Magnetic Fields in the Multiphase Interstellar Medium

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Outline

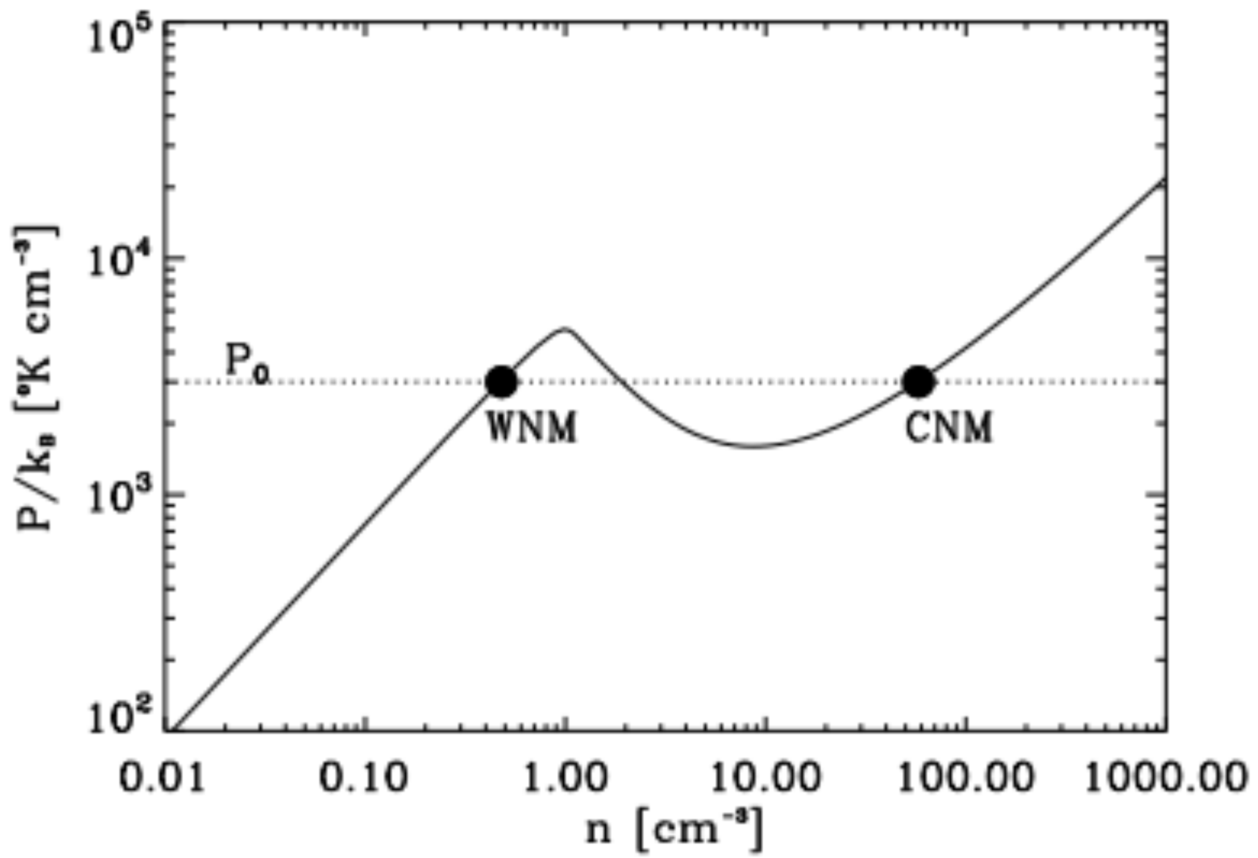
- **Introduction: ISM Phases and Measuring Their Magnetic Fields**
- **Faraday Rotation of the Five Phases**
- **Zeeman Splitting and Linear Polarization**
- **Zeeman Splitting in the Neutral Components, Molecular Clouds, and Masers**
- **Linear Polarization in the Neutral Components and Molecular Clouds**

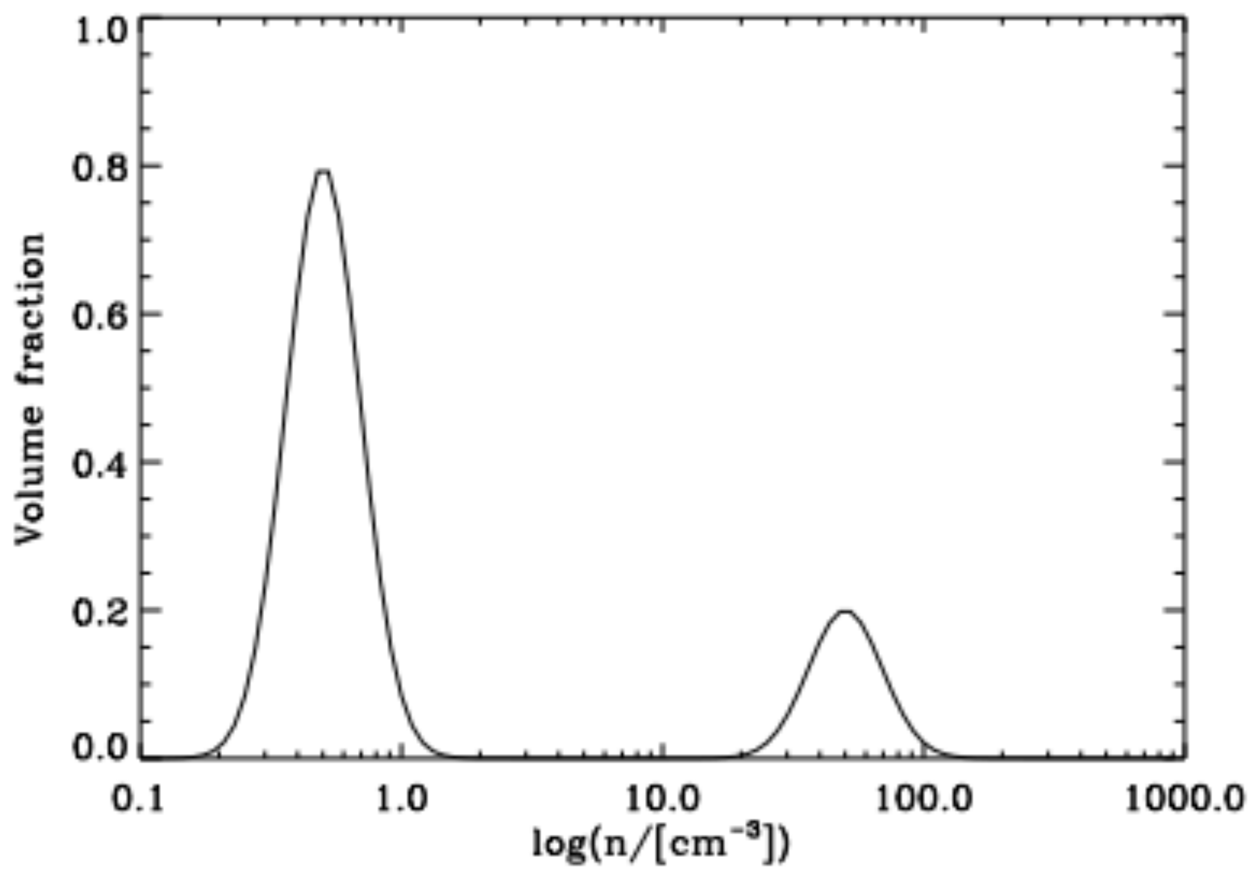
Introduction

phases of ISM

- **self-gravitating: molecular clouds**
- **negligible gravity: diffuse ISM**
- **Neutral Media: Cold (~50K)/Warm (~5000K)**
  not enough electron for Faraday rotation
- **Ionized Media: Warm (~8000K)/Hot (~10^6K)**
  prominent in Faraday Rotation; Zeeman splitting only WIM; no significant alignment due to high T and high n_{e-}
- **Warm Partially Ionized Medium: T<WIM, χ_e~1/2, small n_e and N_e so no Hα, but enough N_e for rotation.**

phases of ISM



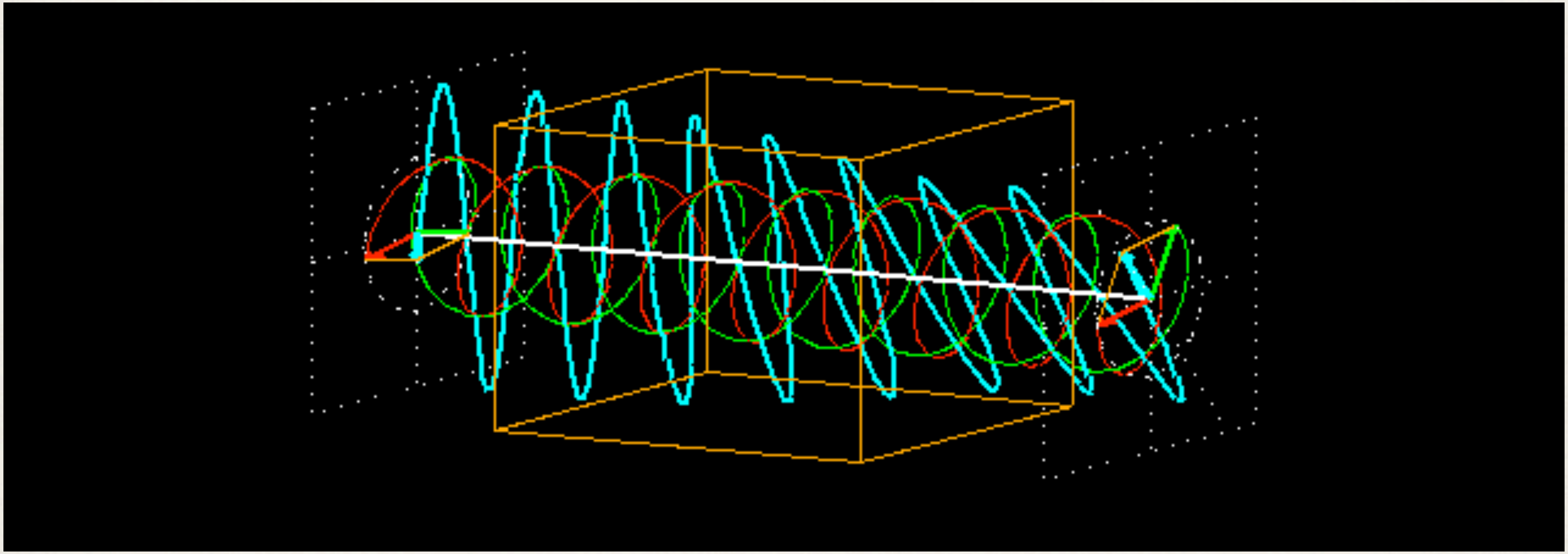


Vazquez-Semadeni (2009)

5 diffuse phases

Property	CNM	WNM	WIM	WPIM[a]	HIM
$\frac{P_{\mathrm{th}}}{k}$ (cm^{-3} K)	4000	4000	4000	2000	10000
T (K)	50	6000	8000	7000	1.5×10^6
n_{Hn} (cm^{-3})	80	0.7	0.25	0.2	0.0034
$\frac{n_e}{n_{\mathrm{Hn}}}$	2×10^{-4}	1×10^{-3}	1	$\frac{1}{2}$	1
$N_{\mathrm{typ,Hn},20}$	0.5	1	0.08	0.06	0.01
$N_{\mathrm{typ},e,20}$	1×10^{-4}	1×10^{-3}	0.08	0.03	0.01
$N_{\perp,\mathrm{Hn},20}$	1.5	1.5	1.0	?	0.1
$N_{\perp,e,20}$	3×10^{-4}	1.5×10^{-3}	1.0	?	0.1

Faraday rotation



Faraday rotation

- **A linearly-polarized wave polarized in the x-direction,**

$$A\cos(\omega t)\hat{x}$$

can be decomposed into a sum of left- and right-circularly polarized waves at the same frequency:

$$A_{\text{left}} = \frac{A}{2}\cos(\omega t)\hat{x} + \frac{A}{2}\sin(\omega t)\hat{y}$$

$$A_{\text{right}} = \frac{A}{2}\cos(\omega t)\hat{x} - \frac{A}{2}\sin(\omega t)\hat{y}$$

Faraday rotation

- **These left and right circularly-polarized components travel at different speeds through a plasma rendered anisotropic due to a magnetic field.**

$$v_{R,L} = \frac{c}{\epsilon_{R,L}}$$ **where** $$\epsilon_{R,L} = 1 - \frac{\omega_p^2}{\omega(\omega \pm \omega_B)}$$ **are the effective dielectric constants for the two circular polarizations,**

ω_p **is the plasma frequency, and**

$$\omega_B = \frac{eB}{m_e} = 1.76 \times 10^{11}\mathrm{radians/s}\left(\frac{B}{\mathrm{Tesla}}\right)$$

is the cyclotron frequency.

Faraday rotation

- **Upon exiting the plasma, the left- and right-circular polarization modes have picked up a net phase difference, say 2ϕ , which we can split evenly between the two modes,**

$$A_{\text{left}} = \frac{A}{2}\cos(\omega t + \phi)\hat{x} + \frac{A}{2}\sin(\omega t + \phi)\hat{y}$$

$$A_{\text{right}} = \frac{A}{2}\cos(\omega t - \phi)\hat{x} - \frac{A}{2}\sin(\omega t - \phi)\hat{y}$$

- **So that the net electric field,** $A_{\text{left}} + A_{\text{right}} =$

$$\frac{A}{2}[\cos(\omega t + \phi) + \cos(\omega t - \phi)]\hat{x} + \frac{A}{2}[\sin(\omega t + \phi) - \frac{A}{2}\sin(\omega t - \phi)]\hat{y}$$

$$= A\cos(\omega t)\cos\phi\hat{x} + A\cos(\omega t)\sin\phi\hat{y} = A\cos(\omega t)[\cos\phi\hat{x} + \sin\phi\hat{y}]$$

, which is linearly-polarized in the direction $\cos\phi\hat{x} + \sin\phi\hat{y}$

- **Thus a magnetized plasma rotates the plane of polarization of a linearly-polarized electromagnetic wave.**

5 diffuse phases

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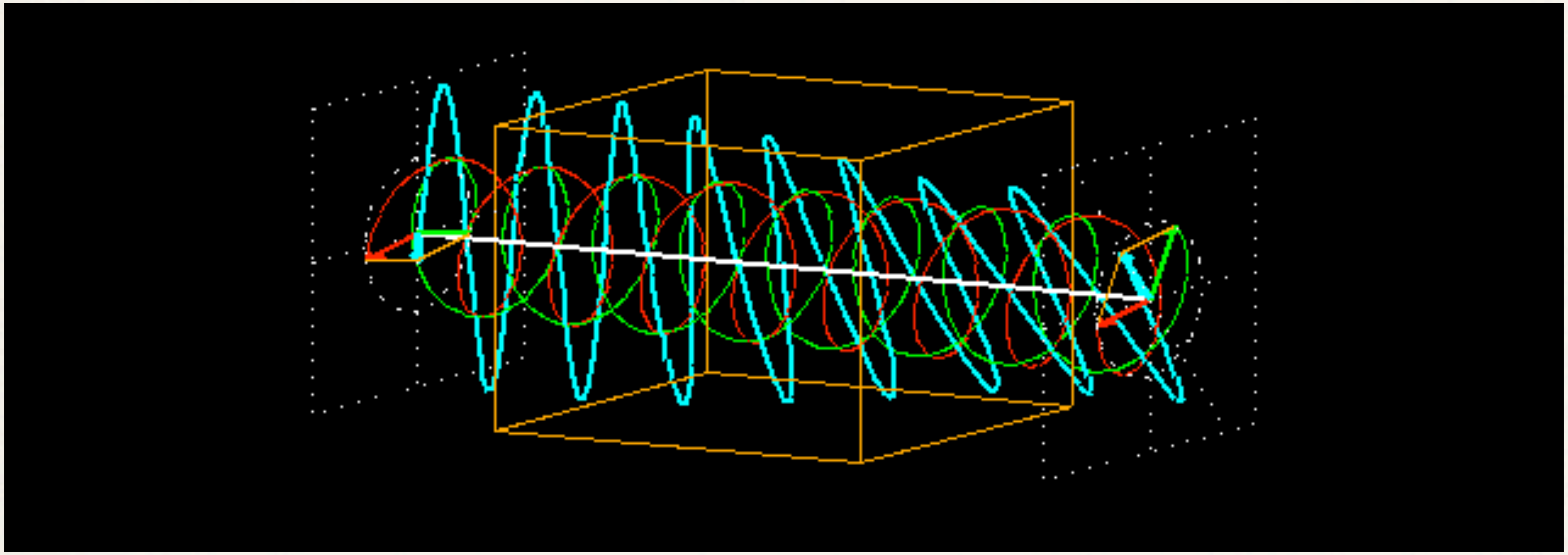
$$RM = 26 n_e B_{||} L_{20} = 26 N_{e,20} B_{||}$$

Faraday rotation



$$\beta = \mathrm{RM}\lambda^2$$

$$\mathrm{RM} = \frac{e^3}{2\pi m^2 c^4} \int_0^d n_e(s) B_{||}(s)\, \mathrm{d}s$$

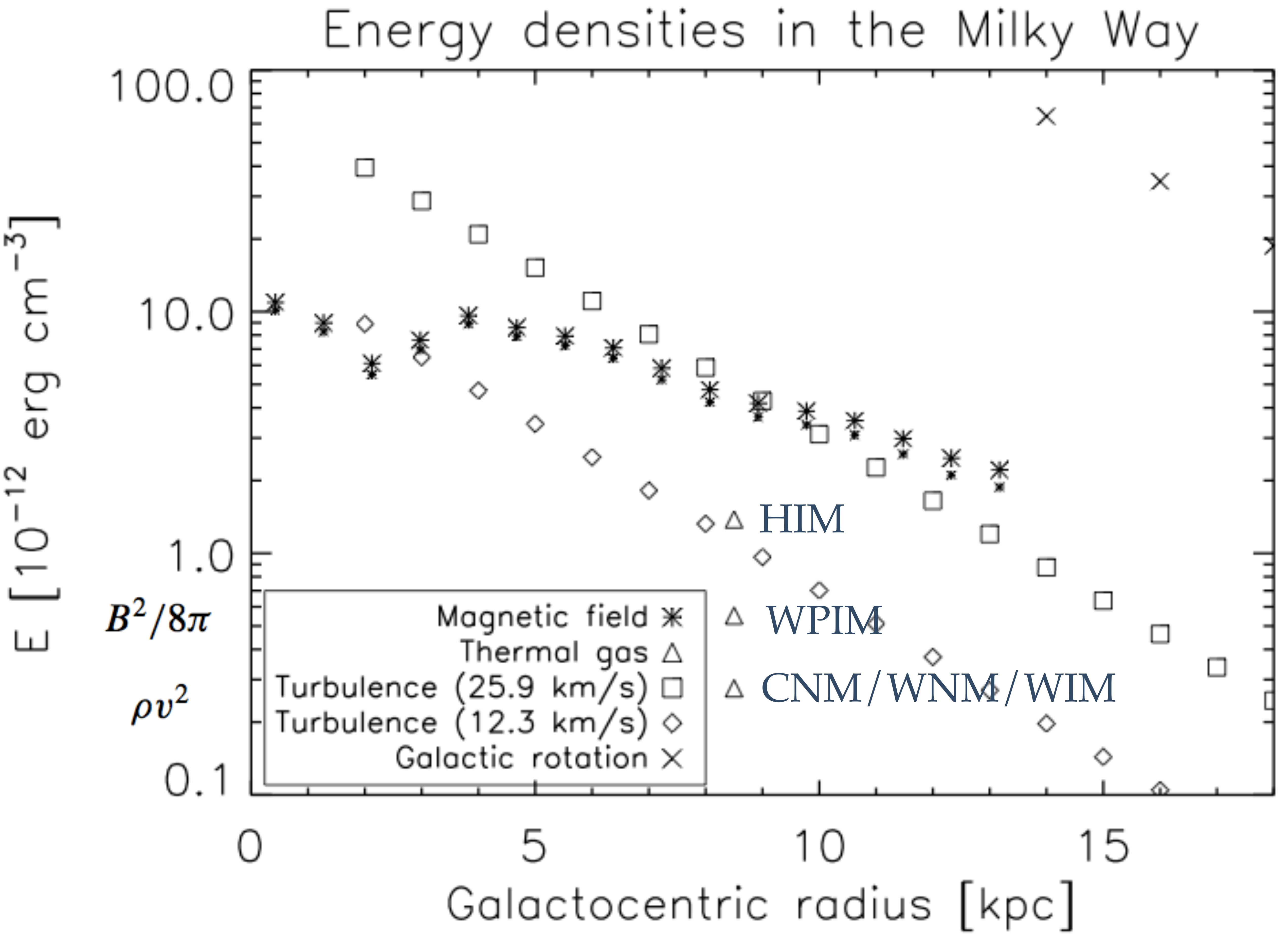
- **The integral is taken over the entire path from the source to the observer.**

Approximate Pressure Equality Between the Gas Phases

- **with no turbulence, the mechanism of thermal instability produces well-defined phases: thought as quasi-static morphologies**
- **PDF of volume density shows well-defined peaks**
- **turbulence is in fact induced by supernovae, spiral density waves...**
- **based on a phenomenological understanding of these processes, the PDF of ionization fraction should be bimodal**
- **Can turbulence change the bimodal PDF of ionization fraction to a smoother PDF, as it does with gas density?**

Vazquez-Semadeni (2009)

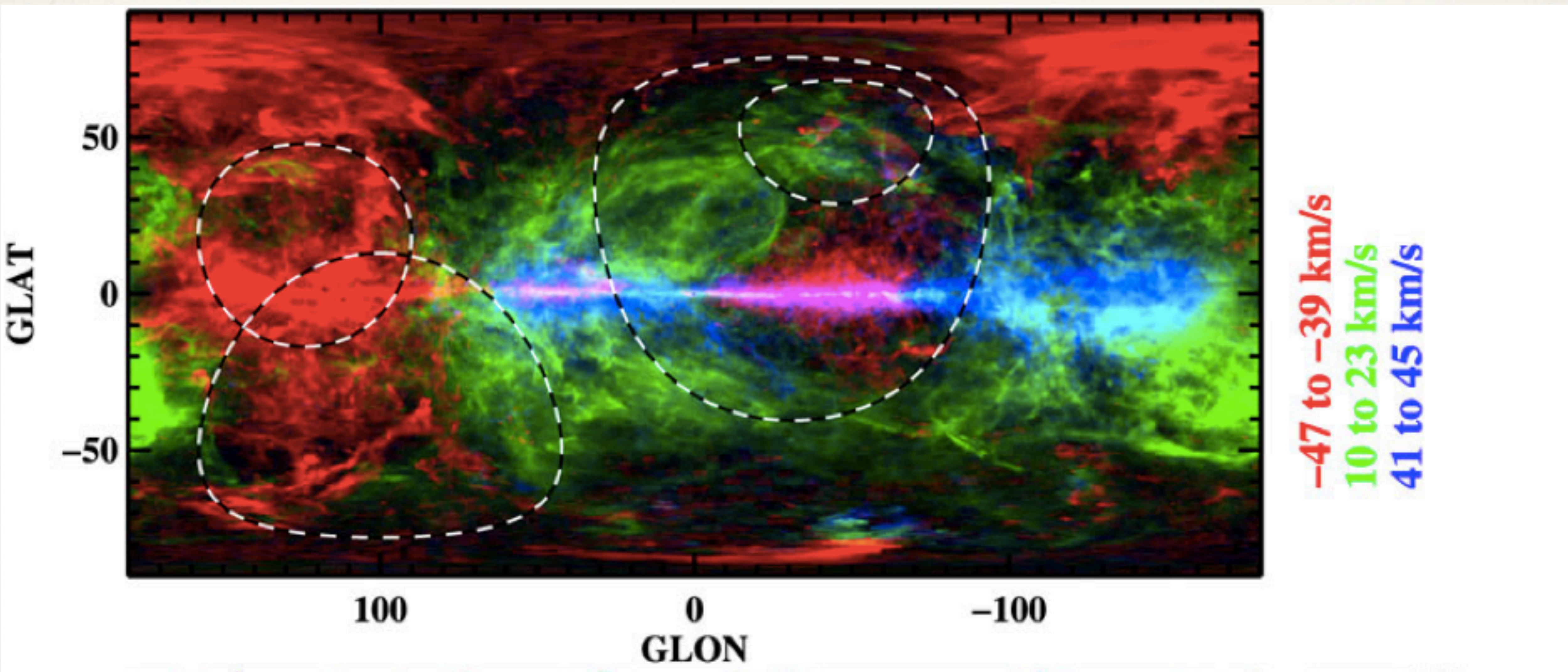
Approximate Equipartition Between ISM Components



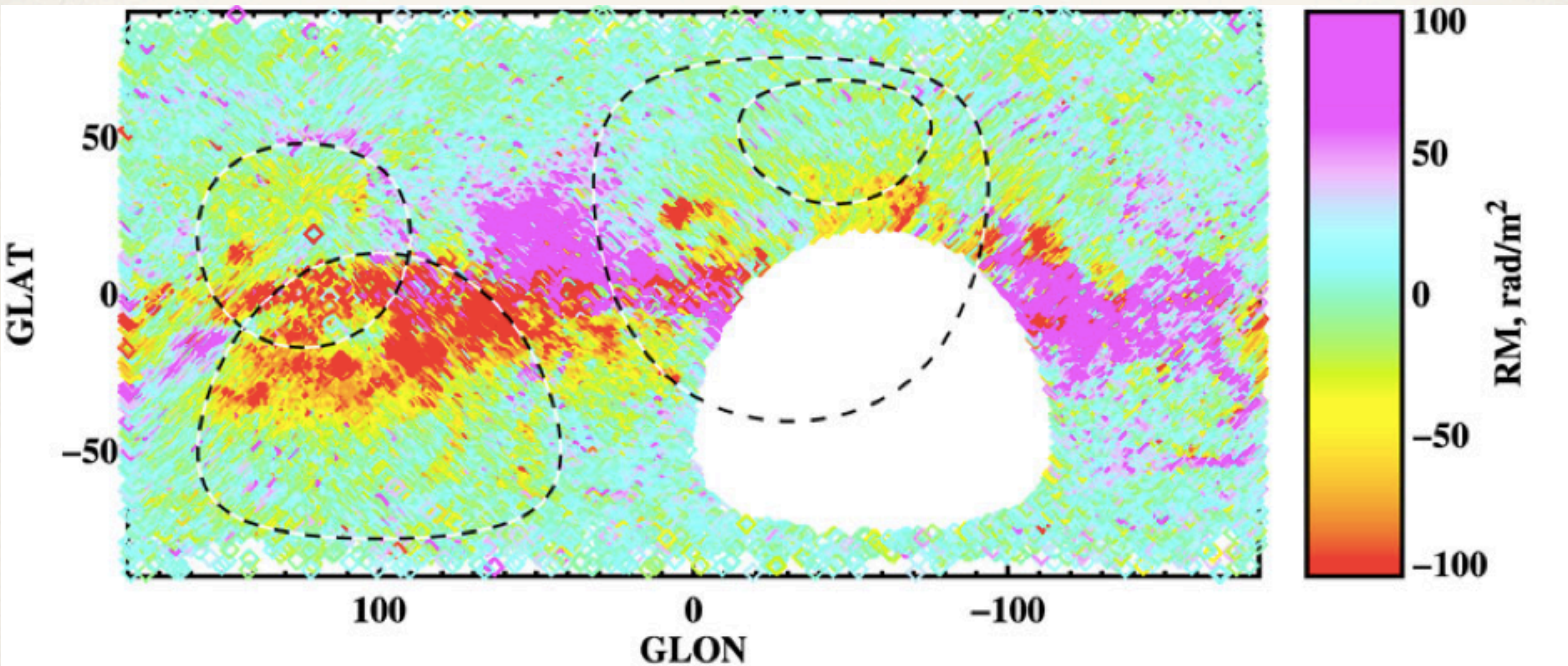
on large scale

Let's Look at Some Data

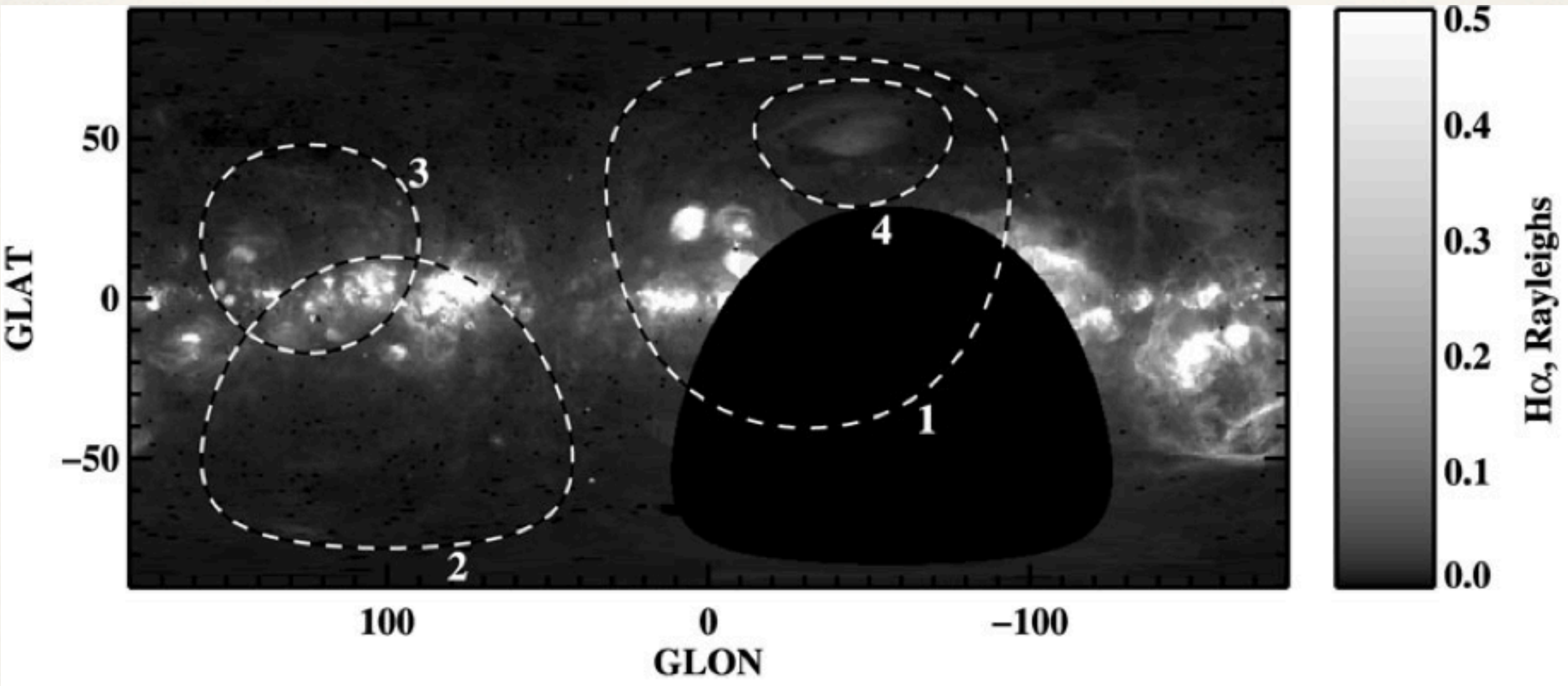
CNM/WNM: 21cm line



Rotation Measure



WIM: Hα (HIM traced in high energy superbubbles)



Why these correspondence?

- **influence of individual interstellar structures on the observed RMs**
- **association of RMs and HI filaments is strange: HI is usually too neutral to produce significant RMs**
- **Some of these associations are a distinct change in RM across an HI filament**
- **HI may be a shock-produced edge of an HIM region**
- **presence of partially ionized HI or very weak Hα emission associated with the HI structures: the WPIM**

Why these correspondence?

- **influence of individual interstellar structures on the observed RMs**
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- **Som… an HI fila…**

RMs may be best way to probe WPIM!

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