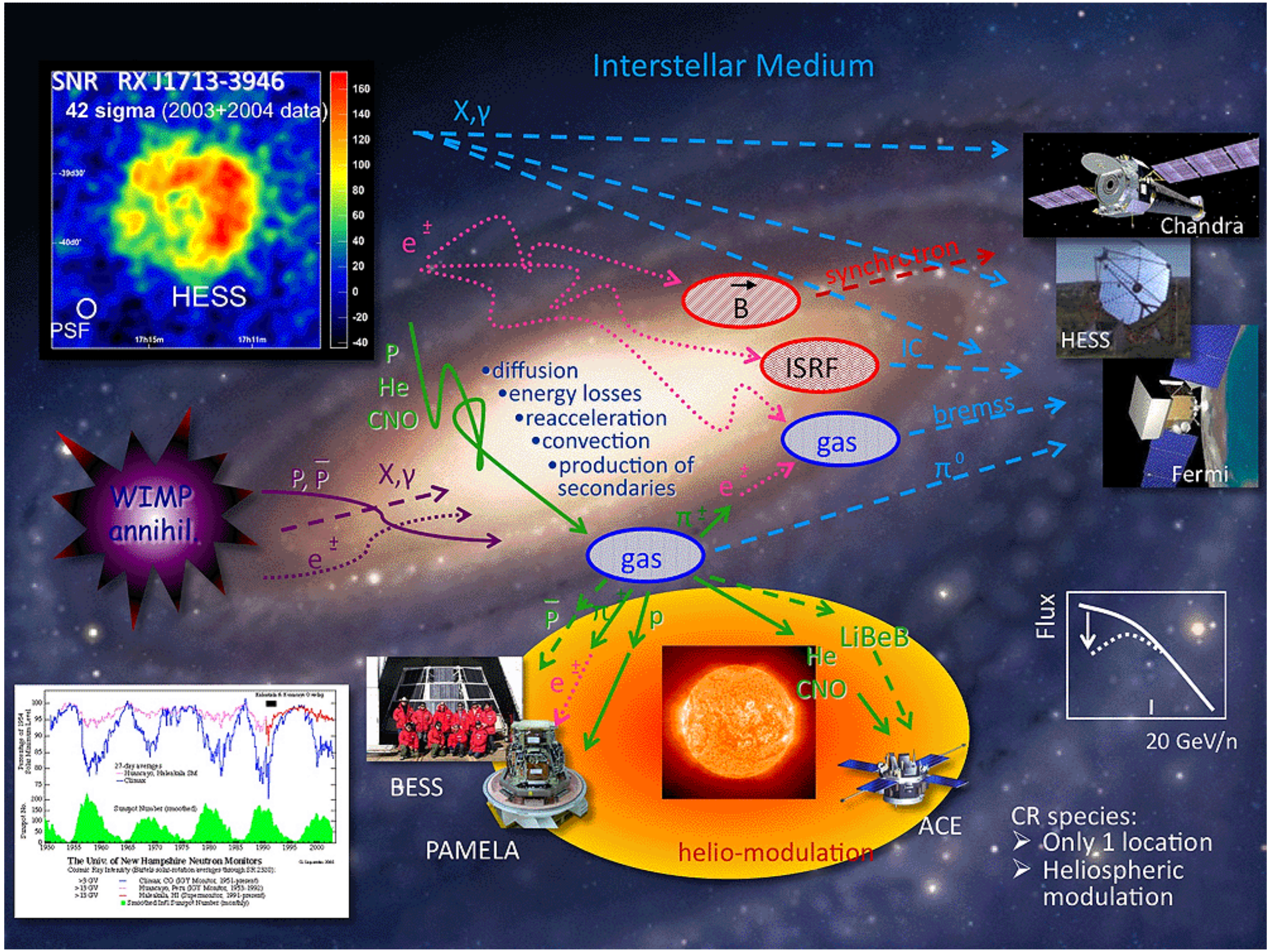
Turbulence and Cosmic Ray Propagation



Alex Lazarian
UW-Madison

Structure of the talk:

1. Role of MHD turbulence in turbulent world
2. Foregrounds are turbulent and magnetic turbulence produces polarized fluctuations
3. Importance of Alfven Mach number for CR research
4. Higher resolution polarimetry + Gradient Technique to find Alfven Mach number.

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We live in a turbulent world

We live in a turbulent world

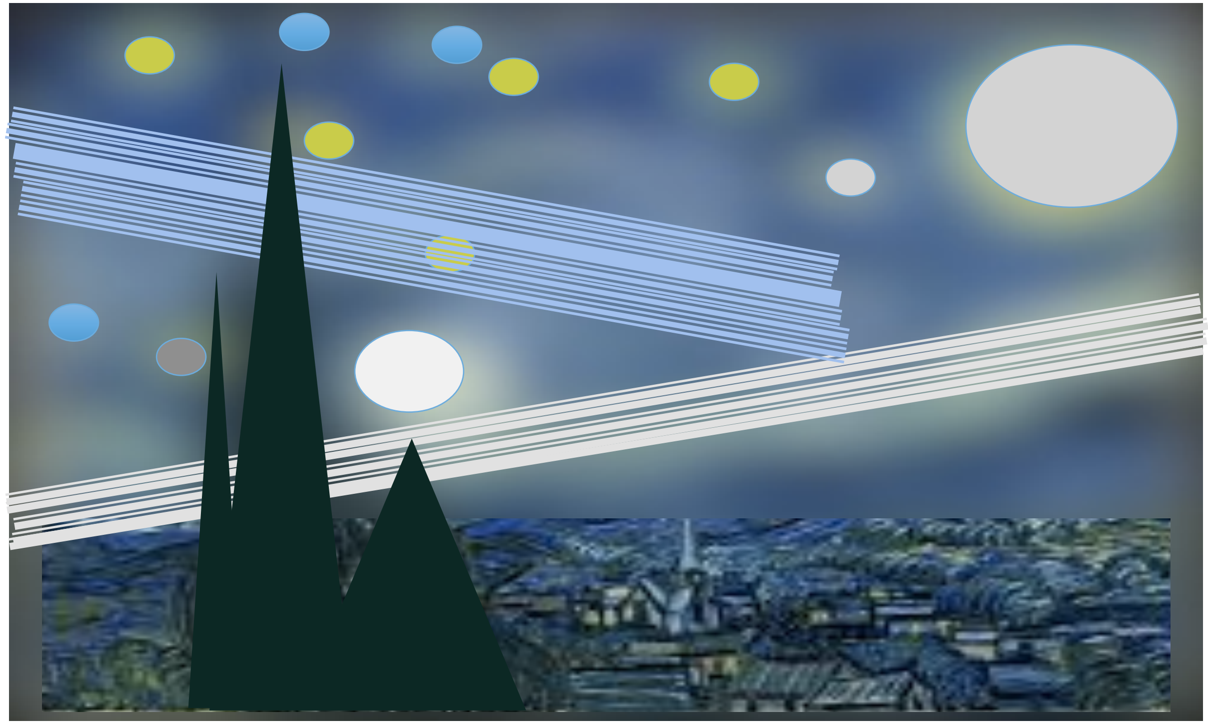
We live in a turbulent world

Starry Night

WITH turbulence

WITHOUT turbulence

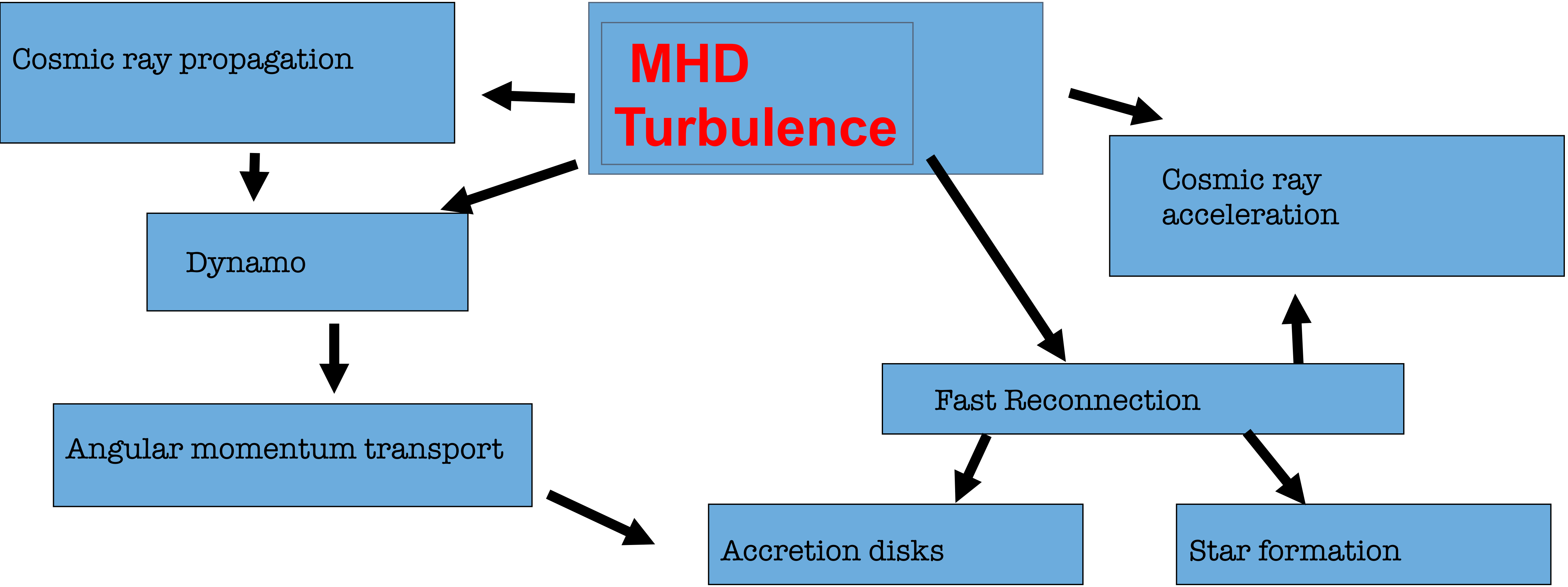
Van Gogh



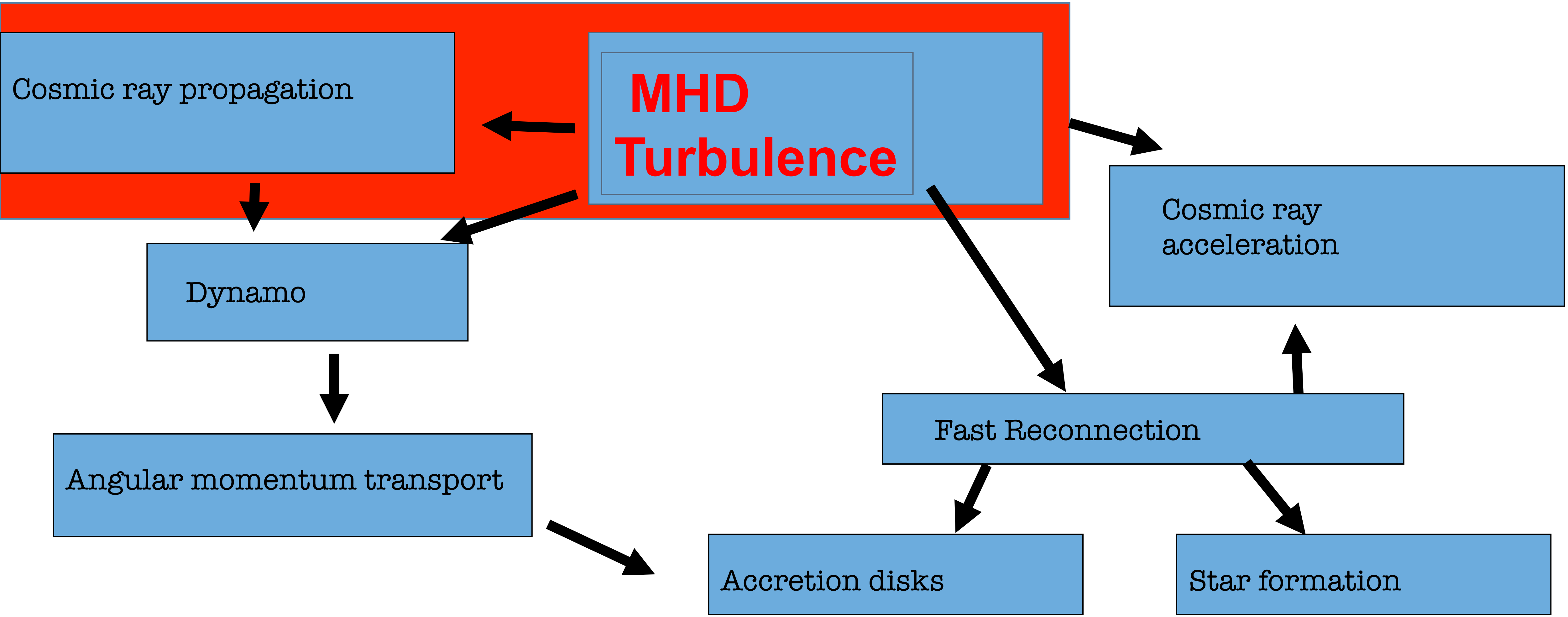
S. Xu

It would take 4 month for coffee to get sweet if not for turbulence

MHD turbulence plays crucial role for key astrophysical processes



MHD turbulence plays crucial role for key astrophysical processes



We discuss only the dependance of CR propagation on Alfven Mach number M_A =\delta B/B

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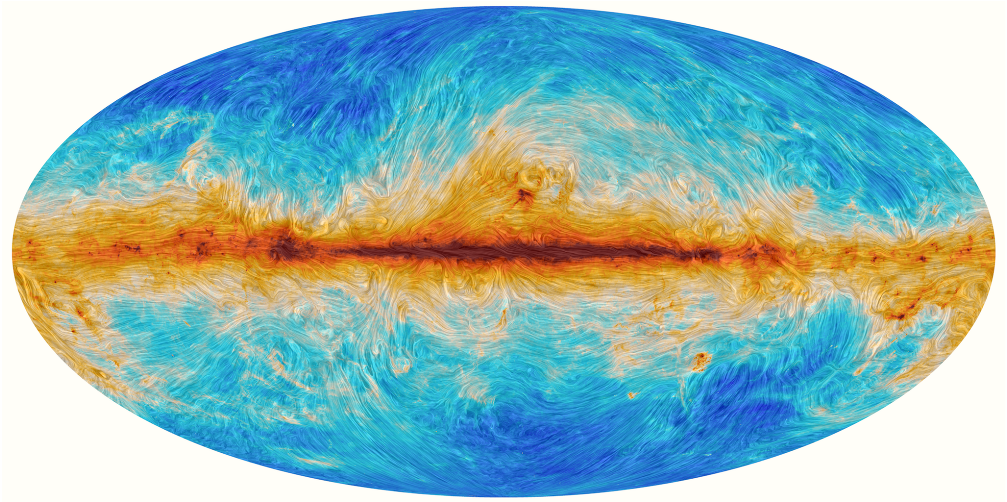
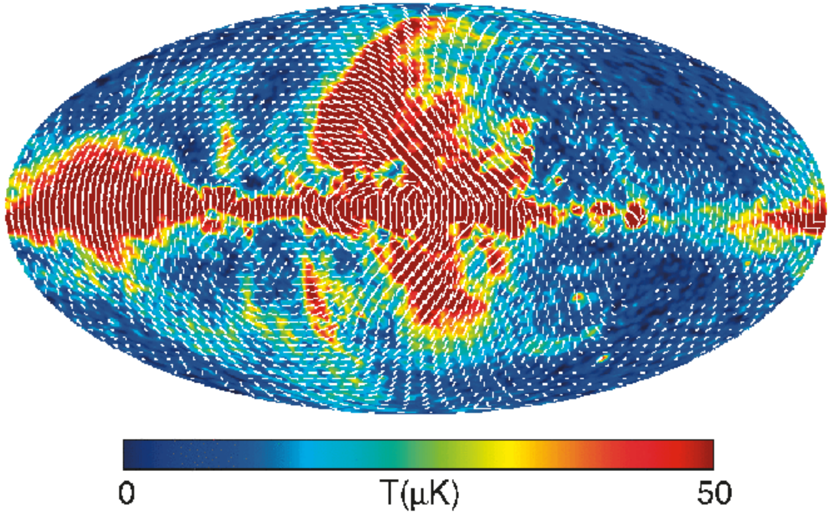
Are foreground E/B, TE correlations arise from turbulence?





Hinshaw et al. 2008

Model: subAlfvenic turbulence as the variations of magnetic field directions are limited

Are foreground E/B, TE correlations from turbulence?

THE ASTROPHYSICAL JOURNAL, 839:91 (12pp), 2017 April 20
https://doi.org/10.3847/1538-4357/aa679c

CrossMark

Dust-polarization Maps and Interstellar Turbulence

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[2] Center for Cosmology and Astroparticle Physics, The Ohio State University, 191 West Woodruff Lane, Columbus, OH 43210, USA
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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

Yes, E/B, TE correlations are from turbulence!

Statistical properties of galactic CMB foregrounds: dust and synchrotron

D. Kandel,[1,2] A. Lazarian[3] and D. Pogosyan[2]
[1] Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94309, USA
[2] Physics Department, University of Alberta, Edmonton, T6G 2E1, Canada
[3] Department of Astronomy, University of Wisconsin, 475 North Charter Street, Madison, WI 53706, USA

26 February 2018

ABSTRACT
Recent *Planck* observations have revealed some of the important statistical properties of synchrotron and dust polarizations, namely, the B to E mode power and temperature-E (TE) mode cross-correlation. In this paper, we extend our analysis in Kandel et al. (2017) that studied B to E mode power ratio for polarized dust emission to include TE cross-correlation and develop an analogous formalism for synchrotron signal, all using a realistic model of magnetohydrodynamical (MHD) turbulence. Our results suggest that the *Planck* results for both synchrotron and dust polarizations can be understood if the turbulence in the Galaxy is sufficiently sub-Alfvénic. We also show how B to E ratio as well as the TE cross-correlation can be used to study media magnetization, compressibility, and level of density-magnetic field correlation.

Yes, E/B, TE correlations are from turbulence!

Statistical properties of galactic CMB foregrounds: dust and synchrotron

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CMB studies constrain Alfven Mach number $M_A = V_L/V_A$

ABSTRACT
Recent *Planck* observations have revealed some of the important statistical properties of synchrotron and dust polarizations, namely, the B to E mode power and temperature-E (TE) mode cross-correlation. In this paper, we extend our analysis in Kandel et al. (2017) that studied B to E mode power ratio for polarized dust emission to include TE cross-correlation and develop an analogous formalism for synchrotron signal, all using a realistic model of magnetohydrodynamical (MHD) turbulence. Our results suggest that the *Planck* results for both synchrotron and dust polarizations can be understood if the turbulence in the Galaxy is sufficiently sub-Alfvénic. We also show how B to E ratio as well as the TE cross-correlation can be used to study media magnetization, compressibility, and level of density-magnetic field correlation.

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M_A determines the perpendicular diffusion of cosmic rays in the Milky Way

Realized by Jokipii & Parker 69, Jokipii 73 but turbulence model was not right

The study with modern understanding of MHD turbulence is in AL& Vishniac 99

Strong subAlfvenic turbulence at scales $s<l_{trans}$ results in superdiffusion:

$$\ell_\perp^2 \sim \frac{s^3}{27L} M_A^4,$$

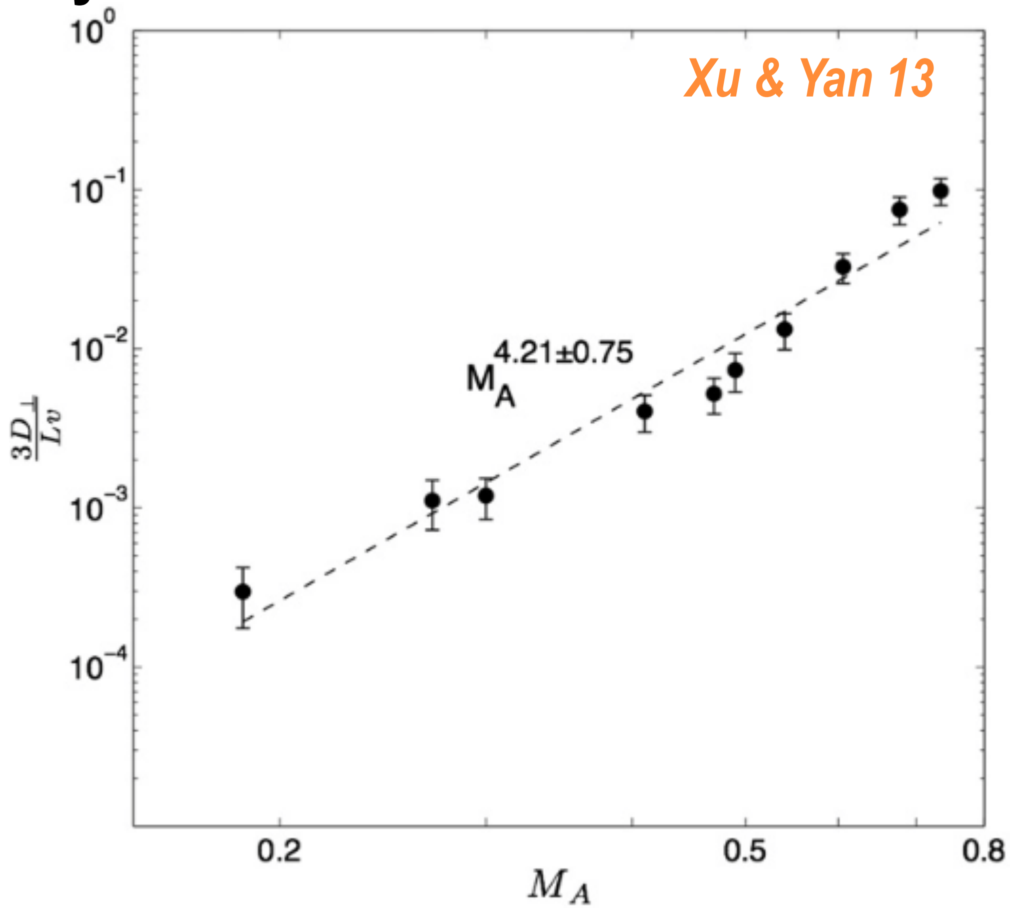
At scales $s>l_{trans}$ results in ordinary diffusion:

$$\ell_\perp^2 \sim sLM_A^4.$$

Differs from the textbook (see Jokipii & Parker 69) M_A^2 dependence

The dependence on forth power of Alfven Mach number is confirmed numerically

Diffusive regime



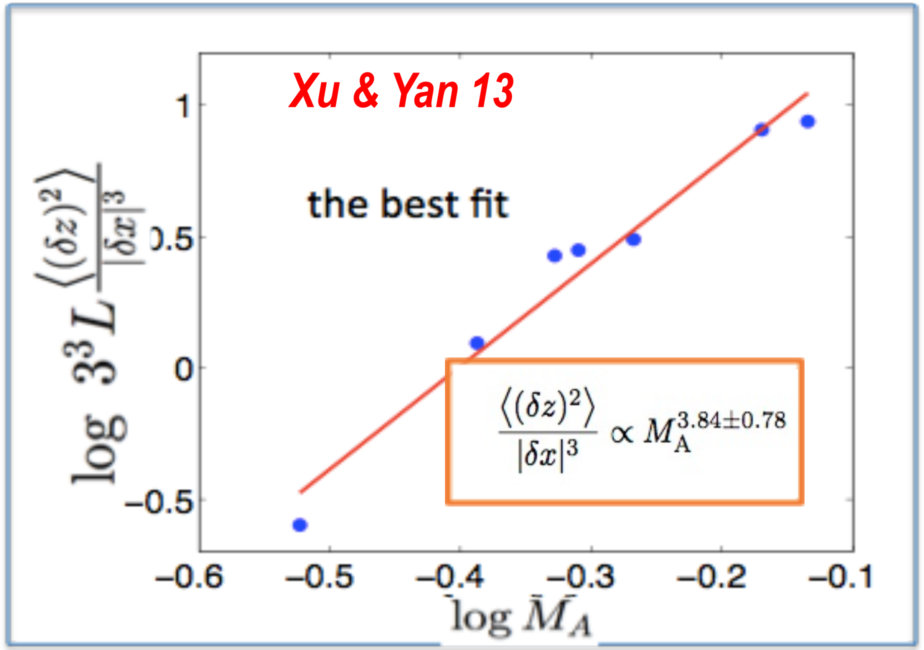
To compare with $D_{\perp,\mathrm{global}} \approx D_\parallel M_A^4,$ *in AL06, Yan & AL08*

The dependence on forth power of Alfven Mach number is confirmed

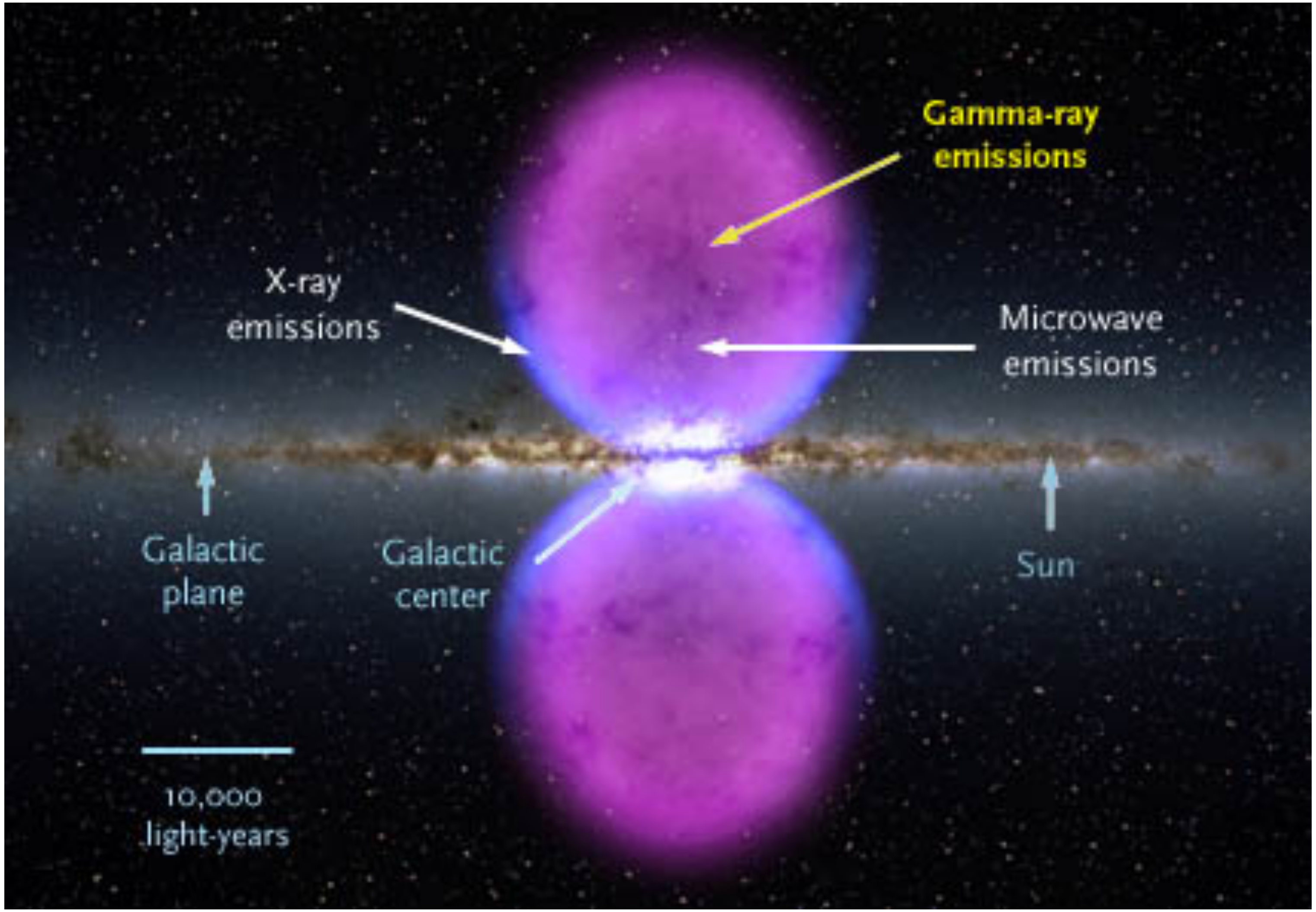
$$< (\delta z)^2 >= \frac{|\delta x|^3}{3^3 L} M_A^4$$

AL & Vishniac 1999;
Yan & AL 2008

Superdiffisive regime



Streaming instability limits the parallel diffusion of cosmic rays

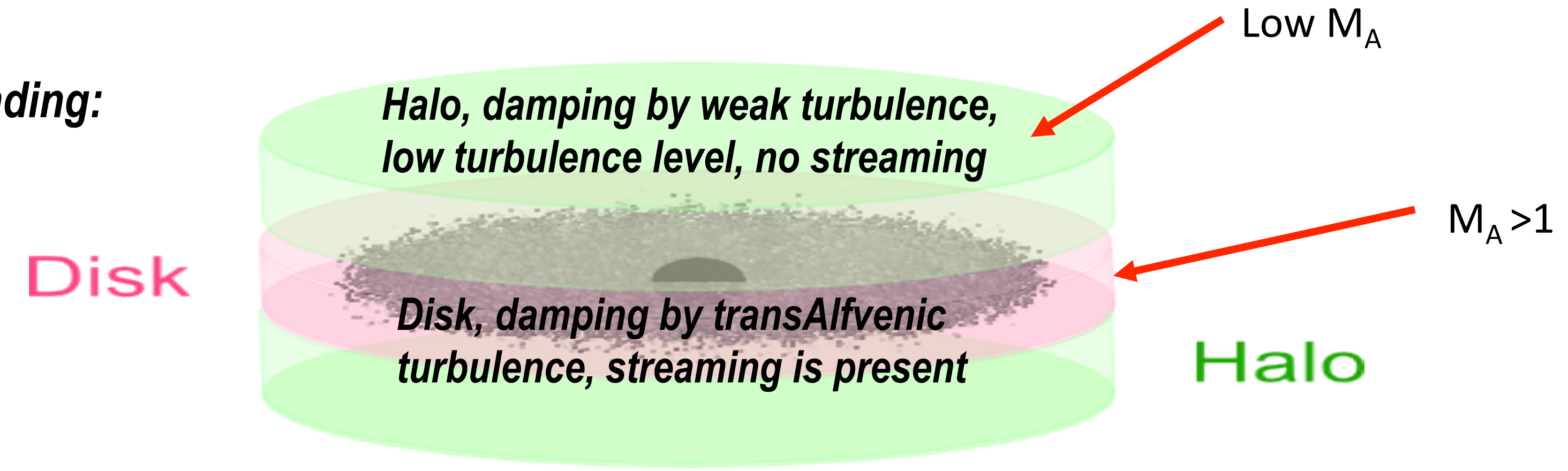


AL16 obtained the expressions for CR instability as a function of M_A

AL16 "new leaky box" model is valid if the level of turbulence in Halo is small

CRs stream in the disk where turbulence is transAlfvenic and randomize by streaming instability in the halo.

New understanding:



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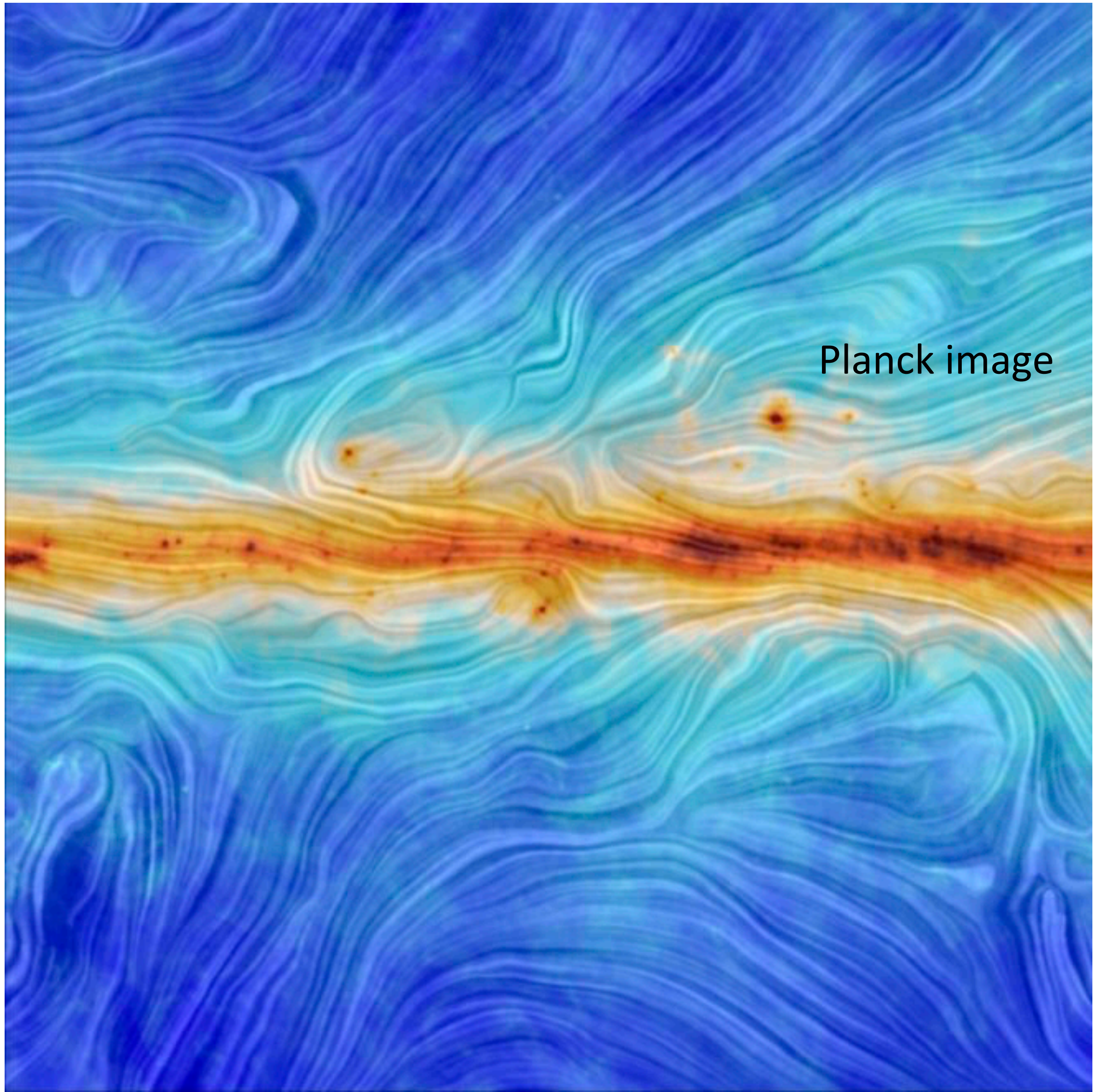
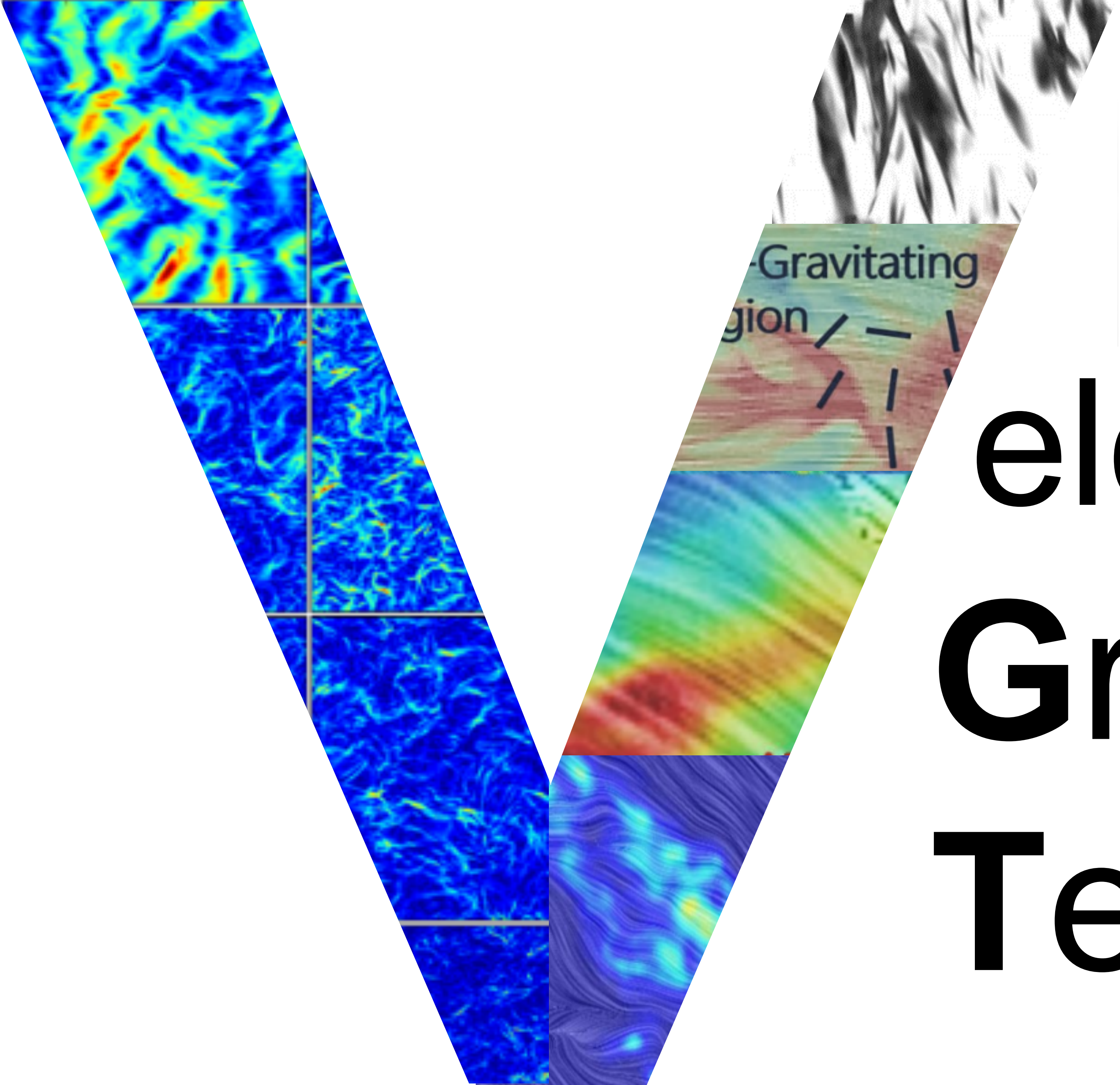
M_A can be estimated from tangling of magnetic field inferred from polarimetry



The higher the resolution, the better

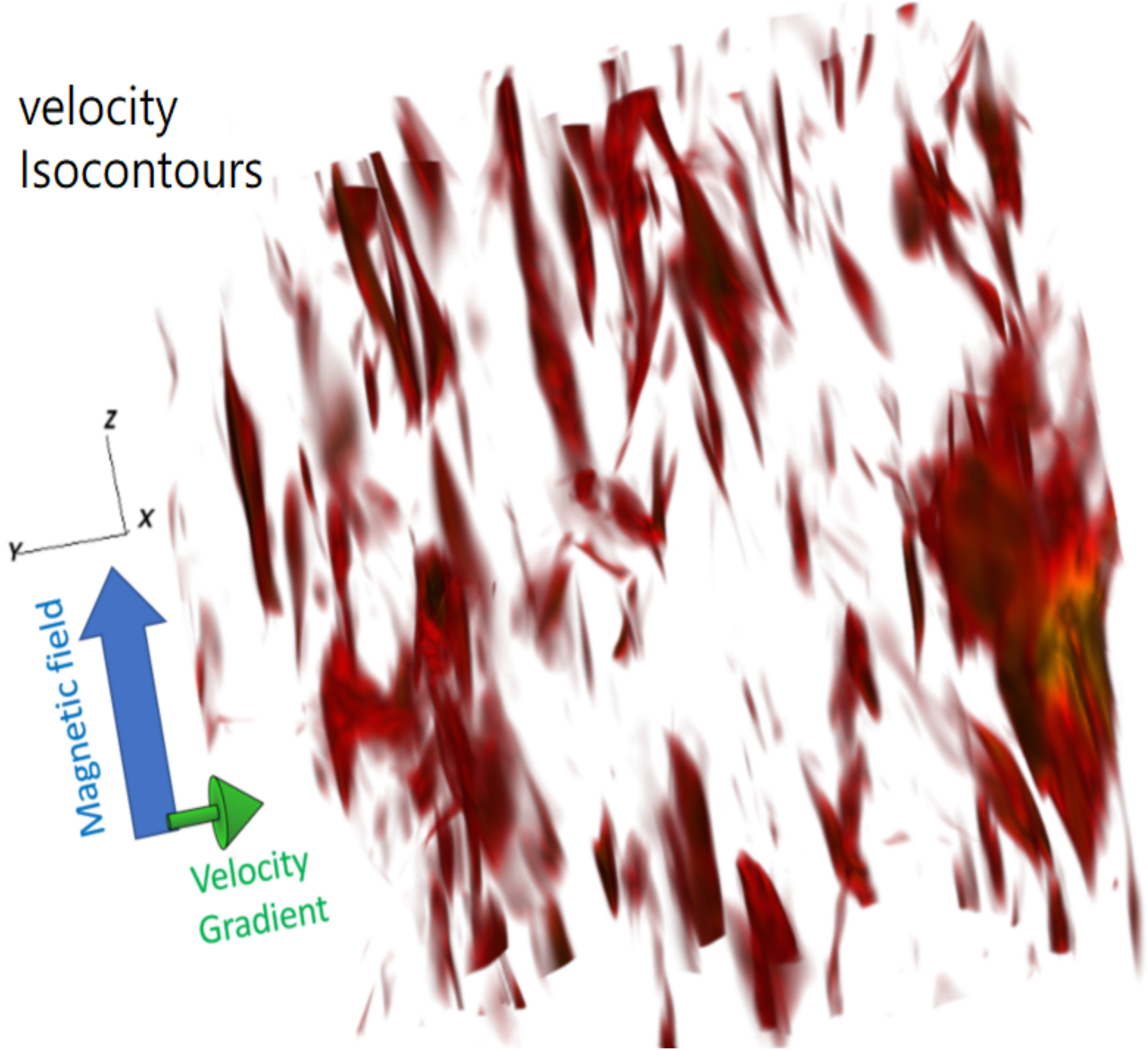


elocity

Gradient

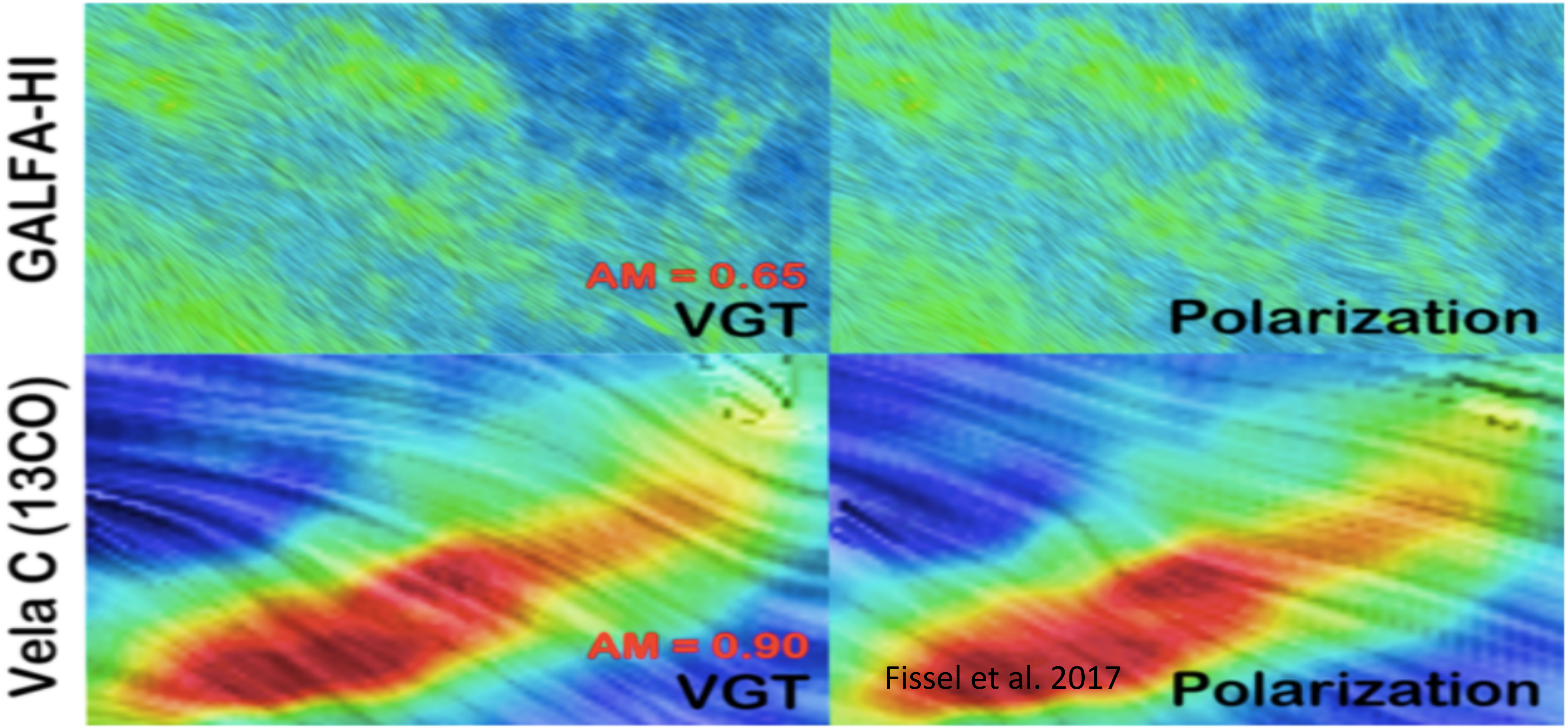
Technique

Illustration of Velocity Gradients: Velocities in MHD turbulence are perpendicular to the local magnetic field direction in diffuse media

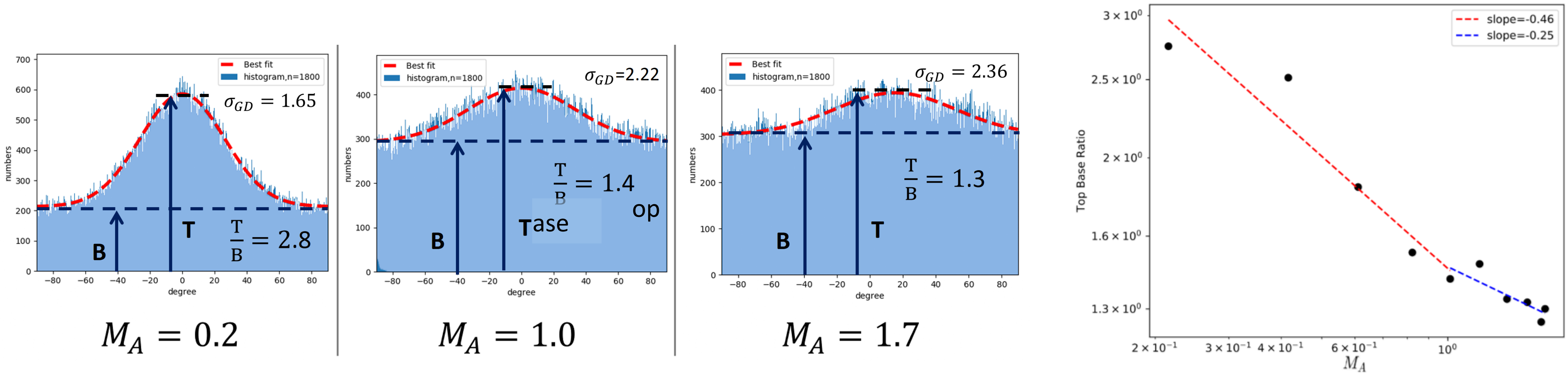


MHD subAlfvenic simulations
AL & Yuen 2018

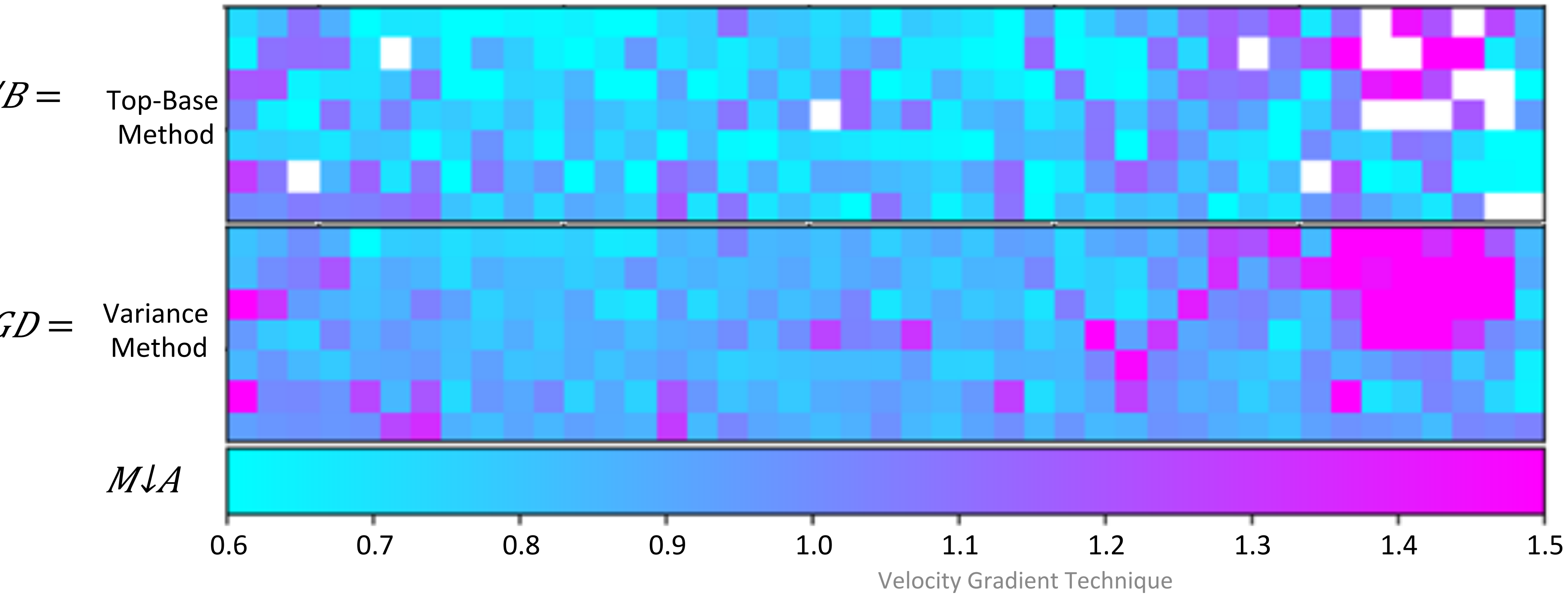
Radically new way to study magnetic fields: Velocity Gradients



AL & Yuen 2018

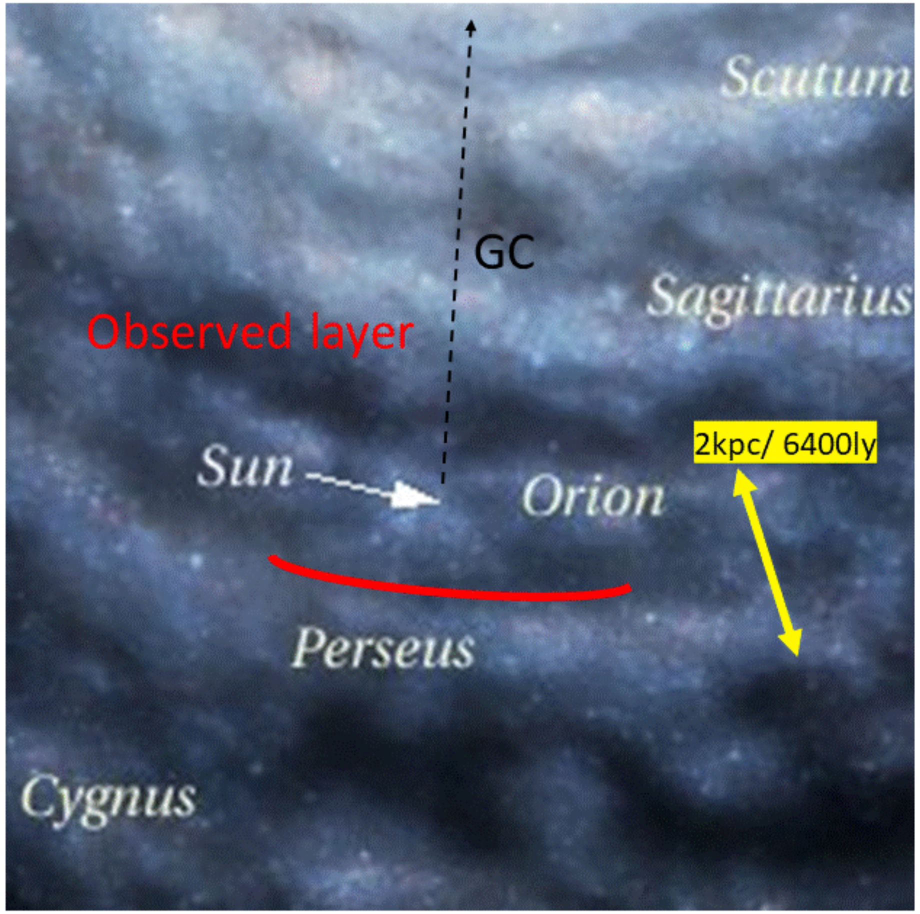


Statistics of gradient angles $\rightarrow M_A$

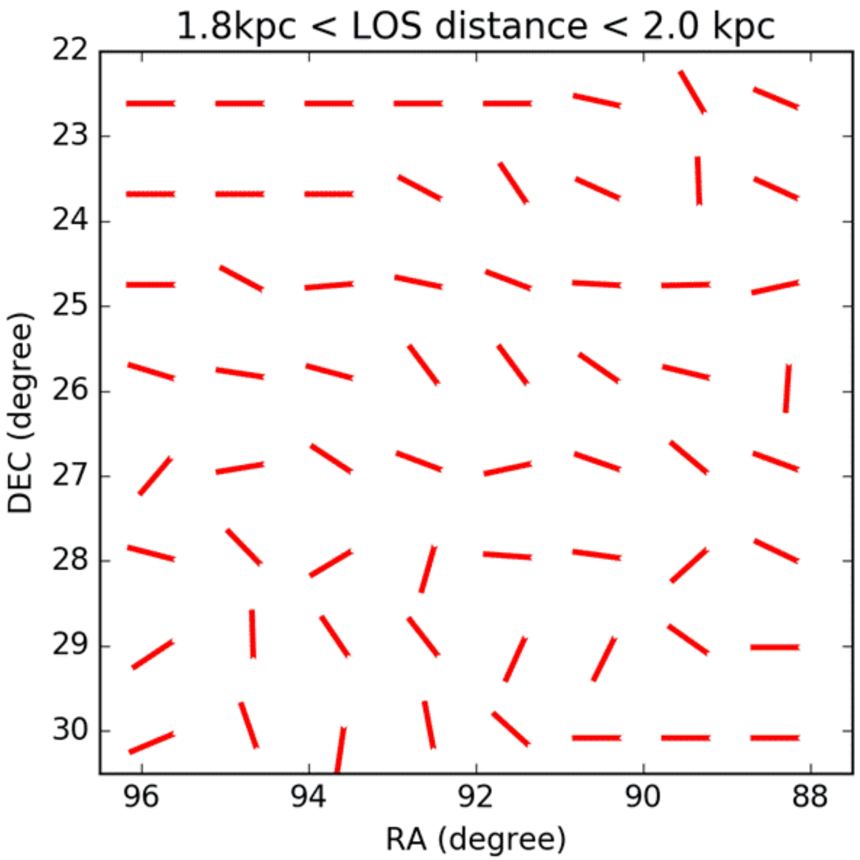


AL et al. 2018

3D Field Tracing using VGT with Galactic Rotation Curve

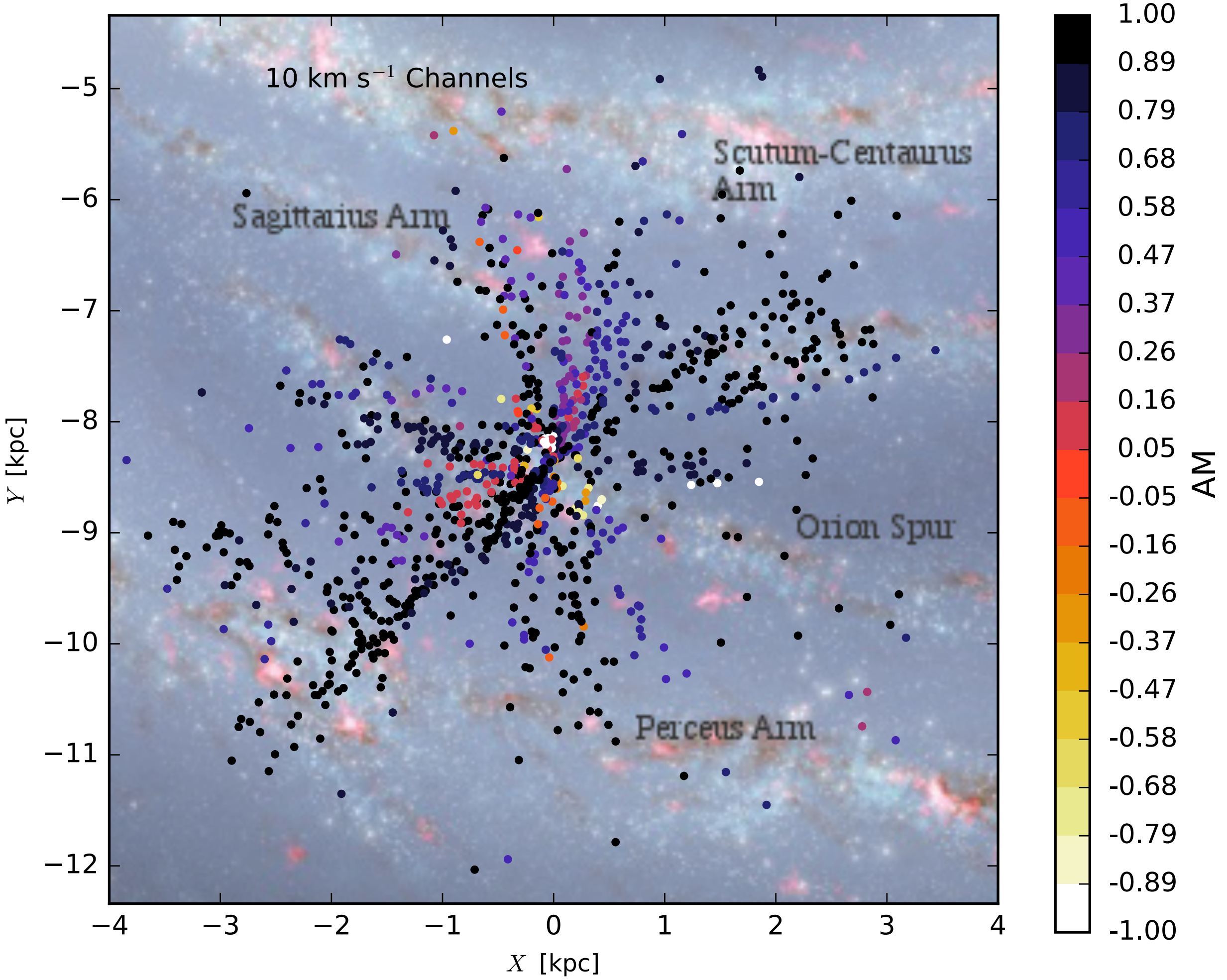


Casanova & Lazarian (2018), Yuen & Lazarian (in prep)



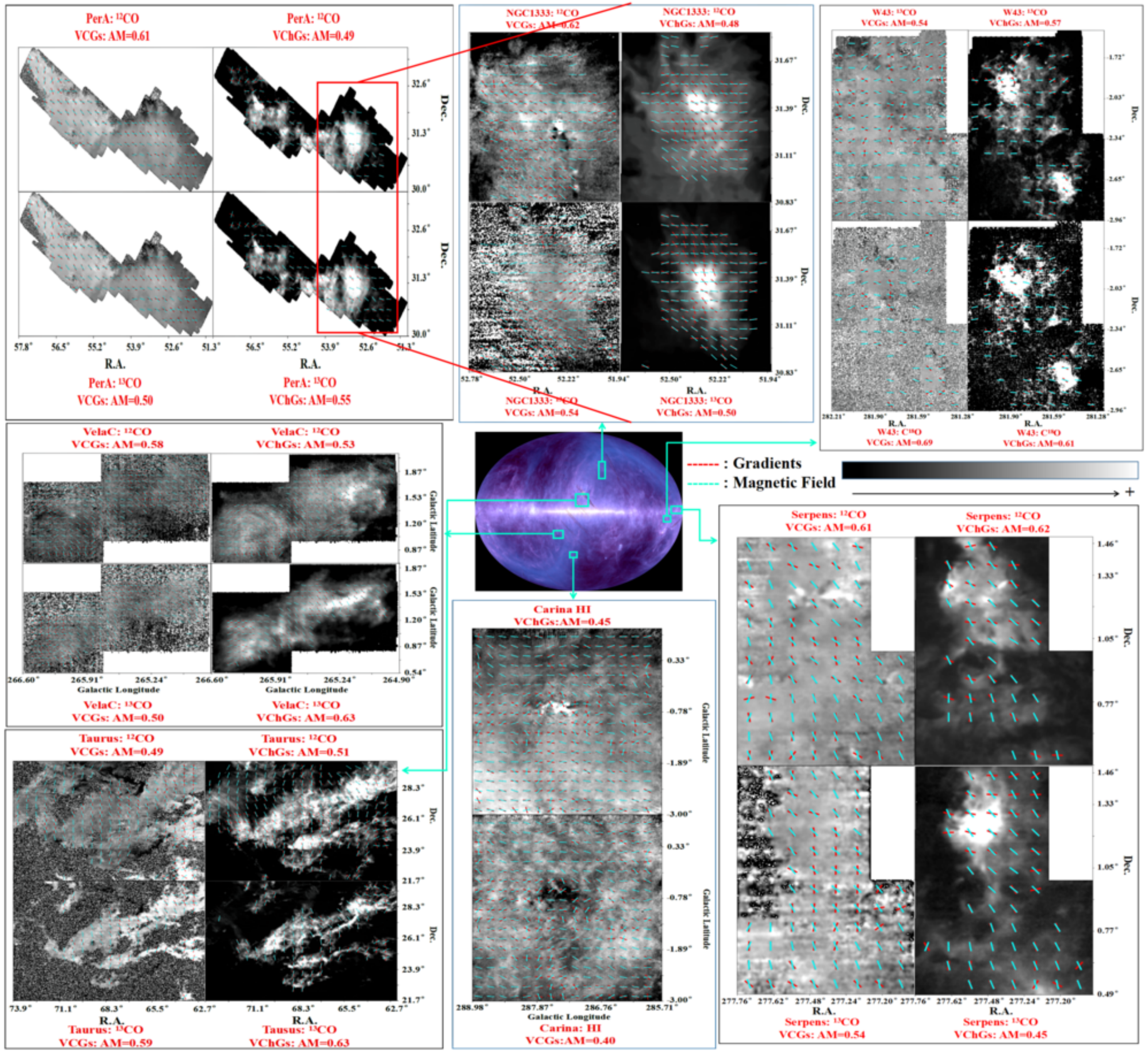
Similarly we can have 3D maps of M_A

Testing the obtained 3D B-field distribution with starlight polarization



Star polarization versus predictions with our 3D model of galactic magnetic field. This demonstrates that the model is correct!

Gonsalvez-Casanova & AL 2018



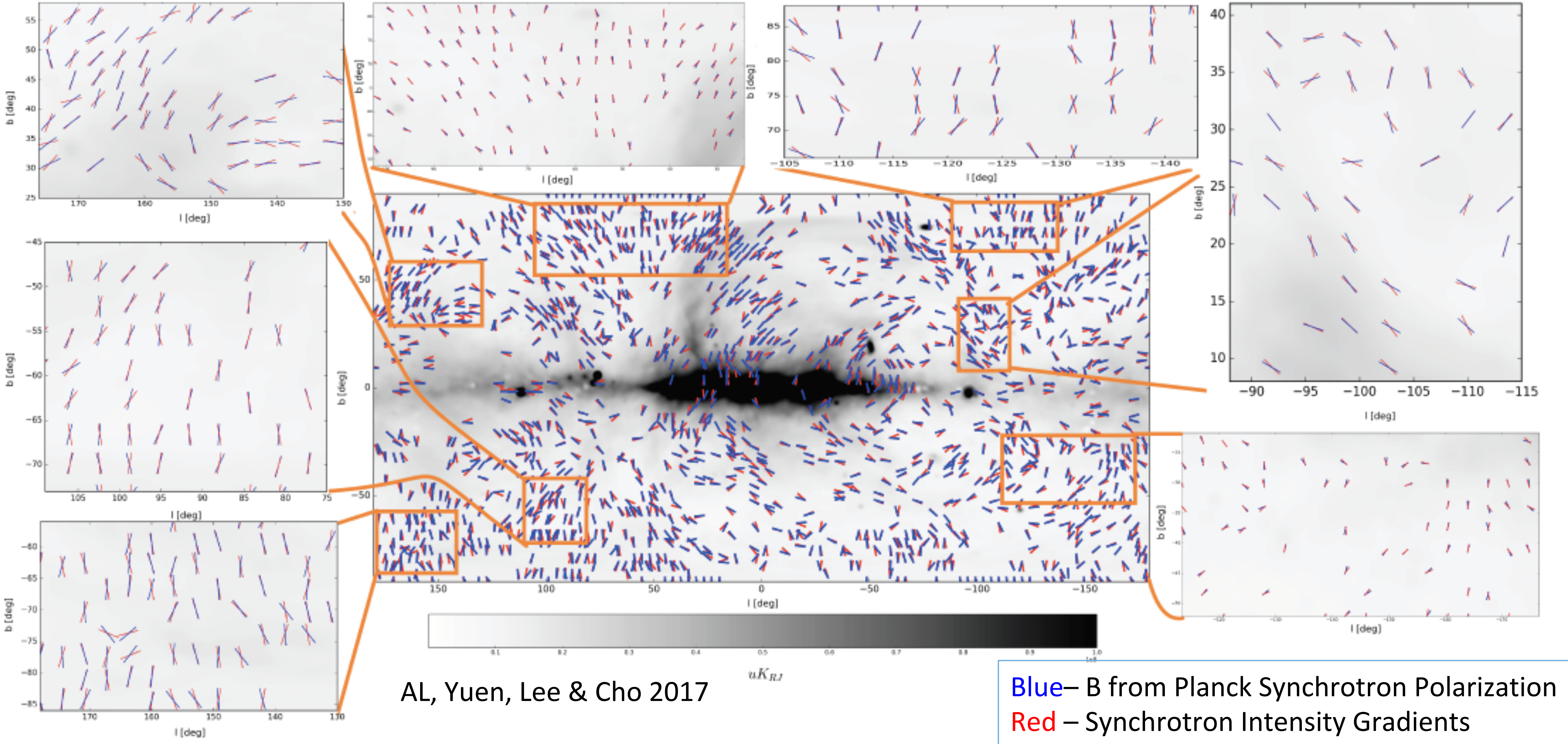
1st VGT Survey on molecular clouds

Comparing Gradients with Polarization in both low-mass and high-mass molecular clouds

Region Type	Cloud Region	Molecule Type
Low mass	Serpens[14]	^{12}CO & ^{13}CO
	Taurus[14]	^{12}CO & ^{13}CO
	Perseus A[14]	^{12}CO & ^{13}CO
	NGC1333[15]	^{12}CO & ^{13}CO
High mass	Carina[16]	HI
	Vela C[17]	^{12}CO & ^{13}CO
	W43[18]	^{13}CO & $C^{18}O$

Hu et al. 2018

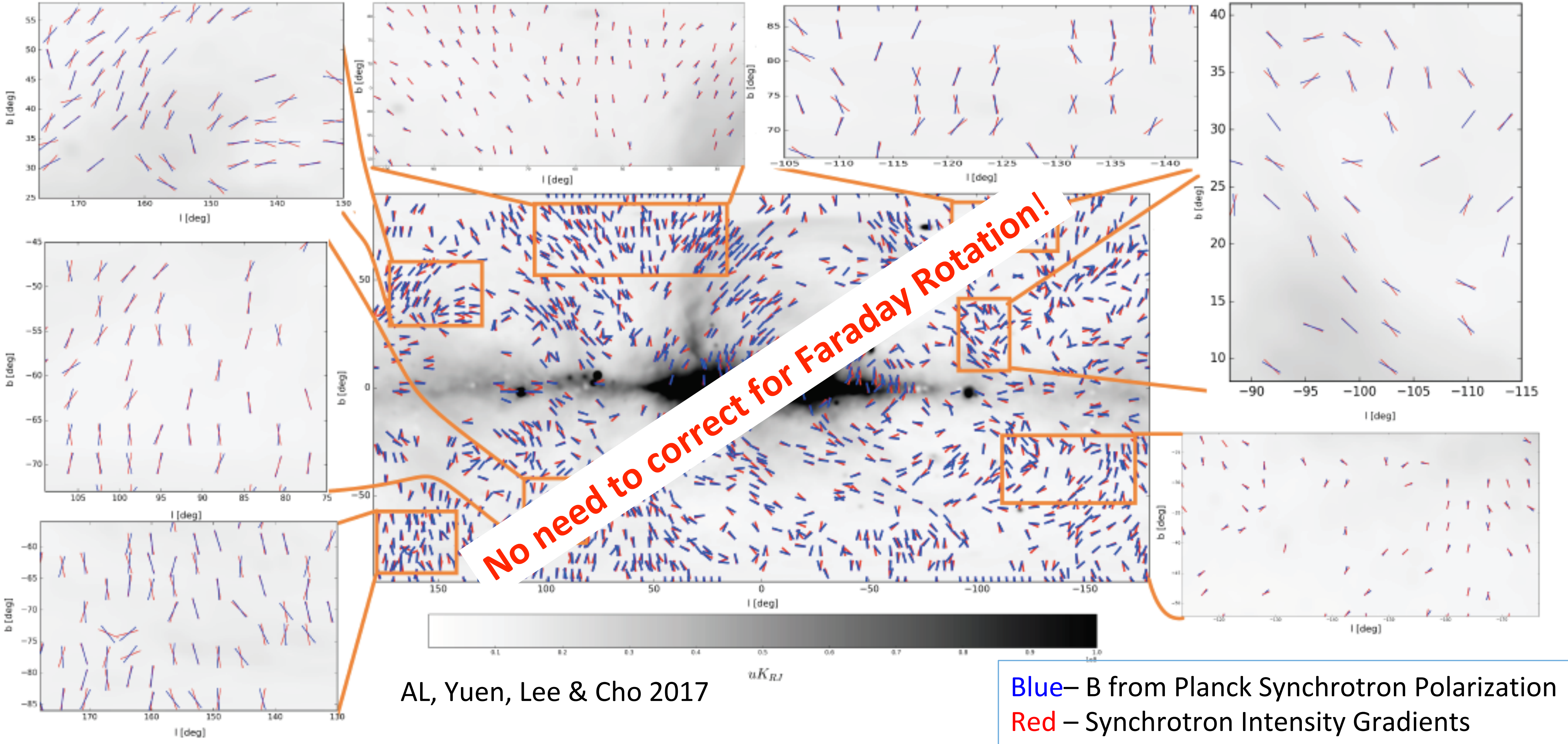
Synchrotron Intensity Gradients: another new way to study B



AL, Yuen, Lee & Cho 2017

Blue– B from Planck Synchrotron Polarization
Red – Synchrotron Intensity Gradients

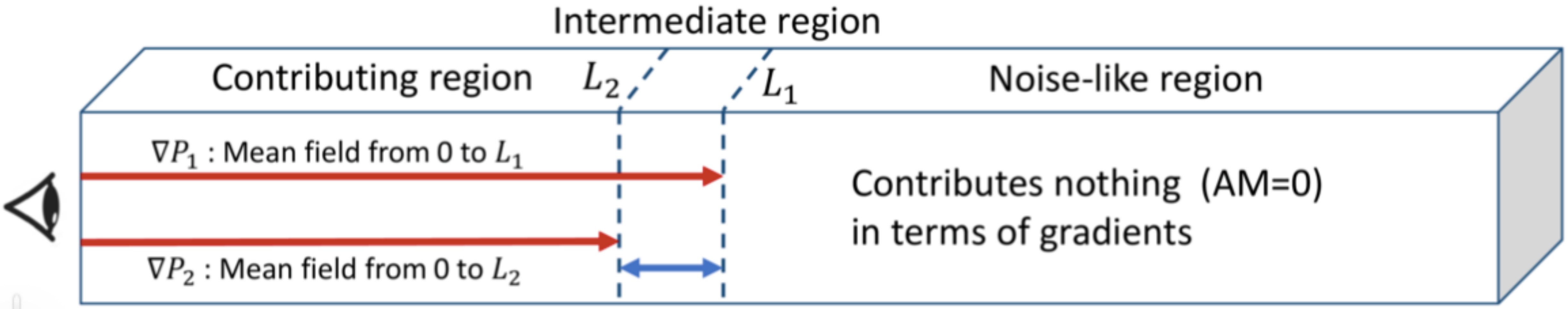
Tracing magnetic field without measuring polarization



AL, Yuen, Lee & Cho 2017

Blue– B from Planck Synchrotron Polarization
Red – Synchrotron Intensity Gradients

Polarization gradients allow 3D tomographic studies of magnetic fields



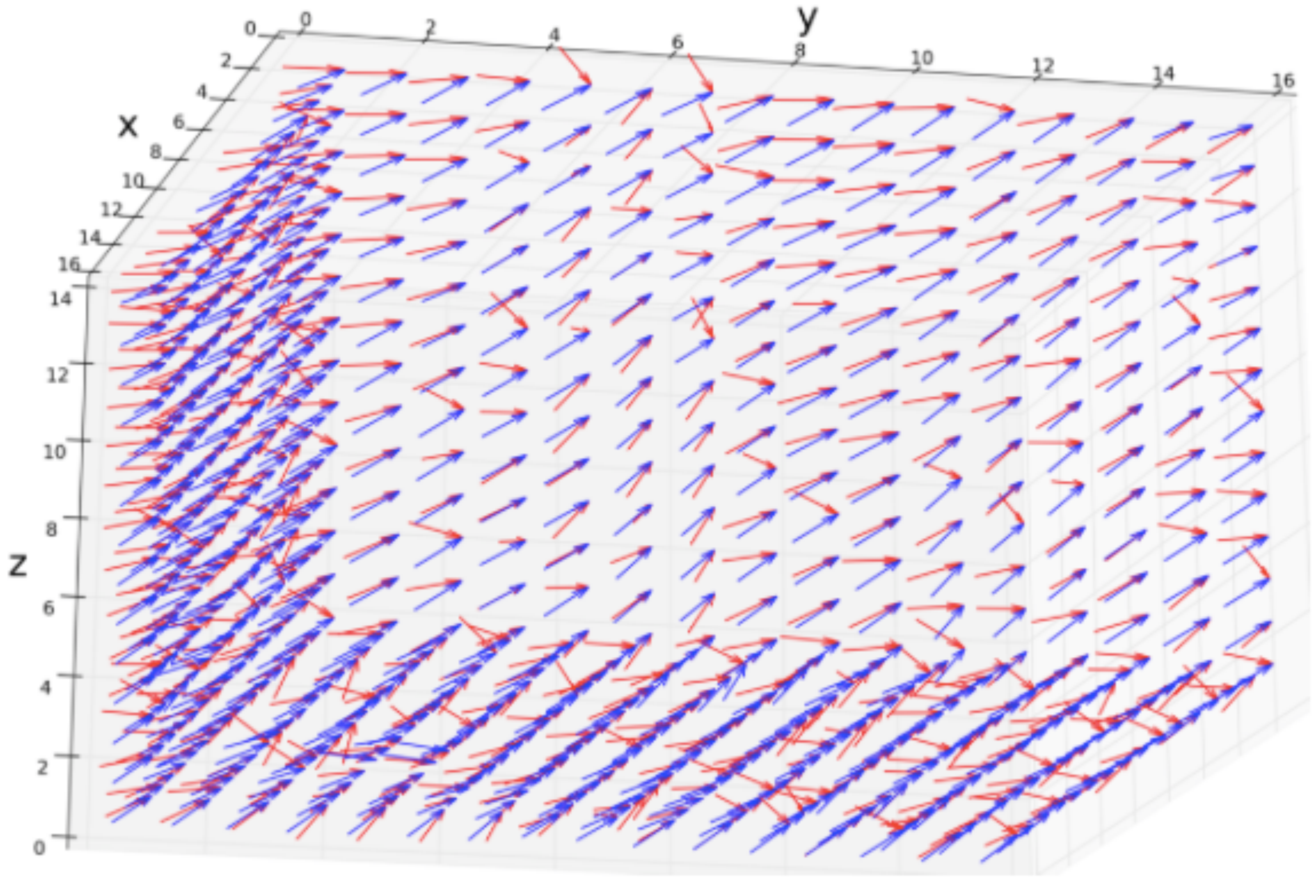
$$\nabla(\Delta P) = \nabla \int_{L_2}^{L_1} dz P_i \, e^{2i\lambda_1^2 \phi(z)}$$

tells the mean field in slice $l \in [L_2, L_1]$

AL & Yuen 2018

Example: 3D B-field distribution restored from synthetic data

An additional information is coming from gradients of $\frac{dP}{d\lambda^2}$

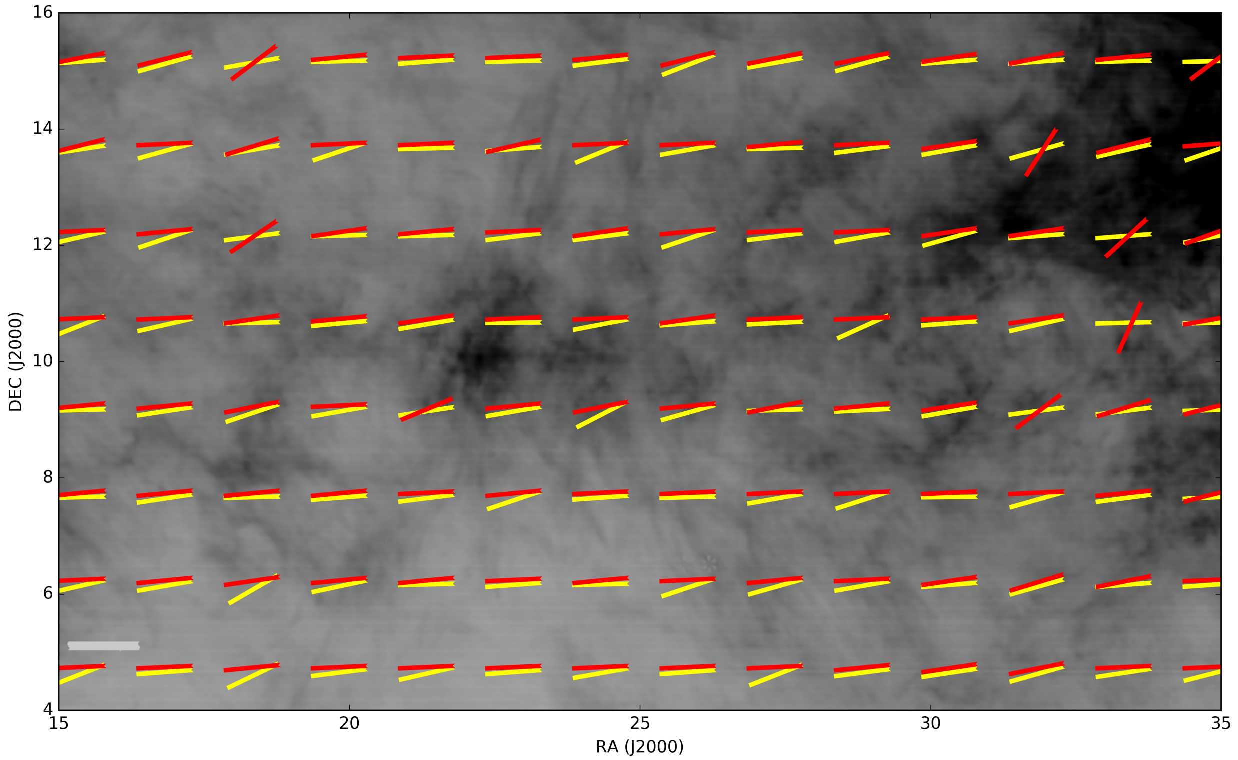


AL & Yuen 2018

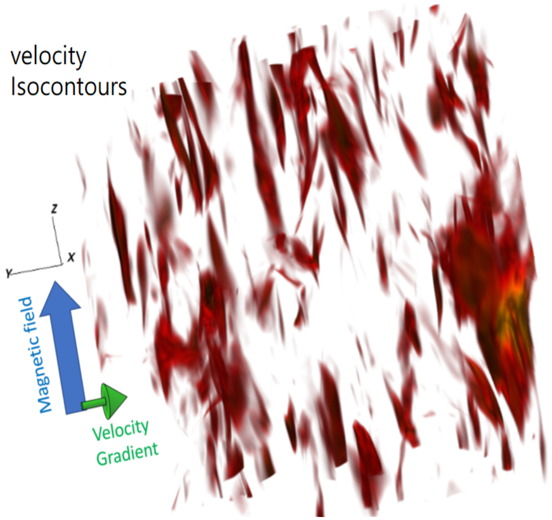
Blue- underlying 3D vectors, Red – vectors restored with the technique

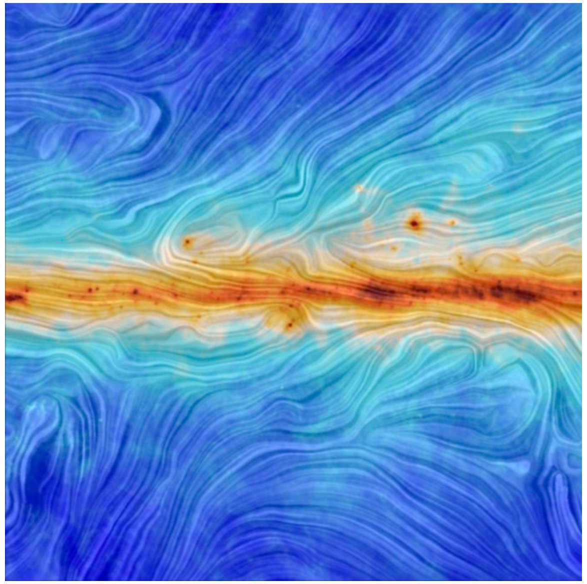
Complementary Nature:

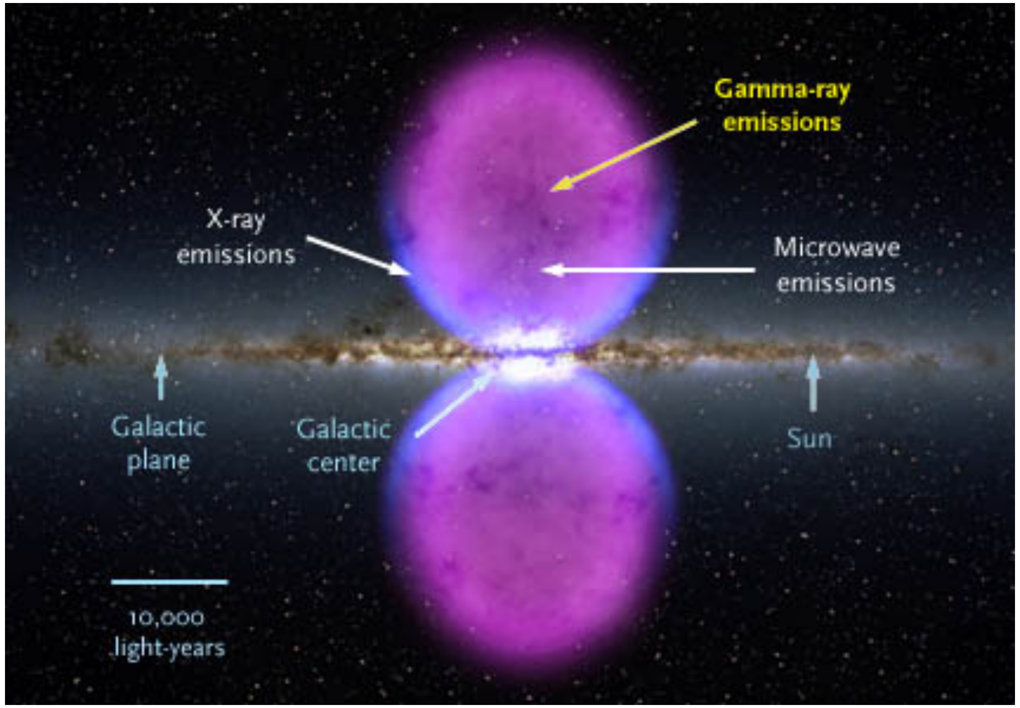
1. If we know the magnetic field structure with the gradient technique we can predict the polarization from dust.
2. If we know the magnetic structure and see the variations in synchrotron with frequency, we can study CR propagation.
3. Variations of structures obtained with gradients and polarization give insight into star formation.



Summary







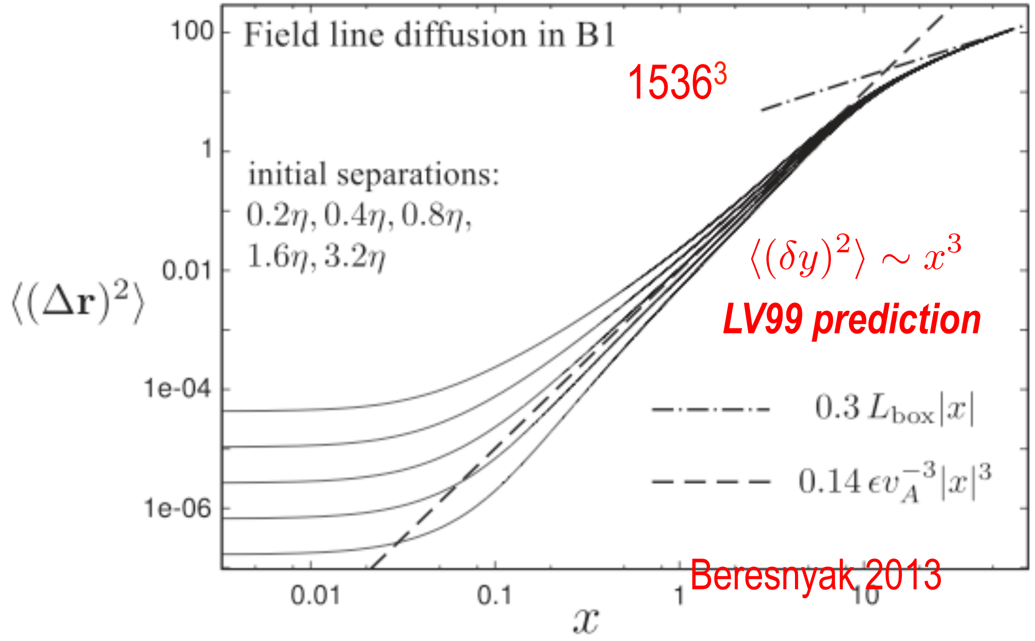
Better understanding of magnetic field structure means better models of CRs

Perpndicular diffusion of cosmic rays is dominated superdiffusion (superballistic behavior) as CRs following magnetic field

$$\langle (\delta y)^2 \rangle \sim x^3$$

Prediction in AL & Vishniac 1999

Superdiffusion acts on scales x less than the injection scale of MHD turbulence



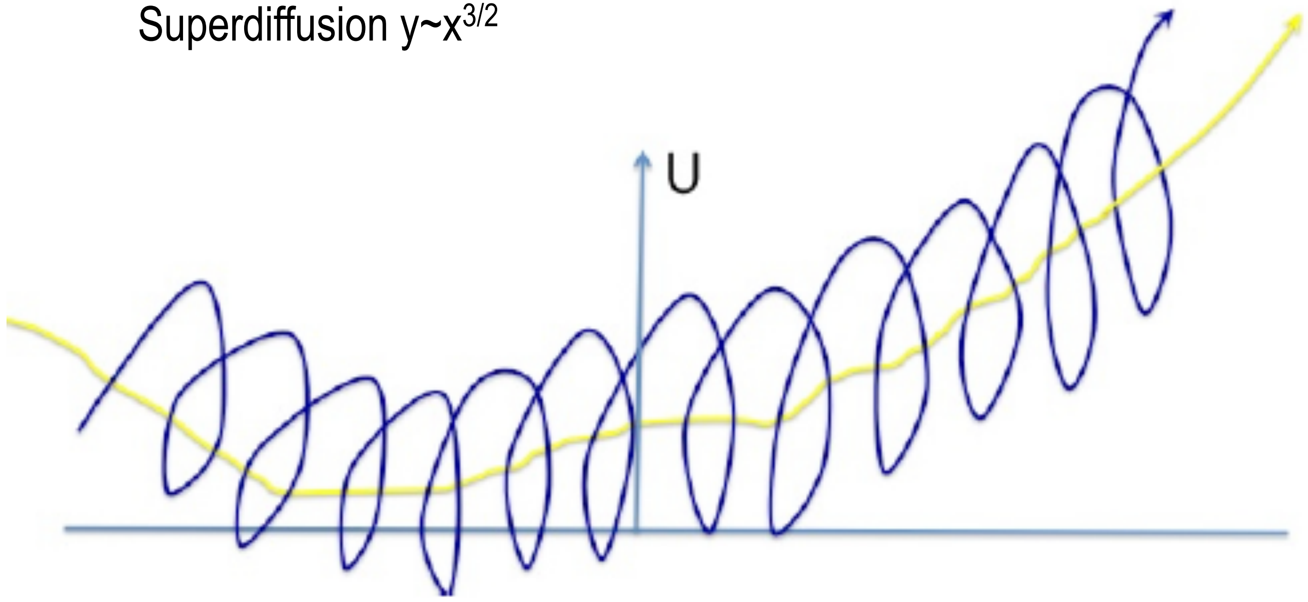
Injection scale of turbulence in the Galaxy is about 100 pc

Superdiffusion changes the accepted formalism for parallel and perpendicular shock acceleration

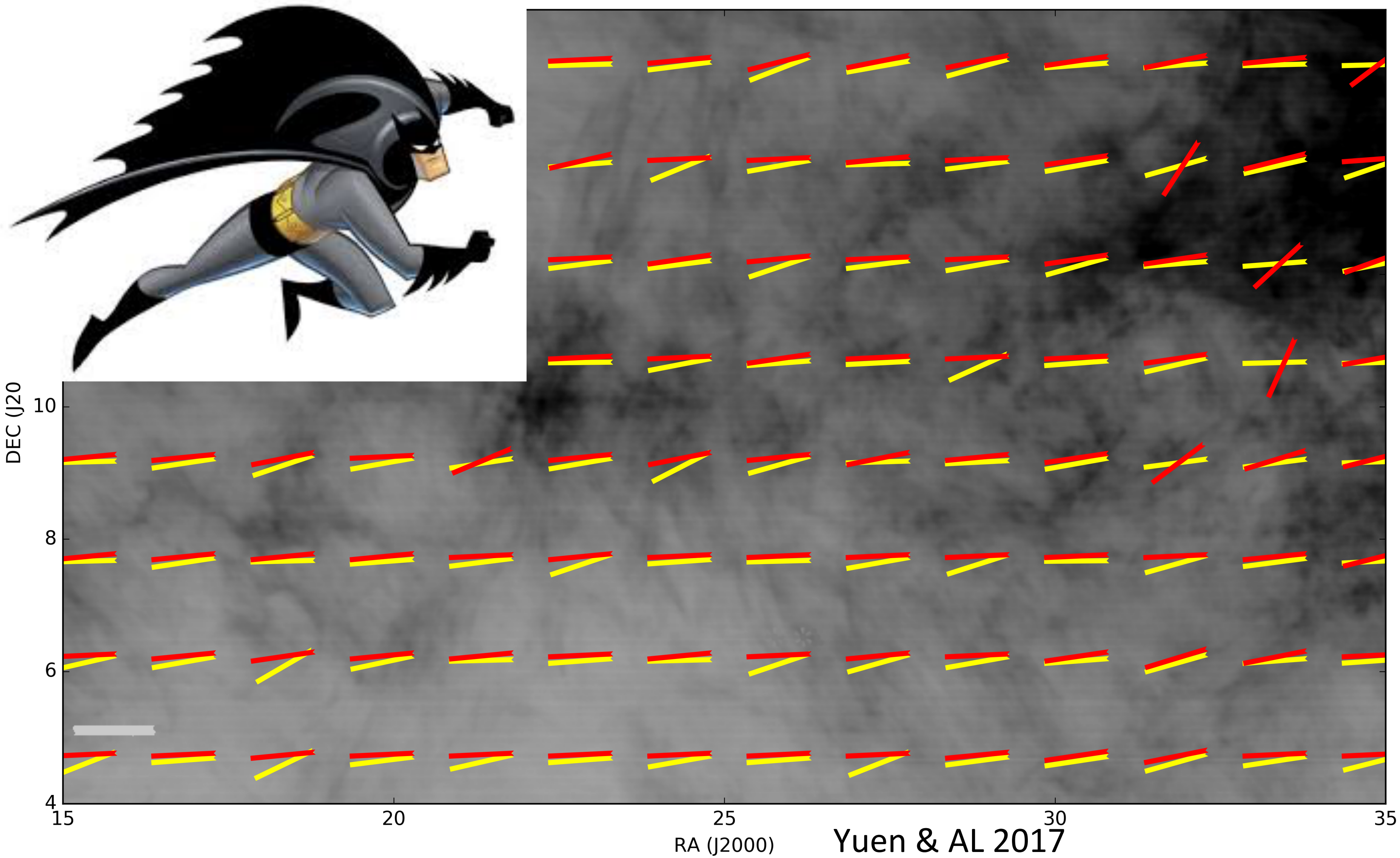
$$\frac{\kappa_\perp}{\kappa_\parallel} = \frac{1}{1+(\lambda_{CR}/r_L)^2}$$

Accepted expression

Superdiffusion $y \sim x^{3/2}$



Initially we had only one superhero: Tracing of magnetic field in 2D by gradients

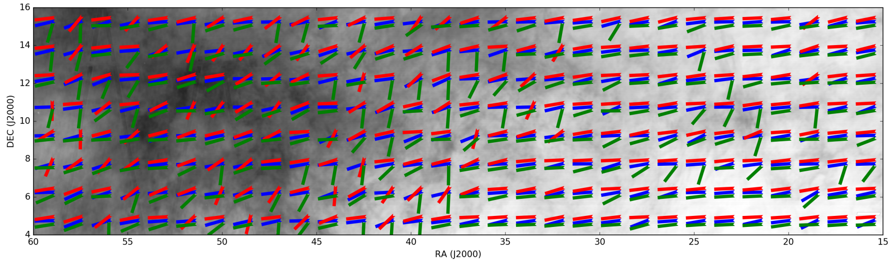


Yuen & AL 2017

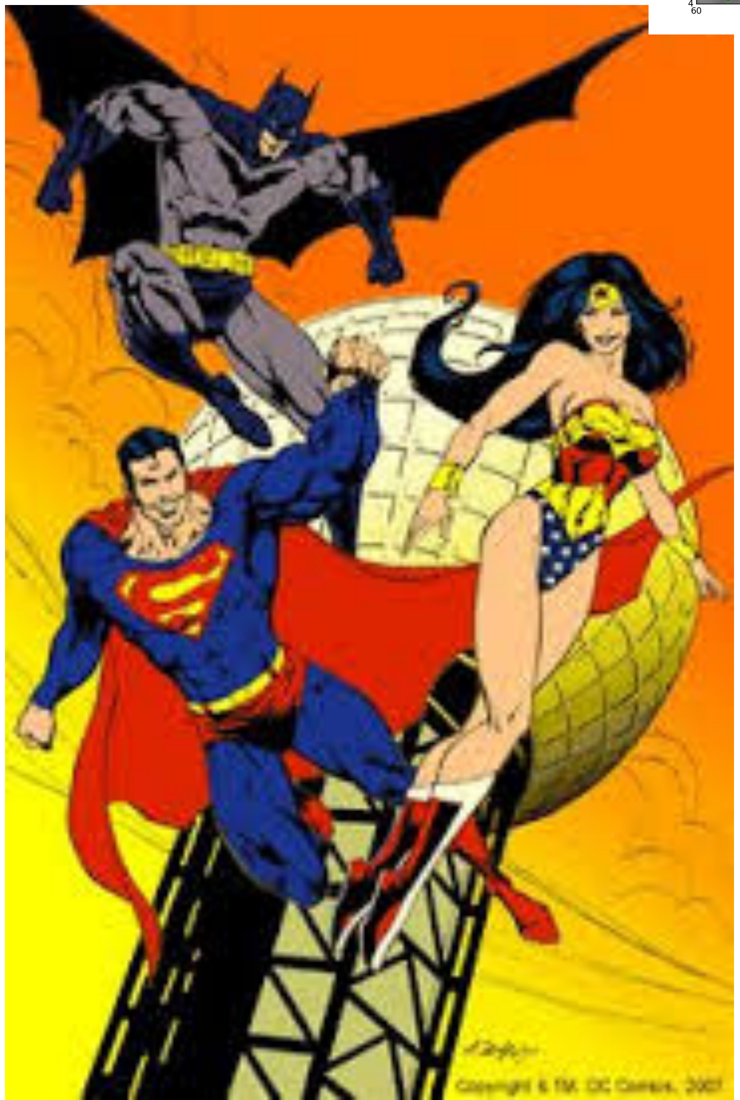
RED : Velocity Gradients
Yellow: Magnetic field

GALFA data compared with Planck polarization

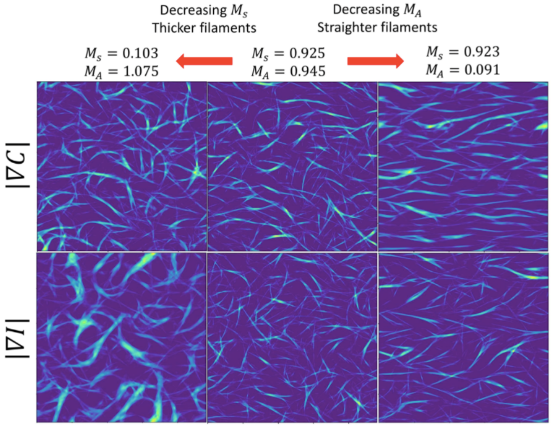
3 Superheroes of Gradient Technique



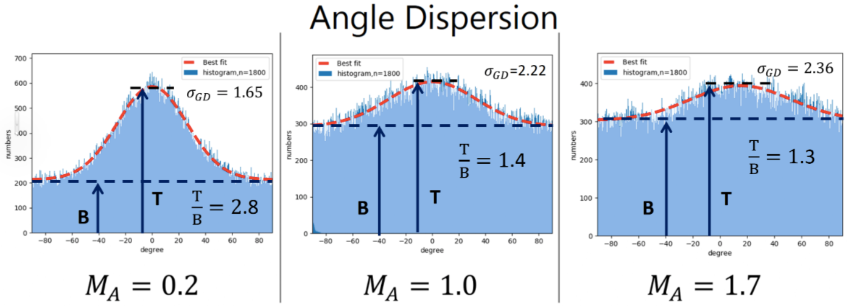
Gradient direction



Gradient amplitude



Gradient distribution function



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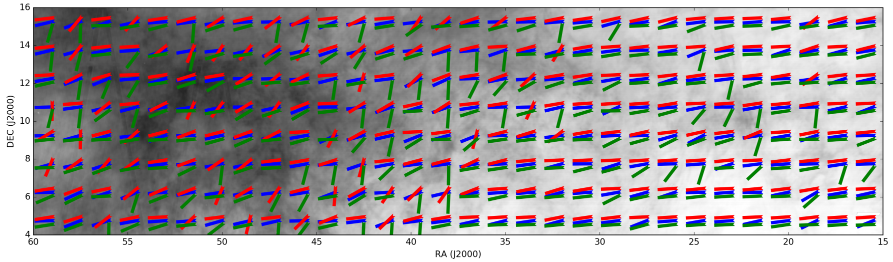
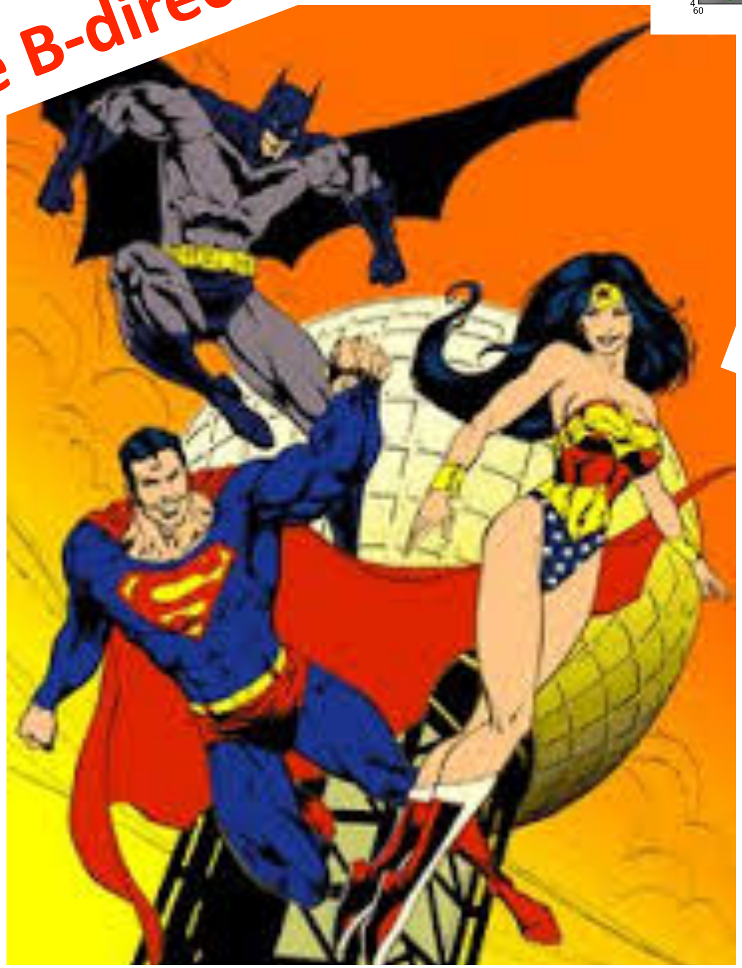


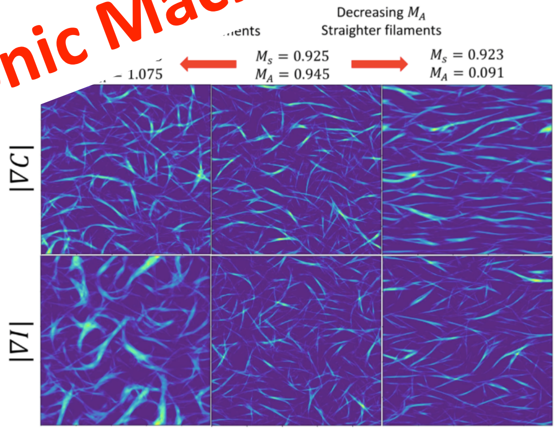
Gradient … tion

Trace B-direction



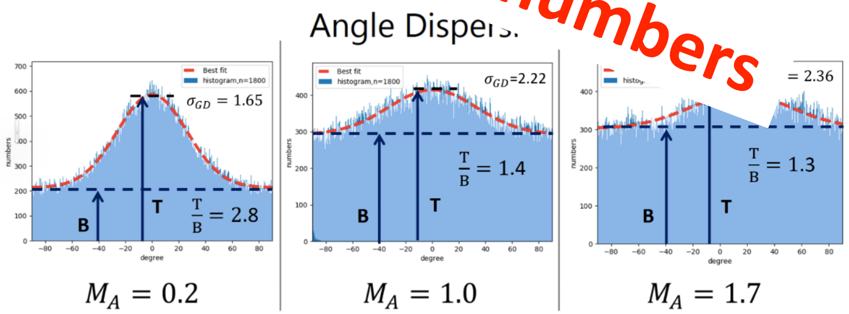
Gradient … ude

Trace sonic Mach numbers



… distribu… …tion

Trace Alfven Mach numbers



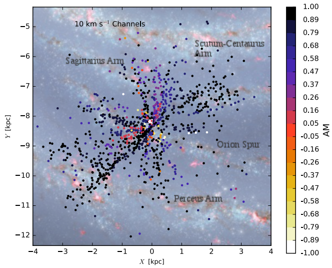
Can study 3D B-fields, shocks, regions of gravitational collapse

Present day: 3D distribution of B-fields is cool!

With Velocity Channel Gradients

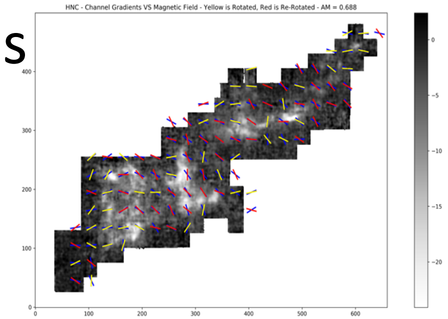
Using Galactic rotation curve

For HI



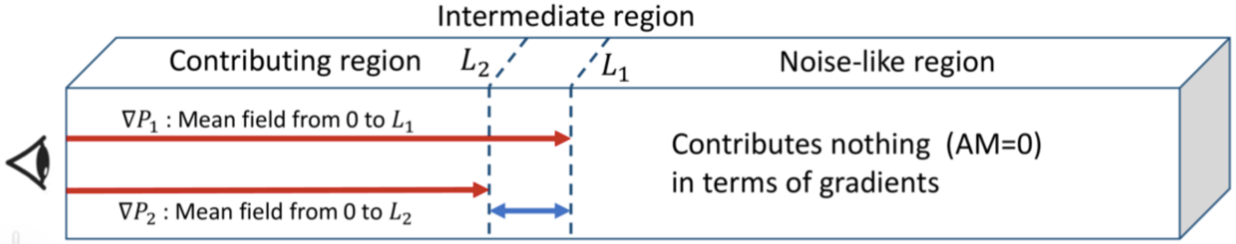
For molecular clouds in disk

Using different emission species

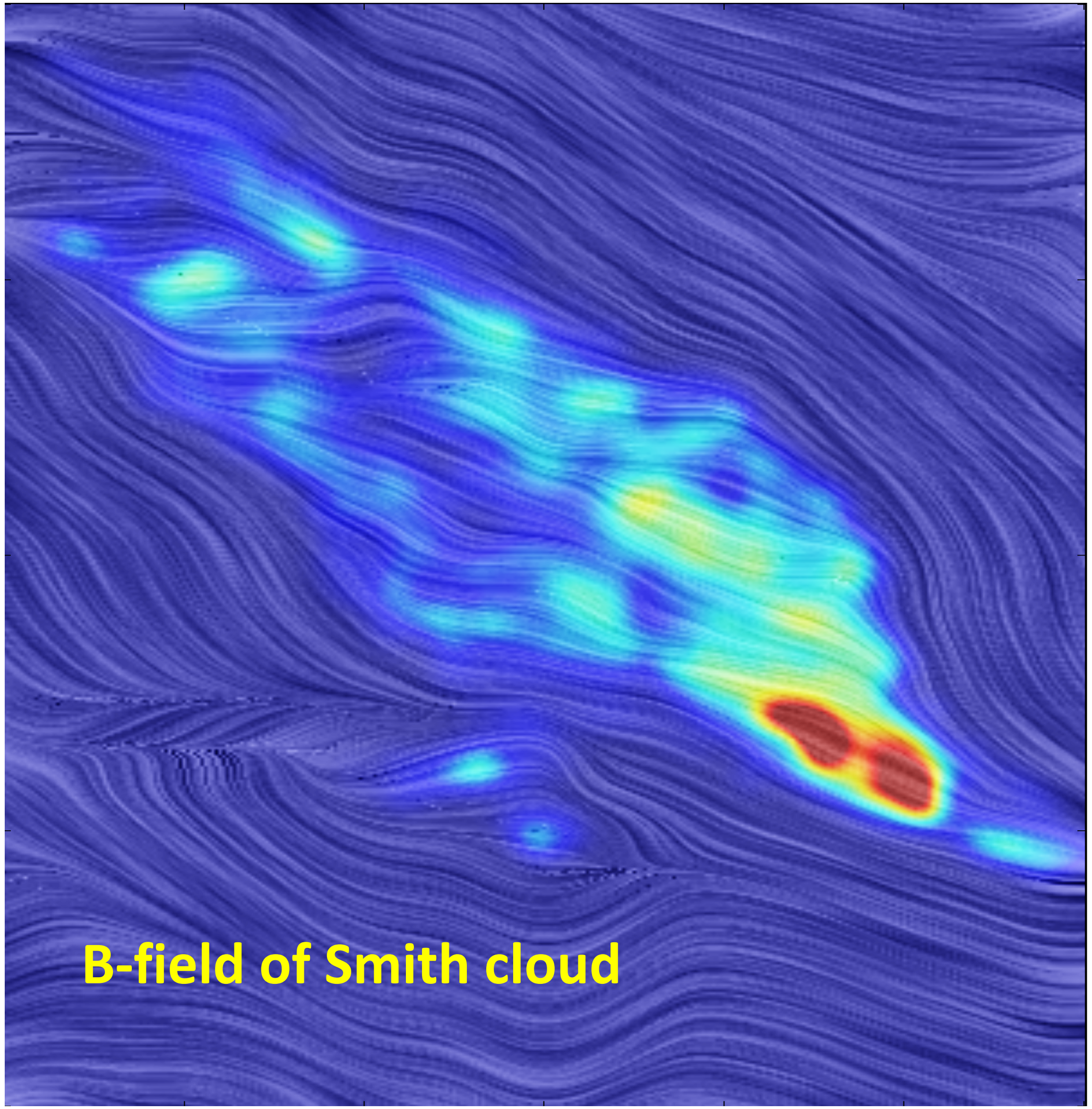


With Synchrotron Polarization Gradients

Using Faraday depolarization



Velocity gradients provide unique ways to study B-fields: high velocity clouds as an example

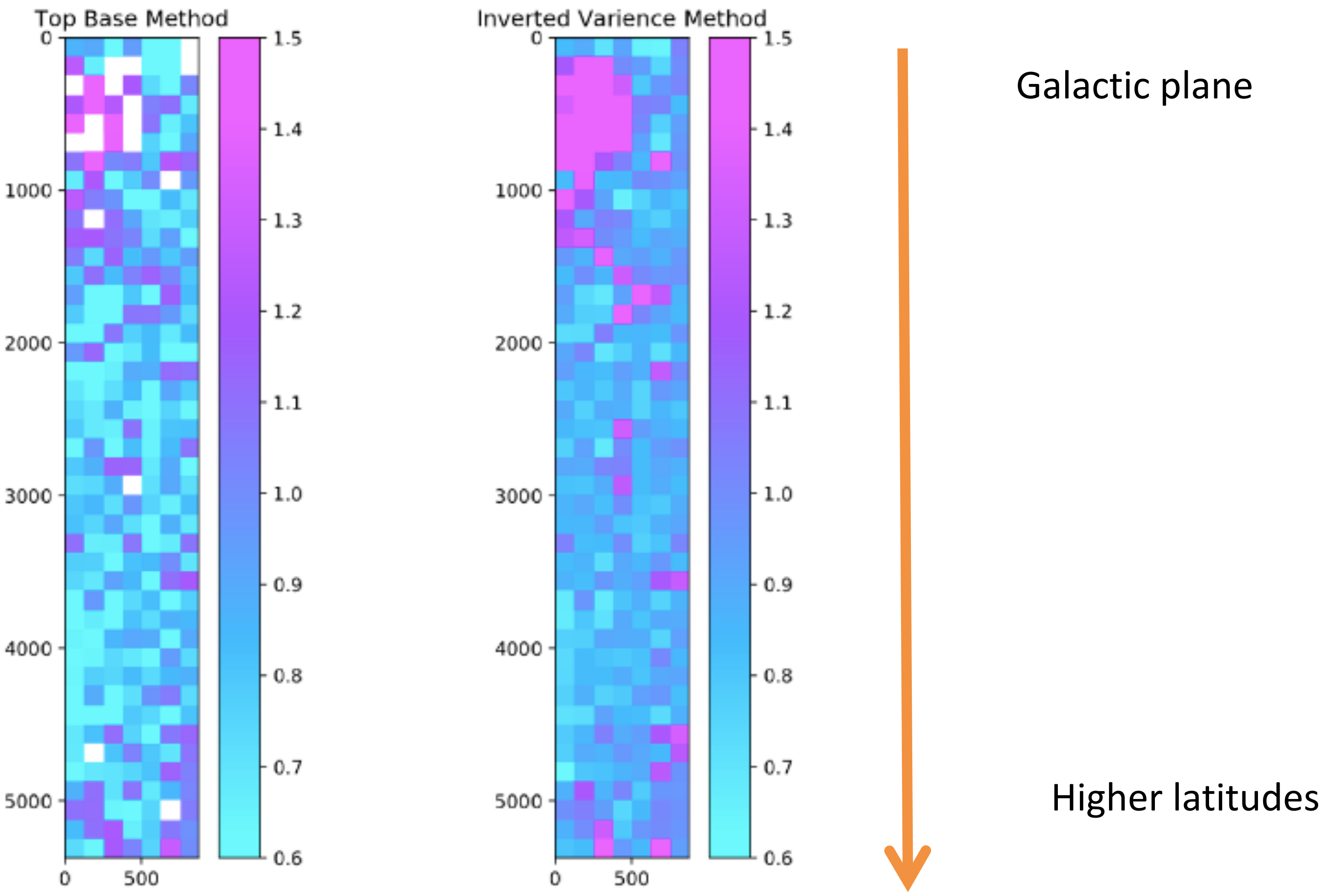


No other way to study these fields.

Distribution of M_A with velocity gradient distribution function of galactic HI

$$M_A = \frac{V_L}{V_A}$$

V_L is turbulent velocity
V_A is Alfven velocity

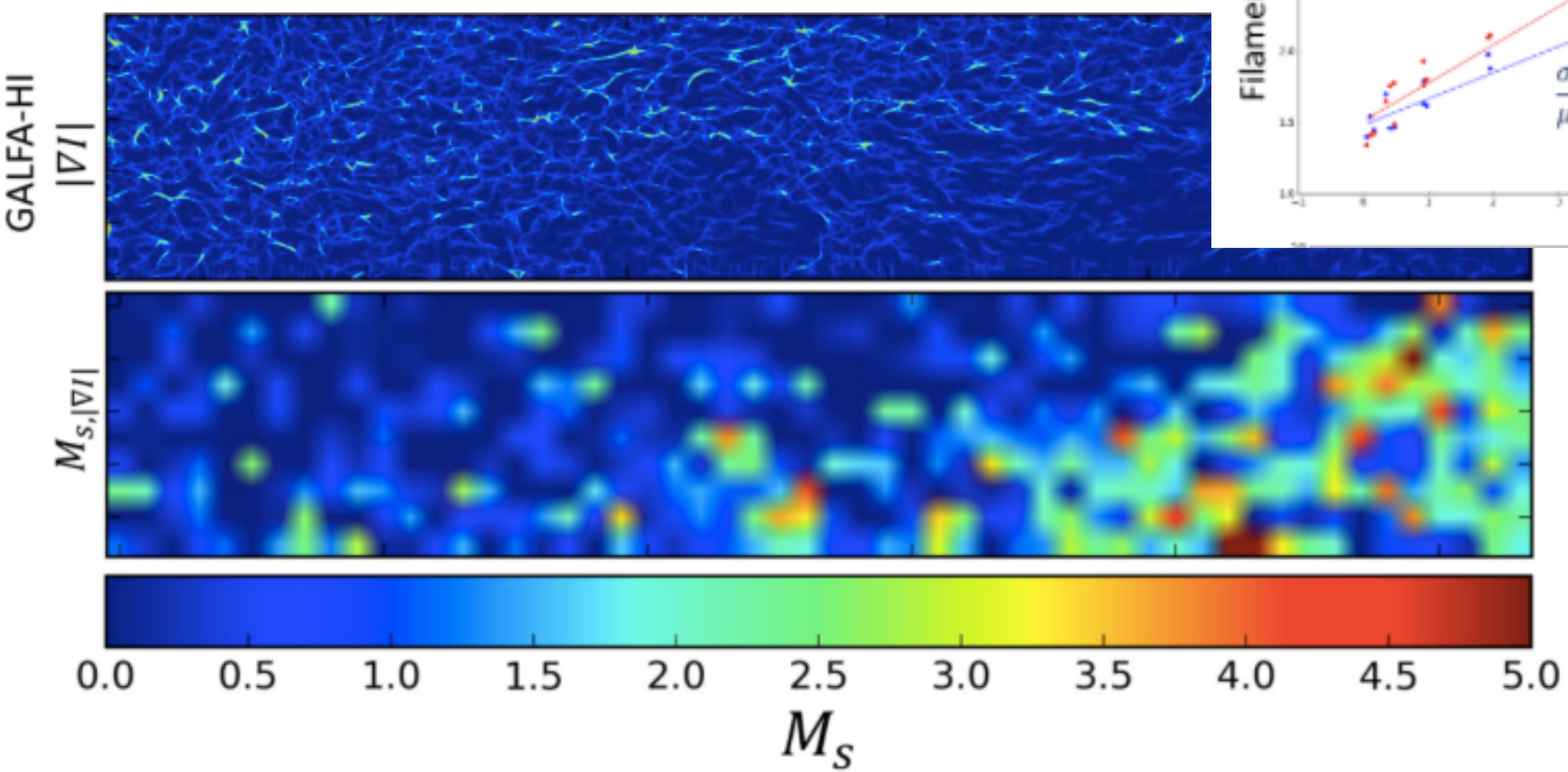


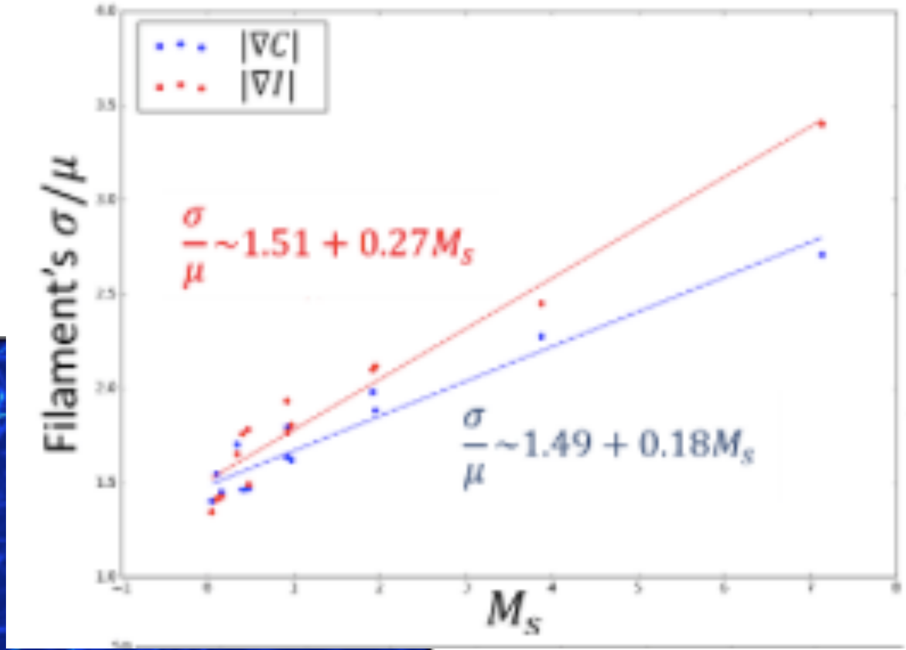
AL et al 2018

Determining M_s using gradient amplitudes

$$M_A = \frac{V_L}{V_s}$$

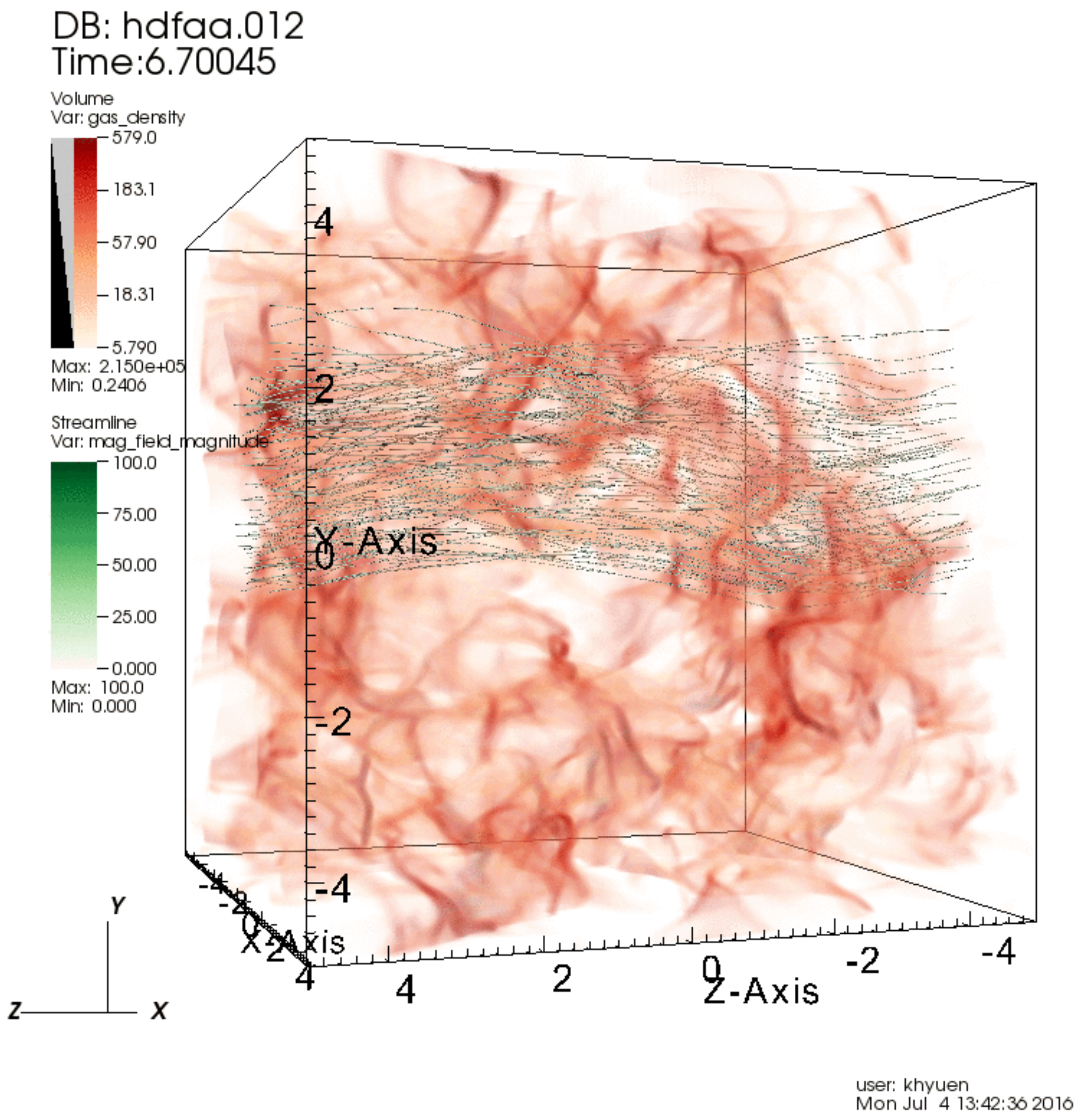
V_L is turbulent velocity
V_s is sound velocity





Yuen, Lazarian, AL 2018

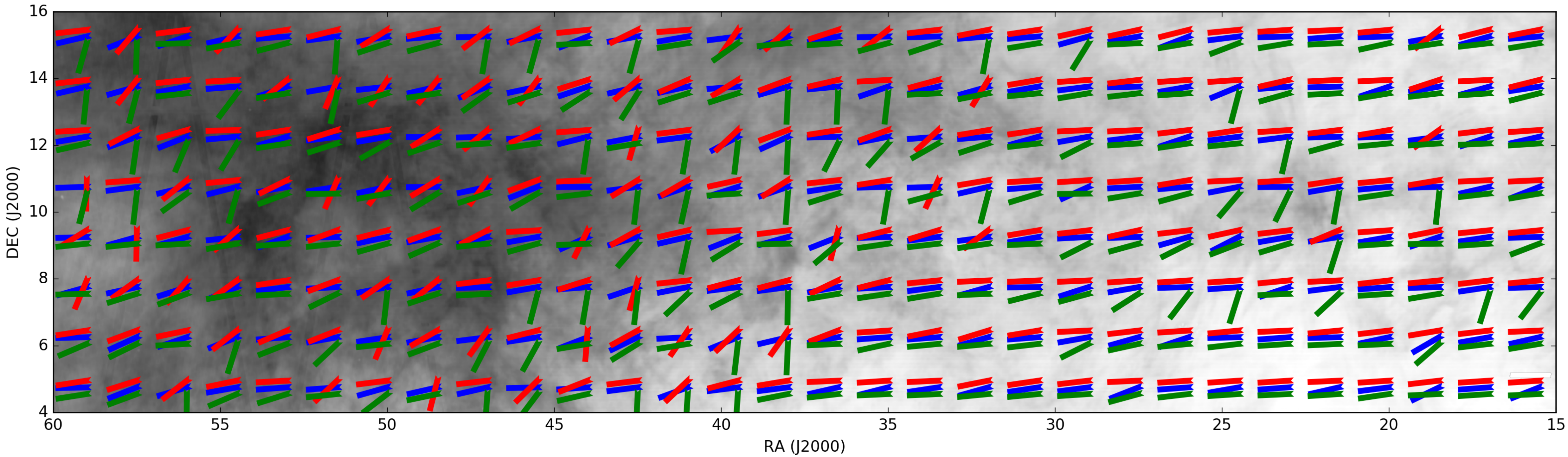
Density structures are mostly perpendicular to magnetic fields for supersonic flows



Density fluctuations are a good tracer of shocks

Intensity Gradient Technique: Application of all our tools, e.g sub-block averating, to intensity gradients

GALFA data

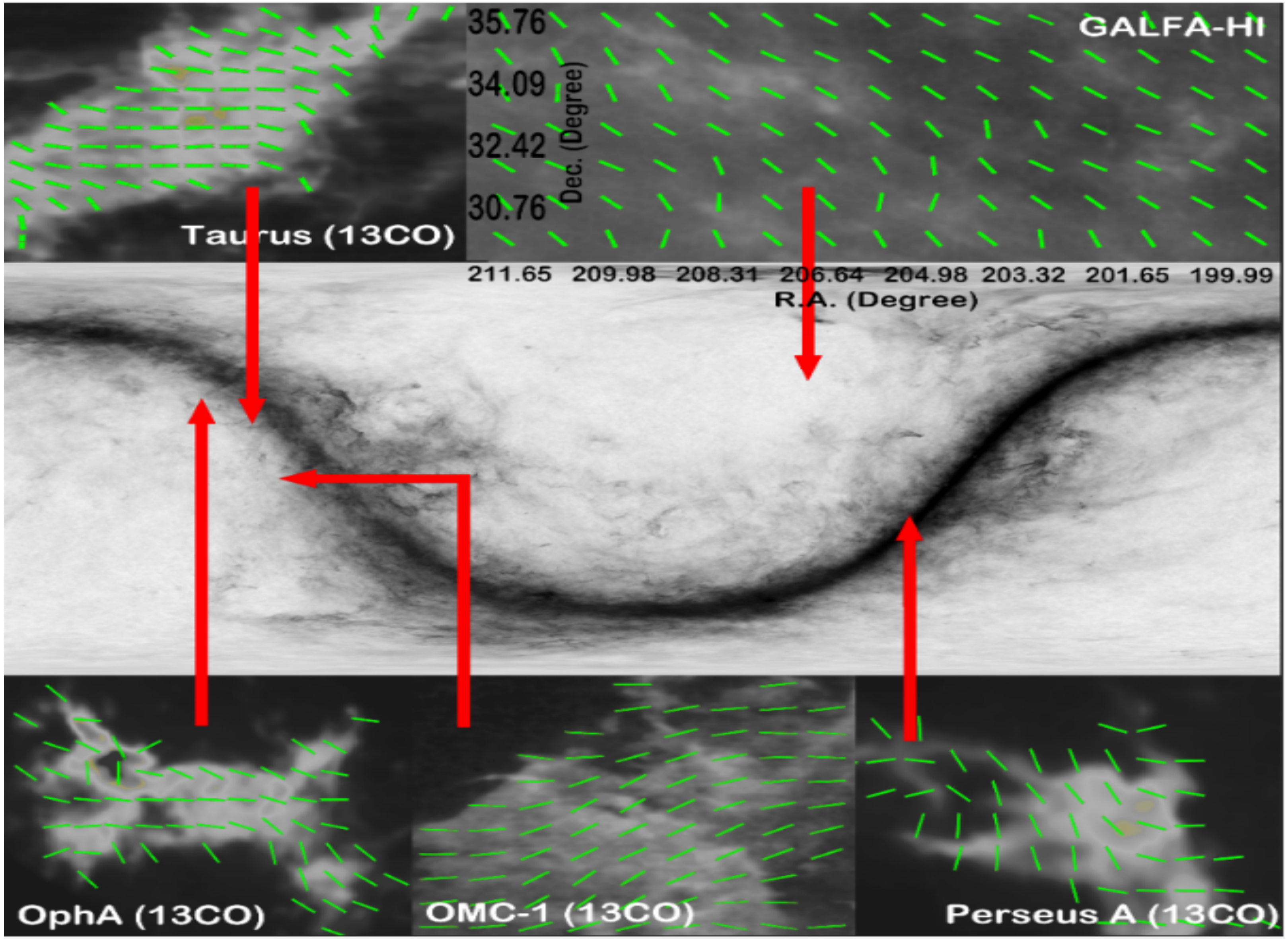


Yuen & AL 2017

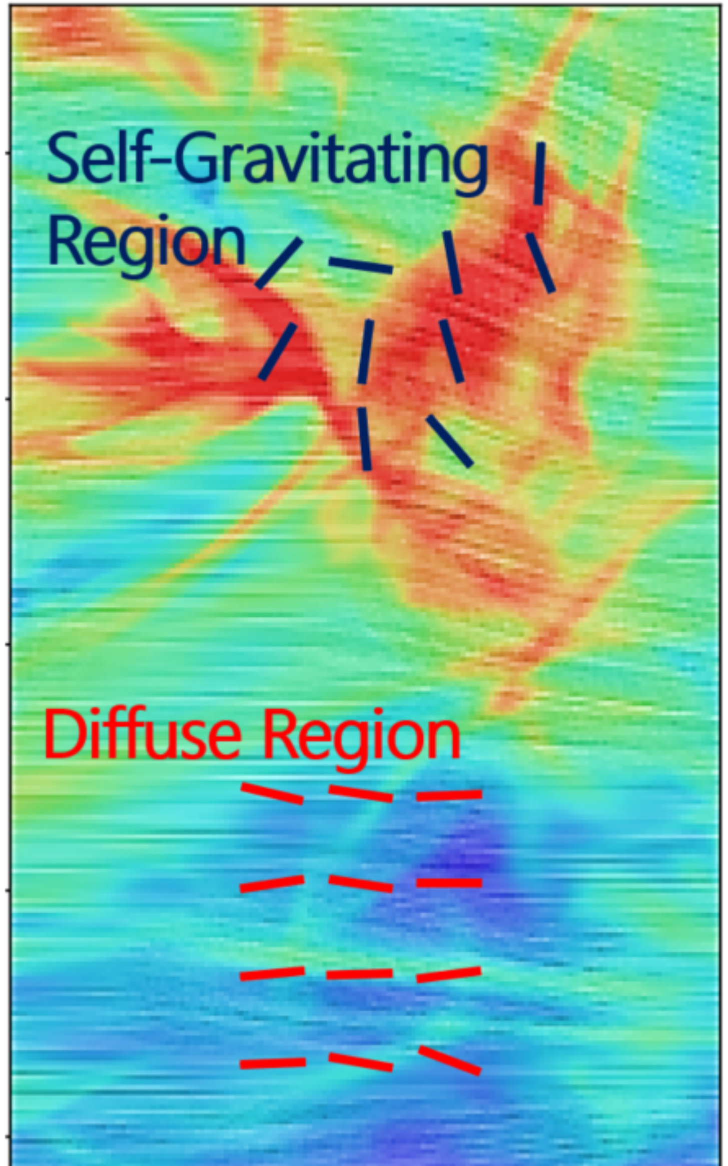
RED: VG
GREEN: DG
BLUE: B

Synergy: tracing both magnetic fields and shocks!

Ongoing work on the survey of galactic B-fields



Velocity gradients are perpendicular to local direction of B-field in diffuse regions and parallel to B-field in regions of gravitational collapse

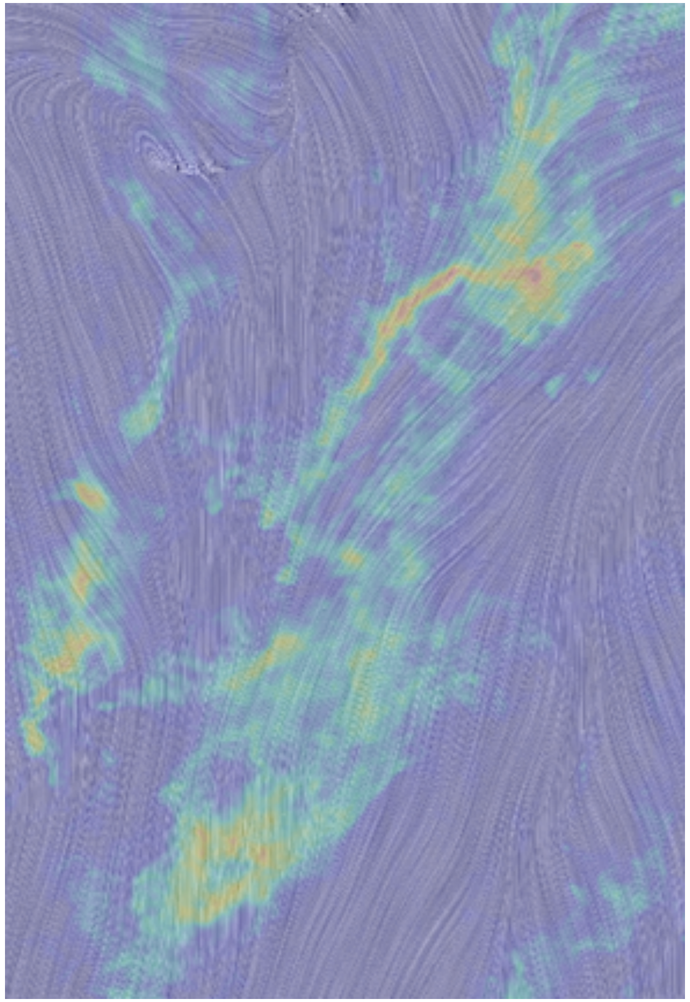


The change of the dispersion of gradient allows us to identify the regions where the direction of gradients flips 90 degrees (see AL & Yuen 2018)

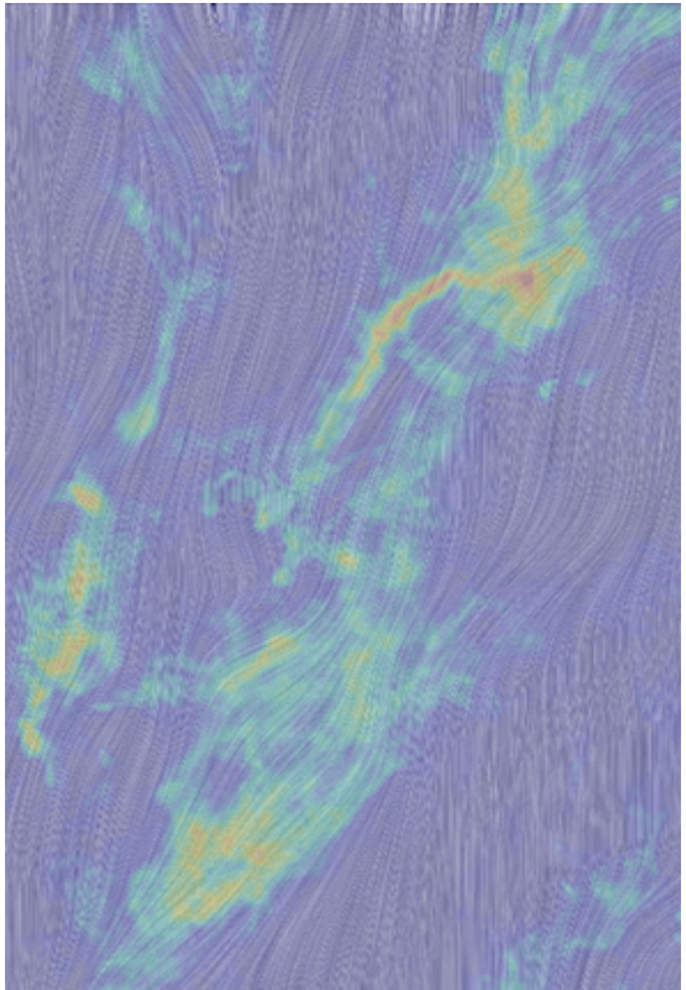
Yuen & AL 2018

The procedure of identifying collapsing regions works well with observations

B-field from Velocity gradients

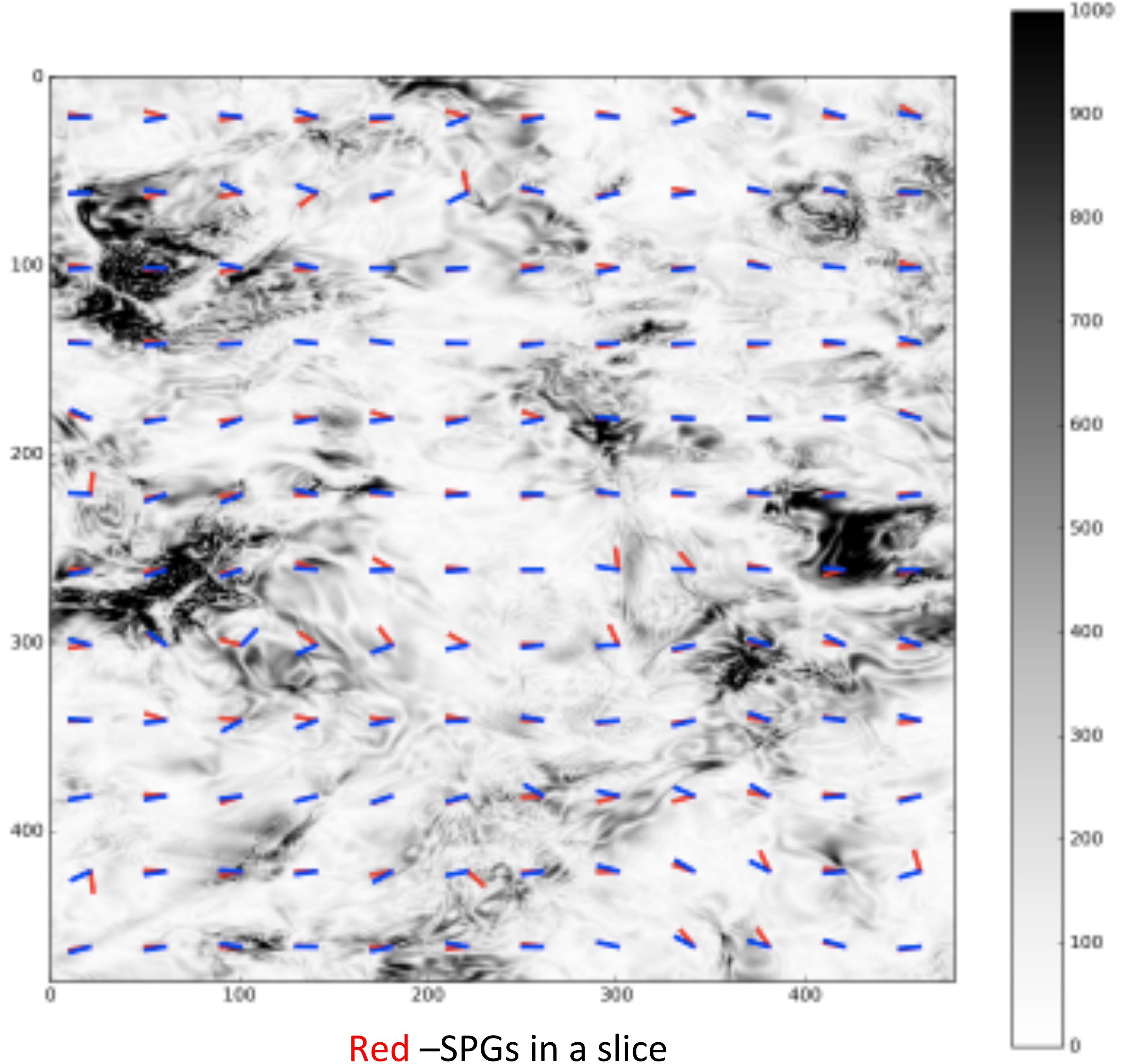


B-field from Planck



Taurus cloud

Comparison of the SPG tomography and B-field in a slice of 3 data cube



Red –SPGs in a slice
Blue –B-field in a slice

AL & Yuen 2018

I am happy to discuss with you MHD turbulence and its implications as well as new ways to study magnetic fields :

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