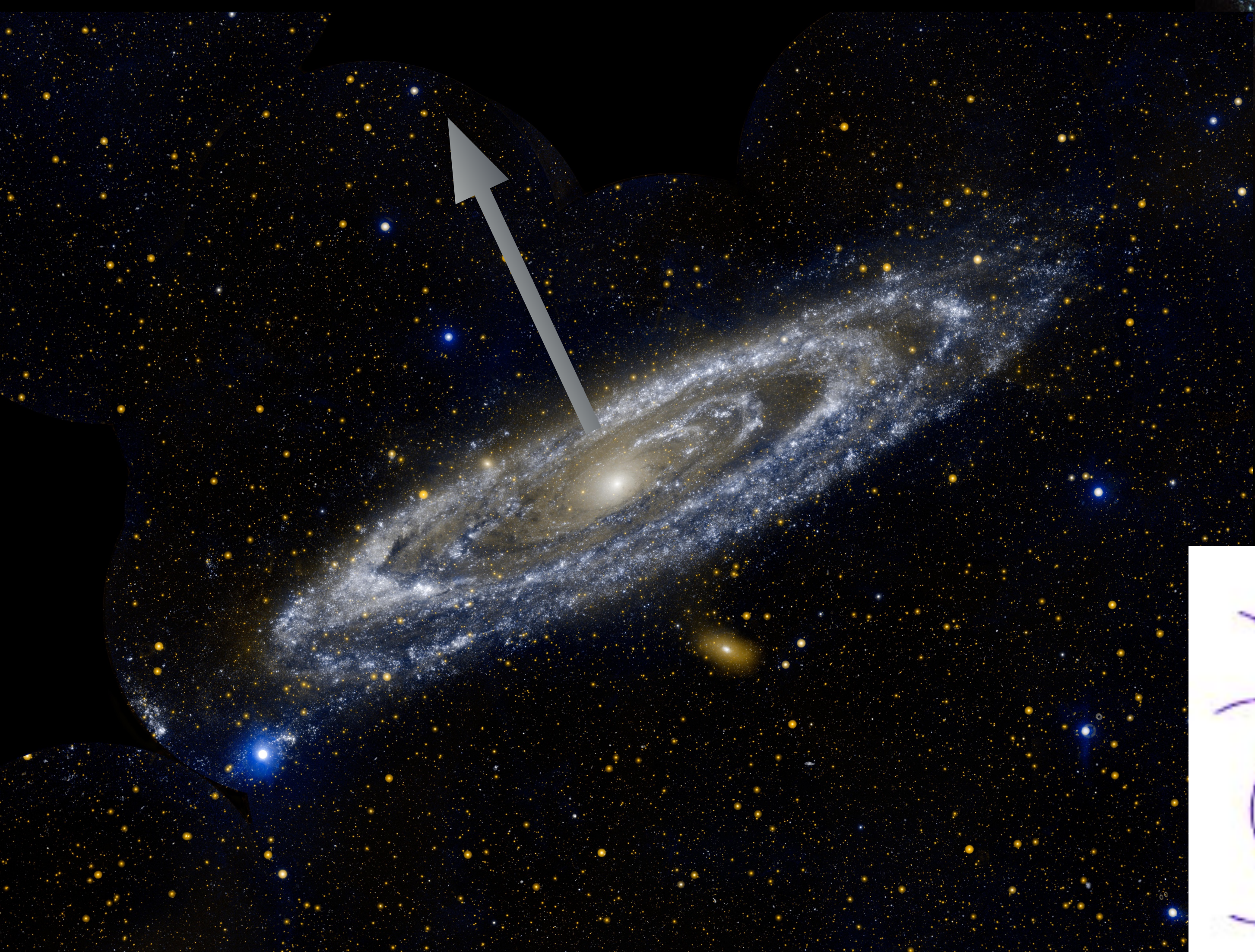
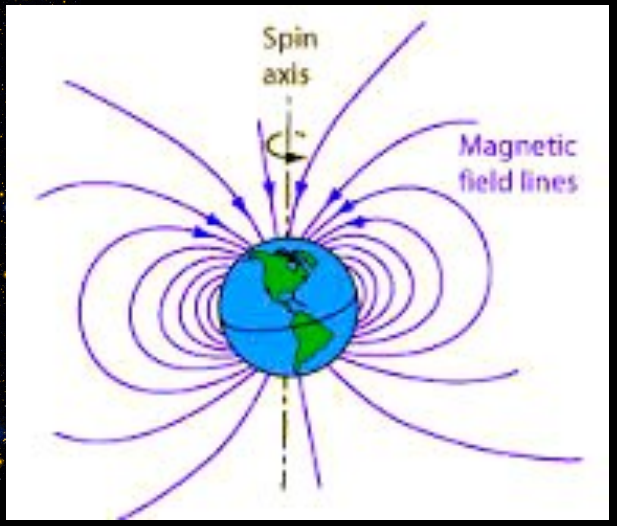
Towards modeling the Galactic Magnetic Field

Glennys Farrar (NYU) and Michael Unger (KIT)
building on work in collaboration with R. Jansson, D. Khurana and M. Sutherland

Sources of Galactic Cosmic Rays, APC, Paris Dec. 7, 2016

Does the Milky Way have a large scale magnetic field (like the Earth and Sun)?



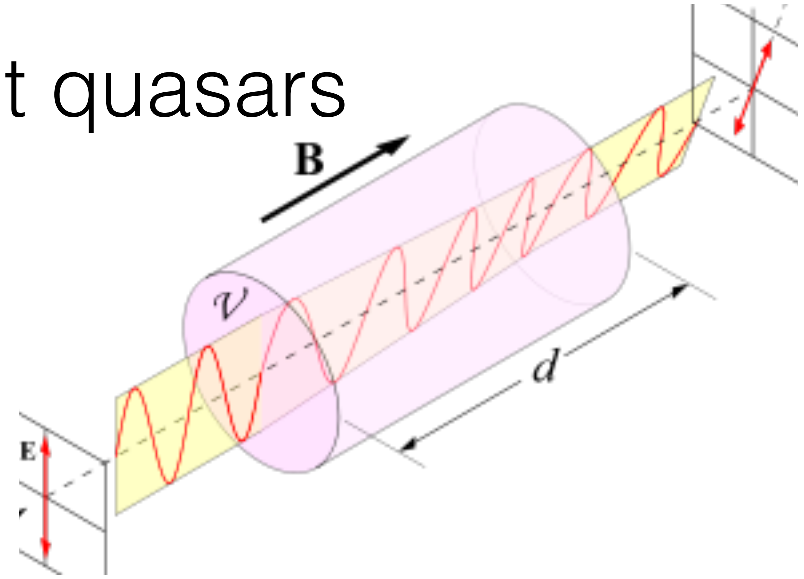


Earth's magnetic field:
- extends beyond surface
- oriented by spin axis

But how can we discover what the Galactic Magnetic Field is?

Need "observables" sensitive to the magnetic field… so far, the best are:

- Faraday Rotation Measure of distant quasars
  - polarization angle rotates by RM x λ^2
  - RM ~ $\int n_e B_{||} ds$



- Polarized Synchrotron Emission
  - radiation from electrons spiraling around magnetic field lines
  - PI ~ $\int n_e B_{\perp}^2 ds$

Jansson-Farrar strategy, I. *Data*

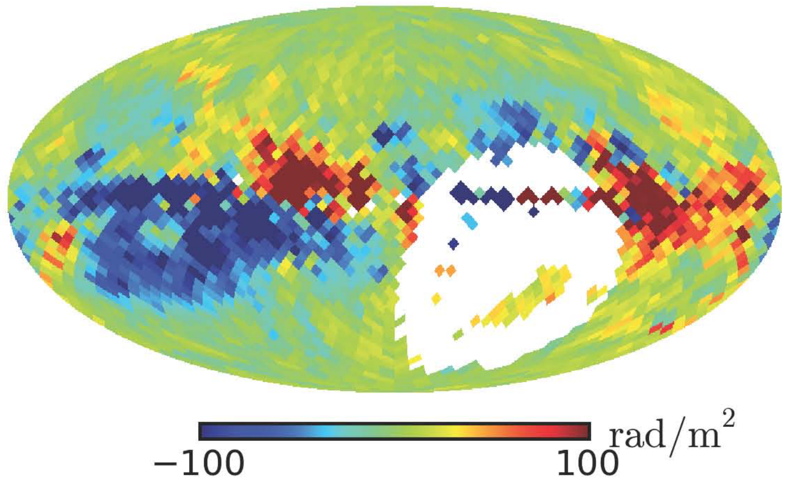
~40k datapoints for each

Rotation Measures $\sim \int_{\text{line of sight}} dz\, n_e(\mathbf{x})\, B_{||}(\mathbf{x})$

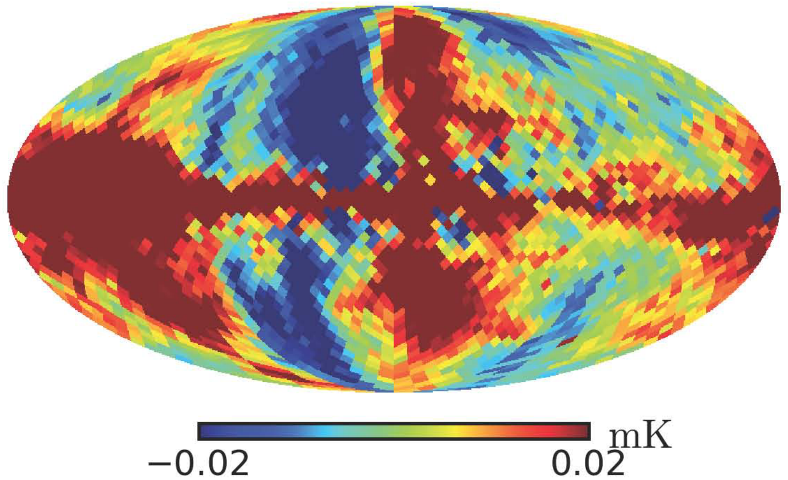
Polarized synchrotron $\sim \int_{\text{line of sight}} dz\, n_{cre}(\mathbf{x})\, B_{\perp}^2(\mathbf{x})$

Complementary!

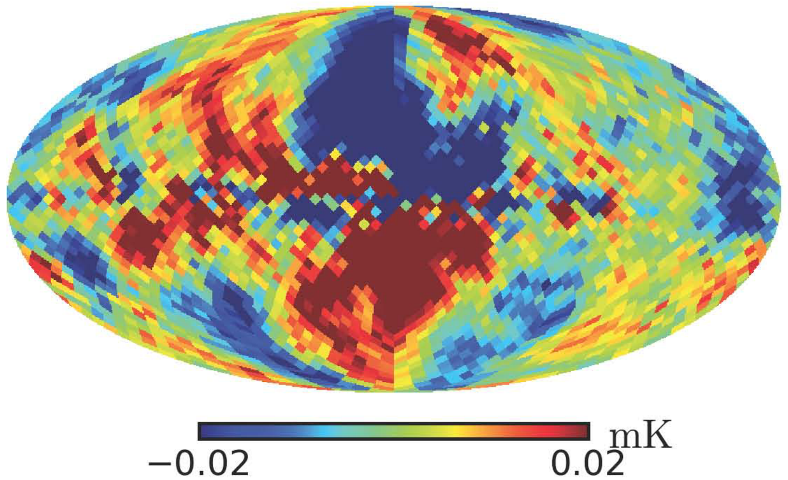
RM



Q (polarized synch)



U (polarized synch)

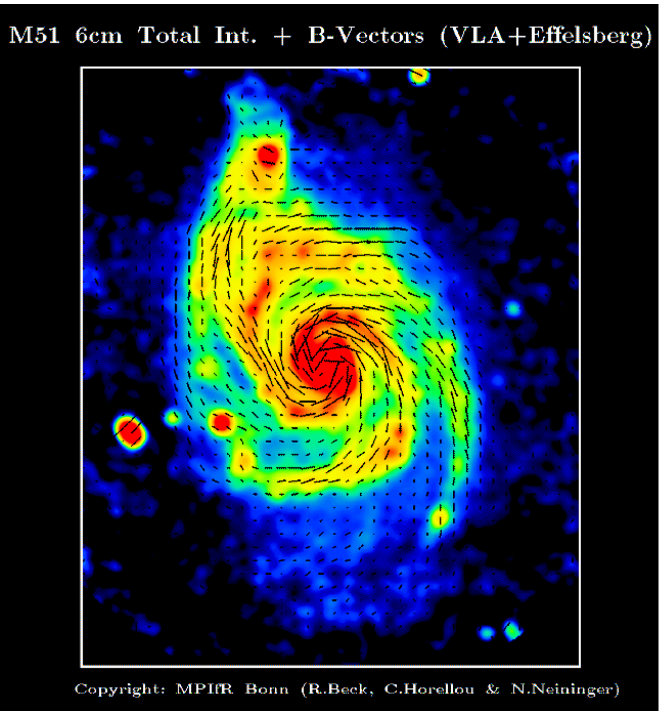


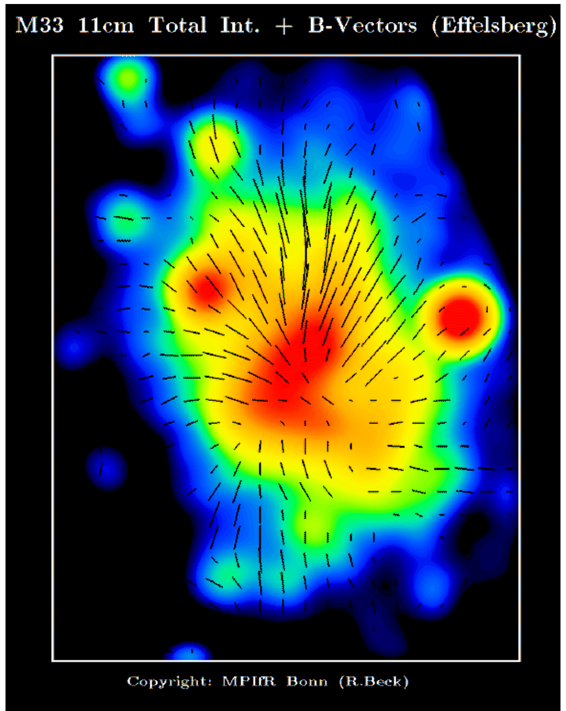
GMF modeling   Jansson-Farrar 2012

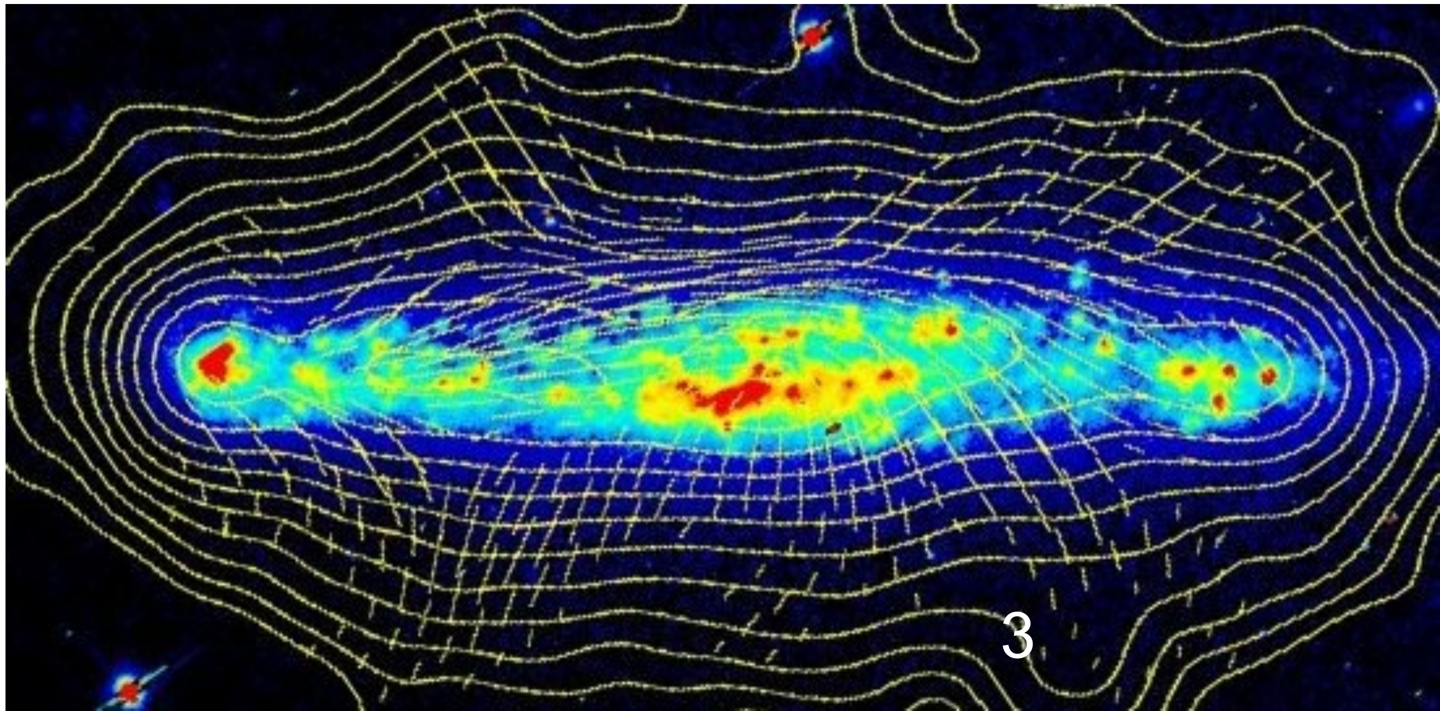
Question: How should we model the magnetic field?

Theoretical constraint: magnetic flux is conserved!

Observational guidance: external galaxies

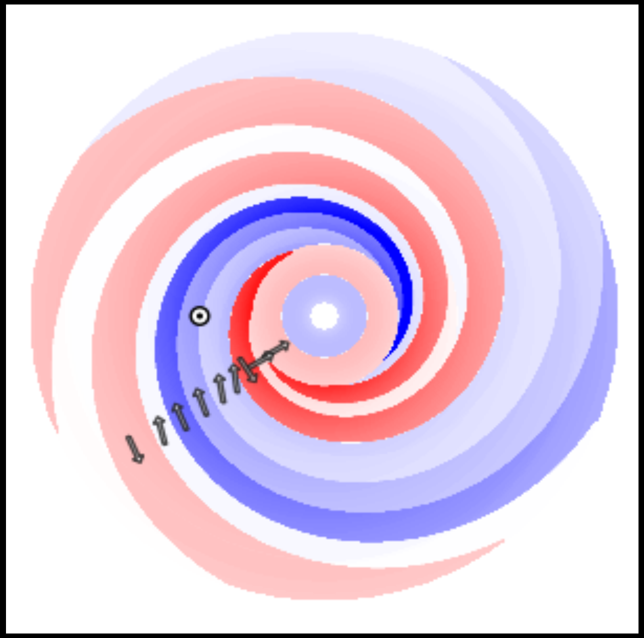




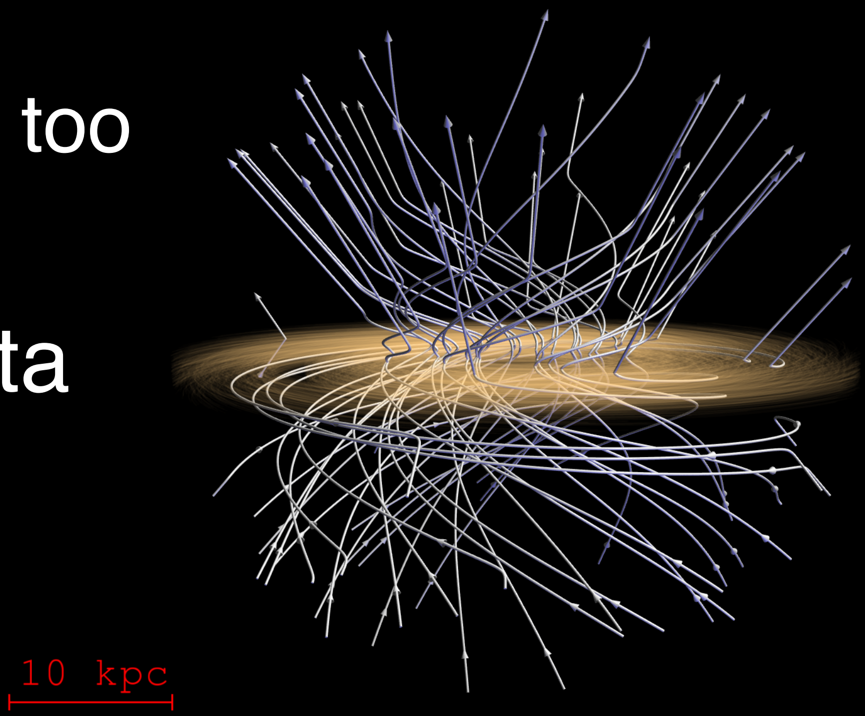


35-parameter GMF (JF12)

- **Eight magnetic spiral arms** in the Galactic disk
-



- **Helical field** in the halo
- Striated (ordered random) and fully random, too
- Adjust model parameters to best-fit data
- Typical field strength ~ 1 micro-G



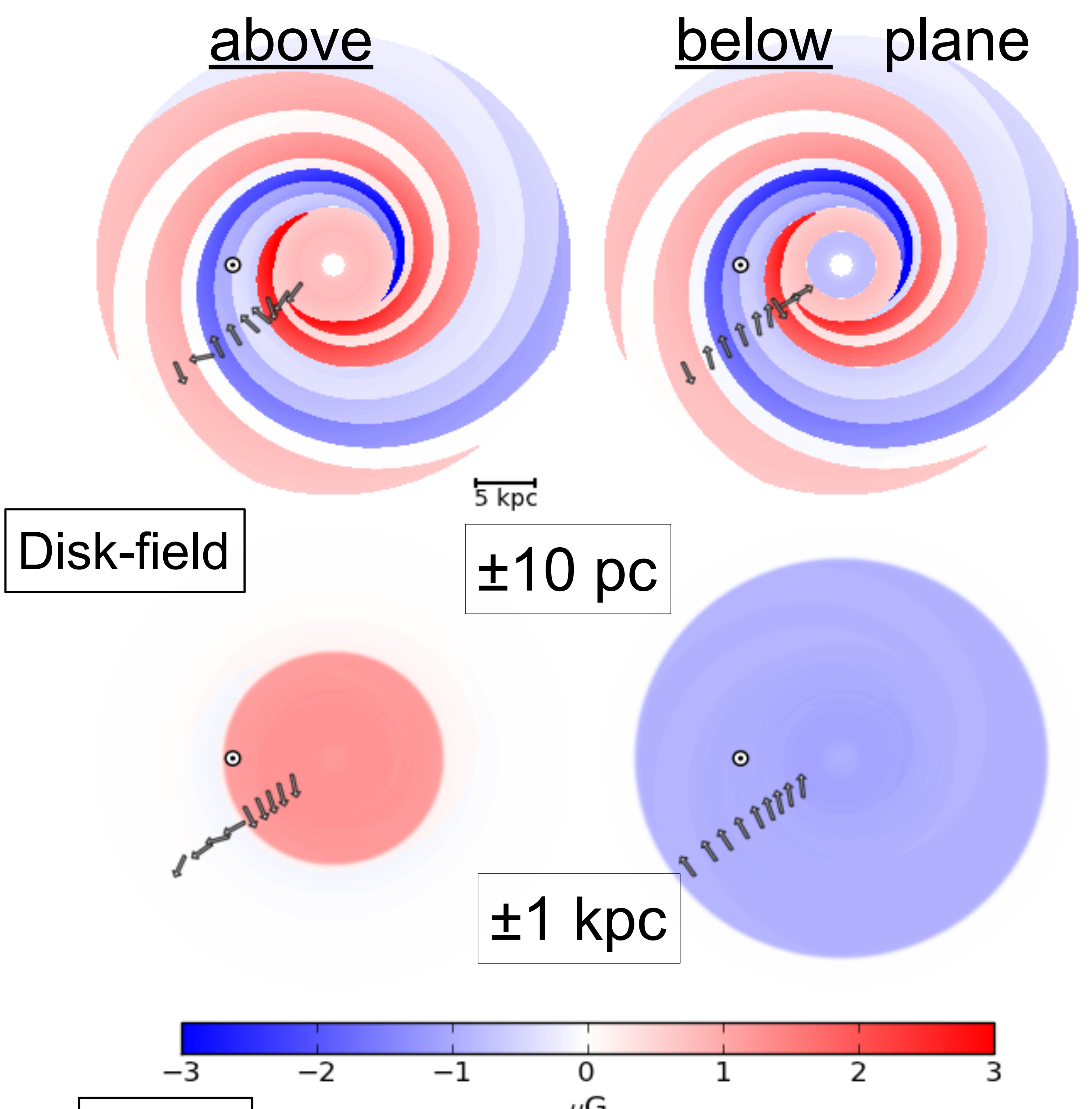
JF12 Coherent Field

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 $b_1, ..., b_7$
	$b_{ring} = 0.1 \pm 0.1\,\mu G$	ring at 3 kpc $< r < 5$ kpc
	$h_{disk} = 0.40 \pm 0.03$ kpc	disk/halo transition
	$w_{disk} = 0.27 \pm 0.08$ kpc	transition width
Toroidal halo	$B_n = 1.4 \pm 0.1\,\mu G$	northern halo
	$B_s = -1.1 \pm 0.1\,\mu G$	southern halo
	$r_n = 9.22 \pm 0.08$ kpc	transition radius, north
	$r_s > 16.7$ kpc	transition radius, south
	$w_h = 0.20 \pm 0.12$ kpc	transition width
	$z_0 = 5.3 \pm 1.6$ kpc	vertical scale height
X halo	$B_X = 4.6 \pm 0.3\,\mu G$	field strength at origin
	$\Theta^0_X = 49 \pm 1°$	elev. angle at $z = 0, r > r^c_X$
	$r^c_X = 4.8 \pm 0.2$ kpc	radius where $\Theta_X = \Theta^0_X$
	$r_X = 2.9 \pm 0.1$ kpc	exponential scale length
striation	$\gamma = 2.92 \pm 0.14$	striation and/or n_{cre} rescaling

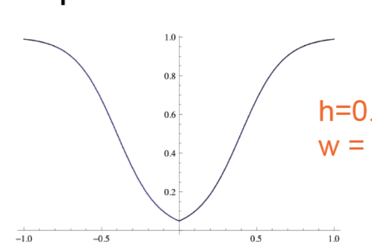
Note. — For the parameter r_s only a lower 68%-bound is given.

22 parameter fit, 10k dof
very well-constrained

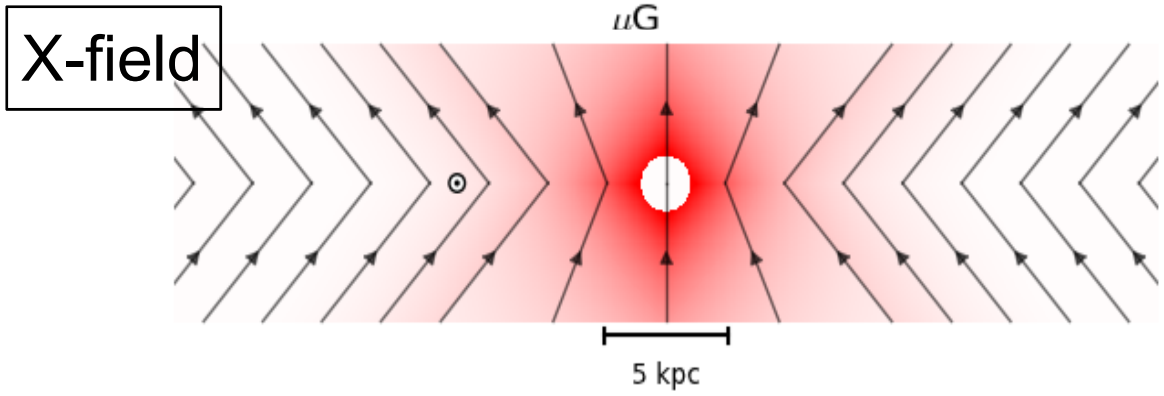


- Disk
  - > 5 kpc: 8 spiral arms, geometry as in NE200
  - 3-5 kpc: purely azimuthal "molecular ring"
  - B=0 for r < 1 (not adequately constrained by data) and r > 20 kpc
- Halo
  - purely toroidal (fit prefers this to spirals with arbitrary angles)
  - Different strength and scale height in N and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

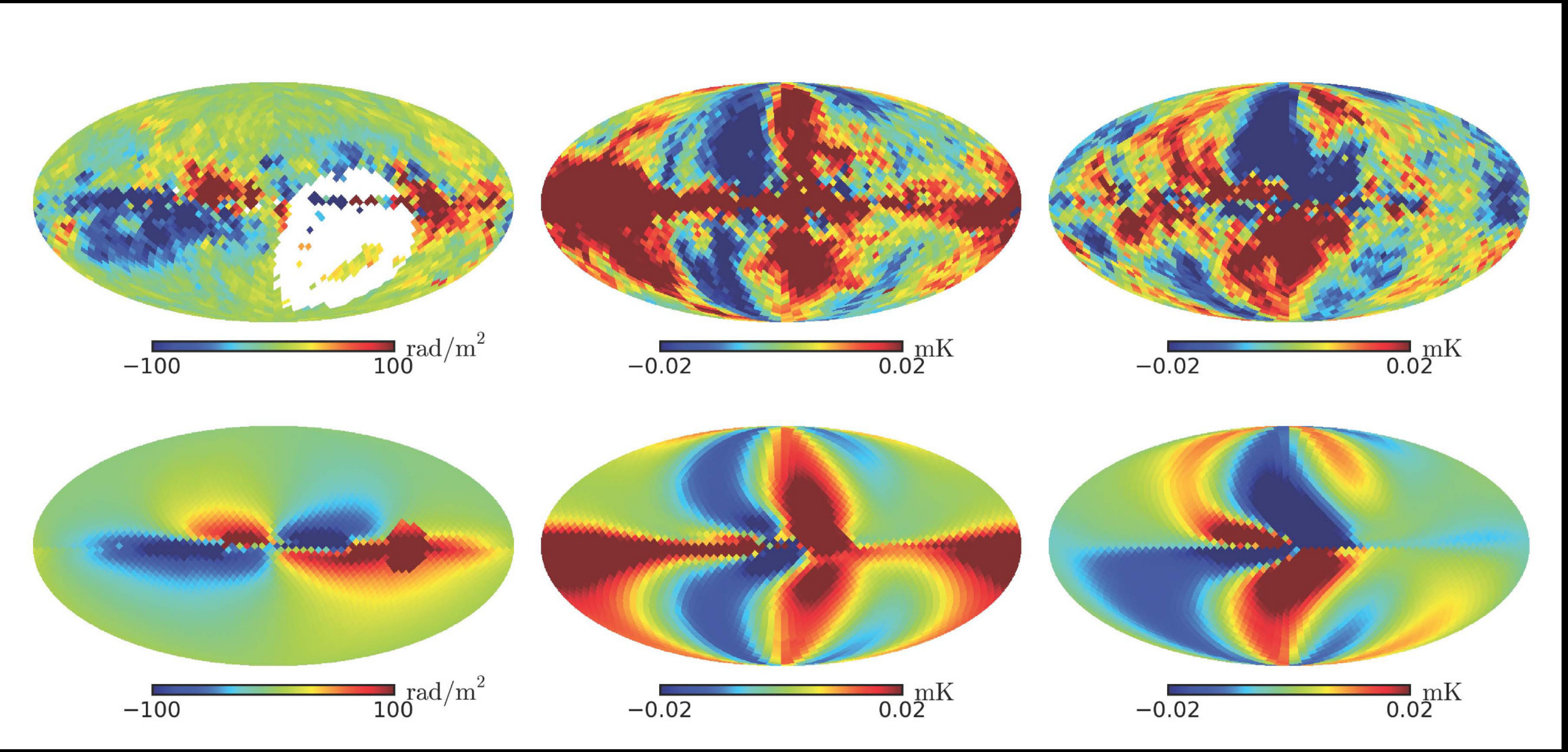
$$L(z,h,w) = \left(1 + e^{-2(|z|-h)/w}\right)^{-1}$$



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

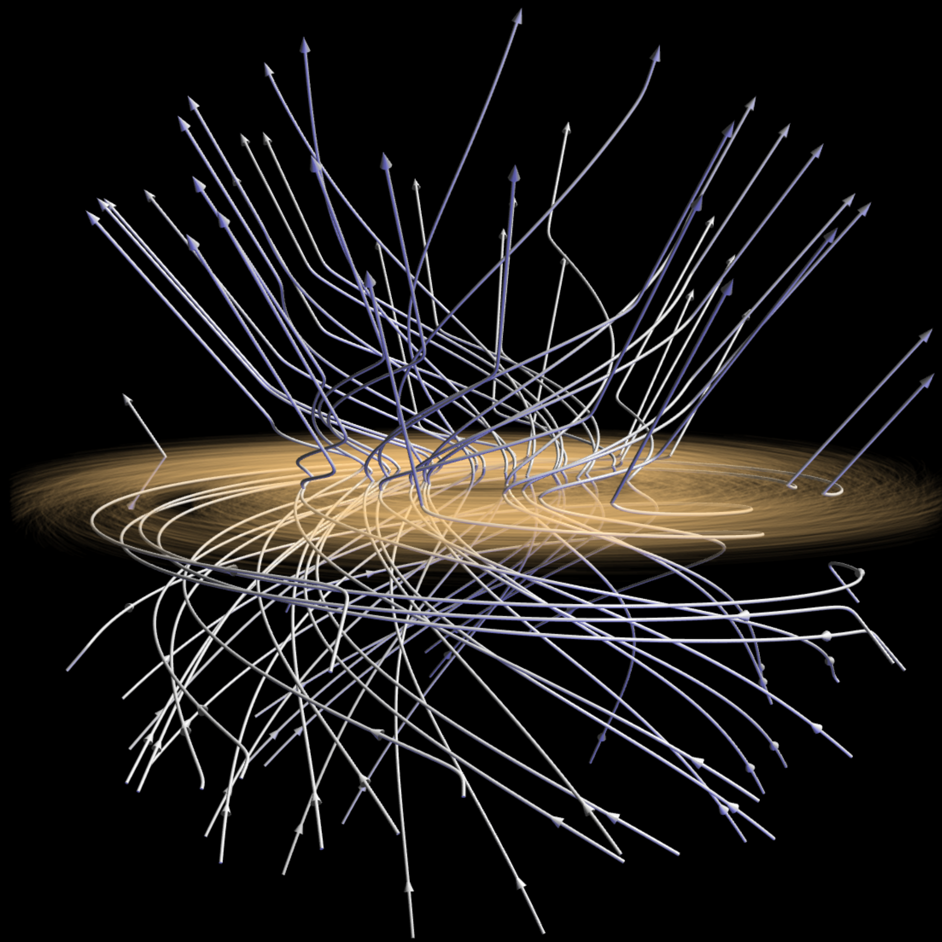


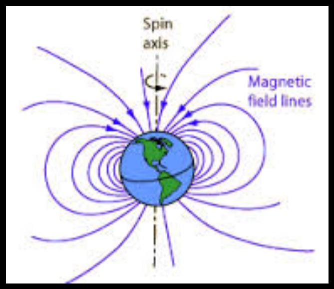
Messy-looking data:



but key features explained by a simple model…

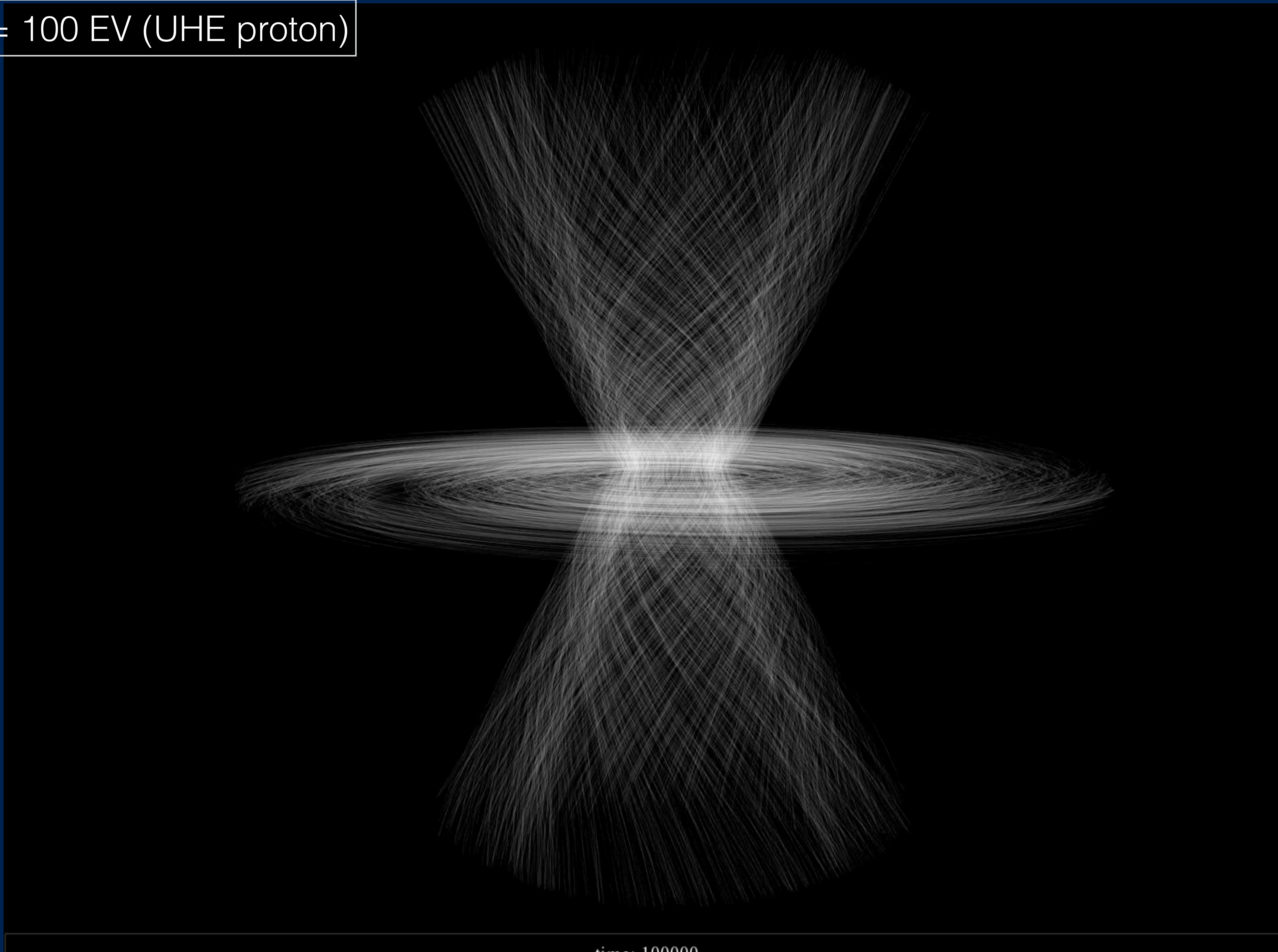
Reveals a spiral field extending into the Galactic halo!



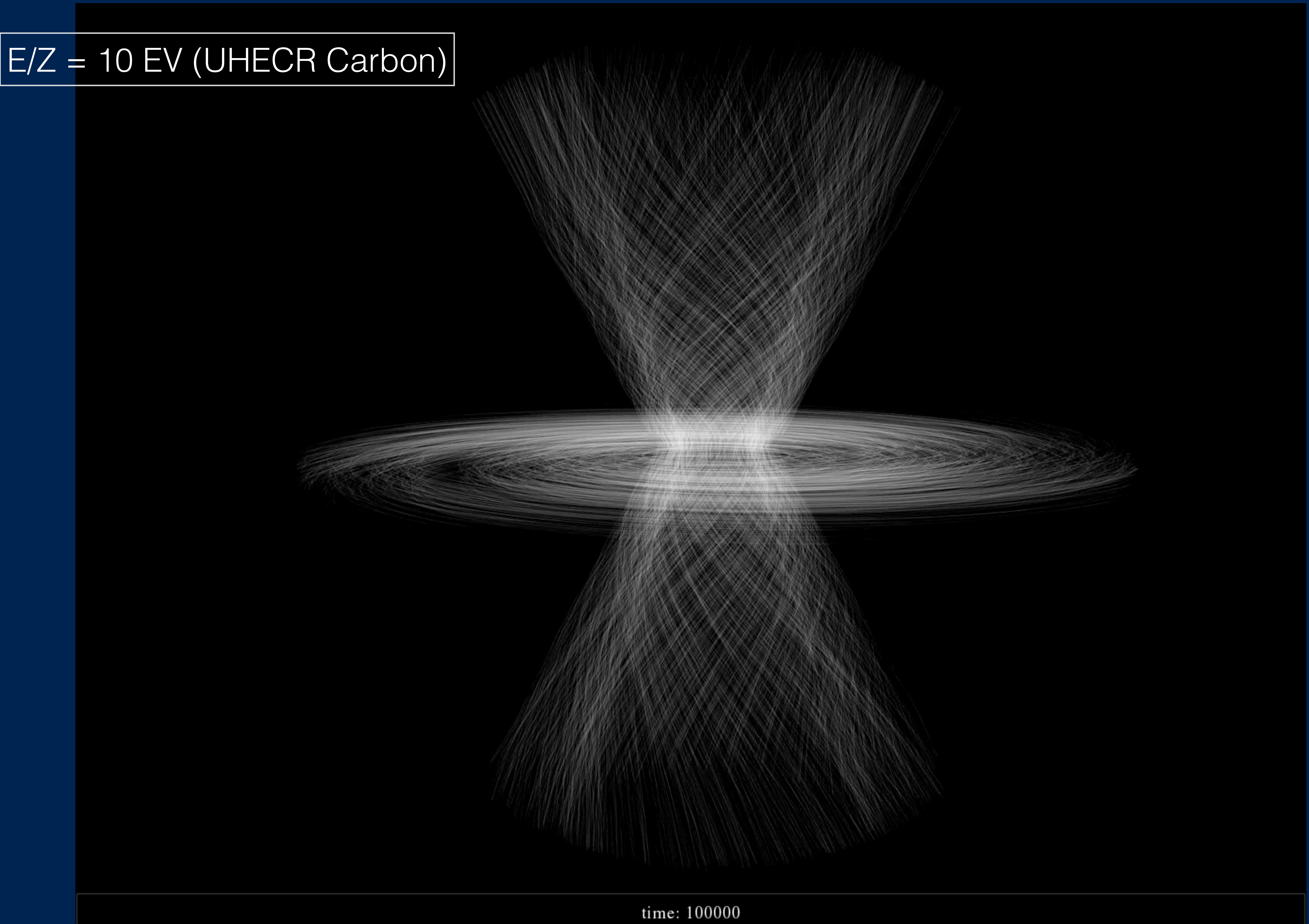


UltraHighEnergyCosmicRay deflections in the GMF

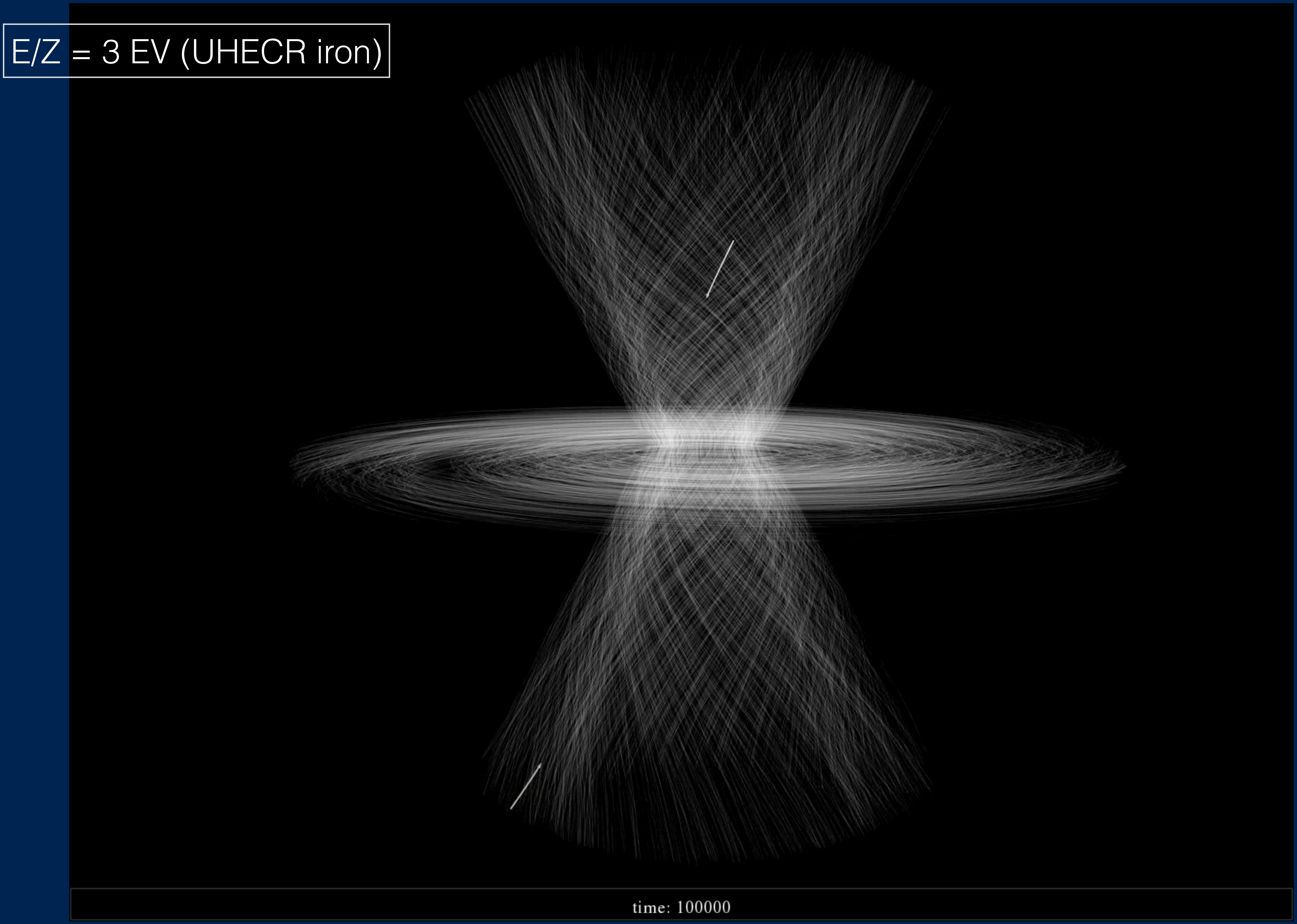
E/Z = 100 EV (UHE proton)



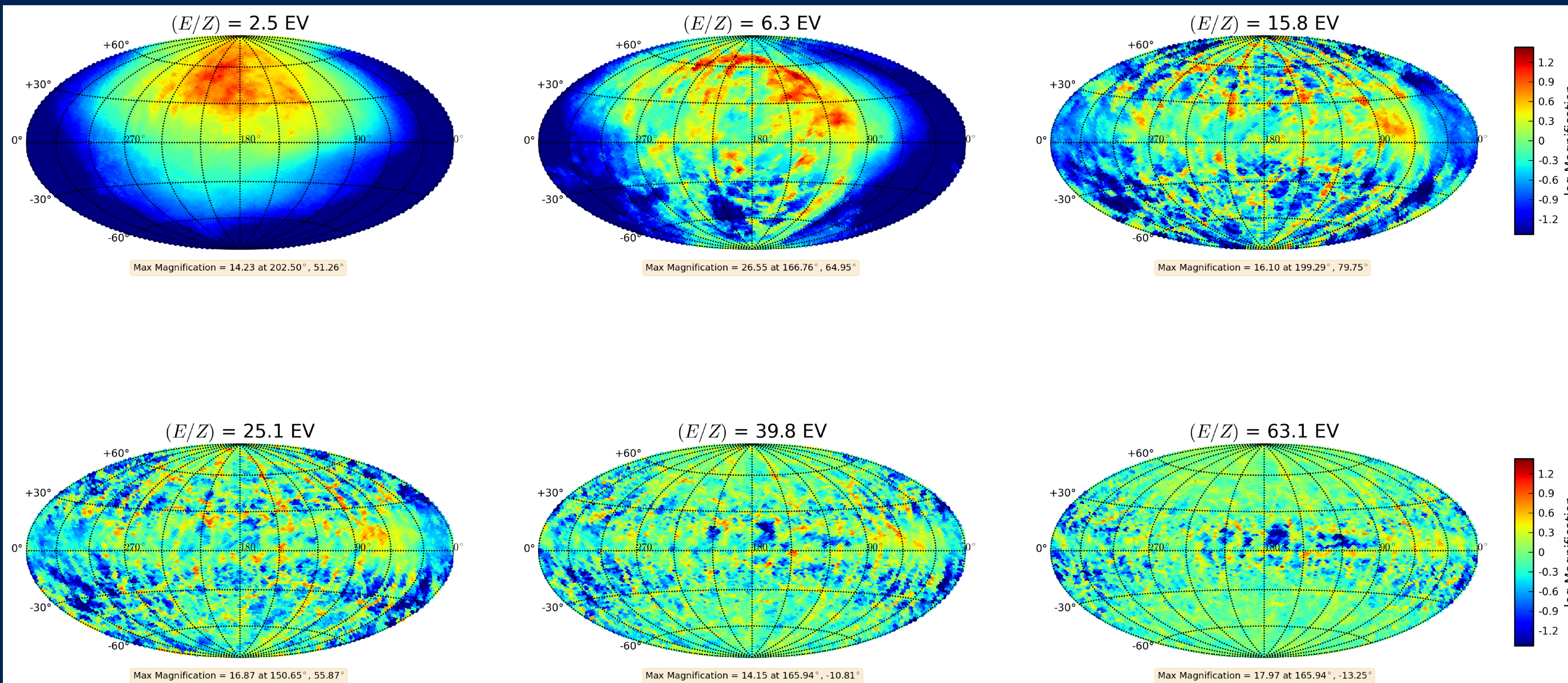
UHECR deflections in the GMF



UHECR deflections in the GMF



GMF acts as a lens for **U**ltra**H**igh **E**nergy **C**osmic **R**ays => magnification and blind regions



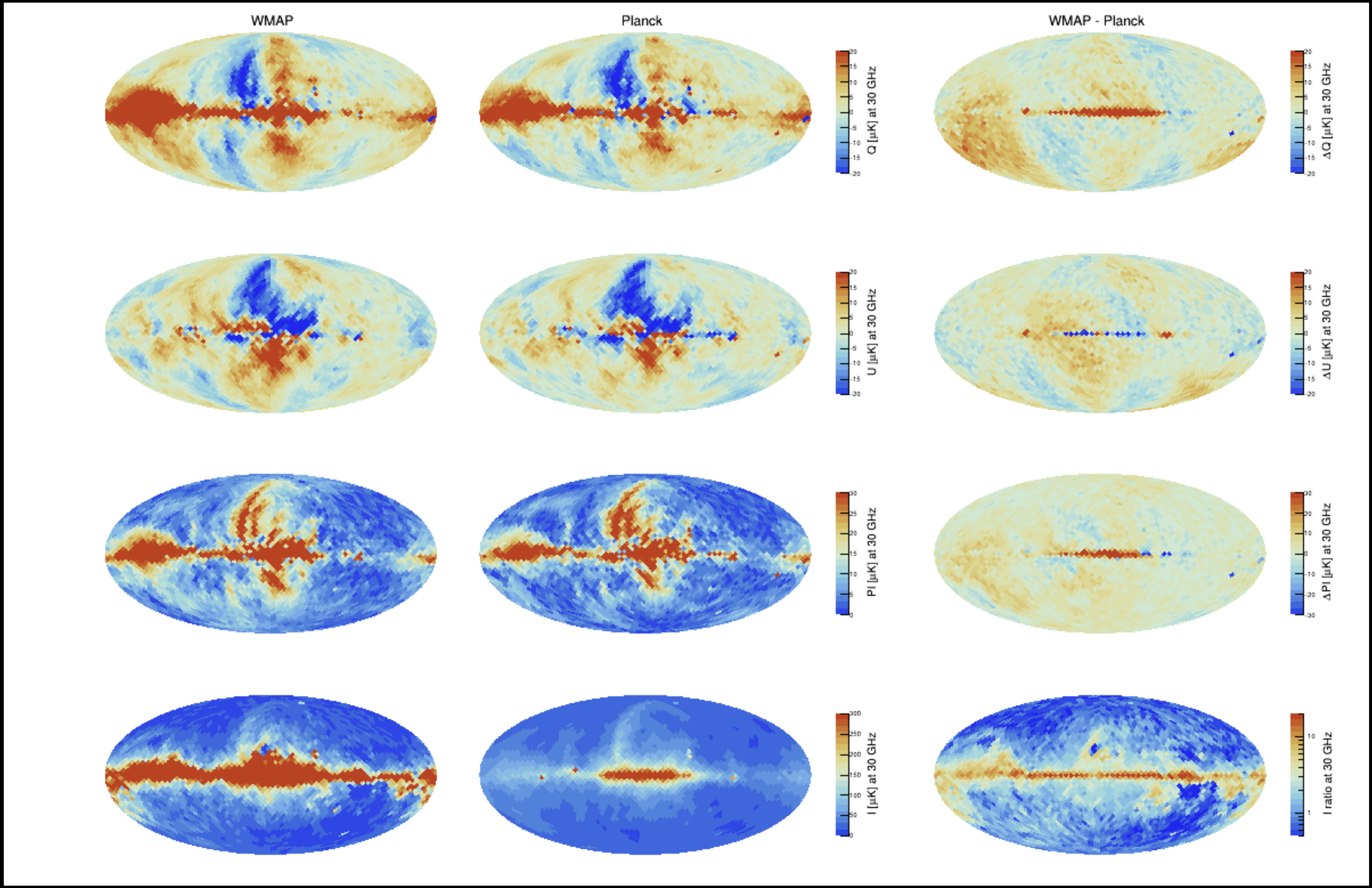
- UHE: E > ~ 5 10^{19} eV = 50 EeV **CM energy > 10x LHC**
- NASA-Pleiades supercomputer to calculate trajectories, sims run by M. Sutherland

Update on JF12

- Planck vs WMAP synchrotron QUI
- Improved models of n_e & n_{cre}
- Alternate descriptions of magnetic field
- Correlations in fluctuations of n_e & B, detailed modeling of B_{stri} , coherence scale, …

Planck vs WMAP

bigger difference than you might think!



Planck vs WMAP

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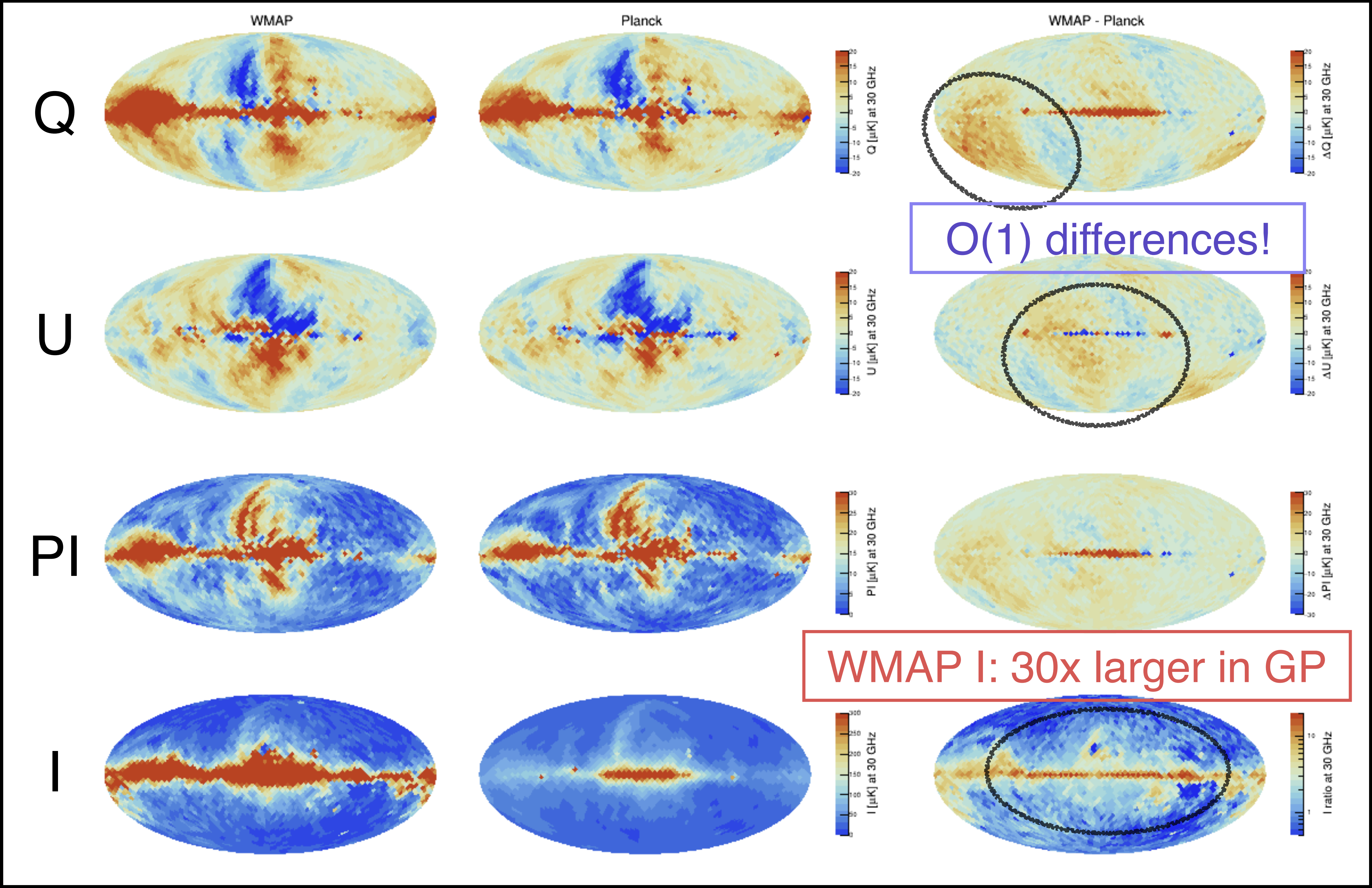
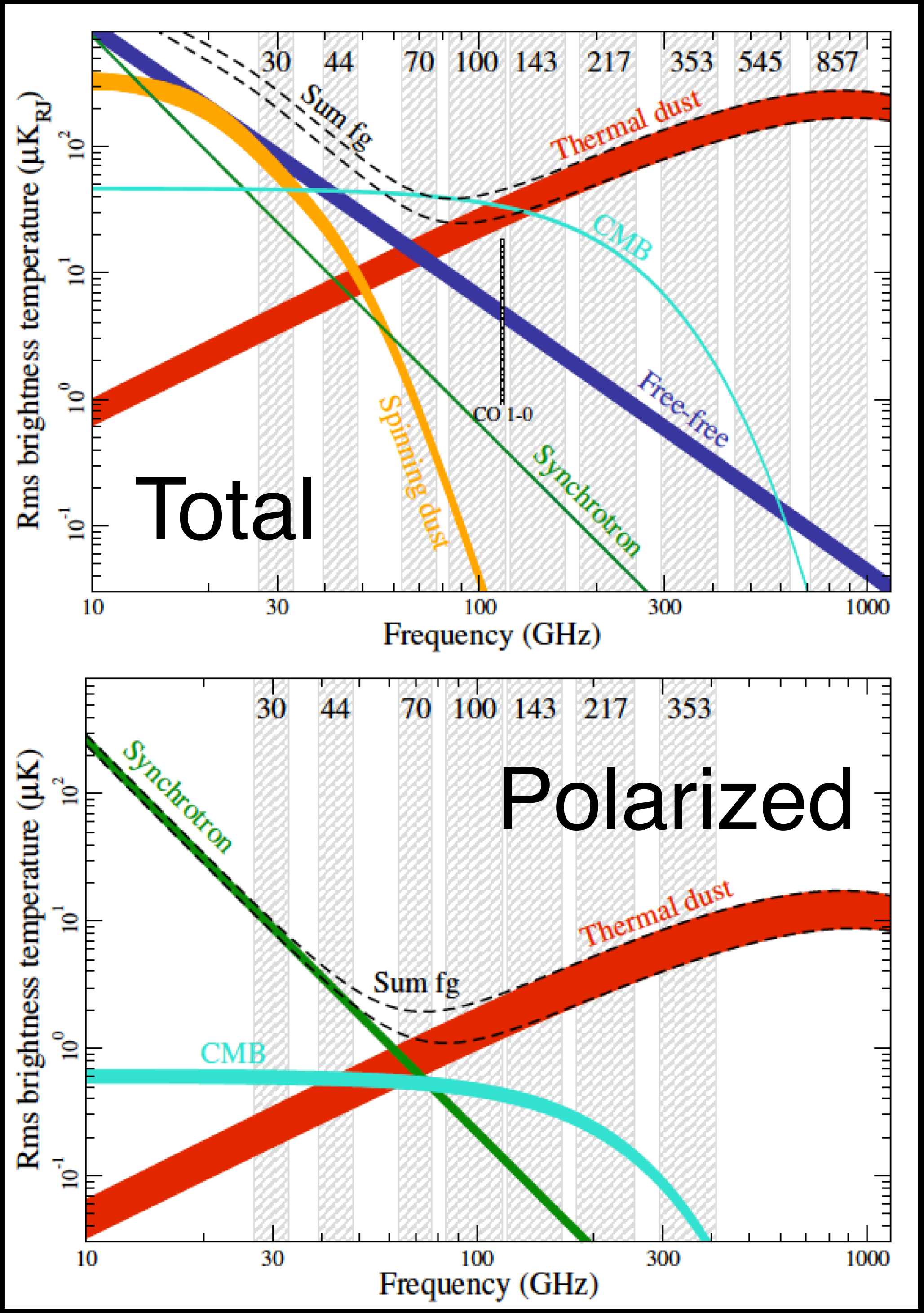


Foreground Separation

- Intensity:
  - WMAP did not fit/subtract spinning dust contribution
  - Planck is better (?)
- Polarized Synchrotron:
  - Negligible bkg to subtract at 22/30 GHz
  - Why do they differ???

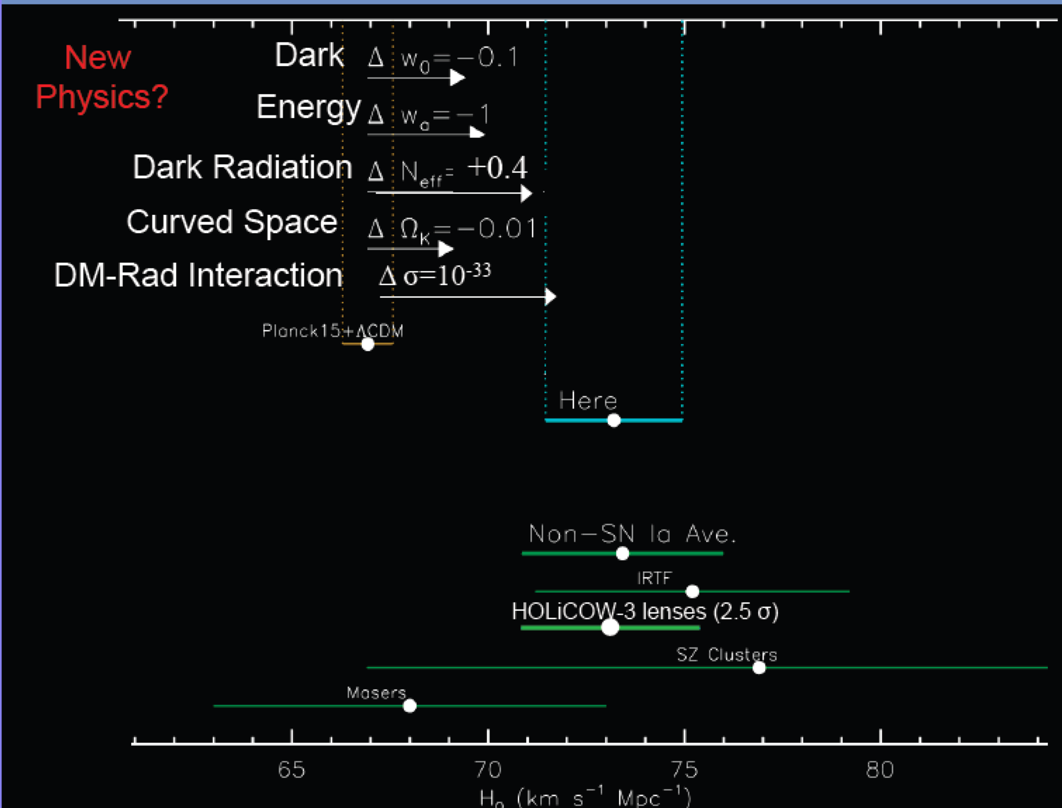


Planck Collaboration: Diffuse component separation: Foreground maps

Could Planck be correcting incorrectly?

hint from H_0 discrepancy… (?)

H_0, Measured vs. Predicted from Initial Conditions (CMB)

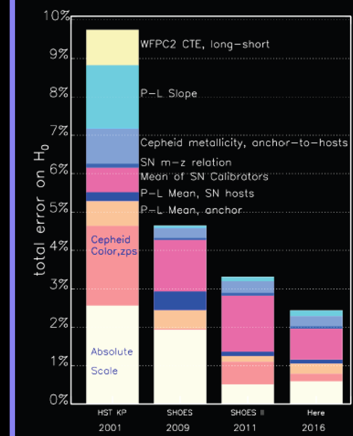


- 3.4 σ tension!
- New Physics* ?
- Planck vs WMAP vs l?

* "If a persuasive case can be made that a direct measurement of H_0 conflicts with these estimates, then this will be strong evidence for additional physics beyond the base ΛCDM model. "-Planck Team Paper, 2015

- SHOES (Reiss+16): H_0 = 74.24 +- 1.74 km/s
- Planck 2015: 67.8 +- 0.9 km/s
- Planck H_0 from low-l (no foreground) ~5 sigma closer to than hi-l

Error Budget for H_0 from 2016; 2.4% uncertainty



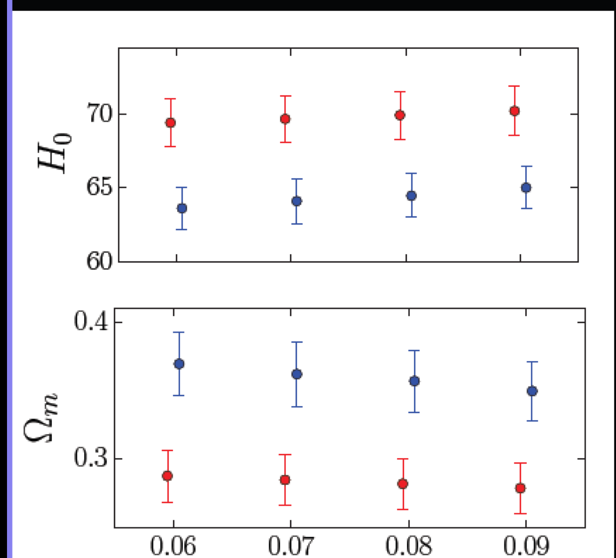
H_0=73.24 +/- 1.74 km/s/Mpc (Riess et al. 2016)

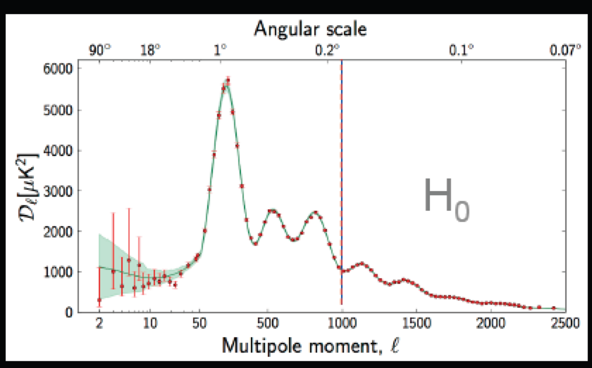
Term	KP LMC %	R09 4258 %	R11 ALL %	R16 ALL %
Anchor distance	5.0	3.0	1.3	1.3
Cepheid reddening, zeropoints (anchor-to-hosts)	4.5	0.3	1.4	0.3
P-L slope, d log P (anchor-to-hosts)	4.0	0.5	0.6	0.5
Cepheid metallicity dependence (anchor-to-hosts)	3.0	1.1	1.0	0.5
WFPC2 CTE, long-vs-short zeropoints	3.0	–	–	–
Mean of SN Ia calibrators	2.5	2.5	1.9	1.2
Mean of P-L in anchor	2.5	1.5	0.8	0.7
Mean of P-L in SN hosts	1.5	1.5	0.6	0.4
SN Ia m-z relation	1.0	0.5	0.5	0.4
Analysis Systematics	NA	1.3	1.1	1.0
Total, % error H_0	10	4.8	3.3	2.4

Evidence for a systematic error in the Planck CMB data?

Claimed 2.5 σ Tension Between Halves of Planck CMB data, ℓ>1000 vs ℓ<1000 (WMAP)

Addison, Huang, Watts, Bennett, Halpern, Hinshaw, Weiland 2016, ApJ, 818, 132
Planck Team, arXiv: 1608.02487—"2.5 σ like 1.8 σ for 6 parameters", but we measure H_0 !





— Planck TT 2015 $2 \le \ell < 1000$ — Planck TT 2015 $1000 \le \ell \le 2508$

Update on JF12

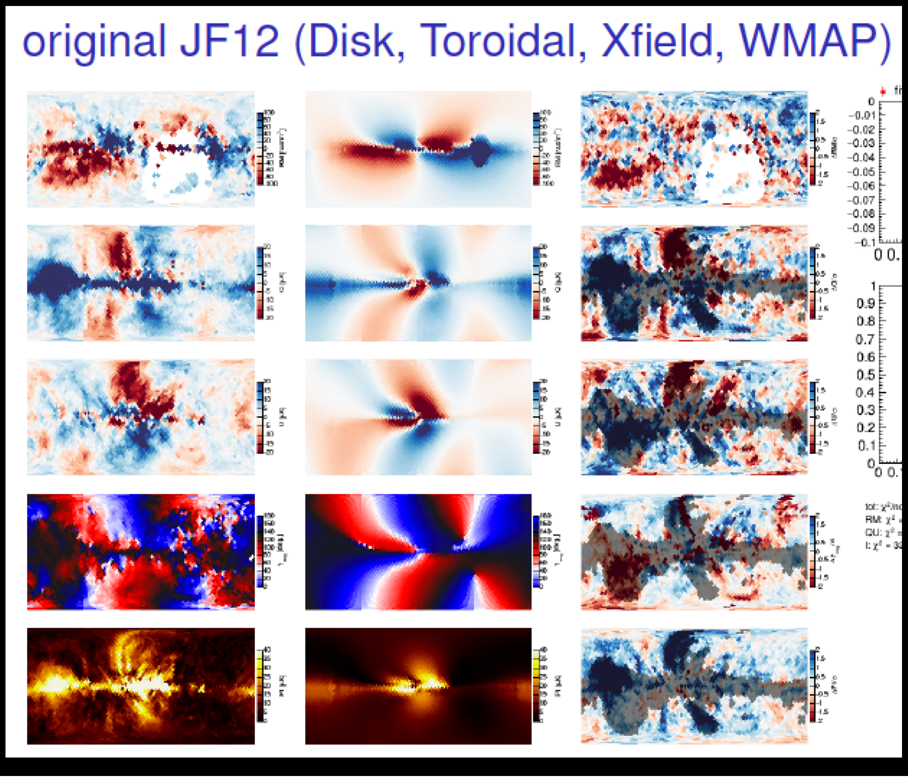
- Planck vs WMAP synchrotron QUI
  - Need to resolve discrepancy between WMAP & Planck foreground analyses or data. (GMF and GCR should eventually help with spatially varying spectra)
- Improved models of n_e & n_{cre}
- Alternate descriptions of coherent magnetic field
- Correlations in fluctuations of n_e & B, detailed modeling of B_{stri} , coherence scale, …

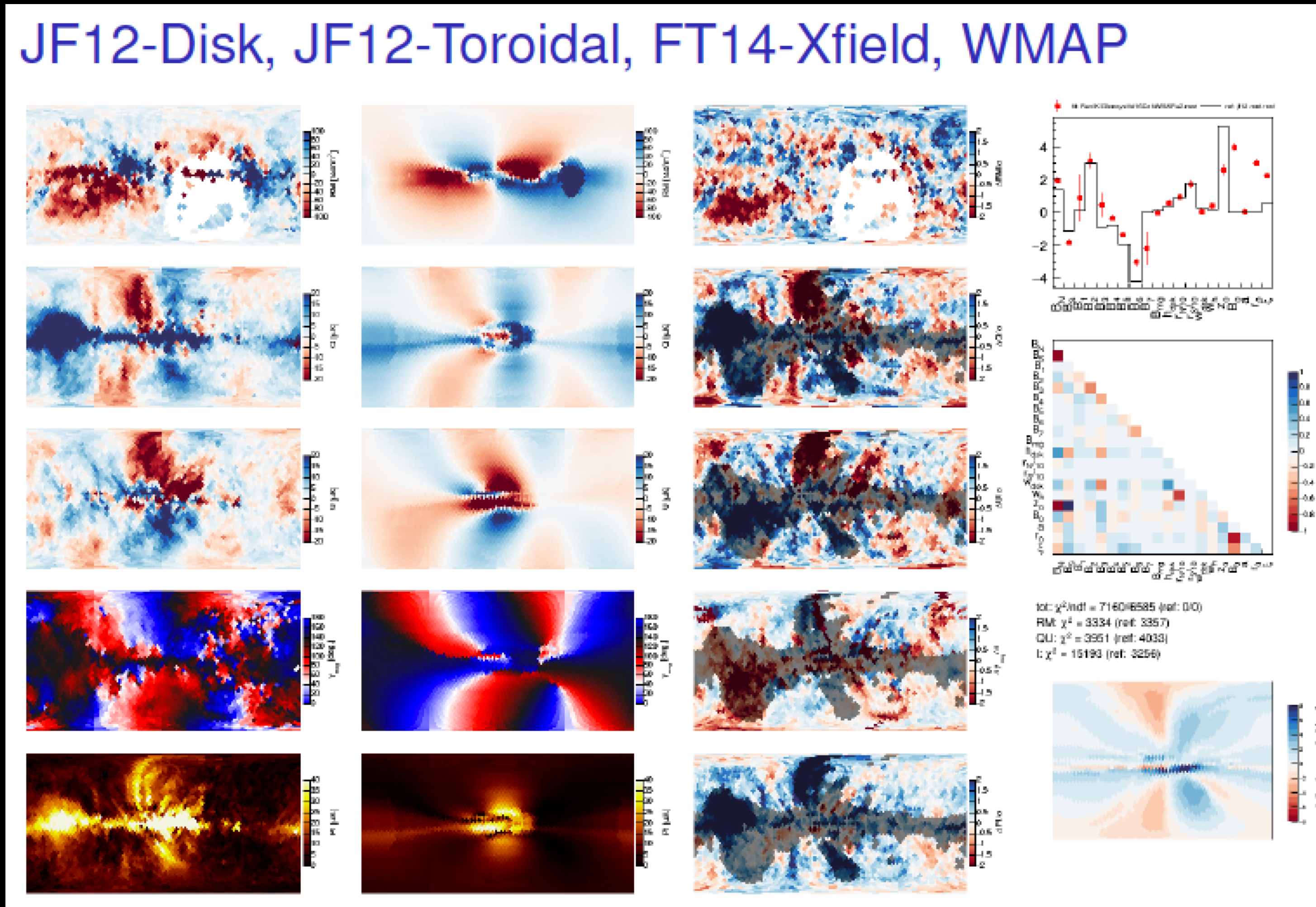
Impact of alternate X-field on coherent B

D. Khurana*

- Parabolic X-field** slightly improves fit; closely resembles original JF12 halo field => KF16
- Changing orientation: data prefers **J** and **B aligned** as in JF12
- Allowing flux to flow between disk & halo: data prefers flux separately conserved, as in JF12
- Can no reversals fit? Maybe…
- Bottom line: JF12 ROBUST
  - qualitatively and quantitatively
  - henceforth use KF16

original



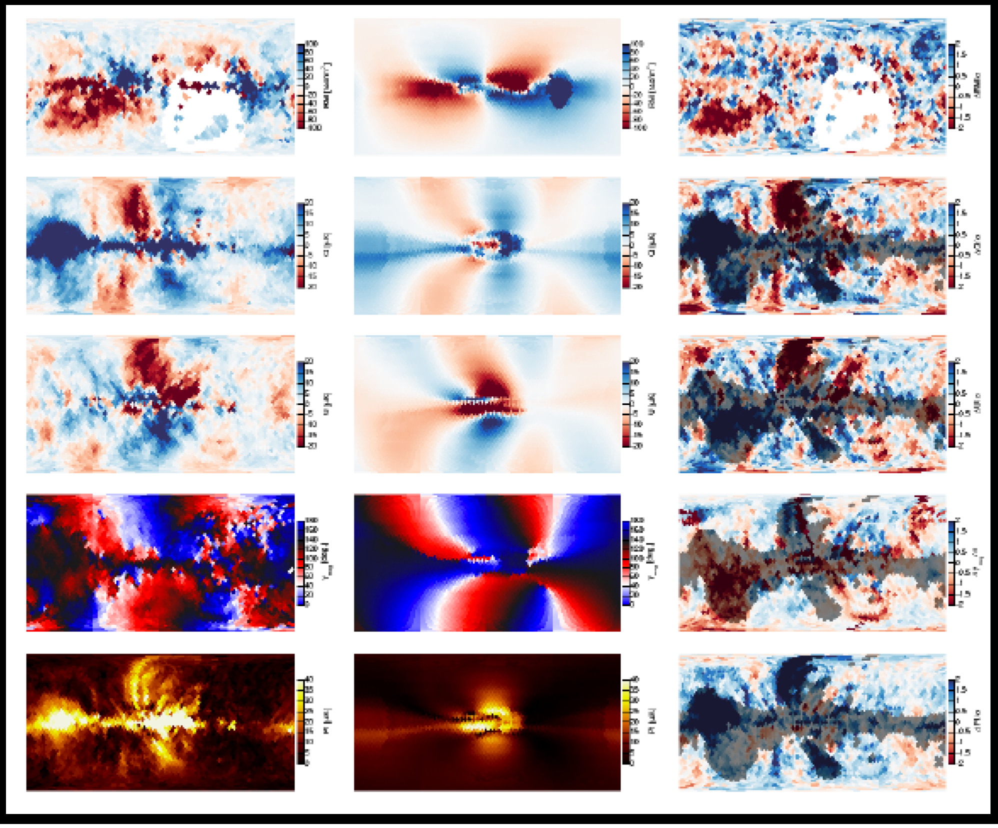


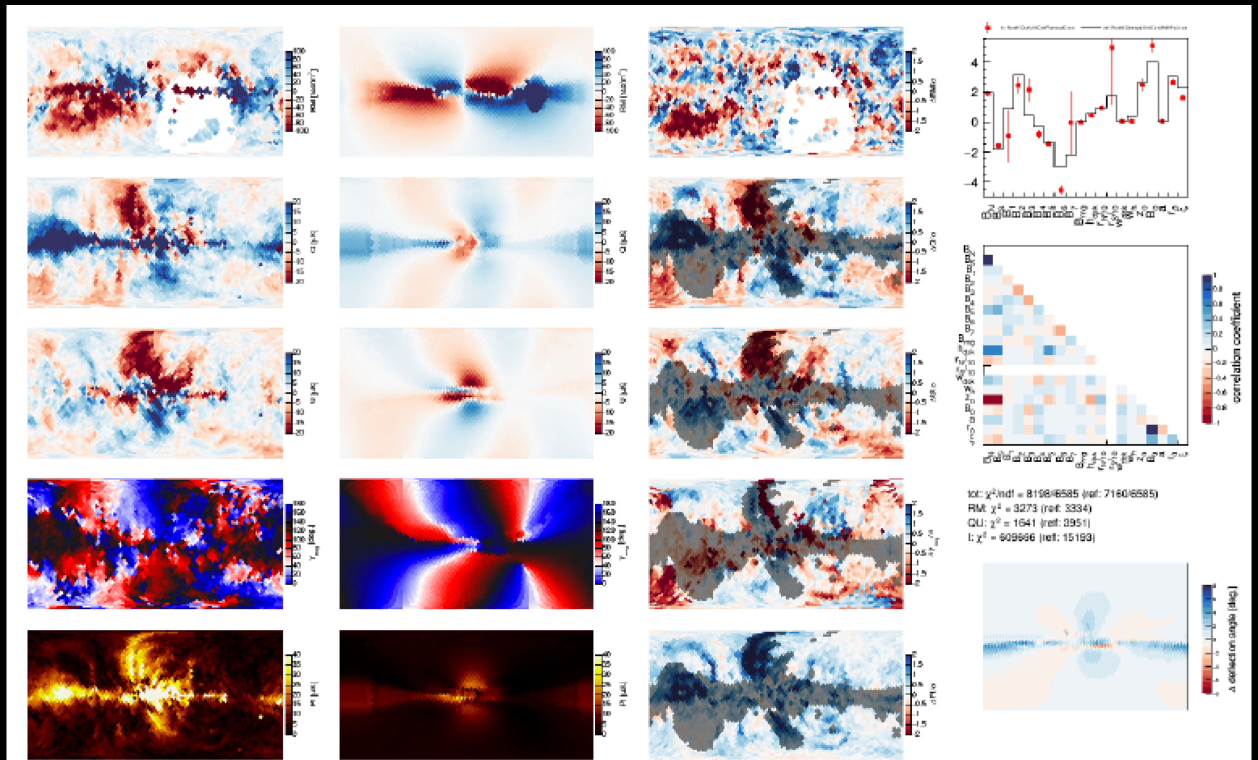
* continuing analysis & plots, M. Unger

** parabolic X-field: Ferriere-Terral 2014 model C

Impact of WMAP->Planck on coherent B
VERY PRELIMINARY!

- Parameter fitting with Planck data not yet complete.
- Current-best minimum gives roughly similar parameter values to KF16
  n.b., uses JF12 n_e & n_{cre}
- NO CONCLUSIONS POSSIBLE YET



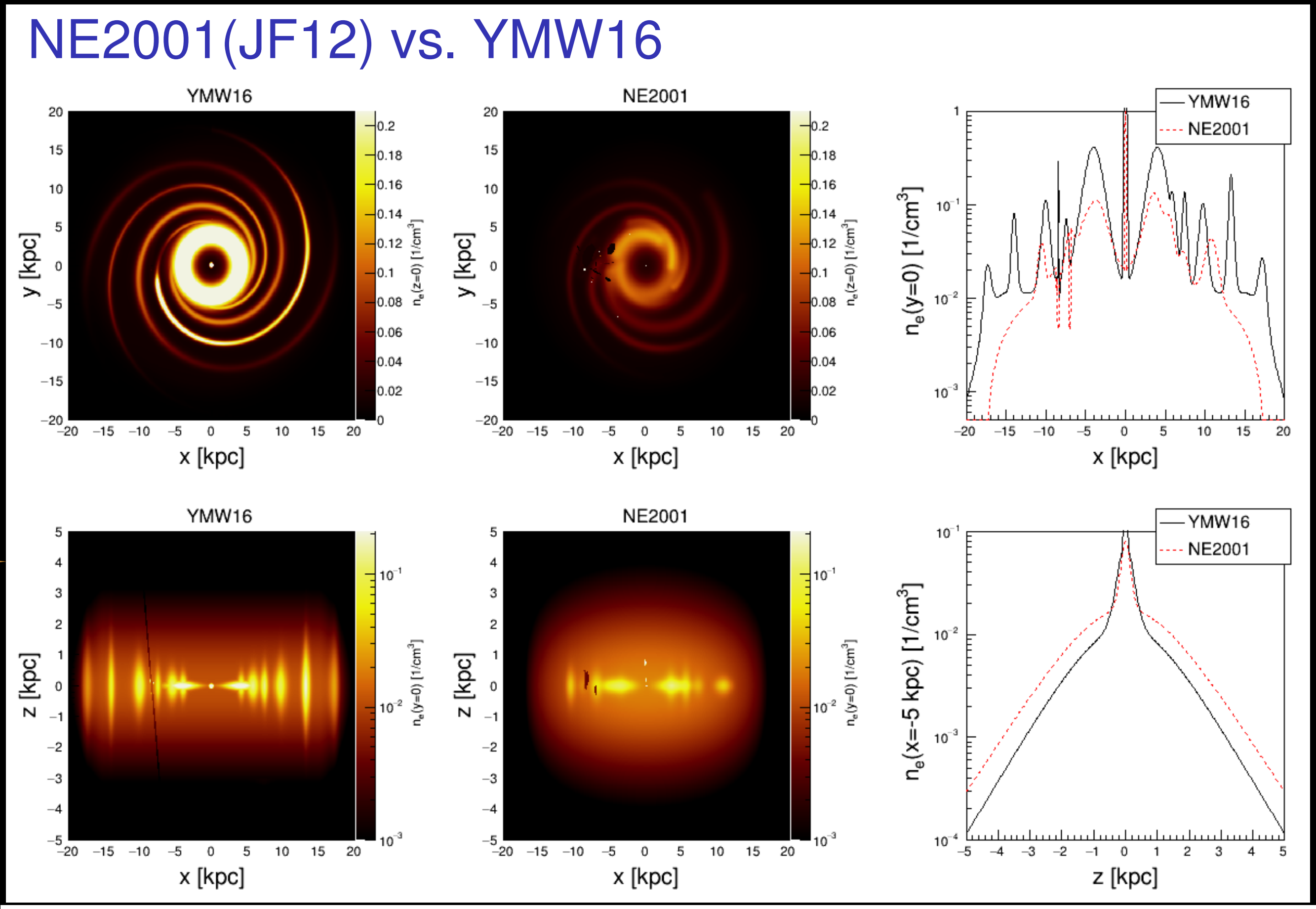


Update on JF12

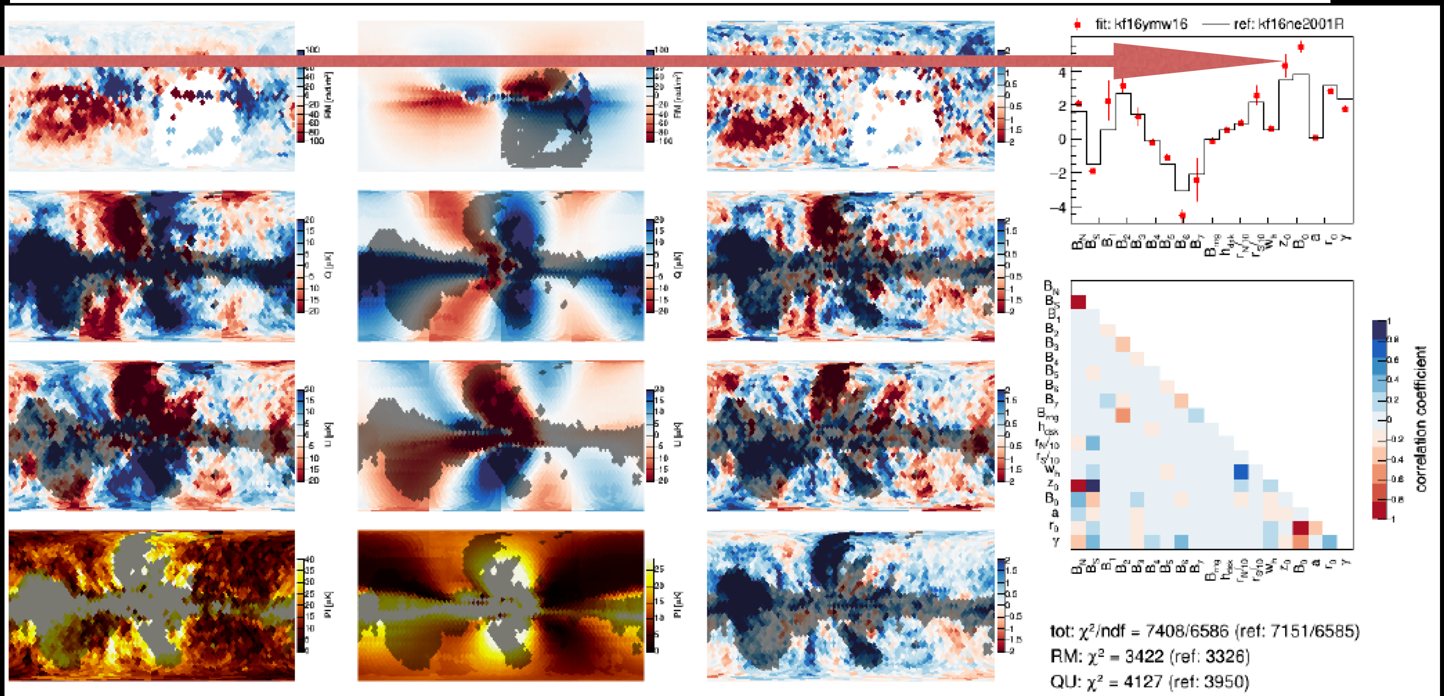
- Planck vs WMAP synchrotron QUI
- Improved models of n_e & n_{cre}
- Alternate descriptions of coherent magnetic field
  - basic structure of JF12 remains preferred (orientation, X->parabolic, flux conservation)
- Correlations in fluctuations of n_e & B, detailed modeling of B_{stri} , coherence scale, …

n_e : thermal electron model

- JF12 used Cordes-Lazio NE2001, with revised scale height (Gaenssler)
  - New models have appeared (Schnitzler +2012, Yao Manchester Wang 2016)
  - Important differences from NE2001, ex. YMK16



- Change GMF: $n_e \downarrow \Rightarrow B \downarrow$
  - Some changes in spiral arm B's
  - B in halo increases

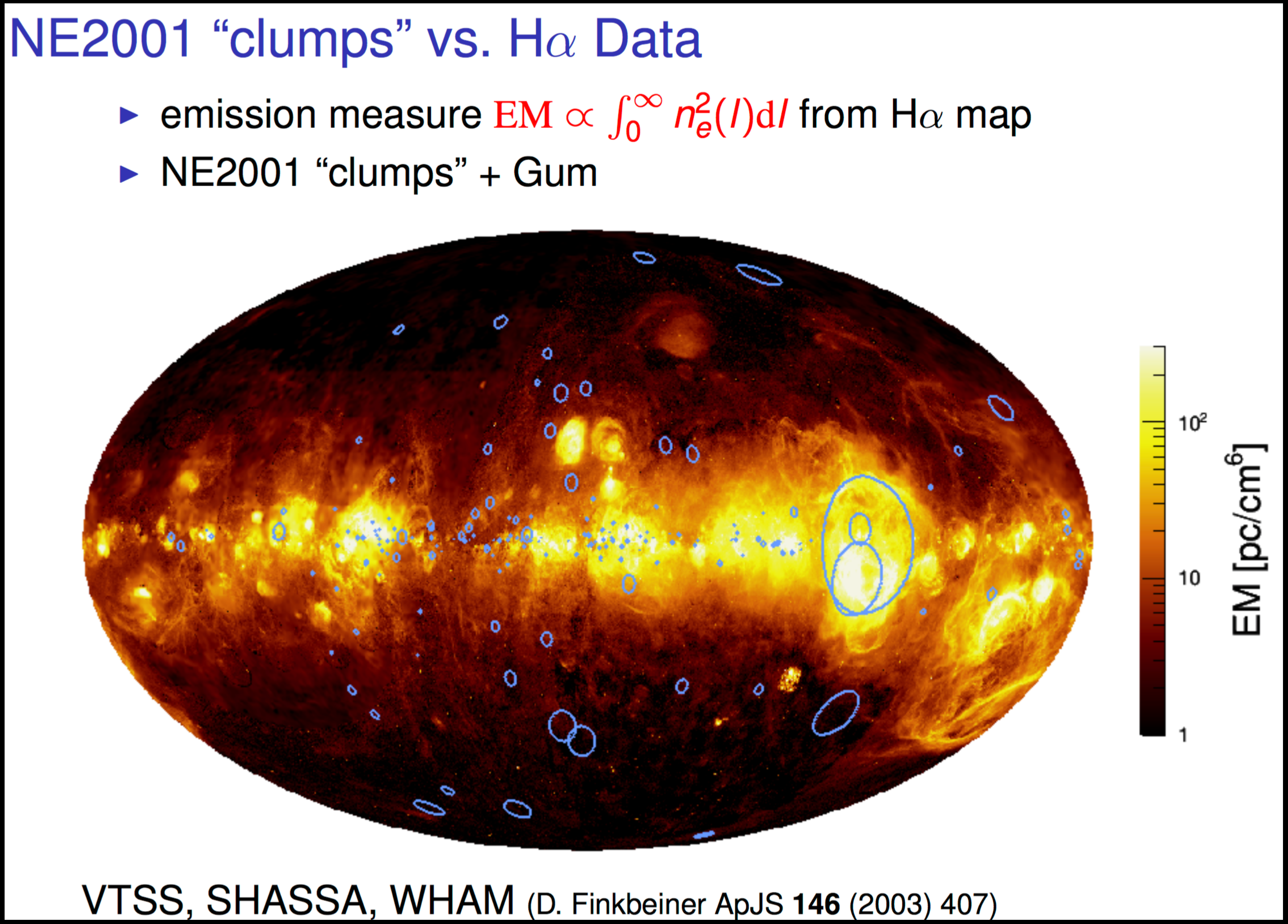


- Effort underway UF?? to add known structure (need for pulsar RMs to be used)

plots by M. Unger

More detailed n_e
(UF??)

- Combine a variety of data
  - H_{alpha} emission measures ~ n_e^2
  - HII regions to locate
- Improve noise subtraction in RM



from M. Unger talk, Madison B-field workshop 2016)

More detailed n_{cre}

- **Random field from synchrotron emission ⇔ must know n_{cre}**
- Accurate n_{cre} model ⇔ must treat electron propagation well:
  - diffusion out of disk via X-field
  - anisotropic diffusion difficult to treat technically…
- Awaiting help from this audience!!!

Random field model

- Synchrotron emission ~ B^2 ⇨
  - Total intensity I: if Planck replaces WMAP
    - I ~ B^2 : decreases by factor ~30
    - Expect B_{rand} in disk to decrease by factor ~5
  - PI: smaller difference between Planck & WMAP
    - B_{coh} and B_{stri} are only mildly affected (as we saw…)
- Must have accurate n_{cre} to find correct B_{rand}
- Updated GMF model pending better understanding of Planck data processing.

Conclusions

Summary

UF?? is coming, but its hard work!

- *Planck vs WMAP synchrotron QUI*
- *Improved models of n_e & n_{cre}*
    - n_e
- Alternate descriptions of magnetic field
- *Also:*
    - correlations between fluctuations of n_e & B_{rand}
    - detailed modeling of B_{stri}
    - coherence scale, …