Turbulence in Interstellar Matter: dissipation signatures? (II)

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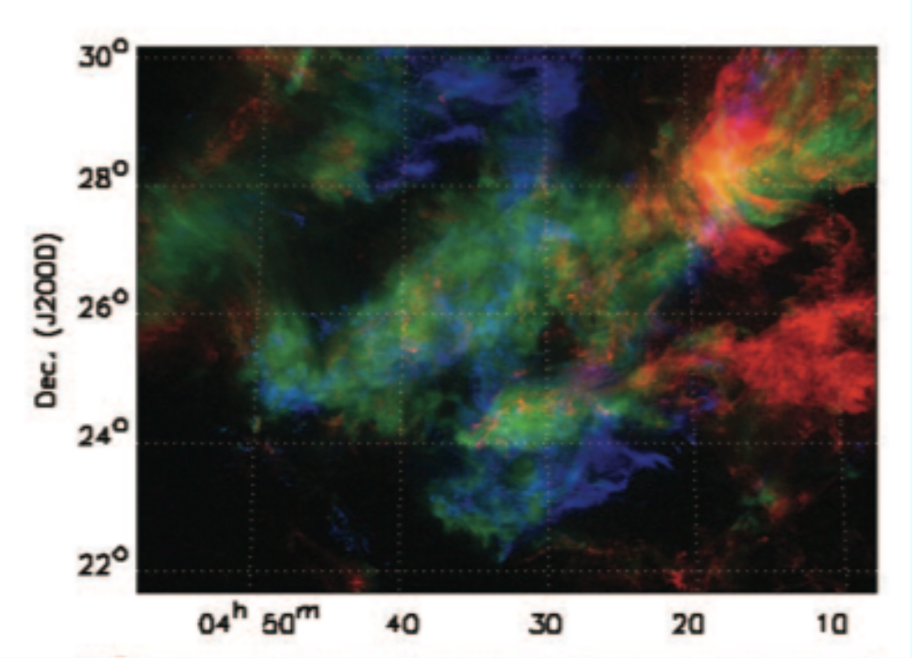
Outline

1 – Molecular lines at high spectral resolution
2 – Coherent structures of vorticity
3 – Dissipation MHD turbulence
  3.1 - Dedicated simulations
  3.2 - Observables
4 – Chemistry driven by turbulent dissipation
5 – Following the energy trail …

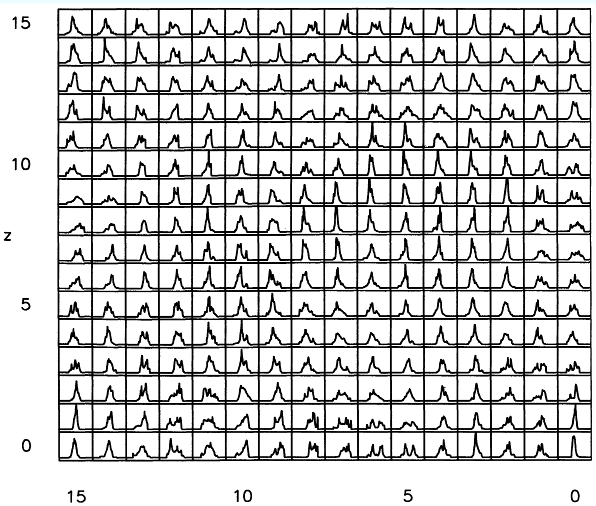


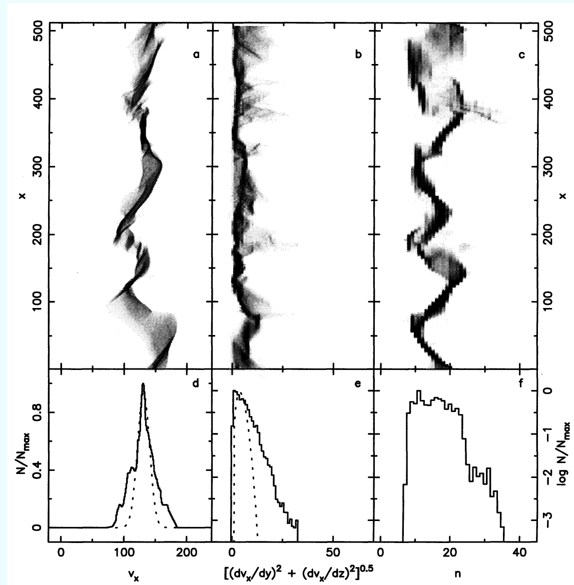
Map of ^{12}CO line centroid velocity
Goldsmith + 08

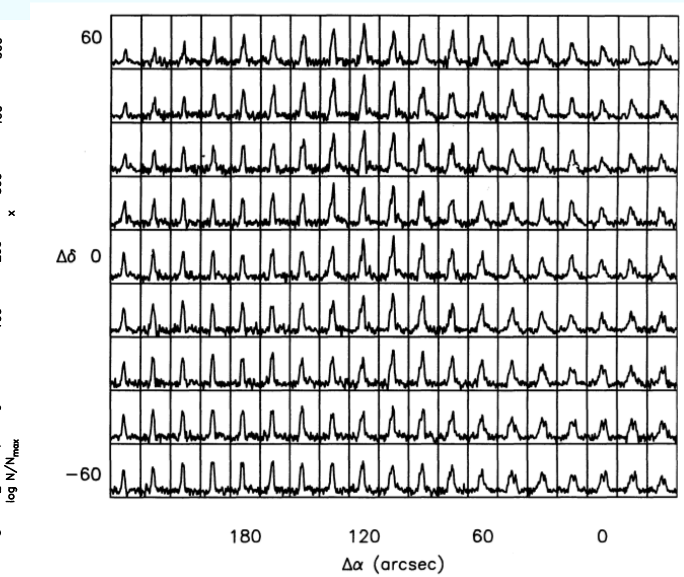
« Advances in Geophysical and Astrophysical Turbulence », IESC, Cargèse, July 2016

I - Molecular line imaging at high spectral resolution

Molecular line imaging at high spectral resolution







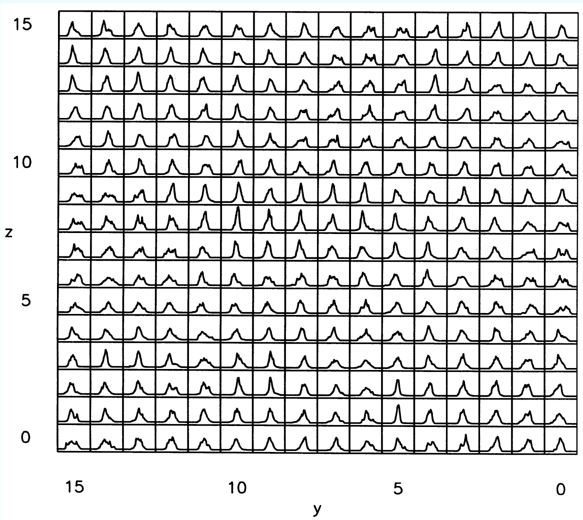
At time = 0.5 L/c_s = acoustic time /2
Just after shock formation

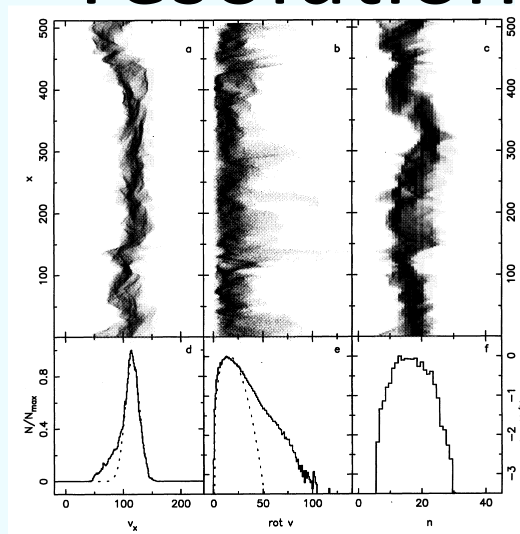
CO line observations

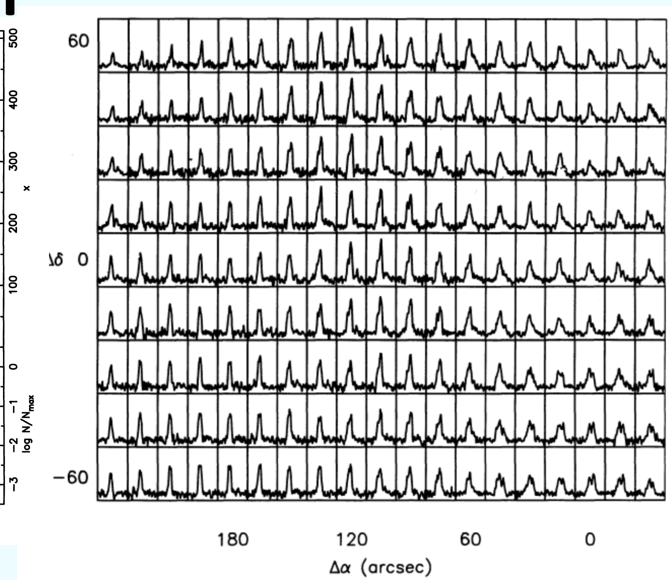
512^3 3-dim decaying turbulence
Weakly compressible rms Mach (t=0)=1.1
PPM method = optimizes treatment singularities

Porter, Pouquet, et al. 1994

Molecular line imaging at high spectral resolution







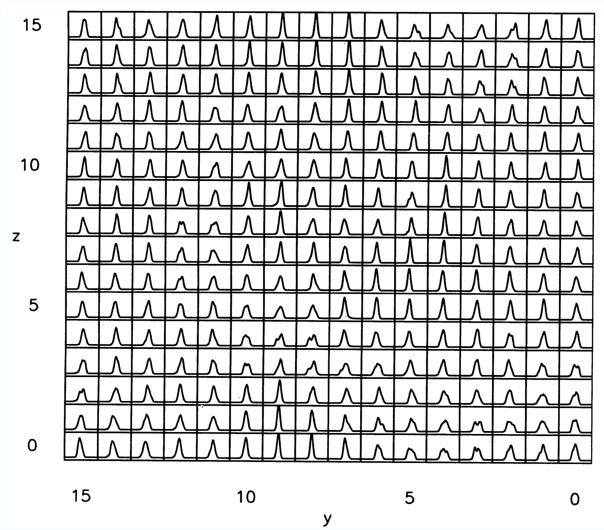
At time = 1.2 L/c_s = 1.2 acoustic time
Solenoidal small-scale modes empowered

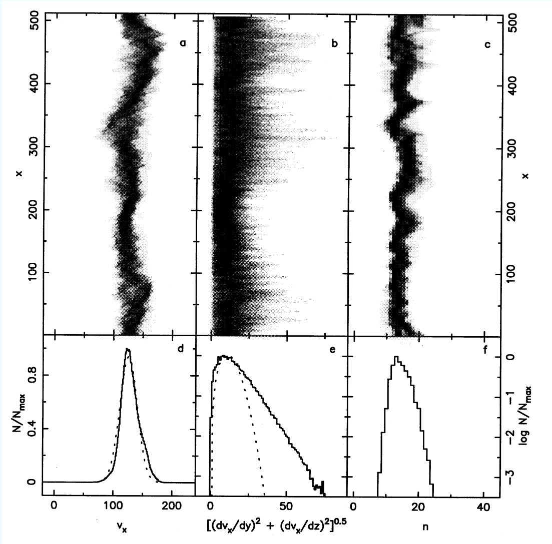
CO line observations

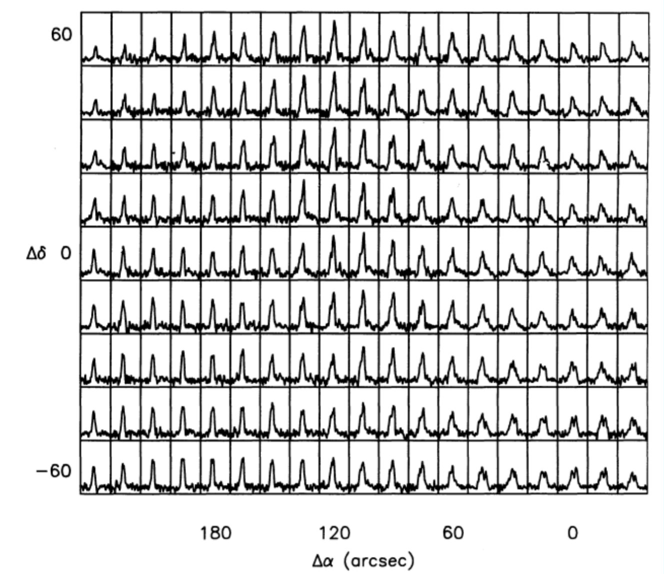
512^3 3-dim decaying turbulence
Weakly compressible rms Mach (t=0)=1.1
PPM method = optimizes treatment singularities

Porter Pouquet et al. 1994

Molecular line imaging at high spectral resolution







At time = 2.4 L/c_s = 2.4 x acoustic time
Largest inertial range
Energy in incompressible modes >> in compressible modes

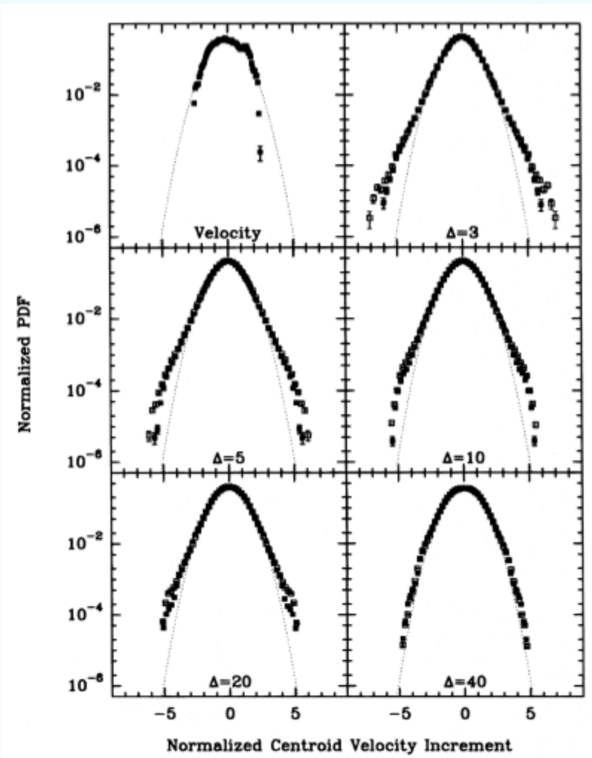
CO line observations

512^3 3-dim decaying turbulence
Weakly compressible rms Mach (t=0)=1.1
PPM method = optimizes treatment singularities

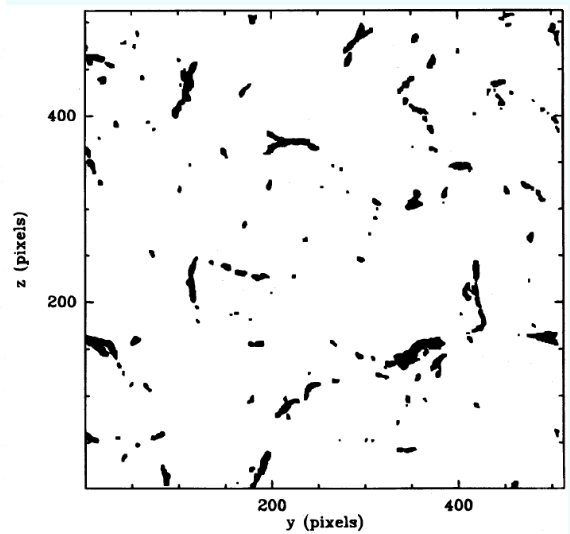
Porter Pouquet et al. 1994

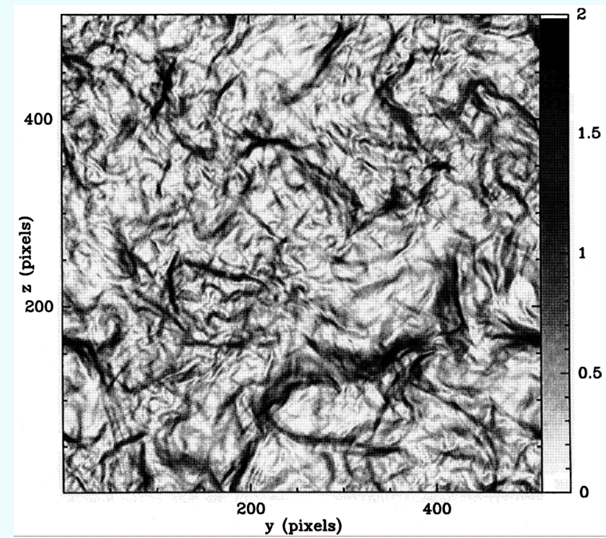
Line Centroid Velocities

PDF of line centroid velocities (CVI) are quasi-Gaussian
PDF of increments of line centroid velocities are non-Gaussian
Departure from Gaussian increases at small lags



$$\langle v_x\rangle(\mathbf{r}+\Delta) - \langle v_x\rangle(\mathbf{r})$$





Spatial distributions of:

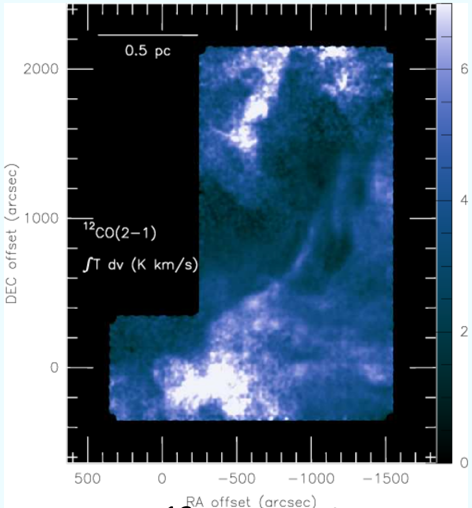
Positions where CVI > 3

$$[\langle(\mathrm{rot}\,\mathbf{v})_y\rangle^2 + \langle(\mathrm{rot}\,\mathbf{v})_z\rangle^2]^{1/2}$$

Lis + 1996

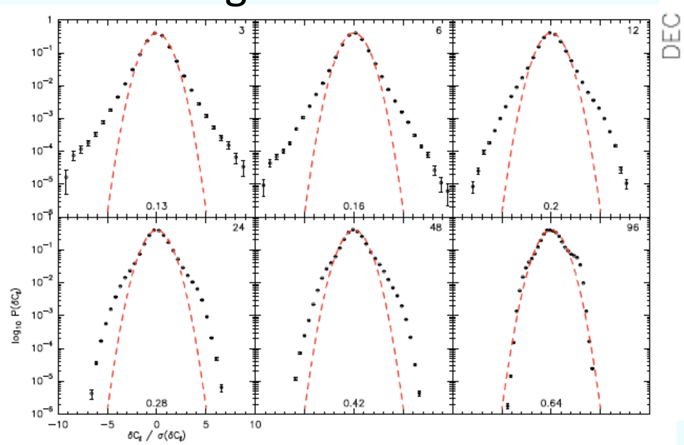
II - Coherent structures of « vorticity » and « current »

Non-Gaussian statistics of velocity increments

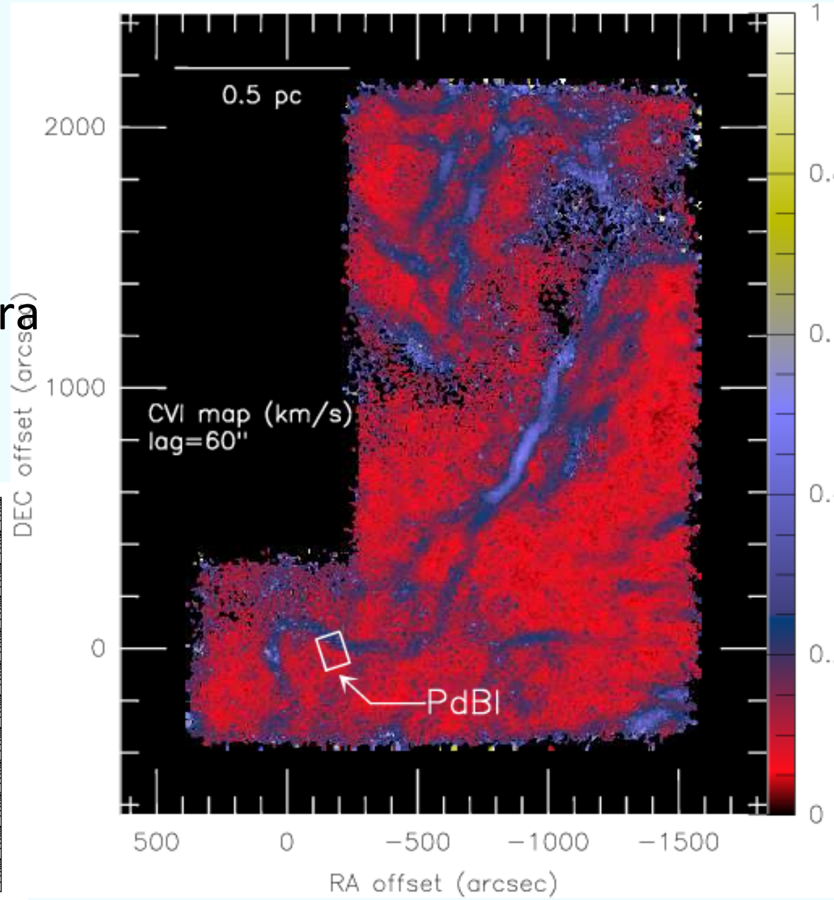


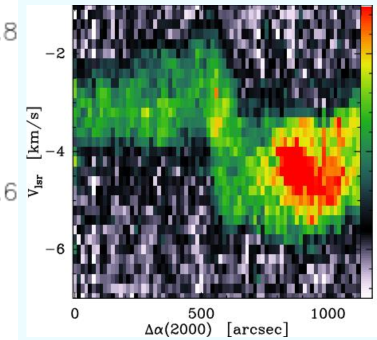
IRAM-30m ^{12}CO(2-1)
A few 10^5 independent spectra

smallest lags …



… largest lags



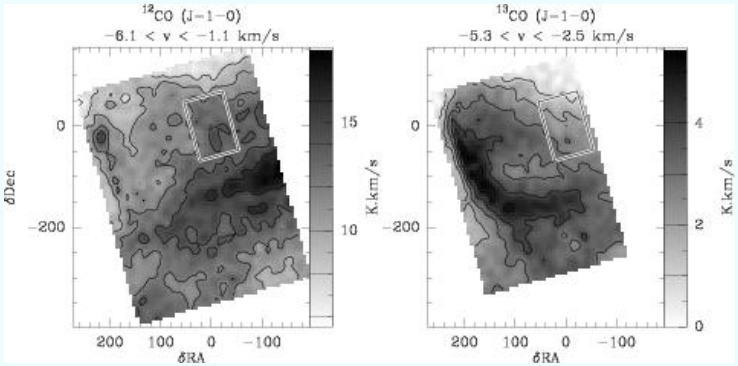


Velocity-shear
40 km s^{-1} pc^{-1}

Hily-Blant + 08, 09

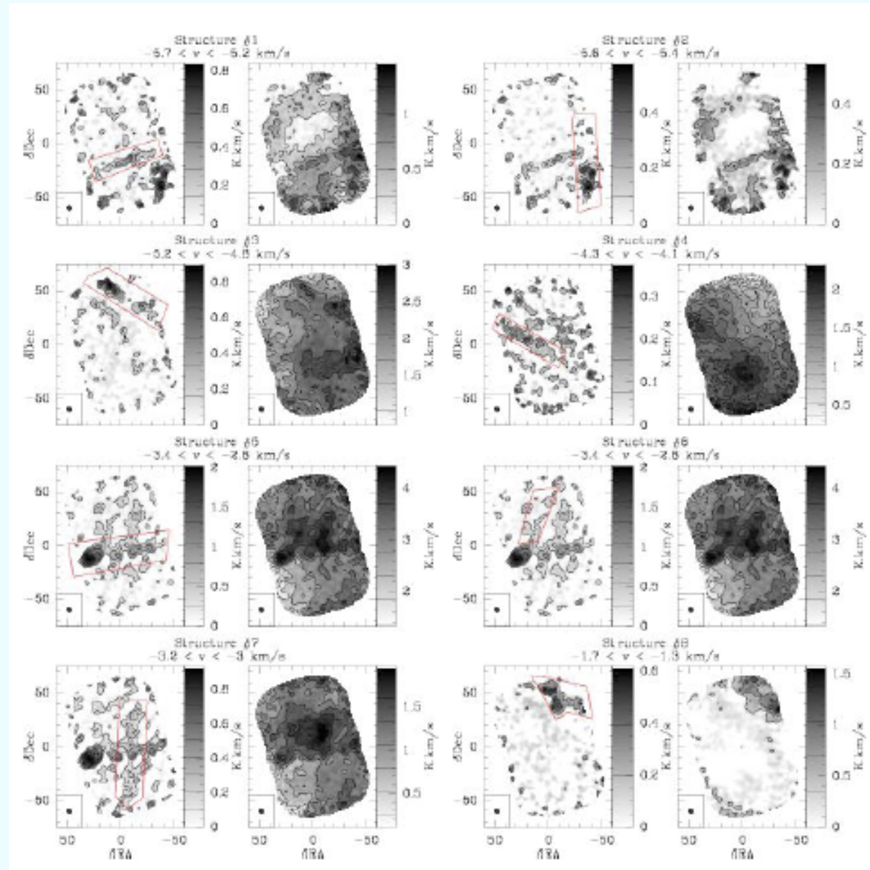
⇨ pc-scale coherent structures of velocity-shear

^{12}CO emission structures ~ 10 mpc thin



Polaris Flare
IRAM-Pdbi mosaic print
(13 fields)

Schedule filling source
More than 200 hours kept
(out of 400 hours observed)



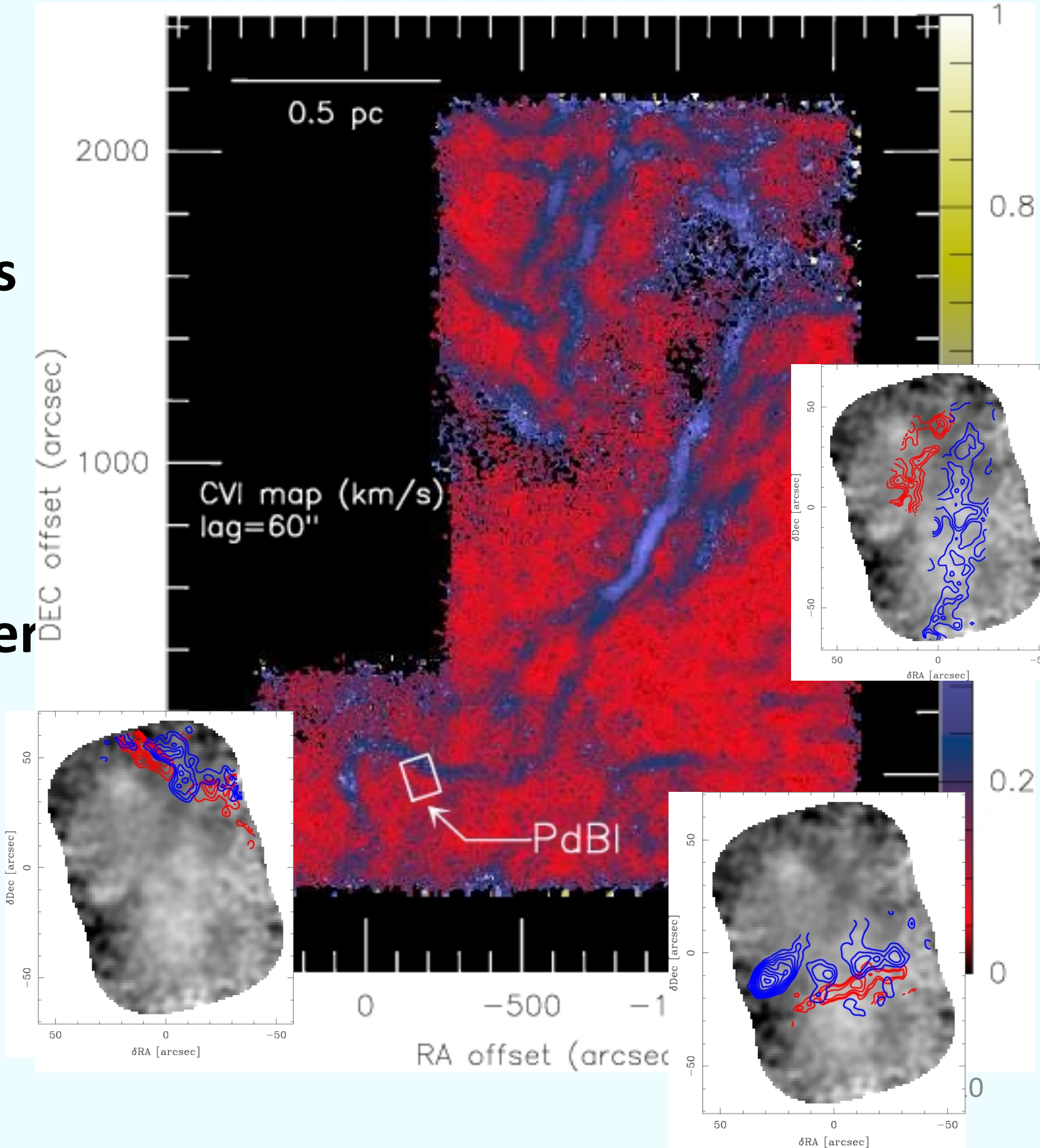
Left: PdBI-only, *Right:* PdBI + IRAM-30m short spacings

Falgarone + 2009

⇨ no cut-off in turbulent power spectrum down to 10mpc

Velocity-shears at pc- and mpc-scale

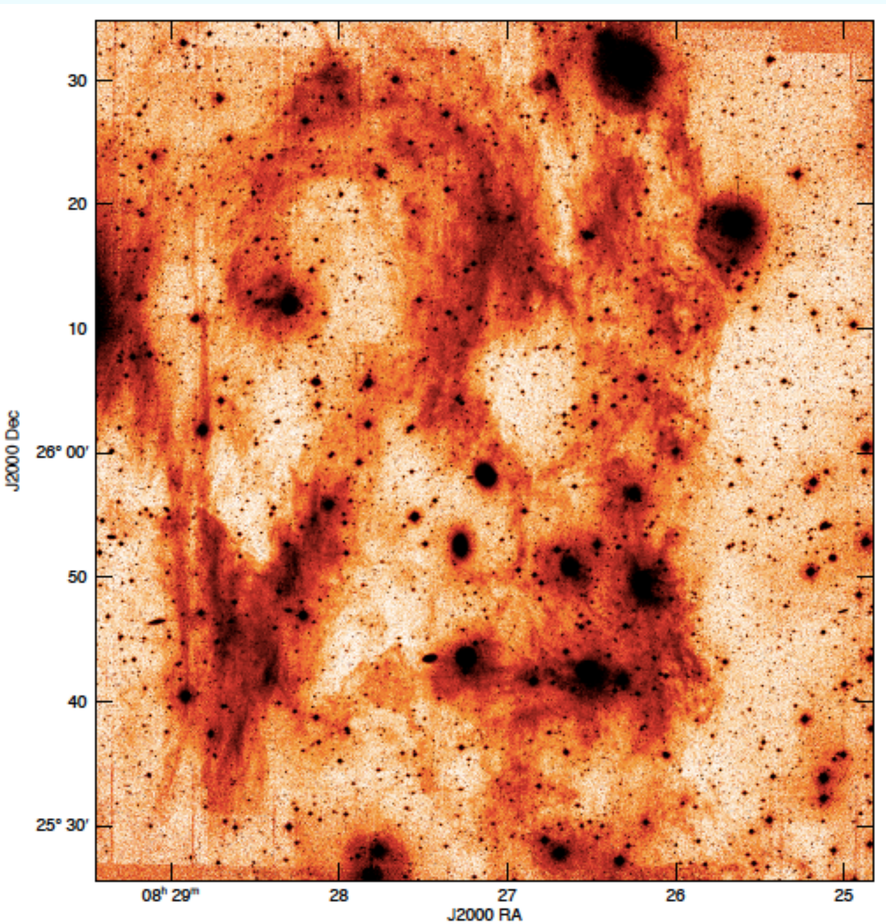
- 8 **straight** CO structures 3 to 10 mpc thick
- **sharp edges of CO layers**
- 6 are parallel pairs at different velocities = **velocity-shears** up to 700 km s^{-1} pc^{-1}
- **large (and similar) scatter of orientations found for mpc- and pc-scale shears**

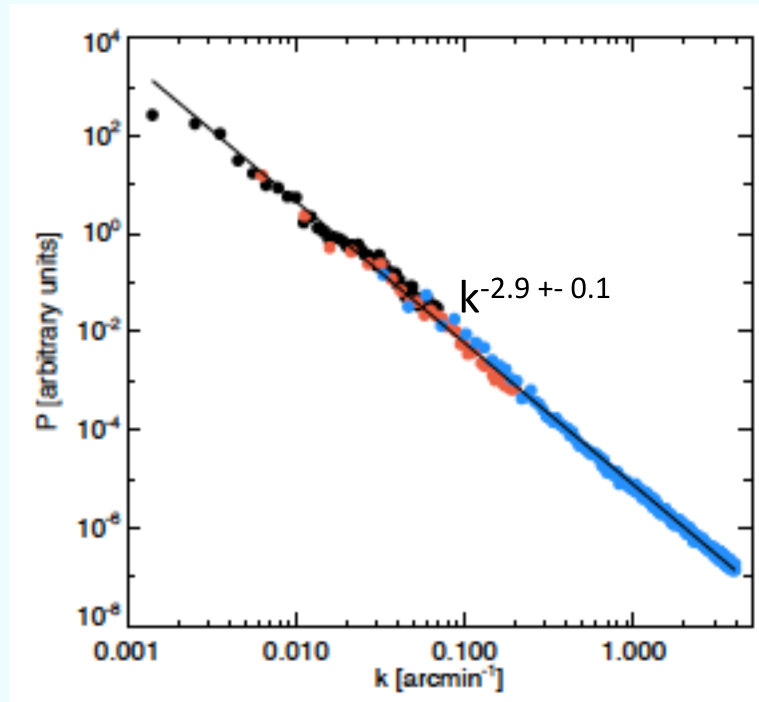


Complex topology

IRAM-PdBI, Falgarone et al. 2009

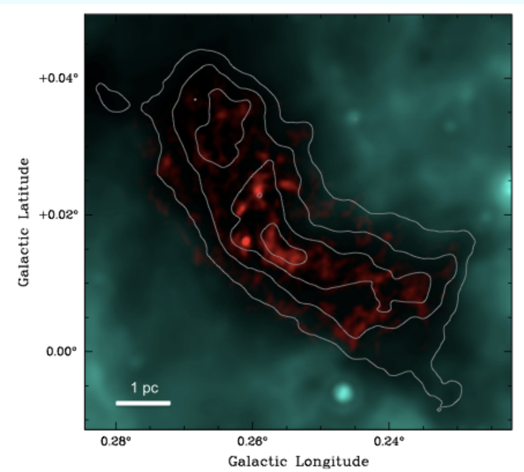
No sign of energy dissipation above 10mpc





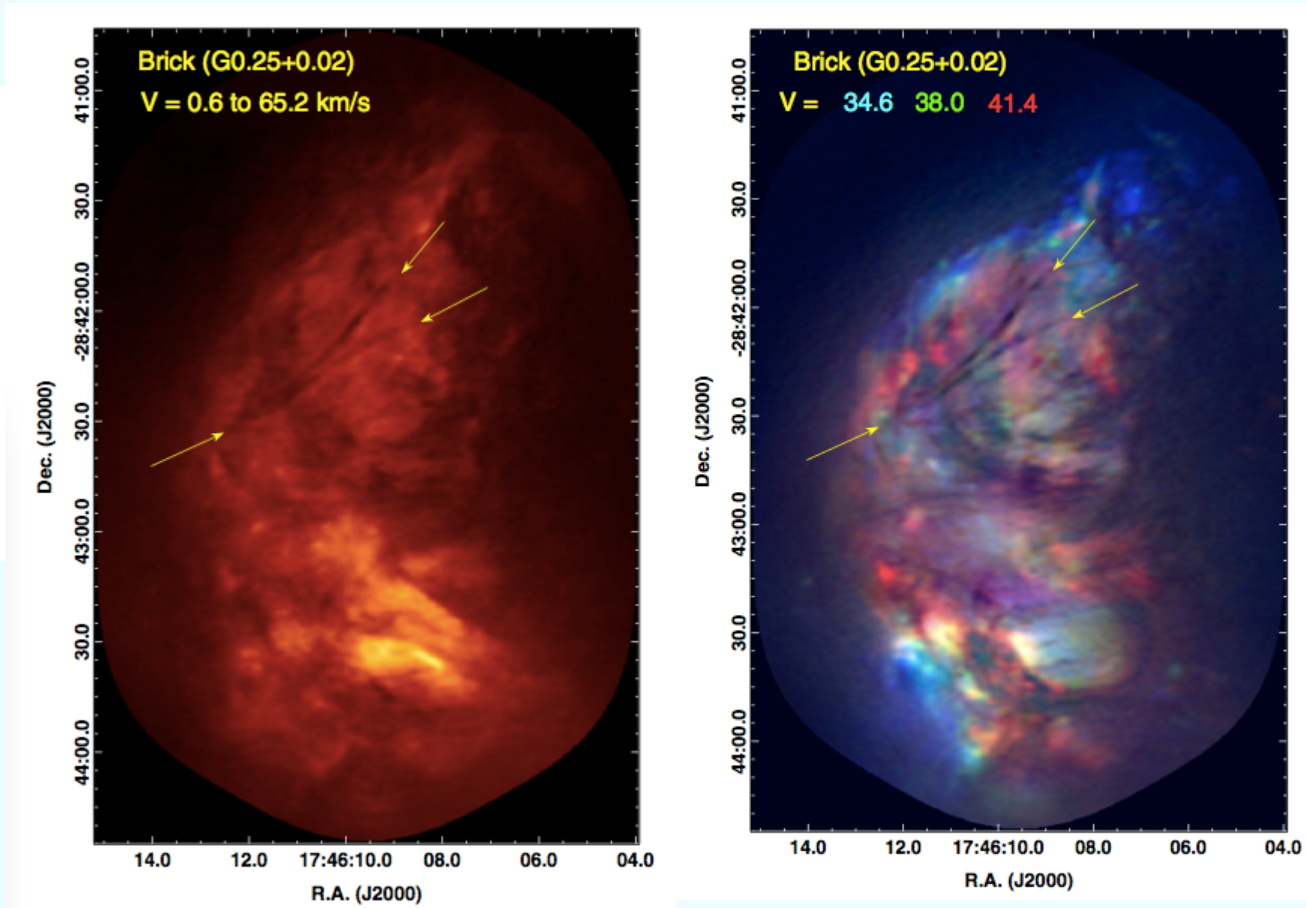
Energy spectrum Planck (black), WISE (red), Visible (blue)
Miville-Deschênes + 16

Broad HCO^+(1-0) absorption: 0.1 pc



IRDC dust:
24 mic Spitzer (green)
3mm ALMA (red)
450 mic JCMT (contours)

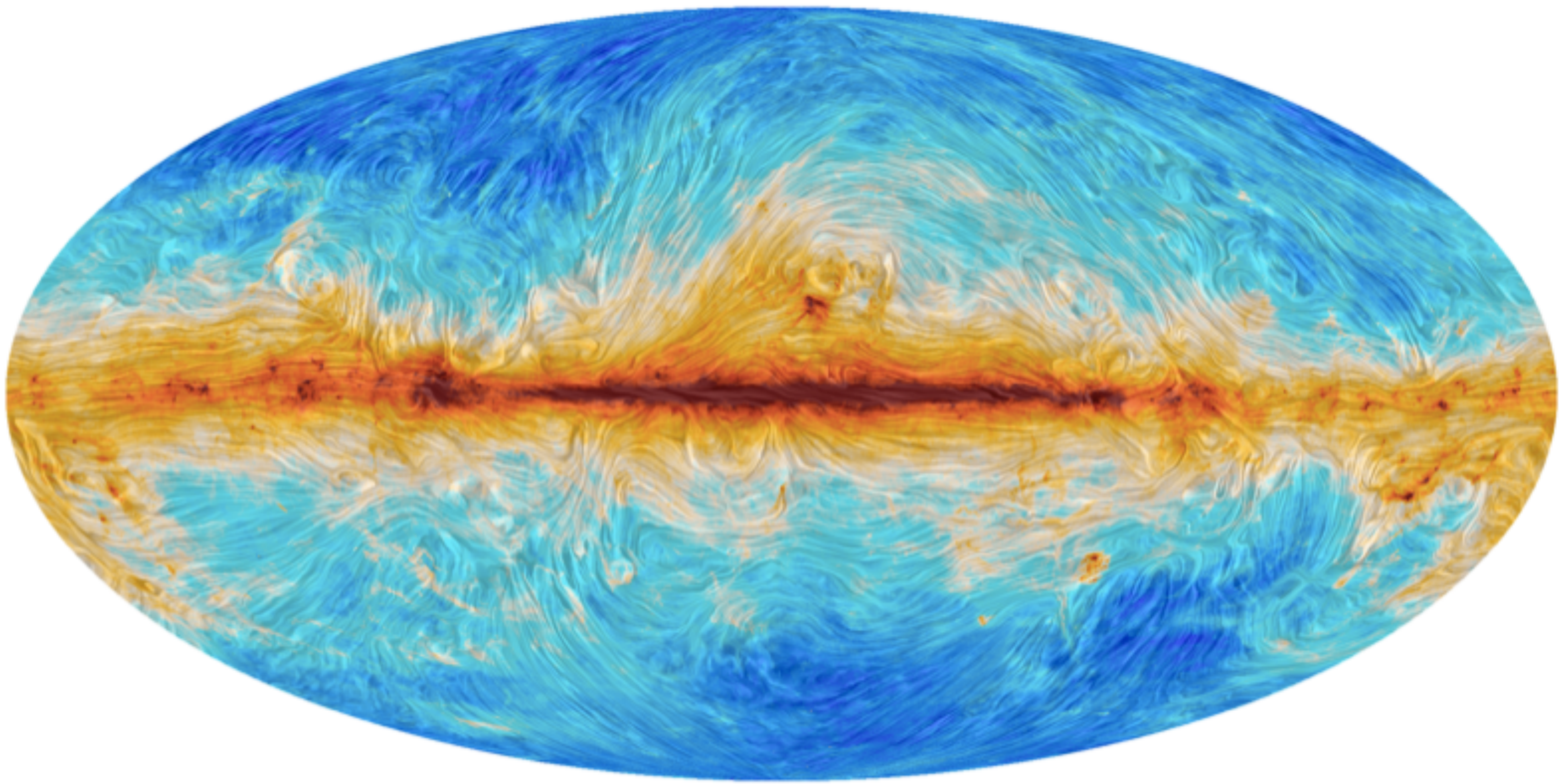
Rathborne + 2015



Bally + 2014

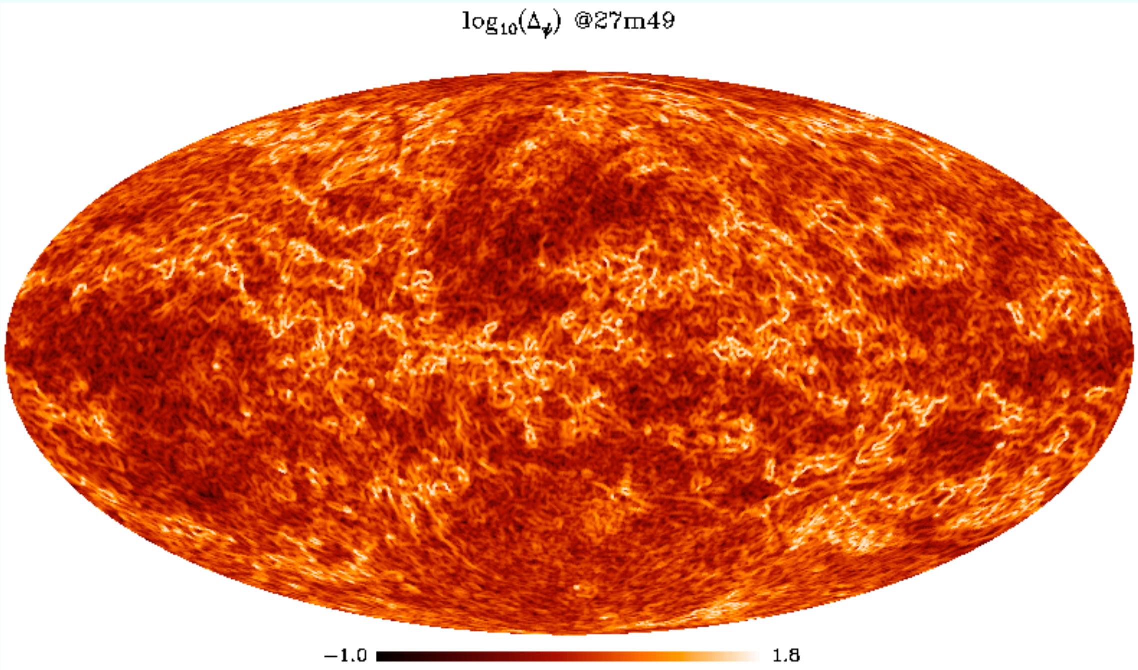
Broad HCO^+ absorption filaments:
Thickness 0.07-0.14 pc
Length 1.2-1.8 pc
Velocity dispersion 20 km/s

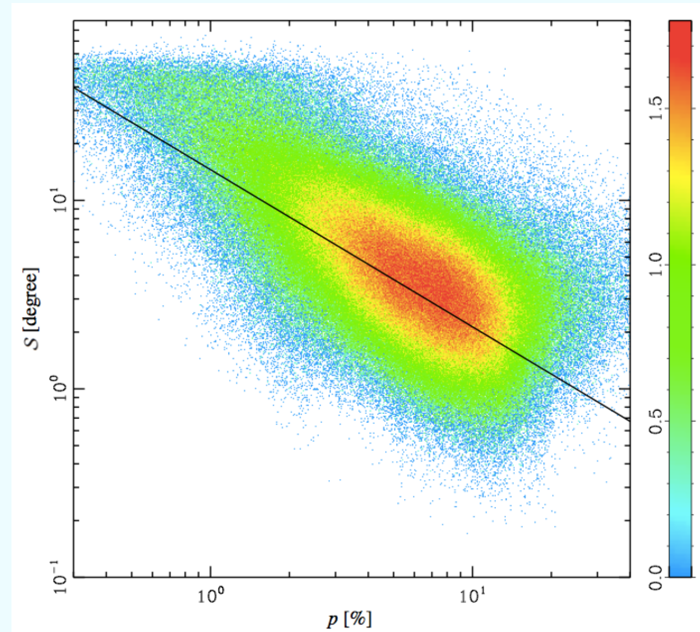
Planck all sky 353 GHz



Color scale : 353 GHz intensity
Drapery : B field POS projection

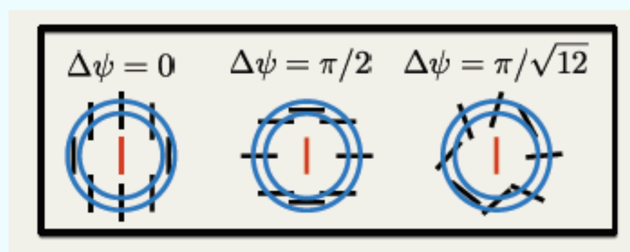
Polarization angle dispersion function





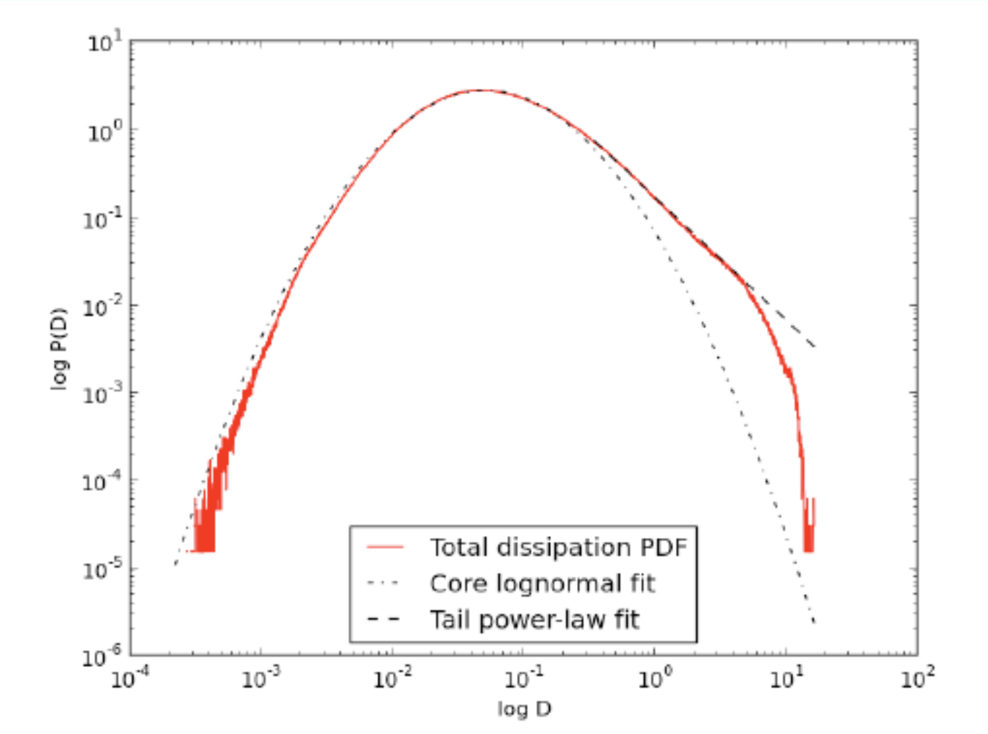
p = polarization fraction

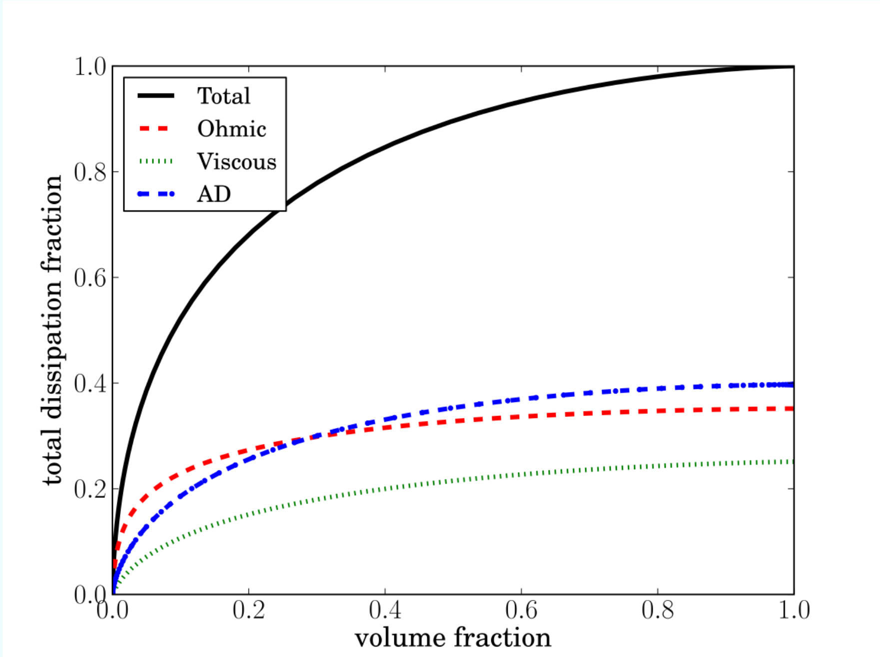
$$\Delta\psi^2(l) = \frac{1}{N}\sum_{i=1}^{N}\left[\psi\left(\mathbf{r}\right) - \psi\left(\mathbf{r}+\mathbf{l}_i\right)\right]^2$$



III – Simulations of non-ideal MHD turbulence dedicated to dissipation

Non-ideal incompressible MHD turbulence





➮ Half of the total dissipation is concentrated in 10% of the volume

➮ Ohmic, AD and viscous have comparable contributions to total dissipation

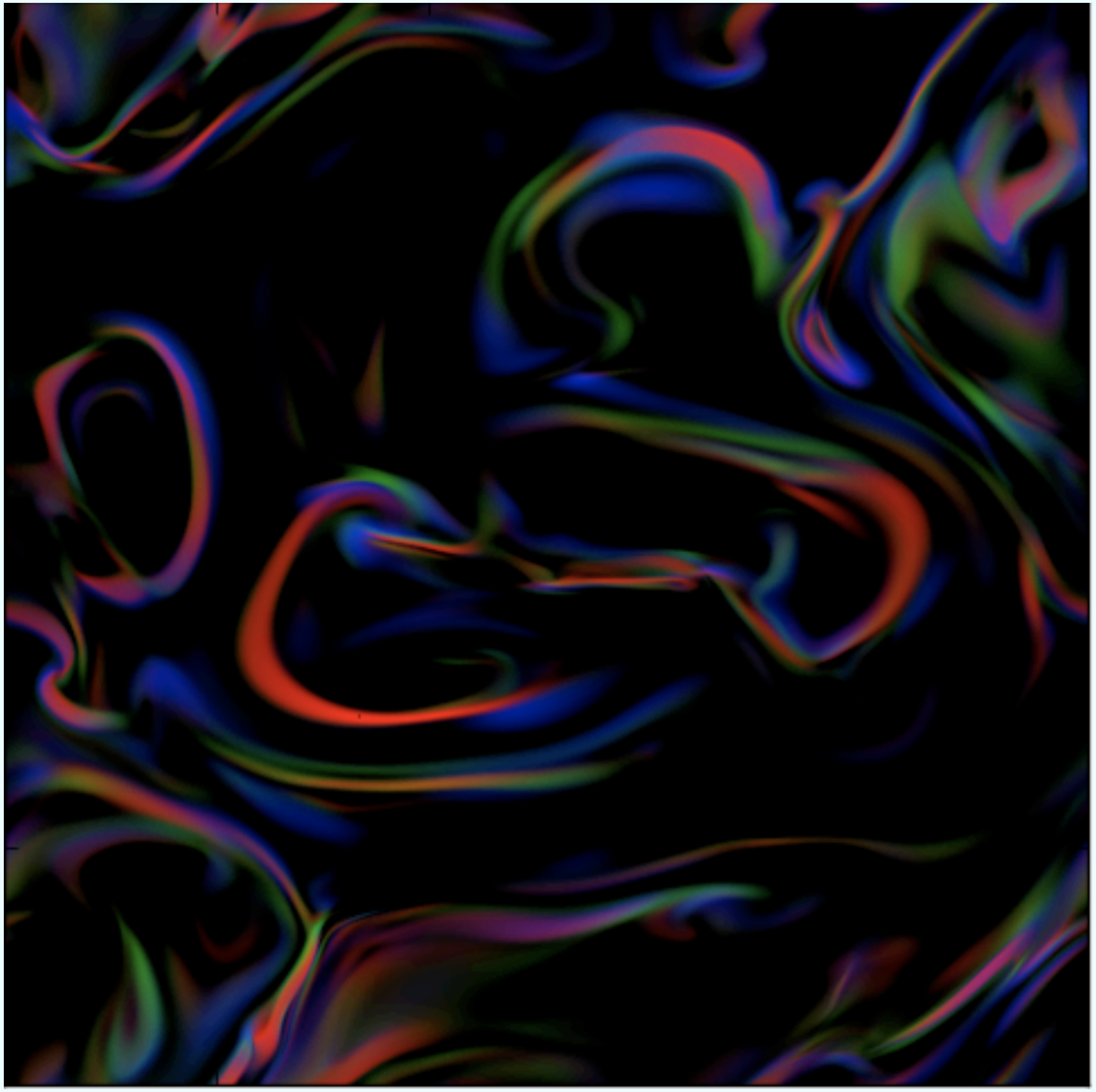
Ohmic dissipation: $D_{ohm} = \eta\, j^2$, $j = \mathrm{curl}\, B$

Viscous dissipation: $D_{visc} = \nu \omega^2$

Dissipation by ion-neutral friction (AD):

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

512^3 Spectral NS, decaying, different initial conditions Momferratos et al. 2014



Slice

Extrema of dissipation

Ohmic dissipation:

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

Viscous dissipation:

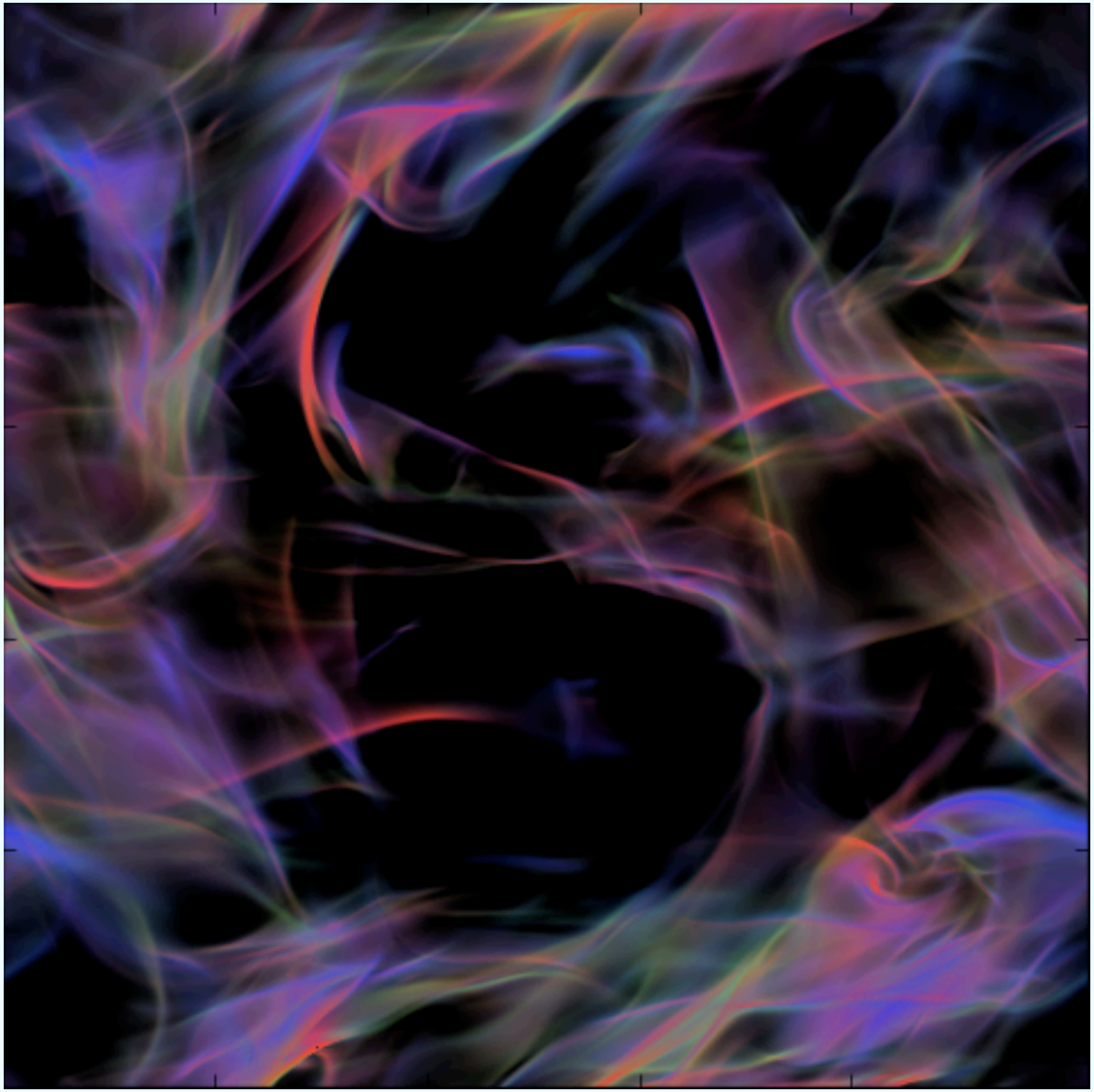
$D_{visc} = \nu\omega^2$

Dissipation by ion-neutral friction:

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

- ➪ AD produces force-free field at small scales
- ➪ AD dissipation regions larger

Extrema of dissipation



Full box

Ohmic dissipation:

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

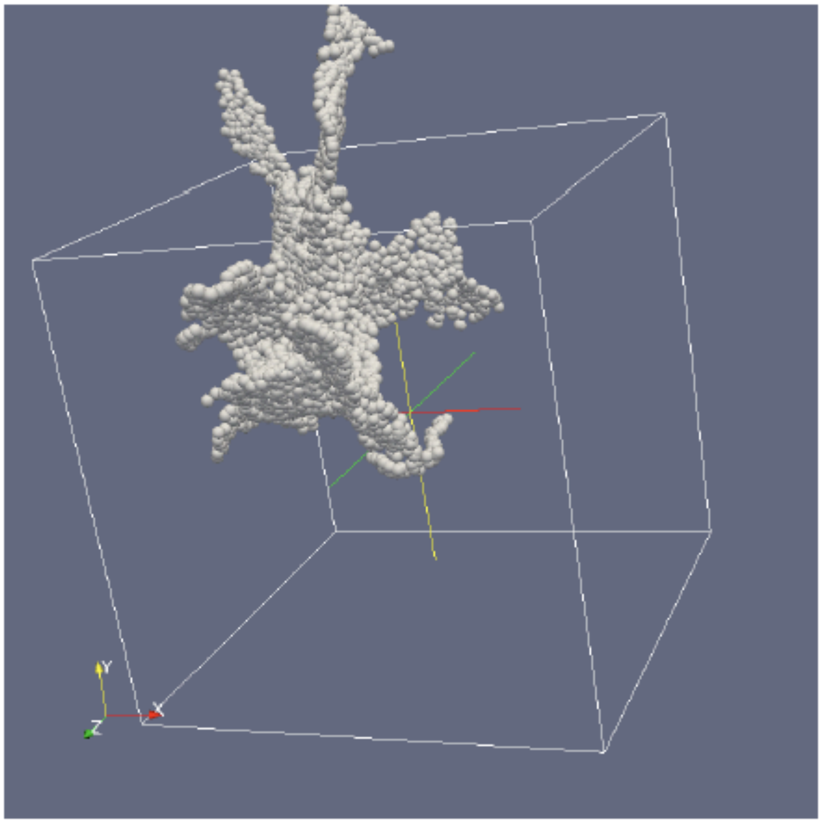
Viscous dissipation:

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

Dissipation by
 ion-neutral friction:

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

Extraction of structures of dissipation rate extremum



Momferratos et al. 2014

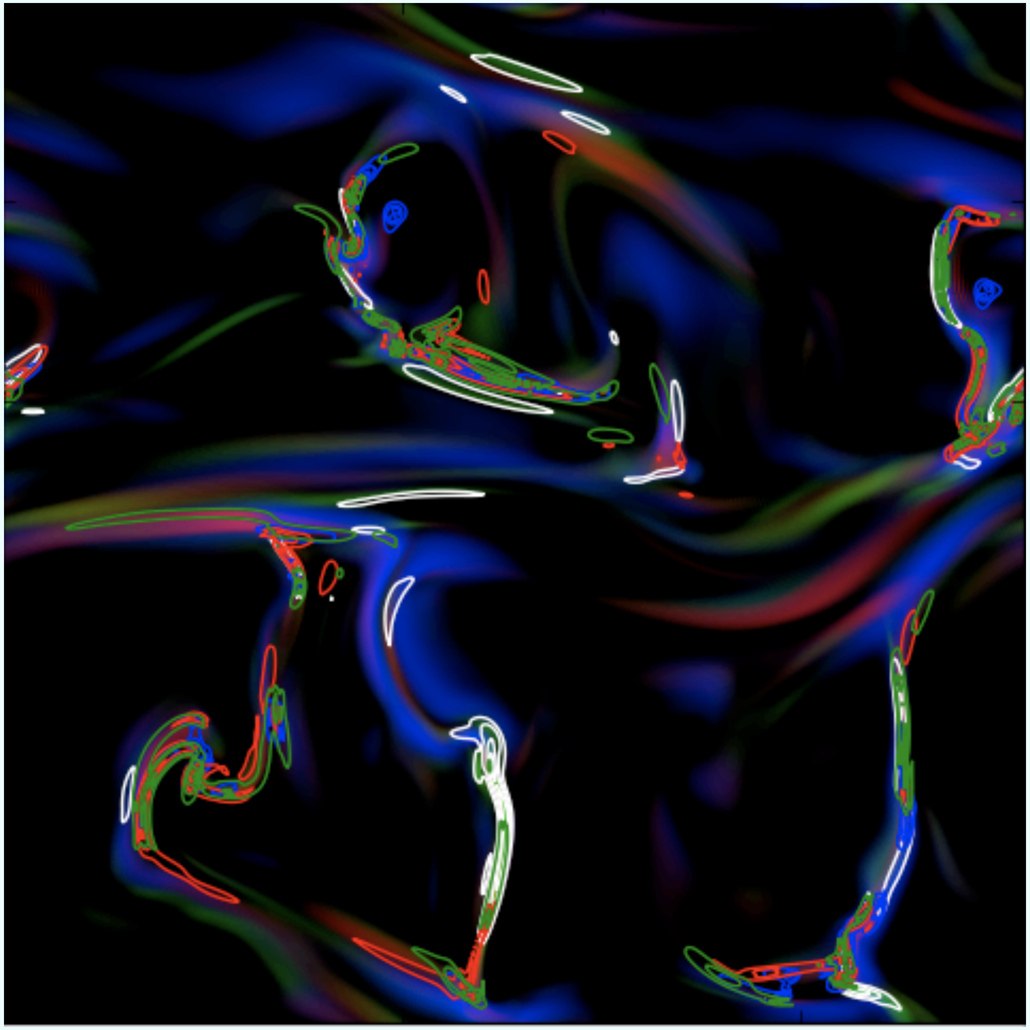
Connected sets of points with total dissipation rate 3σ above mean value

Fractal dimension $X_i \propto L_i^{D_X}$

Scaling of the probability distribution functions

$$\mathcal{P}(X_i) \propto X_i^{-\tau_X}$$

➪ sheet like geometry



$L_{box}/64$

Comparison to observables

- Dissipation rates

Ohmique Viscous AD

- Observables

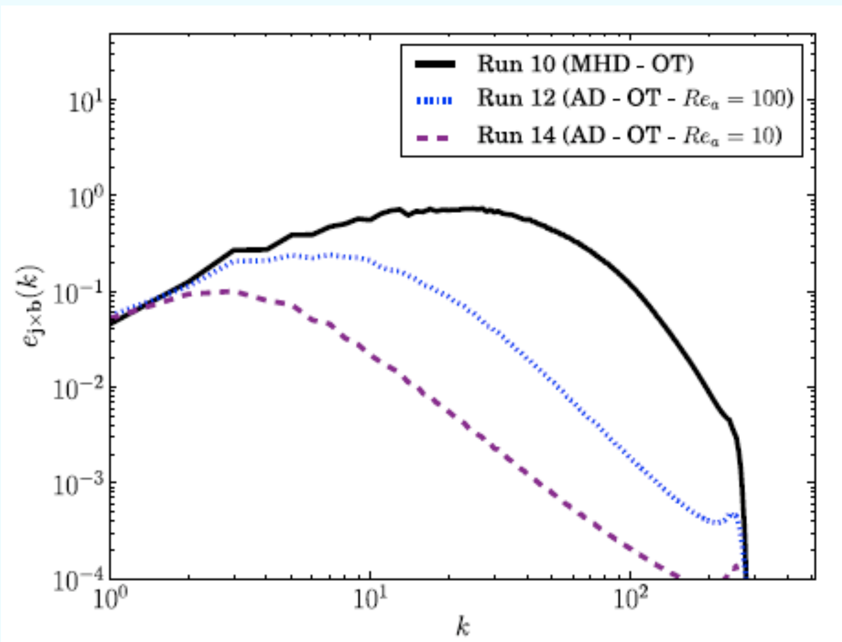
= Increments of integrated:

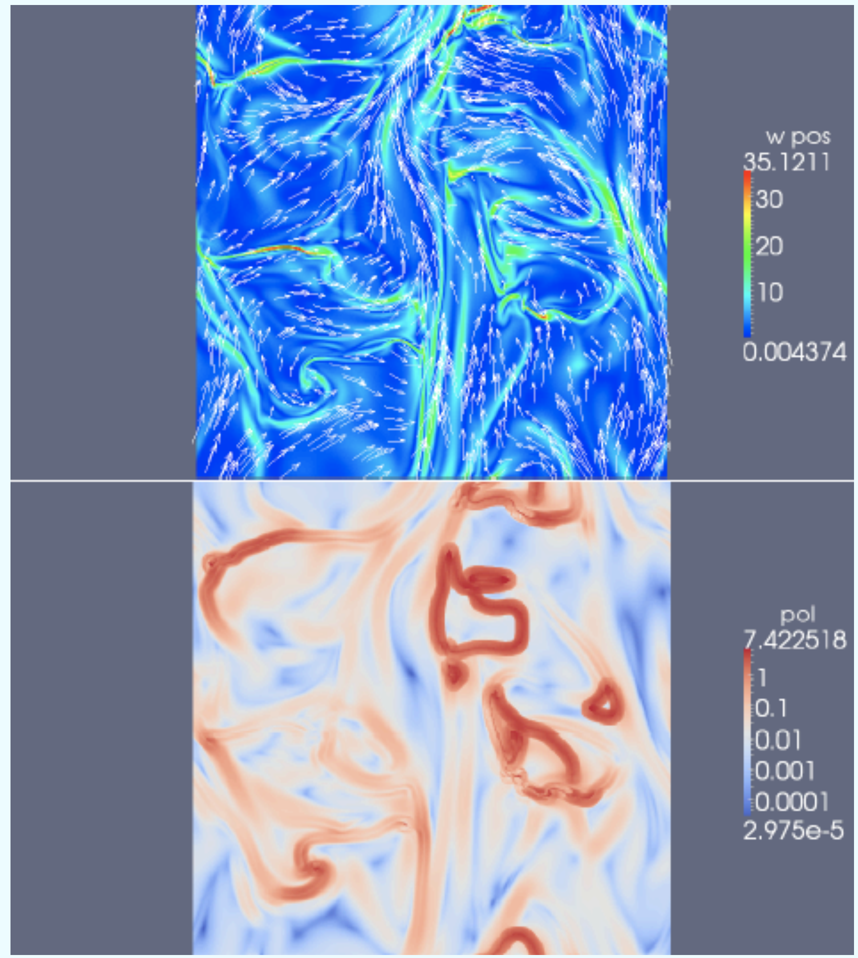
- LOS velocity (white)
- Stokes Q (green)
- Stokes U (red)
- POS magnetic field direction (blue)

Comparison with observables

Vorticity POS projection and B_{POS}

Energy spectra j x B



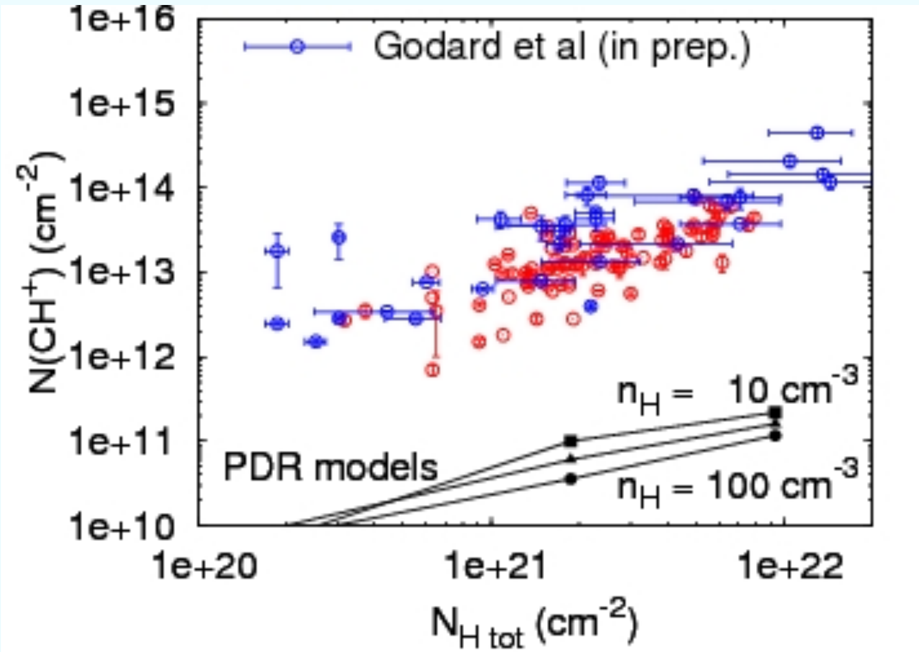


➪ AD producing force-free field at small scales

Increments of polarization orientation

Missing energy source in the diffuse ISM

Large CH^+ abundances in diffuse gas



Red: visible absorption lines
Blue: Submm lines
Godard et al. 2014

Extremely short lifetime
(destroyed by collisions H – H_2)

$$t = 1\mathrm{yr}/f_{\mathrm{H_2}}(n_{\mathrm{H}}/50\,\mathrm{cm}^{-3})^{-1}$$

Energy formation
$C^+ + H_2 \rightarrow CH^+$

$$E_{form} = 0.5\mathrm{eV}$$

⇨ **Need for a supra-thermal energy source**

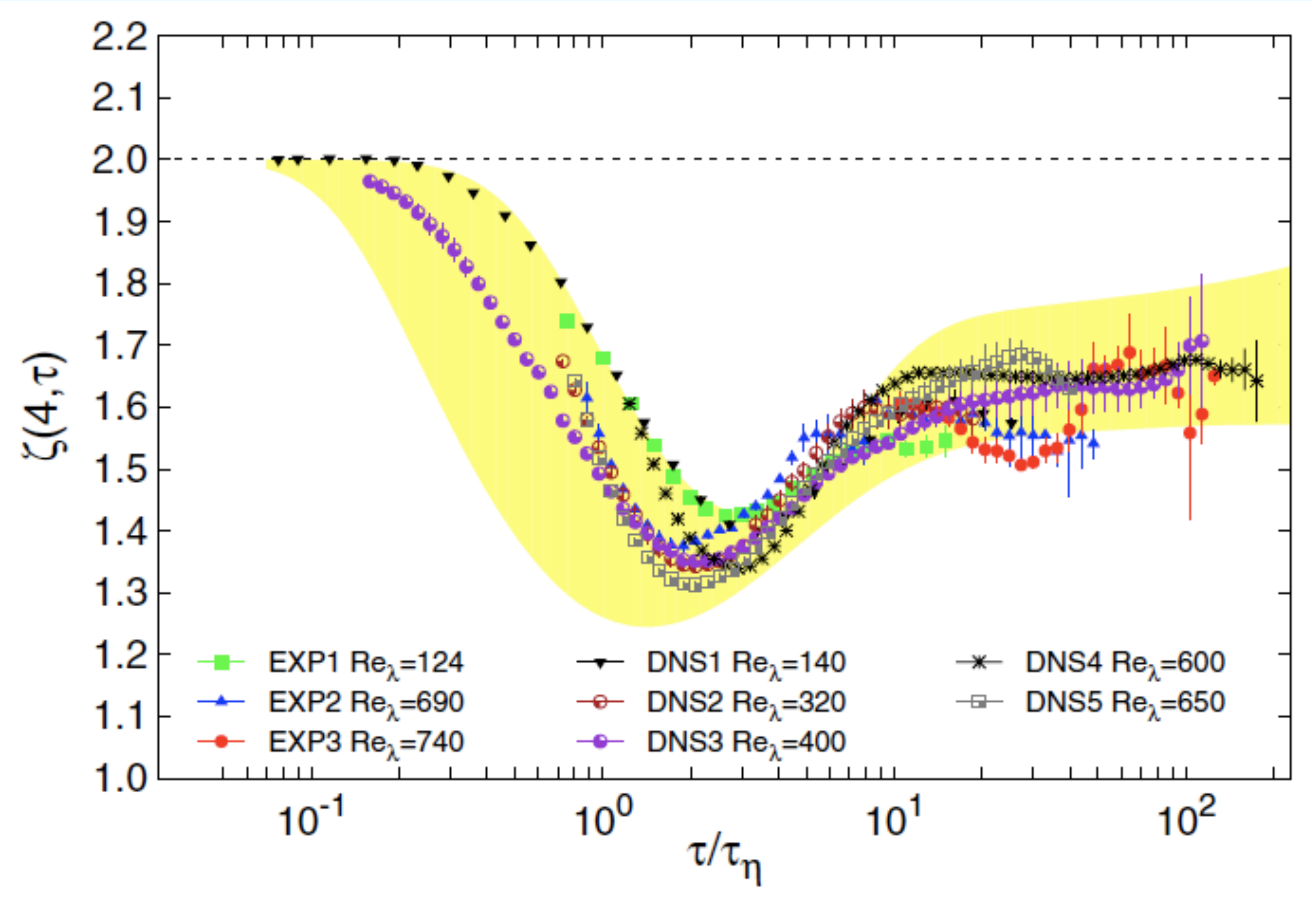
Other manifestations : H_2 pure rotational emission, CO richness, …

IV -Warm chemistry driven by turbulent dissipation

$$S_i^{(p)}(\tau) = \langle [v_i(t+\tau) - v_i(t)]^p \rangle$$

Lagrangian intermittency

$$\zeta_i(p,\tau) = \frac{d \log S_i^{(p)}(\tau)}{d \log S_i^{(2)}(\tau)}$$



← *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

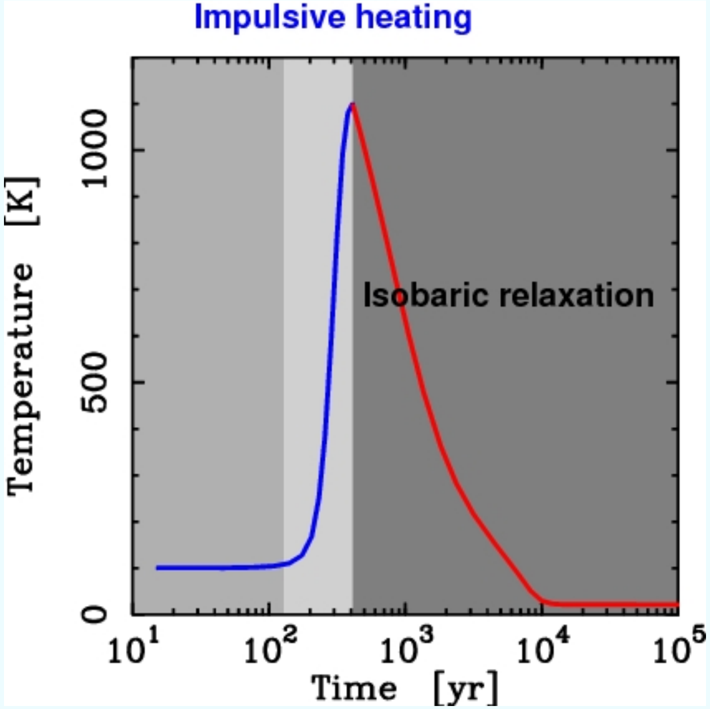
Arneodo et al. 2008

Models of Turbulent Dissipation Regions

- **Bursts of dissipation** in magnetized Burgers vortices (= solution of Helmholtz equation for vorticity)

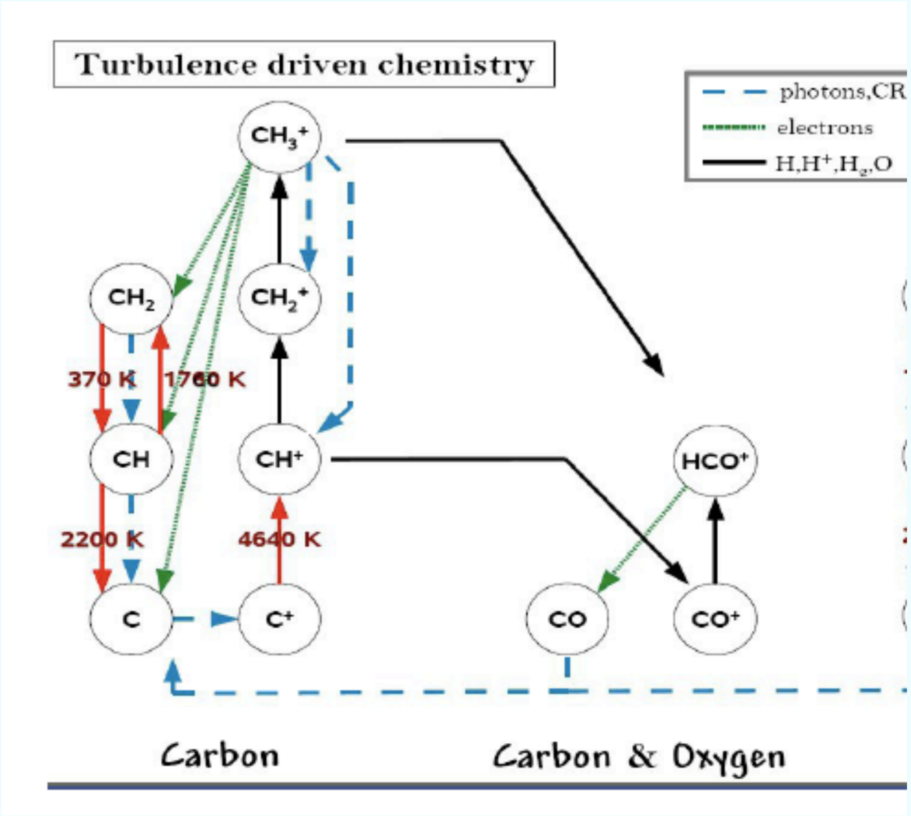
  ~ 10 AU, ~ 100 yr ➪ **non-equilibrium chemistry**
- Dissipation : Lagrangian treatment viscous + ion-neutral friction

  ➪ **warm chemistry**
- Thermal and chemical relaxation : 100 yr to several 10^4 yr
- **Few free parameters** constrained by ambient turbulence
- **3 phases :** active and relaxation phases (a few %) + ambient medium



Joulain et al. 1998;
Godard et al. 2009, 2014

Turbulent dissipation : the promises of warm chemistry



- **PDR models : C^+**

  $C^+ + OH$ and $H_2O \rightarrow CO$

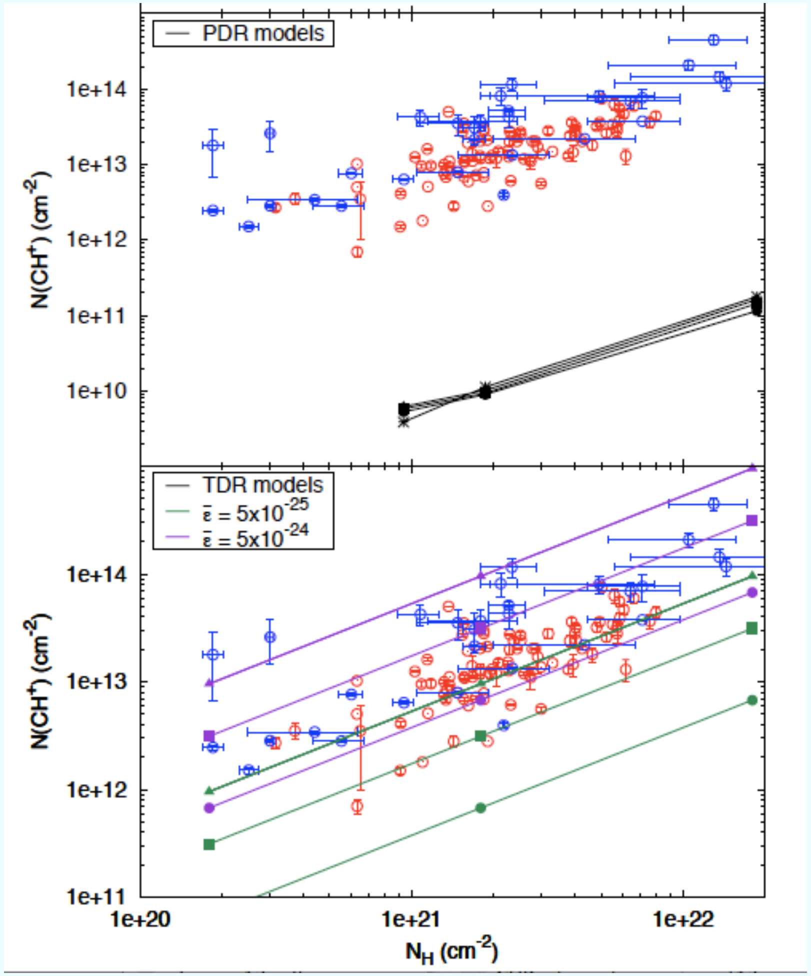
- **Alternative: CH_3^+**

  if highly endothermic route $C^+ + H_2 \rightarrow CH^+$ opened

  $CH^+ + H_2 \rightarrow CH_2^+ \rightarrow CH_3^+$

  ➪ **warm chemistry fed by intermittent turbulent dissipation**

Models of Turbulent Dissipation Regions in diffuse gas



TDR models for n_H= 30, 50, 100 cm^{-3}

Godard et al. 2014

- ➪ $N(CH^+)$ increases with UV-field
- ➪ $N(CH^+)$ proportional to **turbulent injection rate**

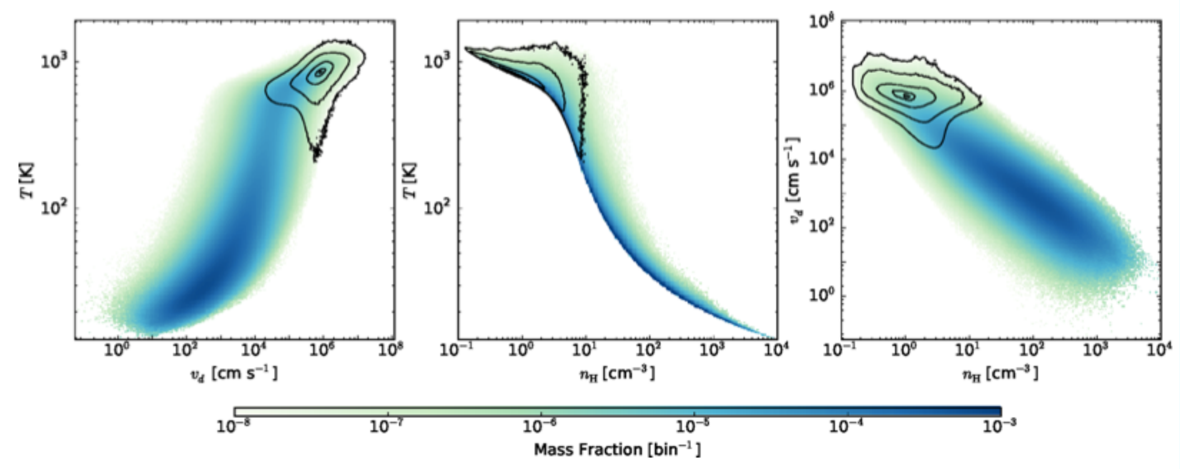
➪ **Direct measure of the energy flux:**

$$\dot{E} = \mathcal{N}(\mathrm{CH}^+) E_{form}/t$$

Warm chemistry driven by ion-neutral friction

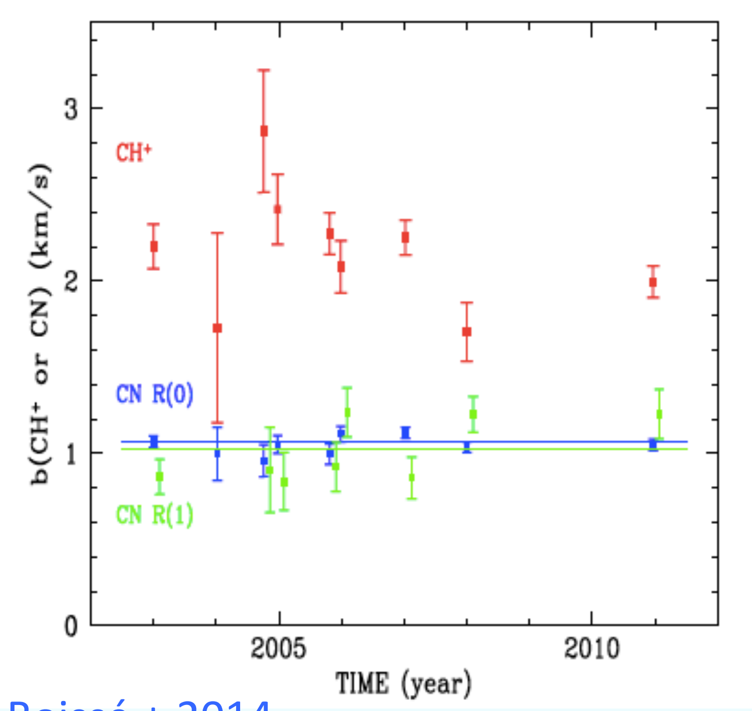
Alternative approaches

- Low velocity C-shocks Draine & Katz 1986
- Irradiated low-velocity C-shocks Lesaffre + 2013
- Alfvén waves Federman + 1996
- Turbulent mixing CNM /WNM, non-steady state H_2 abundances Valdivia + 2016, in prep.
- MHD turbulence in diffuse gas Myers + 2015



MHD simulations, post-treatment of chemistry, steady-state H_2 abundances
Reproduce observations but treatment of microphysics disputable.

Tiny Scale Atomic Structure



Boissé + 2014

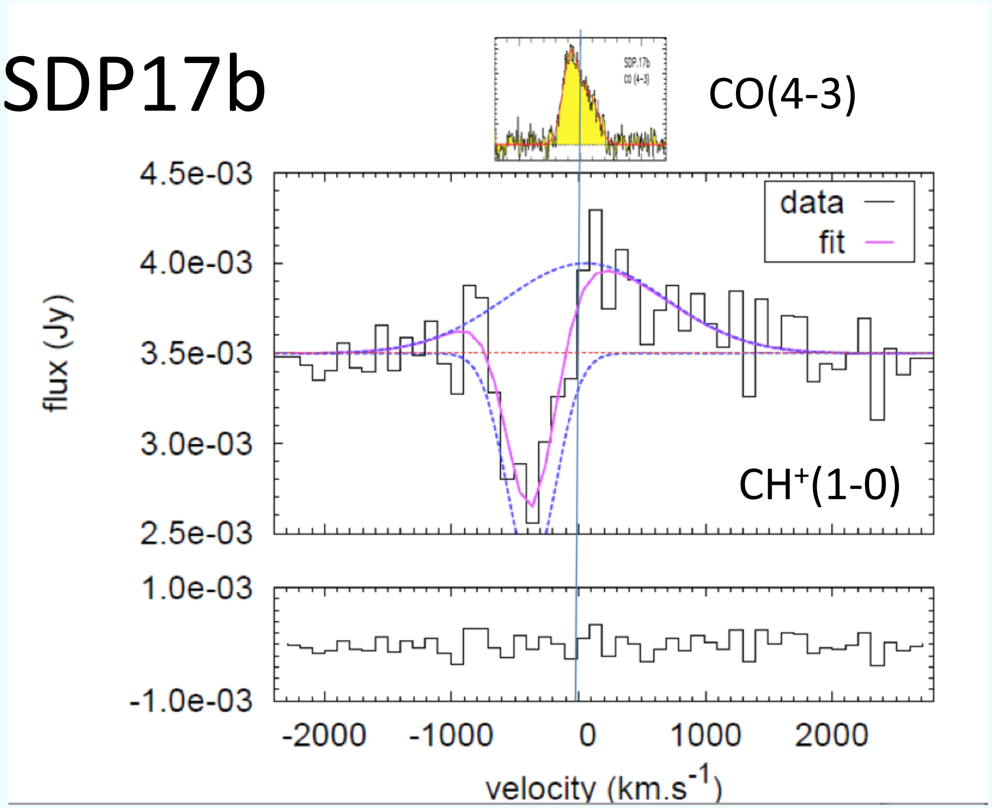
Time variations of molecular absorption lines towards Zeta Per using proper motion
➪ 1 -20 AU scales sampled

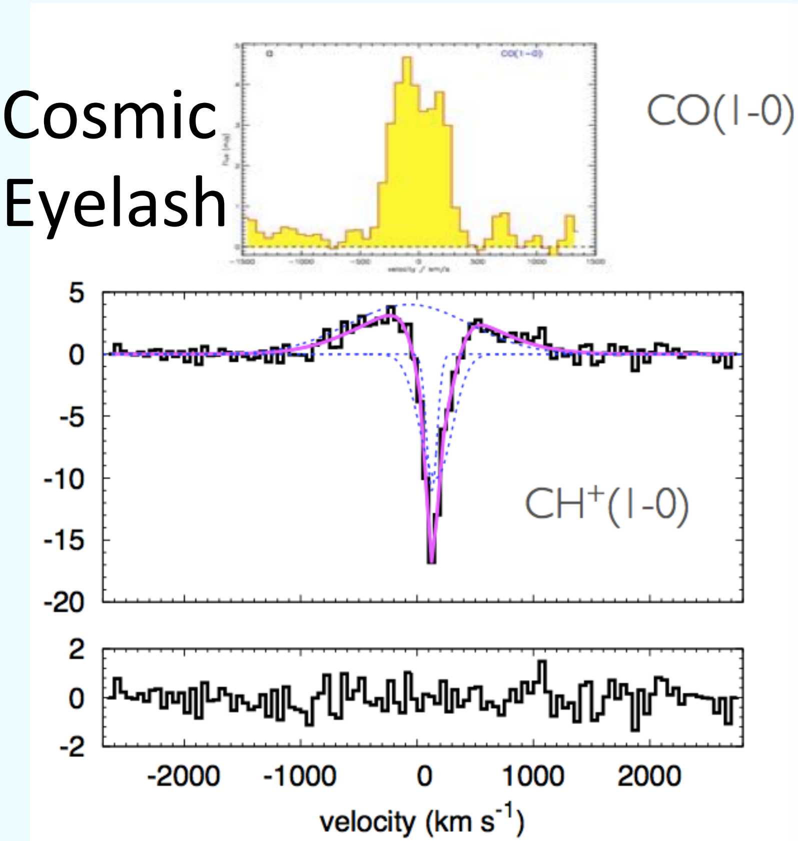
11% variations of CH^+ due to variations in linewidth
<6% variations for CH and CN

Validity of the fluid approximation ?
Hall MHD: kinetic effects, ion-electron decoupling, different coherent structures of current and vorticity
Stawarz and Pouquet 2015

V – Following the energy trail

ALMA CH^+ detections in strongly lensed starbursts at z ~ 2.5





CH^+ emission lines much broader than known CO lines

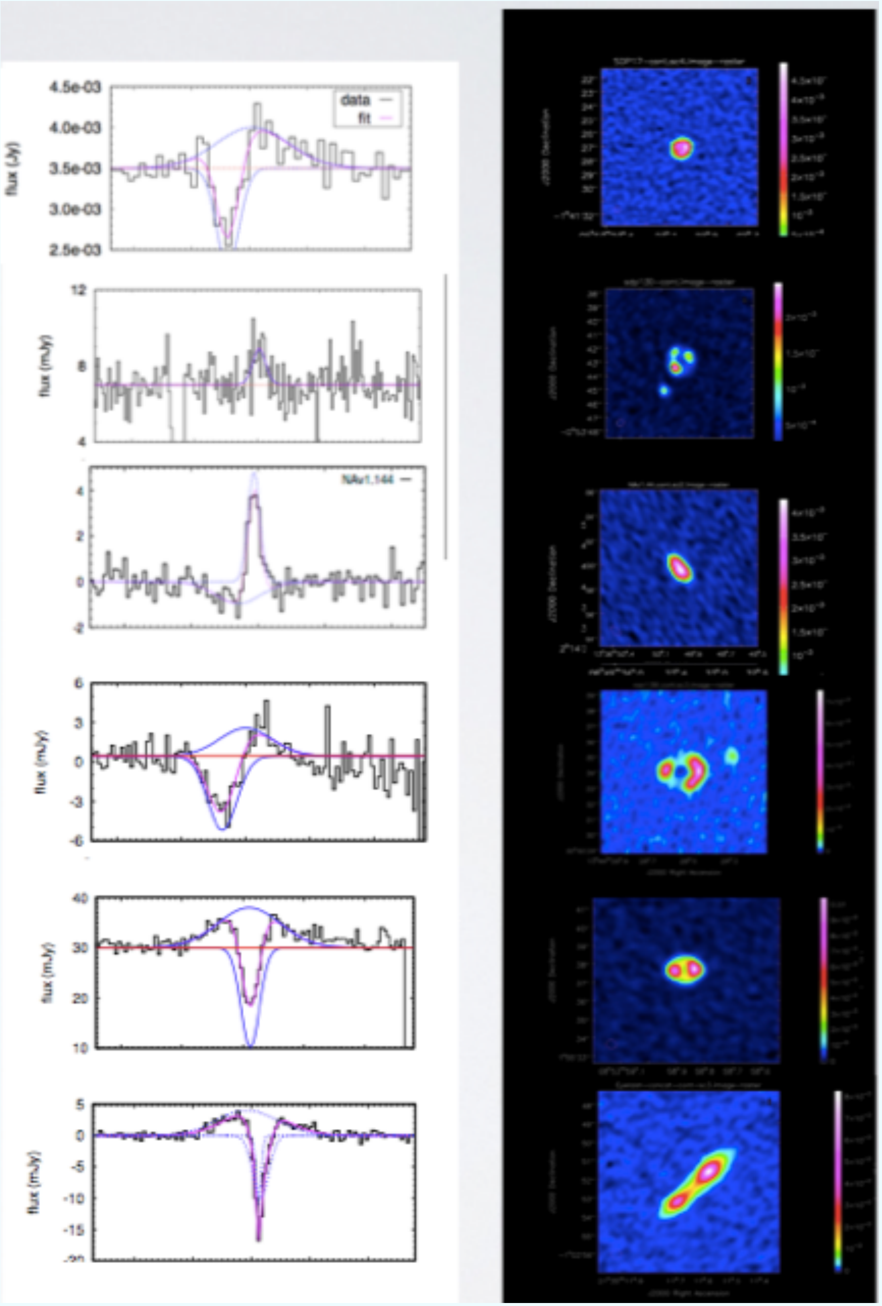
Falgarone + 2014, in prep.

Detection:

➪ **absorption**: large reservoirs of highly-turbulent low density gas

➪ **emission**: myriads of low velocity C-shocks with very high velocity dispersion

➪ **turbulence acts as a buffer of matter and gravitational energy**



Elements of answers

- Dissipation of turbulence: one of the drivers of molecule formation in very diffuse neutral gas.