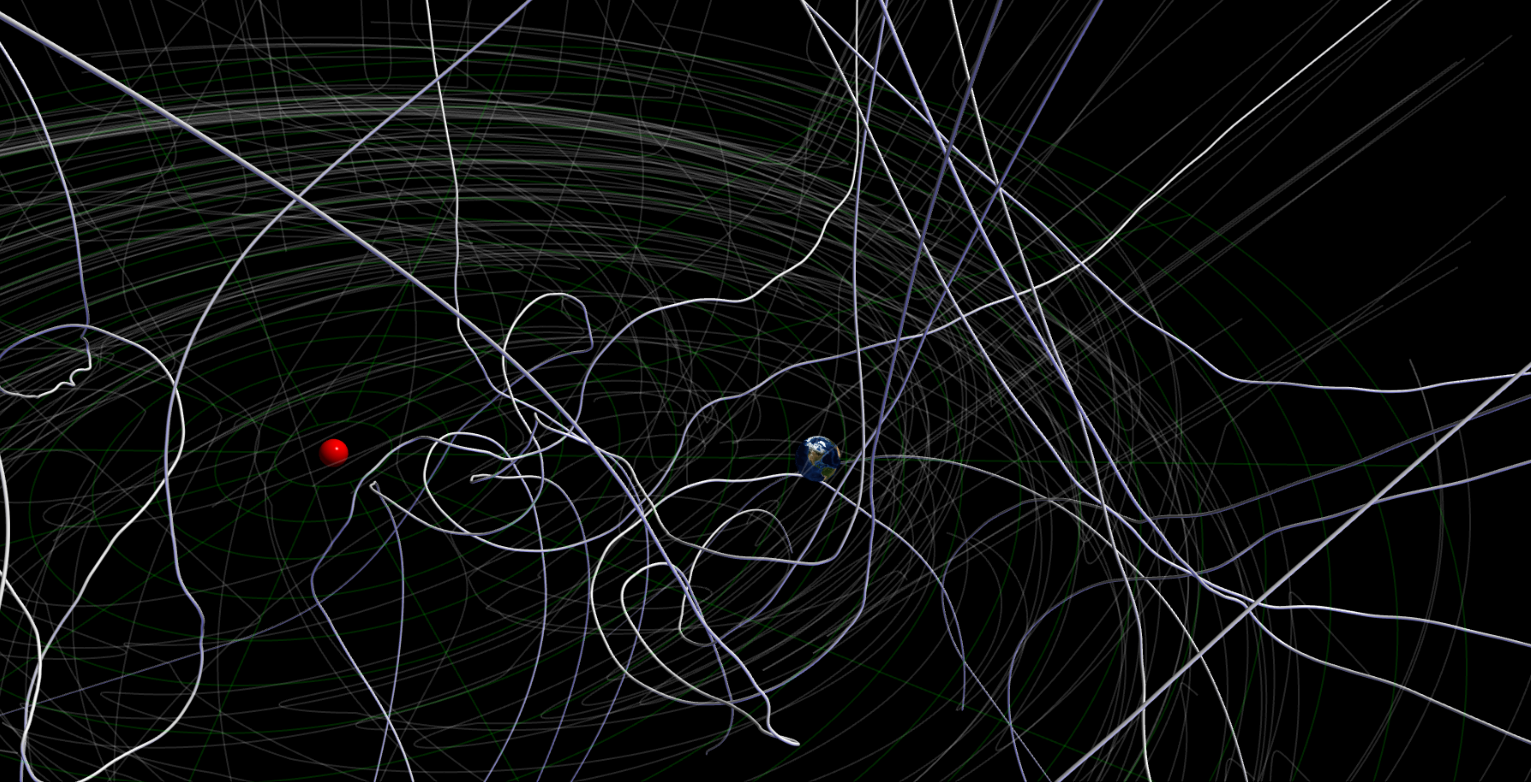

# Impact of the Turbulent Galactic Magnetic Field on the Arrival Distributions of Ultra-High Energy Cosmic Rays


THE OHIO STATE UNIVERSITY

CCAPP

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**in collaboration with Glennys Farrar (NYU)**

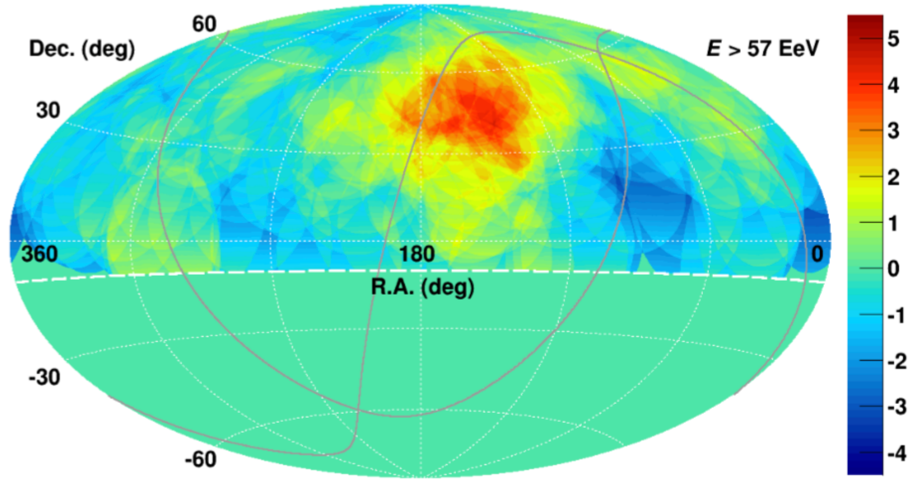


TeVPA, Columbus OH

August 11, 2017

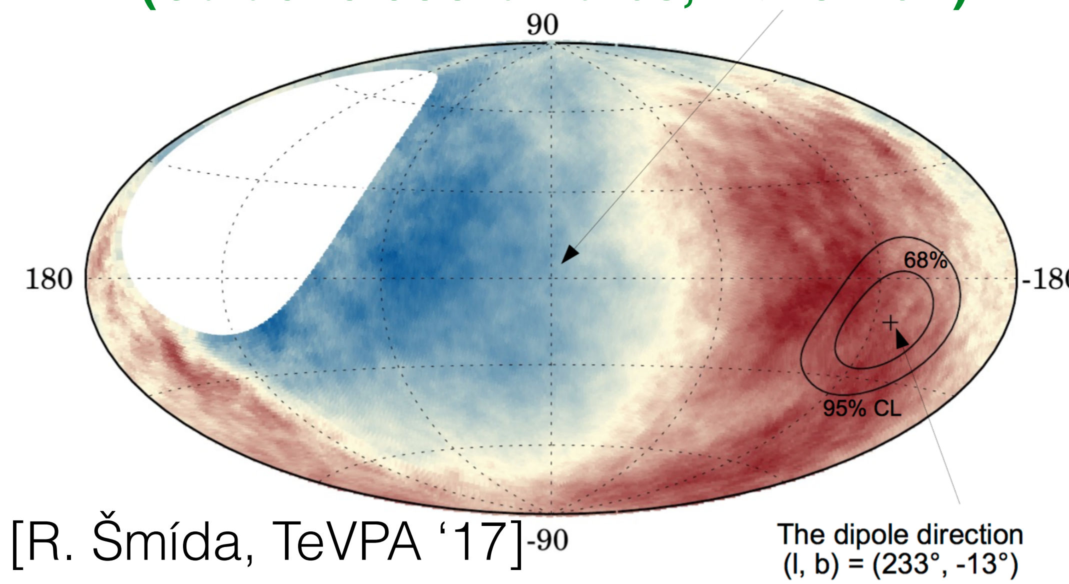
# Clues about UHECR sources?

**TA Hotspot Significance Map (Equatorial coordinates)**



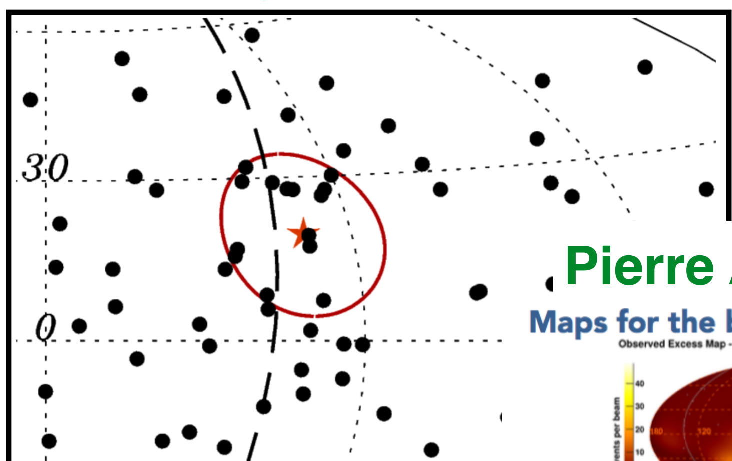

[T. AbuZayyad, TeVPA '17]

**Pierre Auger dipole analysis (Galactic coordinates, E > 8 EeV)**



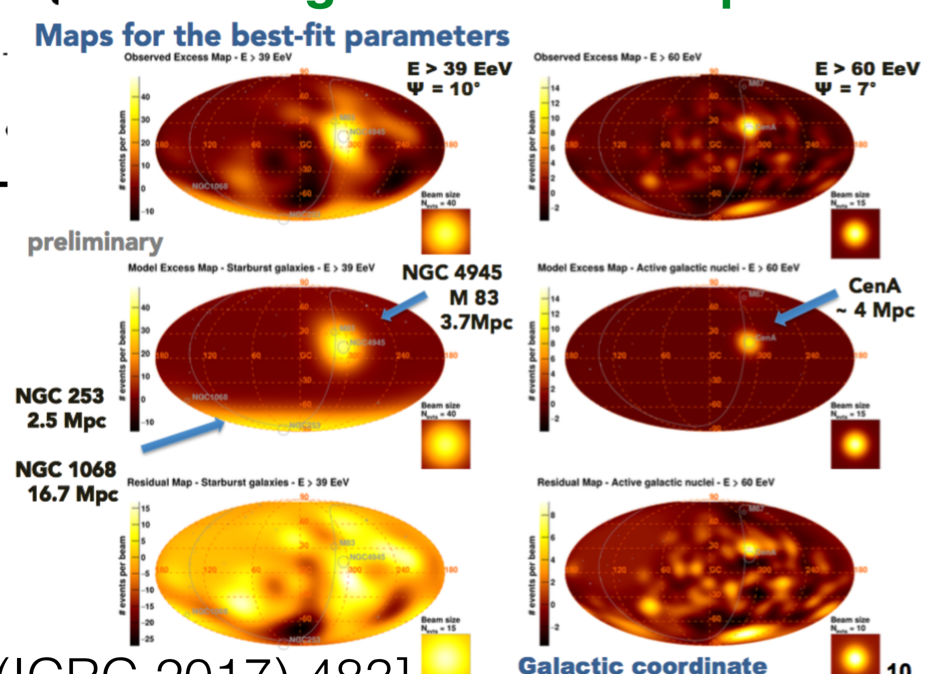

[R. Šmída, TeVPA '17]

**Pierre Auger Cen A analysis**




[arXiv:1411.6111]

**Pierre Auger ICRC 2017 Update**




[PoS (ICRC 2017) 483]

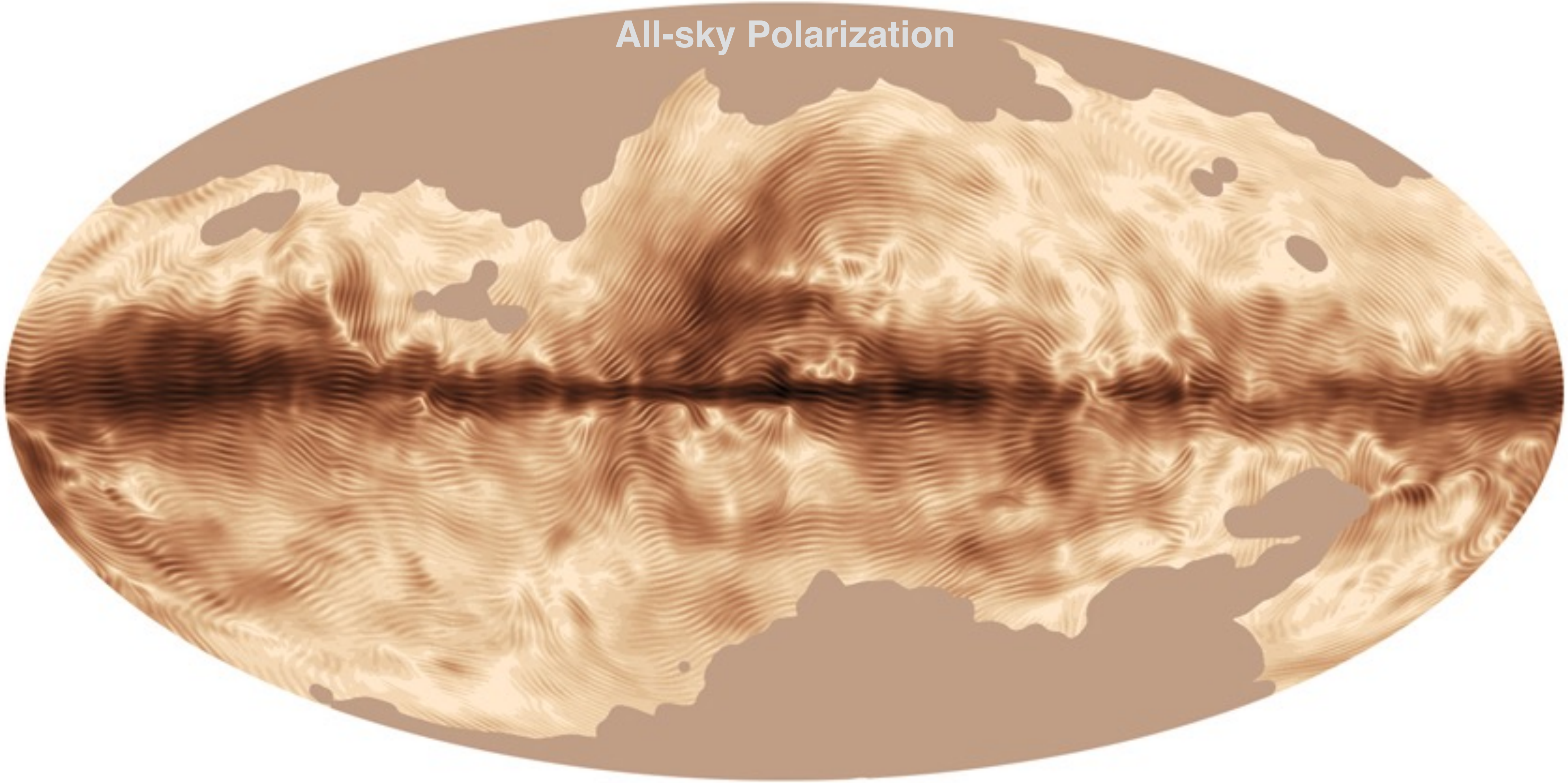
**No significant *a posteriori* correlations but "interesting features" in skymaps**

<u>Xmax fractions:</u>

(mostly) Low *E* protons ⟶ (mostly) High *E* N / Si

# Active and integral component of the Milky Way

**The Galactic Magnetic Field …** **distributes energy from supernovae**
**enables star formation, heats the interstellar medium**
**controls density and distribution of cosmic rays**




[sciencenews.org; ESA / Planck Collab.]

**Understanding the GMF is crucial for answering many astrophysical questions, ranging from potential signatures of dark matter to observations of ultra-high energy cosmic rays (UHECRs)**

# Importance of GMF turbulence

UHECR source identification **must** accurately account for magnetic deflection

The random (turbulence) field is only now beginning to become constrained

- There are models for the field strength but the coherence length is poorly understood

(e.g., [Haverkorn+ 2008 (arXiv:0802.2740); Fletcher+ 2010 (arXiv:1001.5230); Beck, Wielebinski 2013 (arXiv:1302.5663); Beck+ 2016 (arXiv:1409.5120)])

Turbulent smearing introduces non-Gaussian structures in UHECR arrival distributions

[Keivani+ 2014 (arXiv:1406.5249)]

- Implications for modeling deflections in source / correlation studies

Simulation-wide persistent field realization allows different particles traversing same region to experience *the same magnetic field*

- "On-the-fly" random field averages over ensembles, leading to smoothing

# Jansson-Farrar GMF model

**Based on astronomical radio, microwave observations of WMAP7 synchrotron emission and extragalactic rotation measures**

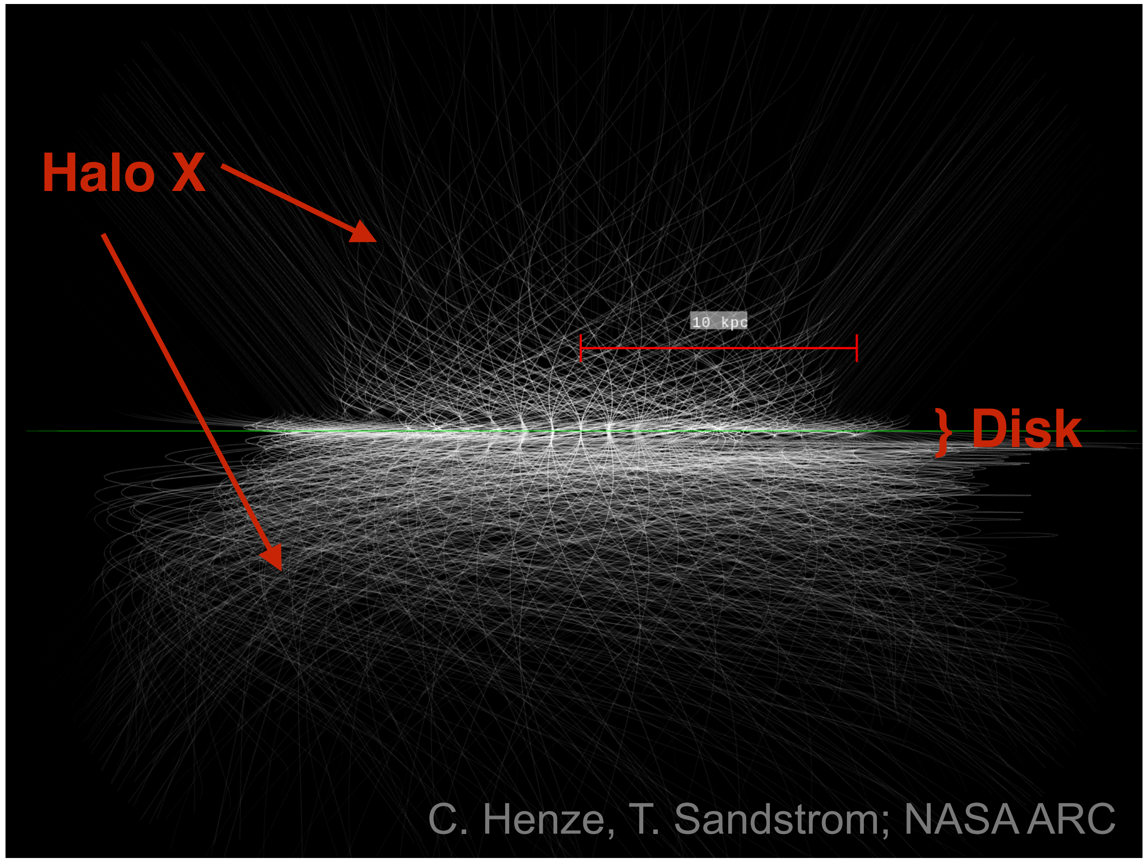
**Coherent + random field descriptions**

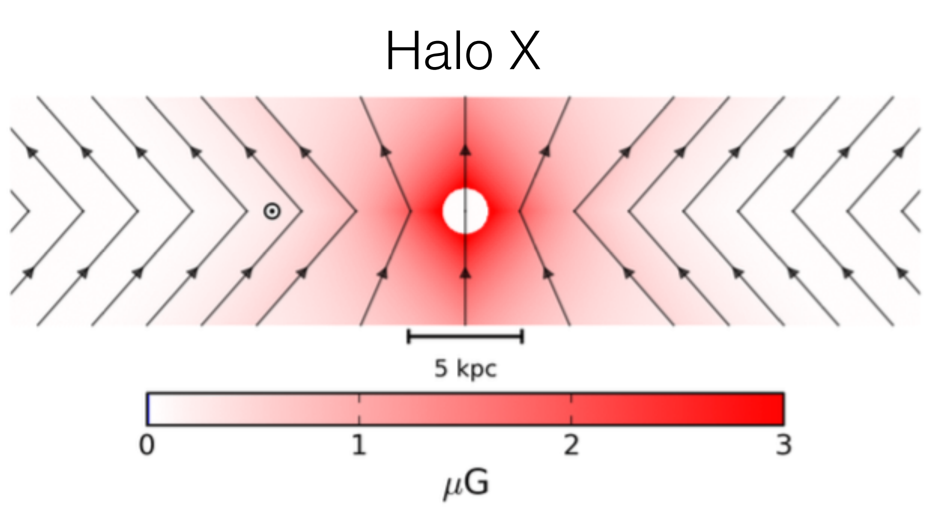
ApJ (2012) 757, 14 [arXiv:1204.3662]

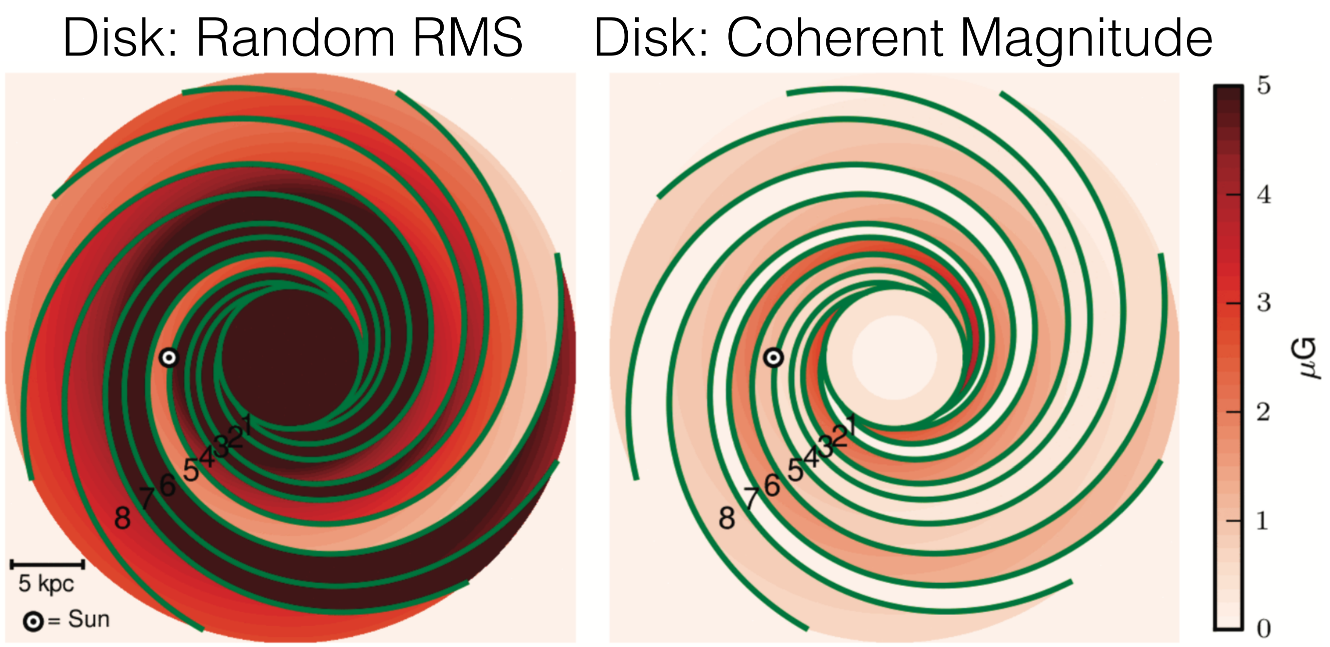
ApJ (2012) 761, L11 [arXiv:1210.7820]

**Halo field: poloidal X and toroidal components**

**Provides better fit to wider range/ types of observations than previous models**

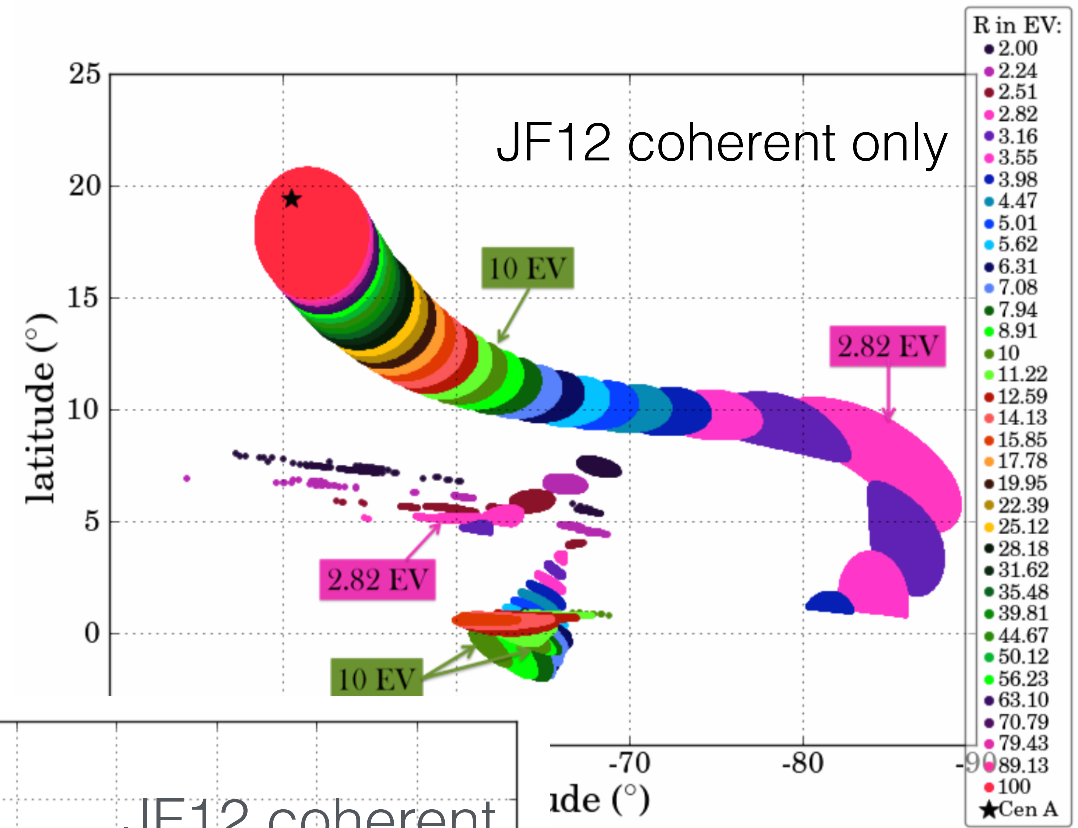


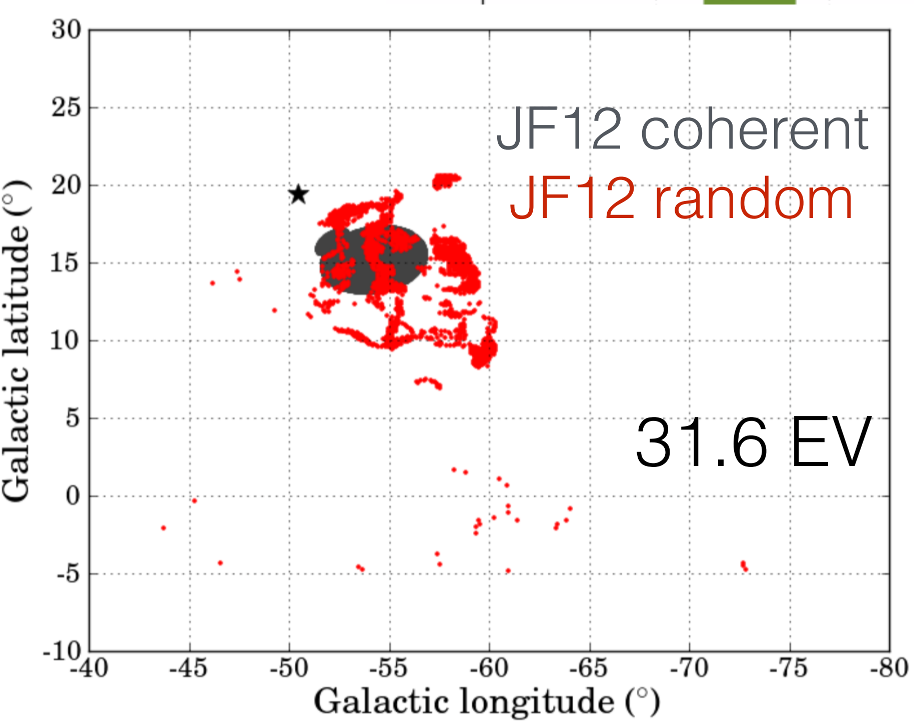



# Prior JF12 field study

Protons backtracked to determine arrival distributions for events from Cen A




[Keivani+ 2014 (arXiv:1406.5249)]

<u>When including turbulence…</u>

- At rigidities of ≃ 10 EV and below, individual deflection magnitudes can be very large and the **arrival direction distributions span a large fraction of the sky.**

- The mean deflection and the RMS spread in arrival directions for a given rigidity varies a few degrees from one realization to another. These **properties depend much more on the rigidity of the CR than on the specific realization** of the random field.

- The **distribution of arrival directions has considerable structure**: it has hot-spots and edges, and would not typically be well-described by a 2-D gaussian.

**How do these results change with more realistic turbulence realizations, more rigidities, and generalized source directions?**

# This work

*CRT* - public propagation code [Sutherland+ 2010 (arXiv:1010.3172)]

3 turbulence realizations with coherence lengths $L_{coh}$ bracketing expected values (e.g., [BW 2013])
100 pc, 30 pc, 30 pc w/ different random seed

Backtrack protons using HEALPix resolution 11 map ($5.1 \times 10^{7}$ directions)

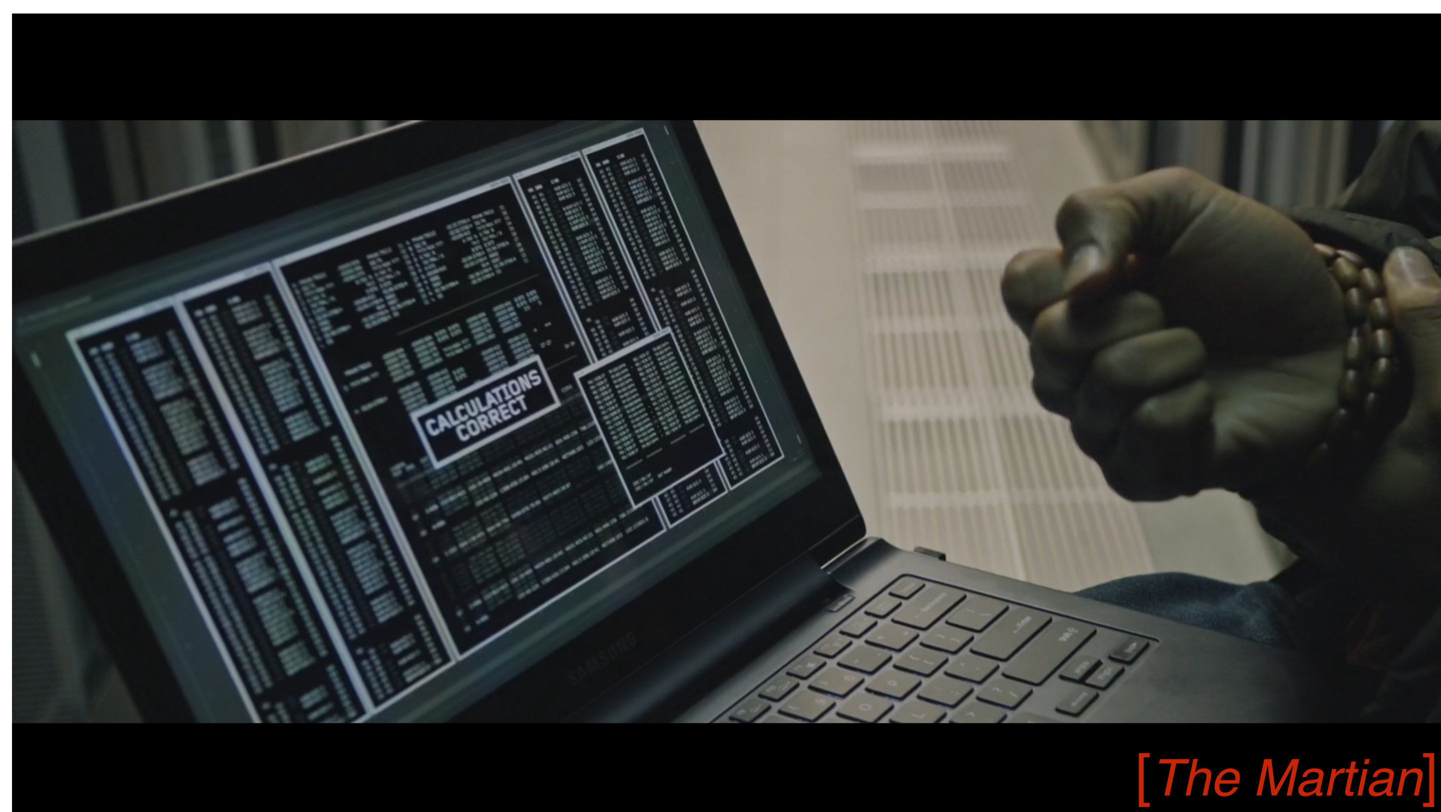
Wide range of rigidities $R \equiv E / Z$

| log(*R* / EV) | 18.0 | 18.1 | 18.2 | 18.3 | 18.4 | 18.5 | 18.6 | 18.7 | 18.8 | 18.9 | 19.0 | 19.2 | 19.4 | 19.5 | 19.6 | 19.8 | 20.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *R* / EV | 1.0 | 1.3 | 1.6 | 2.0 | 1.5 | 3.2 | 4.0 | 5.0 | 6.3 | 7.9 | 10.0 | 15.8 | 25.1 | 31.6 | 39.8 | 63.1 | 100 |

Variety of selected "source" directions
-isotropic, radio galaxies
[van Velzen+ 2012 (arXiv:1206.0031);
He+ 2016 (arXiv:1411.5273)]

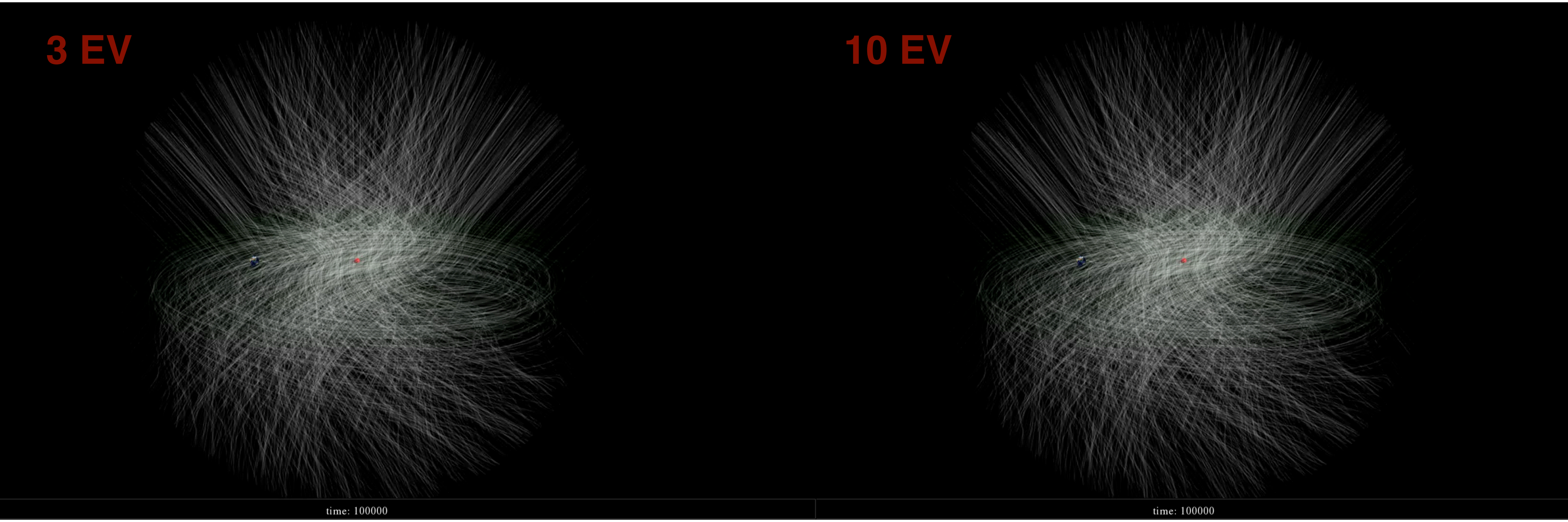
**Pleiades resources provided by NASA High-End Computing (HEC) Program through the NASA Advanced Supercomputing (NAS) Division at Ames Research Center**

**Special acknowledgement to Chris Henze, Tim Sandstrom @ NAS for trajectory movies**




[*The Martian*]

# Example particle trajectories




[C. Henze, T. Sandstrom; NASA ARC]

**Higher rigidity particles reaching Earth confined within "tighter beam"**

**Lower rigidity particles frequently "turn on a parsec", wrap around Earth**

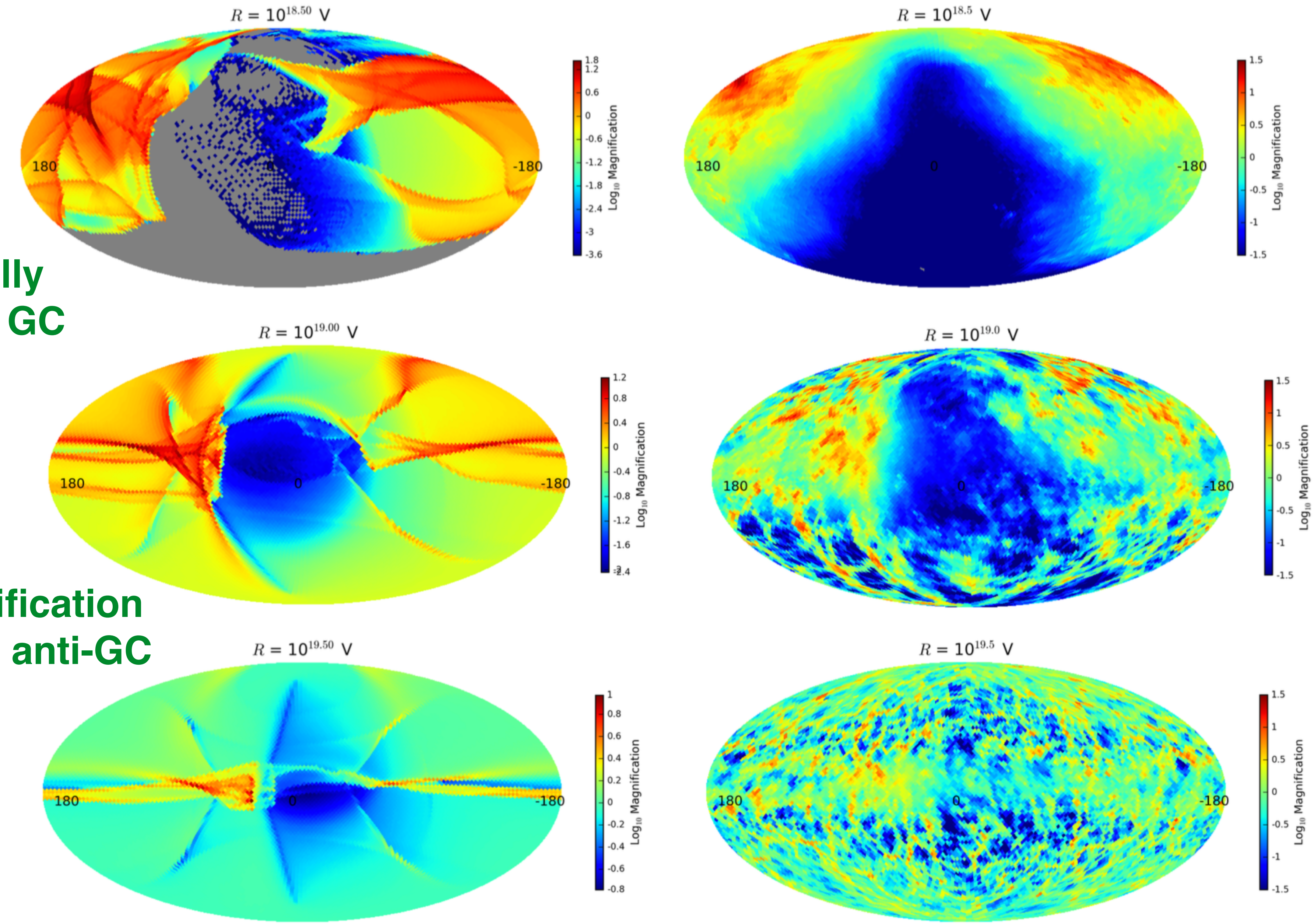
# Comparison of magnification properties

$$M = \frac{N_{events}\ (B)}{N_{events}\ (B=0)}$$

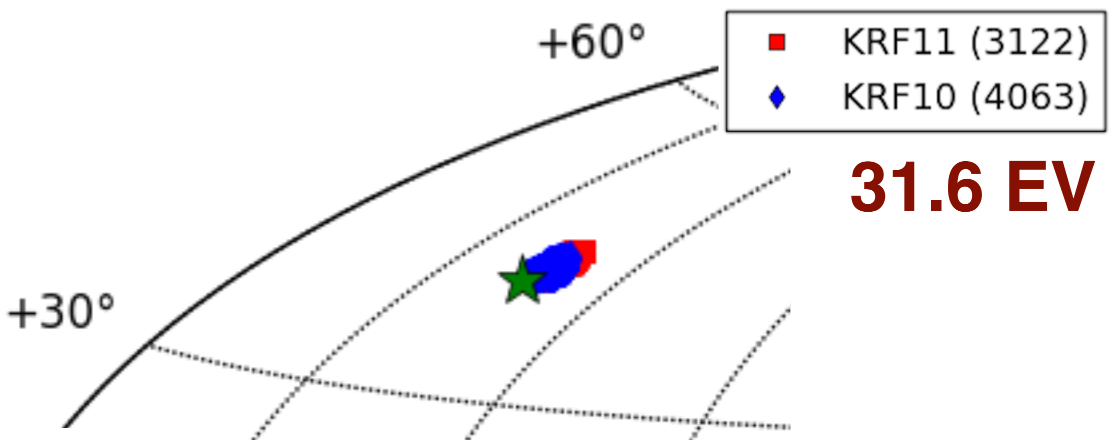
**JF12 Coherent only** | **JF12 Coherent + 100 pc Random**

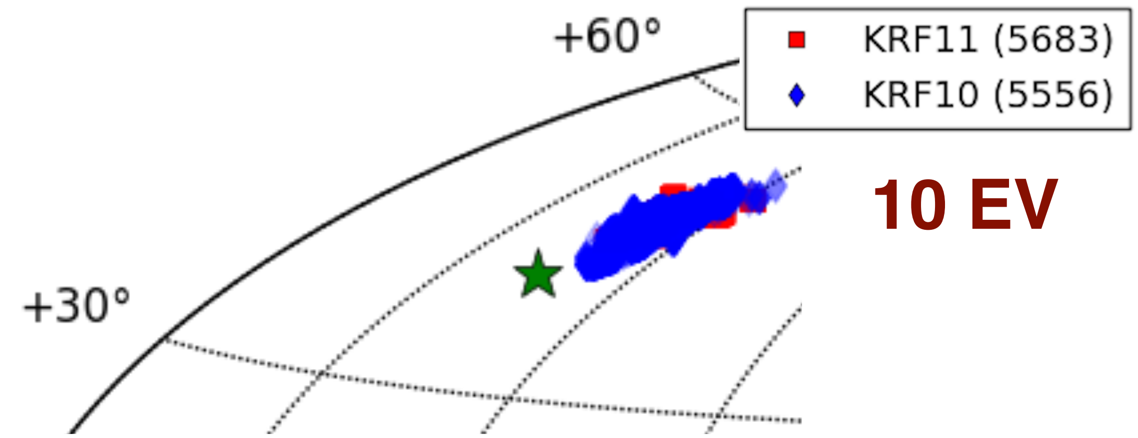
**Sources essentially invisible towards GC**

**Significant magnification towards northern anti-GC**

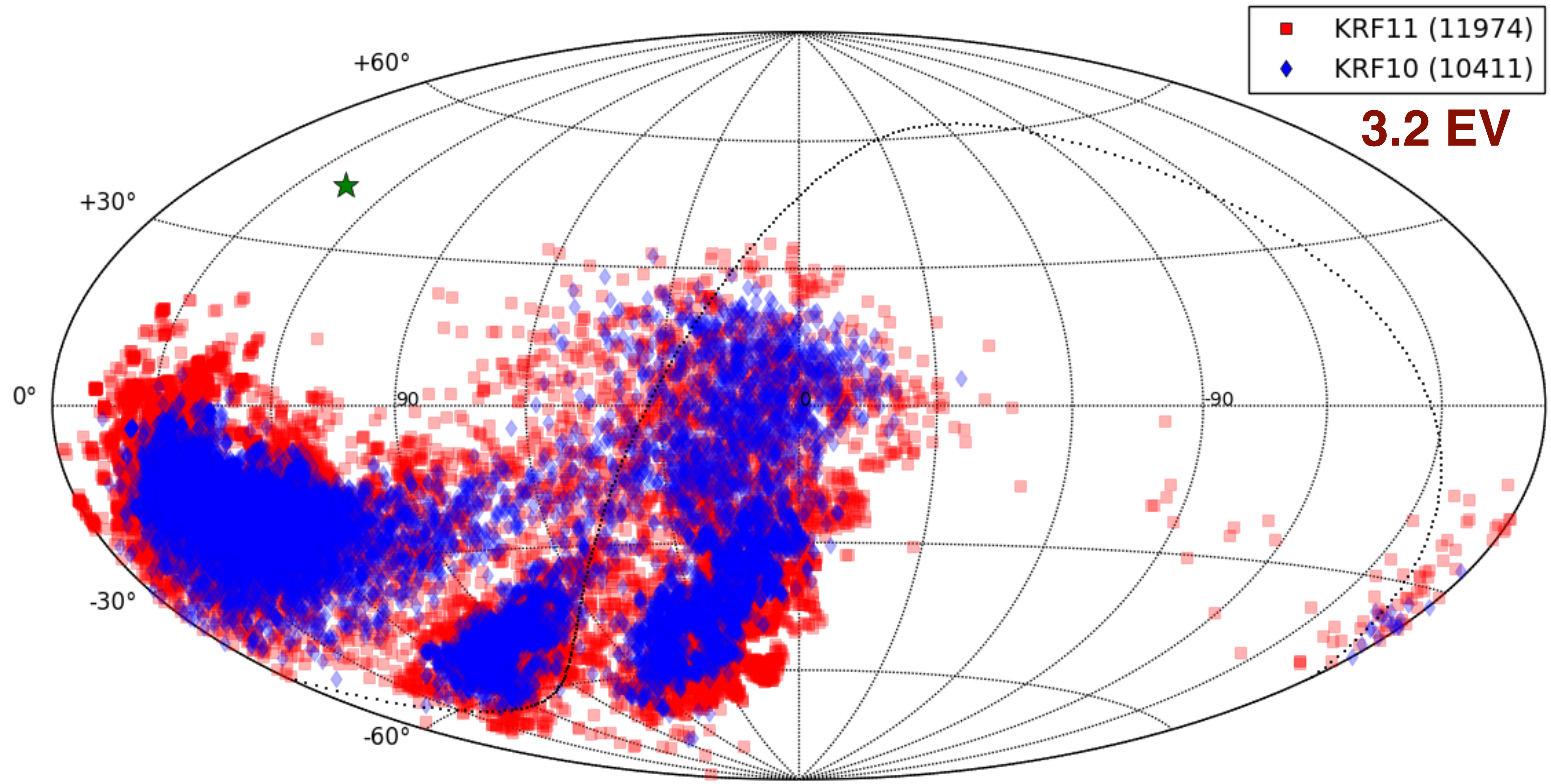


# Comparing both 30 pc fields

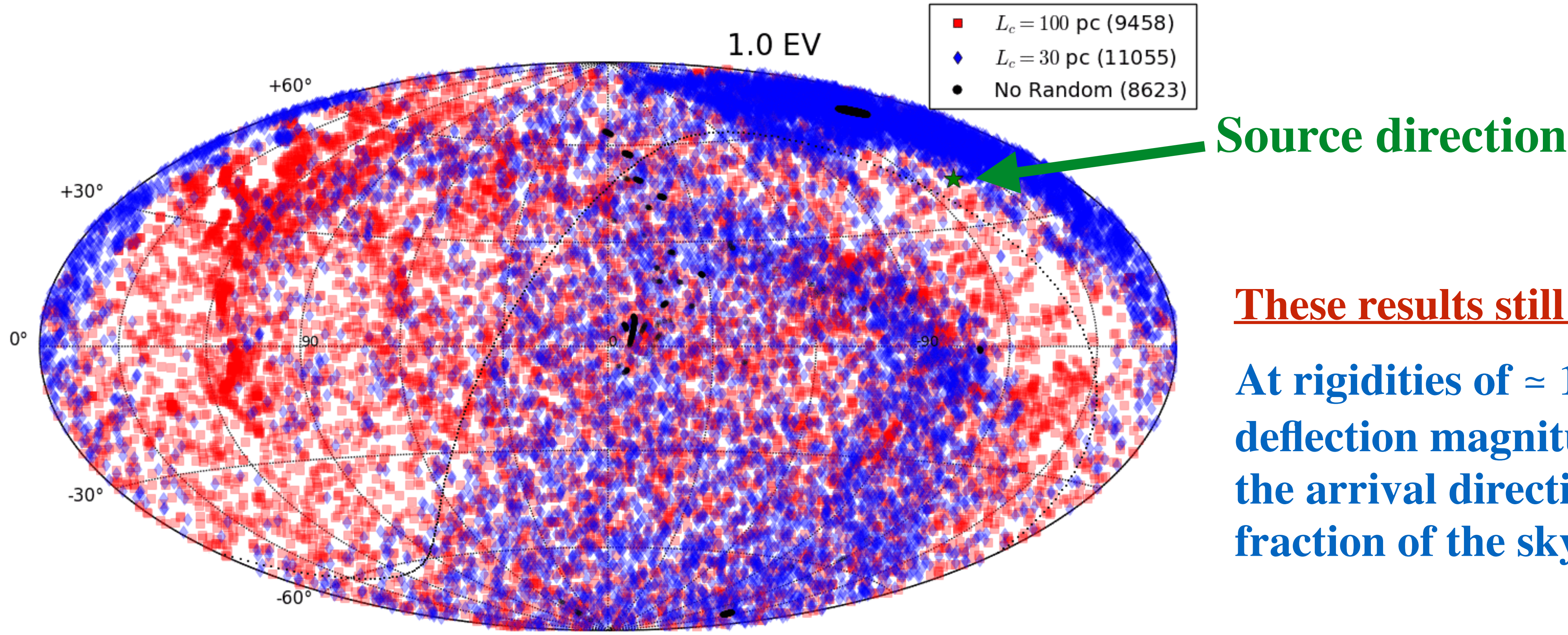



**Relative insensitivity to specific realizations across rigidity / source still seen**



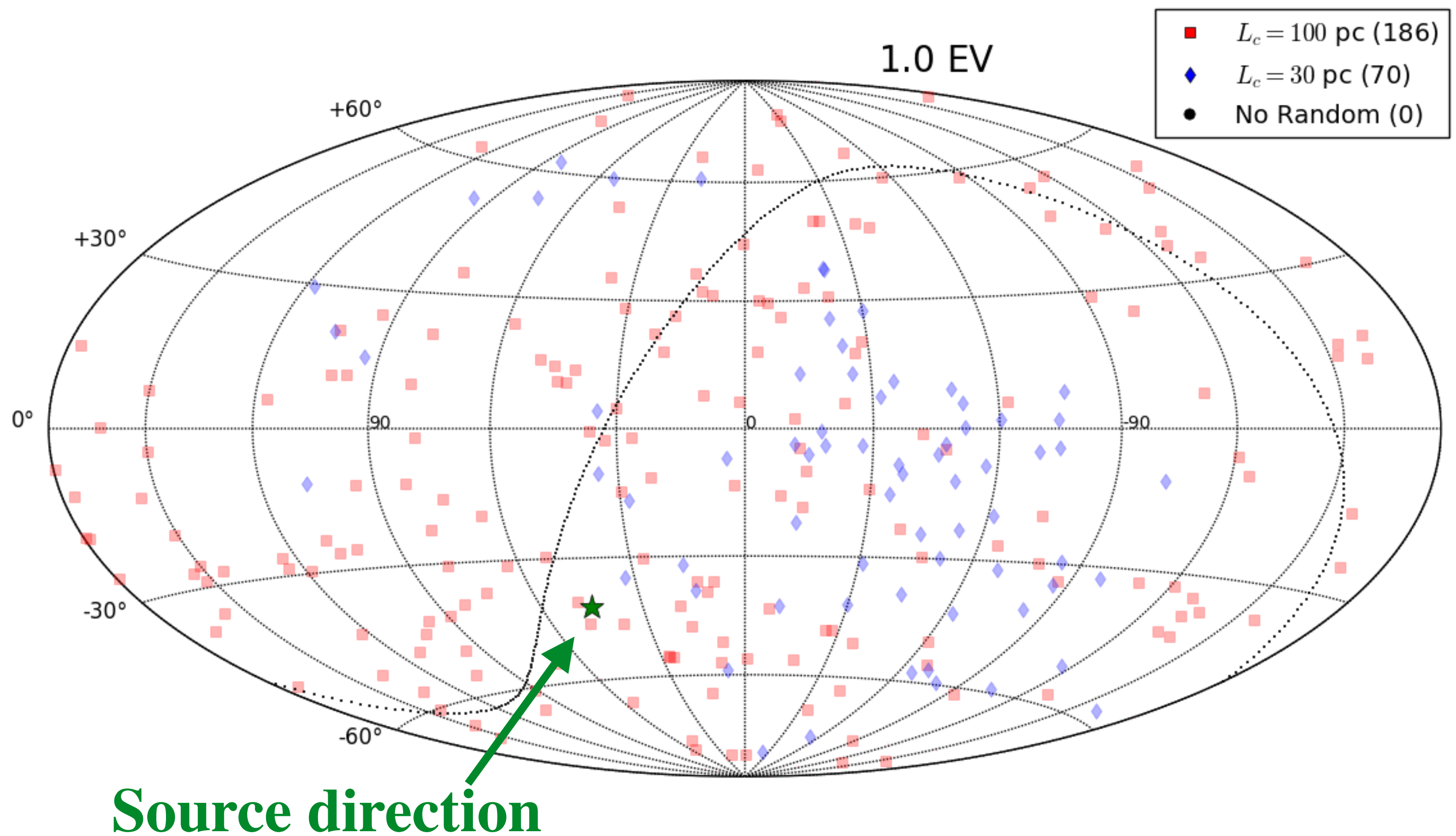
# Comparing various random field effects




**These results still hold:**

**At rigidities of ≃ 10 EV and below, individual deflection magnitudes can be very large and the arrival direction distributions span a large fraction of the sky.**

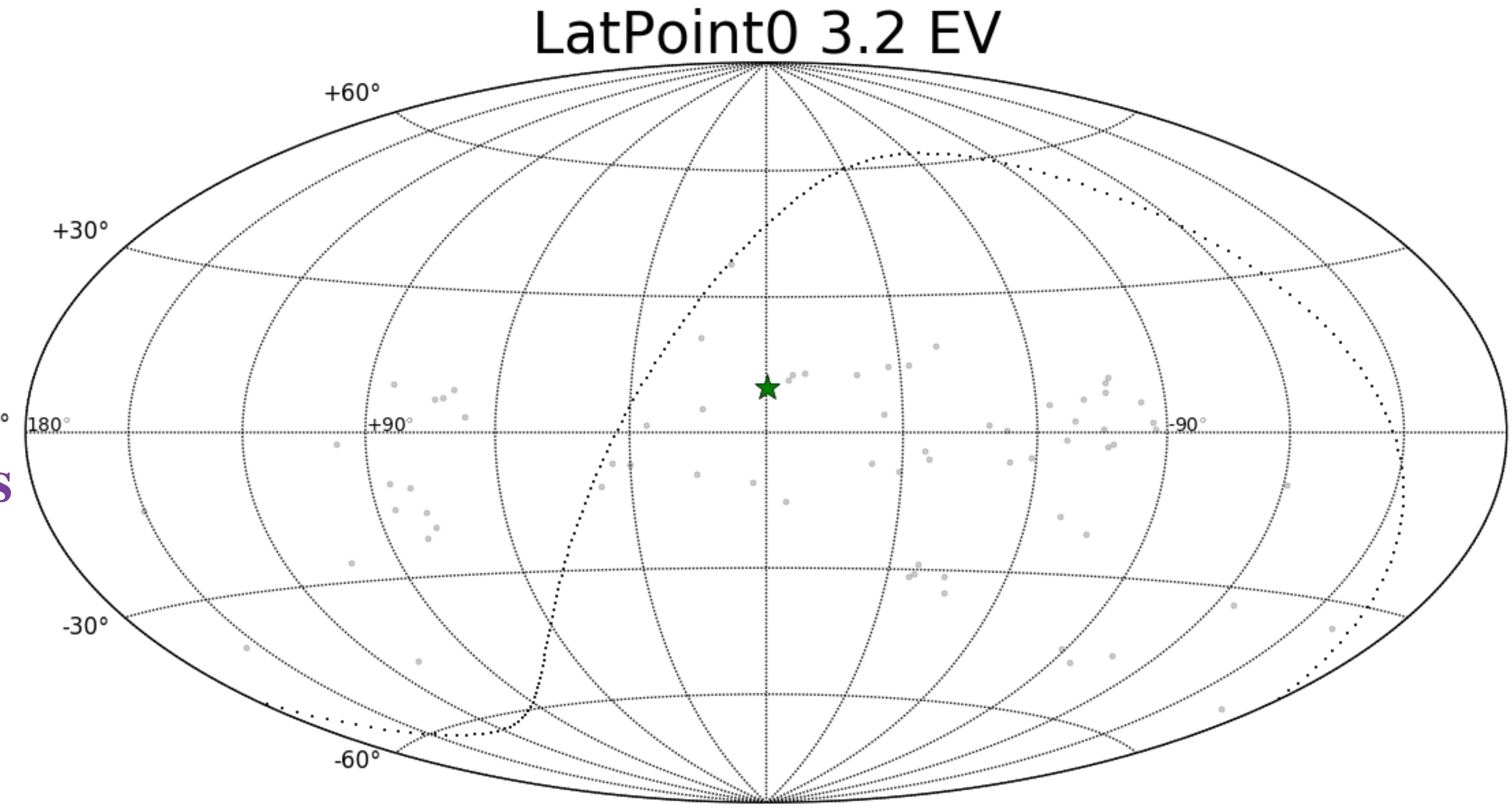
**The distribution of arrival directions has considerable structure: it has hot-spots and edges, and would not typically be well-described by a 2-D gaussian.**




**New:**

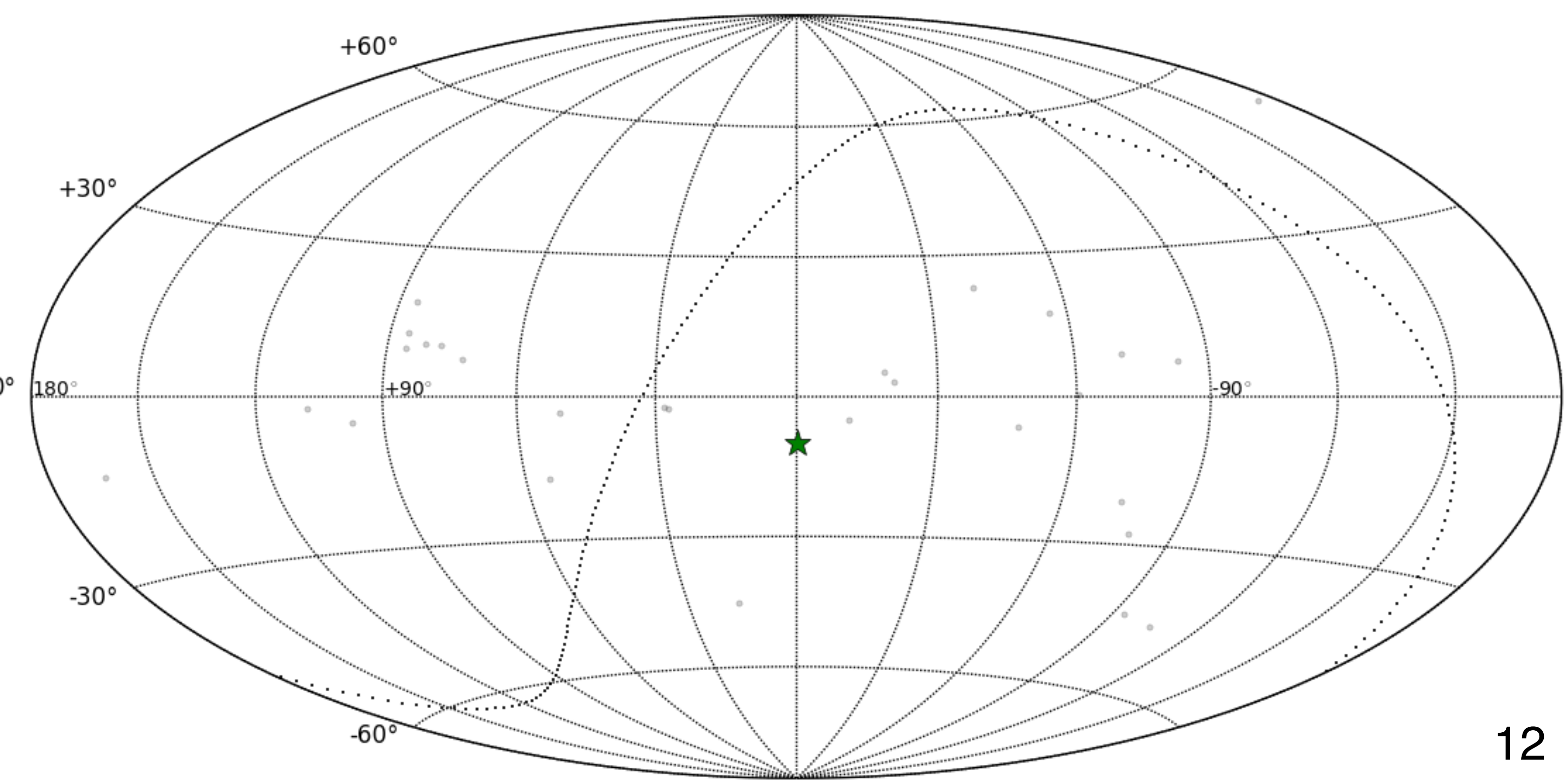
**Wide variation in distribution behavior (extent, $N_{evt}$, etc.) for different source directions**

# Scans along Galactic latitude




**The distribution of arrival directions has considerable structure: it has hot-spots and edges, and would not typically be well-described by a 2-D gaussian.**

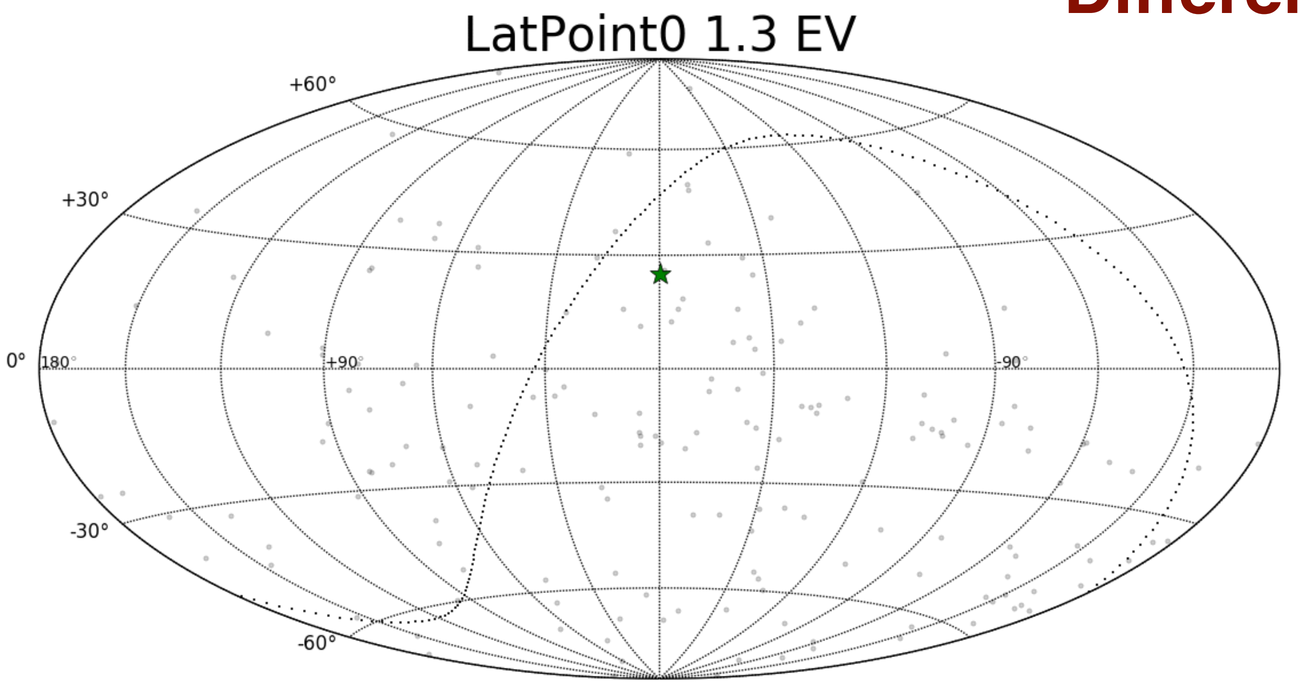
***b* = ±10°**

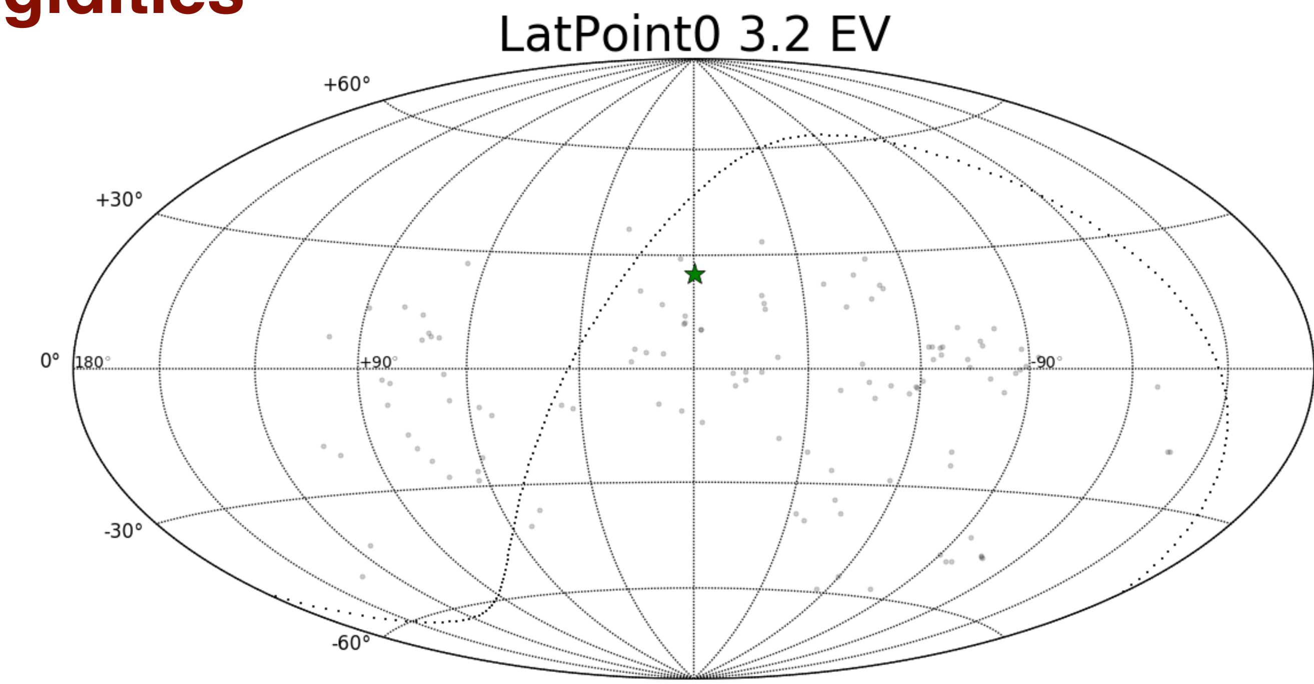


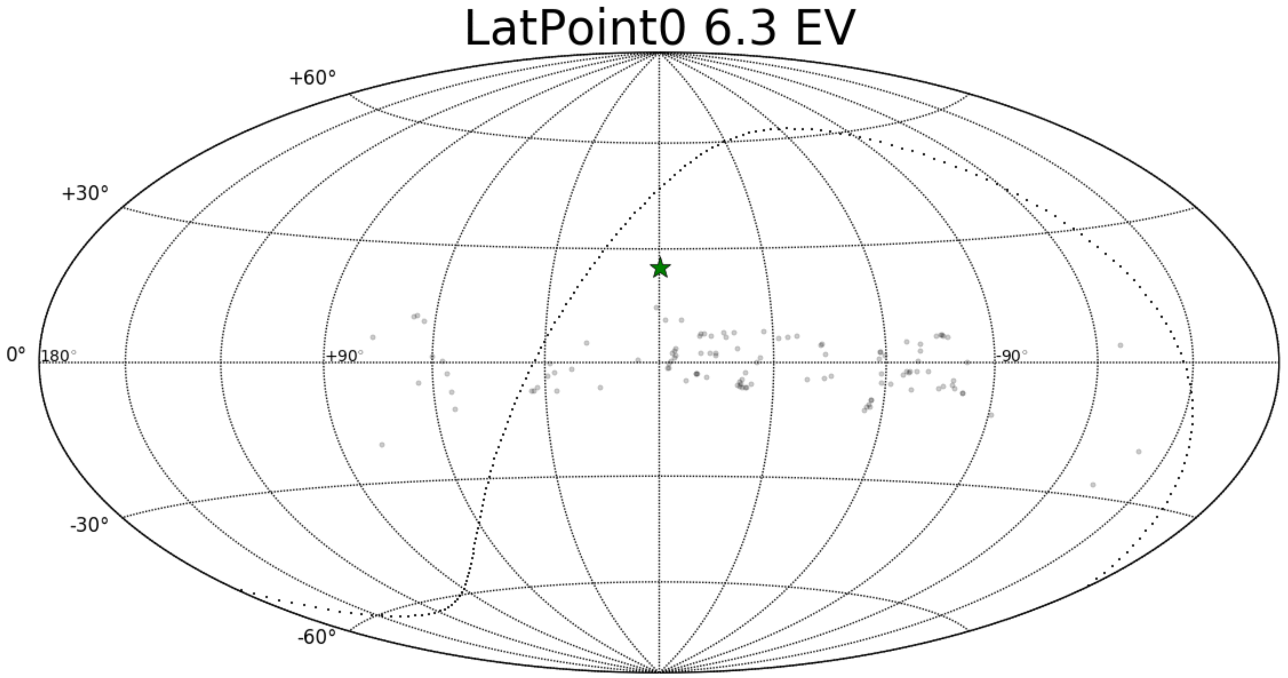

**Wide variation in distribution behavior (extent, $N_{evt}$, etc.) for different source directions**

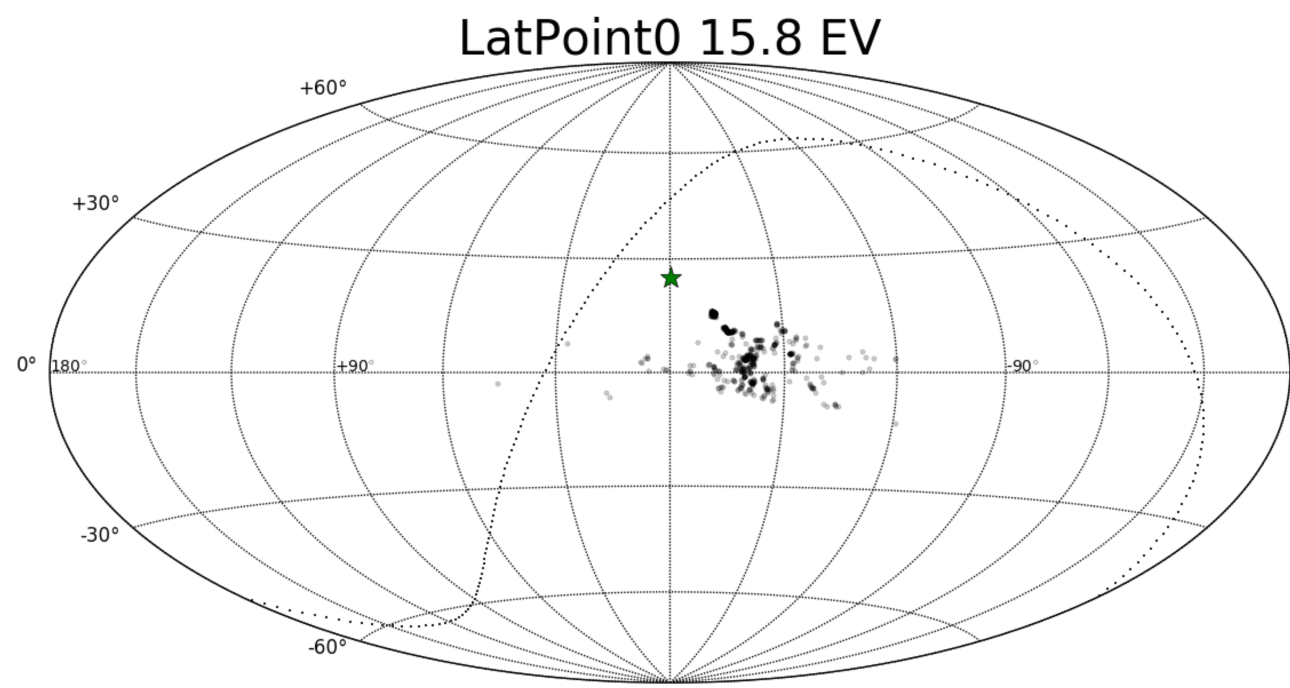
# Scans along Galactic latitude

**Different rigidities**



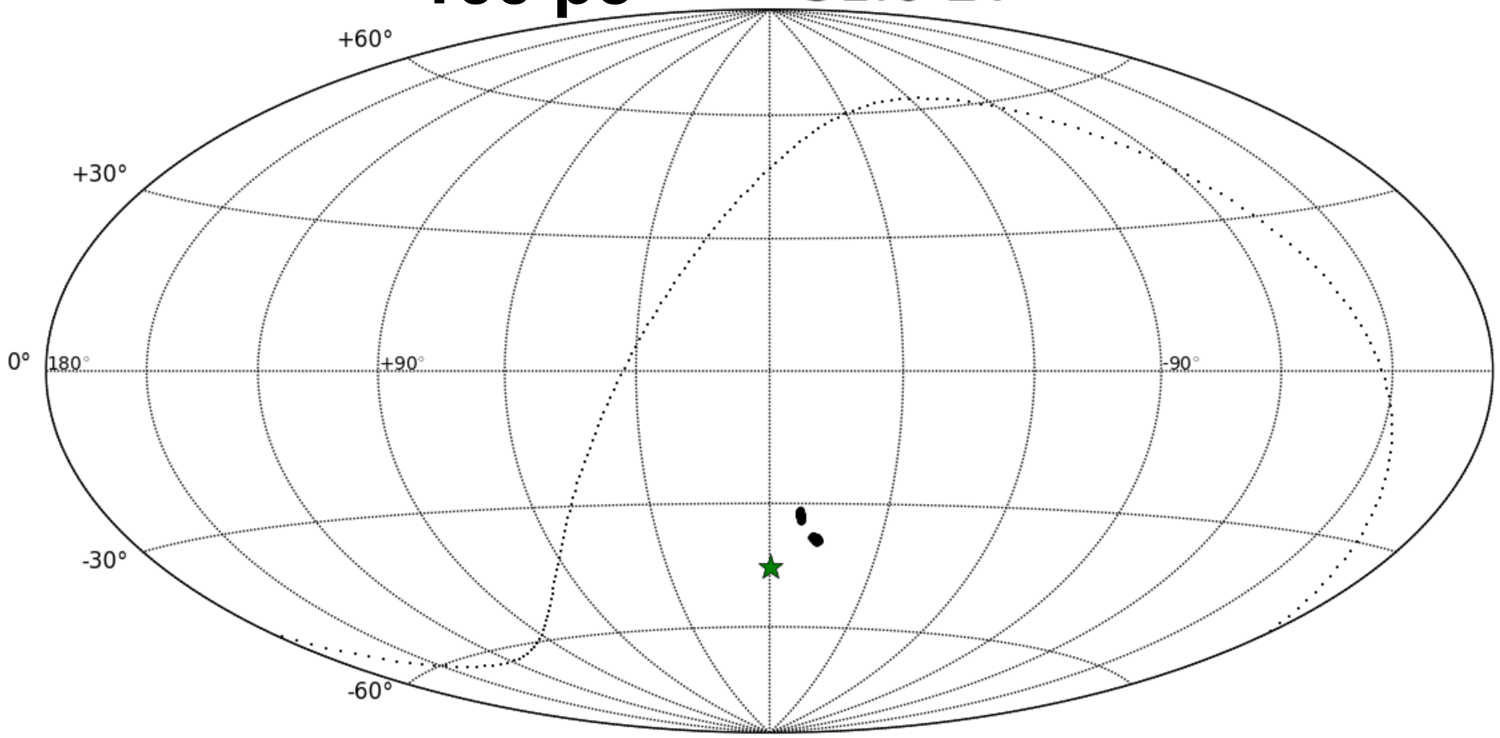



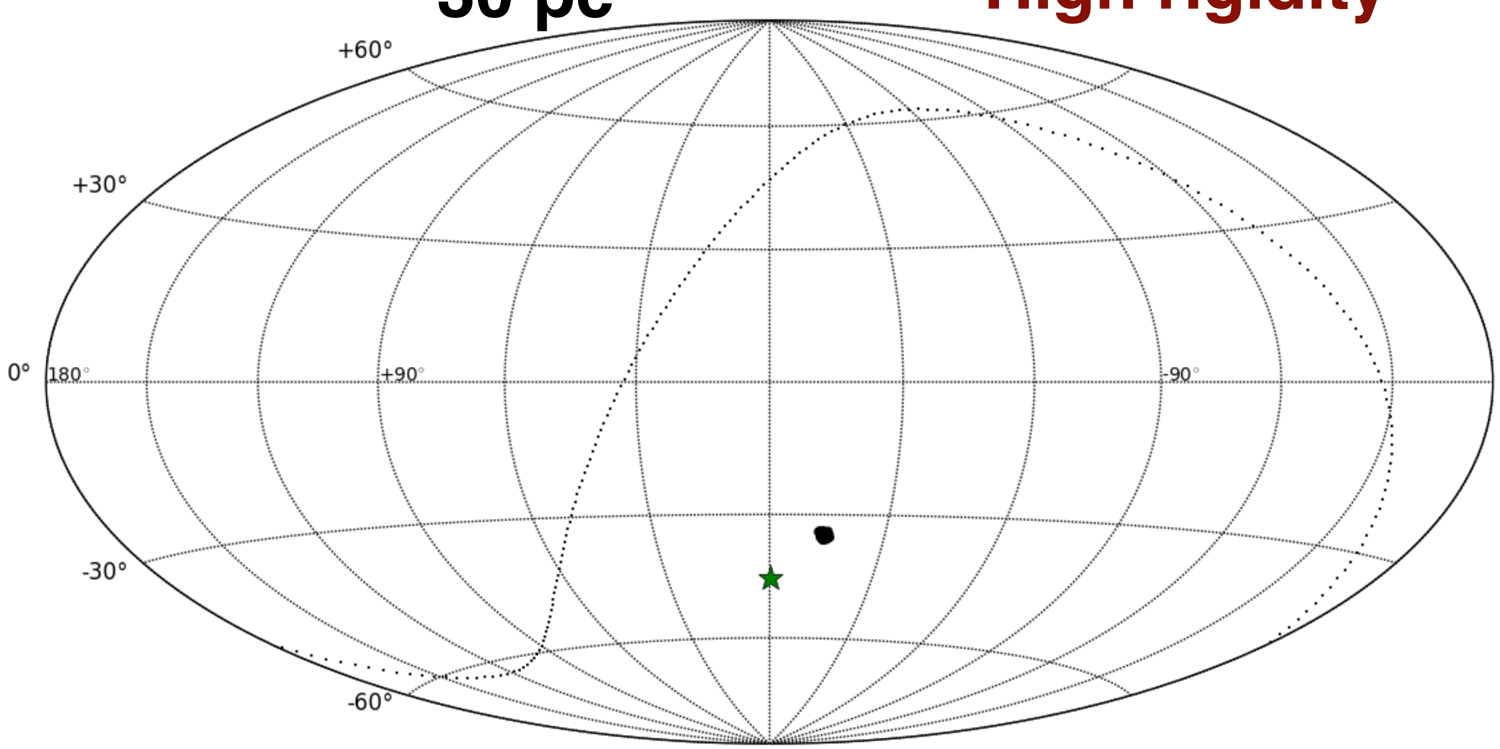
# Scans along Galactic latitude

**100 pc** 31.6 EV




**Different fields**
**High rigidity**

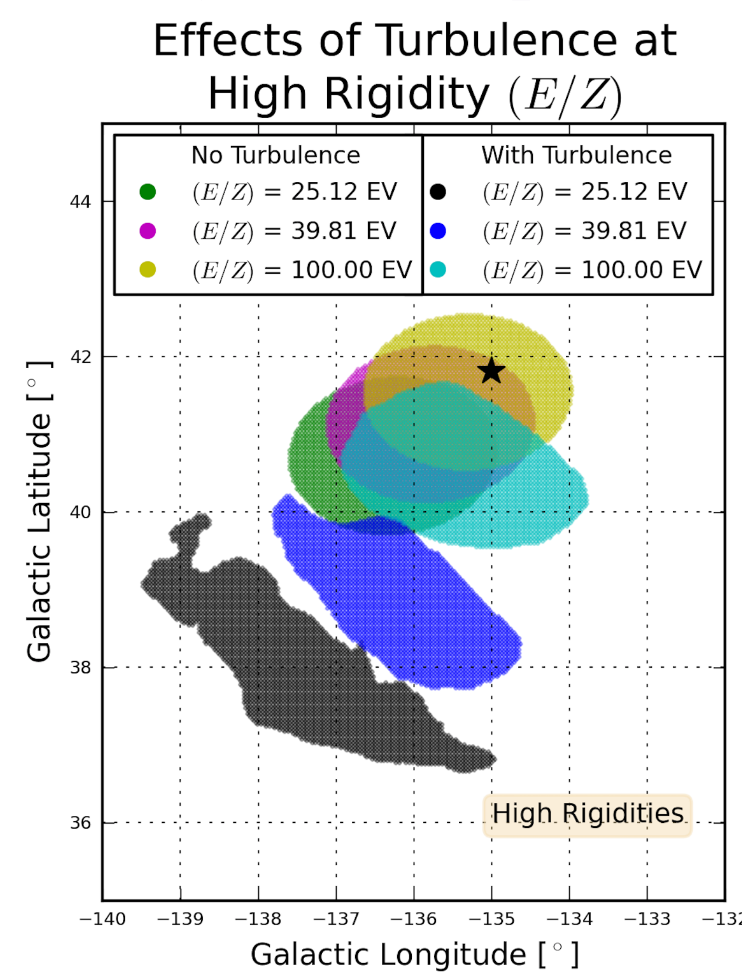
**30 pc**




**Distributions behave similarly even for fields with $L_{coh}$ bracketing expected values**

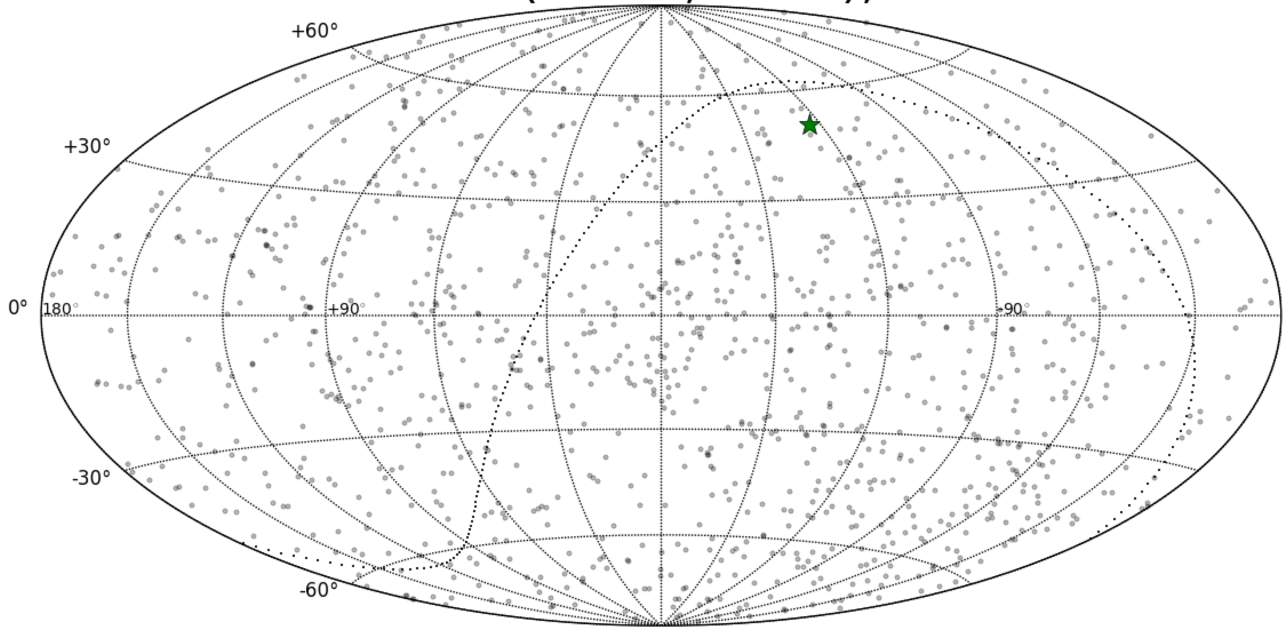
**Field acts as magnetic spectrometer but direction / magnitude depends on source**

**Distributions still not accurately described by Gaussian p.d.f.**

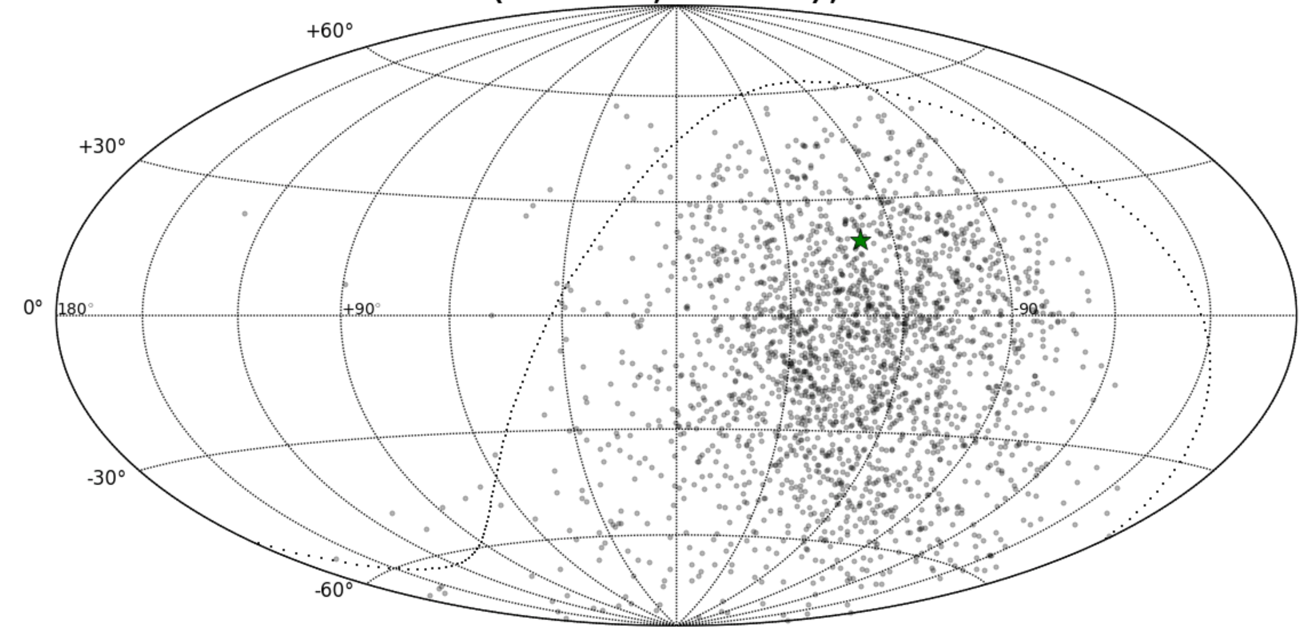


# Radio galaxies, $L_{coh}$ = 30 pc

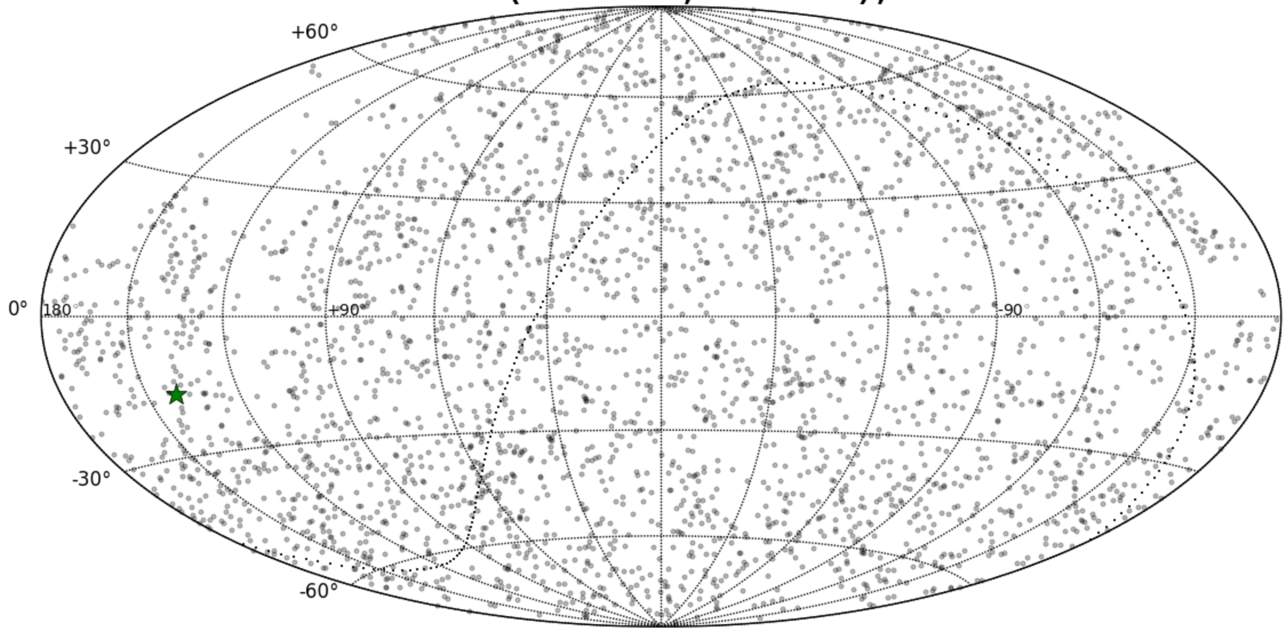
NGC4782 (-55.9°, 50.3°), 1.0 EV



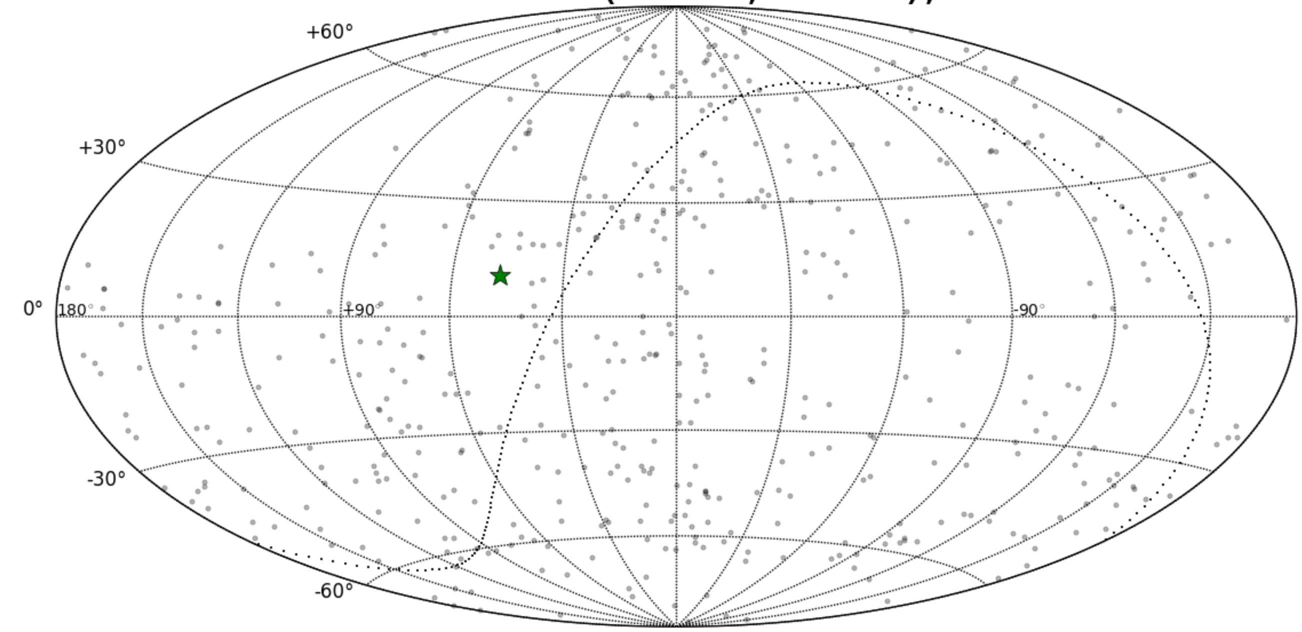

CENA (-50.5°, 19.4°), 1.0 EV




UGC1841 (140.2°, -16.8°), 1.0 EV




CGCG114-025 (47.0°, 10.5°), 1.0 EV



# Summary

Extension of the work in Keivani+ 2014 to include more realistic realizations and rigidities, investigate many possible source directions

**Dramatic variation in arrival distribution behavior as function of source position, in addition to confirming the prior results**

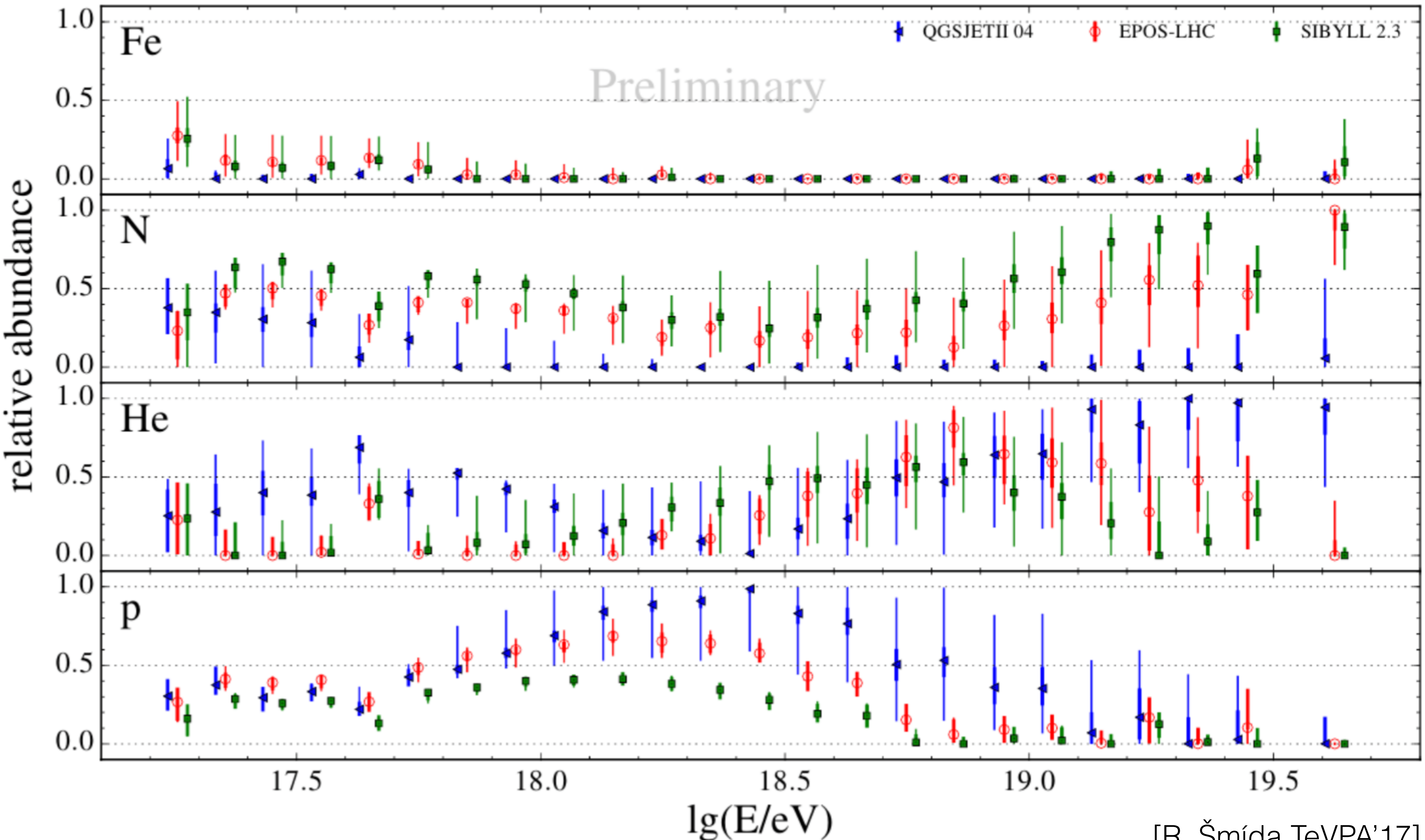
- At rigidities of ≃ 10 EV and below, individual deflection magnitudes can be very large and the **arrival direction distributions span a large fraction of the sky.**

- The mean deflection and the RMS spread in arrival directions for a given rigidity varies a few degrees from one realization to another. These **properties depend much more on the rigidity of the CR than on the specific realization** of the random field.

- The **distribution of arrival directions has considerable structure**: it has hot-spots and edges, and would not typically be well-described by a 2-D gaussian.

**At low rigidities, Earth becomes blind to sources toward the Galactic center, whereas strong magnification occurs toward the northern anti-GC**

**These results have strong implications for interpretation of UHECR arrival direction distributions**




[R. Šmída TeVPA’17]