The Galactic Magnetic Field

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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

Cosmic Magnetism, Nordita, June 25, 2015

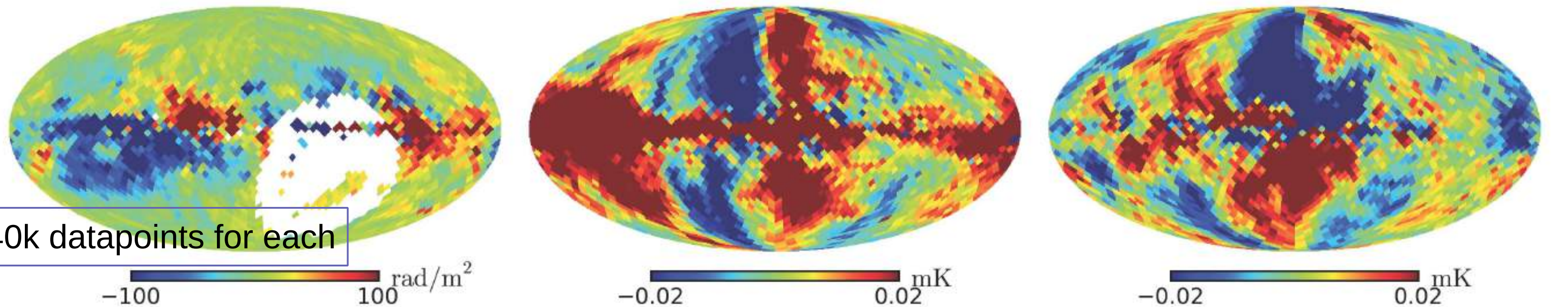
Jansson-Farrar strategy, I. *Data*

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)



~40k datapoints for each

GMF modeling — Jansson Farrar 2012

Question: How should we model the magnetic field?

No (accepted) theory for galactic magnetogenesis

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No obvious model (functional form) to use

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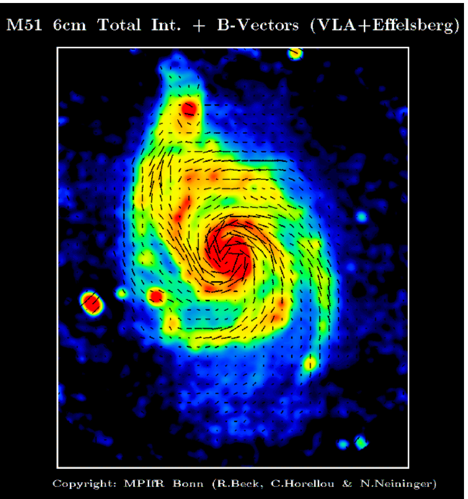
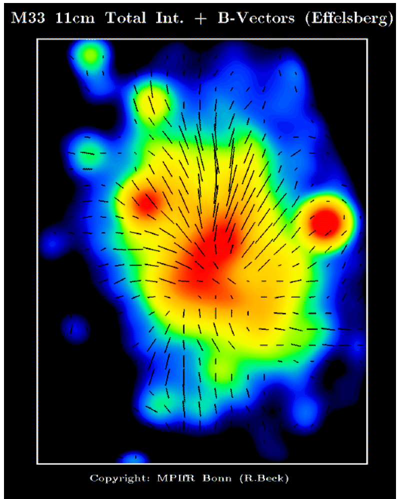
Infinite choice of models…

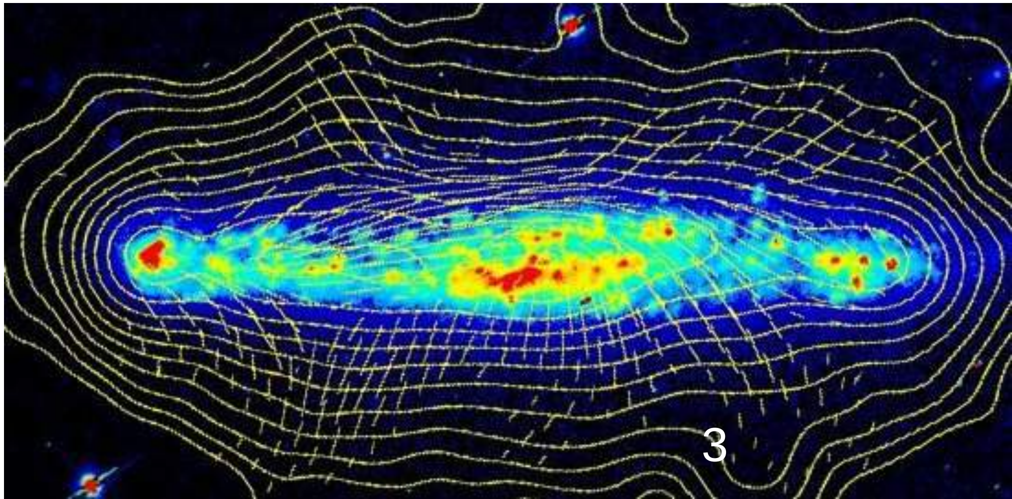
How to model the GMF?

Theoretical constraint: magnetic flux is conserved!

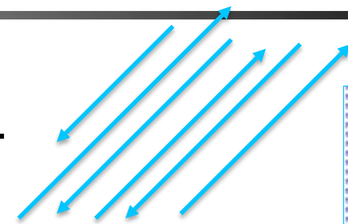
Observational guidance: external galaxies

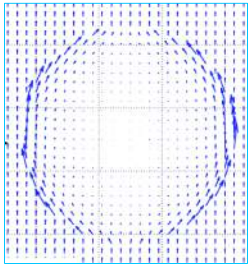






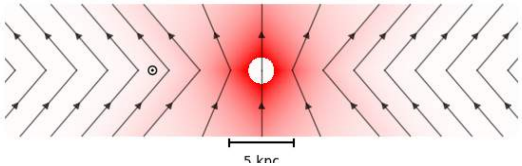
JF12 coherent field model





- *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.



Original JF12 X-field

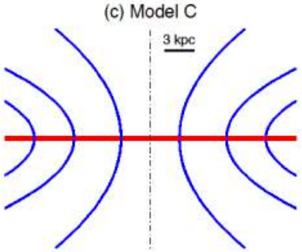
B_0, r_B, r_X, asymptotic angle

2015 update (D. Khurana+GF in prep)

test form proposed by Ferriere-Terral 2013

B_0, r_B, r_X , exponent=2

Essentially identical fit.



- & 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
- **Constrain with WMAP7 22 GHz total Intensity map**
    - Time saver: Average over random field by computing synchrotron intensity with

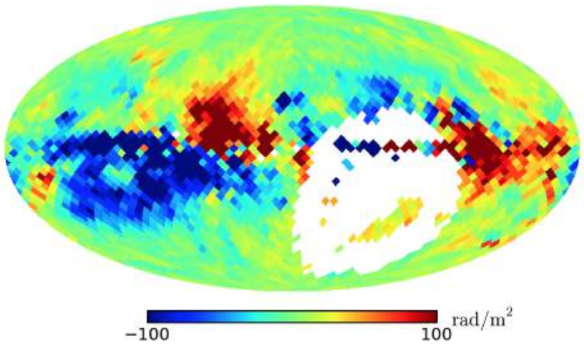
$$B_{\mathrm{reg}}^2 \rightarrow \alpha\,(1+\beta)\,B_{\mathrm{reg,model}}^2 \left(1 + \frac{2}{3}\frac{B_{\mathrm{rand}}^2}{(1+\beta)B_{\mathrm{reg,model}}^2 \sin^2\theta}\right)$$

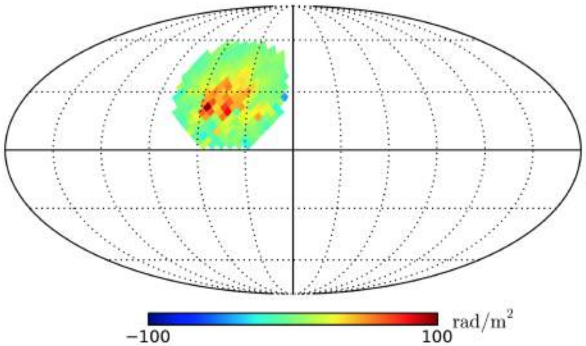
Input I: RMs

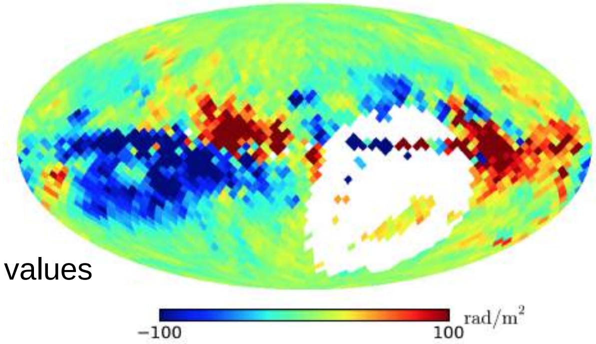
- **40403 extragalactic RMs**
  - some are duplicate measurements of same source
- Map to 8 10^{-4} sq-deg Healpix pixels; 50M
  - if multiple measurements, take the best quality ones
  - average. => 38627 pixels with RMs
- Remove outliers
  - for each pixel, measure mean & variance of neighbors
  - 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) as available [Wolleben et al (2010)]

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

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







Input II: Synchrotron Maps

- WMAP 7-yr K-band, 22 GHz synchrotron maps
    - primary improvement from Planck will be more accurate separation between synchrotron and dust emission, and foreground removal
- Bin to 2067 pixels (13.4 sq-deg)
- Measure variance from sub-pixels
- Foreground
    - contributes ~$1/r^2$; needs masking (?)
    - try 4 masks:
        - WMAP polarization (black, upper plot) 27%
        - extended WMAP to remove hi-PI regions attributable to local structures (grey) 35%, …
    - try no mask!
    - **Fit is virtually unchanged (< 1 σ)**

VINDICATES METHODOLOGY

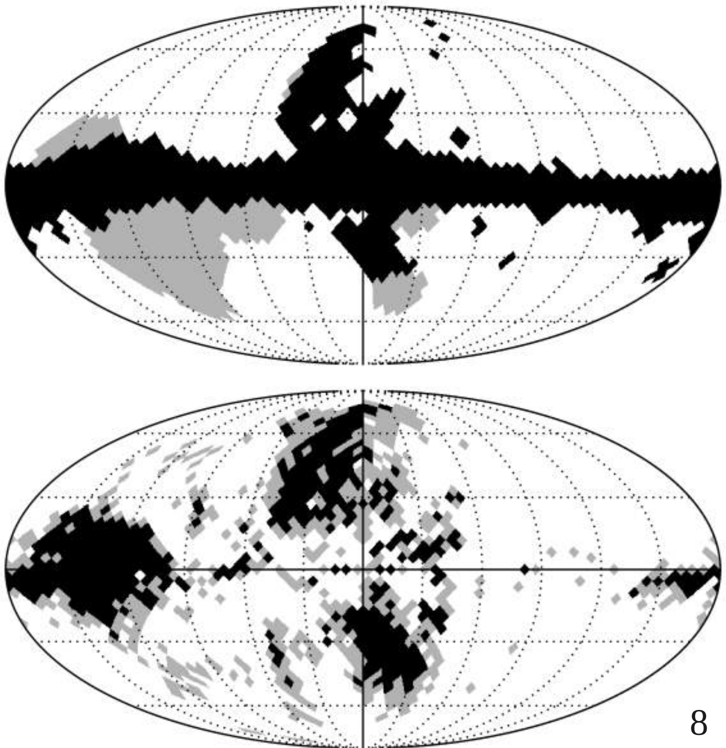
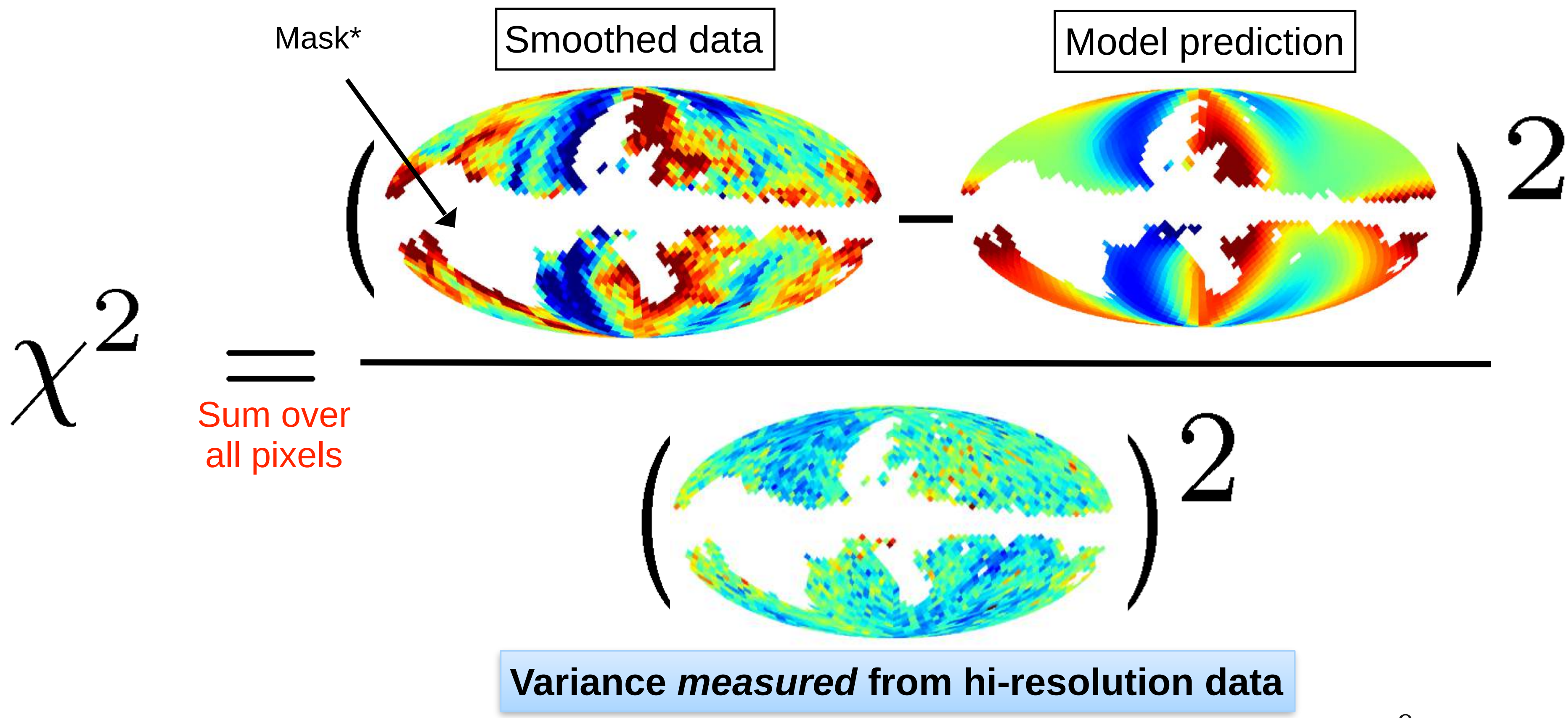


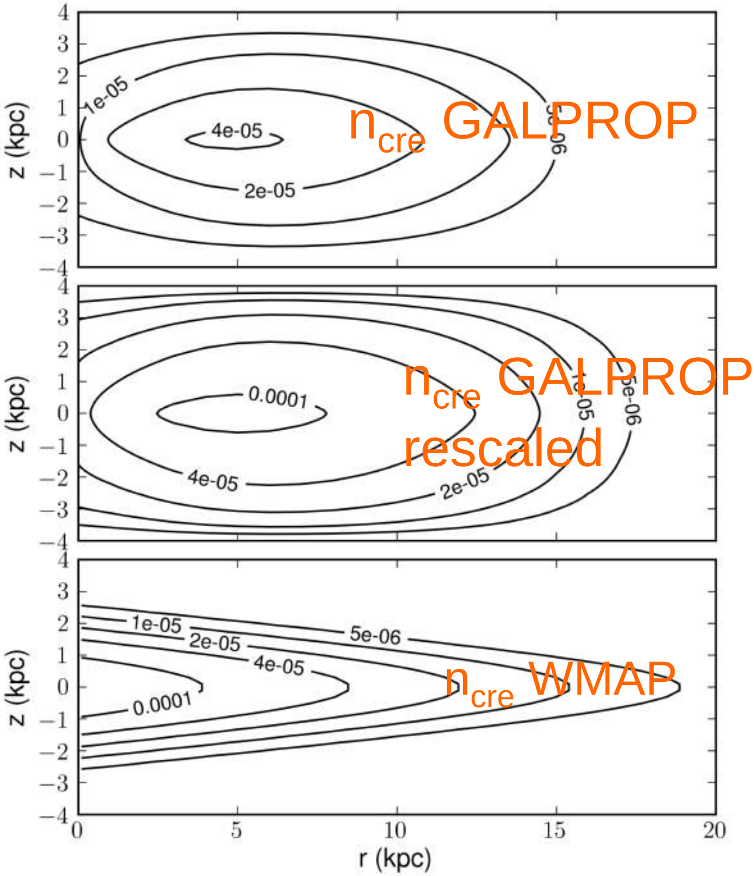
Figure-of-Merit used for JF12



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

Input III: electron densities

- Thermal electrons n_e from Cordes-Lasio NE2001 (with larger scale-height)
- Relativistic electrons n_{cre}
  - GALPROP (courtesy A. Strong, 2009)
    - rescale
- electron densities are the weakest link in the analysis…



v2: **BETTER MODELING of e's**

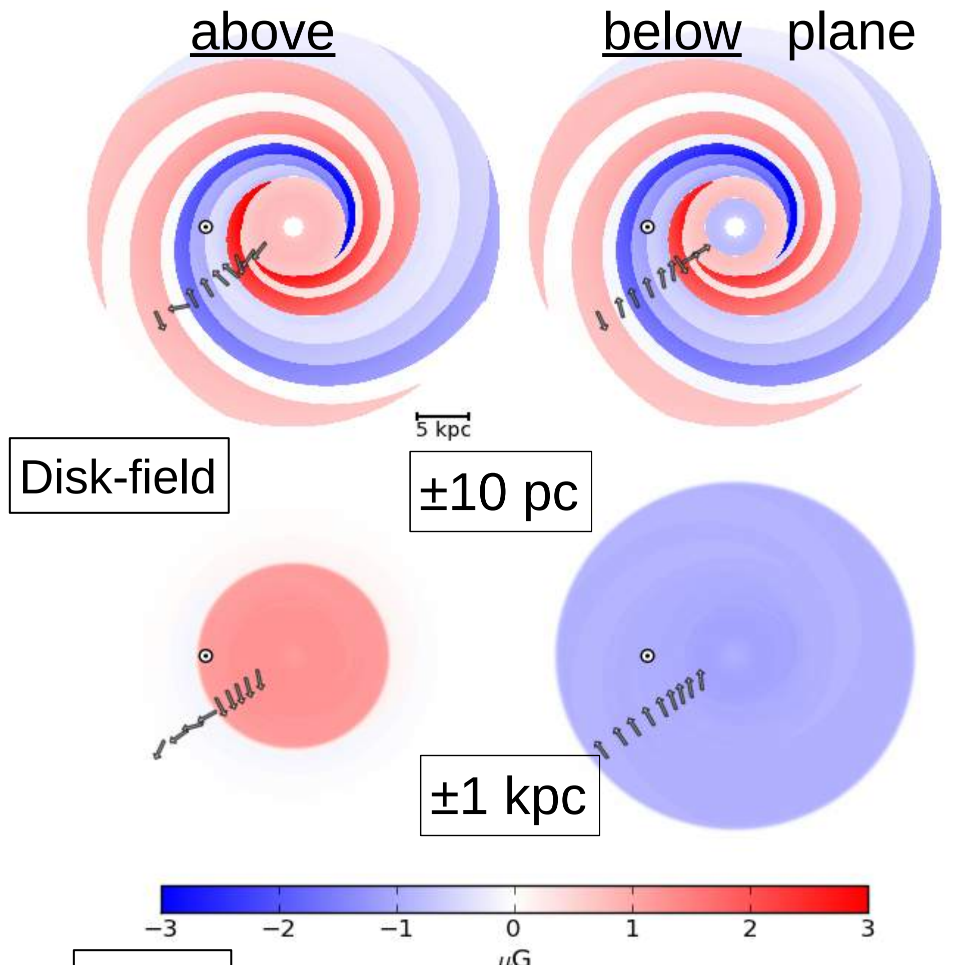
- new n_e & n_{cre} models
  - anisotropic diffusion along magnetic field lines
  - more realistic source distribution

JF12 Coherent Field

BEST-FIT GMF PARAMETERS WITH $1-\sigma$ INTERVALS.

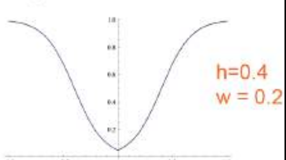
Field	Best fit Parameters	Description
Disk	$b_1 = 0.1 \pm 1.8\,\mu$G	field strengths at $r = 5$ kpc
	$b_2 = 3.0 \pm 0.6\,\mu$G	
	$b_3 = -0.9 \pm 0.8\,\mu$G	
	$b_4 = -0.8 \pm 0.3\,\mu$G	
	$b_5 = -2.0 \pm 0.1\,\mu$G	
	$b_6 = -4.2 \pm 0.5\,\mu$G	
	$b_7 = 0.0 \pm 1.8\,\mu$G	
	$b_8 = 2.7 \pm 1.8\,\mu$G	inferred 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.

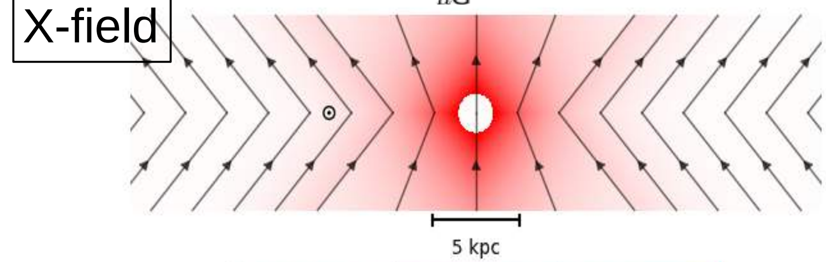


- Disk
  - > 5 kpc: 8 spiral arms, geometry as in NE200
  - 3-5 kpc: purely azimuthal "molecular ring"
  - B=0 for r < 1 (not adequately constrained by data) and r > 20 kpc
- Halo
  - purely toroidal (fit prefers this to spirals with arbitrary angles)
  - Different strength and scale height in N and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



Random GMF Model

R. Jansson + GRF, Ap. J. Lett. (2012)

Field	Best-fit Parameters	Description
Disk component	$b_1 = 10.81 \pm 2.33\ \mu G$	Field strengths at $r = 5$ kpc
	$b_2 = 6.96 \pm 1.58\ \mu G$	
	$b_3 = 9.59 \pm 1.10\ \mu G$	
	$b_4 = 6.96 \pm 0.87\ \mu G$	
	$b_5 = 1.96 \pm 1.32\ \mu G$	
	$b_6 = 16.34 \pm 2.53\ \mu G$	
	$b_7 = 37.29 \pm 2.39\ \mu G$	
	$b_8 = 10.35 \pm 4.43\ \mu G$	
	$b_{int} = 7.63 \pm 1.39\ \mu G$	Field strength at $r < 5$ kpc
	$z_0^{disk} = 0.61 \pm 0.04$ kpc	Gaussian scale height of disk
Halo component	$B_0 = 4.68 \pm 1.39\ \mu G$	Field strength
	$r_0 = 10.97 \pm 3.80$ kpc	Exponential scale length
	$z_0 = 2.84 \pm 1.30$ kpc	Gaussian scale height
Striation	$\beta = 1.36 \pm 0.36$	Striated field $B_{stri}^2 \equiv \beta B_{reg}^2$

Disk Component:

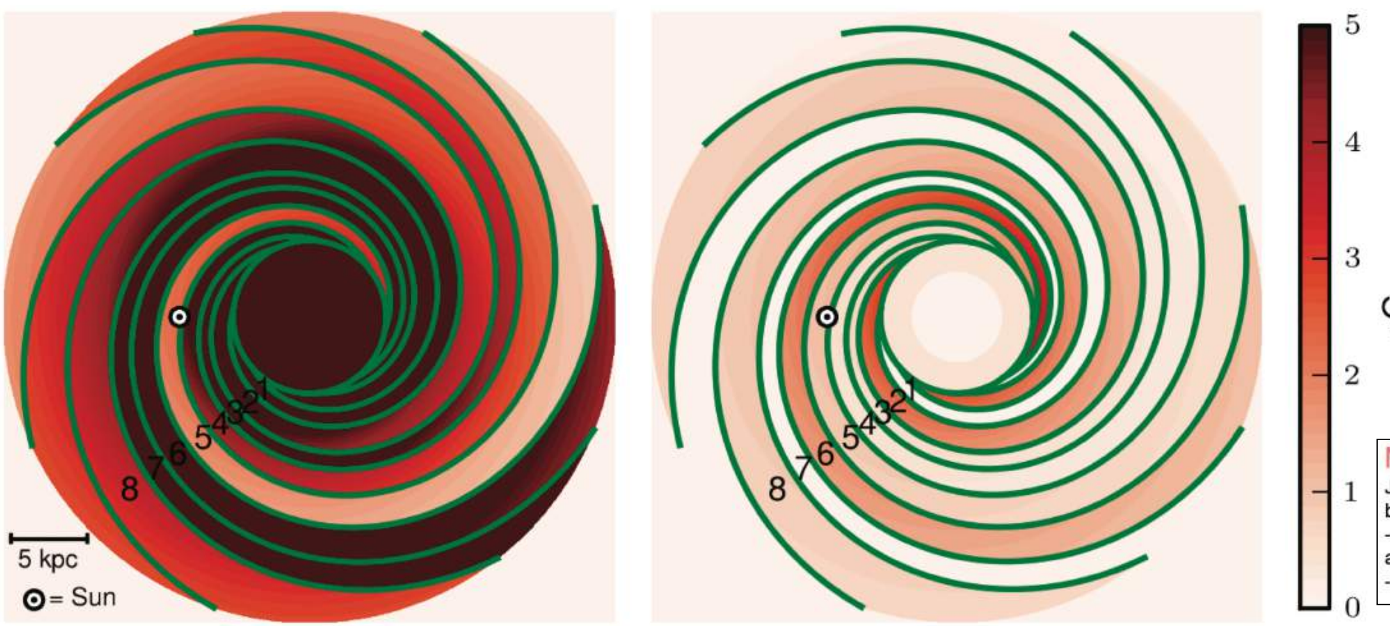
8 arms as in JF12; B~1/r;

fit separately for B_{rms} in each arm

Central region: constant B_{rms}

Gaussian vertical profile; 600 pc

Halo: strength, scale height, radial scale



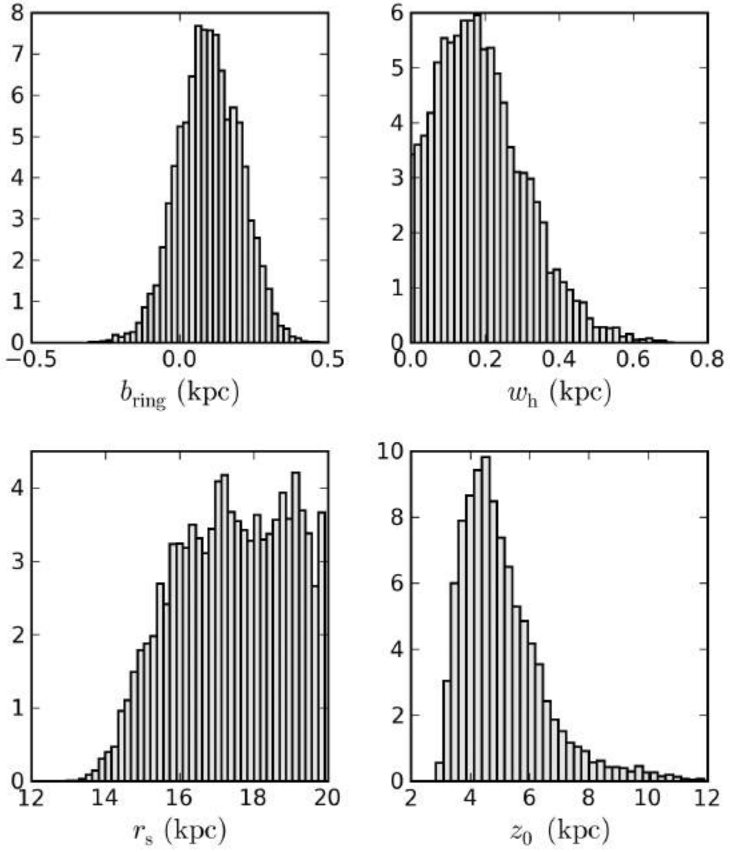
Random Regular disk

χ^2 = 1.065 per d.o.f.

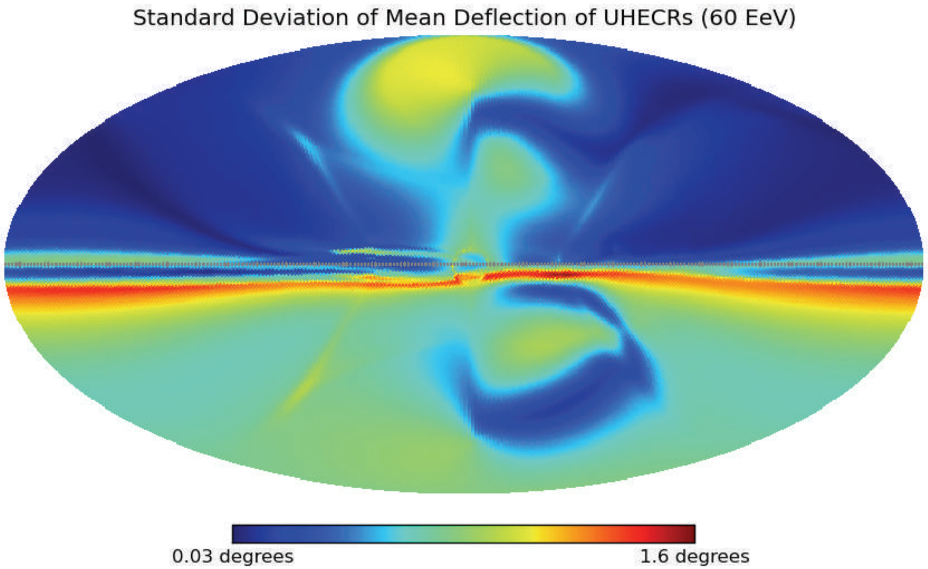
(2957 d.o.f.)

N.b.:
JF12 disk random field gives an upper bound to B_{rms}, because
- n_{cre} is likely structured, not azimuthally symmetric as in GALPROP.
- n_{cre} and B_{rms} are likely (positively) correlated.

How well constrained are parameters? VERY! (true uncertainty is bigger)



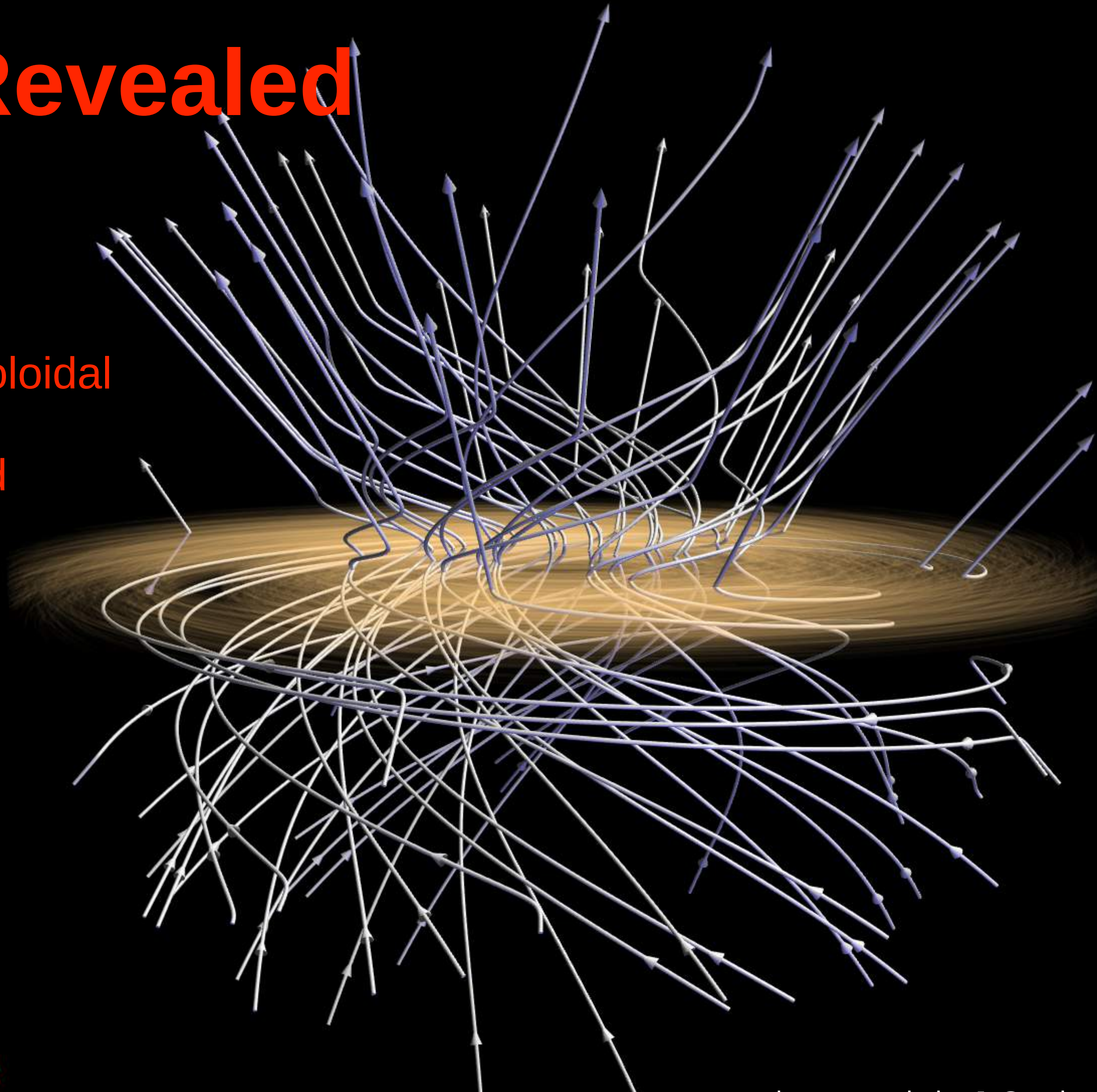
Histogram of MCMC parameter values for 4 worst cases



Uncertainty of CR deflections from JF12 parameter uncertainty

JF12 **Revealed**

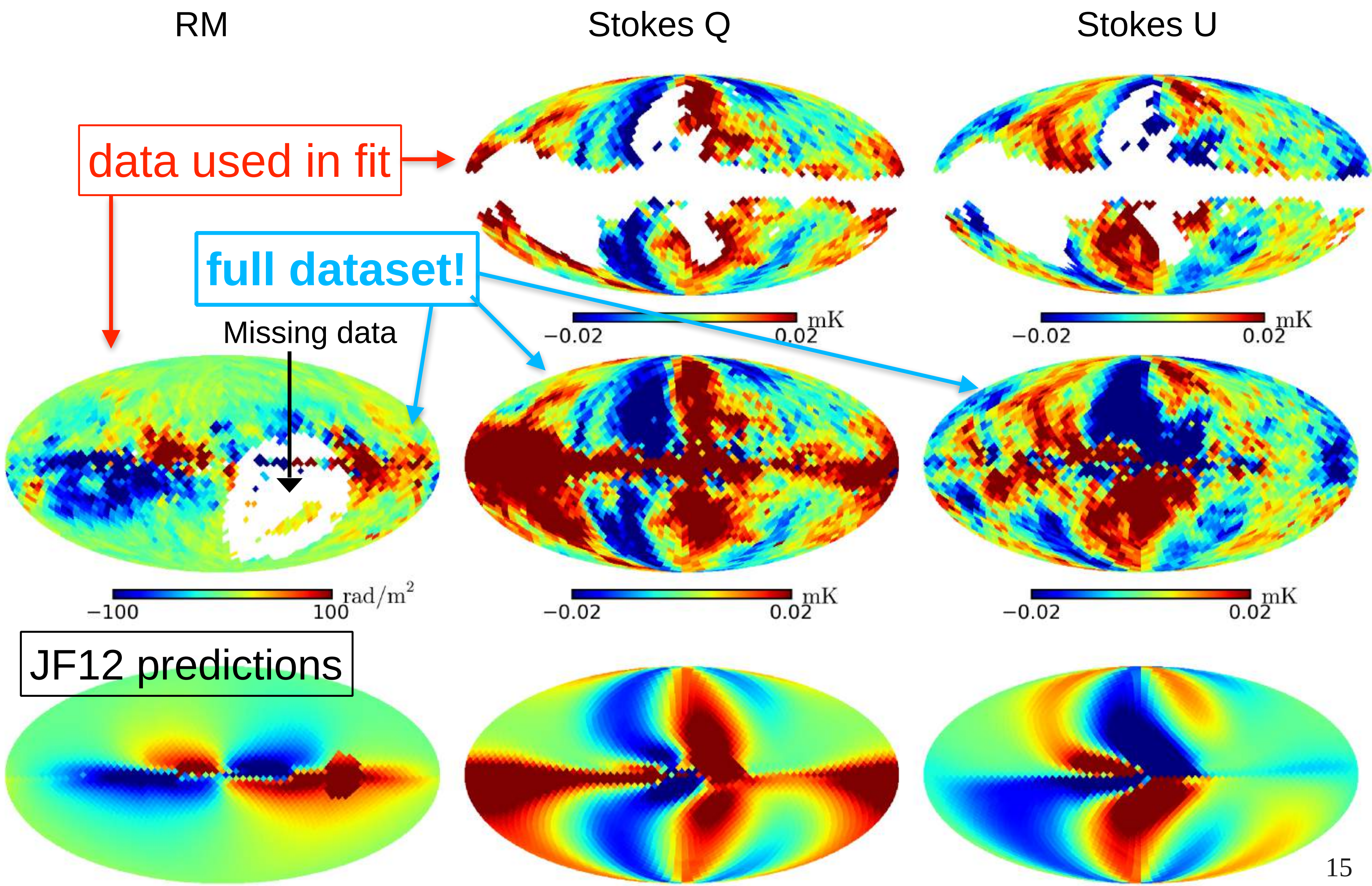
- directed, poloidal *halo field*
- striated field



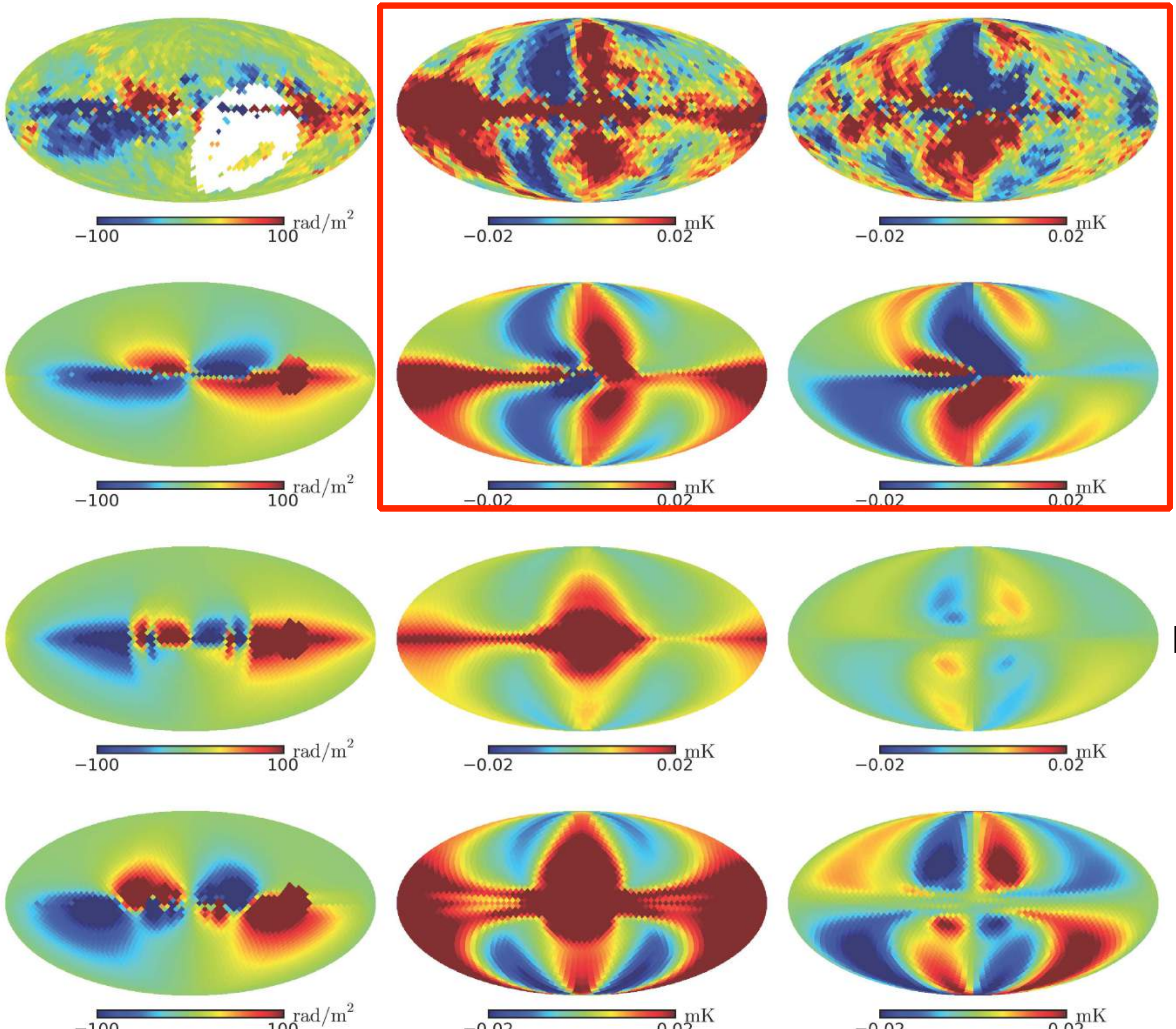
10 kpc

image made by J. Sandstrom, NASA

JF12 describes data well



Spiraling X-field ↔ distinctive L-R, up-down pattern in Q, U



Observed data

Simulated data

JF 2012

χ^2 = 1.096 per d.o.f.

for 6605 observables

Pshirkov+ 2011

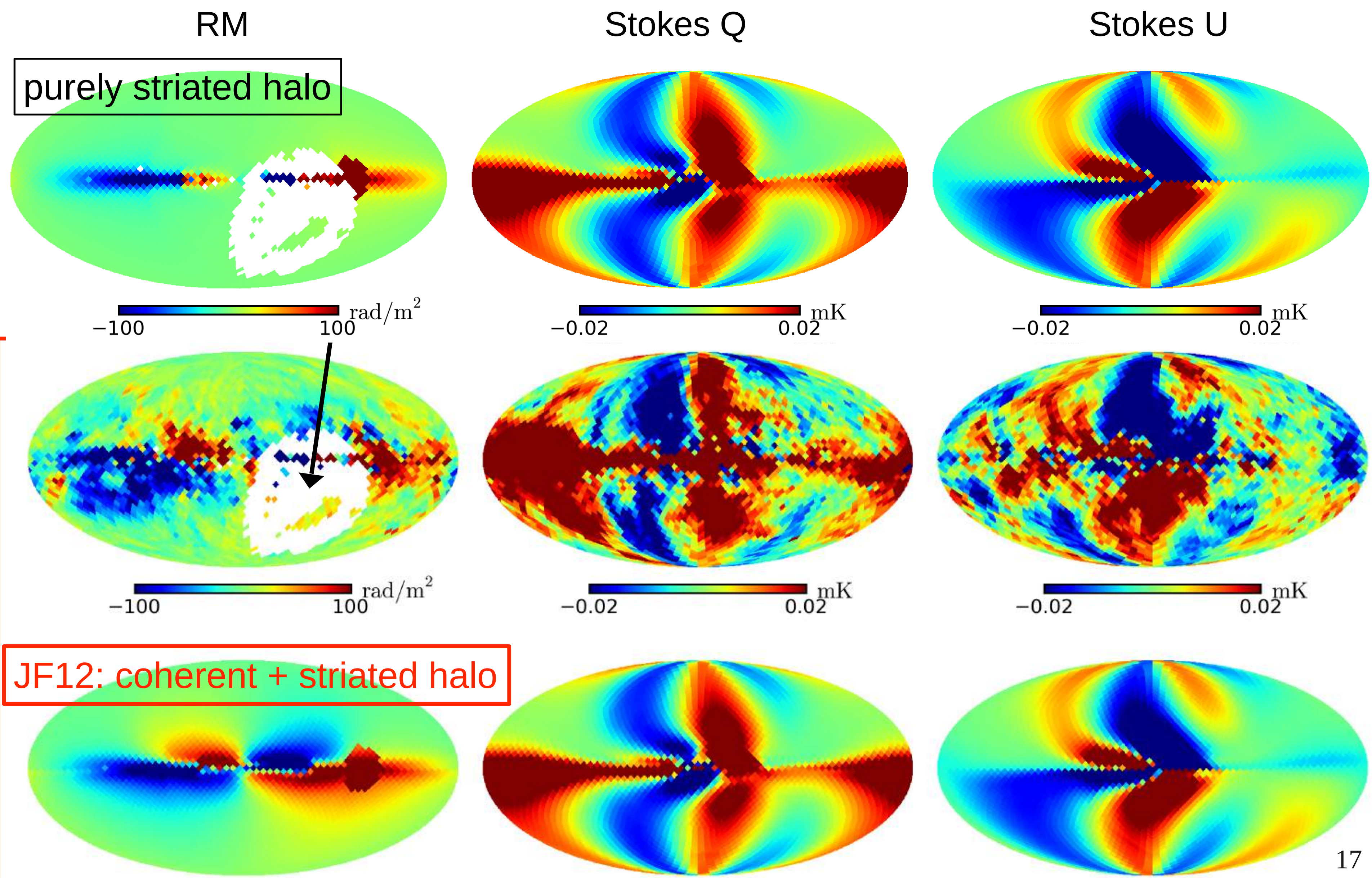
χ^2 = 2.66 per dof

No X-field

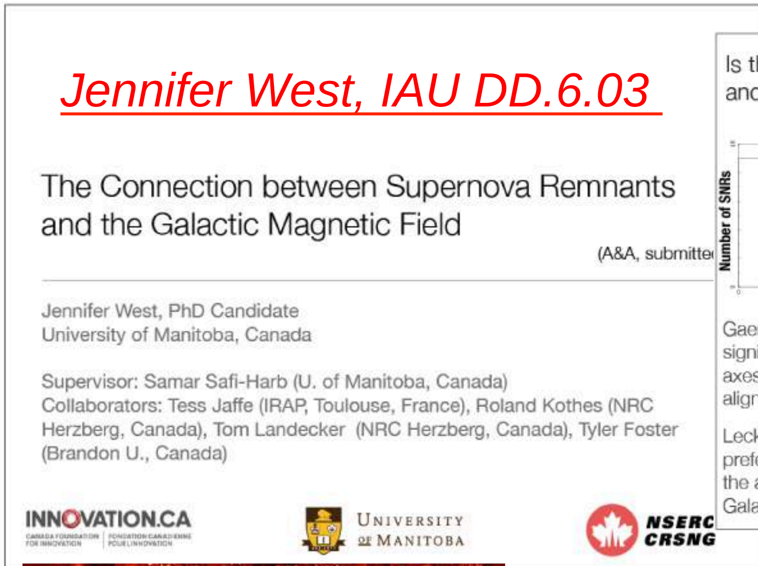
Sun et al.,2010

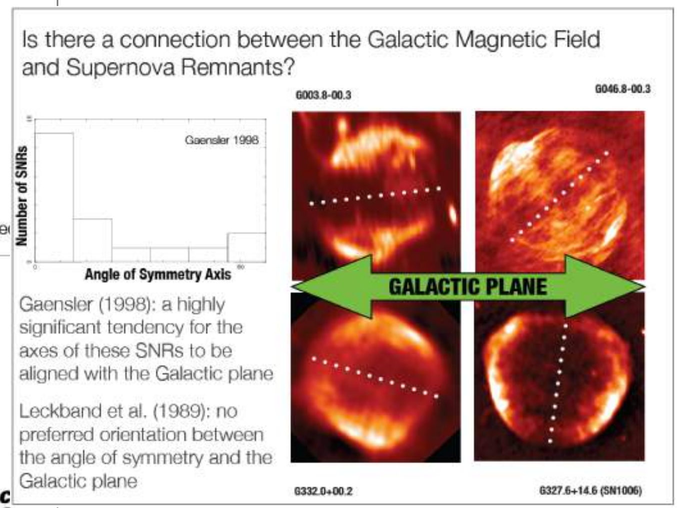
χ^2 = 1.67 per dof

The halo field is DIRECTED, not just striated

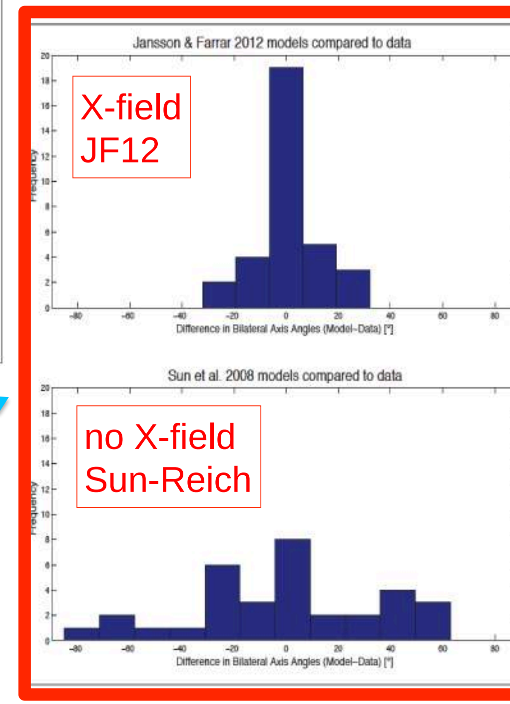


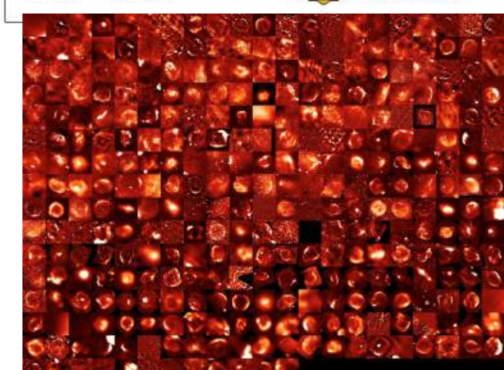
Independent evidence for JF12 X-field, from orientation of Supernova Remnants

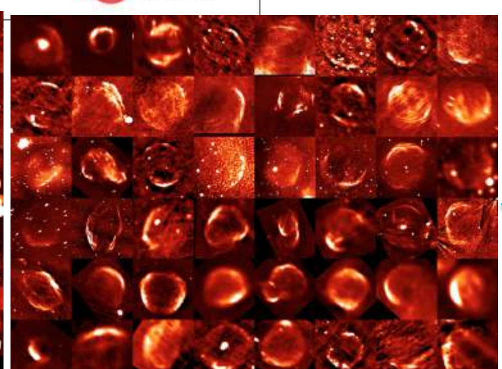




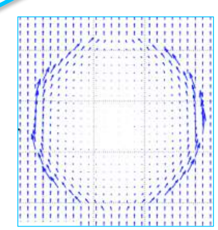
Predicted - observed



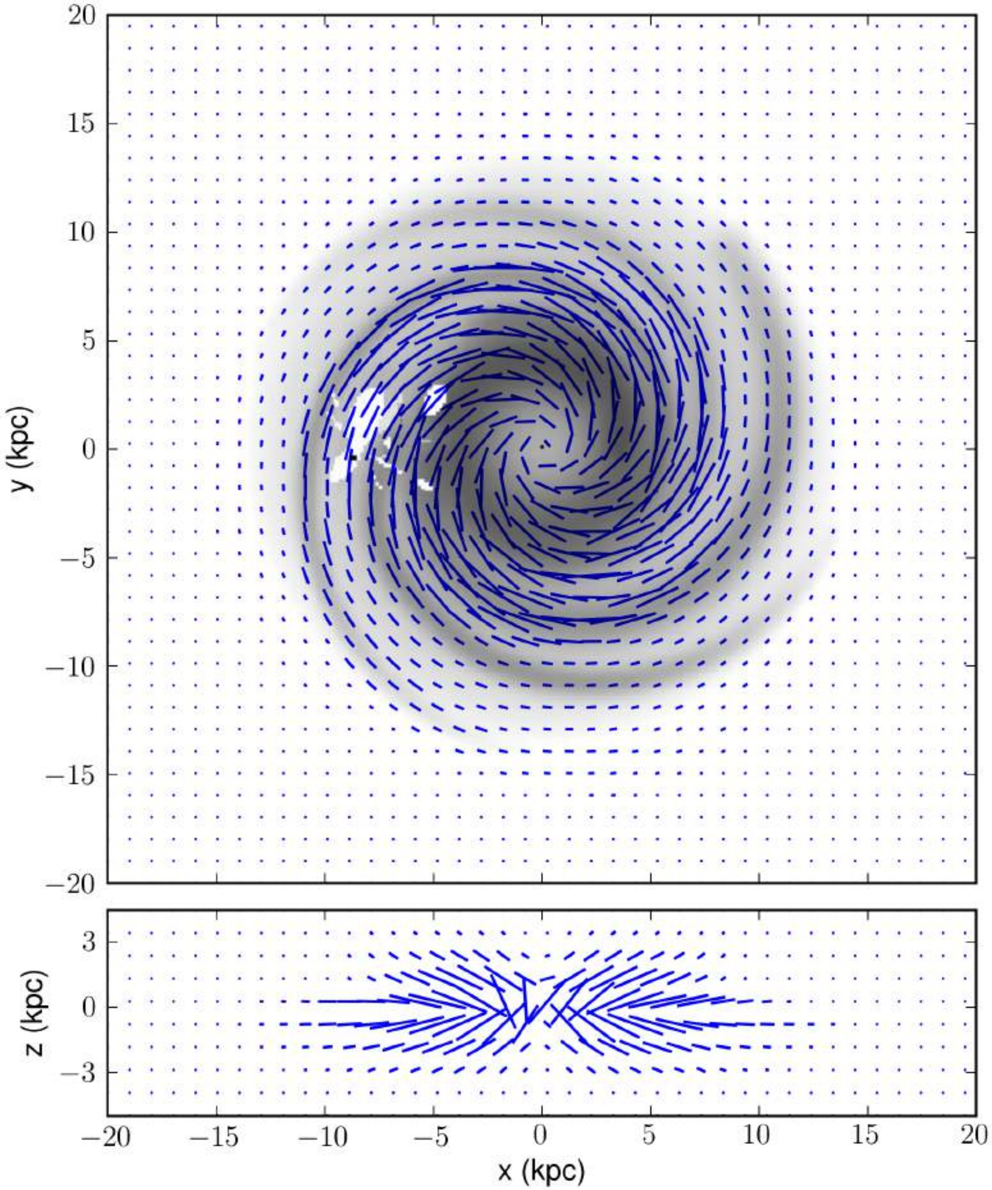




Orientation relative to model prediction

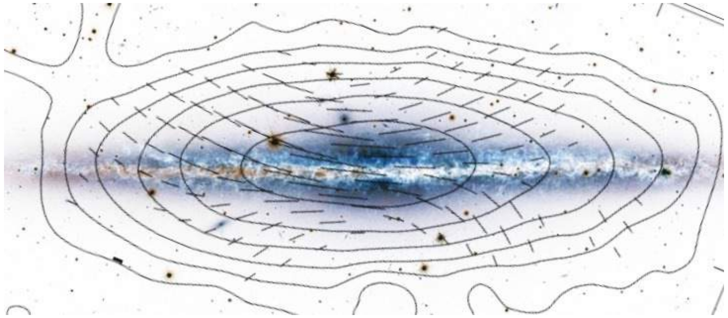


The Milky Way to an extragalactic radio observer

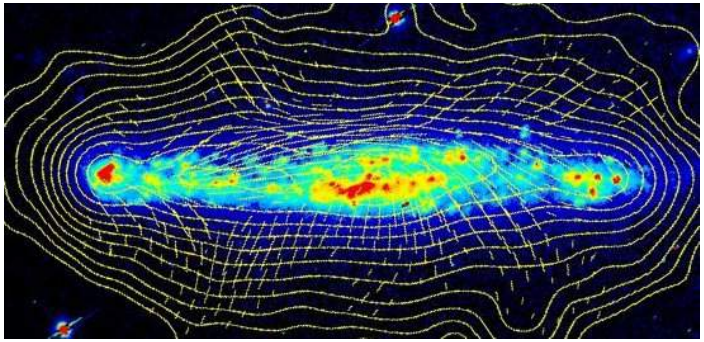


Milky Way analogues:

NGC 891

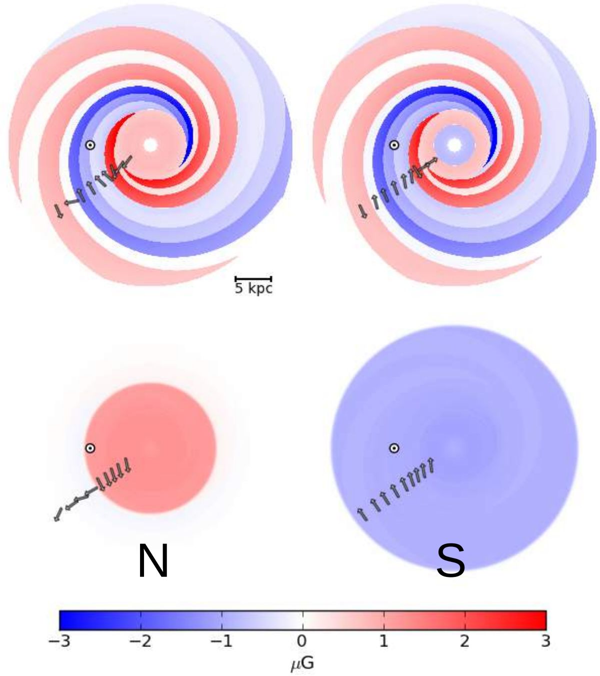


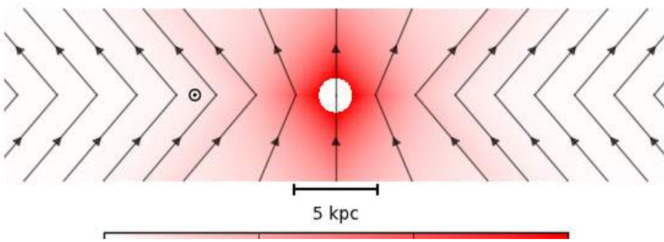
NGC 5775

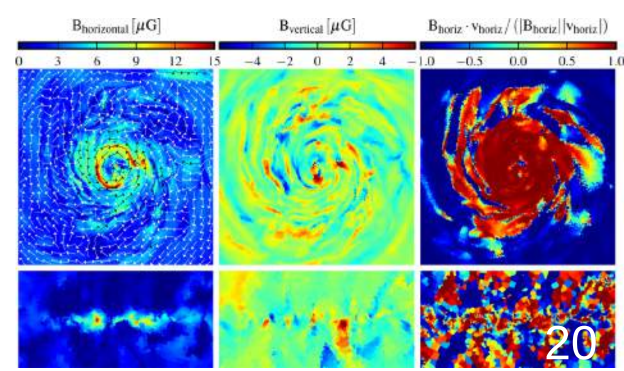


Possible origin of the ordered fields

- Differential sheer acting on “X”-field gives toroidal field
  - vertical and radial differential rotation both contribute
  - correctly predicts the observed orientations
  - **A0 dynamo mode: combo of X and toroidal fields is quasi-stable**
    but is dynamo time-scale compatible with creation of X ??
- Coherent “X” (out-of-plane) component
  - concentration of pre-Galactic field during Galaxy formation?
    scale and magnitude required for initial field is reasonable:
    0.1 nG over 1 Mpc => ~ 4 μG in central Galaxy
- “Striated fields”
  - explosions compress coherent field
  - compression or shearing of random turbulent fields
  - **result of anisotropic turbulence???**
- Coherent Disk fields
  - amplified random fluctuations? (is there really a reversal??)
- Simulations & theory needed. (Pakmor, Marinacci,Springel14; Hanasz)

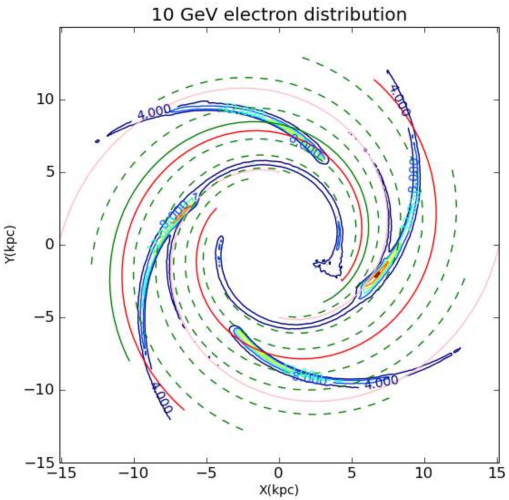






Principal caveats re. JF12

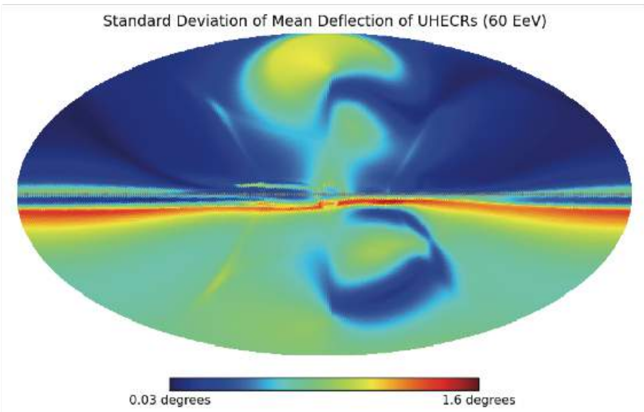
- **Disk random field probably too large:**
  - synchrotron emission $\sim \int_z^\infty dz \, n_{cre}(\mathbf{x}) \, B_\perp^2(\mathbf{x})$
  - n_{cre} is probably structured rather than azimuthally symmetric as in GALPROP, e.g., Benyamin-Shaviv13 and Werner+14
  - *factor 3 reduction in B_{rms}* .
  - Halo field and coherent field also affected but probably less so.



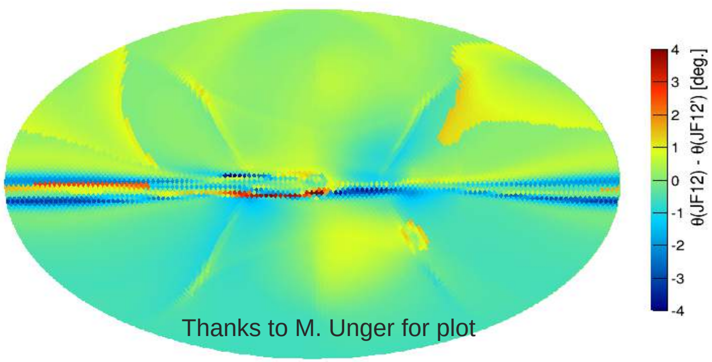
- **$B_{coh(||)}$ subject to errors in n_e**
- **Functional form may not be general enough**

Variations to JF12 and uncertainties

JF12 parameter uncertainty: < 2°



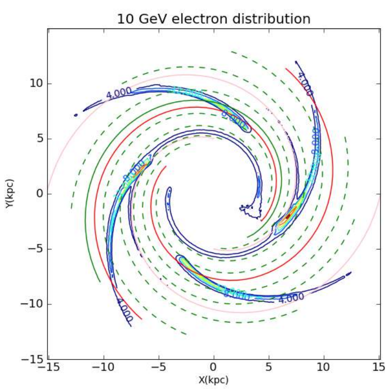
JF12 X-field parameterization: mostly < 1°



- 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.



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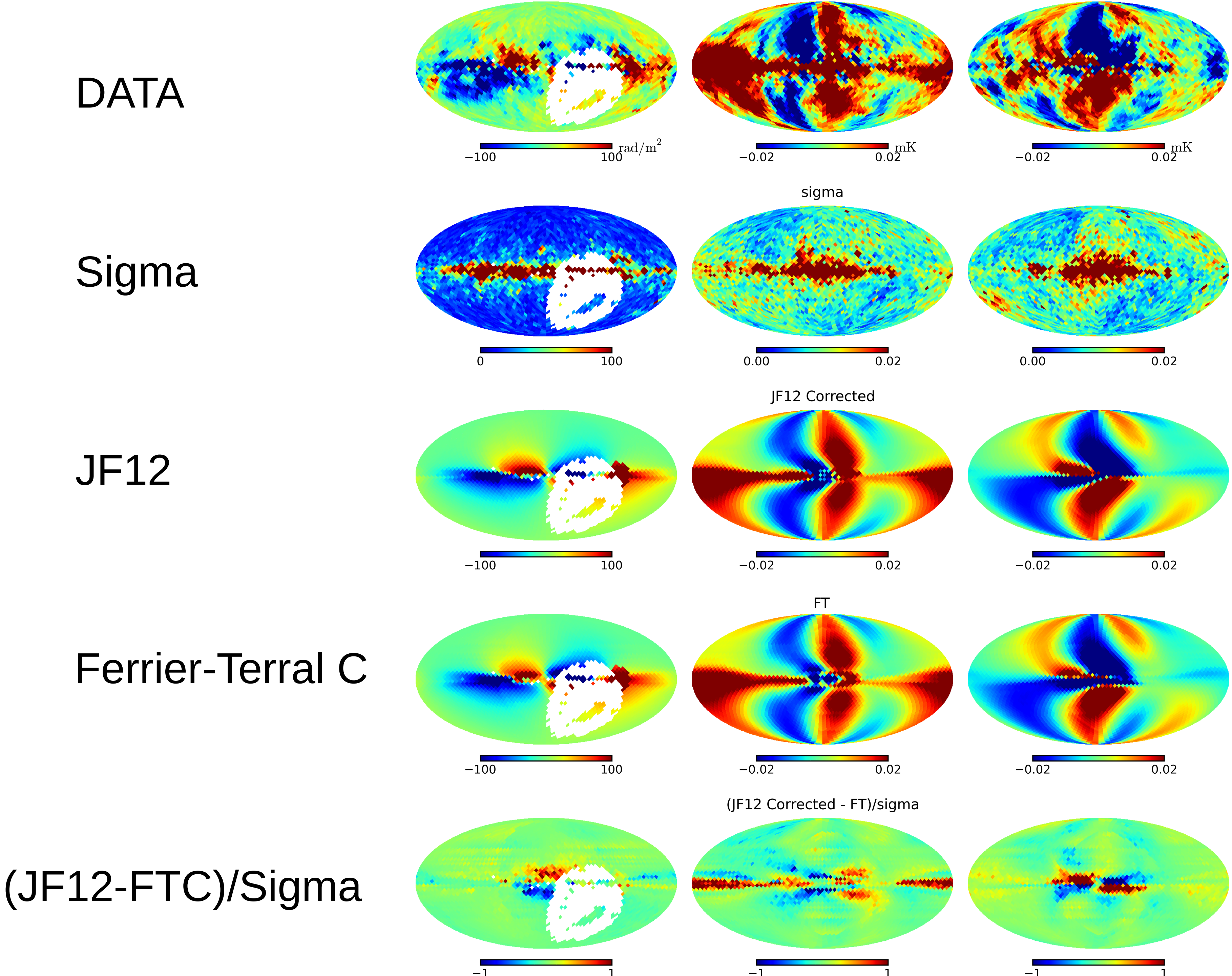
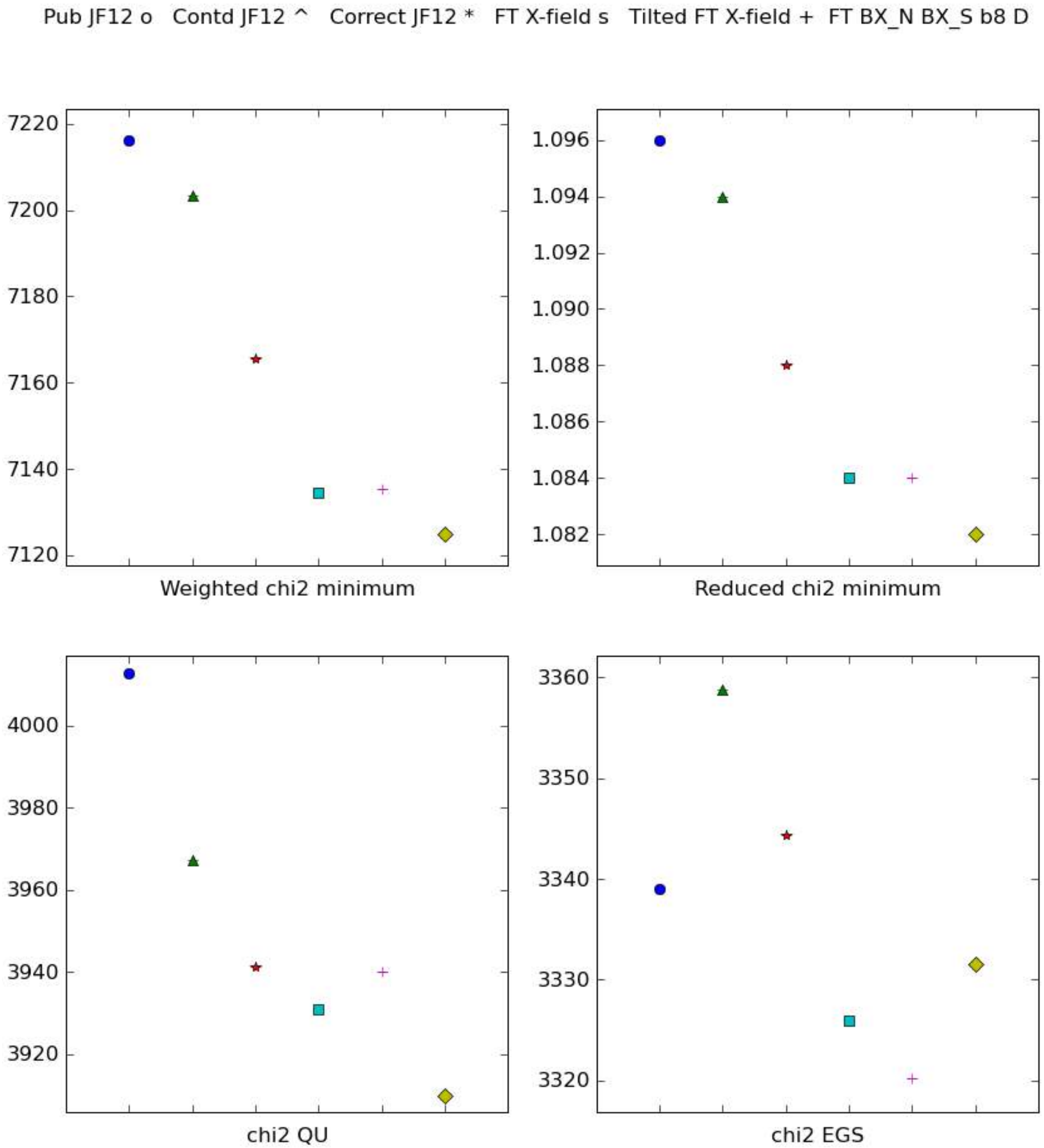
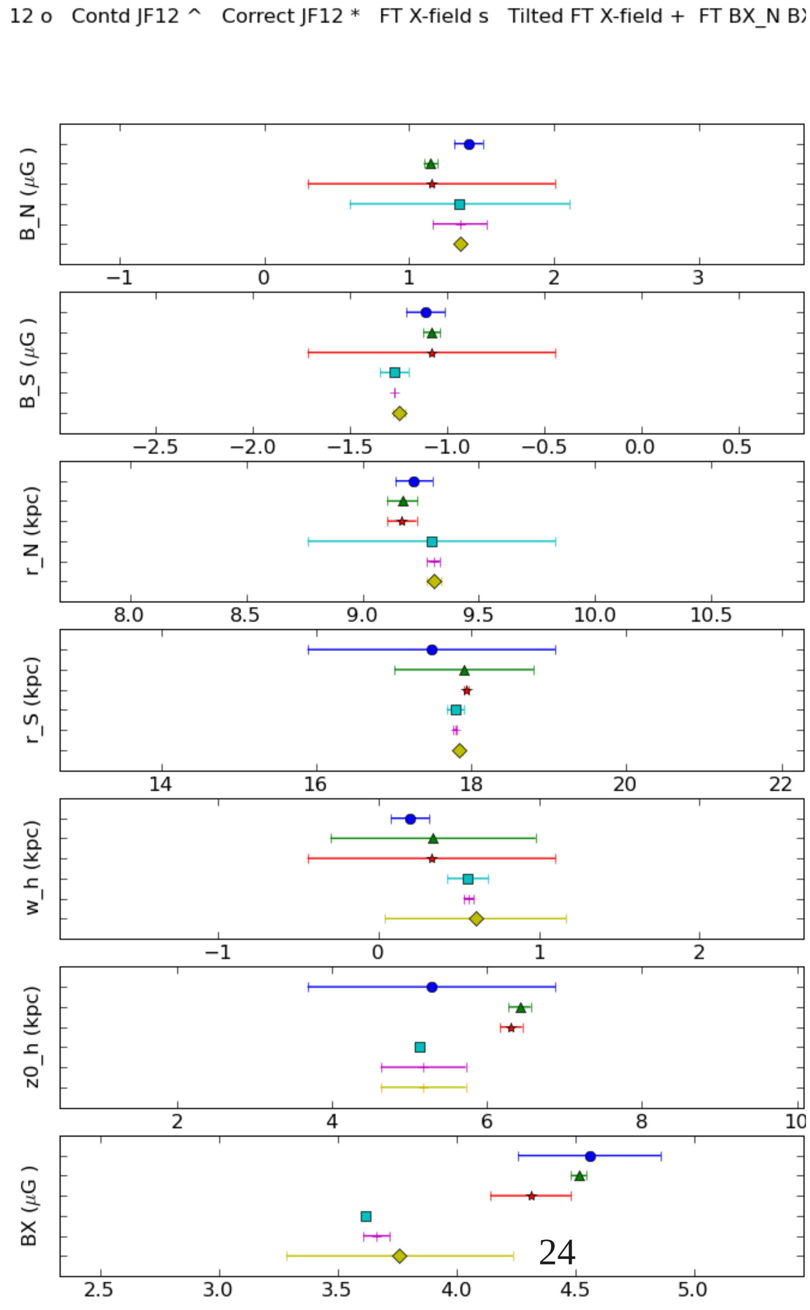
FTC gives slightly better fit; plots next page



DATA
rad/m^2
−100
100
mK
−0.02
0.02
mK
−0.02
0.02
sigma
Sigma
0
100
0.00
0.02
0.00
0.02
JF12 Corrected
JF12
−100
100
−0.02
0.02
−0.02
0.02
FT
Ferrier-Terral C
−100
100
−0.02
0.02
−0.02
0.02
(JF12 Corrected - FT)/sigma
(JF12-FTC)/Sigma
−1
1
−1
1
−1
1

Model differences





Summary

- *$B_{striated}$ ~ 1.25 B_{coh} ; aligned with B*
- *B in halo: coherent S-to-N, spiraling "X" field*
- JF12 method is robust
- Next stage: Improve n_e, n_{cre} & functional form

Backup Slides

JF12 Model compared to WMAP

Just first step; need simultaneous fitting.

Intensity

Data | Model

22 GHz Synchroton Total Intensity

note plots are saturated

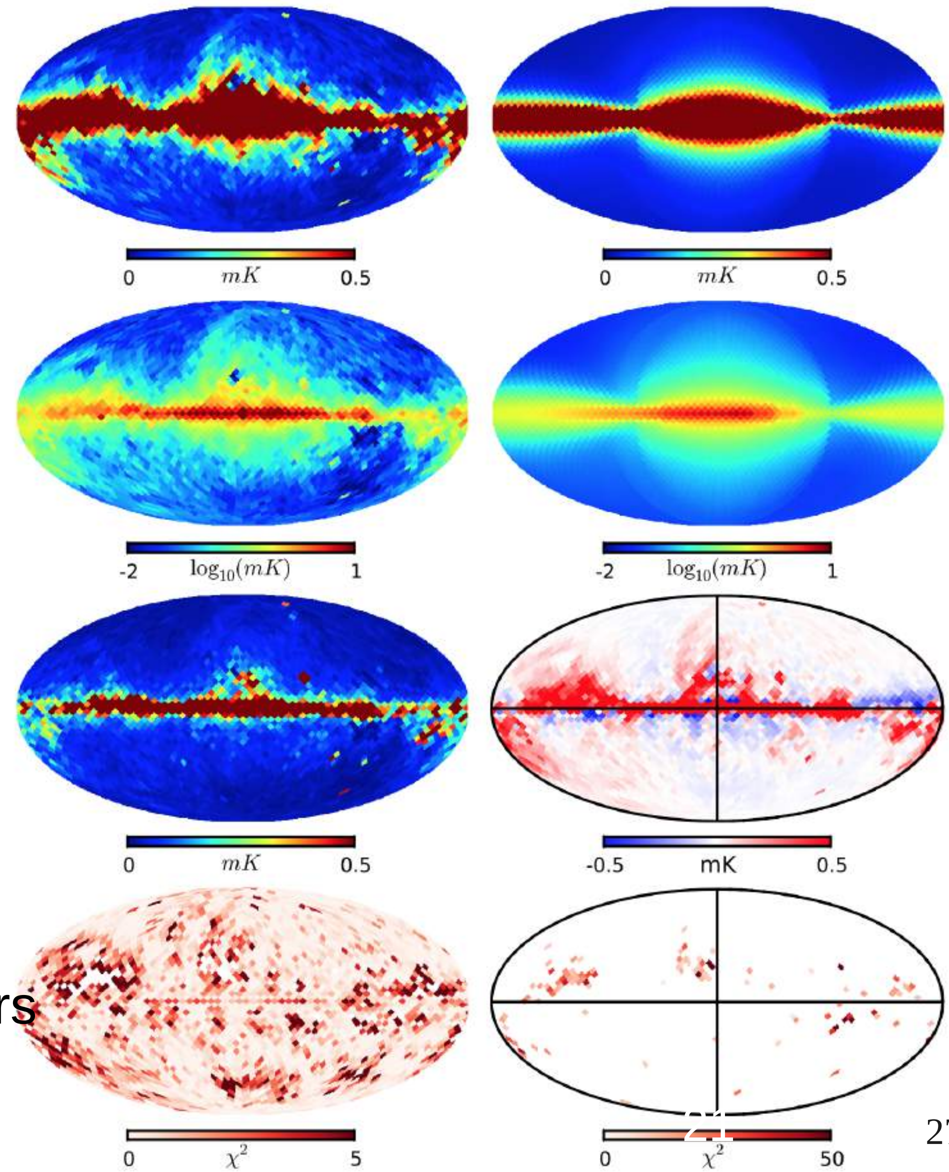
Log_{10} Intensity

Left: Variance σ for I

Right: data – model

L: chi-sq of fit in each pixel

R : chi-sq of dropped outliers



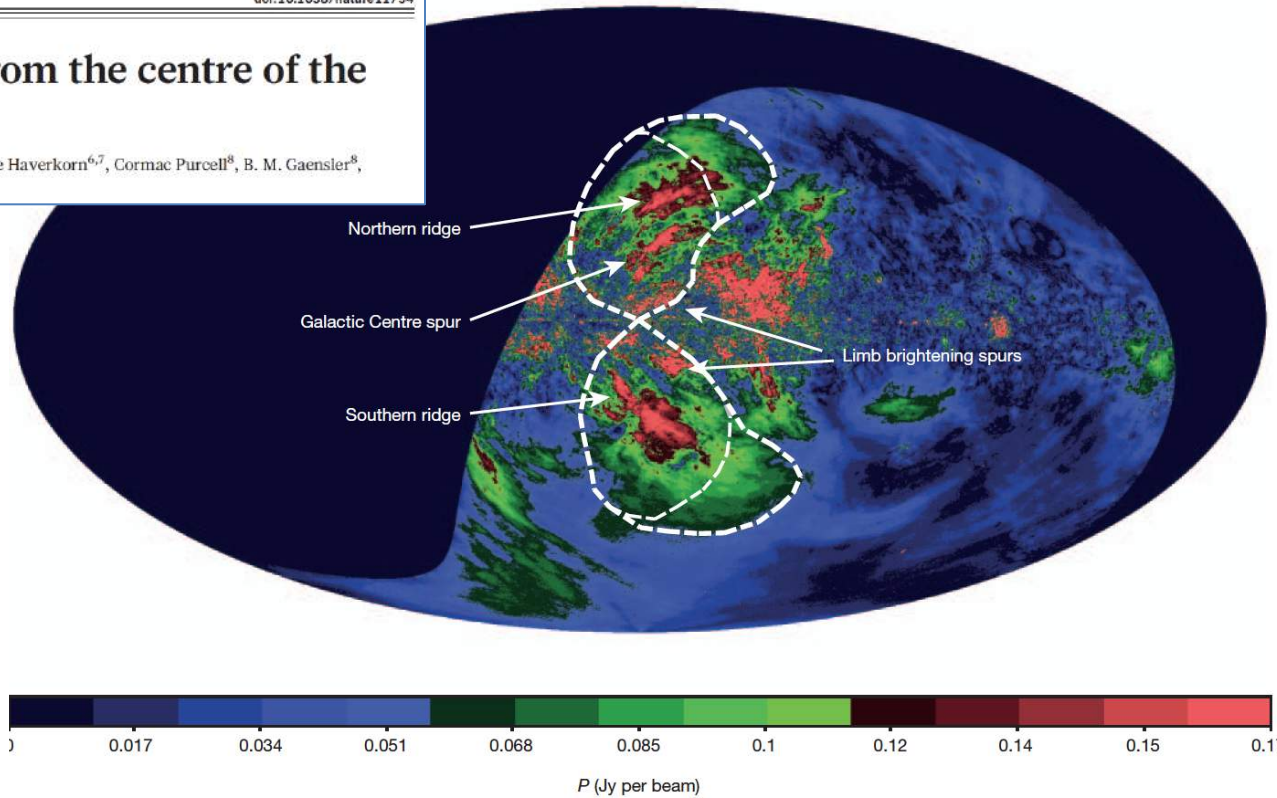
Fermi Bubble or Coherent halo-field?

LETTER

doi:10.1038/nature11734

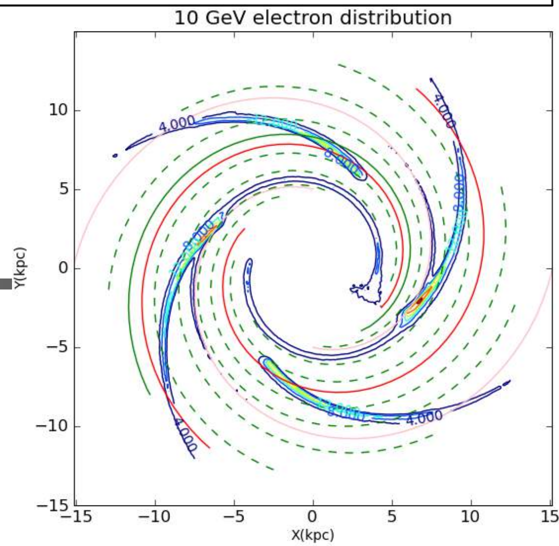
Giant magnetized outflows from the centre of the Milky Way

Ettore Carretti[1], Roland M. Crocker[2,3], Lister Staveley-Smith[4,5], Marijke Haverkorn[6,7], Cormac Purcell[8], B. M. Gaensler[8], Gianni Bernardi[9], Michael J. Kesteven[10] & Sergio Poppi[11]



igure 1 | **Linearly polarized intensity *P* at 2.3 GHz from S-PASS.** The thick lashed lines delineate the radio lobes reported in this Letter, while the thin lashed lines delimit the γ-ray Fermi bubbles[2]. The map is in Galactic coordinates, centred at the Galactic Centre with Galactic east to the left and Galactic north up; the Galactic plane runs horizontally across the centre of the nap. The linearly polarized intensity flux density *P* (a function of the Stokes parameters *Q* and $U, P \equiv \sqrt{Q^2+U^2}$) is indicated by the colour scale, and given n units of Jy per beam with a beam size of 10.75′ ($1\,\mathrm{Jy} \equiv 10^{-26}\,\mathrm{W\,m^{-2}\,Hz^{-1}}$). The lobes' edges follow the γ-ray border up to Galactic latitude $b \approx |30|°$, from which the radio emission extends. The three polarized radio ridges discussed in he text are also indicated, along with the two limb brightening spurs. The ridges appear to be the front side of a continuous winding of collimated structures around the general biconical outflow of the lobes (see text). The Galactic Centre spur is nearly vertical at low latitude, possibly explained by a projection effect if it is mostly at the front of the northern lobe. At its higher latitudes, the Galactic Centre spur becomes roughly parallel with the northern ridge (above), which itself exhibits little curvature; this is consistent with the overall outflows becoming cylindrical above 4–5 kpc as previously suggested[11]. In such a geometry, synchrotron emission from the rear side of each cone is attenuated by a factor $\gtrsim 2$ with respect to the front side, rendering it difficult to detect the former against the foreground of the latter and of the Galactic plane (see Supplementary Information).

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



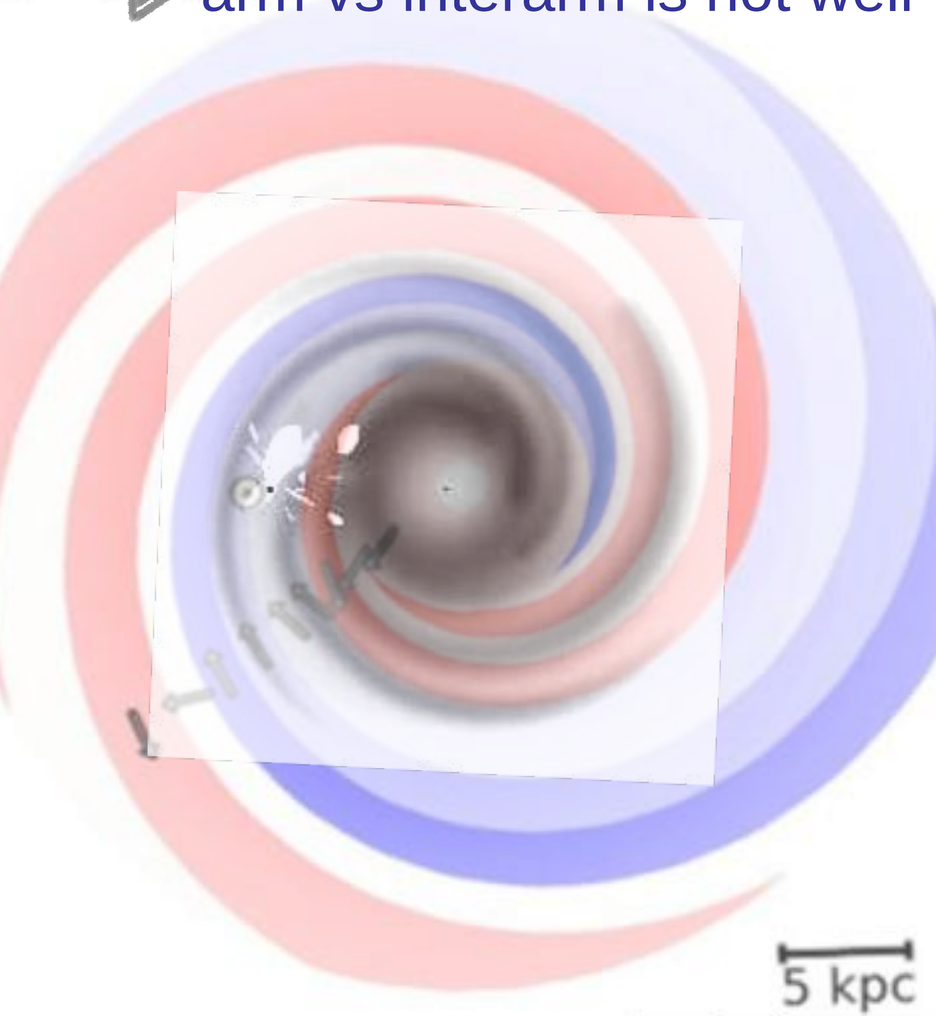
Improving on JF12

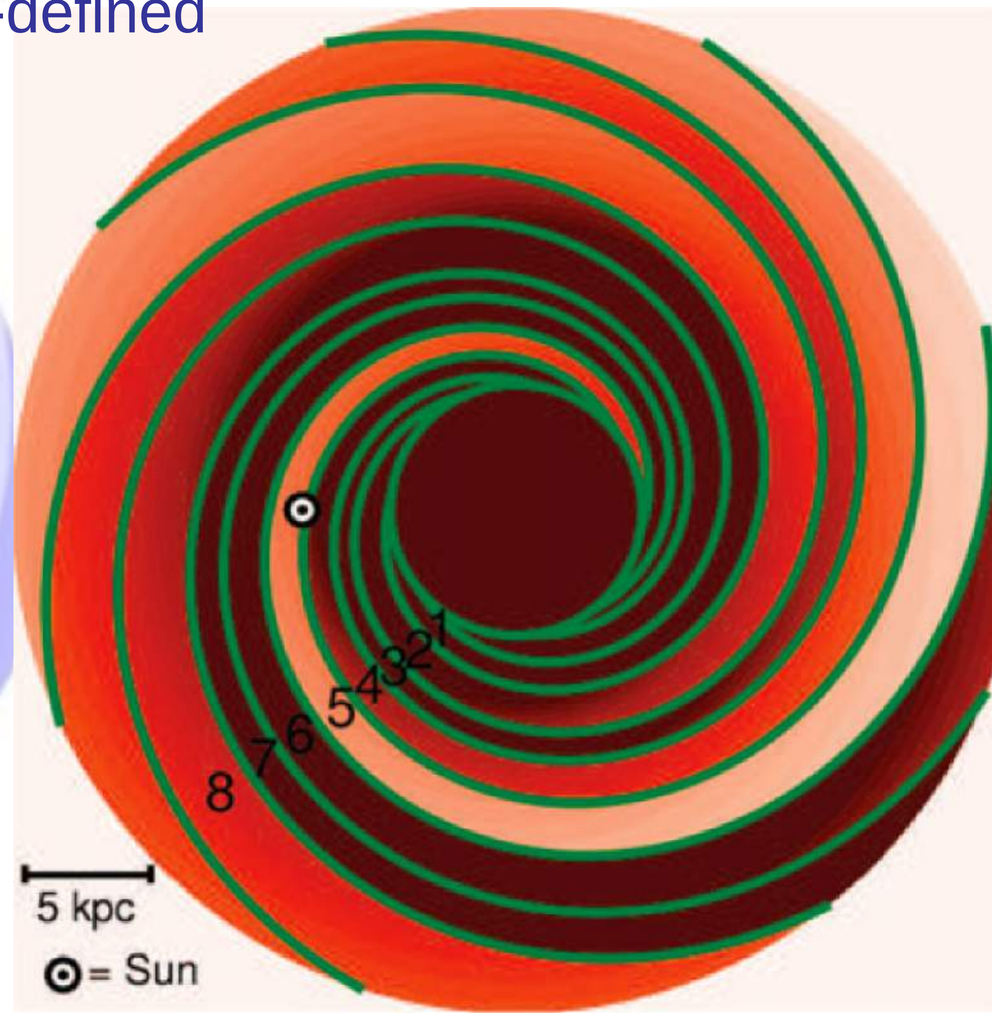
with Deepak Khurana, Sean Quinn, Michael Unger

- **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***

Field strength & spiral arms

- JF12 used spiral arm geometry of Brown+07
- not the same as in NE2001
- ▶ arm vs interarm is not well-defined





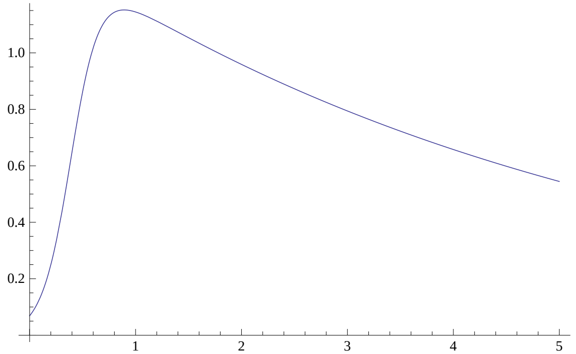
Overlay of NE2001 and JF12

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
  - 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



profile in z of toroidal field at solar circle