Galactic Magnetic Deflections of UHECRs including realistic random field

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Babak Tafreshi

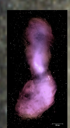
Outline

Galactic Magnetic Field

- JF12 regular
- JF12 random (Kolmogorov)

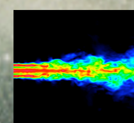
Tracking UHECRs

- Method



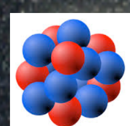
Centaurus A

- Arrival directions
- Event excess



Random Field

- Example



Mass Composition

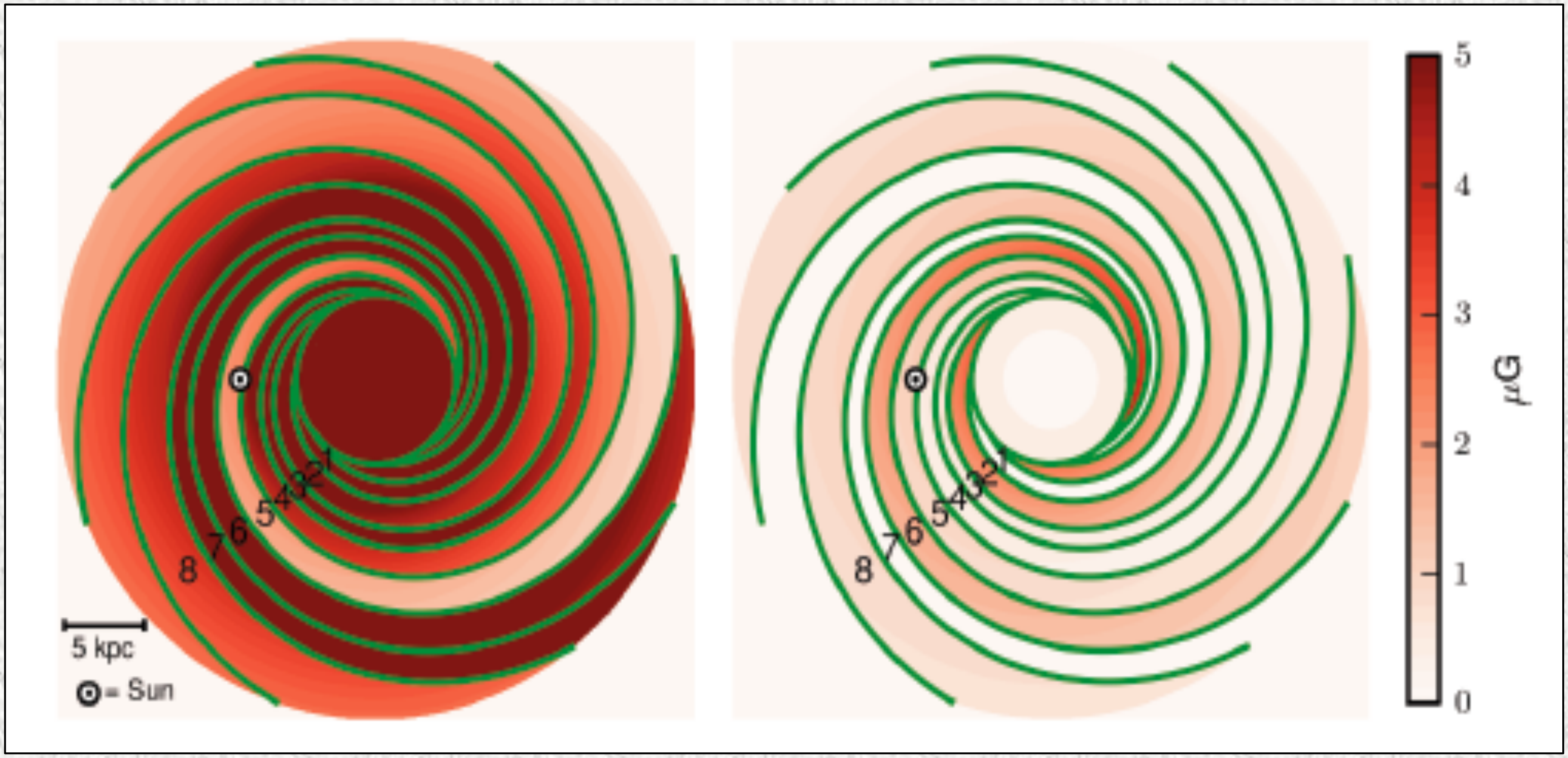
- Method
- Examples

Jansson-Farrar GMF Model (JF12)

This model includes:

- Regular large scale component
- Random field component
- Striated random field component

Fit to the observational data: More than 40k extragalactic RM and the WMAP7 22 GHz polarized and total intensity synchrotron emission maps



R. Jansson and G. R. Farrar, ApJ 761 (2012)

JF12 Random Field

- Superposition of a disk component and an extended smooth halo component*

- 13 Free parameters

- Coherence length of 100 pc

*R. Jansson and G. R. Farrar, ApJ 761 (2012)

Kolmogorov Random Field (KRF)

Kolmogorov Power Spectrum α k $^{-5/3}$

Previous works:
Giacinti, et al (2012)
Harari, et al (2002)

Scale the **KRF** with **JF12** field strengths

Kolmogorov Random Field

Work in a Fourier Space:

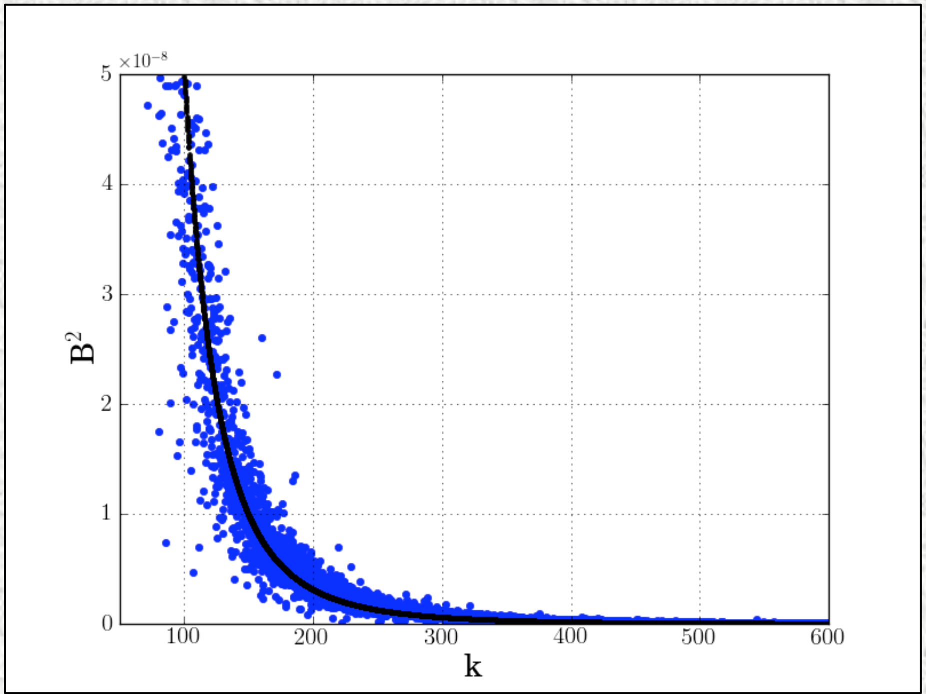
$|\mathbf{B}(k)|^2 = \beta\, k^{-11/3} \rightarrow B = \text{Gaussian}(0, |\mathbf{B}(k)|^2)$

$B_1^2 + B_2^2 + B_3^2 = B^2$

Divergence free: $\mathbf{B.k} = 0 \rightarrow B_1k_1+B_2k_2+B_3k_3=0$

Superpose wave modes with $k_{min} \leq |k| \leq k_{max}$

Using FFT to find the B values in real space

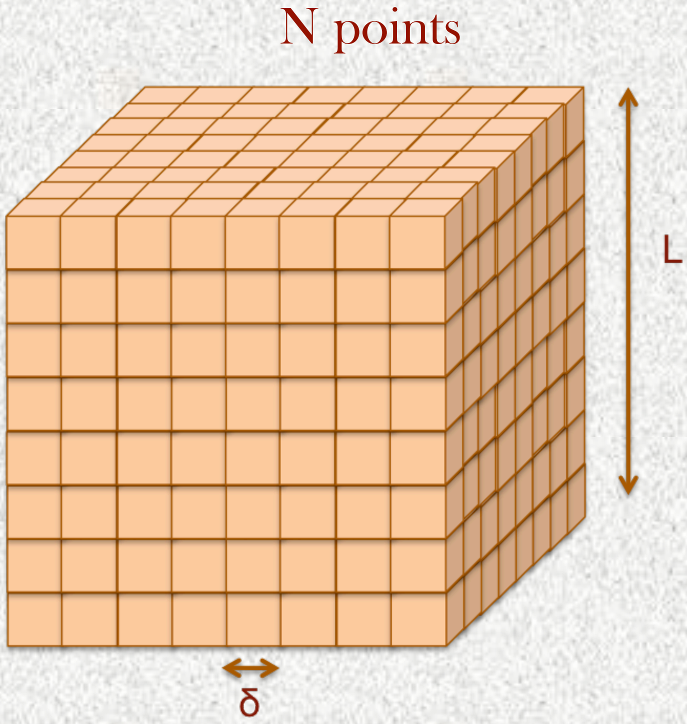


$k_1(m,n,p)=2\pi\, m/L$
$k_2(m,n,p)=2\pi\, n/L$
$k_3(m,n,p)=2\pi\, p/L$

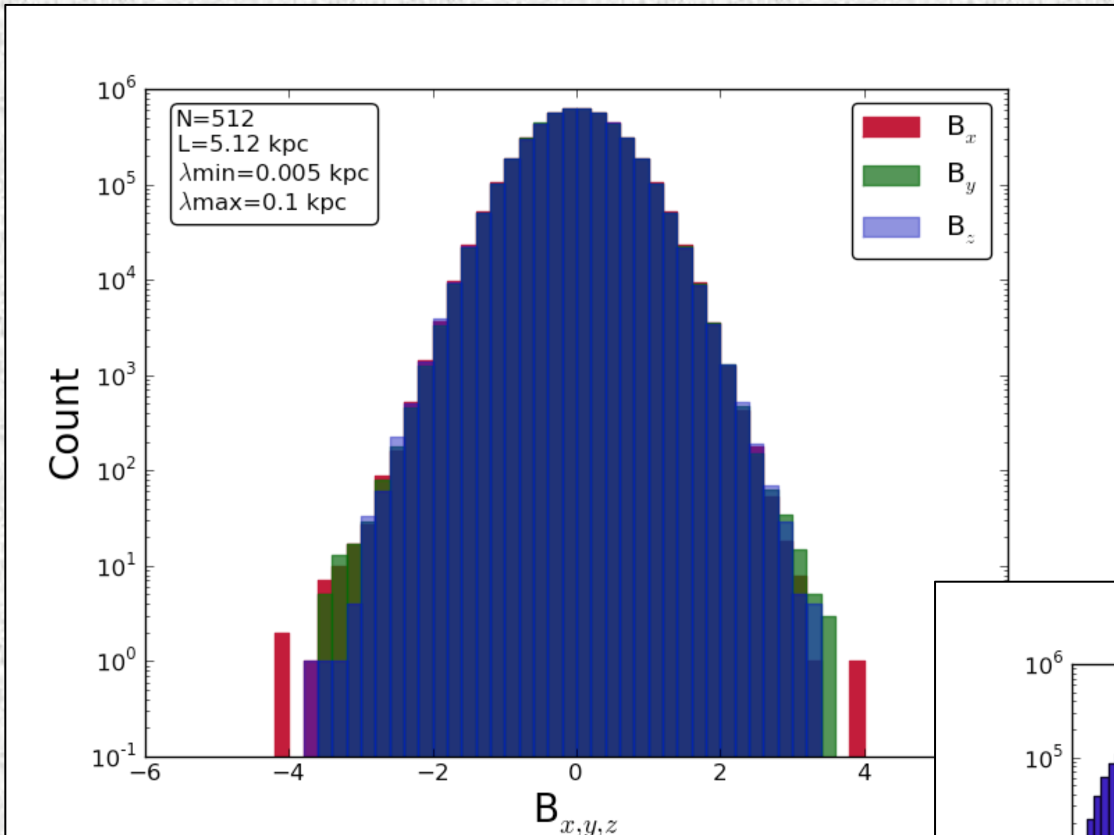
$L = 5.12$ kpc
$N = 512$
$\delta = 10$ pc

$\lambda_{min} = 5$ pc
$\lambda_{max} = 100$ pc

Basic cube:
3D cubic grid

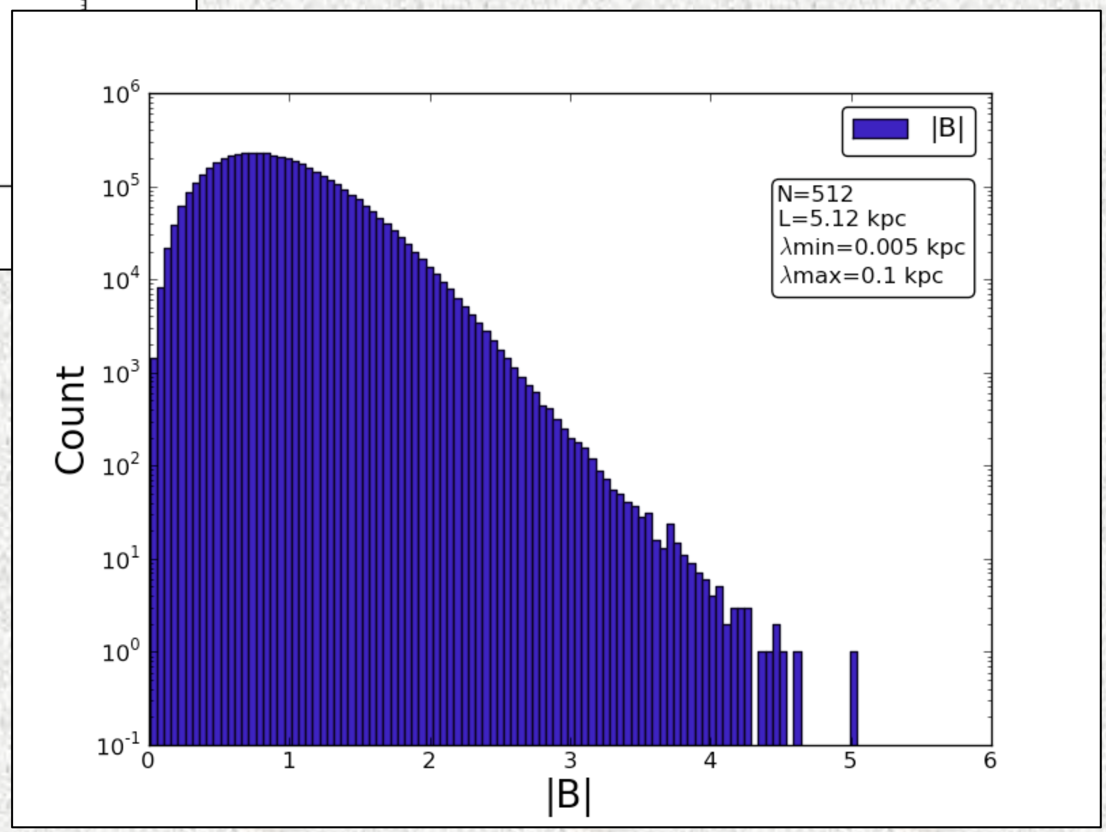


Kolmogorov Random Field (continued)



Model test:
B_x, B_y, B_z distributions are isotropic and symmetric

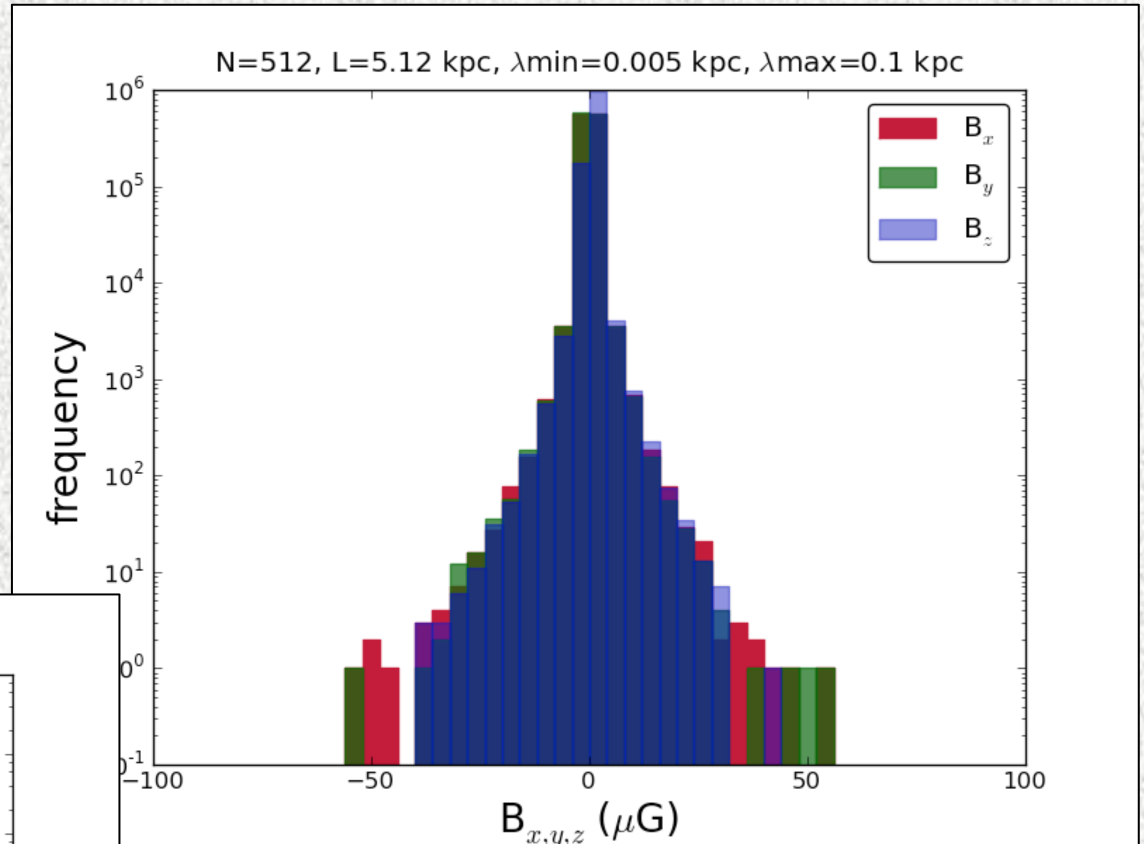
Histogram of |B|
B_{rms} =1



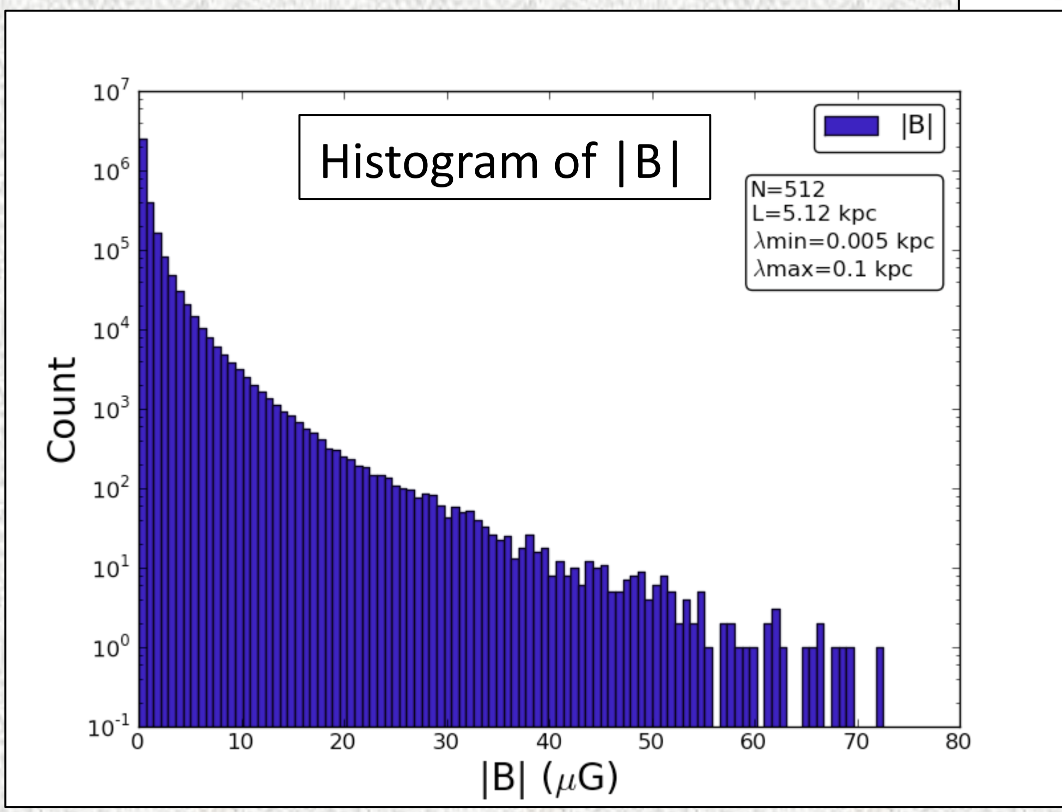
Kolmogorov Random Field in the Galaxy

We repeat the cube in the Galaxy, but randomly changing its orientations

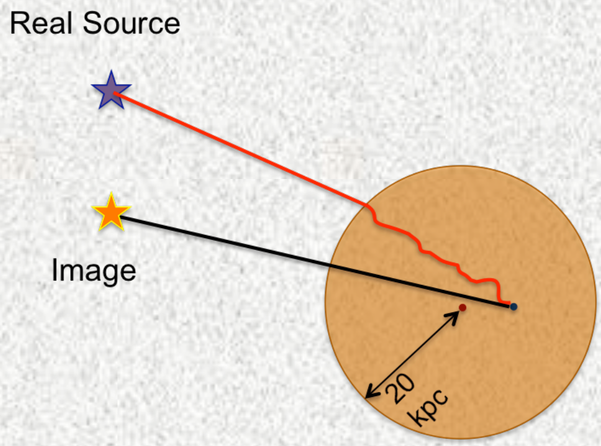
We scale B_x, B_y, B_z by JF12_random strengths at each point in the Galaxy



Histogram of B_x, B_y, B_z



Back-tracking



We should consider the effect of the GMF to identify the sources of UHECRs

- Use CRT to propagate the cosmic rays

Michael Sutherland, et al (2010)

- Use HEALPix initial positions to back-track the cosmic rays
  - Res=11, Npixels: 50,331,648
  - Res=9, Npixels: 3,145,728

http://healpix.jpl.nasa.gov/index.shtml

Most simulations are done with Pleiades NASA HEC clsuter

- Recording the final velocity direction and position

Plot the sky maps of the source directions

JF12_reg

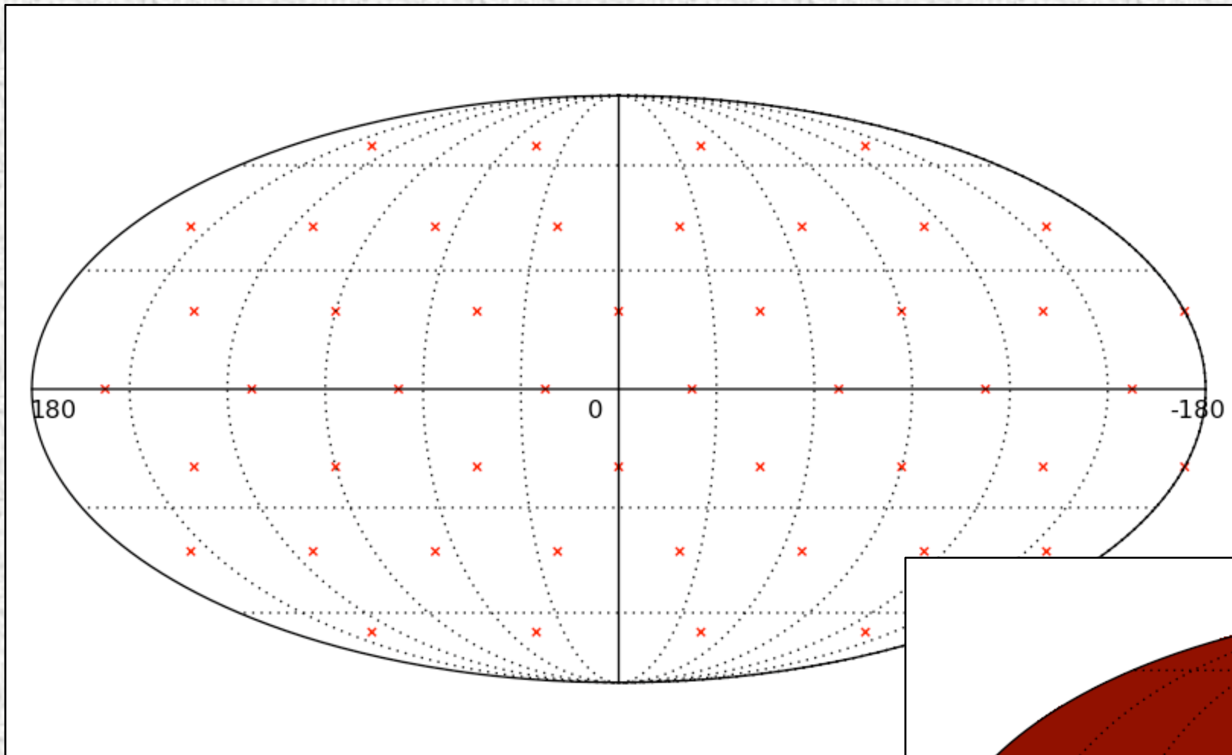
R = Rigidity == E/Z: 2 - 100 EV
$Log_{10}(R)$ = 0.3 – 2.0 in steps of 0.05

JF12_R1

R = 10, 100 EV

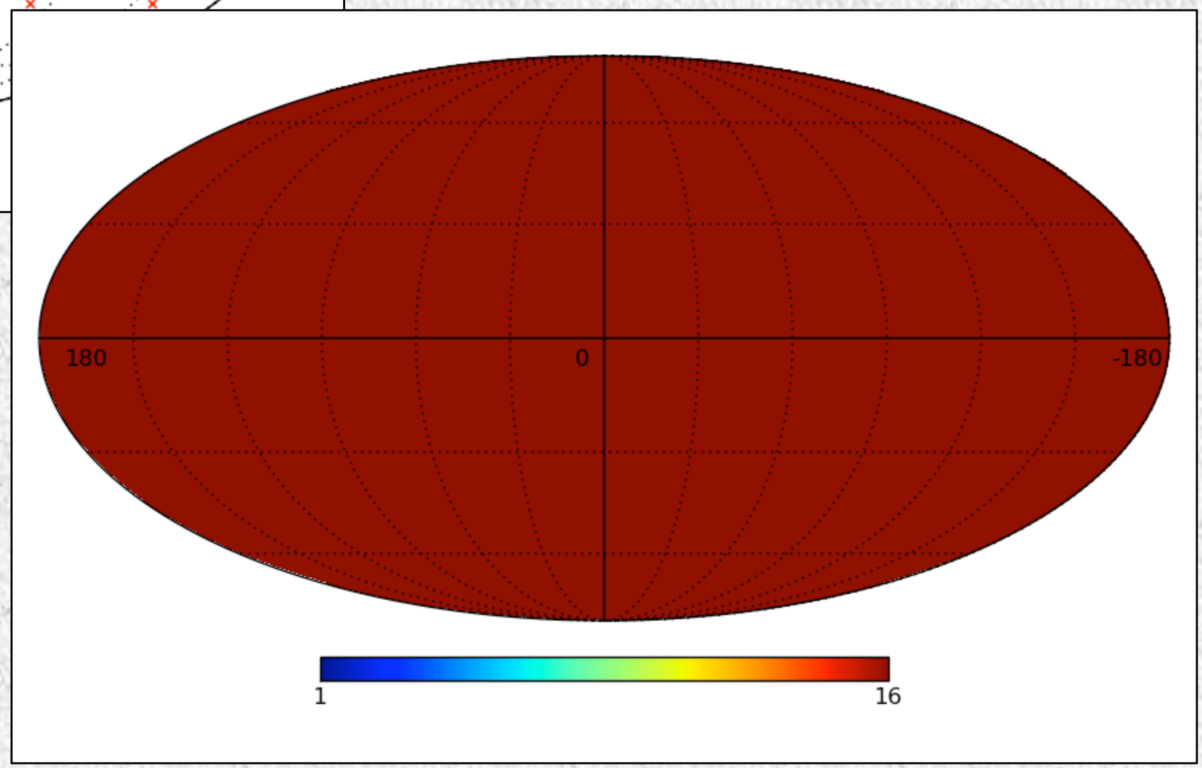
JF12 Regular Component, R==E/Z=31 EV

Initial Directions



HEALPix res=1 map
48 points

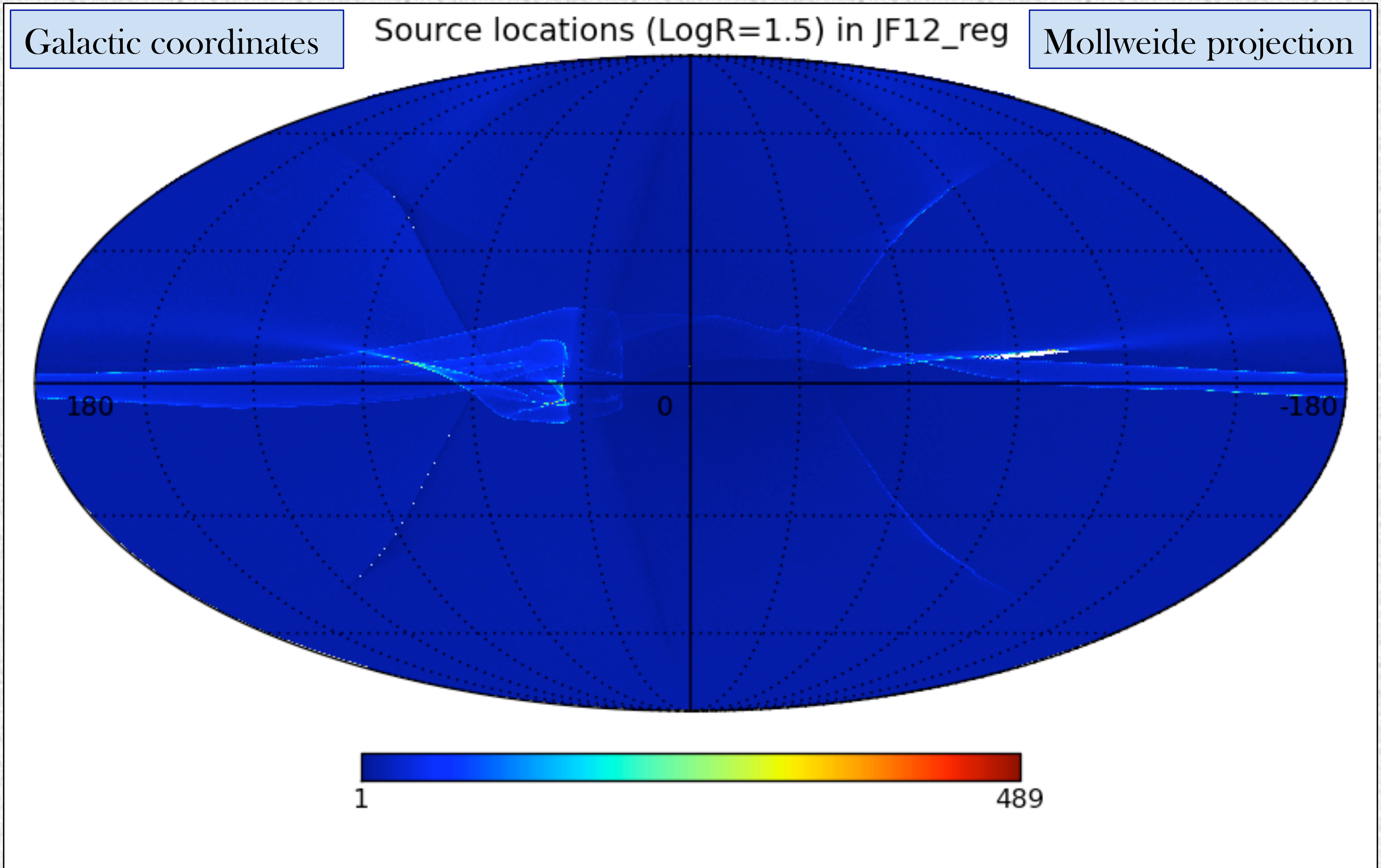
Healpix res=9 map
Res=11: 50M points



Mollweide projection

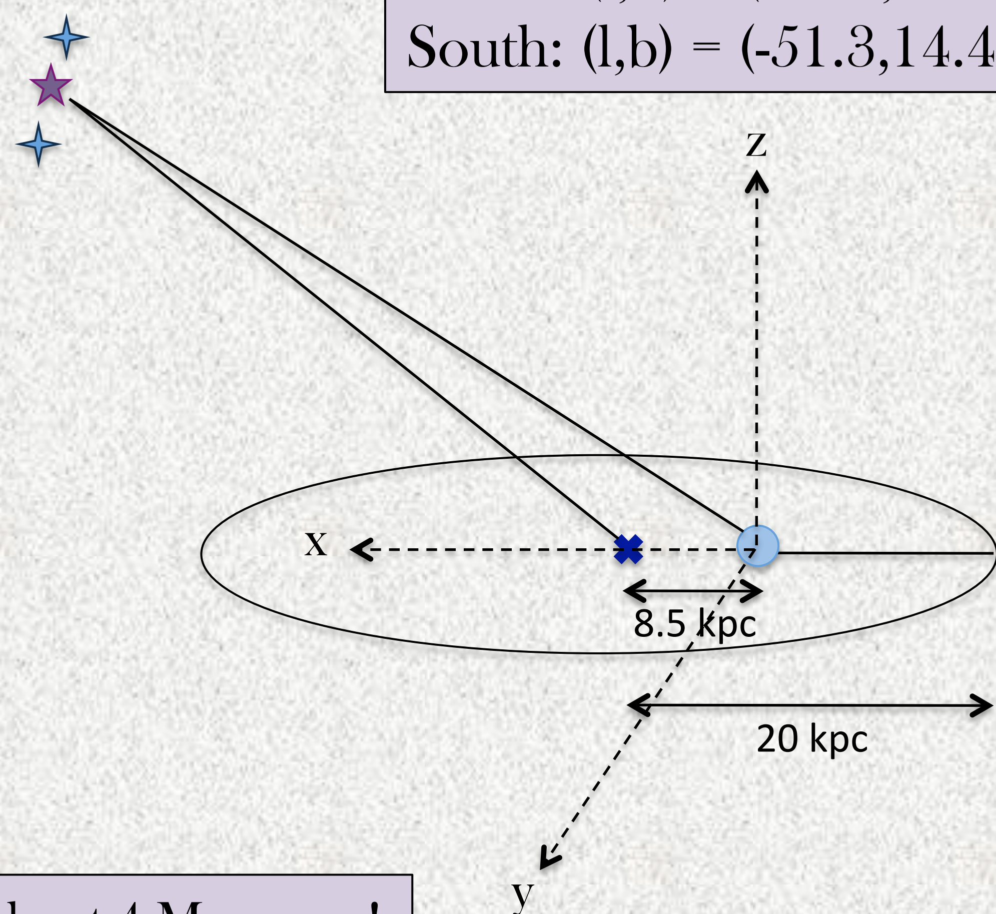
JF12 Regular Component, R==E/Z=31 EV

Source Directions



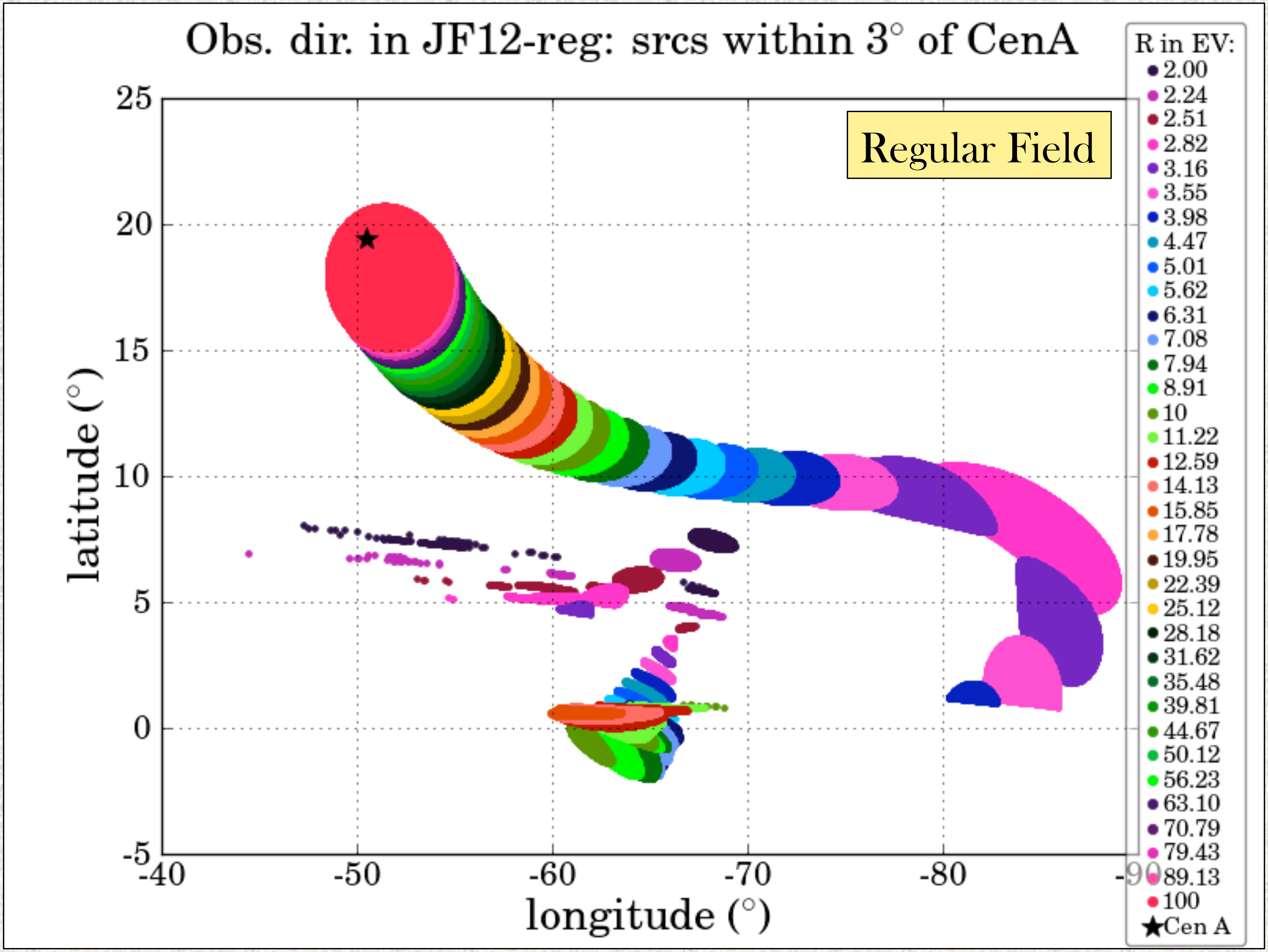
Centaurus A

Center: (l,b) = (-50.5,19.4)
North: (l,b) = (-49.8,24.4)
South: (l,b) = (-51.3,14.4)

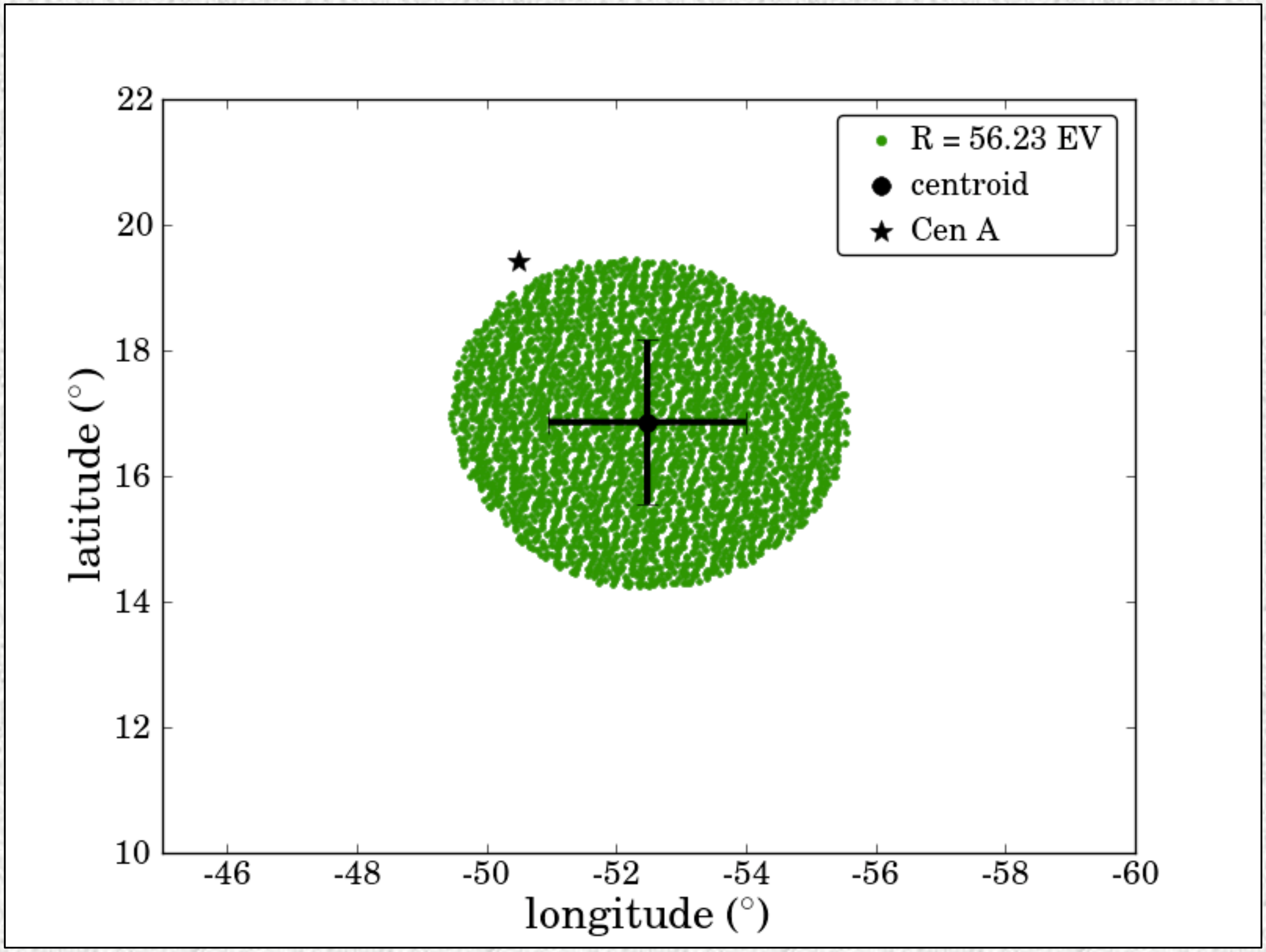


Cen A is about 4 Mpc away!

Simulated events from near Center of Cen A



Centroid and standard deviation of simulated events at each rigidity

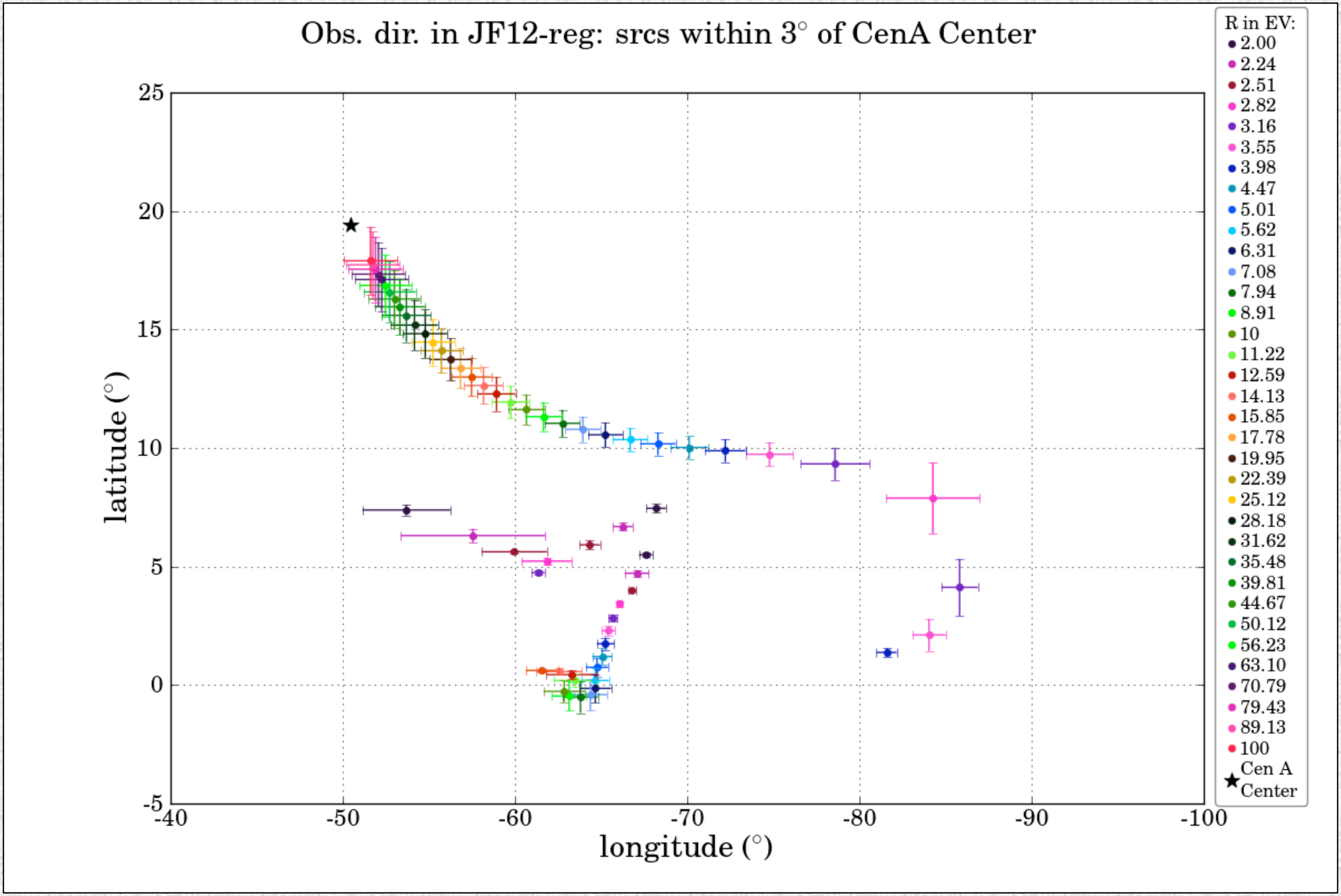


Observed arrival directions:
R = E/Z = 56.23 EV

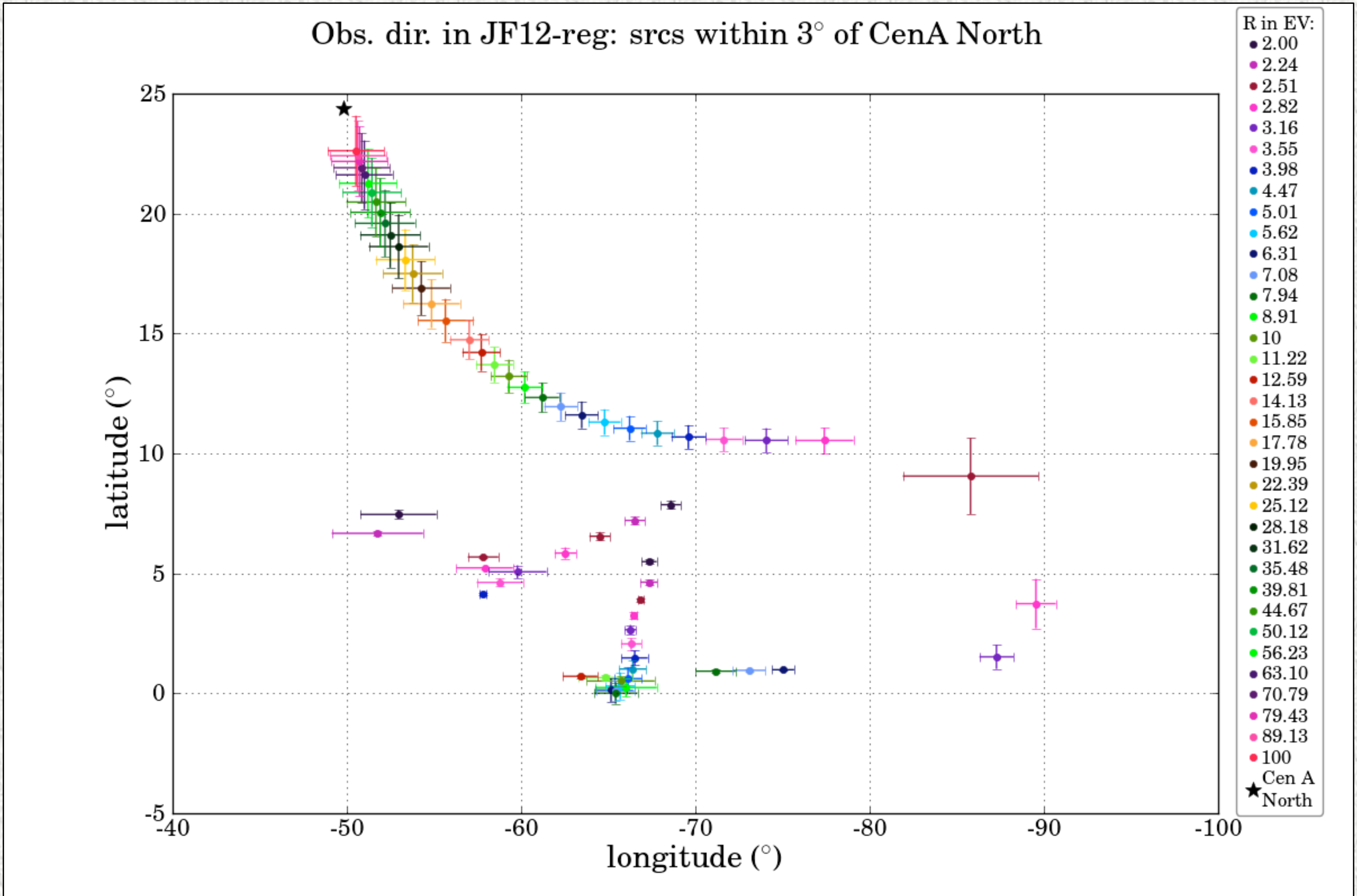
Events within 3° around Cen A center
The centroid is shown
The error bars: standard deviation in (l,b)

Instead of showing all events at each rigidity, we can show their centroid and standard deviation

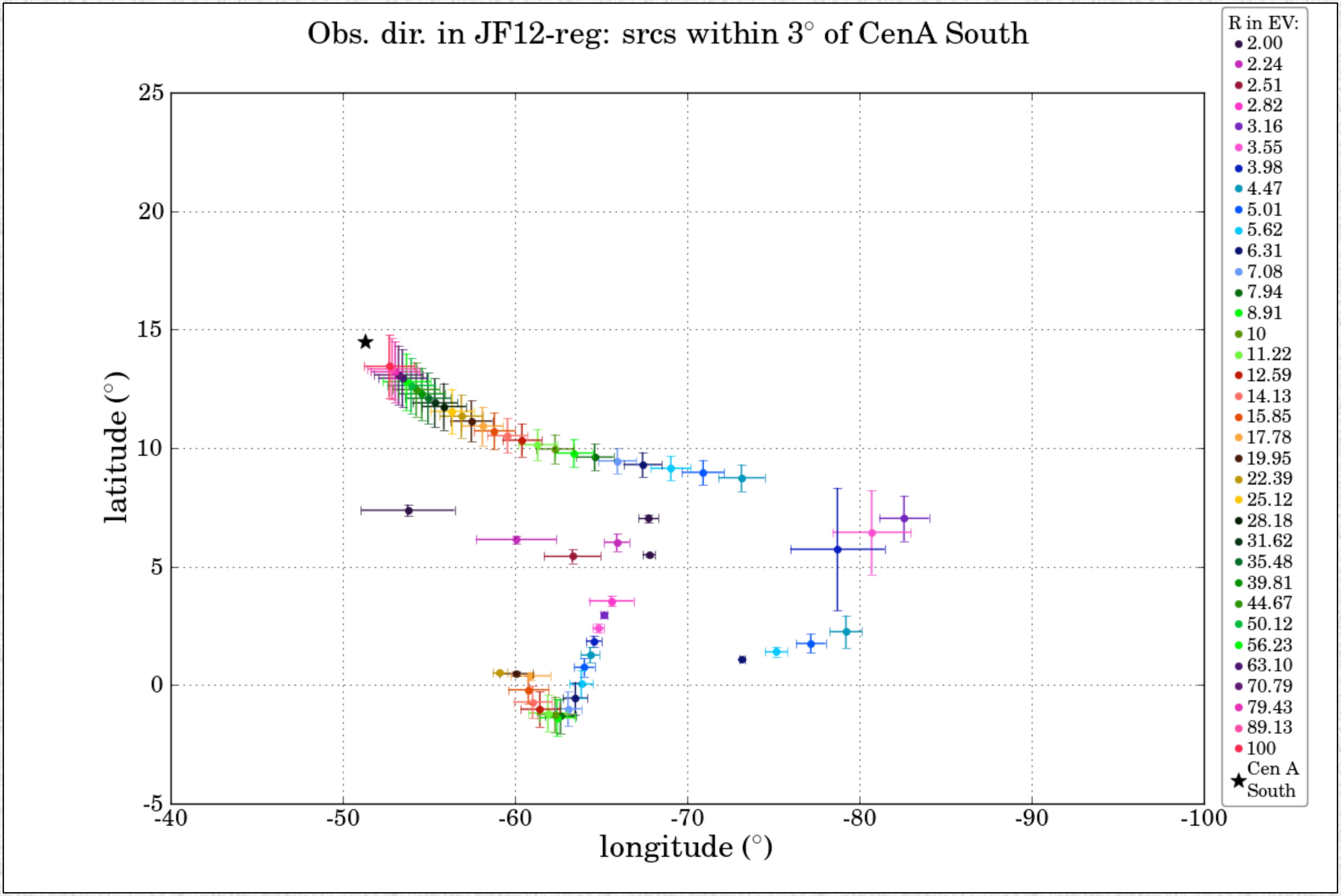
Centroids of Simulated events: Center of Cen A



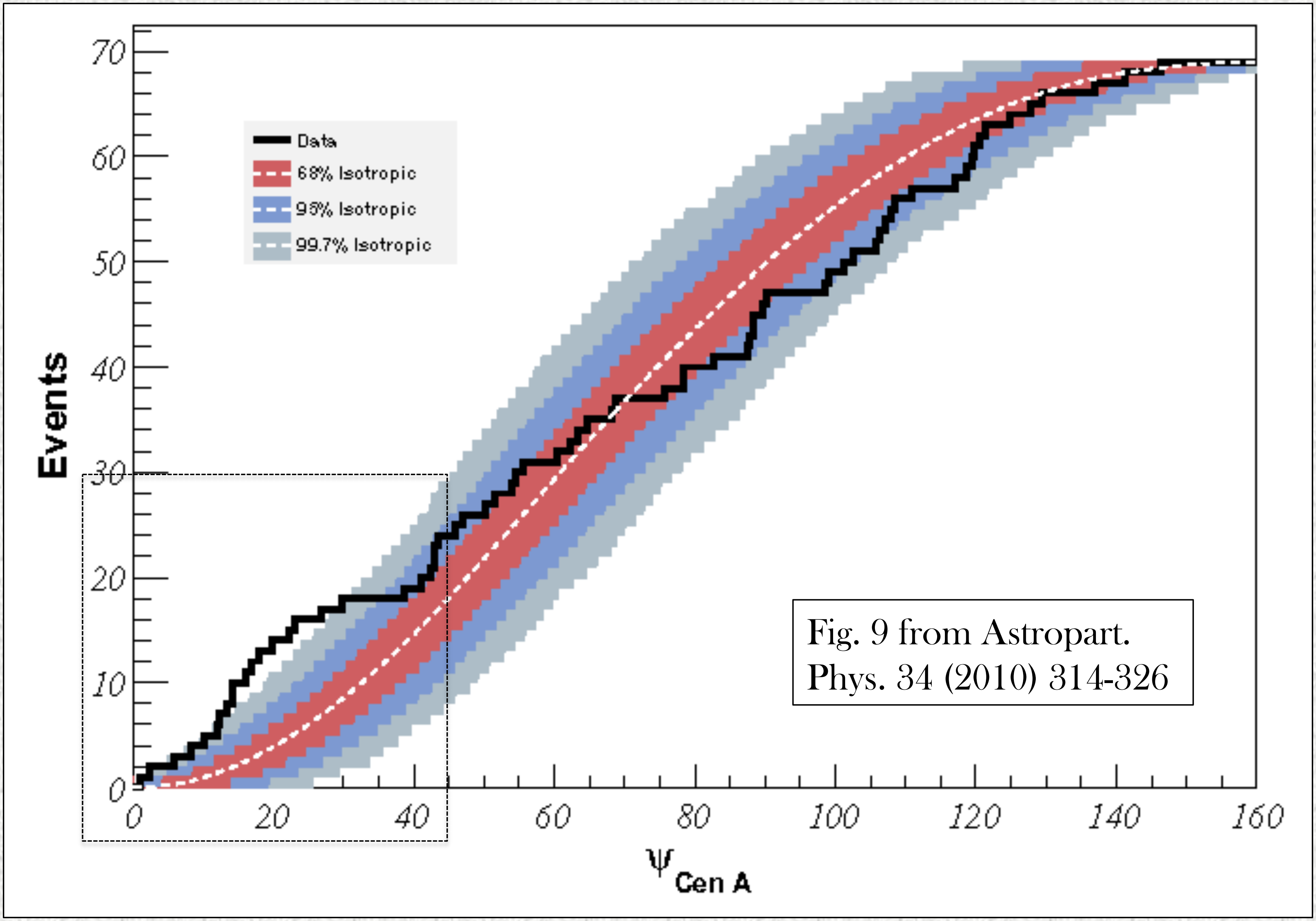
Centroids of Simulated events: North of Cen A



Centroids of Simulated events: South of Cen A



Cumulative number of Auger events vs. angular separation from Cen A

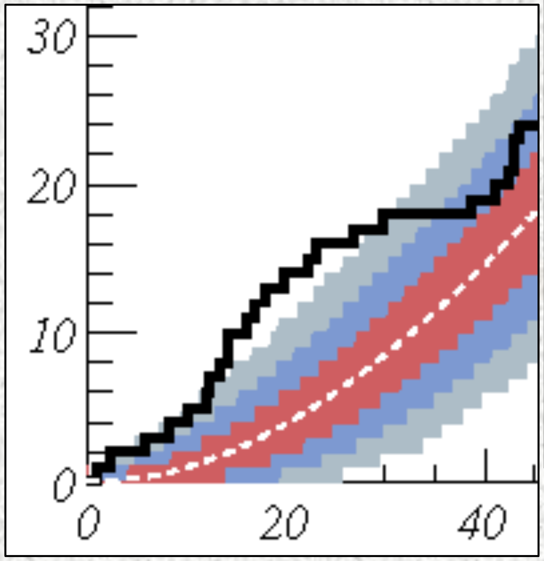


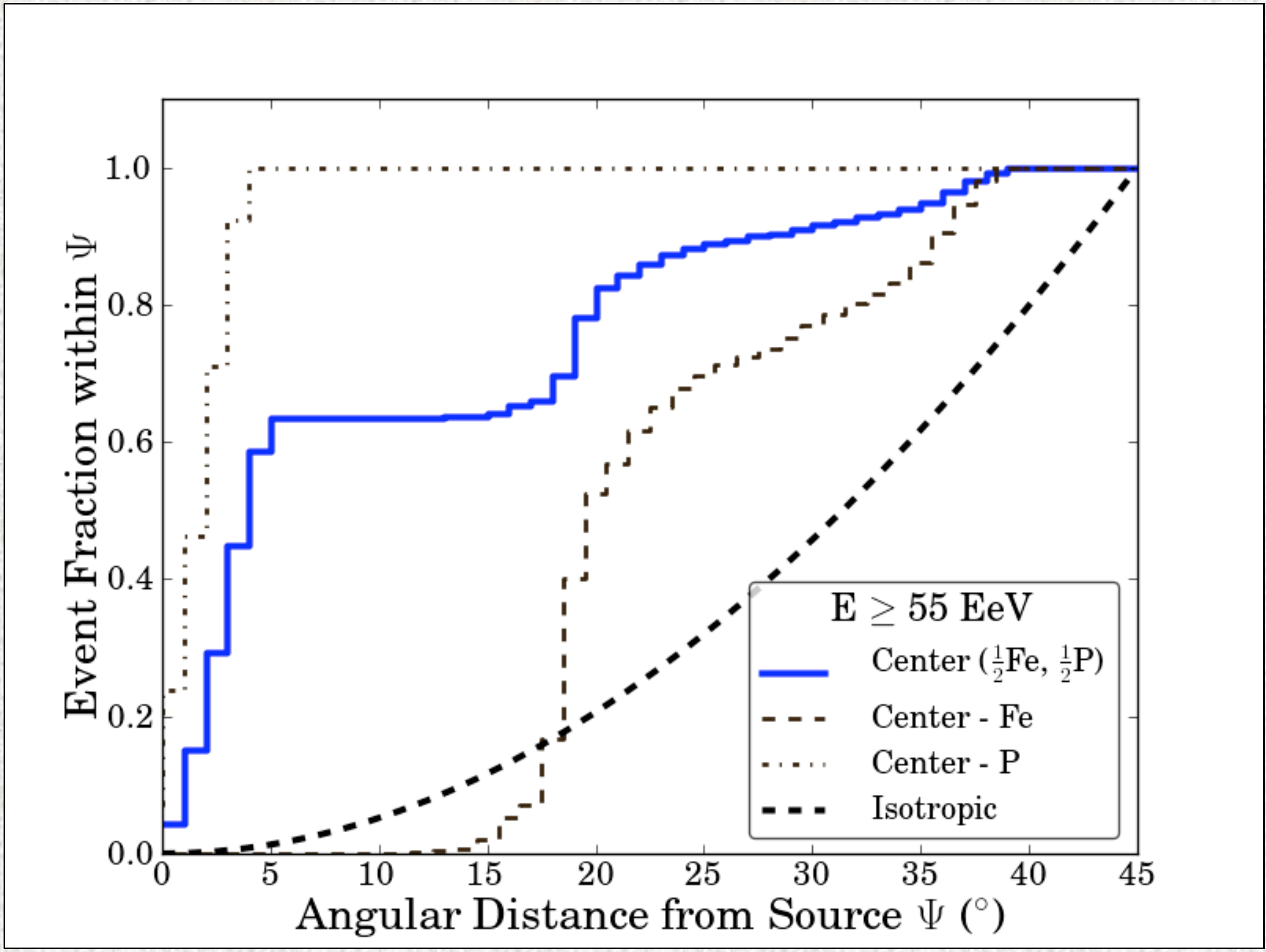
Cumulative number of events vs. angular separation from Cen A

Sources: within 3° of center of Cen A
Observed directions: Within 45° of Cen A

Events are ½ protons and ½ iron nuclei with E ≥ 55 EeV

We observe an excess above isotropy in the simulations





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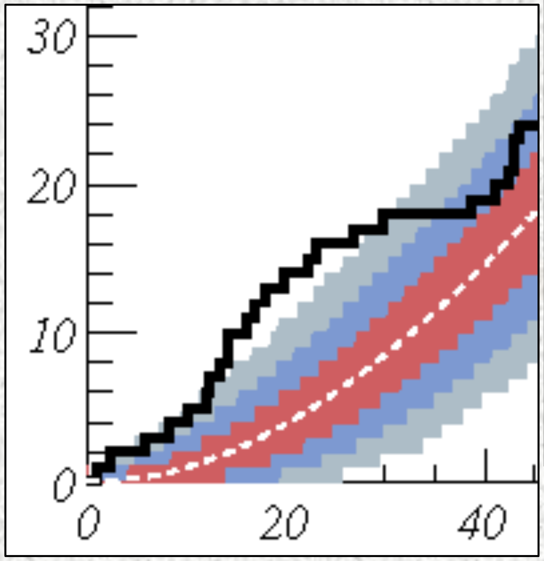
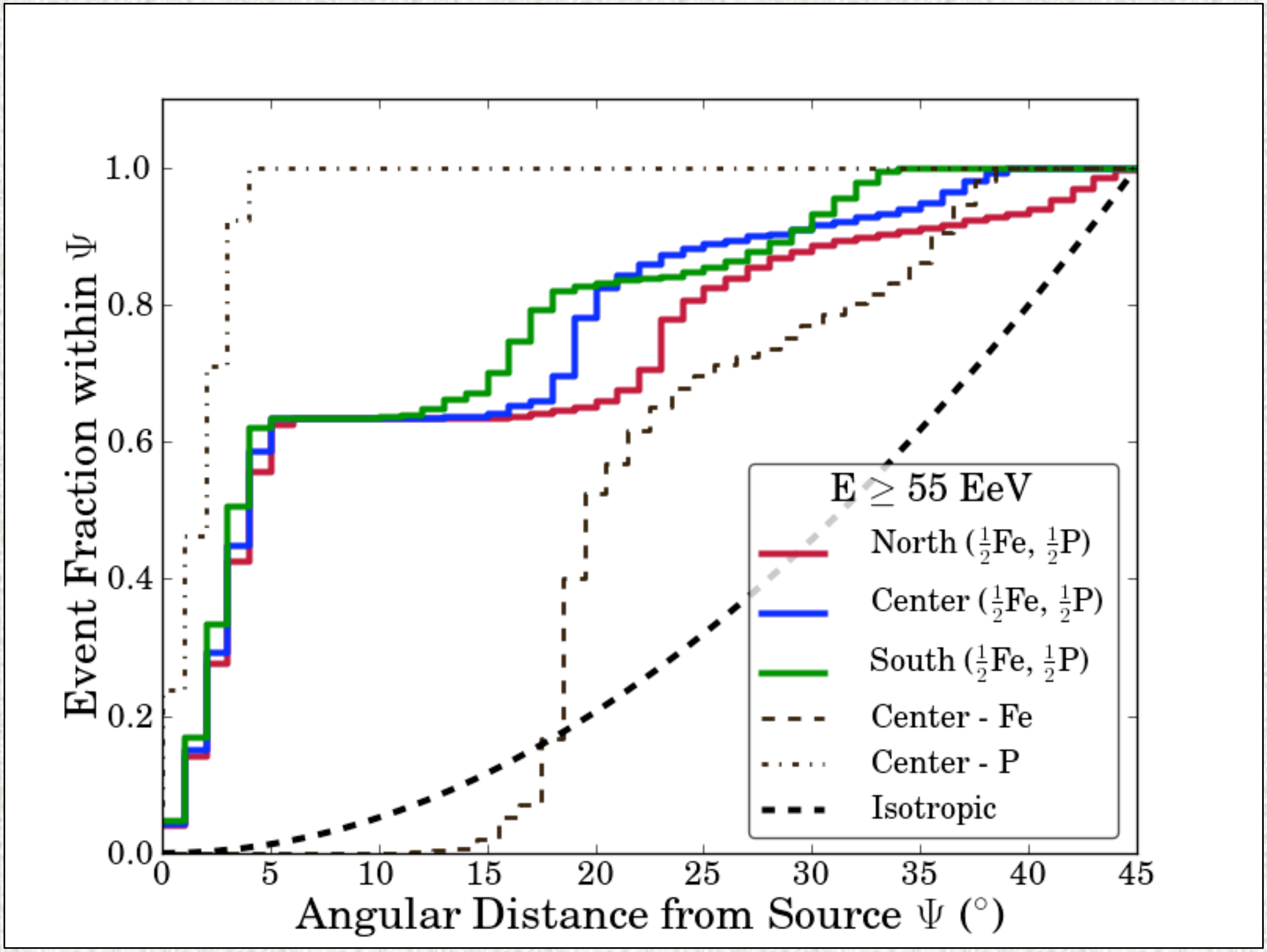
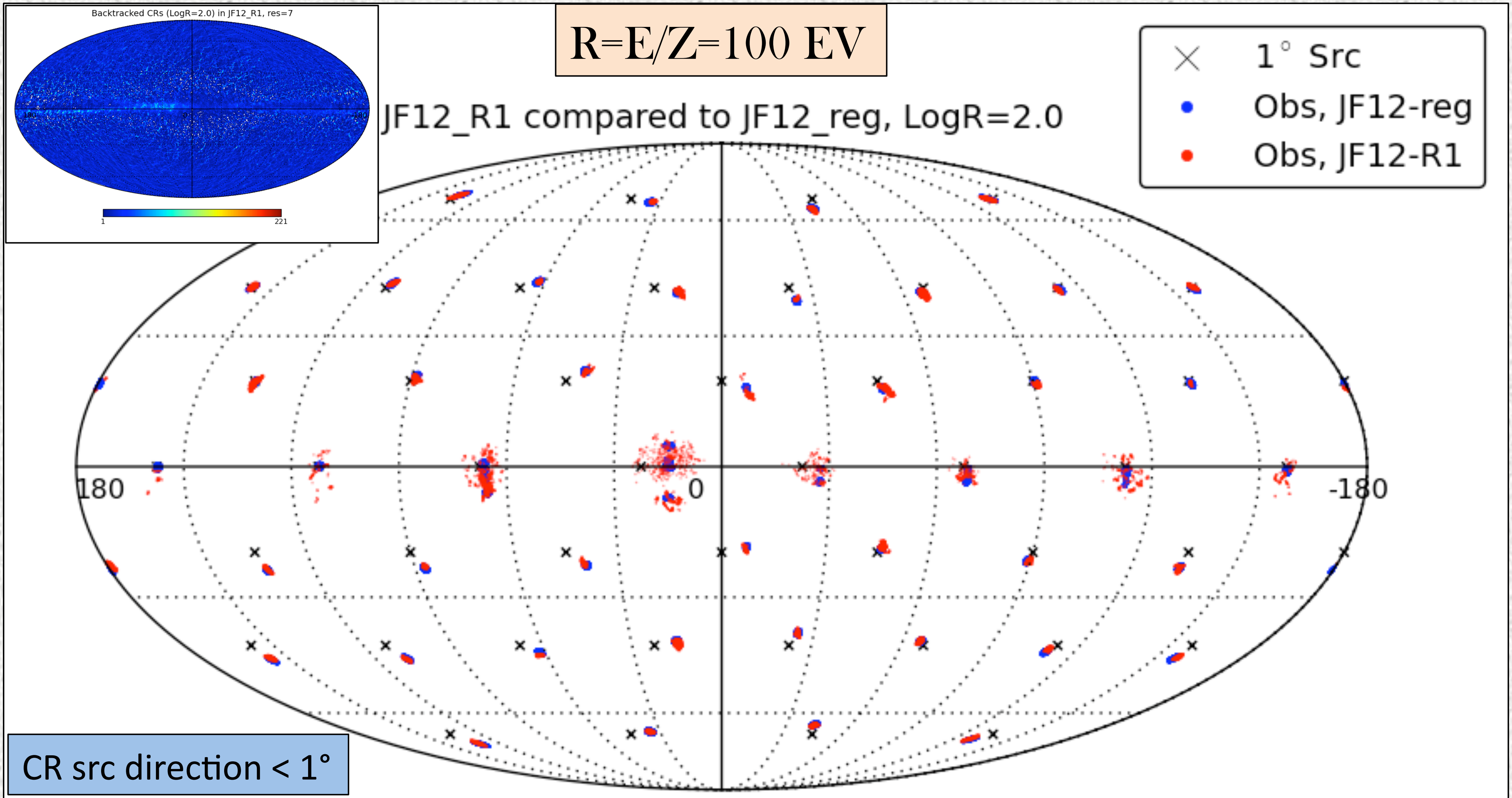




JF12 Regular + Random field

R=E/Z=100 EV

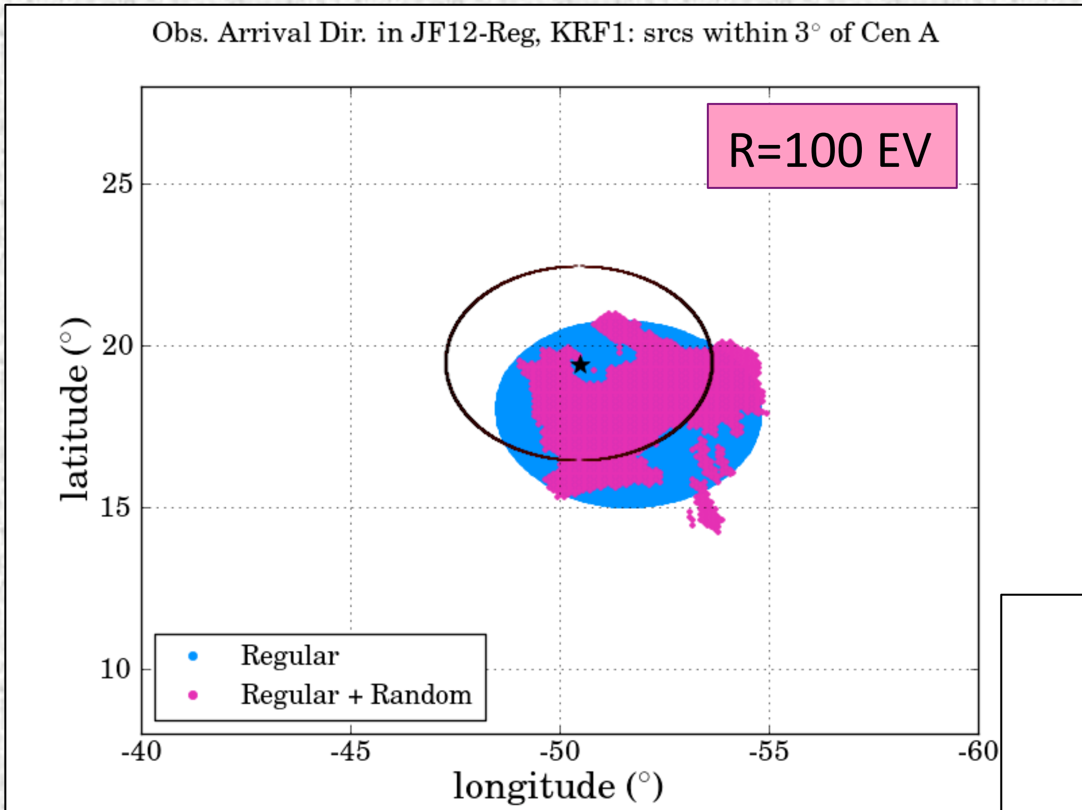


CR src direction < 1°

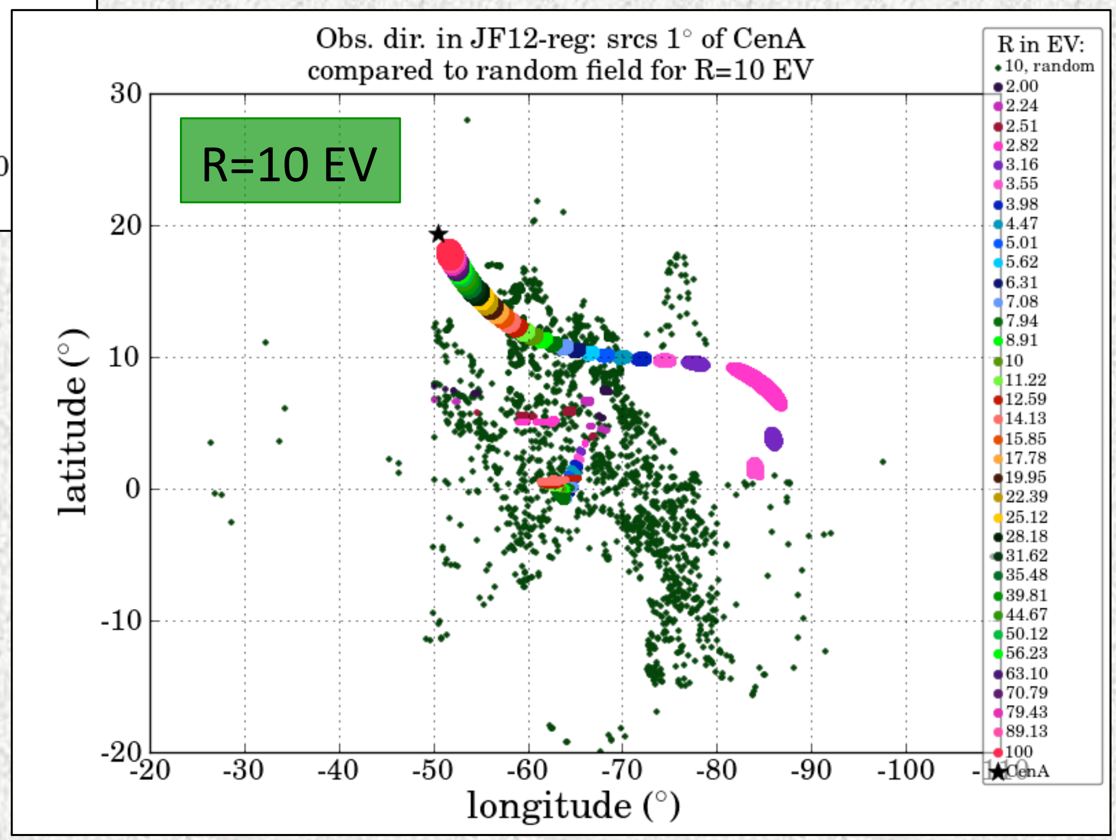
Observed direction

48 Sources, for clarity

JF12 Regular + Random field



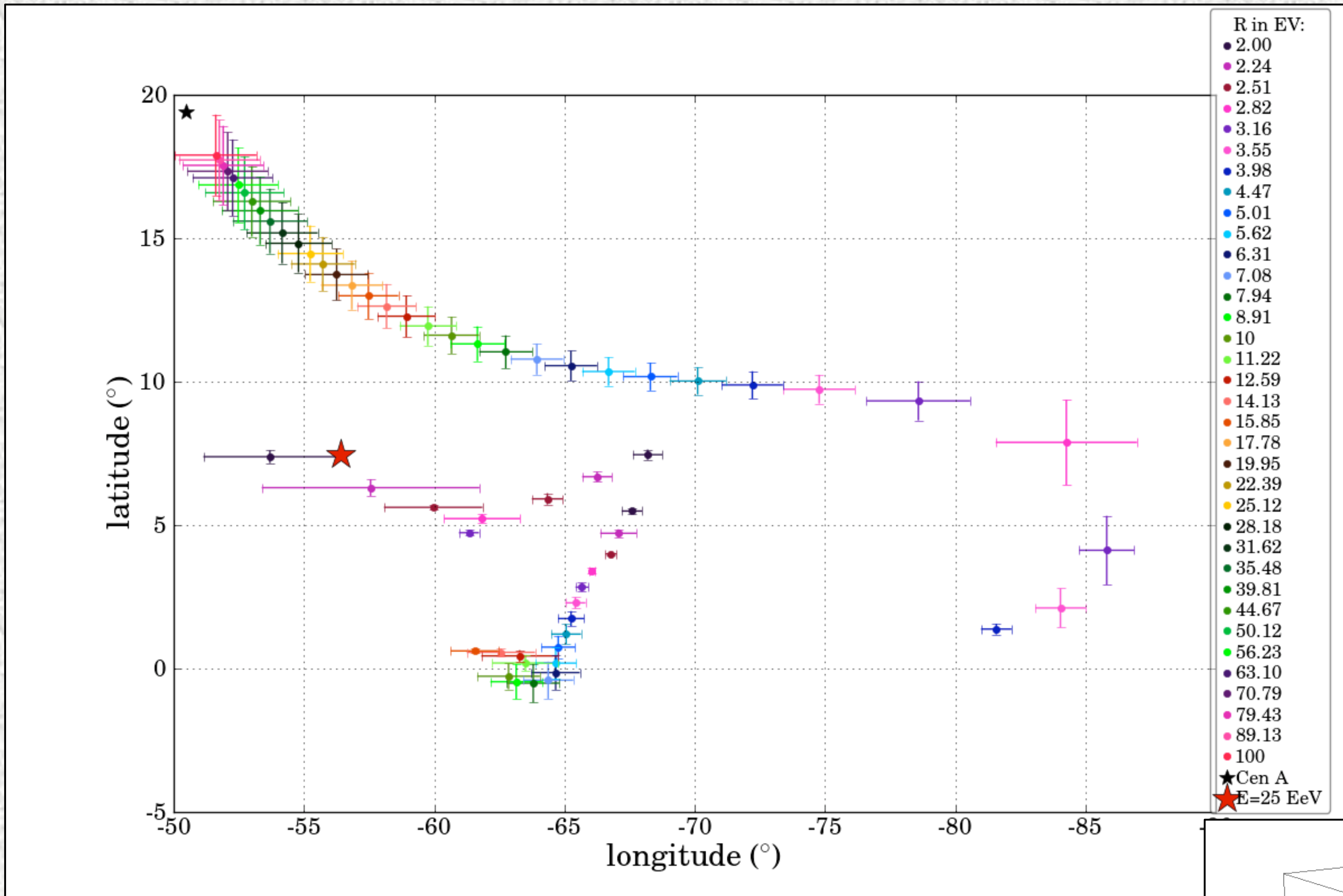
At high energies adding random field would not significantly change the average deflections from Cen A



Random field scatters the low energy CR a lot more than the regular field

AK, G. Farrar and M. Sutherland, in prep

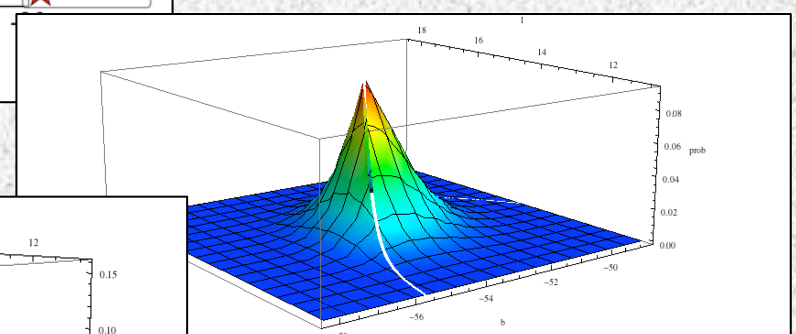
Mass composition: Assign charges to events



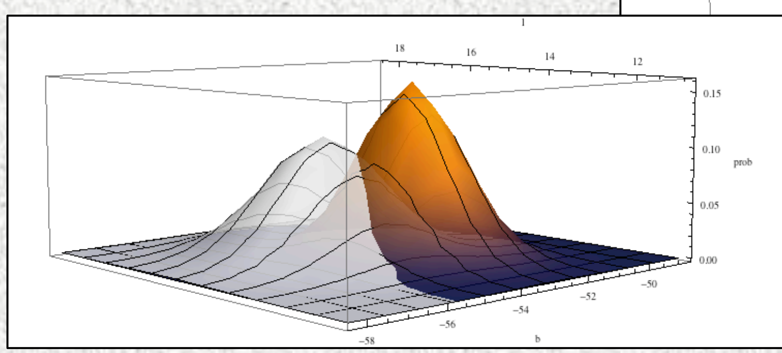
Assume the asterisk is an Event with known energy and arrival direction

Each event has an uncertainty on (l,b) and also on energy

Consider a 2D Gaussian distribution around each event with (<l>,<b>)and standard deviation of (σ_l, σ_b)



Calculate the volume of the overlap Gaussians of one event and one simulated point: Find the maximum (probability) → E/R = Z

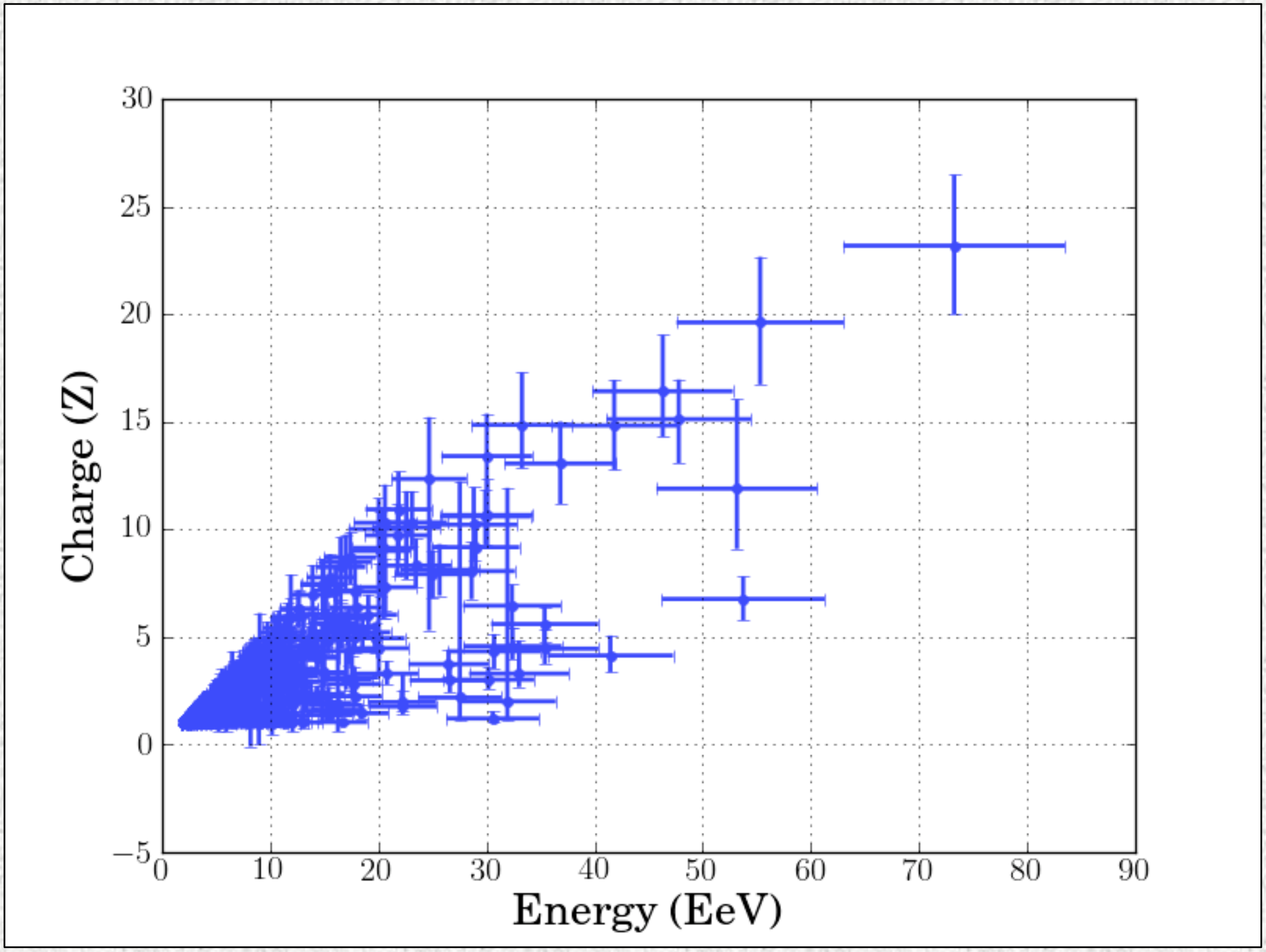


Assigned charges (Z) vs. energy

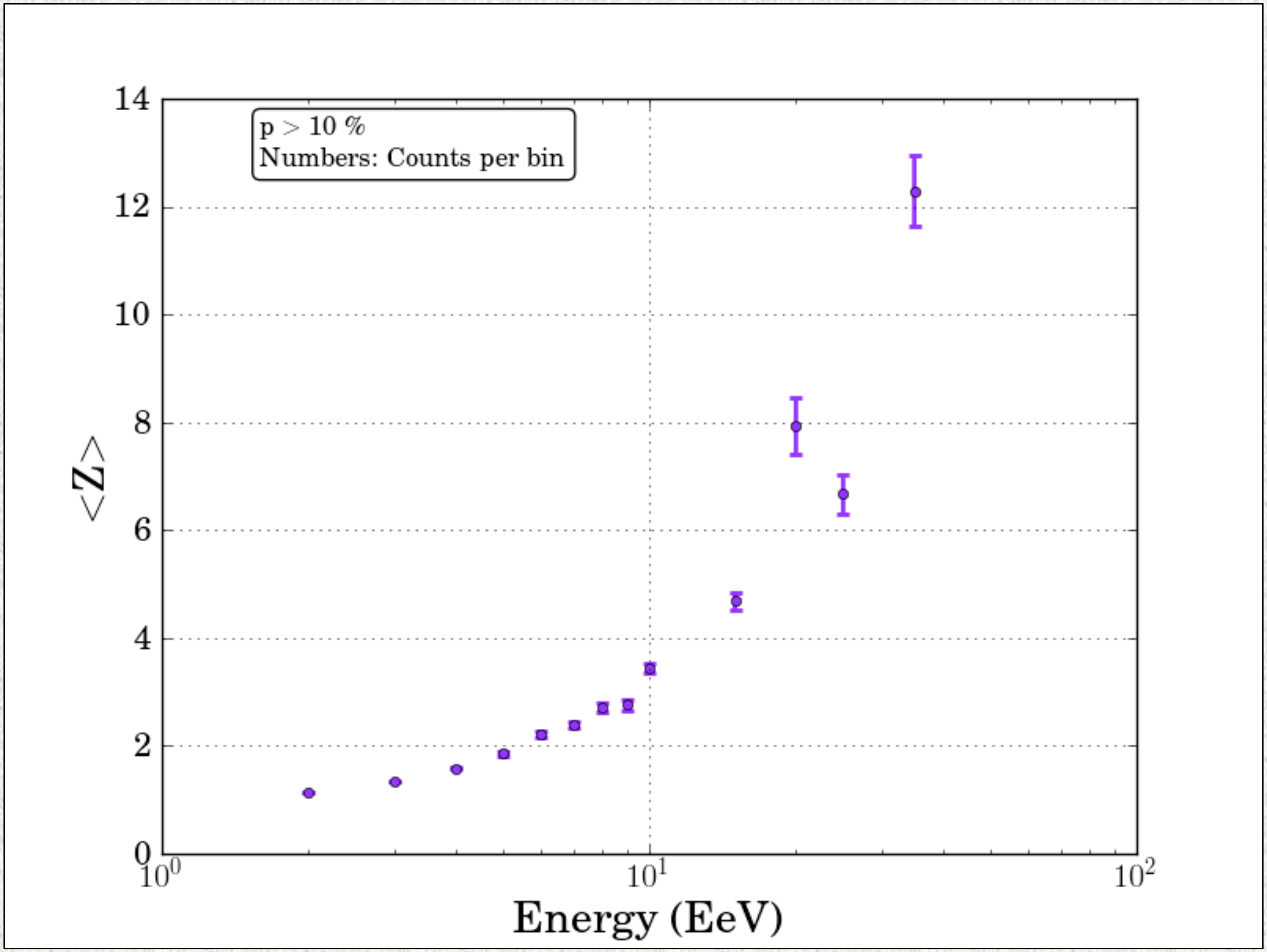
Events with probability > 10%

Each event is assigned a certain charge with a calculated probability

Each event is smeared in energy and position (related to the error bars)



<Z> vs. Energy



Lower energies:
Bins of 1 EeV

Middle:
Bins of 5 EeV

Last bin:
E>35 EeV

Going to higher energies we see a general increase of Z

Summary

- We have found the arrival direction locations of UHECR with different rigidities in our simulations.
  - Simulations are done for R=100 EV down to 2 EV in regular field.
  - A rigidity of 2 EV can be a 2 EeV proton or a 52 EeV iron.

- We see an excess of simulated proton and iron within 45 degrees of CenA.

- The random field can induce larger deflection magnitudes than a sole regular field depending on the source direction and the energy

- We introduced a method to calculate the charge of a CR event.
  - Based on the hypotheses that the events are from Cen A and correlating with simulated regions, we are able to assign a charge to each event.

Thanks for your attention