Turbulence

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Nature uses only the longest threads to weave her patterns, so that each small piece of her fabric reveals the organization of the entire tapestry.

Richard P. Feynman

Post-meeting note: I am well aware, after having discussed with many of you after my talk, that I missed the goal of my review. And I apologize for that.
Indeed, I did not want to repeat what had been already said and written in the papers I quoted at the beginning of my talk (next slide).
I planned instead to focus on what I thought were new important developments, not necessarily in the field of astrophysical turbulence. By doing so, I unfortunately stayed very far from your expectations and immediate concerns.
The following slides are the few I managed to show (I think).
I will try to do better in the written version!

Outline

Planck galactic
thermal dust emission

Recent reviews:

Elmegreen & Scalo (ARAA, 2004),
Scalo & Elmegreen (ARAA, 2004),
McKee & Ostriker (ARAA, 2007),
Lazarian et al. (Space Sci. Rev. 2012),
Hennebelle & Falgarone (AARv, 2012),
Heitsch in « Physical Processes in the ISM » (MPE, 2013),
Falceta-Gonçalves et al. (NPG, 2014)

1 - Setting the stage
2 - A few recent highlights in the field of turbulence
3 - What are the observed scaling laws telling us?
4 - The « turbulent » parsec scale environment of low mass cores
5 - Intermittency of turbulent dissipation

The ISM cycle

Why ISM phases do not mix?
Because ISM not isolated and
exchanges matter and energy with stars

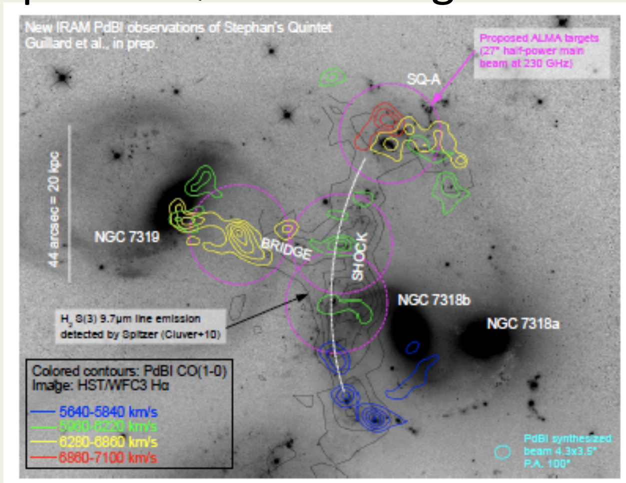
➪ No fine tuning !

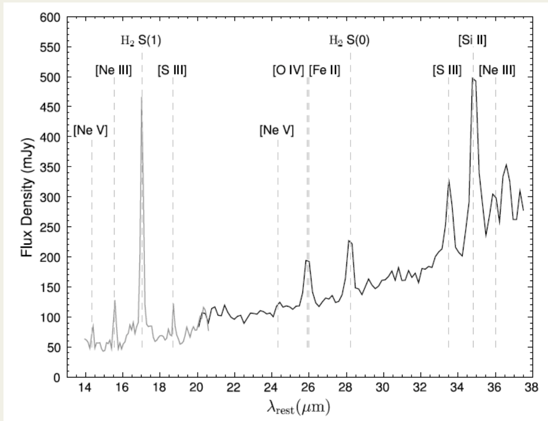
➪ ISM maintained far from thermal equilibrium by cycle driven by SF and feedback + extragalactic infall

➪ Equipartition Kinetic Magnetic Cosmic Rays energy density
Conversion of gravitational energy

Feedback?
Breakthrough :
Ubiquitous H_2 pure rotational lines (*Spitzer* IRS)
Major coolant
➪ **Support of an energy cascade**

Stephan's Quintet intergalactic shock





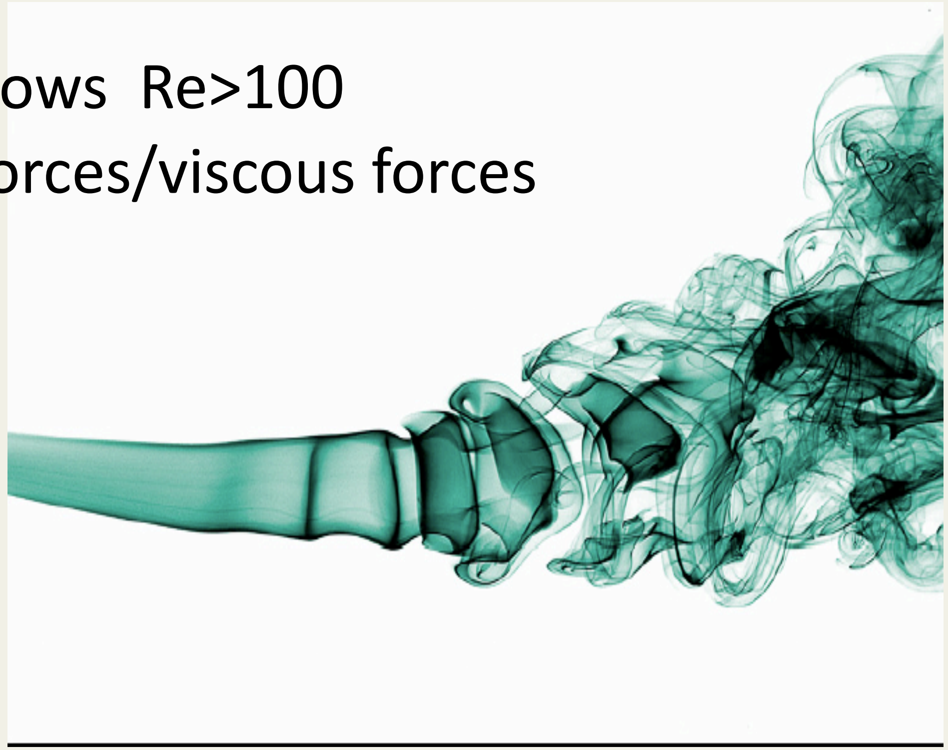
Cluver + 10, Appleton + 14, Guillard + 09,14

Turbulence is an energy cascade

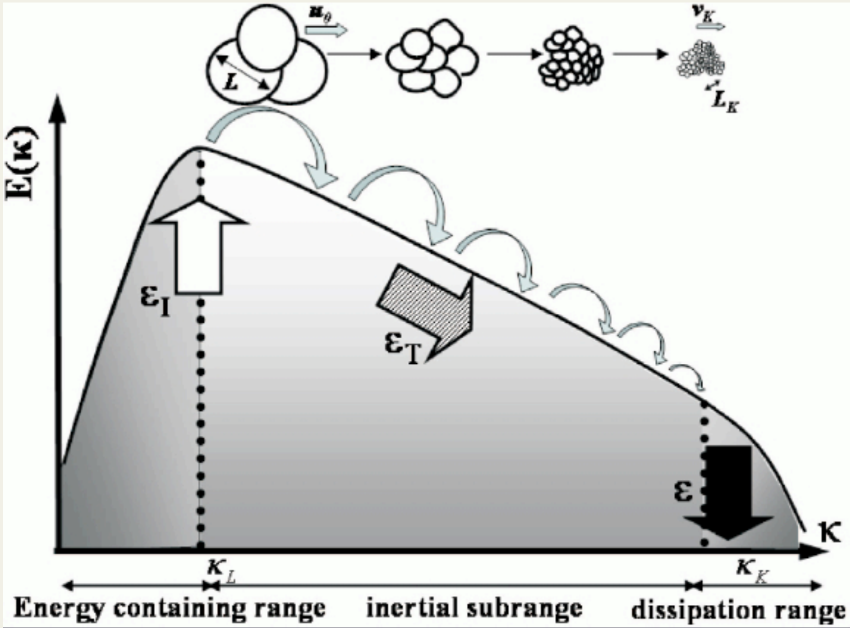
Turbulence : instability of laminar flows Re>100

Reynolds number Re=Lv/ν = inertial forces/viscous forces

Cold Diffuse ISM: Re > 10^7



Power spectrum



$l_{diss} \propto (\nu^3/\varepsilon)^{1/4}$

Hydro 2D: inverse cascade

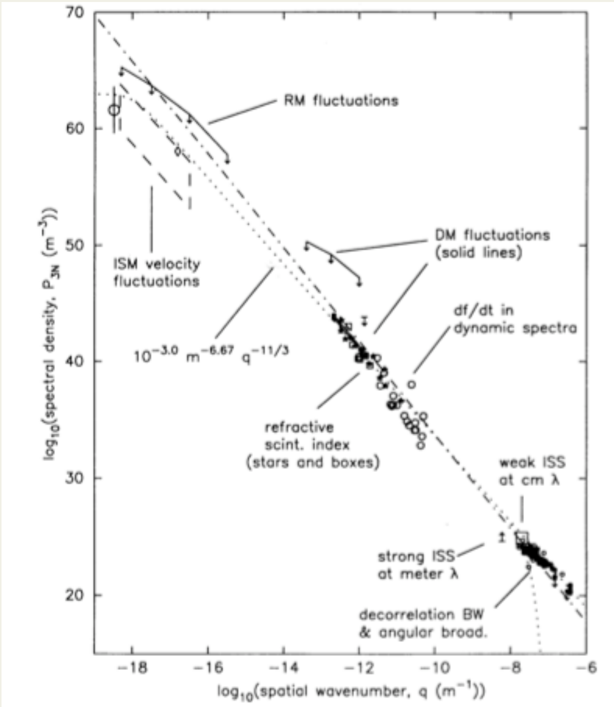
Magnetic field / rotation

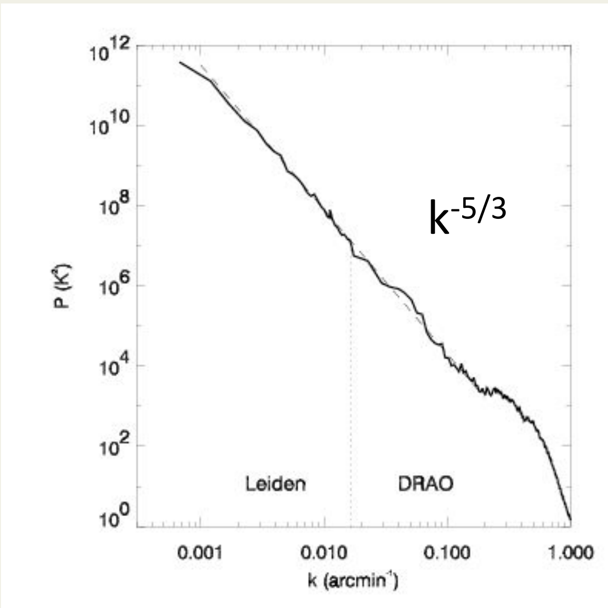
➪ anisotropy

➪ transition from forward to inverse cascade Alexakis et al. 2014

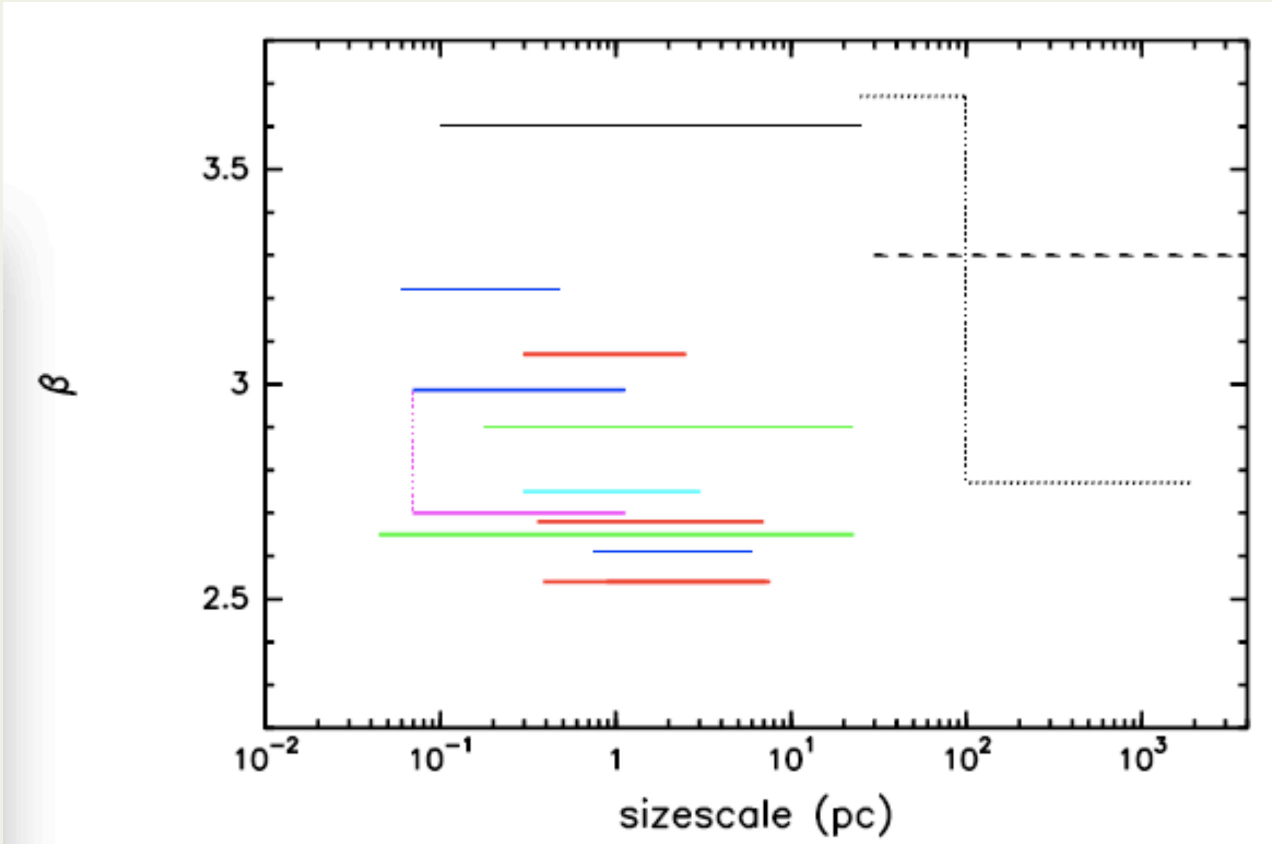
Power spectra

Power spectrum of electron density
Fluctuations Rickett + 95





Energy sectrum
HI 21cm emission
Miville-Deschênes + 03

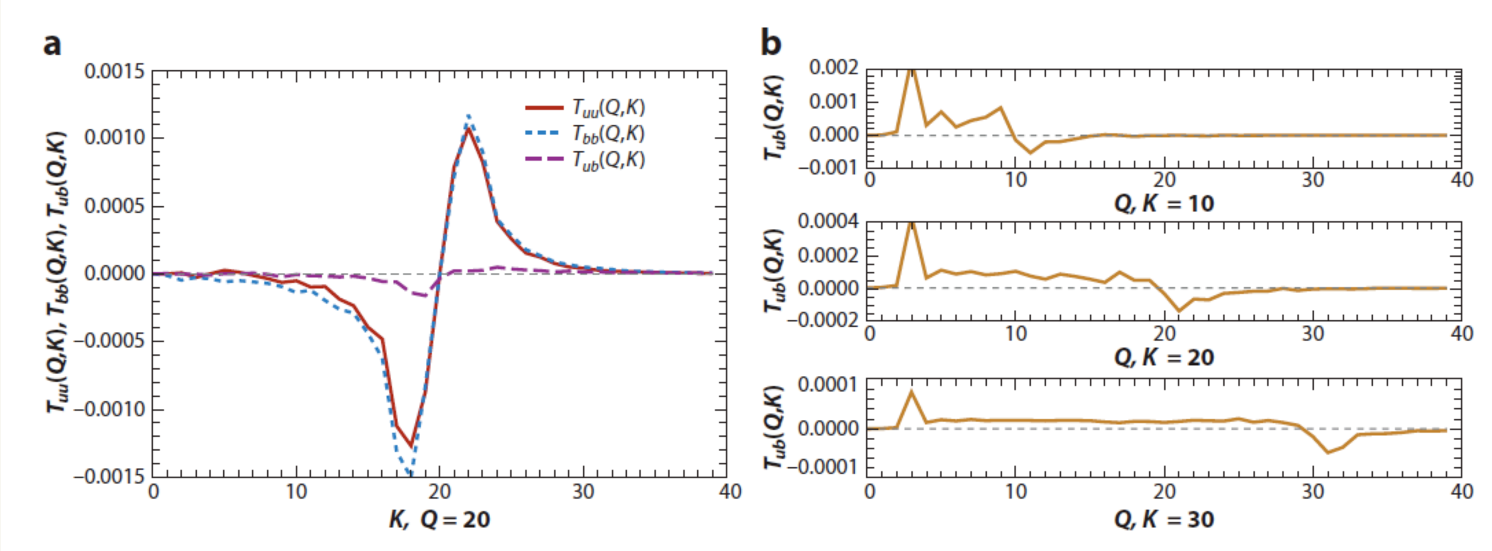


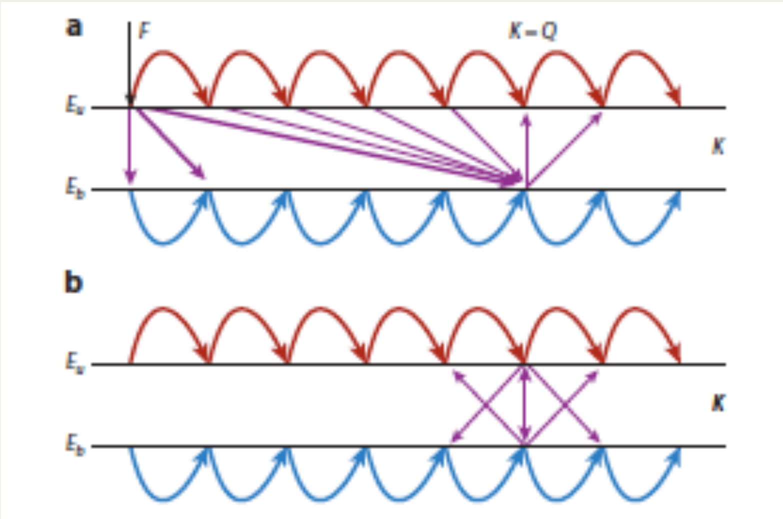
HI, dust, CO power spectra
Hennebelle & Falgarone 12

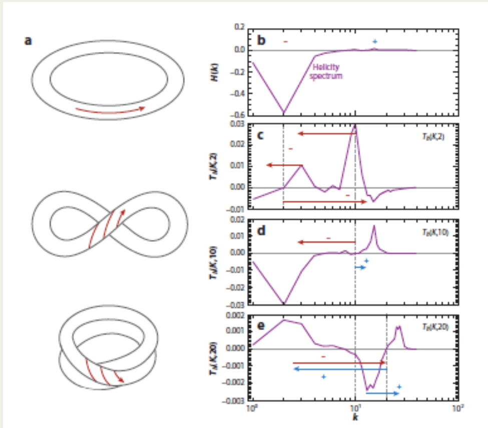
Local and non-local energy transfers

MHD forced turbulence

The large scale flow injects energy to B at all scales



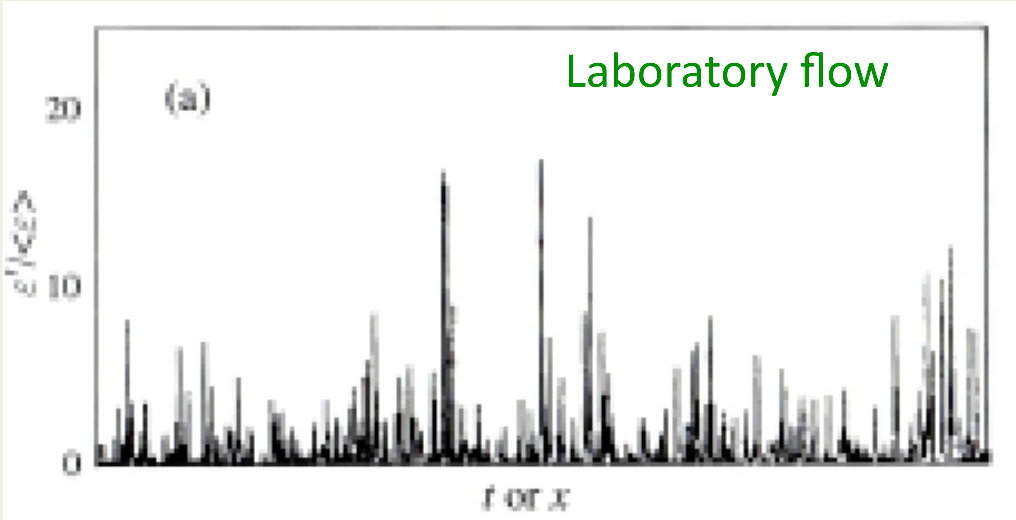




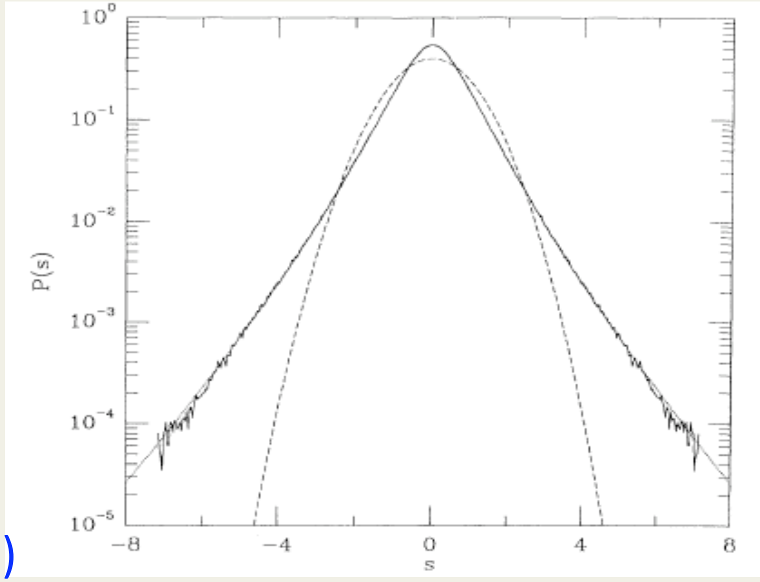
Transfer of magnetic helicity in the stretch, twist and fold mechanism

Mininni ARFM 2011, Alexakis + 05

Turbulent space-time intermittency



Méneveau & Sreenivasan (1991)



- Dissipation bursts

- Non-Gaussian PDF of velocity increments

She 1991

- Anomalous scaling of high-order structure functions

Dissipation rate :

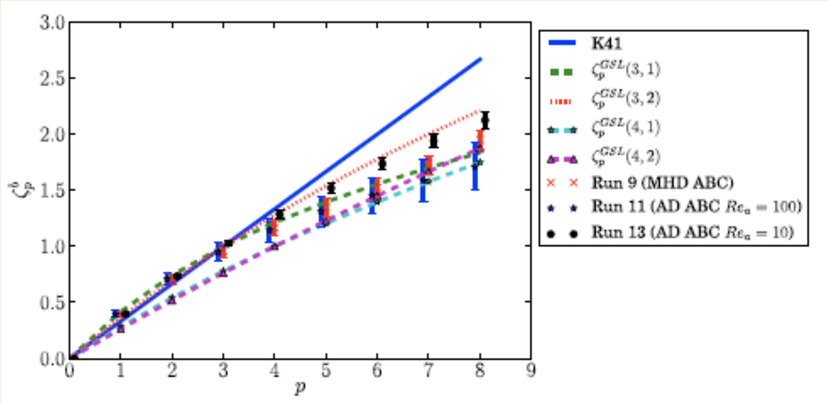
$$\varepsilon \propto \; |\nabla \times u|^2_{symm} \;\text{ and }\; |\nabla . u|^2$$

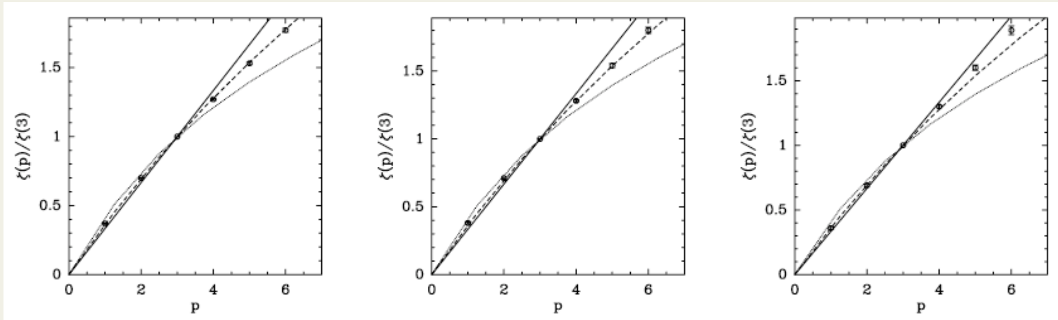
Signature : 2-point velocity statistics

$$S_p^u(r) = \langle (\delta u_\parallel(r))^p \rangle, \quad \delta u_\parallel(r) = (\mathbf{u}(\mathbf{x}+\mathbf{r}) - \mathbf{u}(\mathbf{x})) \cdot \hat{\mathbf{r}}$$

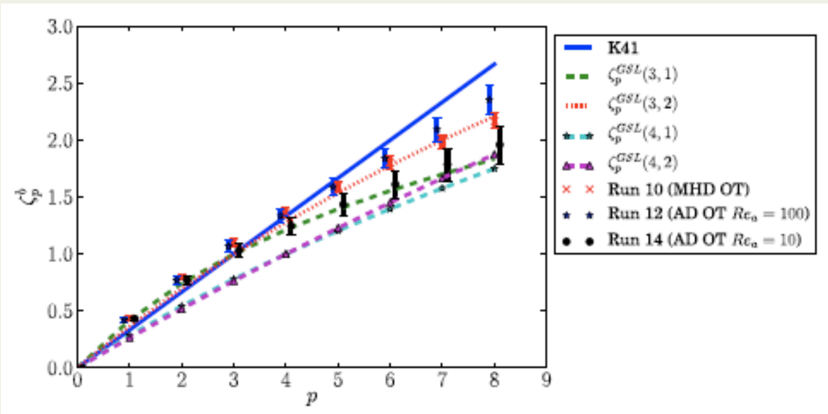
$$S_p^u(r) \propto r^{\zeta_p^u}, \qquad l_d \ll r \ll L$$

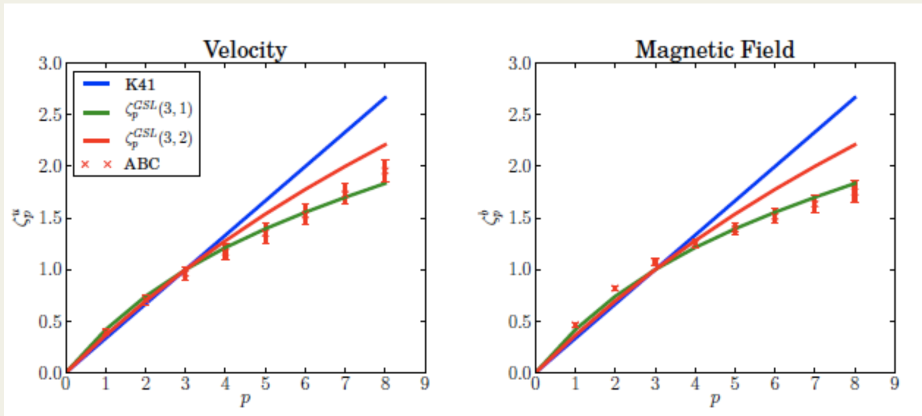
She & Lévêque 94
Boldyrev + 02





CO observations Hily-Blant + 08

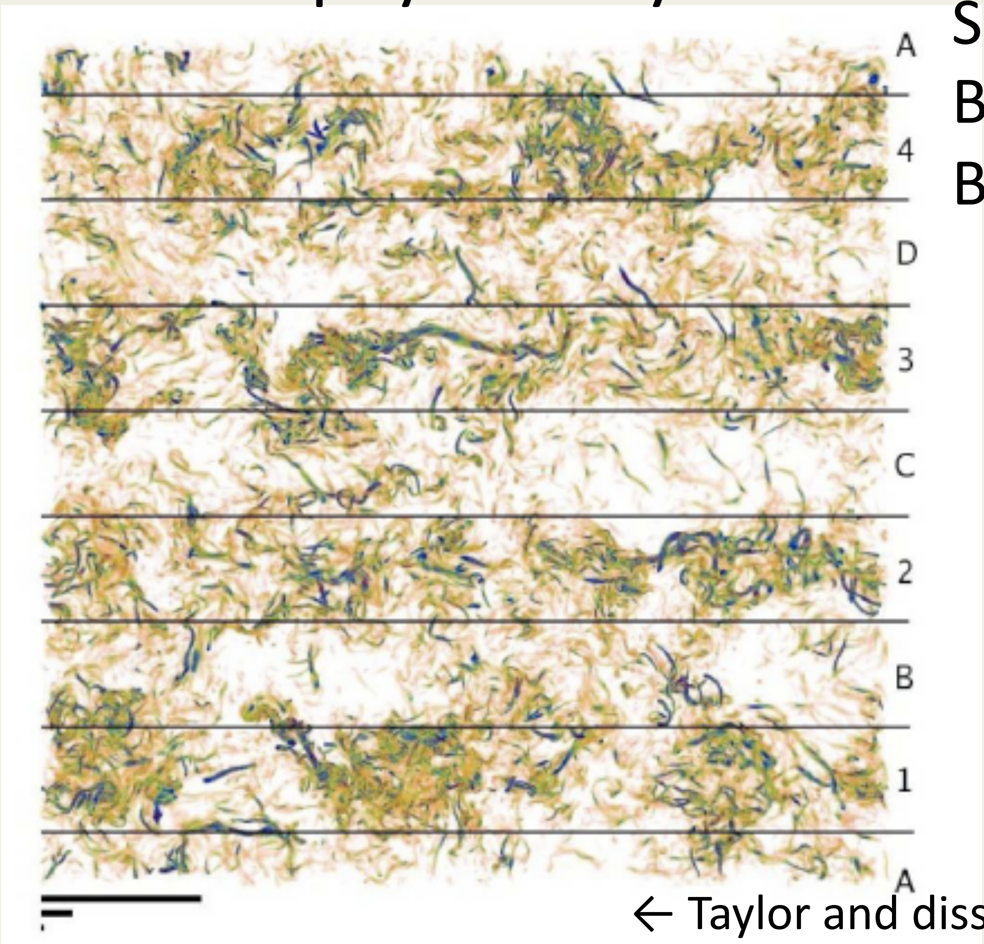




Spectral MHD simulations Momferratos + 14

Large scale flow effects

Enstrophy density field



← Taylor and dissipation scales

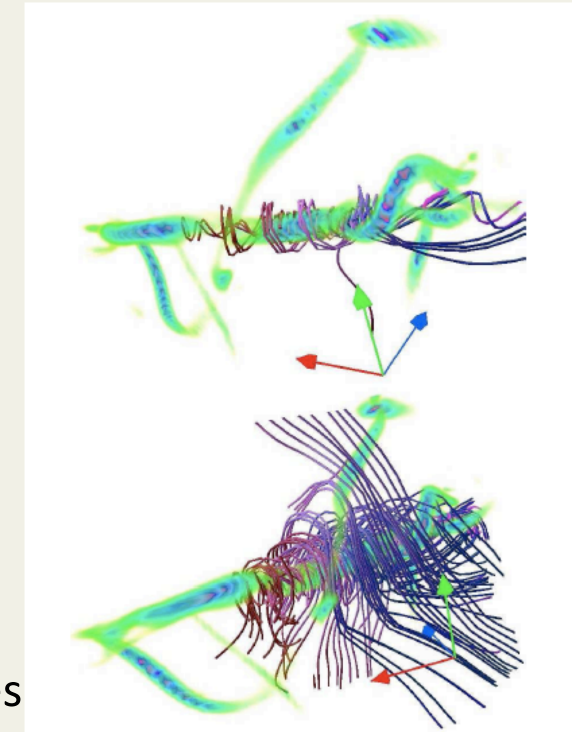
1024^3 NS incompressible turbulence

Mininni, Alexakis, Pouquet 2006

Shear external forcing:

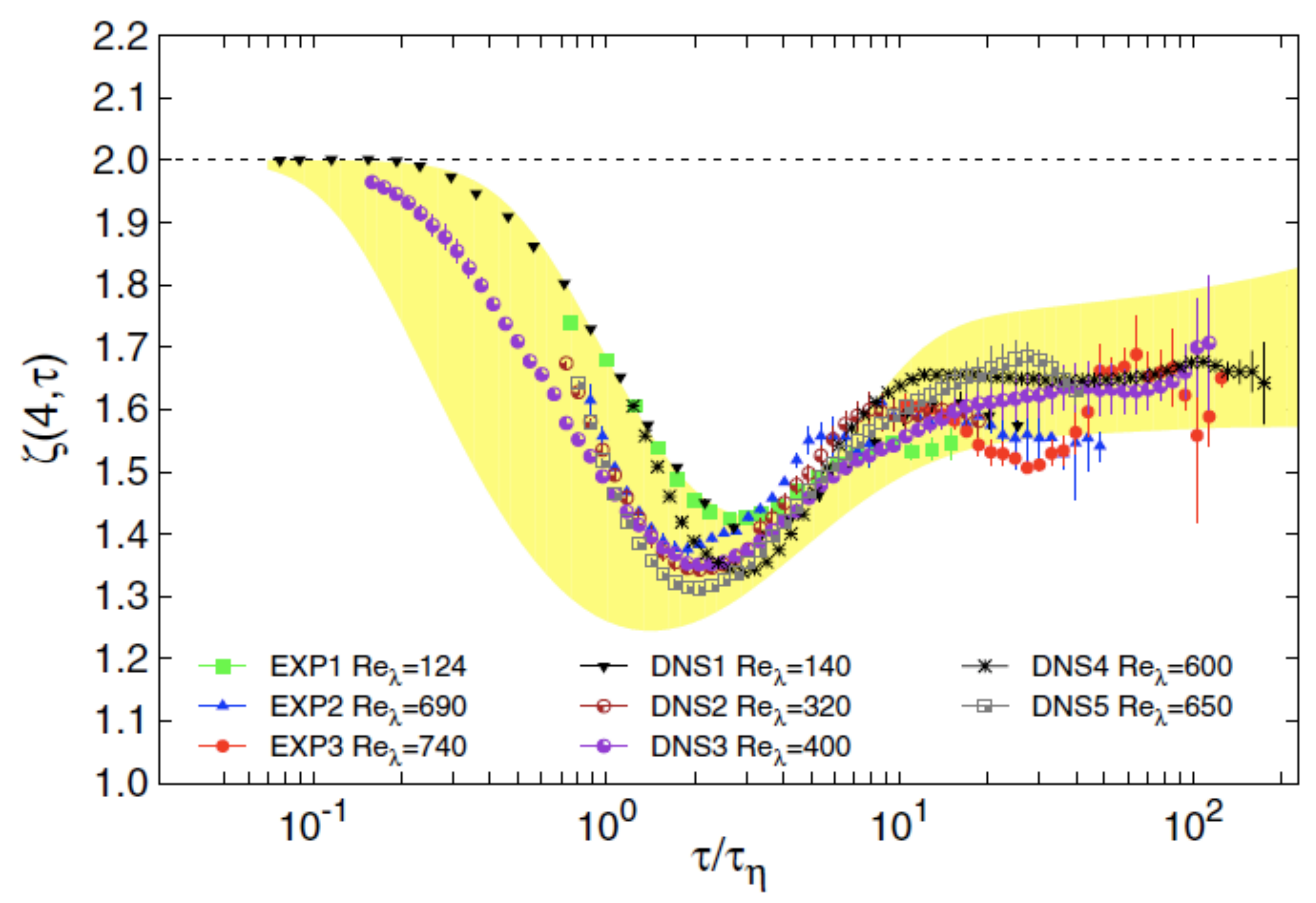
Bands 1, 2, 3, 4: strong

Bands A, B, C, D : weak



Zoom on large enstrophy region

Universal intermittent properties of particle trajectories : Lagrangian intermittency

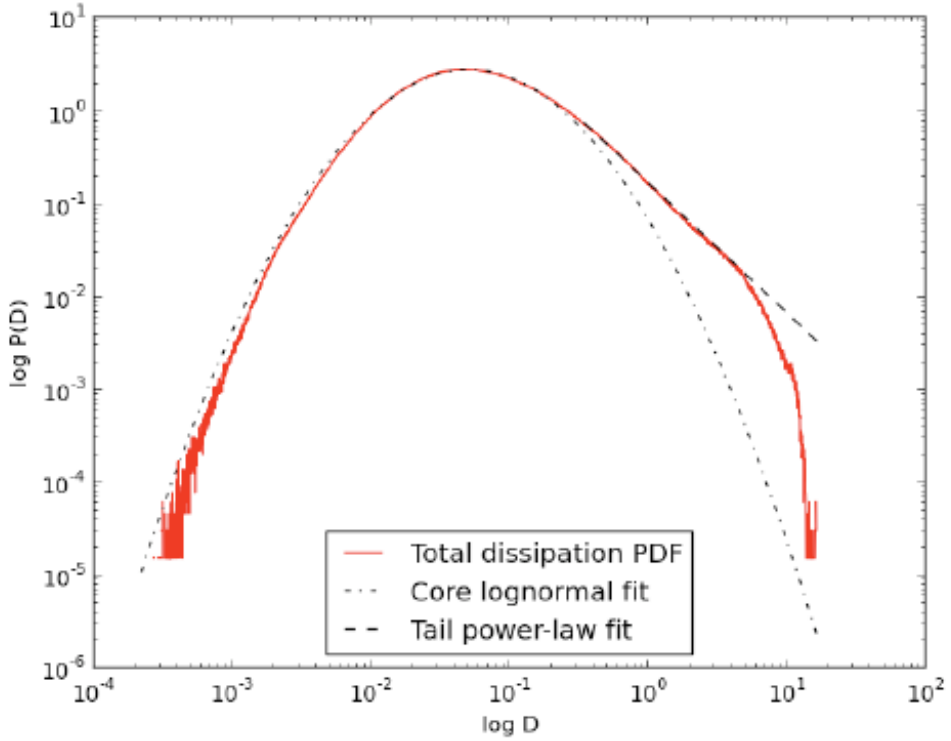


← *Dashed line:*
Non-intermittent value
← *Yellow band:*
Predictions of the Parisi-Frisch multifractal model
Frisch 1995
Méneveau 1996

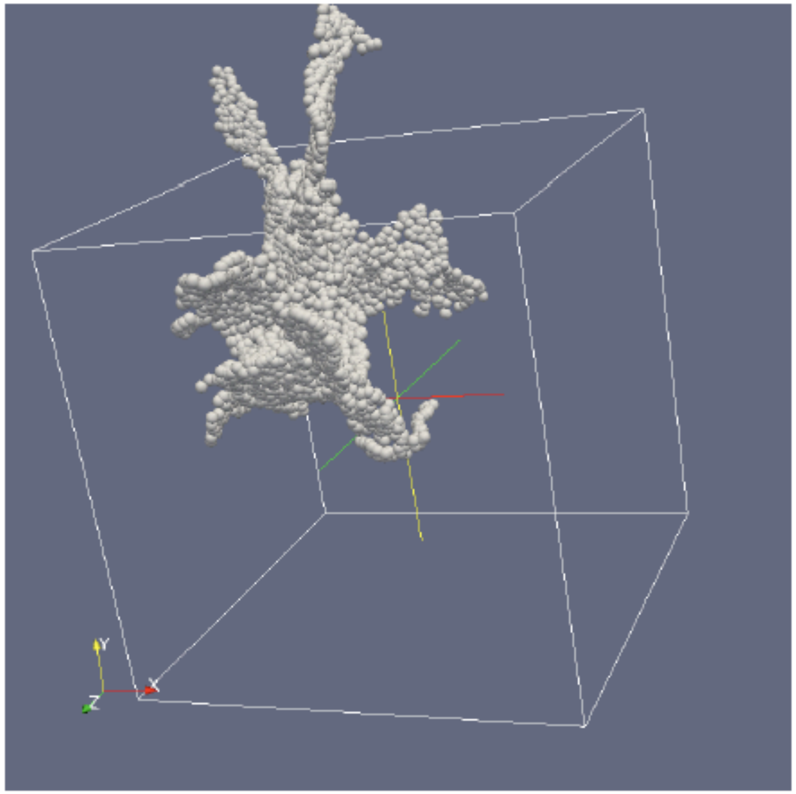
Structure functions of all data sets collapse onto each other over 3 decades of temporal scales
Depth of the dip follows the statistical weight of the vortex filaments

Arneodo et al. 2008

Intermittency of dissipation : ohmic, viscous and ambipolar diffusion



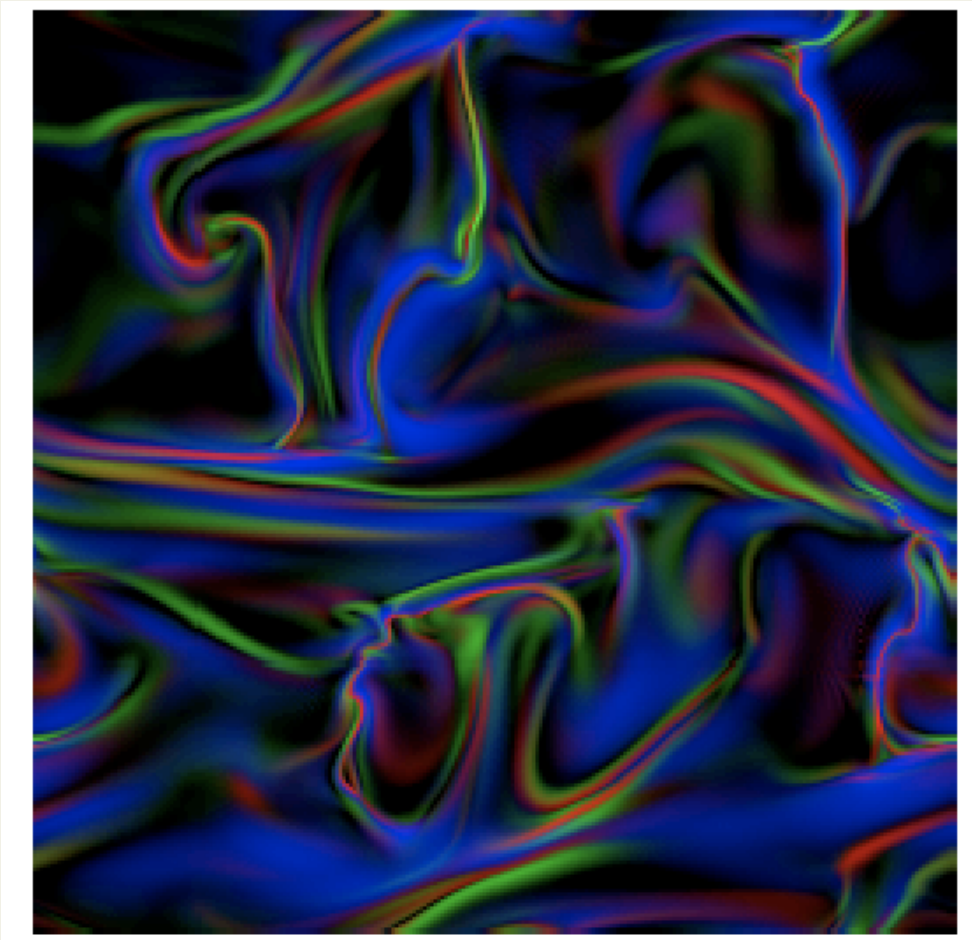
The 10% most dissipative events contribute to 30% of total dissipation



Structure of dissipation rate extremum

Momferratos et al. 2014

Non-ideal incompressible turbulence



Slice 512^3 spectral NS, Momferratos et al 2014

Ohmic dissipation:

$D_{ohm} = \eta\, j^2$

Viscous dissipation:

$D_{visc} = \nu\omega^2$

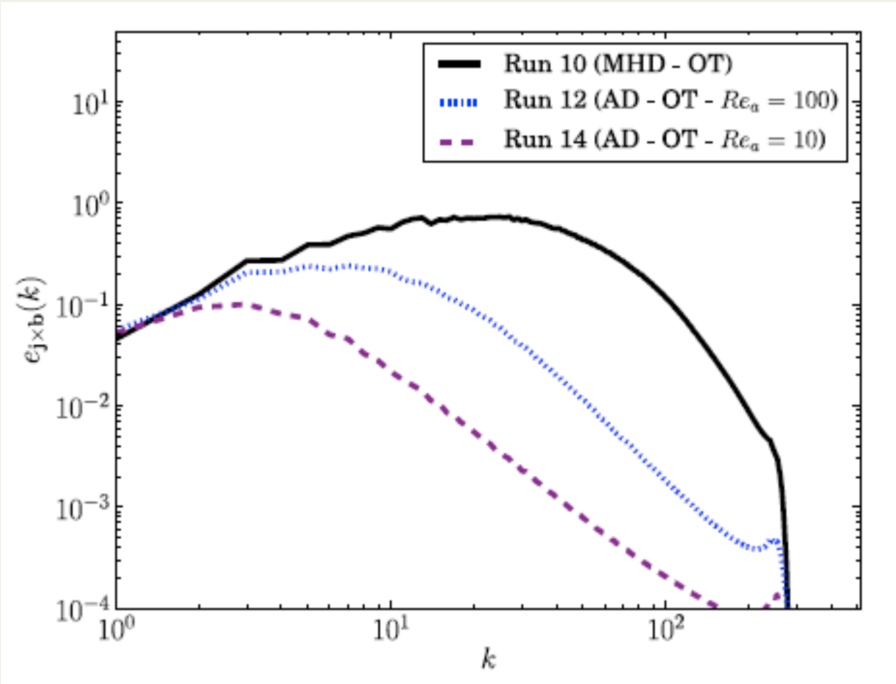
Dissipation by ion-neutral drift (ambipolar diffusion):

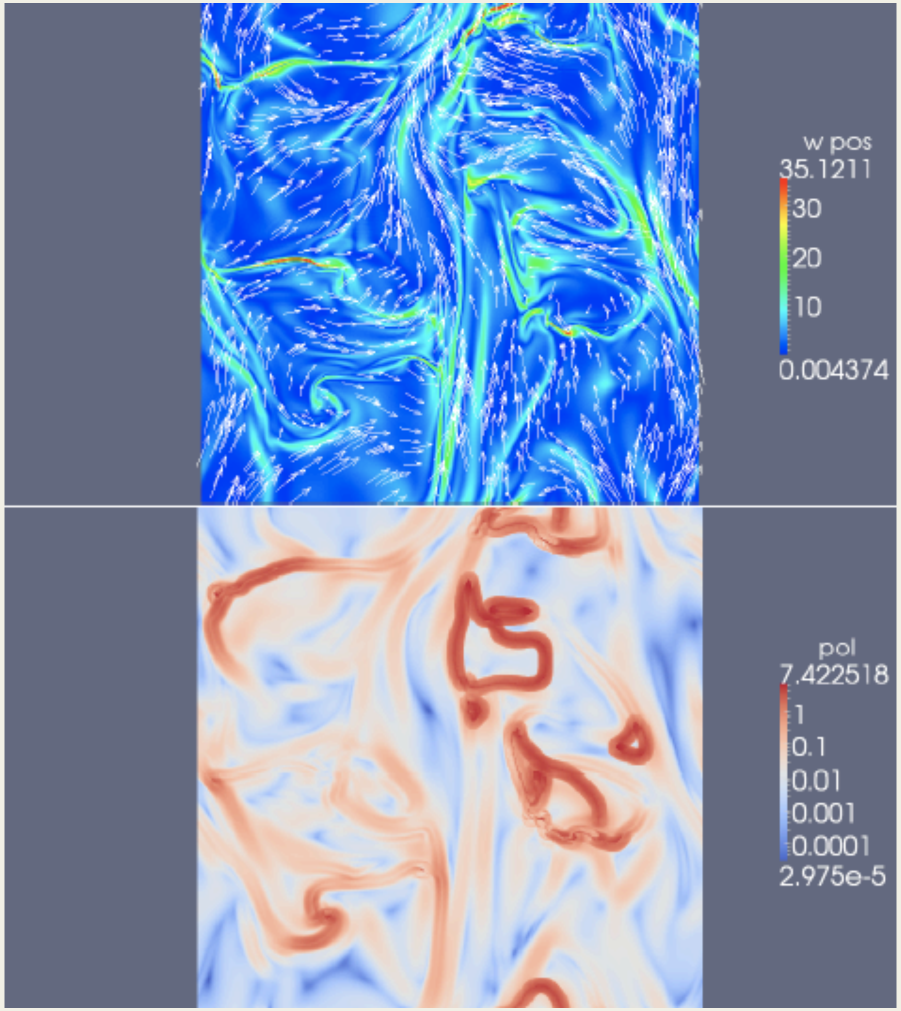
$D_{AD} = \alpha(j\times B)^2$

Comparison with observables

Vorticity POS projection and B_{POS}

Energy spectra: j x B



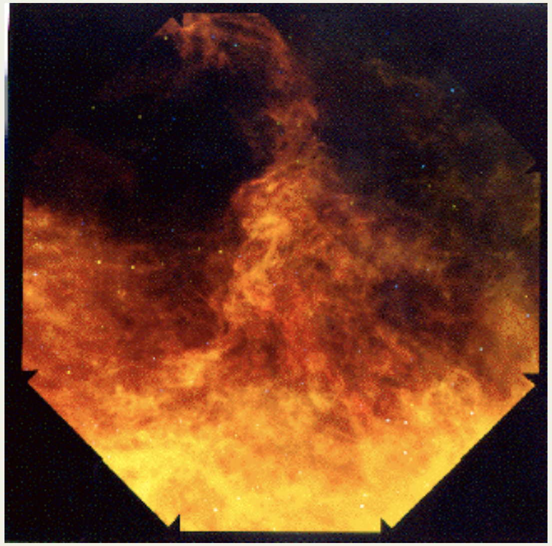


➪ AD producing force-free field at small scales

Increments of polarization orientation

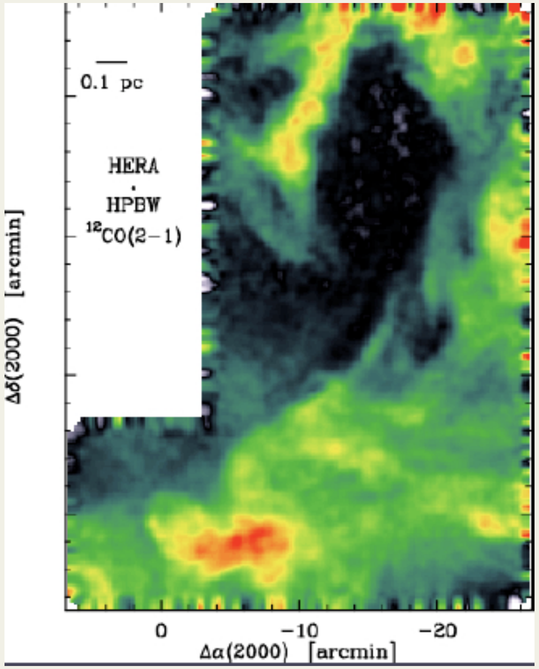
What are the observations telling us?

- Scaling laws
- Turbulent environment of low mass dense cores



100 pc to 0.2 pc

IRAS 100µm



2 pc to 7 mpc,

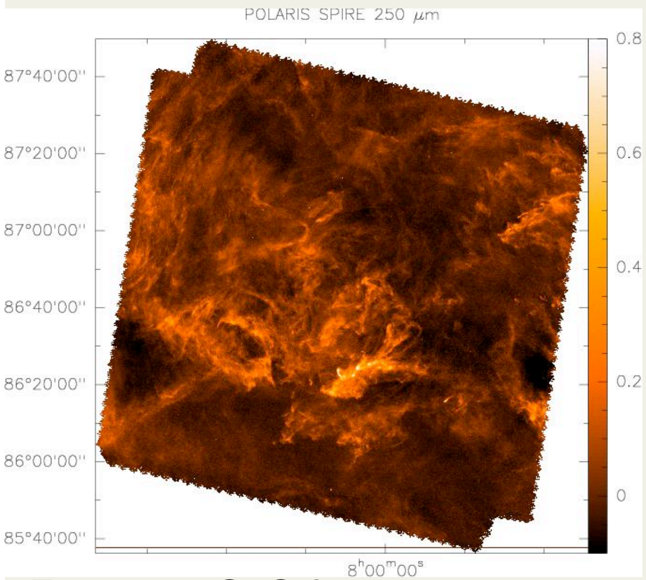
IRAM $^{12}CO(2-1)$ Hily-Blant et al. 2008

Polaris Flare

- highly turbulent,
- only two (prestellar?) dense cores

Heithausen et al. 2002

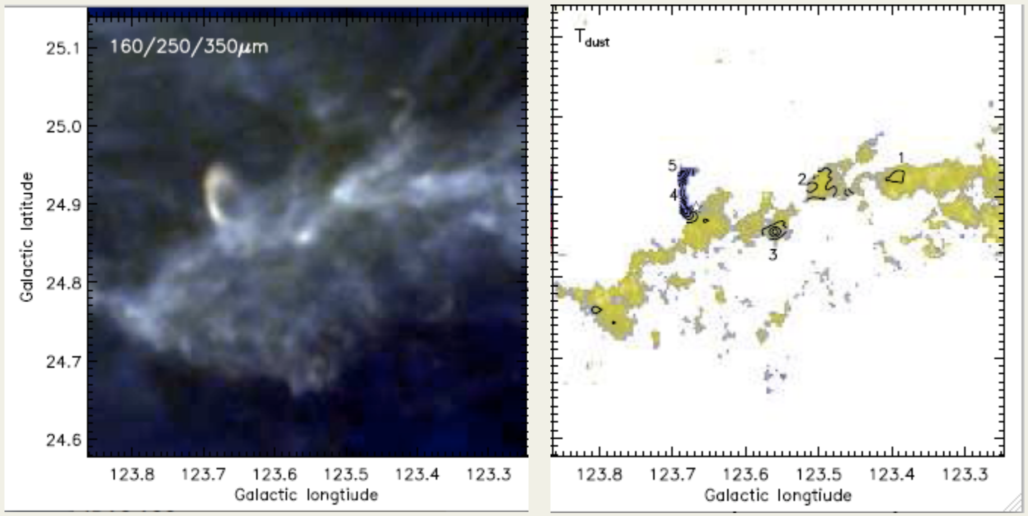
Ideal template to study early phases of star formation



5pc to 0.01 pc

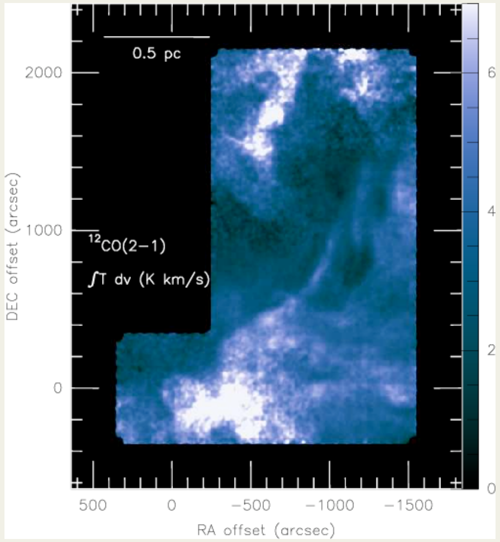
Herschel/SPIRE 250 µm

Men'shchikov et al 2010



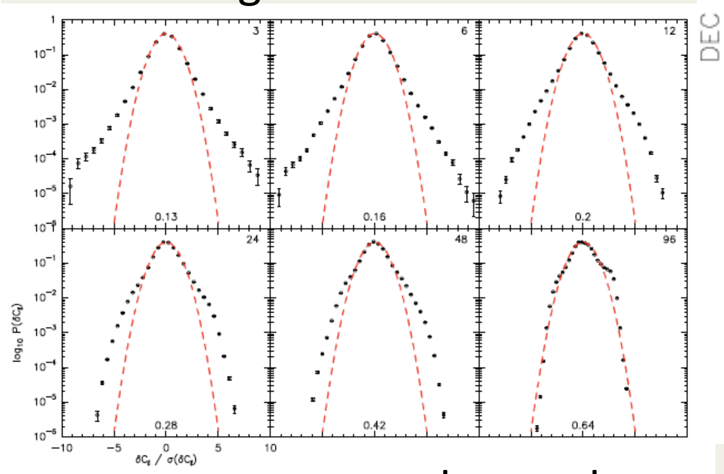
Ward-Thomson et al. 2010

Non-Gaussian statistics of velocity increments

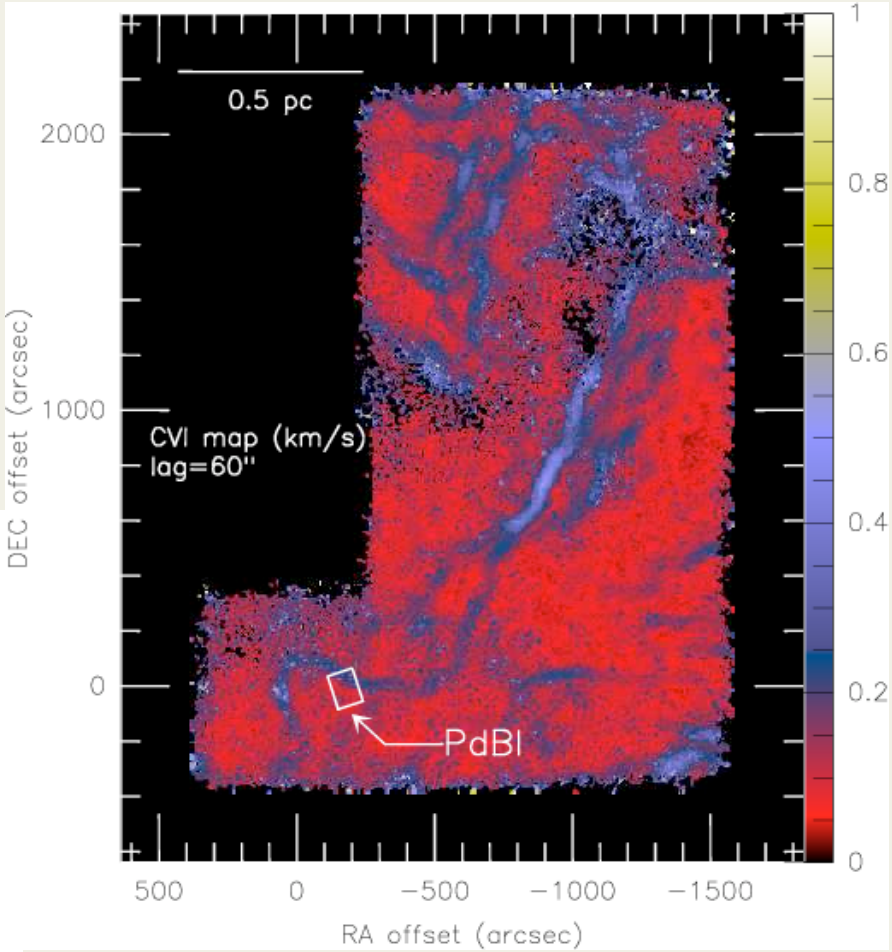


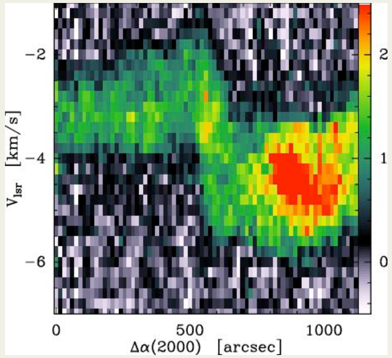
IRAM-30m $^{12}CO(2\text{-}1)$
A few 10^5 independent spectra

smallest lags …



… largest lags



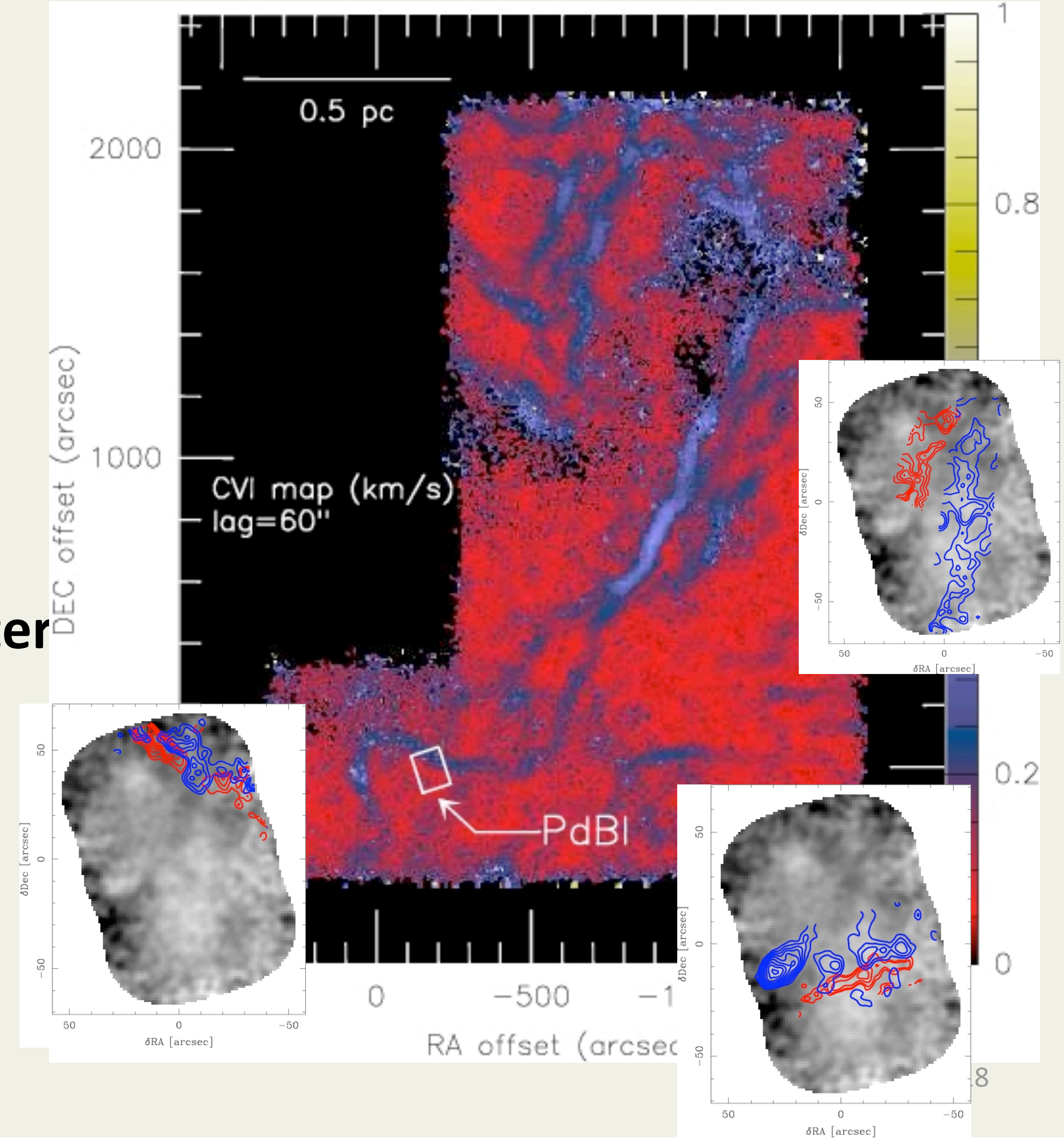


Velocity-shear
40 km s^{-1} pc^{-1}

➯ pc-scale coherent structures of velocity-shear

Velocity-shears at pc- and mpc-scale

- 8 **straight** CO structures 3 to 10 mpc thick
- **sharp edges of layers**
- 6 are parallel pairs at different velocities = **velocity-shears** up to 700 km s^{-1} pc^{-1}
- **large (and similar) scatter of orientations found for mpc- and pc-scale shears**

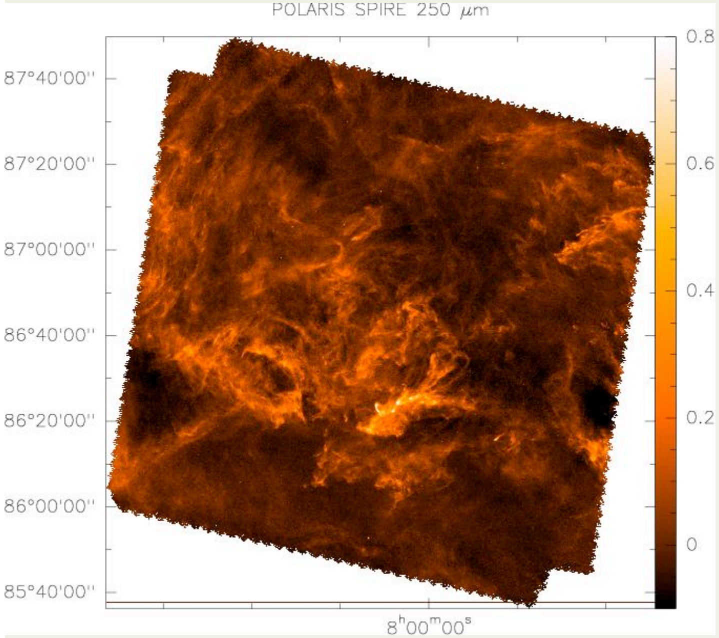


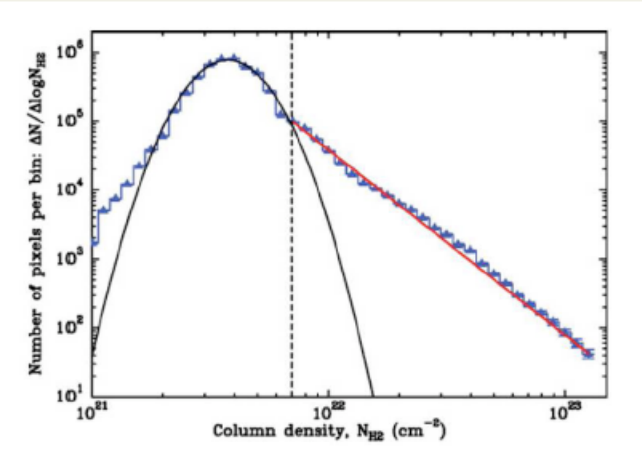
Complex topology

IRAM-PdBI, Falgarone et al. 2009

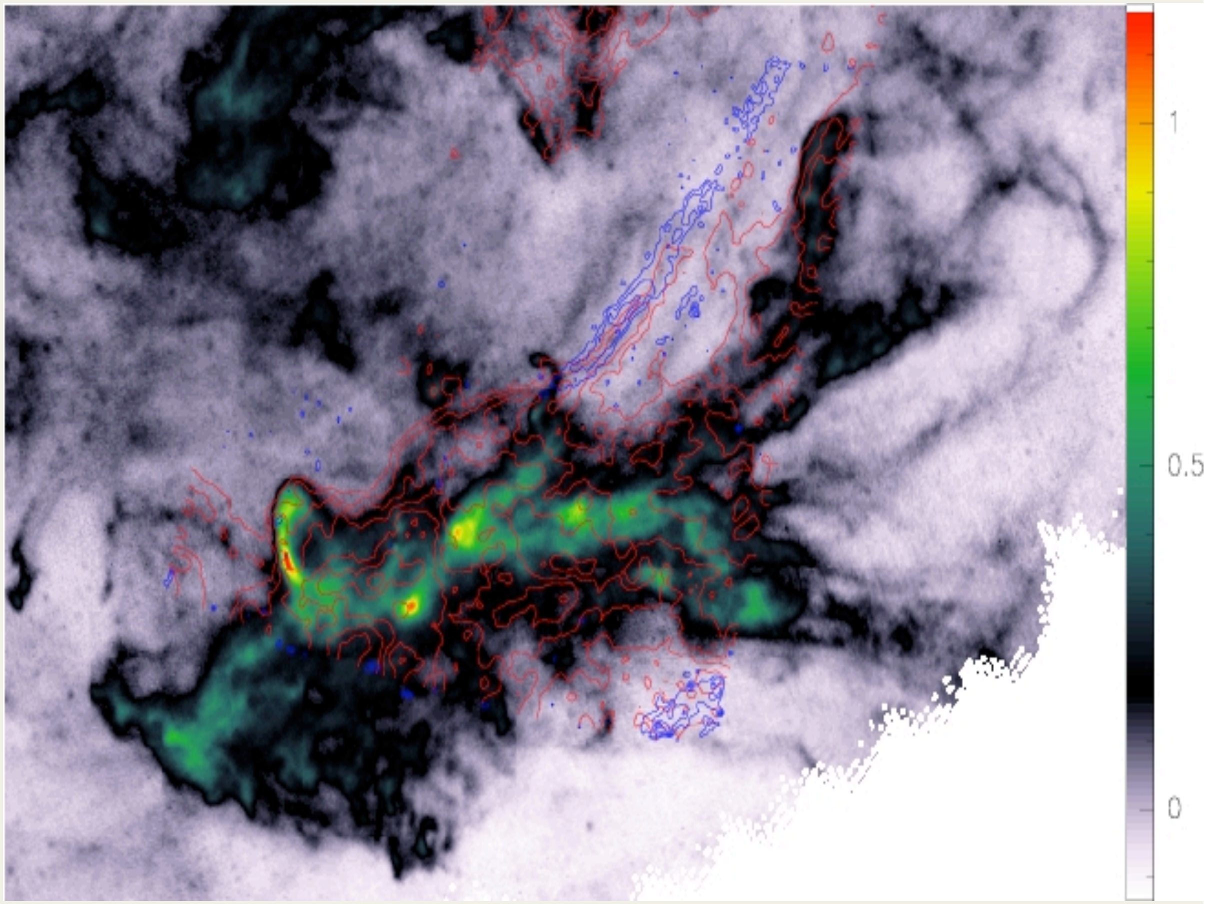
Seeding dense structures ?

dust 250µm, CO(2-1) (red), extreme velocity-shears (blue)





Distribution of N_H of filaments in Aquila Rift André et al 2011



Herschel/SPIRE 250µm map (André et al. 2010)

In summary …

- Truly turbulent gas motions do exist
- Turbulent cascade forward/inverse (velocity, magnetic field)
  - ➪ coupling large/small scales
- Intermittency of turbulent dissipation impacts chemistry, CR acceleration, reconnexion…
- Structure in matter may be seeded in velocity field structure