The Galactic Magnetic Field and UHECR Optics

Glennys R. Farrar   &   Mike Sutherland (OSU),

Center for Cosmology and Particle Physics
New York University

Ronnie Jansson & GRF, Ap.J. 757, 14 (2012)   coherent & striated
RJ & GRF, Ap.J.Lett. 761, L11 (2012)   random & n_{cre}
GRF, RJ, I Feain & B. Gaensler JCAP (2012)   Cen A
GRF Comptes Rendu Physique (2014)   review
Deepak Khurana & GRF, in preparation (2015)   robustness of JF12
Nafiun Awal & GRF, in preparation (2015) Galactic sources
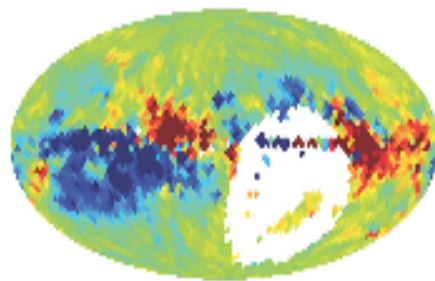GRF, RJ, A. Keivani, M.Sutherland in prep (2015)   CR deflections

ICRC 2015, Den Haag, Jul 31, 2015
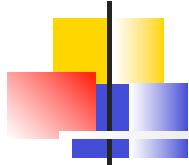
Jansson-Farrar strategy, I. *Data*

Rotation Measures

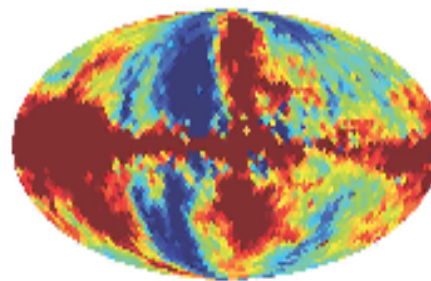$$\sim \int_{\sim}^{\infty} dz\, n_e(\mathbf{x})\, B_{\parallel}(\mathbf{x})$$

line of sight

Polarized synchrotron

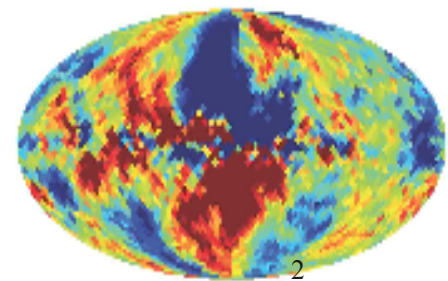$$\sim \int_z^{\infty} dz\, n_{cre}(\mathbf{x})\, B_{\perp}^2(\mathbf{x})$$

line of sight

Complementary!

~40k datapoints for each; smooth to 16x smaller bins (2.5k); *measure variance in each pixel*

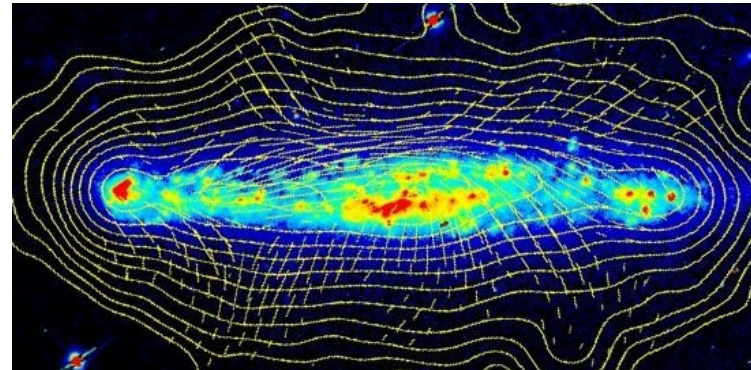
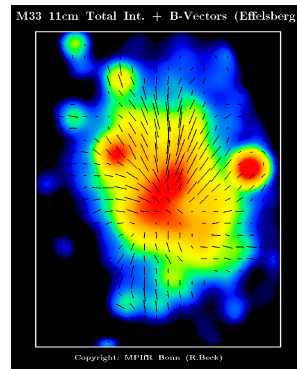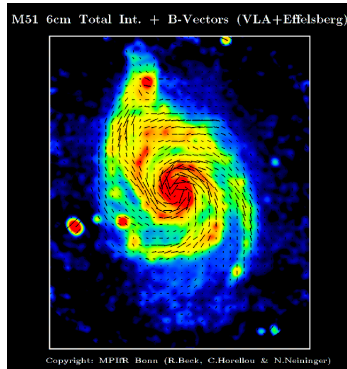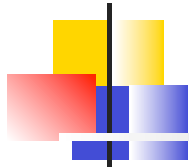RM   Q (polarized synch)   U (polarized synch)
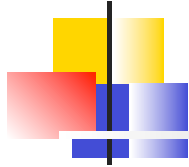
How to model the GMF?

Theoretical constraint: magnetic flux is conserved!

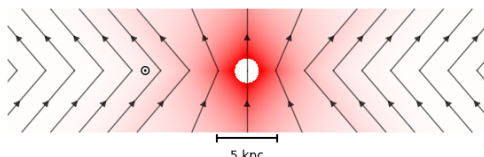Observational guidance: external galaxies

JF12 coherent field model

- **Striated**: aligned (with the regular field), but average value is 0.

    - Contributes to Polarized Synchrotron emission, but not RMs.

    - Can result from an explosion-created shell in a coherent field or from stretching a random field.

    - With only Polarized Synchrotron & RM, cannot distinguish between striated and coherent B, or rescaled $n_{cre;}$ Fitting for the random field using total synchrotron intensity => separate.
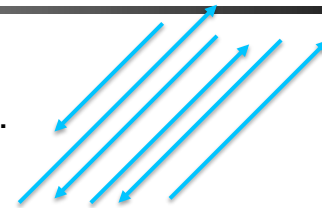
- **X-field**: Poloidal component, allowed to be coherent &/or striated.

(c) Model C

3 kpc

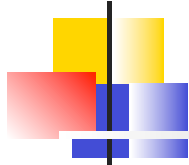*2015 update (D. Khurana+GF in prep)*
test form proposed by Ferriere-Terral 2013
B_0, r_B, r_X , exponent=2

5 kpc

Original JF12 X-field
B_0, r_B, r_X, asymptotic angle
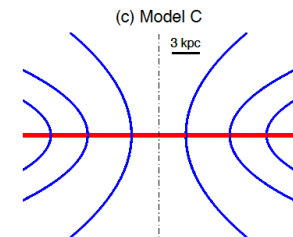
- + toroidal halo & spiral arm disk components -- coherent & striated.

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JF12 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
- **Constrained with WMAP7 22 GHz total Intensity map**
  - Doesn't constrain coherence length
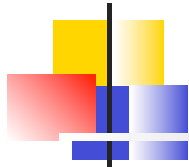
Mask*

Smoothed data

Model prediction

$$\chi^2 = \frac{(\text{Smoothed data} - \text{Model prediction})^2}{(\quad)^2}$$

Sum over all pixels

Variance *measured* from hi-resolution data

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

Input Data

- **40403 extragalactic RMs**

  - bin to 2067 pixels (13.4 sq-deg)

  - *Measure variance from sub-pixels*

  - Subtract foreground where available [Wolleben et al (2010)]

    - ☑ **Fit is virtually unchanged (< 1 σ): VINDICATES METHODOLOGY**

      - Future: Fill in hole; use RM synthesis data to identify foregrounds.

- **WMAP 7-yr K-band, 22 GHz synchrotron maps**

  - Bin to 2067 pixels; measure variance from sub-pixels

  - Do fit with 4 different masks (JF12) or no mask (KF15)

    - **Fit is virtually unchanged (< 1 σ): VINDICATES METHODOLOGY**

      - Future: Planck synchrotron map (minor improvement)

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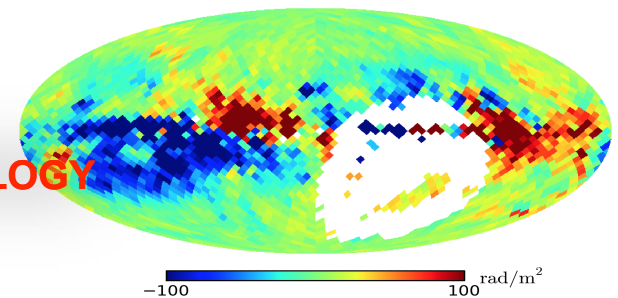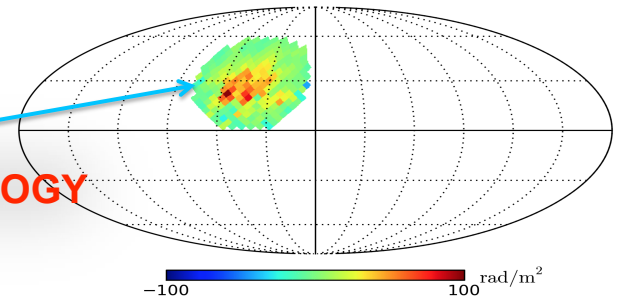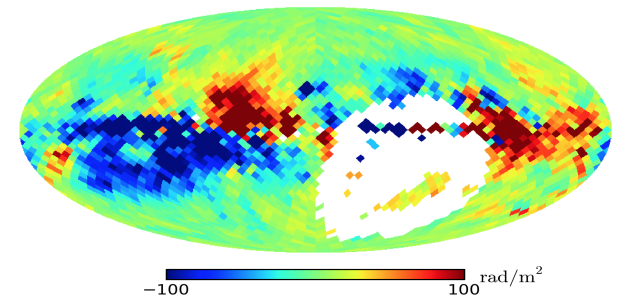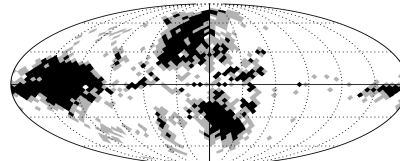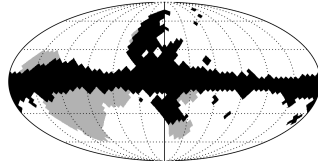
New Insight: field in halo is poloidal & directed (S to N)

10 kpc

Jansson-Farrar 2012 GMF
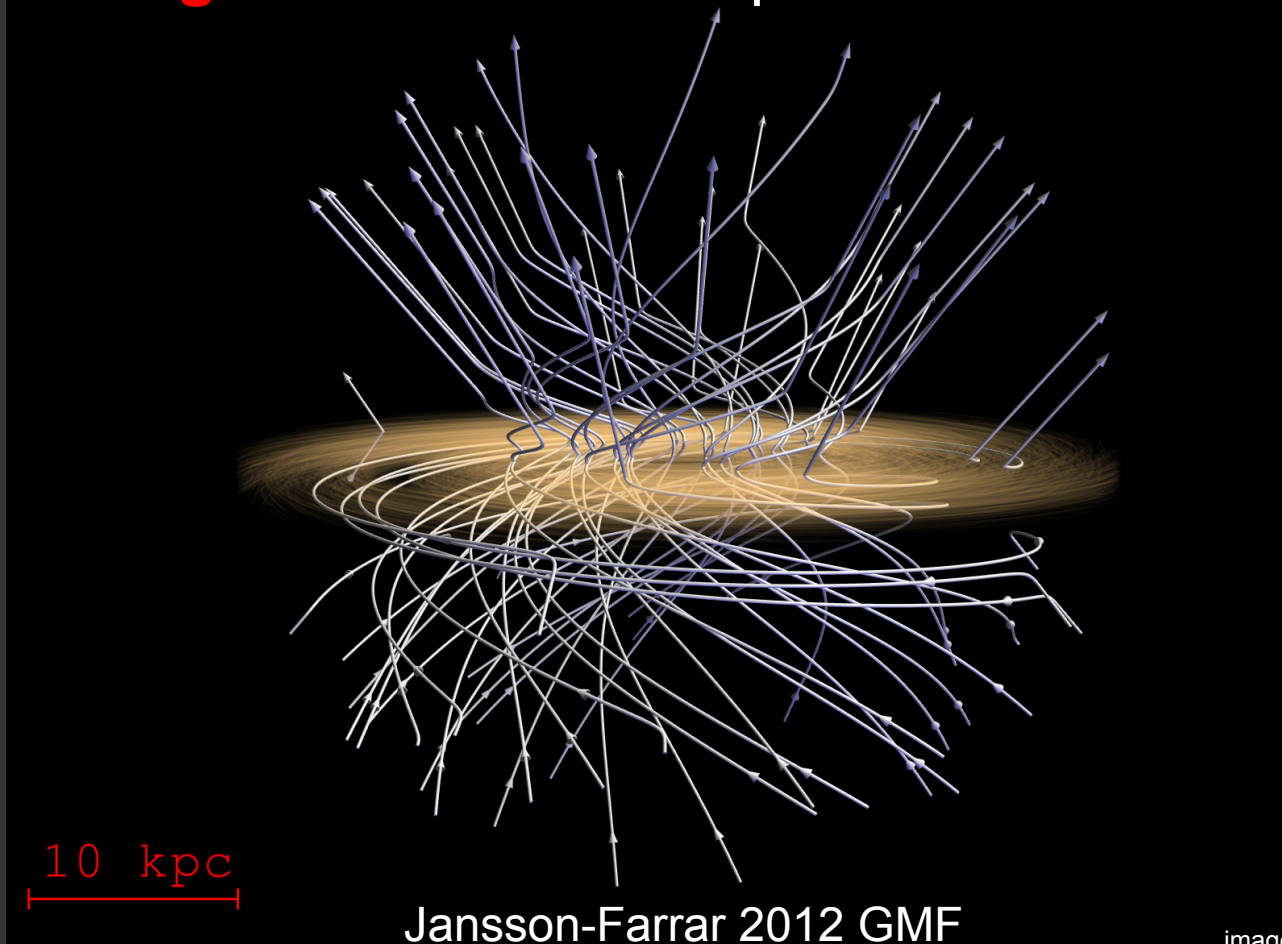
image made by J. Sandstrom, NASA

Data versus JF12 predictions

RM   Stokes Q   Stokes U

data used in fit

full dataset!

Missing data

-0.02 0.02 mK -0.02 0.02 mK

-100 100 rad/m^2 -0.02 0.02 mK -0.02 0.02 mK

9
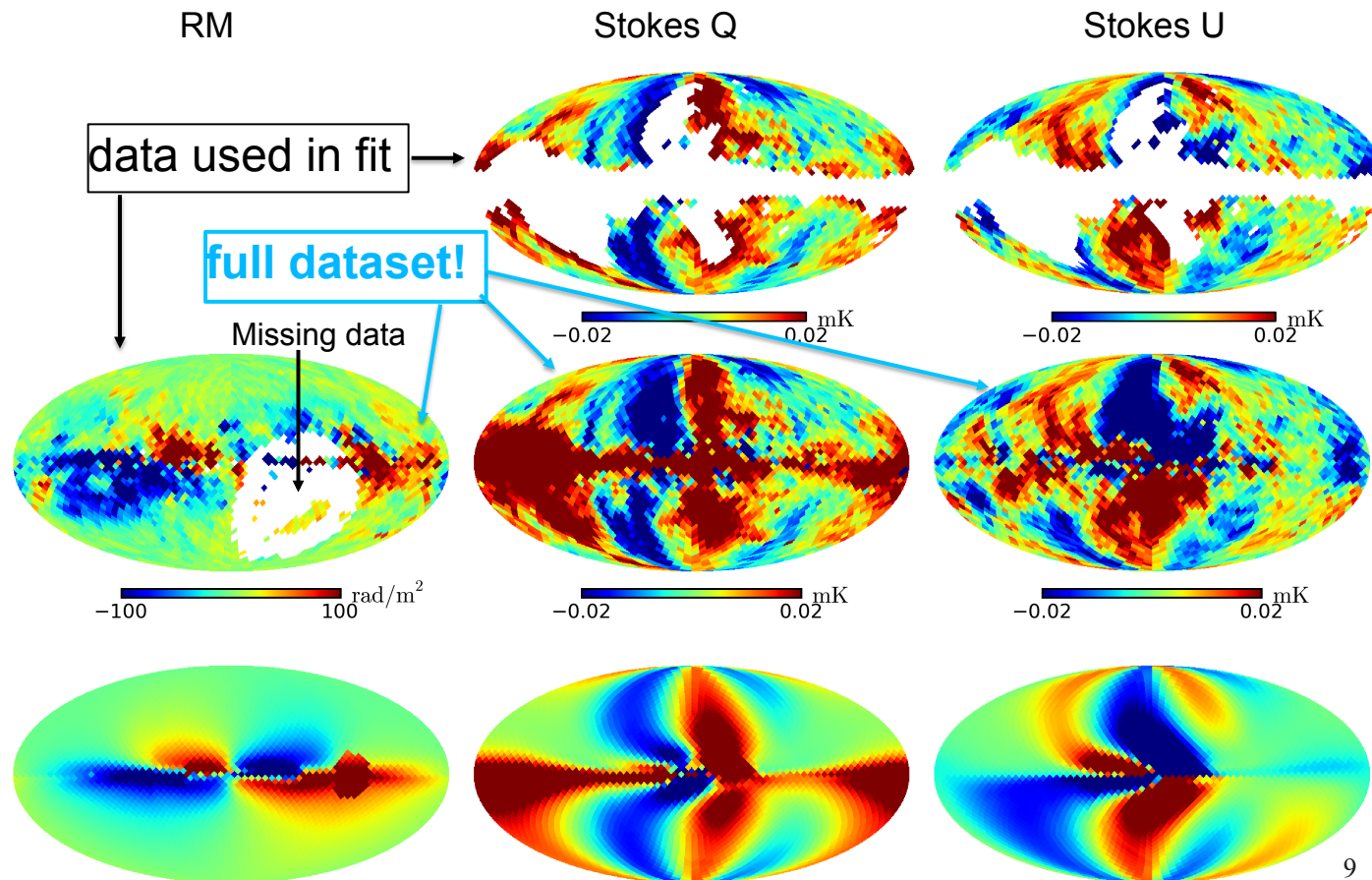
Predictions of 3 most recent GMF models
JF12 spiraling X-field generates distinctive pattern in Q, U data

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

10
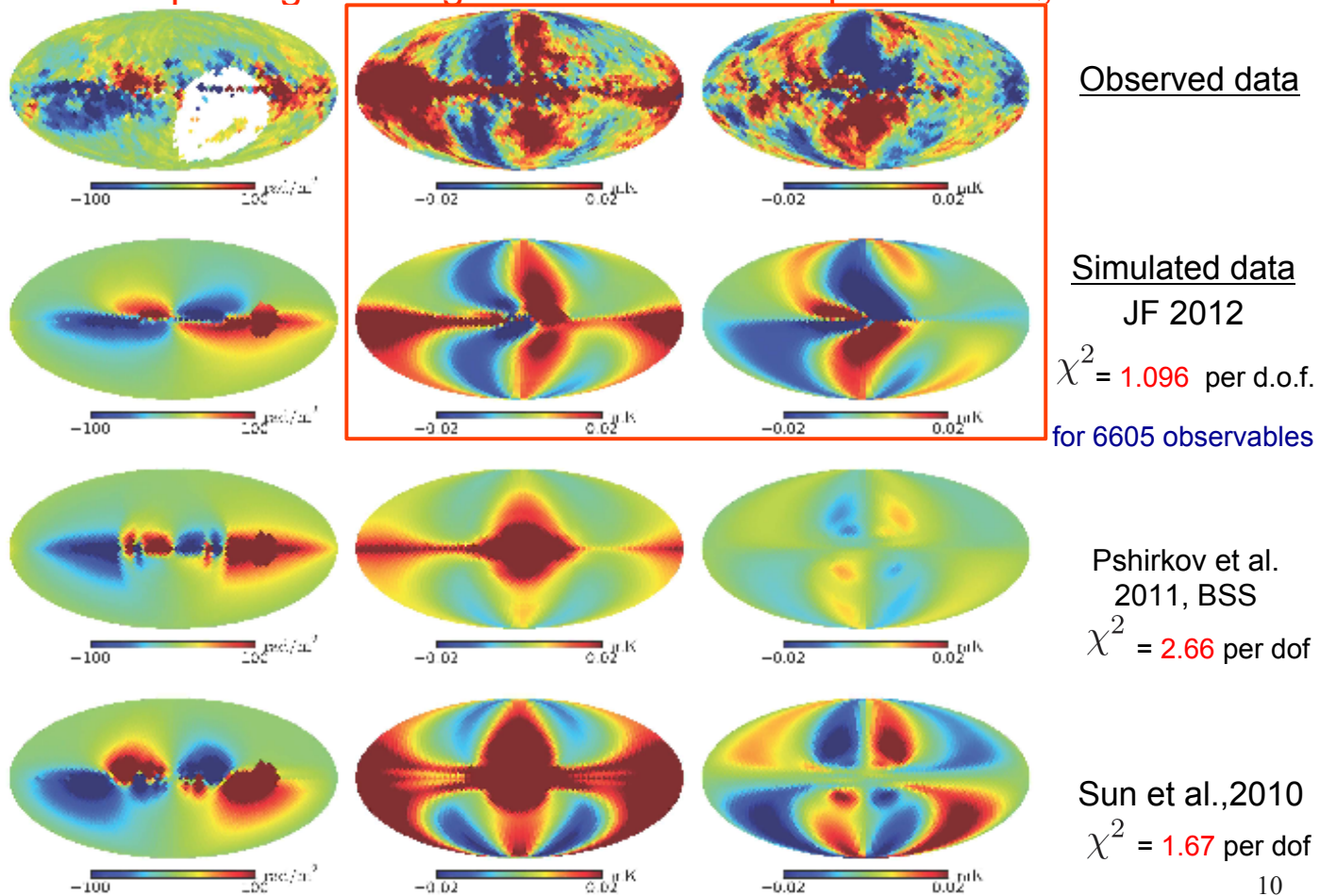
Halo field: DIRECTED, not just striated

RM   Stokes Q   Stokes U

purely striated halo

JF12: coherent + striated halo

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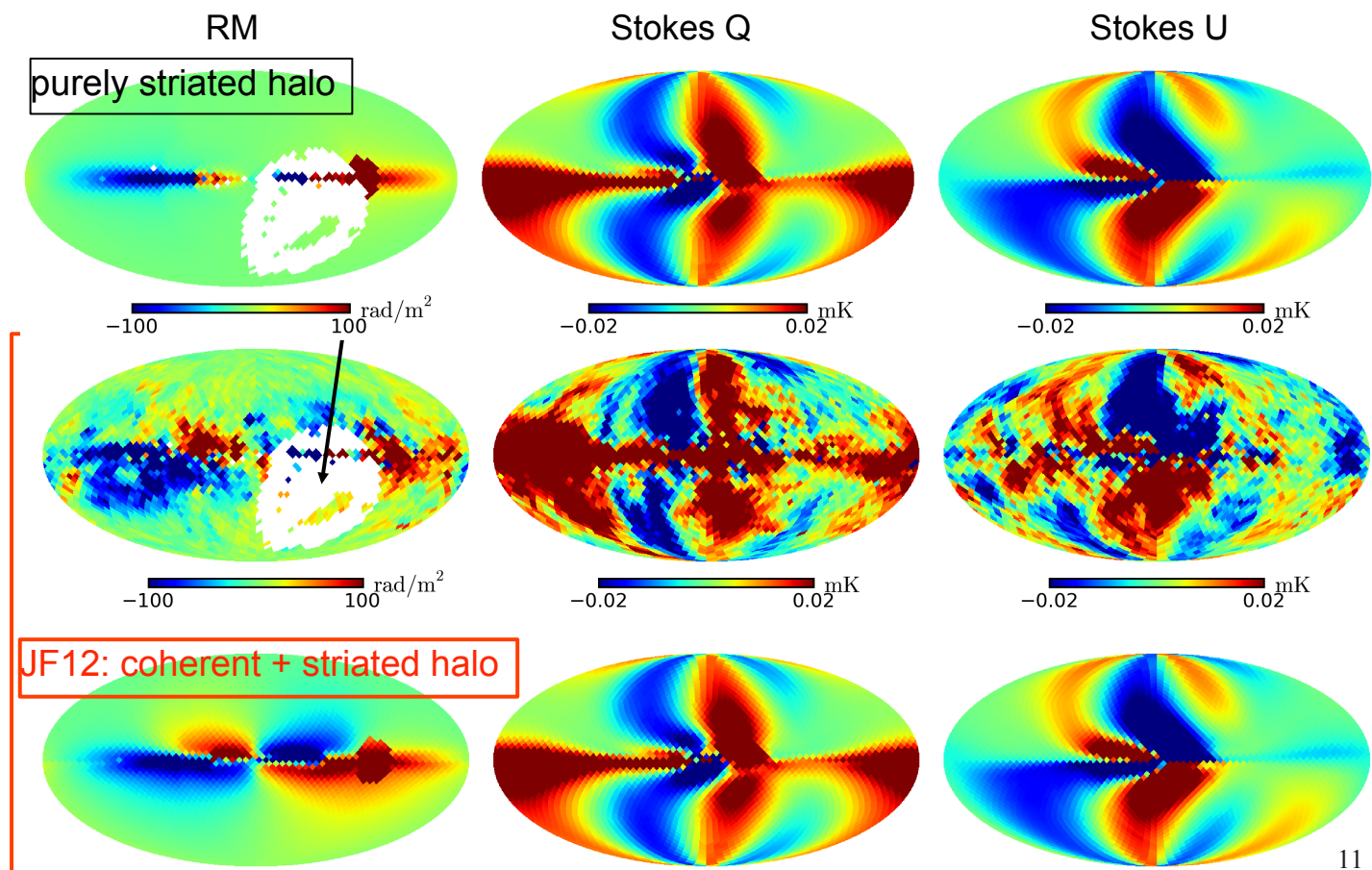
Variations to JF12 and uncertainties

JF12 parameter uncertainty: < 2°

Standard Deviation of Mean Deflection of UHECRs (60 EeV)

0.03 degrees   1.6 degrees
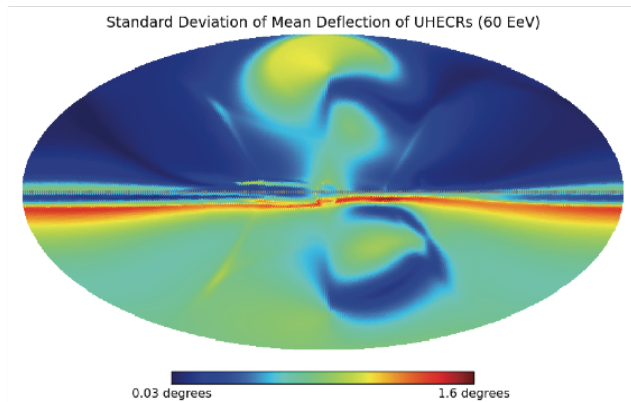
JF12 X-field parameterization: mostly < 1°

Thanks to M. Unger for plot
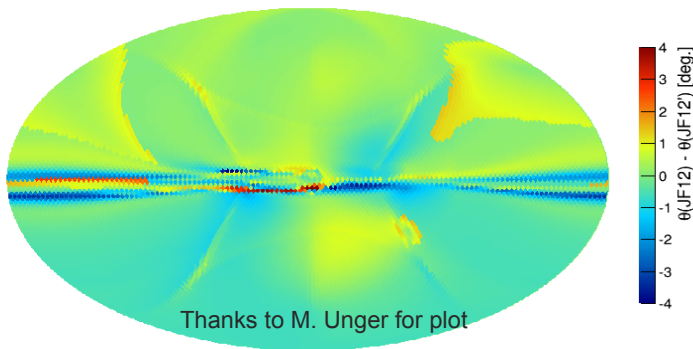
Field parameters change < 1 sigma from JF12
 when:

• Tilt axis of halo field
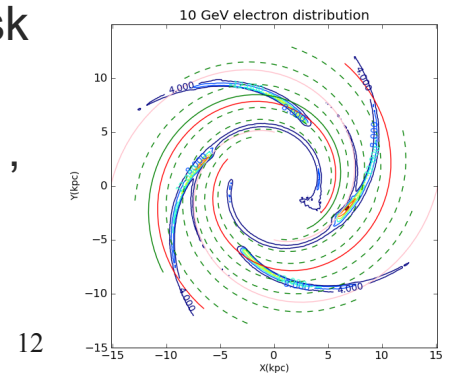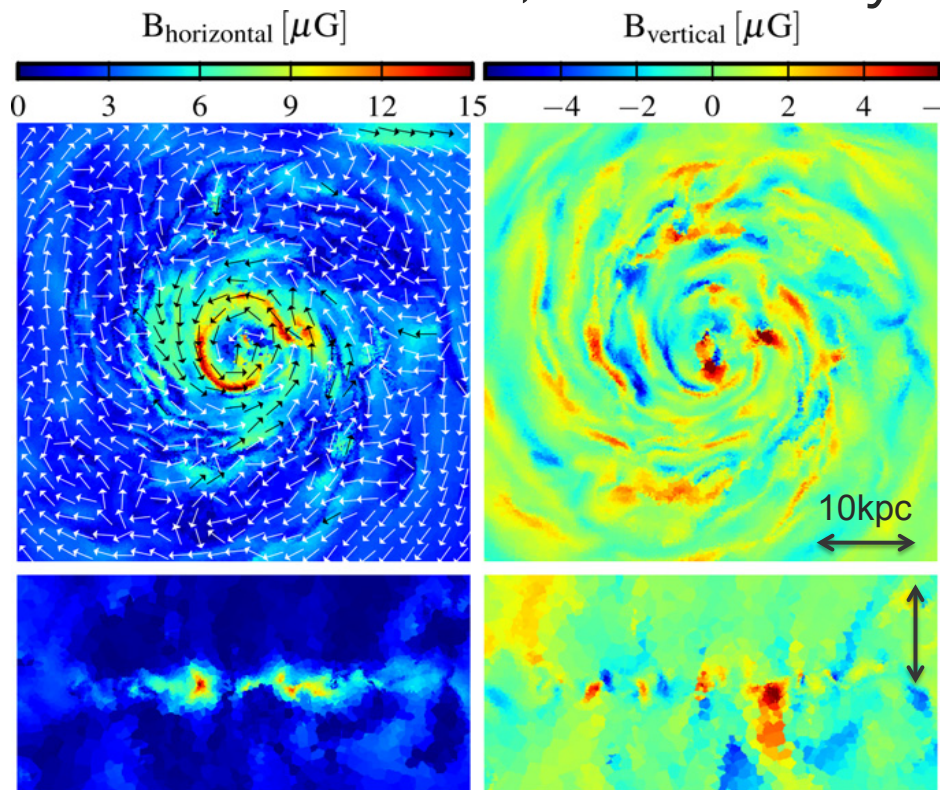• Use Ferriere-Terral functional form for X-field
• Allow disk field to flow into halo

Varying n_{cre} by adding spiral arms reduces
random field strength in disk

Crucial to improve n_e & n_{cre} ,
especially for disk field.

10 GeV electron distribution

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N.b., GMF may be complicated…

simulated galaxy formation in MHD
Pakmor, Marinacci, Springel 2014

- Need to formulate more general, less-orderly field models to constrain with data (flux conservation will be key)

- Present GMF models must be used judiciously

  - Details likely wrong

  - General lessons may be valid

  - UHECRs may eventually help, with more, composition-tagged events.
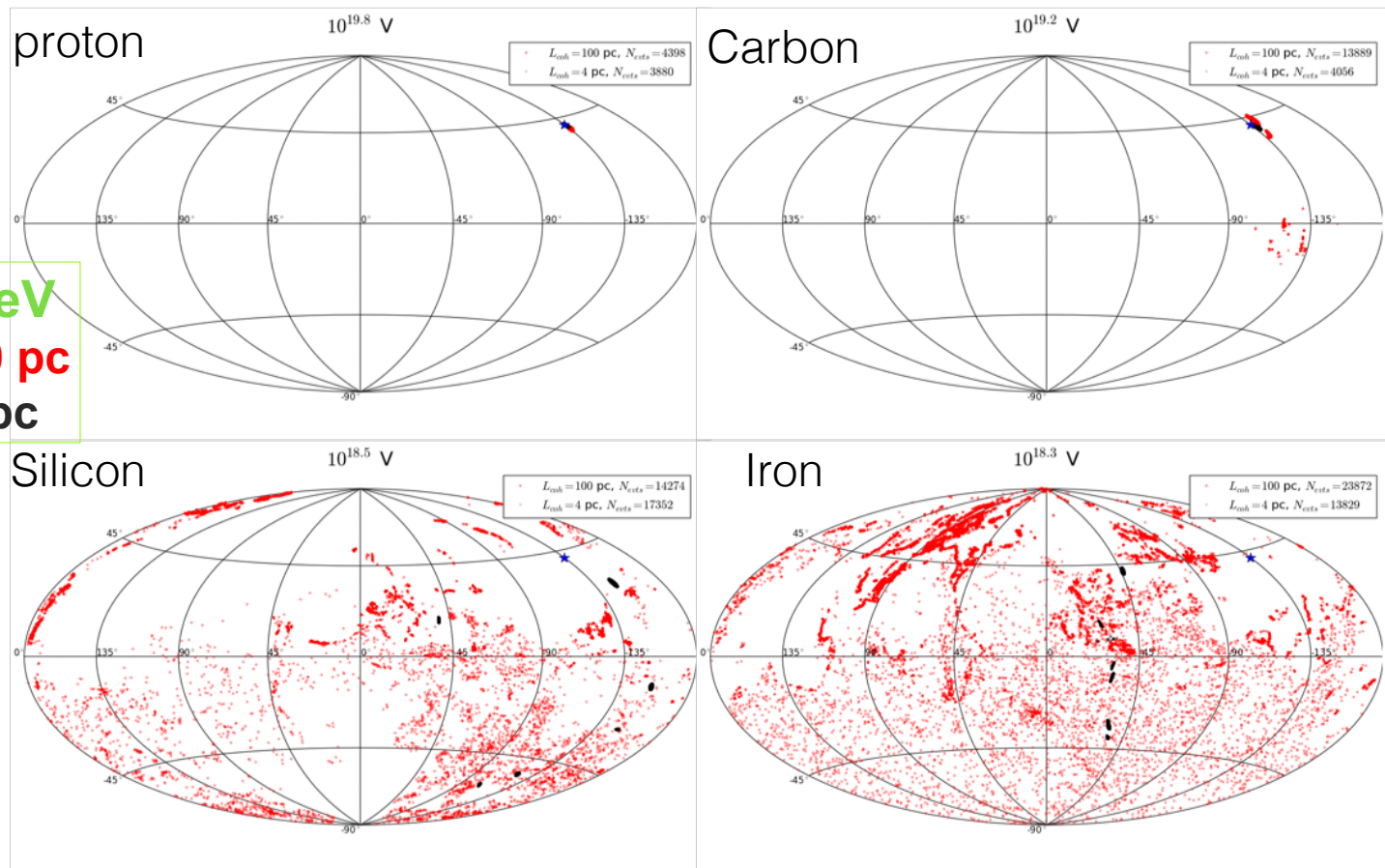
Impact of GMF on CR propagation

for JF12 regular + random (Kolmogorov spectrum,100 pc coherence length)

10 kpc
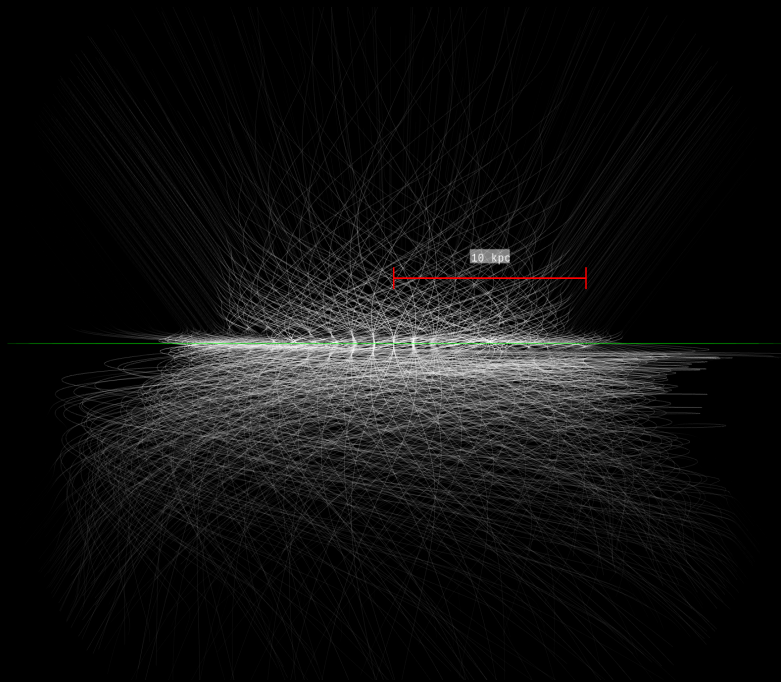
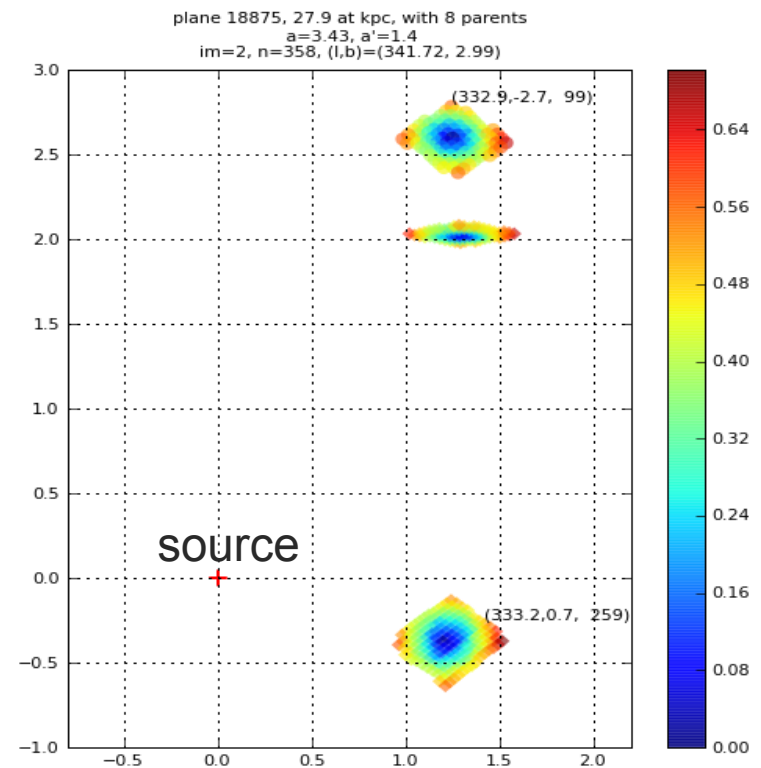# Deflections depend on composition and GMF turbulent coherence lengths
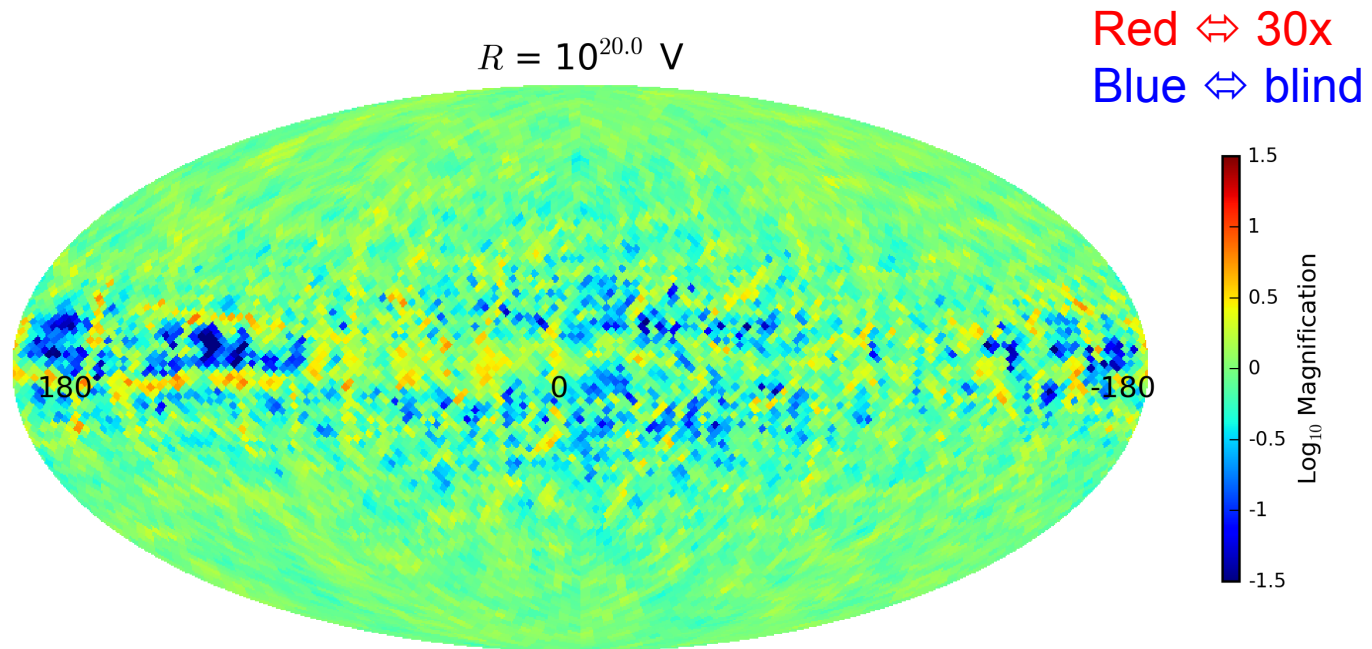

E = 60 EeV
L_{coh} = 100 pc
= 4 pc

Lensing

- Due to lensing of GMF, CRs in multiple parts of arrival plane can reach Earth.

- => flux (de)magnification.

- Very nice analysis in terms of caustics: Harari, Mollerach, Roulet(+) 2002-2010.

- MS & GF: what is the effect of lensing for a realistic model, including random fields.
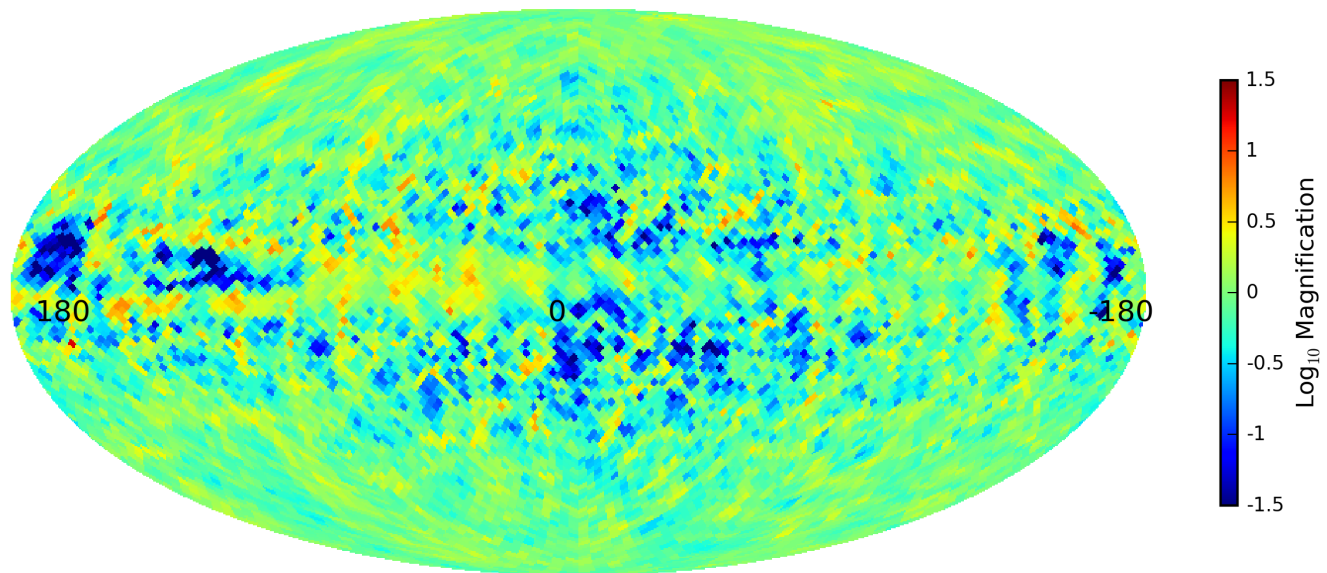

plane 18875, 27.9 at kpc, with 8 parents
a=3.43, a'=1.4
im=2, n=358, (l,b)=(341.72, 2.99)

Magnification as a function of source direction

$R = 10^{20.0}$ V

Red ⟺ 30x
Blue ⟺ blind

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

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Magnification as a function of rigidity

$R = 10^{19.8}$ V

180   0   -180

Log_{10} Magnification

rigidity = 63 **EV**

Magnification as a function of rigidity
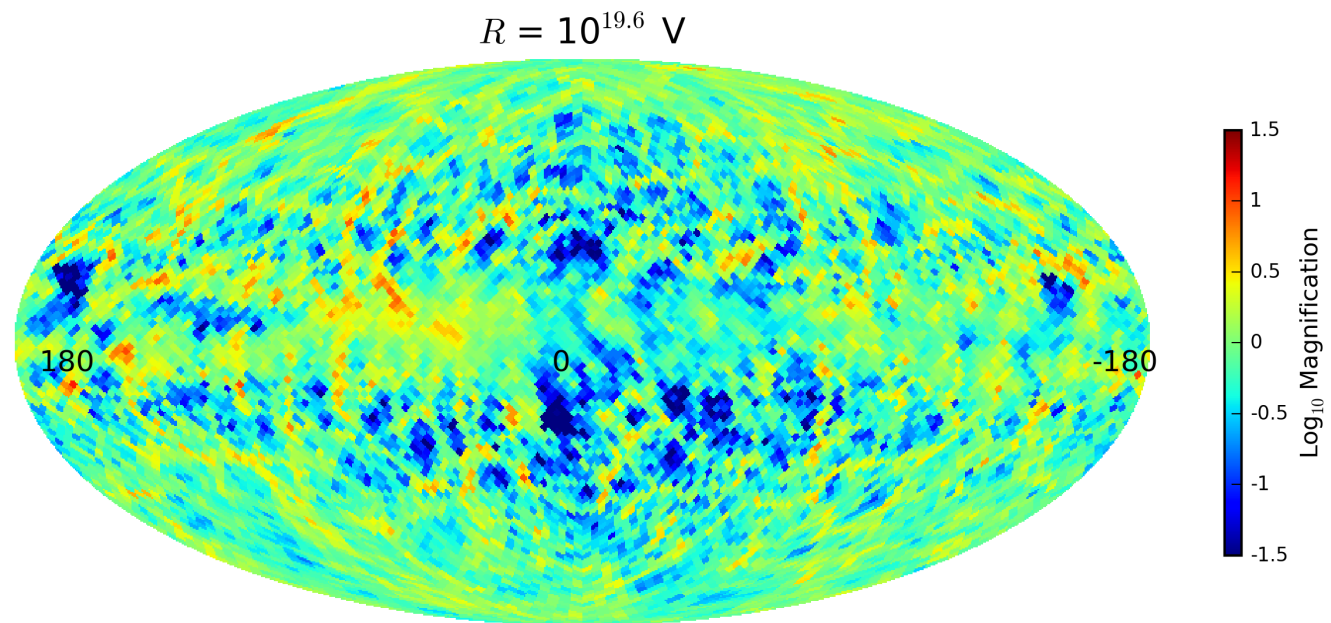
$$R = 10^{19.6} \text{ V}$$

rigidity = 40 **EV**

19

Magnification as a function of rigidity

$R = 10^{19.4}$ V

rigidity = 25 **EV**

Magnification as a function of rigidity

$R = 10^{19.2}$ V

180   0   -180

Log_{10} Magnification

rigidity = **16 EV**

21

Magnification as a function of rigidity

$R = 10^{19.0}$ V

180   0   -180

Log_{10} Magnification

1.5
1
0.5
0
-0.5
-1
-1.5

rigidity = **10 EV**

22

Magnification as a function of rigidity

$R = 10^{18.8}$ V

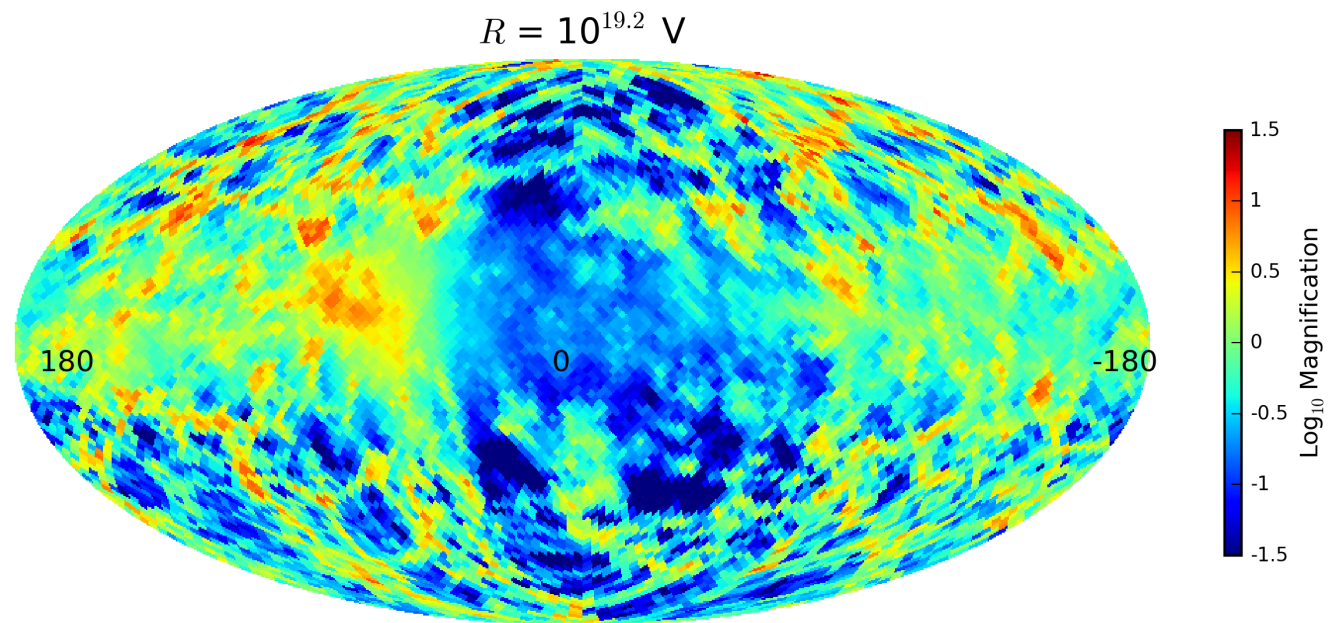rigidity = 6E**V**

23

Magnification as a function of rigidity

$R = 10^{18.6}$ V

180   0   -180

Log$_{10}$ Magnification

1.5
1
0.5
0
-0.5
-1
-1.5

rigidity = **4 EV**

24

Magnification as a function of rigidity

$R = 10^{18.5}$ V

180   0   -180

Log$_{10}$ Magnification

1.5
1
0.5
0
-0.5
-1
-1.5
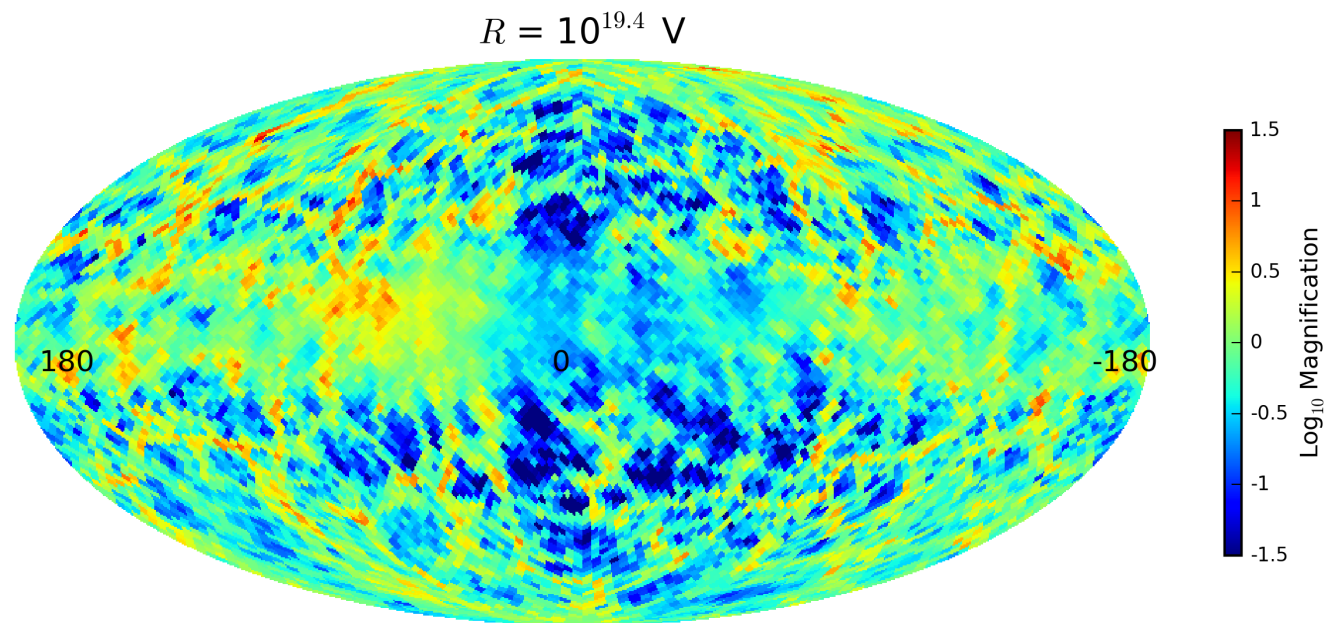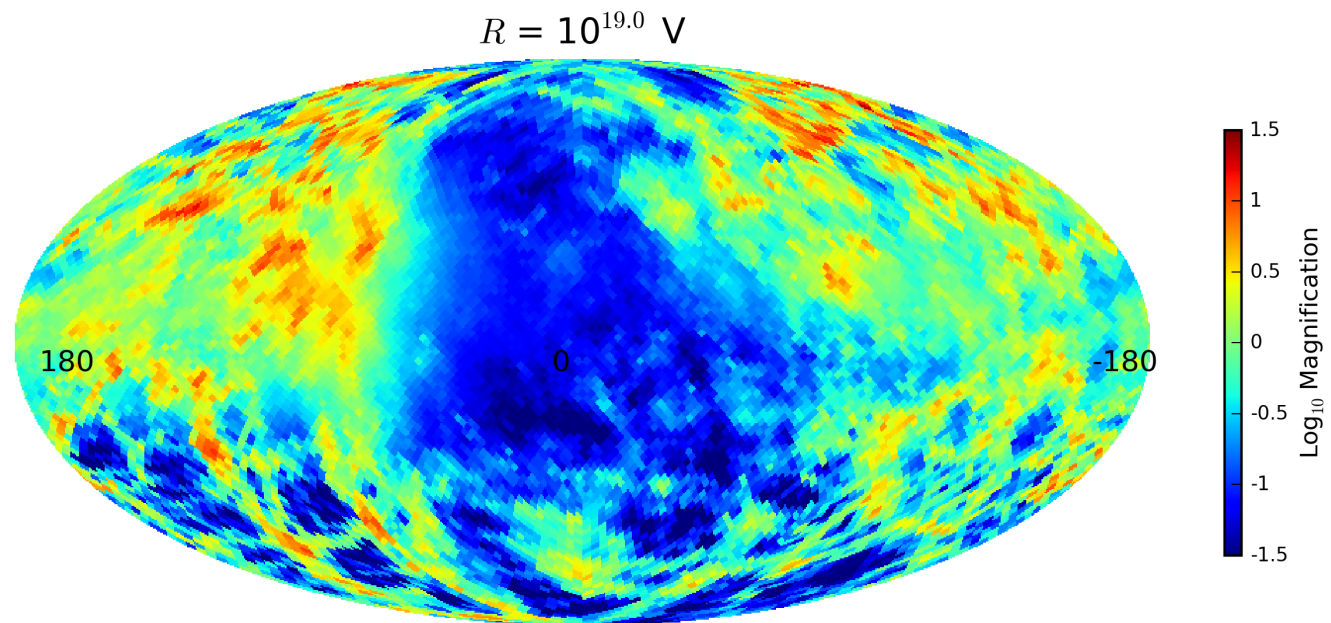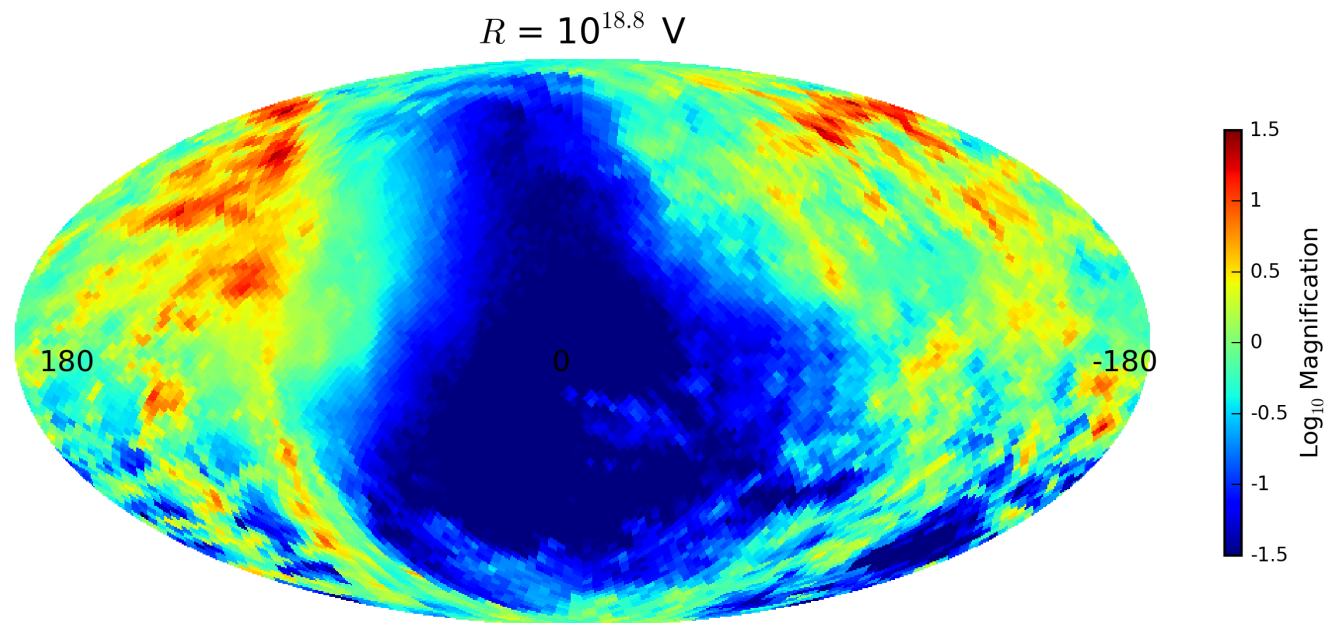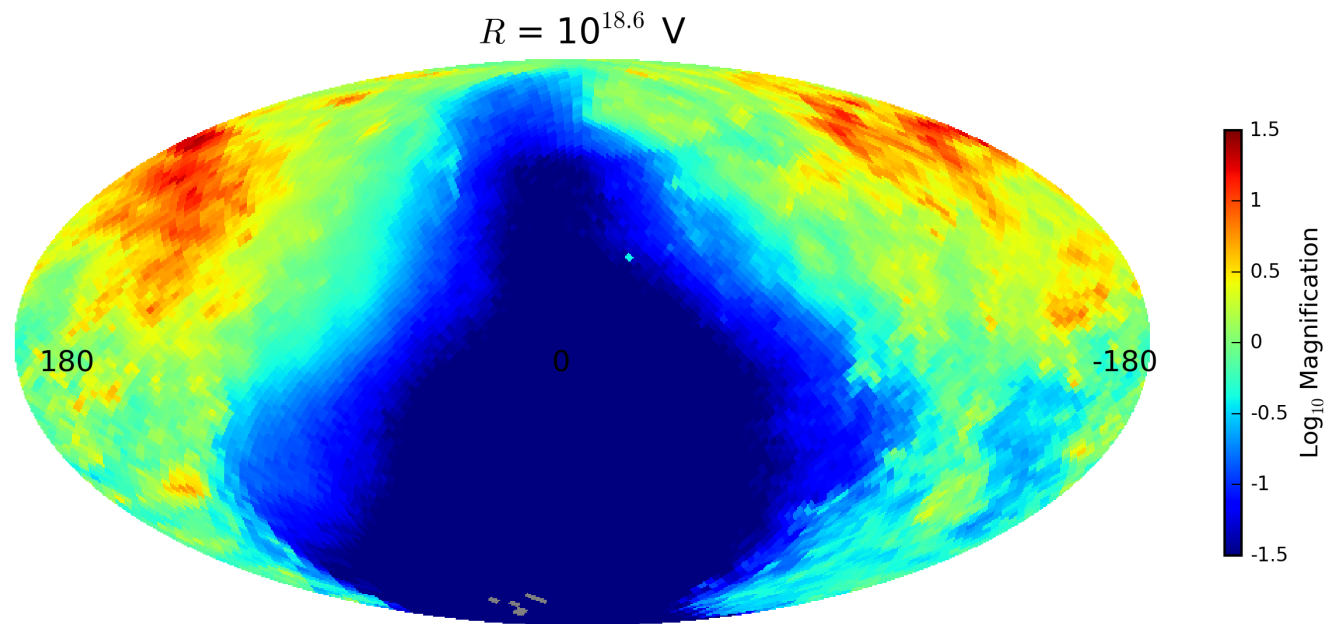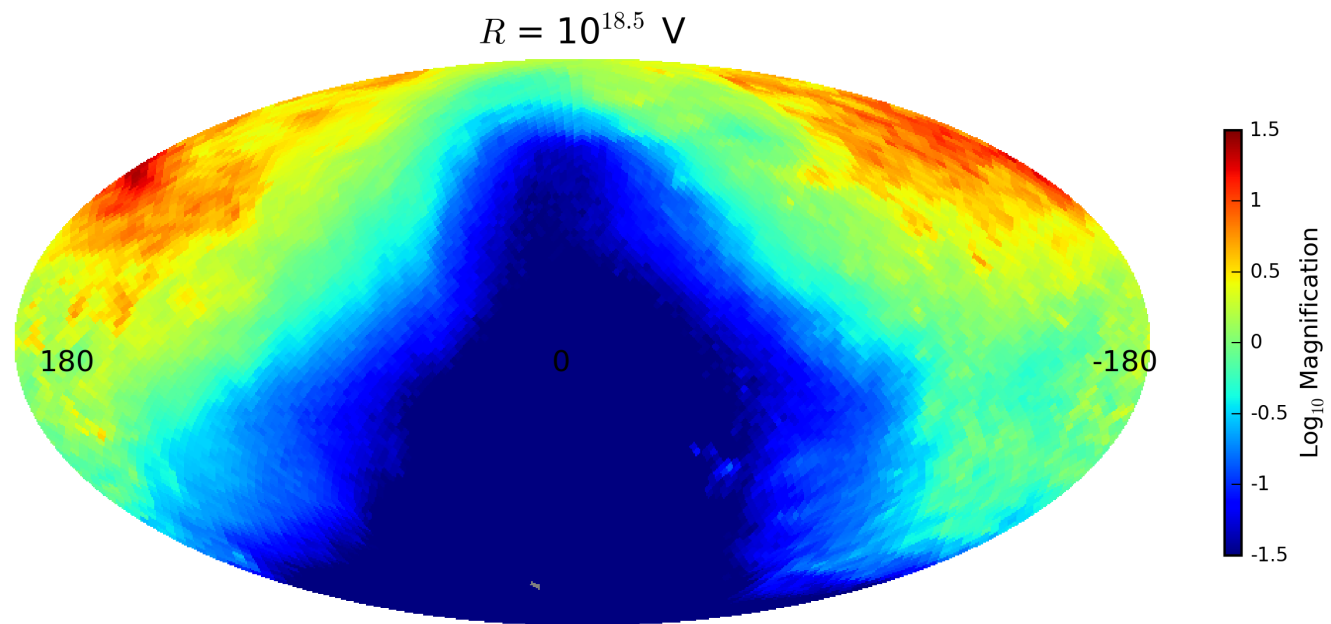
rigidity = **3 EV**

Magnification as a function of rigidity

$R = 10^{18.4}$ V

180   0   -180

Log_{10} Magnification

rigidity = 2.5 E**V**
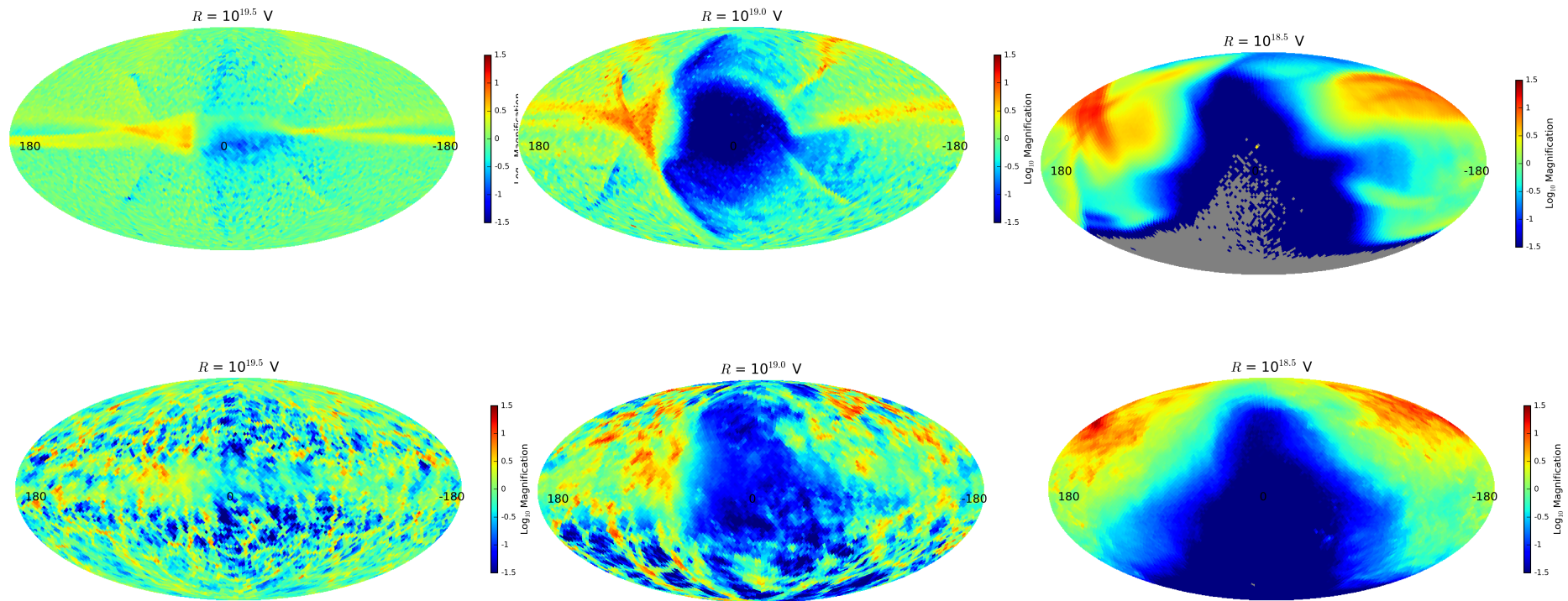
Magnification as a function of rigidity

$R = 10^{18.3}$ V
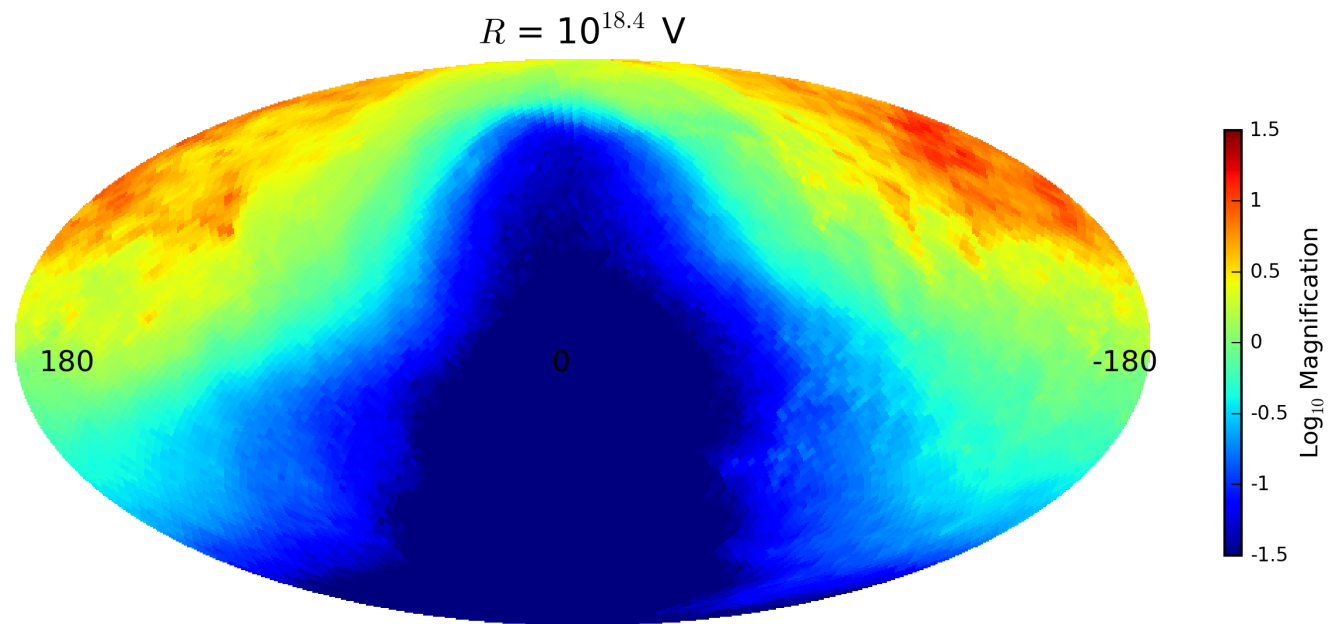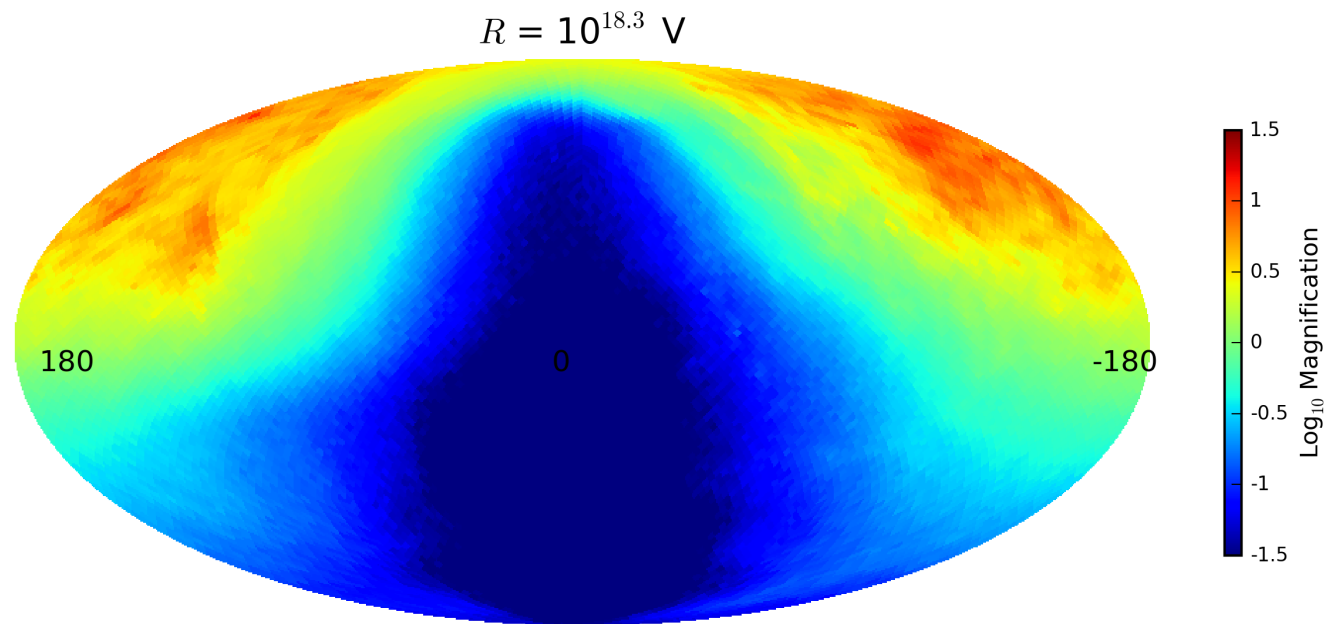
rigidity = 2 E**V**

Magnification as a function of source direction
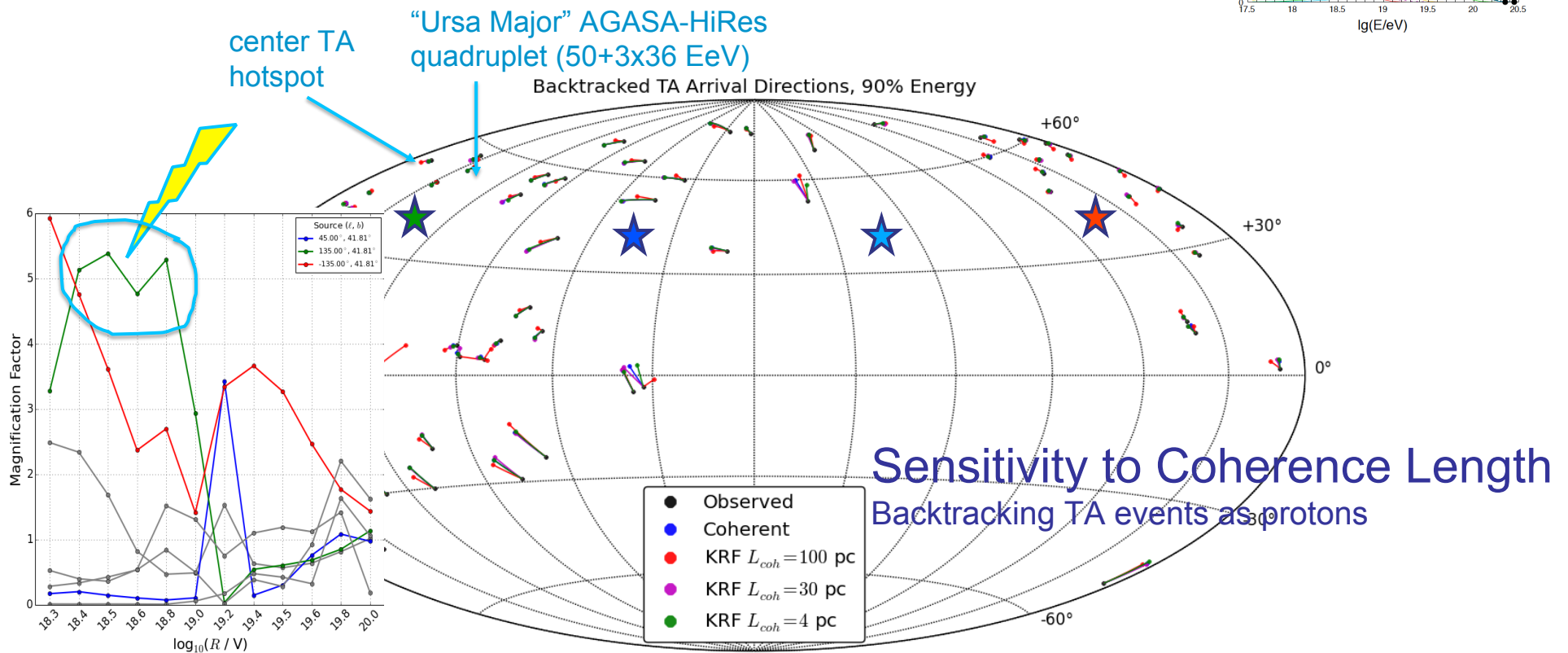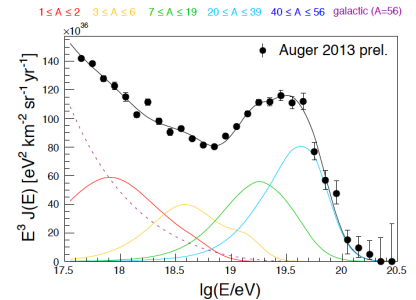## Dependence on L_{coh} (30 pc vs 100 pc)

Red ⇔ 30x
Blue ⇔ blind

28

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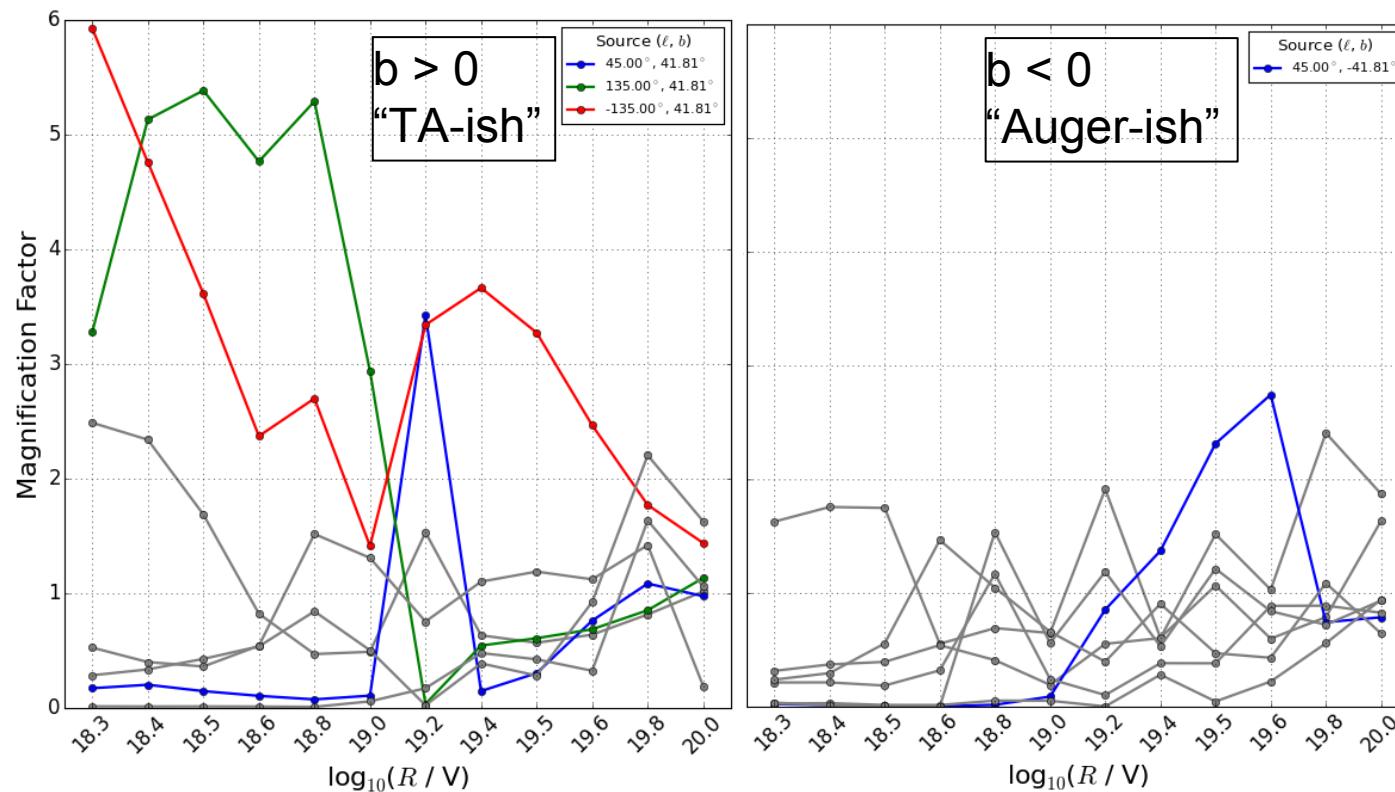
TA Hotspot:

E>57 EeV [UFA (Tues 3:45, World Forum): primarily Si] =>
E/Z ~ 4 EV => magnification ~ 5!

$1 \le A \le 2$ $3 \le A \le 6$ $7 \le A \le 19$ $20 \le A \le 39$ $40 \le A \le 56$ galactic (A=56)

Auger 2013 prel.

center TA hotspot

"Ursa Major" AGASA-HiRes quadruplet (50+3x36 EeV)

Backtracked TA Arrival Directions, 90% Energy

Source (ℓ, b)
45.00°, 41.81°
135.00°, 41.81°
-135.00°, 41.81°

Observed
Coherent
KRF $L_{coh}=100$ pc
KRF $L_{coh}=30$ pc
KRF $L_{coh}=4$ pc

Sensitivity to Coherence Length
Backtracking TA events as protons

Arrival Directions from CGCG291-028

rigidity = 6EV

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Arrival Directions from CGCG291-028

rigidity = **4 EV**

32
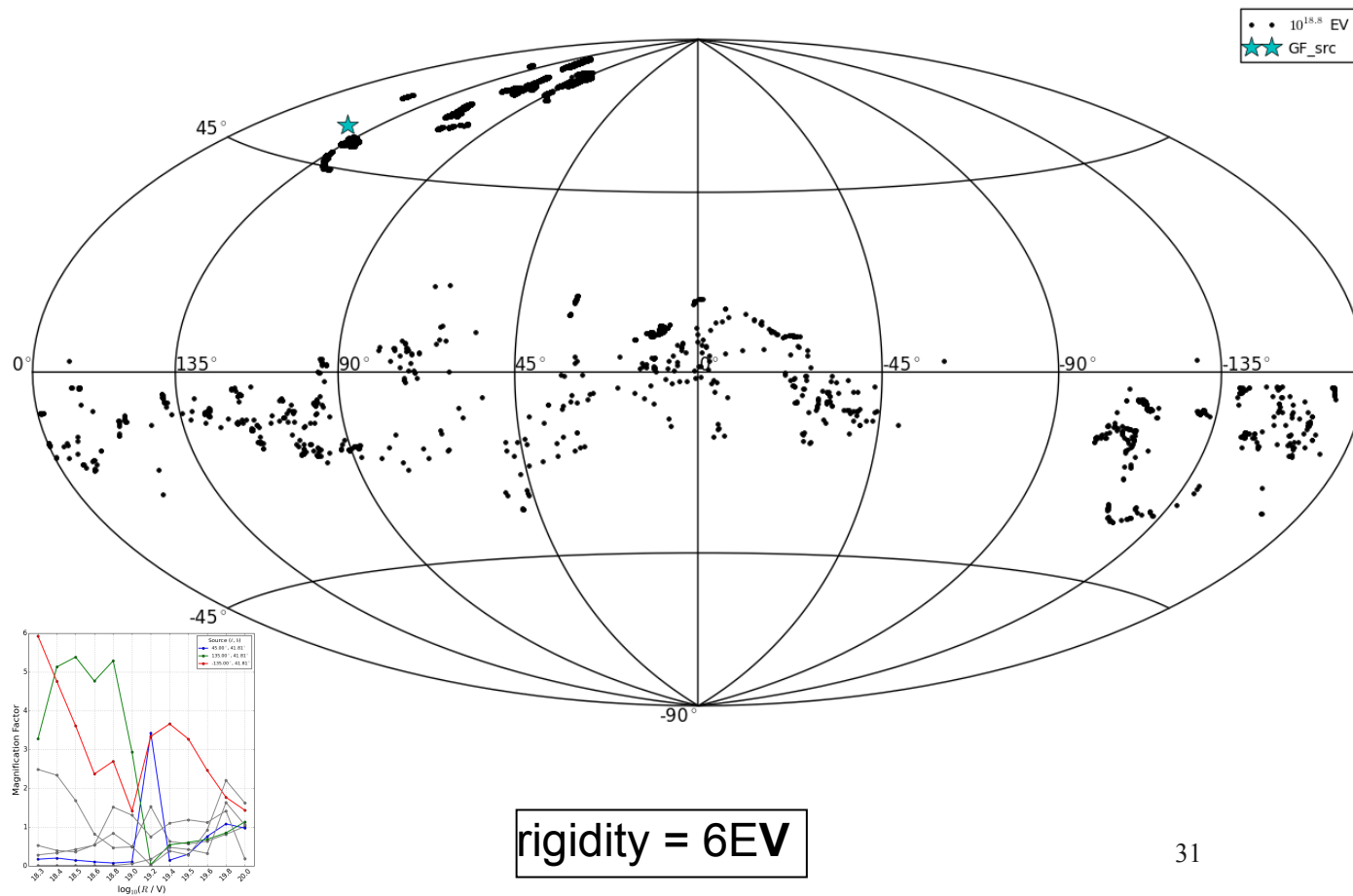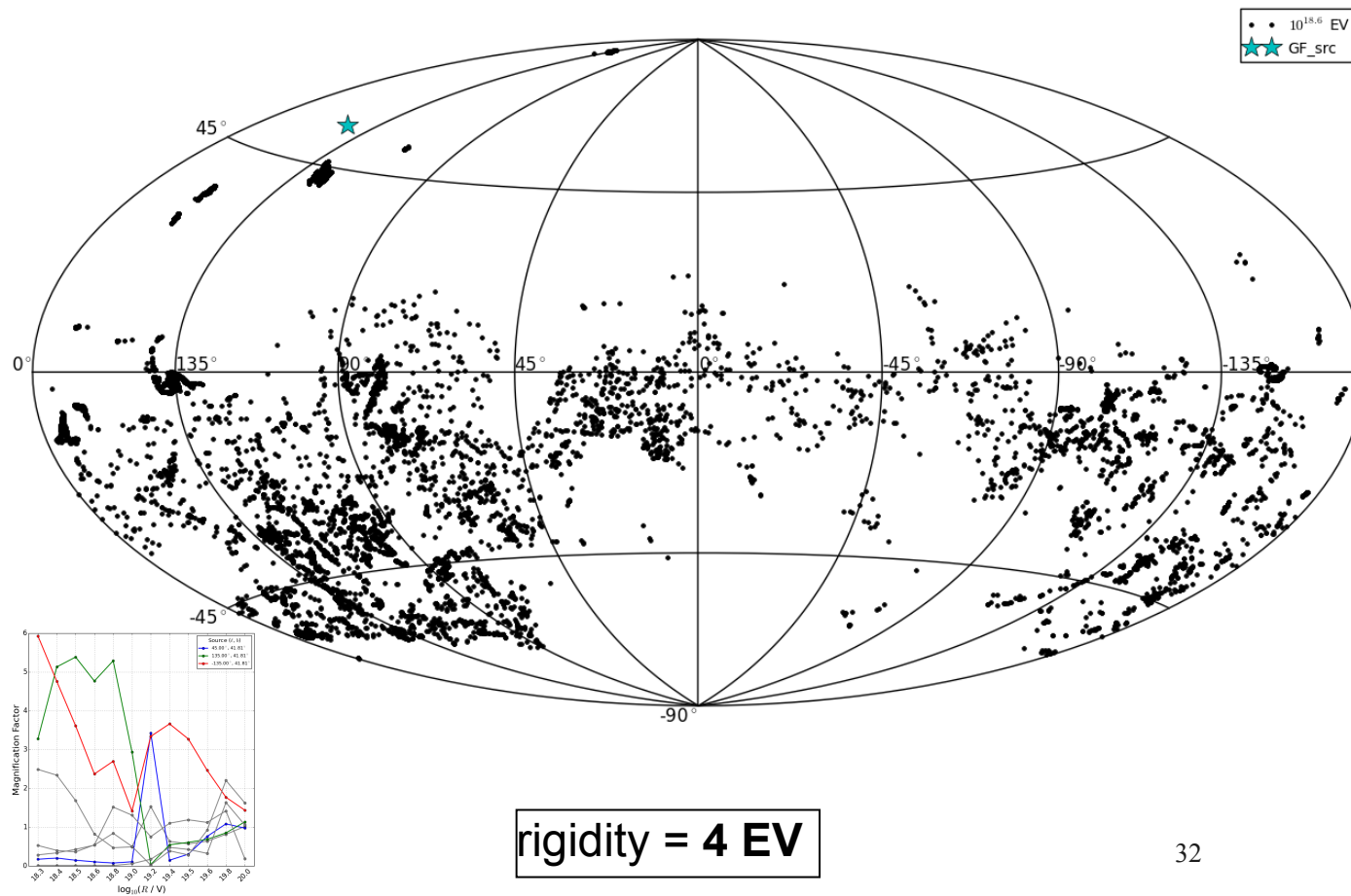
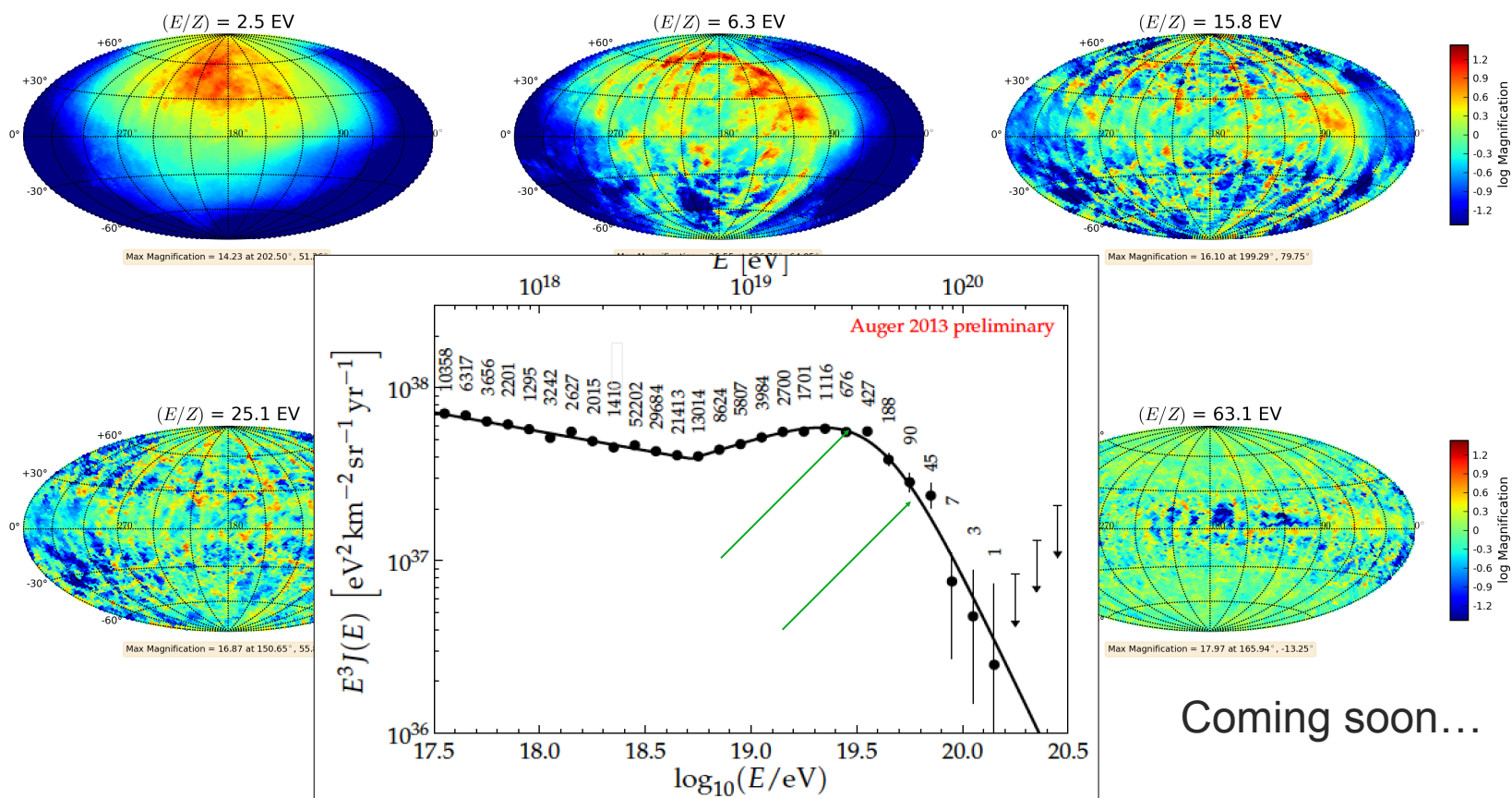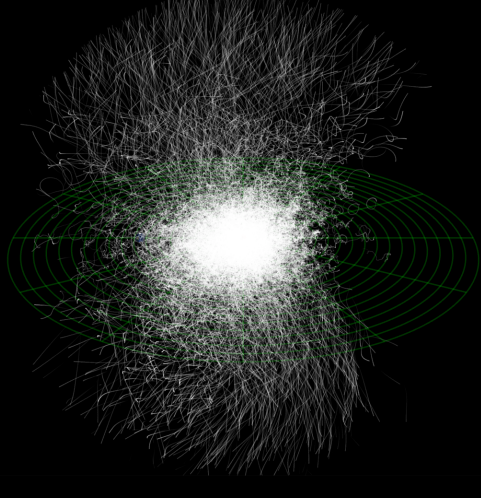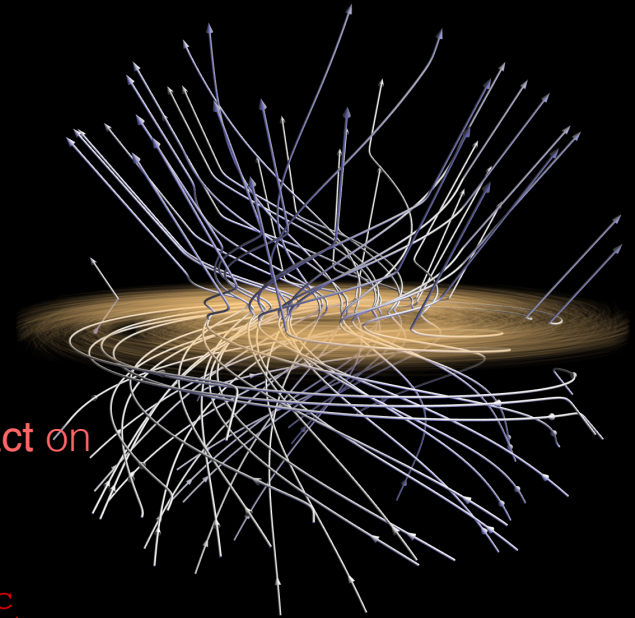# Can structure (?) in Auger spectrum be a GMF magnification effect?

Movies

- Four movies were too big to upload so they've simply been removed. Those are:

  - Trajectories of 20 isotropically-arriving, 60 EeV Fe.

    - Shows that the GMF shields Earth from UHECRs arriving from behind the Galactic Center, and that the UHECRs we see arre primarily produced by sources in the quadrant of the anti-center.

  - Top and side views of a transient source at the Galactic center; top view of a transient source near the Sun.

    - Show how anisotropic the diffusion in the GMF is, and that CRs escape vertically on a much shorter timescale than horizontally.

Summary

- The structure of the Galactic magnetic field is emerging
  Next generation of modeling needs better:
  - Thermal and relativistic electron distributions
  - Theoretical understanding/description of field structure
  - Foreground subtraction

- Deflection and magnification in the GMF has major impact on
  - interpreting UHECR spectrum and anisotropies, and
  - diffusion of Galactic CRs

10 kpc