Polarization maps and Zeeman Effect: MHD simulations

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Most of it done with the collaboration of:

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Measuring B in the ISM

B_{LOS}

Faraday rotation

Ionized medium (diffuse ISM)

B ~ few microG

Zeeman effect

denser regions

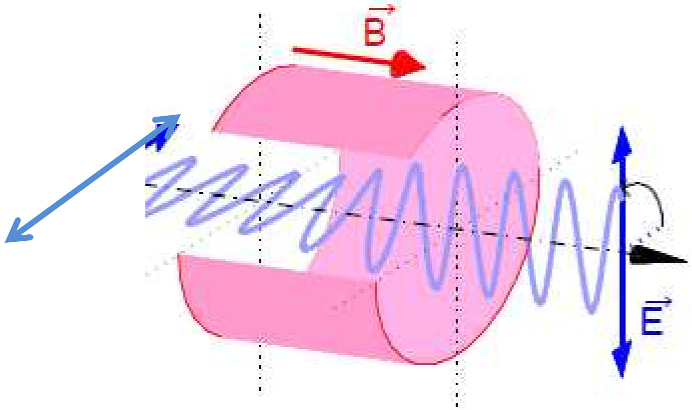
B ~ μG – mG

B_{SKY}

unrotated polarization of dust emission & abs, synchrotron, atomic lines, etc.

Faraday Rotation in the diffuse ISM

- Birefringence in a magnetized ionized plasma



$$\Delta\theta = RM\,\lambda^2$$

$$RM \propto \int n_e\, B_{||}\, ds$$

- multiple wavelength polarization ⟶ B_{los} if $n_e(s)$ is known

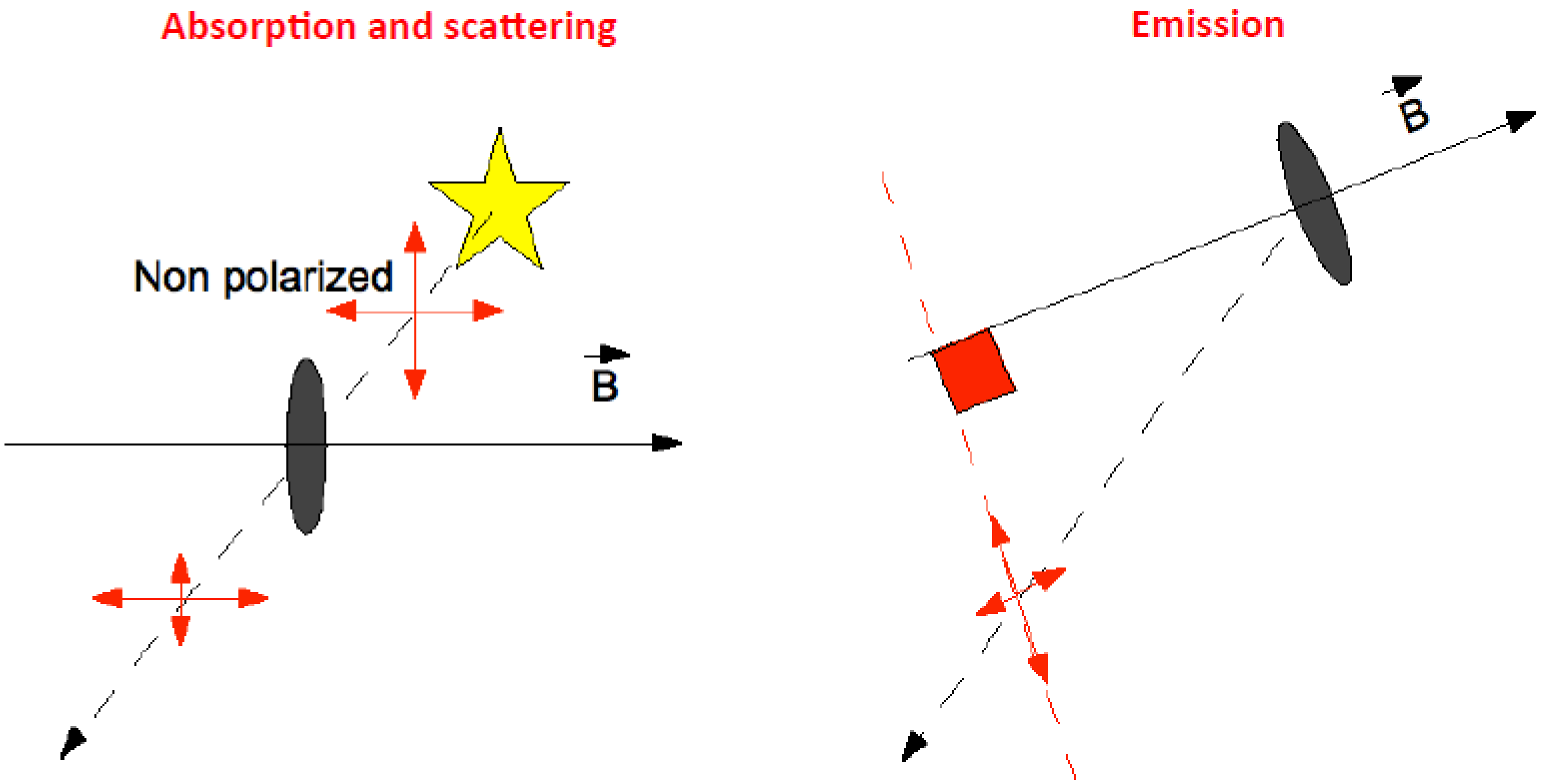
Faraday Rotation in the diffuse ISM

But, I will focus on the denser ISM:

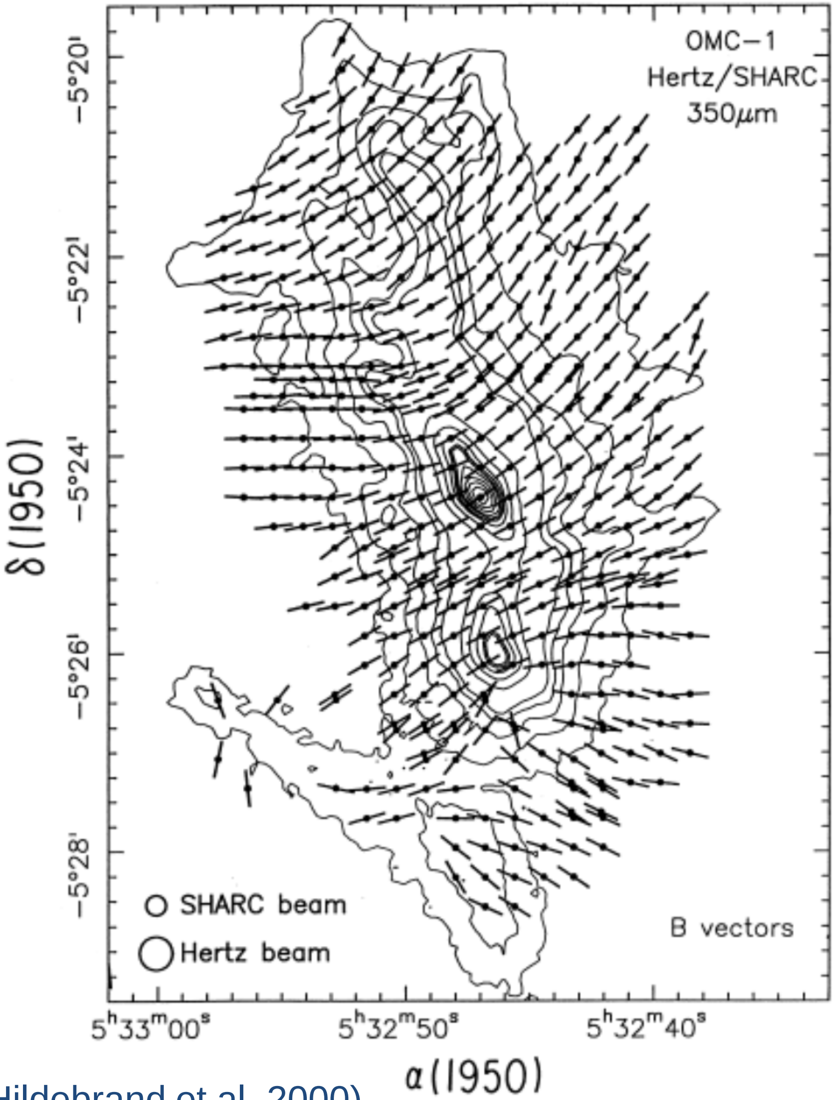
dust polarization & Zeeman effect

Dust Polarization in the ISM

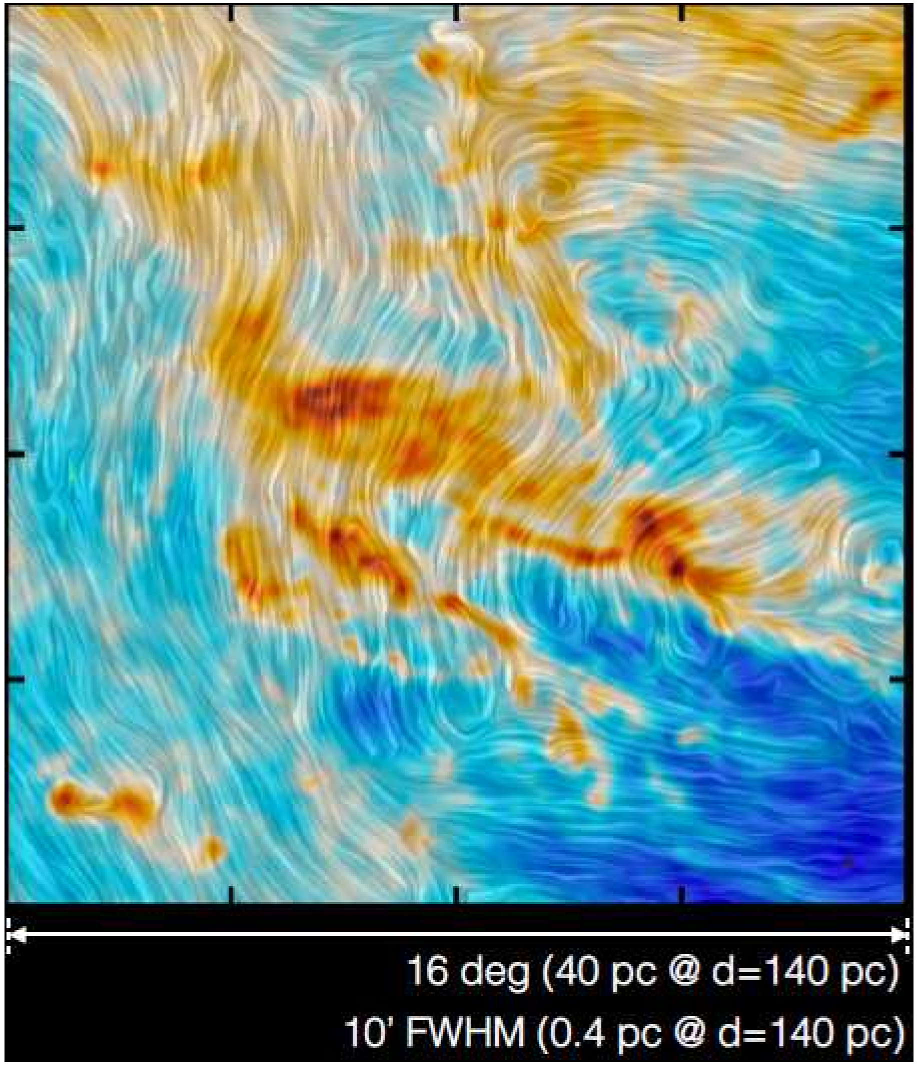
- Asymmetric dust particles spin around B
- Light is preferentially emitted (or extinct) given this asymmetry



Dust Polarization in the ISM



(Hildebrand et al. 2000)

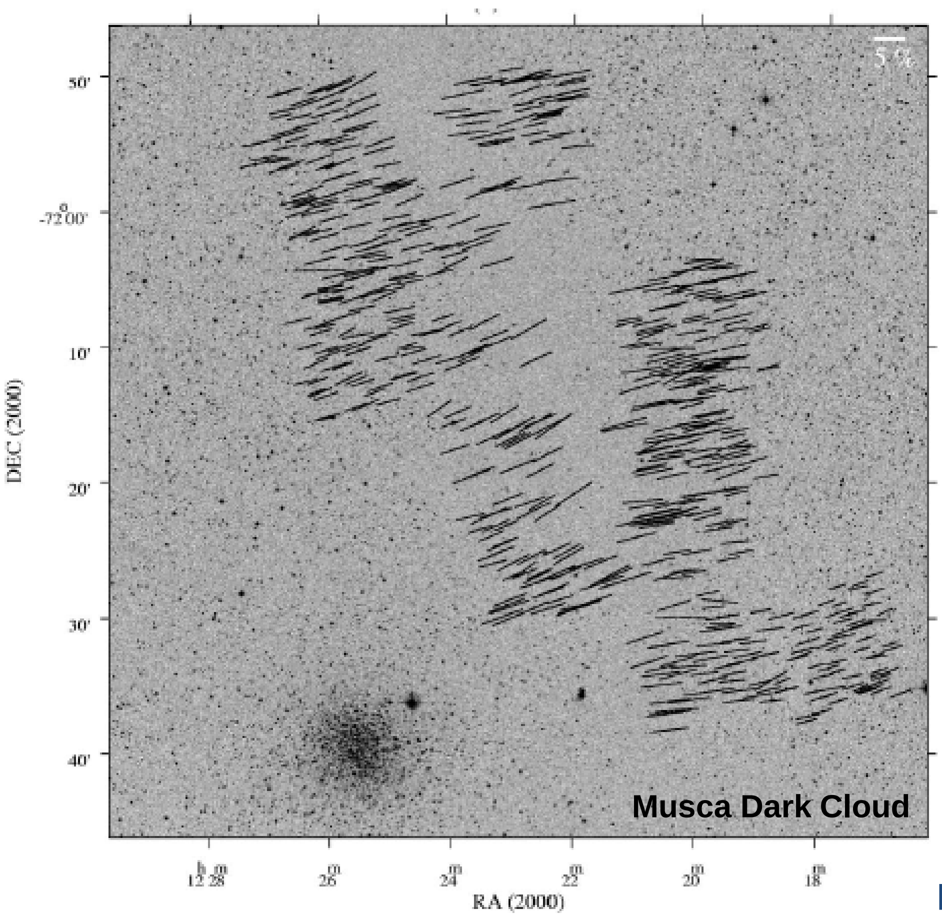


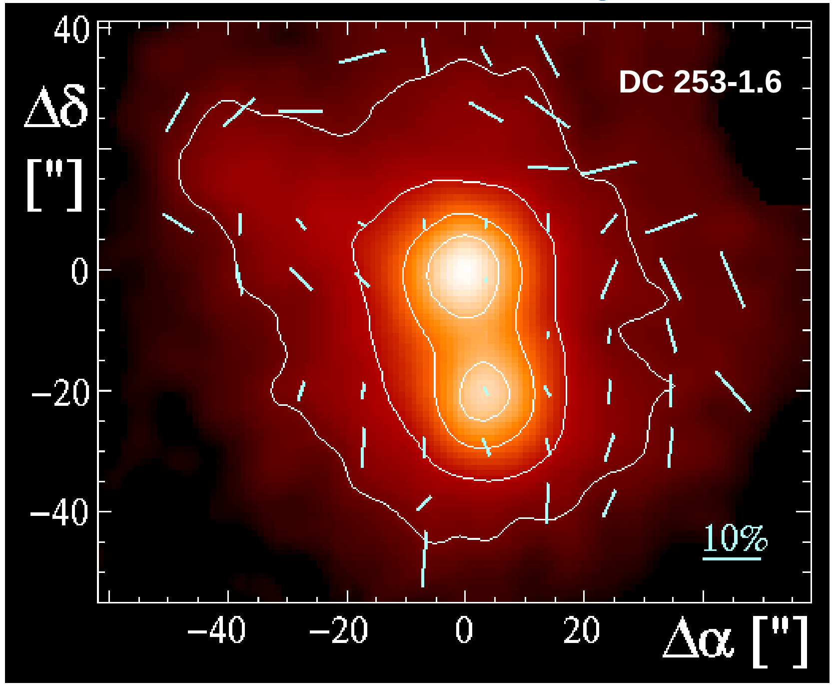
Planck Collaboration XXXV (Soler et al. 2015)

Dust Polarization in the ISM

Why polarization maps look so different?

Henning et al. 2001

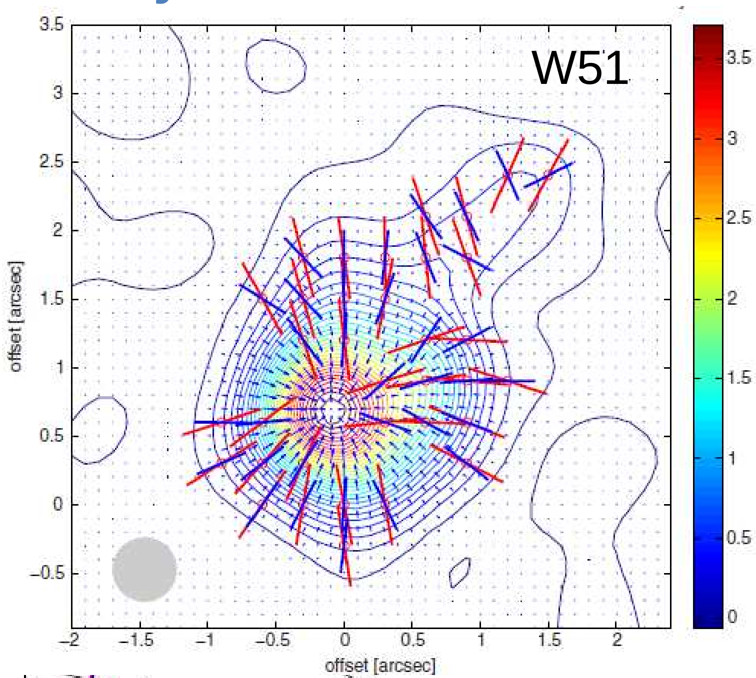


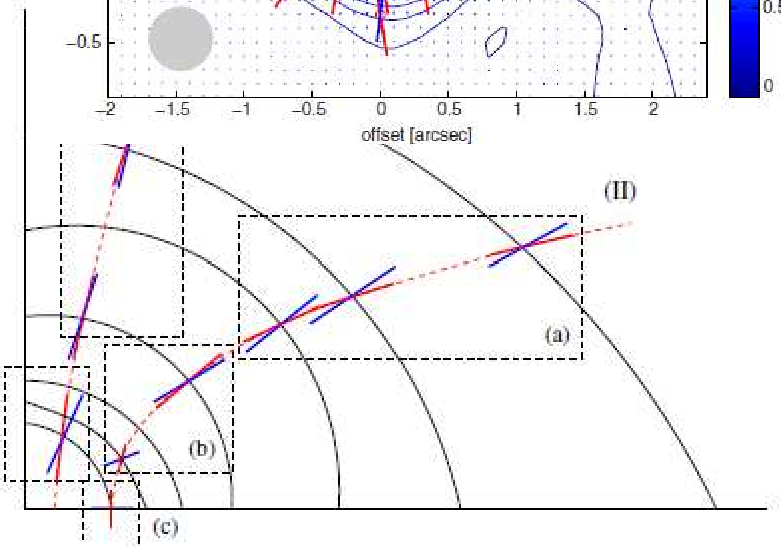


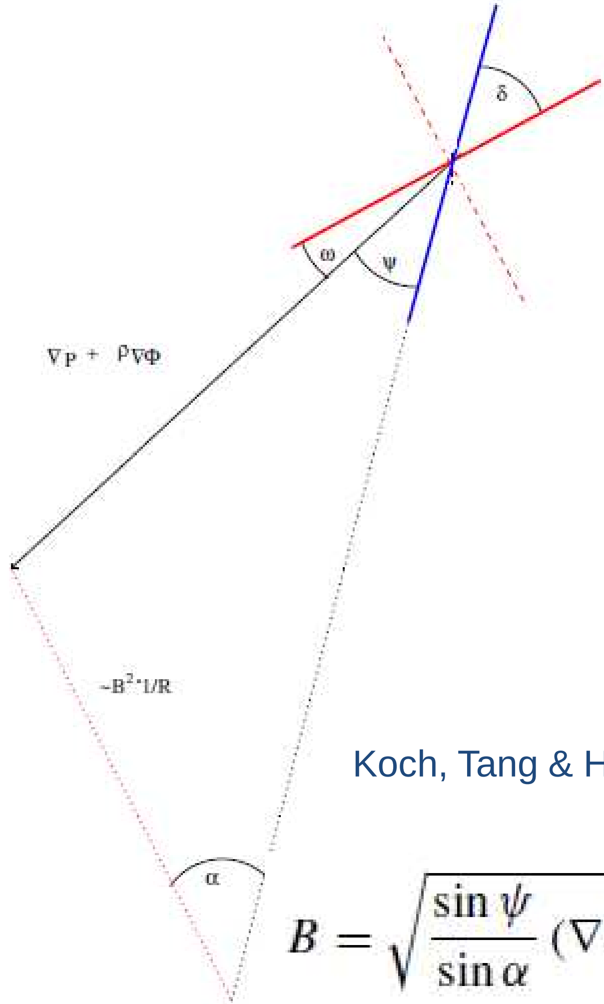
Pereyra & Magalhaes 2004

Dust Polarization in the ISM

Gravity?





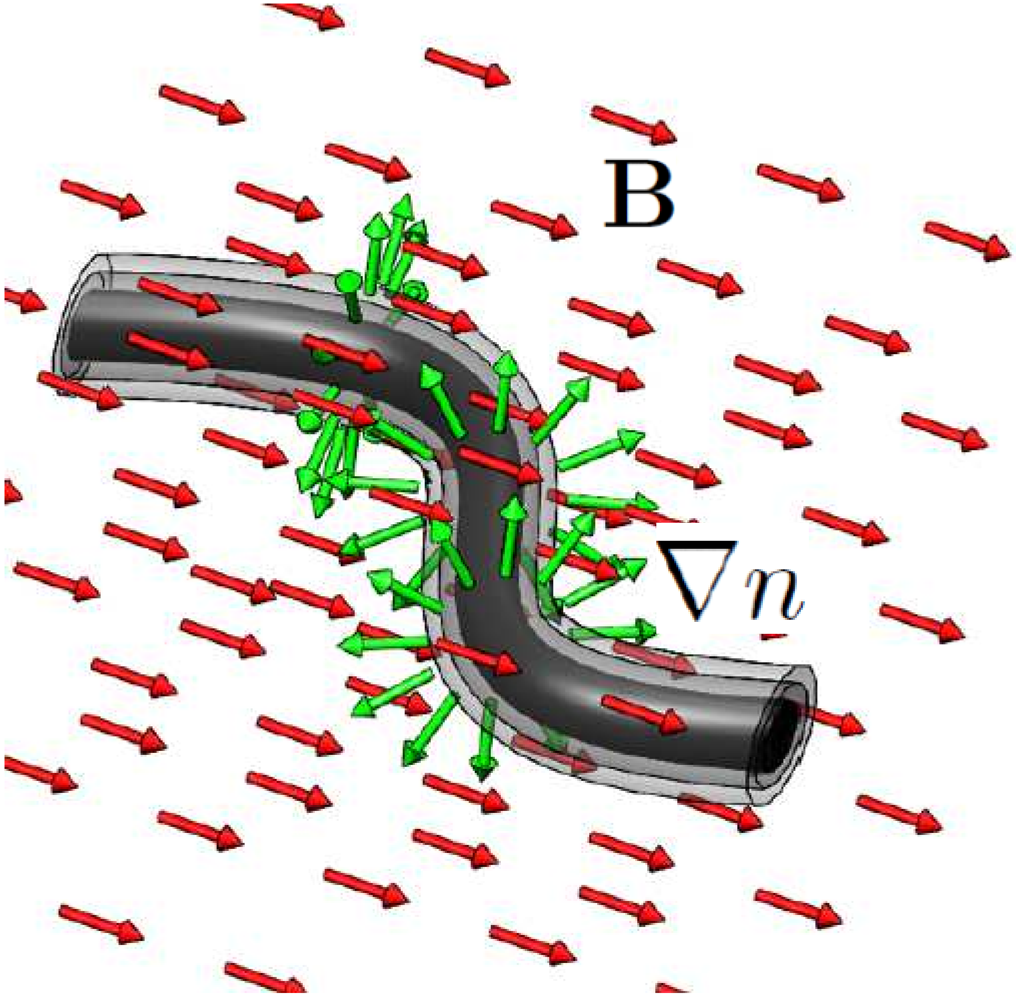


Koch, Tang & Ho (2012)

$$B = \sqrt{\frac{\sin\psi}{\sin\alpha}\left(\nabla P + \rho\nabla\phi\right)4\pi R},$$

Dust Polarization in the ISM

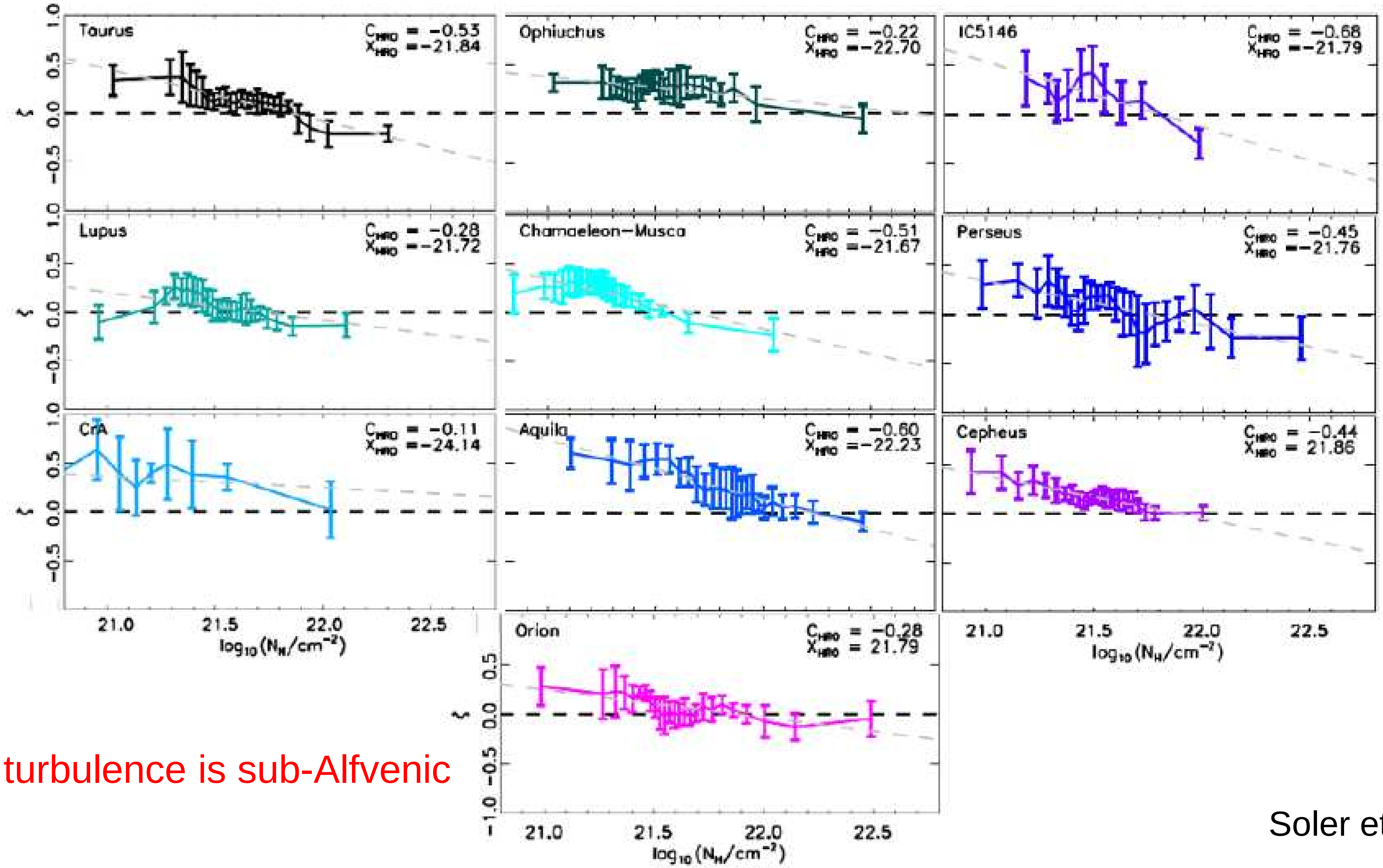
HRO – Relative Orientation between gas and B



Soler et al (2013)

Dust Polarization in the ISM

HRO – Relative Orientation between gas and B



ISM turbulence is sub-Alfvenic

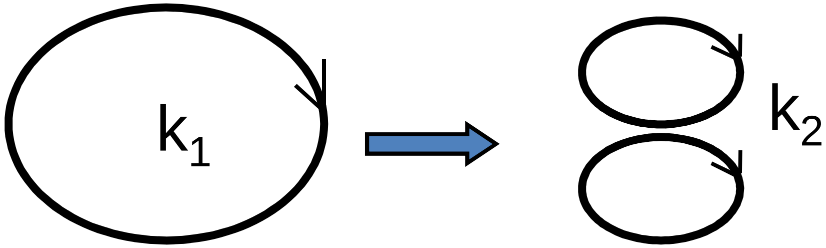
Soler et al.

Turbulence & magnetic fields in the ISM

Turbulence: *Kolmogorov's theory*

incompressible fluids:

Homogeneity + Isotropy + Scale invariance + Locality



Energy "flows" from large to small scales: $\dot{\varepsilon} \approx \delta v_l^{\,2} / \tau_l$

being $\tau_l \approx l / \delta v_l$, ***therefore*** $\delta v_l \approx (\dot{\varepsilon} l)^{1/3}$

since $\delta v_l^{\,2} \approx \int_{k=1/l}^{\infty} E(k') dk'$ ***we get***

$$E(k) \approx \dot{\varepsilon}^{2/3} k^{-5/3}$$

Turbulence & magnetic fields in the ISM

Magnetic fields

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} = -\frac{\nabla p}{\rho} + \nu\nabla^2\mathbf{u} + \frac{(\nabla\times\mathbf{B})\times\mathbf{B}}{4\pi\rho} + \mathbf{F} \quad + \quad \frac{\partial \mathbf{B}}{\partial t} = \nabla\times(\mathbf{u}\times\mathbf{B}) + \eta\nabla^2\mathbf{B}$$

weak wave-wave interactions

$$\tau_{\rm A}(l) \sim l_{\|}/v_{\rm A}$$

$$\tau_{\rm s}(l) \sim l/\delta u_l$$

$$l_{\|}/l \sim 1$$

Isotropy

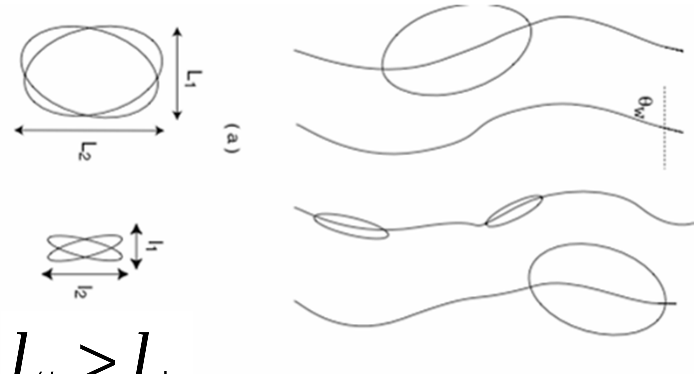
$$E(k) \sim (\epsilon v_{\rm A})^{1/2} k^{-3/2}$$

strong wave-wave interactions

$$\tau_{\rm A} \sim \tau_{\rm s} \quad \Leftrightarrow \quad l_{\|}/l_{\perp} \sim v_{\rm A}/\delta u_l$$

$$l_{\|} \sim v_{\rm A}\epsilon^{-1/3} l_{\perp}^{2/3} \sim k_{\|0}^{-1}(l_{\perp}/l_*)^{2/3}$$

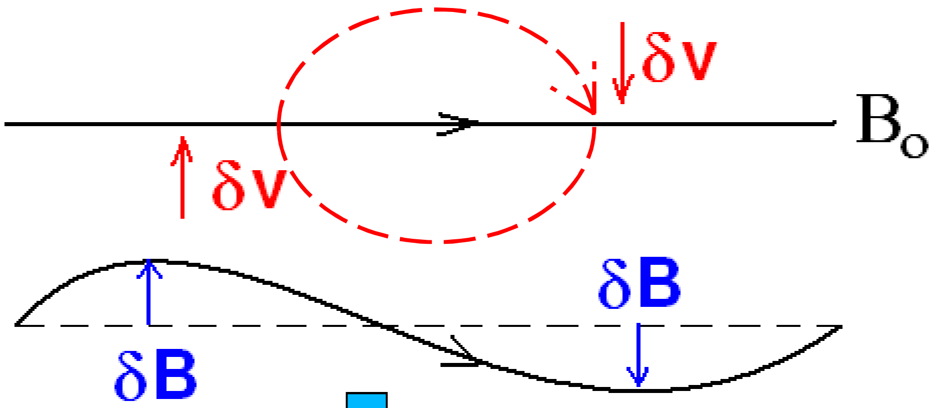
Anisotropy

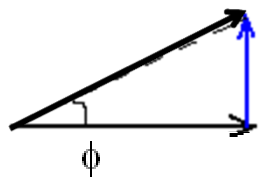


$$l_{//} > l_{\perp}$$

Dust Polarization in the ISM

- Interplay of magnetic and kinetic energy





$$\frac{1}{2}\rho\delta v^2 \cong \frac{\delta B^2}{8\pi}$$

$$\delta\phi \cong \frac{\delta B}{B_p}$$

Chandrasekhar & Fermi (1953), Zweibel (1993), Myers & Goodman (1991), Ostriker et al (2001) Heitsch et al. (2001)

$$B_p = \xi\sqrt{4\pi\rho}\,\frac{\delta v_{LOS}}{\delta\phi}$$

Dust Polarization in the ISM

- Corrections (Falceta-Gonçalves et al. 2008)

1. In the weak field limit δB is isotropic

$$B_p + \delta B = \xi \sqrt{4\pi\rho} \frac{\delta v_{LOS}}{\tan(\delta\phi)}$$

2. Statistical integration of polarization vectors along LOS

3. Resolution dependence: $B_{\rm CF} = B^0_{\rm CF}\left(1 + \frac{C}{R^{0.5}}\right)$

Tests ???

Direct Numerical Simulations (DNS)

- Godunov method (3 steps):
  grid-interpolation (5th order MP scheme)
  Riemann Solver (HLLD)
  Runge-Kutta integration (4th order, 10 steps)

- MHD equations

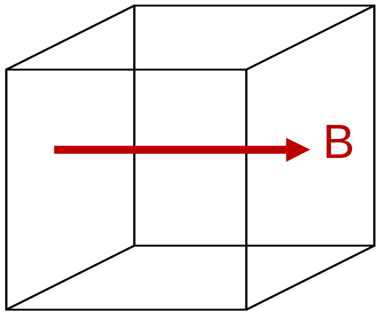
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0,$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot \left[\rho \boldsymbol{v}\boldsymbol{v} + \left(p + \frac{B^2}{8\pi} \right) \boldsymbol{I} - \frac{1}{4\pi} \boldsymbol{B}\boldsymbol{B} \right] = \rho \boldsymbol{f},$$

$$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = 0,$$

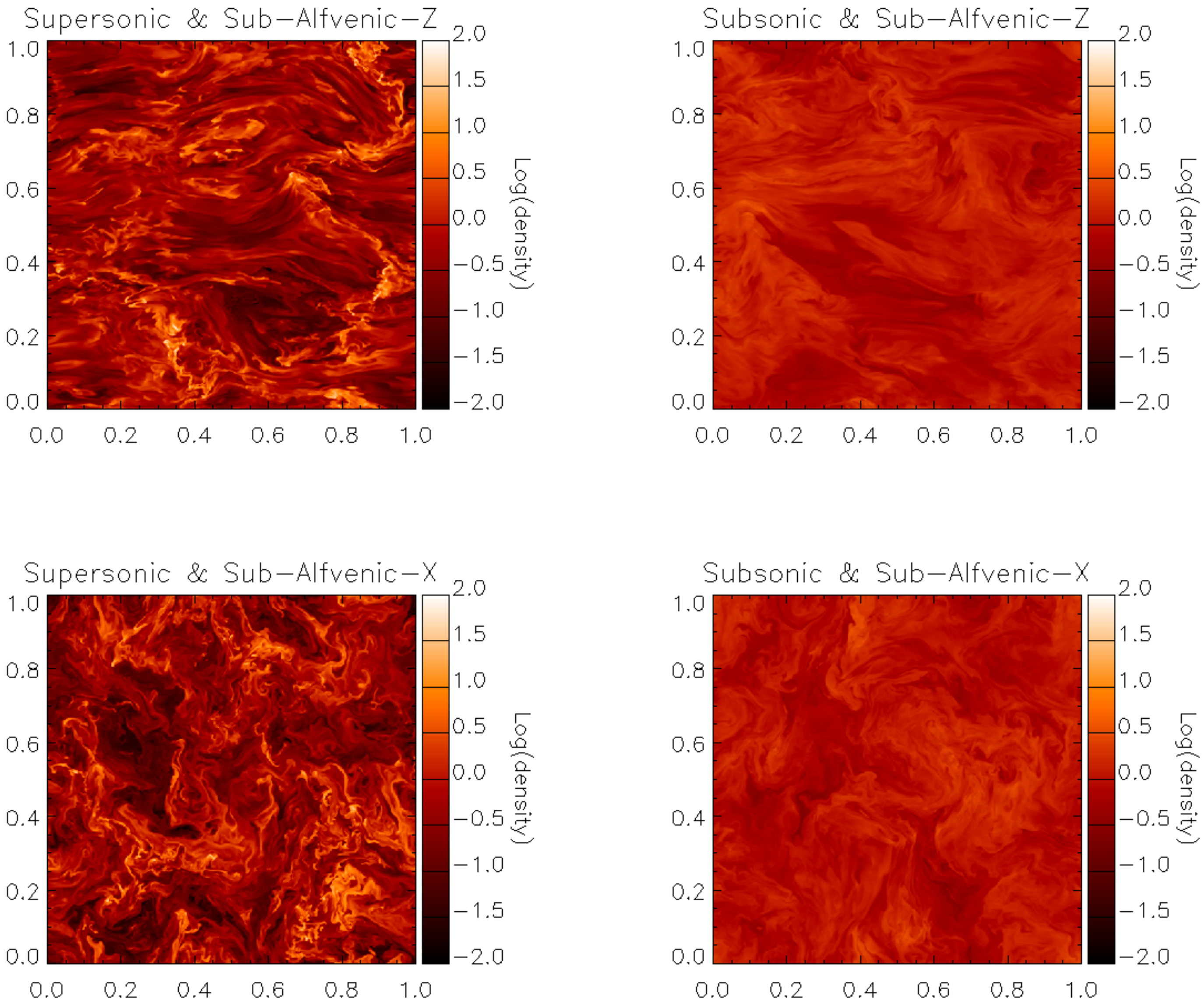
- explicit terms:
  forcing, gravity

Initial conditions:



- uniform B
- ρ homogenous
- periodic
- solenoidal forcing in velocity

Direct Numerical Simulations (DNS)



Direct Numerical Simulations (DNS)

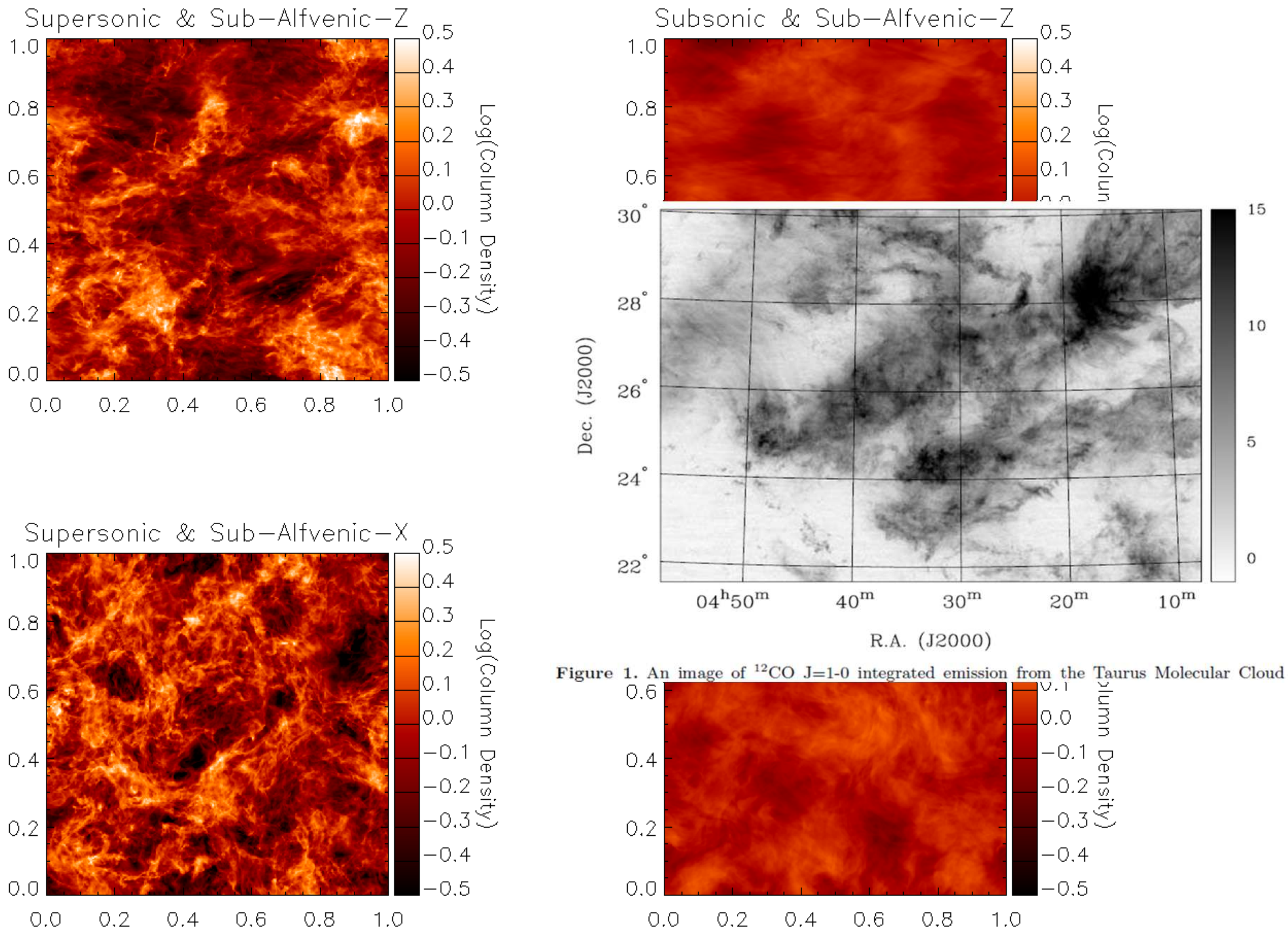
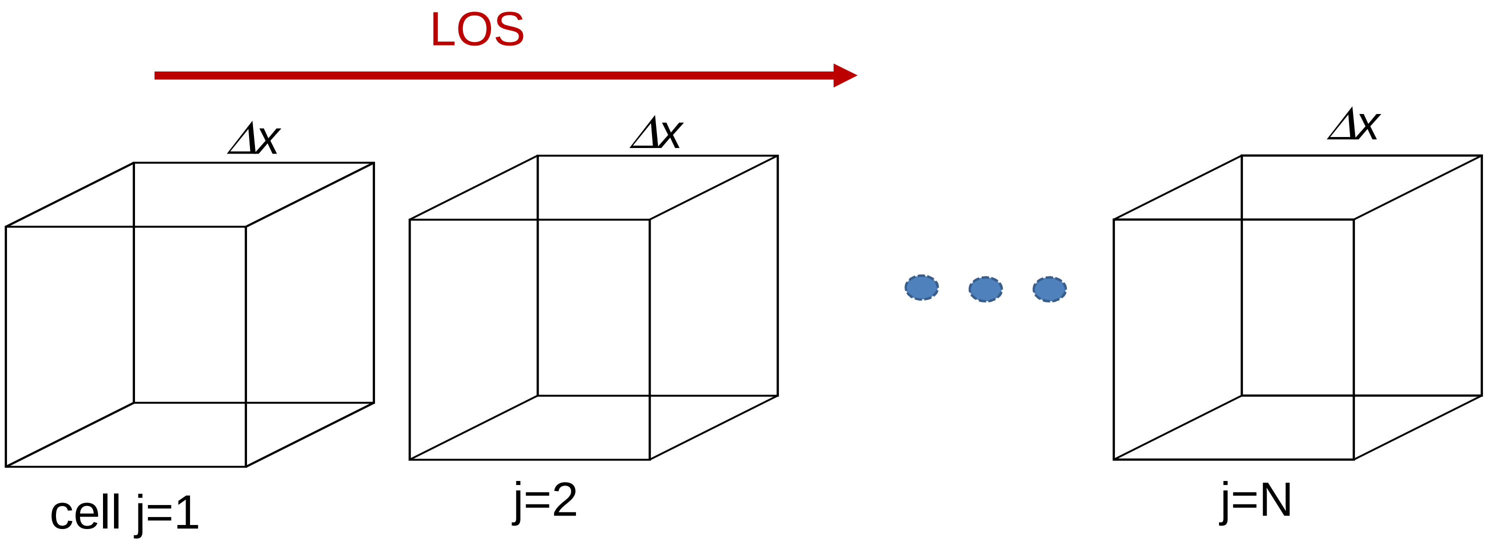


Figure 1. An image of ^{12}CO J=1-0 integrated emission from the Taurus Molecular Cloud

Polarized dust emission from DNS



$$q = \epsilon\rho \cos 2\psi \sin^2 i \;\Delta x$$
$$u = \epsilon\rho \sin 2\psi \sin^2 i \;\Delta x$$

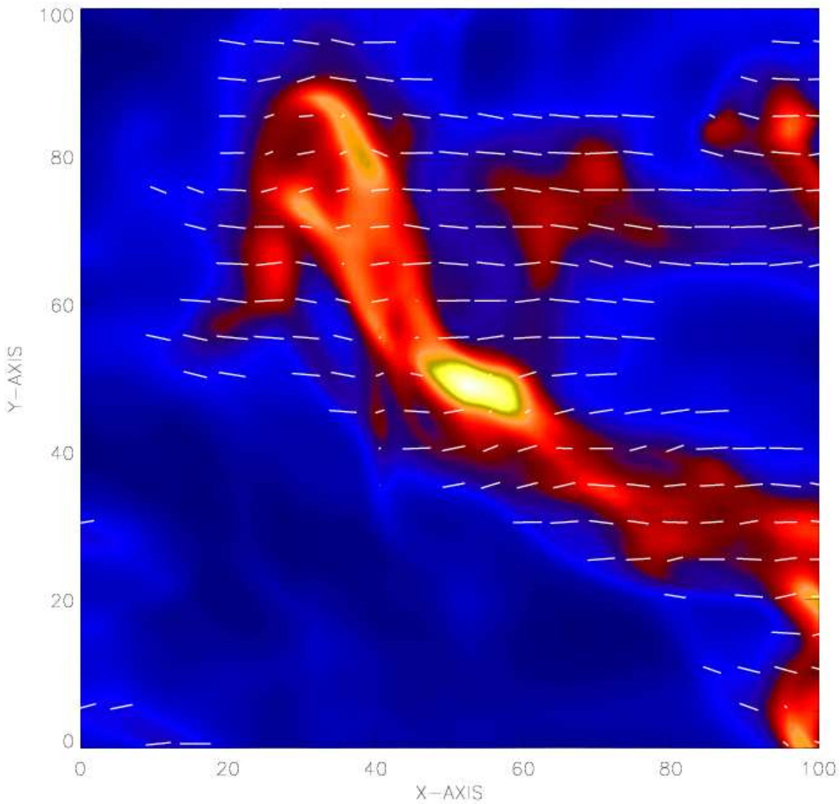
Integrate from j=1 to N

$$Q = \sum_{j=1}^{N} q_j \qquad U = \sum_{j=1}^{N} u_j$$

$$p = \sqrt{Q^2 + U^2}/I$$
$$\phi = \arctan(U/Q)/2$$

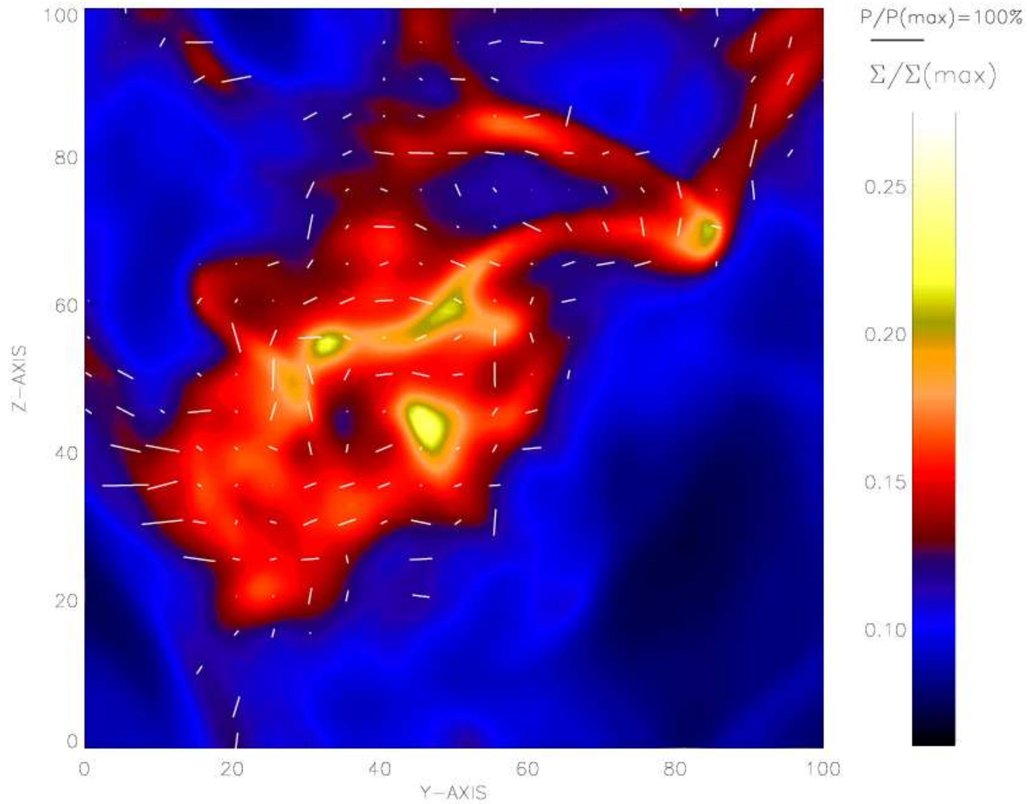
Polarized dust emission from DNS

Dust polarization



Supersonic and sub-Alfvénic

M_S	M_A
7.0	0.7

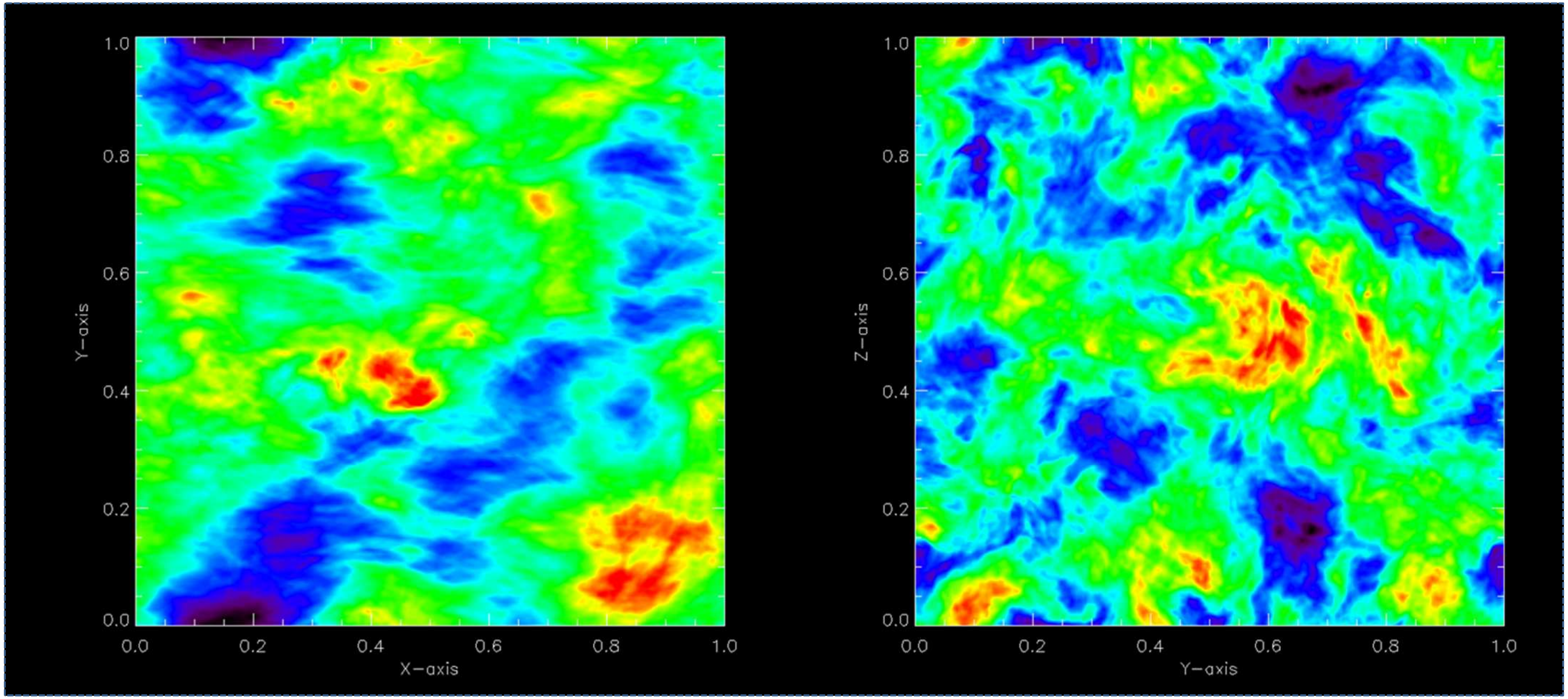


Supersonic and super-Alfvénic

M_S	M_A
7.0	2.0

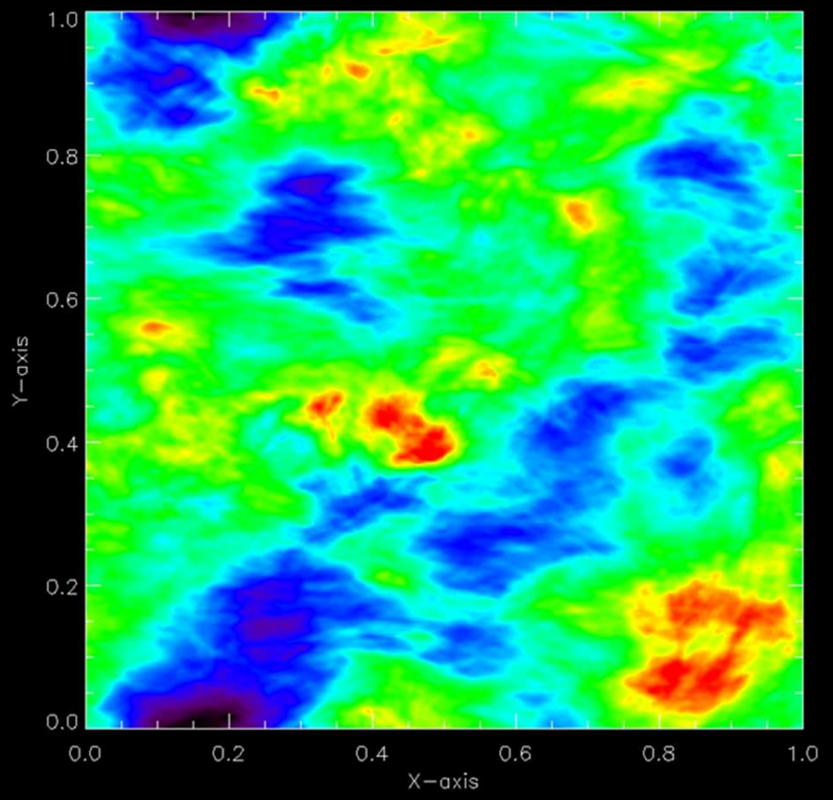
Polarized dust emission from DNS

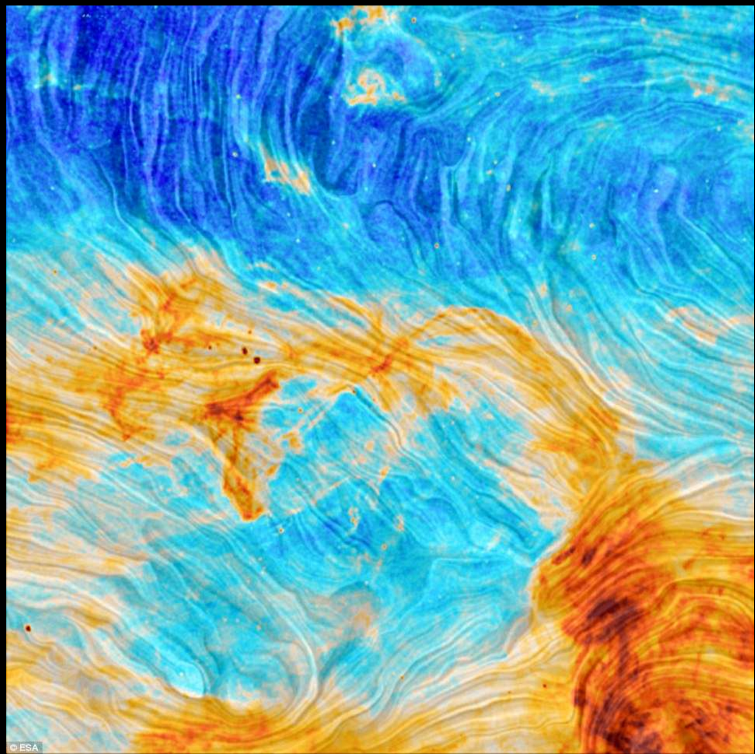
Line integral convolution



Polarized dust emission from DNS

Line integral convolution





LIC to PLANCK data (Soler et al. 2015)

Dust Polarization in the ISM

- Corrections (Falceta-Gonçalves et al. 2008)

Table 2: CF method estimates

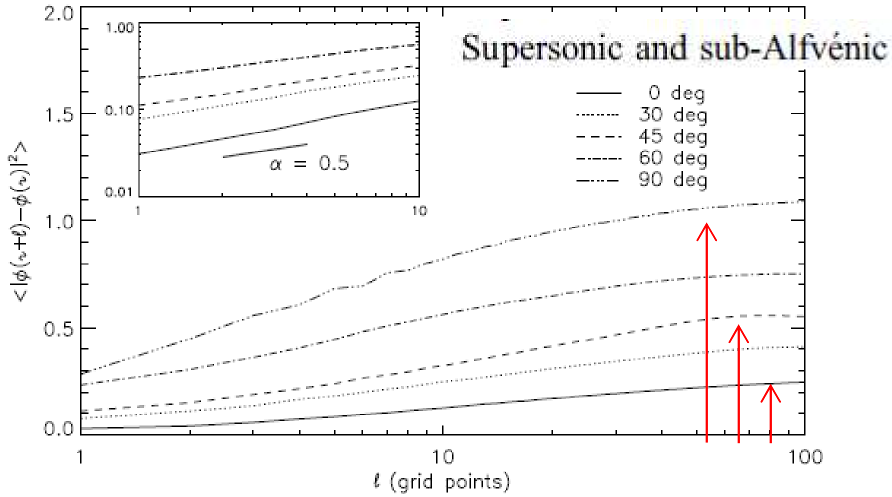
Model	$\theta(°)$	C	B^0_{CF}/B_{ext}	B^{ext}_{sky}/B_{ext} [a]	B_{tot}/B_{ext} [b]
3	0	20 ± 5	1.24 ± 0.09	1.00	1.25
3	30	24 ± 5	0.98 ± 0.08	0.87	1.11
3	45	25 ± 5	0.78 ± 0.07	0.71	0.96
3	60	33 ± 5	0.48 ± 0.05	0.50	0.75
3	90	31 ± 5	0.26 ± 0.03	0.00	0.24
1	0	7 ± 5	0.97 ± 0.08	1.00	1.11
2	0	10 ± 5	1.07 ± 0.07	1.00	1.16
4	0	34 ± 5	1.18 ± 0.07	1.00	1.41

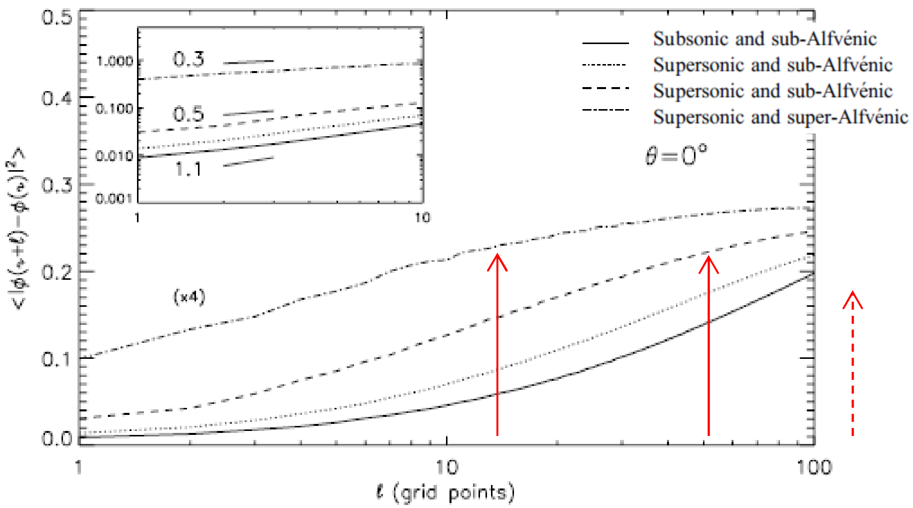
[a] Mean field adopted for the model, projected into the plane of sky, i.e. $B^{ext}_{sky} = B_{ext} \cos\theta$

[b] Total field of the model, projected into the plane of sky, i.e. $B_{tot} = B^{ext}_{sky} + \delta B$

Polarized dust emission from DNS

Statistics of polarization → Determination of B, and turbulence





Structure Function

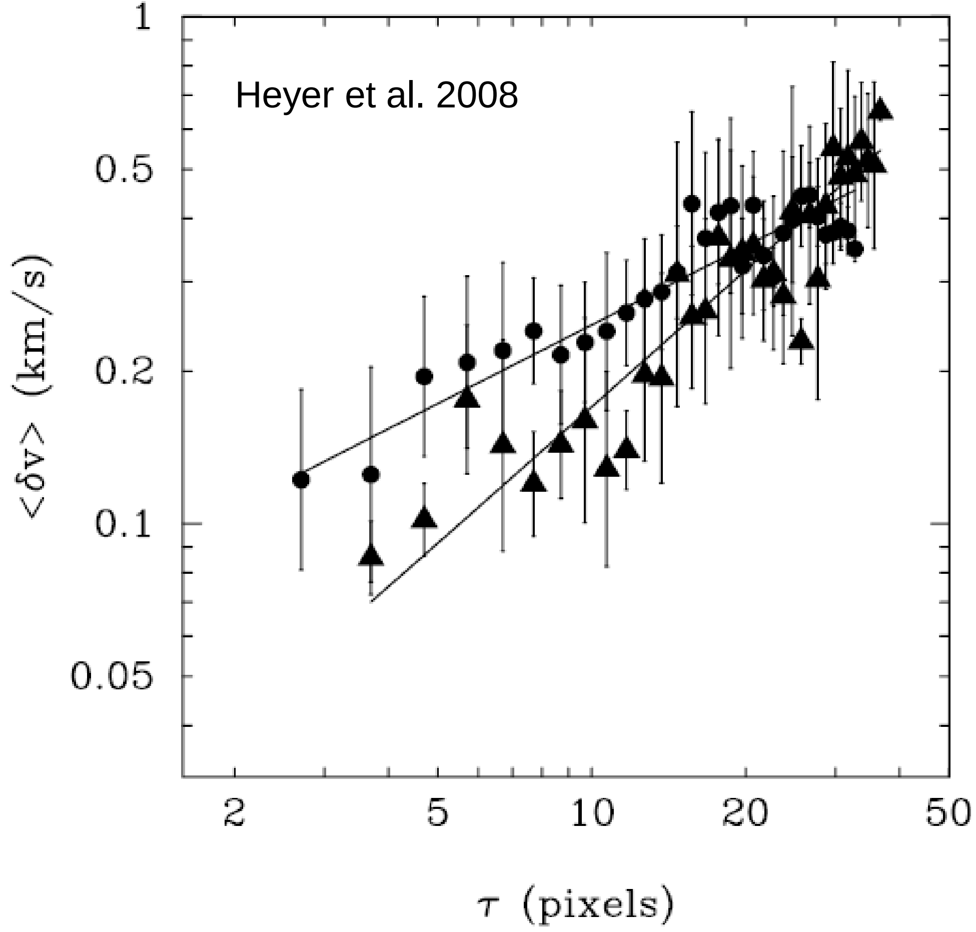
$$S_p(l) = \langle\{[\mathbf{u}(\mathbf{r}+\mathbf{l}) - \mathbf{u}(\mathbf{r})]\cdot \mathbf{l}/l\}^p\rangle$$

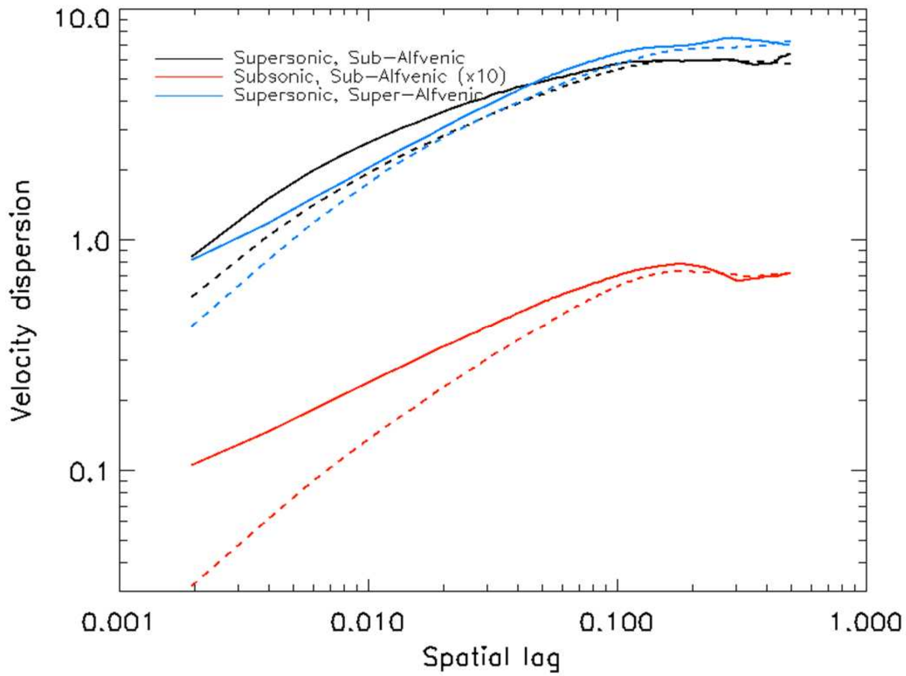
see also:

Hildebrand et al (2009), Houde et al. (2009, 2011, 2013)

B - δv correlation (anisotropy)

2-point statistics (correlation functions)





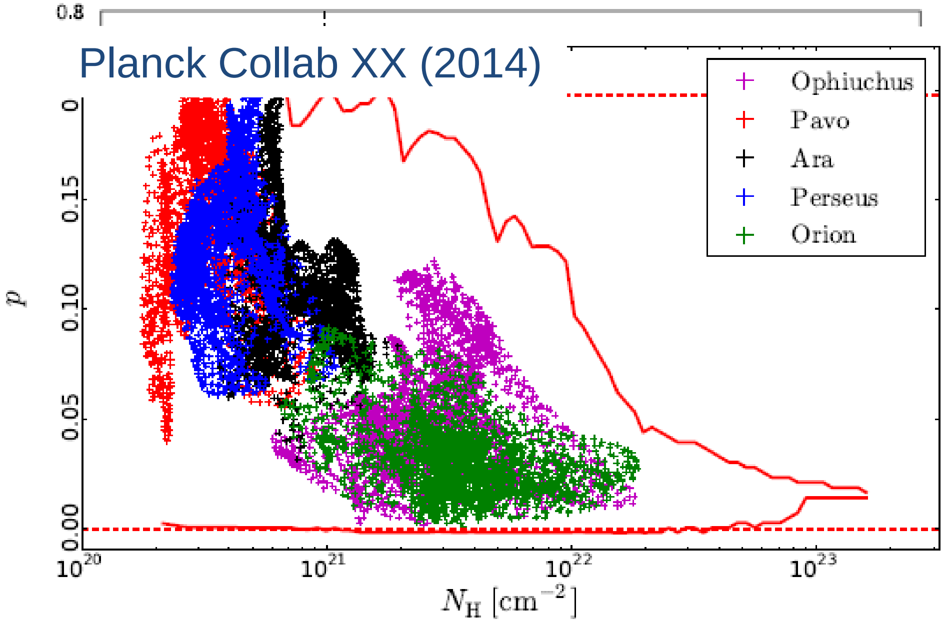
Velocity anisotropy aligned to magnetic fields!

B - ρ Correlation

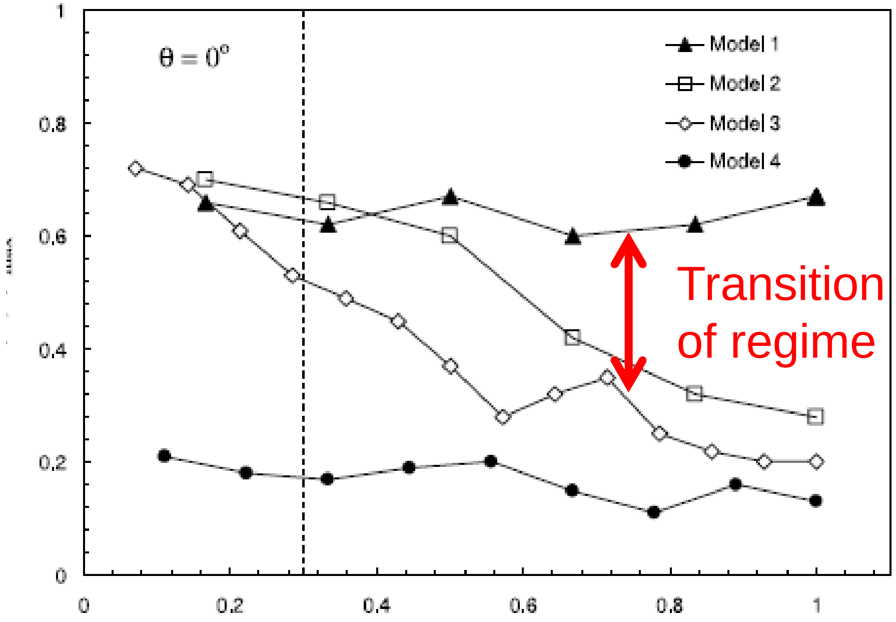
"observed" $B_\perp$ - Σ correlation

Falceta-Goncalves et al. (2008)

Planck Collab XX (2014)



Σ / Σ_{max}

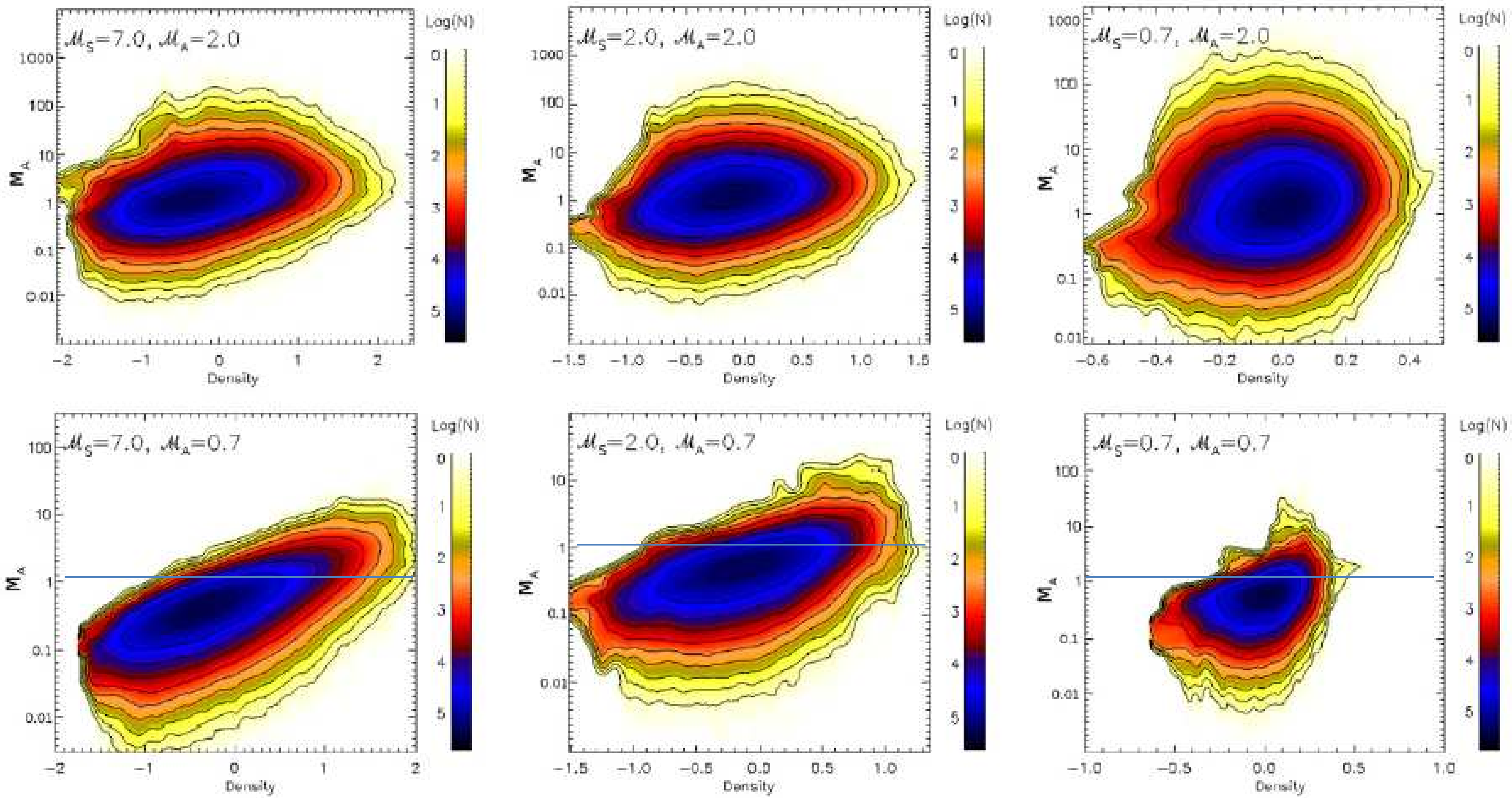


- Projection effects: ~25% of depolarization
- Transition of regime: more important!

B - ρ Correlation

B - ρ correlation

Burkhart et al. 2009



Transition from low to high Alfven Mach number within turbulent cascade!

Polarized dust emission from DNS

THE ASTROPHYSICAL JOURNAL, 777:112 (15pp), 2013 November 10
doi:10.1088/0004-637X/777/2/112

MAGNETIC FIELD COMPONENTS ANALYSIS OF THE SCUPOL 850 μm POLARIZATION DATA CATALOG

FRÉDÉRICK POIDEVIN[1], DIEGO FALCETA-GONÇALVES[2,3], GRZEGORZ KOWAL[3],
ELISABETE DE GOUVEIA DAL PINO[4], AND ANTONIO MÁRIO MAGALHÃES[4]

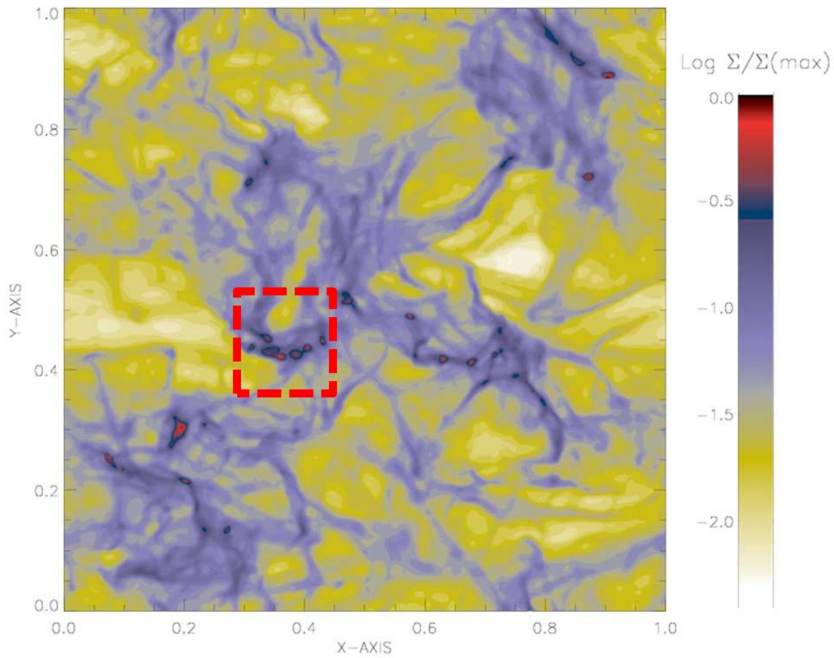
ABSTRACT

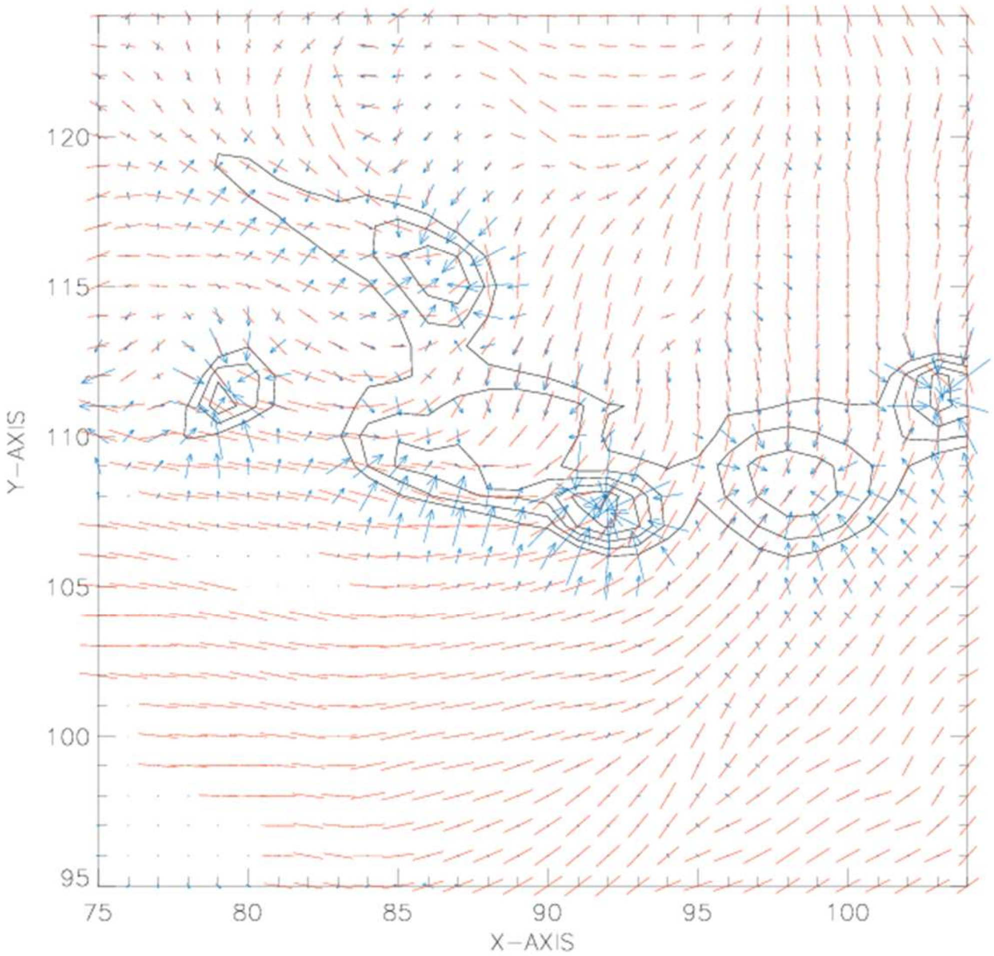
We present an extensive analysis of the 850 μm polarization maps of the SCUBA Polarimeter Legacy (SCUPOL) Catalogue produced by Matthews et al., focusing exclusively on the molecular clouds and star-forming regions. For the sufficiently sampled regions, we characterize the depolarization properties and the turbulent-to-mean magnetic field ratio of each region. Similar sets of parameters are calculated from two-dimensional synthetic maps of dust-emission polarization produced with three-dimensional magnetohydrodynamics (MHD) numerical simulations scaled to the S106, OMC-2/3, W49, and DR21 molecular cloud polarization maps. For these specific regions, the turbulent MHD regimes retrieved from the simulations, as described by the turbulent Alfvén and Sonic Mach numbers, are consistent within a factor one to two with the values of the same turbulent regimes estimated from the analysis of Zeeman measurements data provided by Crutcher. Constraints on the values of the inclination angle α of the mean magnetic field with respect to the line of sight are also given. The values obtained from the comparison of the simulations with the SCUPOL data are consistent with the estimates made by using two observational methods provided by other authors. Our main conclusion is that simple, ideal, isothermal, and non-self-gravitating MHD simulations are sufficient in order to describe the large-scale observed physical properties of the envelopes of this set of regions.

What is the role of gravity?

Polarized dust emission from DNS

Gravity?





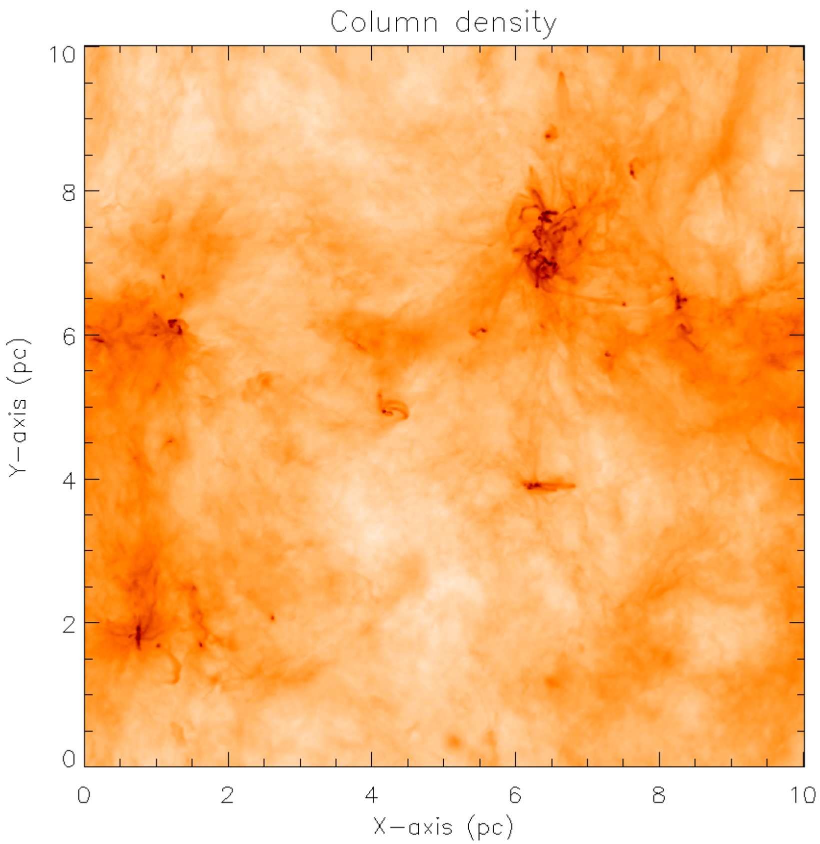
HRO–technique

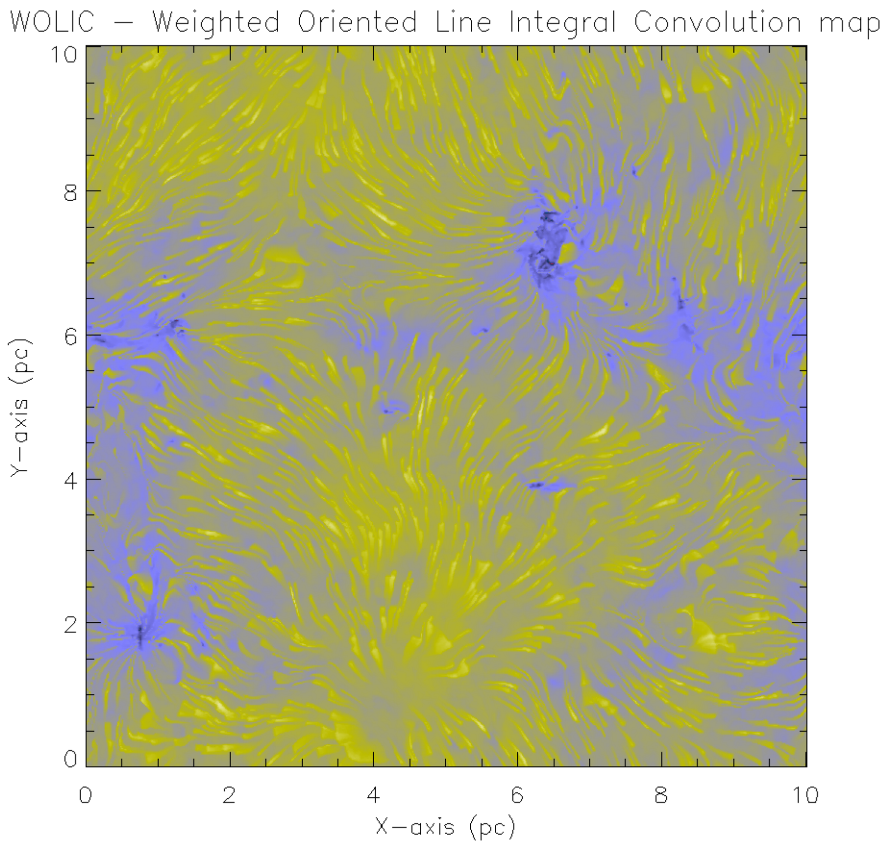
Soler et al. (2013)

Polarization distortion by gravity?

Koch, Tang & Koh (2012)

Turbulence & magnetic fields in the ISM

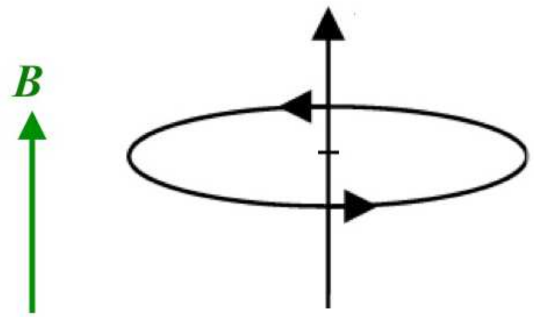




Gravity → gas flows onto/along filaments →(?) polarization orientation

Zeeman effect

- magnetic force   angular momentum for charges



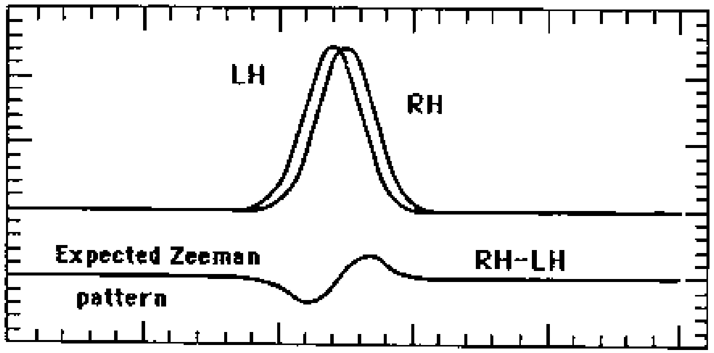
- Atoms/molecules with unpaired electrons have charge angular momentum

- Energy associated appears as a shift in the spectral line

e.g., for 1 e

$$\Delta\nu = qB/4\pi mc = 1.4\ \mathrm{Hz}/\mu\mathrm{G}$$

probe B_{los}

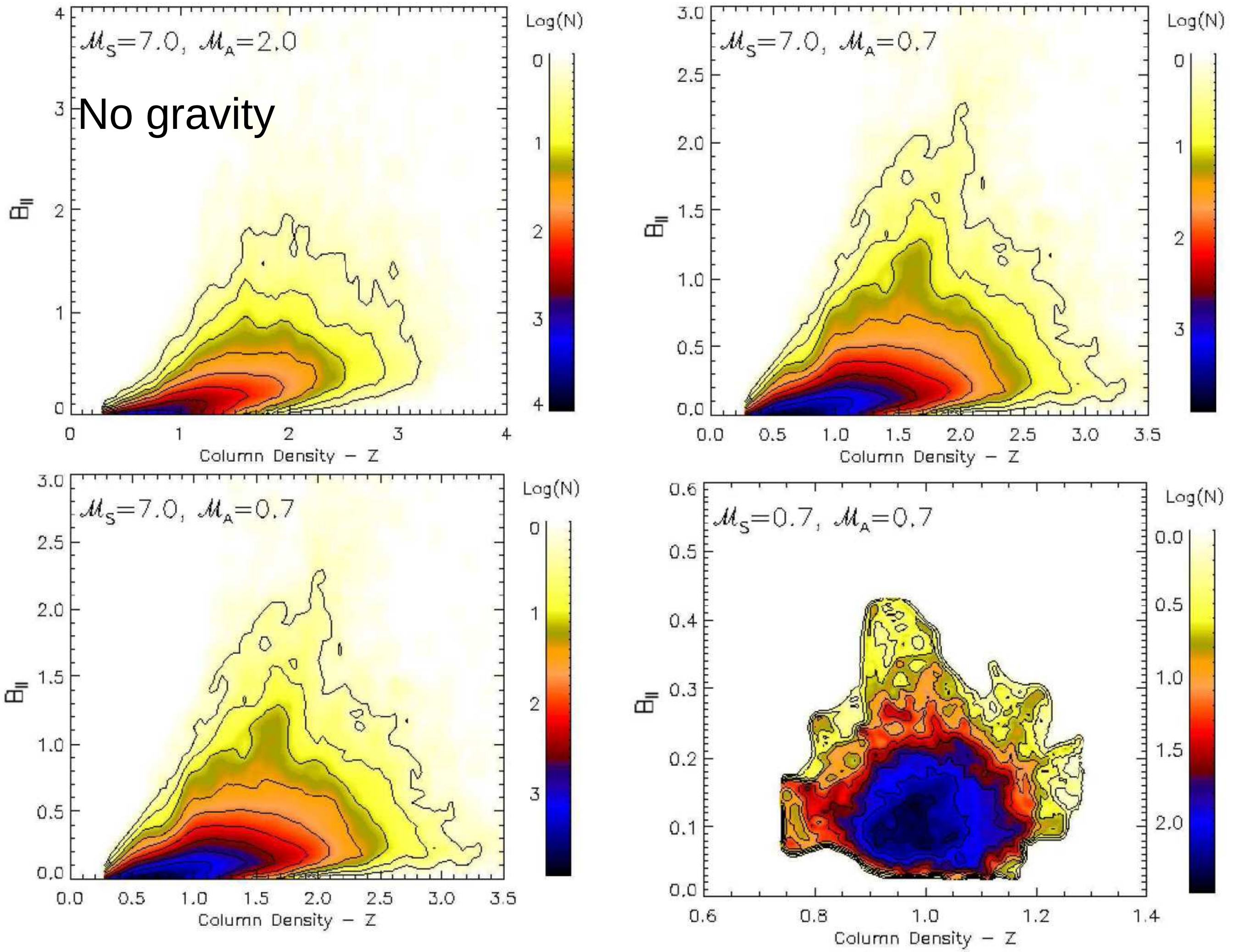


- In practice: $V = \frac{1}{2}\, z\, B_{los}\, dI/d\nu$

Zeeman effect (as seen from MHD sims)

projected $B_{//}$ - Σ correlation

Burkhart et al. 2009



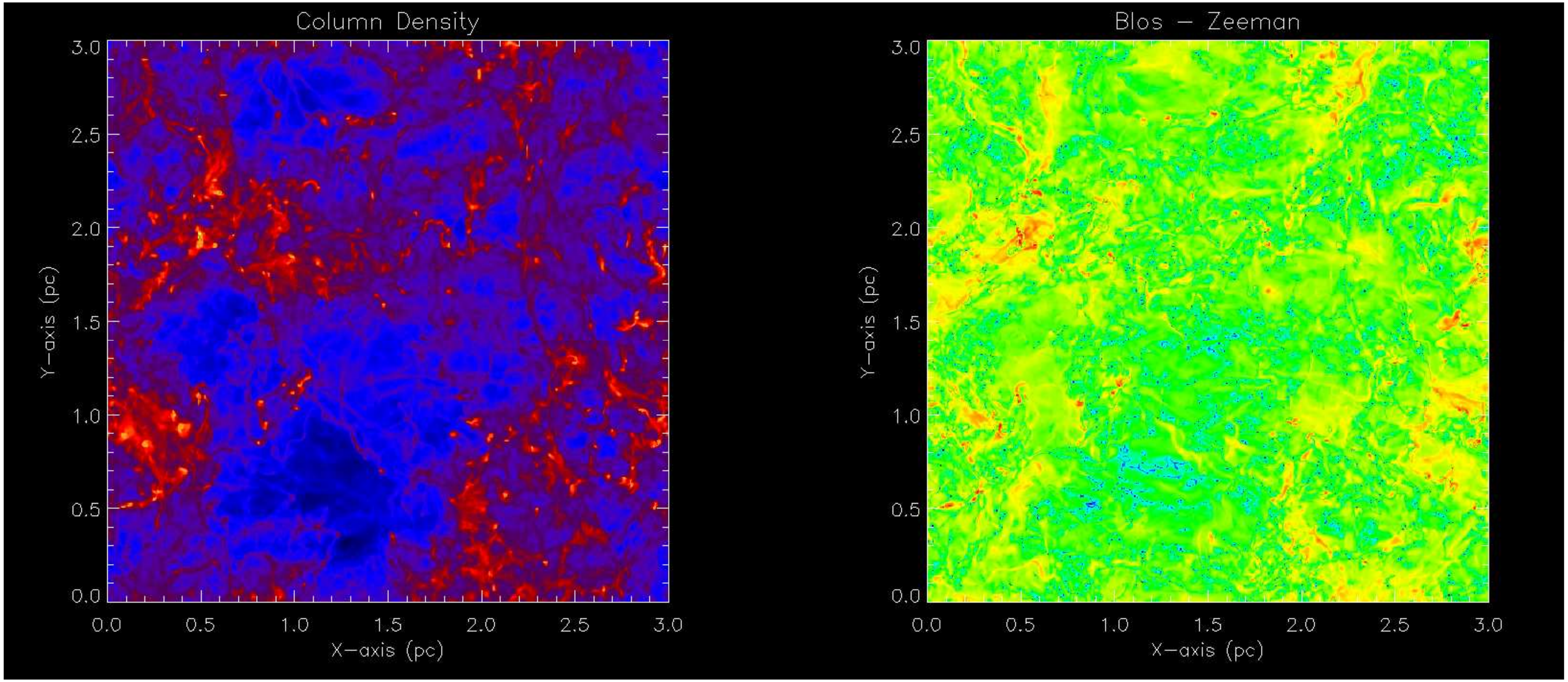
see also Padoan et al. 2014; Li, McKee & Klein. 2015

Zeeman effect (as seen from MHD sims)

“observed” $B_{//}$ - Σ

Self-gravitating

Falceta-Goncalves et al. (2015, in prep)

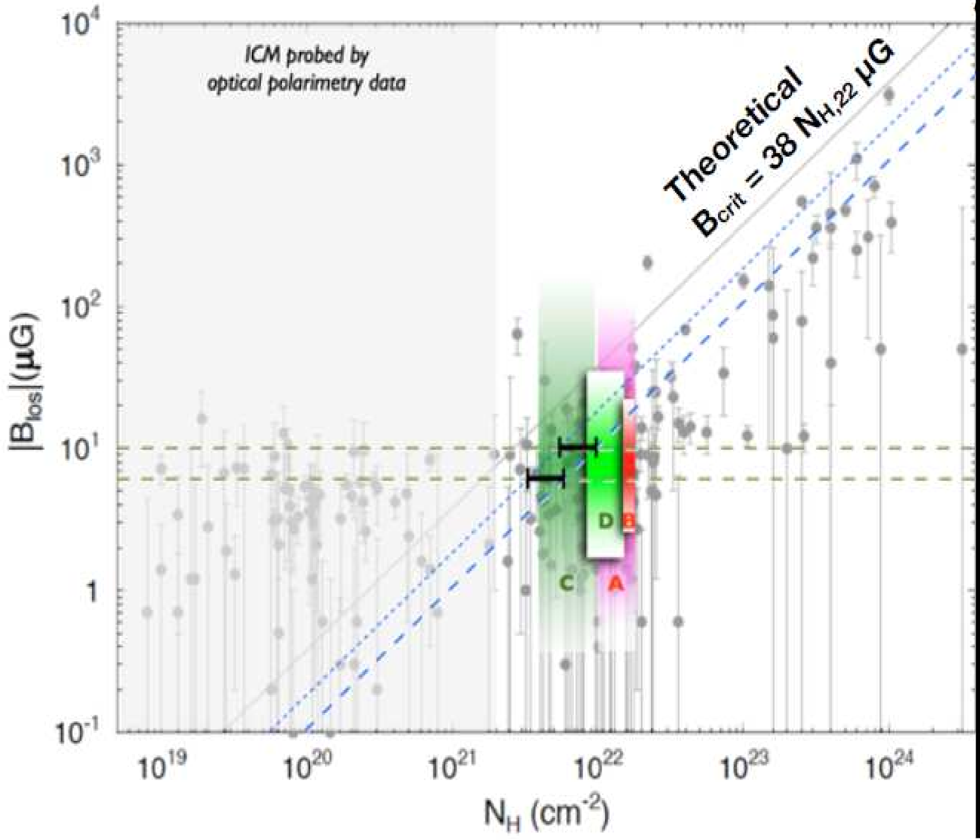


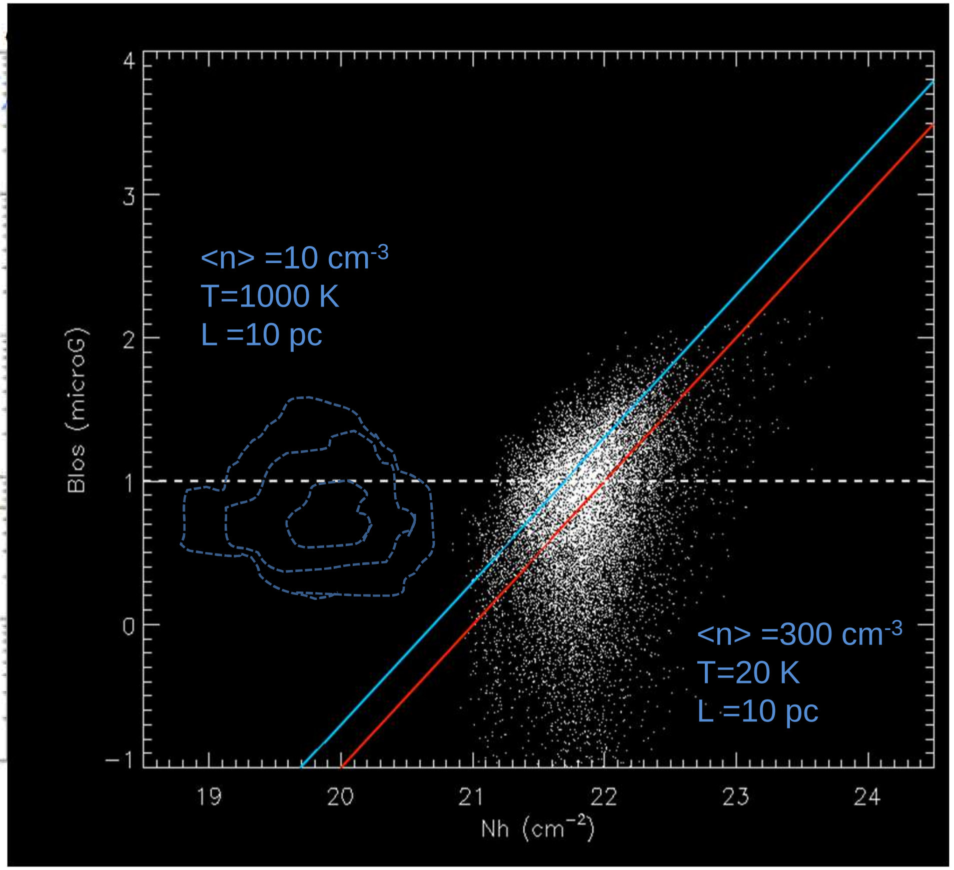
<n> =300 cm^{-3}
T=20 K
L =10 pc

Zeeman effect (as seen from MHD sims)

“observed” $B_{//}$ - Σ

Falceta-Goncalves et al. (2015, in prep)





Li (2014), Crutcher (2012), Heiles & Troland (2005)

Summary

- ISM magnetic field estimates are now available from different techniques, e.g. polarization & Zeeman

- Polarization probes not only B, but ISM turbulence itself

shows that gravity has minor impact (in general)
transition of regime at denser regions (signs of compressible and sub-Alfvenic at large scales)

- MHD models agree, in general, with statistics of polarization

provides a more complete (3D) view of the ISM (if not degenerate)

- Zeeman probes (now) vast range of densities, also presenting transition of regimes

- MHD models agree well with this picture if gravity is considered

•