Cosmic-ray anisotropy and the role of the heliosphere

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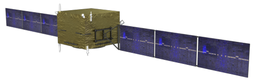
arXiv:2610.18384

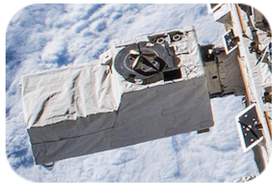
Nov 3, 2026

context
observations

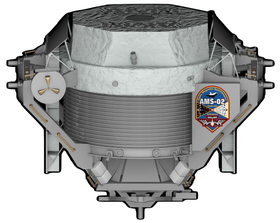
Cosmic-ray energy spectrum

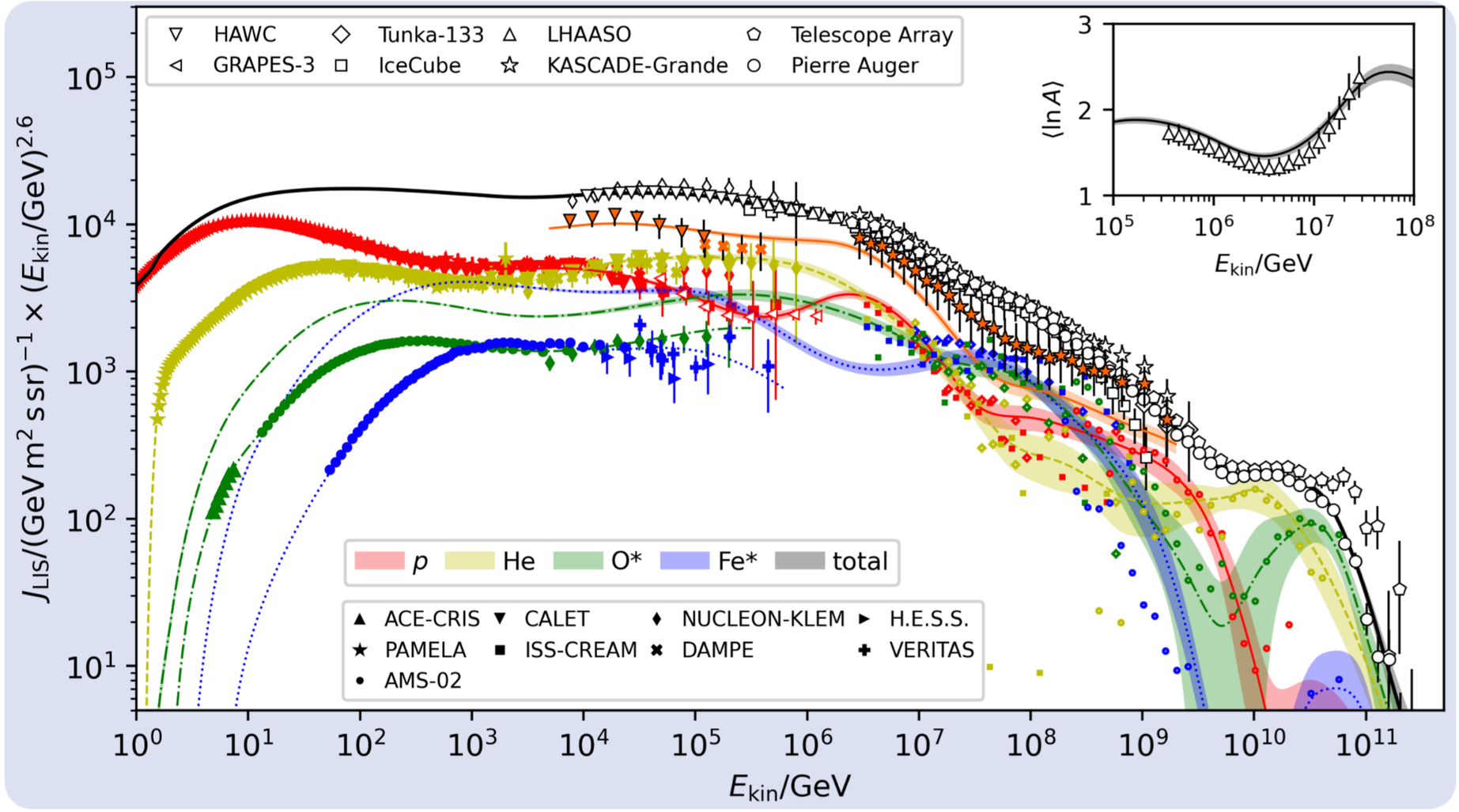
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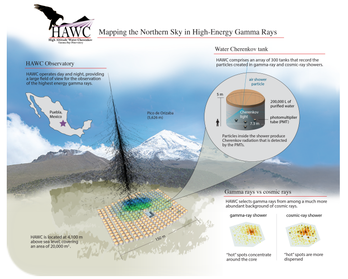


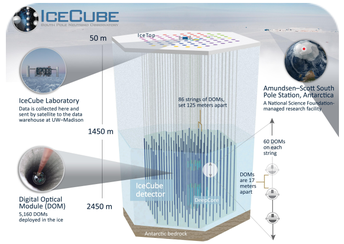


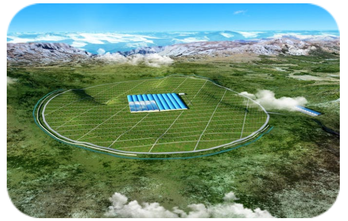


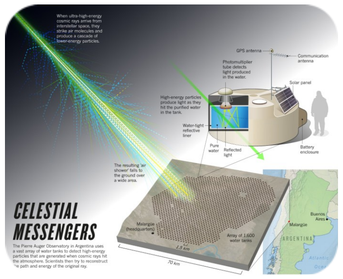










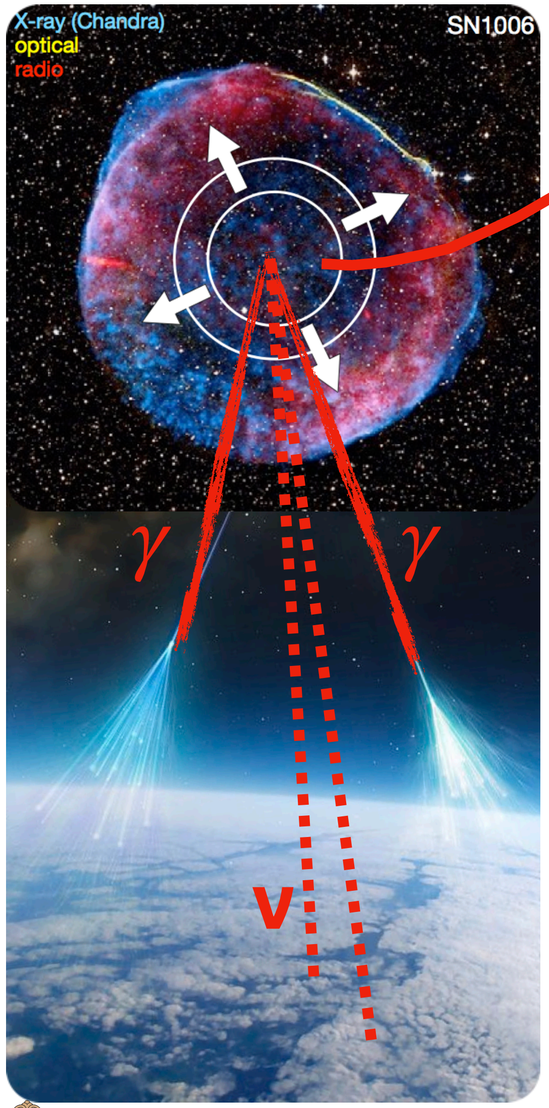


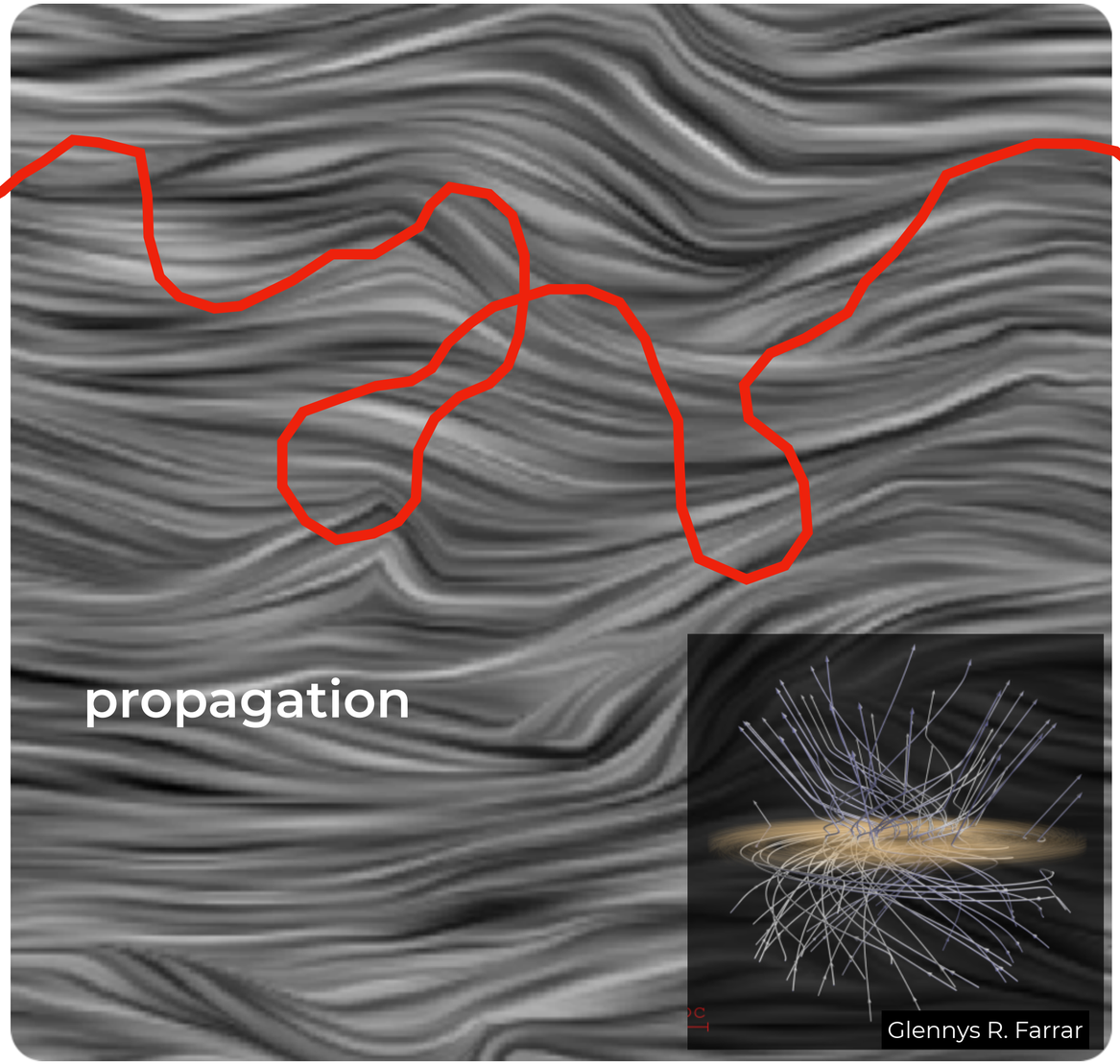
Cosmic-ray's journey in our Galaxy

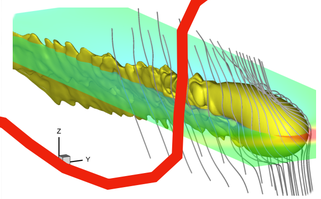
accelerator

interstellar medium magnetic fields

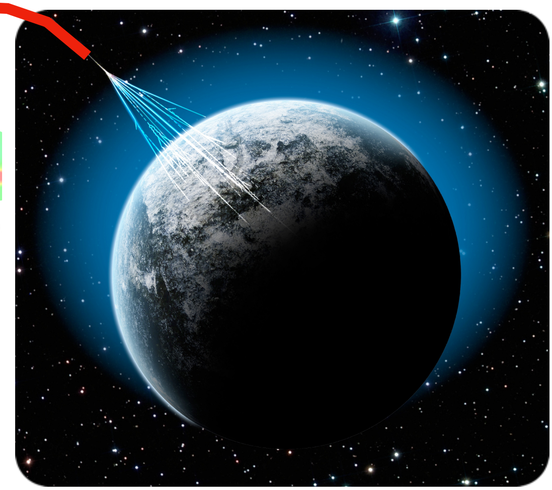
Earth's atmosphere dynamic target





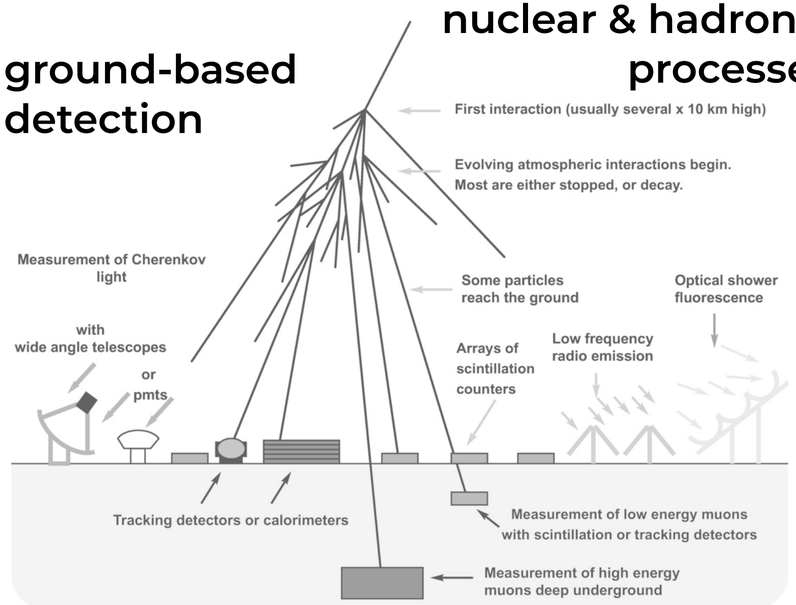


Heliosphere

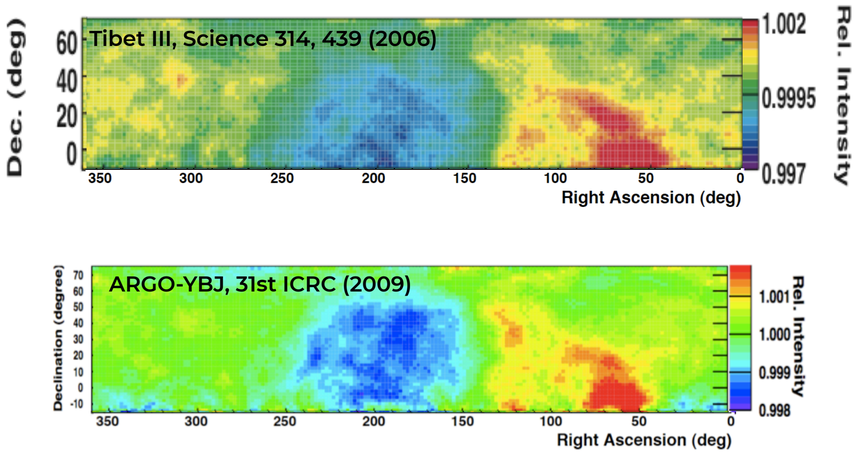


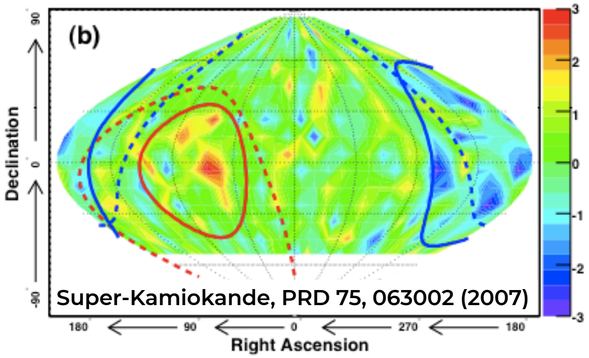
nuclear & hadronic processes

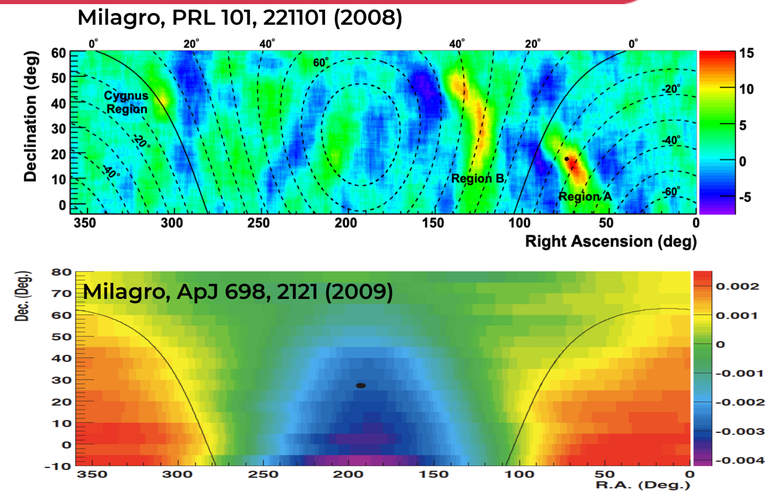
ground-based detection



TeV anisotropies - early 2000's



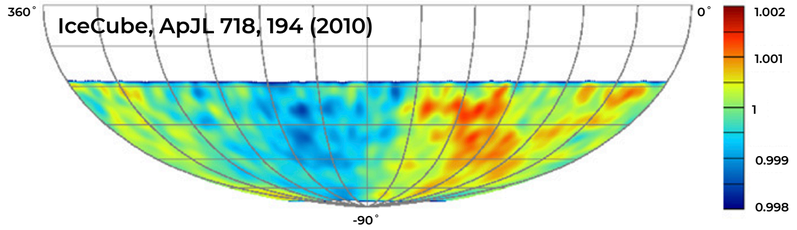




Ground-based experiments collecting a **large number** of TeV-scale cosmic-ray events

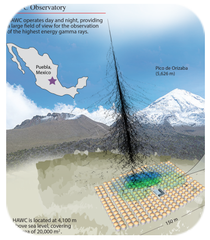
Early **sky maps** of cosmic-ray arrival direction distributions

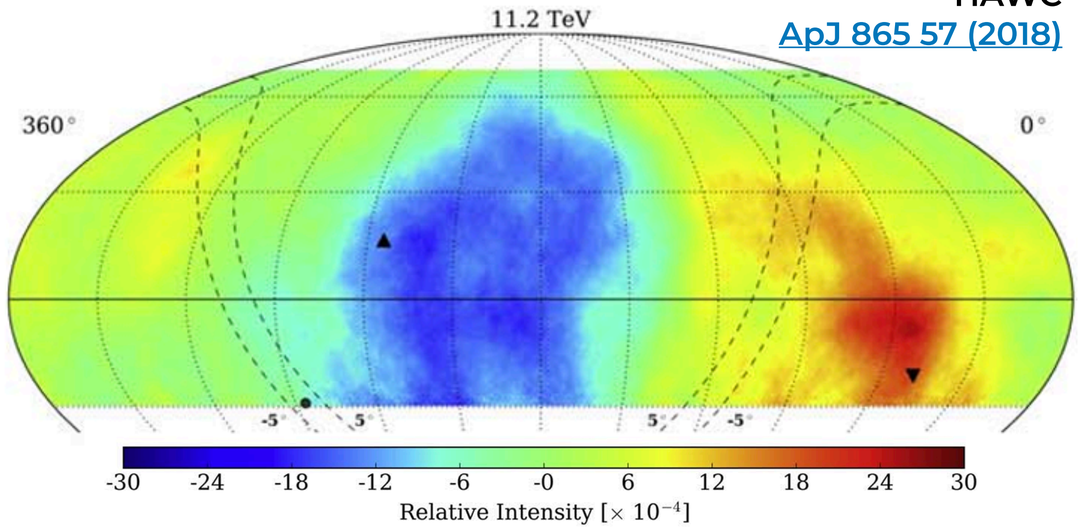
Due to the **small size** of the anisotropies (10^{-4} - 10^{-3}), quantitative studies require careful separation of detector effects from the observations

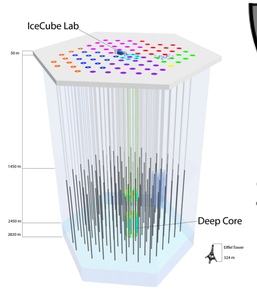


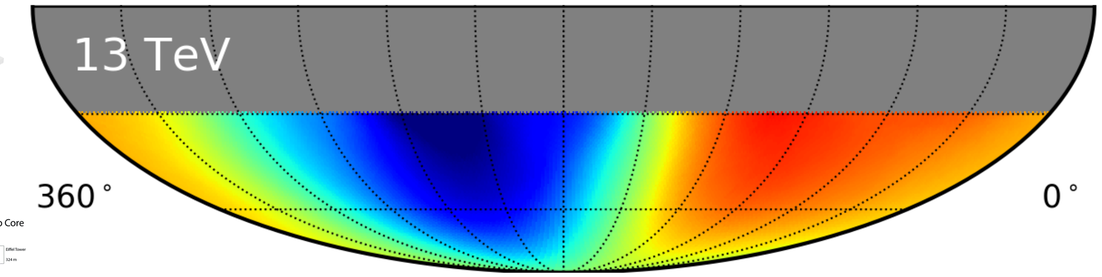
All-sky anisotropy

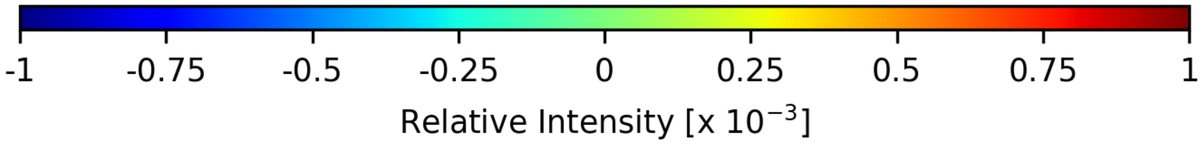
HAWC
ApJ 865 57 (2018)





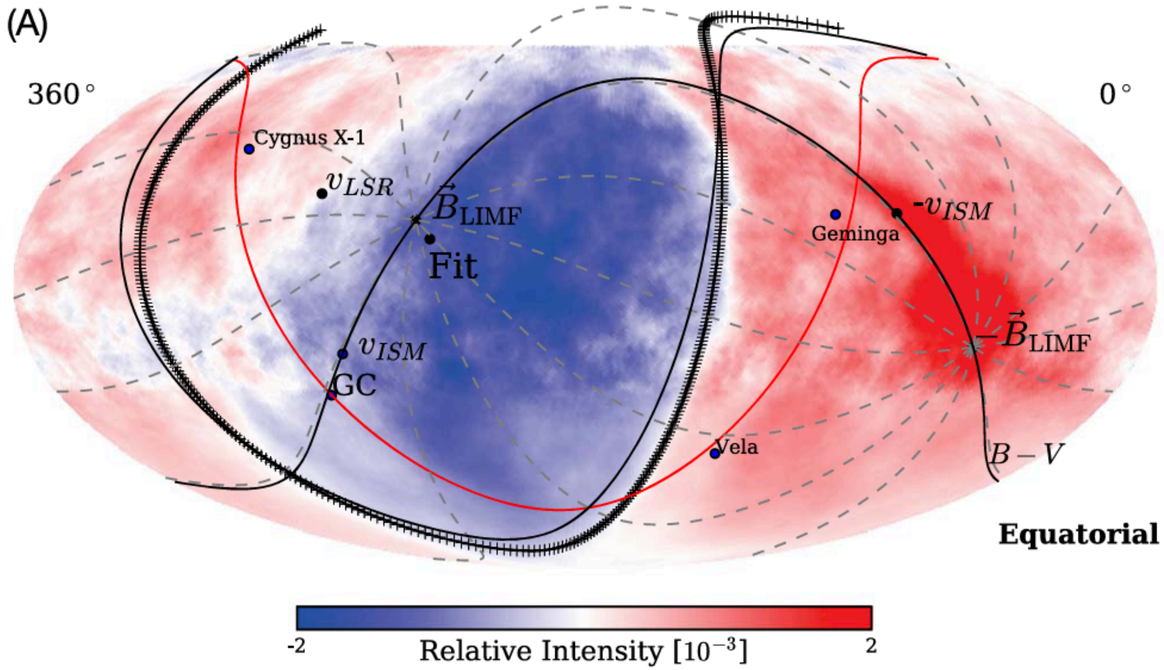






IceCube
ApJ 981 182 (2025)

10 TeV



HAWC/IceCube - Abeysekara+ (2019)

What do these observations tell us about the cosmic-ray journey?

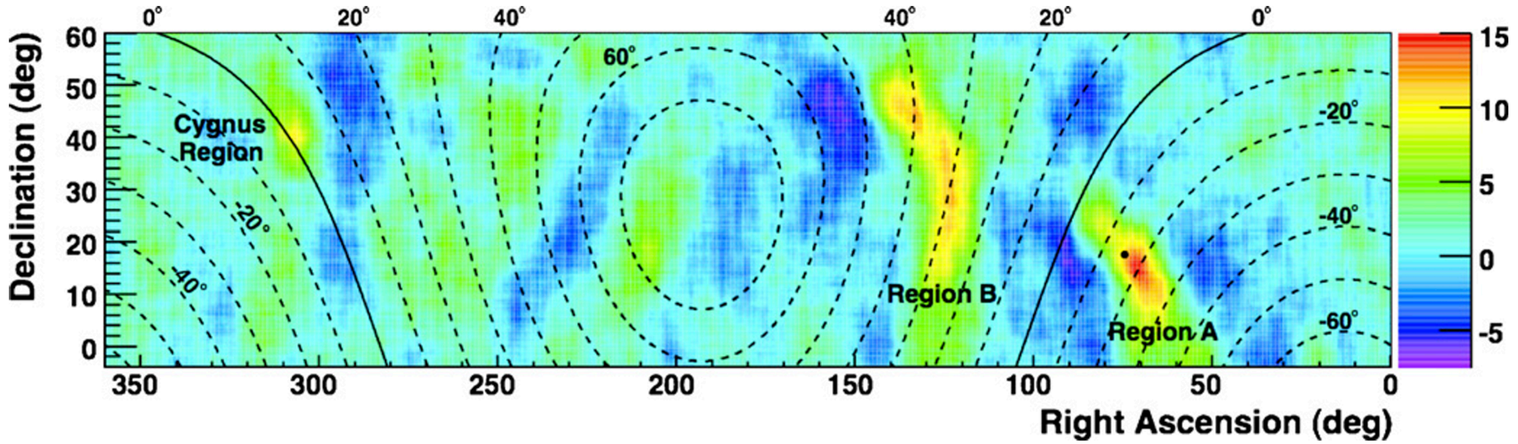
Understanding cosmic rays and the medium they traverse

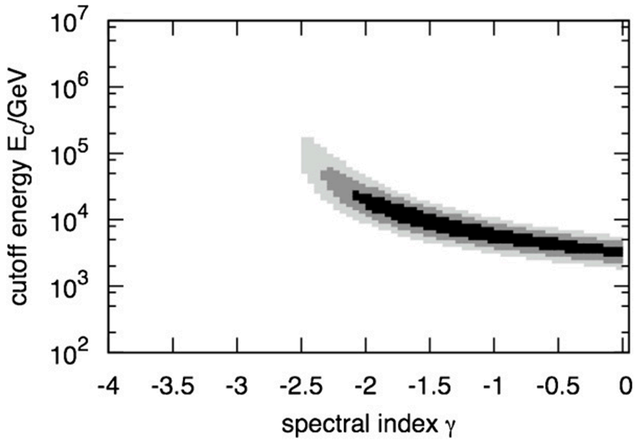
- anisotropies as complementary information to spectrum & composition
- distribution of cosmic-ray sources in the Milky Way
- properties of particle propagation in astrophysical plasmas
- properties of **interstellar magnetic turbulence**
- properties of the local **interstellar medium** & the **heliosphere**

2008

Cosmic-ray excess from heliotail

Milagro Abdo+ (2008)

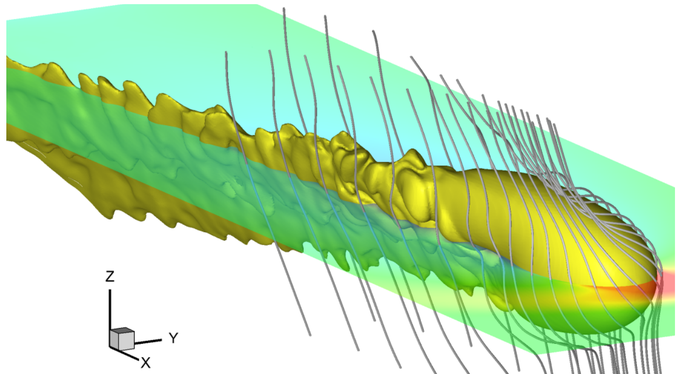




ARGO-YBJ Bartoli+ (2012)

HAWC Abeysekara+ (2014)

- $\sim 10^\circ$ localized excess
- fractional excess of $\sim 6 \times 10^{-4}$
- preference for higher energies
- heliosphere's tail direction

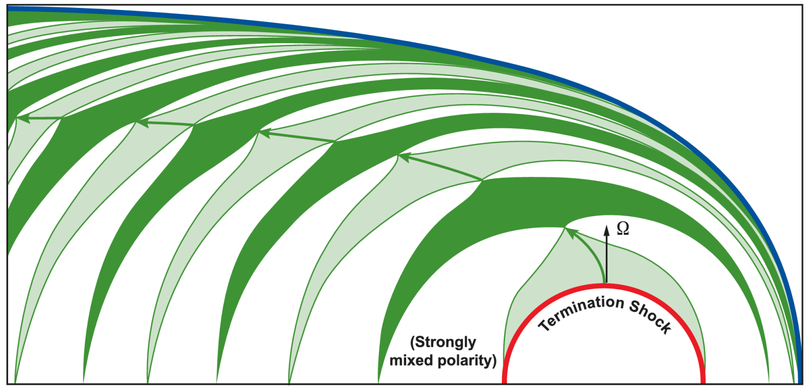


Borovikov, Heerikhuisen, Pogorelov (2015)

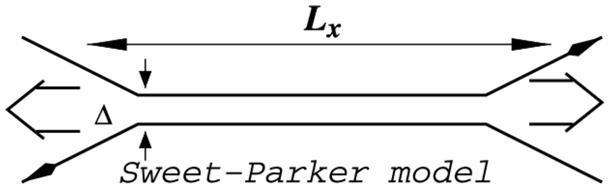
2010

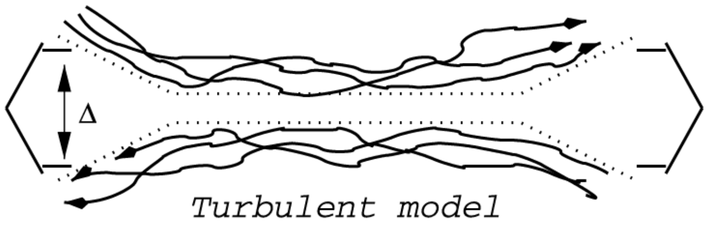
Cosmic-ray excess from heliotail

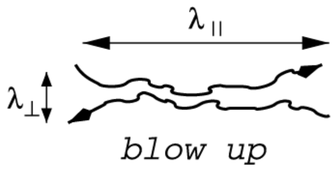
Lazarian & PD (2010)

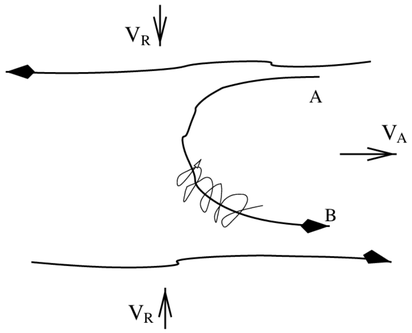


- Each **solar cycle** flips the field polarity, and the solar wind stacks opposite fields in the heliotail.
- **Magnetic reconnection**: protons bounce between contracting flux tubes and gain energy on every pass.
- Re-acceleration to TeV-scale
- Lower-energy particles scatter to a broad excess







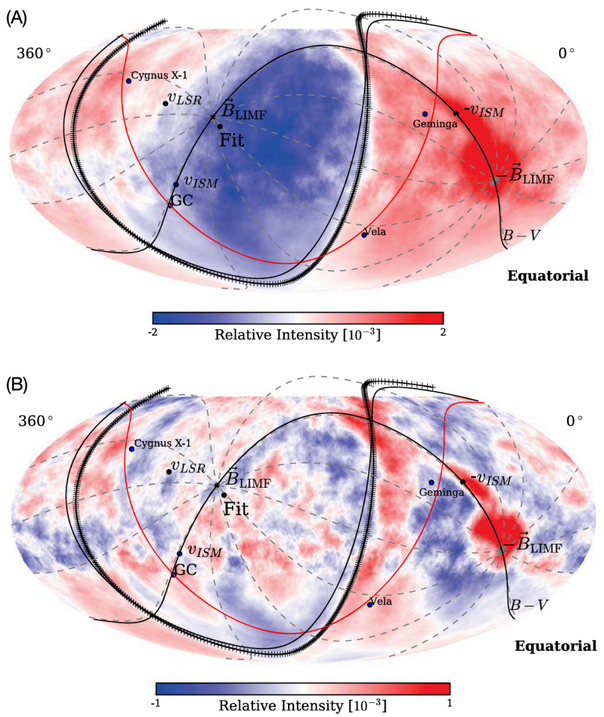


Takeaway

The heliotail may act as a local cosmic-ray accelerator

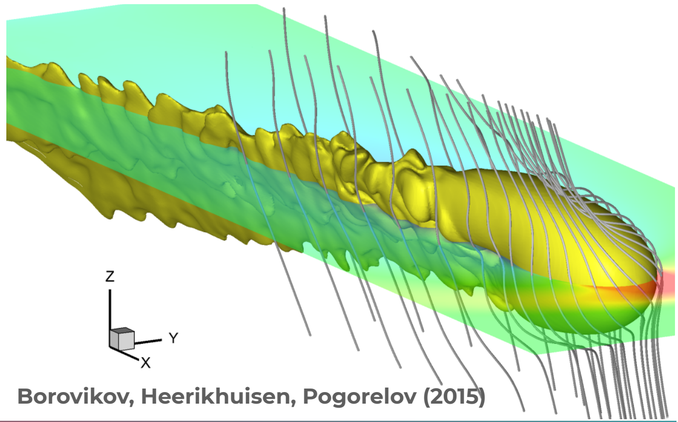
2012

Can the heliosphere reshape anisotropy?



HAWC/IceCube - Abeysekara+ (2019)

- non-smooth anisotropy with localized regions — PD & Lazarian (2012)
- not from diffusion but from interactions at the **boundary**
- $R_L \approx 760 \left(\frac{E}{10\,TeV}\right)\left(\frac{3\,\mu G}{B}\right) AU$ (local effect)
- <100 TeV: scattering redistributes particles to the heliotail and the local field direction. Steep gradients appear as hot spots
- >100 TeV: interstellar effects take over



Borovikov, Heerikhuisen, Pogorelov (2015)

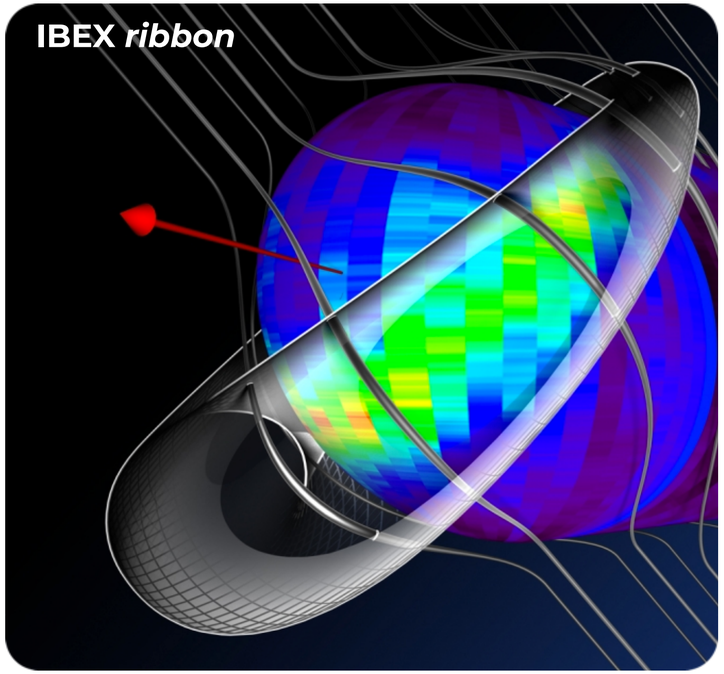
Takeaway

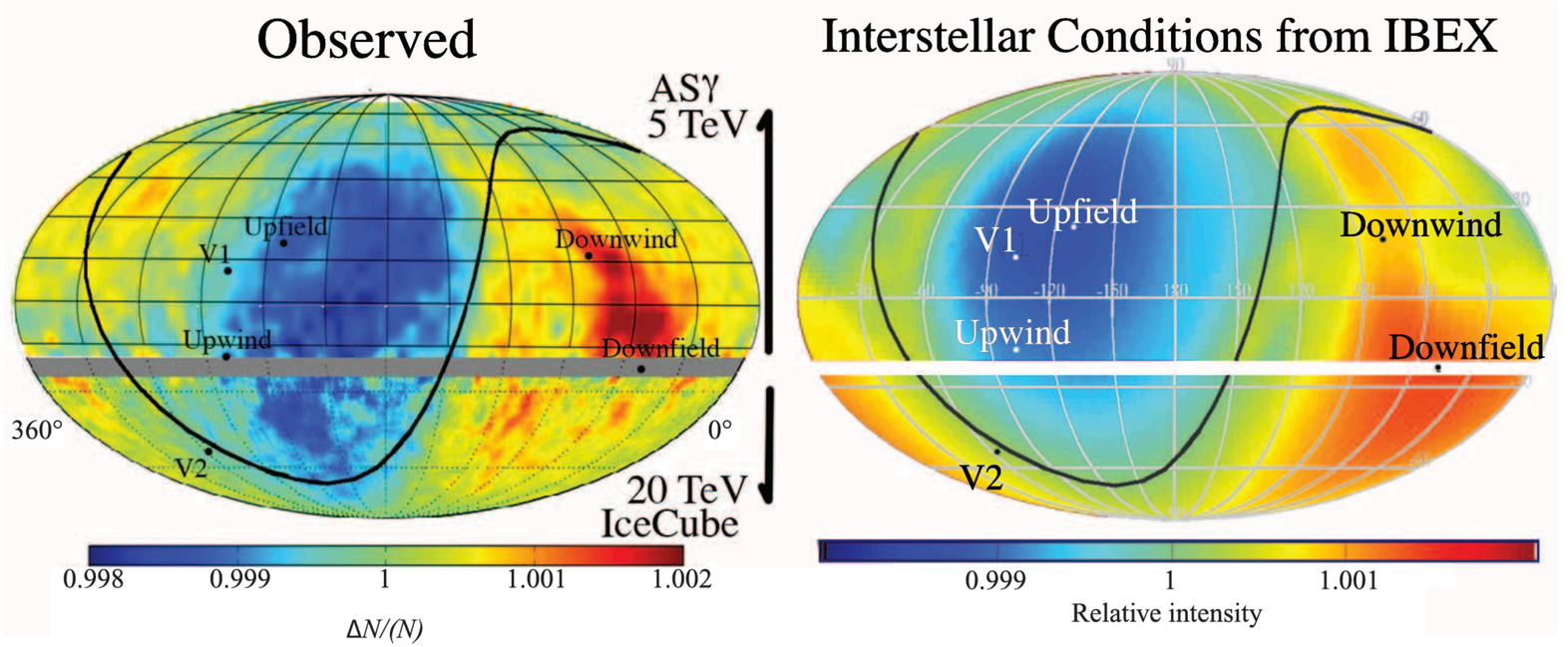
The TeV anisotropy may carry a heliospheric imprint and could map the interstellar field just outside the heliosphere.

2014

Local ISM field & TeV cosmic rays

Schwadron, ..., PD, et al., Science (2014)





Takeaway

The same interstellar field that shapes the IBEX ribbon organizes the large-scale TeV cosmic-ray anisotropy

2016

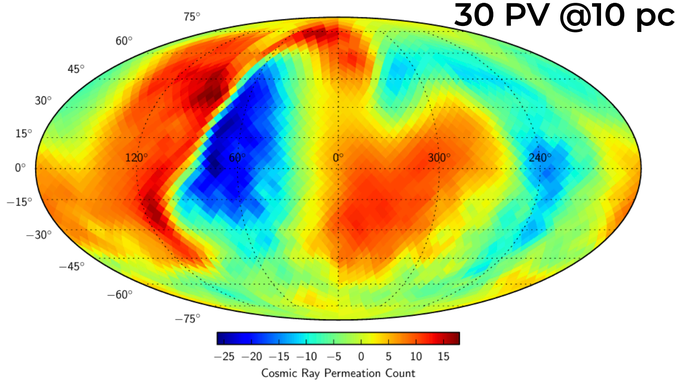
Local ISM magnetic turbulence

residual anisotropy
(after dipole subtraction)

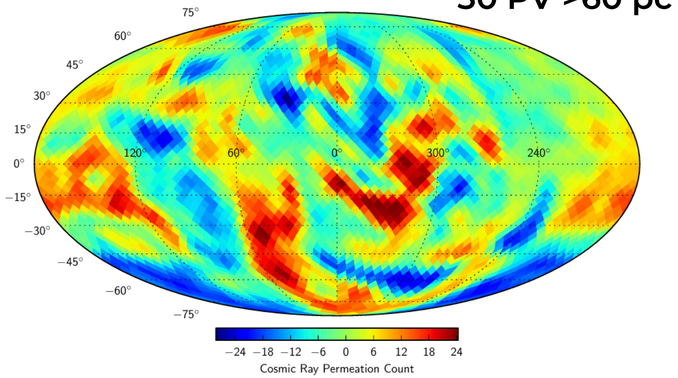
López-Barquero, Farber, Xu, PD & Lazarian (2016)

compressible MHD turbulence
Cho & Lazarian (2002)

30 PV @10 pc



30 PV >60 pc



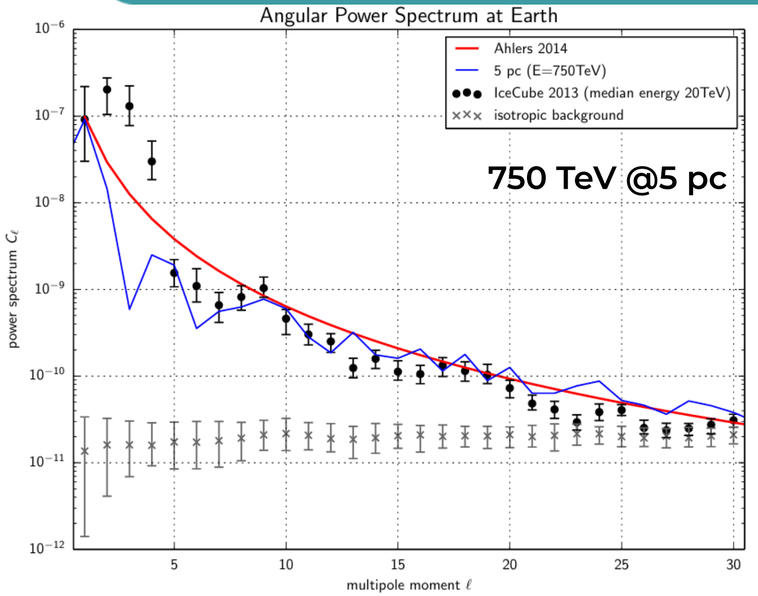
- How to separate heliospheric influence from the ISM?
- MHD turbulence produces small-scale features as well
- Dipole density gradient broken up to small scales

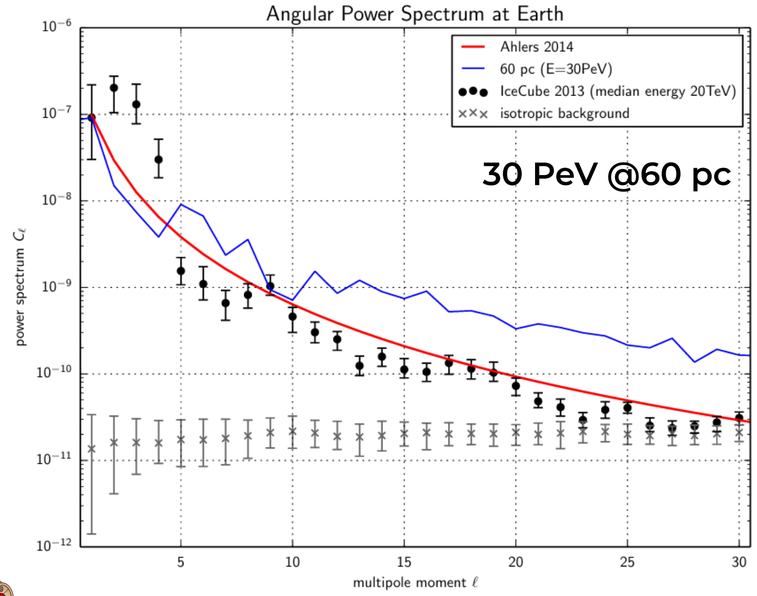
Takeaway

The small-scale anisotropy can be a local imprint of turbulent magnetic fields

2016

Local ISM magnetic turbulence





López-Barquero, Farber, Xu, PD & Lazarian (2016)

compressible MHD turbulence
Cho & Lazarian (2022)

- The angular power spectrum shows how scale-cascading evolves
- Higher energies give more fine structures
- The 750 TeV spectrum resembles IceCube's at ~20 TeV median energy. Scattering there may be underestimated

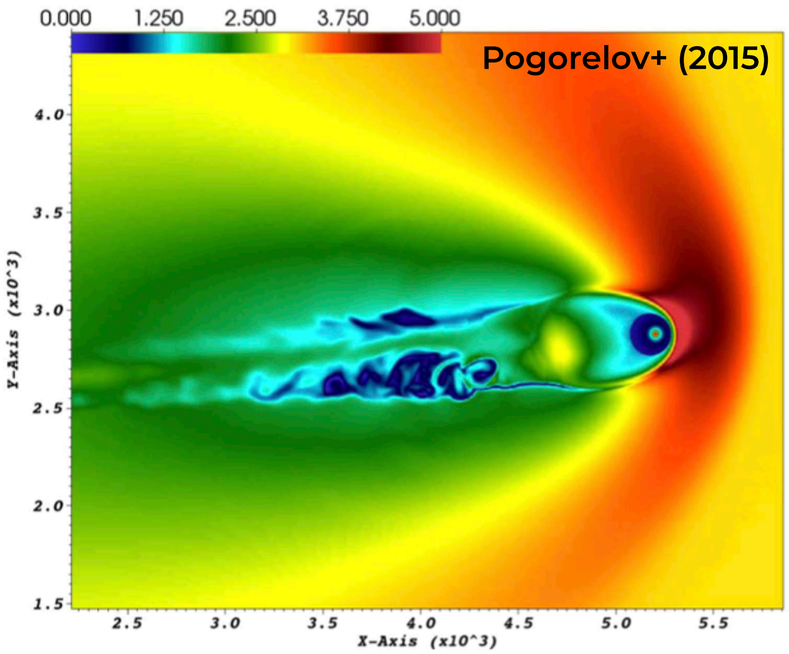
Takeaway

Not only compressible MHD turbulence is responsible for the observation

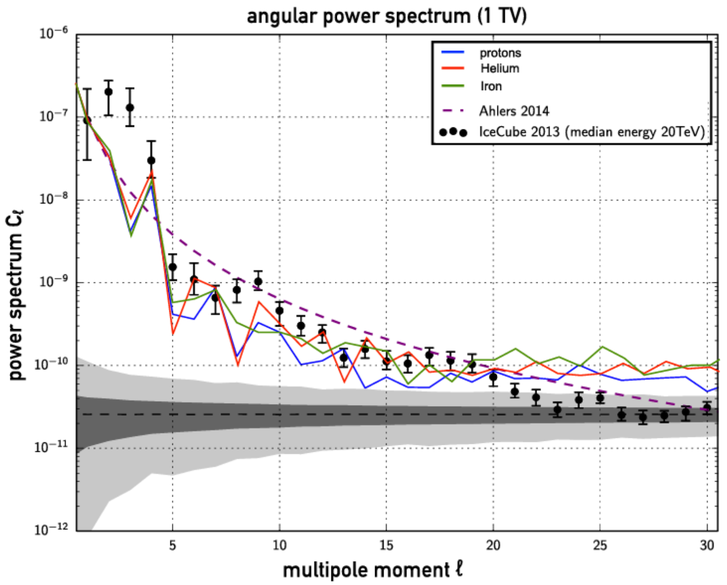
2017

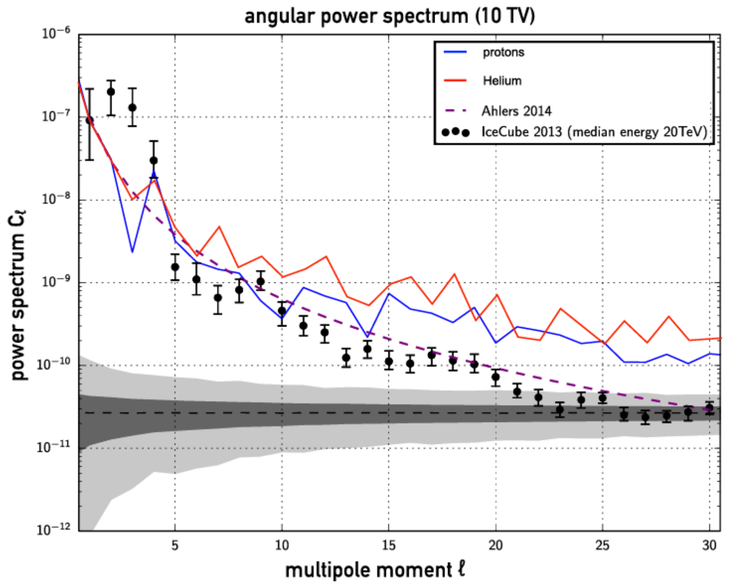
Heliosphere boundary reshapes anisotropy

López-Barquero, Xu, PD, Lazarian, Pogorelov & Yan (2017)



- A coherent magnetic field produces a similar angular power spectrum of MHD turbulence
- No stochastic scattering, but temporary trapping and magnetic drift





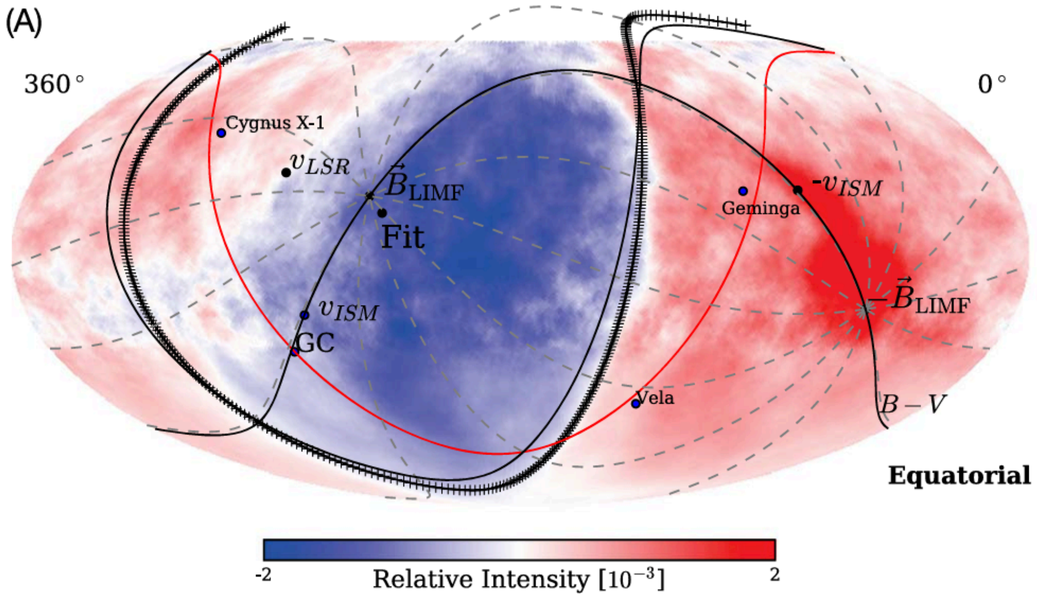
Takeaway

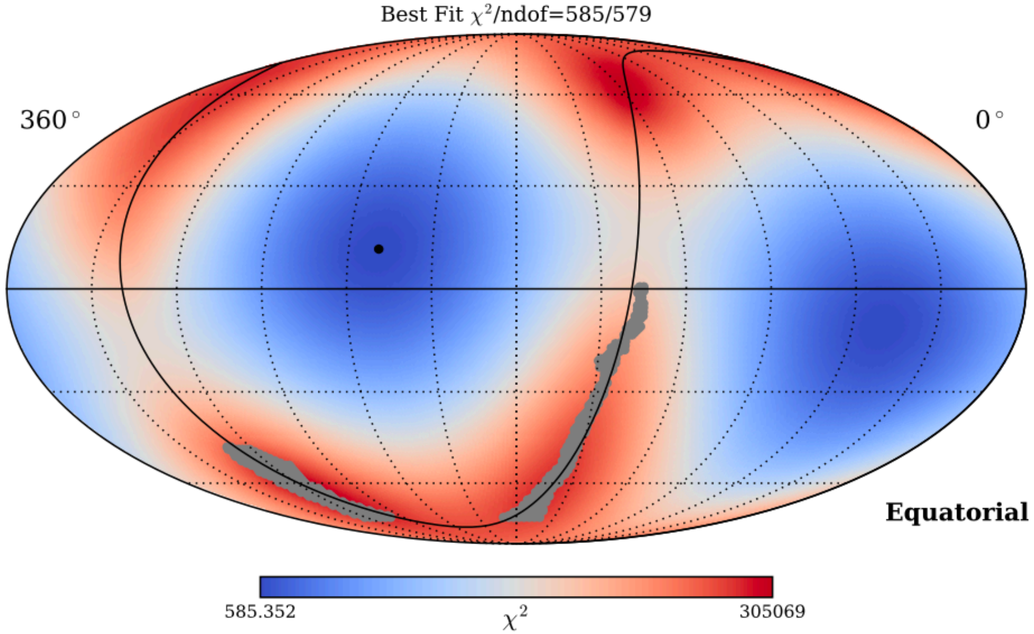
The heliosphere is not transparent to TeV cosmic rays; its boundary helps shape the observed angular power spectrum.

2019

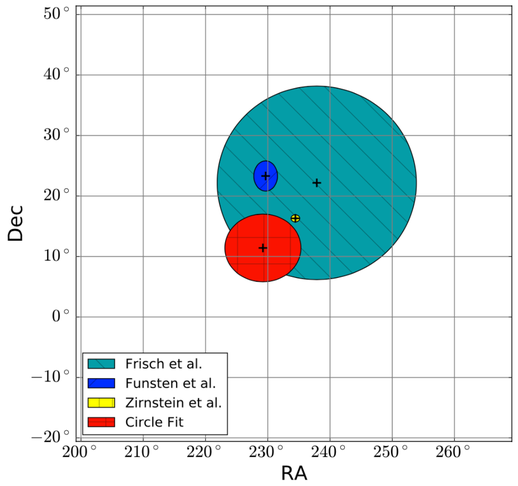
Recovering interstellar field direction

HAWC - Abeysekara+ (2019)





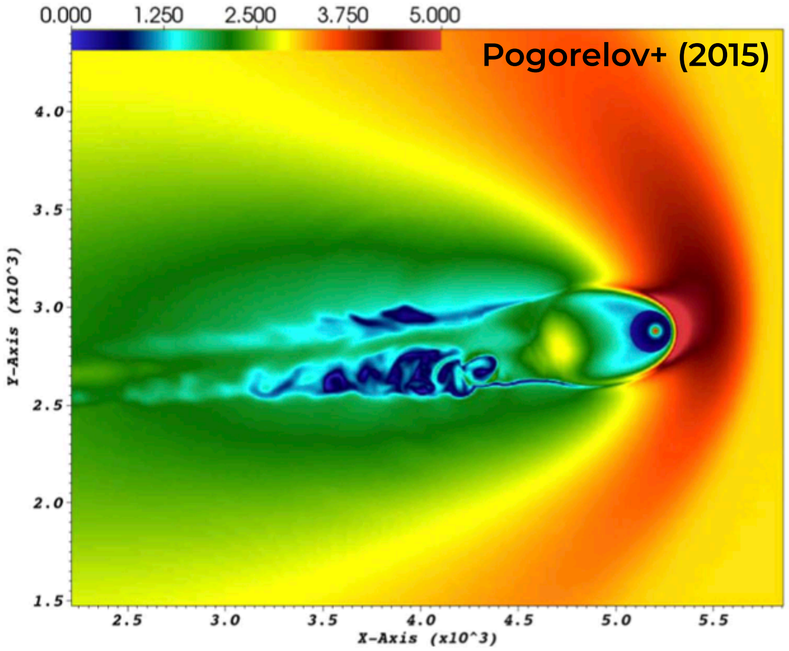
- The cosmic-ray distribution is deformed by the heliosphere while preserving ISM imprint



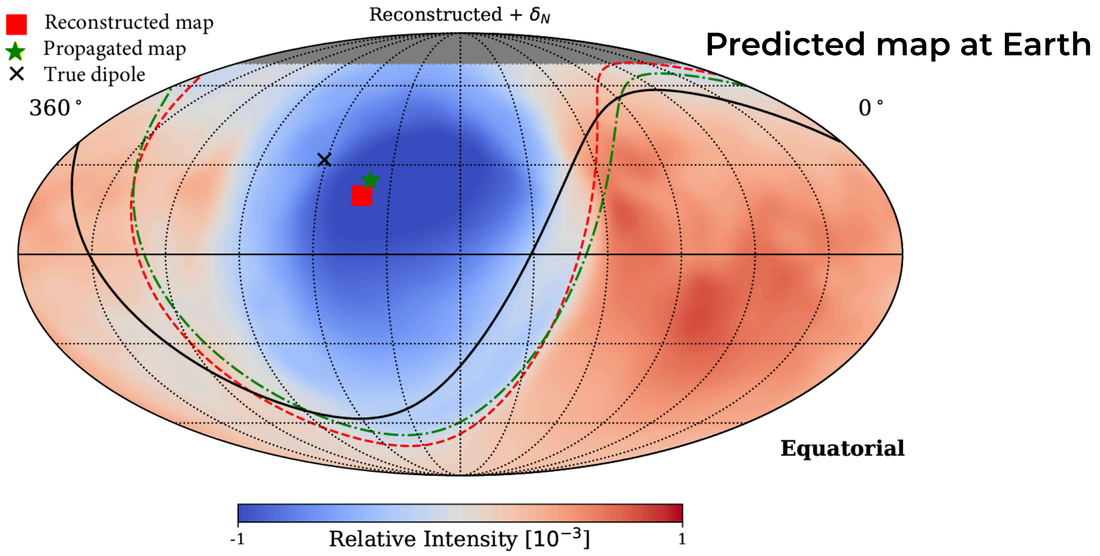
2019

Recovering interstellar field direction

Díaz Vélez & PD PoS(ICRC2019)1076



- Particles in a model of the heliosphere
- Earth ↔ ISM trajectory mapping
- Reproduce experimental response function
- Restore N-S component → more accurate ISM map



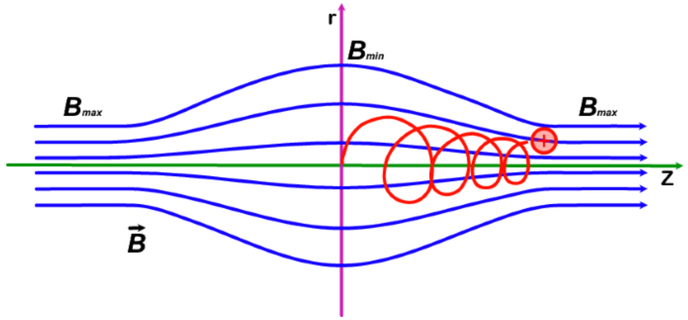
Takeaway

Heliospheric lensing at 10 TV keeps the anisotropy ordered by the interstellar field, and the full pattern lets us undo it

trapping and chaotic dynamics

López-Barquero & PD (2025)

Simple magnetic bottle model to study particle dynamics under trapping conditions



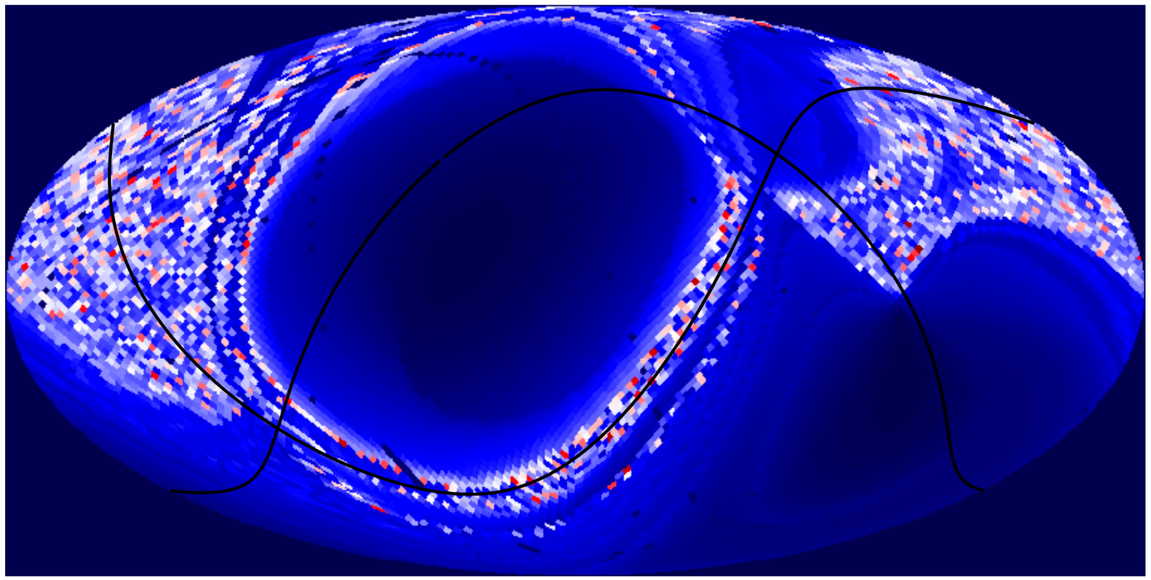
- **Magnetic bottle** to mimic the heliosphere's flanks and field draping. Slow field changes mimic the solar cycle
- Finite-time Lyapunov exponent λ: the rate at which trajectories that start almost together drift apart.
- $\lambda \sim 17\, t^{-1.04}$ $\lambda \times$ escape time $\sim$ constant: each particle leaves after about the same total divergence λt

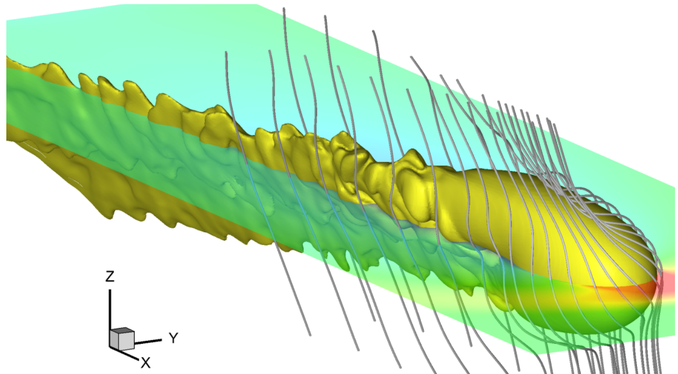
Takeaway

The boundary between chaotic and laminar regions of the sky could make TeV anisotropy maps change over a solar cycle

trapping and chaotic dynamics

- Asymmetry of the **real heliosphere**
- All trajectories reaching Earth are connected to the ISM
- Long paths through the draping region should become fully chaotic.



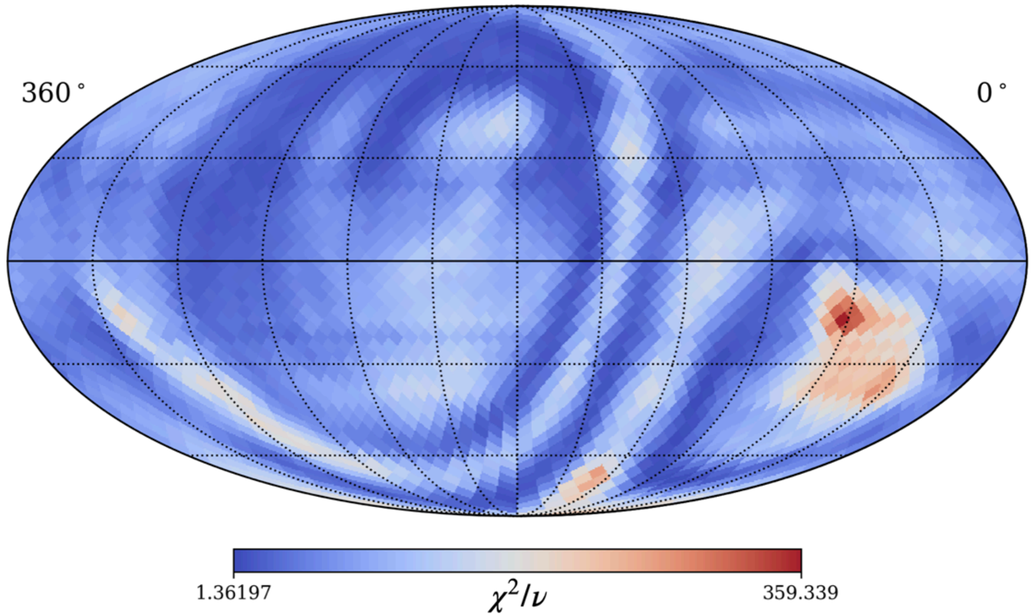


Borovikov, Heerikhuisen, Pogorelov (2015)

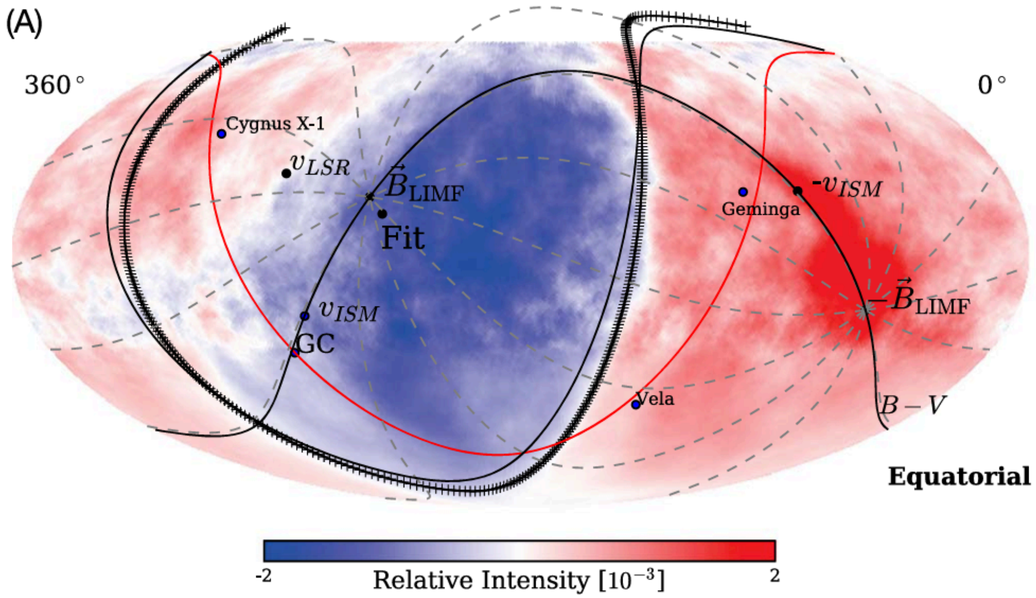
2025

heliosphere and spectral anisotropy

López-Barquero, Portuguez, PD & Díaz-Vélez
PoS(ICRC2025)325



HAWC - Abeysekara+ (2019)



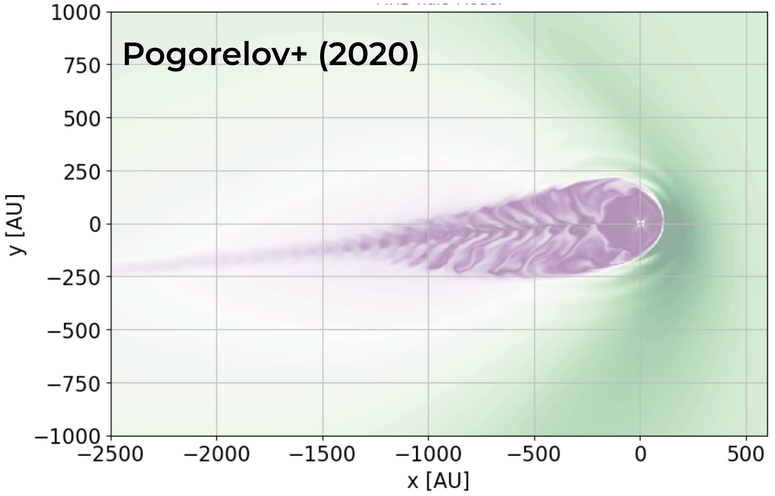
- Energy-dependent ***resonance*** from particles trapped at specific arrival directions
- At 7 TV, some regions exhibit spectra that differ from the all-sky spectrum

Takeaway

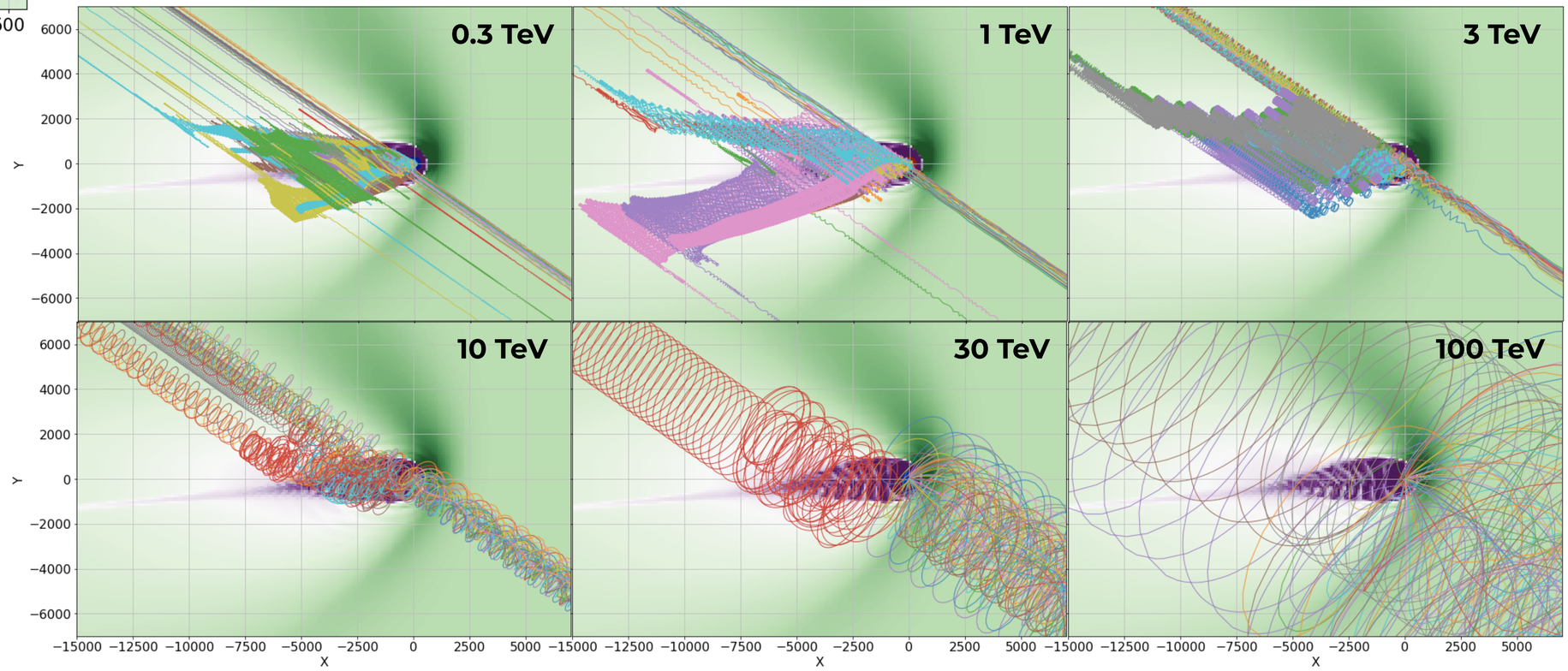
The heliosphere may shape not only where TeV cosmic rays arrive from, but also their energy spectrum in each direction

recovering interstellar anisotropy

recovering interstellar anisotropy

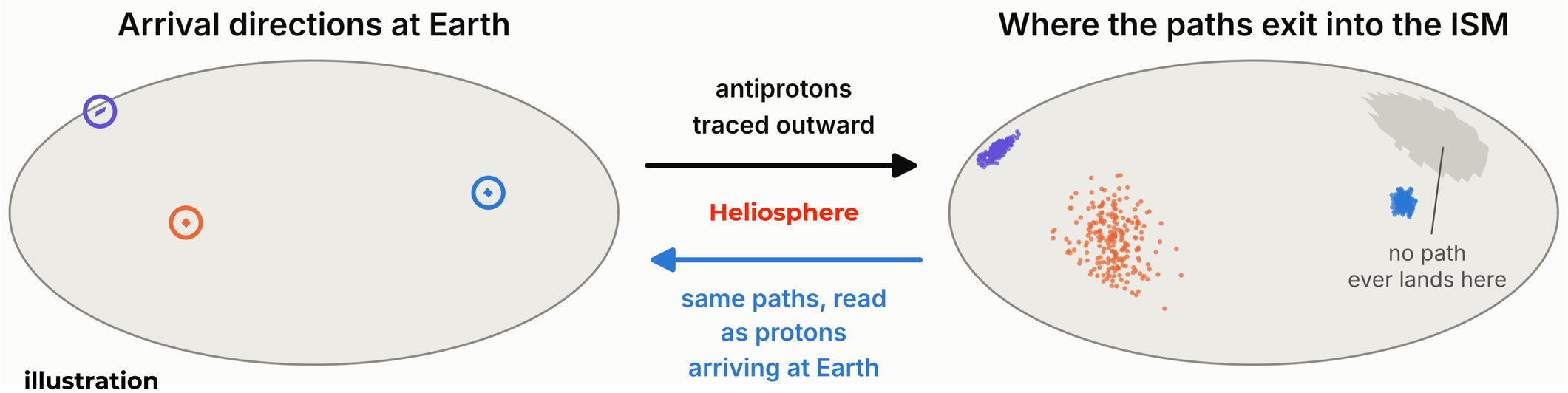


- Back-traced anti-protons
- Continuous energy = 100 GeV - 100 TeV



recovering interstellar anisotropy

- Back-traced anti-protons
- Continuous energy = 100 GeV - 100 TeV
- Construct transfer matrices
- Map ISM sky pixels to arrival pixels at Earth

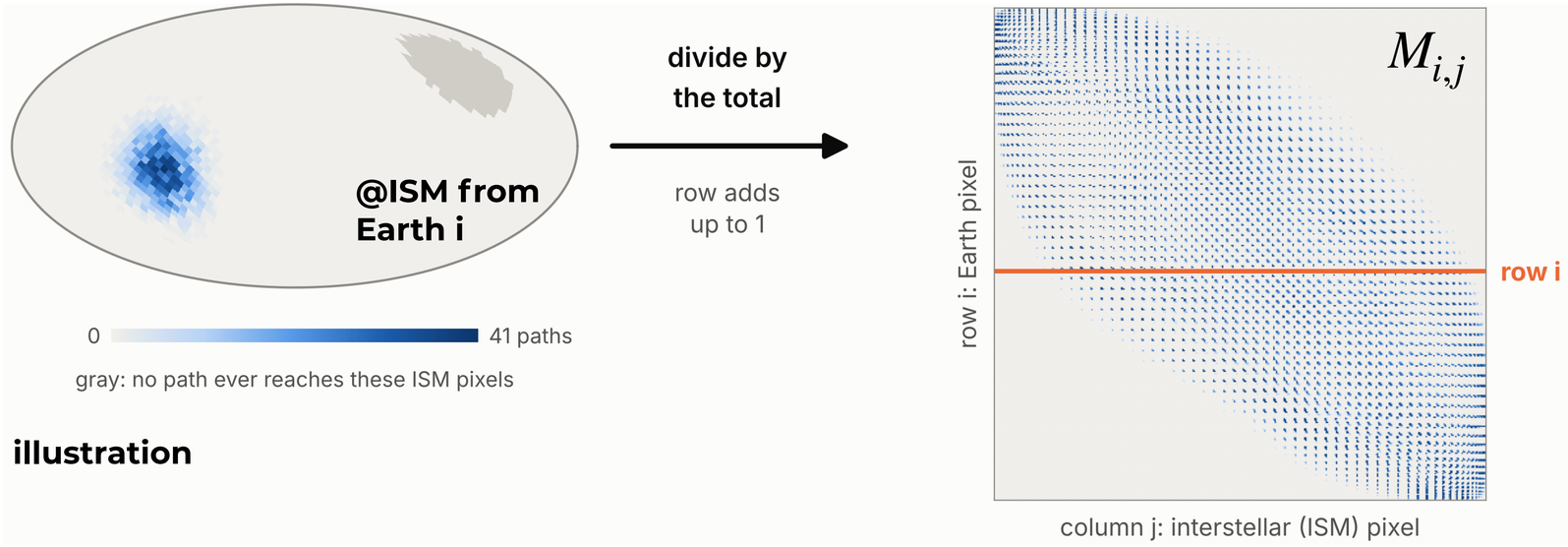


recovering interstellar anisotropy

- Construct transfer matrices
- Map ISM sky pixels to arrival pixels at Earth
- $M_{i,j}$ prob. particle in Earth ***i*** arrives from ISM ***j***
- Use forward proton trajectories

$$I_i^{\text{Earth}} = \sum_j M_{i,j}\, I_j^{\text{ISM}}$$

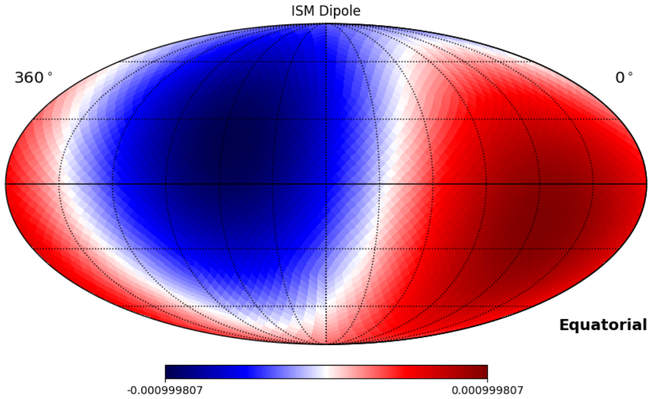
$$\sum_j M_{i,j} = 1$$



recovering interstellar anisotropy

Tom, PD, Díaz Vélez & Zilberman (2025)

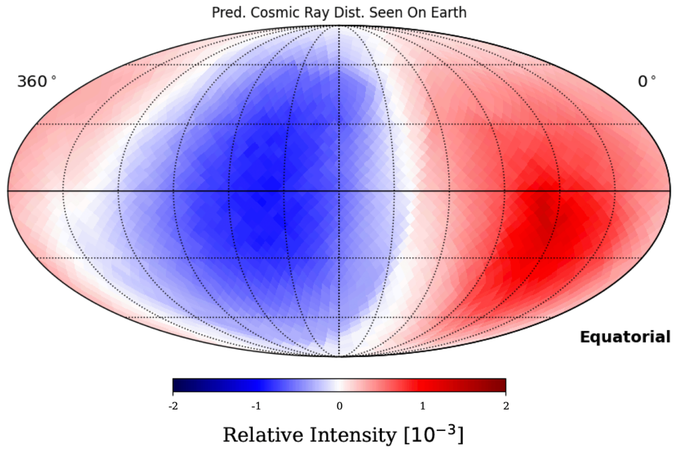
A dipole distribution injected in the ISM (from diffusion)...



transfer matrix $M_{i,j}$ representing the heliosphere's effect

10 TV proton trajectories

...mapped to **Earth's observations** through the heliosphere's model

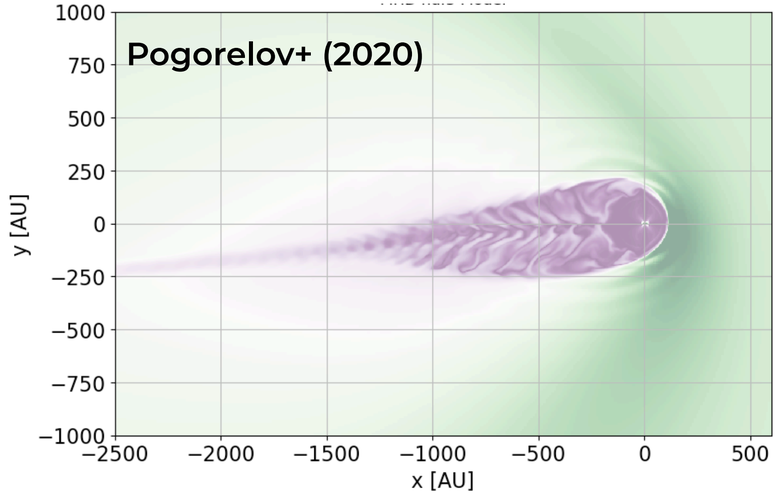


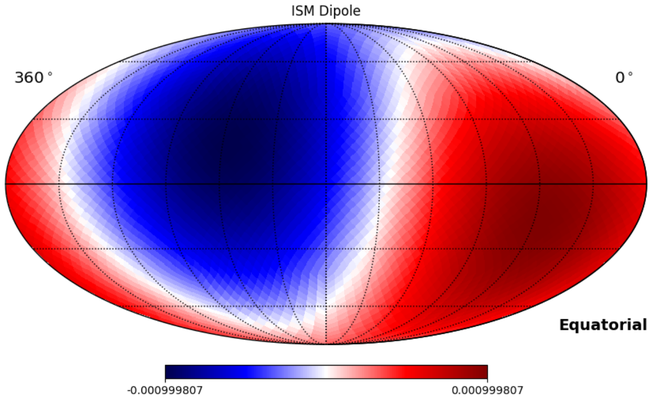
2025

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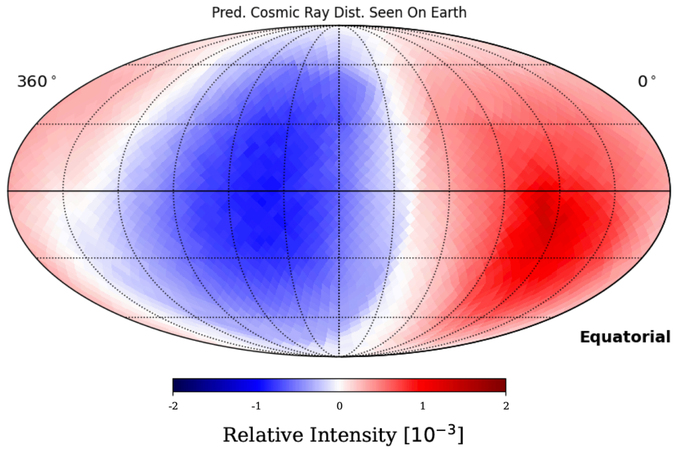
WISCONSIN SPACE GRANT CONSORTIUM

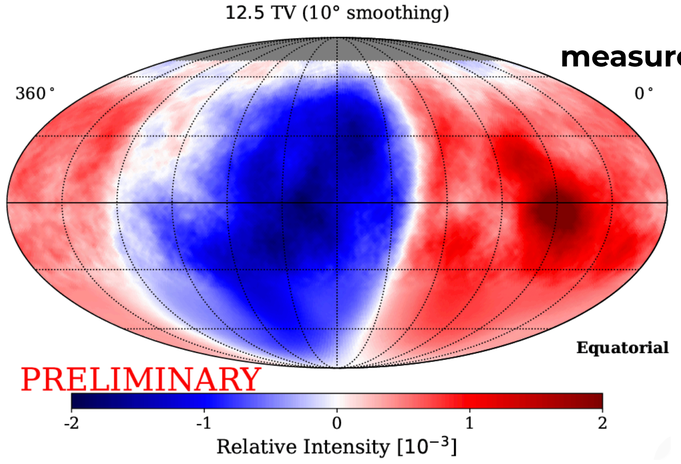
Tom, PD, Díaz Vélez & Zilberman (2025)





10 TV rigidity trajectories





HAWC-IceCube
PoS(ICRC2025)244
ApJ 871 96 (2019)

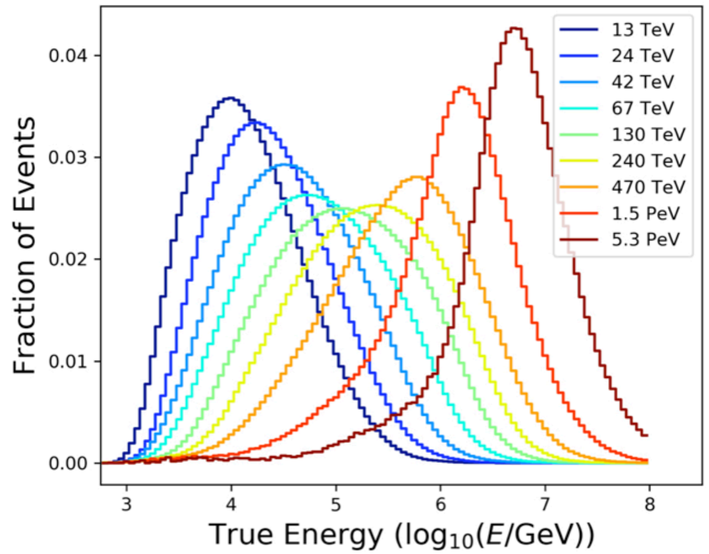
Can I reconstruct back the original ISM pattern from Earth's *measurement*?

recovering interstellar anisotropy

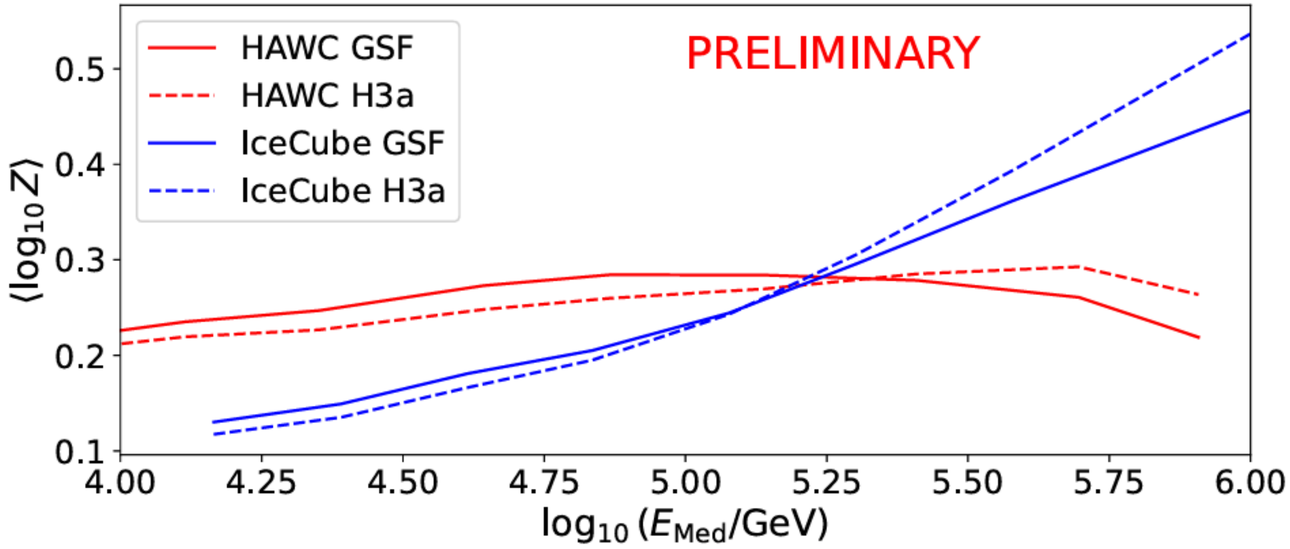
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Tom, PD, Díaz Vélez & Zilberman (2025)

- Account for the experimental response function
- Mass composition (rigidity scaling)
- N-S blindness (absence of $m = 0$ multipoles)



Can I reconstruct back the original ISM pattern from Earth's *measurement*?

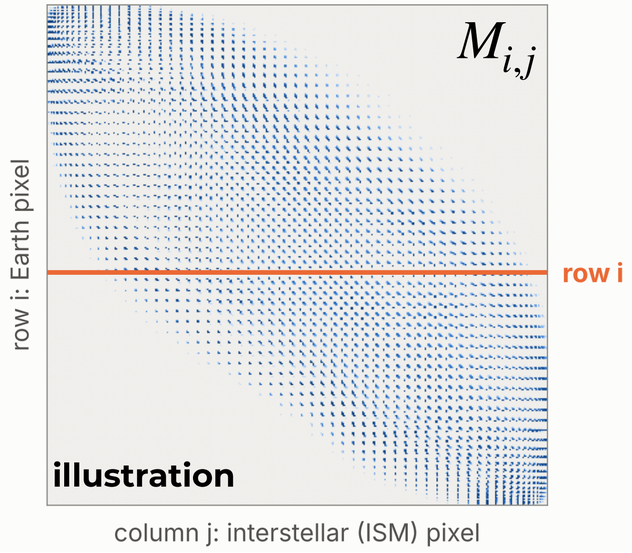


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Tom, PD, Díaz Vélez & Zilberman (2025)

- Inversion of $M_{i,j}$ is **ill-conditioned**
- Different Earth ***i*** map to many overlapping ISM ***j***
- Regions of ISM do not map to Earth
- Different rows of $M_{i,j}$ look alike and are indistinguishable
- Statistical noise & chaotic behavior



Can I reconstruct back the original ISM pattern from Earth's *measurement*?

→

Singular Value Decomposition (SVD)

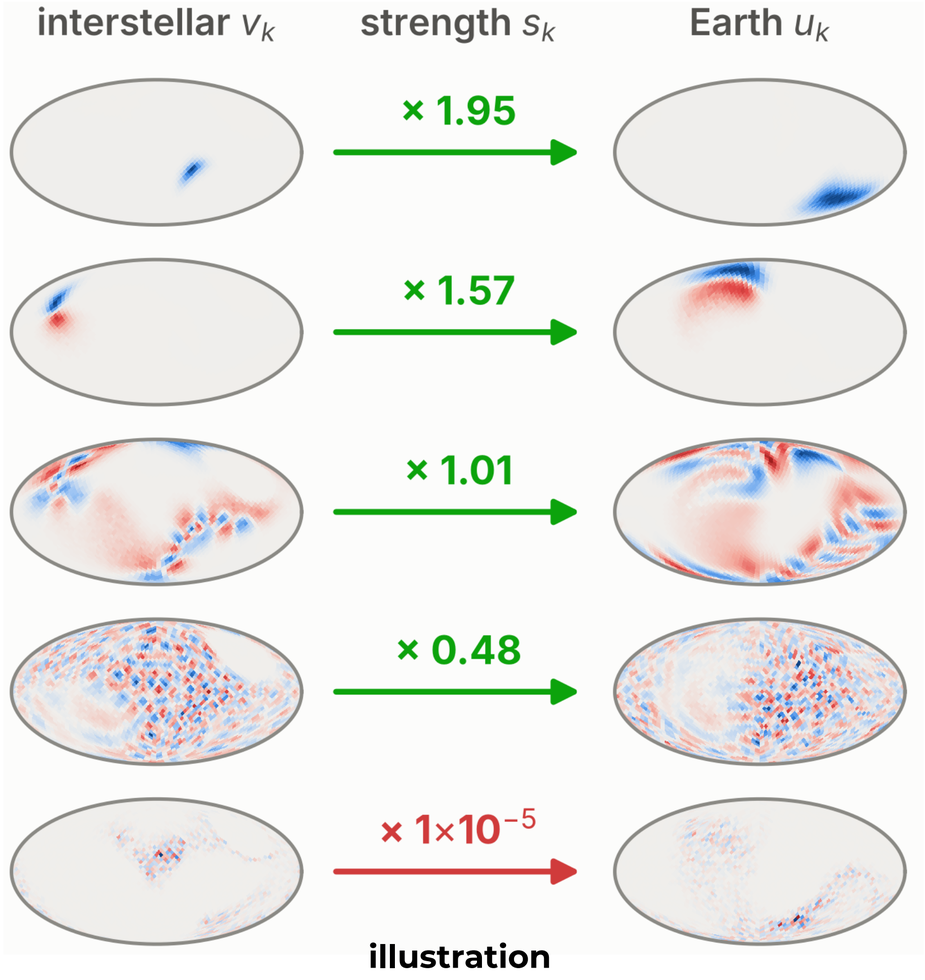
Truncation regularization

$$M = U\,\Sigma\,V^{\top} = \sum_{k}^{r} u_k\, s_k\, v_k^{\top}$$

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$$M = U\,\Sigma\,V^{\top} = \sum_{k}^{r} u_k\, s_k\, v_k^{\top} \qquad u_k, v_k \text{ basis}$$

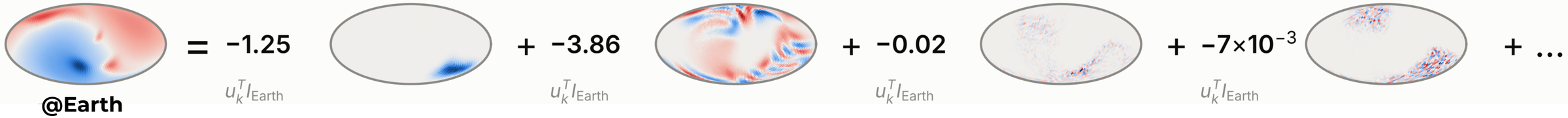
patterns ordered from large- to small-scale

2025

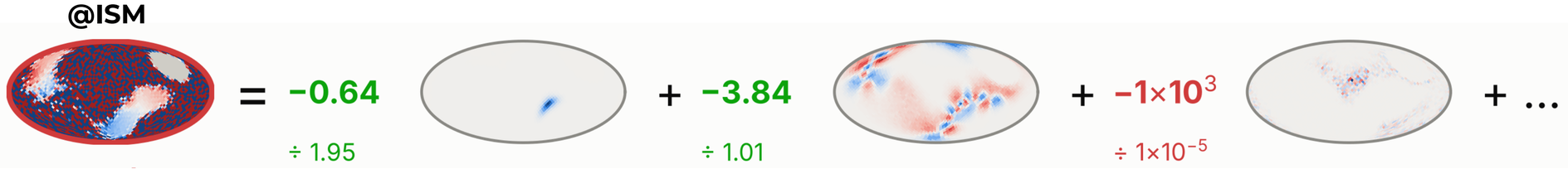
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illustration



Inverting Matrix M



very noisy

must truncate

Pseudo-inversion: truncate SVD to k_0

to avoid amplified noise from small s_k

$$\hat{I}_{\text{ISM}} \approx M_{k_0}^{+} I_{\text{Earth}} = \sum_{k<k_0} \left(\frac{u_k^{\top} I_{\text{Earth}}}{s_k} \right) v_k$$

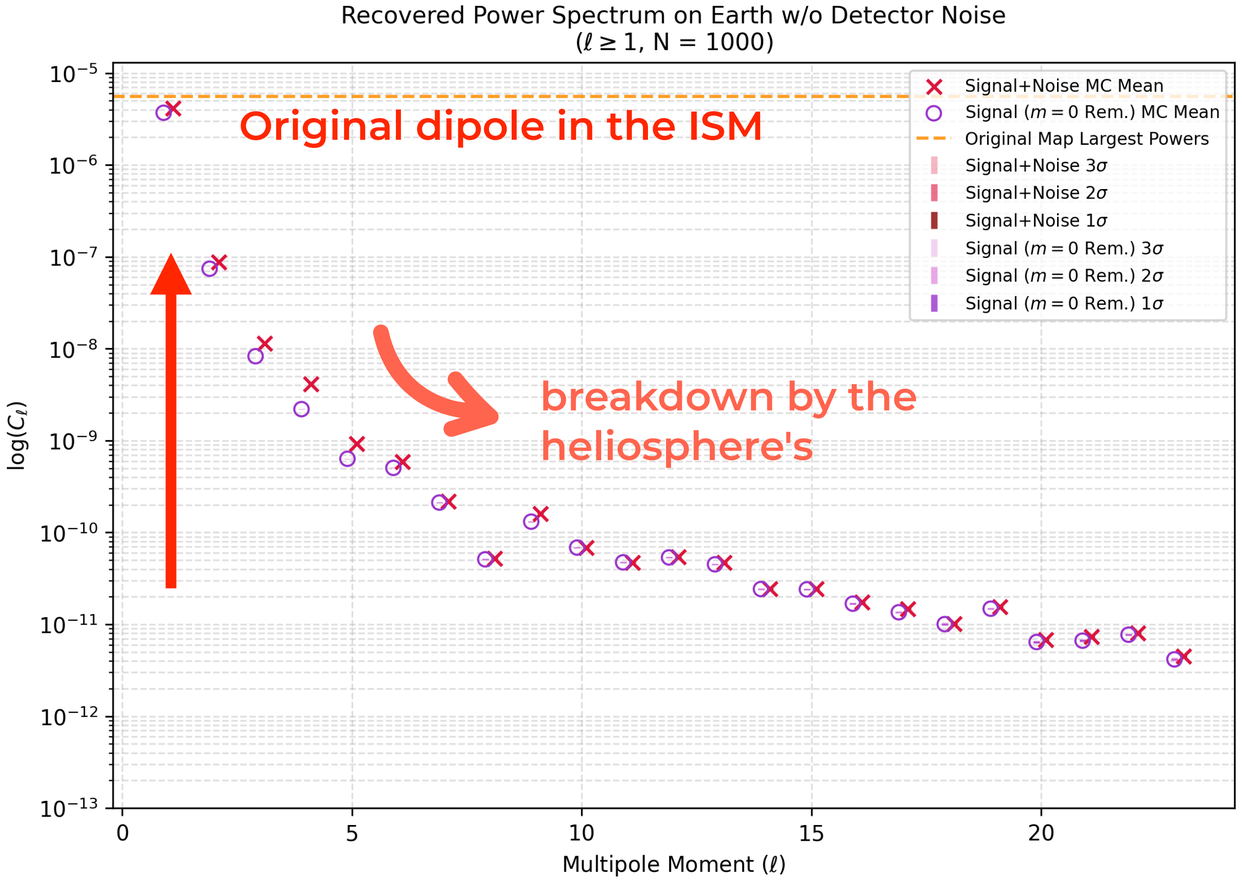
2025

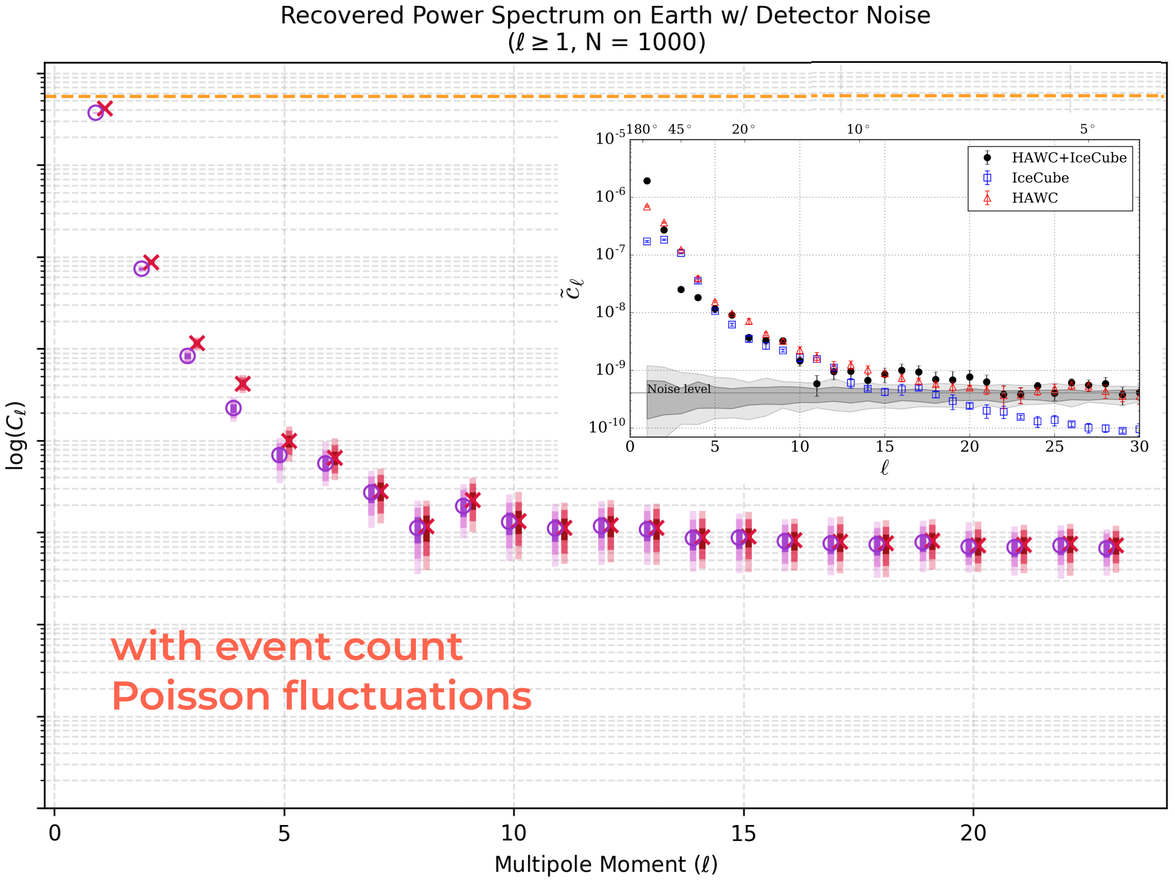
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ISM → Earth

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How a dipole anisotropy in the ISM is *transmitted* to Eartn through the heliosphere

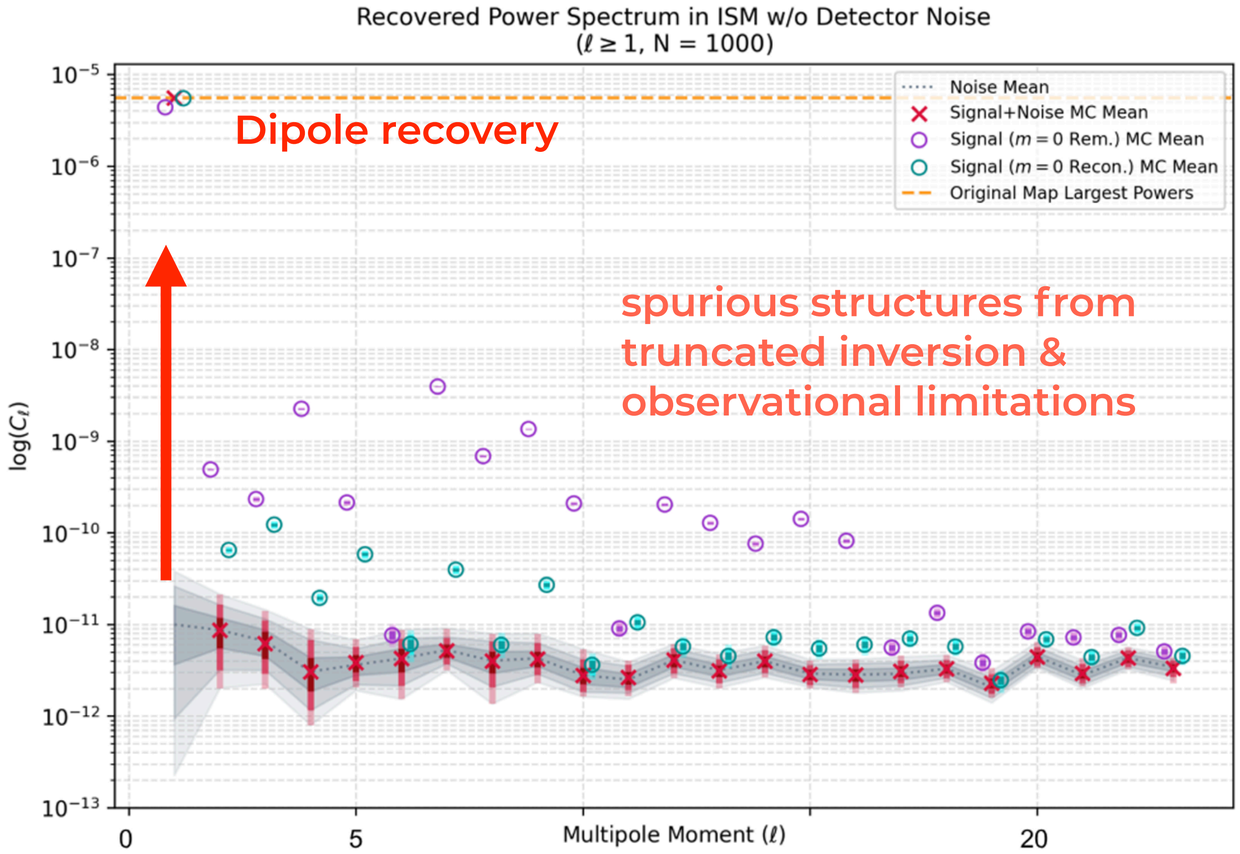
2025

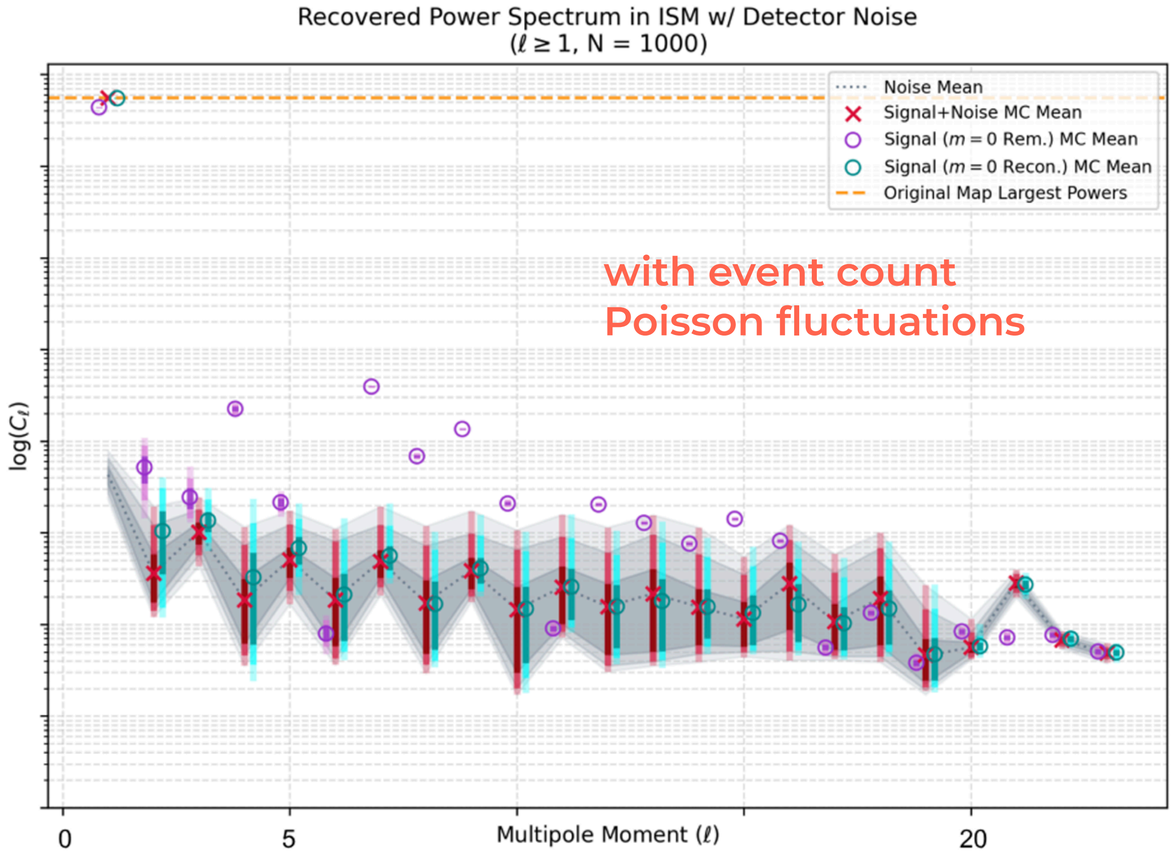
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Earth → ISM

Tom, PD, Díaz Vélez & Zilberman (2025)





How ISM anisotropy is reconstructed from Earth's *measurements*

NEXT: reconstruct measured ISM all-sky anisotropy map and investigate accuracy

Thank you

