Modeling Galactic Magnetic Fields with Polarized Synchrotron and Dust Emission

(ESA, HFI & LFI consortia)

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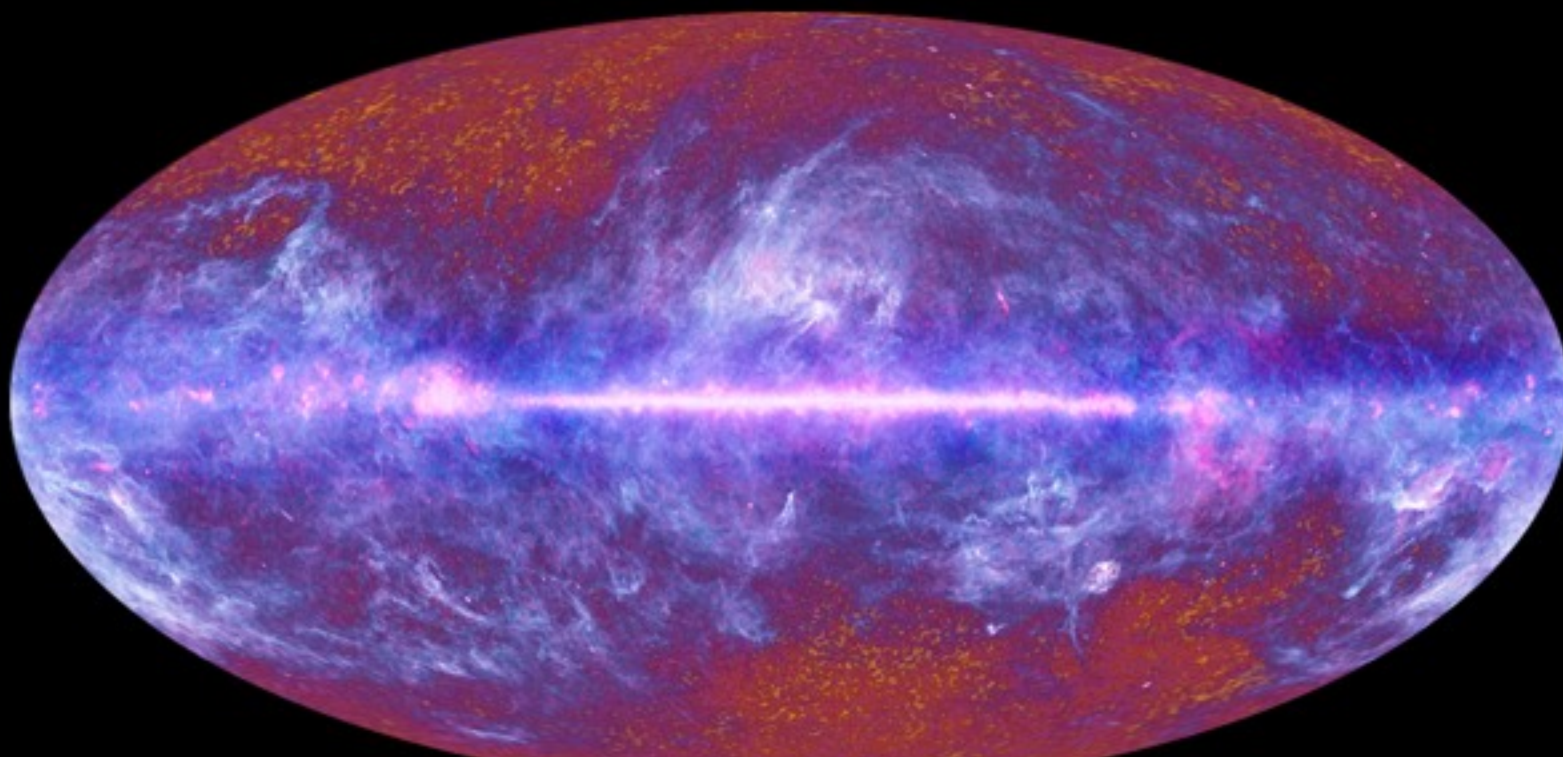
Why ~~should I care~~ are magnetic fields important?

- They are everywhere. (The classical way to try to stump the colloquium speaker: “Have you considered the effect of ...?”)
- They play key roles in:
  - primordial plasma physics;
  - galaxy formation and evolution;
  - hydrostatic balance in the ISM;
  - star formation via Parker instability;
  - turbulence (the other traditional way to try to stump the speaker) in both the ISM and the IGM;
  - supernovae remnant expansion;
  - UHECR deflection;
  - molecular cloud collapse;
  - ....
- **They are central to cosmic microwave background component separation.**

CMB foregrounds: Planck view



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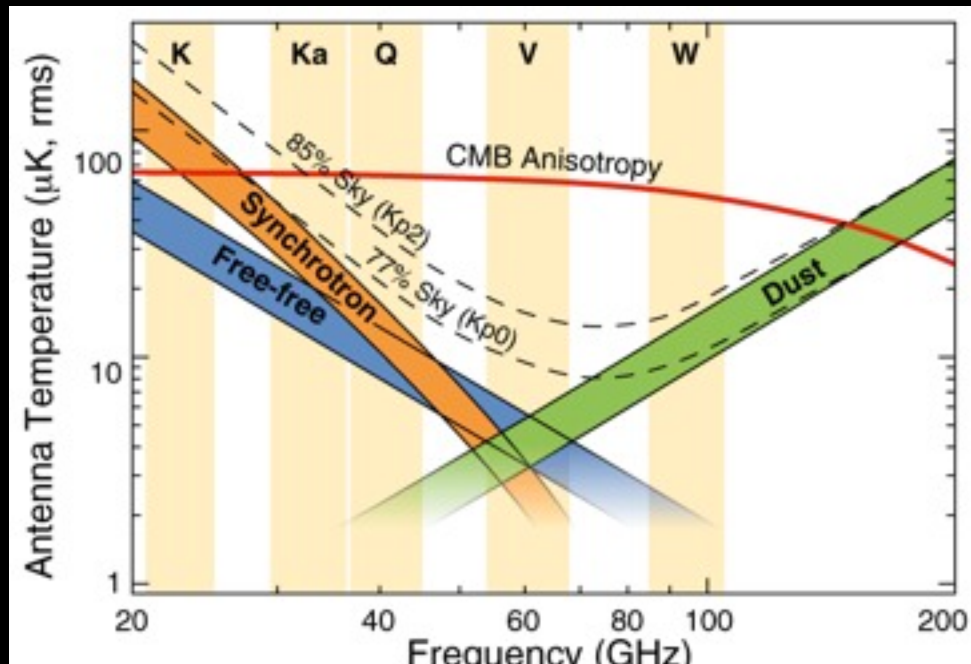
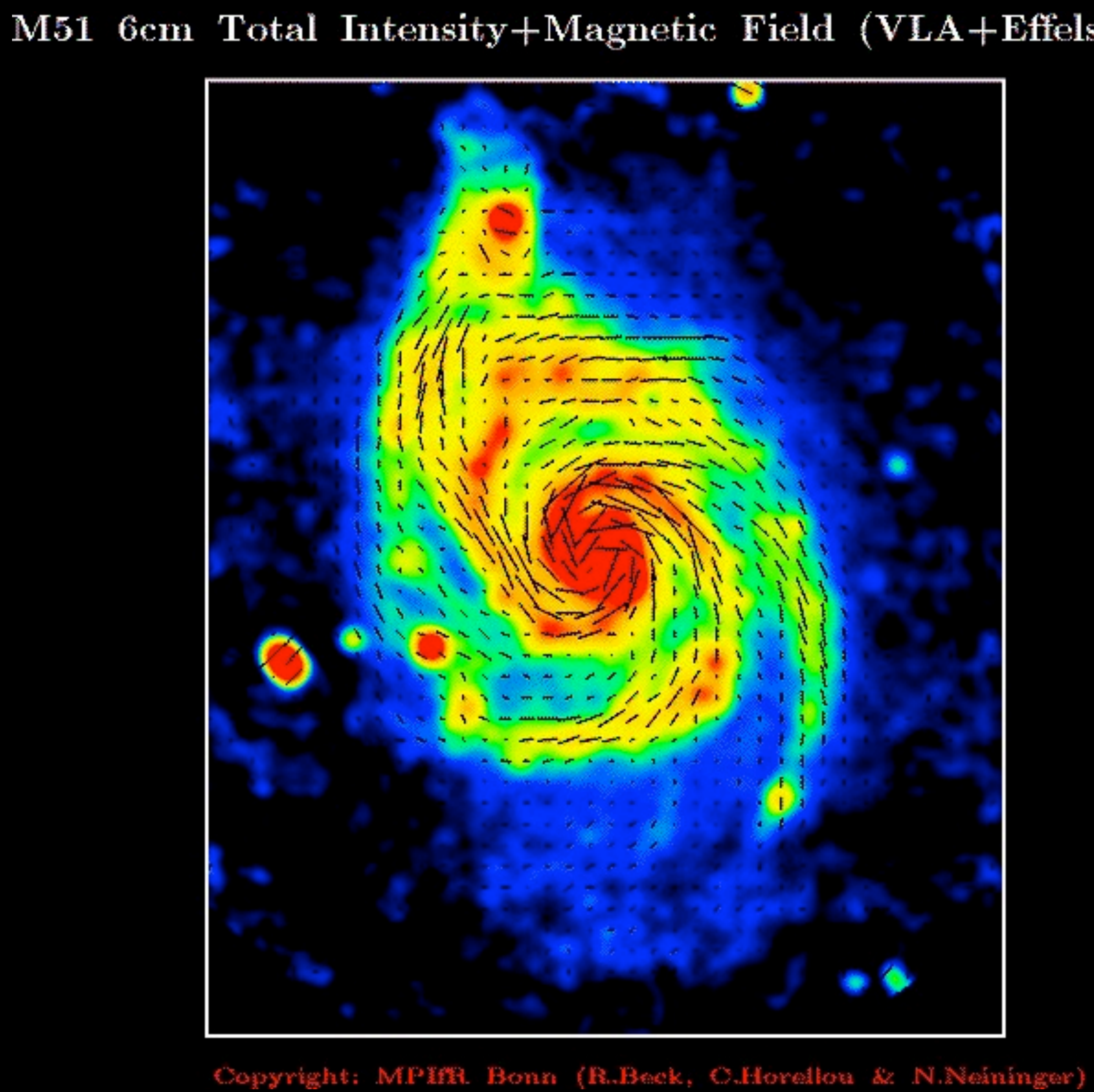


WMAP team

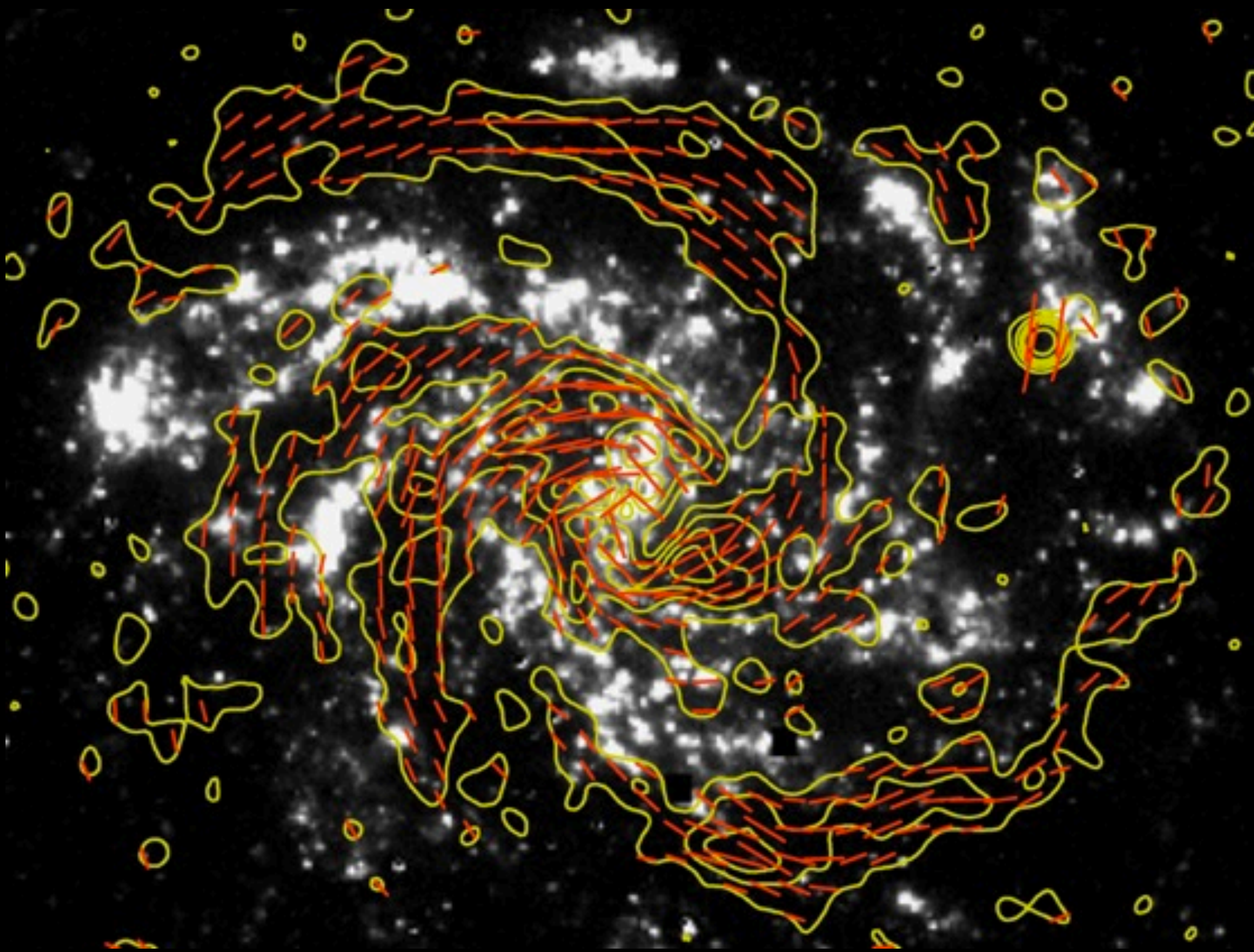
- CMB observations in the sweet spot between different foreground components that would otherwise dominate.
- At low frequencies (few 10s of GHz), the synchrotron dominates the CMB.
- At high frequencies (few 100s of GHz), the dust dominates.
- Note that we do not aim to produce a model to be subtracted from the Planck data, but rather to inform the problem of component separation. (E.g. simulations including statistically accurate turbulence to test separation methods for B-mode extraction.)

External galaxies: one example

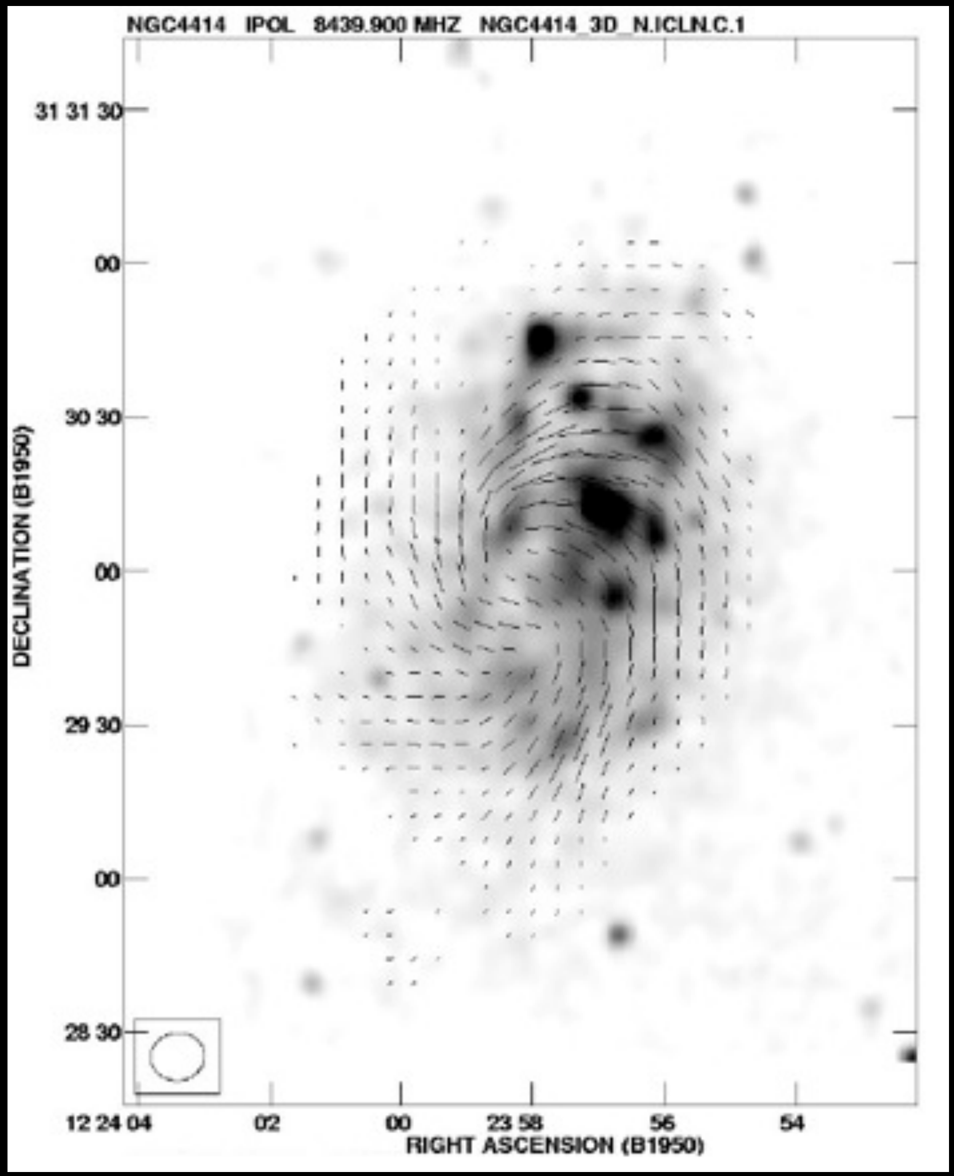


- First order: magnetic fields aligned with matter spiral structure. Can't be coincidental.
- Unfortunately, we cannot see our own galaxy like this.
- Furthermore, in an external galaxy, we cannot see the direction, but only its orientation.

External galaxies: other examples



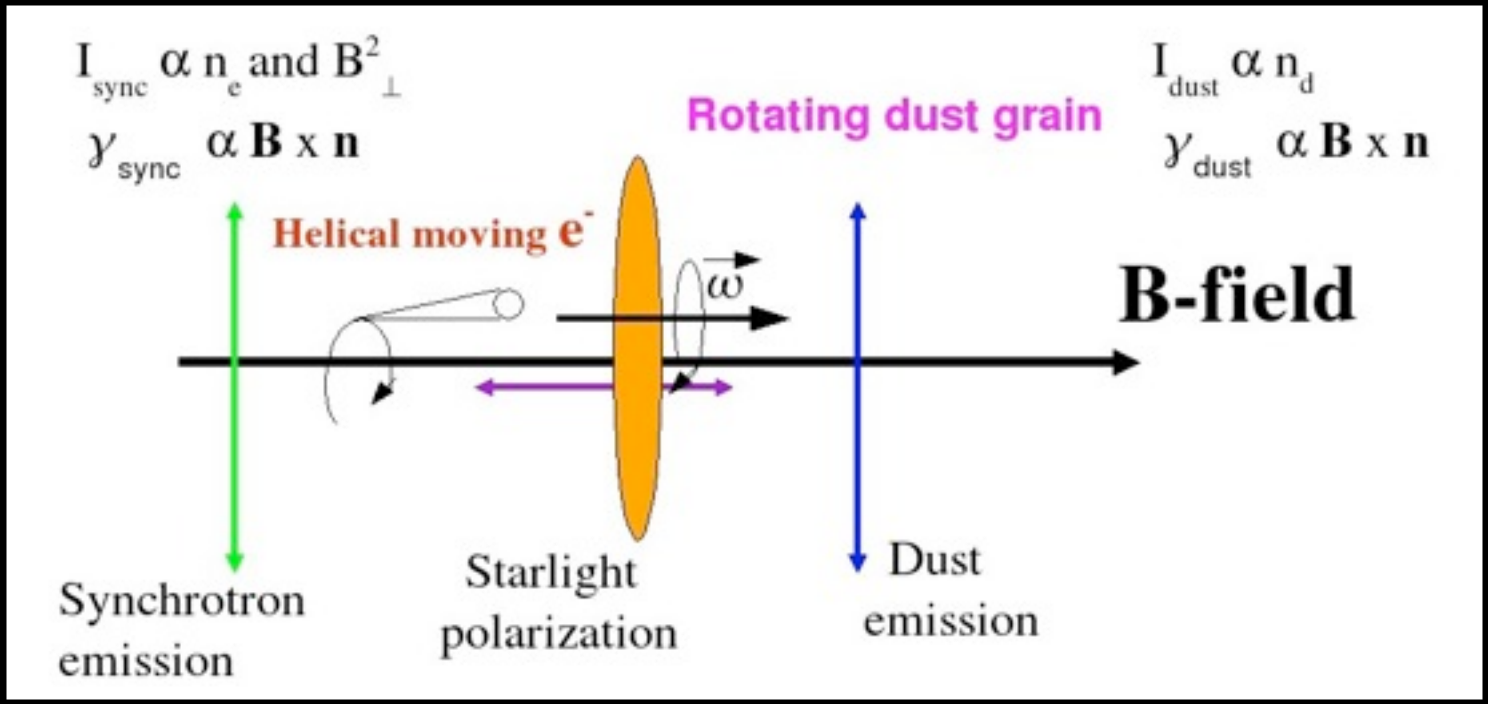
NGC6946 6cm PI over Hα (Copyright R. Beck, MPIfR)



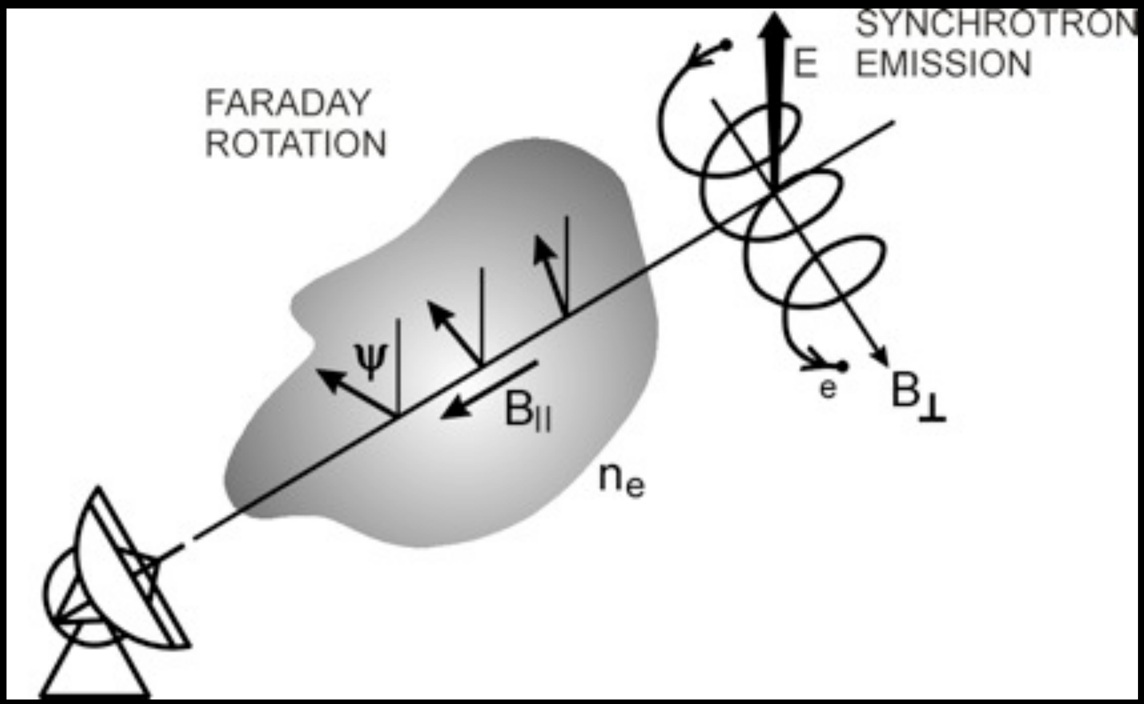
(Soida et al.

Observables

- Synchrotron emission: $I(\nu) \propto \int_{\rm LOS} n_{\rm CRE} B_\perp^2 dl$ i.e. traces component perpendicular to LOS
- Rotation measure: $RM \propto \int_{\rm LOS} n_e B_{||} dl$ i.e. traces component parallel to LOS
- Thermal dust emission: ? traces perpendicular field, but depends on dust environment, grain sizes and shapes, ...
- Starlight polarization, Zeeman splitting, masers, etc.
- ***But:*** electron distributions not well known, dust polarized emission process not well known, data contaminated with other stuff (bremsstrahlung, CMB, intrinsic RM, etc.)



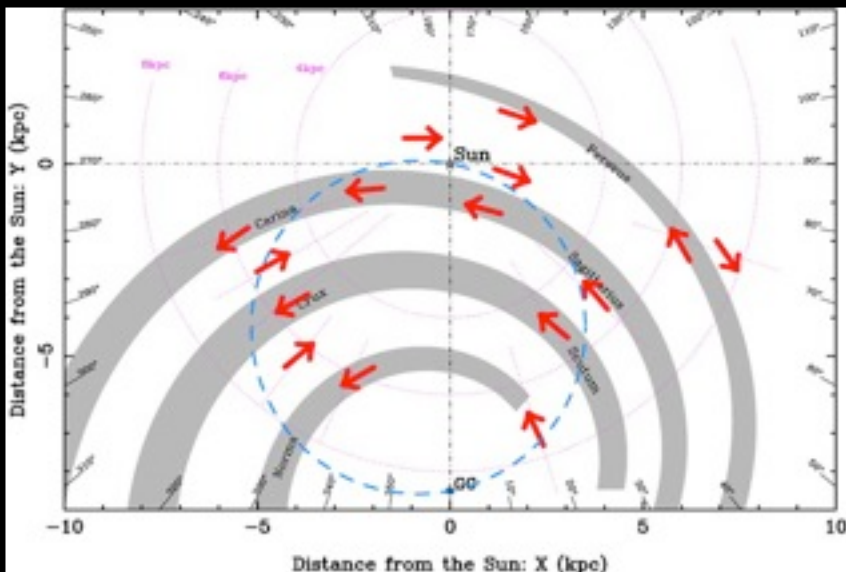
(Courtesy J.F. Macías-



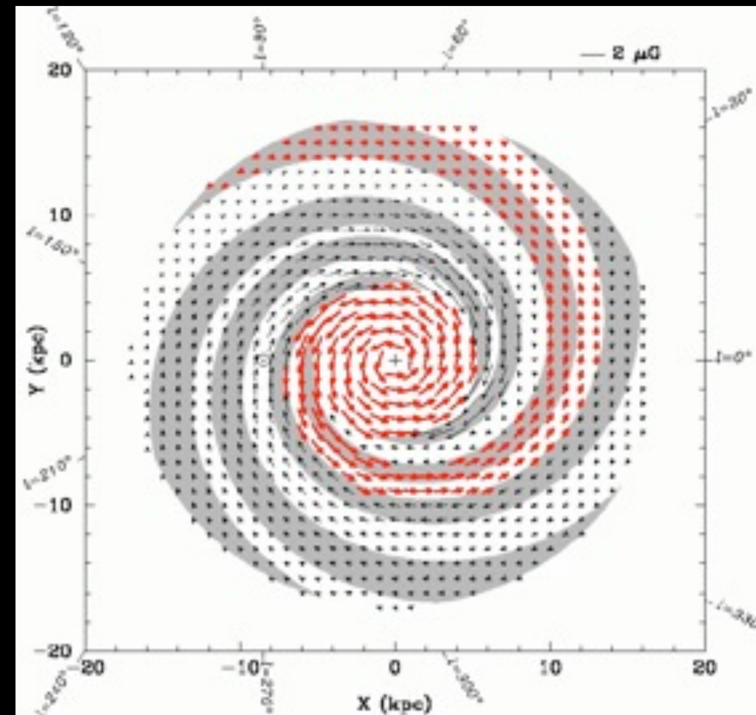
(Courtesy R.

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

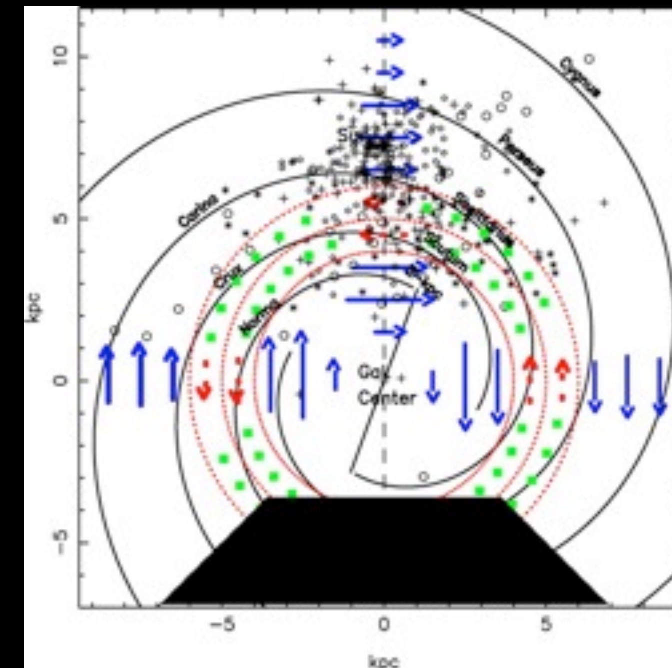
Large-scale models for the Milky Way



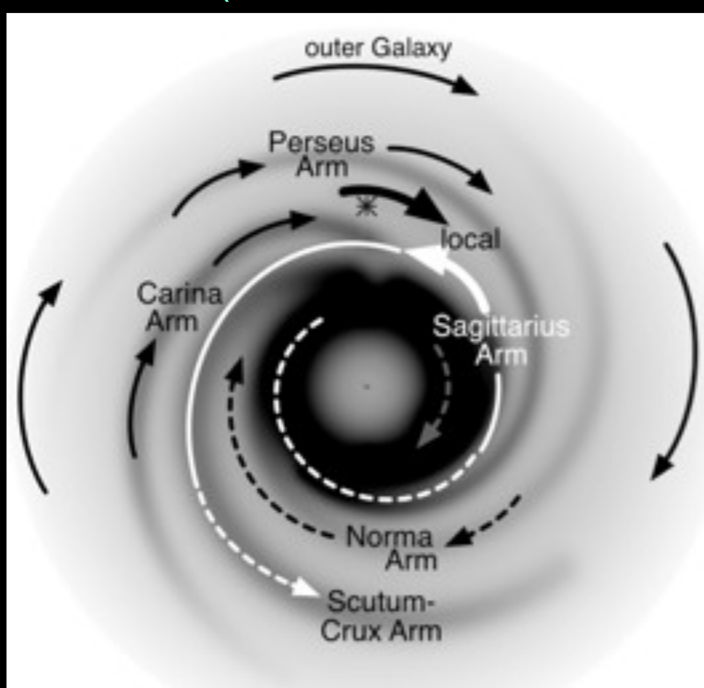
(Han et al.



(Sun et al. (2008)
(courtesy X Sun. & W.



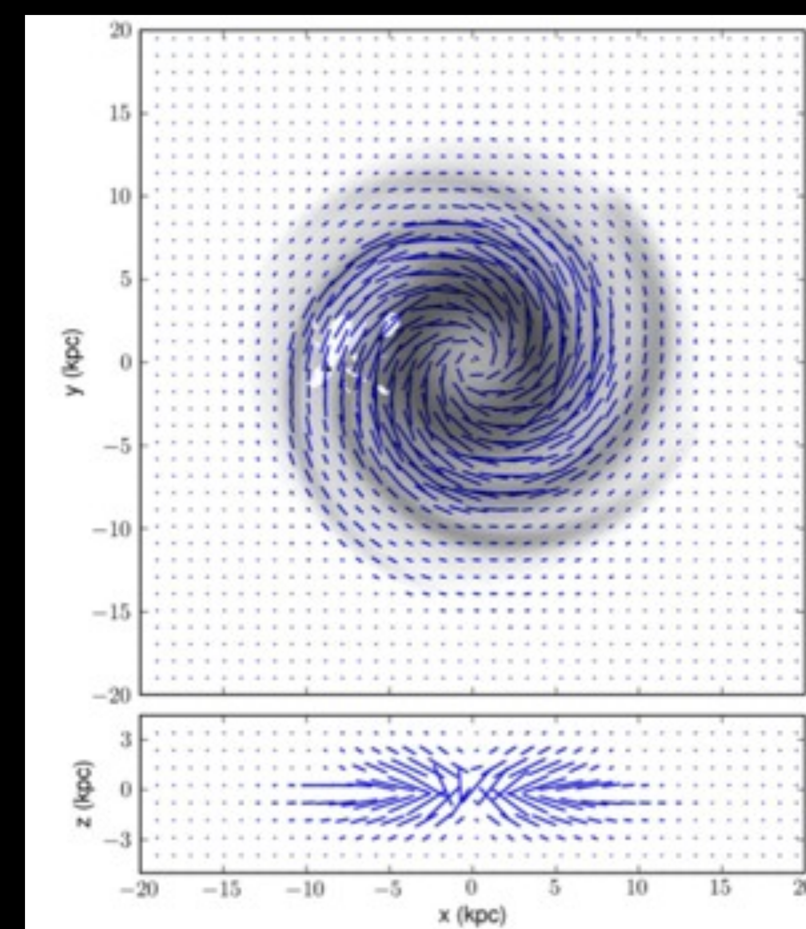
(Vallée et al.



van Eck et al.

The only certainty is that there are puzzling reversals.

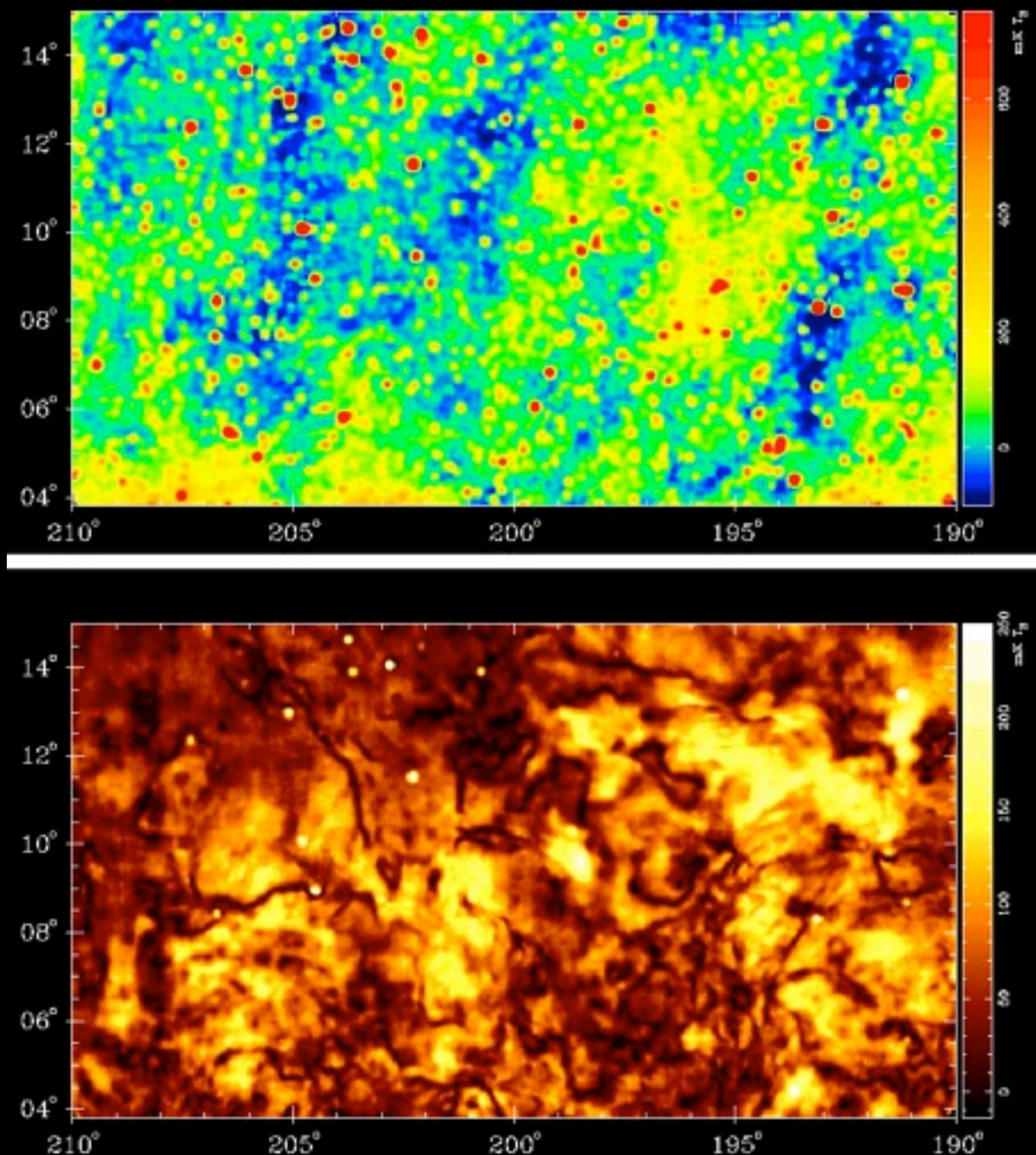
Many models that may fit some of the data (these all largely based on RM). None fit all of the data.



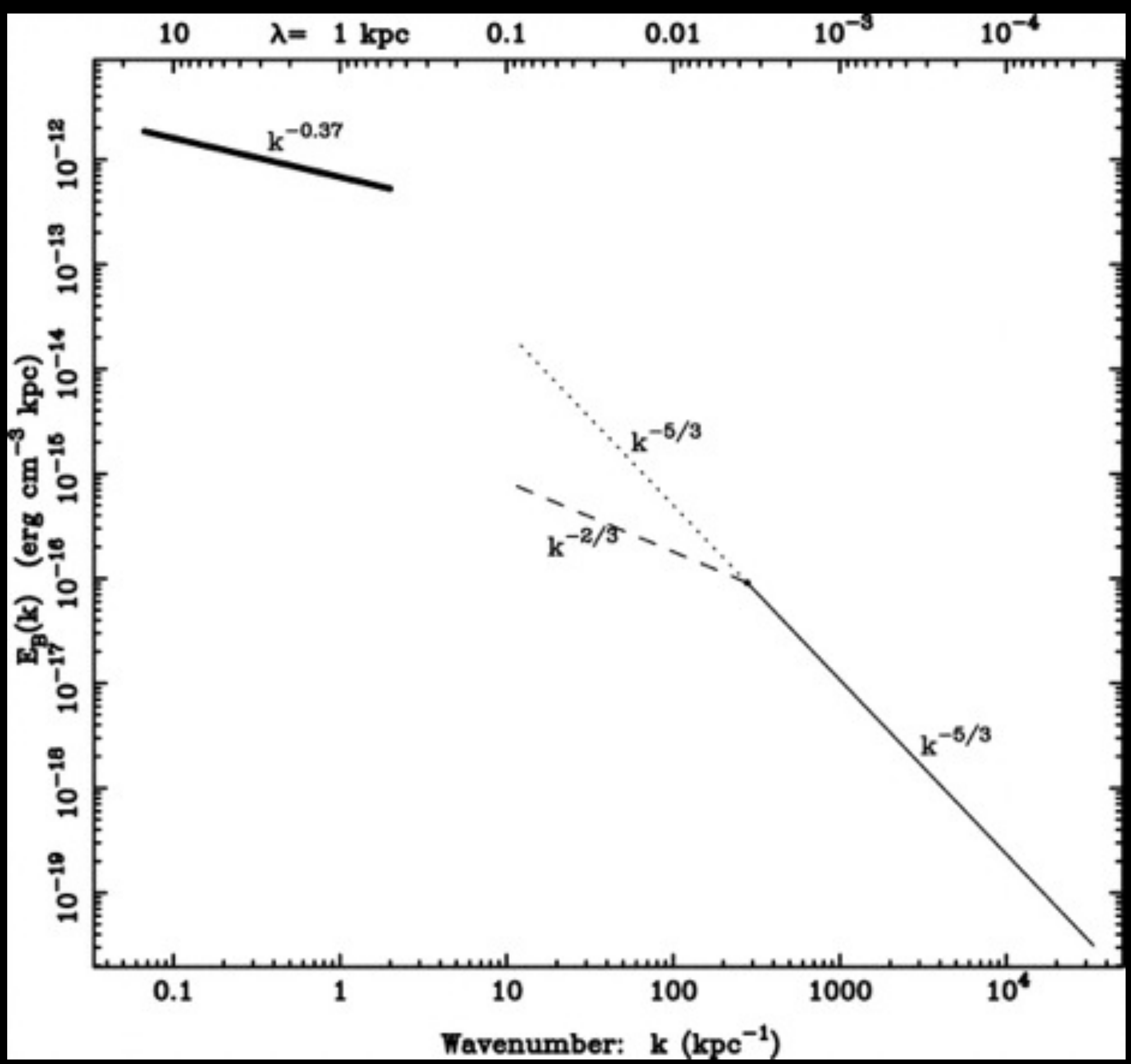
Jansson & Farrar

Small-scale field: Turbulence

EMLS *I* and *PI* (Uyaniker et al.



Magnetic energy spectrum from pulsar data (Han et al.2004)



Previous studies:

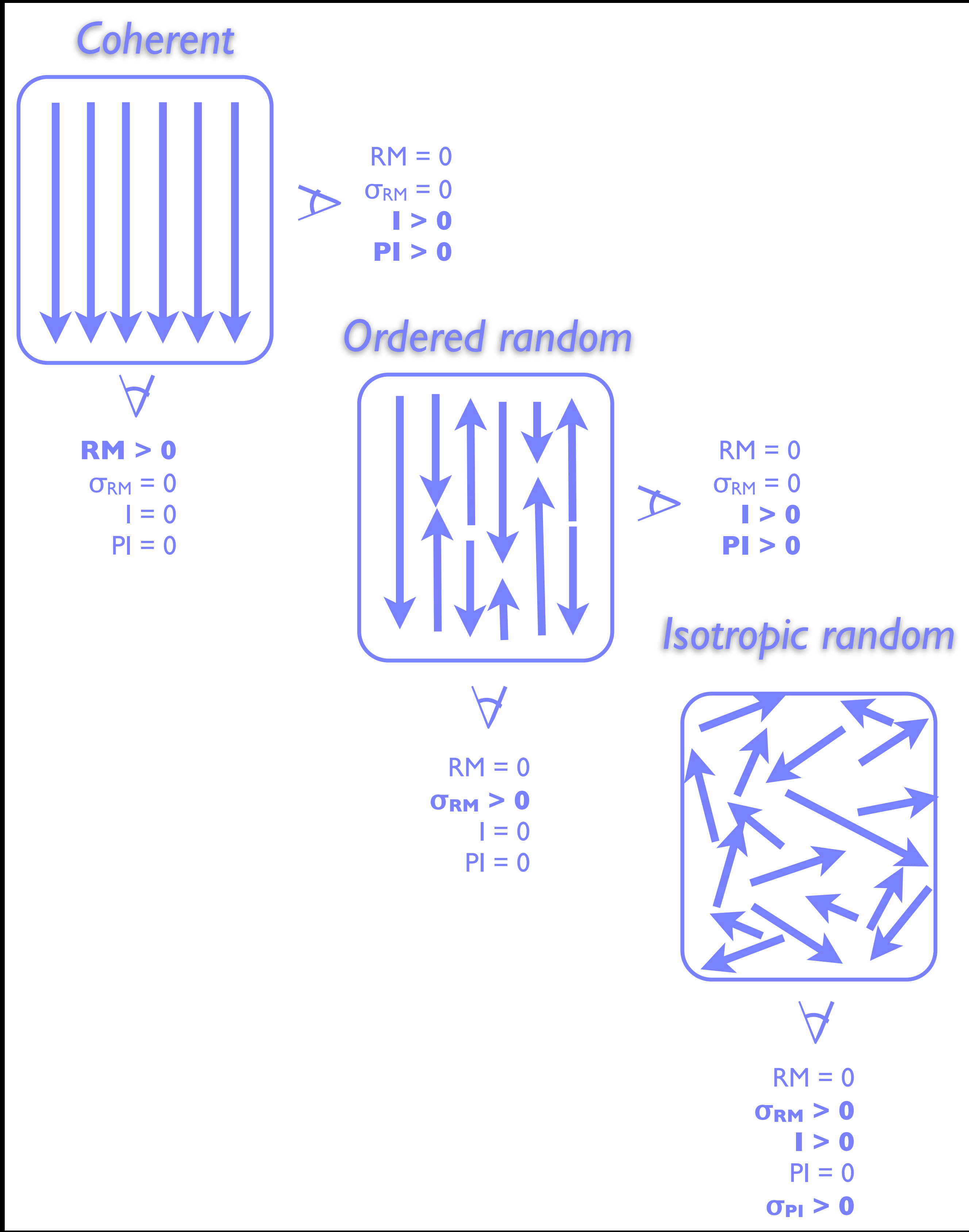
A variety of previous studies, each with a different *focus or advantage*:

- Sun et al. (2008): RMs and synchrotron, include *1.4 GHz depolarization and EM analysis*. Idealized CREs and B-field components.
- Miville-Deschenes et al. (2008): 0.408 and 23 GHz plus *spectral index model*, fitting BSS parameters.
- Fauvet et al. (2010,2011): WMAP + Archeops, *polarized dust model*.
- Strong, Orlando & Jaffe (2011): high latitude low-frequency radio to microwave, GALPROP treatment of *CRE spectral and spatial distributions*.
- Jansson et al. (2009,2012): 23 GHz and RMs, MCMC analysis, *vertical structure, "striated"* (="ordered random") component included (2012).

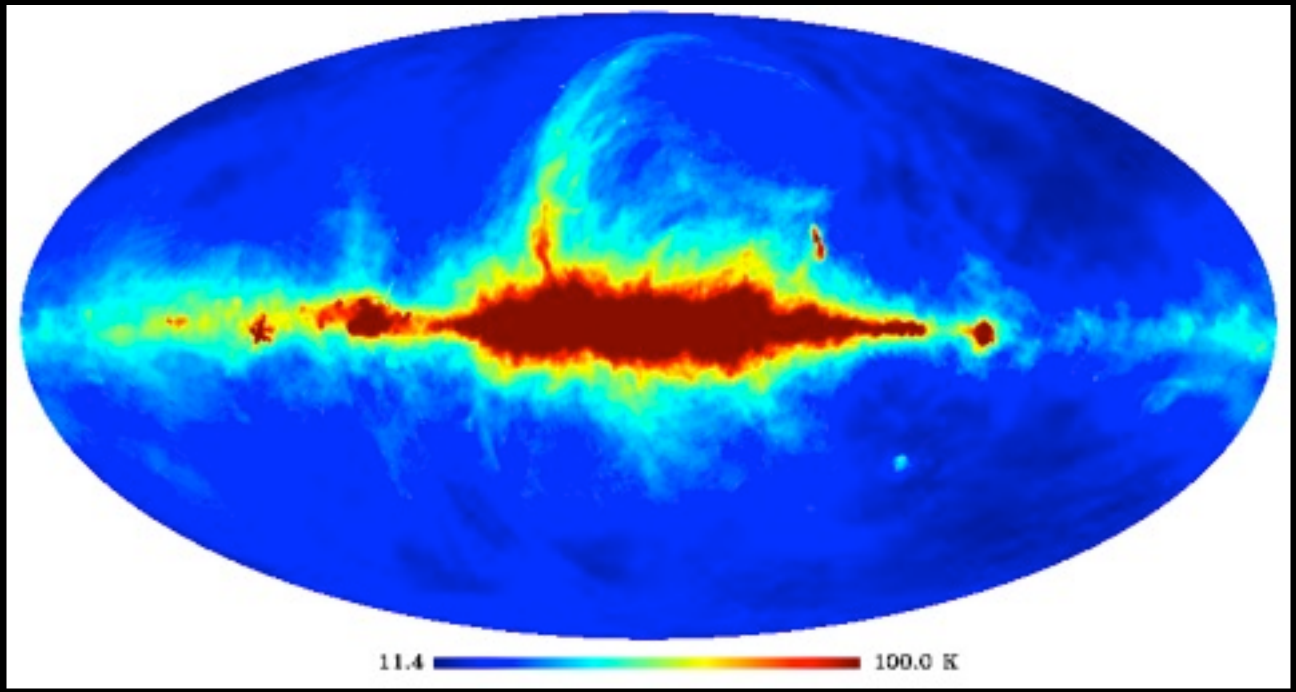
Most assume isotropic turbulence. Uncertainties in inputs often enough to allow contradictory models. **But no longer!**

Geometry

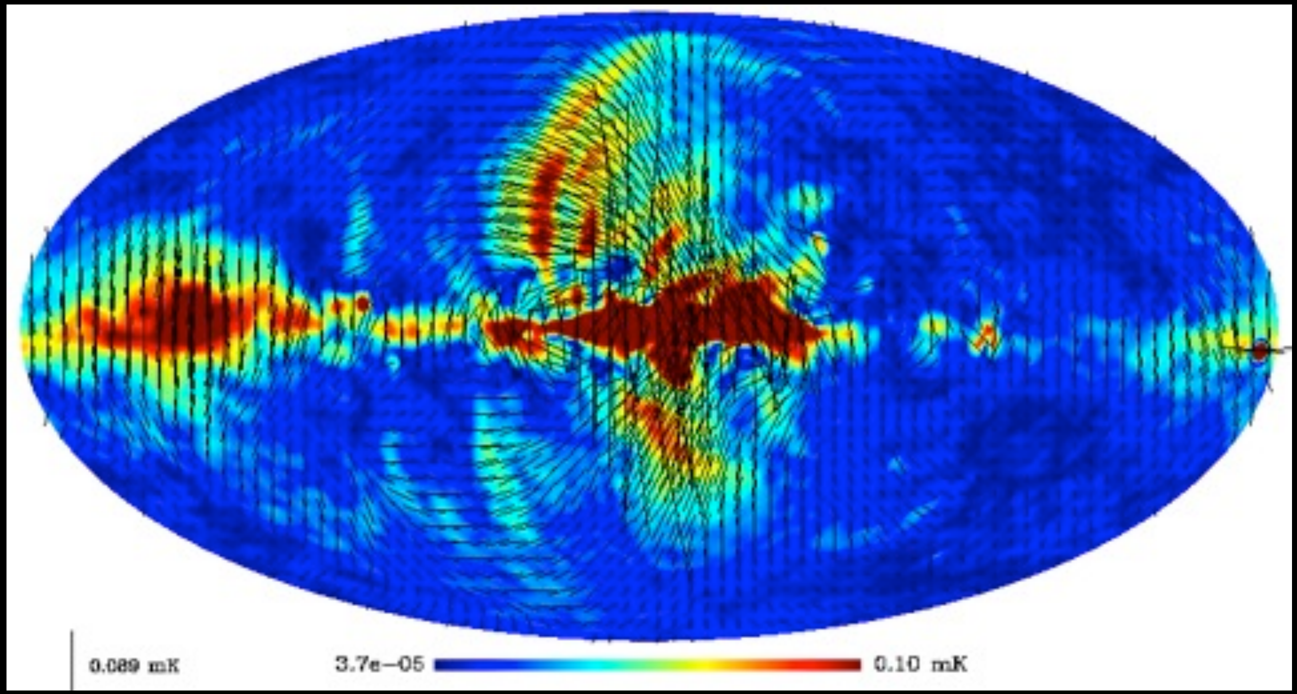
- **Coherent** contributes to RM for $B_{||}$ and to I and PI for B_{perp}.
- **Ordered** contributes to I and PI perpendicular, but to RM variance only.
- **Random** contributes only to I and to PI and RM variance.
- (At high frequencies, outside of Faraday regime.)
- **Careful** when discussing "regular", "random", "turbulent", etc.
- Want I and PI at the same wavelength, but ...



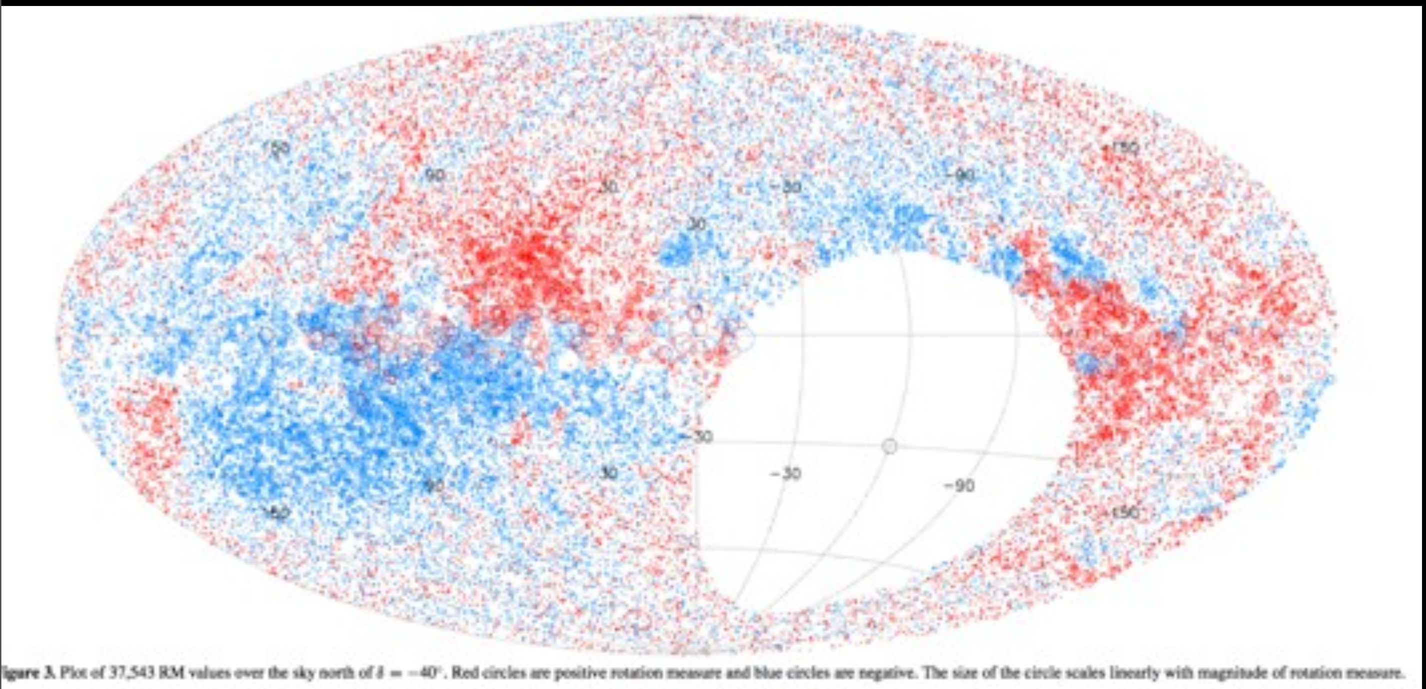
Radio Observations



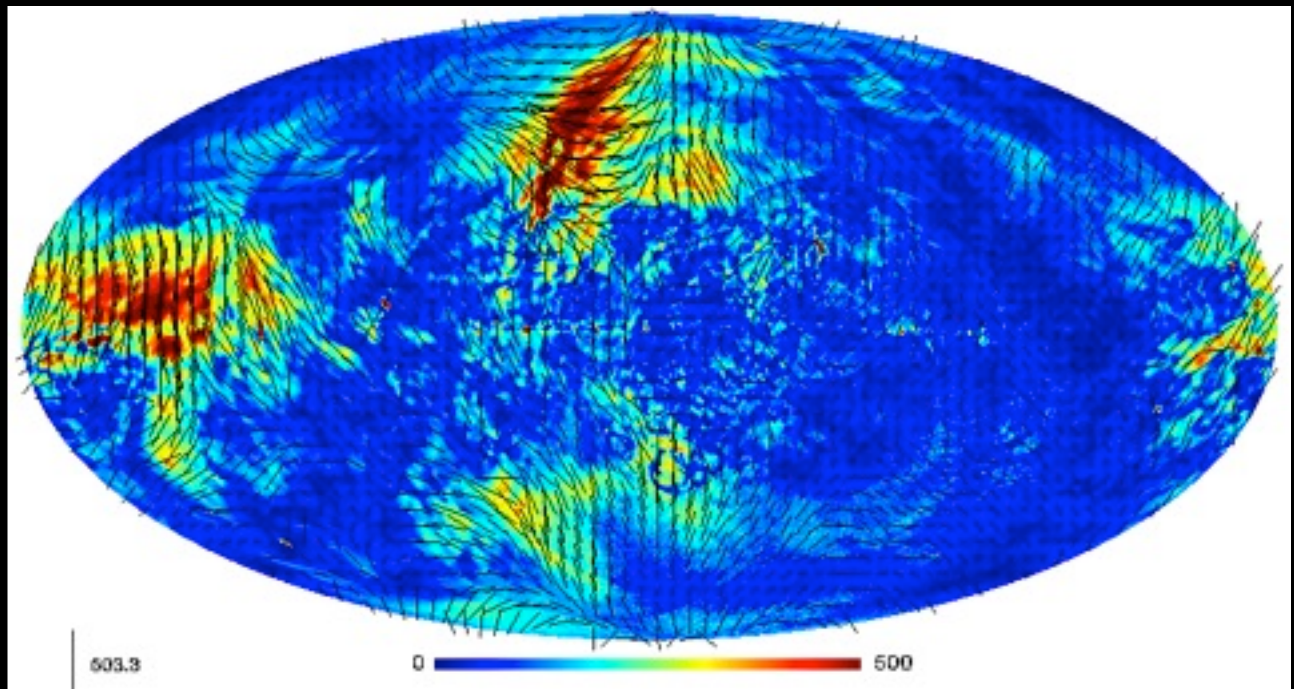
408 MHz total intensity (Haslam et al. 1982)



23 GH polarized intensity (Page et al. 2007)



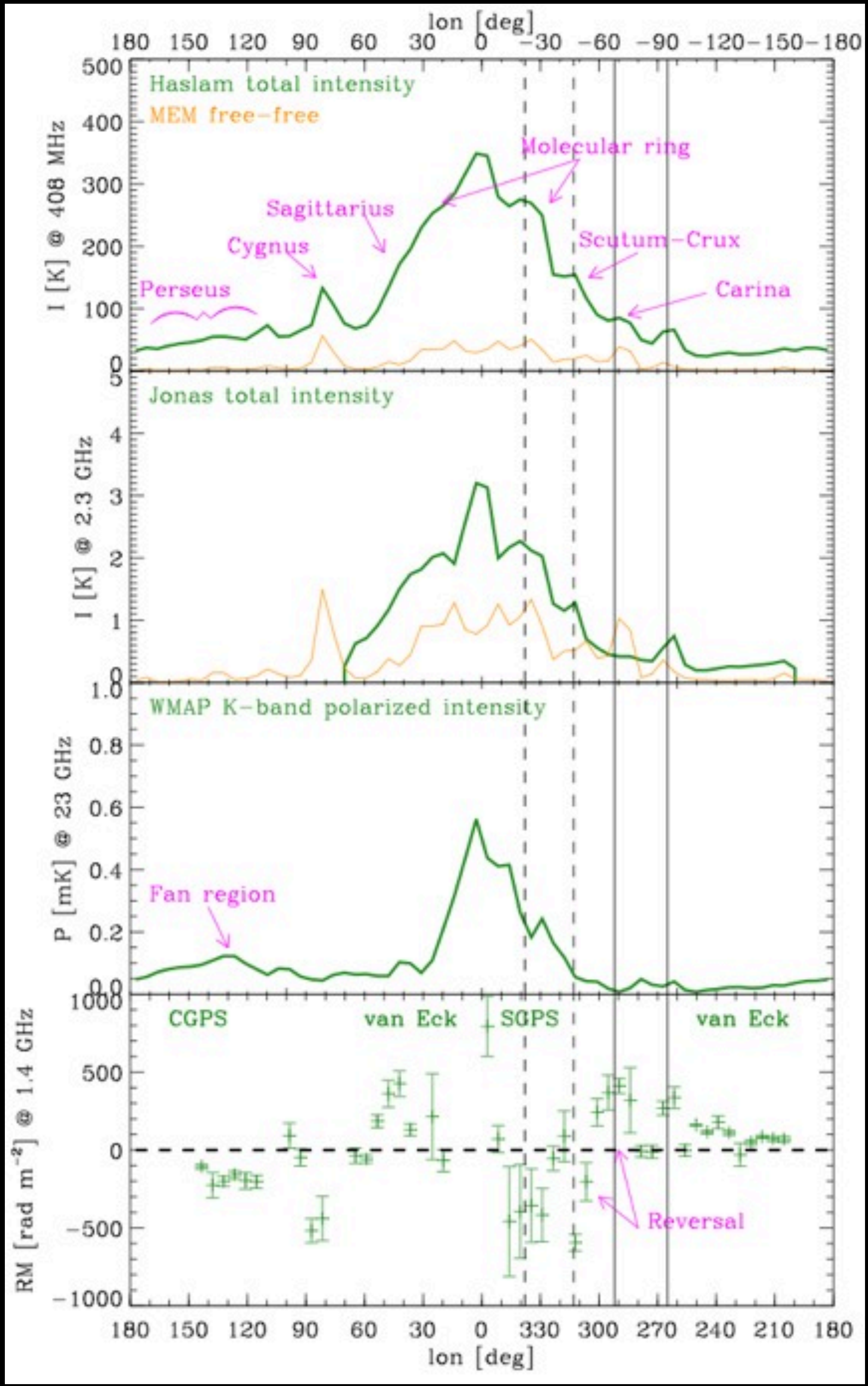
Faraday rotation measure (RM) 1.4 GHz
(Taylor et al. 2010)



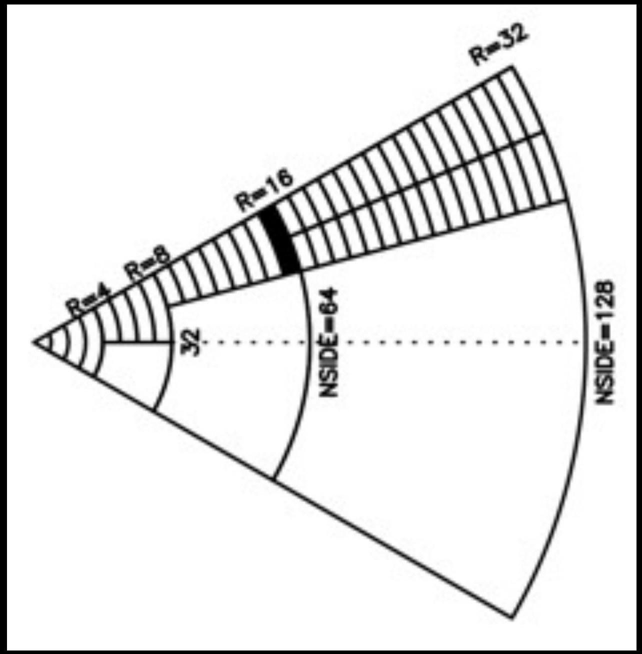
1.4 GHz polarized intensity
(Wolleben et al. 2006, Testori et al. 2008)

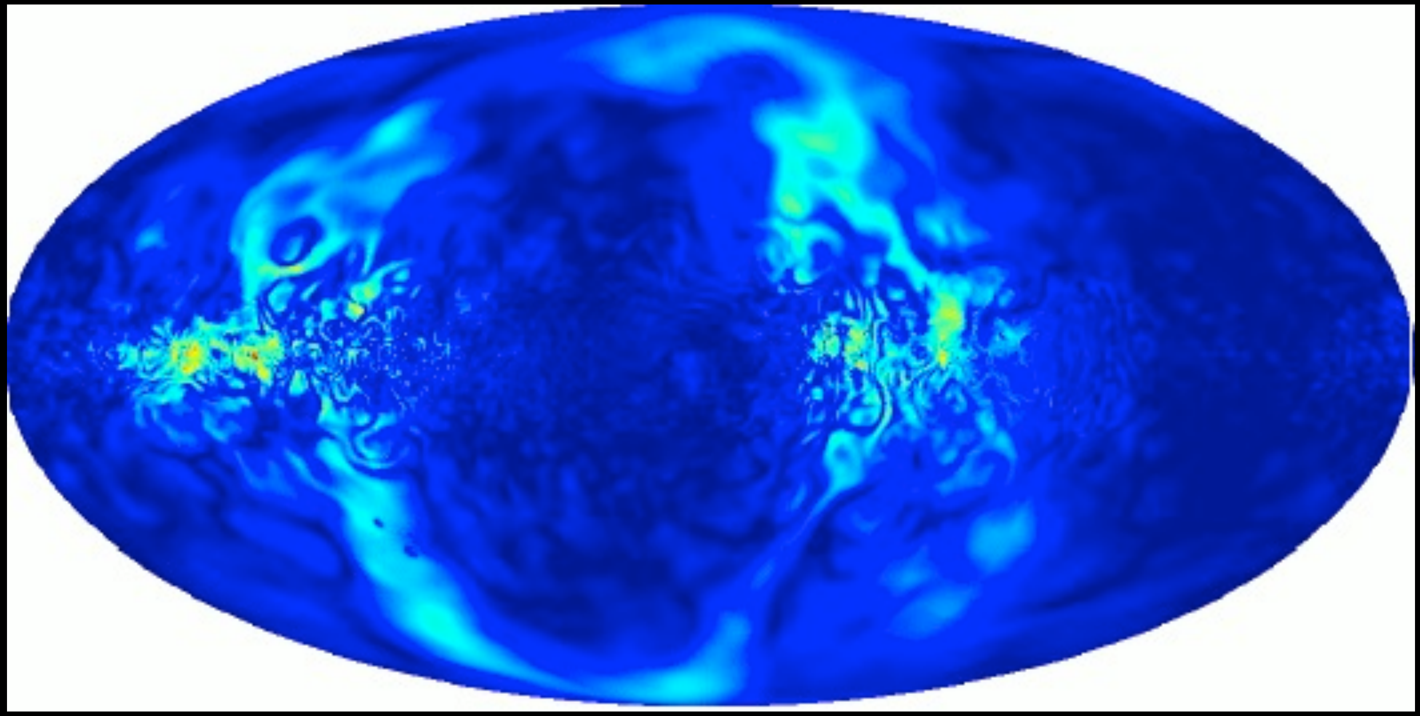
First look at the plane

- Step features in *I*: arm tangents?
- Peaks and troughs in RM: arms?
- Reversals?

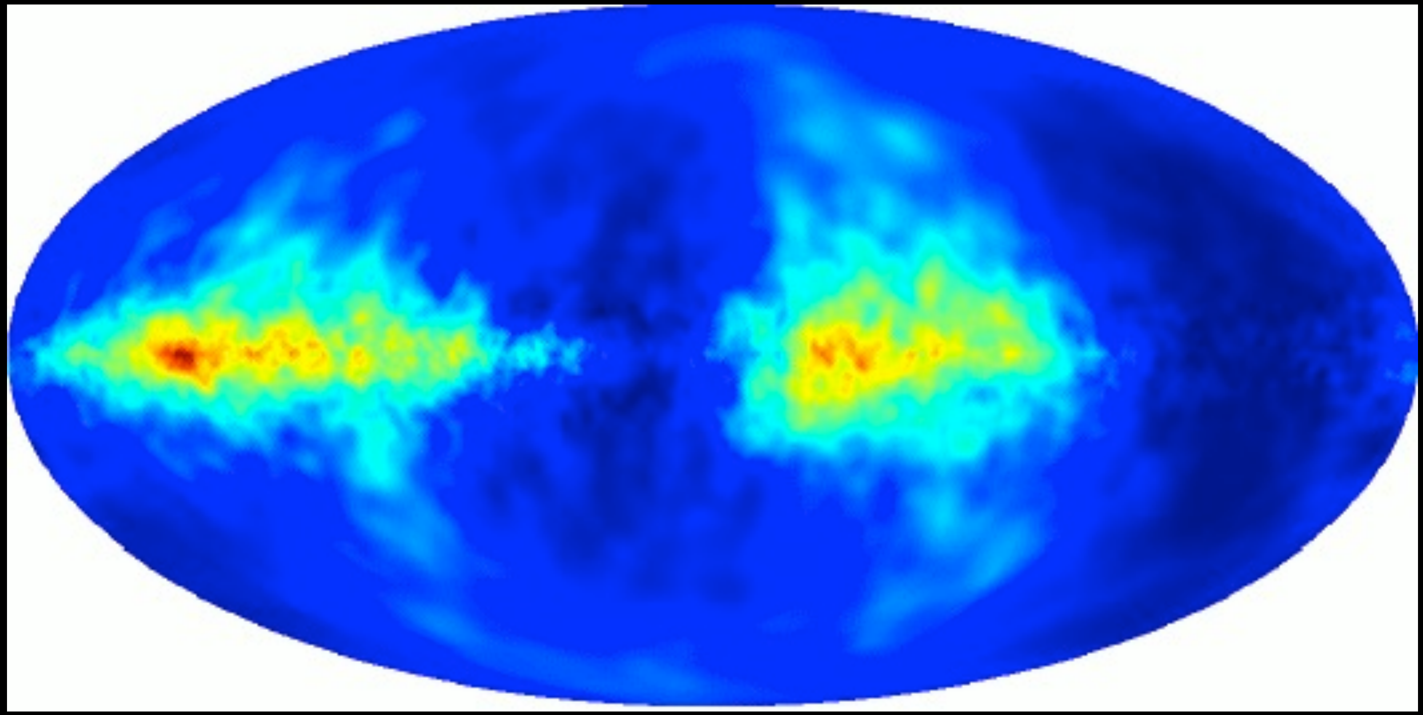


Modeling: hammurabi





1.4 GHz polarized intensity



23 GHz polarized intensity

(Courtesy A. Waelkens.)

- Hammurabi Code* (Waelkens, Jaffe, et al. 2009)
- HEALPix scheme for LOS integration of:
  - Faraday RM;
  - synchrotron I, Q, and U (with Faraday rotation applied);
  - thermal dust I, Q, U (ditto);
  - (EM);
  - (DM)...
- Modular C++; add your own models.

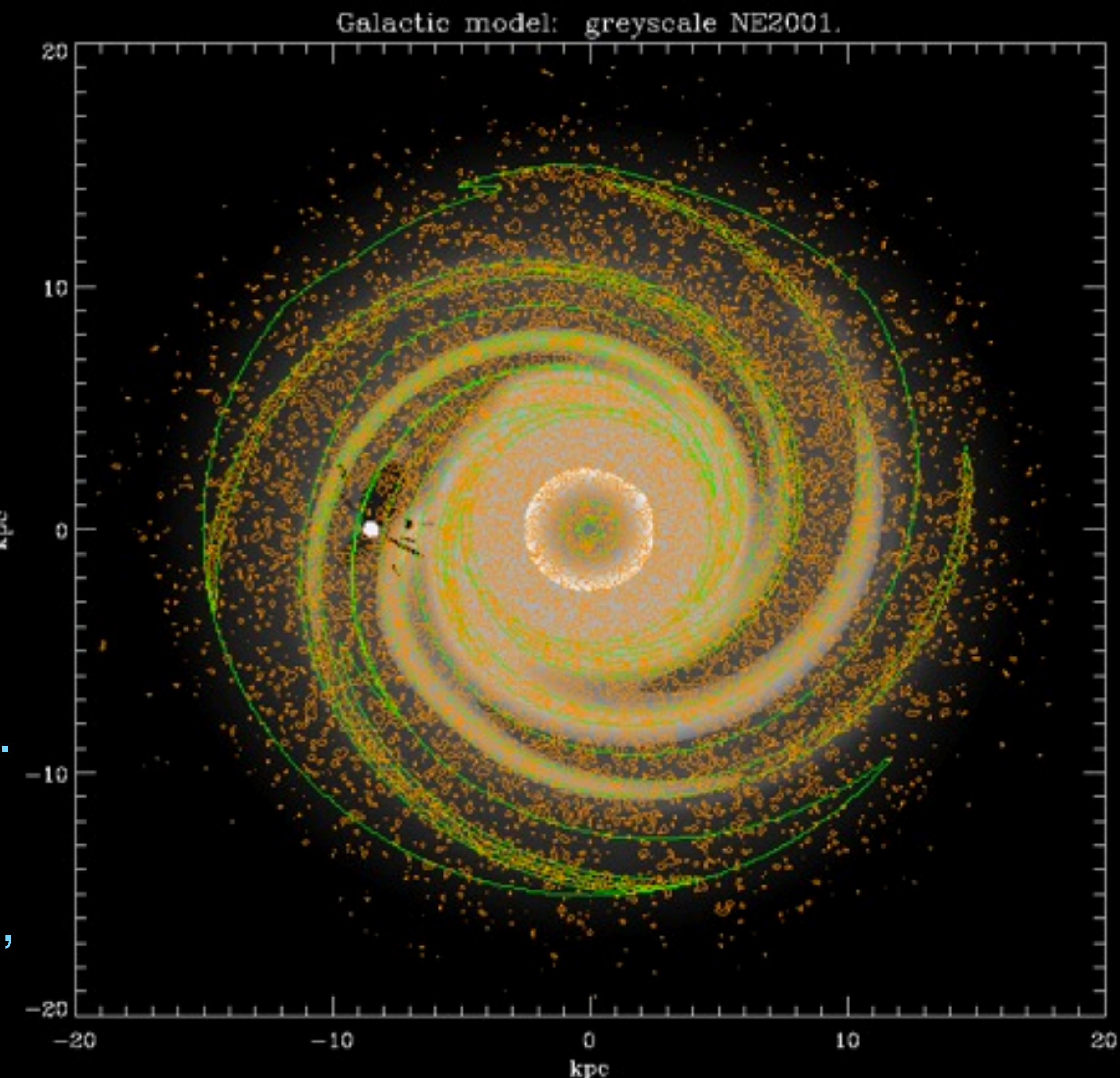
* Publicly available on Sourceforge: http://sourceforge.net/projects/hammurabicode/

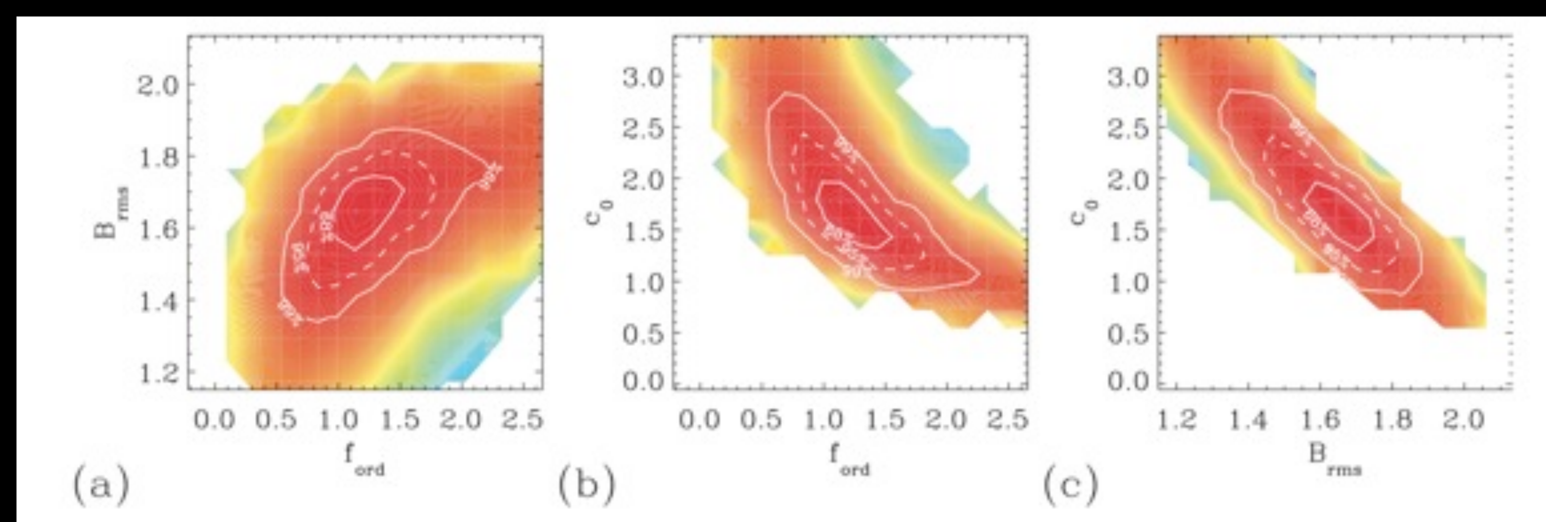
Model inputs:

Motivated by external galaxies:

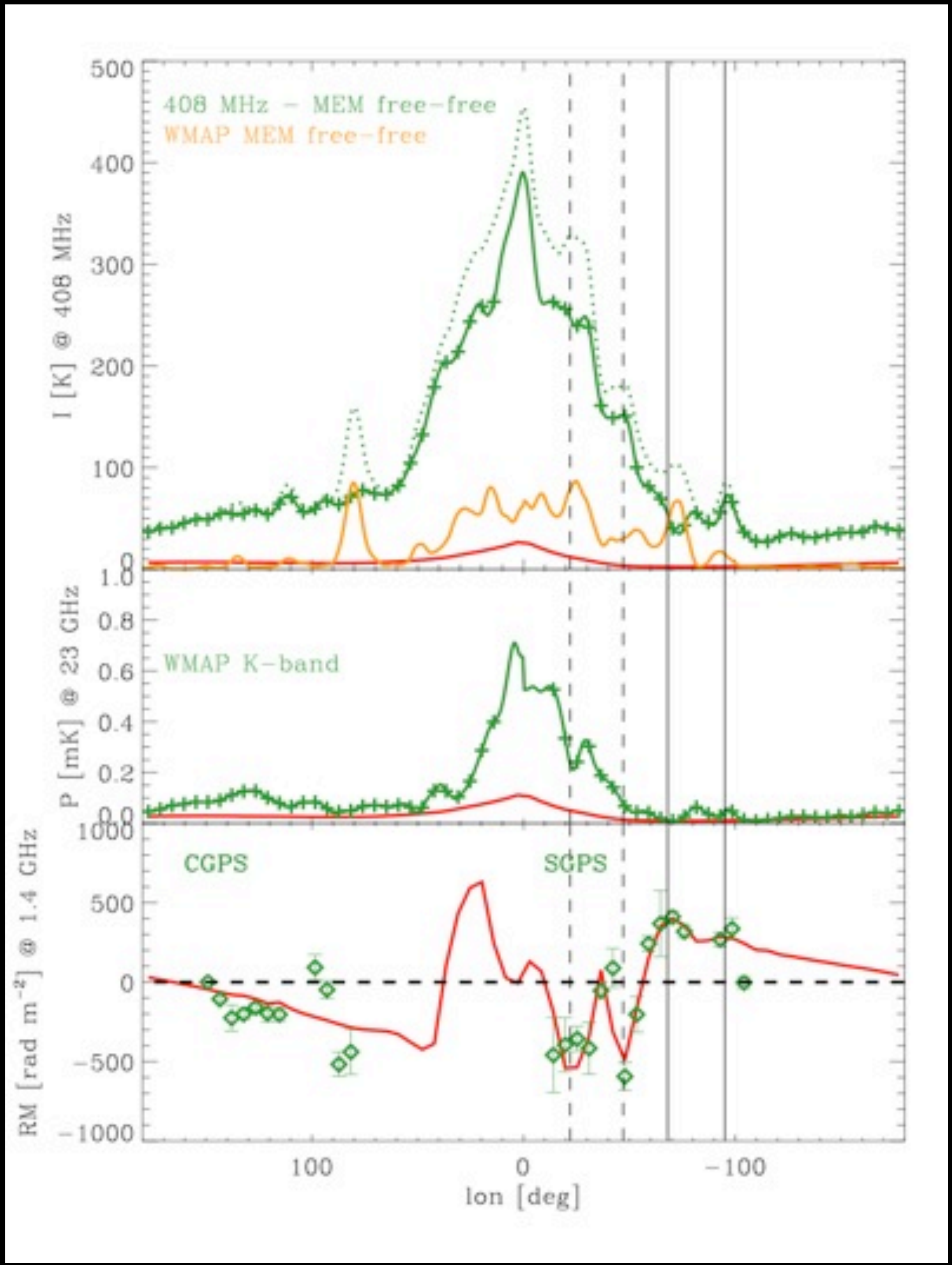
- 3D magnetic field model:
  - spiral arm model for ‘coherent’ field;
  - small-scale turbulence based on GRF with power-law spectrum;
  - compression model amplifies and stretches into anisotropic (‘ordered’) component along arm ridges based loosely on Broadbent (1989).

- 3D CRE density and spectral model: exponential disk with canonical power law, p=-3, normalized with gamma-ray data;
- 3D thermal electron density model: NE2001 (Cordes and Lazio 2002);
- *Hammurabi* to integrate observables along LOS;
- MCMC (cosmoMC) engine to explore parameter space.



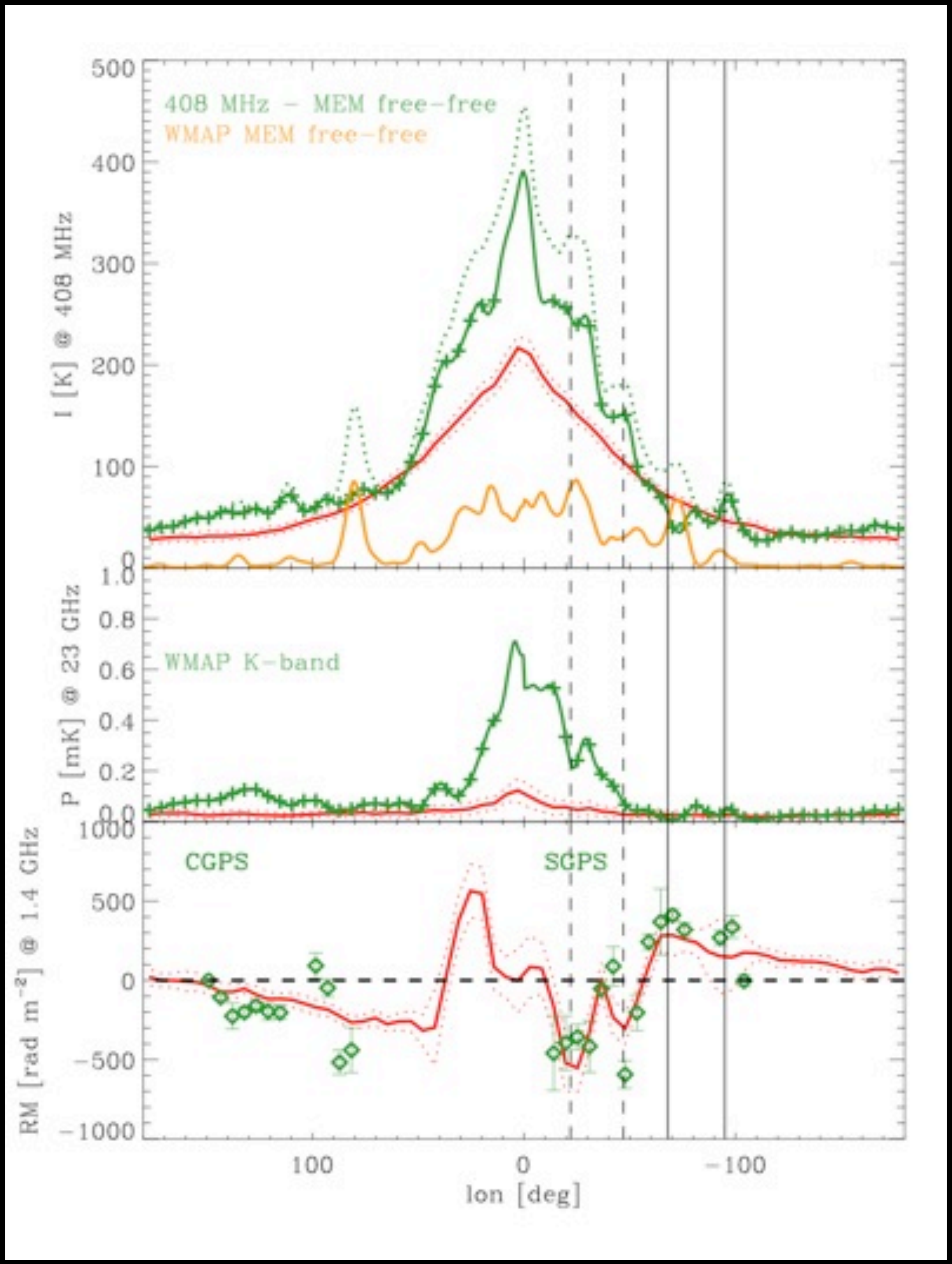


Cartoon example: coherent



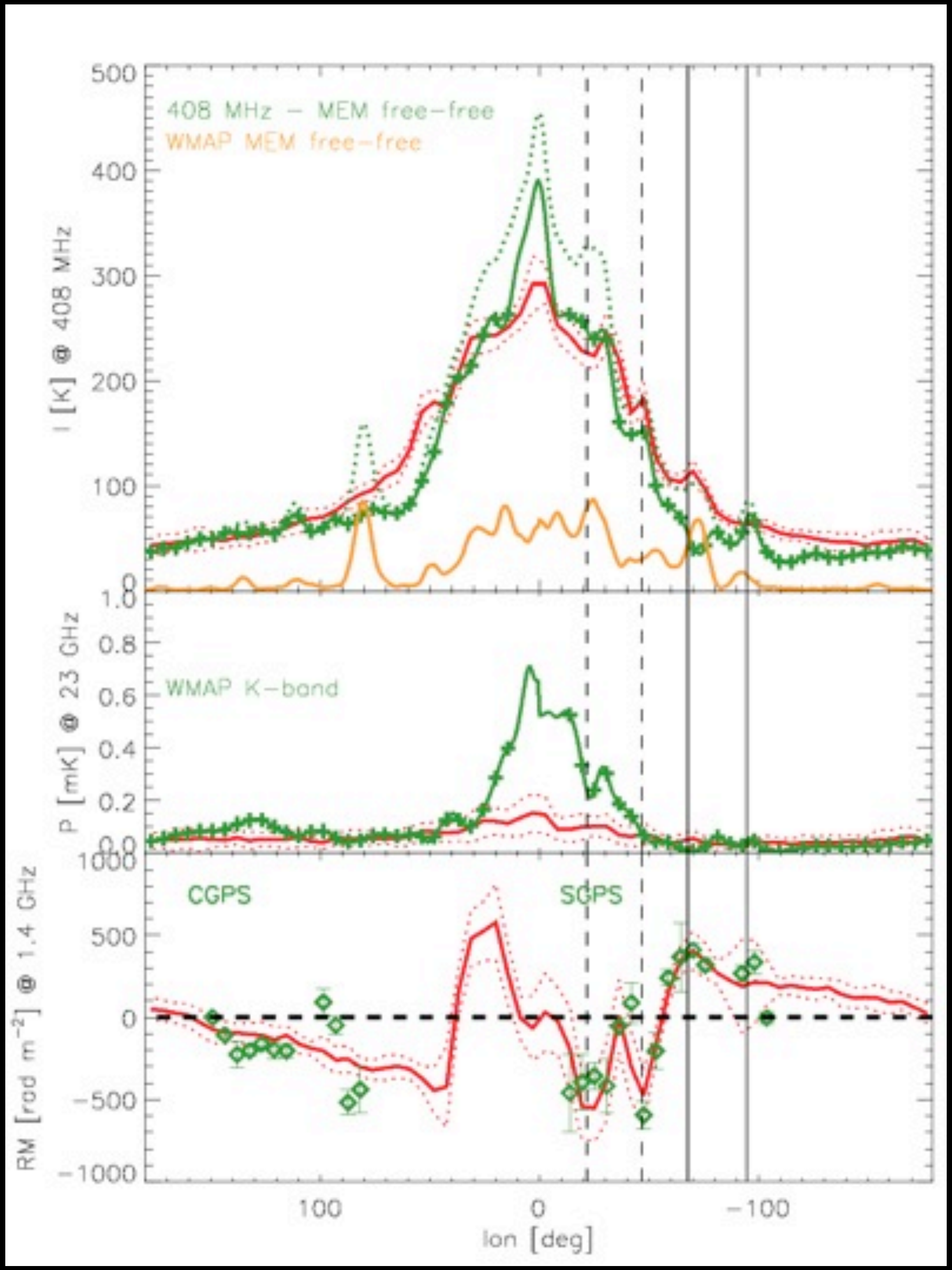
- With a reasonable estimate for n_e, RMs give B_{coh}.
- With a reasonable estimate for n_{CRE}, this shows you need a lot more to get *I* profile.

Cartoon example: Isotropic & homogeneous



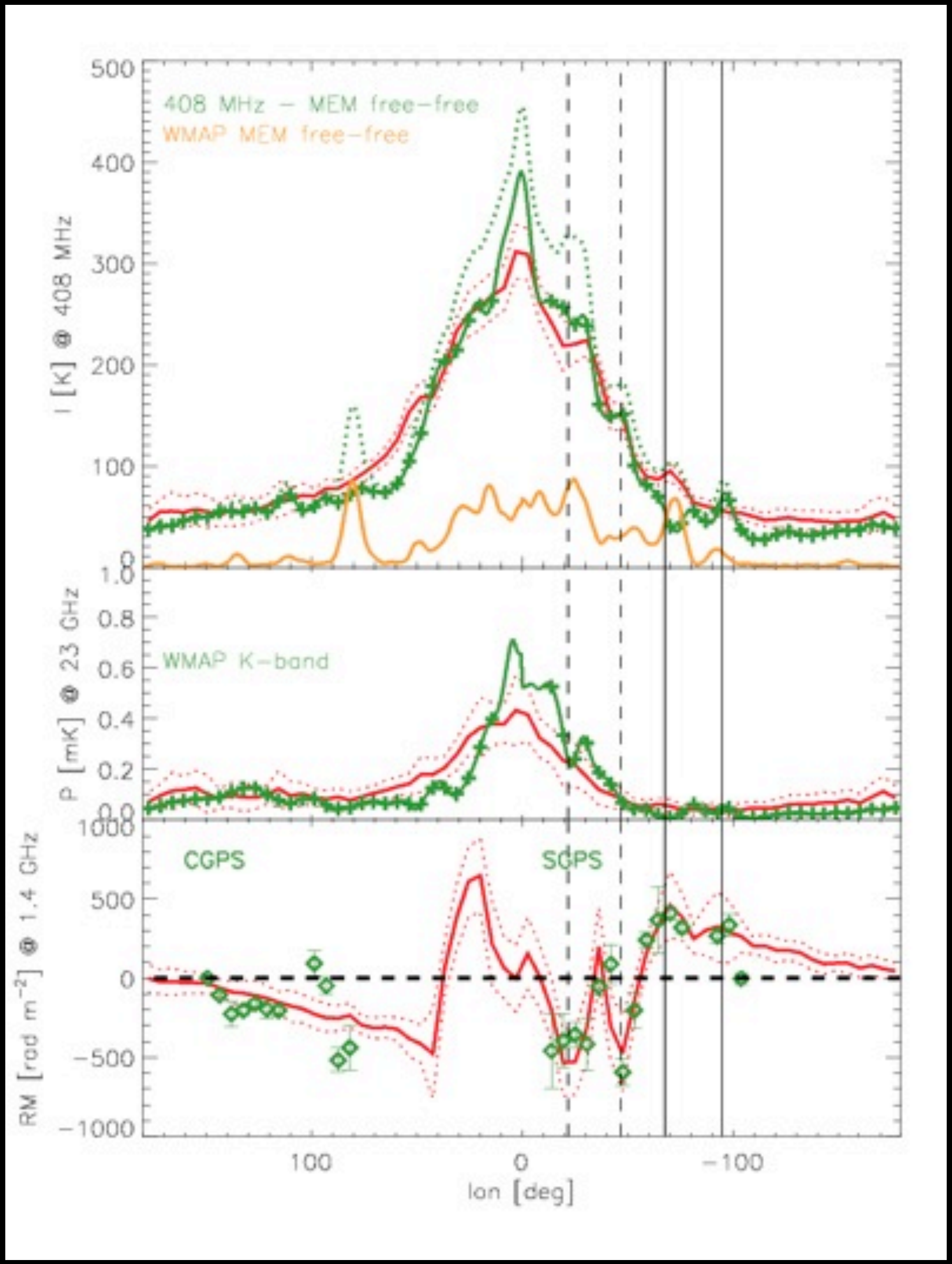
- Added simple GRF.
- No step features => B_{ran} should be amplified in the arms.
- Polarization still lacking, since isotropic random component cancels out, adding only variance.

Cartoon example: isotropic, inhomogeneous



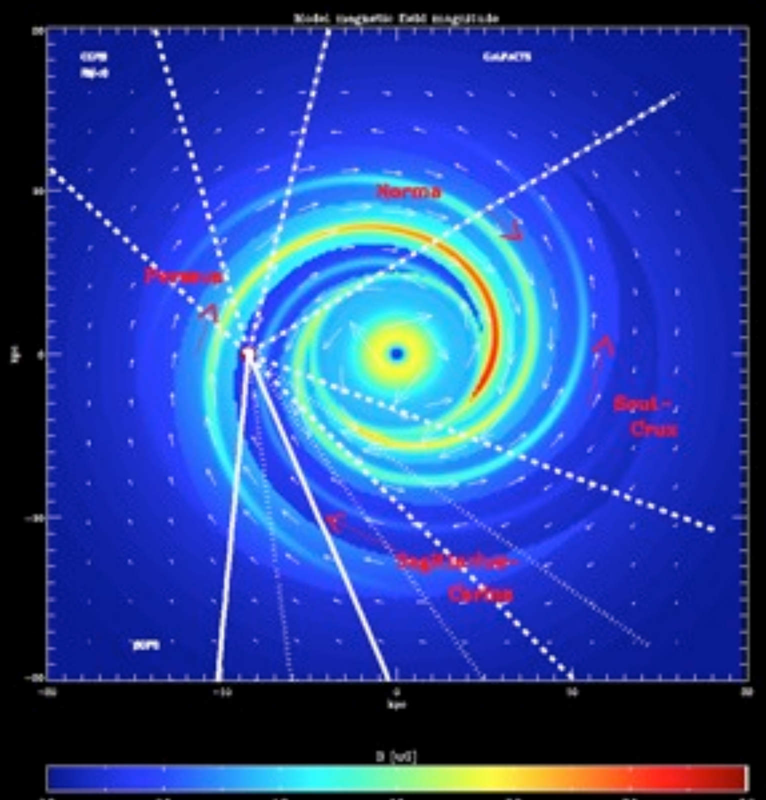
- Amplification of random field in arms, but still isotropic.
- Step features appear, a bit too peaked.
- *PI* remains under-predicted, since as before, isotropic random contributions cancel out.

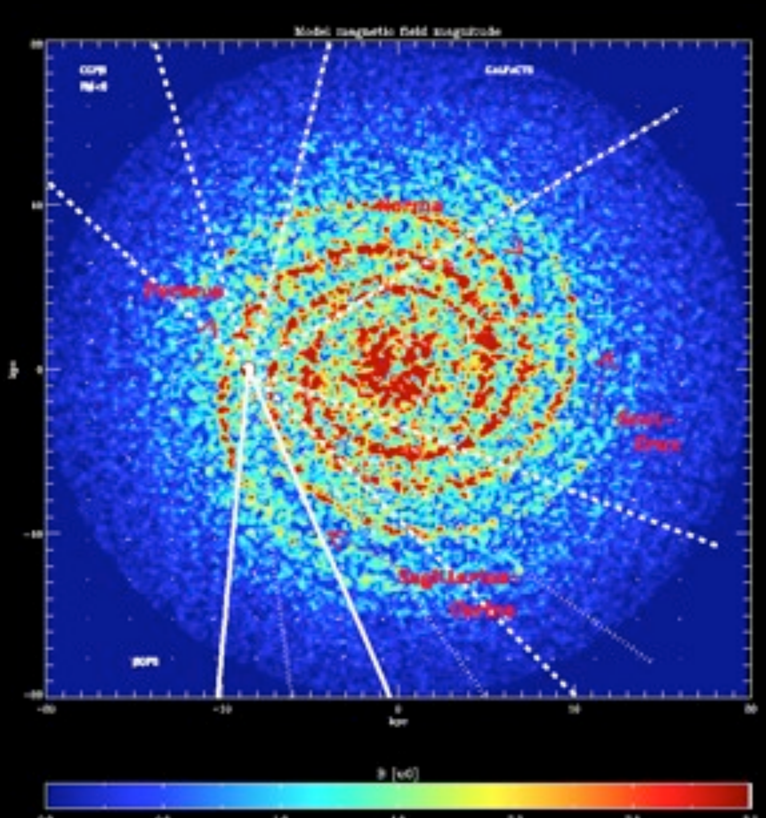
Cartoon example: anisotropic, ‘ordered random’



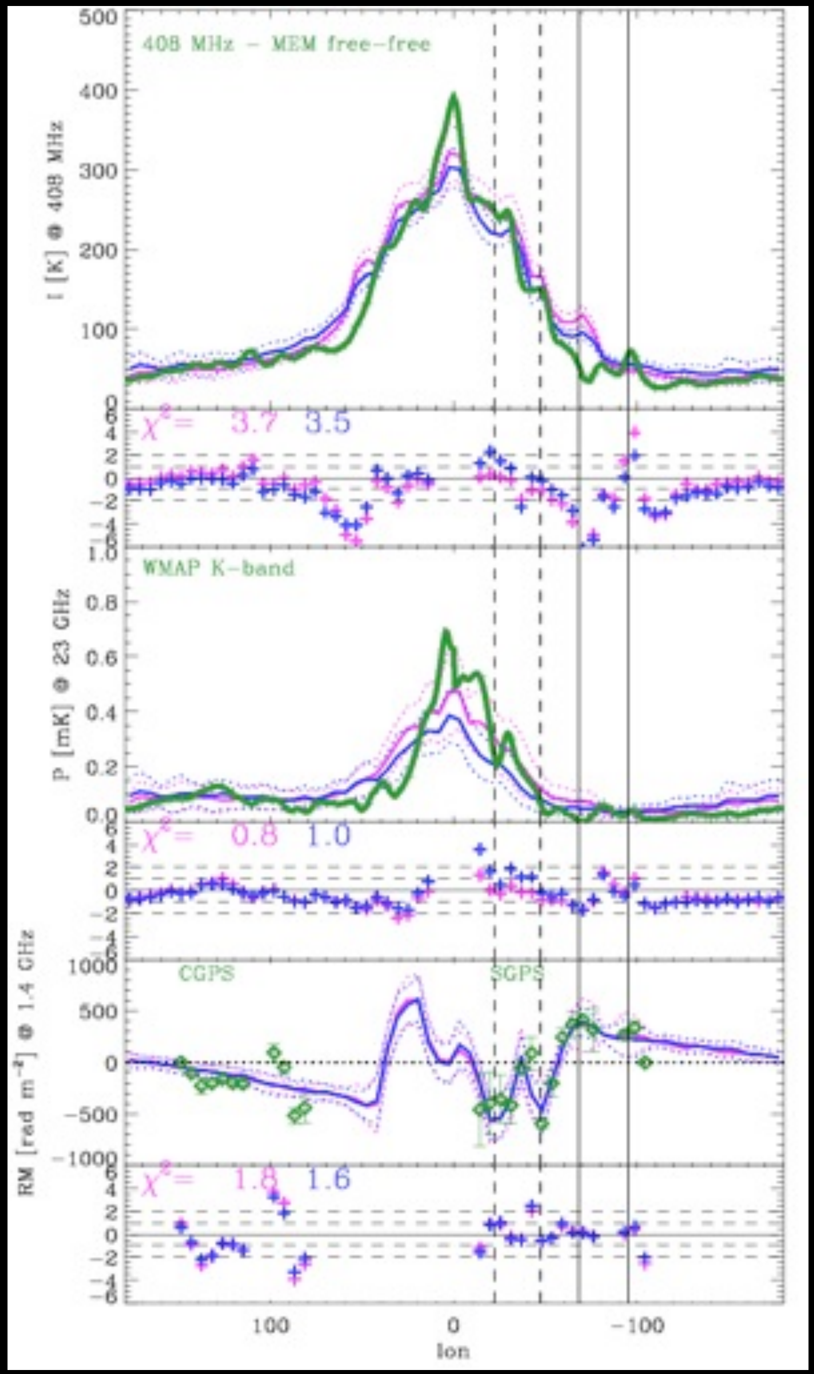
- Random field stretched along arm giving “ordered component” in addition to the isotropic random component.
- Can now fit the three observables.

First results:





- 8 parameters fit: ϕ_0, a_0 - a_4(arms+ring), B_{RMS}, f_{ord}.
- Orientation of spiral matches NE2001 n_e 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? Reversals?



Jaffe et al.

Main limitation: assumes simple power-law CRE spectrum from 0.1 to 1000 GeV. But CRE spectrum is degenerate with f_{ord}. To break the degeneracy, need an additional frequency.

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

CREs: or, real life isn't always a power law.

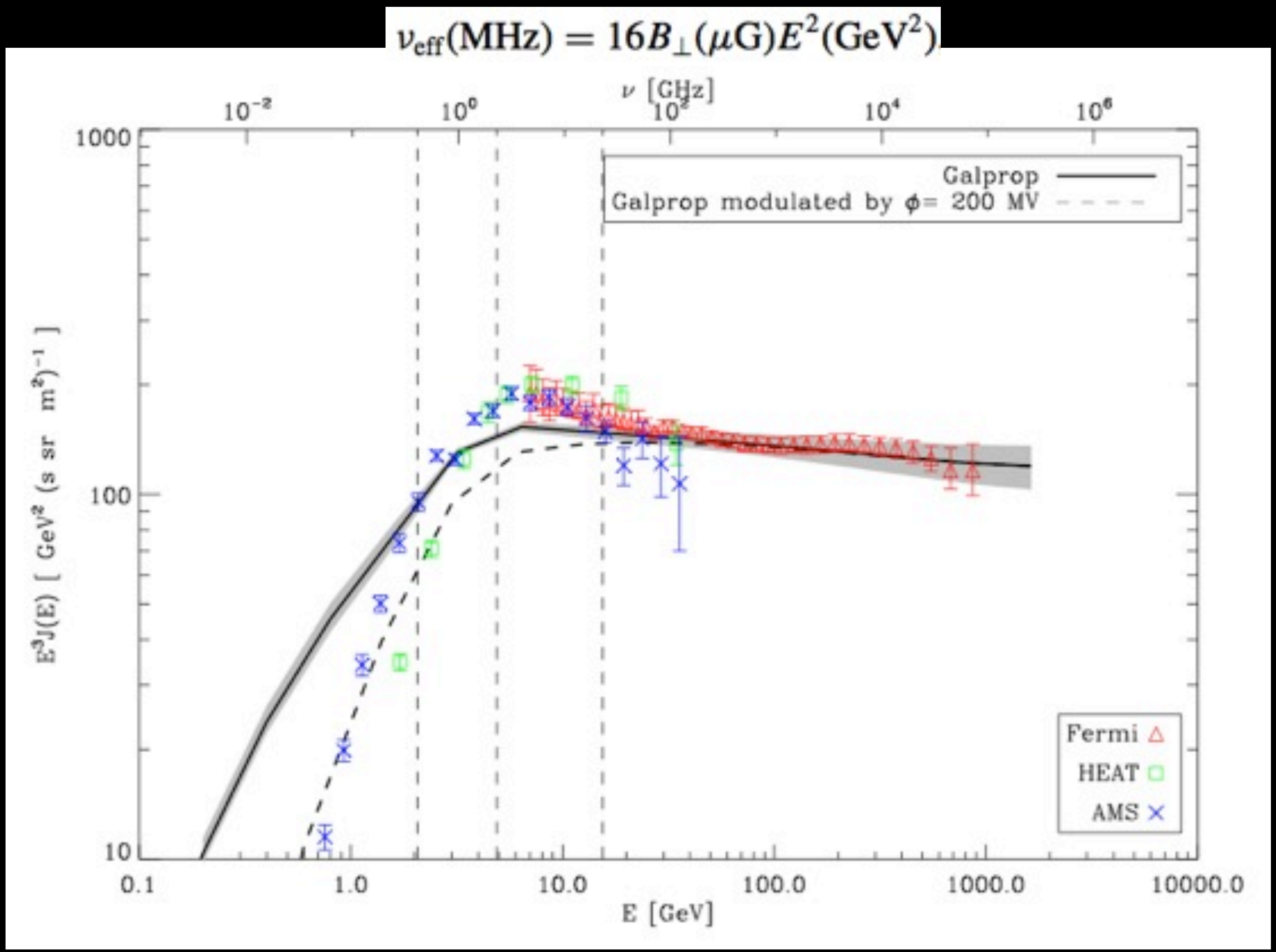
- Next step: link in GALPROP code of Strong and Moskalenko (2001)! Self-consistent in the sense that GALPROP is given the same magnetic field from *hammurabi*.
- Use full integration over CRE energy spectrum at each point in the 3D galaxy model:

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

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

  (see e.g. Rybicki & Lightman)
- Add a synchrotron data point: 2.3 GHz total I from Jonas et al. (1998).
- Add CRE model constrained by gamma-ray data (inverse Compton from the same electrons); see Strong et al. (2010).

CRE results:

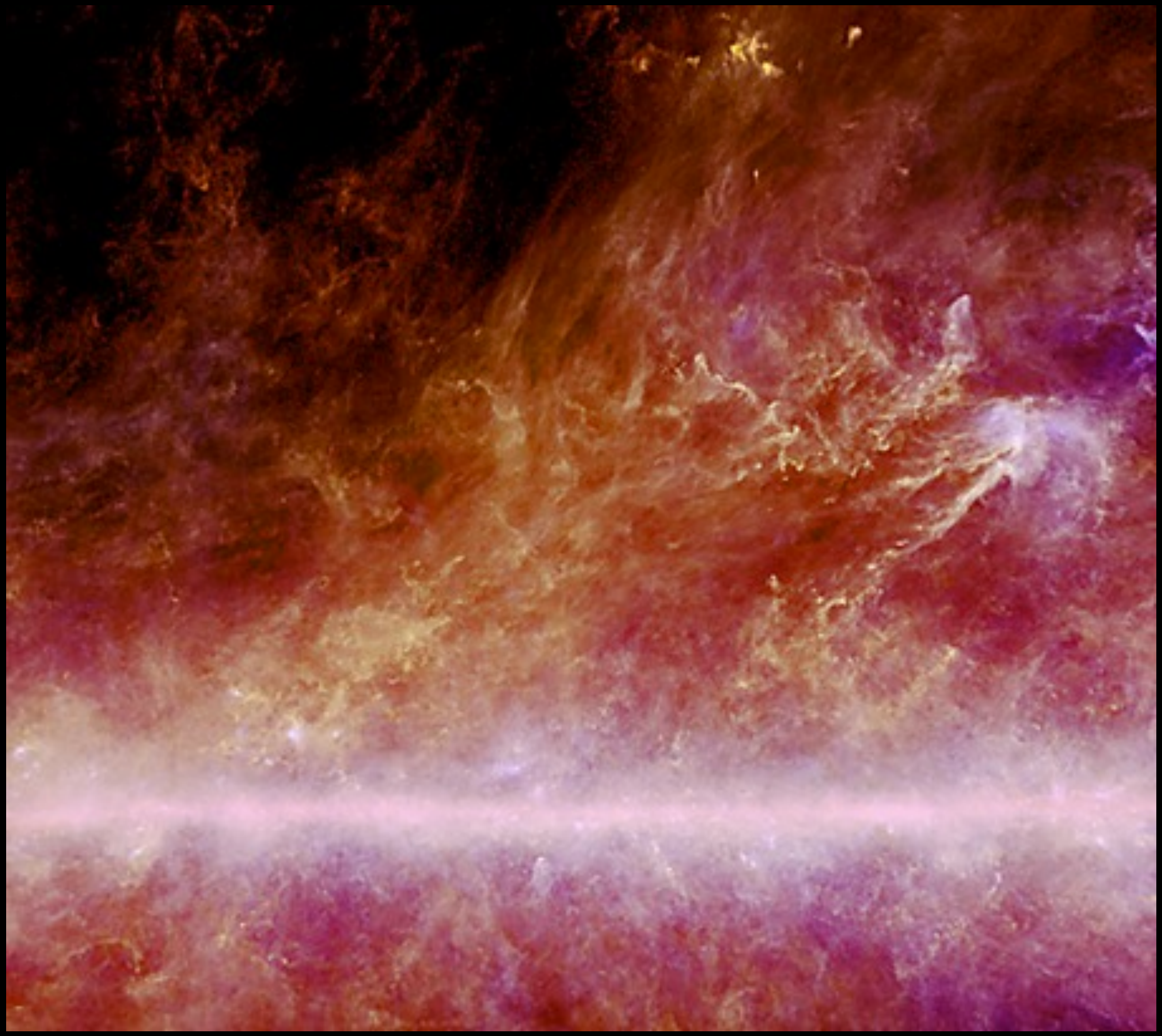


Jaffe et al. (2011): spectra above a few GeV constrained using γ-ray data, Strong et al. (2010).

Data: Fermi LAT collaboration (2009,2010), Duvernois et al (2001), Aguilar et al. (2002).

- Find below few GeV, $J(E) \sim E^{-1.3}$, slightly harder than usually assumed.
- (Break compared to $J(E) \sim E^{-2.3}$ above few GeV.)
- Note that at lower energies, solar modulation affects local measurements.
- Consistent with Strong, Orlando, & Jaffe (2011) high-latitude study from 40 MHz to 23 GHz.
- ***Two results***: firstly, better constraint on B-field components. Secondly, constraint on low-energy end of CRE spectrum otherwise inaccessible.

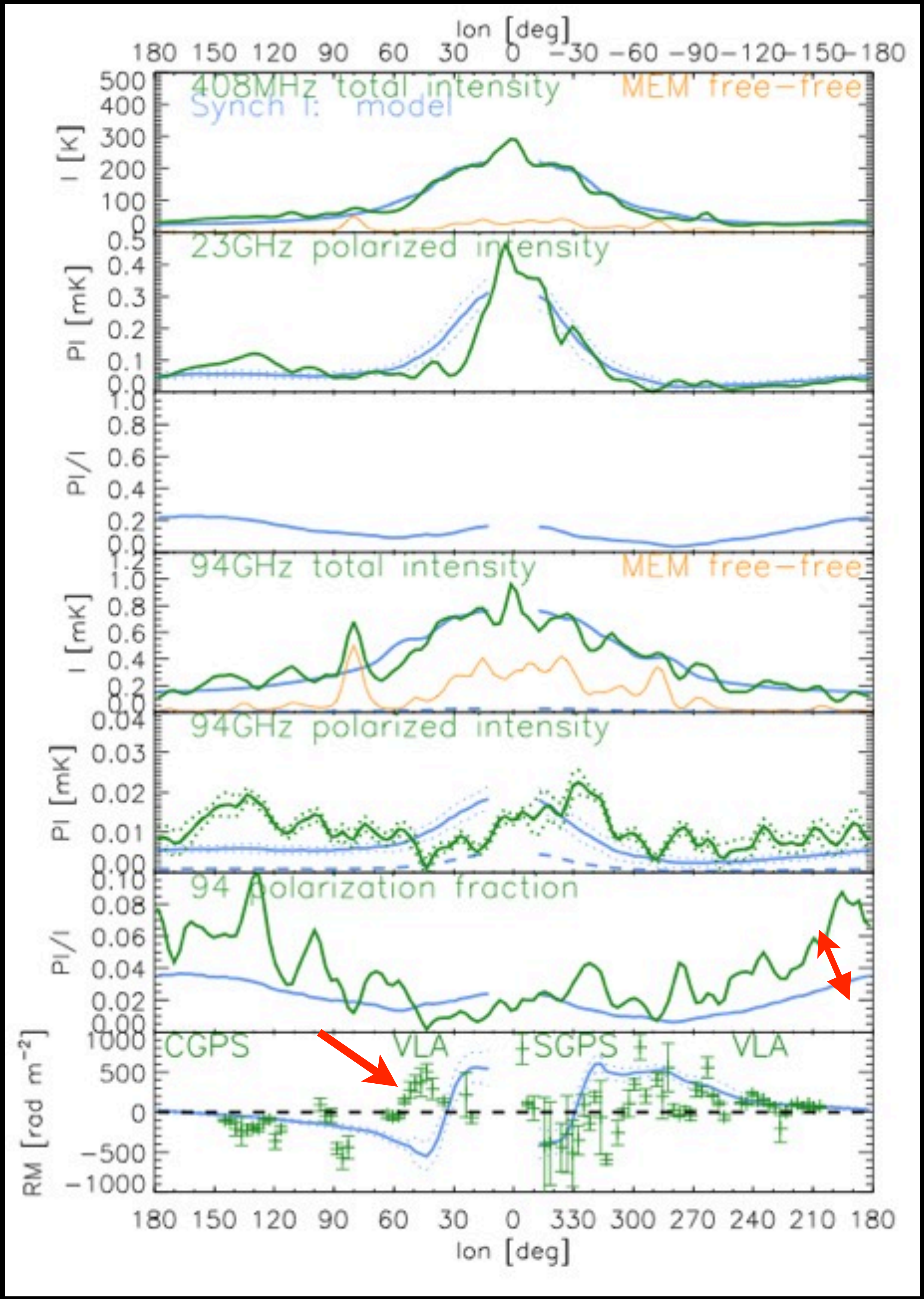
Planck:



Planck and IRAS composite image (ESA).

- Planck project on large scale magnetic field modeling using polarized dust mapped with unprecedented precision.
- Polarized dust emission is then a complementary observable independent of CRE or thermal electron distribution uncertainties affecting synchrotron.
- Using magnetic field geometry constrained by RM and synchrotron, we can study the dust distribution in the disk of the Galaxy.
- Can we probe polarized emissivity, e.g. as a function of dust temperature, radiative torque mechanisms, etc.?
- Informed by modeling of grain alignment processes from detailed studies of small regions, and perhaps vice versa.

Dust: ongoing work

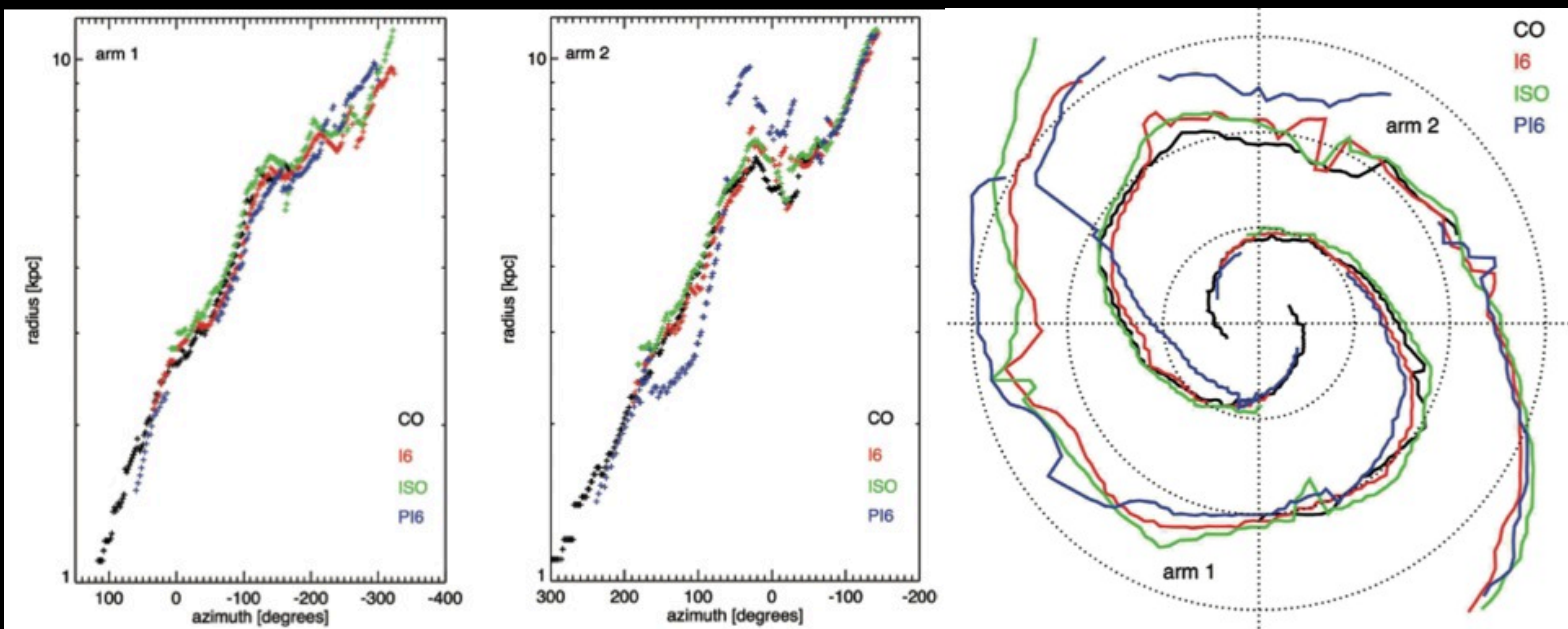


Jaffe et al.

- Simple model for thermal dust polarization does not work even with intrinsic PI/I of 30%. How interesting!
- Note also problem with van Eck data. No simple spirals!
- Polarization degree significantly under-predicted => dust emission coming from regions with more ordered fields.
- One solution is to separate arm ridges in different components.
- Cannot do it by changing dust distribution alone, so this is telling us about the magnetic fields as well.

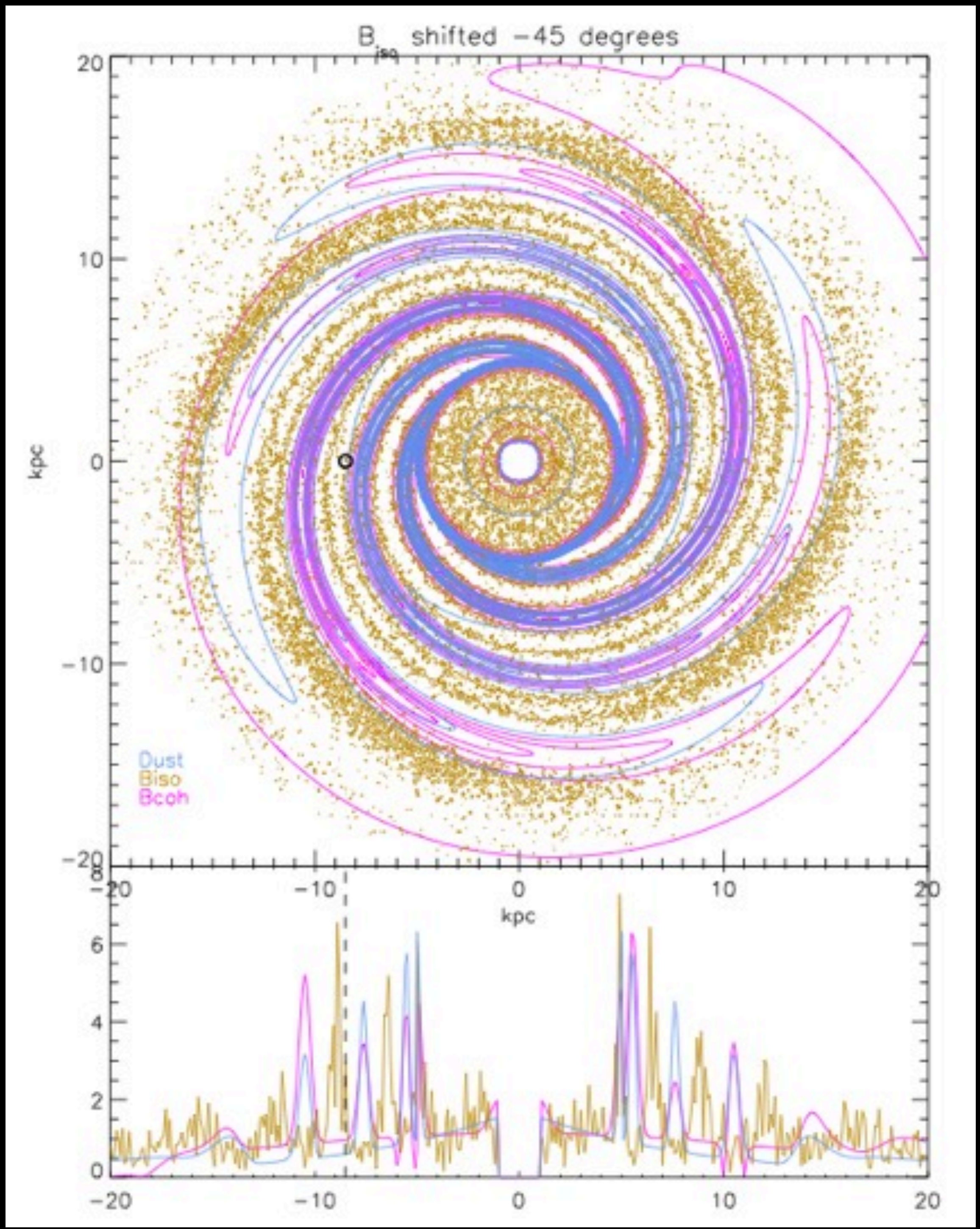
Spiral arm ridges: separable?

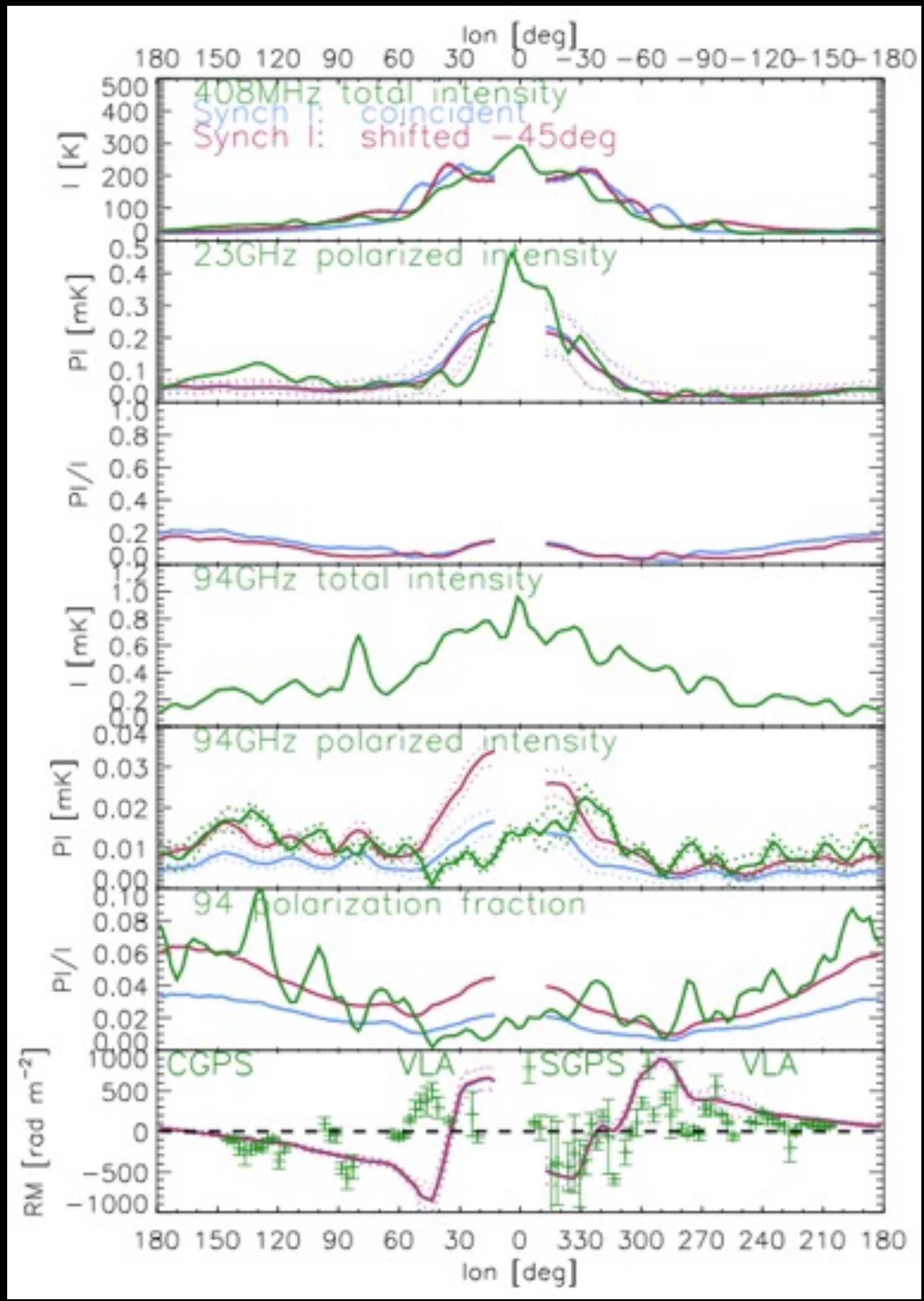
Spiral arm shock triggering star formation? CO and microwave-band dust trace relatively cold molecular clouds, whose collapse is triggered in the shock. Downstream, star formation heats PAHs and dust that emit in sub-mm (ISO). So CO at shock front, star formation trailing? What does this mean for the magnetic field components?



M51 component ridges, Patrikeev et al.

Spiral arm ridges: separable?





Jaffe et al.

T. Jaffe @ DESY, ITP, Hamburg, 28 Nov. 2012

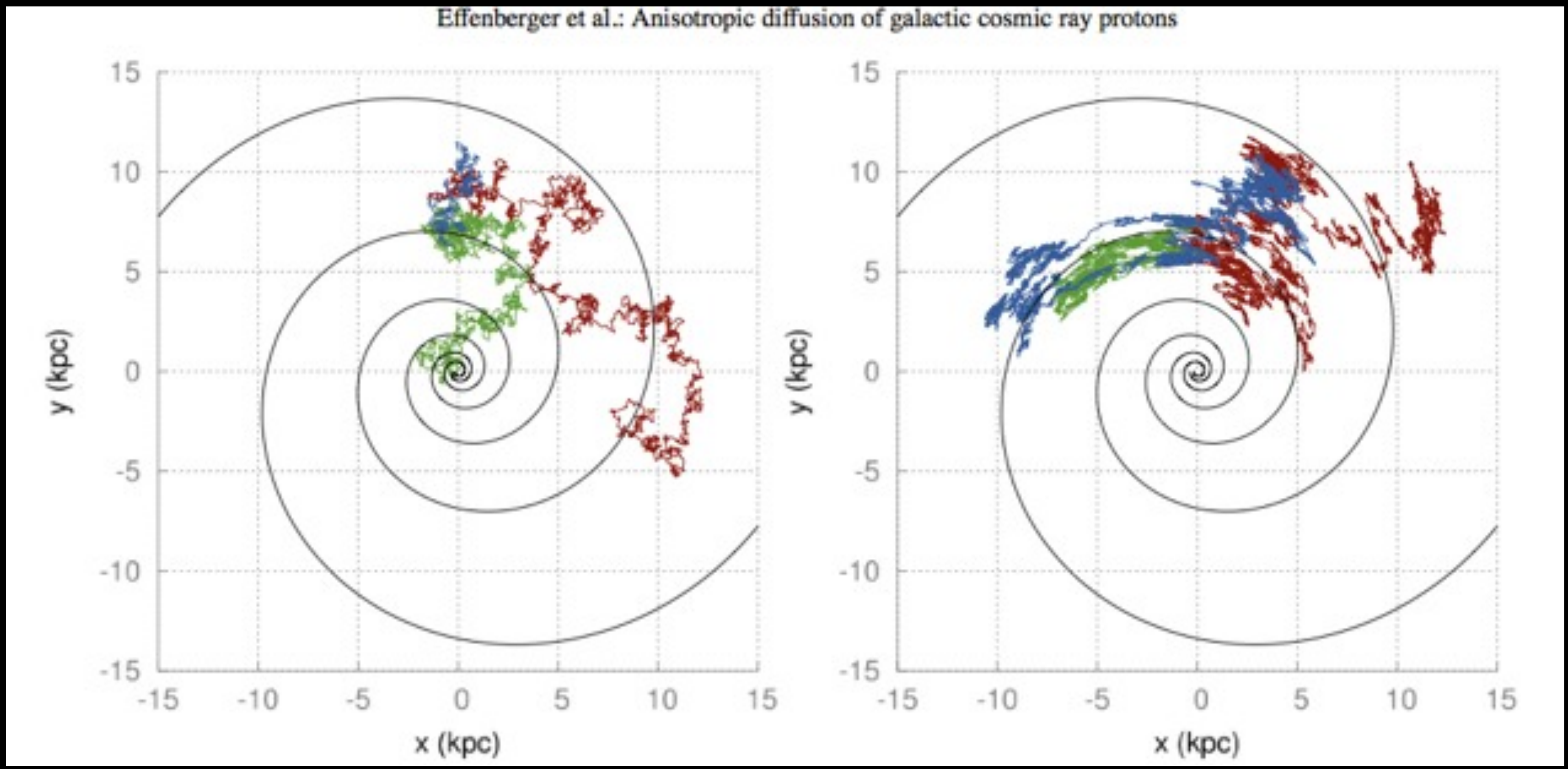
Arm modulation? Synchrotron in M51

M51 and field by Fletcher et al.

- Model of shock compression in spiral arms predicts roughly a factor of four ratio between pre- and post-shock for the component of the fields parallel to the shock, for the gas and dust, and at least that for the CREs.
- This is NOT observed in synchrotron in external galaxies (e.g. M51) or in the gamma-ray emissivity toward the Perseus arm, but it’s not clear whether the observations have the resolution given that the shock region could be fairly narrow.

Arm modulation? Source distribution

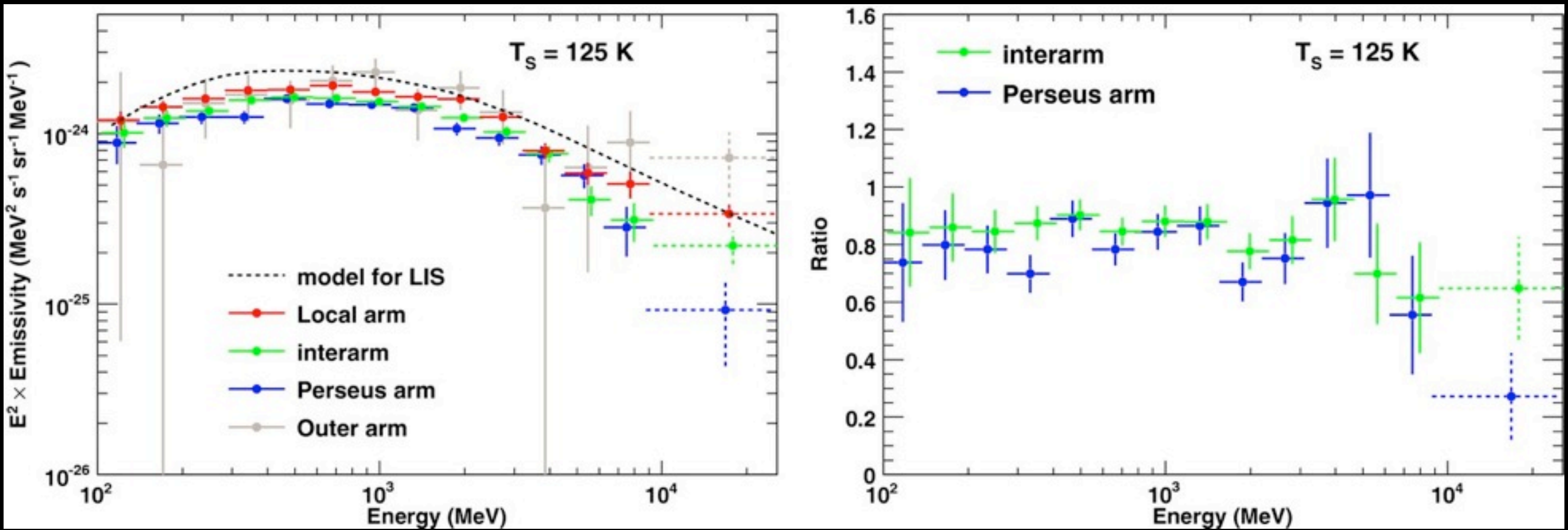
- CRE sources are also not uniformly distributed, and the CREs may remain highly inhomogeneous if the diffusion is highly anisotropic. Two effects, one in shock and one downstream, effectively smoothing it out?
- CRE diffusion depends on spatial distribution of turbulent fields. If CREs accelerated in same SNRs as generate the turbulence, this might result in little modulation.
- So we need a consistent model for both to match observables and theory.



Simulated CR proton propagation with (right) or without (left) anisotropic diffusion

CRE modulation? gamma-ray emissivity

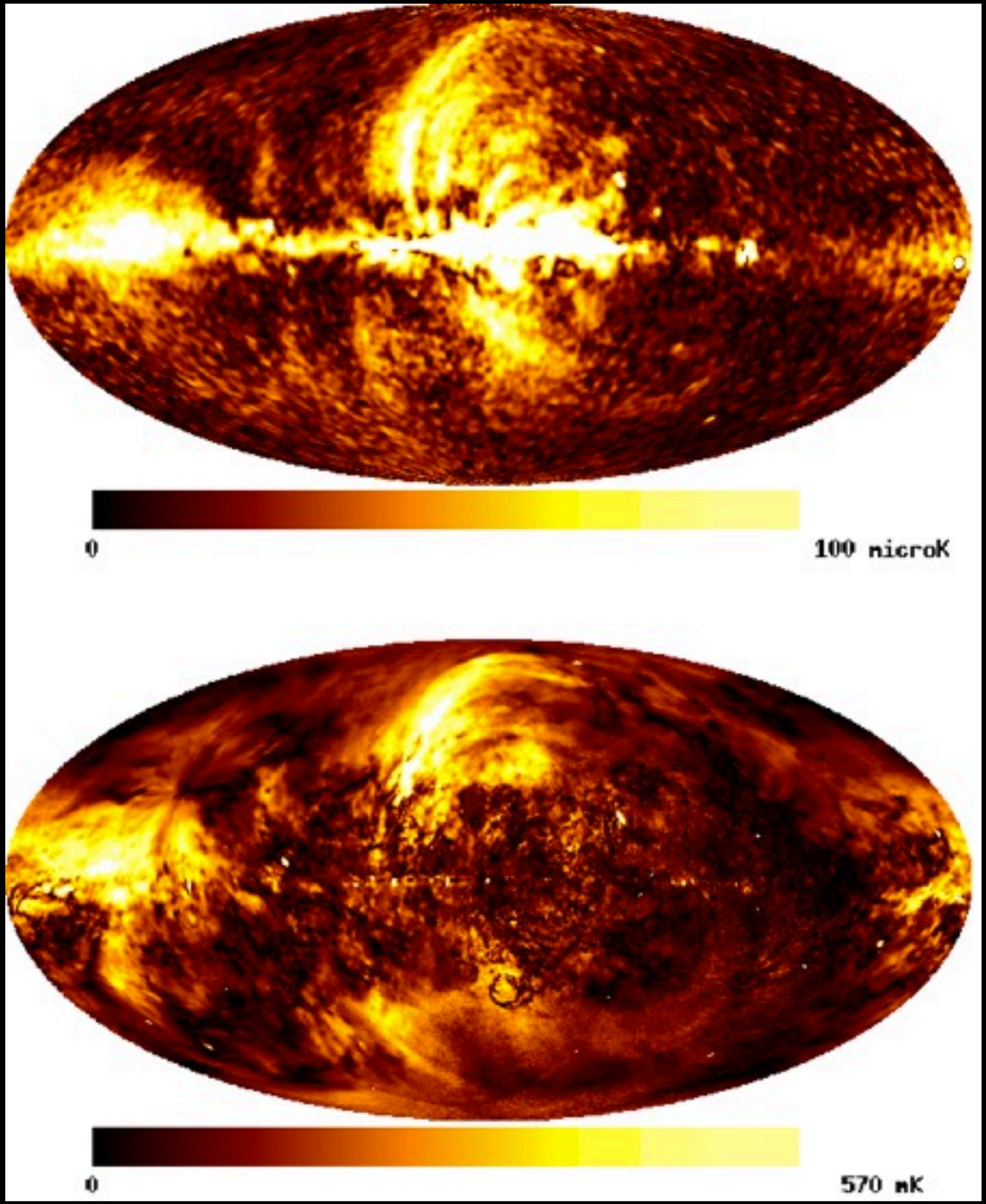
- CRE emissivity separated by comparison with dust, whose velocity information gives Galactocentric distance.
- No CR (proton) modulation seen between local arm, inter-arm region, and Perseus arm.
- CRE density drops with GC distance, so is this masking a modulation? But that distribution seems to need to be very flat for Fermi-based models... ?



Ackermann et al. (2010)

Magnetic field modeling plans

- Can we find a simple and physically motivated model that fits all of the data? E.g. van Eck et al. (2011) data inconsistent with Jaffe et al. (2010) model.
- What can the depolarization band at 1.4GHz tell us about the turbulent field?
- What explains the "Fan" region of high polarization on the plane in both synchrotron and dust emission?
- How does the field in the plane transition to the halo?
- Do the reversals in the plane reflect spiral structure related to the arms or bar?
- What field amplification models remain compatible with the large-scale properties of the field (e.g. CR- or turbulence-driven dynamo, etc.)
- **What does the depolarization band say about CRE diffusion, which relates to the turbulent fields?**
- ...



Top: WMAP 23 GHz polarized intensity.
Bottom: 1.4GHz polarized intensity (Reich & Testori)

Small scales: turbulence and depolarization

- *depth depolarization*, superposition of emission from a changing magnetic field direction along the line of sight;
- *Faraday depth depolarization*, where at low frequencies, emission rotated as it propagates (a.k.a. differential Faraday rotation);
- *beam depolarization*, polarization orientation changes within the observing beam.
- => Can model "Faraday screen", polarization "canals", and **polarization "horizon"**.

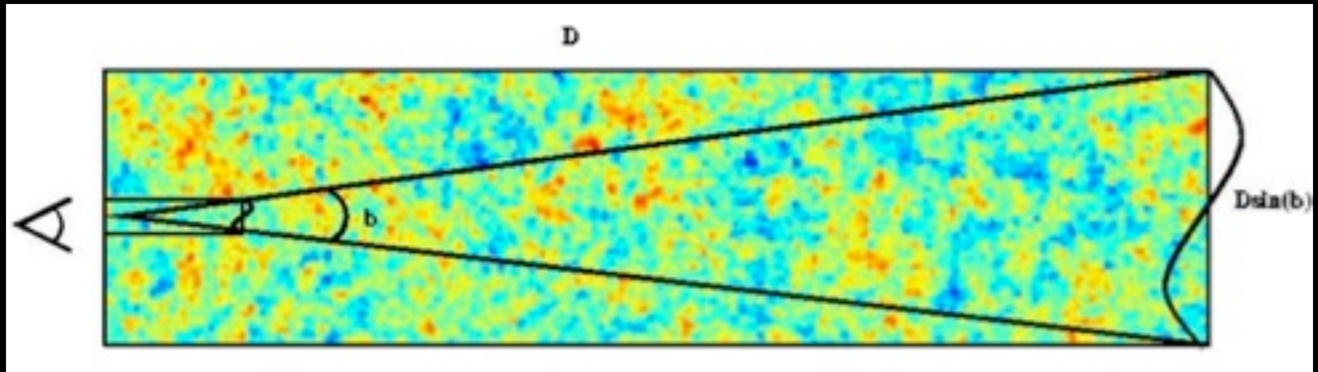
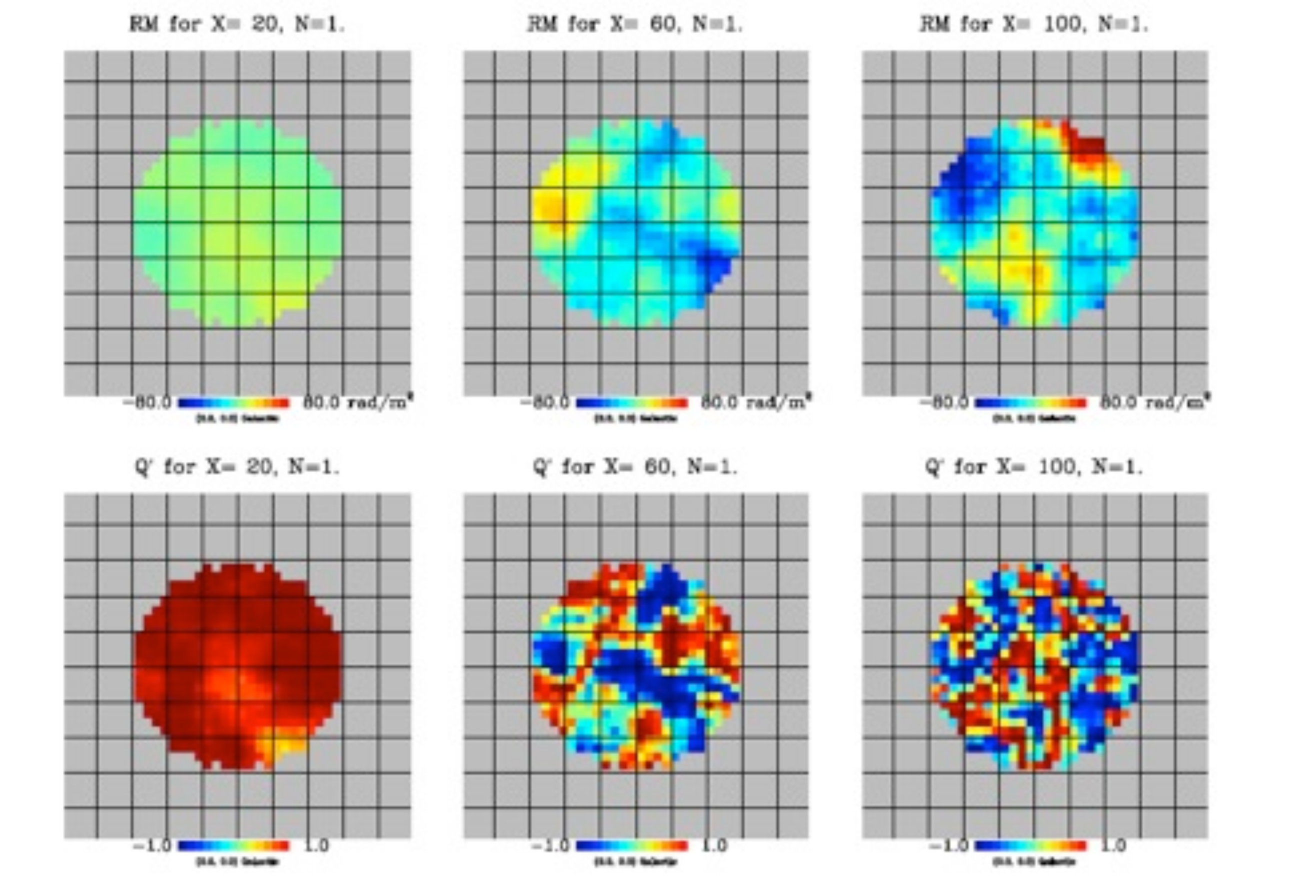


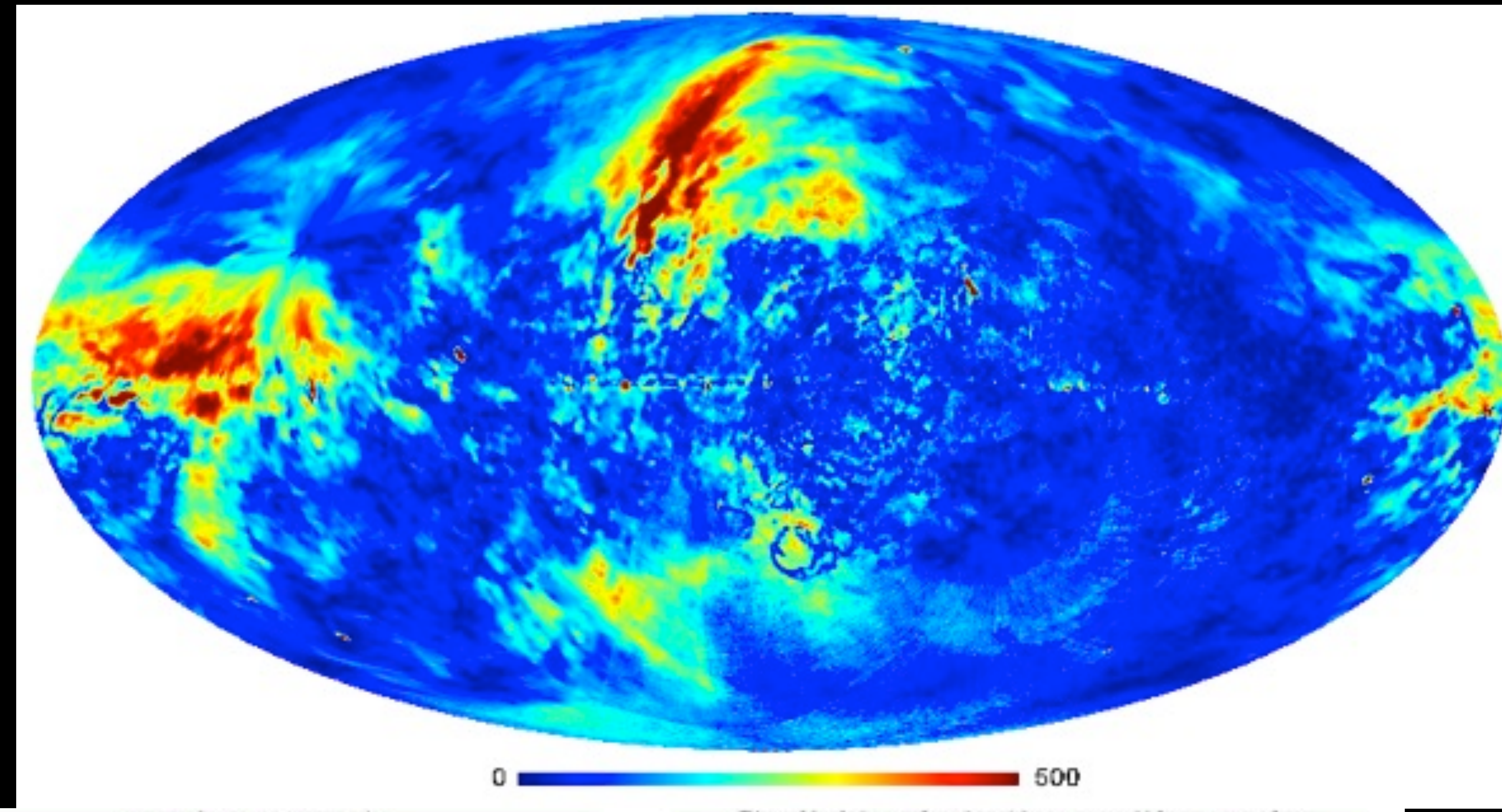
Figure 2. Schematic of a simulation.

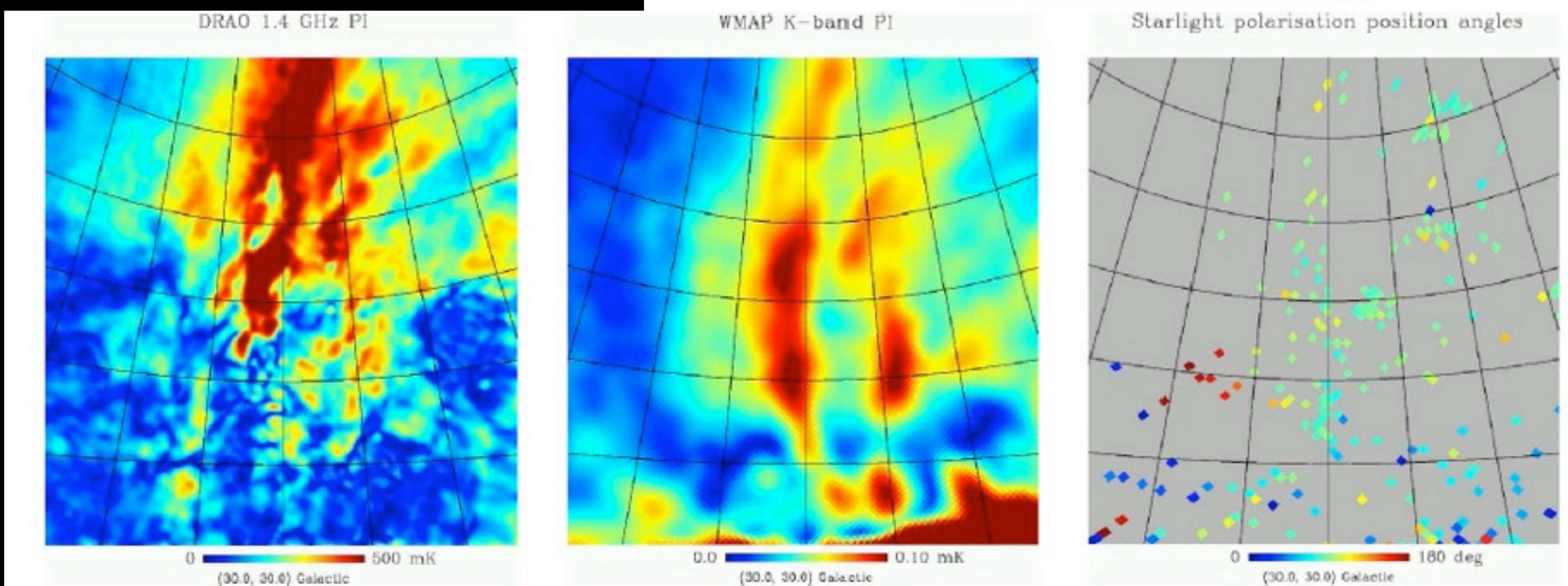


Small-scales: turbulence & NPS?

Intrinsic depolarization (e.g. Wolleben 2007) or Faraday screen? Galactic polarization horizon? Relation to local arms?

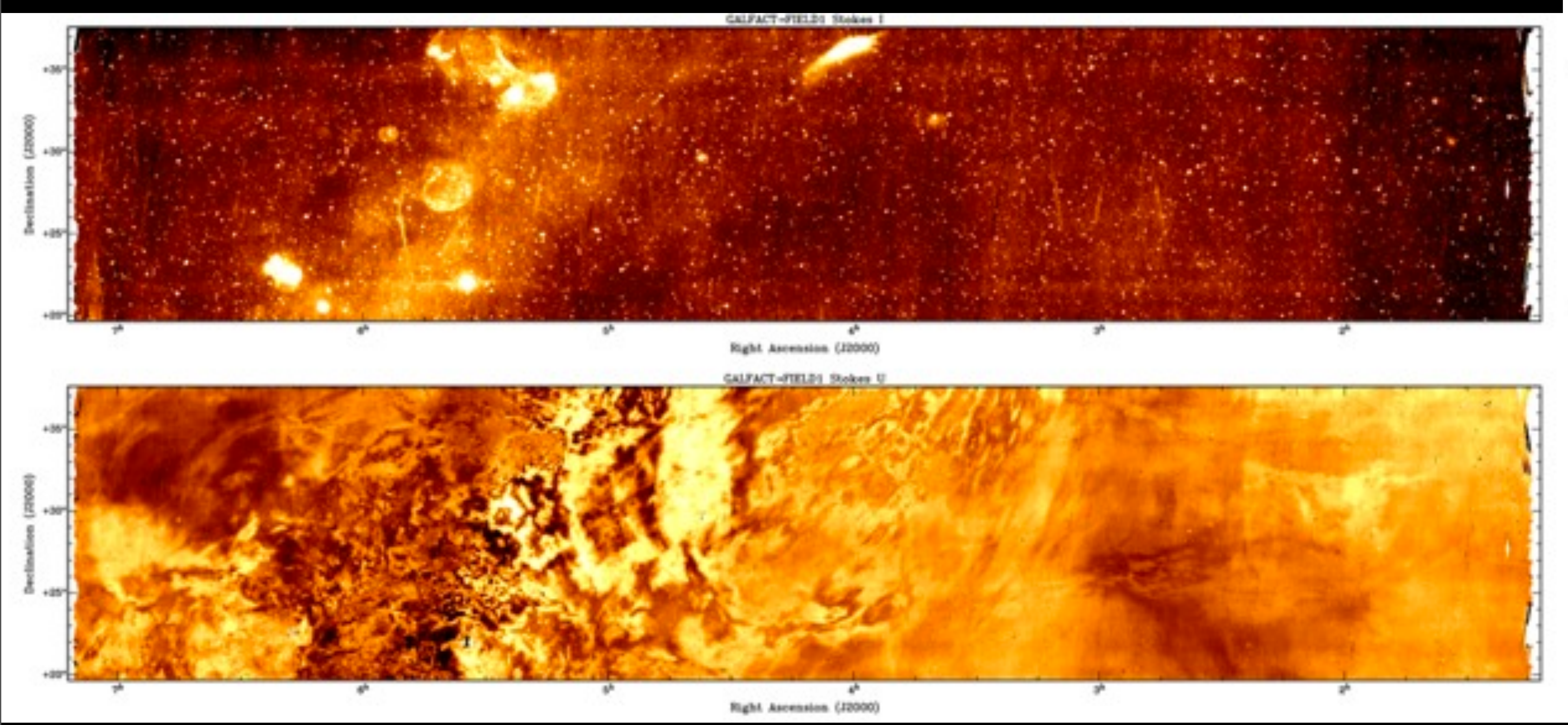
(And the “Fan”?)

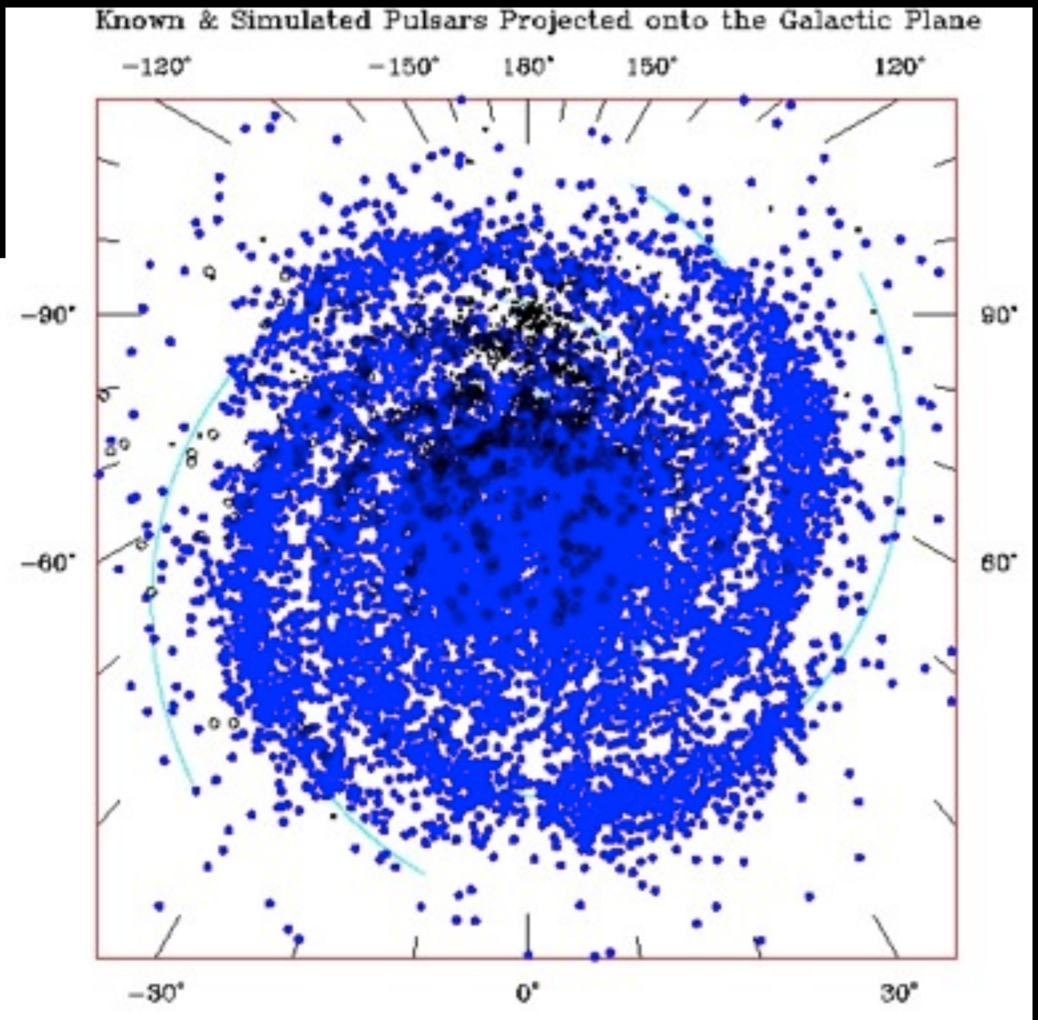




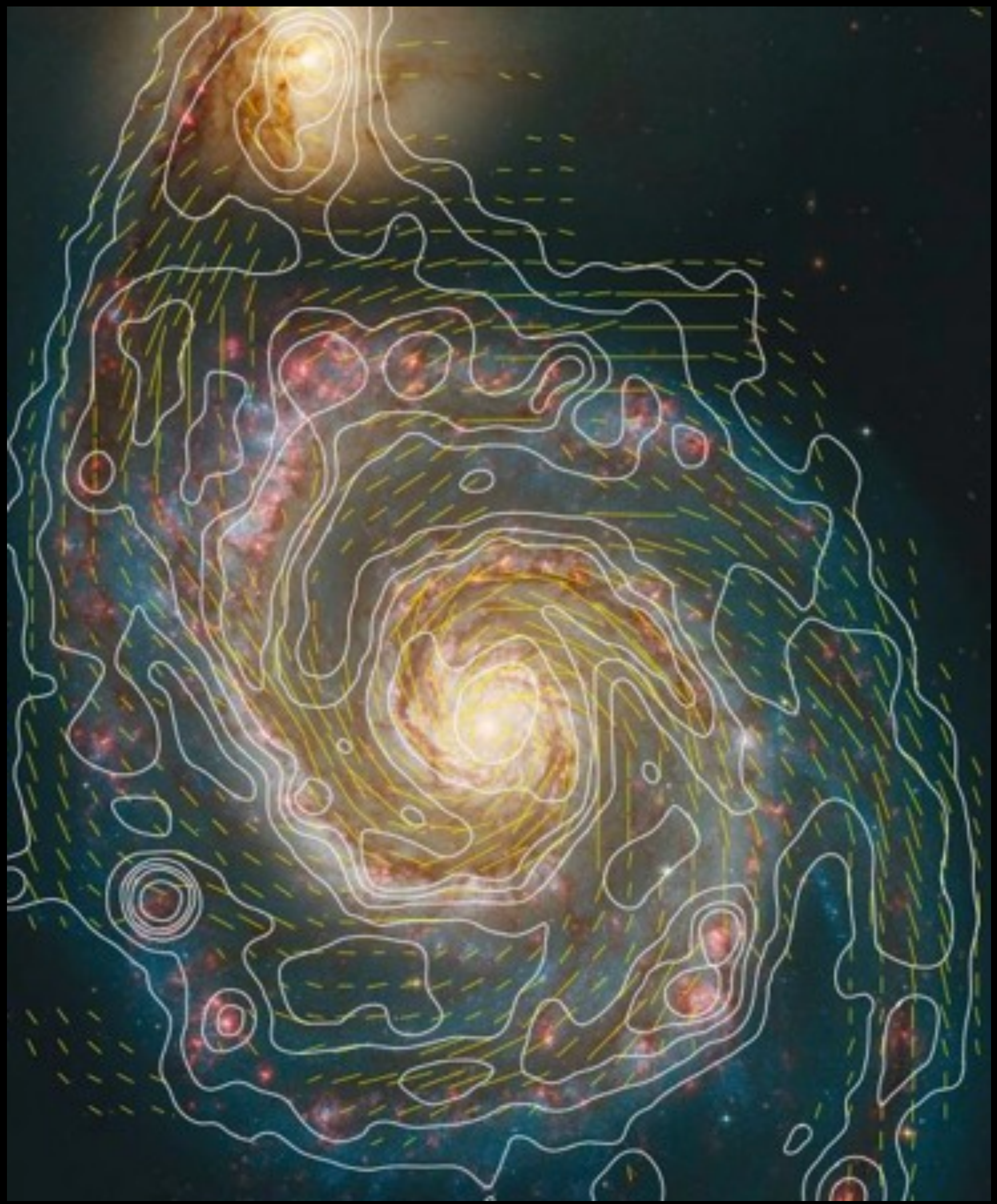
Prospects:

- **C-Band All Sky Survey (C-BASS)** full sky, full Stokes, at 5 GHz. Important for CMB component separation, synchrotron and magnetic field modeling projects, etc.
- **GALFACTS** polarization survey at 1.4GHz from Arecibo. An order of magnitude more extragalactic RM sources as well as diffuse polarized emission for RM synthesis. Can use hammurabi to model turbulence, depolarization horizon, SNa remnants, RM synthesis testing, ...
- **LOFAR** to model fields in Galactic halo, particularly where fields weak, ionized gas tenuous.
- **Gaia** for mapping out dust distribution using stellar extinction and for starlight polarization
- SKA to map all the Galactic pulsars beamed toward us
- PILOT, PIXIE to better map polarized dust
- ...





External galaxies:



M51 in optical (HST) with radio (5 GHz, VLA & Effelsberg) intensity contours and field directions

- Most of the same questions apply.
- A variety of morphologies are apparent in polarized emission, with magnetic arms often, but often not, following arms seen in gas tracers.
- Will use modified hammurabi to model what we will see with LOFAR and SKA.
- Easier than our own Galaxy because we can look from outside, harder because of a lack of RM measurements. **But...**

SKA!

SKA will allow Faraday RM measurements of background sources to get not only orientation but direction: reversals?

Shamelessly stolen figure, simulation from B. Gaensler of M31
with ~10000 background RM sources expected with SKA!

Conclusions: (wake up!)

- It’s a very exciting time to be studying galactic magnetic fields.
- You need many different and complementary observables to study the galactic magnetic field.
- The days of conflicting models being consistent with the data due to degeneracies and uncertain inputs are numbered.
- In the process of attempting to model the magnetic fields, we learn about things from CRE spectra to dust distribution and alignment processes.
- The fact that our models don't fit very well is a Good Thing. It means there's a lot of information there and a lot to do.