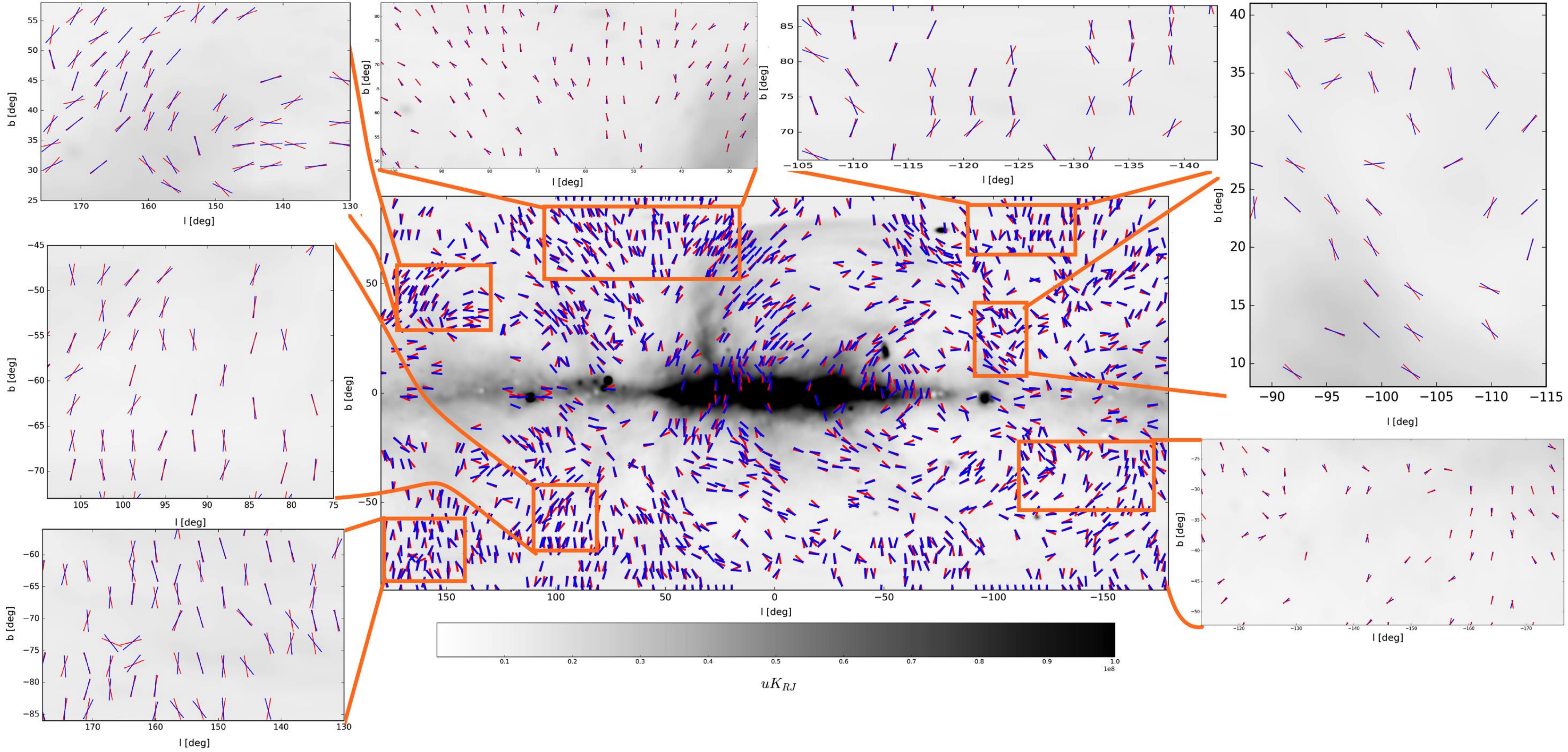
Turbulent Nature of Galactic Foregrounds: Opportunities

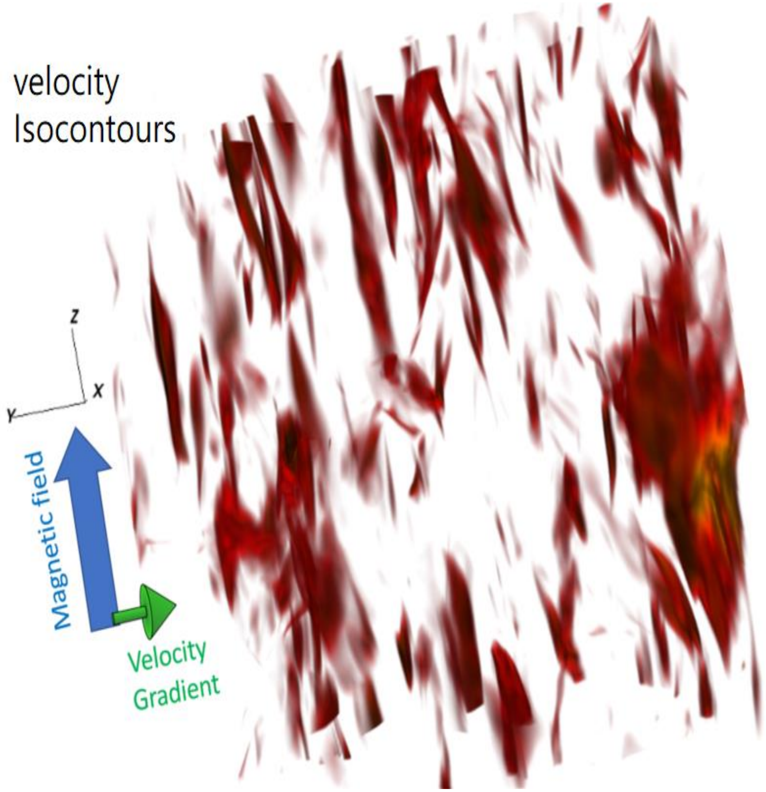


Alex Lazarian (Astronomy, Physics and CMSO)

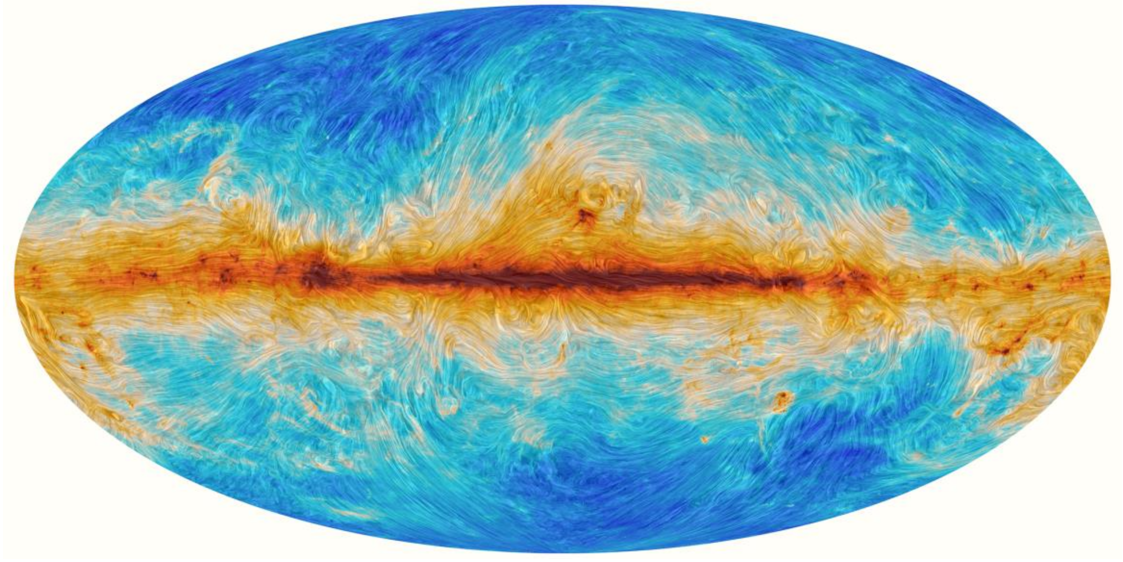
Junior collaborators: K-H. Yuen, D. Gonzales-Casanova, H. Lee

THE UNIVERSITY of WISCONSIN MADISON

My Goal: Engage groups interested in foregrounds in studies based on the modern understanding of MHD turbulence



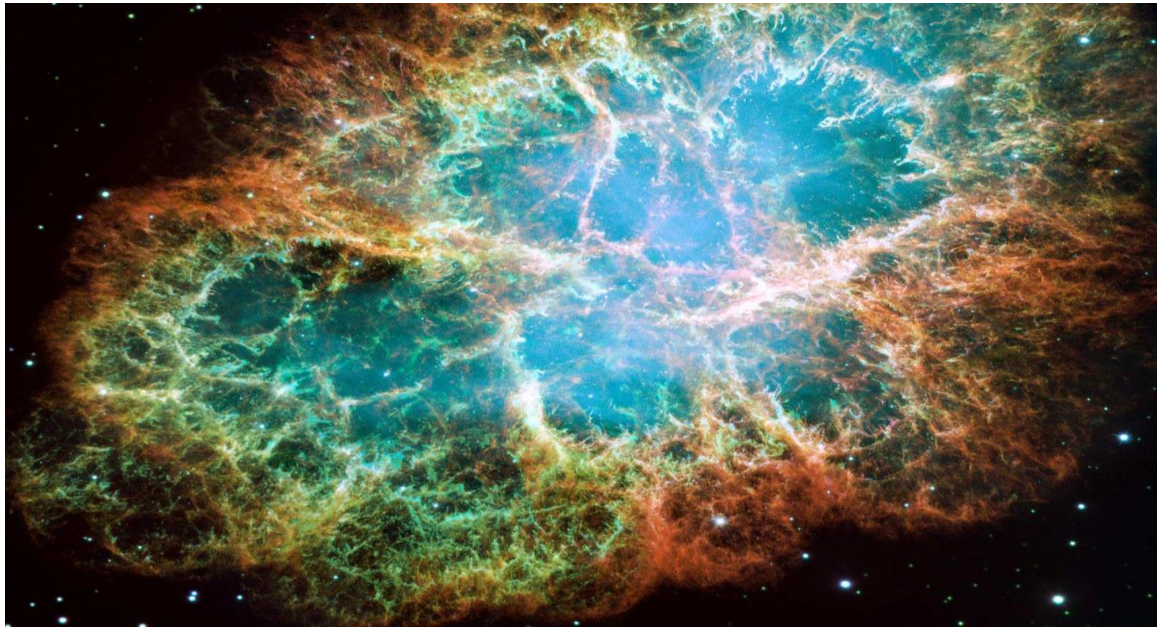
MHD Turbulence

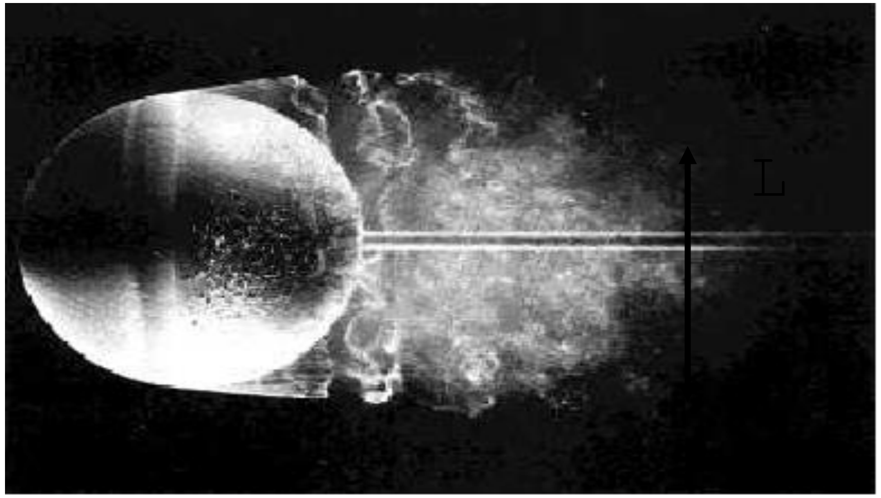


Foreground Fluctuations

We live in a turbulent world!!!

$$Re = LV/\nu = (L^2/\nu)/(L/V) = \tau_{diff}/\tau_{eddy}$$





Astrophysical flows have Re>10^{10}.

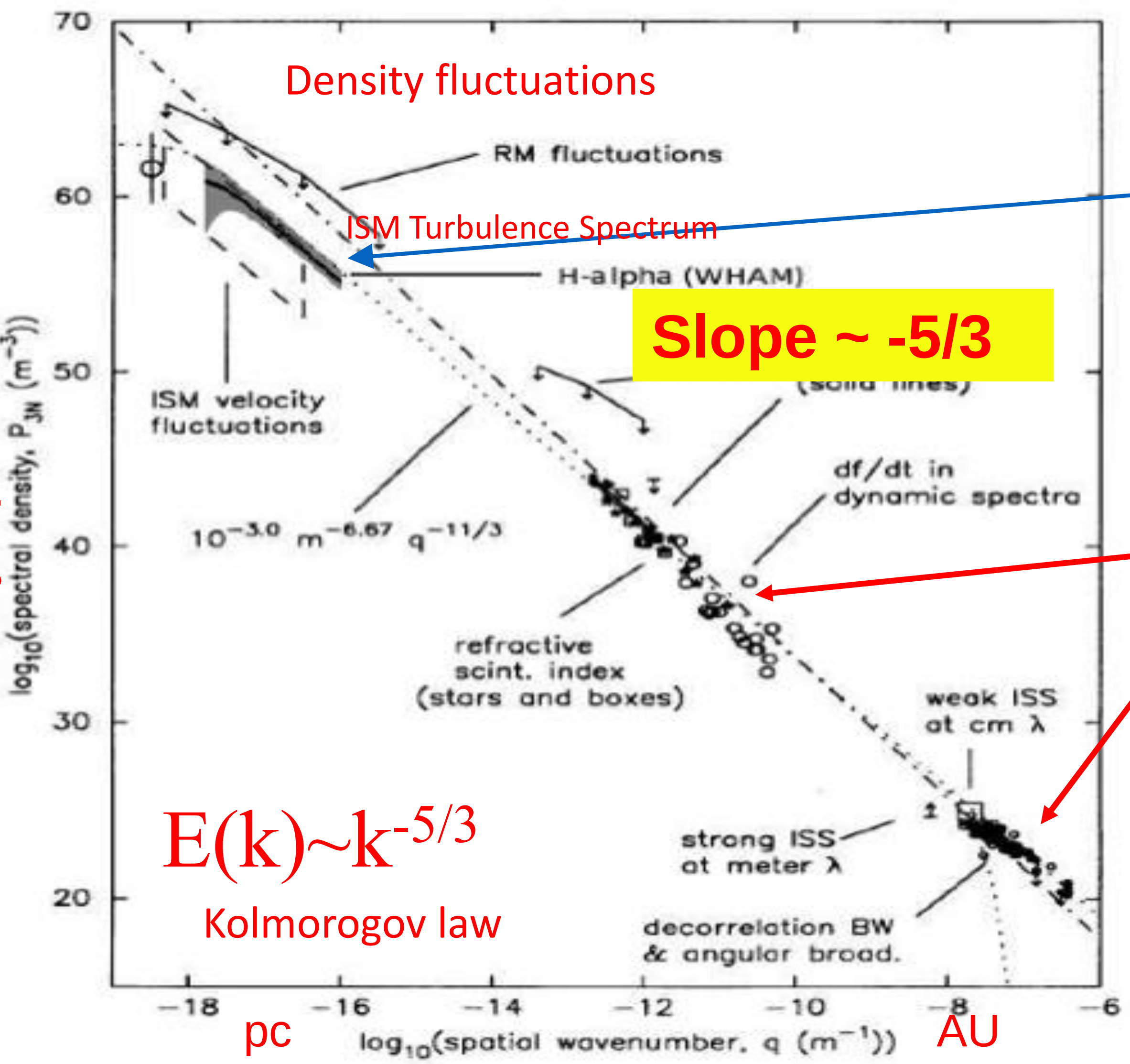
Re>>1 induces turbulence!

We live in a turbulent world!!!

$$Re = LV/\nu = (L^2/\nu)/(L/V) = \tau_{diff}/\tau_{eddy}$$

Kolmogorov Law is measured for electron density fluctuations

Electron density spectrum



Density fluctuations

ISM Turbulence Spectrum

Slope ~ -5/3

$E(k) \sim k^{-5/3}$

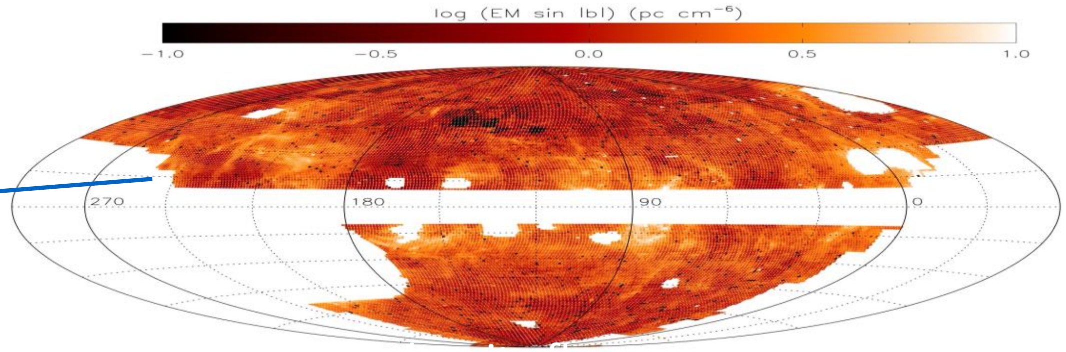
Kolmorogov law

pc

AU

Chepurnov & AL 2010

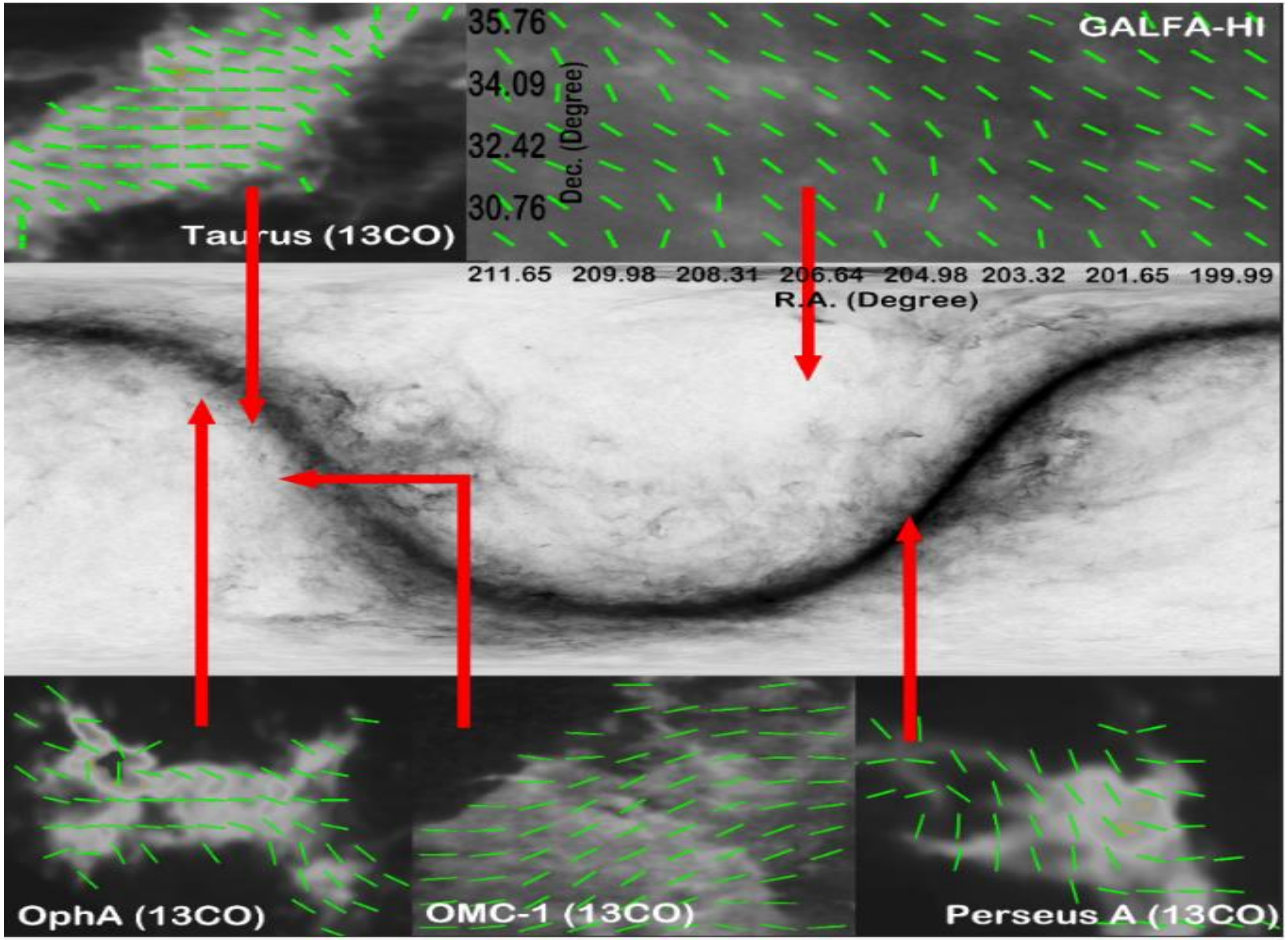
Fig. 5.— WHAM estimation for electron density overplotted on the figure of the Big Power Law in the sky figure from Armstrong et al. (1995). The range of statistical errors is marked with the gray color.



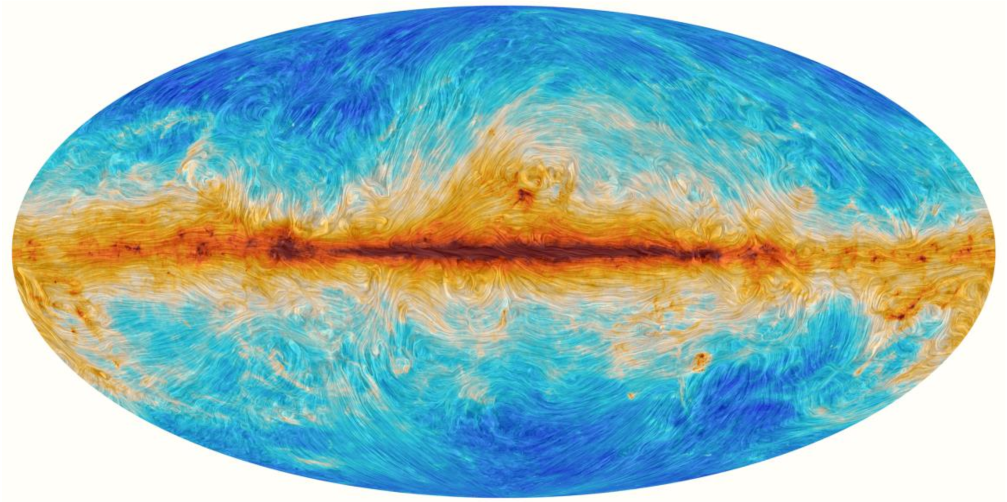
Scincillations and scattering

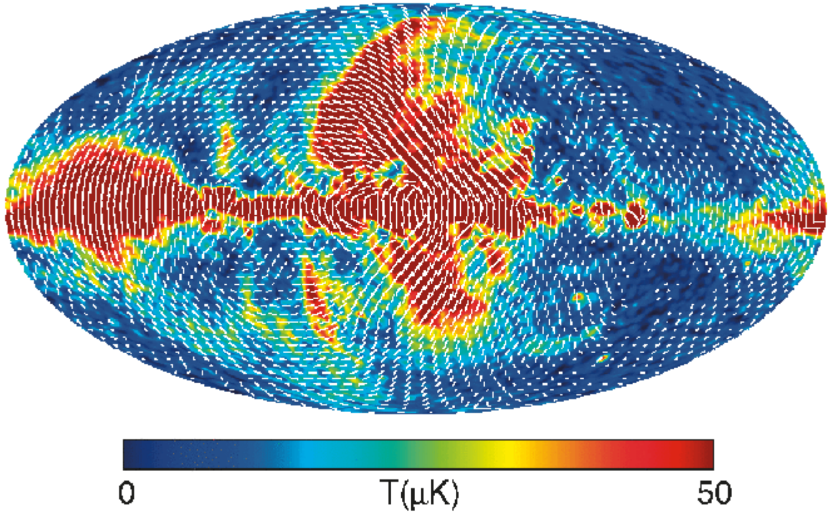
from Armstrong, Rickett & Spanger 1994

Part I: New Ways to map Magnetic field (2D and 3D)



Why does this crowd care? Answer: Polarized foregrounds arise due to galactic B-field



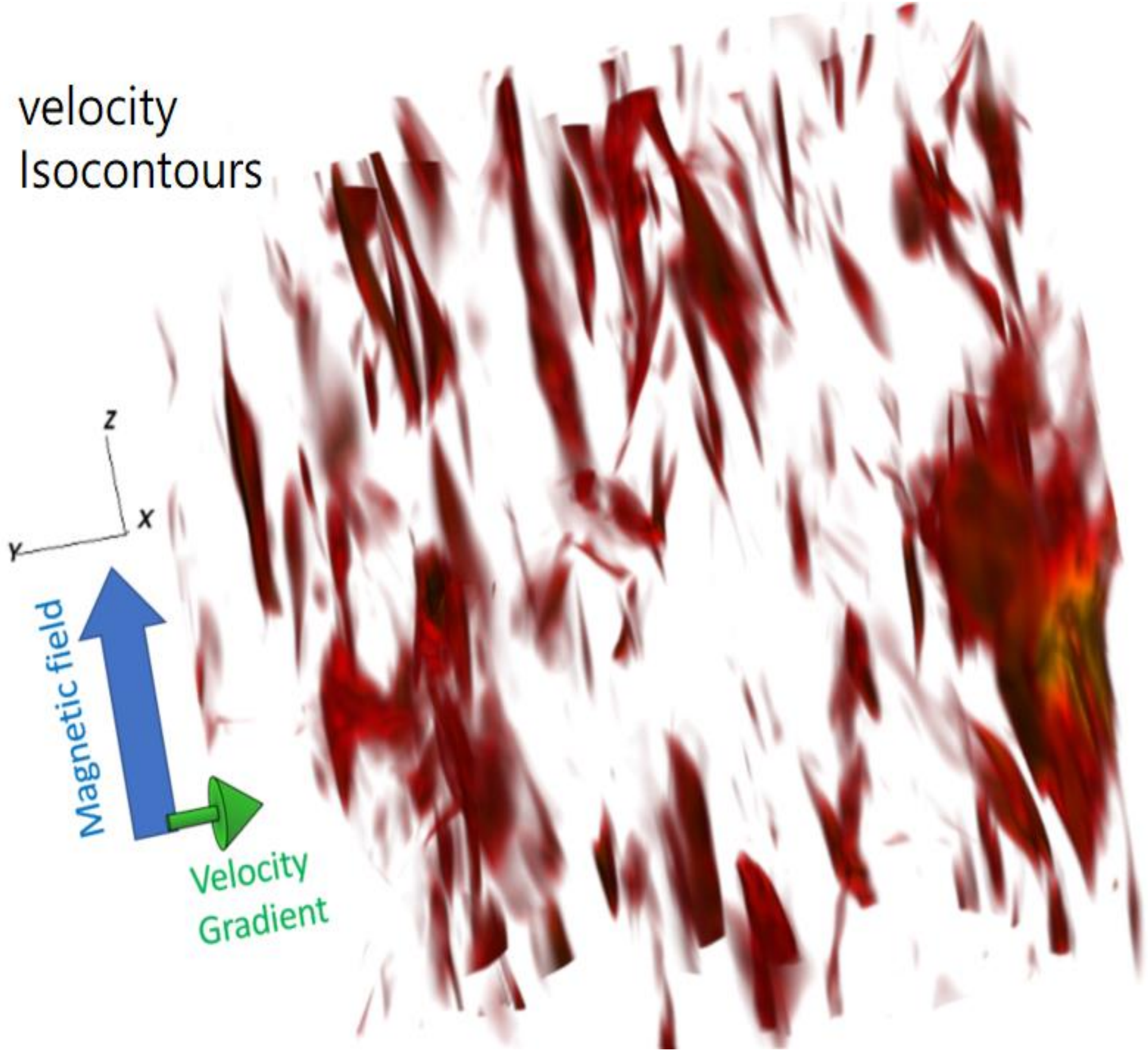


Hinshaw et al. 2008

Both galactic synchrotron and dust

Example: 3D polarization is 3D magnetic field + 3D distribution of dust.
Synchrotron is simpler, as 3D distribution of cosmic rays is smooth

Velocities in MHD turbulence are aligned with local magnetic field direction



Goldreich & Sridhar (1995)

AL & Vishniac (1999)
Cho & Vishniac (2000)
Maron & Goldreich (2001)

Local
direction

Velocity and magnetic field gradients trace local direction of magnetic field

$$v_l \sim l_\perp^{1/3}$$

GS95 prediction

Gradient $\perp$ to B

$$v_l/l_\perp \sim l_\perp^{1/3}/l_\perp = l_\perp^{-2/3}$$

Gradients of velocities (and magnetic field) are maximal perpendicular to local direction of the field

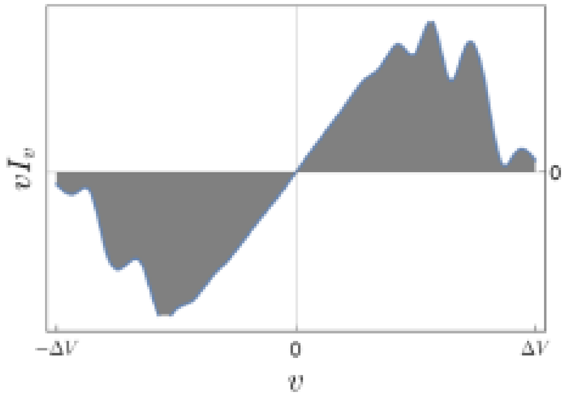
Velocity gradients trace local direction of B-field

$$v_l \sim l_\perp^{1/3}$$ GS95 prediction

Gradient $\perp$ to B $$v_l/l_\perp \sim l_\perp^{1/3}/l_\perp = l_\perp^{-2/3}$$

Gradients of velocities (and magnetic field) are maximal perpendicular ***to local direction*** of the field

Can use velocity centroids to represent velocities from observed dat



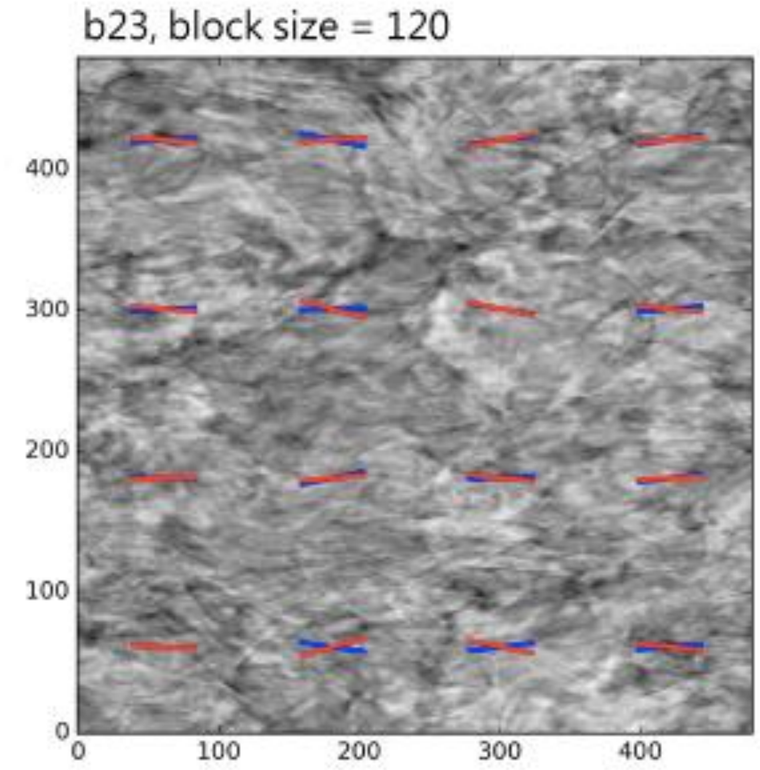
$$C = \int V_z(\mathbf{x})\rho(\mathbf{x})dz = \int V_z \rho_v dV_z$$

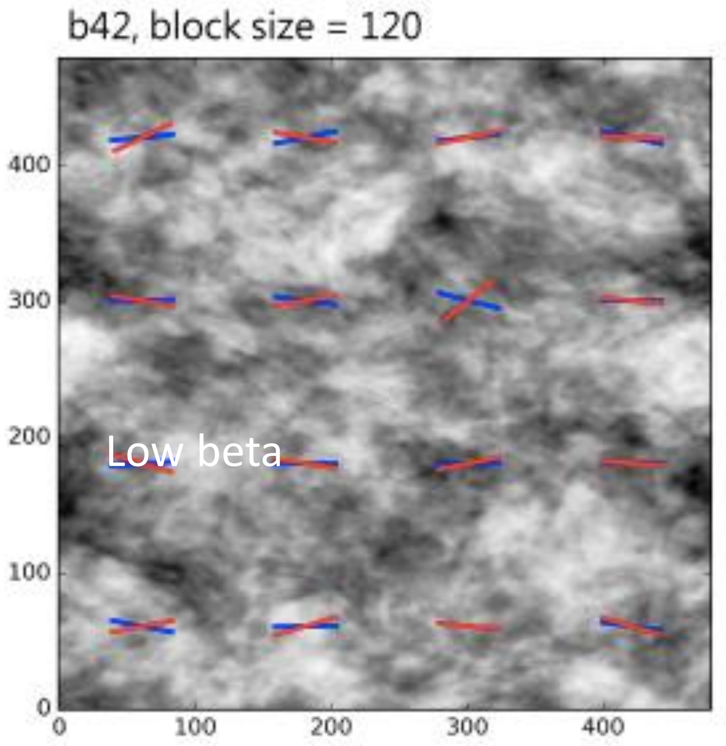
$$gradC = \int grad[V_z(\mathbf{x})\rho(\mathbf{x})]dz$$

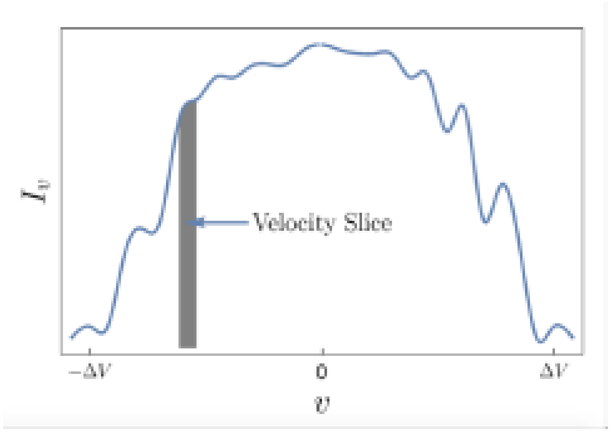
VCG technique: gradients of centroids trace B-field

Intensity fluctuations in thin channel maps trace velocities. Velocity Channel Gradients (VChGs) trace B- field

Thin channels are mostly influenced by velocities (AL & Pogosyan 2000)





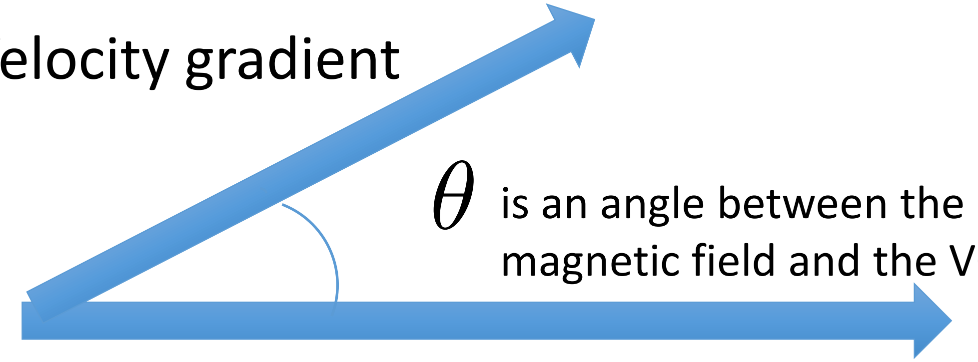


AL, Yuen& Sun 2017

To quantify the B-field tracing we use the alignment measure (AM)

$$AM = 2\langle \cos^2\theta - 1\rangle$$

Gonsalvez-Casanova & AL 2017



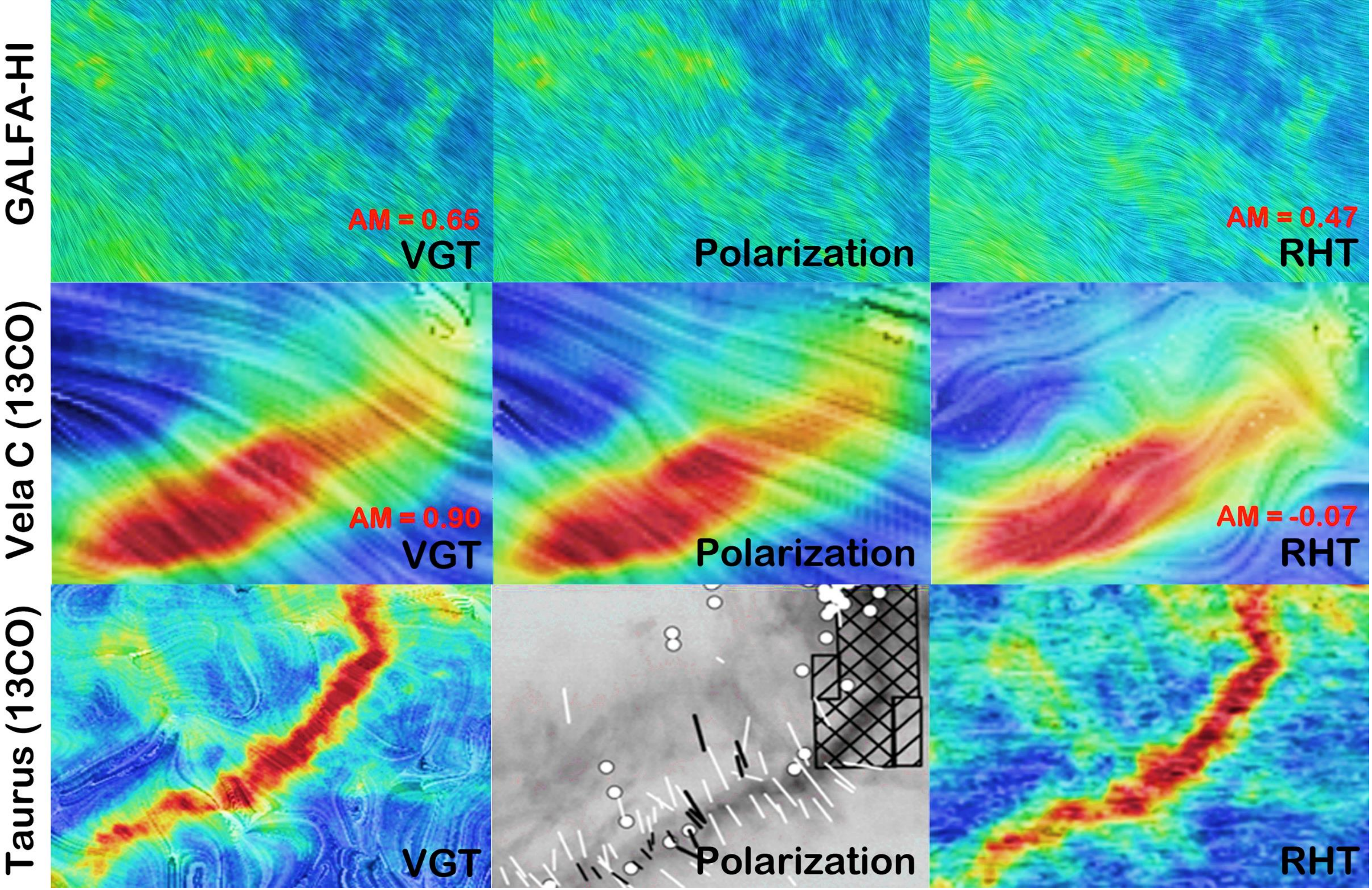
Velocity gradient

θ is an angle between the projected magnetic field and the VCGs

B

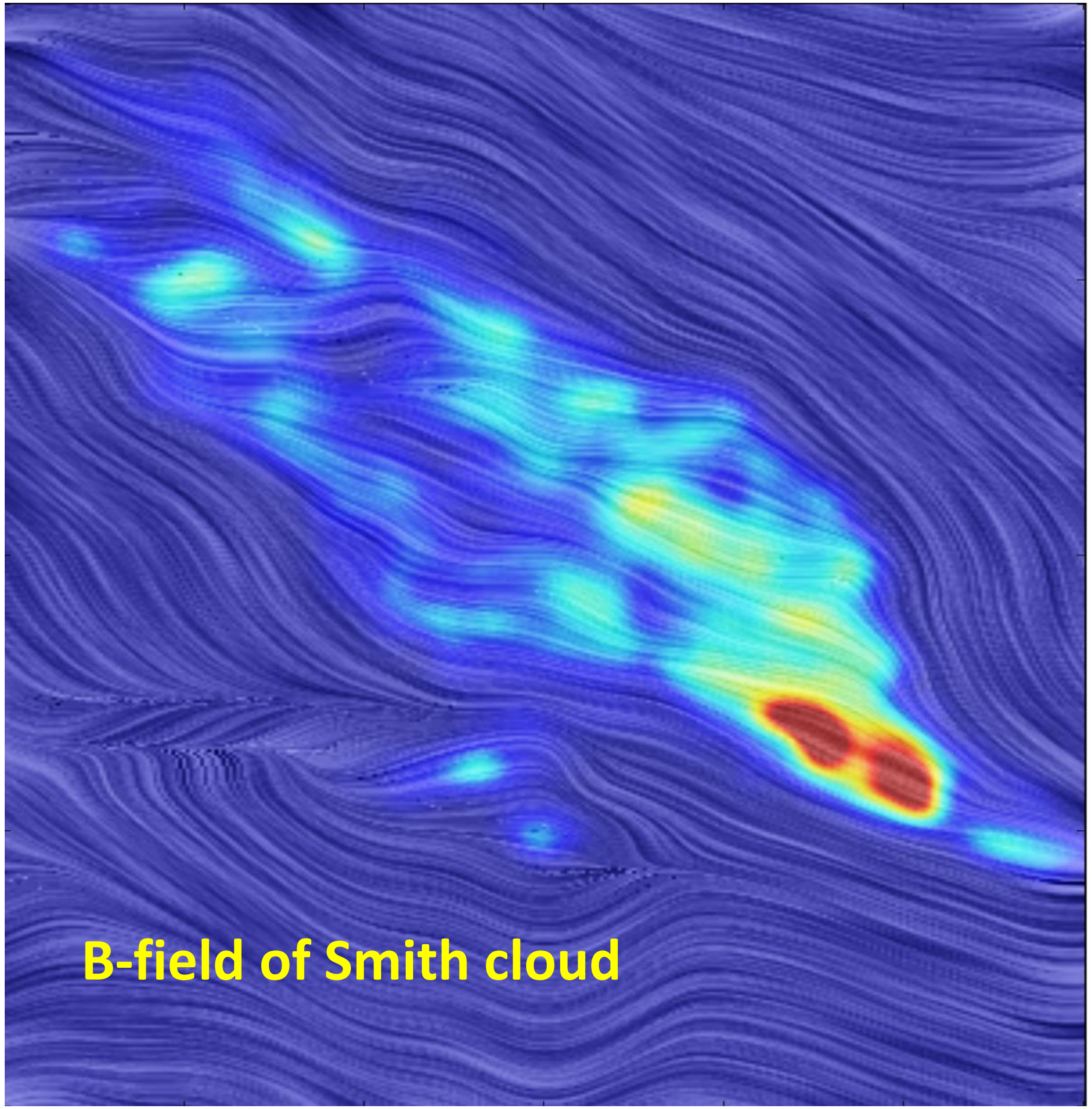
Perfect alignment AM=1
No alignment AM=0

Borrowed from grain alignment theory (e.g. AL 2007)

GALFA-HI
Vela C (13CO)
Taurus (13CO)
AM = 0.65
VGT
Polarization
AM = 0.47
RHT
AM = 0.90
VGT
Polarization
AM = -0.07
RHT
VGT
Polarization
RHT

AL & Yuen 2017

Velocity gradients allow us to study 3D B-fields: high velocity clouds as an example

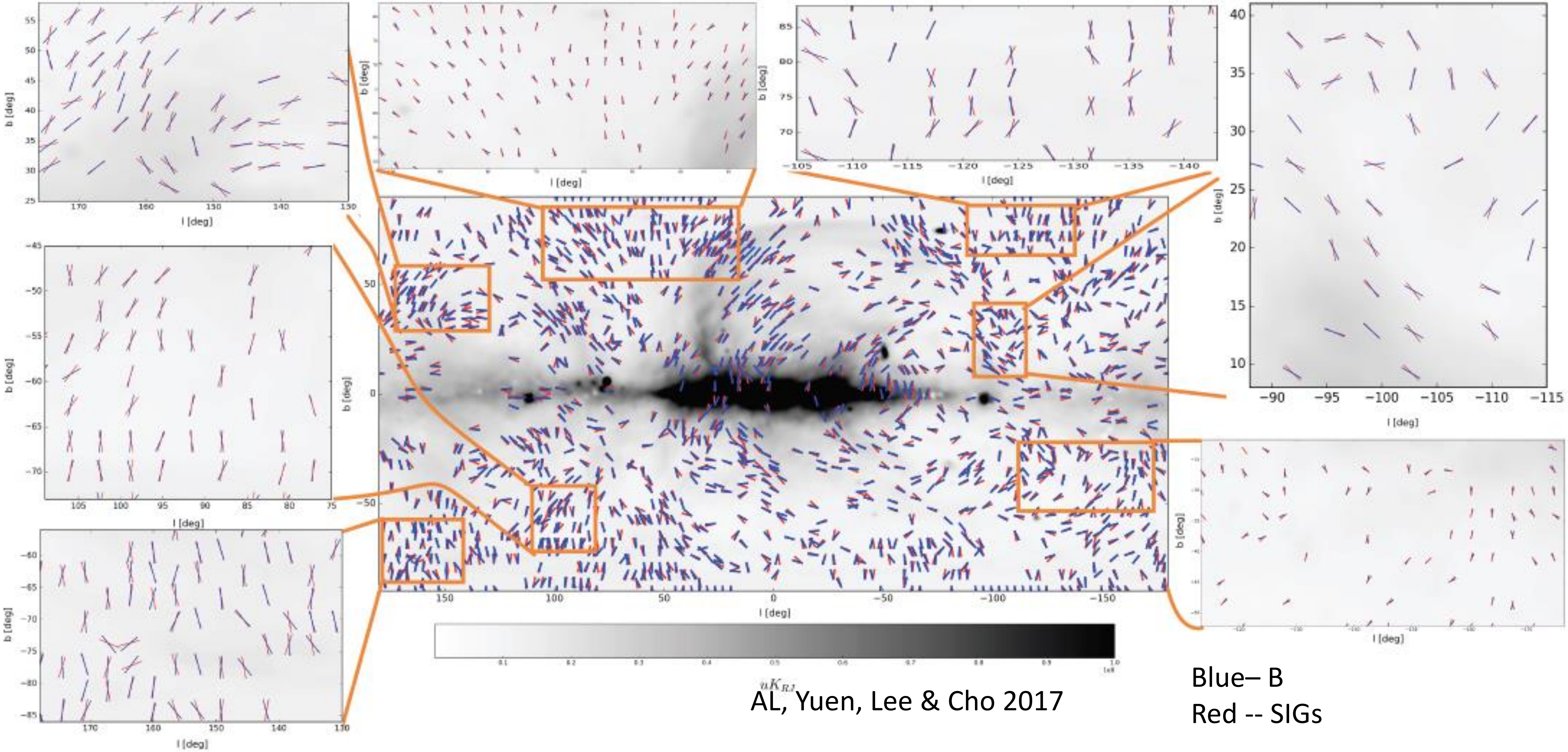


No other way to study these fields.

Check of validity: perpendicular alignment of velocity and density gradients (see more in the talk by Ka Ho Yuen)

	This proposal	Well-accepted observational method		Recently proposed alternative technique
	Velocity Gradient Technique	**Polarimetry** Dust, starlight, extinction & synchrotron	**Zeeman measurements**	**Rolling Hough Transform** Clark+2014
Probe plane-of-sky B-field directions?	☑ GL17, YL17ab	☑ e.g. Planck+2015, BLASTPol	✗ Only Line-of-Sight B-field (strength) is given	☑ e.g. Clark+2015
Provide B-field strength estimate?	☑ This proposal, Sec 3.2: $B\sim\sqrt{4\pi\rho}\frac{\delta v}{\sqrt{\delta\phi_v}}$	⚠ e.g. Chandrasekhar-Fermi method (1953), but **need spectroscopic info** for δv, which may be from different region	☑ e.g. Troland & Crutcher 2008, Crutcher+2010	✗
Works on diffuse ISM?	☑ e.g. YL17a, LY17 on neutral Hydrogen	☑ e.g. Planck+2015 high latitude	☑ e.g. Crutcher+2010 HI lines	☑ e.g. Clark+2015 on neutral Hydrogen
Works in molecular clouds?	☑ This proposal, Fig 5 on Vela C and Taurus 13CO data	⚠ Very low P% in star forming regions (Lazarian 2007)	☑ e.g. Crutcher+2010 OH & CN samples (up to $n\sim10^6 cm^{-3}$)	✗ This proposal, right row of Fig 5 clearly shows RHT gives disastrous prediction of B-field
Reliance of observational data	Spectroscopic data only	Polarimetry + Spectroscopic data esp. if you need $\|B\|$	Spectral line polarimetry	Spectroscopic data only

Sister Technique: Synchrotron Intensity Gradients also provide a new way to study B



AL, Yuen, Lee & Cho 2017

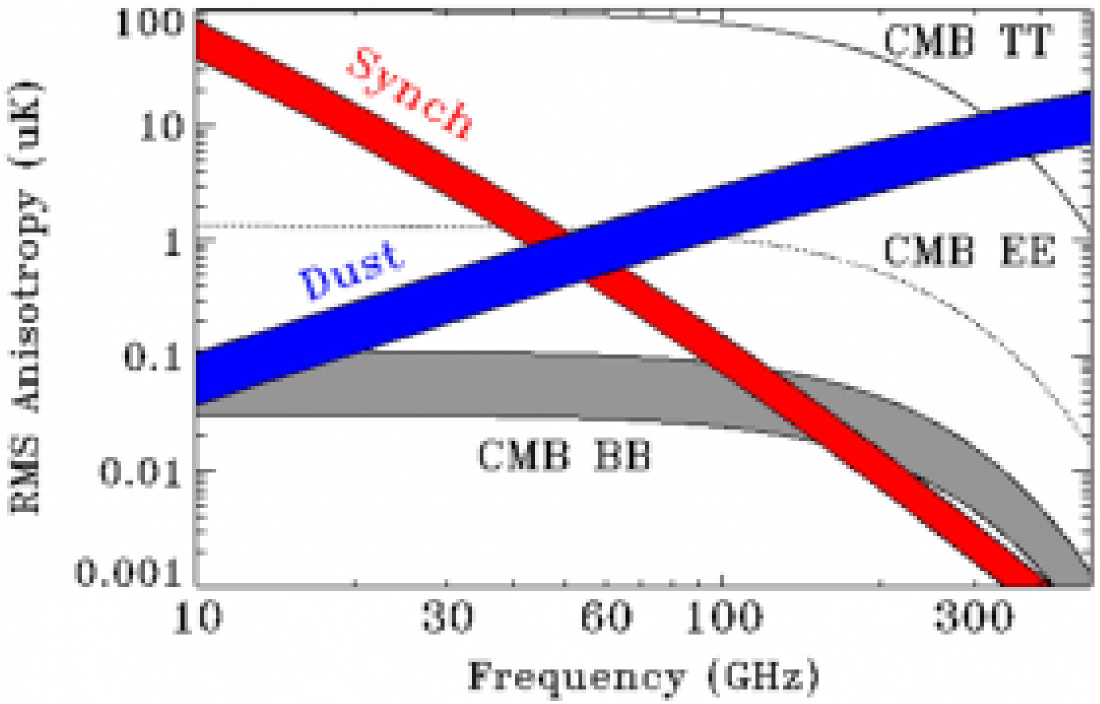
Blue– B
Red -- SIGs

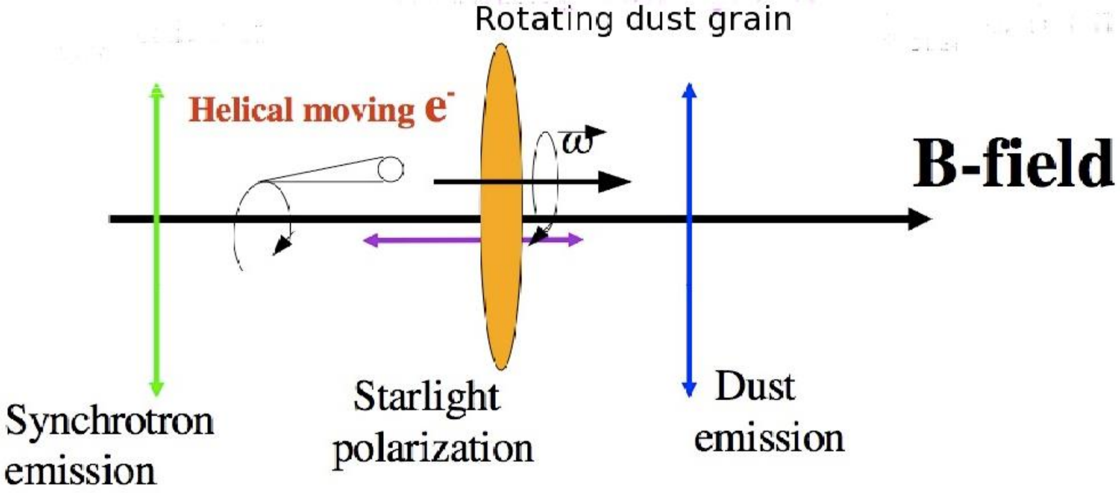
It is important to use the gradient information to filter the foregrounds

1. Use velocity gradients as prior for the polarized foreground analysis (similar to the suggestion by Susan Clark for filaments).
2. Use the Milky Way rotation curve to get 3D structure of B-field for better modeling (again similar to what Susan is going to do with filaments).

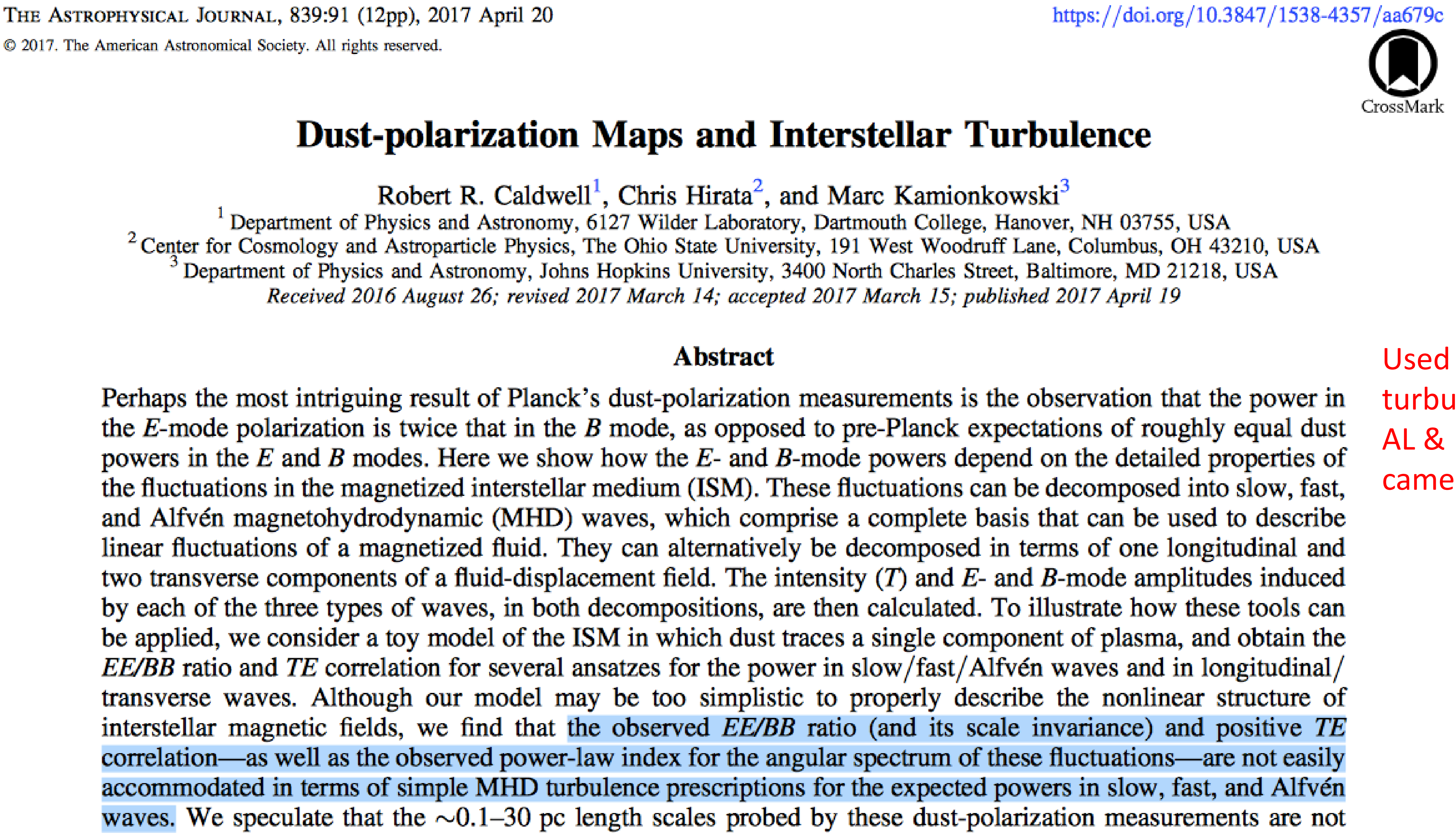
3. Combine velocity and synchrotron intensity gradients to separate the dust versus synchrotron contribution.
4. Stay tuned for new developments ☺

Part II: MHD turbulence is responsible for B/E ratio for dust and synchrotron





Is there any problem with the turbulence picture that we know?



The Astrophysical Journal, 839:91 (12pp), 2017 April 20
https://doi.org/10.3847/1538-4357/aa679c

Dust-polarization Maps and Interstellar Turbulence

Robert R. Caldwell[1], Chris Hirata[2], and Marc Kamionkowski[3]
[1] Department of Physics and Astronomy, 6127 Wilder Laboratory, Dartmouth College, Hanover, NH 03755, USA
[2] Center for Cosmology and Astroparticle Physics, The Ohio State University, 191 West Woodruff Lane, Columbus, OH 43210, USA
[3] Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218, USA

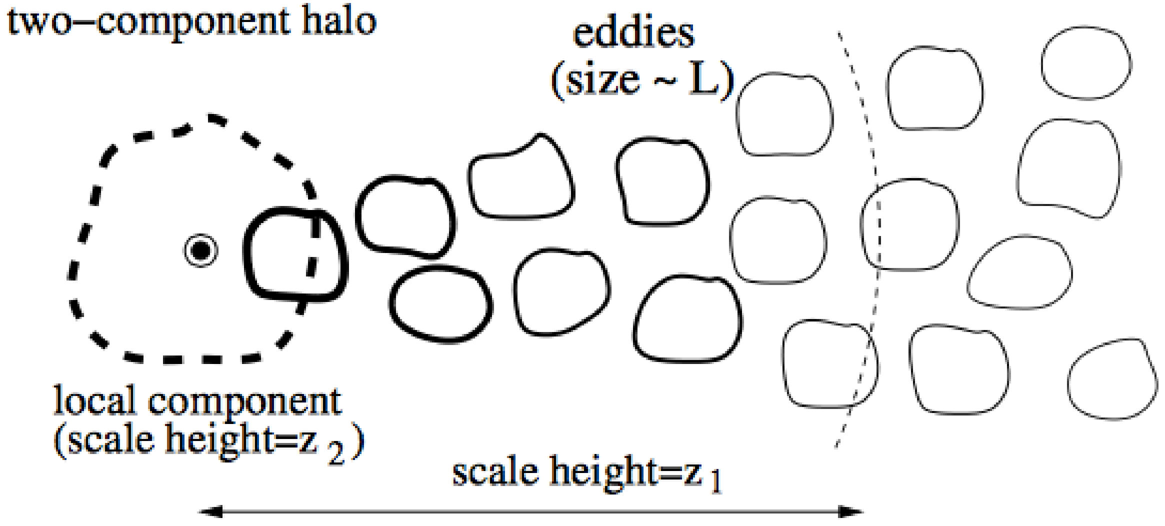
Received 2016 August 26; revised 2017 March 14; accepted 2017 March 15; published 2017 April 19

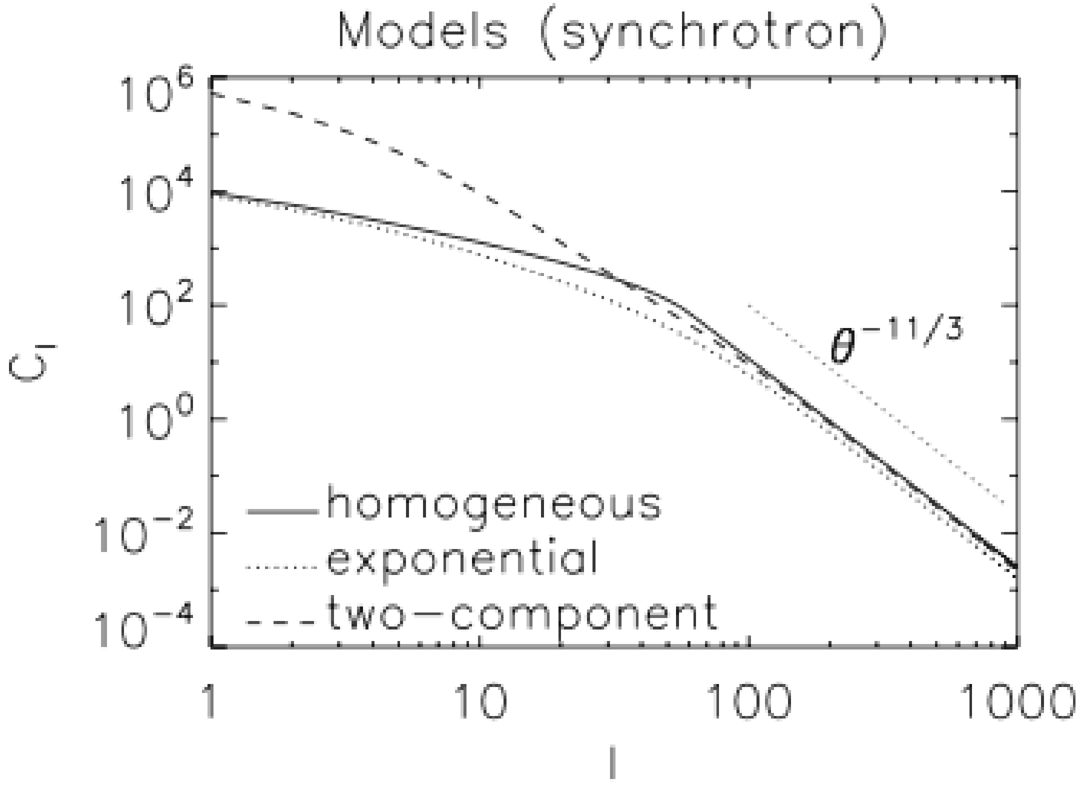
Abstract

Perhaps the most intriguing result of Planck's dust-polarization measurements is the observation that the power in the *E*-mode polarization is twice that in the *B* mode, as opposed to pre-Planck expectations of roughly equal dust powers in the *E* and *B* modes. Here we show how the *E*- and *B*-mode powers depend on the detailed properties of the fluctuations in the magnetized interstellar medium (ISM). These fluctuations can be decomposed into slow, fast, and Alfvén magnetohydrodynamic (MHD) waves, which comprise a complete basis that can be used to describe linear fluctuations of a magnetized fluid. They can alternatively be decomposed in terms of one longitudinal and two transverse components of a fluid-displacement field. The intensity (*T*) and *E*- and *B*-mode amplitudes induced by each of the three types of waves, in both decompositions, are then calculated. To illustrate how these tools can be applied, we consider a toy model of the ISM in which dust traces a single component of plasma, and obtain the *EE/BB* ratio and *TE* correlation for several ansatzes for the power in slow/fast/Alfvén waves and in longitudinal/transverse waves. Although our model may be too simplistic to properly describe the nonlinear structure of interstellar magnetic fields, we find that the observed *EE/BB* ratio (and its scale invariance) and positive *TE* correlation—as well as the observed power-law index for the angular spectrum of these fluctuations—are not easily accommodated in terms of simple MHD turbulence prescriptions for the expected powers in slow, fast, and Alfvén waves. We speculate that the ∼0.1–30 pc length scales probed by these dust-polarization measurements are not

Used the description of turbulent modes from AL & Pogosyan 2012 and came to this paradox

A model of the galactic disk and the halo changes the spectral index





Cho & AL 2010

For high latitudes the magnetic field is more regular, i.e. small Alfven Mach number

Alfven Mach number $$M_A = \frac{\text{inection velocity}}{\text{Alfven velocity}} \approx \frac{\delta B}{B}$$ Is less than unity

Planck provided the measurements of the parameters of the synchrotron and dust foregrounds

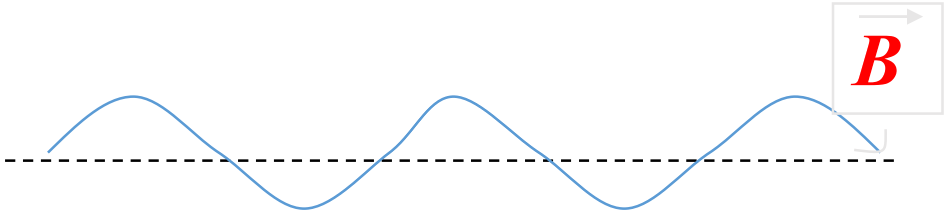
B to E ratio

$$R = \frac{\int \mathrm{d}\Omega \tilde{B}^2}{\int \mathrm{d}\Omega \tilde{E}^2}$$

TE Correlation

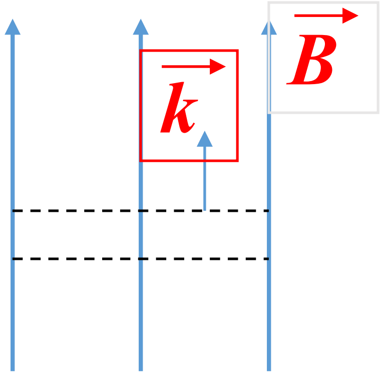
$$r_i = \frac{\int \mathrm{d}\Omega \left\langle TE \right\rangle}{\sqrt{\int \mathrm{d}\Omega \left\langle TT \right\rangle}\sqrt{\int \mathrm{d}\Omega \left\langle EE \right\rangle}}$$

Basic Modes of MHD motions

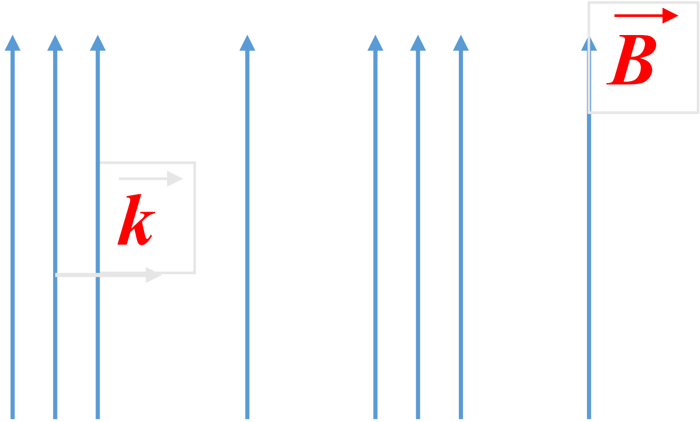


Alfven mode ($v=V_A\cos\theta$)

incompressible;
restoring force=mag. tension



slow mode ($v=c_s\cos\theta$)



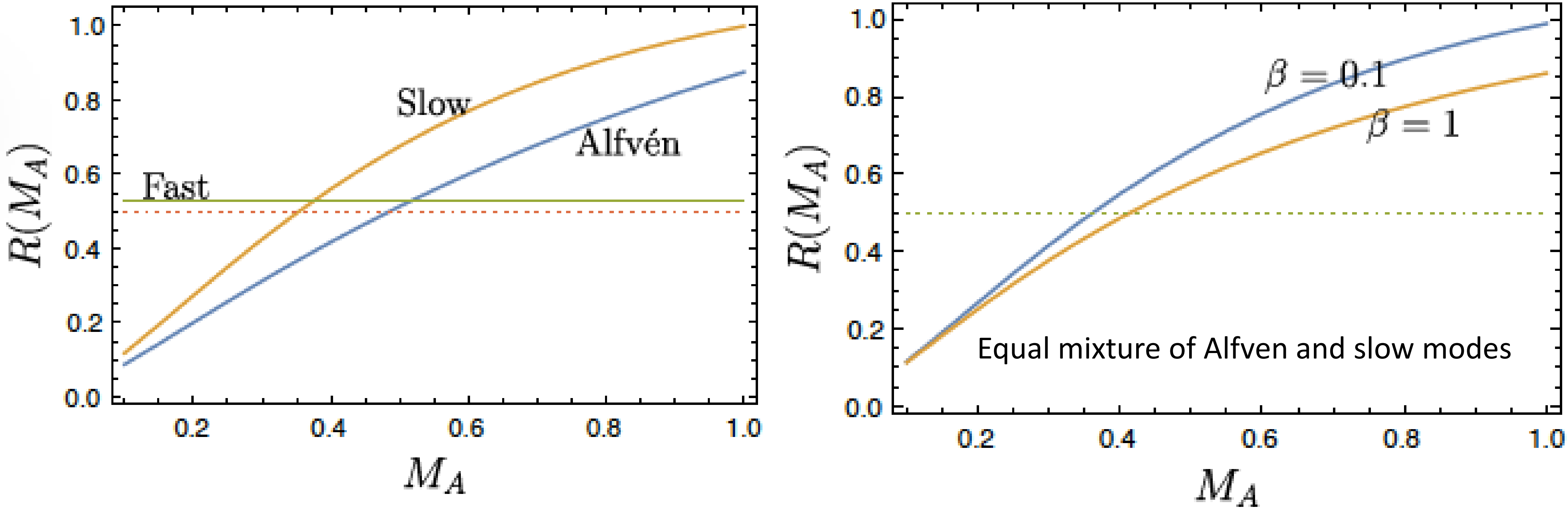
fast mode ($v=V_A$)

R for the equal mixture of Alfven and slow modes

$$M_A = \frac{\text{inection velocity}}{\text{Alfven velocity}} \approx \frac{\delta B}{B}$$

$$\beta = \frac{P_{gas}}{P_{mag}}$$

Dust polarization



Kandel, AL & Pogosyan 2017

Results in Kandel, AL & Pogosyan 2017 support MHD nature of foreground fluctuations

Measure	observed value	Required M_A	Dominant MHD modes
Synchrotron B/E ratio	0. 35	<0.5	mixture of Alfven and slow modes
Polarized dust B/E ratio	0. 5	<0.5	mixture of Alfven and slow modes
Synchrotron TE correlation	positive	no limitation	anything
Polarized dust TE correlation	positive	no limitation	slow>fast modes, no n-B correlation

The spectral index of dust polarization fluctuations can arise from changes of emissivity along the line of sight

Summary

Understanding of MHD Turbulence

Understanding foregrounds

???

B to E ratio for synchrotron and dust

TE ratio for synchrotron and dust

Synchrotron intensity gradients for tracing B-fields

velocity gradients for tracing B-fields