Magnetic fields in the Galactic interstellar medium

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Methods, results, and open questions

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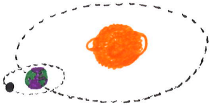
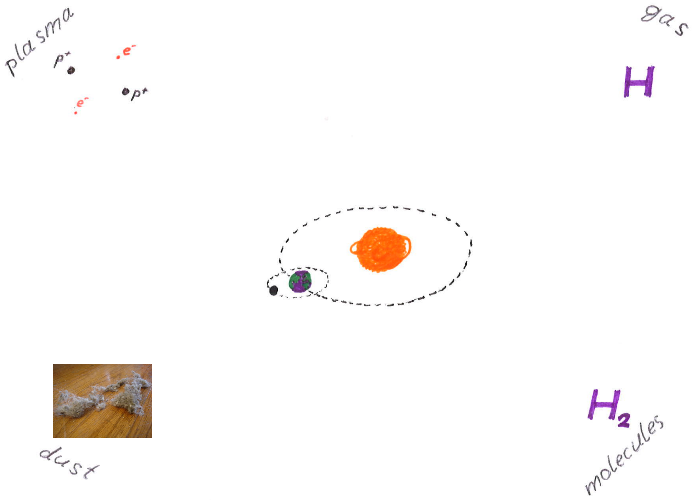
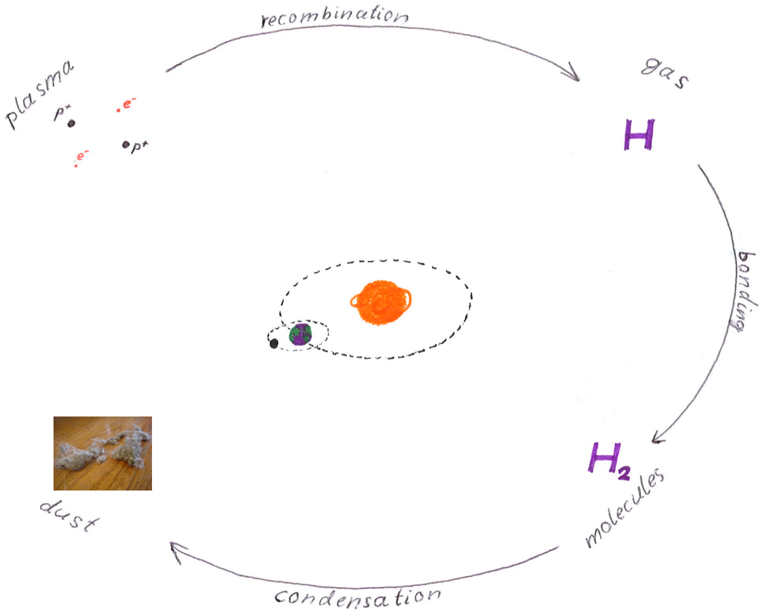
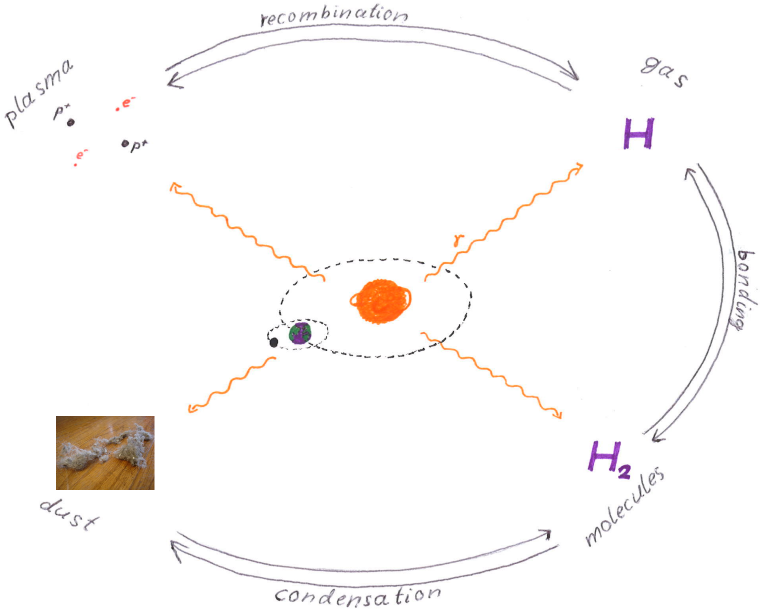
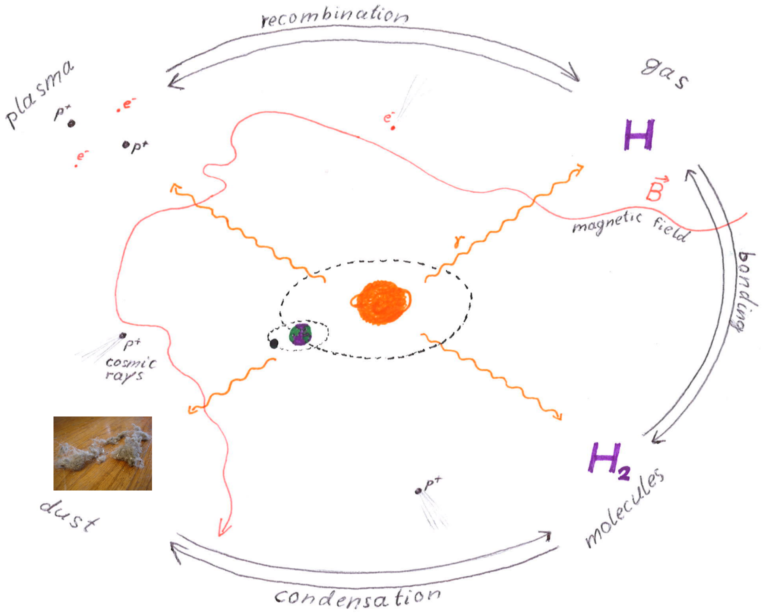
CHANG-ES meeting, Kingston, 2014-07-24

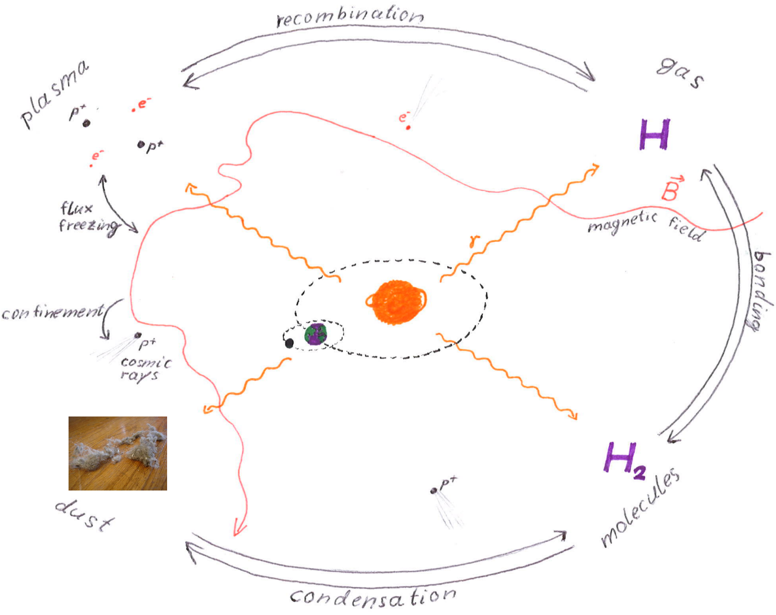



plasma
p^+
e^-
e^-
p^+
gas
H
H_2
molecules
dust


recombination
gas
H
bonding
H2
molecules
condensation
dust
plasma
p+
e-
p+
e-


recombination
plasma
p^+
e^-
e^-
p^+
gas
H
bonding
γ
H_2
molecules
condensation
dust


recombination
plasma
gas
p^+
e^-
e^-
p^+
e^-
H
$\vec{B}$
magnetic field
γ
bonding
p^+
cosmic rays
H_2
molecules
p^+
dust
condensation


recombination
plasma
gas
p^+
e^-
e^-
p^+
e^-
H
$\vec{B}$
magnetic field
flux freezing
γ
bonding
confinement
p^+
cosmic rays
H_2
molecules
p^+
dust
condensation

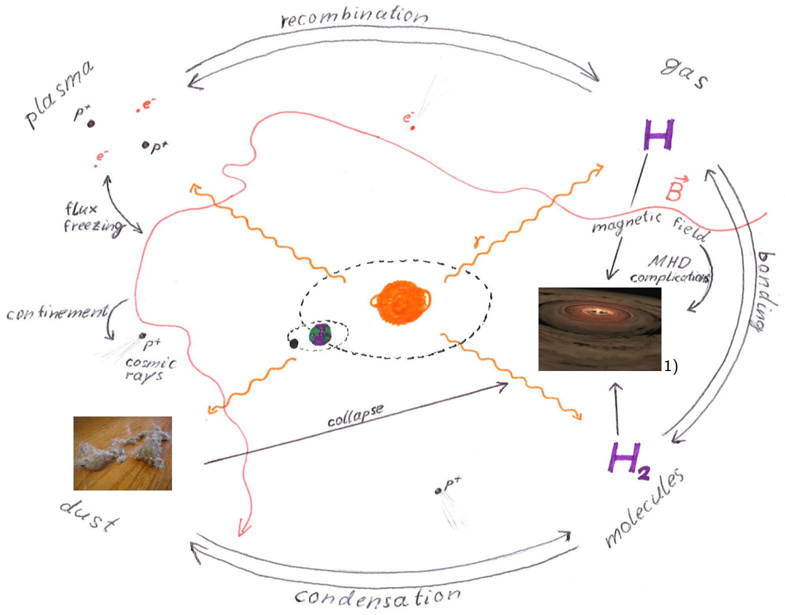


Image credits: 1) D. Darling

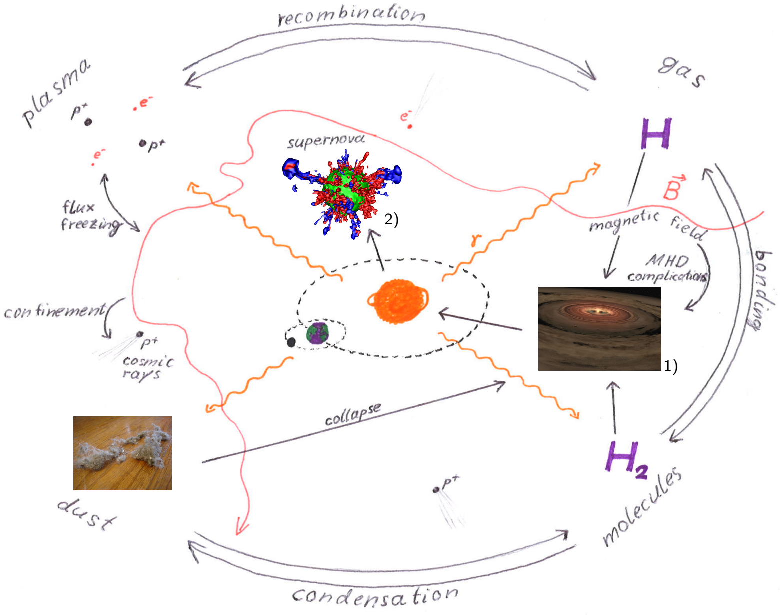


Image credits: 1) D. Darling; 2) N.J. Hammer/MPA

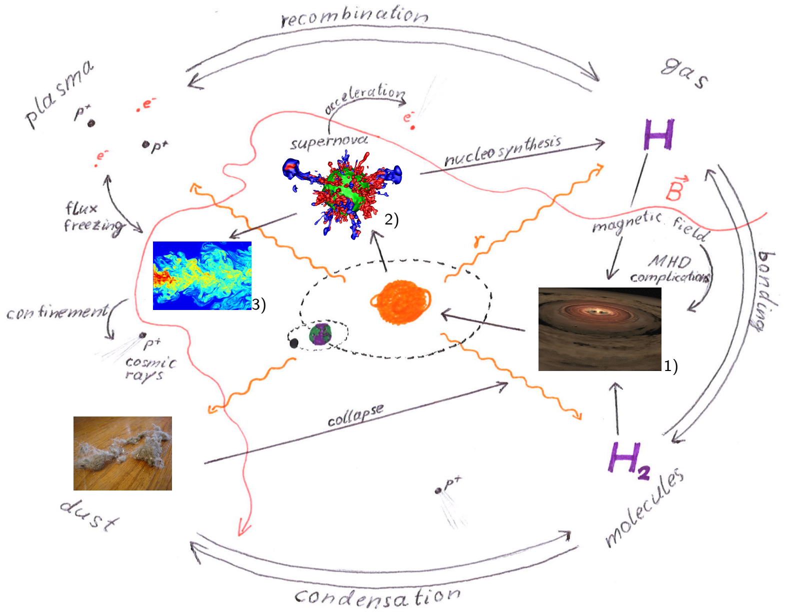


Image credits: 1) D. Darling; 2) N.J. Hammer/MPA; 3) C. Fukushima/TUDelft

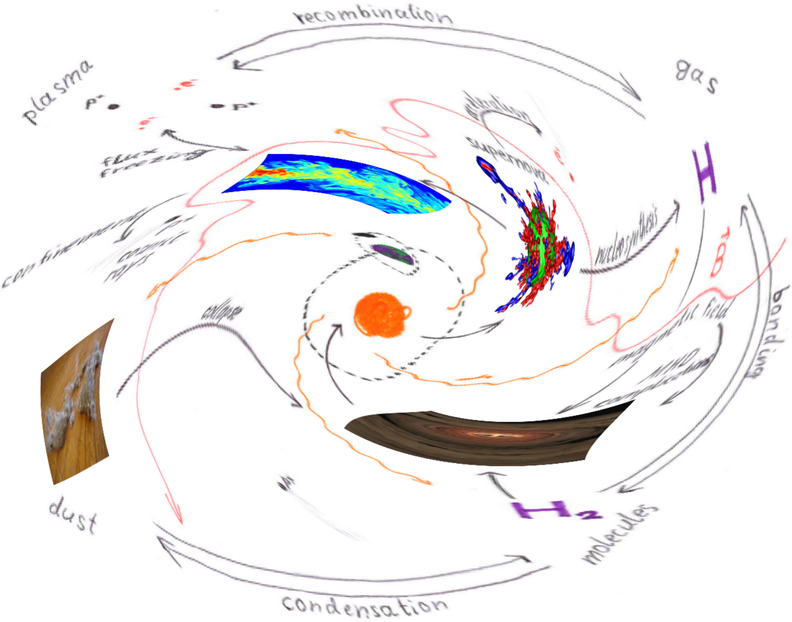
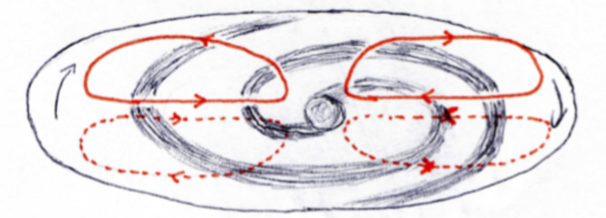


Image credits: 1) D. Darling; 2) N.J. Hammer/MPA; 3) C. Fukushima/TUDelft

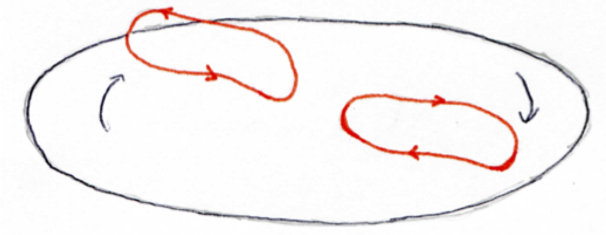
Overview

- Theory
- Observation
  - Synchrotron
  - Dust
  - Faraday rotation
- Modeling
- Helicity

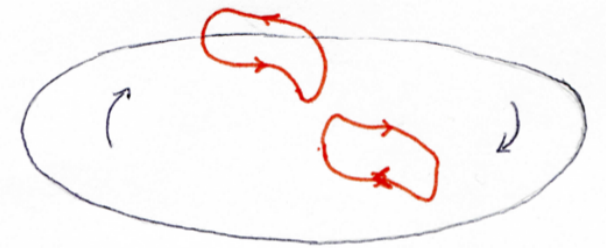
Theory: α-Ω-dynamo



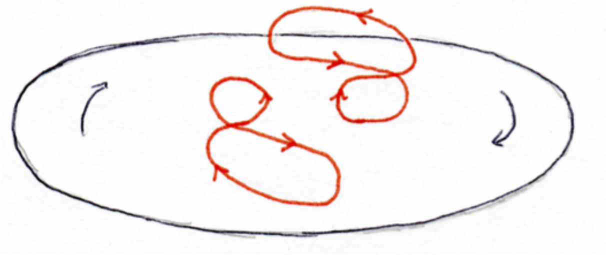
Theory: α-Ω-dynamo



Theory: α-Ω-dynamo



Theory: α-Ω-dynamo



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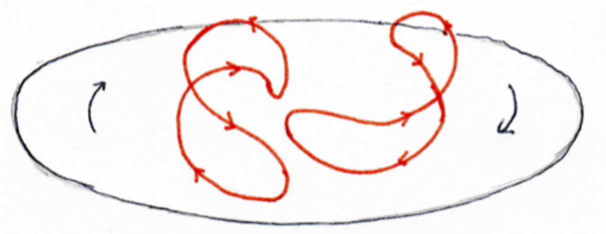
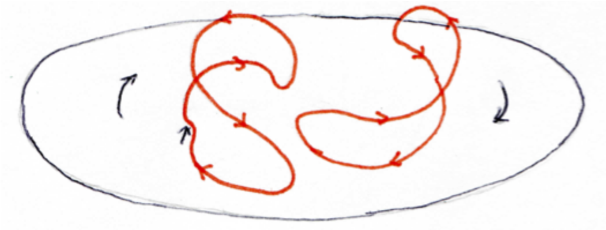
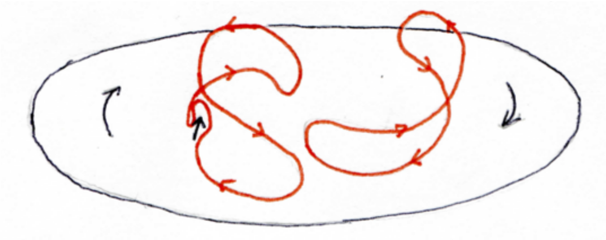


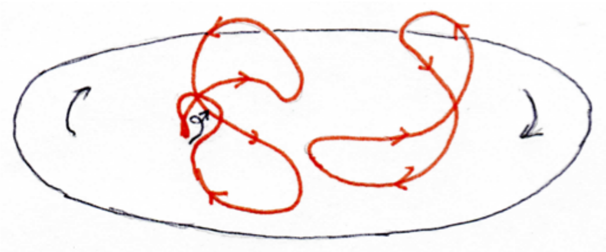
Theory: α-Ω-dynamo



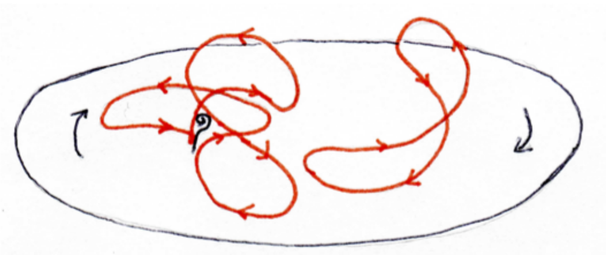
Theory: α-Ω-dynamo



Theory: α-Ω-dynamo



Theory: α-Ω-dynamo



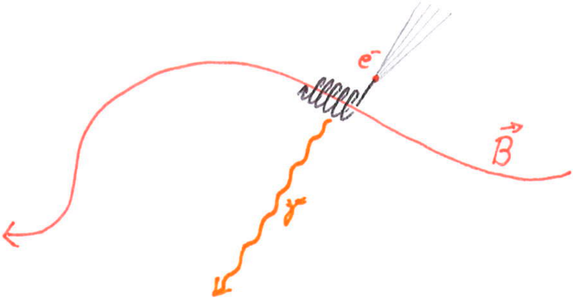
Theory: Magnetic field components

coherent

isotropic random

“ordered random”

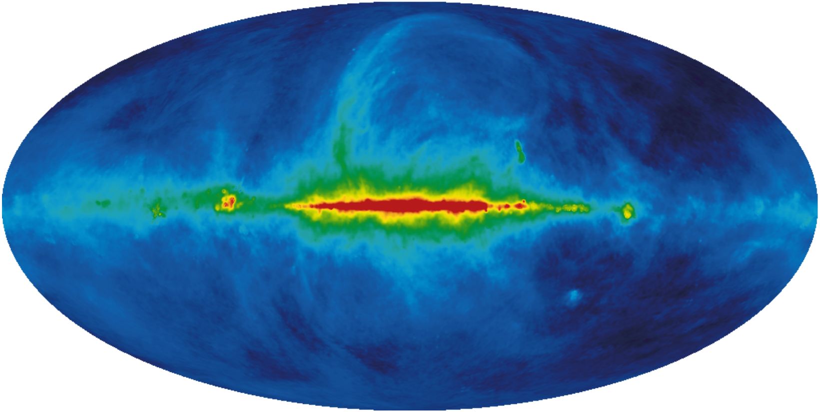
Synchrotron



for $n_{\mathrm{CRE}}(E) \propto E^{-\gamma}$:

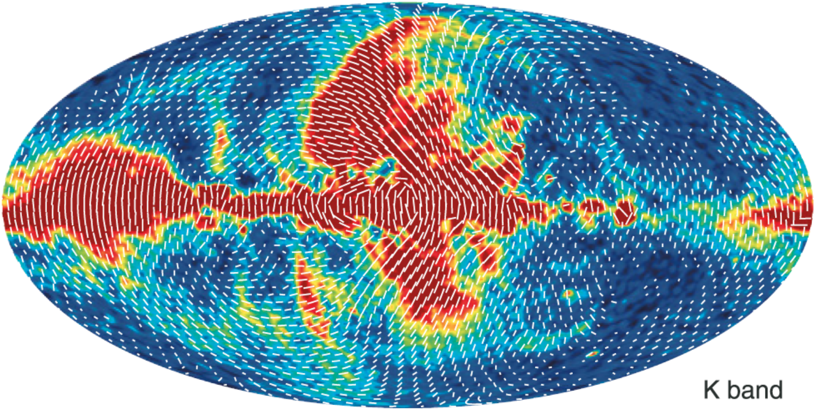
$$P(\lambda) = Q(\lambda) + iU(\lambda) \propto \lambda^{\frac{\gamma-1}{2}} \int \mathrm{d}z\, n_{\mathrm{CRE}}\, B_{\perp}^{\frac{\gamma+1}{2}}\, \mathrm{e}^{2i\chi}$$

Synchrotron



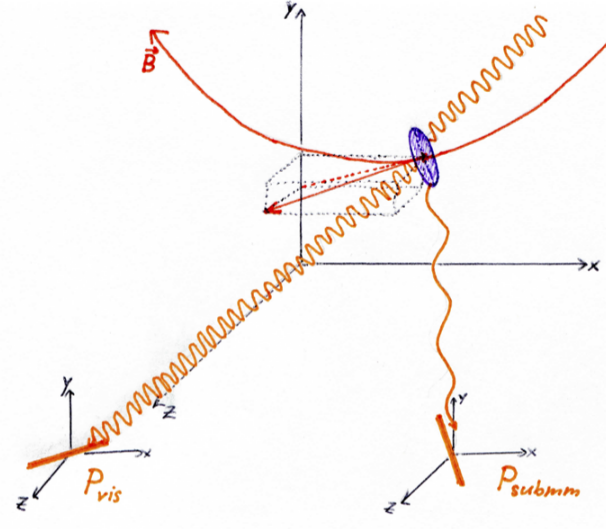
Haslam et al. (1981)

Synchrotron

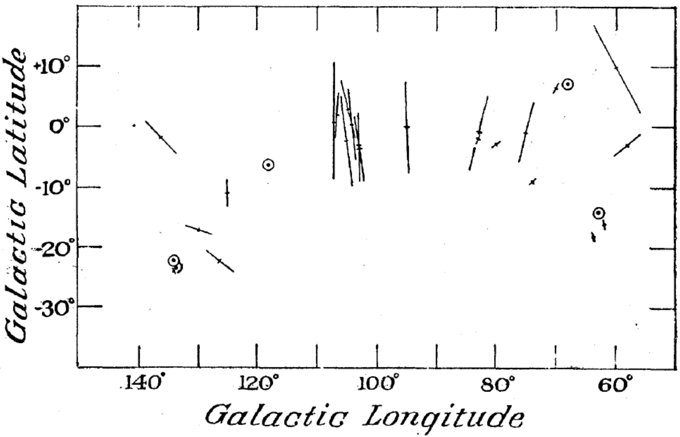


Hinshaw et al. (2009)

Dust

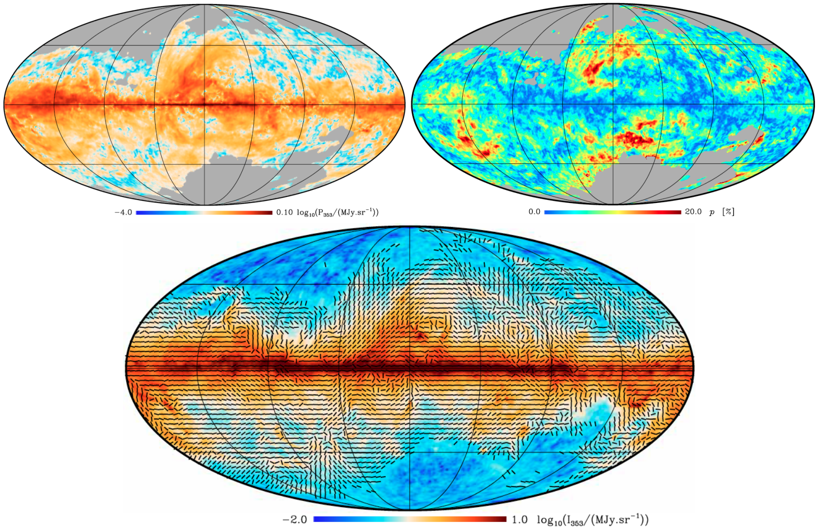


Dust



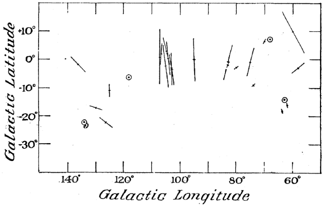
Hall (1949)

Dust

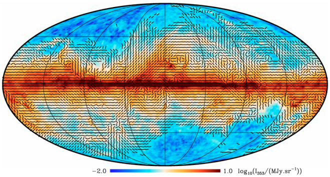


Planck Collaboration Int. XIX (2014)

Dust

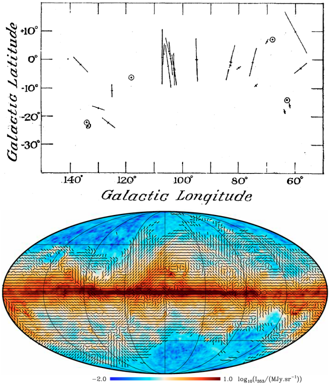


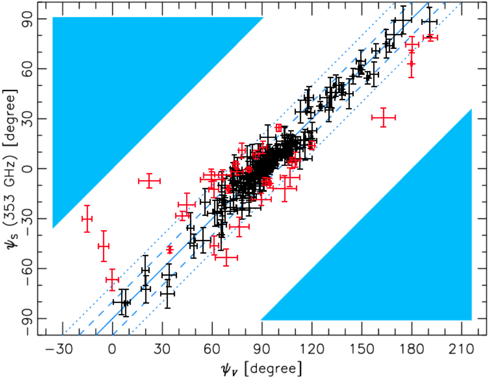
Galactic Latitude
+10°
0°
-10°
-20°
-30°
140°
120°
100°
80°
60°
Galactic Longitude



−2.0
1.0 log10(I353/(MJy.sr−1))

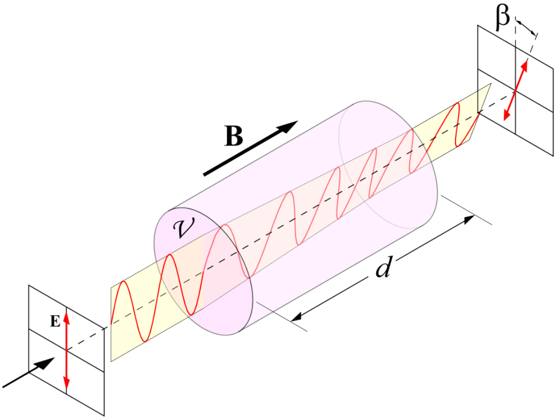
Dust





Planck Collaboration Int. XXI (2014)

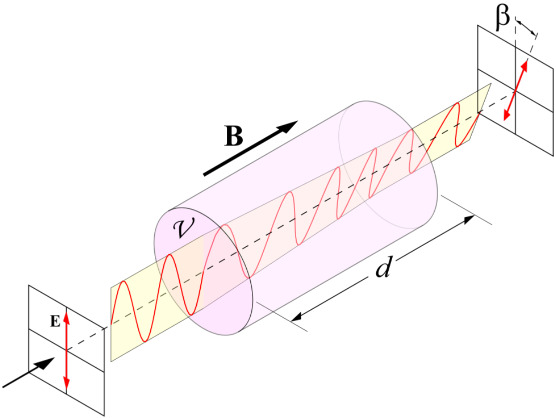
Faraday rotation



$$\mathrm{d}\beta \propto \lambda^2 n_{\mathrm{e}}(\vec{x}) B_r(\vec{x}) \mathrm{d}r$$

$$\Rightarrow \quad \beta \propto \lambda^2 \int_{r_{\mathrm{source}}}^{0} n_{\mathrm{e}}(\vec{x}) B_r(\vec{x}) \mathrm{d}r$$

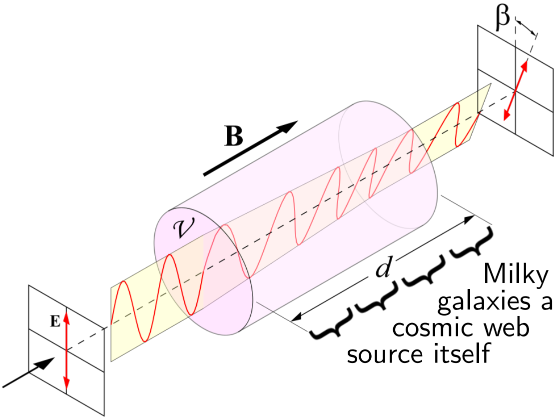
Faraday rotation

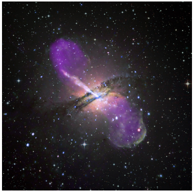


$$\text{Faraday depth: } \phi \propto \int_{r_{\mathrm{source}}}^{0} n_{\mathrm{e}}(\vec{x}) B_r(\vec{x}) \mathrm{d}r$$

$$\beta = \phi \lambda^2$$

Faraday rotation

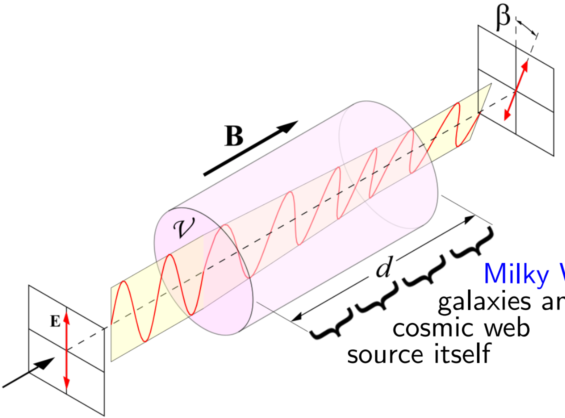


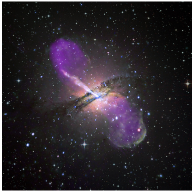


Faraday depth: $\phi \propto \int_{r_{\mathrm{source}}}^{0} n_{\mathrm{e}}(\vec{x}) B_r(\vec{x}) \mathrm{d}r$

$$\beta = \phi\lambda^2$$

Faraday rotation

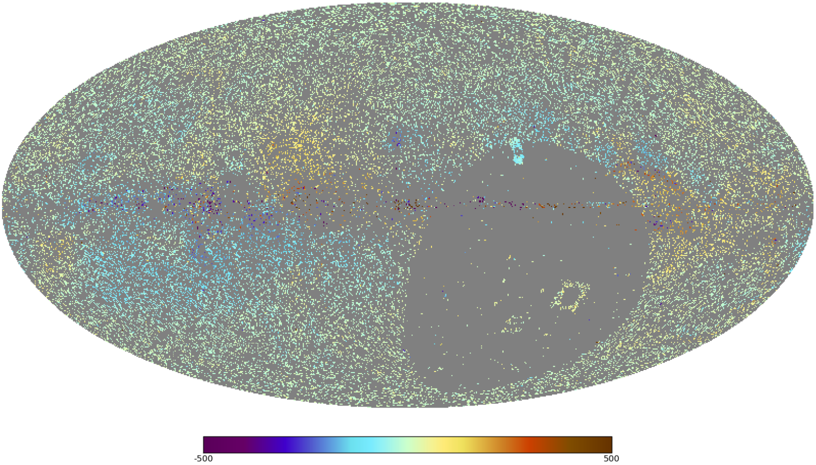




Galactic Faraday depth:

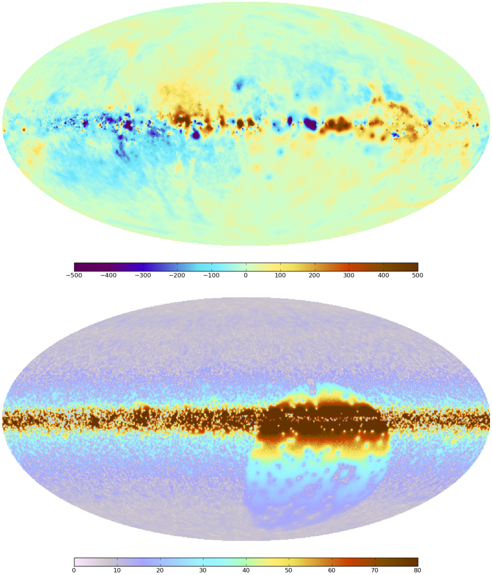
$$\phi_{\mathrm{g}} \propto \int_{r_{\mathrm{MilkyWay}}}^{0} n_{\mathrm{e}}(\vec{x}) B_r(\vec{x}) \mathrm{d}r$$

Faraday rotation



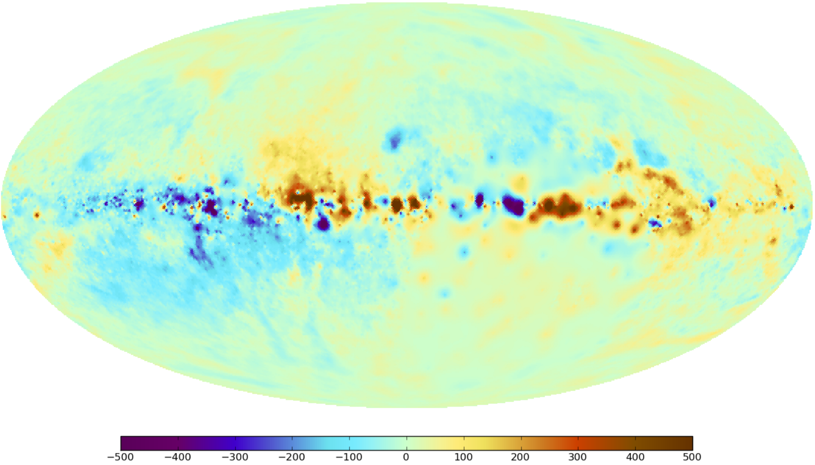
41 330 data points

Faraday rotation



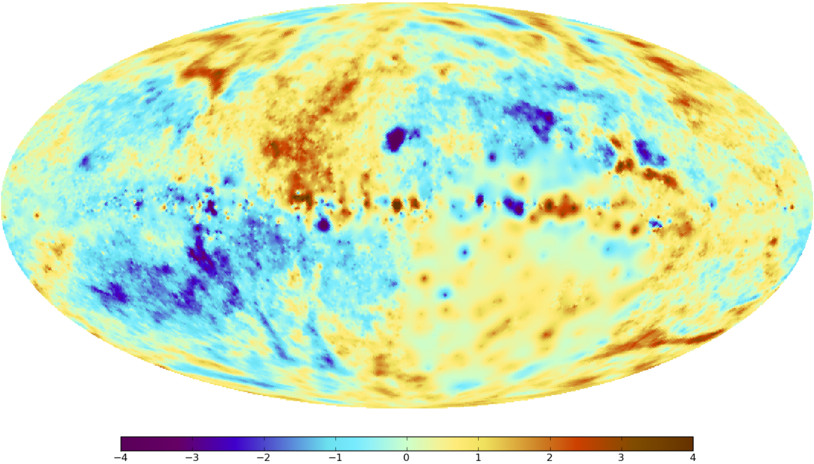
Oppermann et al. (2012/2014)

Faraday rotation



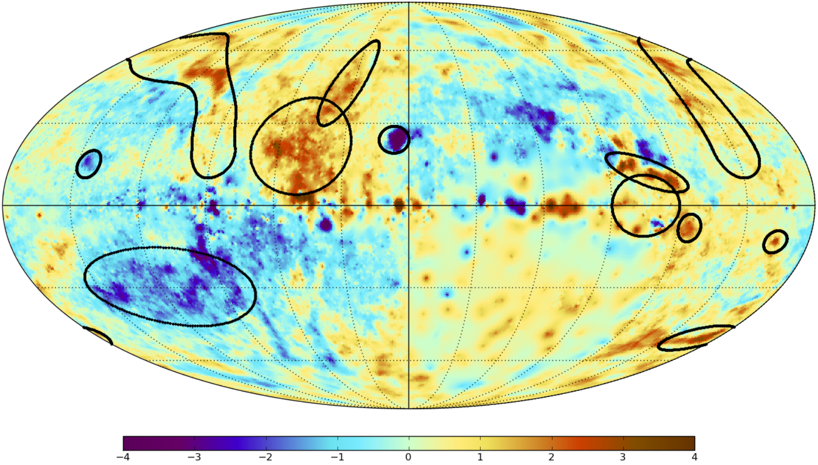
Oppermann et al. (2012/2014)

Faraday rotation



Oppermann et al. (2012/2014)

Faraday rotation



Oppermann et al. (2012/2014)

Rotation measure synthesis

Faraday rotated synchrotron radiation

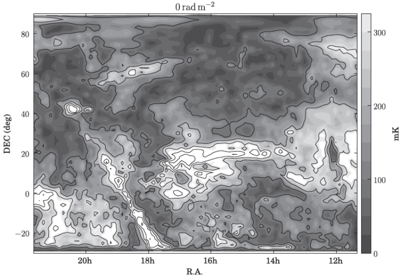
$$P(\lambda) \propto \int_{-\infty}^{\infty} \mathrm{d}\phi \, p(\phi) \, \mathrm{e}^{2i \, \lambda^2 \, \phi(z)}$$

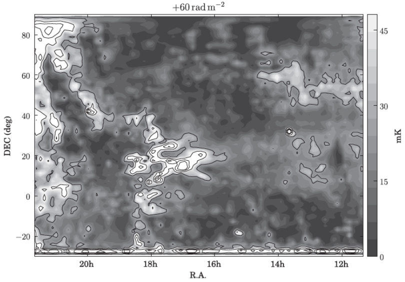
$$\Rightarrow \quad p(\phi) = \int_{-\infty}^{\infty} \mathrm{d}\lambda^2 \, P(\lambda^2) \, \mathrm{e}^{-2i \, \lambda^2 \phi}$$

Faraday dispersion function

Rotation measure synthesis

GMIMS (here: northern, ca. (1.3 - 1.8) GHz)





Wolleben et al. (2010)

Rotation measure synthesis

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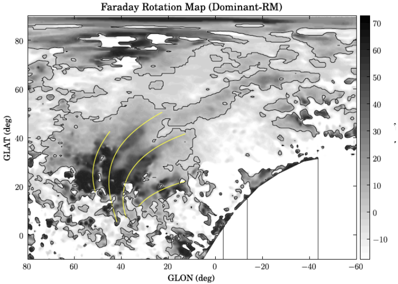
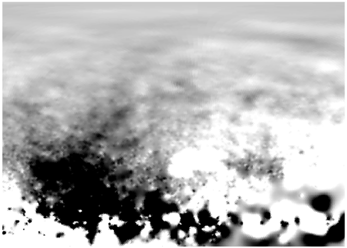


Wolleben et al. (2010)



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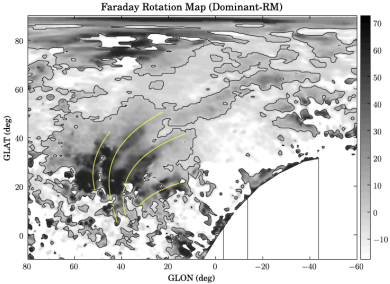
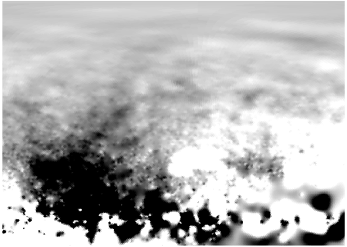
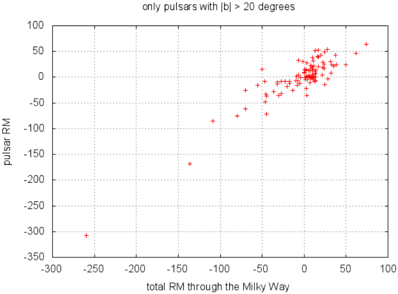
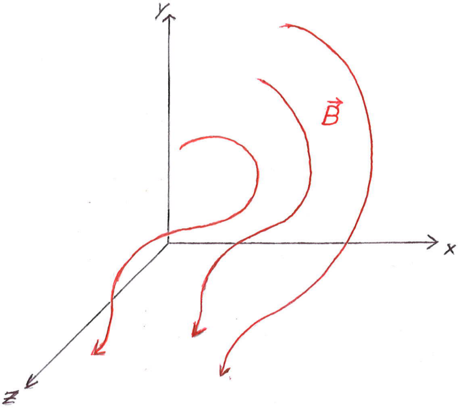


Wolleben et al. (2010)

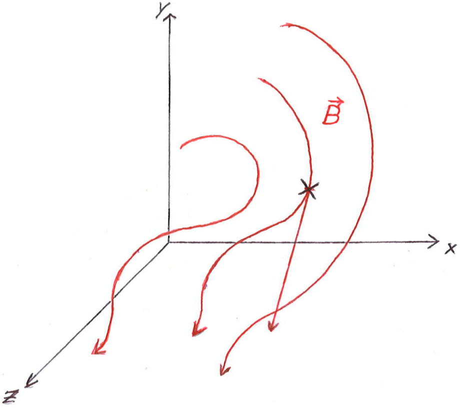




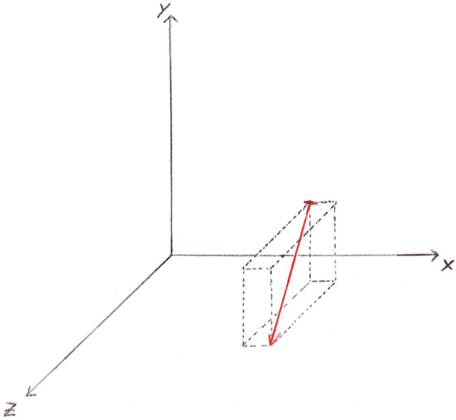
Magnetic field modeling



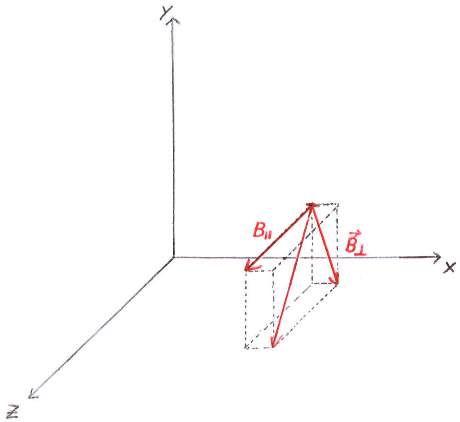
Magnetic field modeling



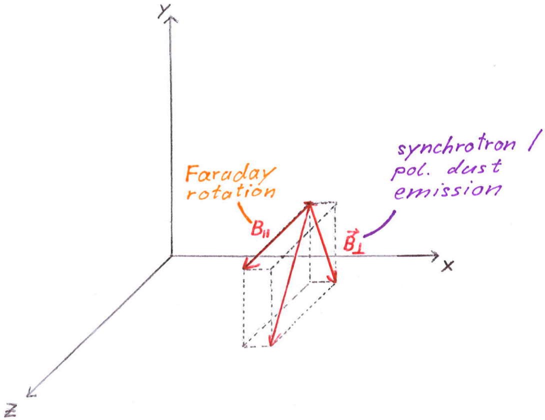
Magnetic field modeling



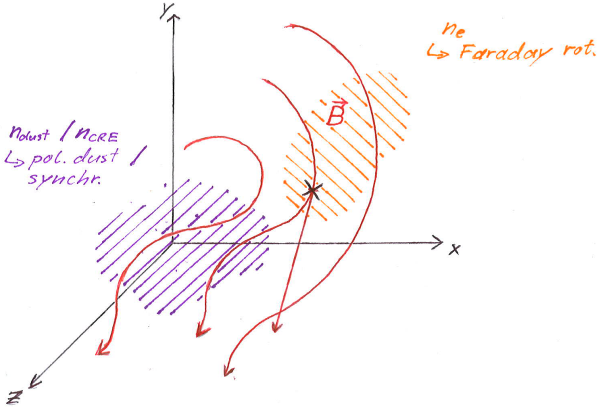
Magnetic field modeling



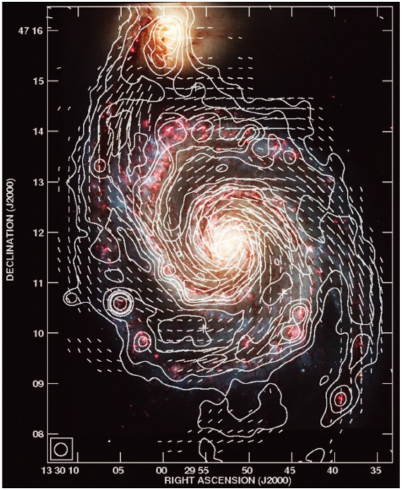
Magnetic field modeling



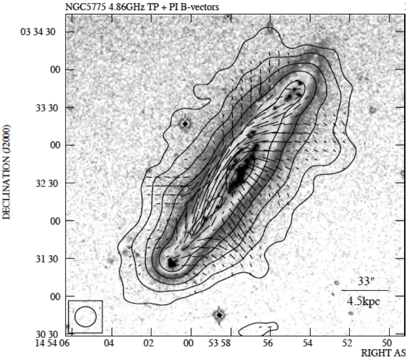
Magnetic field modeling



Magnetic field modeling



Fletcher et al. (2011)



Tüllmann et al. (2000)

Magnetic field modeling

ref	TRACER[a]	D/H	MODELS[b]	MODEL RESULTS	p
[24]	149 EGS RMs 120 pulsar RMs	Q4[c] disk	spiral	one reversal	$-11.5°$
[39]	WMAP5 I 23GHz; ARCHEOPS 353GHz I 408MHz	all	modified log spiral $B_z + B_{ran}$	$B_z = 0.4\ \mu$G	$-30°$
[12]	I 408MHz WMAP P 23GHz 269 EGS RMs	disk	ASS, log spiral, B_{ran}, compression	$B_{reg} : B_{ran} : B_{ani} = 1:5:4$ Field config as in model 1	$-11.5°$ IN
[16]	WMAP5 PI 23GHz 1433 EGS RMs	disk	BSS/ASS -S/-A, ring, lit. models	no good models, disk and halo separate	$+35°$
[11]	WMAP7 PI 23GHz $\gtrsim$37000 EGS RMs	all	spiral, B_{ran}, B_{ani}, B_z	one reversal $B_{ani} = 1.7 B_{reg}$, $B_z = 4.6\ \mu$G at GC[d]	$-11.5°$ IN
[40]	482 pulsar RMs	disk	ASS, BSS, ring	no good models, slight preference for ASS	
[53]	I 408MHz WMAP PI 23GHz	halo	BSS, B_{ran}	$B_{ran} = 0.57 B_{reg}$	$-8.5°$
[25]	133 pulsar RMs 107 EGS RMs	Q4[d] disk	log spirals	QSS/many reversals preferred	
[15]	WMAP3 PI 23GHz	halo	log spirals, B_z	B_z at 25° tilt	$-55°$ [d]
[49]	$\gtrsim$37000 EGS RMs	all	ASS, BSS, ring	ASS best in disk; odd in halo	$-5°$
[54]	WMAP5 PI 23GHz	halo	ASS, BSS, ring, bi-toroidal, B_z	ASS preferred, $B_z = 1\ /mu$G	$-24°$[e]
[38]	I 408MHz WMAP PI 23GHz $I + PI$ 1.4GHz	all	ASS, BSS, ring	ASS best in disk, odd in halo	$-12°$ IN
[55]	354 pulsar RMs	disk	rings with p	one reversal only	$-12°$ IN
[41]	1373 EGS RMs 557 pulsar RMs	disk	ASS, BSS, ring combinations	no single model for complete Galaxy	0° or $-11.5°$ IN

[a] I = total intensity; PI = polarized intensity; EGS = extragalactic sources; WMAPi = Wilkinson Microwave Anisotropy Probe data over i years.
[b] ASS = axisymmetric spiral; BSS = bisymmetric spiral; QSS = quadrisymmetric spiral; -A/-S = (anti-)symmetric with respect to Galactic plane.
[c] Qi = ith quadrant of the Milky Way; GC = Galactic Center.
[d] taking into account their deviating definition of pitch angle, see Section 2.3.
[e] actually given as $p = +24°$ in the paper, but with the opposite definition of azimuth direction.

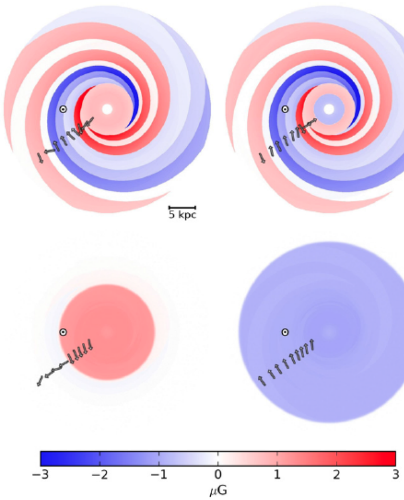
Haverkorn (2014)

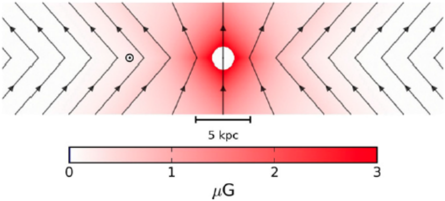
Magnetic field modeling

Coherent component

in plane

out of plane





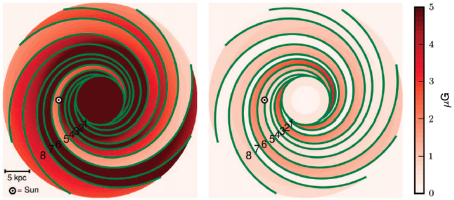
Jansson et al. (2012a,b)

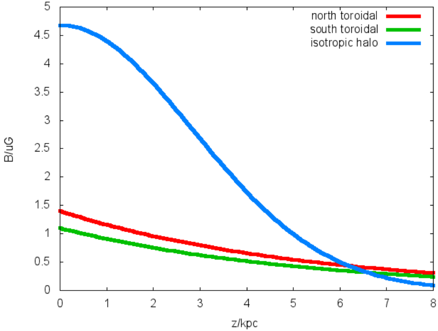
Magnetic field modeling

Random components

isotropic

"ordered"





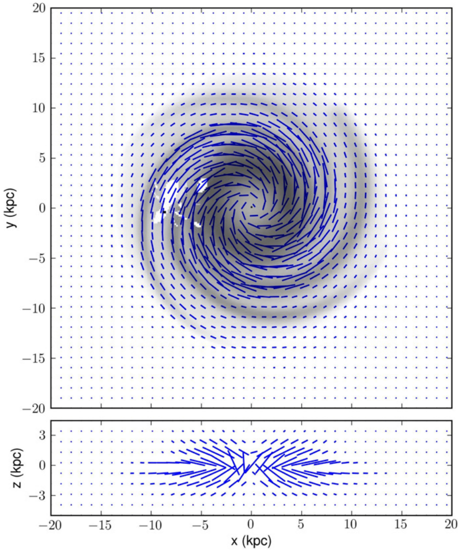
$$B_{\text{ordered}} \parallel B_{\text{coherent}}$$

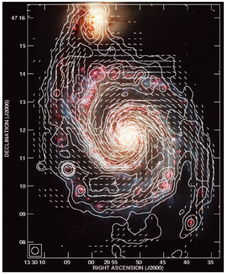
$$B^2_{\text{ordered}} \propto B^2_{\text{coherent}}$$

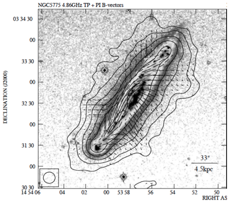
Jansson et al. (2012a,b)

Magnetic field modeling

An outside observer



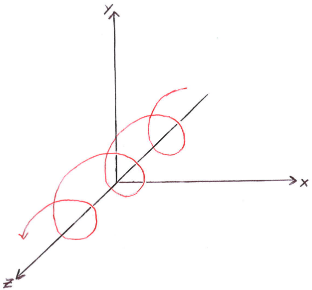




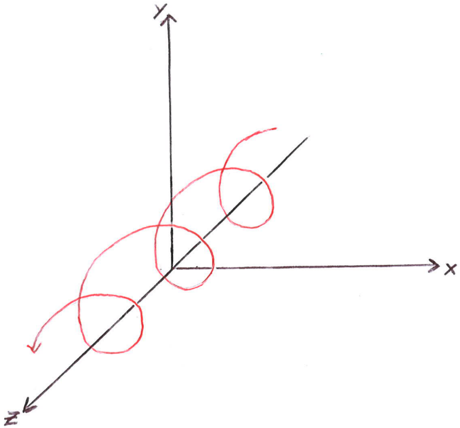
Jansson et al. (2012a)

Helicity

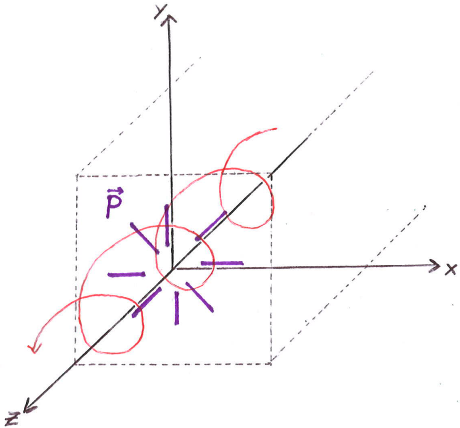
- $H = \int A \cdot B$
- produced in many dynamo scenarios
- observed (tentatively) on large scales
- present on small scales?



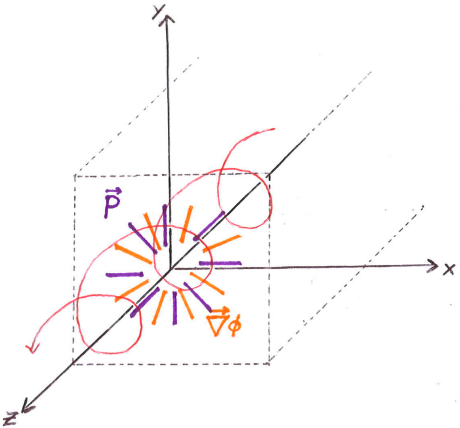
Helicity



Helicity

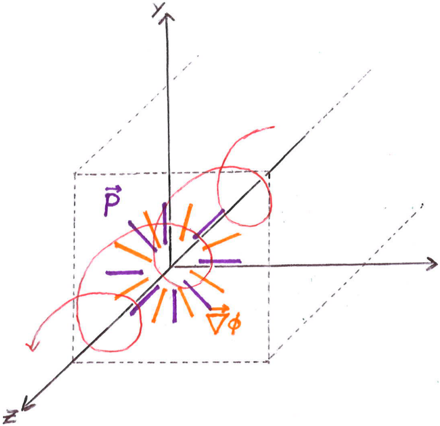


Helicity



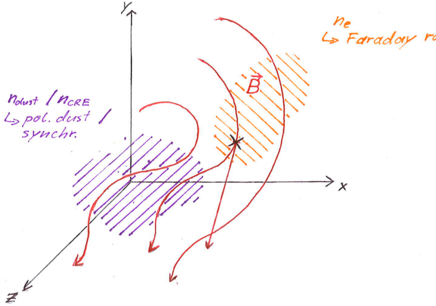
Junklewitz et al. (2011)
Oppermann et al. (2011)

Helicity

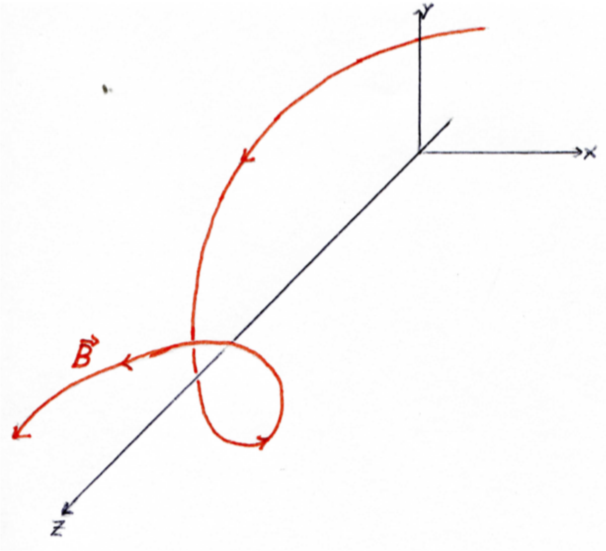


Junklewitz et al. (2011)
Oppermann et al. (2011)

but:

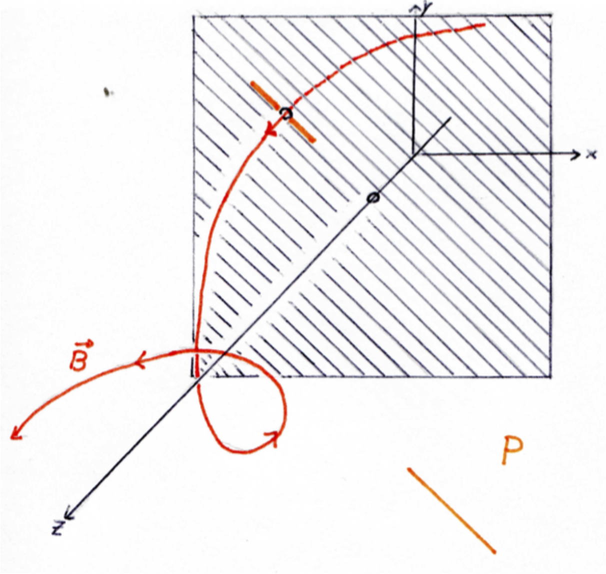


Helicity



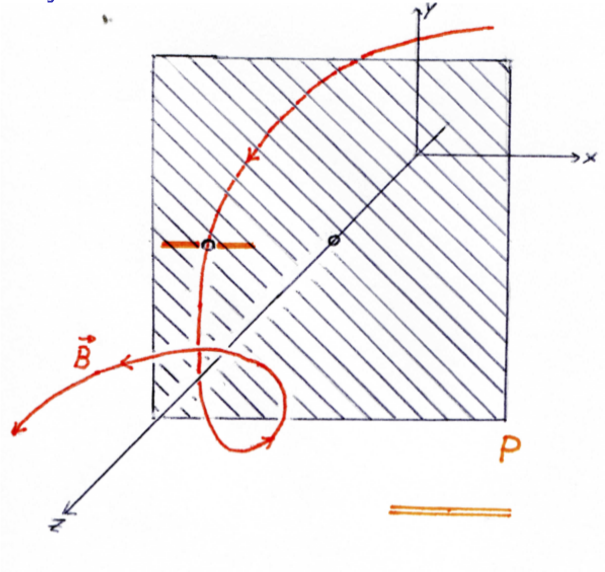
Brandenburg et al. (2014)

Helicity



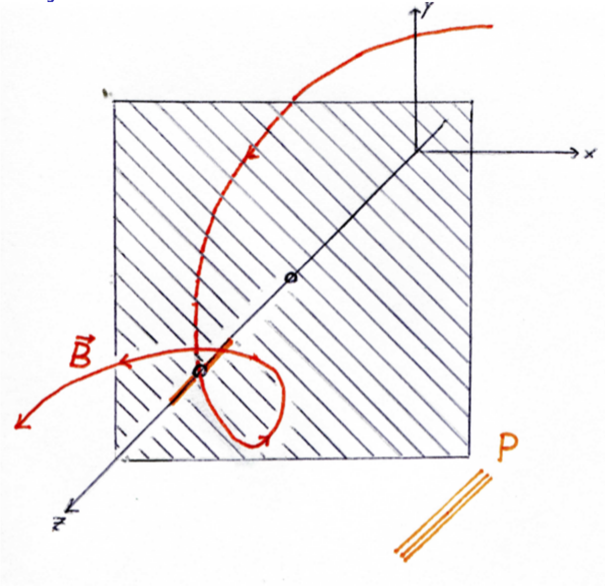
Brandenburg et al. (2014)

Helicity



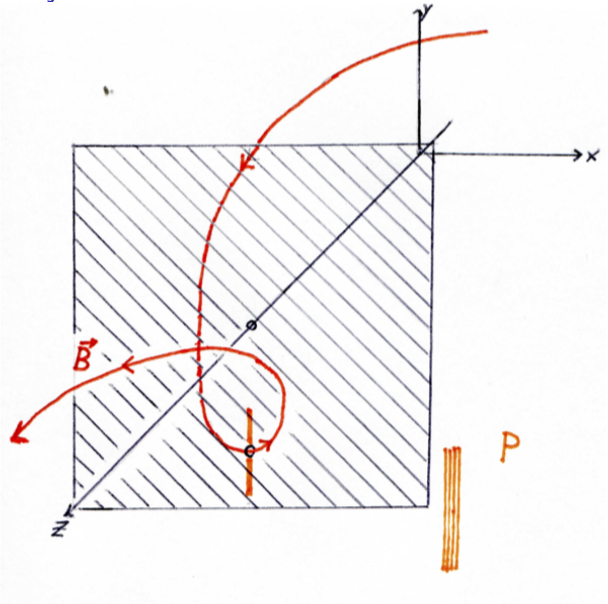
Brandenburg et al. (2014)

Helicity



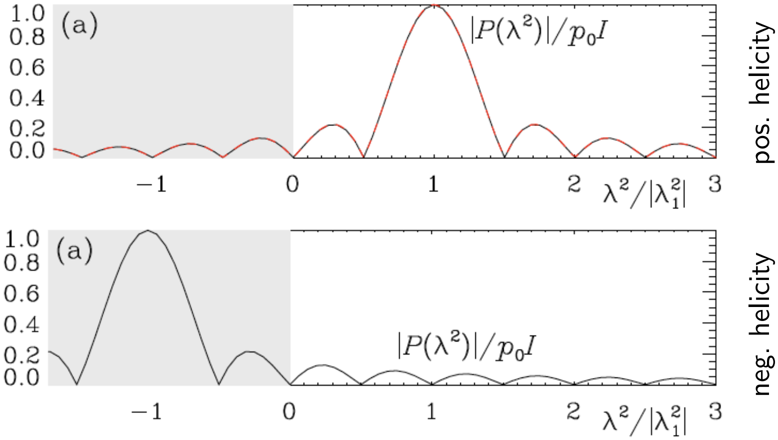
Brandenburg et al. (2014)

Helicity



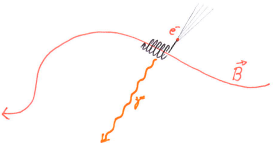
Brandenburg et al. (2014)

Helicity

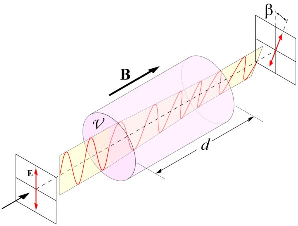


Brandenburg et al. (2014)

Summary



partially hard
to reconcile



azimuthal halo field

isotropic random
field dominant
small-scale
ISM structures?

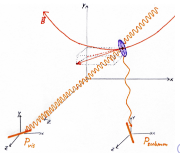
disk field spiral
one reversal
pitch angle ca. 12°

ordered random
field present

X-shaped out-of-plane component

helical?

helical



use

Thanks.

See you at dinner.