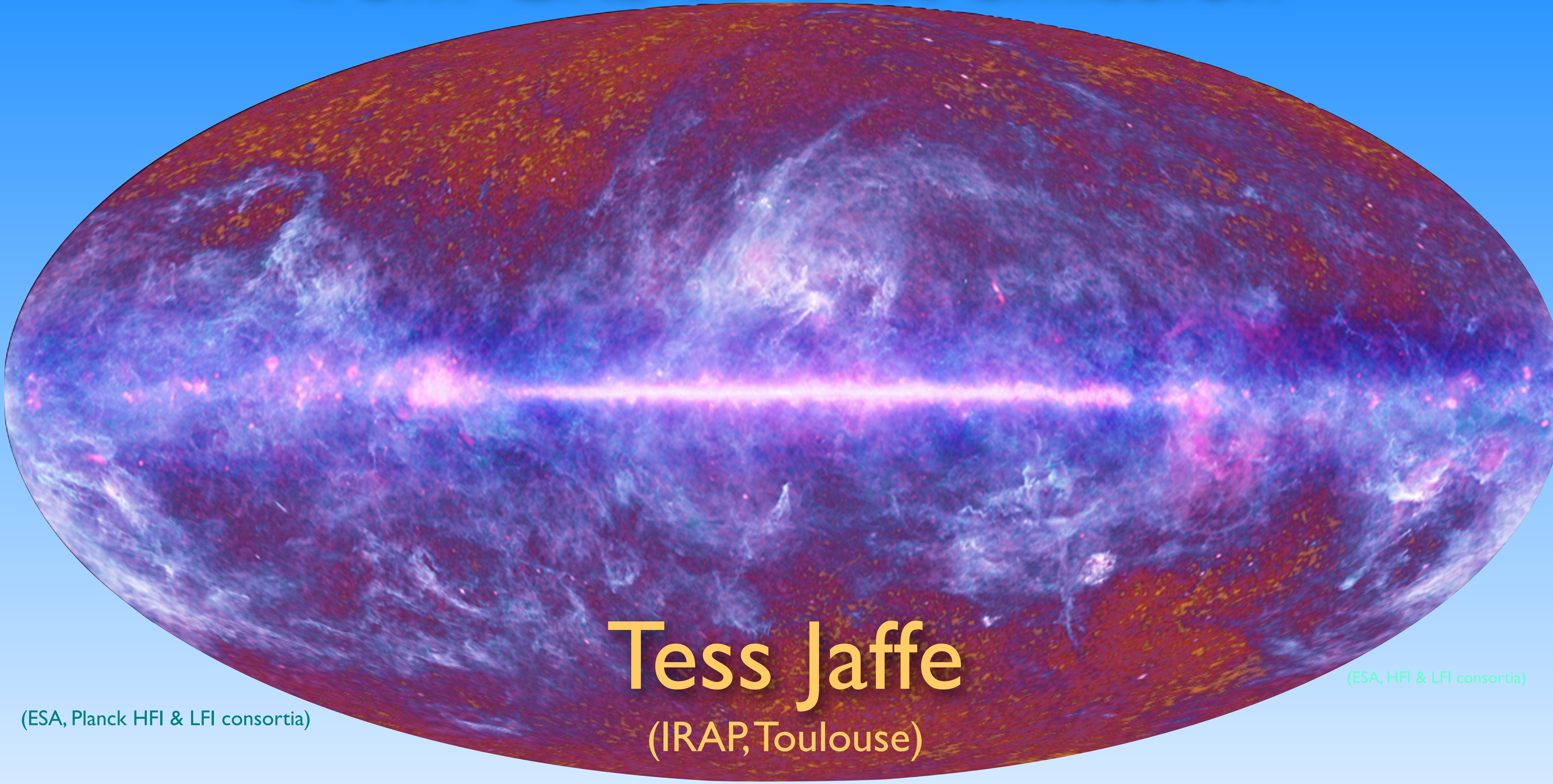
The multi-wavelength ISM: from CRs to dust emission



(ESA, Planck HFI & LFI consortia)

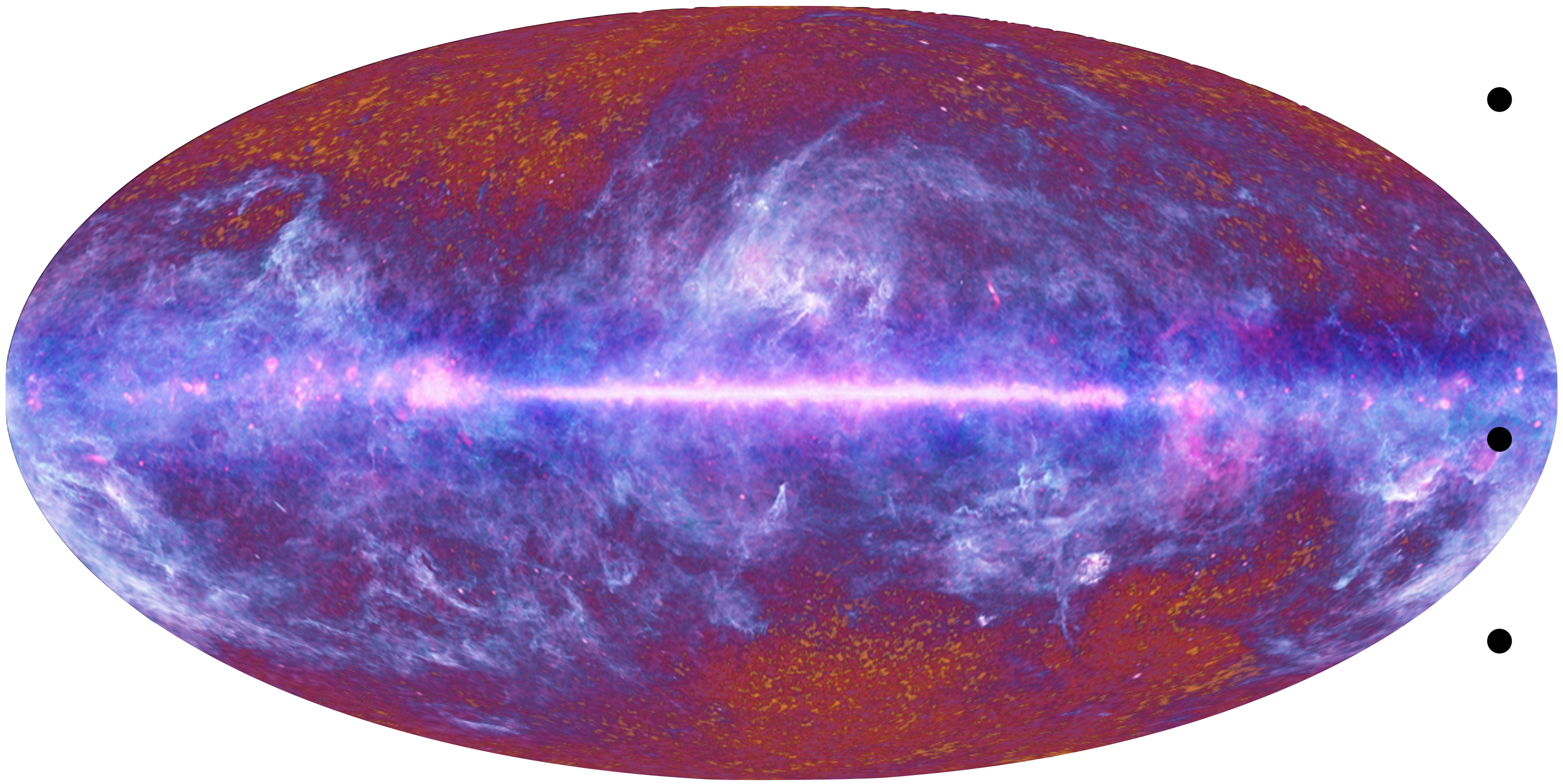
(ESA, HFI & LFI consortia)

Tess Jaffe

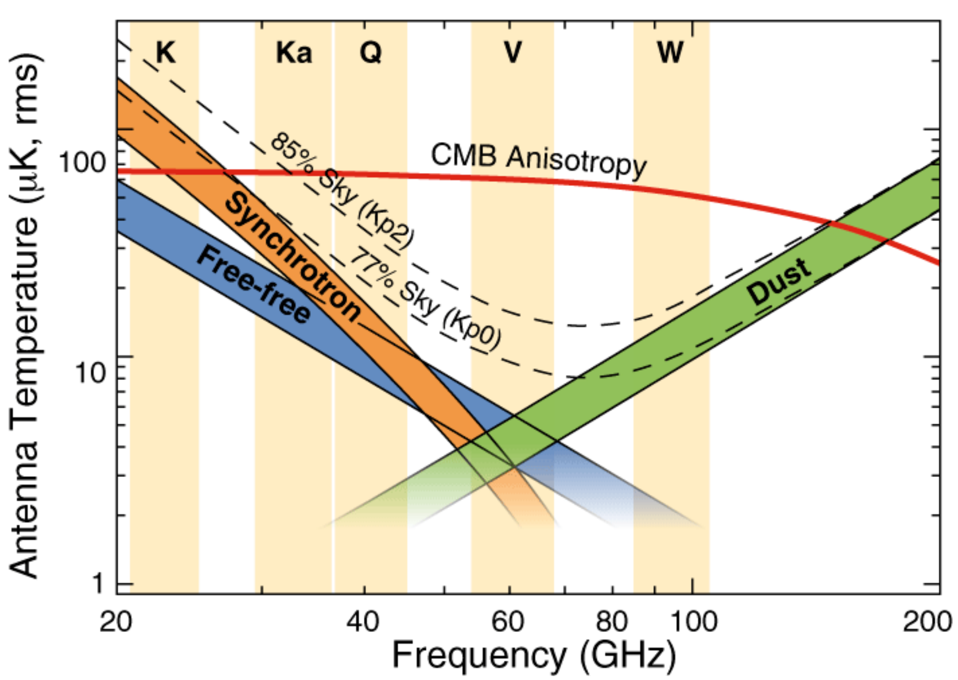
(IRAP, Toulouse)

with A. J. Banday and K. Ferrière (IRAP); J.P. Leahy (JBCA); A.W. Strong (MPE); J. Macías-Perez and C. Combet (LPSC); L. Fauvet and J. Tauber(ESTEC); E. Orlando (Stanford) and more....

CMB foregrounds



(ESA, Planck HFI & LFI consortia)



(WMAP team)

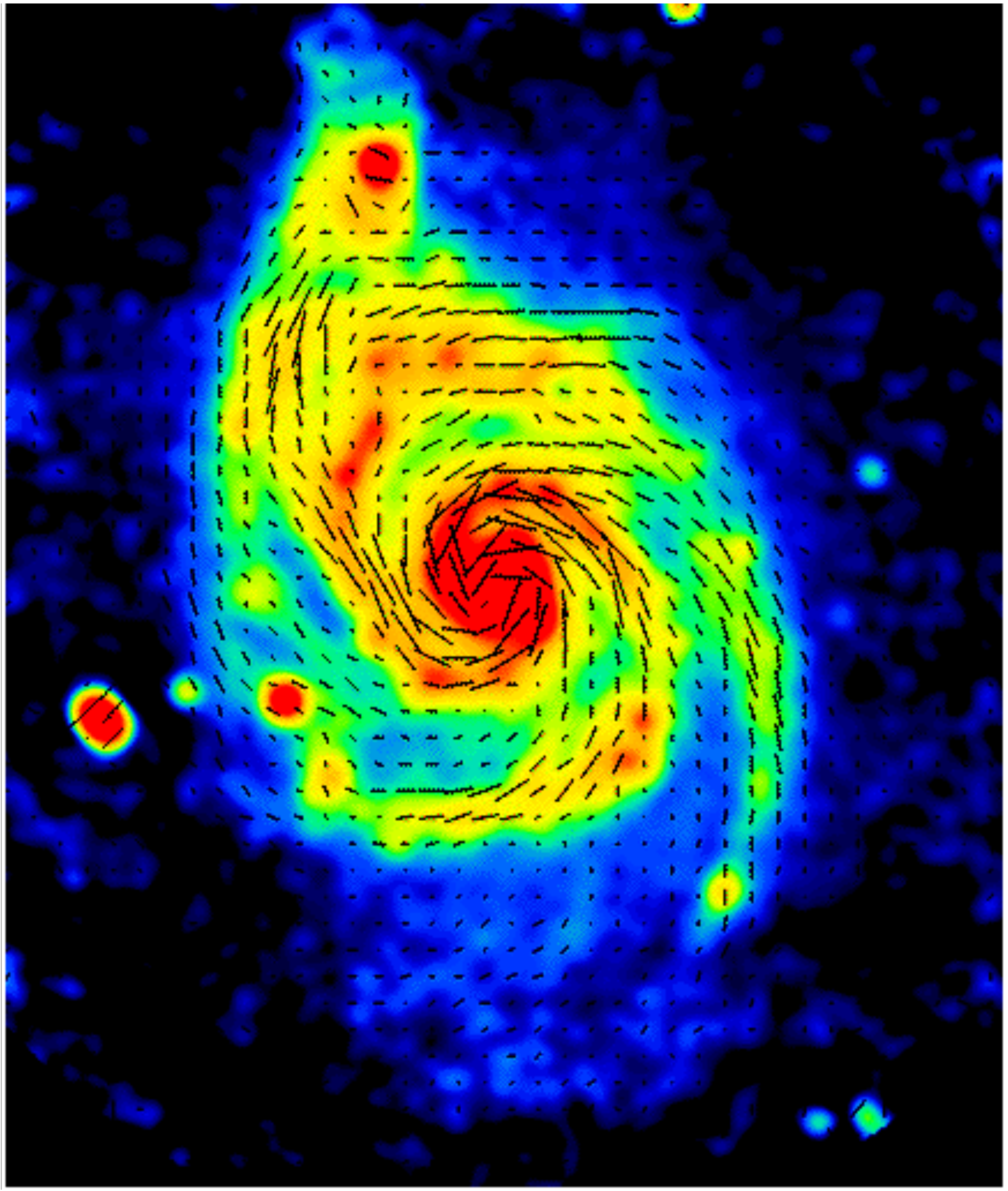
- CMB observations in the sweet spot between different foreground components that would otherwise dominate.
- At low frequencies (few 10s of GHz), the synchrotron dominates the CMB.
- At high frequencies (few 100s of GHz), the dust dominates.
- Both are polarized.

  => Magnetic fields.

- Use radio to submm emission to constrain magnetic fields and then CR propagation.

External galaxies: one example

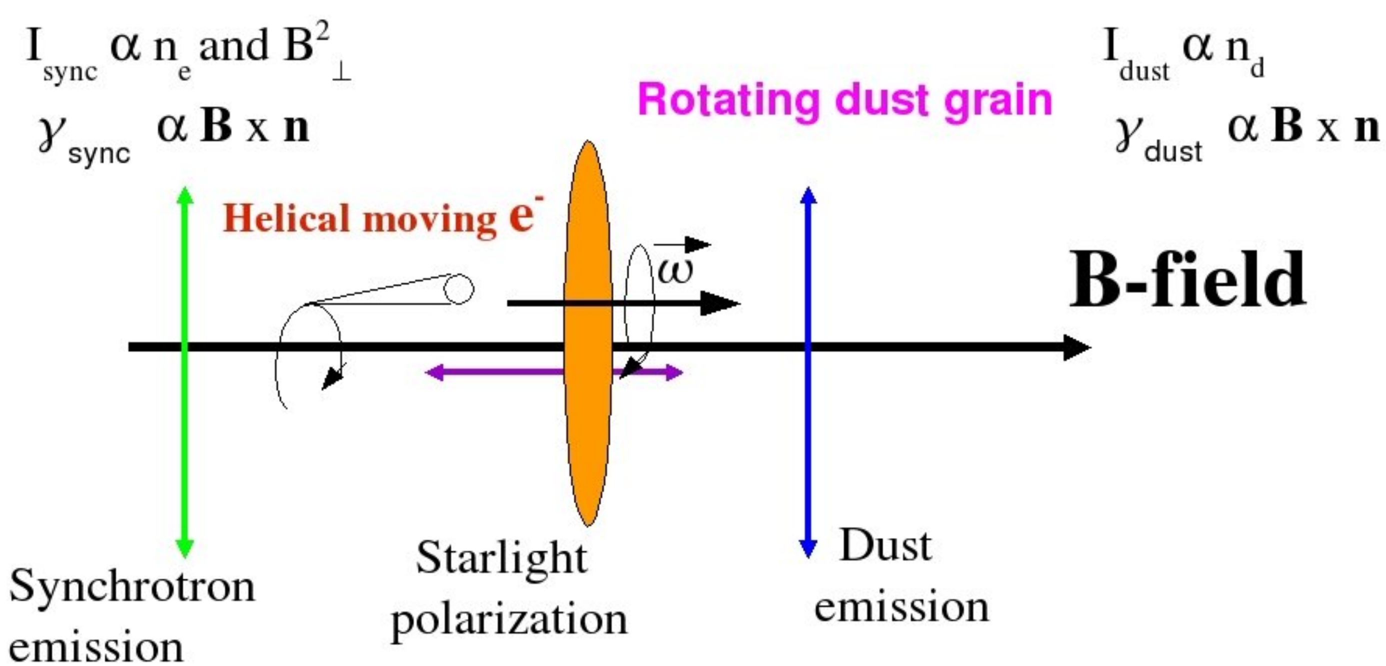
M51 6cm total intensity + magnetic field (VLA+Effelsberg)



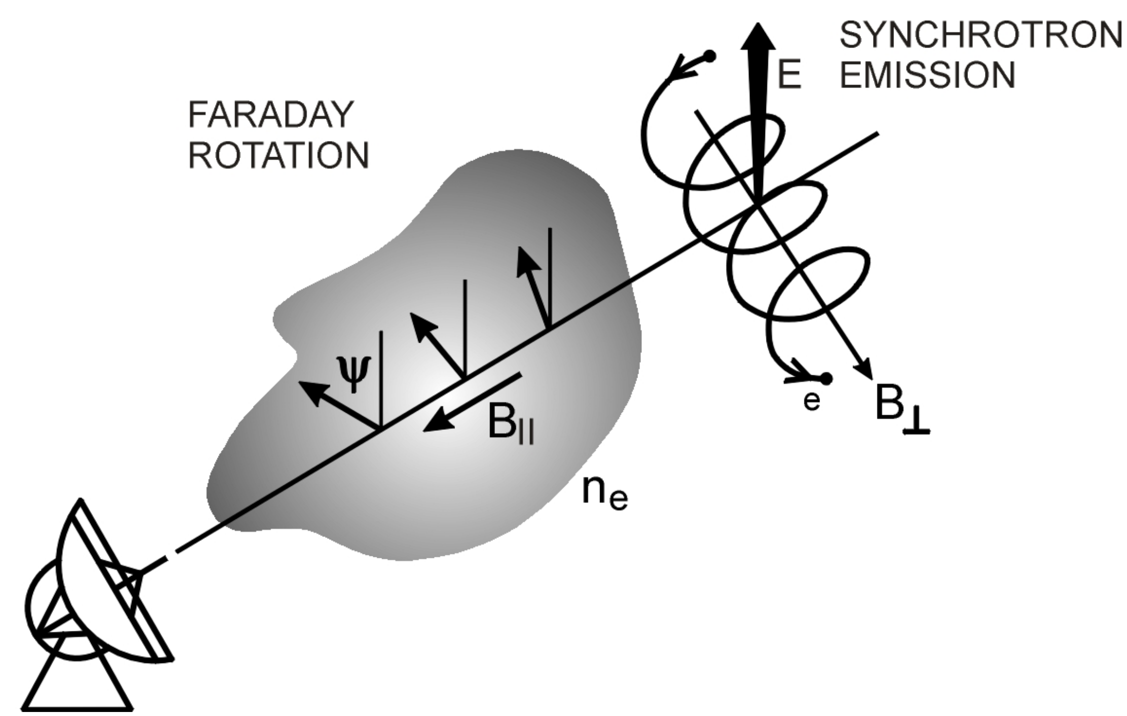
- First order: magnetic fields aligned with matter spiral structure. Can't be coincidental.
- But not always.
- Unfortunately, we cannot see our own galaxy like this.
- Furthermore, in an external galaxy, we cannot see the direction, but only its orientation.

Observables

- Synchrotron emission: $I(\nu) \propto \int_{LOS} n_{CRE} B_\perp^2 dl$ i.e. traces component ***perpendicular*** to LOS
- Rotation measure: $RM \propto \int_{LOS} n_e B_{||} dl$ 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-Pérez)

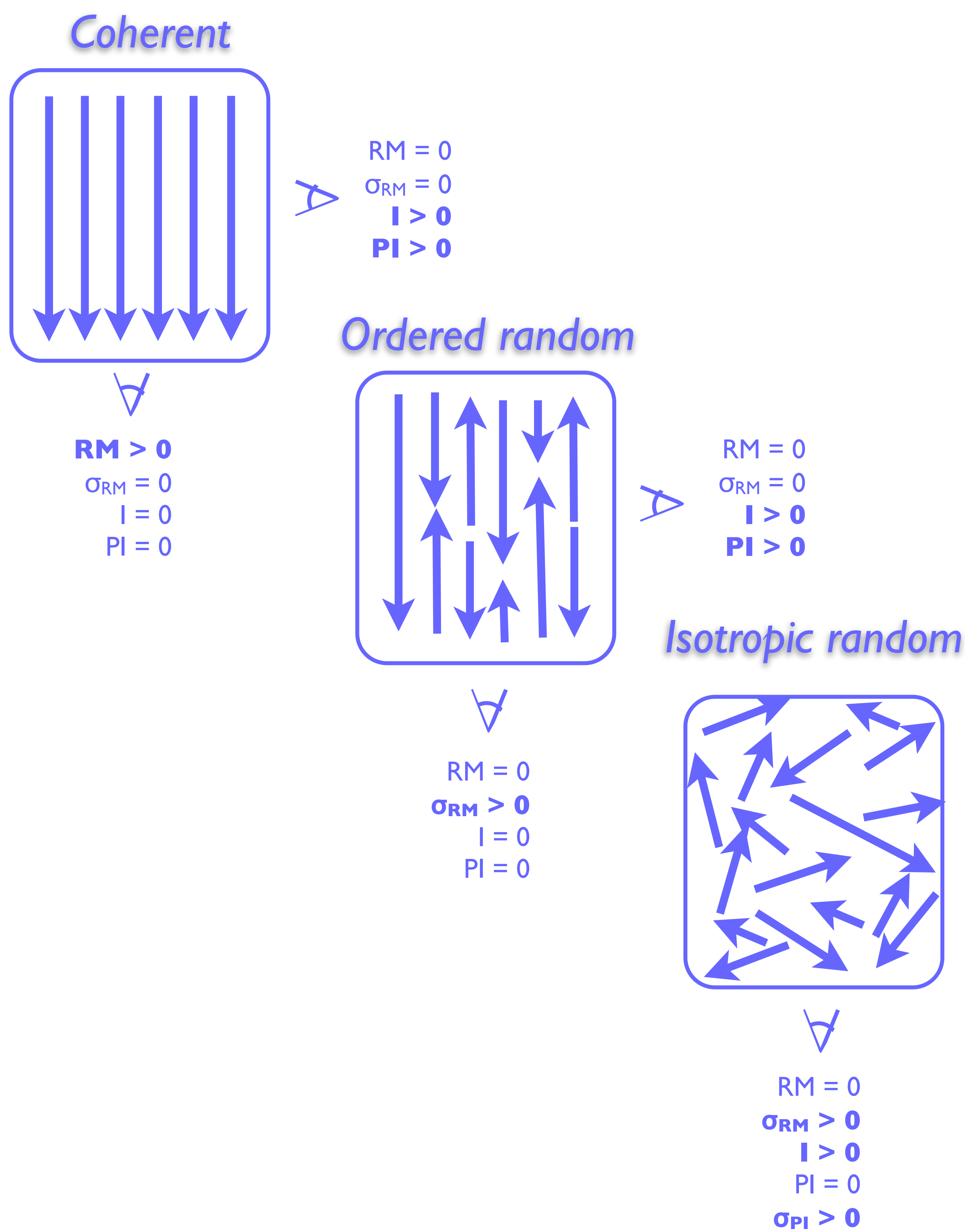


(Courtesy R. Wielebinski)

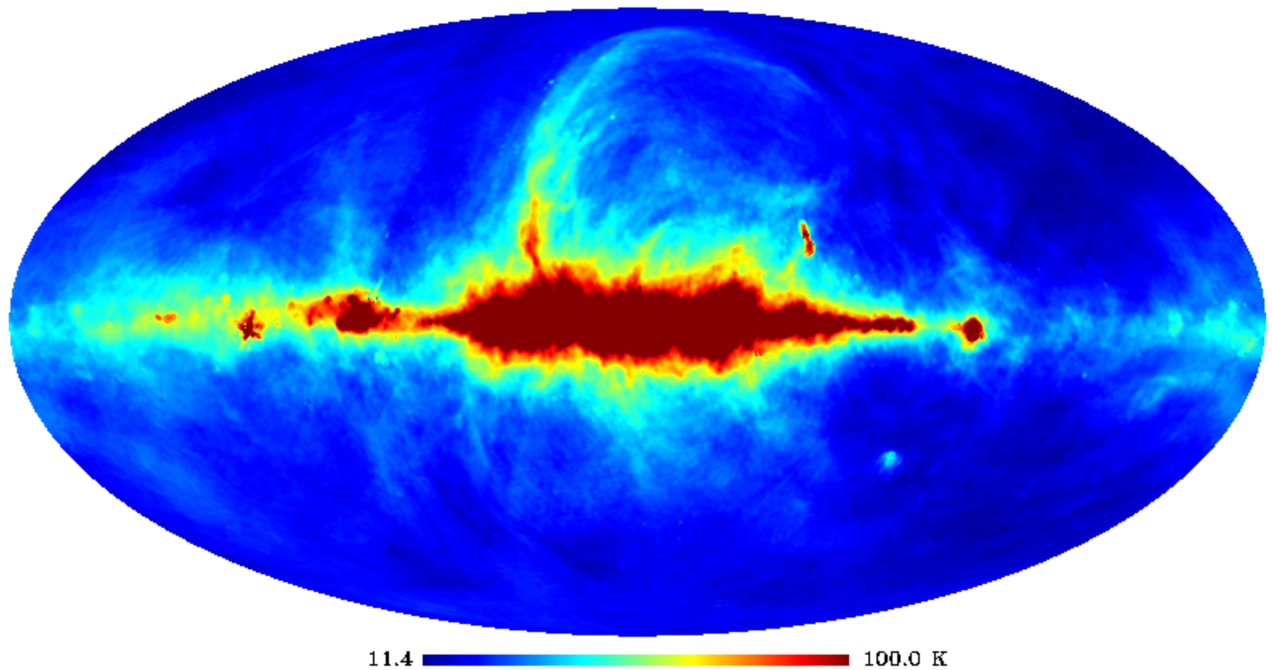
Note that plots of polarization vectors are often rotated 90deg to show B-field direction

Geometry

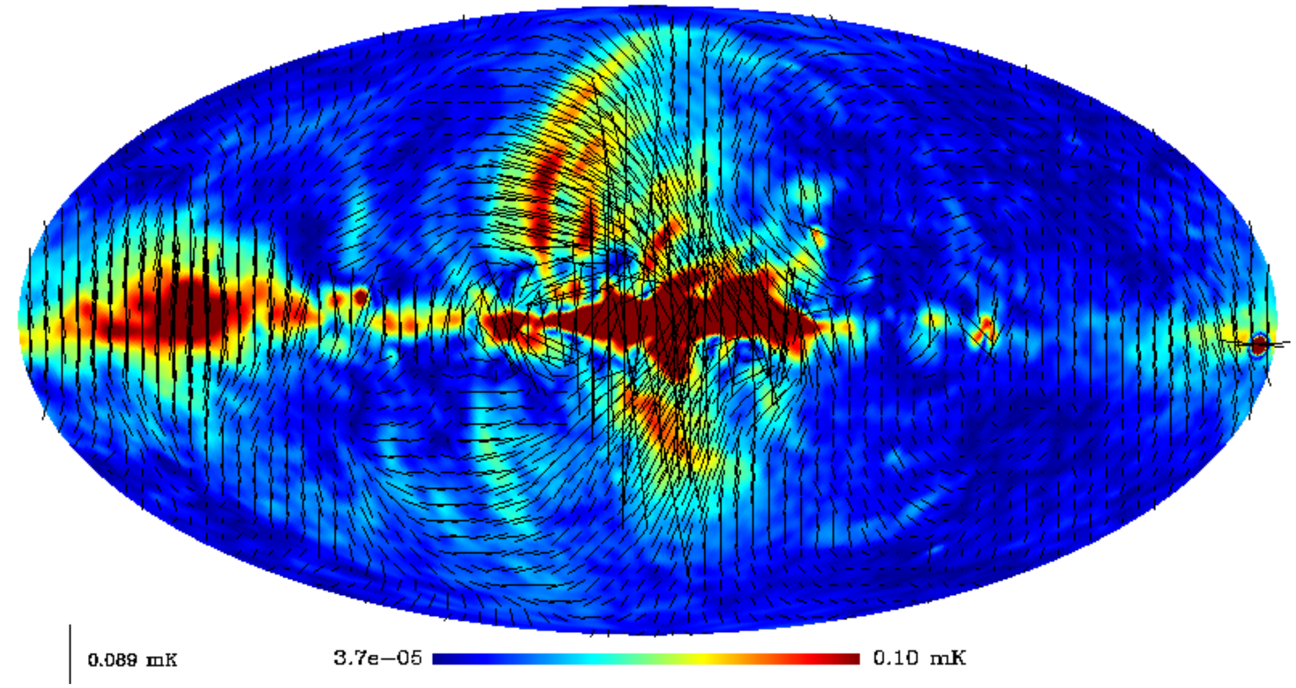
- Coherent contributes to RM for $B_{||}$ and to I and PI for $B_{\perp}$.
- Ordered random contributes to I and PI perpendicular, but to RM variance only.
- Isotropic random contributes only to I and to PI and RM variance.
- (At microwave frequencies, outside of Faraday regime.)
- Careful when discussing “regular”, “random”, “turbulent”, etc.
- And correct separation of these components matters for CR acceleration and propagation.
- Want I and PI at the same wavelength, but ...



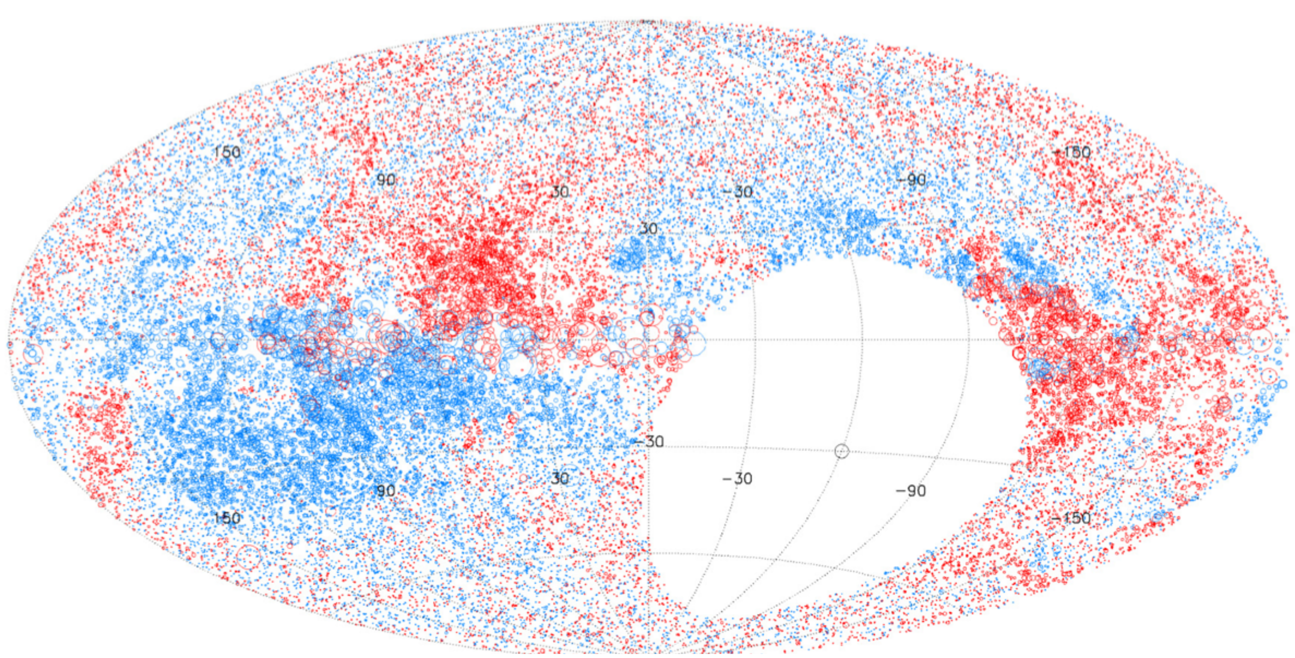
Radio Observations



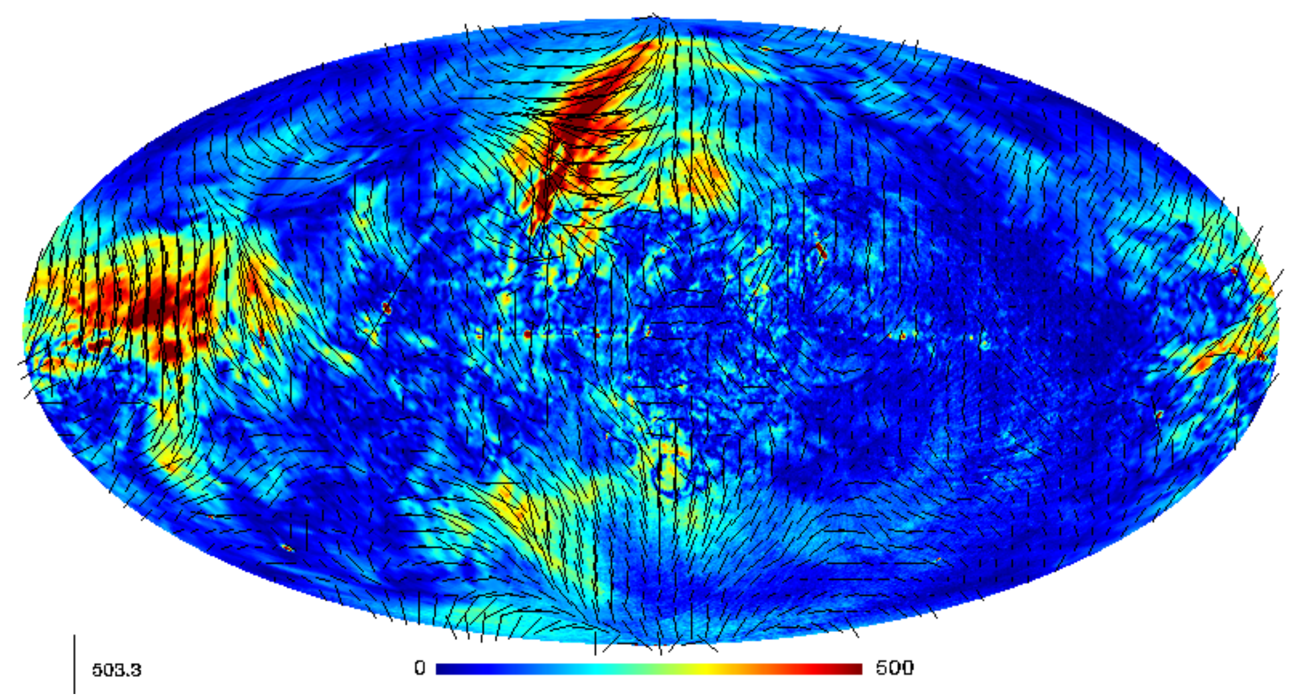
408 MHz total intensity (Haslam et al. 1982)



23 GH polarized intensity (Page et al. 2007)

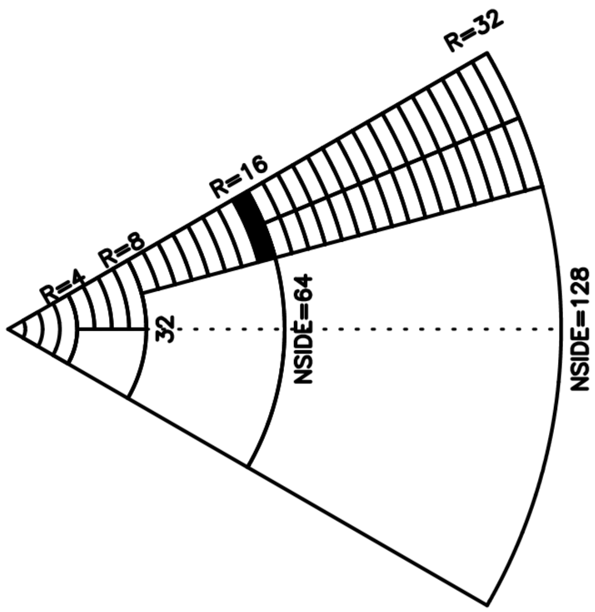


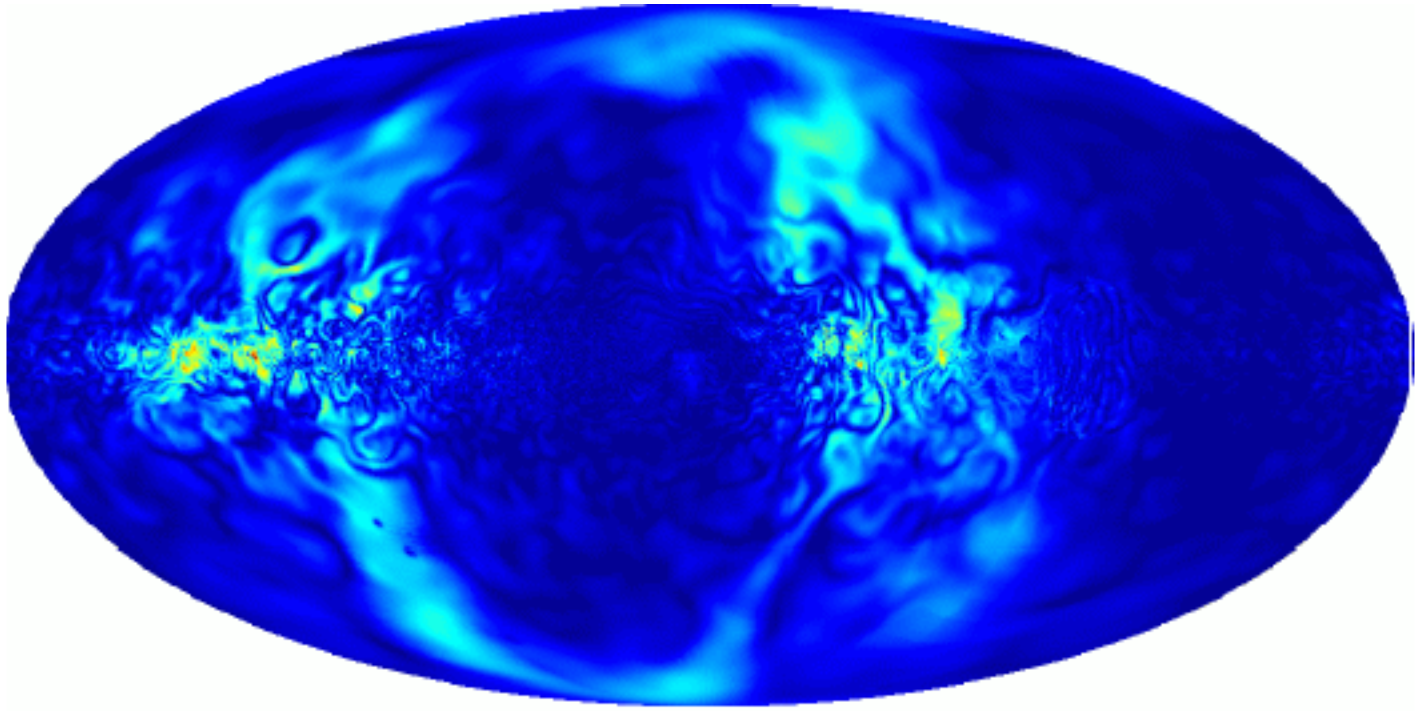
Faraday rotation measure (RM) 1.4 GHz
(Taylor et al. 2010)



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

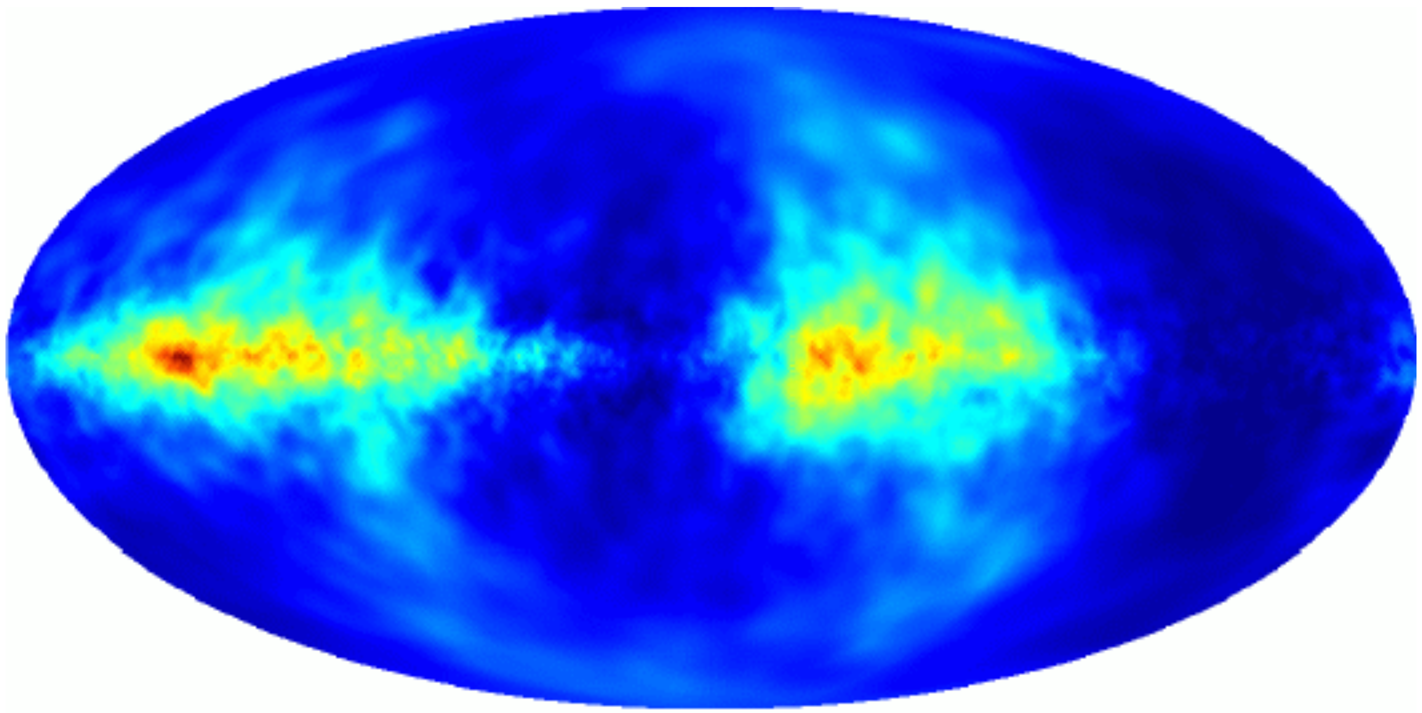
Modeling: hammurabi





1.4 GHz polarized intensity

- 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.



23 GHz polarized intensity

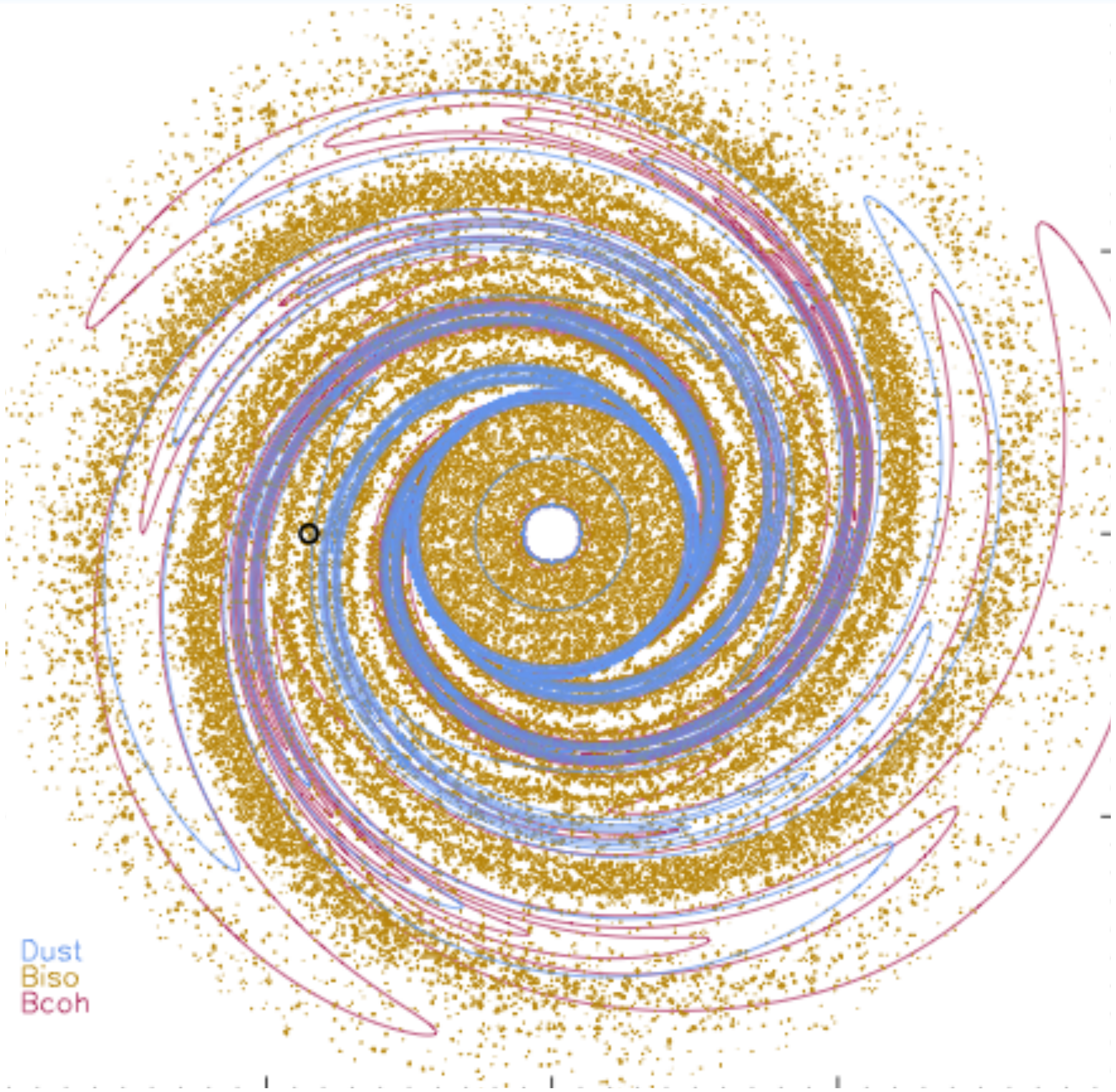
(Courtesy A. Waelkens.)

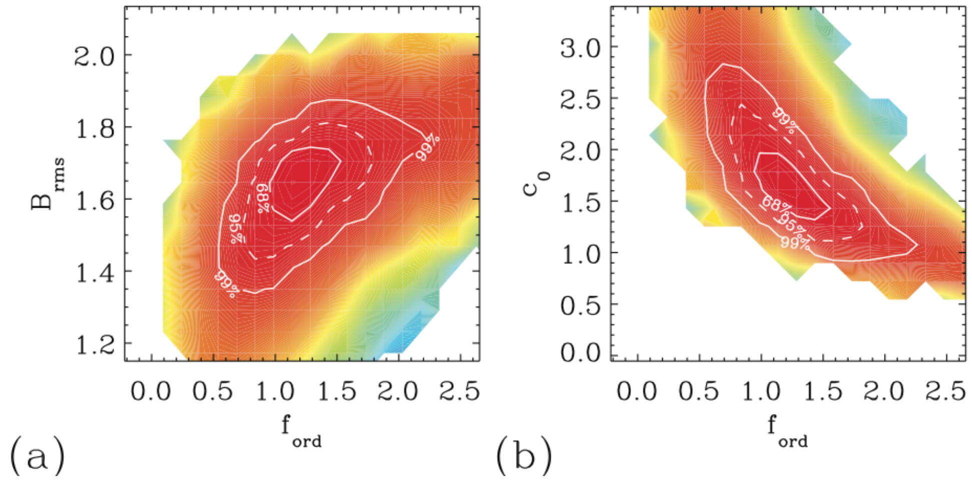
* Publicly available on Sourceforge: http://sourceforge.net/projects/hammurabicode/

Model inputs:

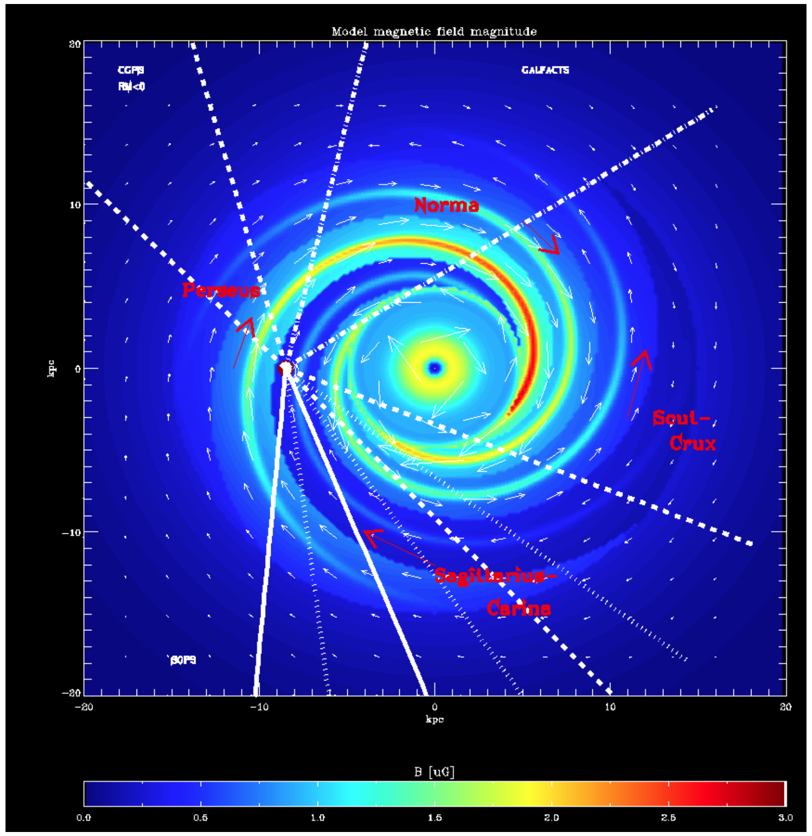
Motivated by external galaxies:

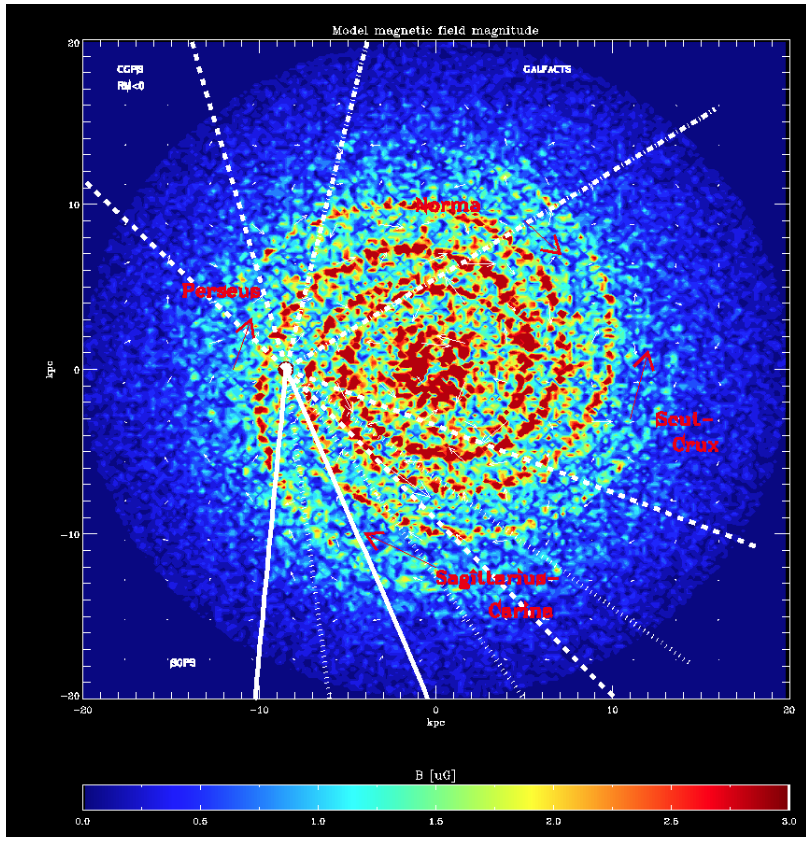
- 3D magnetic field model:
    - spiral arm model for ‘coherent’ field;
    - small-scale turbulence, e.g., based on GRF with power-law spectrum;
    - anisotropic turbulence, aka “ordered random” or “striated” field.
- 3D CRE density and spectral model: e.g., exponential disk with canonical power law, or GALPROP etc. constrained by gamma-rays;
- 3D thermal electron density model: NE2001 (Cordes and Lazio 2002, Gaensler et al. 2008);
- Hammurabi to integrate observables along LOS;
- Model selection, i.e. likelihood function to explore parameter space, e.g. MCMC.
- Sun et al. (2008,2010); Jaffe et al. (2010,2011,2013); Fauvet et al. (2011,2012); Jansson & Farrar (2009,2012a,b)





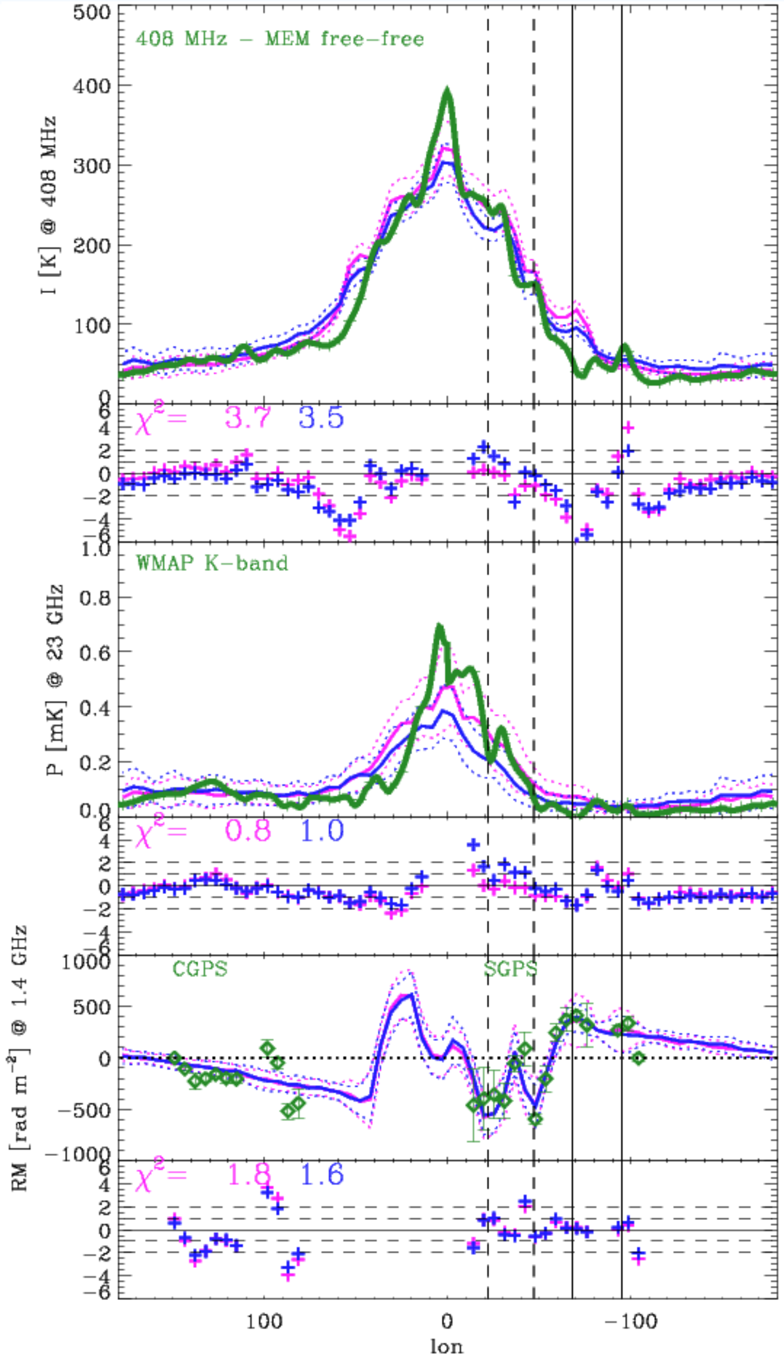
First results in the plane: field ordering





Three observables => three field components constrained.

- 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!

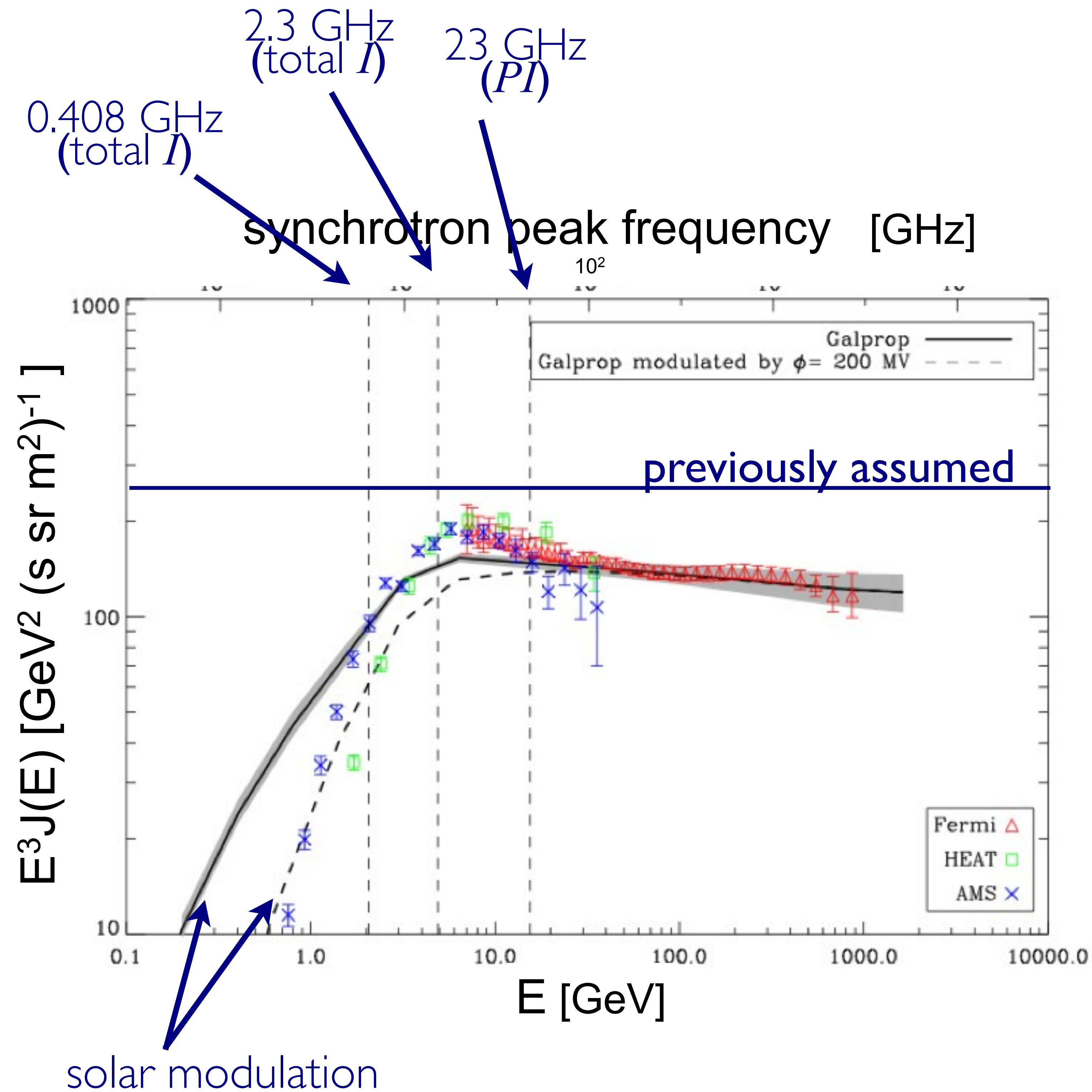
CREs: or, real life isn't always a power law.

- 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:

$$I(\nu) \propto \int_{LOS} dl \int_0^\infty dx B_\perp n_{CRE}(\gamma) F(x) \qquad x \equiv \frac{\omega}{\omega_c} \qquad \omega_c \equiv \frac{3\gamma^2 B_\perp}{2mc}$$

  (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); 'z04LMPDS' from Strong et al. (2010).

CRE results:

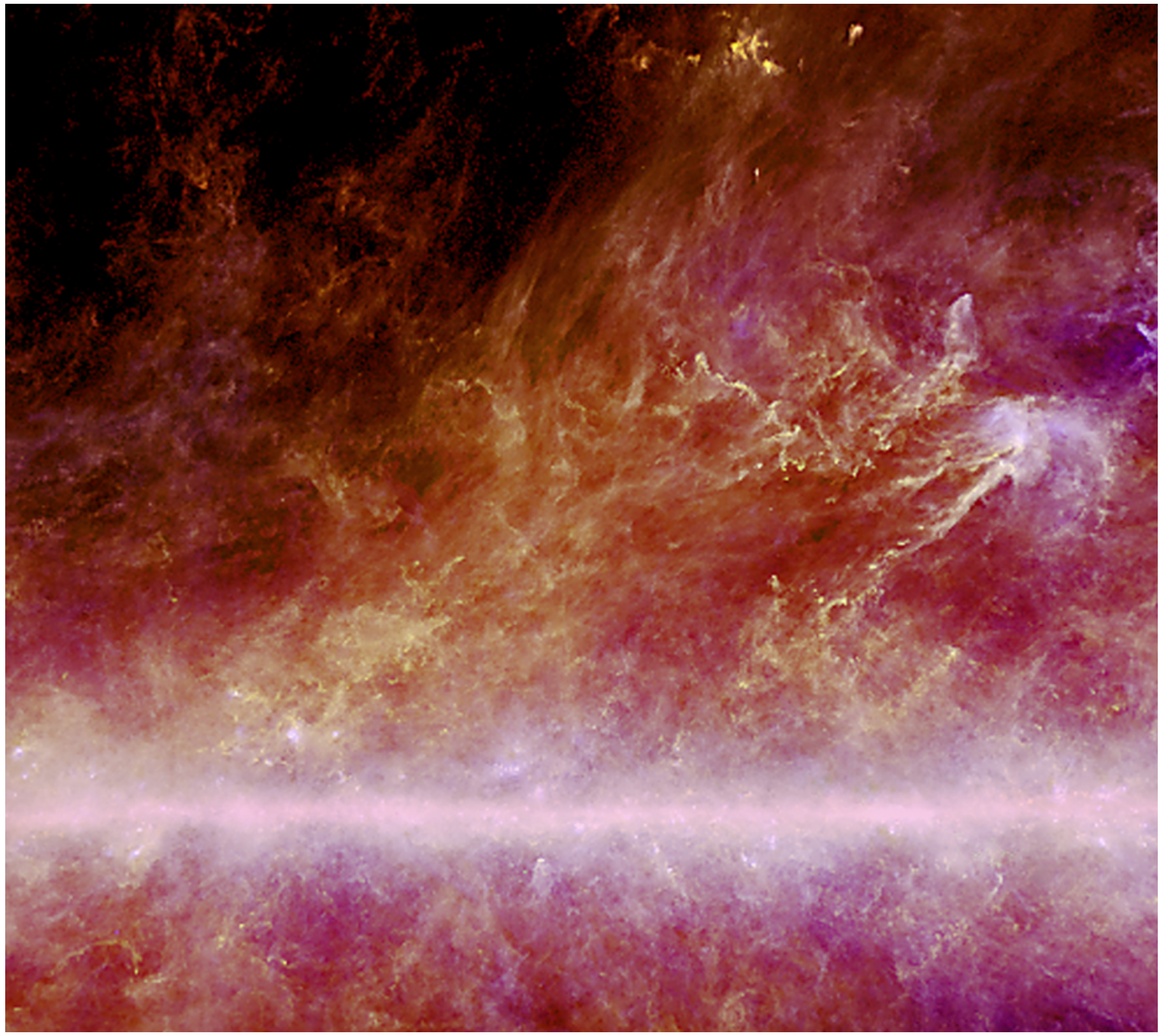


Jaffe et al. (2011)
(See also Strong, Orlando, & Jaffe 2011)

- Find below few GeV, $J(E)\sim E^{-1.3}$, slightly harder than usually assumed, compared to $J(E)\sim E^{-2.3}$ above.
- 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 difficult to constrain.

Re-acceleration?

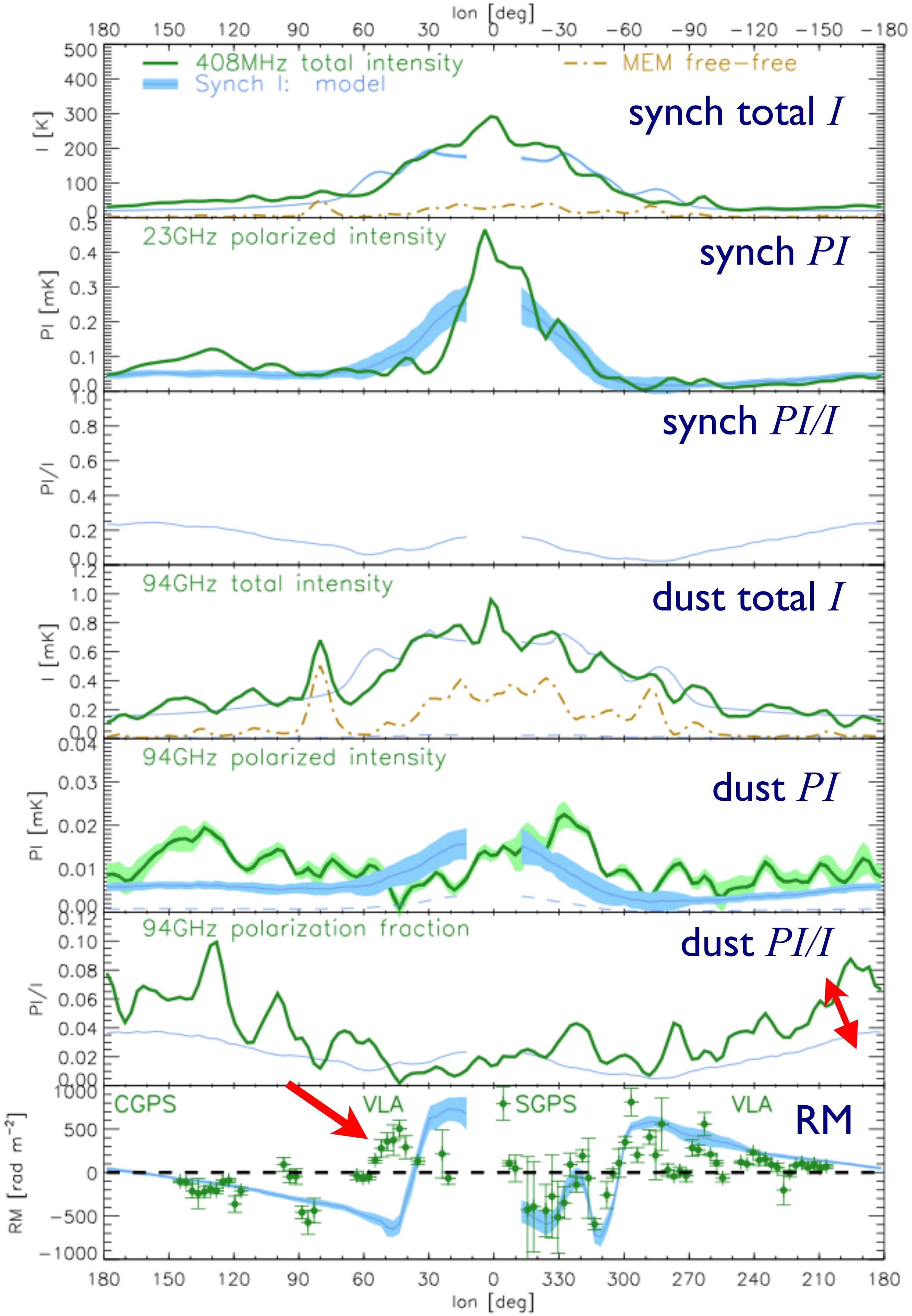
What about dust?



Planck and IRAS composite image (ESA).

- Polarized dust emission is a complementary observable independent of CRE or thermal electron distribution uncertainties affecting synchrotron or RM.
- And the dust distribution is better constrained than that of CREs, so we can then constrain spatial distribution of field components.
- Informed by modeling of grain alignment processes from detailed studies of small regions, and perhaps vice versa.
- Improved B-field model then allows better understanding of CR propagation.

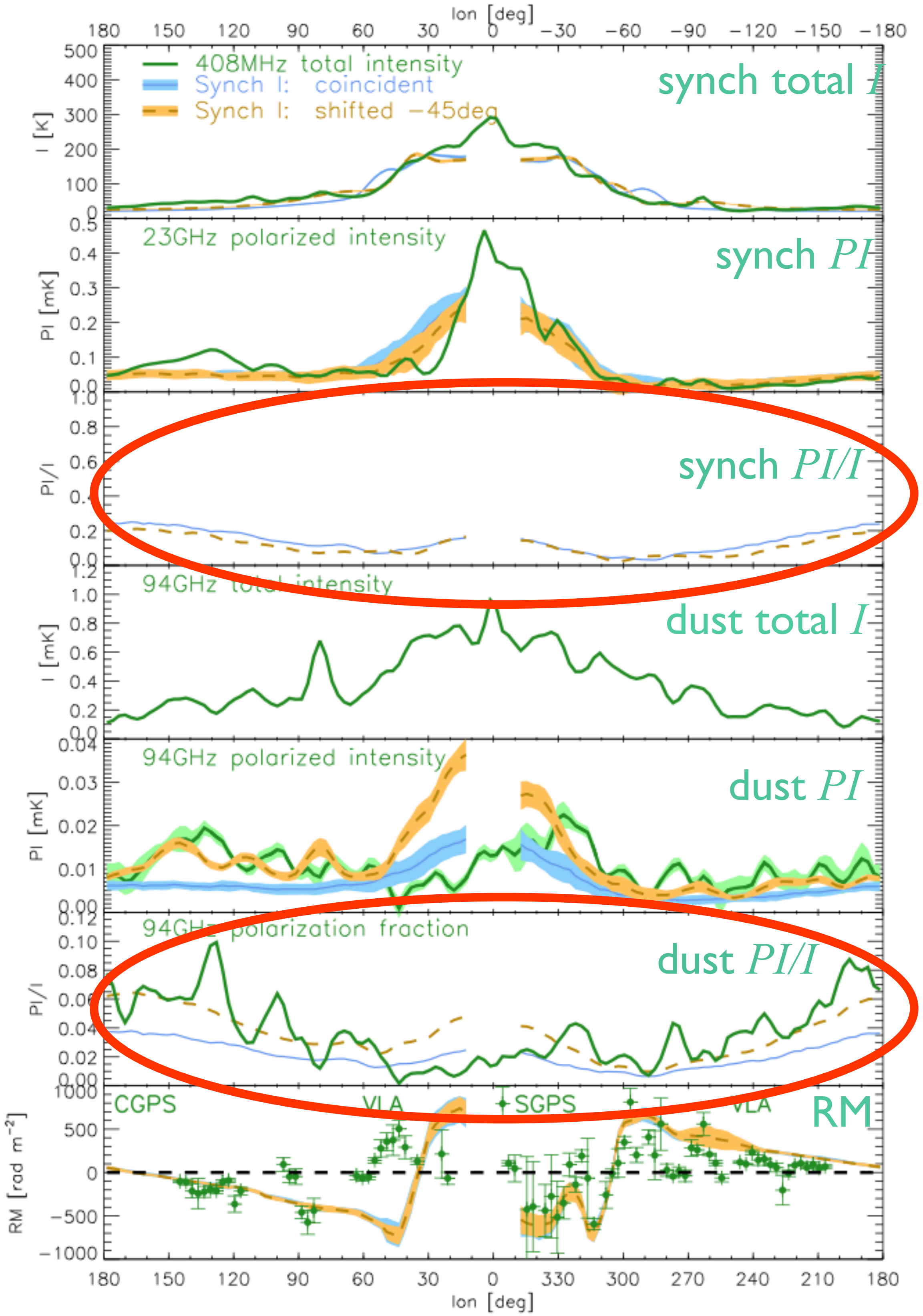
Dust: first look with *WMAP* 94GHz

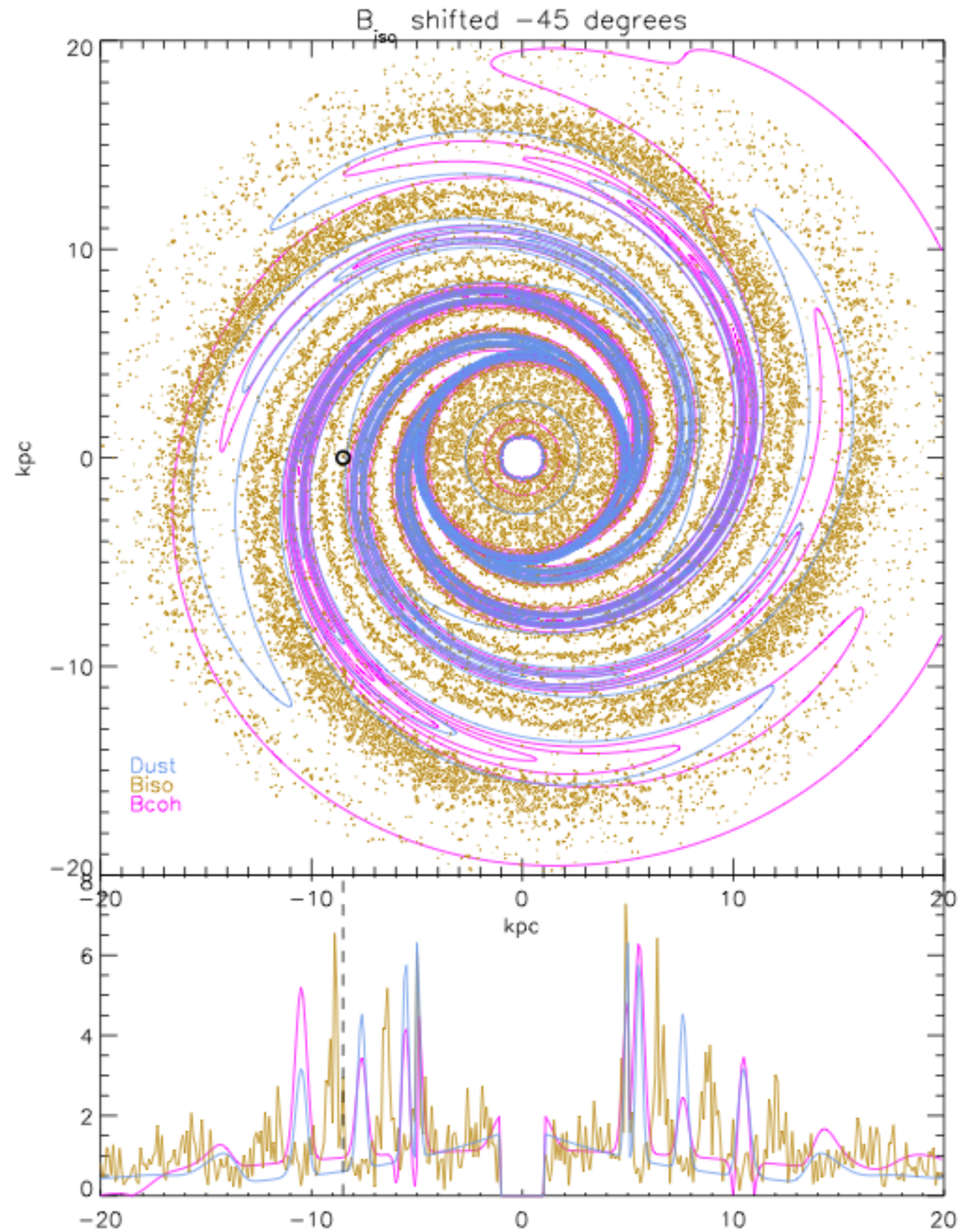


Jaffe et al. (2013.)

- Simple model for thermal dust polarization does not work even with sub-grid PI/I of 30%. (Planck PIP XIX 2014 predicts 20%.)
- Polarization degree significantly under-predicted => dust emission coming from regions with more ordered fields.
- Cannot model it by changing dust distribution alone, but must change the fields in a way that remains compatible with synchrotron.
- This means we can begin to separate spatially the different components of the magnetized ISM.
- This is telling us about not only about the average strengths of the field components but about their relative locations, even from our position within the disk.
- Knowing where the fields are ordered and where they are disordered has implications for CR diffusion, CR acceleration sites, etc.

One idea: separable spiral arm ridges?





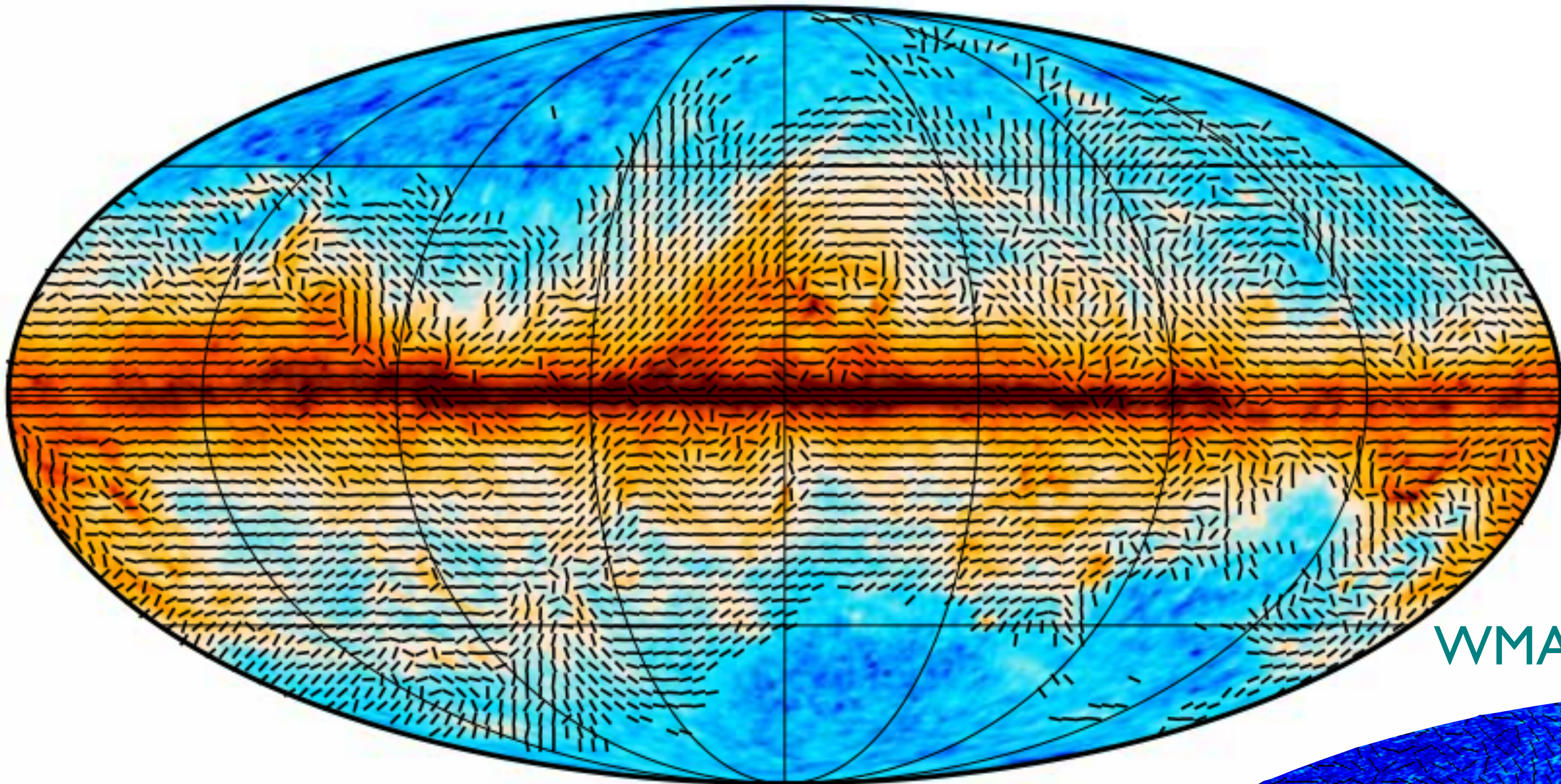
Jaffe et al. (2013)

Planck project

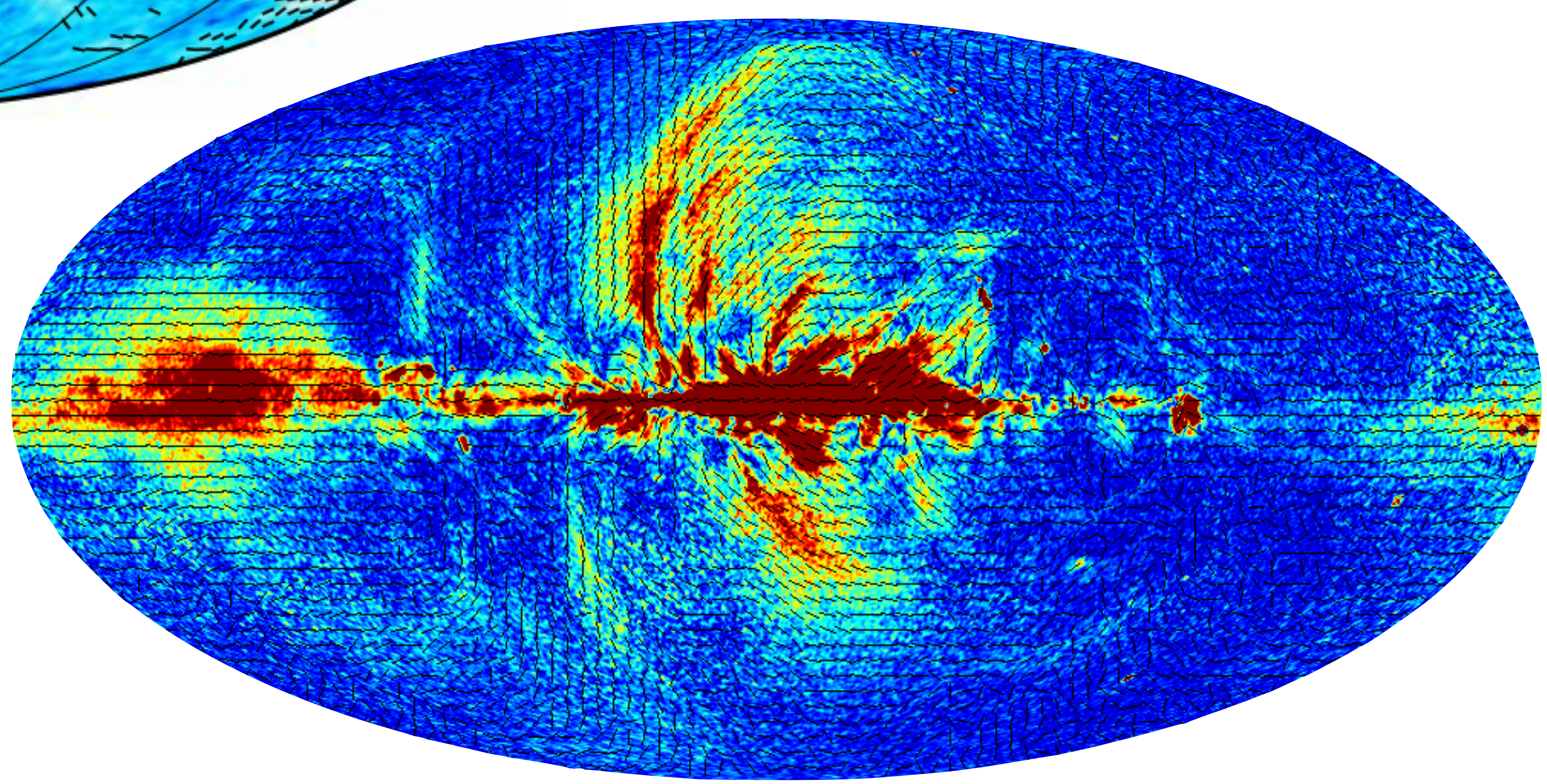
(See talk by E Falgarone)

Planck 353GHz total I with B orientation

(Planck Collaboration, PIP XIX, 2014)



WMAP 22 GHz PI with B orientation



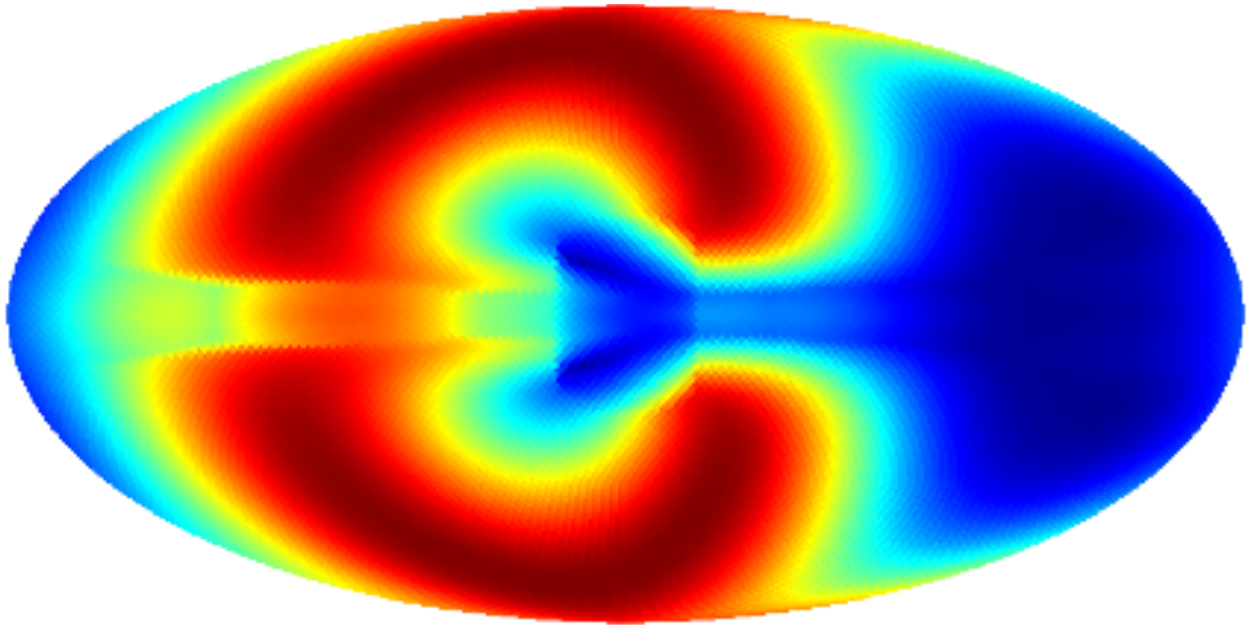
Planck project on large-scale Galactic B

- Simultaneous modeling of synchrotron and thermal dust emission
- Planck LFI 30GHz and HFI 353GHz polarization data
- Models in the literature:
  - Sun et al. 2010 (RM, synch I and PI)
  - Jansson & Farrar 2012a,b (RM, synch I and PI)
  - Fauvet et al. 2012 (synch and dust PI)
  - Jaffe et al. 2010,2013 (RM, synch and dust I and PI)
- Synchrotron versus dust geometry is unintuitive.

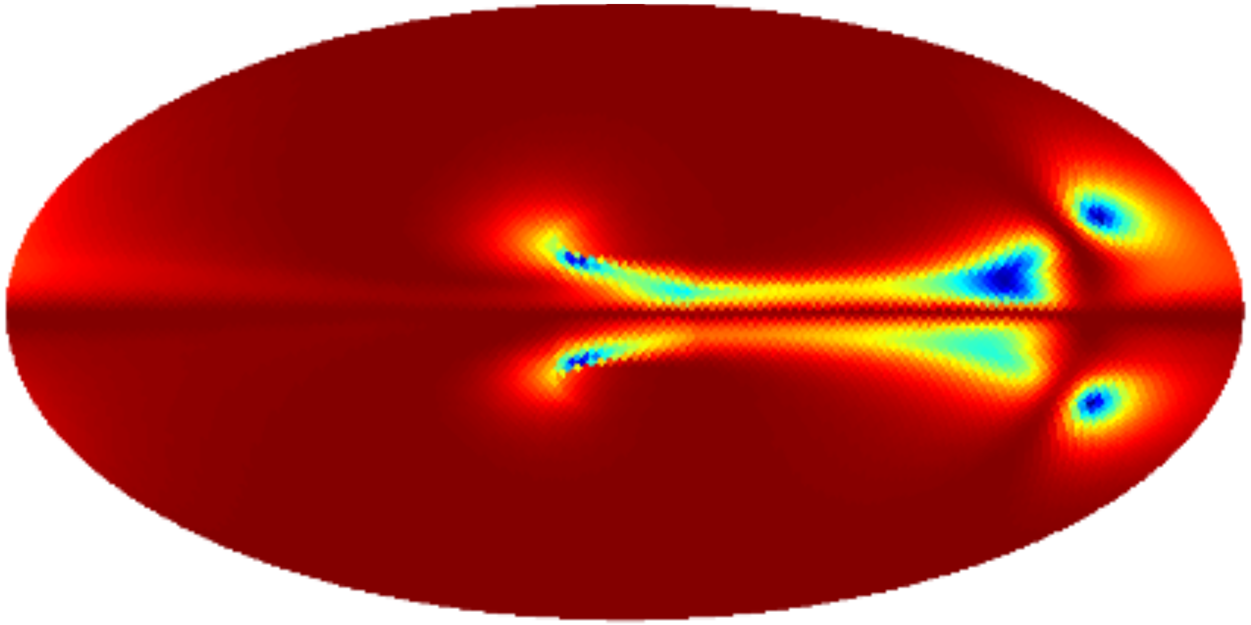
Synchrotron versus Dust

- Even with a **toy model** of uniform particle distributions in a Galactic box, the polarization geometry comes out differently for the same coherent field.
- Planck PIP XIX (2014) showed simple comparisons of dust and synchrotron: some regions show strong correlations (NPS, Fan), but most of the sky shows none.
- Difficult to interpret without a model. Ongoing work on joint modeling of synchrotron and dust.
- Inner versus outer Galaxy seen in Jaffe13? Other models?

Dust polarization
(relative to maximum)



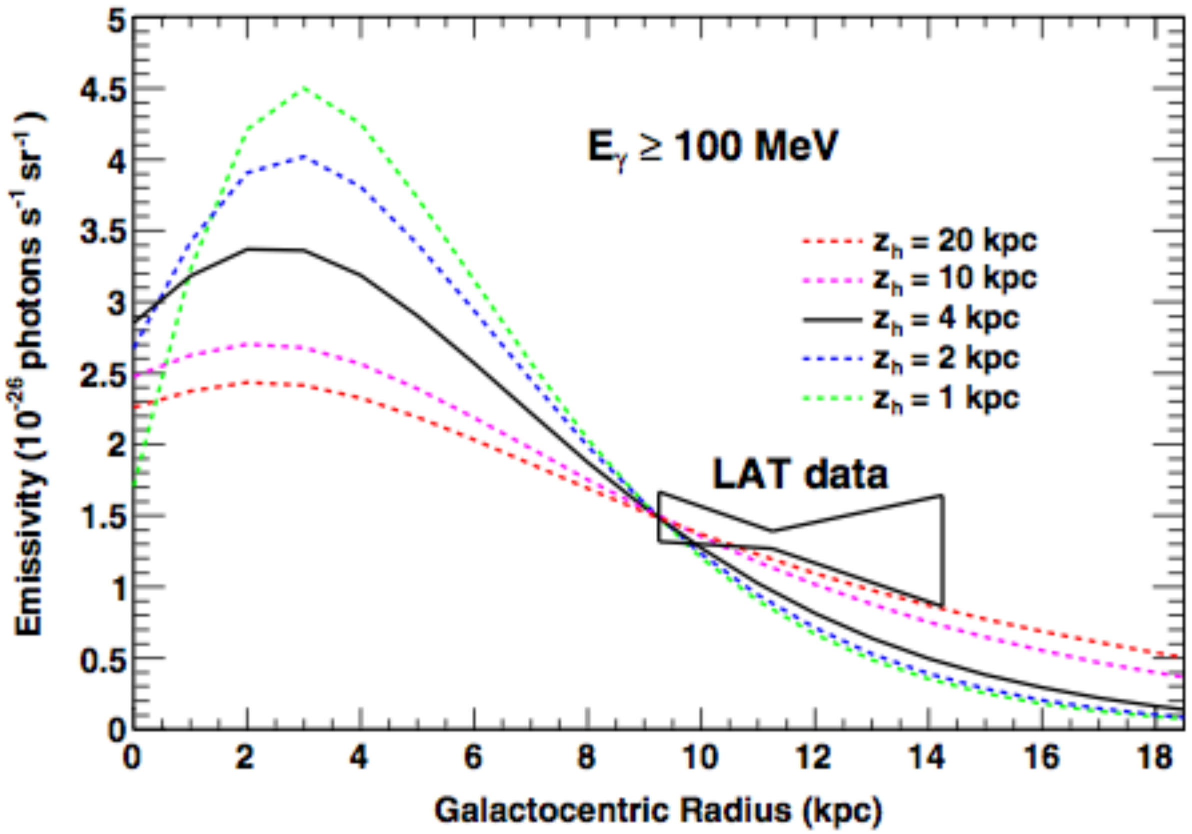
Synchrotron polarization
(relative to maximum)



(Simple axisymmetric spiral field from *WMAP* (Page et al. 2007))

gamma-ray gradient problem?

- CREs that produce synchrotron also produce gamma-rays through Inverse Compton and gas collisions. Observed distribution depends on:
  - Cosmic ray source distribution? Assumed supernovae, following pulsars.
  - Diffusion?
  - Vertical distribution scale height? Difficult to measure, $1<h<10\mathrm{kpc}$
  - Turbulent magnetic fields
- Current predictions have too many gamma-rays in the outer Galaxy compared to Fermi constraints (problem since EGRET).

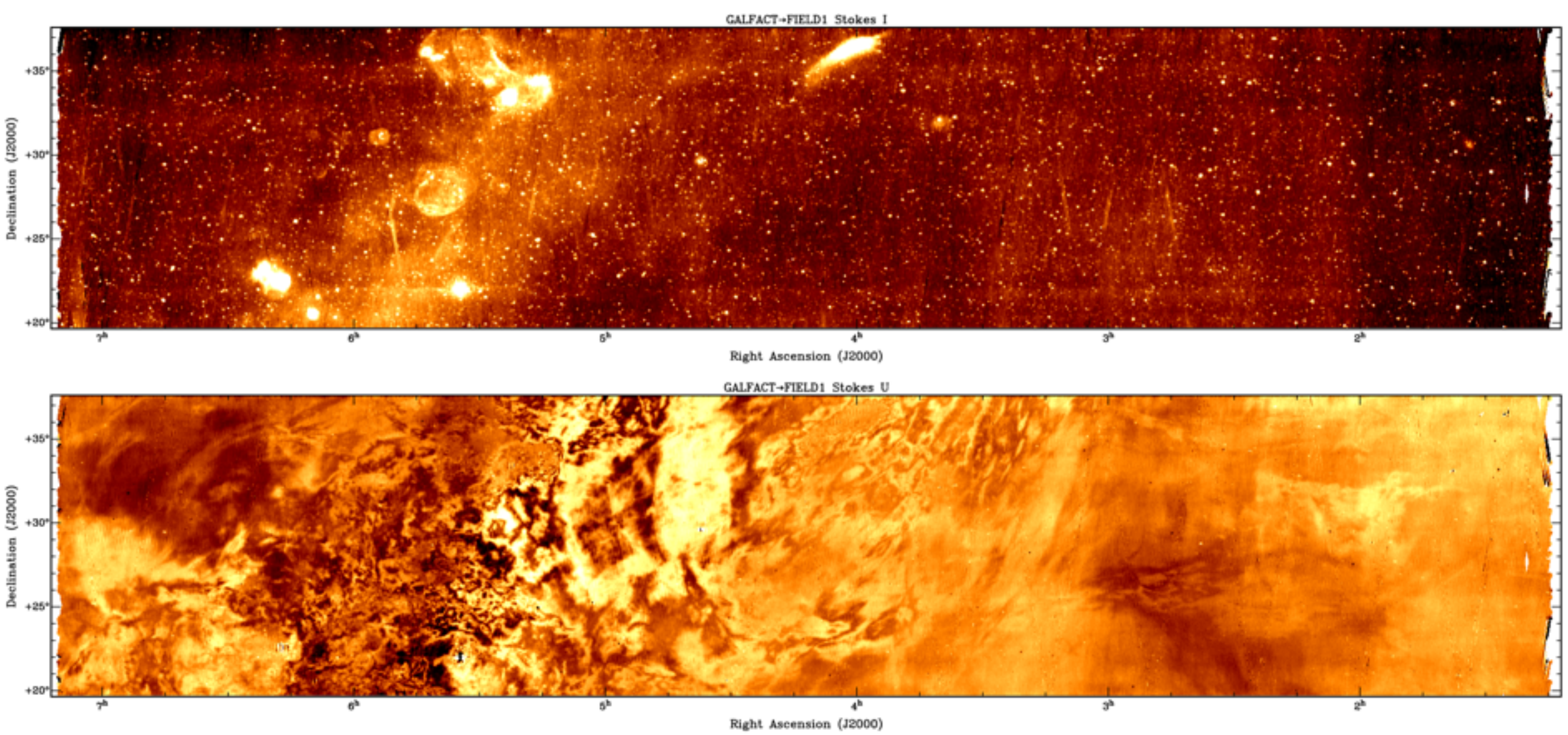


Ackermann et al. (2011, ApJ, 726, 81)

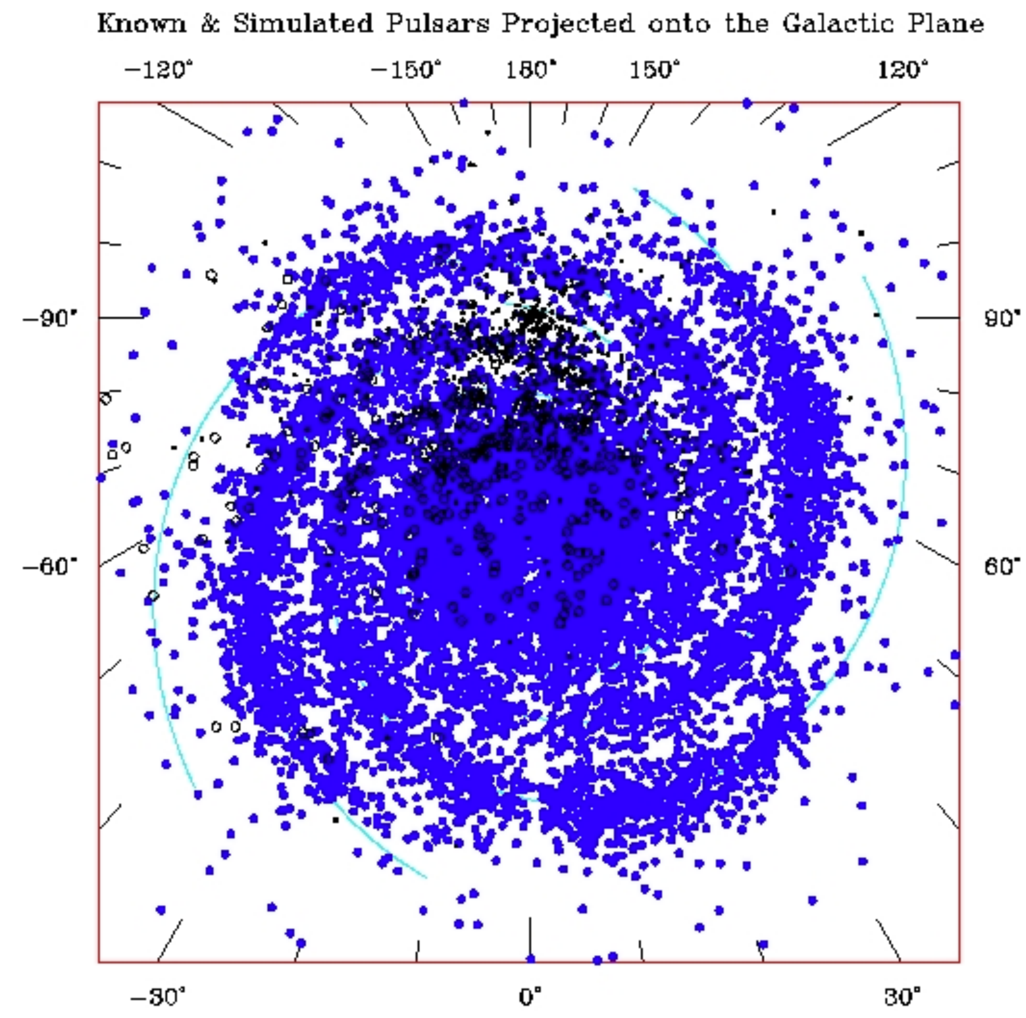
Precisely what is mysterious in dust vs synch (Jaffe et al. 2013)

Prospects:

- 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. External galaxies.
- Gaia for mapping out dust distribution using stellar extinction
- PILOT (COrE, PIXIE?) for sub-mm polarization
- SKA...



GALFACTS field (George et al., ADASS, 2010)



SKA simulation (Cordes)

Conclusions:

- 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 over.
- Better models of the magnetic fields lets us learn about other things like the CRE spectrum and propagation.
- There's still a lot of information in the existing data (i.e. ways our models don't fit!) and a lot of data on the horizon.