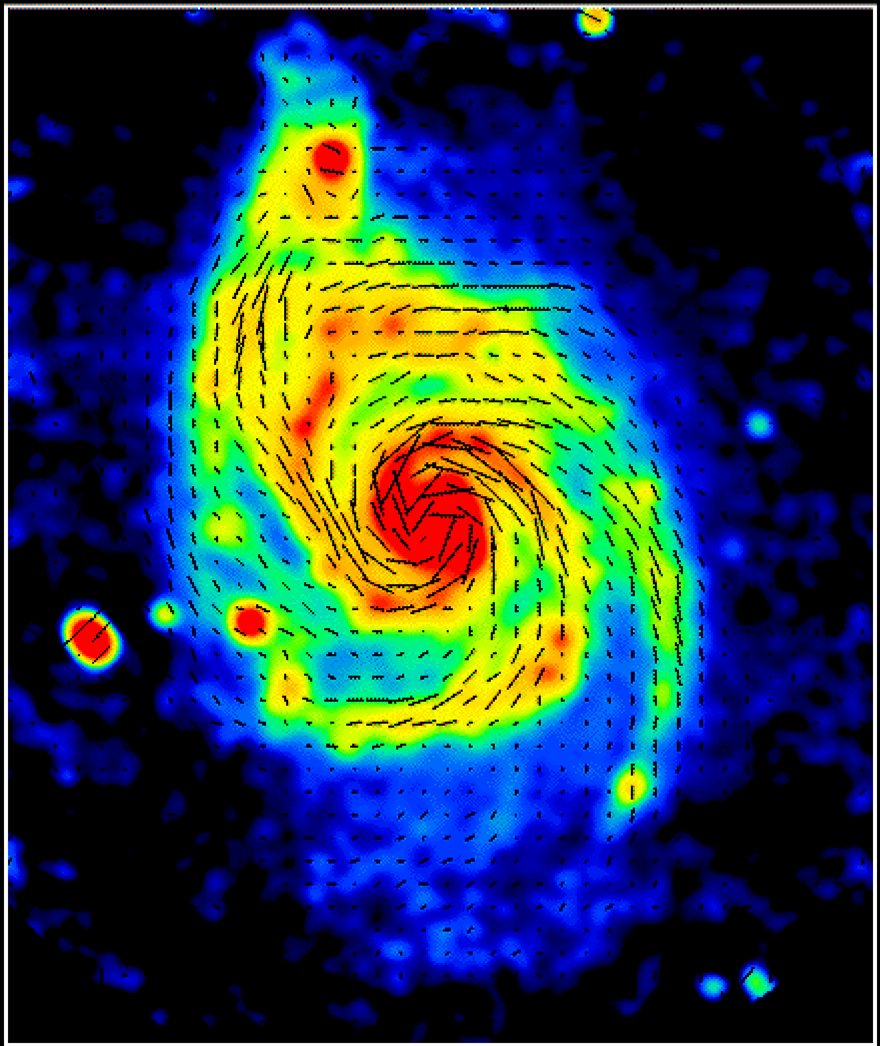
Studying the (large scale) Galactic Magnetic Field in the plane (so far)

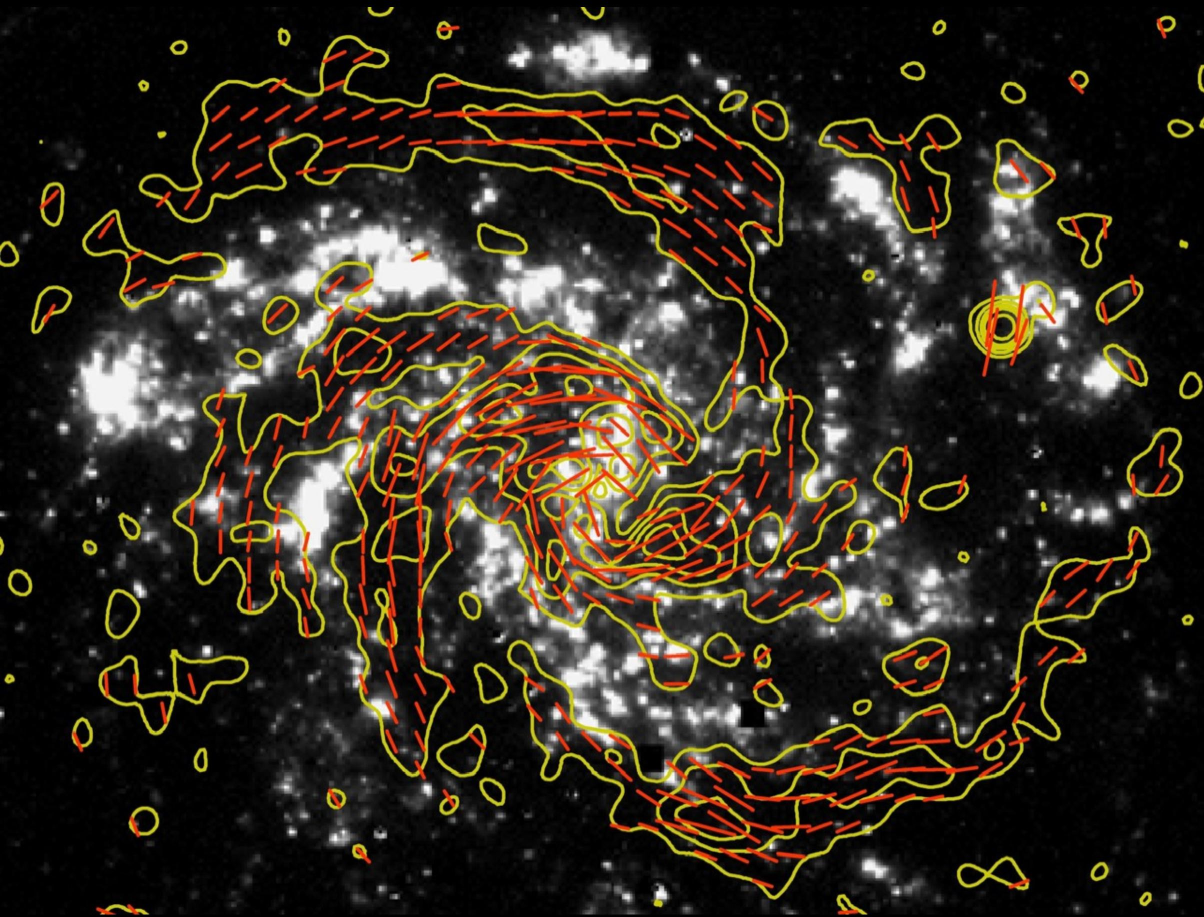
Tess Jaffe,

with Tony Banday, Andy Strong, Paddy Leahy,
Juan Macias-Perez, Lauranne Fauvet,
Sam Leach, and many others.



M51, Total I plus B-vectors, Neininger et al. (1992), image courtesy MPIfR

Other Galaxies:



NGC6946 6cm PI over Hα (Copyright R. Beck, MPIfR)

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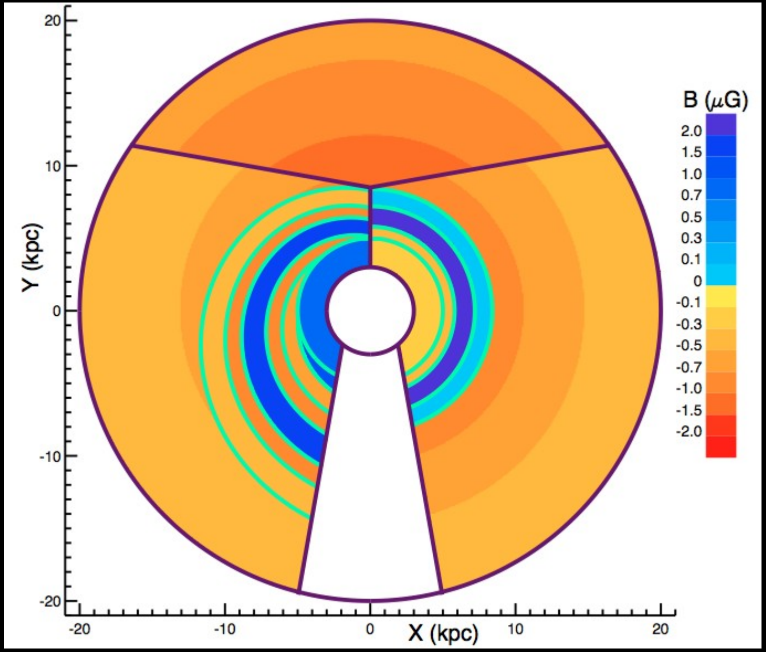
First order: magnetic fields aligned with matter spiral structure. Unlikely to be coincidental.

BUT many galaxies show more complexity: anti-correlated, uncorrelated, partly correlated, etc.

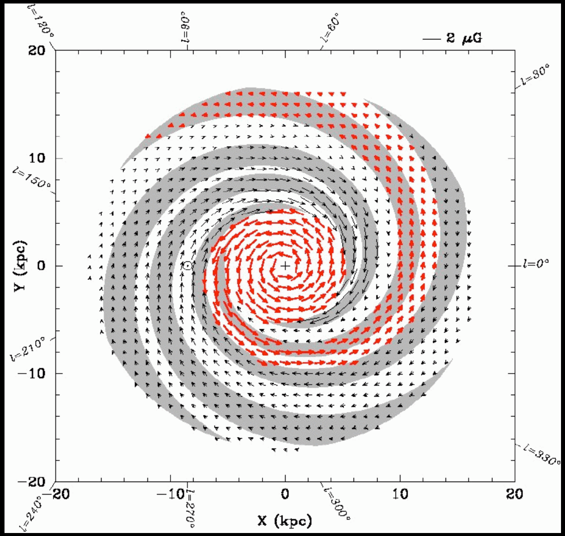
Unfortunately, we cannot see our own galaxy like this.

Furthermore, in an external galaxy, we cannot see the *direction*, but only its orientation.

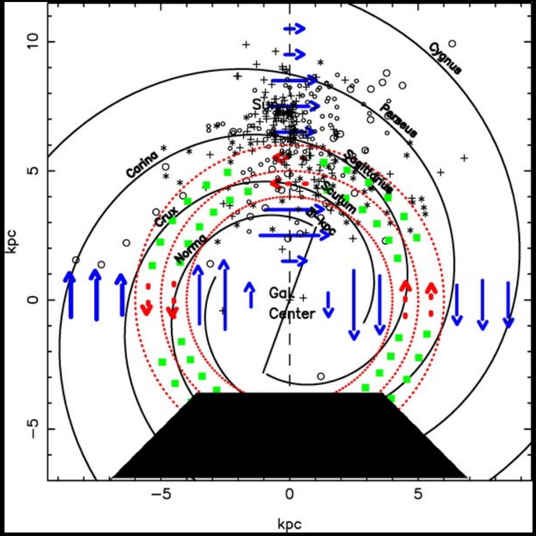
Large-scale models for Milky Way



van Eck et al. (2010)



(Sun et al 2008, courtesy X Sun)

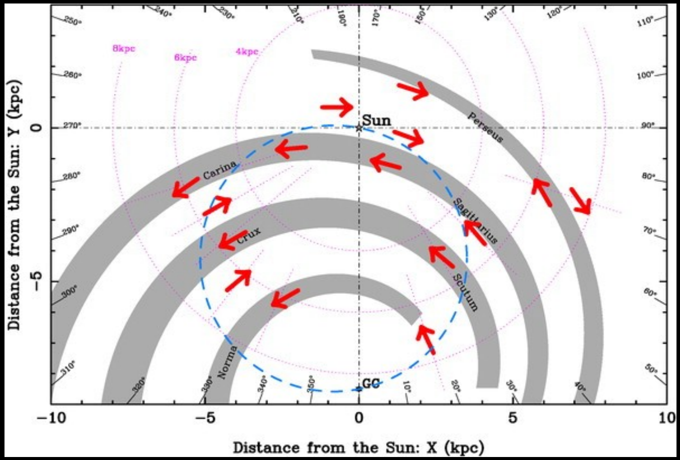


(Vallée et al. 2005)

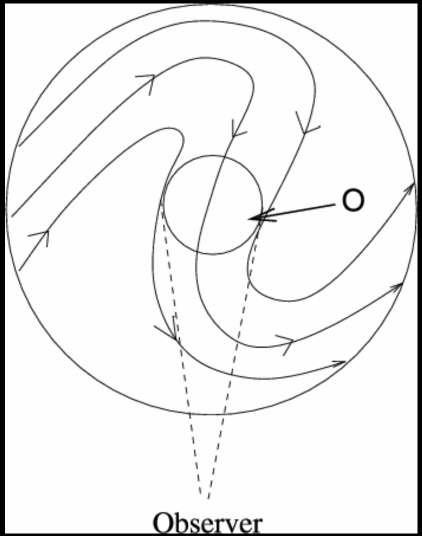
The only certainty is that there are puzzling reversals.

Many models that may fit some of the data (these all largely based on RM). None fit *all* of the data.

Previous estimates of B_{RMS}/B_{reg} flawed, IMHO.



(Han et al. 2006)

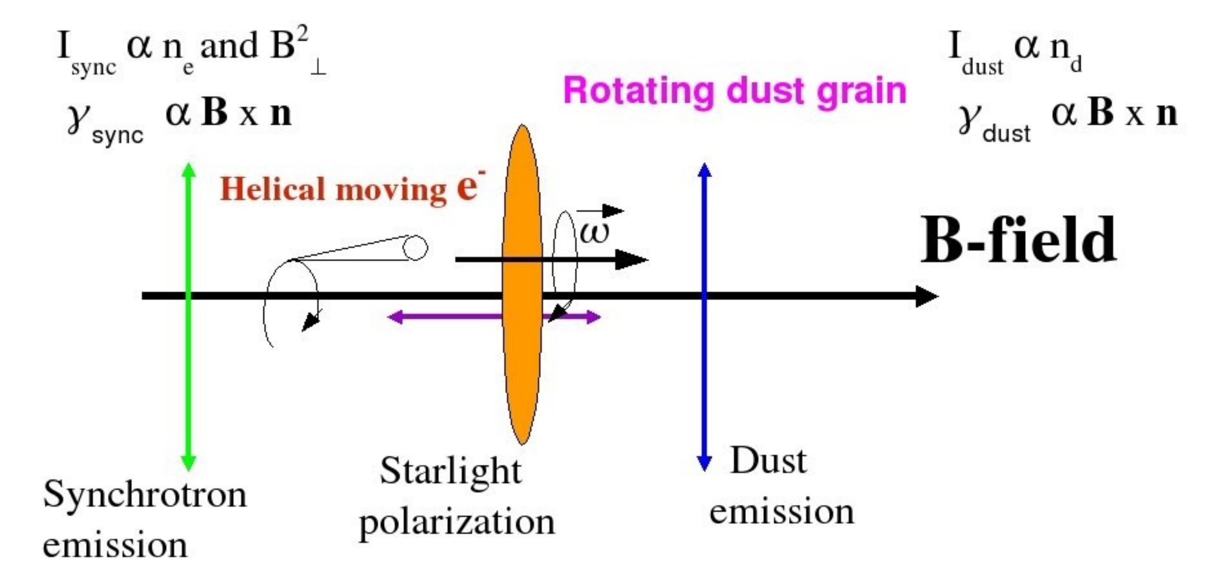


(Roy et al. 2008)

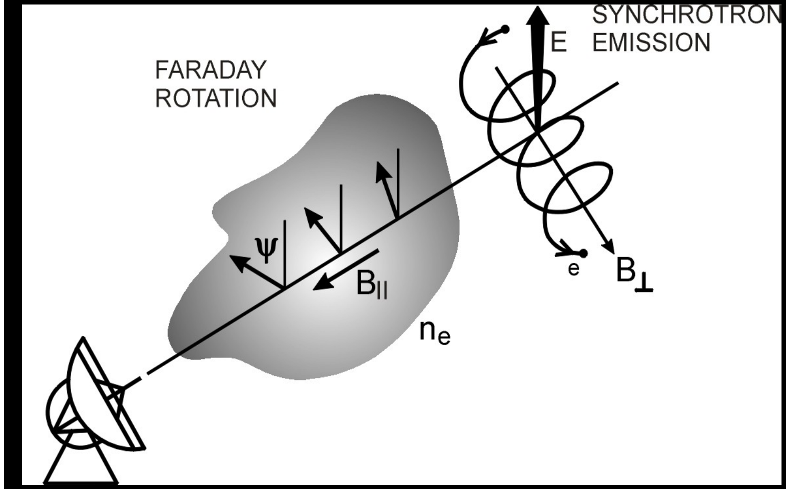
Observables

- **Synchrotron emission** $I(\nu) \propto \int_{LOS} n_{CRE} B_{perp}^2 \, dl$ (simplified!)
- **Rotation measure** $RM \propto \int_{LOS} n_e B_{\|} \, dl$ $\theta = RM \lambda^2$
- **Thermal dust emission (see e.g. Hoang talk)**
- Starlight polarization, Zeeman splitting, masers, etc.

Note: electron distributions not well known, dust polarized emissivity not well understood, data contaminated with other stuff (bremsstrahlung, CMB, intrinsic RM, etc.)



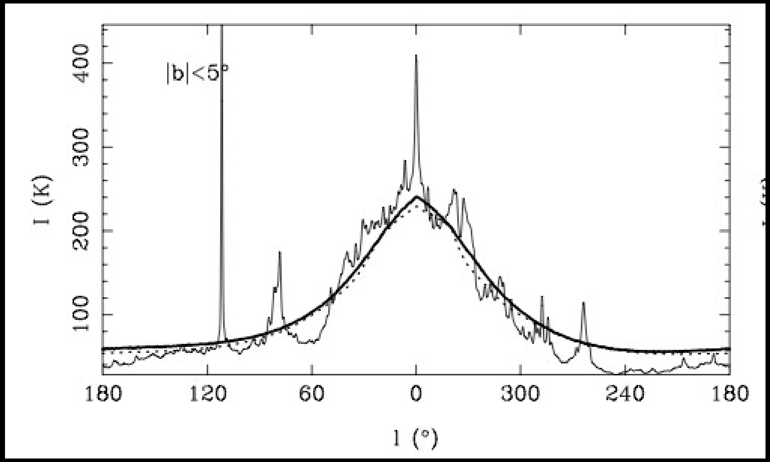
(Courtesy J.F. Macías-Pérez)



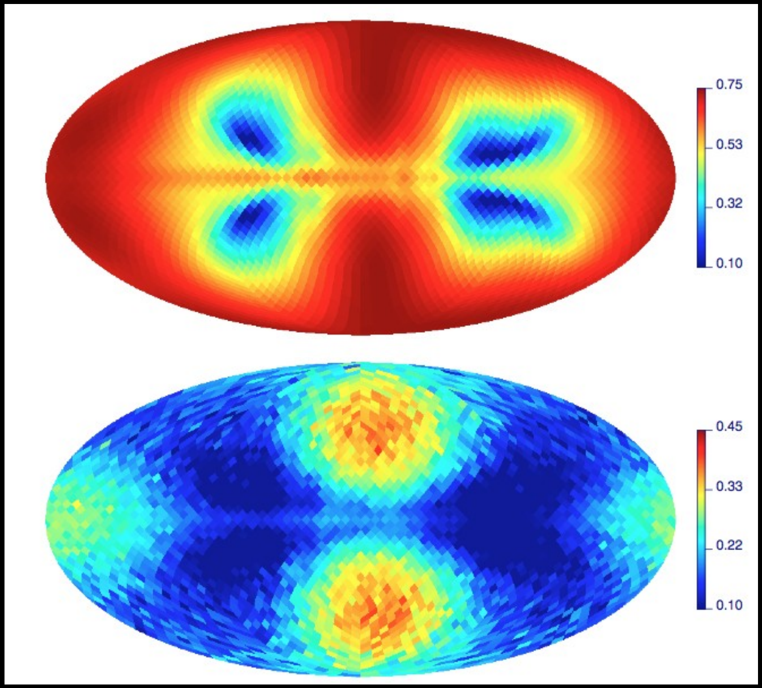
(Courtesy R. Wielebinski)

Note that plots of polarization vectors are often rotated 90deg to show B-field direction

Previous work



Sun et al. (2008) total I @ 23 GHz
B_{reg} = 2 μG B_{ran} = 3 μG



Miville-Deschênes et al. (2008) model PI/I
B_{reg} = 3 μG B_{ran} = 1.7 μG

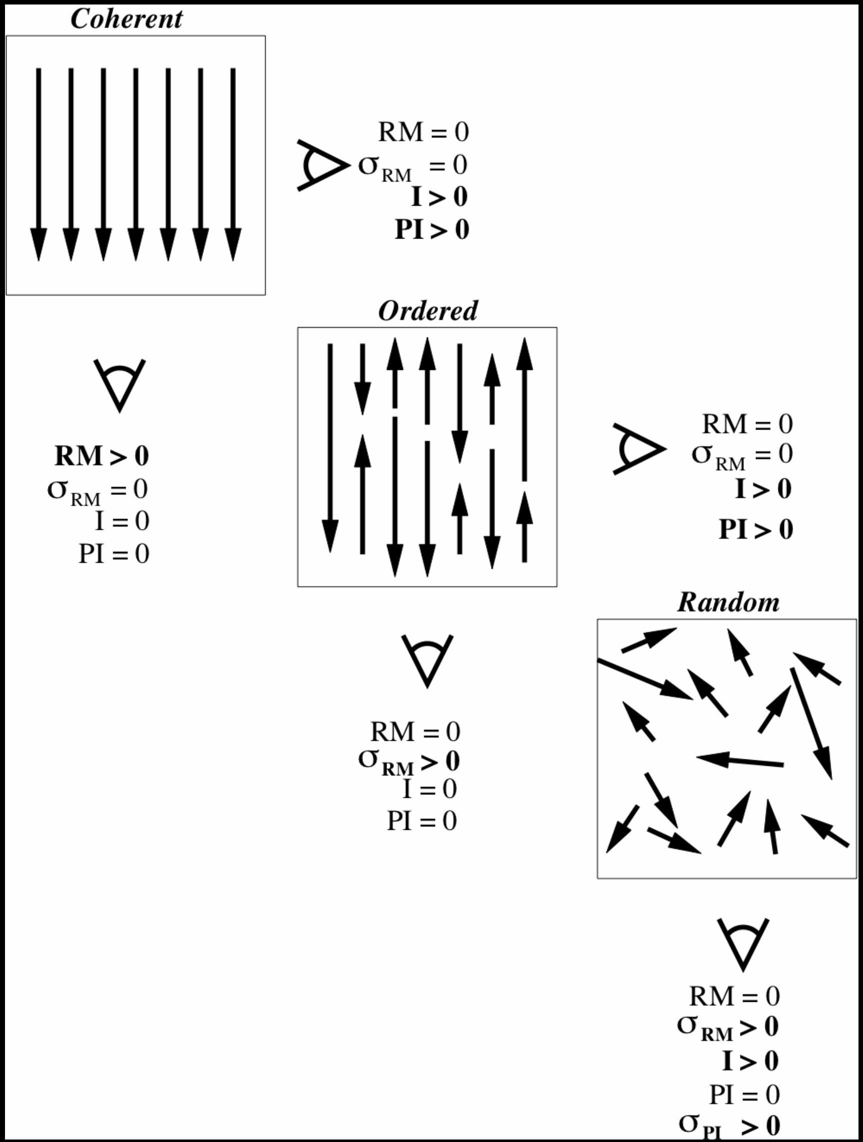
- Sun et al.: RMs and synchrotron at 0.408, 1.4, and 23 GHz. Also studying thermal electron filling factor, coupling of thermal electrons and turbulent field.
- Miville-Deschênes (2008): templates at 408 MHz and 23 GHz plus spectral index model, fitting BSS B-field parameters.
- Jansson et al. (2009): 23 GHz plus RMs, MCMC analysis.

Common feature: isotropic turbulence. Uncertainties in inputs often enough to allow contradictory models. But not for much longer!

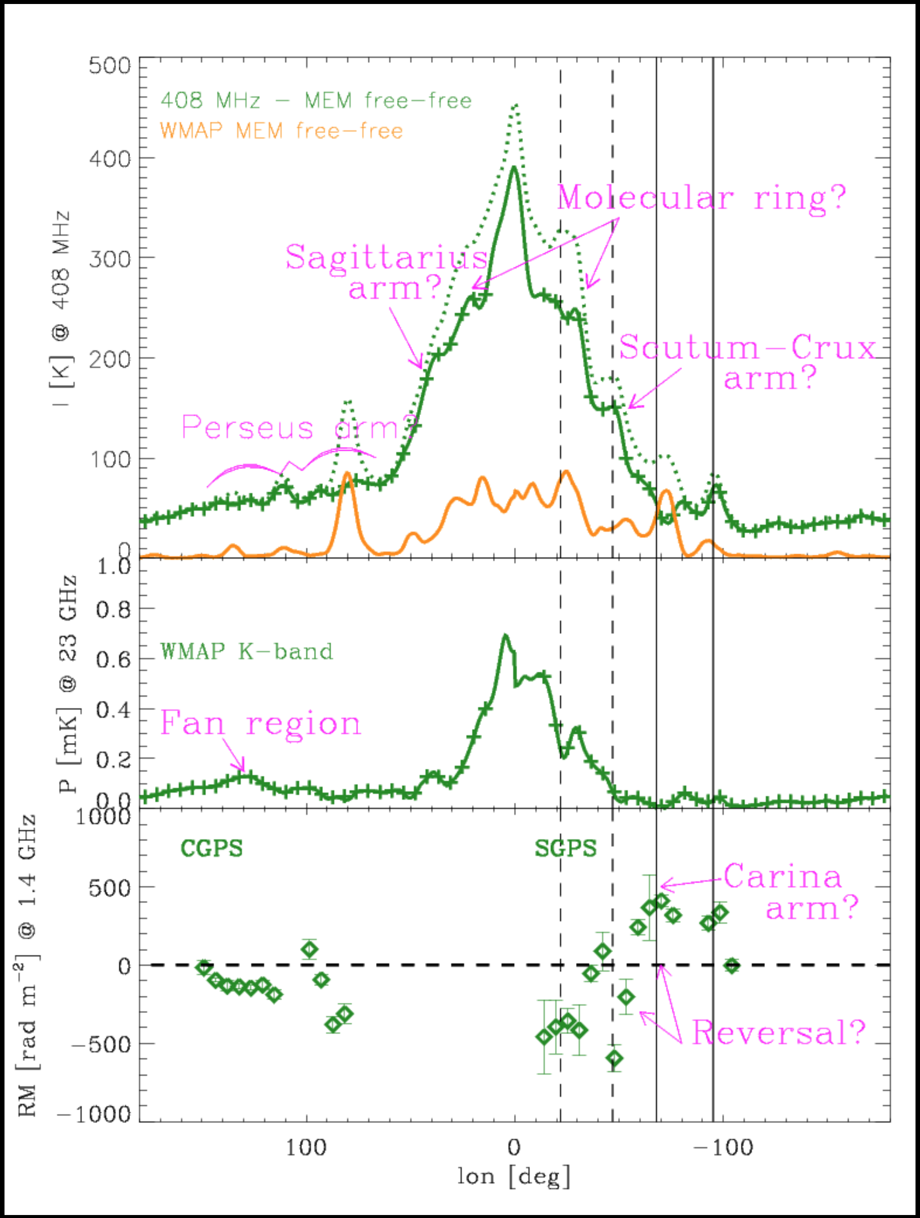
Geometry

- **Coherent** contributes to RM for $B_{||}$ and to I and PI for B_{perp}.
- **Ordered** contributes to I and PI perpendicular, but to RM variance only.
- **Random** contributes only to I and to PI and RM variance.
- (At high frequencies, outside of Faraday regime.)
- ***Be careful*** when reading about and discussing “regular”, “random”, “turbulent”, etc.

Our first aim: separate these three components.



On the plane

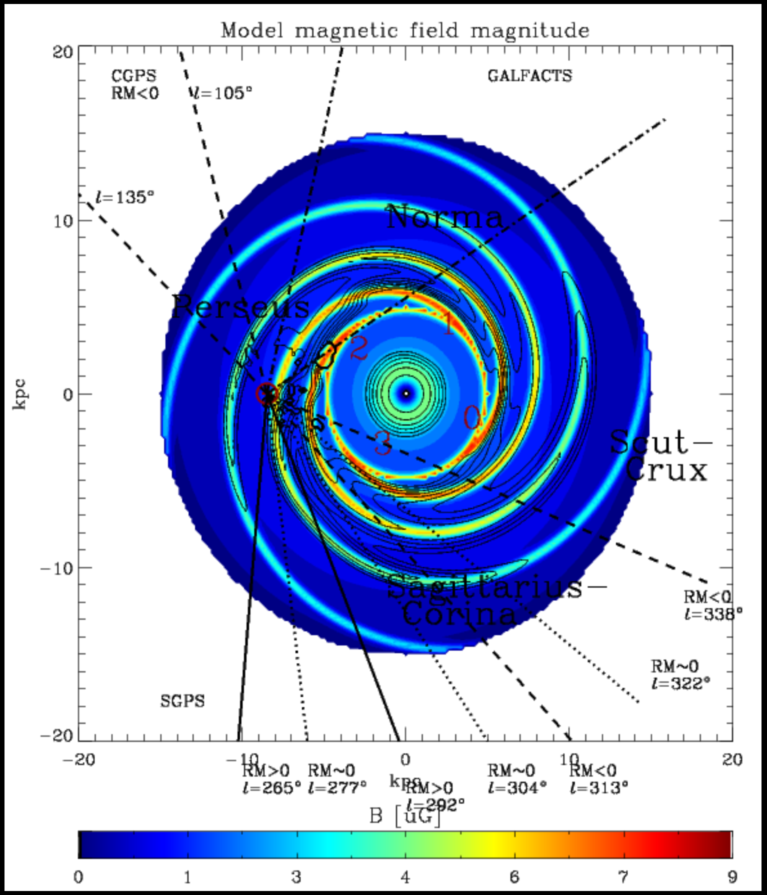


- Ideally, want total I and PI at same frequency. But you can't .
- Synchrotron total I low enough to avoid free-free contamination but high enough to avoid absorption.
- Synchrotron PI high enough to avoid Faraday depolarization effects.
- Need extragalactic RMs to trace full LOS through Galaxy
- Step features in I: arms?
- Peaks and troughs in RM: arms?
- Reversal(s)?

Modeling

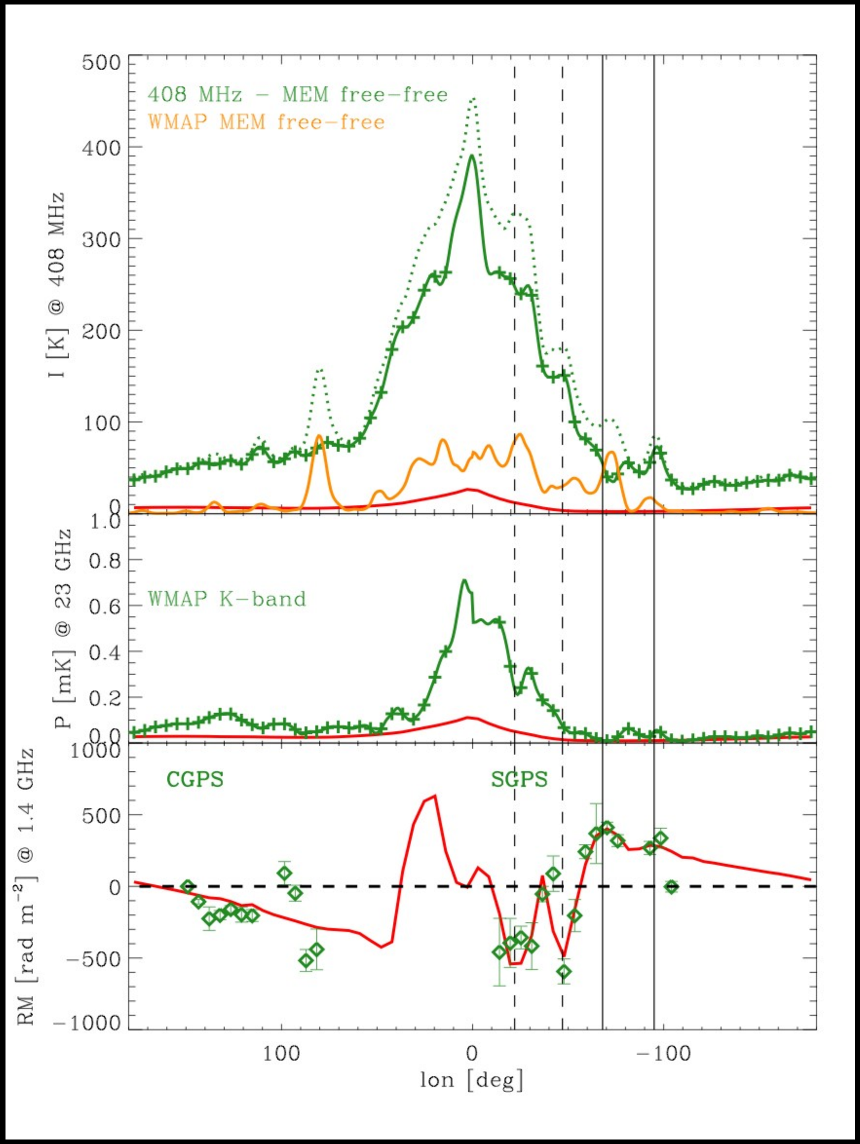
Motivated by external galaxies:

- 3D magnetic field model:
  - spiral arm model for 'coherent' field;
  - small-scale turbulence based on GRF with power law spectrum;
  - compression model to produce amplification as well as stretched anisotropic (ordered) component along arm ridges based loosely on Broadbent (1989).
- 3D CRE density and spectral model: exponential disk with power law spectrum, p=-3, normalized based on gamma-ray data.
- 3D thermal electron density model: both constant as well as NE2001 (Cordes and Lazio 2002).
- ***Hammurabi*** code (Waelkens, Jaffe, et al. 2009) to integrate observables along LOS.
- MCMC (cosmoMC) engine to explore parameters.



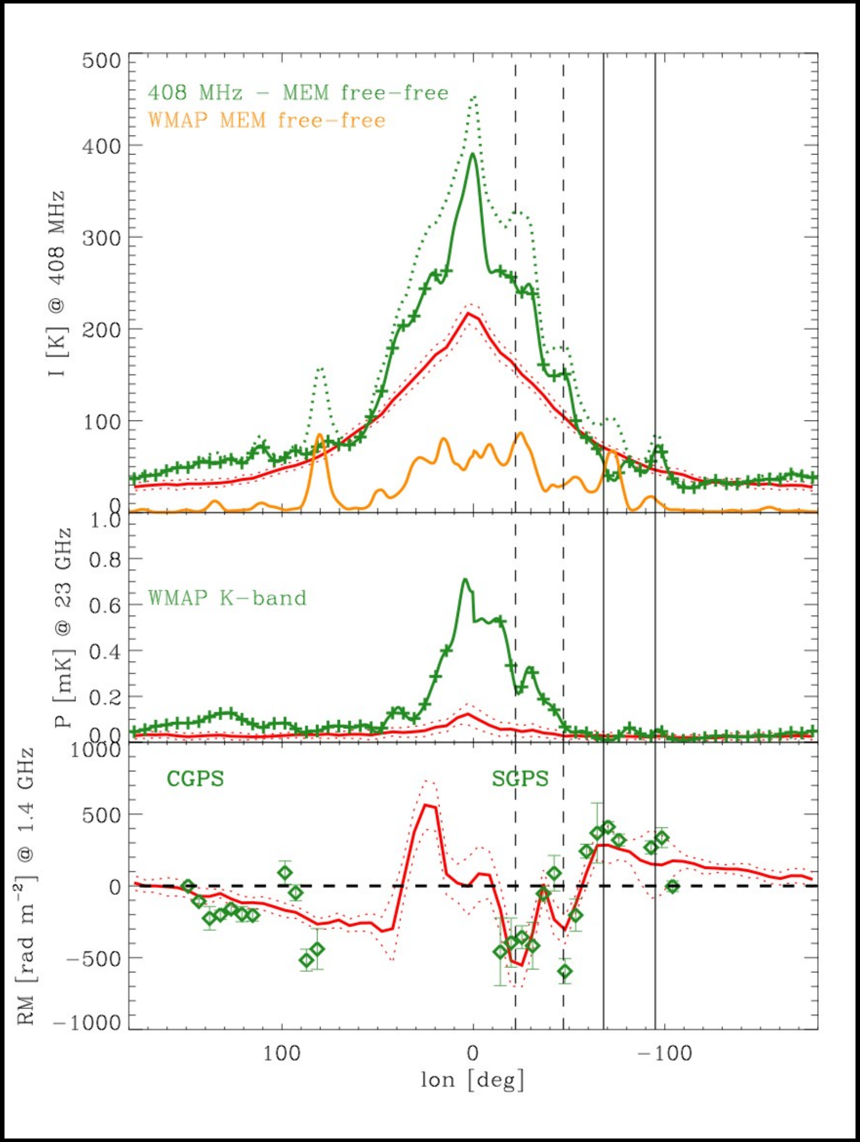
An example of the coherent field model.

Examples: coherent



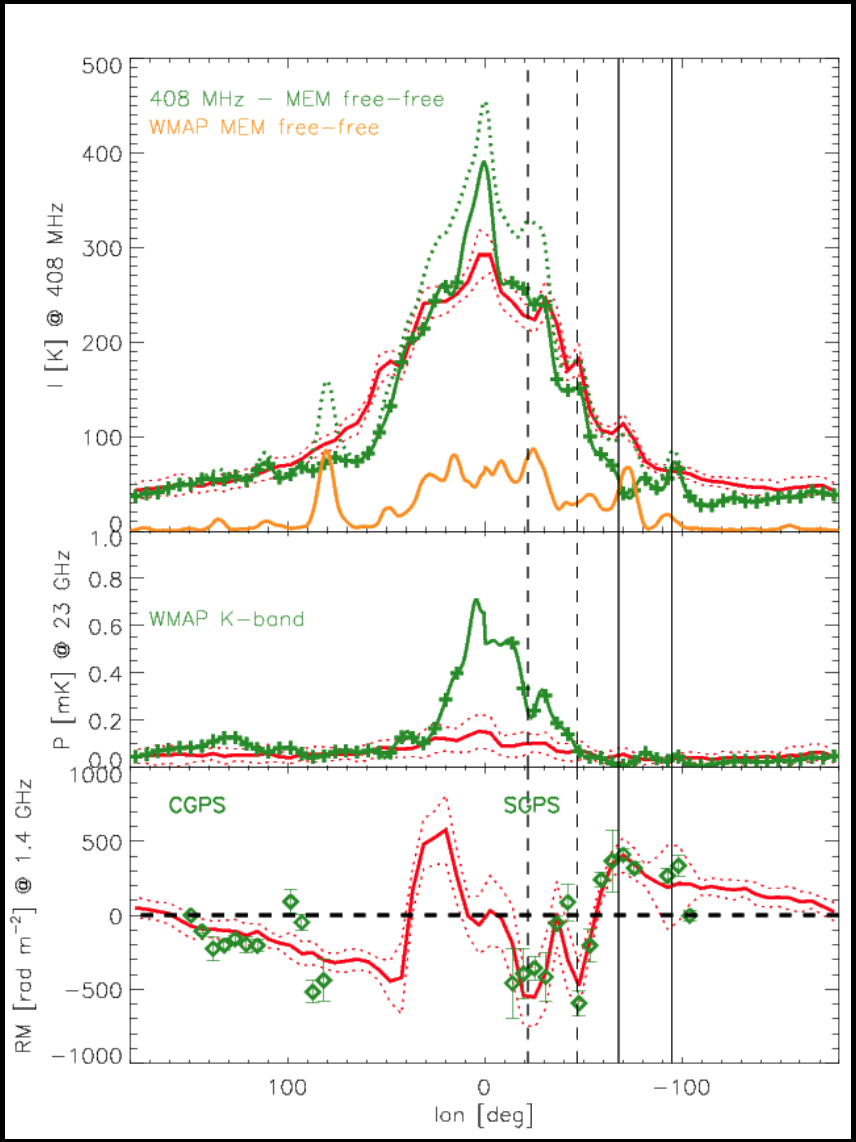
- With a reasonable estimate for n_e, RMs give B_{coh}.
- With a reasonable estimate for n_{cre}, this shows you need a lot more to get *I* profile.

Examples: isotropic & homogeneous



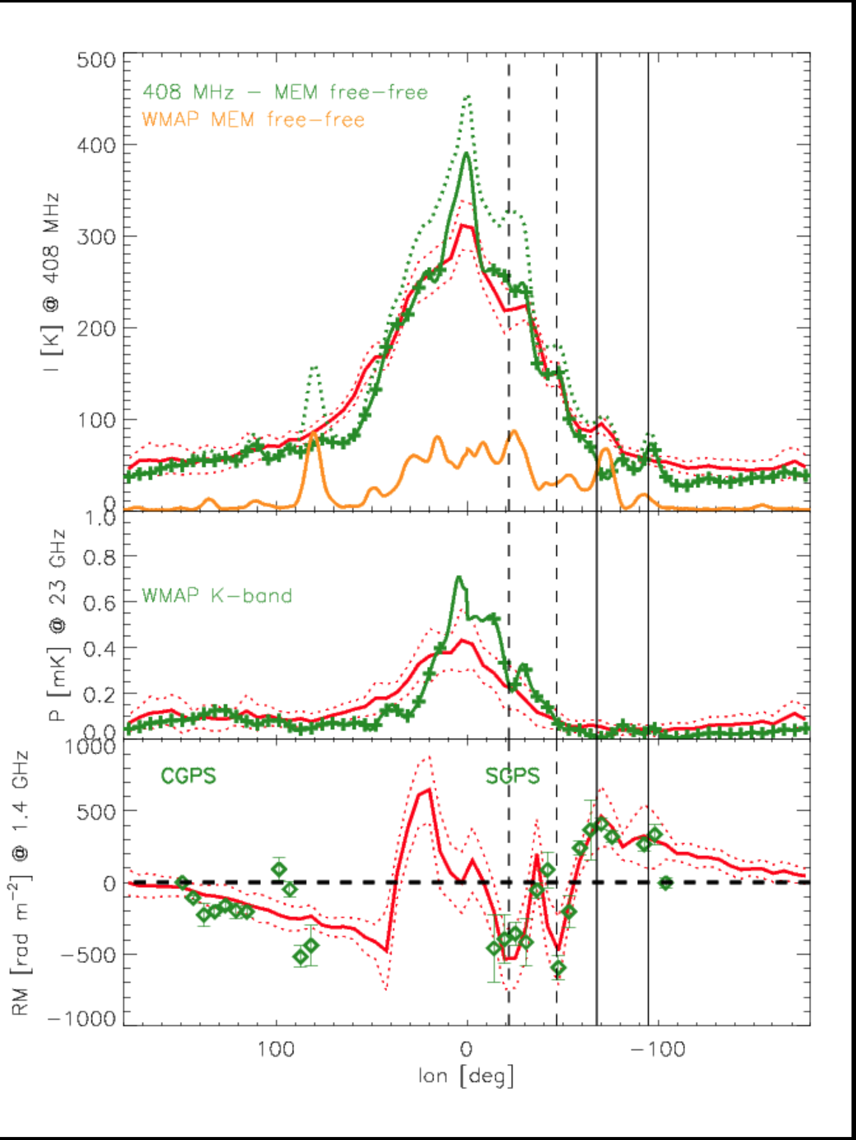
- Added simple GRF.
- No step features => B_{ran} should be amplified in arms.
- Polarization still lacking, since isotropic random component cancels out, adding only variance.

Examples: isotropic



- Amplification of random field in arms, but still isotropic.
- Step features appear, though too peaked.
- PI remains underpredicted, since as before, isotropic random contributions cancel out.

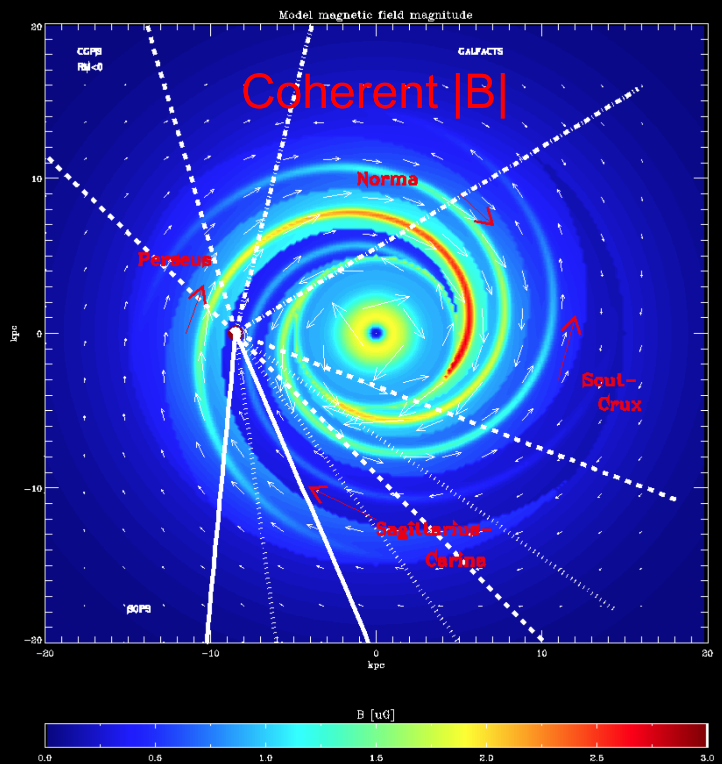
Examples: compressed/sheared

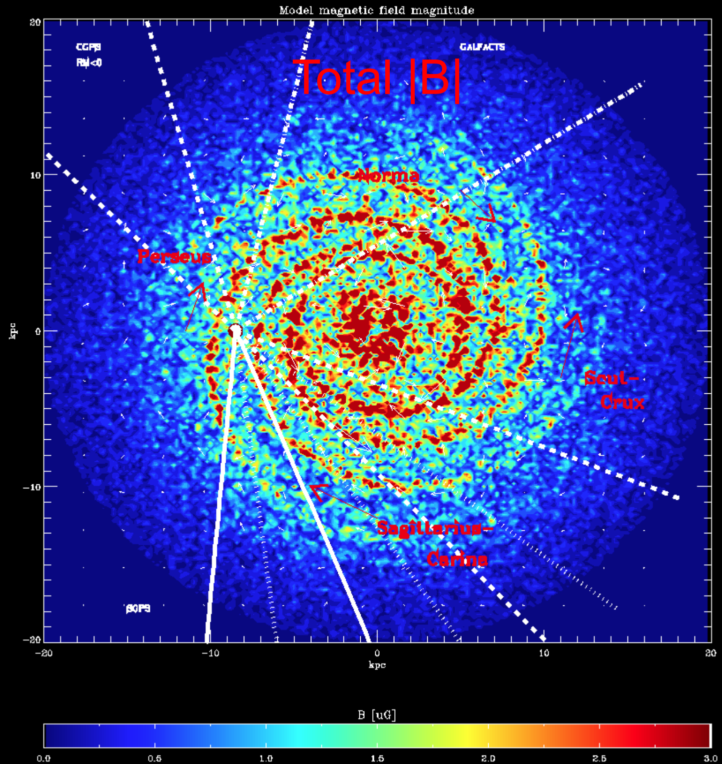


Random field stretched along arm giving ordered component in addition to the isotropic random component. Now roughly matches all three observables.

PI not very well modeled in inner galaxy. More to do!

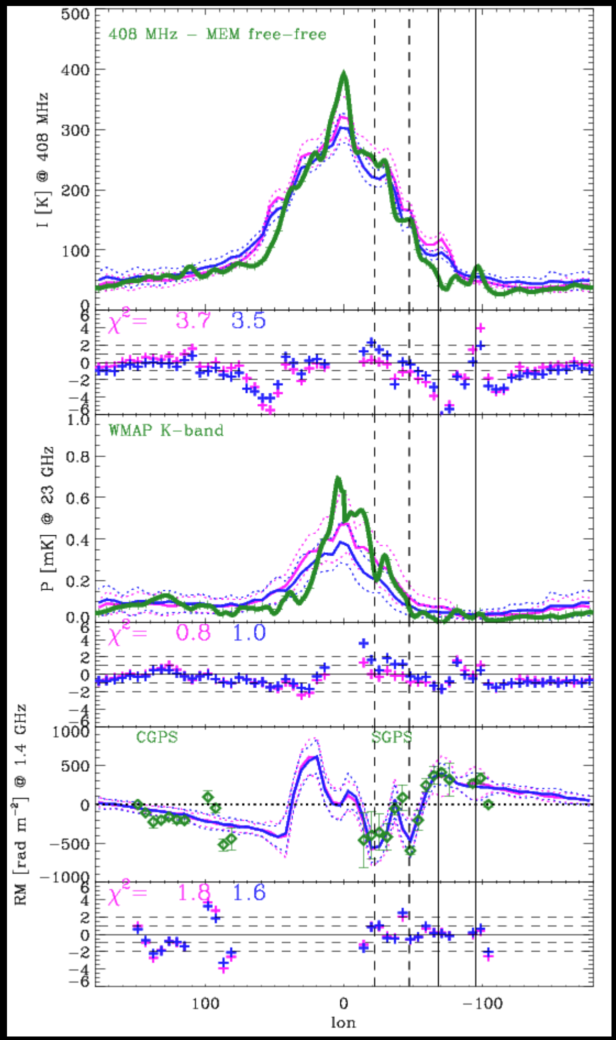
(Note that this is essentially a cartoon to illustrate the effects, not a fit to the data.)





First results

- 8 parameters fit: φ_0, a_0-a_4 (arms+ring), B_{RMS}, f_{ord}
- Orientation of spiral matches NE2001 thermal electron model.
- Reversal in Scutum-Crux arm and "molecular ring".
- Coherent, isotropic random, ordered field energy densities in ratios of 1:5:3. (Roughly 2, 4, and 3 μG along arm ridges.)
- Weak Sag-Carina arm? Mentioned in Benjamin et al. (2005) using GLIMPSE counts. Two dominant arms? But what about reversal(s)?



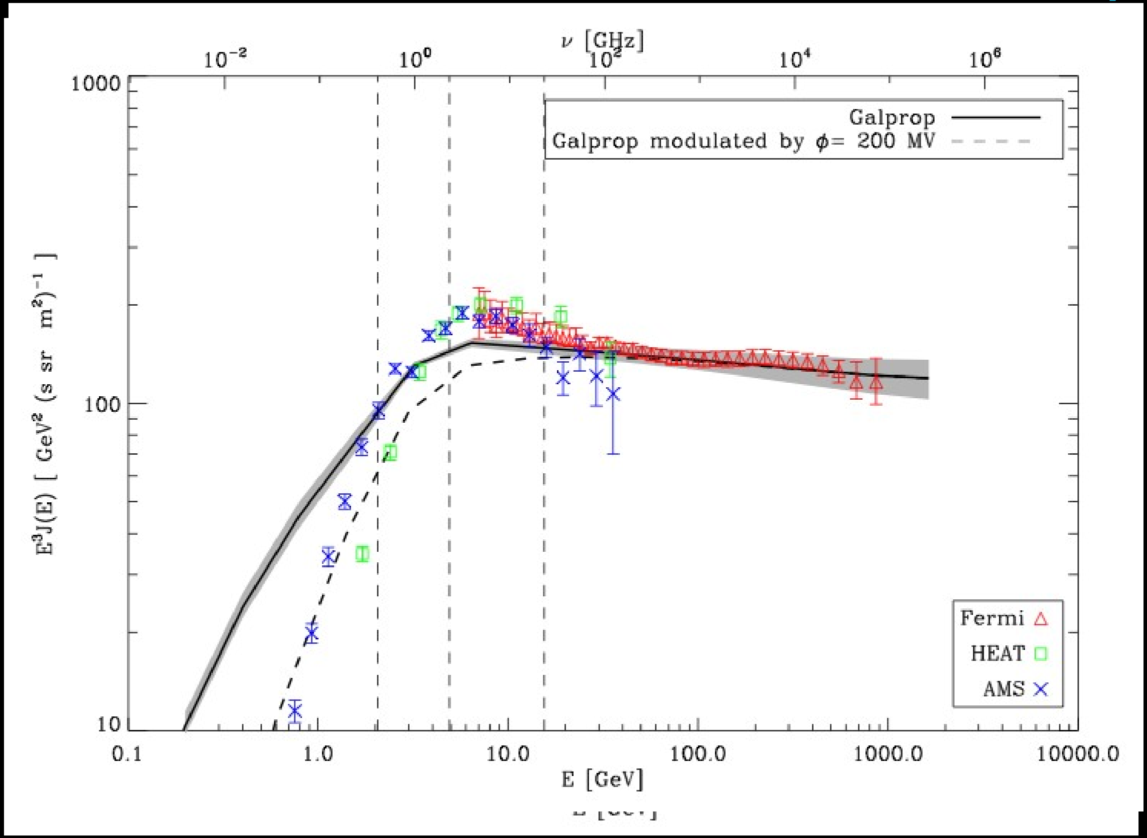
Jaffe et al. (2010)

Main limitation: assumes simple power law CRE spectrum from 408 MHz to 23 GHz. But CRE spectrum degenerate with $f_{ord.}$ To break the degeneracy, need additional dataset.

Interestingly, 2.3 GHz total I is not compatible with this model!

Cosmic ray electrons:

or, real life isn't a power law



Use full integration over CRE energy spectrum at each point in 3D galaxy model:

(See, e.g., Rybicki & Lightman)

$$I(\nu) \propto \int_{LOS} dl \int_0^\infty dx \, B_{perp} n_{CRE}(\gamma) F(x)$$

$$x \equiv \frac{\omega}{\omega_c} \qquad \omega_c \equiv \frac{3\gamma^2 B_{perp}}{2mc}$$

Then add a synchrotron data point to analysis, e.g. 2.3 GHz total I.

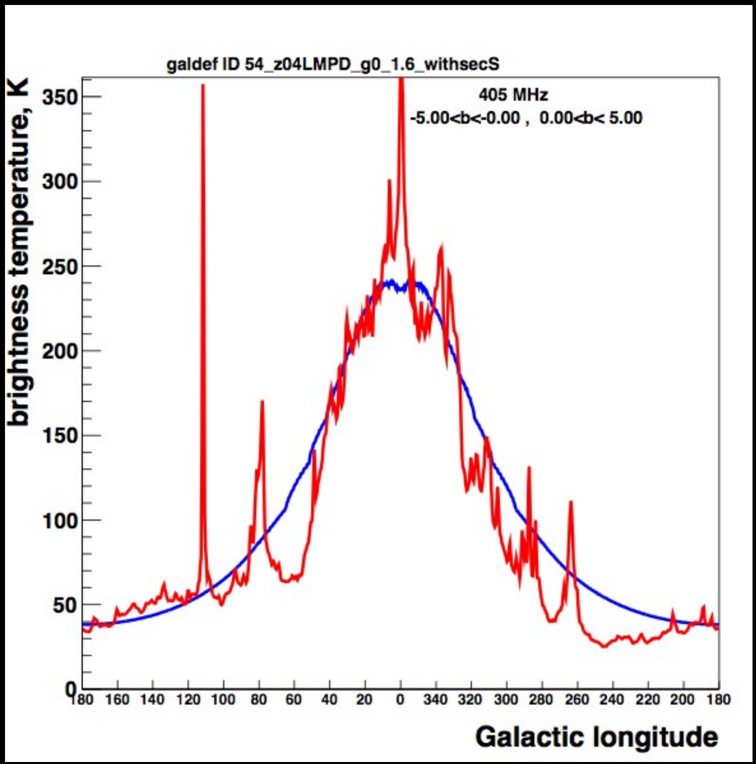
Note that at low energies, solar modulation affects local measurements.

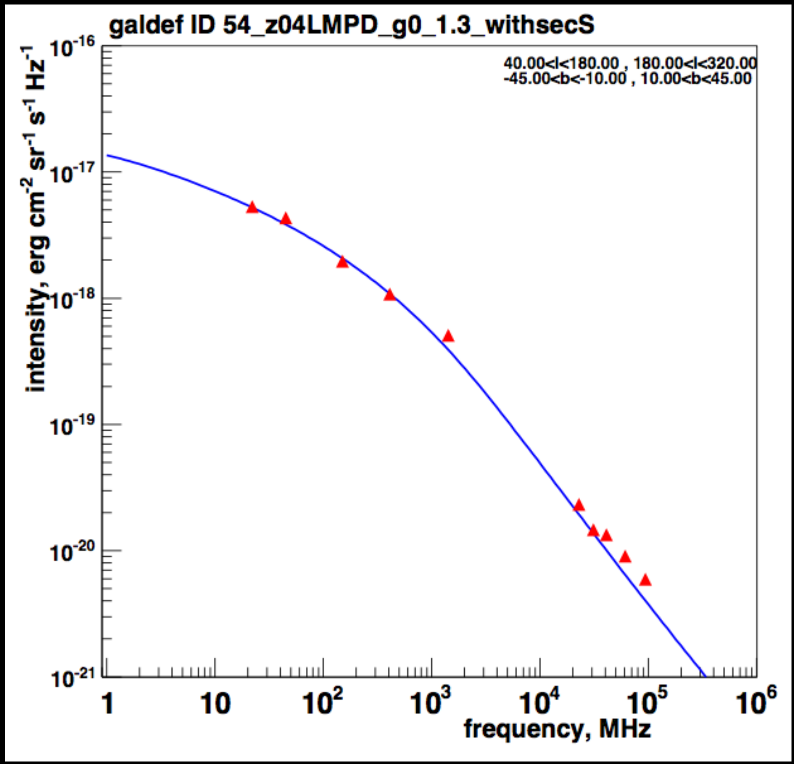
Jaffe et al. (2011): Spectra above few GeV constrained using γ-ray data, Strong et al. (2010). Below a few GeV, determined using synchrotron: J(E) ~ $E^{-1.3}$, slightly harder than usually assumed.

(GALPROP code: Strong & Moskalenko 2001;
Data: Fermi LAT Collaboration 2009-10, Duvernois et al. 2001, Aguilar et al. 2002)

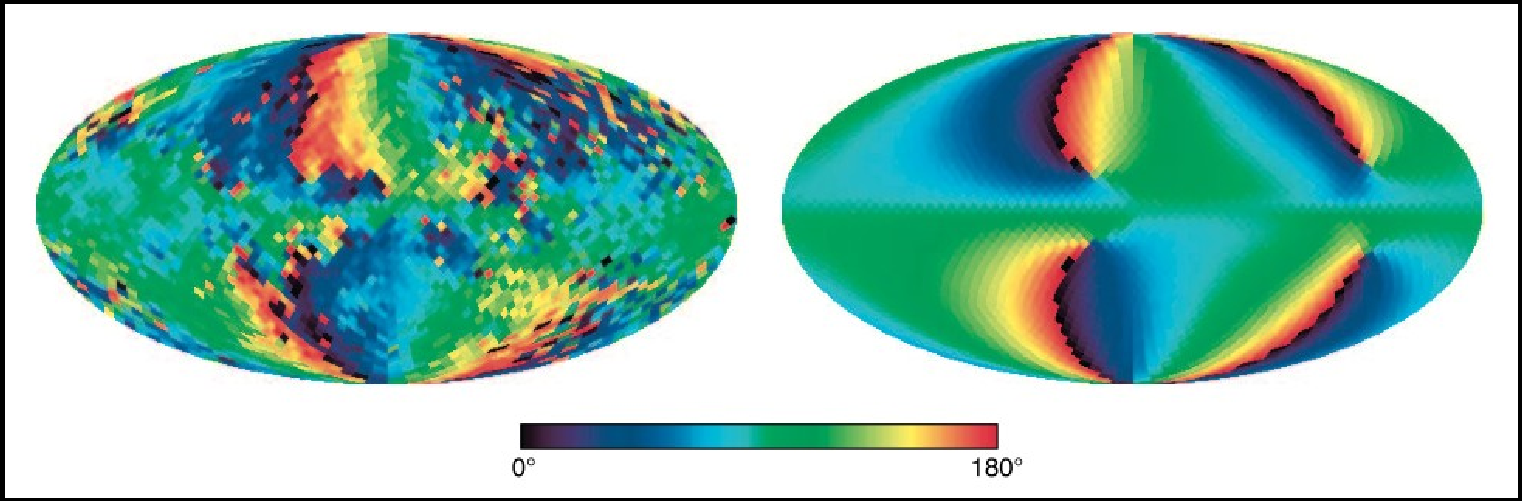
High-latitude with CRE spectrum

- Strong, Orlando, & Jaffe (2011) analysis of synchrotron from 45 MHz to 23 GHz constrains low-energy (< few GeV) CRE spectrum.
- Using Fermi CRE and gamma-ray data.
- GALPROP CRE propagation as well as synchrotron prediction.
- Hints of fairly large CRE halo (~4kpc).





More high-latitude data



WMAP K-band polarization angle compared to prediction for AS spiral model field. Planck will do even better and include polarized dust, and C-BASS will do 5GHz.

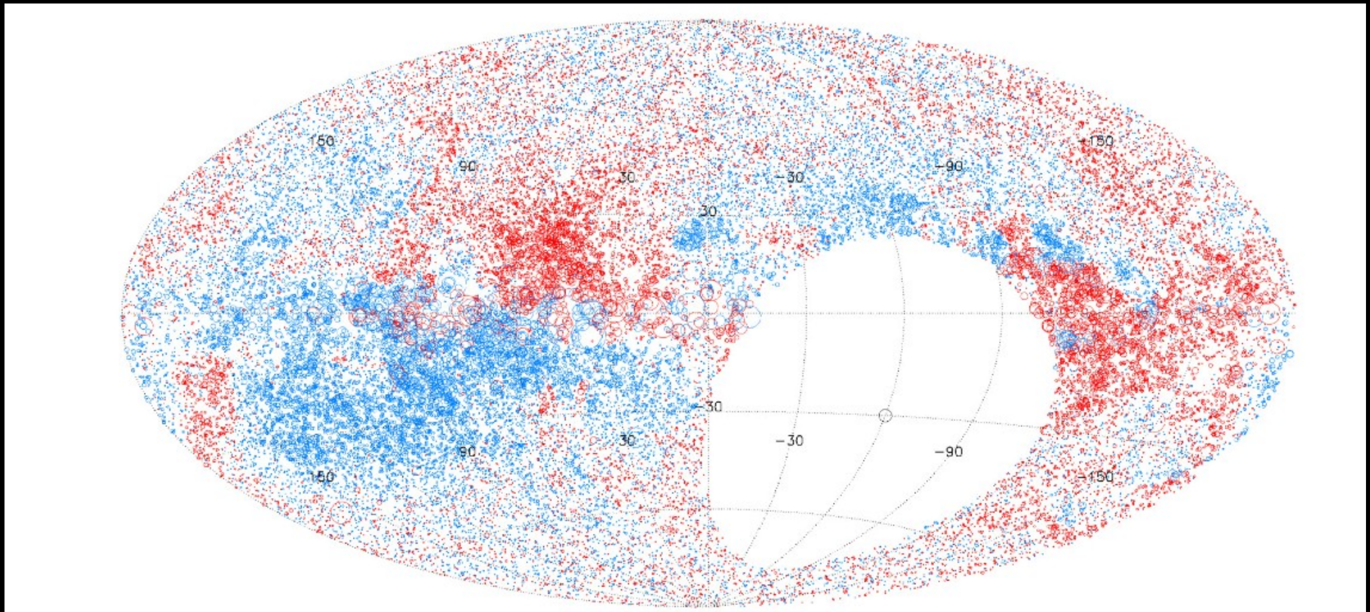


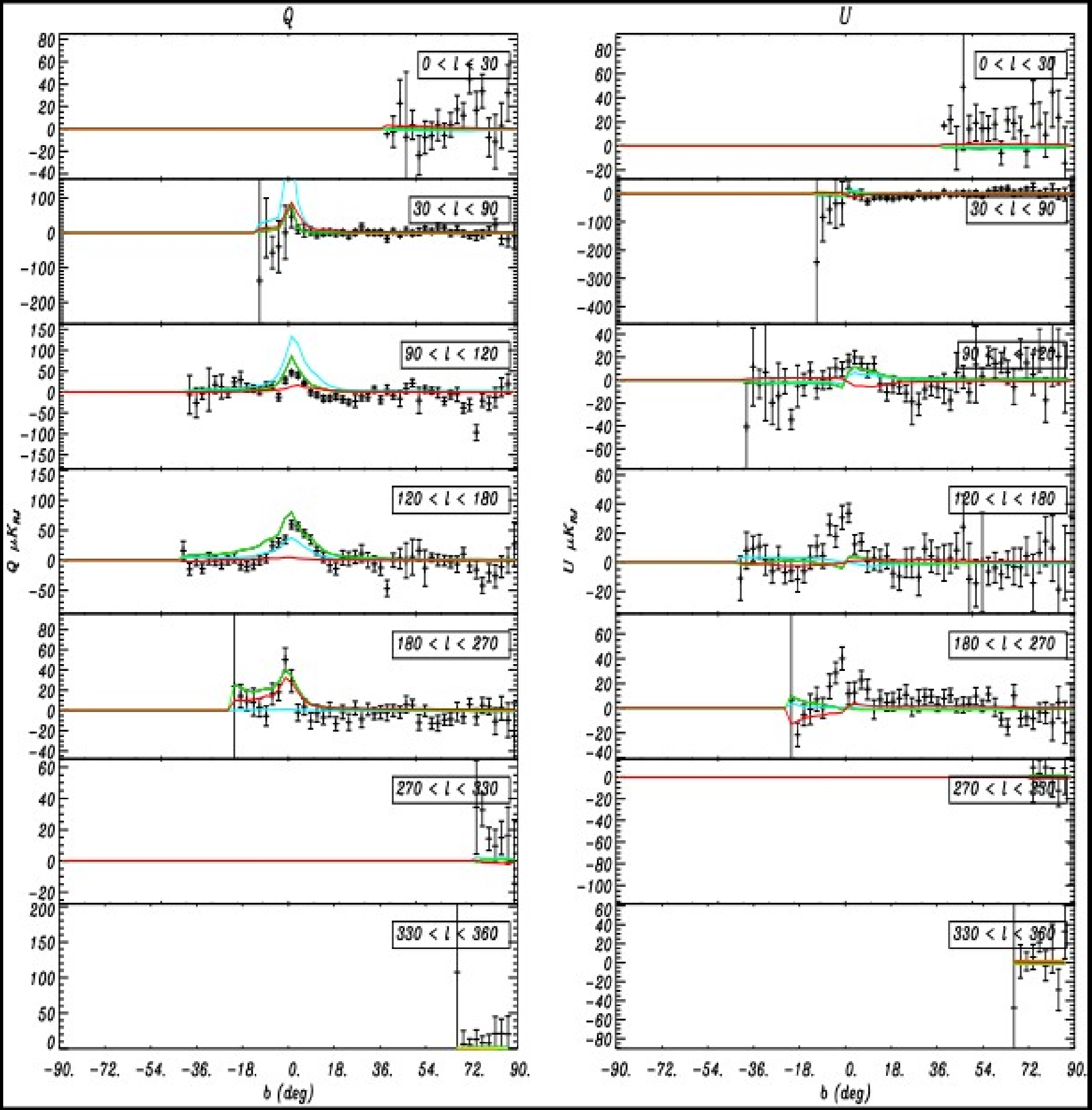
Figure 3. Plot of 37,543 RM values over the sky north of $\delta = -40°$. Red circles are positive rotation measure and blue circles are negative. The size of the circle scales linearly with magnitude of rotation measure.

Taylor et al. (2009) RM catalog. GALFACTS will do even better over Arecibo sky.

High-latitude including dust

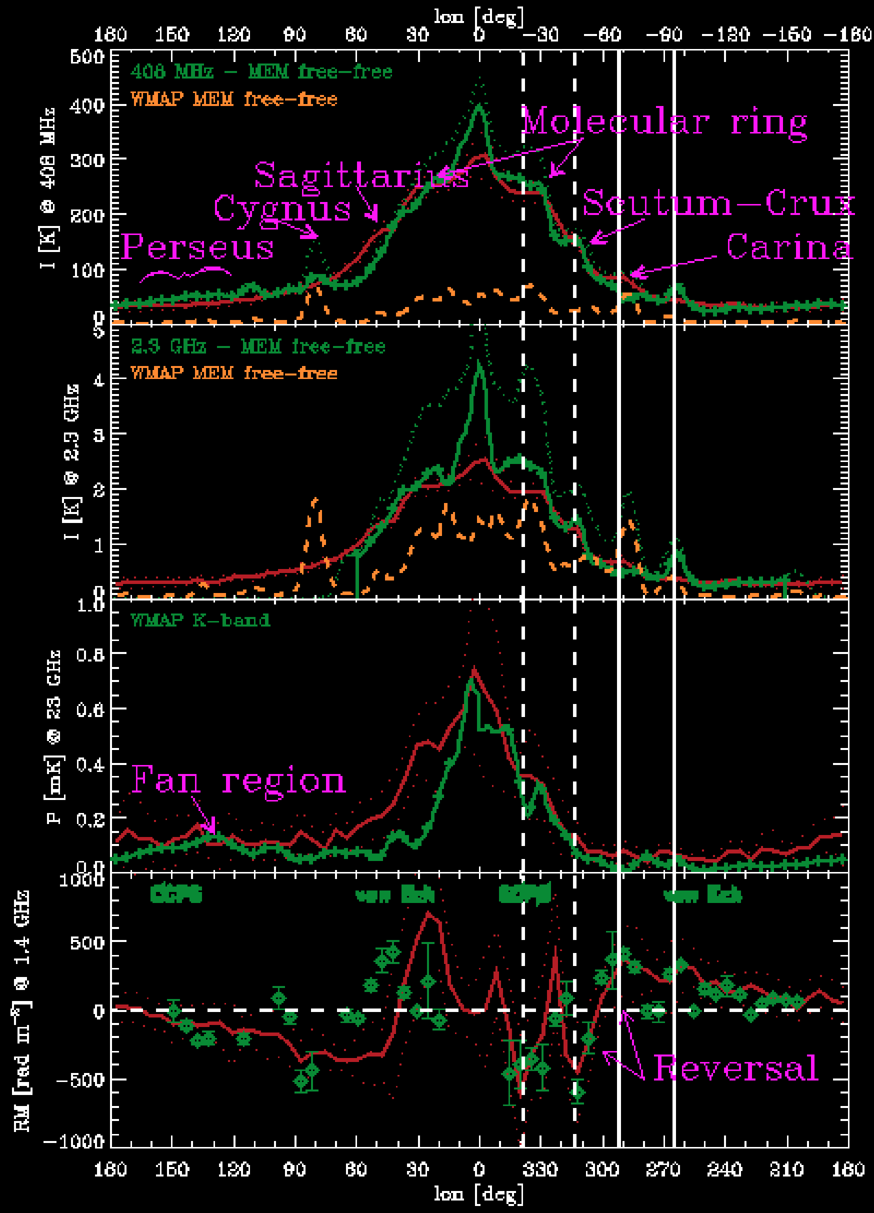
- Fauvet et al. (2011) joint modeling of synchrotron and dust using profiles in lon and lat, WMAP K-band and ARCHEOPS 353 GHz.
- Results used to predict polarized foregrounds for Planck, including high-latitude power spectra.

See also poster by L. Fauvet.



Ongoing work

- Add polarized dust emission. Our simple models completely wrong at 94 GHz; interesting! Try Hoang & Lazarian models
- New RM data from Van Eck et al. (2011) filling gap toward Sag and ring tangent. Not compatible with a logarithmic spiral? Interesting!
- Can we constrain the relationship between B-field and gas spiral arms?



Planck:

- Better synchrotron/free-free separation, particularly when combined with C-BASS.
- More sensitive polarized dust maps at multiple frequencies.

To remember:

- You need many different and complementary observables to study the different components of the galactic magnetic field. In particular, an **anisotropic/ordered turbulent component cannot be neglected** in any estimate of a “regular” or “random” component based on diffuse emission like synchrotron and thermal dust.
- We need to improve our **component separation** on the plane and to understand both the free-free intensity and the **polarized emissivity of thermal dust**. **Planck!**
- We need to better study the impact of realistic magnetic field models, including turbulence, on **foreground separation for CMB** experiements.
- The **prospects look good** with Planck, Fermi, C-BASS, GALFACTS, SKA, etc.