

Magnetic fields in the multiphase ISM

Amit Seta

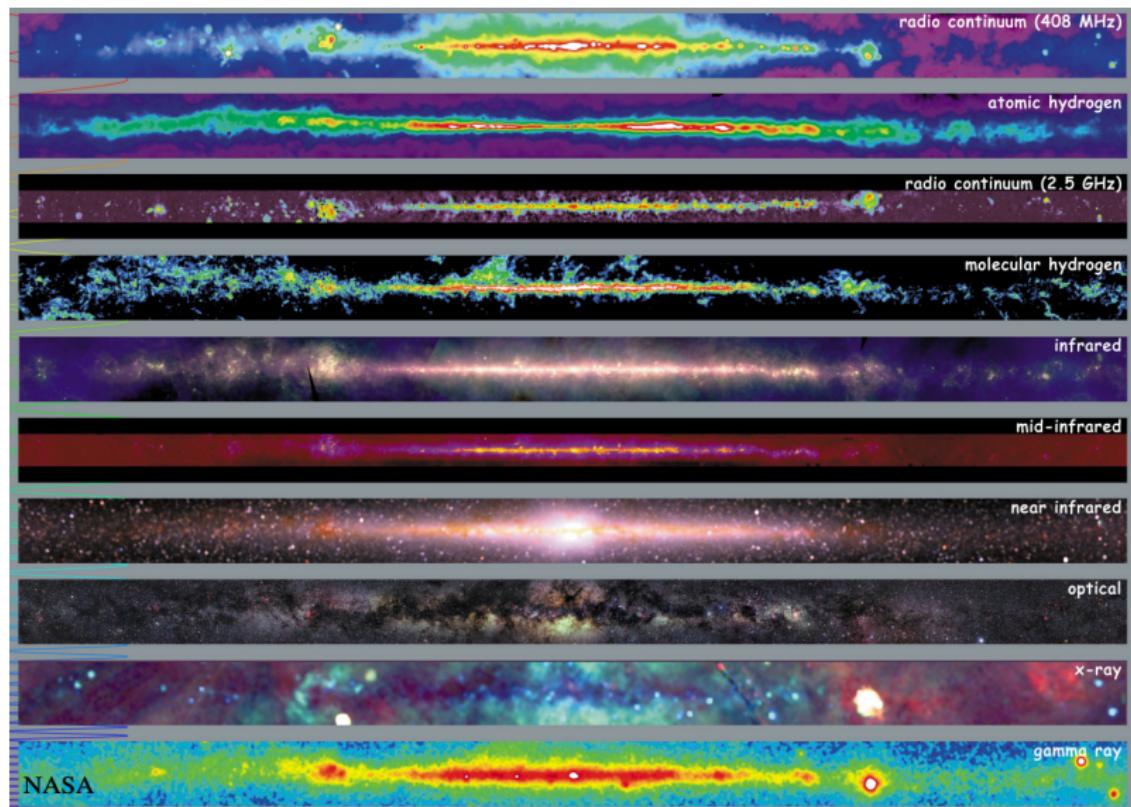
Research School of Astronomy and Astrophysics
Australian National University

6th Oct 2022

amit.seta@anu.edu.au

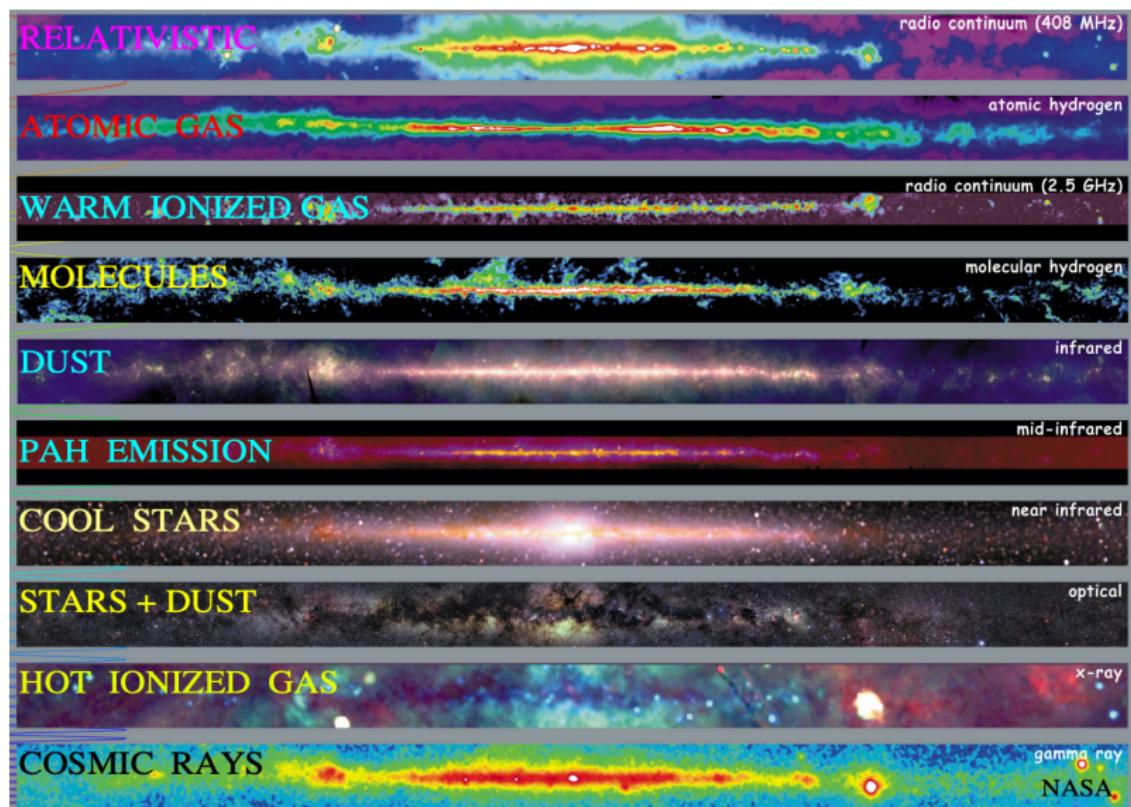
Astrophysical Gas Dynamics
ASTR4012 / ASTR8002

The Multiwavelength Milky Way

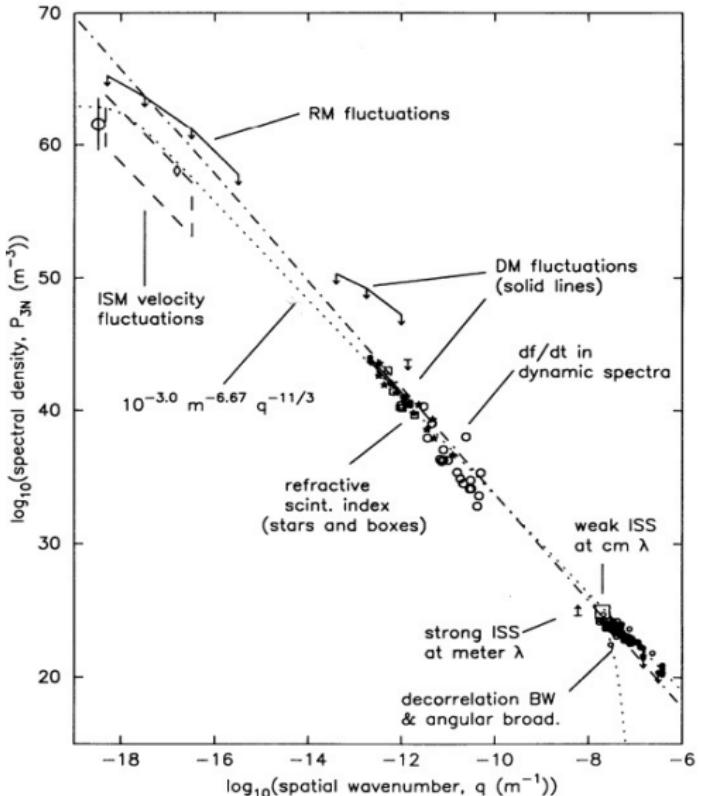


NASA

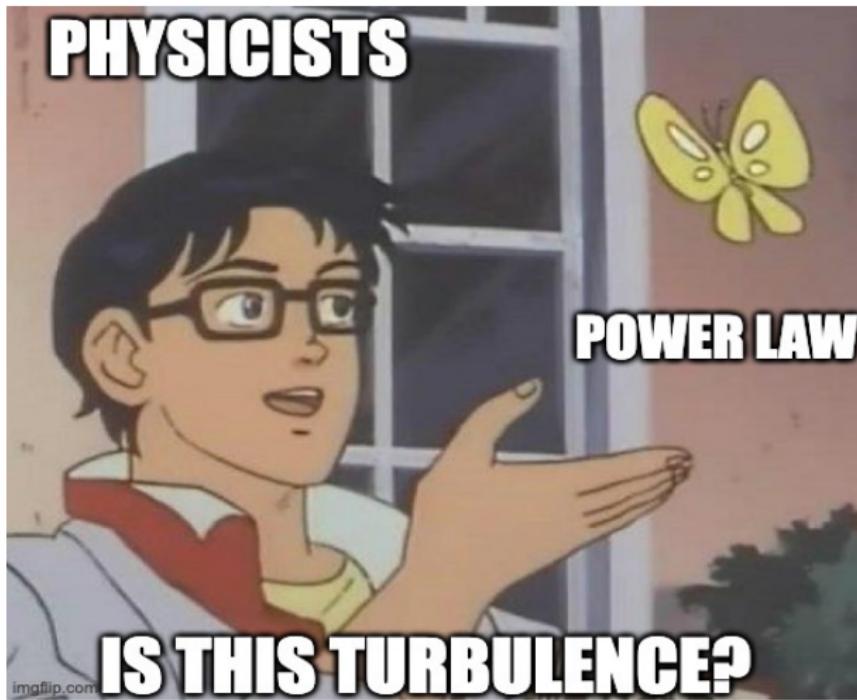
The Multiwavelength Milky Way: probes



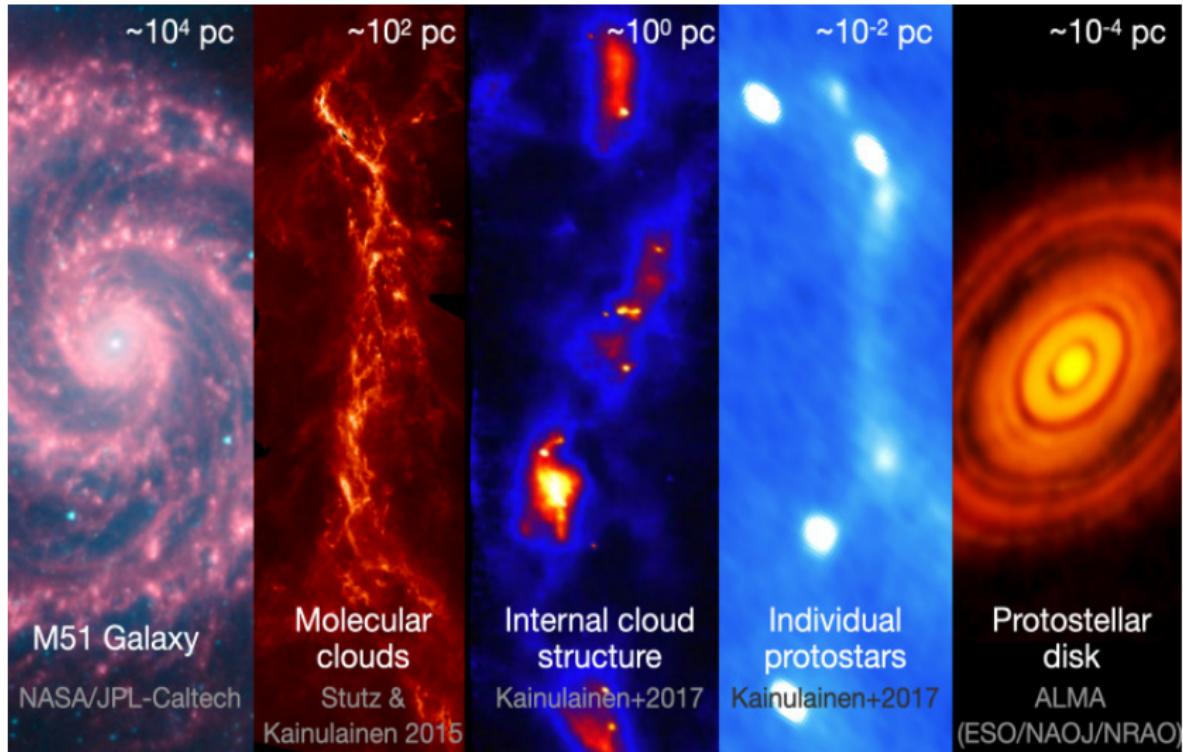
ISM turbulence



(Armstrong et al 1995)



Star formation: multiple scales

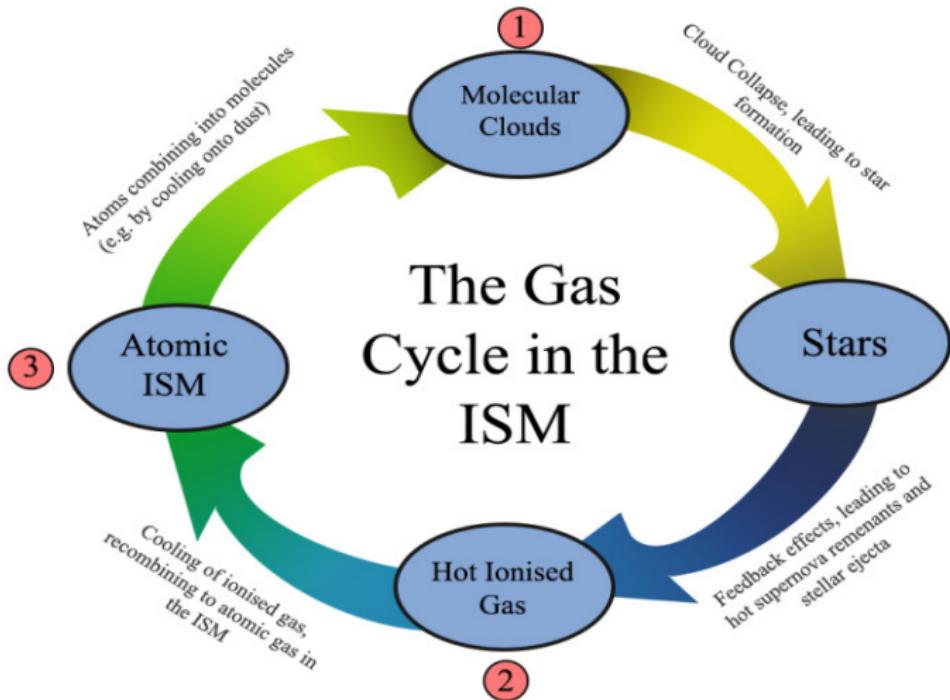


Star formation structures: M74



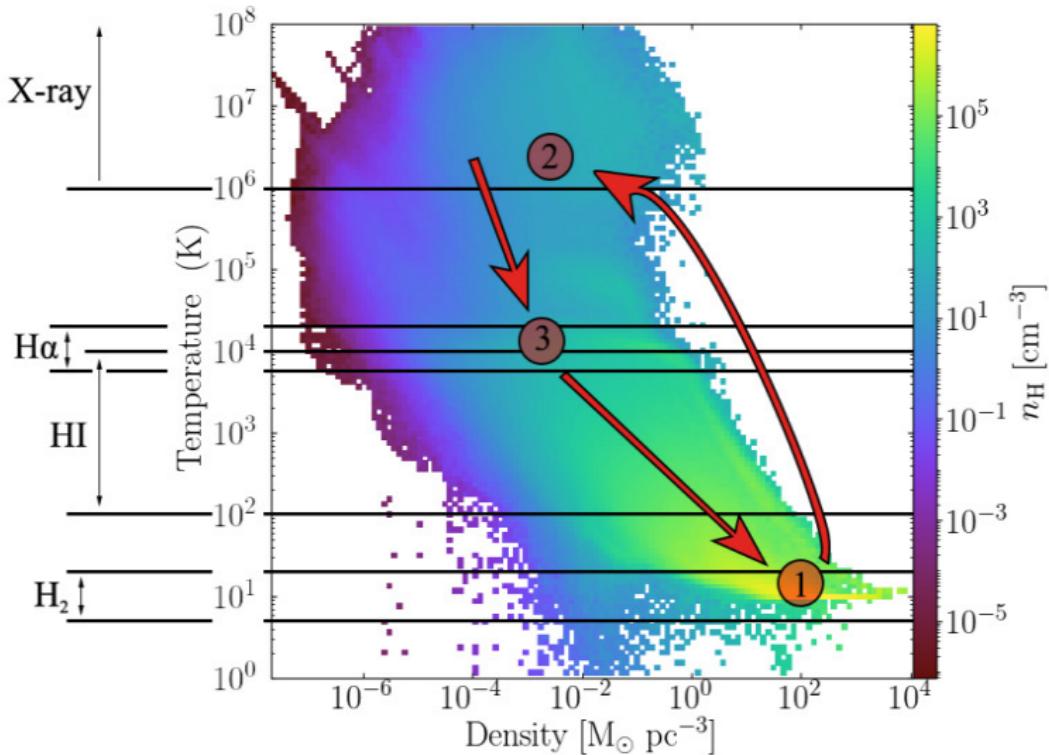
(NASA: HST + JWST)

Gas cycle



(Ejdetjarn 2019)

Phase space



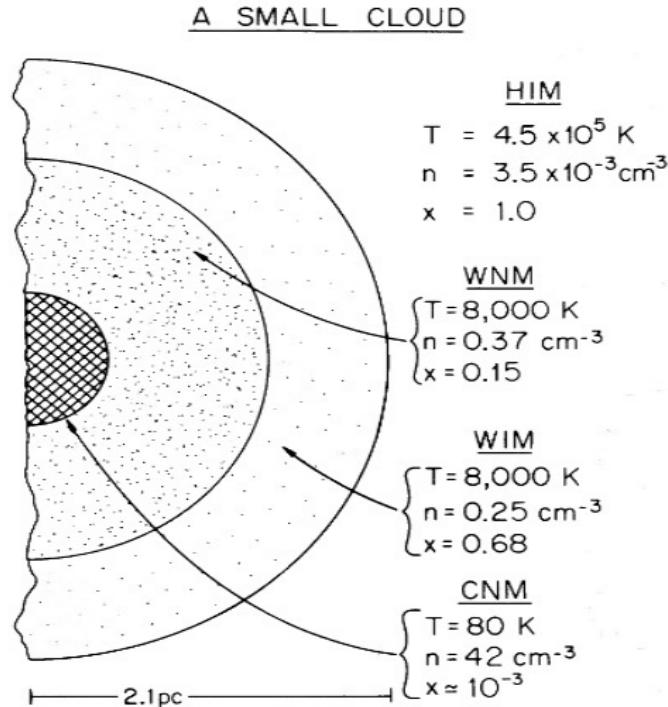
Range of densities and temperature!

(Ejdetjarn 2019)

ISM phases

Two phase ISM: Field, Goldsmith, & Habing 1969

Three phase ISM: McKee & Ostriker 1977

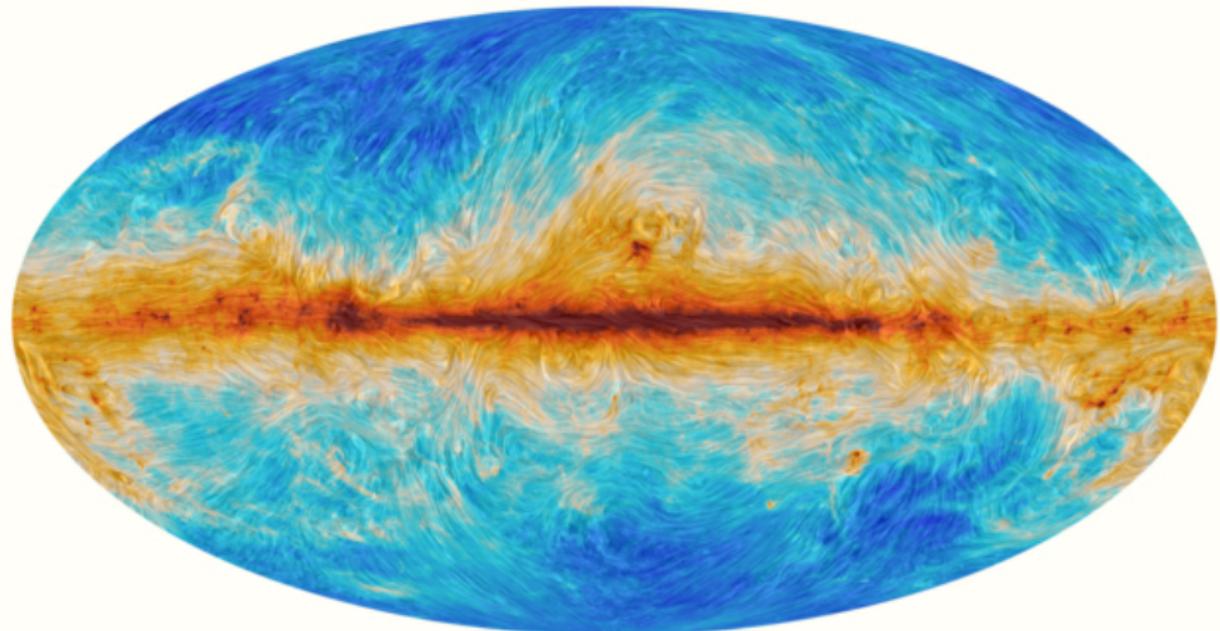


Properties of ISM phases

Properties	Hot	Warm	Cold
Temp., T (K)	10^6	10^4	10^2
No. density, n_0 (cm^{-3})	10^{-3}	10^1	10
Filling fraction, ff ,	$0.6 - 0.8$	$0.2 - 0.4$	< 0.02
Sound speed, c_s (km s^{-1})	100	10	1
Turbulent speed, v_0 (km s^{-1})	30	10	3
Mach no. $\mathcal{M} = v_0/c_s$	0.3	1	3
Typical turbulent scale, l_0 (pc)	100	30	10

(Adapted and modified from Ferrière 2020)

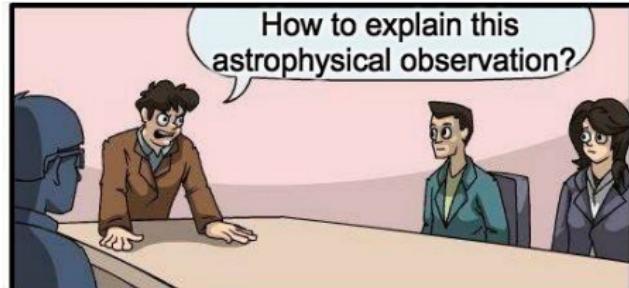
Milky Way Magnetic Fields from Planck



(ESA and the Planck Collaboration)

Mag. energy density \sim turbulent kin. energy density \sim thermal energy density \sim cosmic ray energy density... then also...

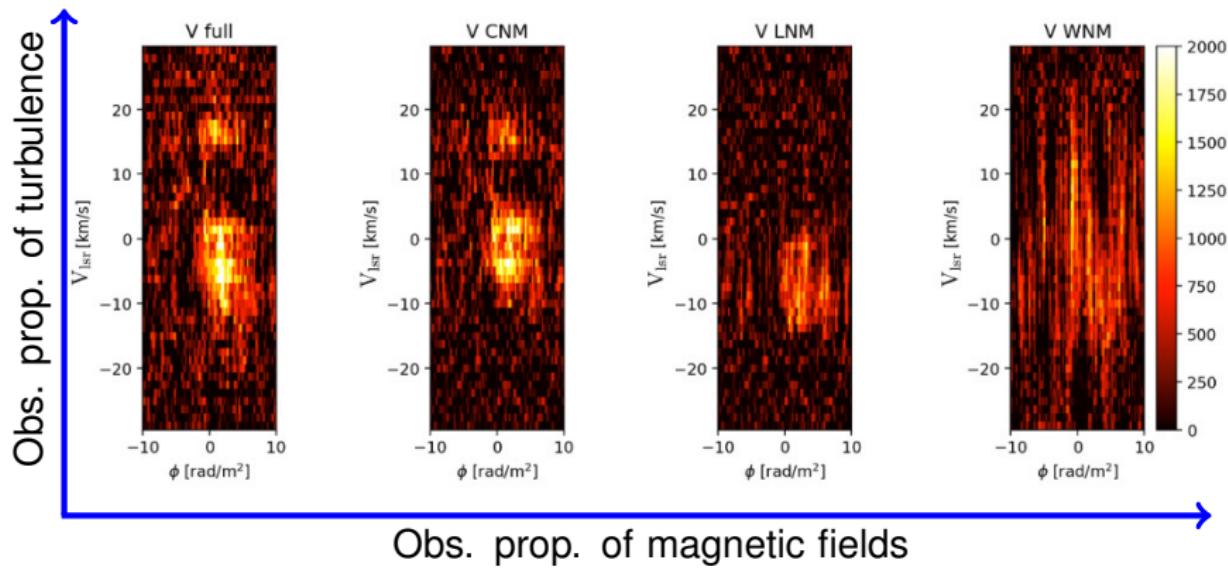
Meme time II



Magnetic fields in the multiphase ISM: Milky Way

Field 3C196: LOFAR and Effelsberg-Bonn HI Survey data

Radio (HI) data → phases

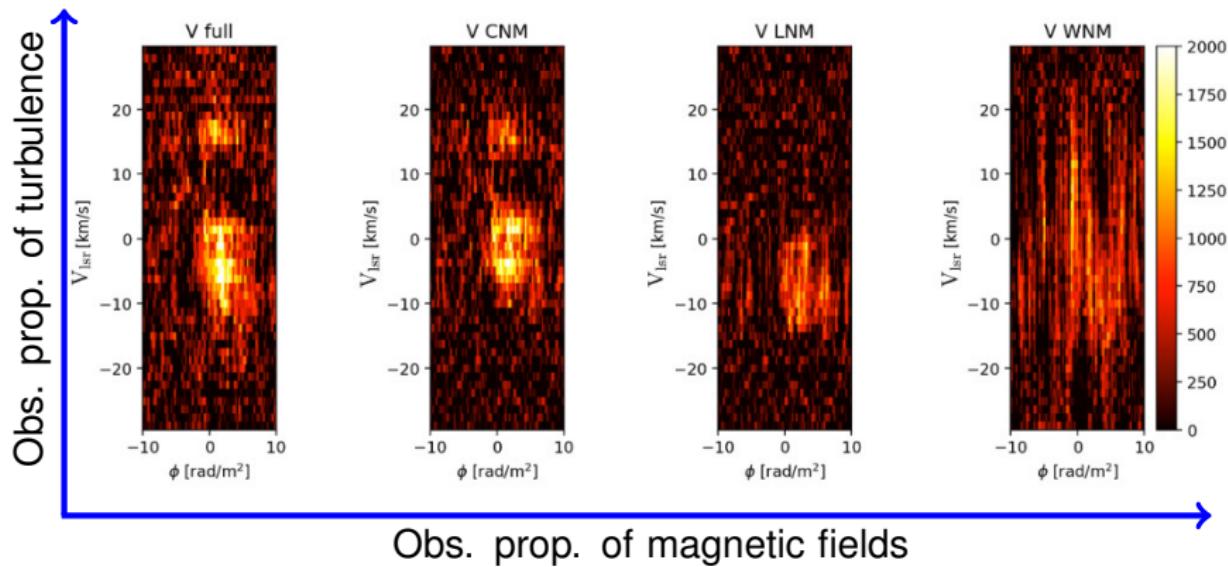


(Bracco et al., 2020)

Magnetic fields in the multiphase ISM: Milky Way

Field 3C196: LOFAR and Effelsberg-Bonn HI Survey data

Radio (HI) data → phases



(Bracco et al., 2020)

Turbulence and magnetic field properties differ with the ISM phase!

Magnetic fields in the multiphase ISM: M51

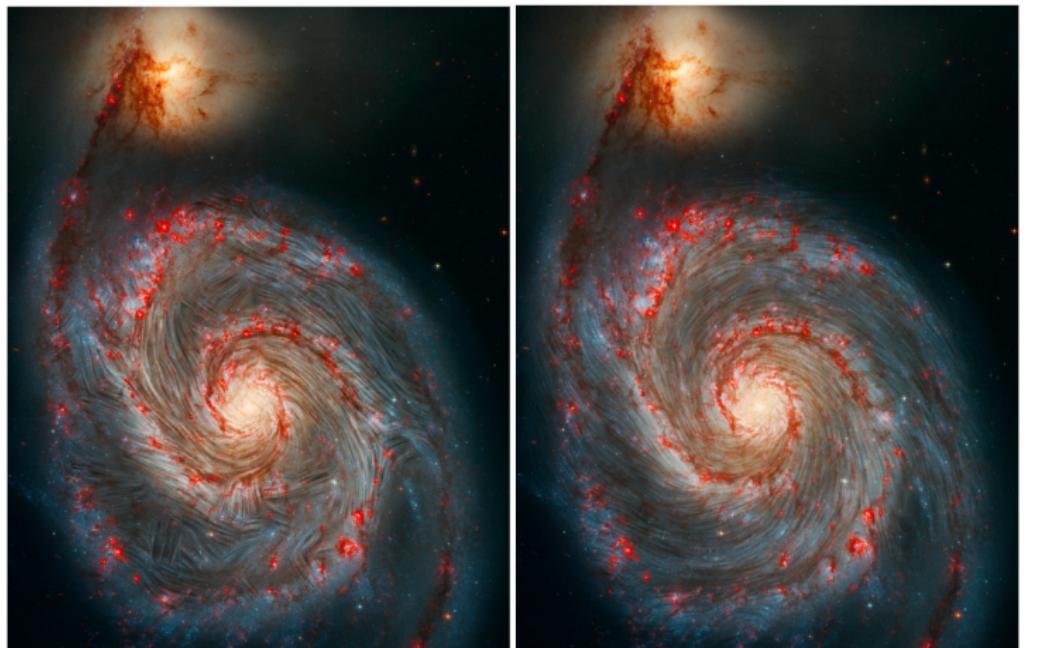


FIR (cold, dense)

Radio (hot/warm, diffuse)

(Borlaff et al 2021, SOFIA + VLA)

Magnetic fields in the multiphase ISM: M51



FIR (cold, dense)

Radio (hot/warm, diffuse)

(Borlaff et al 2021, SOFIA + VLA)

Magnetic field properties differ with the ISM phase!

Magnetic field, scale-wise!



Large scale (\sim a few kpc)

Magnetic field, scale-wise!



Large scale (\sim a few kpc)



Small scale (\lesssim 100 pc)

Physically!

Induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

Physically!

Induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

→ \mathbf{u} dep. on the ISM phase!

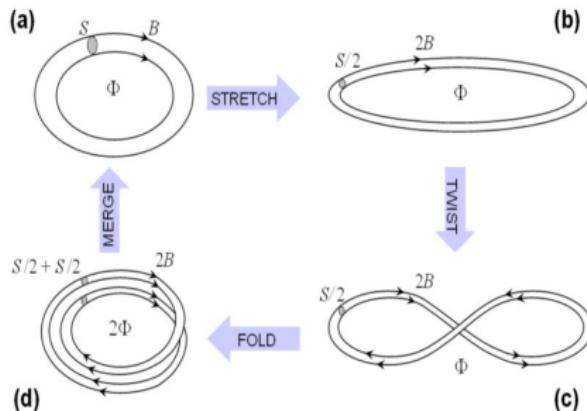
Physically!

Induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

→ \mathbf{u} dep. on the ISM phase!

Turbulent dynamo



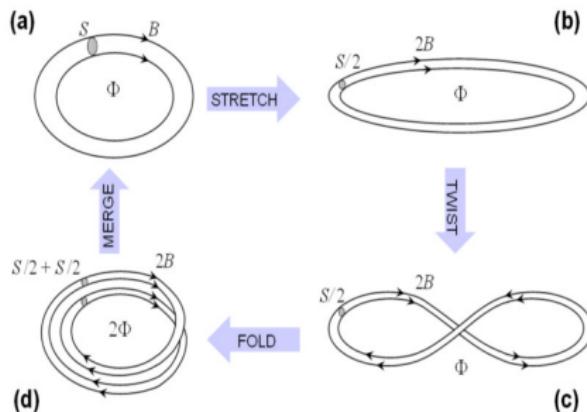
Physically!

Induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

→ \mathbf{u} dep. on the ISM phase!

Turbulent dynamo



Works till field strong, η imp., also for the field structure! (Seta+ 2020, 2021)

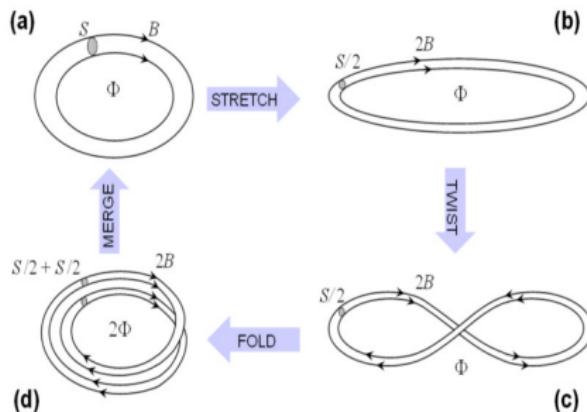
Physically!

Induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

→ \mathbf{u} dep. on the ISM phase!

Turbulent dynamo

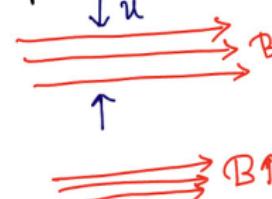


Works till field strong, η imp., also for the field structure! (Seta+ 2020, 2021)

Tangling of large-scale field



Compression due to shocks



(App. A in Seta et al 2018)

Simulations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \quad (1)$$

$$\begin{aligned} \frac{\partial(\rho \mathbf{u})}{\partial t} + \nabla \cdot \left(\rho \mathbf{u} \otimes \mathbf{u} - \frac{1}{4\pi} \mathbf{b} \otimes \mathbf{b} \right) + \nabla p_{\text{tot}} = \\ \nabla \cdot (2\nu\rho\tau) + \rho \mathbf{F}_{\text{dri}}, \end{aligned} \quad (2)$$

$$\frac{\partial \mathbf{b}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{b}) + \eta \nabla^2 \mathbf{b}, \quad \nabla \cdot \mathbf{b} = 0, \quad (3)$$

$$\begin{aligned} \frac{\partial e_{\text{tot}}}{\partial t} + \nabla \cdot \left((e_{\text{tot}} + p_{\text{tot}}) \mathbf{u} - \frac{1}{4\pi} (\mathbf{b} \cdot \mathbf{u}) \mathbf{b} \right) = \\ \rho \mathbf{u} \cdot \mathbf{F}_{\text{dri}} + n_{\text{H}} \Gamma - n_{\text{H}}^2 \Lambda(T) + 2\rho\nu|\tau|^2 + \frac{\eta}{4\pi} (\nabla \times \mathbf{b})^2, \end{aligned} \quad (4)$$

Ideal monoatomic gas ($\gamma_g = 5/3$), FLASH code, Riemann solver (Waagan et al 2011), uniform grid, periodic box, 512^3 grid points.

(Seta & Federrath 2022)

Parameters and Initial conditions

Various processes heat and cool the ISM (Sutherland & Dopita 1993)

$$\Gamma = 2 \times 10^{-26} \text{ erg s}^{-1}, \quad (5)$$

$$\frac{\Lambda(T)}{\Gamma} = \left[10^7 \exp\left(\frac{-1.184 \times 10^5}{T + 1000}\right) + 1.4 \times 10^{-2} T^{1/2} \exp\left(\frac{-92}{T}\right) \right] \text{ cm}^3, \quad (6)$$

(Koyama & Inutsuka 2000, 2002; Vazquez-Semadeni et al 2007)

Parameters and Initial conditions

Various processes heat and cool the ISM (Sutherland & Dopita 1993)

$$\Gamma = 2 \times 10^{-26} \text{ erg s}^{-1}, \quad (5)$$

$$\frac{\Lambda(T)}{\Gamma} = \left[10^7 \exp\left(\frac{-1.184 \times 10^5}{T + 1000}\right) + 1.4 \times 10^{-2} T^{1/2} \exp\left(\frac{-92}{T}\right) \right] \text{ cm}^3, \quad (6)$$

(Koyama & Inutsuka 2000, 2002; Vazquez-Semadeni et al 2007)

Driving: Ornstein–Uhlenbeck process, $u_{\text{rms}} = 10 \text{ km s}^{-1}$, $k_{\text{dri}} = 2$,
Sol & Comp

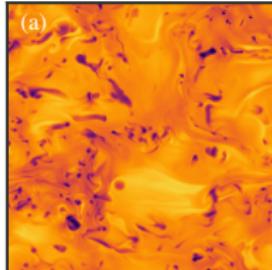
$L = 200 \text{ pc}$, $\rho_0 = 1 \text{ cm}^{-3}$, $T = 5000 \text{ K}$, $l_0 = L/2$, $t_0 = 10 \text{ Myr}$, $\text{Re} = \text{Rm} = 2000$, $b_{0,\text{rms}} = 10^{-10} \text{ G}$ ($k^{3/2}$)

(Seed field strength and configuration shouldn't change the turbulent dynamo properties; Seta & Federrath 2020)



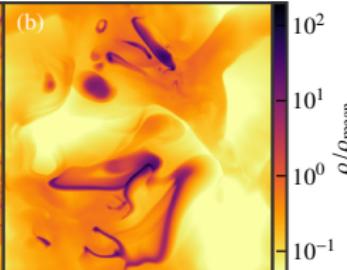
Structures

Sol, sat ($t/t_0 = 100$)

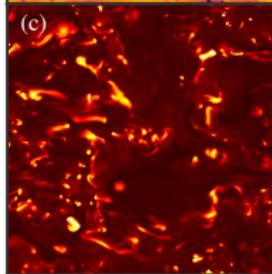


(a)

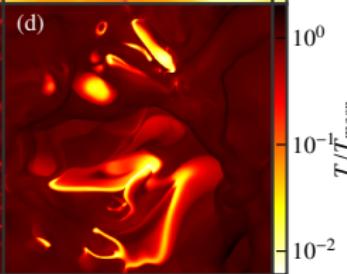
Comp, sat ($t/t_0 = 140$)



(b)

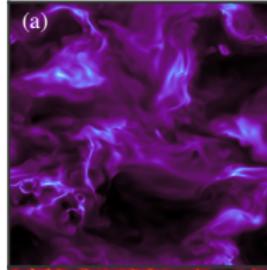


(c)



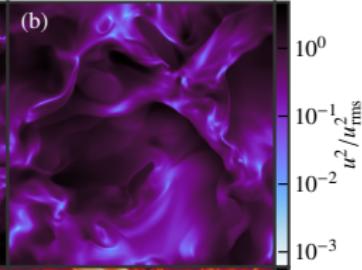
(d)

Sol, sat ($t/t_0 = 100$)

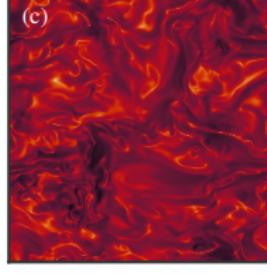


(a)

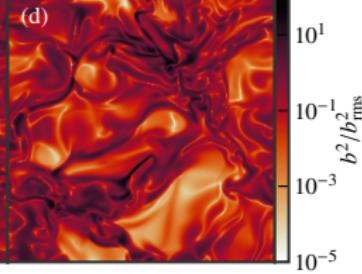
Comp, sat ($t/t_0 = 140$)



(b)



(c)

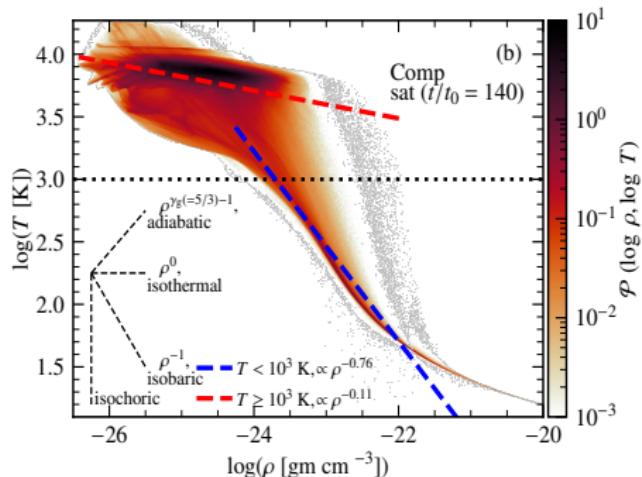
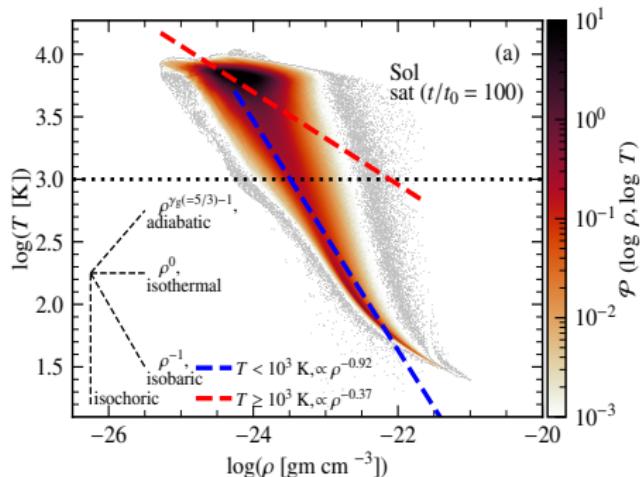


(d)

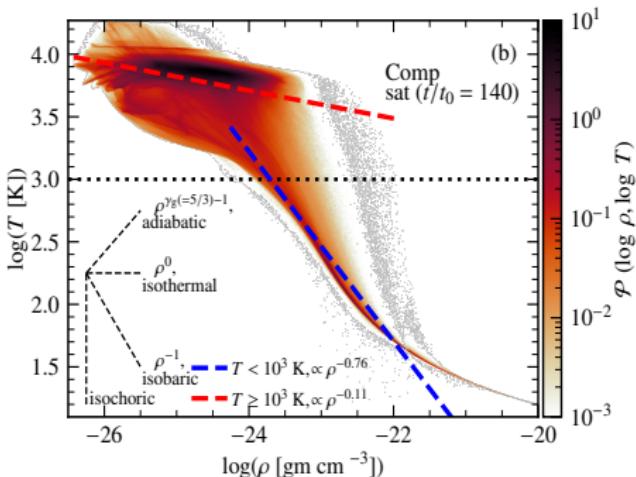
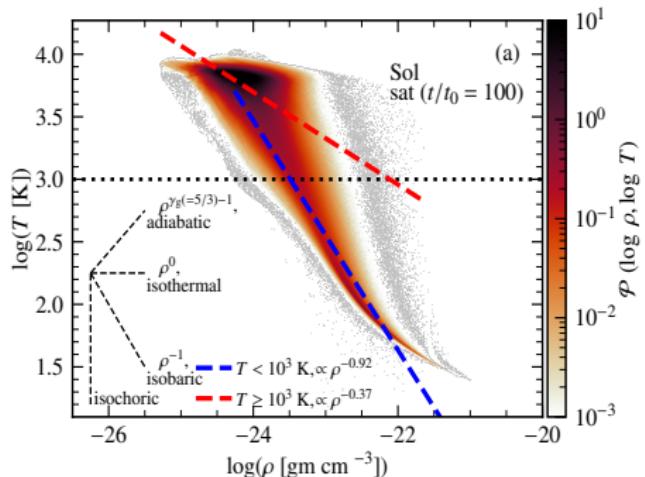
Cold, dense structures in the Sol case are smaller in size but numerous compared to the Comp case.

Magnetic field structures exists at scales smaller and larger than the size of dense structures.

$\rho - T$ 2D PDFs

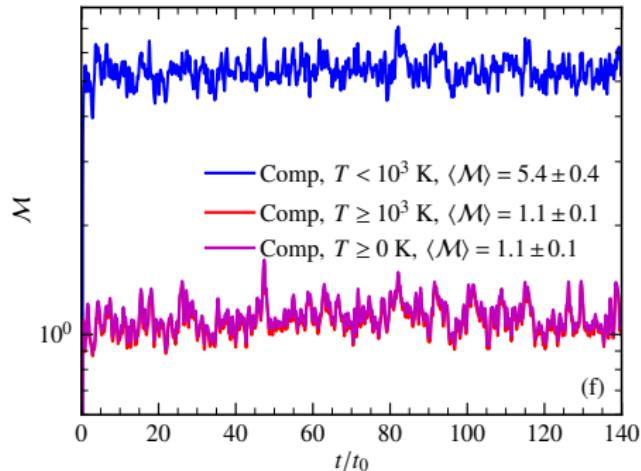
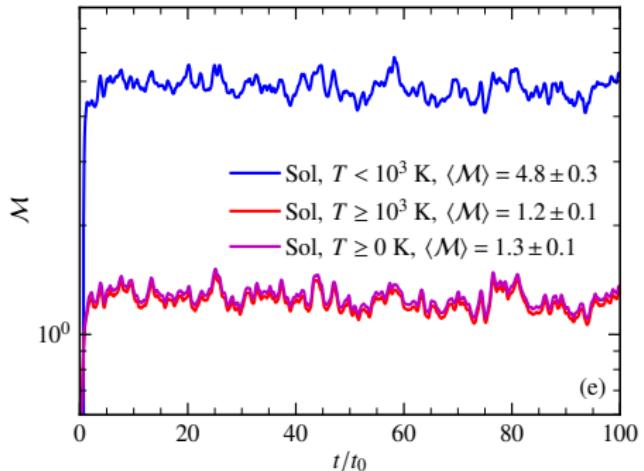


$\rho - T$ 2D PDFs



Only division: warm and cold (no hot gas since no SN explosions).

Complex dependence, roughly isobaric in the cold phase and flattens in the warm phase (broadly agrees with Field et al. 1969, McKee & Ostriker 1977, Cox 2005, Mac Low et al. 2005).

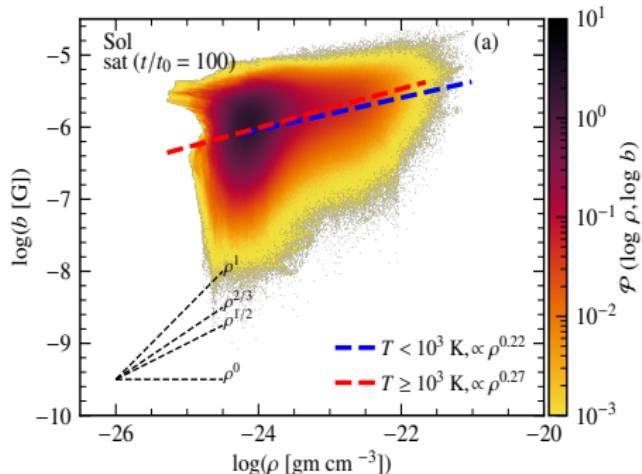


$$\mathcal{M}(\text{cold}) \sim 5, \mathcal{M}(\text{warm}) \sim 1$$

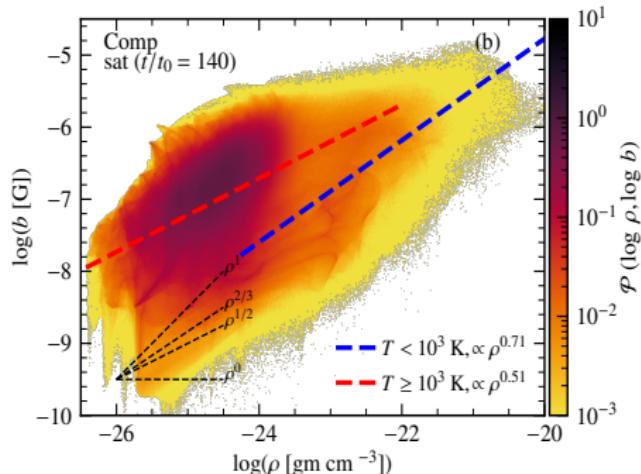
$$\mathcal{F}(\text{cold}) \sim 5\%, \mathcal{F}(\text{warm}) \sim 95\%$$

(Obs.: Gaensler et al. 2011, Schneider et al. 2013, Marchal & Miville-Deschenes 2021)

$\rho - b$ 2D PDFs



Dependence roughly similar in both phases (significant mixing)!

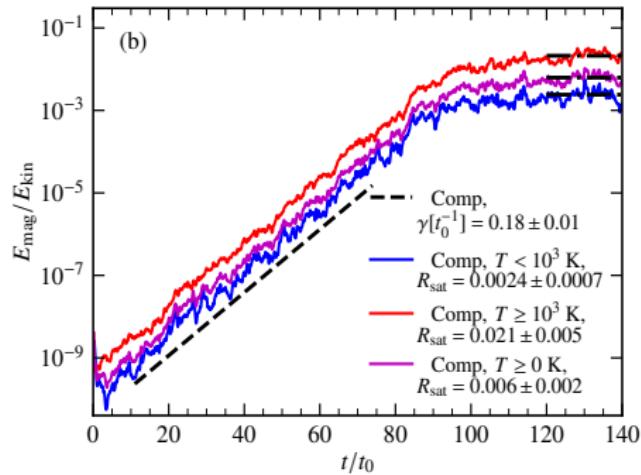
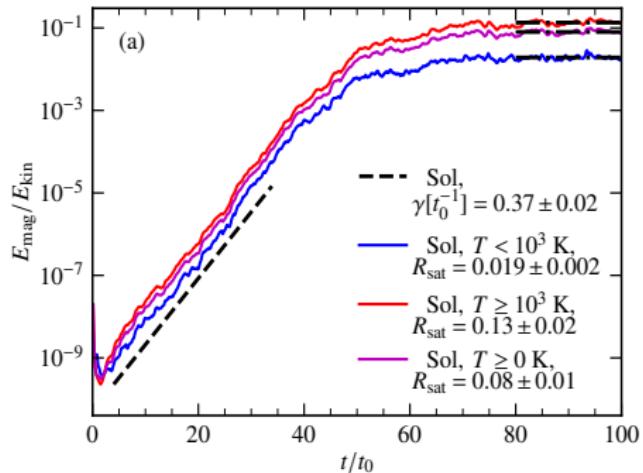


Higher dependence in the cold phase (significant compressions)!

But trends do not fit the data well!

Only density information is insufficient to determine field strength!

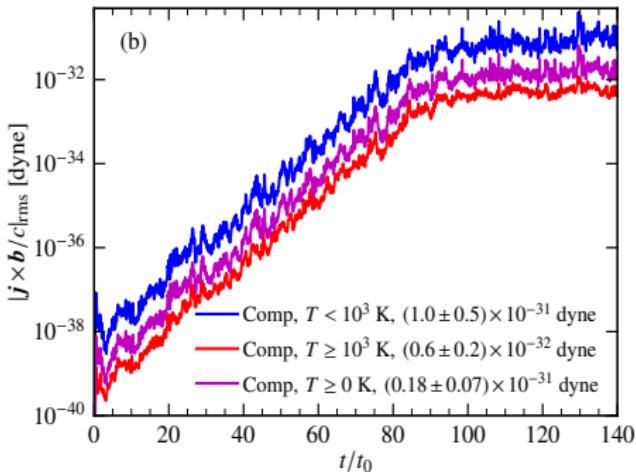
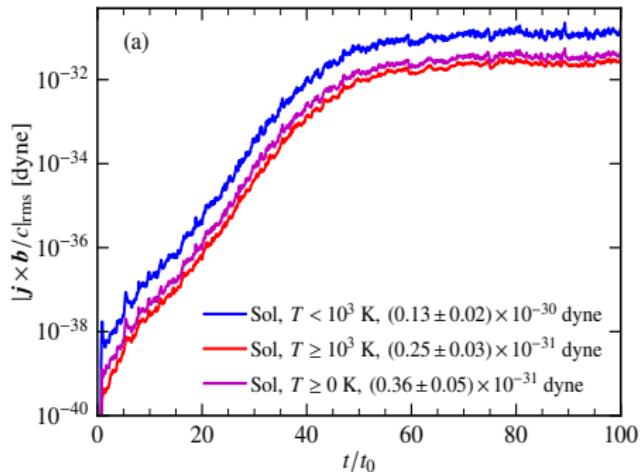
Turbulent dynamo



The growth rate same and the saturation level is lower for the cold phase.

Both differ significantly from isothermal simulations ($\gtrsim 40\%$)

Diff. saturation level → Lorentz force



Lorentz force higher in the $T < 10^3$ K phase!

Magnetic field strength and structure are different!

To sum up...

- ISM is a multiscale and multiphase medium.
- Turbulence and magnetic fields vary with the phase, ongoing research!
- Rich field requires theory, observations, and simulations!

Seta & Federrath 2022, MNRAS (arXiv:2202.08324)

amit.seta@anu.edu.au

 amitseta90