Pre-collapse phase studies before Herschel

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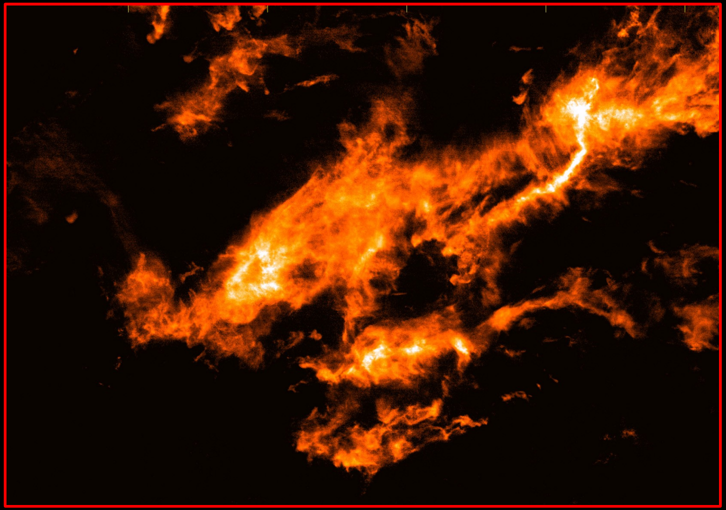
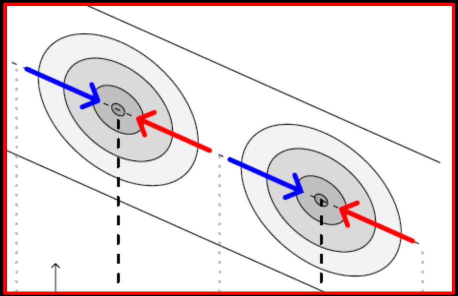
Plan of the talk

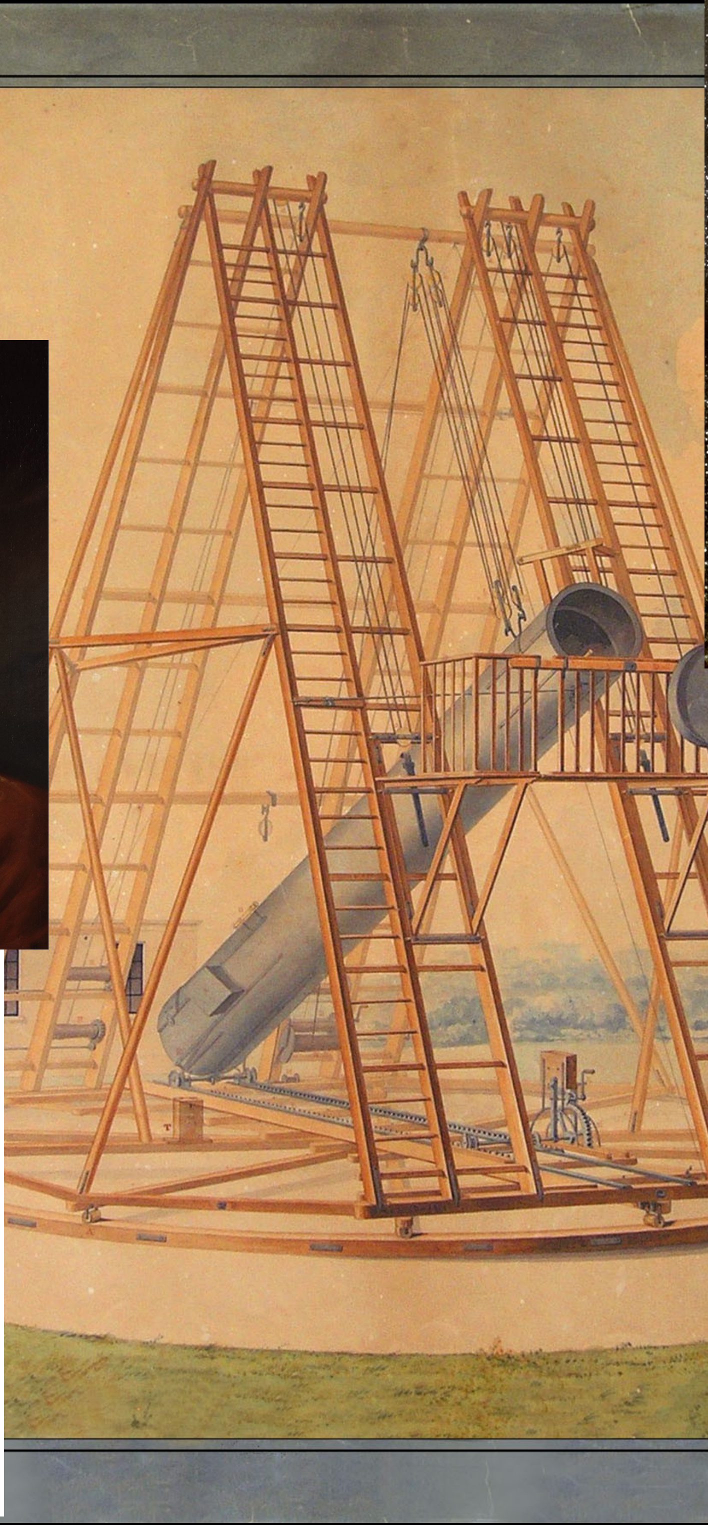
Large Scale
(clouds)

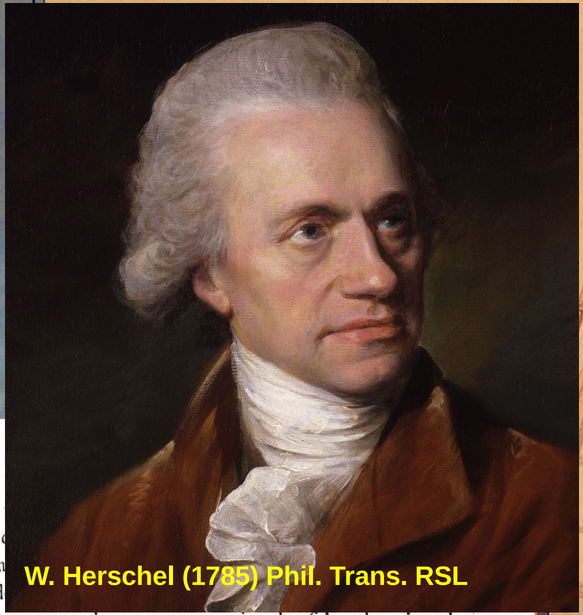


Small Scale
(cores)

From clouds
to cores







hundreds
the nebul
extended a
for the d
great one to approach nearer to us in the fides than in other parts. Nay, poffibly, there might originally be another very large joining branch, which in time became feparated by the condenfation of the ftars; and this may be the reafon of the little remaining breadth of our fyftem in that very place: for the nebulæ of the ftratum of the Coma are brighteft and moft crowded juft oppofite our fituation, or in the pole of our fyftem. As foon as this idea was fuggefted, I tried alfo the oppofite pole, where accordingly I have met with a great number of nebulæ, though under a much more fcattered form.

An Opening in the heavens.

Some parts of our fyftem indeed feem already to have fuftained greater ravages of time than others, if this way of expreffing myfelf may be allowed; for inftance, in the body of the Scorpion is an opening, or hole, which is probably owing to this caufe. I found it while I was gaging in the parallel from 112 to 114 degrees of north polar diftance. As I approached the milky way, the gages had been gradually running up from

"..among the most surprising things in connection with these nebula-filled holes are the vacant lanes that so frequently run from them for great distances."

E.E. Barnard (1907)

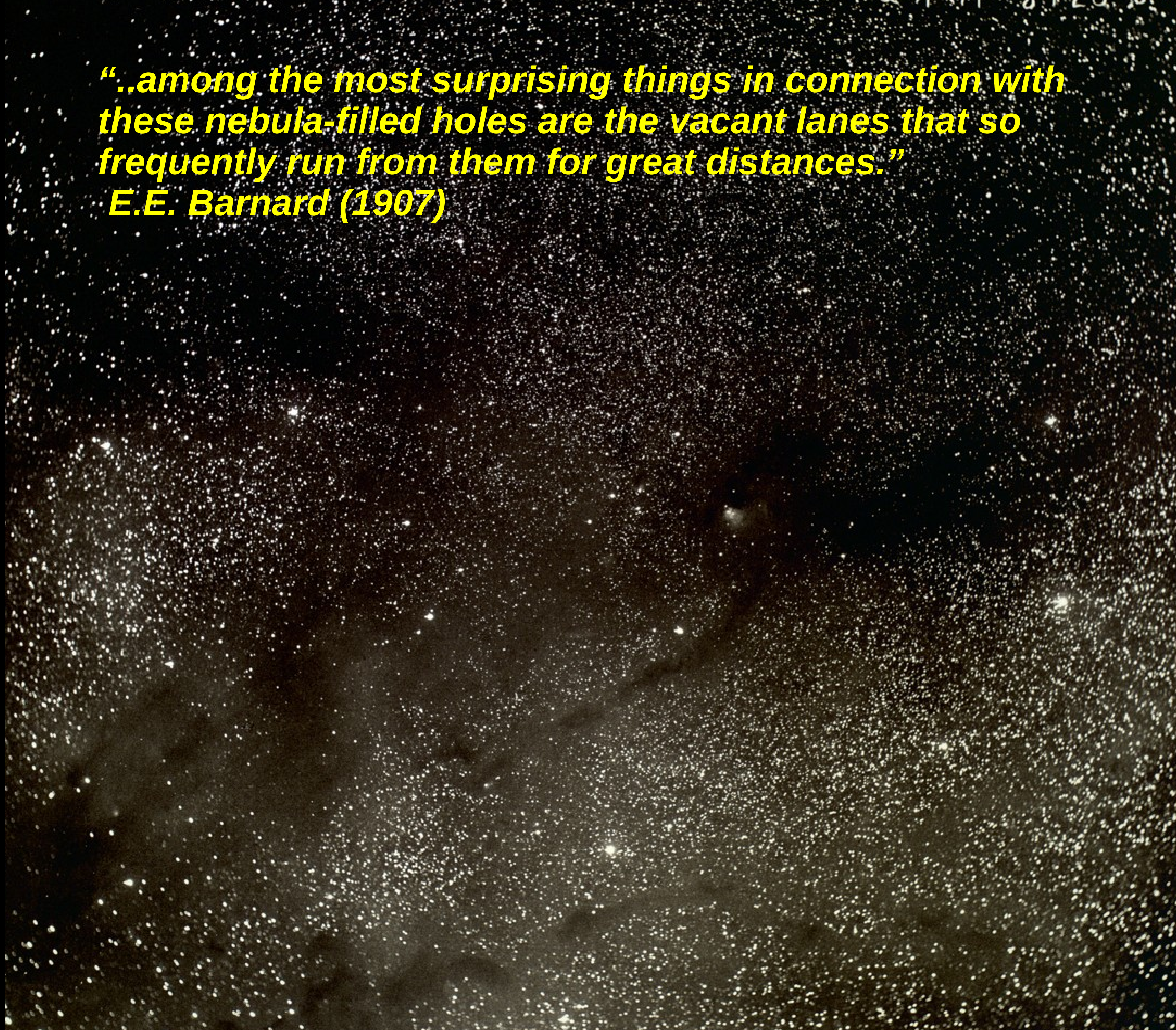


Figure 7. NGC 1333 in the west part of Perseus, in a deep optical image (nightskyphotography.com), showing the embedded cluster and five filamentary extensions. The scale bar indicates 1 pc.

(A color version of this figure is available in the online journal.)

Figure 1 shows a deep optical image of the reflection nebula NGC 7023, situated in the hub of high extinction in L1174 (Lynds 1962; tvdavisastropics.com). The extinction extends south in L1172 and can be seen for nearly 5 pc, as a single filamentary lane with a small side branch to the east. This hub with a single filament resembles the "head–tail" structure described by Tachihara et al. (2002), whereas all of the other

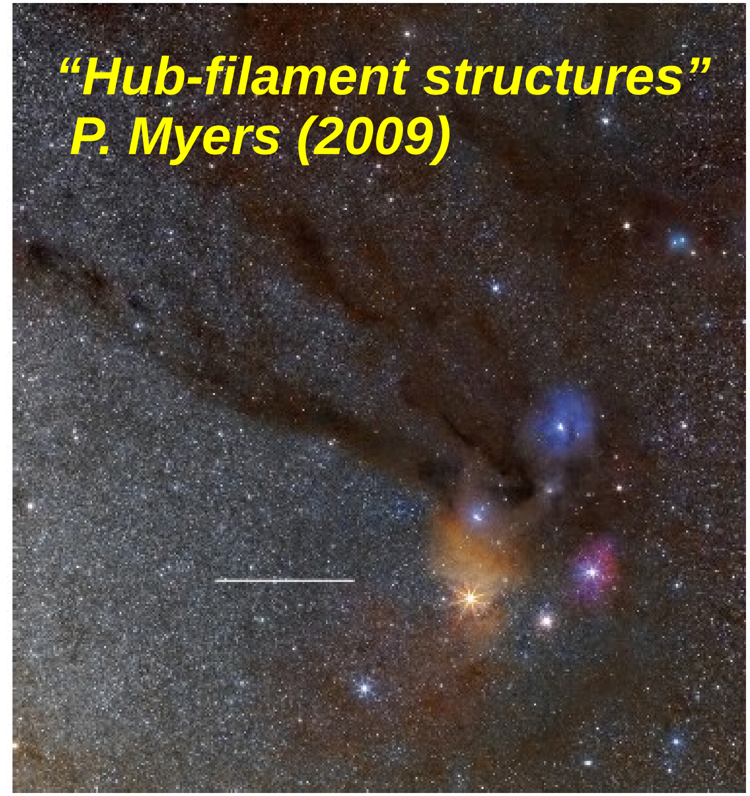
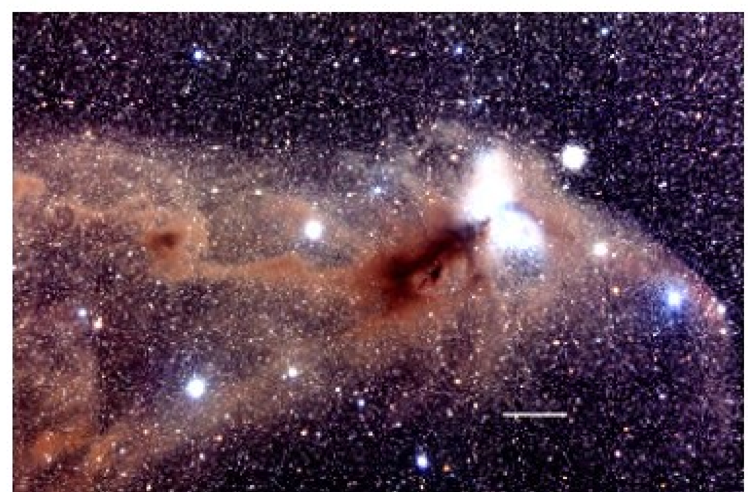


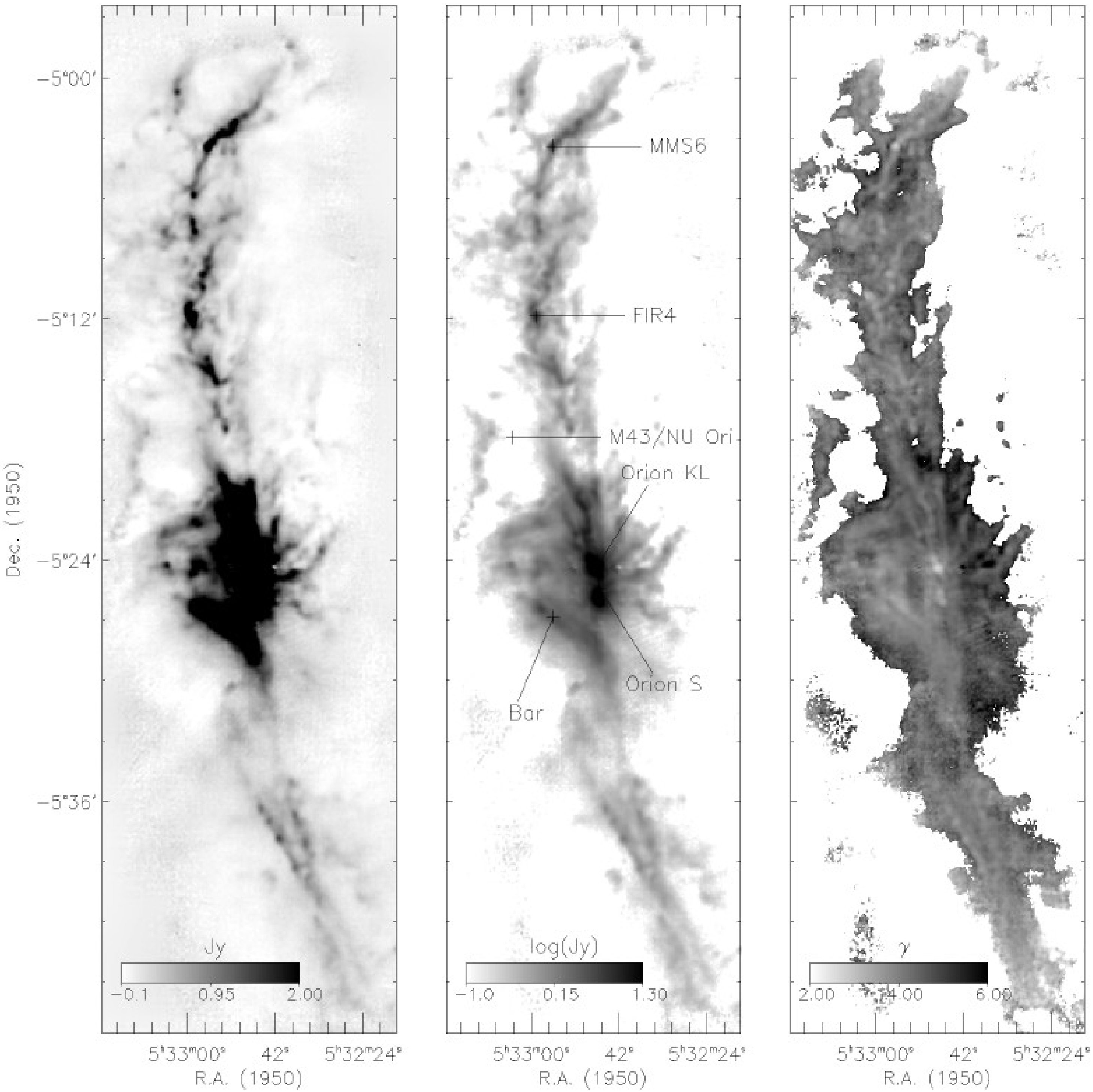
Figure 8. Ophiuchus complex in a deep optical image (astromodelismo.es), showing the embedded cluster and four nearly parallel filaments extending to the NE, two curving filaments to the south, and a neighbor filament offset to the NW. The scale bar indicates 5 pc.

(A color version of this figure is available in the online journal.)

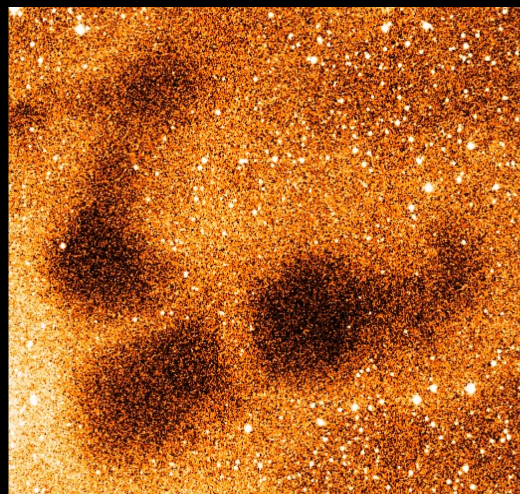


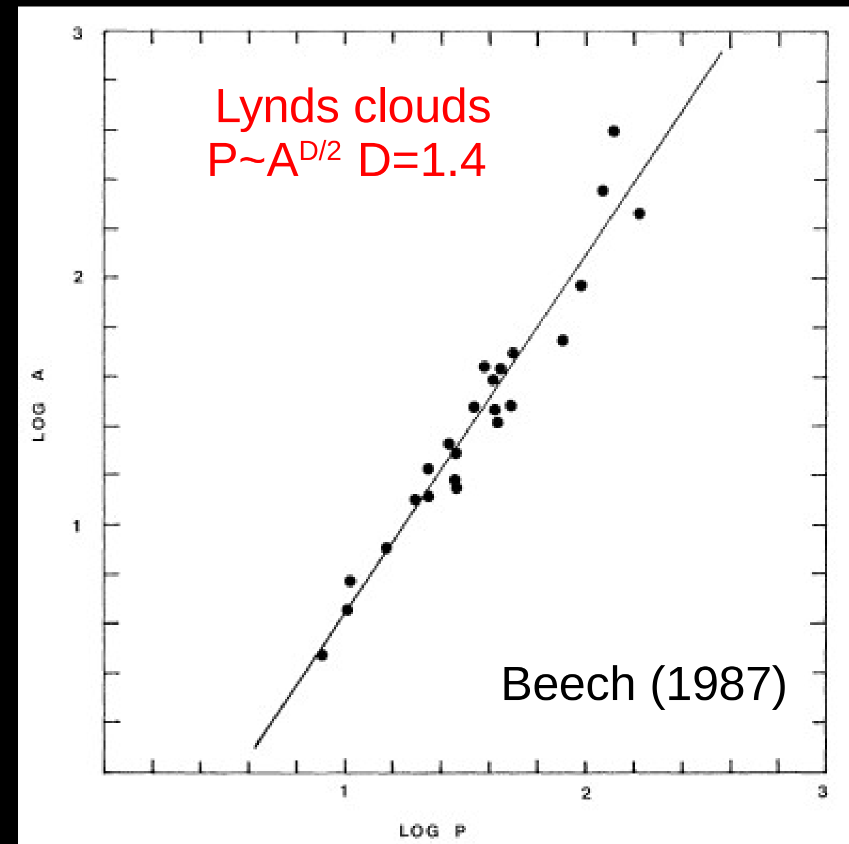
INTEGRAL-SHAPED FILAMENT IN ORION

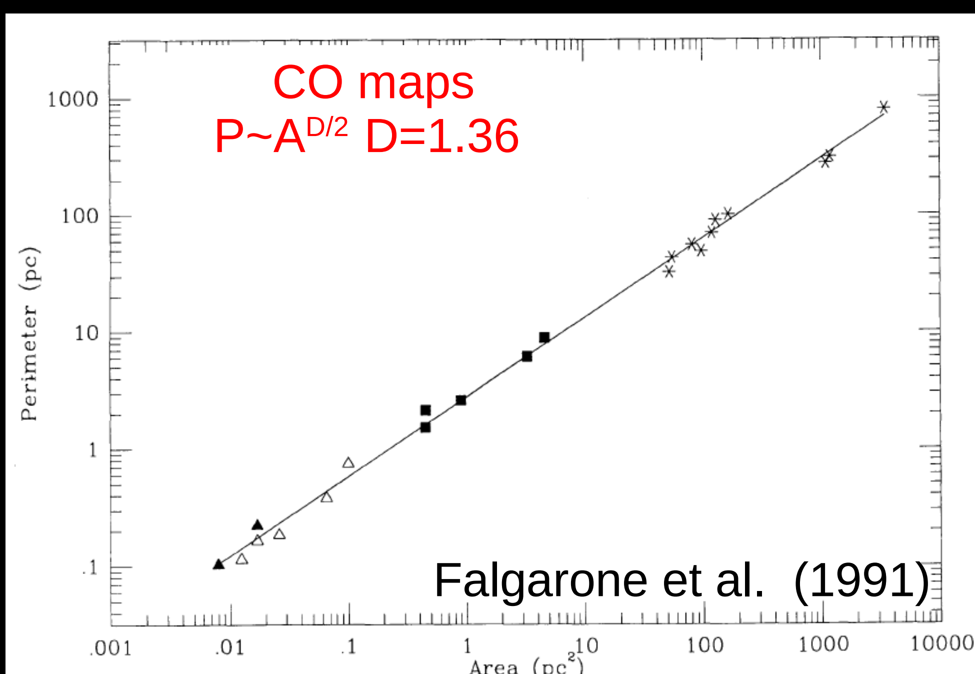
Johnstone & Bally (1999)

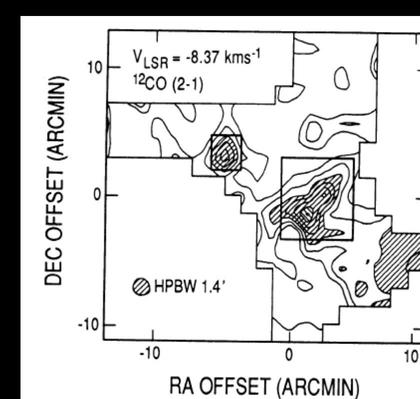


Quantifying cloud structure: fractals







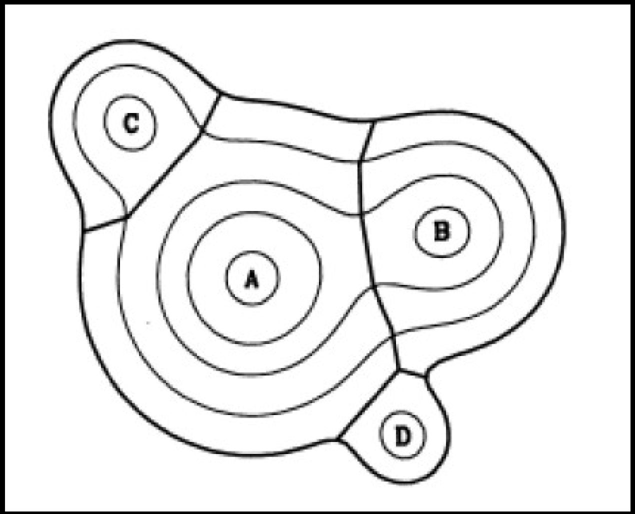


Quantifying cloud structure: fractals

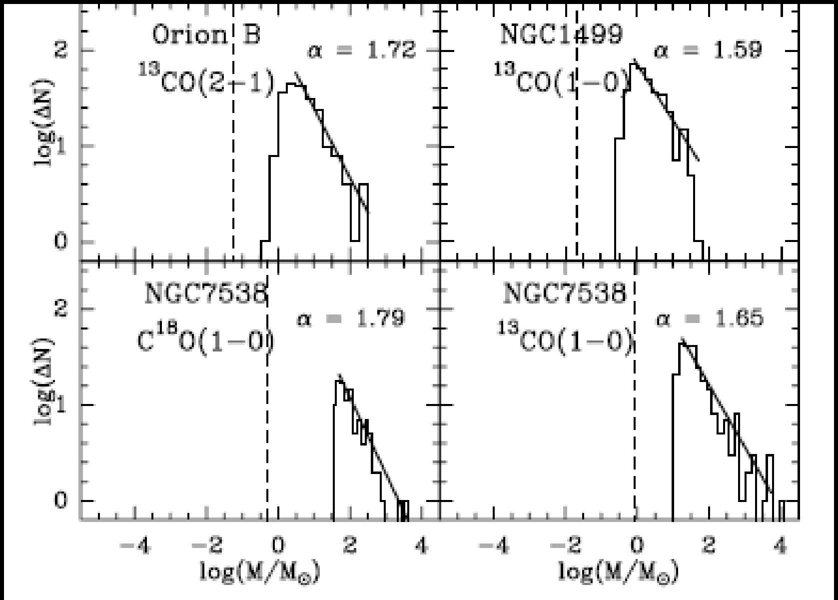
- Similar fractal dimensions
  - IRAS maps (Scalo 1990)
  - HI in high velocity clouds (Wakker 1990)
  - Laboratory turbulence (Sreenivasan 1991)

- What is the fractal dimension of Herschel cloud PACS/SPIRE maps?

Quantifying cloud structure: clumps



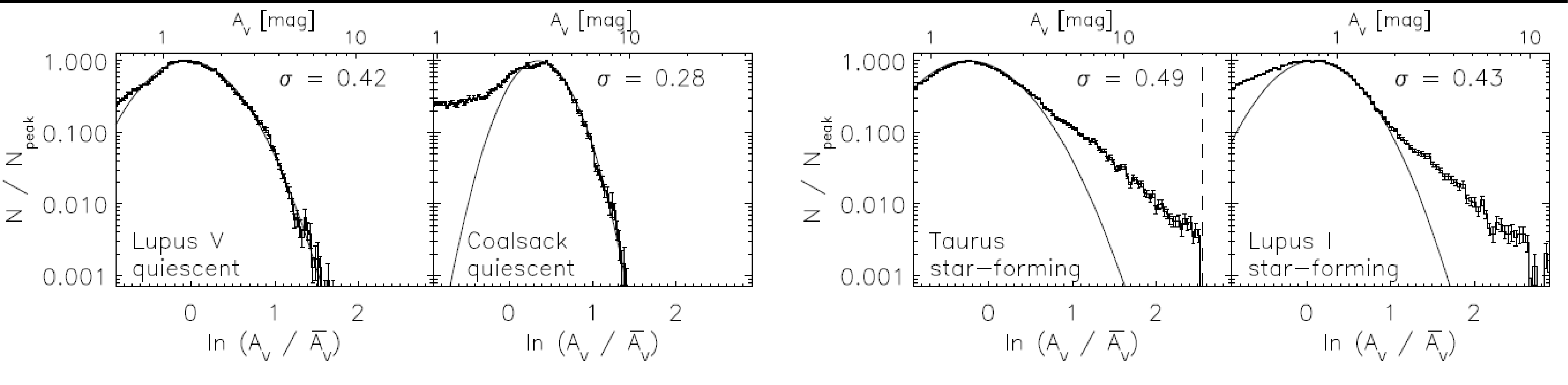
Williams et al. (1994)



Kramer et al. (1998)

- **Automatic clump-finding algorithms**
  - **Structure 10-1000 M$_o$**
  - **CLUMPFIND / GAUSSCLUMP**
- **Histograms: power law with slope ~ 1.7**
  - **consistent with fractal analysis (Elmegreen & Falgarone 1996)**

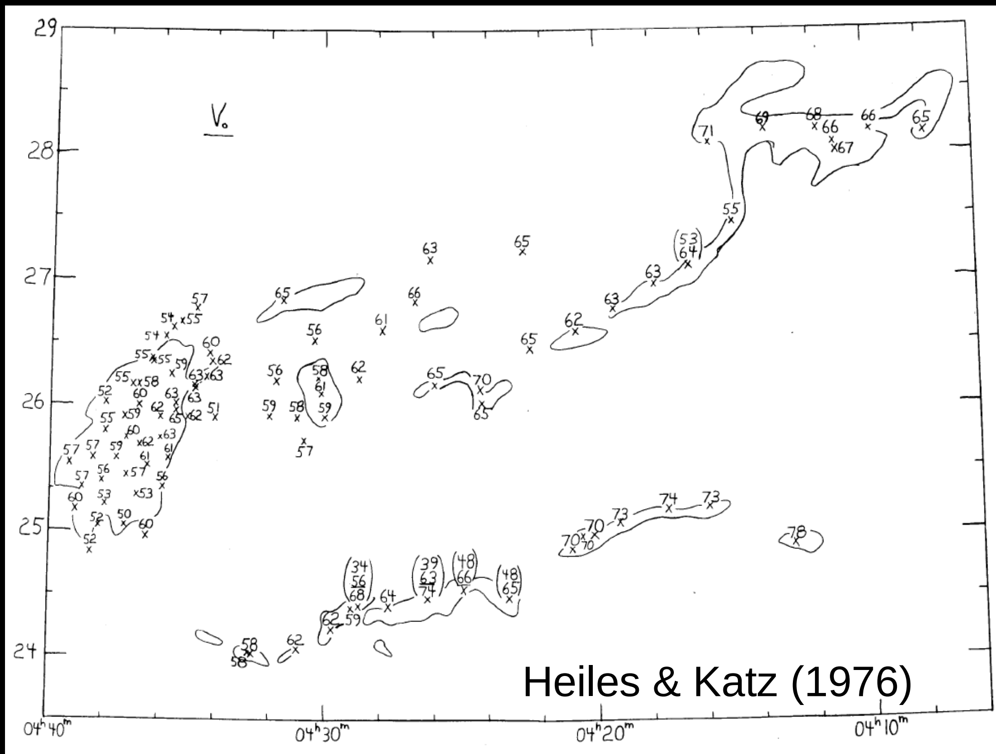
Quantifying cloud structure: PDF



Kainulainen et al. (2009)

- PDF: probability distribution function (volume, col. density,...)
- Isothermal turbulence simulations: log-normal
- Kainulainen et al. (2009)
  - 2MASS-derive extinction data for 23 clouds
  - linear tail at high column density if cloud is star-forming
  - gravity-dominated regime?

Velocity structure



Heiles & Katz (1976)

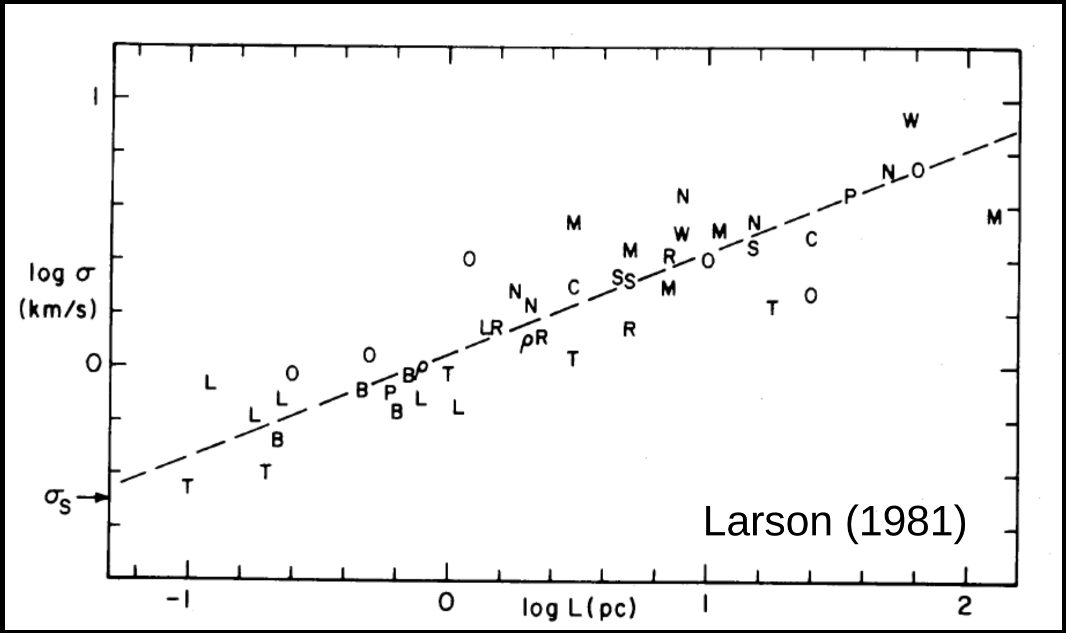
Table 1 Characteristic values of specific angular momentum

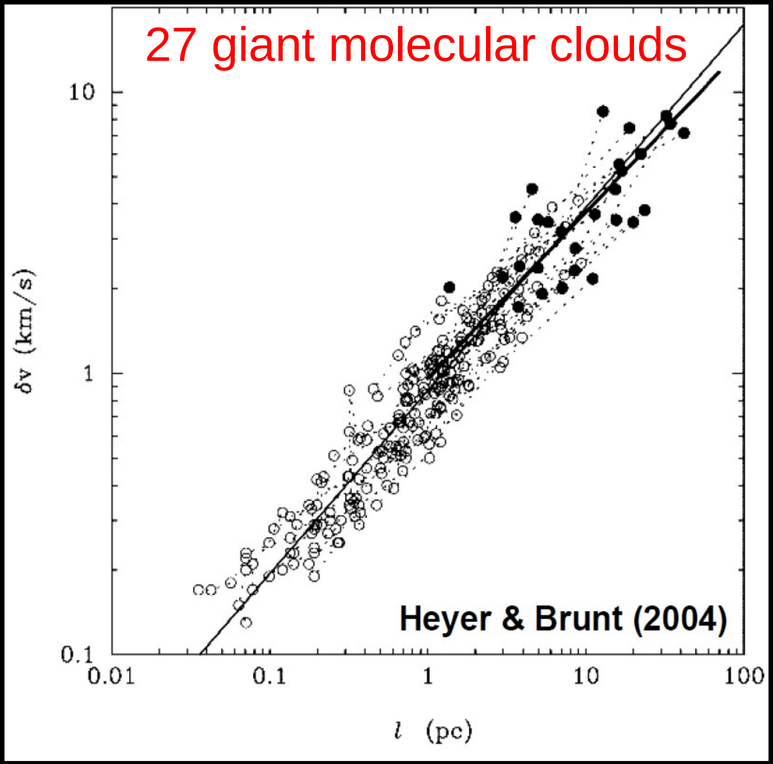
Object	J/M (cm^2 s^{-1})
Molecular cloud (scale 1 pc)	10^{23}
Molecular cloud core (scale 0.1 pc)	10^{21}
Binary (10^4 yr period)	4×10^{20}–10^{21}
Binary (10 yr period)	4×10^{19}–10^{20}
Binary (3 day period)	4×10^{18}–10^{19}
100 AU disk (1 $M_\odot$ central star)	4.5×10^{20}
T Tauri star (spin)	5×10^{17}
Jupiter (orbit)	10^{20}
Present Sun	10^{15}

Bodenheimer (1999)

- Clouds do not show global patterns of rotation, expansion or infall
- Cloud specific angular momentum is orders of magnitude larger than cores and stars
  - “angular momentun problem”

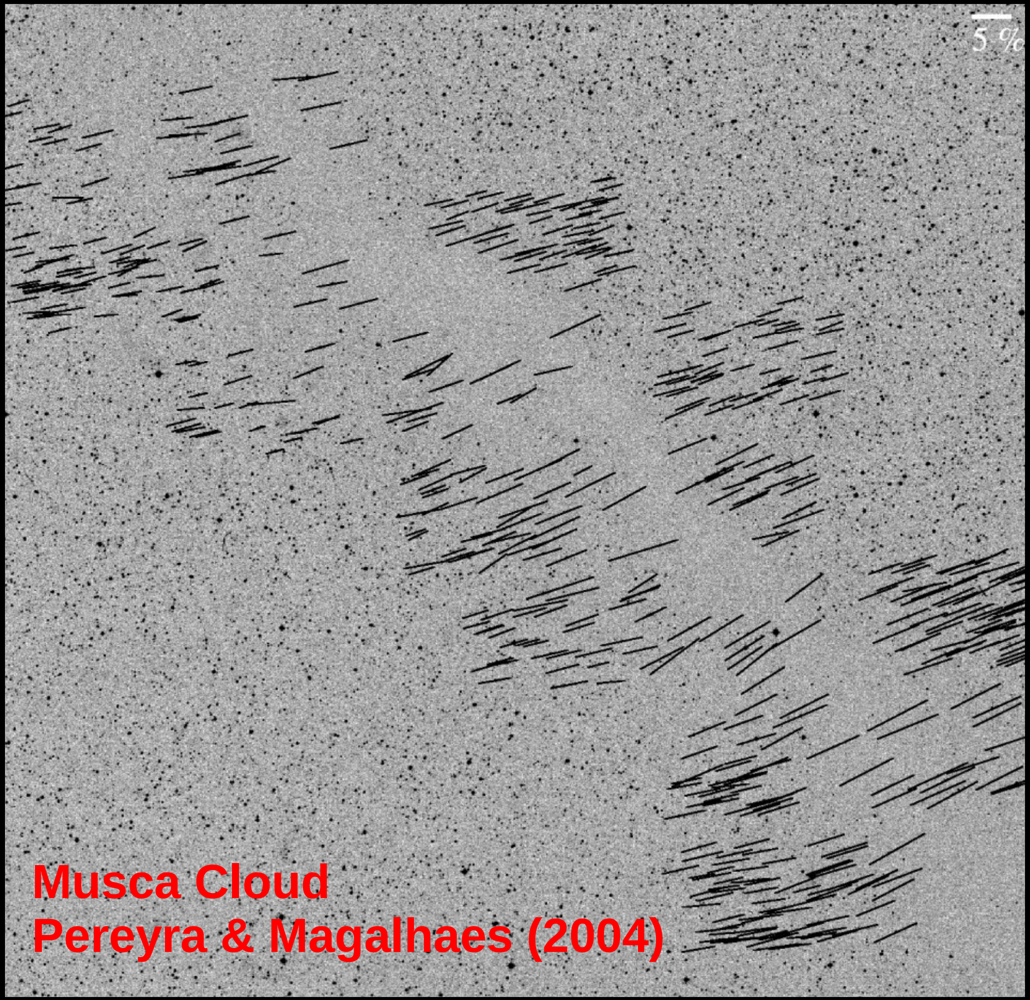
Velocity structure: turbulence?

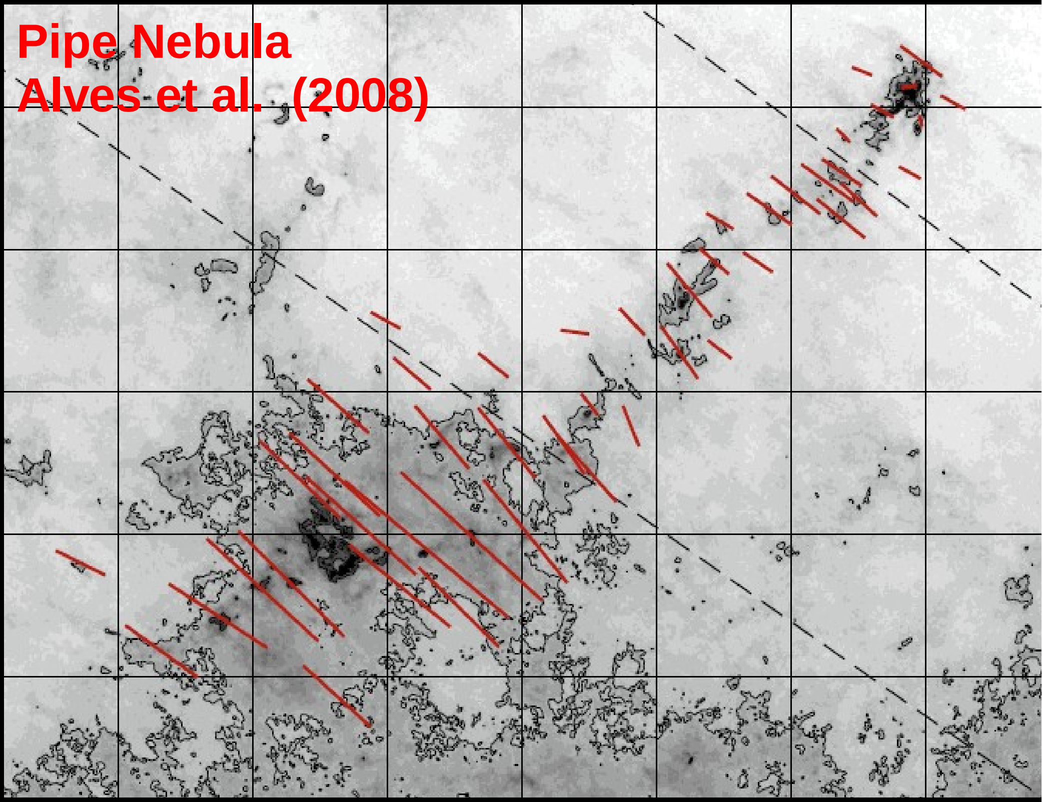




- Velocity dispersion proportional to cloud size
  - $\sigma(V)$ [km/s] = 1.1 L(pc)$^{0.38}$
  - Larson relation
- Reminiscent of turbulent motions

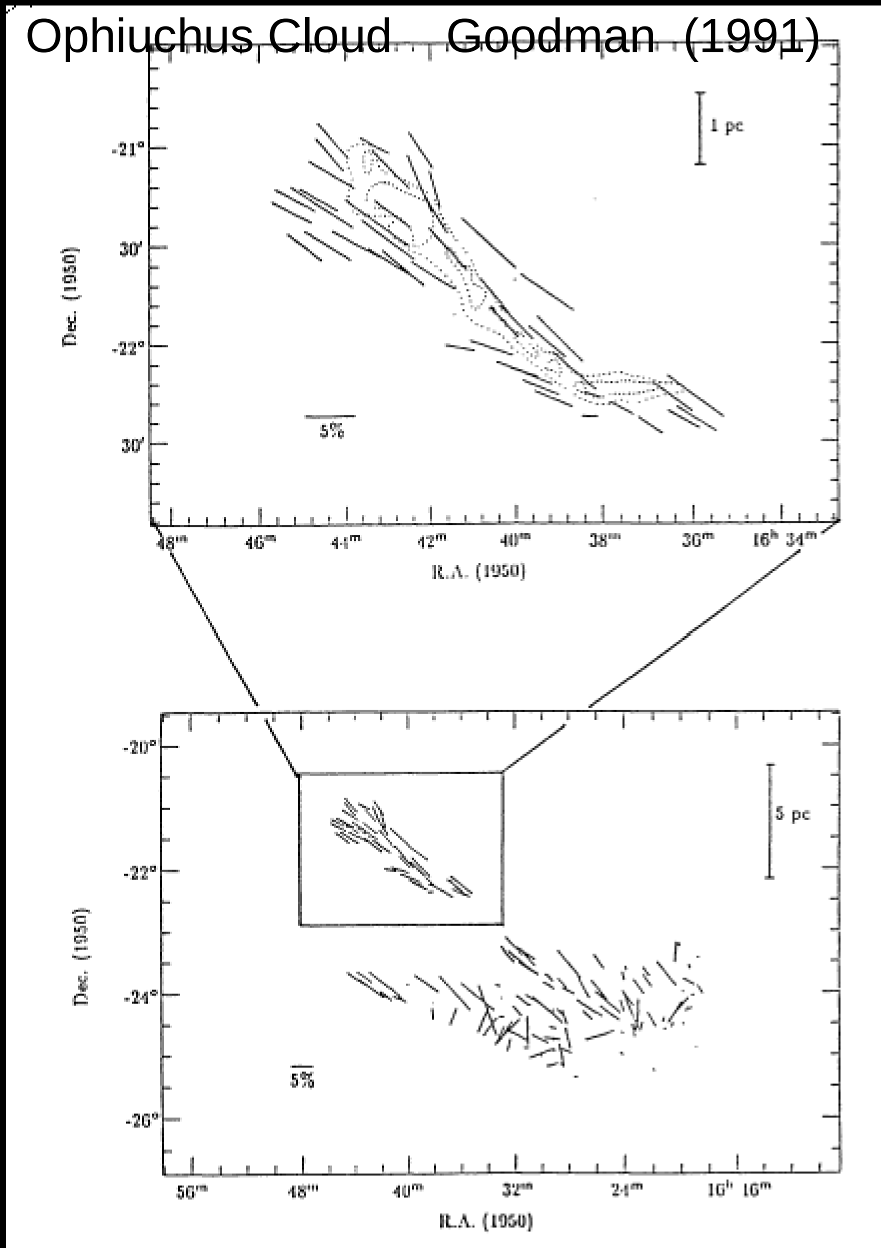
Magnetic field: geometry

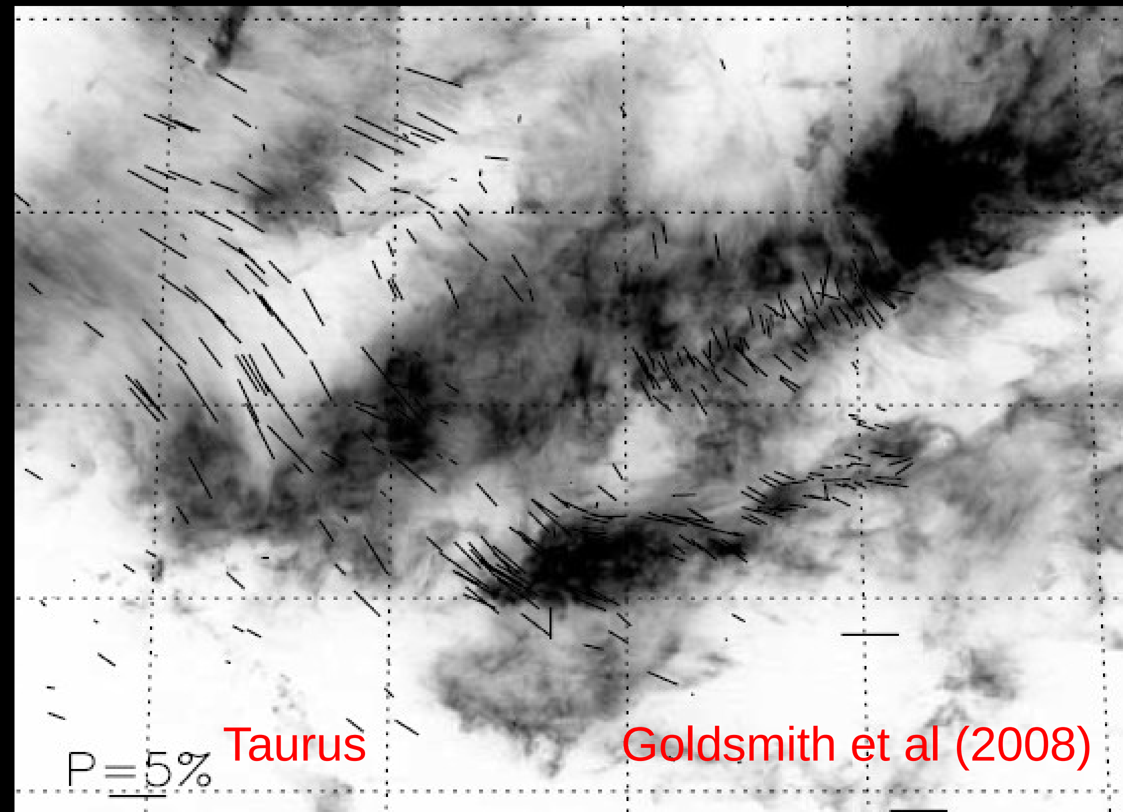




- Often cases of polarization (and B field) perpendicular to cloud axis
- Suggestive of contraction along field lines

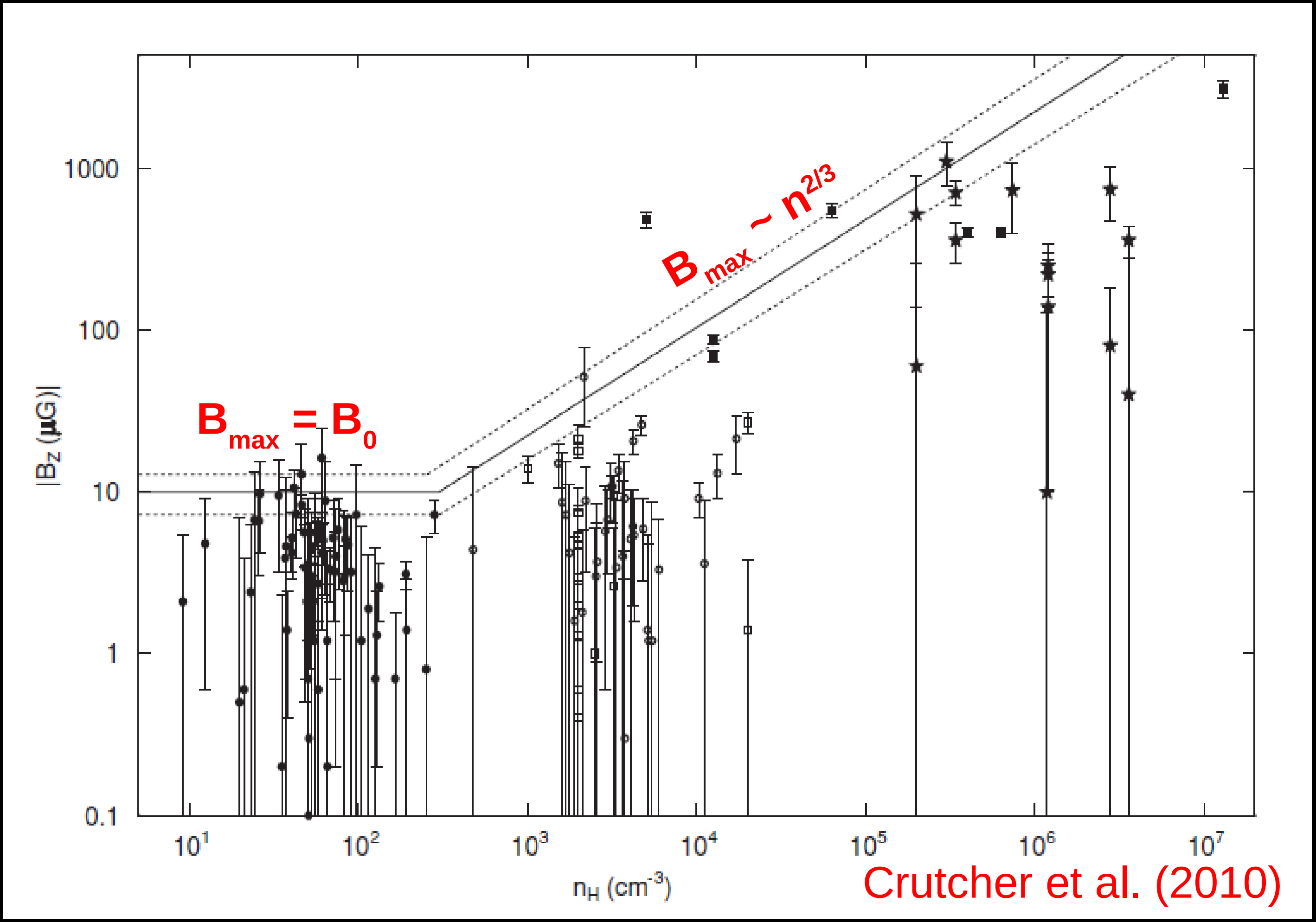
Magnetic field: geometry





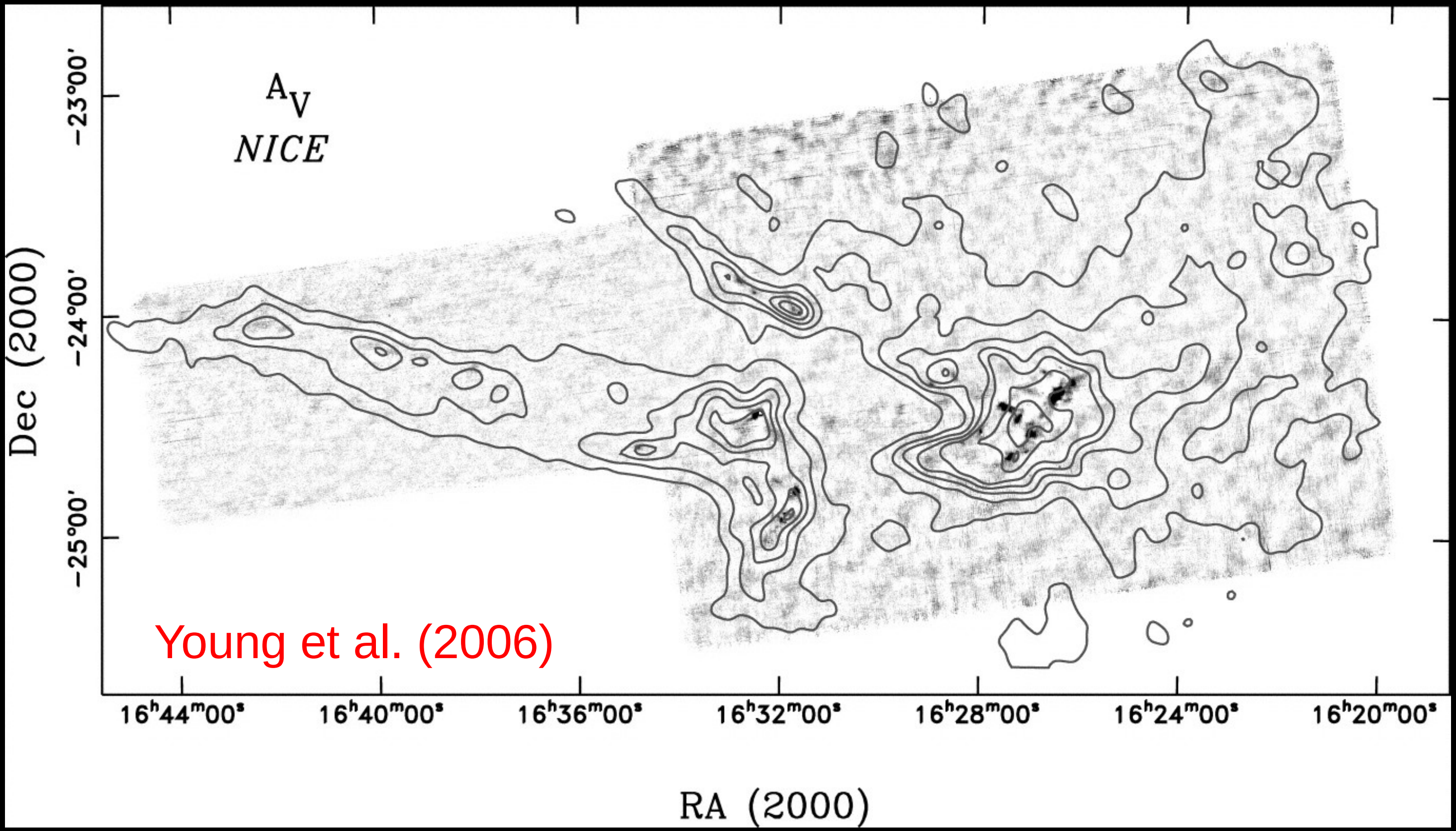
- Often complex pattern
  - parallel & perpendicular
- Taurus whiskers
  - magnetized outer layers

Magnetic field: strength



- Zeeman measurements (HI, OH, CN): field strength
  - Bayesian analysis
- "often too weak to dominate star-formation process"

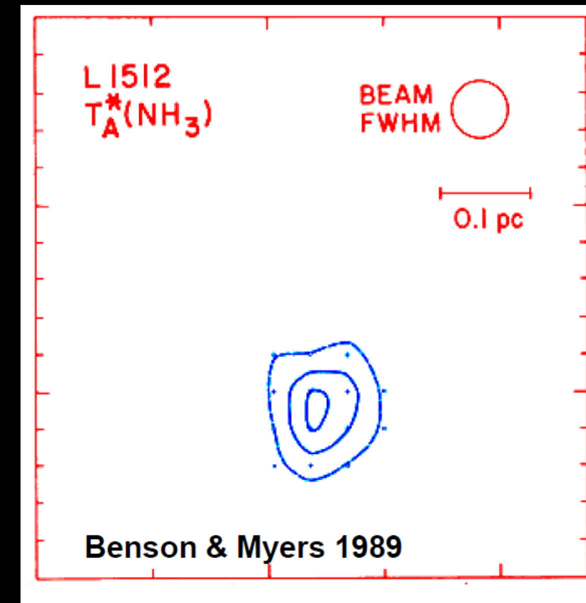
Dense Cores

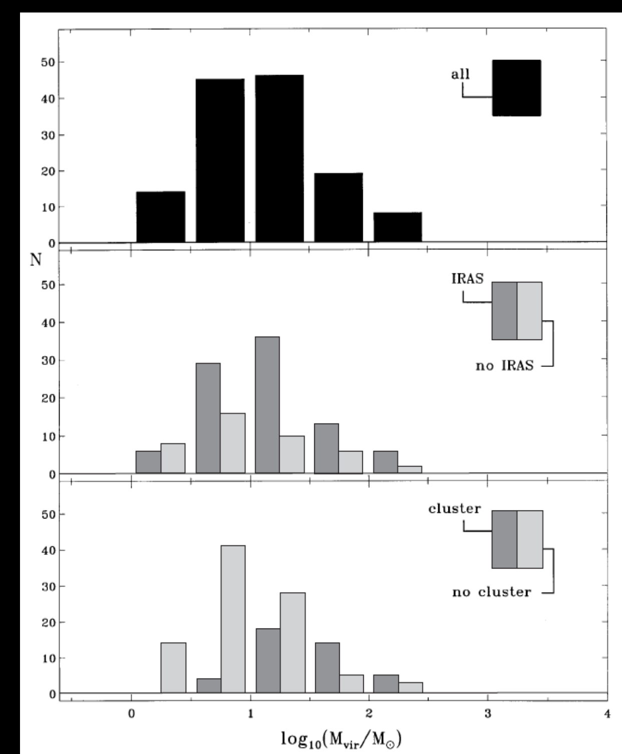


- Only a small fraction (few %) of cloud gas becomes dense core
  - may explain low star-formation rate
- Need of threshold? (Johnstone et al. 2004)

Dense cores: global properties

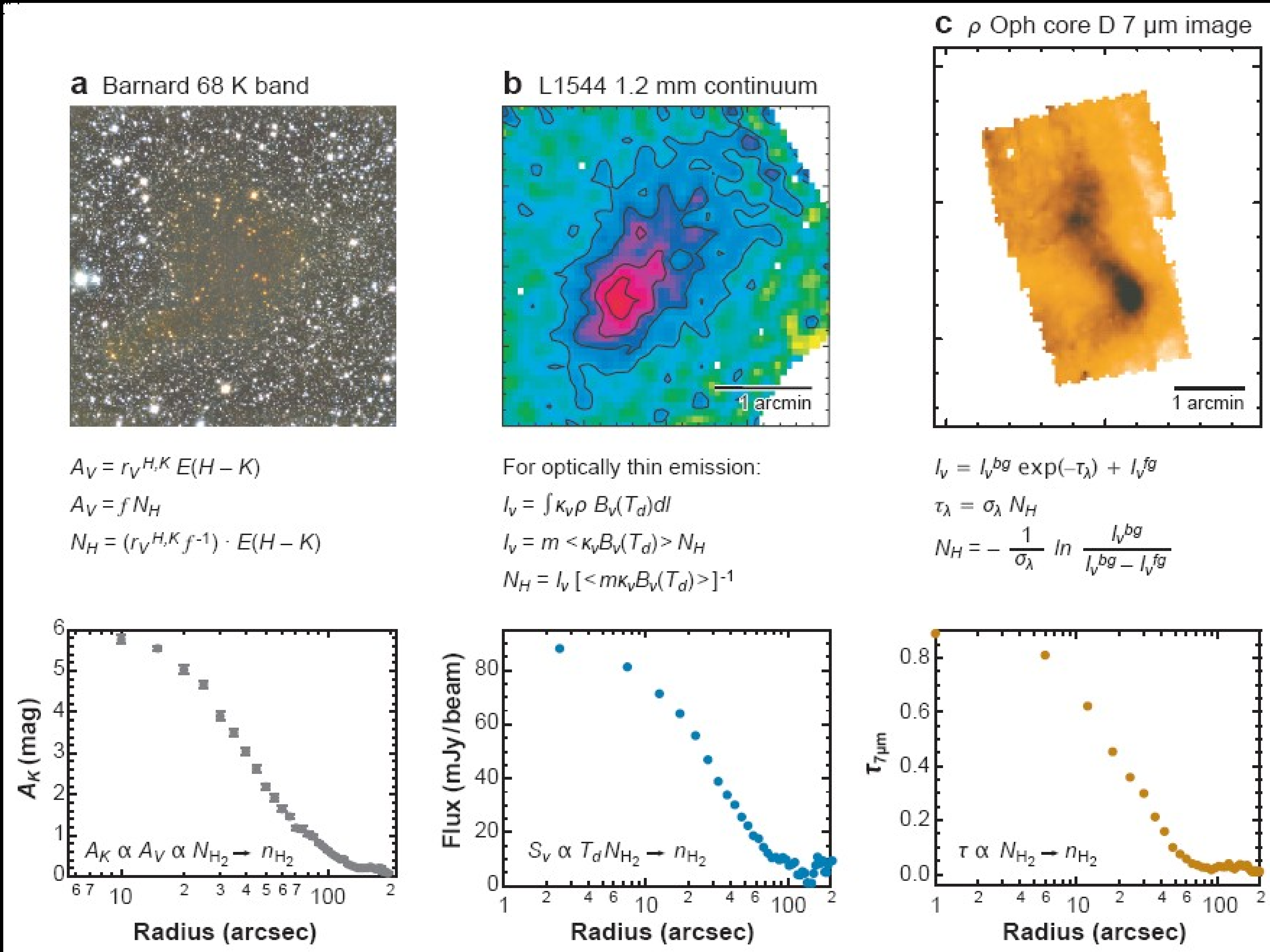
- Global properties (NH_3)
  - M ~ few Mo
  - D ~ 0.1 pc
  - T_k ~ 10 K
  - $n(H_2)$ ~ few 10^4 cm^{-3}
- IRAS Taurus observations
  - 50/50 star/starless
- Starless cores represent the initial conditions of (low-mass) star formation





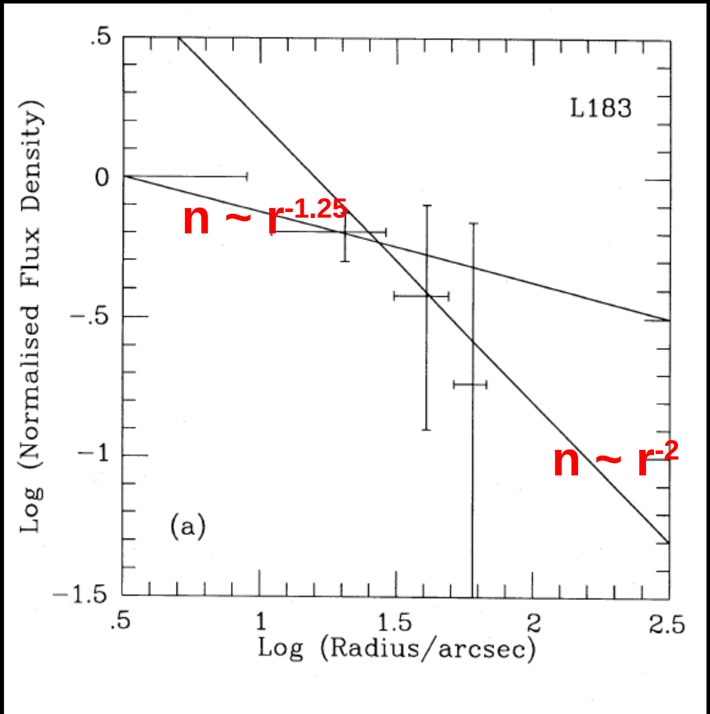
Jijina et al. (1999)

Dense cores: density structure

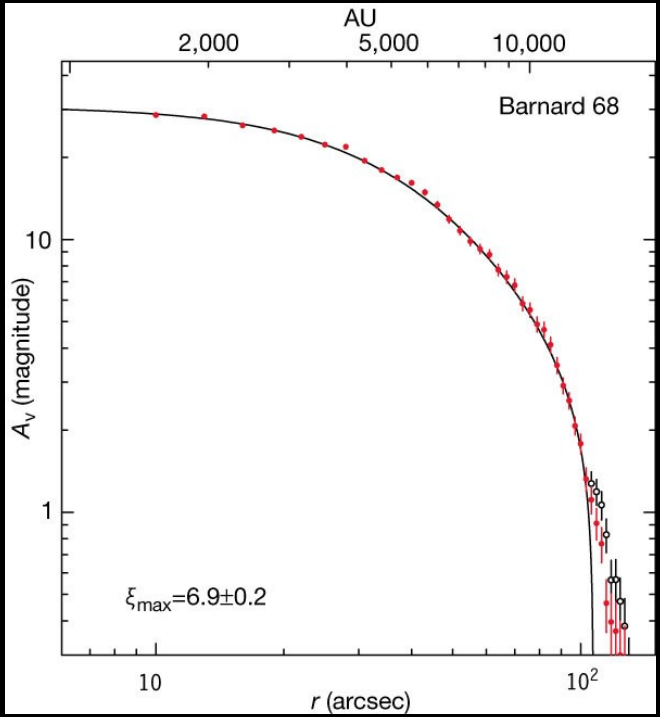


Bergin & Tafalla (2007) with data from Alves et al. (2001), Ward-Thompson et al. (1999), and Bacmann et al. (2000)

Dense cores: density structure



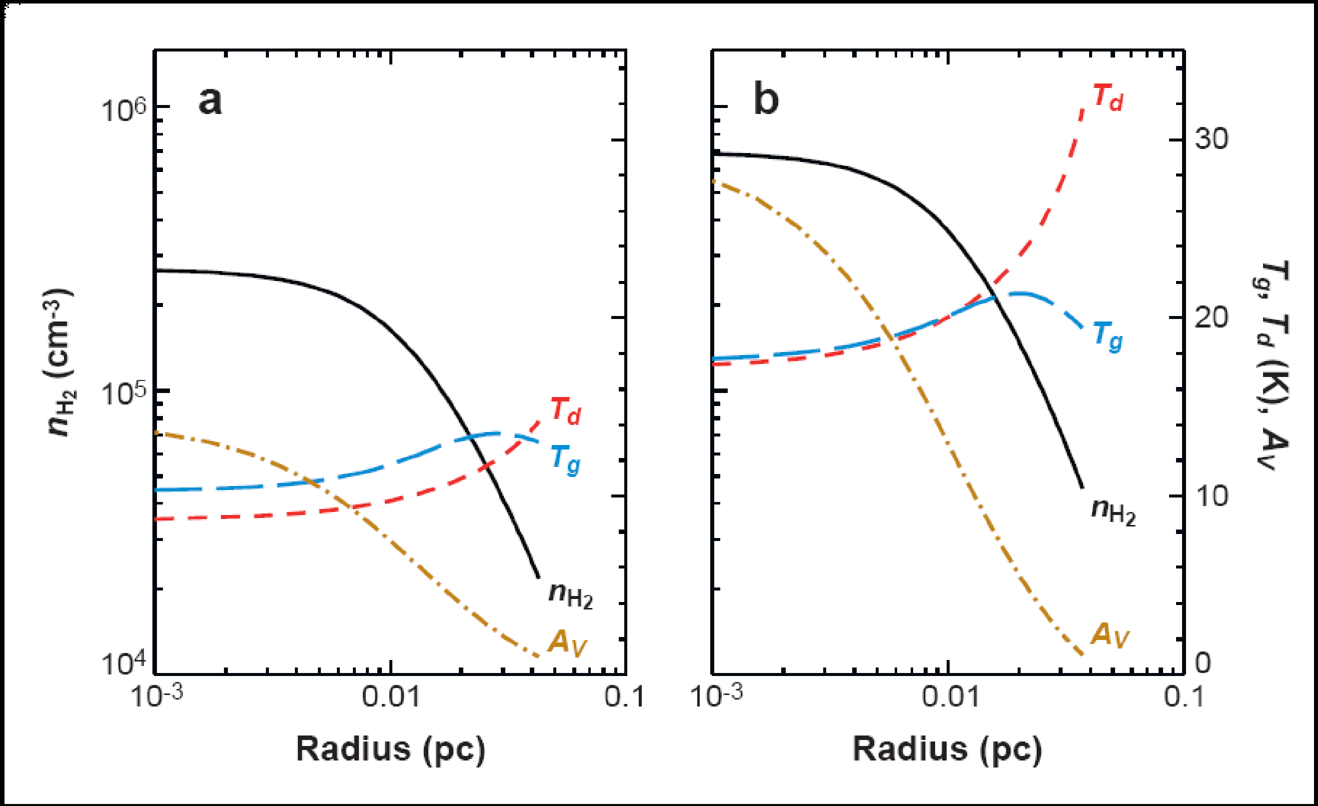
Ward-Thomspon et al. (1994)



Alves et al. (2001)

- Central flattening
  - Singular isothermal sphere expected
  - $n_0 = 10^5$-10^6 cm^{-3} & r_0 = 5,000-10,000 AU
- Bonnor-Ebert (isothermal sphere) fits
  - true pressure-only equilibrium?
  - most cores not spherical

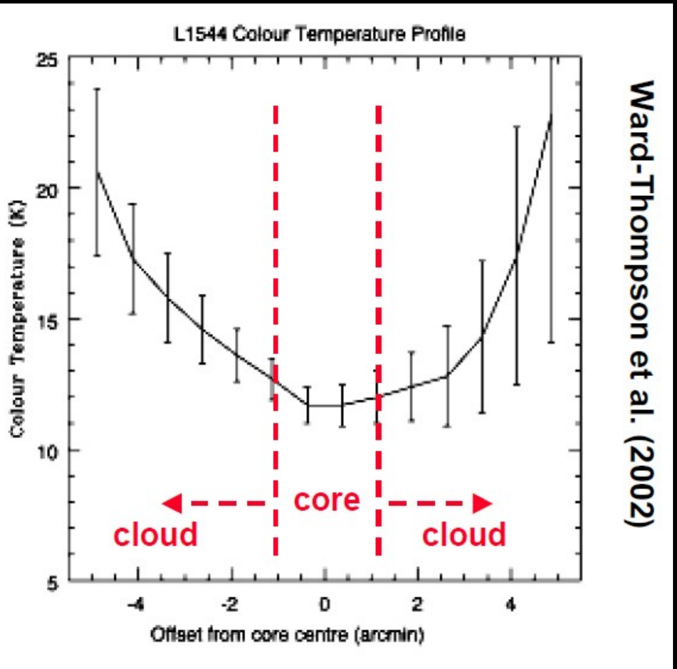
Temperature: dust vs gas

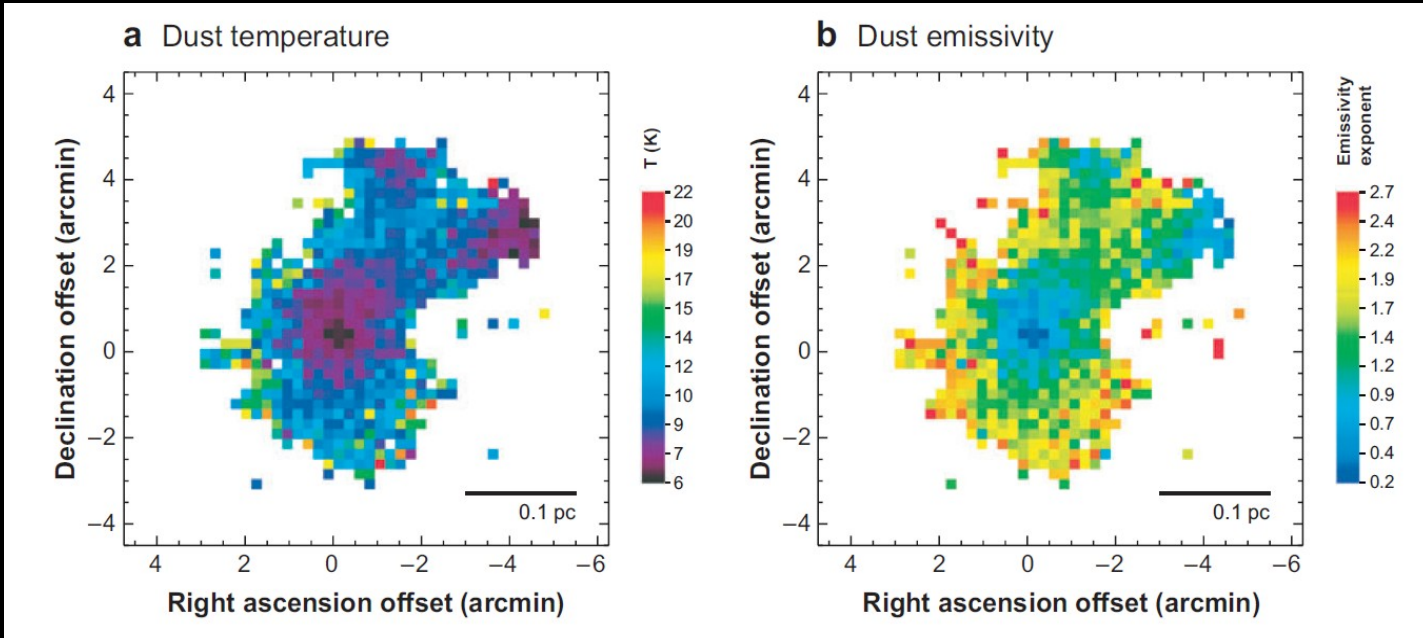


Galli et al. (2001)

- Dust and gas can have different temperatures
  - set by balance between heating and cooling
  - for densities > 10^5 cm^{-3}, dust and gas couple thermally

Dust temperature

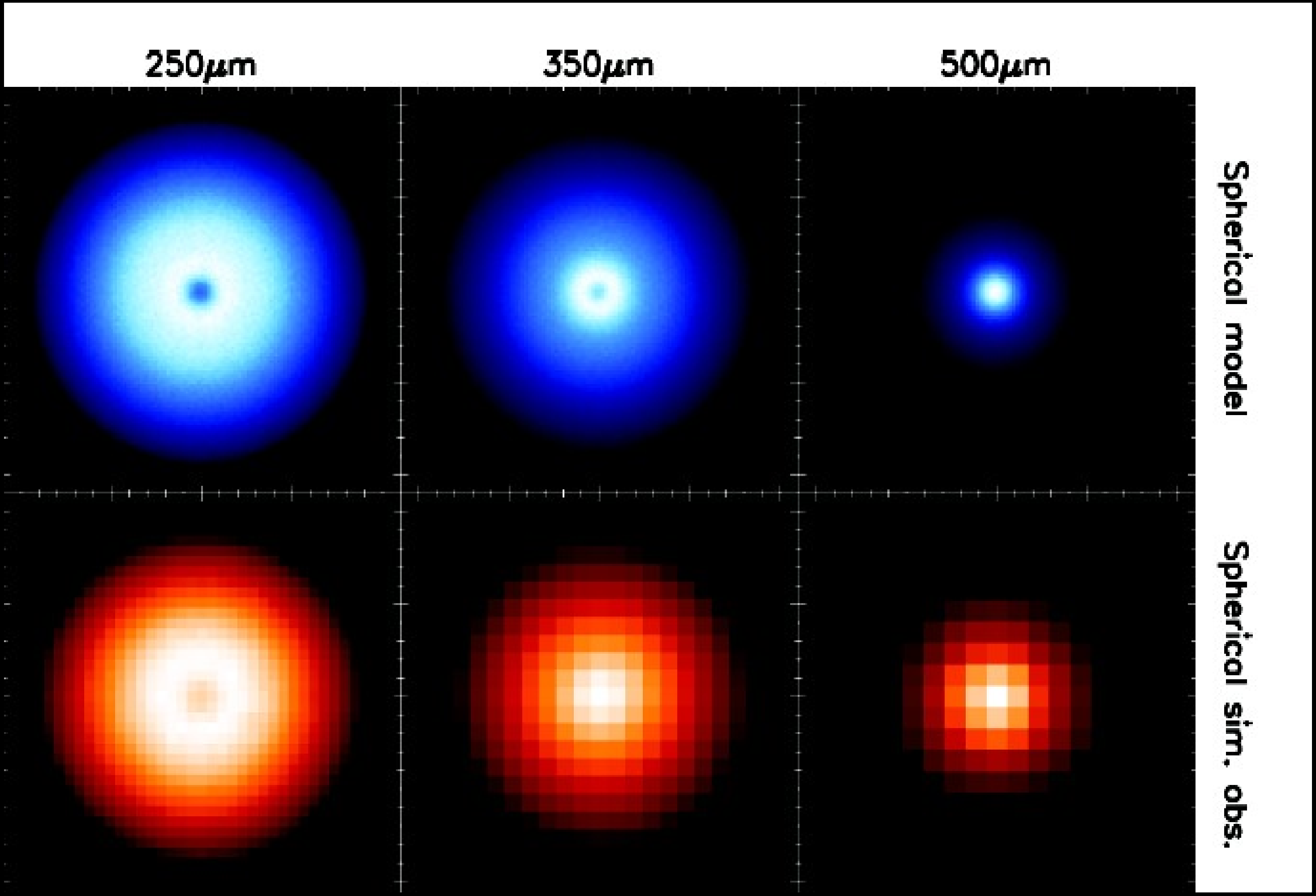




Schnee & Goodman (2005)

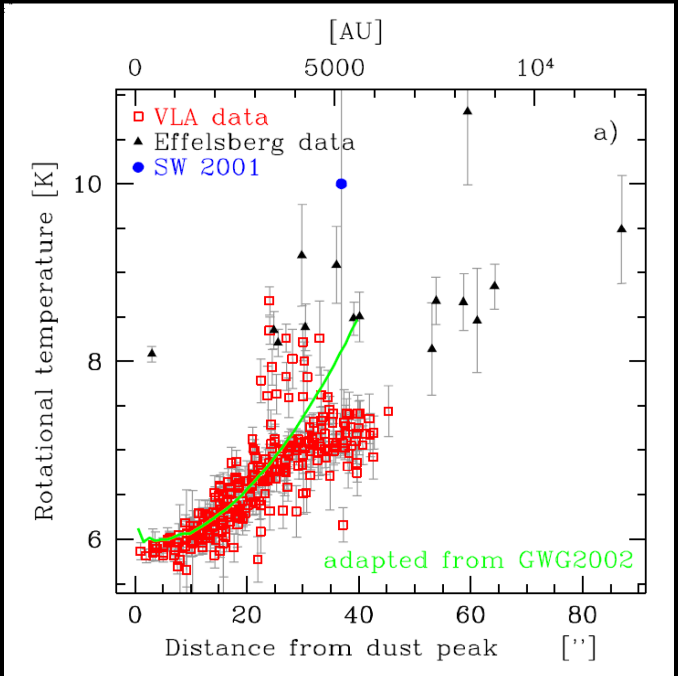
- Indications of temperature drop
  - core vs cloud & internal in core
  - consistent with expectation from ISRF attenuation
- Determination coupled with dust emissivity
  - grain evolution by coagulation

Herschel contribution

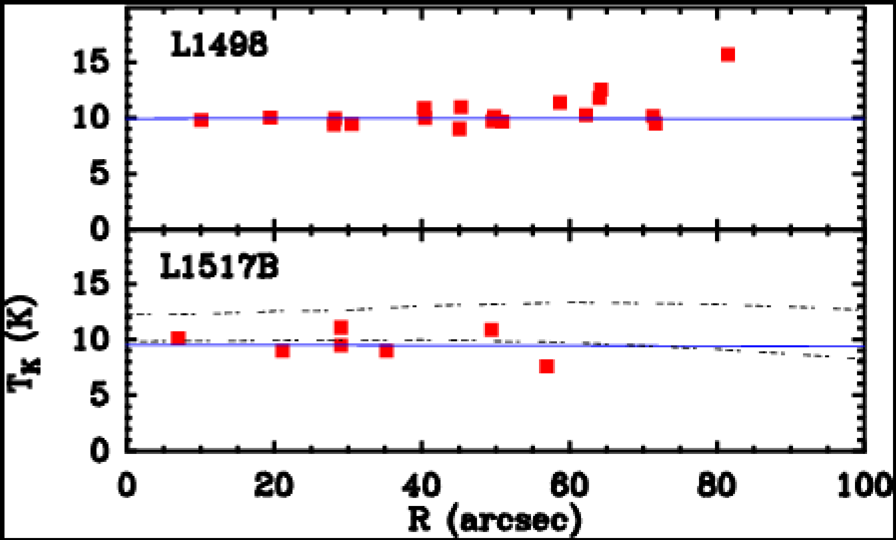


Stamatellos et al. (2010)

Gas temperature



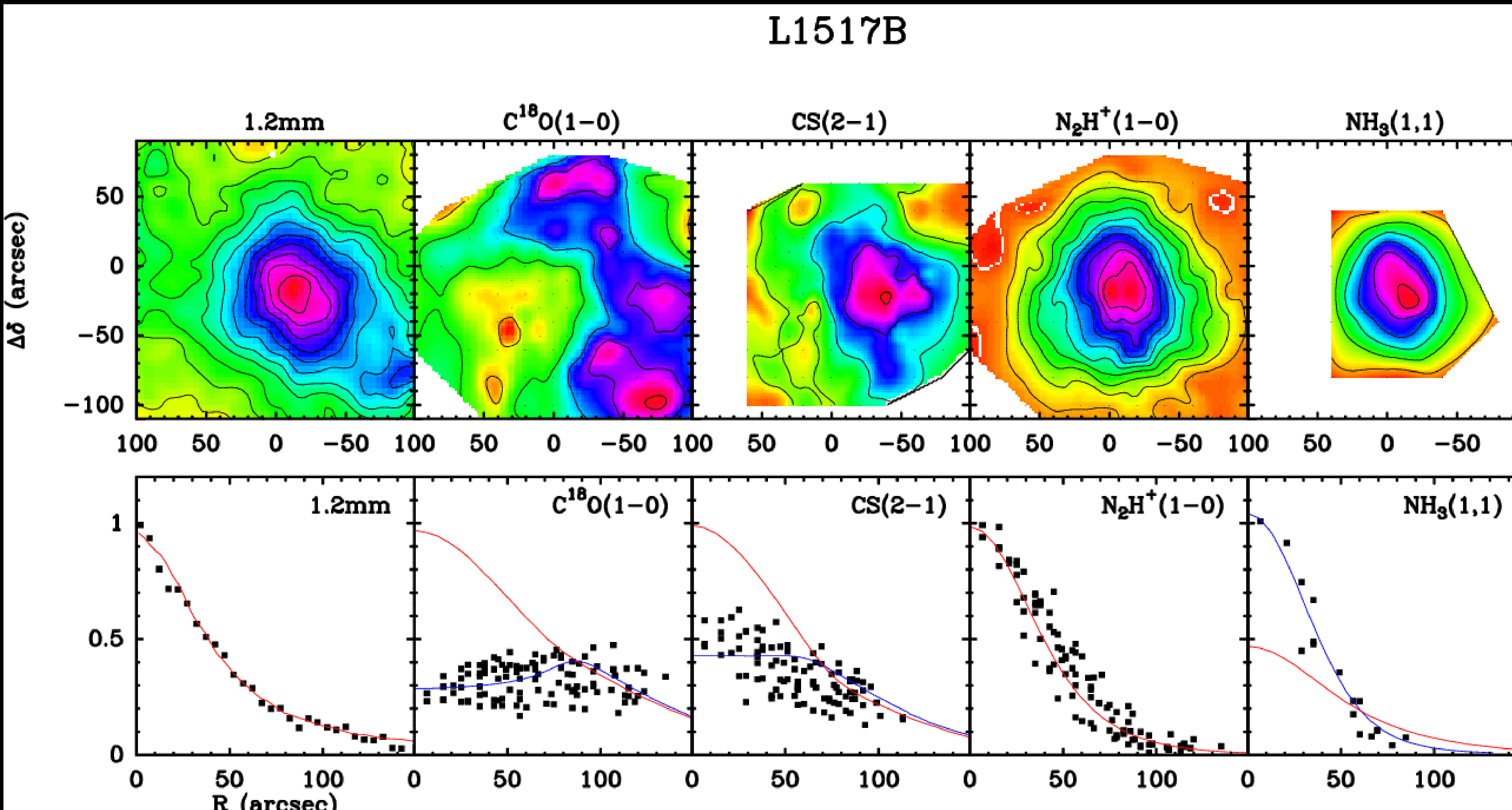
Crapsi et al. (2007)



Tafalla et al. (2004)

- Gas temperature determines thermal pressure
- Large-scale quasi-constant value of 10 K
- Central drop in L1544 consistent with models
  - further studies urgently needed
  - distribution stellar masses may depend on gas thermodynamic state (Japsen et al. 2005, Larson et al. 2005)

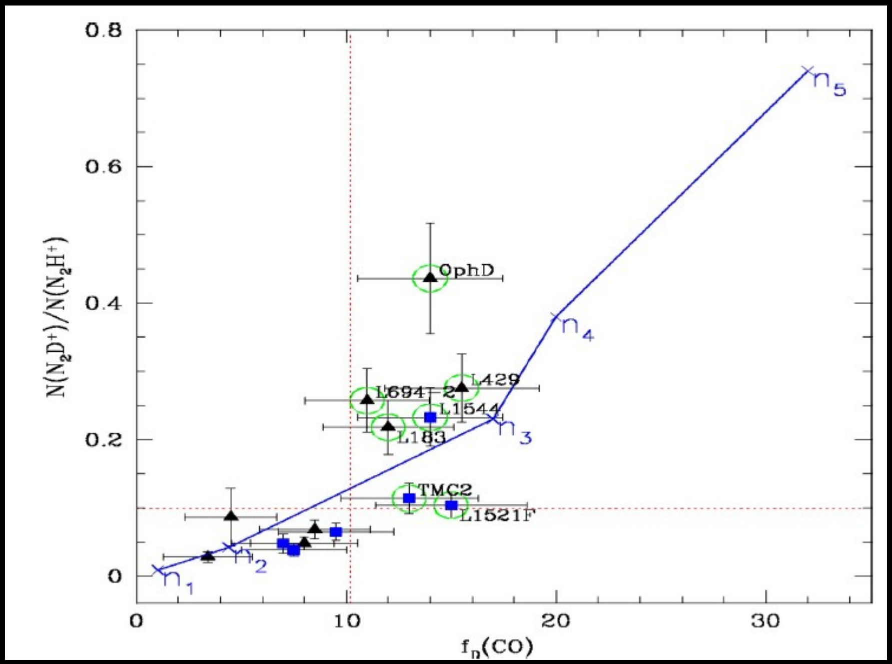
Chemical differentiation



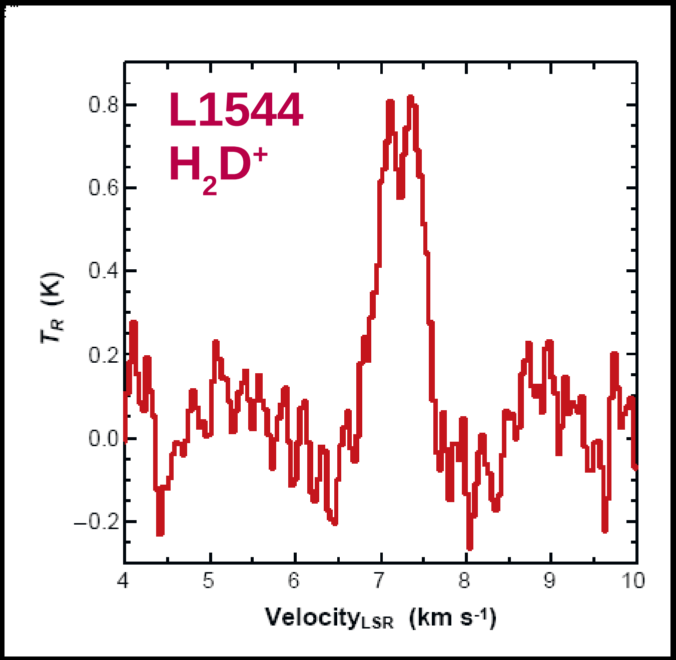
Tafalla et al. (2004)

- Abundance of C-bearing molecules drops towards center
- N-bearing species seem to survive (NH_3 enhanced!)
- Consistent with freeze out onto cold dust grains

Deuterium fractionation



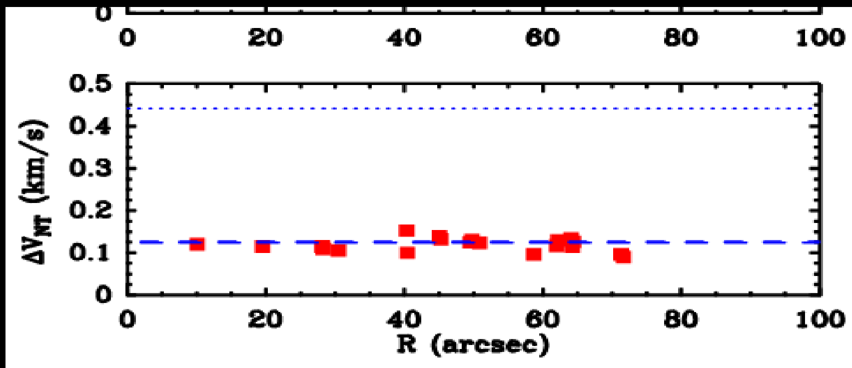
Crapsi et al. (2005)

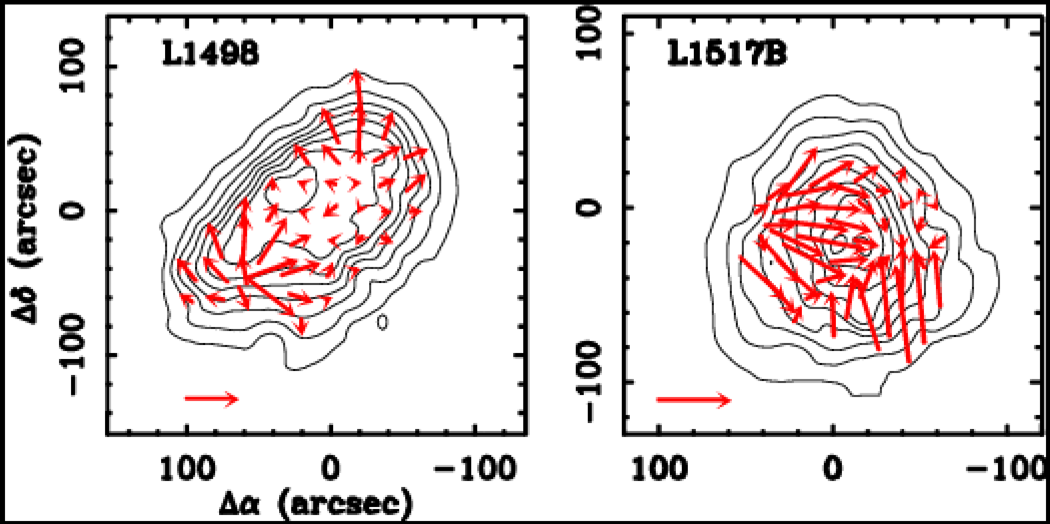


Caselli et al. (2003)

- Consequence of CO freeze out
- H_2D^+ abundance enhanced
- D is passed down to other species
- Observed correlation between N_2D^+/N_2H^+ and CO depletion

Kinematics: internal motions

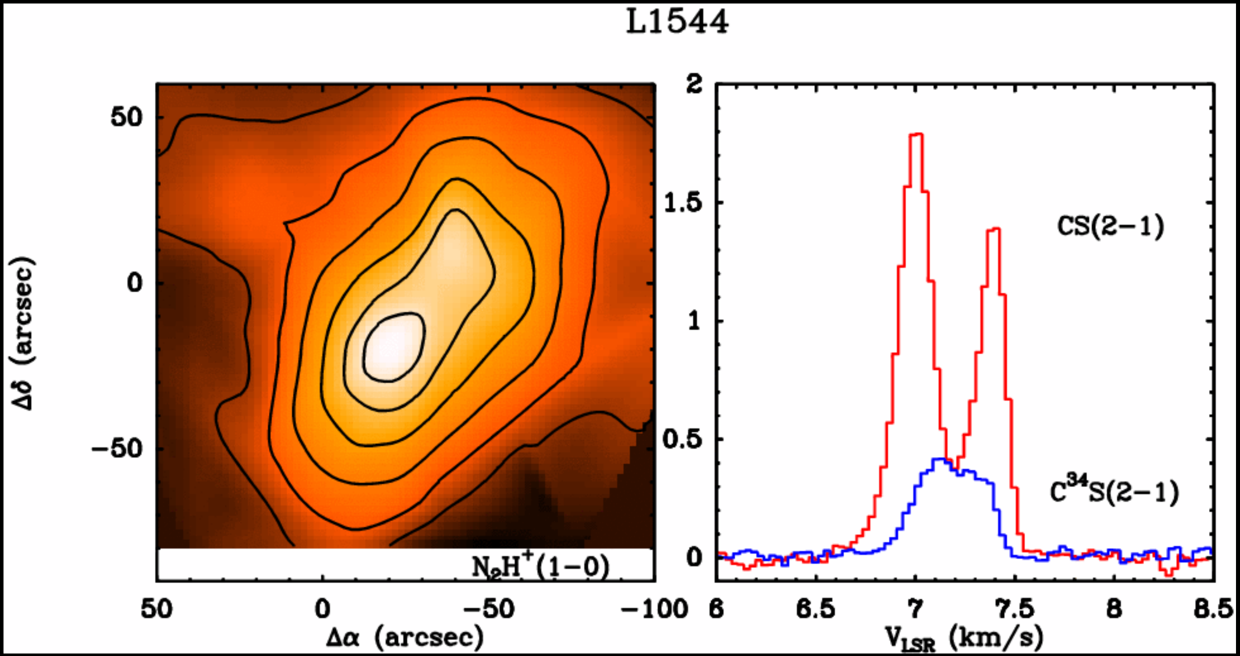




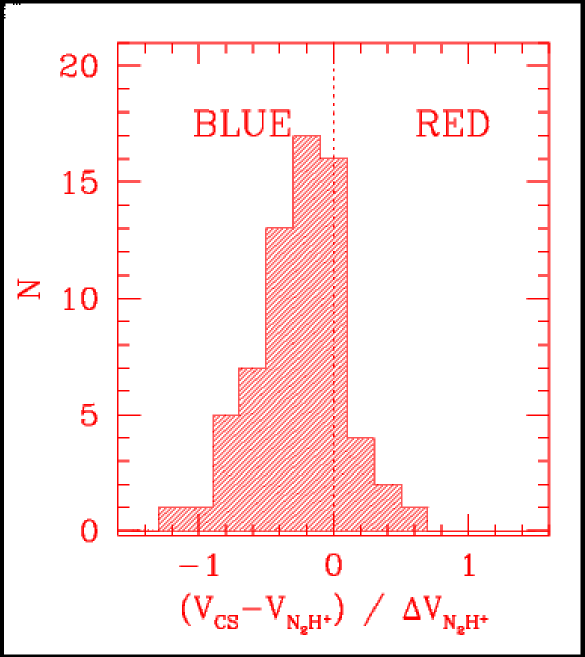
Tafalla et al. (2004)

- Internal motions: traced with NH_3 and N_2H^+
  - subsonic: $(P_T/P_{NT} = (c/\sigma_{NT})^2 > 1)$
  - coherent (break in Larson's relation)
  - no simple systematic inner pattern (no rotation)

Kinematics: external motions



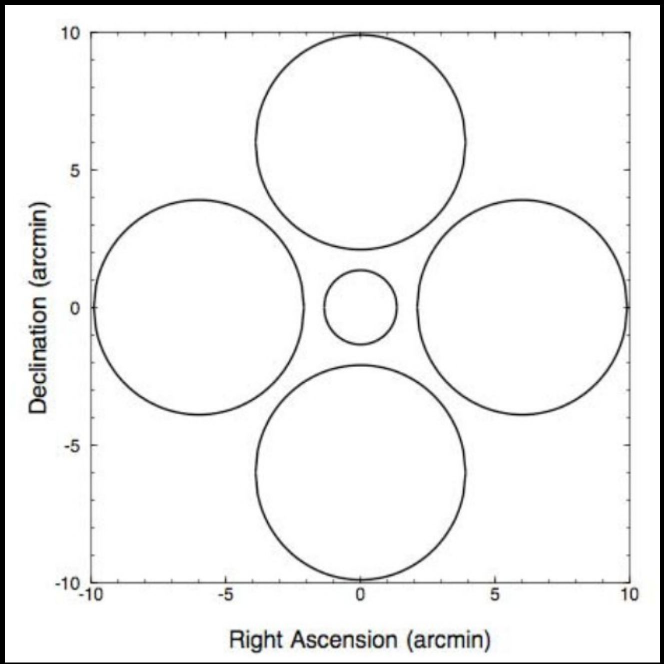
Tafalla et al. (1998)

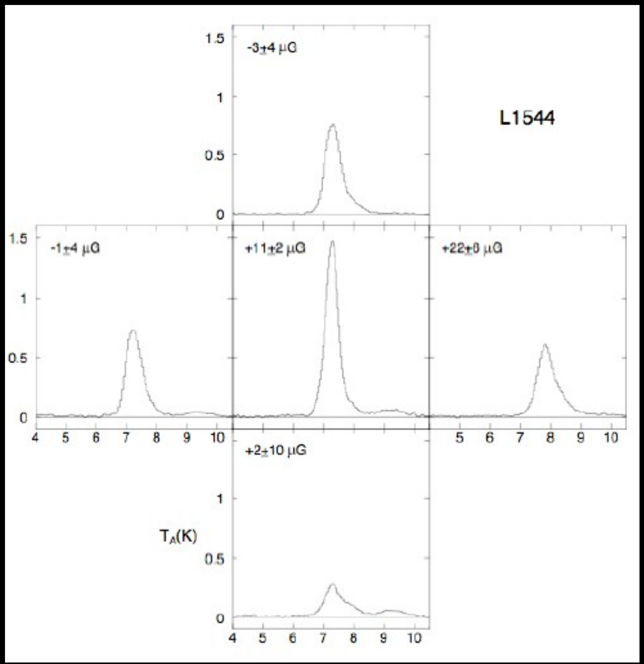


Lee et al. (1998)

- Traced combining thick and thin tracers
- Evidence for inward or outward motions
- Prevalence of inward motions
    - subsonic (~ 0.1 km/s), extended (~0.1 pc)
    - gravitational collapse? core forming motions?
    - but reversals / differences between species

Core magnetic field





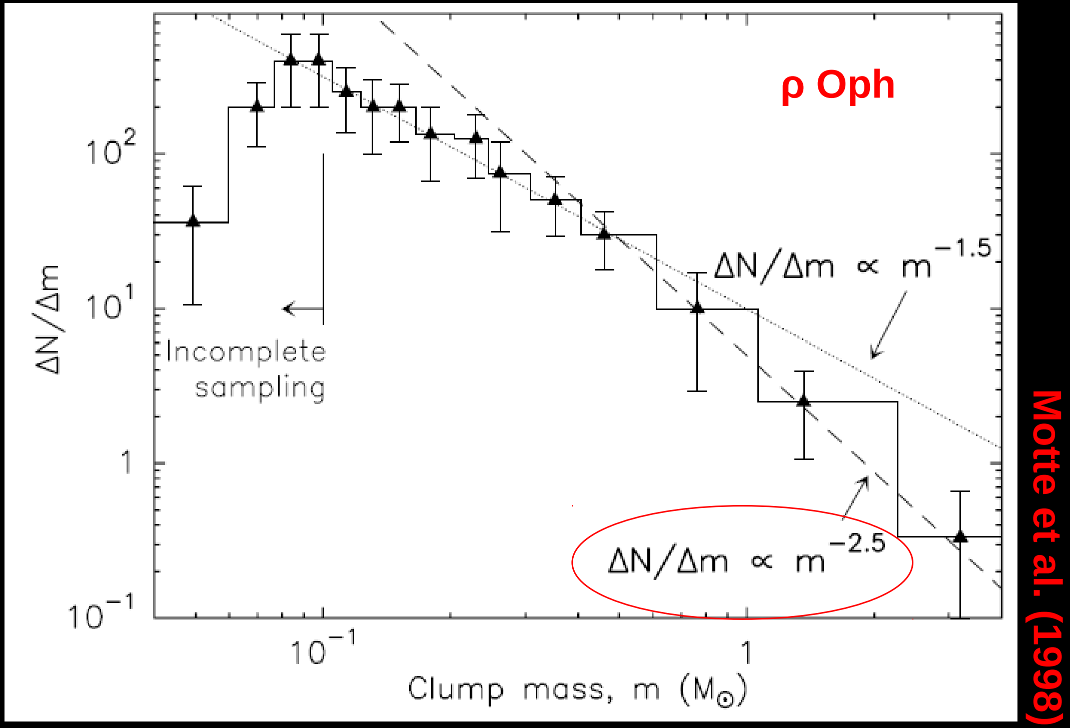
$$\text{Mean } \frac{M/\Phi(\text{core})}{M/\Phi(\text{envelope})} = 0.35 \pm 0.14$$

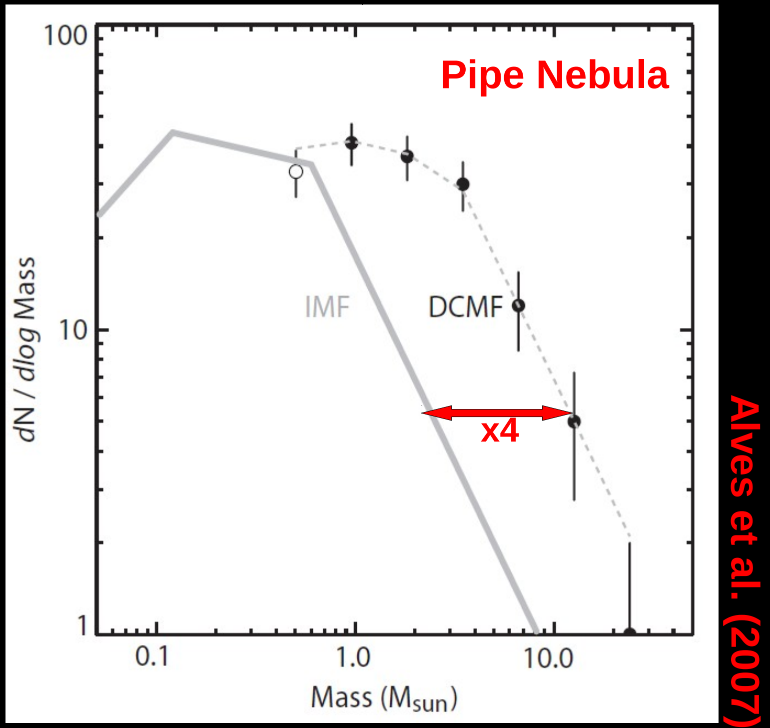
~ 2 predicted by ideal ambipolar diffusion models

Crutcher et al. (2009)

- Study of 4 cores by Crutcher et al. (2009)
- OH Zeeman observations (Arecibo + GBT)
- Compare mass-to-flux ratio in core and envelope
- Ambipolar diffusion models predict higher M/Φ in core
- Observation finds opposite
  - magnetic field does not seem to control core formation

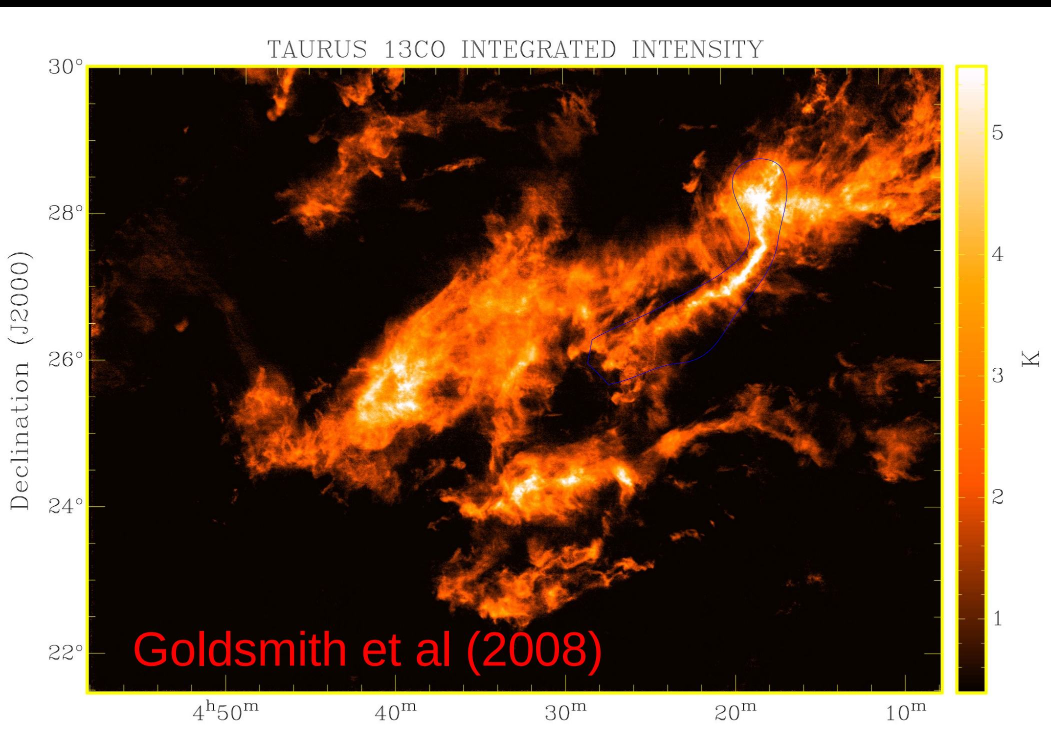
Core mass function

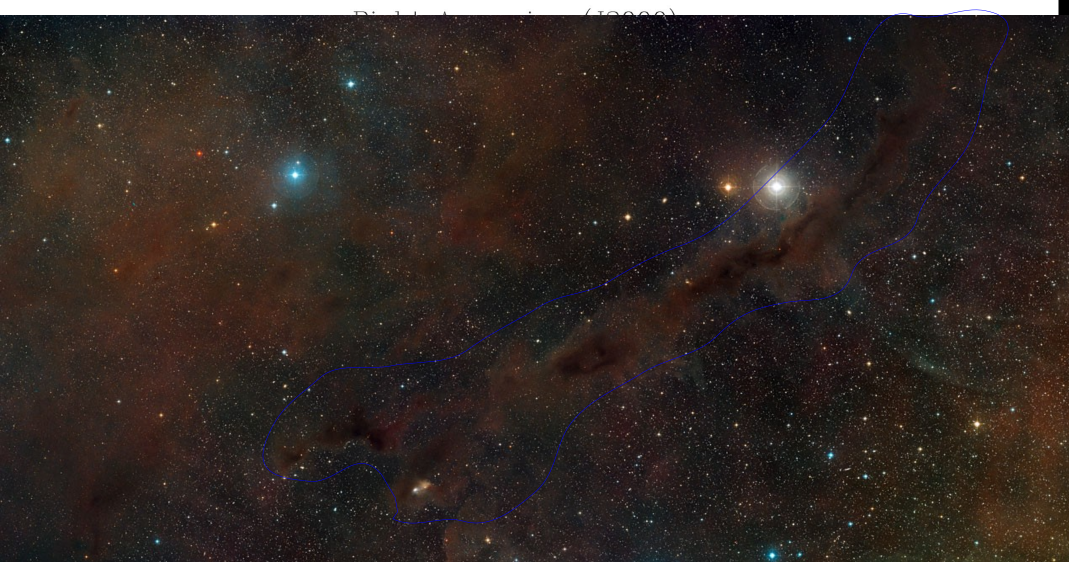




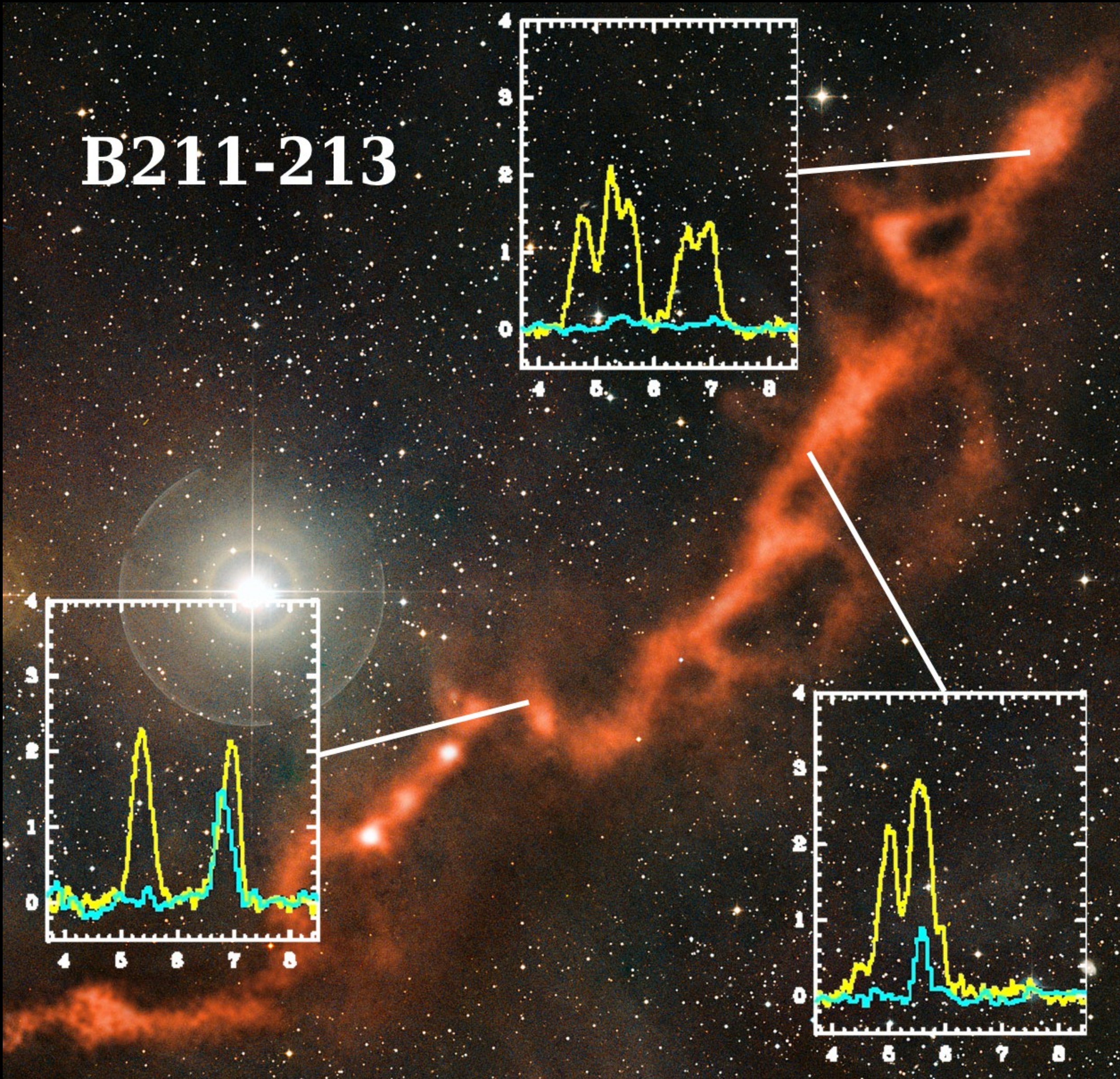
- Distribution of core masses
  - same slope as stellar Salpeter IMF
  - flattening at lower masses (like stellar IMF)
- Factor of 4 displacement: 25% efficiency?
- Core formation process determines IMF?

Core formation in B213 (Taurus)





- B213 is most prominent filamentary structure in Taurus (10 pc)
- Simple geometry
- ~20 cores (star & starless)
- Study core formation: FCRAO $C^{18}O(1\text{-}0)$ & $N_2H^+(1\text{-}0)$
- LABOCA 850 µm
- See poster Hacar et al.



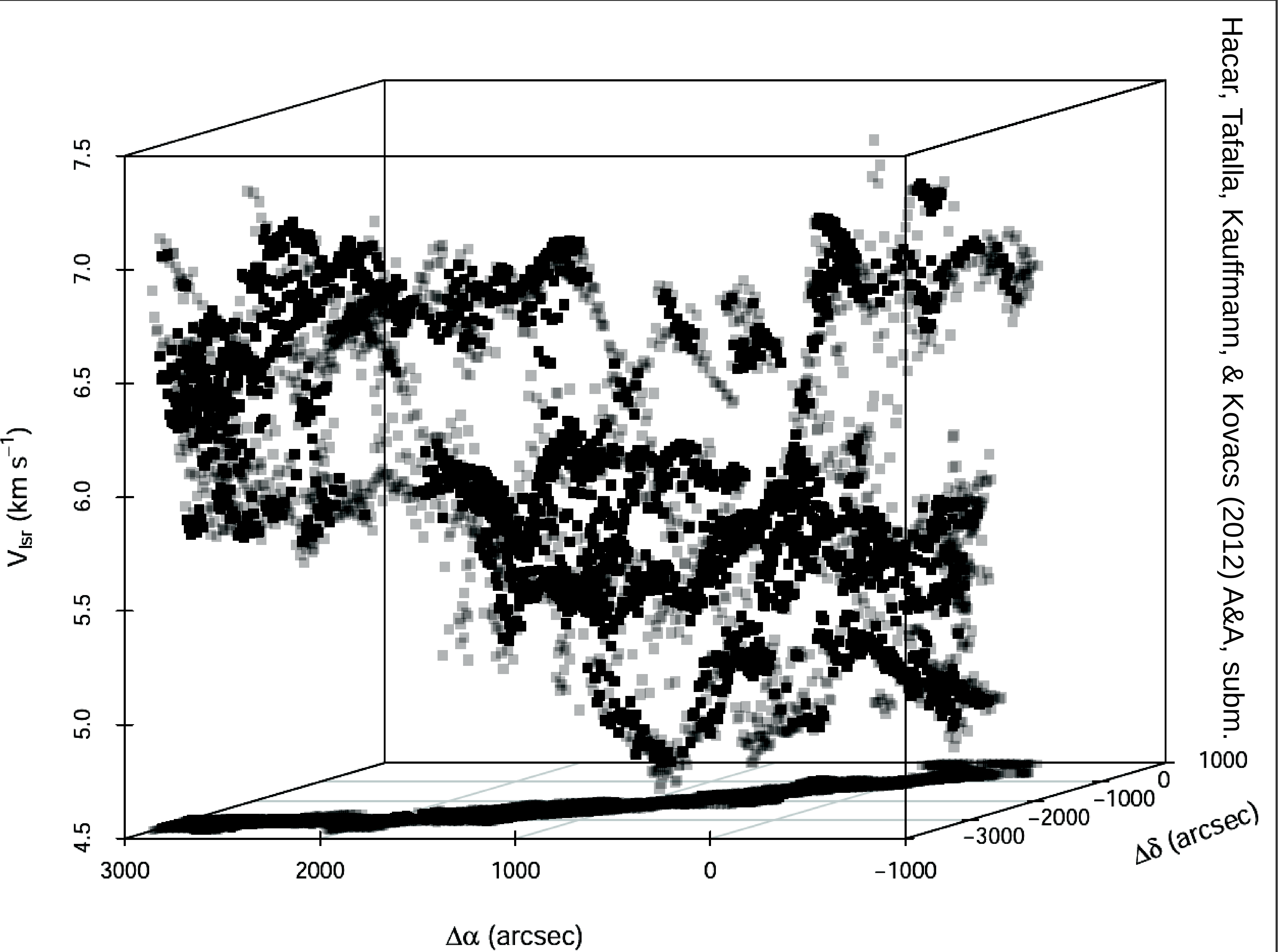
B211-213
4
3
2
1
0
4
5
6
7
8

Disentangling complex kinematics

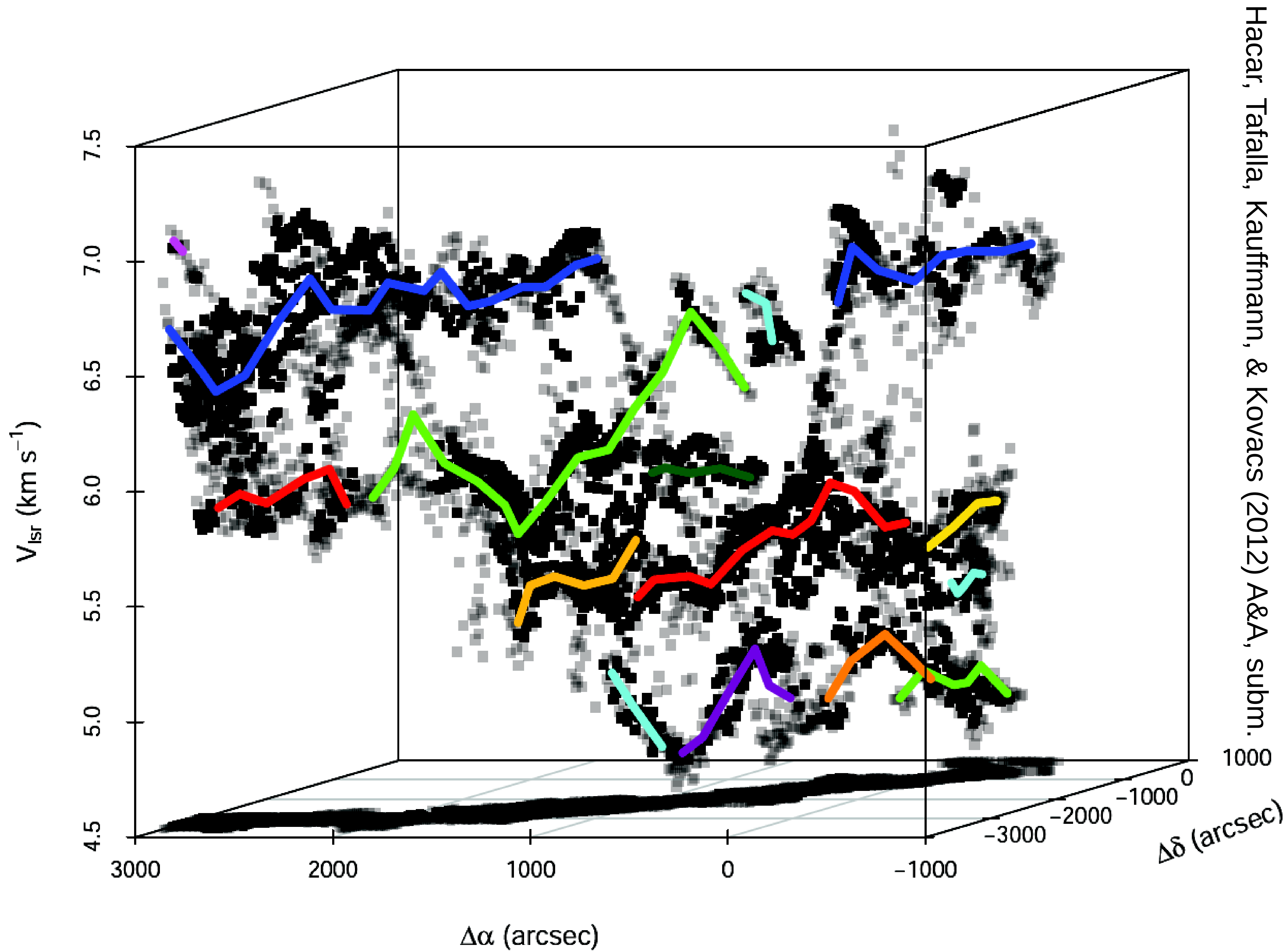
- Goal: identify and disentangle multiple velocity components

- New algorithm: FIVe (Alvaro Hacar, see poster)
  - fit multiple gaussians to $C^{18}O$ and N_2H^+ spectra
  - search for individual components in position-position-velocity (PPV)
  - friends-of-friends approach (Huchra & Geller 1982)

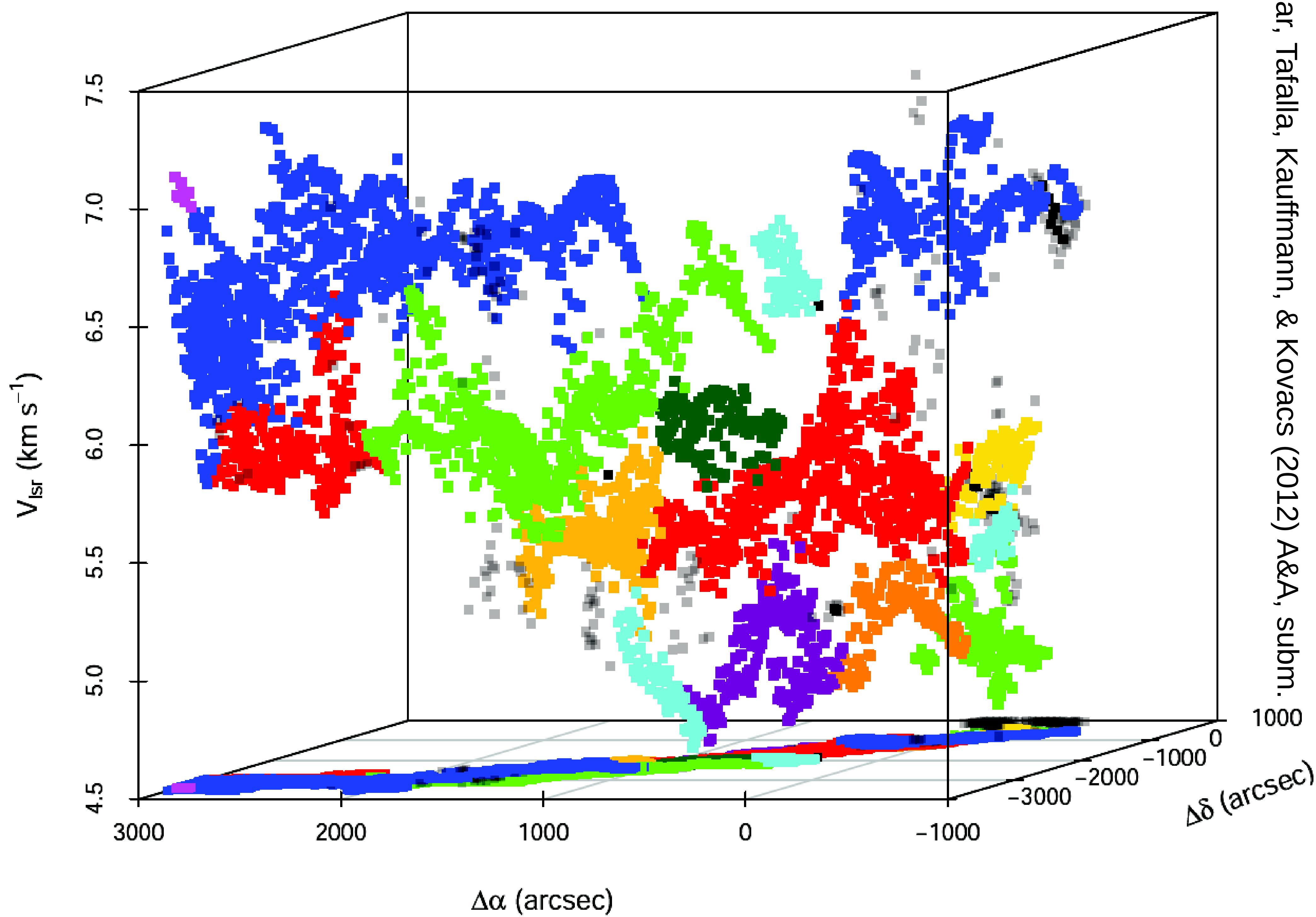
- B213 consists of network of overlapping filaments



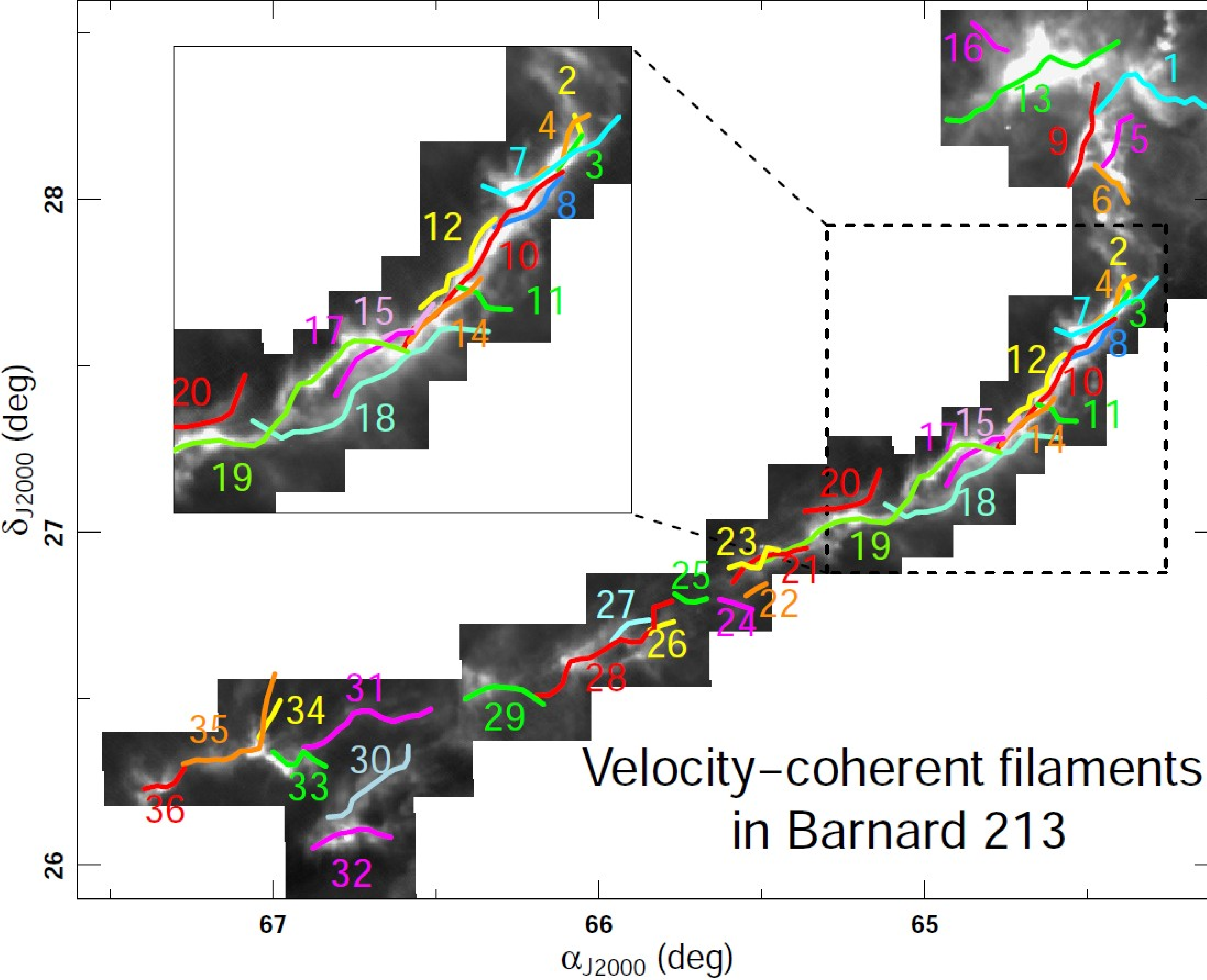
Hacar, Tafalla, Kauffmann, & Kovacs (2012) A&A, subm.
V_{lsr} (km s^{-1})
7.5
7.0
6.5
6.0
5.5
5.0
4.5
3000
2000
1000
0
−1000
Δα (arcsec)
1000
0
−1000
−2000
−3000
Δδ (arcsec)



Hacar, Tafalla, Kauffmann, & Kovacs (2012) A&A, subm.
7.5
7.0
6.5
6.0
5.5
5.0
4.5
V_{lsr} (km s^{-1})
3000
2000
1000
0
−1000
Δα (arcsec)
1000
0
−1000
−2000
−3000
Δδ (arcsec)

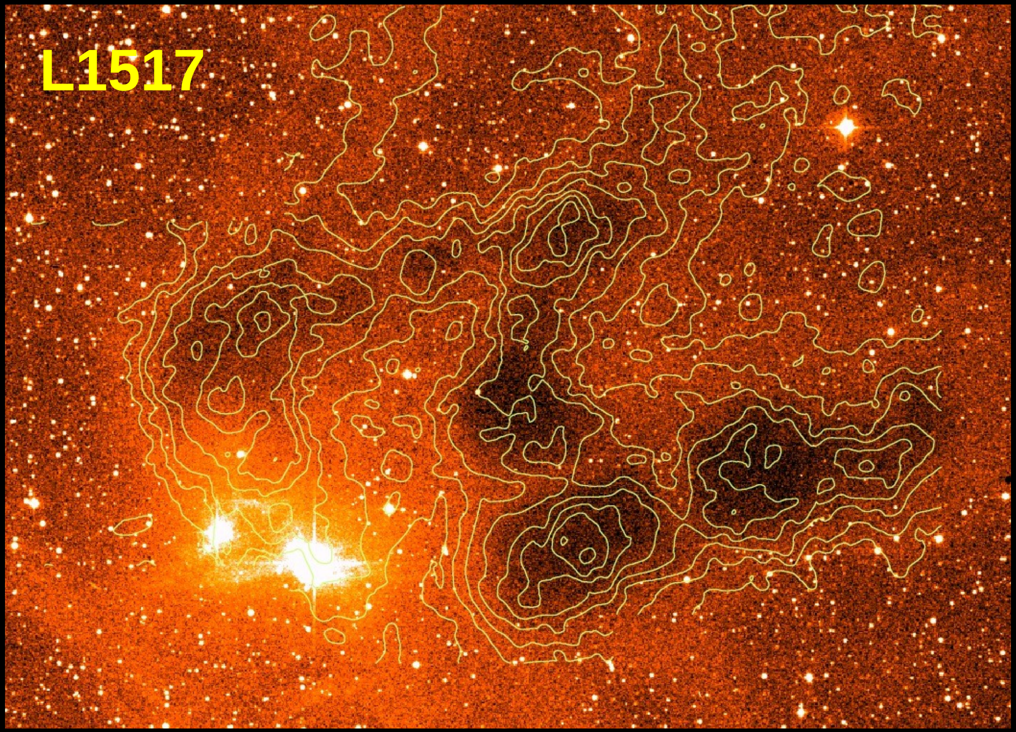


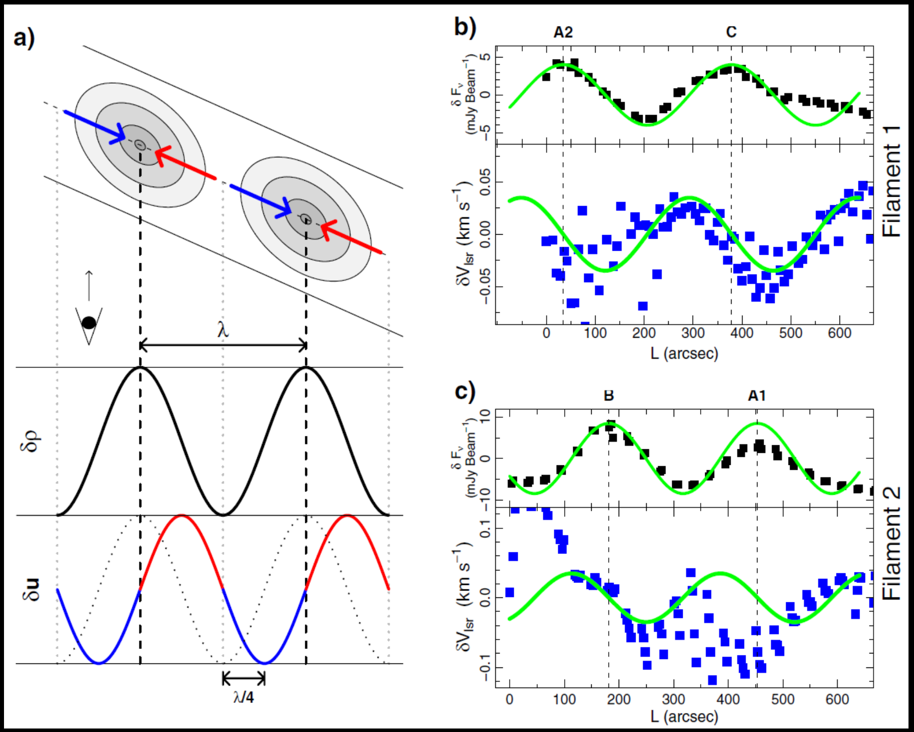
Hacar, Tafalla, Kauffmann, & Kovacs (2012) A&A, subm.



$C^{18}O$ filaments from Hacar et al. (2012) . Herschel image from the "Gould Belt Survey" (Andre et al. 2010). See also poster by Palmeirim et al. in this meeting

Implications: dense core formation





Hacar & Tafalla (2011)

- Core formation occurs via **hierarchical fragmentation**
- Cloud fragments into **velocity-coherent** filaments
  - subsonic/transonic
- Some filaments fragment into **cores**
  - no supersonic collisions between gas flows
  - likely **gravity-driven**

Some questions for HSO

- Why are clouds so fragmented but still so close to virial equilibrium?
- Why do they produce a small fraction of dense cores? (and a small fraction of stars?)
- Are cores equilibrium structures or just brief snapshots of the star formation sequence?
- How do they fragment from the cloud gas? (and why?)
- What happens to a core after it has formed a star?