Dense Cores

From their internal structure to their connection with the surrounding cloud

Mario Tafalla
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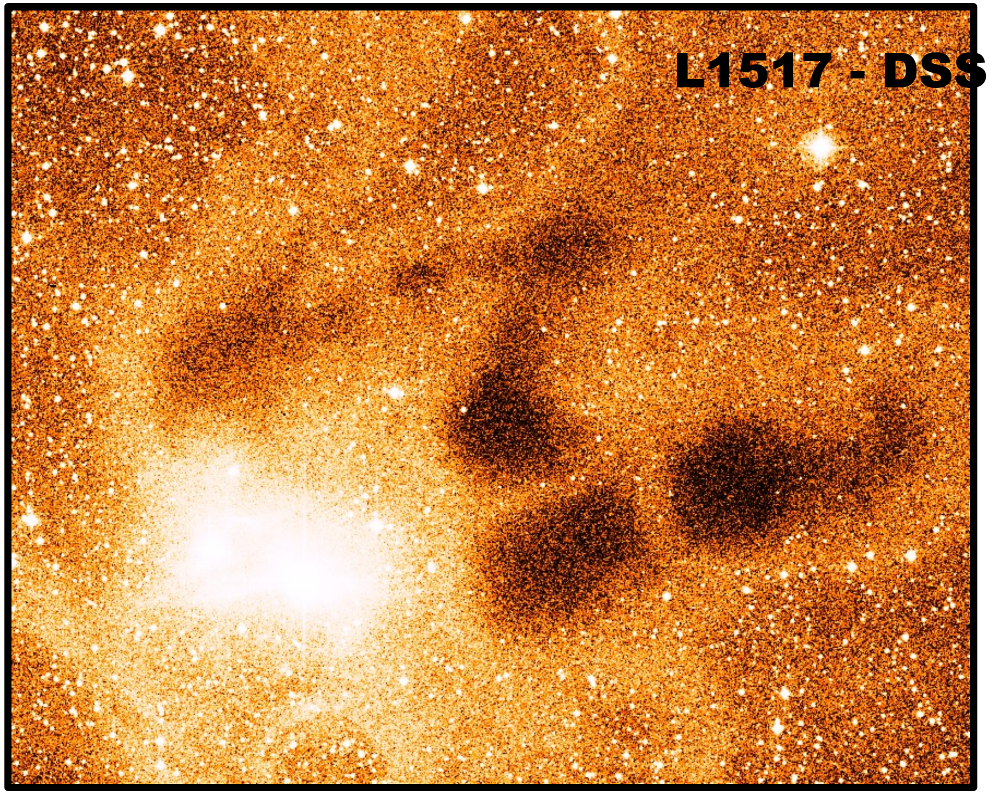
Outline:

- Global properties
- Internal properties
- Connection with the large scales

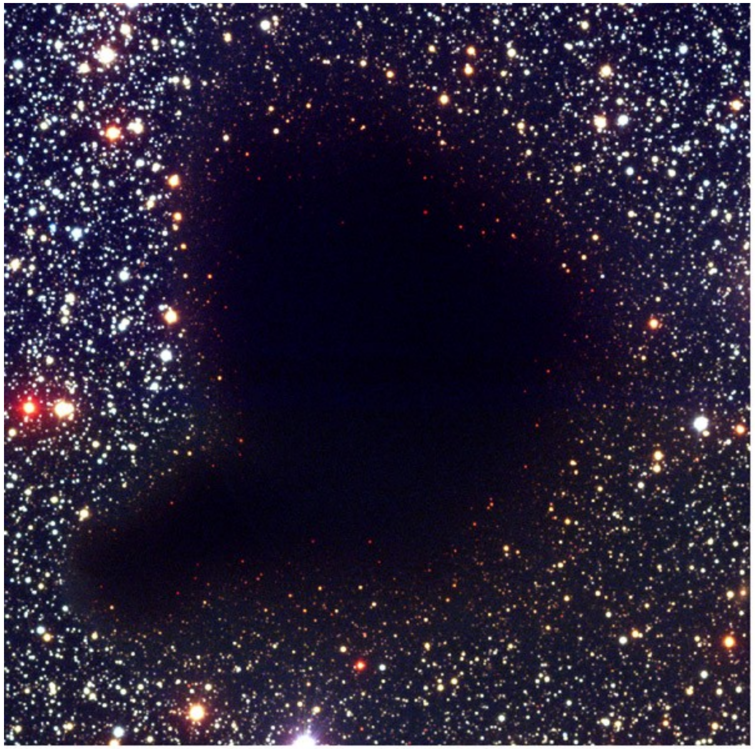
Original identification: opaque regions

- 1980's: “visually opaque regions”
  - Palomar plates
  - few arcmin
- Common in nearby dark clouds (Taurus, Ophiuchus)
- Related to star formation
  - in the vicinity of TT stars
- First catalogs (~100 objects):
  - Myers et al. (1983)



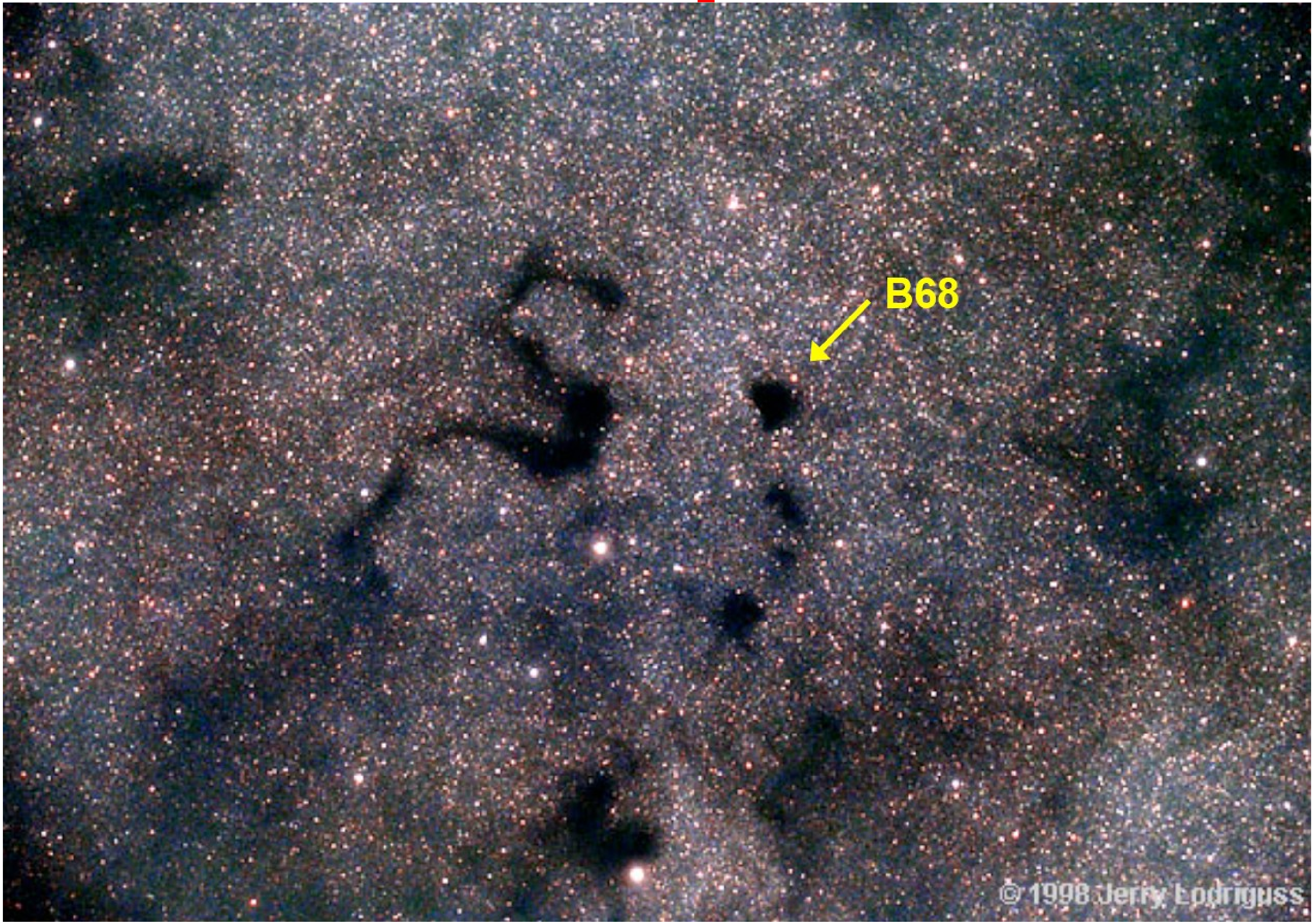
Bok globules

- Bok globules
  - also optically defined
  - isolated
  - great variety of sizes and masses
- Dense compact glubules
  - Similar properties to dense cores
  - form low-mass stars


B68 (Alves et al.)

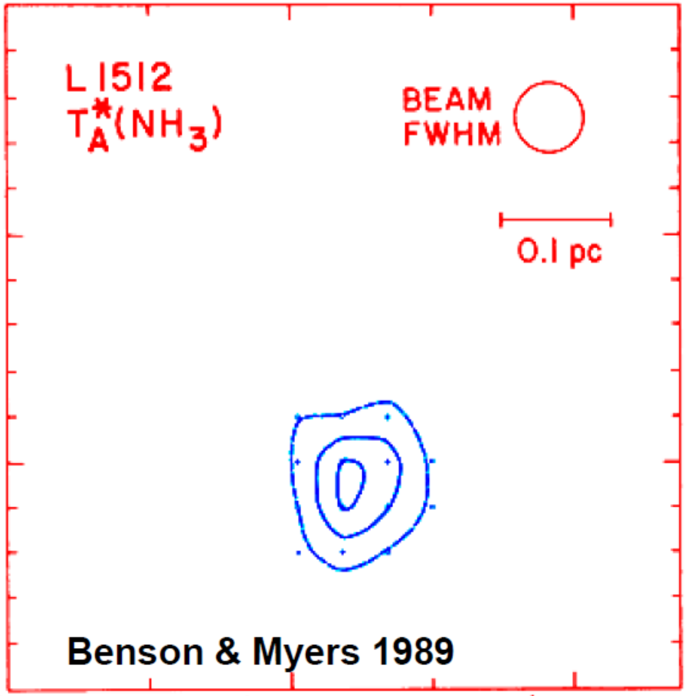
- Possible origin: dense core exposed by external (ionization, etc.) event (Reipurth 1983)

Globules as exposed cores



Global physical properties

- Cores in Taurus, Auriga, Oph (plus globules) Benson & Myers (1989)
  - diameters ~ 0.1 pc
  - masses ~ several Mo
  - temperatures ~ 10 K
  - mean densities ~ few 10^4 cm^{-3}
- When observed in FIR (IRAS)
  - some have central object (50/50)

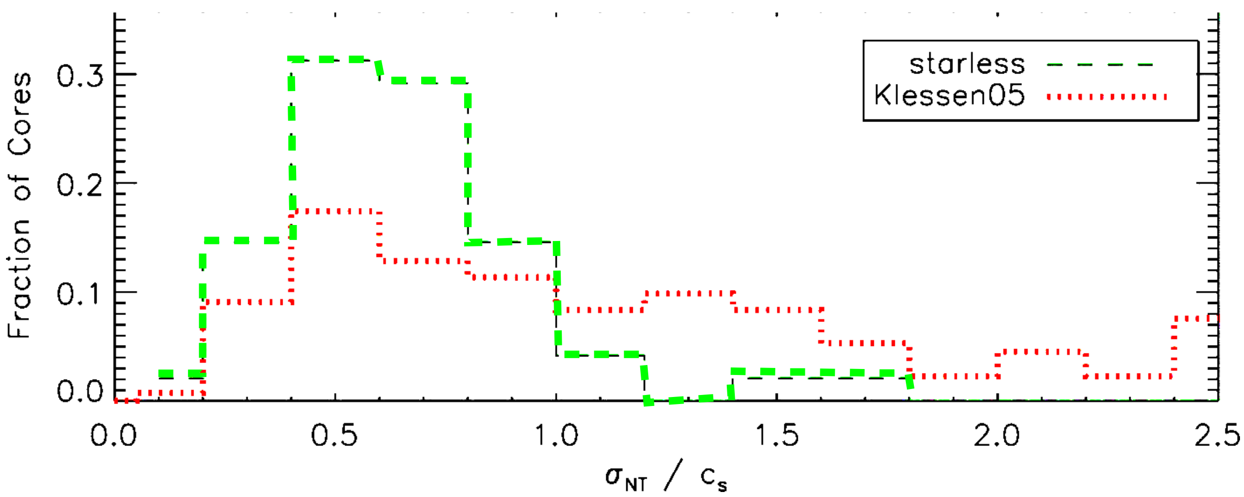


- Cores are the simplest star-forming sites
  - individual Sun-like stars (or binaries)
- Starless cores display the initial conditions of star formation

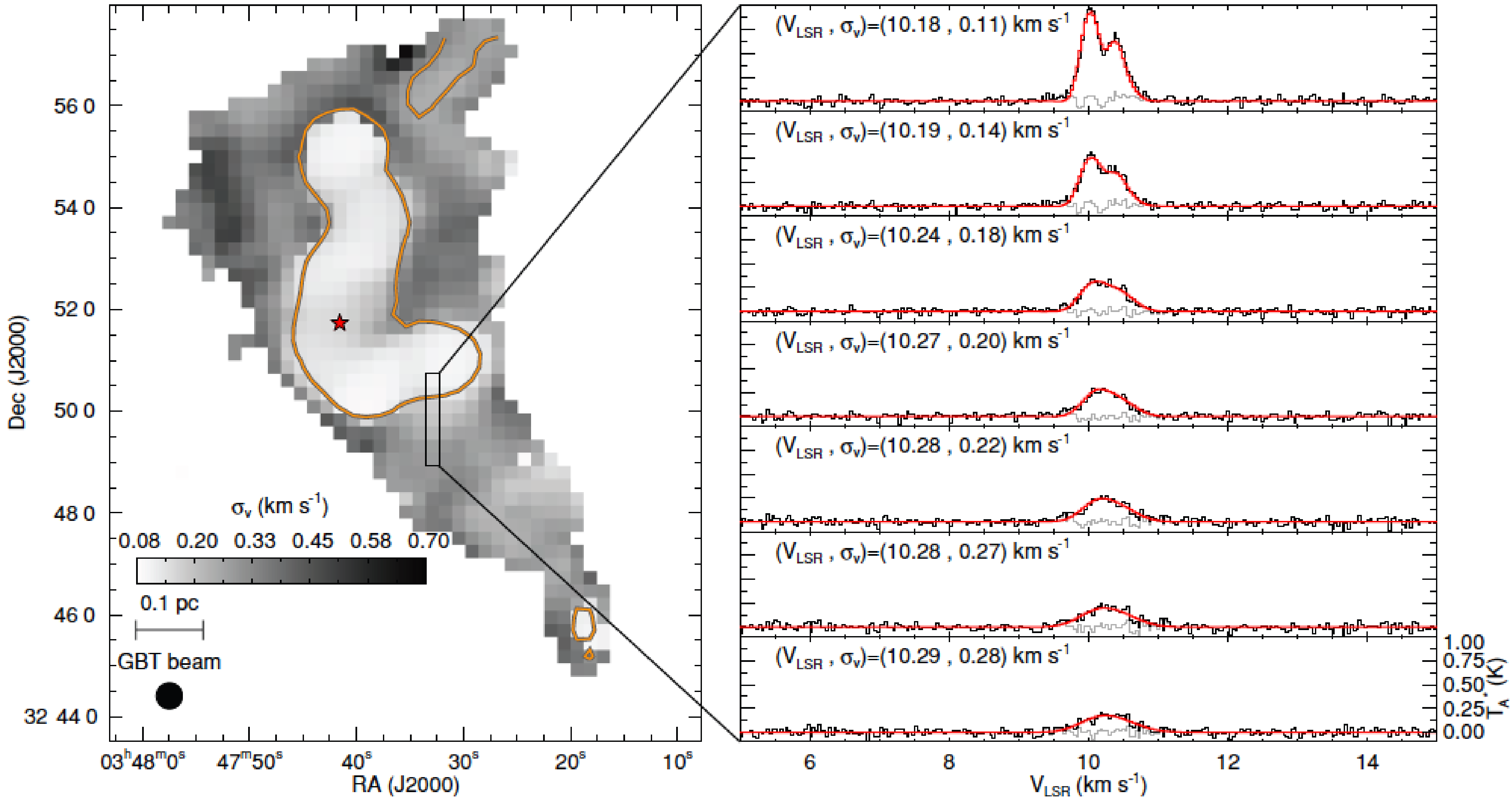
Subsonic internal motions

- **Internal kinematics dominated by subsonic motions**
  - **Myers et al. (1983)**
  - **cores are "velocity coherent" (Goodman et al. 1998)**

- **Sample of +150 cores in Perseus (H. Kirk et al. 2007)**



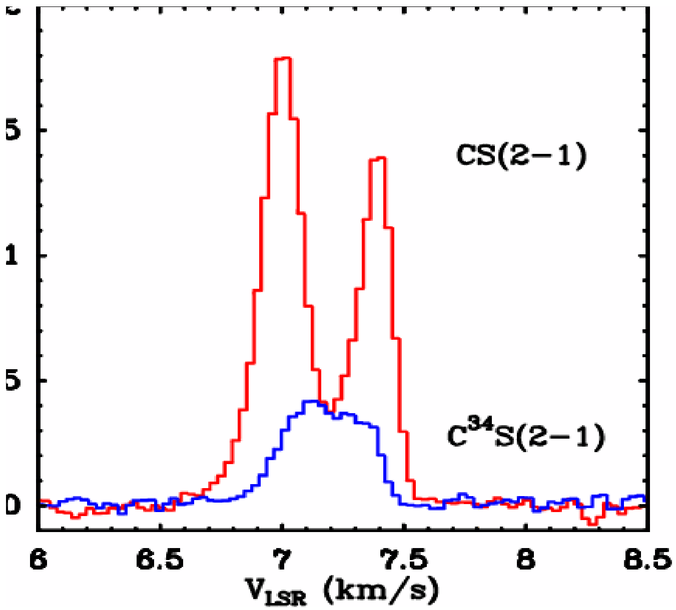
Subsonic internal motions



Pineda et al. (2010)

- **Sharp transition at core boundary**
- **0.5 pc long core or filament?**

Prevalence of inward motions

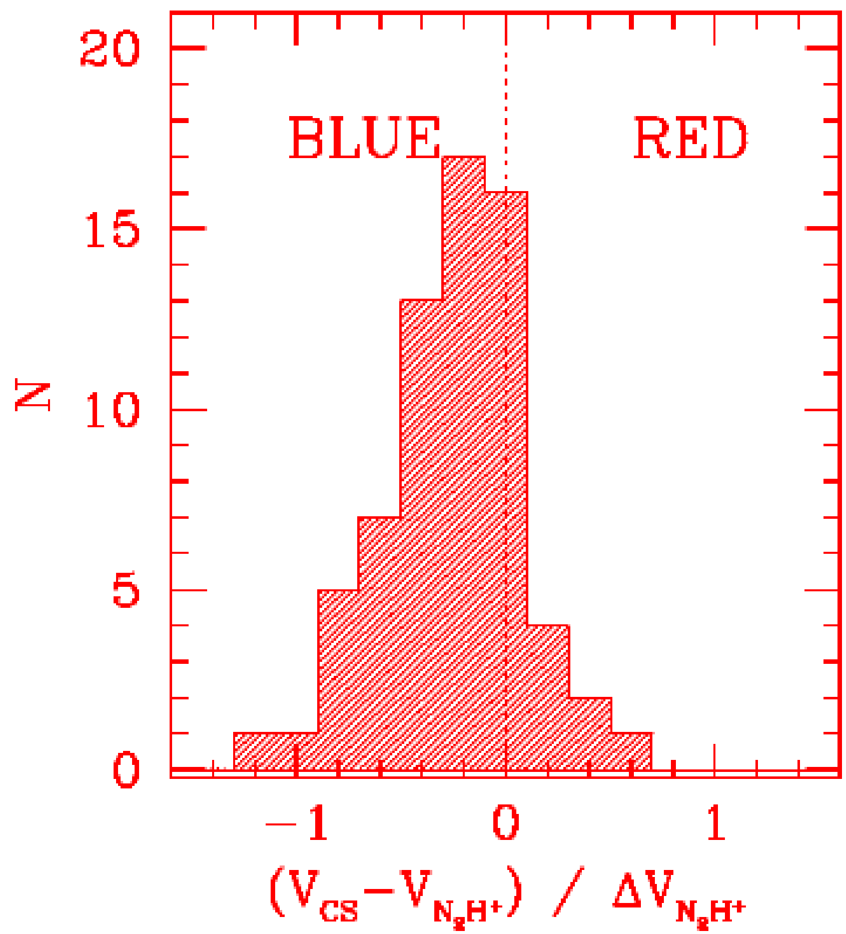


Simple indicator: difference of line peaks thick and thin tracers:

$$\delta V = (V_{\rm thick} - V_{\rm thin})/\Delta V_{\rm thin}$$

- **Inward motions are prevalent in starless cores**
  - **CS red-shifted self-absorption is more common**

67 starless cores

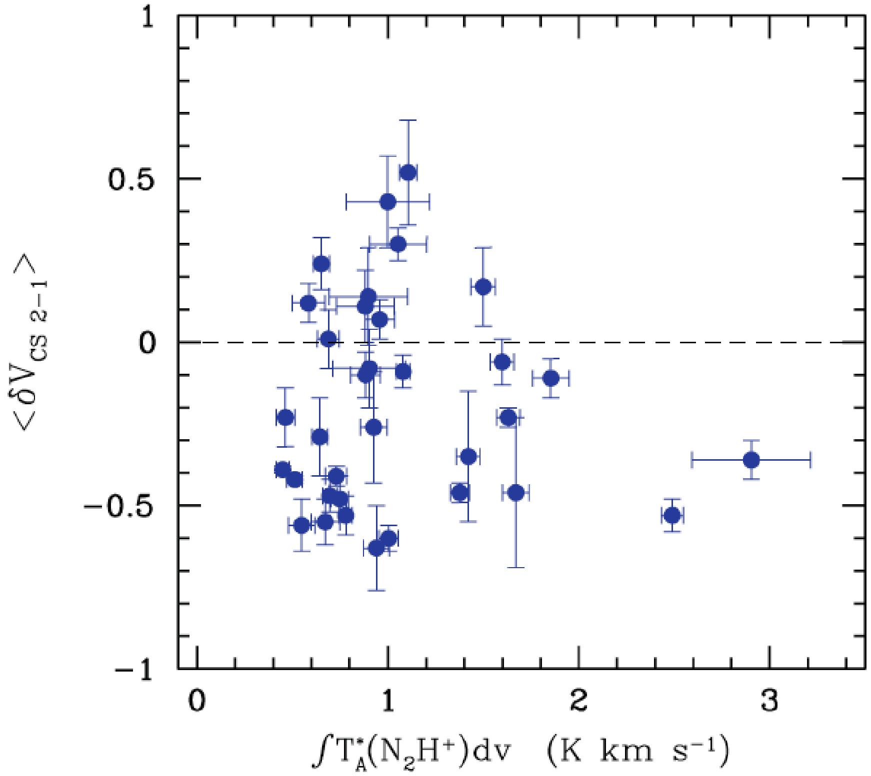


Lee et al. (1999)

Prevalence of inward motions

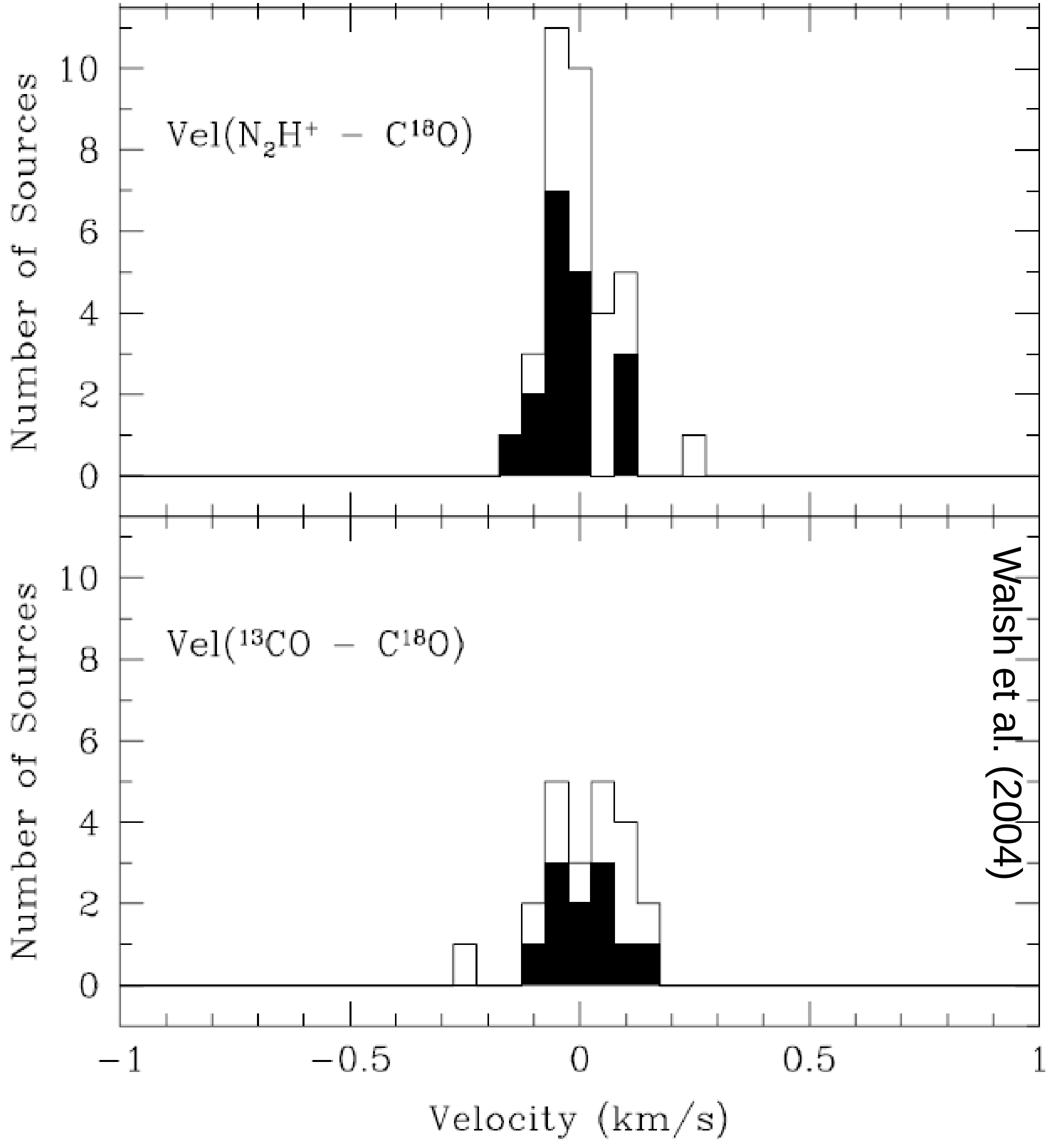
- Prevalence of blue profiles increases with central column density

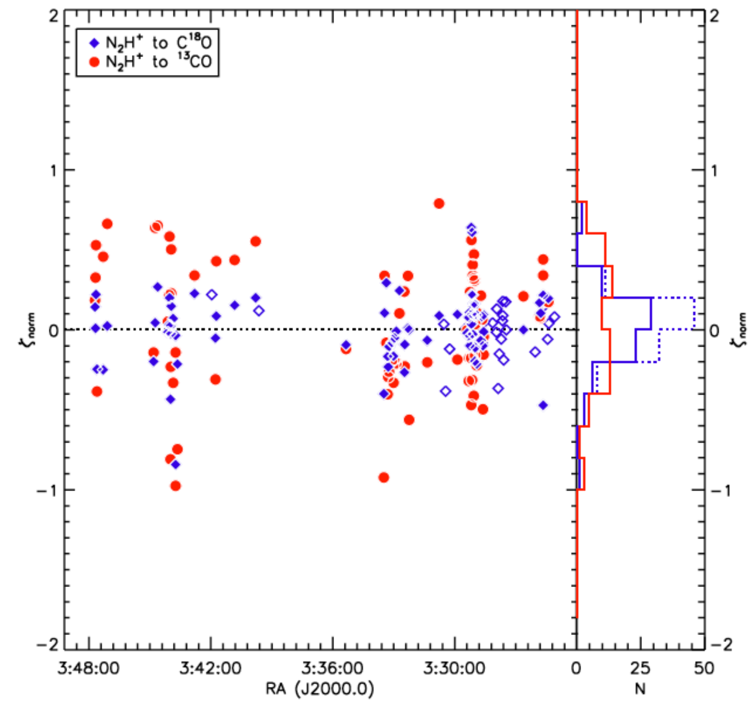
- Evolutionary sequence
  - static (3 10^5 yr)
  - oscillation/expanding (3 10^5 yr)
  - collapsing (8 10^5 yr)



Lee & Myers (2011)

Cores and their environment

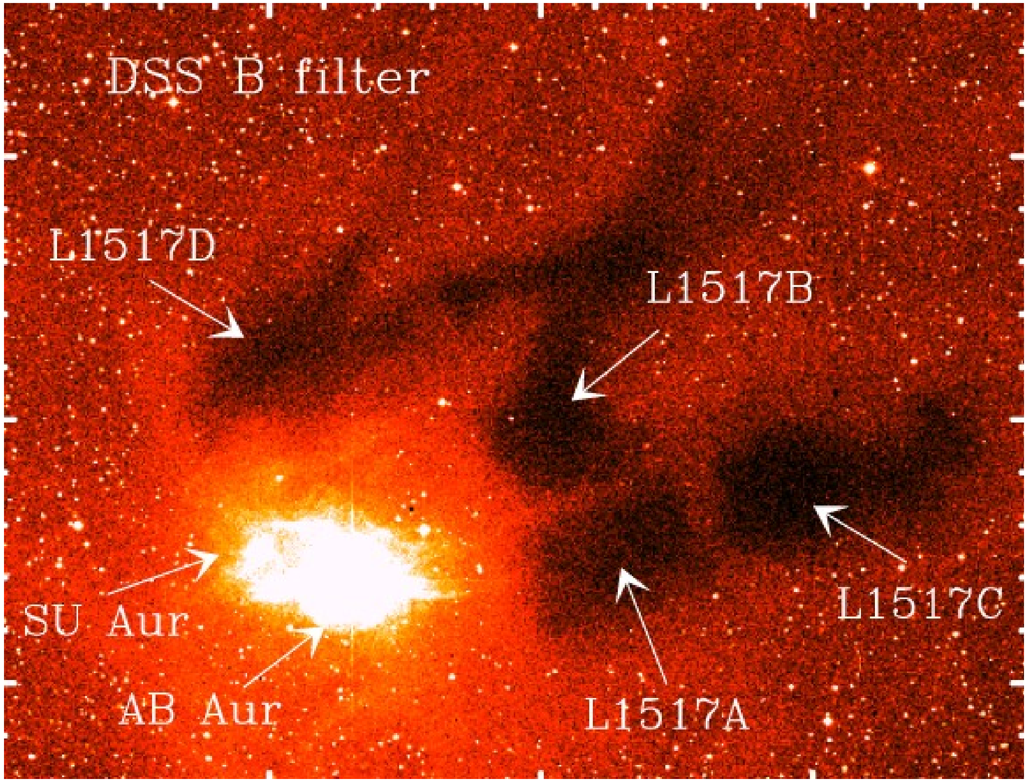


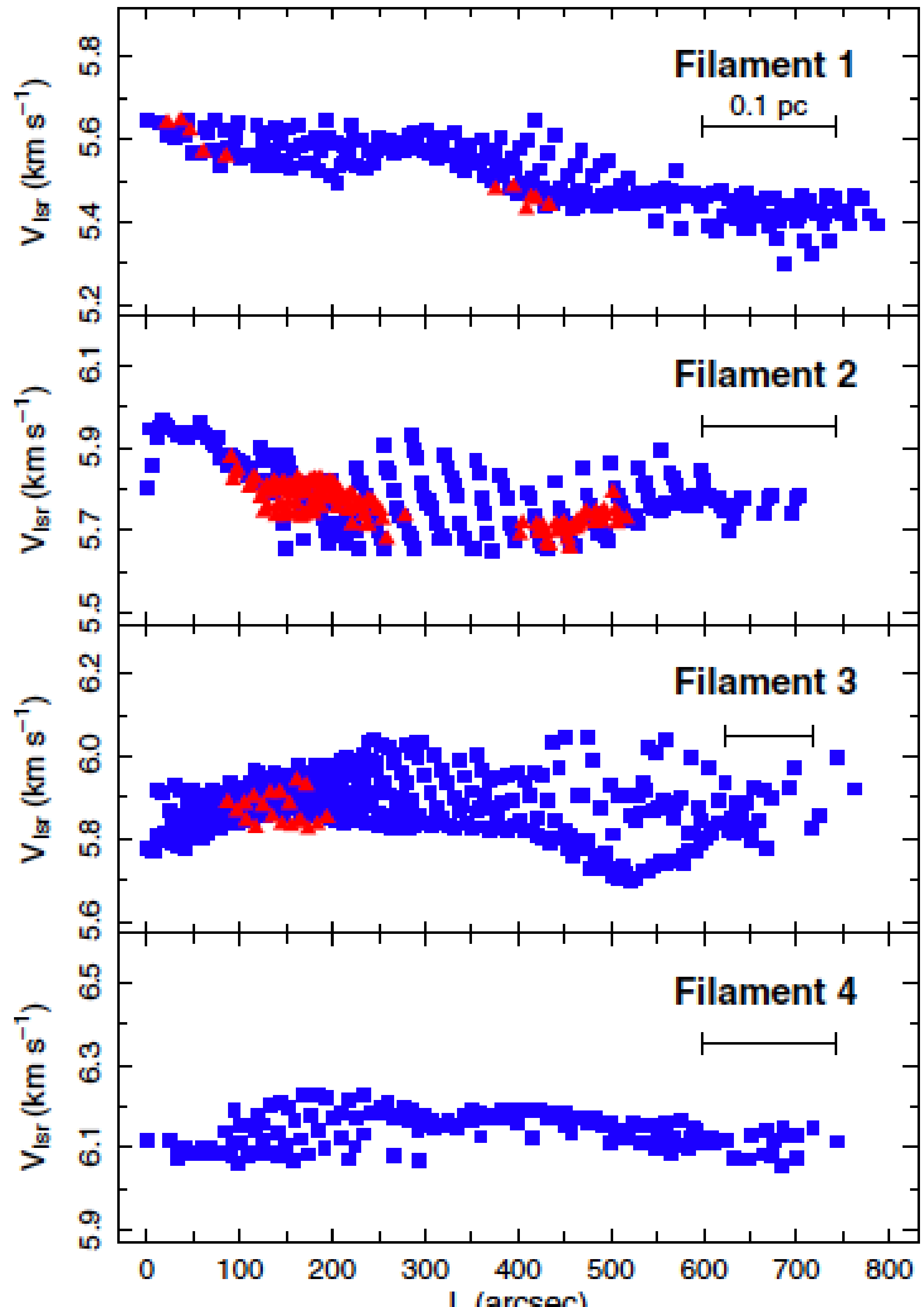


Kirk et al. (2010)

- **Isolated cores**
  - **Walsh et al. (2004)**
  - **< 0.1 km/s**
- **Perseus cloud**
  - **Kirk et al. (2010)**
  - **< 1/3 ^{13}CO linewidth**
- **Cores are almost stationary wrt environment**

Cores and their environment



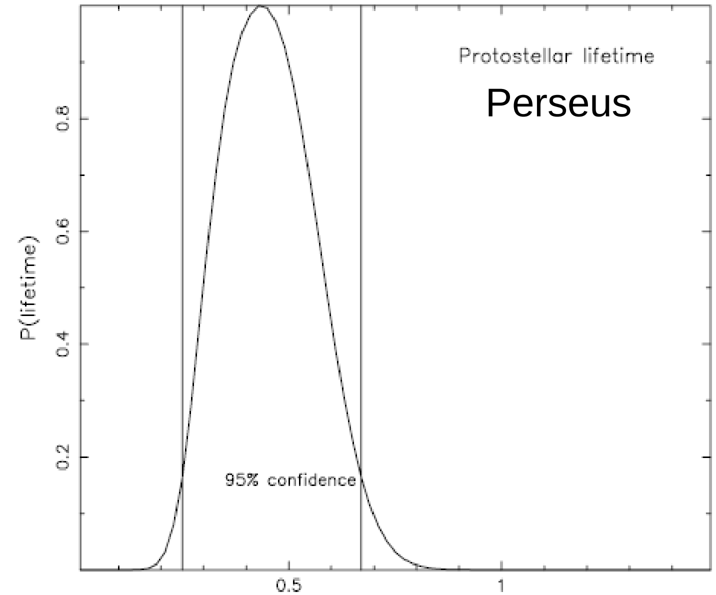


Hacar & Tafalla (2011)

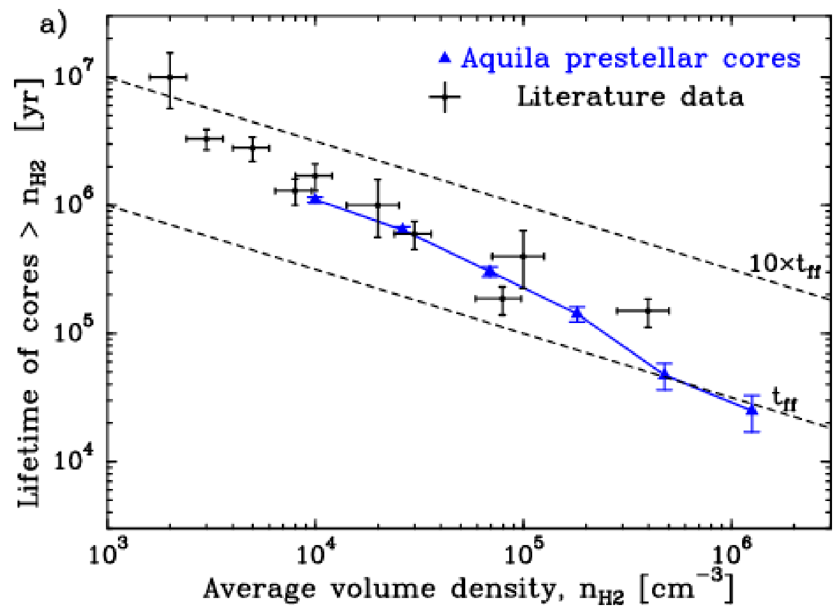
- **Cores stationary wrt filament**
- **Core velocity gradients inherited from filament**
- **Signature of fragmentation**

Lifetimes

- **Derived from ratio cores with and without YSOs + estimate YSO lifetime**
- **N_{SL}/N_{emb} ~ 1**
  - Pers (Hatchell et al. 2007)
  - Pers, Serp, Oph (Enoch et al. 2008)
- **N_{SL}/N_{emb} ~ 3**
  - Lee & Myers (1999) lower density
  - Aquila (Könyves et al. 2010, Bontemps et al. 2010)
- **T ~ 0.3 – 1.5 Myr**
  - $1\ \tau_{ff} < T < 10\ \tau_{ff}$

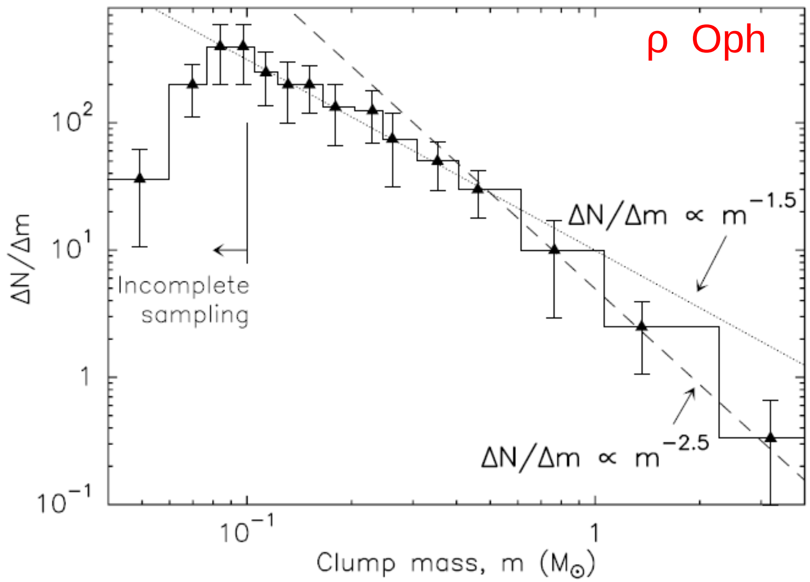


Hatchell et al. (2007)

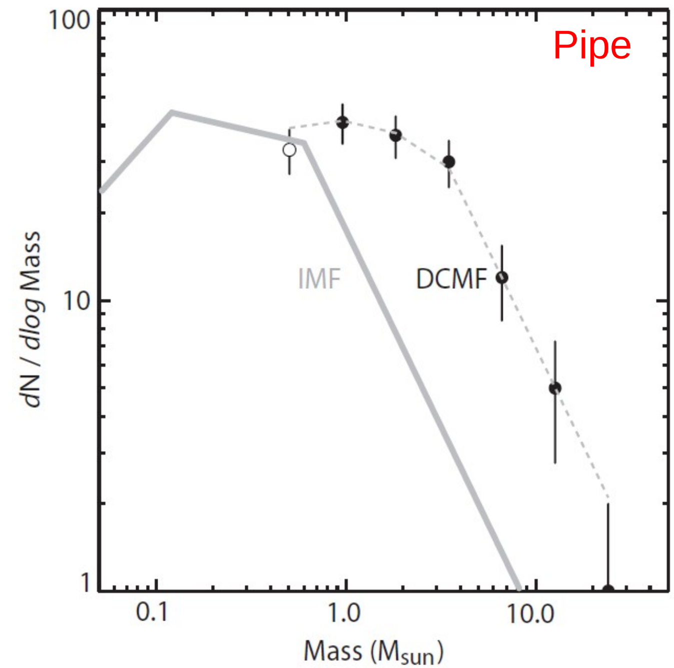


Jessop & Ward-Thomson (2000) + Andre et al. (2013)

Core mass function and the IMF

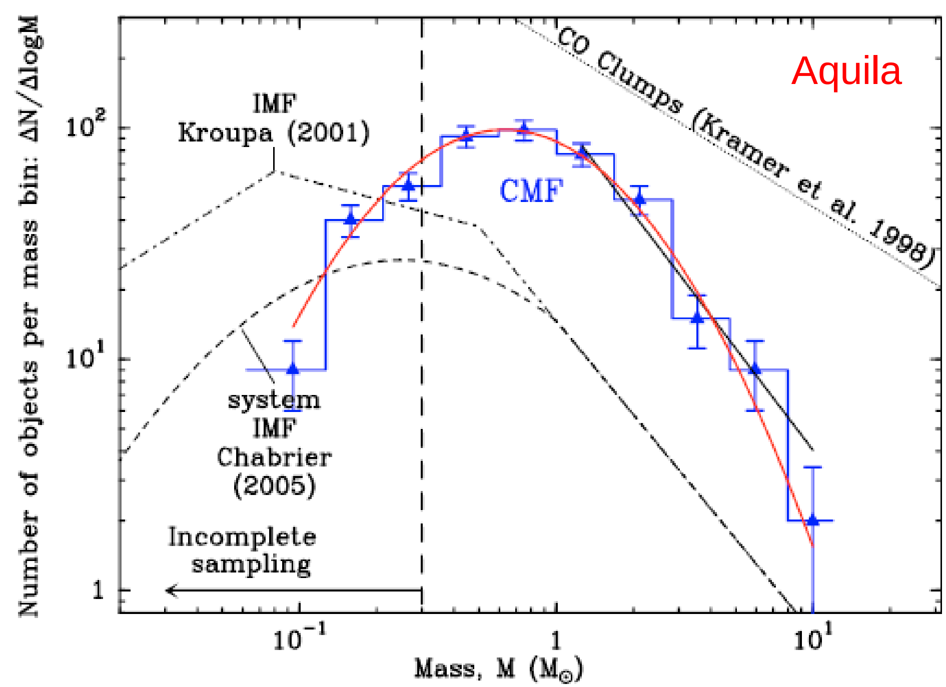


Motte et al. (1998)



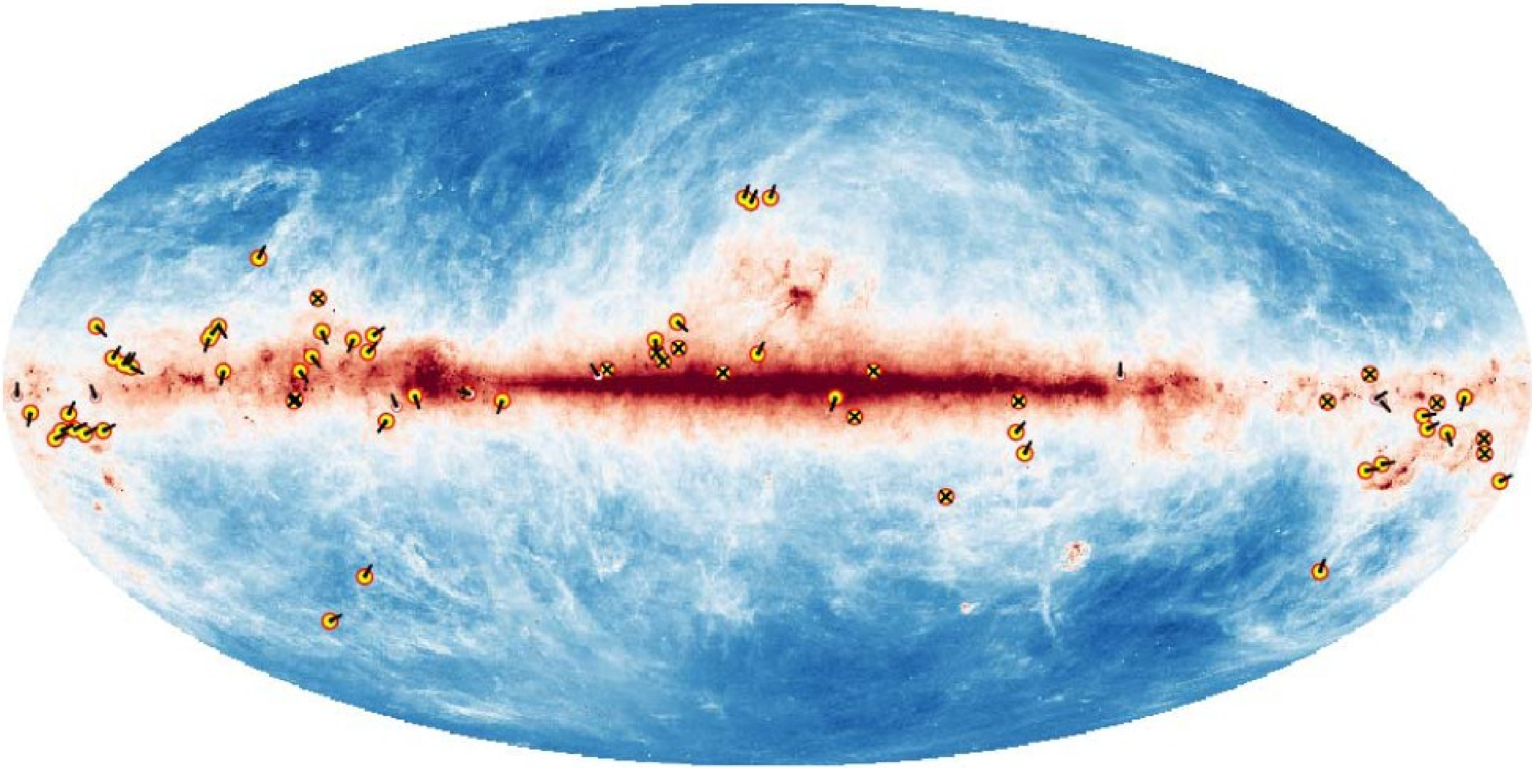
Alves et al. (2007)

- **Statistics of starless core masses: CMF**
- **Comparison with stellar IMF**
  - **similar high mass slope**
  - **peak mass displaced ~ x3**
- **IMF defined at core formation?**
  - **~1/3 star-forming efficiency?**



Könyves et al. (2010)

Planck-Herschel Survey



- **Selection of coldest and most compact Planck sources**
  - **Cold clump catalog of Planck Objects (C3PO): 10,000**
  - **dominated by ~1pc clumps, not cores (large beam)**

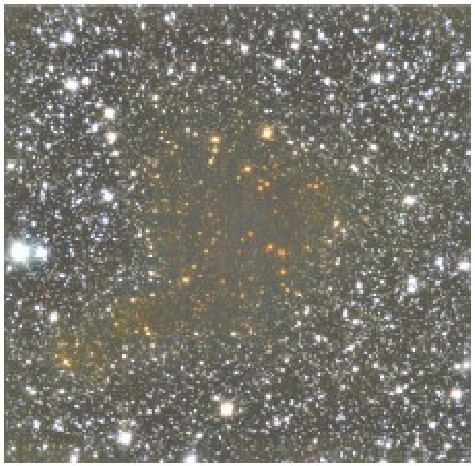
- **Talk by Sarolta Zahorecz**

Outline:

- Global properties
- **Internal properties**
- Connection with the large scales

Density structure: in dust we trust

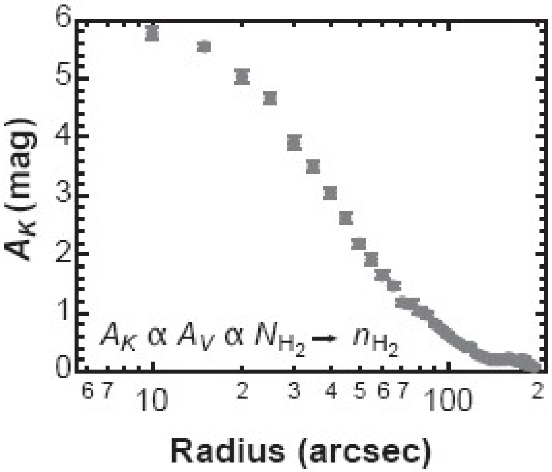
a Barnard 68 K band



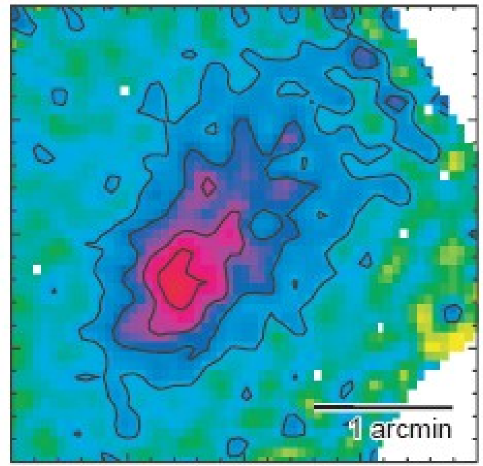
$A_V = r_V^{H,K} E(H-K)$

$A_V = f N_H$

$N_H = (r_V^{H,K} f^{-1}) \cdot E(H-K)$



b L1544 1.2 mm continuum

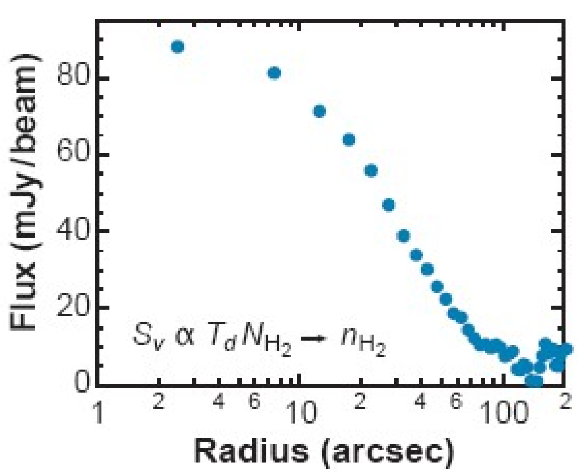


For optically thin emission:

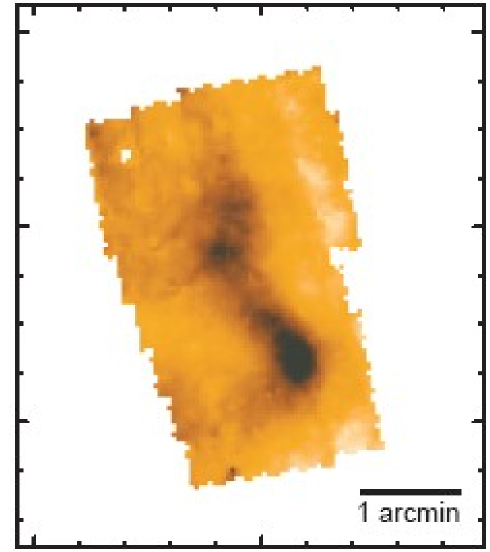
$I_\nu = \int \kappa_\nu \rho \, B_\nu(T_d) dl$

$I_\nu = m < \kappa_\nu B_\nu(T_d) > N_H$

$N_H = I_\nu \, [< m \kappa_\nu B_\nu(T_d) >]^{-1}$



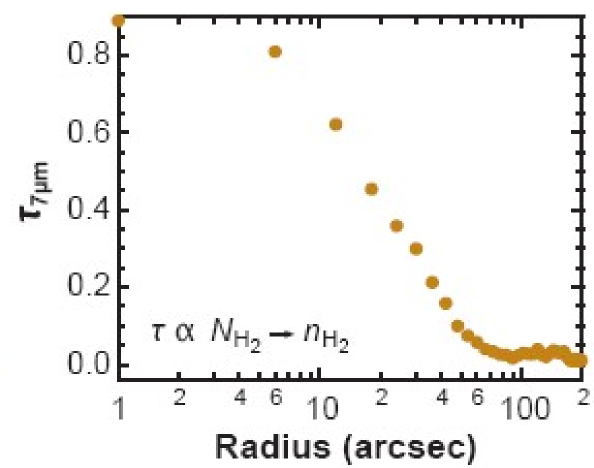
c ρ Oph core D 7 µm image



$I_\nu = I_\nu^{bg} \exp(-\tau_\lambda) + I_\nu^{fg}$

$\tau_\lambda = \sigma_\lambda N_H$

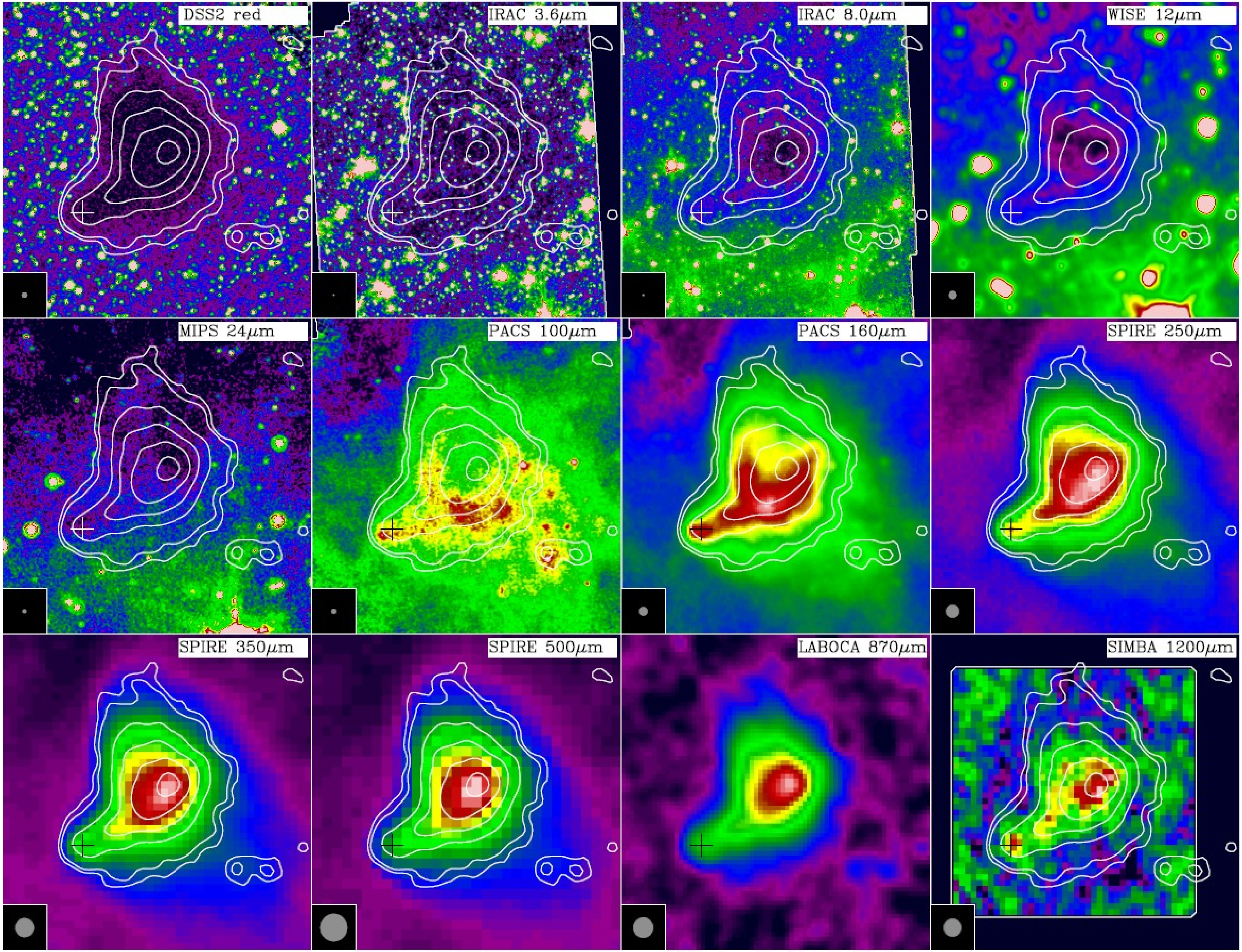
$N_H = -\frac{1}{\sigma_\lambda} \ln \frac{I_\nu^{bg}}{I_\nu^{bg} - I_\nu^{fg}}$



Alves et al. (2001) – Ward-Thomson et al. (1999) – Bacmann et al. (2000)

Compiled by Bergin & Tafalla (2007)

Density structure of the B68 globule



Nielbock et al. (2012)

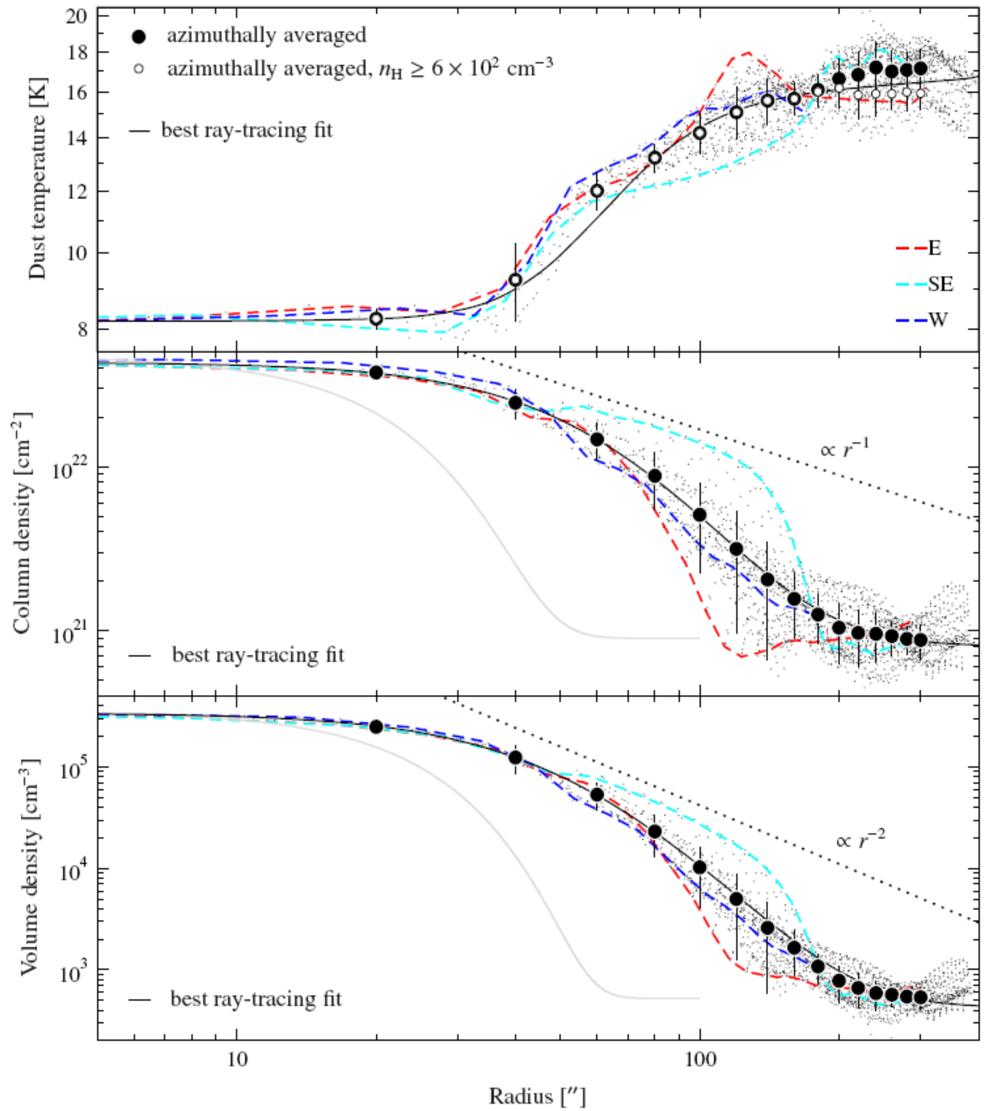
Density structure of the B68 globule

- **EpoS Herschel Program**
- **Dust temperature gradient**
  - **8 K to 16 K**
  - **externally heated by ISRF**
- **Flattened density profile**
  - **Plummer-like profile**

But

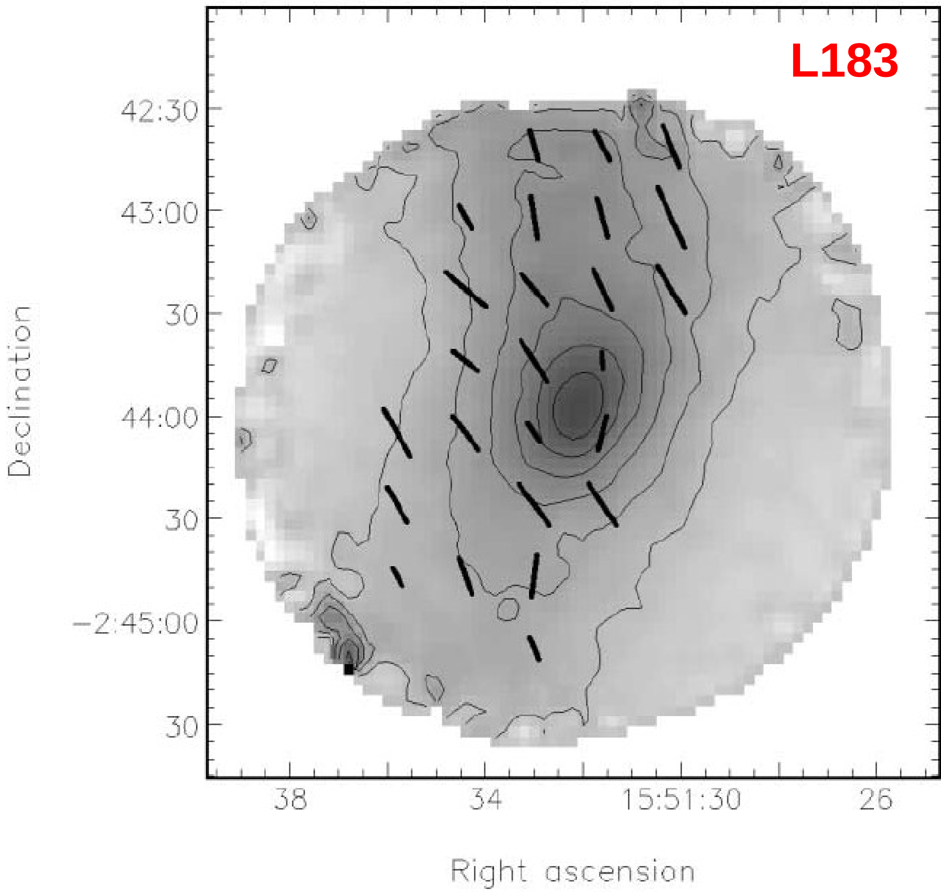
- **Dependent on grain model**
  - **constant emissivity with depth**

- **See also Launhardt et al. (2013), Suutarinen et al. (2013)**

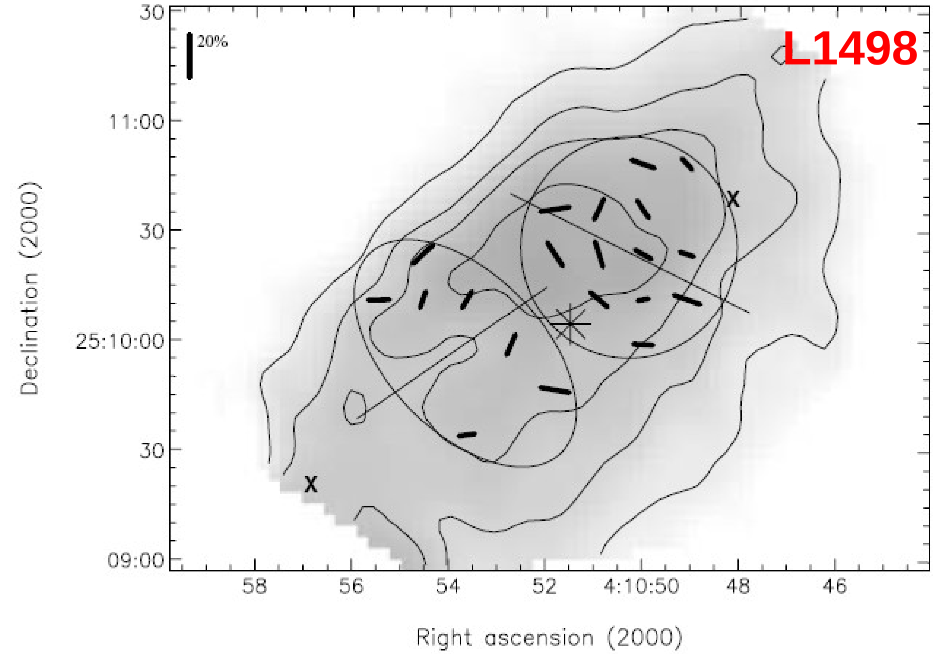


Nielbock et al. (2012)

Shapes and magnetic fields



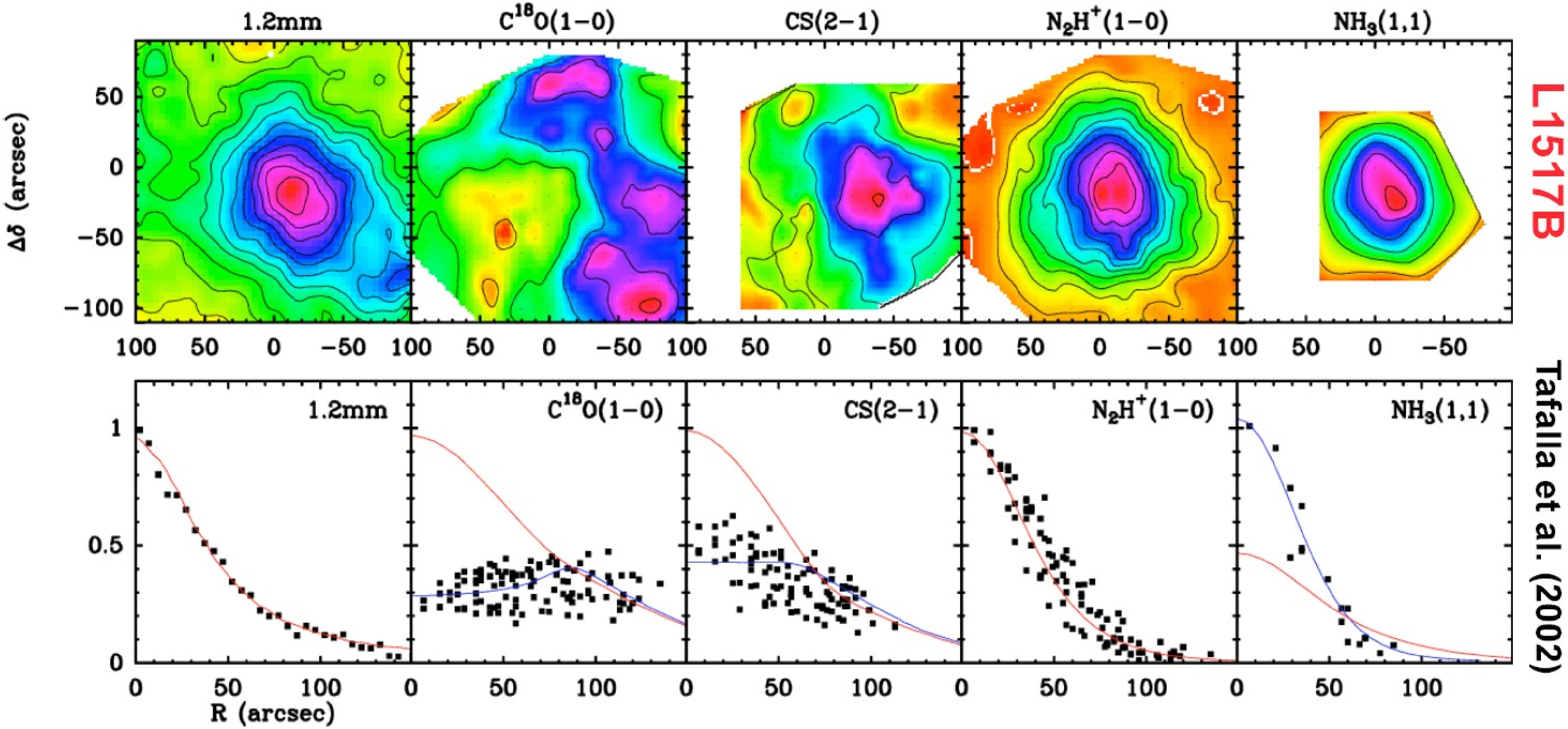
Crutcher et al.(2004)



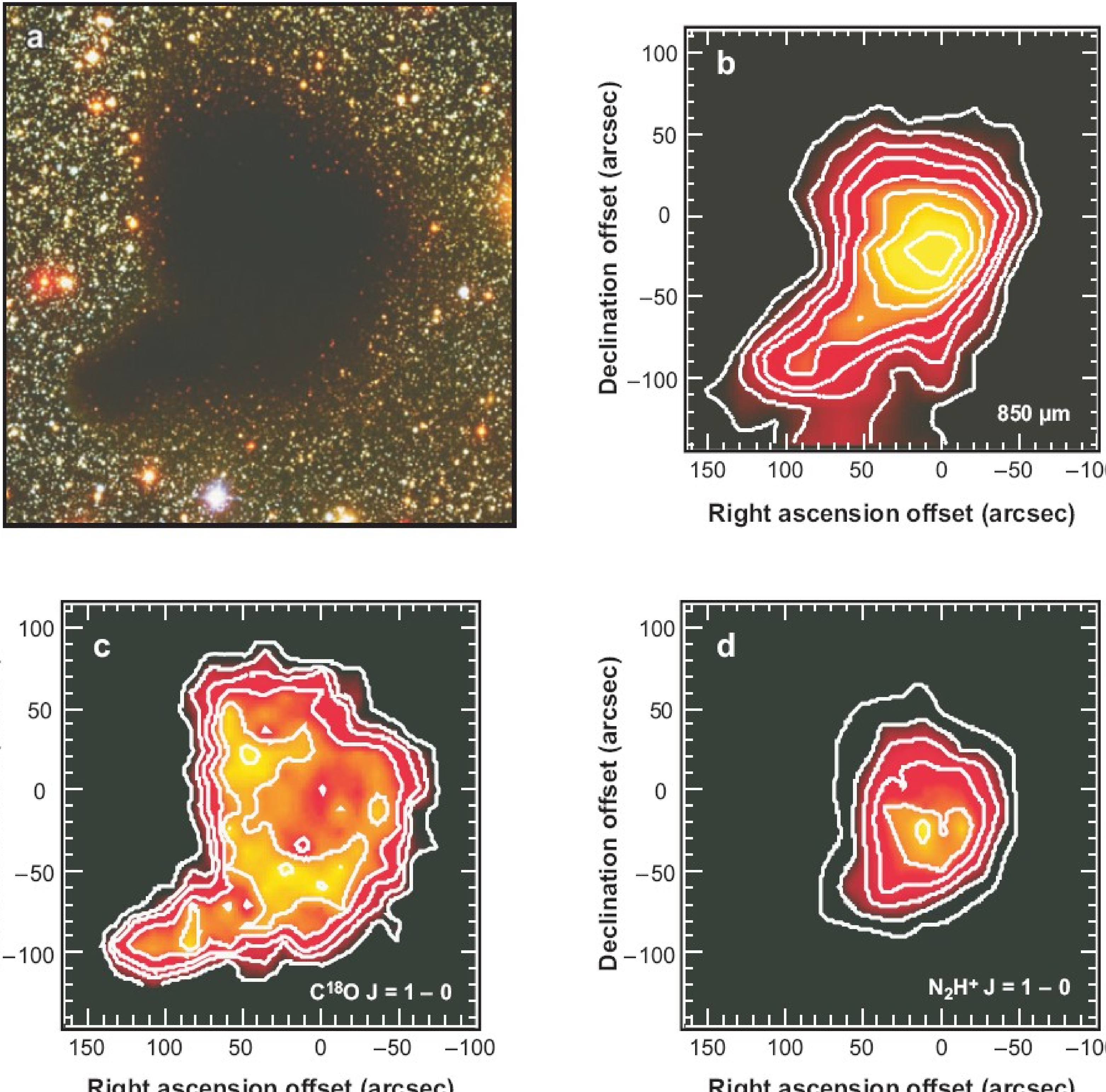
Kirk et al. (2006)

- **Cores show significant deviations from spherical symmetry**
  - **2:1 axial ratio (Myers 1991)**
- **Oblate vs prolate**
  - **Filaments favor prolate shapes**
- **No clear correlation between B and core shape**
  - **uncertain projection**
  - **B ~ 10-100 μG**
- **Unlikely than B controls core shapes**

Chemical composition



- **Systematic abundance pattern**
  - **C-bearing species dissapear from core center**
  - **N-bearing species remain at core center**

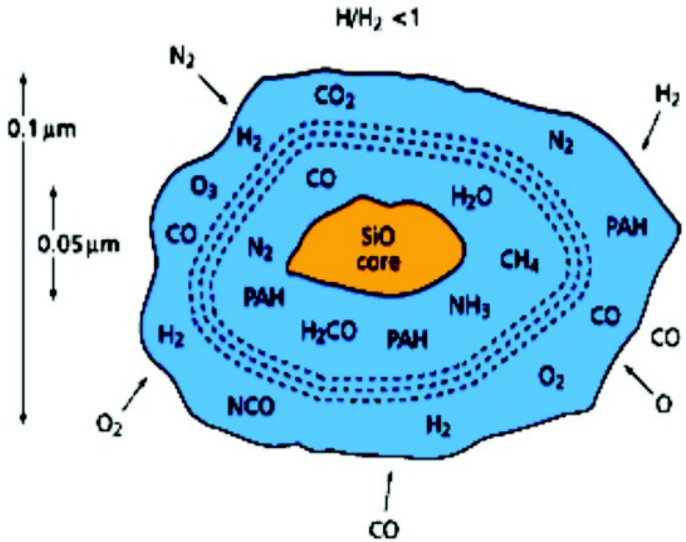


B68

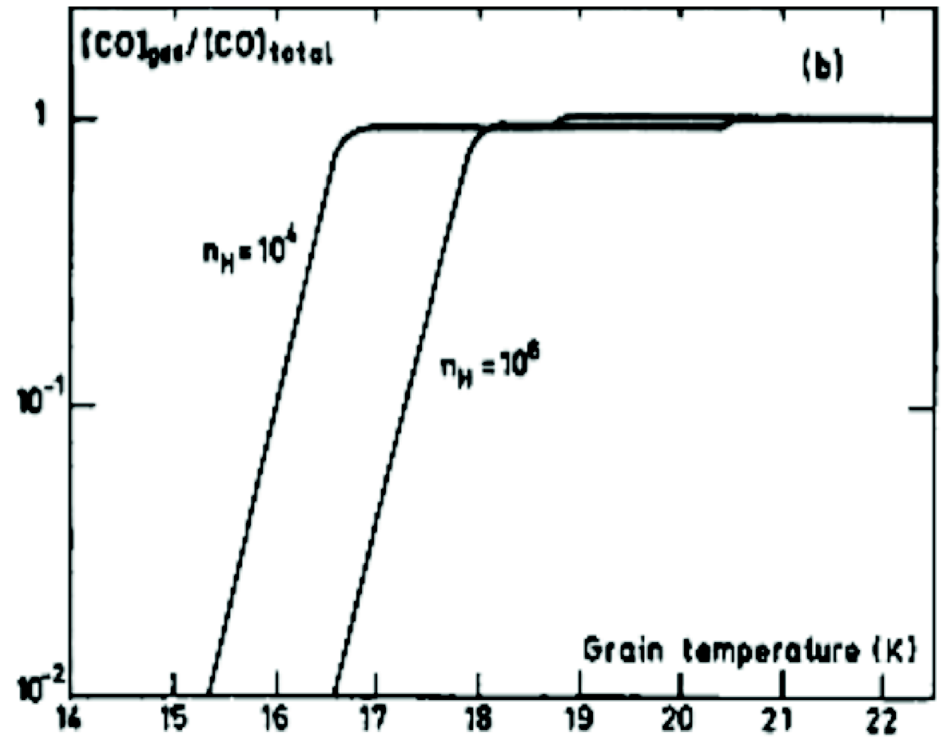
Bergin et al. (2002)

Molecular freeze-out

- **Gas-grain equilibrium (sticking vs evaporation)**
  - **If $T_{grain} > T_{freezeout}$, most molecules in gas phase**
  - **If $T_{grain} < T_{freezeout}$, most molecules on grains**



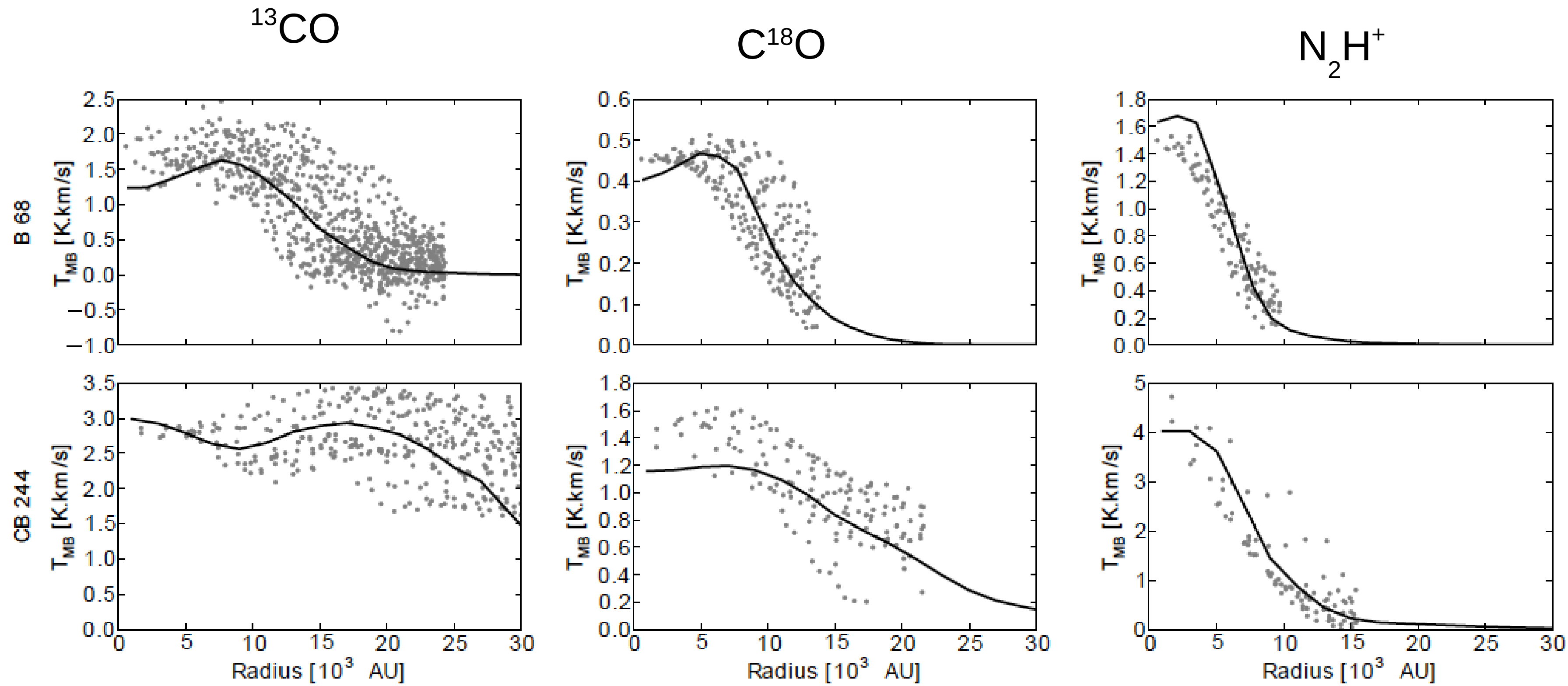
Scott Sandford



Leger (1983)

- **Under core conditions (Tgrain < 10 K)**
  - **molecules stick on grains and do not evaporate**
  - **freeze out**

CO depletion in Herschel era



Lippok et al. (2014)

- **Combine density and temperature from Herschel with mm-wave observations to model abundance profiles**
- **Need to multiply density by 2-3 to fit emission**
  - **do we need a new dust model?**

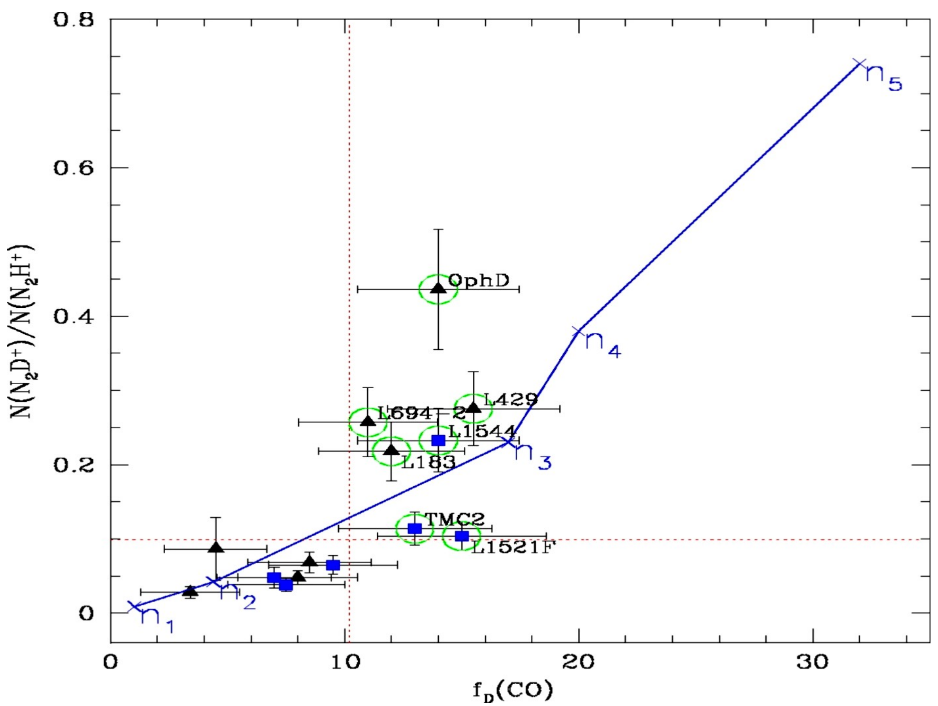
CO freeze-out enhances D-fractionation

- CO depletion has profound consequences in core chemistry
  - triggers a number of second-order effects
- Deuterium fractionation of molecules is driven by

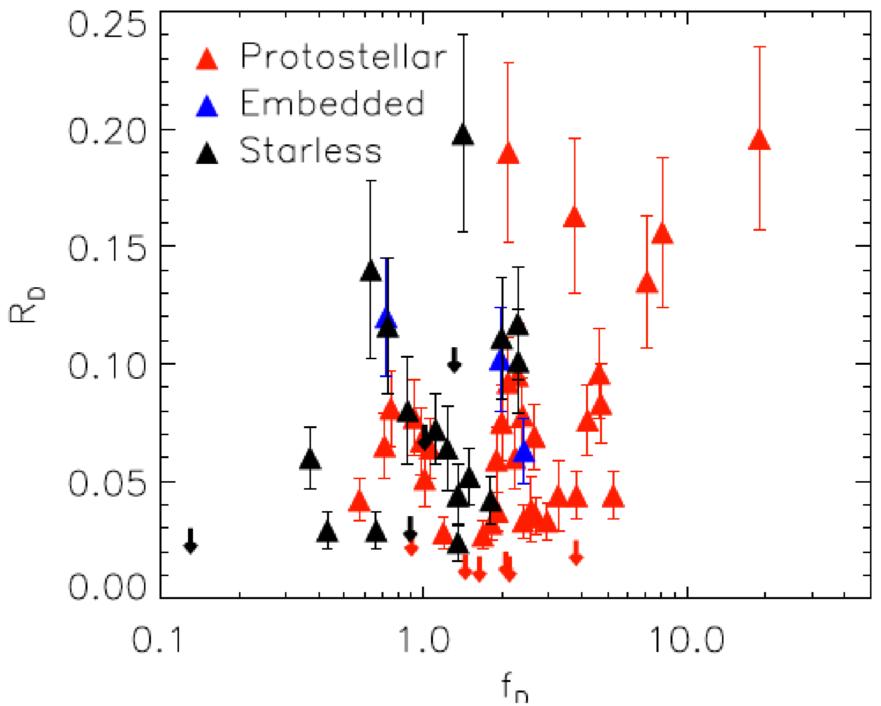
$$H_3^+ + HD \leftrightarrow H_2D^+ + H_2 + 230\ K$$

- At low temperature (e.g., 10 K), H_2D^+ is enhanced
  - Deuterium is passed down to other species such DCO+, DCN
- If no CO depletion
  - H_2D^+ abundance is limited by CO destruction (+e)
  - D enrichment of order of 1-10 %
- If CO depletion (and low e)
  - H_2D^+ is further enhanced, which further enhances N2D+, NH2D, etc.
  - even D_2H^+ and D_3^+ are produced: multiply deuterated species

CO freeze-out enhances D-fractionation

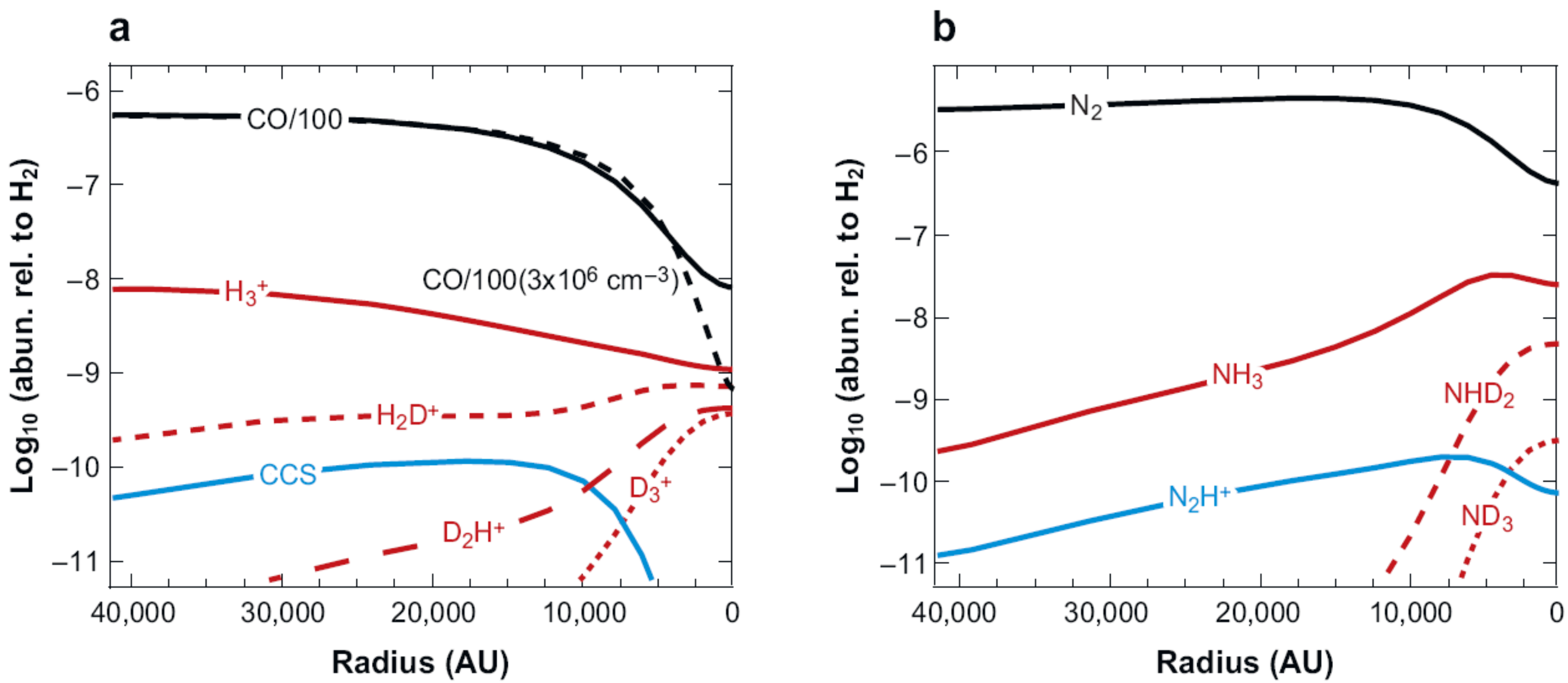


Crapsi et al. (2005)

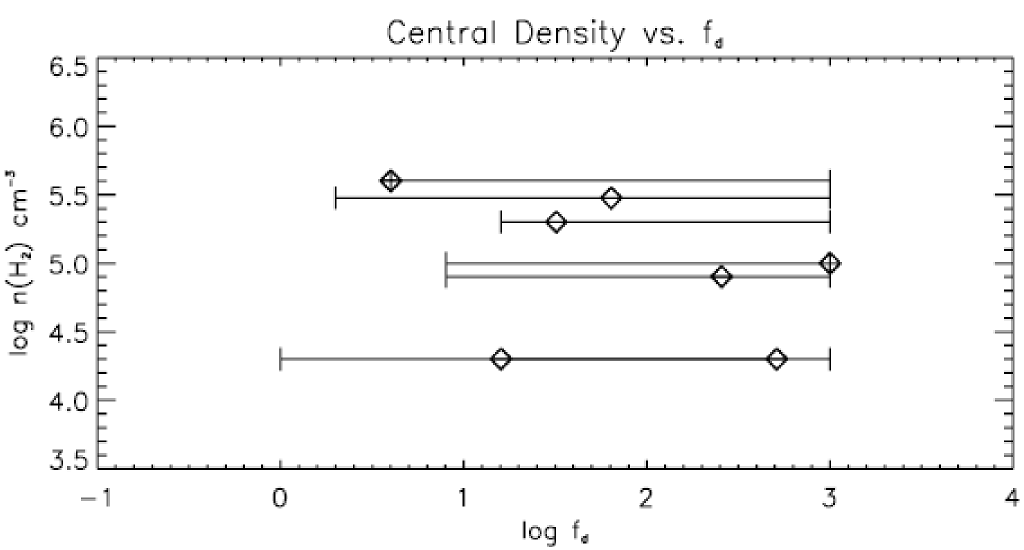


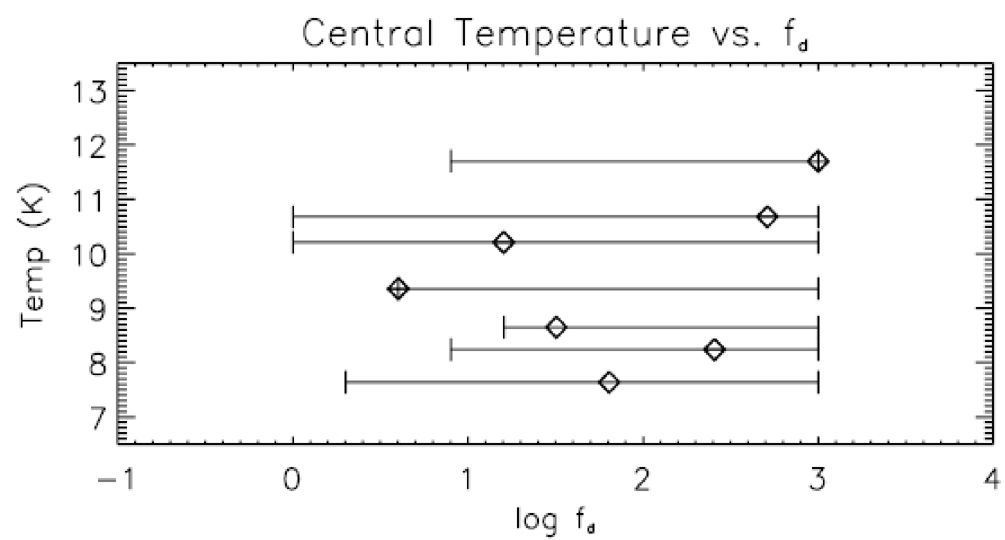
Friesen et al. (2013)

Comparison with models



Aikawa et al. (2005)

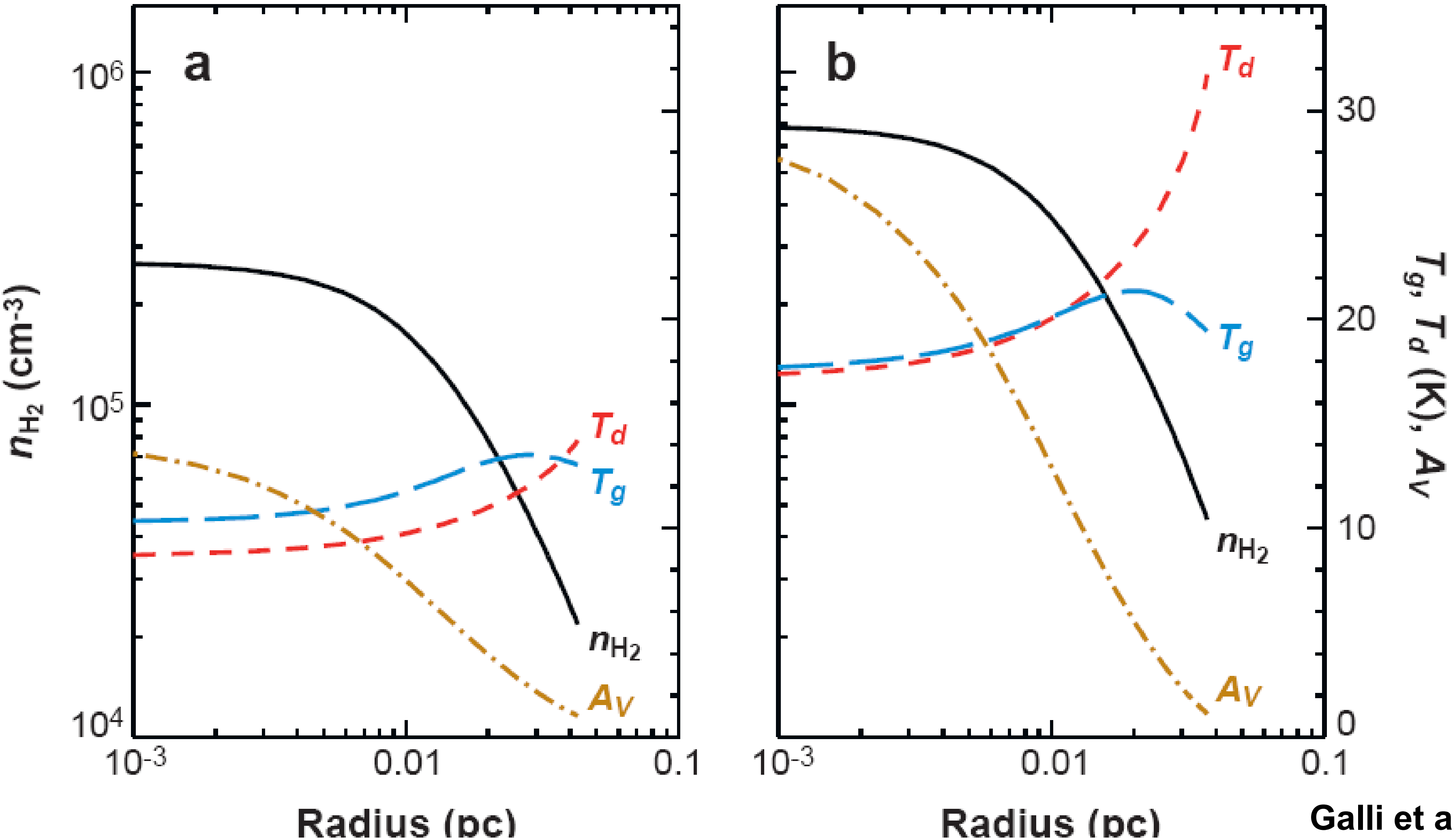




Ford & Shirley (2011)

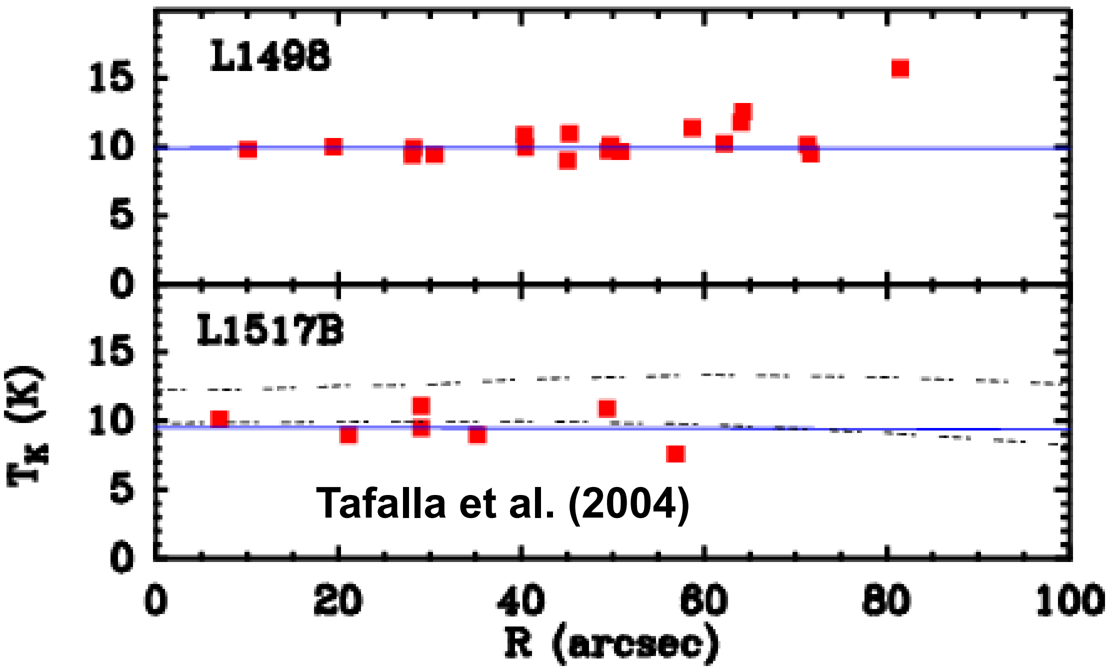
Gas-dust thermal coupling

- **Dust and gas can have different temperatures**
  - **temperature set by heating = cooling**
  - **for densities < 10^5 cm^{-3}, dust and gas are not coupled thermally**

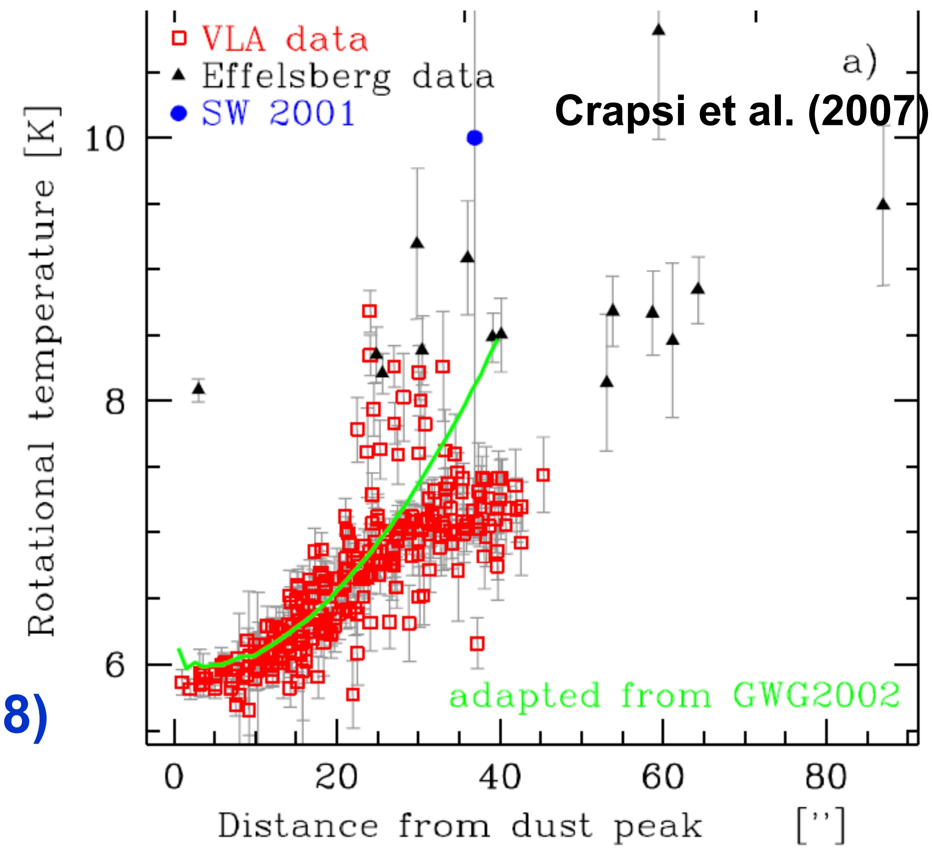


Galli et al. (2002)

Gas temperature. Radial profiles



- Approx. constant in moderately dense cores. T = 10 K
  - L1498 & L1517B
  - $n(H_2)$ = 1-2 10^5 cm-3



- Central drop in L1544
  - n(H2) = 2 10^6 cm-3
- T = 6 K
- Suggestive of gas-dust thermal coupling
  - change in EOS
  - prestellar/starless (Keto & Caselli 2008)

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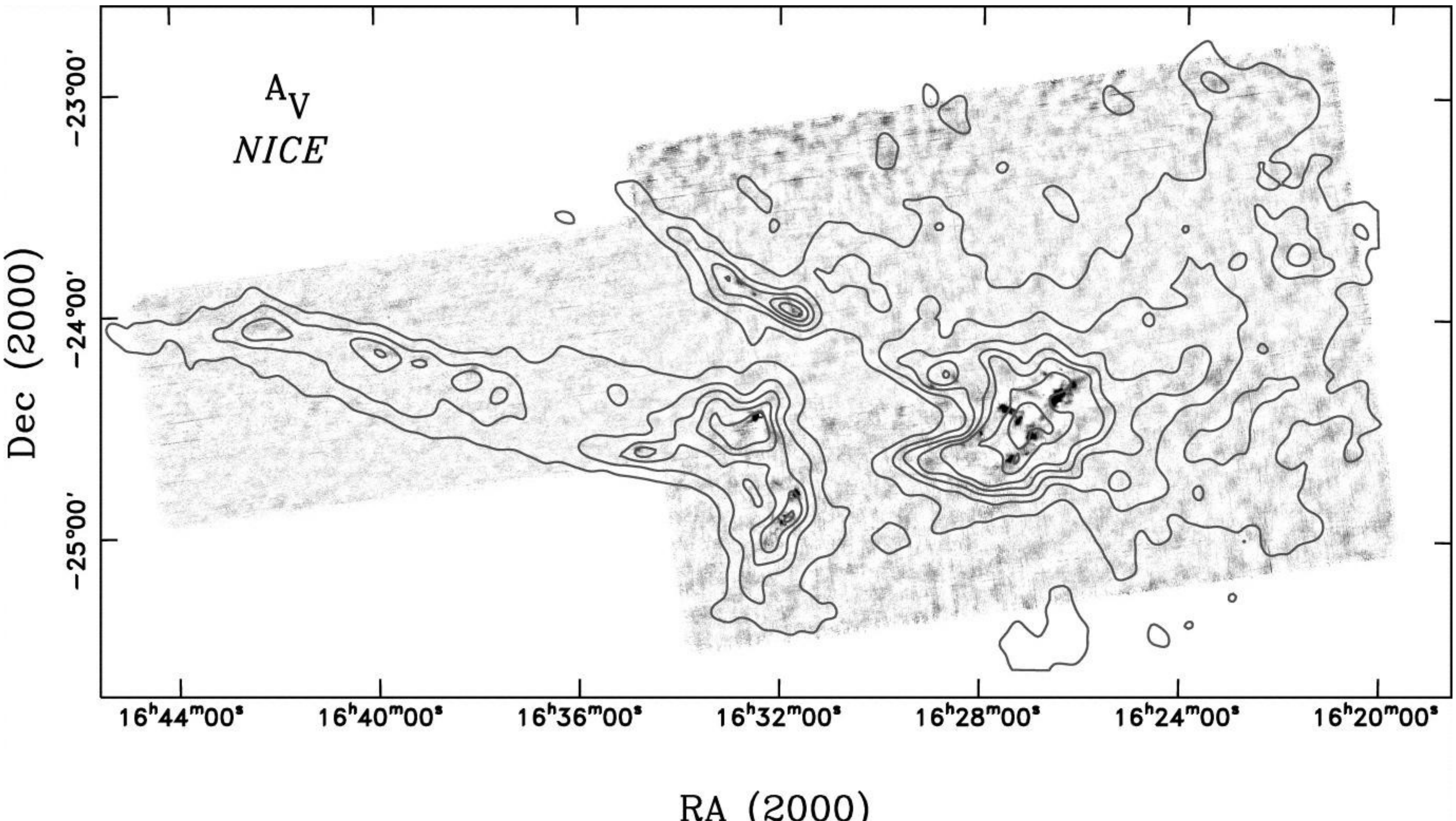
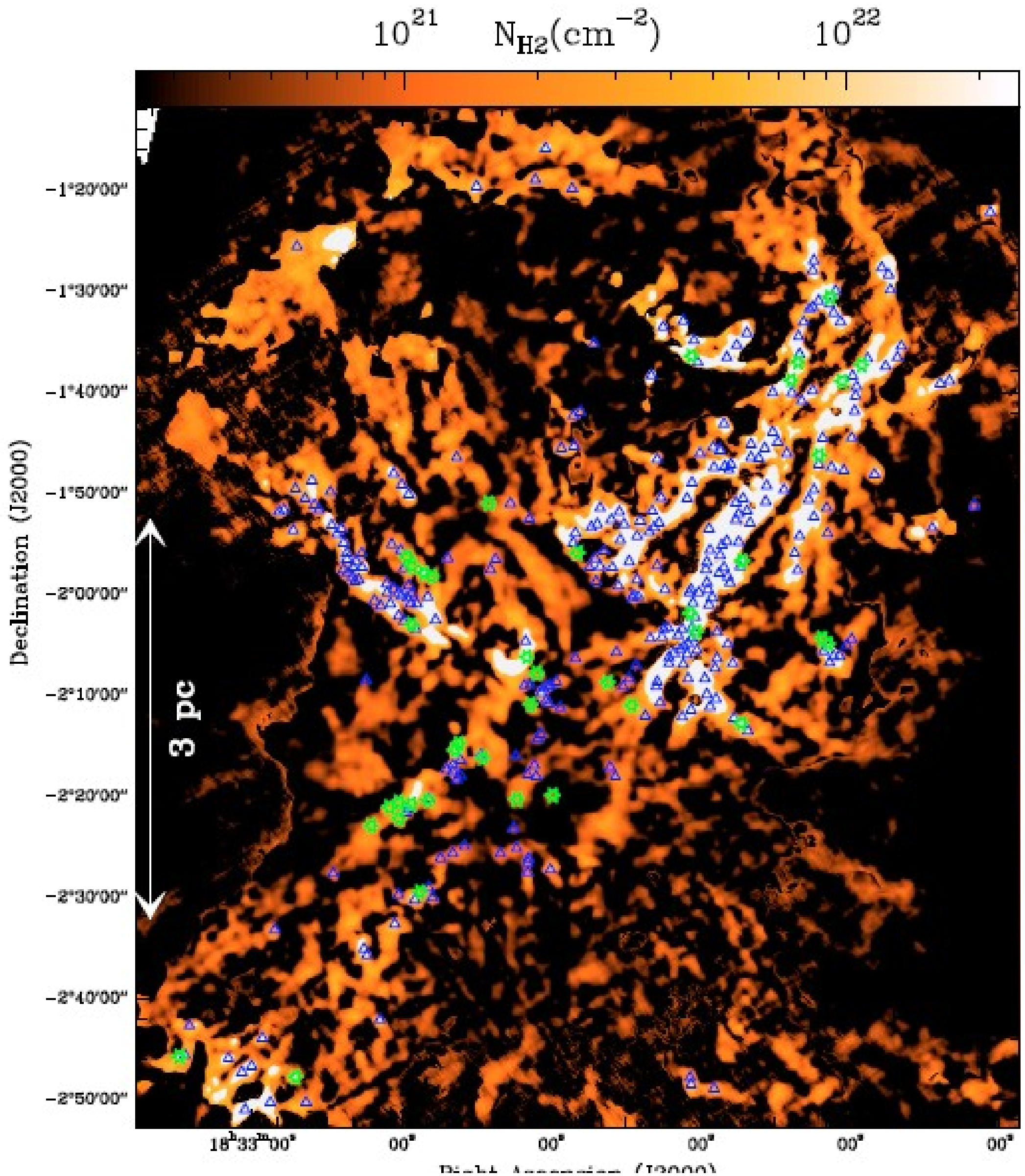
Cores are special places



- **Not all gas makes transition to core regime**
  - **about 5-10% in mass**
  - **core-formation bottleneck may be related to low SFE**
  - **possible threshold (Johnstone at al. 2004, Enoch et al. 2006)**

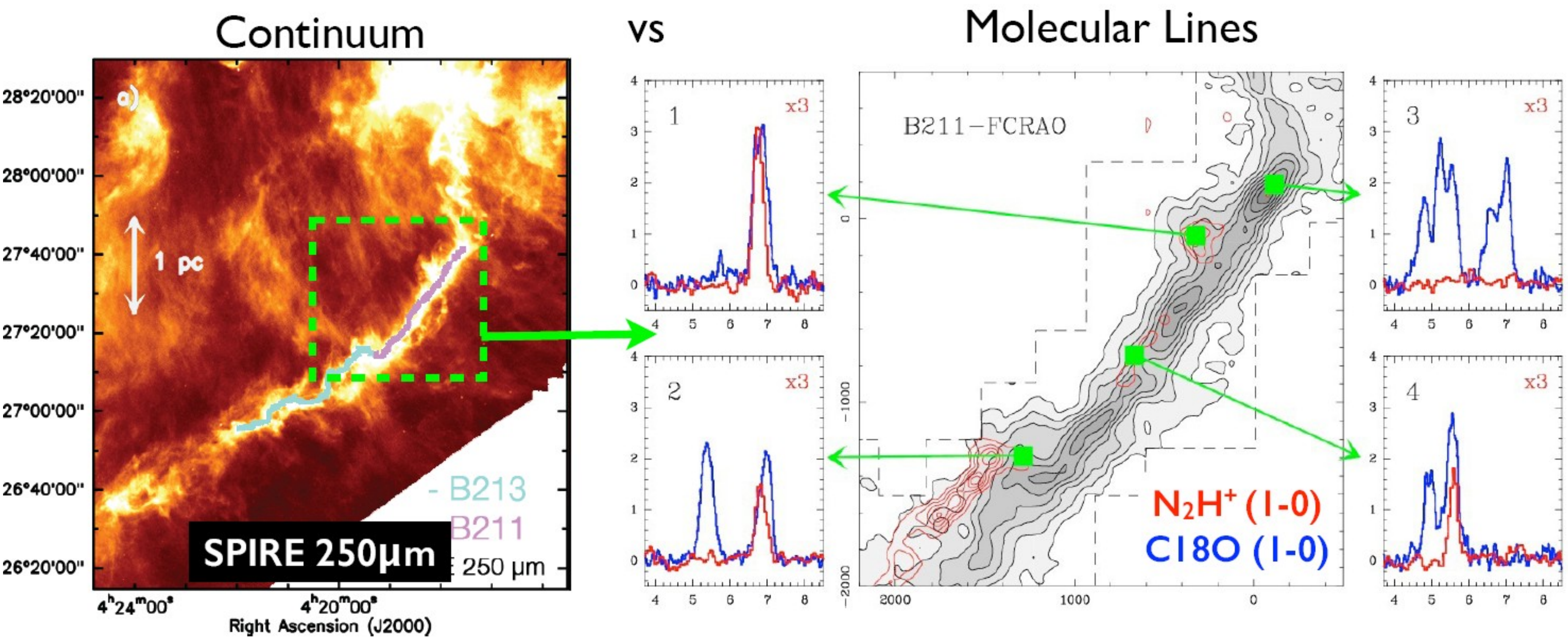
Cores lie along filaments

- **Talk by Frederique Motte**
- **About 70% of pre-stellar cores in Aquila located in filaments (André et al. 2010)**
  - **beads in string**
  - **off-filament cores are less massive (Polychroni et al. 2013)**
- **Fragmentation interpretation seems unavoidable**
- **How is the filament to core transition?**



Könyves et al. (2010)

The importance of velocity information

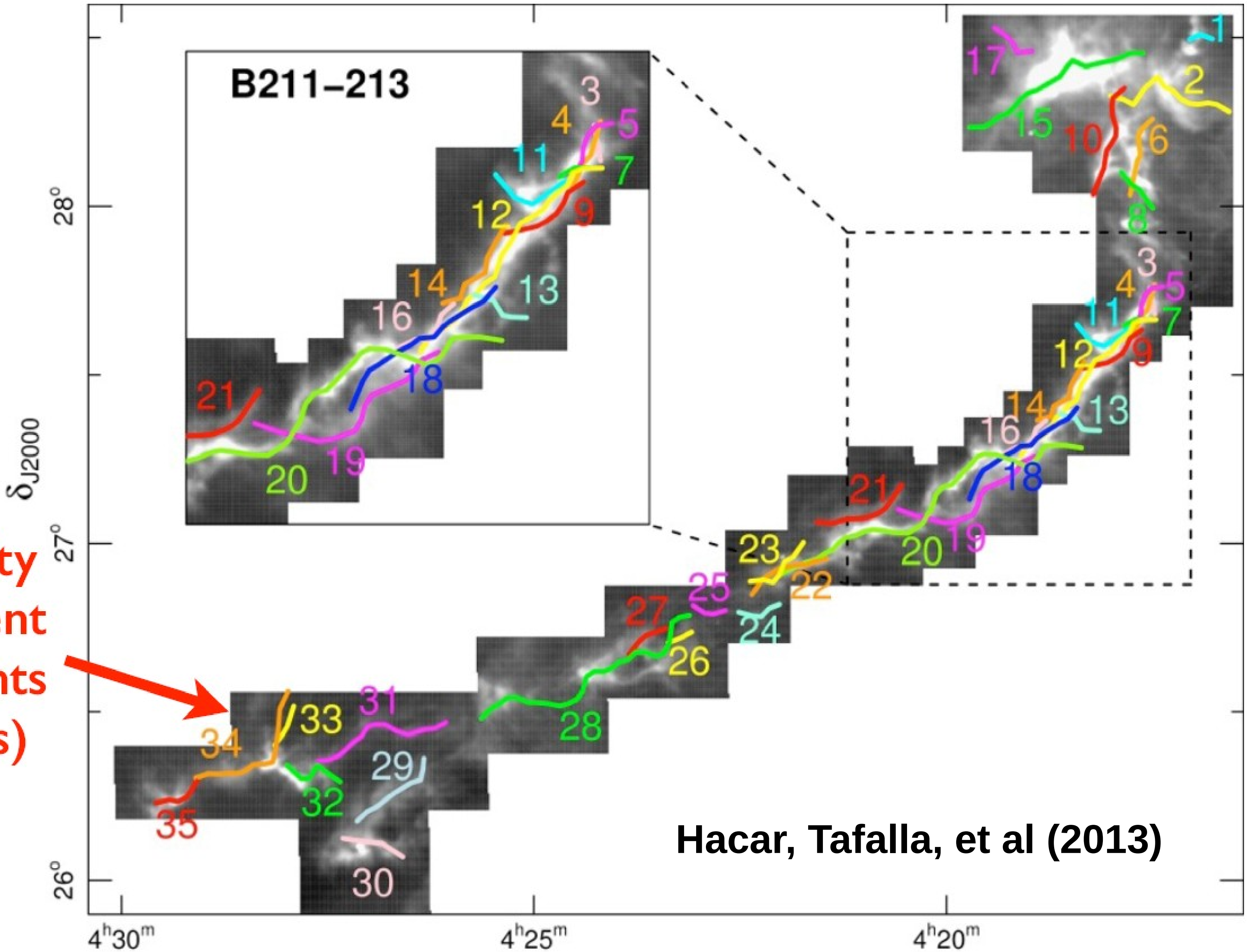


Palmeirim et al. (2013)

Hacar, Tafalla et al. (2010)

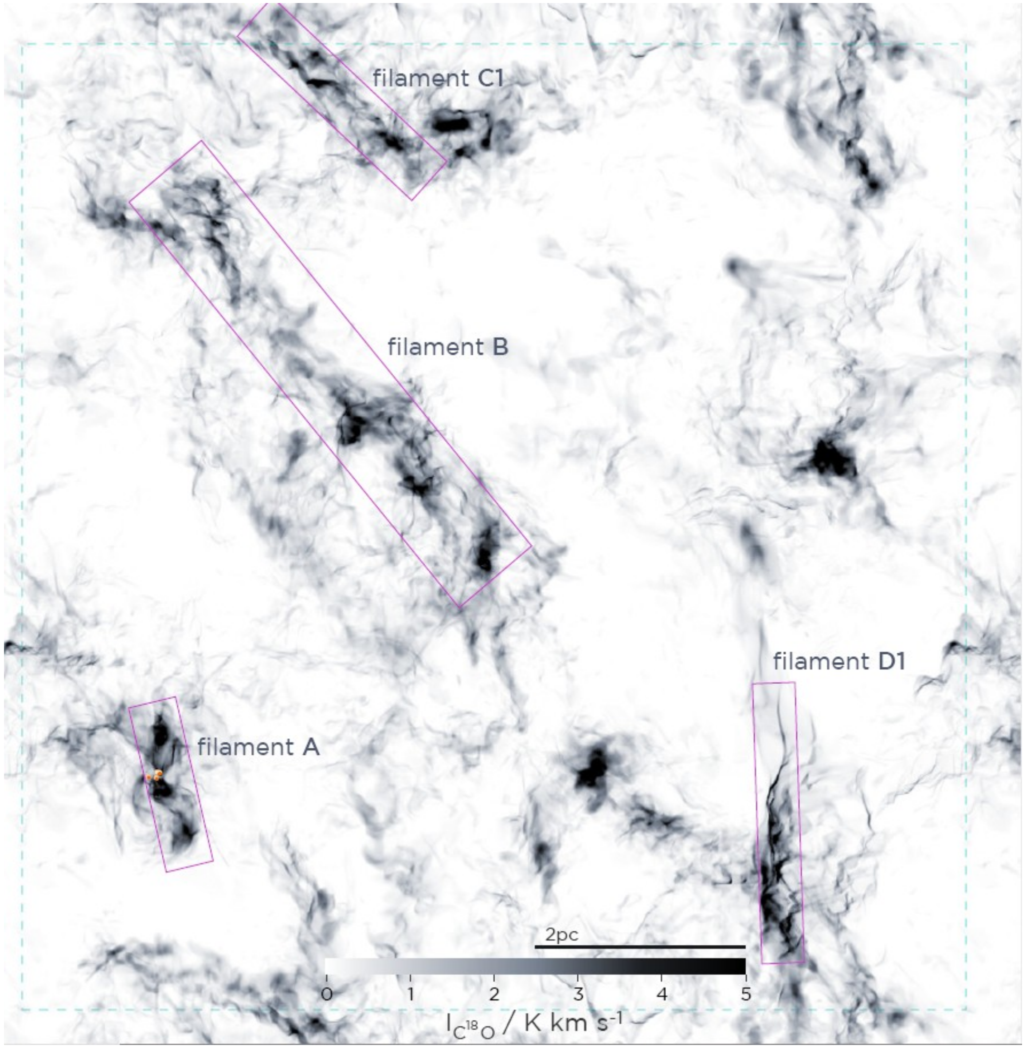
From filaments to fibers

Velocity coherent filaments (fibers)



Background: Herschel SPIRE Archive Image
Gould Belt Project (PI: P. Andre)
see also Palmeirim+ 2013

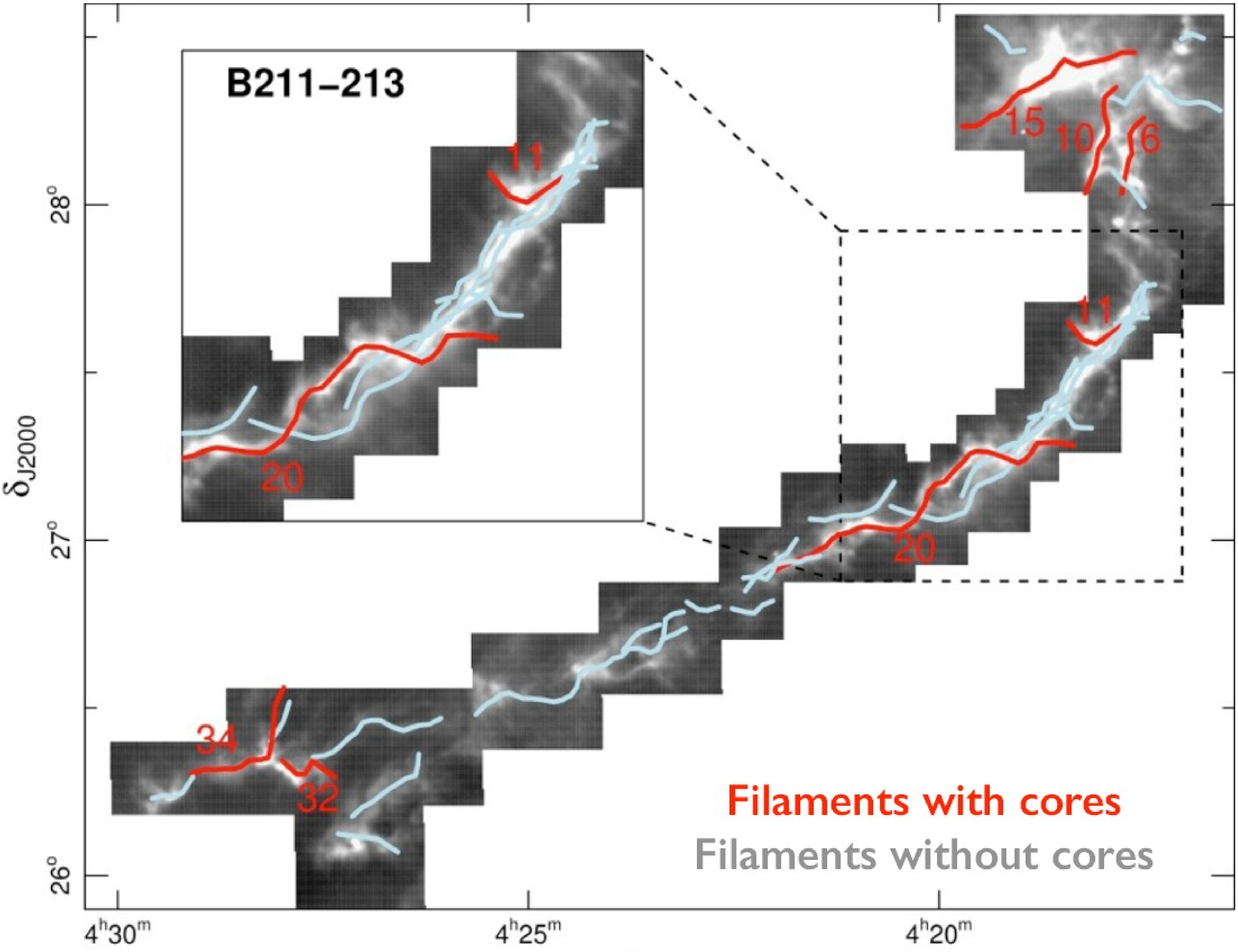
From filaments to fibers



Moeckel & Burkert (2014)

- **Fibers/ribbons appear naturally in turbulence simmulations:**
  - **Rowan Smith**
  - **Alexei Kritsuk**

From fibers to cores



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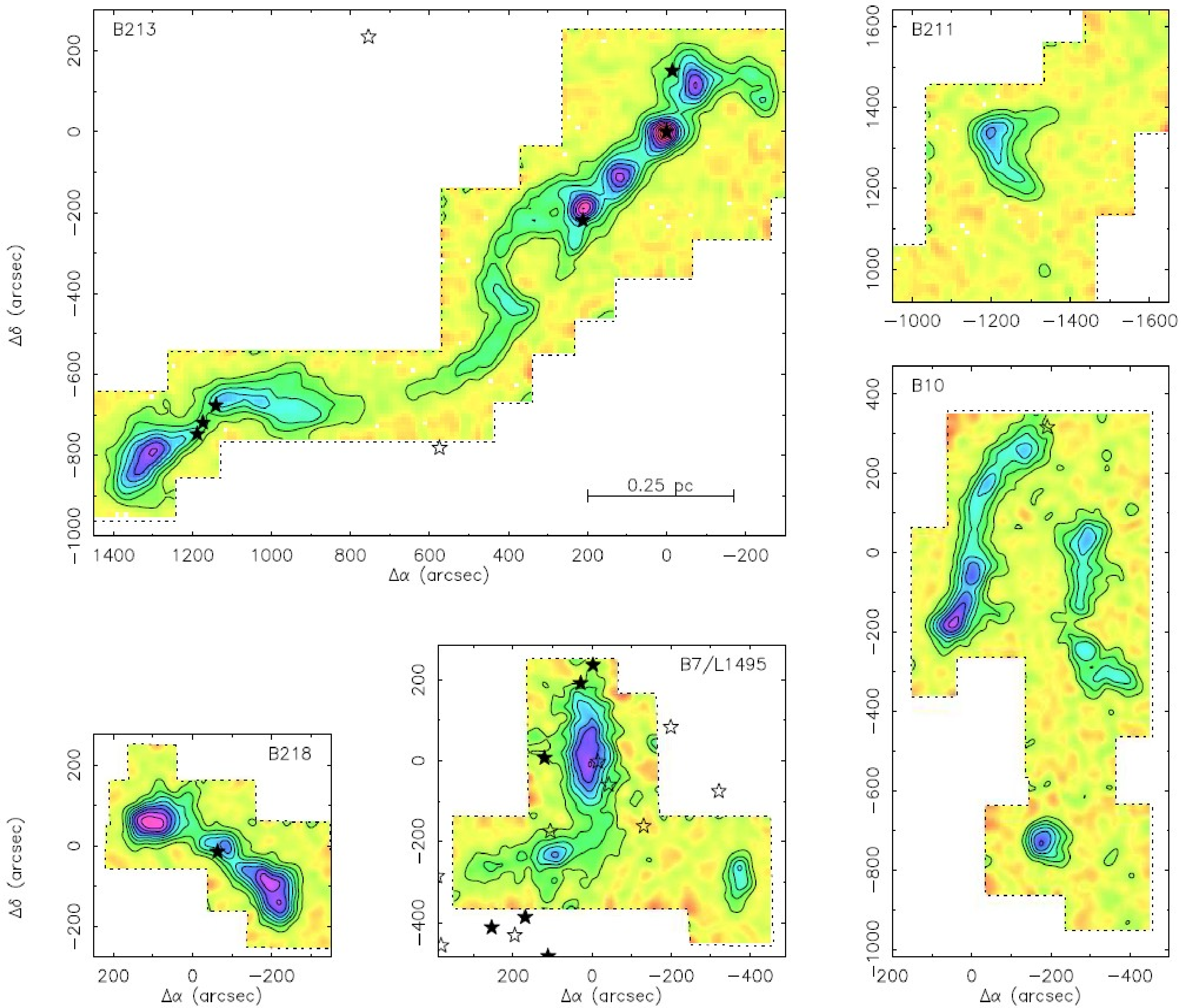
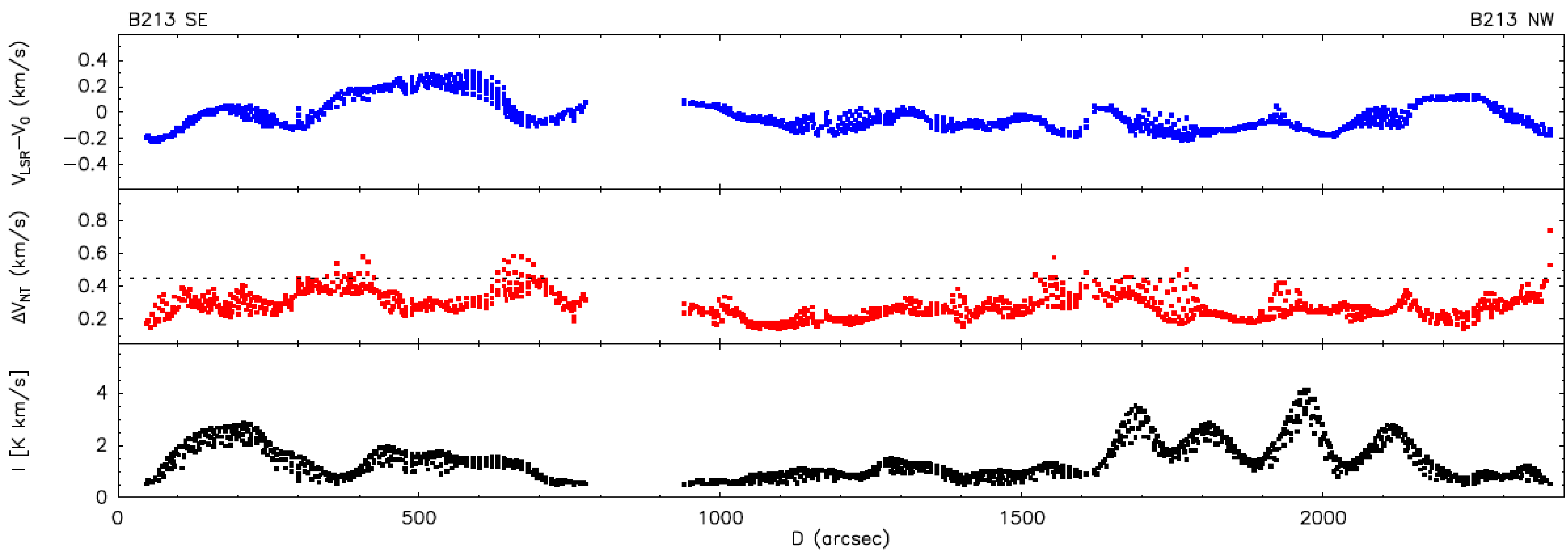
Chains of cores



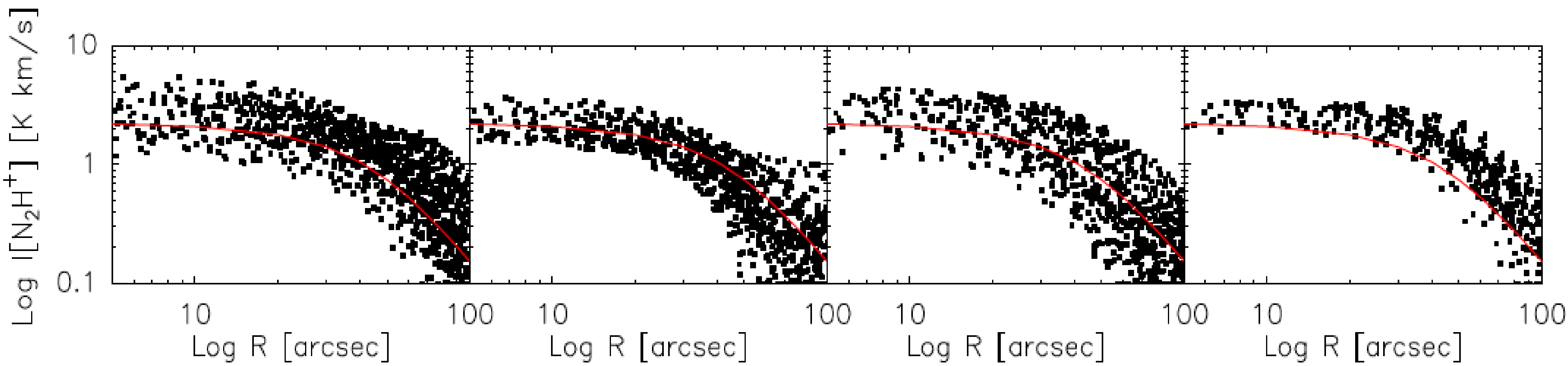
Tafalla & Hacar (2014, in prep)

Chains of cores. Fragmentation

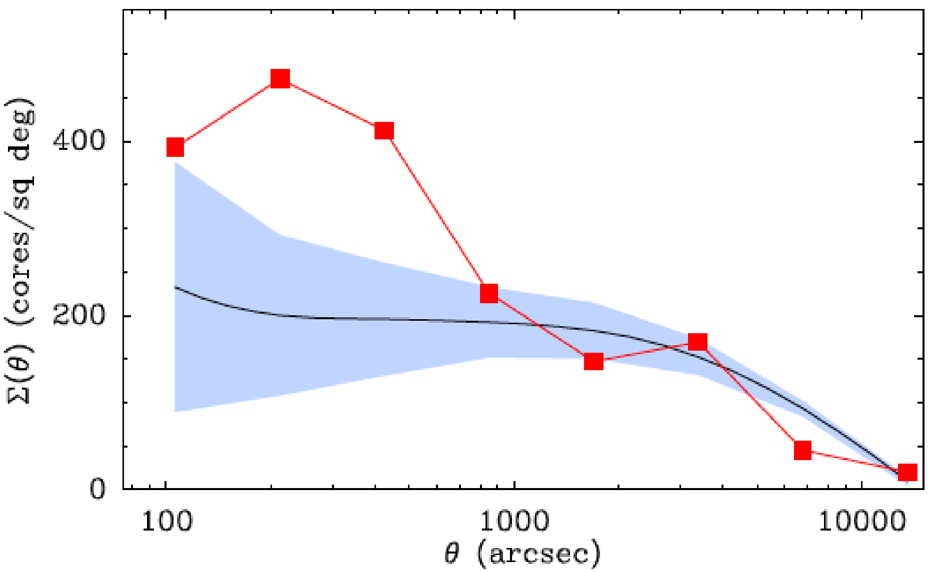


- **Velocity coherence over > 1pc**
  - **smooth velocity oscillations**
  - **subsonic motions (apart from outflow feedback)**
- **Fibers are not "turbulent"**
- **Core formation involves minimal velocity change**

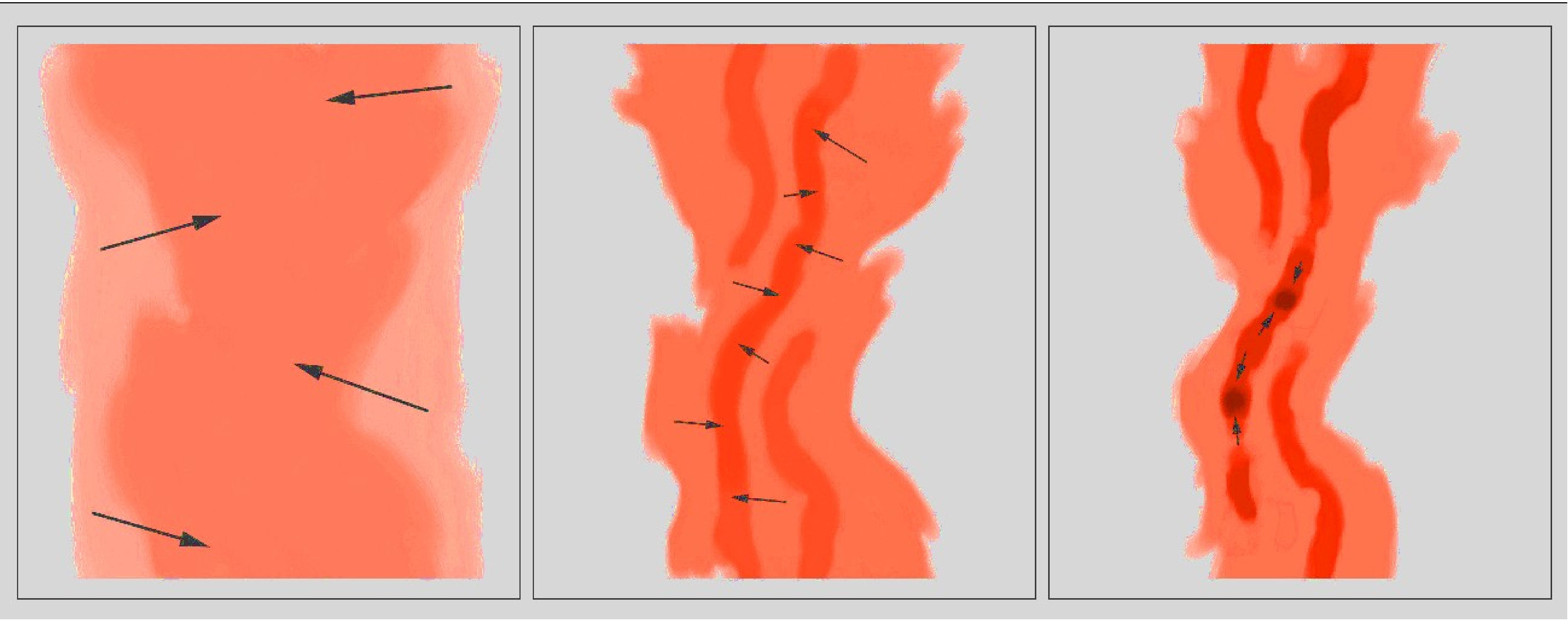
Evidence for grav. fragmentation



- **Radial profiles fitted with isothermal cylinder**
  - **$n(H_2) \sim 10^5$ cm^{-3}**
- **Distance between peaks consistent with grav. fragmentation**
- **Caveats: finite length, star-starless mix along chains**



"Fray and fragment" scenario



- **Large scale flows accumulate cloud gas**
- **Internal shocks fray gas into fibers**
- **Fibers fragment gravitationally if they accumulate enough mass**

Fray and fragment in Orion?

Summary

- Herschel has provided a true flood of dense core data
  - spatial distribution of cores
  - internal properties
- To analyze these data we need
  - realistic models of transfer and chemistry
  - better understanding of dust properties
  - velocity information from lines
- To make sense of the data we need
  - close collaboration observers-theorists
  - also simple models (e.g., “fray & fragment”)