

Lecture 5: Molecular Cores Observational Properties



Pipe Nebula, Yuri Beletsky

Sizescales

100 pc

< 0.1 pc

10 Myr

Cloud complexes OB associations

Timescales

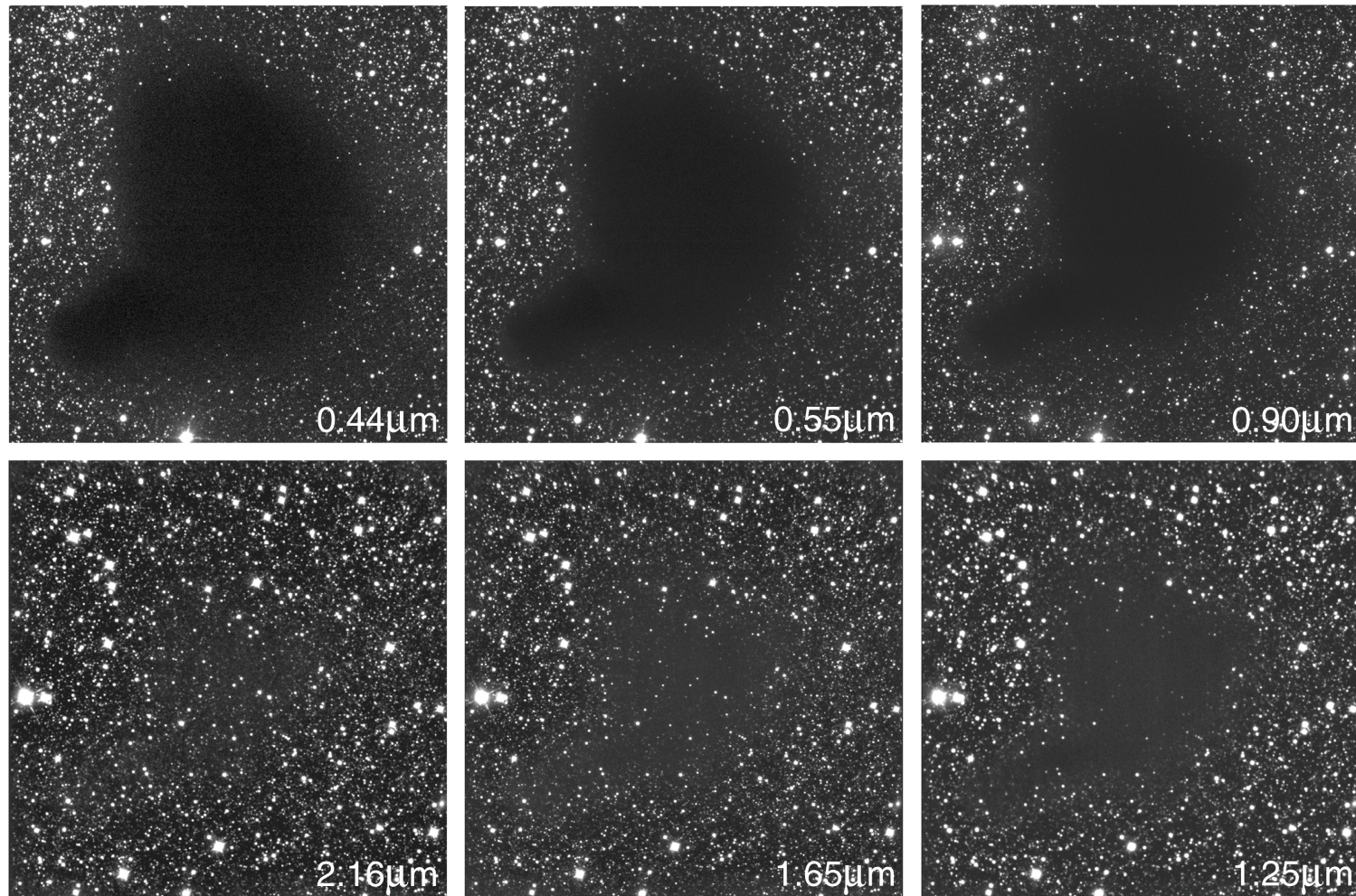
Individual Clouds

Clusters and Clumps

1 Myr

Cores and Protostars

Extinction Mapping



The Dark Cloud B68 at Different Wavelengths (NTT + SOFI)

Converting From Color Excess to Column Density

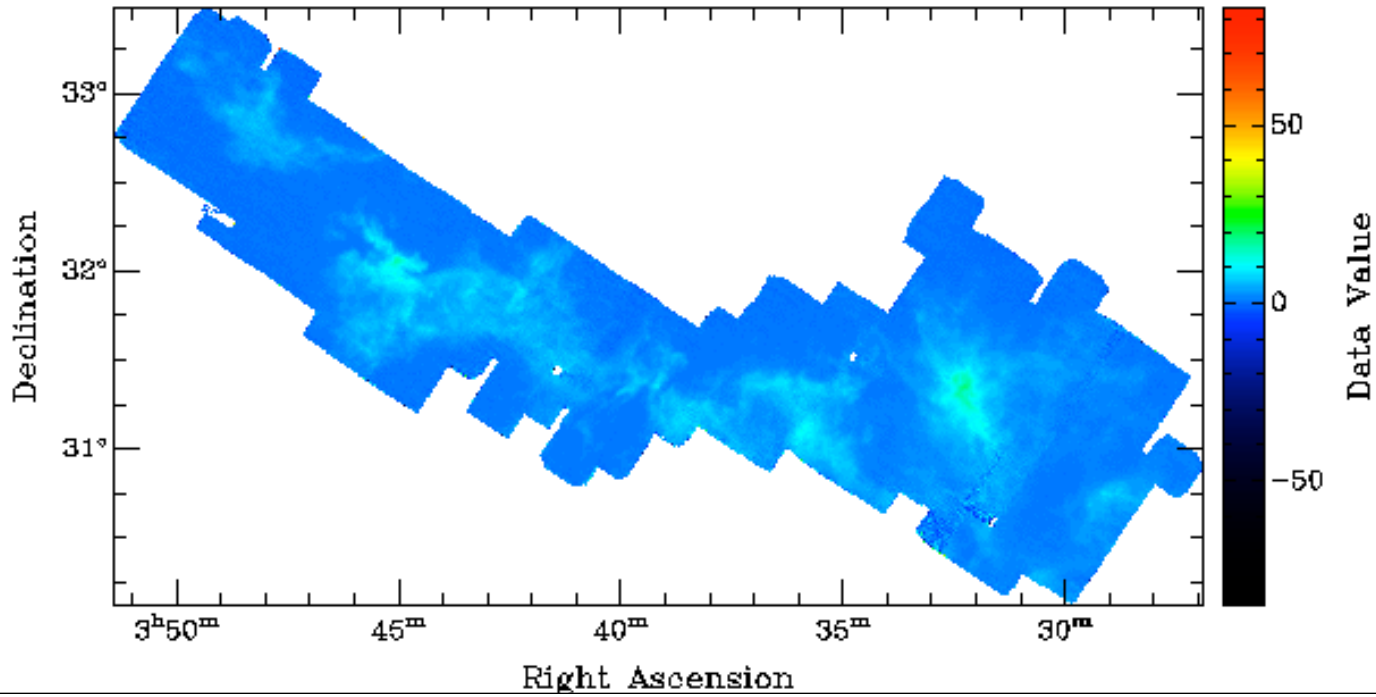
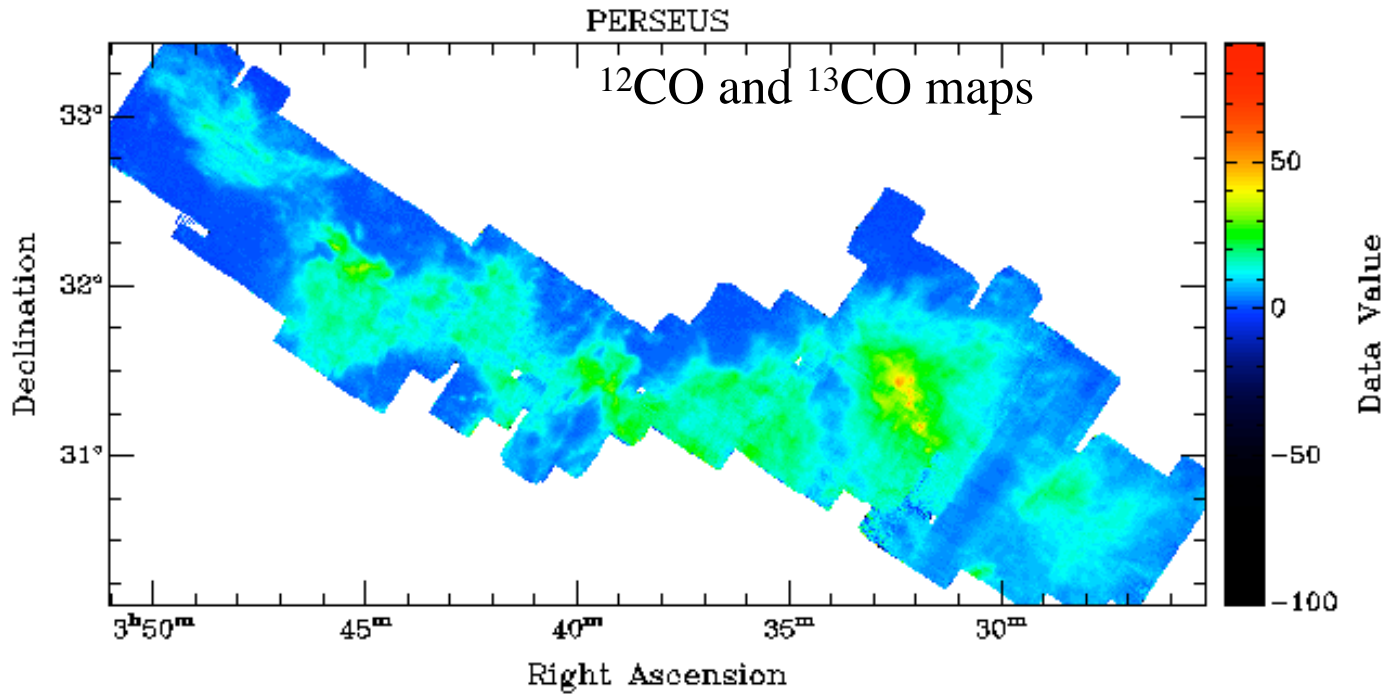
$$E(H - K) = (H - K)_{\text{observed}} - (H - K)_{\text{intrinsic}}$$

$$(H - K)_{\text{intrinsic}} = 0.20 \pm 0.13 \text{ mag}$$

$$A_V = 15.87E(H - K)$$

$$N(H_2) = 1 \times 10^{21}(A_V) \text{ cm}^{-2}$$

http://www.cfa.harvard.edu/COMPLETE/data_html_pages/data.html



Thermal Emission

In optically thin limit ($\tau_\nu \ll 1$):

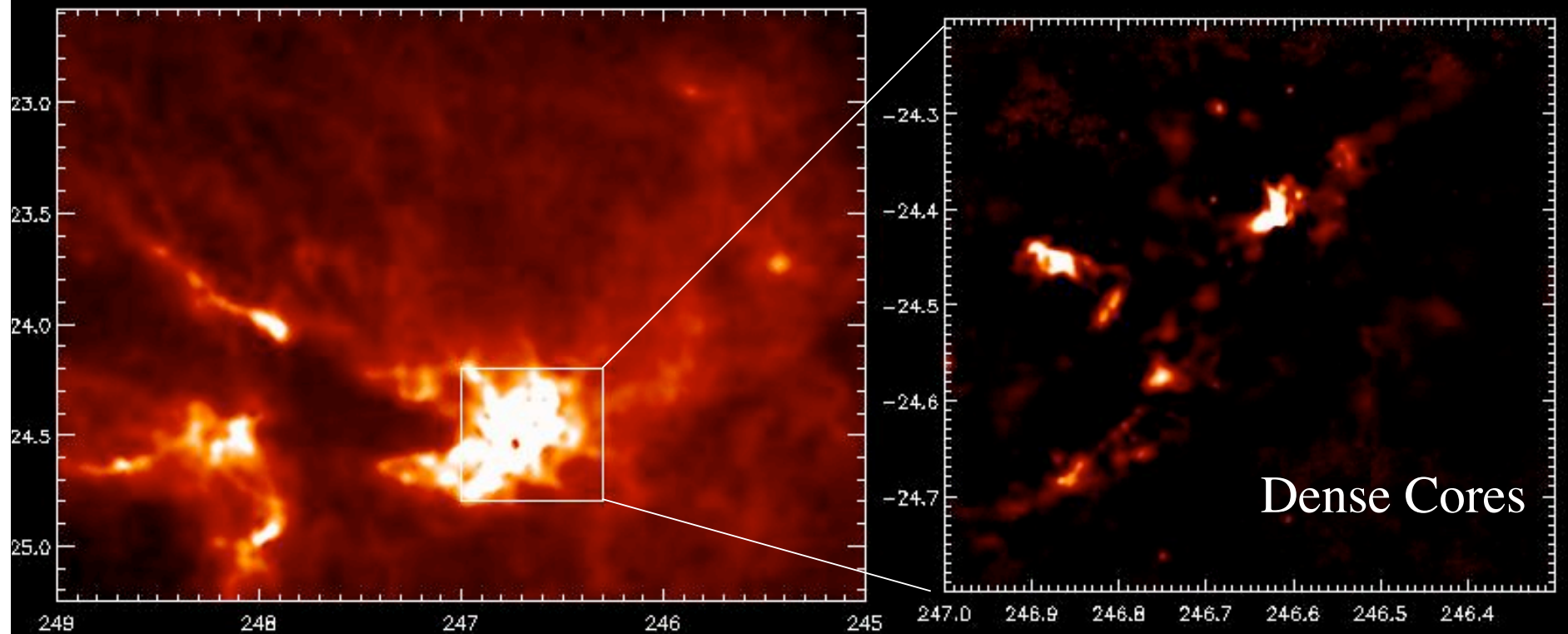
$$\begin{aligned} I_\nu &= B_\nu(1 - e^{-\tau_\nu}) \\ &= \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1} (1 - e^{-\tau_\nu}) \\ &= \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1} \tau_\nu \end{aligned}$$

Solve for T and τ_ν and use the following relationship to find N_H :

$$\tau_\nu = \alpha \lambda^{-\beta} N_H$$

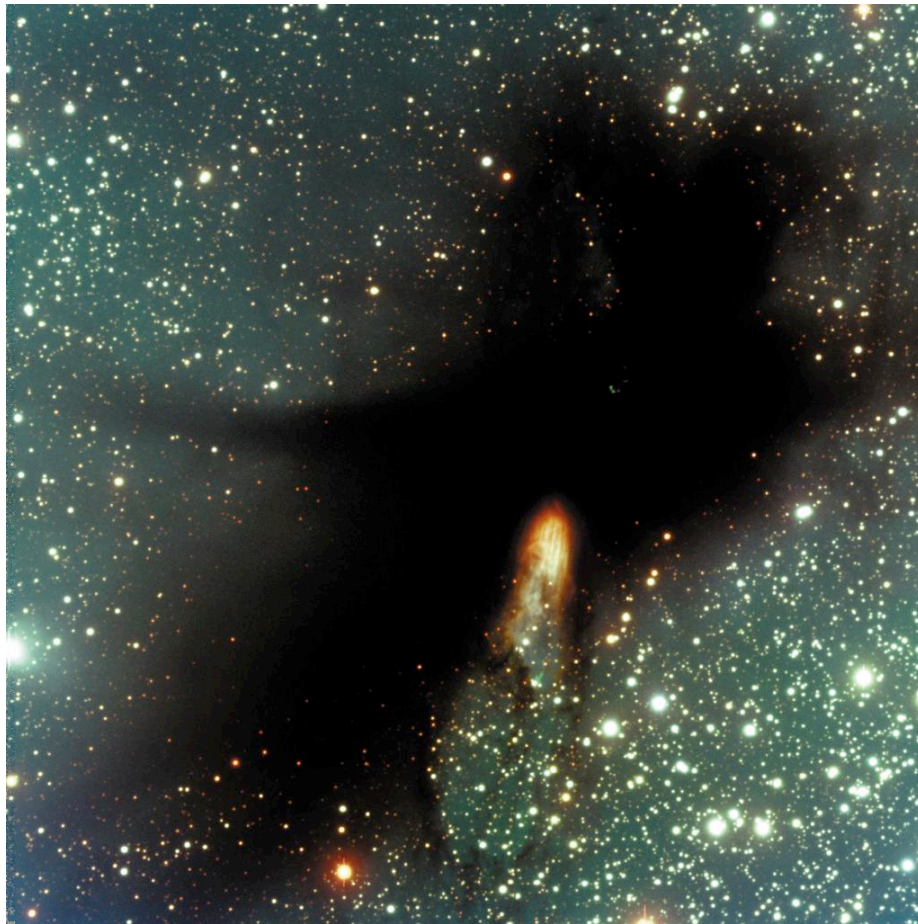
Where α and β are empirically determined.

Dense Cores and Globules

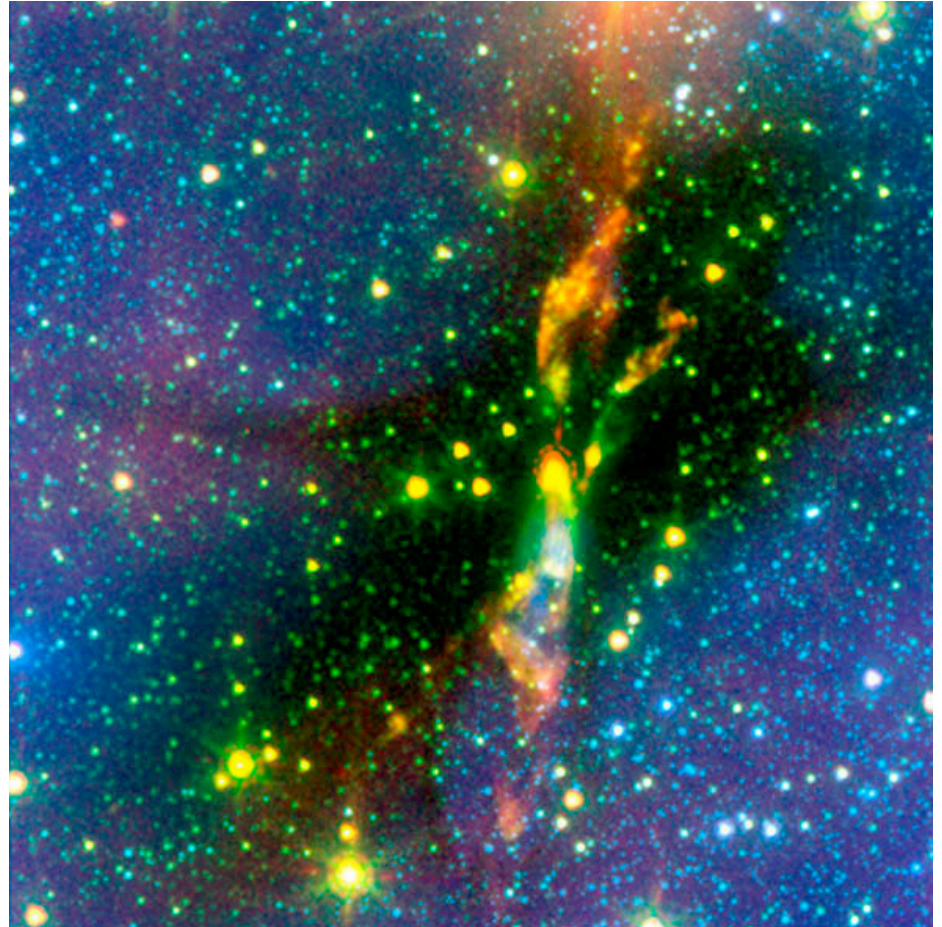


- Dense cores are dense sub-regions in molecular clouds with densities $> 10^4 \text{ cm}^{-3}$
- Implied free fall time $< 3 \times 10^6$ years
- Cores are often split into low and high mass cores.
 - Low mass cores with $M < 10 M_{\text{sun}}$ (forming individual stars or stellar systems)
 - High mass cores with $M > 10 M_{\text{sun}}$ (forming clusters of stars)
- Starless cores: cores without evidence for embedded stars
- Pre-stellar cores: very dense ($> 10^5 \text{ cm}^{-3}$) starless cores that may be on the verge of collapse
- Protostellar cores: cores with protostars

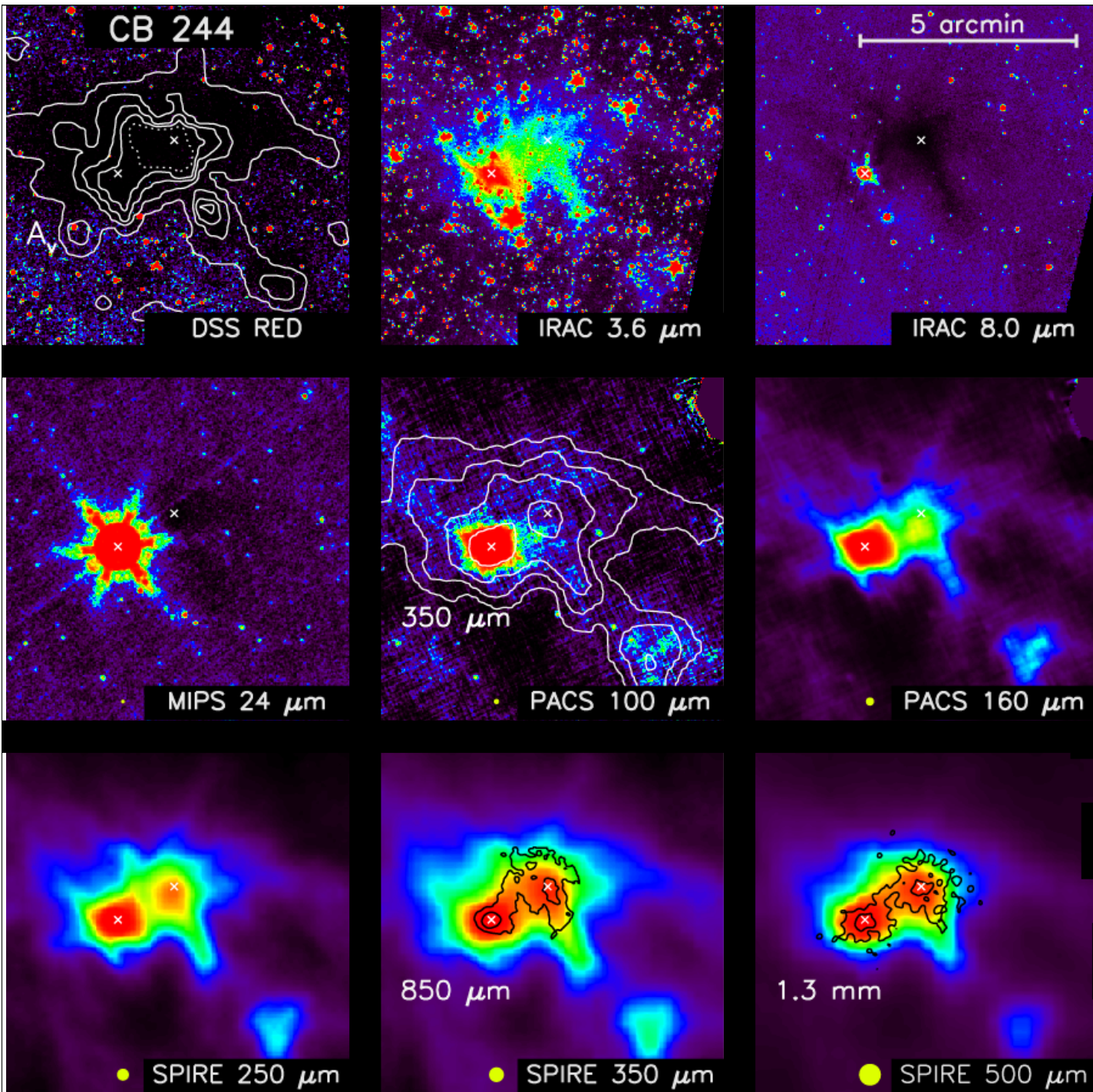
BHR 71: A Dense Core with a Protostar



Visible Light



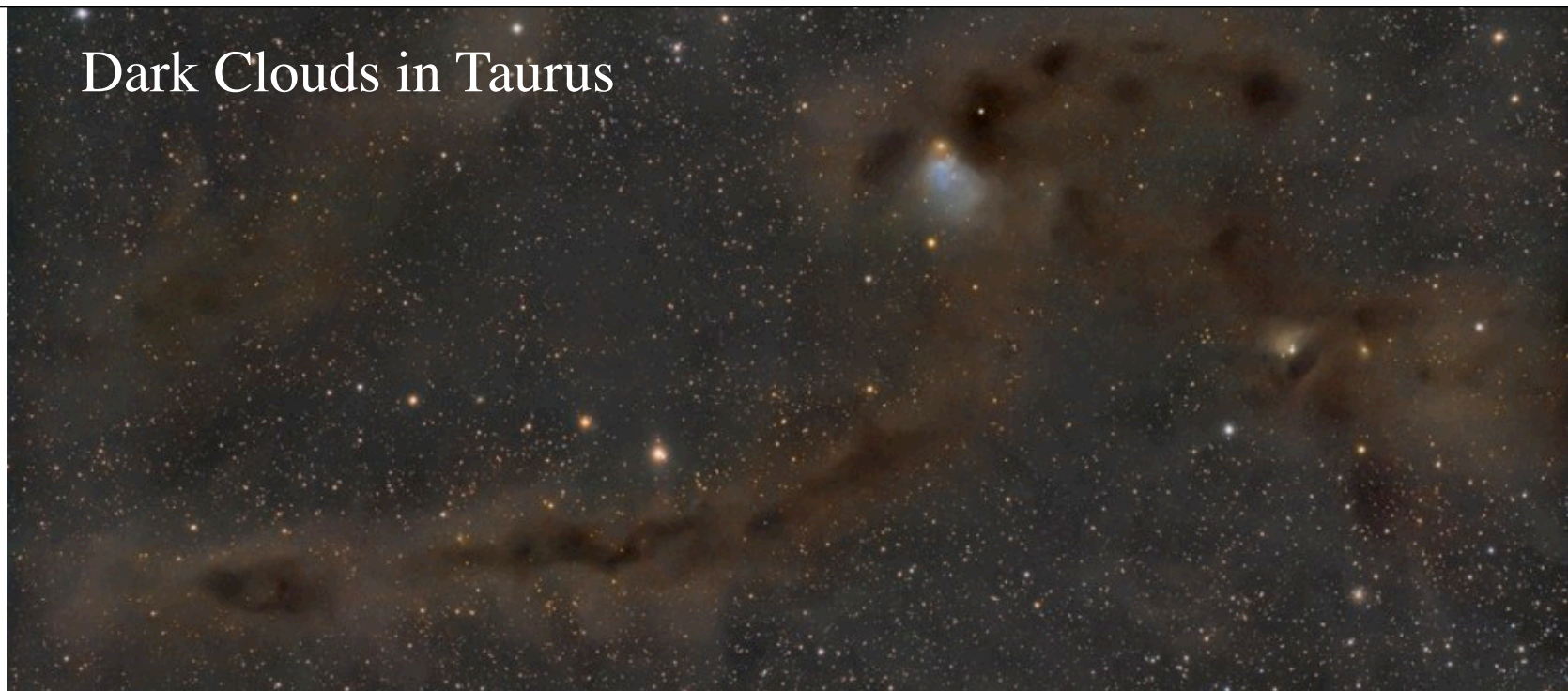
Visible and IR Light



Dense Cores with Herschel

Stutz et al.
2009

Dark Clouds in Taurus



Galactic Longitude [deg]

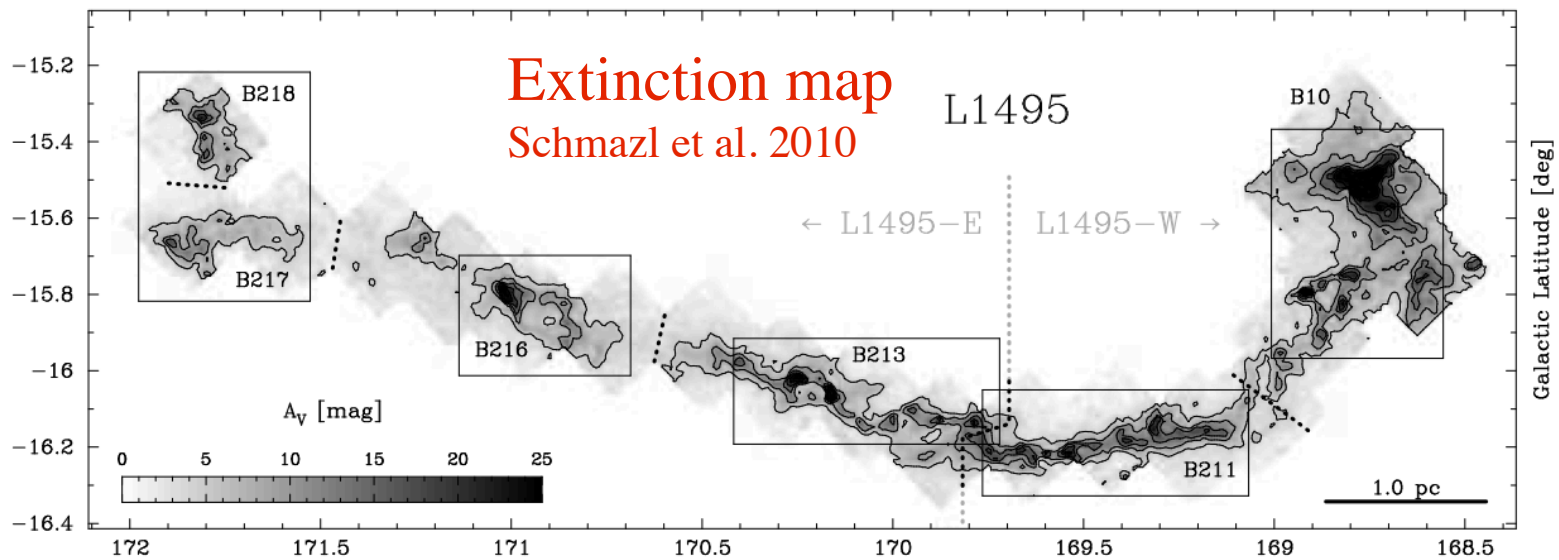


FIG. 5.— Extinction map of the Filament L1495 with a resolution of $0.9'$ derived from deep NIR observations with Omega2000. Contours are plotted in steps of $A_V = 5$ mag. We separate the filament into different subregions, which conform to Barnard's Dark Objects (Barnard et al. 1997). The boxes indicate the positions of the zoom-ins shown in Fig. 6.

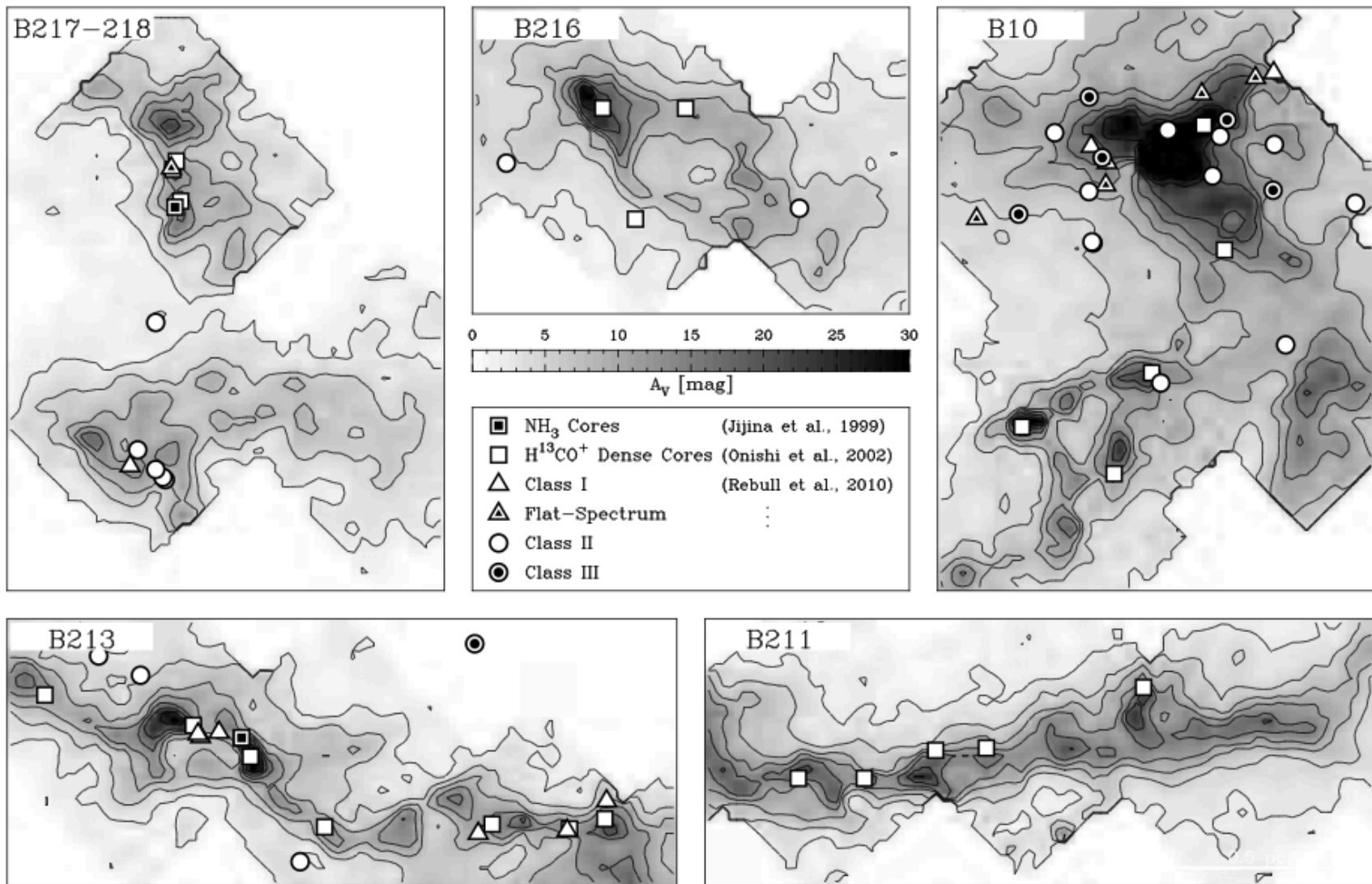


FIG. 6.— Zoom-ins into the extinction map. The scale bar indicated in the bottom panel is common to all sub-plots. Contours are plotted in steps of 5σ each. The positions of dense cores mapped in NH₃ (Jijina et al. 1999), H¹³CO⁺ (OMK02) are overplotted alongside YSOs (Rebull et al. 2010).

Properties of Taurus Cores

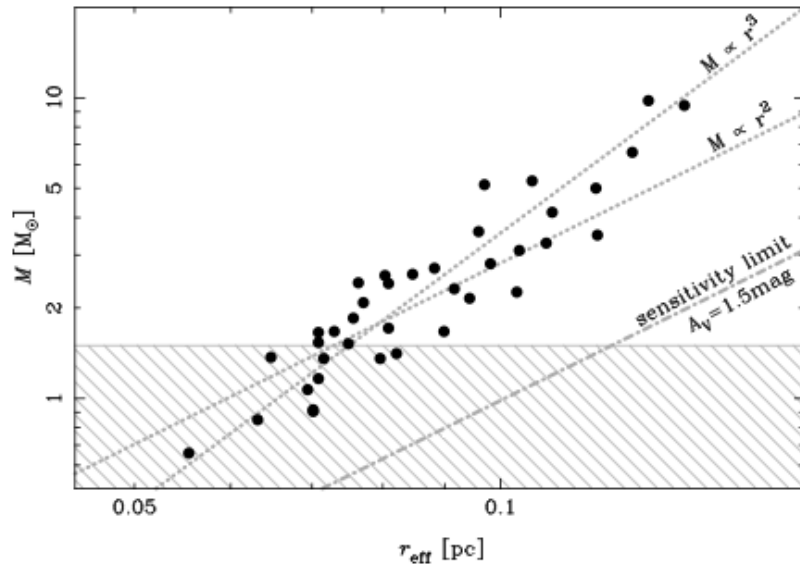


FIG. 8.— Mass-size relation for our cores. The hatched area marks the region of incompleteness. The dotted lines represent the cases of constant volume density $M \propto r^3$ and column density $M \propto r^2$.

Text

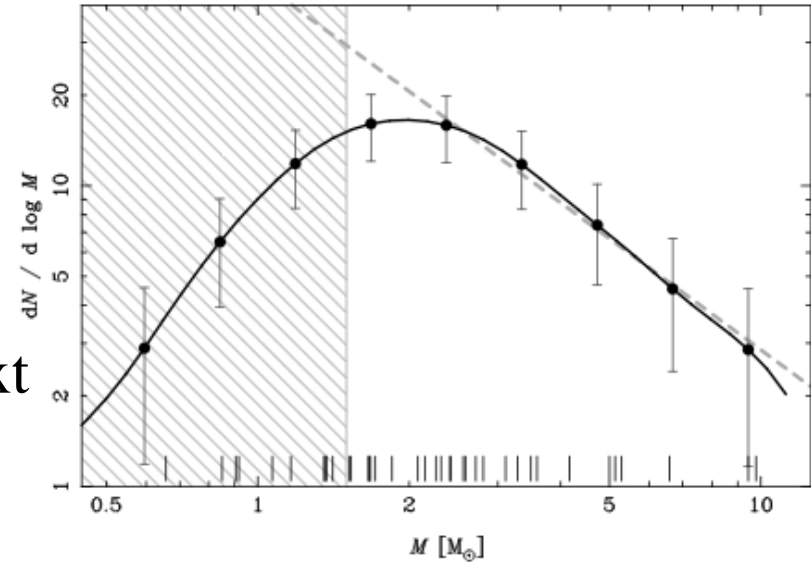
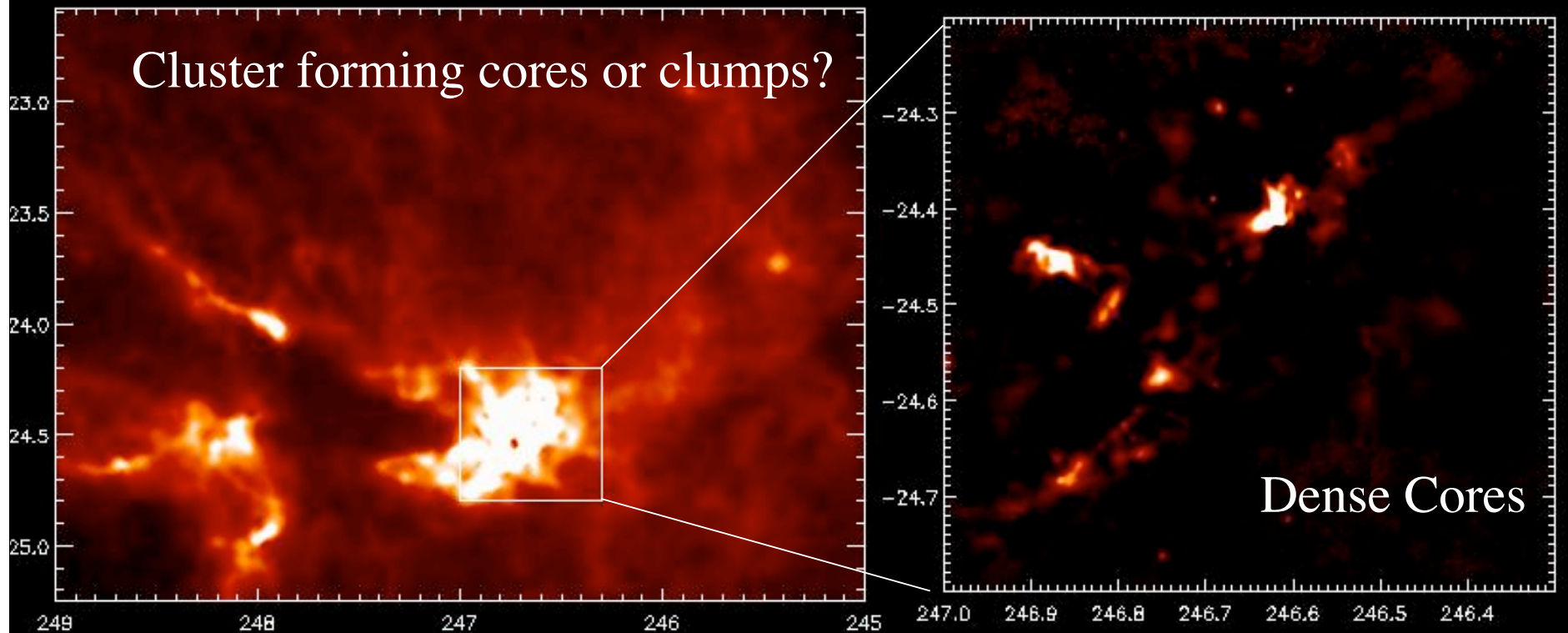


FIG. 9.— The Dense Core Mass Function (DCMF) of L1495-E, which was obtained by smoothing the core masses (indicated as vertical dashes along the abscissa) with a Gaussian kernel with FWHM=0.3 dex. Points with error bars are plotted in separations of 50% of the FWHM. The dashed line shows the power law fit with slope $\Gamma = 1.2 \pm 0.2$ for $M > 2.0 M_{\odot}$. The hatched area indicates the region of incompleteness.

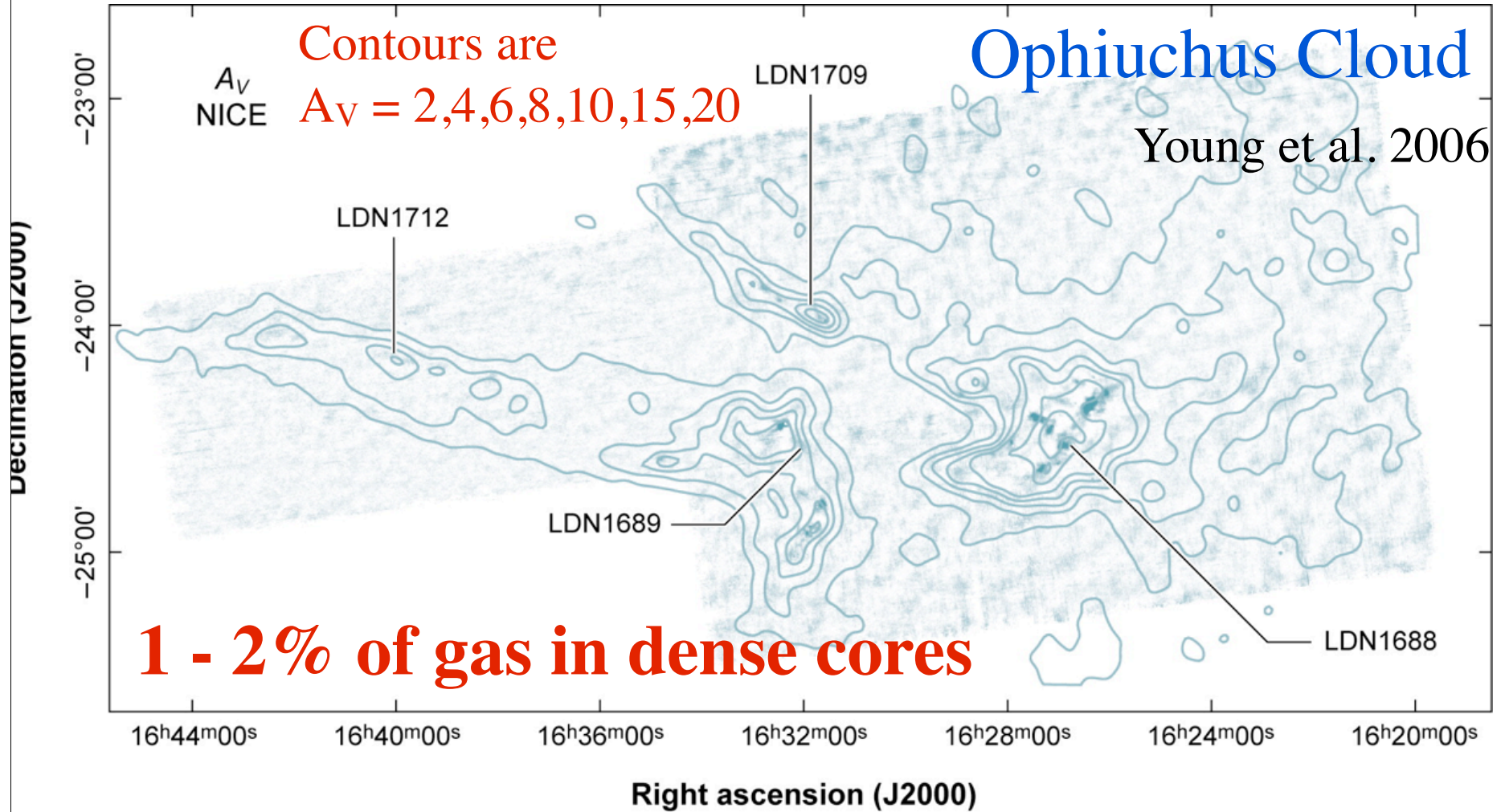
Dense Cores in Ophiuchus

Extinction map made from
background stars.

Submillimeter 850 micron
measurements of thermal emission
from cold dust.



Dense cores are found in high extinction regions.



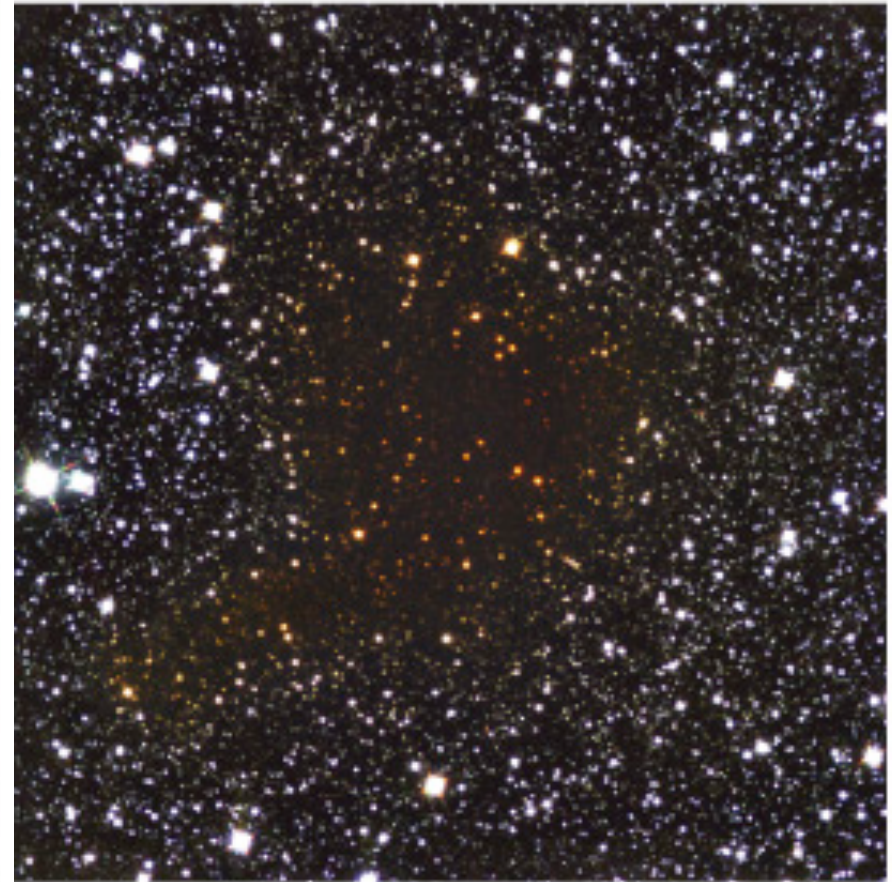
AR Bergin EA, Tafalla M. 2007.
Annu. Rev. Astron. Astrophys. 45:339–96

The Starless Globule B68

(a Bok globule - an isolated dense core)



Visible Light



Infrared Light

Table 1: Properties of Dark Clouds, Clumps, and Cores

	Clouds ^a	Clumps ^b	Cores ^c
Mass (M_{\odot})	10^3 – 10^4	50–500	0.5–5
Size (pc)	2–15	0.3–3	0.03–0.2
Mean density (cm^{-3})	50–500	10^3 – 10^4	10^4 – 10^5
Velocity extent (km s^{-1})	2–5	0.3–3	0.1–0.3
Crossing time (Myr)	2–4	≈ 1	0.5–1
Gas temperature (K)	≈ 10	10–20	8–12
Examples	Taurus, Oph, Musca	B213, L1709	L1544, L1498, B68

^a Cloud masses and sizes from the extinction maps by [Cambr esy \(1999\)](#), velocities and temperatures from individual cloud CO studies

^b Clump properties from [Loren \(1989\)](#) (^{13}CO data) and [Williams, de Geus & Blitz \(1994\)](#) (CO data)

^c Core properties from [Jijina, Myers & Adams \(1999\)](#), [Caselli et al. \(2002a\)](#), [Motte, Andr e & Neri \(1998\)](#), and individual studies using NH_3 and N_2H^+

Lifetimes of Starless Cores

Roughly 75% of cores appear to be starless.

Assume that all starless cores form protostars

Assume that protostellar cores last 0.2 Myr

Assume all cores have the same lifetime

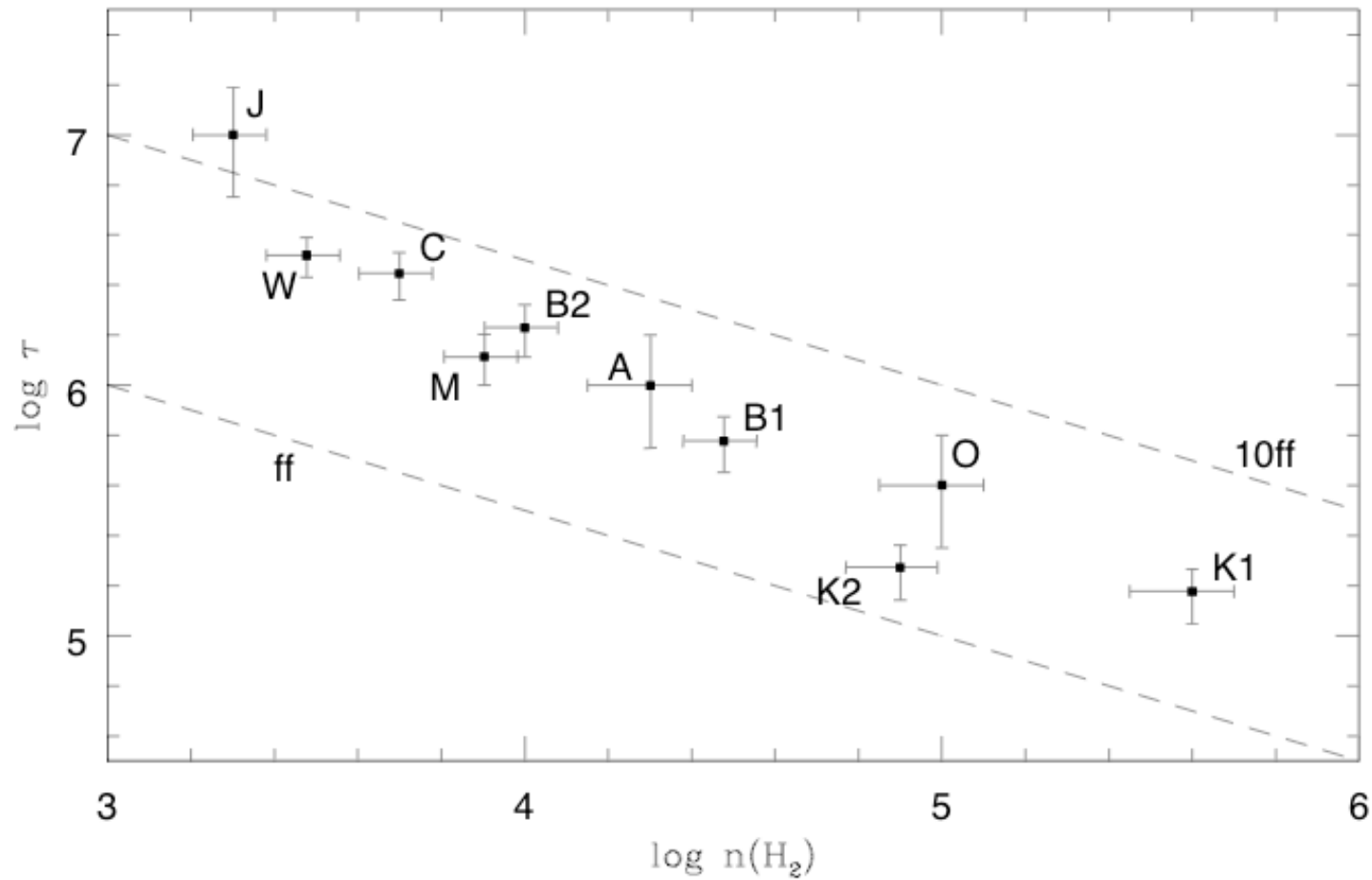
$$t_{\text{core}} = t_{\text{starless}} + t_{\text{proto}}$$

$$t_{\text{starless}} / (t_{\text{core}}) = 0.75$$

$$t_{\text{starless}} = 0.75 / 0.25 t_{\text{proto}} = 0.6 \text{ Myr}$$

Statistics of Starless Cores

Lifetime vs volume density



Ward-Thompson PPV

The Structure of Molecular Cores

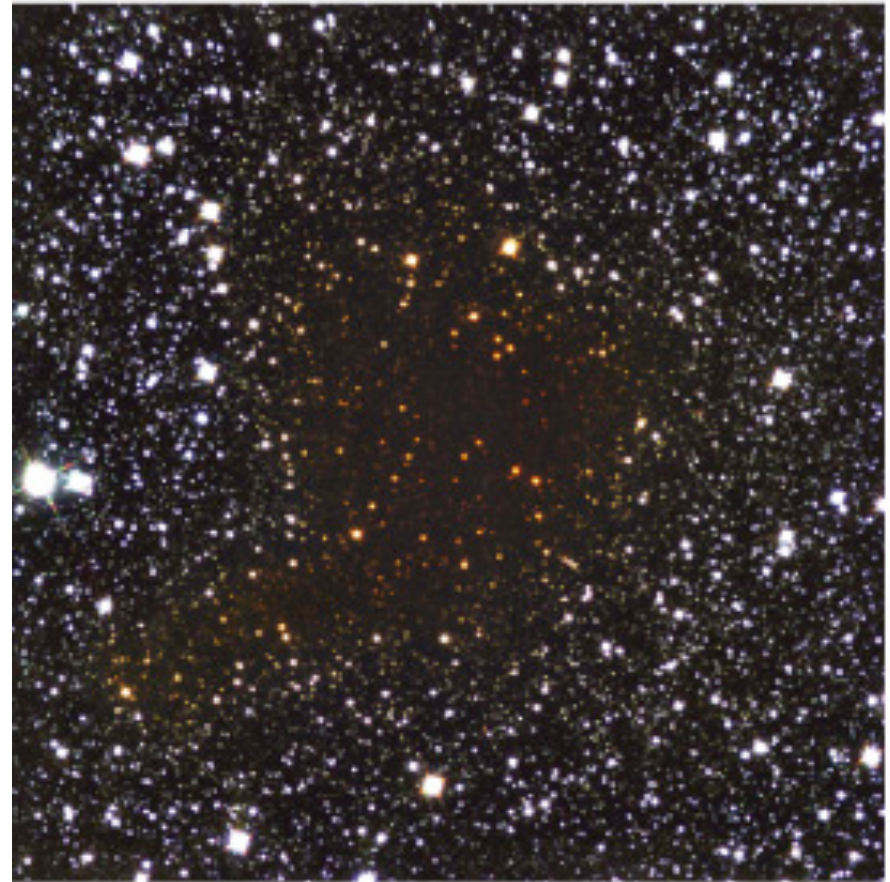
Theory to be addressed in next lecture

The Starless Globule B68

(a Bok globule - an isolated dense core)

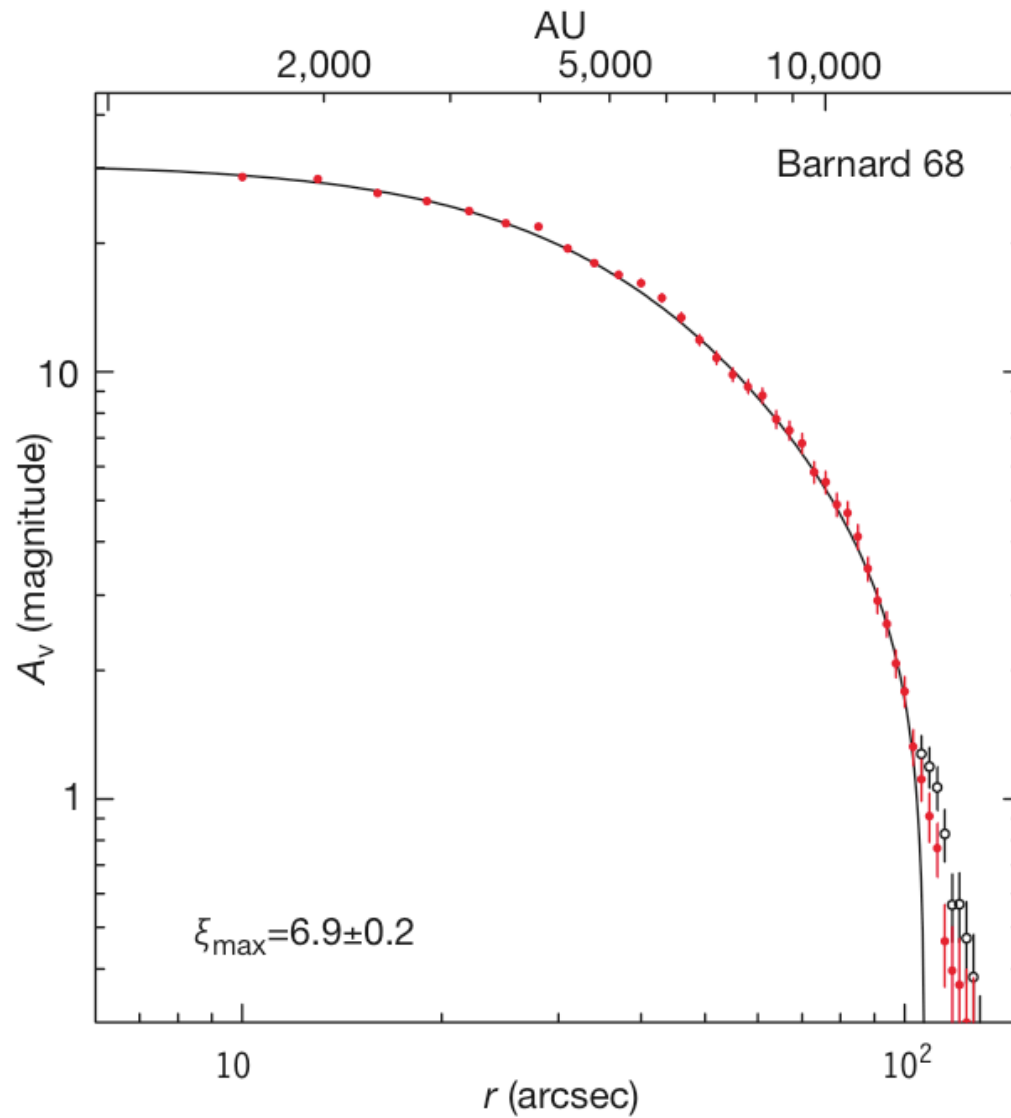


Visible Light

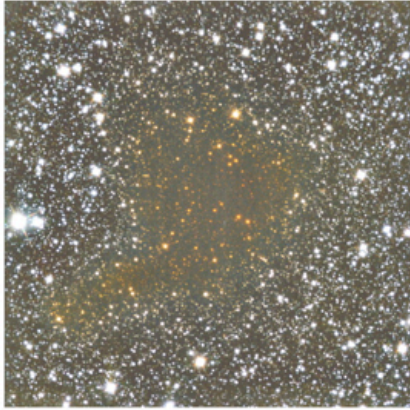


Infrared Light

A Perfect Bonner Ebert Sphere



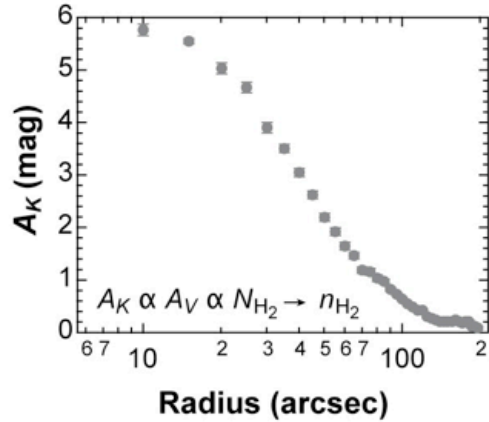
a Barnard 68 K band



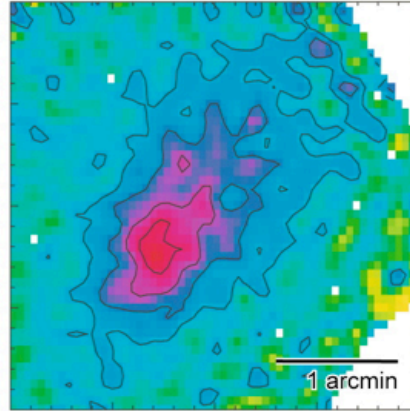
$$A_V = r_V^{H,K} E(H - K)$$

$$A_V = f N_H$$

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



b L1544 1.2 mm continuum

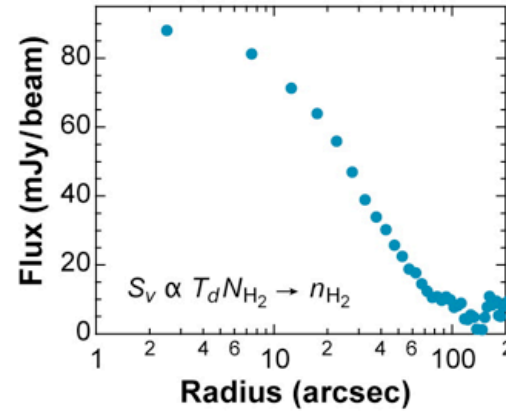


For optically thin emission:

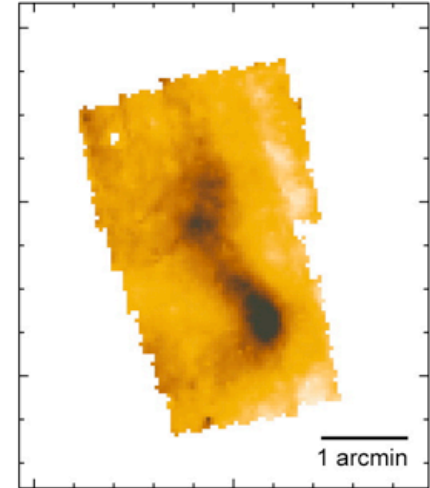
$$I_\nu = \int \kappa_\nu \rho B_\nu(T_d) dl$$

$$I_\nu = m \langle \kappa_\nu B_\nu(T_d) \rangle N_H$$

$$N_H = I_\nu [\langle m \kappa_\nu B_\nu(T_d) \rangle]^{-1}$$



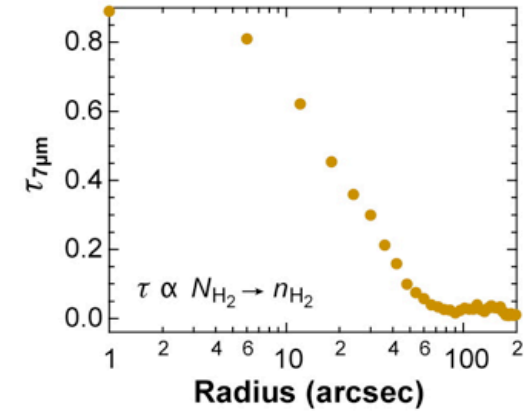
c ρ Oph core D 7 μ m image




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

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

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



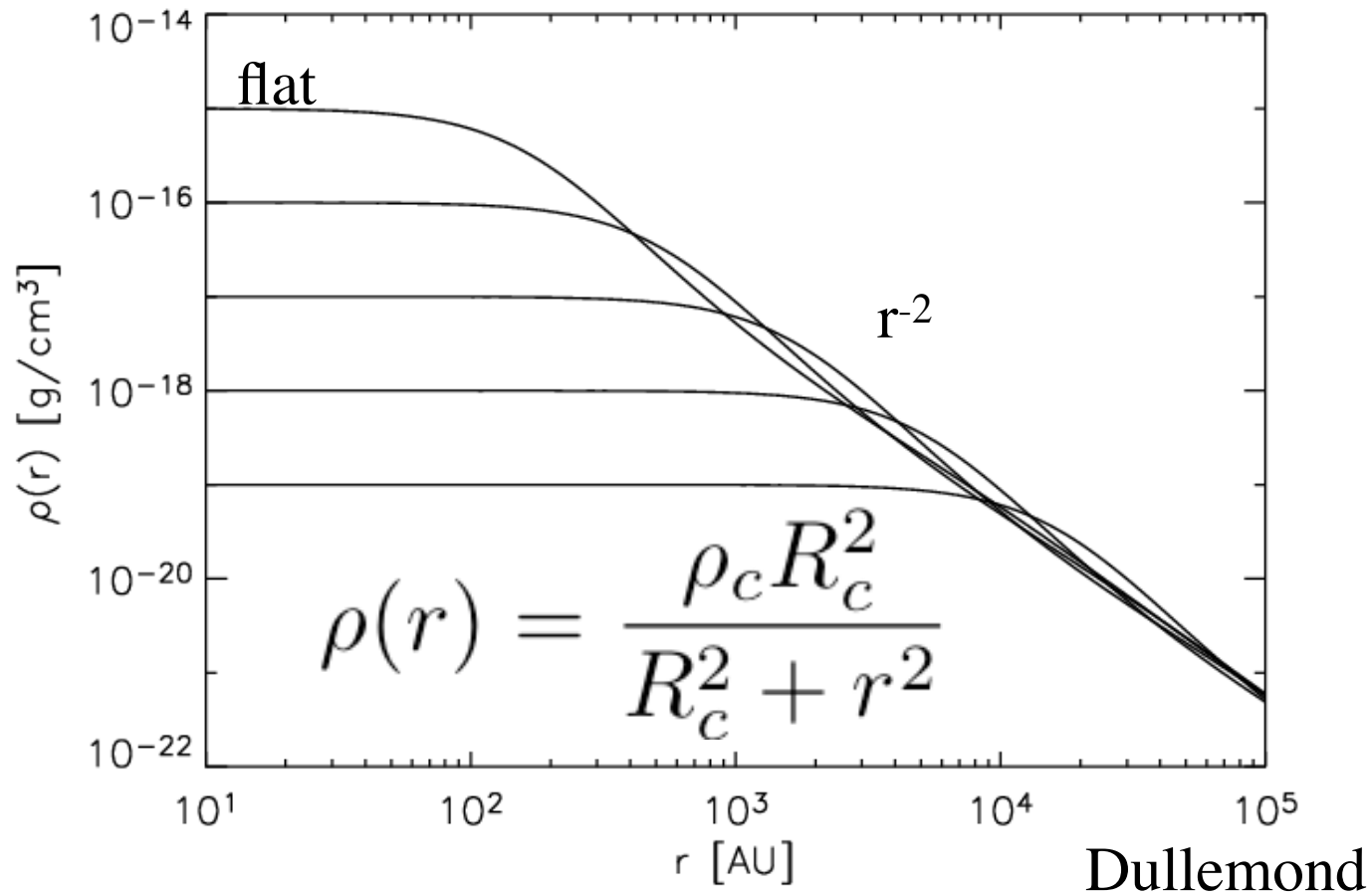
 Bergin EA, Tafalla M. 2007.
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Alves et al 2001, Ward Thompson et al.. 1999, Bacman et al. 2000

Hydrostatic self-gravitating spheres

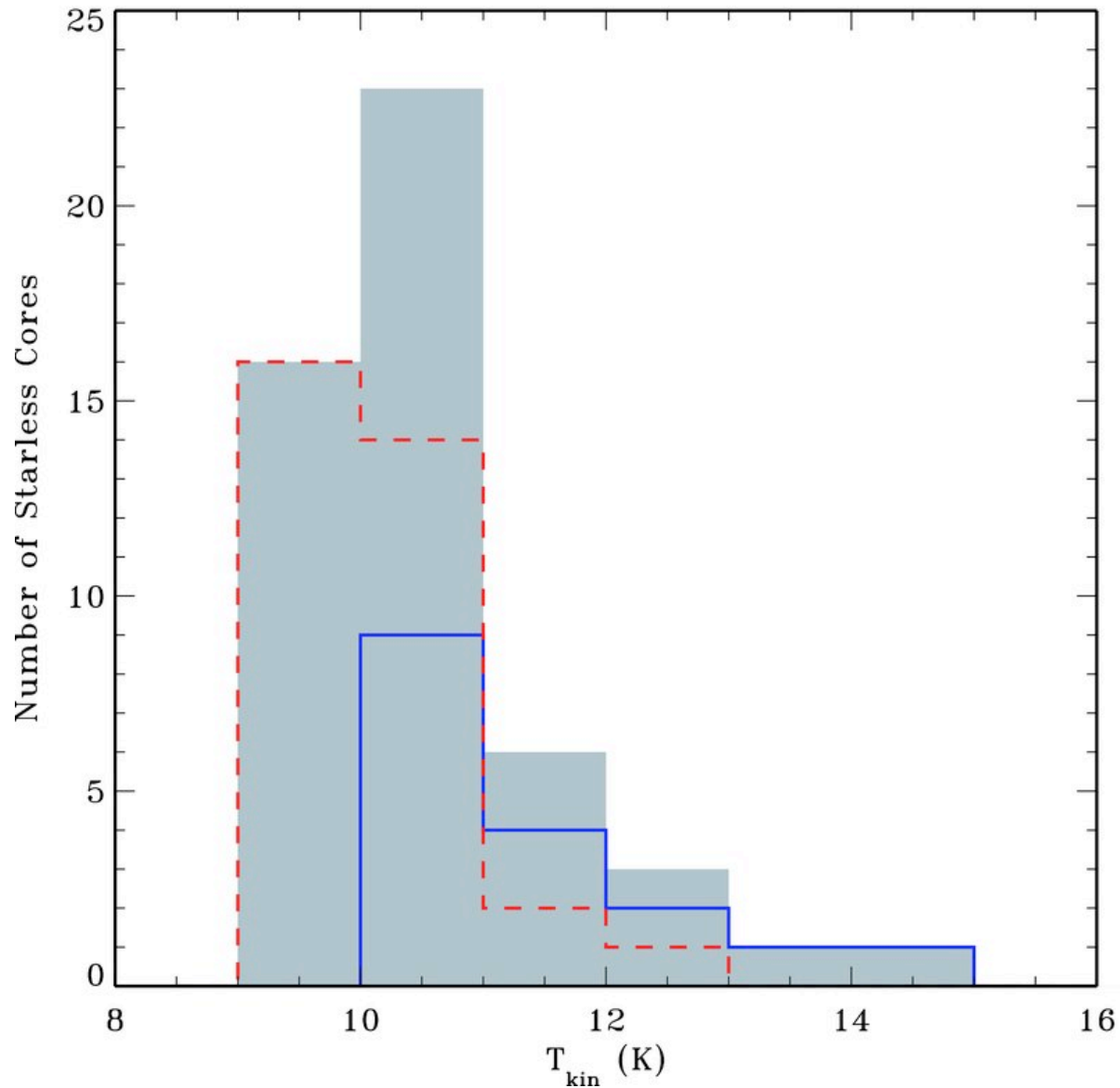
Numerical solutions:

Different starting ρ_0 :
a family of solutions

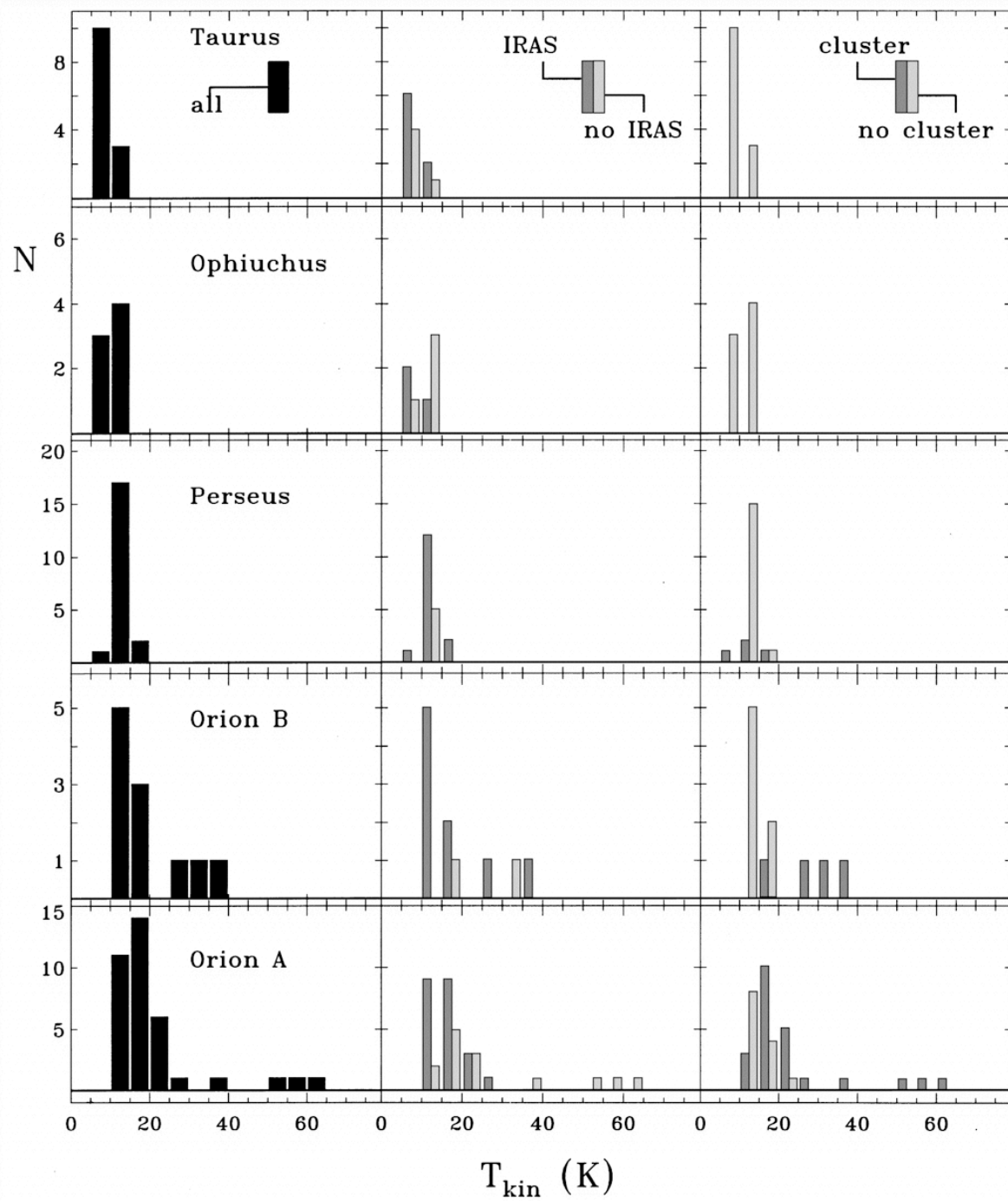


Kinetic Temperatures inside Cores

Kinetic Temperatures of Cores in the Perseus Cloud

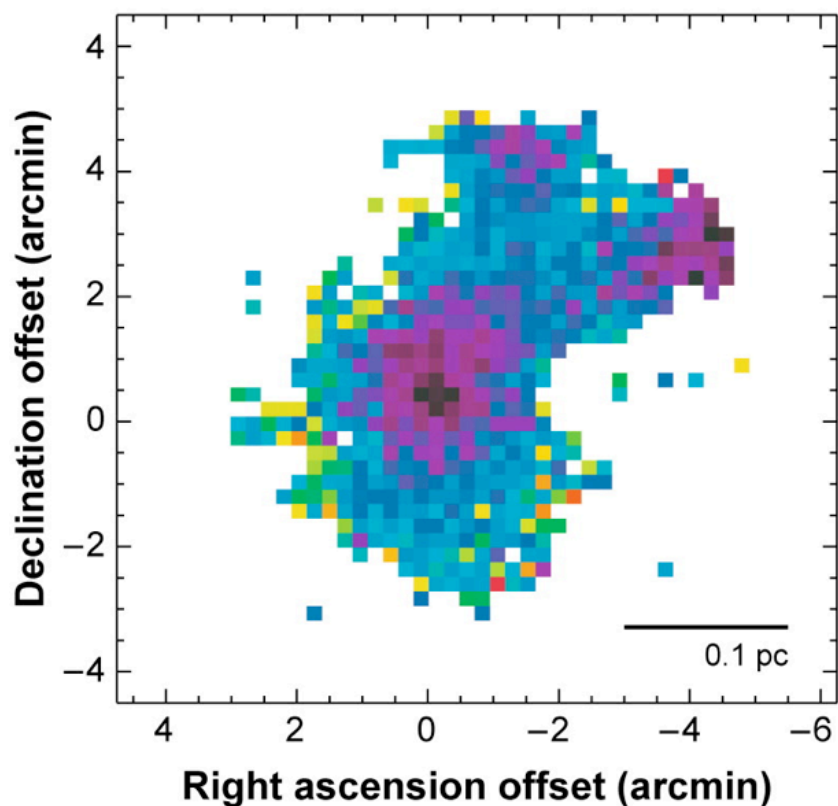


Temperature
measured from
 NH_3

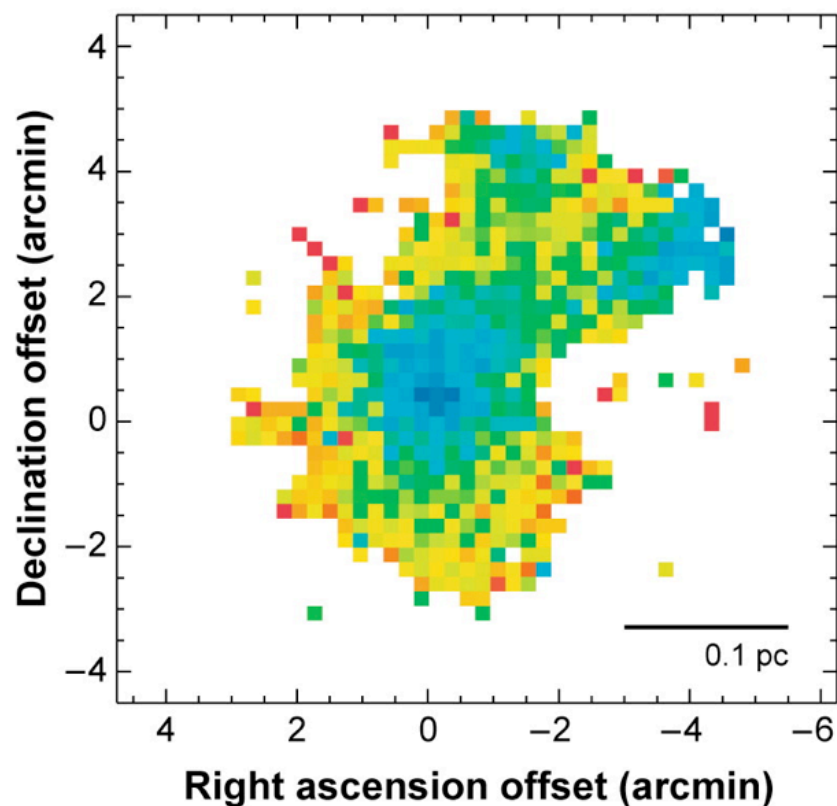


Temperatures inside Cores

a Dust temperature



b Dust emissivity



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Schnee & Goodman: TMC-1

Tracing Dense Cores with Molecules:
Chemistry in some of the coldest
regions of the universe

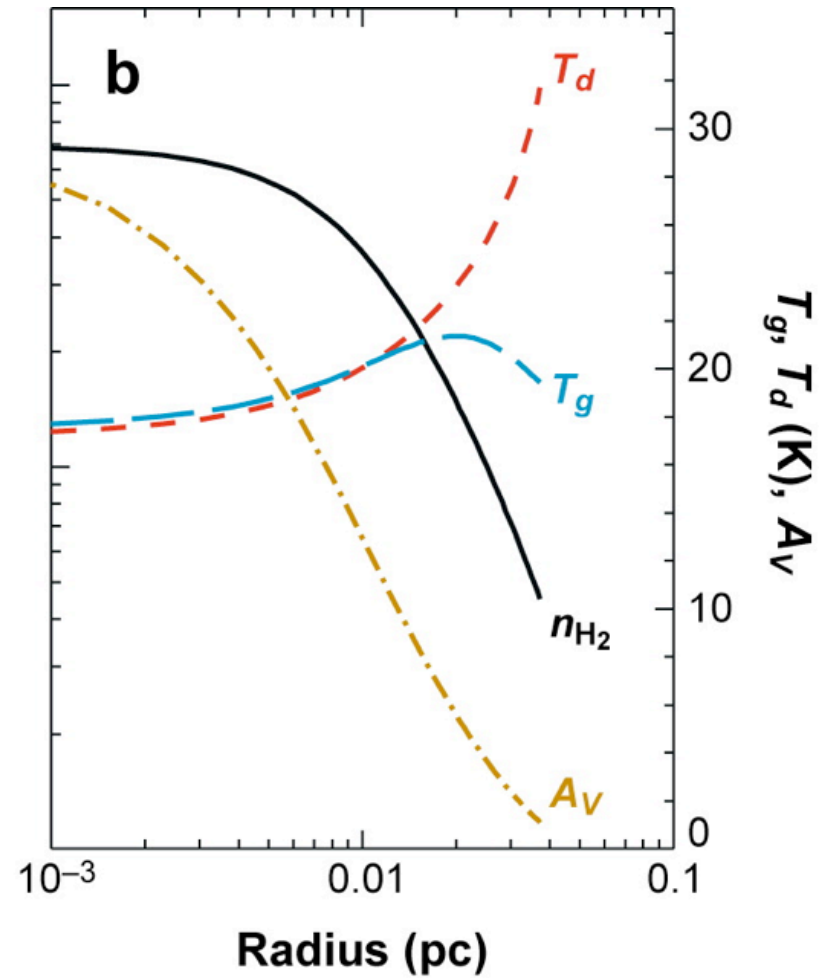
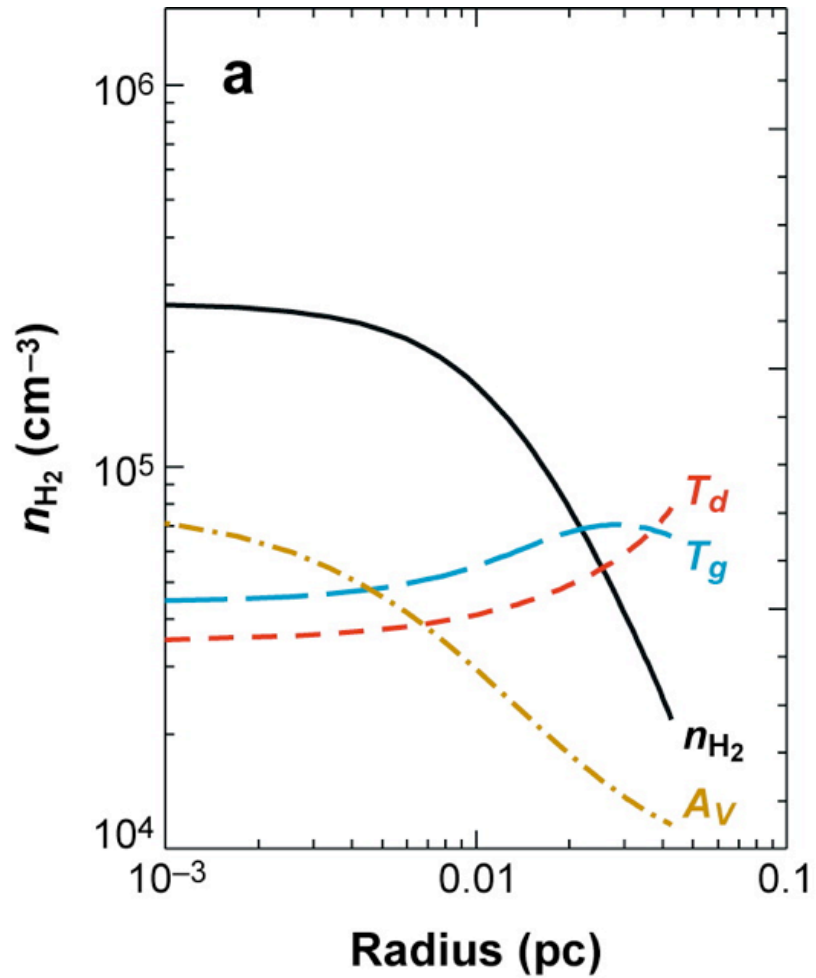
Critical Densities and Abundances of Molecules

Critical densities

CO J = 1-0	700 cm ⁻³
NH ₃	2000 cm ⁻³
CS J = 1-0	20000 cm ⁻³
CS J = 2-1	300,000 cm ⁻³
N ₂ H ⁺ J = 1-0	200,000 cm ⁻³

Abundances relative to H₂

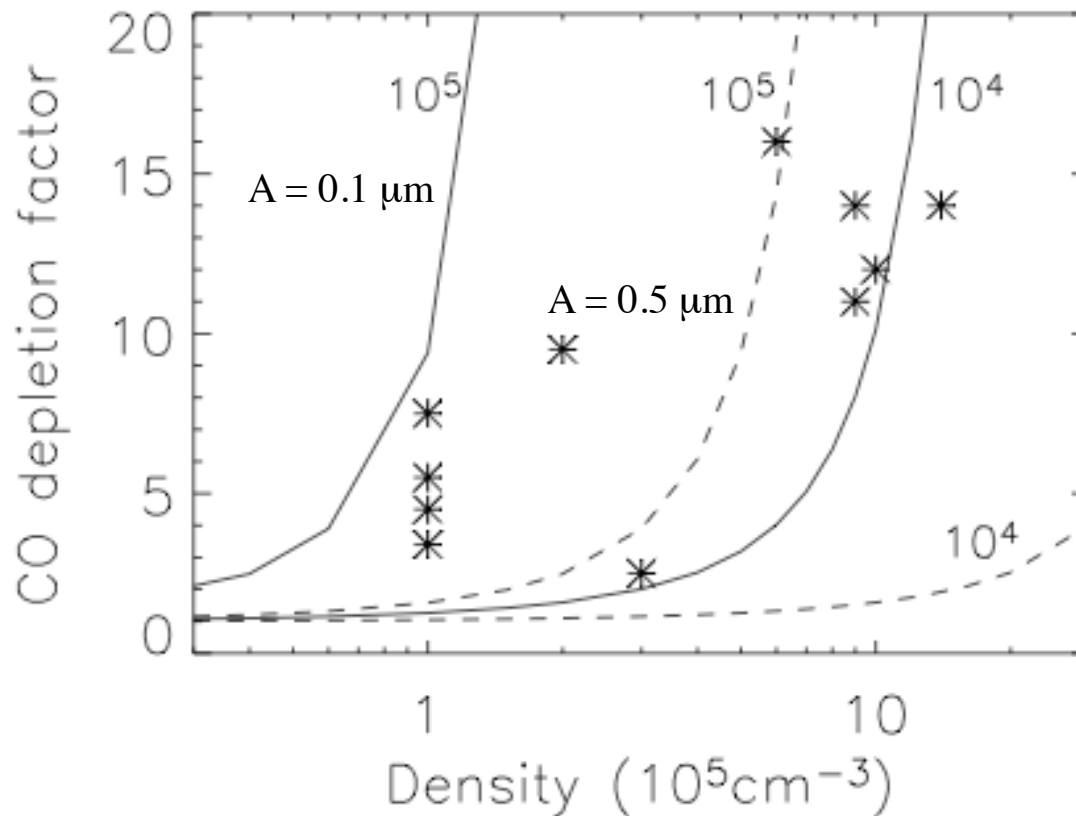
CO	10 ⁻⁴	NH ₃
	10 ⁻⁷	CS
	10 ⁻⁸	N ₂ H
+	10 ⁻⁹	



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Galli et al. 2002

Derivation of Sticking

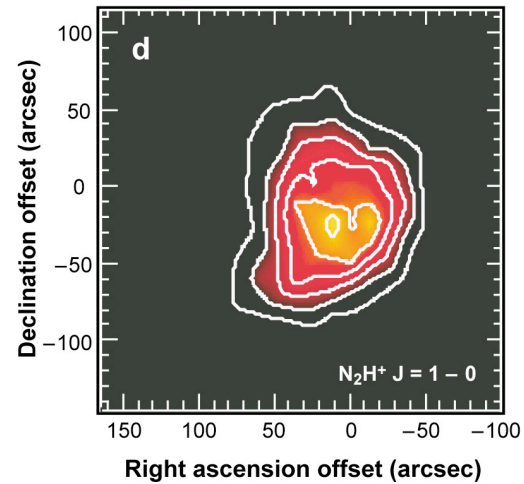
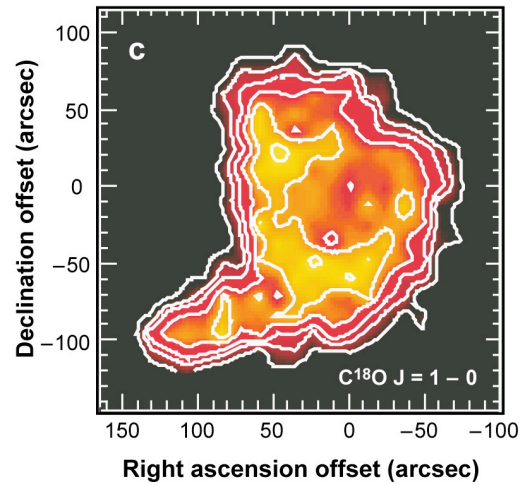
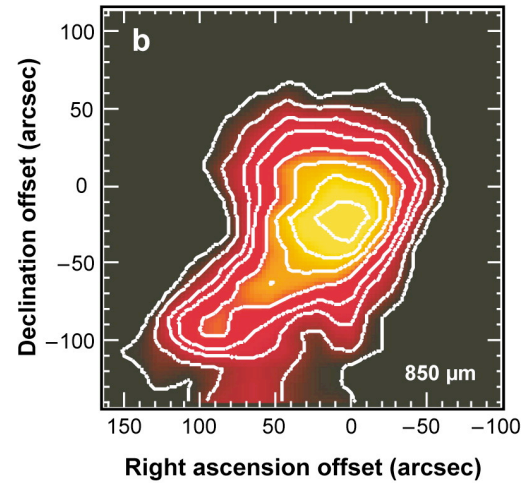
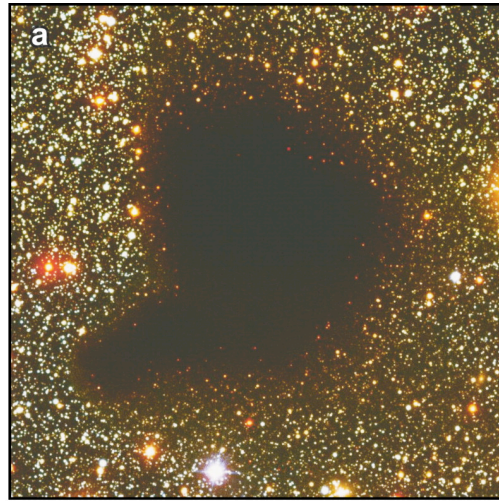



Balanced by release
by cosmic ray heating

$$K_{\text{cr}} = 9.8 \times 10^{-15} \text{ s}^{-1}$$

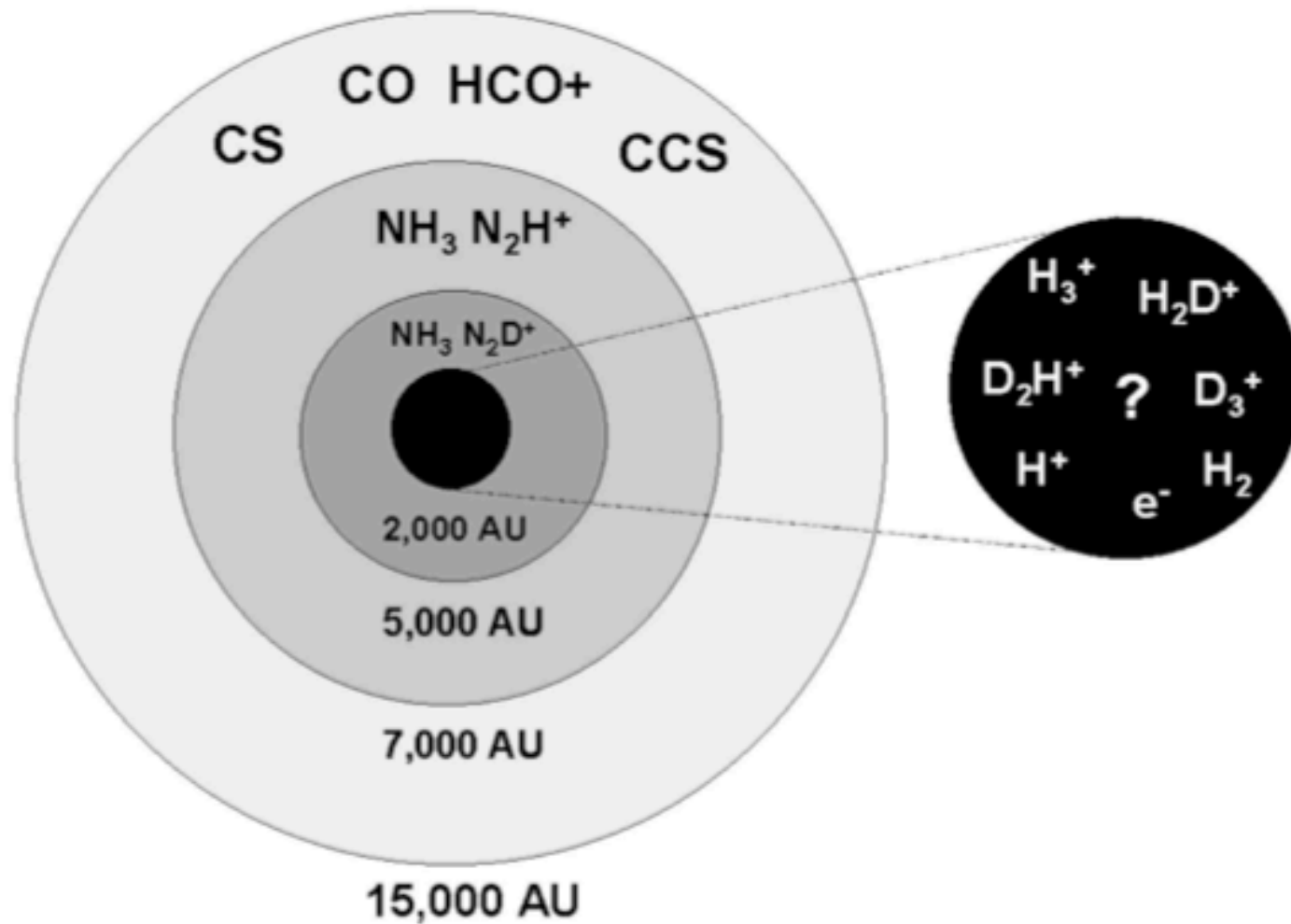
$$k_{\text{freeze}} = S \langle \pi a_{\text{gr}}^2 v_{\text{CO}} \rangle n_{\text{g}},$$

Chemistry in the B68 Globule



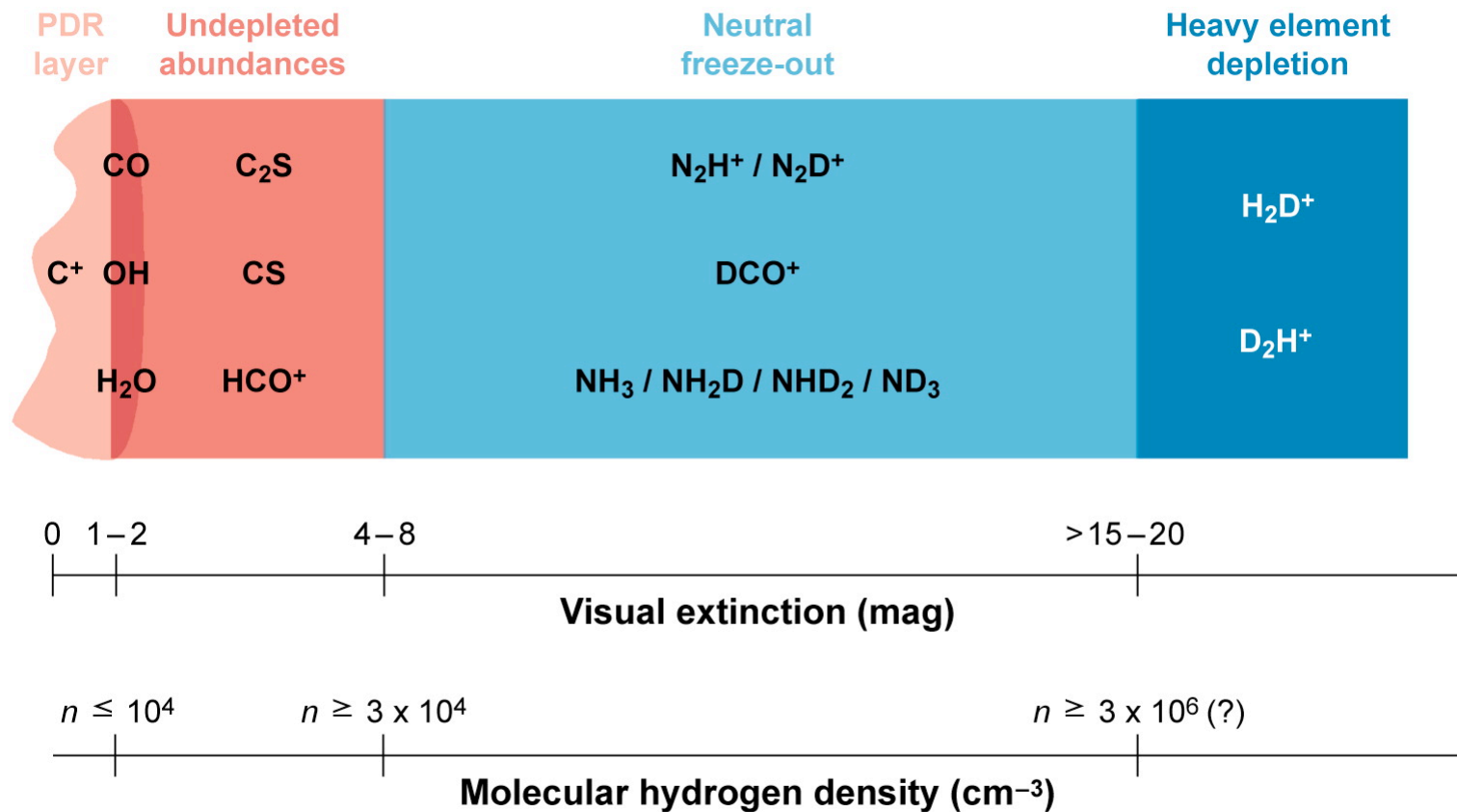
 Bergin EA, Tafalla M. 2007.
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Deuteration in Prestellar Cores



Chemical Structure of Starless Cores

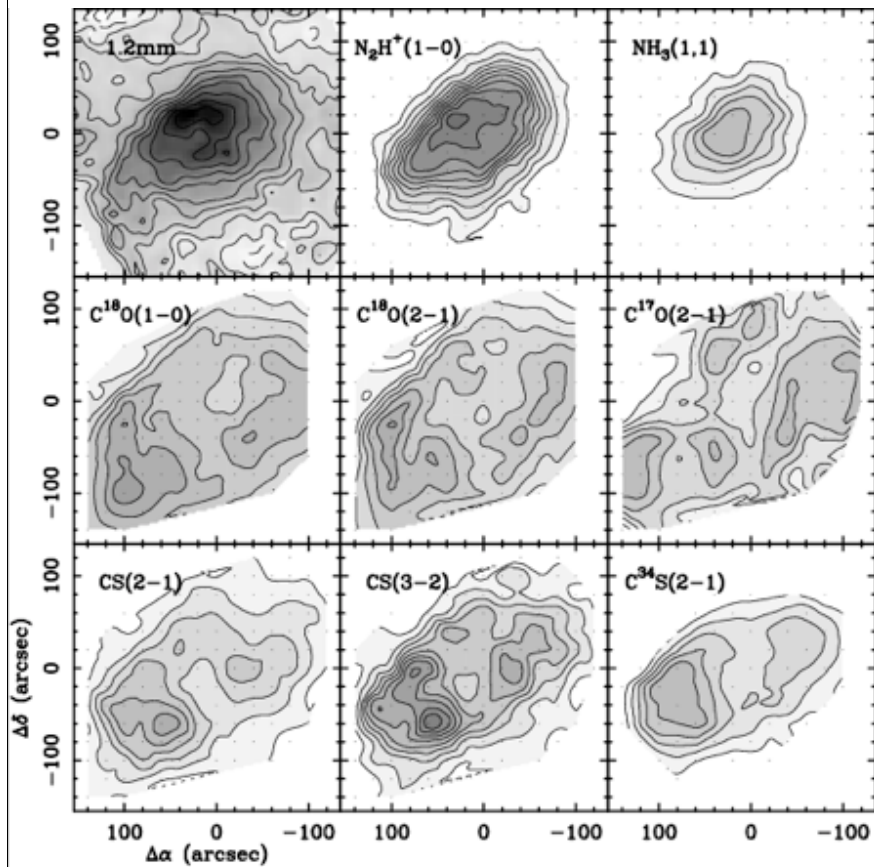
Major gas-phase tracers in starless cores



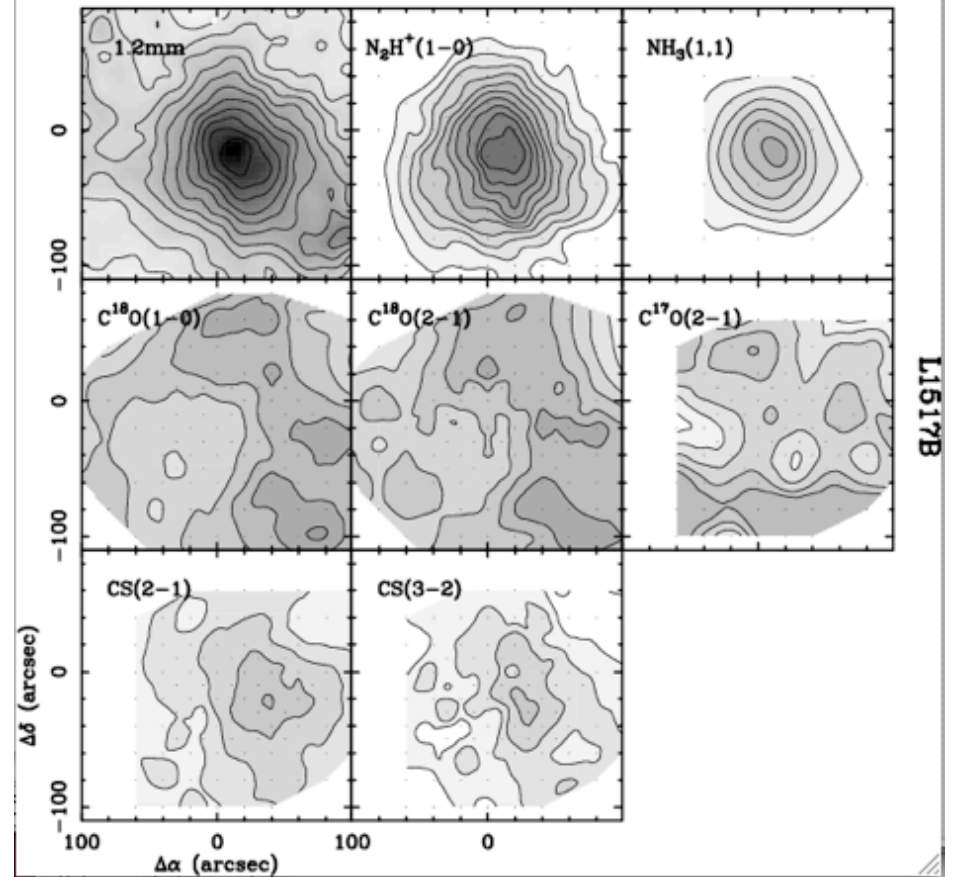
 Bergin EA, Tafalla M. 2007.
Annu. Rev. Astron. Astrophys. 45:339-96

Two Starless Cores

L1498



L1517B

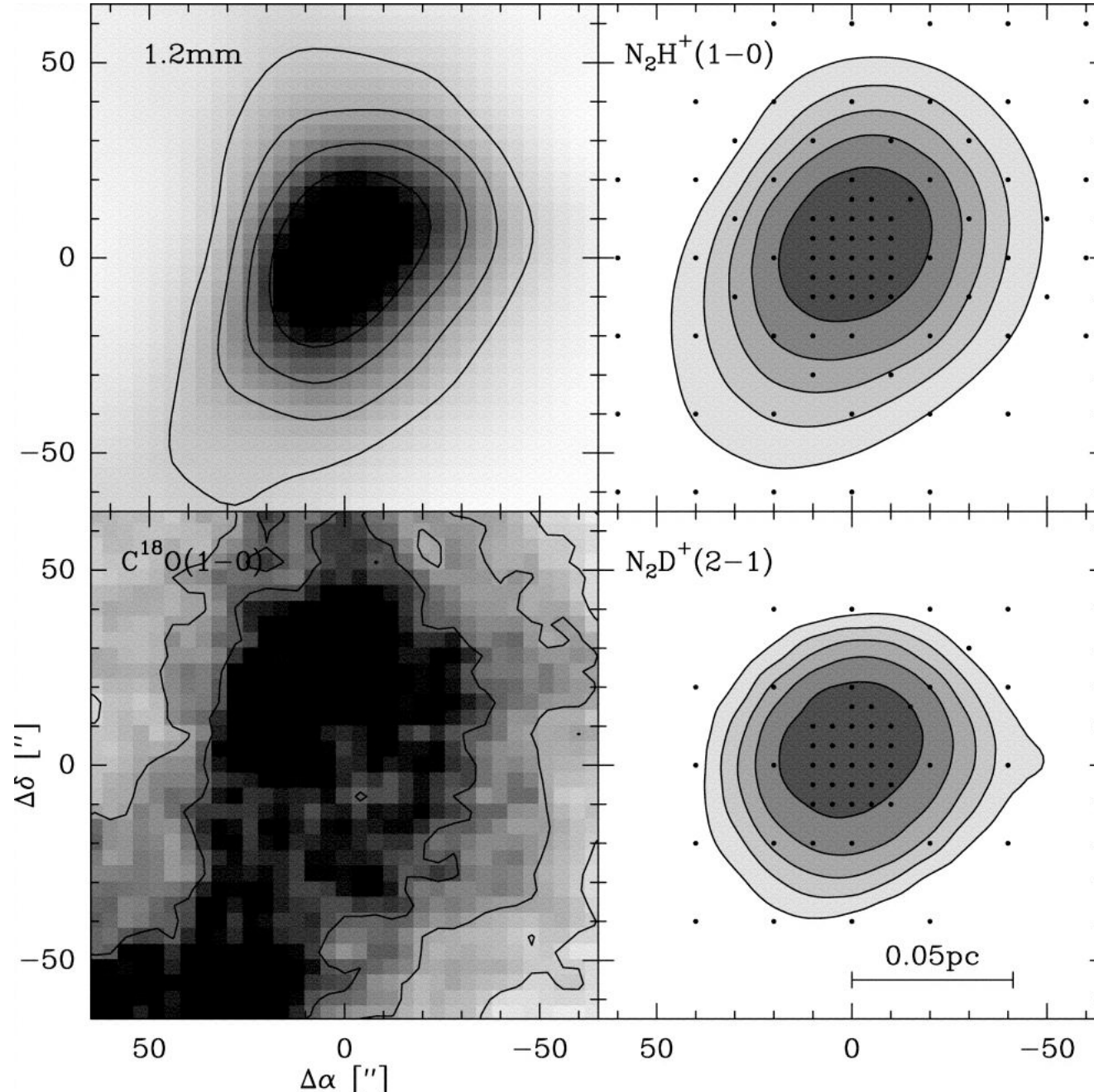


Tafalla et al. 2004 A&A 416, 916

Detecting the centers of prestellar cores

Crapsi et
al. 2005

Lynds 694



Motions inside Cores

Core Rotation

Caselli et al. 2002

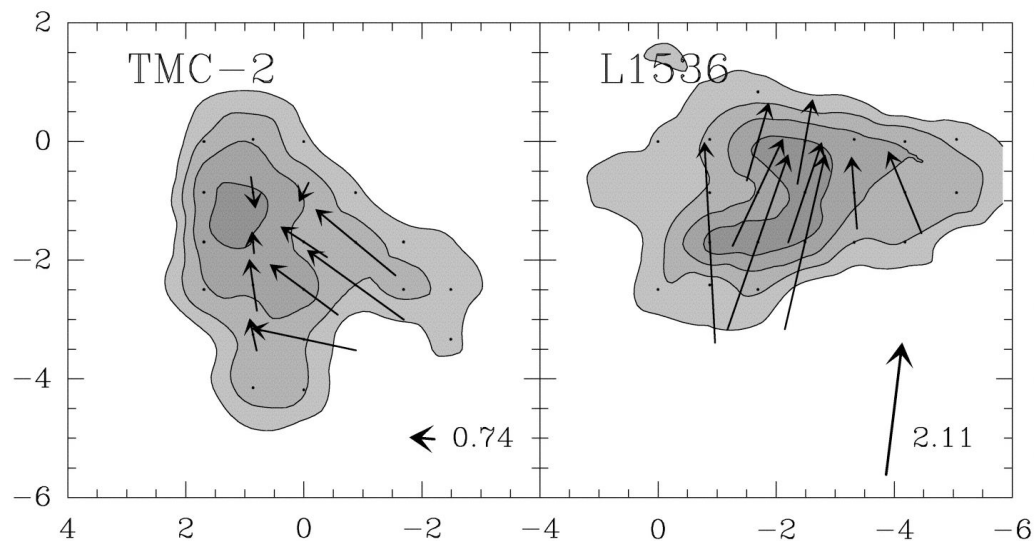
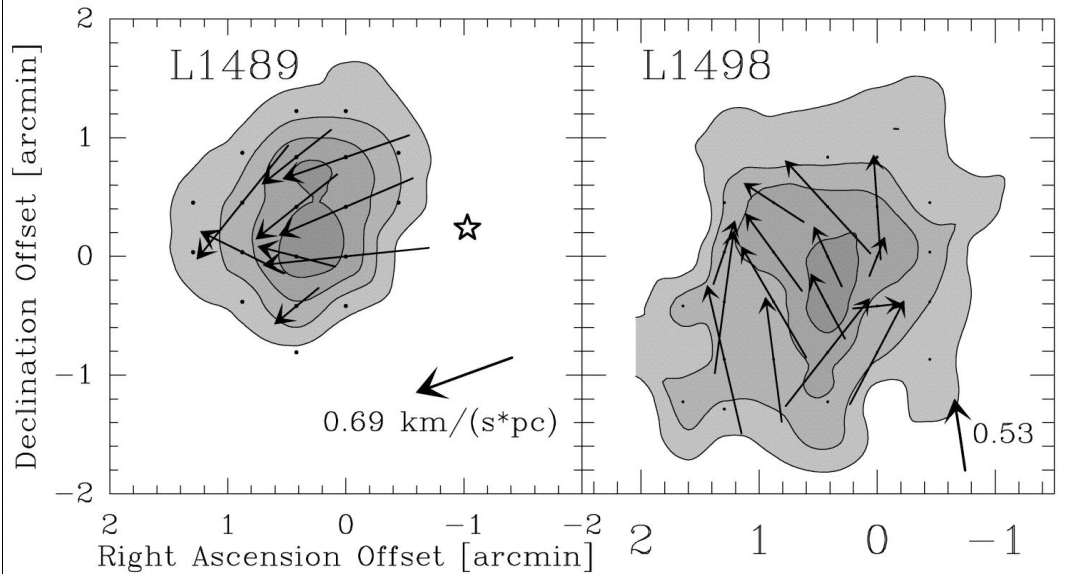
ApJ 572, 238

N_2H^+ maps of dense cores

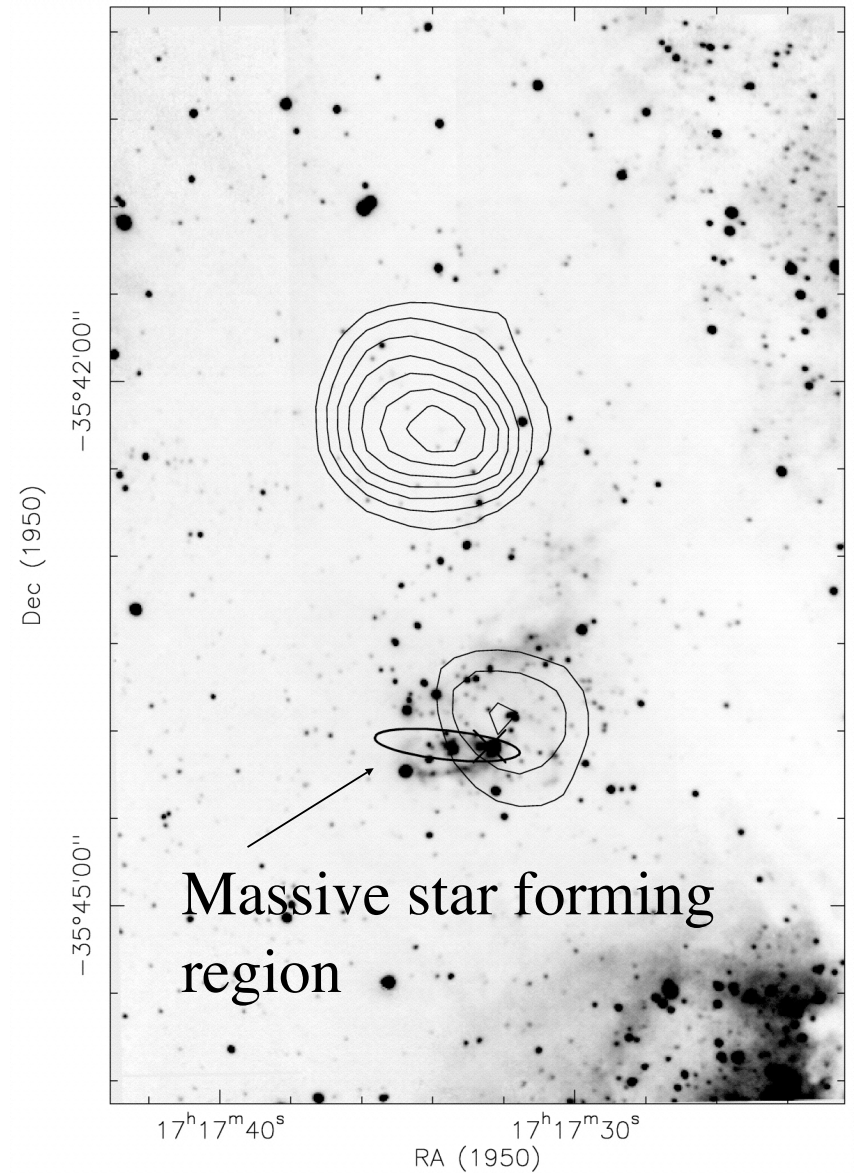
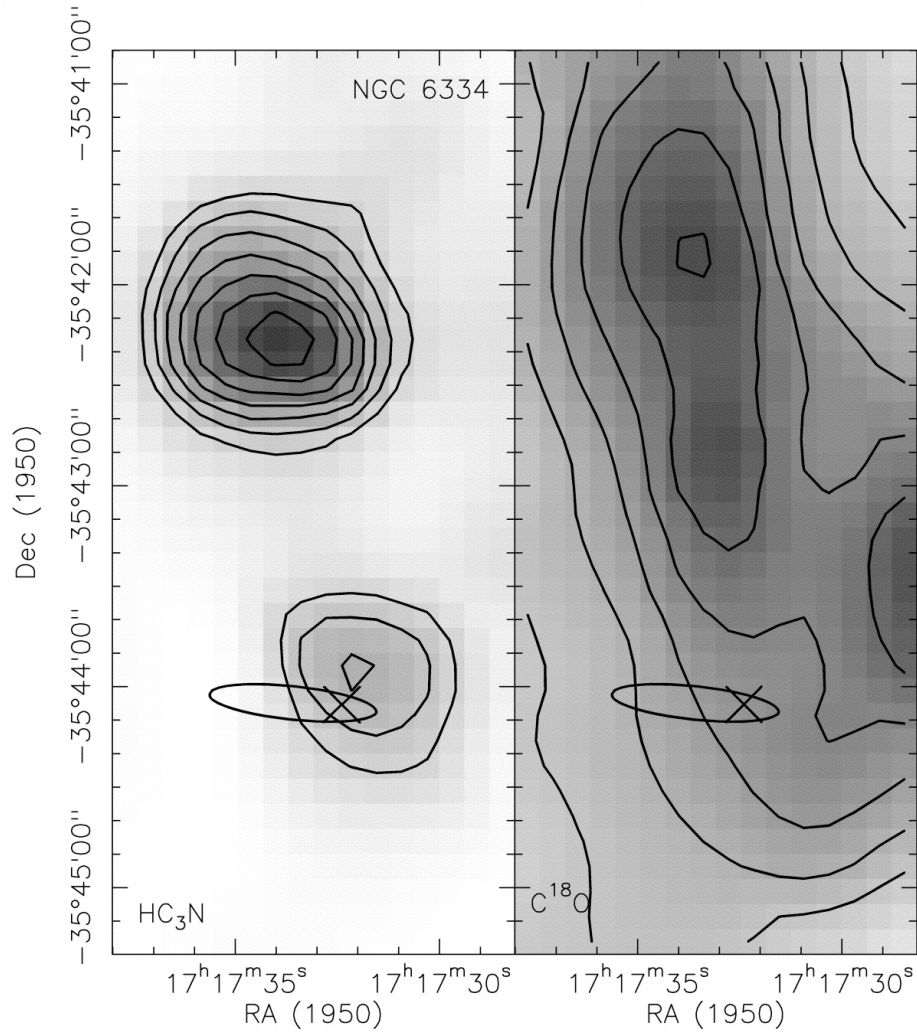
Gradients:

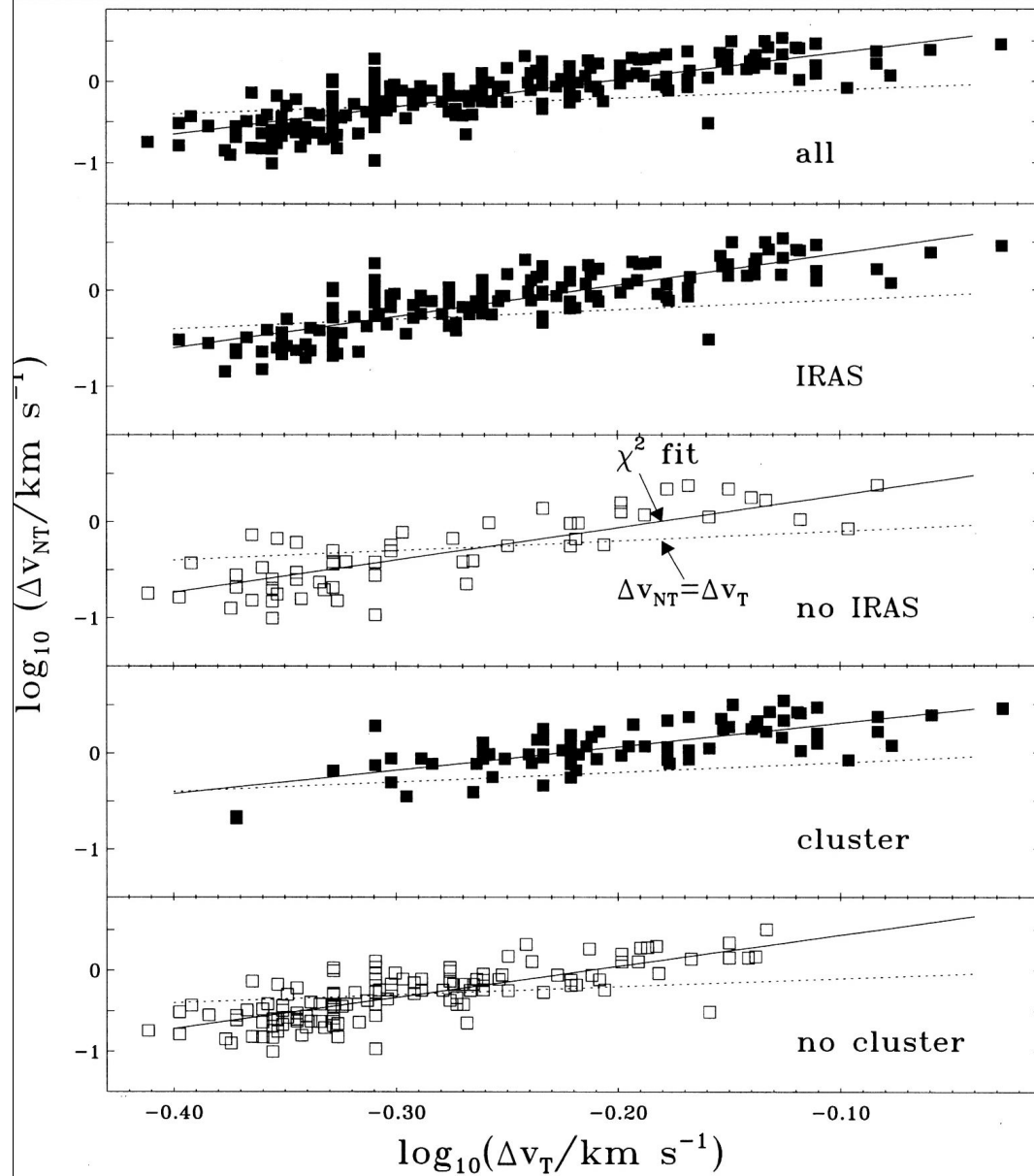
$0.5\text{-}6 \text{ km s}^{-1} \text{ pc}^{-1}$

Rotation kinetic energy/gravitational energy = 10^{-4} to 0.07



Massive Star Forming Cores



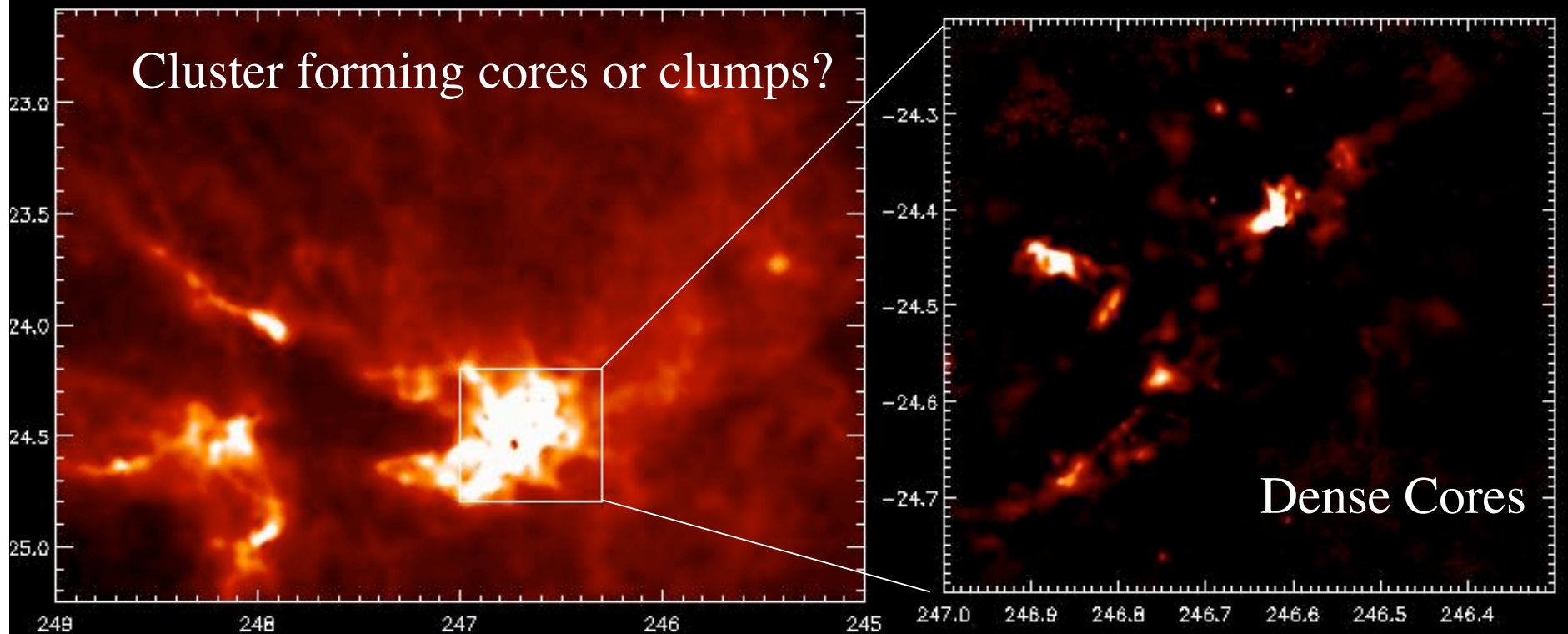


Turbulent Cluster Forming Cores or Cluster Forming Clumps (Jjina)

Dense Cores

Extinction map made from
background stars.

Submillimeter 850 micron
measurements of thermal emission
from cold dust.



Cores in Clusters (Cores within Cores)

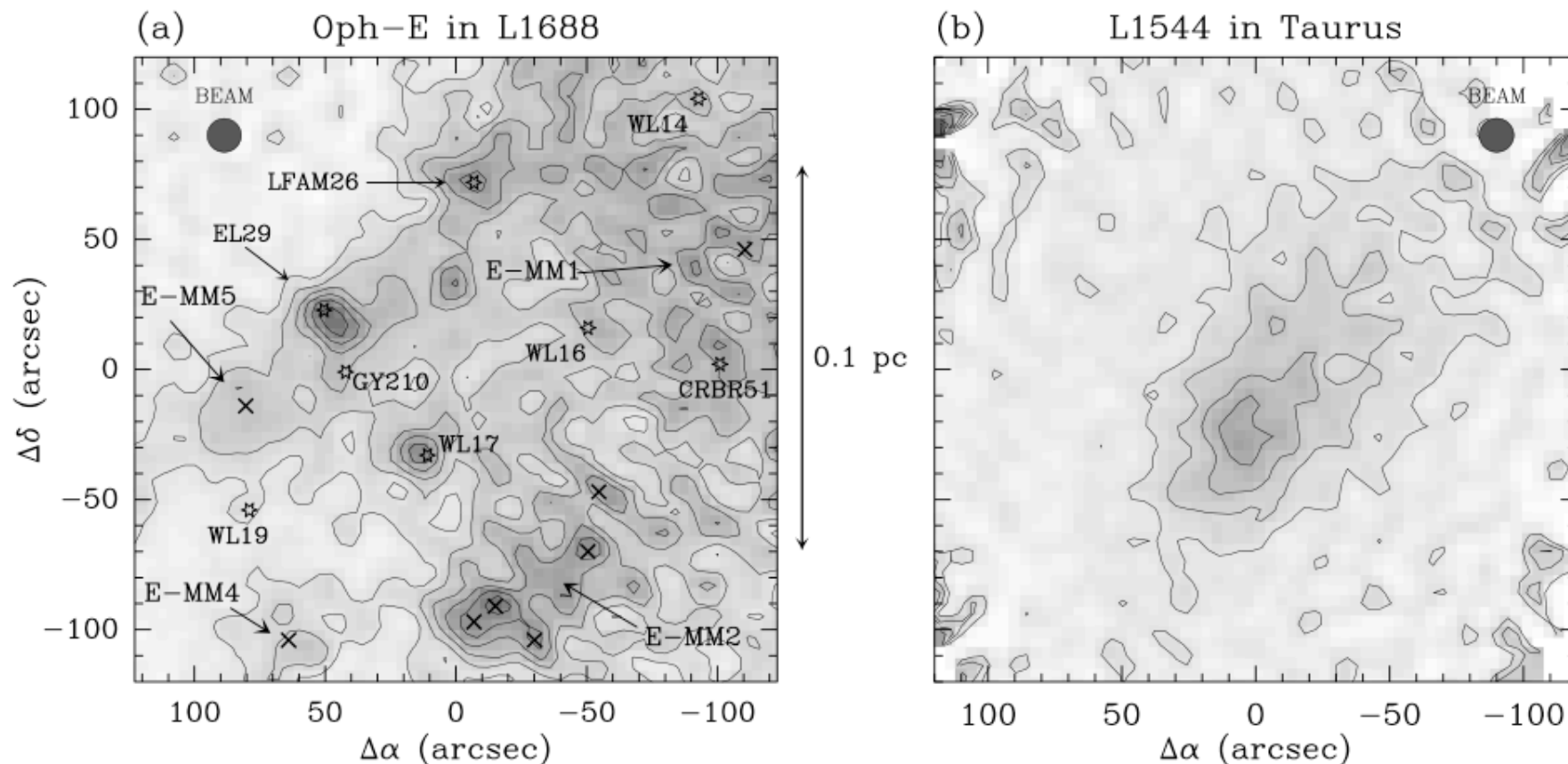
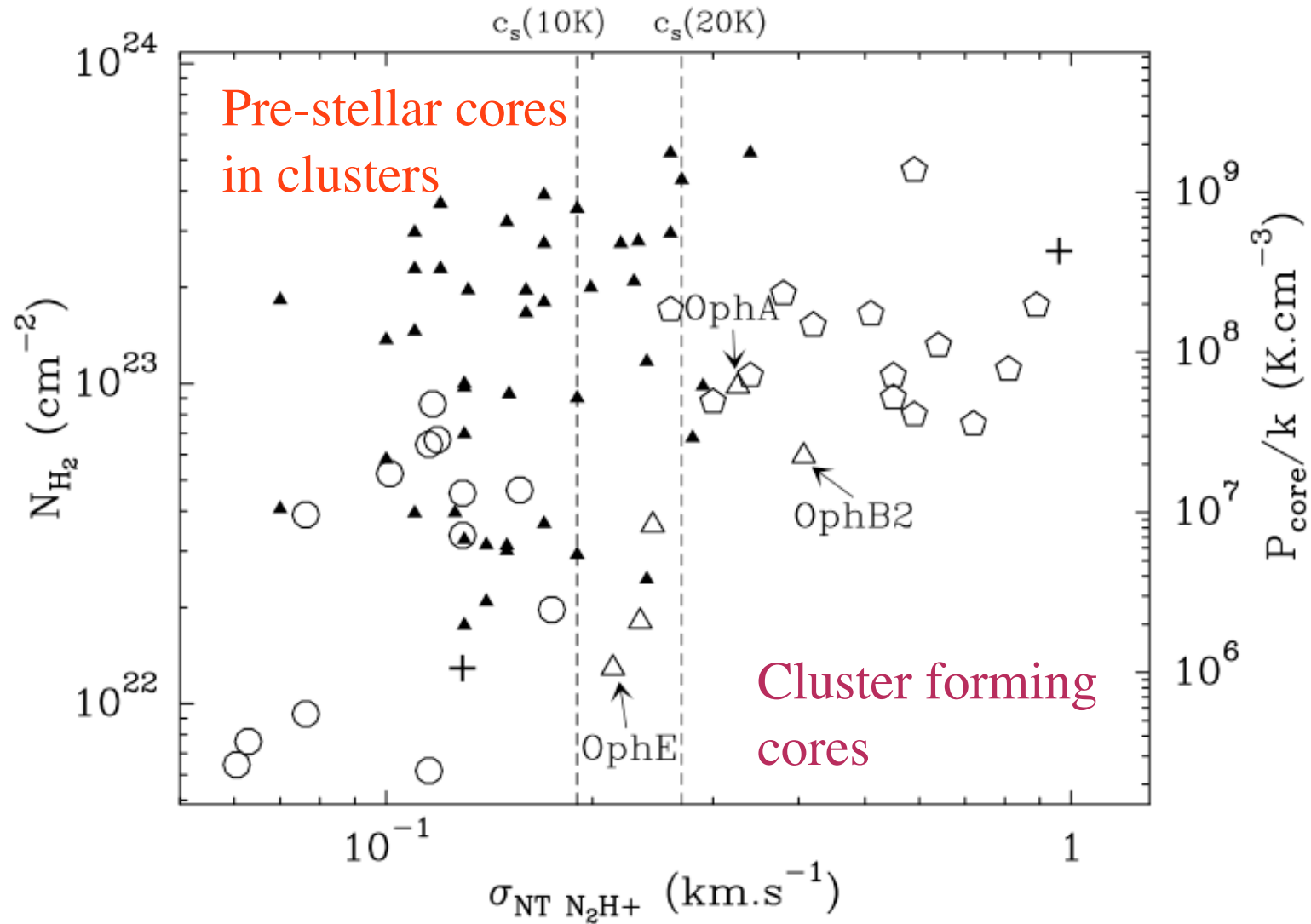
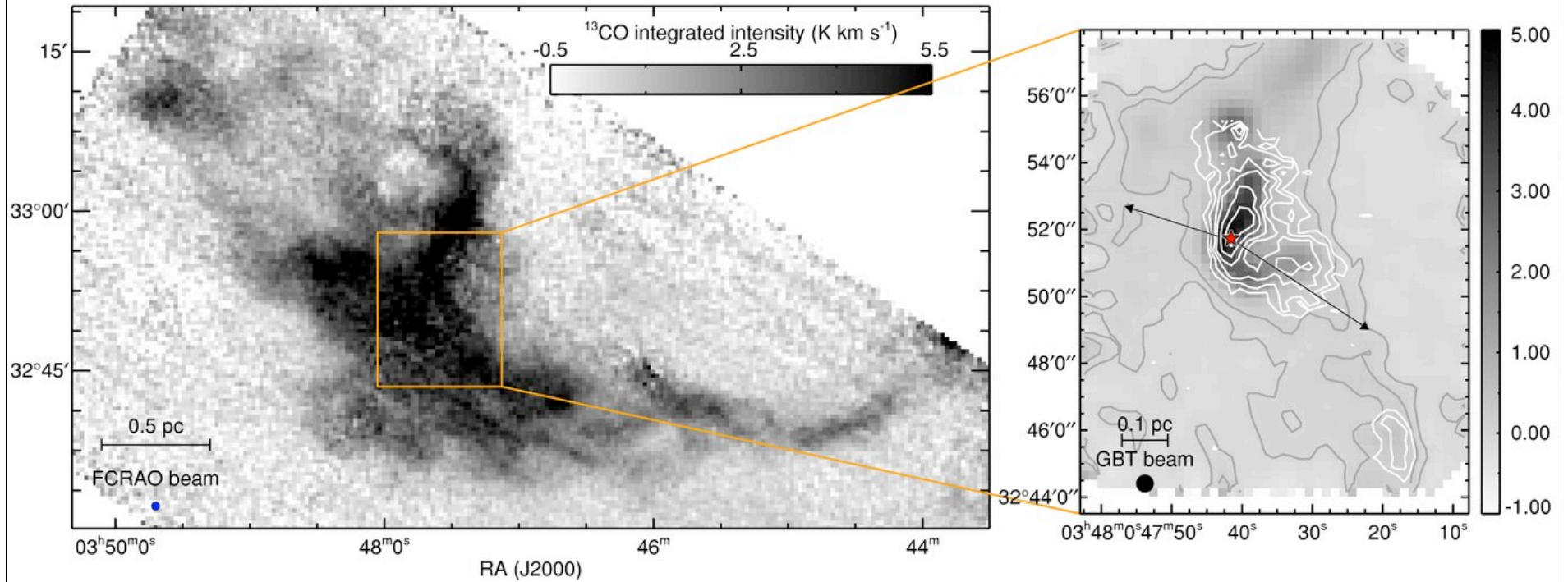


Fig. 5.— Millimetre dust continuum images of ρ Oph-E (left) and Taurus (right) taken at the same resolution with the IRAM 30-m telescope (from *Motte et al.*, 1998 and *Ward-Thompson et al.*, 1999 respectively). Note how the cluster-forming ρ Oph core shows far more substructure than the more isolated Taurus pre-stellar core at the same linear scale. In the left-hand image the crosses mark starless cores and the stars mark protostellar objects.

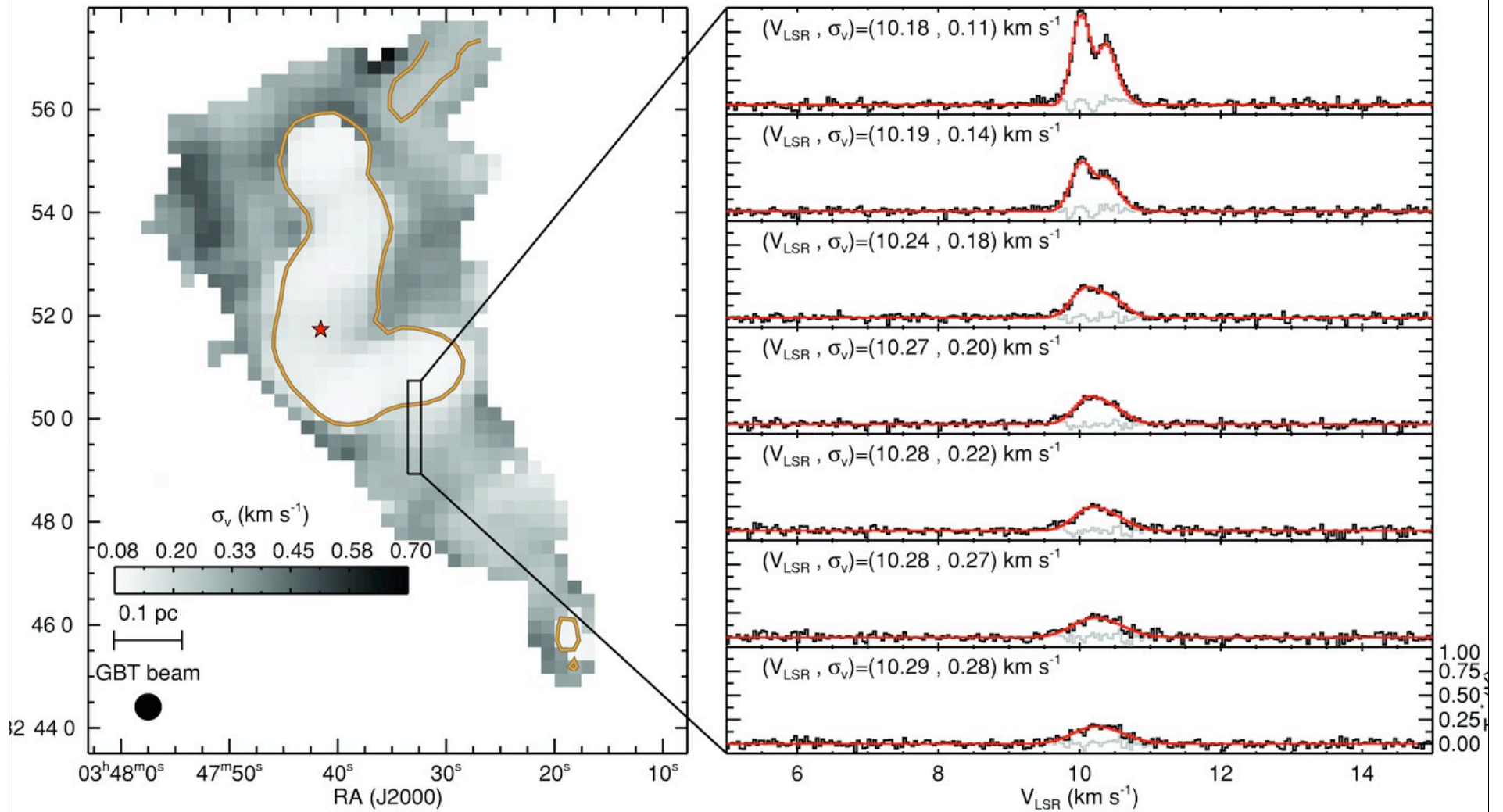
Linewidth Velocity



The B5 Core in Perseus



Islands of Coherence



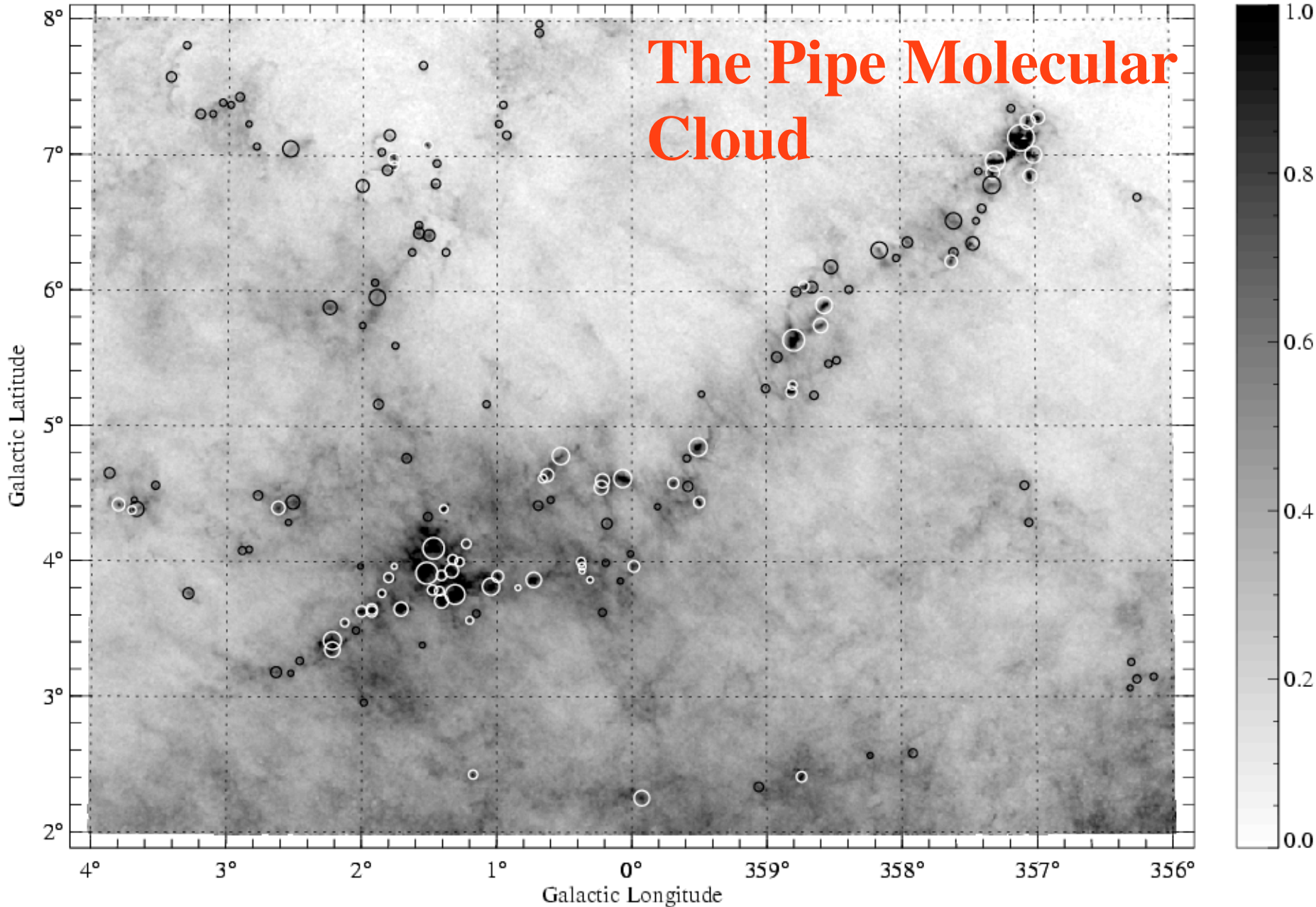
Cores as the Precursors of Stars

The Pipe Molecular Cloud

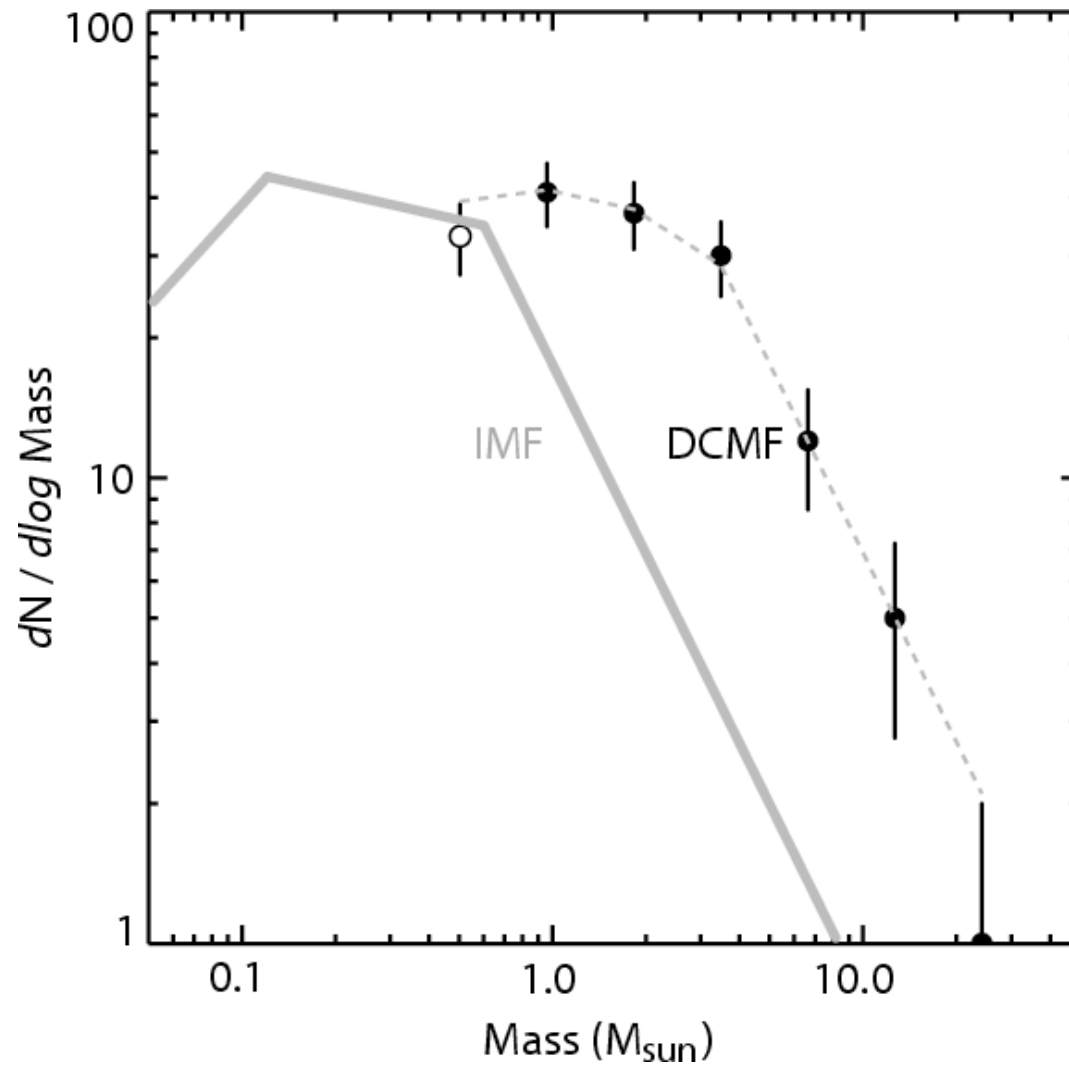
The image displays a vast field of stars, with a prominent concentration of blue stars scattered throughout. The background is a mix of reddish-brown and dark brown hues, indicating the presence of interstellar dust. Dark, filamentary structures, characteristic of molecular clouds, are visible against the lighter background. The overall appearance is that of a rich, multi-colored stellar population within a dusty environment.

Pipe Nebula, Yuri Beletsky

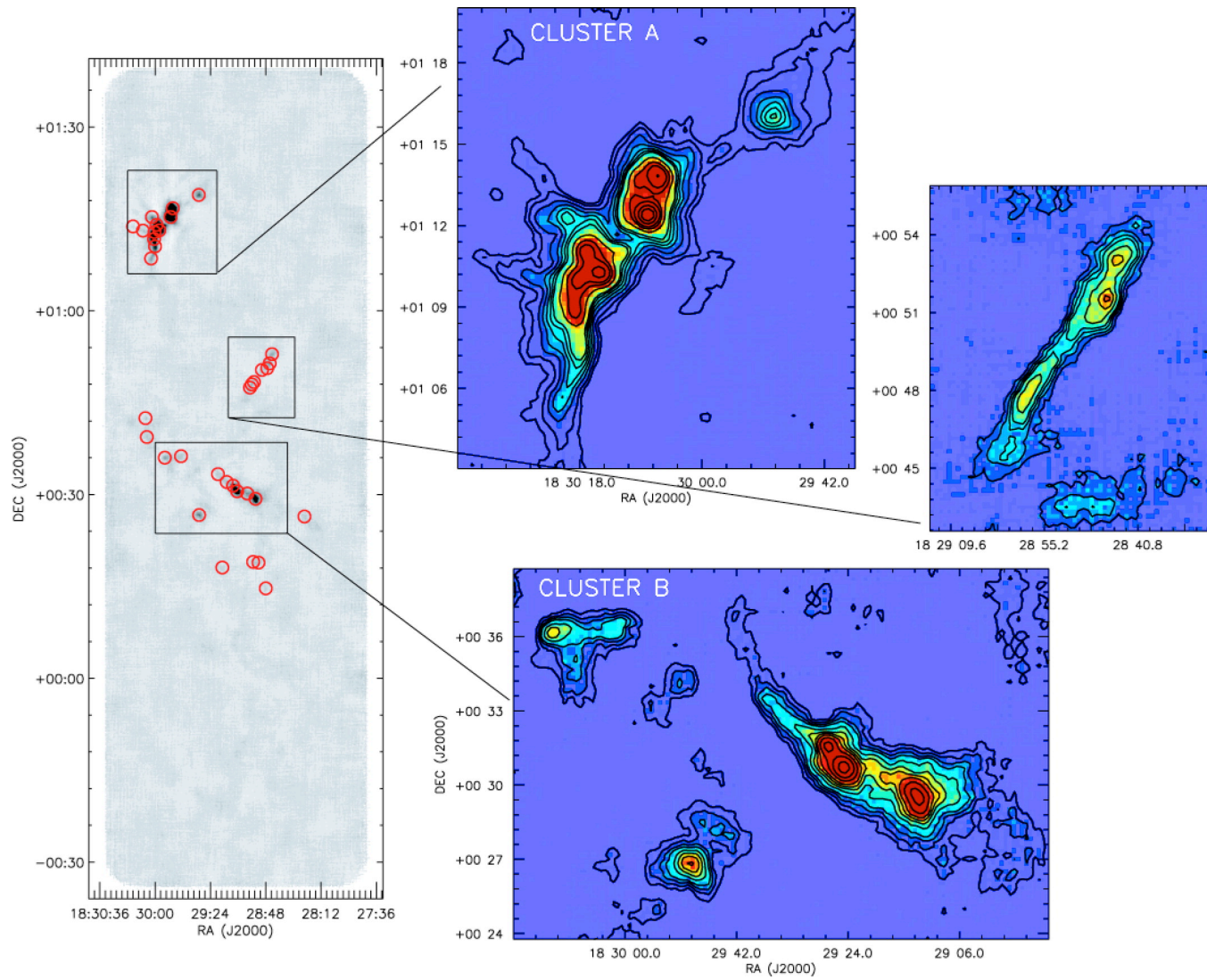
The Pipe Molecular Cloud



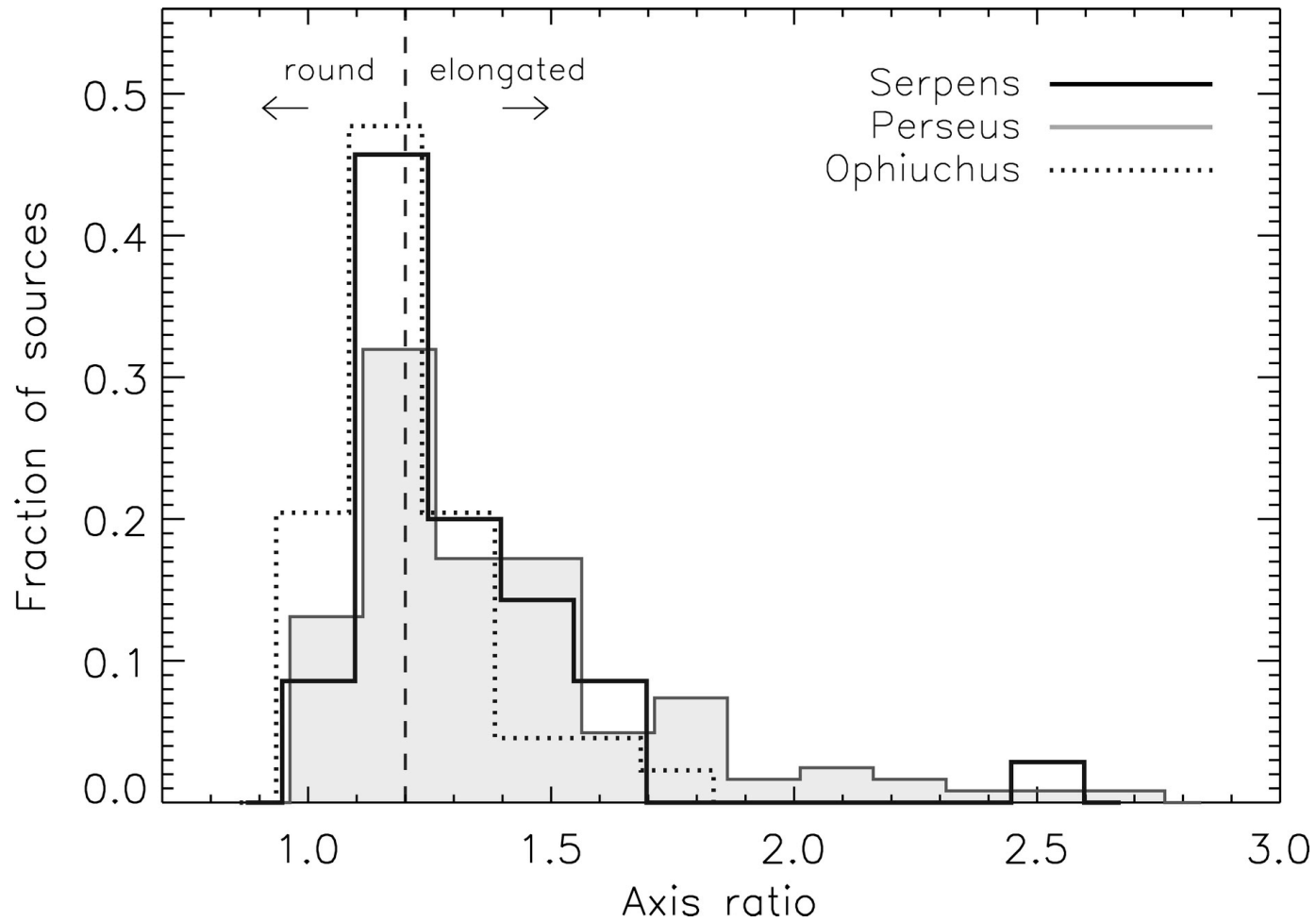
The Core Mass Function



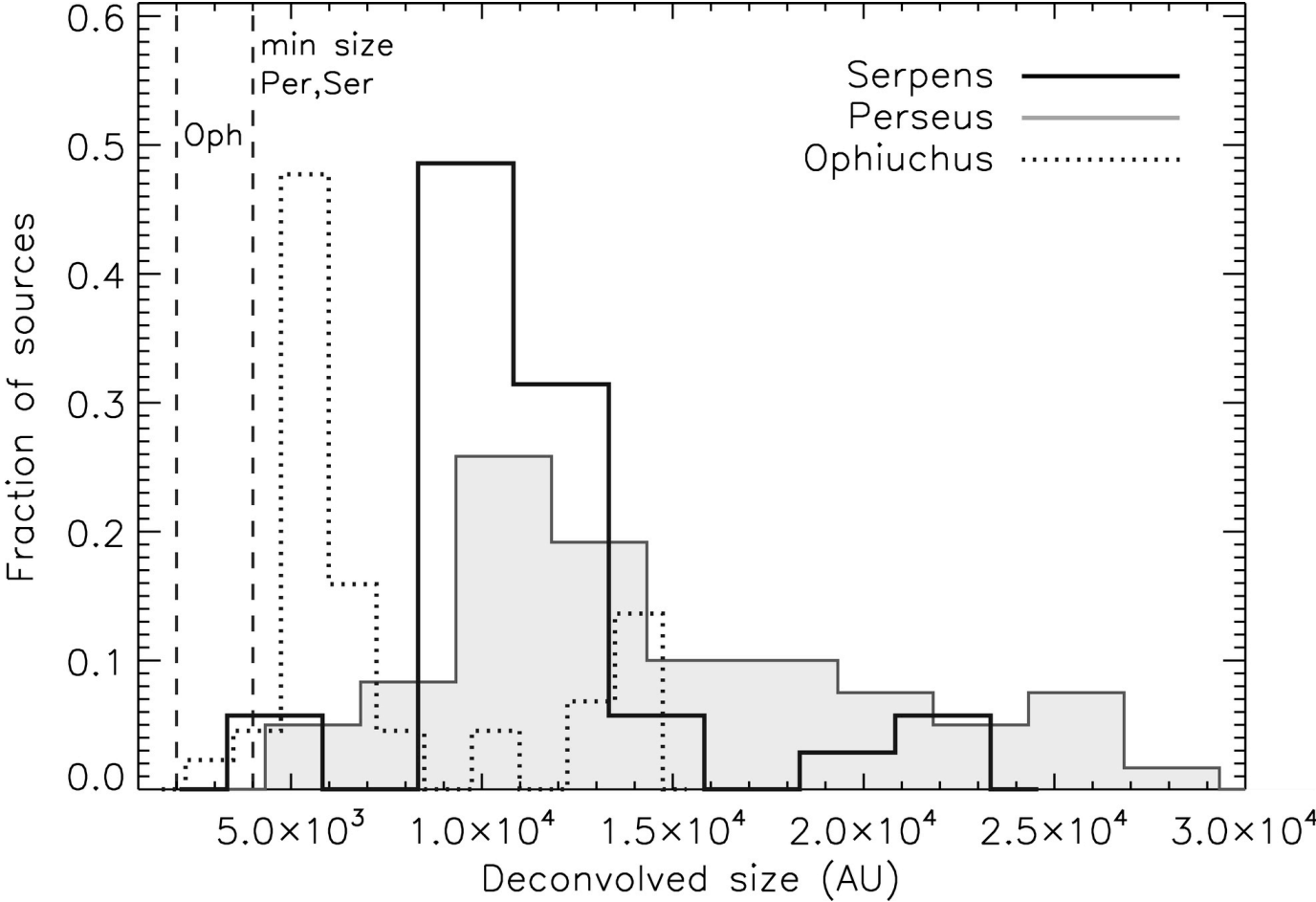
Bolocam Survey



Elongation of Cores

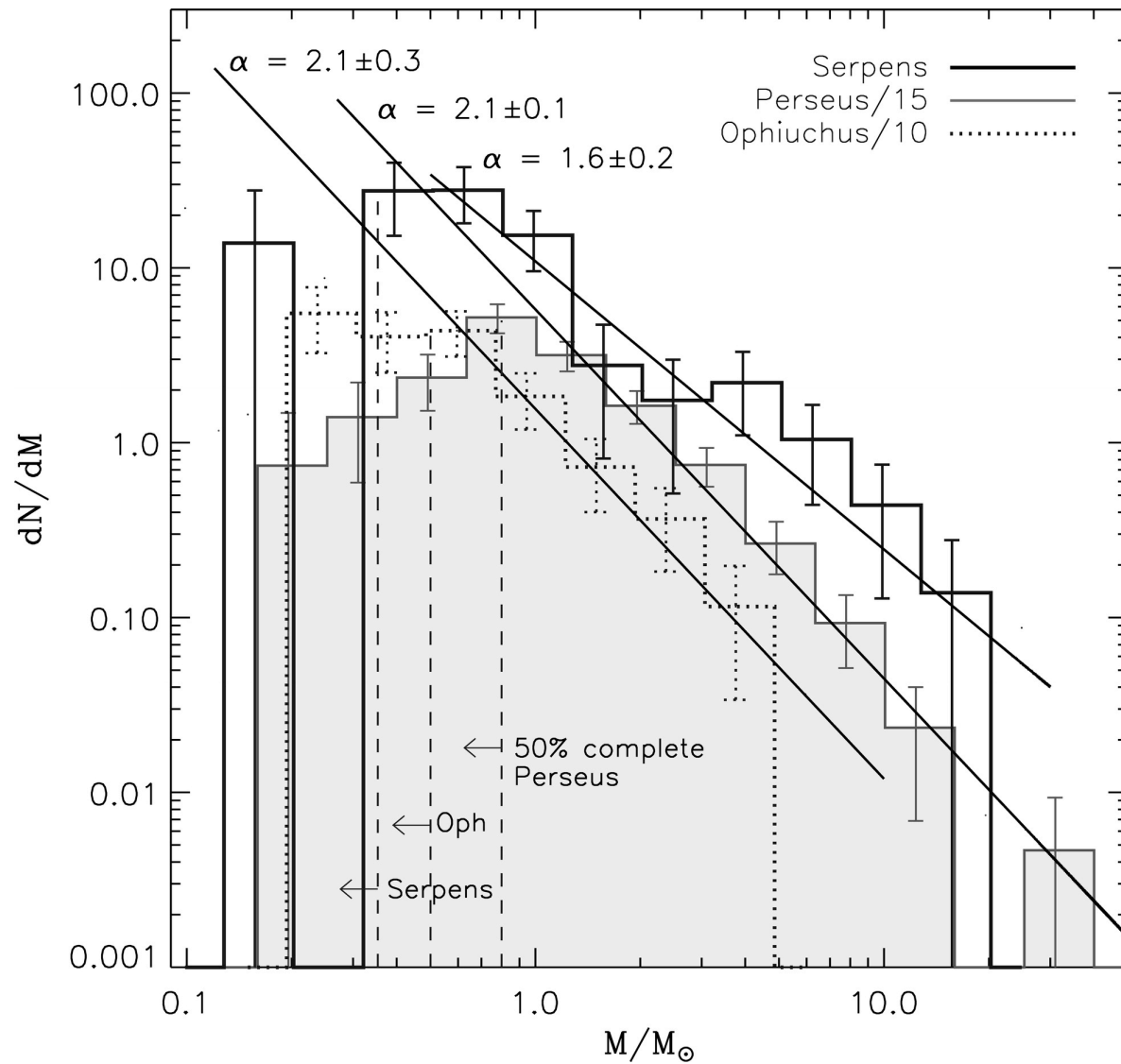


Core Sizes



Core Mass Functions

Enoch



Summary

- Dense cores are < 1 pc, $n(\text{H}_2) > 10^4 \text{ cm}^{-3}$ condensations found in molecular clouds
- Bok Globules are isolated dense cores
- Temperatures can go down to 8 K
- Masses range from 1-10 M_{sun} in low mass star forming regions
- Cores with masses $> 10 M_{\text{sun}}$ may be forming clusters, may contain dense cores
- In low mass cores, linewidth may be thermal (islands of coherence)
- These low mass cores may be forming individual stars, follow IMF