Instituto de Ciencias Nucleares UNAM

STUDYING THE INTERSTELLAR MAGNETIC FIELD MEASURING THE ANISOTROPY IN VELOCITY

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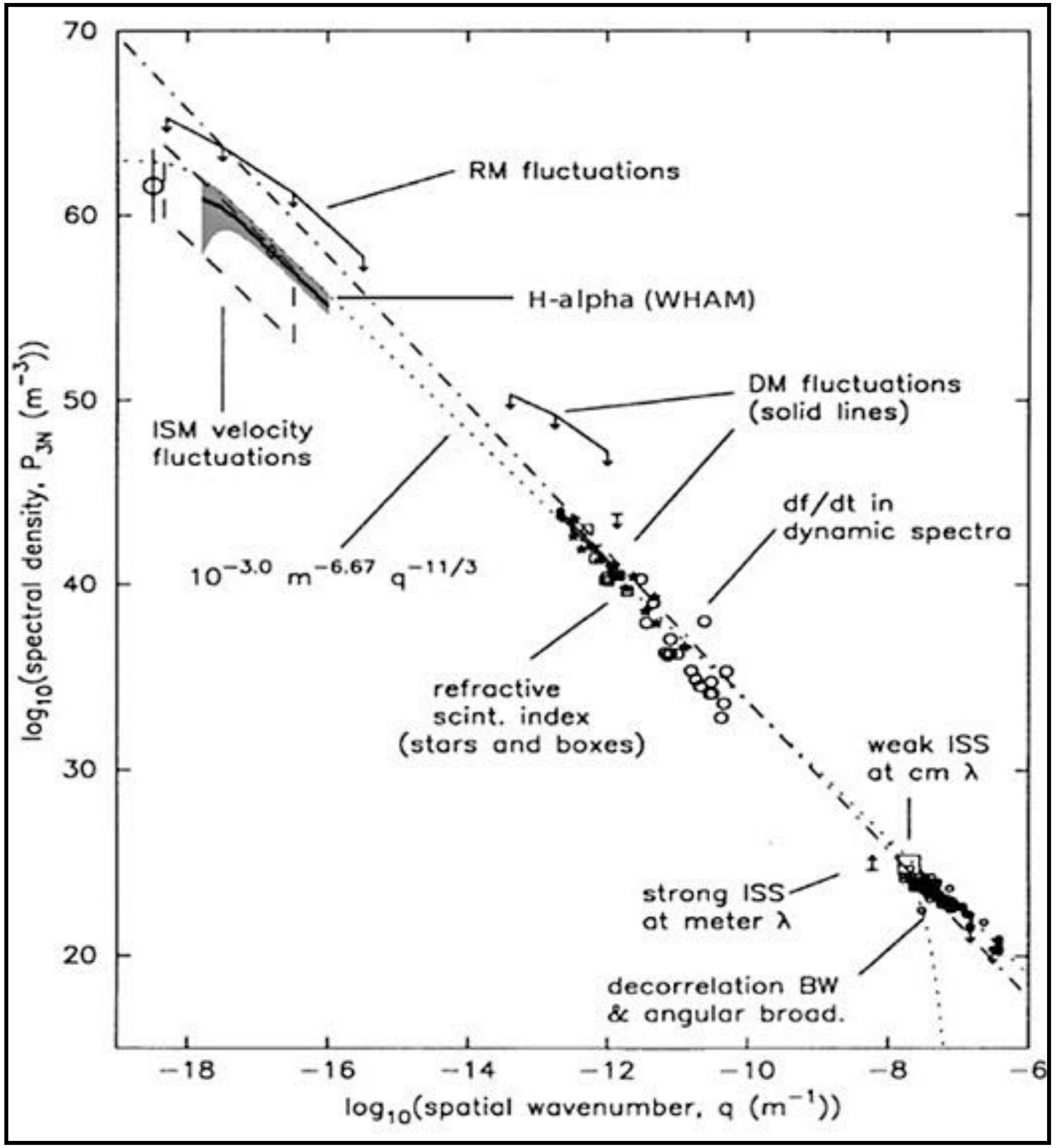
Magnetic Fields in the Universe VI: From Laboratory and stars to the primordial structures (Natal, Brazil)

THE INTERSTELLAR MEDIUM (ISM) IS TURBULENT

- Theory
  - The Reynolds number in the ISM: $Re > 10^8$ (current computers can only reach $\sim 10^4$)
- Observations
  - Line widths show a "non-thermal" component.
  - Density/velocity/magnetic field fluctuations show a self-similar structure.
- Important for:
  - cosmic ray scattering and acceleration,
  - molecular cloud dynamics,
  - star formation,
  - mixing of elements,
  - magnetic field generation,
  - accretion processes,
  - … virtually any transport process in the ISM.



"The great power law in the sky"
Chepurnov & Lazarian (2010)

HOW DO WE STUDY TURBULENCE?

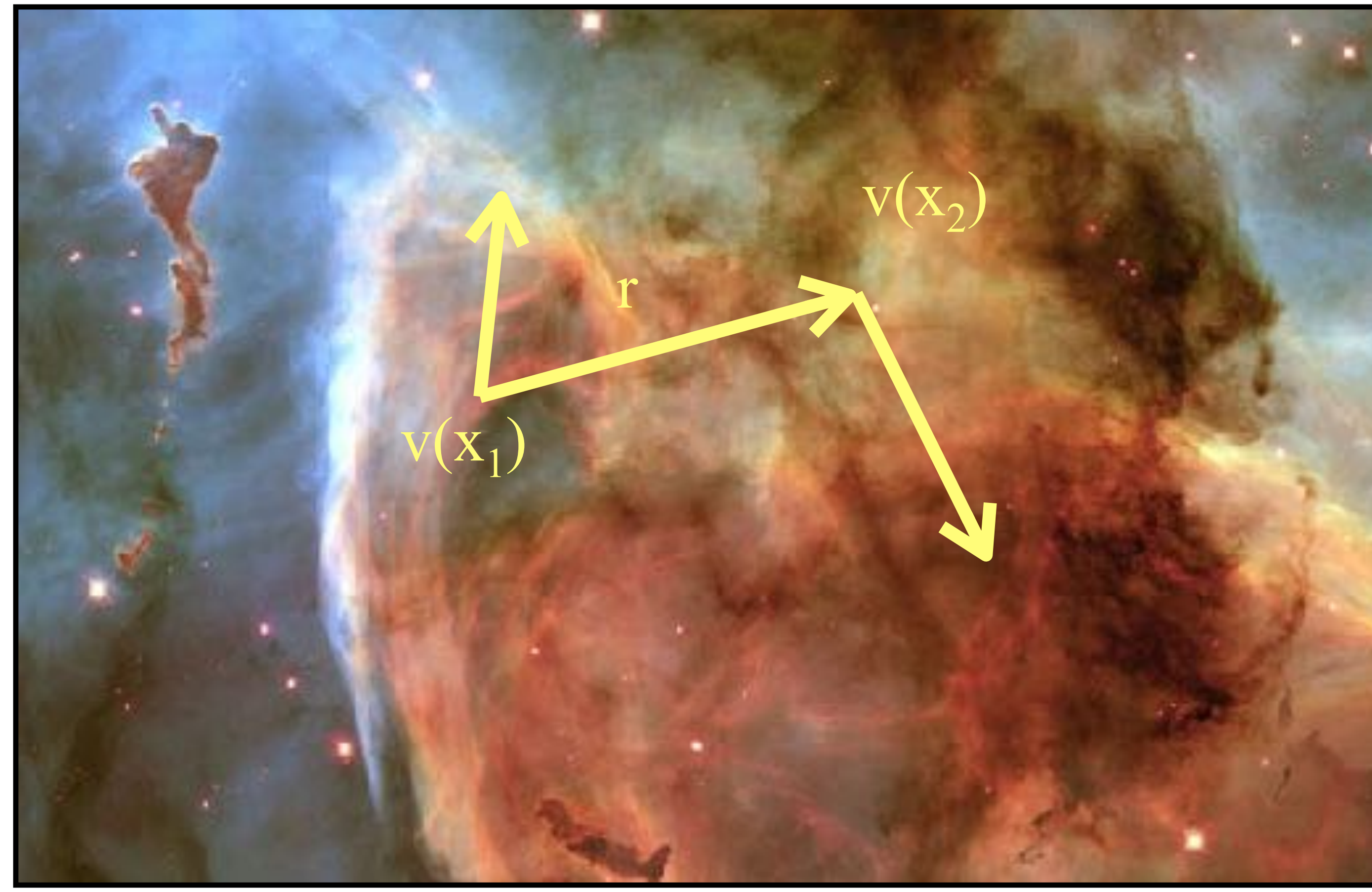
- Statistical tools, such as:
  - structure/correlation functions,

$$SF(r) = \left\langle \left[v(x_1) - v(x_2) \right]^2 \right\rangle$$

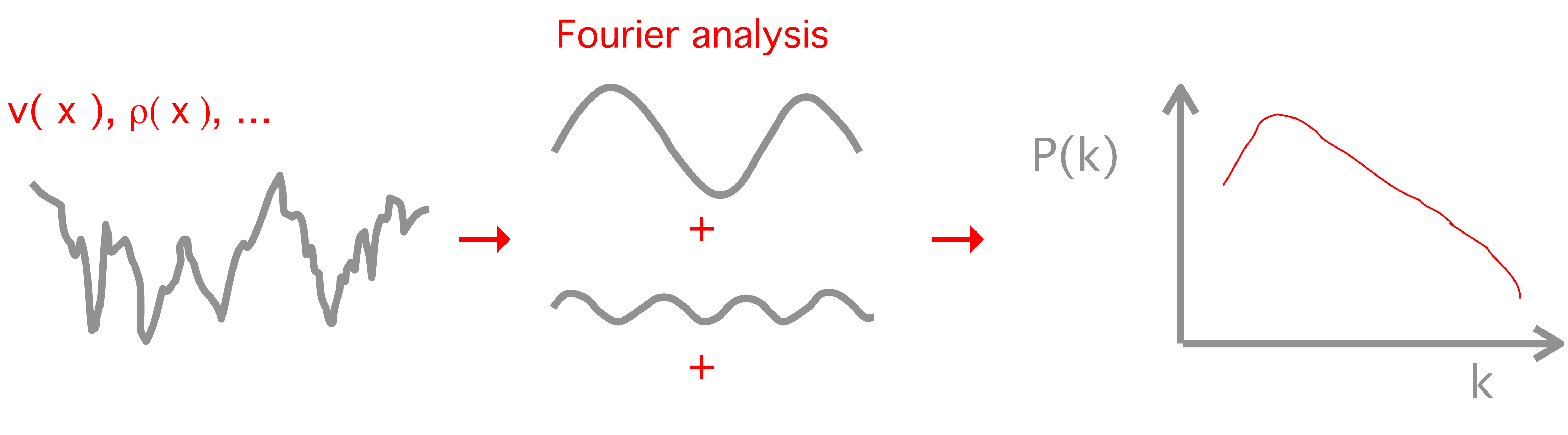
$$r = |x_2 - x_1|$$

$$CF(r) = \left\langle v(x_1) \cdot v(x_2) \right\rangle$$

$$SF(r) = 2\left[CF(0) - CF(r) \right]$$



  - or power spectra



KOLMOGOROV MODEL OF TURBULENCE

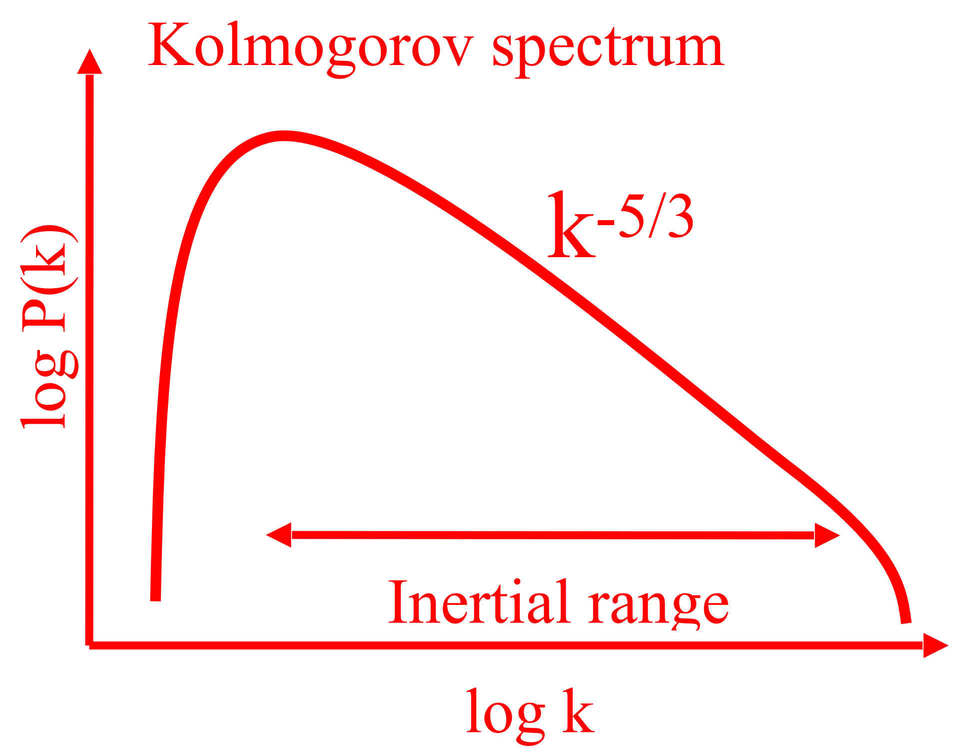
- Model for incompressible HD turbulence
  - Energy injected at large scales, cascades without losses until dissipation takes over (inertial range).
  - Constant Energy transfer rate $\dot{\mathcal{E}} \approx \frac{\rho\, v_\ell^2}{\tau} \sim \frac{v_\ell^2}{\ell/v_\ell} \sim \frac{v_\ell^3}{\ell} \Rightarrow v_\ell \propto \ell^{1/3} \sim k^{-1/3}$
  - The energy power spectrum *P(k)*

$$\int P(k)dk \propto v_\ell^2 \Rightarrow P(k) \propto \frac{k^{-2/3}}{k} \sim k^{-5/3}$$

In 1D: $P(k) \propto k^{-5/3}$

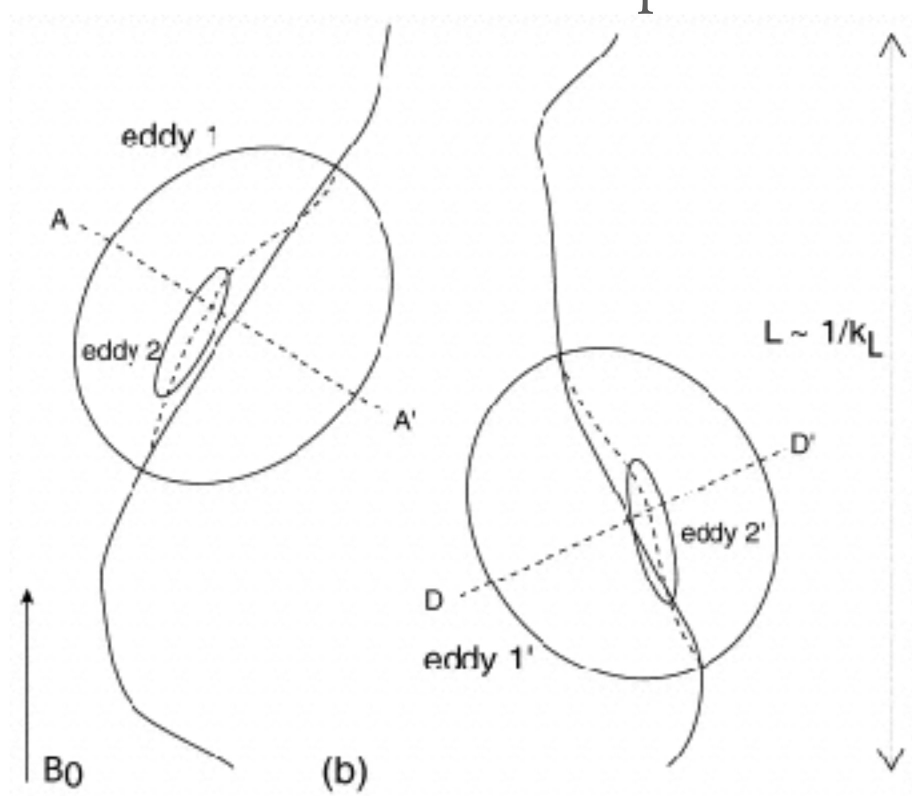
In 2D: $P(k) \propto k^{-8/3}$

In 3D: $P(k) \propto k^{-11/3}$



MHD TURBULENCE IS ANISOTROPIC (AND SCALE DEPENDENT)

- Goldreich & Sridhar (1995) MHD turbulence model
  - Anisotropic cascade:
    - Motions perpendicular to B follow a Kolmogorov type cascade $v_l \propto l_\perp^{1/3}$
    - Parallel B are dominated by Alfvénic perturbations
    - A *critical balance* condition relate the two $\frac{v_\perp}{l_\perp} \sim \frac{v_A}{l_\parallel} \Rightarrow l_\parallel \sim l_\perp^{2/3}$
  - Later confirmed with numerical simulations (Cho & Vishniac 2000, Maron & Goldreich 2001)
    - The anisotropy should be measured with respect to the ***local*** magnetic field



Cho, Lazarian & Vishniac (2002)

GRID OF MHD MODELS

- Ideal 3D MHD simulations of fully developed (driven at large scales) turbulence.
- Isothermal, in a periodic Cartesian grid.
- The parameters that control the simulations are the Alfvén and the sonic Mach numbers.

$$M_{\rm s} \equiv \frac{v_{\rm L}}{c_{\rm s}}; \quad M_{\rm A} = \frac{v_{\rm L}}{v_{\rm A}}$$

- where

$$c_{\rm s} = \sqrt{\frac{P}{\rho}}; \quad v_{\rm A} = \frac{B}{\sqrt{4\pi\,\rho}}$$

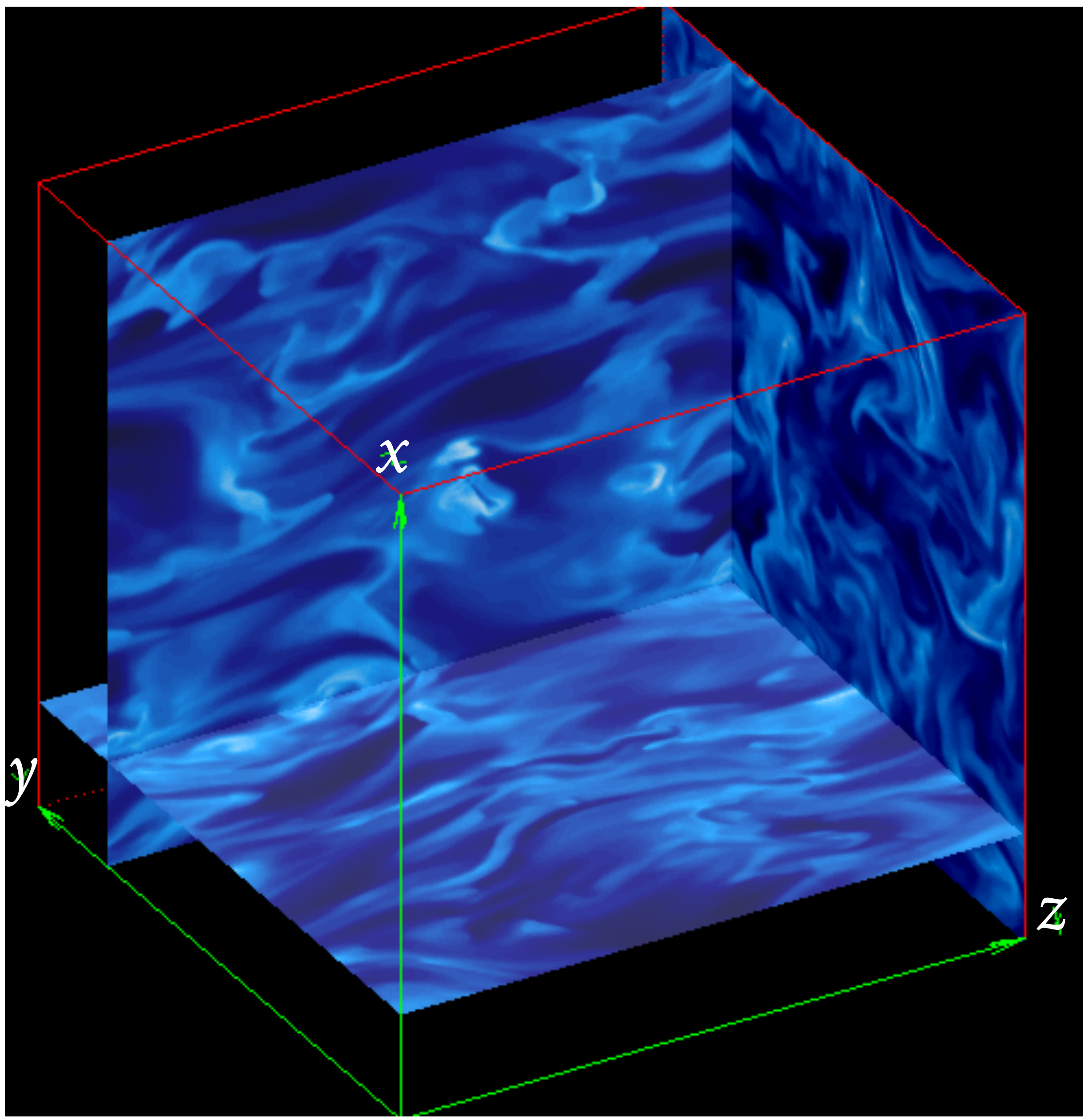
- B_0 is in the *x* direction.
- We take the output of the simulations to create synthetic spectroscopic observations of optically thin media.

Model	$v_{A,0}$	$P_{gas,0}$	$\mathcal{M}_A$	$\mathcal{M}_s$	β
M1	0.1	0.0049	~ 8.3	~ 11.9	~ 0.49
M2	0.1	0.0100	~ 7.7	~ 7.7	~ 1.0
M3	0.1	0.0250	~ 7.4	~ 4.7	~ 2.5
M4	0.1	0.0500	~ 7.6	~ 3.4	~ 5.0
M5	0.1	0.1000	~ 8.2	~ 2.6	~ 10.0
M6	0.1	0.7000	~ 7.6	~ 0.9	~ 70.0
M7	0.1	2.0000	~ 7.0	~ 0.5	~ 200.0
M8	1.0	0.0049	~ 0.8	~ 10.8	~ 0.0049
M9	1.0	0.0077	~ 0.8	~ 8.6	~ 0.0077
M10	1.0	0.0100	~ 0.7	~ 7.4	~ 0.01
M11	1.0	0.0250	~ 0.8	~ 4.8	~ 0.025
M12	1.0	0.0500	~ 0.8	~ 3.4	~ 0.05
M13	1.0	0.1000	~ 0.8	~ 2.7	~ 0.1
M14	1.0	0.7000	~ 0.8	~ 1.0	~ 0.7
M15	1.0	2.0000	~ 0.7	~ 0.5	~ 2.0
M16	2.0	0.0100	~ 0.4	~ 7.6	~ 0.0025
M17	2.0	0.1000	~ 0.4	~ 2.7	~ 0.025
M18	2.0	1.0000	~ 0.5	~ 1.0	~ 0.25
M19	3.0	0.0100	~ 0.3	~ 8.2	~ 0.001
M20	3.0	0.1000	~ 0.3	~ 2.6	~ 0.01
M21	3.0	1.0000	~ 0.3	~ 1.0	~ 0.1
M22	5.0	0.0100	~ 0.2	~ 9.0	~ 0.0004
M23	5.0	0.1000	~ 0.2	~ 2.7	~ 0.004
M24	5.0	1.0000	~ 0.2	~ 0.9	~ 0.04

SYNTHETIC OBSERVATIONS

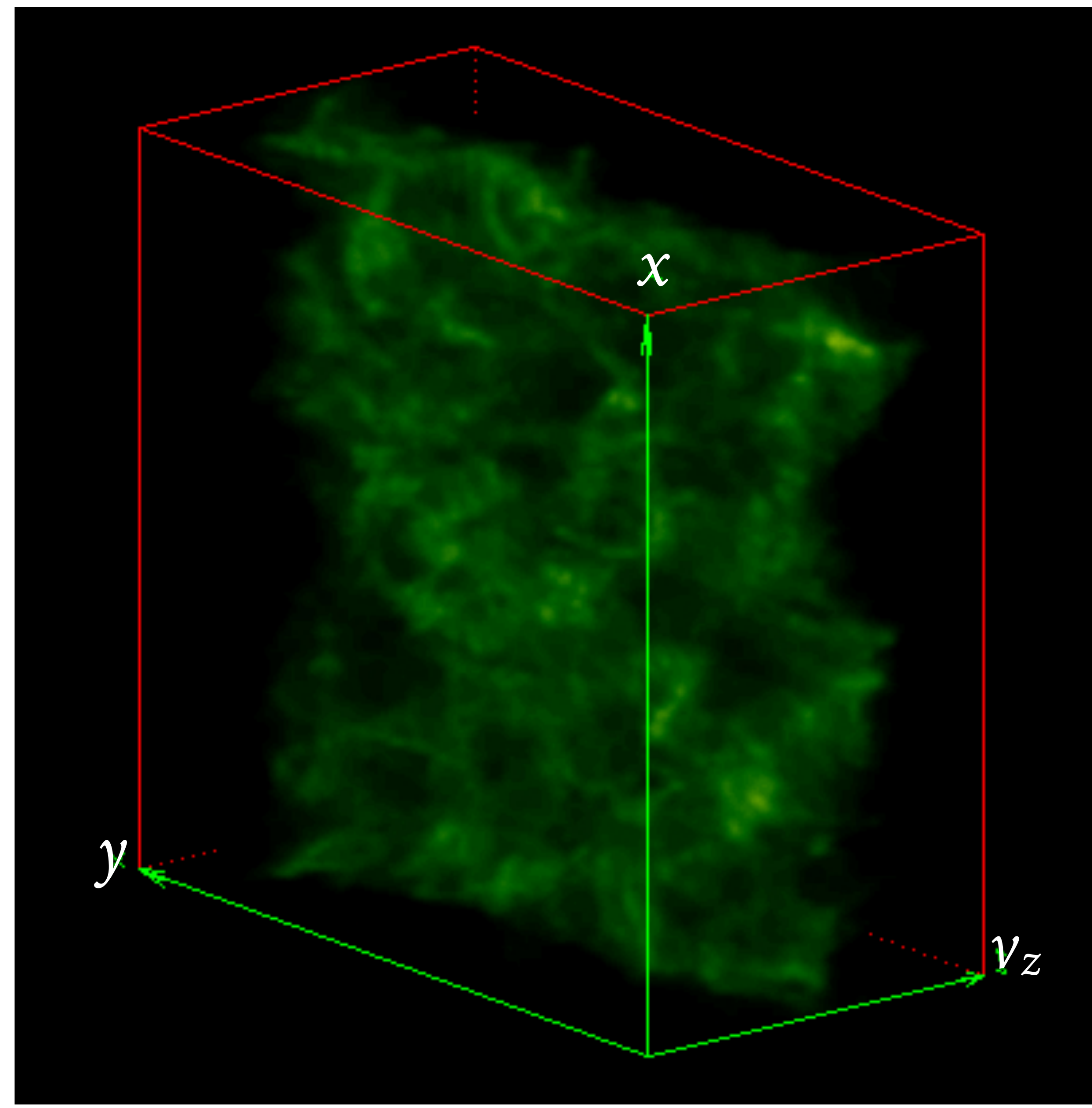
Model M13 (with M_S=2.7 and M_A=0.8)

Simulation PPP (x,y,z) space



Density cuts

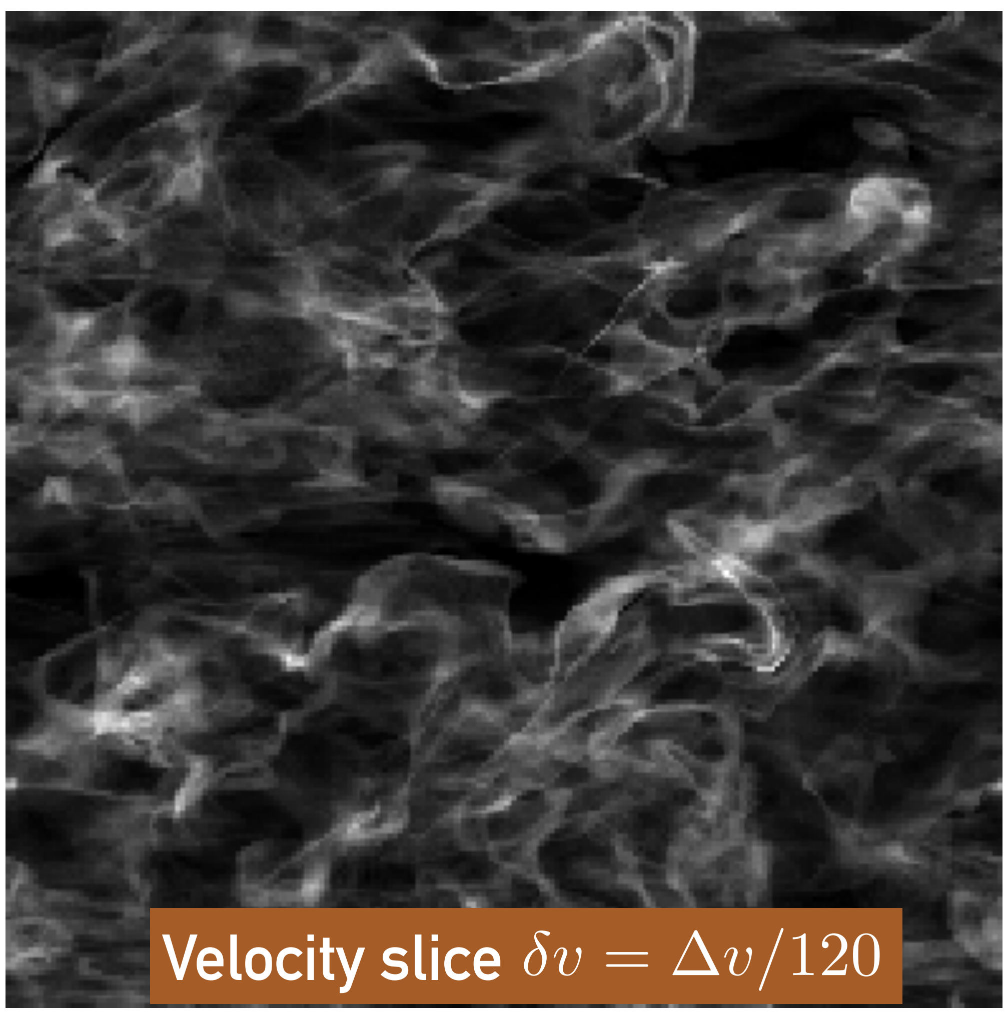
Synthetic Observations
PPV (x,y,v_z) space

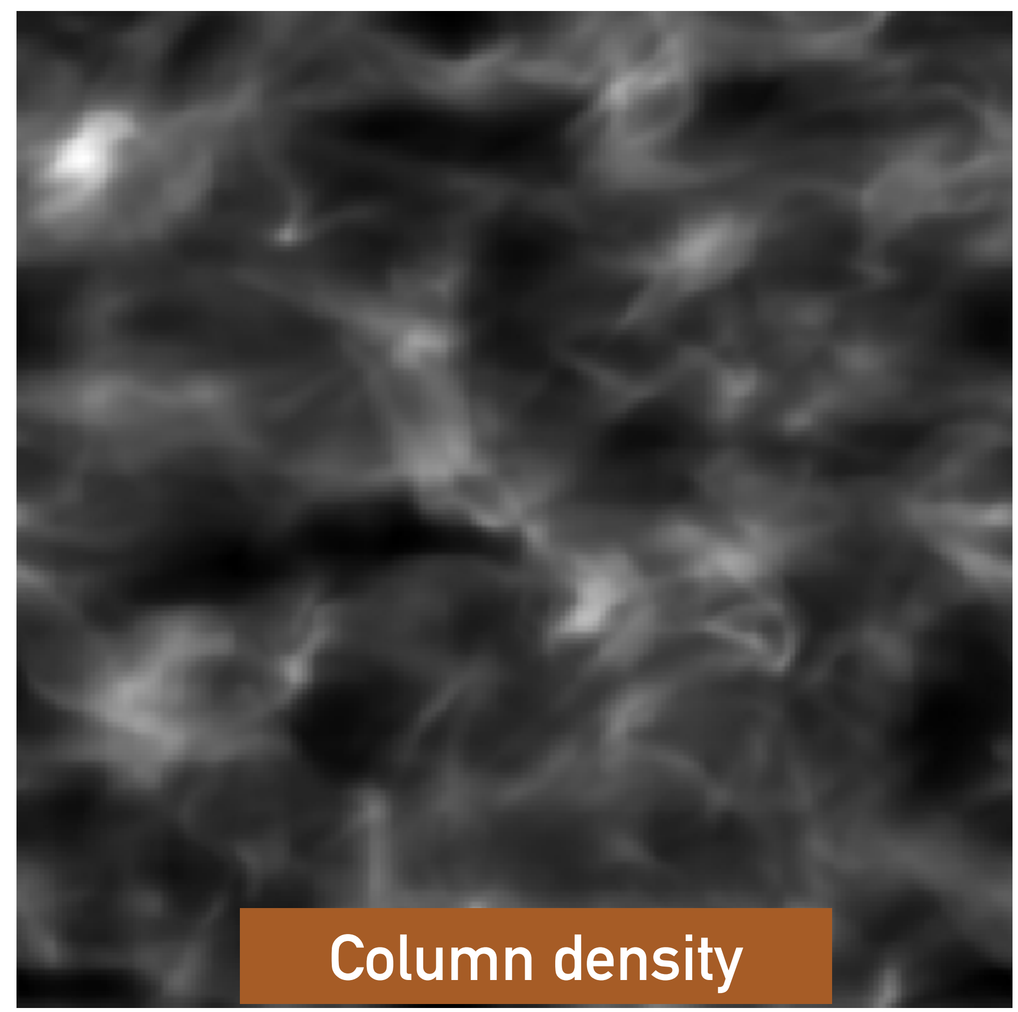


Intensity $\propto \rho$

PPV DATA: THE EFFECT OF VARYING RESOLUTION

- Emissivity in PPV data depends on density and velocity at the same time.
- Lazarian & Pogosyan (2000) study the effect of varying the thickness in velocity channels (velocity resolution) to obtain the velocity spectral index from observations.
  - As we lower the velocity resolution, the contribution of density becomes more prominent. In thinner velocity channels the velocity can dominate the spectrum.

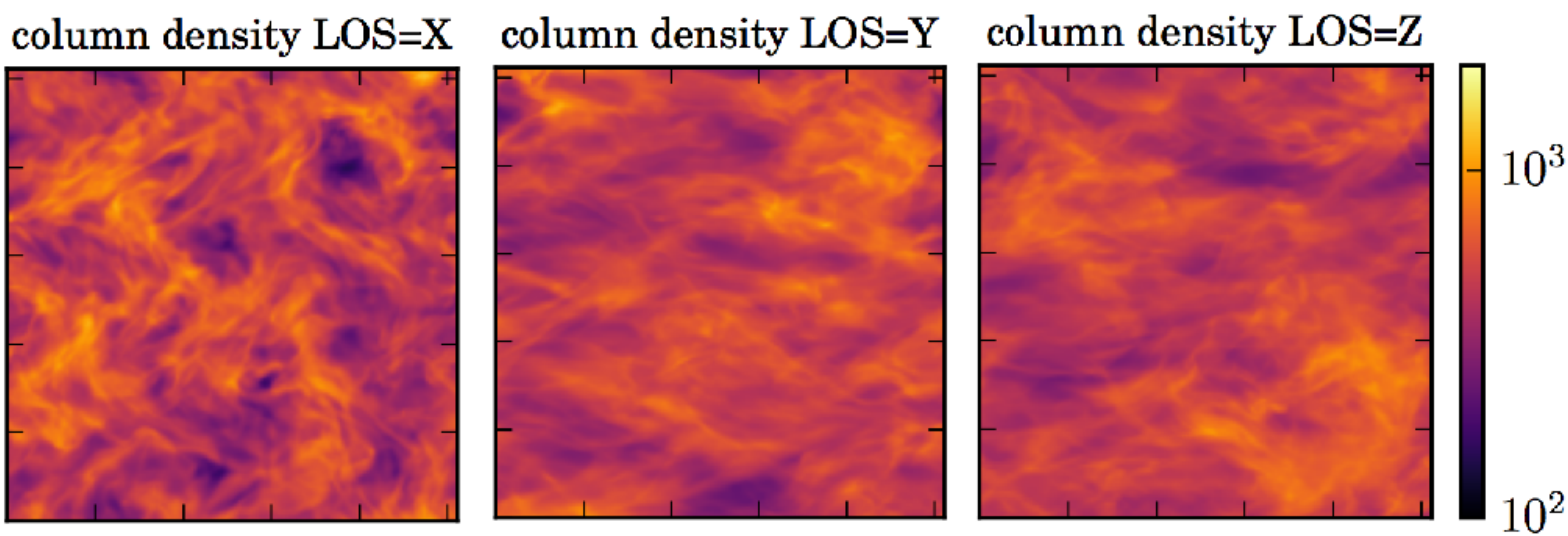




(SYNTHETIC) OBSERVATIONAL DATA

Column density $$N(x,y) = \int I(x,y,v_{\rm los})\, dv_{\rm los},$$

$$N(x,y) = \int \rho(x,y,z)\, dz$$ *(Optically thin media, LOS=z)*

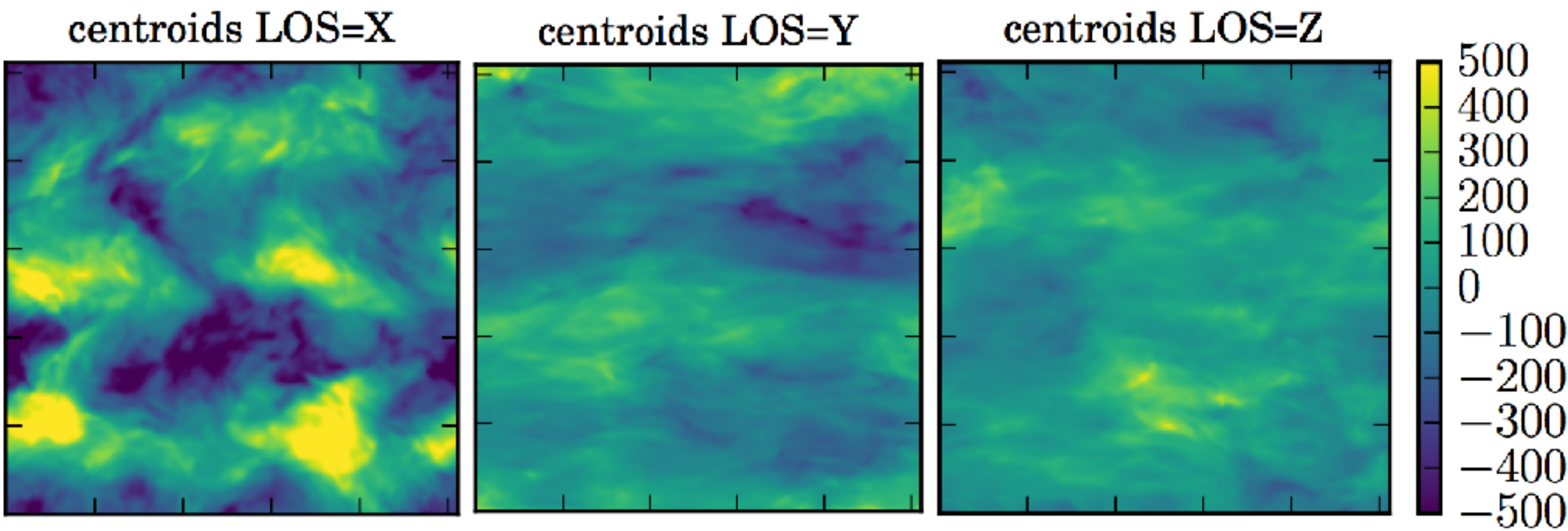


(SYNTHETIC) OBSERVATIONAL DATA

Velocity Centroids (unnormalized)

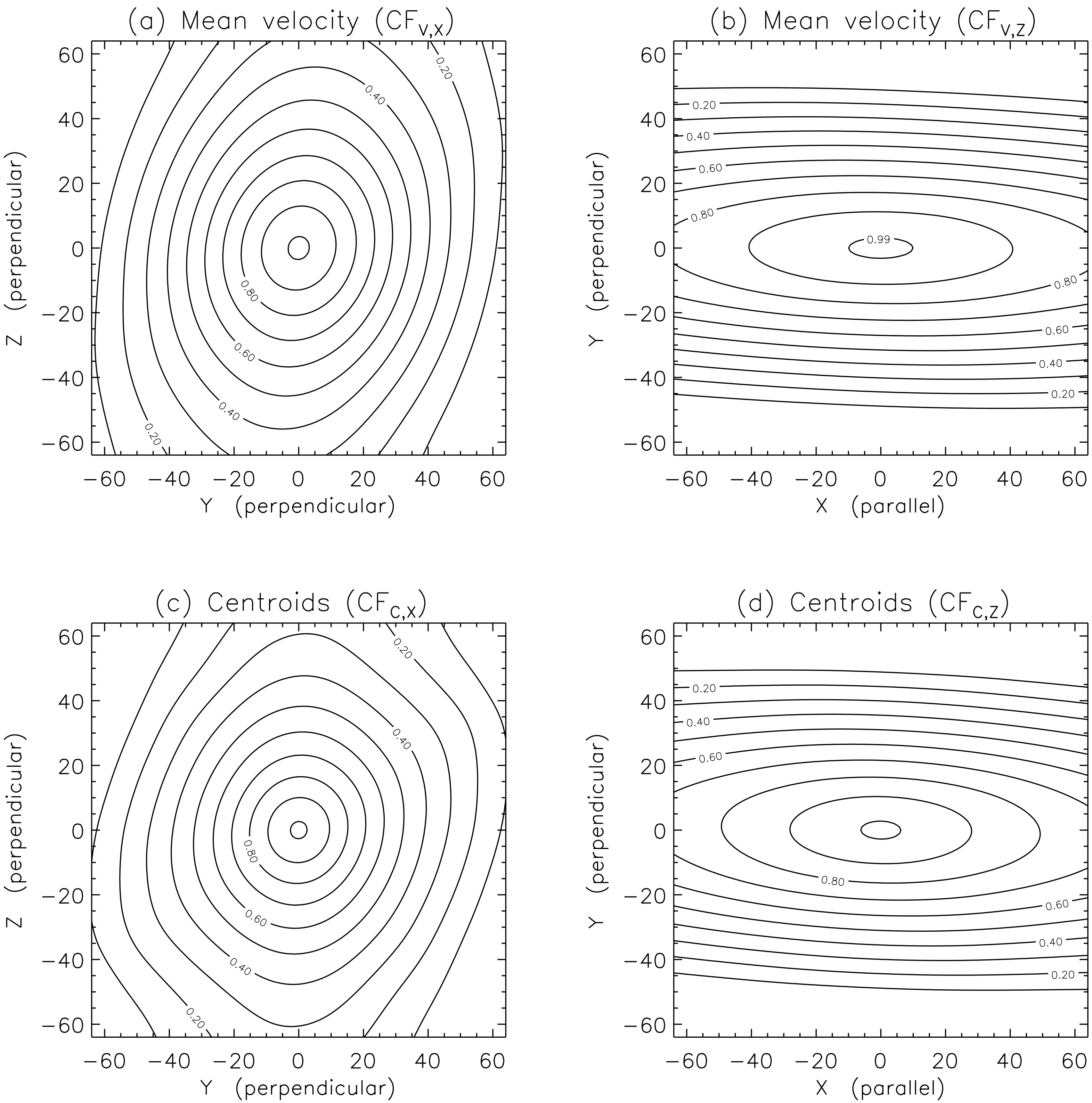
$$C_{\rm los}(x,y) = \int I(x,y,v_{\rm los})\, v_{\rm los}\, dv_{\rm los},$$

$$C_{\rm z}(x,y) = \int \rho(x,y,z)\, v_{\rm z}(x,y,z) dz$$ *(Optically thin media, LOS=z)*



ANISOTROPY IN VELOCITY CENTROIDS

- The structure function of velocity centroids $SF(\mathbf{R}) = \langle [C(\mathbf{X}) - C(\mathbf{X}+\mathbf{R})]^2 \rangle$,



Velocity centroids are a combination of density and velocity fluctuations. To isolate velocity one can use from the simulations maps of mean LOS velocity, e.g.

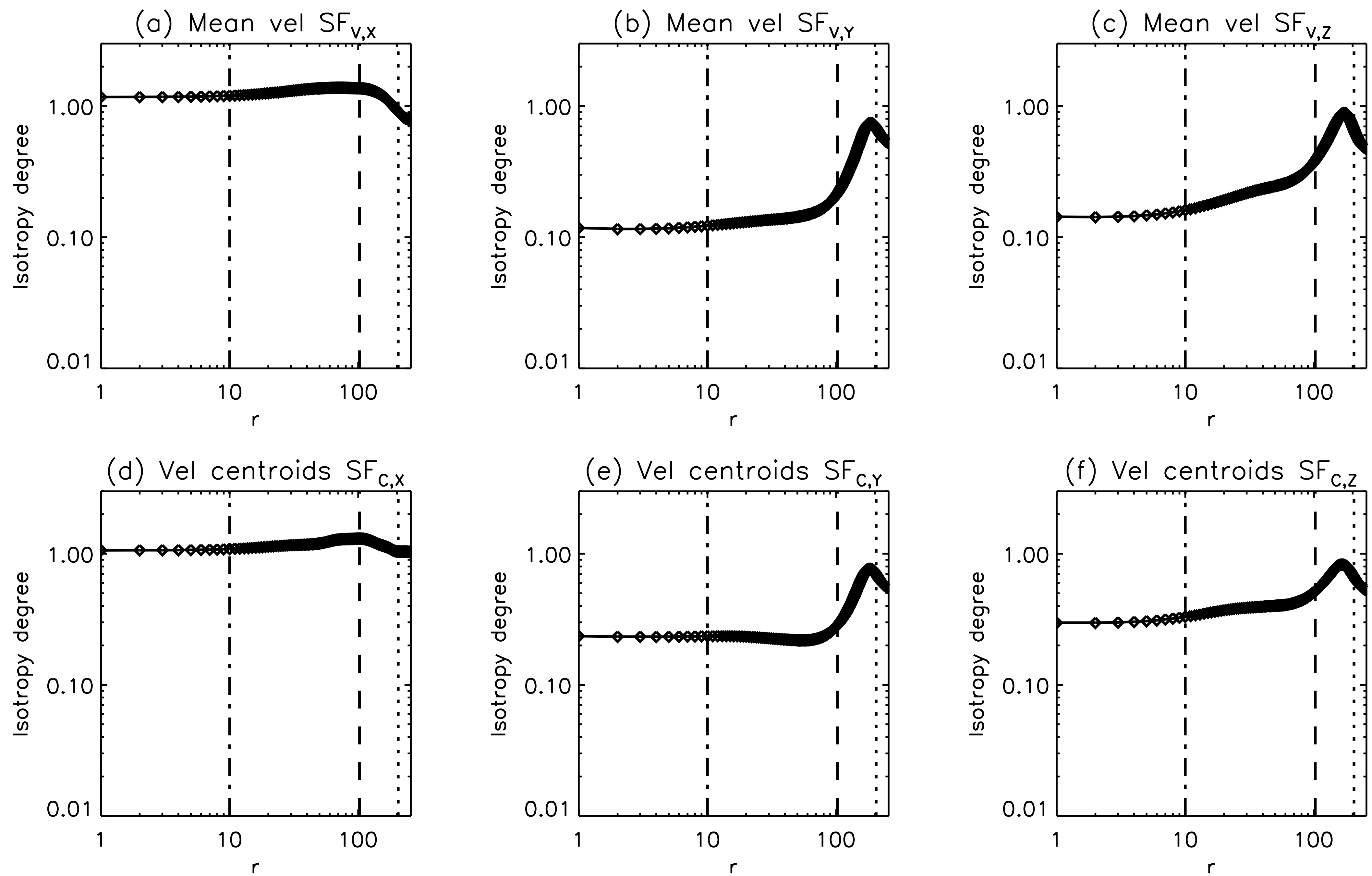
$$V_z(x, y) = \frac{1}{N_z} \int v(x, y, z)\, dz$$

The SFs are elongated in the direction of the mean magnetic field.

Esquivel & Lazarian (2011)

HOW DOES THE ANISOTROPY OF CENTROIDS DEPENDS ON SCALE

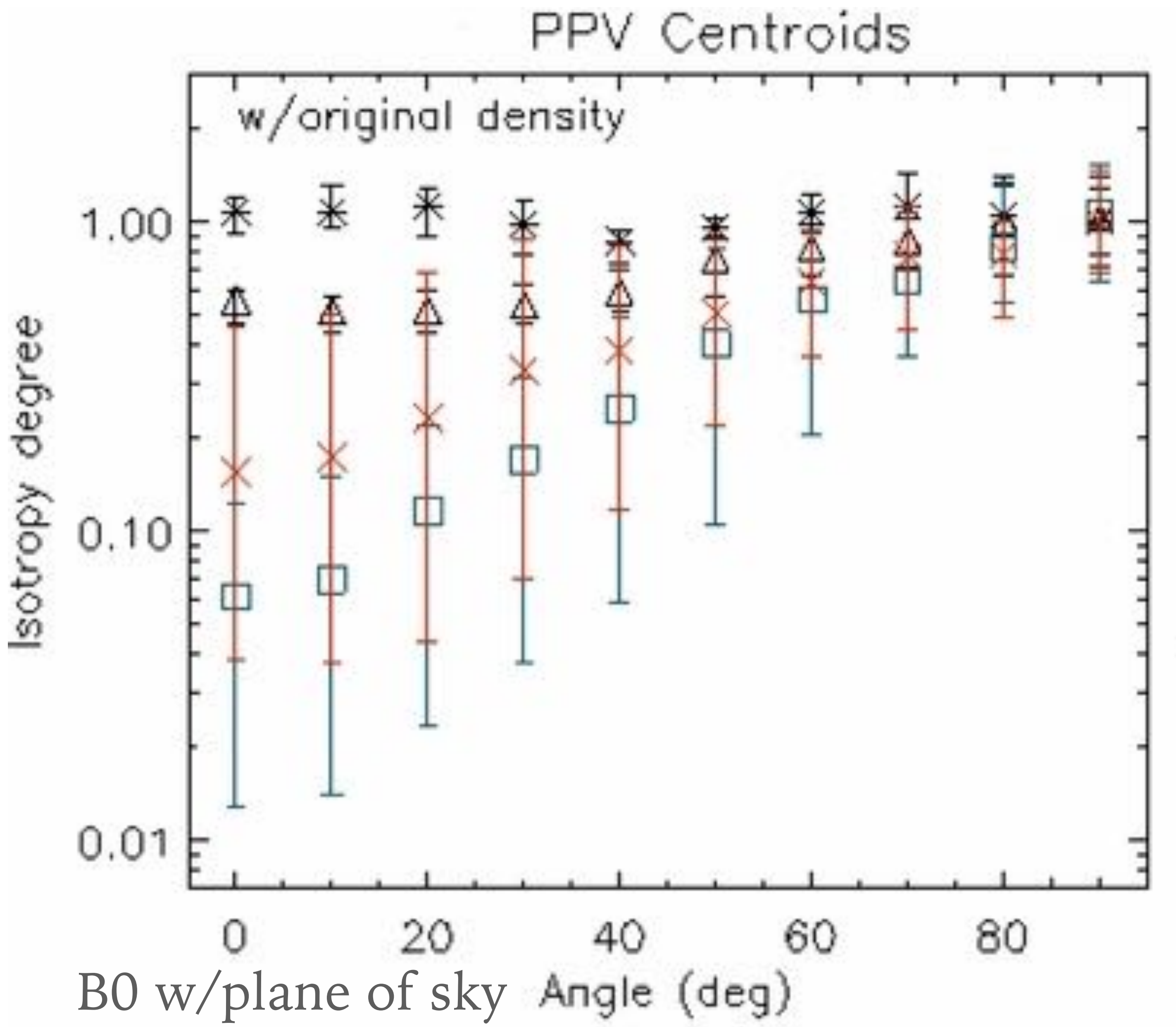
- Velocity centroids sample the entire LOS at a given velocity, thus one probe the mean magnetic field (as opposed to the local one)
  - $$\text{Isotropy degree}(\ell) = \frac{SF\left(R_{\parallel}\right)}{SF\left(R_{\perp}\right)}.$$
  - velocity centroids anisotropy is (mostly) SCALE INDEPENDENT.



Esquivel & Lazarian (2011)

AVERAGE ISOTROPY DEGREE

Higher magnetization → more elongated structure functions, but…



B0 w/plane of sky

Burkhart et al. (2014)

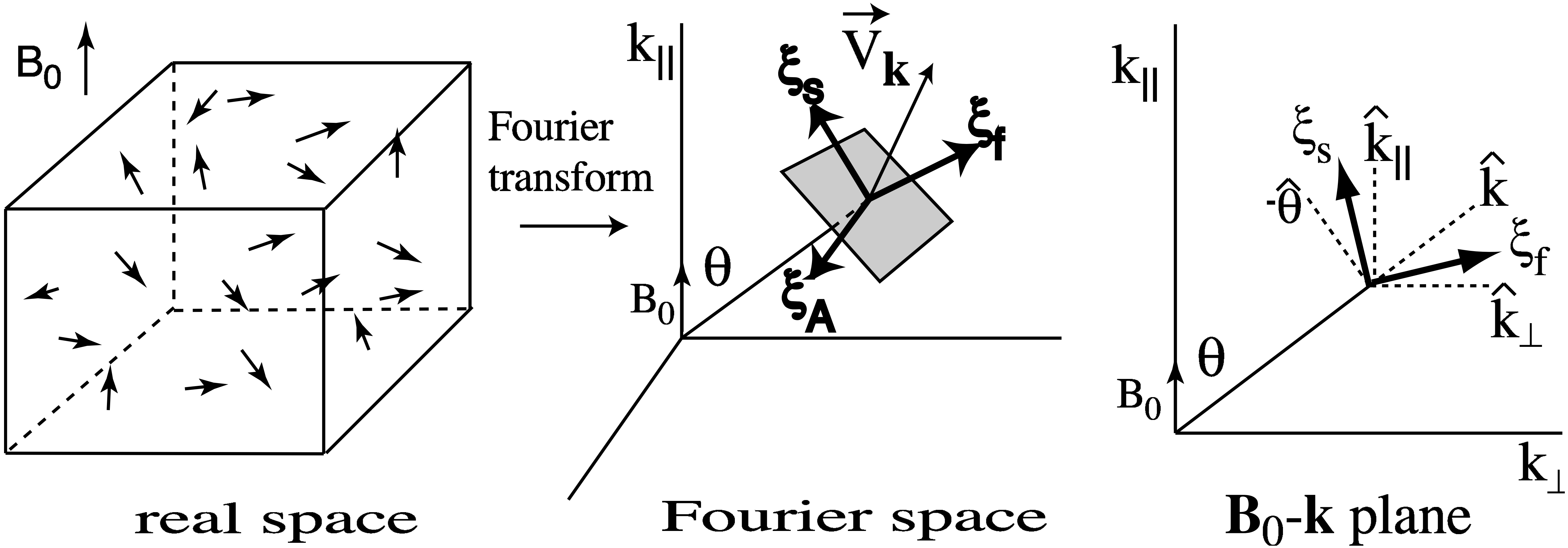
ADVANTAGE OF CENTROIDS: WE HAVE THEORY BEHIND THEM

- Recently Kandel, Lazarian & Pogosyan (MNRAS, 2016a,b) extended the VCA formalism to study the anisotropy in PPV and velocity centroids.
- They study the level of anisotropy in the different velocity modes in the SF of velocity centroids (at a constant density)
  - Alfvén Mode:
    anisotropic at low and high β, with more pronounced anisotropy at small M_A.
  - Slow mode:

    Same general behavior as the Alfvén mode, but with vanishing signal at an angle perpendicular to B_0.
  - Fast mode:
    Isotropic in high-β, but anisotropic in low-β

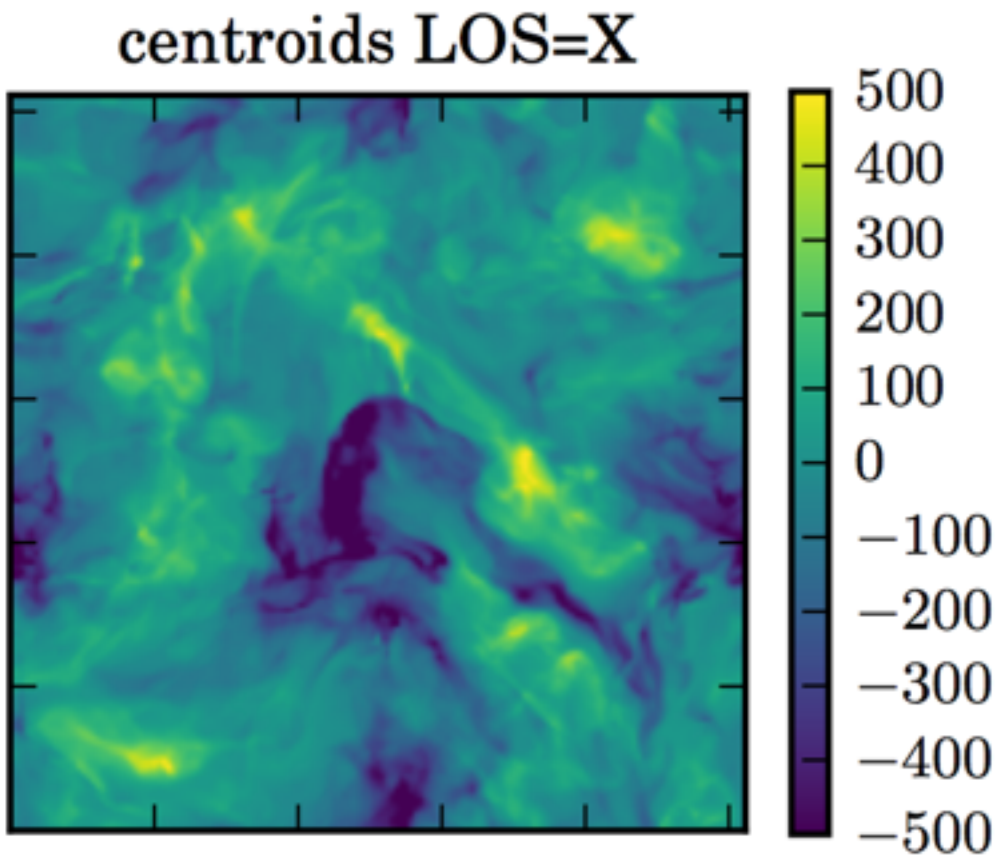
DIFFERENT MHD MODES ARE ALL PRESENT IN THE VELOCITY

- We decompose the velocity into Alfvén, Fast and Slow magneto-sonic modes.
- We take each of the velocity fields and compute the mean LOS velocity, and centroids combining such velocities with the original velocity.

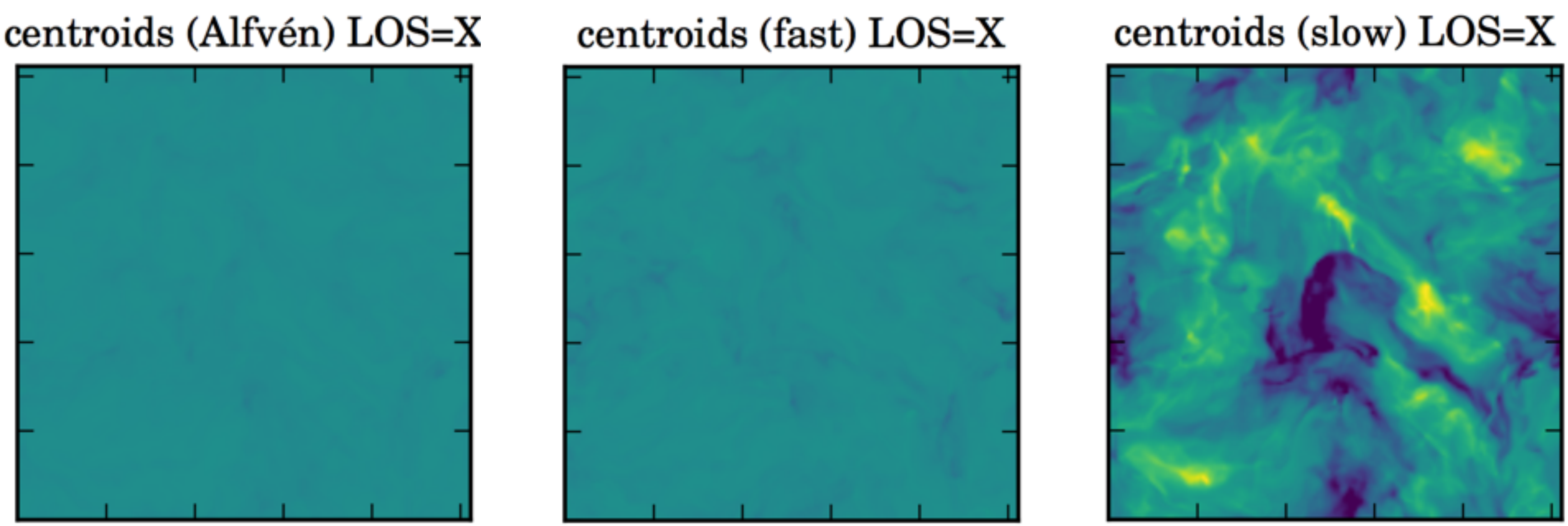


Cho & Lazarian 2002

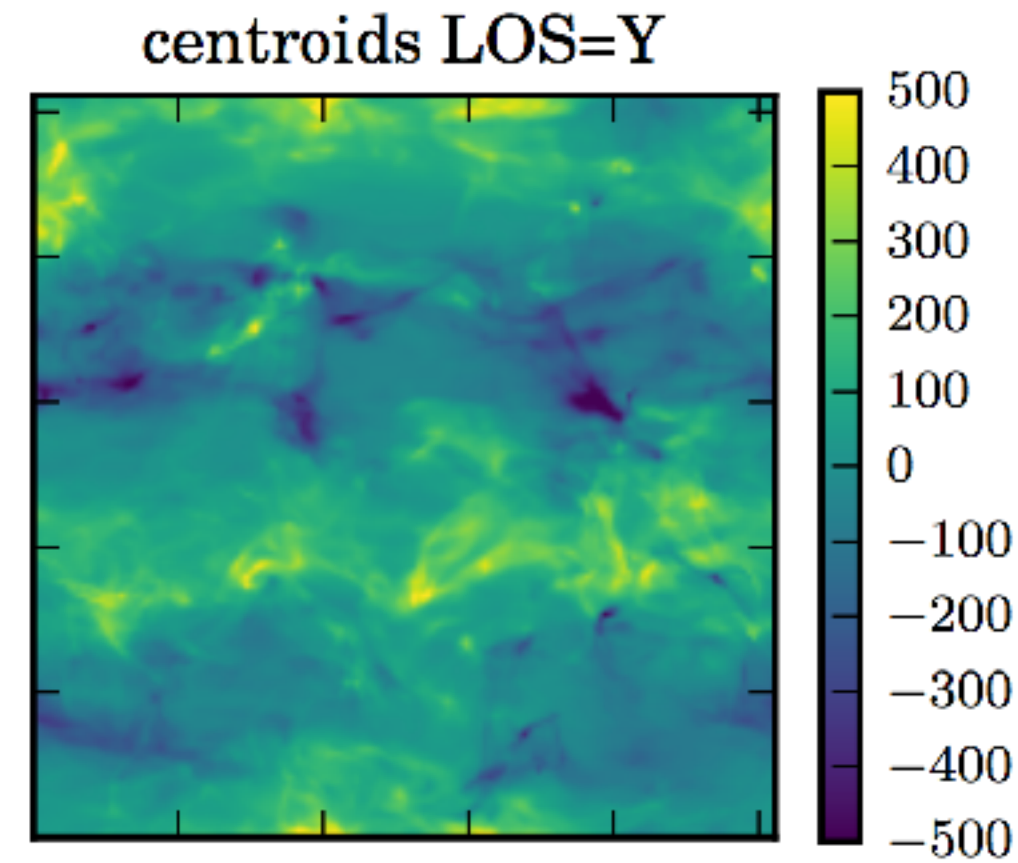
EXAMPLE OF DECOMPOSED MODES MAPS (PARALLEL TO B_0)



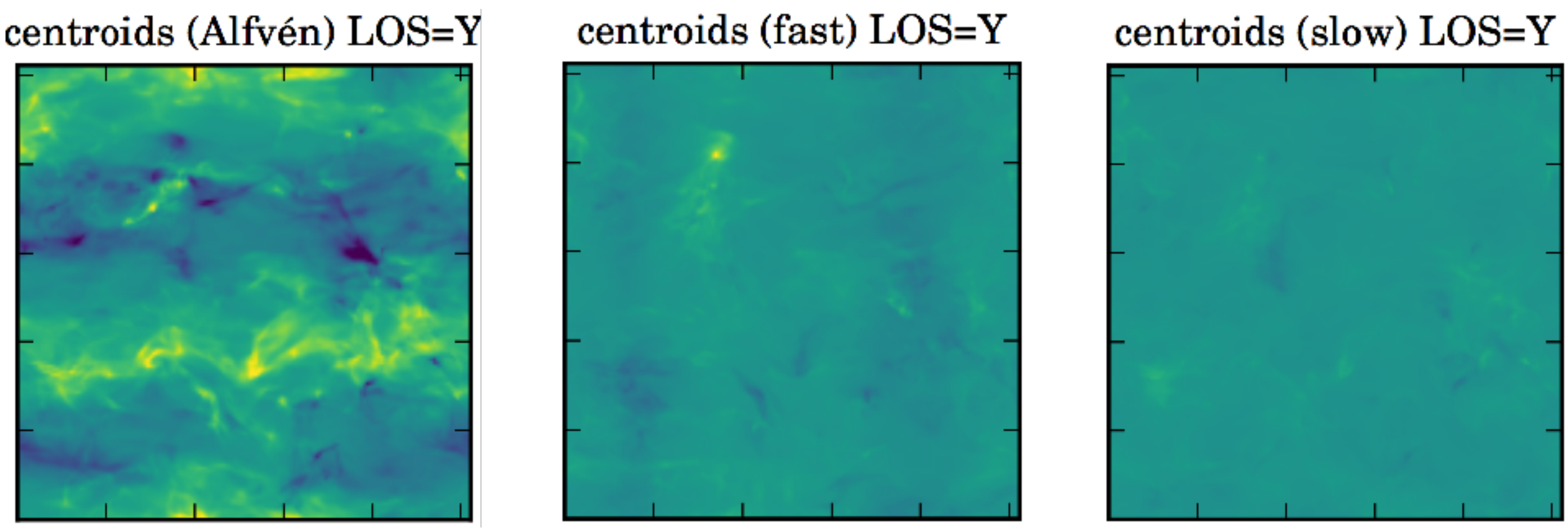
$$C_x(y,z) = \int \rho(x,y,z)\, v_x(x,y,z)\, dx$$



EXAMPLE OF DECOMPOSED MODES MAPS (PERPENDICULAR TO B_0)

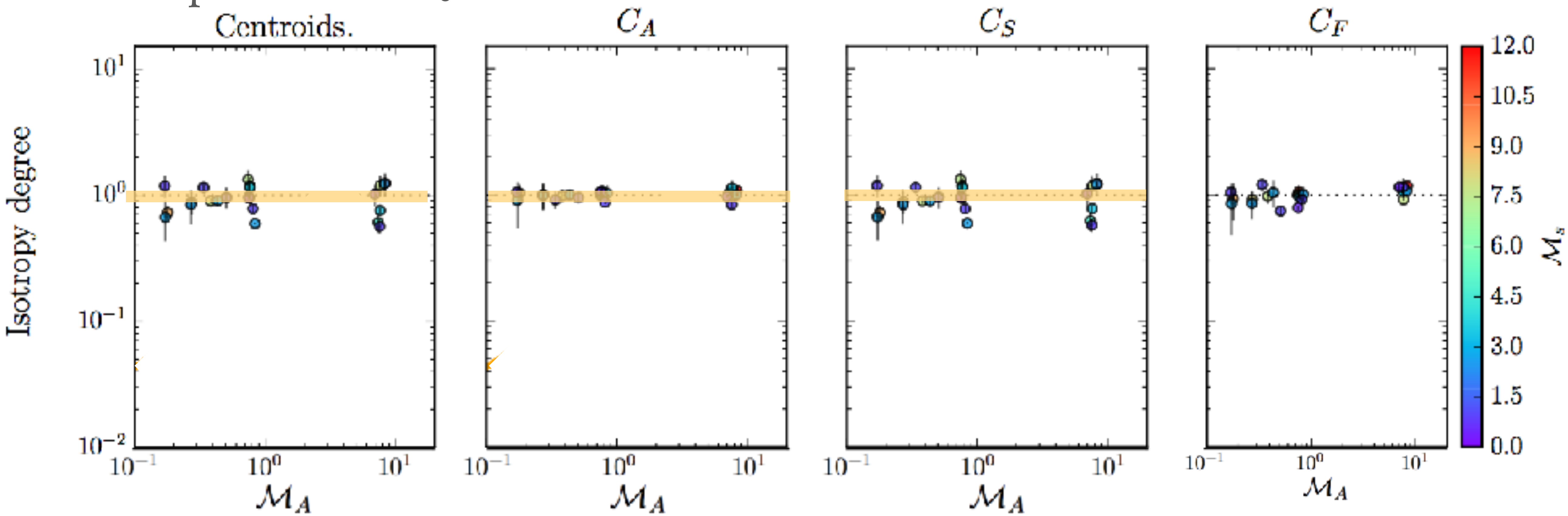


$$C_{\mathrm{y}}(x,z) = \int \rho(x,y,z)\, v_{\mathrm{y}}(x,y,z)\, dy$$

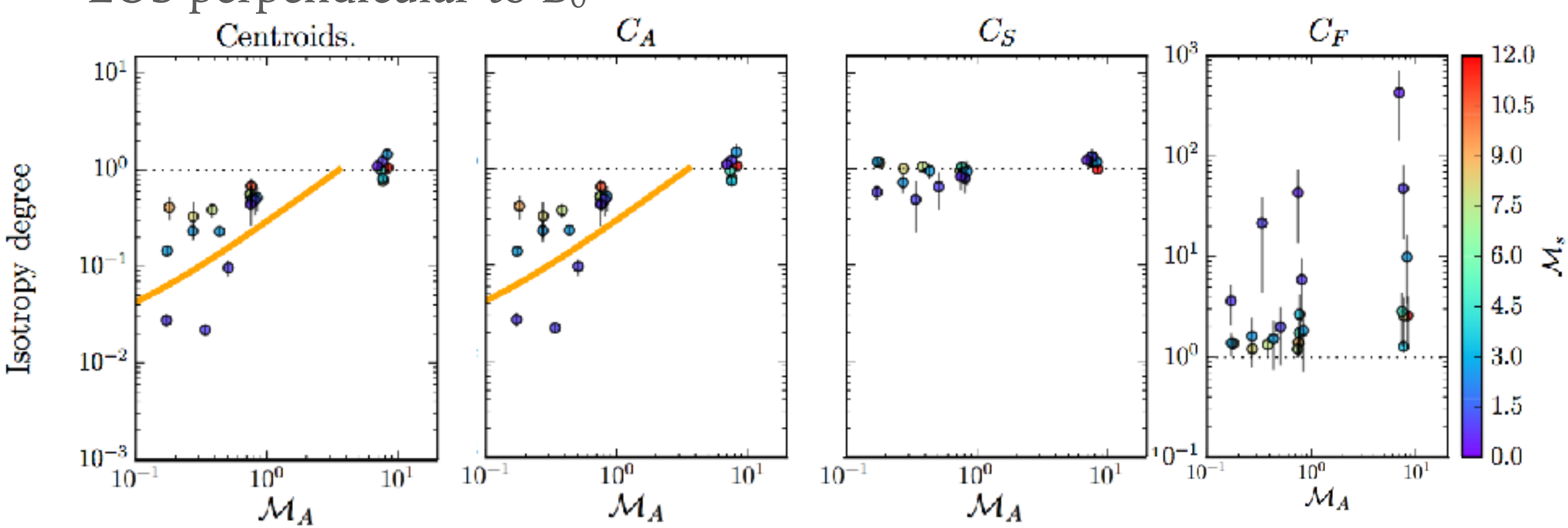


AVERAGE ISOTROPY DEGREE FOR ALL MODES

LOS parallel to B_0



LOS perpendicular to B_0



SUMMARY/CONCLUSSIONS

- Structure functions in velocity centroids are anisotropic.
- Such anisotropy points in the direction of the plane of the sky B field.
- The degree of anisotropy increases with the strength of B_0 (i.e. $\sim 1/M_A$), with a secondary dependence on the sonic Mach number (M_S).
  - Thus given an estimate of M_S one can infer an upper bound on the Alfvénic Mach number.
  - With help of other techniques/measurements for the LOS component one could determine M_A .
- The Alfvén mode is the dominant contribution to the centroids map, and thus their structure function when the LOS is perpendicular to B_0 (maximum anisotropy).
- The slow mode dominates in the case of LOS parallel to B_0, but the SFs are isotropic from that point of view.
- These results are consistent with those previously obtained with velocity centroids (Esquivel & Lazarian 2011, Burkhart et al. 2014).
- Also consistent with analytical predictions for the Alfvén modes by Kandel et al. 2016.