Observed signposts of turbulence dissipation in molecular clouds

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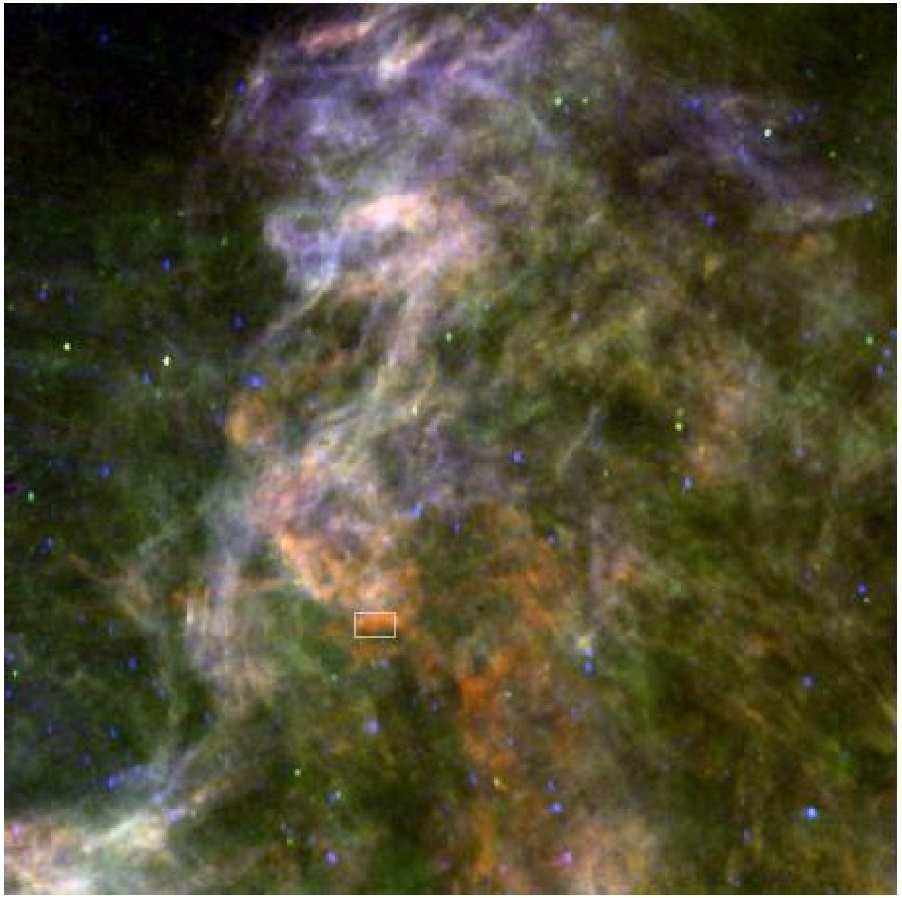
- Comparison of two similar fields in different gravitational environments
- Extrema of line Centroid Velocity Increments (E-CVI): an ombilical cord of dense cores in molecular clouds?
- Why dissipative structures?

"Star formation through cosmic time", Santa Barbara, November 2007

Large scale environments: 30-parsec scale

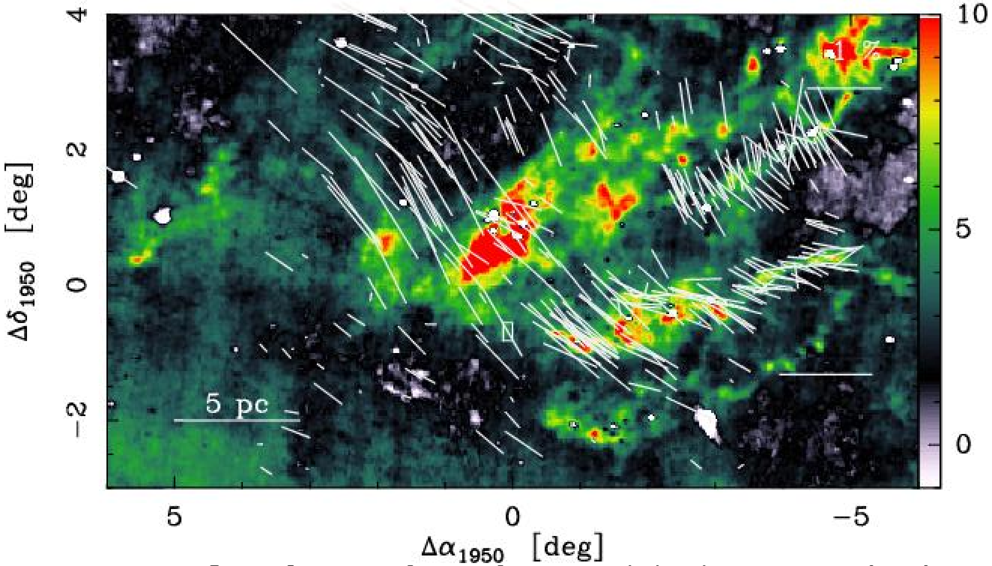


Polaris flare: 27 pc $\times$ 27 pc field

100 (red), 60 (green) and 12 μm (blue)

reprocessed IRAS maps

Miville-Deschênes & Lagache 2005



Taurus-Auriga clouds: cold dust emission

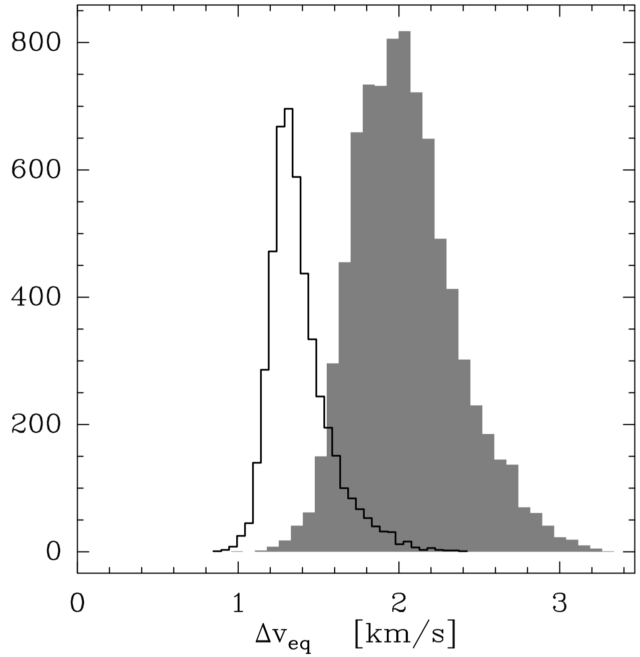
Hily-Blant 2004 and $B_\perp$ Heiles 2000

30 pc-scale:

same virial mass, $M_V \sim 4 \times 10^4$ M$_\odot$

- Polaris: $M_{gas}/M_V \sim 0.16$
- Taurus: $M_{gas}/M_V \sim 1$

Compared properties of the two parsec-scale fields



Parsec-scale:

• **turbulent**

$M \sim 5$ in Polaris,

$M \sim 2$ in Taurus

• **translucent**

$A_v \sim 0.8$ to 1 mag in both fields

• **Polaris:** trans-Alfvénic turbulence

dense core environment

• **Taurus:** cloud edge, no dense core

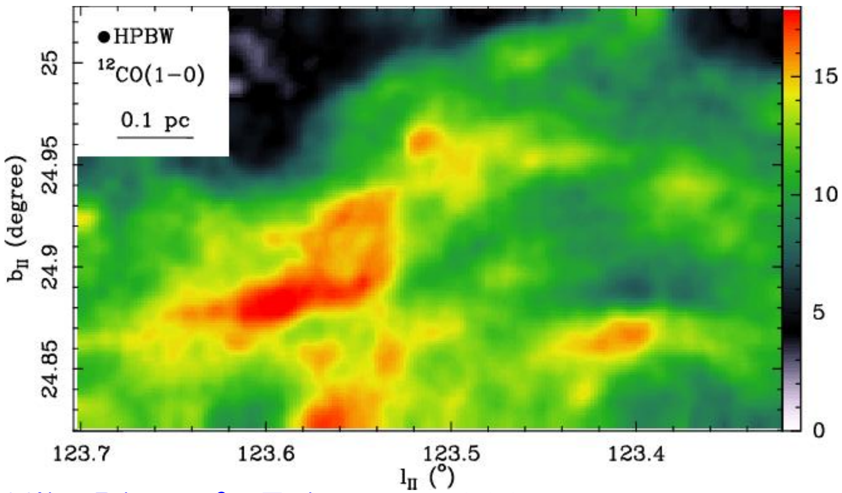
Taurus (left) – Polaris (right)

The tool: statistics of increments of line centroid velocities

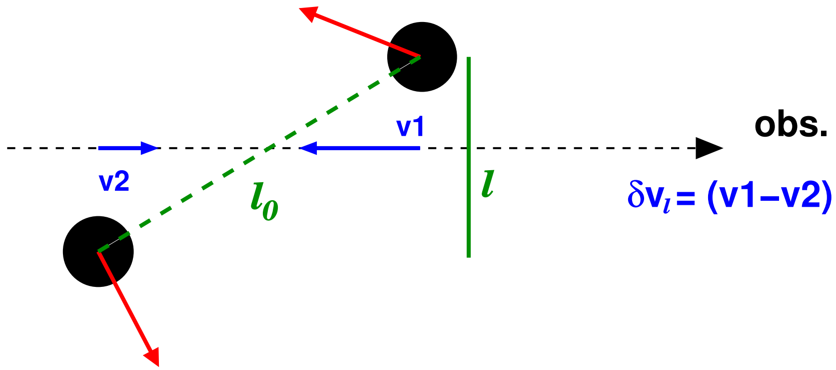
IRAM-30m,

8000 spectra (now 35000, resol 11")

Fully sampled, resolution 20"



Hily-Blant & Falgarone 2007



Line centroid velocity:

$C(\mathbf{r}) = \int T(\mathbf{r}, v_x) v_x dv_x / \int T(\mathbf{r}, v_x) dv_x$

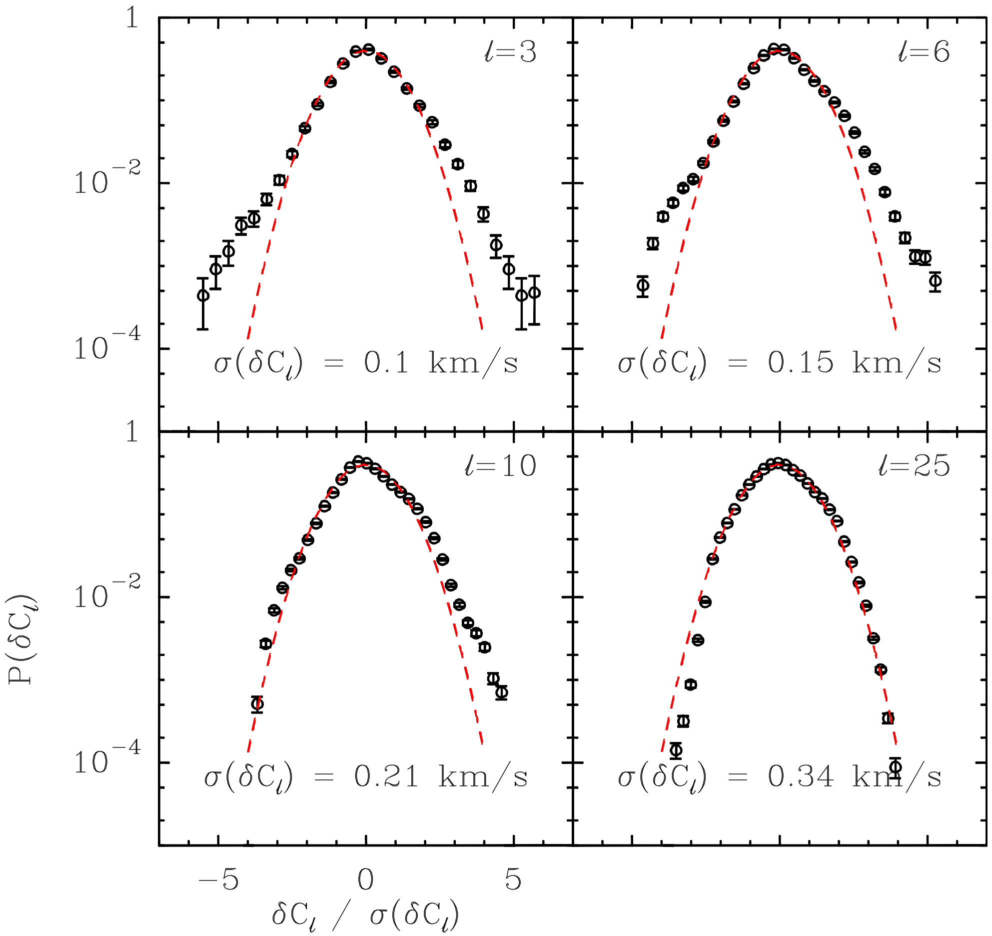
Miesch & Scalo 1999, Pety & Falgarone 2003, Brunt et al. 2003, Ossenkopf et al. 2206, Esquivel & Lazarian 2005,...

Extrema of line centroid increments **(E-CVIs)** trace extrema of $(\langle \omega_y \rangle^2 + \langle \omega_z \rangle^2)^{1/2}$

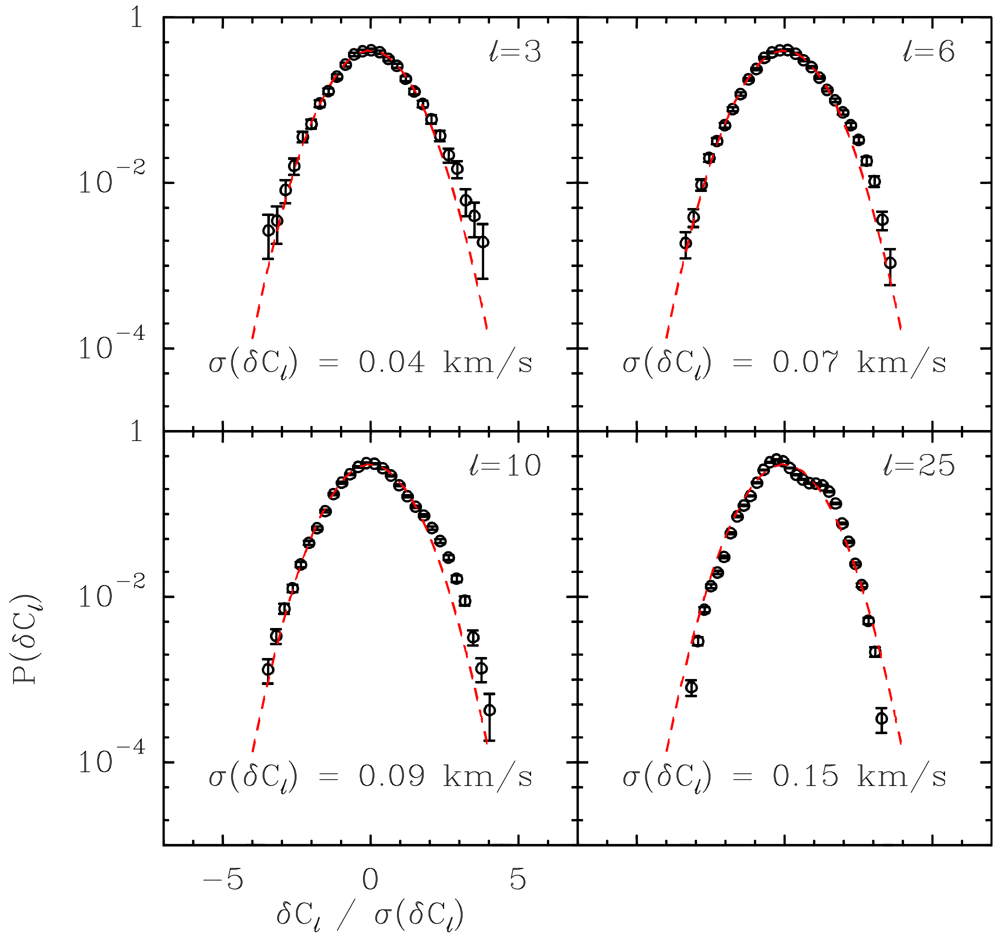
Lis et al. 1996

PDFs of Centroid Velocity Increments with variable lags

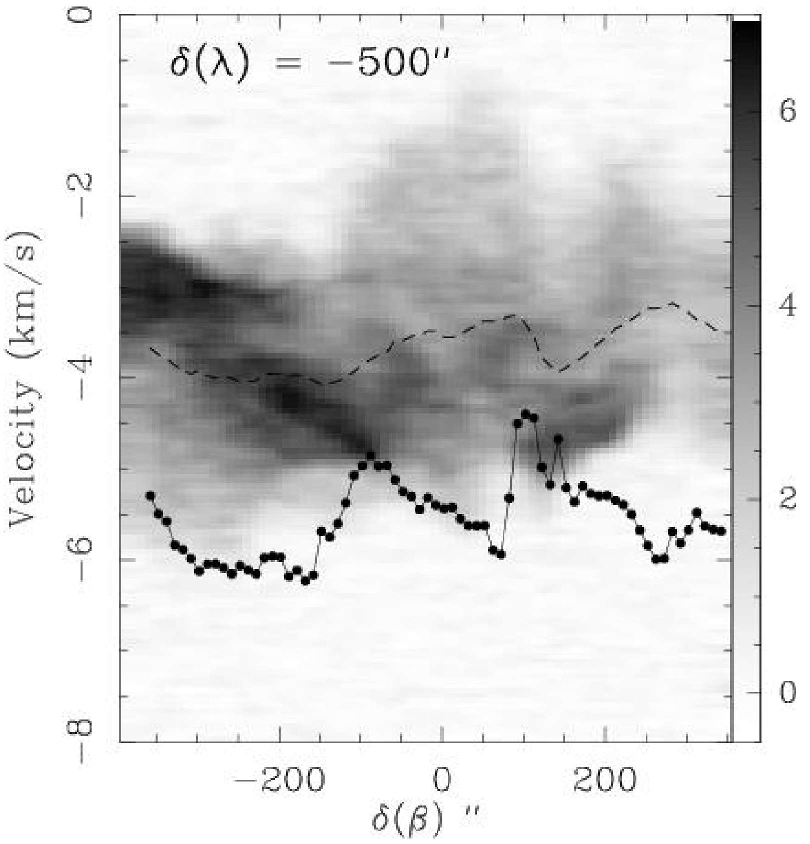
Polaris

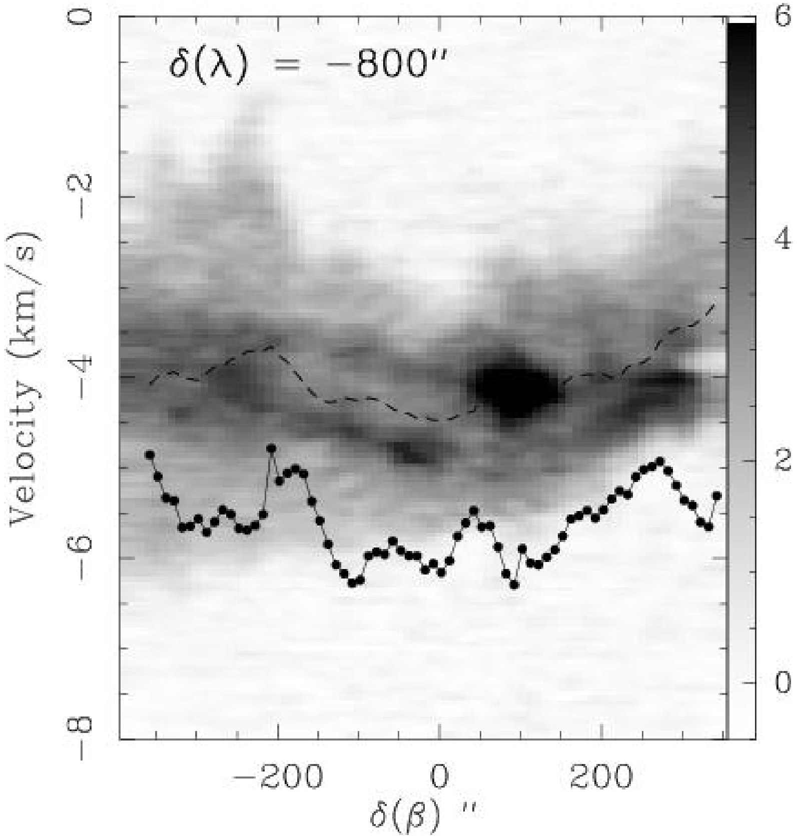


Taurus



Where do the non-Gaussian tails of CVI-PDFs come from?





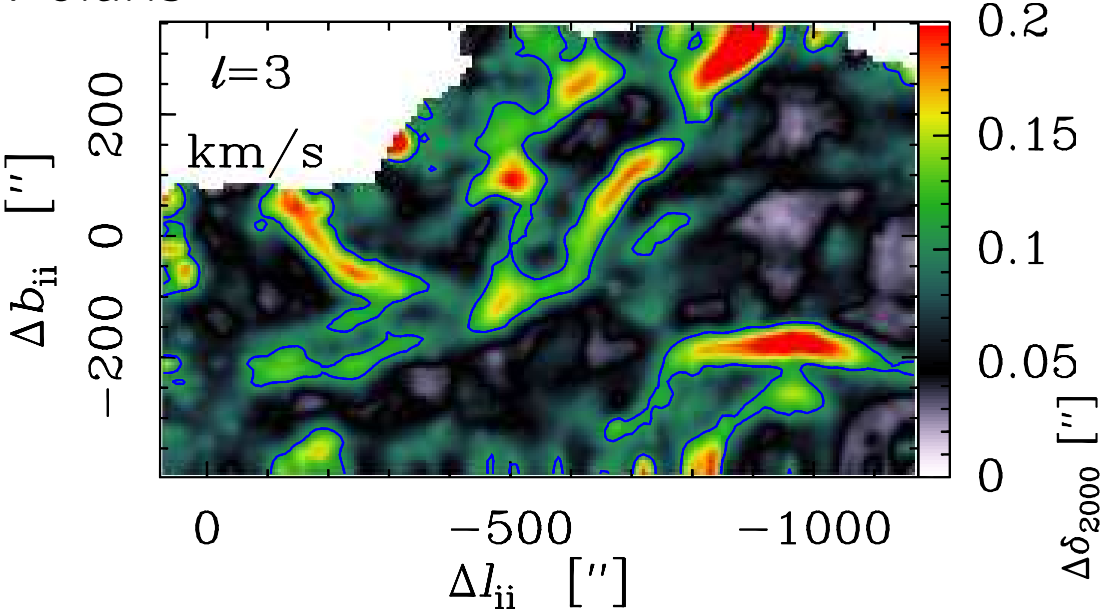
Space-velocity cuts of ^{12}CO(1-0) line intensity, (grey scale in K), line centroid (dashed), CVIs (dots) Hily-Blant & Falgarone 2007

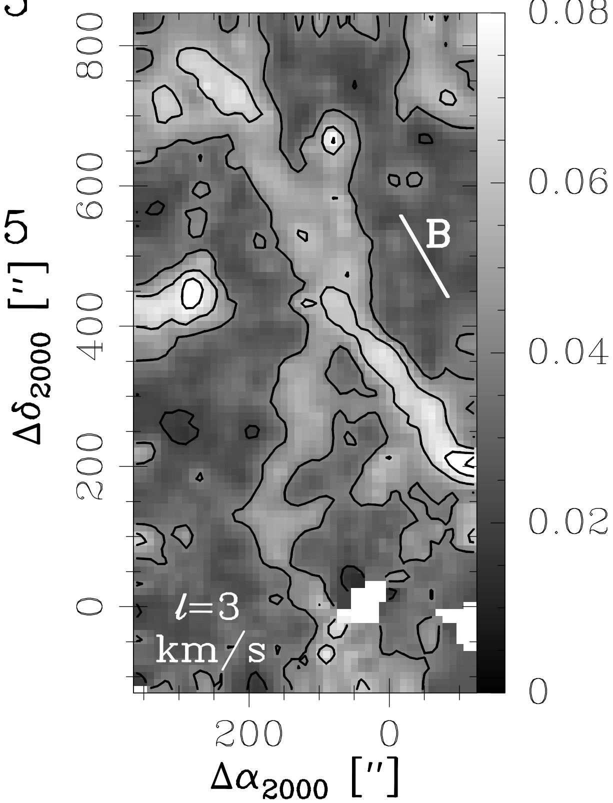
E-CVIs trace sharp local variations of ^{12}CO linewing

Spatial distribution of E-CVIs

Taurus

Polaris

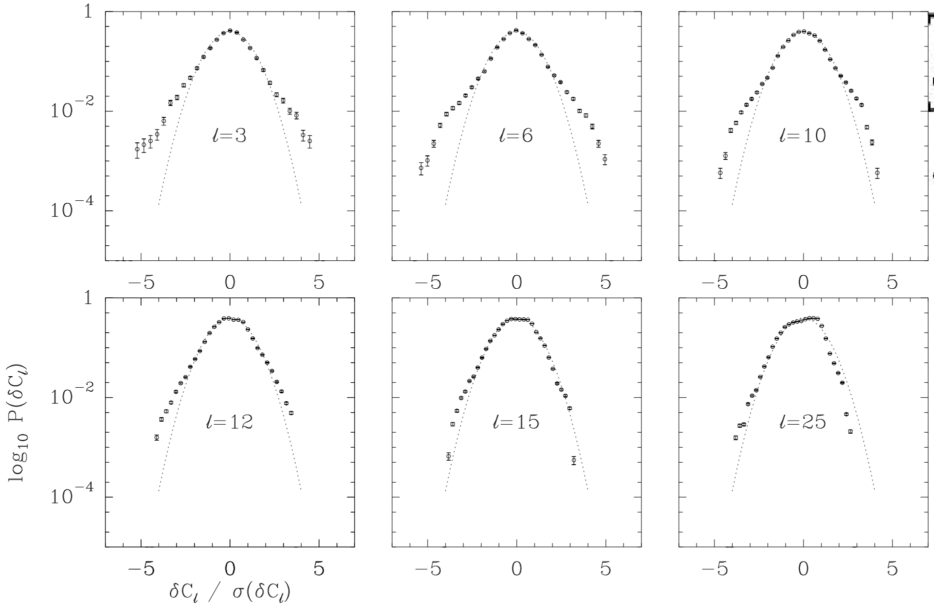


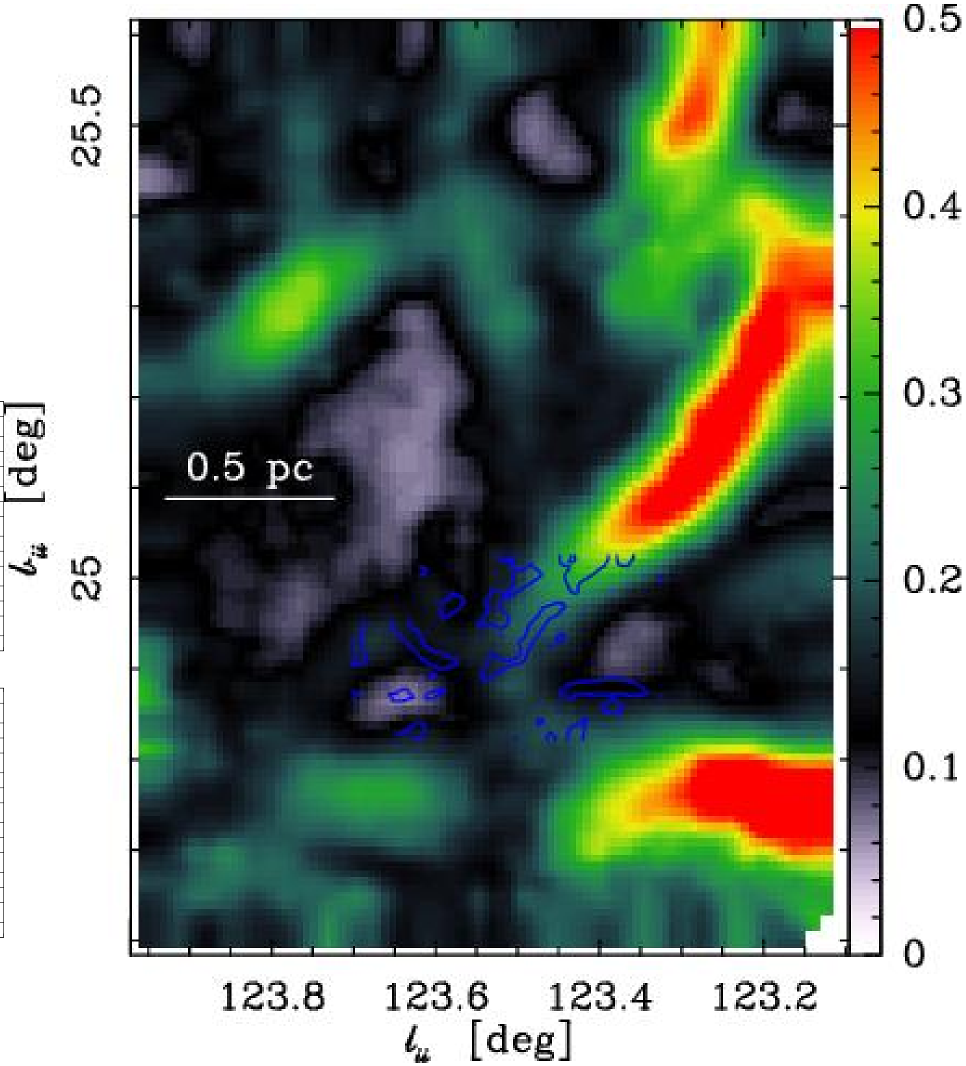


- Elongated structures of thickness $\leq$0.03 pc
- **Taurus:** parallel to $B_\perp$,
- **Polaris:** rms orientation of 30°
- CVI$_{max}$ in Polaris $\sim$ 3 CVI$_{max}$ in Taurus

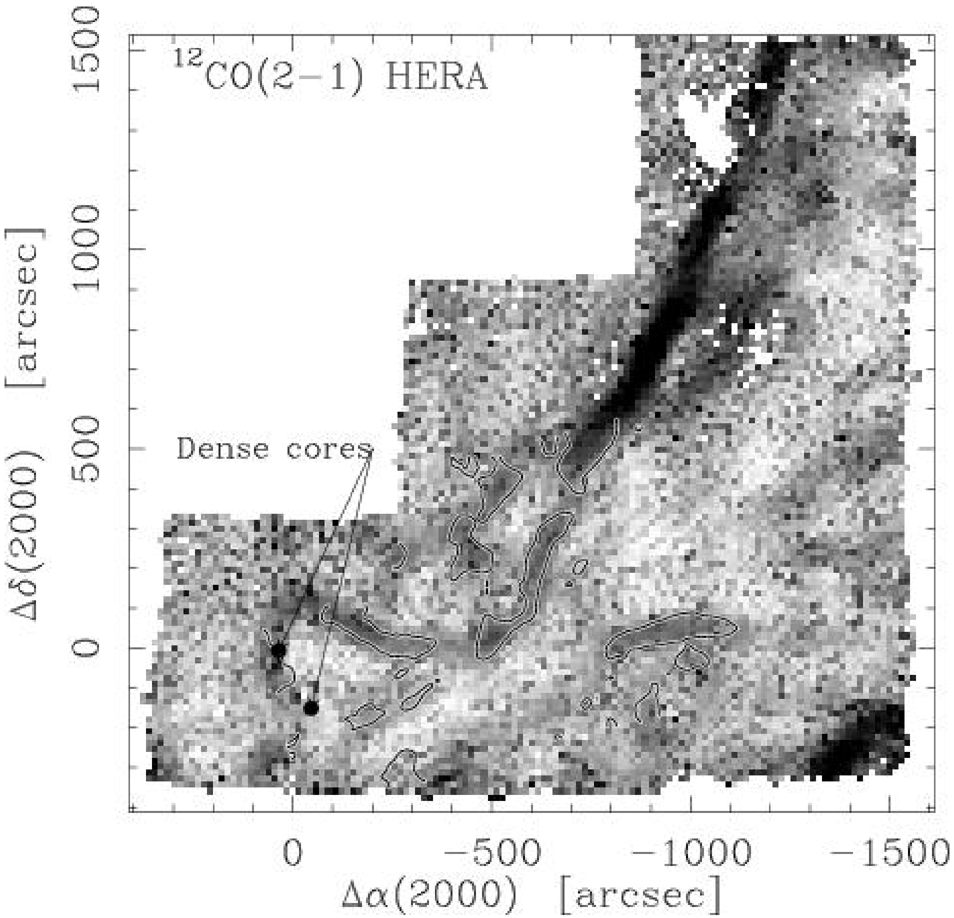
Self-similarity of PDFs of CVIs

Polaris large scale (5 pc)
KOSMA data, resolution 120'',
Bensch et al . 2001



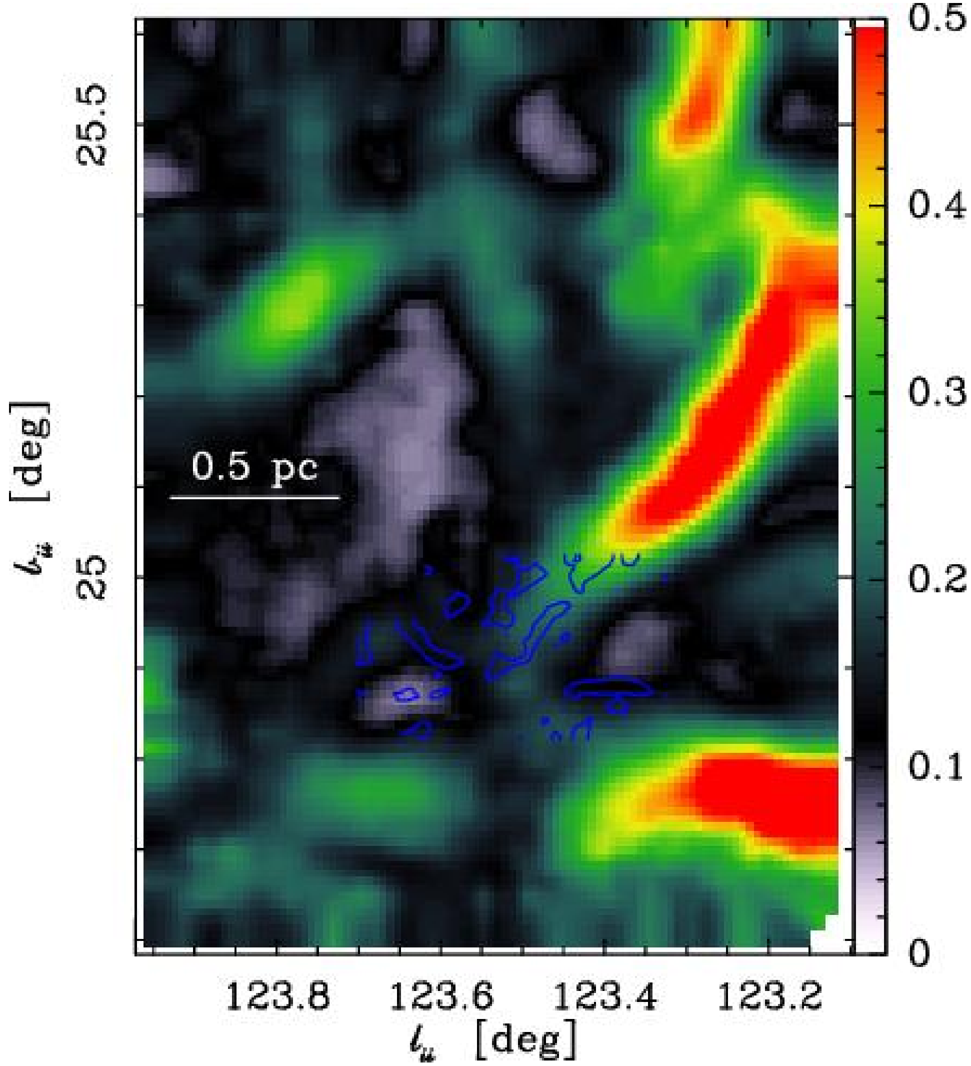


Parsec scale coherence of E-CVIs

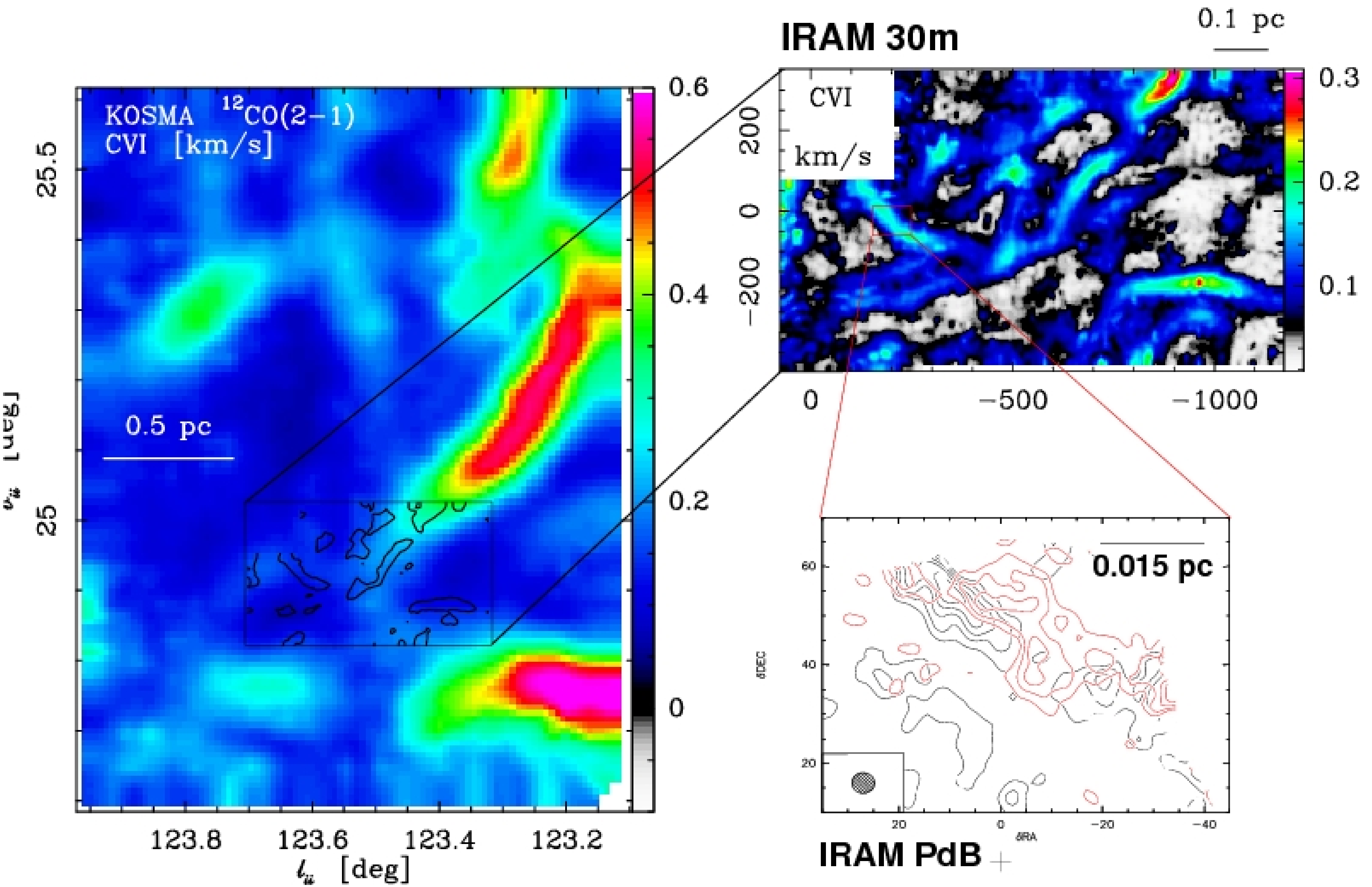


IRAM OTF-FS HERA (map in progress)

resolution 11", Hily-Blant et al. 2008

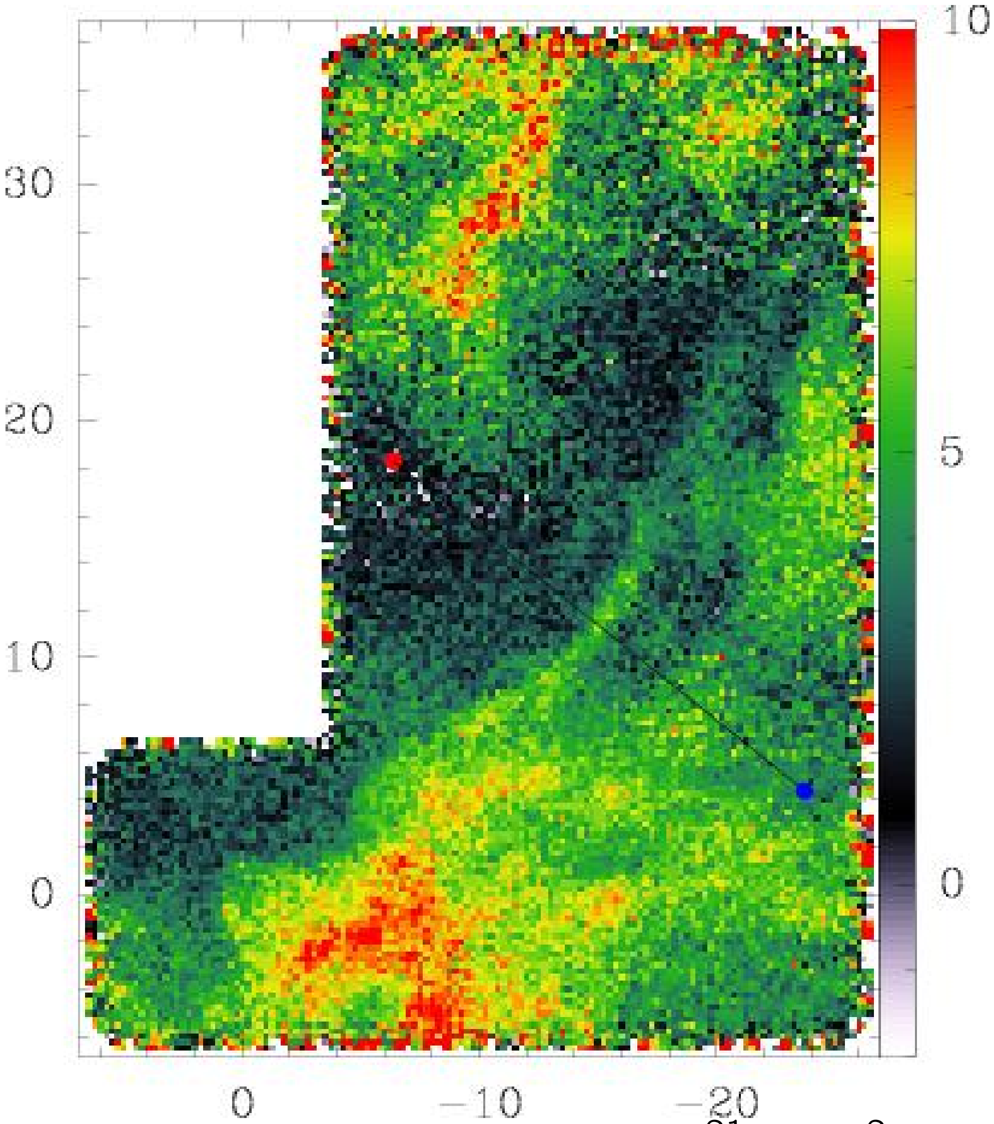


From 7 mpc to 3 pc

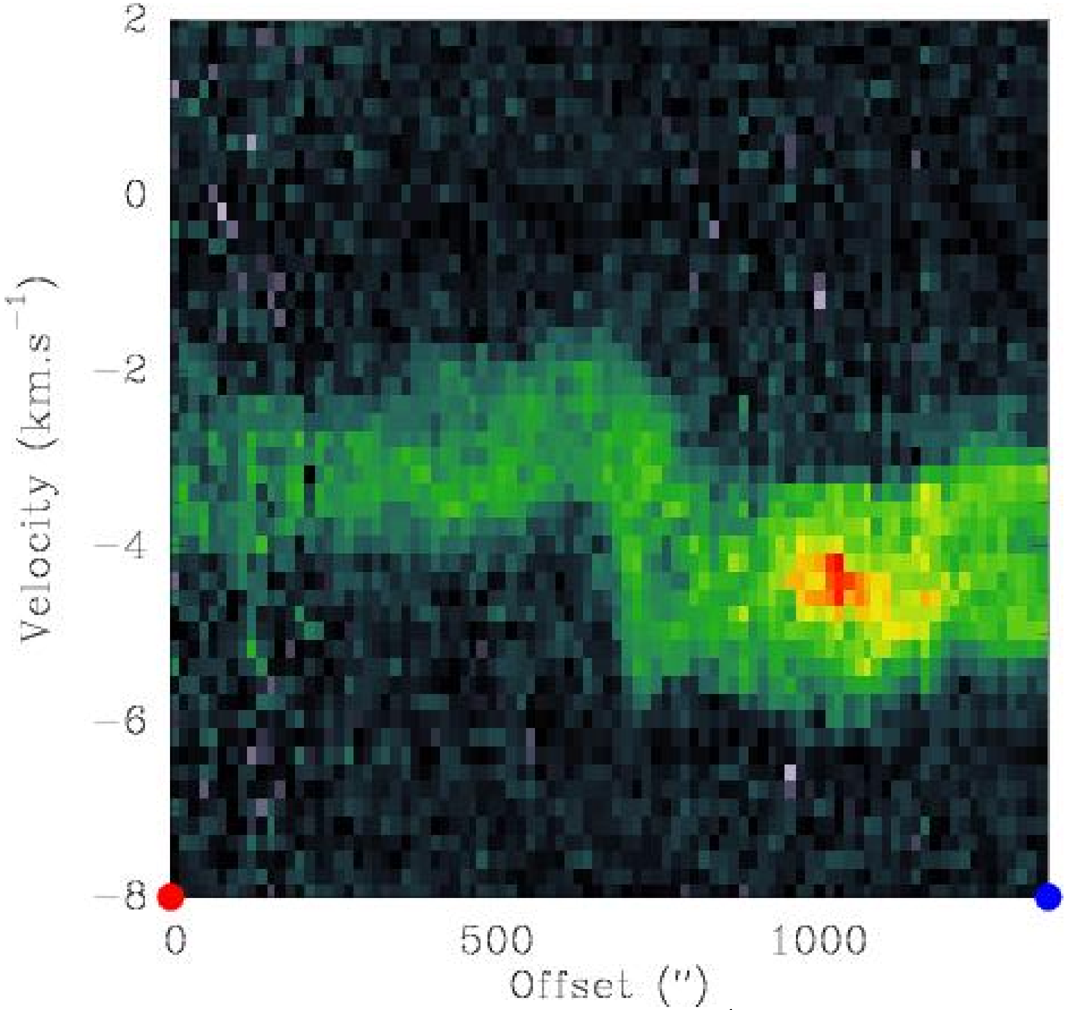


Space-velocity cuts

^{12}CO(2-1) integrated intensity (K km s^{-1})

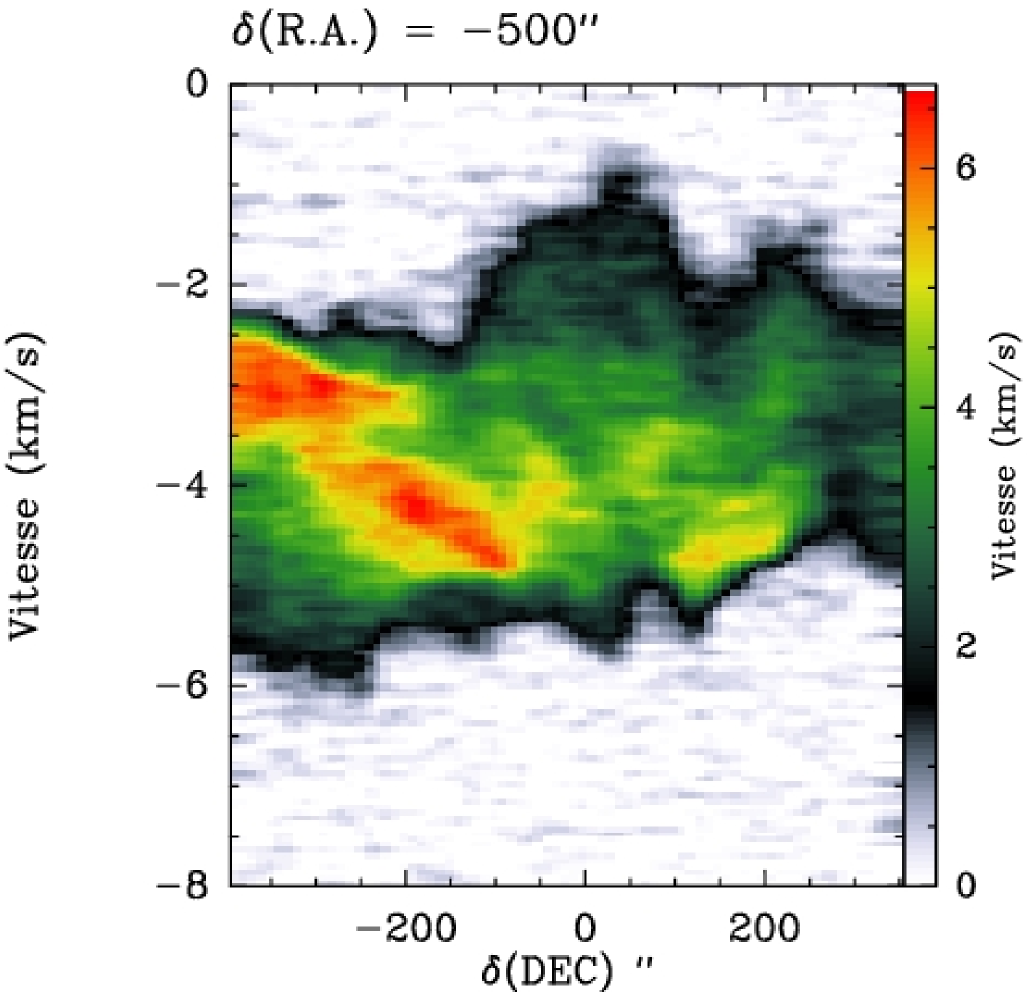


Max N_{H} across E-CVI $\sim 2 \times 10^{21}$ cm^{-2}



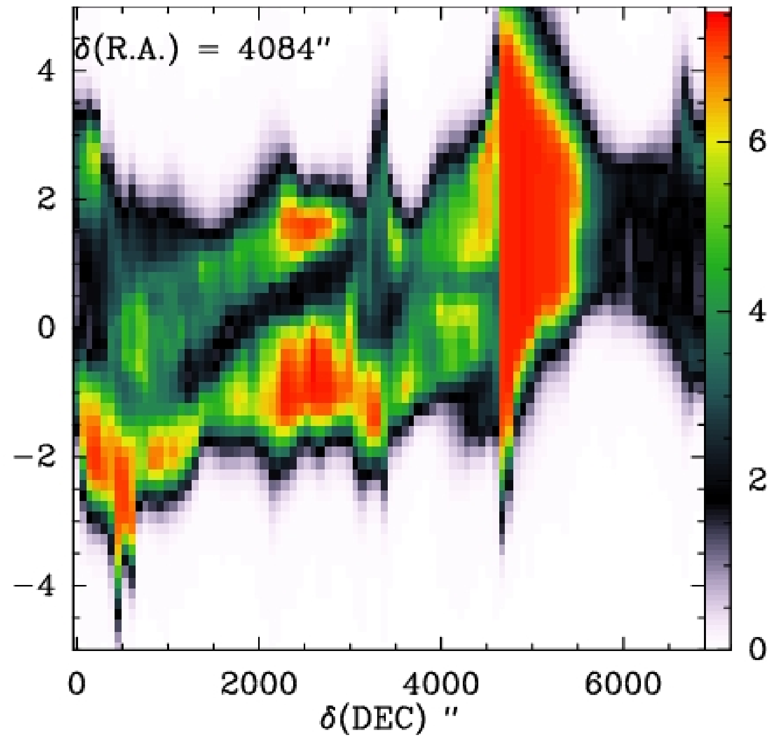
Max velocity shear: ~ 40 km s^{-1}/pc

Space-velocity slices: observations and MHD simulations



^{12}CO(1-0) l-v slices

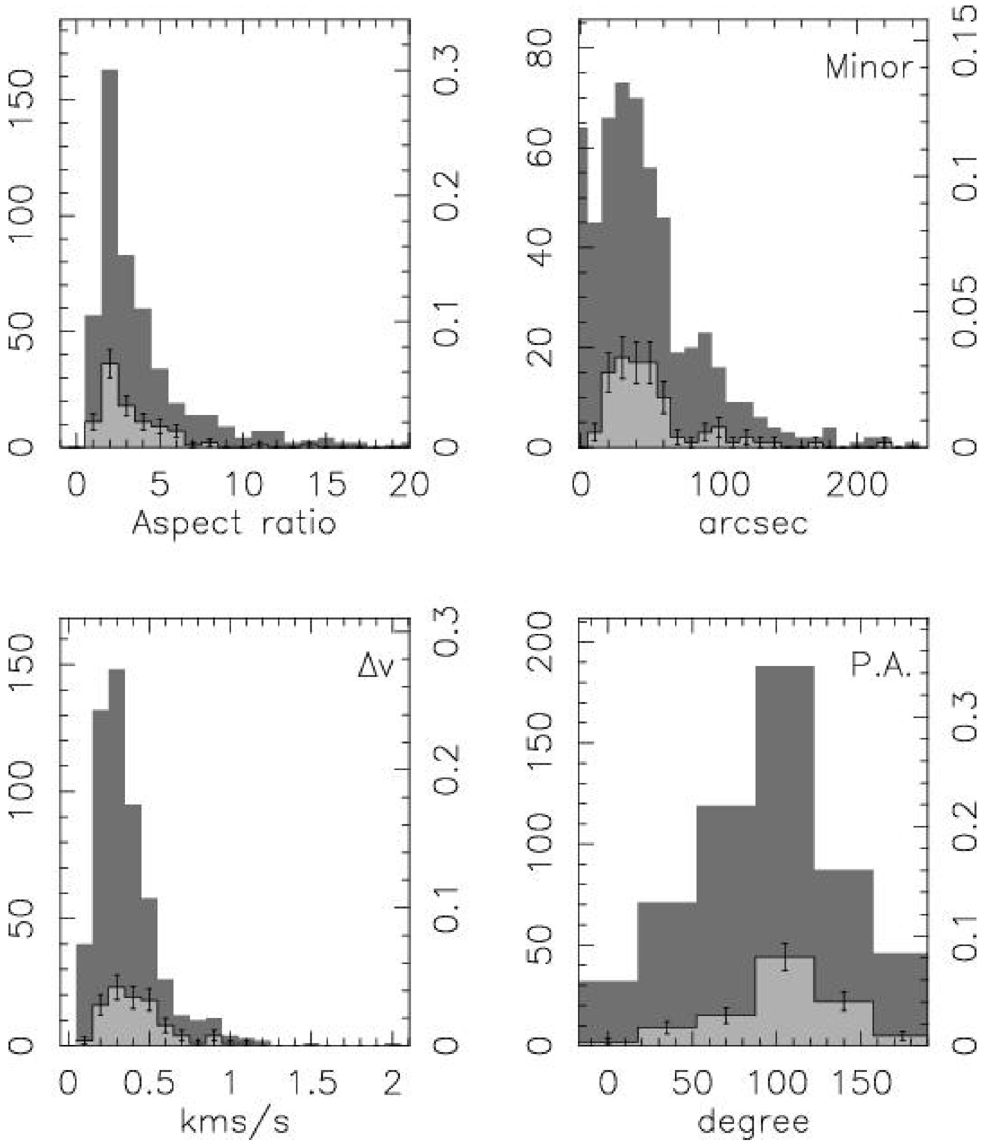
in Polaris Flare, across a large-CVI structure



SuperAlfvénic MHD turbulence and radiative transfer

(Padoan & Juvela, private communication)

Why trans-Alfvénic turbulence?



Structures in ^{12}CO(1-0) linewing emission (CLUMPFIND): Histograms of their aspect ratios, minor axis, internal velocity dispersions, position angles, Φ

From the rms dispersion of Φ:

$B_{pos} \propto n_{\rm H}^{1/2} \Delta v / \delta \Phi \sim 15 \mu$G

for $n_{\rm H} = 500$ cm^{-3}

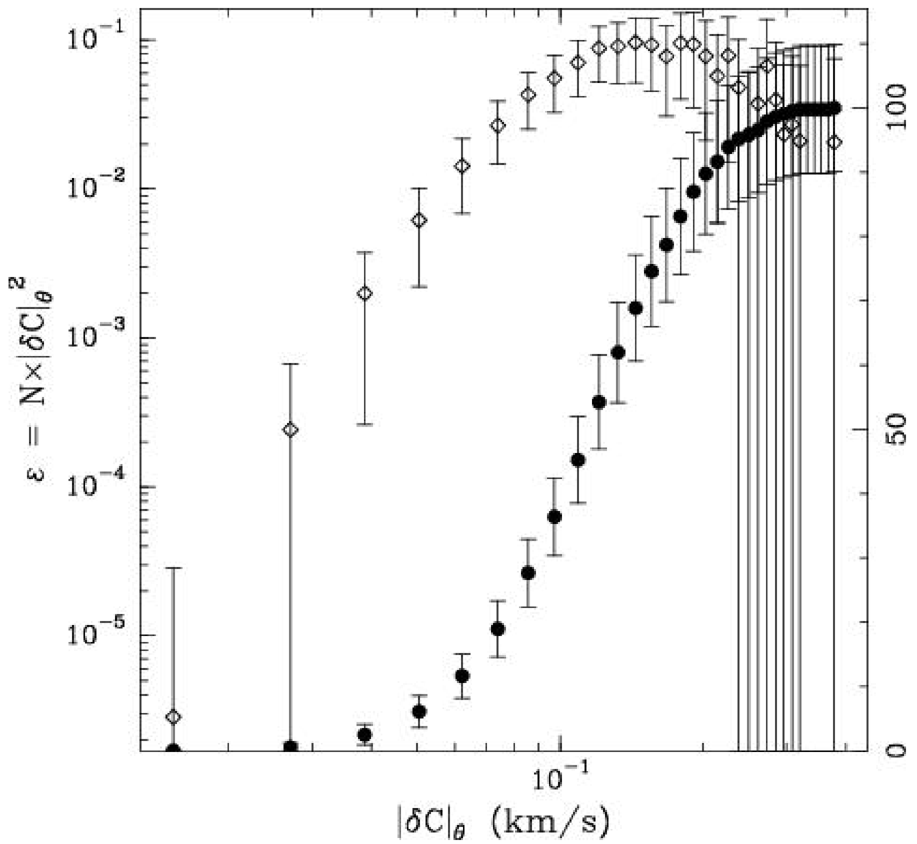
Chandrasekhar & Fermi 1953

and:

$\overline{v} \sim v_A$

Hily-Blant & Falgarone 2007

Why do E-CVIs matter?



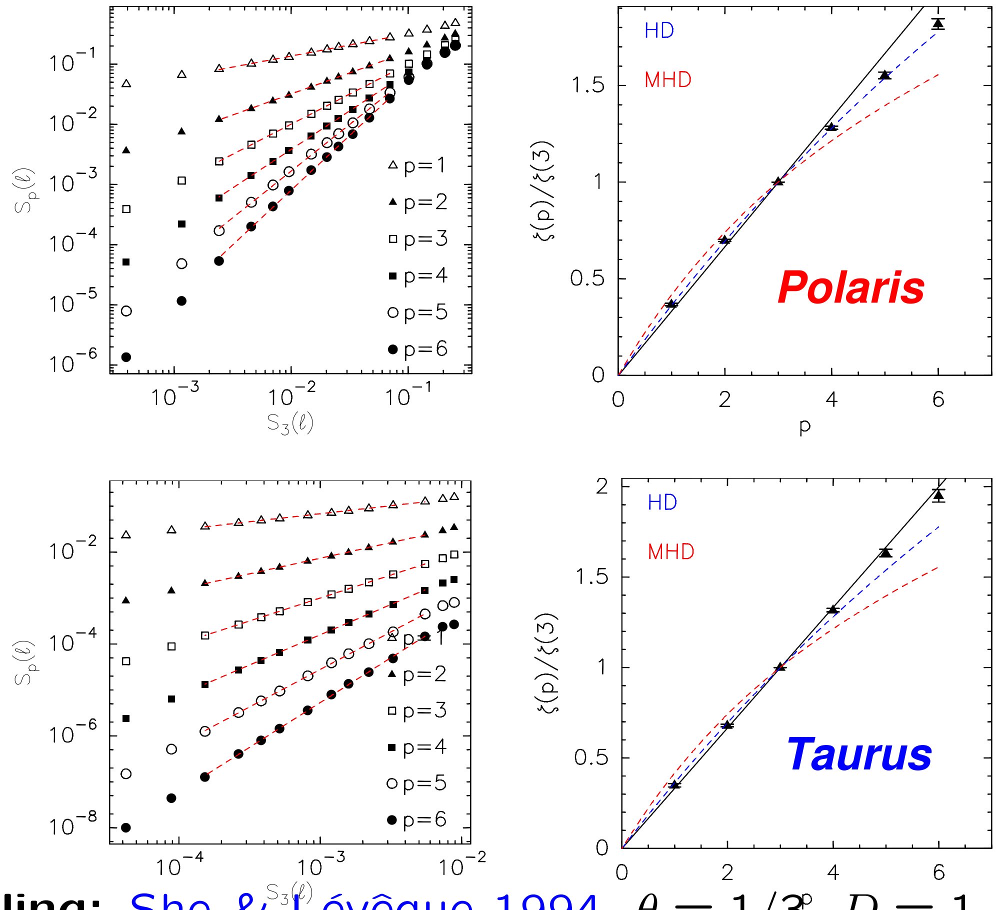
Hily-Blant, Falgarone & Pety 2007

Histogram of $N(CVI) \times CVI^2$ for $l = 3$ (diamonds)
and cumulative histogram (full dots)

$\rightarrow$ E-CVIs above 1.5 σ of PDFs (PDF for $l = 3$: $\sigma = 0.1\,\mathrm{km\,s^{-1}}$) contribute $\sim$ 30% of the energy dissipation

Scaling of CV p^{th}-order structure functions with p

Extended Self-Similarity exponents Benzi et al. 1993



HD scaling: She & Lévêque 1994, $\theta = 1/3$, $D = 1$, $\beta = 2/3$

MHD scaling: Boldyrev et al. 2002, $\theta = 1/3$, $D = 2$, $\beta = 1/3$

E-CVIs as tracers of “intermittency”

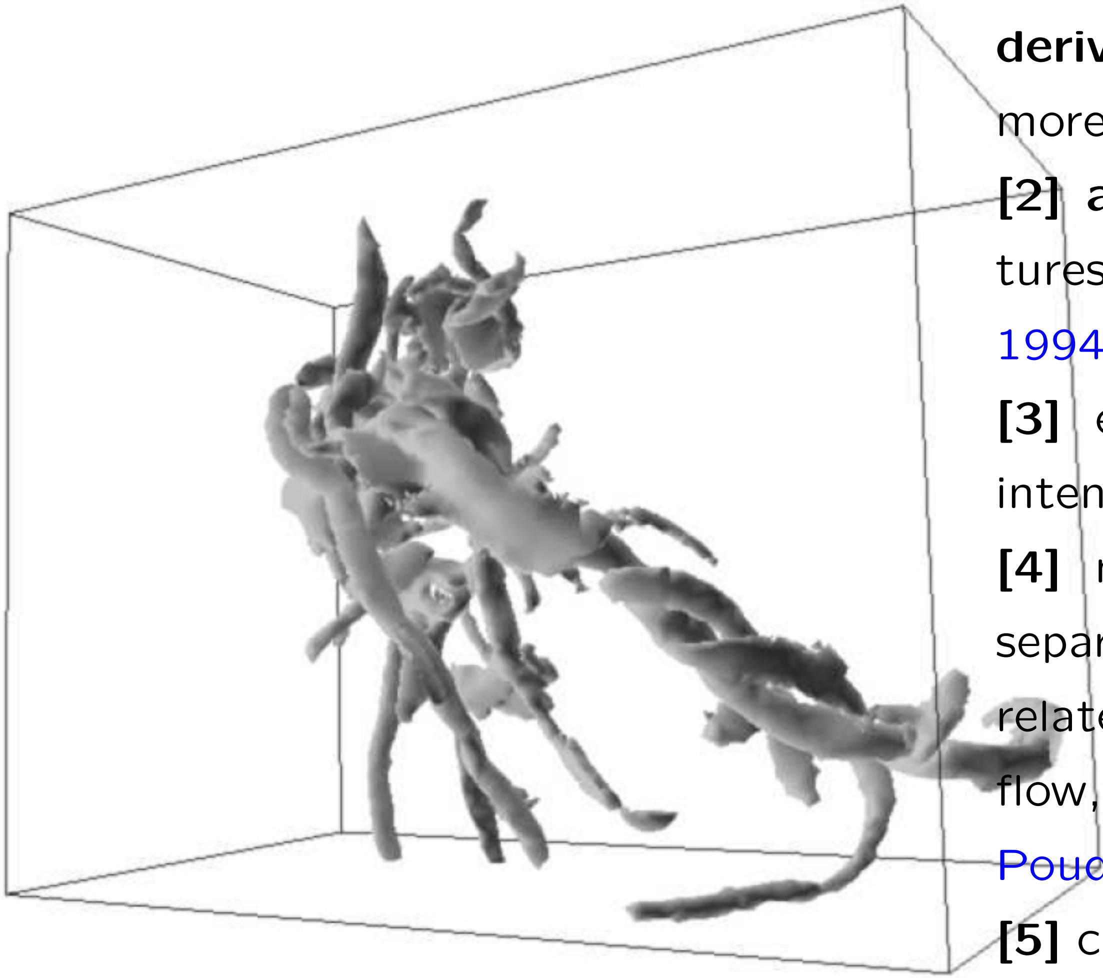
Same statistical and structural properties as intermittency of **velocity field** in incompressible or mildly compressible turbulence, magnetized or not:

- non-Gaussian tails of PDFs increase at small lags **[1]**
- anomalous scaling of CV structure functions **[2]**
- thin (0.02 pc) elongated structures of E-CVIs, coherent over > 1pc **[3]**
- E-CVIs trace intense velocity shears (PdBI data: velocity shear $\sim$ 200 km s^{-1} pc^{-1} over 7 mpc) **[1]**

not associated with density/column density peaks

- most turbulent field at large scale (Polaris) is most intermittent at small scale **[4]**

Intermittency in incompressible and mildly compressible turbulence



Moisy & Jimenez JFM 2004

[1] non-Gaussian statistics of **velocity derivative** signals
more pronounced at small scale

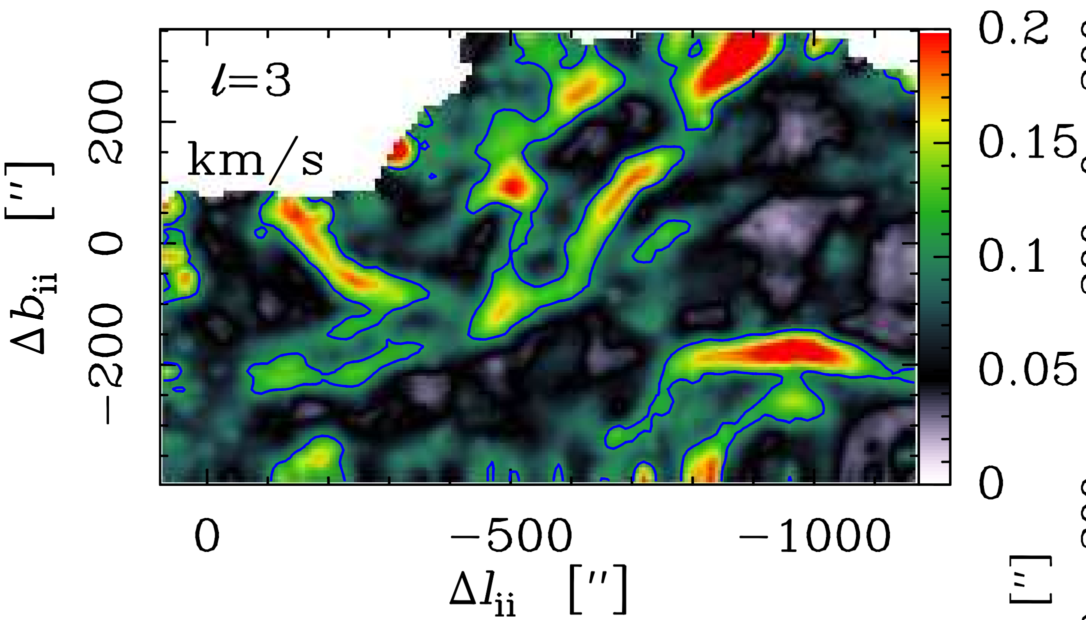
[2] **anomalous scaling** of p^{th} order structures functions $\zeta_p \neq p/3$ She & Levêque 1994

[3] existence of **coherent structures** of intense vorticity, shear, rate of strain, ...

[4] non-local interactions between widely separated scales: small scale intermittency related to large scale properties of the flow, in HD and MHD Mininni et al. 2006, Pouquet et al. 2006

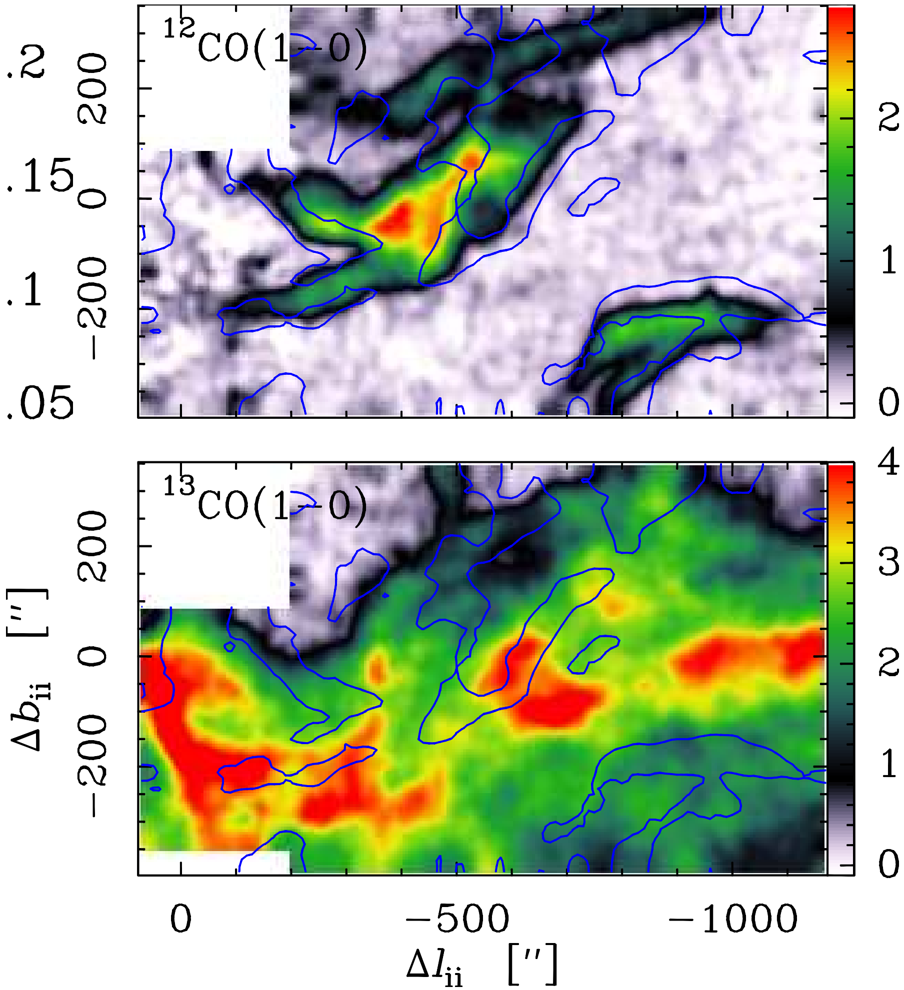
[5] clustering of coherent structures, inertial range intermittency Moisy & Jimenez 2004

E-CVIs as tracers of local enhanced dissipation: CO emission



E-CVIs uncorrelated with ^{13}CO emission (bottom right)

E-CVis follow boundaries of optically thin ^{12}CO(1-0) (top right)



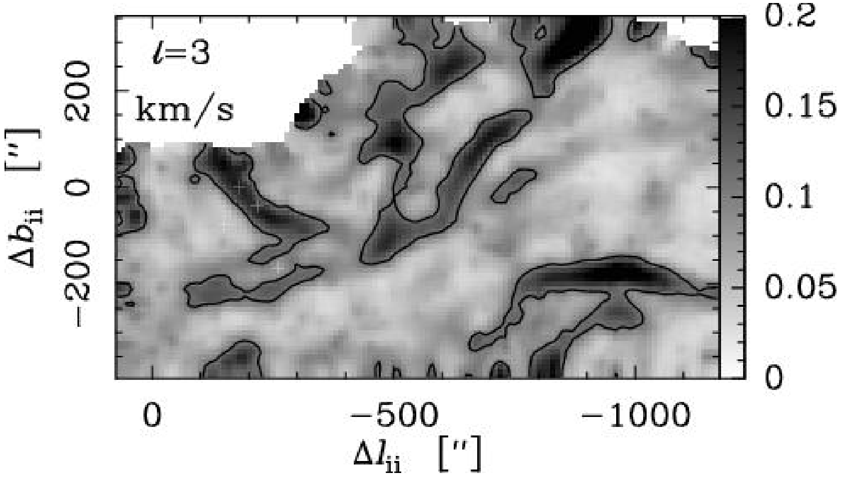
Optically thin ^{12}CO(1-0) emission: $[^{12}\mathrm{CO}]/[^{13}\mathrm{CO}] > 35$

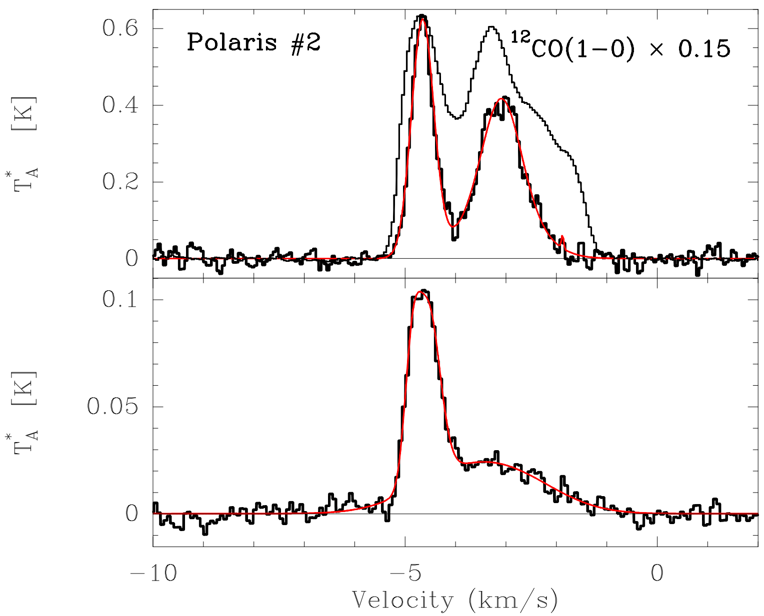
LVG analysis and translucent constraint :

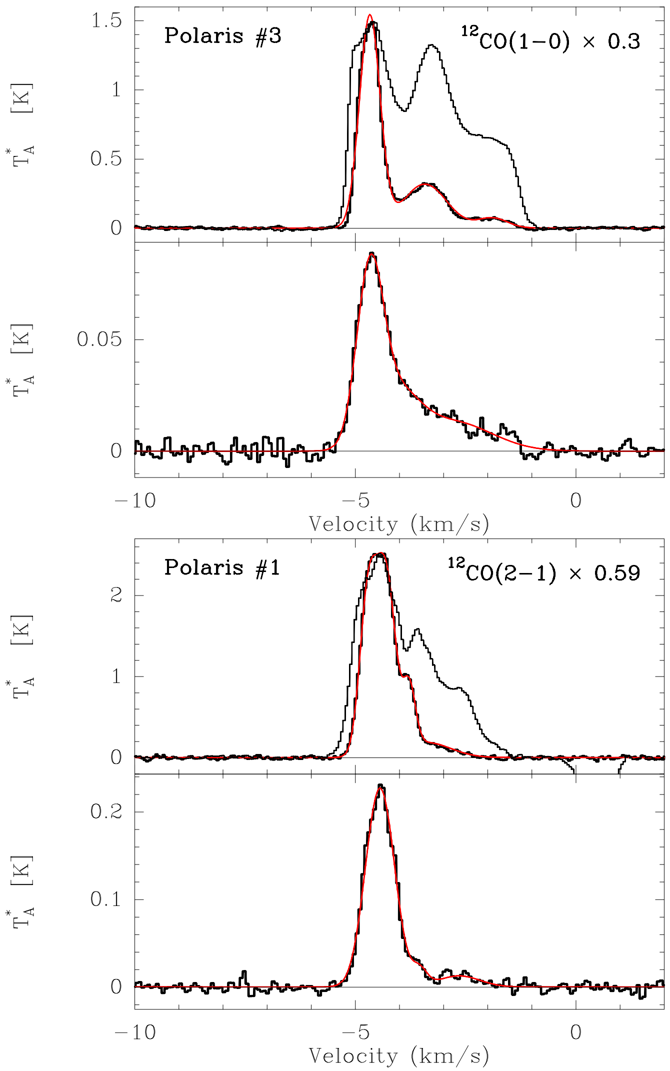
dense and cold solutions ruled out: $n_{\mathrm{H_2}} < 10^3\,\mathrm{cm}^{-3}$, $T_k > 25$K

Gas in E-CVIs regions may be as warm as 200K

E-CVIs as tracers of local enhanced dissipation: HCO^+(1-0)



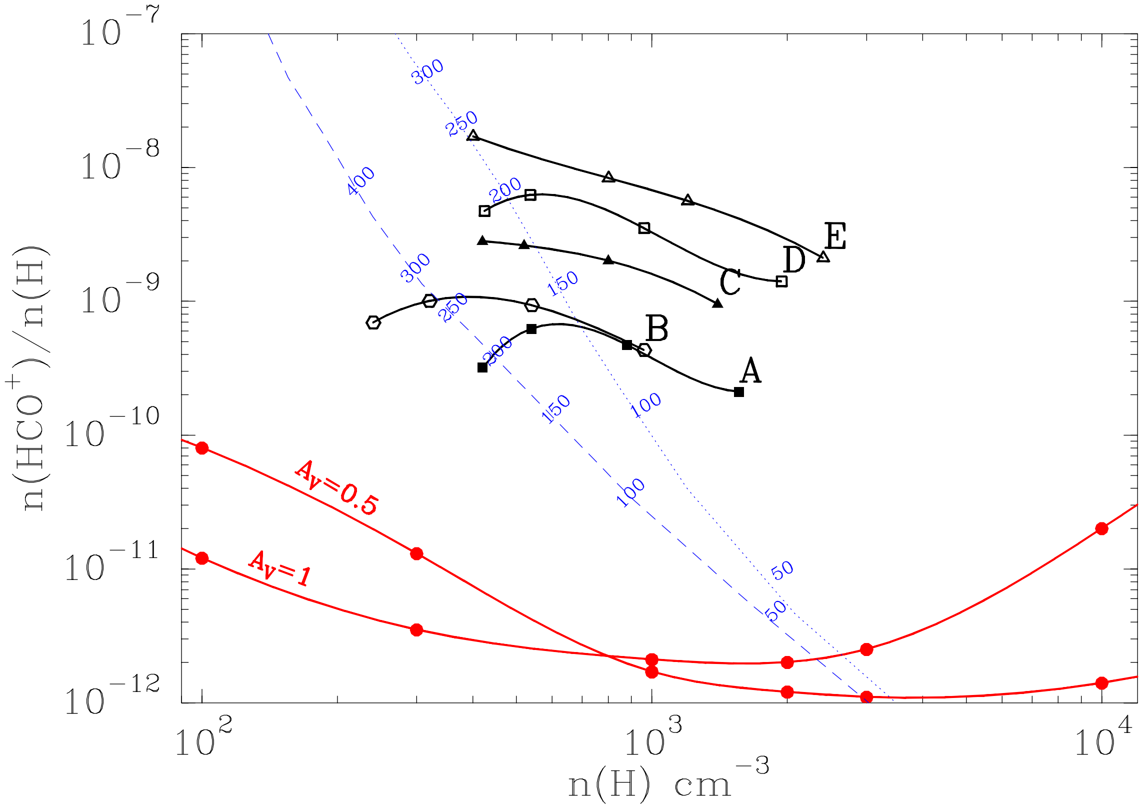




Observed HCO^+ abundances are **more than one order of magnitude** above predictions of **steady-state chemical models**: non-equilibrium chemistry

Falgarone, Pineau des Forêts, Hily-Blant & Schilke 2006

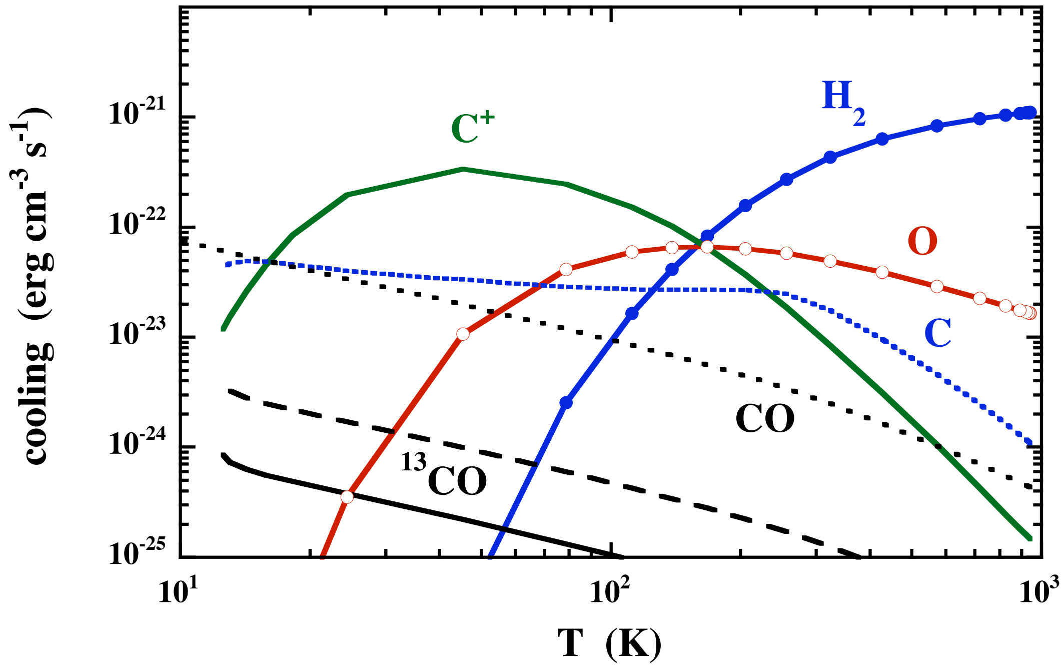
Relaxation tracks versus observed HCO^+ abundances



Cooling tracks for same initial density and two different UV shieldings, $A_v = 0.5$ and 1 mag.

Observations meet models in the range $T = 100$–200 K, $n = 200$–$10^3\,\mathrm{cm}^{-3}$

Energy balance: observations versus relaxation model



For gas at $T_k = 100$ to 200 K, $\Lambda_{tot} = 30$ to $40\ \Lambda_{CO}$
Radiation of the wing structures balances the turbulent energy input for a volume filling factor:
$f_v = \bar{\epsilon}_{turb}/\Lambda_{tot} = 0.02$ to 0.03
for $\Lambda_{tot} = 2\text{–}3\times10^{-22}$ erg cm^{-3}s^{-1} and $\bar{\epsilon}_{turb} = 6\times10^{-24}$ erg cm^{-3}s^{-1}

Conclusions and Open Questions

In translucent molecular gas:

• intermittency of velocity field similar to that of incompressible/mildly compressible turbulence

• intermittency more pronounced in most turbulent field at large scale

• observed intermittent structures: thickness: $\leq$ 0.02 pc, down to 7mpc, coherent over $\sim$ 3pc or more

• signposts of turbulence dissipation (thermal, chemical, radiative)

Open questions:

- nature of these structures, unlikely to be shocks
- role of magnetic fields
- actual smallest scale (ALMA) and radiative cooling rate (Herschel/HIFI)