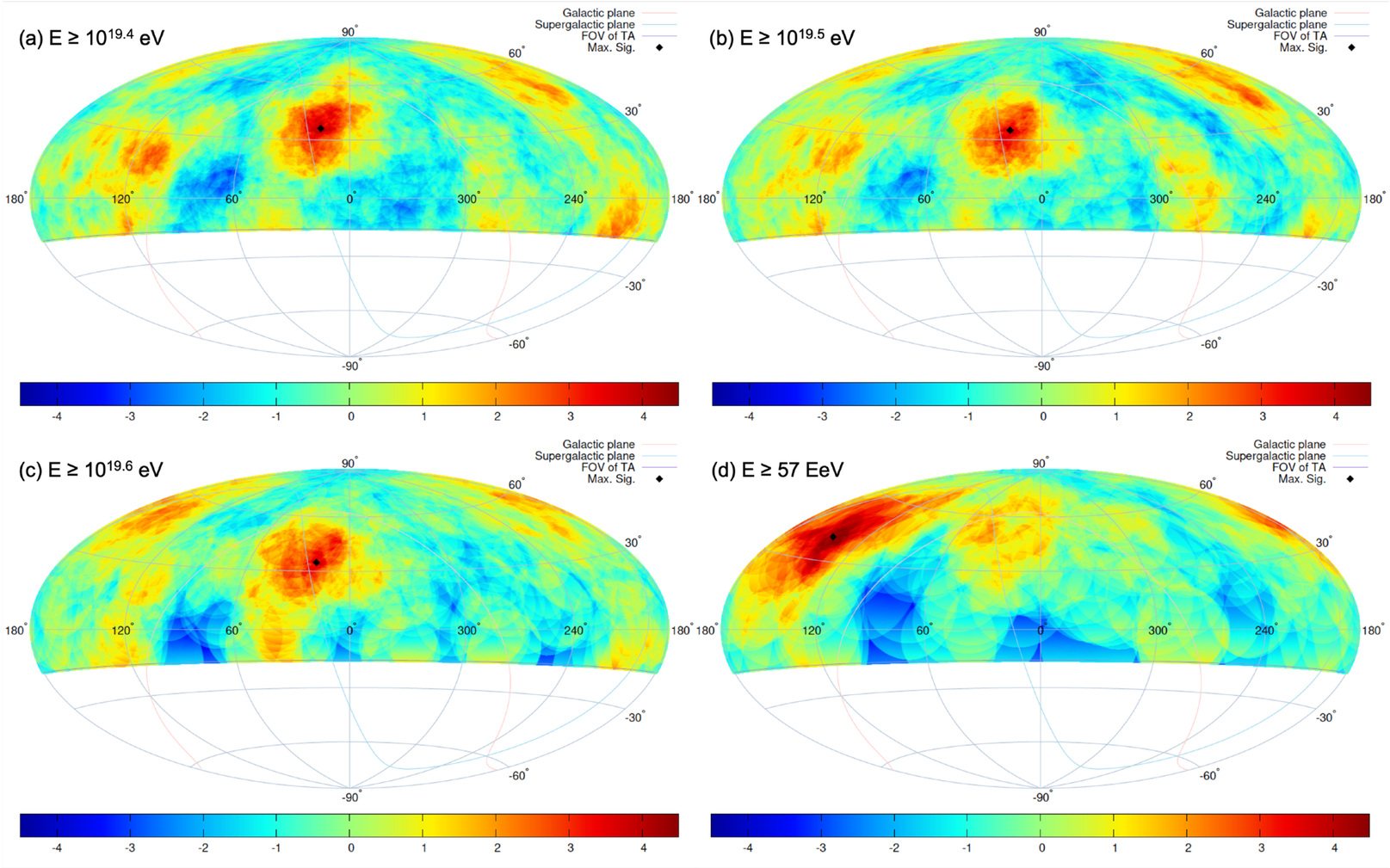

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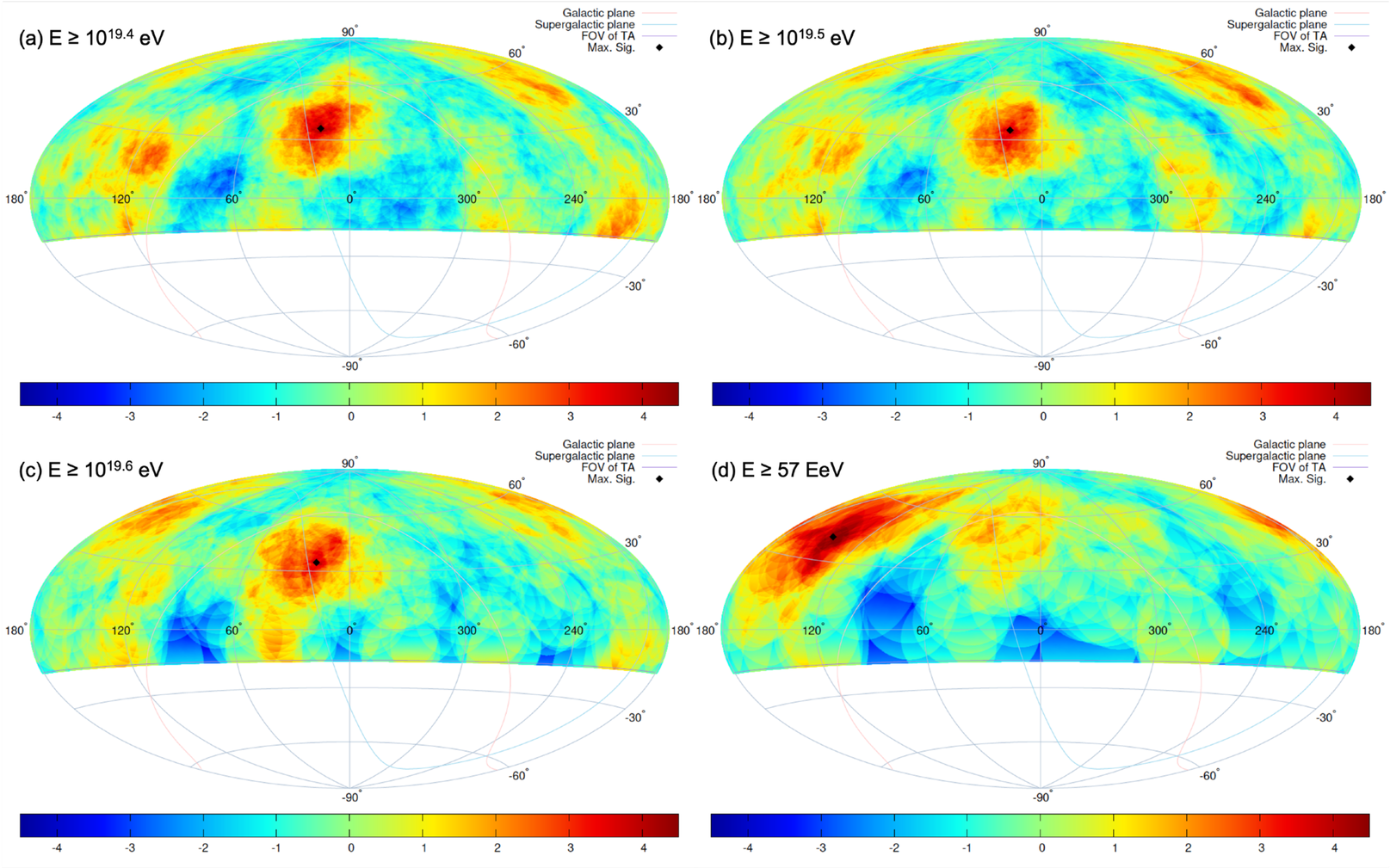
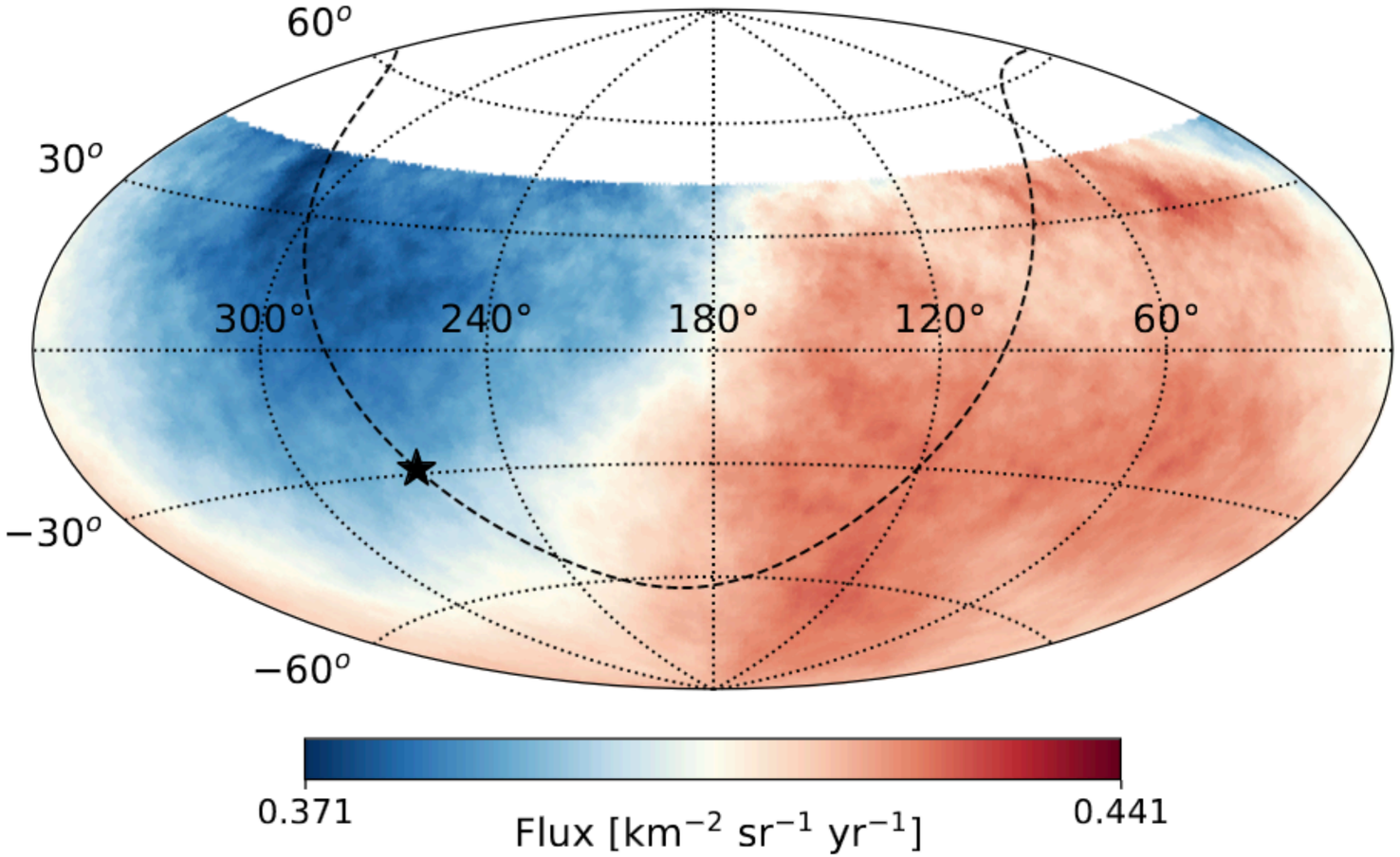
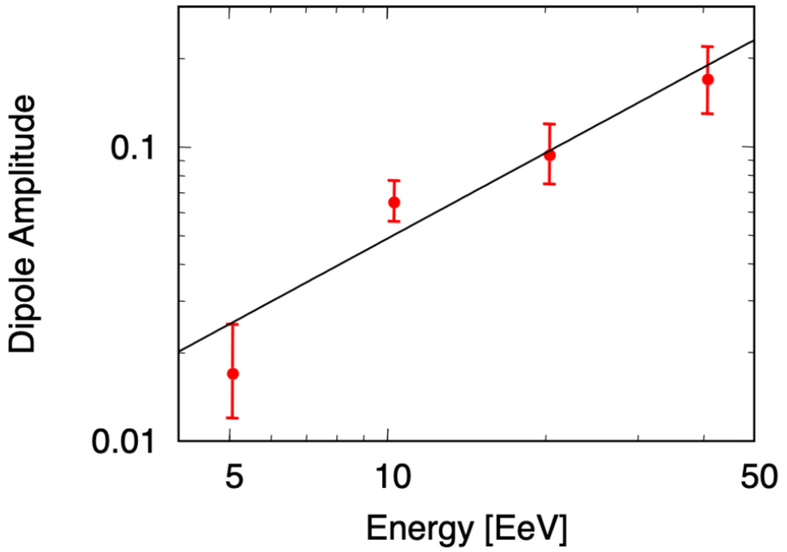


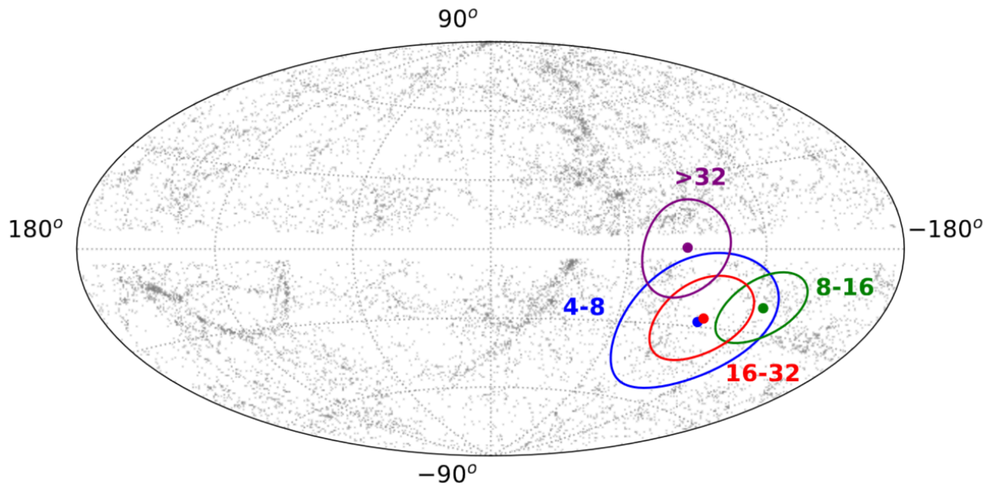
- Northern hemisphere hotspots (possible Perseus-Pisces supercluster correlation)

CR measurements. large-scale anisotropies

Golup for the Auger Collaboration. PoS (ICRC2023) 252.

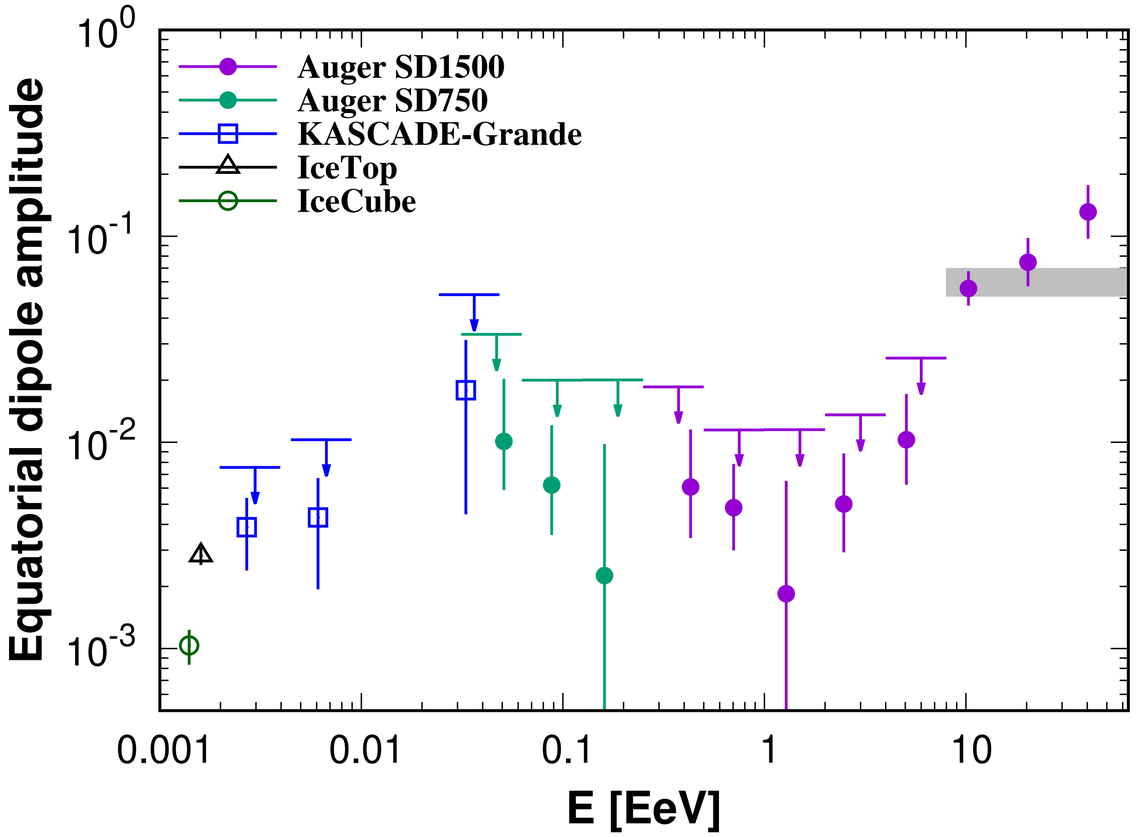


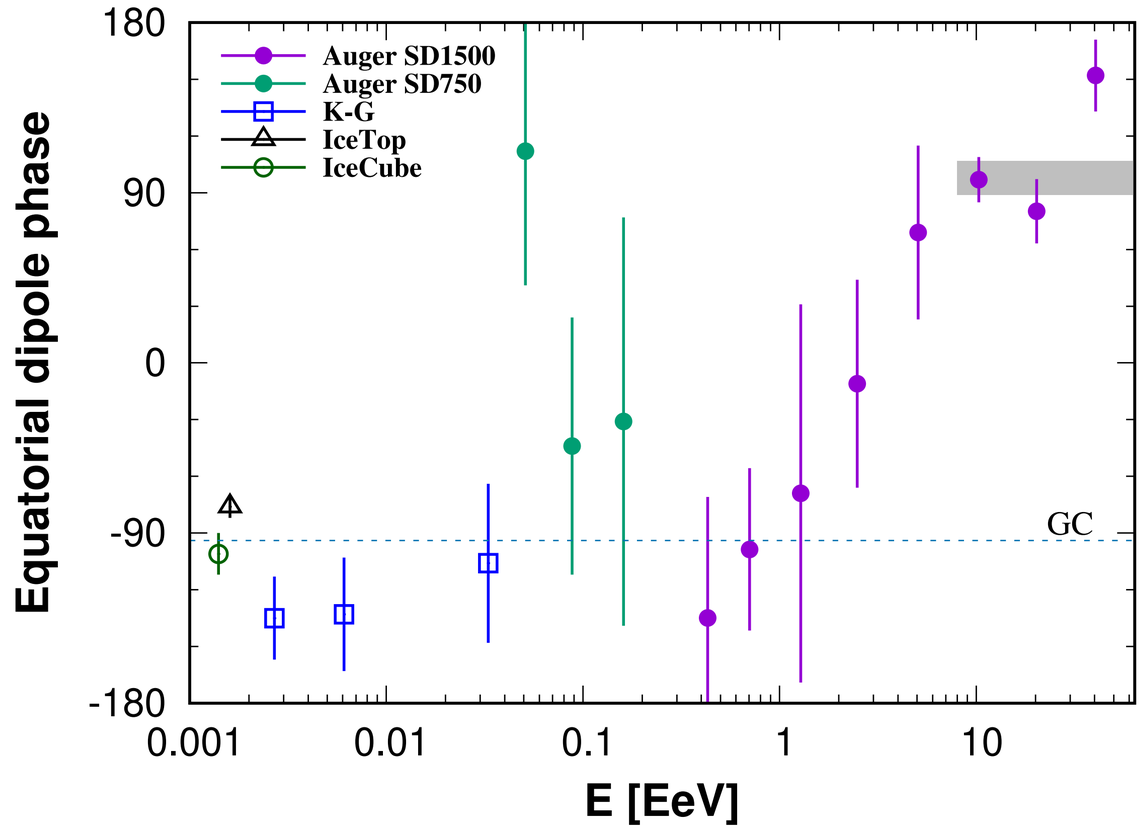




CR measurements. dipolar anisotropies

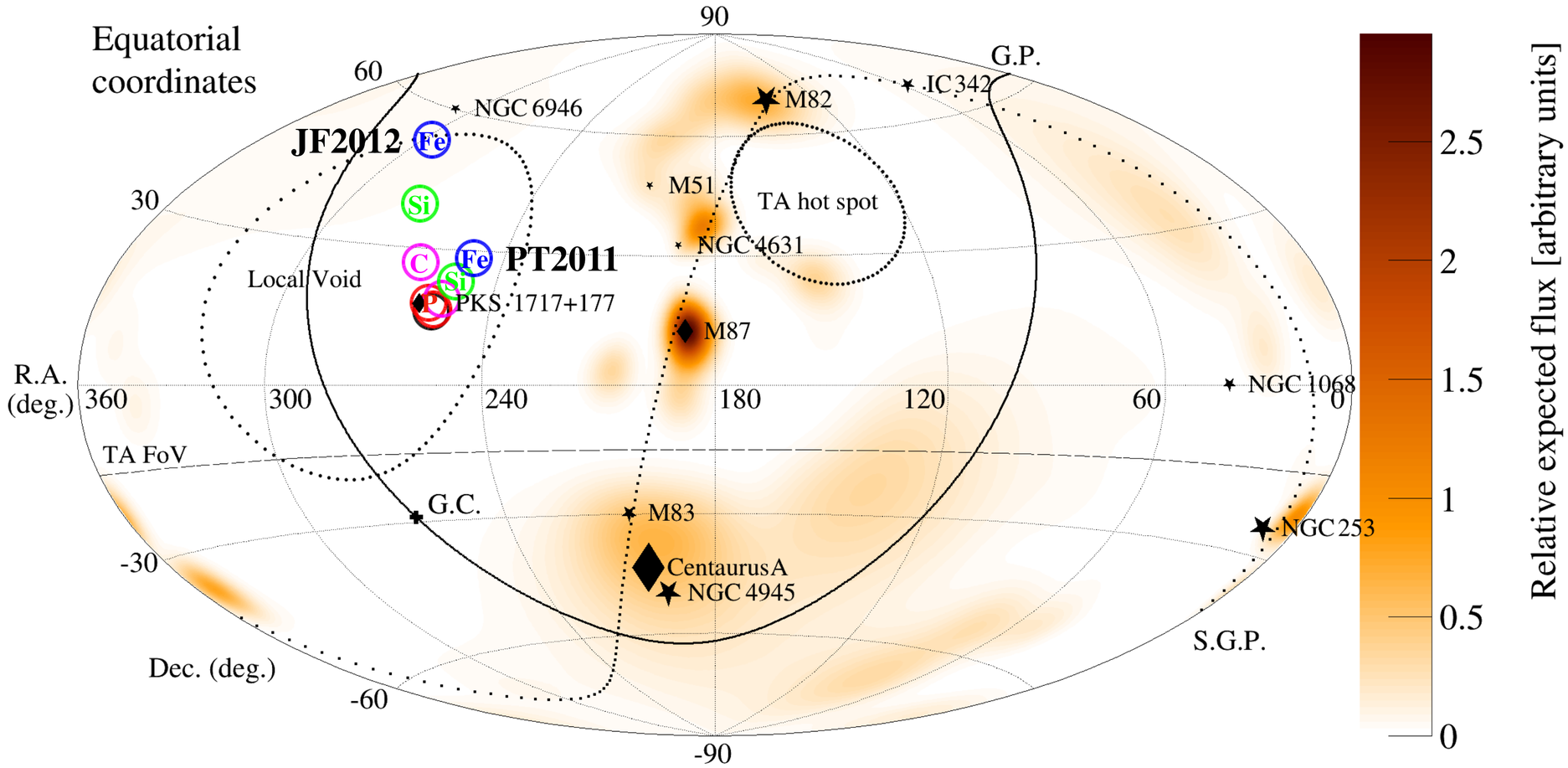
Coleman et al. Astroparticle Physics 149 (2023) 102819. arXiv:2205.05845





the second most energetic event ever: Amaterasu

Telescope Array Collaboration. Science 382 (2023) 903.. arXiv:2311.14231



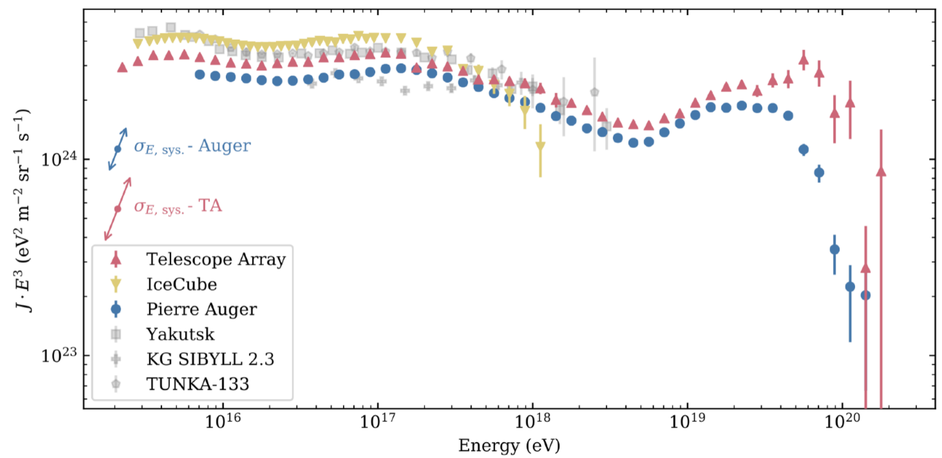
- 244 EeV ± 29 (+51,-76) EeV
- no correlation with known sources (*supposedly*)

interpreting UHECR measurements. cosmogenic neutrinos and photons

interpreting UHECR measurements. cosmogenic neutrinos and photons

CR measurements. spectrum

Coleman et al. Astroparticle Physics 149 (2023) 102819. arXiv:2205.05845



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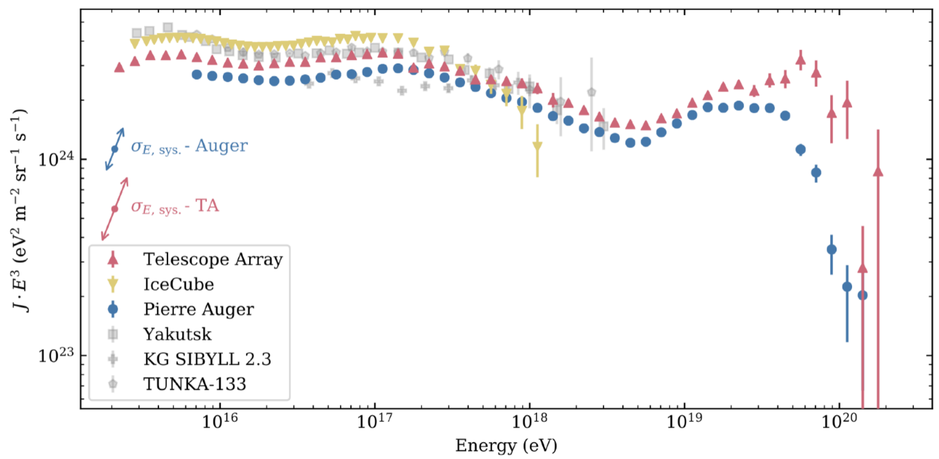
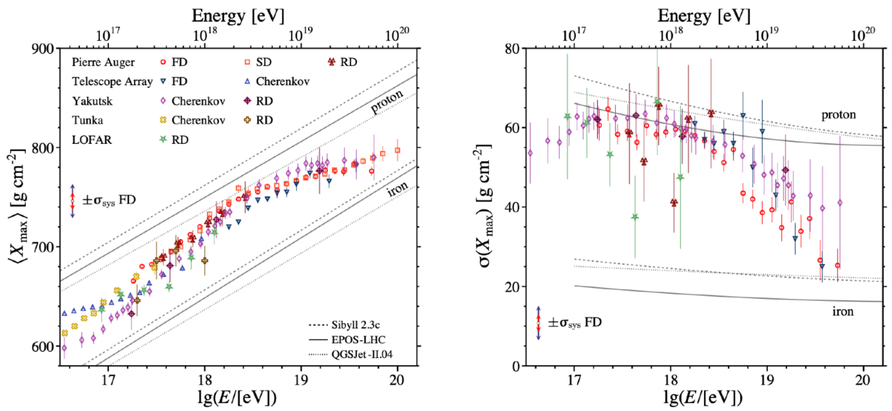


CR measurements. composition

Coleman et al. Astroparticle Physics 149 (2023) 102819. arXiv:2205.05845



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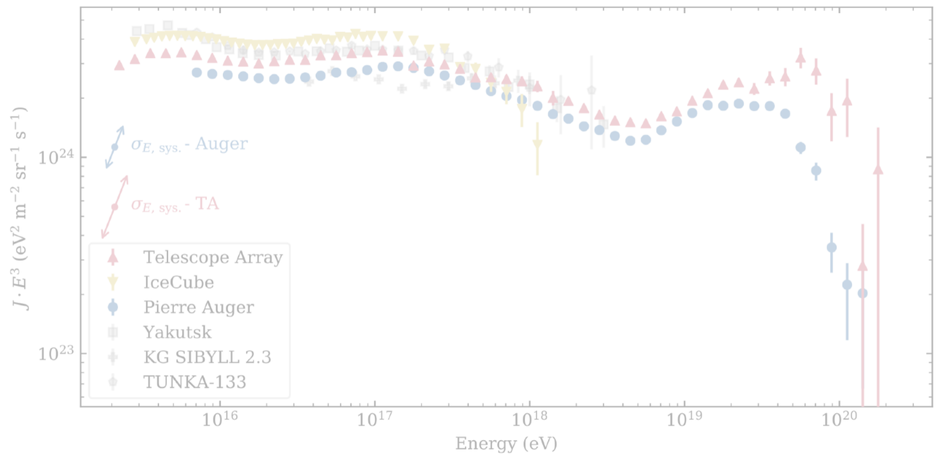

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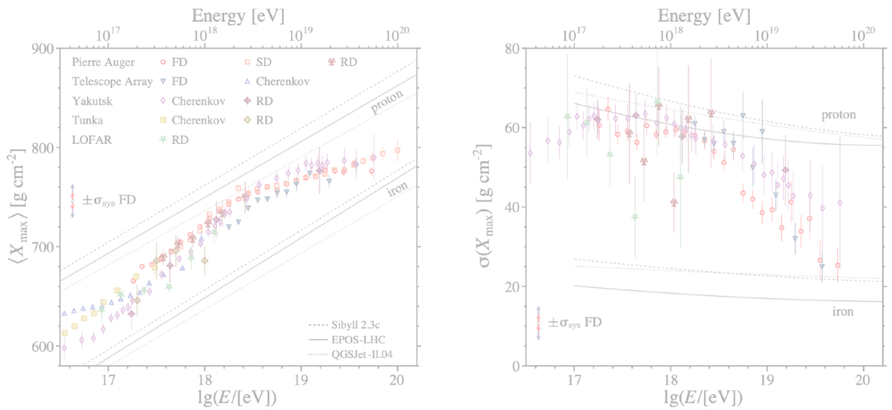

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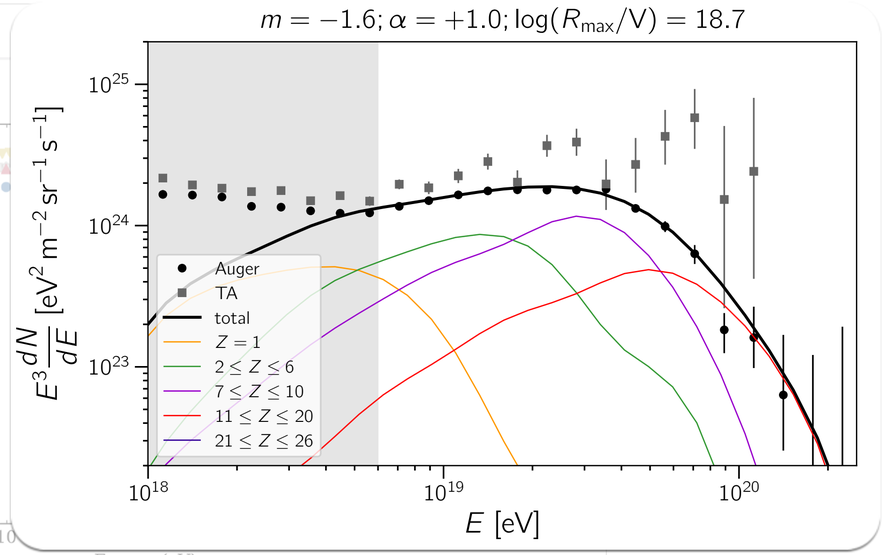

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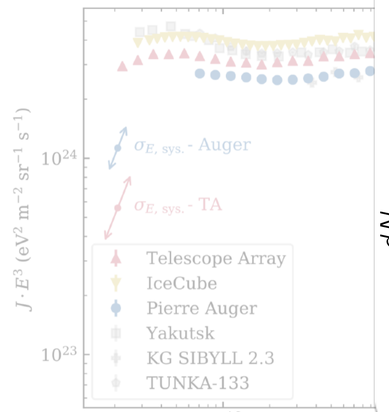

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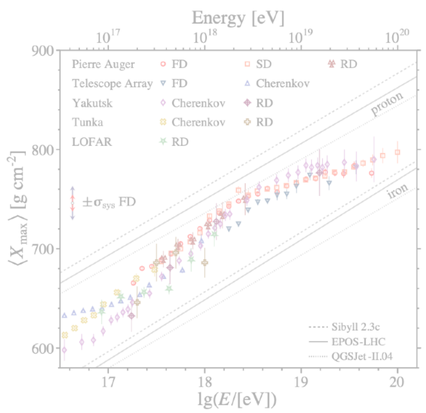
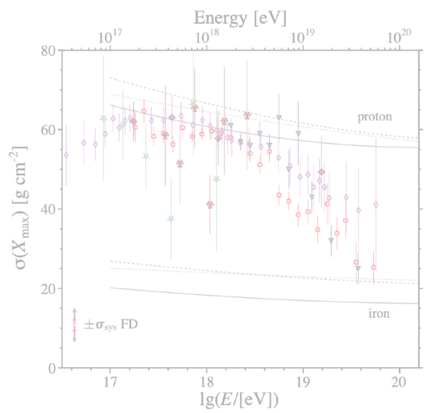
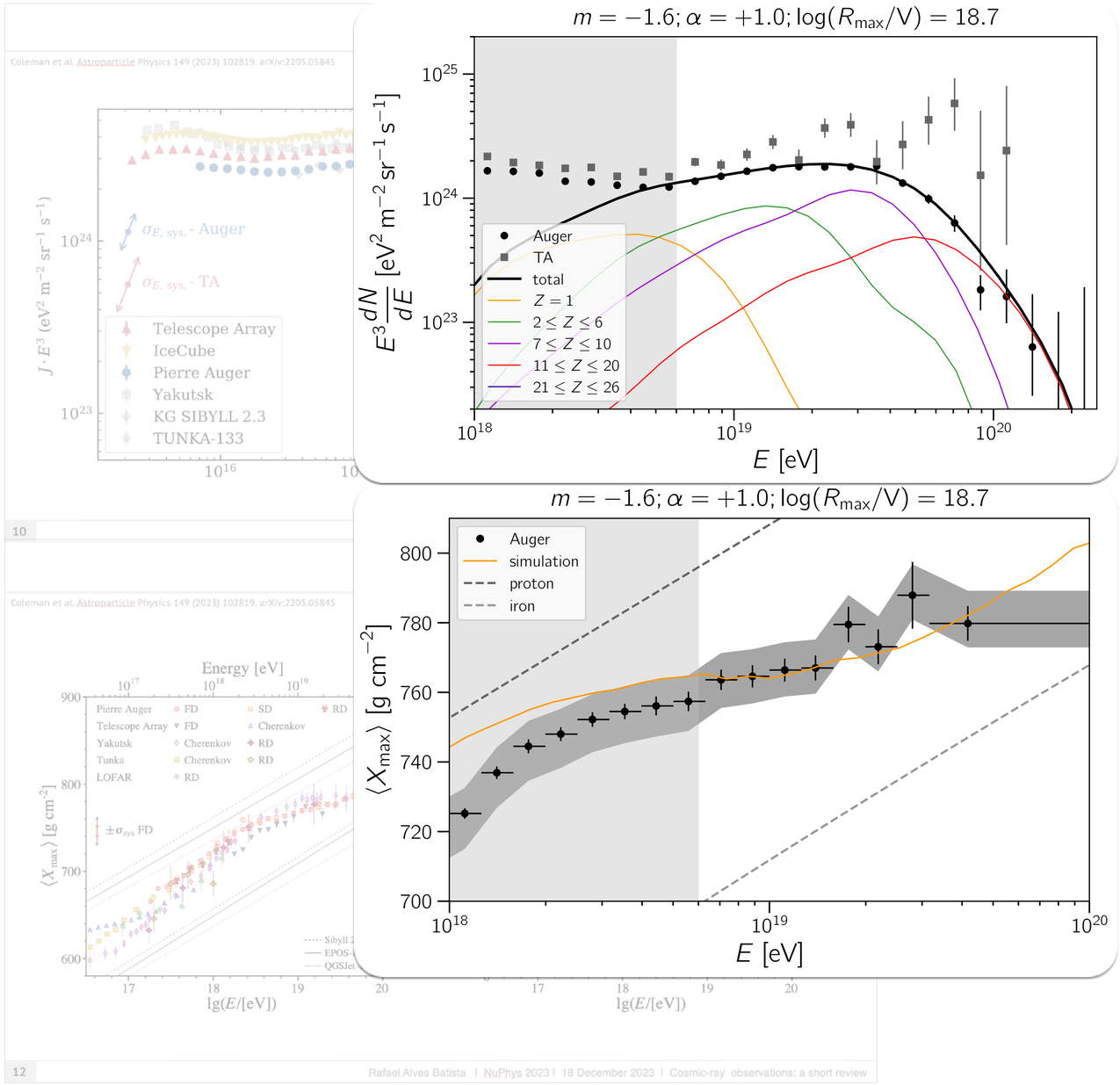


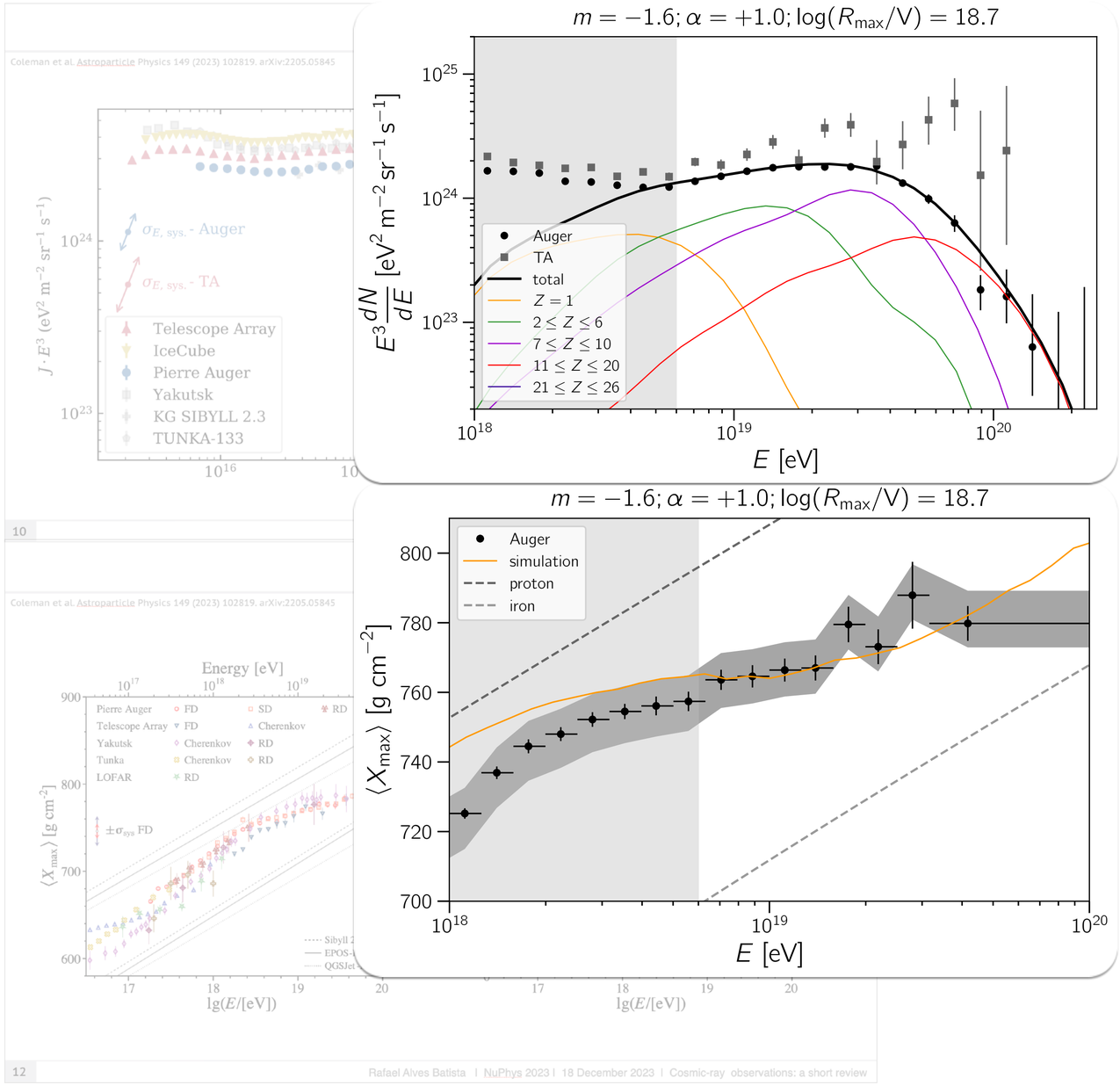


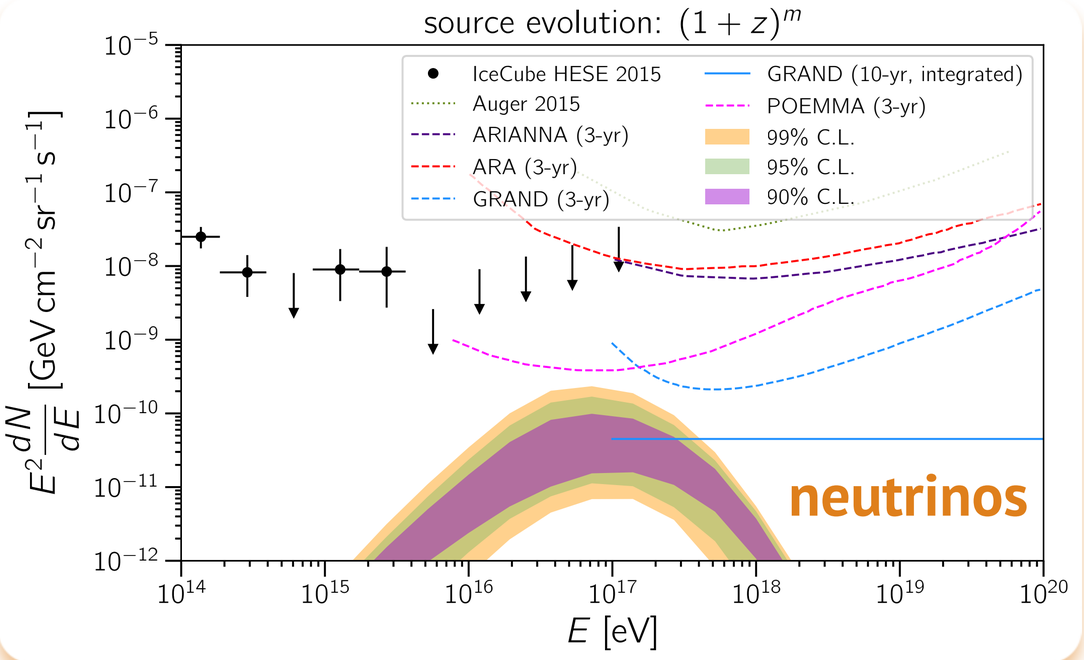
interpreting UHECR measurements. cosmogenic neutrinos and photons

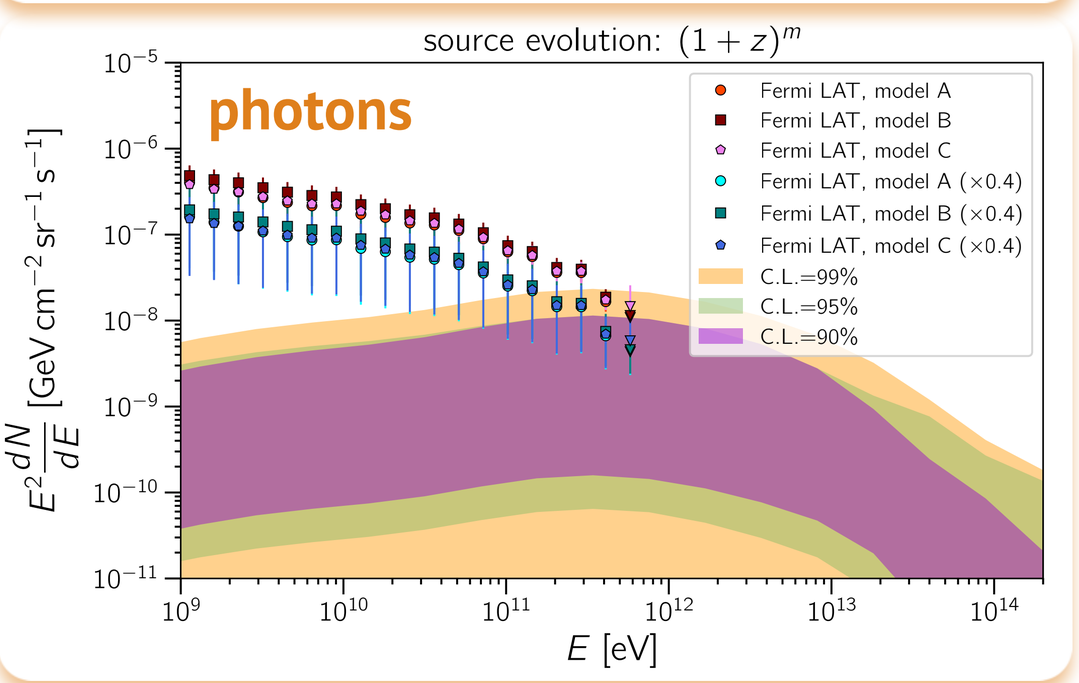


interpreting UHECR measurements. cosmogenic neutrinos and photons

Alves Batista, de Almeida, Lago, Kotera. JCAP 01 (2019) 002. arXiv:1806.10879

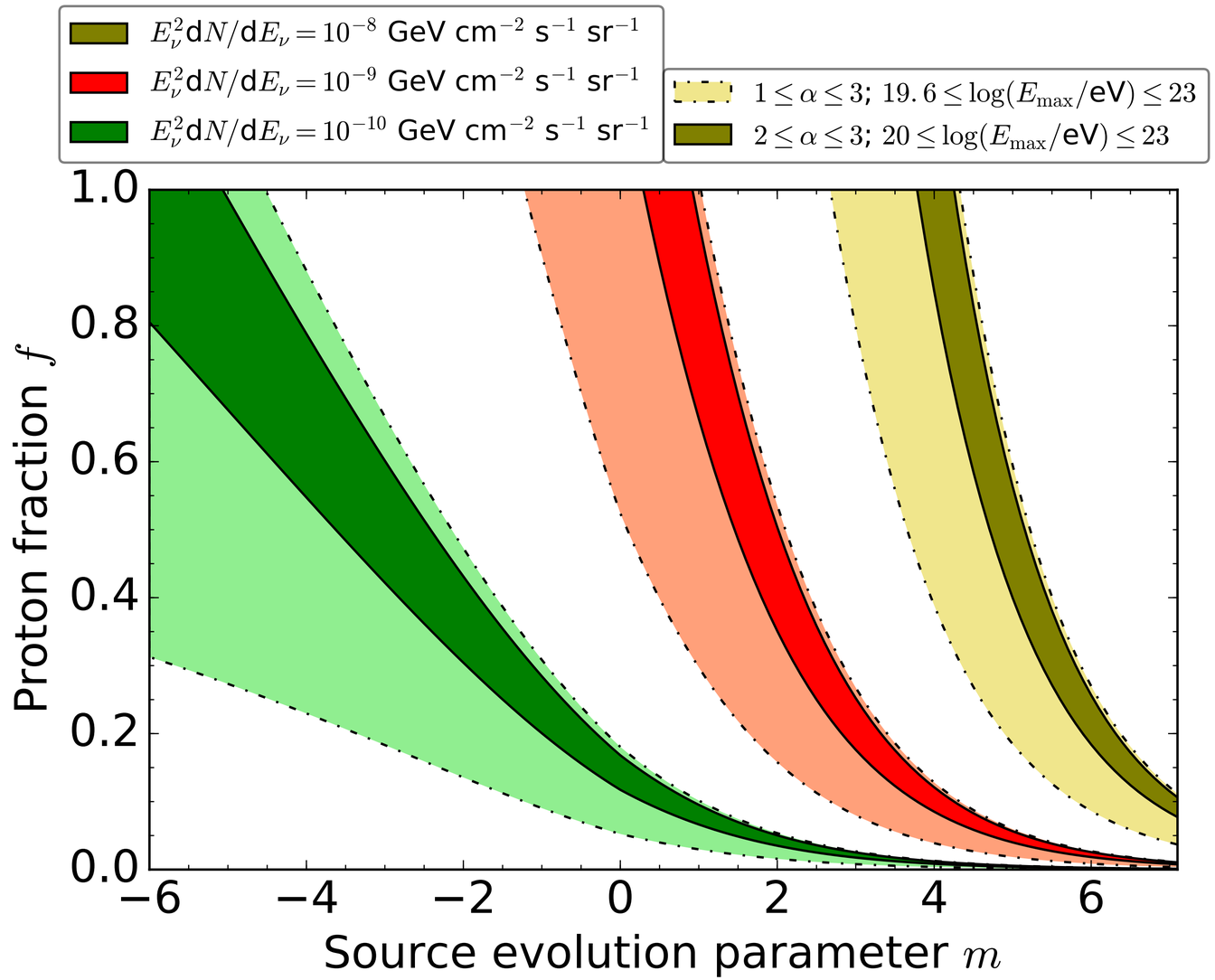






the fraction of protons at UHE: neutrino constraints

van Vliet, Alves Batista, Hörandel. Physical Review D 100 (2019) 02312. arXiv:1901.01899



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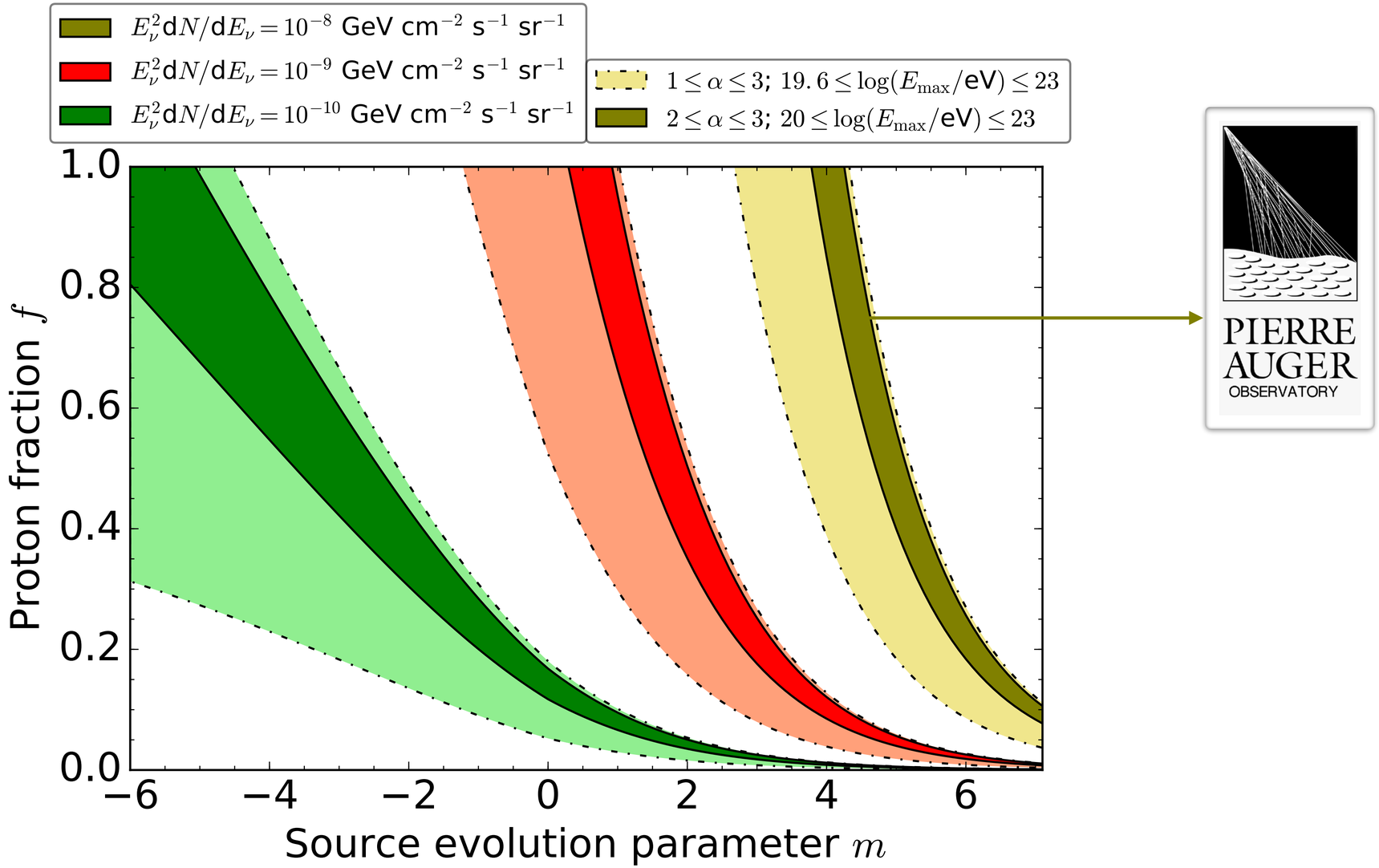

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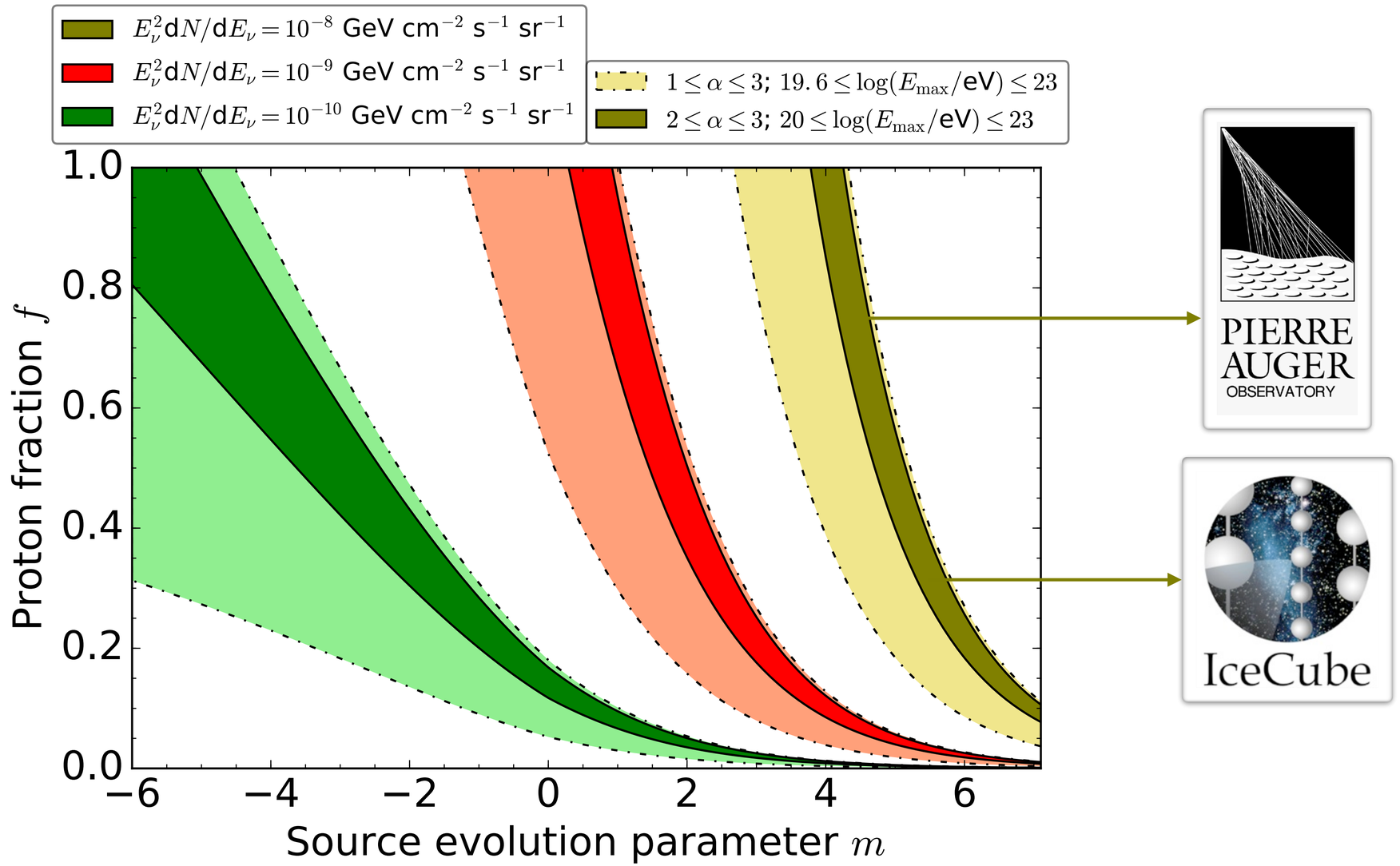

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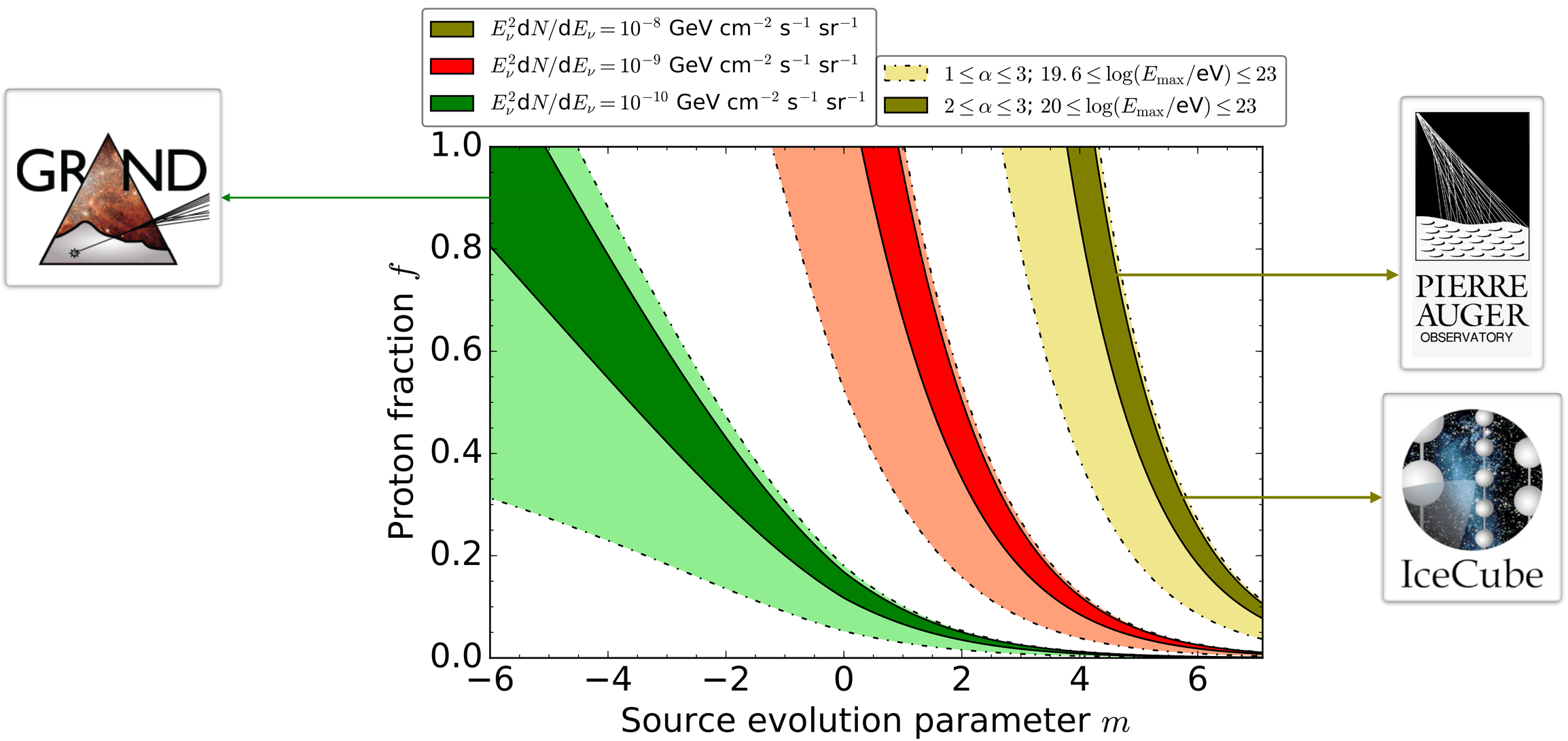

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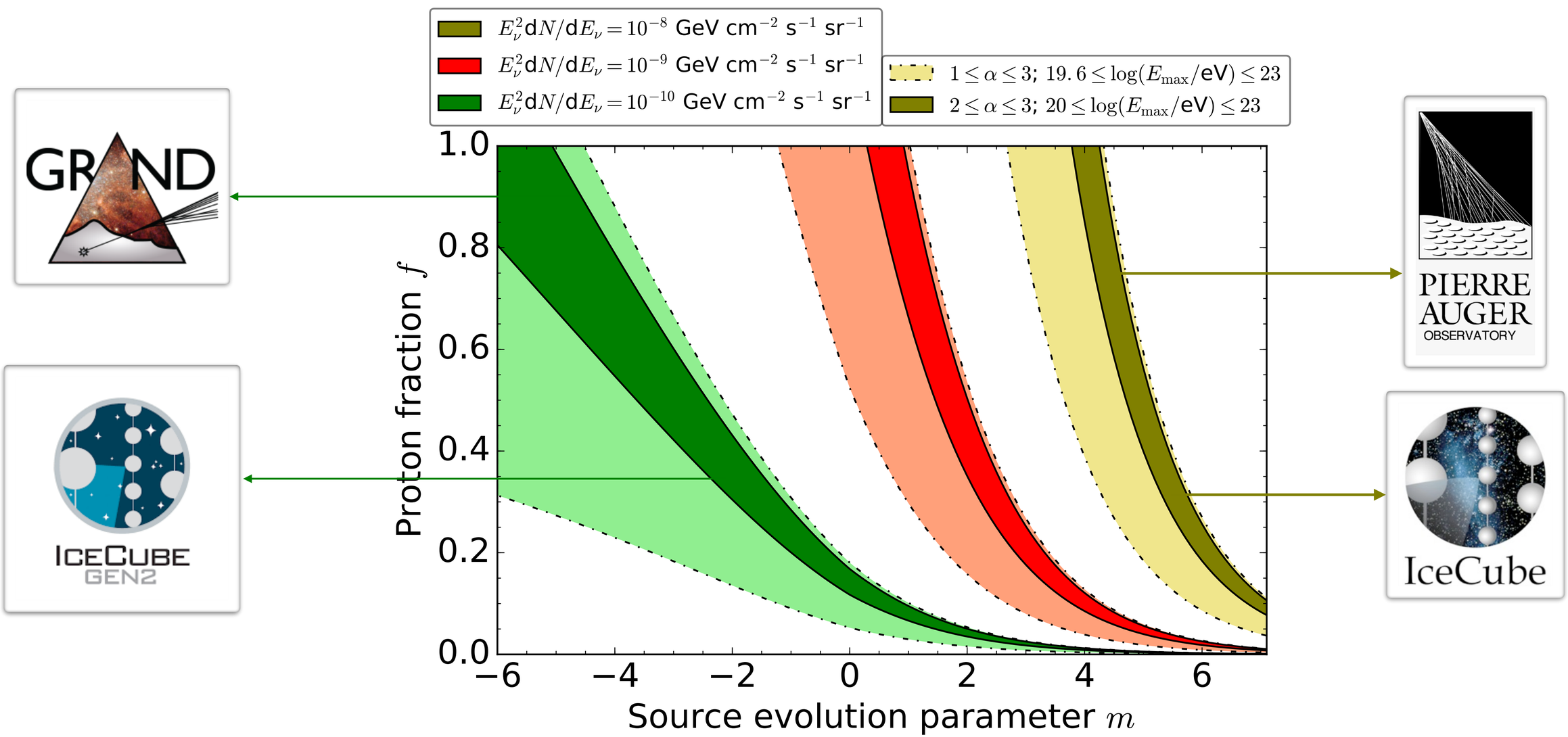


the future

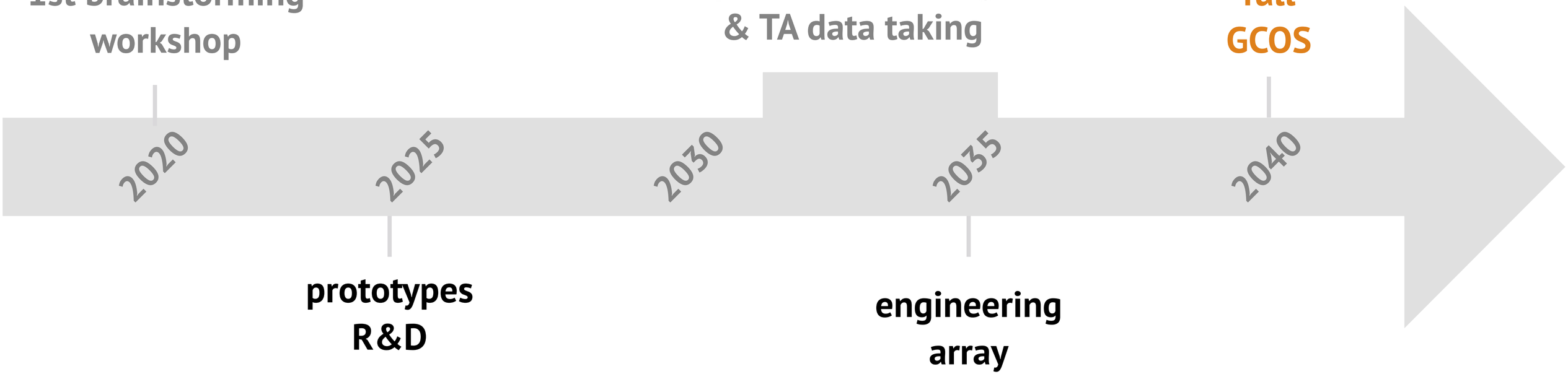
Experiment	Feature	Cosmic Ray Science*	Timeline
Pierre Auger Observatory	Hybrid array: fluorescence, surface e/μ + radio, 3000 km^2	Hadronic interactions, search for BSM, UHECR source populations, $\sigma_{\text{p-Air}}$	AugerPrime upgrade
Telescope Array (TA)	Hybrid array: fluorescence, surface scintillators, 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.

GCOS. Global Cosmic-ray Observatory

R. Alves Batista for the GCOS Collab. PoS (ICRC2023) 978. arXiv:2205.05845



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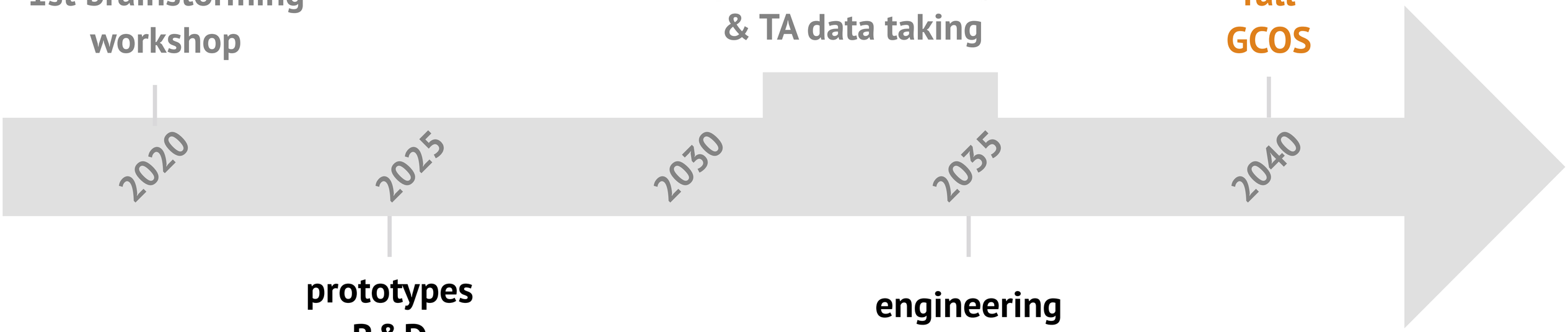
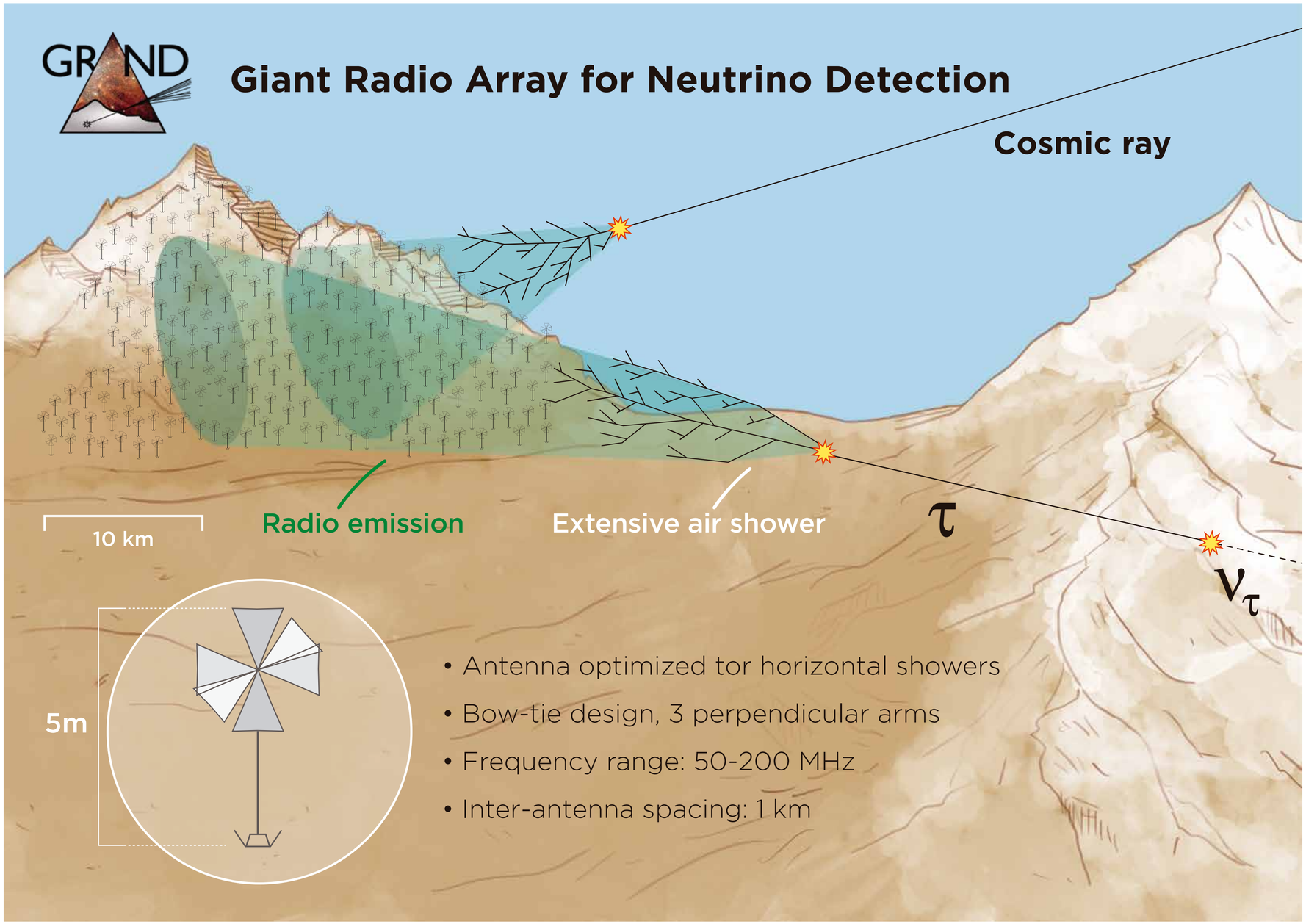


- **area:** 40,000 to 80,000 km^2 (⩾ 2 sites)
- **energy range:** full efficiency above ~10 EeV
- **energy resolution:** < 10%
- **muon resolution:** < 10%
- **X_{max} resolution:** < 20 g/cm^2
- **angular resolution:** < 1°

GRAND. Giant Radio Array for Neutrino Detection

GRAND Collaboration. Science China 63 (2020) 219501. arXiv:1810.09994



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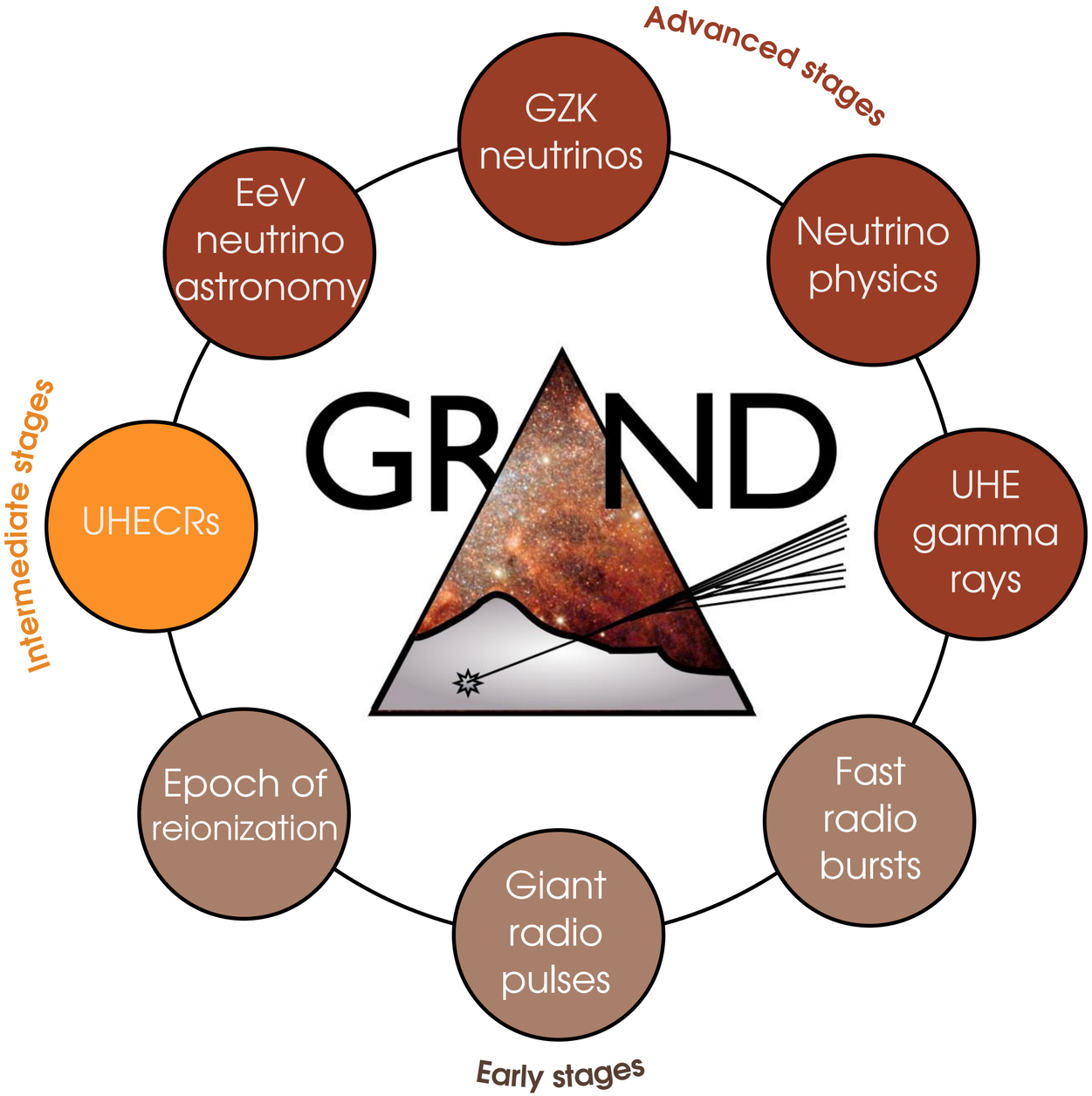

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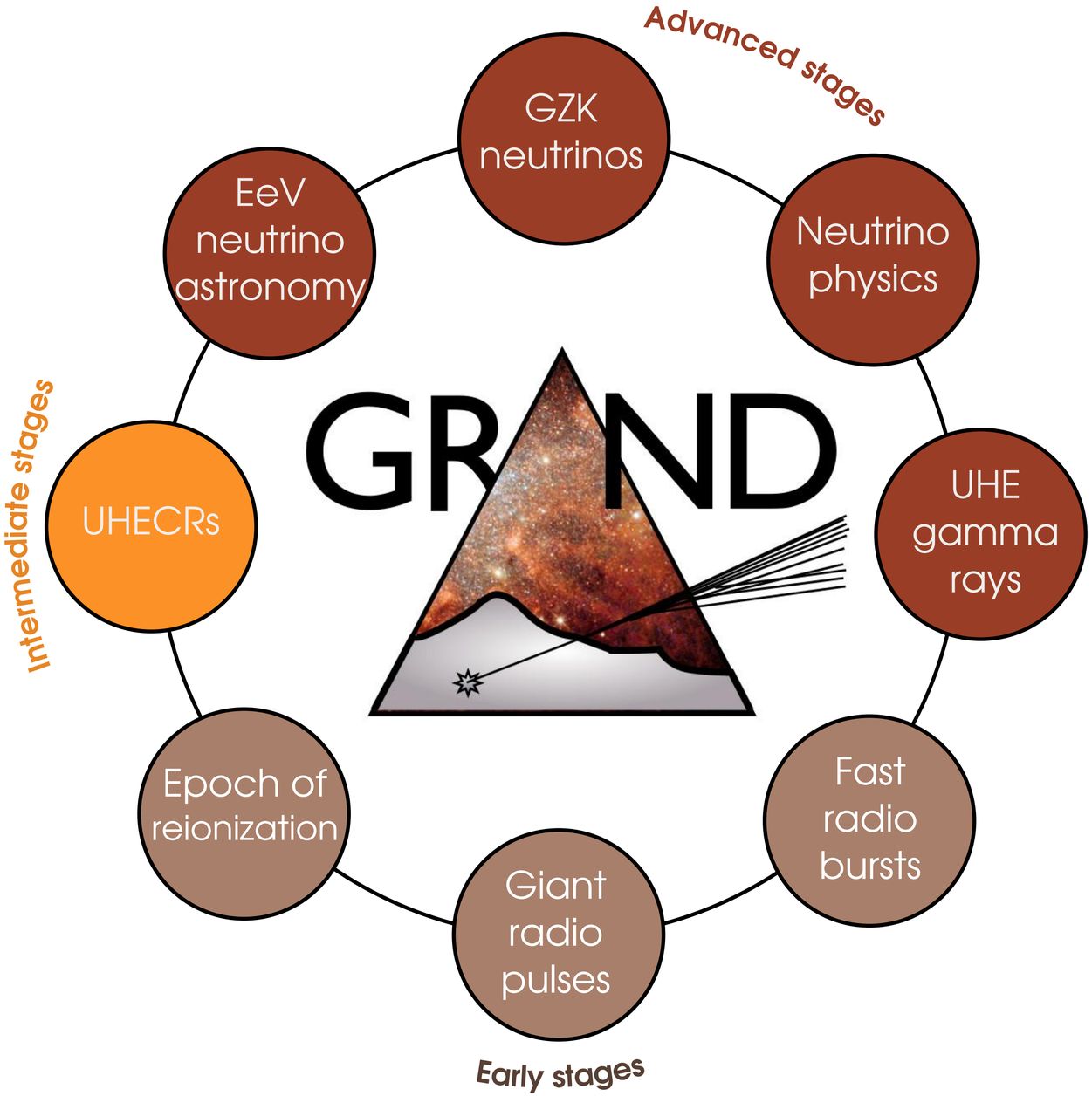

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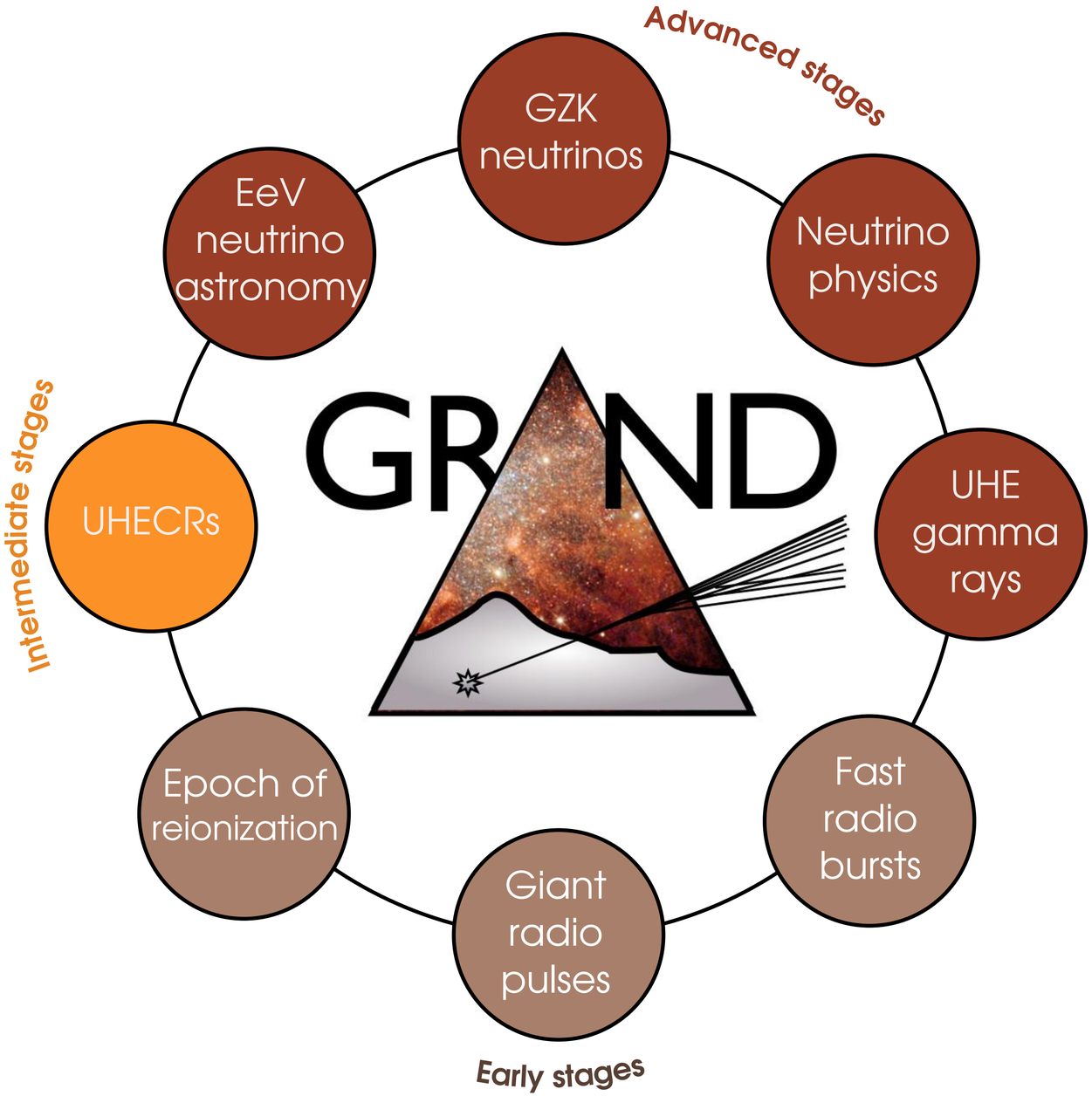

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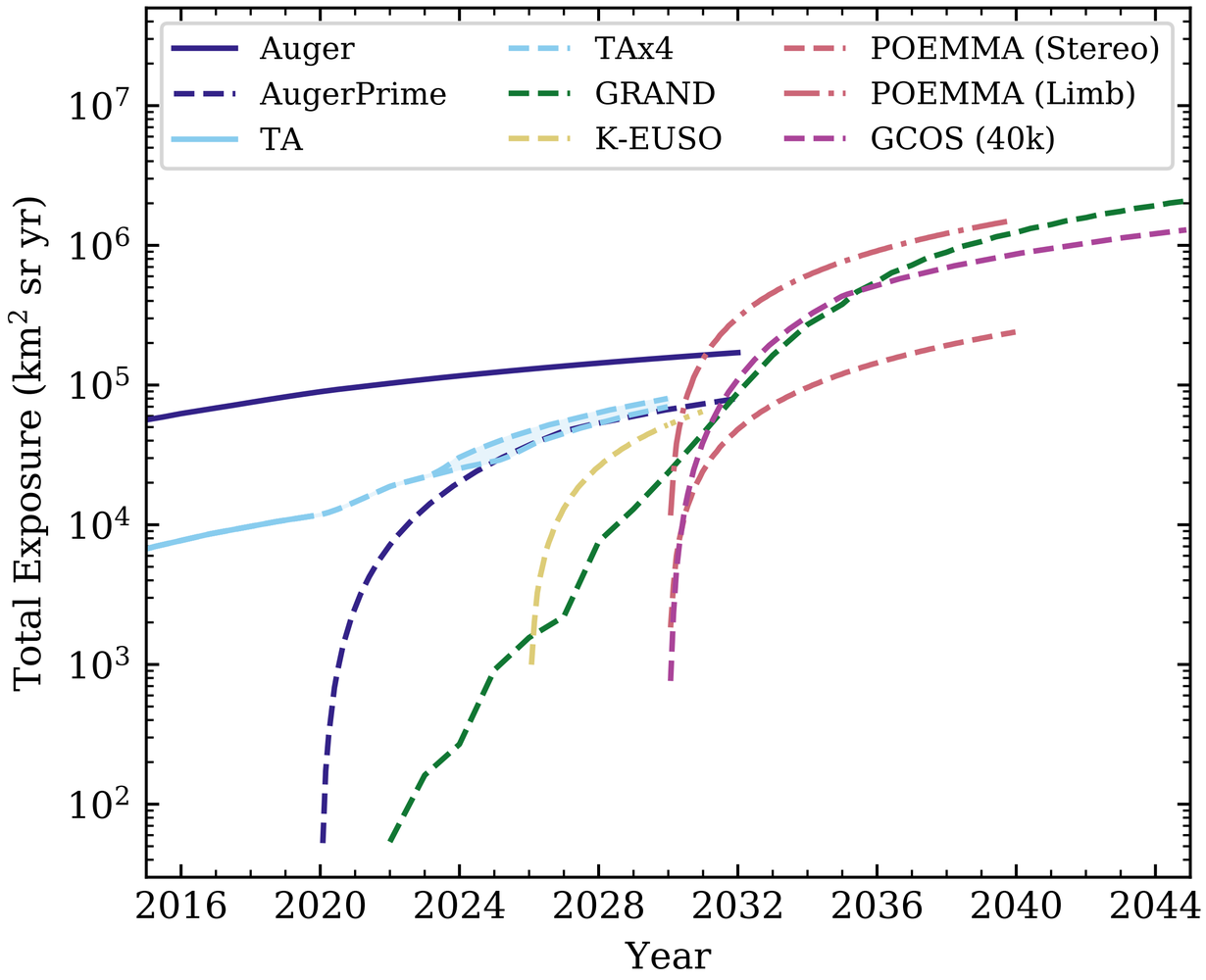

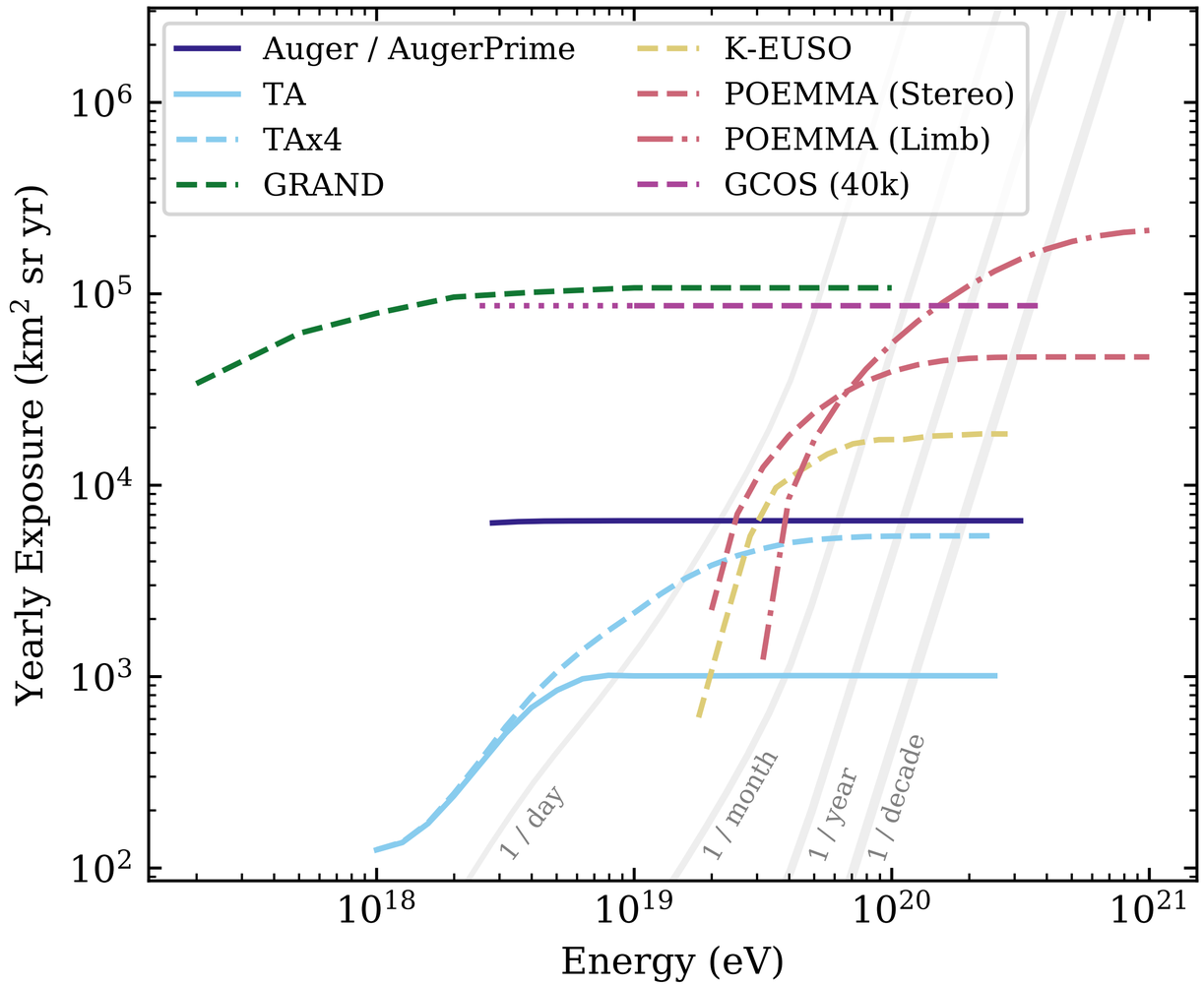

outlook

summary & outlook

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- possible relationship between diffuse fluxes of high-energy CRs, gamma rays, and neutrinos

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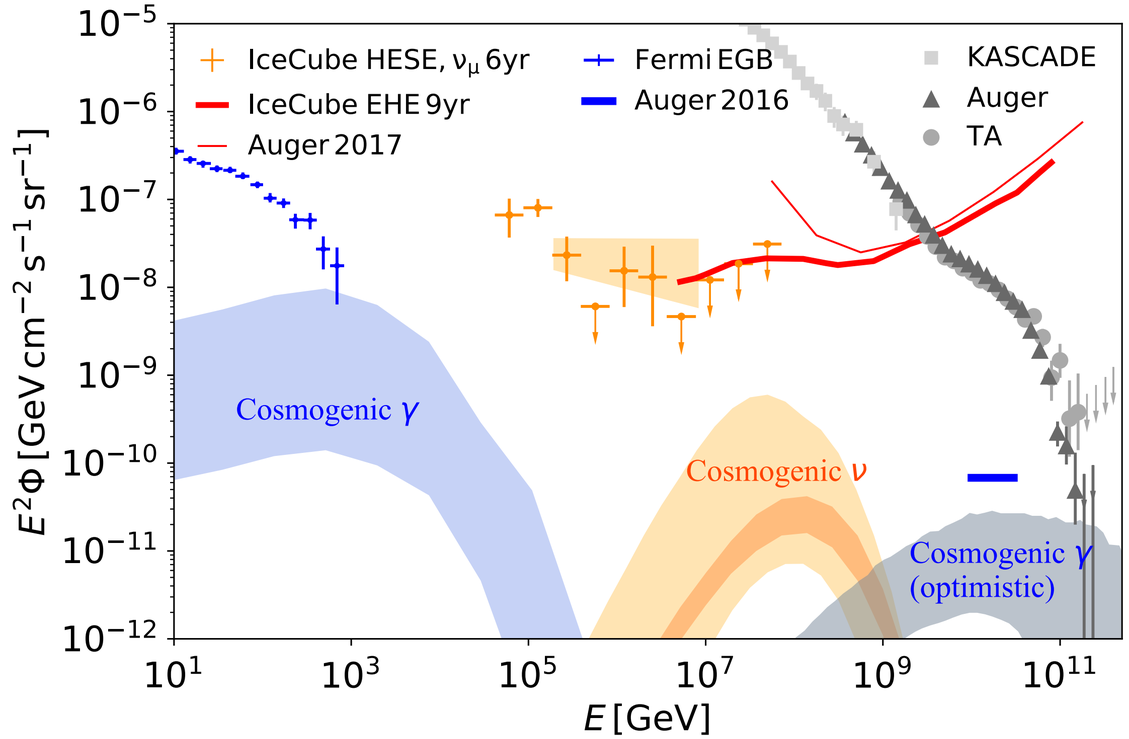
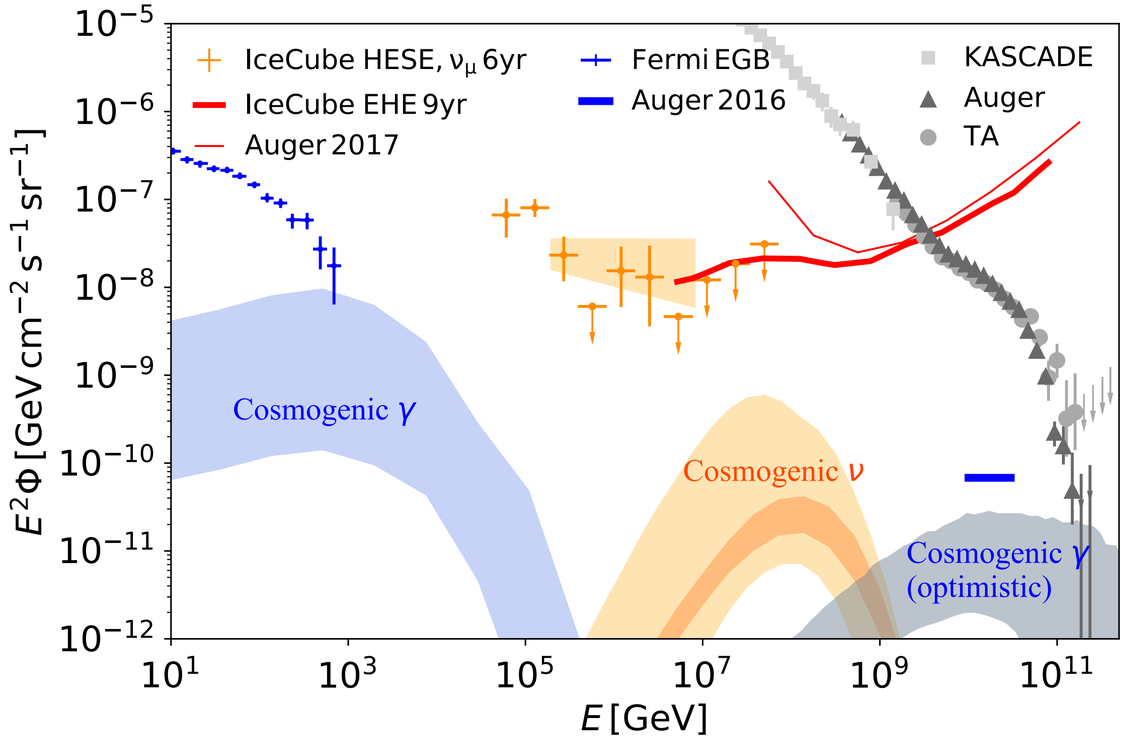


summary & outlook

- possible relationship between diffuse fluxes of high-energy CRs, gamma rays, and neutrinos
- open questions:



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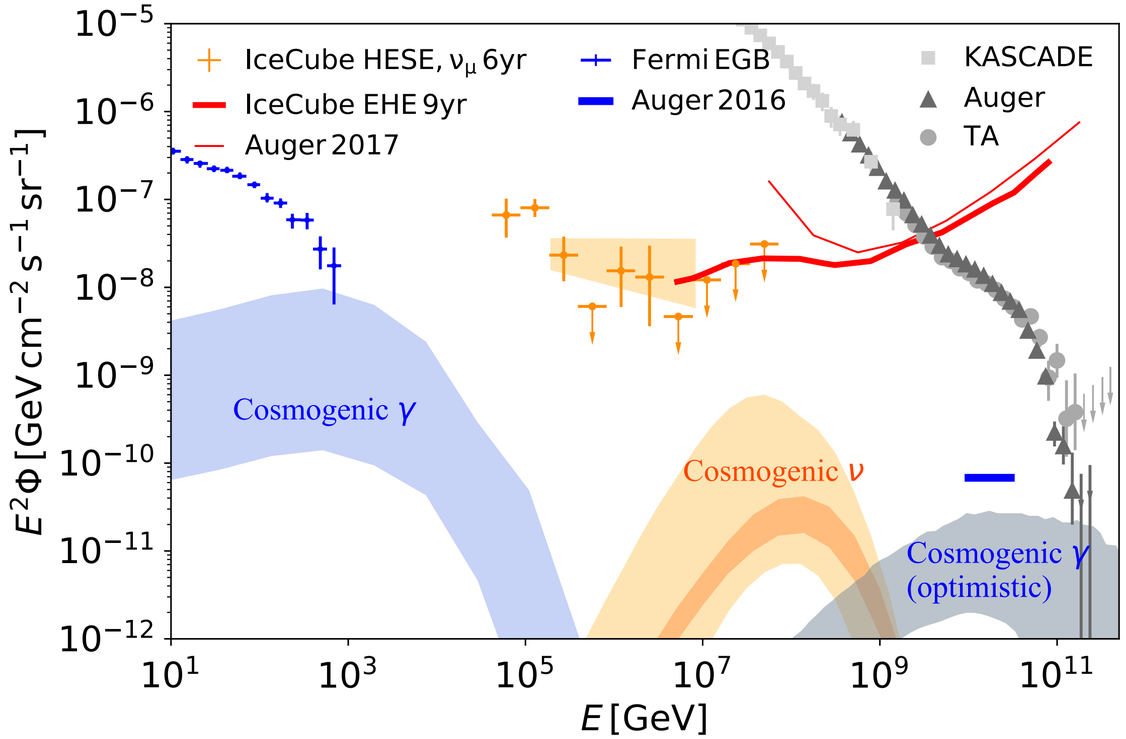

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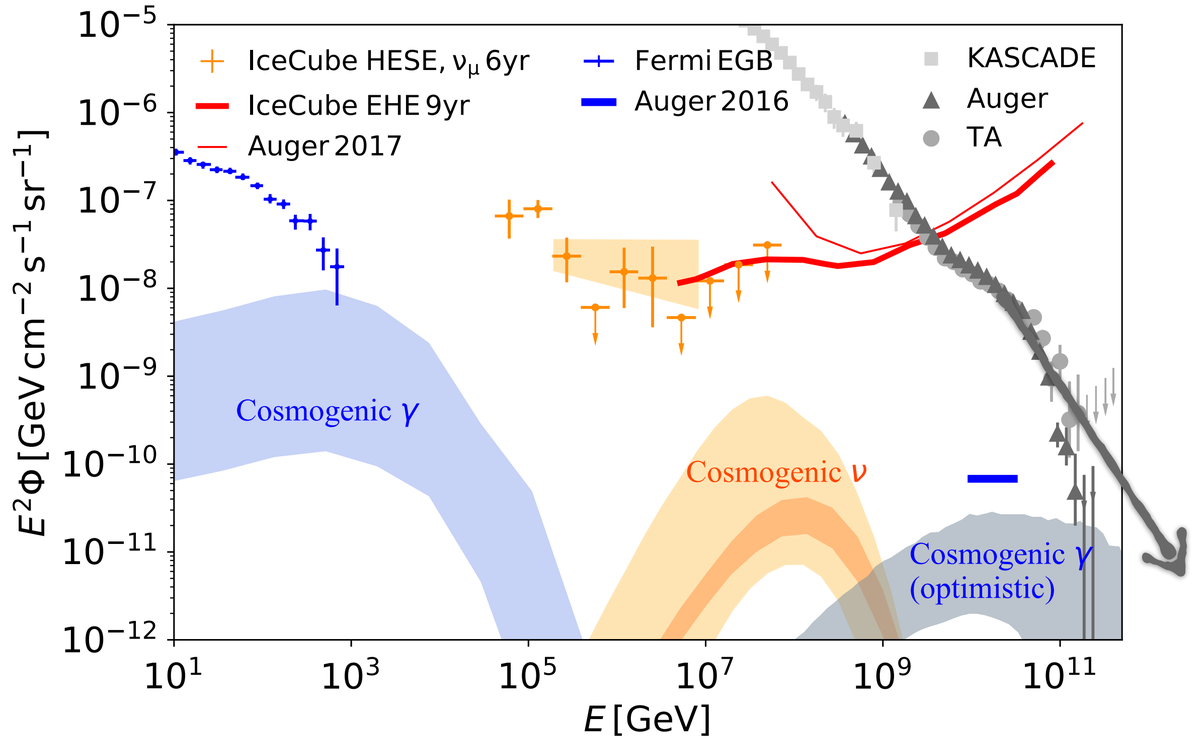

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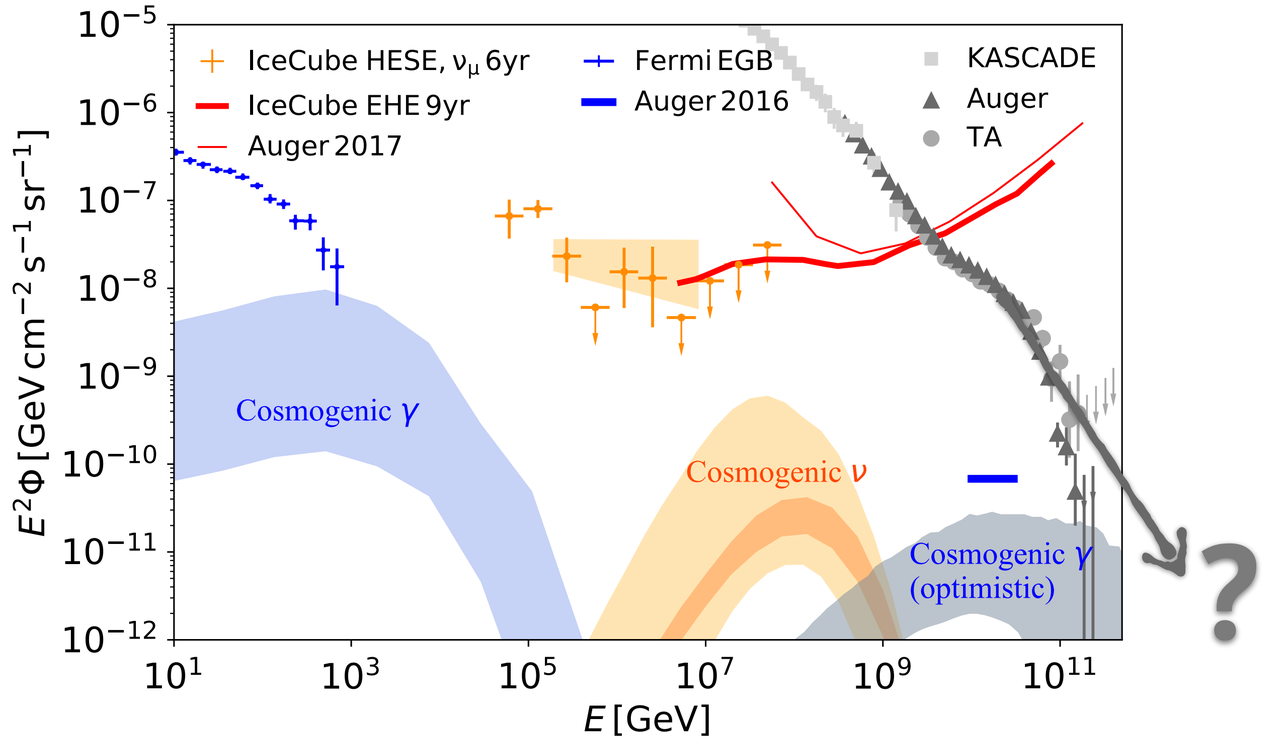

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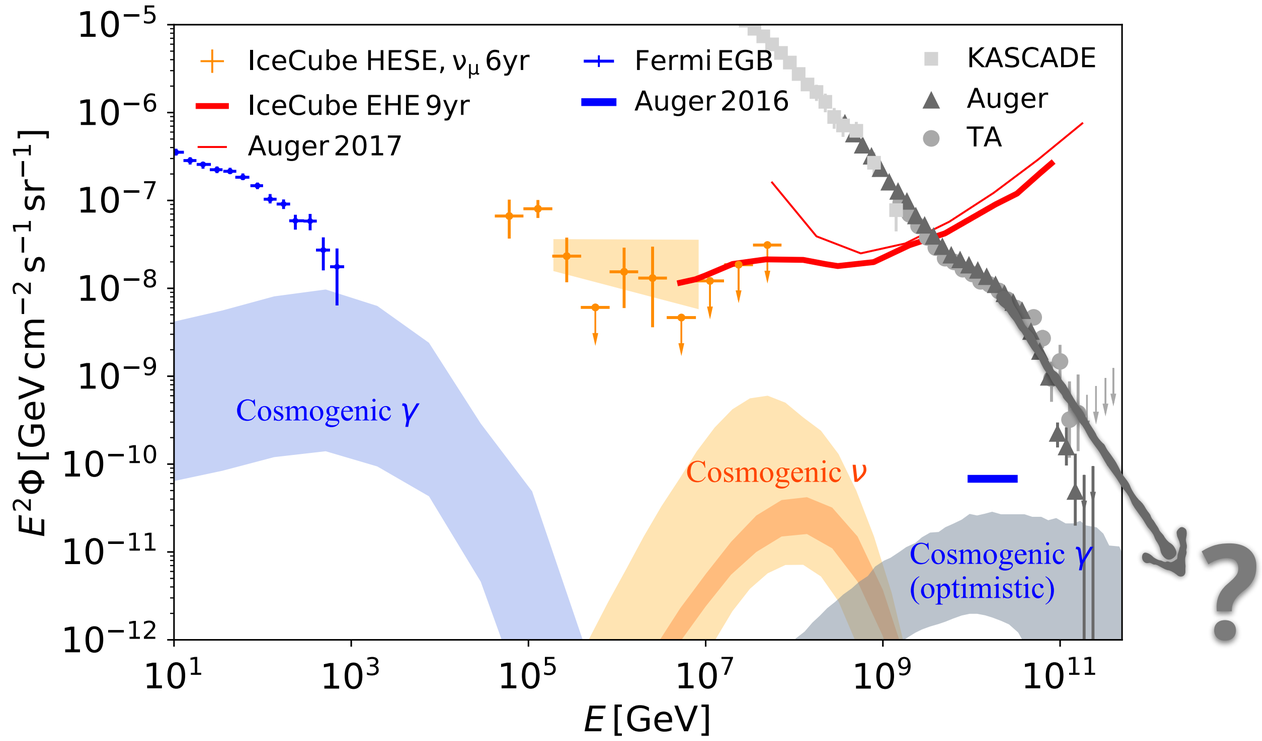

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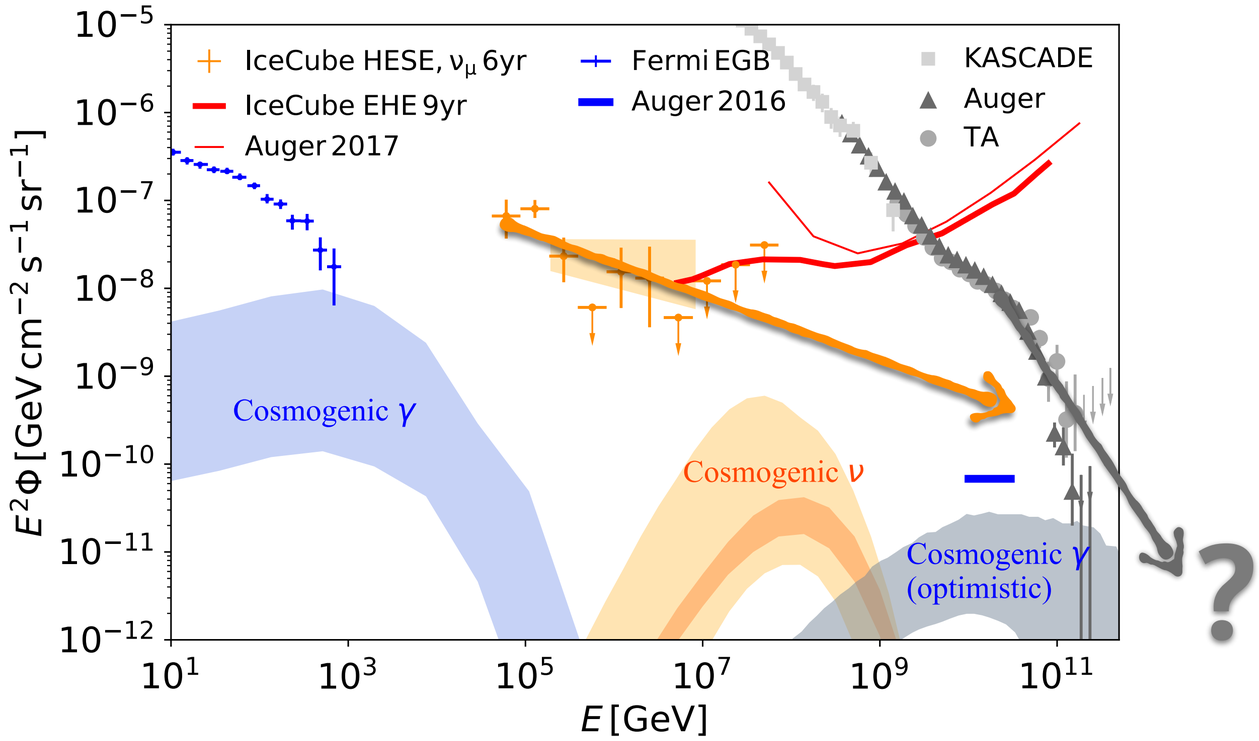

summary & outlook

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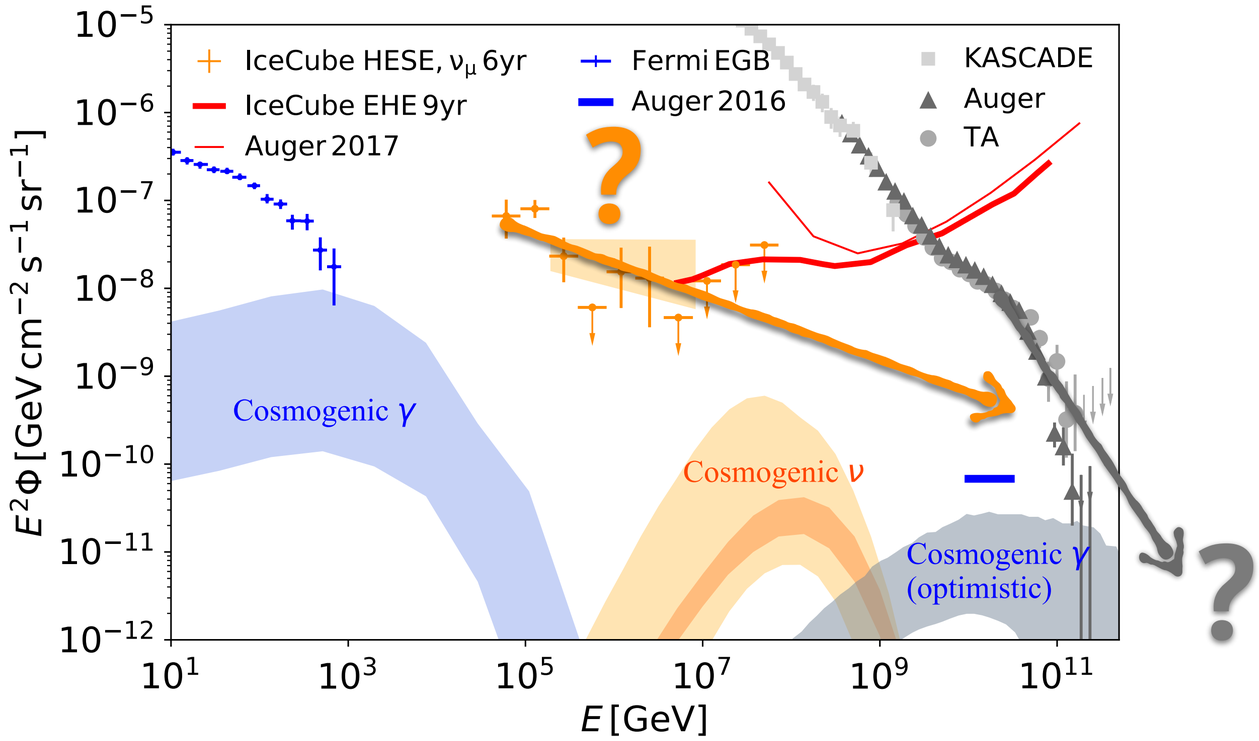

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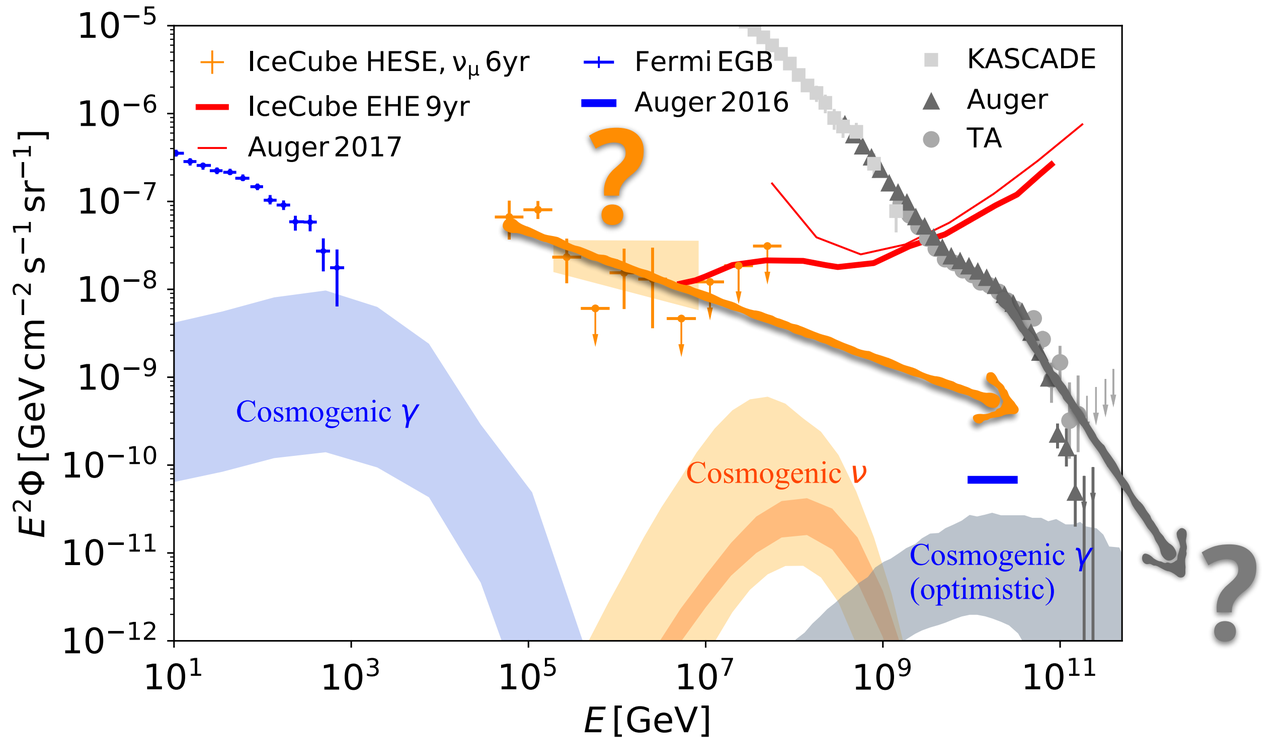

summary & outlook

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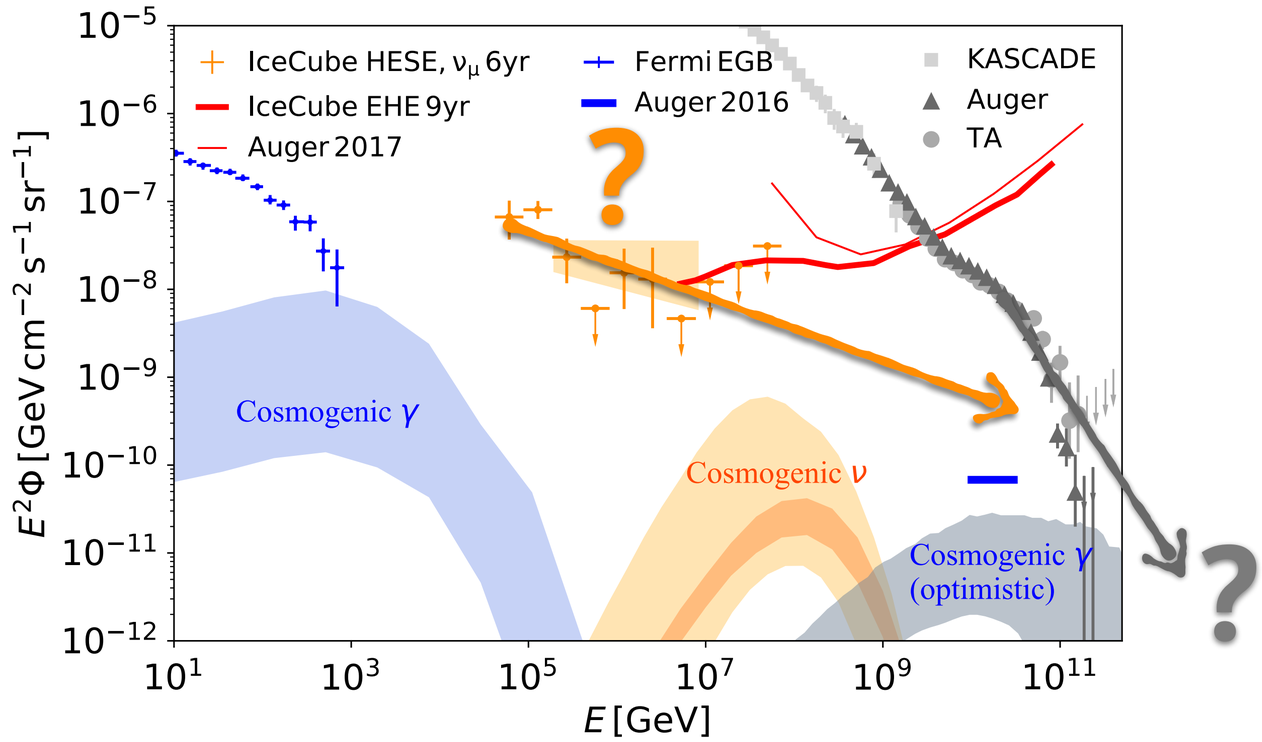
- CR observatories are true multimessenger facilities → self-consistent observations



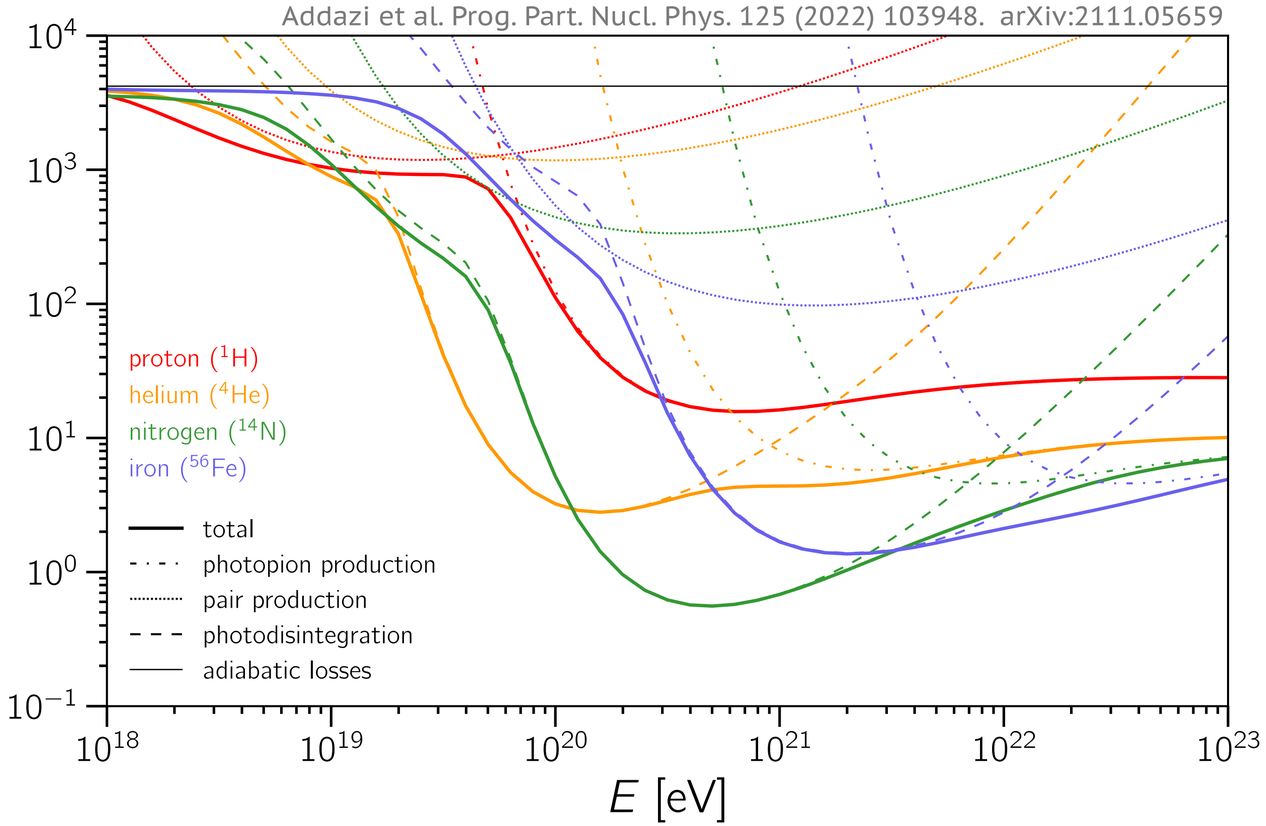
acknowledgements

thank you 😊

"la Caixa" Foundation

back-up

UHECR propagation: interactions



photopion production

$p + \gamma_{bg} \rightarrow p + \pi^0$ $\quad\quad$ $\pi^0 \rightarrow \gamma + \gamma$

$p + \gamma_{bg} \rightarrow n + \pi^+$ $\quad\quad$ $\pi^+ \rightarrow \nu_\mu + \mu^+$

$\mu^+ \rightarrow e^+ + \nu_e + \underline{\nu_\mu}$

(similar for nuclei)

Bethe-Heitler pair production

$\text{nucleus}(A,Z) + \gamma_{bg} \rightarrow \text{nucleus}(A,Z) + e^- + e^+$

photodisintegration

$\text{nucleus}(A,Z) + \gamma_{bg} \rightarrow \text{nucleus}(A\text{-}1,Z) + n$

$\text{nucleus}(A,Z) + \gamma_{bg} \rightarrow \text{nucleus}(A\text{-}1,Z\text{-}1) + p$

...

nuclear decays

$\text{nucleus}(A,Z) \rightarrow \text{nucleus}(A\text{-}4,Z\text{-}2) + \alpha$

$\text{nucleus}(A,Z) \rightarrow \text{nucleus}(A,Z\text{+}1) + e^- + \underline{\nu_e}$

$\text{nucleus}(A,Z) \rightarrow \text{nucleus}(A,Z\text{-}1) + e^{-+} + \nu_e$

$\text{nucleus}(A,Z)^* \rightarrow \text{nucleus}(A,Z) + \gamma$

UHECRs from Centaurus A

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- correlation with starburst galaxies

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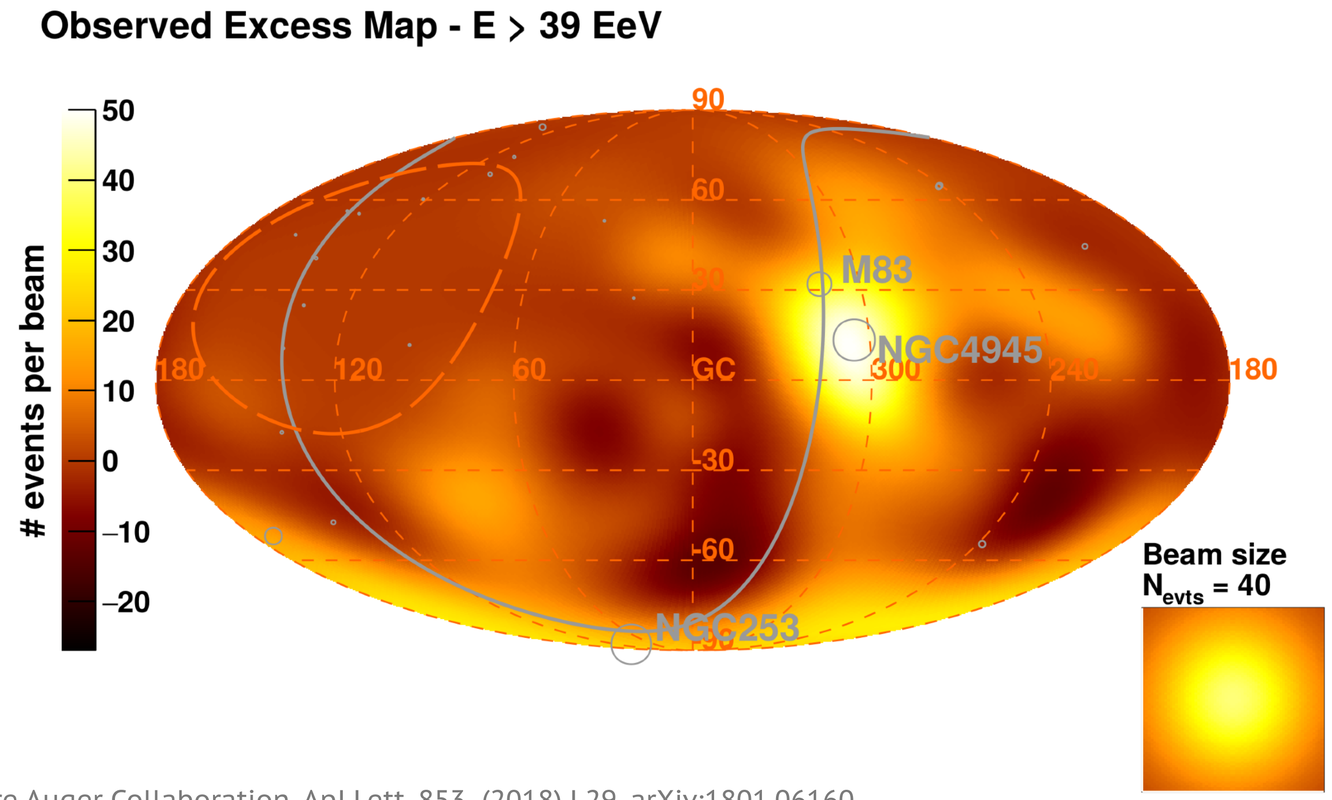

Pierre Auger Collaboration. ApJ Lett. 853 (2018) L29. arXiv:1801.06160

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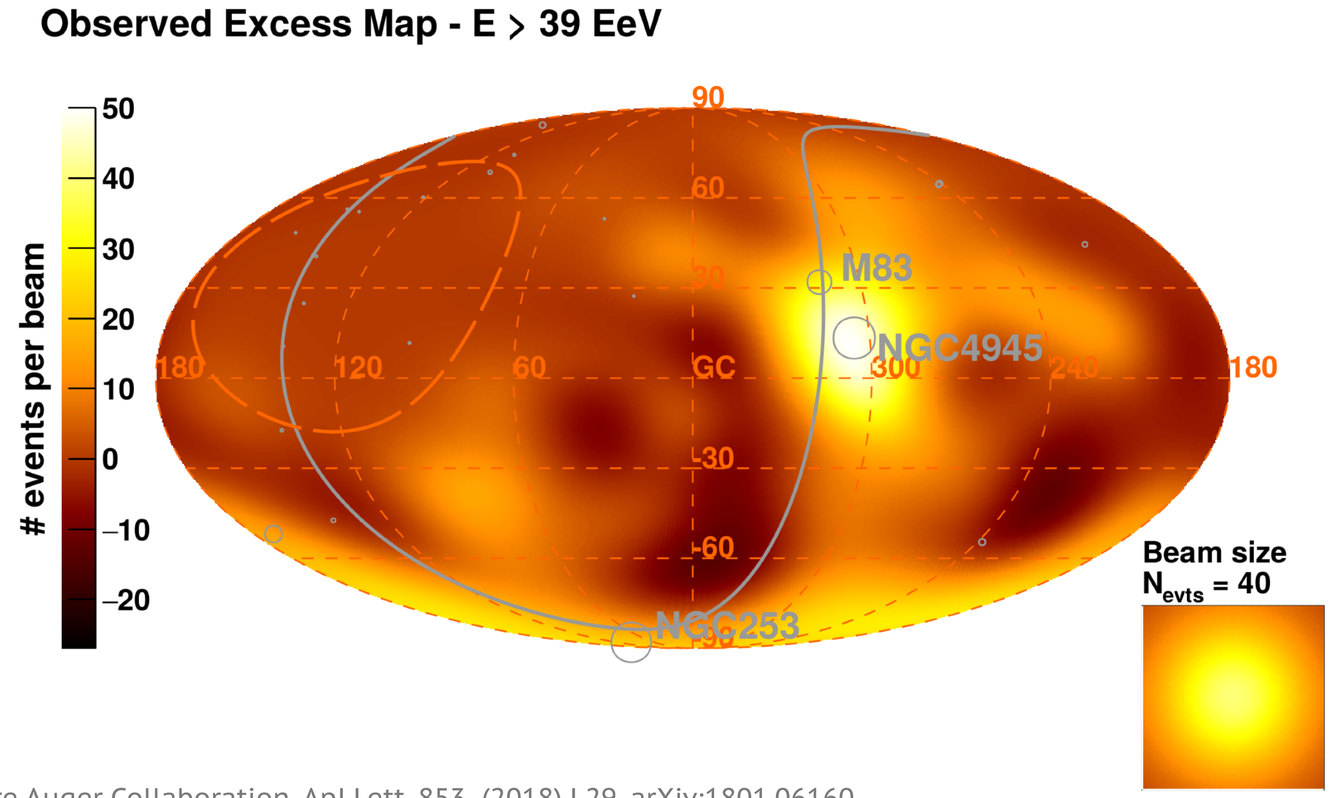

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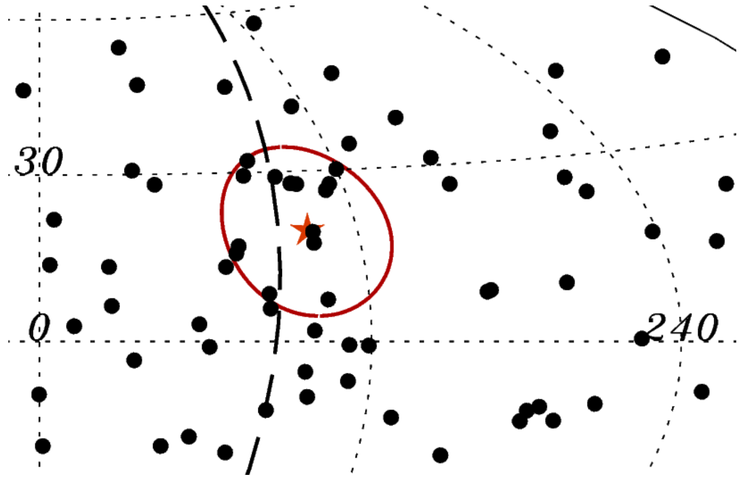

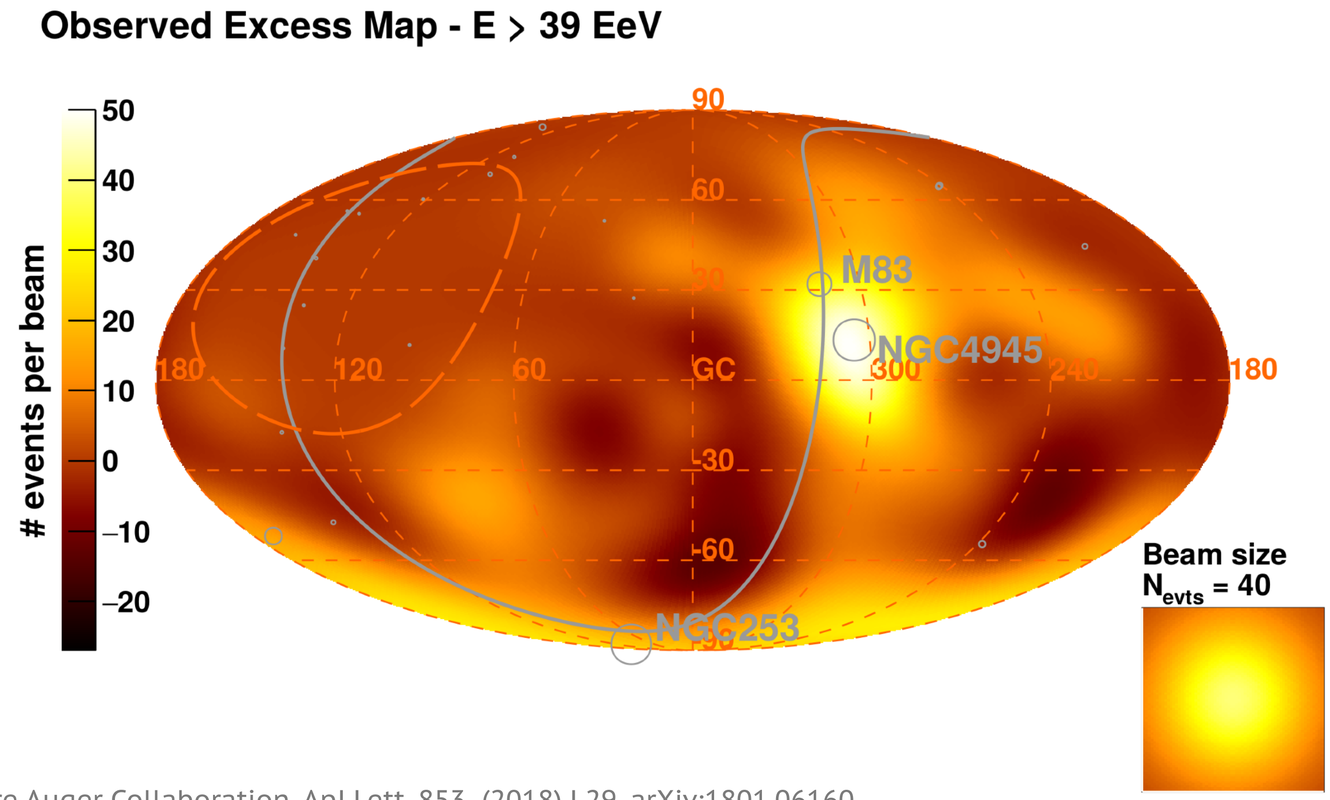

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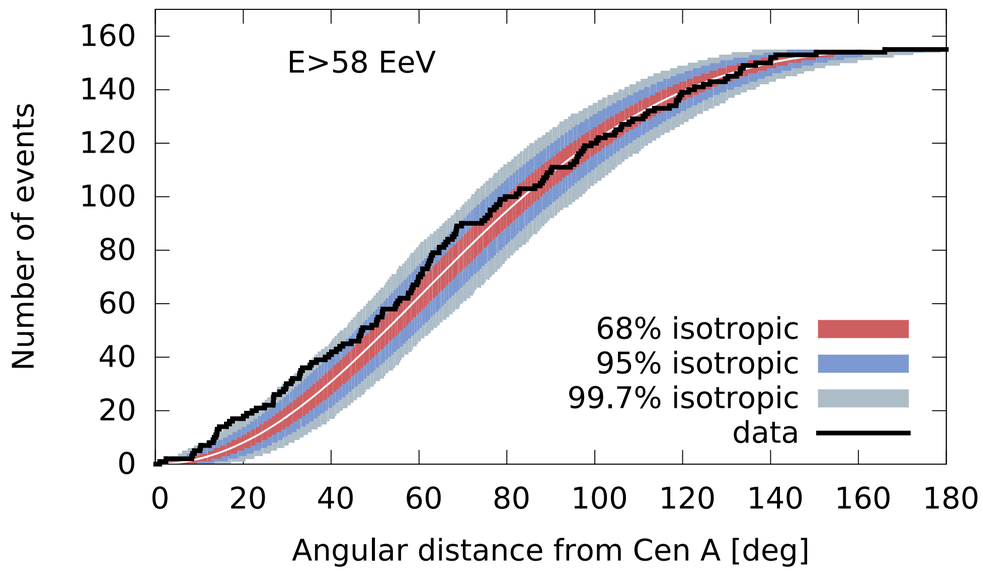
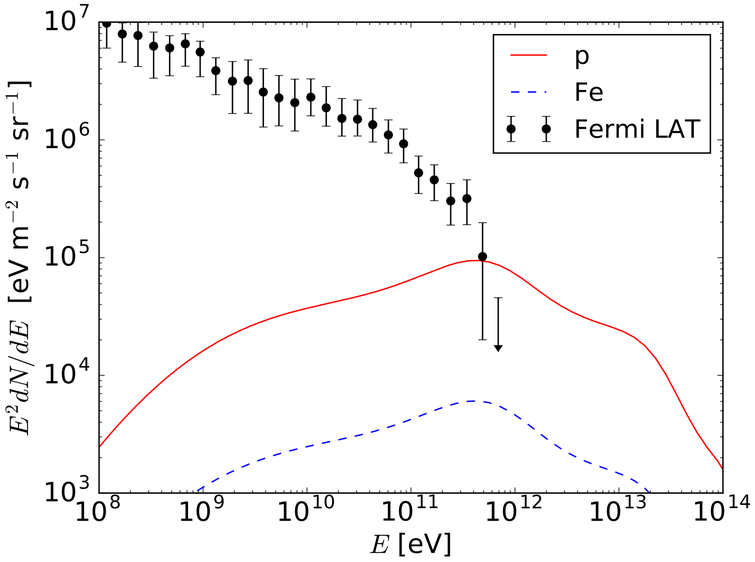


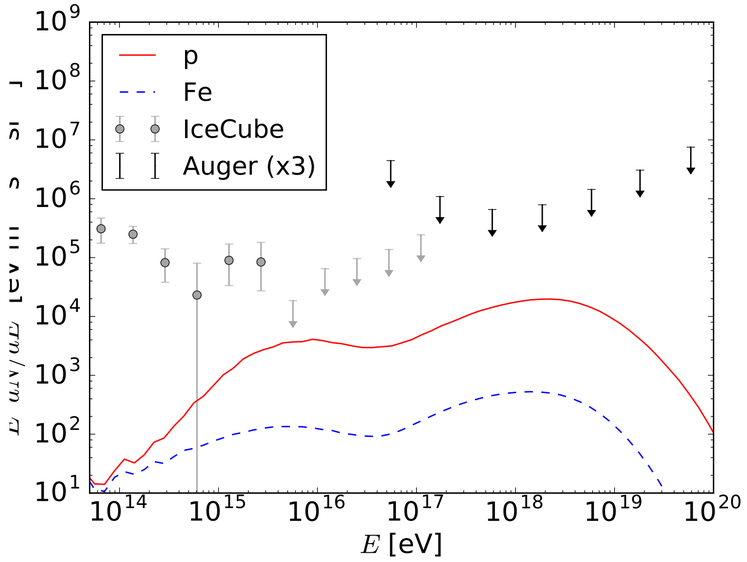
Pierre Auger Collaboration. ApJ 804 (2015) 15. arXiv:1411.6111

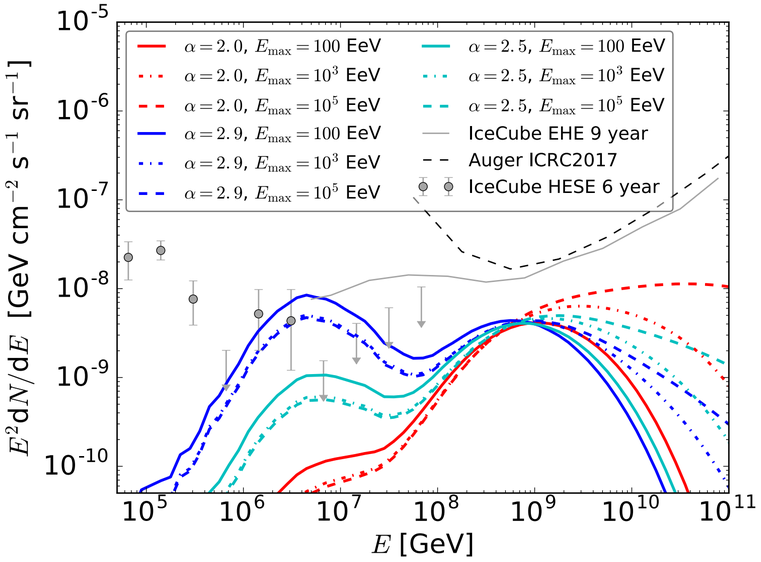
UHECR composition. cosmogenic neutrinos and photons

van Vliet, Alves Batista, Hörandel. PoS (ICRC2017) 562. arXiv:1707.04511

- the neutrino fluxes from the fit are understandably low because of the composition
- UHE protons tend to produce more secondaries than UHE nuclei
- the higher the fraction of protons at UHE, the higher the flux of cosmogenic neutrinos
- cosmogenic fluxes can be used to constrain the fraction of protons at UHE

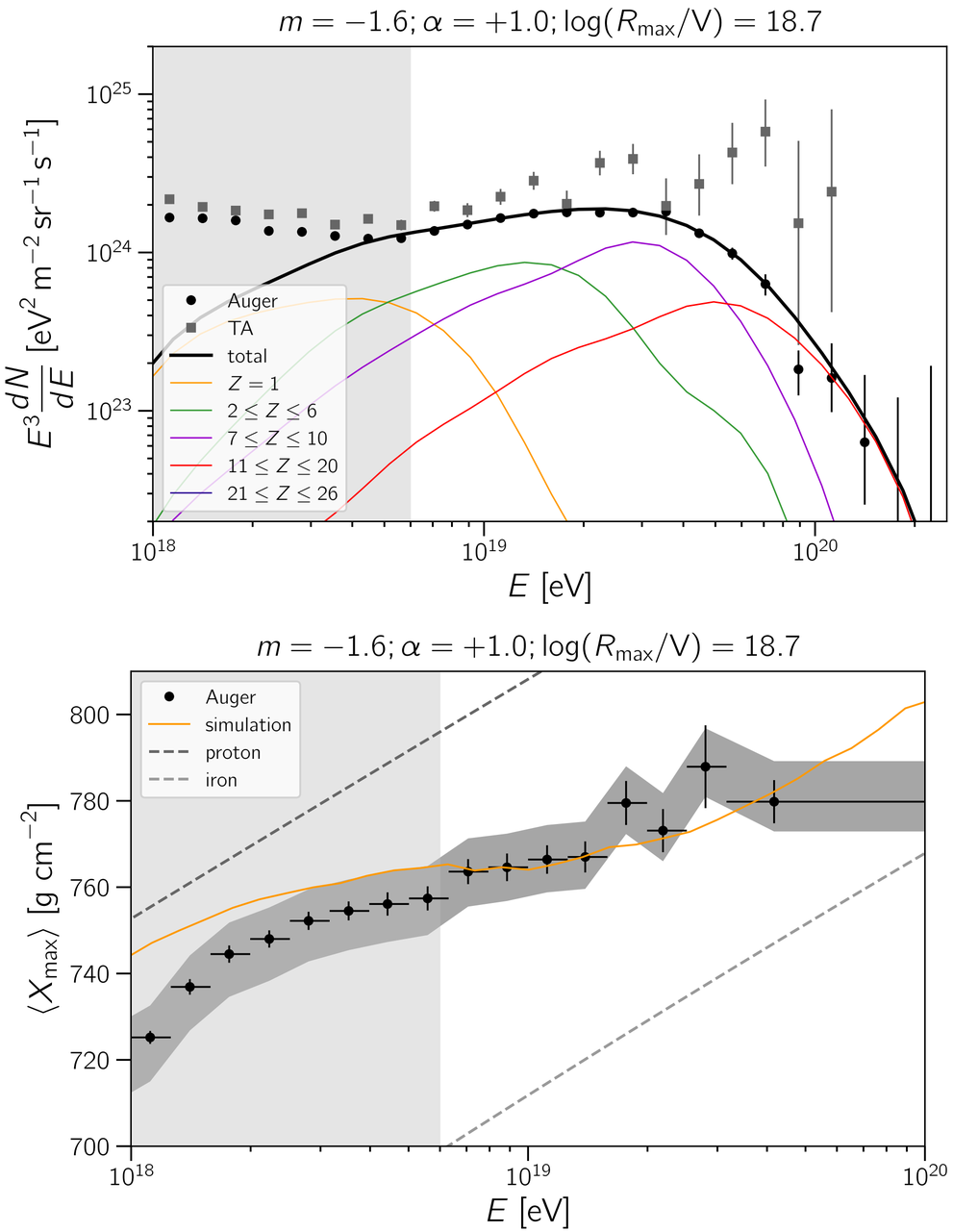






fitting the UHECR observations

Alves Batista, de Almeida, Lago, Kotera. JCAP 01 (2019) 002. arXiv:1806.10879



- **goal:** for a family of source models, find the best match to the measurements
- **assumptions**
  - emission: power-law with rigidity-dependent exponential cut-off
  - five nuclear species (H, He, N, Si, Fe)
  - sources uniformly distributed, evolving as $(1+z)^m$ up to $z_{max}=1$ → extremely *conservative*
- **results**
  - spectrum of UHECRs leaving the source is hard (lower spectral indices preferred)
  - fit favours negative source evolution
  - this means the sources that contribute to the bulk of the flux comes from the closest sources

UHE particle astronomy?

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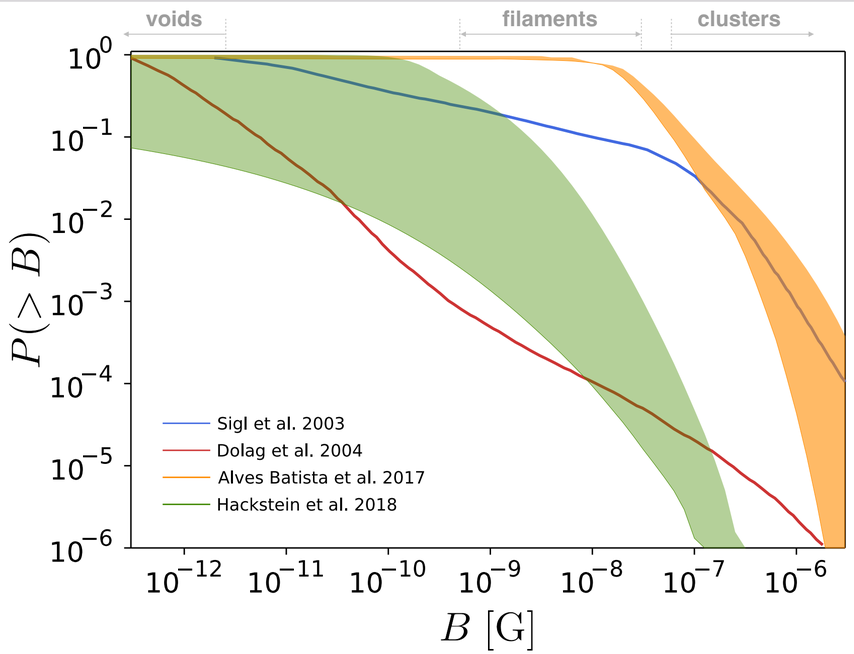

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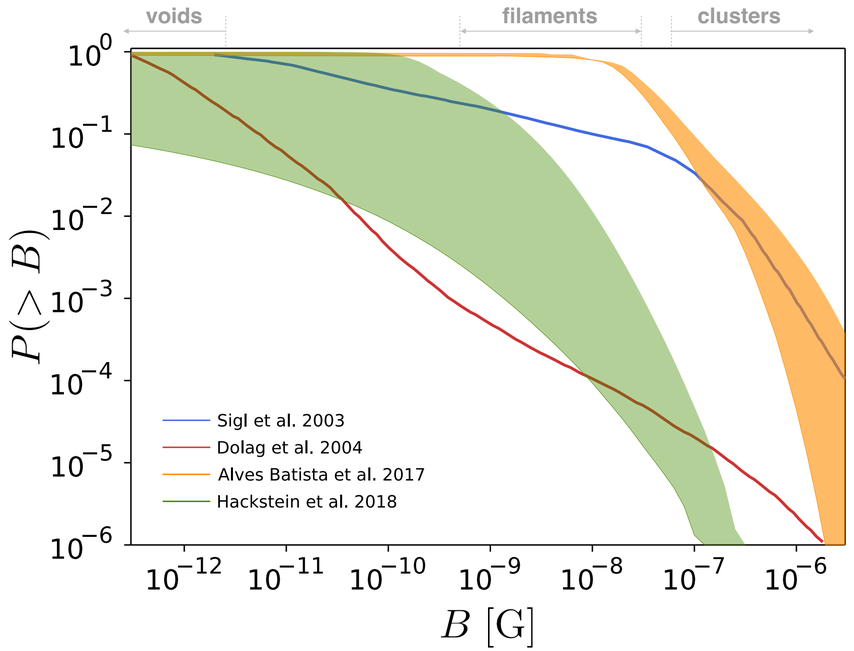

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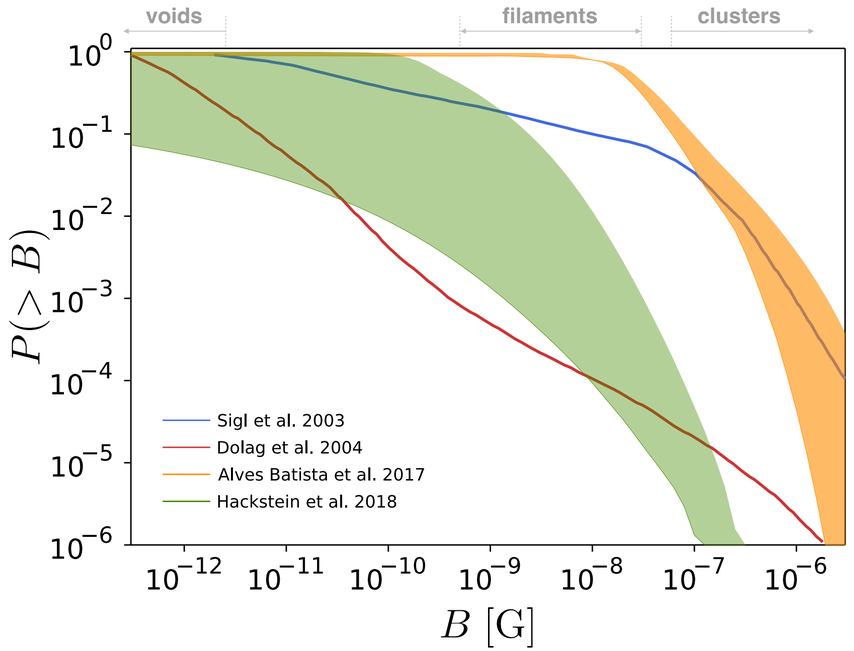

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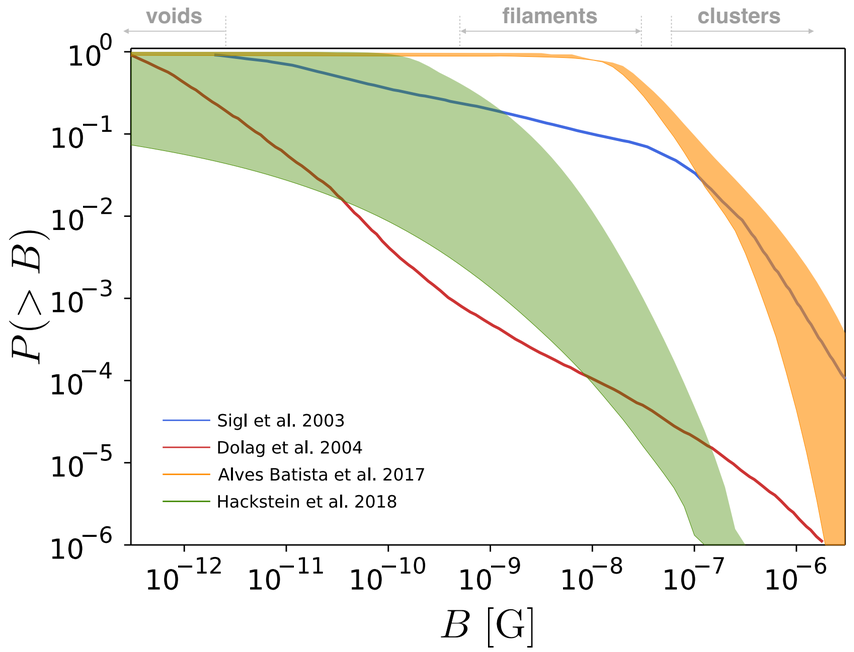

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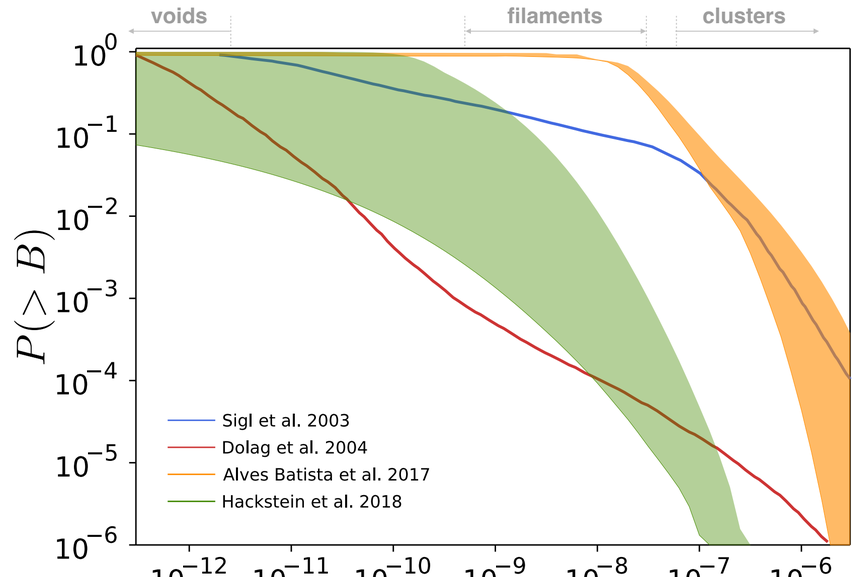

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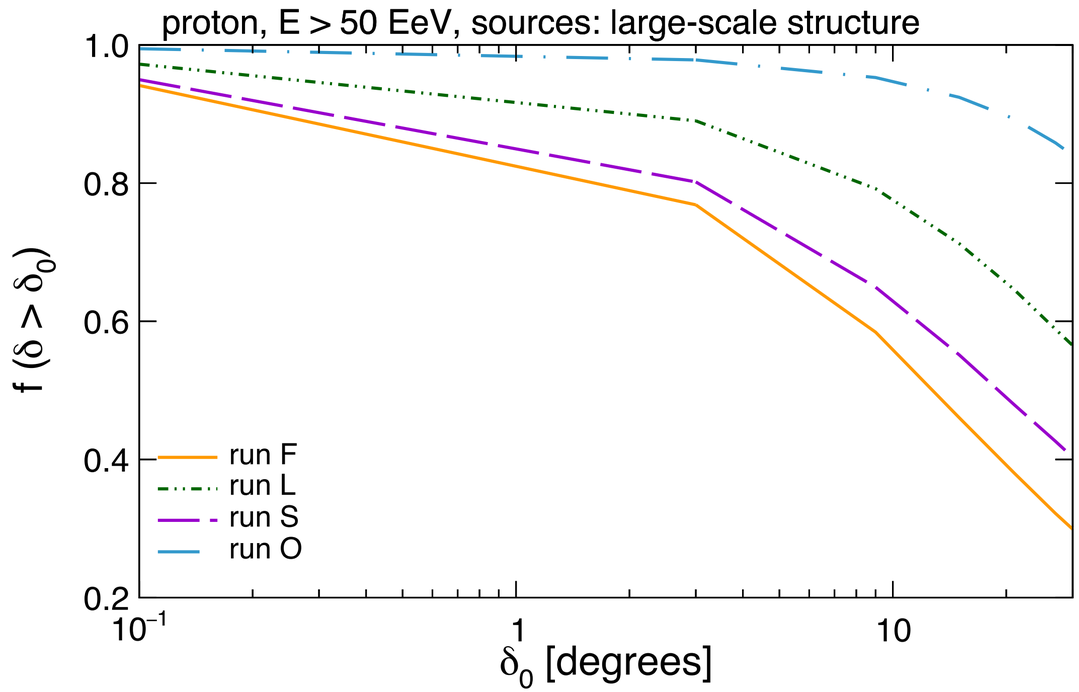

Alves Batista, Shin, Devriendt, Semikoz, Sigl. PRD, 96 (2017) 023010. arXiv:1704.05869

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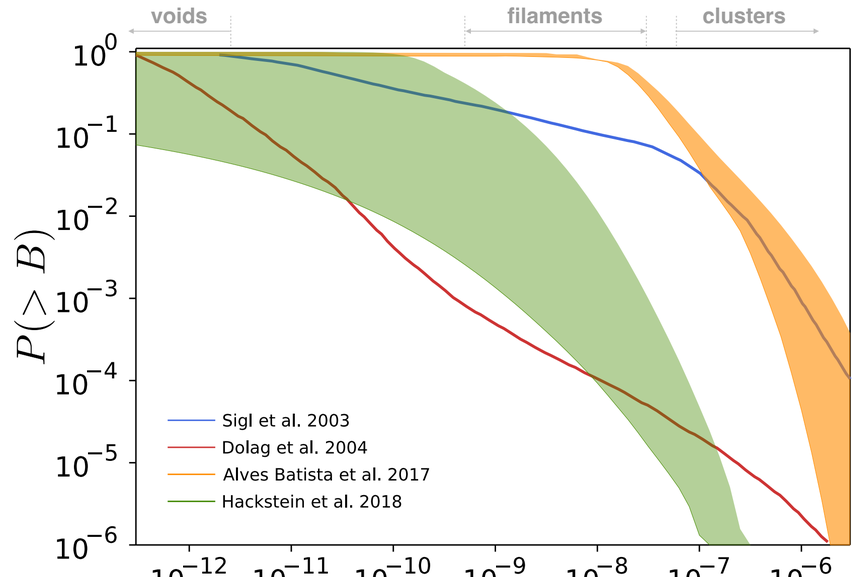

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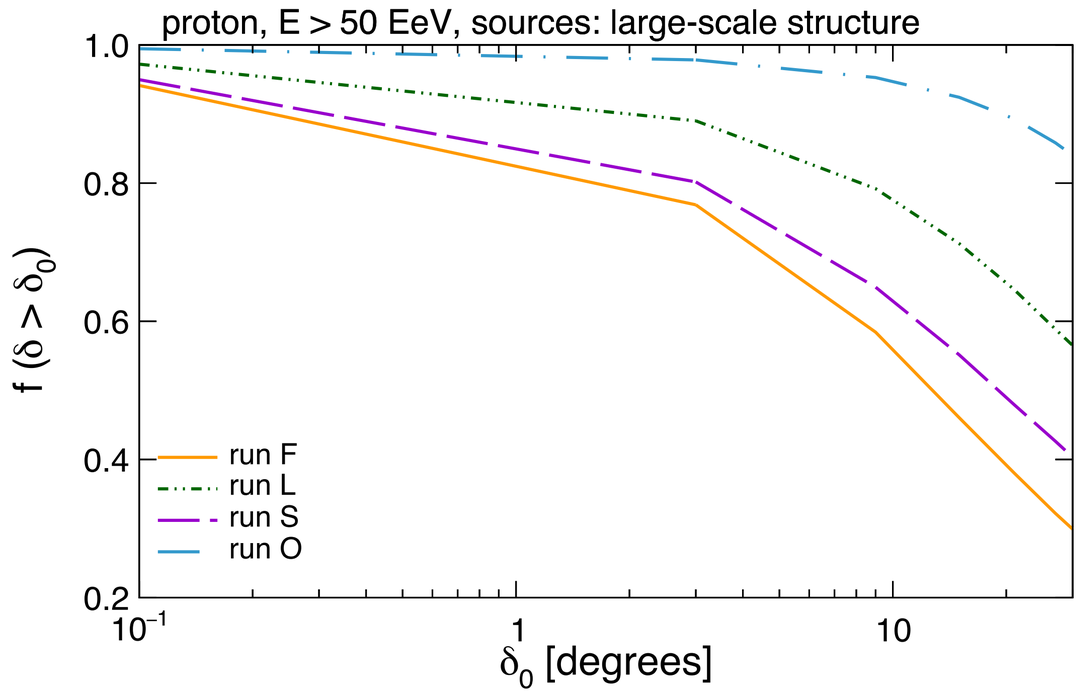

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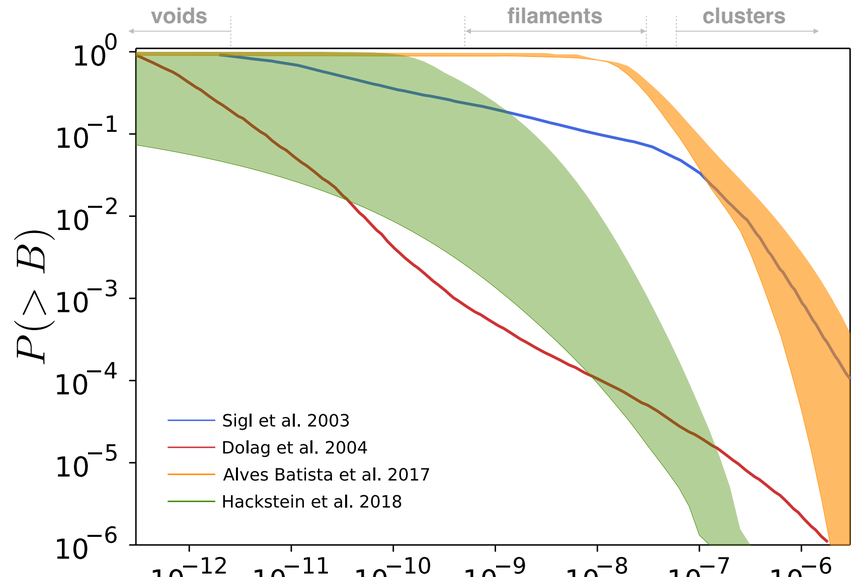
- *possible does not mean easy* ... information delivered by other messengers is essential to grasp the full picture



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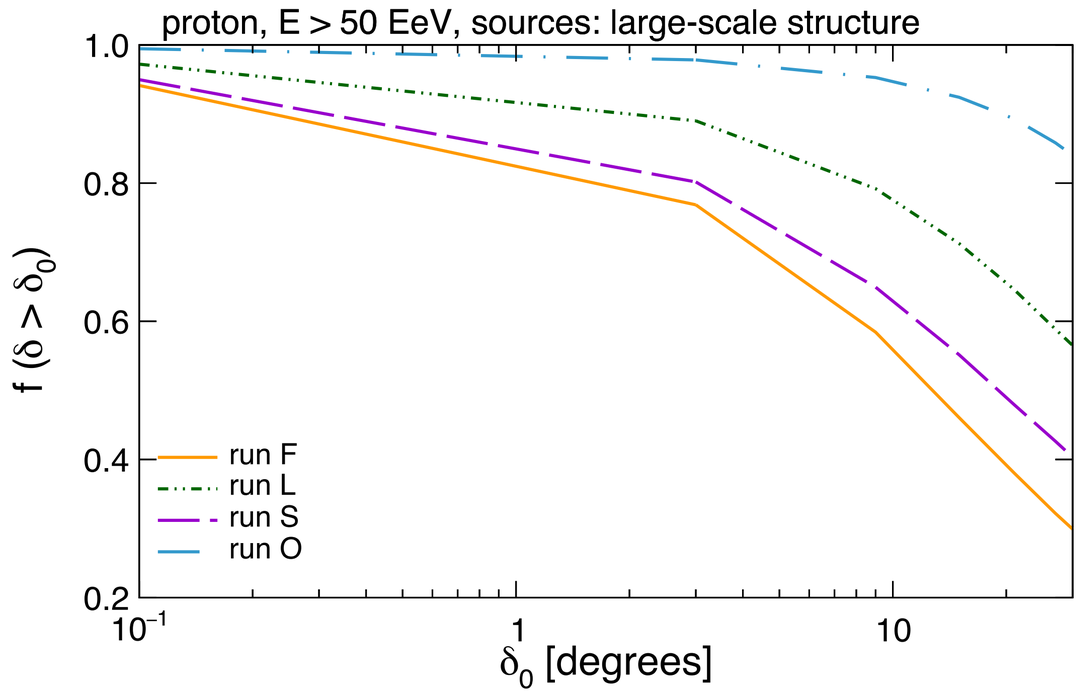

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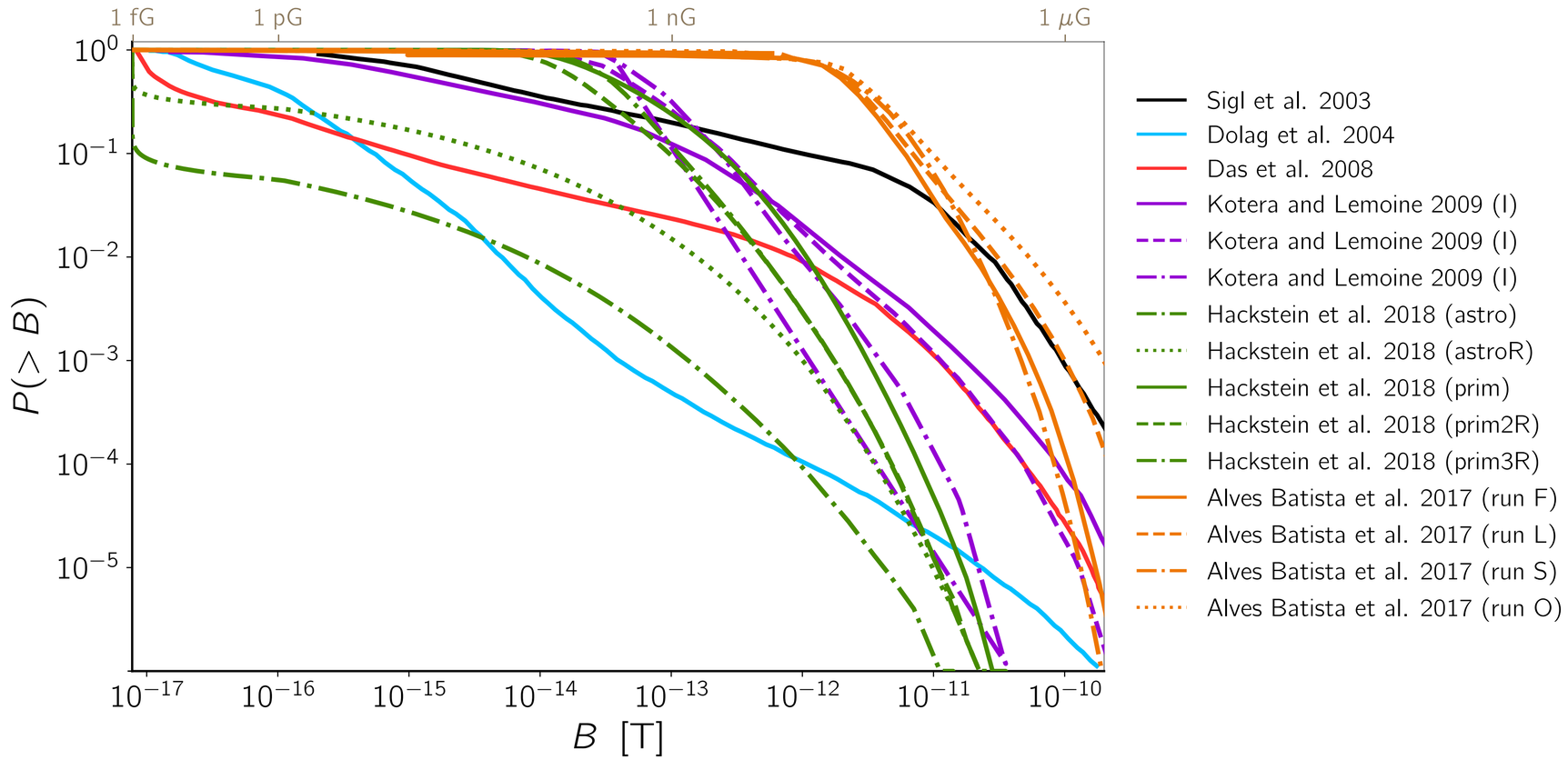
magnetic fields in the large-scale structure of the universe



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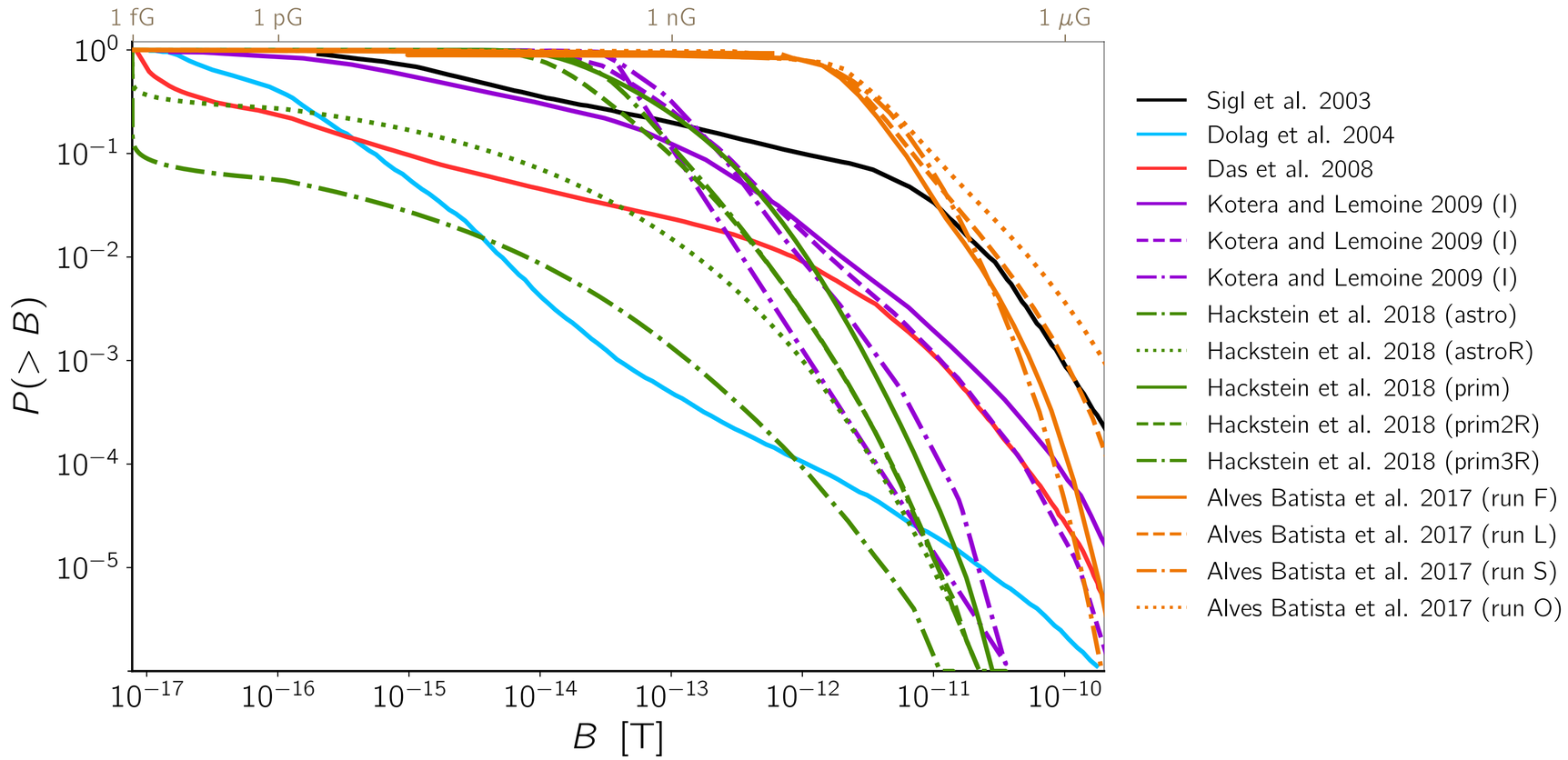

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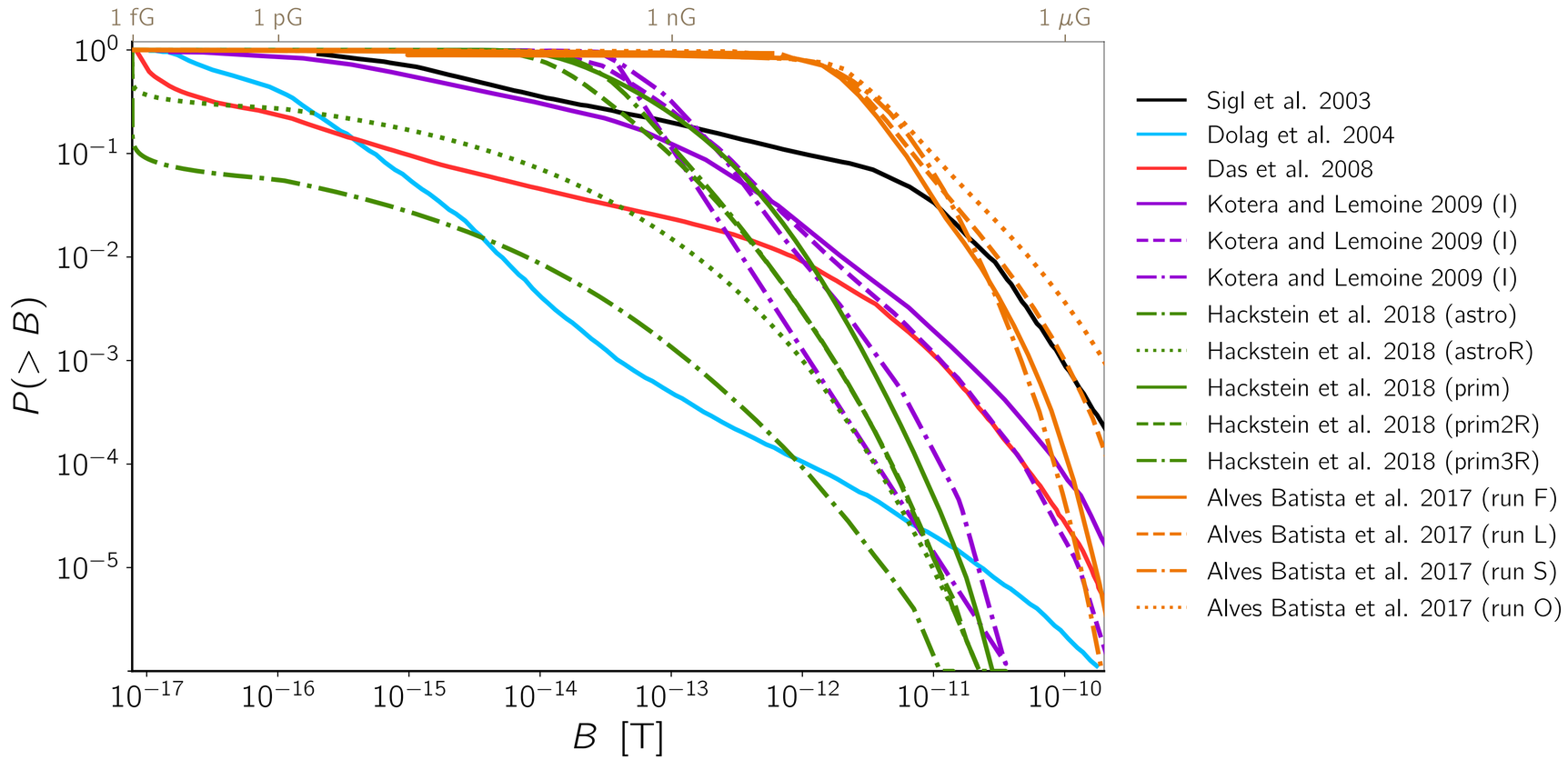

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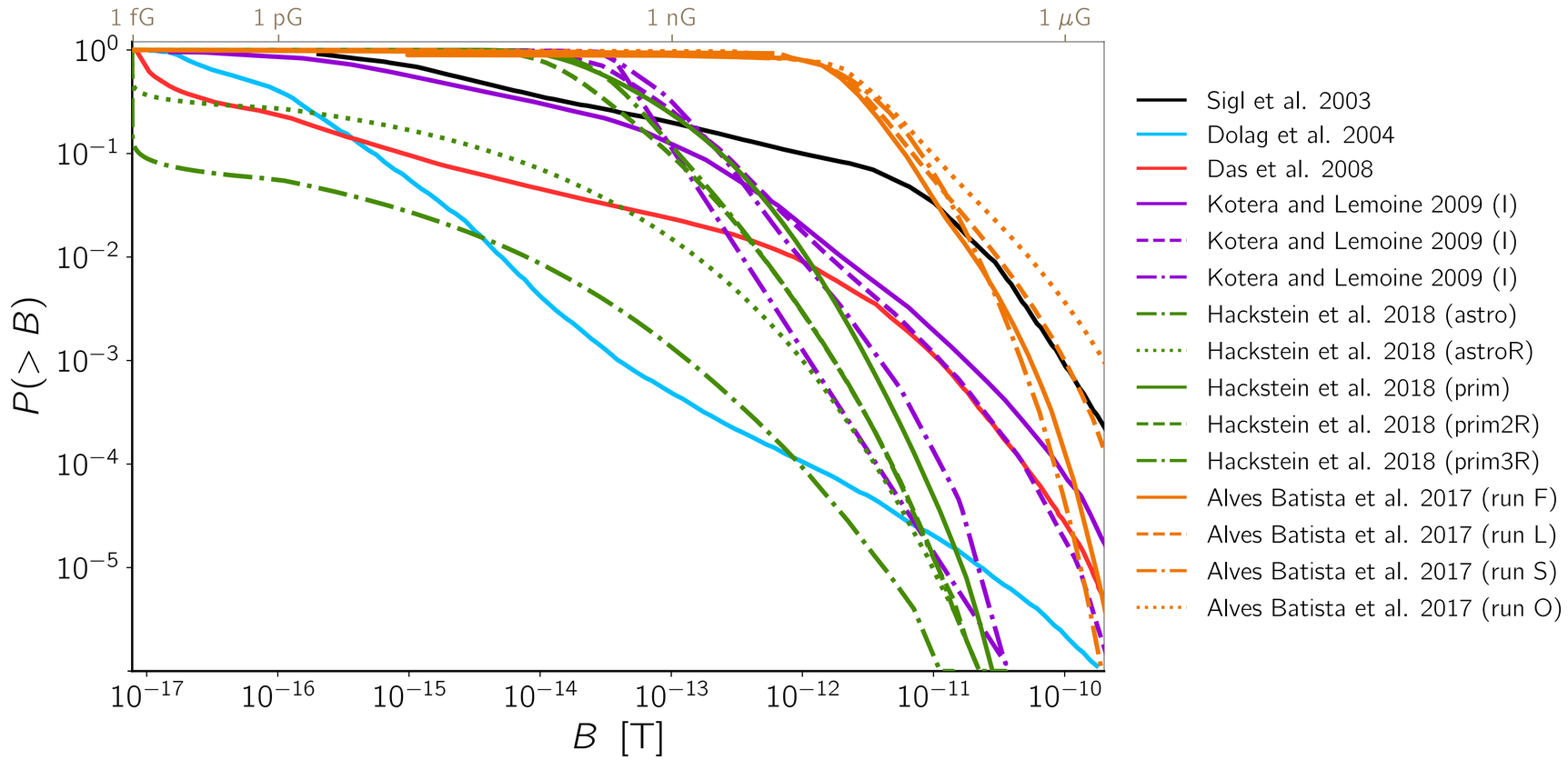

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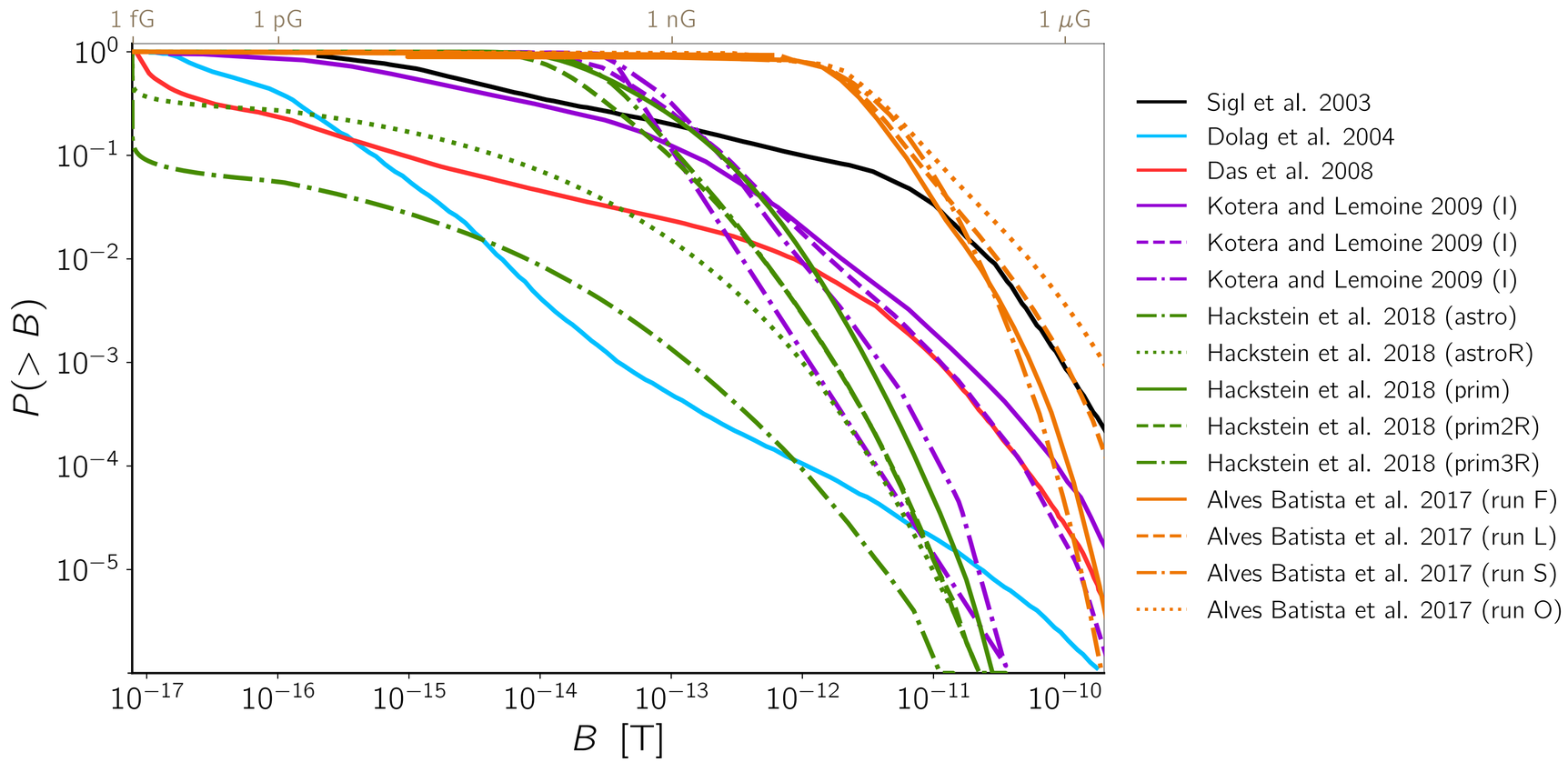

deflections

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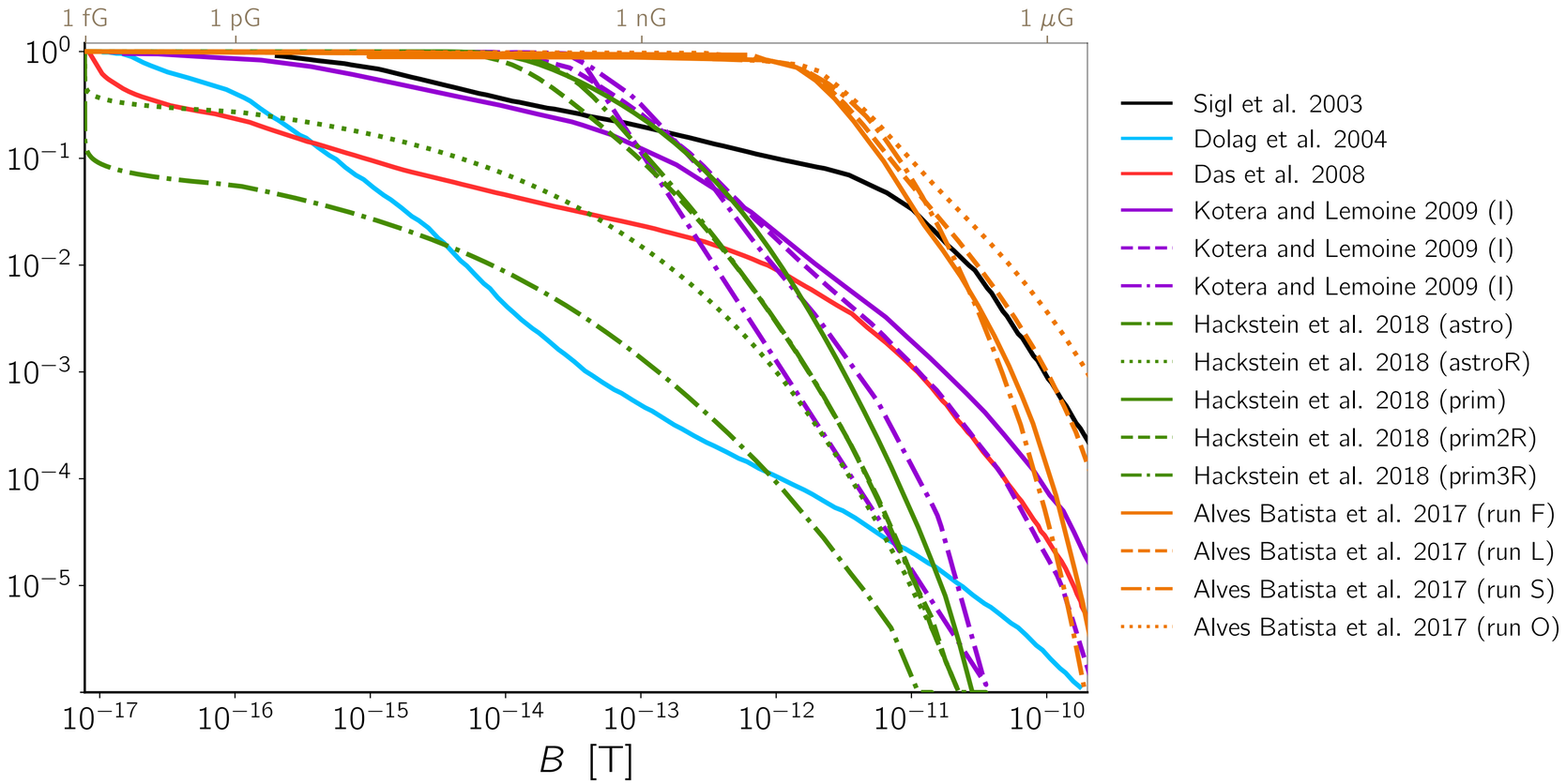

deflections

$$\delta \simeq \begin{cases} 0.05^{\circ} Z \left(\frac{E}{100\ \mathrm{EeV}}\right)^{-1} \left(\frac{B}{\mathrm{nG}}\right) \left(\frac{D}{\mathrm{Mpc}}\right) & \text{if } D \ll L_B \\ 0.05^{\circ} Z \left(\frac{E}{100\ \mathrm{EeV}}\right)^{-1} \left(\frac{B}{\mathrm{nG}}\right) \left(\frac{D}{\mathrm{Mpc}}\right)^{\frac{1}{2}} \left(\frac{L_B}{\mathrm{Mpc}}\right)^{\frac{1}{2}} & \text{if } D \gg L_B \end{cases}$$

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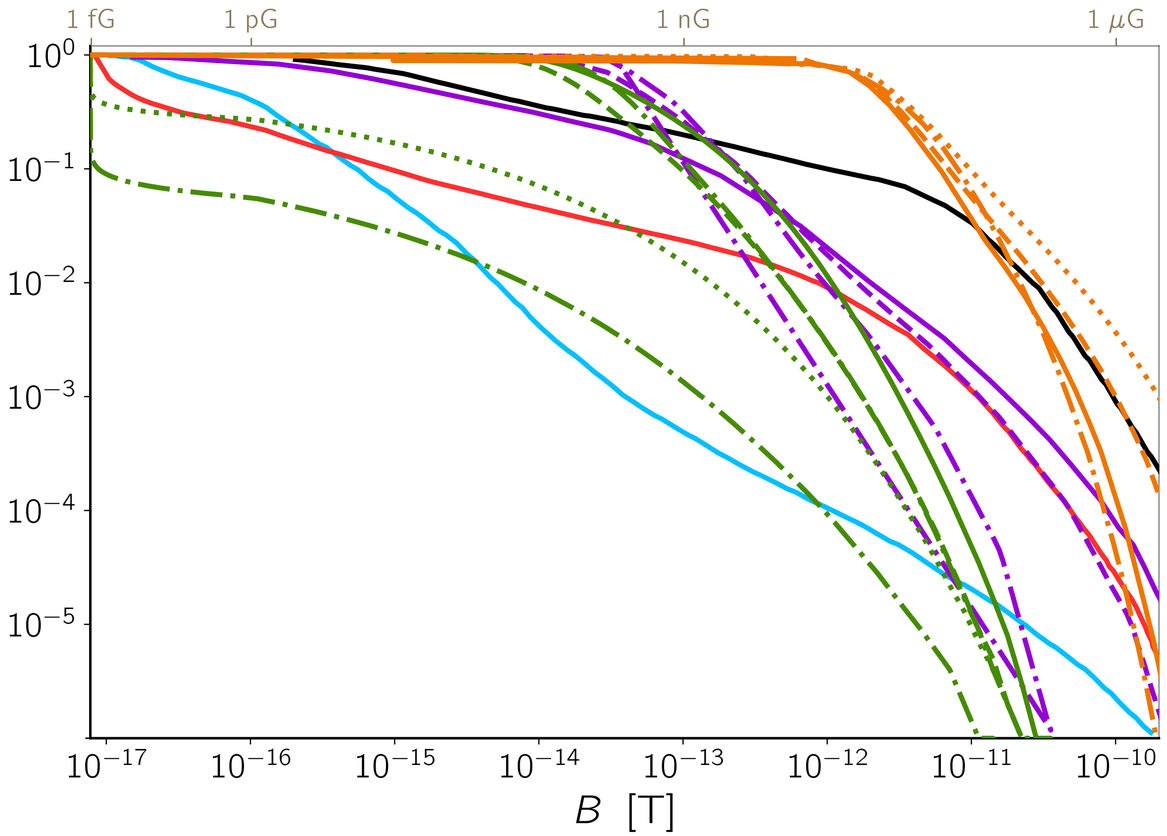

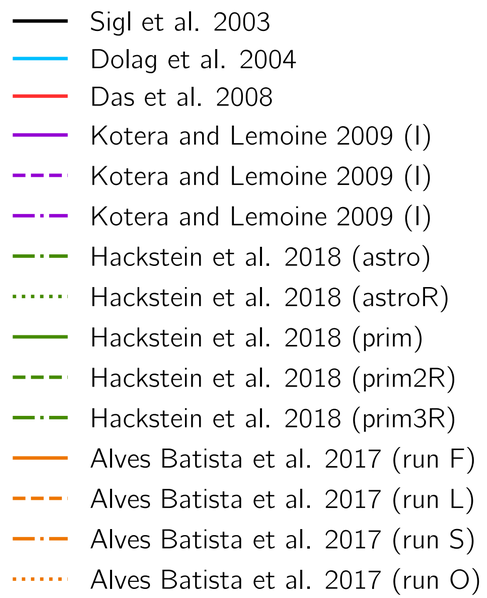

deflections are completely uncertain (they can be huge)

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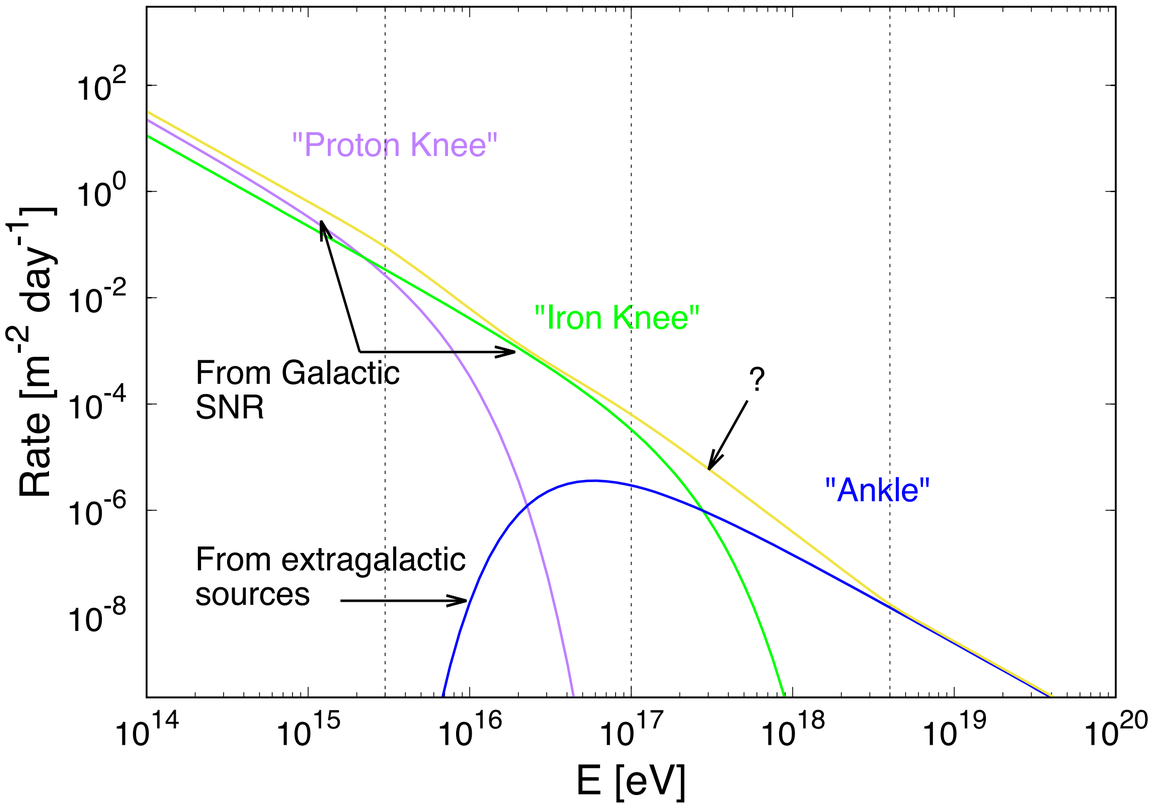

Alves Batista et al. Front. Astron. Space. Sci. 6 (2019) 23. arXiv:1903.06714

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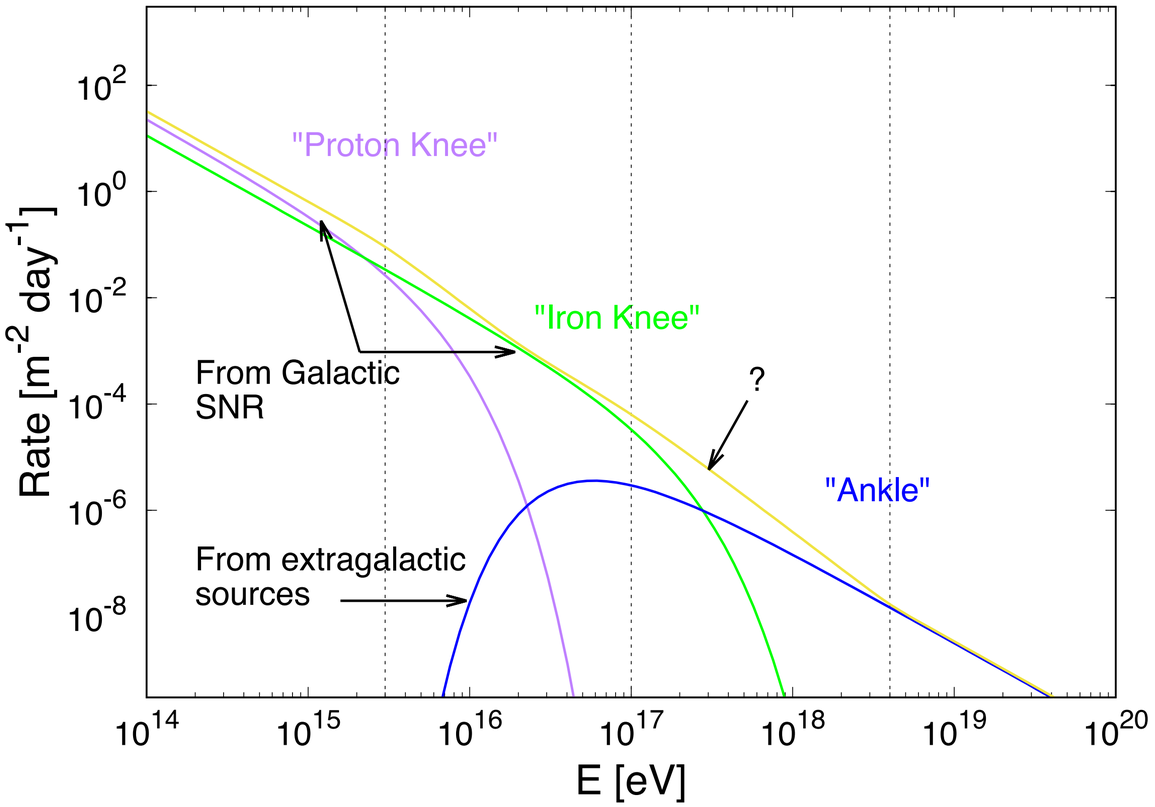

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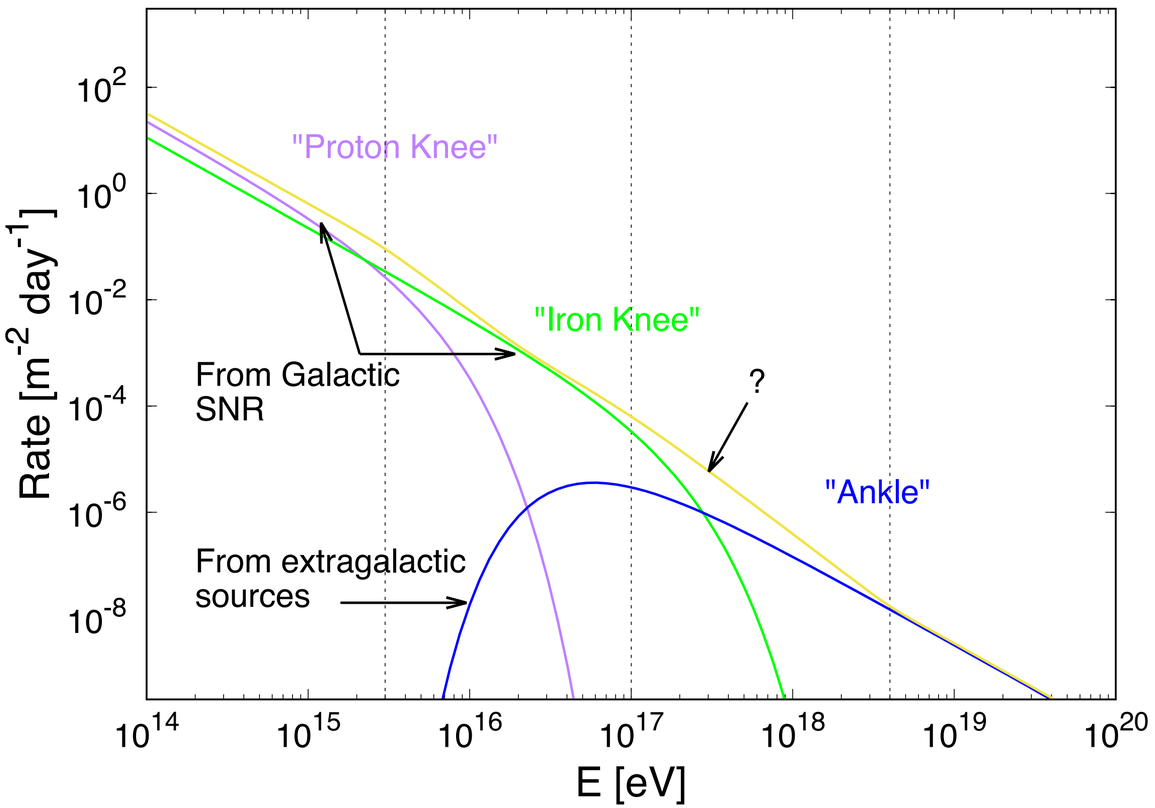

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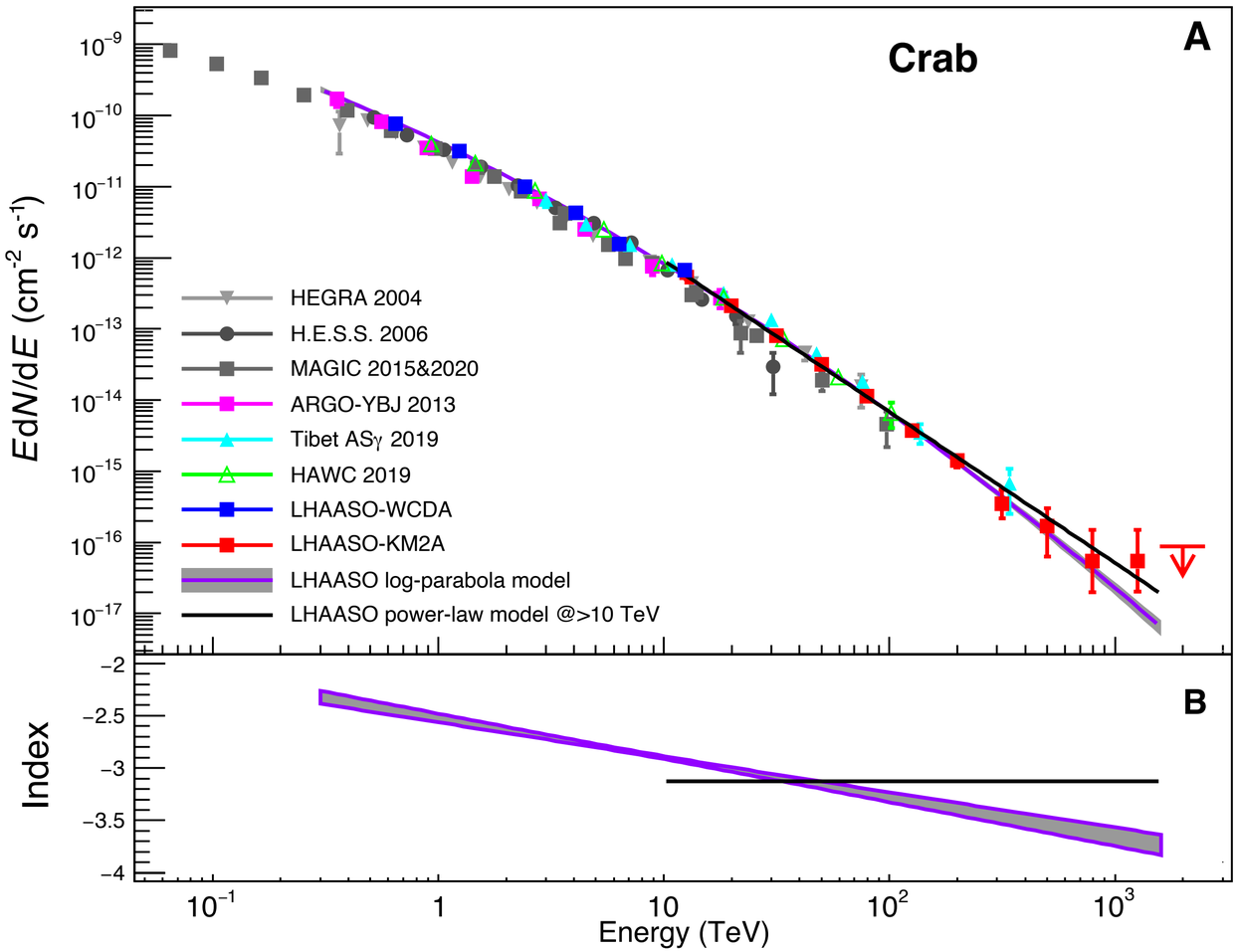

LHAASO Collaboration. Nature 594 (2021) 33.
LHAASO Collaboration. Science 373 (2021) 425. arXiv:2111.06545

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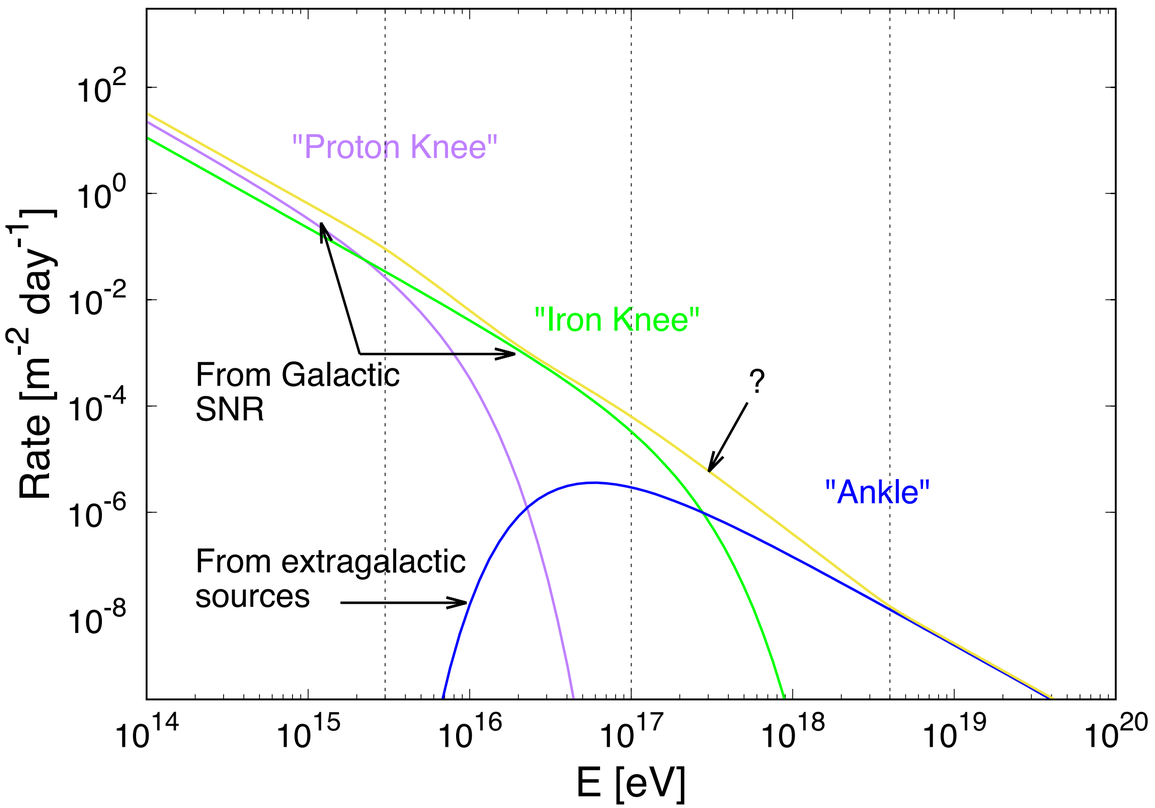
- ~PeV photons from Galactic sources observed
  - ~PeV photons imply CRs with ~10 PeV - 0.1 EeV



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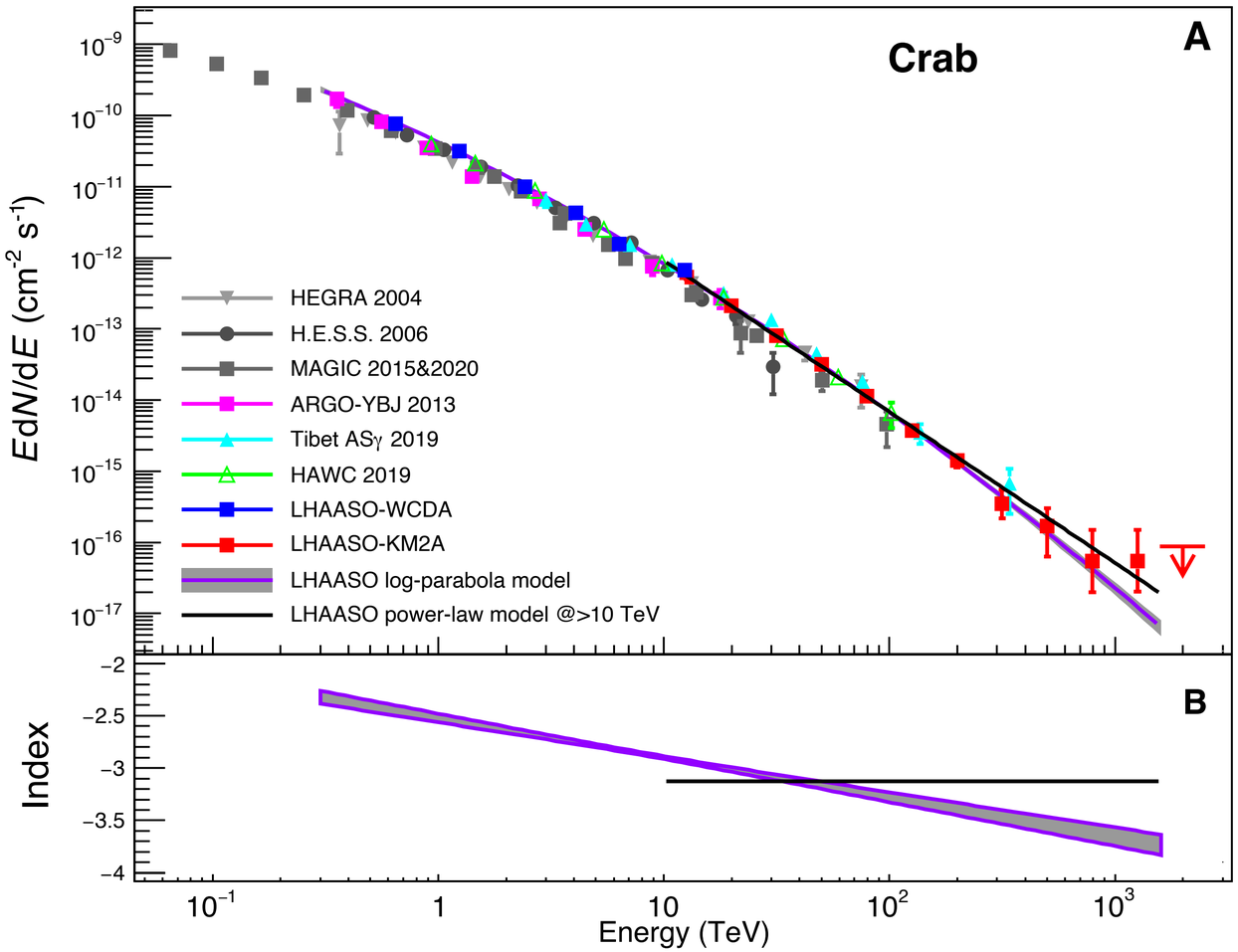

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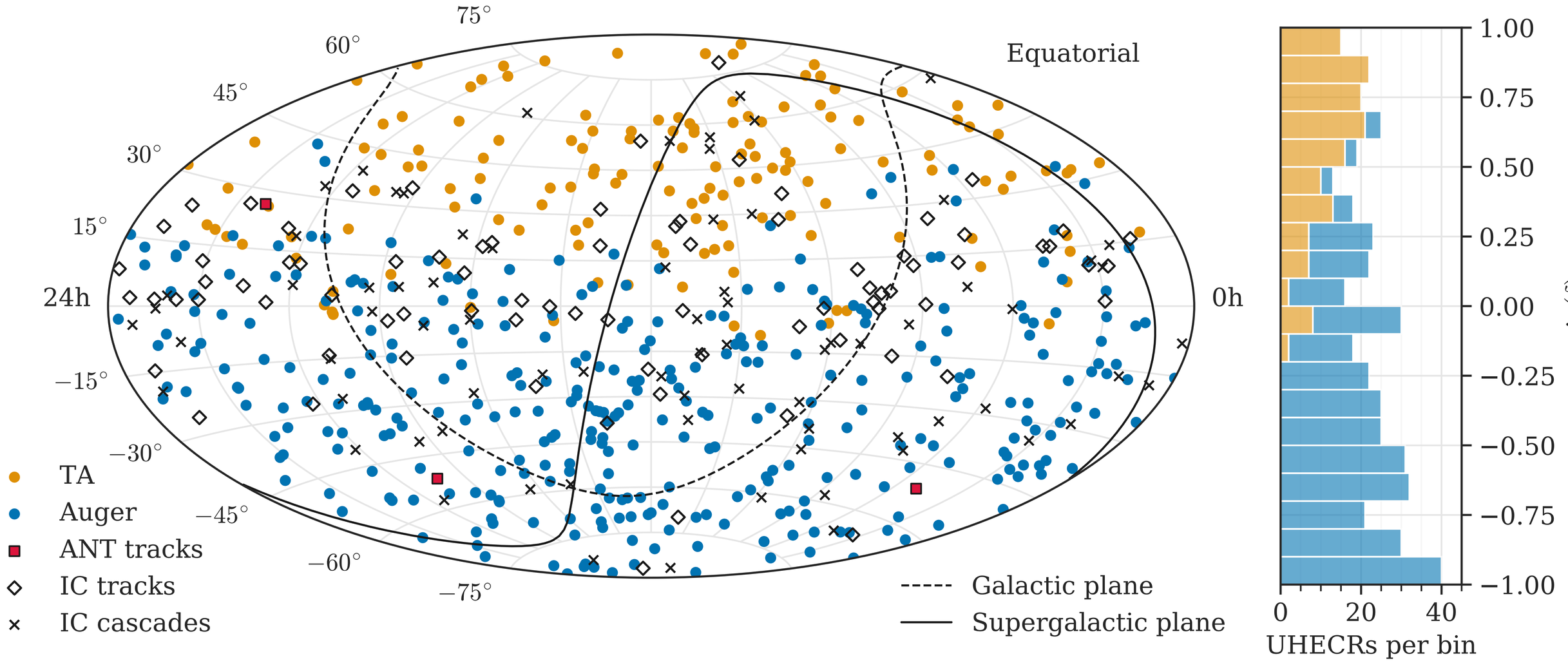

ANTARES, IceCube, Pierre Auger, and Telescope Array Collaborations. arXiv:2201.07313

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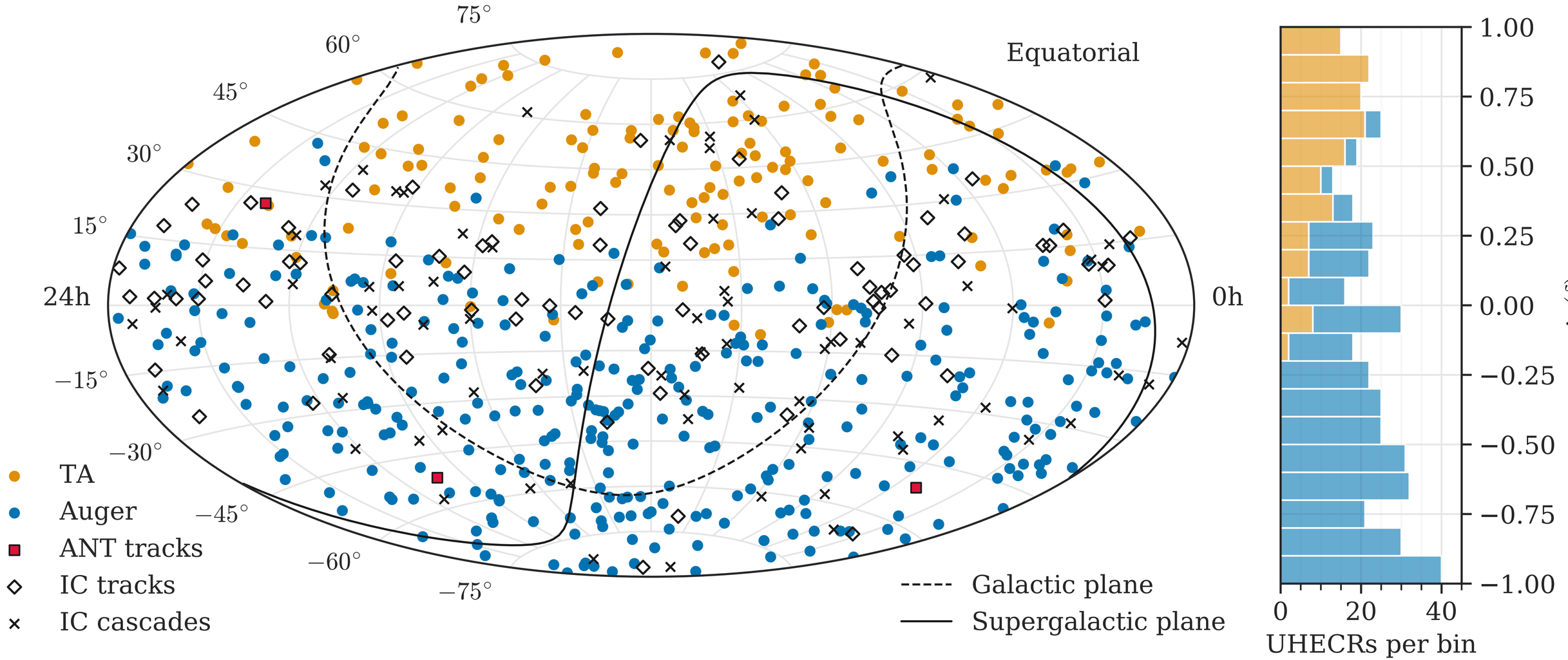
- **do we see correlations between HE neutrinos and UHECRs?**
  - no



ANTARES, IceCube, Pierre Auger, and Telescope Array Collaborations. arXiv:2201.07313