arXiv:2609.10784 [astro-ph.HE]

Low-Mass Magnetic Monopoles in the Galaxy: Simulations and Comparison with UHECR Data

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2026.09.13

Motivation

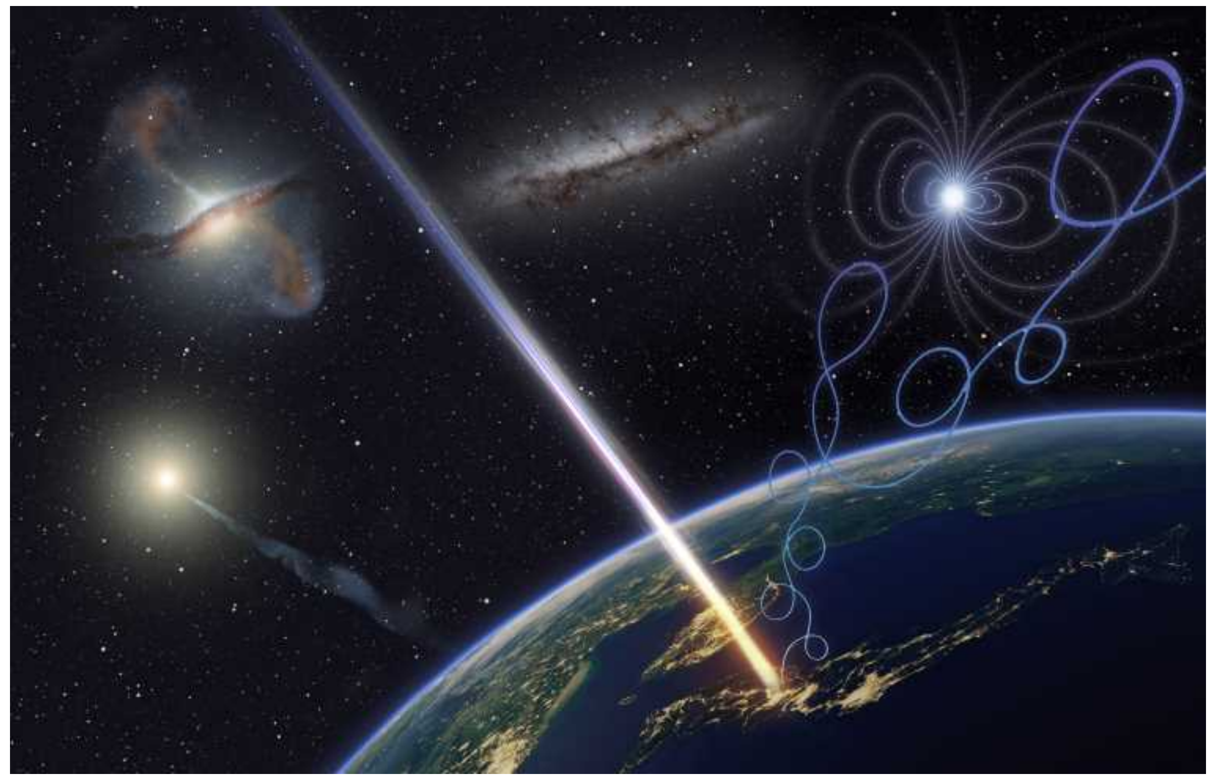


Image credit: Osaka Metropolitan University/L-INSIGHT, Kyoto University/Ryuunosuke Takeshige, CC BY-NC-SA.

- ✳ Some UHECRs lie above the expected GZK suppression scale
- ✳ The 240 EeV Amaterasu event points toward Local Void
- ✳ Their extreme energies and lack of an obvious nearby source leave their origin and composition uncertain
- ✳ Cosmological relic MMs may enter the Galaxy as an approximately isotropic population

Whether some of the UHECR events with puzzling features could be MMs

This analysis: Simulation of arrival directions & energies of low-mass MMs and comparison with Auger dataset of UHECRs

Outline

Simualtion w/ custom extension to CRPropa → **Simualtion results** → **Likelihood analysis with Auger dataset**

Simualtion w/ custom extension to CRPropa:

- MMs simulation framework
- Simulation assumptions and settings
- Scenario I: acceleration in galactic fields
- Scenario II: acceleration in intergalactic fields

Simualtion results:

- “Galactic magnetic funnel”
- Implications for future terrestrial detector

Likelihood analysis with Auger dataset:

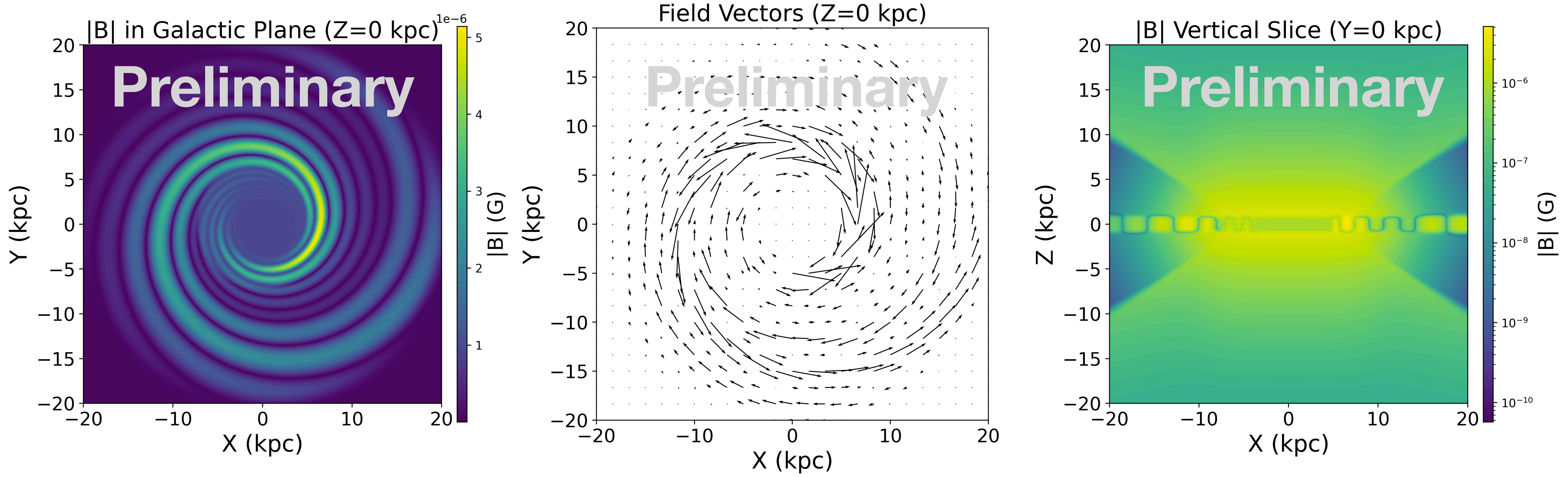
- Arrival direction only
- Arrival direction + energy

Simulation framework & settings

Custom MM propagation in CRPropa

$$\frac{d\mathbf{P}}{dt} = g\mathbf{B} + q\mathbf{v} \times \mathbf{B},\ E_{rad} \text{ included}$$

- Custom Cash-Karp propagation and radiative losses modules
- m = 1, 100 TeV/c²
- g = $\pm 1 g_D, \pm 6 g_D$
- Coherent UF23 galactic magnetic field models



UF23 base model

Pipeline:

20 kpc injection sphere w/ Lambertian distribution → **propagate in GMF** → **record at Earth**

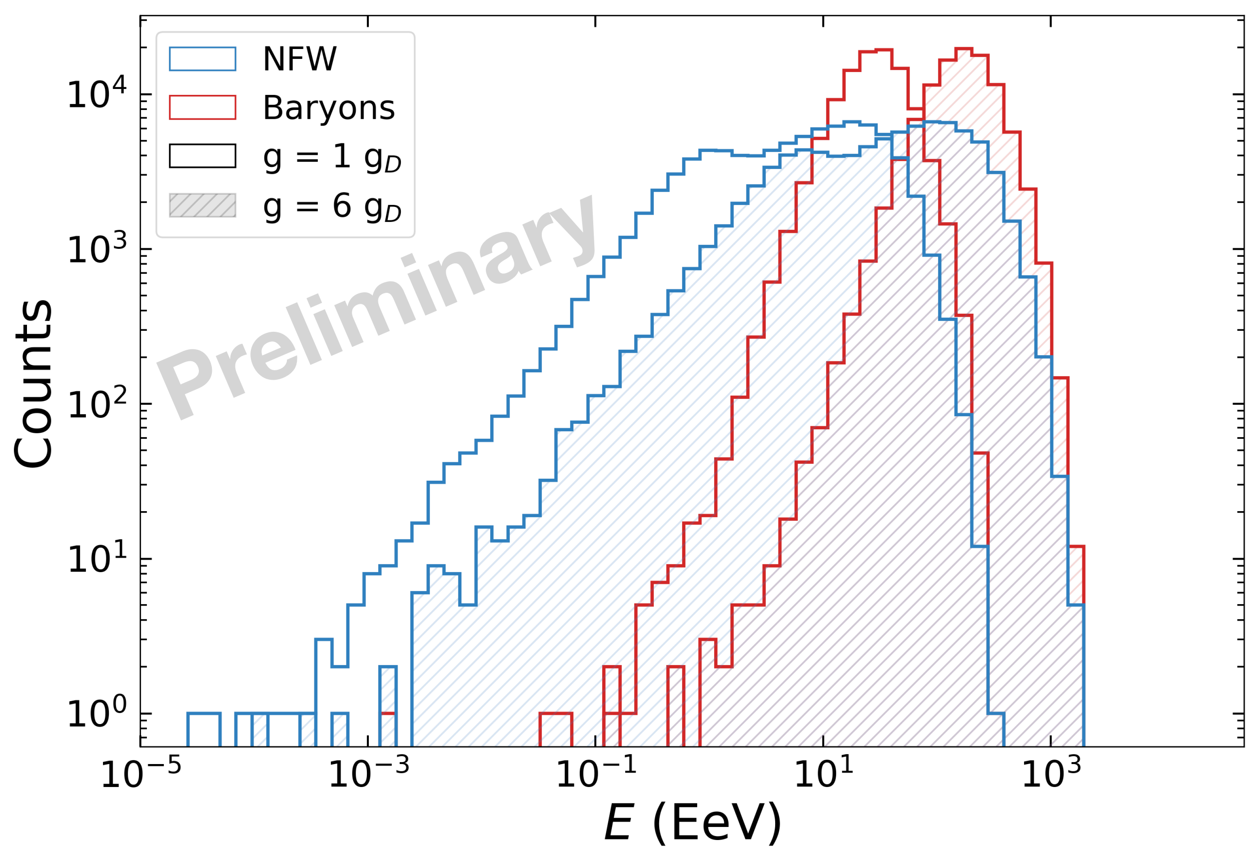
Initial kinetic energy assumptions

Scenario I: Galactic acceleration

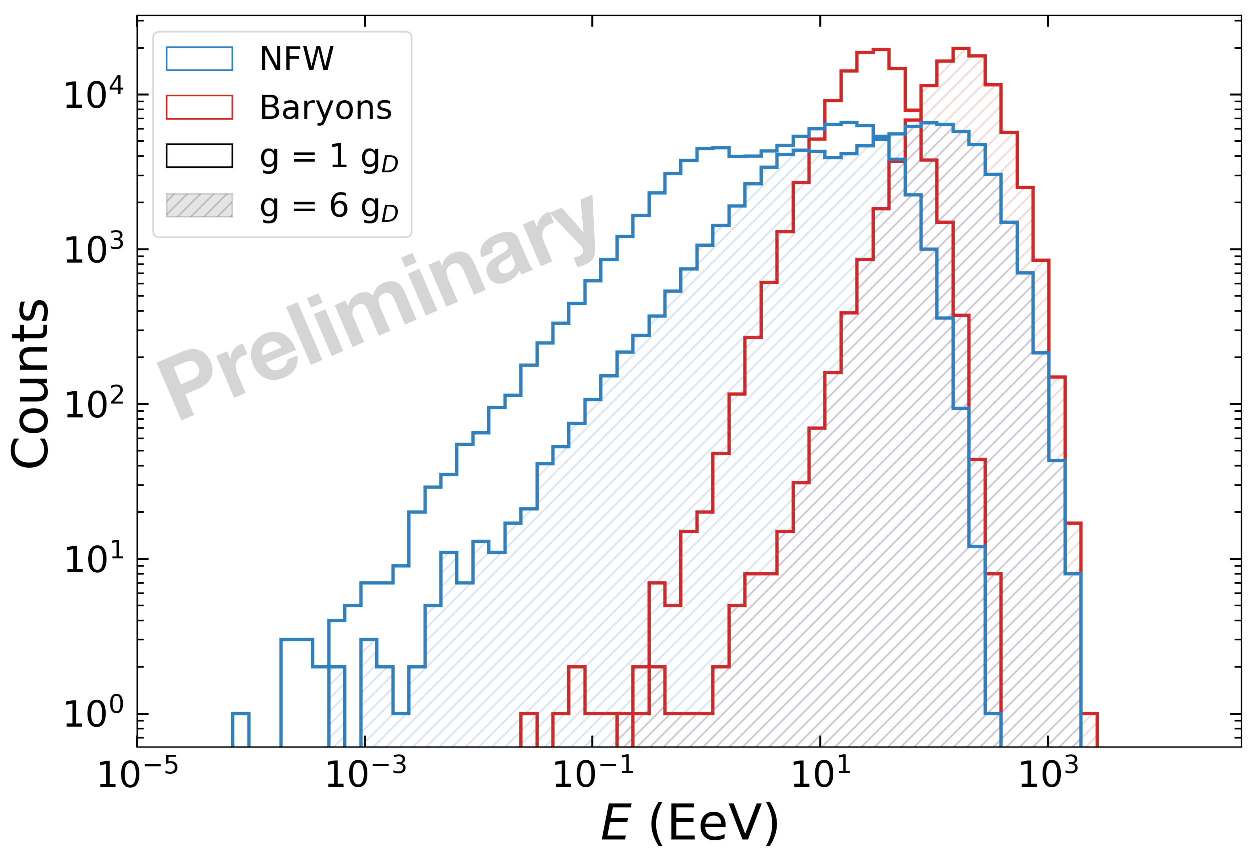
- Small-scale dynamo → initially clustered in a host galaxy
- Accelerated by its turbulent magnetic field
- Baryonic or NFW spatial distribution
- Broad initial kinetic energy distribution

Baryonic: large charge & small mass

NFW: small charge & large mass



m = 1 TeV/c²



m = 100 TeV/c²

[1] D. Perri, K. Bondarenko, M. Doro, and T. Kobayashi, "Monopole acceleration in intergalactic magnetic fields," Phys. Dark Univ., vol. 46, p. 101704, Dec. 2024.

Initial kinetic energy assumptions

Scenario I: Galactic acceleration

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- Accelerated by its turbulent magnetic field
- Baryonic or NFW spatial distribution
- Broad initial kinetic energy distribution

m = 1 TeV/c²

m = 100 TeV/c²

Scenario II: Intergalactic acceleration

- Never clustered in a host galaxy
- Accelerated by intergalactic magnetic fields
- Benchmark monochromatic kinetic energy

$$m \lesssim \frac{B_I^2}{4\pi v_p^2 F_I} \sim 10^7\ \mathrm{GeV} \left(\frac{B_I}{10^{-14}\ \mathrm{G}}\right)^2 \left(\frac{F_I}{10^{-18}\ \mathrm{cm^{-2}s^{-1}sr^{-1}}}\right)^{-1} \quad [1]$$

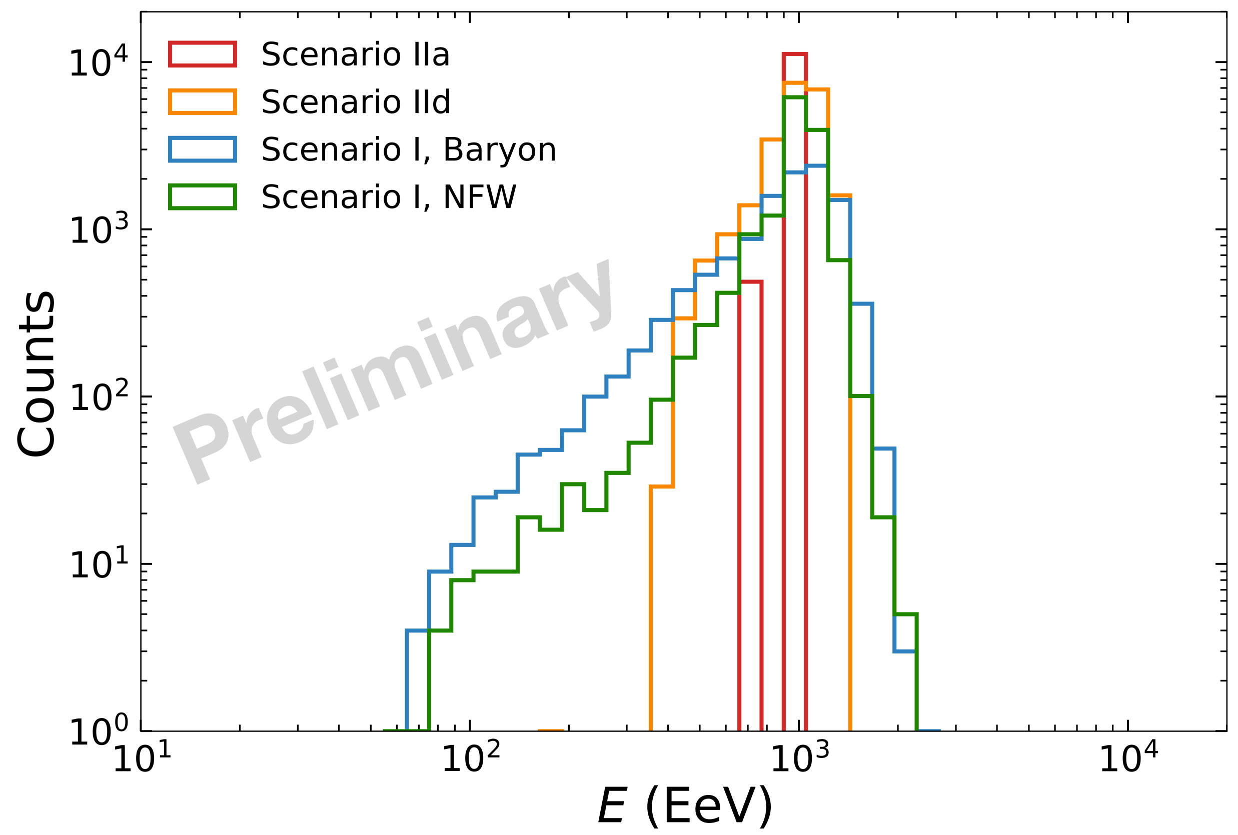
$$E_{kin} = m(\gamma - 1) \approx \frac{B_I^2}{8\pi F_I}$$

Case	B_I (G)	F_I ($\mathrm{cm^{-2}s^{-1}sr^{-1}}$)	E_{kin}^i (GeV)
IIa	10^{-14}	10^{-18}	6
IIb	10^{-14}	10^{-20}	6×10^2
IIc	10^{-10}	10^{-18}	6×10^8
IId	10^{-10}	10^{-20}	6×10^{10}

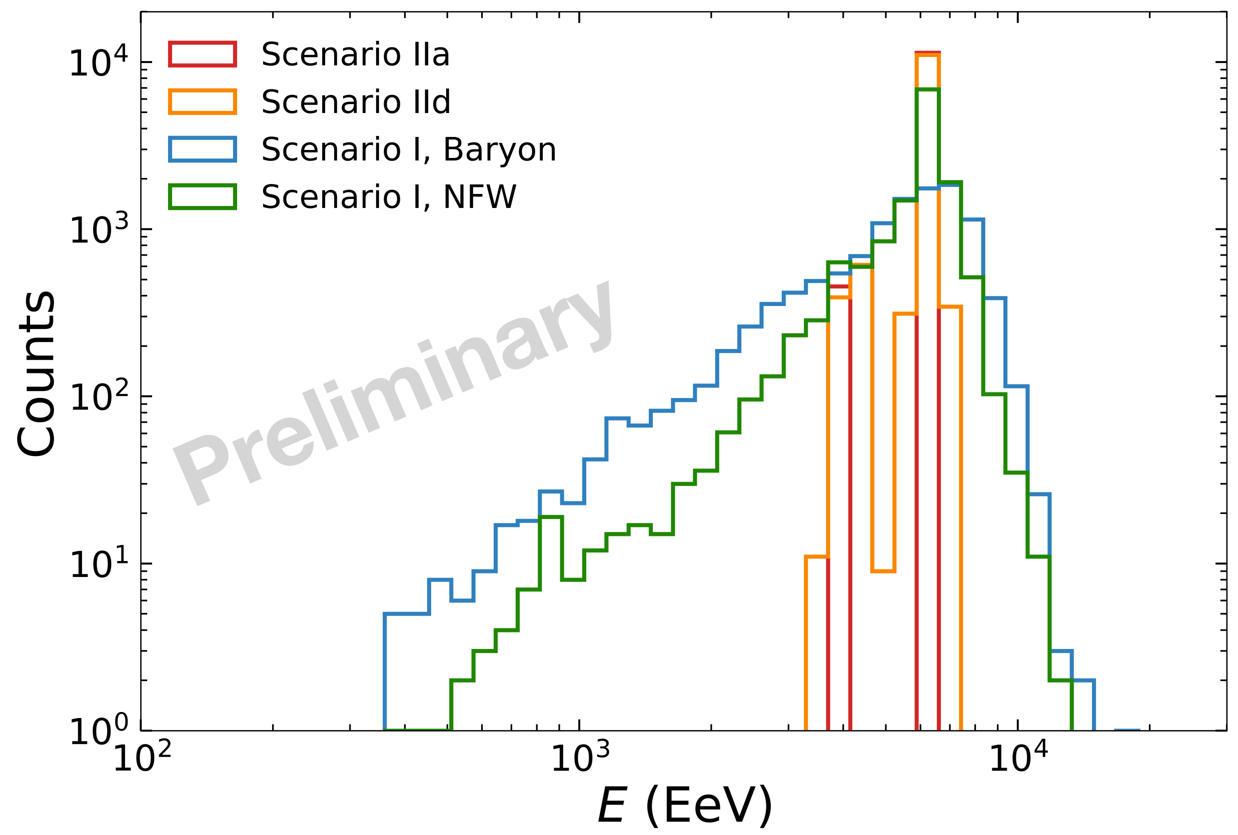
Simulation Results

Arrival kinetic-energy distirbutions of MMs at Earth
UF23 base, m = 100 TeV/c²

$g = 1\ g_D$

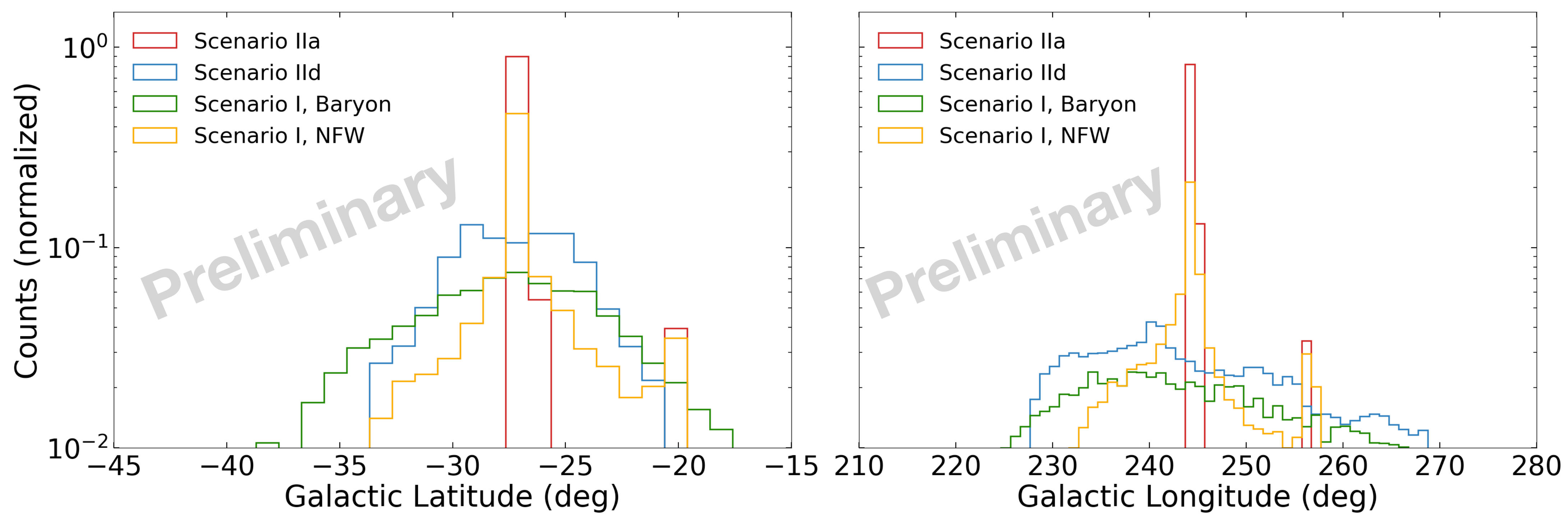


$g = 6\ g_D$



Arrival angular distributions of MMs at Earth
UF23 base, m = 100 TeV/c²

$g = 1\ g_D$



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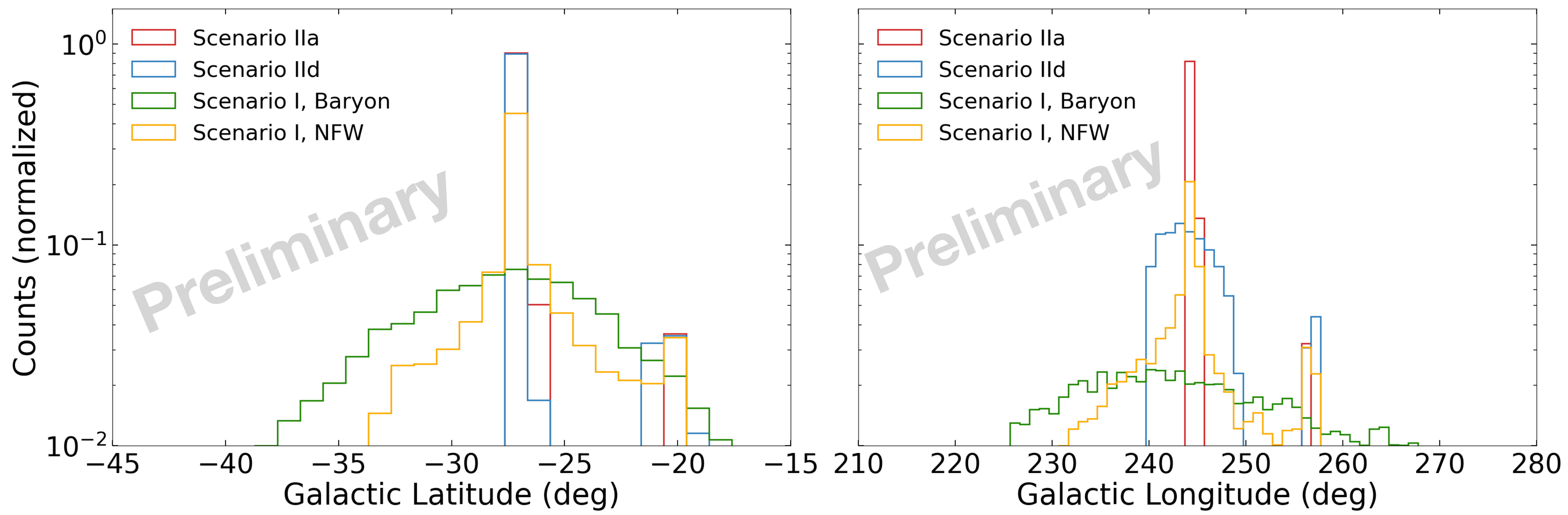
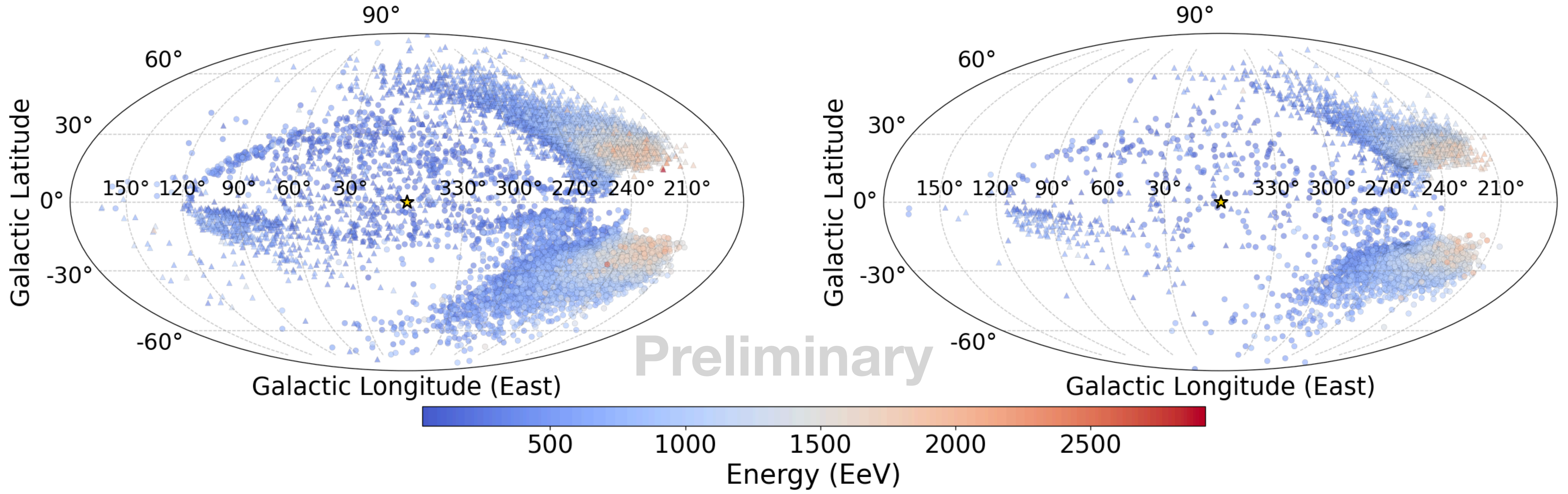


- The position of the distribution peak is determined by the magnetic charge
- Arrival directions are concentrated within narrow regions of the sky

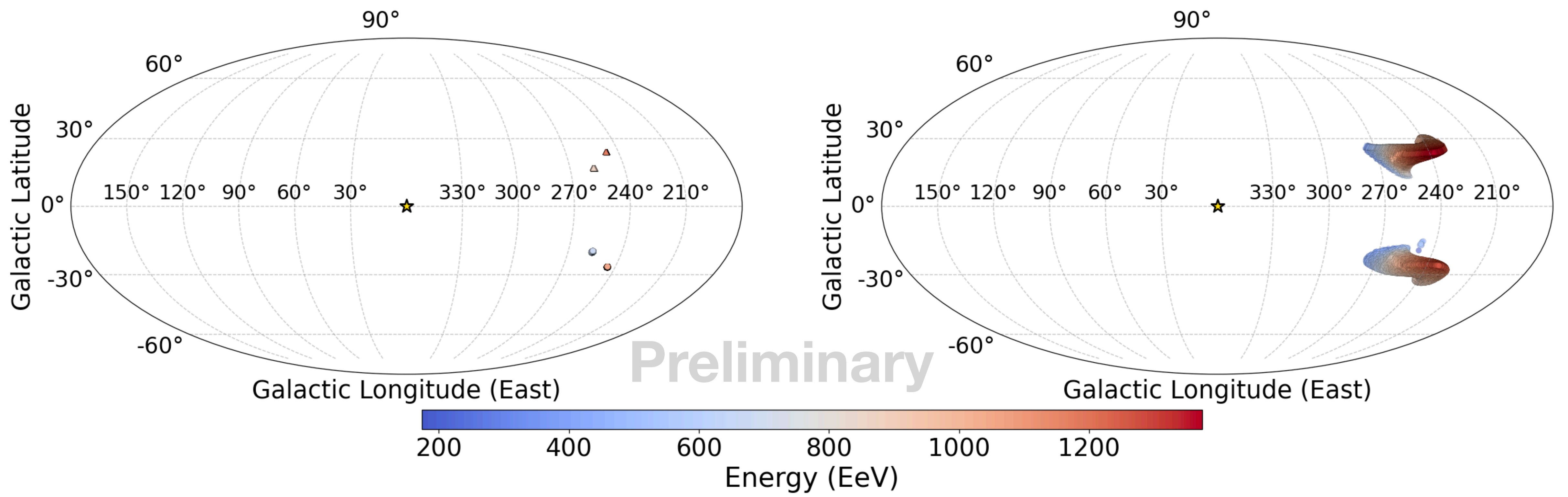
Simulation Results

Skymap of the arrival directions of relic MMs and anti-MMs
UF23 base, m = 100 TeV/c²



Baryons, $g = \pm 1\, g_D$

NFW, $g = \pm 1\, g_D$



Scenario IIa, $g = \pm 1\, g_D$

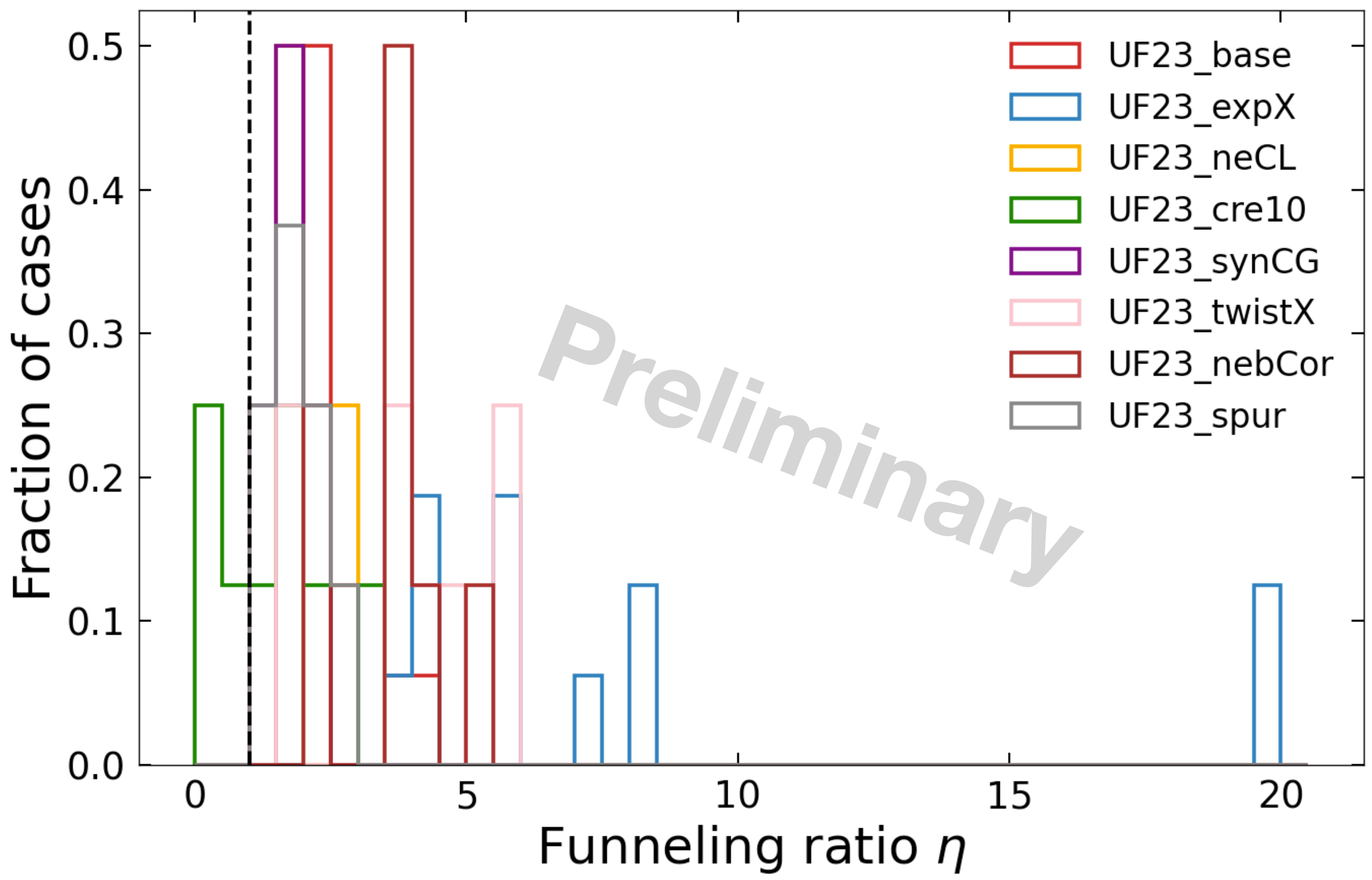
Scenario IId, $g = \pm 1\, g_D$

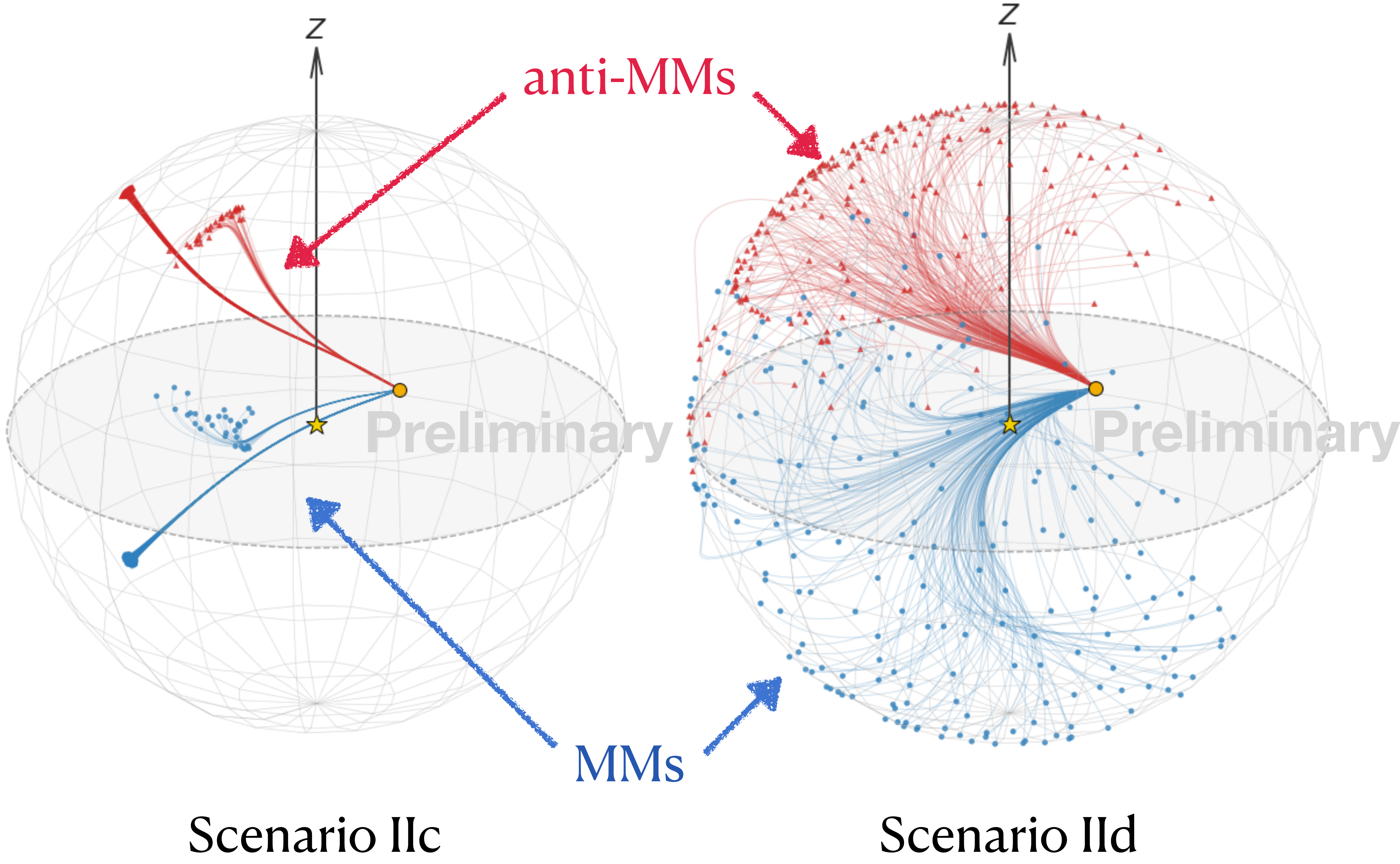
- ✳ MMs and anti-MMs arrive from different sky regions, showing highly symmetric patterns
- ✳ The degree of anisotropy depends strongly on the initial kinetic energy

Galactic Magnetic Funnel

- MMs experience focusing effect when they propagate through the galactic magnetic field

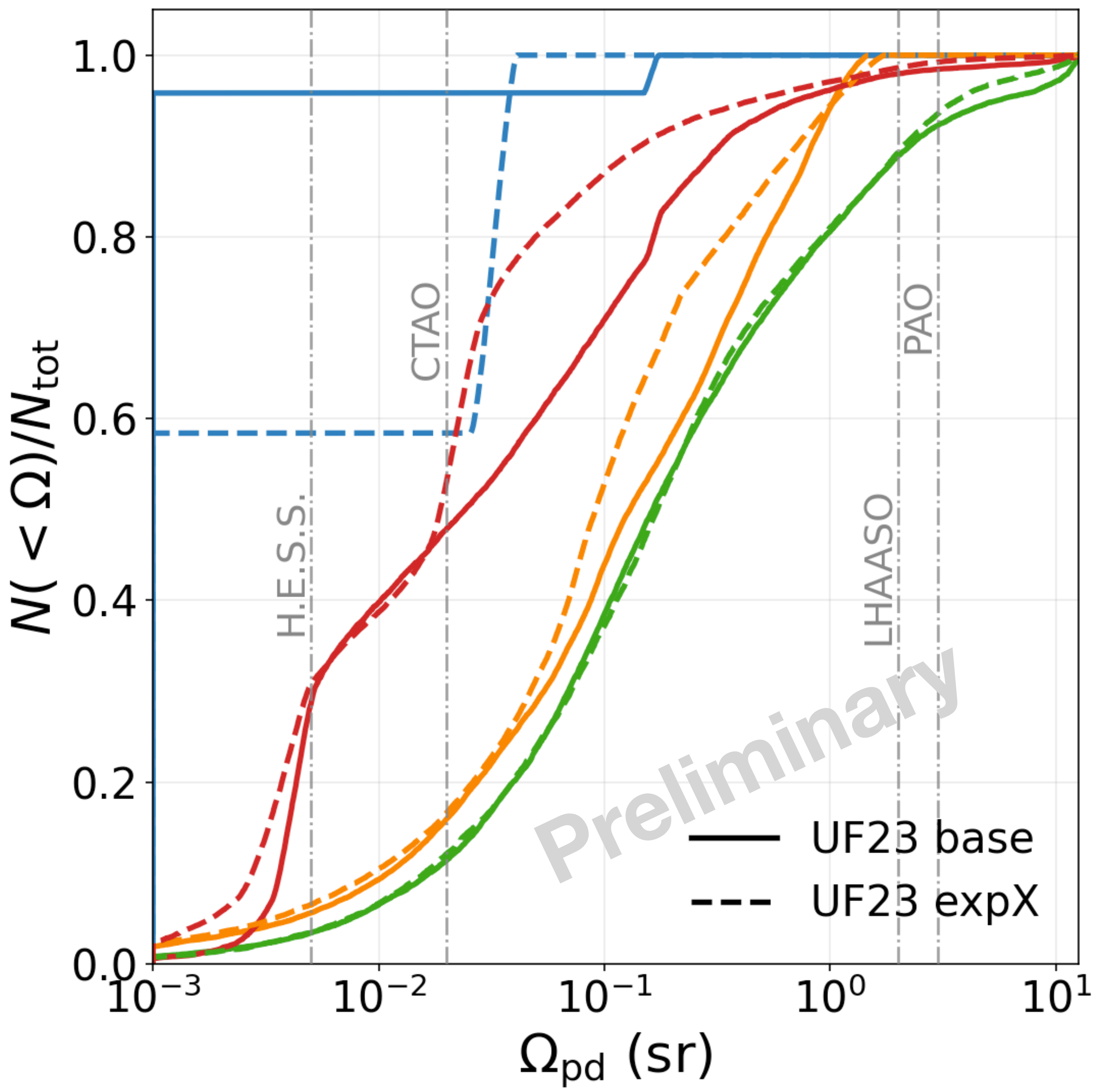
$$\eta = P_{earth}/P_{iso}$$



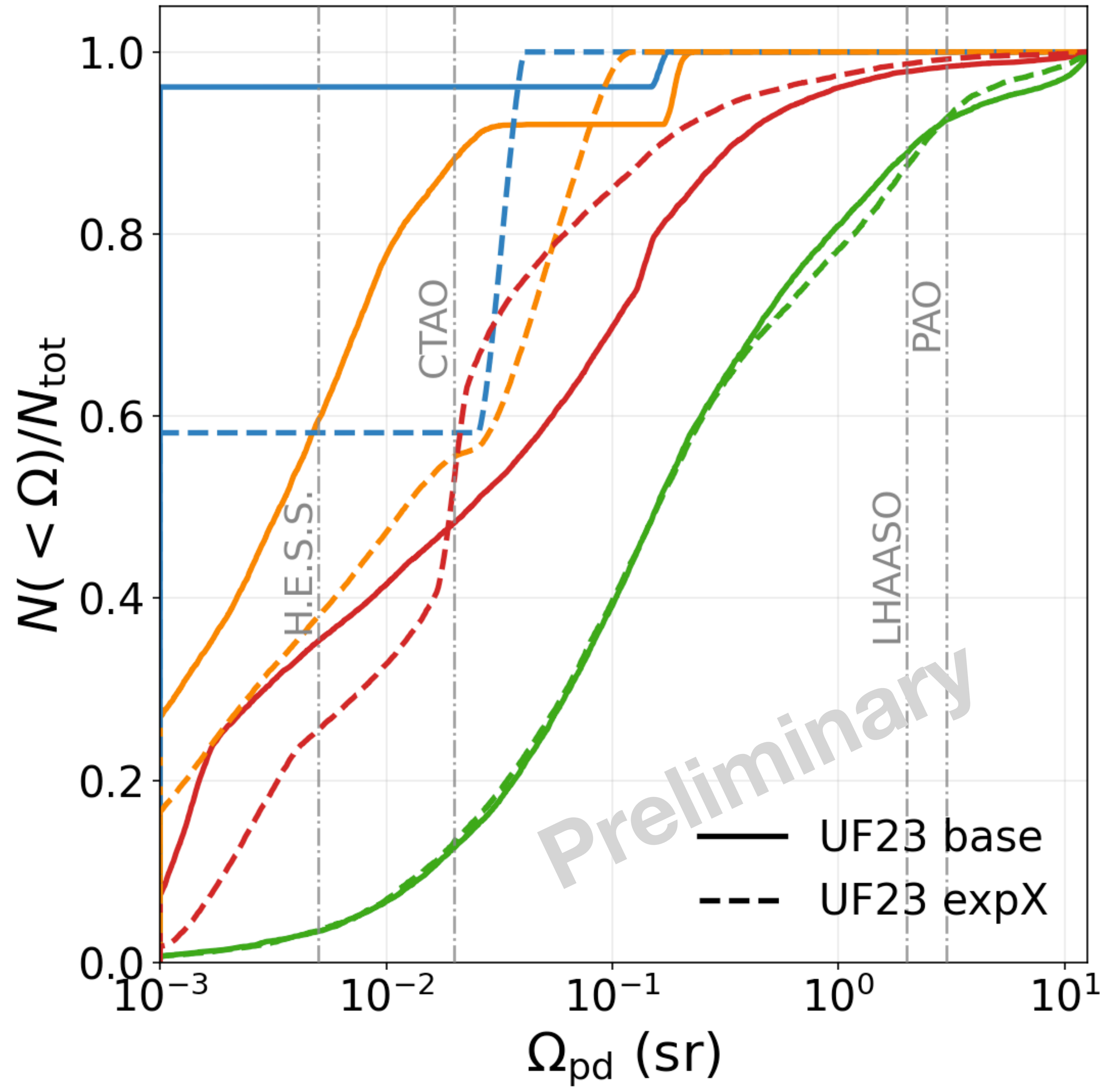


- The existence of magnetic funnels will enhance the constraining power of terrestrial experiments
- Corrected flux limit: $F < F_{*}\eta^{-1}$

Implications for future experiments



$g = 1\ g_D$



$g = 6\ g_D$

green: I-baryons, red: I-NFW,

blue: IIa, orange: IId

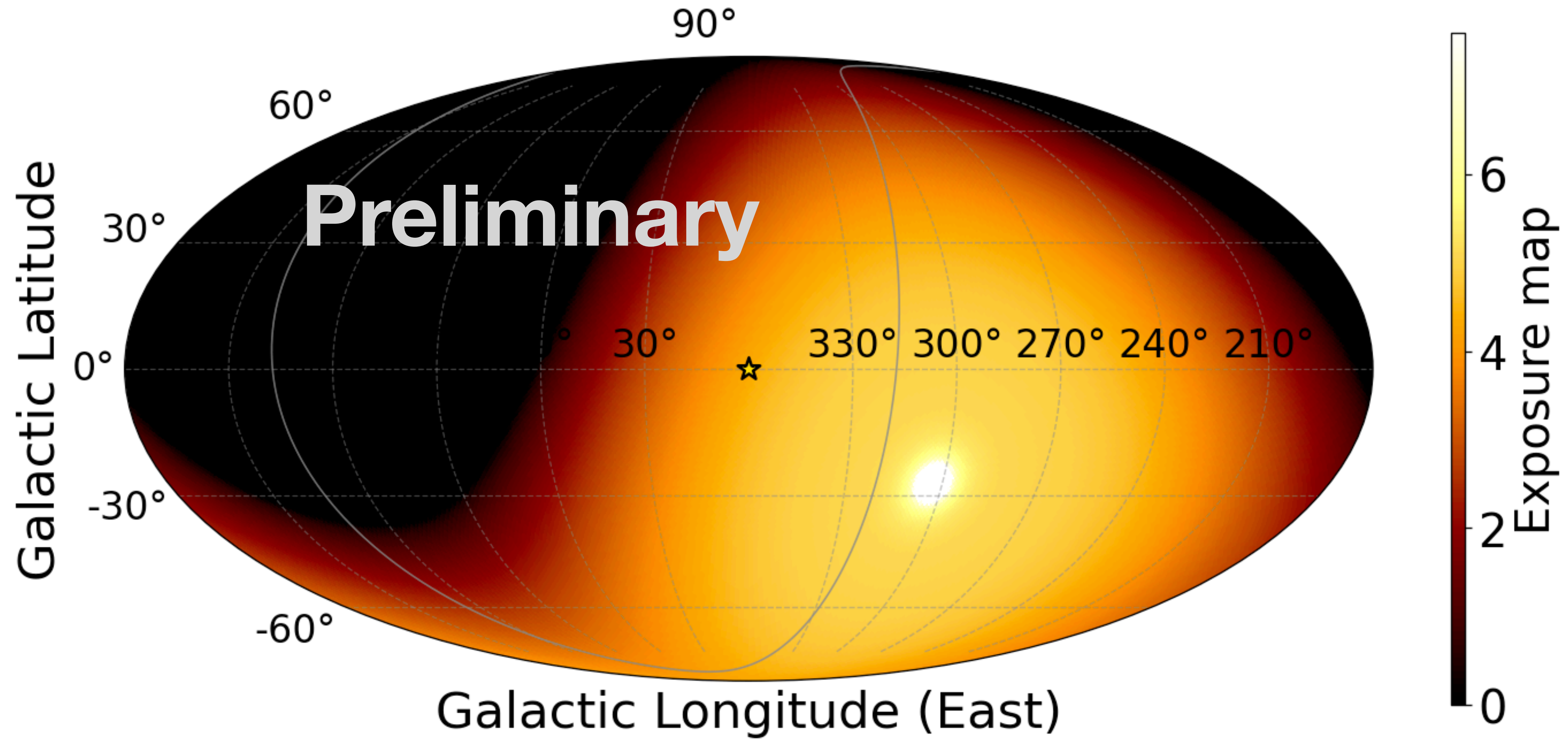
✳ Smaller, high-precision detectors may set stronger constraints if they cover the preferred arrival region

Likelihood analysis with Auger dataset

- Pierre Auger Phase I: 2004–2020, containing 2635 events with E ≥ 32 EeV
- Directional exposure included
- Auger assumed that MMs interact with matter exclusively through electromagnetic energy losses ⟶ strong but model dependent result
- Our approach: impose no shower assumption

Likelihood-ratio test:

- Arrival direction only
- Arrival direction + energy



Likelihood-ratio test

Direction-only likelihood test

Null hypothesis n_0:
- Isotropic flux distribution
- weighted w/ exposure map

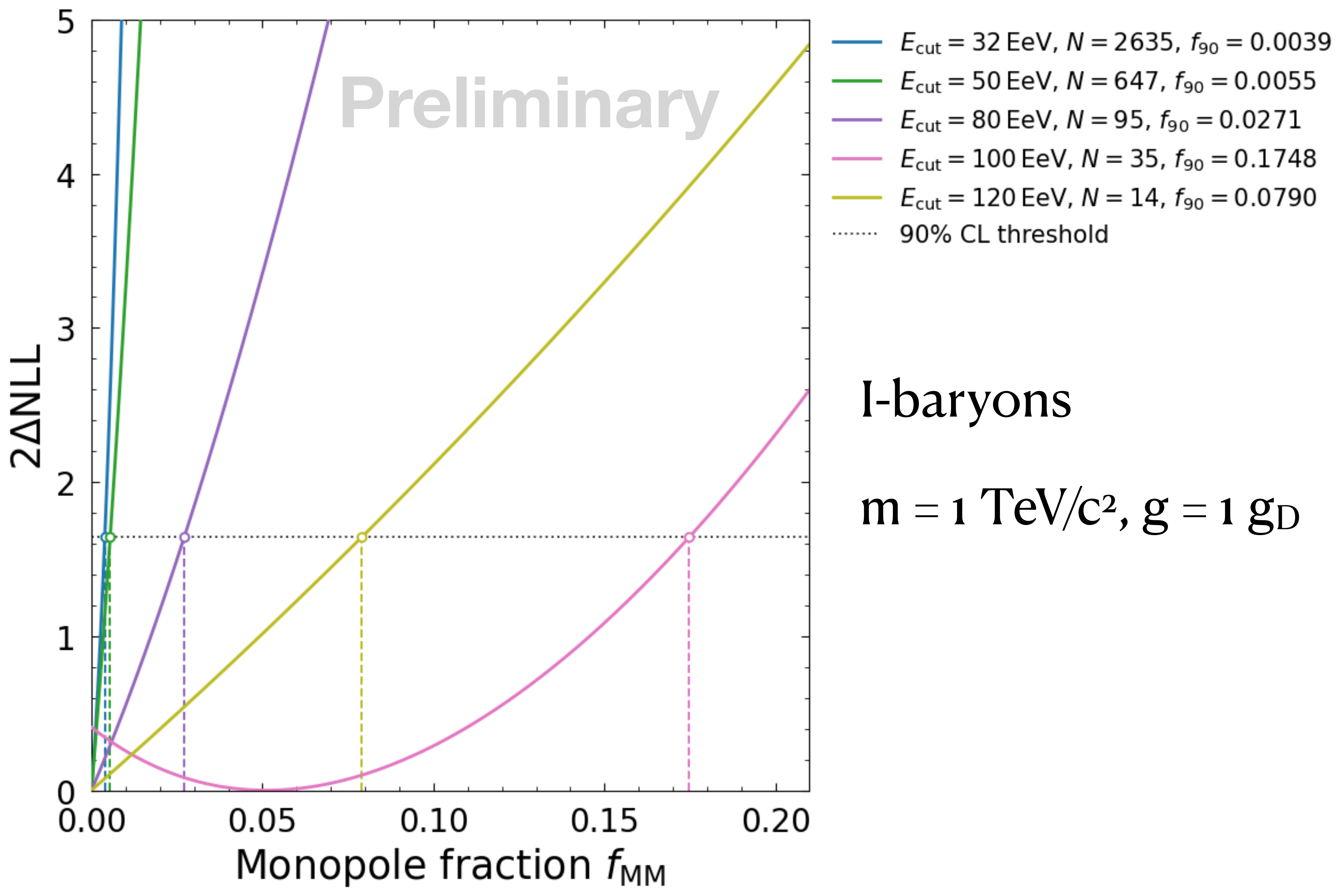
Monopole component:
- Direction info from sims
- folded w/ exposure map

normalization

Alternative hypothesis:

$$n(u) = (1 - f_{\mathrm{MM}}) \times n_0(u) + f_{\mathrm{MM}} \times n_{\mathrm{MM}}(u)$$

- Profile likelihoods
- $\mathrm{TS} = -2\ln(L_0/L)$



l-baryons

$m = 1$ TeV/c^2, $g = 1\, g_D$

Likelihood-ratio test

Direction-only likelihood test

Null hypothesis n_0:
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- weighted w/ exposure map

Monopole component:
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- folded w/ exposure map

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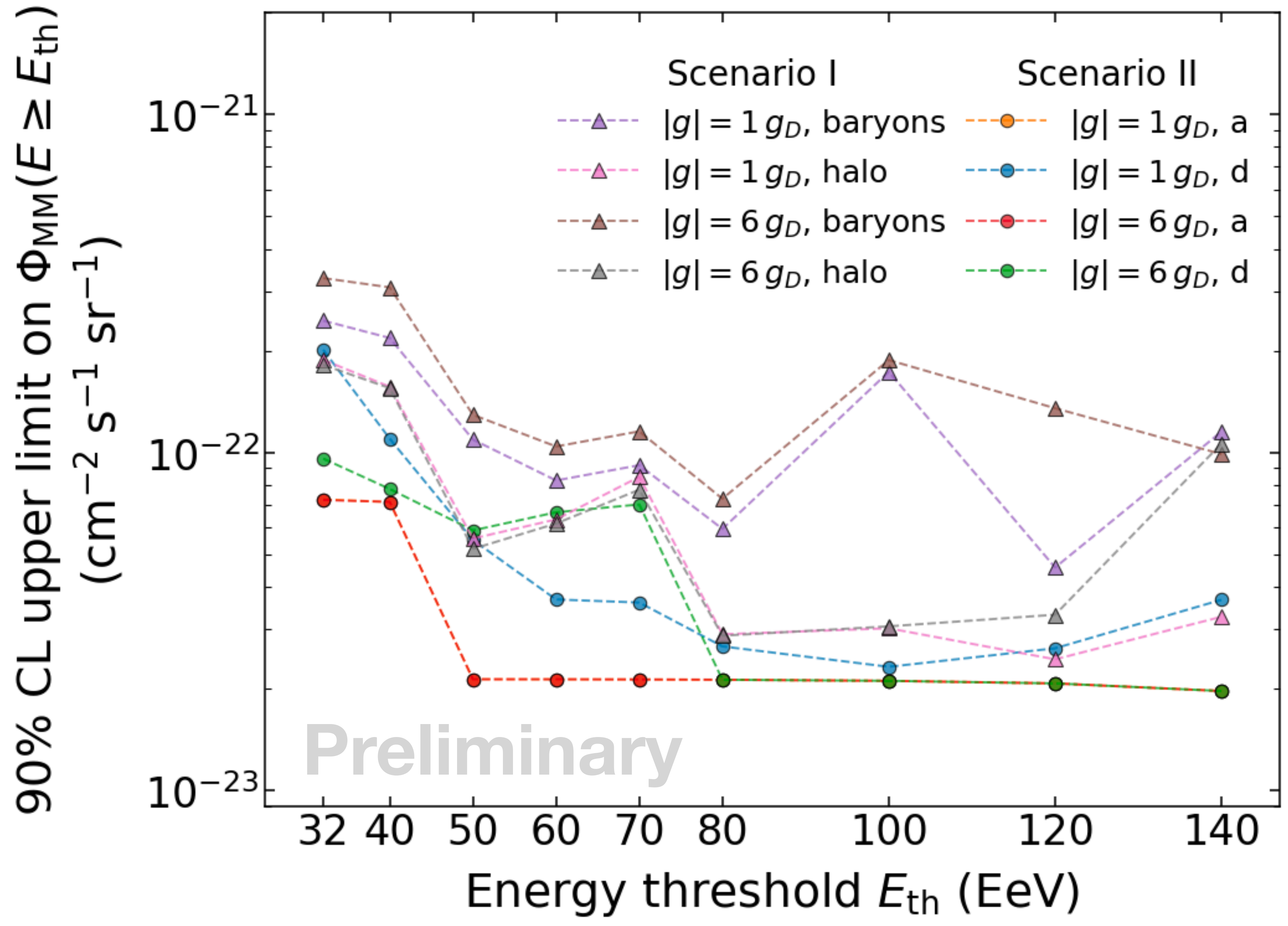

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- Profile likelihoods
- TS = $-2\ln(L_0/L)$

Energy-direction likelihood test

- For simplicity, energy and arrival direction are assumed to be independent
  - $n_i(u, E) = n_i(u) \times n_i(E)$

$$n(u, E) = (1 - f_{\mathrm{MM}}) \times n_0(u, E) + f_{\mathrm{MM}} \times n_{\mathrm{MM}}(u, E)$$

- 90% C.L. upper limits on the MM fraction are nearly identical across all cases
- MM flux upper limit of $< 2.1 \times 10^{-23} \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$

Conclusions

✴ Galactic magnetic funnel

- Low-mass MMs with m≲100 TeV/c^2 are guided by the coherent Galactic magnetic field, producing distinct and highly localized arrival regions for MMs and anti-MMs
- The predicted anisotropy is robust across the initial conditions and UF23 field models considered, while magnetic focusing typically enhances the Earth-reaching flux

✴ Comparison w/ Auger

- No statistically significant evidence for an MM contribution is found
- $\Phi^{90}_{\mathrm{MM}} < 2.1 \times 10^{-23}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ Preliminary

✴ Implications

- A dedicated detector covering the preferred arrival region may provide stronger and more robust constraints than a larger general-purpose observatory

Thanks for your attention!!

Backup

Simulation framework & settings

Custom MM propagation in CRPropa

$$\frac{d\mathbf{P}}{dt} = g\mathbf{B} + q\mathbf{v} \times \mathbf{B},\ E_{rad} \text{ included}$$

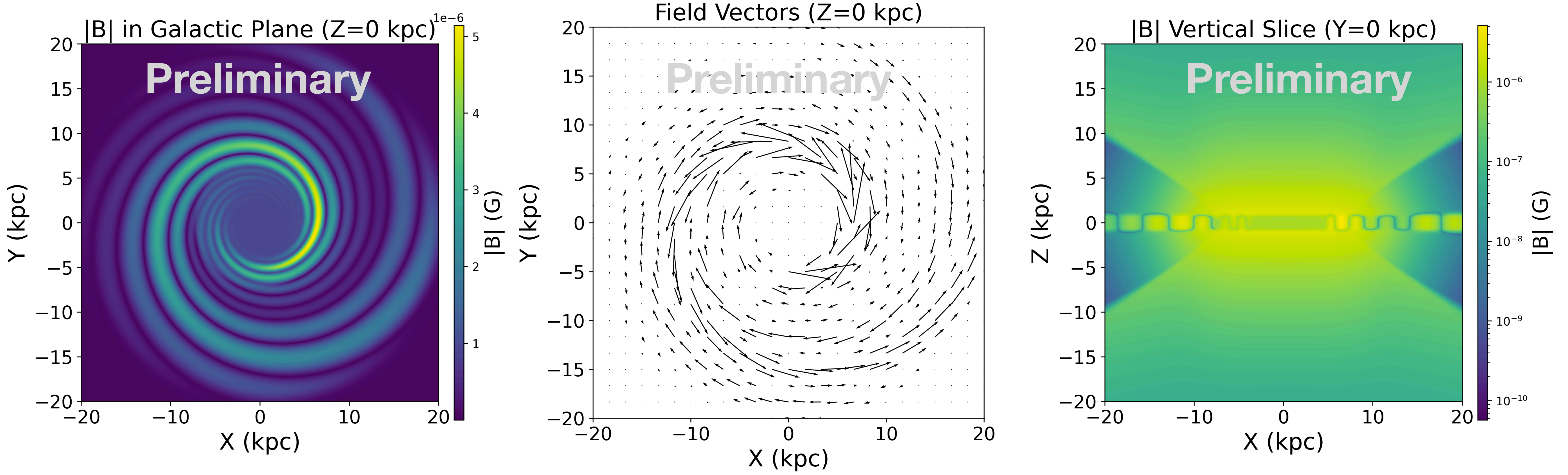
$$P = \frac{\mu_0 g^2}{6\pi m^2 c^3}\gamma^2\left(\left(\frac{d\mathbf{p}}{dt}\right)^2 - \frac{1}{c^2}\left(\frac{dE}{dt}\right)^2\right) = \frac{\mu_0 g^2}{6\pi m^2 c^3}\left(\mathbf{F}^2 + \frac{\gamma^2}{c^2}|\mathbf{v} \times \mathbf{F}|^2\right)$$

- Custom Cash-Karp propagation and radiative losses modules
- m = 1, 100 TeV/c^2
- g = $\pm 1 g_D, \pm 6 g_D$
- Eight coherent UF23 galactic magnetic field models
- Initial population of 2×10^{10} MMs per simulation

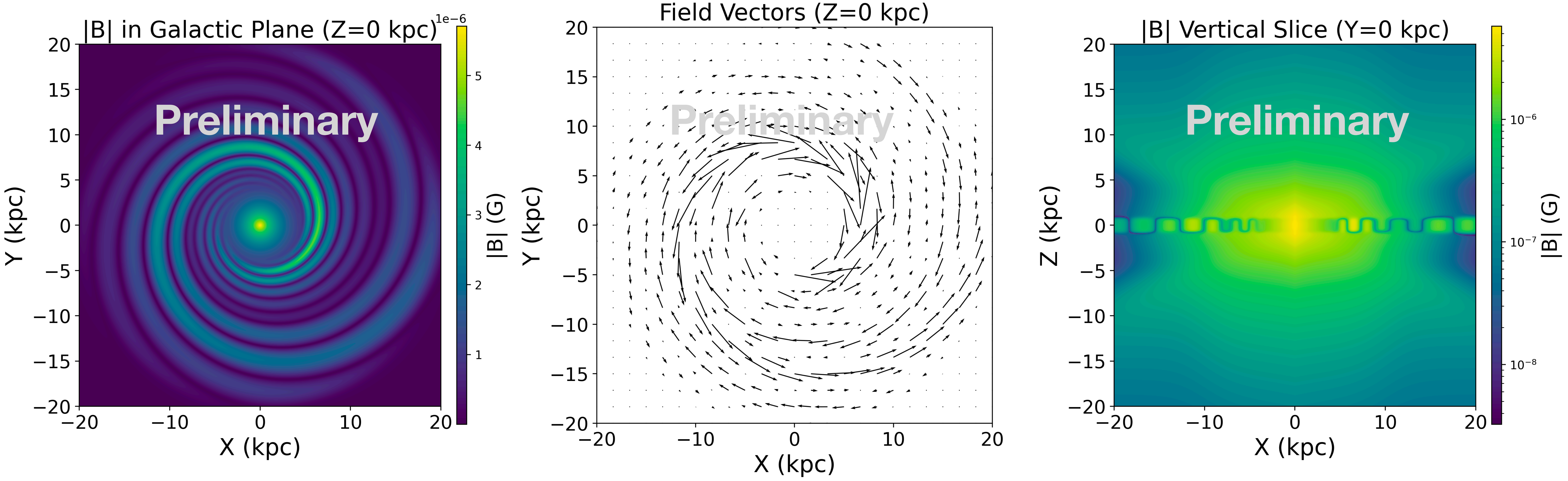
- Earth: 8.2 kpc from the galactic center
- Detection region: 35 pc radius
- Get killed if they exit the galaxy
  - distance from the Galactic center exceeds 25 kpc
  - total travel distance exceed 50 kpc

Pipeline:

20 kpc injection sphere w/ Lambertian distribution → **propagate in GMF** → **record at Earth**

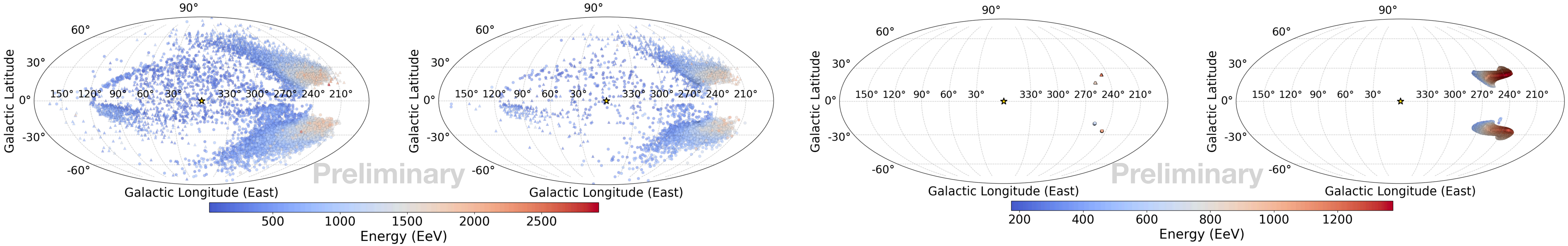


UF23 base model

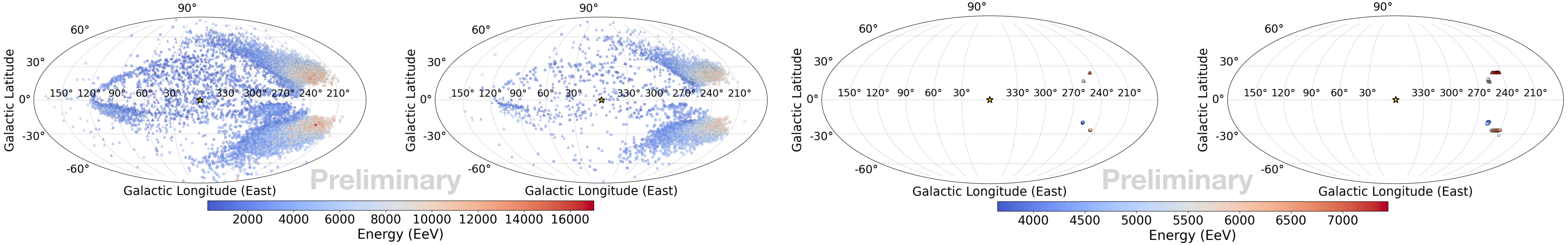


UF23 expX model

Skymap of the arrival directions of relic MMs and anti-MMs
UF23 base, m = 100 TeV/c^2



Baryons, $g = \pm 1\, g_D$ NFW, $g = \pm 1\, g_D$ Scenario IIa, $g = \pm 1\, g_D$ Scenario IId, $g = \pm 1\, g_D$

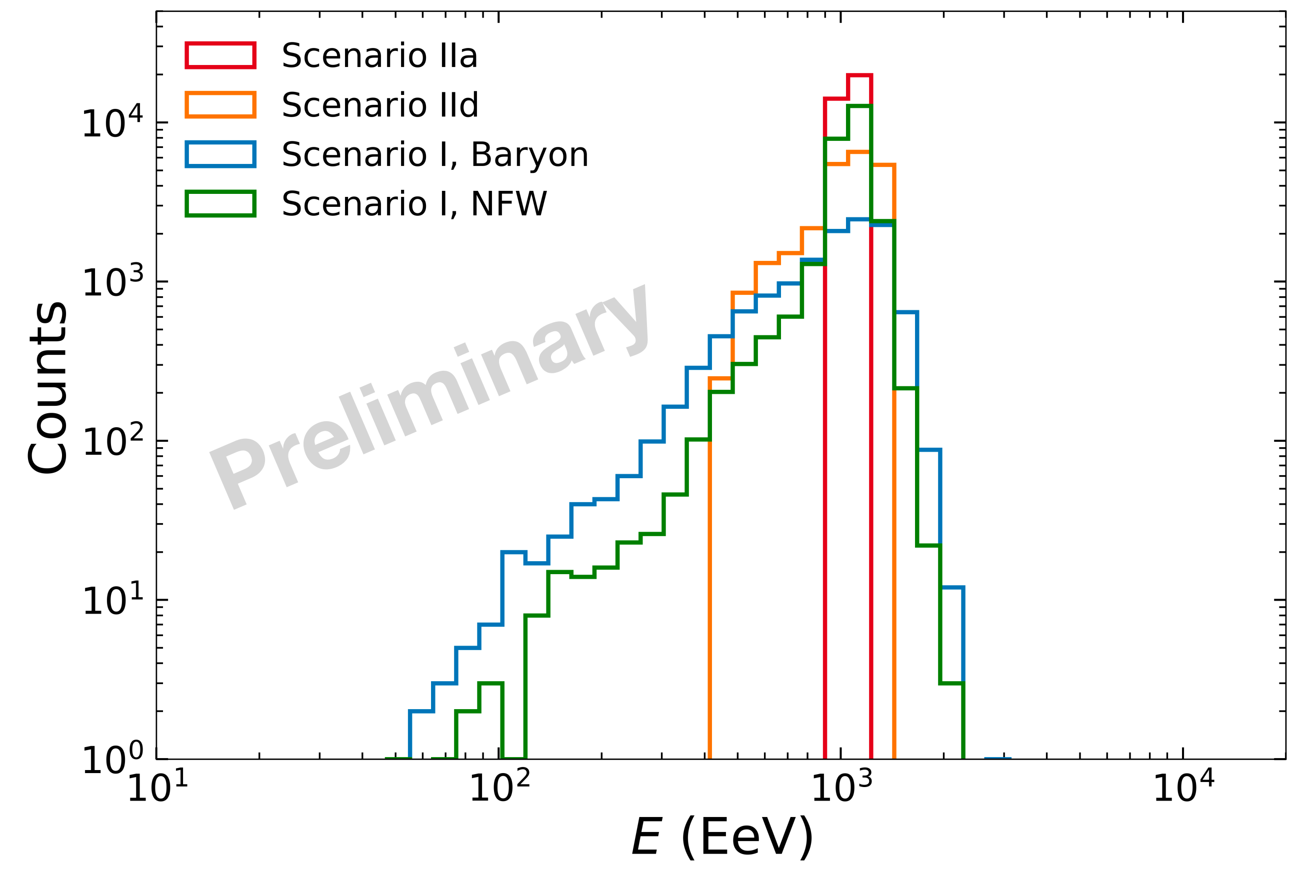


Baryons, $g = \pm 6\, g_D$ NFW, $g = \pm 6\, g_D$ Scenario IIa, $g = \pm 6 g_D$ Scenario IId, $g = \pm 6\, g_D$

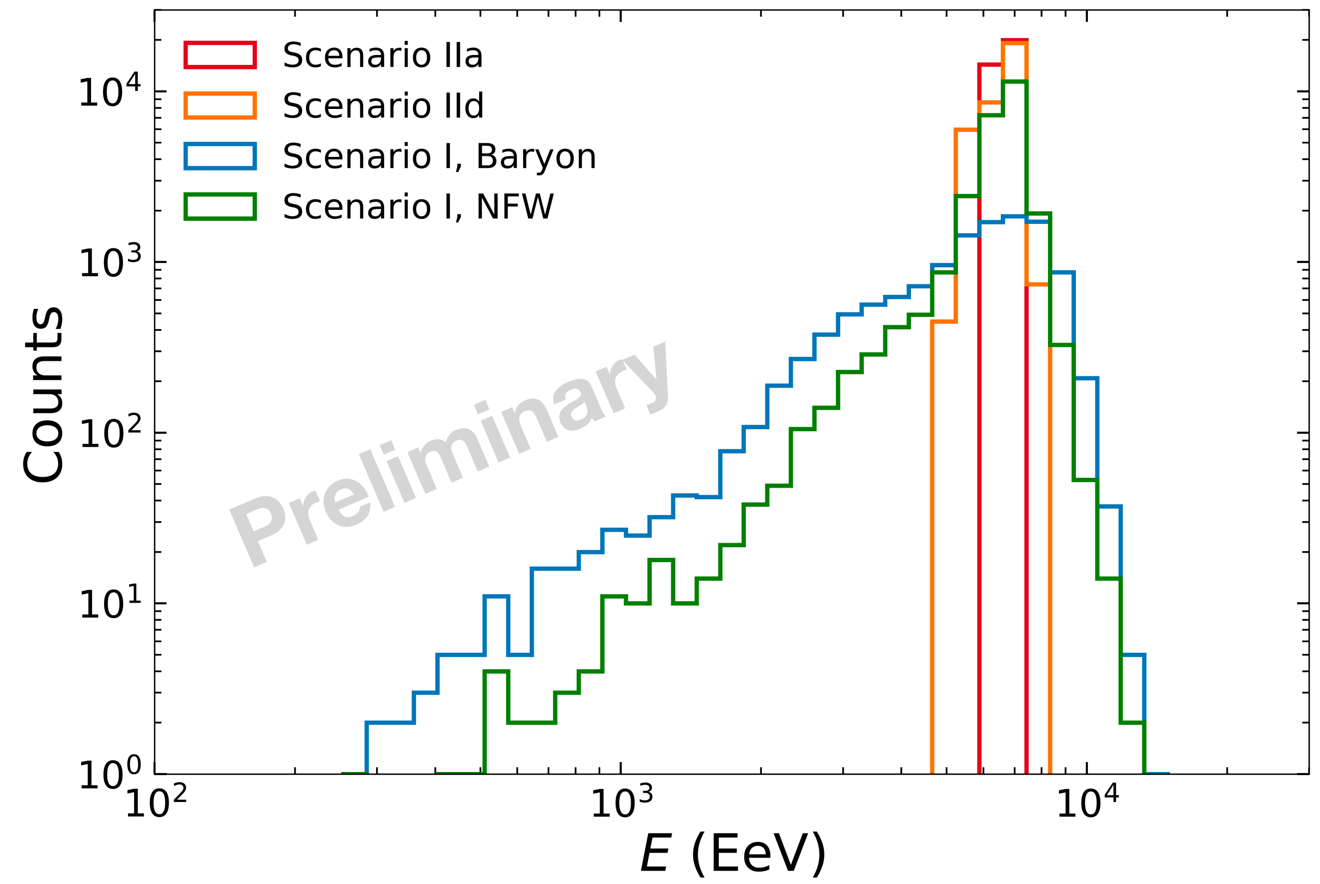
Simulation Results for expX

Arrival kinetic-energy distirbutions of MMs at Earth
UF23 base, m = 100 TeV/c²

$g = 1\, g_D$

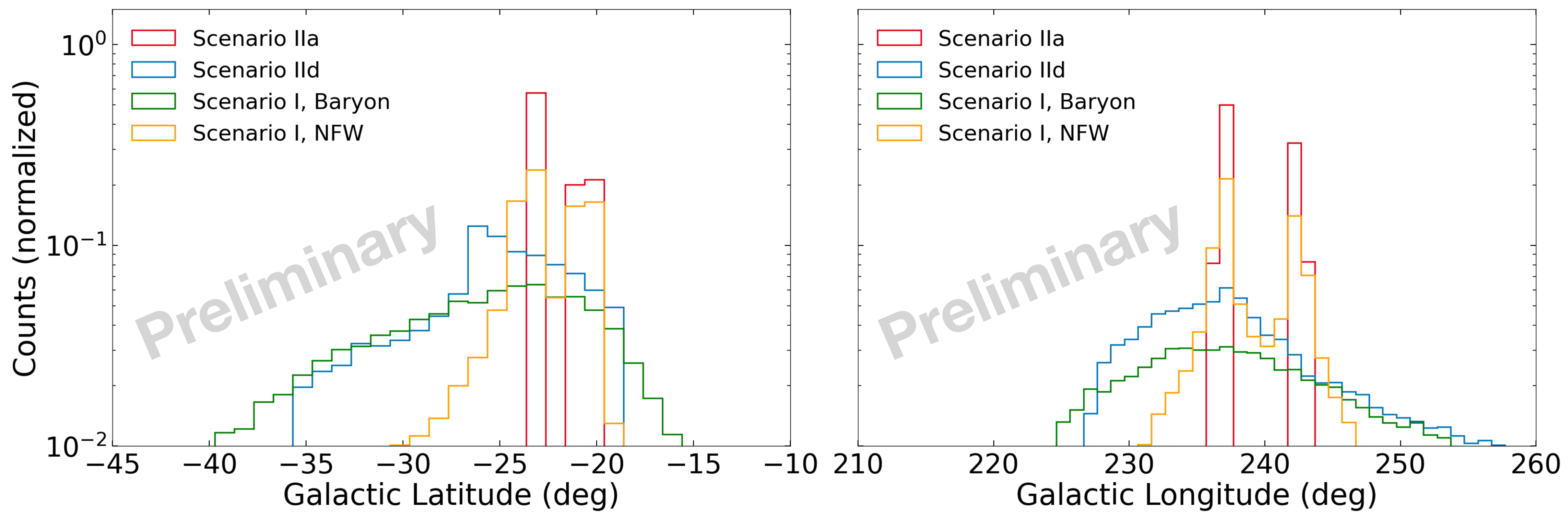


$g = 6\, g_D$

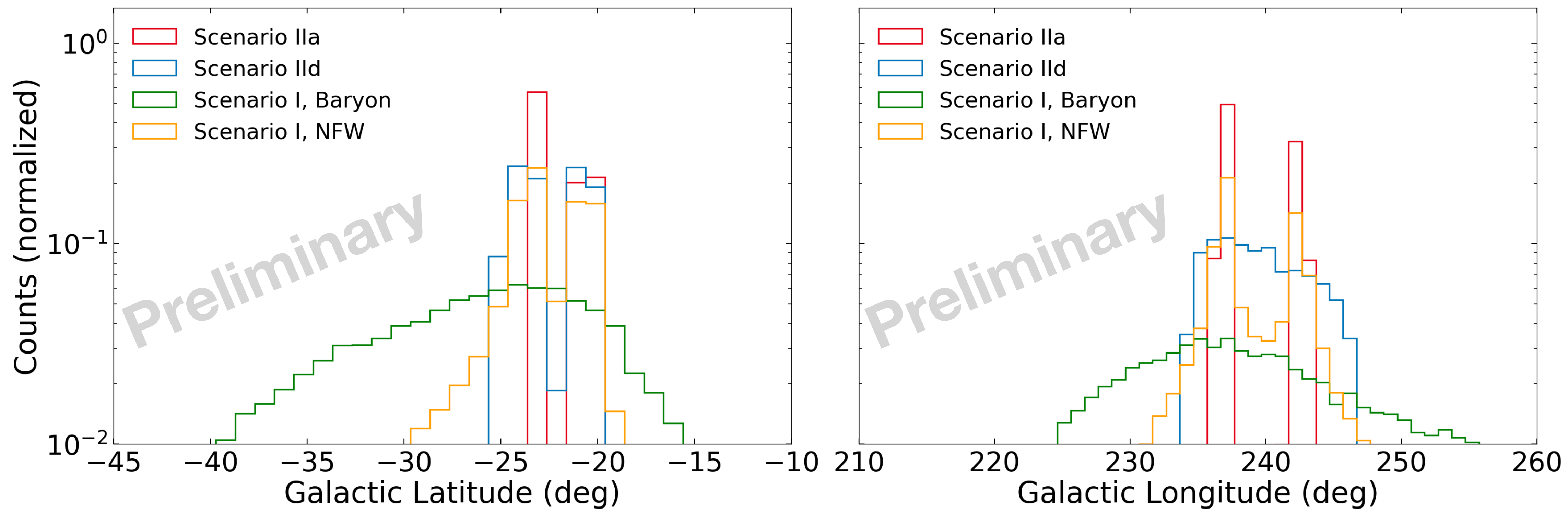


Arrival angular distributions of MMs at Earth
UF23 base, m = 100 TeV/c²

$g = 1\, g_D$



$g = 6\, g_D$



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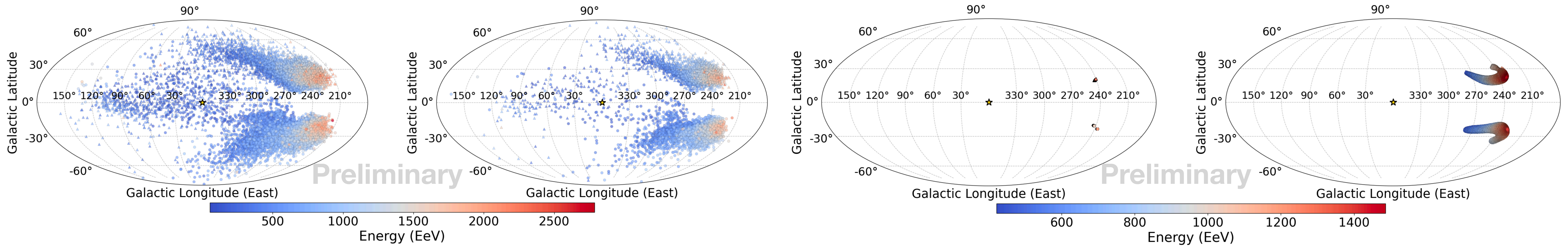
Skymap of the arrival directions of relic MMs and anti-MMs
UF23 expX, m = 100 TeV/c²



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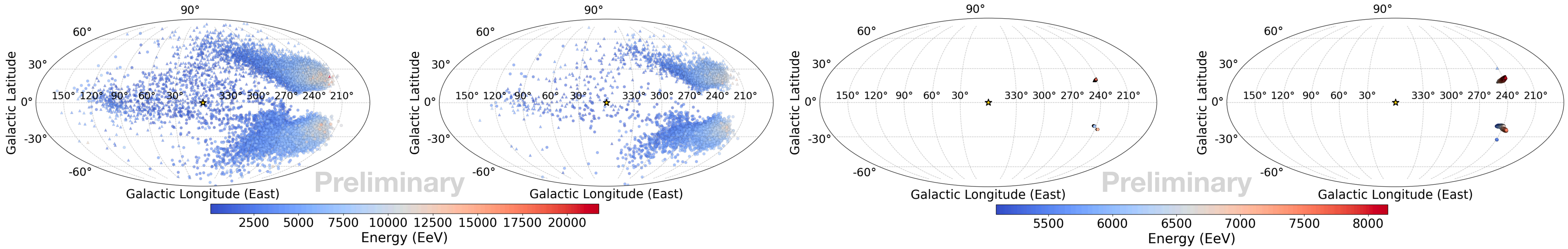


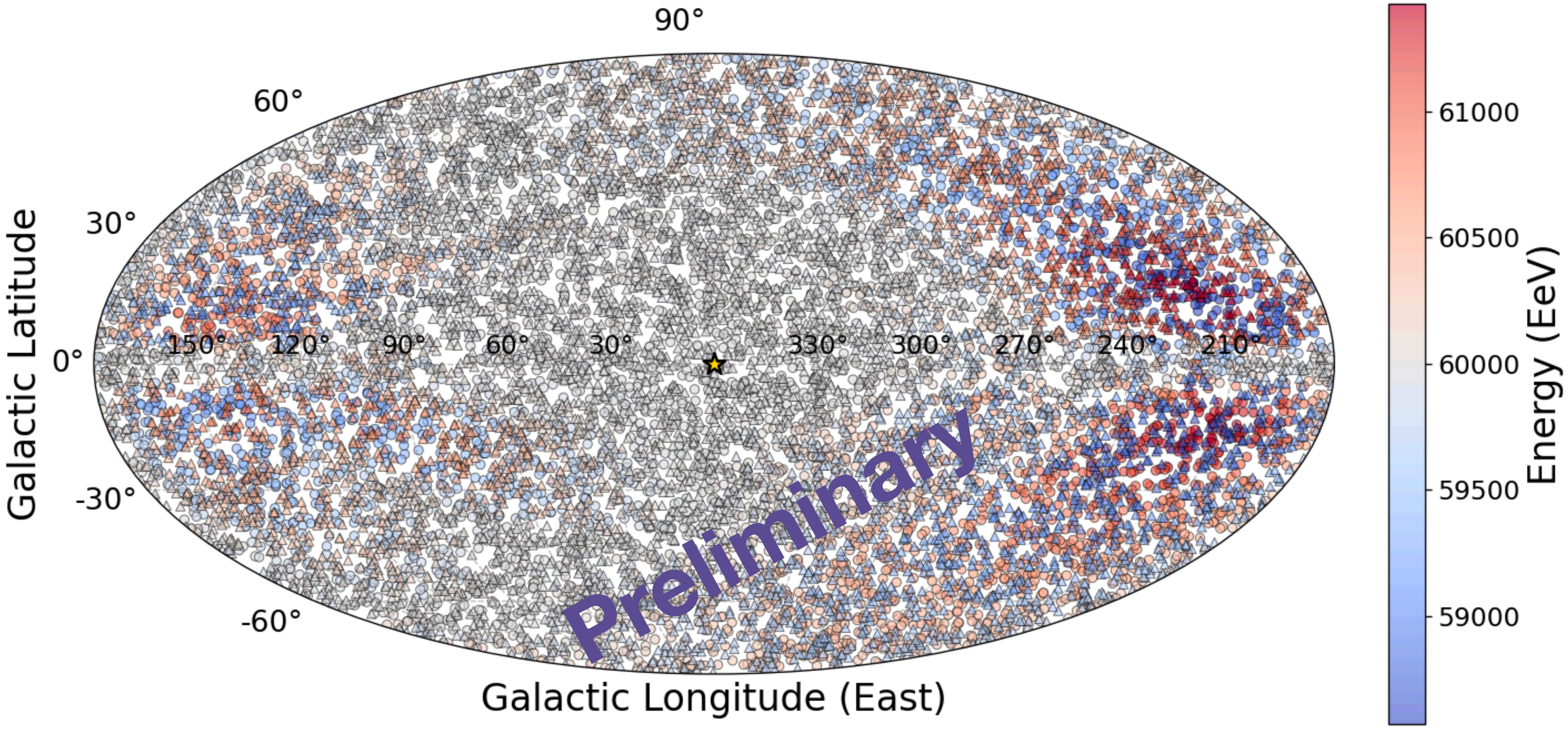
Baryons, $g = \pm 6\ g_D$ NFW, $g = \pm 6\ g_D$ Scenario IIa, $g = \pm 6 g_D$ Scenario IId, $g = \pm 6\ g_D$

Simulation results

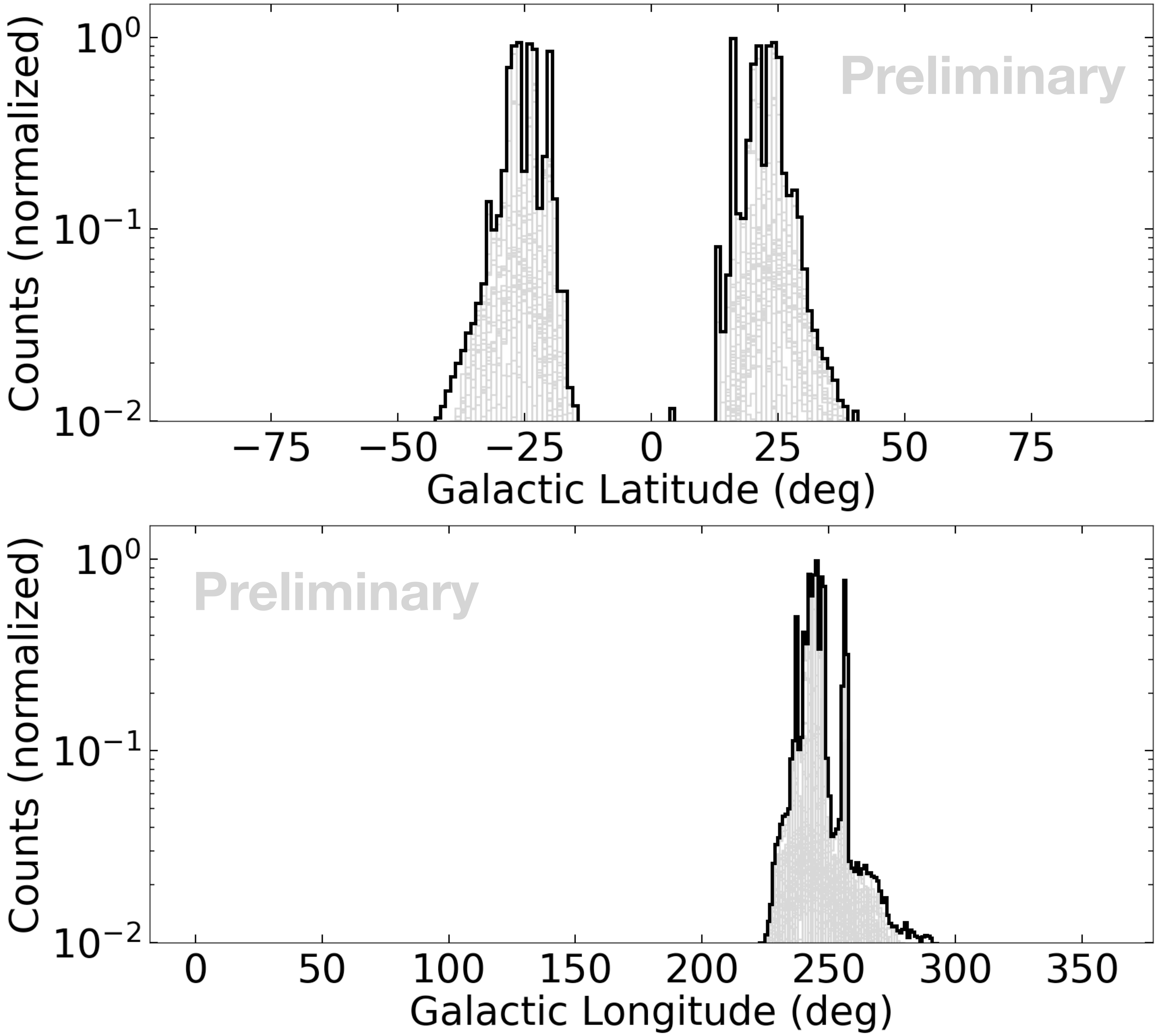
Scenario IIe

UF23 base, KE$_i$ = 6×10^4 EeV, m = 1 TeV/c², |g| = $\pm 1 g_D$

- The energy gain inside the Galaxy is negligible compared with the initial MM kinetic energy



- Strong anisotropy persists across all simulated configurations and UF23 field models



Effect of turbulent component