XII IAG/USP Advanced School on Astrophysics

Molecular Clouds

Low Mass Star Formation

Disks and Flows

High Mass Star Formation

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18 researchers

Direction of thesis

Ph. D. Program in Astronomy

Molecular Clouds and Star Formation

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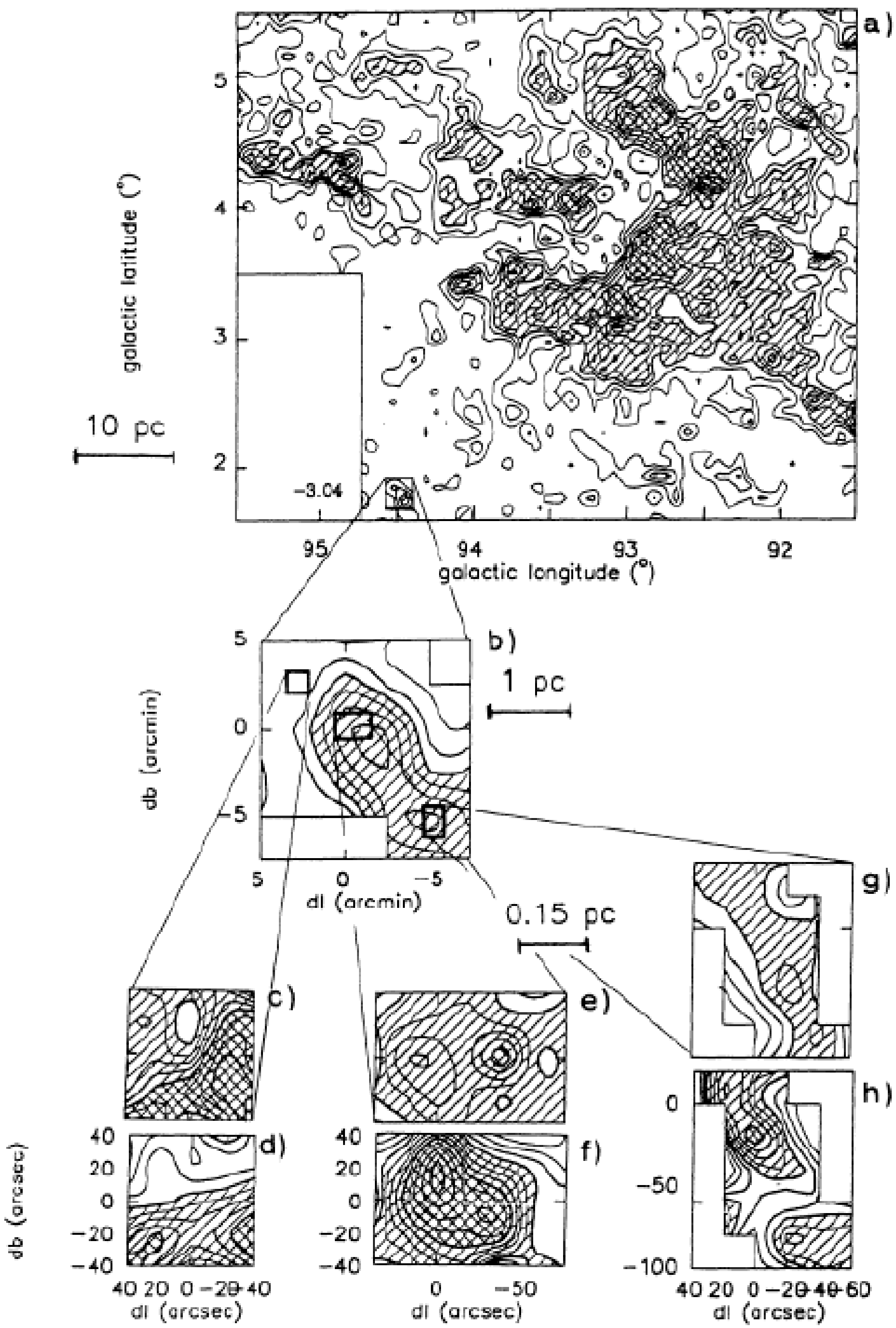
Molecular Clouds: Structure

- Most molecular gas in the ISM is in Giant Molecular Clouds, with masses of 10^{5-6} M_{sun}, sizes of tens of pc, and average H_2 (prime constituent) densities of about 100 cm^{-3}.
- Very inhomogeneous in density, with a lot of substructure (clumps and cores).



Falgarone et al. (1992)

CO observations of Cyg OB7 field

Bordeaux (2.5-m) and IRAM (30-m) radio telescopes

“Clumps and Cores”

- Clump: masses of 10^3 M_{sun}, sizes of pc, and average H_2 densities of 10^3 cm^{-3}. Sites where stellar clusters may form.
- Core: masses of a few M_{sun}, sizes of 0.1 pc, and average H_2 densities of 10^4 cm^{-3} and higher. Sites where single stars or small multiple systems (i. e. binaries) may form.

M.-M. Mac Low and R. S. Klessen: Control of star formation by supersonic turbulence

TABLE I. Physical properties of interstellar clouds.

	Giant Molecular Cloud Complex	Molecular Cloud	Star-Forming Clump	Protostellar Core[a]
Size (pc)	10–60	2–20	0.1–2	$\lesssim 0.1$
Density [$n(H_2)/cm^3$]	100–500	10^2–10^4	10^3–10^5	$>10^5$
Mass ($M_\odot$)	10^4–10^6	10^2–10^4	10–10^3	0.1–10
Linewidth (km s^{-1})	5–15	1–10	0.3–3	0.1–0.7
Temperature (K)	7–15	10–30	10–30	7–15
Examples	W51, W3, M17, Orion-Monoceros, Taurus-Auriga-Perseus complex	L1641, L1630, W33, W3A, B227, L1495, L1529		see Sec. II.E

[a]Protostellar cores in the "prestellar" phase, i.e., before the formation of the protostar in its interior.

However, more than "clouds, clumps, and cores", we have a continuum of structures...

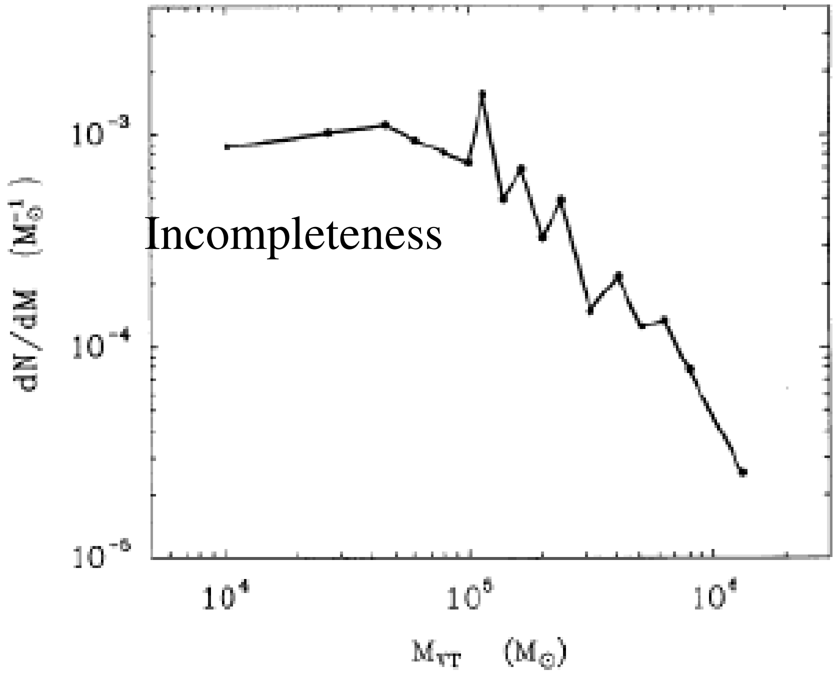


FIG. 3.—The molecular cloud mass spectrum dN/dM. A fit to the data above $M = 7 \times 10^4\ M_\odot$ gives $dN/dM \propto M^{-3/2}$. There are 15 clouds in each bin and the standard deviation is $\pm 24\%$. The turnover at low mass is due to undercounting of smaller clouds in the more distant parts of the galactic disk.

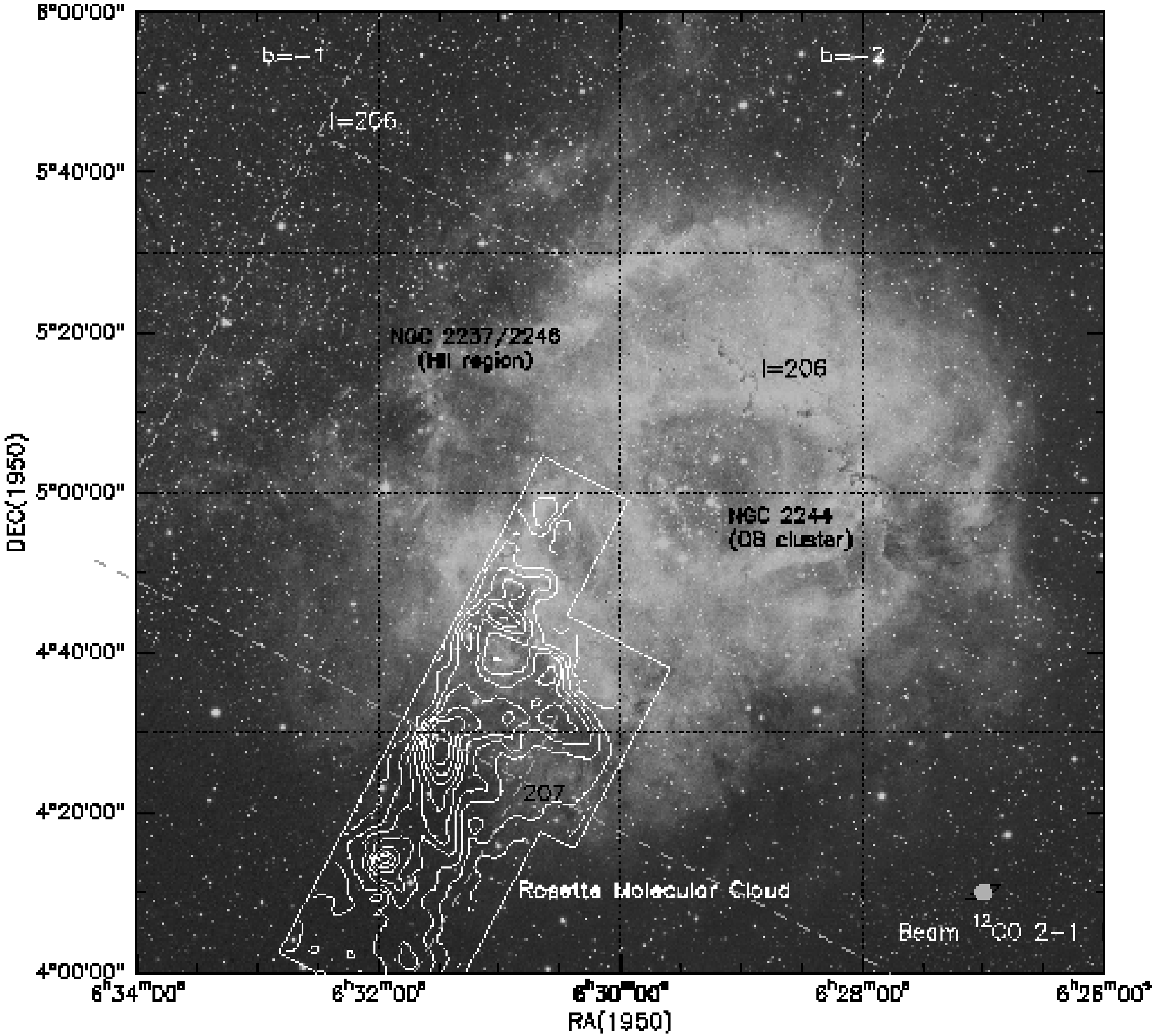
Solomon et al. (1987)

273 molecular clouds observed in CO (J=1-0)

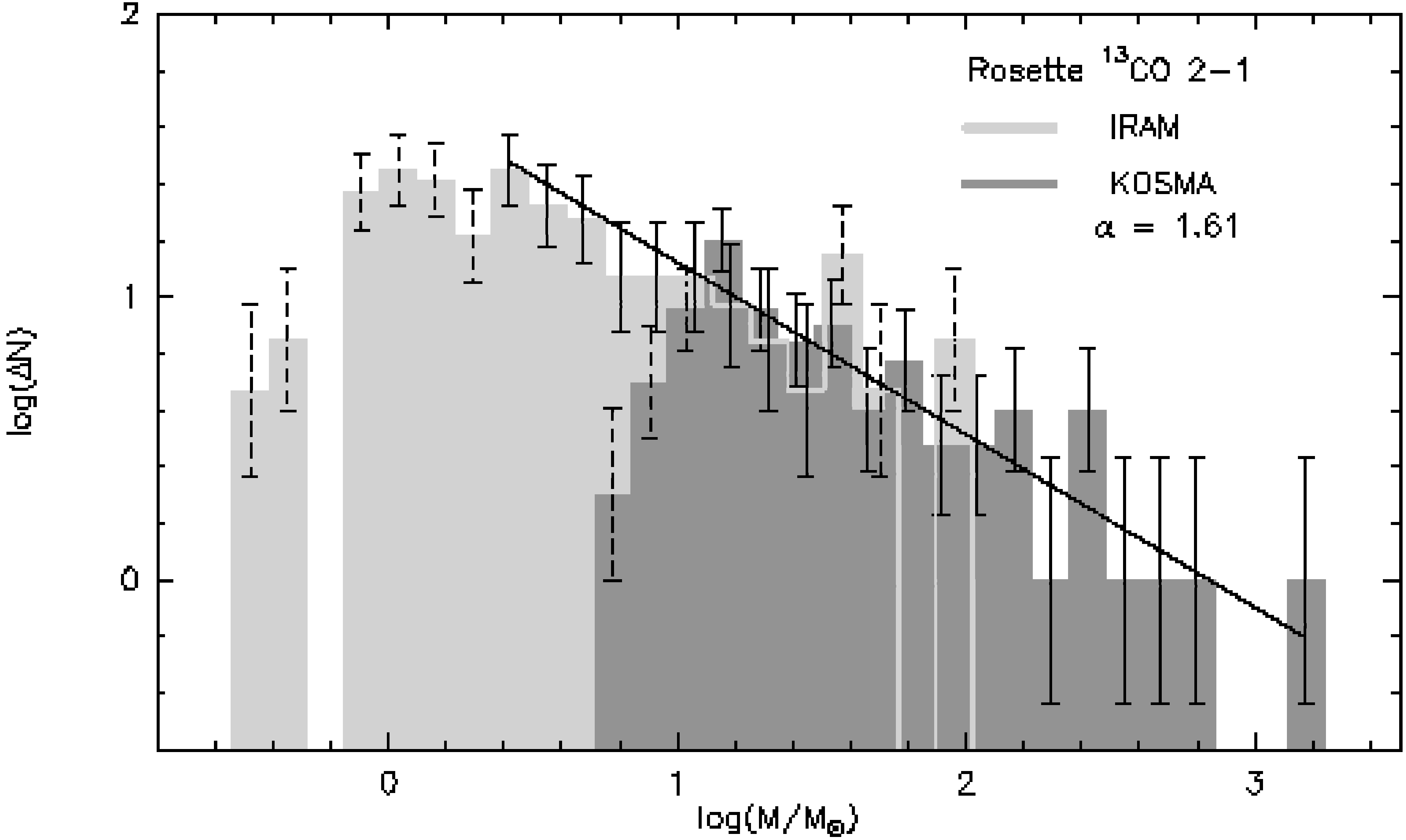
Massachusetts- Stony Brook Galactic Plane Survey

Molecular cloud mass spectrum: $dN/dM \propto M^{-3/2}$

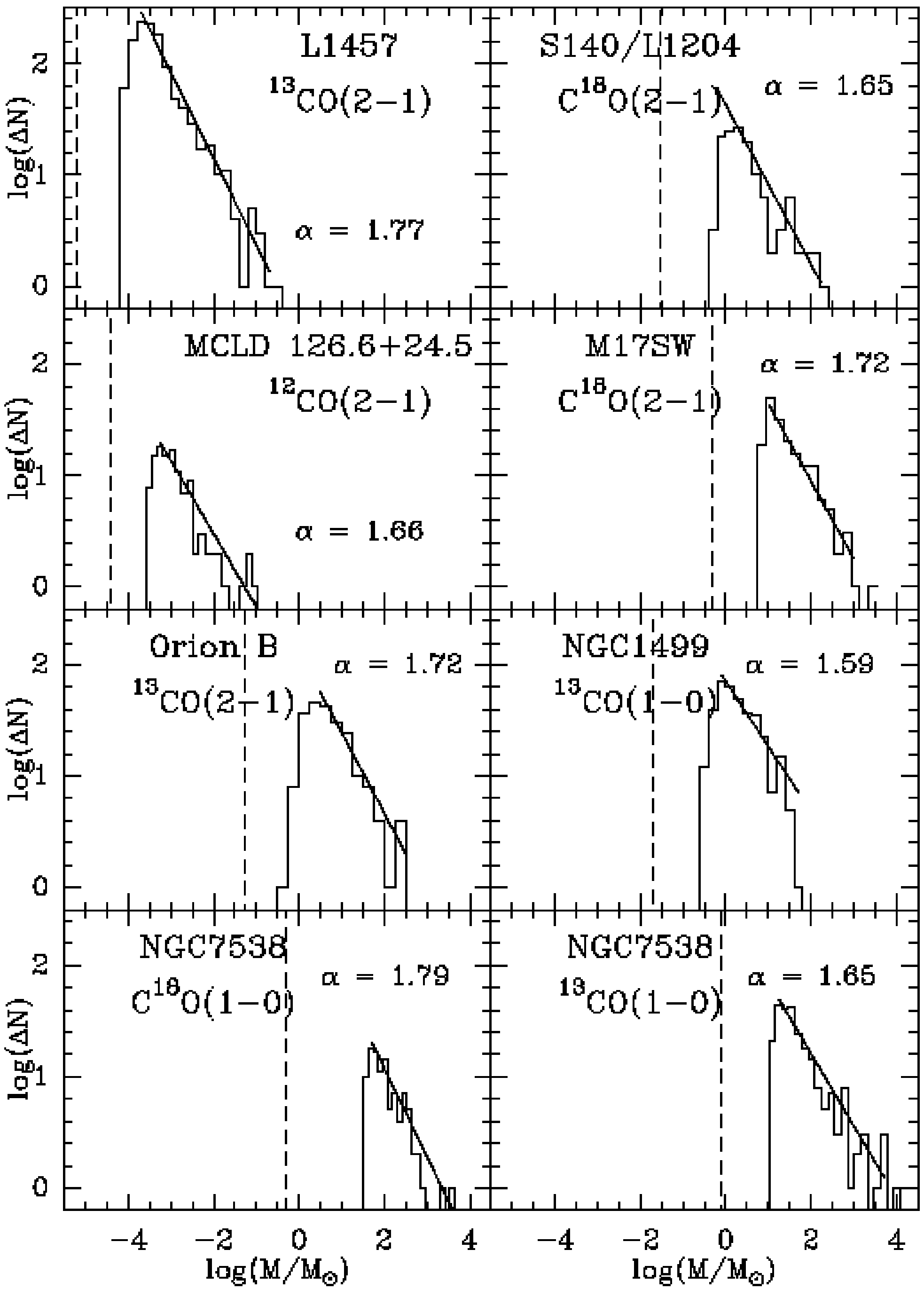
Similar power law fits have been found in a variety of studies and this relation seems to be robust.



Rosette Molecular Cloud (Schneider et al. 1998), KOSMA data



Schneider et al. (1998), KOSMA 3-m and IRAM 30-m

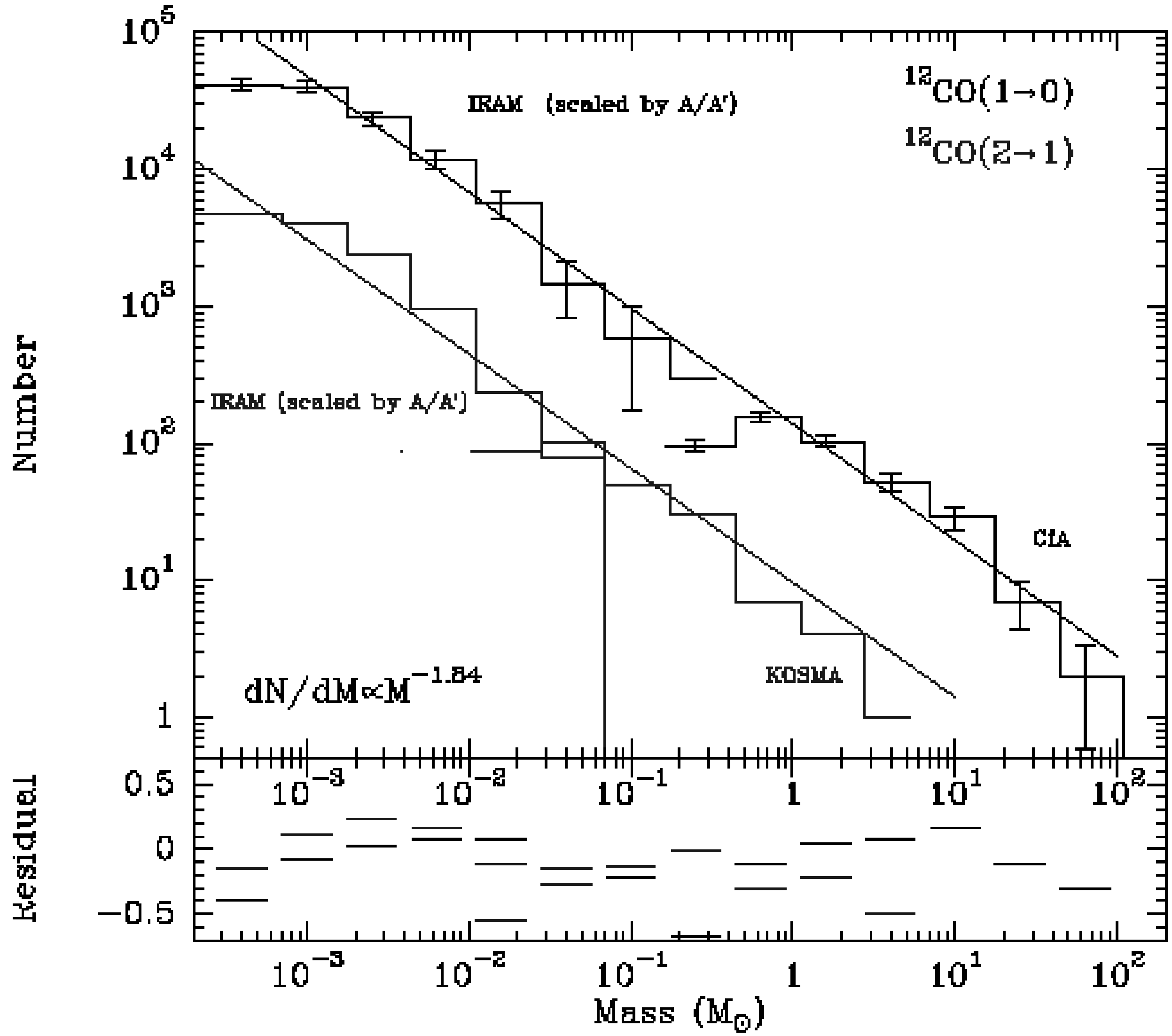


Kramer et al. (1998)

Several molecular clouds

KOSMA, NAGOYA, FCRAO, and IRAM radio telescopes.

Power law indices in the 1.6 to 1.8 range.



Note different transitions

Heithausen et al. (1998), IRAM 30-m, KOSMA 3-m and CfA 1.2-m radio telescopes, CO observations of Polaris flare.

Why is CO such a good tracer of low density structures?

- Abundance is a factor, but in reality it traces gas at modest densities (molecular hydrogen densities of 100 cm^{-3} and higher) because it “thermalizes” at these low densities.
- Other molecules like NH_3, CS, HCN, etc., need much higher densities to thermalize and become detectable.
- Let´s try to explain this...

Radiation Transfer

$$I_\nu = Specific\ Intensity$$

$$\frac{dI_\nu}{dl} = -\kappa_\nu I_\nu + j_\nu$$

$dl = differential\ of\ path$

$\kappa_\nu = absorption\ coefficient$

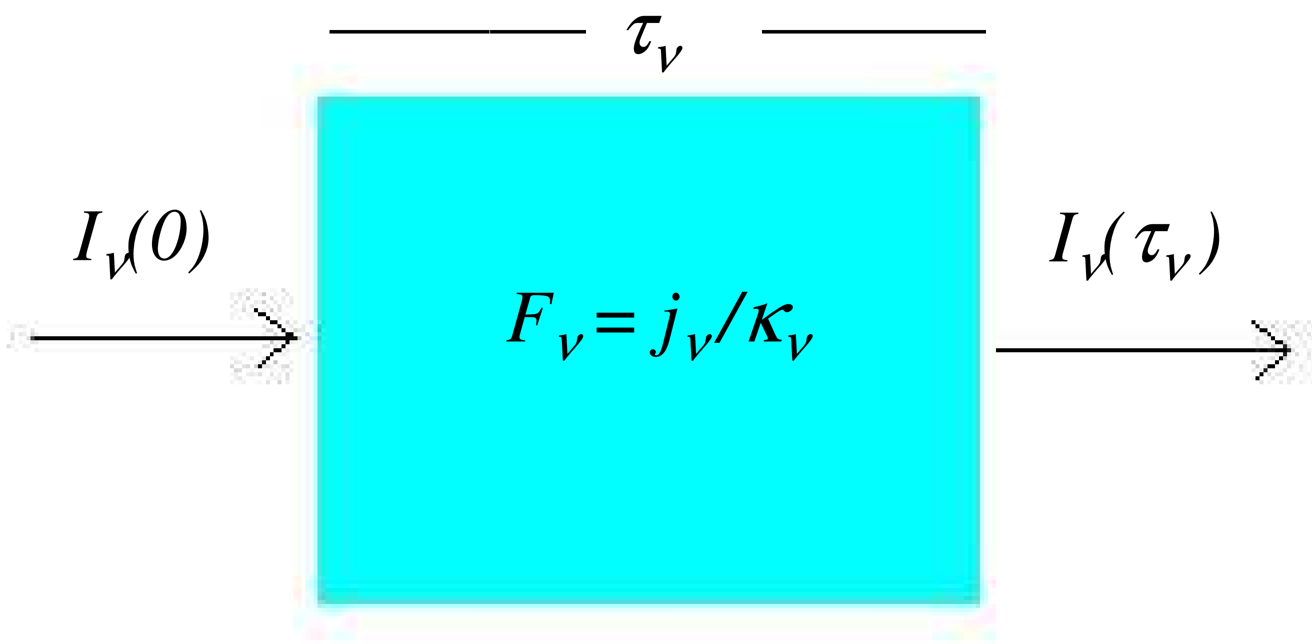
$j_\nu = emissivity$

$d\tau_\nu = \kappa_\nu dl = differential\ of\ optical\ depth$

$F_\nu = j_\nu / \kappa_\nu = source\ function$

$$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + F_\nu$$

(Neglects scattering)


τ_ν
$I_\nu(0)$
$F_\nu = j_\nu/\kappa_\nu$
$I_\nu(\tau_\nu)$

Radiation Transfer

For a homogeneous medium:

$$I_\nu(\tau_\nu) = I_\nu(0)\,e^{-\tau_\nu} + F_\nu\,(1 - e^{-\tau_\nu})$$

$I_\nu(0)$ = Background intensity

In radio astronomy one measures the signal on-source minus an off-source signal, namely:

$$\Delta I_\nu = I_\nu(\tau_\nu) - I_\nu(0) = (F_\nu - I_\nu(0))(1 - e^{-\tau_\nu})$$

In the case of molecular lines from clouds:

F_ν is a blackbody function at T_{ex} , the excitation "temperature" of the line, given by $n_u/n_l = \exp(-h\nu/kT_{ex})$.

Radiation Transfer

$$\Delta I_\nu = I_\nu(\tau_\nu) - I_\nu(0) = (F_\nu - I_\nu(0))(1 - e^{-\tau_\nu})$$

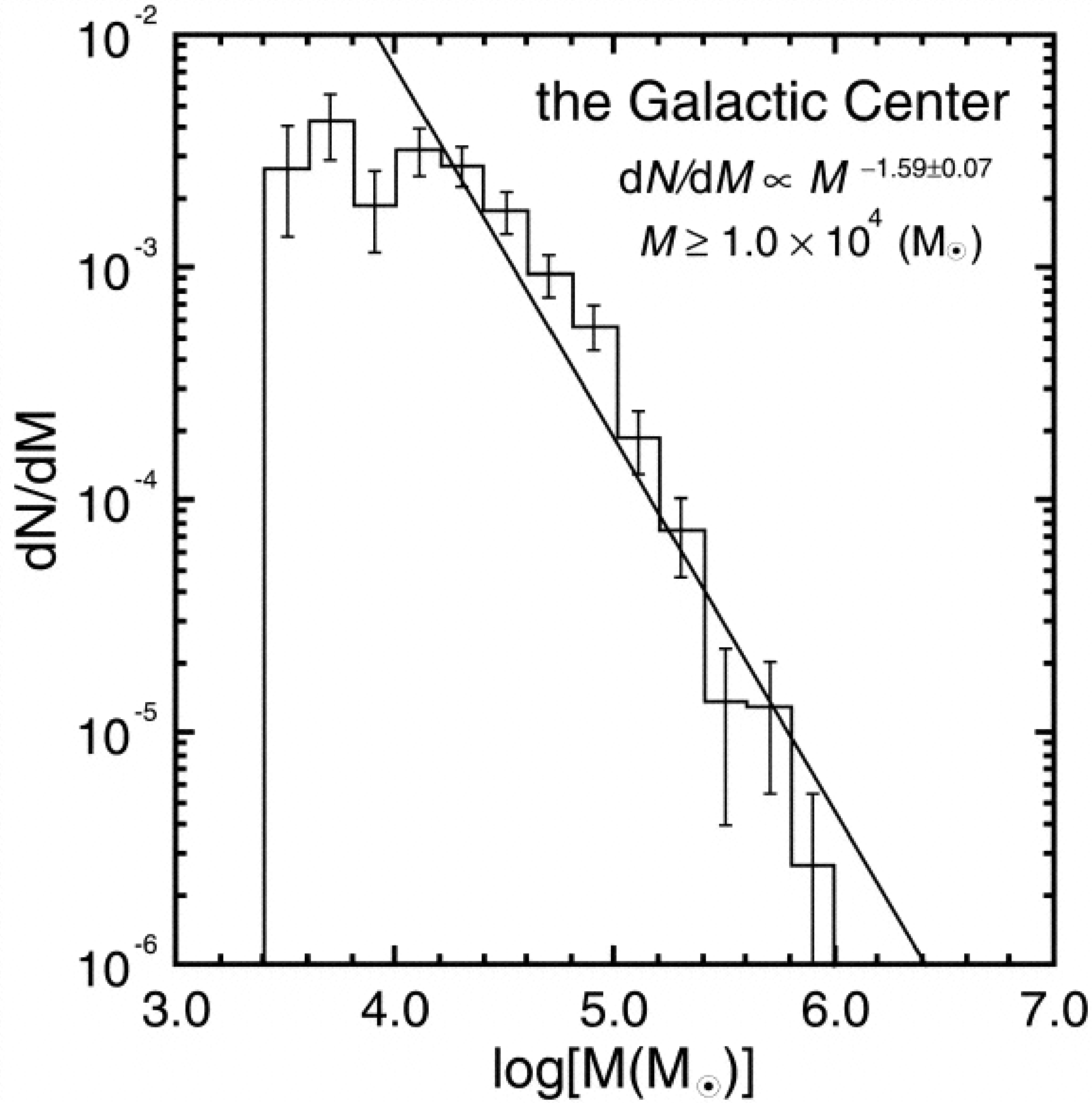
$I_\nu(0)$ is also a blackbody function at T_{bg} = 2.7 K (the cosmic microwave background).

The T_{ex} that goes into F_ν is determined by the relative importance of collisions with respect to radiative processes.

If collisions dominate $T_{ex} \rightarrow T_{coll} \approx$ 10-100 K, $F_\nu > I_\nu(0)$, and line is seen in emission.

However, if radiative processes dominate $T_{ex} \rightarrow T_{bg}$ = 2.7 K and $F_\nu = I_\nu(0)$: we cannot see the line!

=> Lines with large A_{ul} (Einstein´s coefficient of spontaneous emission) need high densities (for collisional processes to dominate) in order to become detectable.



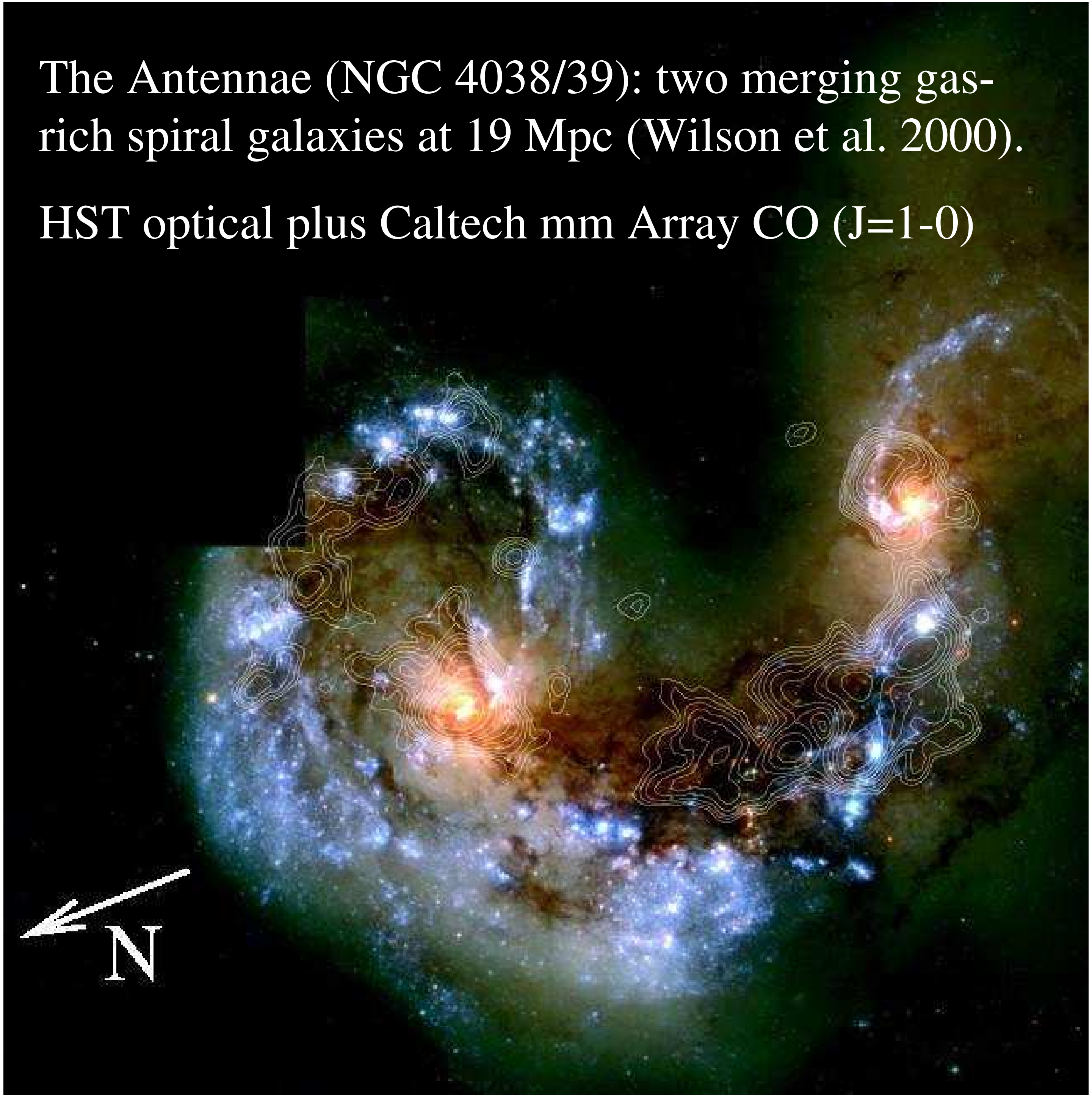
Miyazaki and Tsuboi (2000)

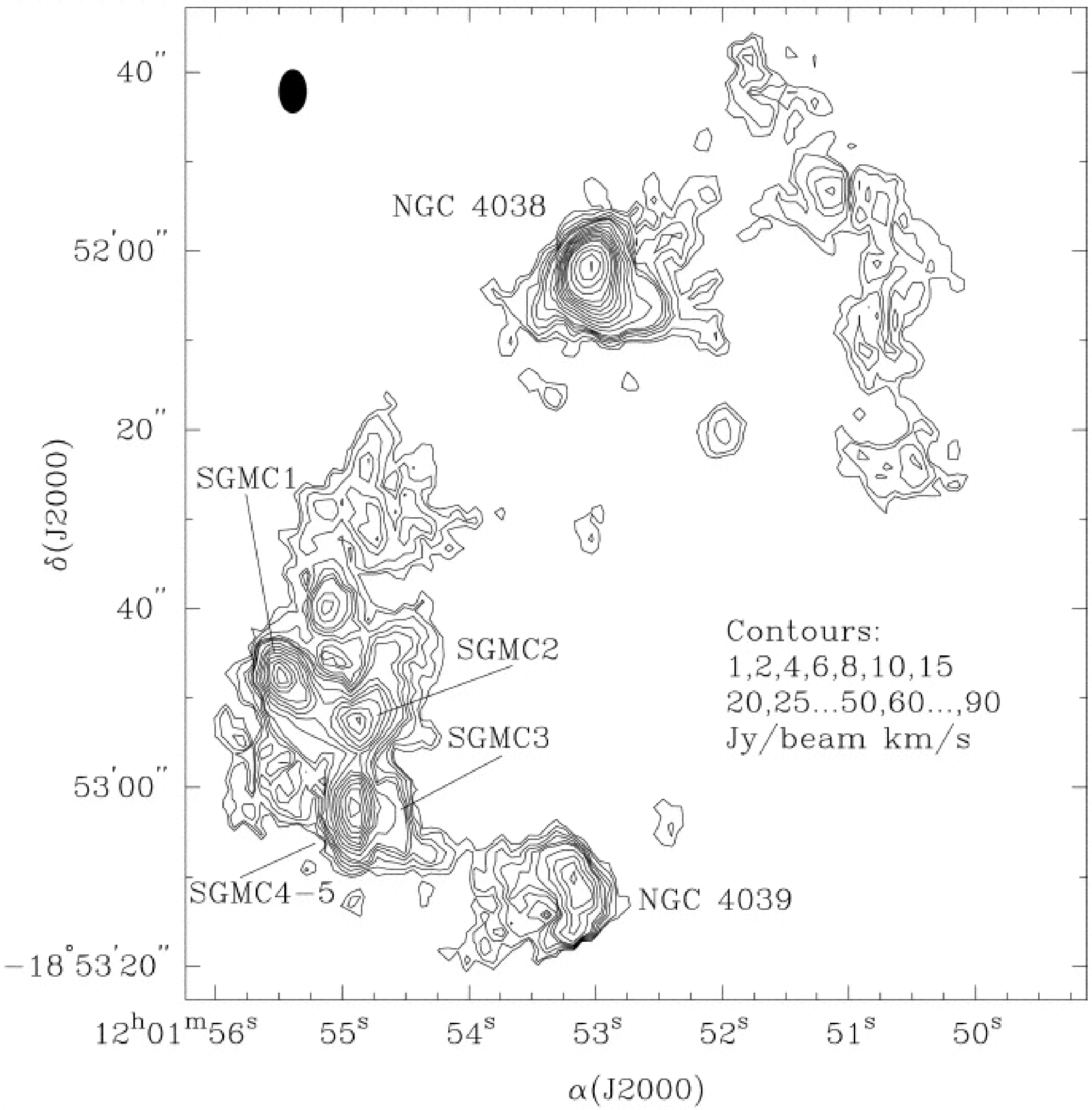
To avoid confusion from many clouds there used CS (J=1-0)

Nobeyama 45-m

159 molecular clouds

Relation valid even in “special” regions such as our galactic center. What about in other galaxies?


The Antennae (NGC 4038/39): two merging gas-rich spiral galaxies at 19 Mpc (Wilson et al. 2000).
HST optical plus Caltech mm Array CO (J=1-0)
N



Wilson et al. (2000)

Detect CO in both galactic nuclei and in SuperGiant Molecular Complexes (SGMCs), with masses of up to 3-6 $\times 10^8 M_{sun}$

Data consistent with $dN/dM \propto M^{-1.4}$

Observational Prospects

- The study of mass spectra of molecular clouds in external galaxies (angular scales 0.1-10 arcsec) will be a major research target of ALMA.
- Not only mass spectrum but kinematics, relation to star formation, chemistry, etc.

Observational Prospects

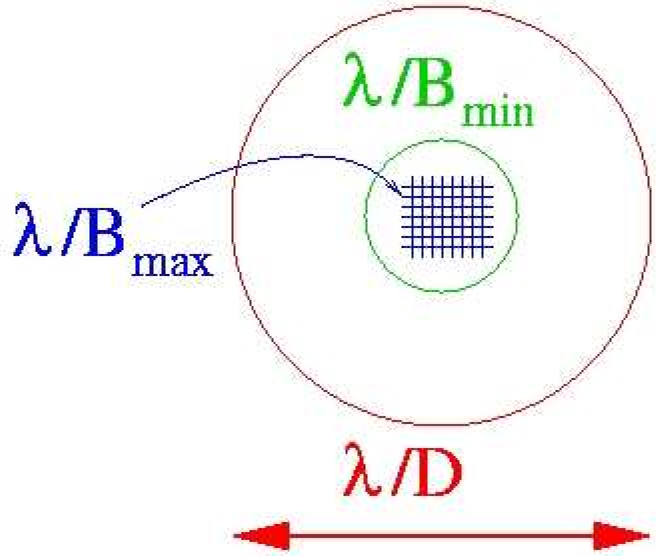
- Similar studies in our own galaxy will require not only interferometers, but single-dish observations (KOSMA, IRAM, LMT, GBT, etc.) as well.
- This is so because large scales are expected (arcmin to degrees) and interferometers are essentially "blind" to structures larger than a given angular size.

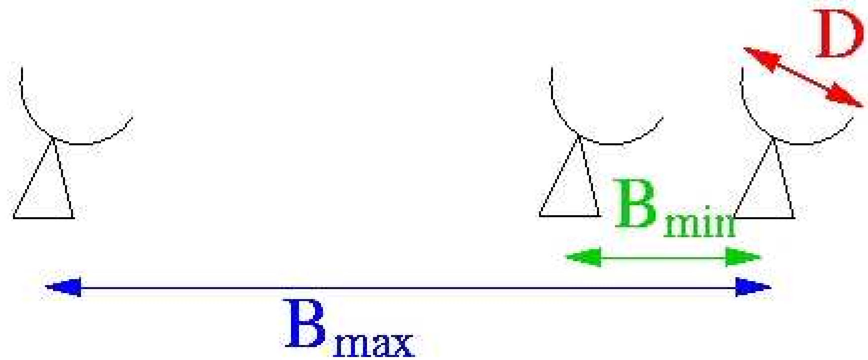
D = Diameter of Antenna

B_{min} = Minimum Separation

B_{max} = Maximum Separation

λ = Wavelength





Mass spectrum from molecular observations: $dN/dM \propto M^{-1.6\pm0.2}$

- $\int_{M}^{10M} M\, dN \propto M^{0.4}$
- That is, there is 2.5 times more mass in 10 M to 100 M range that in 1 M to 10 M range: most mass in large, massive structures of low density.
- Two important consequences of this simple conclusion (Pudritz 2002).

Mass spectrum from molecular observations: $dN/dM \propto M^{-1.6\pm0.2}$

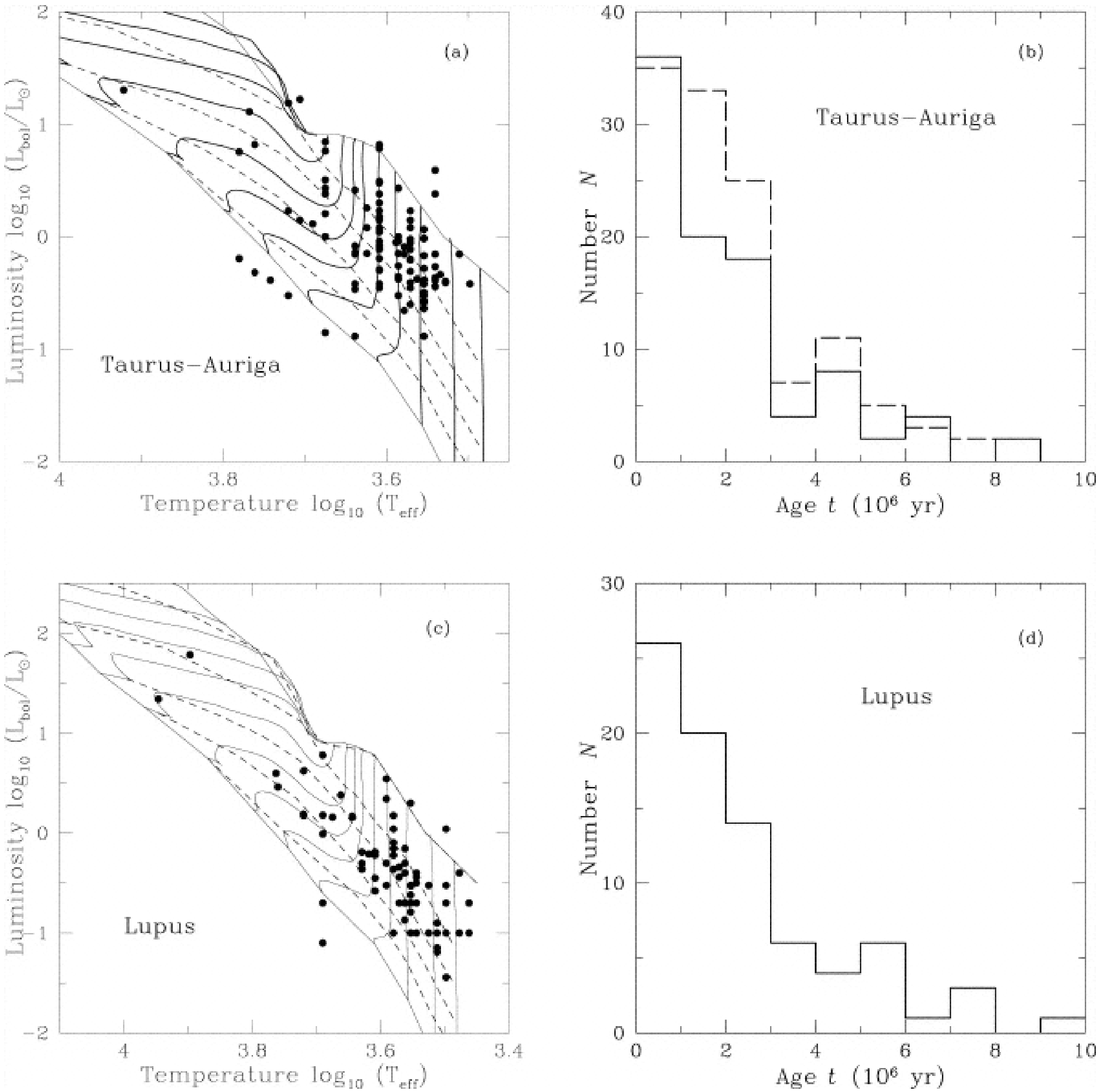
- 1. Star formation efficiency is low because most molecular mass is in large, low-density, "inactive" structures.
- 2. On the other hand, this assures existence of relatively massive clumps where massive stars and clusters can form (if mass spectrum were steeper we would have mostly low mass stars).

What is the explanation of mass spectrum?

- Both gravitational fragmentation (Fiege & Pudritz 2000) and turbulent compression and fragmentation (Vazquez-Semadeni et al. 1997) models can produce mass spectra similar to that observed.
- This takes us to the ongoing debate about the origin and lifetime of molecular clouds.

Two points of view

- Quasistatic star formation: Interplay between gravity and magnetic support (modulated by ambipolar diffusion). Clouds should live for 10^7 years.
- “Turbulent” or “dynamic” star formation: Interplay between gravity and supersonic turbulent flows. Clouds should live for only a few times 10^6 years.



Palla & Stahler (2000)

Accelerating star formation over last 10^7 years

Table 1
Star forming regions

Region	$< t >$ (Myr)	Molecular gas?
Coalsack	–	yes
Cha III	?	yes
Orion Nebula	1	yes
Taurus	2	yes
Oph	1	yes
Cha I,II	2	yes
Lupus	2	yes
MBM 12A	2	yes
IC 348	1-3	yes
NGC 2264	3	yes
Upper Sco	2-5	no
Sco OB2	5-15	no
TWA	~ 10	no
η Cha	~ 10	no

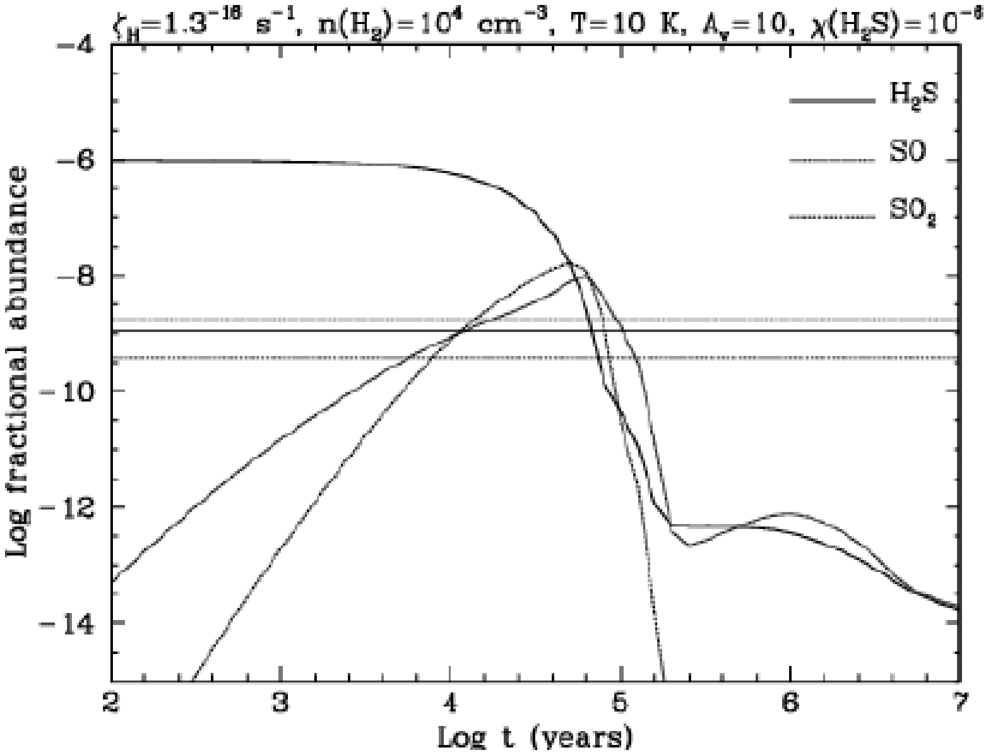
Hartmann (2003) favors shorter lifetime for clouds, of order 1-3 million years.

Questions Palla & Stahler results:

Last 1-3 million years unique

"Tail" of older stars is really the result of including older foreground stars, as well as problems with the isochrone calibration in the higher mass stars.

Chemical clocks?

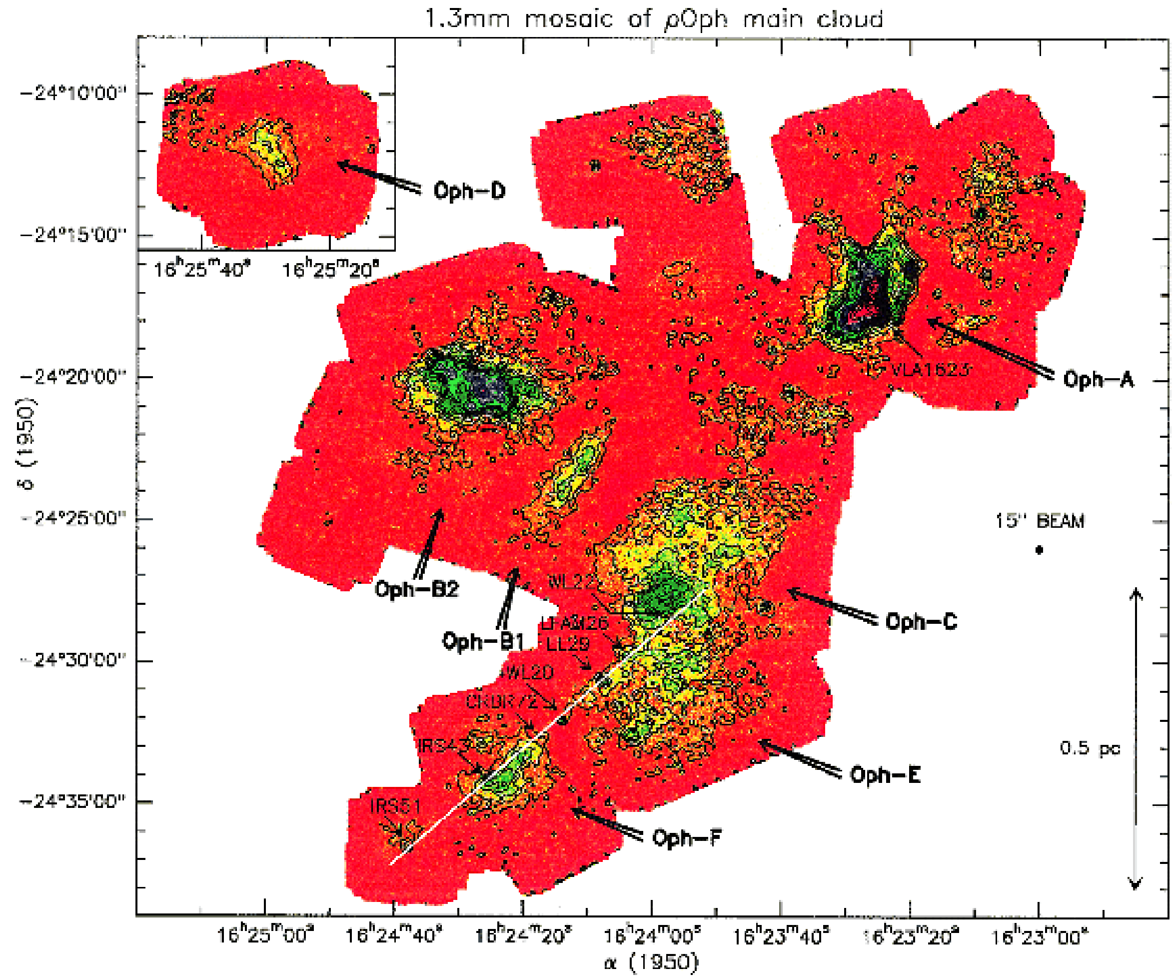


Buckle & Fuller (2003), see also van Dishoeck & Blake (1998, ARA&A, 36, 317).

Promising tool to study "age" of molecular clouds. Too many uncertainties in history of cloud (density, temperature, cosmic ray ionization, etc.).

What is the relation of the cloud mass spectrum with the IMF?

- Cloud spectrum from molecular observations gives $dN/dM \propto M^{-1.6}$
- IMF (stars) gives $dN/dM \propto M^{-2.5}$, much steeper
- Most molecular mass in massive clouds, however most stellar mass in low-mass stars
- Recently, observations of mm dust continuum emission suggest spectra for clouds with slope similar to that of the IMF

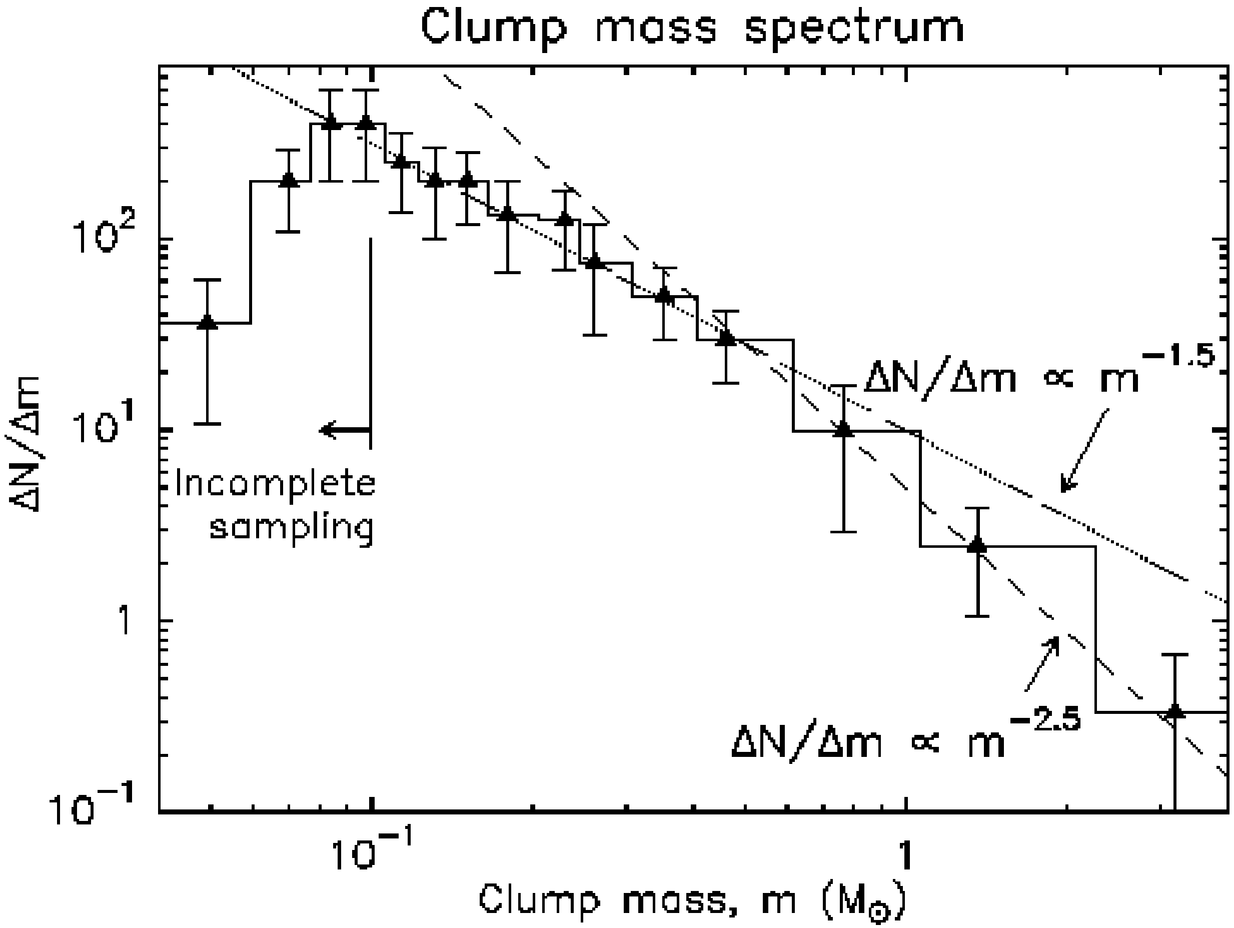


ρ Oph

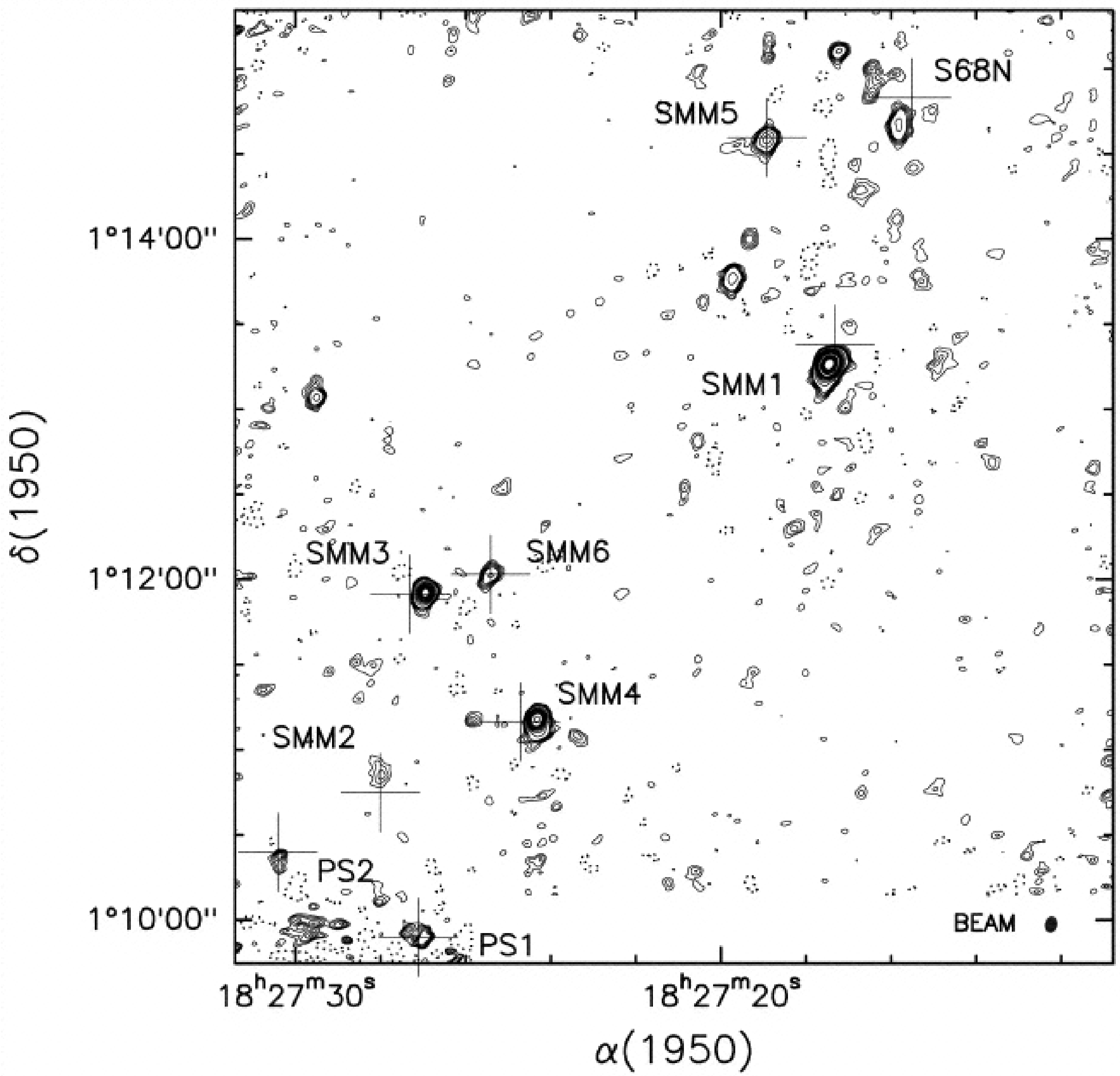
58 clumps

1.3 mm dust continuum observations of Motte et al. (1998)

IRAM 30-m radio telescope + MPIfR bolometer



Motte et al. (1998) present evidence for two power law indices, -1.5 below 0.5 M_{sun} and –2.5 above 0.5 M_{sun}



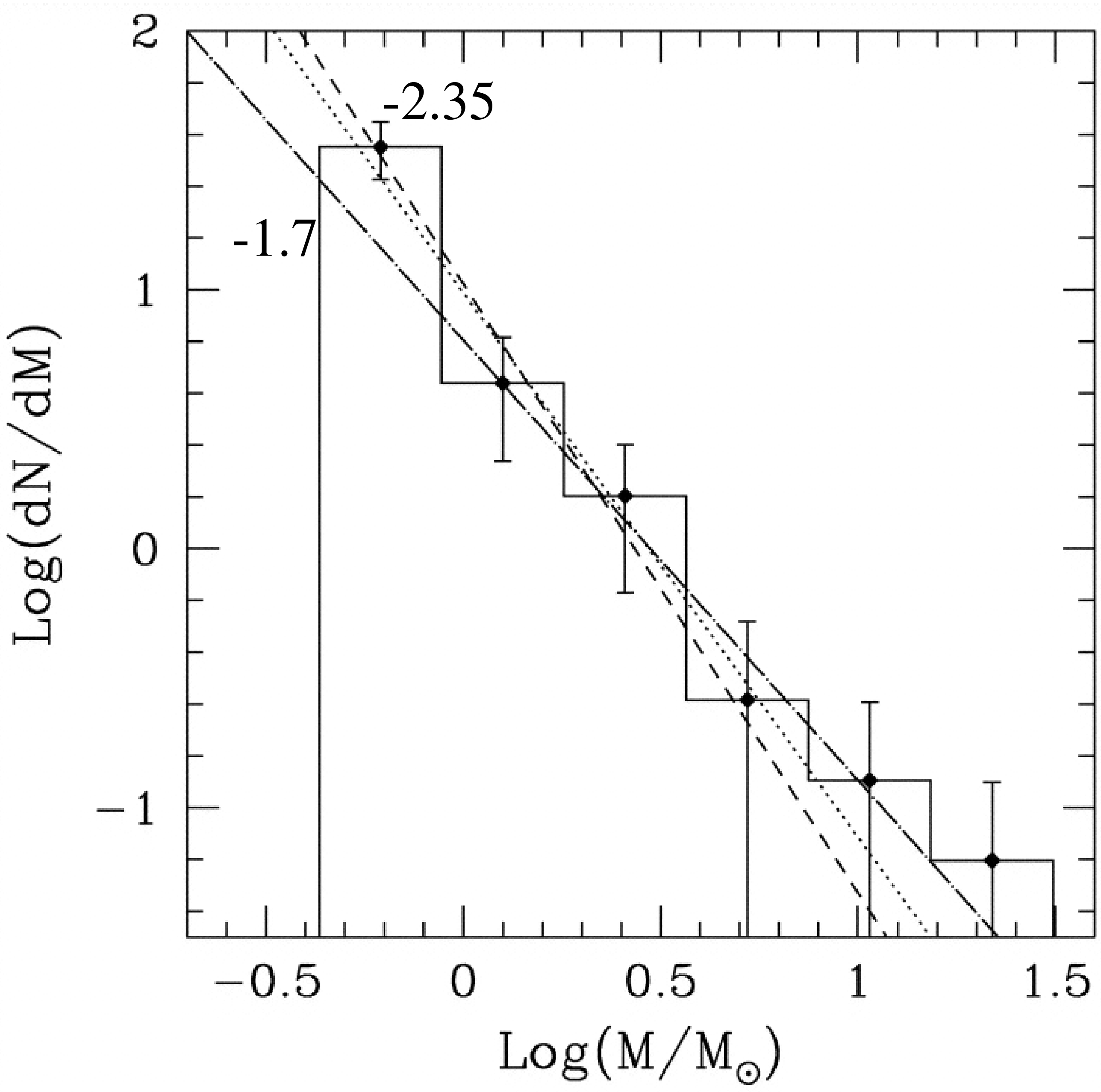
Testi & Sargent (1998)

Serpens Core

3 mm dust continuum

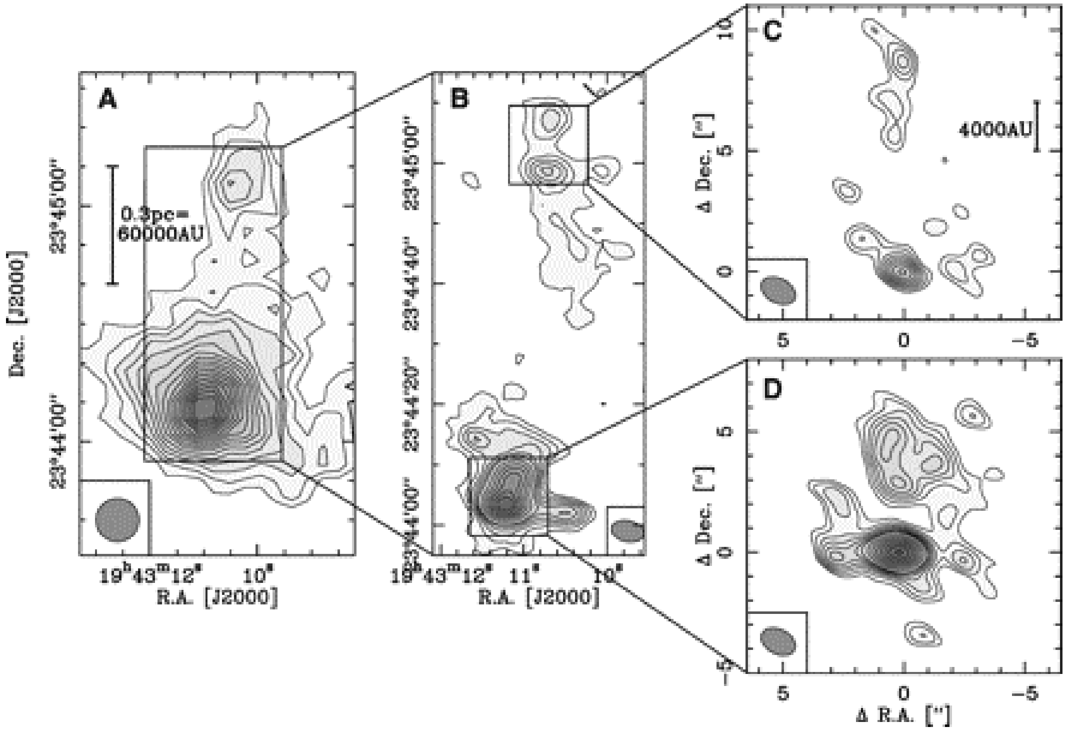
OVRO interferometer

32 discrete sources



Favor single power law with index of –2.1

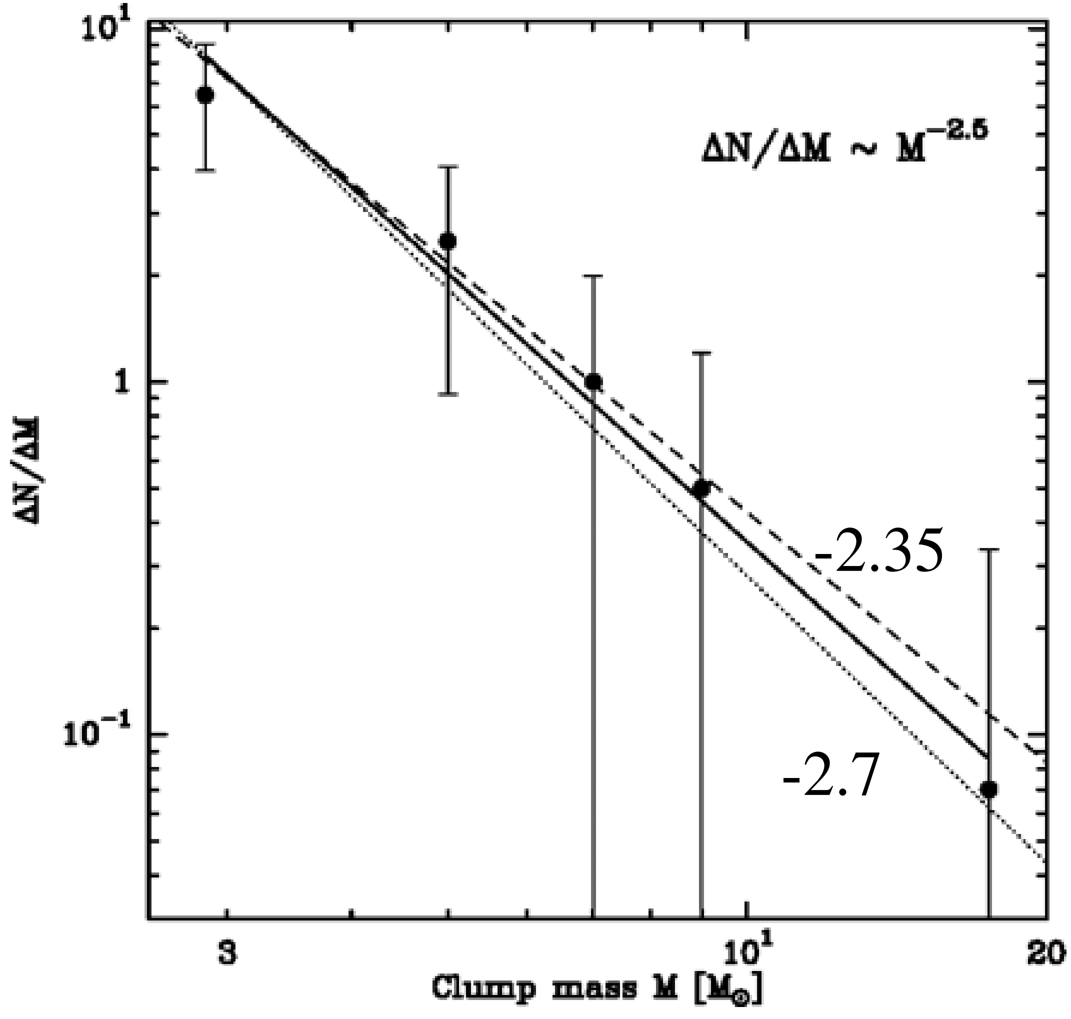
Few sources in sample, obviously type of work that will be done better with ALMA



Beuther & Schilke (2004), IRAS 19410+2336, region of massive star formation

1.3 and 3 mm dust continuum, IRAM 30-m and PdBI

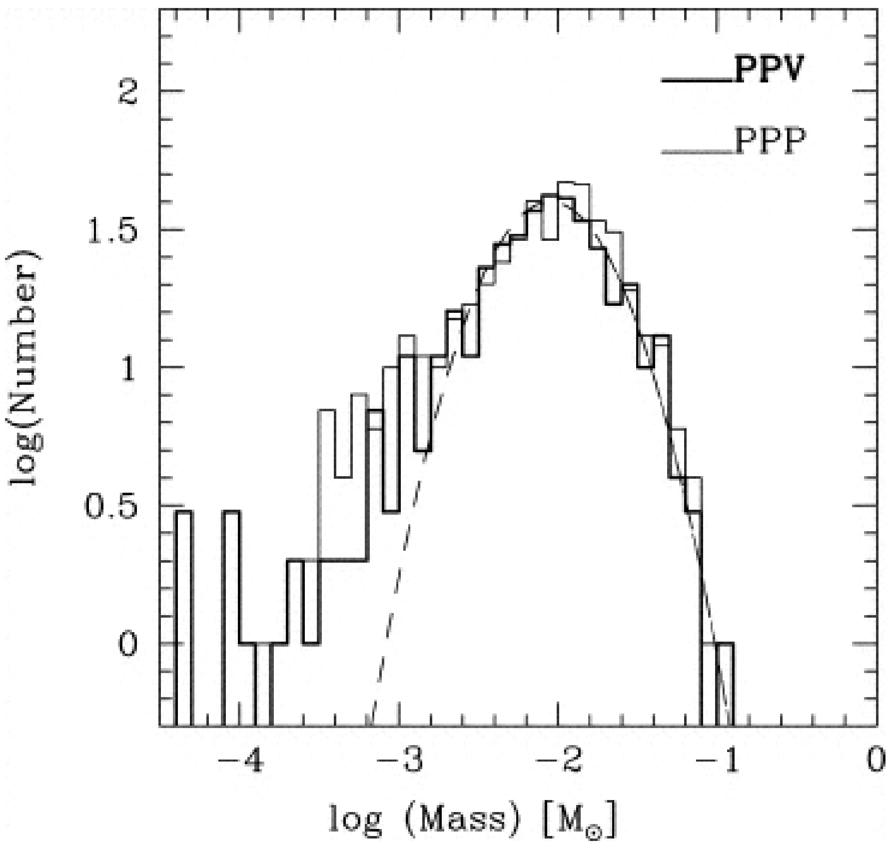
About a dozen components



Noisy spectrum, but consistent with IMF

Molecular versus Dust Mass Spectra

- Dust traces hotter component than molecular emission.
- Apparent discrepancy not yet understood
- Clearly, much better data, specially in dust emission will greatly help.



Ballesteros-Paredes (2001) suggest from numerical simulations of turbulent molecular clouds that mass spectrum can be lognormal and not power law: different power laws at different masses.

However, lognormal cannot explain single power laws seen over many decades of mass with molecular data.

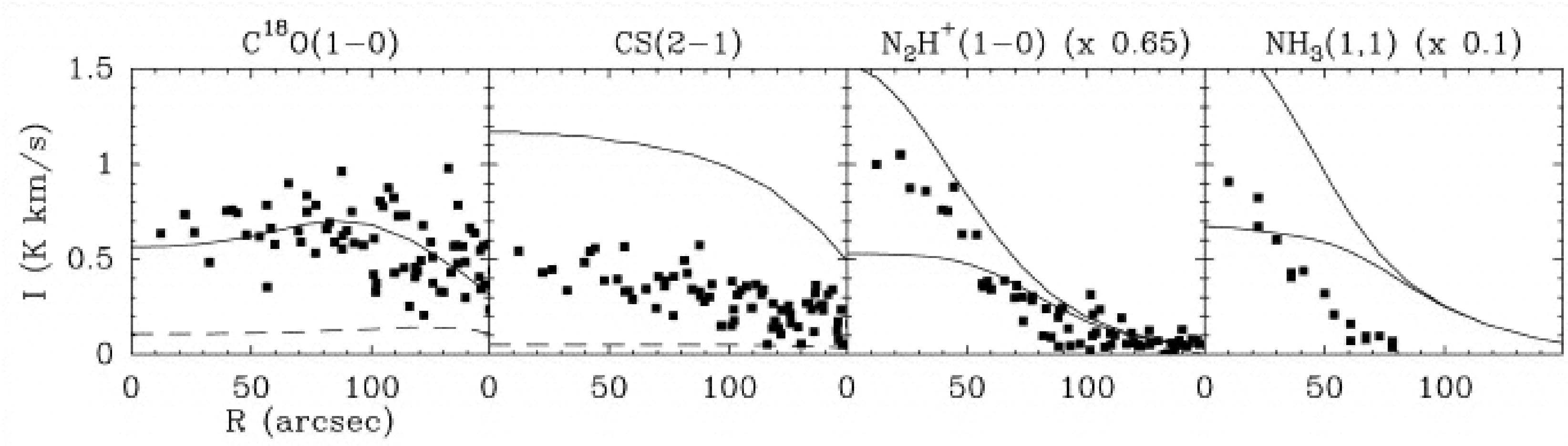
Gaussian: Results from random additive processes

Lognormal: Results from random multiplicative processes

Let´s look at the structure of individual cores

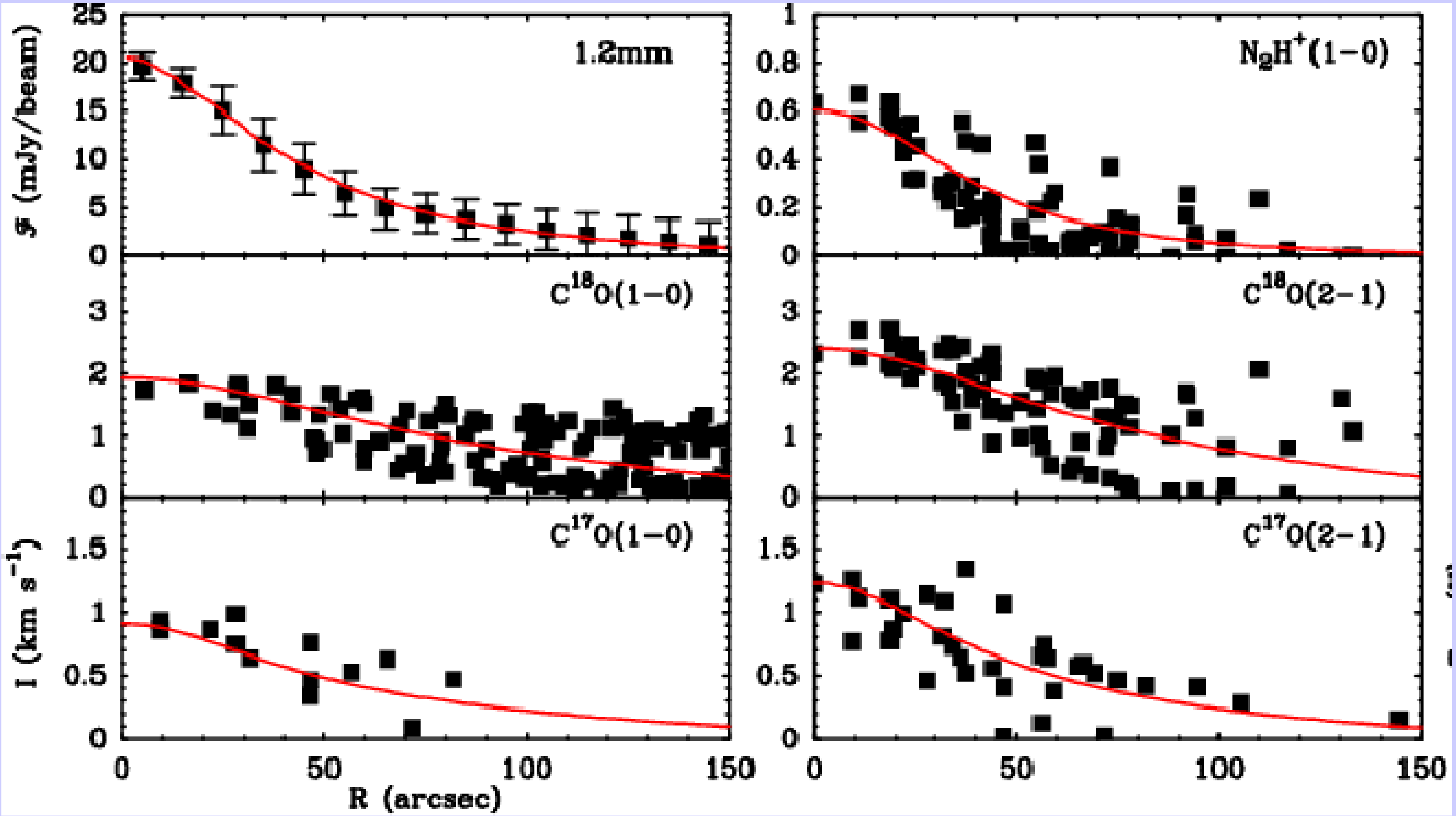
- Molecular observations
- Millimeter and sub-millimeter dust emission
- Extinction from near-IR observations
- However, reliable models will probably require all three kinds of data (Hatchell & van der Tak 2003)
- You observe (projected) column densities

L1517B Starless Core Tafalla et al. (2002)



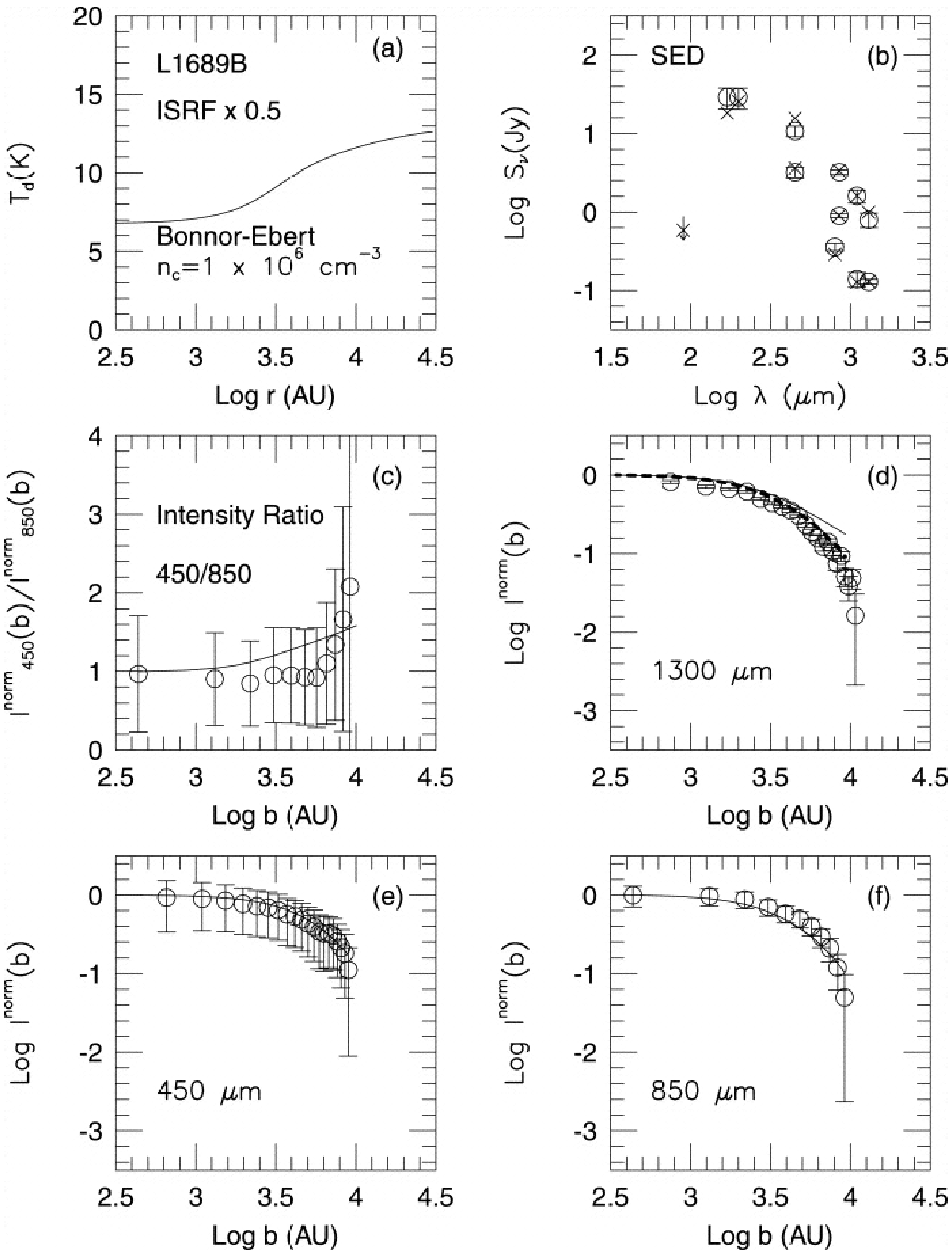
Molecules show "differentiation", that is, their abundance with respect to H_2 can vary along the cloud as a result of chemistry and depletion on dust grains.

There are, however, exceptions



L1521E Starless Core Tafalla & Santiago (2004)

Unaffected by differentiation → Extremely young core?



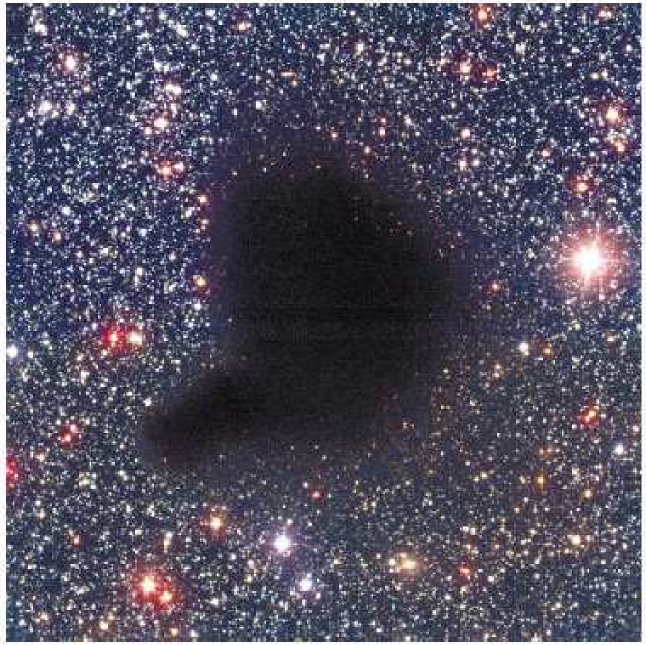
Evans et al. (2001)

mm and sub-mm SCUBA observations

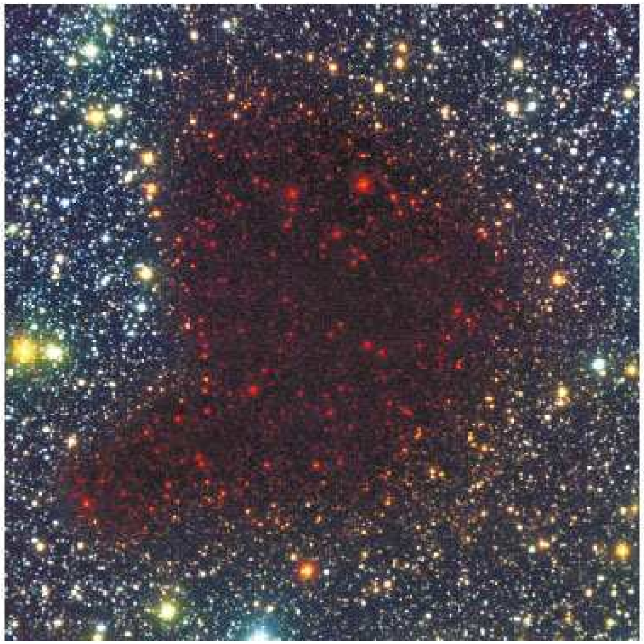
Favor modified (with gradient in temperature) Bonnor-Ebert spheres over power laws.

Classic Bonnor-Ebert spheres: marginally-stable, isothermal spheres that are in hydrostatic equilibrium and are truncated by external pressure.

VISIBLE



NEAR-IR



Alves et al. (2001)

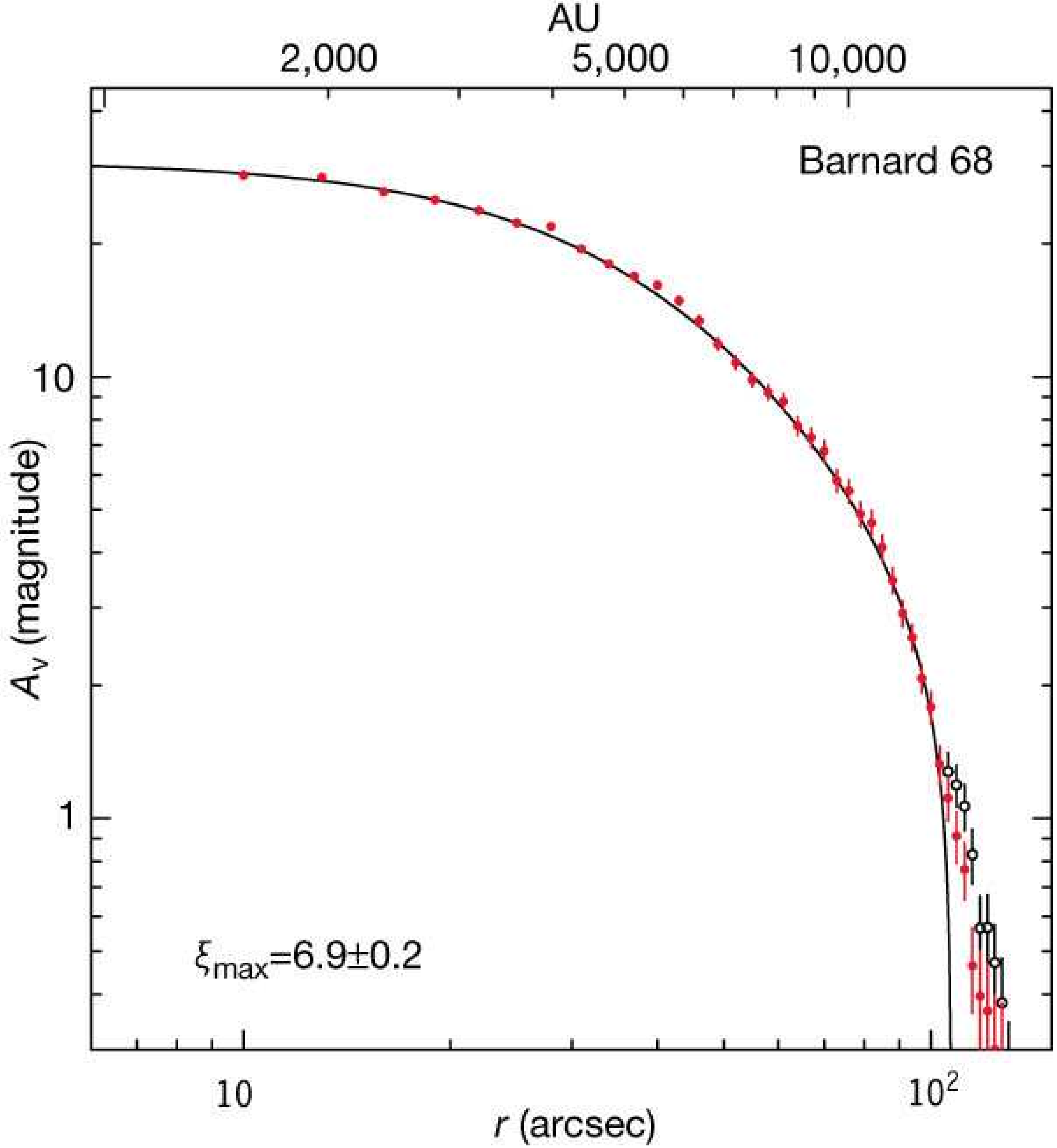
ESO´s VLT and ESO´s NTT

B68, a starless core

Find extinction toward 1000s of stars in image

In principle, technique is not greatly affected by differentiation, depletion, temperature gradients, etc. Only dust opacity counts

Average extinction values in "rings"

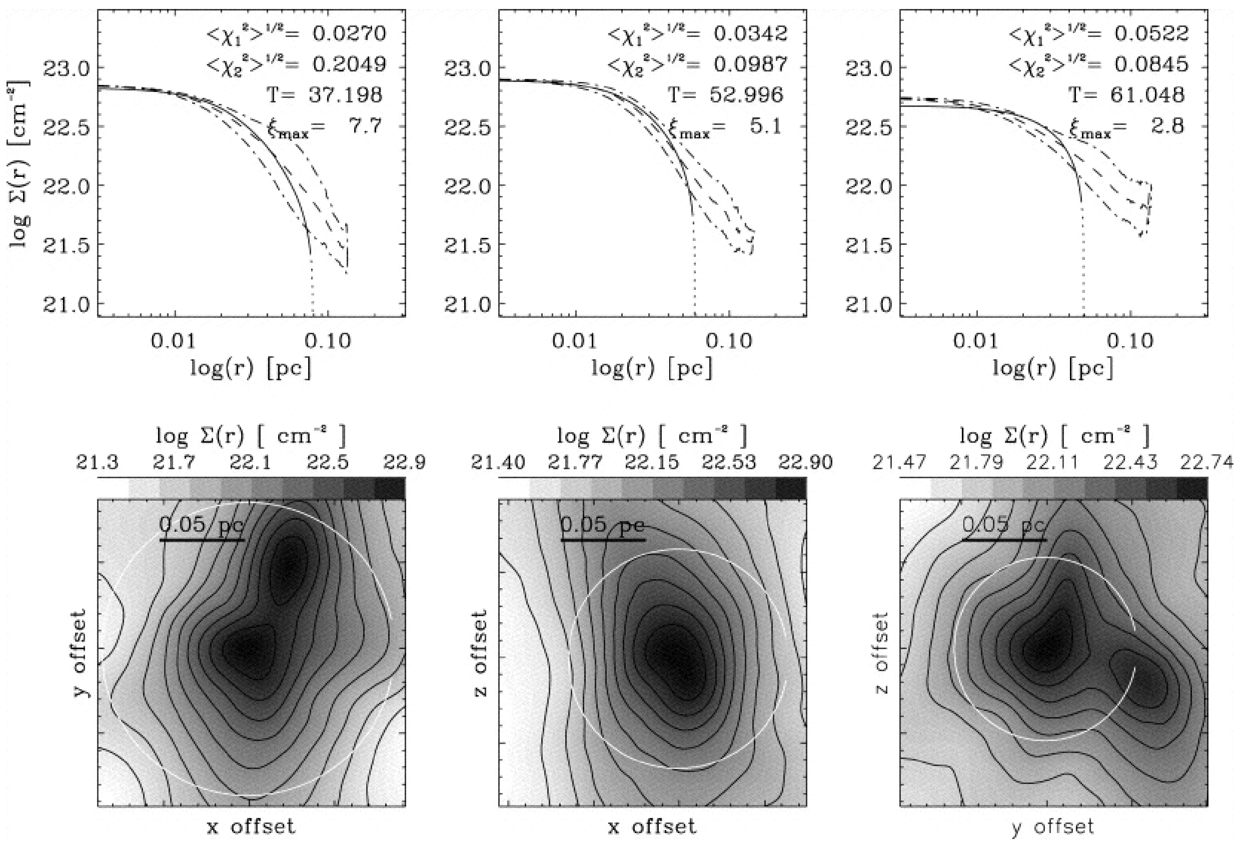


Good fit to Bonnor-Ebert sphere

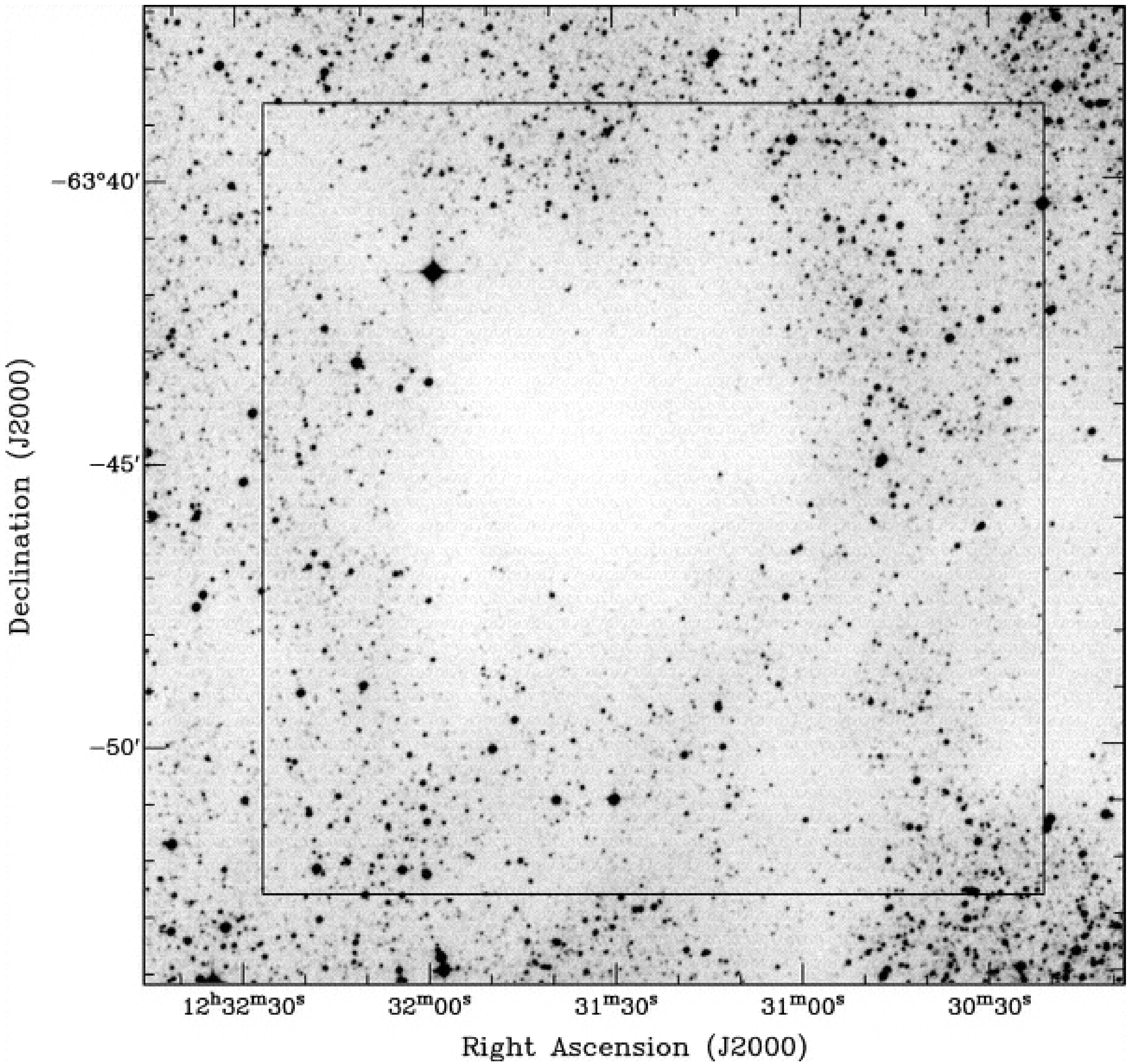
$\xi_{max} = (R/a)(4\pi\ G\ \rho_c)^{1/2}$

Core on the verge of collapse ($\xi_{max} > 6.5$)

Hydrostatic equilibrium favors slow mode of star formation

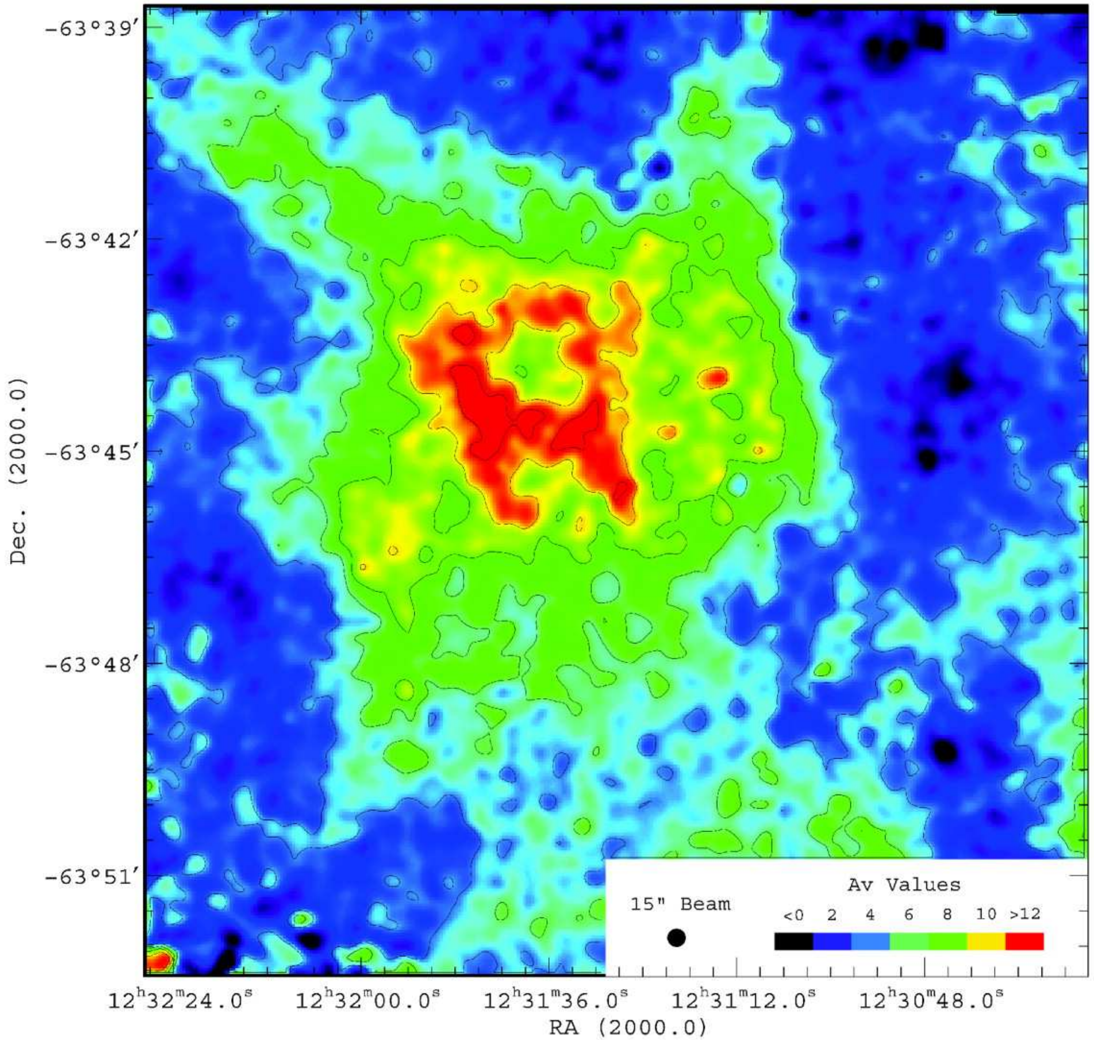


However, Ballesteros-Paredes et al. (2003) argue that also turbulent molecular clouds (from numerical simulations) can match Bonnor-Ebert spheres. Some even appear to be configurations in stable equilibrium ($\xi_{max} < 6.5$).



DSS image of G2 in the Coalsack

Using same technique, Lada et al. (2004) have studied structure of G2, the most opaque molecular cloud in the Coalsack complex.



Extinction image shows central ring

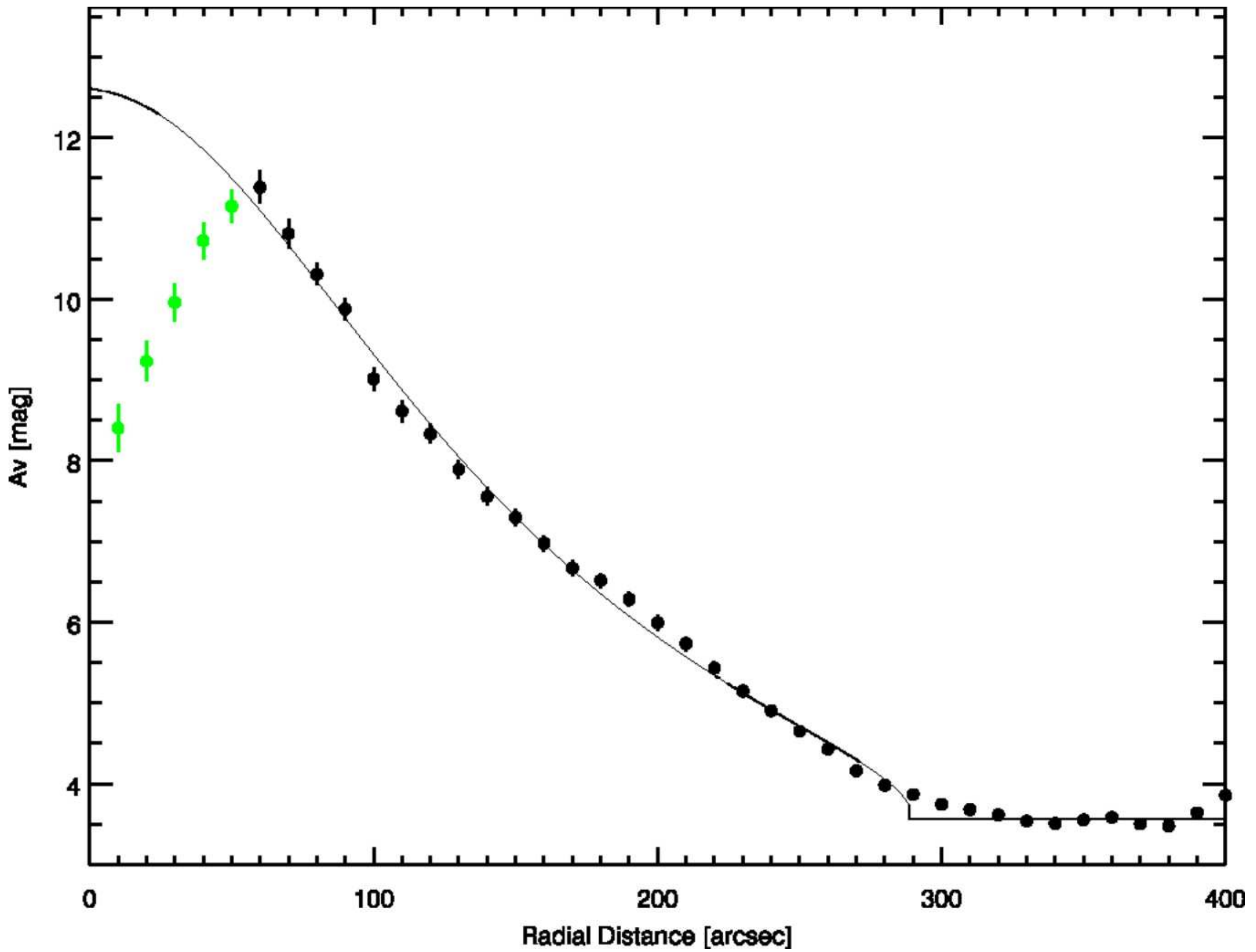
Ring cannot be in dynamical equilibrium

No known star at center

$\langle n \rangle = 3{,}000\ cm^{-3}$

$M = 10\ M_{sun}$

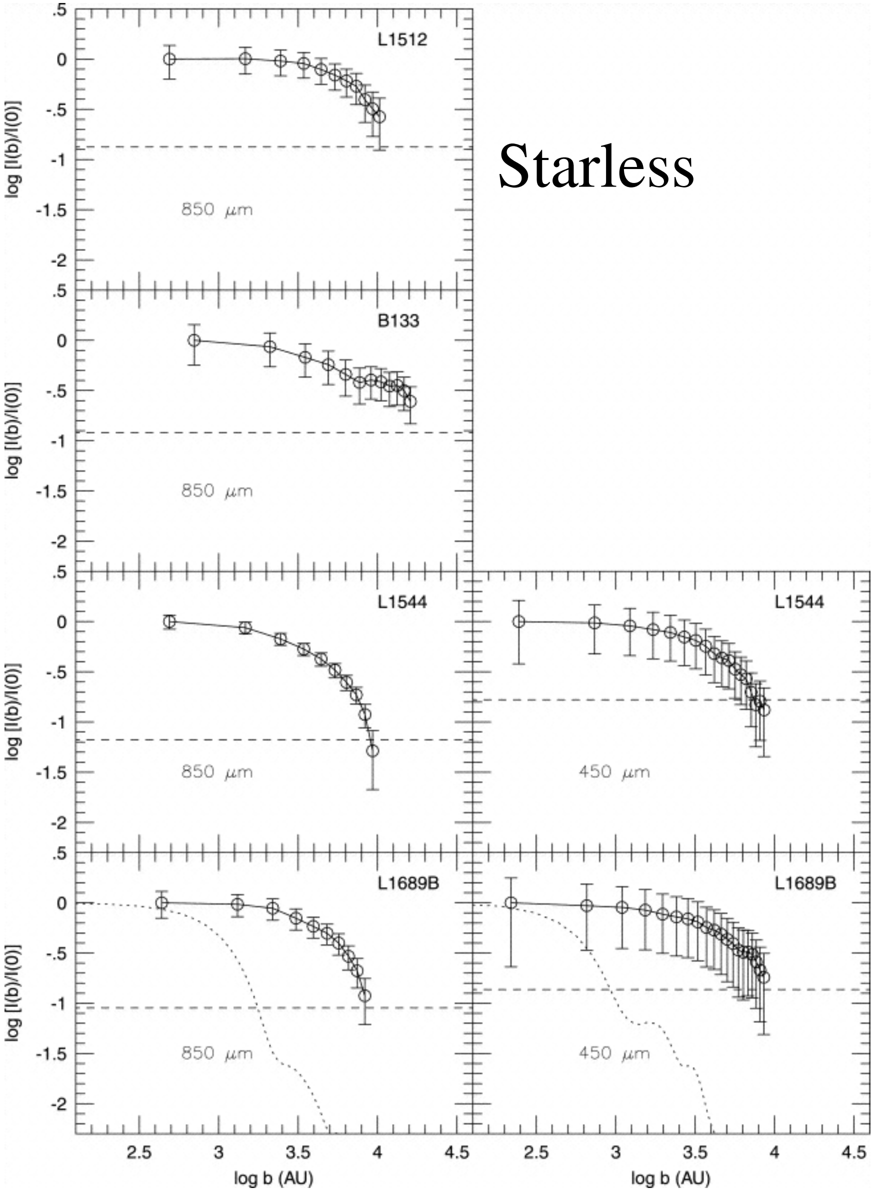
Favor ring as collapsing structure about to form dense core



Outer regions well fitted by Bonnor-Ebert sphere with $\xi_{max} = 5.8$

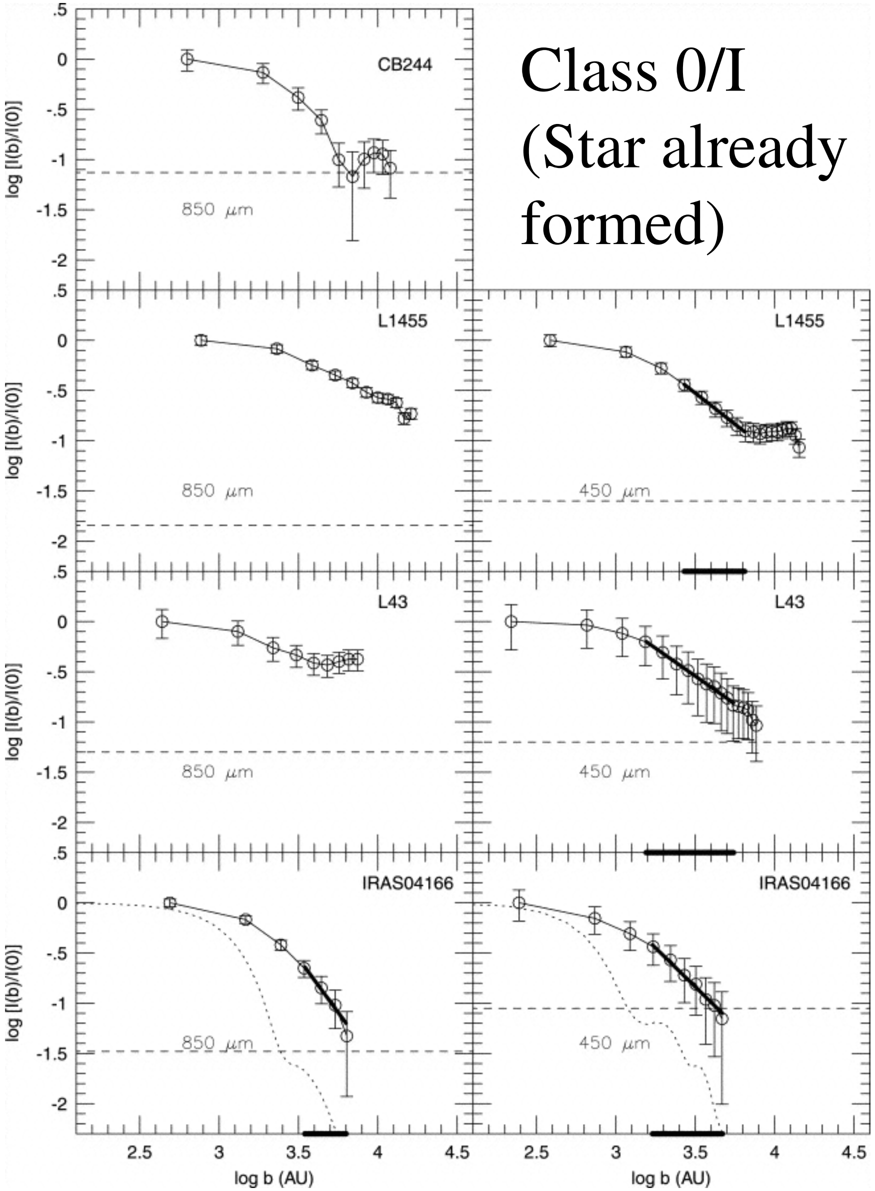
Does structure change with formation of star?

- Power laws seem to fit cores with star formation better than BE spheres.

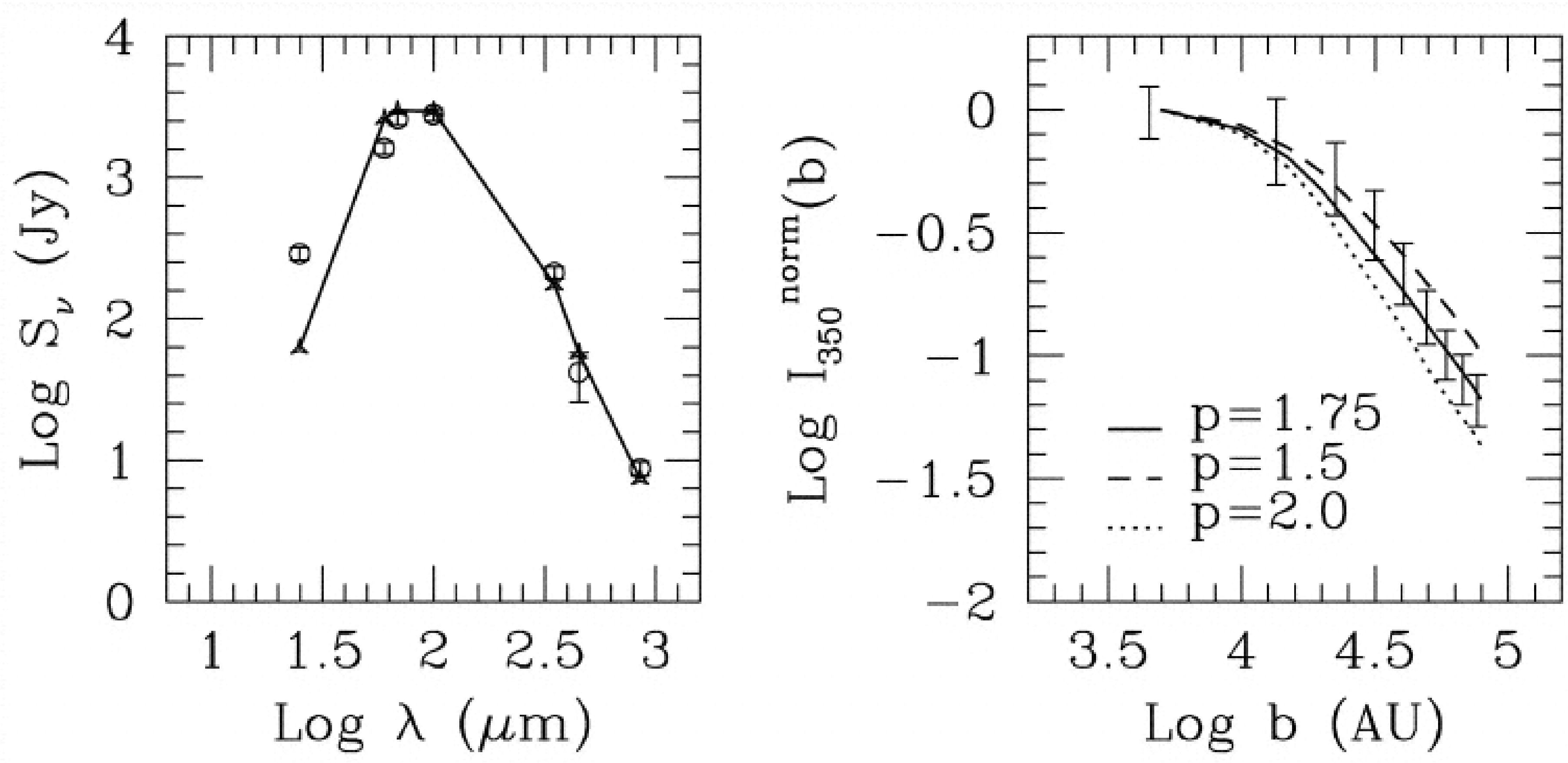


Starless

Class 0/I
(Star already formed)



Shirley et al. (2000): Cores around Class 0/I sources need power laws
Can you use molecular lines to distinguish hydrostatic vs. collapsing?

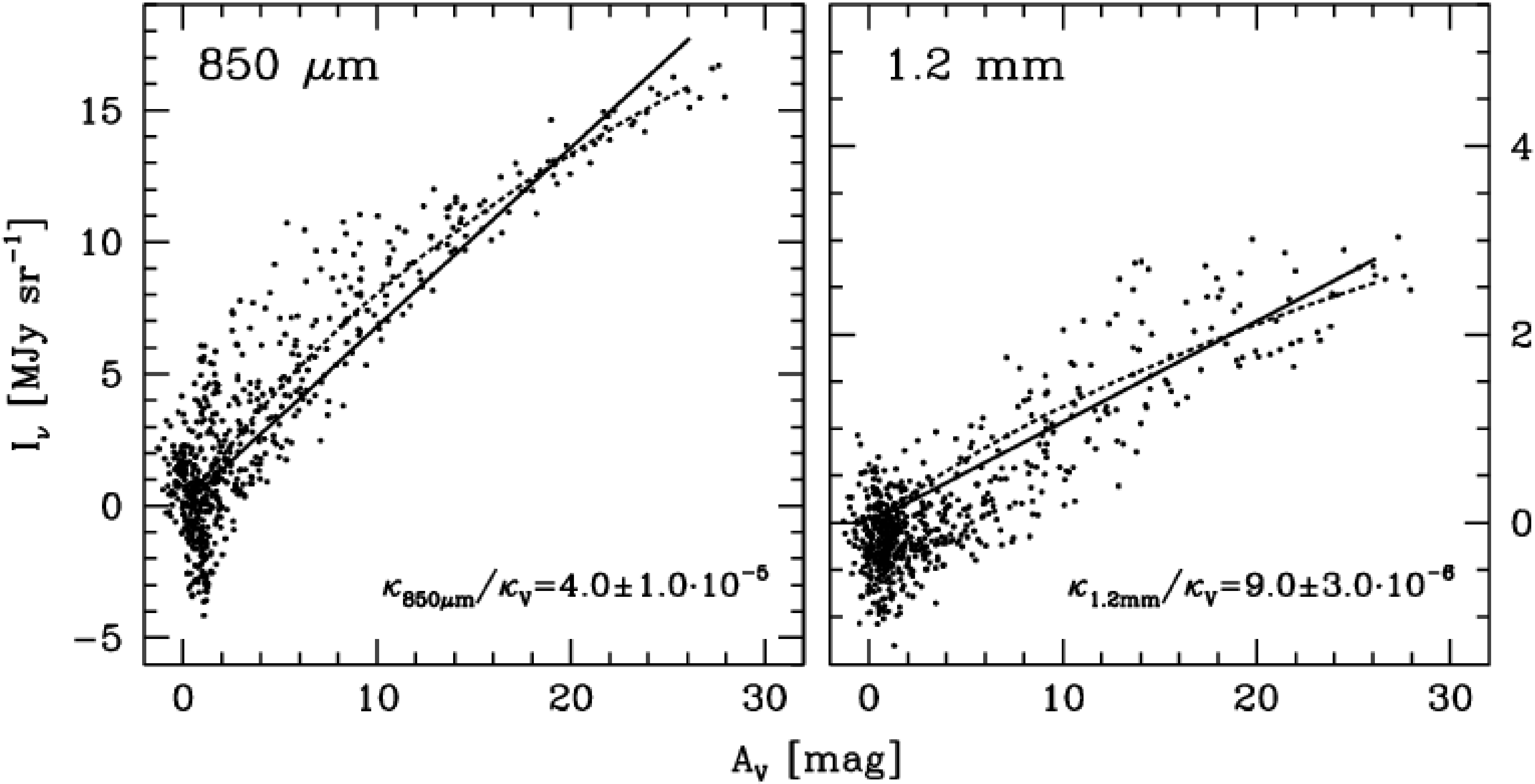


Mueller et al. (2002)   M8E: core with massive star formation

SHARC on 10.4-m Caltech Submillimeter Telescope

Power law fit consistent with value of 2 predicted by inside-out collapse model of Shu and collaborators

Do mm emission and extinction methods give consistent results?



Bianchi et al. (2003) compare dust emission with extinction in B68, finding reasonable correlation.

Conclusions

- Characteristics of molecular gas about to start forming stars still not well understood.
- Data of excellent quality, not yet available, seems required to discriminate among models.
- Fortunately, these instruments are being constructed or planned.