Exploring the Diffuse Ionized Gas in Our Galaxy by means of Long Wavelength Radio Observation (2016 Edition)

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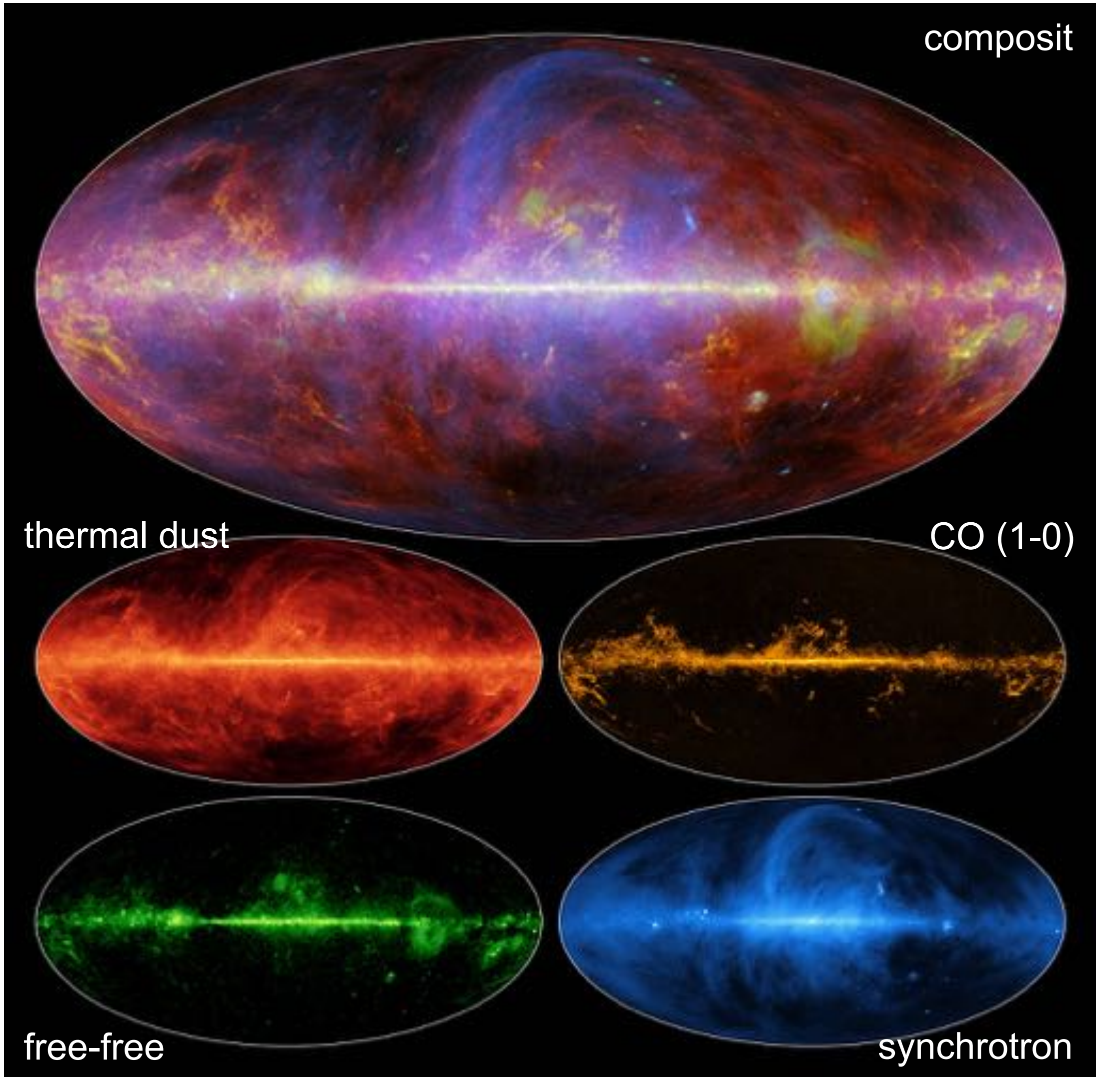
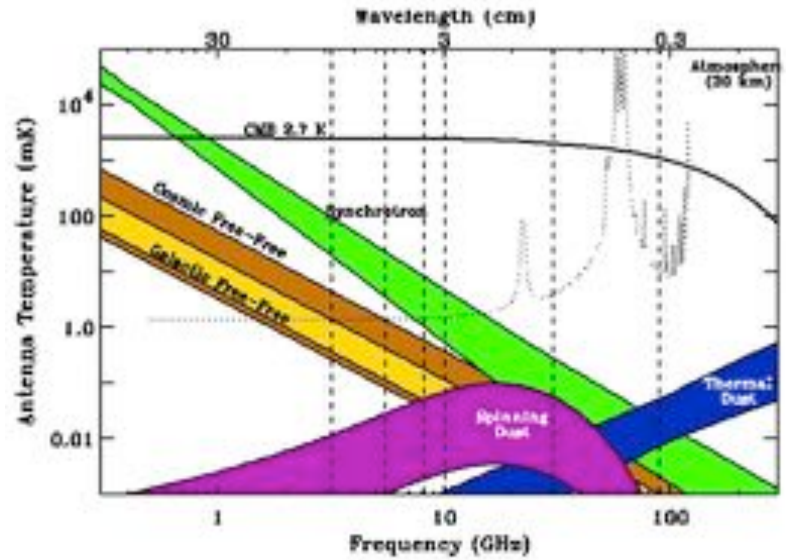
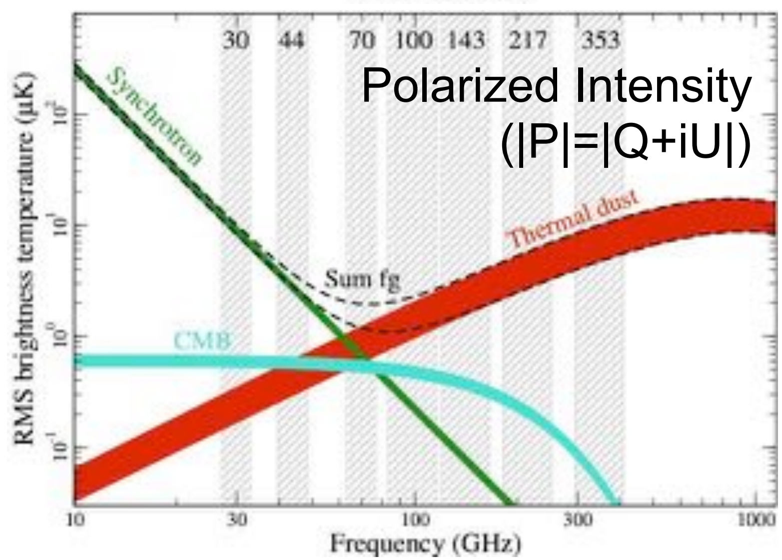
お題
・近年の銀河磁場の観測
・SKA計画で目指すサイエンス

大スケールの銀河磁場と小スケールの分子雲磁場がどのように関連しうるかといった点

1. Introduction
Radio Milky Way

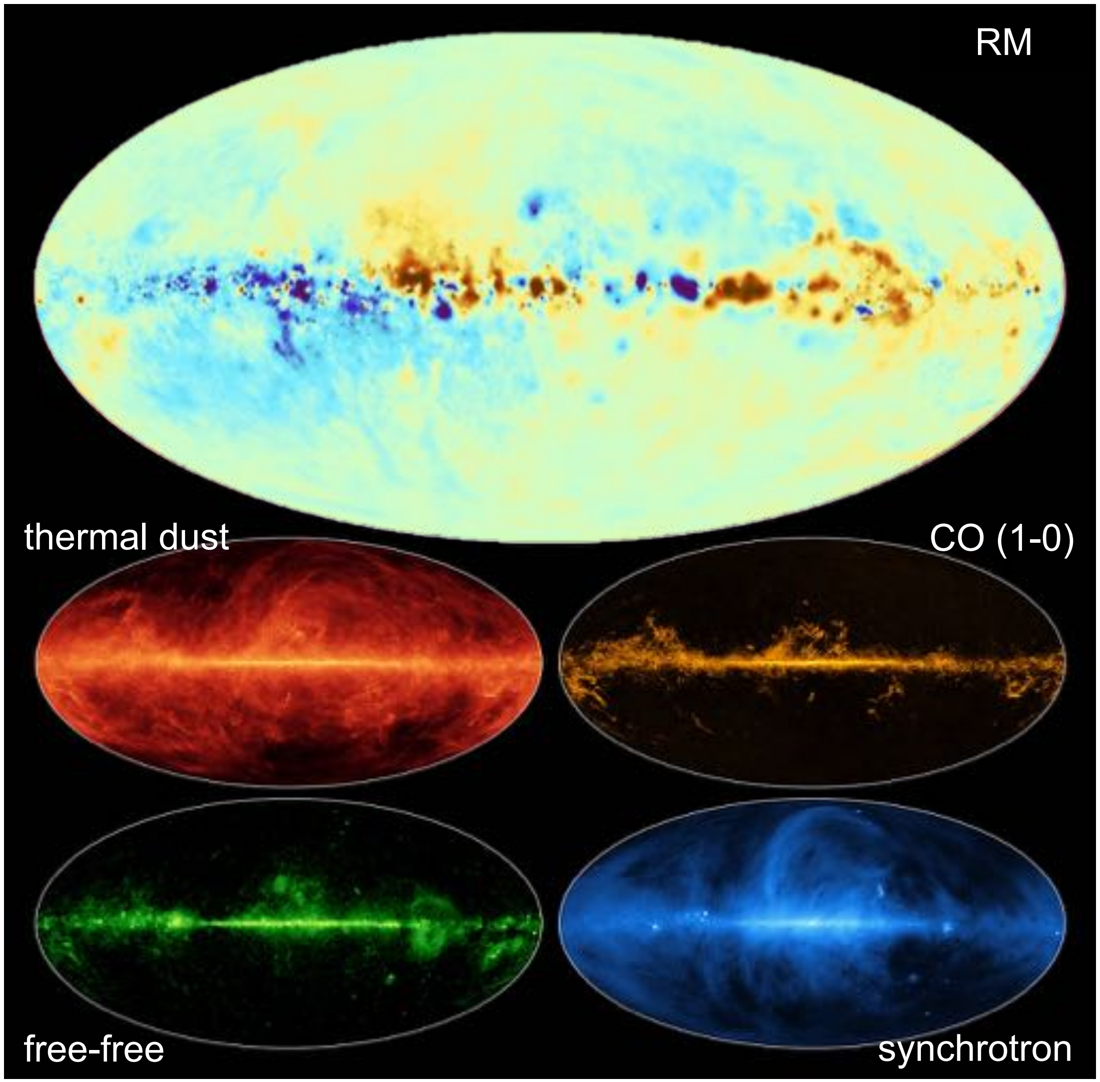


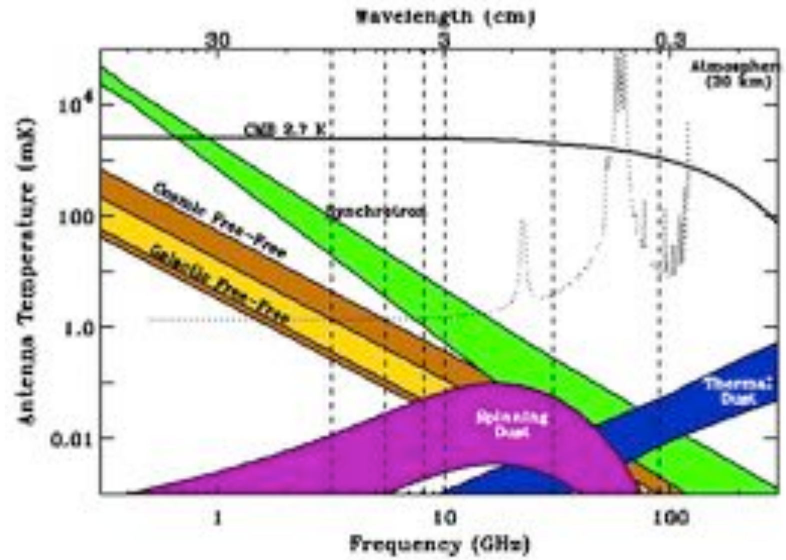


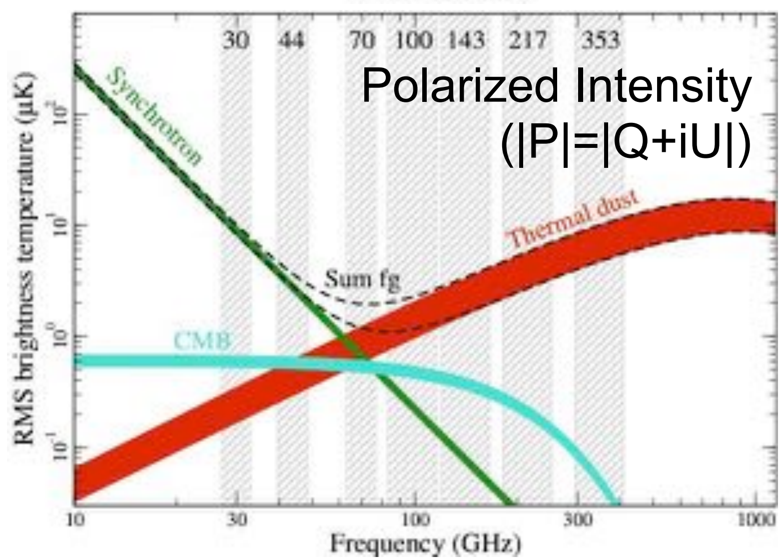


https://www.nasa.gov/jpl/planck/pia18913

1. Introduction
Radio Milky Way







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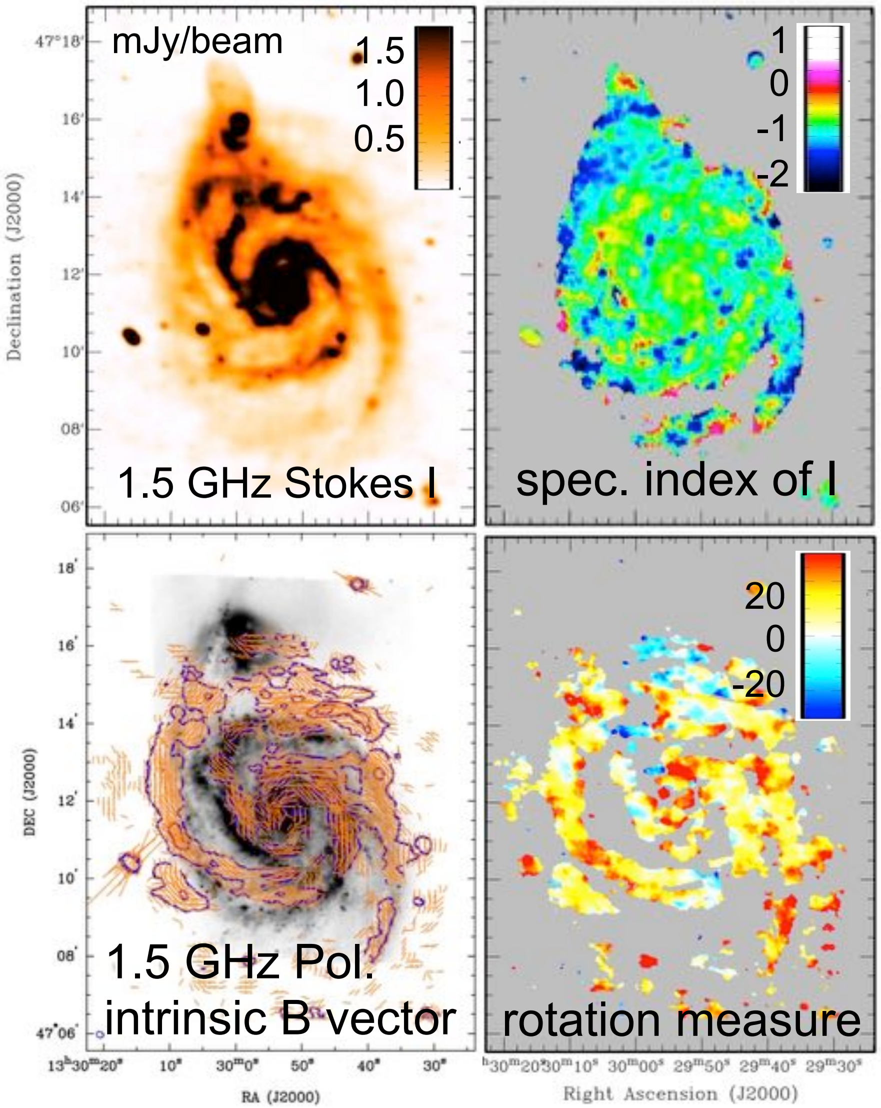
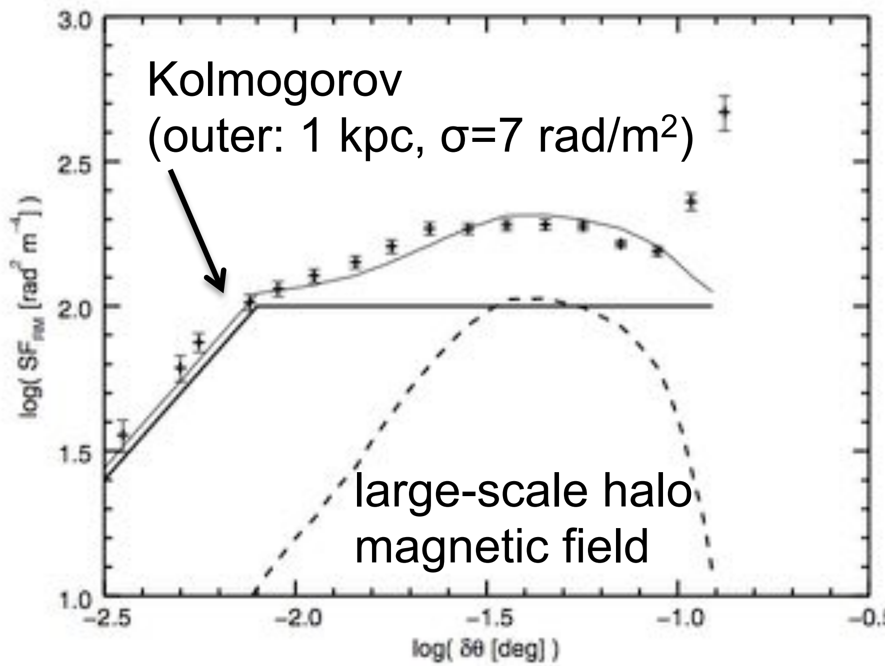
1. Introduction

Capability of cm-m radio: M51



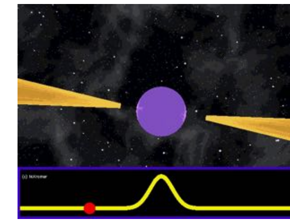


- **Long wavelength radio (centimeter – meter) is a very powerful tool for magnetism.**

Mao et al. 2015, ApJ, 800, 92

Radio pulse observation

❖ Pulsars and Fast Radio Bursts (FRBs)



- Pulse dispersion → dispersion measure (DM)
  - pulse delay time Δt

n_e: free electron density

$$\Delta t\ (\mathrm{msec}) \simeq 4.2 \left(\frac{DM}{\mathrm{pc\ cm^{-3}}}\right)\left(\frac{\nu}{\mathrm{GHz}}\right)^{-2}$$

$$\mathrm{DM} = \int_0^L n_e dl$$

- Diffractive (幾何光学) / refractive (物理光学) scintillations → scattering measure (SM)
  - pulse modulation time Δt

C_N: spectral coefficeint of the density power spectrum

$$\Delta t\ (\mathrm{msec}) \simeq 1.1 \left(\frac{SM}{\mathrm{kpc\ m^{-20/3}}}\right)^{6/5}\left(\frac{L}{\mathrm{kpc}}\right)\left(\frac{\nu}{\mathrm{GHz}}\right)^{-22/5}$$

$$SM = \int_0^L C_N^2 dl$$

- $\langle n_e \rangle \sim DM/L$, or $\langle n_e^2 \rangle \sim SM/L$
  - L: distance (e.g. by annual parallax)

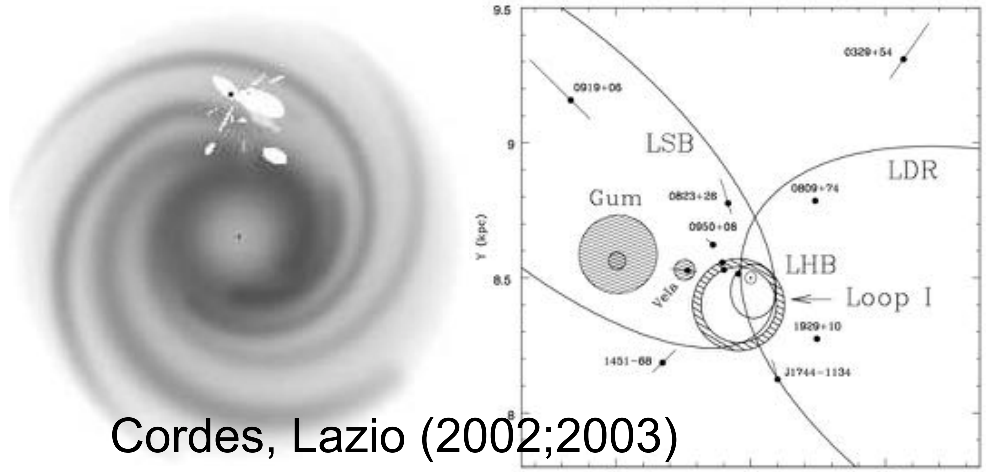
2.1 Thermal electrons

Modified NE2001 model

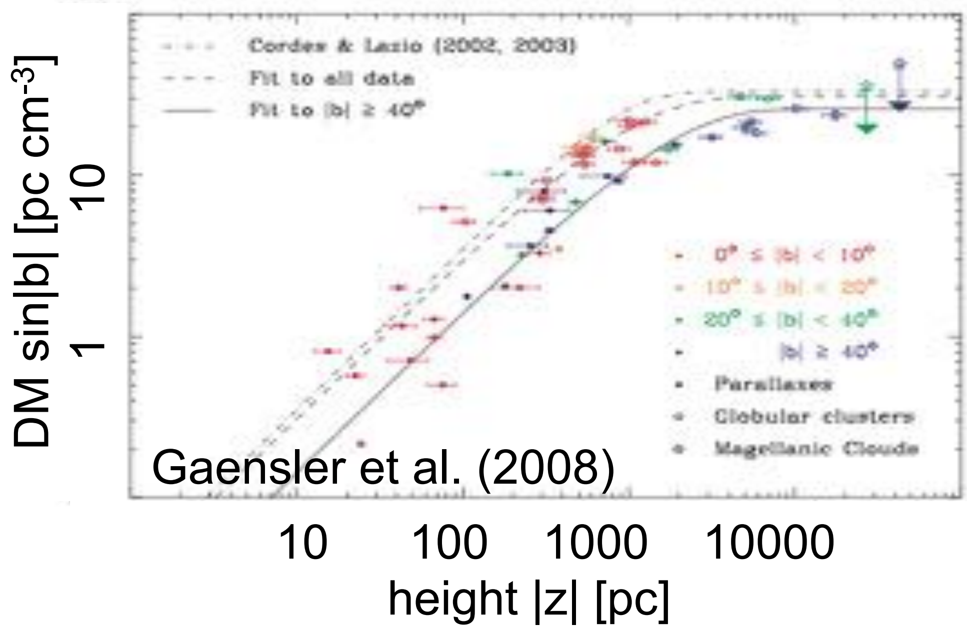
- **NE2001 model**
  - Analytical model of the thermal electron density based on observations
  - Components: thick disk, thin disk, arm, local, clumps, voids
- **Scale height**

$$n(z) = n_0 \exp\left(-\frac{z}{H_n}\right)$$

  - H_n too small in NE2001
  - H_n = 0.97 kpc → 1.8 kpc
  - n_0 → 0.014 cm^{-3}



Cordes, Lazio (2002;2003)

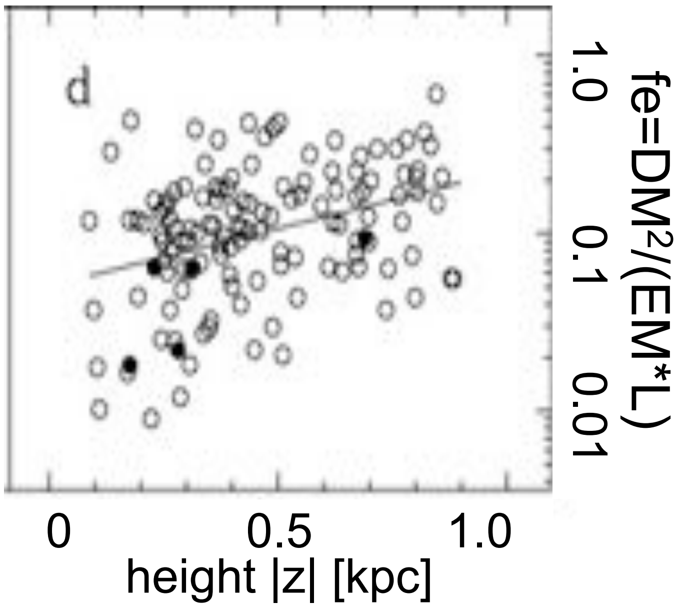


Gaensler et al. (2008)

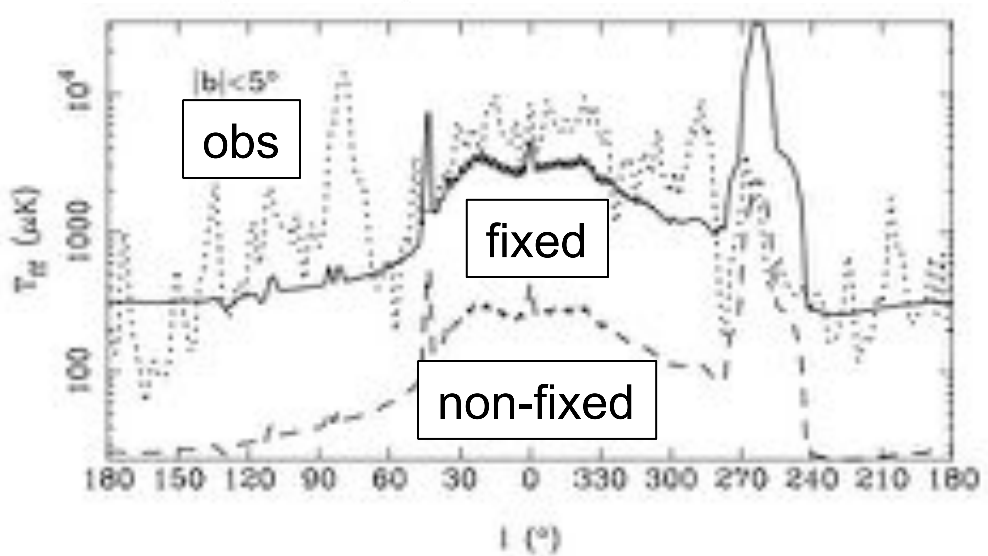
2.1 Thermal electrons
Clumpiness and filling factor

- **DM gives the average of thermal electron density**
  - Electron distribution is clumpy
  - Need the filling factor to reproduce free-free emission

$$\mathrm{EM} = \int_0^L n_\mathrm{e}^2 dl \qquad f_\mathrm{e} = \frac{\langle n_\mathrm{e} \rangle^2}{\langle n_\mathrm{e}^2 \rangle} = 0.07 \exp\left(\frac{|z|}{0.5\ \mathrm{kpc}}\right) \text{ or } 0.32\ (|z| > 0.75\ \mathrm{kpc})$$

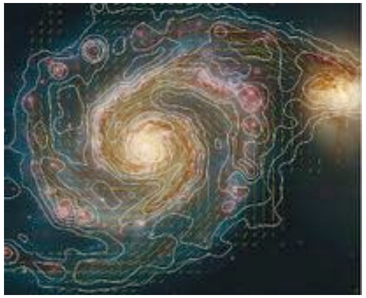


Berkhuijsen et al. (2006)



dotted : 22.8GHz free-free template data
dashed : w/o filling factor, solid: w/ filling factor
Sun et al. (2008)

Faraday rotation measure



❖ Faraday rotation measure of background sources

– Faraday rotation → rotation measure (RM)

- Rotation of polarized angle ΔΦ

$B_{||}$: line-of-sight component of magnetic field

$$\Delta\Phi\ (\mathrm{rad}) \simeq 0.318\pi \left(\frac{\mathrm{RM}}{\mathrm{rad\ m^{-2}}}\right)\left(\frac{\lambda}{1\ \mathrm{m}}\right)^2 \qquad \mathrm{RM} = \int_L^0 n_{\mathrm{e}} B_{||} dl$$

– Depolarization → dispersion of RM (σ_{RM})

- Degree of internal/external Faraday rotation depolarization DPi/DPe

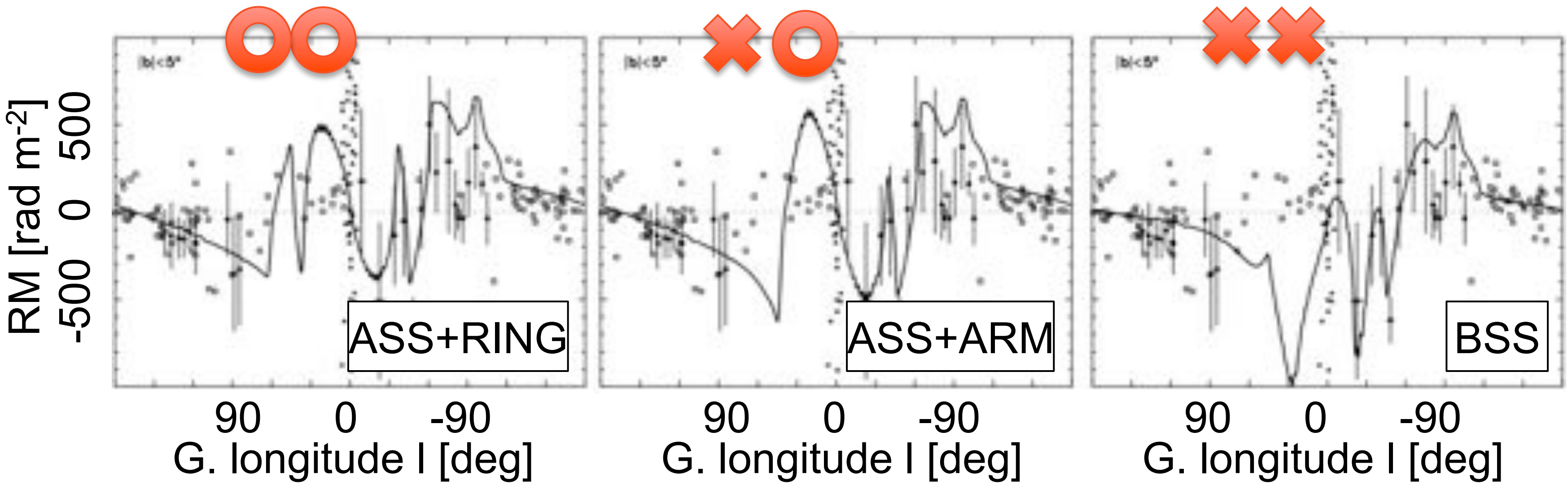
$$\mathrm{DPi} = \frac{1 - \exp(-2\sigma_{\mathrm{RM}}^2 \lambda^4)}{2\sigma_{\mathrm{RM}}^2 \lambda^4} \qquad \mathrm{DPe} = \exp(-2\sigma_{\mathrm{RM}}^2 \lambda^4)$$

– $\langle B_{||} \rangle \sim$ RM/DM

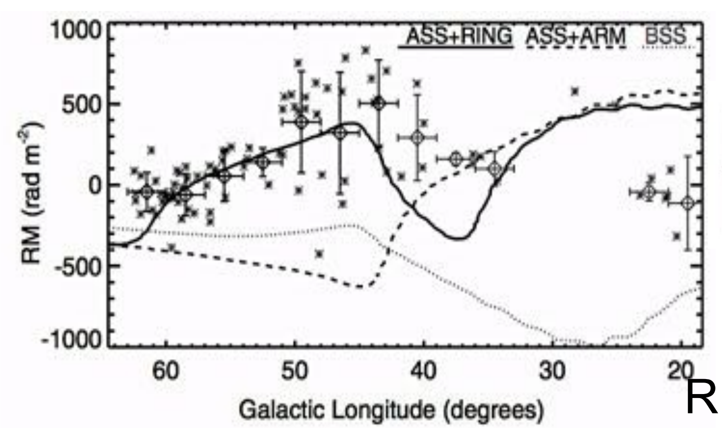
Disk field

❖ **Axi-Symmetric Spiral (ASS) vs. Bi-Symmetric Spiral (BSS)**

– ASS + reversal, B_0~2-6 μG (Sun et al. 2008; Van Eck et al. 2011)



RM (CGPS+SGPS, |b|<5°) Lines：model (Sun+ 2008)



$$\begin{cases} B_{s,R}(R,\Theta,z) = D_1(R,z)D_2(R,\Theta)\sin(p_{s0}), \\ B_{s,\Theta}(R,\Theta,z) = -D_1(R,z)D_2(R,\Theta)\cos(p_{s0}), \\ B_{s,z}(R,\Theta,z) = 0, \end{cases}$$

$$D_1(R,z) = \begin{cases} B_{s0}\exp\left(-\frac{R-R_\odot}{R_{s0}} - \frac{|z|}{z_{s0}}\right) & R > R_{sc}, \\ B_{sc}\exp\left(-\frac{|z|}{z_{s0}}\right) & R \leqslant R_{sc}. \end{cases}$$

$$D_2(R,\Theta) = \begin{cases} +1 & R > 7.5\ \mathrm{kpc}, \\ -1 & 6\ \mathrm{kpc} < R \leqslant 7.5\ \mathrm{kpc}, \\ +1 & 5\ \mathrm{kpc} < R \leqslant 6\ \mathrm{kpc}, \\ -1 & R \leqslant 5\ \mathrm{kpc}, \end{cases}$$

$$D_2(R,\Theta) = \sin\left(\Theta + \frac{1}{\tan p_{s0}} \ln\frac{R}{R_{sb}}\right)$$

RM data (NVSS+CGPS, |b|<3°)
Lines： model (Van Eck et al. 2011)

2.2 Global magnetic field

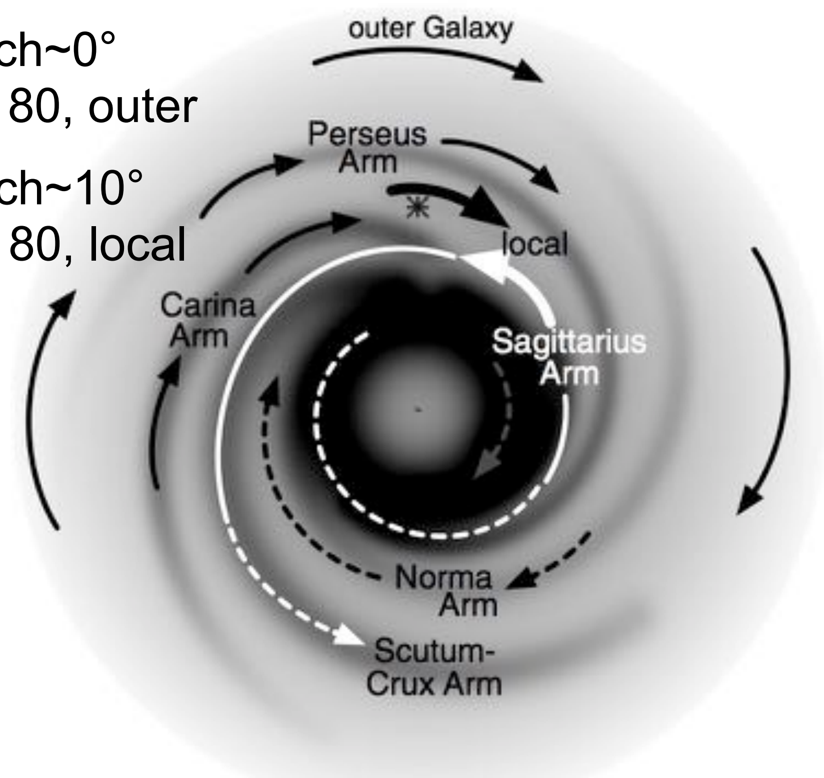
Disk-halo transition

- ❖ **ASS to BSS transition at mid galactic latitudes?**
  - – ASS-RING in the galactic disk, BSS in halo**
  - – Effect of vertical (X-shape) field?

**M51
ASS in disk
BSS in halo

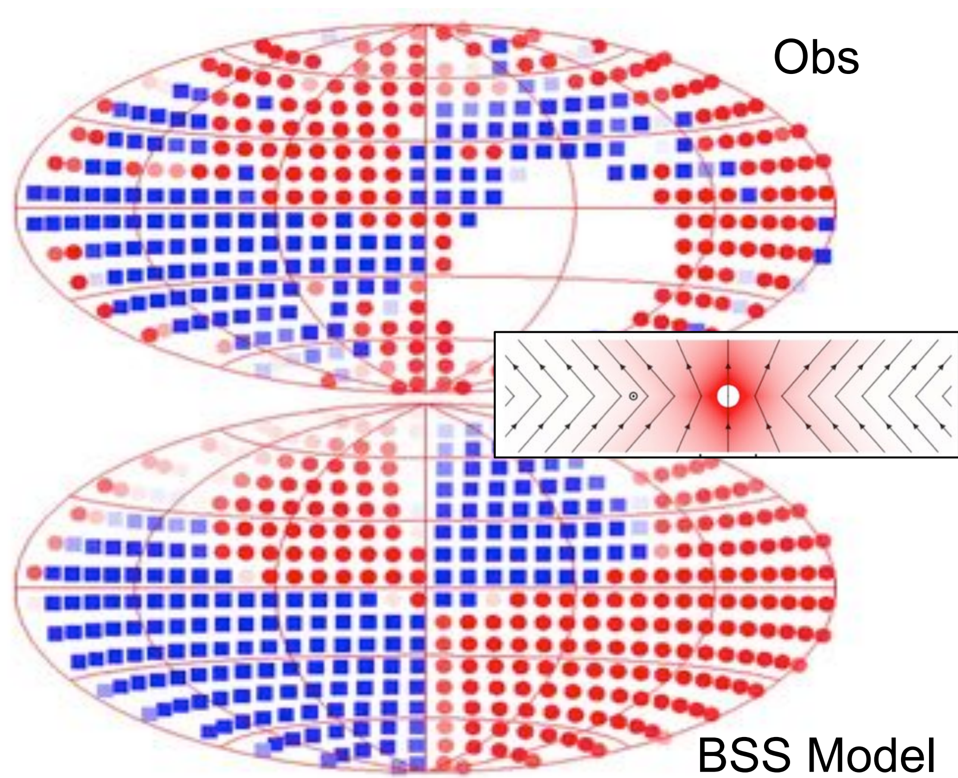
pitch~0°
l=180, outer

pitch~10°
l=180, local



Van Eck et al. (2011)

Obs



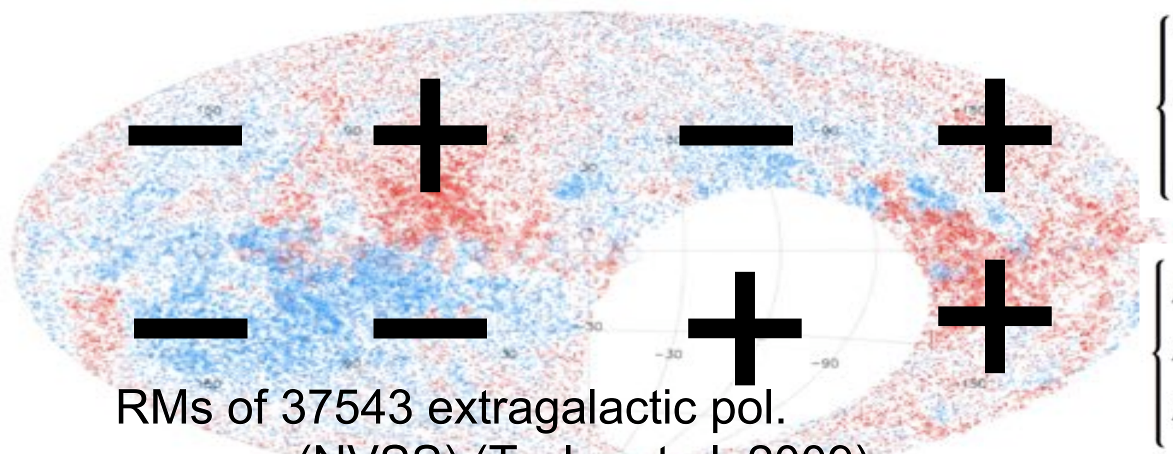
BSS Model

Pshirkov et al. (2011)

2.2 Global magnetic field

Halo field

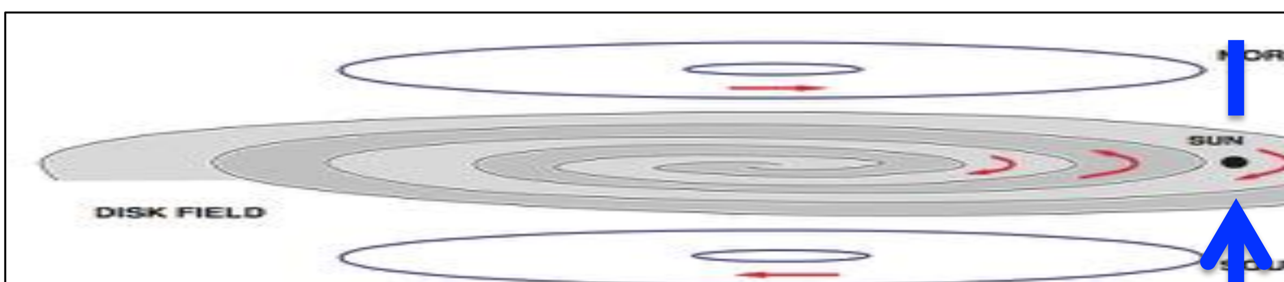
- ❖ **Toroidal field (~2 μG) + vertical field near the Sun**
  - – inner: galactic-center symmetry, outer: galactic-axis symmetry (Taylor et al. 2009; Oppermann et al. 2011)
  - – vertical field toward only south galactic pole (Mao et al. 2010)



RMs of 37543 extragalactic pol. sources (NVSS) (Taylor et al. 2009)

$$
\begin{cases}
B_{t,R}(R,\Theta,z) = 0, \\
B_{t,\Theta}(R,\Theta,z) = \dfrac{\mathrm{sign}(z)^{v} B_{t0}}{1+\left(\frac{|z|-z_{t0}}{z_{t1}}\right)^2} \dfrac{R}{R_{t0}} \exp\left(-\dfrac{R-R_{t0}}{R_{t0}}\right) \\
B_{t,z}(R,\Theta,z) = 0,
\end{cases}
$$

$$
\begin{cases}
B_{x,R}(R,\Theta,z) = \mathrm{sign}(z) B_{x0} \exp\left(-\dfrac{R_p}{R_{x0}}\right)\left(\dfrac{R_p}{R}\right)^{w} \cos\eta, \\
B_{x,\Theta}(R,\Theta,z) = 0, \\
B_{x,z}(R,\Theta,z) = B_{x0} \exp\left(-\dfrac{R_p}{R_{x0}}\right)\left(\dfrac{R_p}{R}\right)^{w} \sin\eta.
\end{cases}
$$



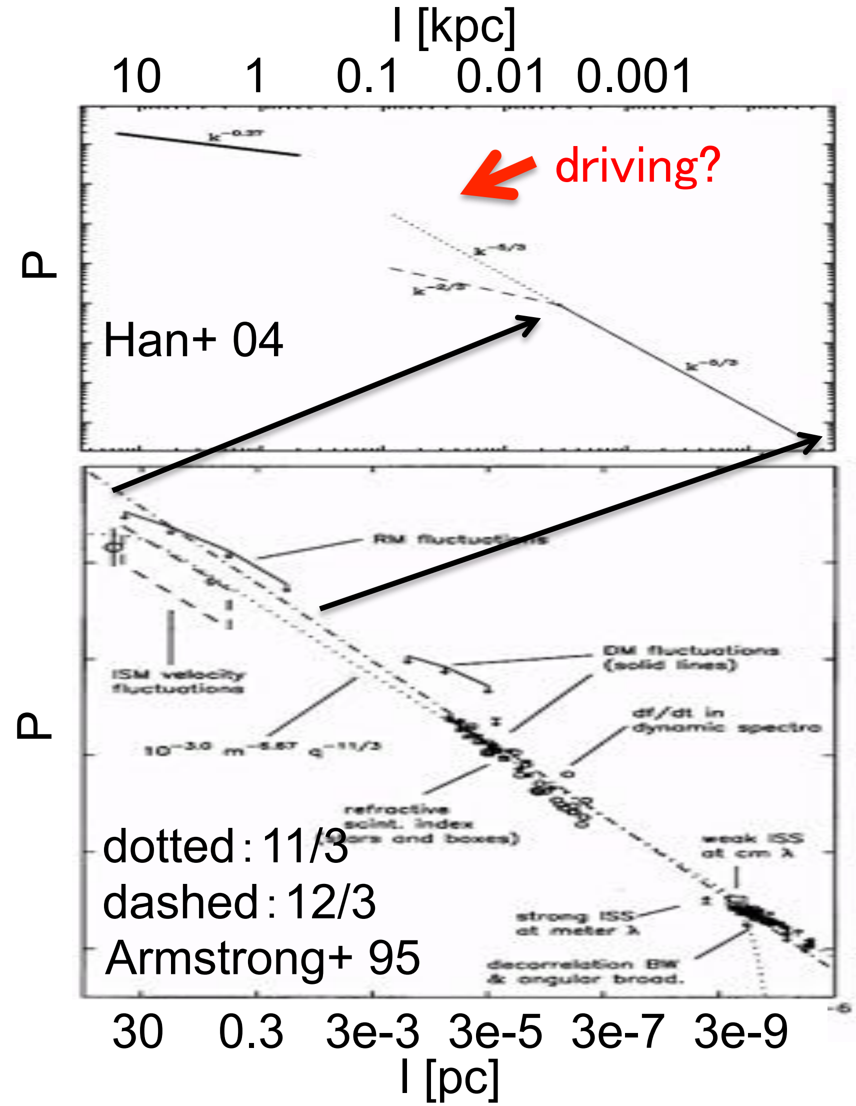
RM ~ +0.0±0.5 rad/m^2
$B_{||}$~0.00±0.02 μG

Mao et al. (2010)

RM ~ +6.3±0.5 rad/m^2
$B_{||}$~0.31±0.02 μG

Properties of turbulence

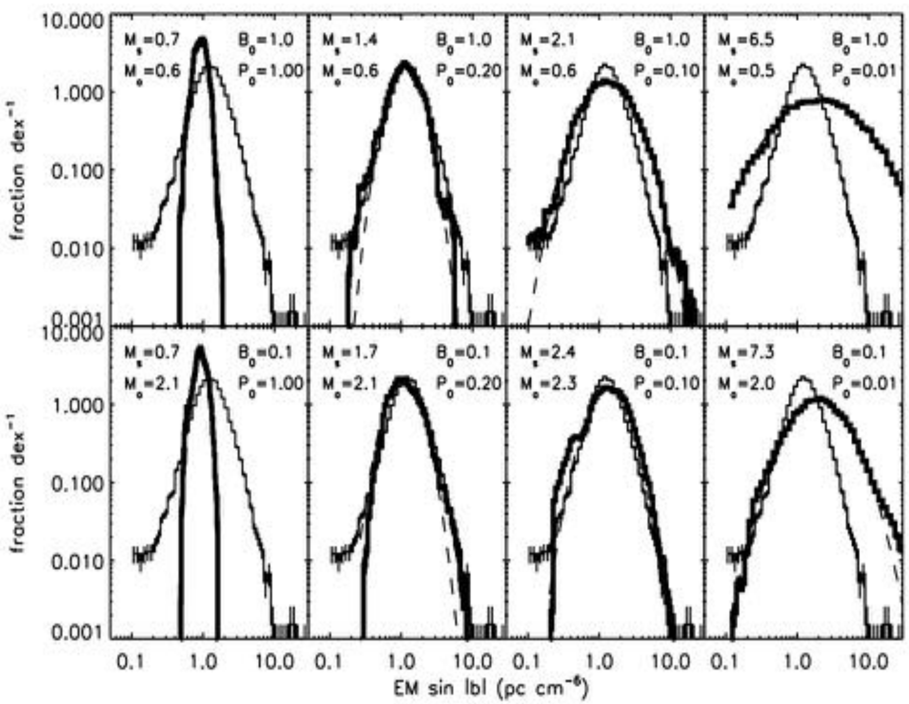
- **Power spectrum, P~k$^{-β}$**
  - Kolmogorov (β=5/3) (Armstrong et al. 1995)
  - Outer scale of > ~1 kpc (β=0.37) (Han et al. 2004)
  - Amplitude: 3-5 μG at disk
- **Driving scale**
  - ~1 pc @ spiral-arms
  - ~100 pc @ inter-arms (Haverkorn et al. 2008)
- **Remarks**
  - Ordered fields (Jaffe et al. 2010)



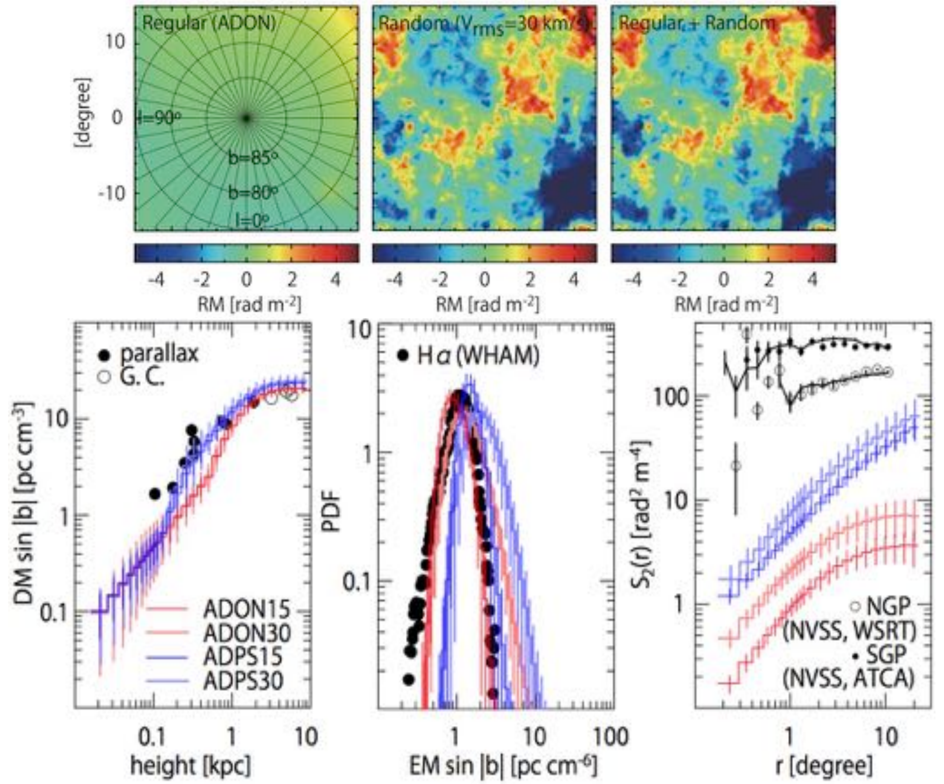
High galactic latitudes

❖ Mach number M, plasma β, and driving scale

- EM + MHD → M~1.4-2.4, l_{drive}~ 500 pc (Hill et al. 2008)
- DM + EM + <RM> + MHD → β~0.1-1, σ_{RM} ~ few rad/m^2



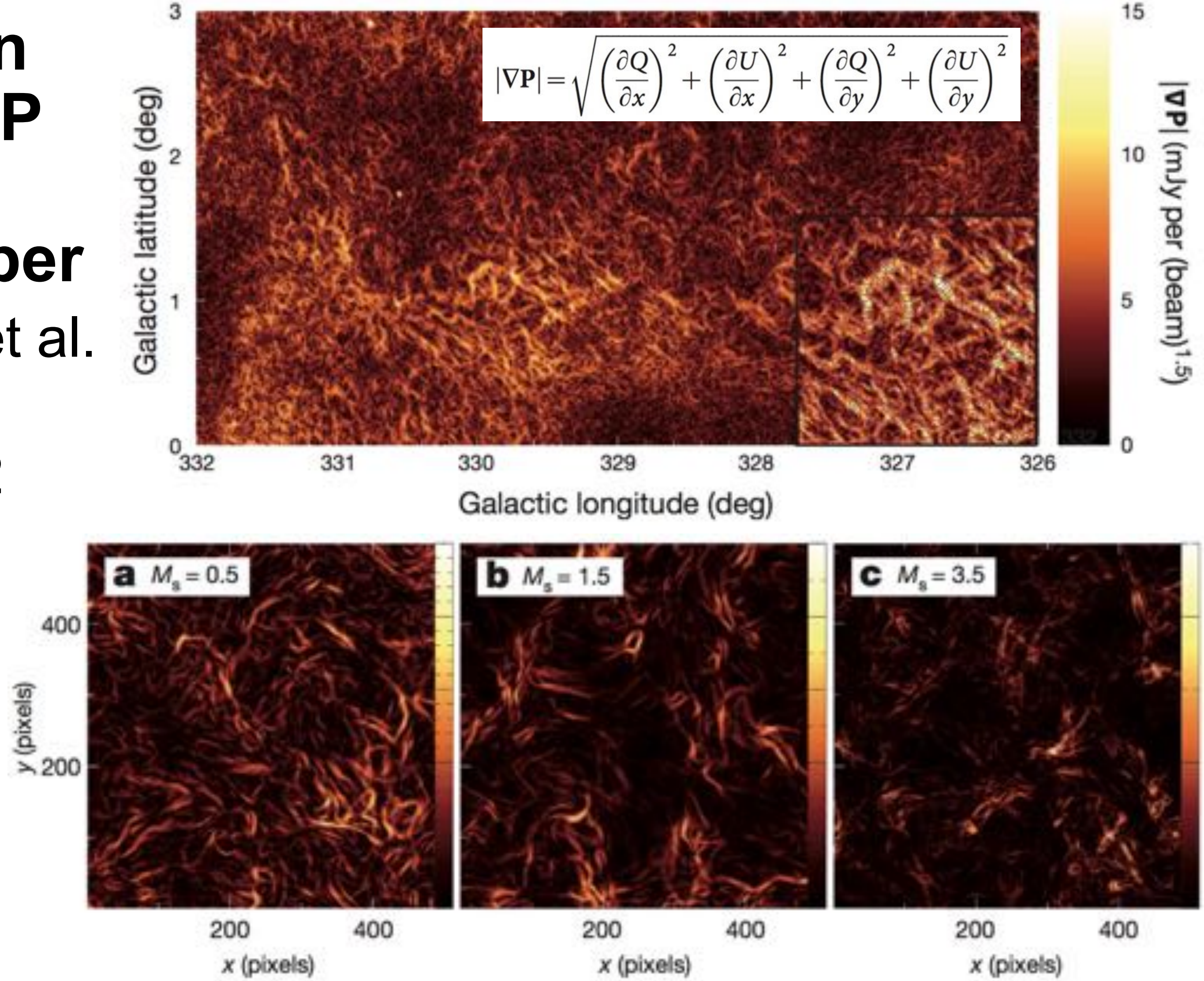
thin: observation, thick: MHD model
Hill et al. (2008)



Akahori et al. (2013)

Plasma diagnostics 1

- **Polarization gradient ∇P unveils the Mach number**
  - Gaensler et al. (2011)
  - prefer M<2



2.2 Magnetic turbulence
Plasma diagnostics 2

- **Alfven velocity (in SI):** $$v_A = \frac{B}{\sqrt{\mu_0 \rho}}$$
- **Rotation measure:**

$$\phi = 2.63 \times 10^{-13} (\mu_e m_p)^{1/2} \mu_0^{1/2} \int n_e^{3/2} \frac{B_\parallel}{\sqrt{\mu_0 \rho}} L dx$$

- **Density-weighted Alfven velocity:**

$$\bar{v}_A = \frac{\int n_e^{3/2} v_A dl}{\int n_e^{3/2} dl} \qquad \bar{v}_A \geq \left[\frac{(\mu_e m_p)^{-1/2} \mu_o^{-1/2}}{2.63 \times 10^{-13}}\right] \frac{|\phi|}{\int n_e^{3/2} dl}$$

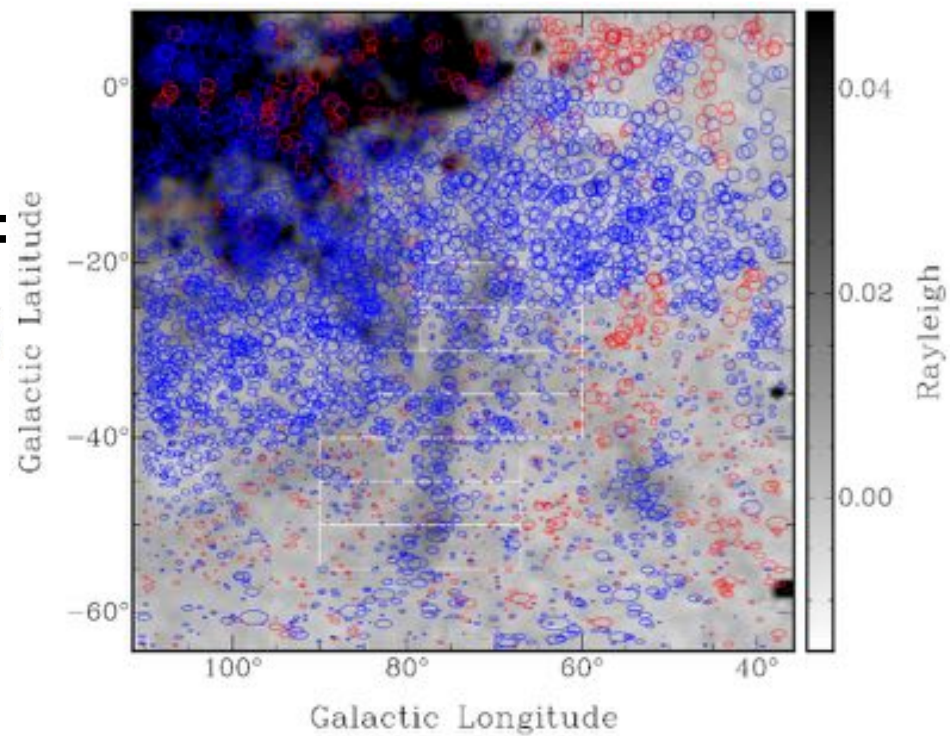
- **Dimensionless factor R**
  - R=1 uniform density, R=1.0755 gaussian

$$\mathcal{R} \equiv \frac{\int n_e^{3/2} dx}{\left[\int n_e^2 dx\right]^{3/4}} = f^{-\frac{1}{4}} L^{-\frac{1}{4}} \frac{\int n_e^{3/2} dl}{EM^{3/4}}$$

$$\bar{v}_A \geq (0.820 \text{ km s}^{-1}) \mu_e^{-1/2} f^{-1/4} \times \times \left(\frac{L}{100 \text{ pc}}\right)^{-1/4} \mathcal{R}^{-1} \left[\frac{|\phi|}{EM^{3/4}}\right]$$

- **Sound speed & plasma β:**

$$c_S = \left(\frac{kT}{\mu m_H}\right)^{1/2} = (8.12 \text{ km s}^{-1})\, \mu^{-1/2} \left(\frac{T}{8000 \text{ K}}\right)^{1/2} \qquad \beta = \frac{p_t}{p_B} = \frac{c_S^2}{v_A^2}$$



H_α at V_{LSR}=-45 km/s,
Extragalactic |RM| max 70 rad/m^2

- **β<~1 in the filaments**
  - β<~0.1 at b~50°

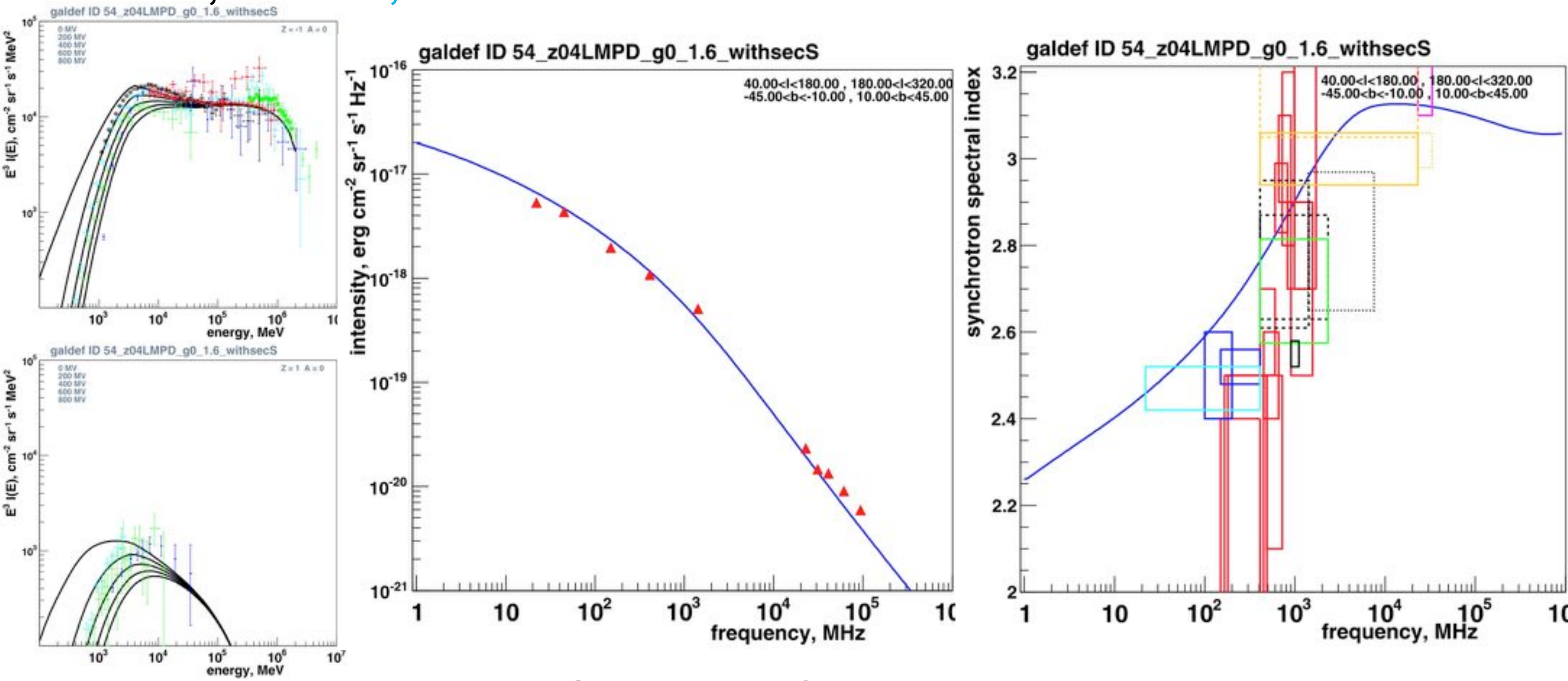
Energy distribution function

❖ Cosmic-ray electrons (CRe): $N(\gamma)d\gamma = N_0\gamma^{-p}d\gamma$

– p~2.5-3 @ ~3-30 GeV CRe

AMS01, CAPRICE, HEAT, Fermi-LAT, PAMELA, ATIC-1-2, HESS

N_0: CRe density normalization (cm^{-3})
γ: Lorentz factor
p: energy spectral index



Strong+11, A&A, 534, 54

2.3 Cosmic-ray electrons

Synchrotron radiation

- ❖ **CRe + B = Synchrotron**
  - – Specific stokes I, Q, U

$$I \propto n_c B_{||}^{(1+p)/2} \omega^{(1-p)/2}$$

$$Q + iU \propto n_c B_{||}^{(1+p)/2} \omega^{(1-p)/2} e^{-2i\chi}$$

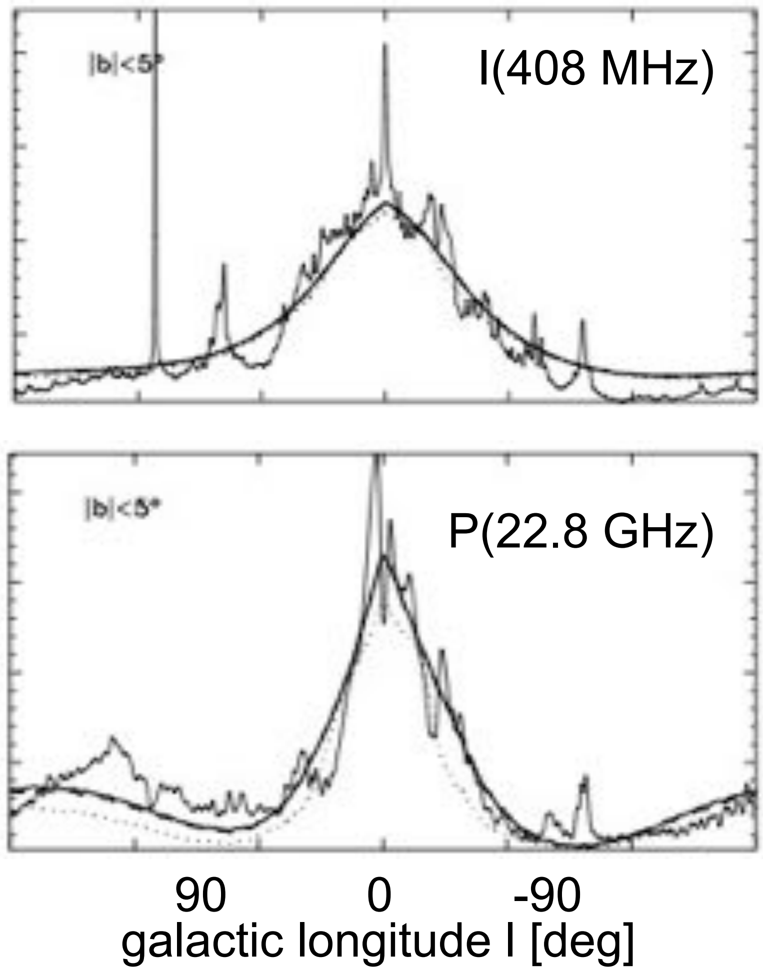
$B_{||}$: LoS component of magnetic field [μG]
ω: 2πν, χ: intrinsic polarization angle (⊥$B_\perp$)

  - – Spectral index I∝ν^α
    - • α=(1-p)/2

- ❖ **Spatial distribution of CRe**
  - – n_{c0} = 5x10^{-5} cm^{-3}, H_c = 0.8 kpc

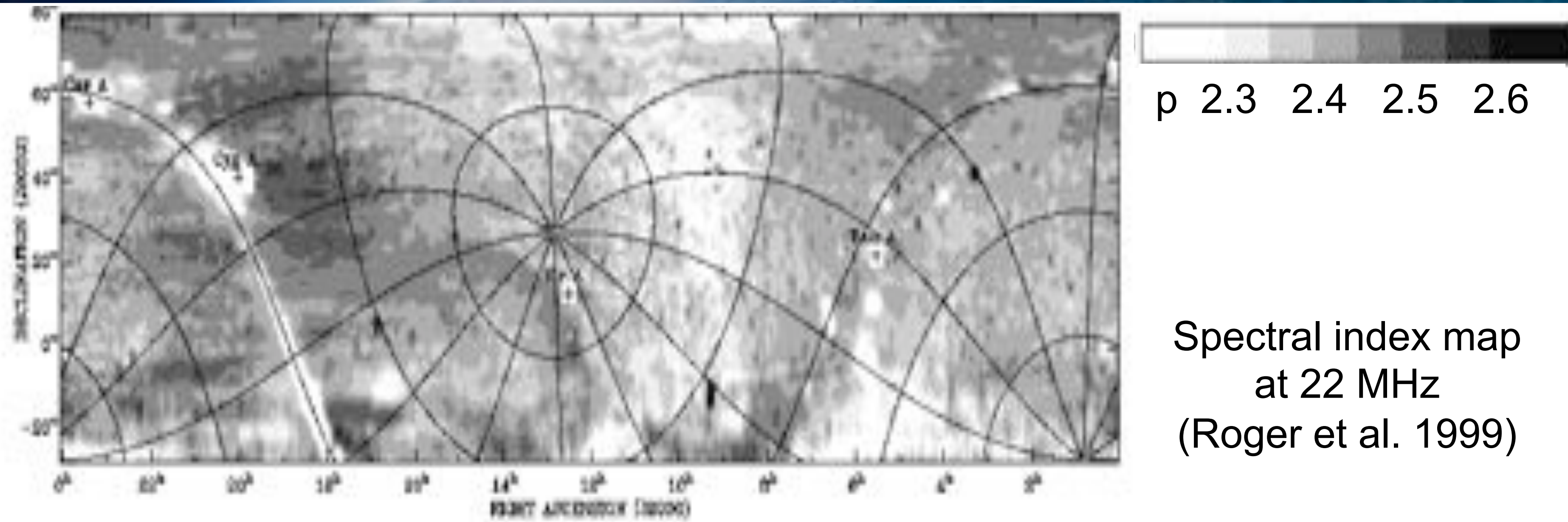
$$n_c(R, z) = n_{c0} \exp\left(-\frac{R - R_\odot}{8\ \mathrm{kpc}} - \frac{|z|}{H_c}\right)$$

dashed : I, P data (|b|<5°)
solid : model (Sun et al. 2008)



2.3 Cosmic-ray electrons

Free-free absorption



Spectral index map at 22 MHz (Roger et al. 1999)

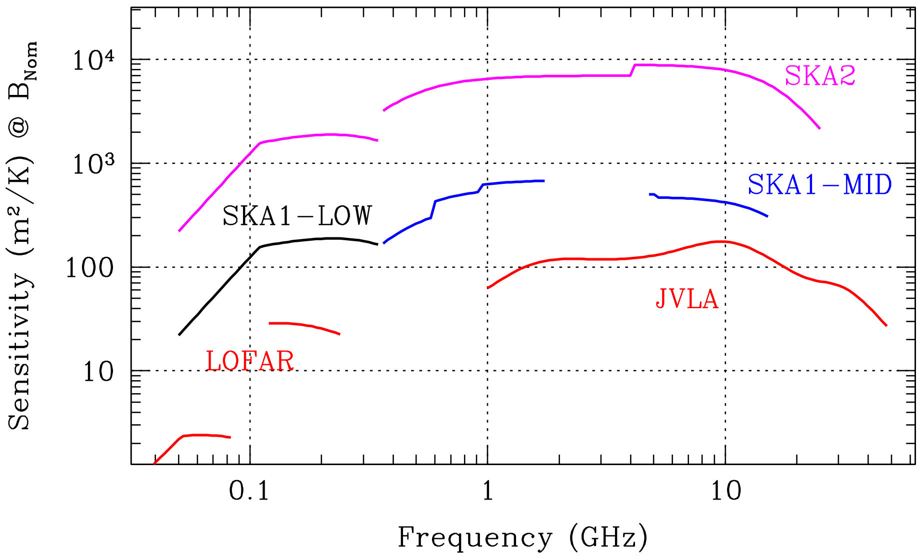
- **Shallower slope (α~-0.5) of Stokes I at 22-408 MHz**
  - Free-free absorption is significant (τ >1); absorption of synchrotron (I, Q, U) ∝ $e^{-\tau}$

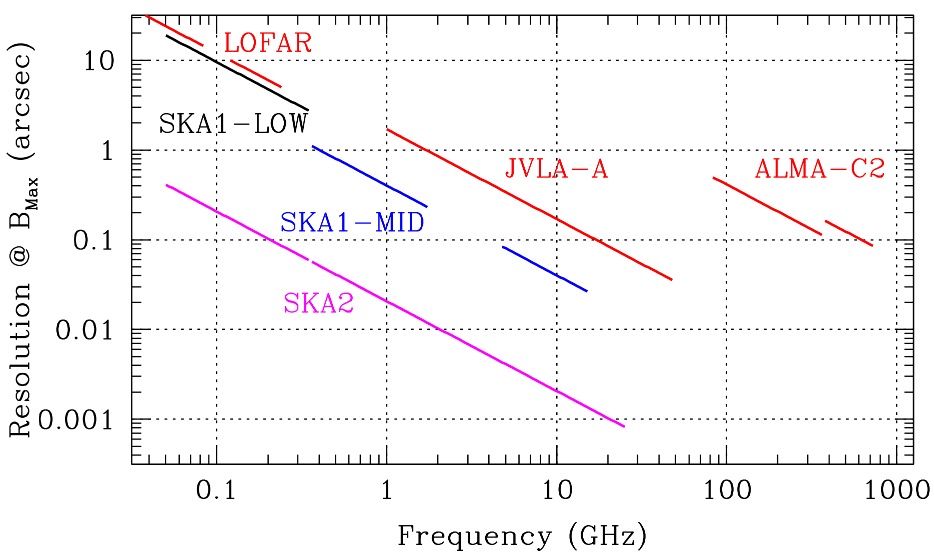
$$\tau = 8.235 \times 10^{-2} T^{-1.35} \nu^{-2.1} EM$$ (e.g. Waelkens et al. 2008)

  - Temperature: Hα observation

$$T_{\rm e}(R,z) = 5780 + 287R - 526|z| + 1770z^2$$ [K] (Paladini+ 04)

Specification





- **Sensitivity**
  - 9000PSR+1400MSP (SKA1)
  - 30000PSR+3000MSP (SKA2)
  - QSOs ~ 200,000,000 (SKA2)
  - dense RM grids / rare objects
- **Angular resolution**
  - ~1″ $(\text{baseline}/60\text{km})^{-1}$ $(\text{frequency}/1\text{GHz})^{-1}$
- **Bandwidth**
  - 0.1 - 25 GHz, 64k ch./band
  - spectral index / depolarization/ Faraday tomography
- **FoV and Image quality**
  - x 100 survey speed of JVLA (SKA1)
  - x $10^{4\text{-}6}$ of JVLA (SKA1)
  - A+B+C+D+**E+A⁺**

SCORPIO (ATCA 1.4 GHz)

4 deg^2, (344.25,0.66), 30 μJy, 14″ x 6.5″

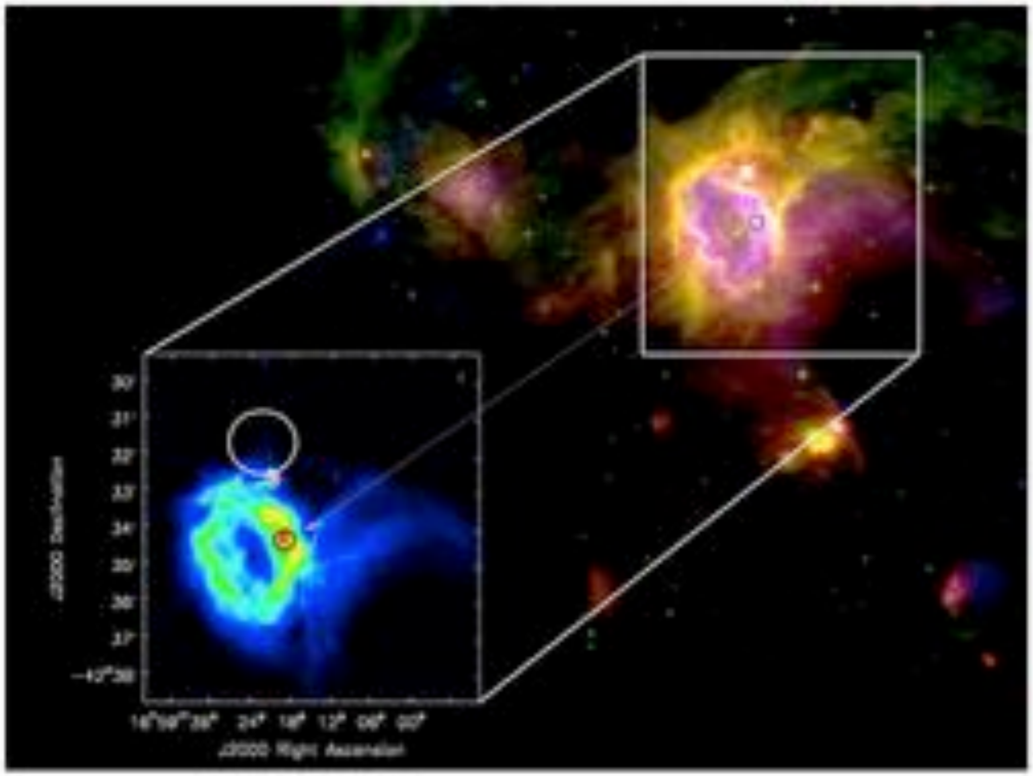
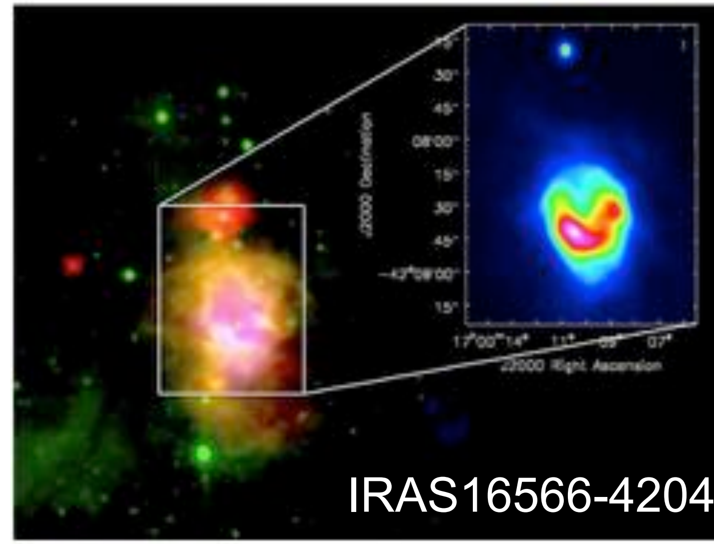
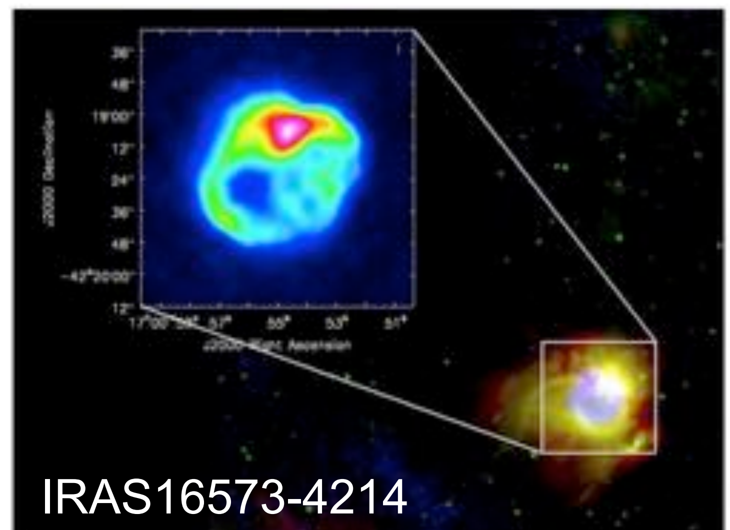


Figure 5. Composite picture of the field centred on [DBS2003] 176. The sub-panel shows only the SCORPIO map, while in the background panel the mid-IR/FIR maps from Spitzer (IRAC, 8 μm, green) and Herschel (PACS, 70 μm, red) are superimposed on the SCORPIO map, in blue. The white arrow indicates the position of the the compact component SCORPIO1_300. The white circle points out that there is no radio emission associated with S16 (see text).

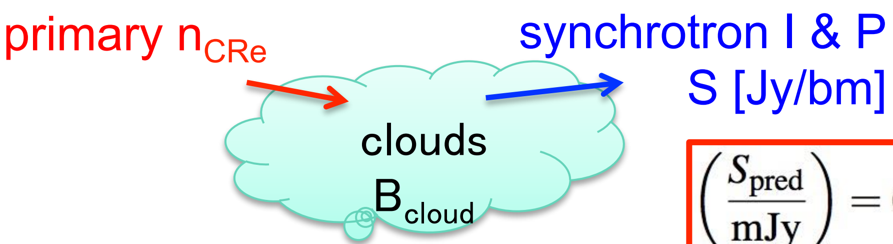




Umana et al. 2015, MNRAS, 454, 902

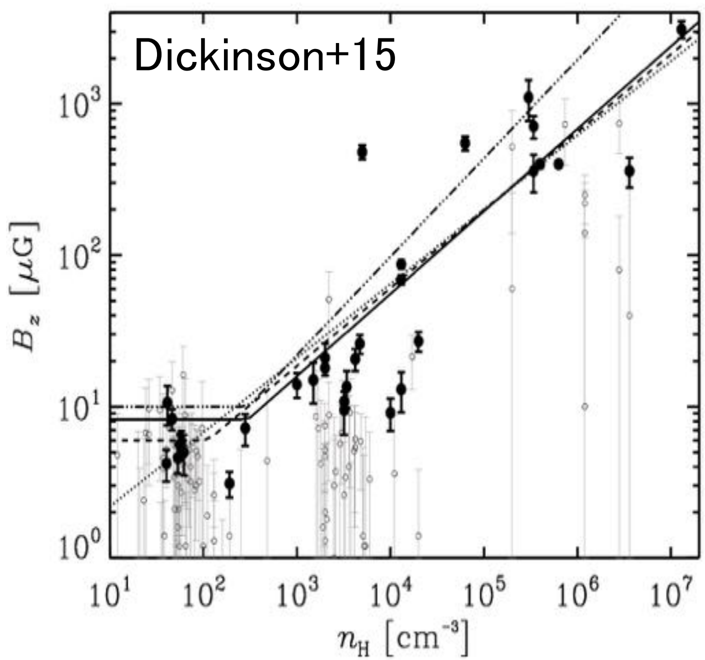
Synchrotron from clouds

❖ **Dense molecular clouds are bright at centimeter**
- Gives field strength & orientation



n_{CRe} : Strong+11, γ~3, α~-1
B_{cloud} : Crutcher+10, $B_z \propto n_H^{\kappa}$, κ~0.6

$$\left(\frac{S_{\rm pred}}{\rm mJy}\right) = 6.6\times10^{6}\left(\frac{\Omega_{\rm src}}{\rm sr}\right)\left(\frac{N_{\rm H}}{10^{23}\,{\rm cm^{-2}}}\right)\left(\frac{n_{\rm H}}{300\,{\rm cm^{-3}}}\right)^{\kappa(\gamma+1)/2-1}$$



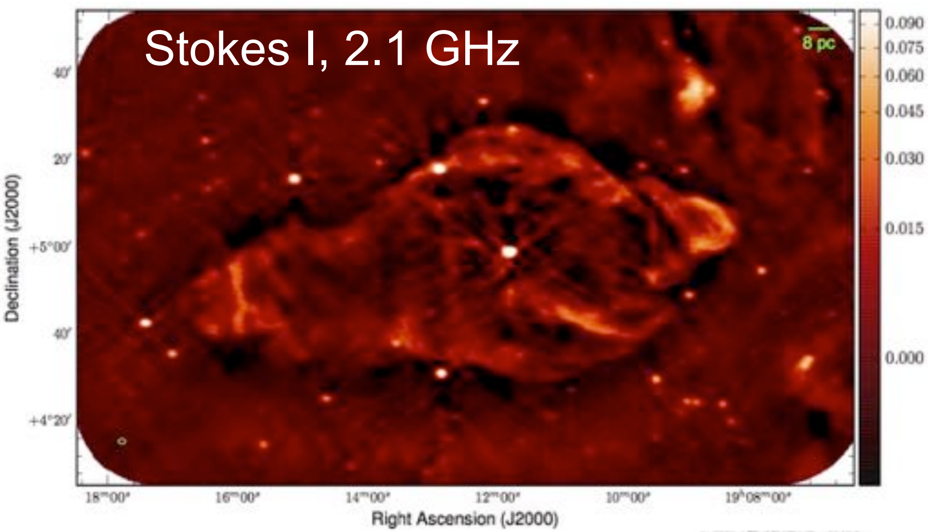
***O*(0.1-1) mJy @ 1 GHz (5″~0.25pc @ 1kpc)**

Name	B_z [μG]	n_{H_2} [cm^{-3}]	R [pc]	D [kpc]	θ [arcsec]	T_{GHz} [mK]	S_{GHz} [mJy]
W3 OH	3100	6.31×10^6	0.02	2.0	4.0	0.06	0.05
DR21 OH1	710	2.00×10^6	0.05	1.8	11.2	0.30	0.27
Sgr B2	480	2.51×10^3	22.0	7.9	1149	1200	1000
M17 SW	450	3.16×10^4	1.0	1.8	236	31	27.0
W3 (main)	400	3.16×10^5	0.12	2.0	24.3	0.49	0.43
S106	400	2.00×10^5	0.07	0.6	48.1	0.74	0.65
DR21 OH2	360	1.00×10^6	0.05	1.8	11.2	0.14	0.13
OMC-1	360	7.94×10^5	0.05	0.4	50.3	2.3	2.0
NGC2024	87	1.00×10^5	0.2	0.4	196	14.6	13.0
W40	14	5.01×10^2	0.05	0.6	34.4	0.04	0.03
ρ Oph 1	10	1.58×10^4	0.03	0.1	91.7	0.14	0.13

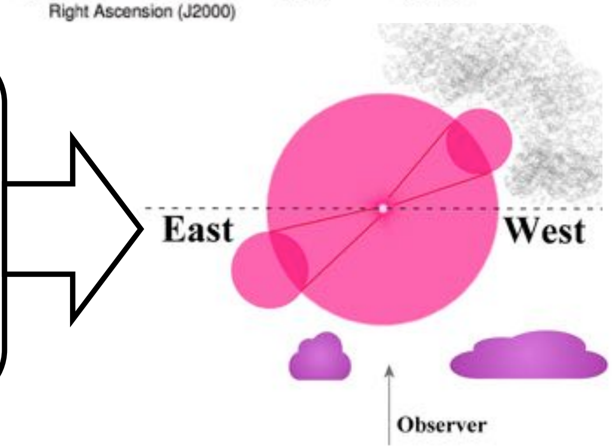
Dickinson+15, arXiv:150100804, PoS102

3. Toward SKA
Terminal shock and Jet

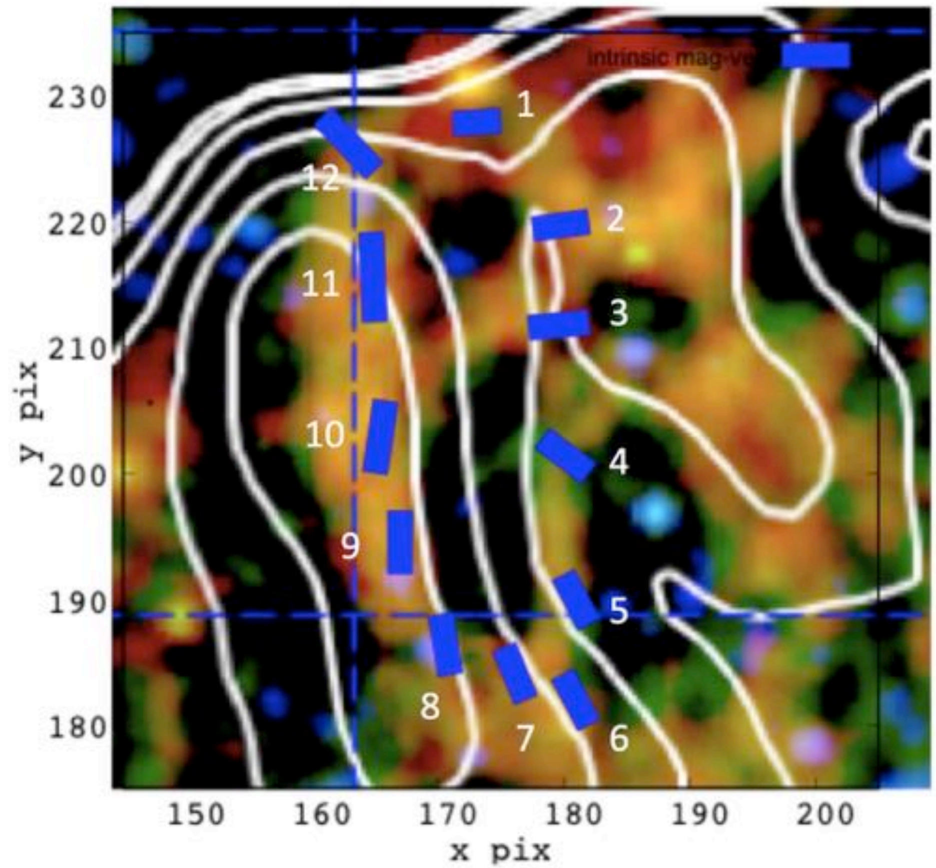
❖ "Manatee" Nebula W50



Stokes I
Stokes QU
RM (Φ)
Hα EM
pulsar DM



Farnes, TA+ (2016) (1604.06552)



X-ray + mangetic field vector
Sakemi et al. (in preparation)

Summary

❖ Diffuse Ionized Gas (DIG) in the Galaxy

- Sophisticated model of thermal electron density (DM, EM, SM)
- ASS/BSS disk + halo toroidal + vertical field (DM, EM, RM)
- Magnetic turbulence (EM, RM, I, P)
- Cosmic-ray electrons (I, P)

❖ Toward Square Kilometer Array (SKA)

- **High sensitivity, high resolution, wide band, wide field**
- Continuum mapping of star-forming regions & clouds
- High resolution imaging of Jet terminal region (shocks, lobes)