What to extract from cloud molecular line surveys?

The power of heterodyne spectroscopy

E. Falgarone
LERMA/LRA, Ecole Normale Supérieure & Observatoire de Paris, France

P. Hily-Blant
IRAM, Grenoble, France

Collaborators: J. Pety (IRAM, France) and **G. Pineau des Forêts** (IAS, Orsay, France).

Mean viscous dissipation rate of turbulence:

$$\epsilon \propto \mid \nabla \times v \mid^2 + \mid \nabla . v \mid^2$$

Two contributions: **solenoidal (vorticity, shear)** and compressional (shocks)

The tool: statistics of increments of line centroid velocities

Line centroid velocity:

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

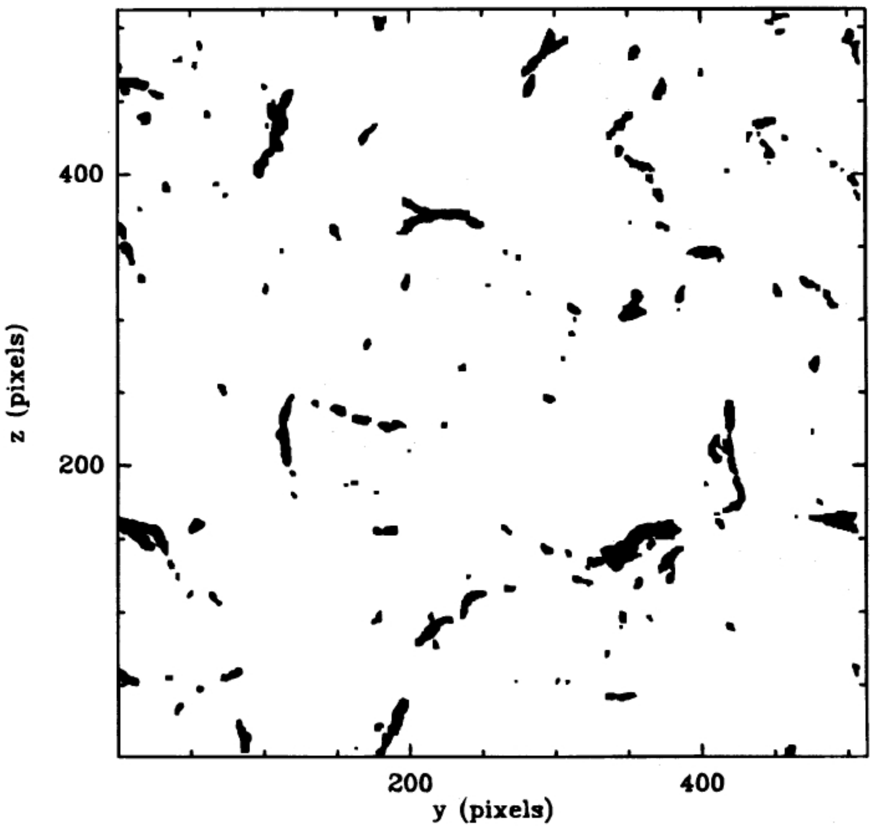
Miesch & Scalo 1999, Brunt et al. 2003, Miville-Deschênes et al. 2003, Levrier 2004, Ossenkopf et al. 2006, Esquivel & Lazarian 2005, ...

Extrema of line centroid increments **(E-CVIs)** trace extrema of:

$(\langle\omega_y\rangle^2 + \langle\omega_z\rangle^2)^{1/2} = (\langle\partial v_x/\partial y\rangle^2_{los} + \langle\partial v_x/\partial z\rangle^2_{los})^{1/2}$

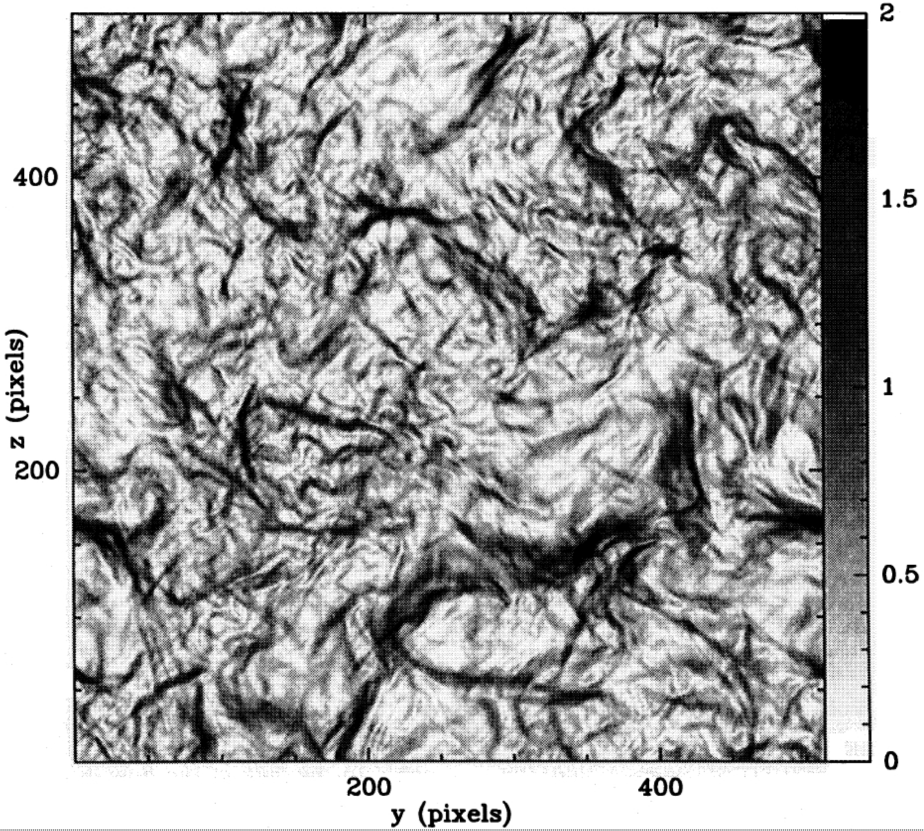
Lis et al. 1996, Pety & Falgarone 2003

E-CVIs as tracers of vorticity distribution



Ensemble of largest CVIs, data cube of mildly compressible turbulence

Porter et al. 1993

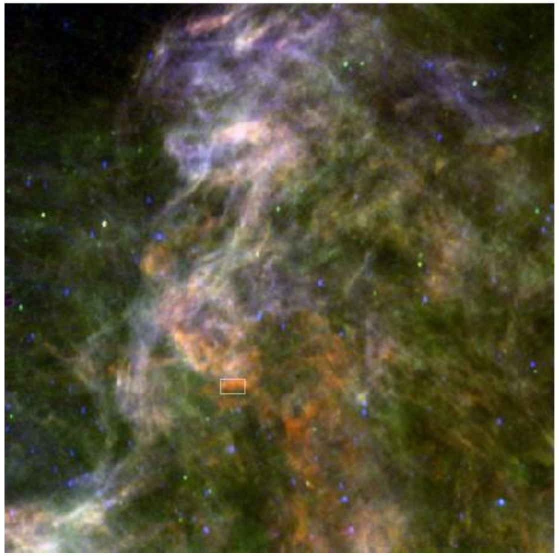


Map of

$$\langle \Omega_{sky} \rangle_{LOS} = (\langle \omega_y \rangle^2 + \langle \omega_z \rangle^2)^{1/2}$$

Lis et al. 1996

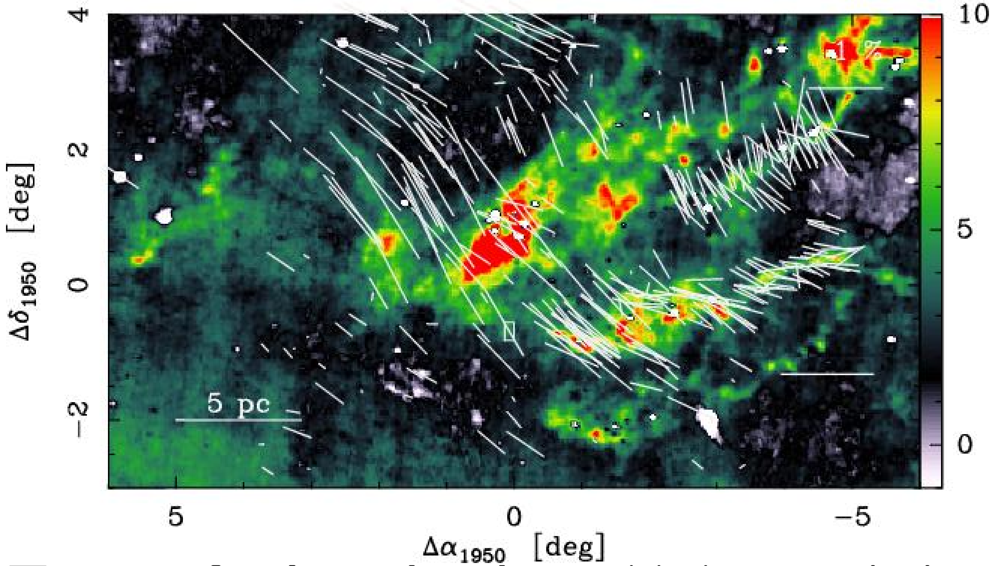
Large scale environments: 30-parsec scale



Polaris flare: 27 pc × 27 pc field

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

Miville-Deschênes & Lagache 2005



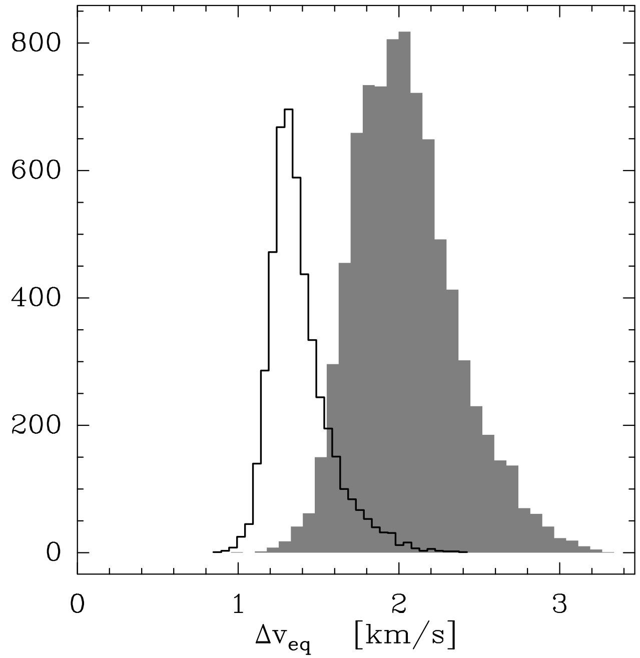
Taurus-Auriga clouds: cold dust emission

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

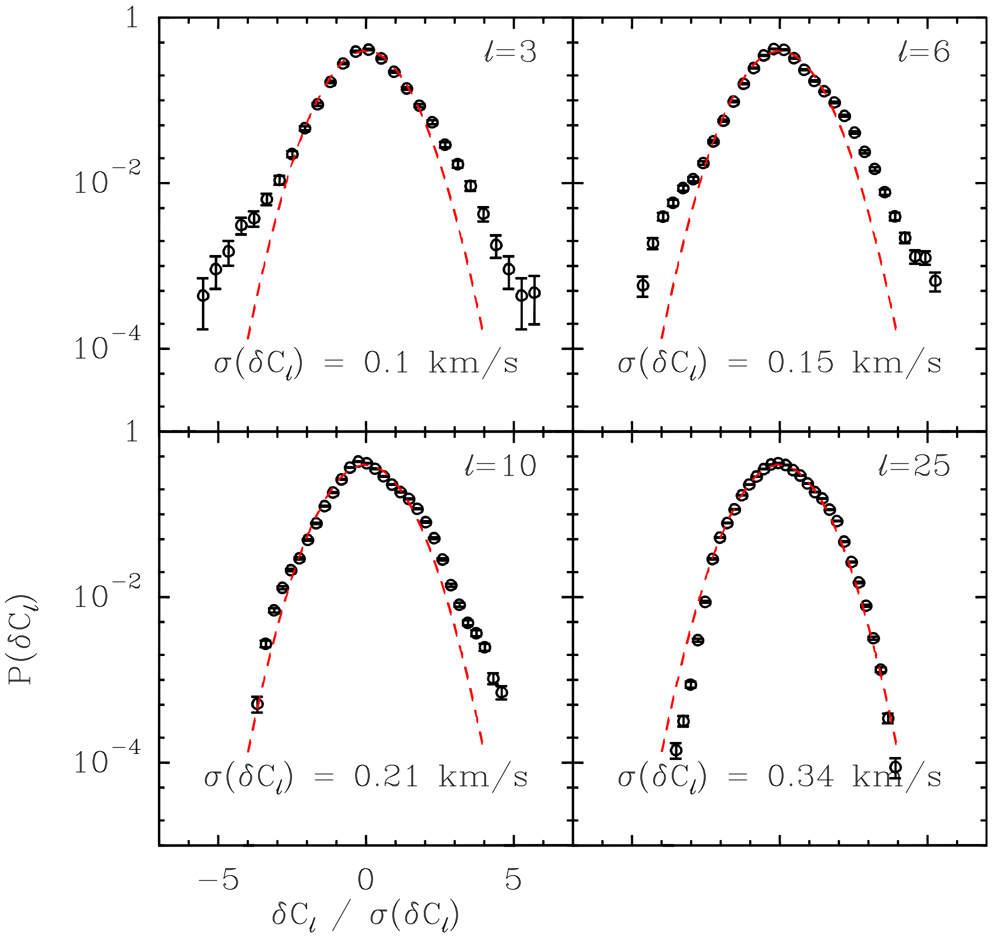
dense core environment

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

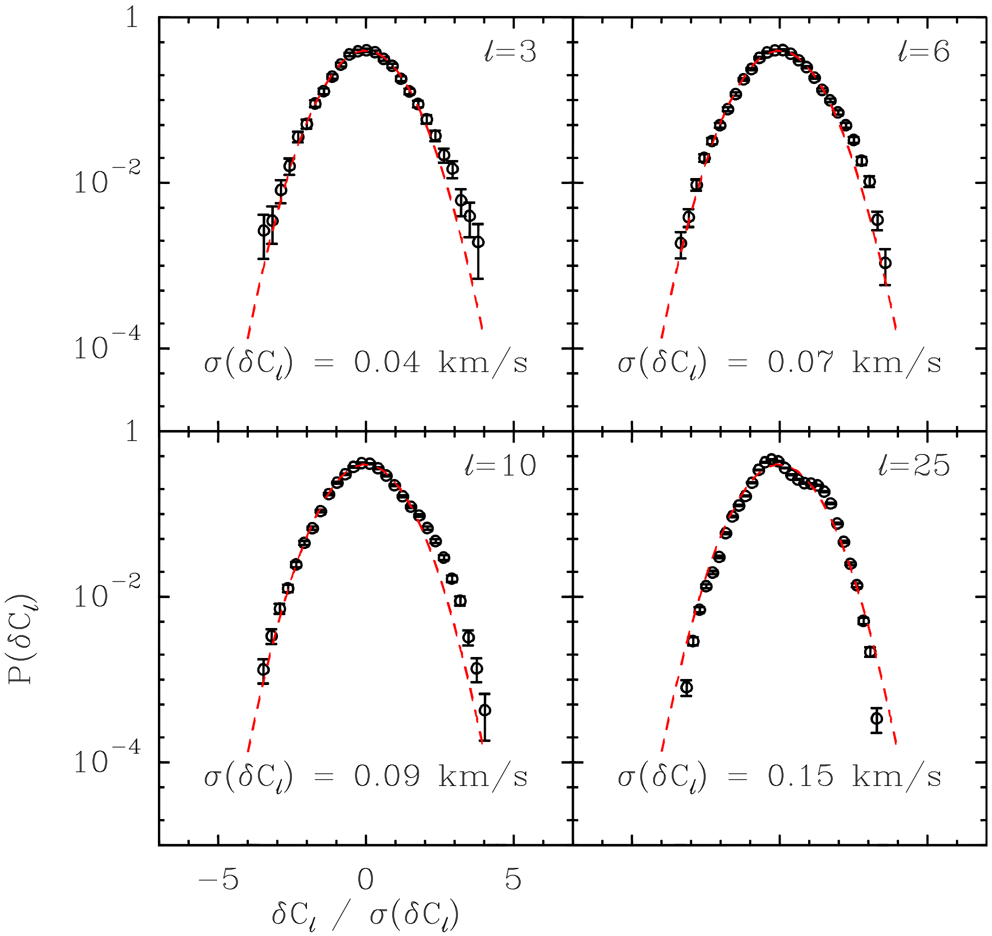
Taurus (left) – Polaris (right)

PDFs of Centroid Velocity Increments with variable lags

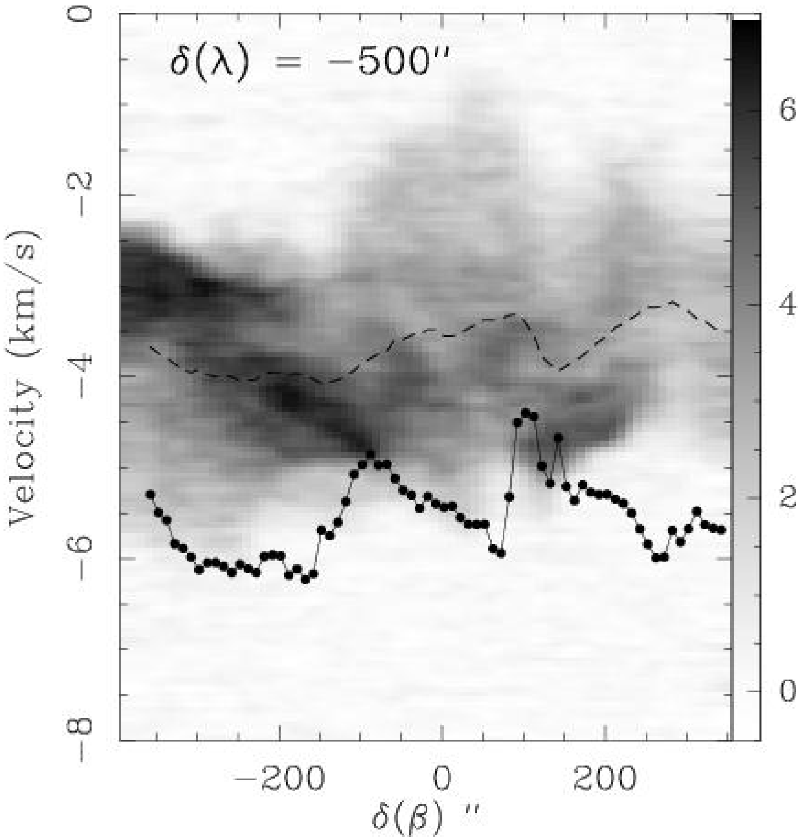
Polaris

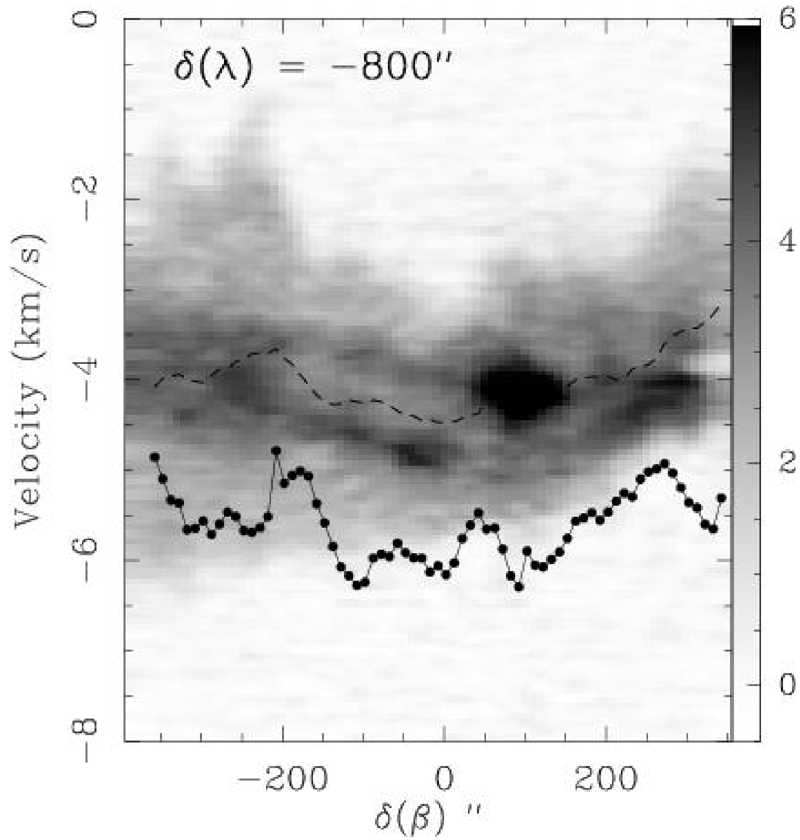


Taurus



Where do the CVI extrema come from?





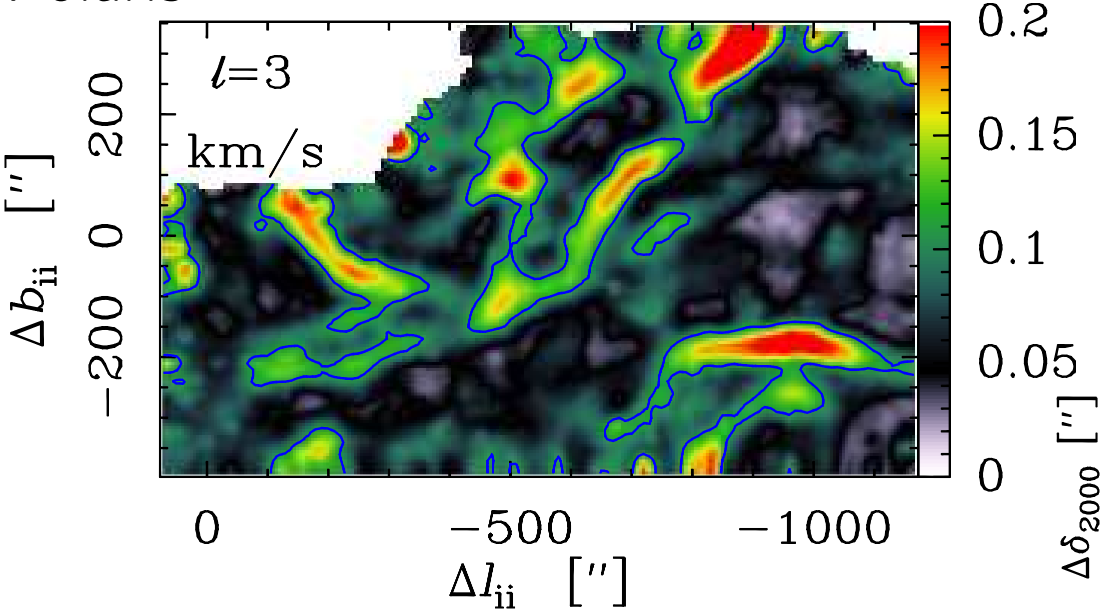
Space-velocity cuts of ^{12}CO(1-0) line intensity, (grey scale in K), line centroid (dashed), CVIs (dots), Hily-Blant, Falgarone, Pety 2007

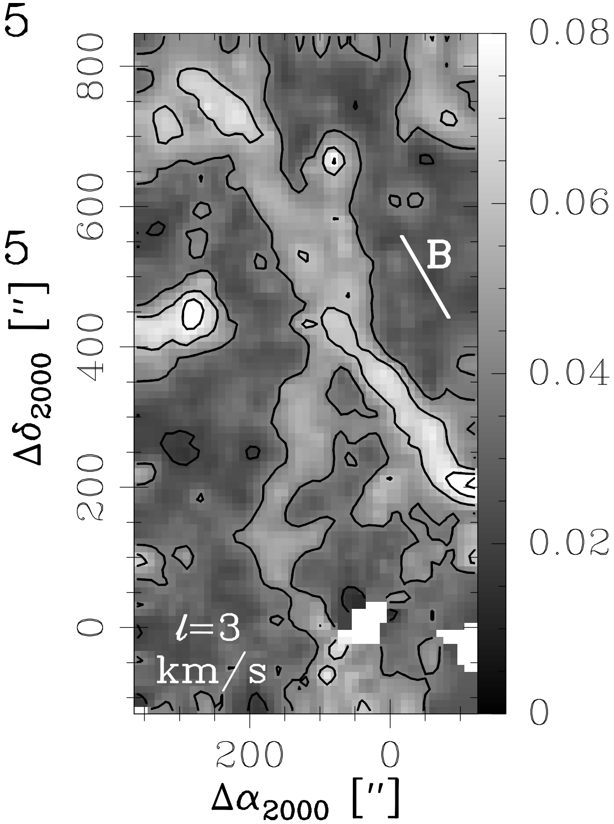
E-CVIs trace sharp local variations of optically thin ^{12}CO linewing

Spatial distribution of E-CVIs

Taurus

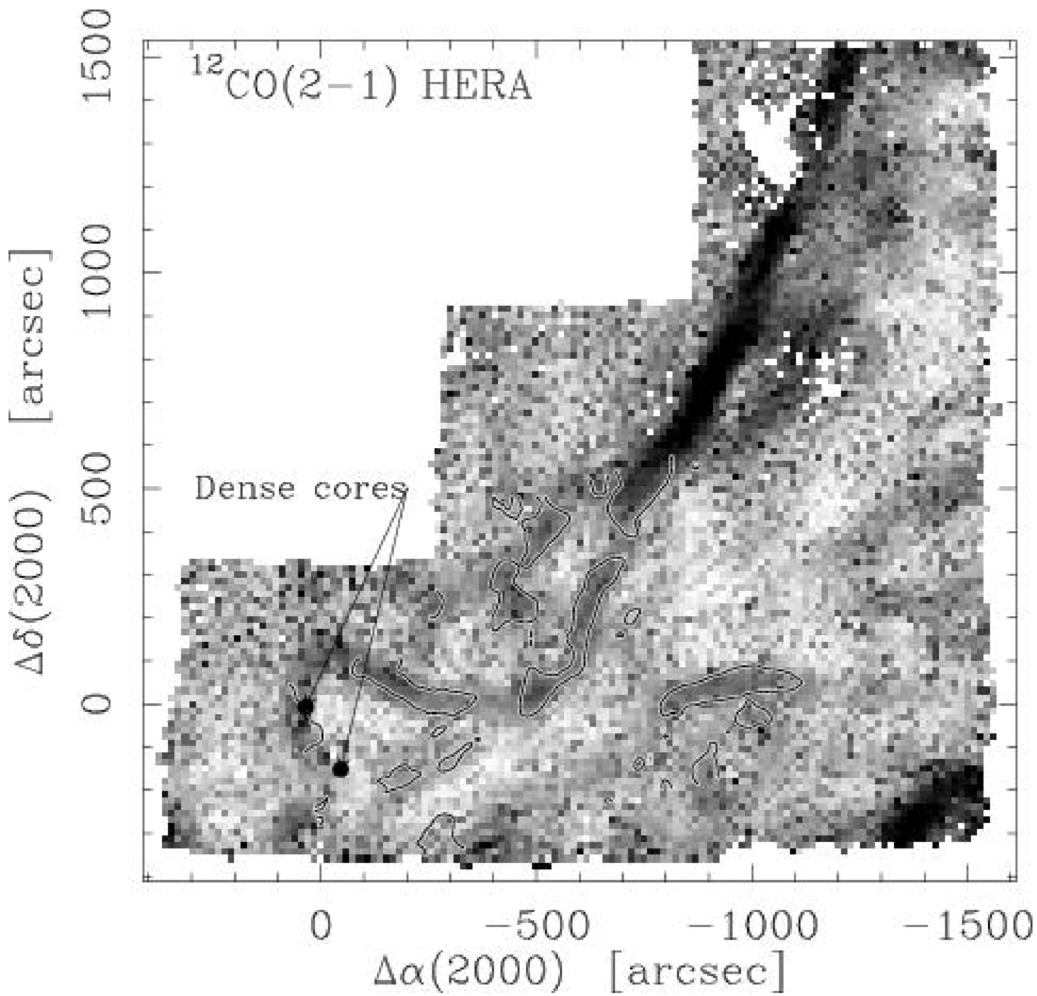
Polaris





- 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

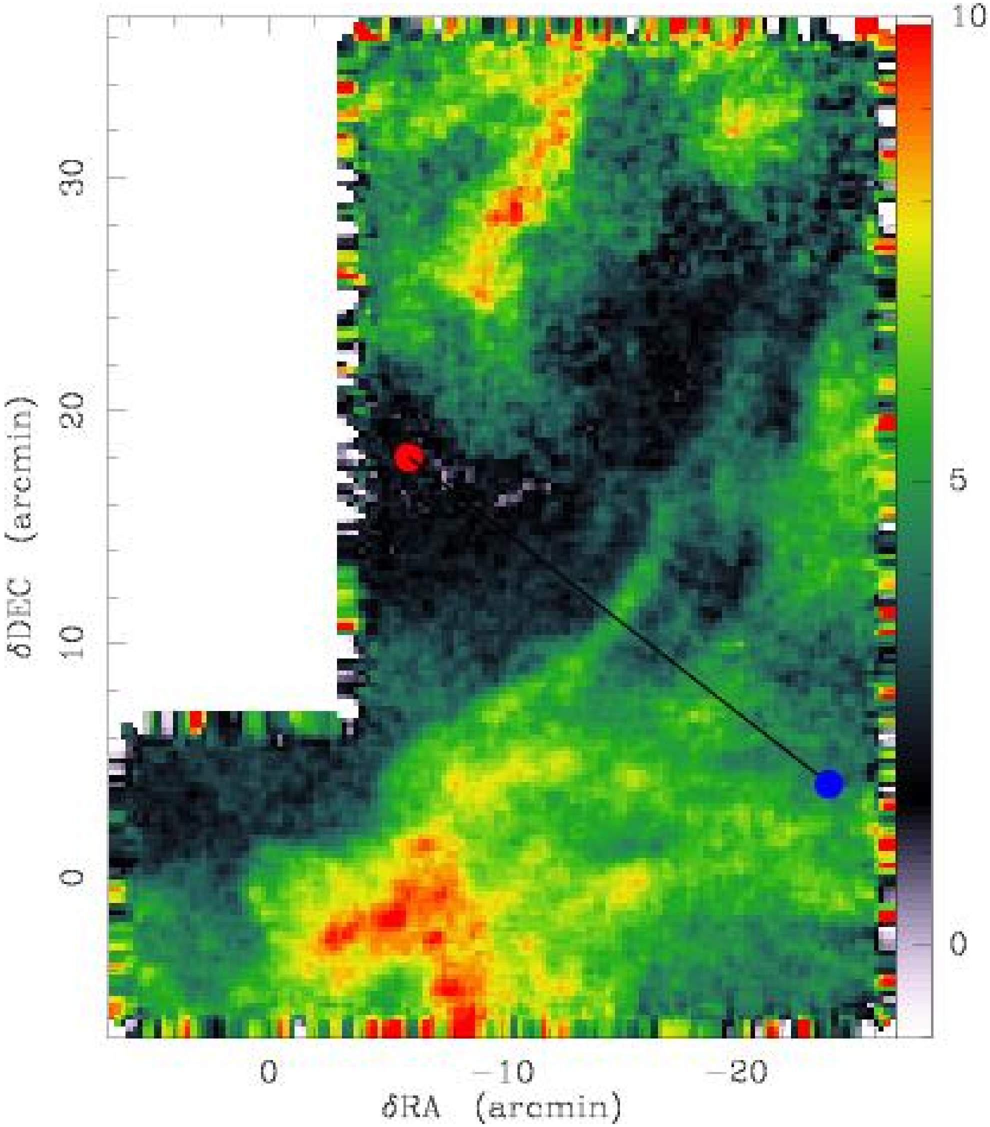
Parsec scale coherence of E-CVIs structures

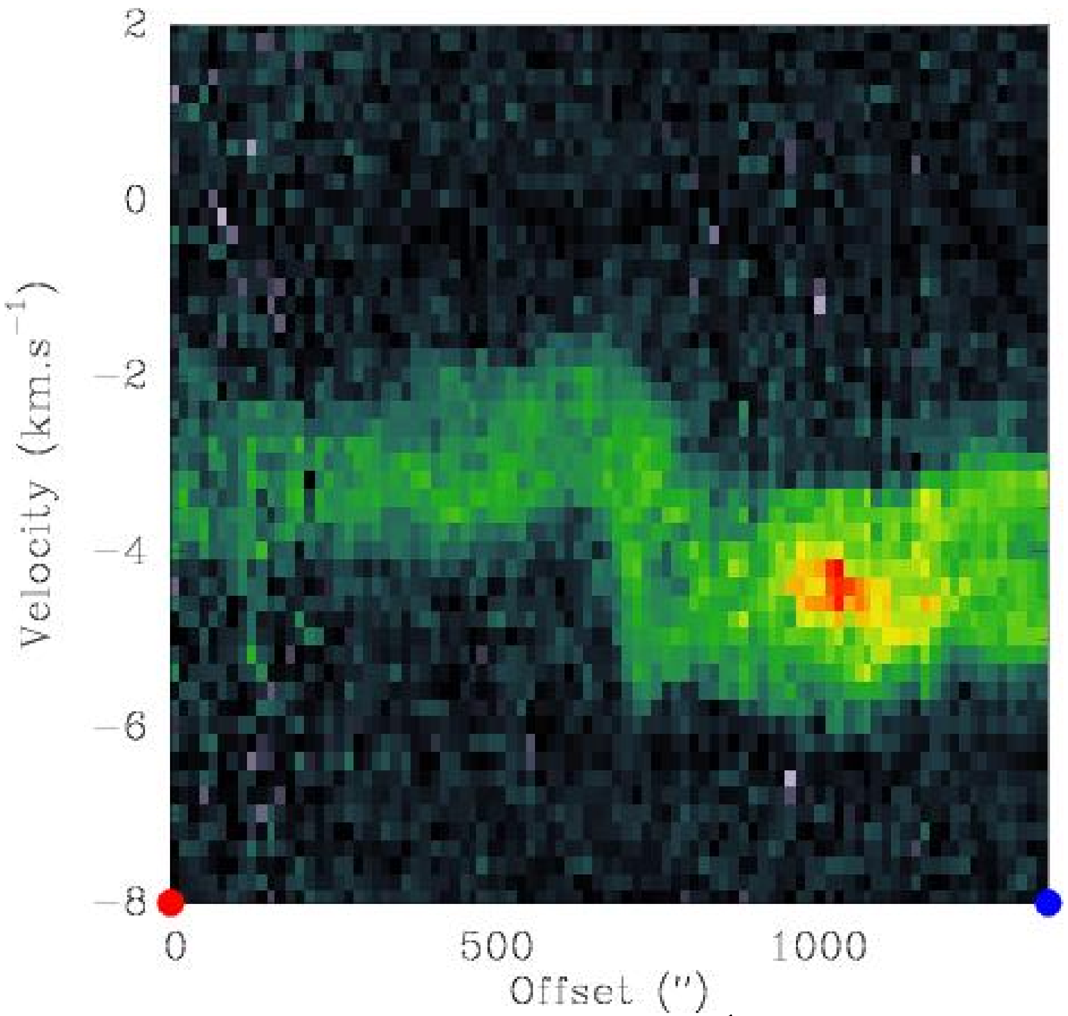


IRAM OTF-FS HERA (map in progress)
resolution 11" or 8 mpc
3.5 10^4 independent spectra
Hily-Blant et al. 2008
Dense cores Bertoldi et al. 2002

^{12}CO(1-0) integrated intensity map and space-velocity cut

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

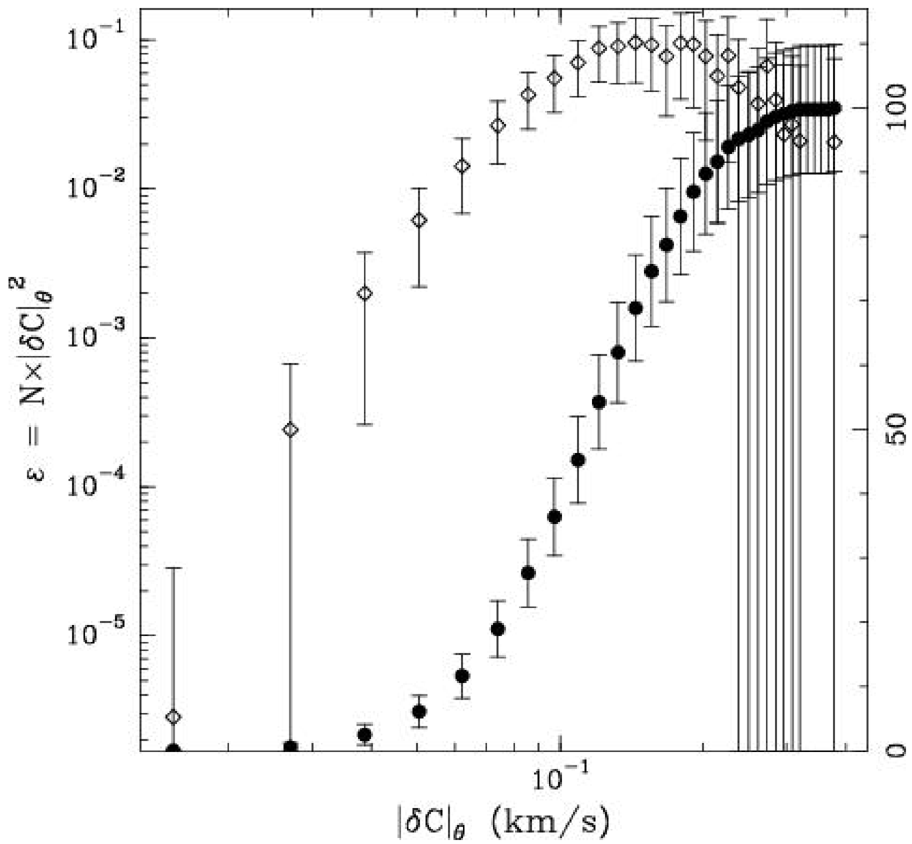




Max velocity shear: ~ 40 km s^{-1}/pc

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

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)

→ 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

Conclusions and Open Questions

In translucent molecular gas:

• highly coherent structures of large velocity shear disclosed with 2-point statistics of line centroid velocity

• intermittency of turbulence dissipation (see talk of November 2)

- dissipation more pronounced in more 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 almost pure velocity structures, unlikely to be shocks
- role of magnetic fields
- actual smallest scale (ALMA) and radiative cooling rate (Herschel/HIFI)