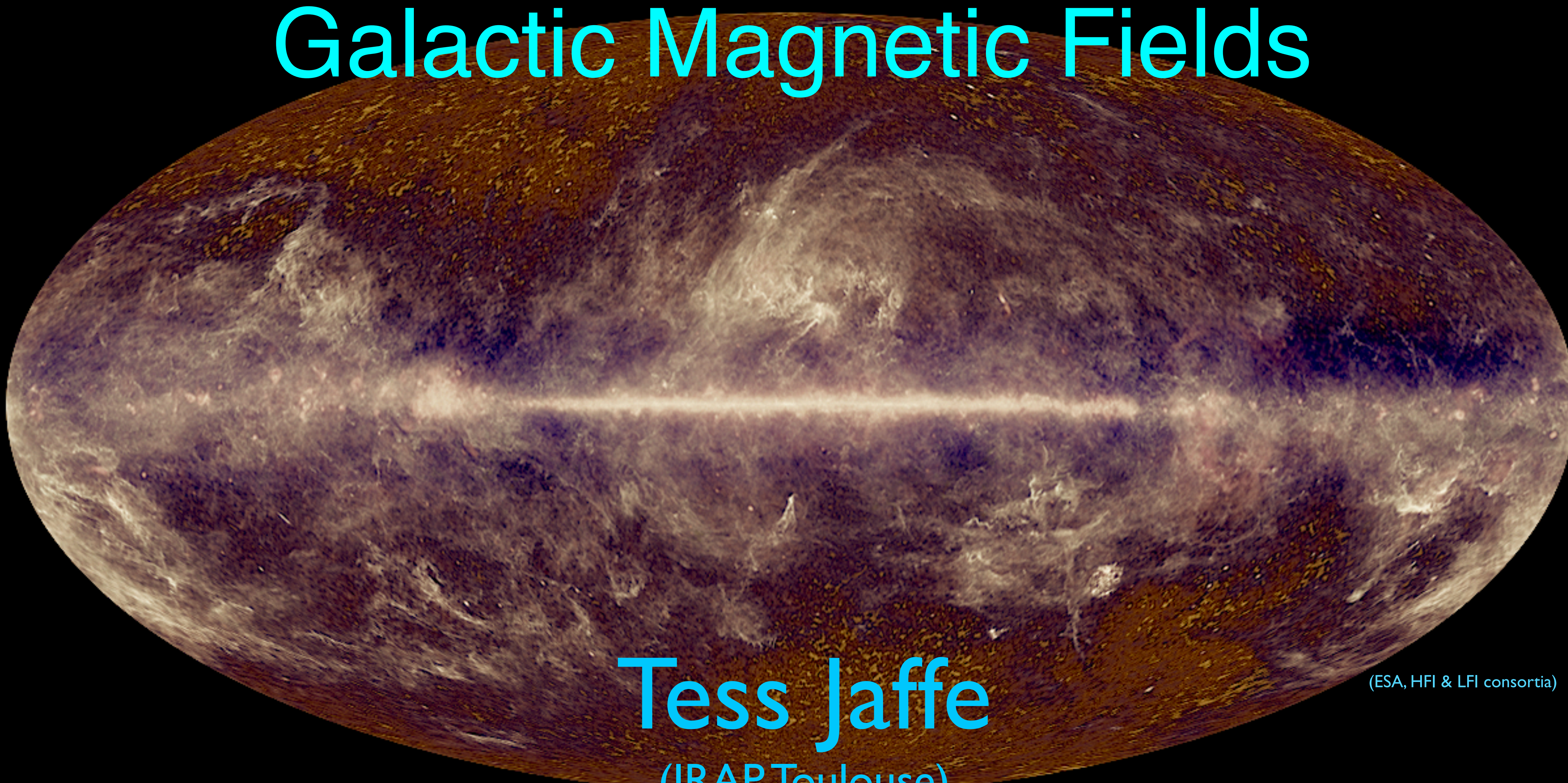
Multi-wavelength Modeling of Galactic Magnetic Fields



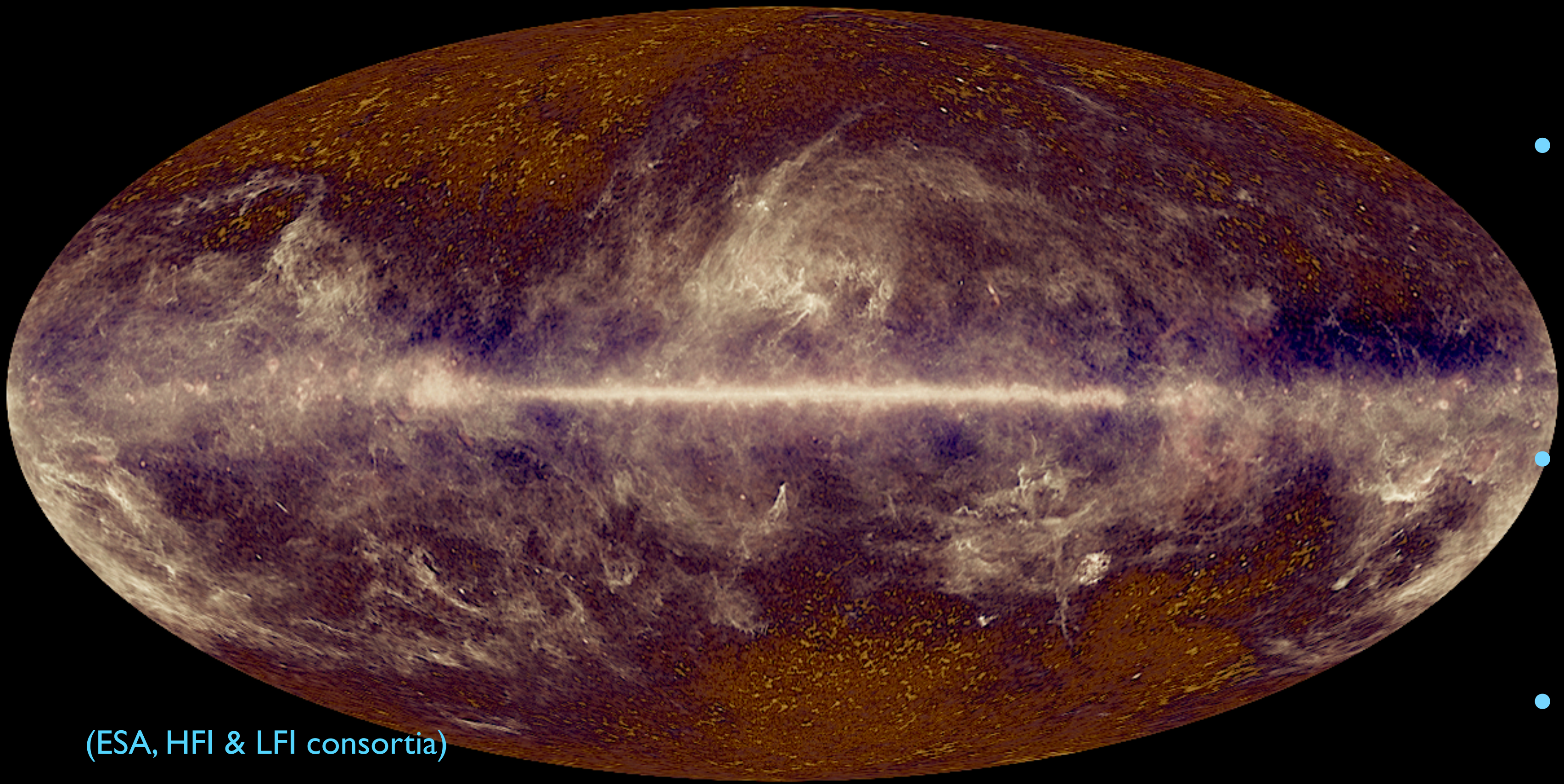
(ESA, HFI & LFI consortia)

Tess Jaffe

(IRAP, Toulouse)

with A. J. Banday (IRAP, Toulouse), J.P. Leahy (JBCA, Manchester), A.W. Strong (MPE, Garching), J. Macías-Perez (LPSC, Grenoble), L. Fauvet (ESTEC), and more....

CMB foregrounds: Planck view



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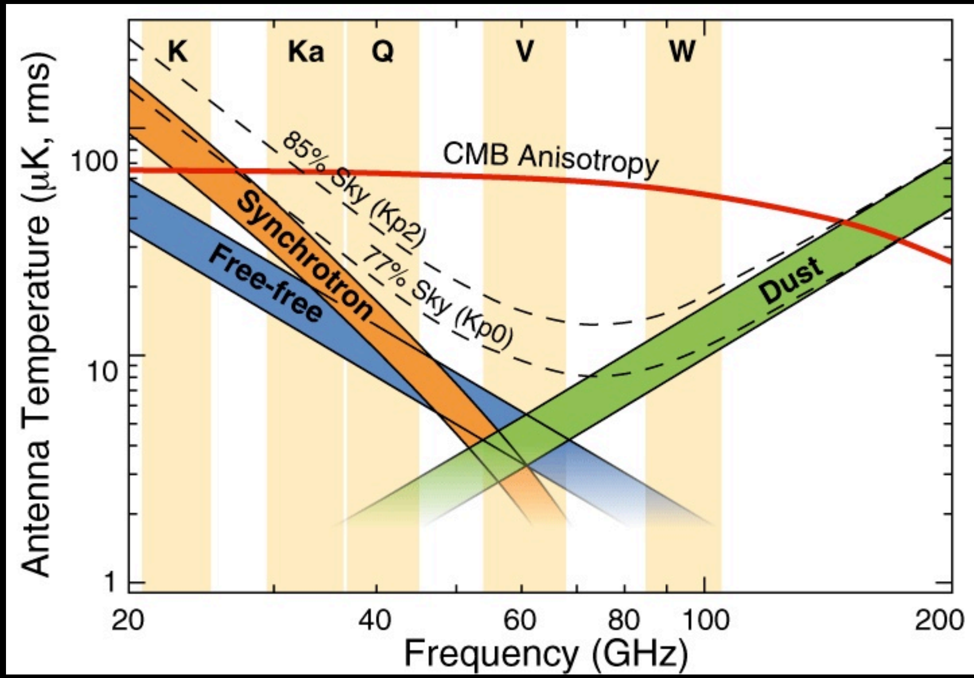
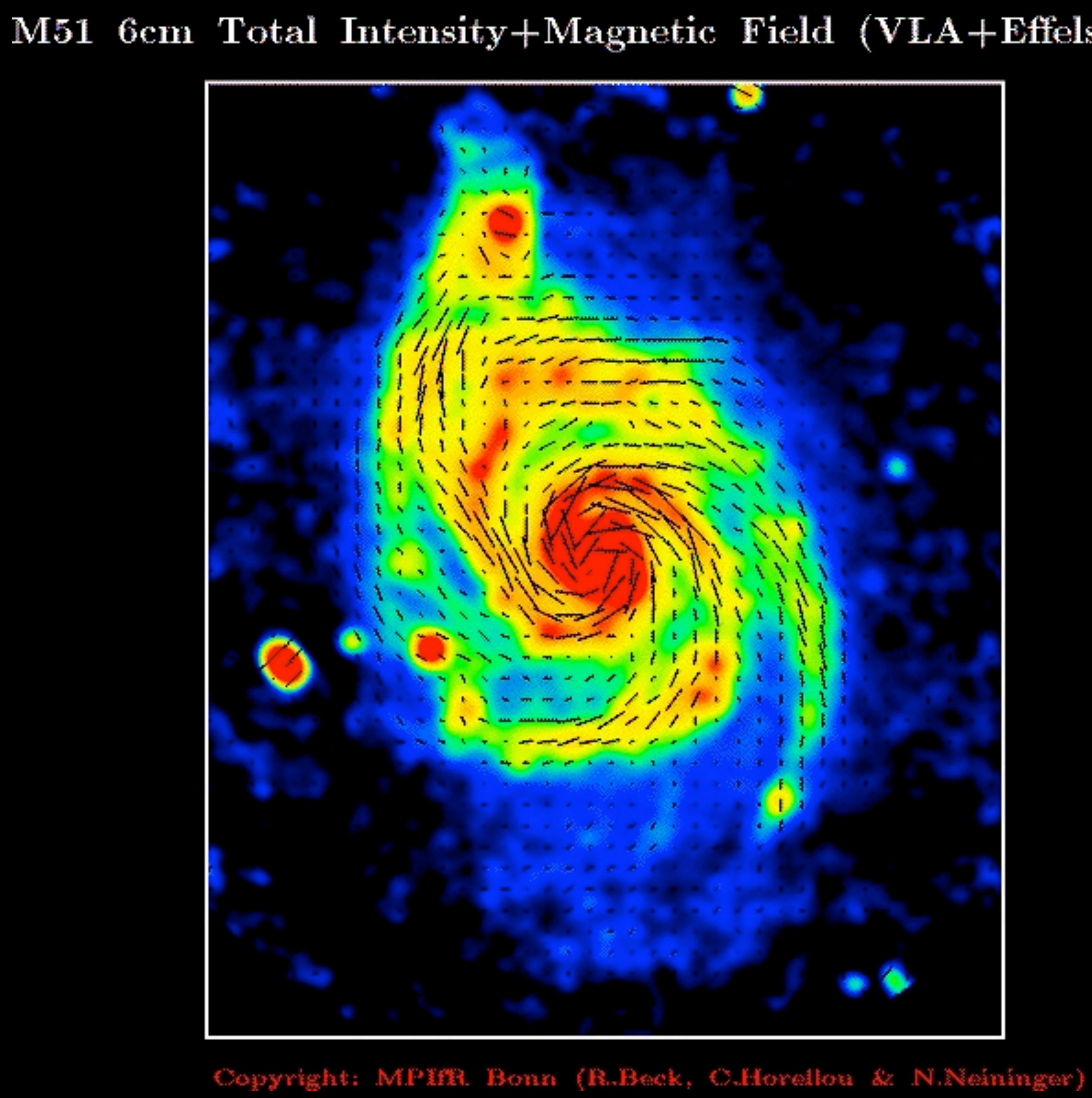


WMAP team

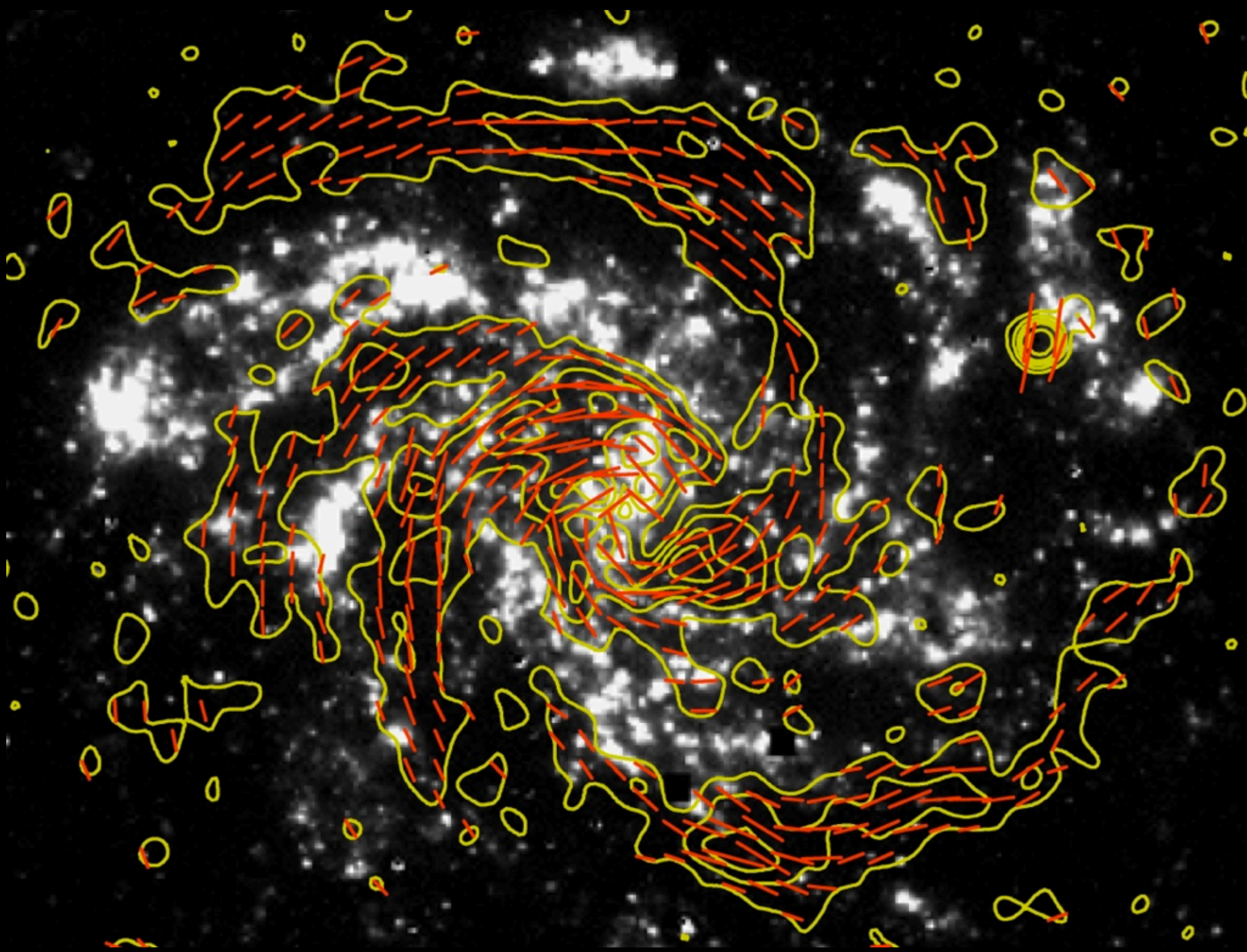
- CMB observations in the sweet spot between different foreground components that would otherwise dominate.
- At low frequencies (few 10s of GHz), the synchrotron dominates the CMB.
- At high frequencies (few 100s of GHz), the dust dominates.
- Note that we do not aim to produce a model to be subtracted 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

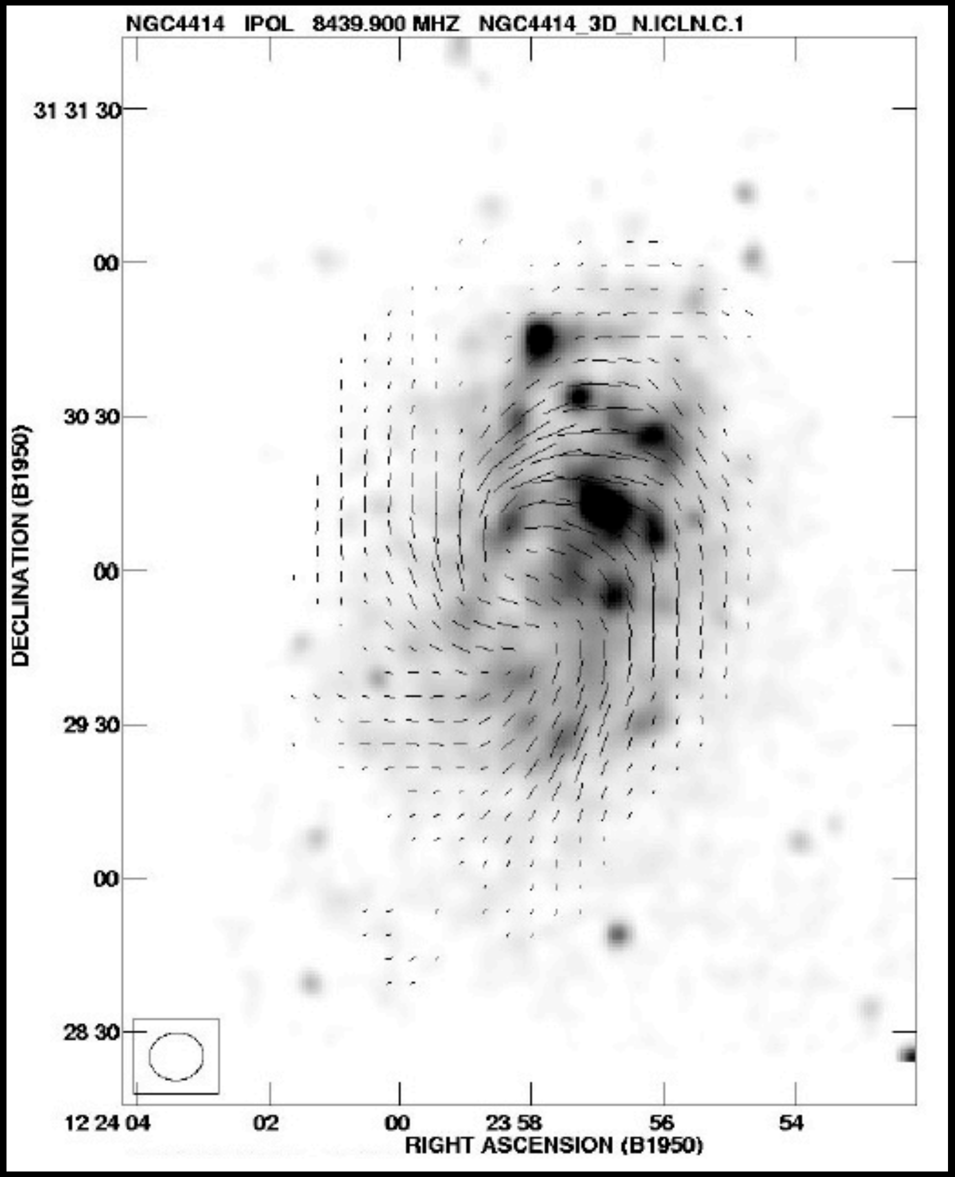


- First order: magnetic fields aligned with matter spiral structure. Can't be coincidental.
- Unfortunately, we cannot see our own galaxy like this.
- Furthermore, in an external galaxy, we cannot see the direction, but only its orientation.

External galaxies: other examples



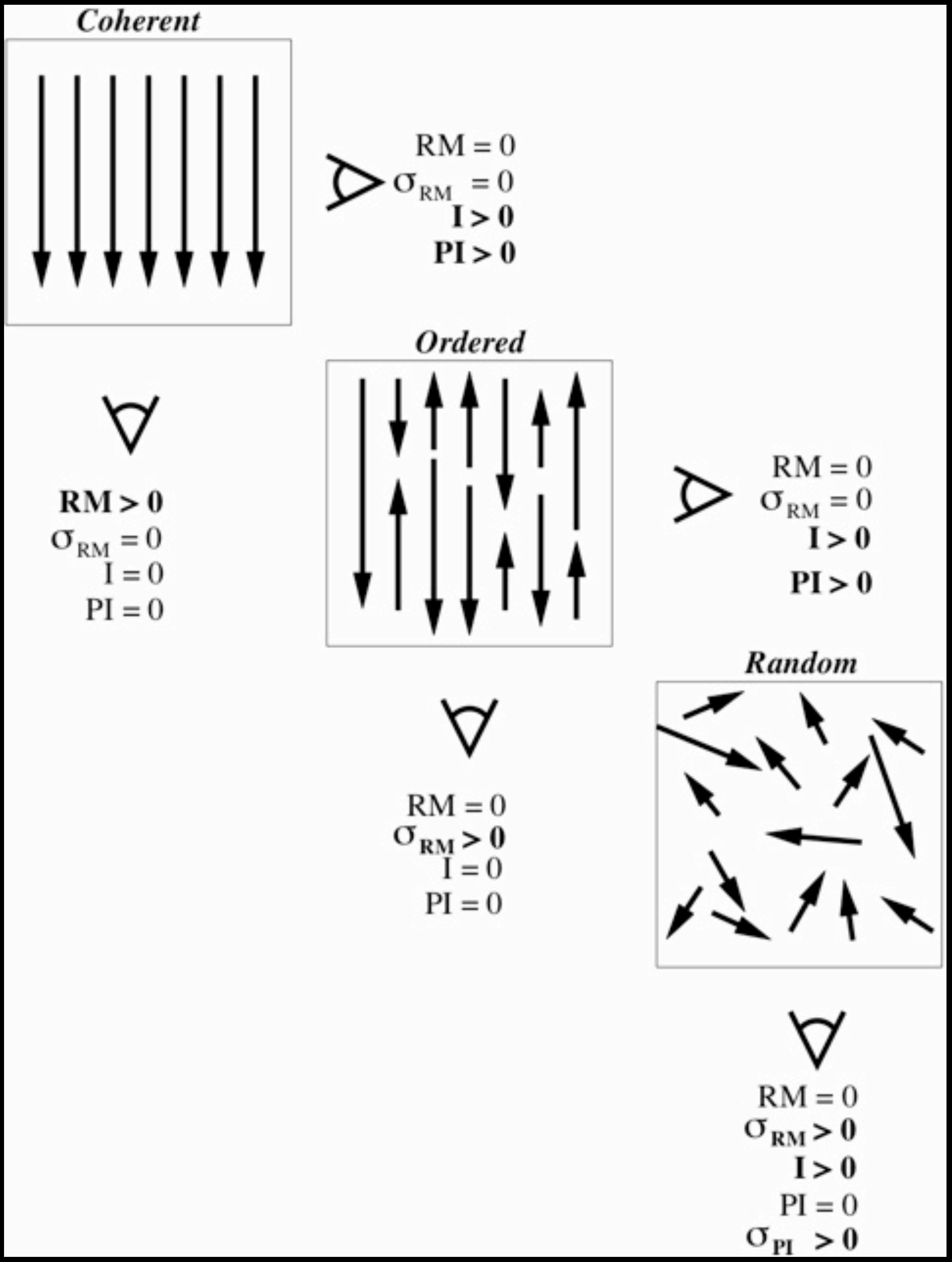
NGC6946 6cm PI over Hα (Copyright R. Beck, MPIfR)



(Soida et al. 2002)

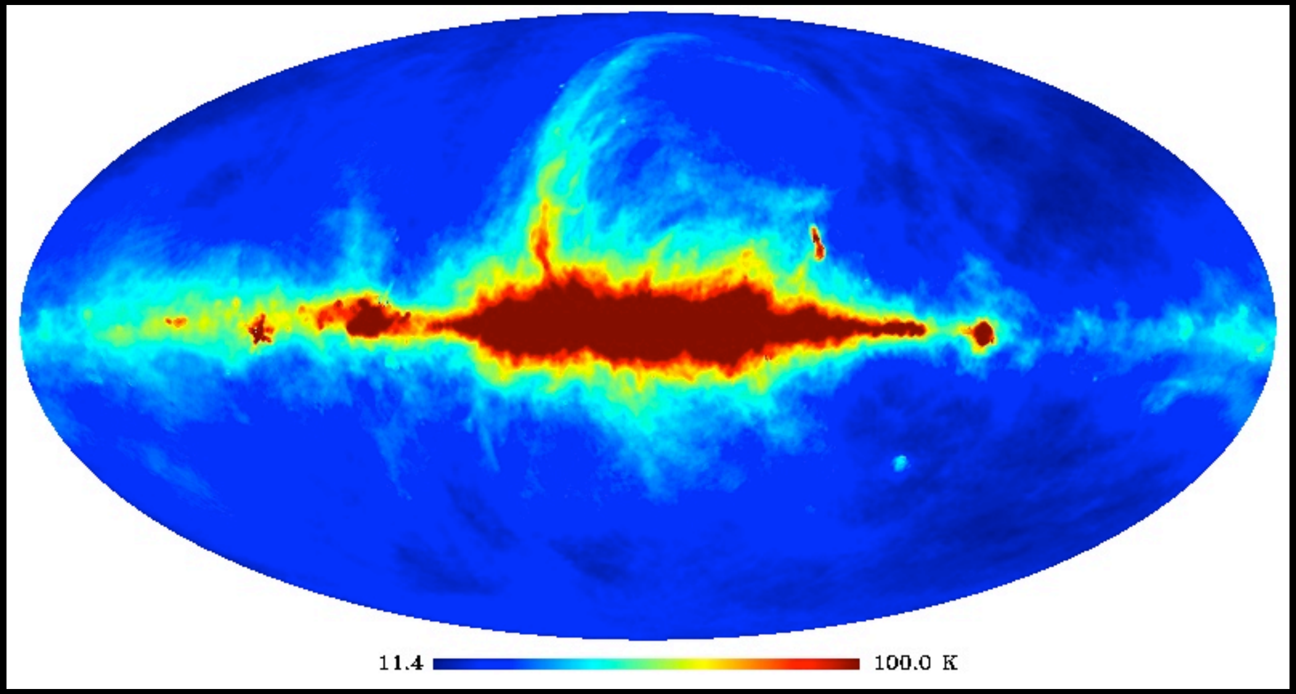
Geometry

- **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.

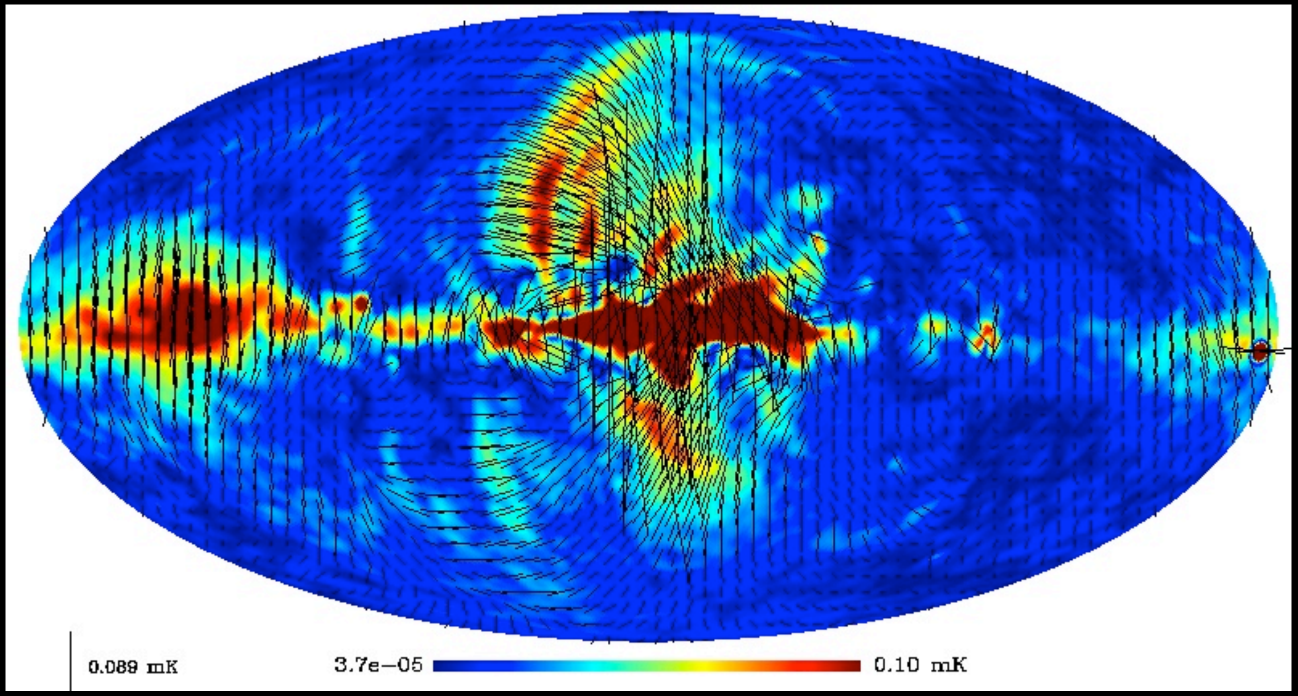


Jaffe et al. (2010)

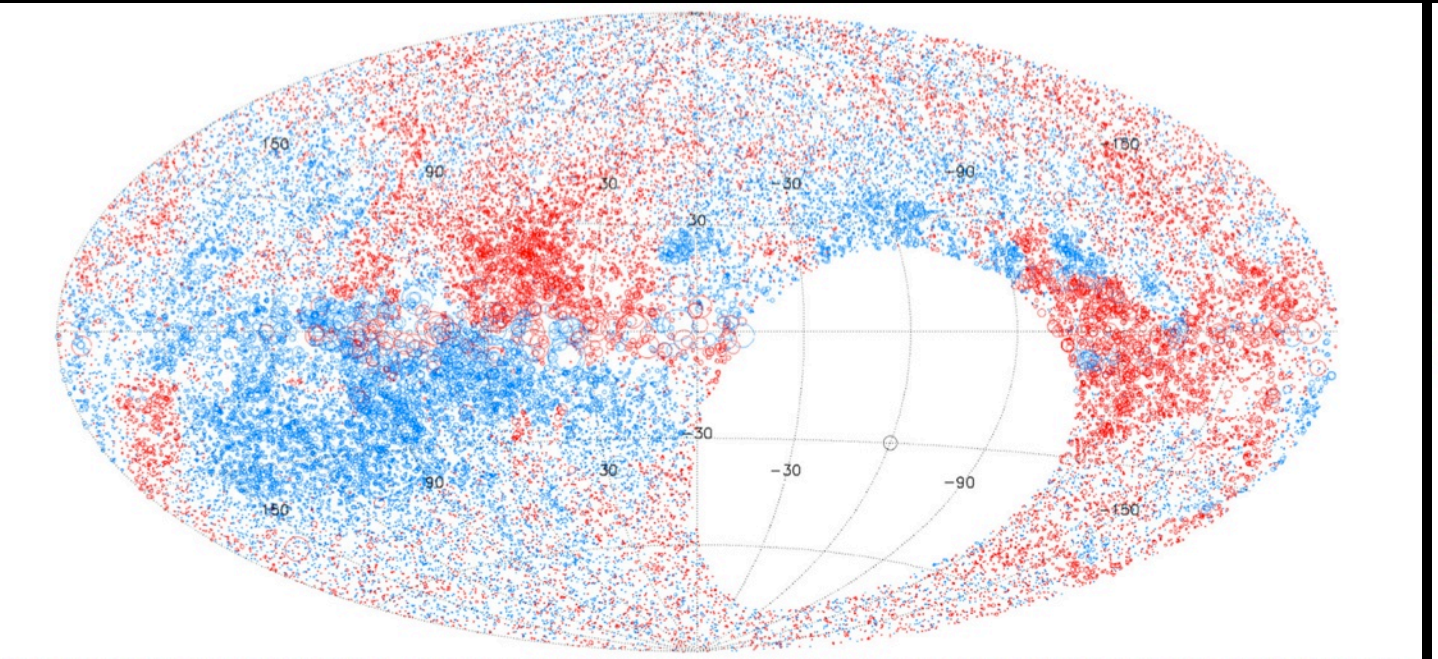
Radio Observations



408 MHz total intensity (Haslam et al. 1982)

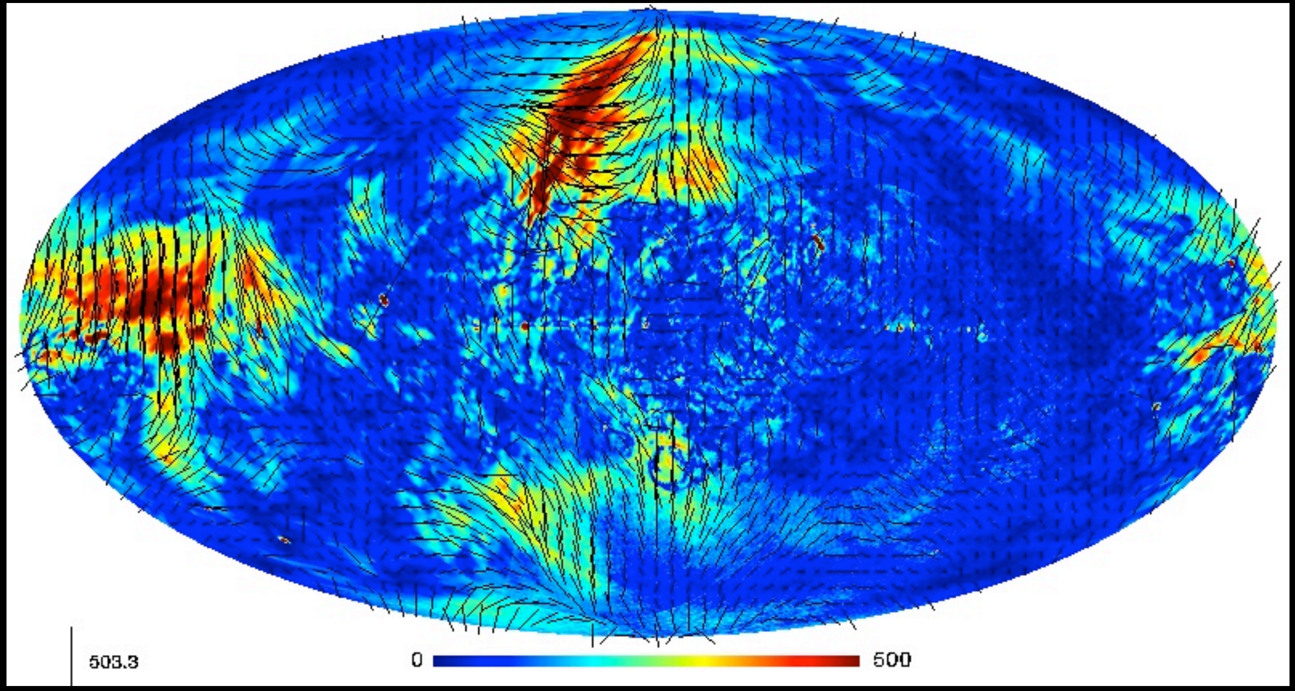


23 GHz polarized intensity (Page et al. 2007)



igure 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.

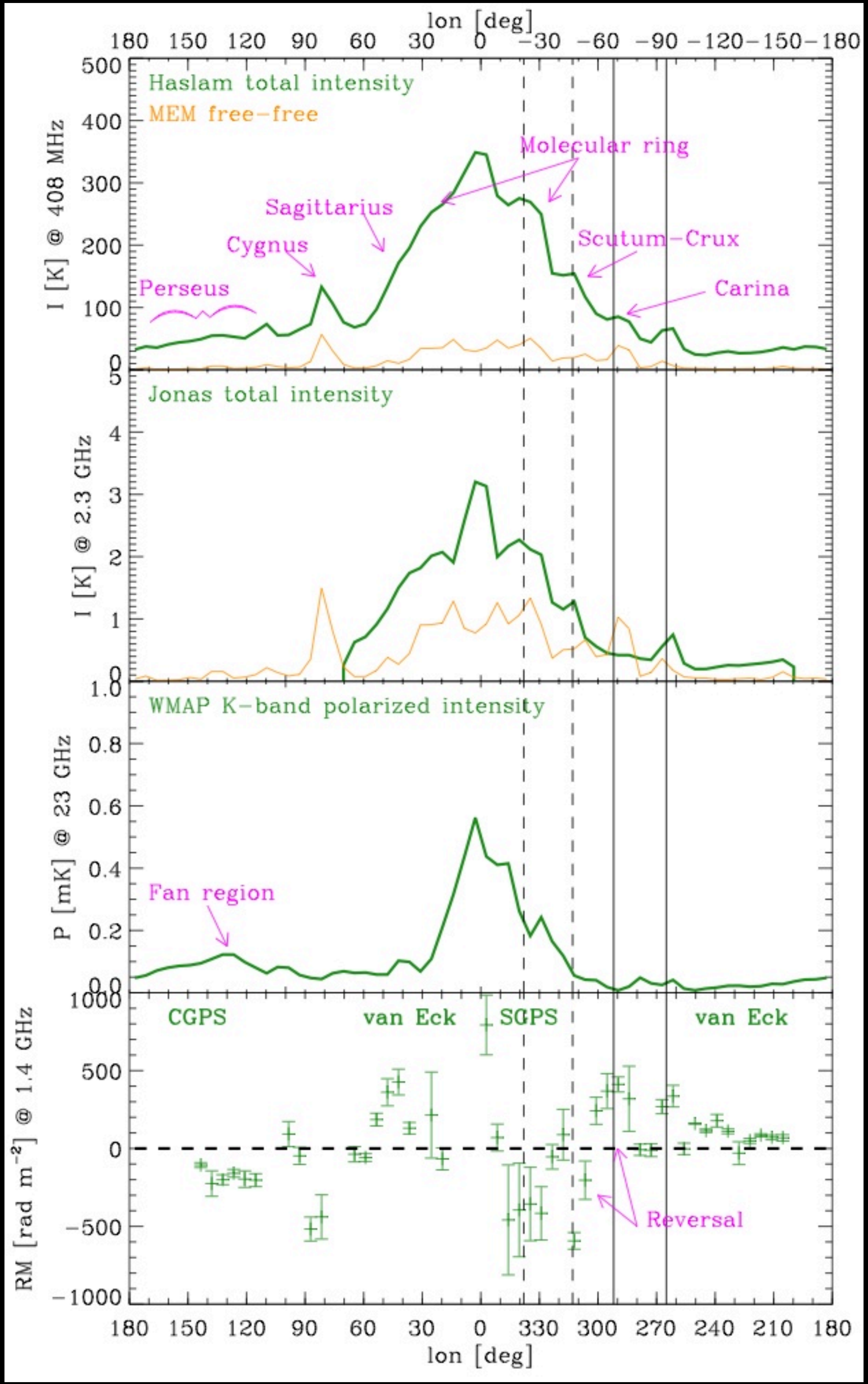
Faraday rotation measure (RM) 1.4 GHz
(Taylor et al. 2010)



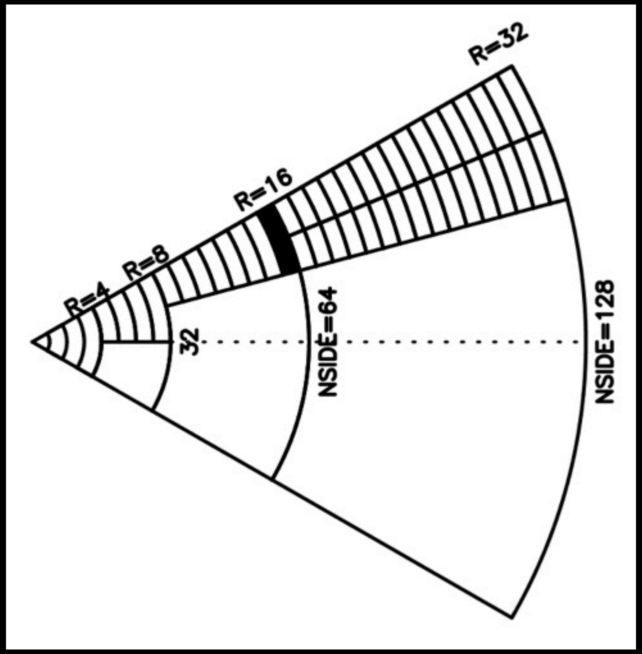
1.4 GHz polarized intensity
(Wolleben et al. 2006, Testori et al. 2008)

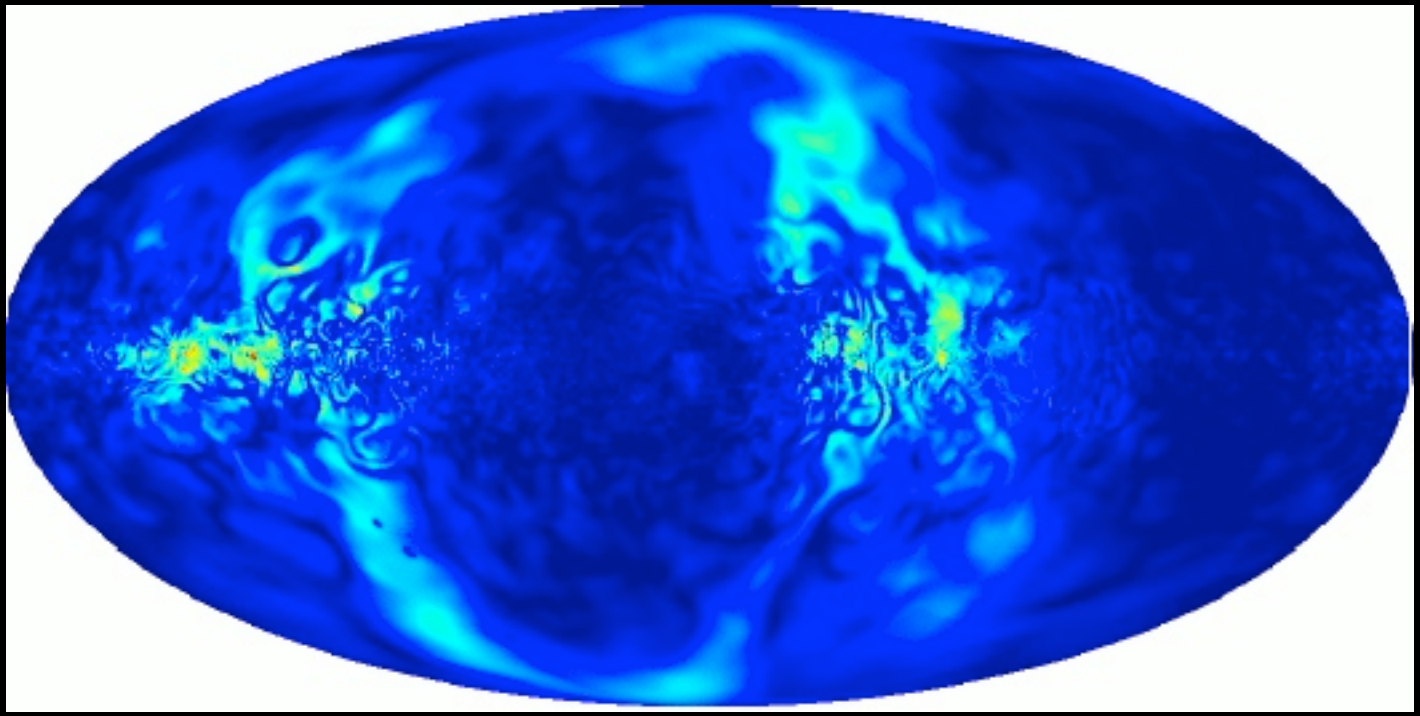
First look at the plane

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

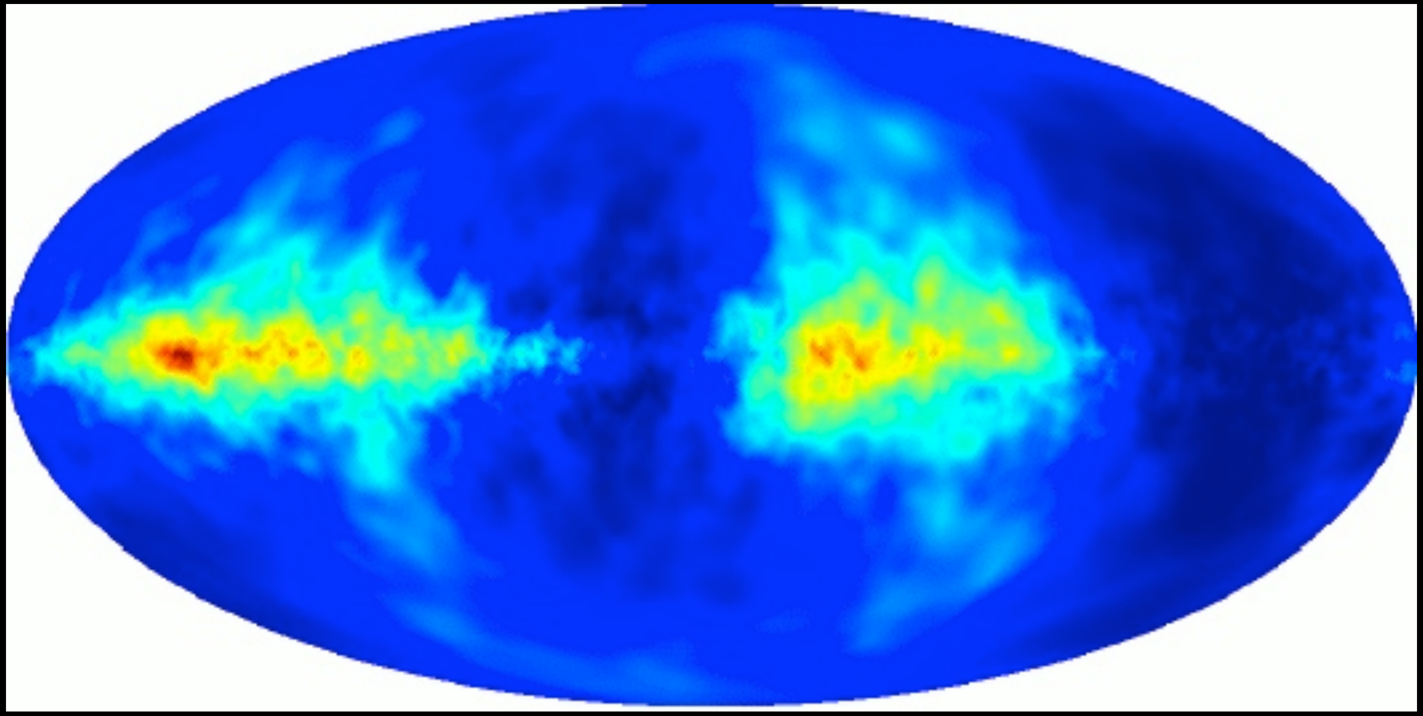


Modeling: hammurabi





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.

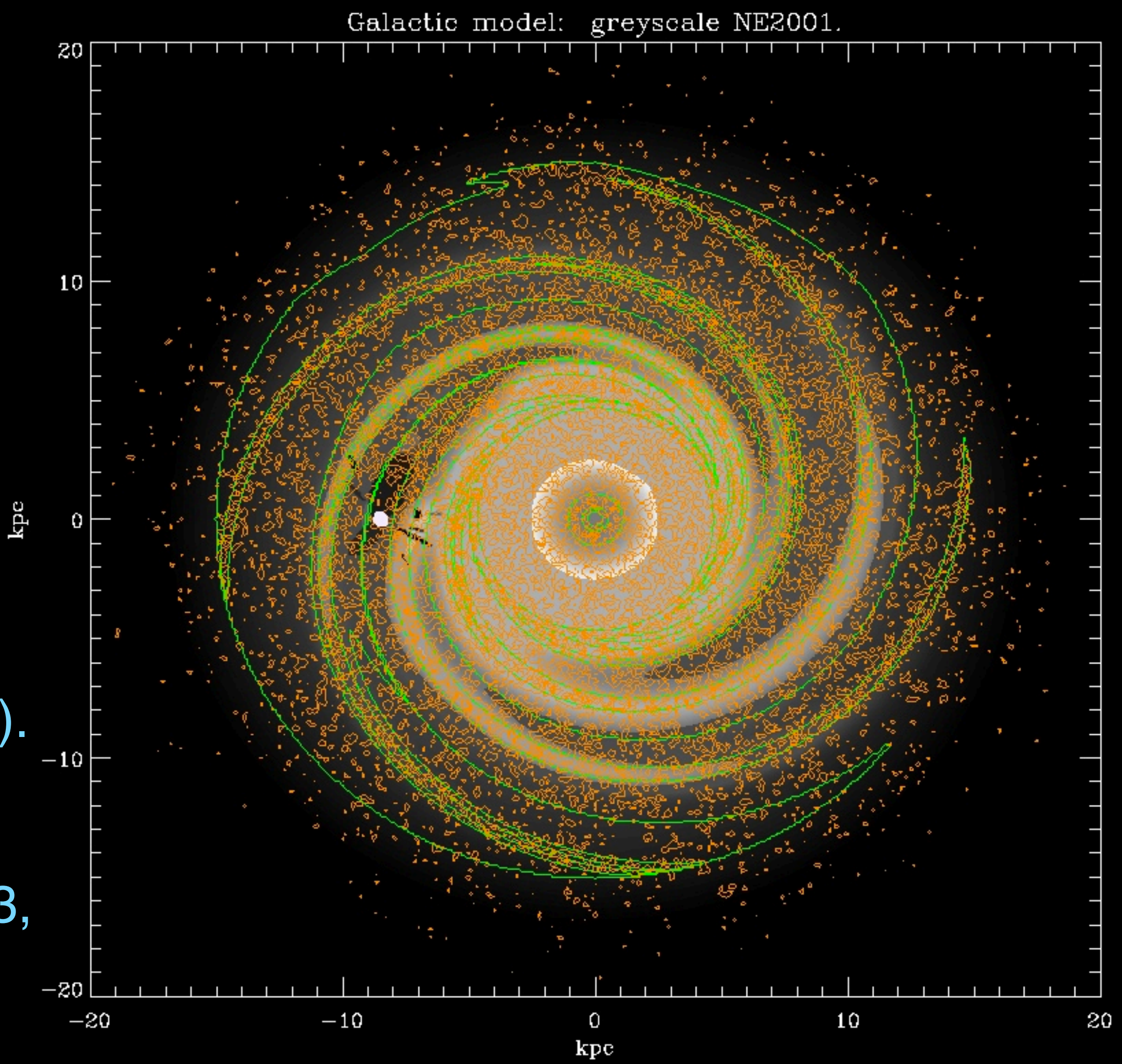
* Publicly available on Sourceforge: http://sourceforge.net/projects/hammurabicode/

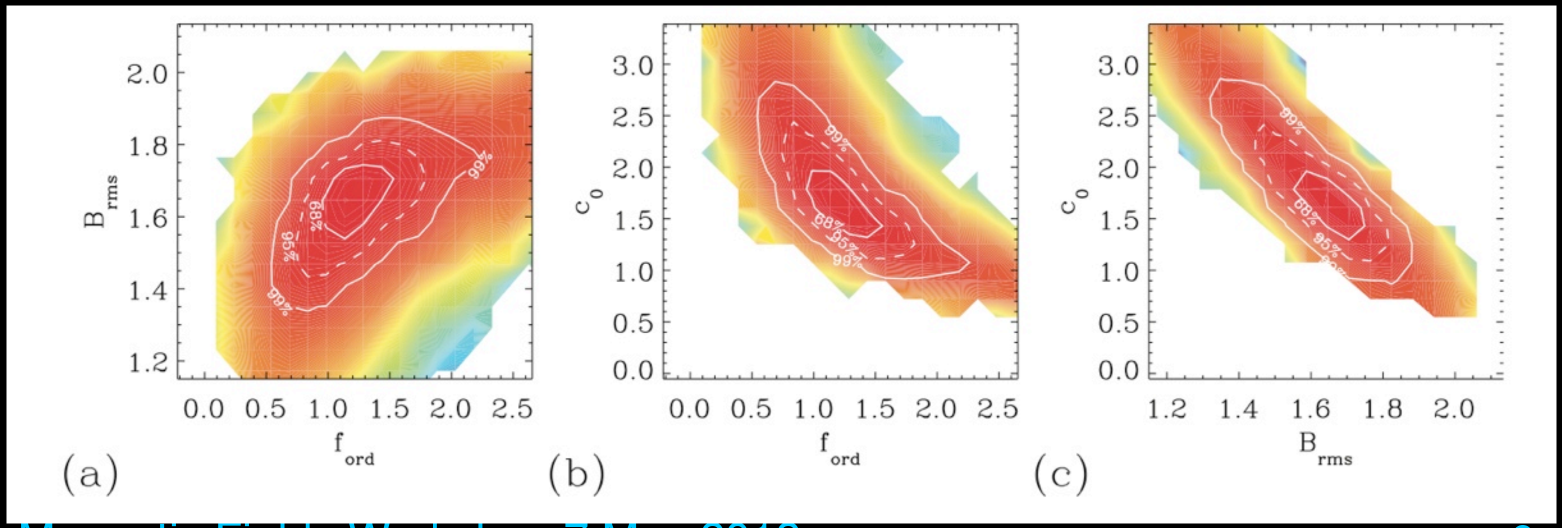
Model inputs:

Motivated by external galaxies:

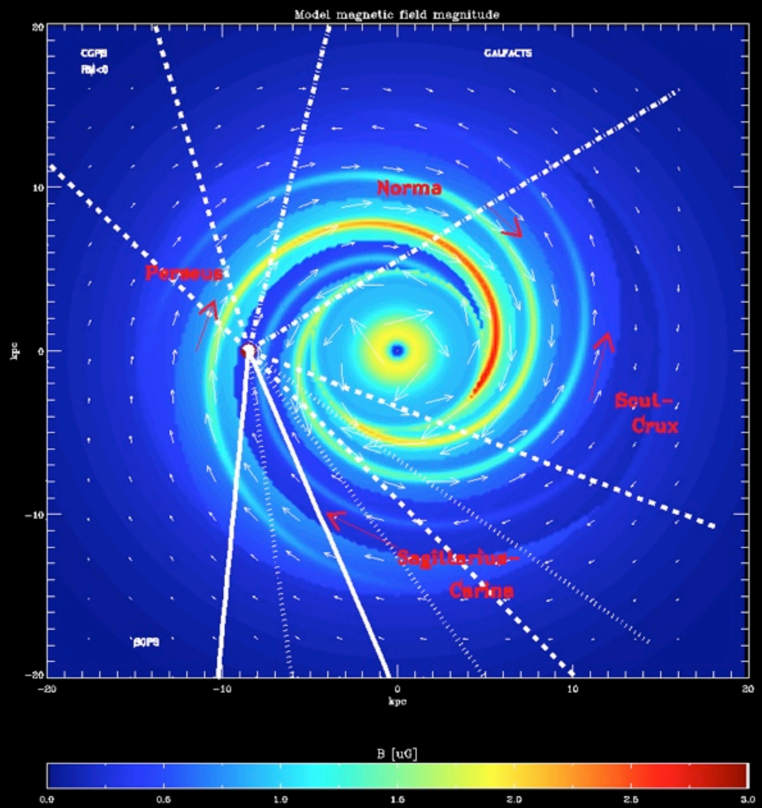
- 3D magnetic field model:
  - spiral arm model for 'coherent' field;
  - small-scale turbulence based on GRF with power-law spectrum;
  - compression model amplifies and stretches into anisotropic ('ordered') component along arm ridges based loosely on Broadbent (1989).

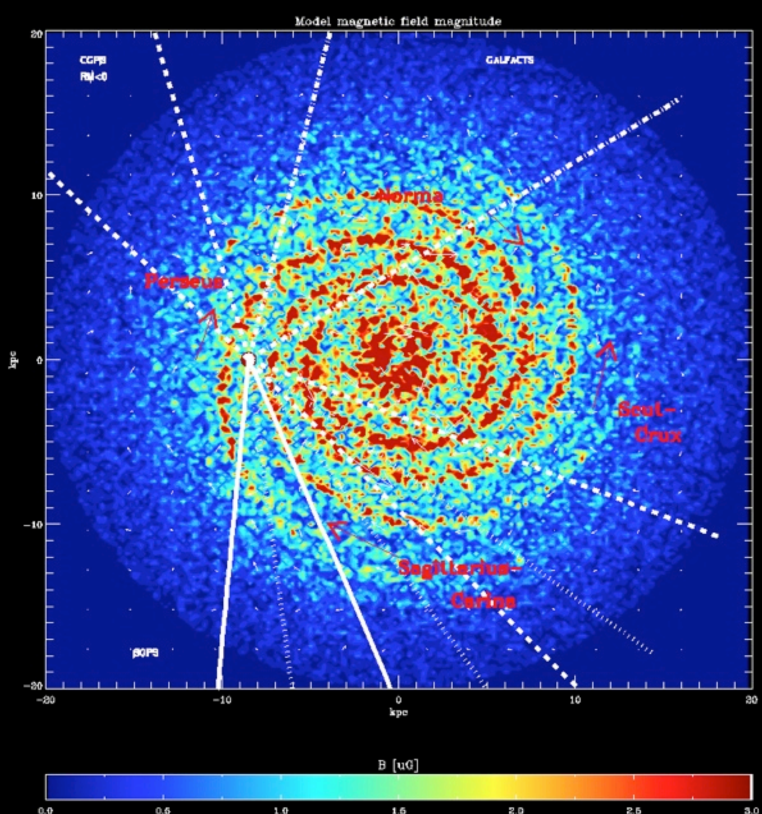
- 3D CRE density and spectral model: exponential disk with canonical power law, p=-3, normalized with gamma-ray data;
- 3D thermal electron density model: NE2001 (Cordes and Lazio 2002);
- *Hammurabi* to integrate observables along LOS;
- MCMC (cosmoMC) engine to explore parameter space.



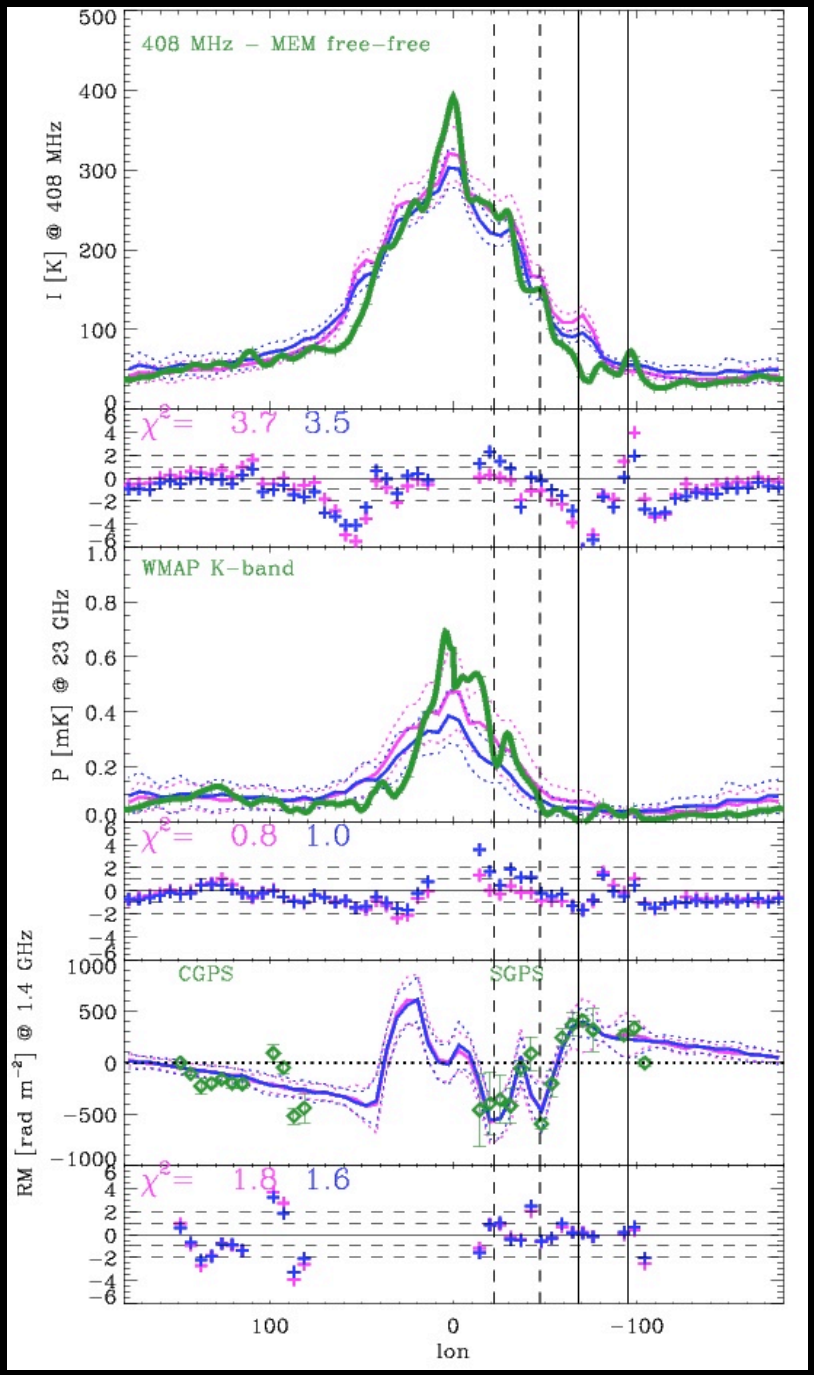


First results:





- 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. (2010)

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:

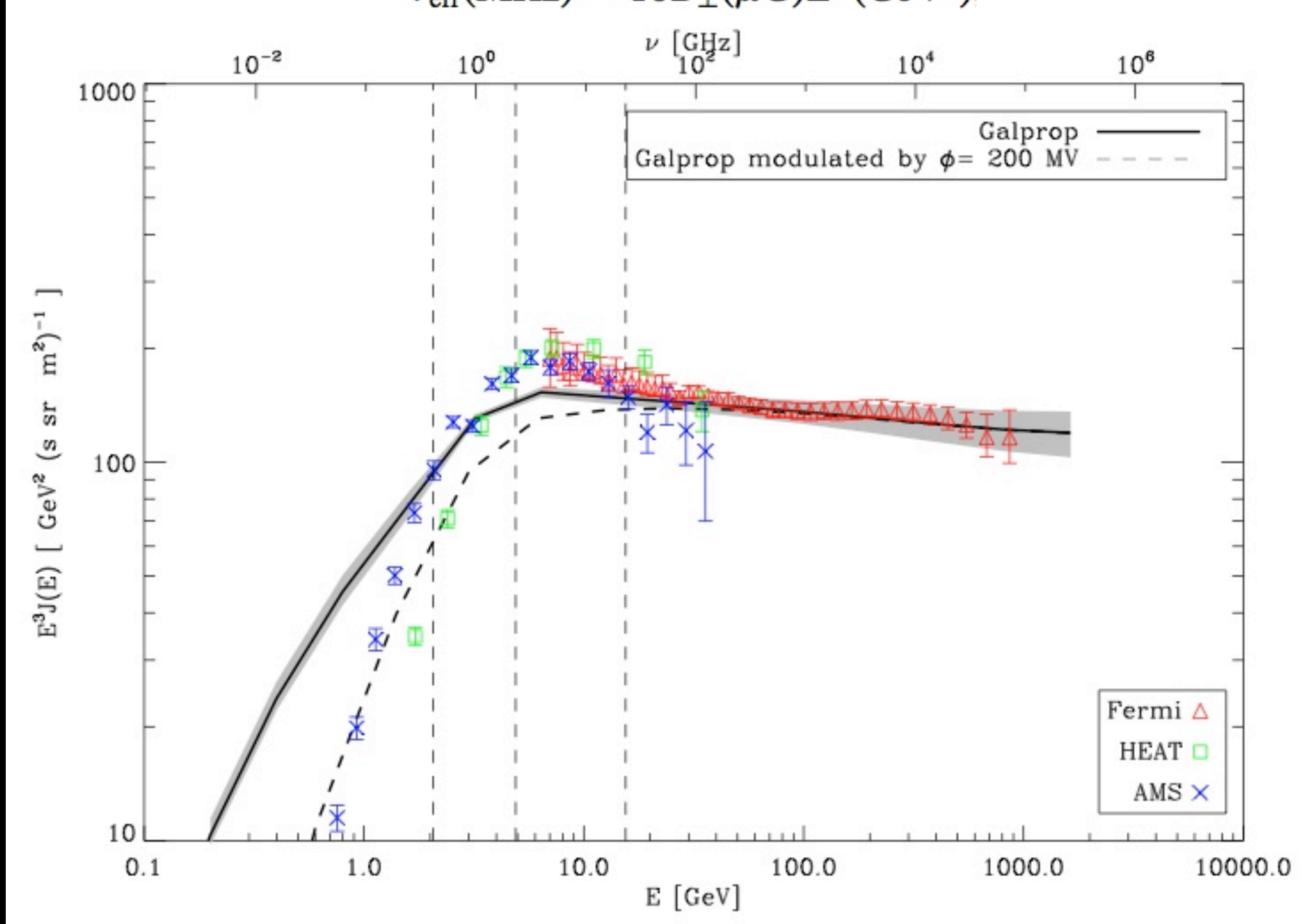
$$I(\nu) \propto \int_{LOS} dl \int_0^\infty dx\, B_{perp}\, n_{CRE}(\gamma)\, F(x)$$

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

  (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).
- ***Two results***: firstly, better constraint on B-field components. Secondly, constraint on low-energy end of CRE spectrum otherwise inaccessible.

CRE results:

$$\nu_{\text{eff}}(\text{MHz}) = 16 B_{\perp}(\mu\text{G}) E^2(\text{GeV}^2)$$

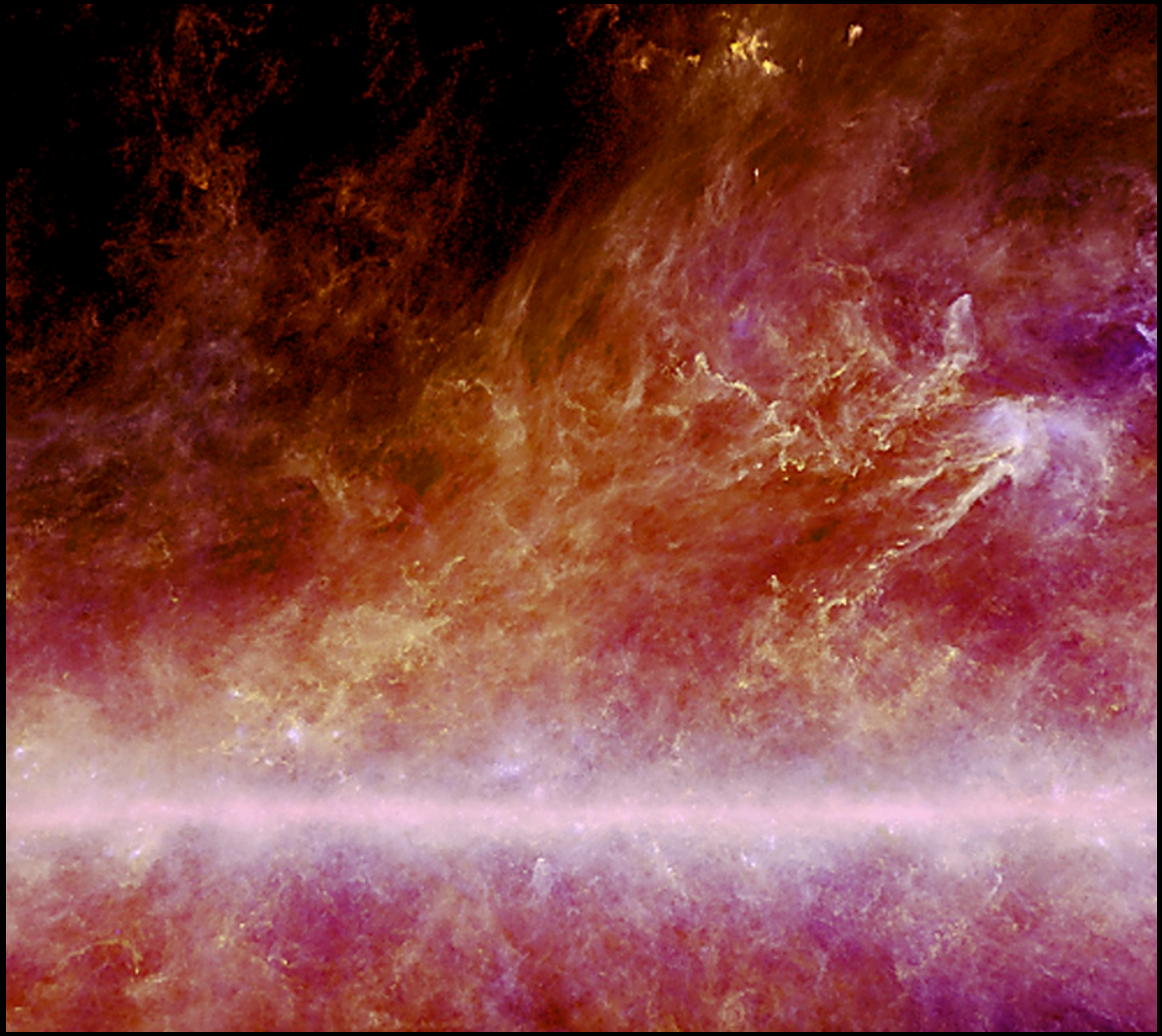


Jaffe et al. (2011): spectra above a few GeV constrained using γ-ray data, Strong et al. (2010).

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.

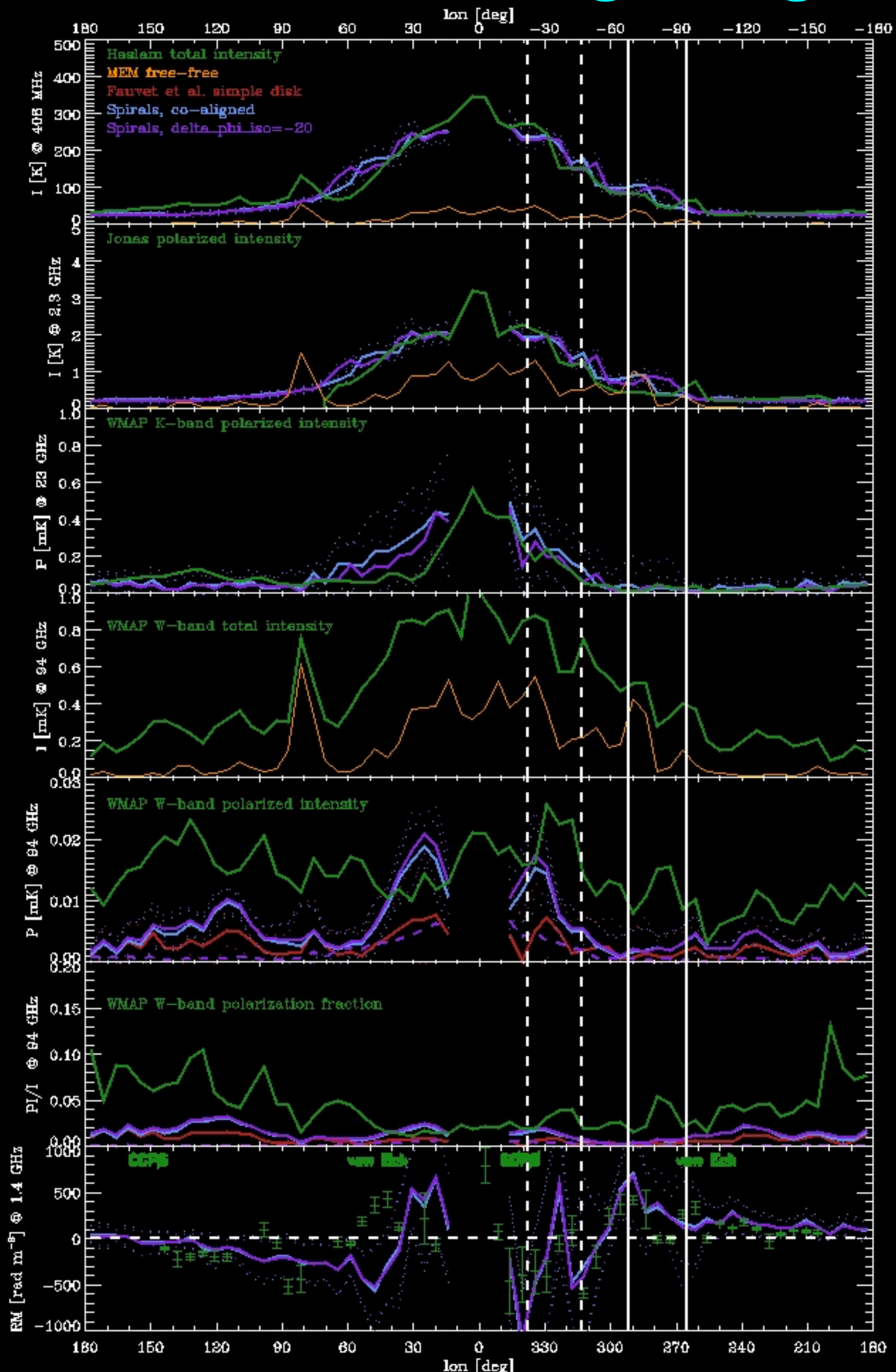
Planck:



Planck and IRAS composite image (ESA).

- Planck project on large scale magnetic field modeling using polarized dust mapped with unprecedented precision.
- Using magnetic field geometry constrained by RM and synchrotron, we can study the dust distribution in the disk of the Galaxy.
- Polarized dust emission is then a complementary observable independent of CRE or thermal electron distribution uncertainties affecting synchrotron.
- 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

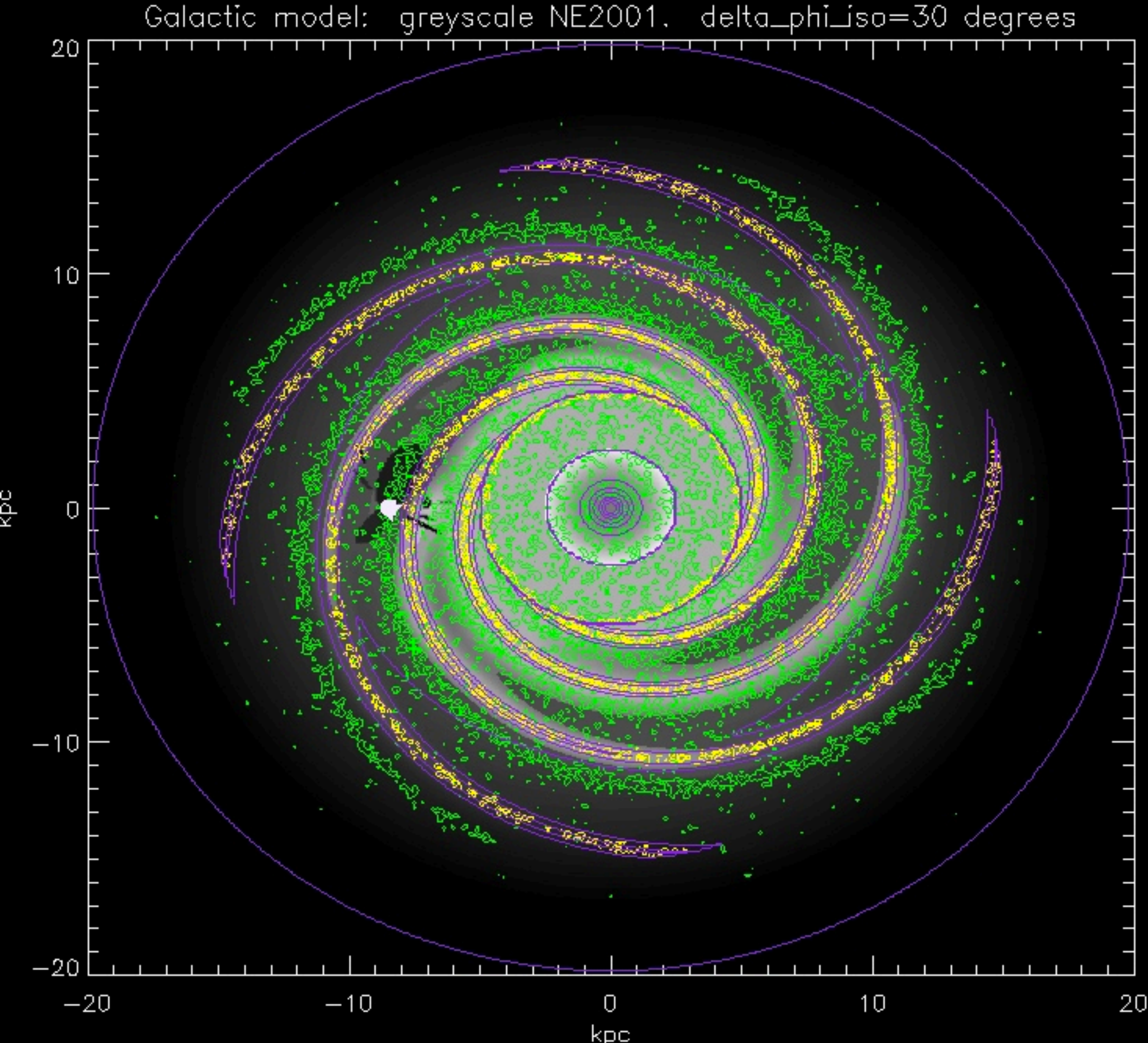


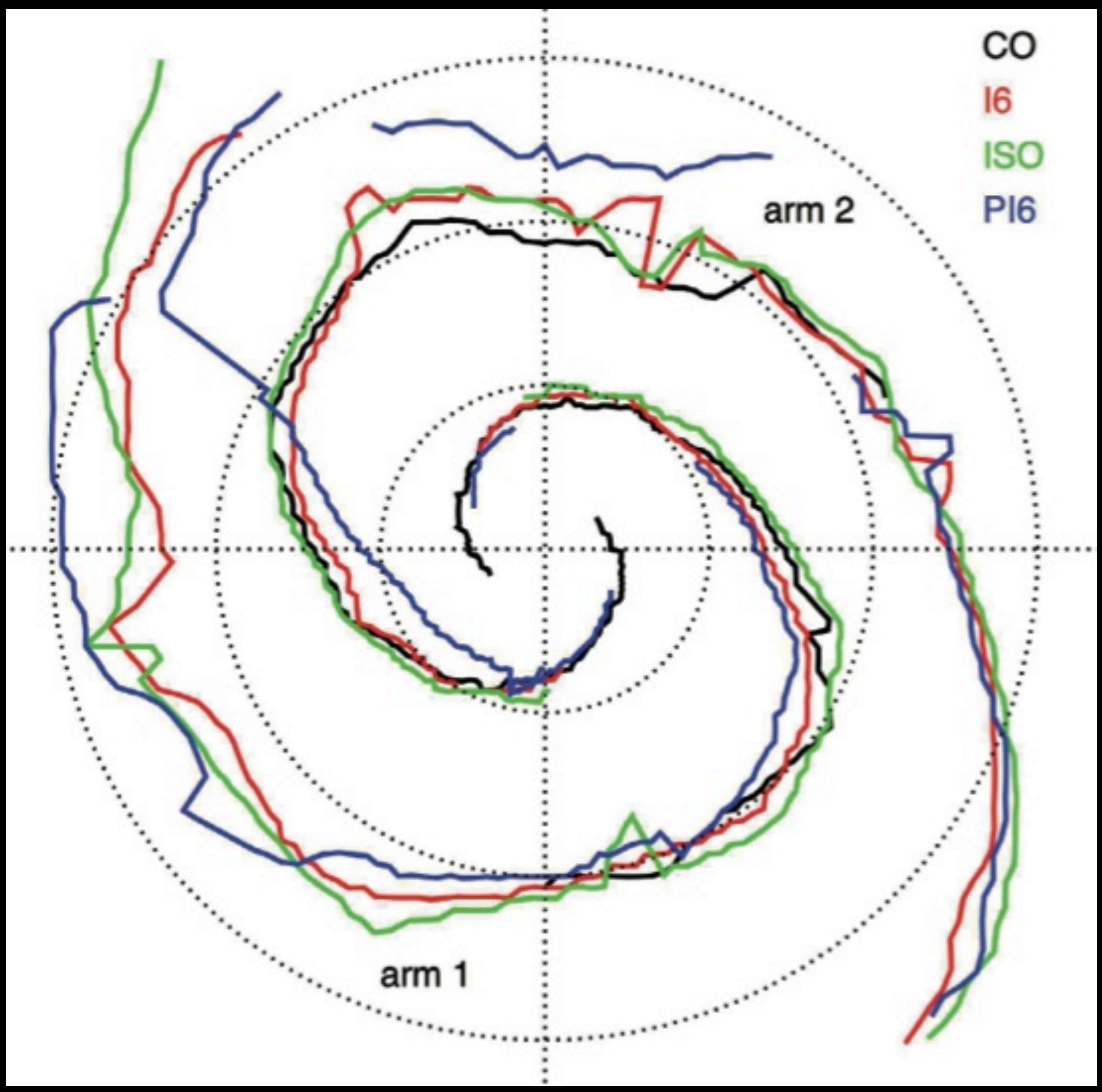
- Simple model for thermal dust polarization does not work. At all. How interesting!
- Dust polarization can help break degeneracies in B vs n_e or vs n_{CRE}.
- Note also problem with van Eck data. No simple spirals!

- Polarization degree significantly under-predicted => dust emission coming from regions with more ordered fields.
- This means we can begin 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 traces molecular clouds, whose collapse is triggered in the shock. Downstream, star formation heats PAHs and dust that emit in sub-mm (ISO). So CO inside (shock front), star formation trailing? What does this mean for the magnetic field components?

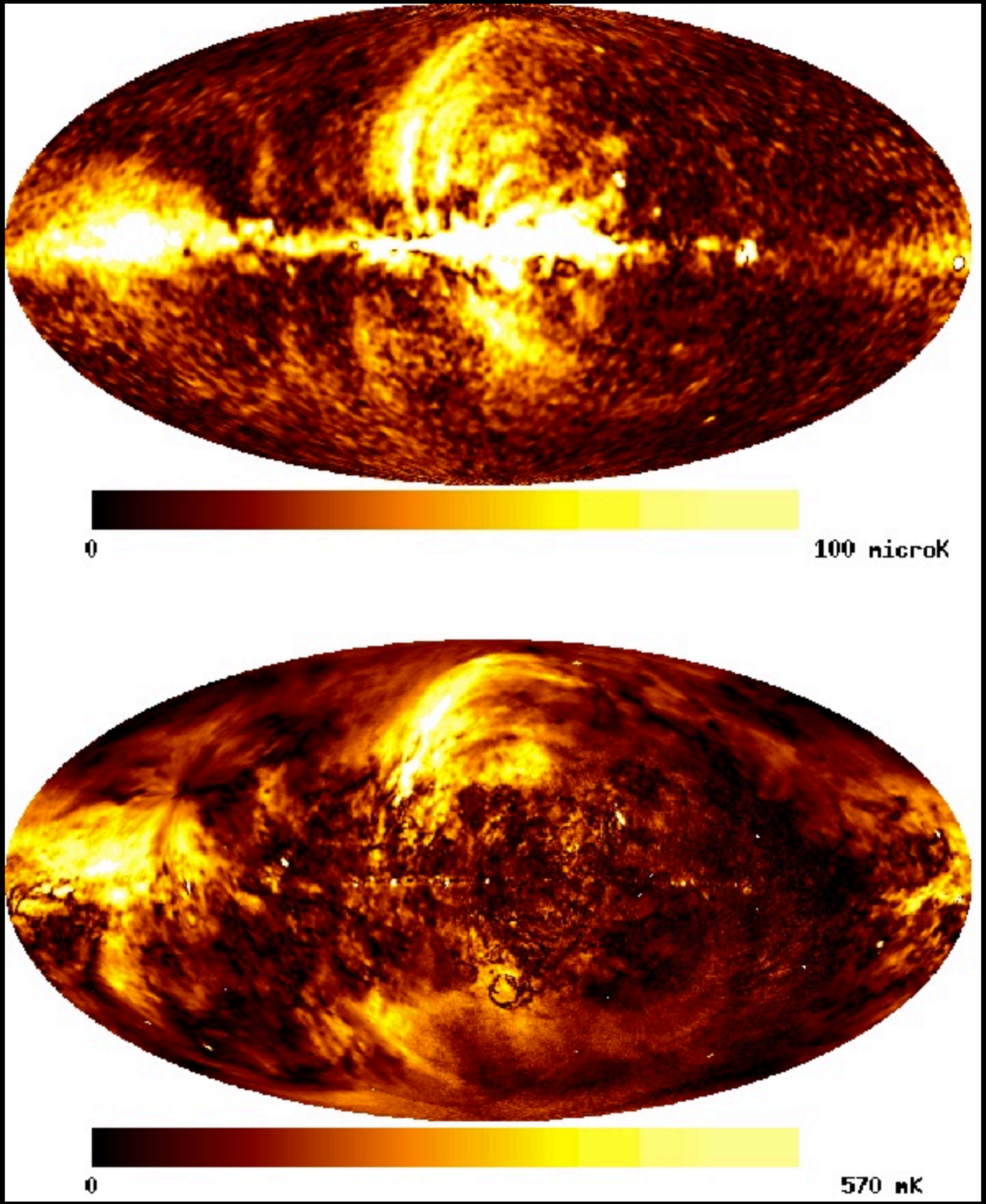




M51 component ridges, Patrikeev et al. (2011)

Magnetic field modeling plans

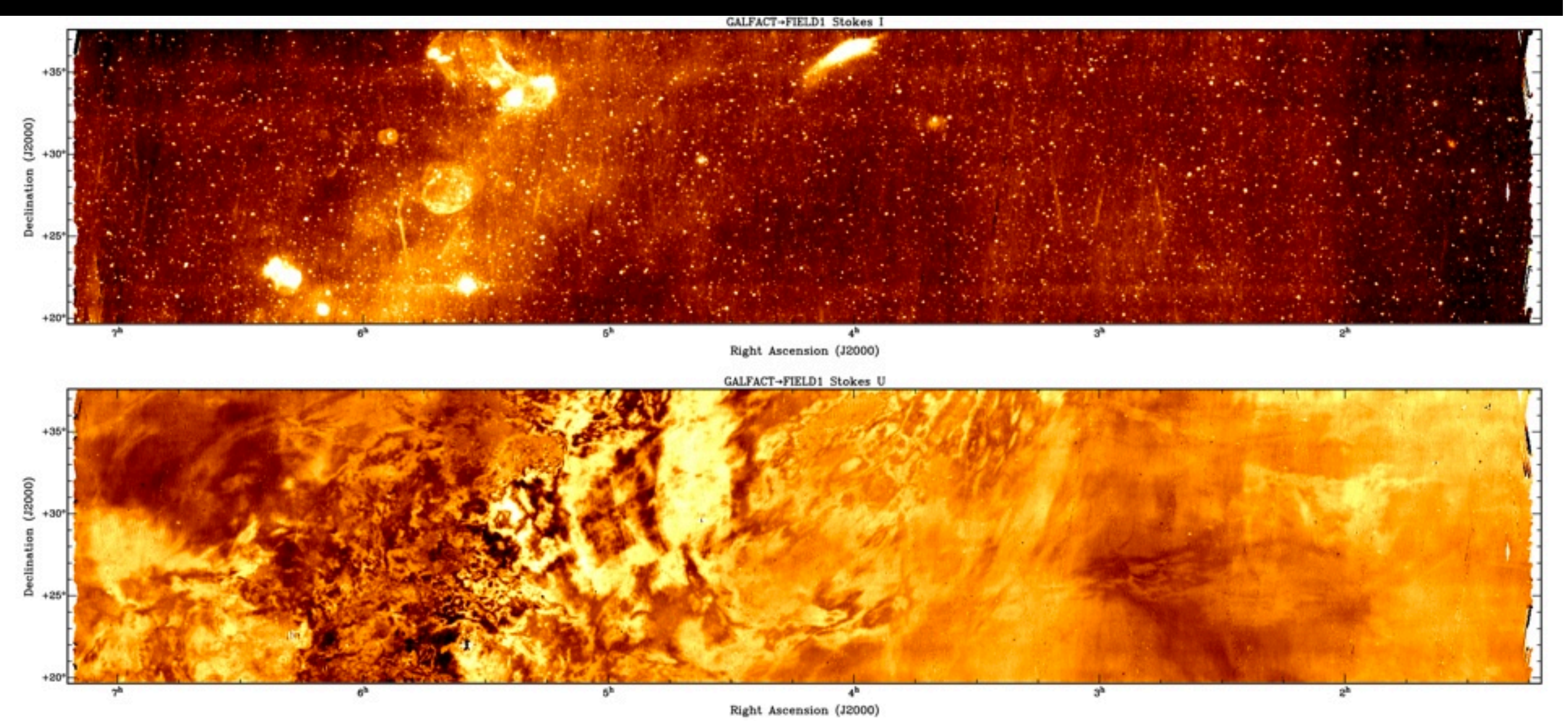
- Can we find a simple and physically motivated model that fits all of the data? E.g. van Eck et al. (2011) data inconsistent with Jaffe et al. (2010) model.
- What explains the "Fan" region of high polarization on the plane in both synchrotron and dust emission?
- What can the depolarization band at 1.4GHz tell us about the turbulent field?
- 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.)
- ...

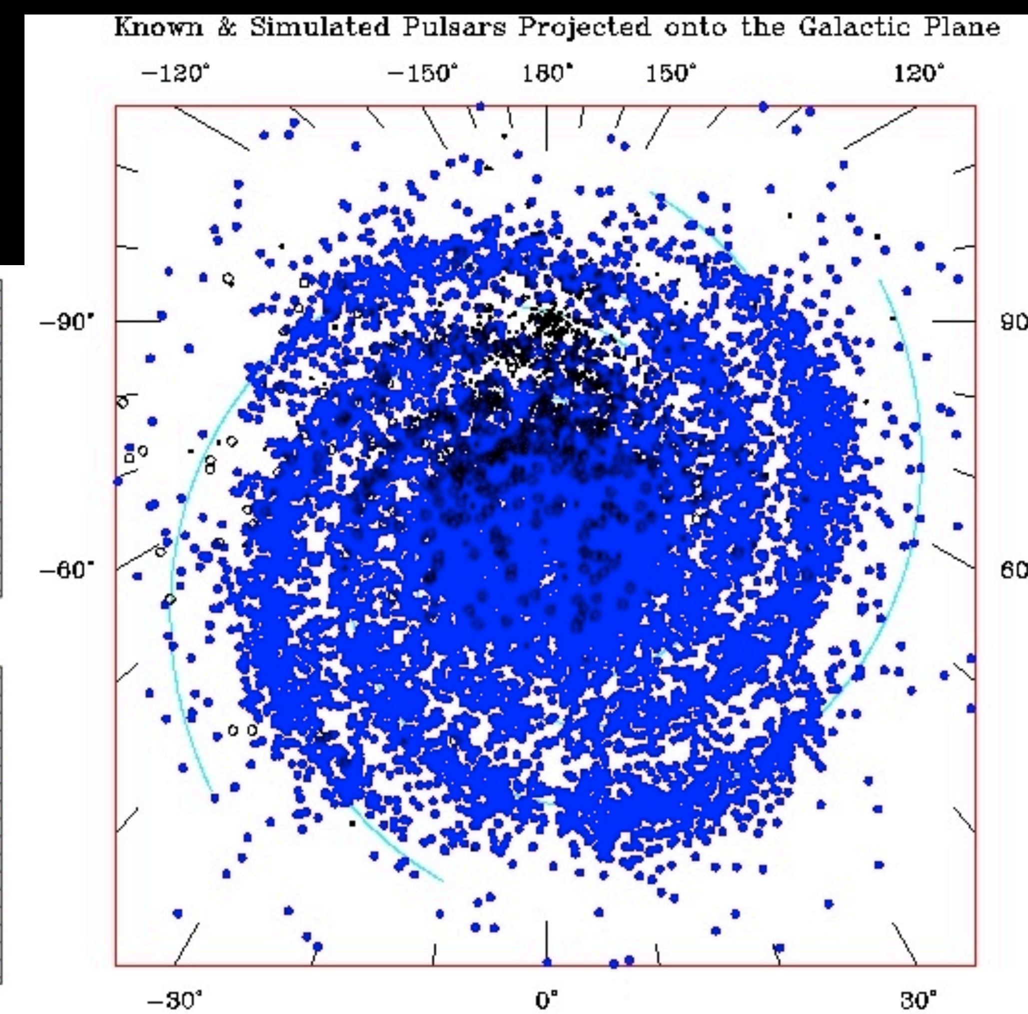


Top: WMAP 23 GHz polarized intensity.
Bottom: 1.4GHz polarized intensity (Reich & Testori)

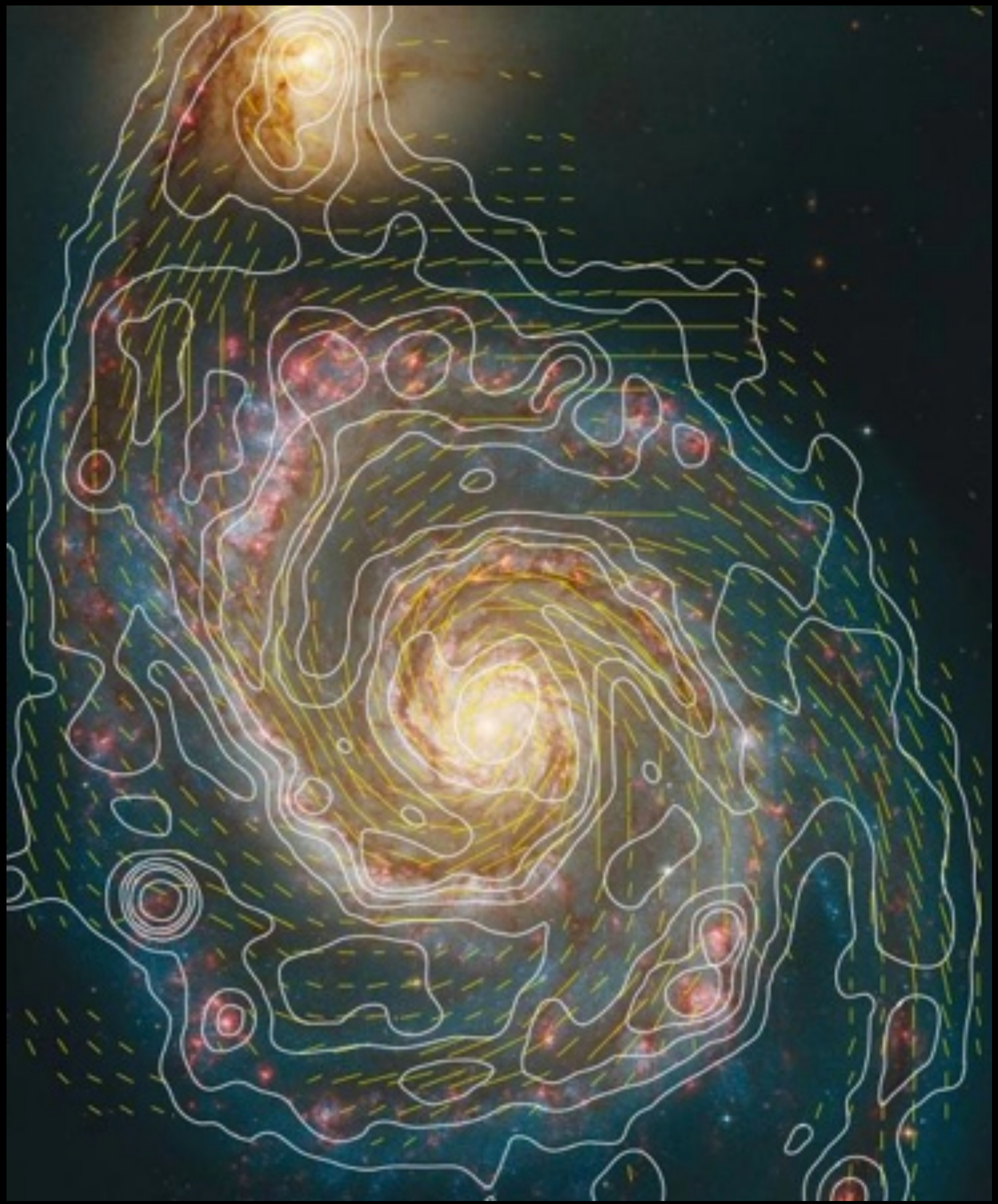
Prospects:

- **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.
- **SKA**
- PILOT, PIXIE...





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, but harder because of a lack of RM measurements. But...
- SKA!

Conclusions:

- 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.