The Galactic Magnetic Field

and Cosmic Ray propagation

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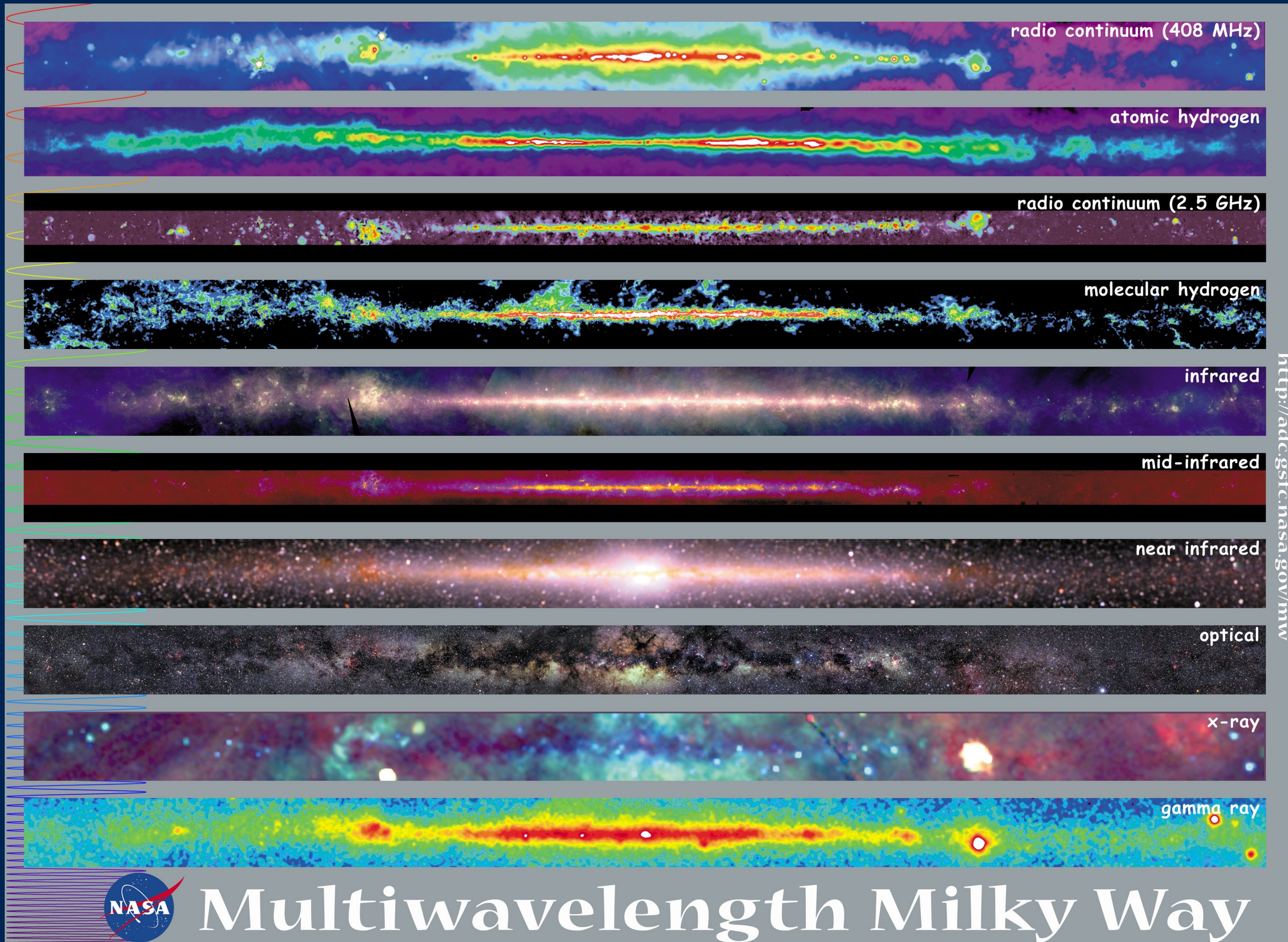
Off the Beaten Track Dark Matter…
ICTP, Apr 15, 2015

Ronnie Jansson, GRF, Waelkens & Ensslin (2009) — *all models fail*
RJ & GRF, Ap.J. 757, 14 (2012) — *JF12 coherent & striated GMF*
RJ & GRF, Ap.J.Lett. 761, L11 (2012) — *JF12 random GMF & n_{cre}*
GRF Comptes Rendu Physique (2014) — *review*
In prep: D. Khurana & GRF; N. Awal & GRF; GRF & M. Sutherland

What you see depends on how you look…



But how can you look,
to “see” a (distant) magnetic field
and reconstruct it, in 3D?

Jansson-Farrar strategy: constrain GMF by its effects

Faraday Rotation Measures of ~40,000 quasars $\sim \int_z^\infty dz\, n_e(\mathbf{x})\, B_{||}(\mathbf{x})$

Polarized synchrotron emission from WMAP ~2x40,000 pixels $\sim \int_z^\infty dz\, n_{cre}(\mathbf{x})\, B_\perp^2(\mathbf{x})$

Complementary!

1st Question: How should we model the magnetic field?

No (accepted) theory for galactic magnetogenesis exists

⬇

No obvious model (functional form) to use

⬇

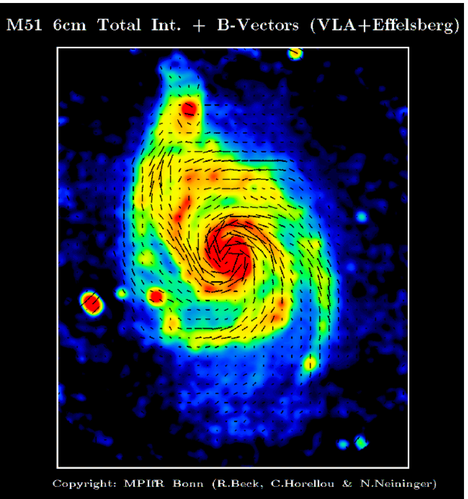
Infinite choice of models… :-(

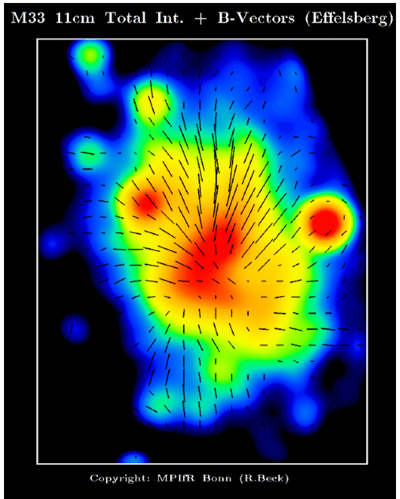
GMF modeling

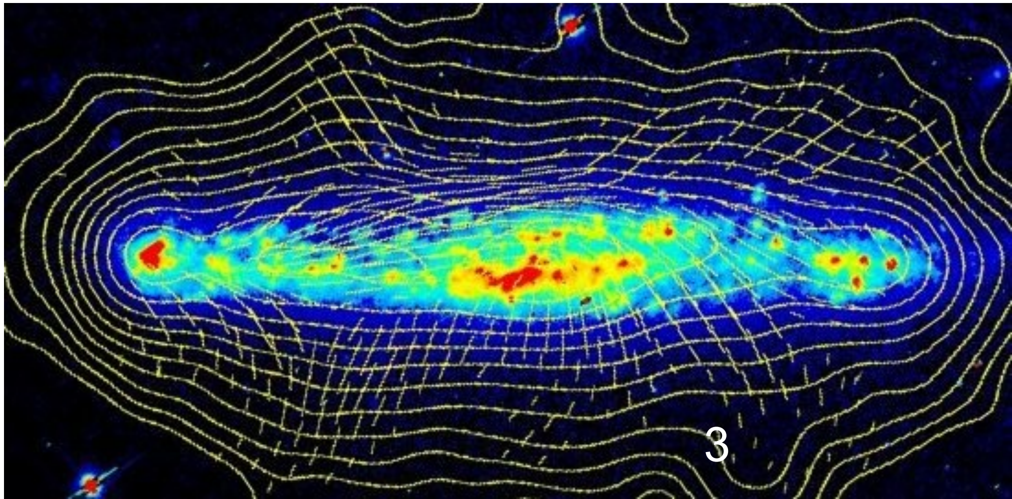
Question: How should we model the magnetic field?

Theoretical constraint: magnetic flux is conserved!

Observational guidance: external galaxies

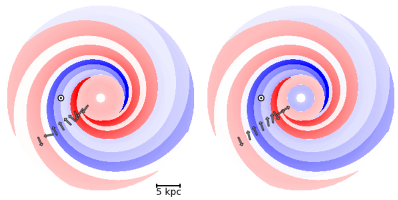




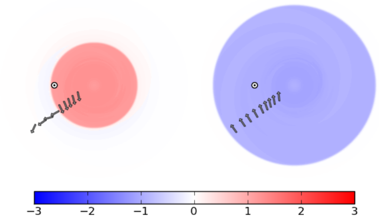


Coherent Field Model

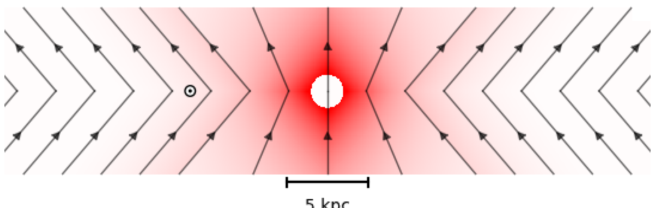
- **Three large-scale components**, each divergence-less
  - Spiral disk (geometry from Brown+2007 ~ NE2001)



  - Toroidal halo field

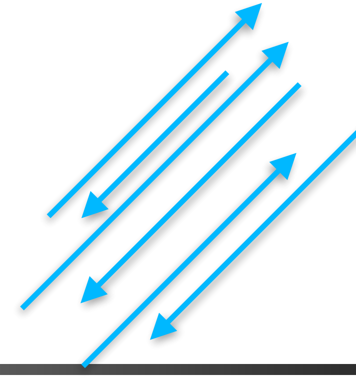


  - Poloidal out-of-plane field:

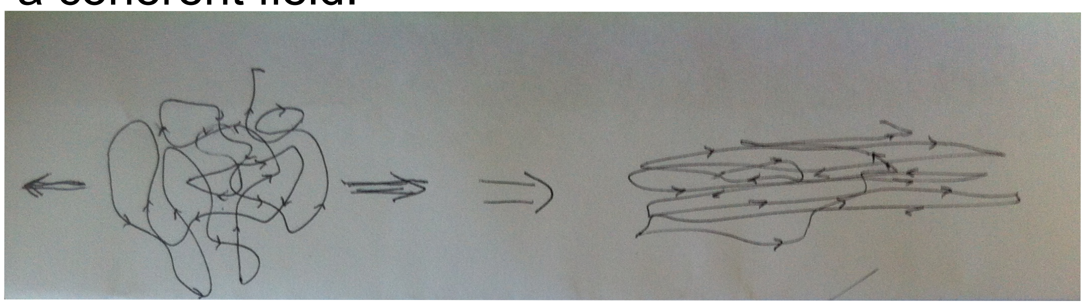


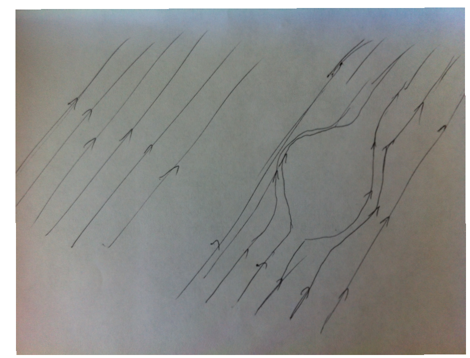
- **21 free parameters:**
  - 10 field strengths
  - thickness of the disk, scale height of halo, radial extent, …
  - geometry of poloidal component
  - striation parameter

“Striated” Component



- Average **B** is 0, but has a preferred orientation.
- Contributes to Polarized Synchrotron emission, but not to RMs.
- Produced by stretching or compressing a random field, or evacuating a bubble in a coherent field.





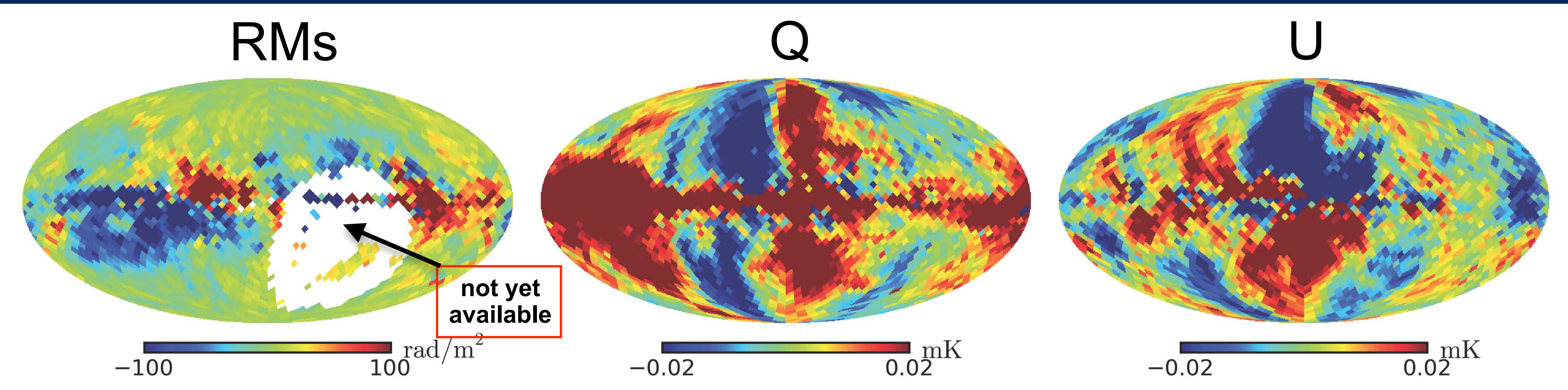
- Fitting only Polarized Synchrotron, ∃ degeneracy between striated field & rescaling n_{cre}.

  $n_{cre} = \alpha\, n_{cre}$; $B^2_{stri} \equiv \beta\, B^2_{reg}$ ⇨ emissivity increases by $\gamma = \alpha\,(1 + \beta)$;

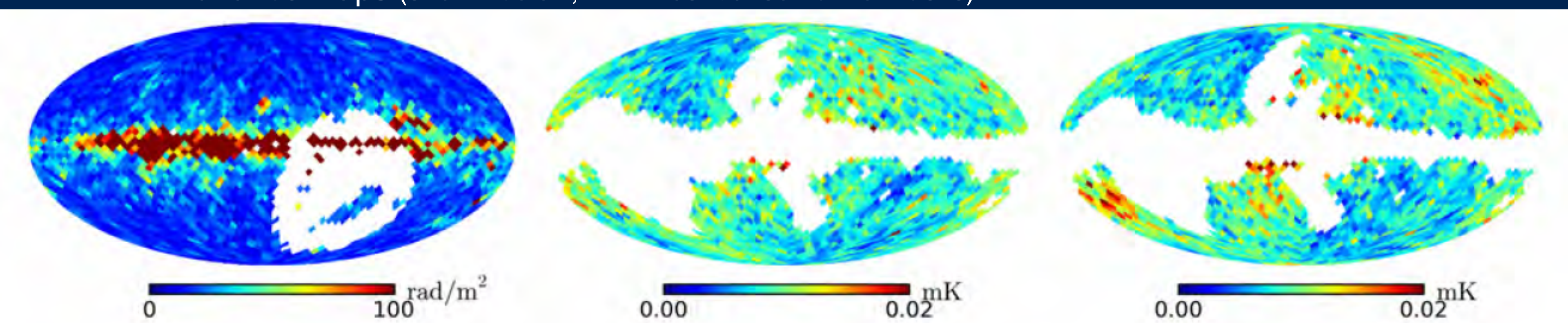
  JF12 fit to Q,U,RM data => $\gamma = 2.8$

  - striated field could be up to 1.4 x coherent field, or
  - need to rescale n_{cre} by a factor up to 2.8, or a combination of both.
- Fitting for the fully random field using total synchrotron intensity allows α and β to be separately determined.

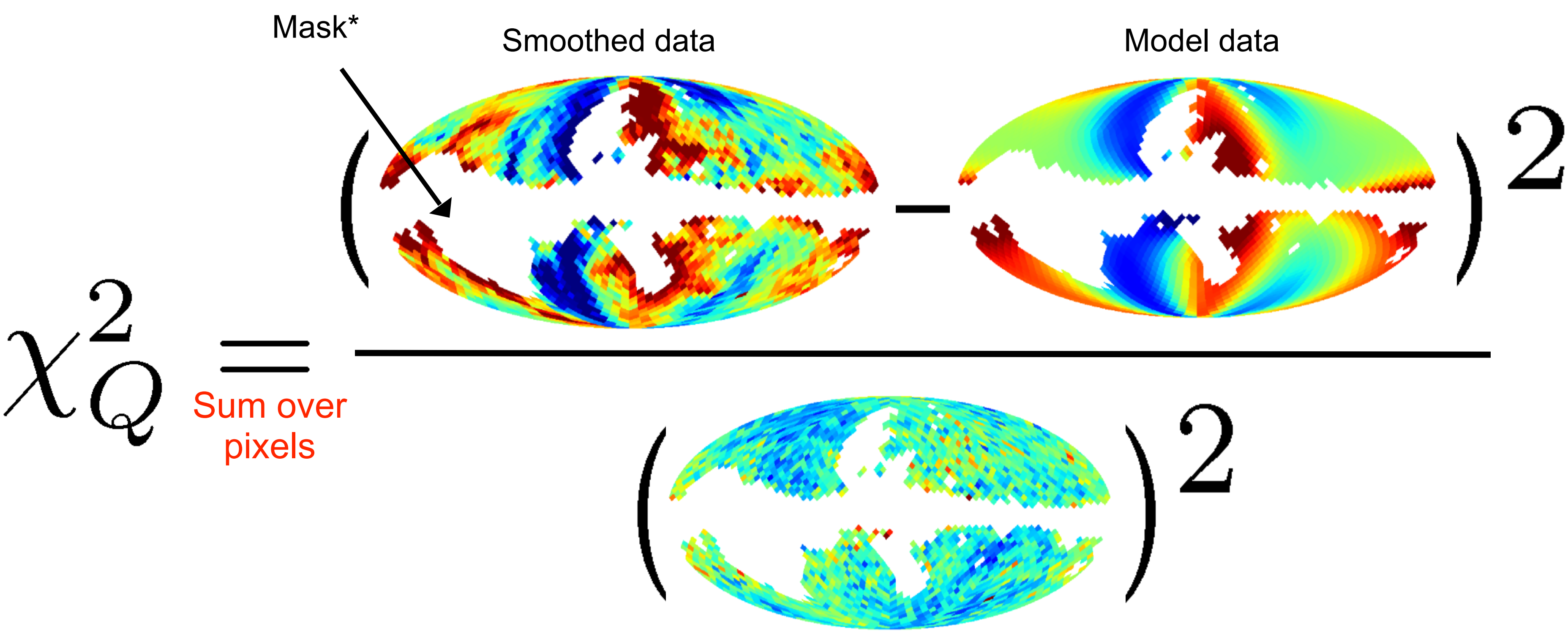
Data used in JF12



- Average data into 13.4 sq-deg pixels
  - 4 π steradians ≈ 40,000 square degrees
  - ~2000 data pixels for Q, U and RM pixels (shown above)
- Measure the variance in each pixel
  - variance maps (shown below, with most conservative masks)



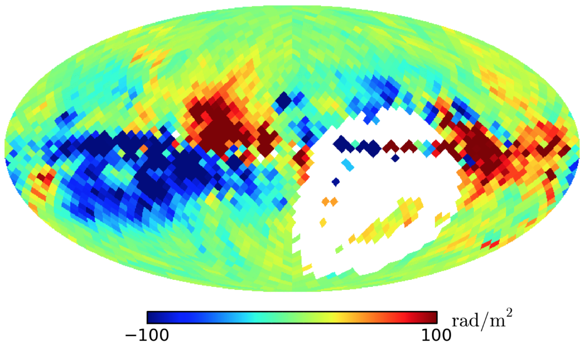
II. Minimize *Figure-of-Merit*



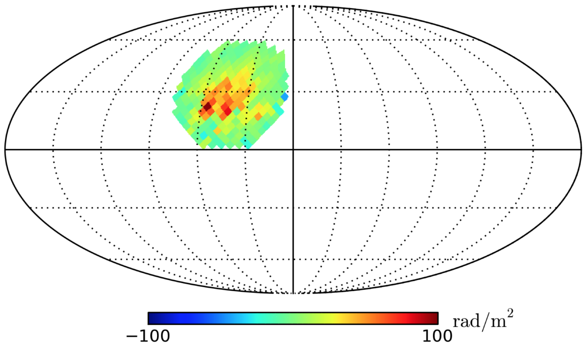
Variance *measured* from hi-resolution data

Sum χ^2 for Stokes Q, U and Rotation Measures; minimize

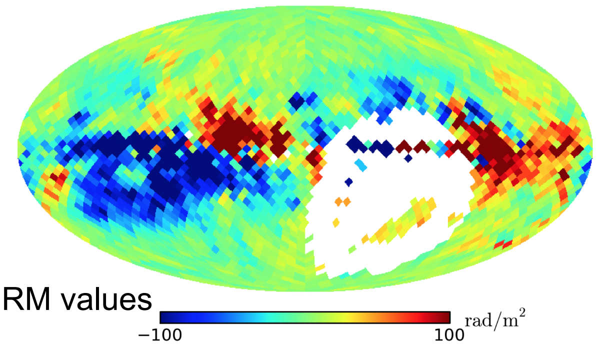
Input I: RMs



- 40403 extragalactic RMs
  - some are duplicate measurements of same source
- Map to 8 10^{-4} sq-deg Healpix pixels; 50M
  - if multiple measurements, take the best quality ones
  - average. => 38627 pixels with RMs



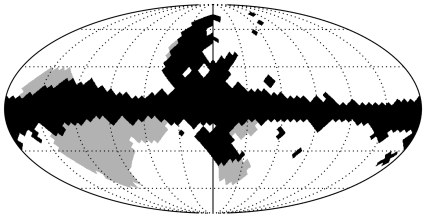
- Remove outliers
  - for each pixel, measure mean & variance of neighbors
  - remove pixels > 3 sigma from local mean; iterate
  - 666 pixels removed

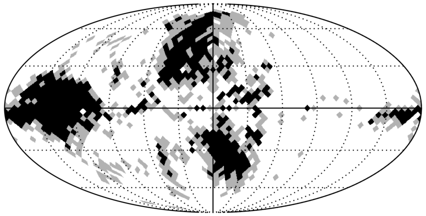


- Bin to 2067 pixels (13.4 sq-deg) sky has 3072; some have no RM values
- *Measure variance from sub-pixels*
- Subtract foregrounds (GMIMs) Wolleben et al (2010)
- Future: Fill in hole; use RM synthesis data to identify foregrounds.

Input II: Synchrotron Maps

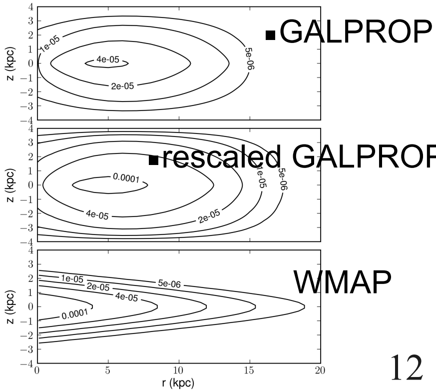
- WMAP 7-yr K-band, 22 GHz synchrotron maps
  - Planck: better separation between synchrotron & dust emission; foreground removal
  - Bin to 2067 pixels (13.4 sq-deg)
  - Measure variance from sub-pixels
  - 4 different masks, or no mask ⇨fit changes < 1 σ





Input III: Electron densities

- Thermal electrons n_e:
  - **Cordes-Lasio NE2001**; *increased scale height*
- Cosmic ray electrons n_{cre} :
  - **GALPROP 2009**; *rescaling improves fit*

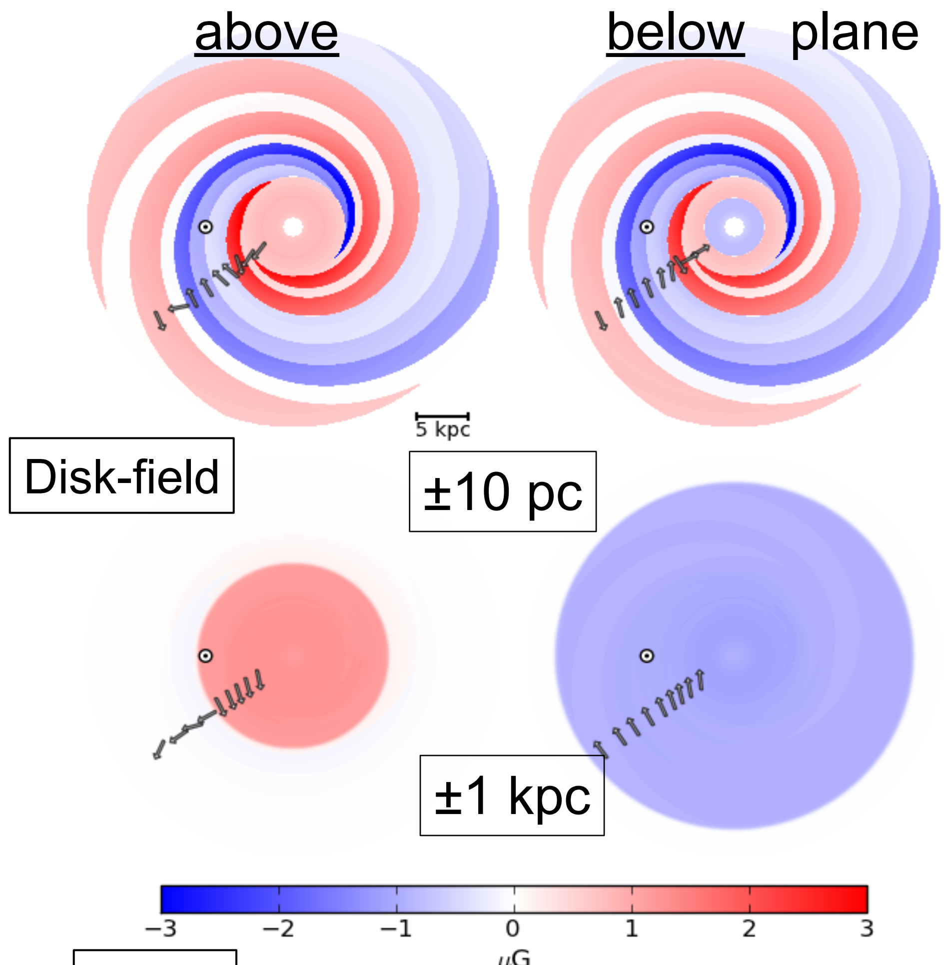


JF12 Coherent Field

Best-fit GMF parameters with $1-\sigma$ intervals.

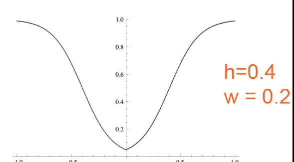
Field	Best fit Parameters	Description
Disk	$b_1 = 0.1 \pm 1.8\,\mu$G	field strengths at $r = 5$ kpc
	$b_2 = 3.0 \pm 0.6\,\mu$G	
	$b_3 = -0.9 \pm 0.8\,\mu$G	
	$b_4 = -0.8 \pm 0.3\,\mu$G	
	$b_5 = -2.0 \pm 0.1\,\mu$G	
	$b_6 = -4.2 \pm 0.5\,\mu$G	
	$b_7 = 0.0 \pm 1.8\,\mu$G	
	$b_8 = 2.7 \pm 1.8\,\mu$G	inferred from $b_1, ..., b_7$
	$b_{\rm ring} = 0.1 \pm 0.1\,\mu$G	ring at 3 kpc $< r <$ 5 kpc
	$h_{\rm disk} = 0.40 \pm 0.03$ kpc	disk/halo transition
	$w_{\rm disk} = 0.27 \pm 0.08$ kpc	transition width
Toroidal halo	$B_{\rm n} = 1.4 \pm 0.1\,\mu$G	northern halo
	$B_{\rm s} = -1.1 \pm 0.1\,\mu$G	southern halo
	$r_{\rm n} = 9.22 \pm 0.08$ kpc	transition radius, north
	$r_{\rm s} > 16.7$ kpc	transition radius, south
	$w_{\rm h} = 0.20 \pm 0.12$ kpc	transition width
	$z_0 = 5.3 \pm 1.6$ kpc	vertical scale height
X halo	$B_{\rm X} = 4.6 \pm 0.3\,\mu$G	field strength at origin
	$\Theta^0_{\rm X} = 49 \pm 1°$	elev. angle at $z = 0, r > r^c_{\rm X}$
	$r^c_{\rm X} = 4.8 \pm 0.2$ kpc	radius where $\Theta_{\rm X} = \Theta^0_{\rm X}$
	$r_{\rm X} = 2.9 \pm 0.1$ kpc	exponential scale length
striation	$\gamma = 2.92 \pm 0.14$	striation and/or $n_{\rm cre}$ rescaling

Note. — For the parameter $r_{\rm s}$ only a lower 68%-bound is given.

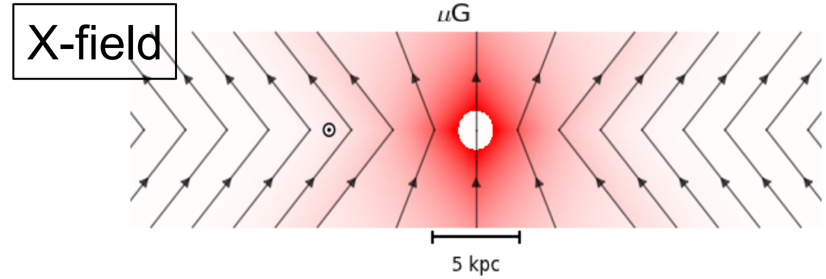


- Disk
  - > 5 kpc: 8 spiral arms, geometry as in NE200
  - 3-5 kpc: purely azimuthal "molecular ring"
  - B=0 for r < 1 (not adequately constrained by data) and r > 20 kpc
- Halo
  - purely toroidal (fit prefers this to spirals with arbitrary angles)
  - Different strength and scale height in N and S
  - Logistic function controls transitions, different parameters for each

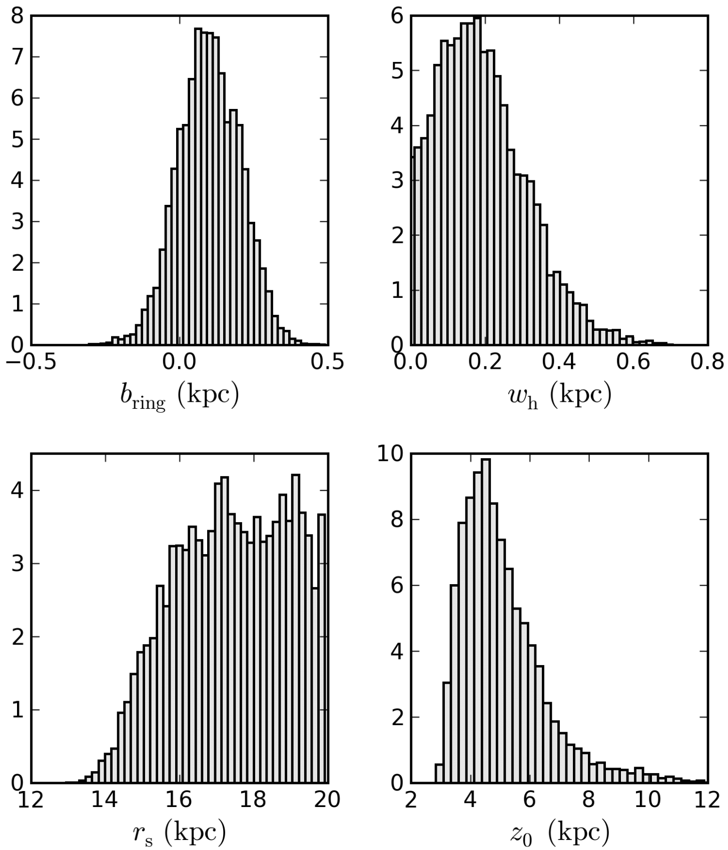
$$L(z,h,w) = \left(1 + e^{-2(|z|-h)/w}\right)^{-1}$$



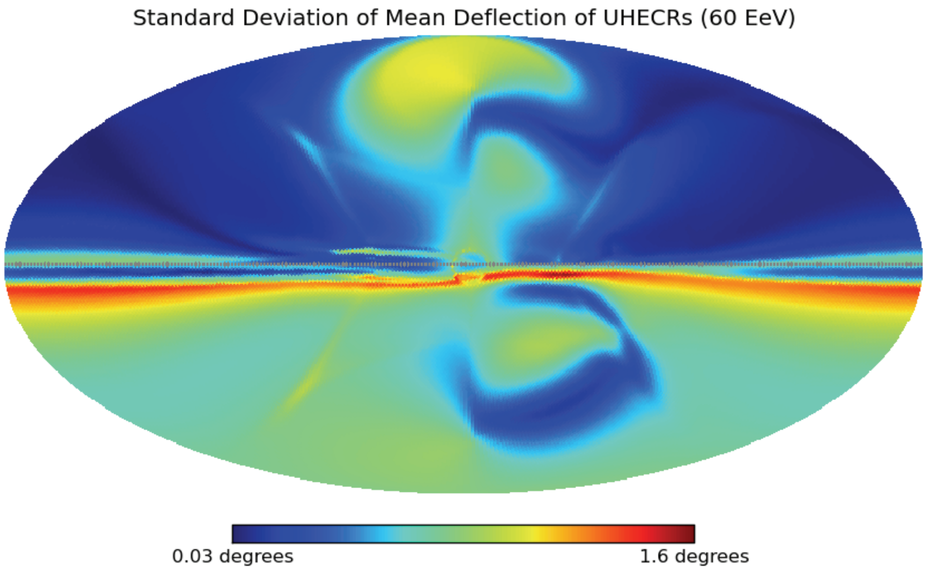
- Out-of-plane "X" field
  - divergenceless
  - need much slower radial fall-off than dipole



How well constrained are parameters? VERY…



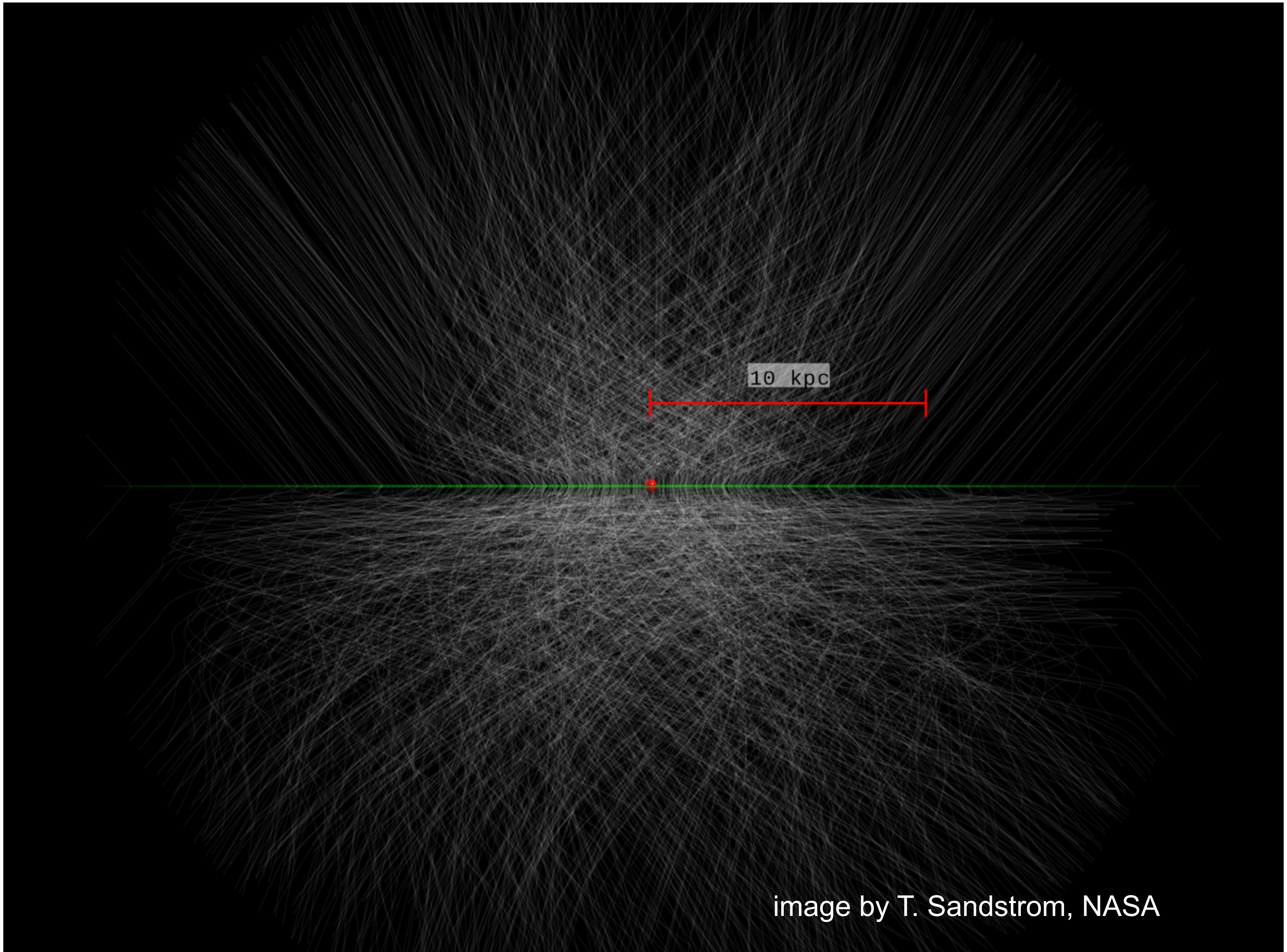
Histogram of MCMC parameter values for 4 worst cases



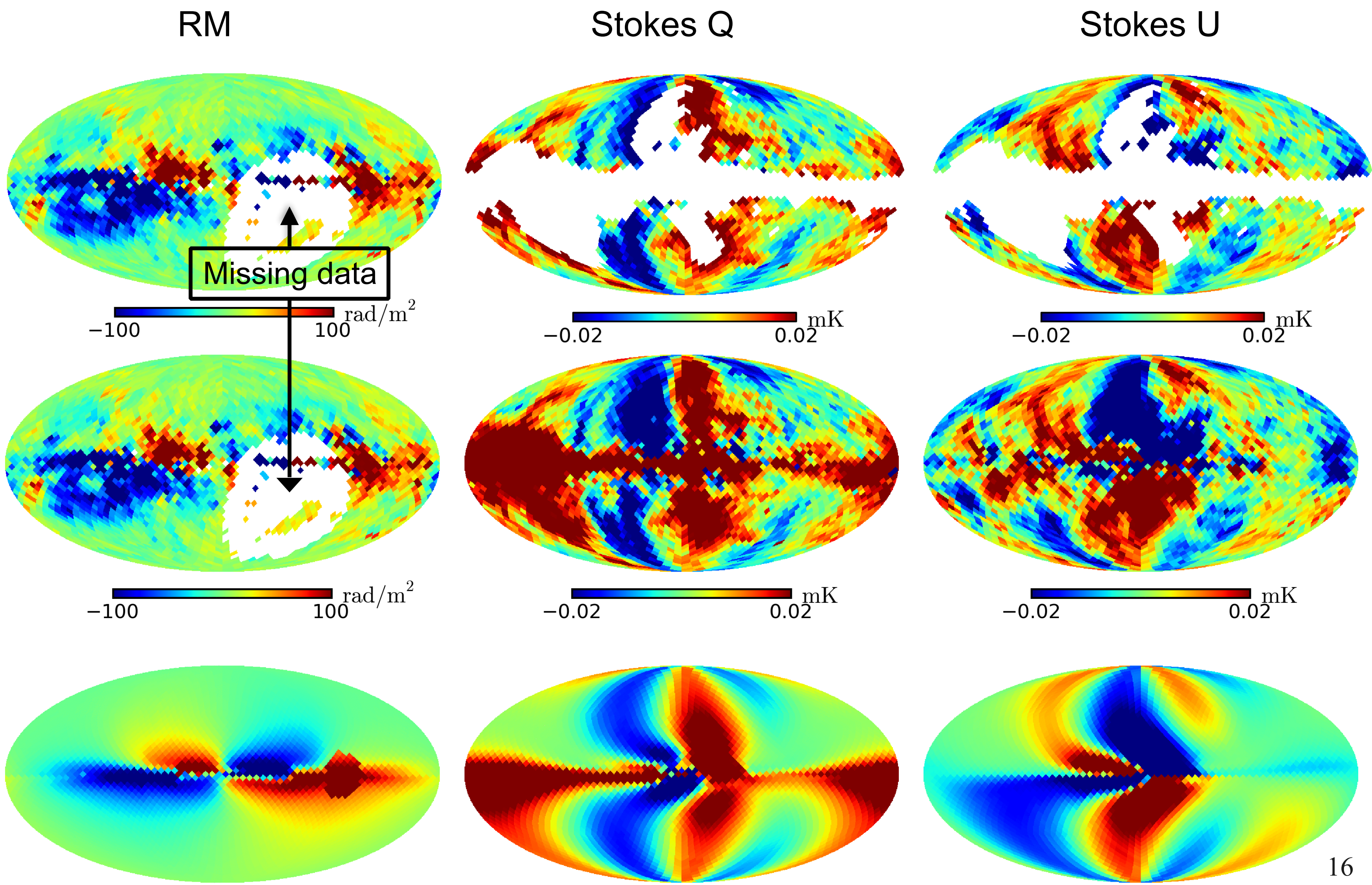
Uncertainty of CR deflections from JF12 parameter uncertainty

Unexpected discovery!

Magnetic Field in the Galactic halo is a **directed**, outwardly-spreading helix

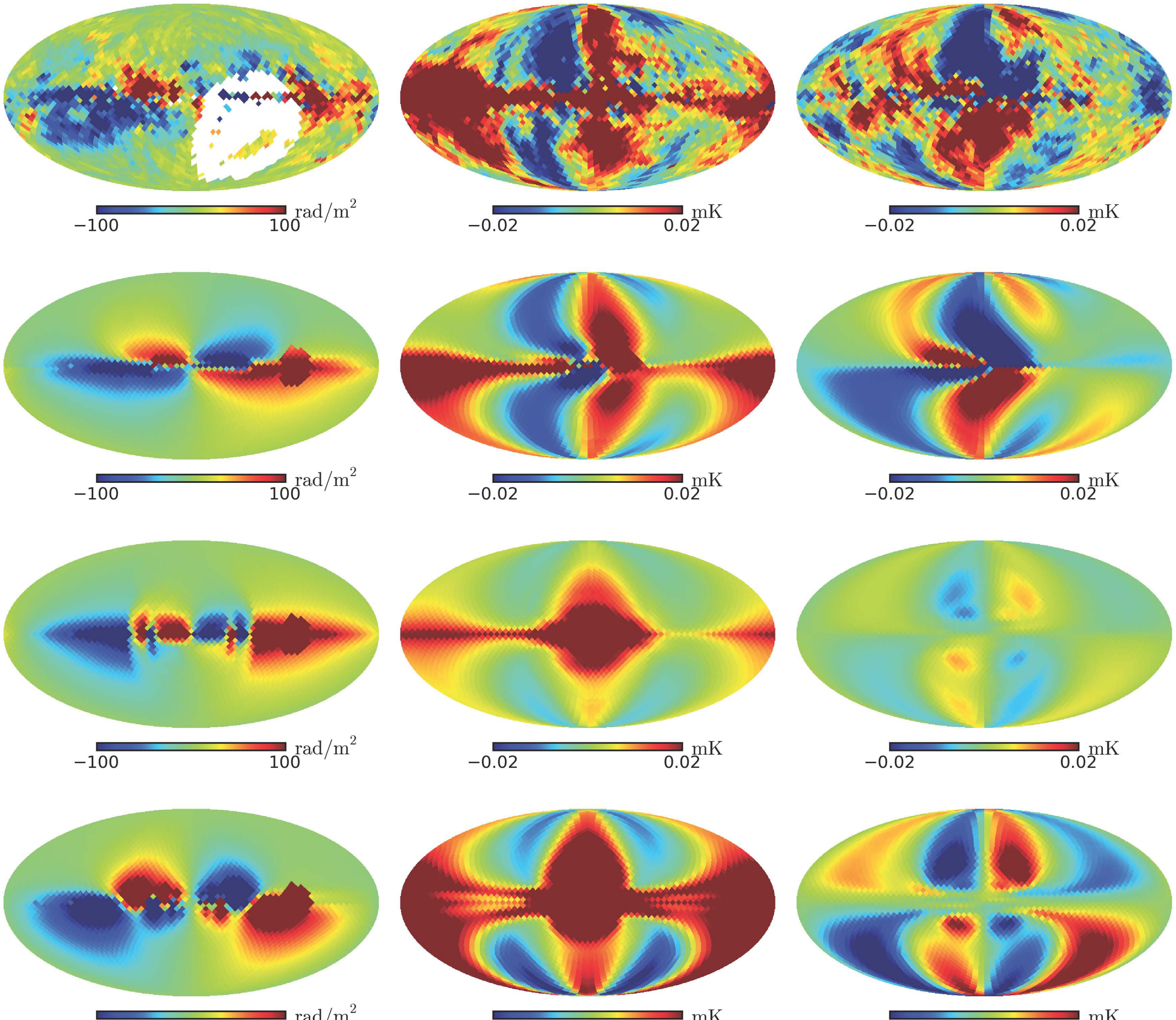


JF12 also agrees well UNMASKED



Comparing GMF Models

JF 12 fit is significantly better than other models



Observed data

Simulated data

JF 2012

χ^2 = 1.096 per d.o.f.

for 6605 observables

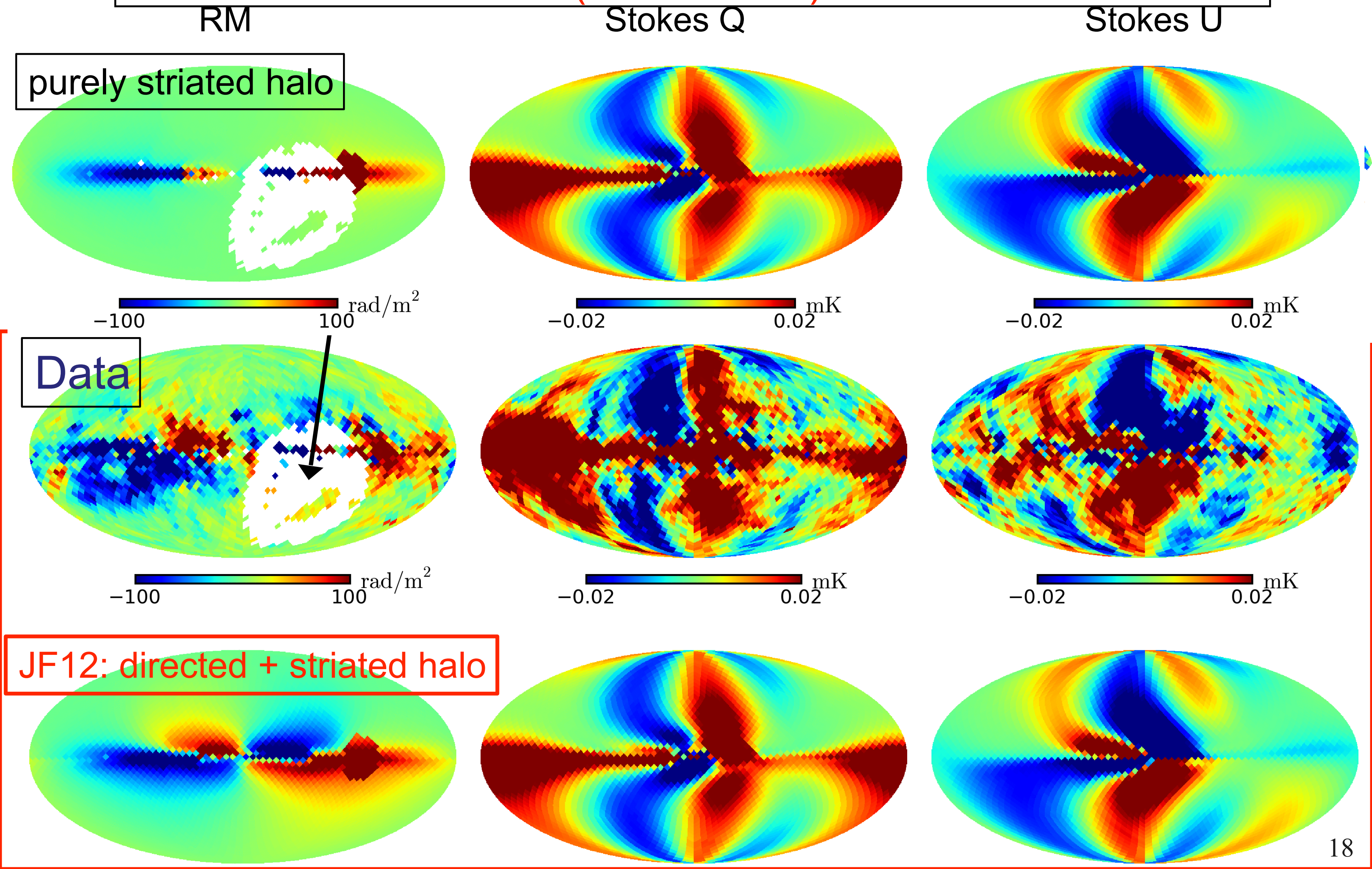
Pshirkov et al. 2011, BSS

χ^2 = 2.66 per dof

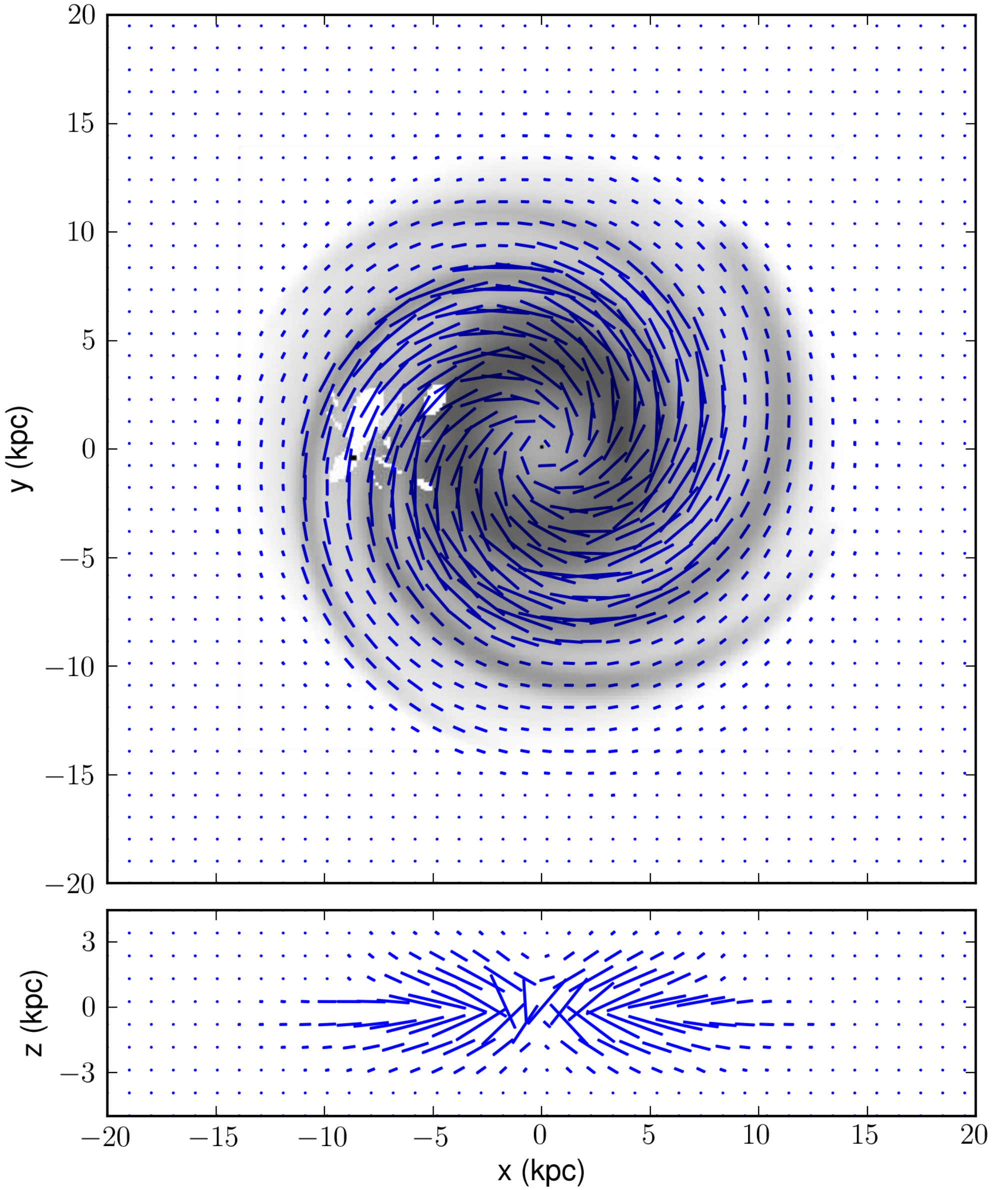
Sun et al.,2010

χ^2 = 1.67 per dof

because of the ***Directed, helical, halo field***
(D. Khurana)

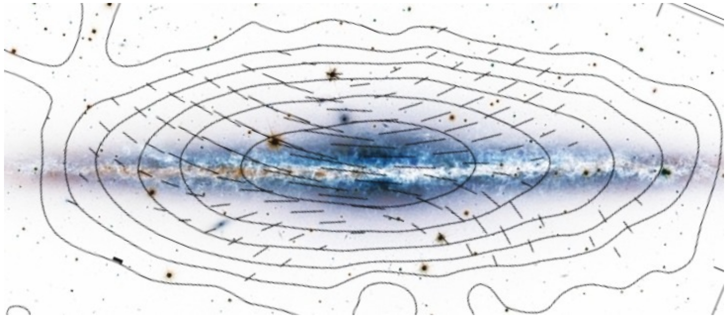


The Milky Way to an extragalactic radio observer

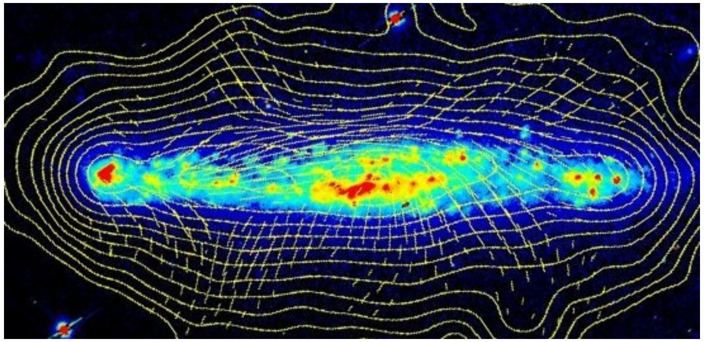


Milky Way analogues:

NGC 891

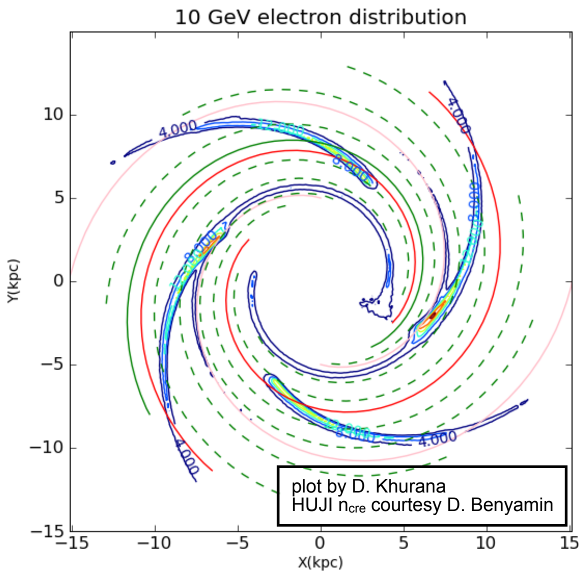


NGC 5775



Caveats and Future

- n_{cre} and n_e (from others in JF12)
  - Q,U: $\sim \int_z^\infty dz\, n_{cre}(\mathbf{x})\, B_\perp^2(\mathbf{x})$
  - RMs $\sim \int_z^\infty dz\, n_e(\mathbf{x})\, B_{||}(\mathbf{x})$



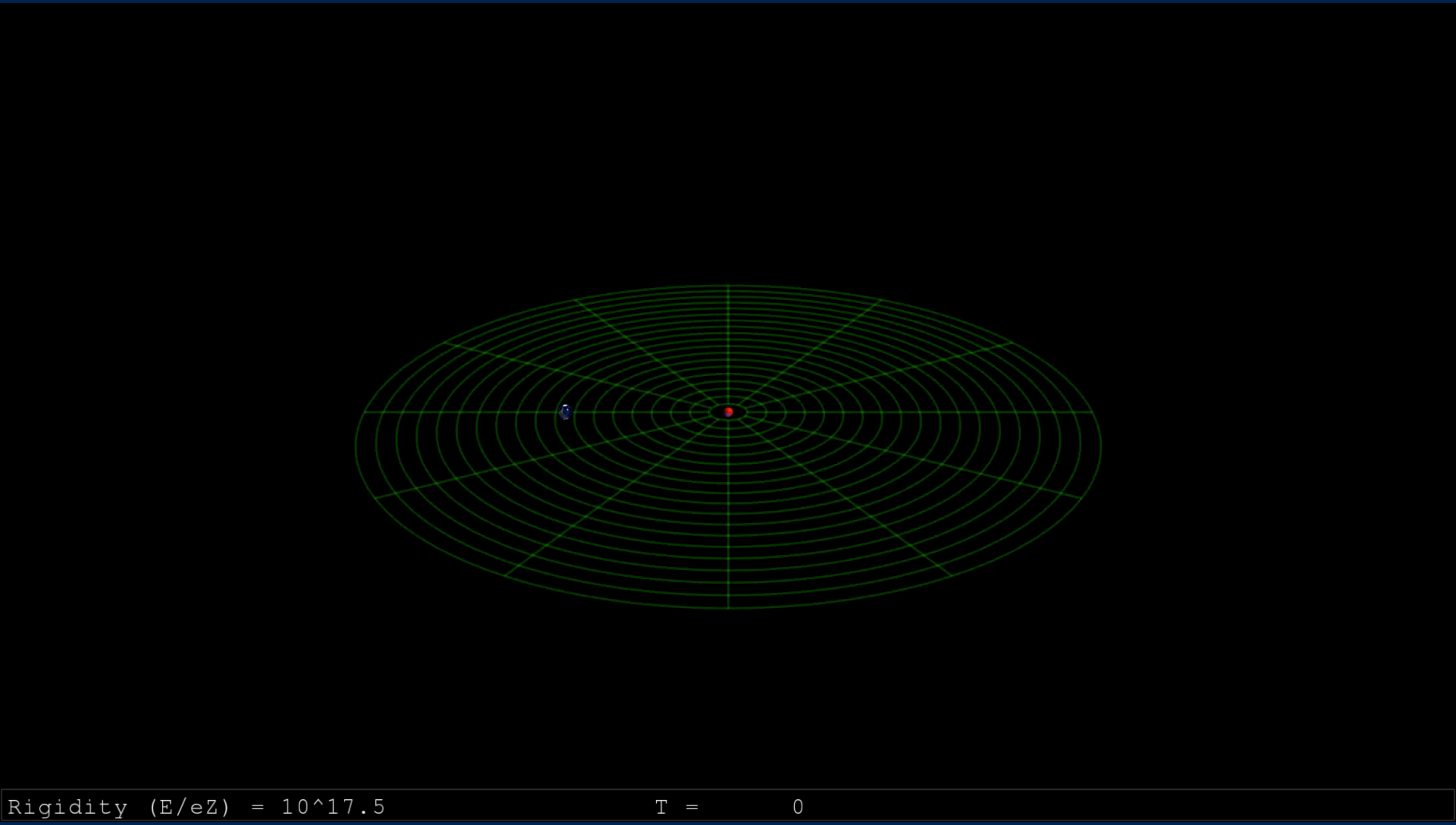
- Functional form for **B**

- Next iteration:
  - more theory input (dynamo, …)
  - fit n_e at NYU
  - self-consistently constrain n_{cre} and n_e
  - try to constrain/understand origin of coherent field

Impact of GMF on CR propagation

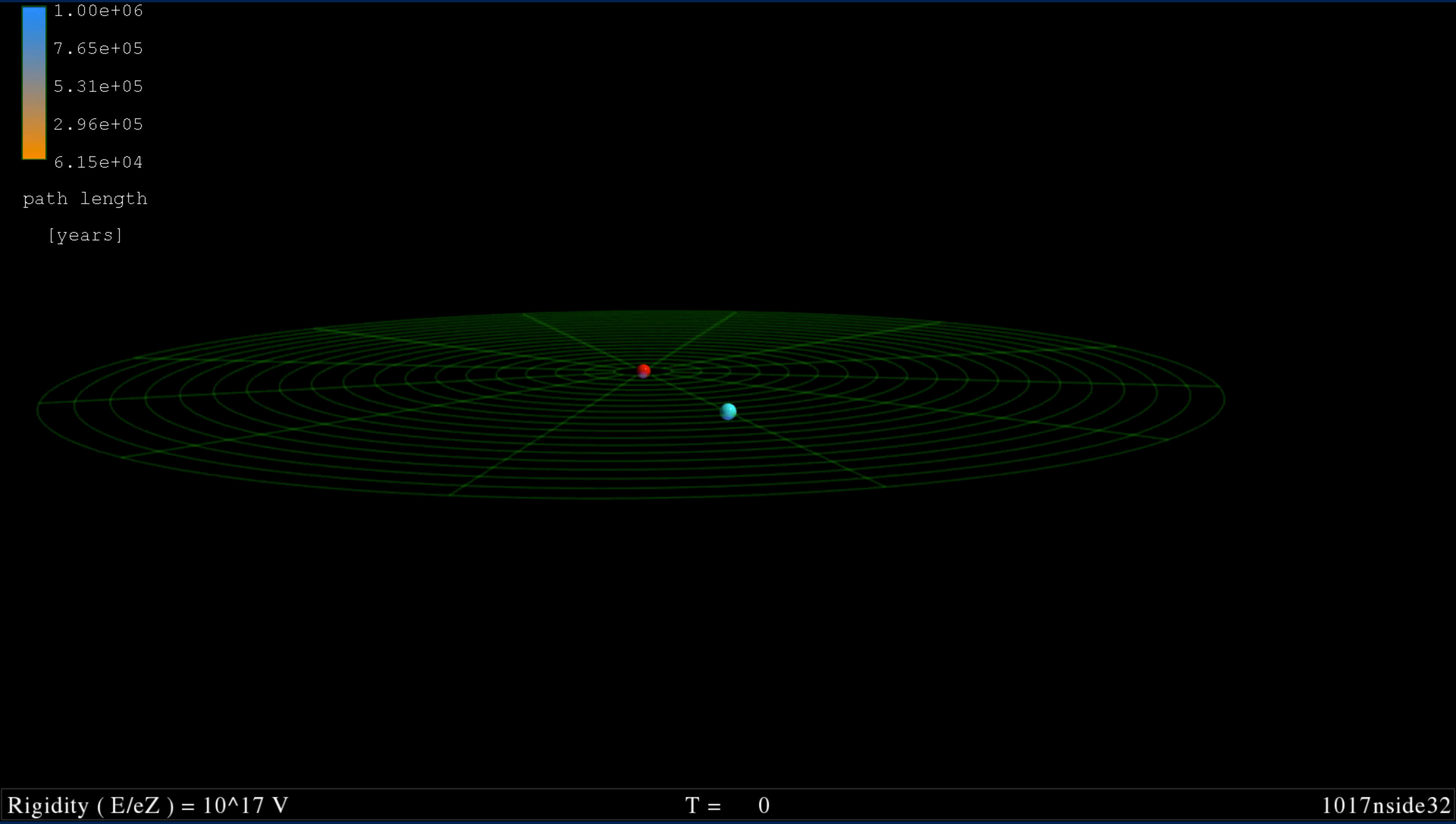
CRs from source at the Galactic Center

N. Awal (NYU) + GRF; movies courtesy T. Sandstrom, NASA



(E/Z = $10^{17.5}$ eV)

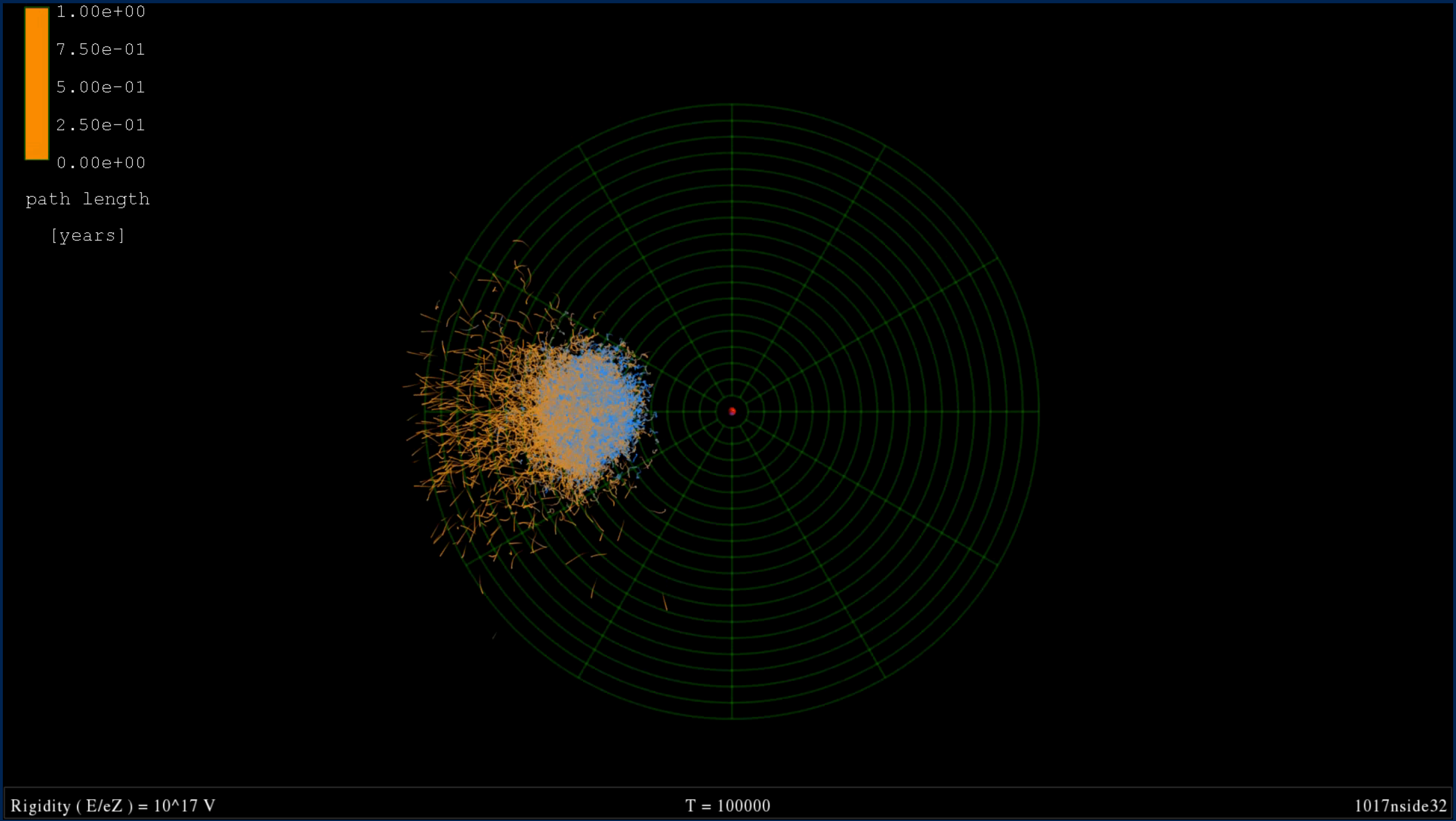
CRs from source nearby
(perspective view)



shown for E/Z = 10^{17} eV

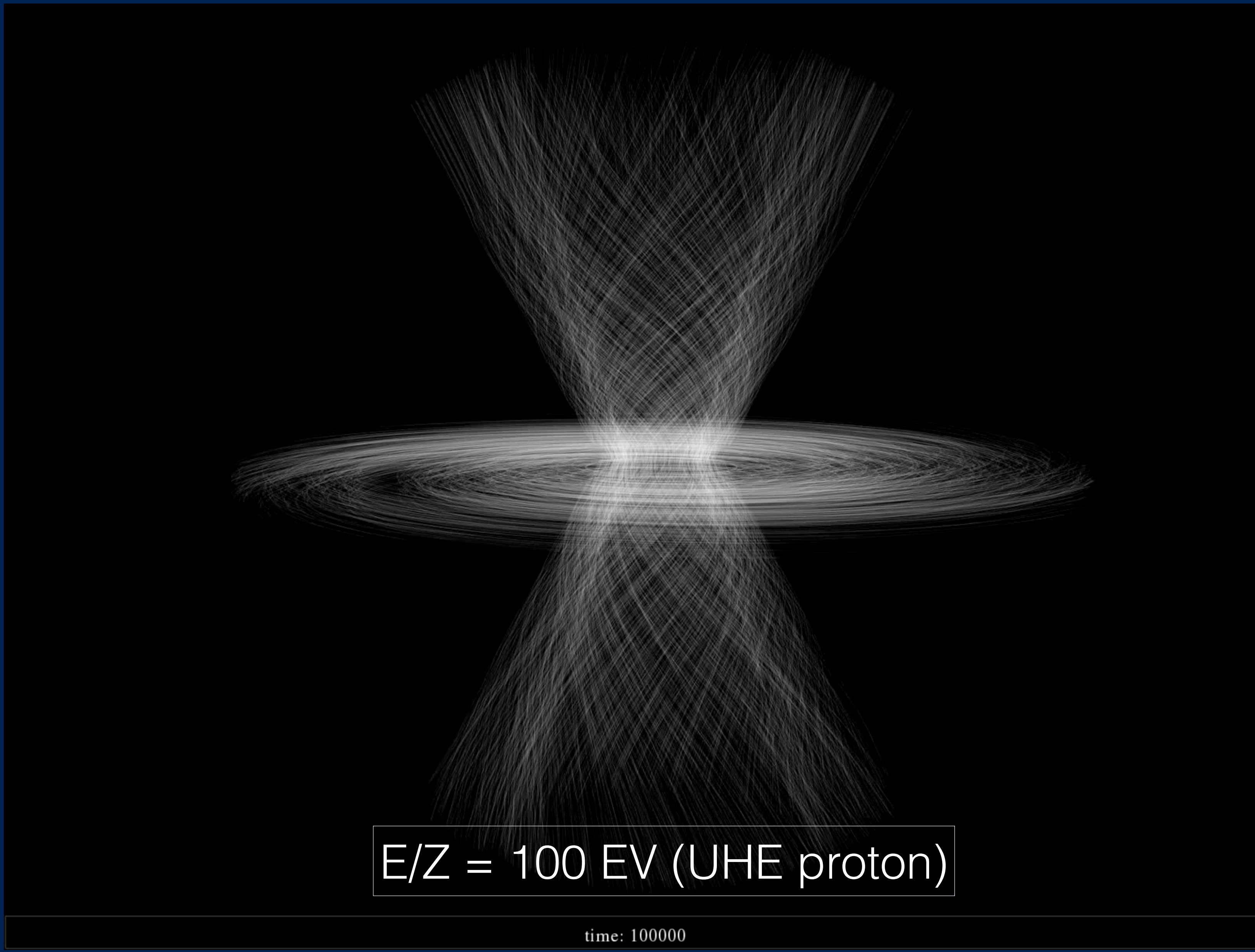
CRs from source nearby (top view)

N. Awal (NYU) + GRF; movies courtesy T. Sandstrom, NASA



shown for $E/Z = 10^{17}$ eV

UHECR deflections in the GMF



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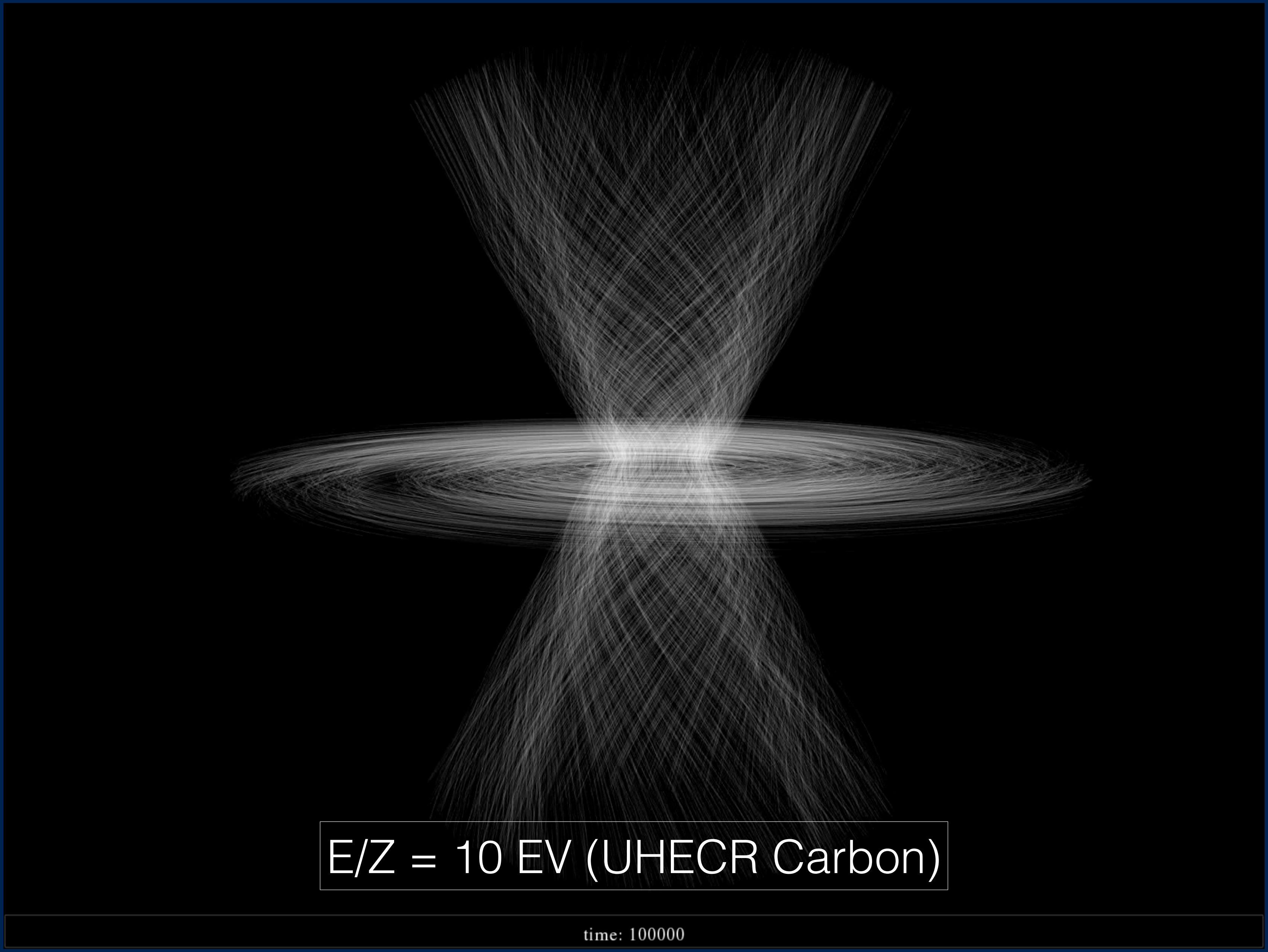
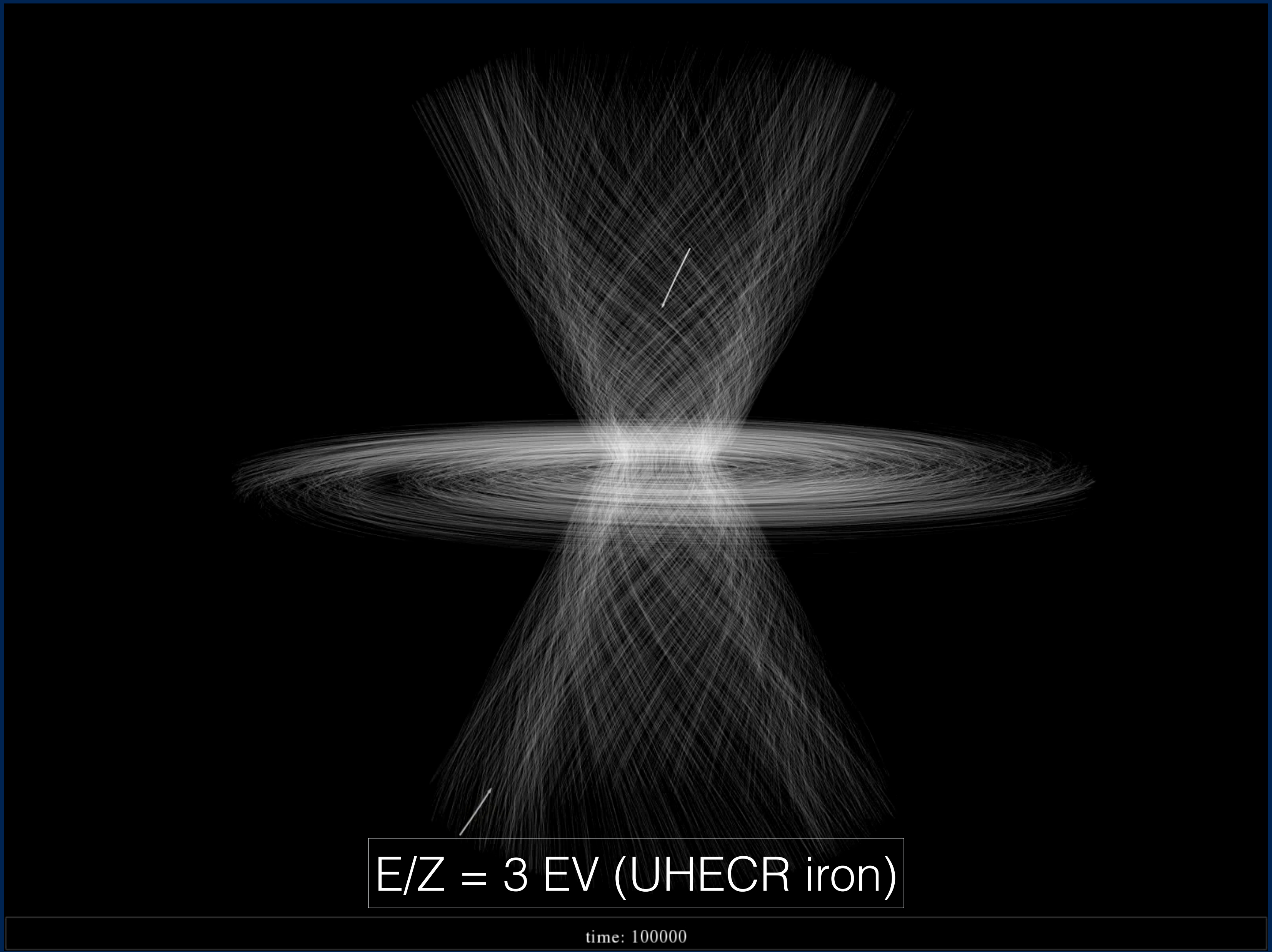
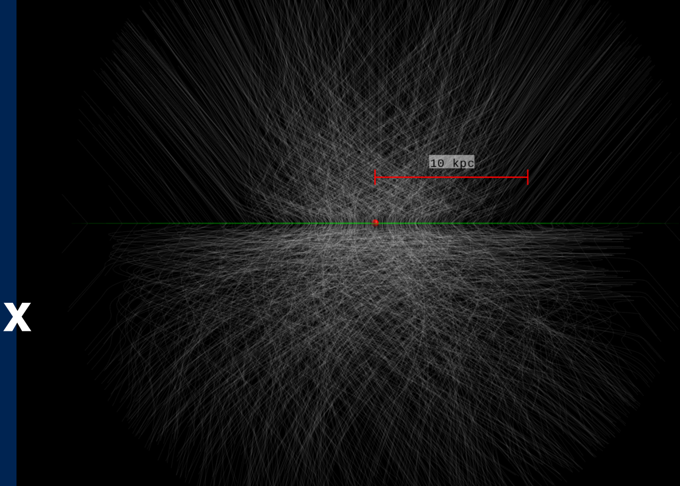


UHECR deflections in the GMF

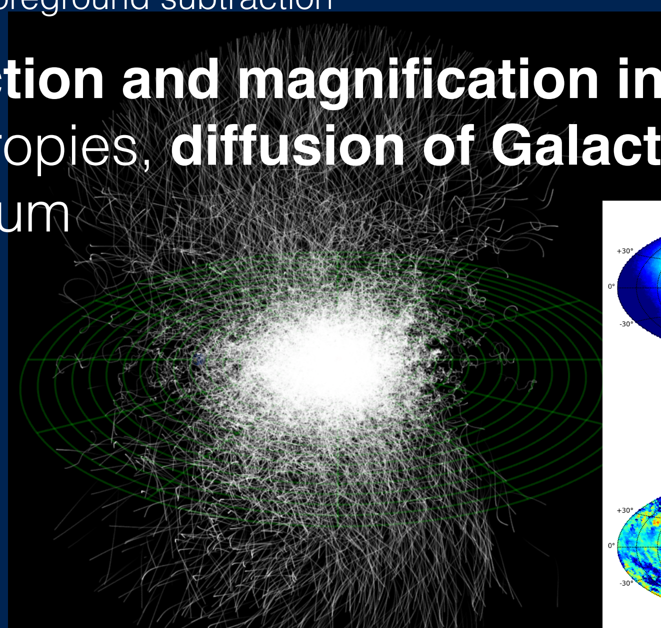


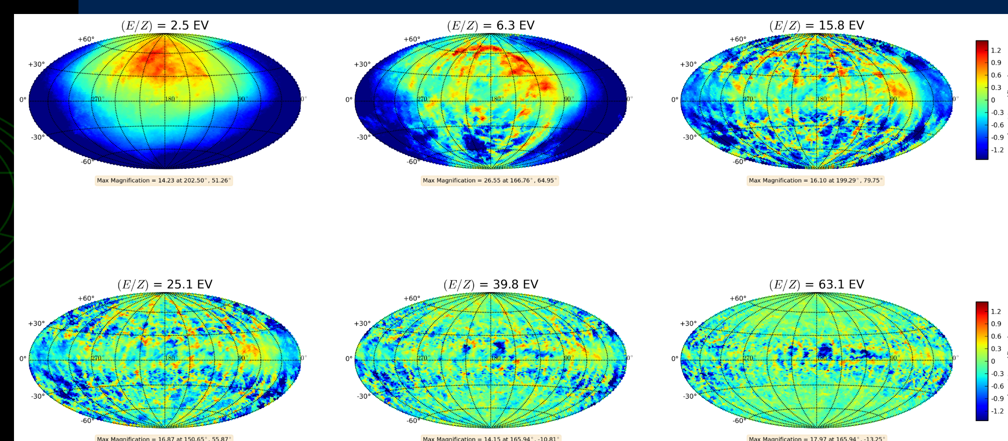
R.Jansson & GRF, Ap.J. 757, 14 (2012) regular
RJ & GRF, Ap.J.Lett. 761, L11 (2012) random
GRF Comptes Rendu Physique (2014) review
GF w N. Awal & M. Sutherland, in prep CR defs

Summary



- **The Galactic magnetic field**
  - Halo: **outwardly-spreading, directed helix**
  - Disk: spiral structure confirmed
  - Striated component ~ 1.4 x coherent
  - Coherent component ~ few micro-gauss; random field usually bigger
- *(Jansson-Farrar approach works)*
  - JF12 model is just 1st step. New model coming soon; better:
    - Thermal and relativistic electron distributions
    - Theoretical understanding of field structure
    - Foreground subtraction
- **Deflection and magnification in the GMF has major impact** on the anisotropies, **diffusion of Galactic CRs** and interpreting **UHECR** spectrum



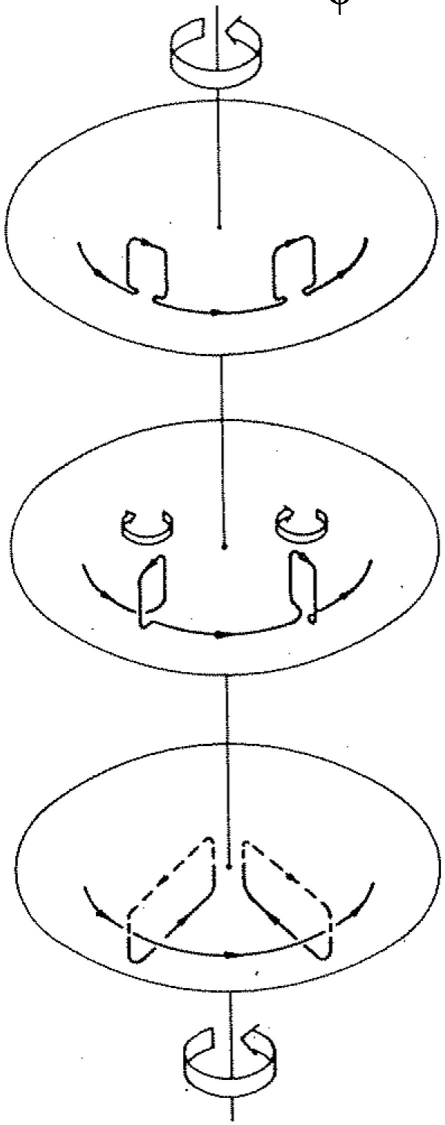


Backup slides

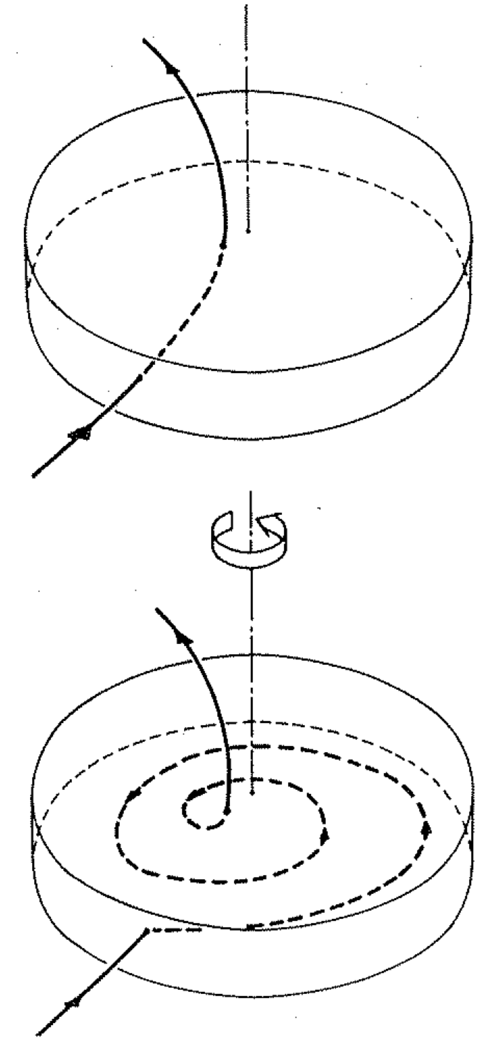
- Magnetic field modeling
- Impact of GMF on UHECRs

The mean-field (large-scale) $\alpha\omega$-dynamo in the galactic disc

α-effect: $B_\phi \rightarrow B_r$



Differential rotation: $B_r \rightarrow B_\phi$



from A. Shukurov

JF12 Coherent GMF Model

- Disk
  - r > 5 kpc: 8 spiral arms, geometry as in NE2001
  - 3-5 kpc: purely azimuthal “molecular ring”
  - B=0 for r < 1 (not adequately constrained by data) and r > 20 kpc
- Halo
  - purely toroidal (fit prefers this to spirals with arbitrary angles)
  - Different strength and scale height in N and S
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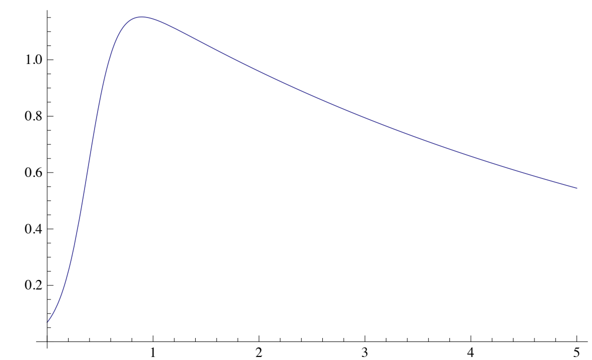
$$L(z,h,w) = \left(1 + e^{-2(|z|-h)/w}\right)^{-1}$$

- Out-of-plane “X” field
  - divergenceless
  - need much slower radial fall-off than dipole



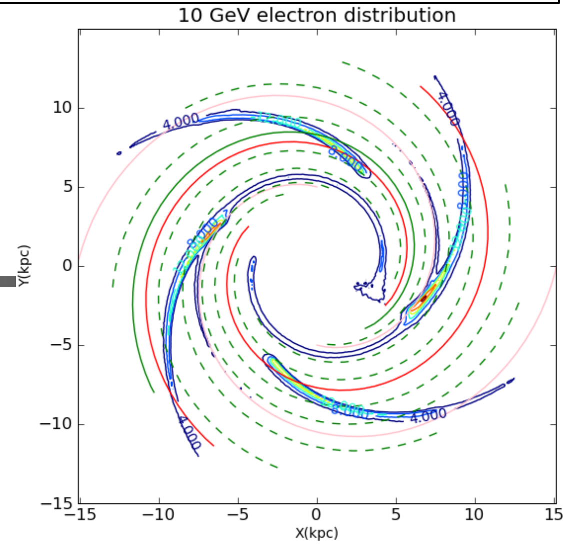
profile in z of toroidal field at solar circle

Random Field Model

- Two large-scale components:
  - Spiral disk (same arm geometry as for regular field)
  - Smooth, extended halo field
- 13 free parameters:
  - Field strengths (8 arms, central disk, extended halo)
  - Thickness of the disk; scale height & radial extent of halo
- **Constrain with WMAP7 22 GHz total Intensity map**
  - Time saver: Average over random field by computing synchrotron intensity with

$$B_{\rm reg}^2 \rightarrow \alpha\,(1+\beta)\,B_{\rm reg,model}^2 \left(1 + \frac{2}{3}\,\frac{B_{\rm rand}^2}{(1+\beta)B_{\rm reg,model}^2\,\sin^2\theta}\right)$$

Benyamin-Shaviv n_{cre} compared to NE2001 & JF12 arms

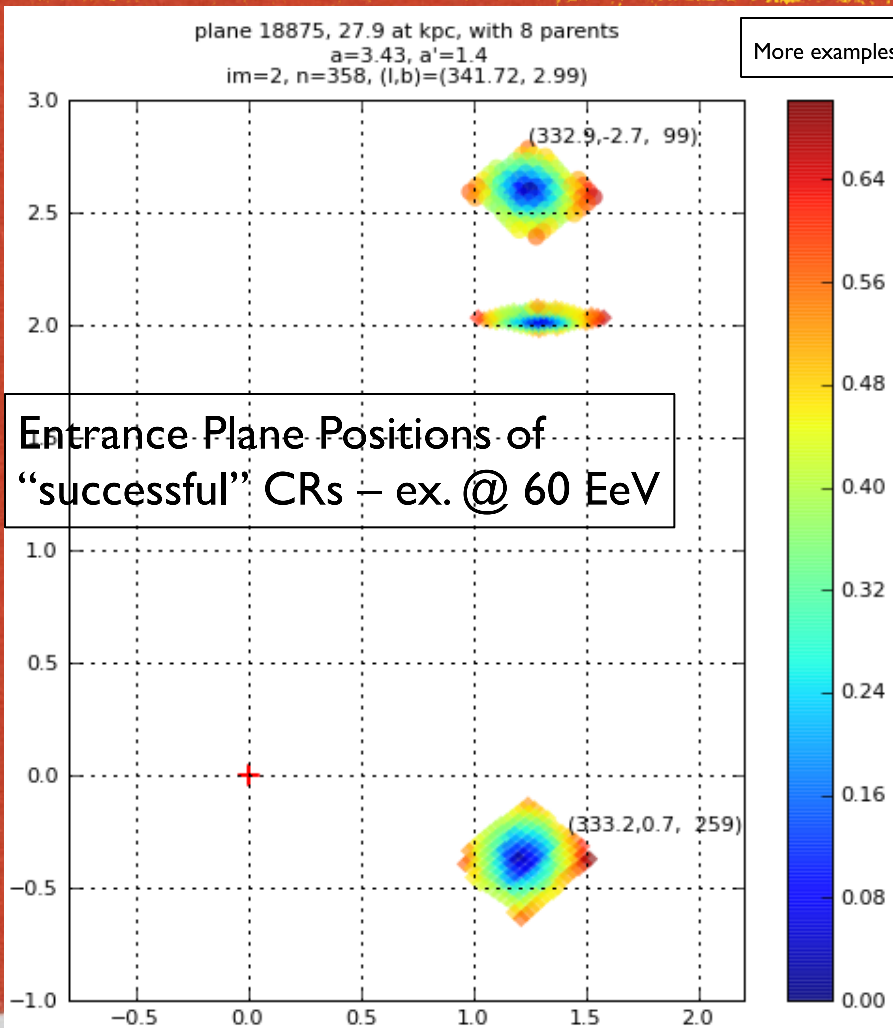


Improving on JF12

with Deepak Khurana Michael Unger

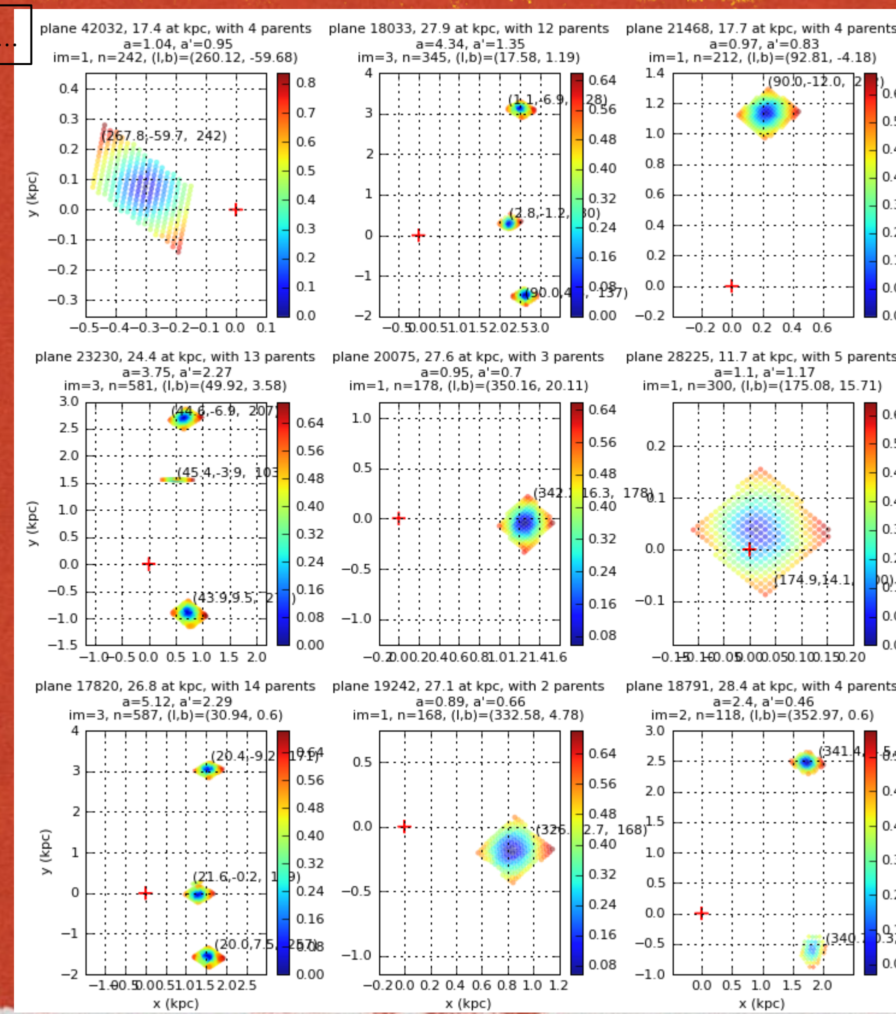
- **Different functional forms for field components**
  - ✔ Ferriere & Terral analytic X-fields (almost identical fit)
  - Shaviv-Benyamin 10 GeV electron distribution; **random field ~ n_{cre}^{p}**
  - **Better (more general; less regular) disk modeling. Is total flux in disk = 0?**
  - Incorporate more info from other galaxies, explore striated component in greater depth
- **Foreground modeling**
  - Frisch et al. Local Bubble info: (\vec{B}, geometry, locally modeled n_e & n_{cre} ; other known fg.
  - Use Planck polarized dust emission map to constrain local region to larger radii (+D. Finkbeiner)
- **Technical improvements**
  - **Better determination of electron densities n_e & n_{cre}**
    - anisotropic diffusion (impacts predicted $e^{\pm}$ distribution because X-field => vertical escape route)
    - spatial variation of n_{cre} spectral indices; correlation between B, n_{cre}, & n_e
  - **Simultaneously fit I, Q, U, RM and key parameters of n_e & n_{cre}**
  - **Better tools:** adaptive observable calculator, state-of-art MCMC.
- **New data:** complete RM sky, Planck Q,U,I, *pulsars with good distances*, *more radio frequencies*, ***RM synthesis!!!***
- ***Determine spatial dependence of coherence length***

Complex GMF =>
non-trivial paths thru Galaxy =>
multiple images & magnification/demagnification

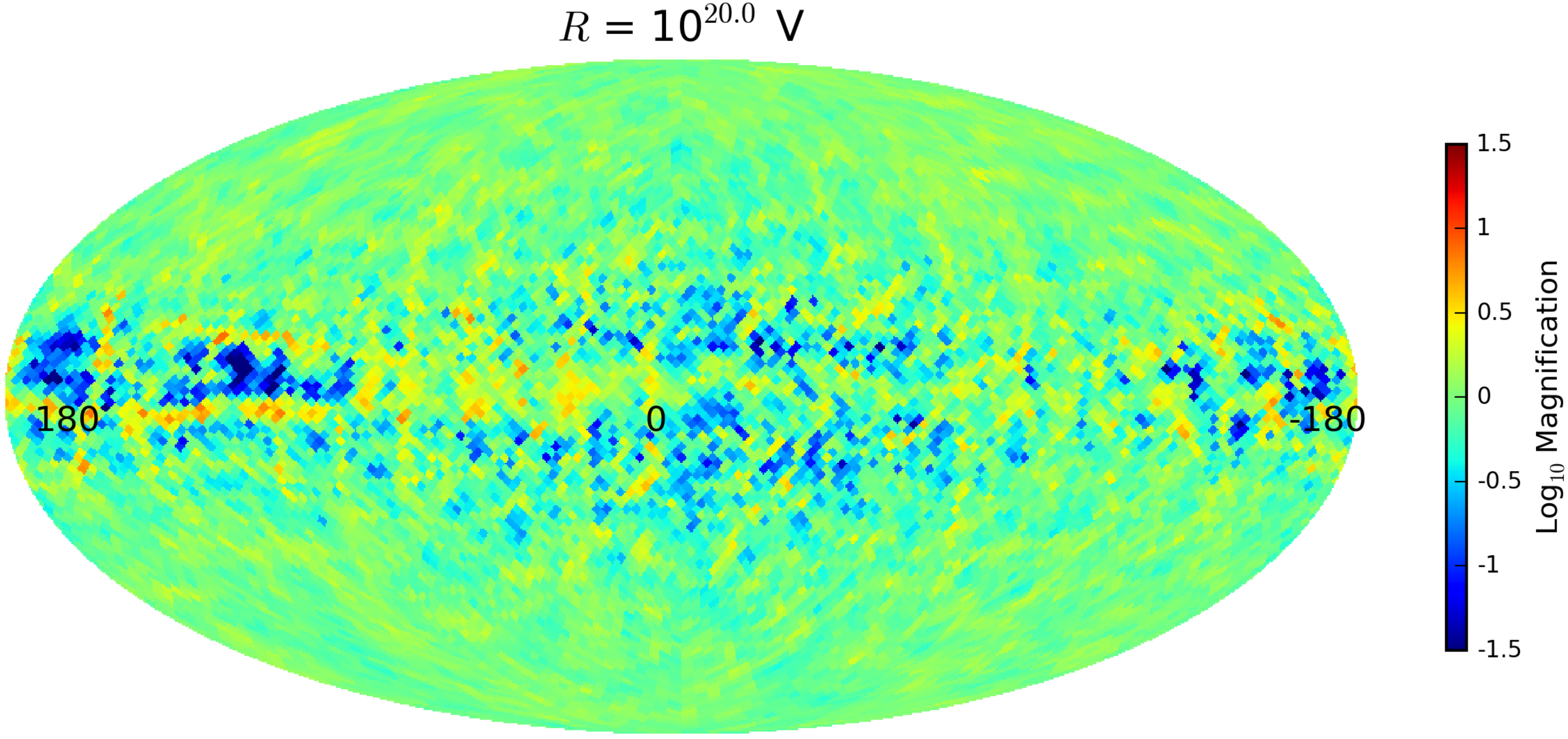


Entrance Plane Positions of "successful" CRs – ex. @ 60 EeV

More examples...

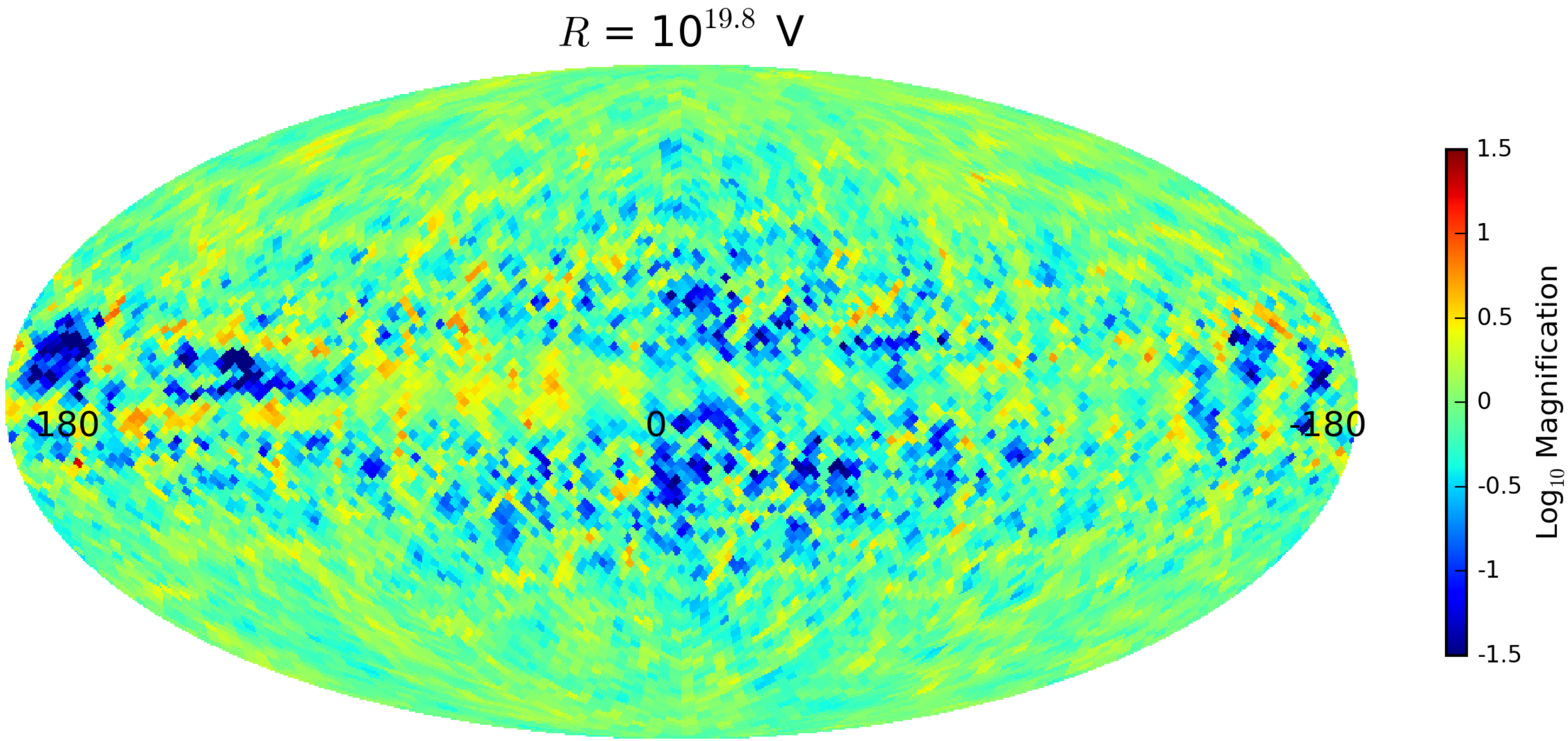


Magnification as a function of source direction



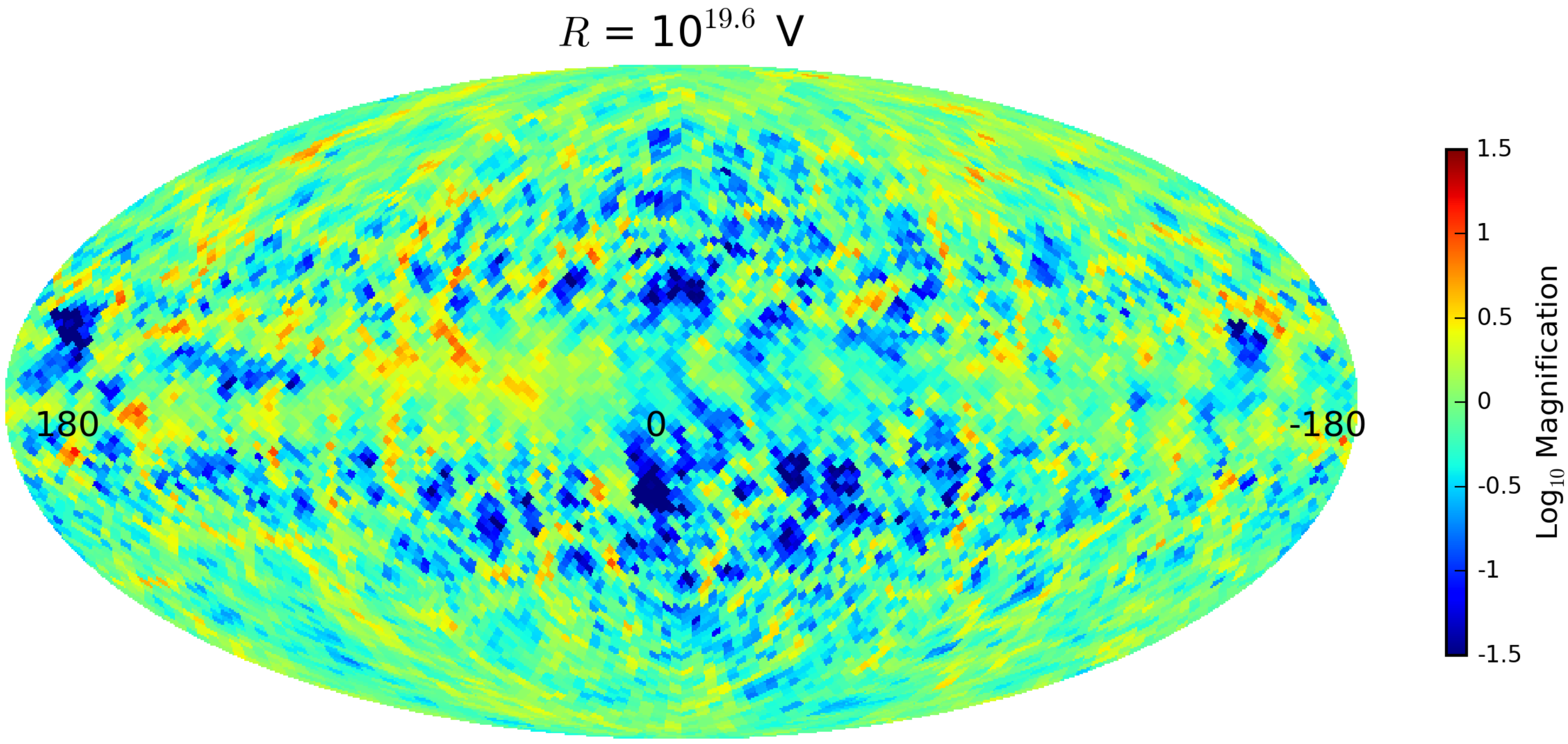
rigidity = E/Z = **10^{20} V**

Magnification as a function of rigidity



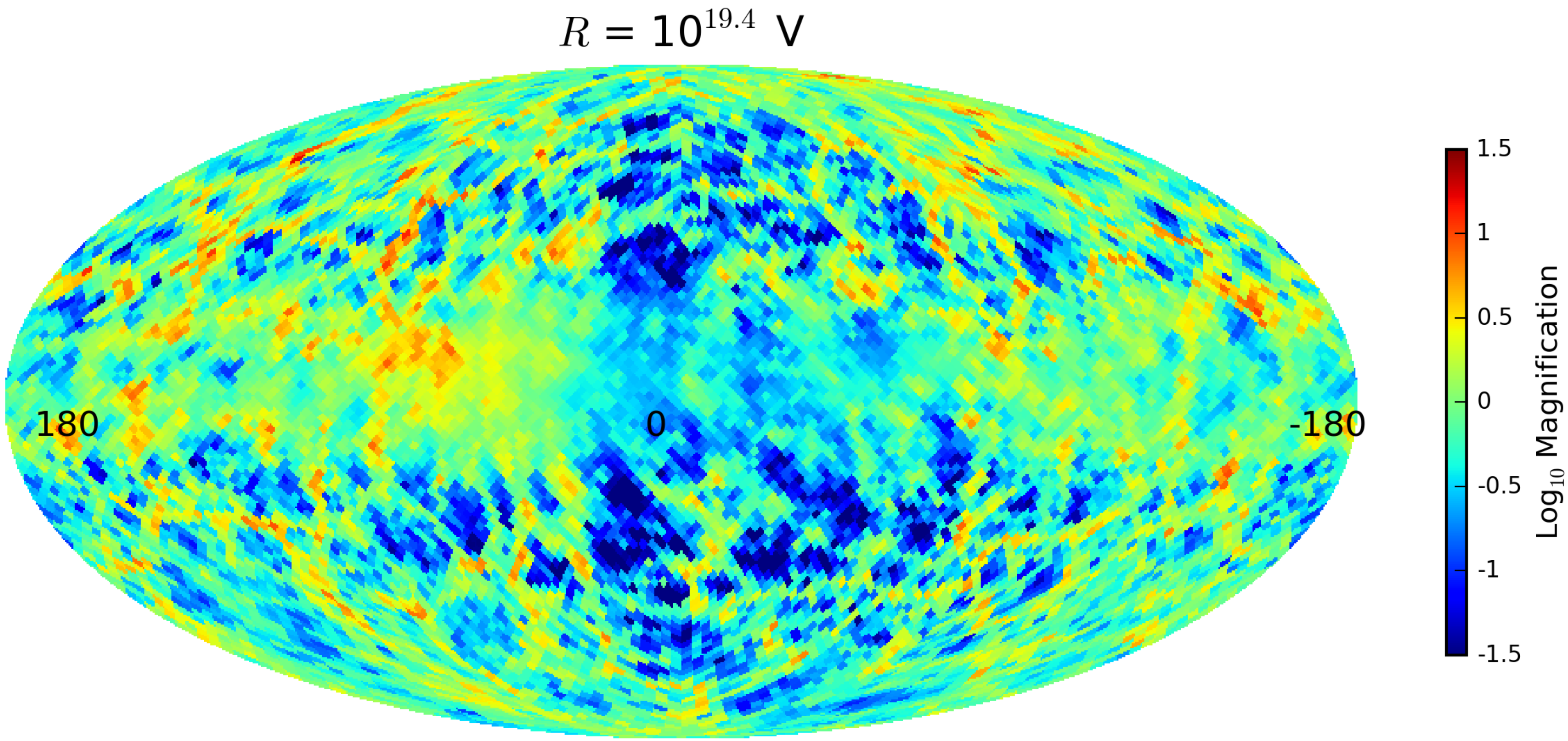
rigidity = 63 **EV**

Magnification as a function of rigidity



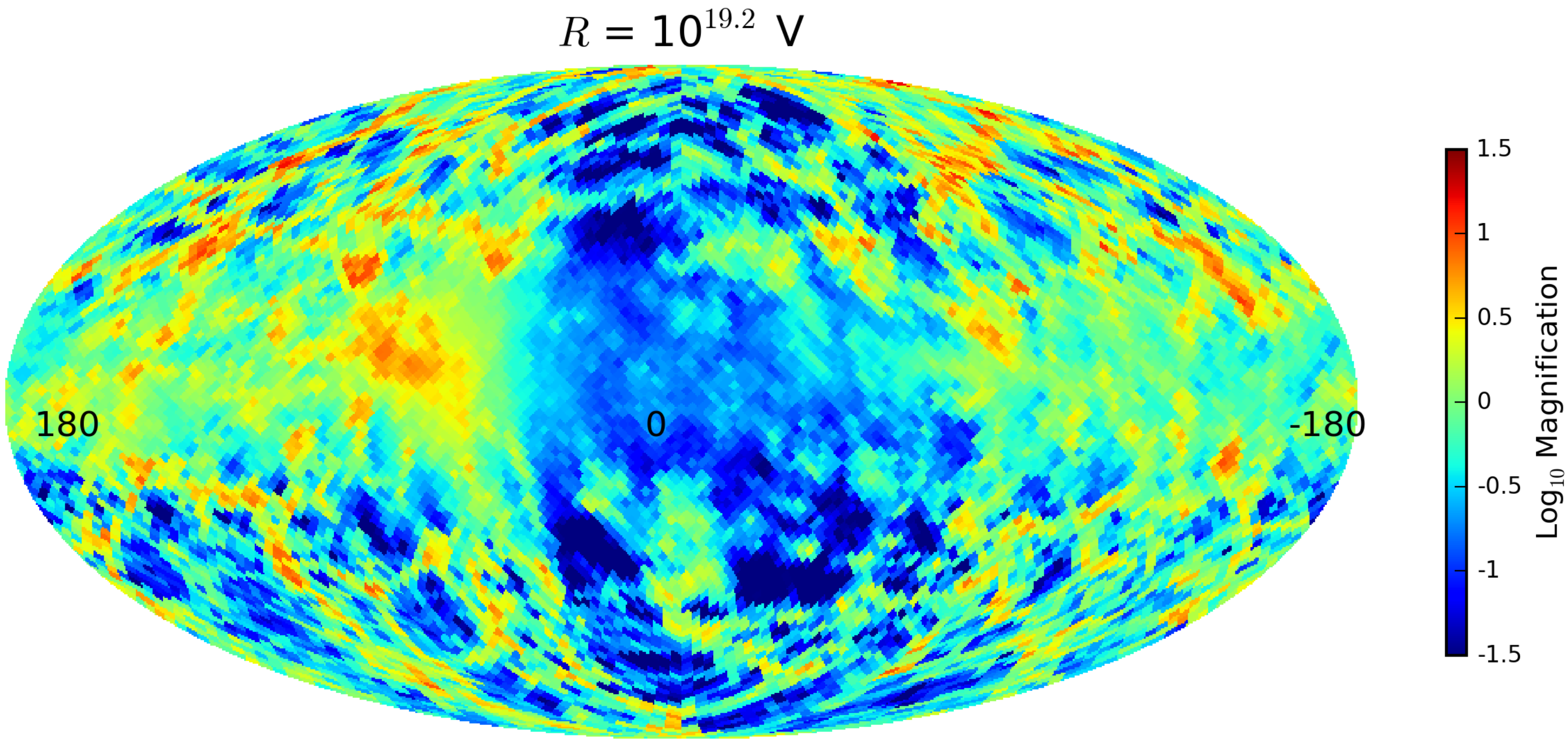
rigidity = 40 **EV**

Magnification as a function of rigidity



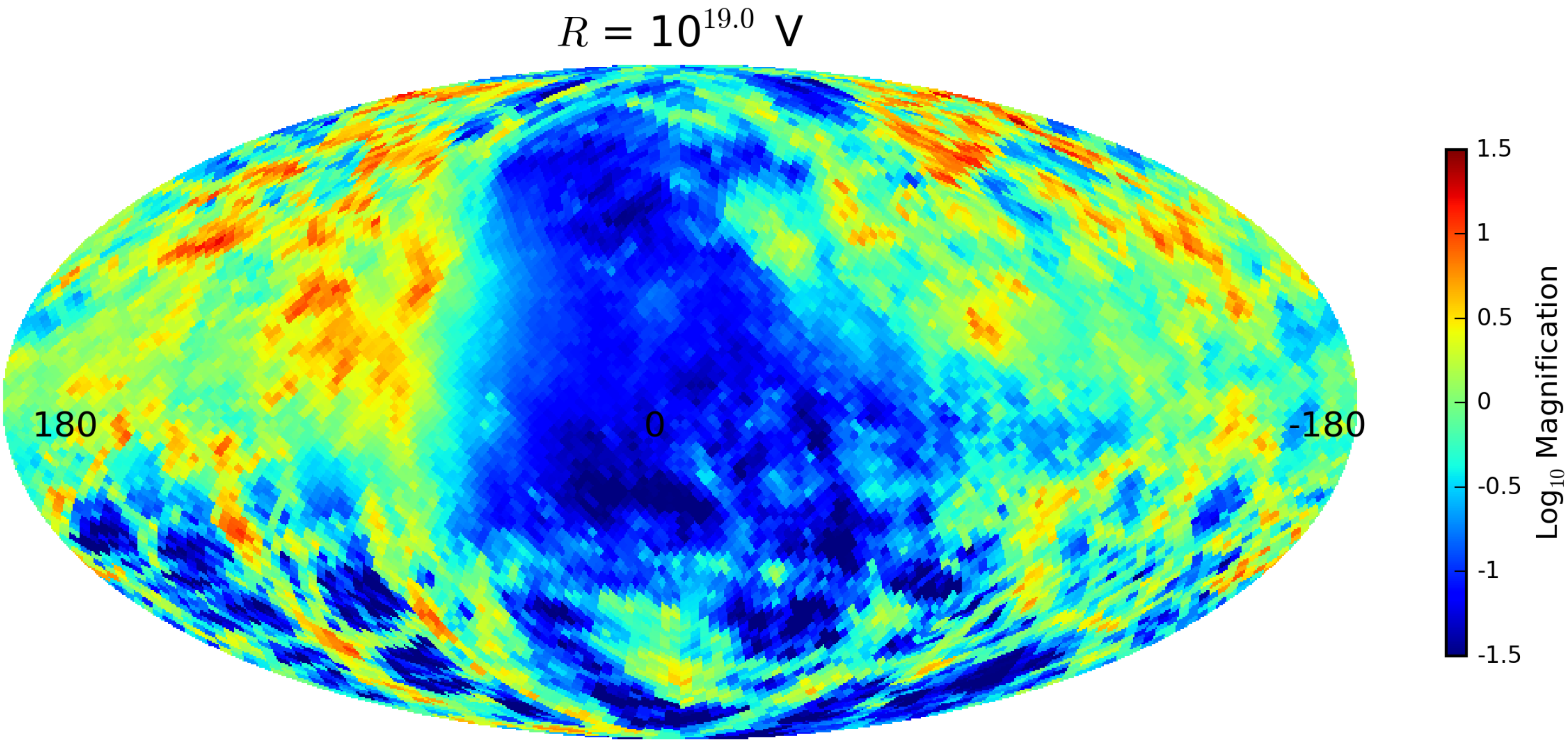
rigidity = 25 **EV**

Magnification as a function of rigidity



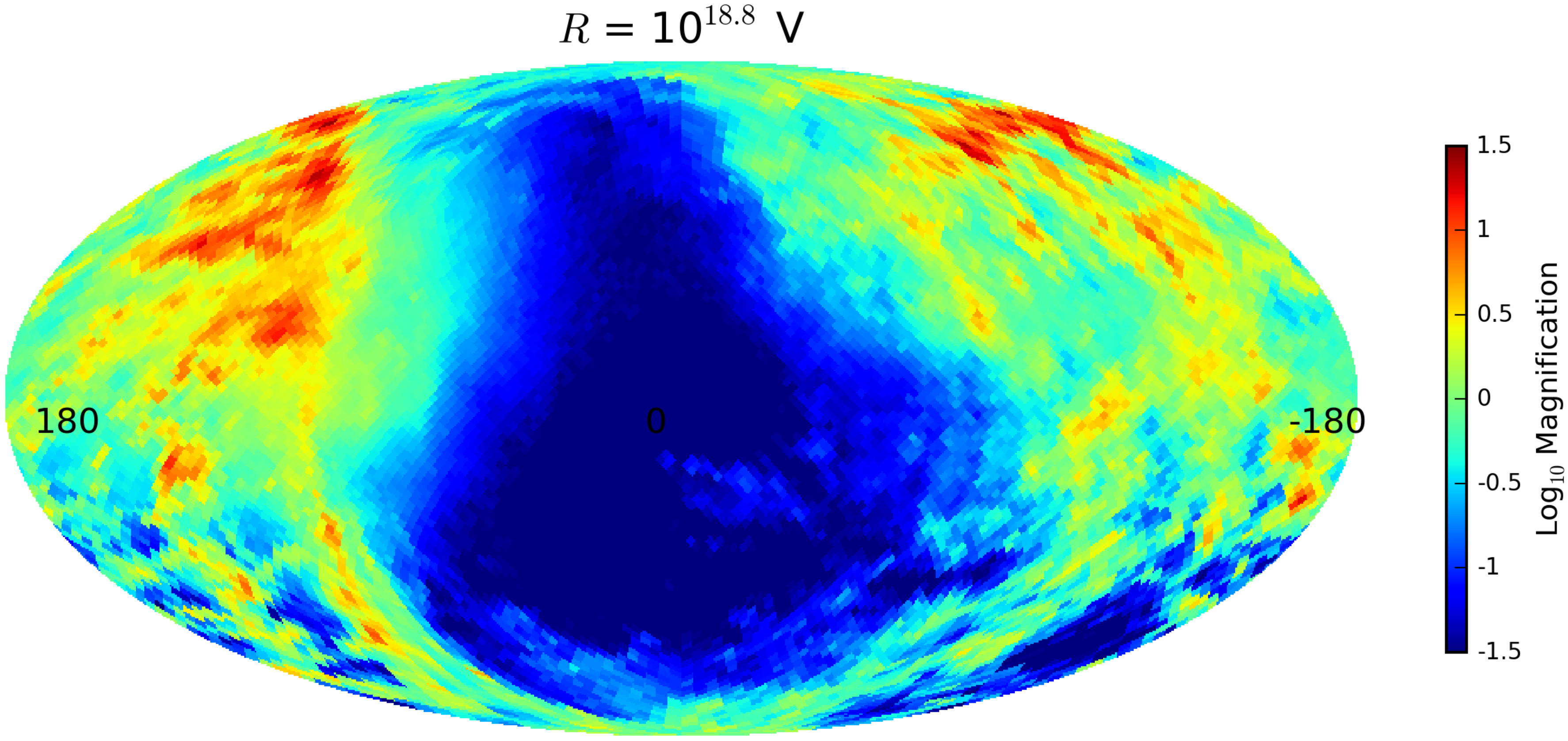
rigidity = **16 EV**

Magnification as a function of rigidity



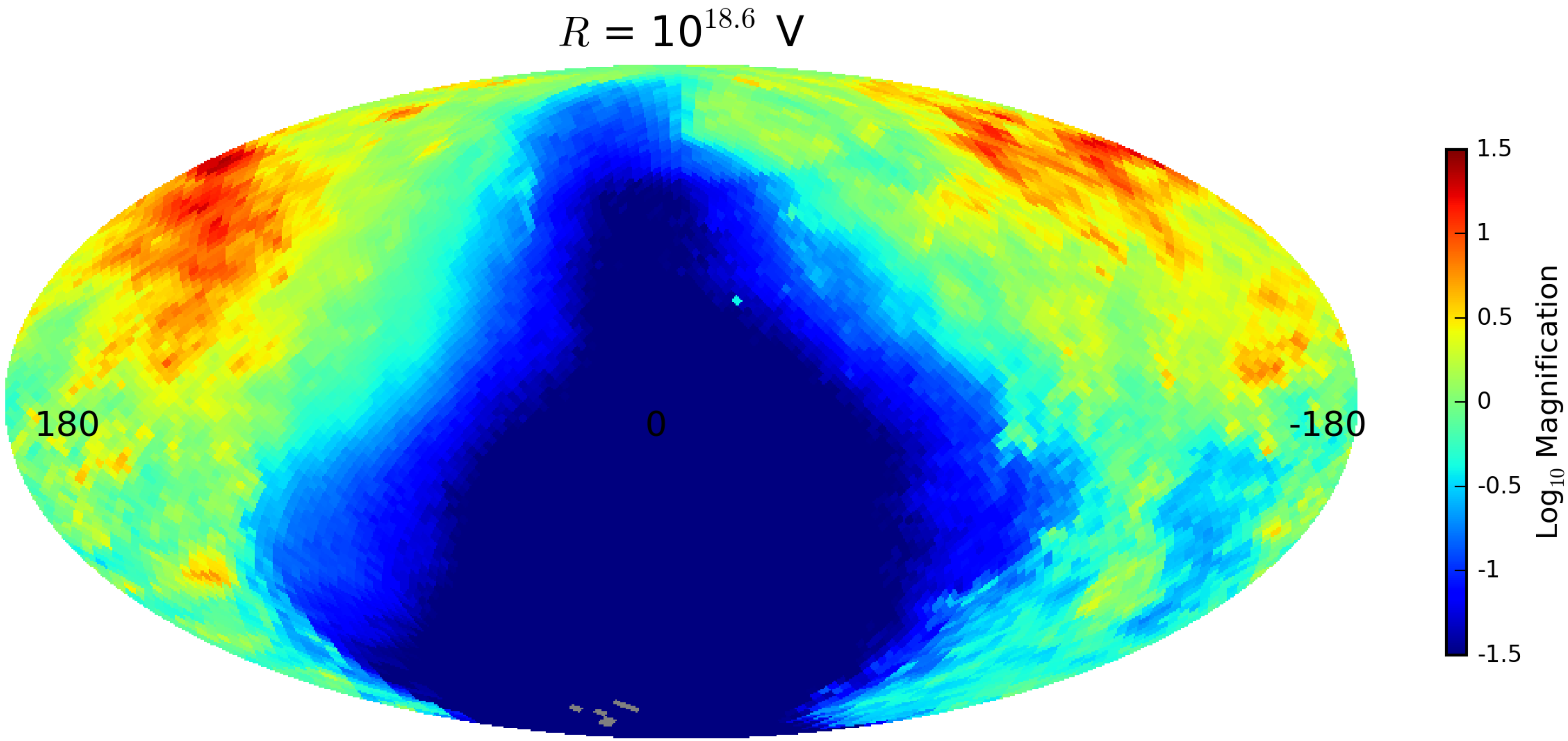
rigidity = **10 EV**

Magnification as a function of rigidity



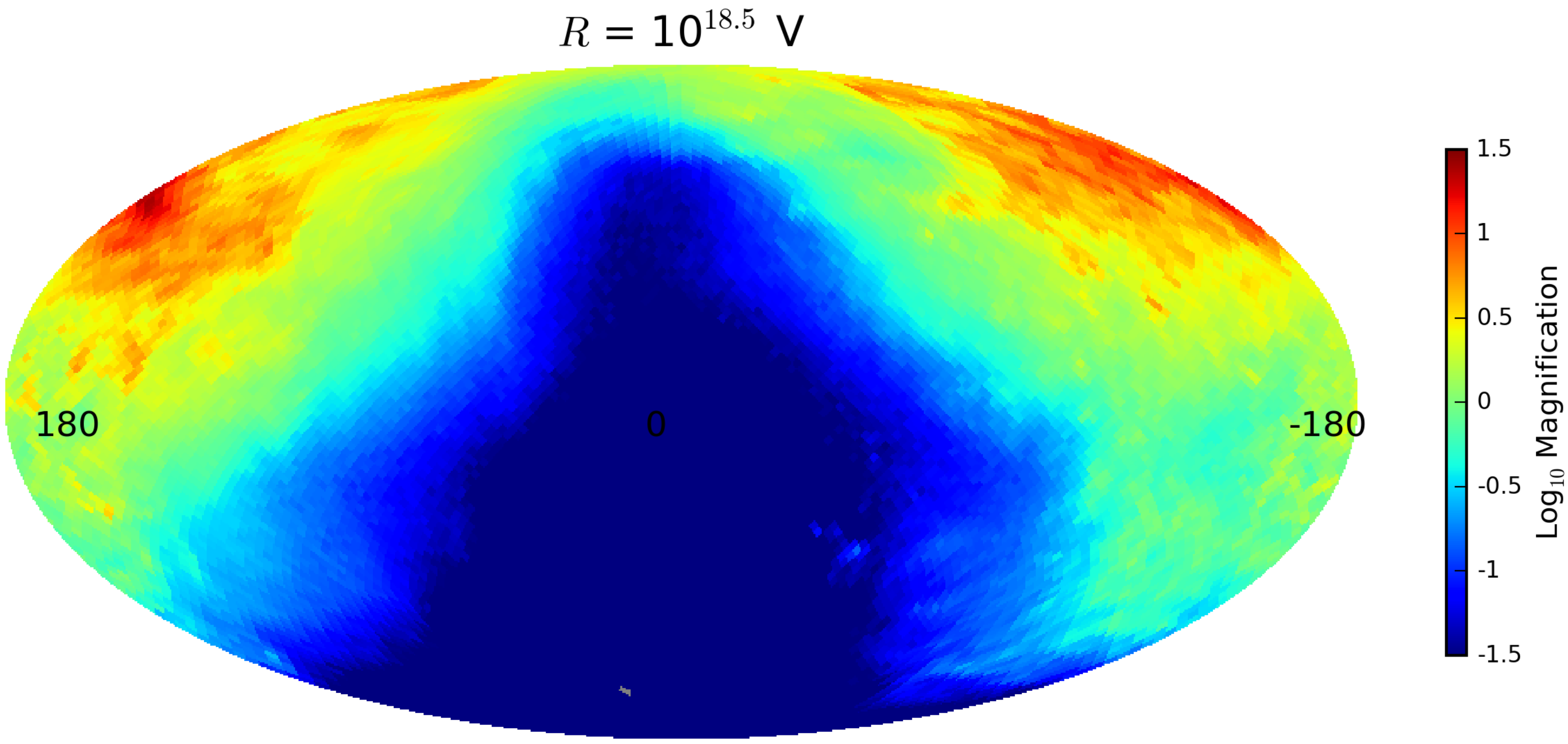
rigidity = 6E**V**

Magnification as a function of rigidity



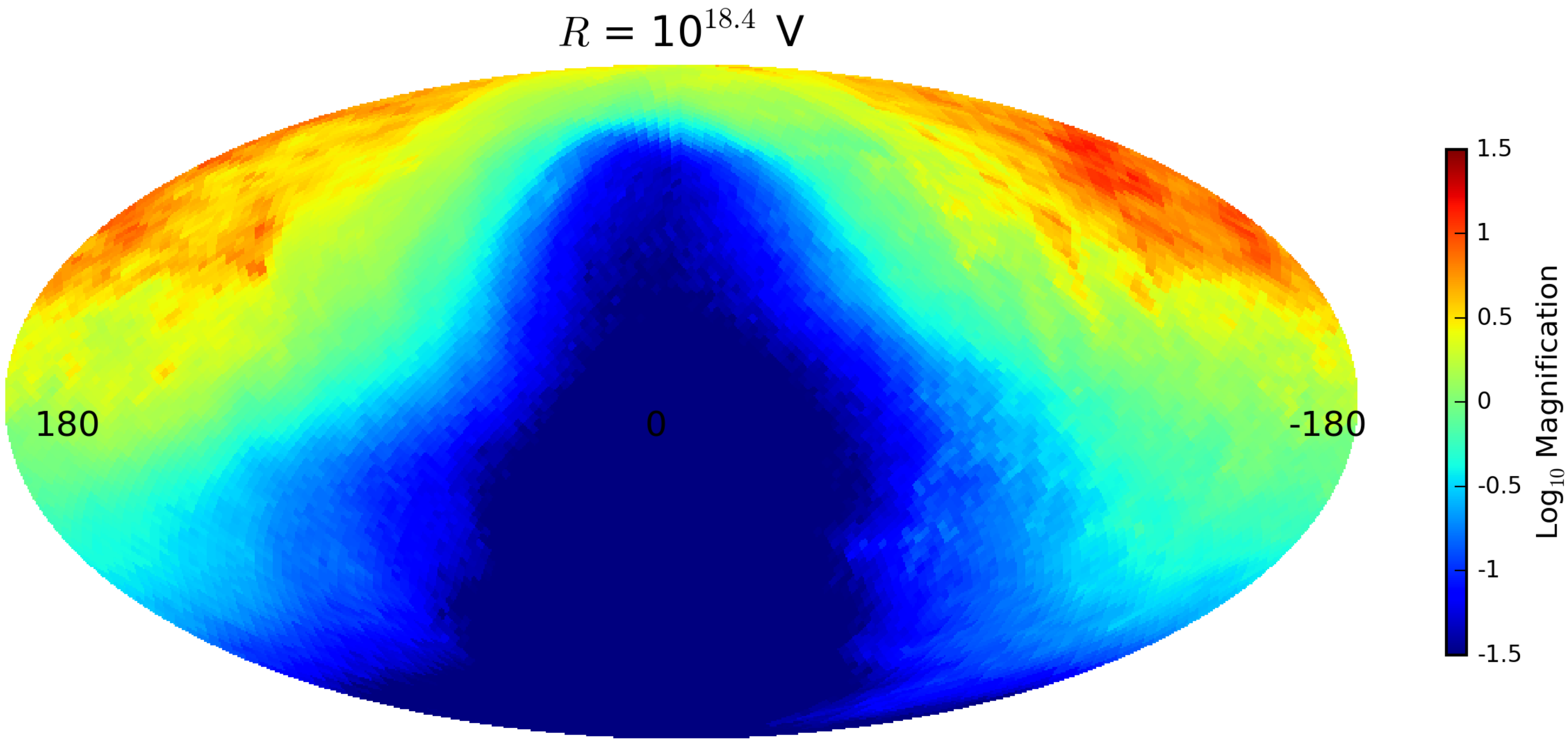
rigidity = **4 EV**

Magnification as a function of rigidity



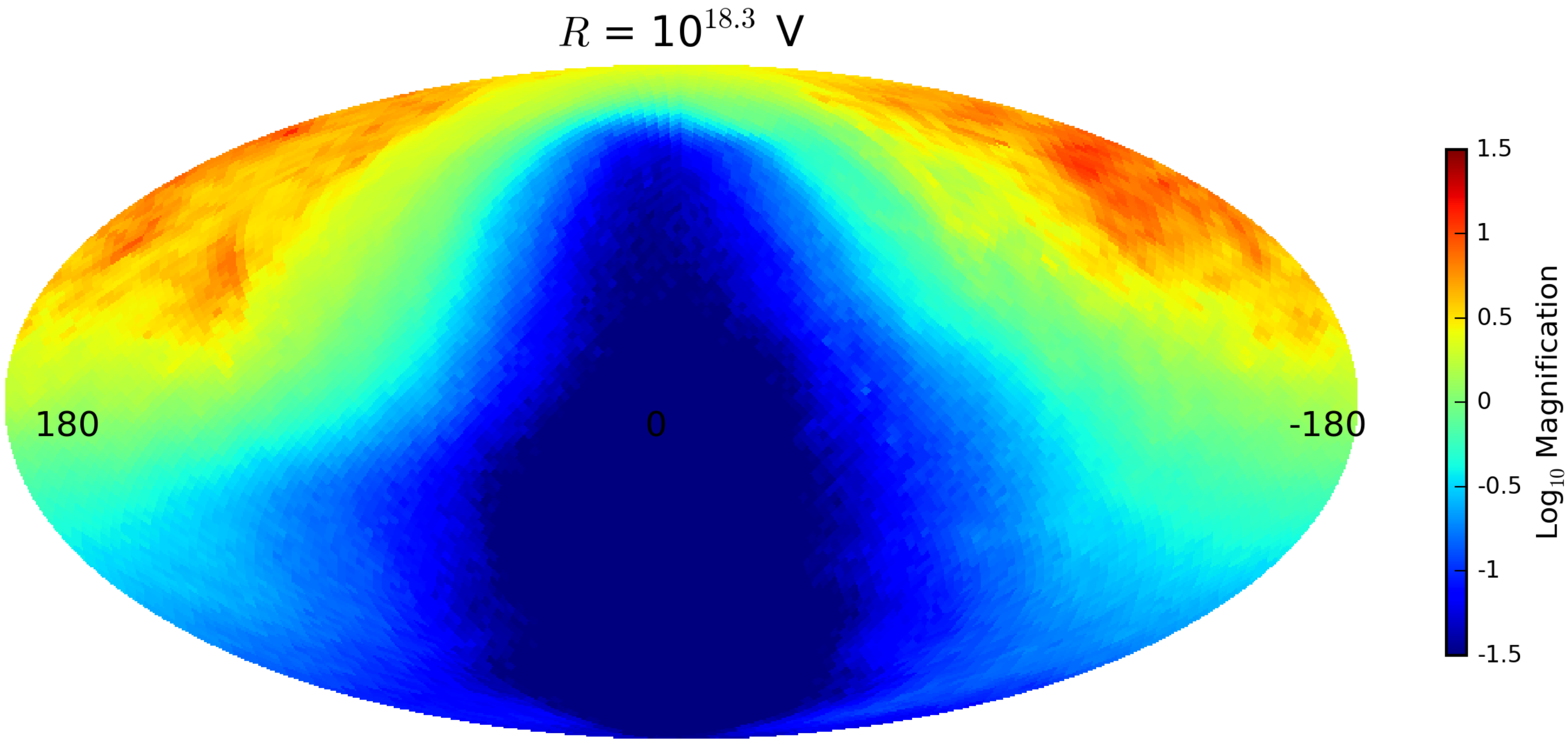
rigidity = **3 EV**

Magnification as a function of rigidity



rigidity = 2.5 E**V**

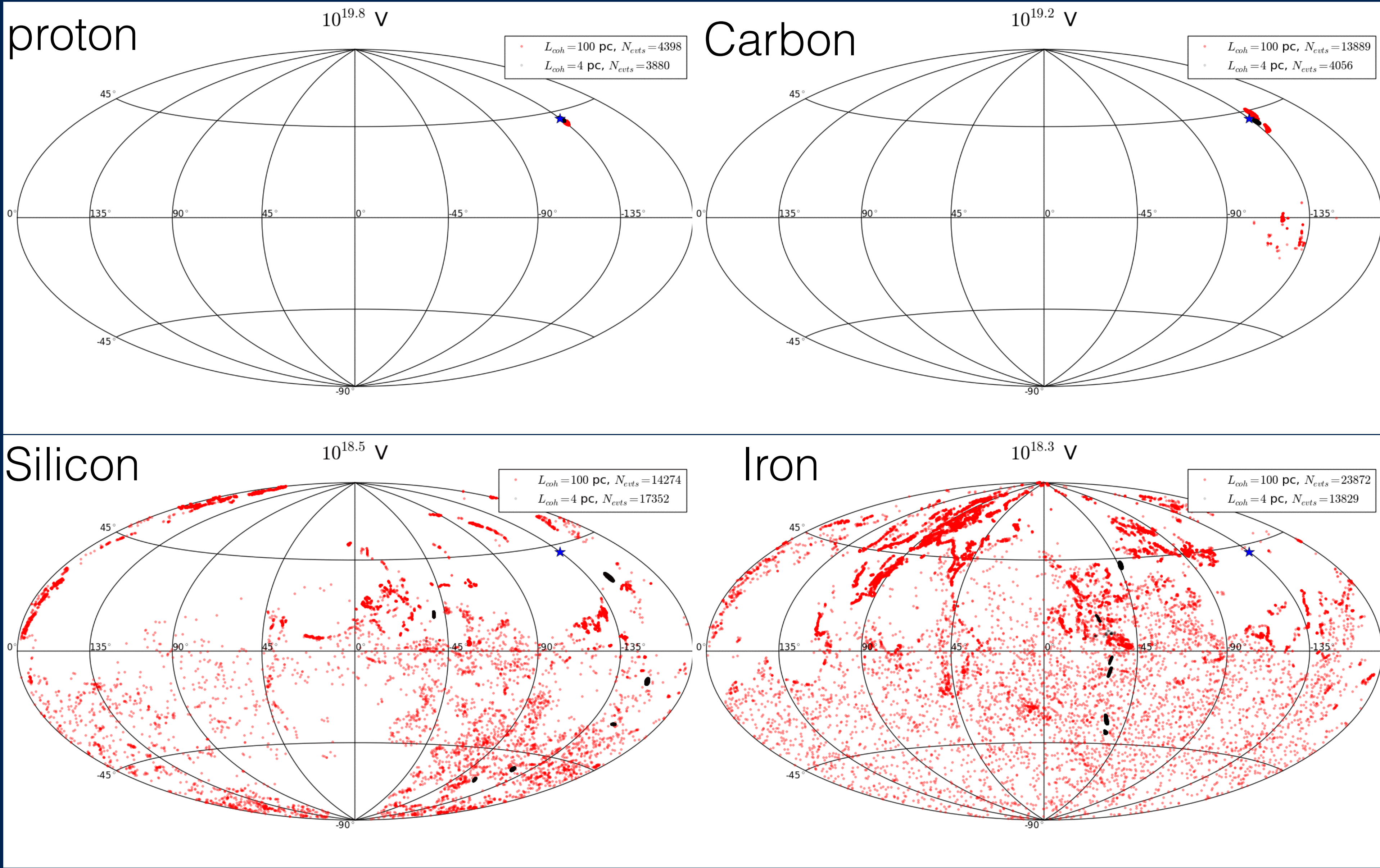
Magnification as a function of rigidity



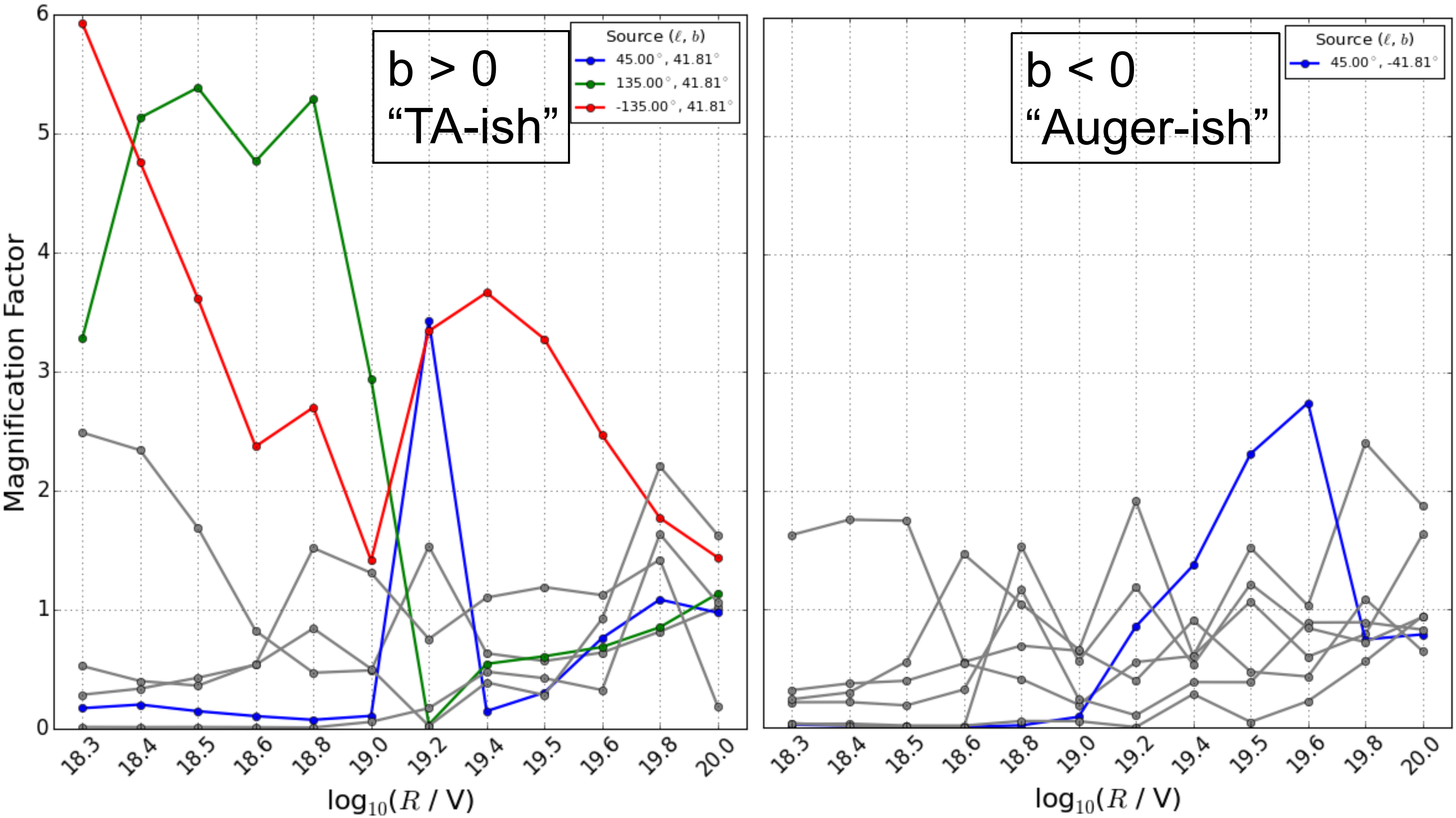
rigidity = 2 E**V**

UHECR deflection in the GMF

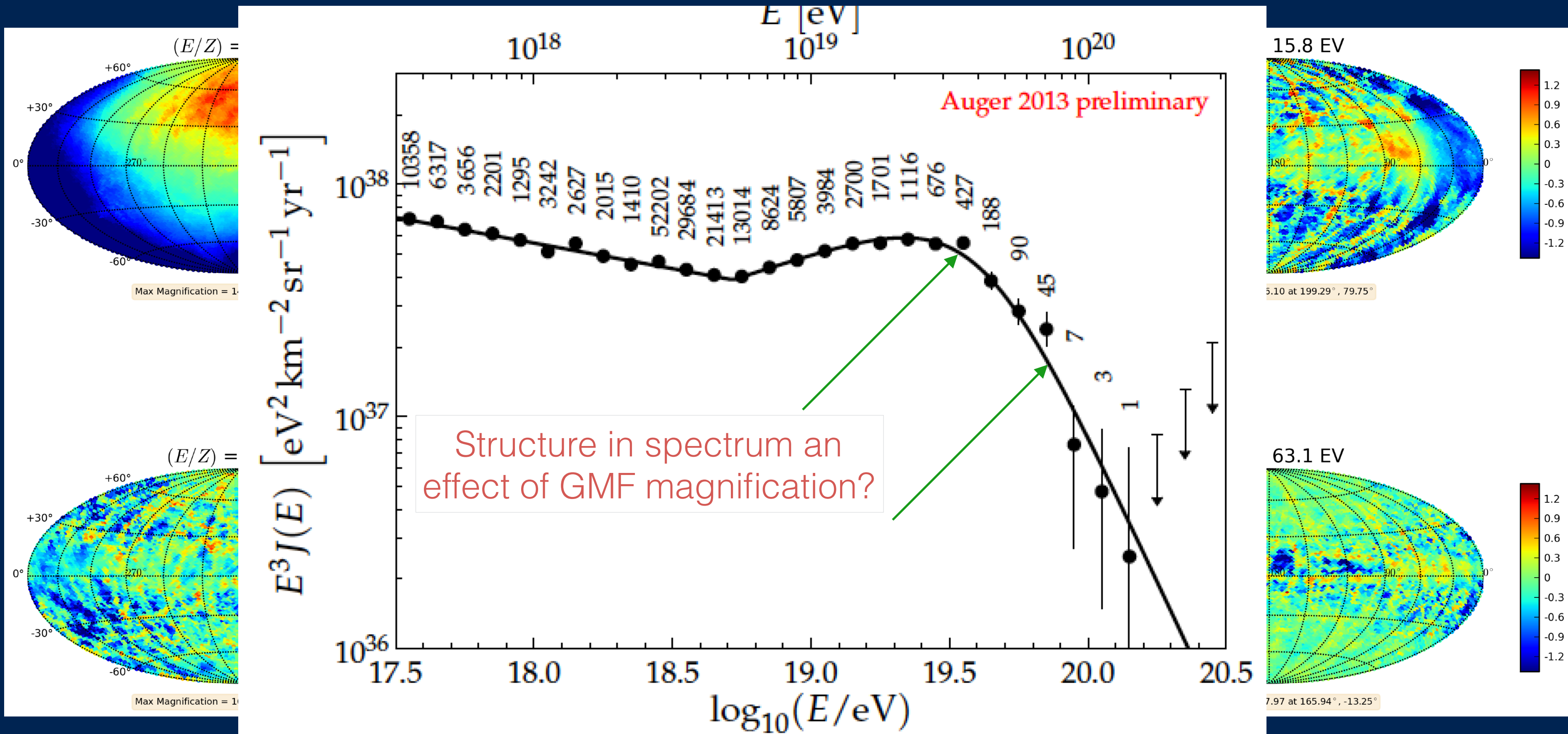
depends on composition and *GMF turbulent coherence lengths*



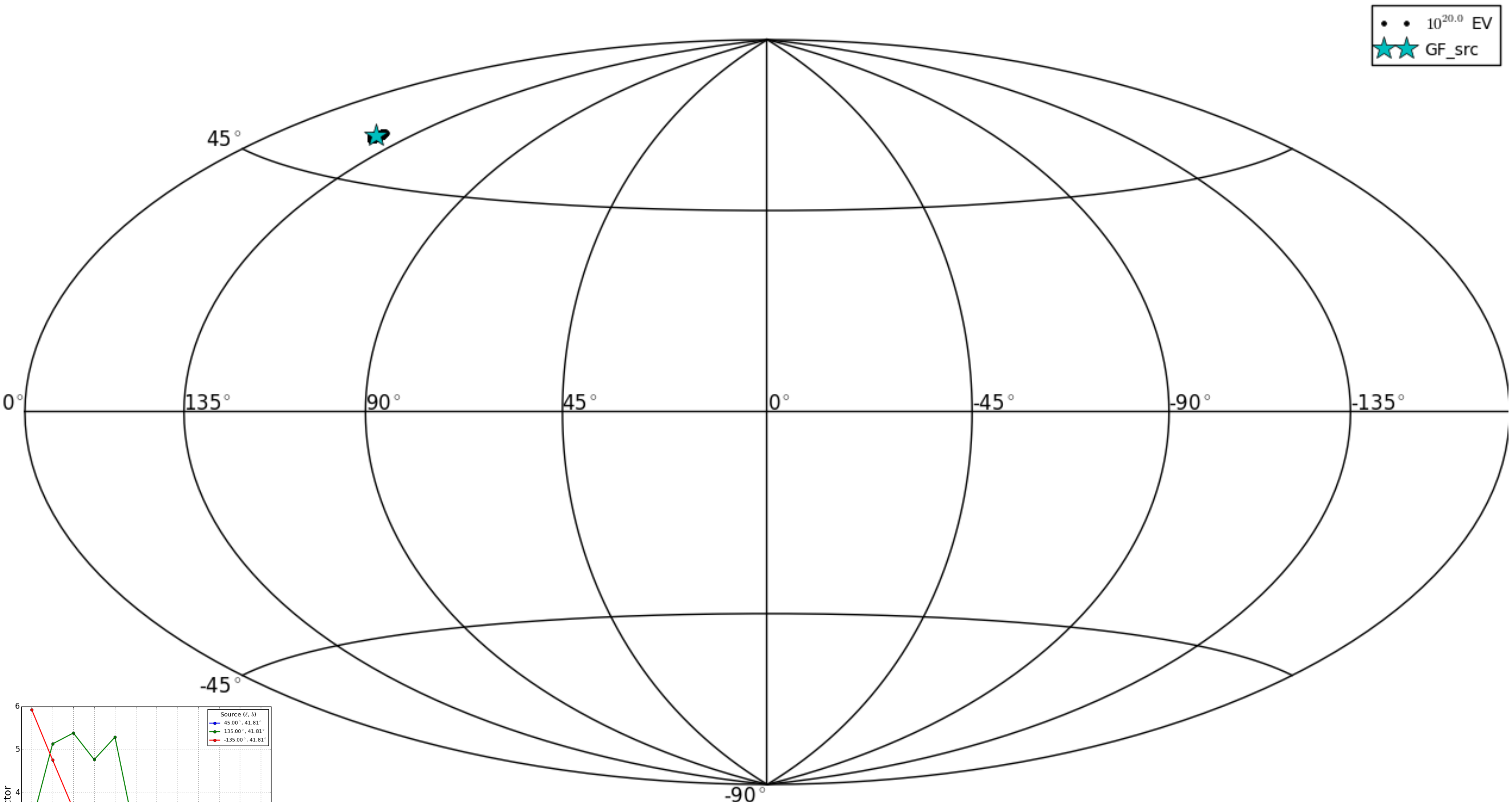
Magnification can be strongly rigidity dependent: illustrated for 14 source positions

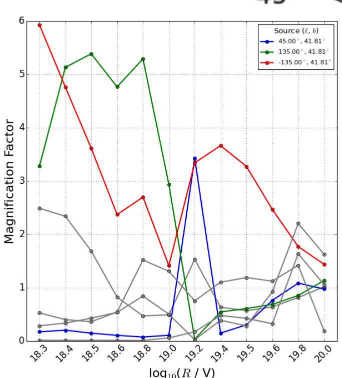


Can structure in Auger spectrum be a GMF magnification effect?



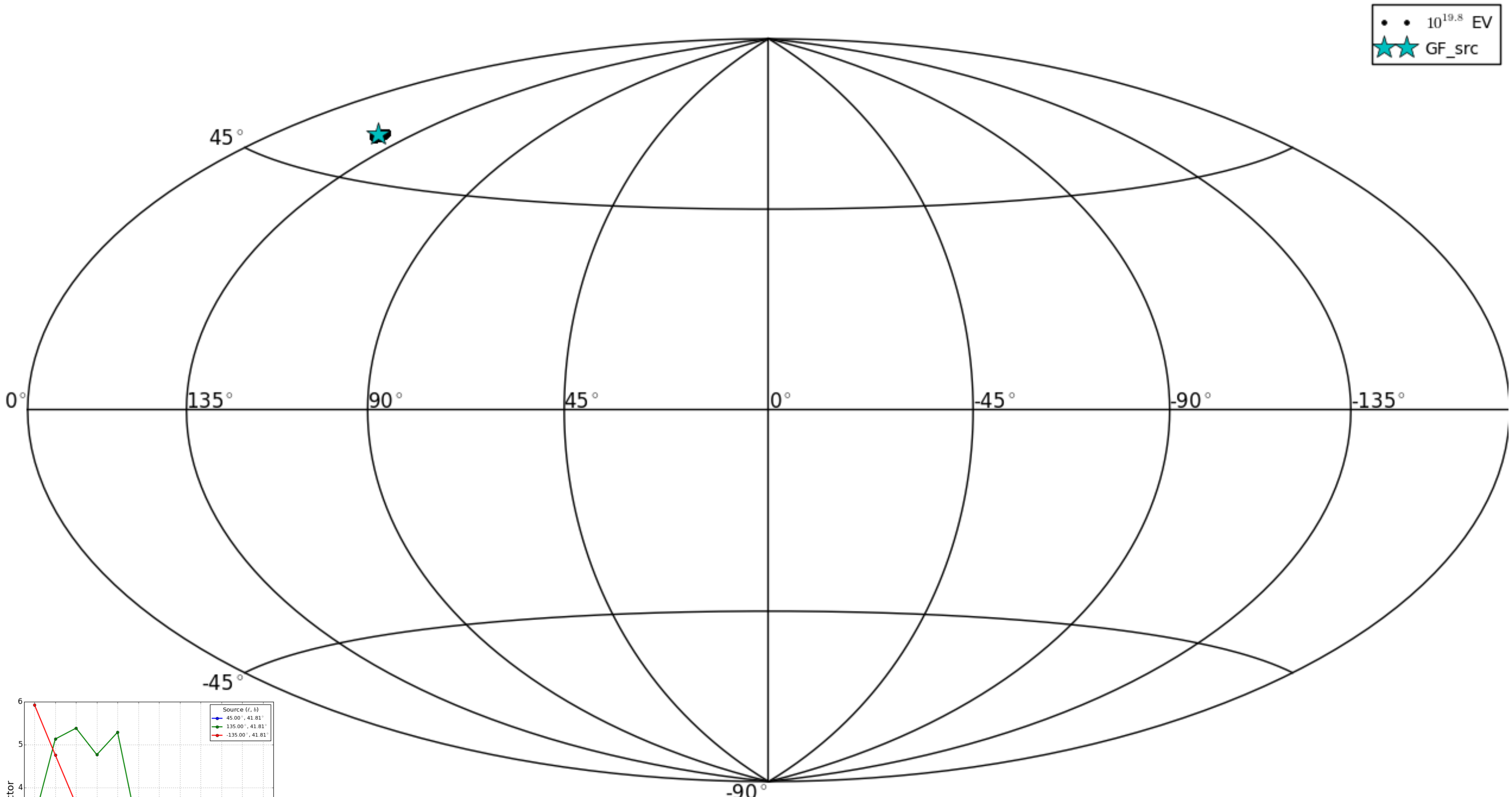
Arrival Directions from CGCG291-028

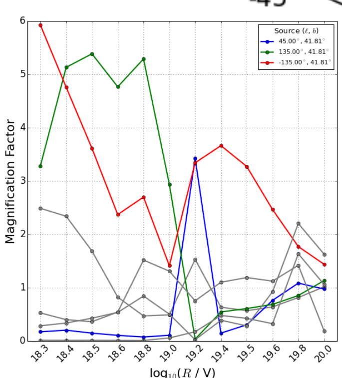




rigidity = **10^{20} V**

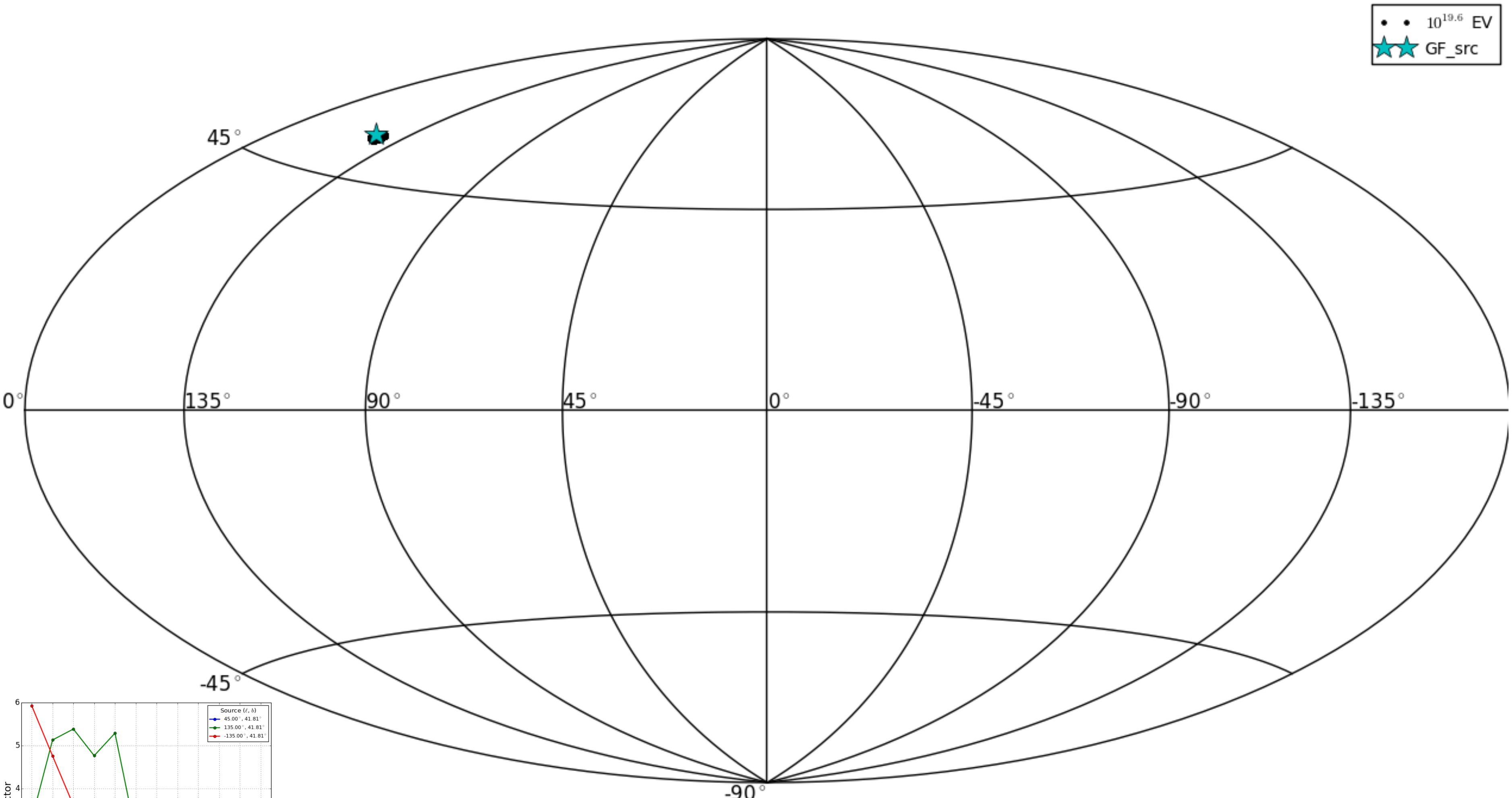
Arrival Directions from CGCG291-028

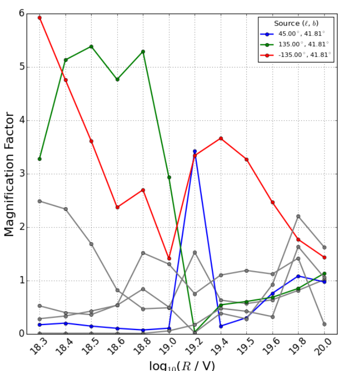




rigidity = 63 **EV**

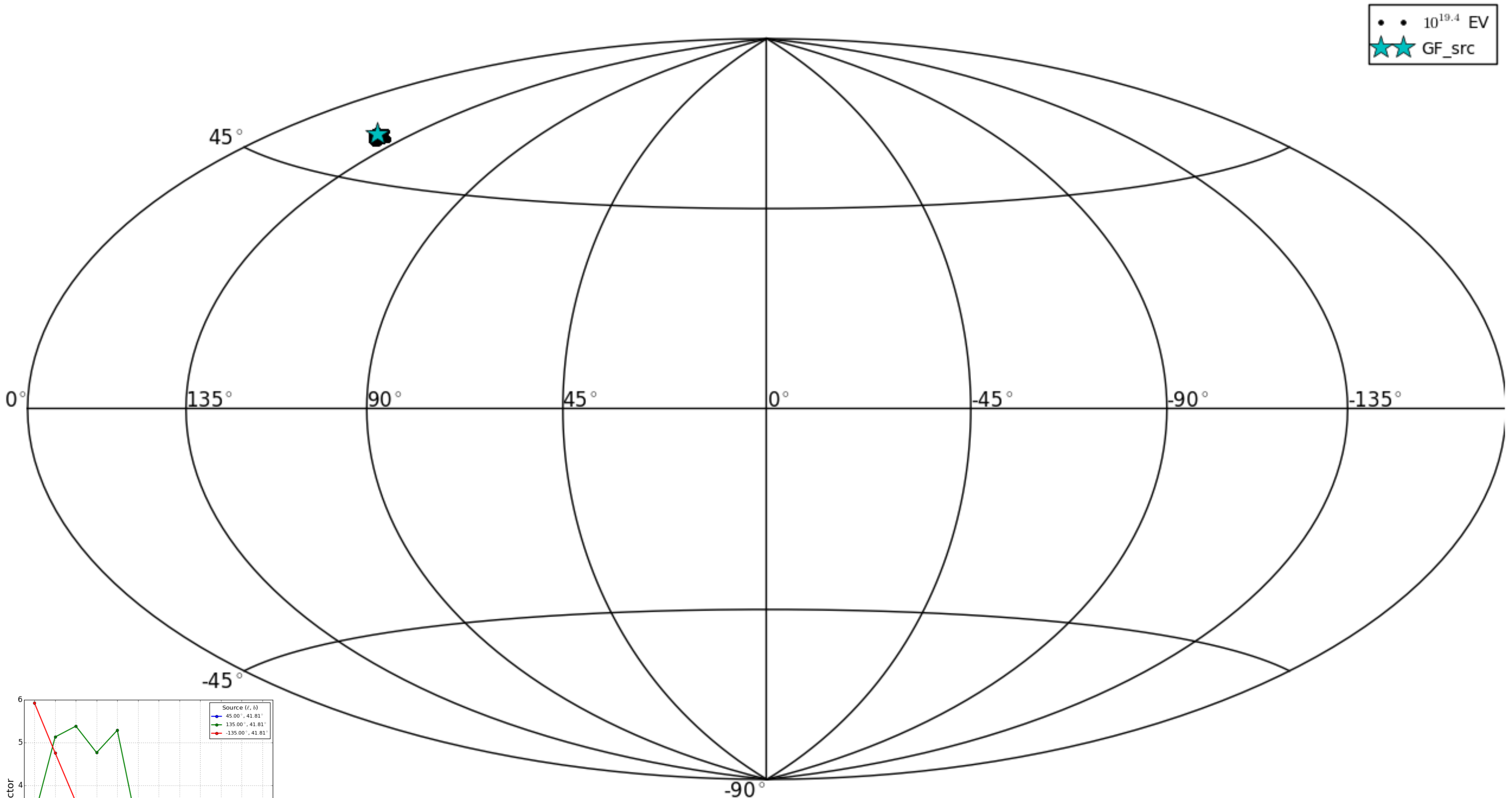
Arrival Directions from CGCG291-028

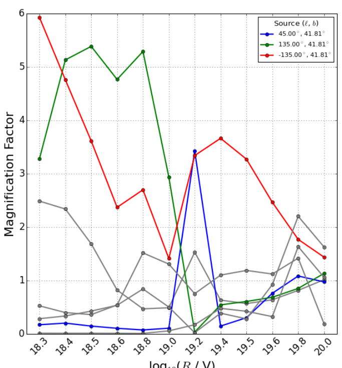




rigidity = 40 **EV**

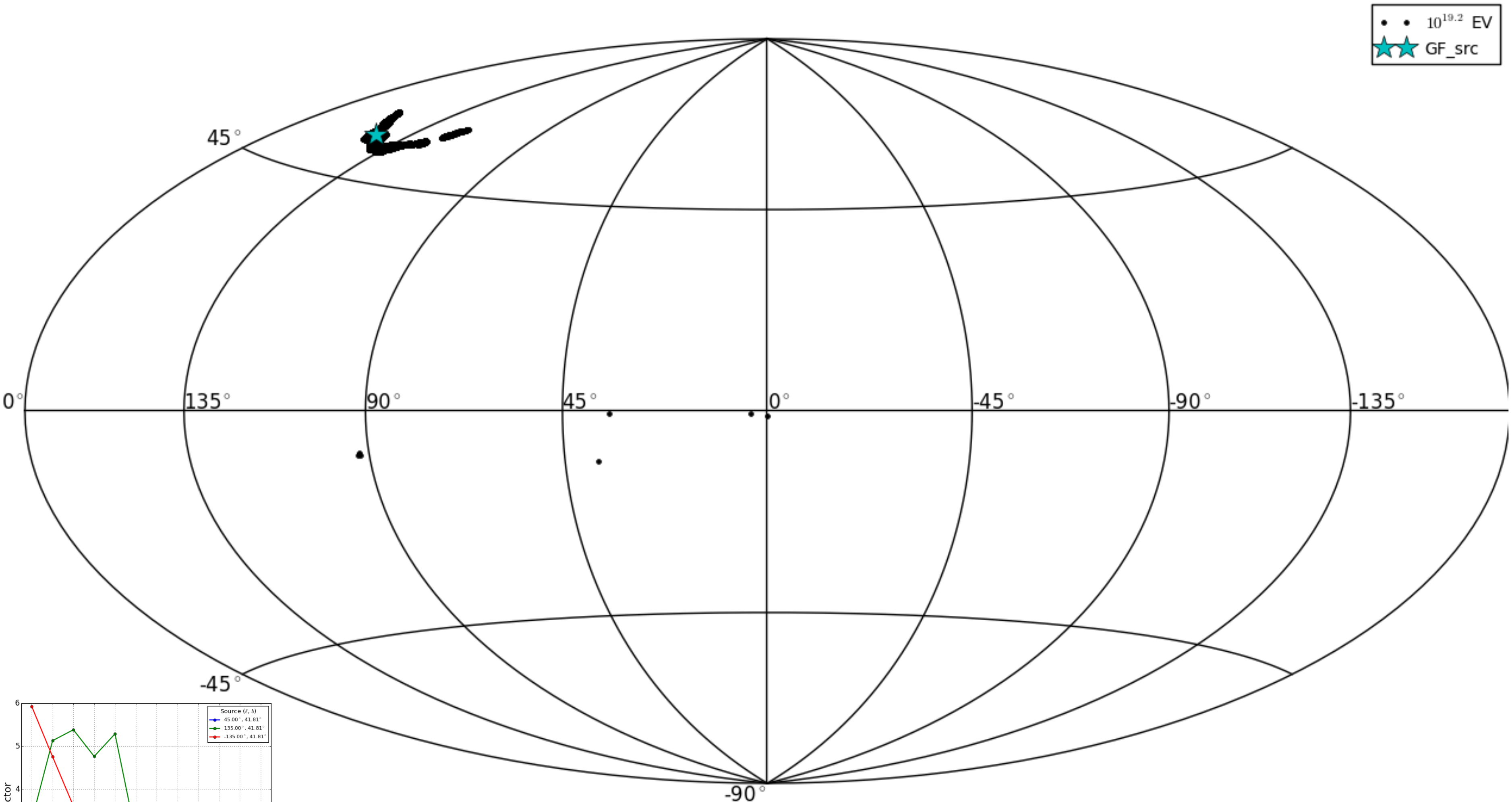
Arrival Directions from CGCG291-028

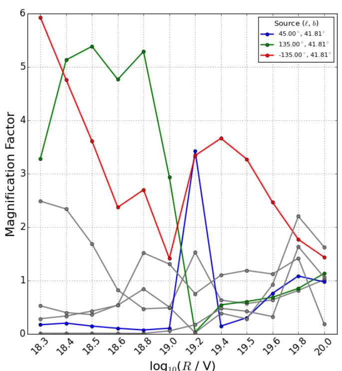




rigidity = 25 **EV**

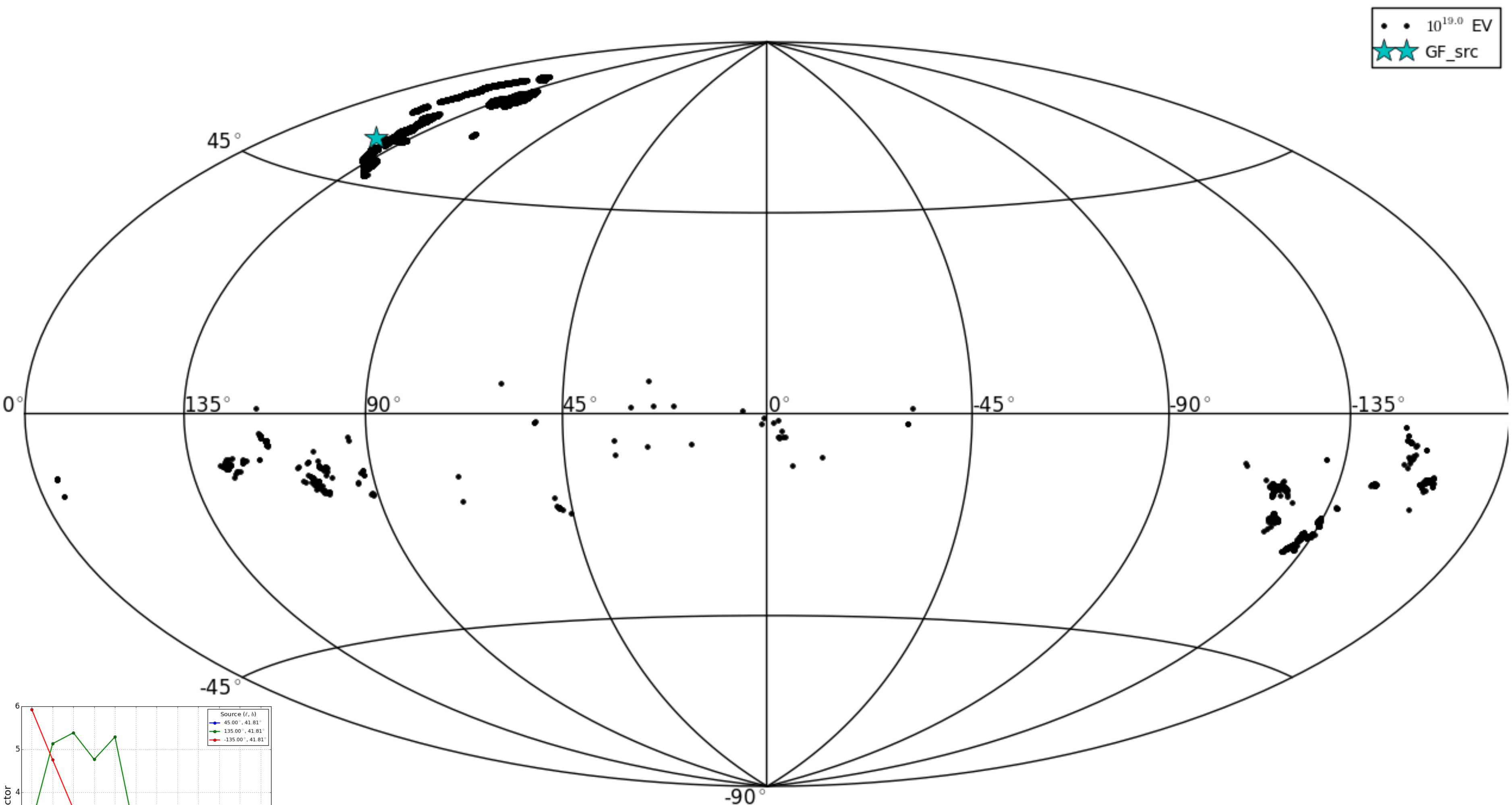
Arrival Directions from CGCG291-028

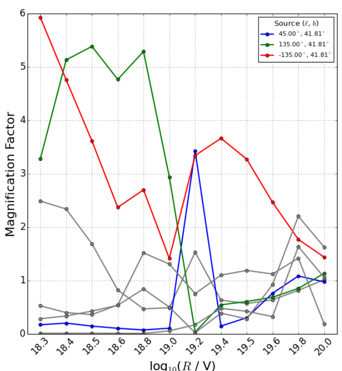




rigidity = **16 EV**

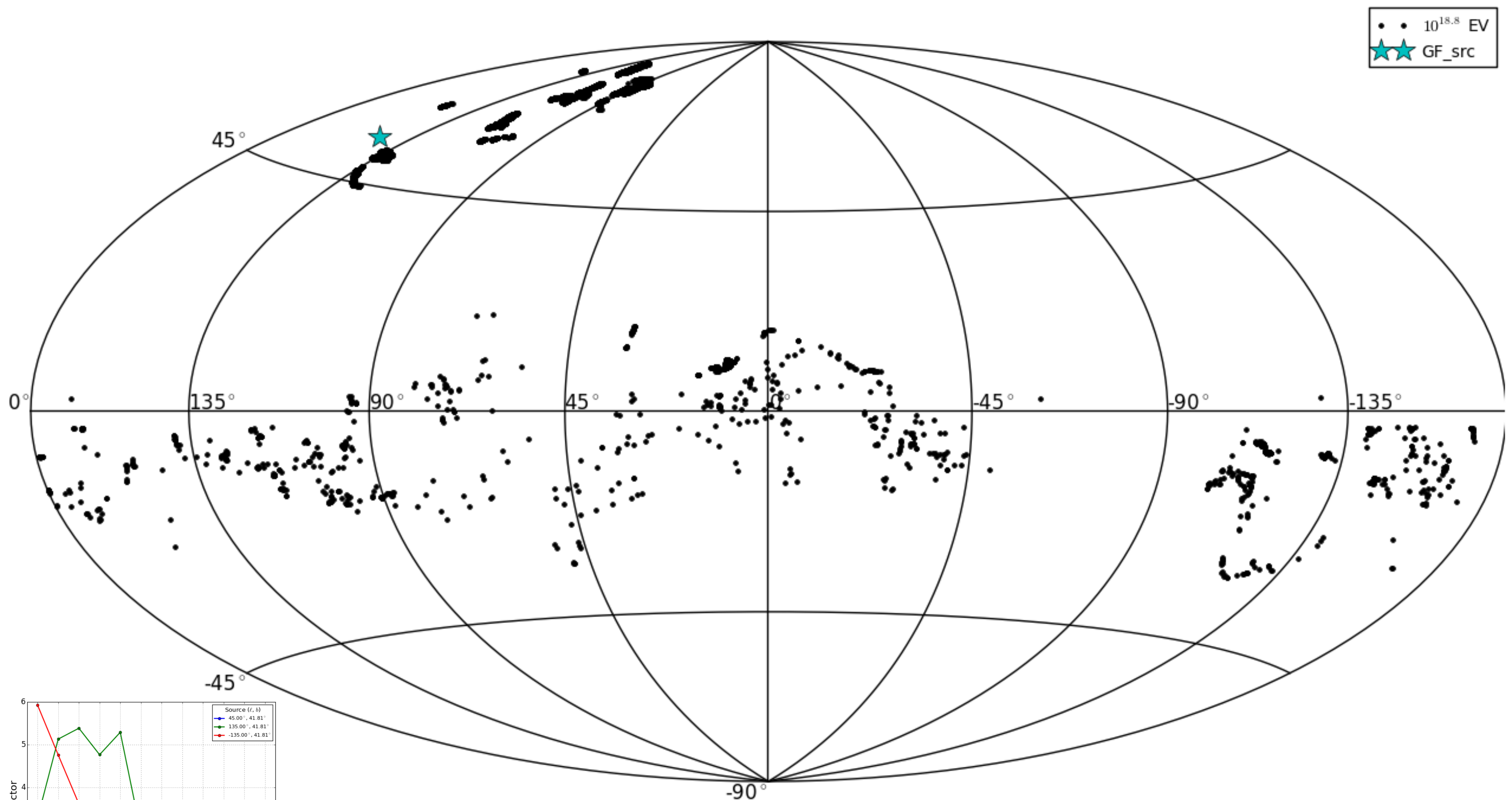
Arrival Directions from CGCG291-028

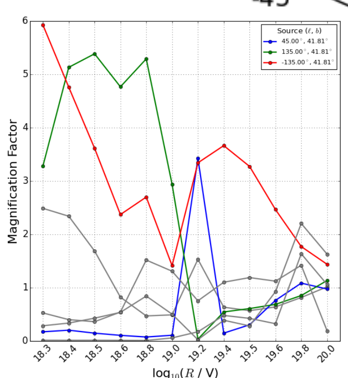




rigidity = **10 EV**

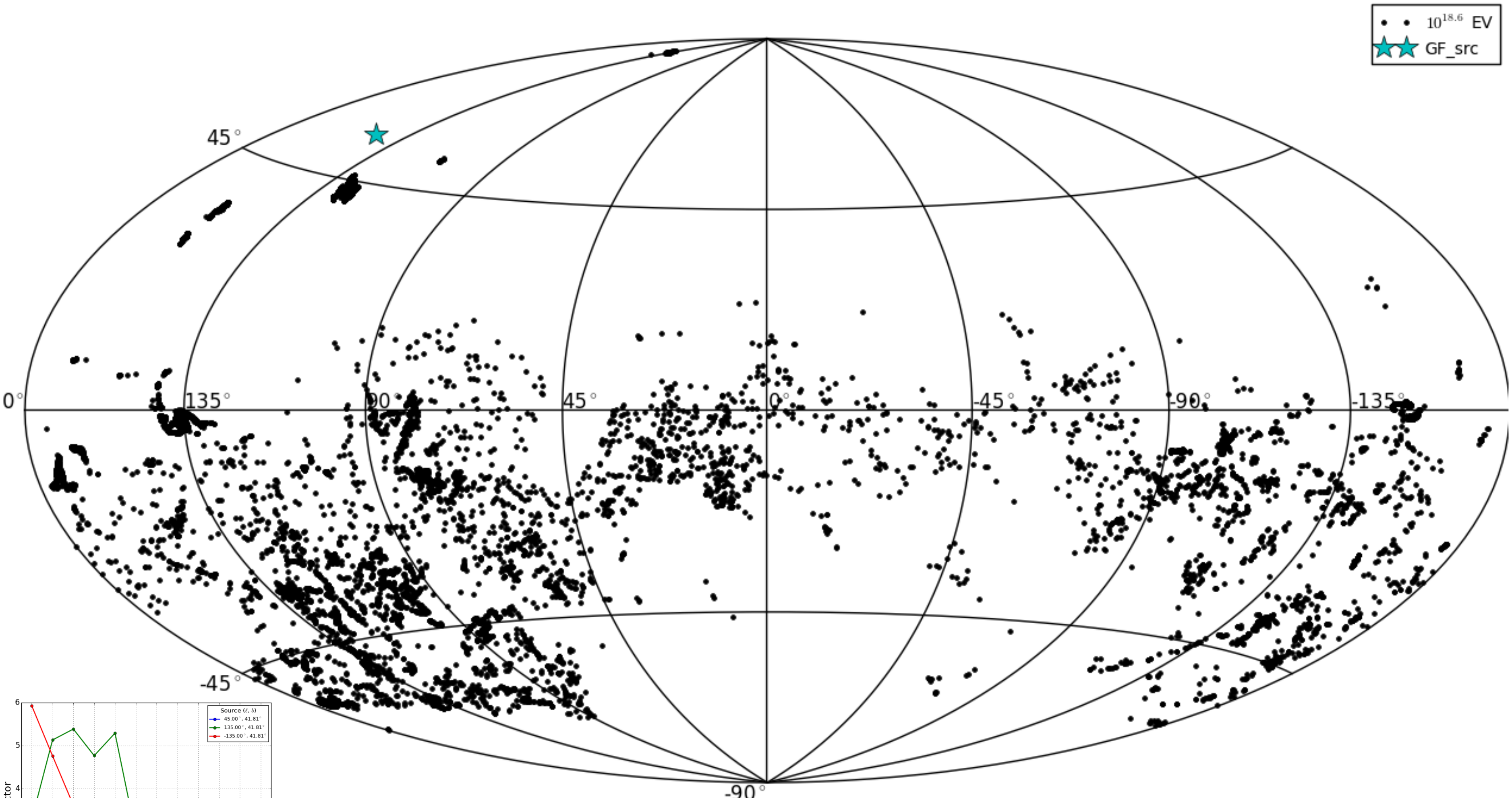
Arrival Directions from CGCG291-028

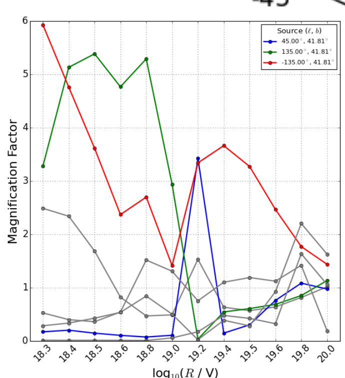




rigidity = 6E**V**

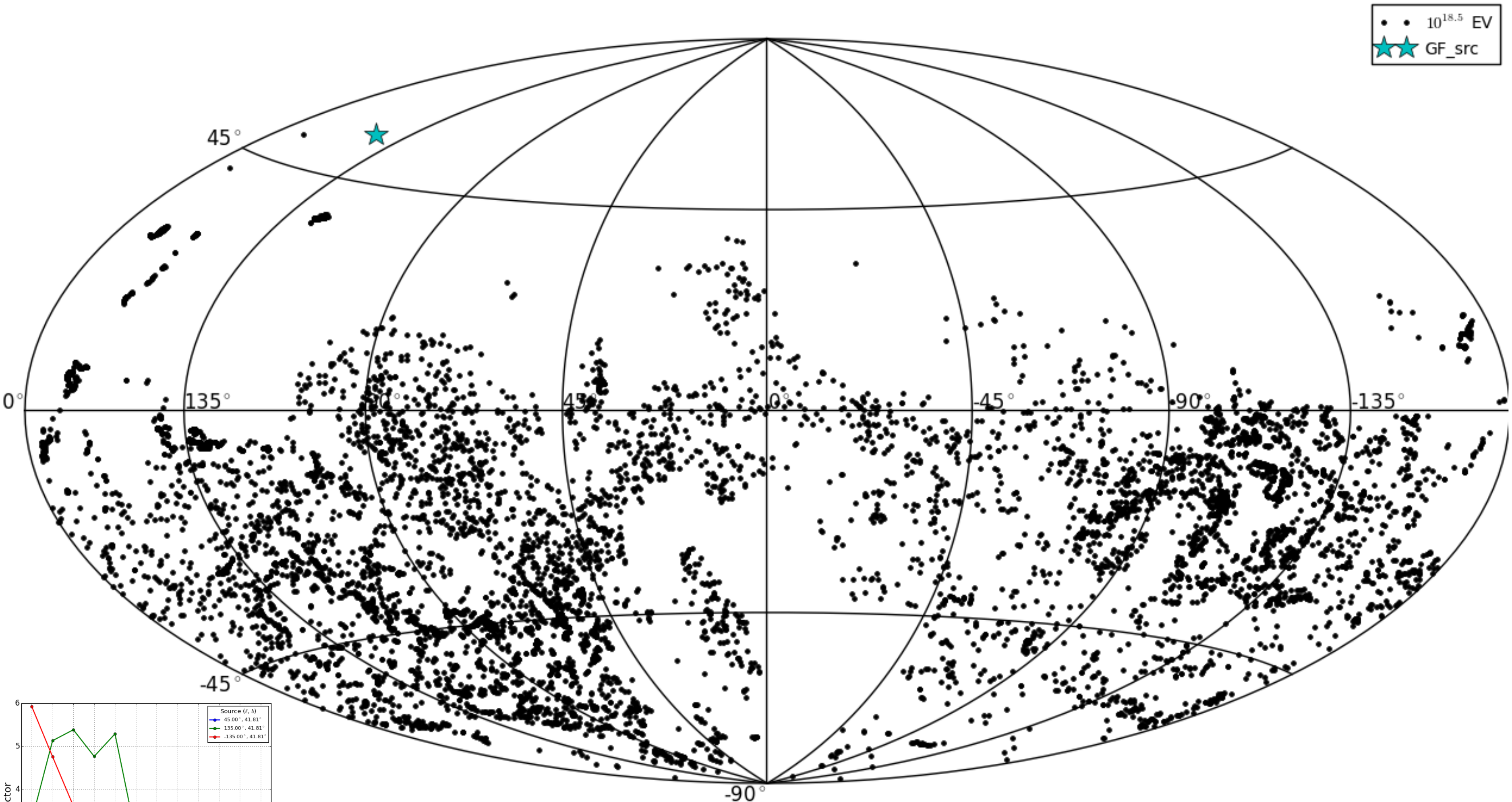
Arrival Directions from CGCG291-028

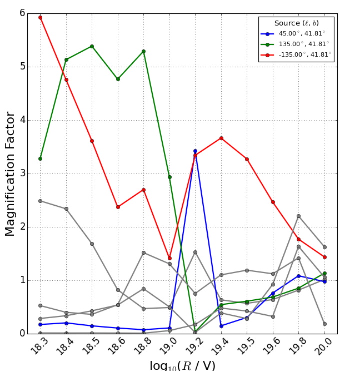




rigidity = **4 EV**

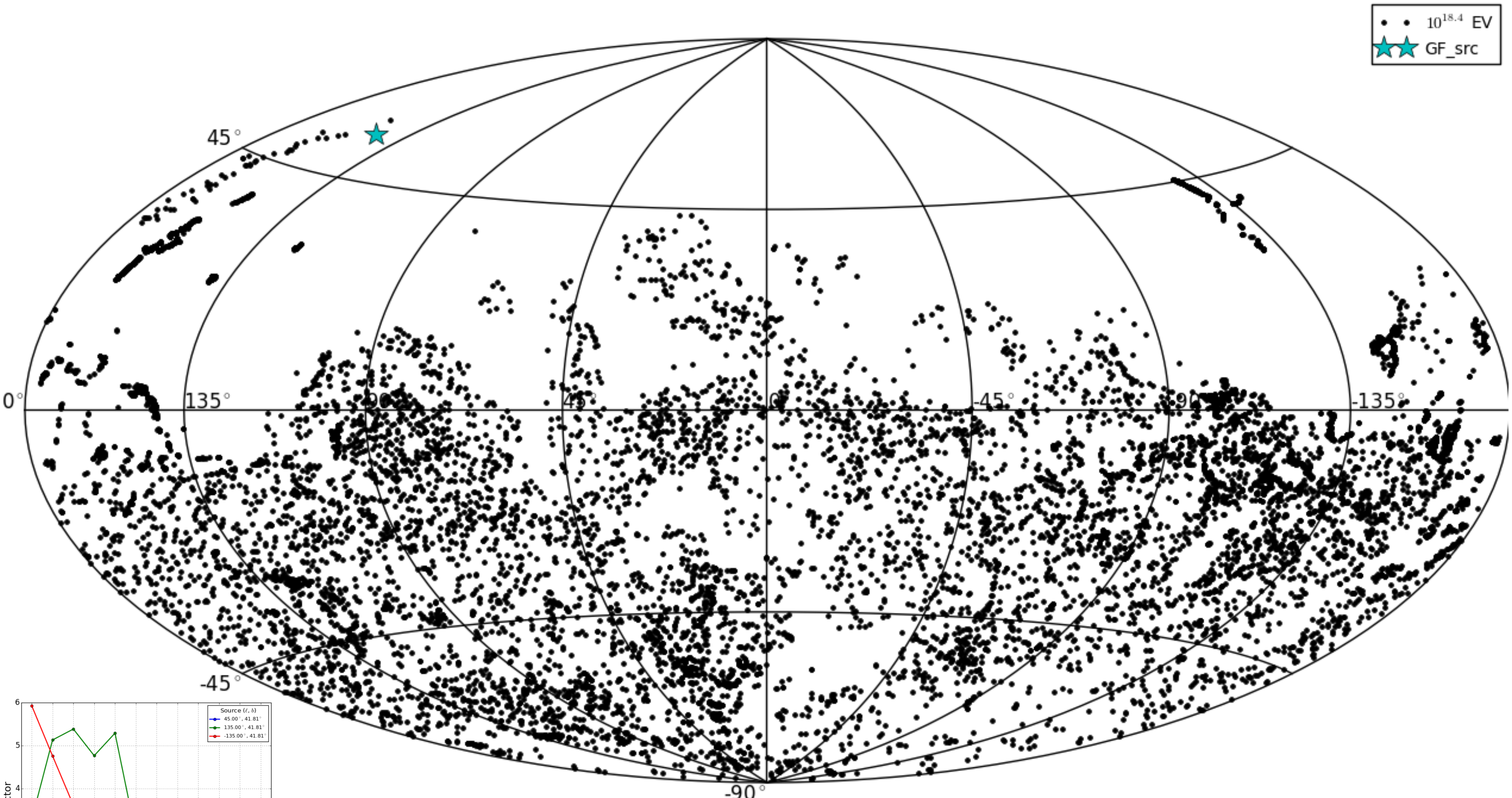
Arrival Directions from CGCG291-028

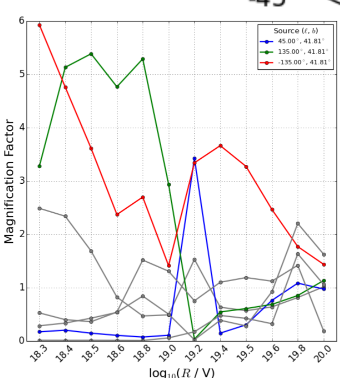




rigidity = 3 EV

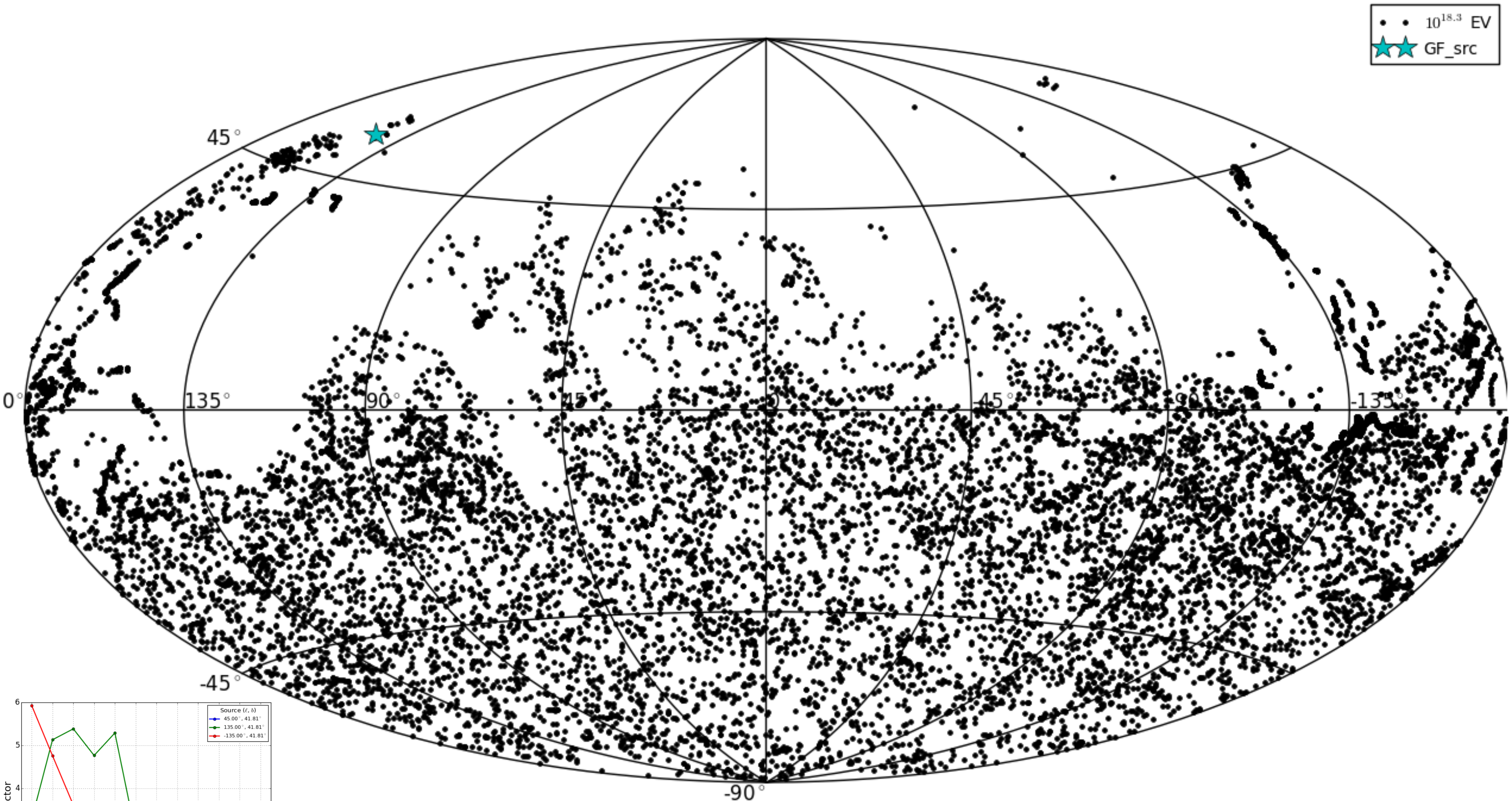
Arrival Directions from CGCG291-028

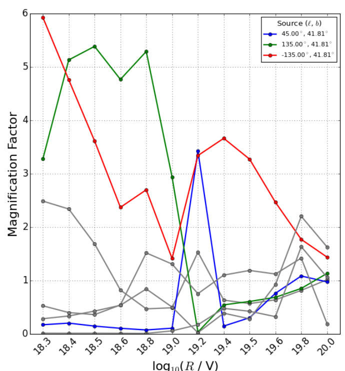




rigidity = 2.5 E**V**

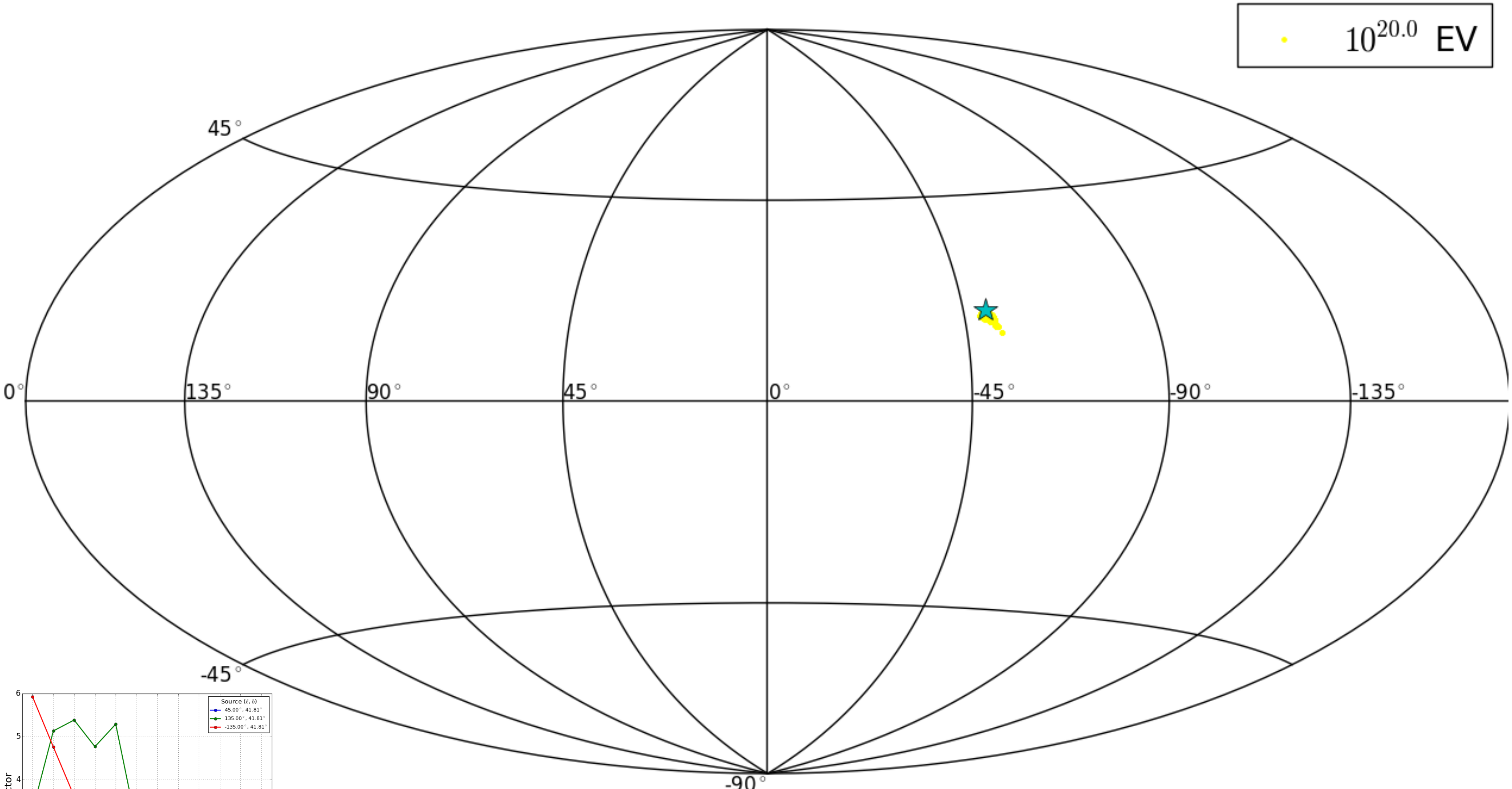
Arrival Directions from CGCG291-028

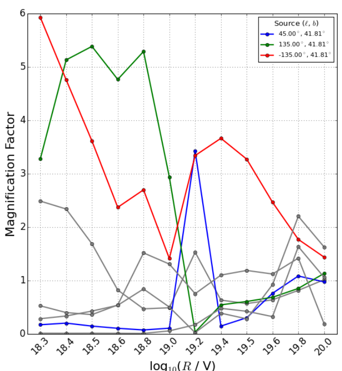




rigidity = $\mathbf{10^{18.3}}$ **V**

Arrival Directions from Cen A nearest plausible source*

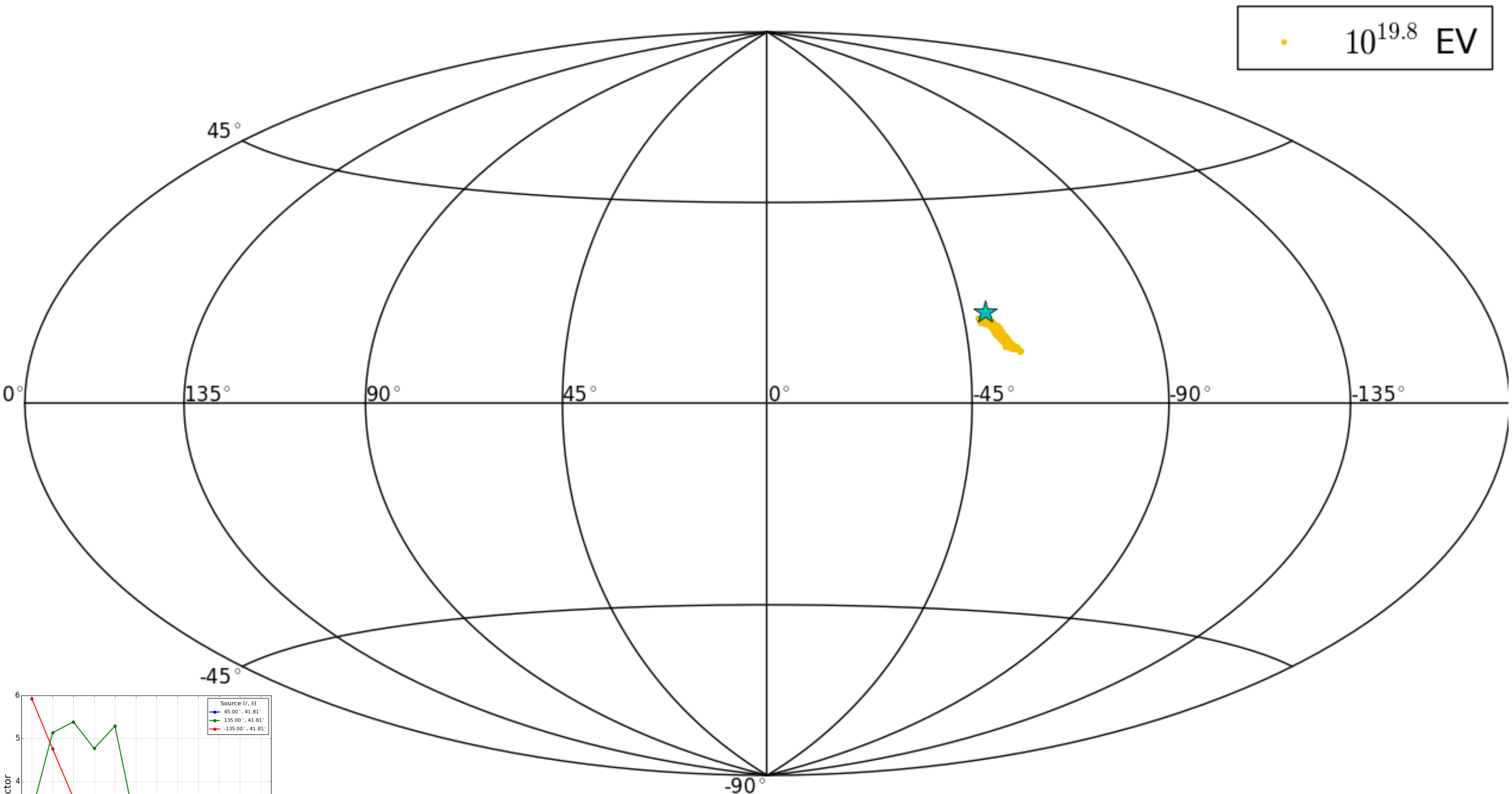


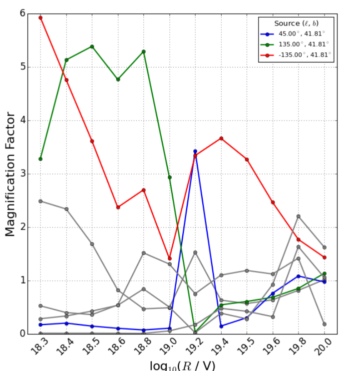


*GRF+T. Piran on sabbatical year at NYU, 1999

rigidity = **100 EV**

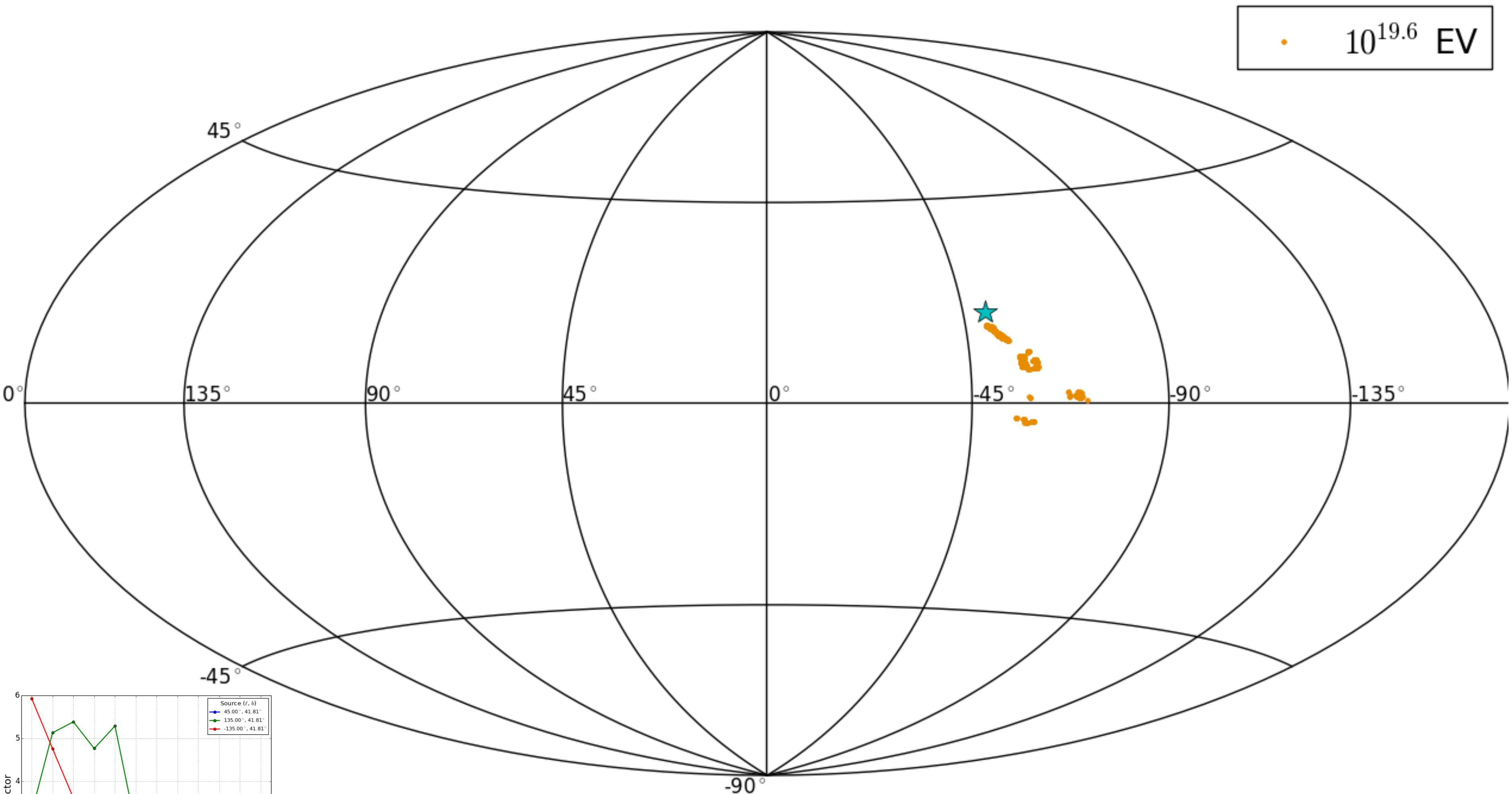
Arrival Directions from Cen A

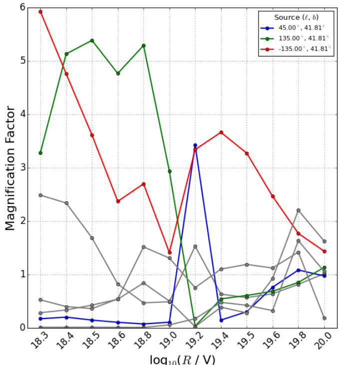




rigidity = 63 **EV**

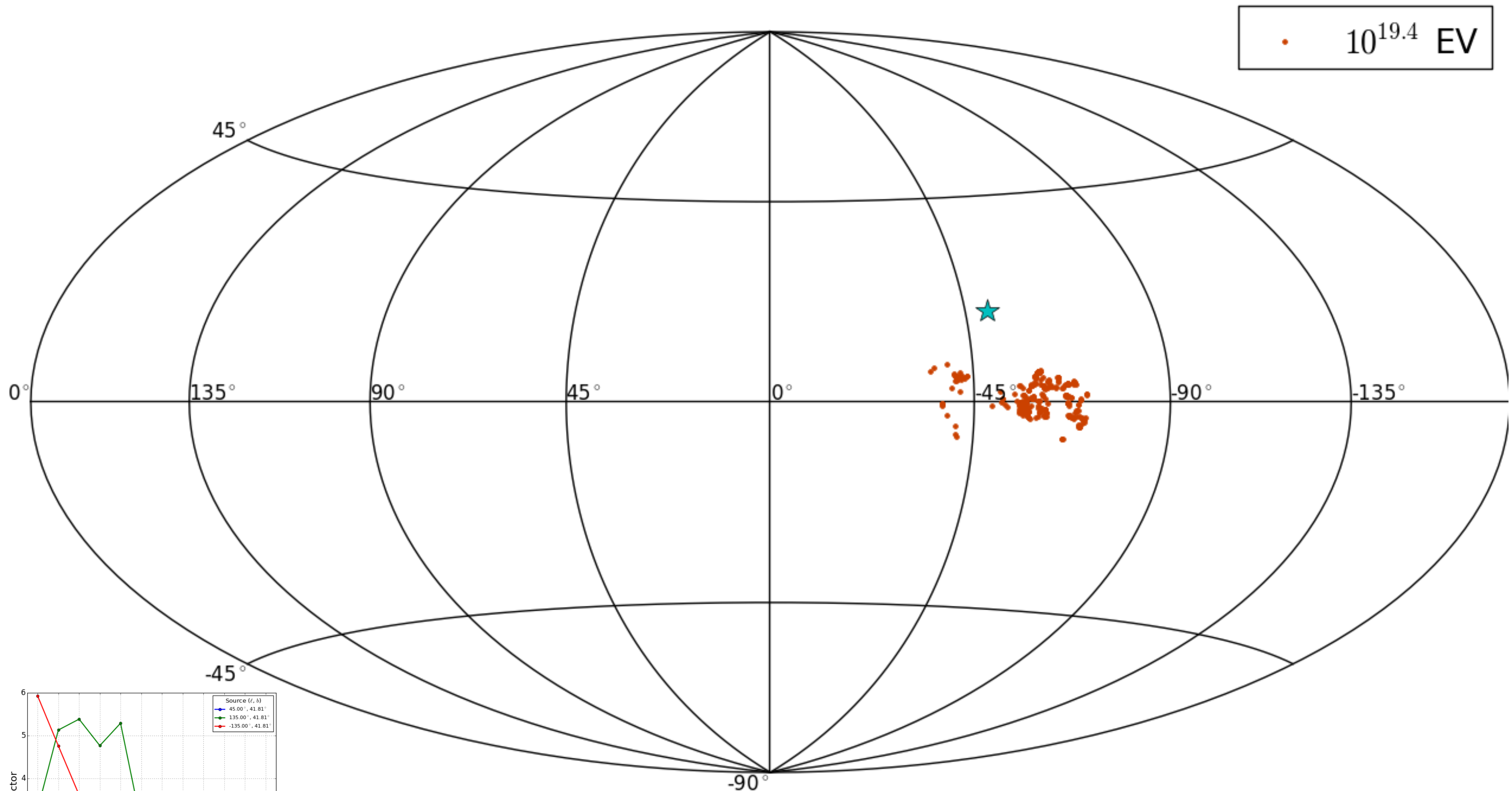
Arrival Directions from Cen A

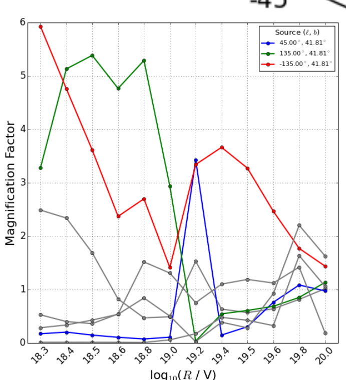




rigidity = 40 **EV**

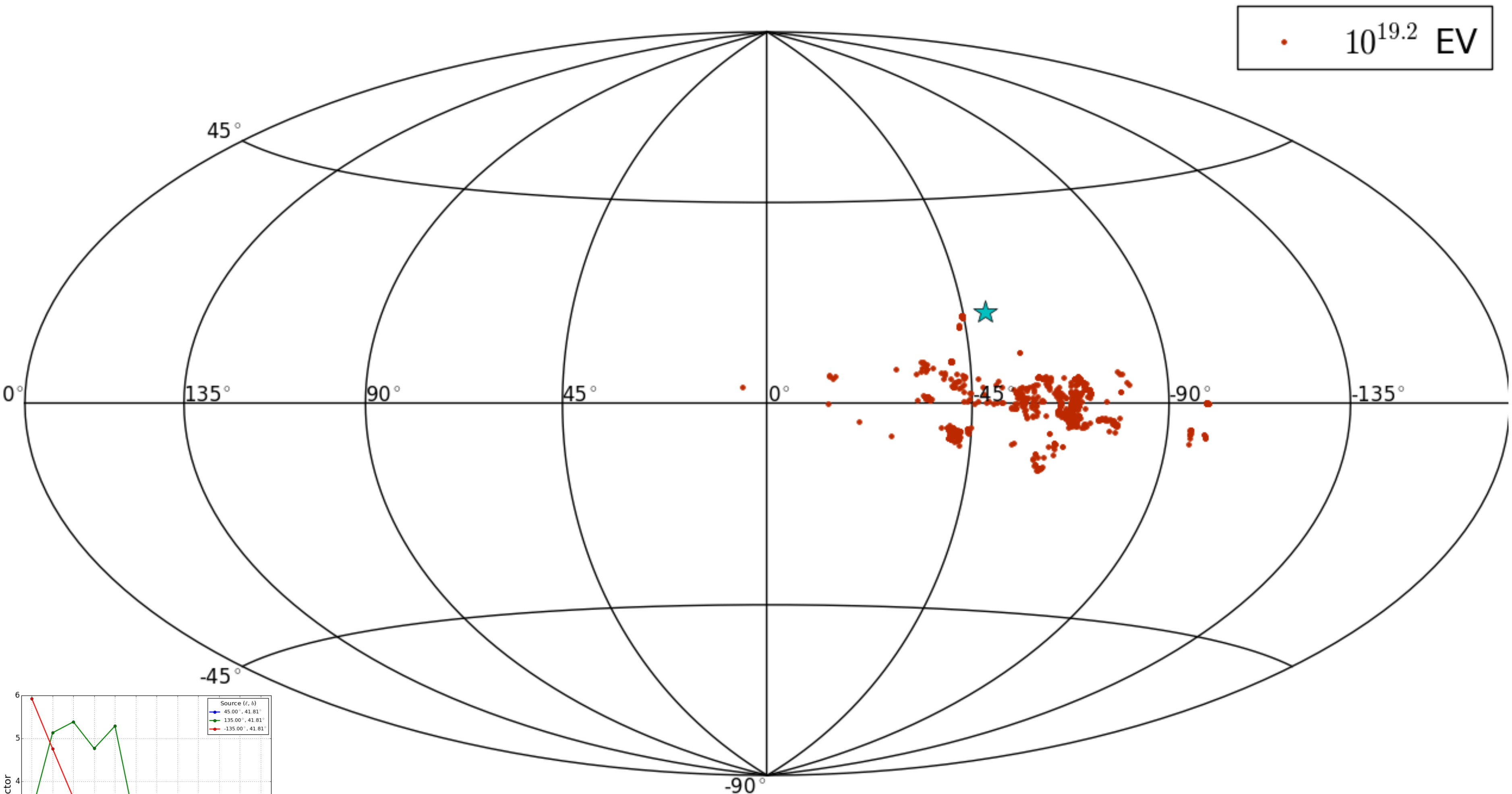
Arrival Directions from Cen A

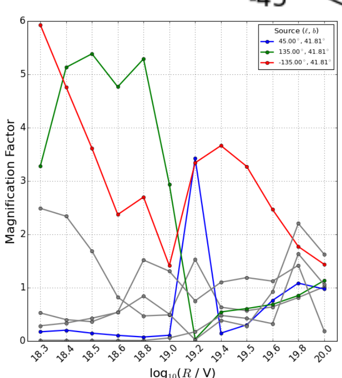




rigidity = 25 **EV**

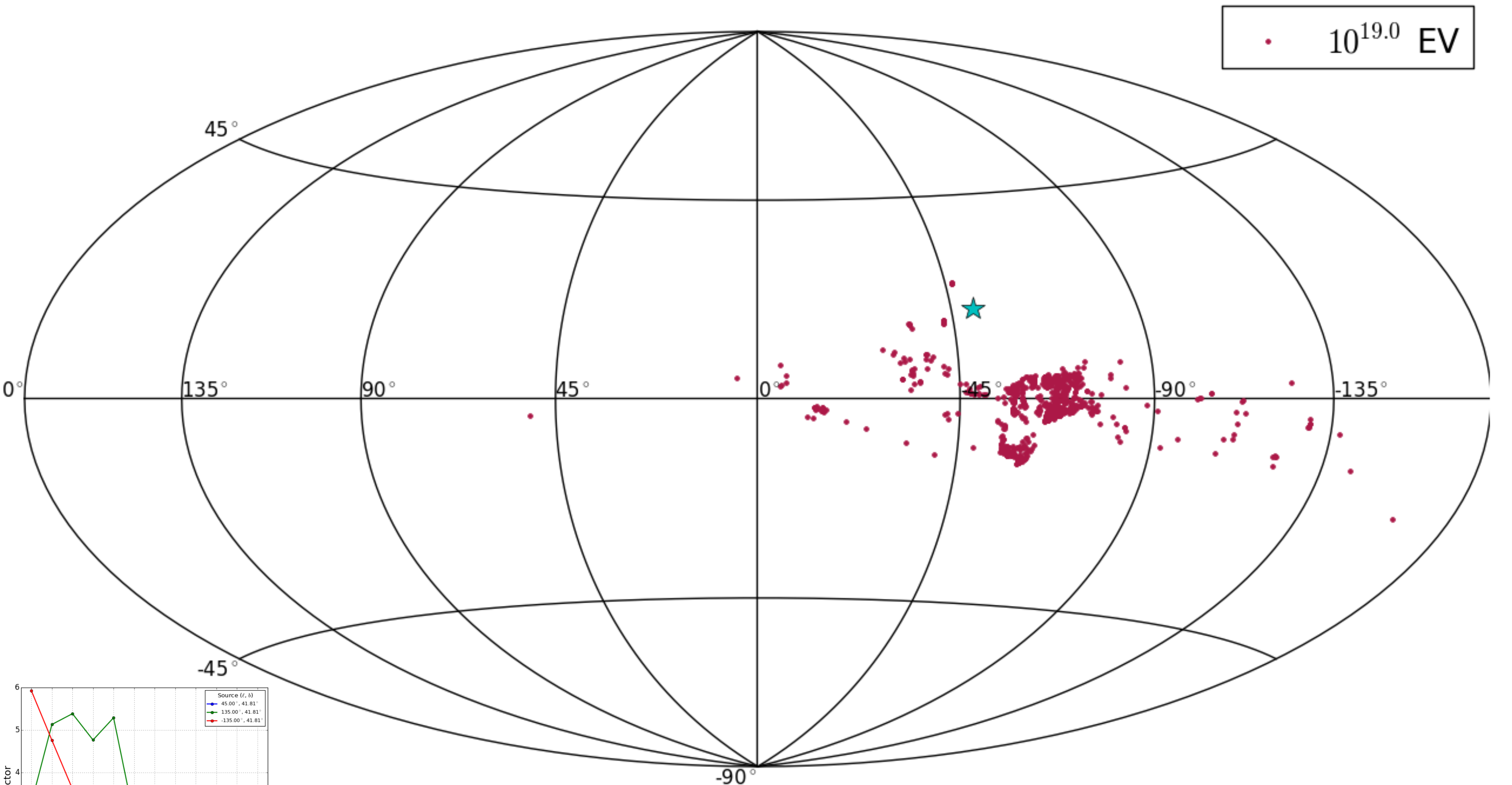
Arrival Directions from Cen A

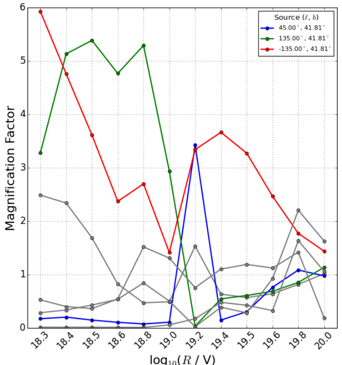




rigidity = **16 EV**

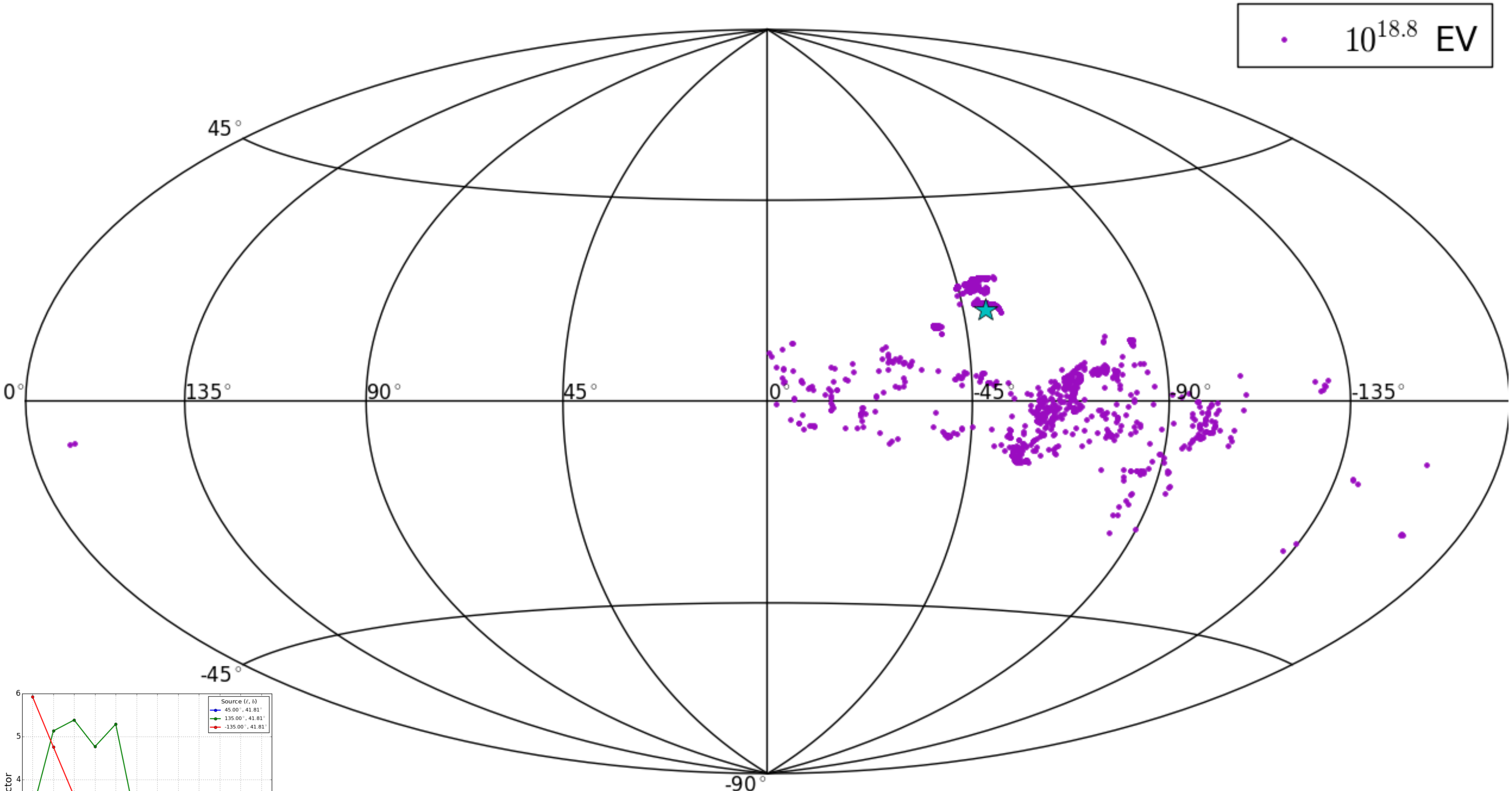
Arrival Directions from Cen A

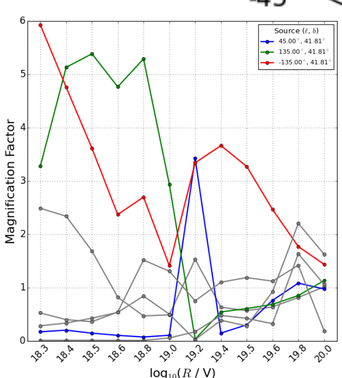




rigidity = **10 EV**

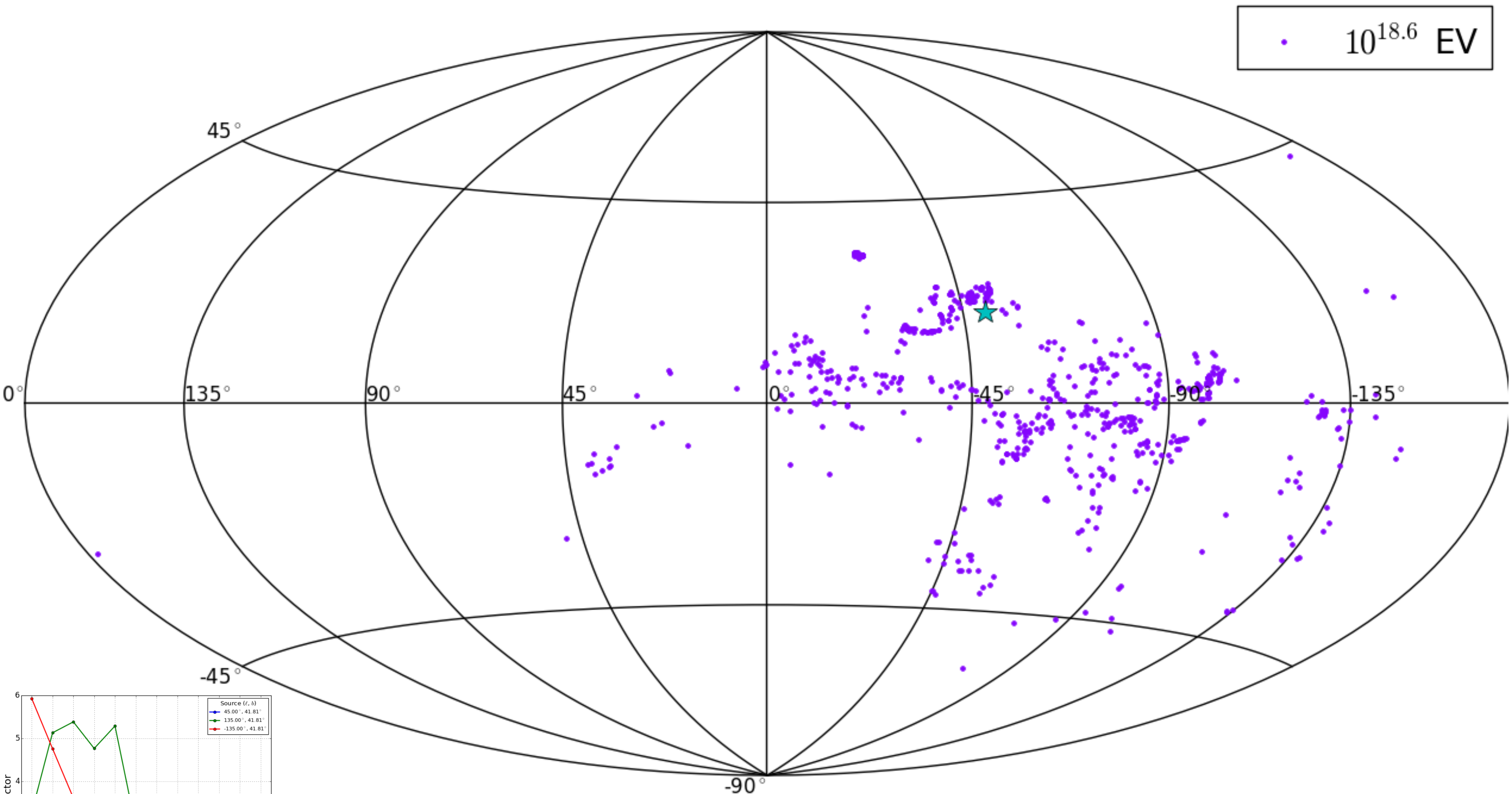
Arrival Directions from Cen A

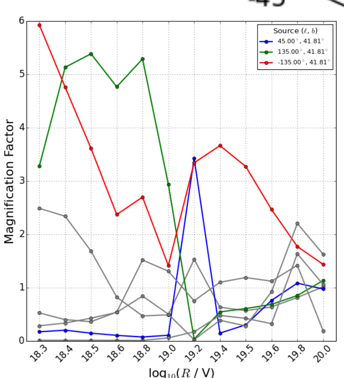




rigidity = 6E**V**

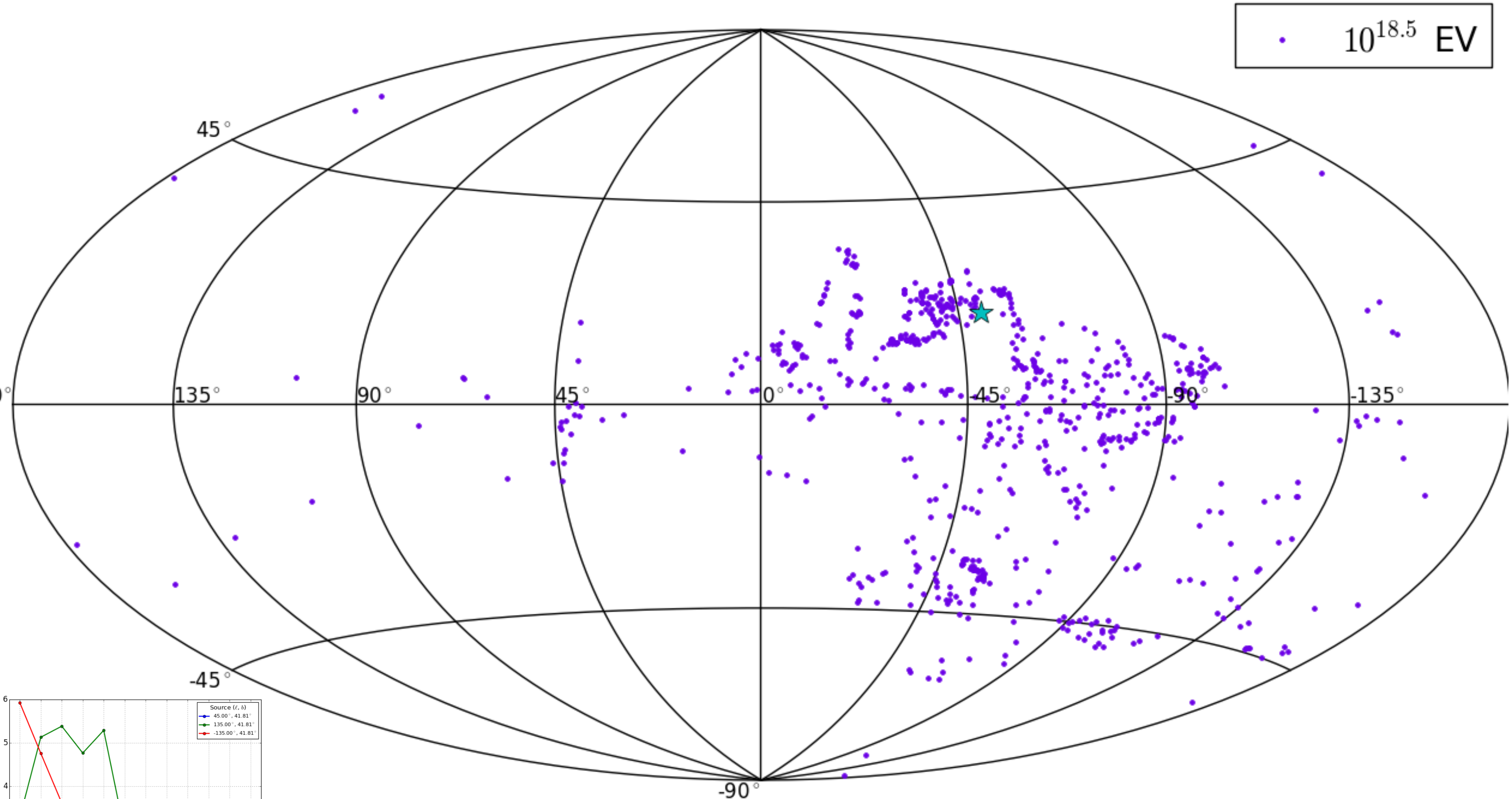
Arrival Directions from Cen A

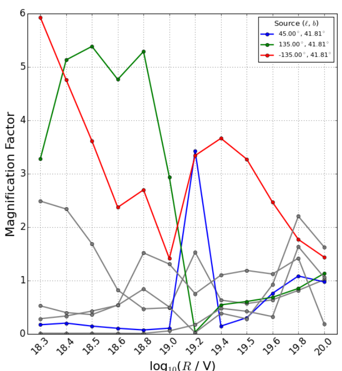




rigidity = **4 EV**

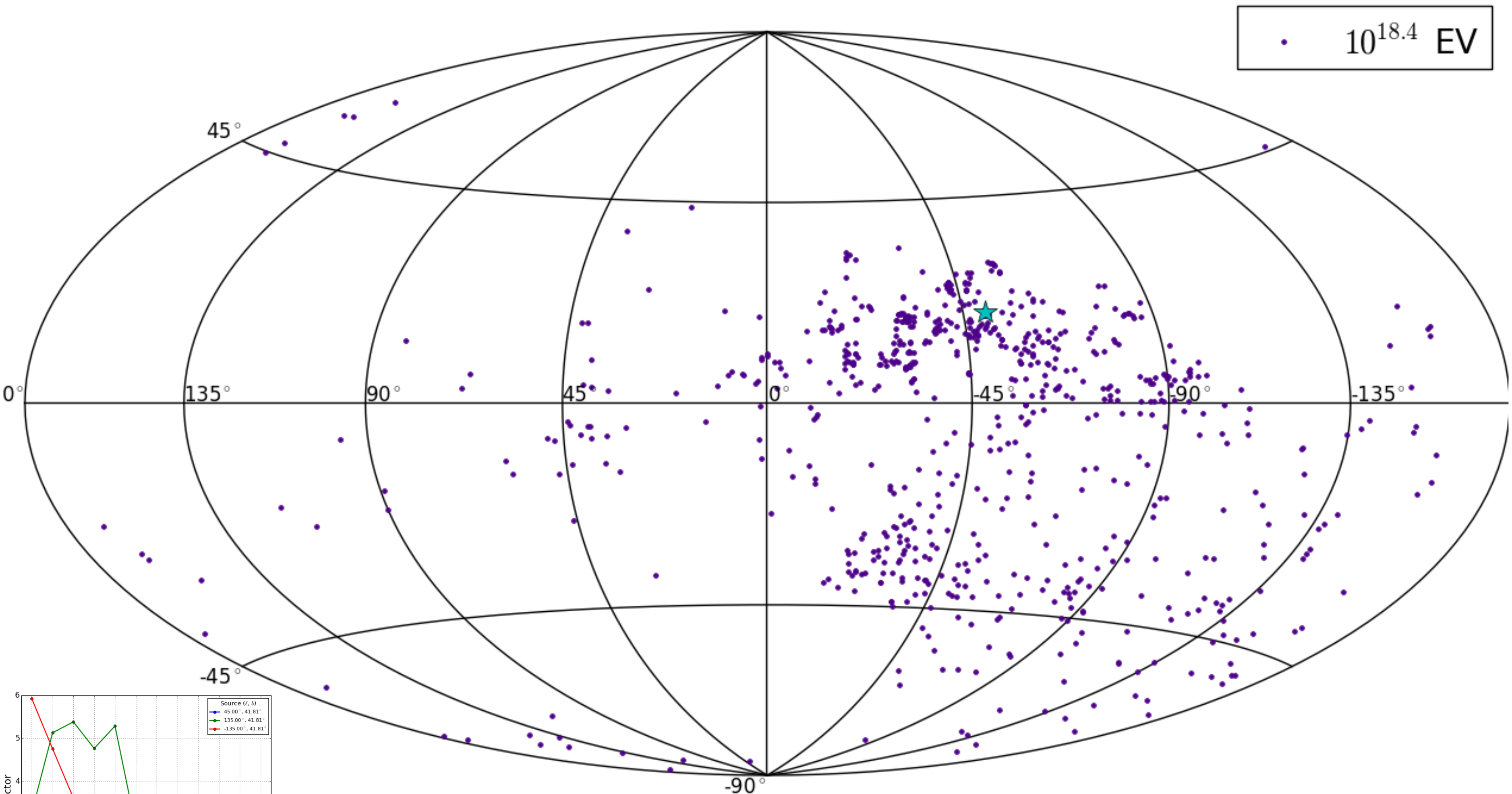
Arrival Directions from Cen A

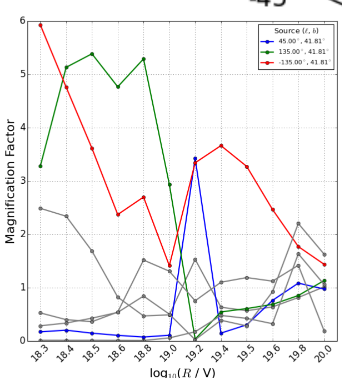




rigidity = **3 EV**

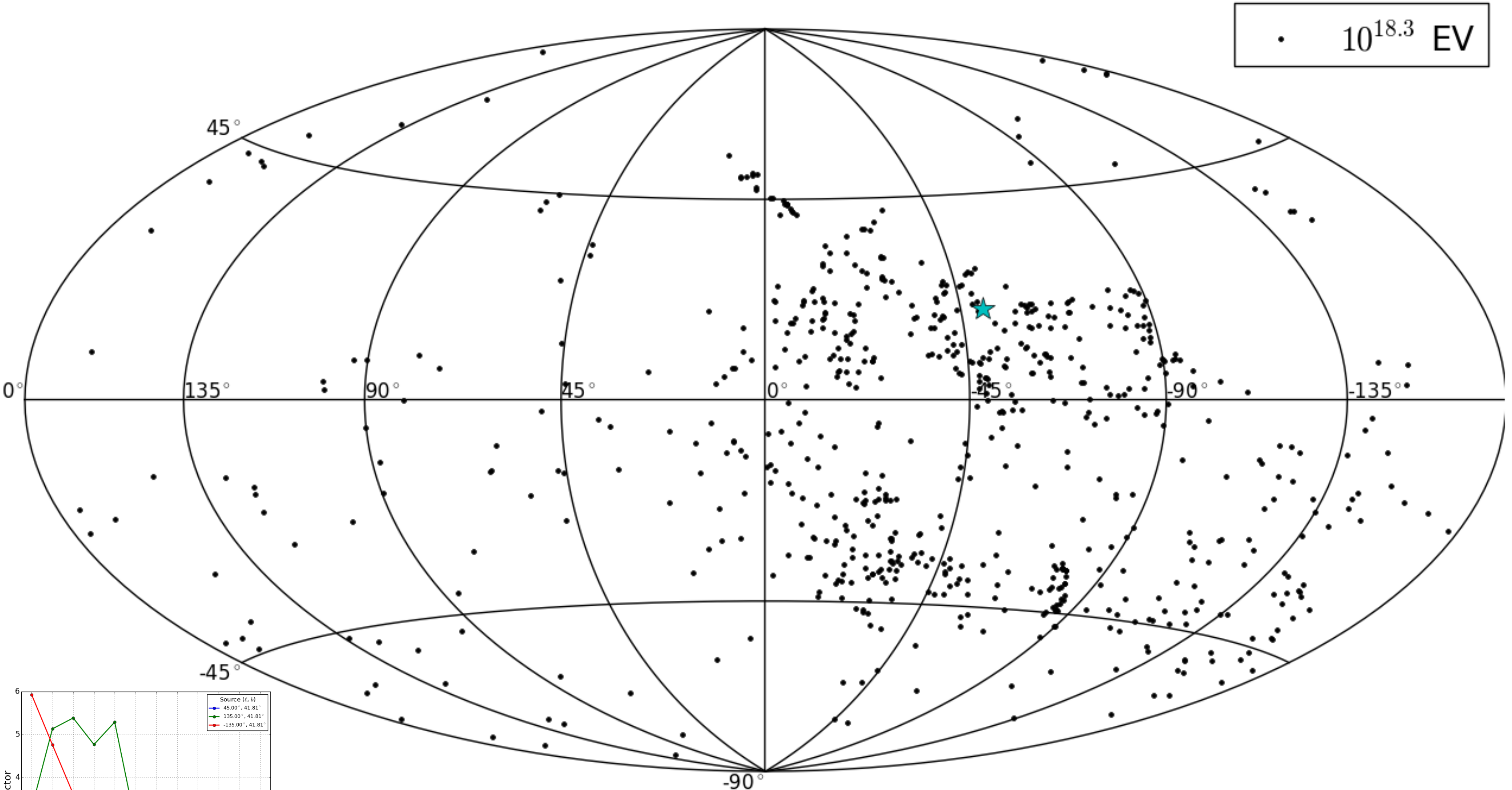
Arrival Directions from Cen A

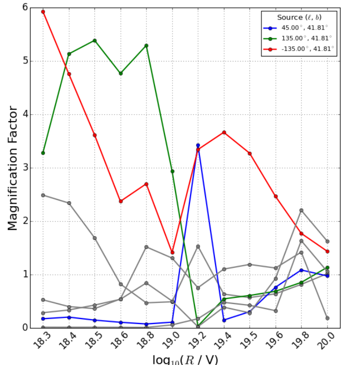




rigidity = 2.5 EV

Arrival Directions from Cen A





rigidity = 2 E**V**