Cores, Stars, and Clusters

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Summary

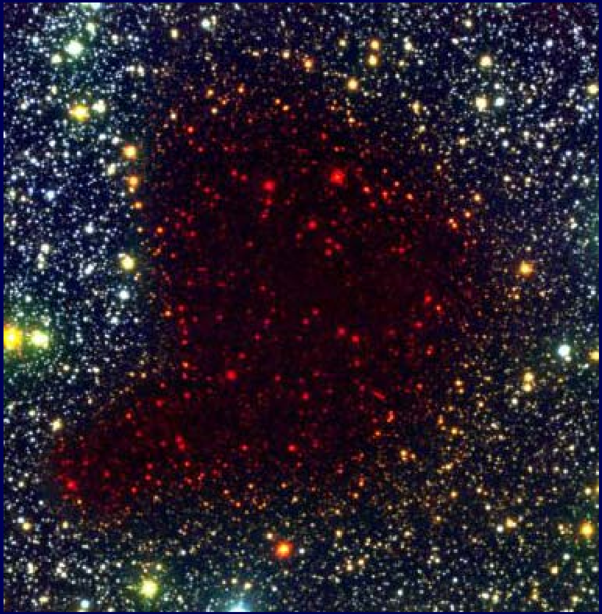
isolated cores... form 0-few low-mass stars

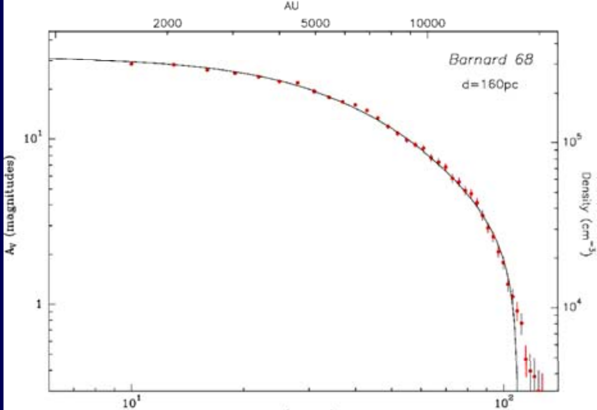
geometry	centrally condensed, aspherical, embedded in filaments
physics	sparse, cold, thermal > turbulent, contracting, ~ magnetic
chemistry	cold: freeze-out (CO), neutral (N_2H^+), enhanced (DX)
models	expanding, self-gravitating, condensing, collapsing
evolution	prestellar cores seem evolved, cores with VLM stars don’t

cluster-forming cores...form more stars, more massive stars

geometry	centrally condensed, aspherical, embedded in “blobs”
physics	numerous, hot, thermal > turbulent, contracting
chemistry	hot: diversity of species, liberation, shocks
models	collapse and accretion in a centrally condensed layer

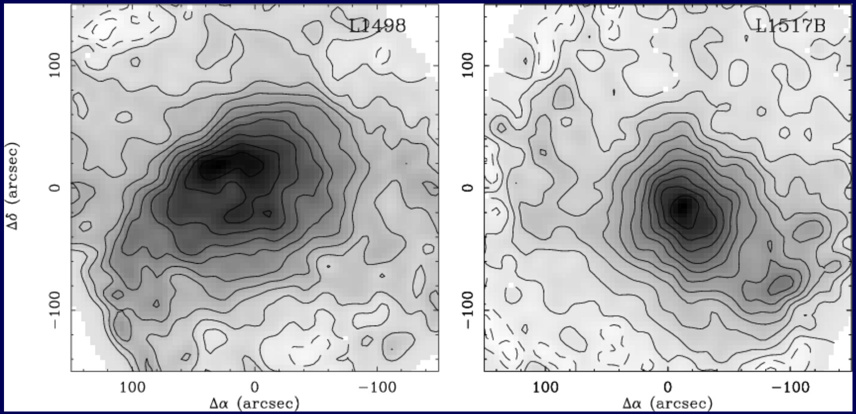
Cores are Centrally Condensed

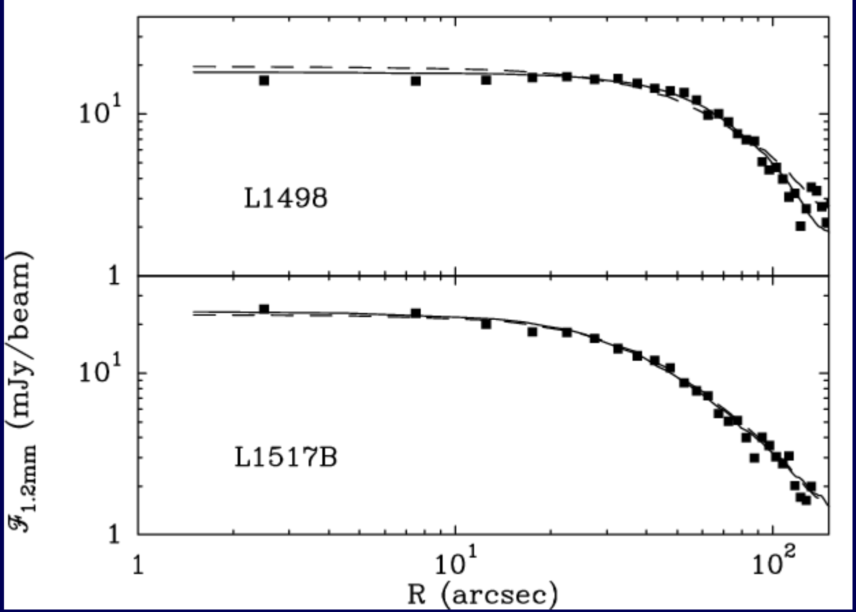




B68 optical, NIR absorption

Alves, Lada & Lada 01





L1498, L1517B millimeter emission

Tafalla et al 04

Many Models Fit Flat-Top Profile

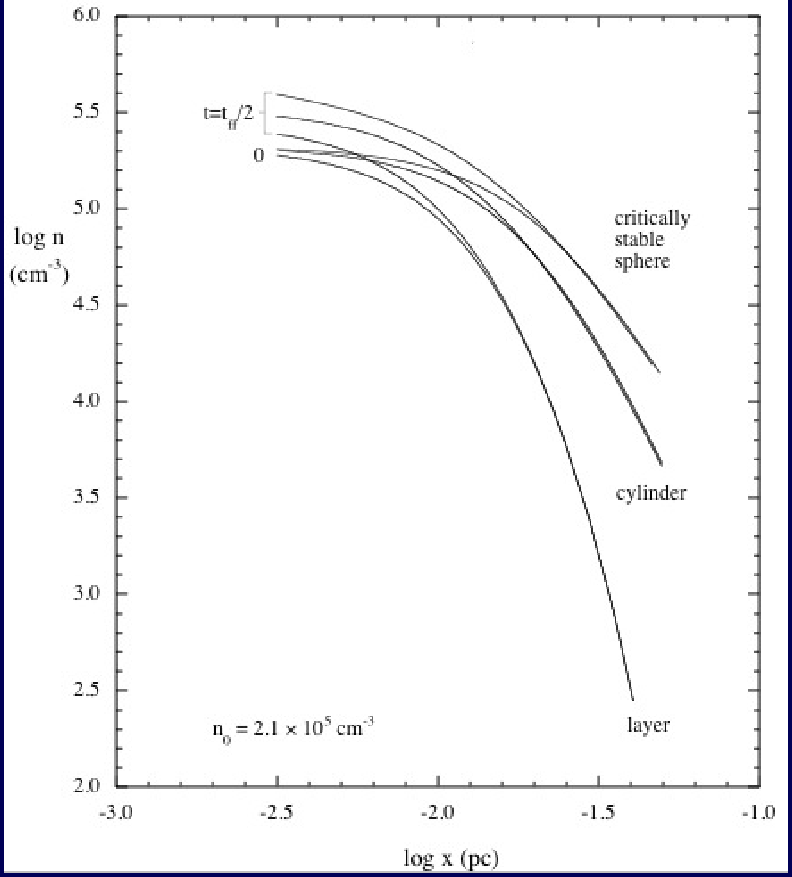
magnetic contraction
Ciolek & Basu 00

spherical isothermal eq.
Lada, Alves & Lada 01

turbulent fragmentation
Ballesteros-Paredes et al 03

early spherical collapse
Whitworth & Ward-Thompson 01

early isothermal collapse
Myers 04

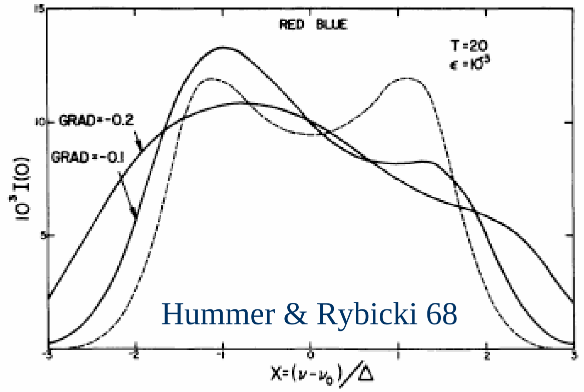


flat top for many shapes, collapse ages

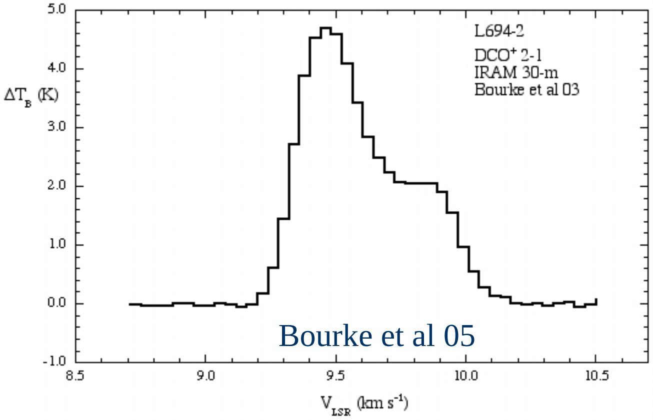
need more information to choose among models

Infall Asymmetry Probes Inward Motion

- Red-shifted self-absorption, increases with τ, v_{in}/σ_v
- To create: $\tau>1$, grad $T_{ex}<0$
- To detect: $\Delta v/\delta v>>1$, $S/N>>1$
- To understand: multi-lines, maps, and models



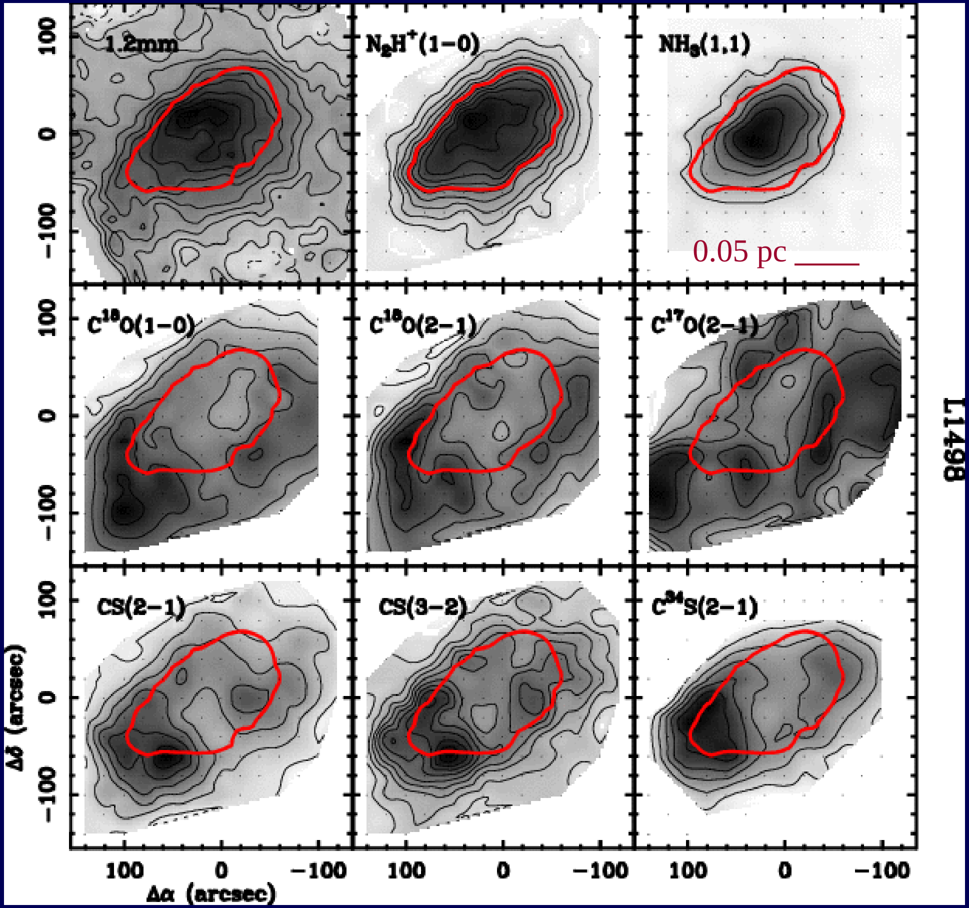
Hummer & Rybicki 68



Bourke et al 05

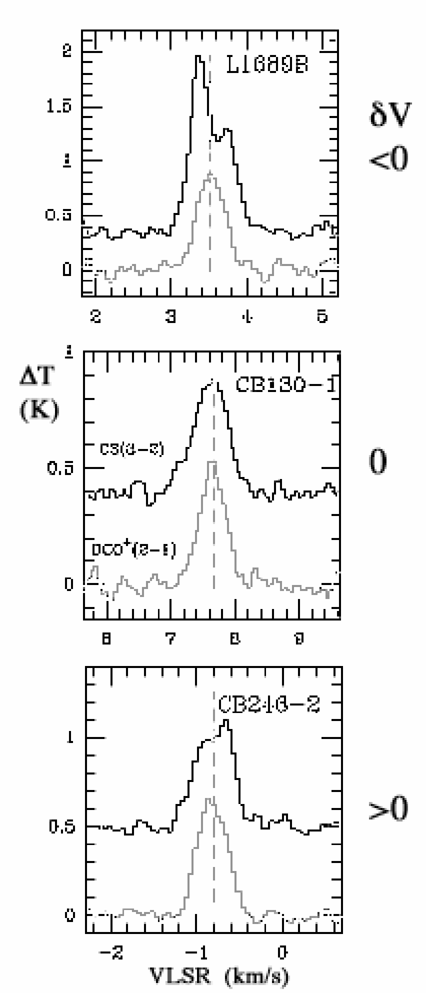
Freeze-out Selects Dense Gas

- CO freeze-out expected in dense gas (Leger 1983).
- CO and CS should deplete more than N_2H^+, NH_3 where $n \sim 10^4\ cm^{-3}$ (Bergin & Langer 1997).
- N_2H^+ and NH_3 follow dust; other species have “depletion holes” r ~ 0.05 pc (Caselli et al 99, Tafalla et al 2002).
- Choose proper lines to probe inner and outer core regions.

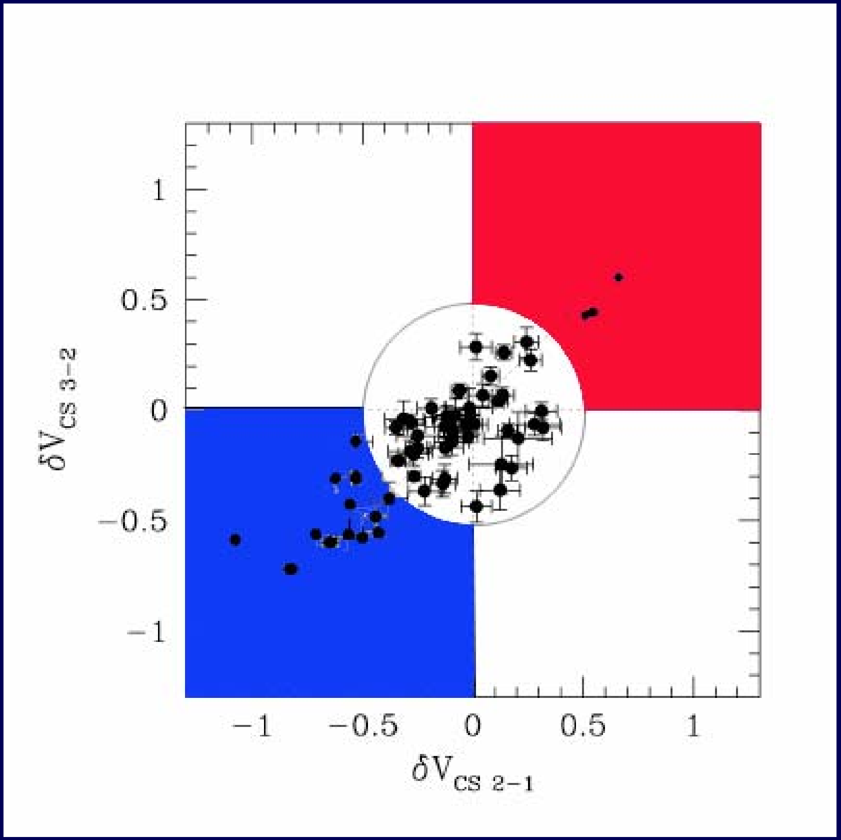


Tafalla et al 2004

Contraction is More Common than Expansion



Lee, Myers & Plume 04



- CS 3-2 and 2-1 line shifts are correlated
- $\delta V = (V_{thick} - V_{thin})/\Delta V_{thin}$
- 14 cores with $\delta V < -0.5$ (22% - common)
- 3 cores with $\delta V > +0.5$ (5% - rare)

Infall Asymmetry in Many Cores and Stars

Table criteria:

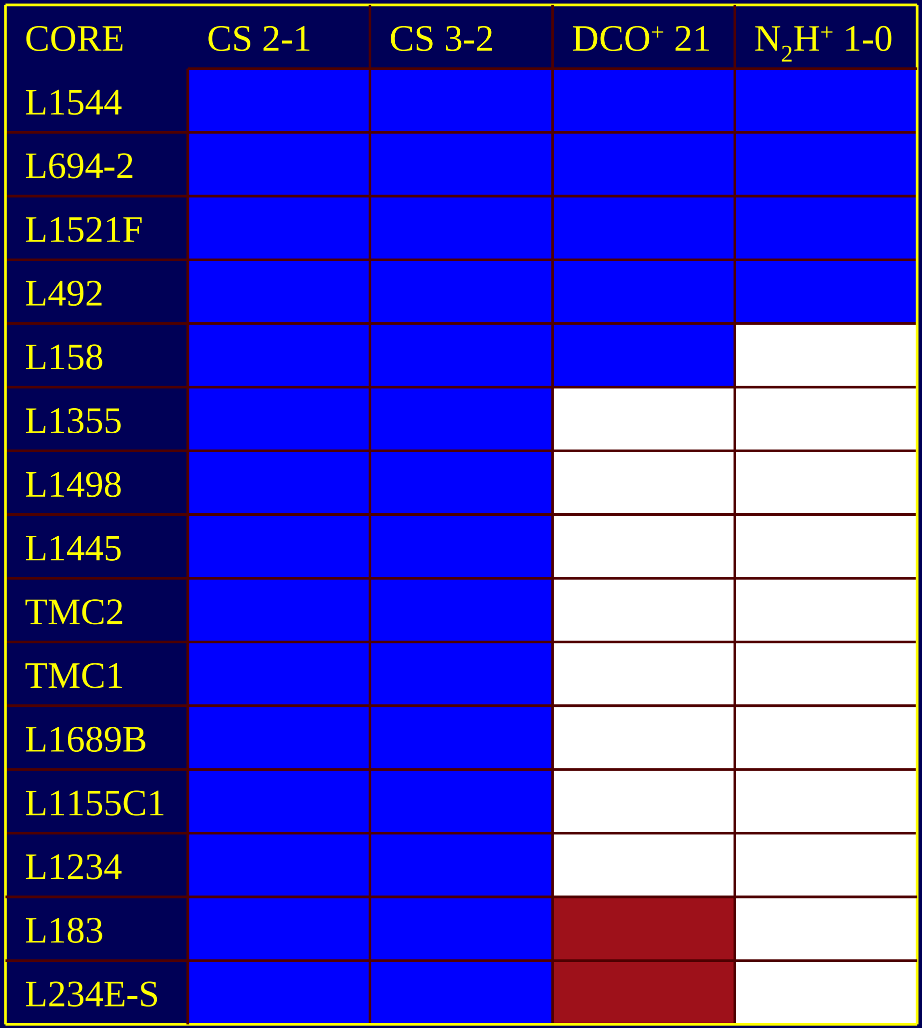
Starless cores with infall asymmetry in at least two of four mapped lines (Lee et al 04, Bourke et al 05)

🟦 Infall asymmetry

⬜ No asymmetry

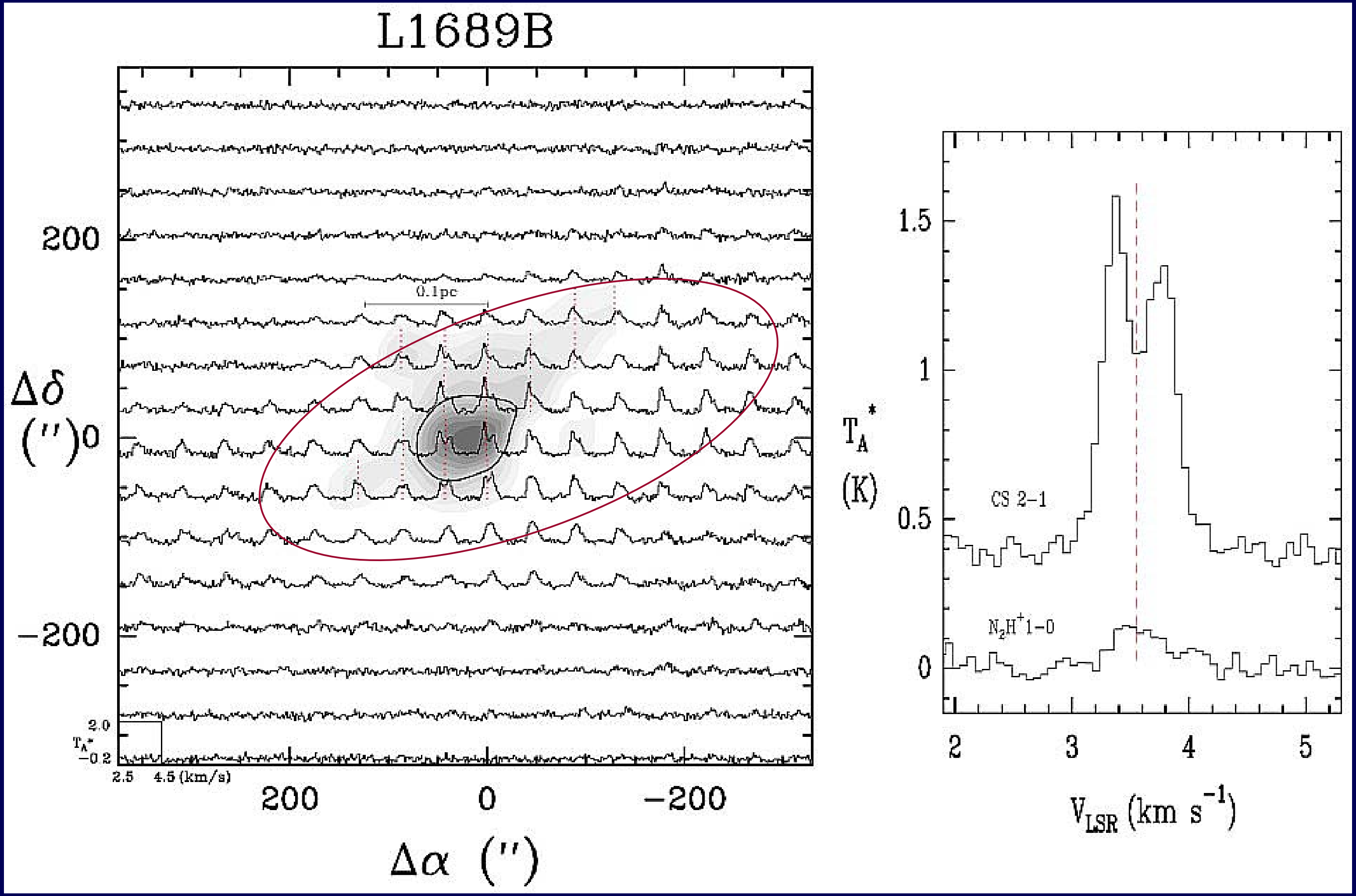
🟥 Expansion asymmetry

Colors of 15 Infall Candidates



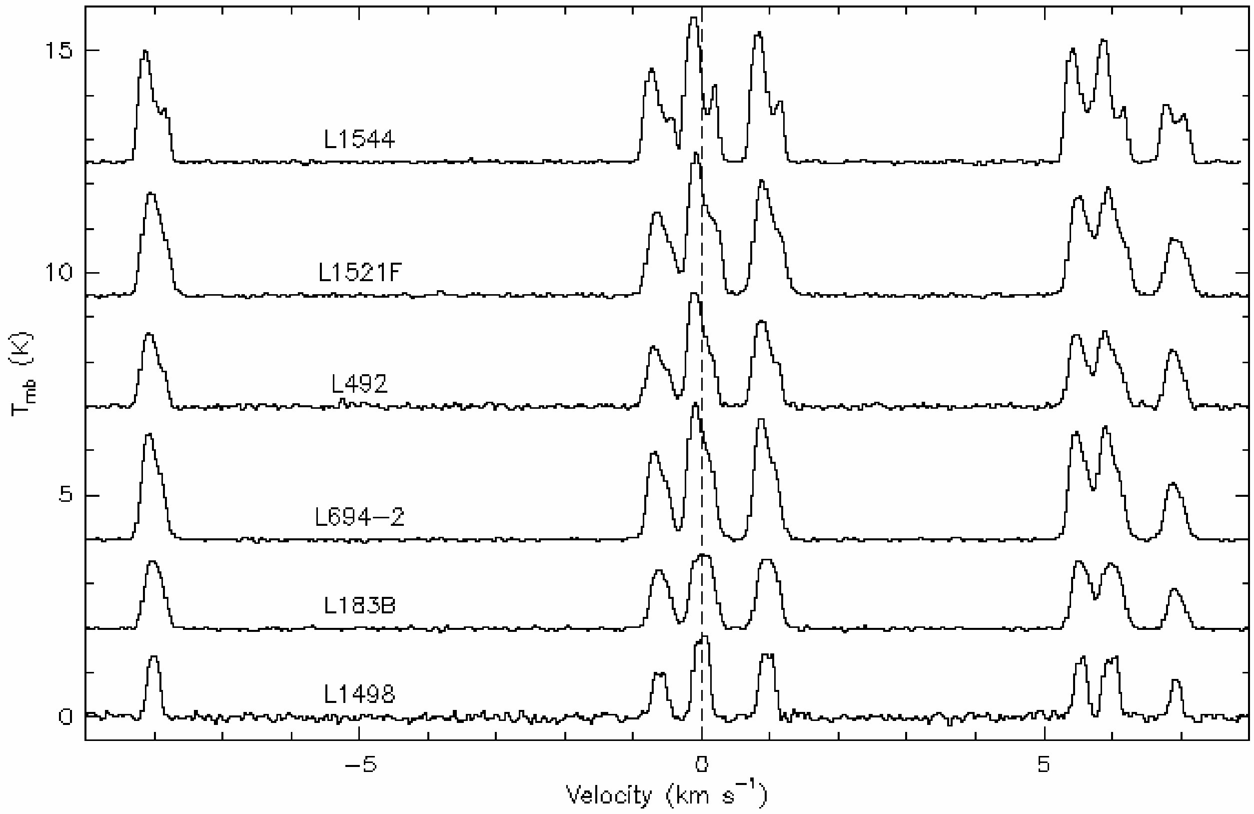
	-----outer-----		-----inner-----	
CORE	CS 2-1	CS 3-2	DCO$^+$ 21	N$_2$H$^+$ 1-0
L1544	🟦	🟦	🟦	🟦
L694-2	🟦	🟦	🟦	🟦
L1521F	🟦	🟦	🟦	🟦
L492	🟦	🟦	🟦	🟦
L158	🟦	🟦	🟦	⬜
L1355	🟦	🟦	⬜	⬜
L1498	🟦	🟦	⬜	⬜
L1445	🟦	🟦	⬜	⬜
TMC2	🟦	🟦	⬜	⬜
TMC1	🟦	🟦	⬜	⬜
L1689B	🟦	🟦	⬜	⬜
L1155C1	🟦	🟦	⬜	⬜
L1234	🟦	🟦	⬜	⬜
L183	🟦	🟦	🟥	⬜
L234E-S	🟦	🟦	🟥	⬜

CS Infall Asymmetry from "Outer Core"



- N_2H^+ 1-0 (gray) traces dense core, extends over ~0.1 pc
- CS 2-1 spectra with infall asymmetry extend over ~ 0.2 pc, typical of 18 maps (Lee et al 2001)

Deep N_2H^+ Spectra Trace Inner Core Motions



infall asymmetry but no infall “wings”

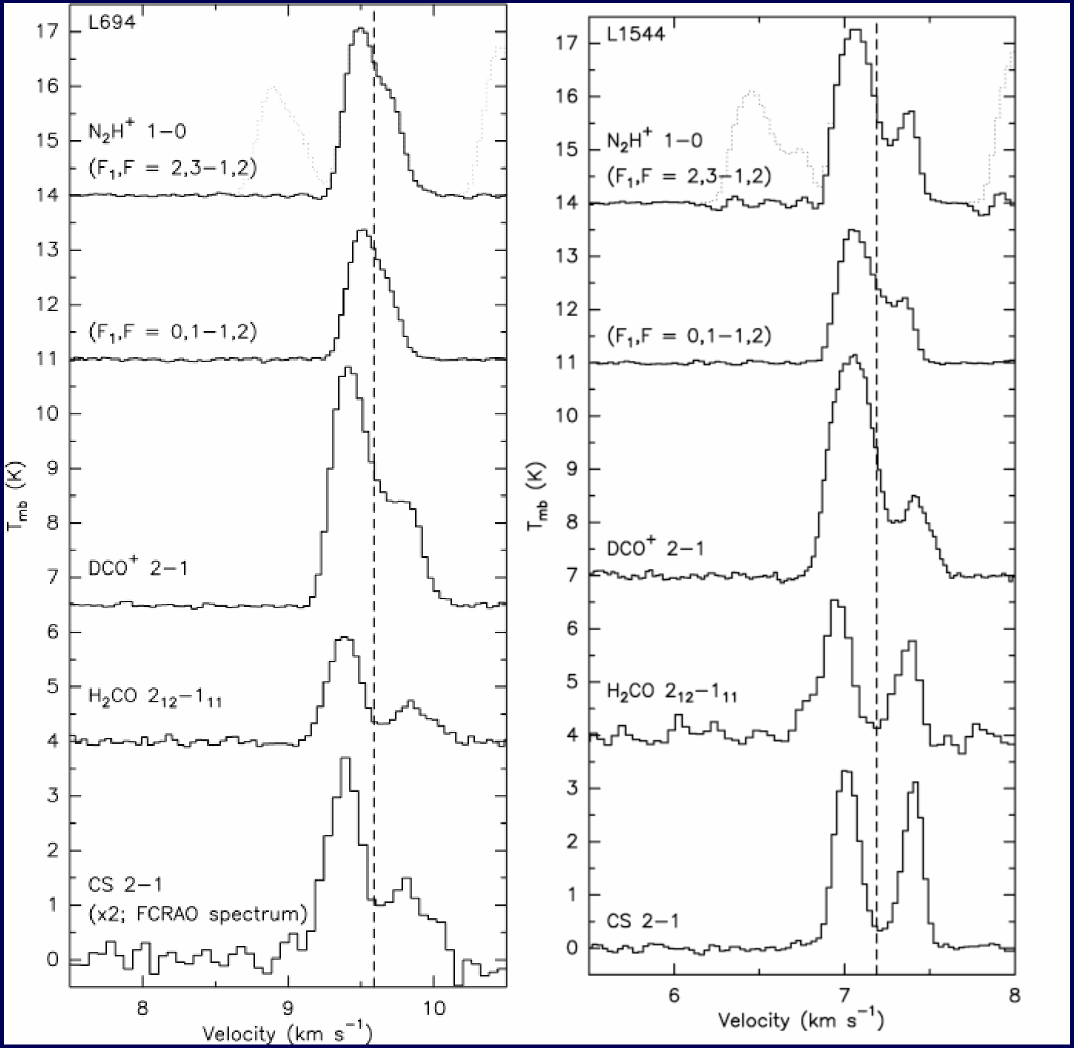
Bourke et al 05

Inner and Outer Core Motions

Outer core -
$n_{cr} \sim 10^4$ cm^{-3}, $\tau > 1$,
freeze-out species
(CS, H_2CO)

Inner core -
$n_{cr} \sim 10^5$ cm^{-3}, $\tau > 1$,
“anti-freeze” species
(N_2H^+, H_2CO)

V_{in}(inner)>V_{in}(outer)
for L1544 and L694



V_{in}
(km s^{-1})

0.1

0.1

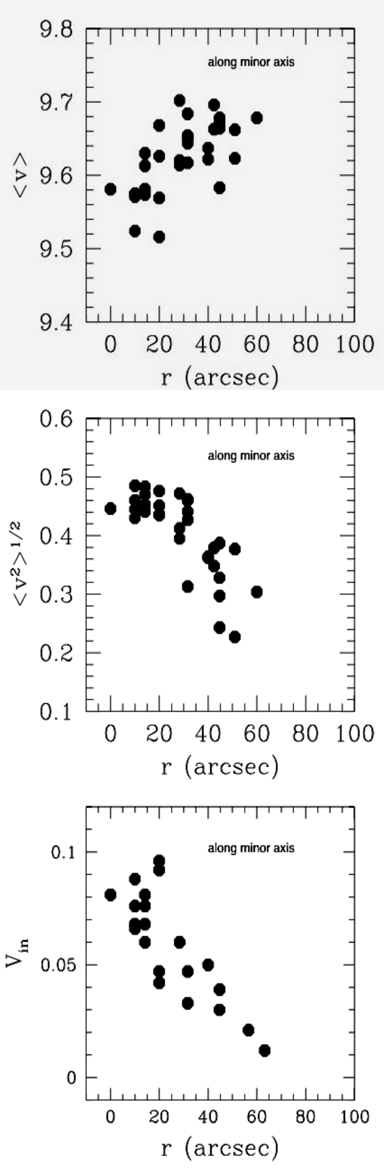
0.1

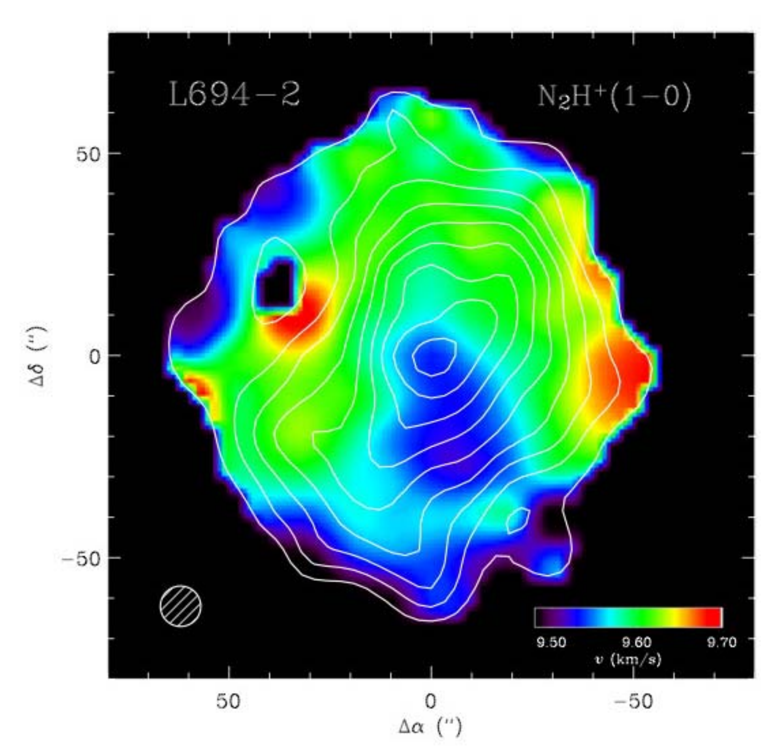
0.04

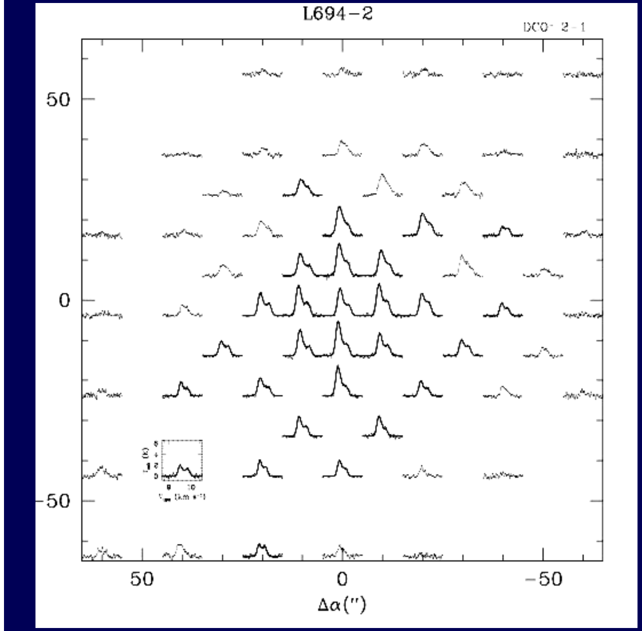
0.02

Bourke et al 05

Velocities Increase Inward in Maps







Lee et al 05

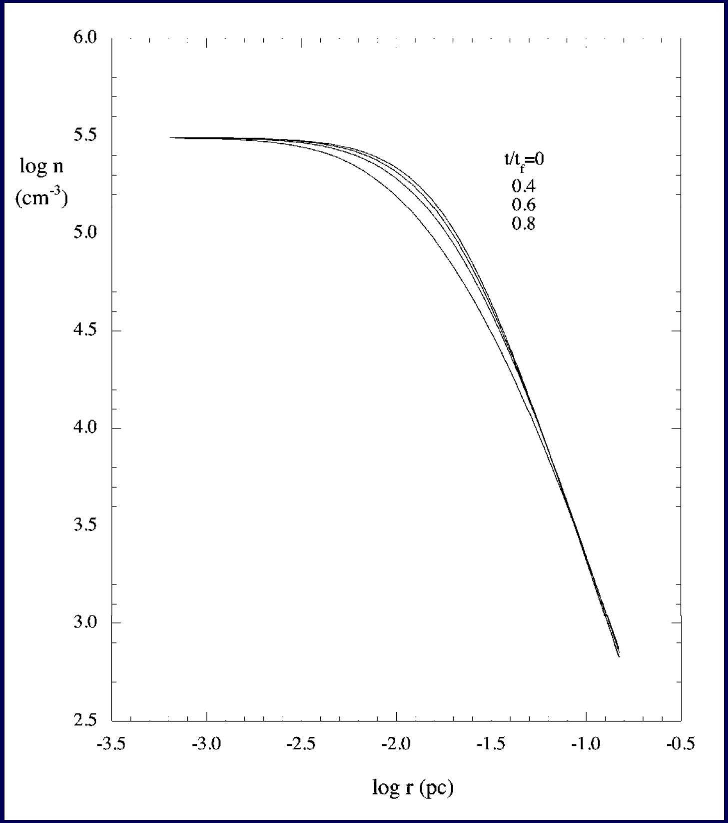
Williams et al 05

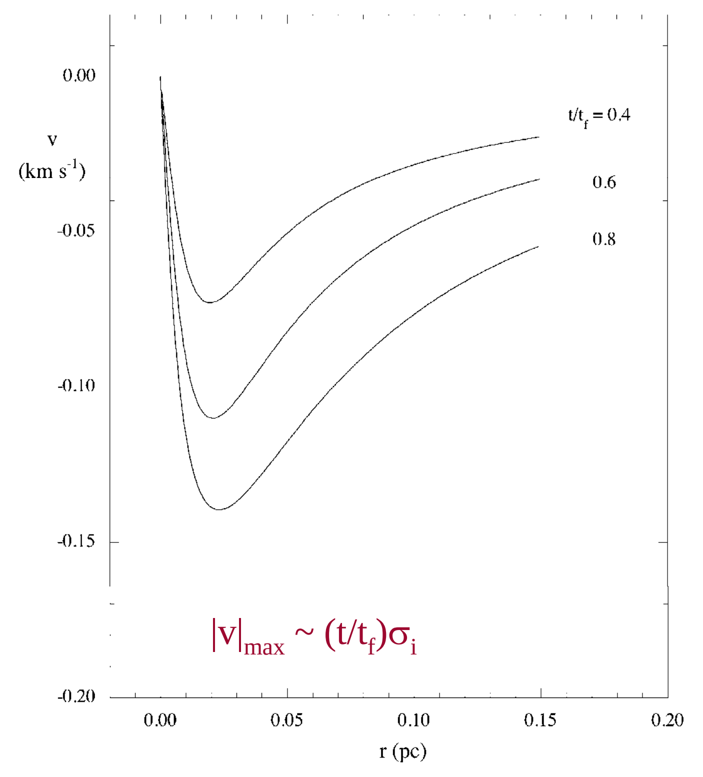
From x ≈ 0.05 to 0.01 pc…

DCO^+ and N_2H^+ lines get brighter, broader, and bluer

model infall speed v_{in} increases from 0.01 to 0.1 km s^{-1}

Static and Collapsing B-E Profiles



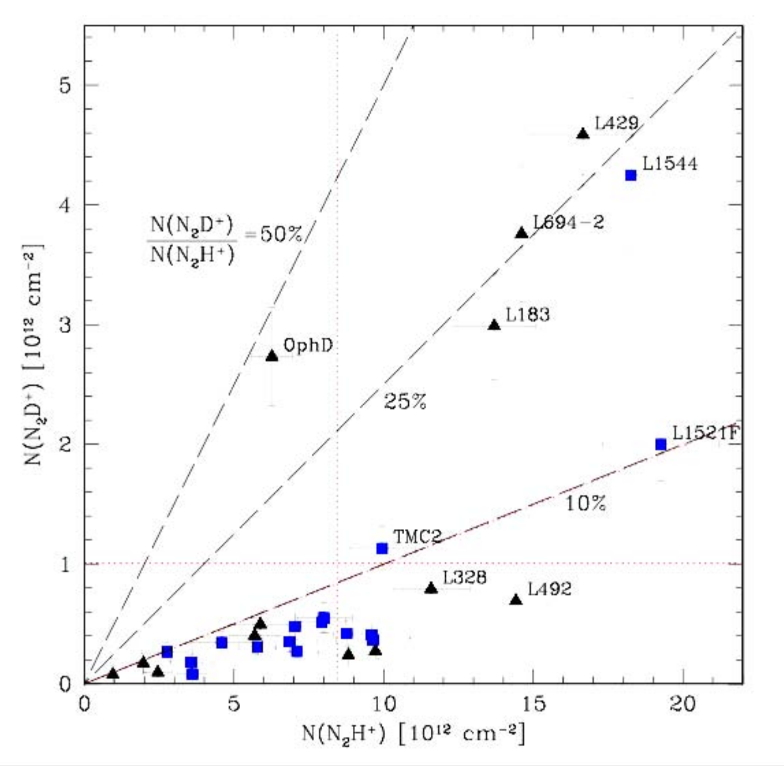


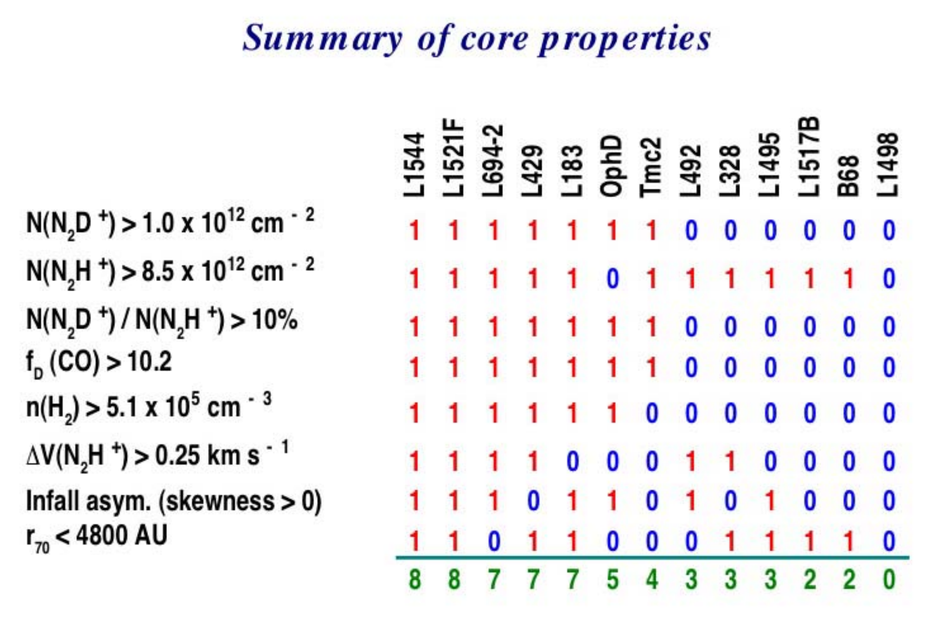
$|v|_{max} \sim (t/t_f)\sigma_i$

Myers 04

density and velocity profiles together: L1544 and L694 may be in early stages of collapse from centrally condensed initial state

Evolution of Starless and Prestellar Cores





Summary of core properties

	L1544	L1521F	L694-2	L429	L183	OphD	Tmc2	L492	L328	L1495	L1517B	B68	L1498
$N(N_2D^+) > 1.0 \times 10^{12}$ cm^{-2}	1	1	1	1	1	1	1	0	0	0	0	0	0
$N(N_2H^+) > 8.5 \times 10^{12}$ cm^{-2}	1	1	1	1	1	0	1	1	1	1	1	1	0
$N(N_2D^+) / N(N_2H^+) > 10\%$	1	1	1	1	1	1	1	0	0	0	0	0	0
f_D (CO) > 10.2	1	1	1	1	1	1	1	0	0	0	0	0	0
$n(H_2) > 5.1 \times 10^5$ cm^{-3}	1	1	1	1	1	1	0	0	0	0	0	0	0
$\Delta V(N_2H^+) > 0.25$ km s^{-1}	1	1	1	1	0	0	0	1	1	0	0	0	0
Infall asym. (skewness > 0)	1	1	1	0	1	1	0	1	0	1	0	0	0
$r_{70} < 4800$ AU	1	1	0	1	1	0	0	0	1	1	1	1	0
	8	8	7	7	7	5	4	3	3	3	2	2	0

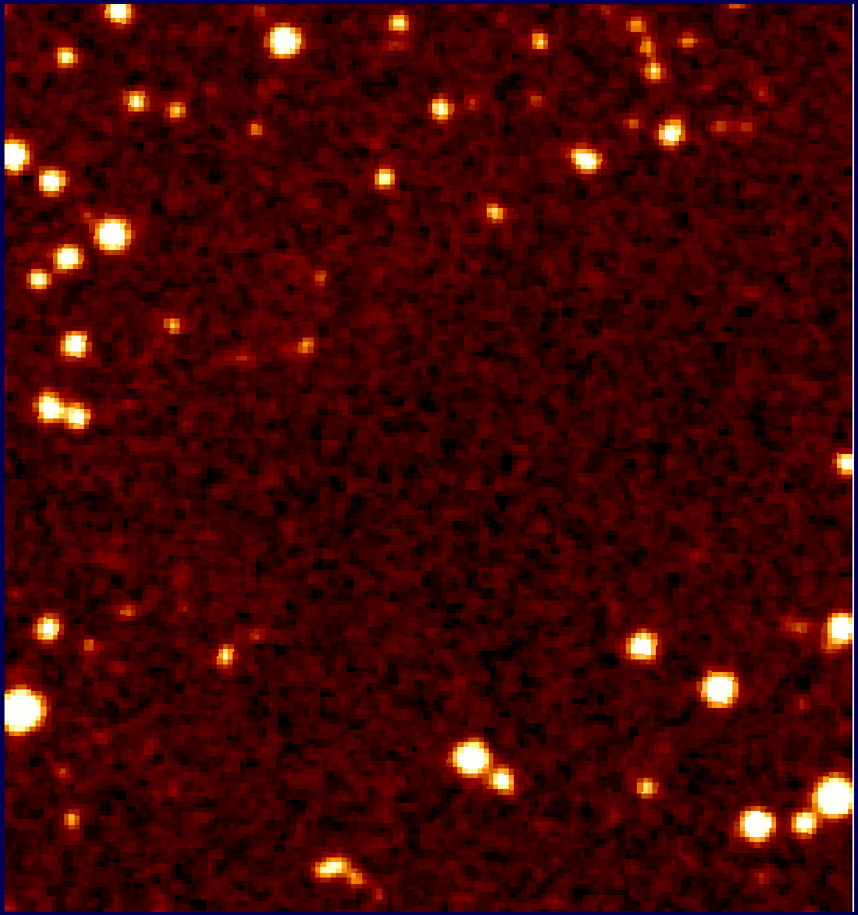
Crapsi et al 2004

Prestellar cores seem more “evolved” than other starless cores in column density, deuteration, CO depletion, dust density, line width, infall asymmetry

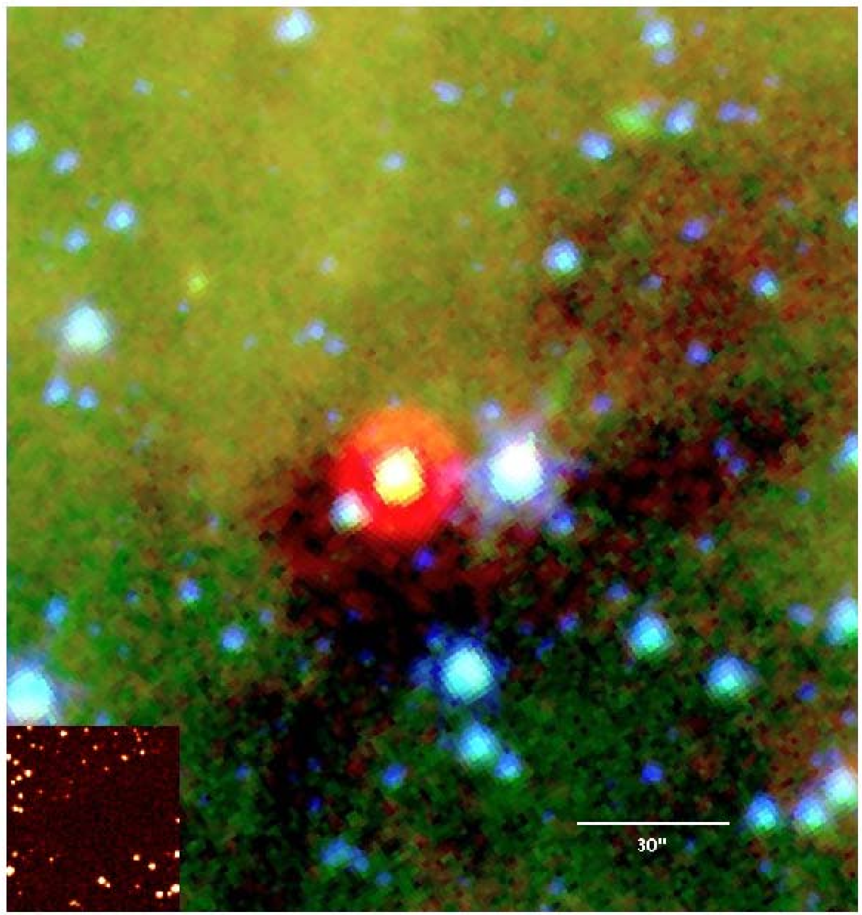
Does every low-mass star form from such a prestellar core? (No...)

A Spitzer Source in a “Starless” Core

L1014



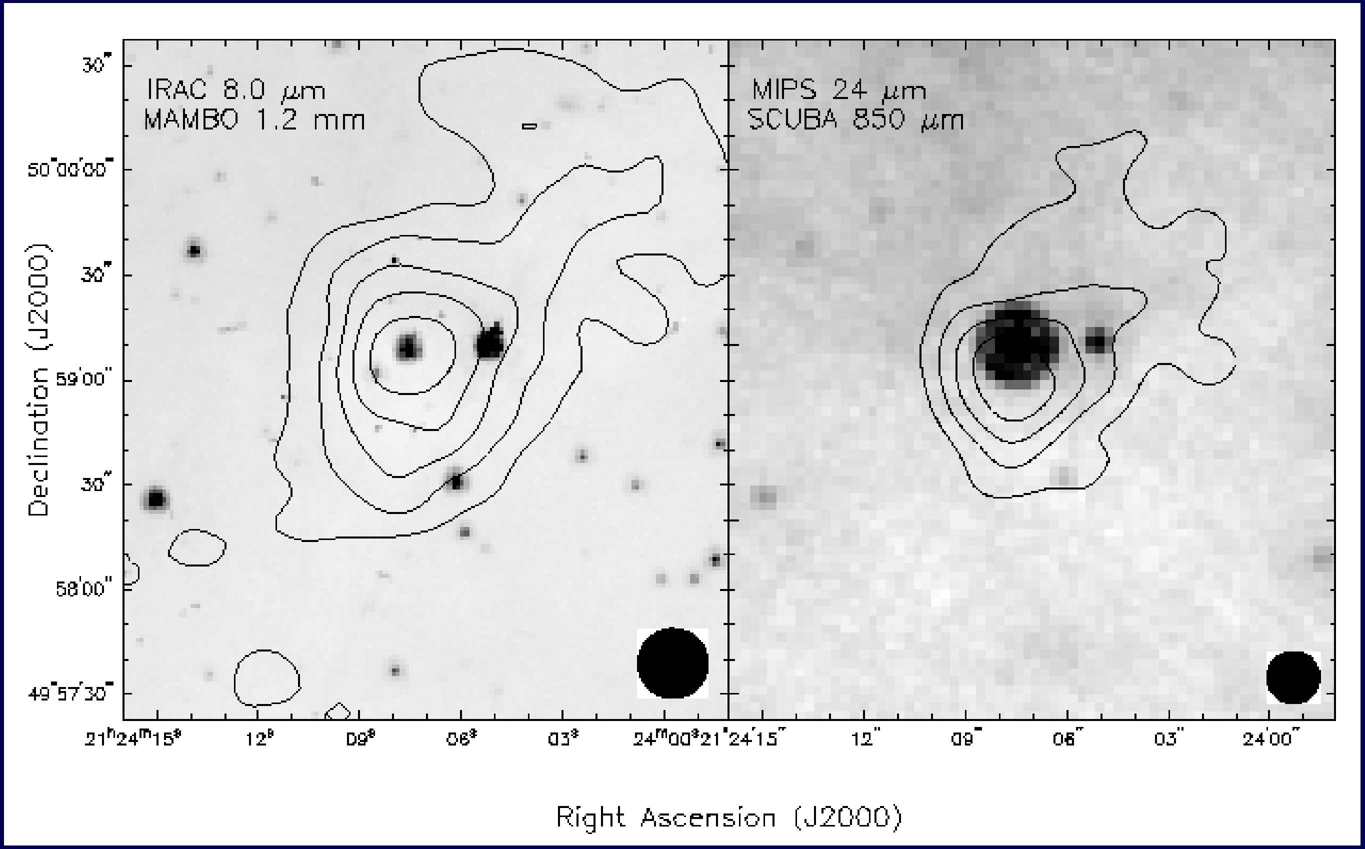
DSS R-band



Spitzer blue=3.6 µm, green=8.0µm, red=24µm
C. Young & c2d team, ApJS 2004, in press

Spitzer Source is Probably A Protostar

L1014



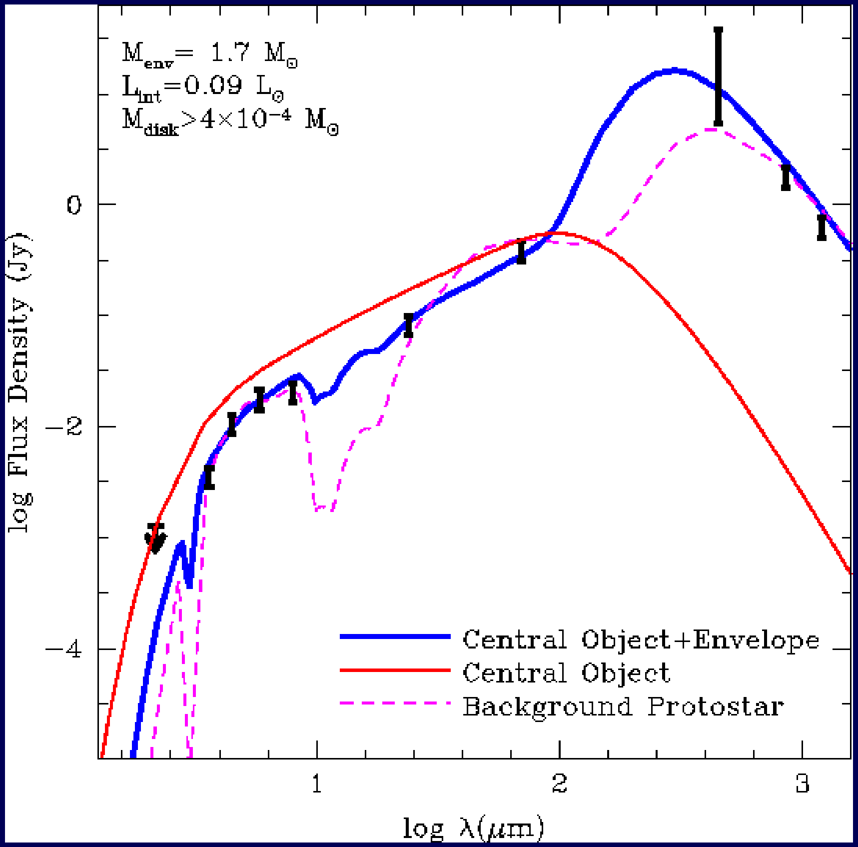
C. Young & c2d team, ApJS 2004, in press

L1014 Source and Core Properties

Source:
model bb+disk+envelope
$M_* << 0.1\ M_\odot$ --a very young protostar or proto-BD (D=200 pc) No CO outflow

Core:
weaker than typical “prestellar” core by factors 2-5 in 1.2 mm dust emission, N, n, $\Delta T_B(N_2H^+)$ --Crapsi et al 05

--a very low-mass “star” in a low-mass core



C. Young & c2d team, ApJS 2004, in press

L1148B - Another Spitzer Surprise

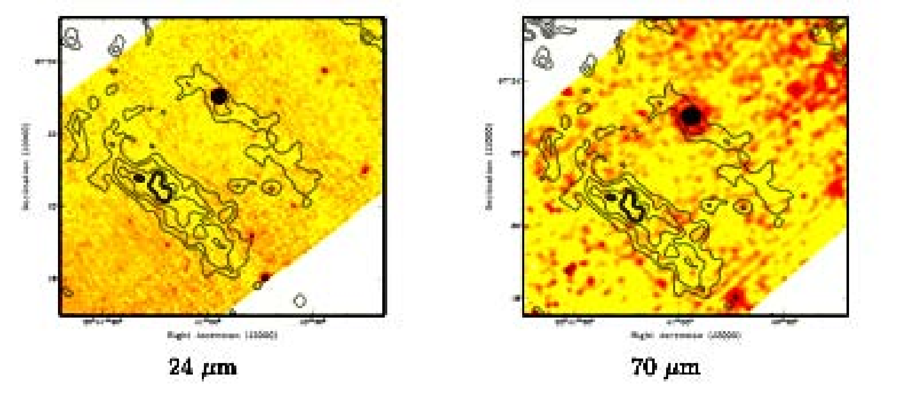
0.1 L_O source near peak of mm emission from an ordinary “starless” core

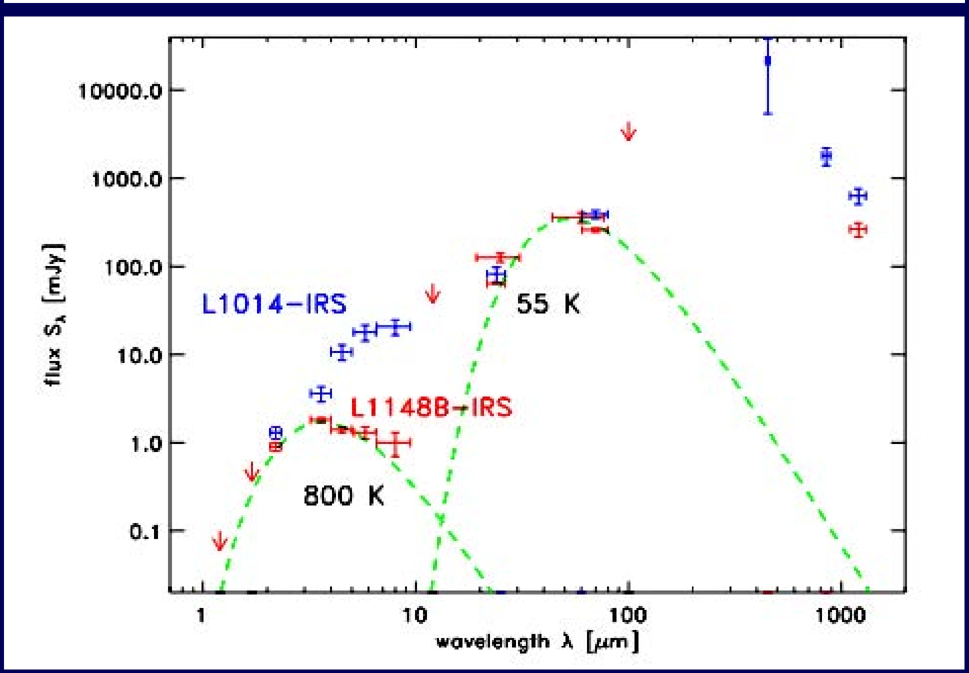
SED similar to that of L1014, but with less emission in mid-IR

Preliminary result, less well studied than L1014

L1014 and L1148B protostars did not form in prestellar cores like L1544

Not all differences among cores are due to evolution

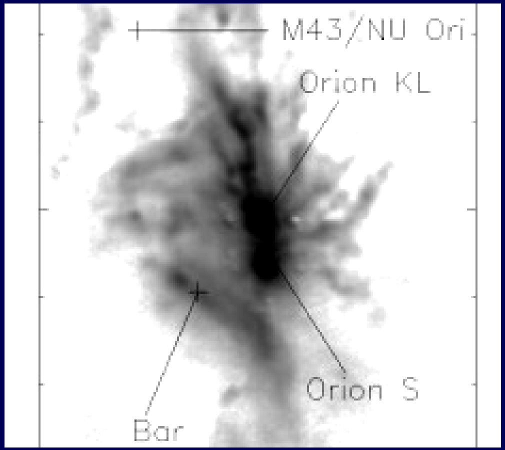




Kauffmann & Bertoldi 05

Where Clusters Form: "Blobs," not "Filaments"

Orion KL



850 μm Johnstone & Bally 99

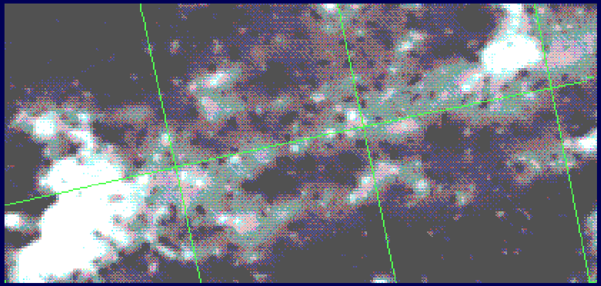
Ophiuchus

photo www.starryscapes.com 04

Corona Australis

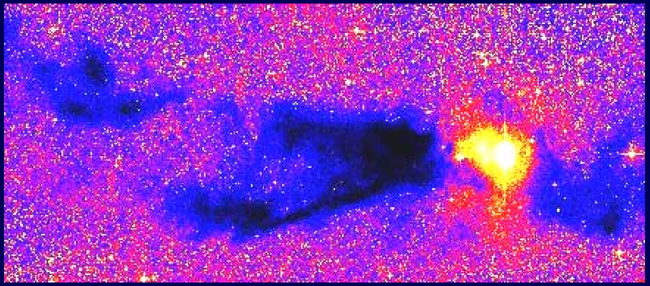
photo www.starryscapes.com 04

Chamaeleon II



A_V Cambresy 99

Lupus III



digital sky survey skyview.gsfc.nasa.gov

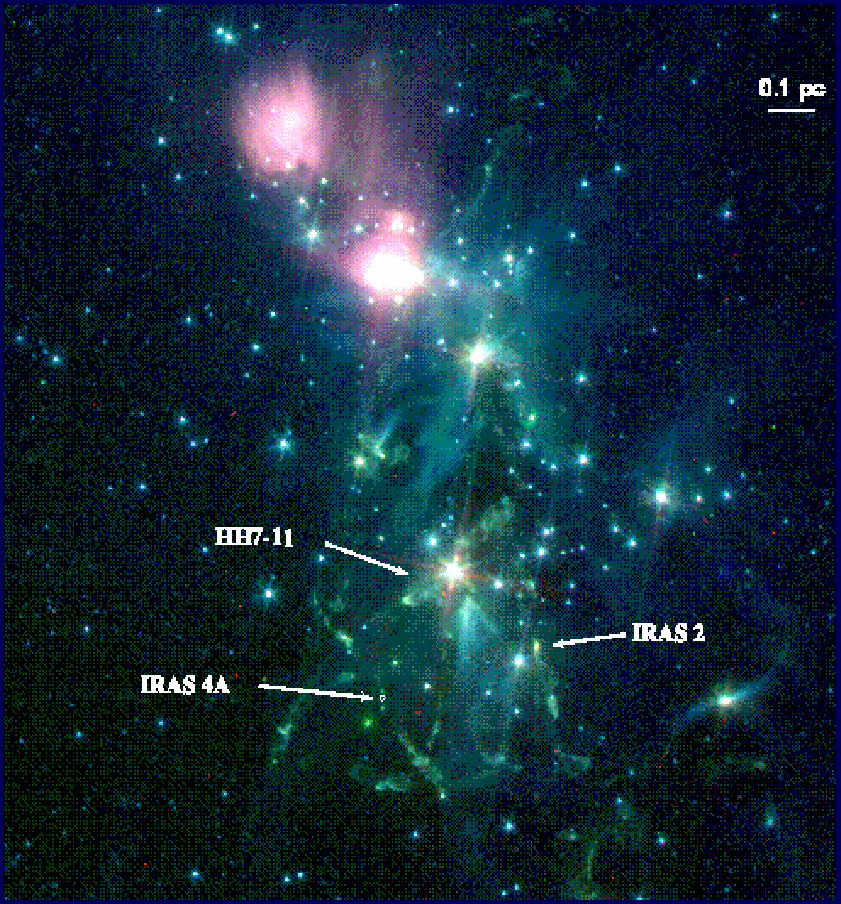
IC 5146

photo www.sbig.com 03

Cluster-forming geometry: blobs are dense, low-aspect-ratio "hubs" for filaments with low density, high aspect ratio, and low star formation efficiency.

Speculation: blobs are "layers" whose geometry promotes star formation

Embedded Cluster NGC 1333

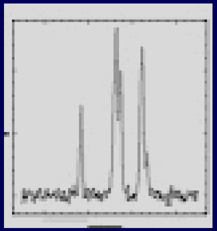


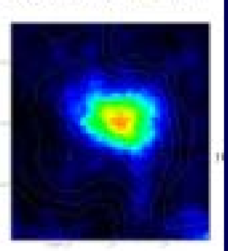
Spitzer IRAC 1,2,3 Porras et al 05

JHK Lada & Lada 2003

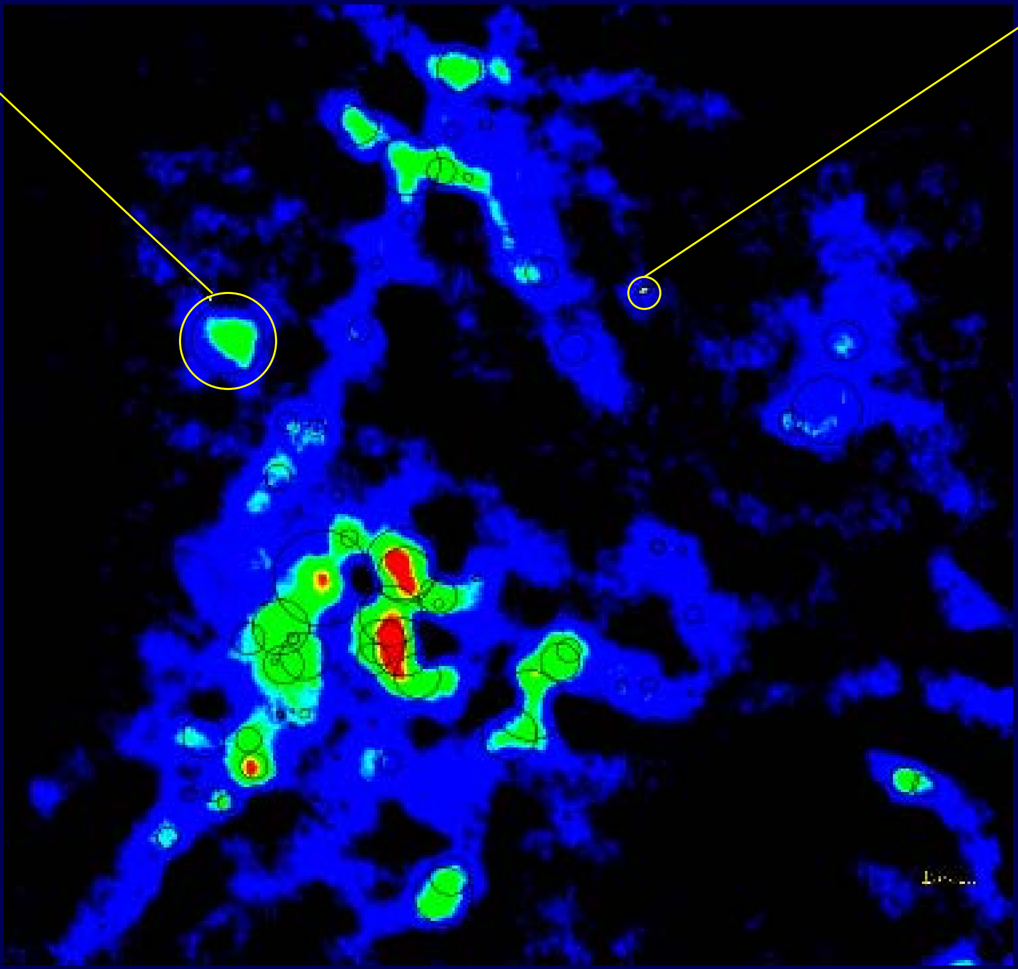
93 N_2H^+ Clumps in NGC1333

big clump
$M=1.6\ M_O$
$R=0.03$ pc
$\Delta v=0.5$ km s^{-1}

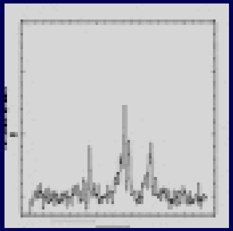


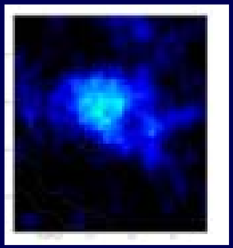


BIMA + FCRAO



small clump
$M=0.05\ M_O$
$R< 0.01$ pc
$\Delta v<0.2$ km s^{-1}



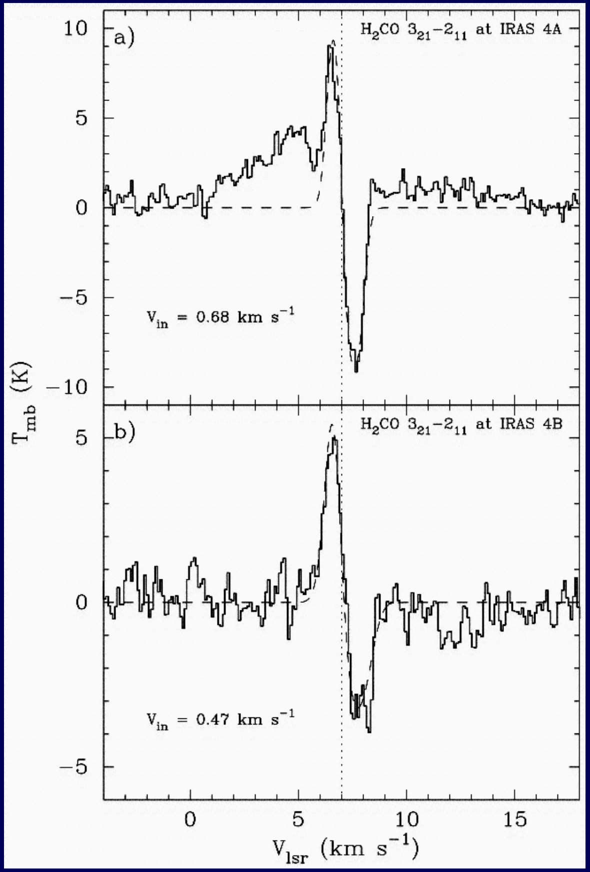


Walsh et al 05

~100 dense clumps in 1 pc^2 - more than in isolated regions

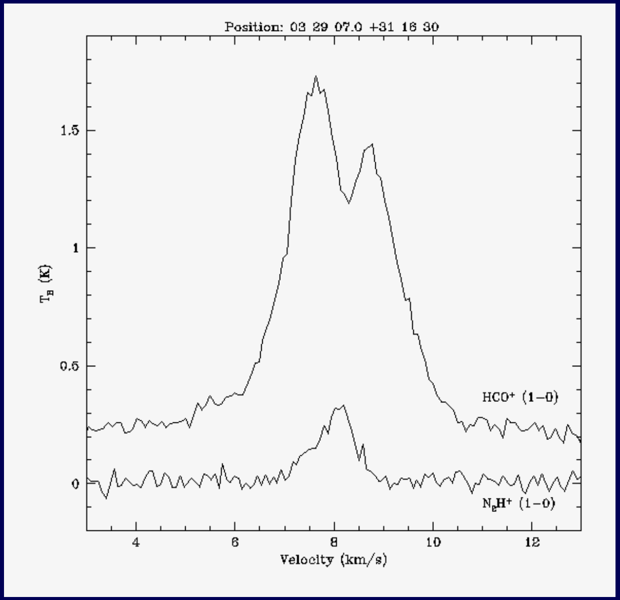
Inward Motions on Many Scales

Localized ~ 0.01 pc



Di Francesco et al (2001)

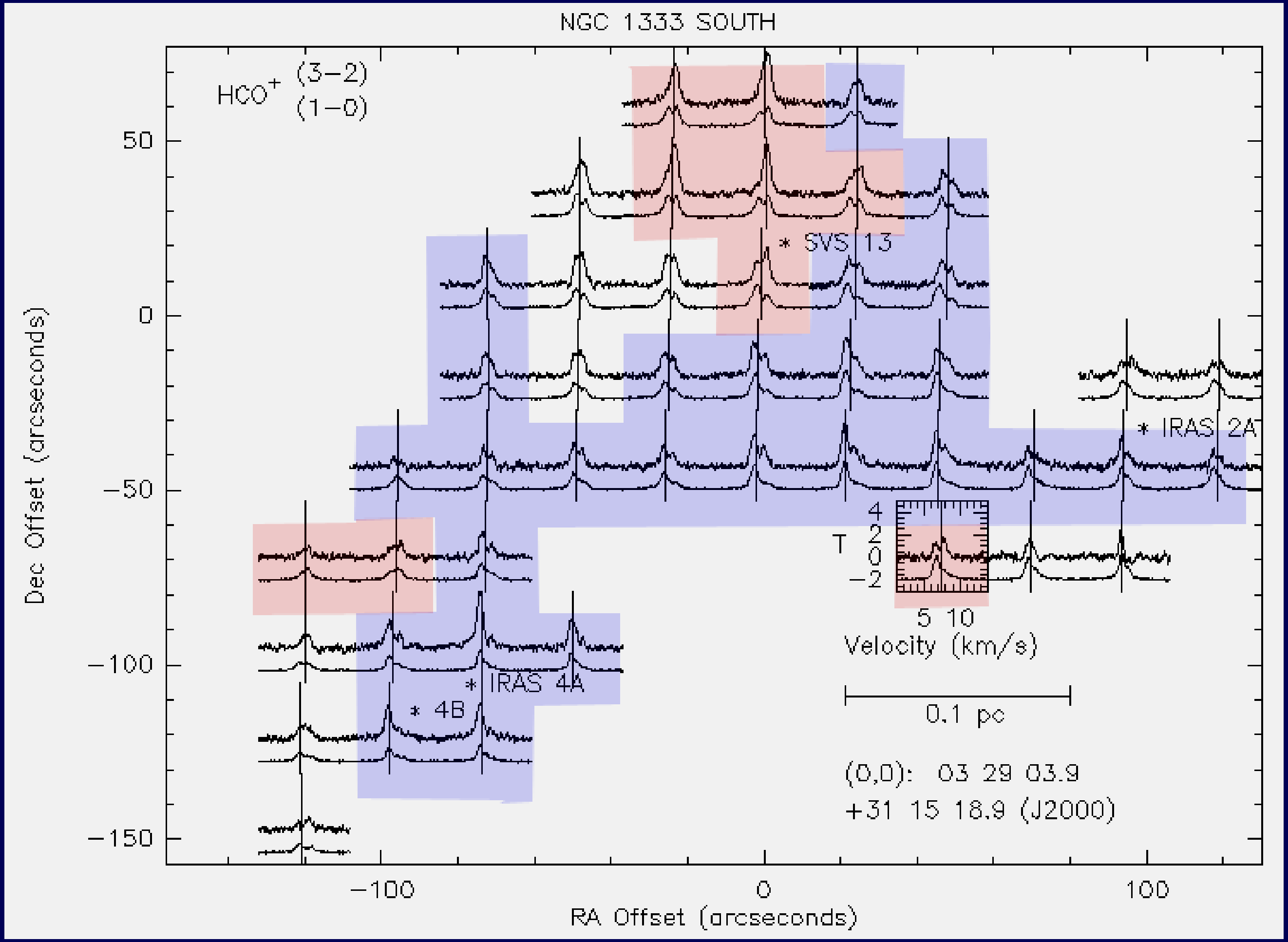
Extended 0.1 - 0.3 pc



Walsh et al (2004b)

V(peak,N_2H^+) ≈ V(dip, HCO^+) $\Rightarrow$ 2 peaks due to self-absorption, not 2 unrelated layers

Inward Motions Near Protostars



“Infall asymmetry” in HCO$^+$ 3-2 and 1-0 extends over > 0.2 pc, includes three protostellar groups, red asymmetry localized to protostars (Walsh et al 2004b)

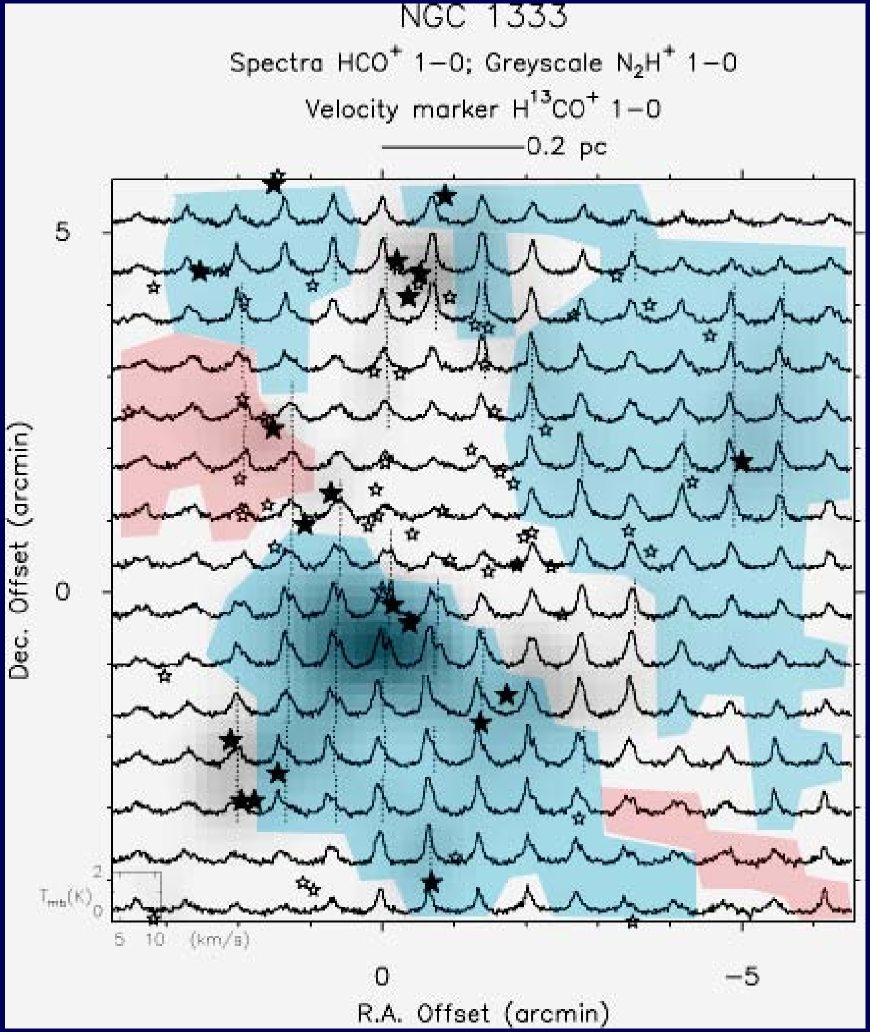
Inward Motions Around Complex

Blue asymmetry in HCO$^+$ 1-0 extends over ~0.6 pc (also some red near protostars)

Similar to HCO$^+$ 3-2 but at lower density, larger scale

Effective inward speed few 0.1 km s^{-1} --> sonic flows

Similar to Serpens (CS 2-1, Williams & Myers 1999)



Walsh et al 05

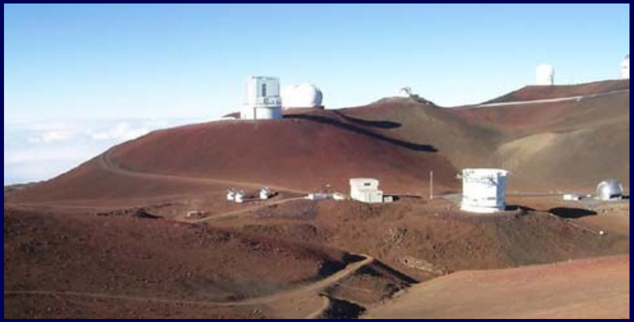
Multiscale Inward Motions

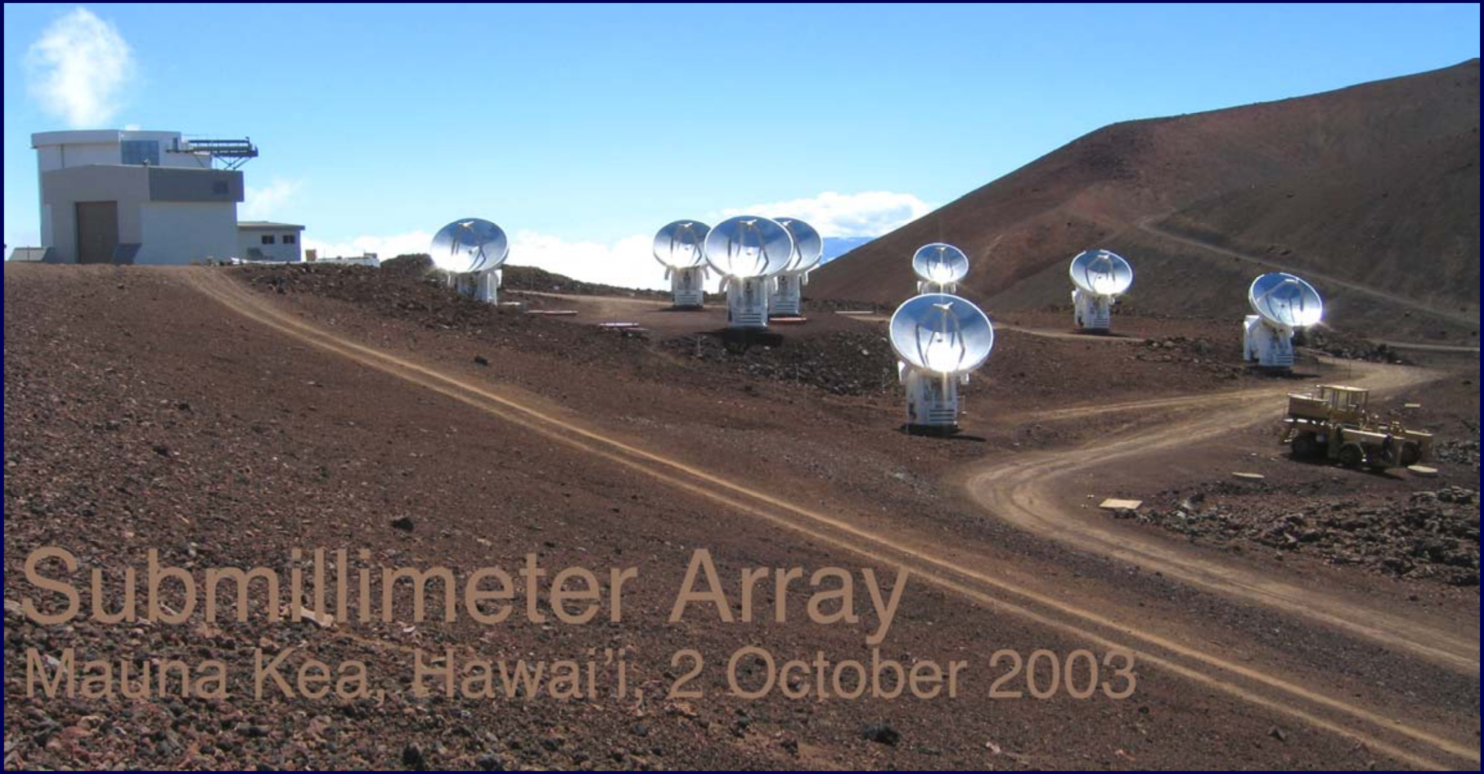
Radius pc	Density cm^{-3}	V_{in} $km\ s^{-1}$	dM/dt $10^{-5}\ M_O\ yr^{-1}$
0.01	$3\ \ 10^5$	0.5	1
0.1	$3\ \ 10^4$	0.1	2
0.3	$2\ \ 10^3$	0.2	3

dM/dt is “star-forming” on small scale but too small to be “cluster-forming” on large scale (late-stage accretion?)

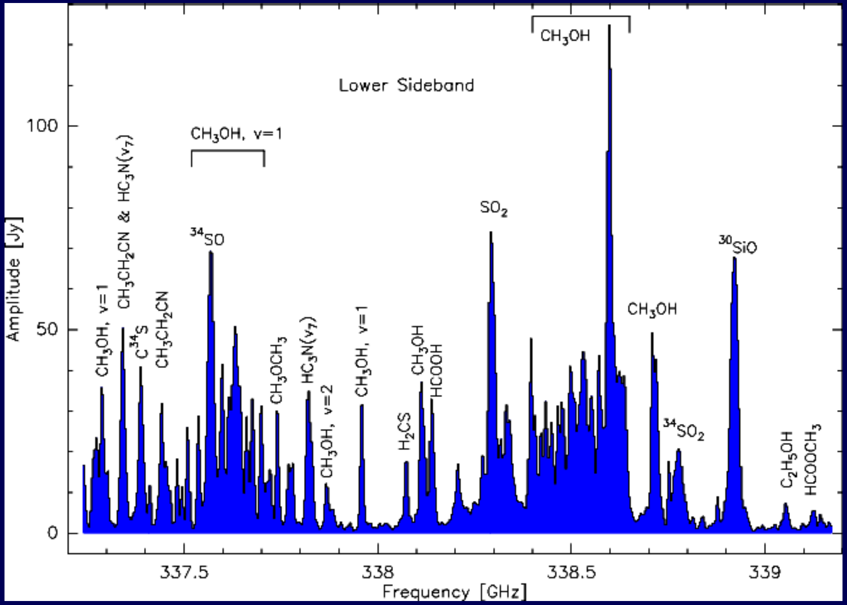
Chemical Diversity in Hot Cores

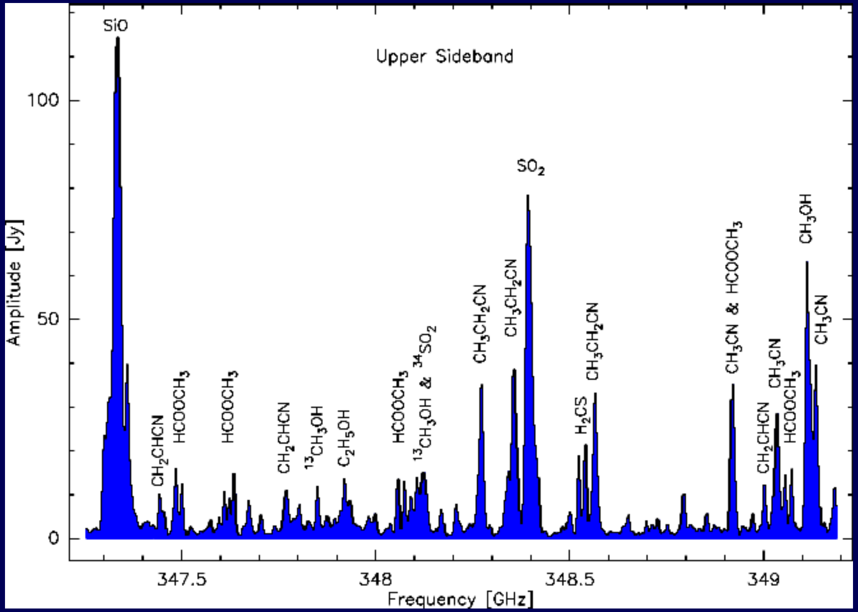
SMA submillimeter observations
of Orion KL - Beuther et al 04





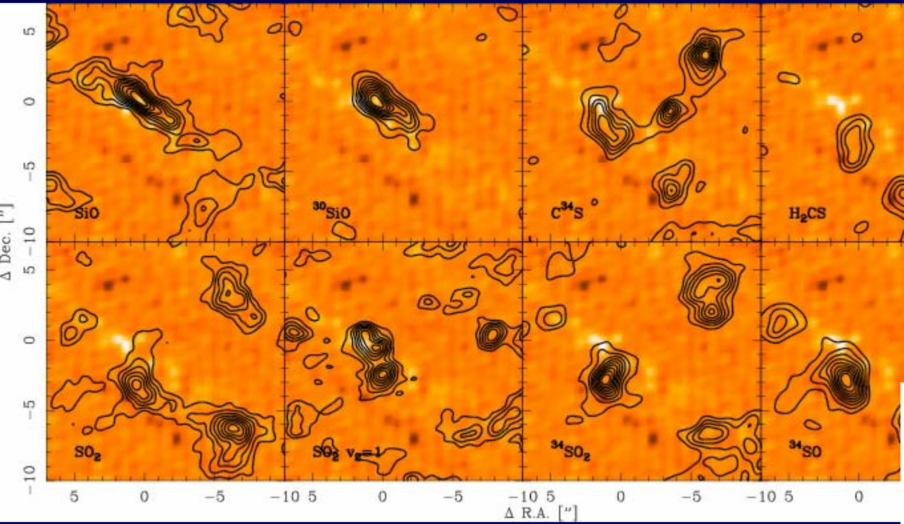
Diverse Species Reveal Hot Chemistry





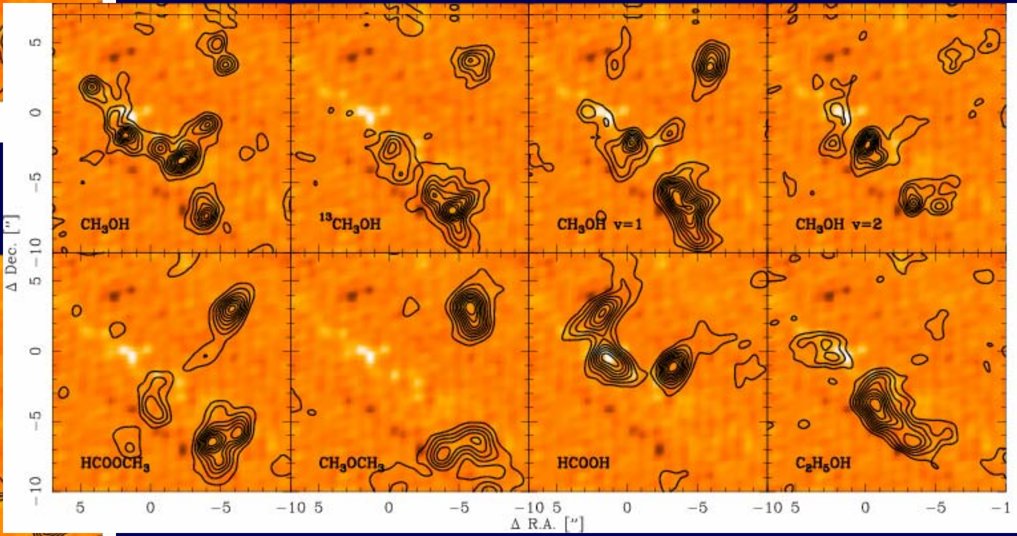
4 GHz SMA bandwidth harbors >50 lines from dozens of species - liberation from grain mantles, shock-enhanced chemistry

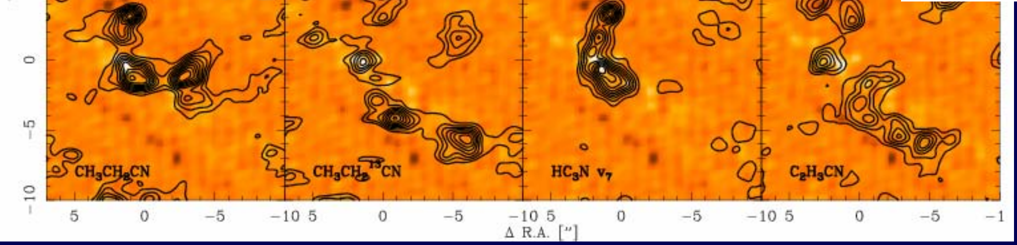
Resolving Abundance Structure



S and Si-bearing molecules

O-bearing molecules





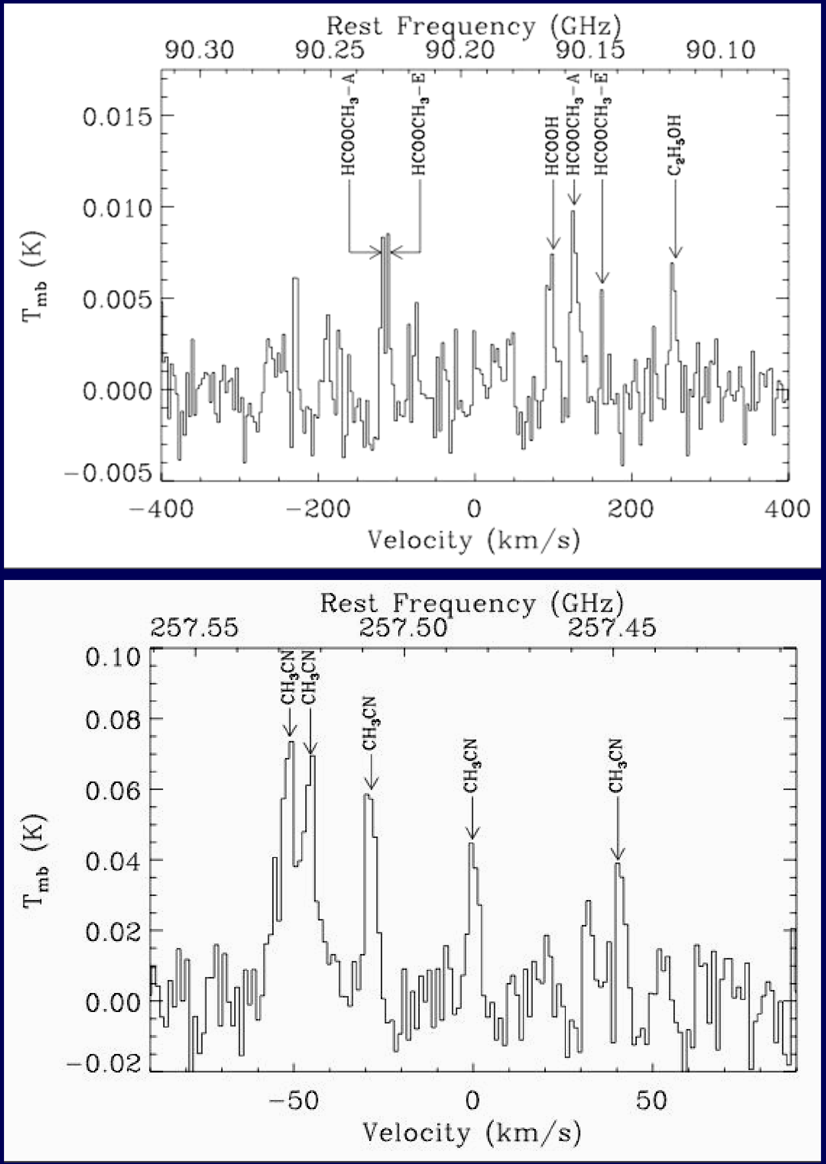
N-bearing molecules

Hot Chemistry in Low Mass Envelopes

Complex species found in low mass protostar envelopes I16293 and NGC1333 IRAS4A at high resolution (IRAM 30-m)

Complex species are no longer limited to hot cores like Orion KL

Molecular composition of ice mantles, liberation by photoheating, gas phase processing may be similar between cold and hot cores



NGC 1333 IRAS 4A Bottinelli et al 04

Modelling Star Formation in Clusters

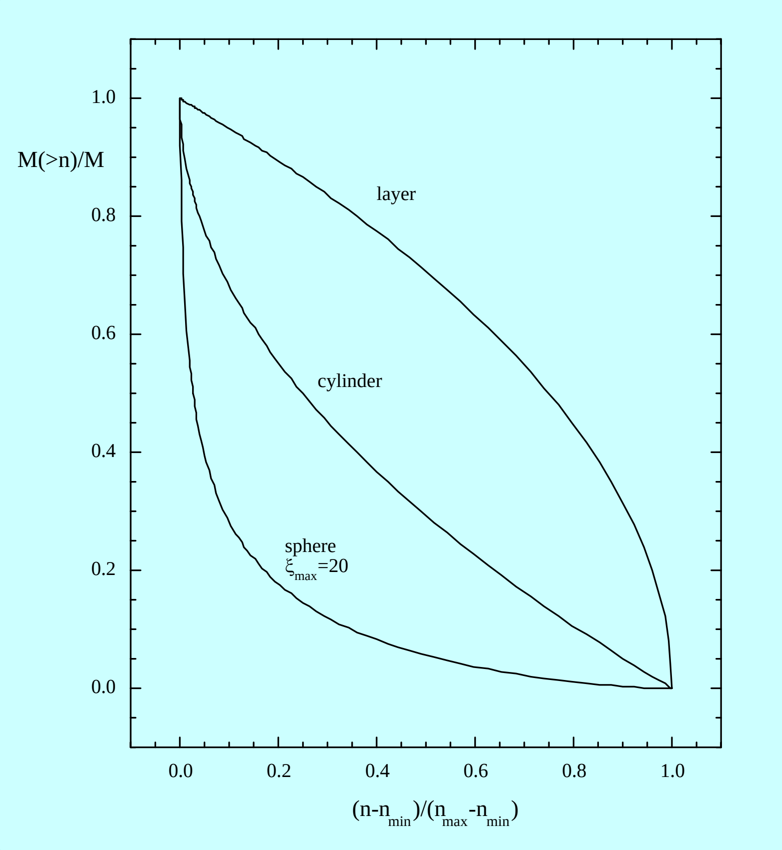
Importance: most stars form in clusters (Lada & Lada 03)

Constraints: high number density of cores
>100 stars in ~ 1 pc^3 in $\sim$ 1 Myr
massive stars
MF of clumps (Motte, André, & Neri 98)
MF of stars (Salpeter 54)

Key model: turbulent fragmentation (Elmegreen 93, Padoan 95, Ballesteros-Paredes et al 99, Klessen et al 00, MacLow & Klessen 04)

Today: collapse and accretion in a centrally condensed layer

Layers Hold More Dense Gas



Spitzer 42, Ostriker 64
Bonnor 56, Ebert 55

A self-gravitating isothermal layer has more than half its mass in gas denser than 0.75 n_{max} ⇒ more dense cores, more accretion than in spheres or cylinders

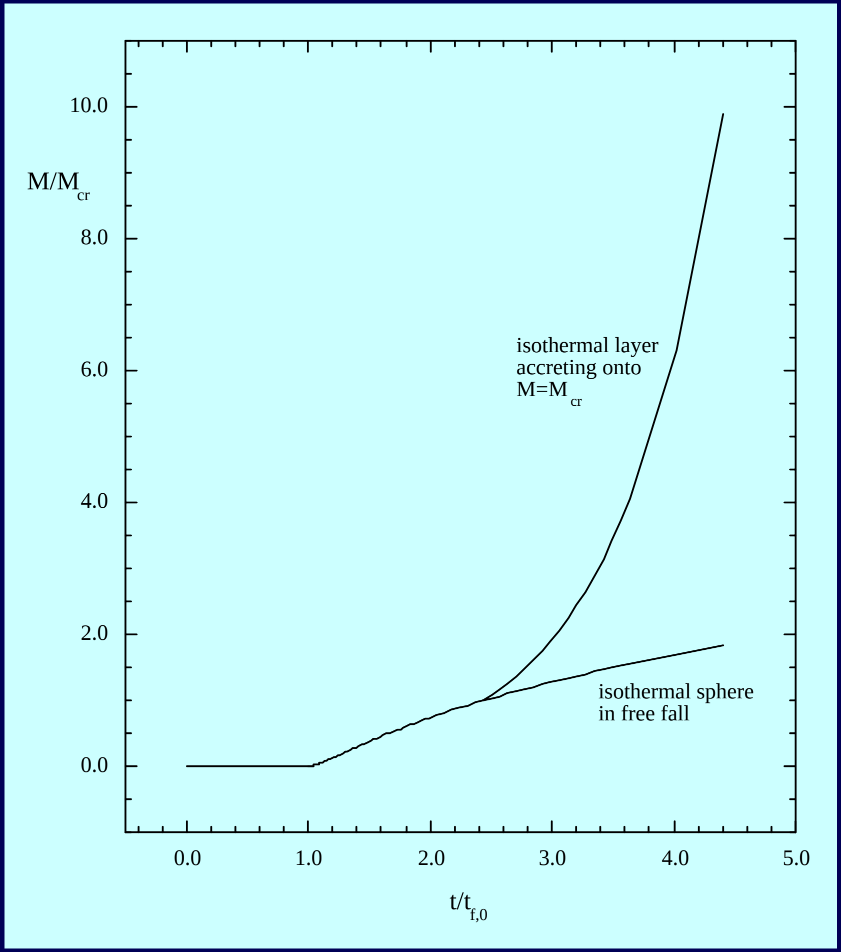
Layer Accretion Can Make Massive Stars

Steady flow onto stationary point source (Bondi 52) has solution for layer flow (2D) but not filament flow (1D).

2D flow is like large-scale disk accretion with no rotation.

$dm/dt \propto m \Rightarrow$ exponential growth with time scale $\tau_{acc} \sim (G\rho_{0,layer})^{-1/2}$

toy model - critical isothermal sphere embedded in layer collapses, then layer accretes.



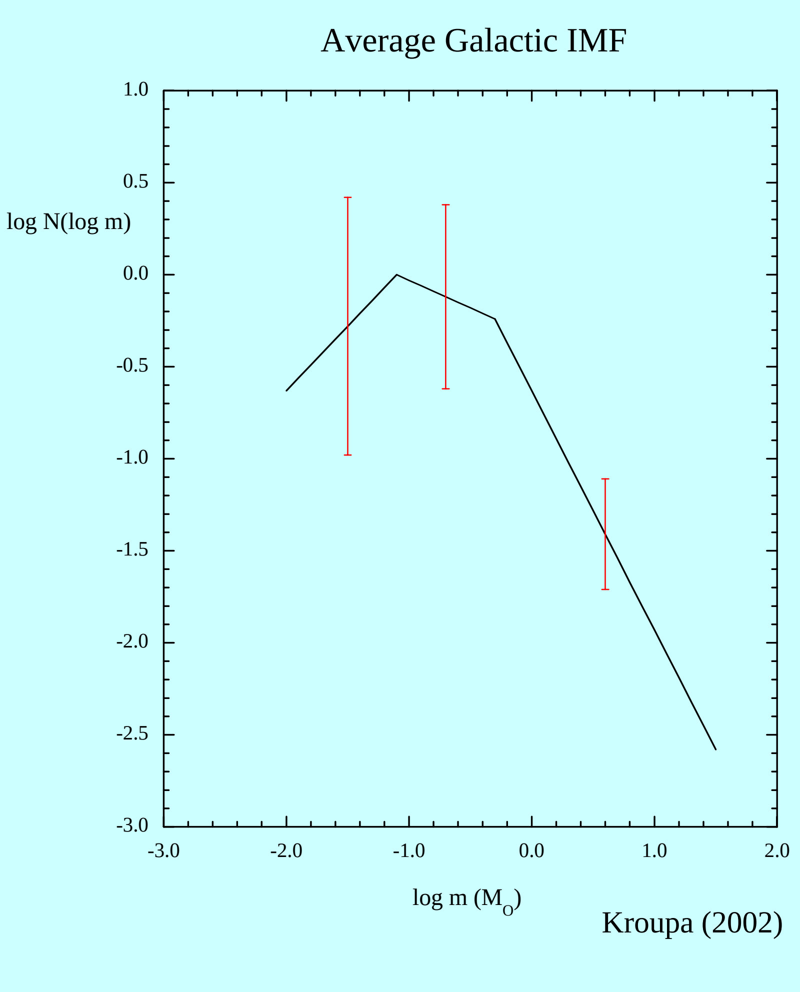
Matching the IMF

Assume densest gas is in isothermal spheres which model ‘prestellar cores’ (Ward-Thompson, Motte & André 94).

spheres are either isolated or ‘embedded’ in filaments or layers (Curry 00).

collapsing spheres accrete layer gas.

outflows, turbulence, ejection, and competition stop collapse and accretion with equal likelihood in each Δt - ‘random stopping’ (Myers 00, Basu & Jones 04)



Kroupa (2002)

cf. Muench et al 02, Lada & Lada 03

Collapse and Accretion Model

spherical collapse + random stopping...

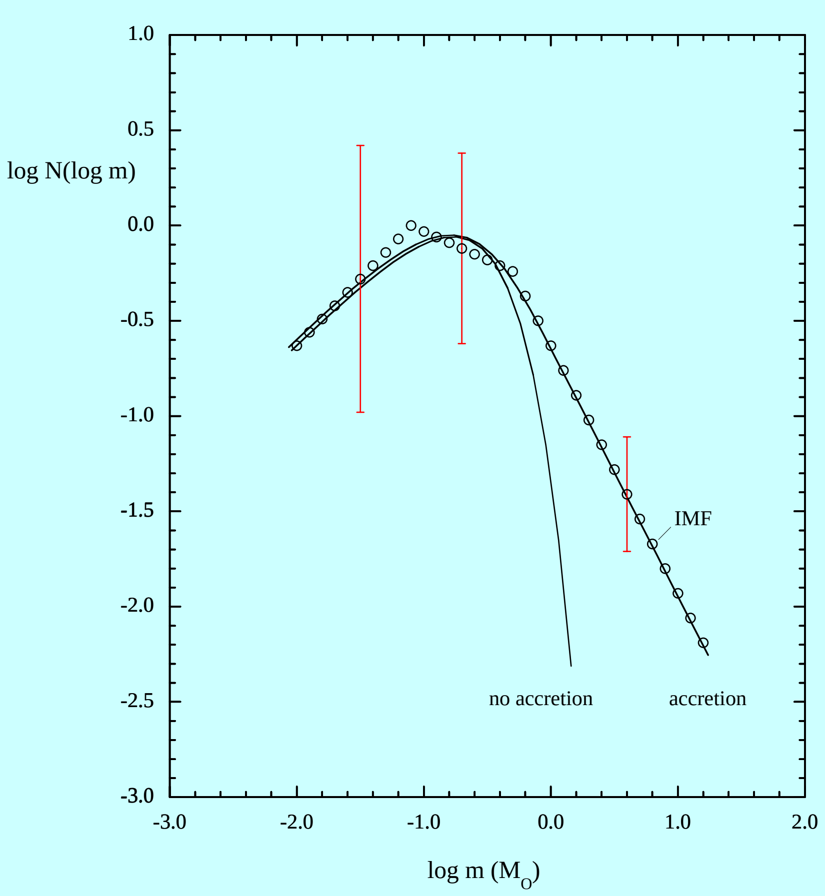
- matches low-mass slope (=2/3, property of isothermal sphere)

- gives peak mass 0.2 M_O for T=10 K, n_0=3-10×10^5 cm^{-3}

- cannot match high-mass IMF slope (Salpeter 55).

accretion + random stopping can match high-mass IMF slope.

high-mass slopes match if mean stopping time=(3/4) τ_{acc}



Summary

isolated cores… form 0-few low-mass stars

geometry	centrally condensed, aspherical, embedded in filaments
physics	sparse, cold, thermal > turbulent, contracting, ~ magnetic
chemistry	cold: freeze-out (CO), neutral (N_2H^+), enhanced (DX)
models	expanding, self-gravitating, condensing, collapsing
evolution	prestellar cores seem evolved, cores with VLM stars don’t

cluster-forming cores…form more stars, more massive stars

geometry	centrally condensed, aspherical, embedded in “blobs”
physics	numerous, hot, thermal > turbulent, contracting
chemistry	hot: diversity of species, liberation, shocks
models	collapse and accretion in a centrally condensed layer