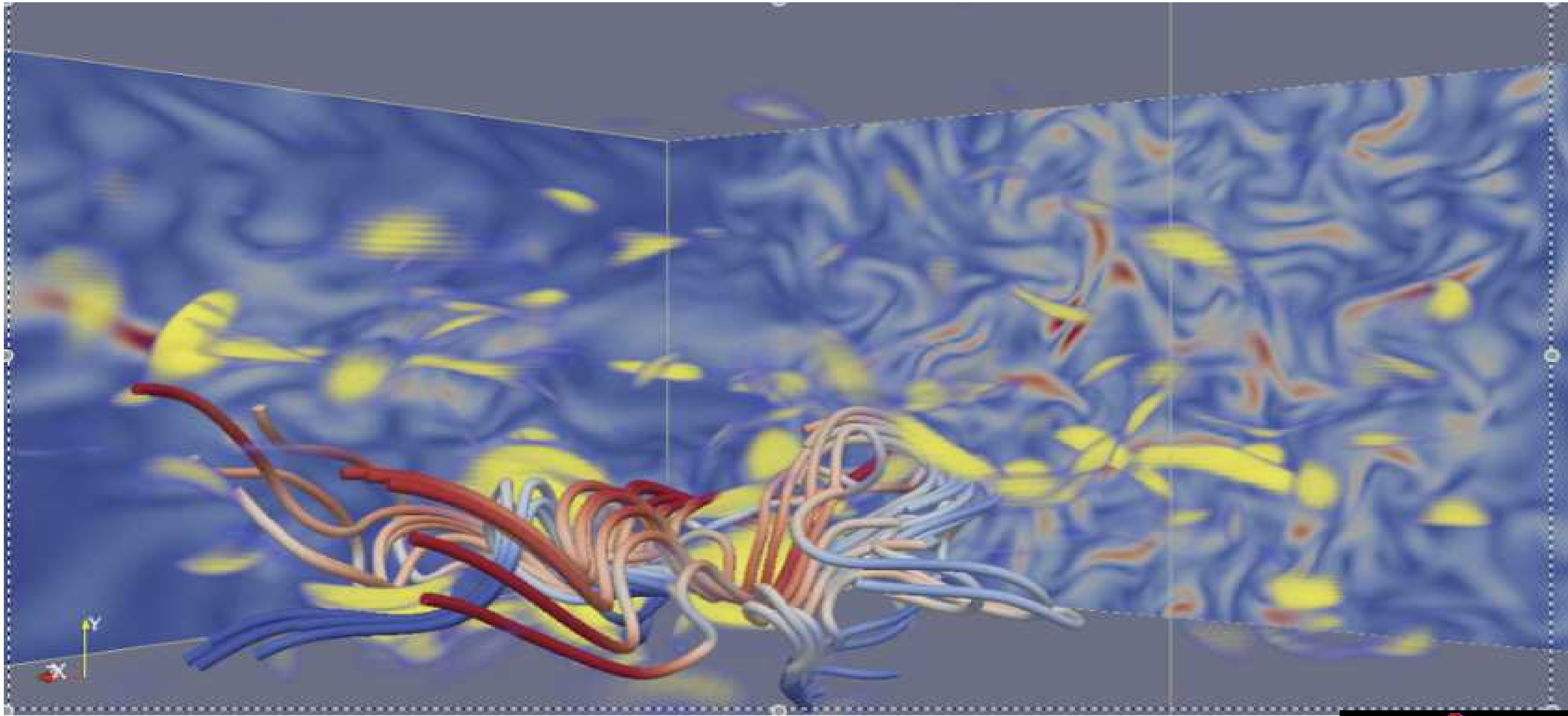
New Ways of Observational Magnetic Field Studies (using deeper understanding of turbulence and reconnection)

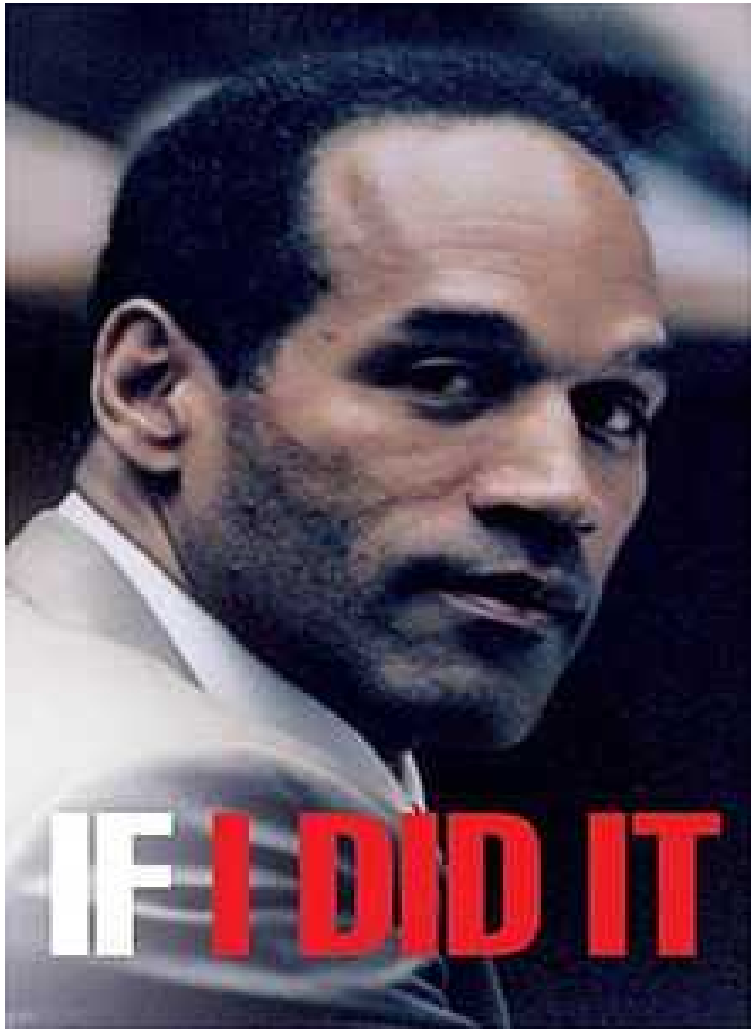


Alex Lazarian (Astronomy, Physics and CMSO)

Collaborators D. Gonzales-Casanova, K-H. Yuen, H. Lee, B. Sun, J. Cho

THE UNIVERSITY of WISCONSIN MADISON

O.J. Simpson wrote the book "If I did it" after the jury found him not guilty in spite of DNA evidence



O. J. Simpson

I start with the similar note: If spectral lines can tell us about magnetic field

If there were the case we could:

1. **Trace 3D distribution of magnetic field in molecular clouds shell by shell using emitting molecules.**
2. **Study magnetic field using cheap spectroscopic rather than polarimetric observations.**
3. **Study magnetic fields in the disk of the Milky Way where the confusion for the polarimetry is great.**
4. **Study magnetic fields at optical depths where grain alignment fails.**
5. **Obtain estimates of magnetic field strength without any polarimetry.**

Points of the talk:

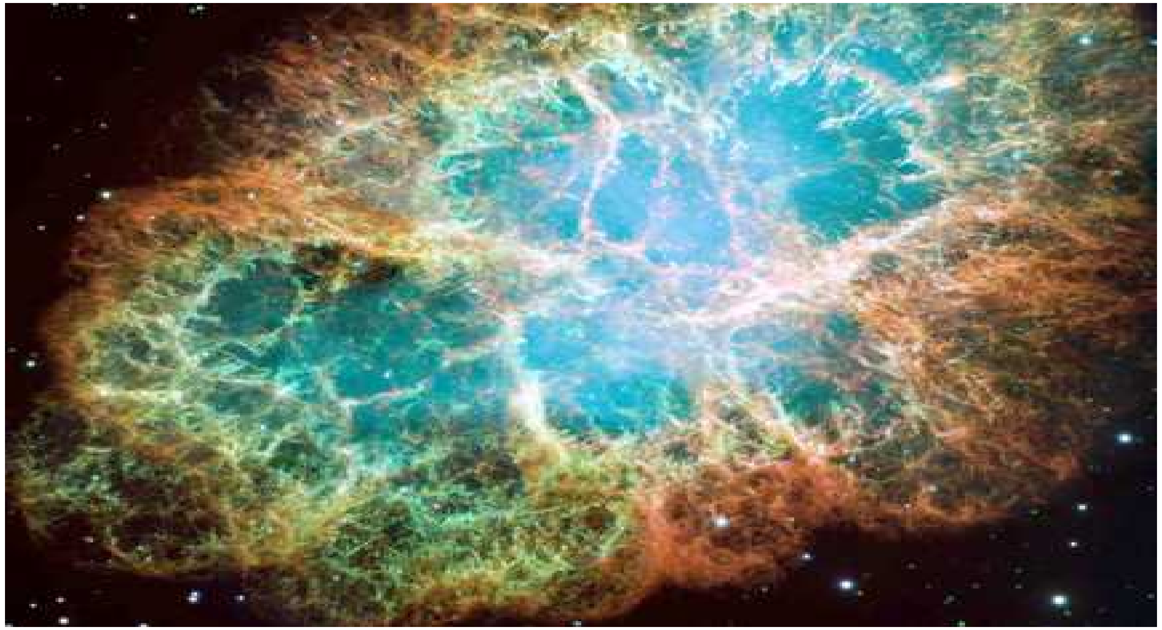
1. Magnetic sonalized outlook.
2. Peculiar
3. MHD turb f eld

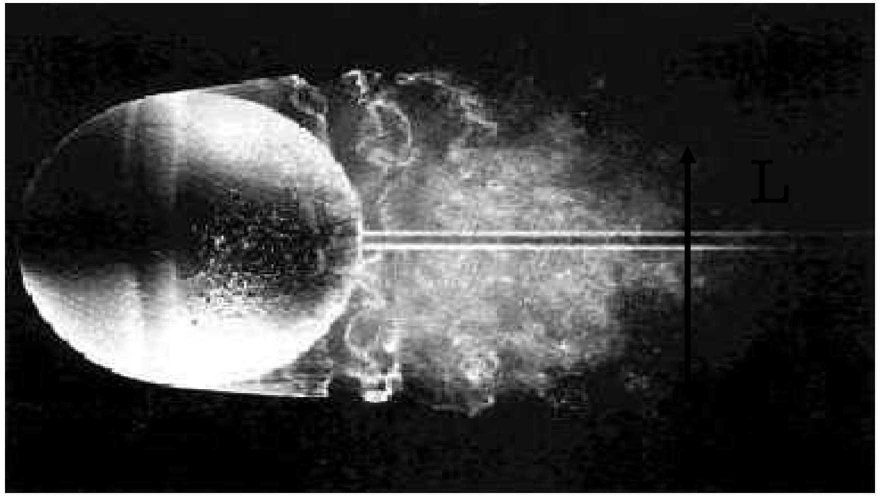
Points of the talk:

1. Magnetic fields and Turbulence: Why do we care? Personalized outlook.
2. Peculiar MHD turbulence properties
3. MHD turbulence allows new ways of tracing magnetic field

We live in a turbulent world!!!

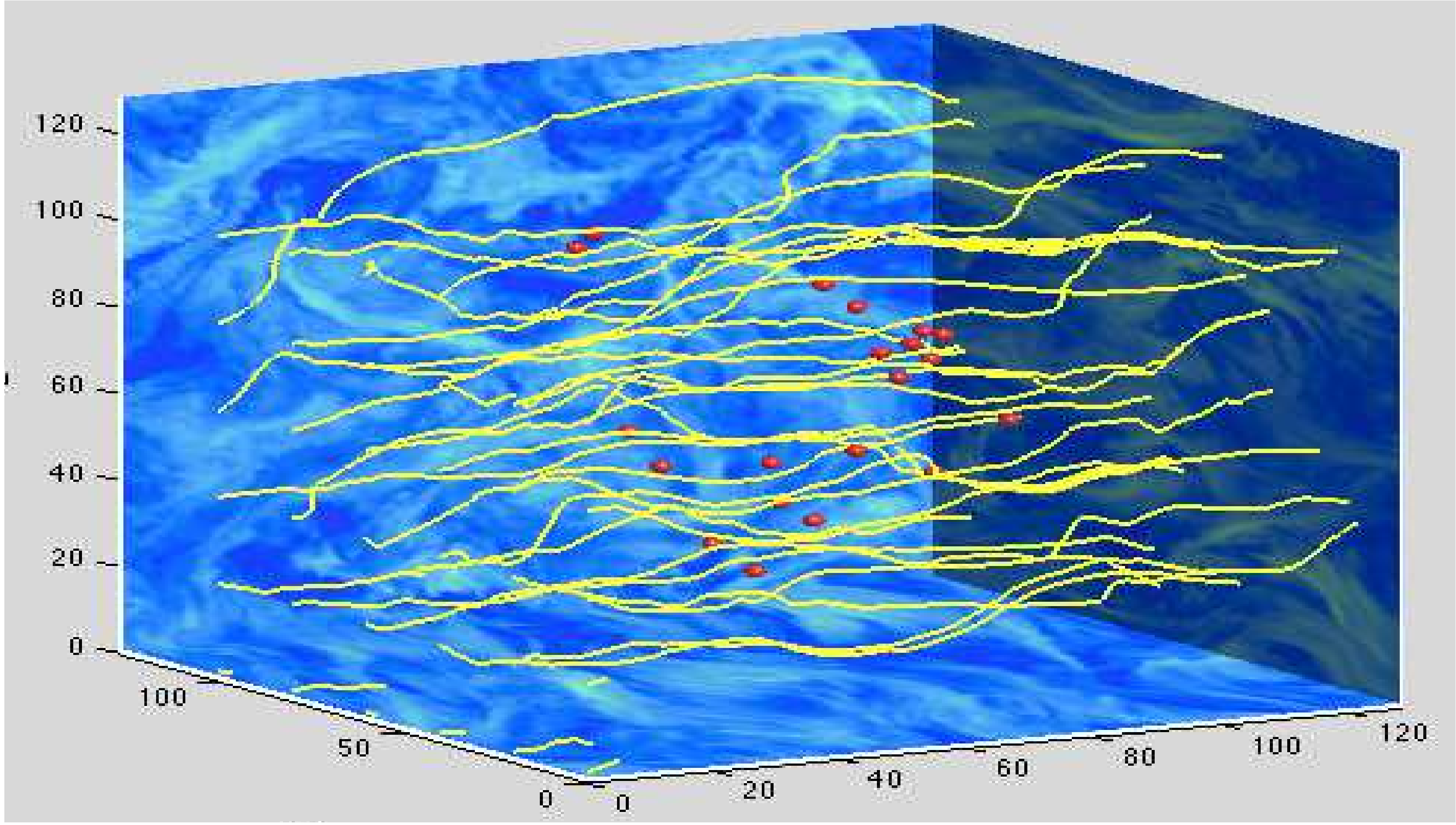
$$Re = LV/\nu = (L^2/\nu)/(L/V) = \tau_{diff}/\tau_{eddy}$$





Astrophysical flows have Re>1010.

Properties of magnetic fields are VERY different when magnetic fields are turbulent



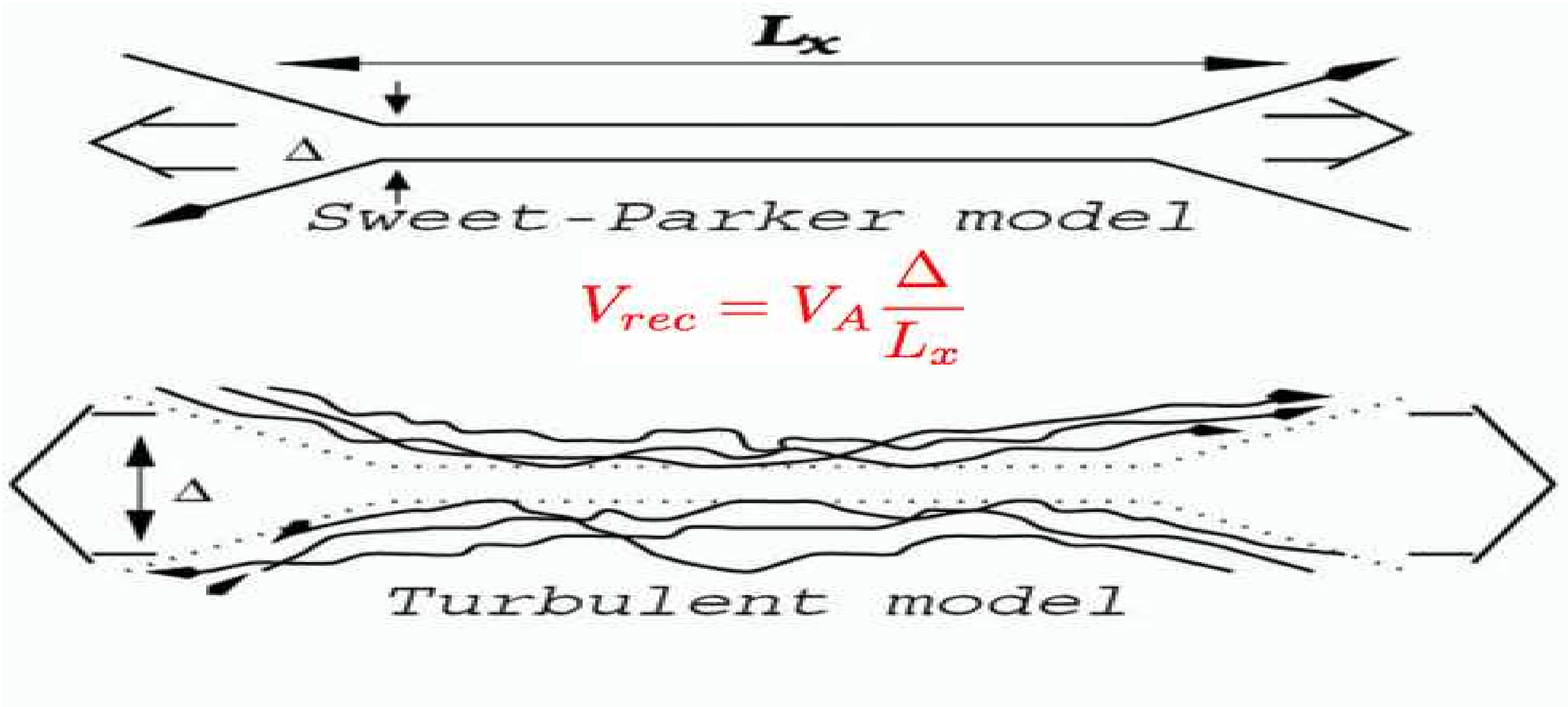
Laminar Sweet-Parker reconnection is slow

$$V_{rec} = V_A \frac{\Delta}{L_x}$$

Turbulence makes magnetic reconnection fast!

Turbulent reconnection:

Outflow is determined by field wandering.



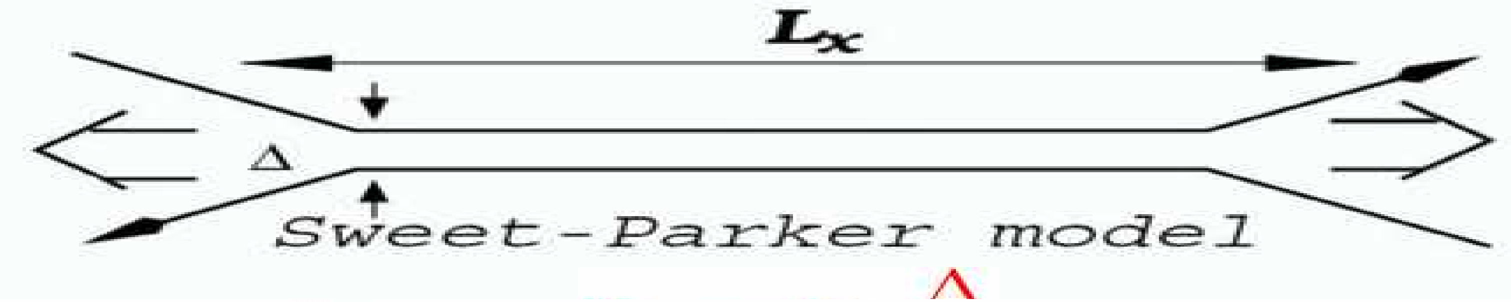
AL & Vishniac (1999)

henceforth referred to as LV99

LV99 model extends Sweet-Parker model for turbulent astrophysical plasmas and makes reconnection fast

Turbulent reconnection:

Outflow is determined by field wandering.



Without turbulence:

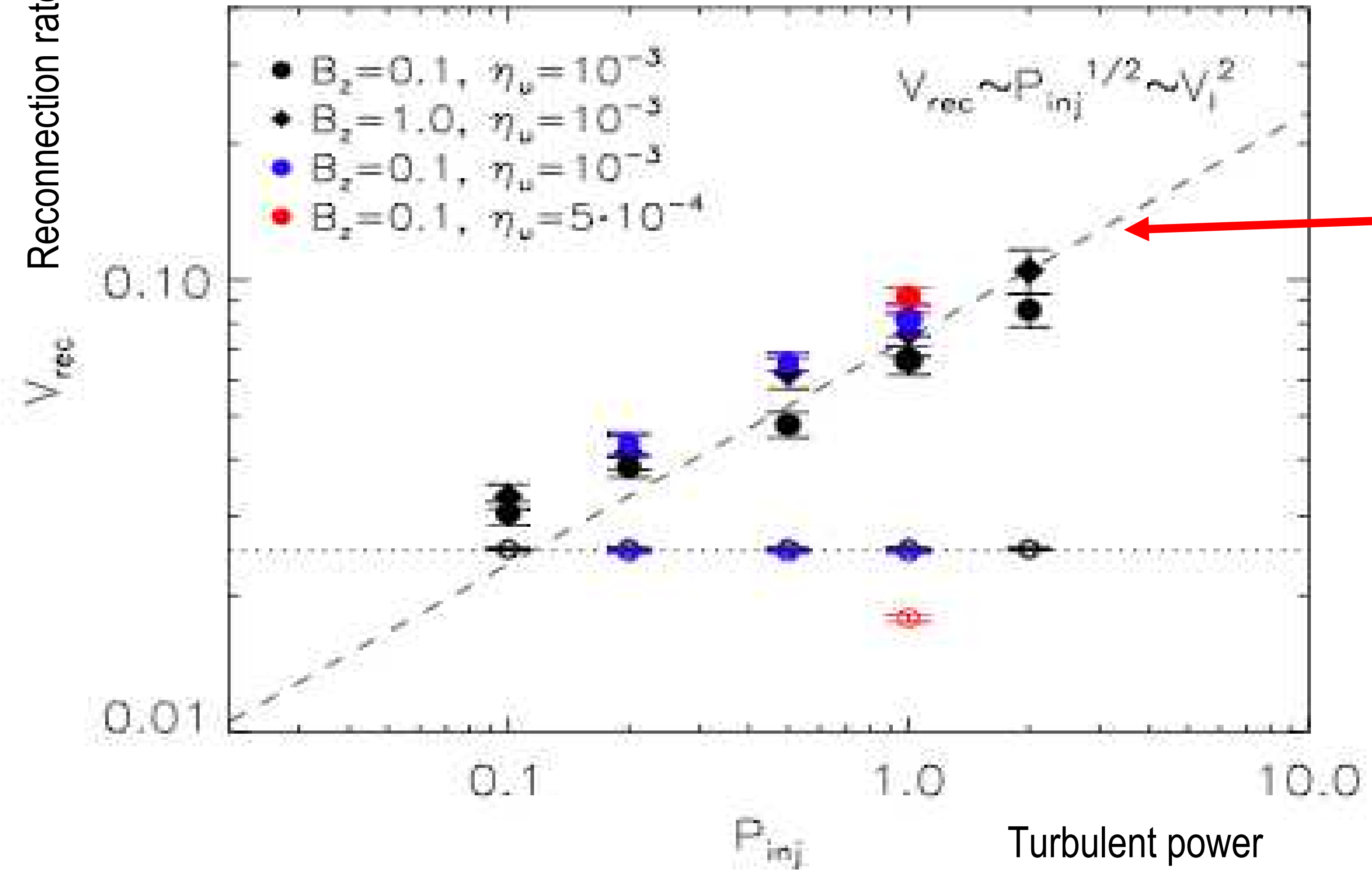
molecular diffusion coefficient D ~10^{-5} cm^2/sec

(← It's for small molecules in water.)

➔ Mixing time ~ (size of the cup)^2/D ~ 10^7 sec ~ 0.3 year !

Numerics confirms that turbulence does it!

Reconnection rate



Turbulent power

AL & Vishniac (1999) prediction is Vrec~ Pinj1/2

More recent studies:
Oishi, Mac Low, Collins, Tamura 2015
Takamoto, Inue, AL 2016
Kowal et al. 2017

Kowal et al. 2012

Big Implication: LV99 means that magnetic field in turbulent fluids is not frozen in

Turbulent reconnection and violation of flux freezing was shown by comparison of simulations and Solar wind data

Lalescu et al. 2015

Hannes Alfven

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Turbulent reconnection and violation of flux freezing was shown by comparison of simulations and Solar wind data

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Hannes Alfven

I feel that “turbulent ambipolar diffusion” is as meaningful as “molecular turbulent

Points of the talk:

1. Magnetic fields and Turbulence: Why do we care? Personalized outlook.
2. Peculiar MHD turbulence properties
3. MHD turbulence allows new ways of tracing magnetic field

Turbulence is a chaotic order

It is good to know the laws of this order and use them

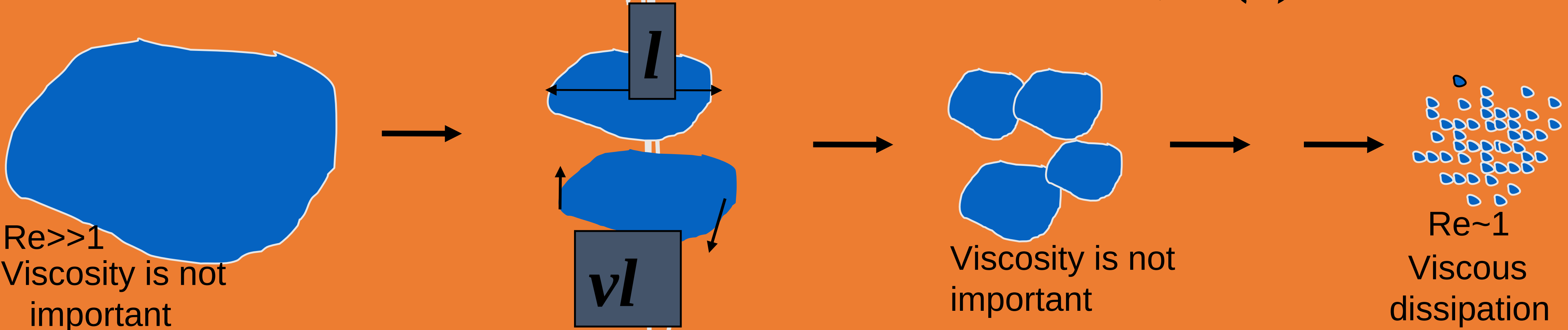
Kolmogorov theory reveals order in chaos for incompressible hydro turbulence

$$\frac{V_l^2}{t_{cas,l}} = const$$

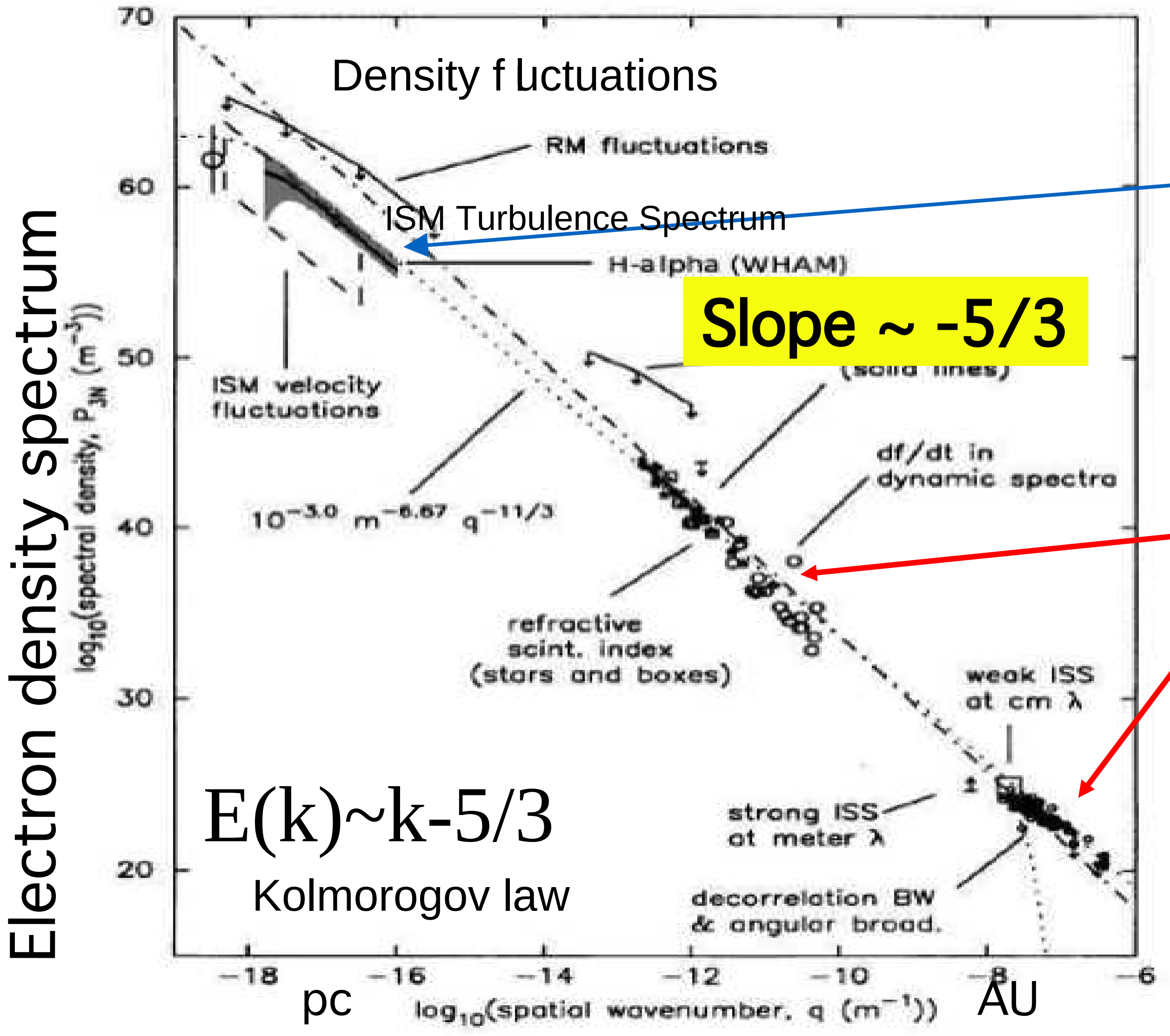
$$t_{cas,l} = l/V_l$$

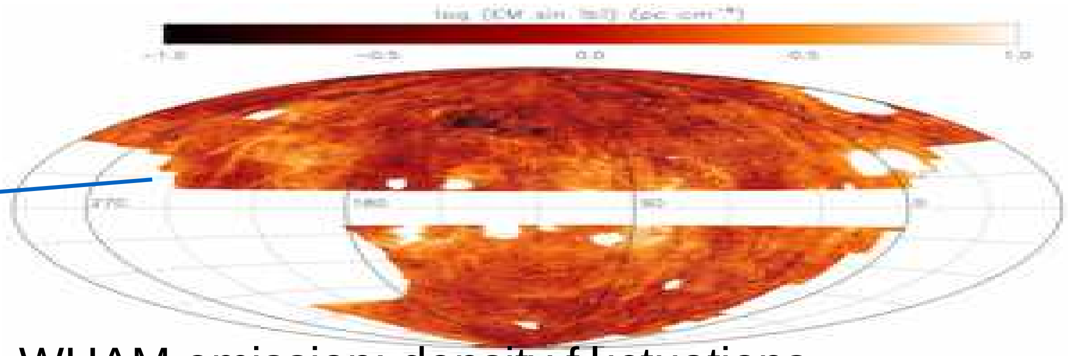
$$\frac{V_l^3}{l} = const,\ V_l \sim l^{1/3}$$

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



Kolmogorov Law is measured for electron density fluctuations





WHAM emission: density fluctuations

Scincillations and scattering

from Armstrong, Rickett & Spanger 1994

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.

Strong MHD turbulence is characterized by a “critical balance”.

- ***Critical balance***

$$\frac{l_\perp}{V_\perp} = \frac{l_\parallel}{B_0}$$

- ***Constancy of energy cascade rate***

$$\frac{V_\perp^2}{t_{cas}} = const$$

$$\frac{V_\perp^2}{(l_\perp / V_\perp)} = const$$

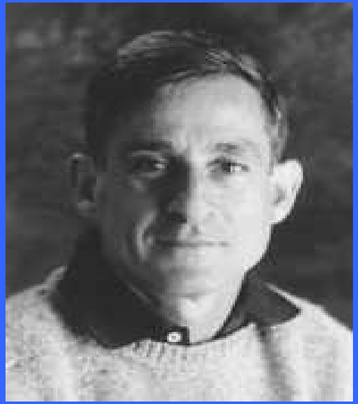
$$V_\perp \sim l_\perp^{1/3}$$

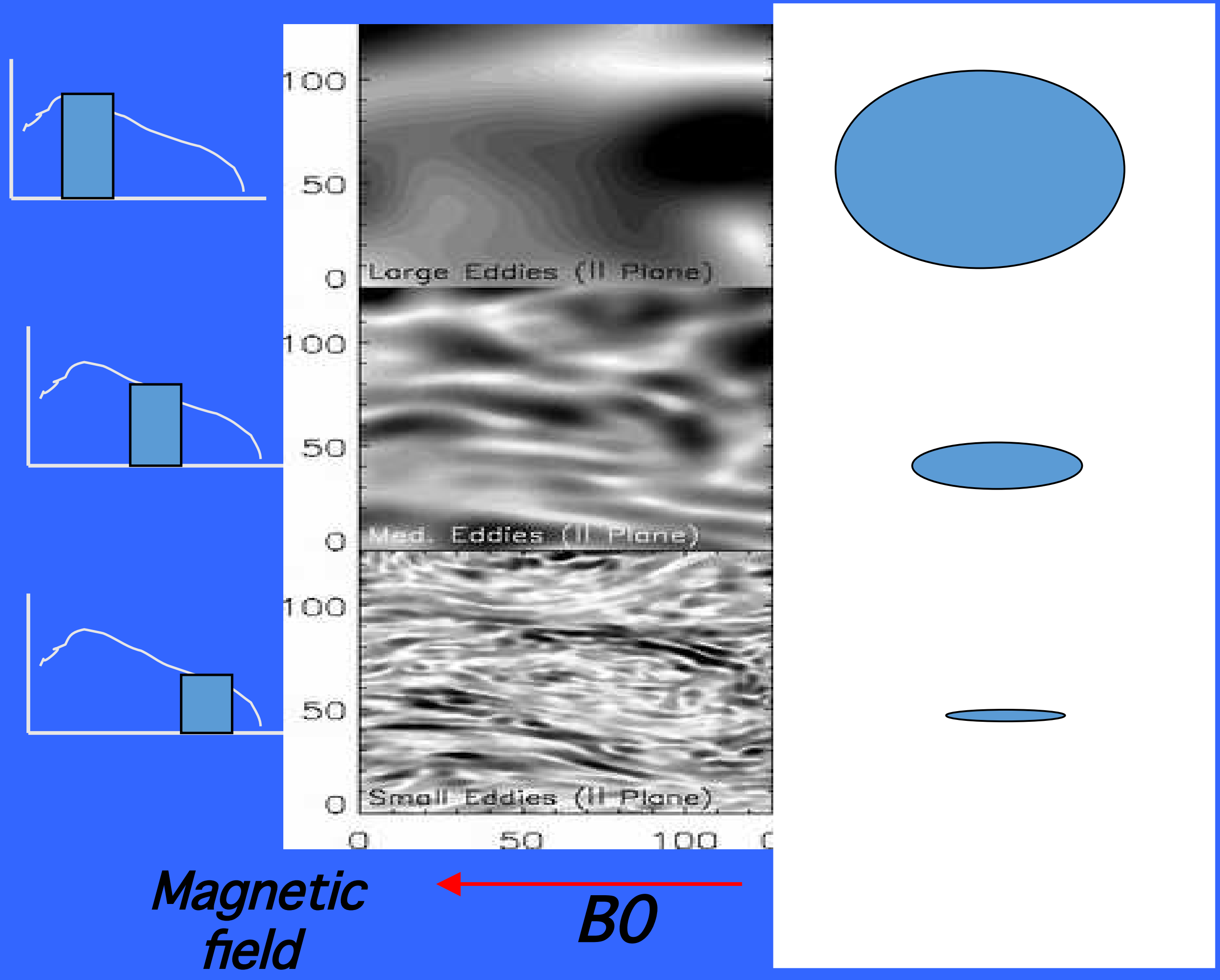
Or, $E(k) \sim k^{-5/3}$

$$l_\parallel \sim l_\perp^{2/3}$$

Goldreich-Sridhar model (1995)

Goldreich & Sridhar (1995): Alfvenic eddies get more and more elongated with the decrease of the scale

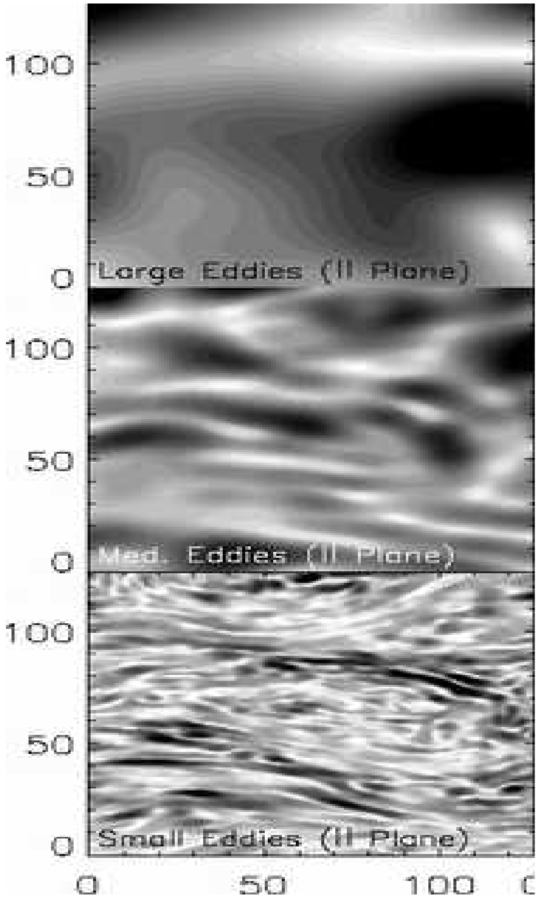


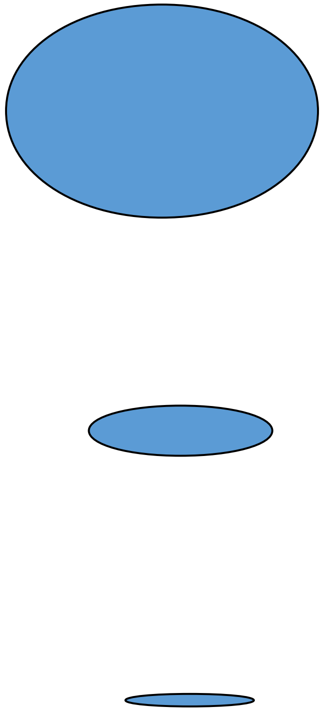


Cho, AL & Vishniac 2003

Practical demonstration of the importance of the local system of reference is in Cho & Vishniac 2000

Goldreich & Sridhar (1995): Alfvenic eddies get more and more elongated with the decrease of the scale





Magnetic field

B0

Cho, AL & Vishniac

Practical demonstration of the importance of the local system of reference is in Cho & Vishniac 2000

Therefore magnetic eddies trace magnetic field and velocity gradients should be perpendicular to the local direction of magnetic field

Points of the talk:

1. Magnetic fields and Turbulence: Why do we care? Personalized outlook.
2. Peculiar MHD turbulence properties
3. MHD turbulence allows new ways of tracing magnetic field
   a. Using spectroscopic information

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

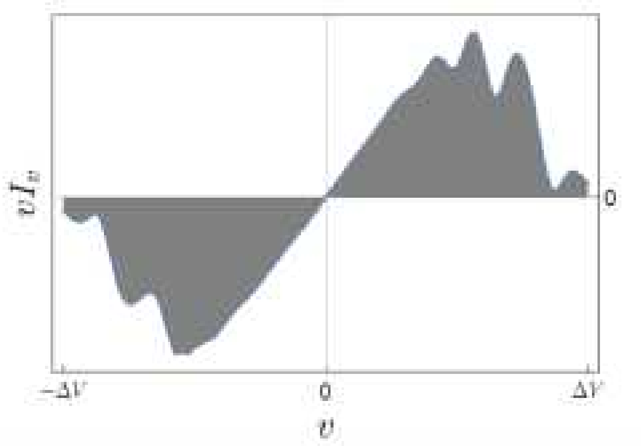
Velocity and magnetic field gradients trace local direction of magnetic field

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

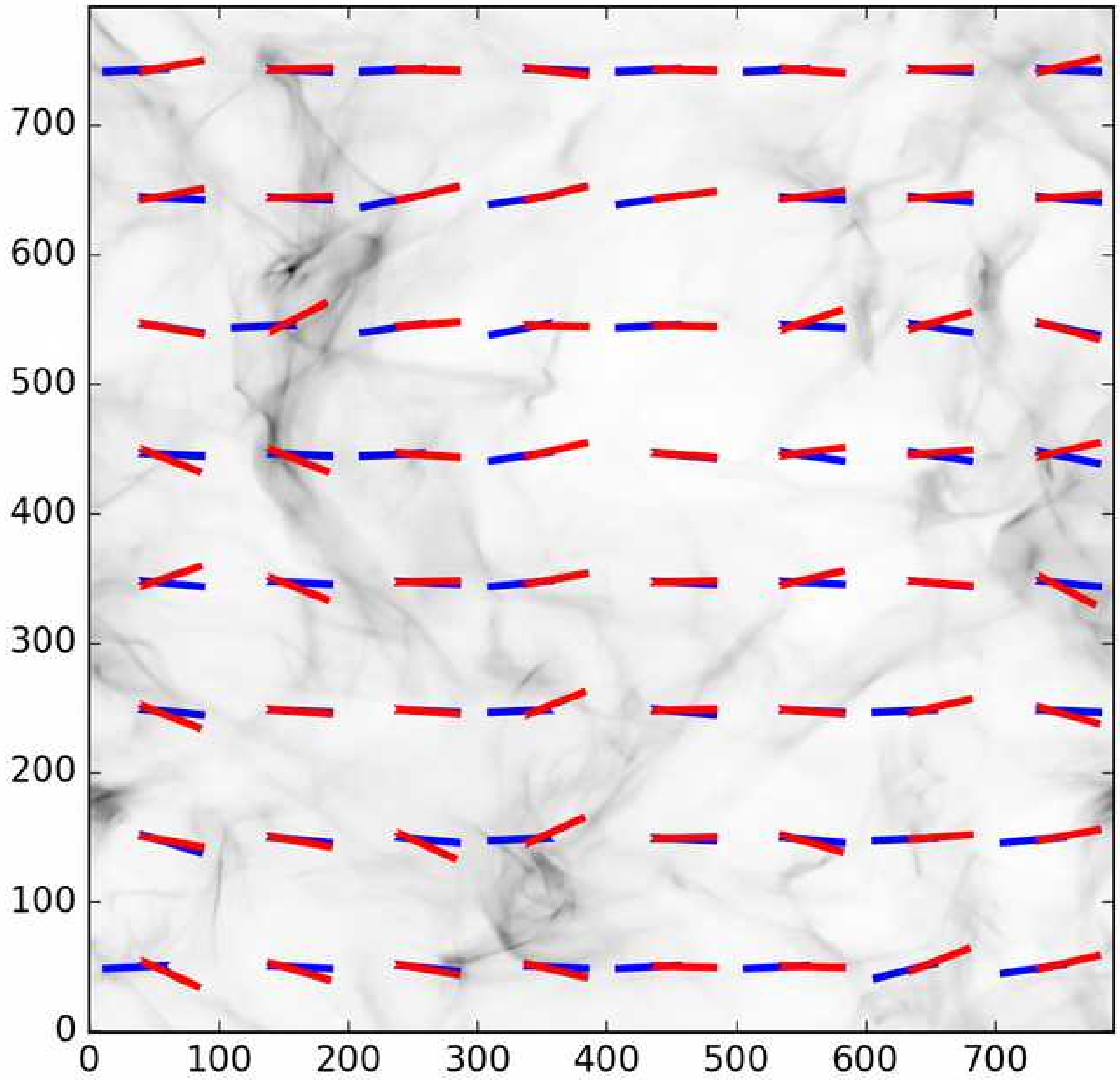
Can use velocity centroids to represent velocities from observed data:



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

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

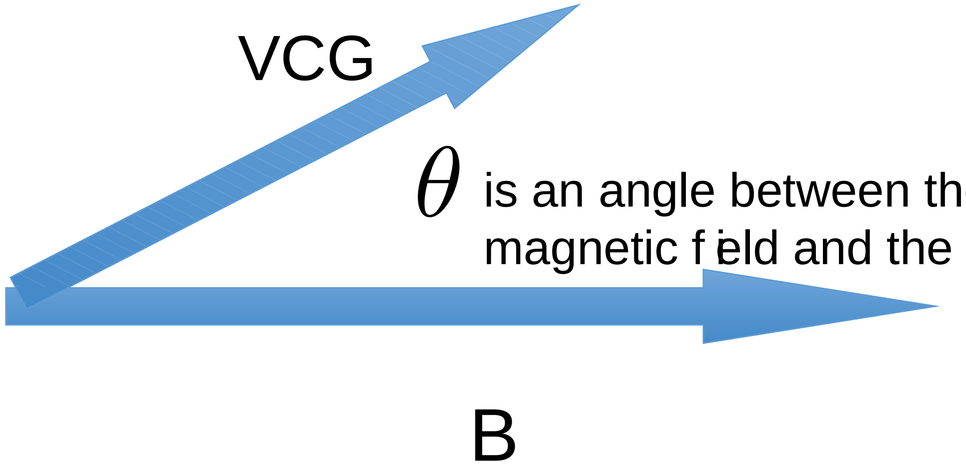
Testing with numerical simulations shows that this is true



RED : Velocity Centroid Gradients (VCGs)
Blue: Magnetic Field

To quantify the alignment we use the alignment measure similar to the one in grain alignment theory (see H. Thiem talk after my talk)

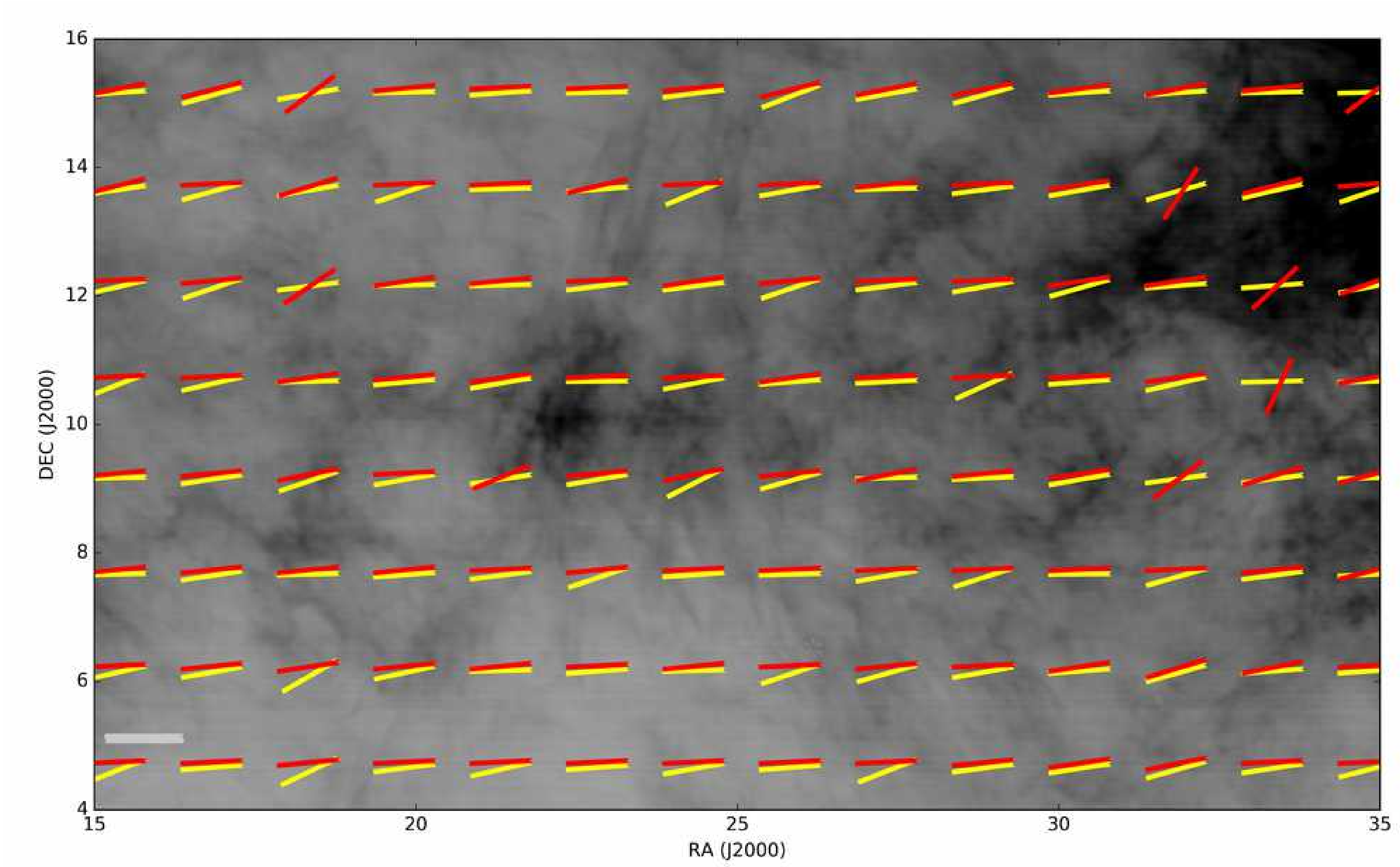
$$AM = 2\langle \cos^2\theta - 1 \rangle$$



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

Casanova & AL 2017

Application to high Latitude HI: Comparison with Planck Polarization

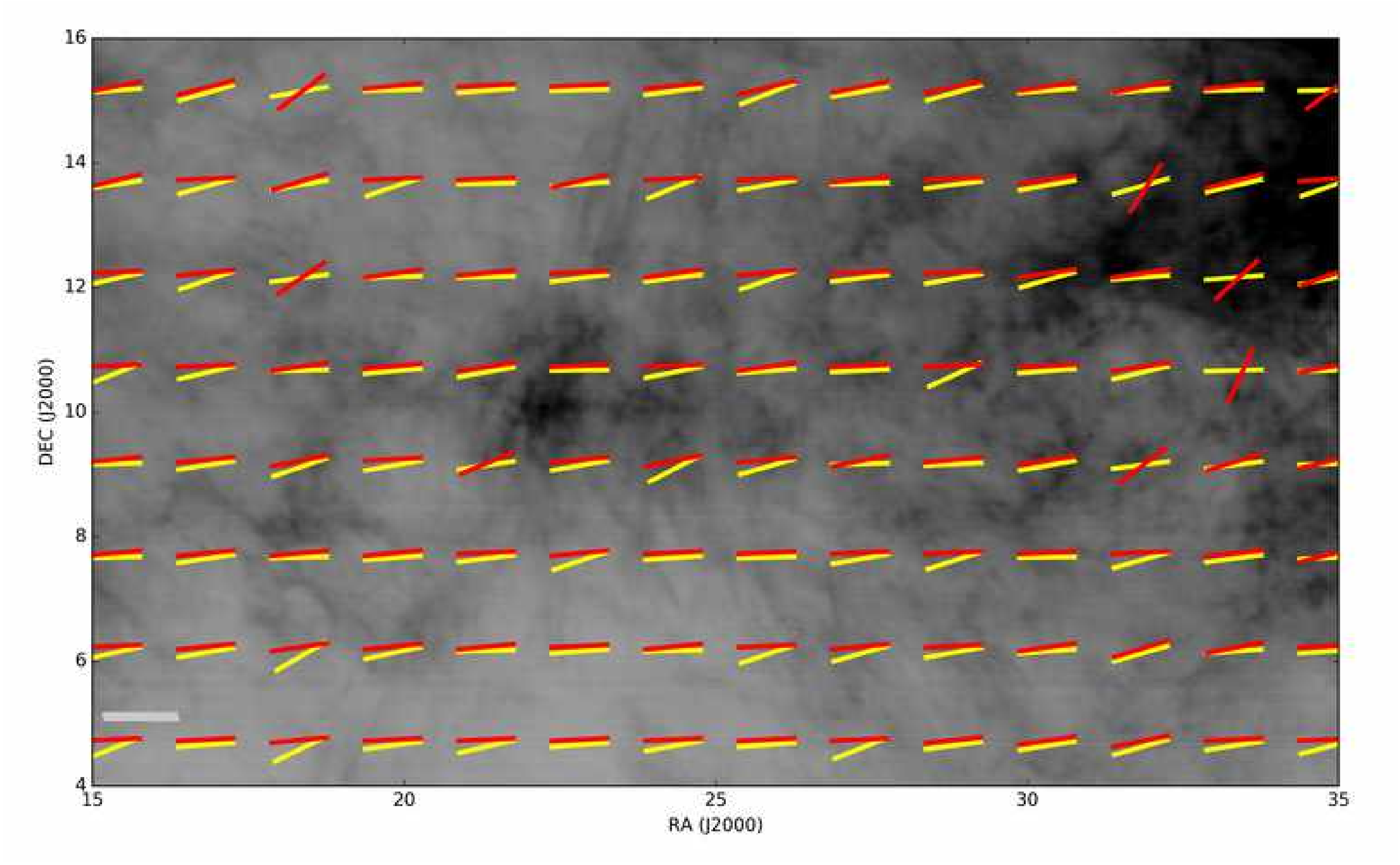


RED : Velocity Centroid Gradients (VCGs)
Yellow: Magnetic field

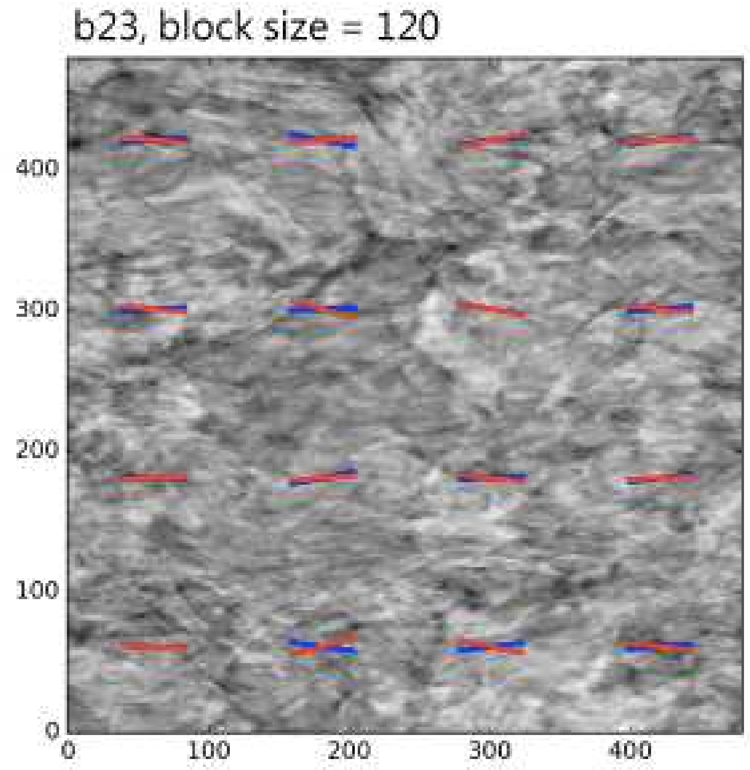
GALFA data

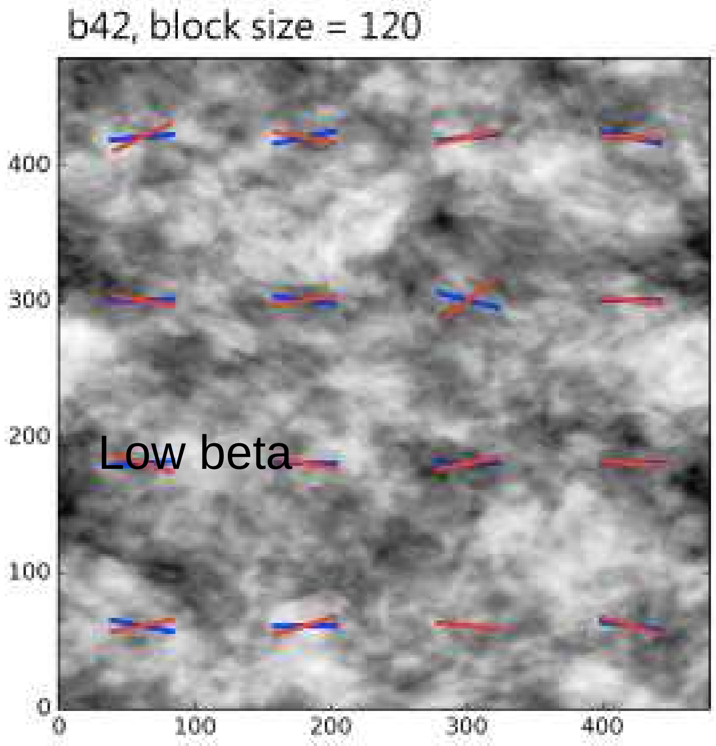
Yuen & AL 2017

Application to high Latitude HI: Comparison with Planck Polarization



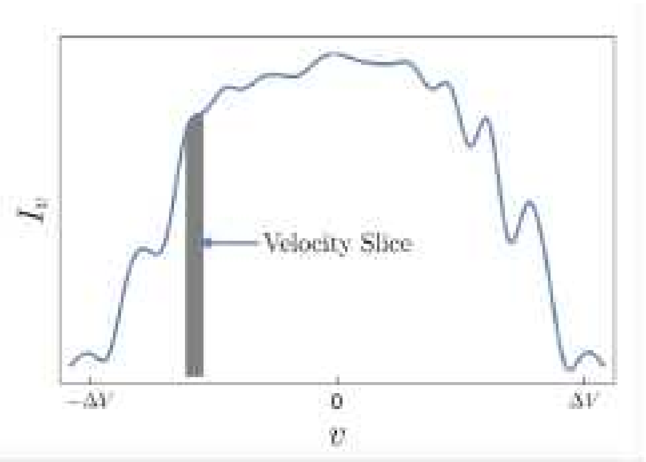
Velocity Channel Gradients (VChGs) follow magnetic field well





Low beta

High beta



AL & Yuen 2017

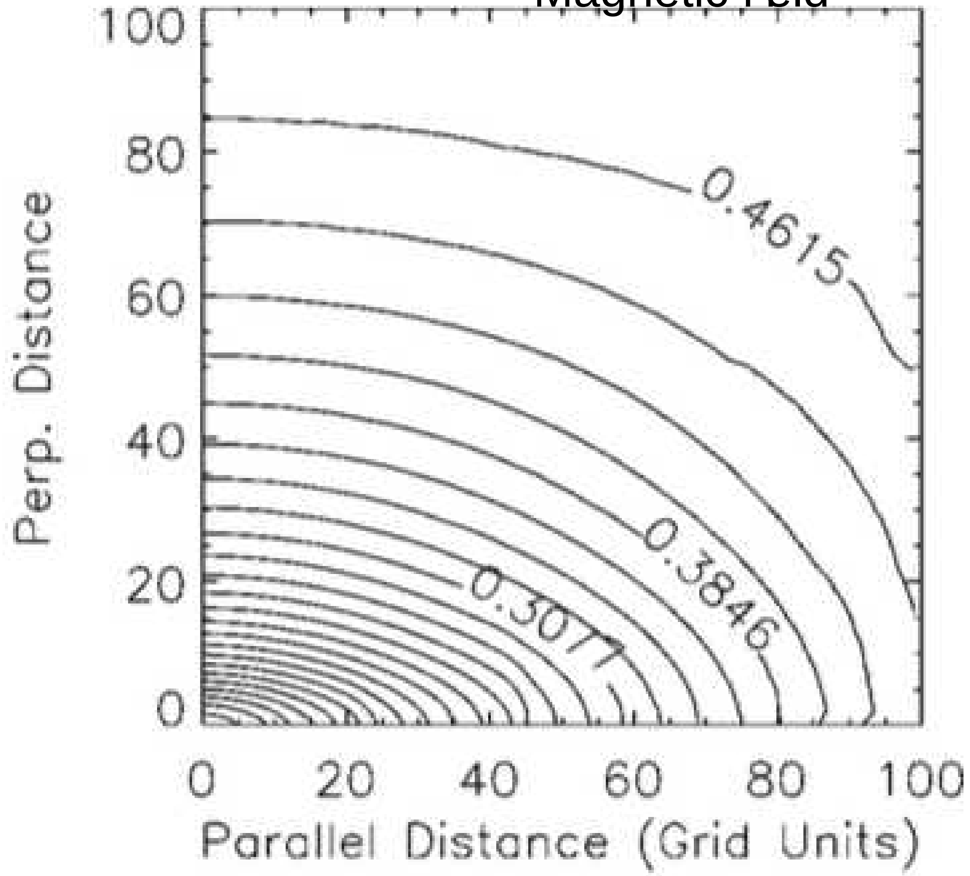
Thin channels are mostly influenced by velocities (AL & Pogosyan 2000)

Can we use density gradients?

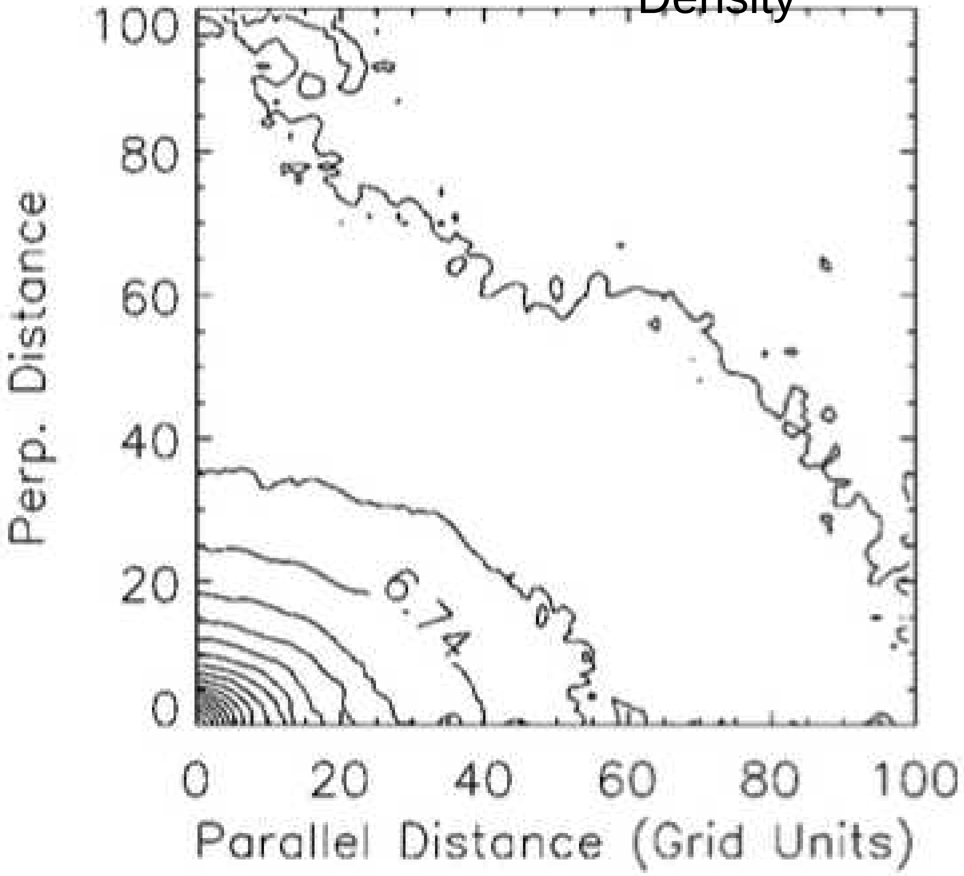
Density fluctuations in supersonic turbulence get isotropic and lose anisotropy

Magnetic field

Ms=10



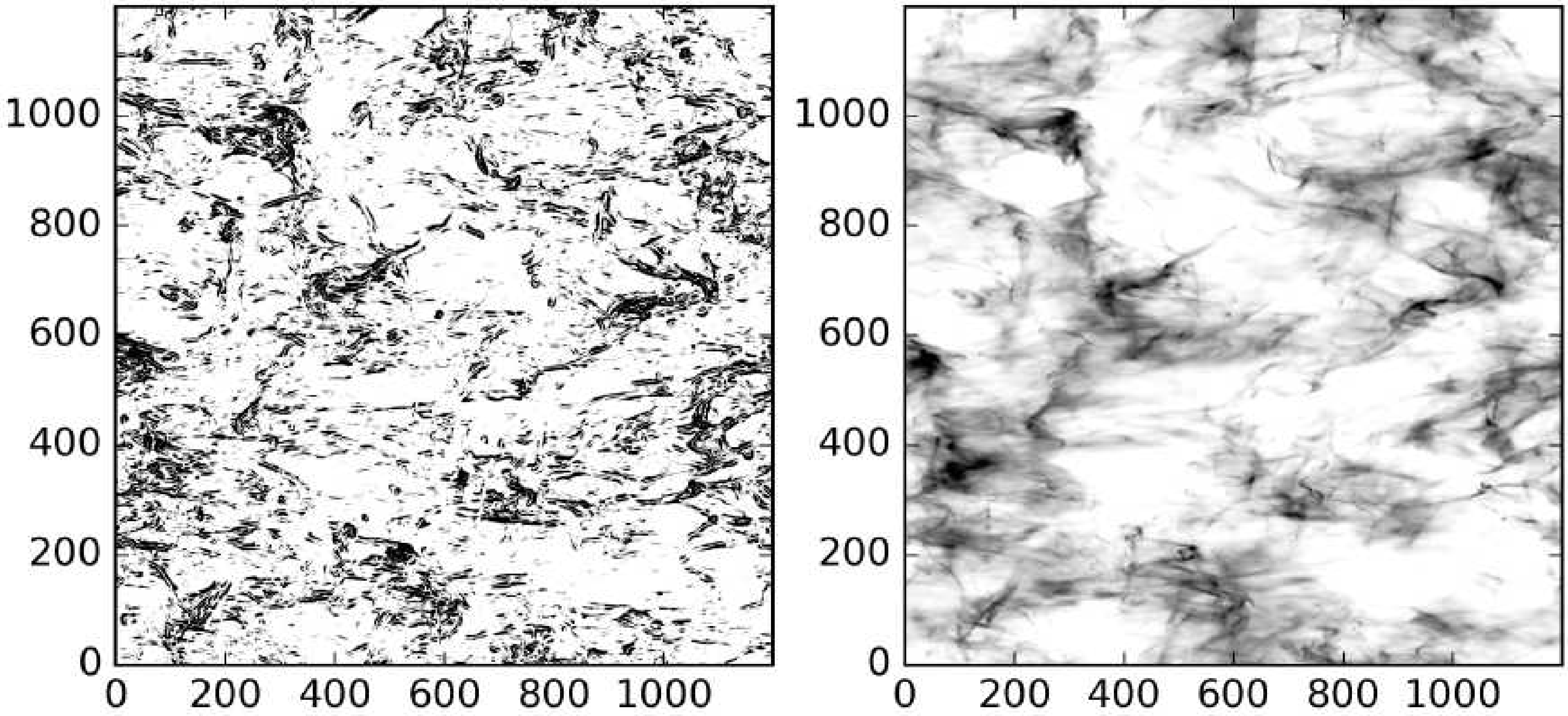
Density



Beresnyak, AL & Cho 05
Kowal, AL & Beresnyak 07

Magnetic field and velocity follow GS95 predictions of anisotropy.
Density is somewhat messy. Statistics changes with the Mach numbe

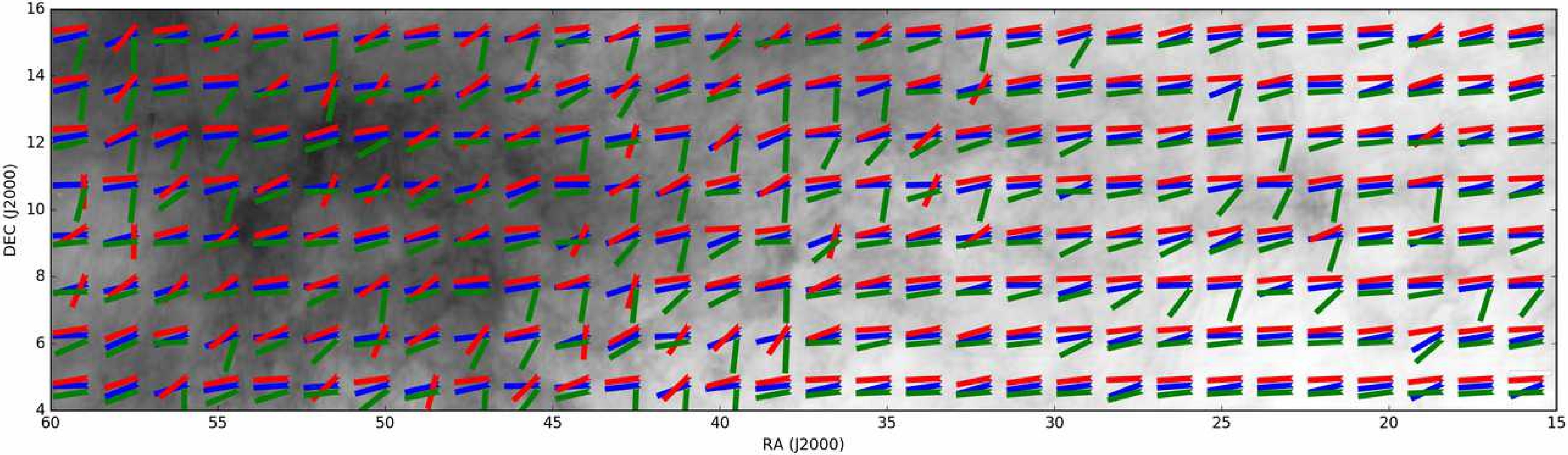
Intensity gradients much more sensitive to shocks compared to velocity gradients



Amplitude of intensity gradients (left) versus shock visualization (right)

Comparison Velocity Gradients, Density Gradients and Magnetic Fields

GALFA data



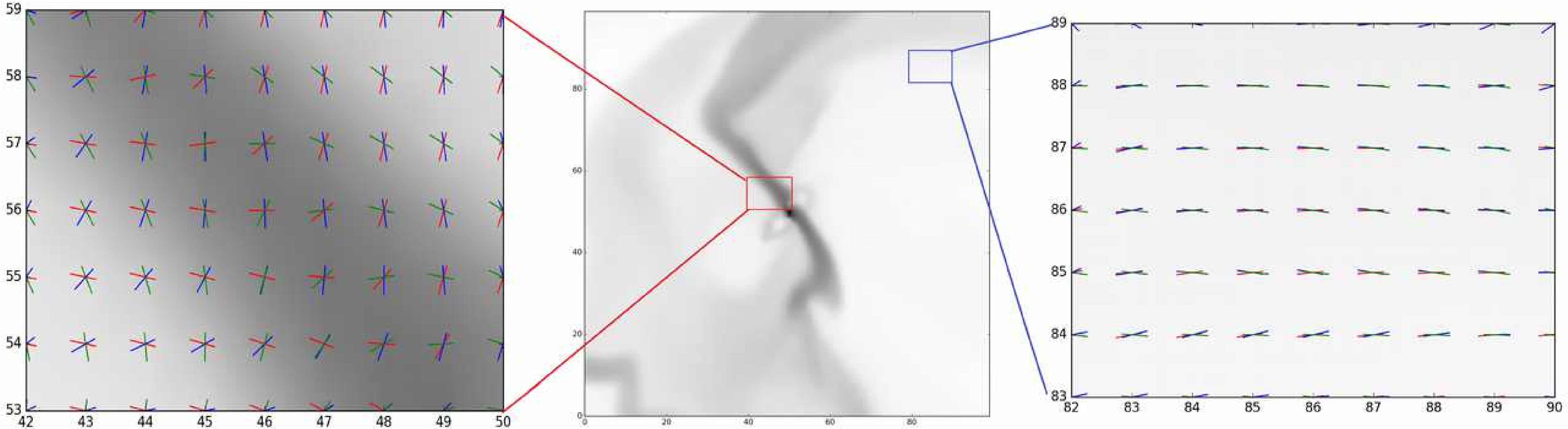
Yuen & AL 2017

RED: VG
GREEN: DG
BLUE: B

Synergy: tracing both magnetic fields and shocks!

If self-gravity dominates the VCG and VChGs behavior is changing

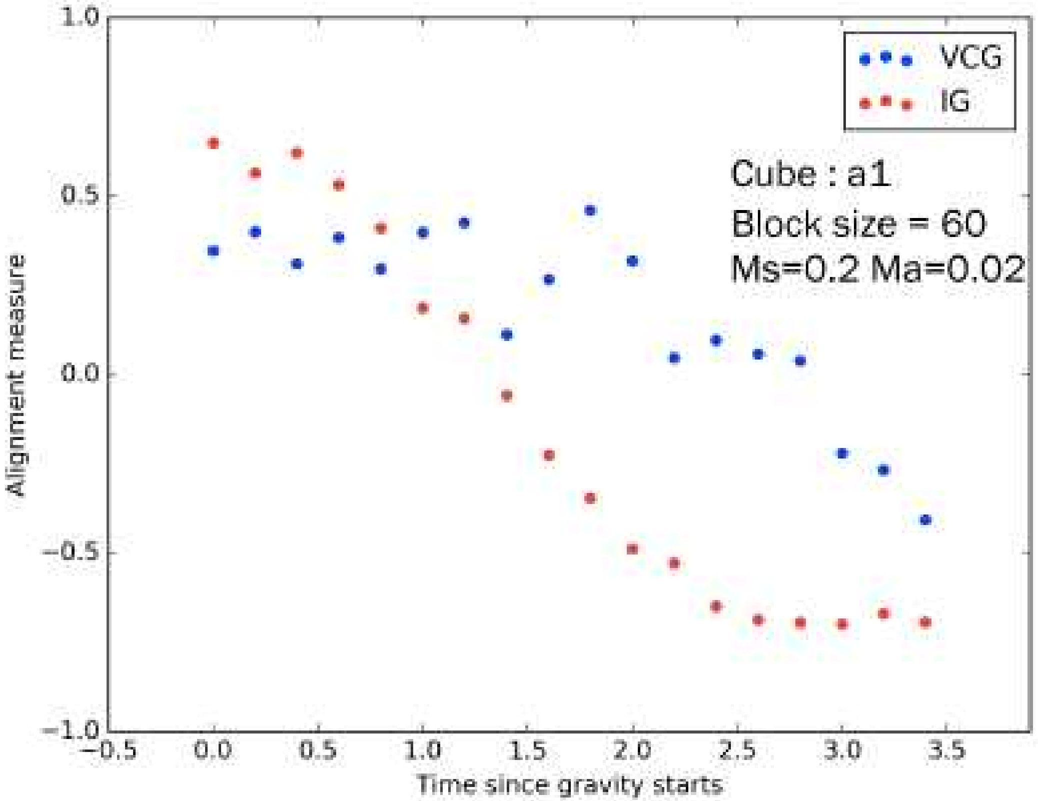
RED: VCG
GREEN: DG
BLUE: B



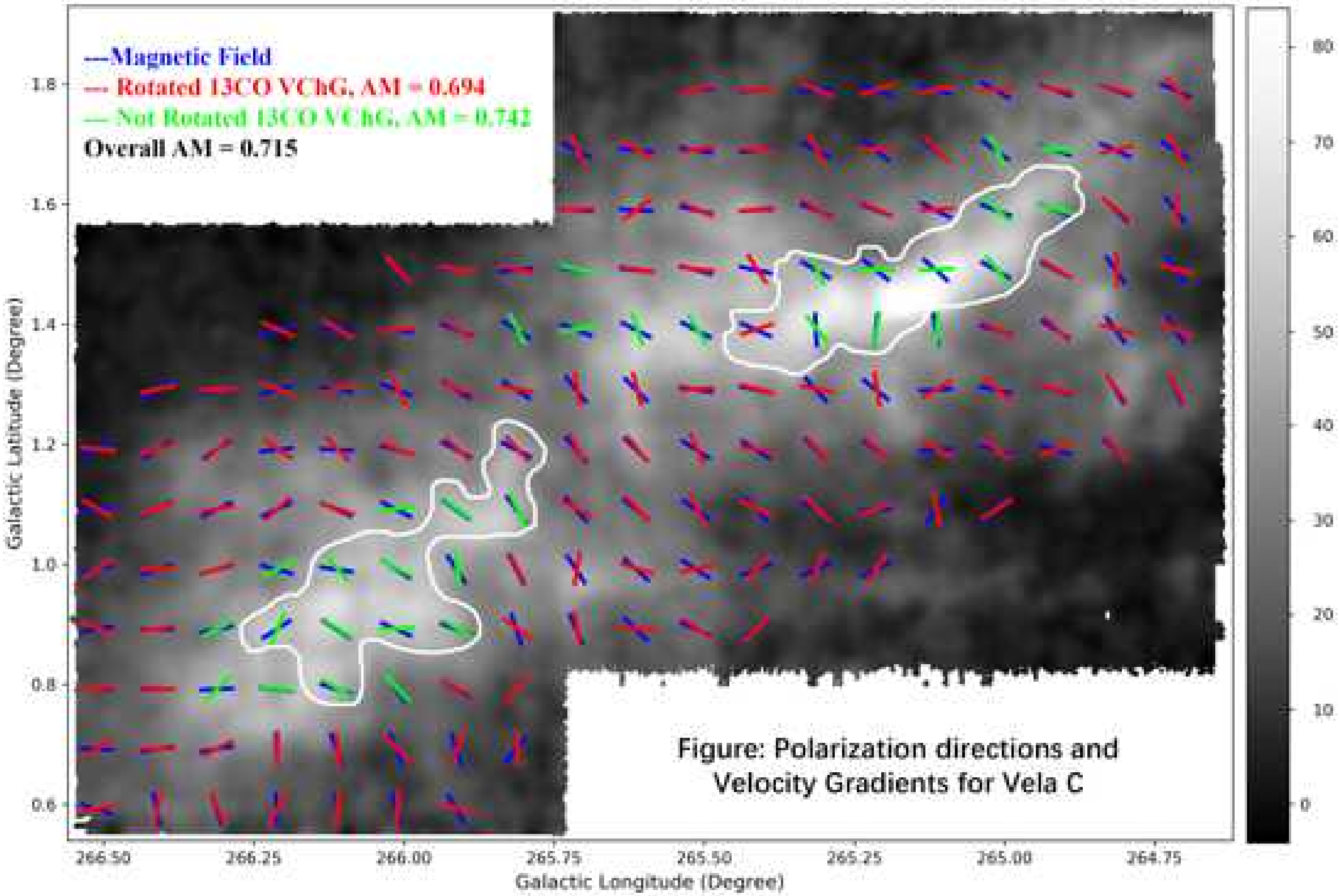
VCGs are mostly perpendicular to B and at large angles with DGs

Yuen & AL 2017

Density gradients respond faster than velocity gradients on the presence of gravity



First application to CO13 data

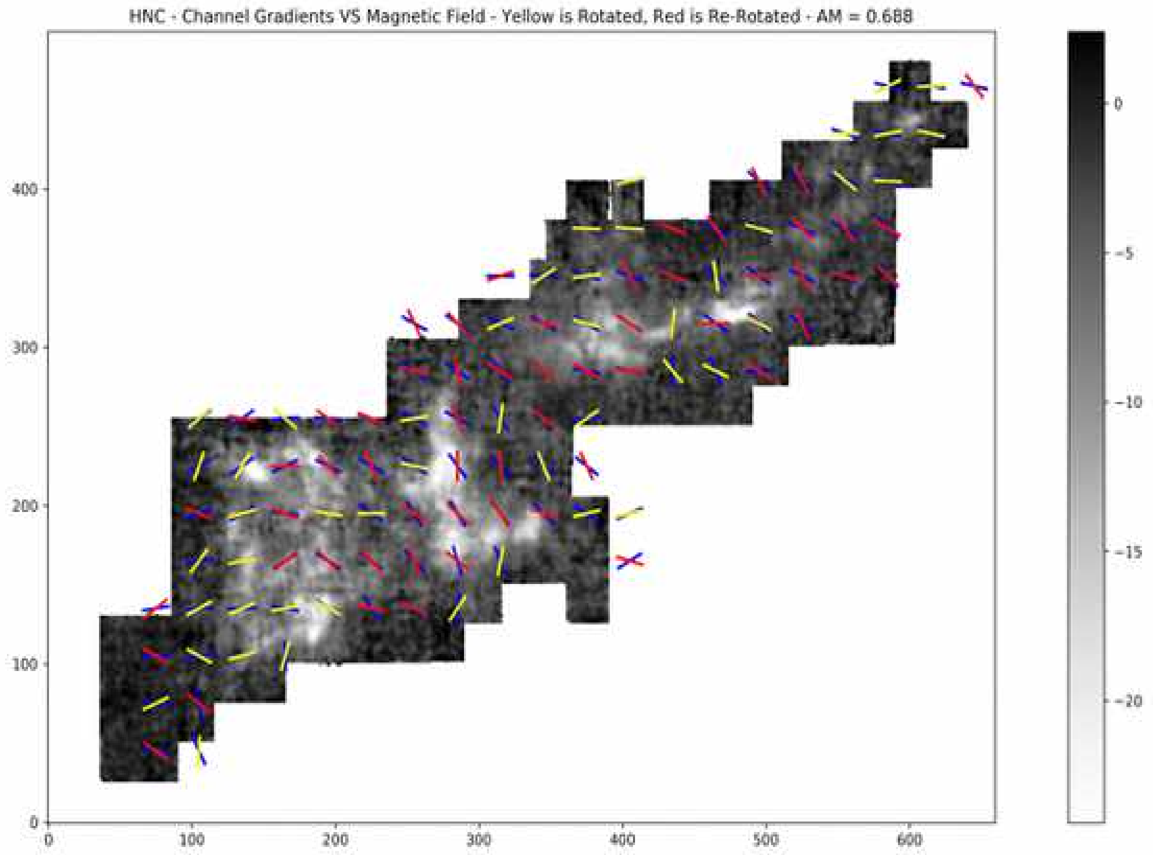


Velocity gradients in channel maps (VChGs) for 13CO. Blue directions correspond to 90 degree rotated measures

AM>0.7

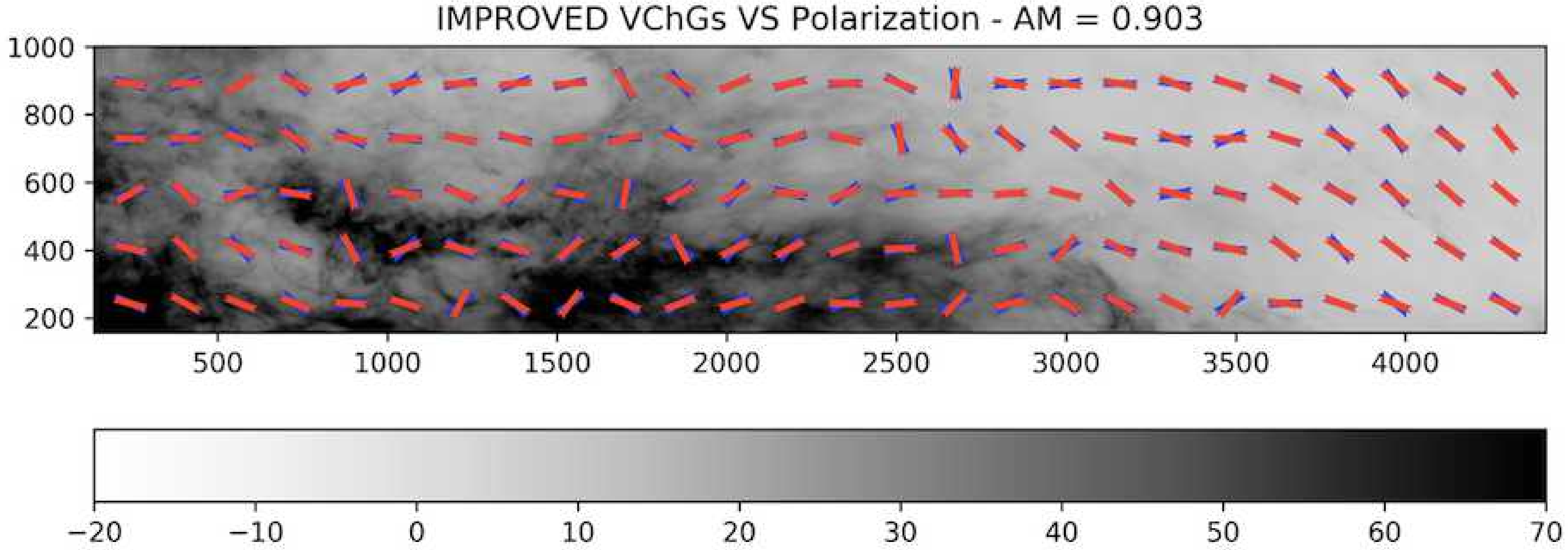
Polarization is provided by L. Fissel

Works also with HNC 1-0 transition



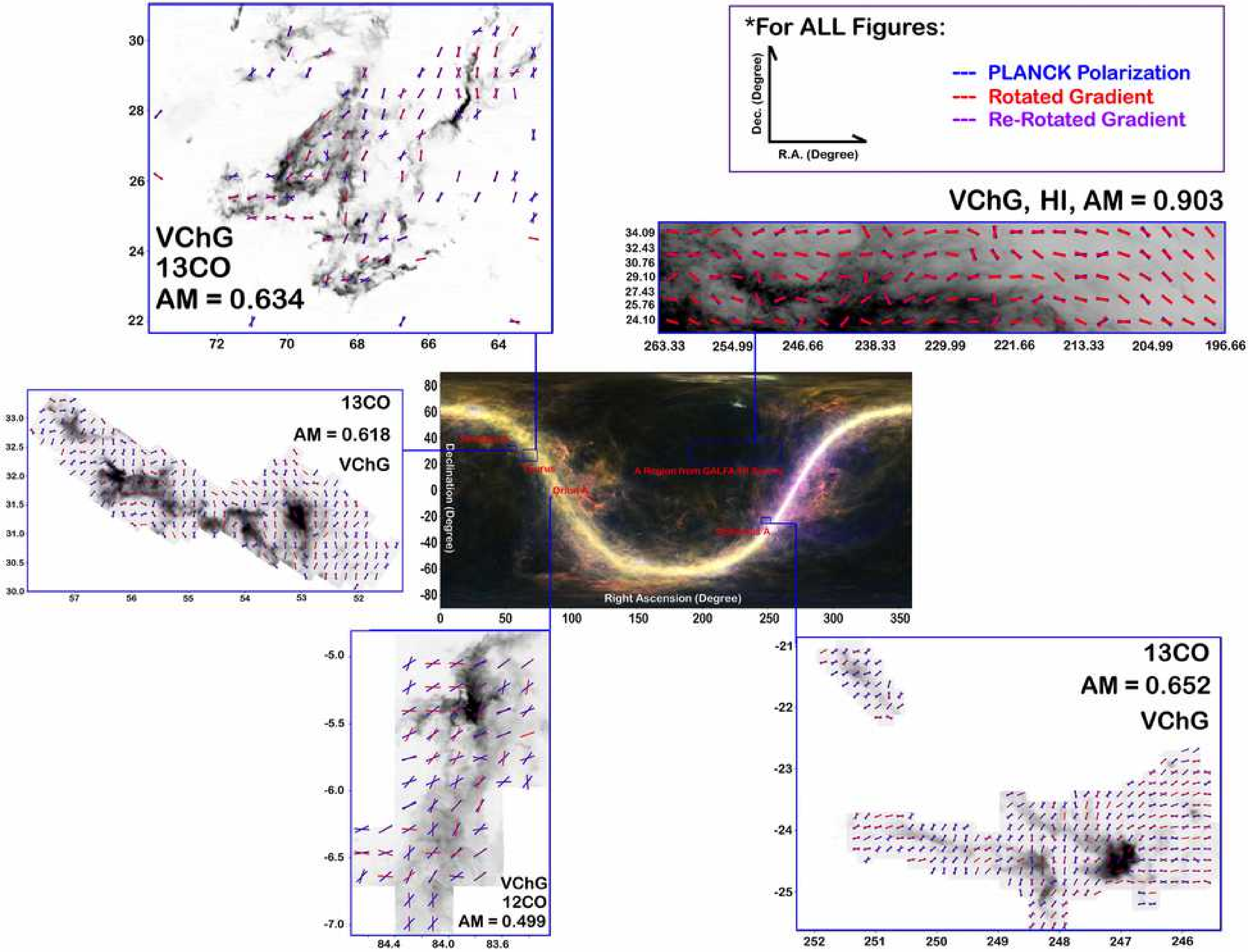
AM>0.6

Improved VChGs technique



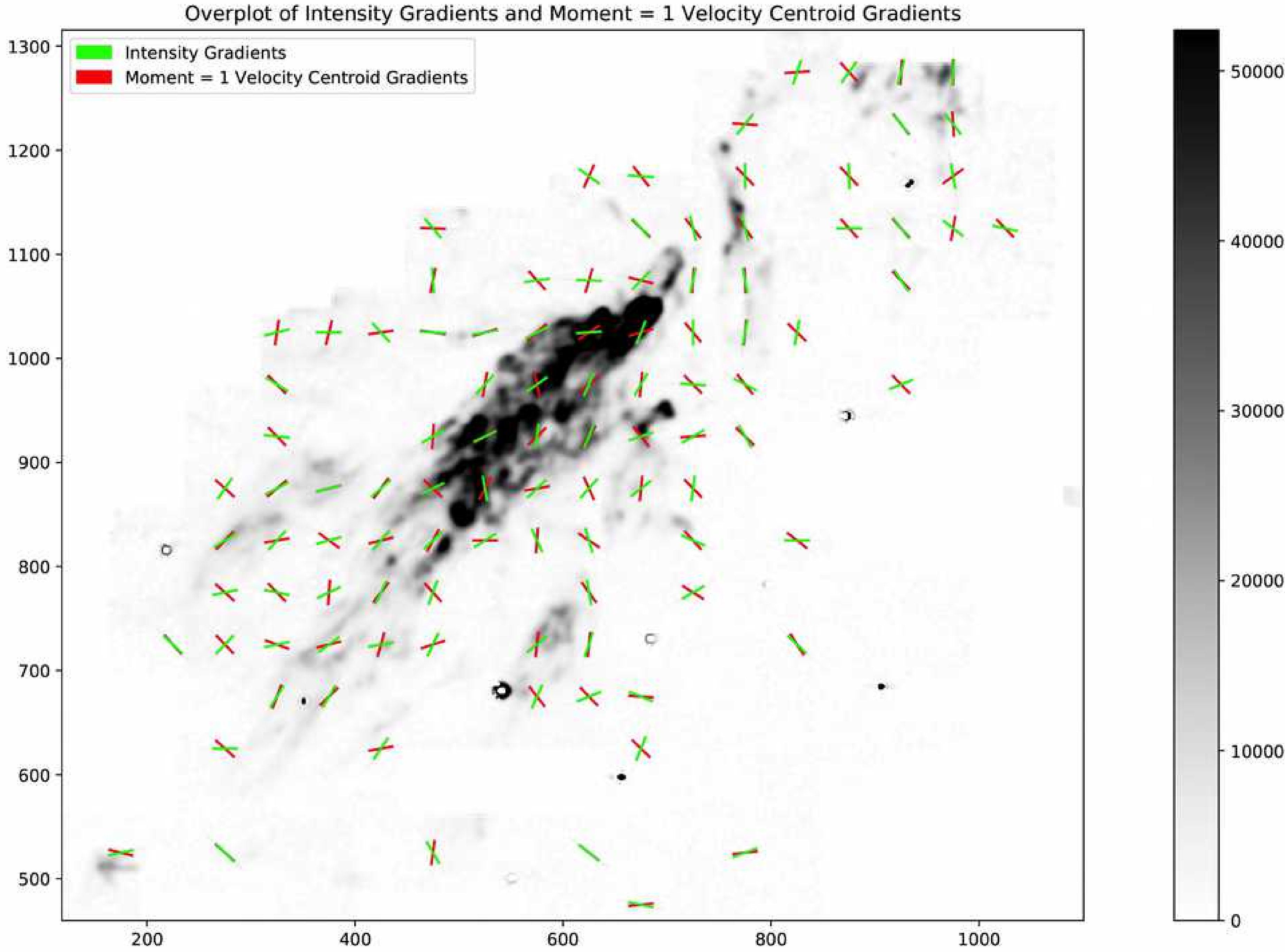
The fact that the dispersion of angle is the same at different scales is used

AL, Yuen & Sun 2017

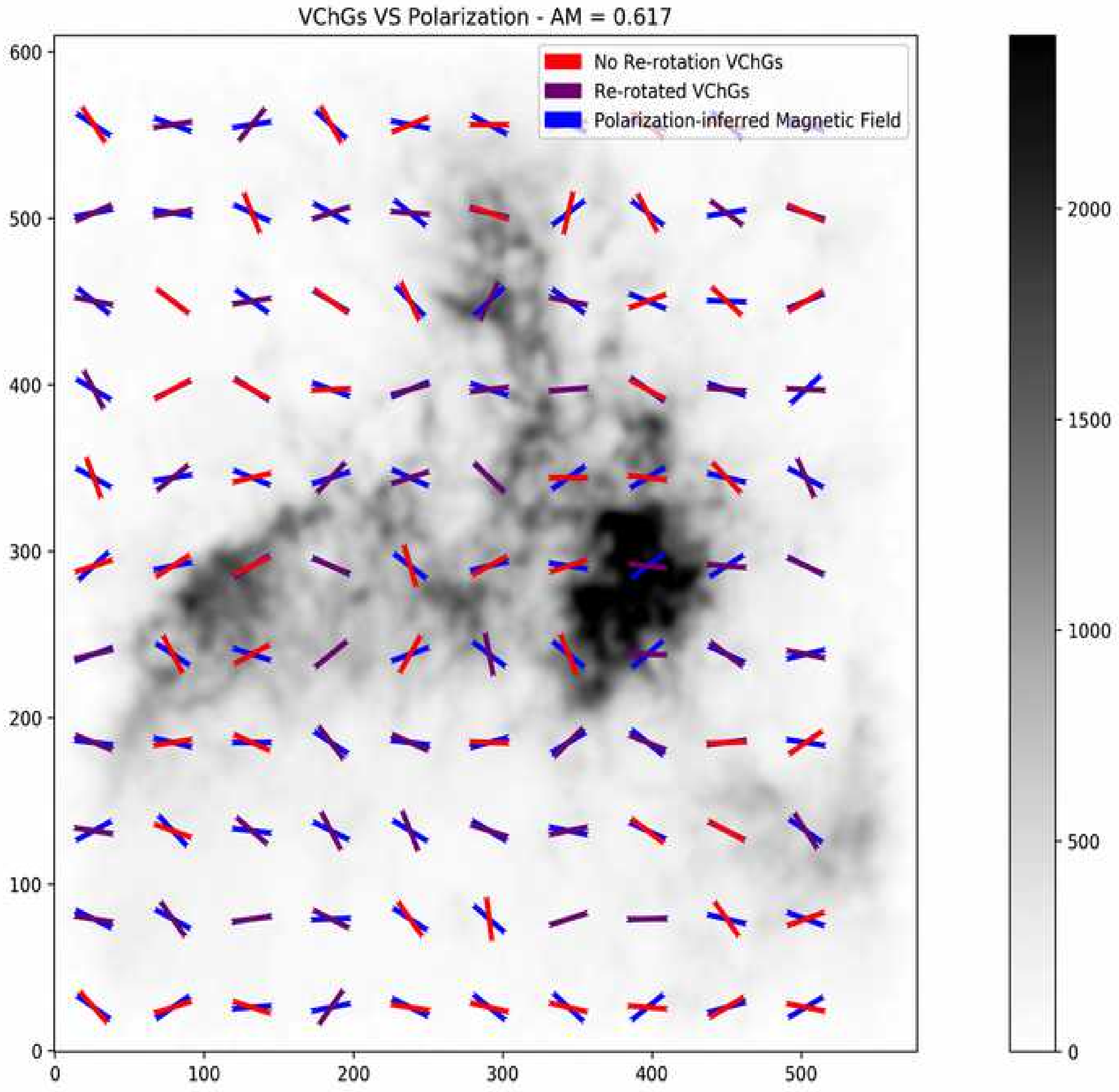


VChGs are proven to work for different species

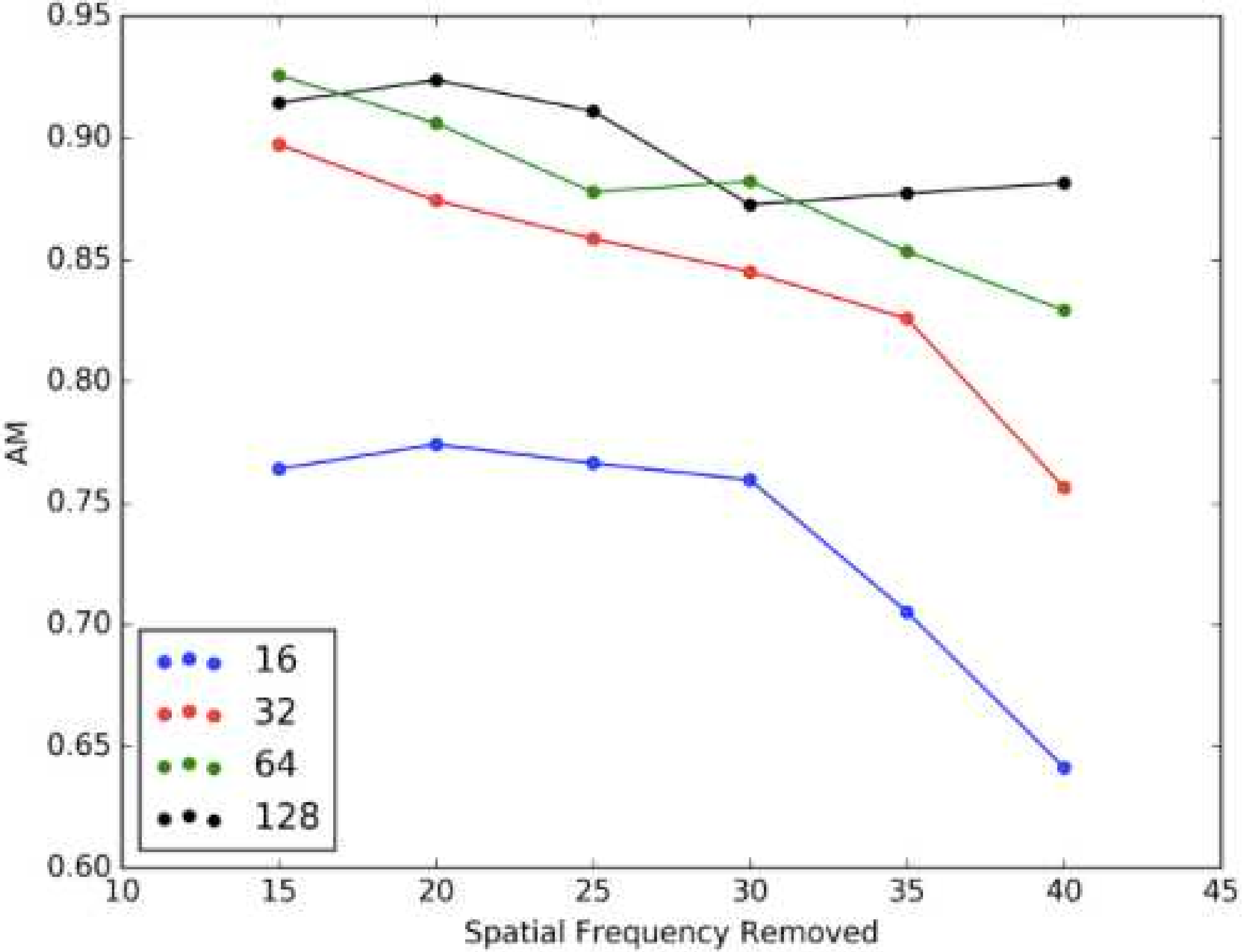
Application of the technique to the high velocity clouds: Smith Cloud



Application of the velocity channel gradients to Small Magellanic Cloud



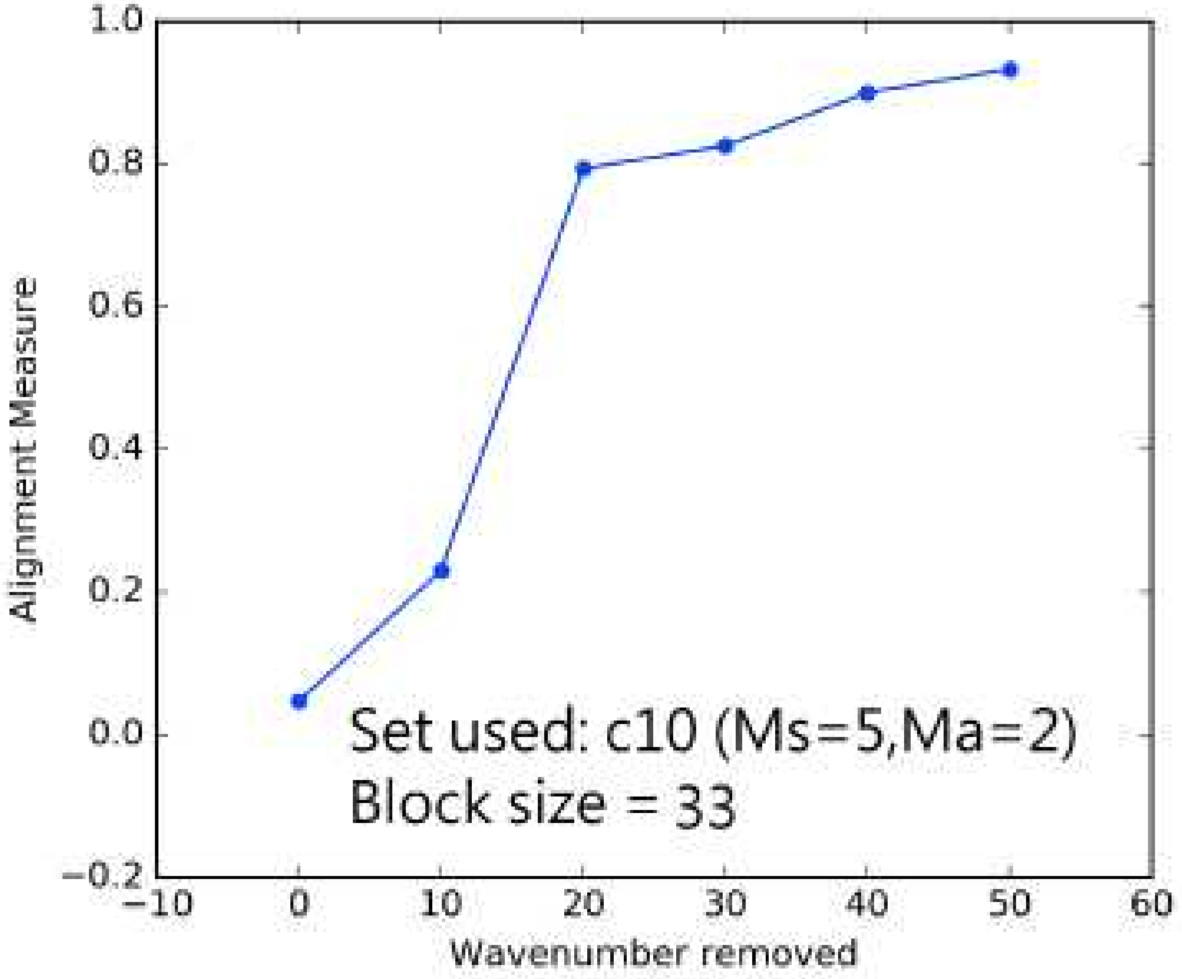
Interferometric studies of magnetic fields are possible without single dish observations (i.e. with missing low spatial frequencies)



AL et al. 2017

Magnetic fields in SuperAlfvenic turbulence can be traced if the lower spatial frequencies are removed

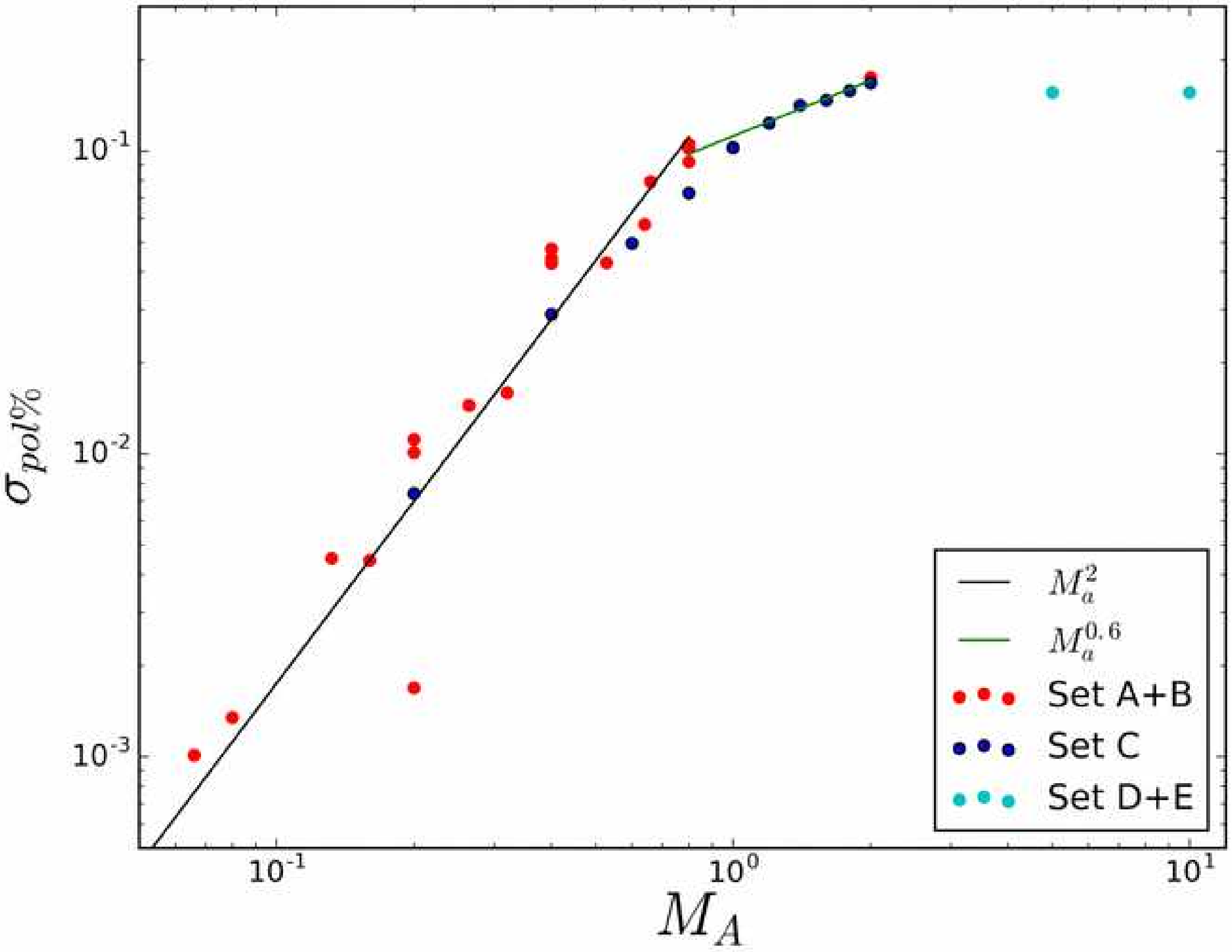
$$AM = 2\langle \cos^2\theta - 1 \rangle$$

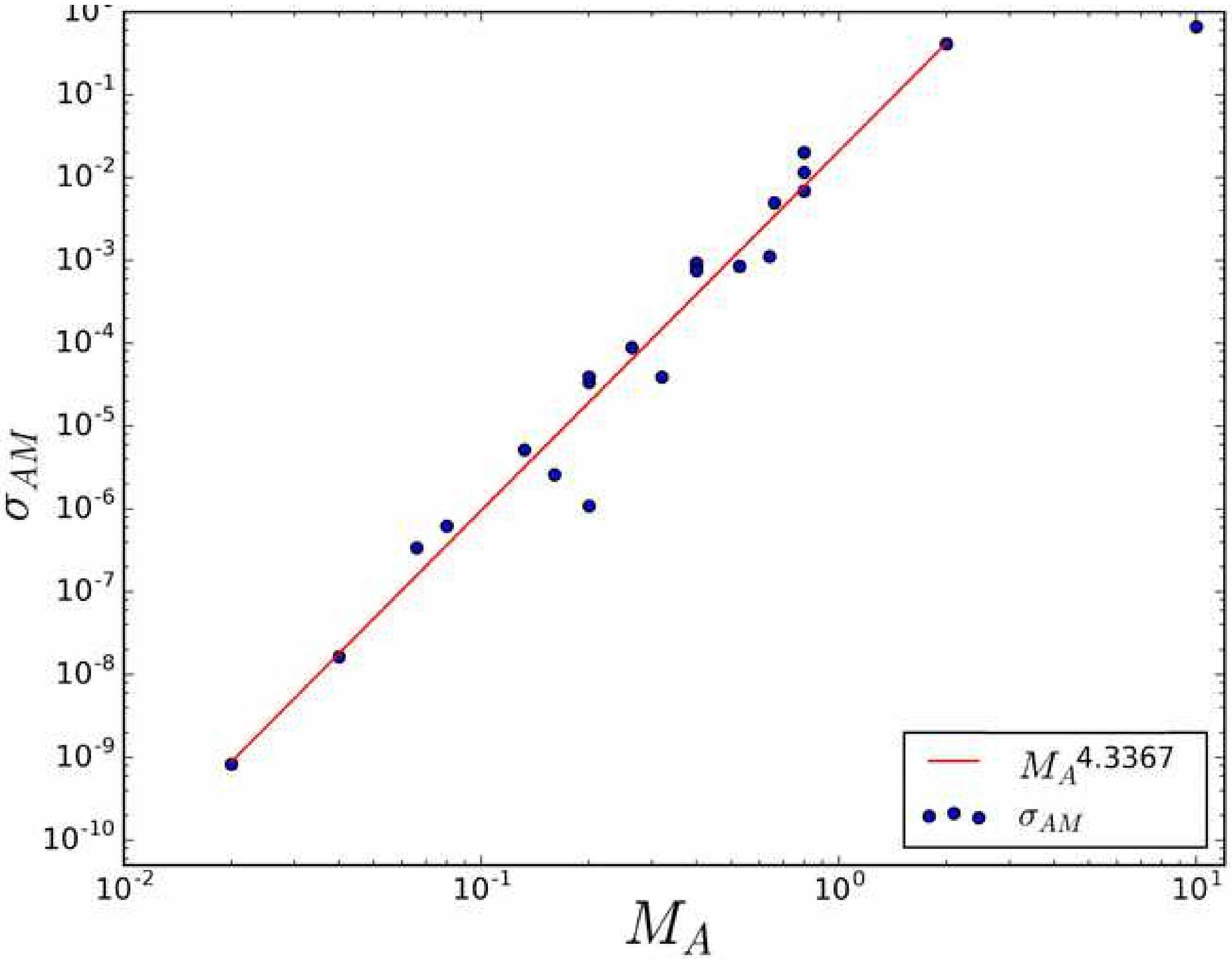


θ is an angle between the projected magnetic field and the VCGs

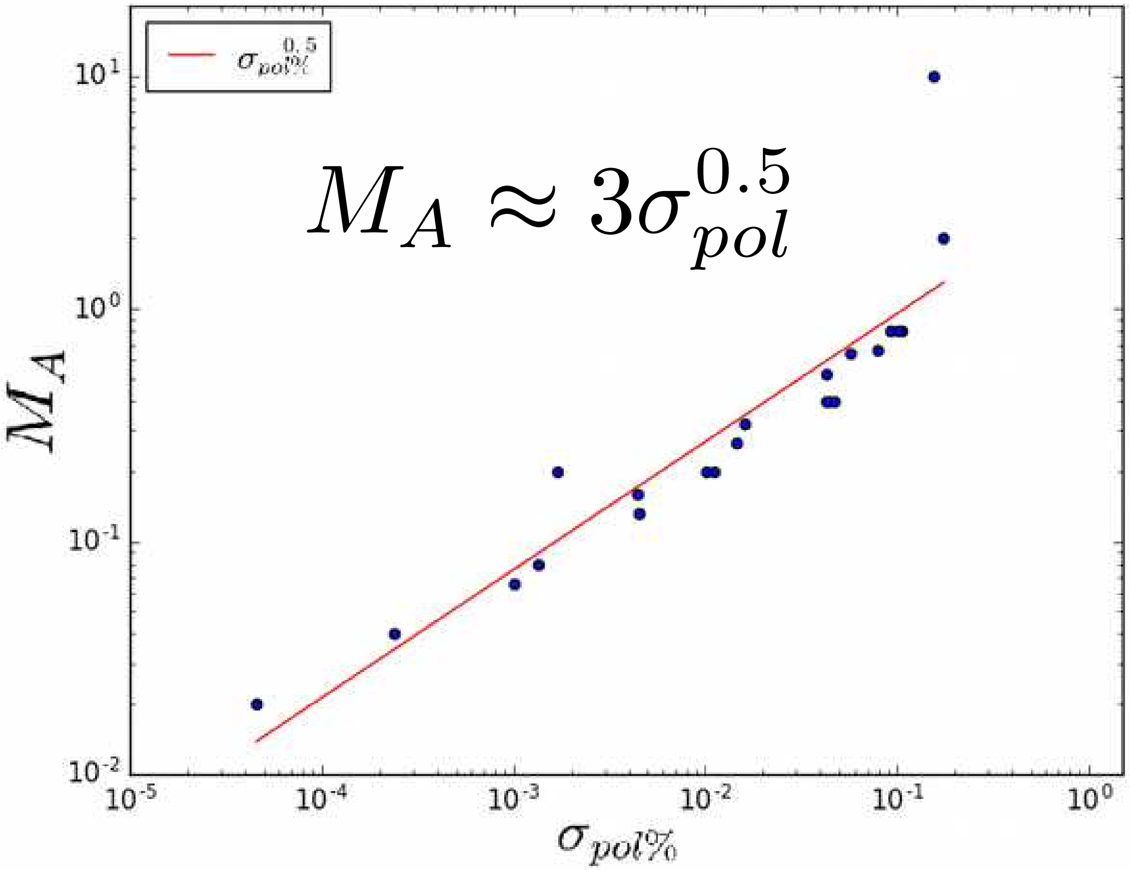
Yuen & AL 2017

locity gradients can trace magnetic field over a wider range of scales compared to polarizat

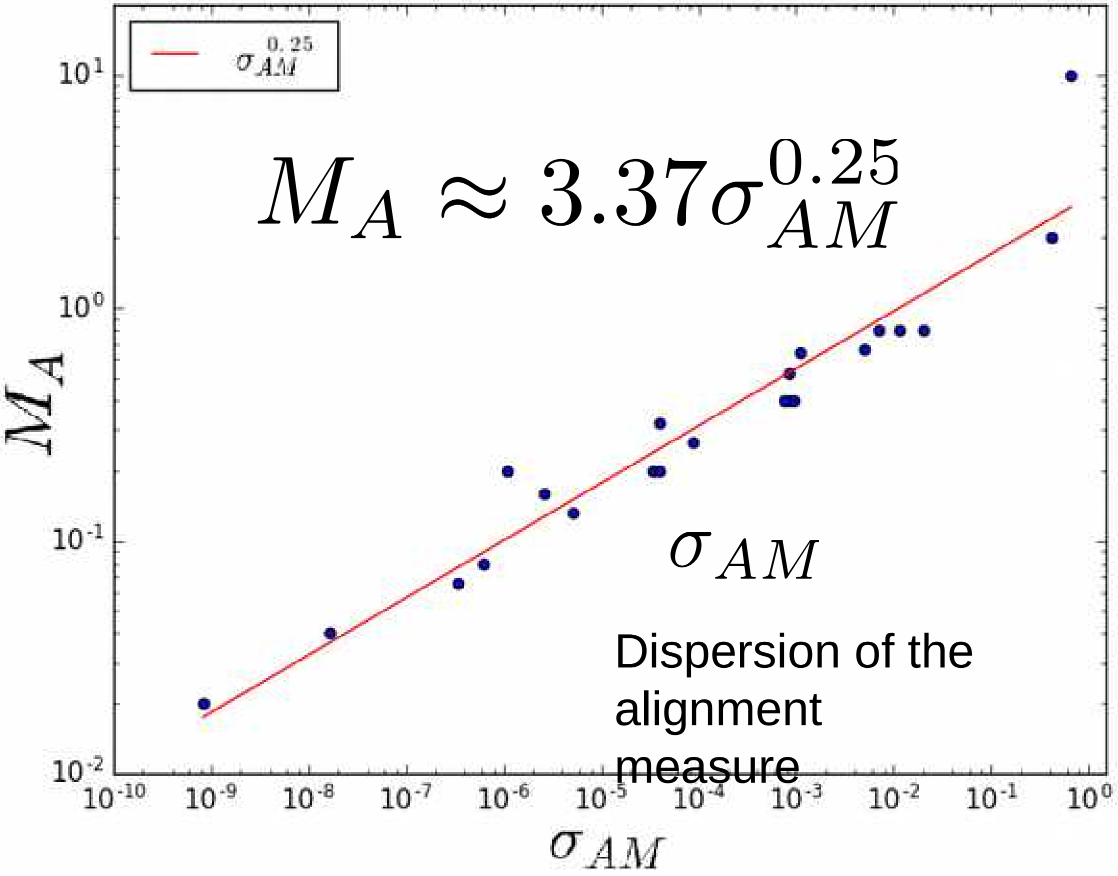




Determining magnetization a new way from polarization and gradients



$$M_A \approx 3\sigma_{pol}^{0.5}$$



$$M_A \approx 3.37\sigma_{AM}^{0.25}$$

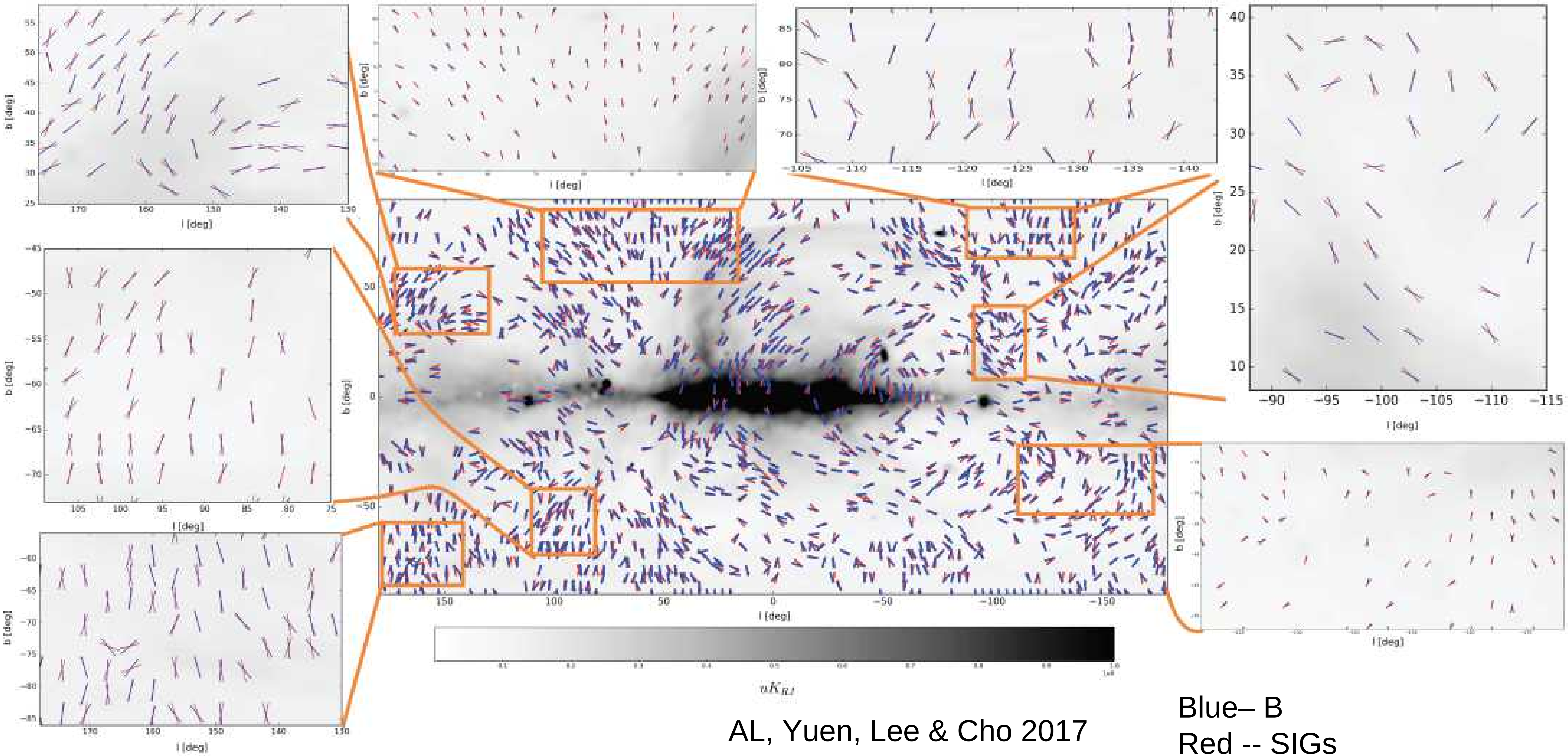
σ_{AM}

Dispersion of the alignment measure

$$B_\perp \approx \frac{\sigma_v}{M_A}\sqrt{4\pi\rho}$$

σ_v Is the velocity dispersion

Synchrotron Intensity Gradients also provide a new way to study B

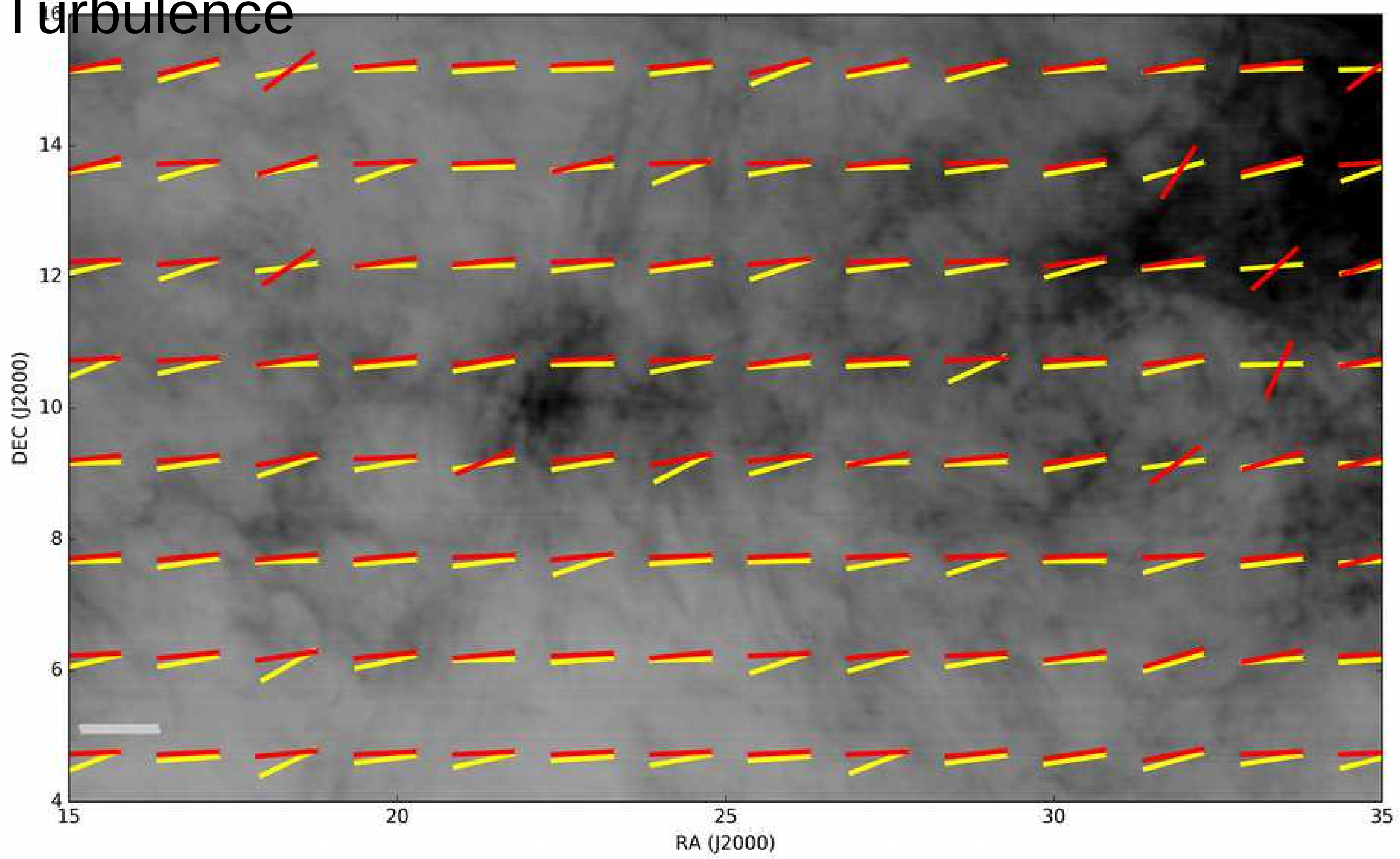


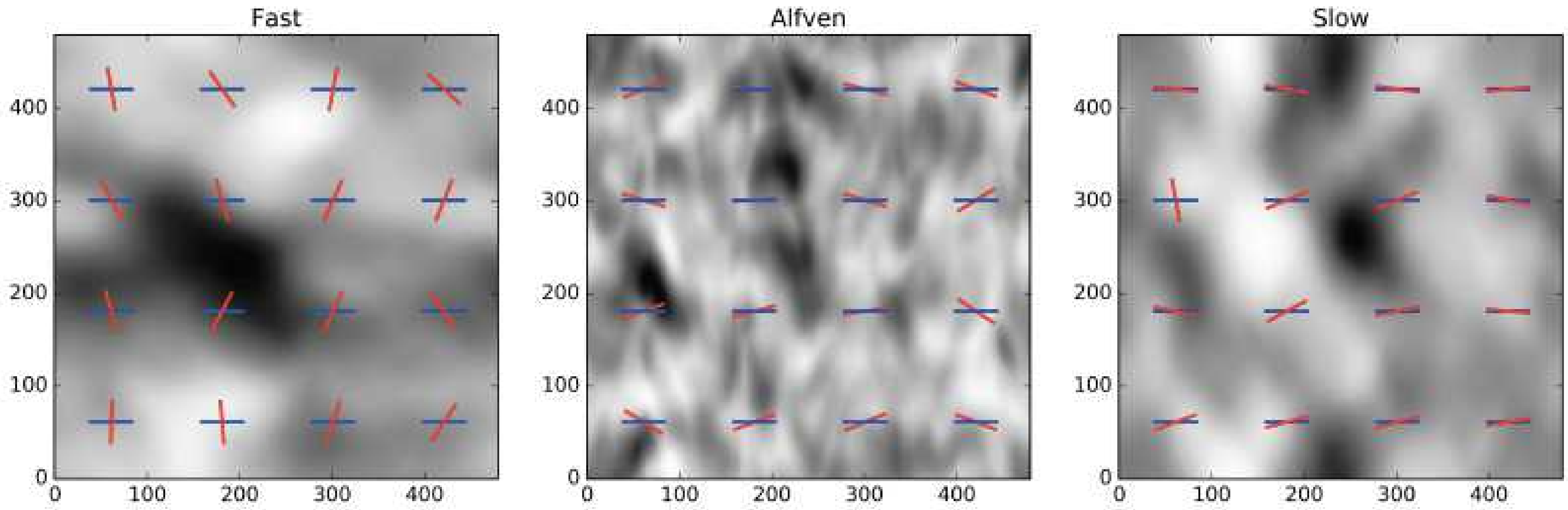
AL, Yuen, Lee & Cho 2017

Blue– B
Red -- SIGs

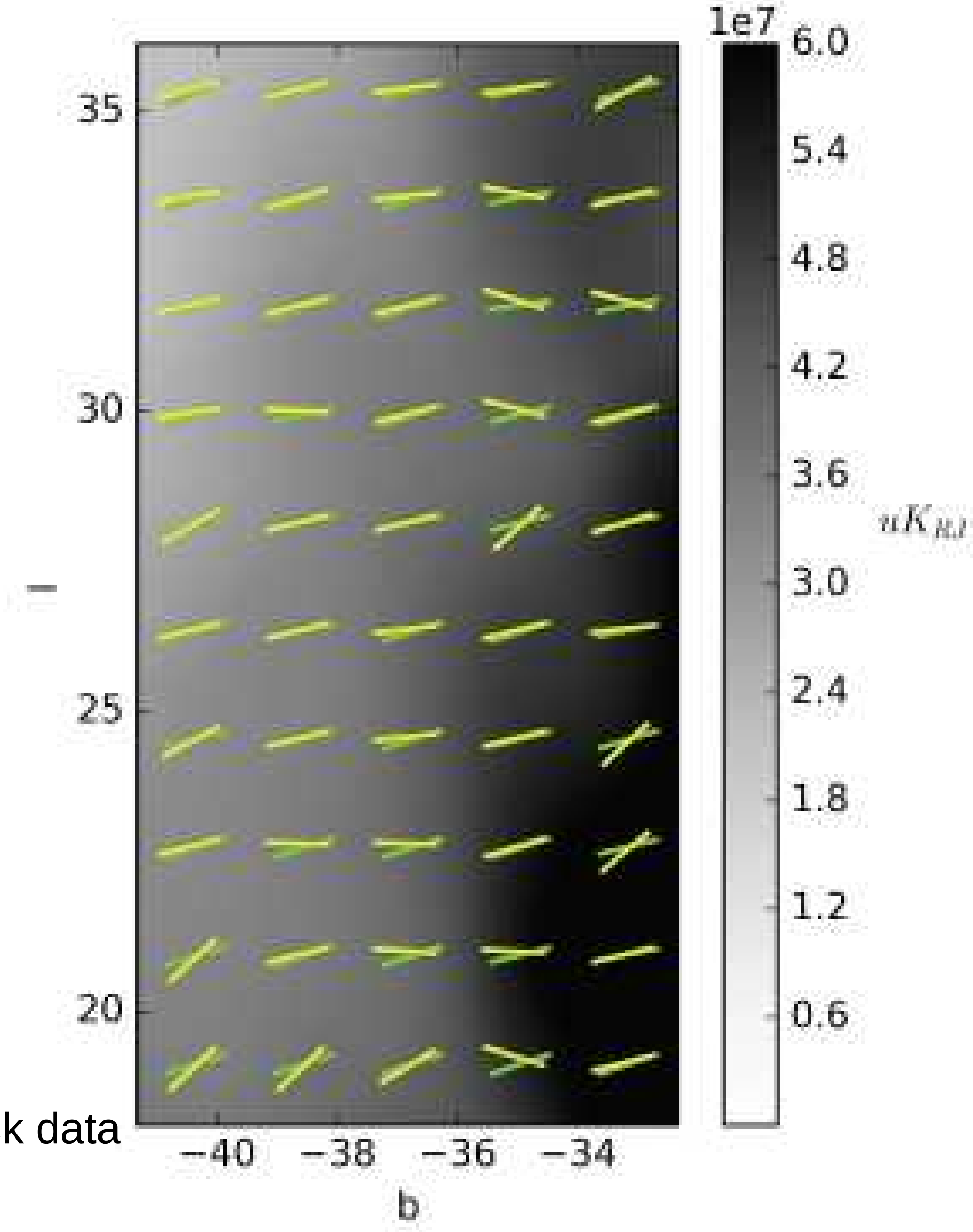
Understanding of MHD Turbulence

New information about magnetic fields





Fast
Alfven
Slow
0
100
200
300
400



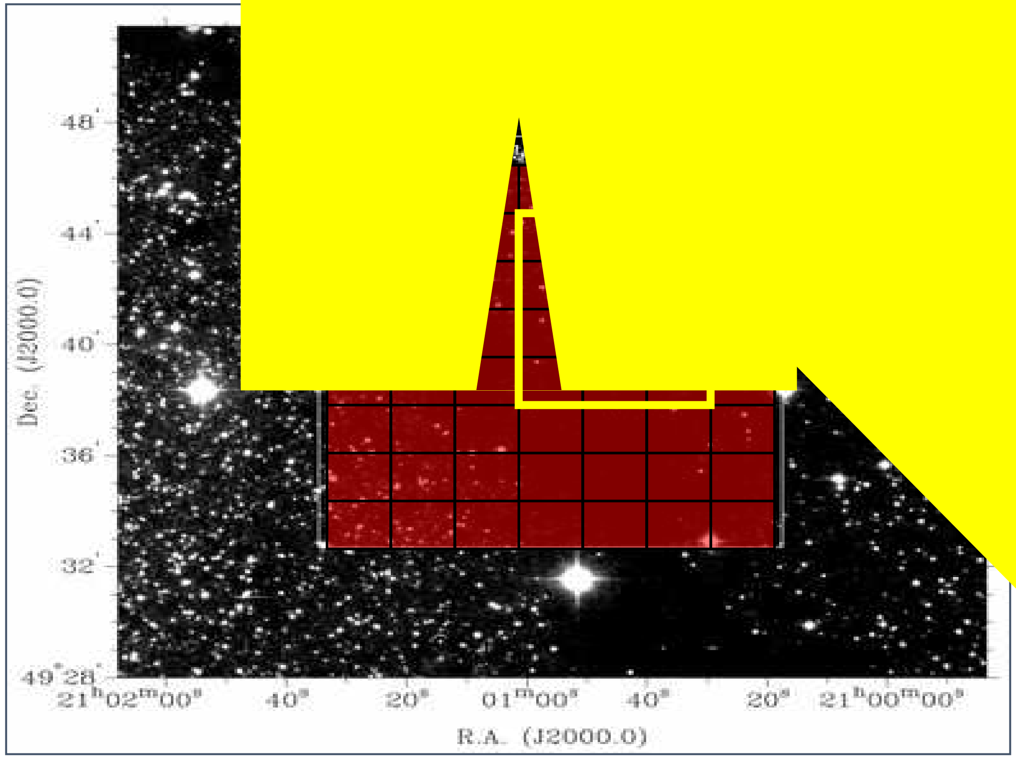
Planck data

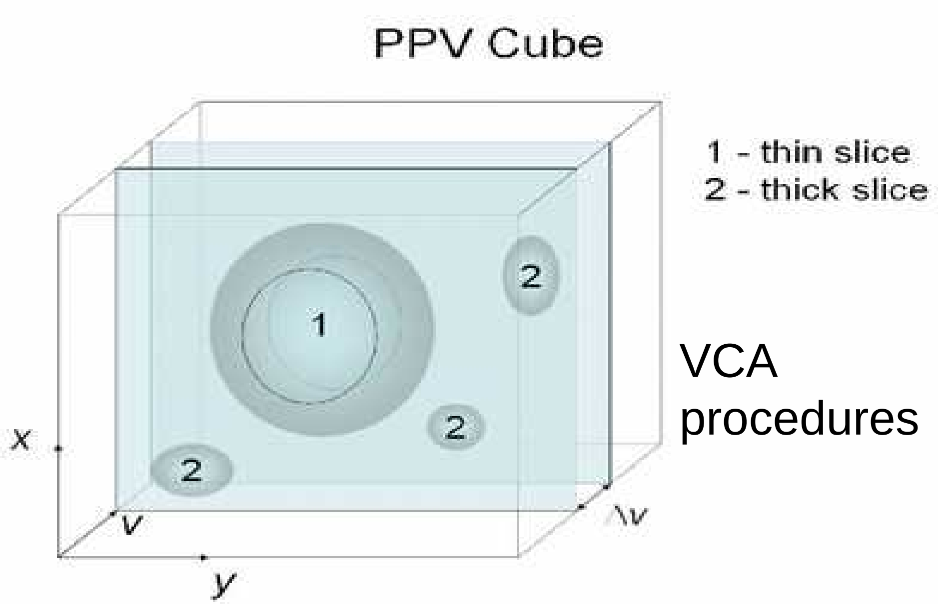
Gradients of synchrotron intensity can trace magnetic fields in interstellar medium

Polarization vectors (Green)
synchrotron intensity gradient (Yellow)

AL, Yuen, Lee & Cho 2017

AL & Pogosyan (2000, 2004) showed that thin slices of PPV cubes carry velocity information





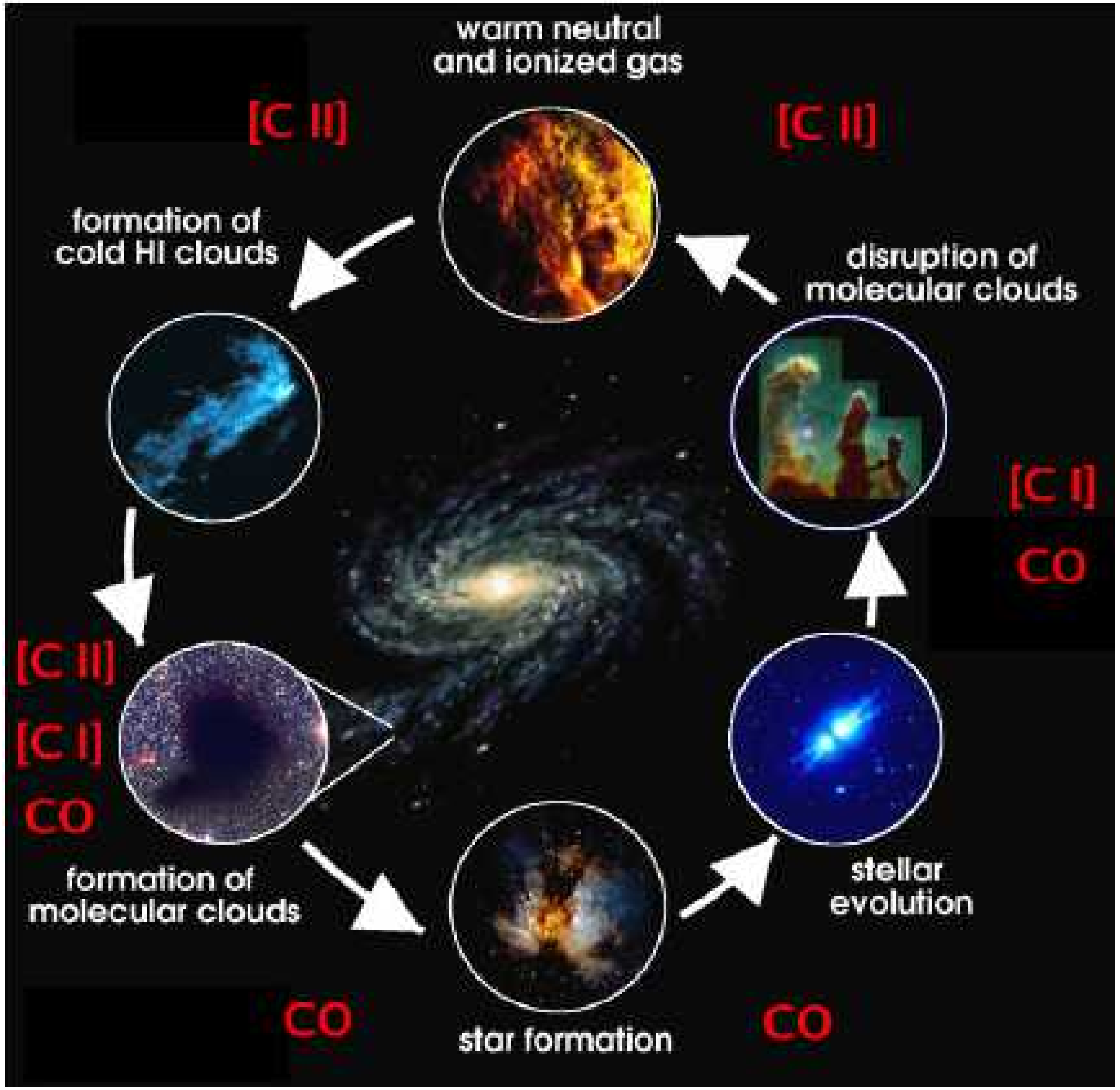
VCA procedures

Developed in Lazarian & Pogosyan 00, 04

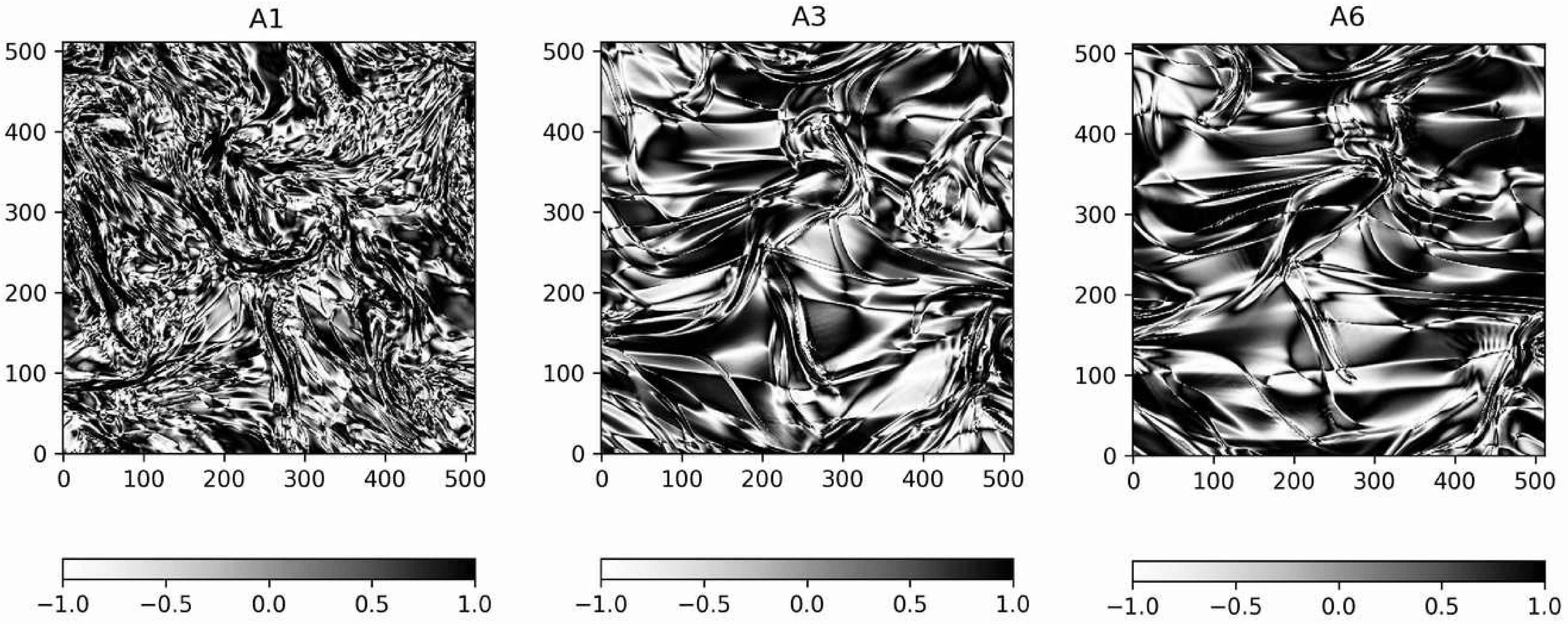

Prospects


PROBLEM
OPPORTUNITY

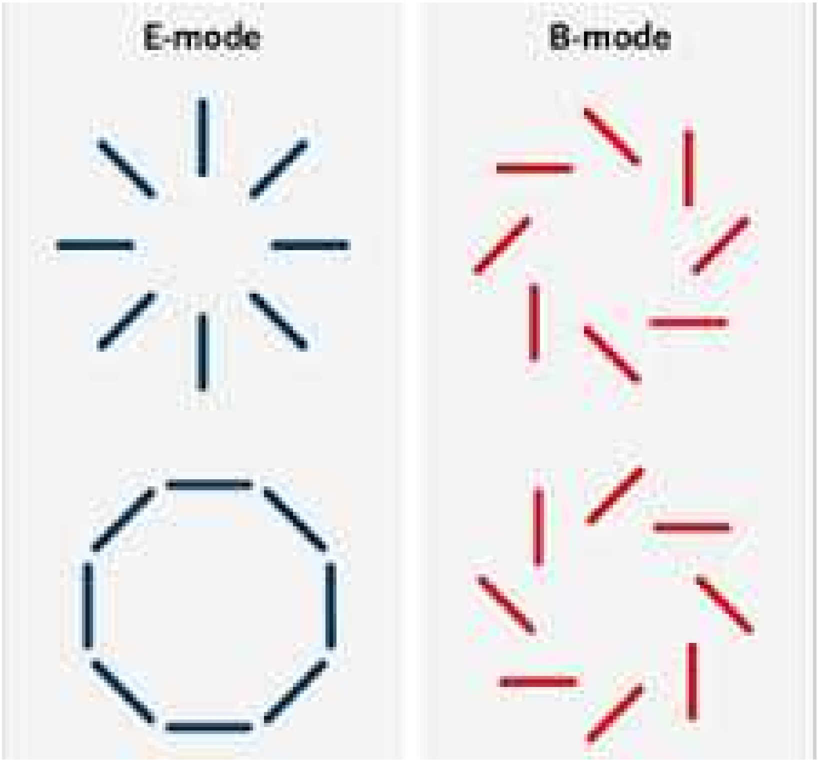
Relation of magnetic fields in different phases of ISM

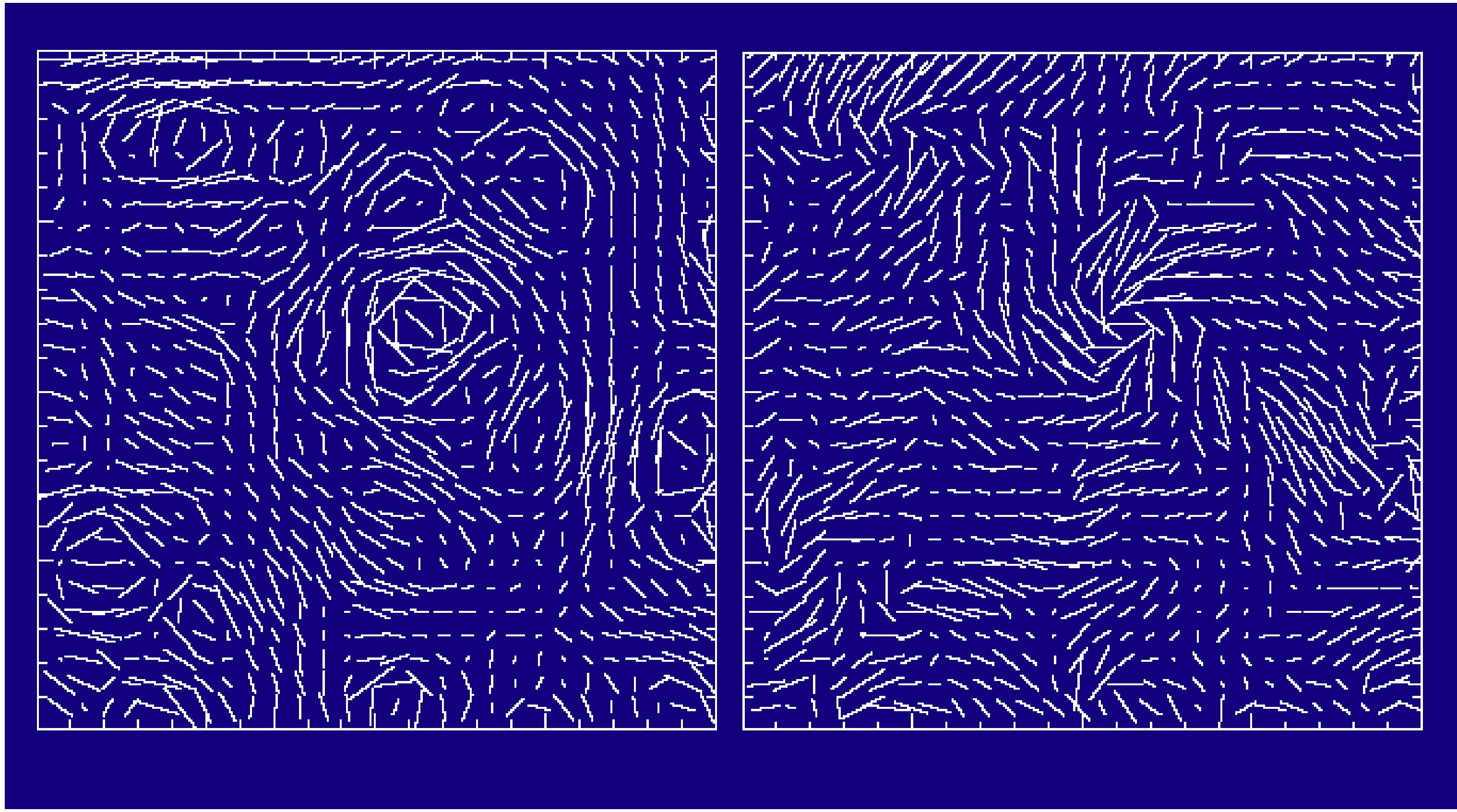


Structure of the polarization pattern changes and this can be used to study magnetization for any Alfven Mach number

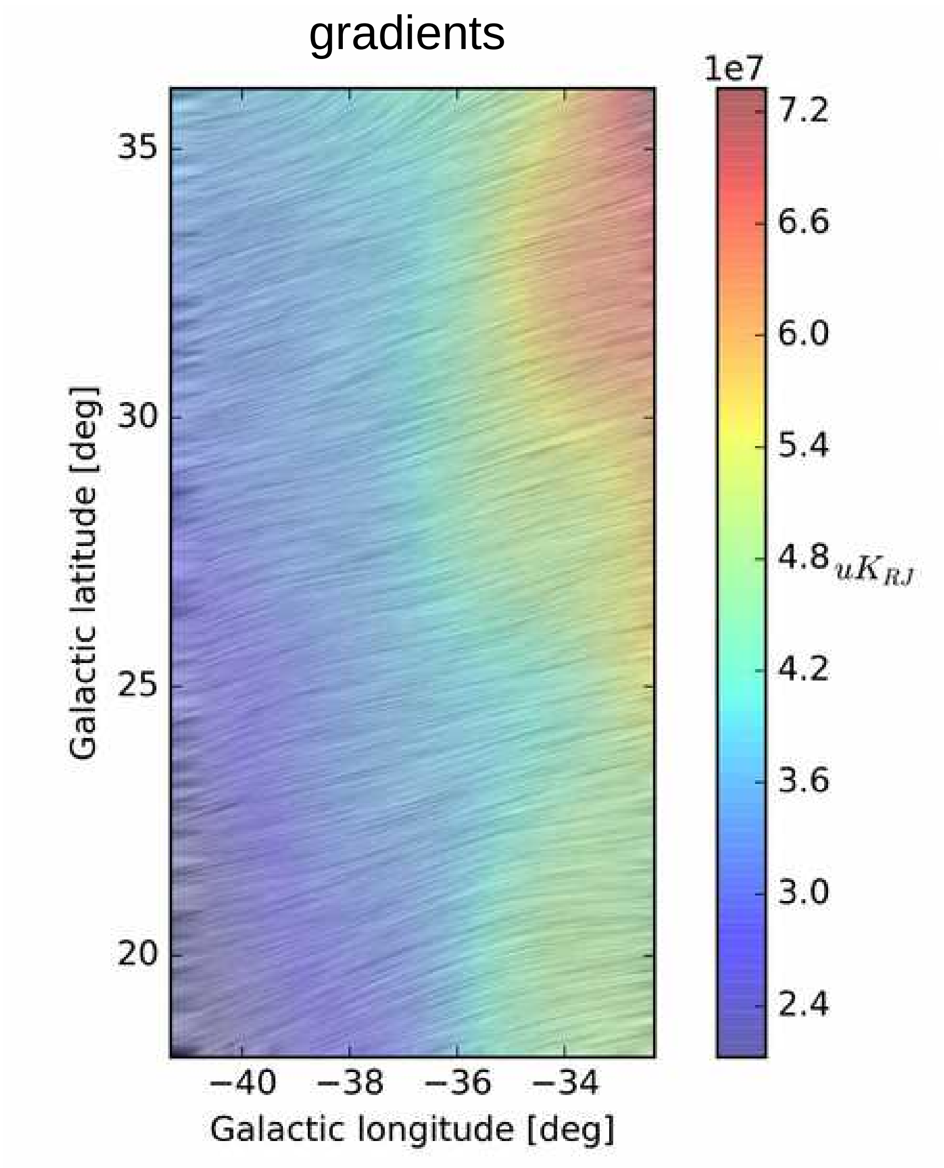


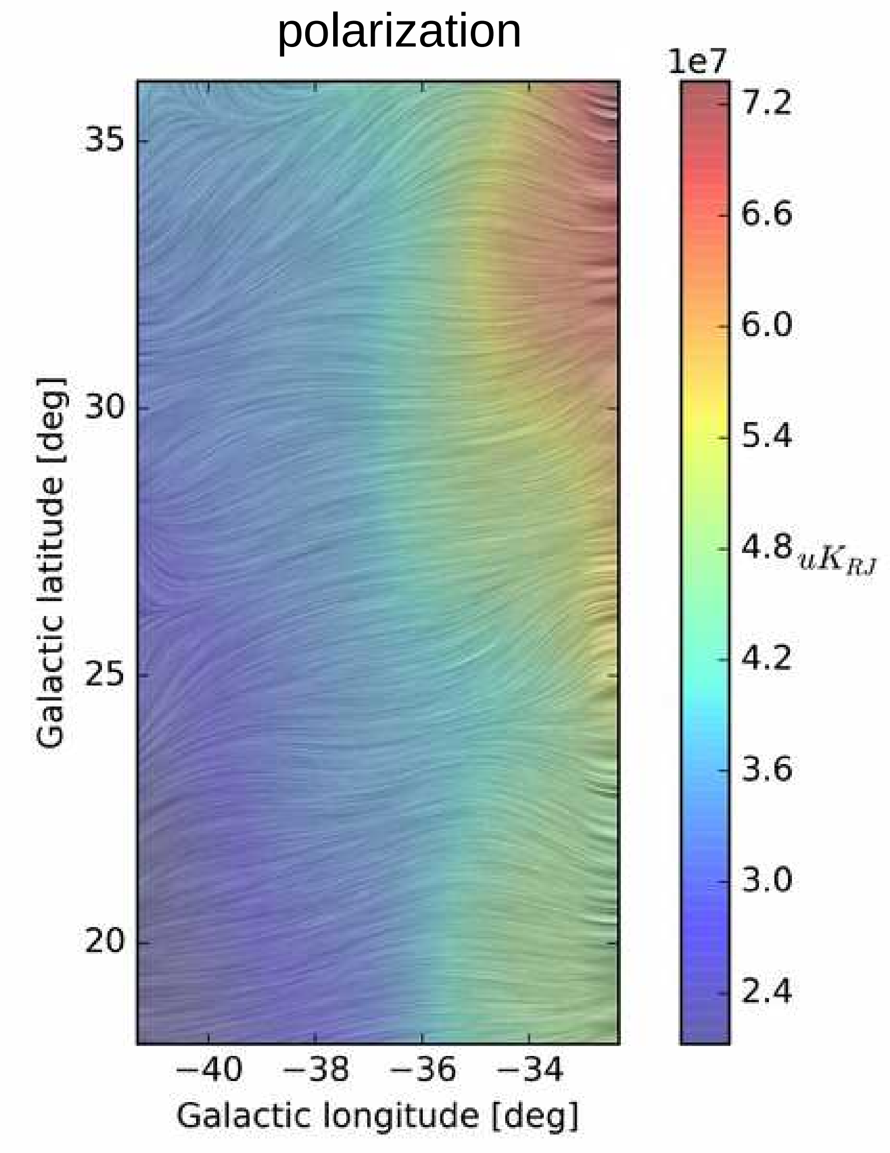
Improving maps to correct for foregrounds within the cosmological B and E mode decomposition





The deviations of the polarization pattern revealed by textures are likely to be due to Faraday effect

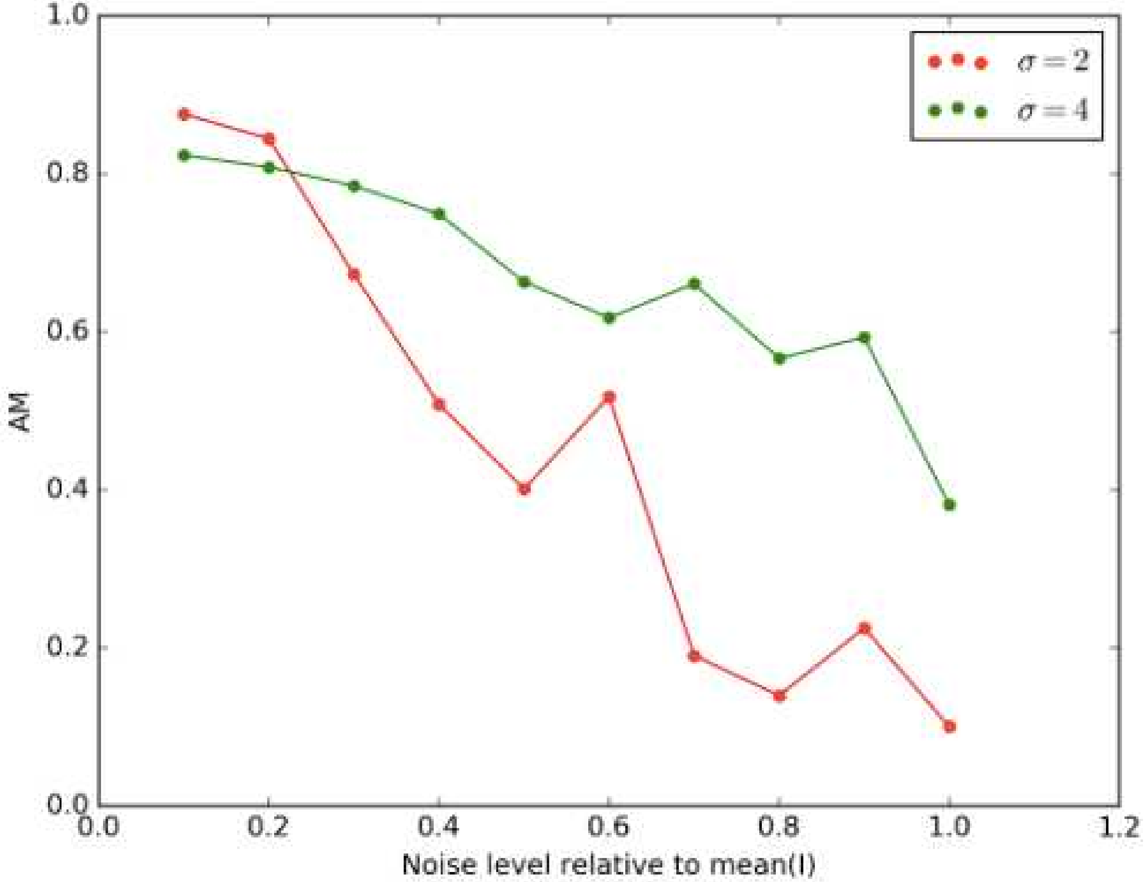




Gradient studies are robust in the presence of noise

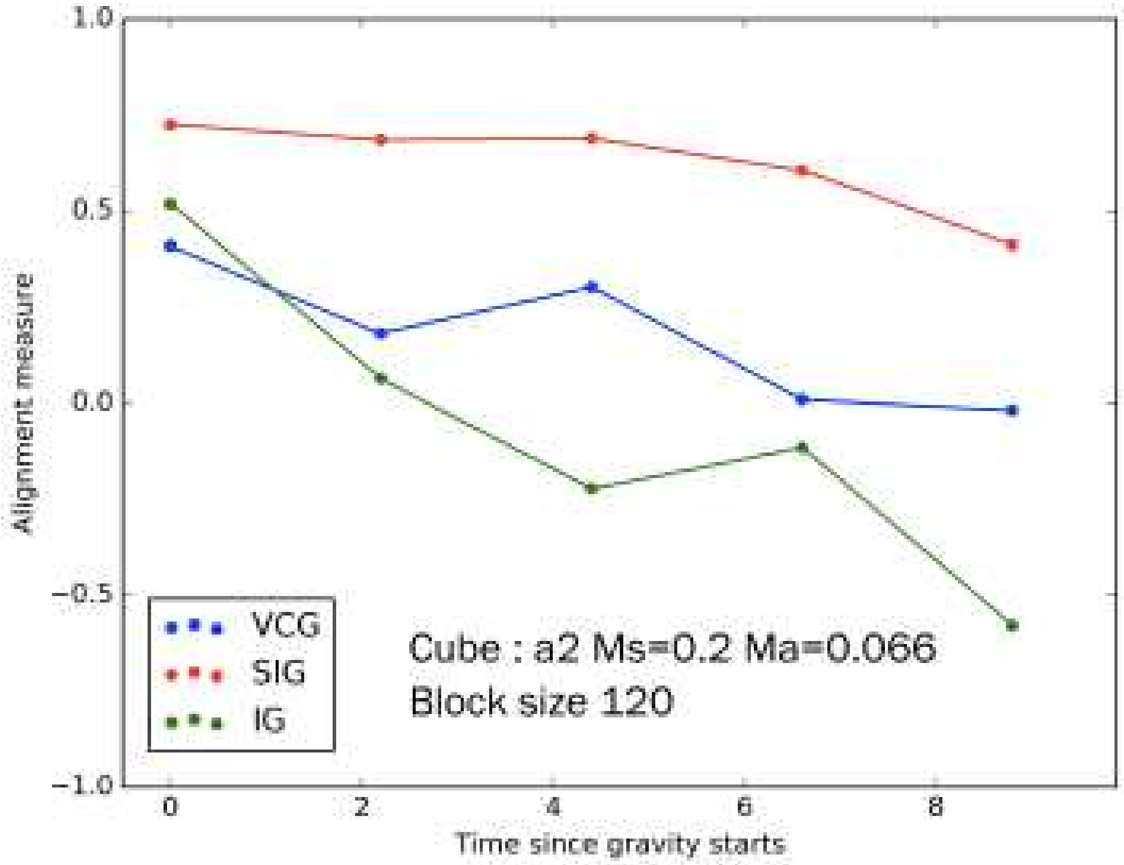
$$AM = 2\langle \cos^2\theta - 1 \rangle, \quad (3)$$

where θ is the angle between the SIG direction and that of the polarization.

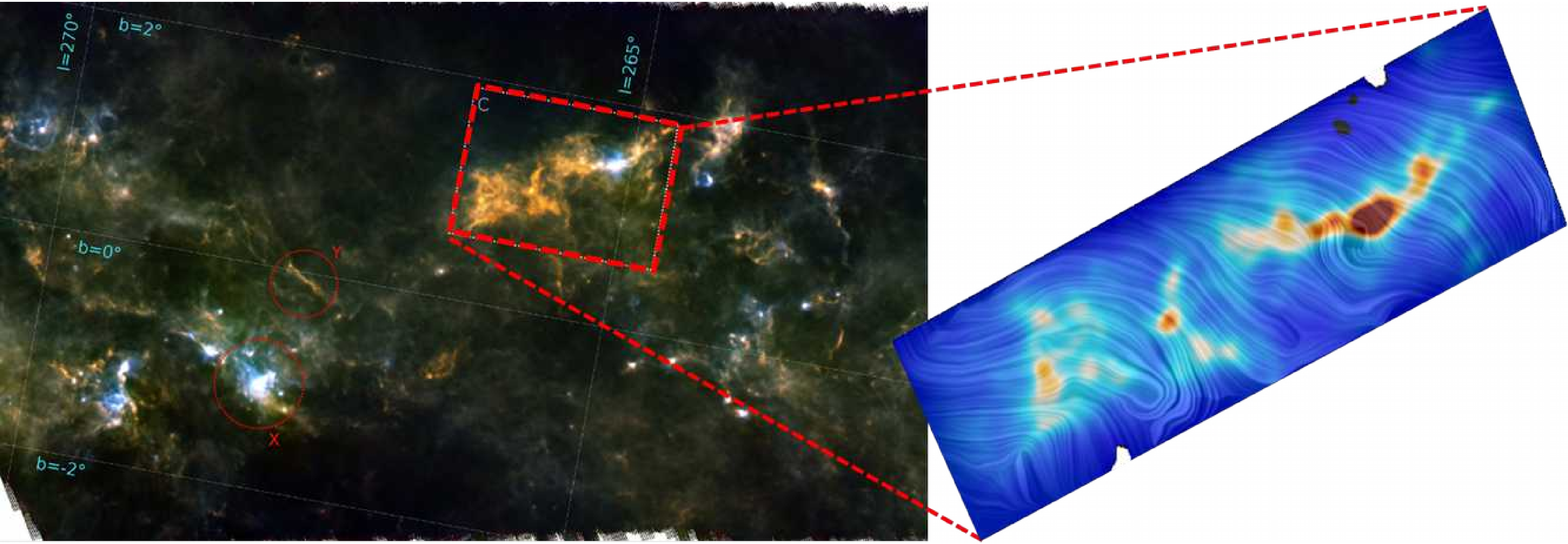


AL et al. 2017

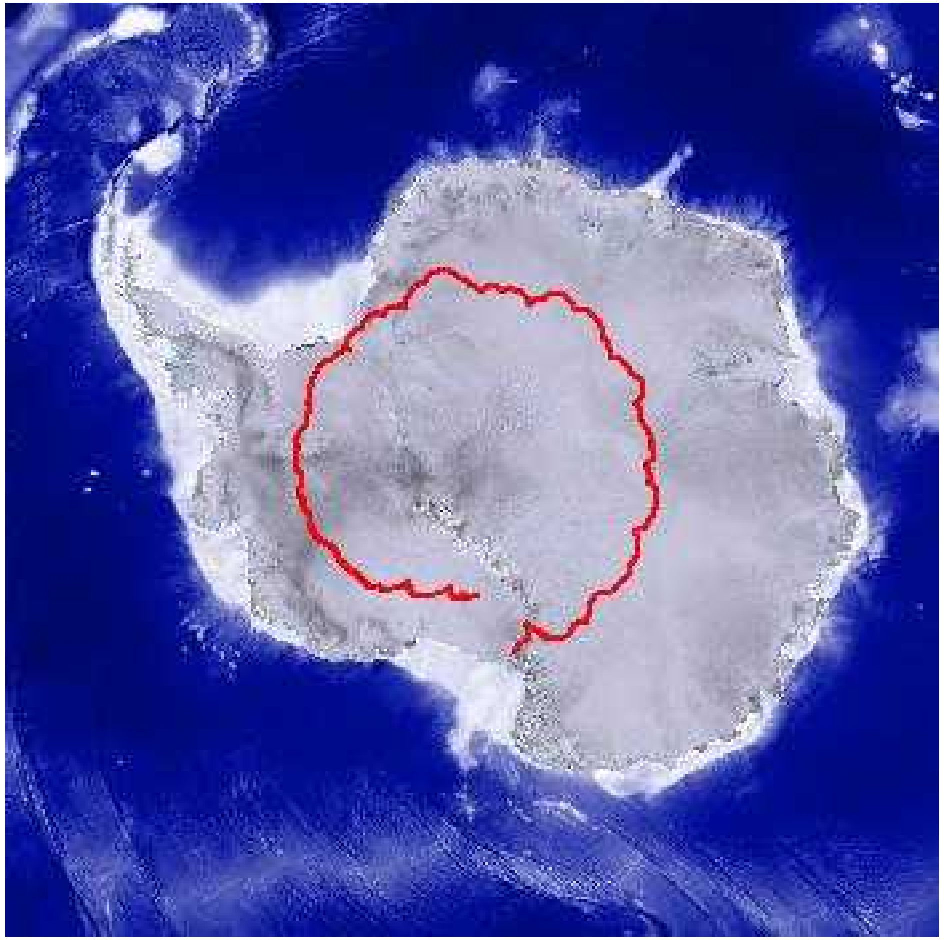
Synergy between different gradient techniques: response to gravity

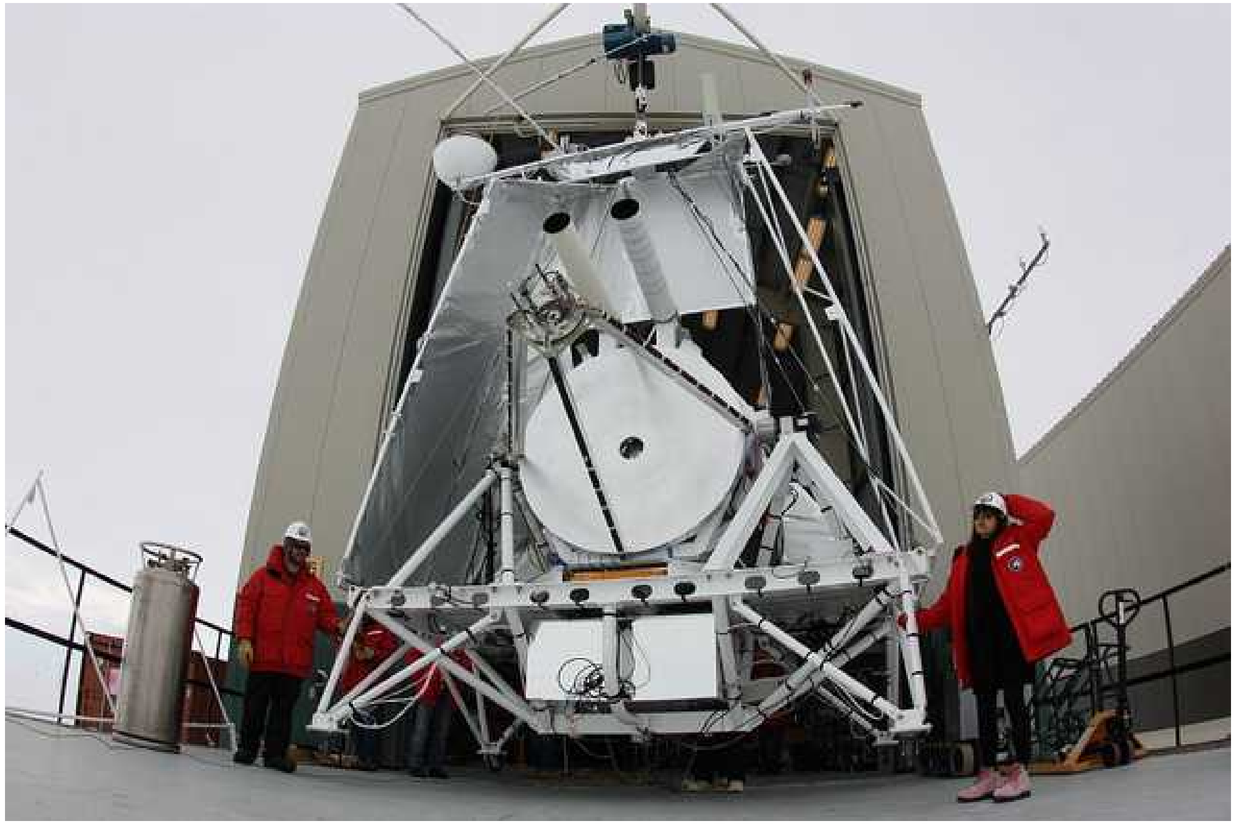


Vela C molecular cloud and BLASTPOL polaremetry

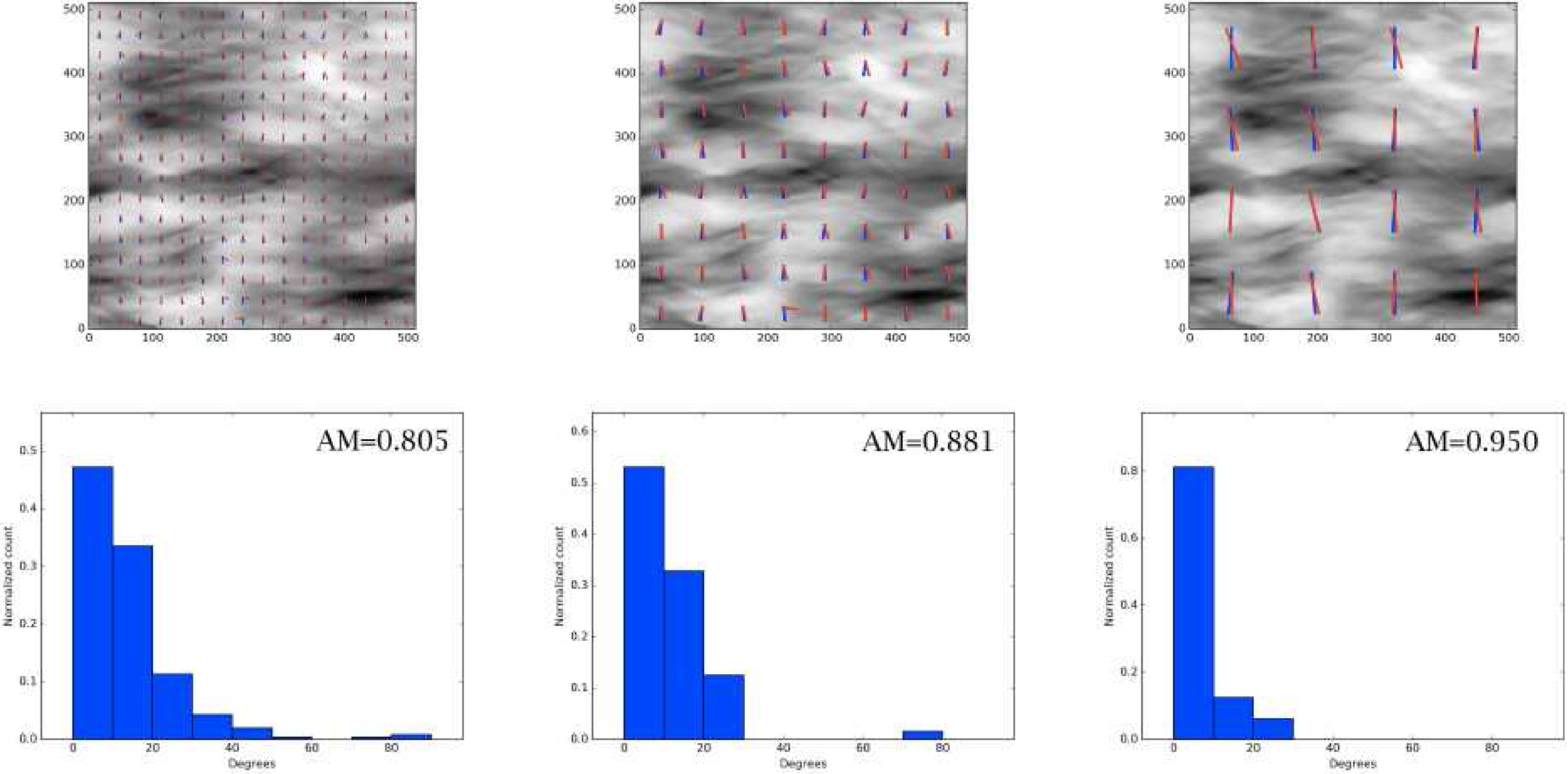


BLASTPOL Experiment



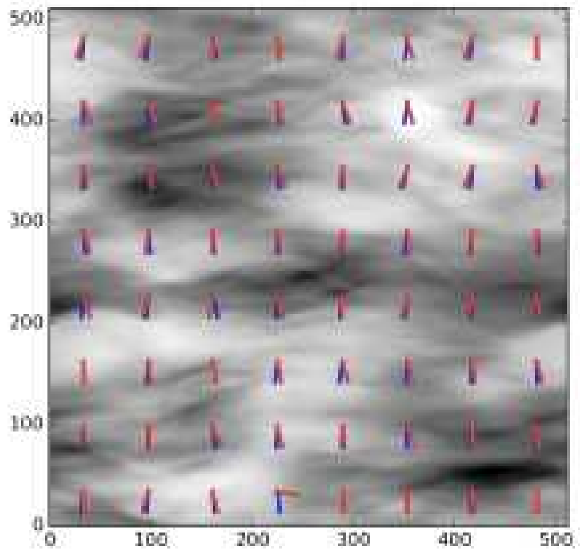


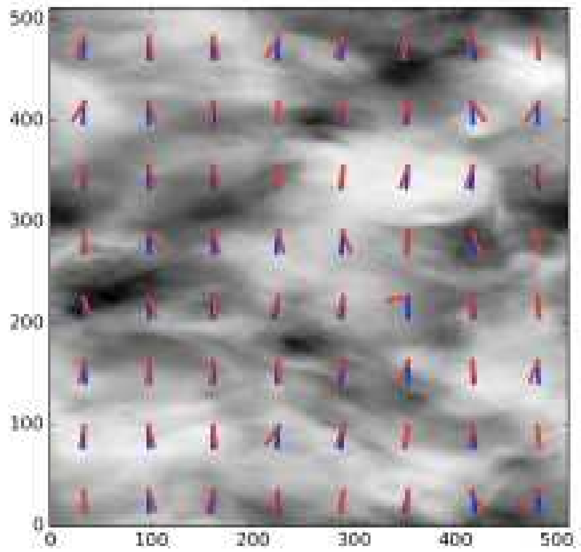
Changes of the SIGs alignment measure with the block size for MA=1 and Ms=0.5

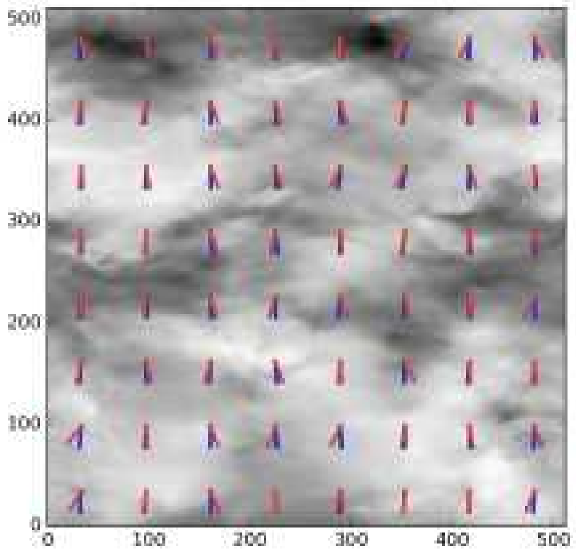


M

Changes of SIGs alignment measure with the Mach number are not big



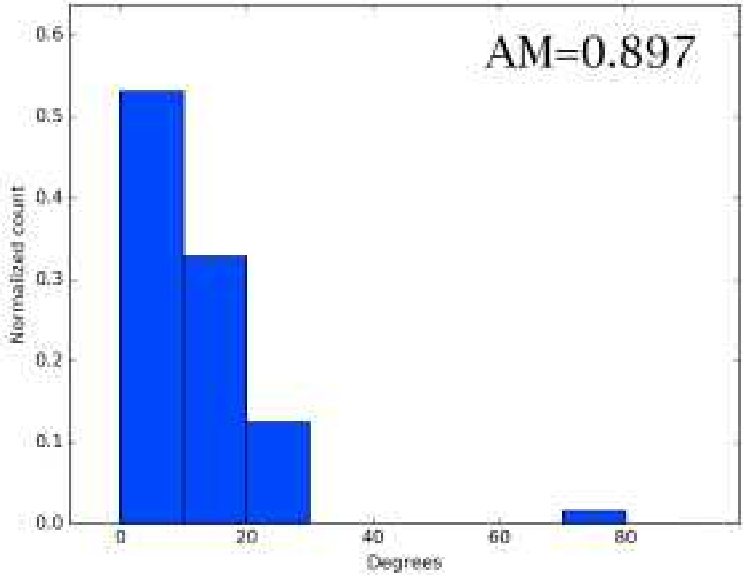


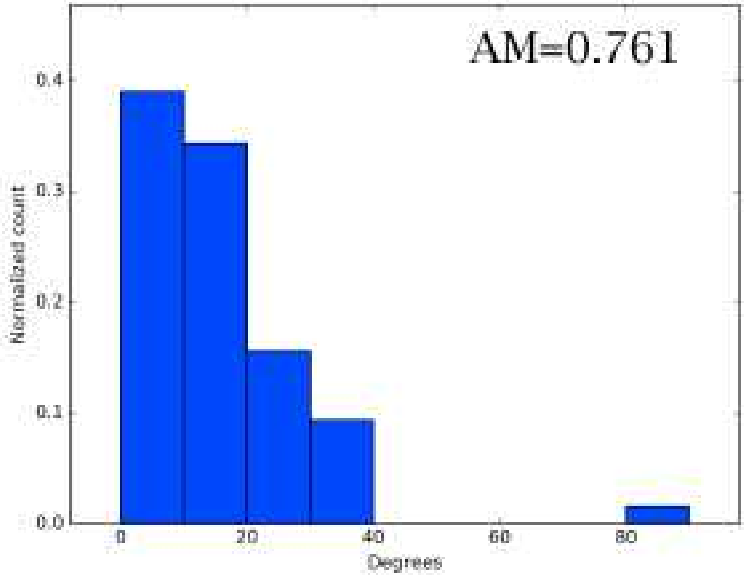


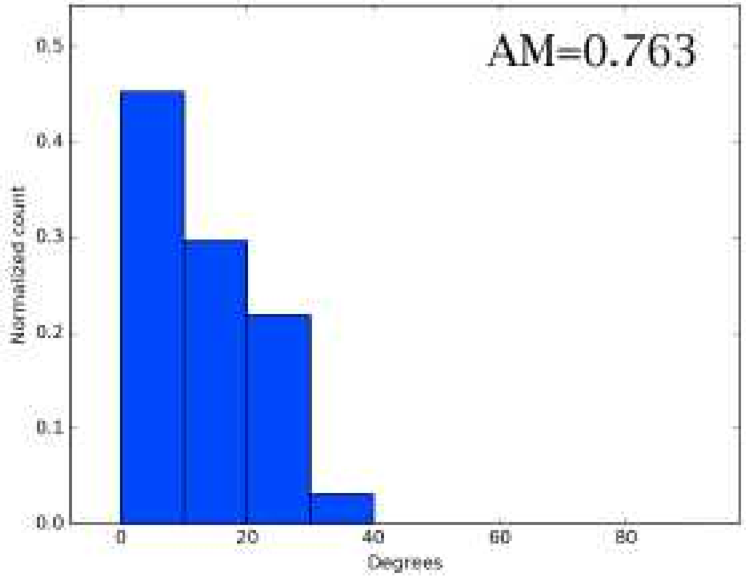
Ms=0.5

Ms=3

Ms=10



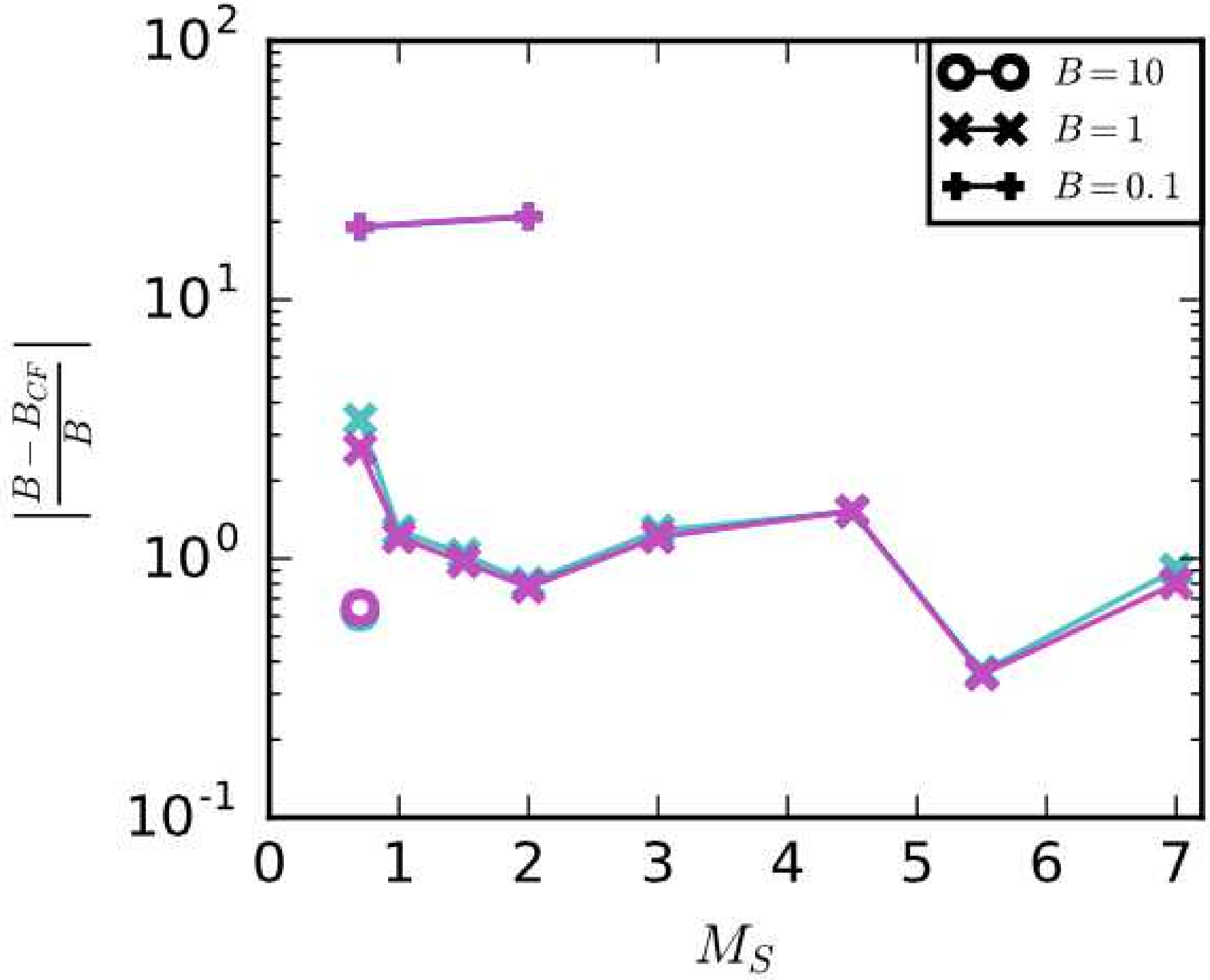




Gradients allow to find the strength of magnetic field without using polarimetry

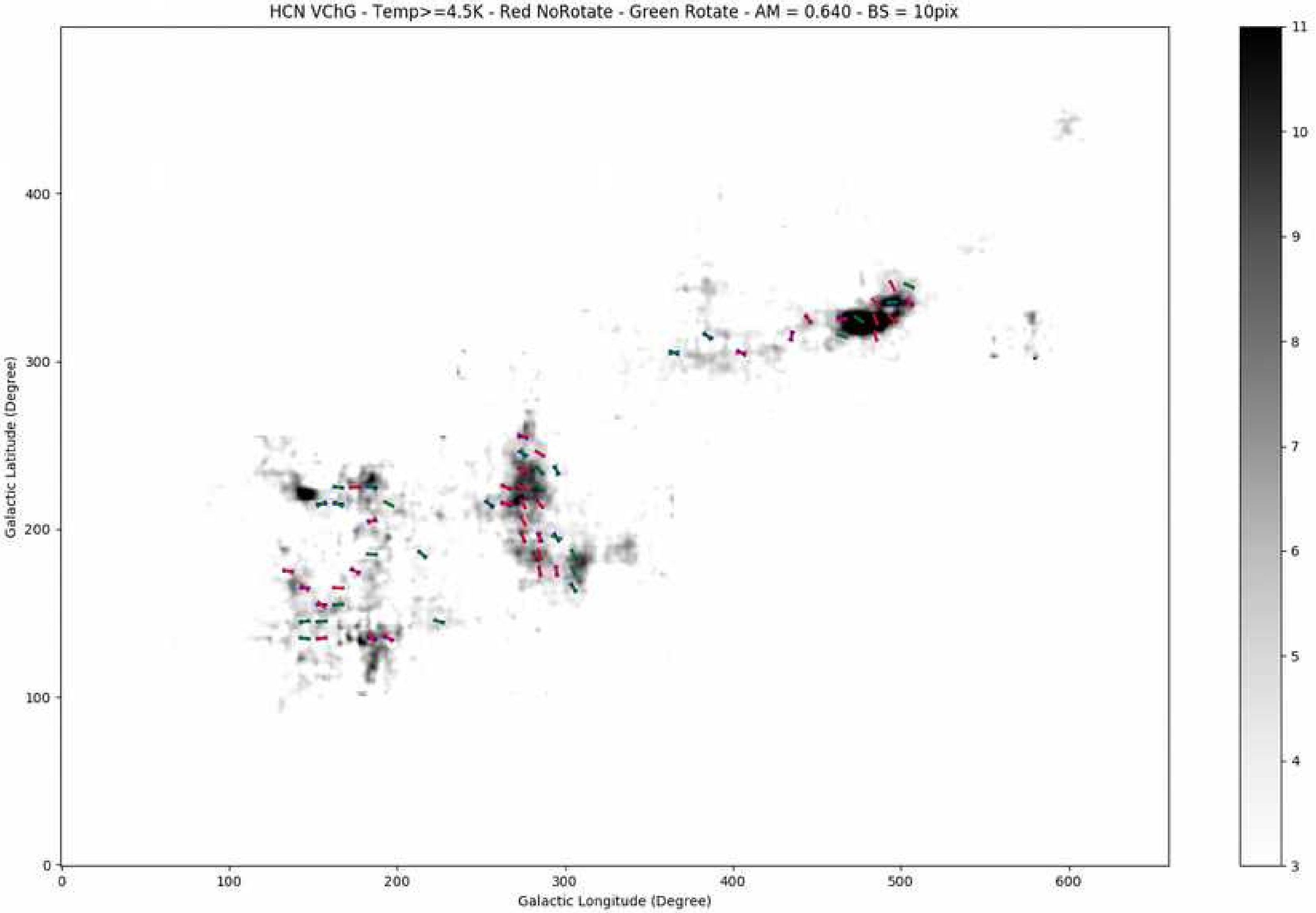
$$B = \gamma \sqrt{4\pi\rho} \frac{\delta v}{\sigma^U} ,$$

From gradients



Gonsalvez-Casanova & AL 2017

Deeper regions show more rotated VGs



Even more rotated VGs for densest regions mapped with CS