# Cosmic rays in the Galactic magnetic field

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# General picture for extragalactic cosmic rays

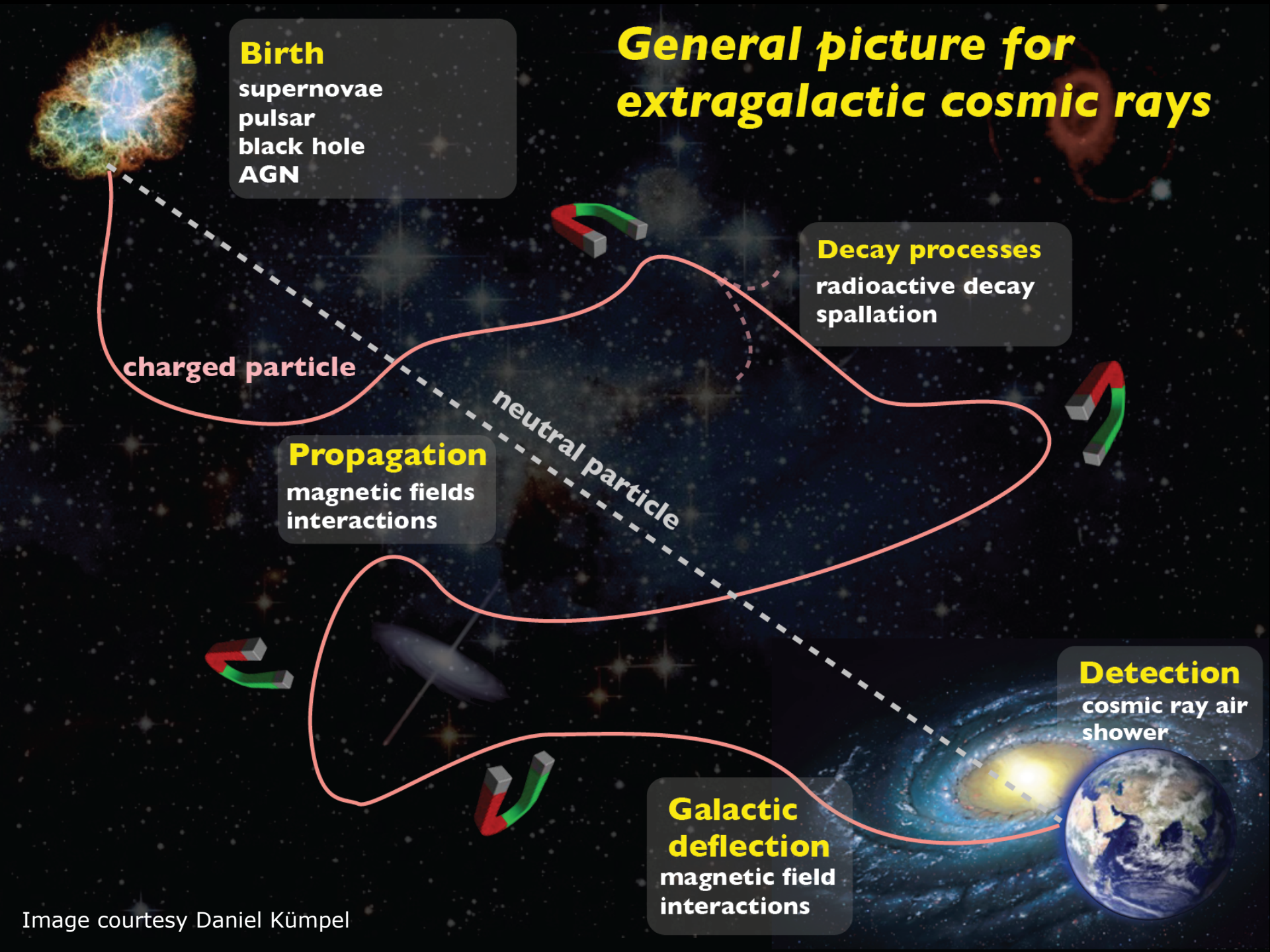



Image courtesy Daniel Kümpel

# Ultra-high energy cosmic rays in a Galactic magnetic field model

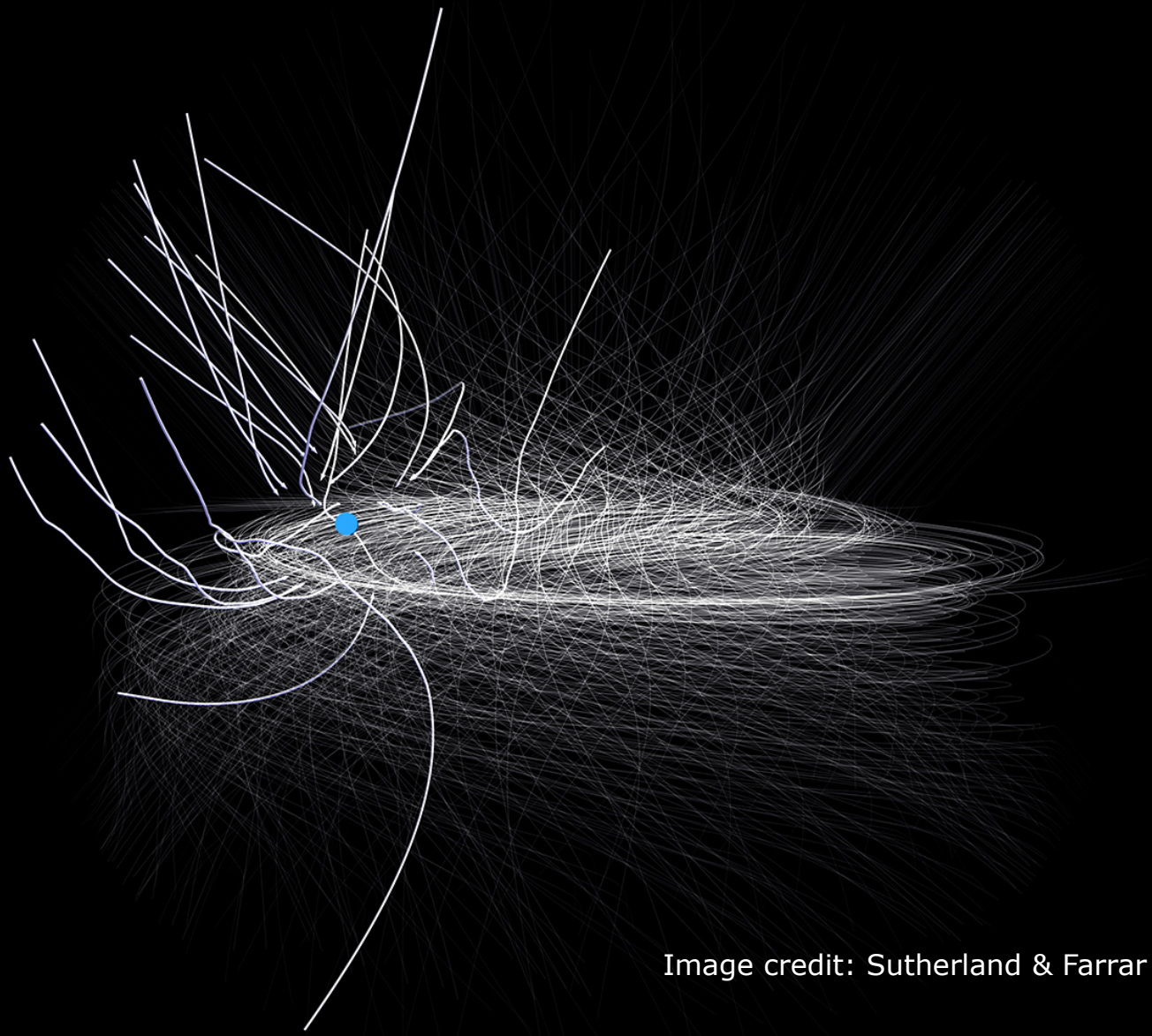
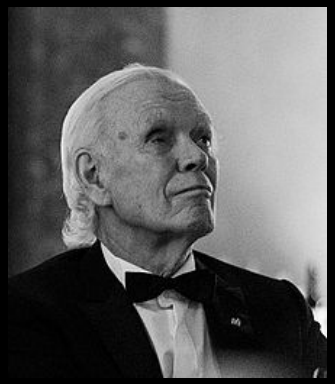


Image credit: Sutherland & Farrar

# HOWEVER: cosmic magnetic fields are hard to observe or to simulate



Lo Woltjer (1967):

"The argument has frequently been a process of elimination: one observes certain phenomena, and one investigates what part of the phenomena could be explained; then the unexplained part is taken to show the effects of the magnetic field…

It is clear in this case that, the larger one's ignorance, the stronger the magnetic field."

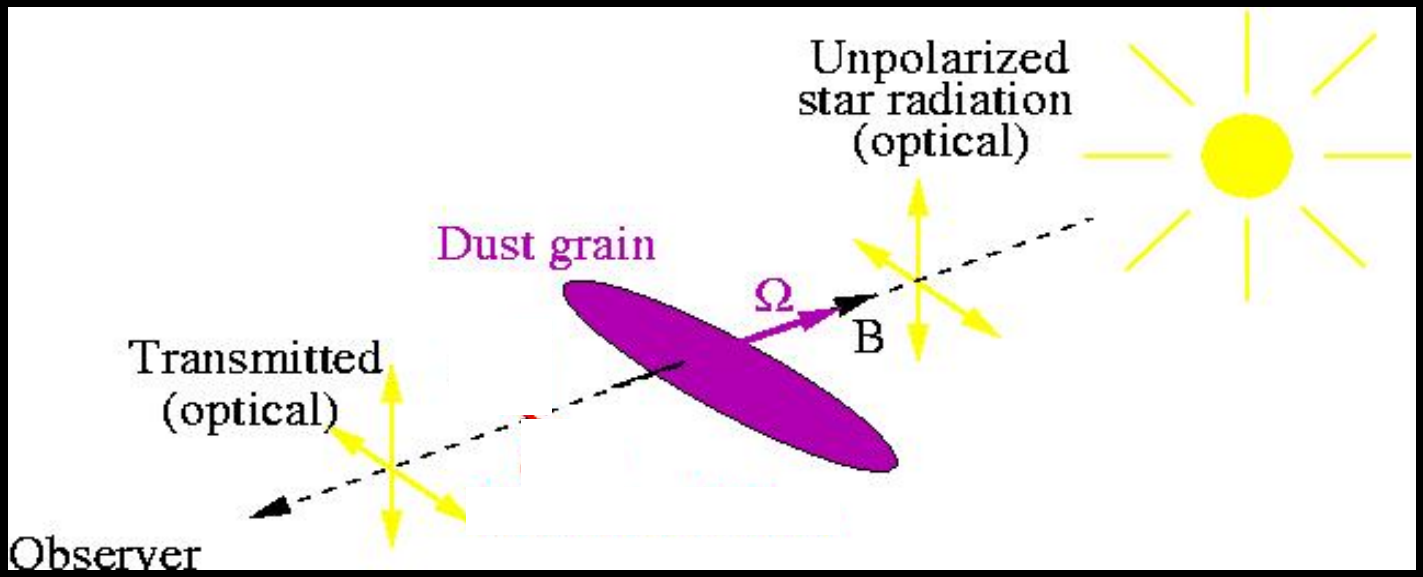
# This presentation:

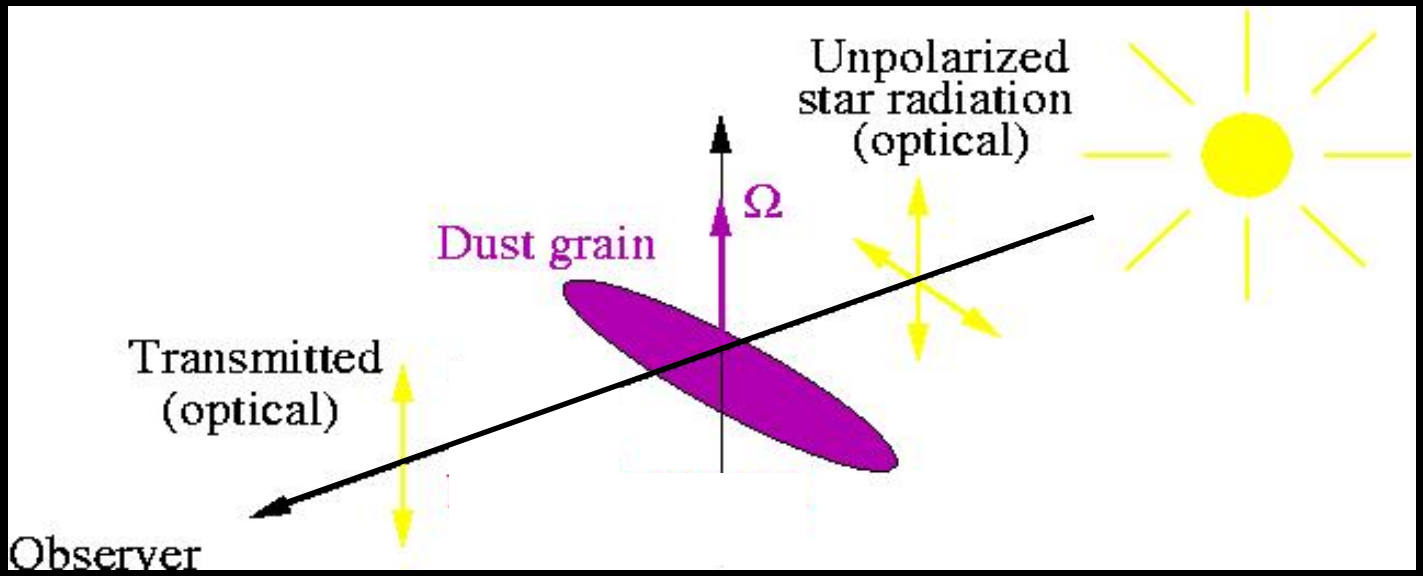
- How to observe Galactic magnetic fields?
  - Polarization of optical/NIR starlight
  - Radio synchrotron radiation
  - Faraday rotation
- What does the Galactic magnetic field look like?
  - magnetic field strength and direction
  - the (im)possibilities of modelling Galactic magnetic fields
- How do Ultra-High Energy Cosmic Rays propagate through it?
  - CR deflection models
  - IMAGINE

# Measuring Galactic magnetic fields

| METHOD | TRACER | FIELD COMPONENT |
|---|---|---|
| polarisation of starlight by rotating magnetized dust grains | diffuse dust | direction;<br>⊥ to line of sight |
| polarised dust emission + Chandrasekhar-Fermi effect | dense dust | direction;<br>⊥ to line of sight.<br>strength of regular field |
| Zeeman effect | cold gas, masers | strength ⊥ or // to line of sight |
| radio synchrotron emission | cosmic rays | strength of total and uniform field |
| Faraday rotation | ionised gas | strength;<br>// to line of sight |

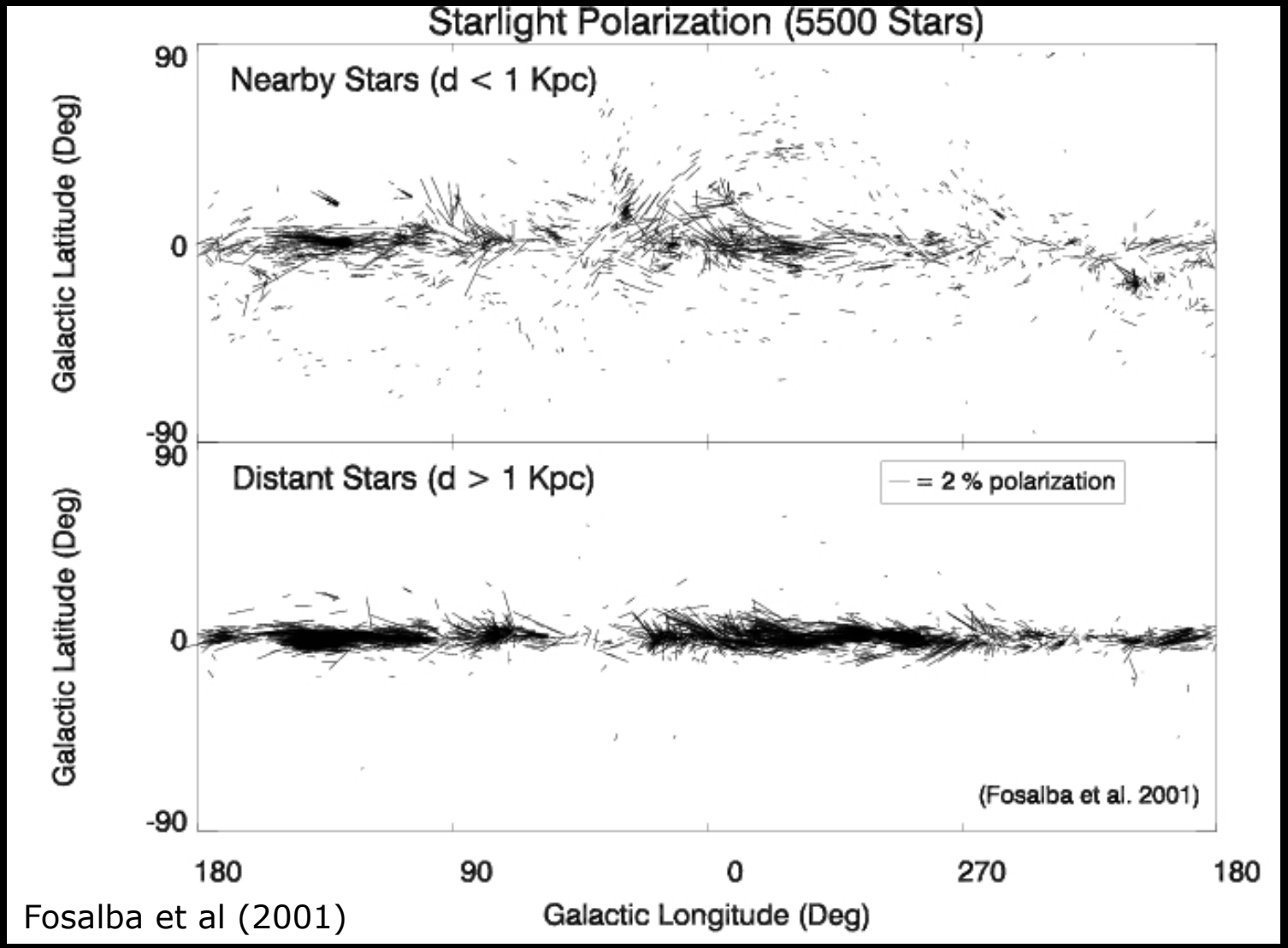
# 1. Polarisation of starlight by rotating dust grains



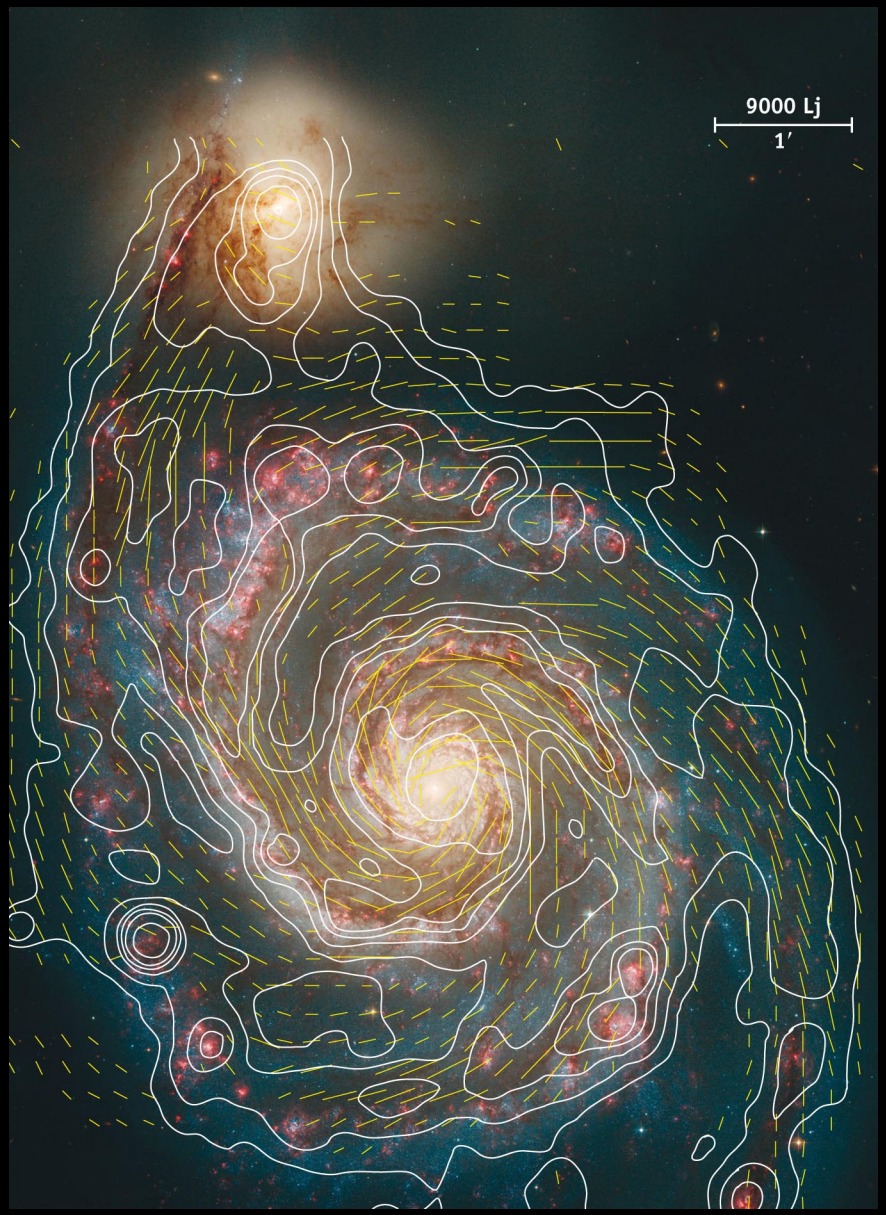

→ parallel to the direction of $B_\perp$ in low-density dust

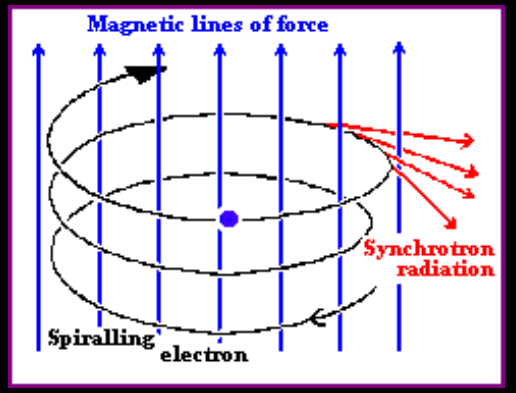
# 1. Polarisation of starlight by rotating dust grains




Fosalba et al (2001)

# 2. Radio synchrotron emission




→ total intensity probes total magnetic field

→ polarized intensity probes regular magnetic field

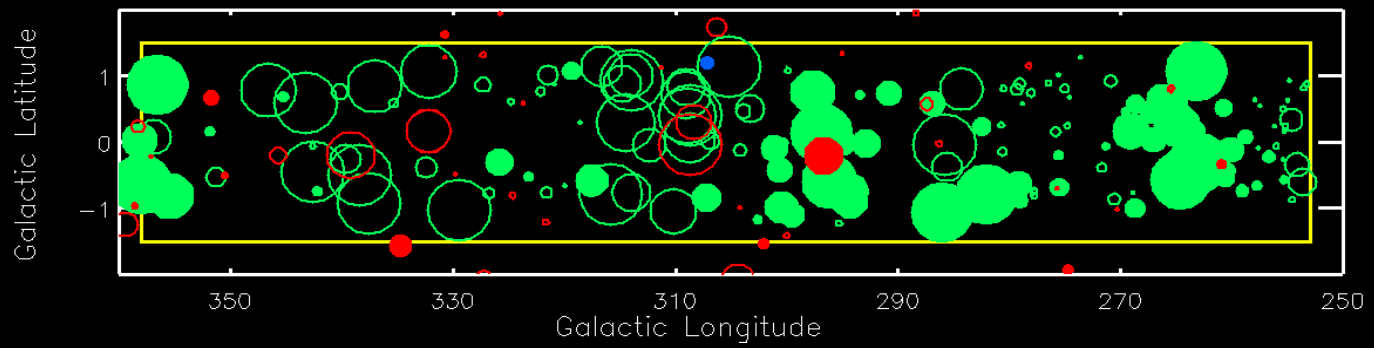
→ polarization angle probes direction of plane-of-sky field

# 3. Faraday rotation


Polarization angle rotates with observing wavelength $\lambda$: $\theta \propto \mathrm{RM}\,\lambda^2$

where rotation measure $\mathrm{RM} \propto \int n_e\, B_{//}\, dl$

Brown et al 2007



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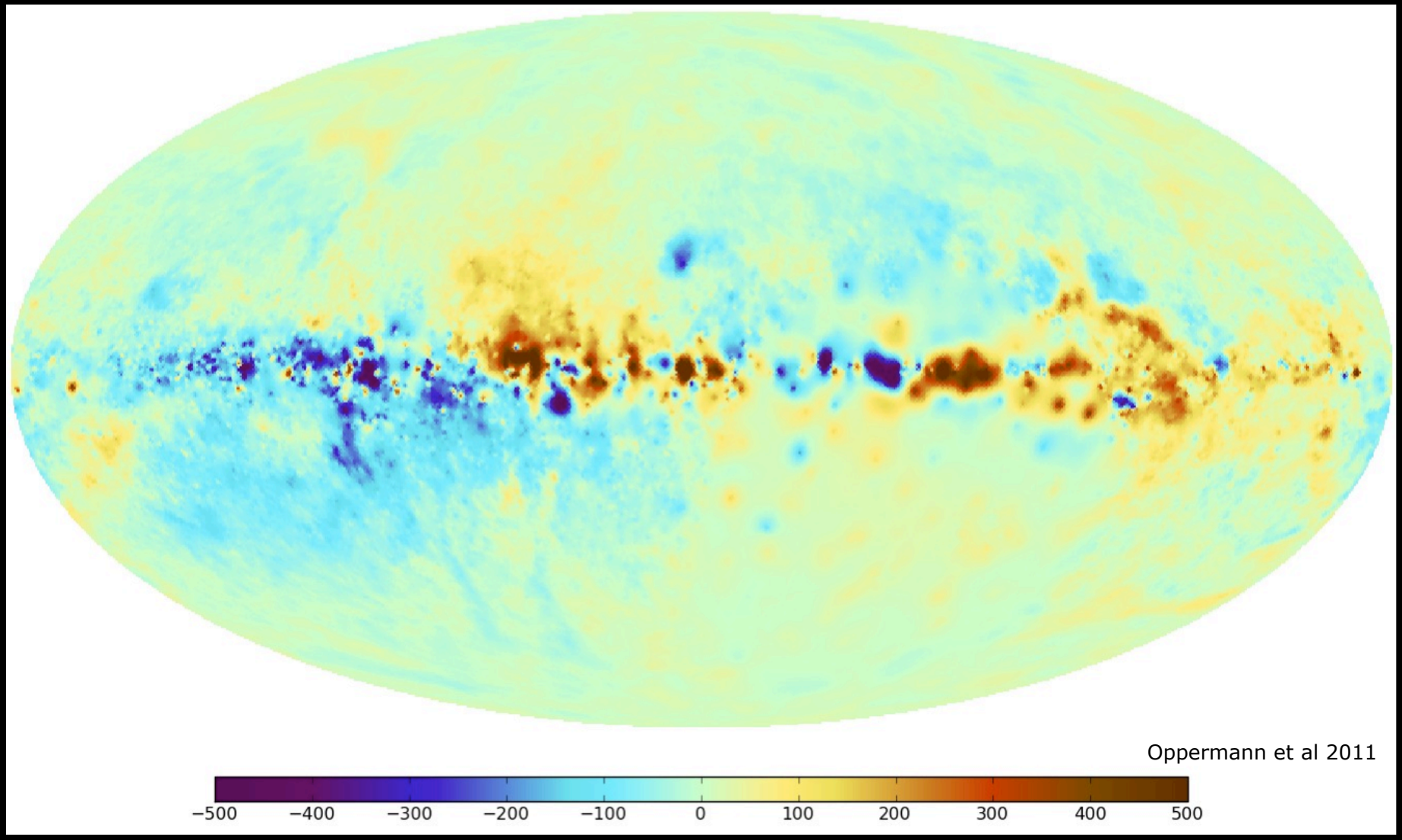


Oppermann et al 2011

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# Magnetic fields in the Galactic disk


$B_{tot}$ ≈ 6 μG at solar circle

$B_{tot}$ ≈ 10 μG at R = 3 kpc

$B_{reg}$ ≈ 2 μG at solar circle

$B_{ran}$ higher in spiral arms
$B_{reg}$ higher in interarms

# Point source RMs can give ambiguous results on the large scale field

$RM \propto \int n_e \, \mathbf{B}\cdot\mathbf{dl}$

Extragalactic source RM

pulsar RM

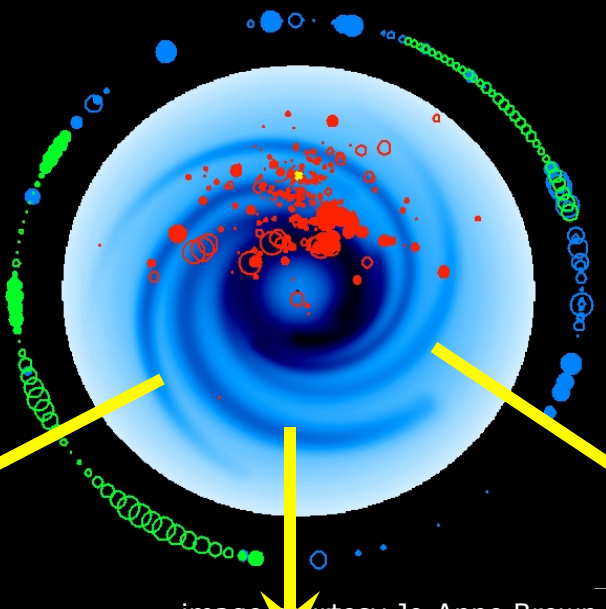
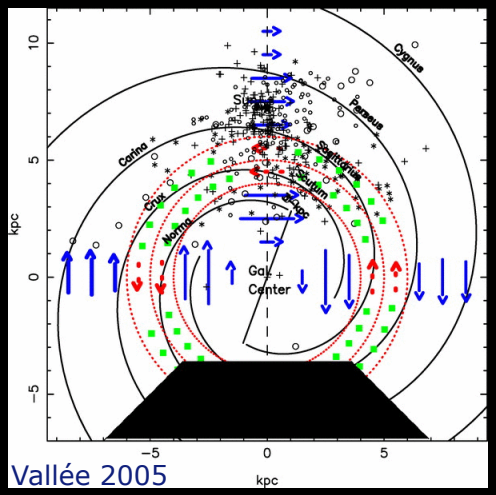
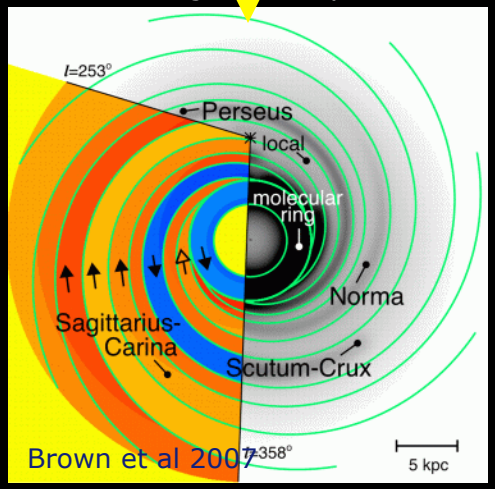


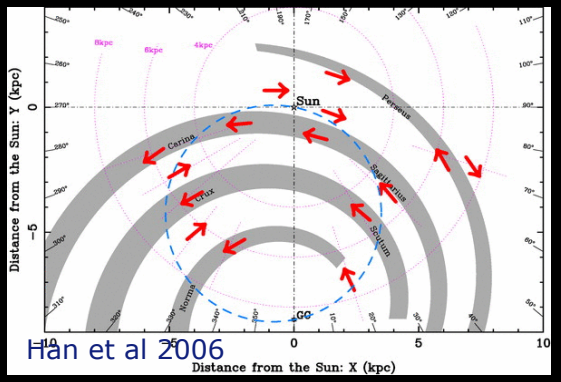
image courtesy Jo-Anne Brown




Vallée 2005

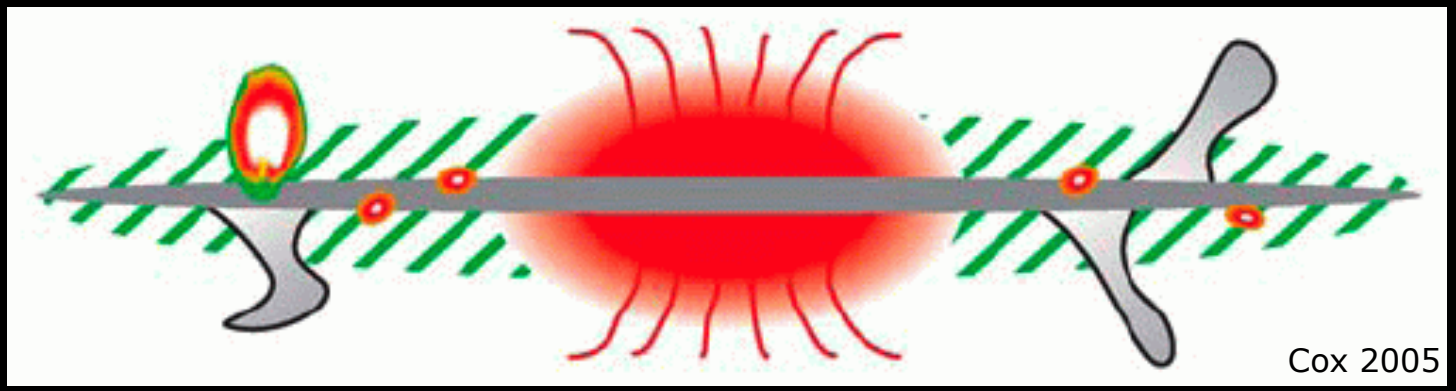



Brown et al 2007



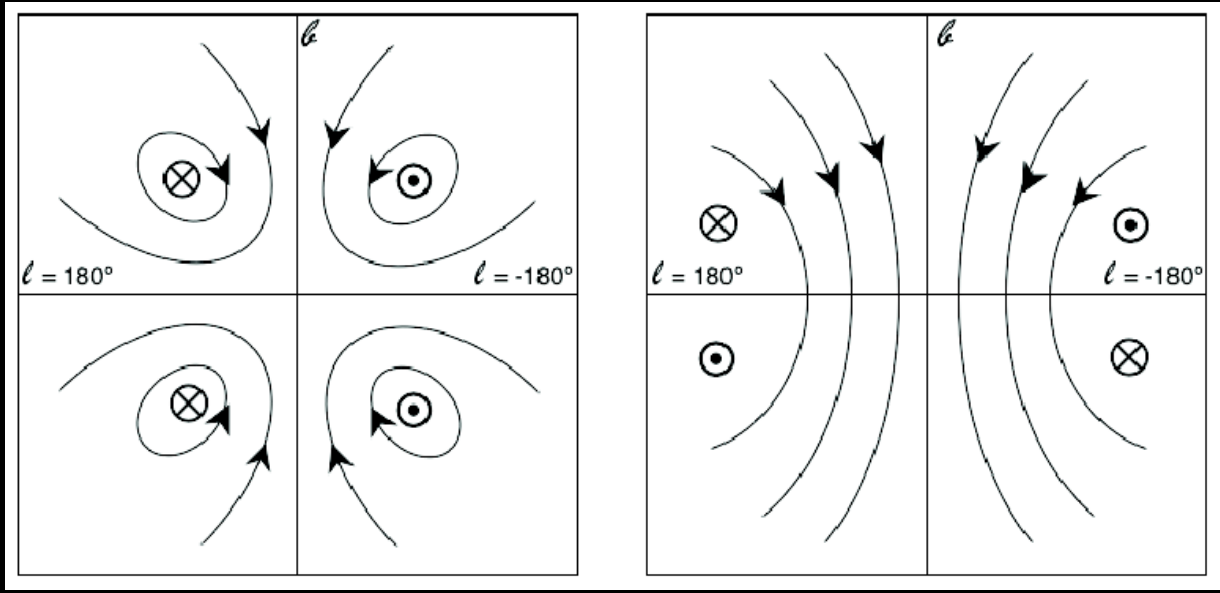

Han et al 2006

# Magnetic fields in the Galactic halo



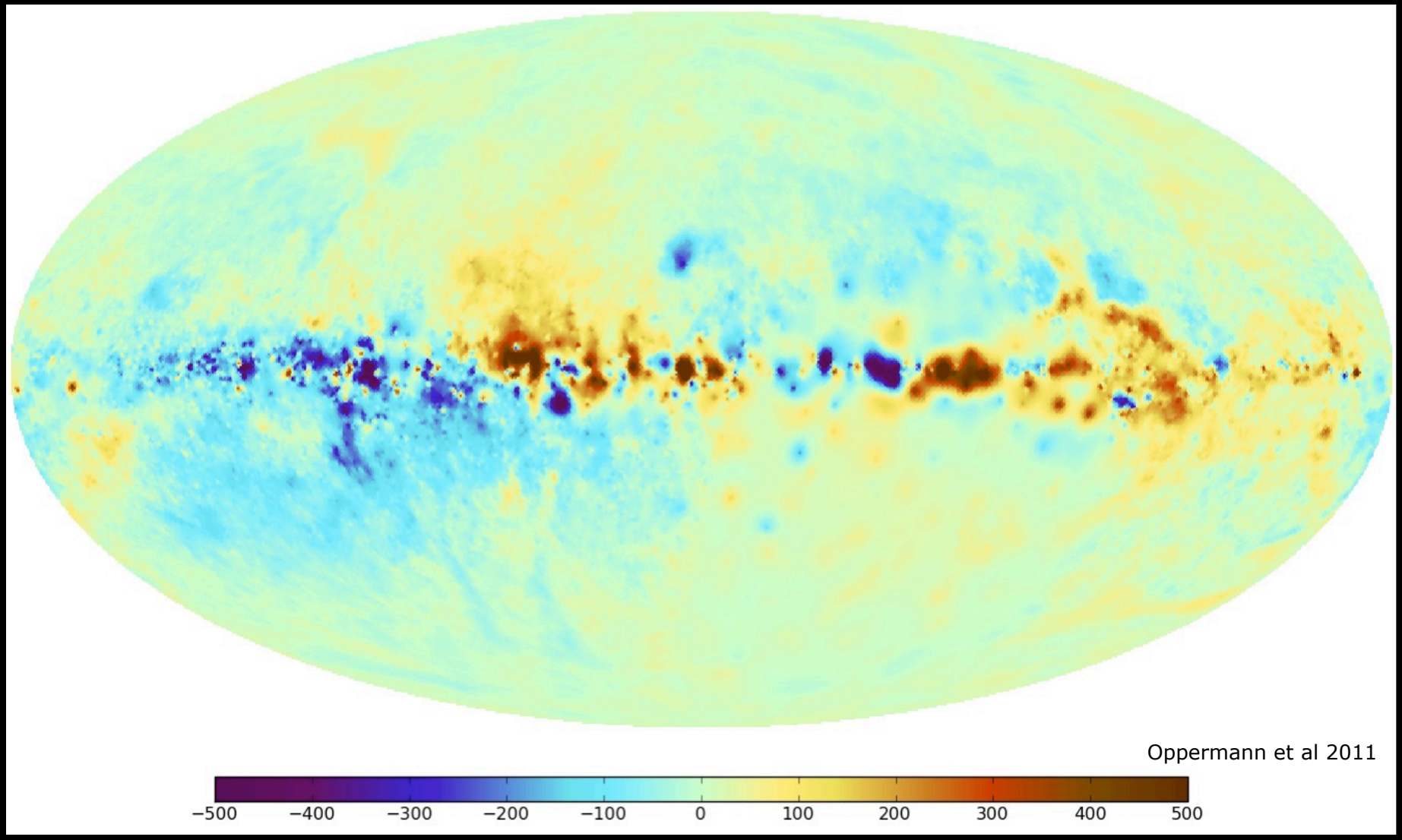

Quadrupolar

Dipolar



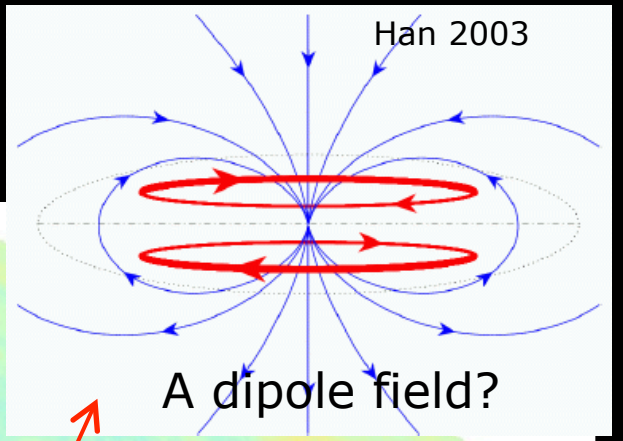

Widrow 2002; Haverkorn & Heesen 2011

# Large-angular-scale patterns in the RM sky:

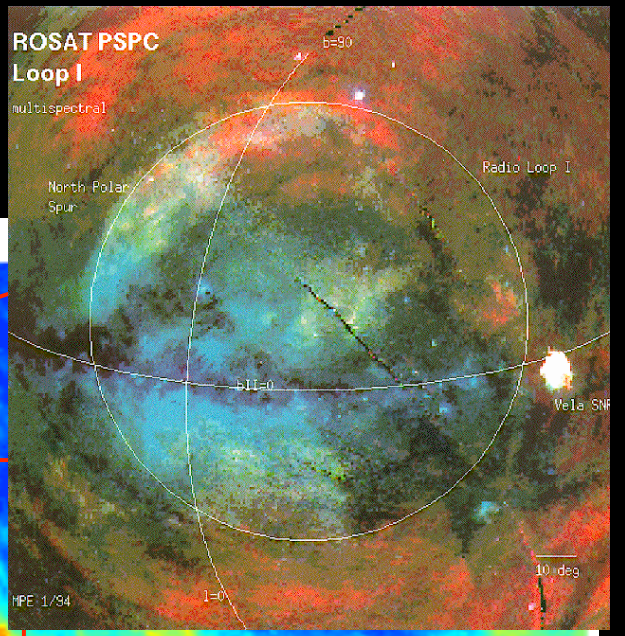



Oppermann et al 2011

# Global RM features?



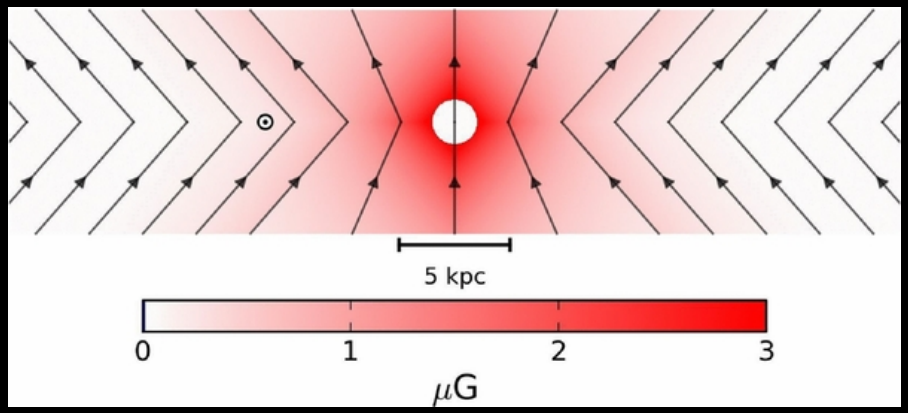
# … Or a local supernova remnant?

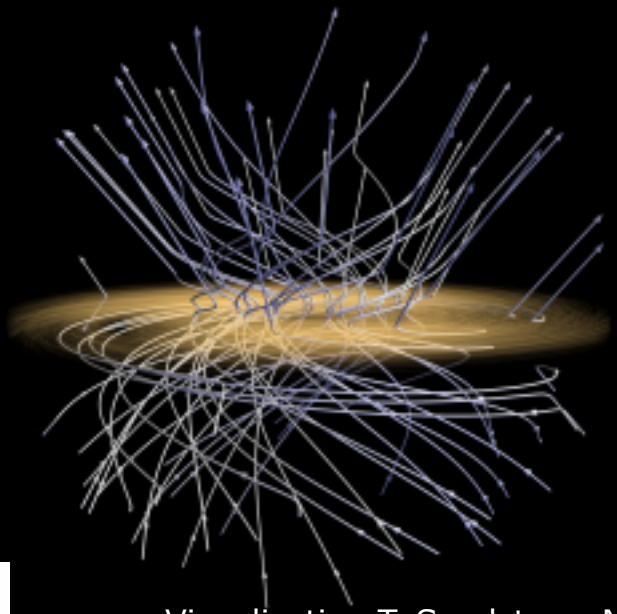


# Milky Way disk+halo magnetic field models:

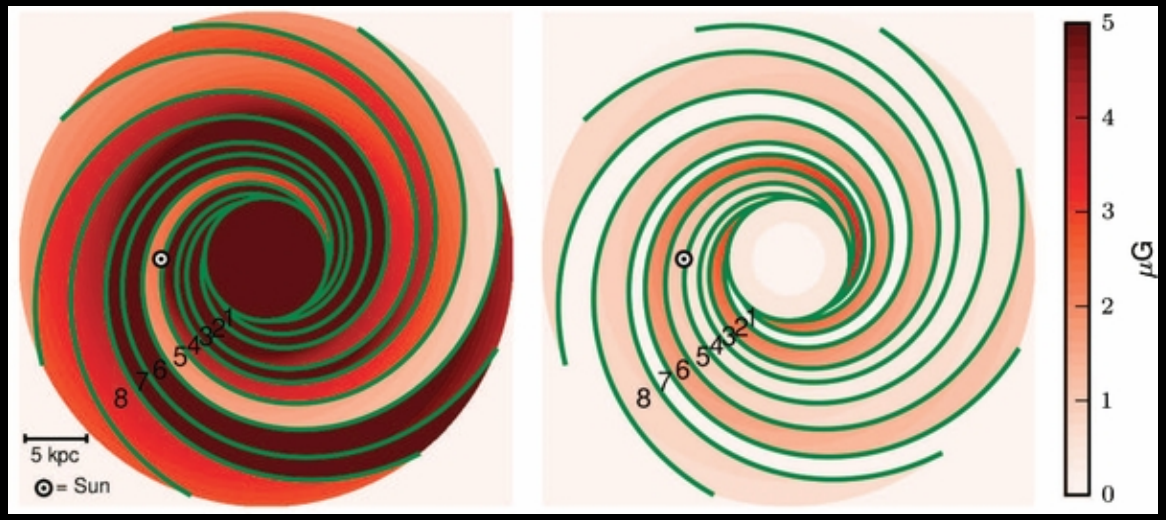
| AUTHOR | DATA | MODELS | RESULTS |
|---|---|---|---|
| Jansson et al 2009 | WMAP 22.8GHz PI<br>1433 EGS RMs | log spiral, Sun, Brown, ring, exponential | Disk and halo separate<br>Sun model best |
| Sun et al 2008 | I 22.8GHz, 408MHz; P 22.8 +1.4GHz; EGS RMs | AS spiral, BS spiral, log spiral, AS+ring, Brown | disk: AS spiral + one reversal in Crux. halo: asym wrt plane |
| Men et al 2008 | 482 Psr RMs $\|b\| > 10°$ | AS spiral, BS spiral, ring | No good fits possible |
| Brown et al 2007 | Pulsar and EGS RMs in plane; 4th Q. | log spiral | Single reversal best, but all high $\chi^2$ |
| Nota & Katgert 2009 | 107 Psr and 131 EGS RMs $\|b\| < 3°$; 4th Q. | log spiral, ring | One reversal around Crux-Norma interarm |
| Noutsos et al 2008 | 150 pulsar RMs | BS spiral, AS spiral; dipole; quadrupole | No good fits possible |
| Kronberg & Newton-McGee 2009 | EGS RMs | symmetry along Gal longitude | AS spiral inner Galaxy; BS spiral outer Galaxy |
| Frick et al 2001 | 551 EGS RMs | wavelet analysis | Even symmetry of local large-scale field |
| Han et al 2006 | 554 Pulsar RMs | l.o.s. dependence of RM | Reversals in every arm and interarm |
| Ruiz-Granados et al 2010 | PI at 22.8 GHz | AS spiral, BS spiral, log spiral, ring | AS spiral halo field, but other models close |
| Fauvet et al 2011 | I at 408 MHz; PI at 22.8 GHz; PI at 353 GHz | log spiral; AS+ring | models comparable, AS+ring slightly better |

# The most advanced model to date: Jansson & Farrar



Visualisation T. Sandstrom NASA




Jansson & Farrar 2012a,b

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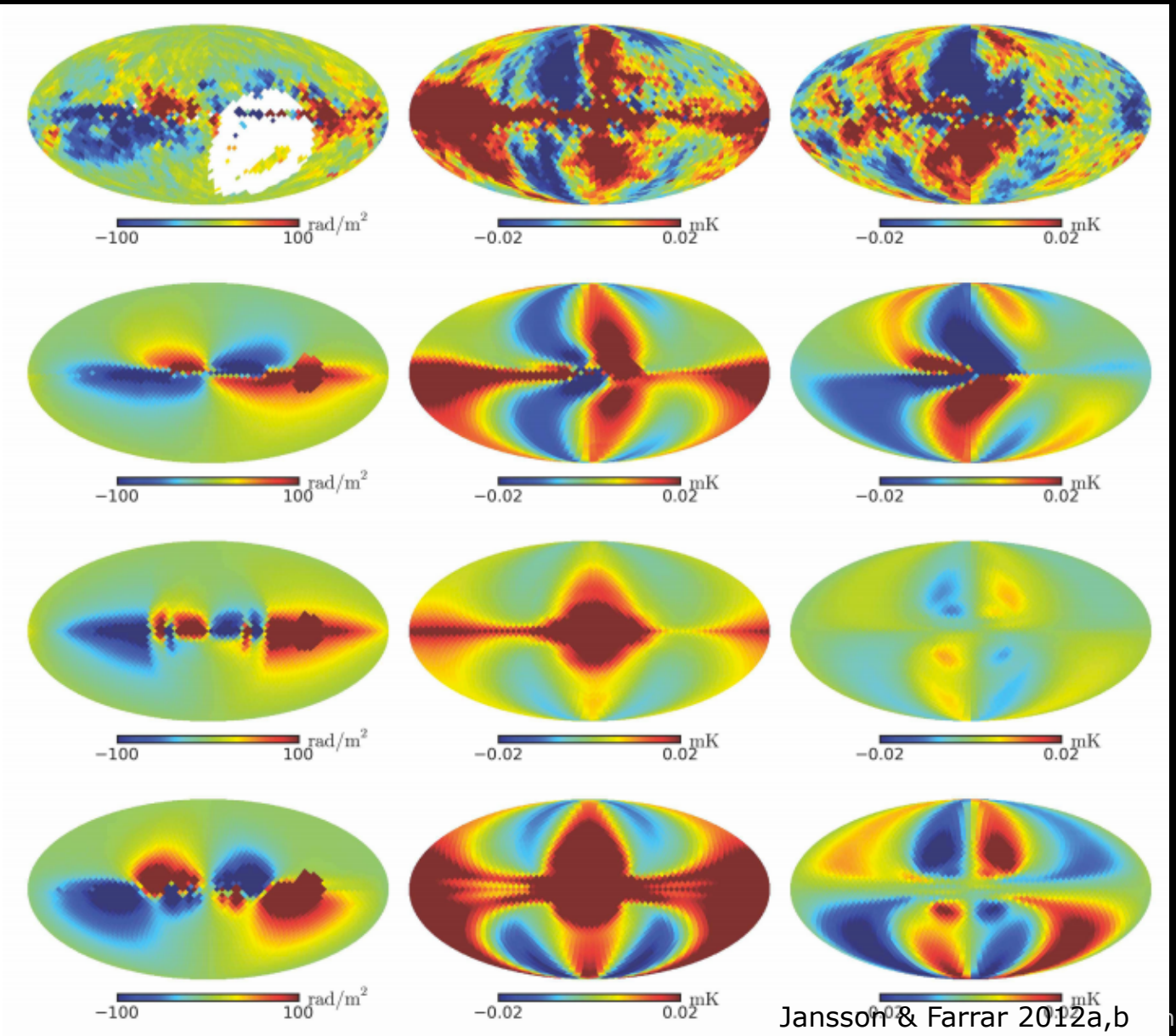
rotation measure | Stokes Q | Stokes U




observed

JF12

Sun & Reich 2010

Pshirkov et al 2011

Jansson & Farrar 2012a,b

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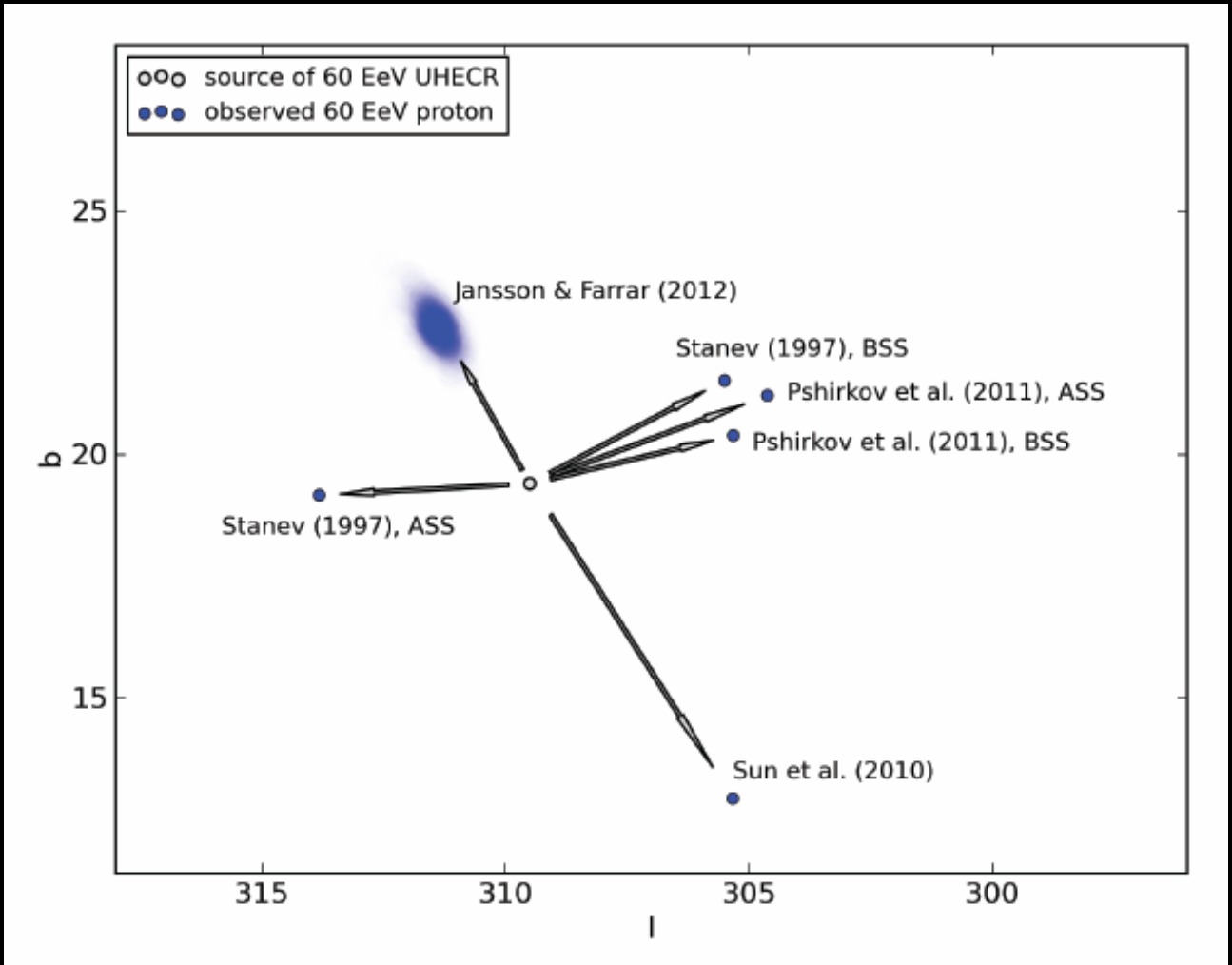
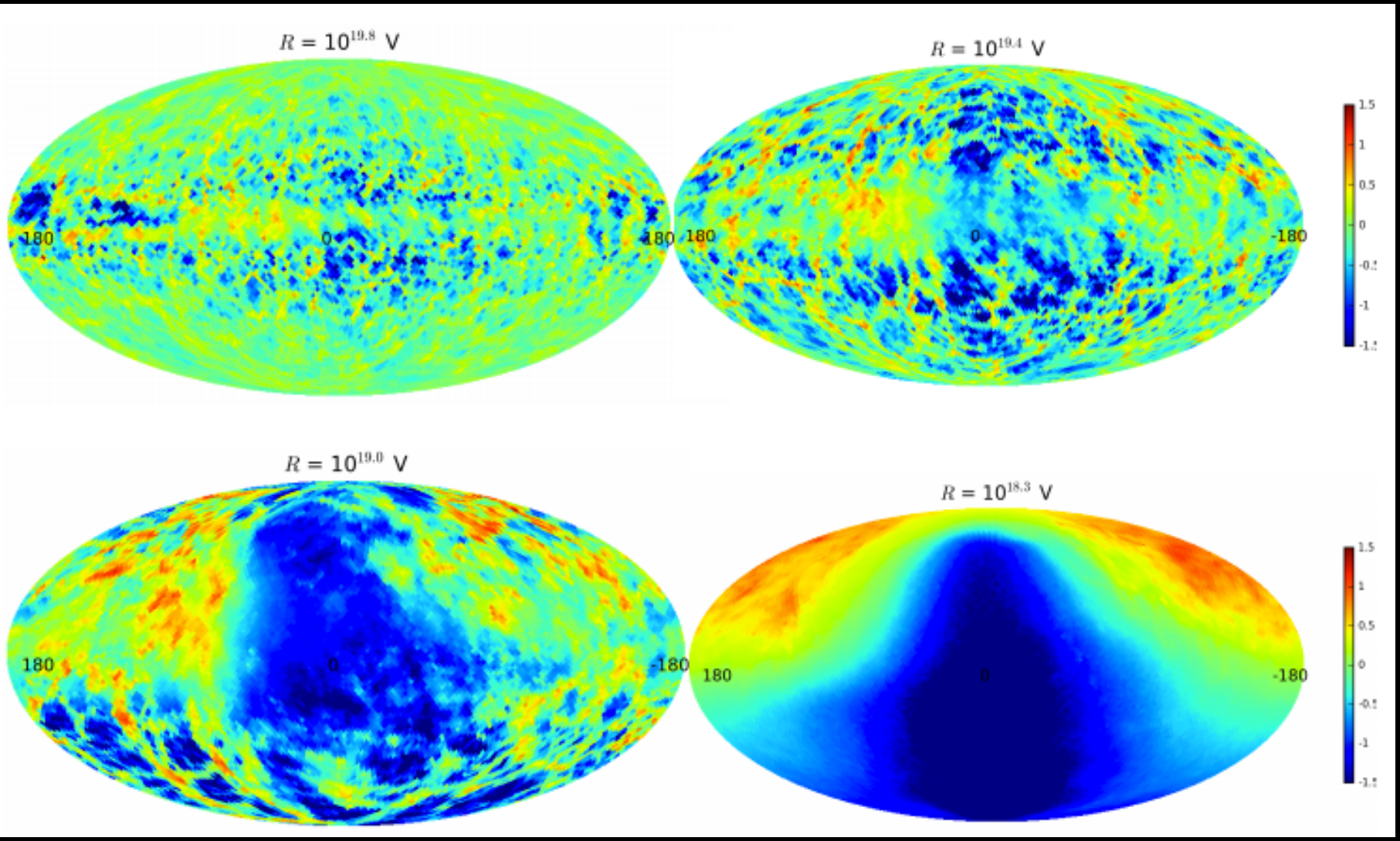
# Cosmic rays from Centaurus A?



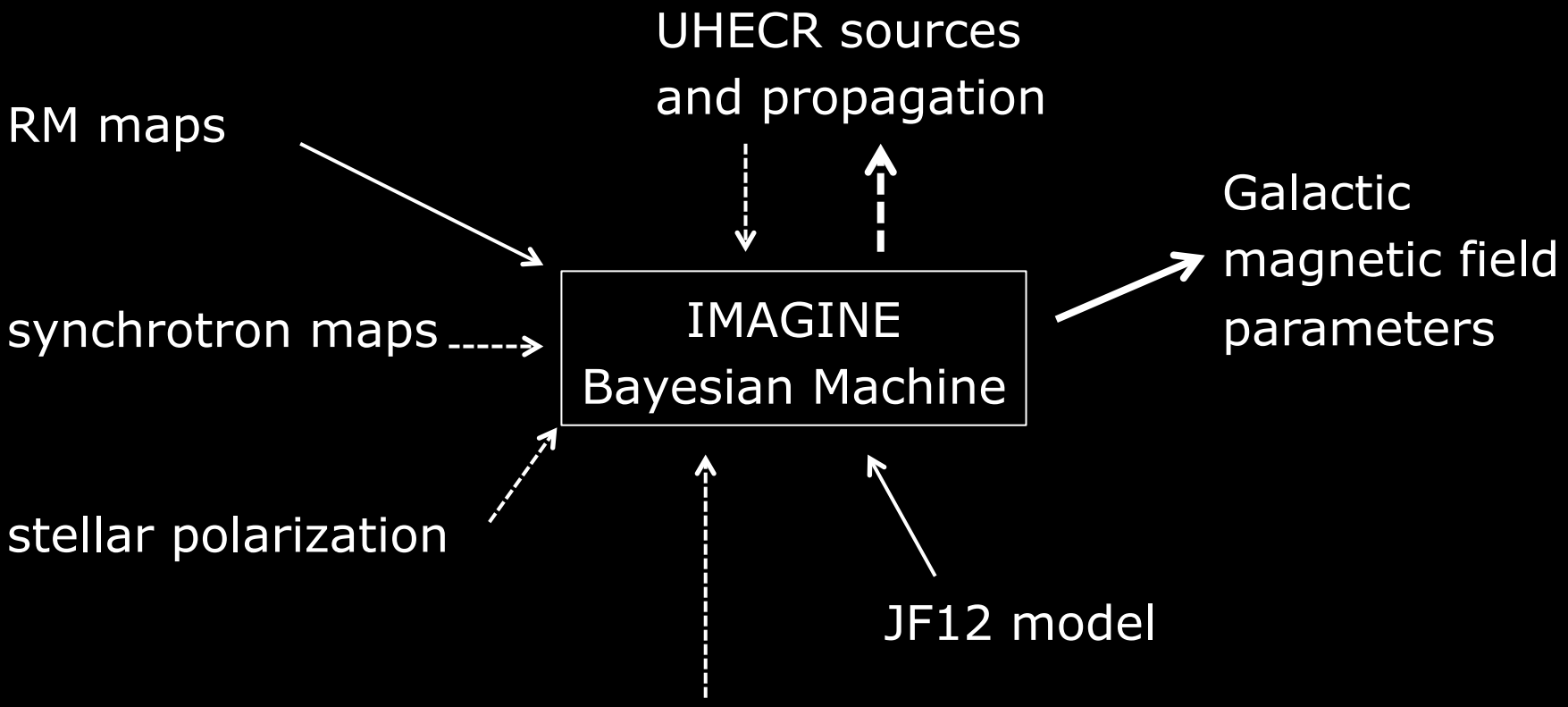

Farrar 2014

# The Galactic magnetic field acts as a **lens**




Farrar et al 2014

# Work in progress: IMAGINE




PIs: Jörg Rachen, Jörg Hörandel, Marijke Haverkorn

co-Is: Nafiun Awal, Torsten Enßlin, Glennys Farrar, Diego Harari, Jens Jasche, Tess Jaffe, Natalia Nowak, Katarzyna Otmianowska-Mazur, Christoph Pfrommer, Luiz Santiago-Rodrigues, Anvar Shukurov, Michael Unger, Todor Stanev, Theo Steininger, Andy Strong, Xiaohui Sun, Robert Tautz, Michael Unger, Arjen van Vliet, Ellert van der Velden

# Summary

Magnetic fields in the Milky Way need complex multiple components: regular and random, disk and halo, …

The most advanced Galactic magnetic field model reasonably fits to rotation measure and radio synchrotron data

The Galactic magnetic field acts as a lens to Ultra-High Energy Cosmic Rays, magnifying or demagnifying flux from certain directions.

The next step: physics-based magnetic field models, inclusion of all observational data → IMAGINE