

Formation and properties of protostars

Lee Hartmann, University of Michigan

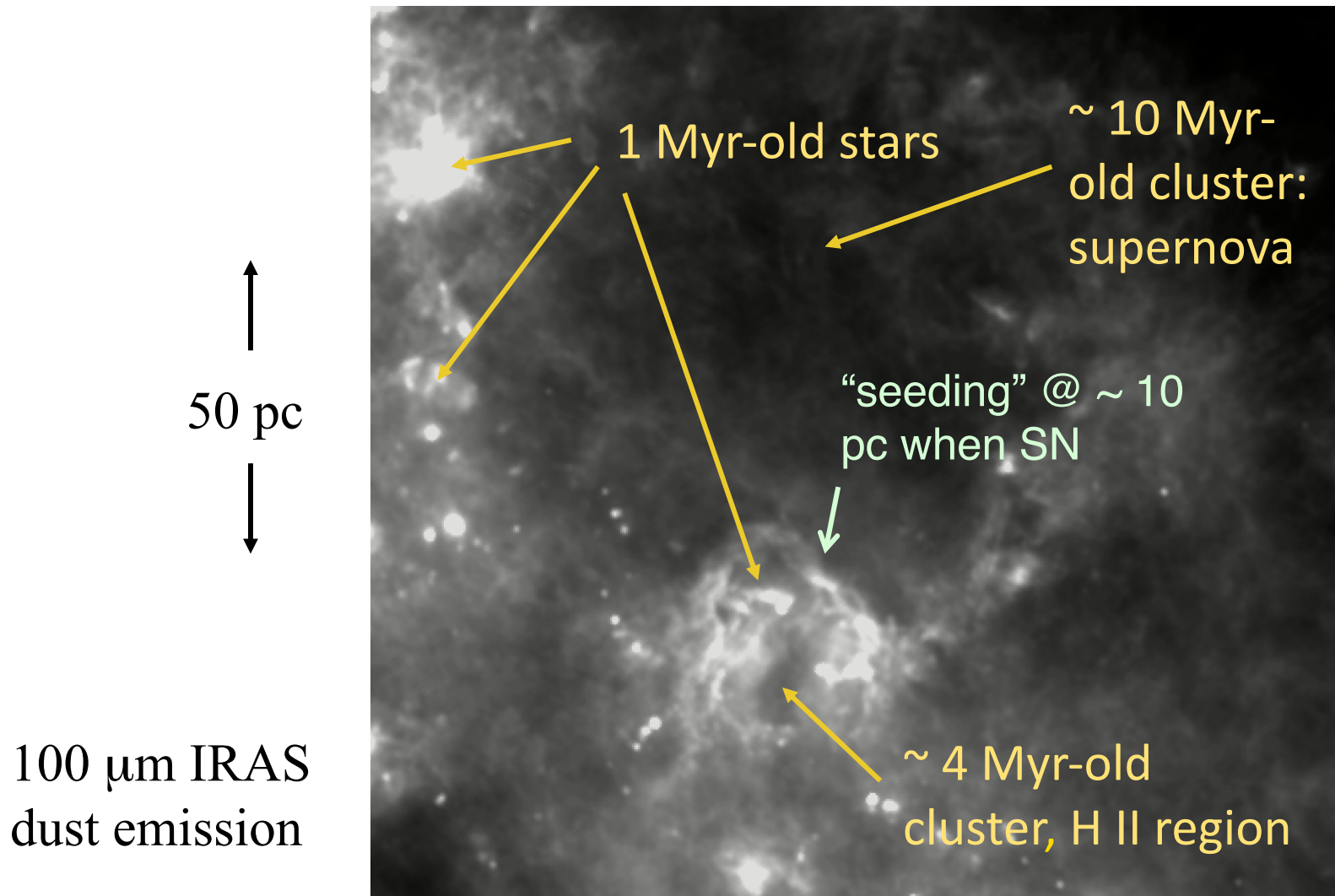
ISIMA 2011



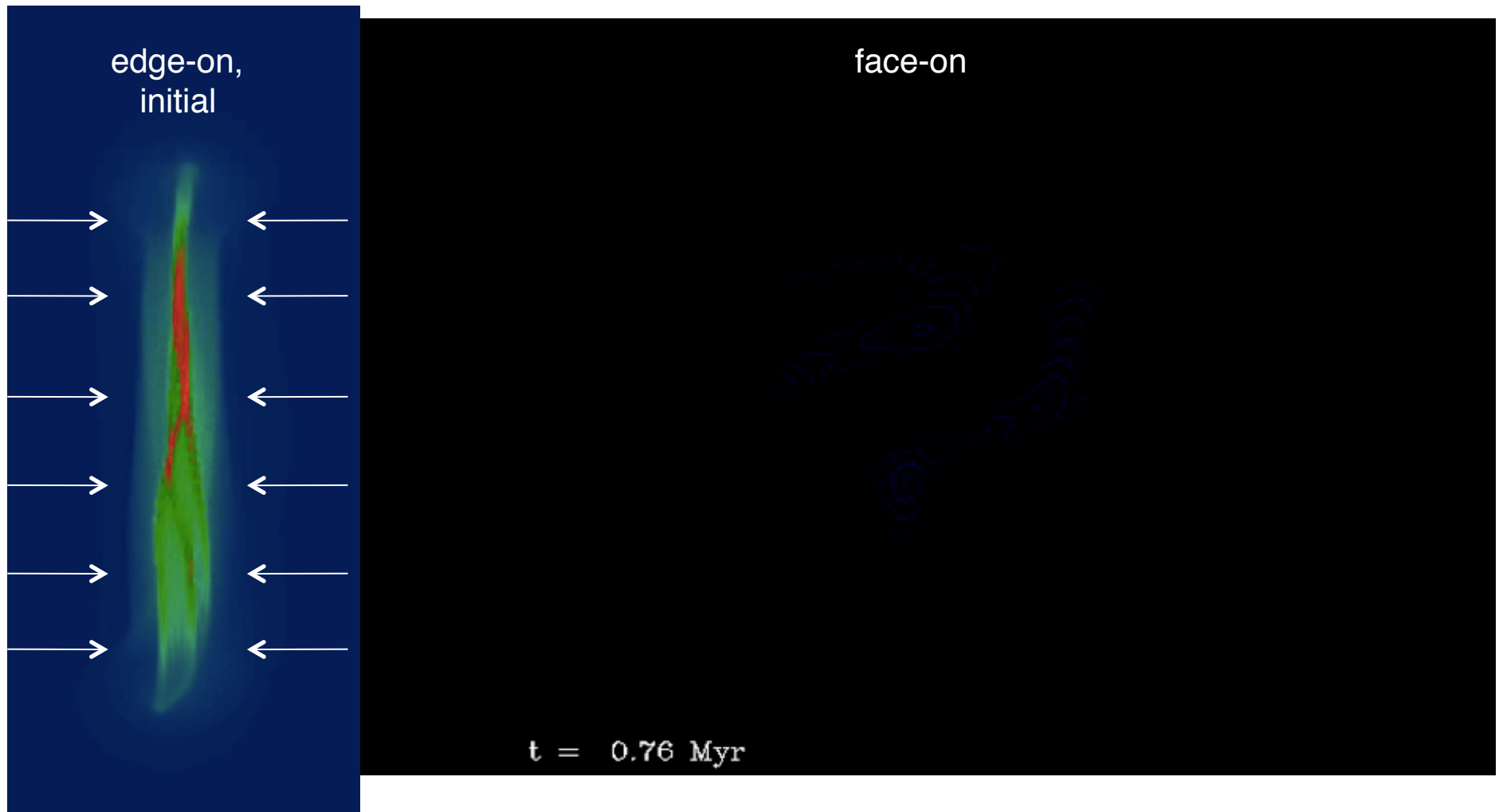
Topics:

- How to fragment into small masses (solar)
- Competitive accretion and high mass stars
- Protostellar core properties
- accretion onto star ultimately through disk

Last time: stellar energy input is important
atomic \rightarrow molecular in low density regions; mostly molecular in
high-density regions, but still must be compressed locally



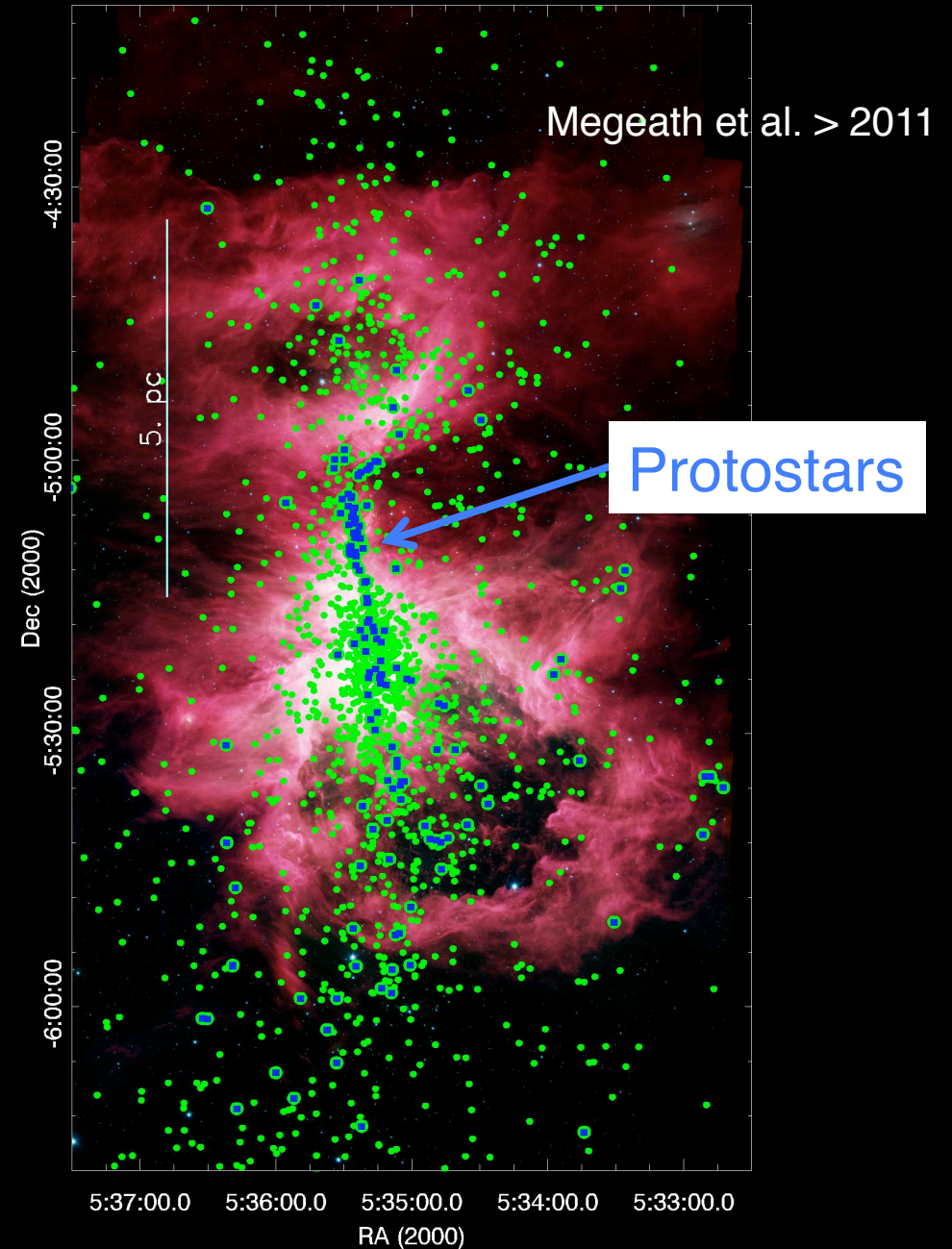
Also last time: fragmentation + gravity



Heitsch+ 2007, 2008; Hennebelle, many; Vazquez-Semadeni+ 2007, 2010

Orion Nebula Cluster

Orion Nebula cluster is not round; new (protostars) form in narrow filament; → EVOLUTION of gas and stellar distribution over few Myr



Magnetic fields?

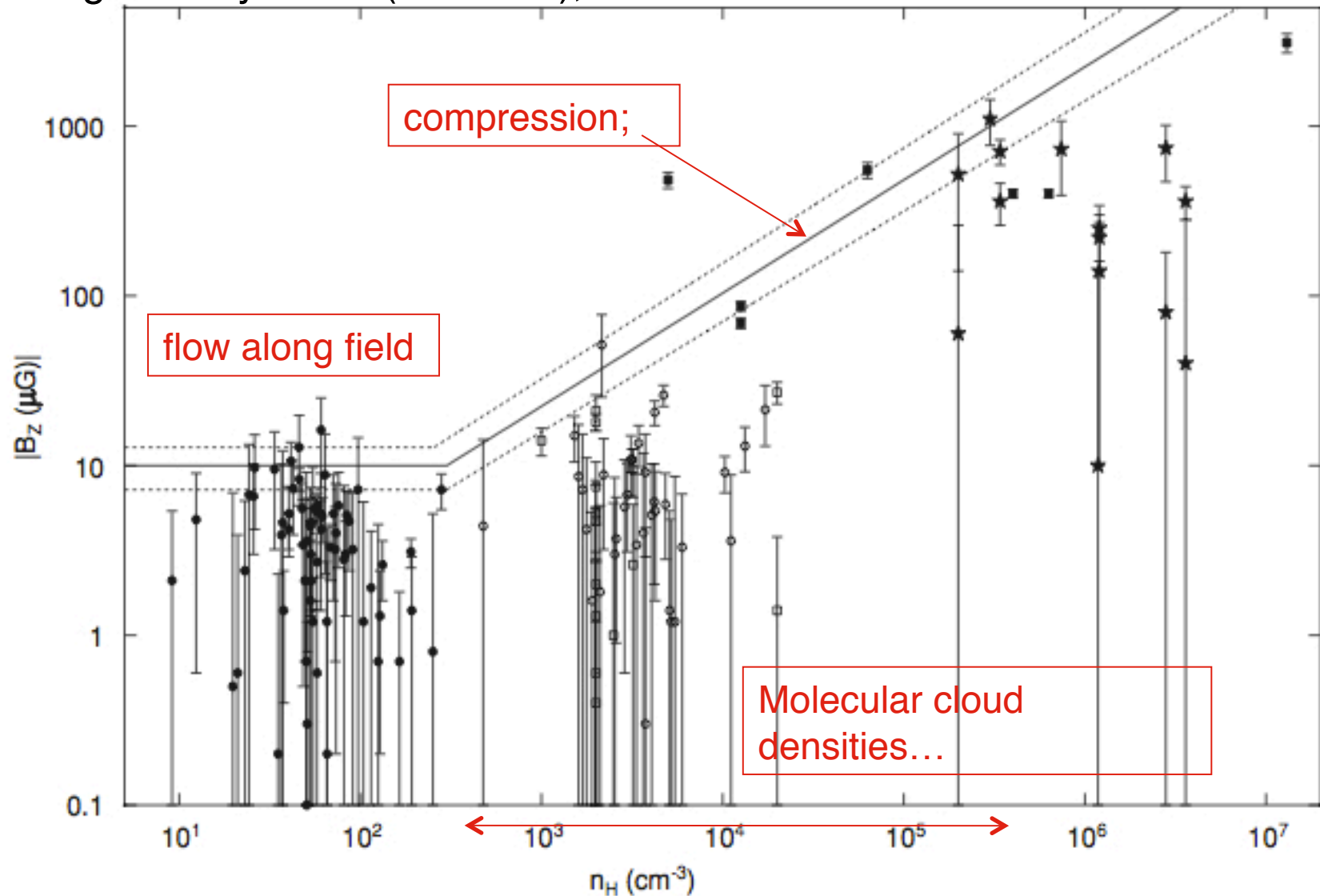
$B R^2 < G^{1/2} M$ for cloud collapse

(magnetic flux through cloud vs. M);

if $M >$ critical flux, can collapse;
if $M <$ critical, cannot collapse unless
gas can slip through field lines

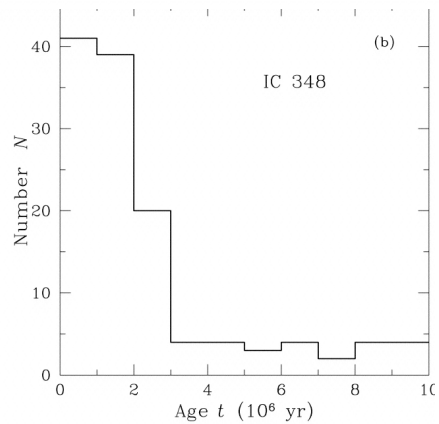
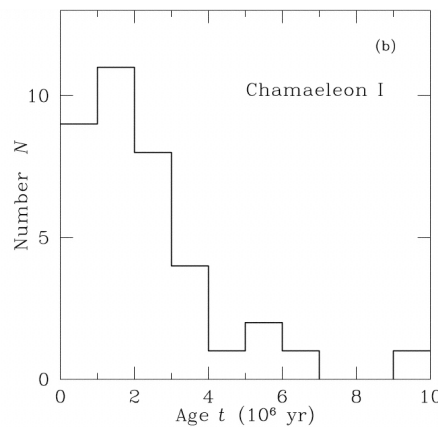
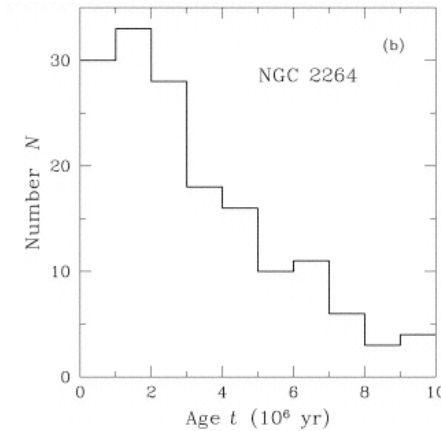
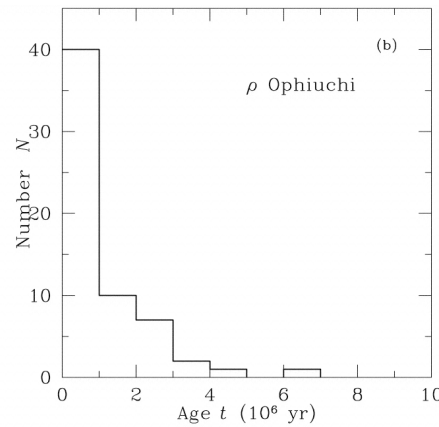
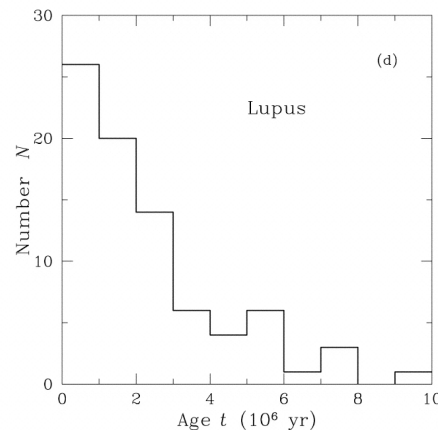
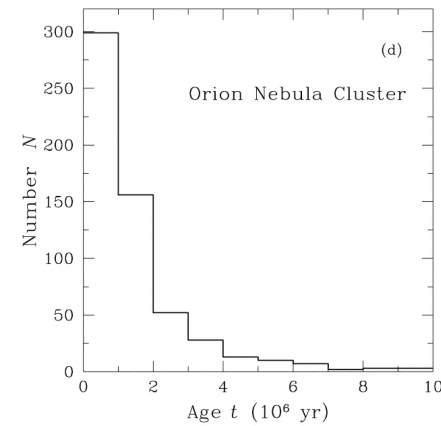
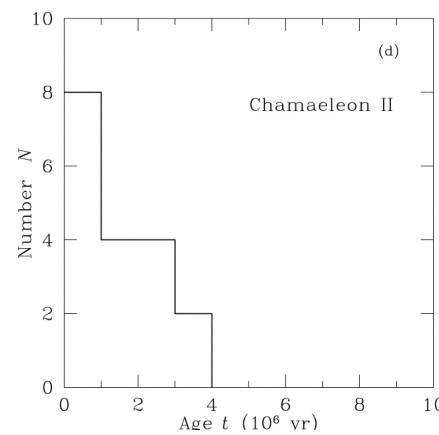
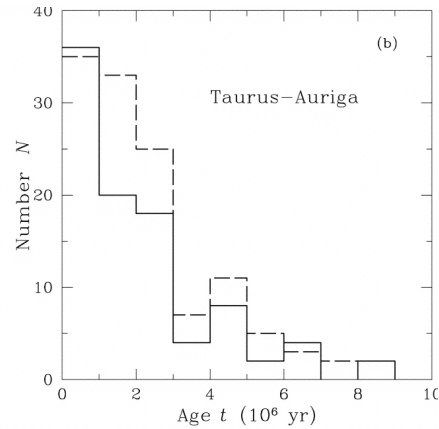
Most nearby molecular clouds have
very young stellar populations; \rightarrow not
slowed down much by ion-neutral drift
(ambipolar diffusion)

wide variation in mass-to-flux ratios in dense clouds; some are magnetically-weak (Crutcher), and these are where stars form



Palla &
Stahler

star-forming
regions; age
peaks \sim
1-2 Myr ago;
no slow
formation



If apparent age
spreads are real;
MAJOR evolution
over few Myr

okay, let's make stars; Jeans mass

The Jeans length and Jeans mass are approximate indicators of the scales over which gravity dominates over gas pressure support. One can use either energy or force balance to arrive at the approximate equilibrium condition

$$\frac{GM}{r^2} \sim \frac{1}{\rho} \frac{dP}{dr} \quad \text{or} \quad \frac{GM}{r} \sim c_s^2, \quad (1)$$

where c_s is the sound speed. Setting $M \sim \pi \rho r^3$, the terms in equations (1) are

$$G\rho r^2 \sim c_s^2, \quad (2)$$

$$r_J \sim \frac{c_s}{(G\rho)^{1/2}} \propto \left(\frac{T}{\rho}\right)^{1/2}, \quad (3)$$

$$M_J \sim \left(\frac{c_s^2}{G}\right)^{3/2} \rho^{-1/2} \propto \frac{T^{3/2}}{\rho^{1/2}}. \quad (4)$$

From (2), GRAVITY WINS for $r > r_J$ and $M > M_J$.

Jeans mass *problems*:

1. what density should we use?

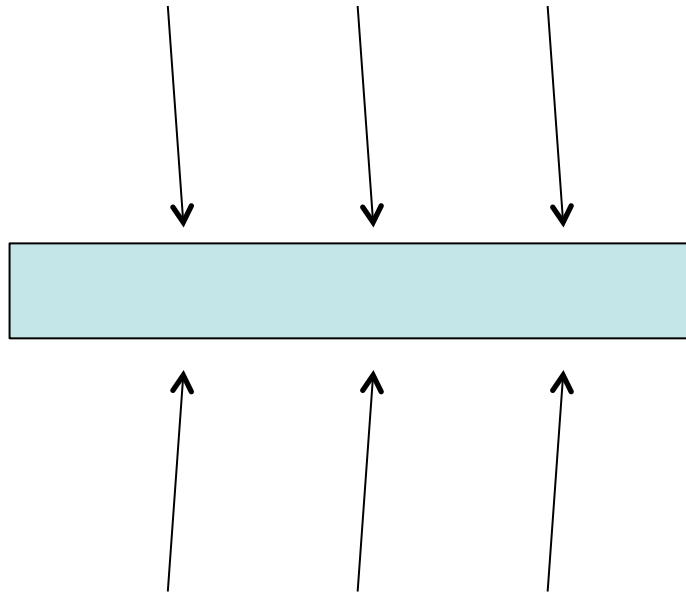
$$\text{collapse if } M > M_J \propto T^2 P^{-1/2}$$

$$T \sim 10\text{-}20 \text{ K (hard to get lower locally)}$$

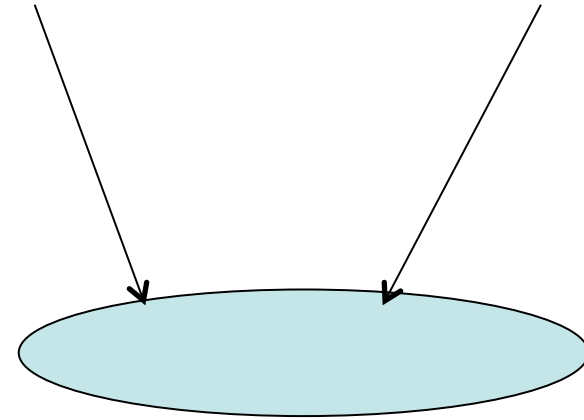
$M_J \approx 0.3 \text{ M(sun)}$ requires a pressure ≈ 1000
times the average ISM

$$0.03 \text{ M(sun)} \Rightarrow P \approx 10^5 \times \langle P \rangle(\text{ISM})$$

Where can we get such P ? GRAVITY
gravitational collapse; to filaments/ disk(-like)
structures: NEED DENSE CLUMPS to beat the
global collapse!

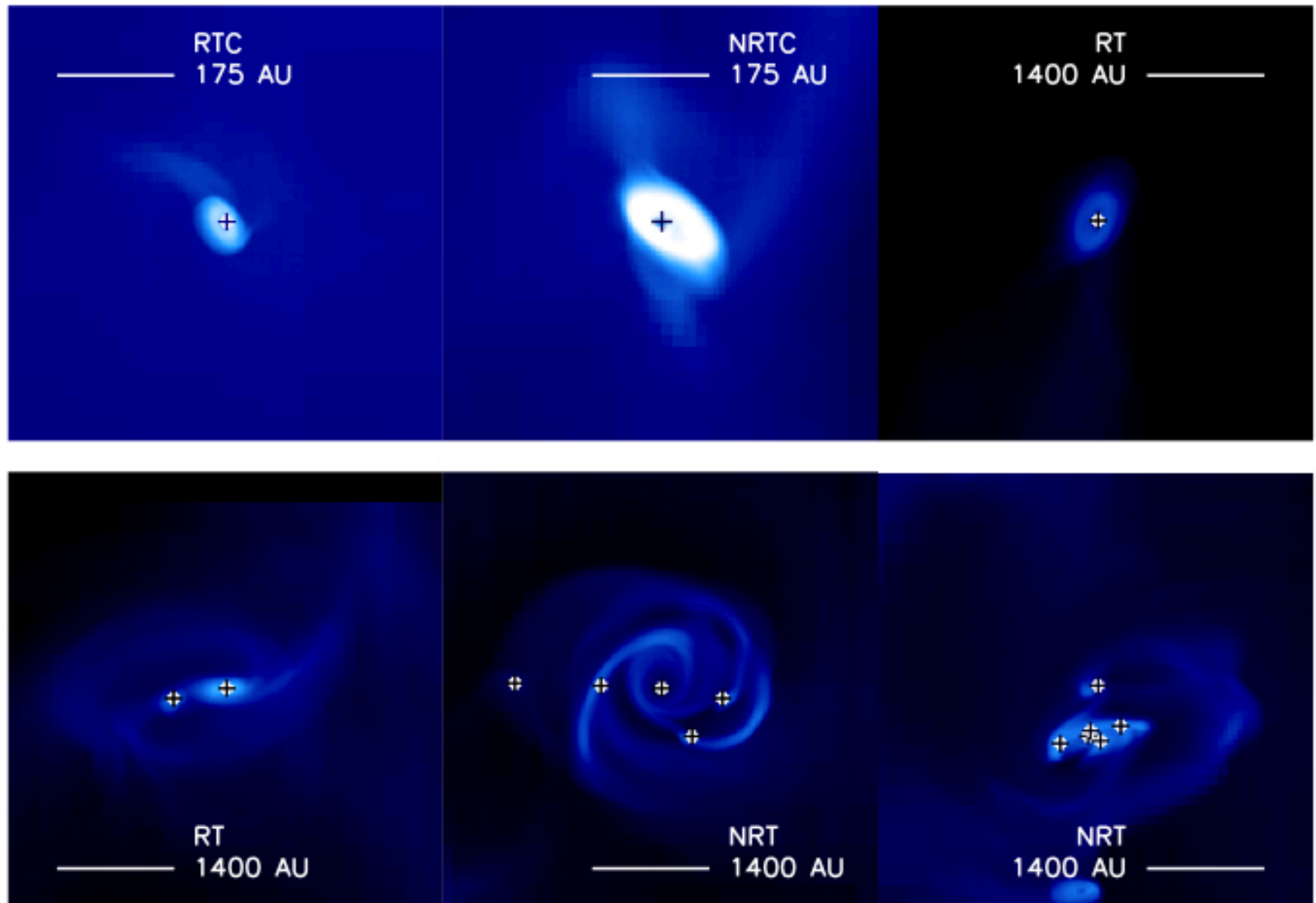


collapse to a filament,
subsonic region can
fragment (Gong & Ostriker,
Ballesteros-Paredes et al.)

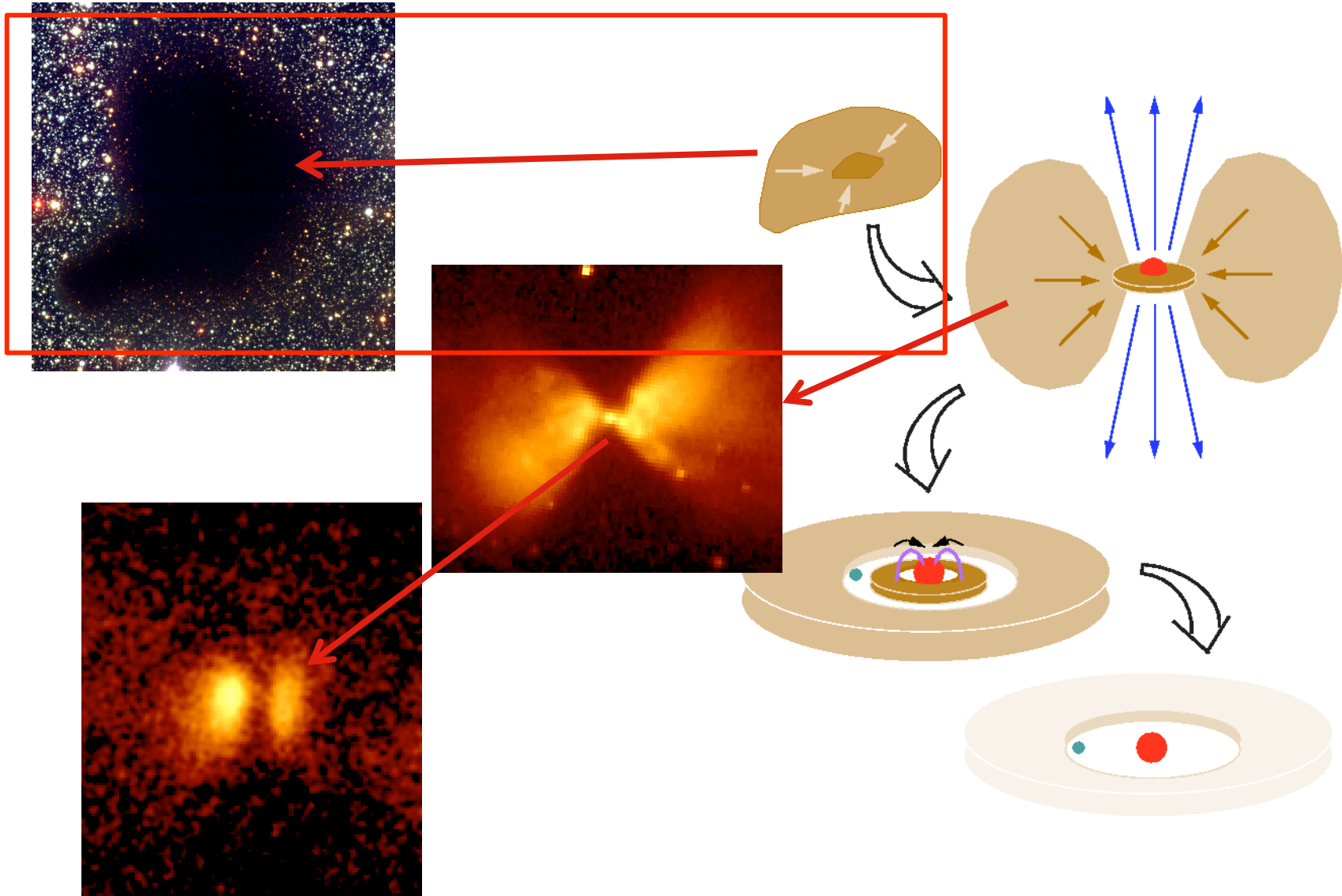


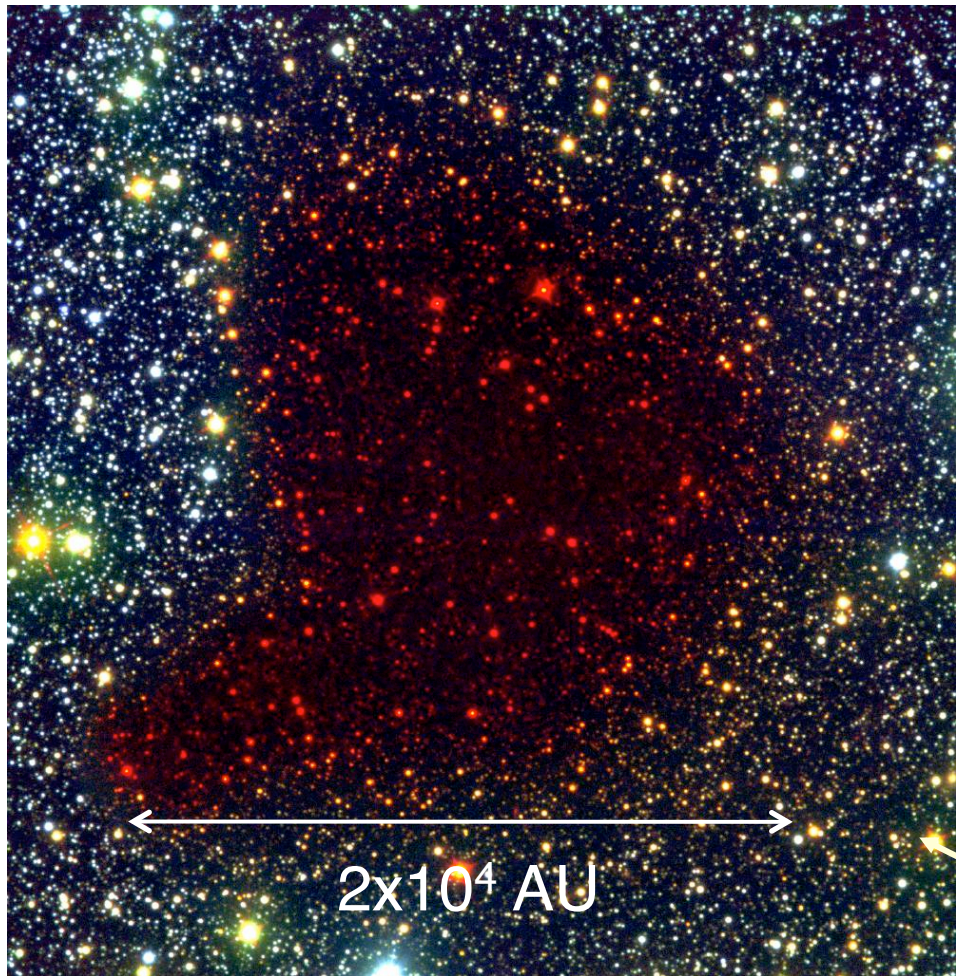
with angular momentum;
collapse to a dense disk;
subsonic region can
fragment

Supersonic infall due to gravity
doesn't dissipate like hydro
turbulence



Protostellar clouds (cores) to protostars





Alves, Lada & Lada 2001

Let's suppose fragmentation occurs somehow...

What should a protostellar cloud (core) look like?

1 $M(\text{sun})$: $T \sim 10\text{K}$;

$r_J \sim 0.1 \text{ pc} \sim 2 \times 10^4 \text{ AU}$

(detailed stability: $\sim \frac{1}{2}$ as big)

density $\sim 2 \times 10^4 \text{ cm}^{-3} (\text{H}_2)$

\Rightarrow that's what we see... so pressure support limit makes some sense...

The “ideal” case,
enhanced by
circular averaging

see supplemental
material for
Bonnor-Ebert
spheres

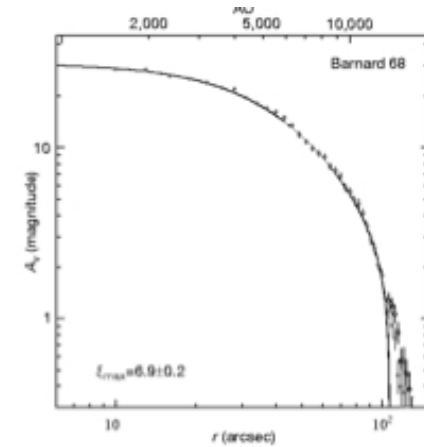
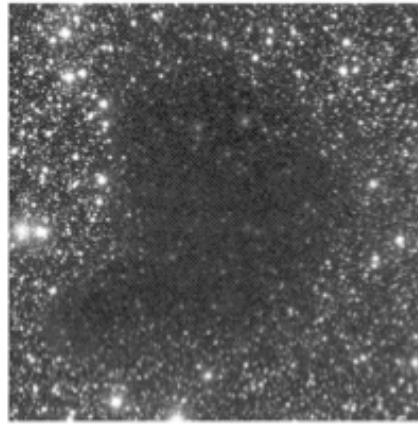
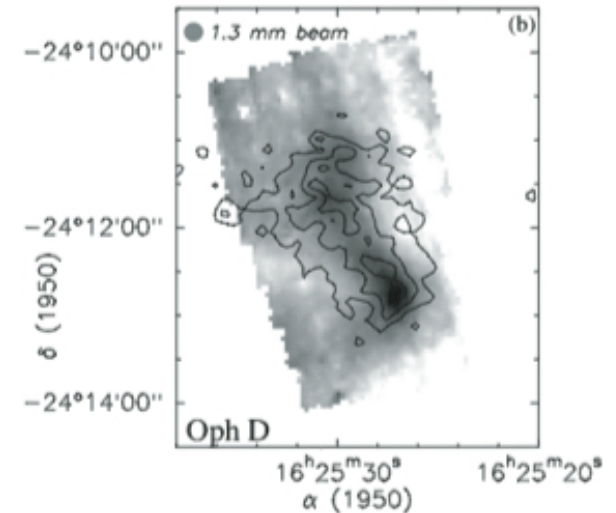
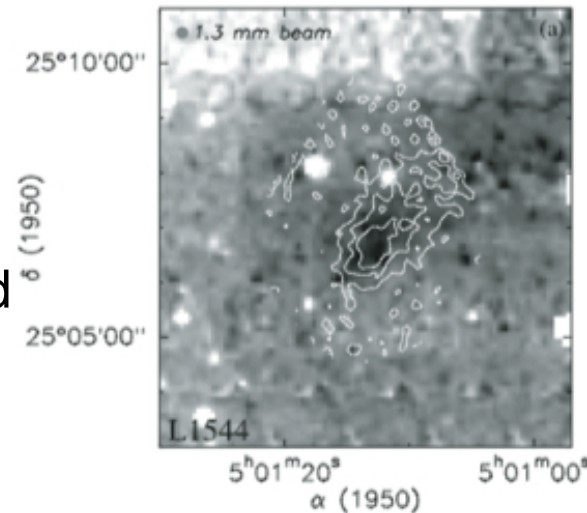


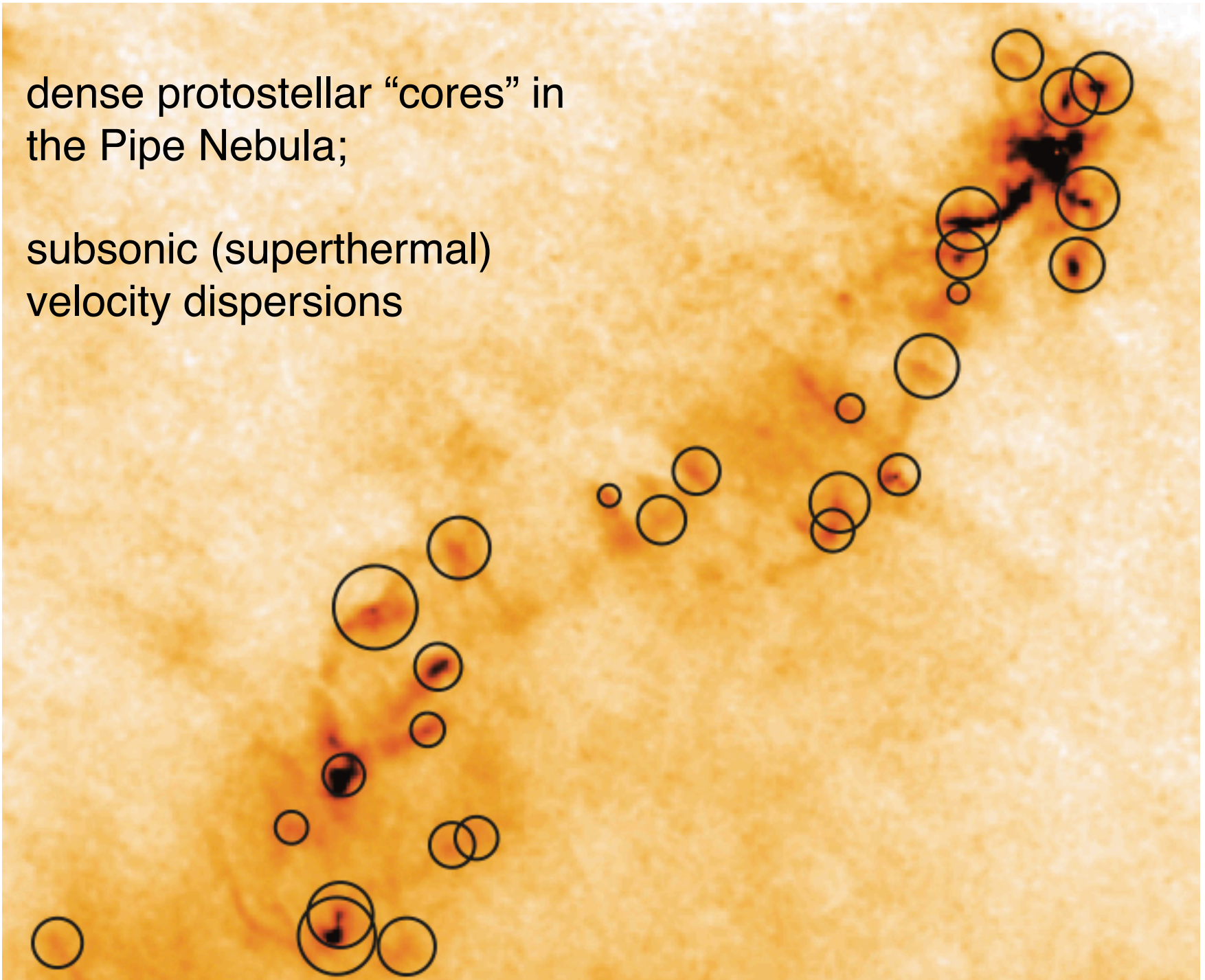
Fig. 3.5. Left panel: near-infrared image of the Bok globule B68. Right panel: azimuthally-averaged column density, inferred from the extinction measurements, compared with a Bonnor-Ebert sphere of $\xi_{max} = 6.9 \pm 0.2$. From Alves *et al.* (2001).

The typical case;
cores are elongated
by factors $\sim 2:1$, and
are more typically
prolate than oblate
(Myers)

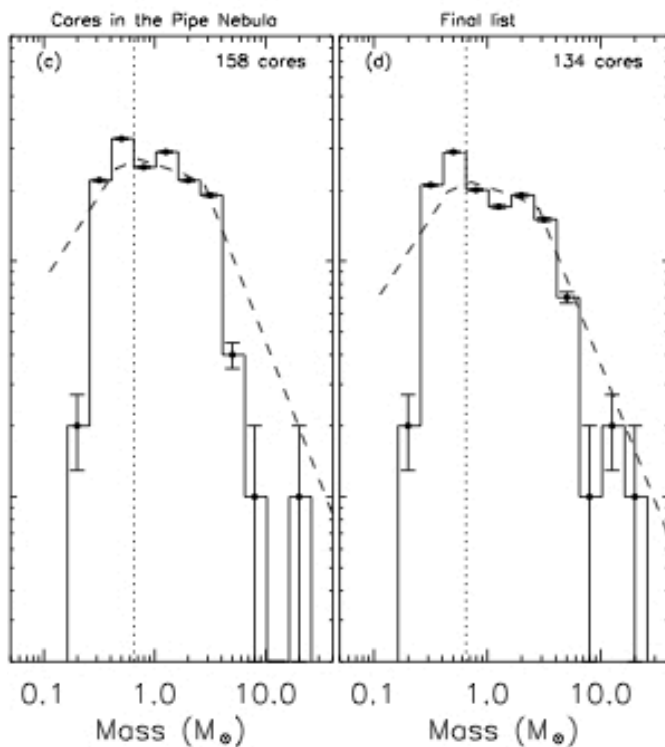


dense protostellar “cores” in
the Pipe Nebula;

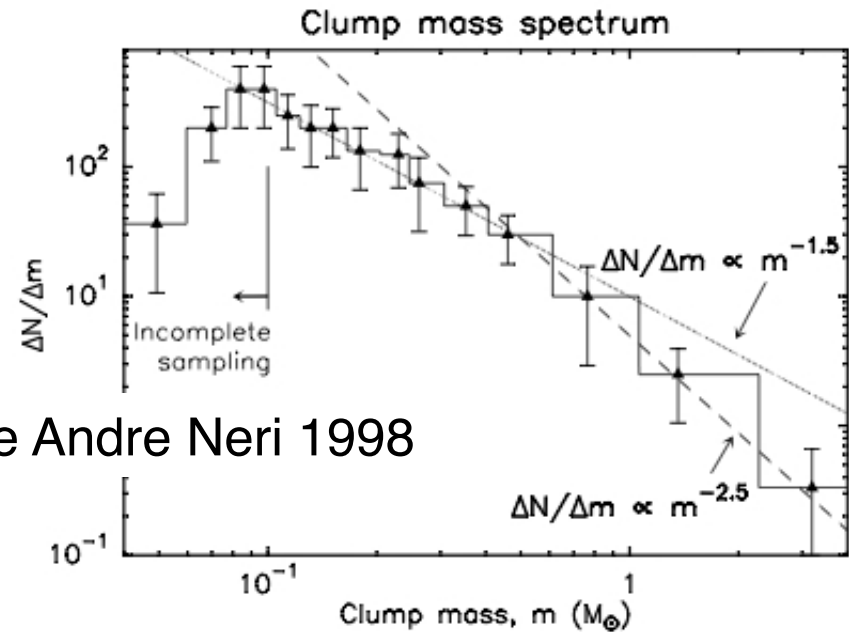
subsonic (superthermal)
velocity dispersions



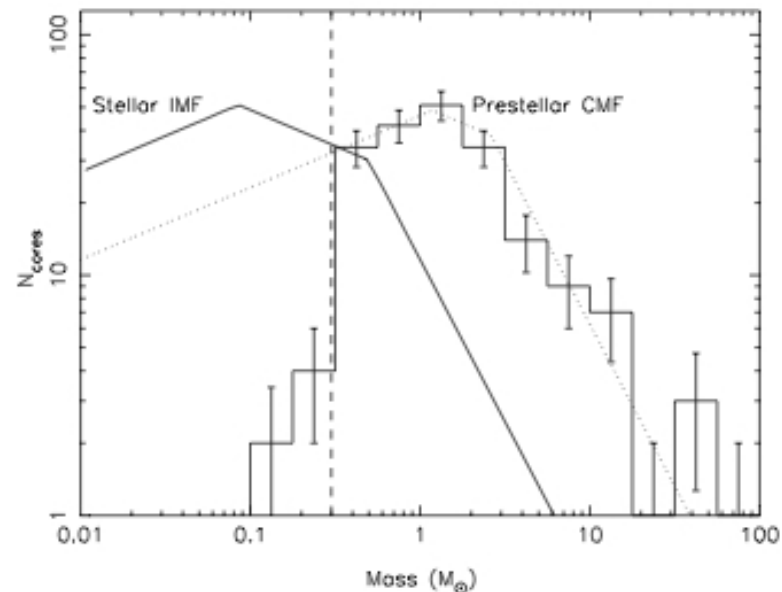
protostellar core mass functions: is there a direct mapping to the stellar mass function?



Rathborne et al. 2009



Motte Andre Neri 1998



Nutter & Ward-Thompson 2007

stellar initial
mass
functions;
appear similar
to core mass
functions...

but low-mass
end of core
IMF not well
known; cores
probably
fragment (see
lecture 3)

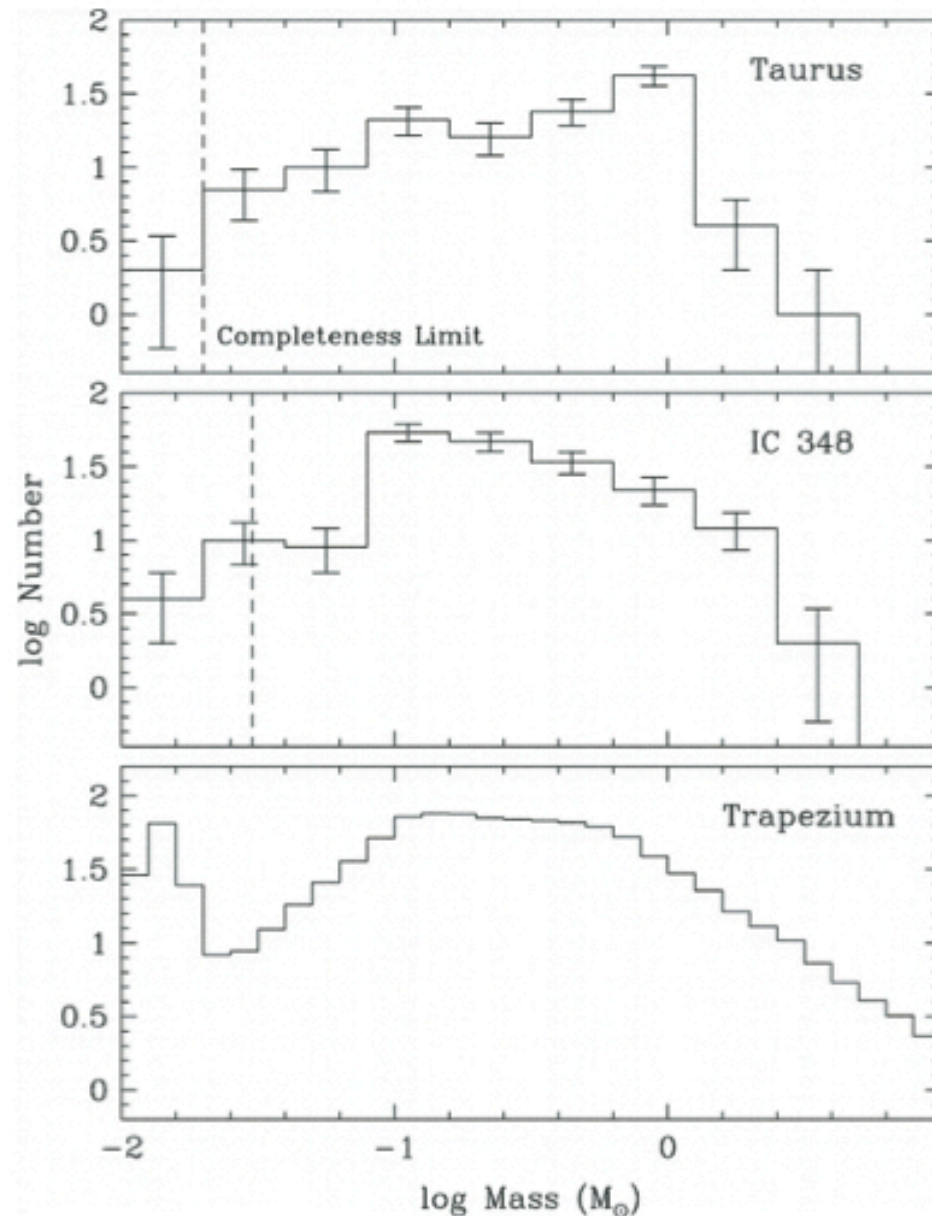


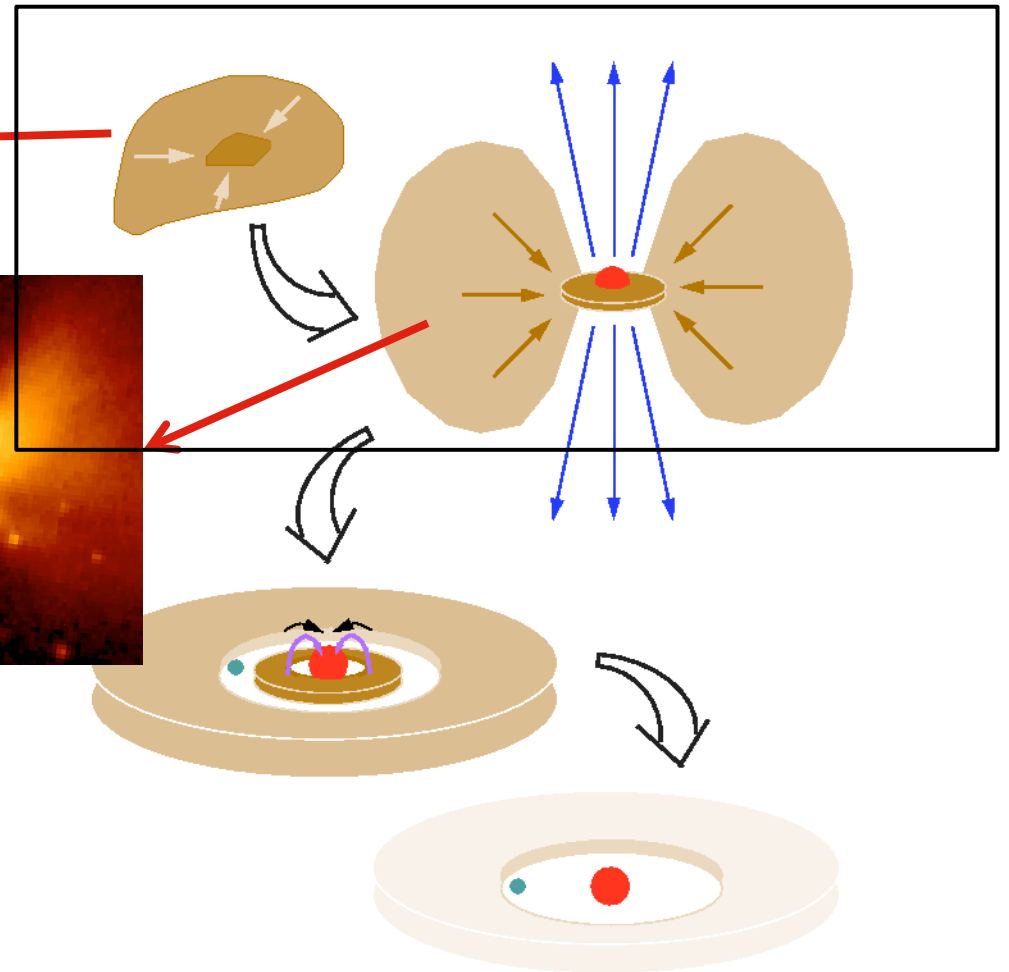
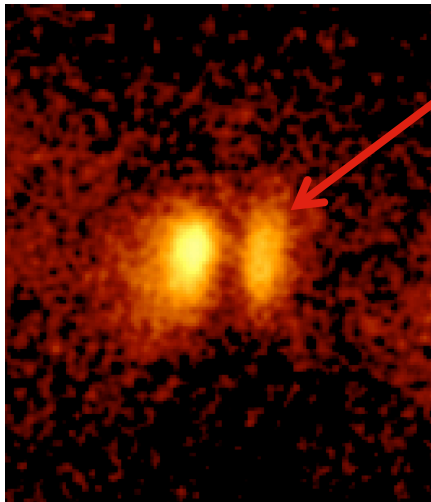
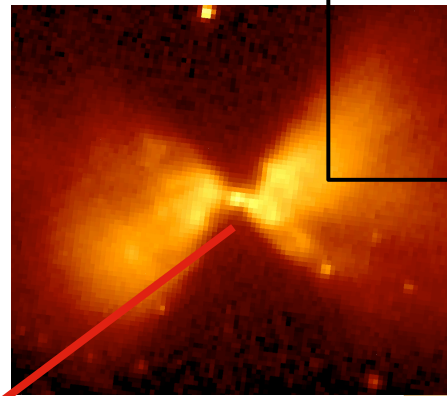
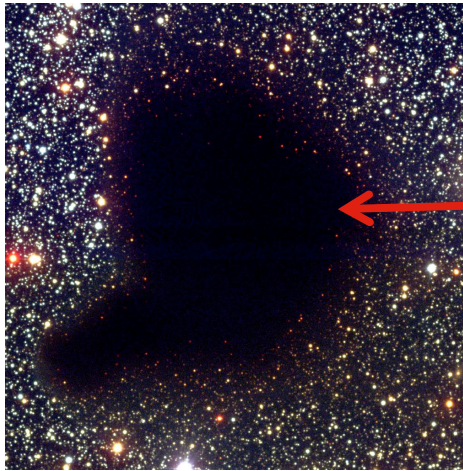
Fig. 6.8. Recent estimate of the IMFs in three nearby star-forming regions. From Luhman (2004) and Muench *et al.* (2002).

Problem (unsolved) with going from core mass function to stellar mass function:

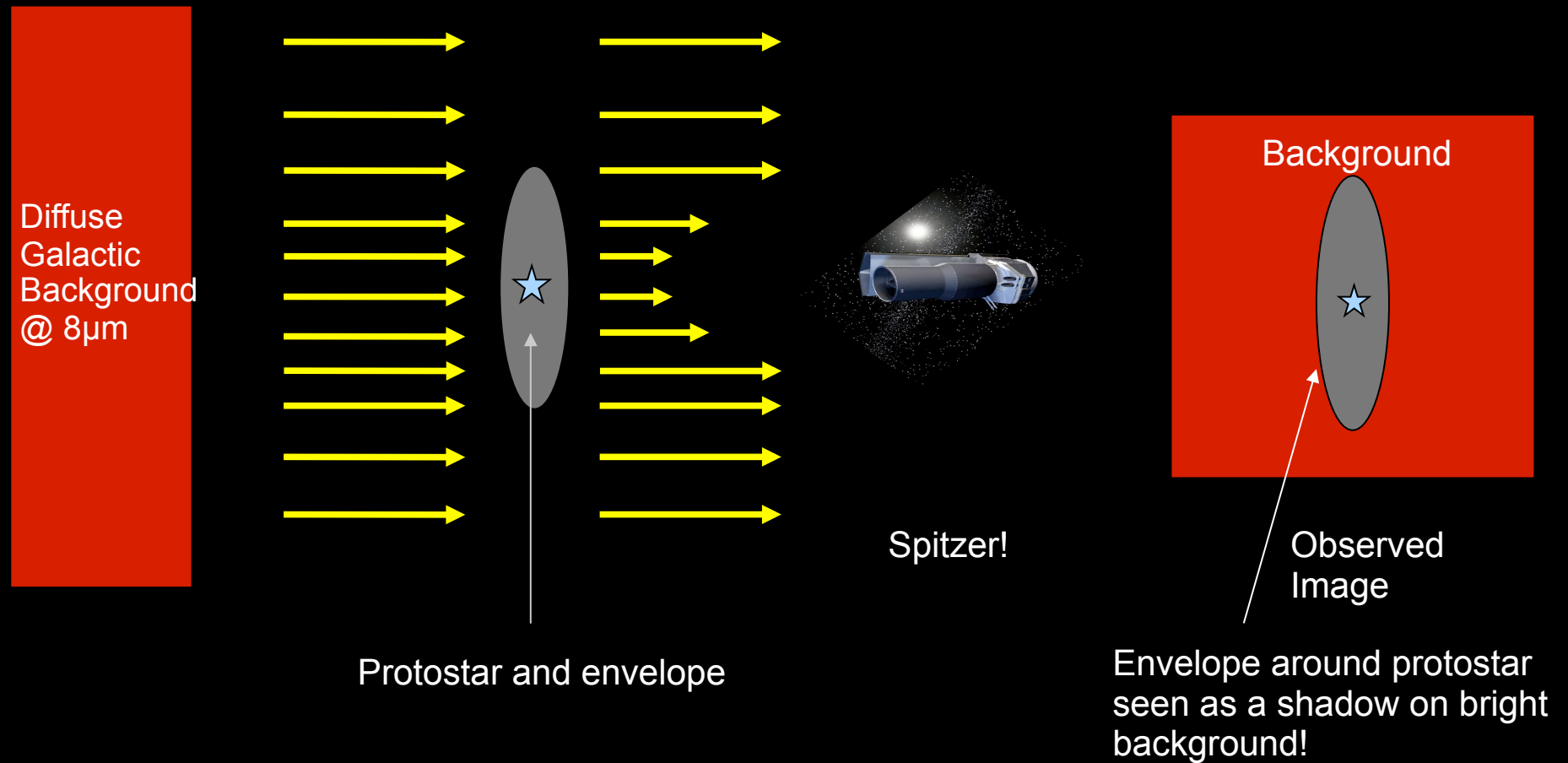
where do you stop?

generally not in a complete vacuum, and gravity is a long range force...

Protostellar clouds (cores) to protostars

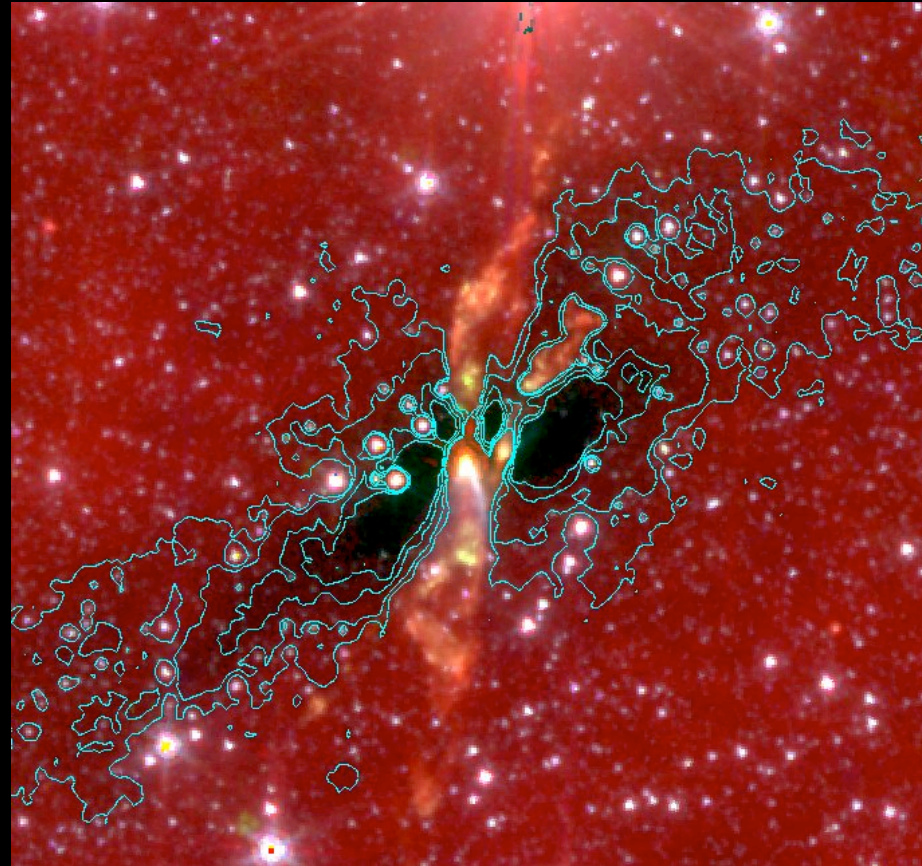


Spitzer 8 μ m Extinction Mapping



Protostellar Zoo

BHR71



Visible (T. Bourke)

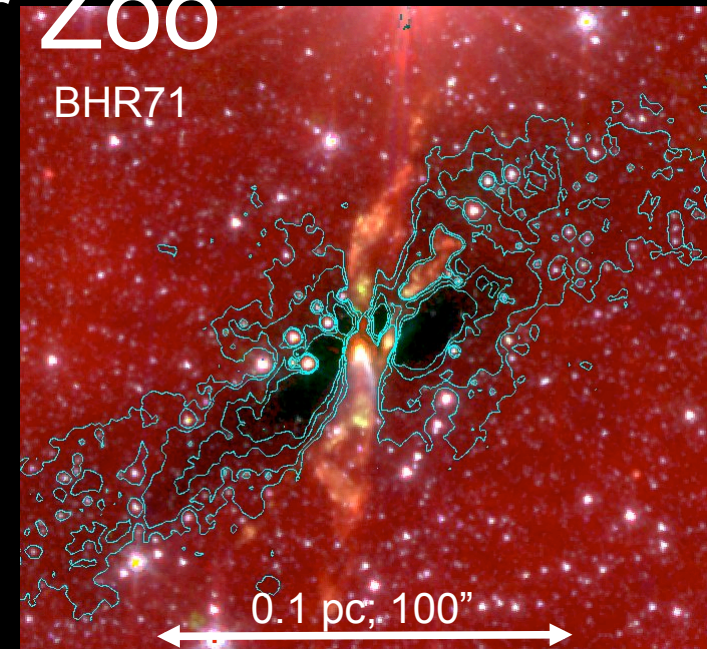
Spitzer

Protostellar Zoo

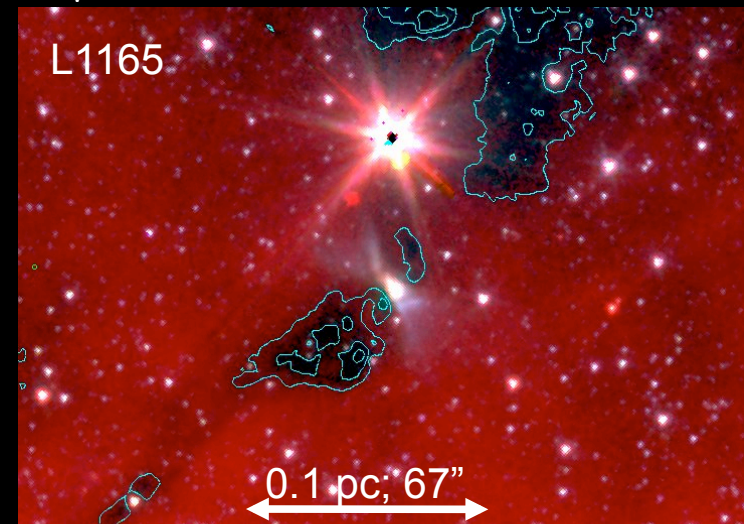


Contours: $A_V = 15, 22.5, 30$

Tobin et al. (2010)

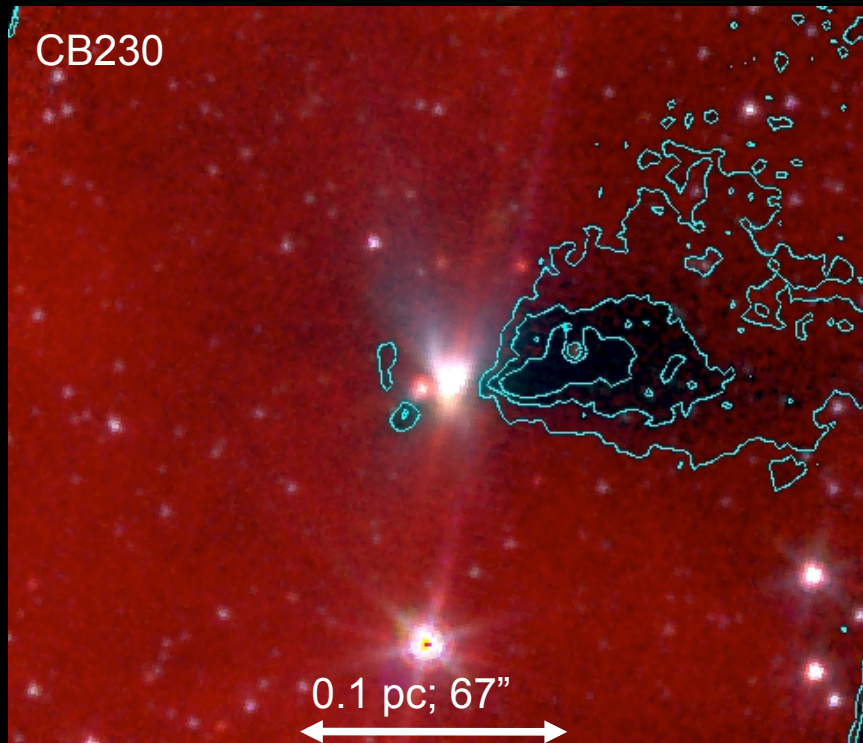


$A_V = 15, 20, 30, 40$

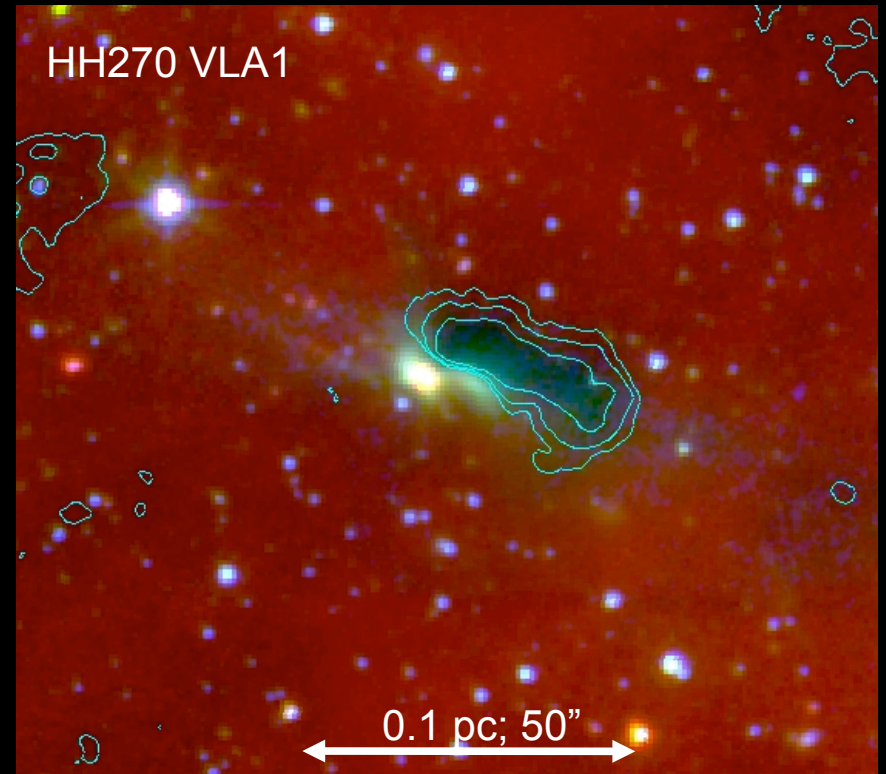


Contours: $A_V = 10, 20, 30$

Protostellar Zoo

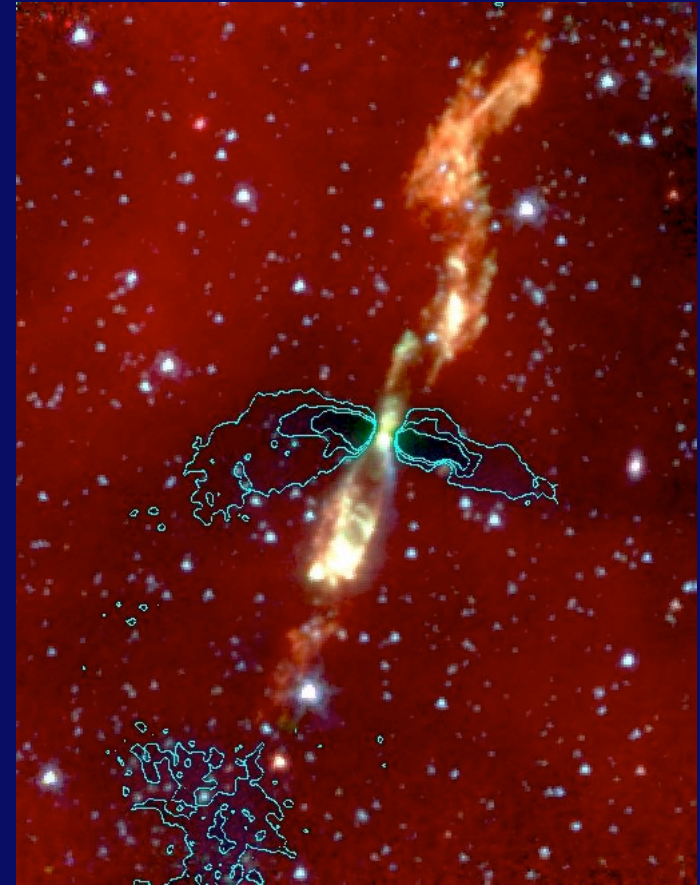
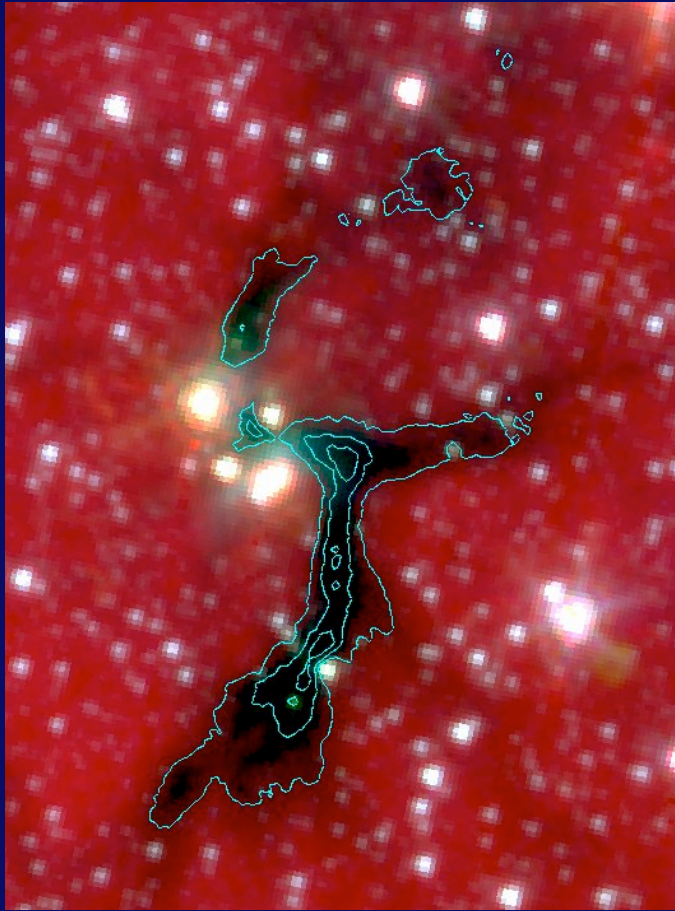


$A_V = 10, 20, 30$



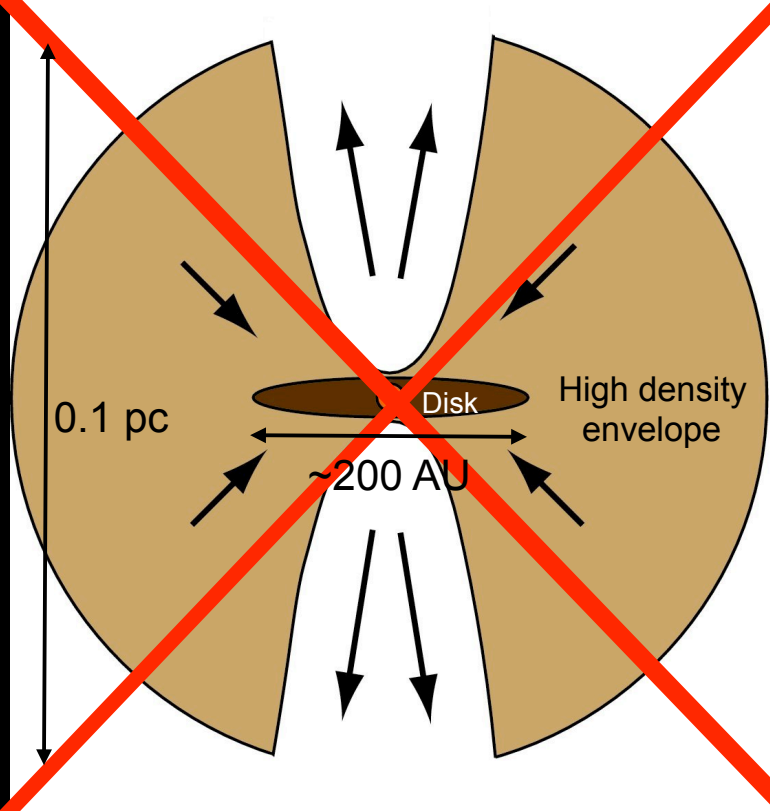
$A_V = 10, 20, 30$

Tobin et al. (2010)

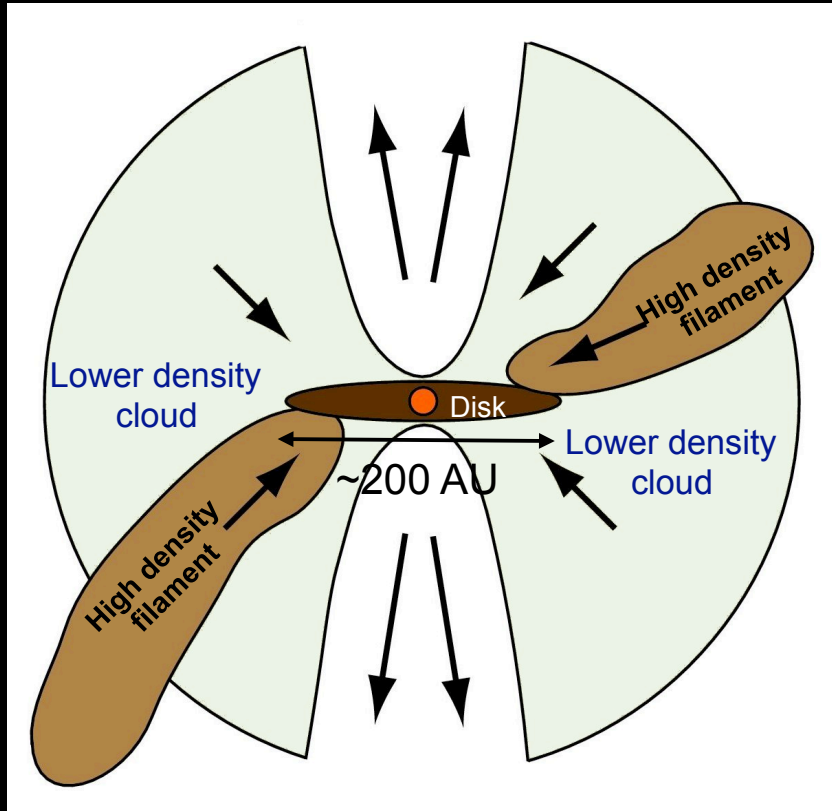


Many examples of complex,
filamentary protostellar infall
(become more anisotropic
during gravitational collapse)

Standard Picture



Idealized collapse



More Typical

Jeans mass *problems*

1. what density should we use?
2. r_J , M_J are **MINIMA**

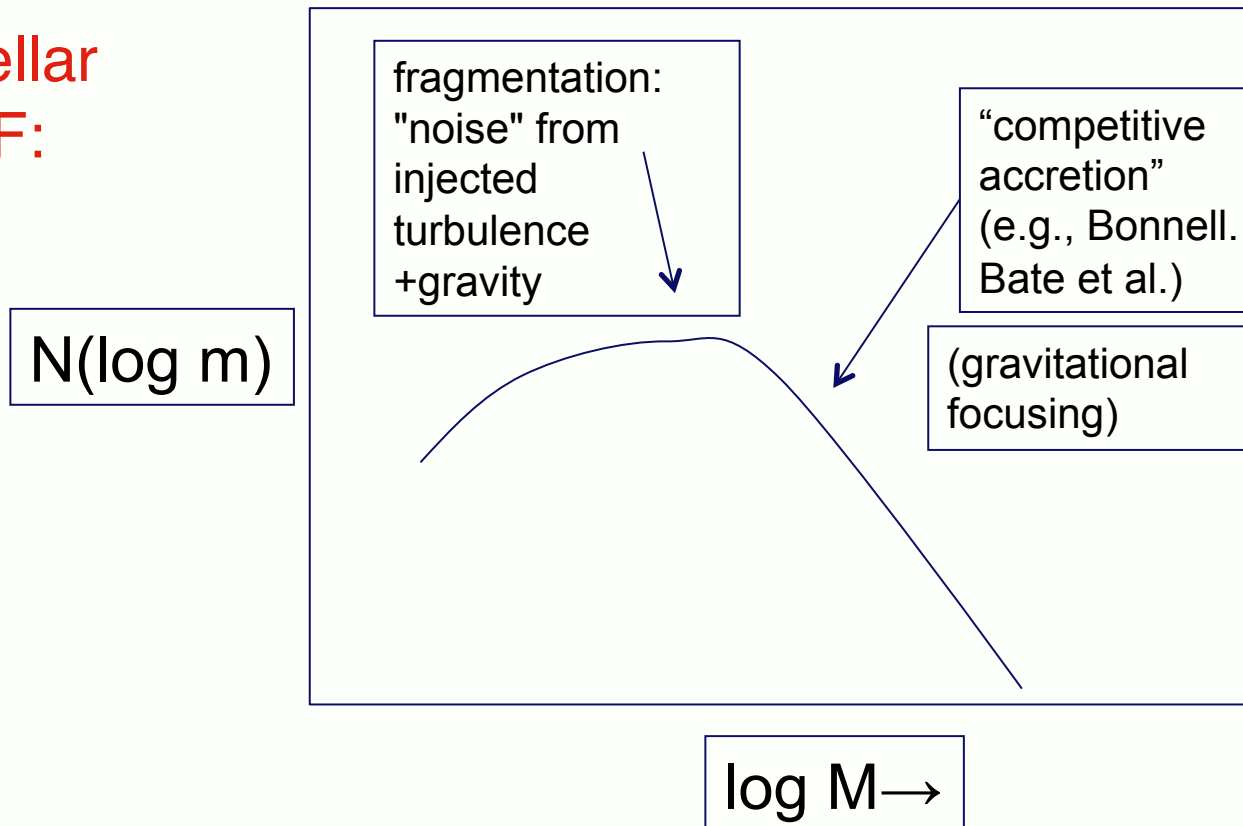
Consider a sphere of radius R with uniform density ρ . At large scales, where gas pressure is not important, all radii fall in at the same time. One can see this from dimensional analysis:

$$v^2 \sim GM/R \sim G\rho R^2; \quad \text{thus} \quad t_{ff} \sim R/v \sim (G\rho)^{-1/2} \quad (1)$$

Gravity is a long range force:

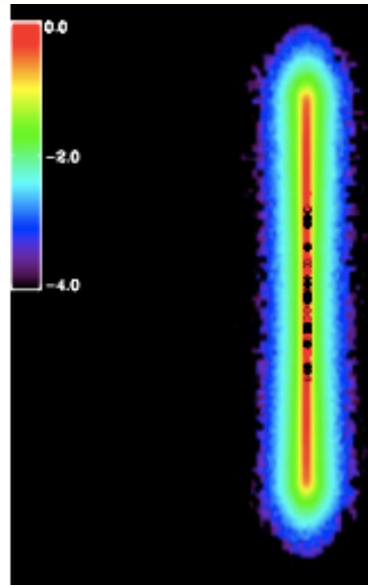
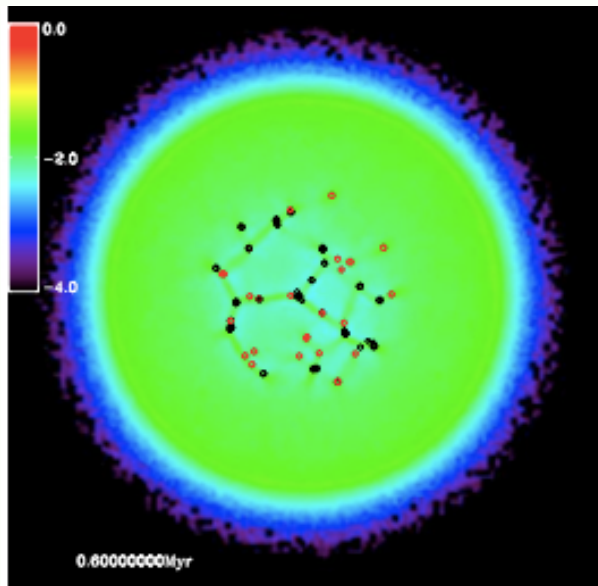
⇒ GRAVITATIONAL FOCUSING is UNAVOIDABLE
because molecular clouds have MANY M_J
("competitive accretion"; make massive stars,
clusters(lecture 1))

Stellar IMF:

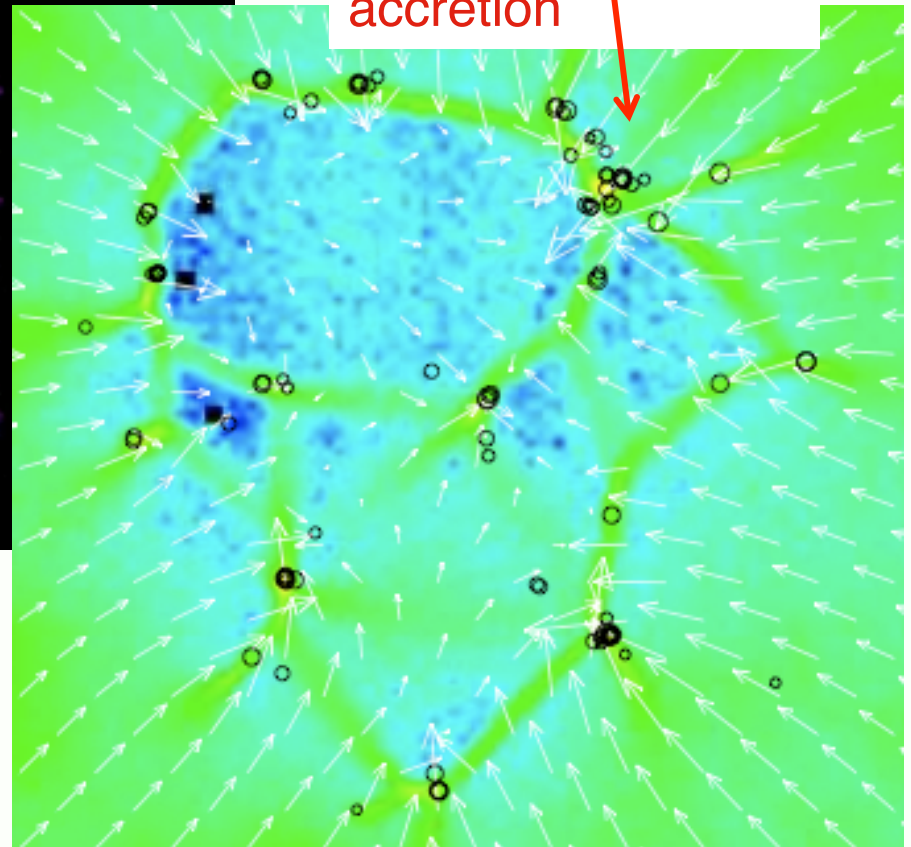


- Low-mass end; Need **MUCH** higher pressures than ISM to make very low mass stars/bds \Rightarrow gravity!
- High-mass end; Jeans mass is **MINIMUM**; “long range” infall needed (need to worry about angular momentum...)

Test of competitive accretion in non-clustered environment; accretion of randomly-placed sink particles in a sheet



“mini clusters” form
(mass segregation
along with
accretion



make filaments naturally, as in
cosmic web

*Hsu, Hartmann, Heitsch,
Gomez 2010*

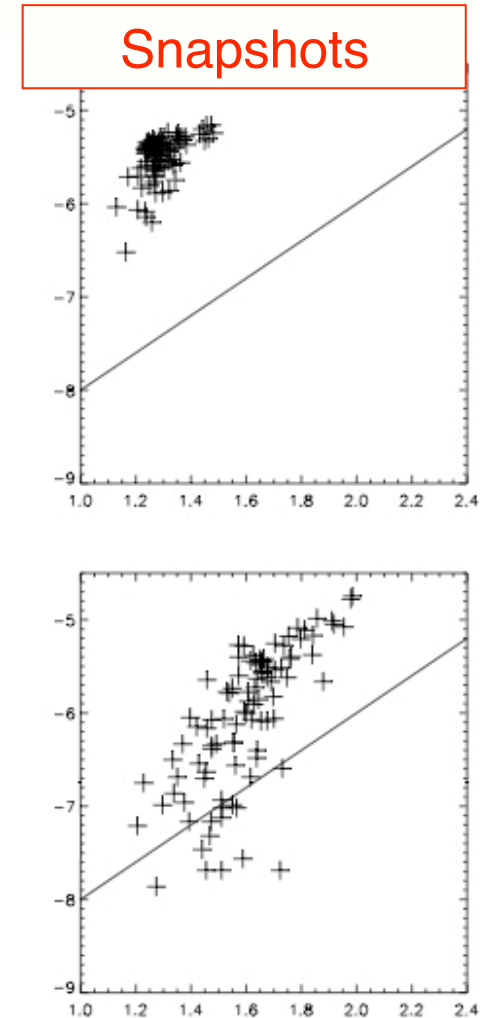
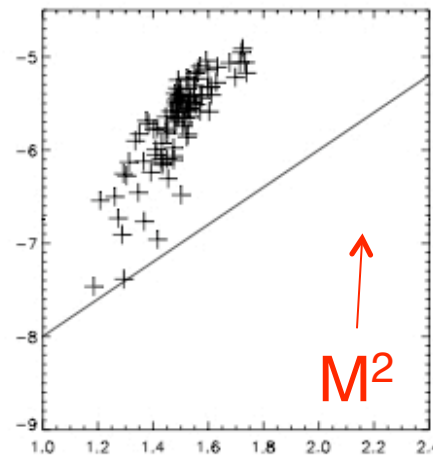
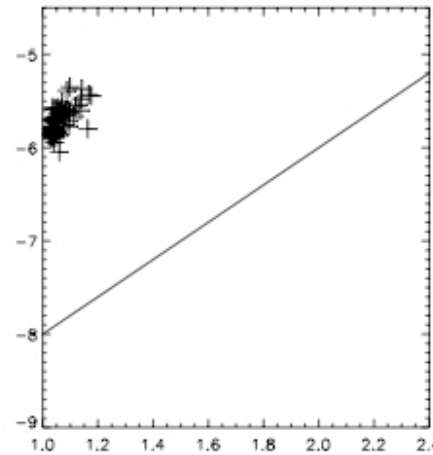
Bondi-Hoyle:

“capture radius”
 $r_c \sim GM/v^2$

$$dM/dt \sim \pi r_c^2 \rho v$$

$$dM/dt \propto M^2 \rho v^{-3}$$

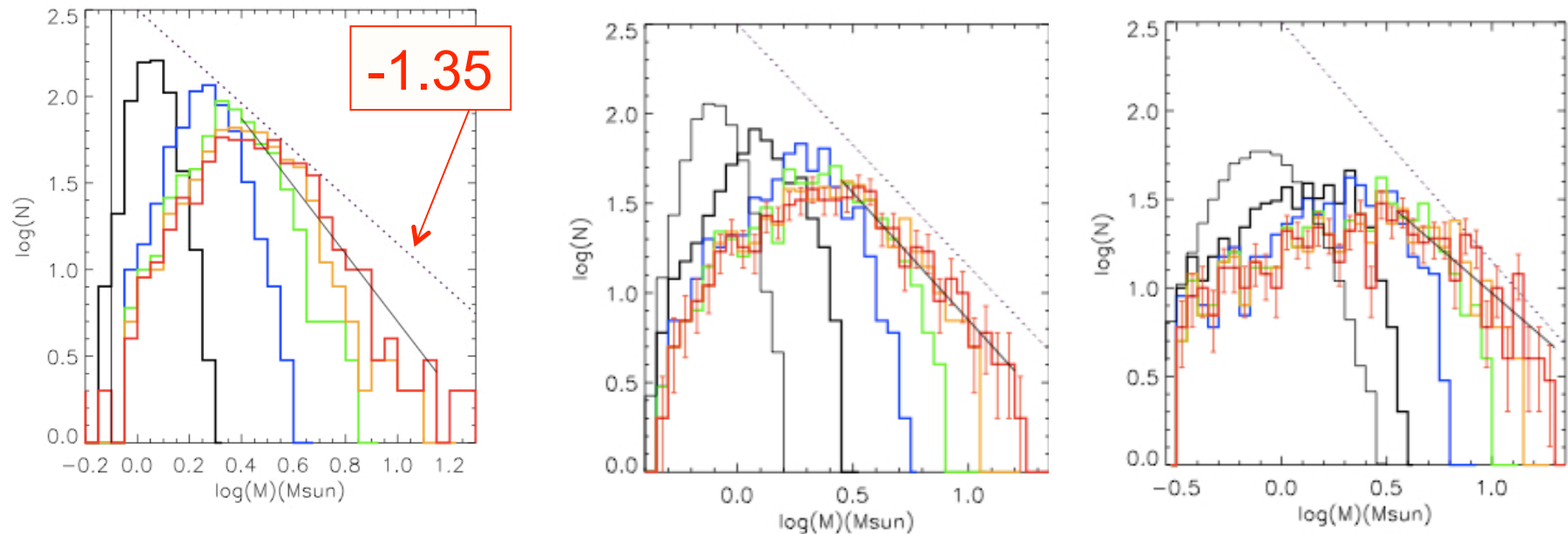
↑
 dM/dt



Growth of high-mass power-law tail:
doesn't require initial cluster
environment, though small groups
probably needed

$\log M \rightarrow$

starting from a single-valued or narrow Gaussian mass distribution, high-mass IMF evolves toward Salpeter ($\Gamma = -1.35$)



$\Gamma \Rightarrow -1$ as limiting slope when $dM/dt \propto M^2$
(Zinnecker 1982; check for yourself)

upper mass depends upon accretion to completion (correlation between slope and upper mass cutoff?)

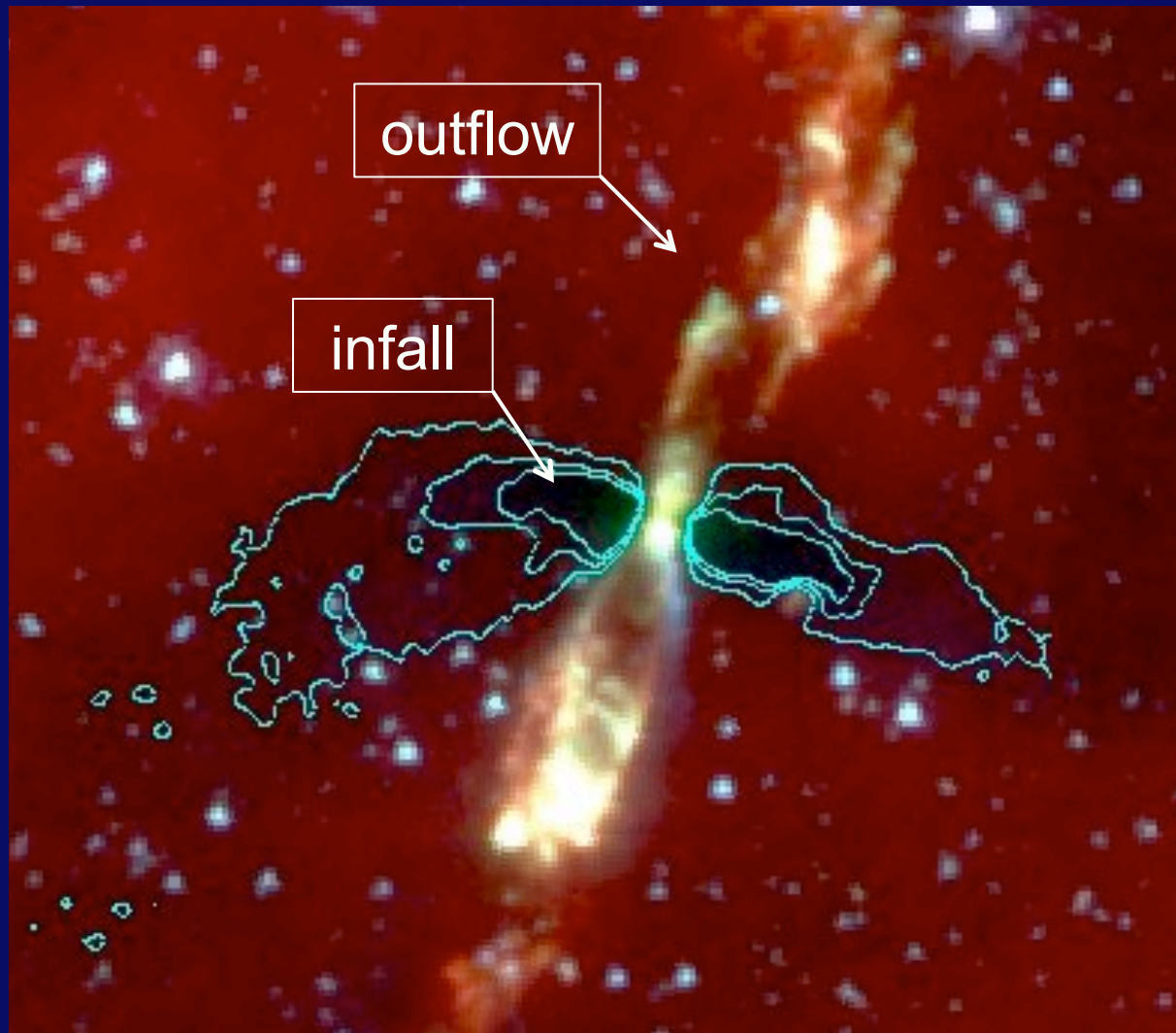
What stops accretion? [$M(\text{core}) > M(\text{star})$]

probably not low-mass outflows – too collimated,
infall too focused

I think there are two mechanisms:

- *Local*; angular momentum \Rightarrow fragmentation
- *Global*; feedback

runaway gravitational acceleration results in star formation in only a small fraction of the cloud which is very dense;
then low-density regions blown away by massive stars (either internal or external!)



⇒ disk-accretion-driven bipolar outflows can't really stop infall

Tobin et al. 2010, 8μm extinction maps from Spitzer

Accretion;

infall to protostar; energy loss must be

$$L(\text{acc}) \sim G M_* dM/dt / R_*$$

what should we detect?

Molecular cloud cores are relatively transparent to their own radiation and thus they cannot heat up during initial contraction. Assuming an initially spherical, thermally-supported cloud, one would expect the infall velocity to scale as

$$v_{in} \sim (GM/R)^{1/2} \sim c_s; \quad (1)$$

therefore, the collapse time is of order $t_{in} \sim R/c_s$ and the mass infall rate is

$$\dot{M} \sim M/t_{in} \sim c_s^3/G. \quad (2)$$

Numerically, for a molecular gas at 10 K, with a sound speed $\sim 0.19 \text{ km s}^{-1}$, the infall rate is $\dot{M} \sim 1.6 \times 10^{-6} \text{ M}_{\odot} \text{ yr}^{-1}$ and thus it would take $\sim 0.6 \text{ Myr}$ to form a 1 M_{\odot} star. Detailed calculations suggest somewhat higher values, at least during an initial phase.

$dM/dt \sim c_s^3/G$: $T \sim 10\text{-}20\text{ K}$, $dM/dt \lesssim 10^{-5}\text{ msun/yr}$

1 Msun then takes $>\sim 10^5\text{ yr}$ to form

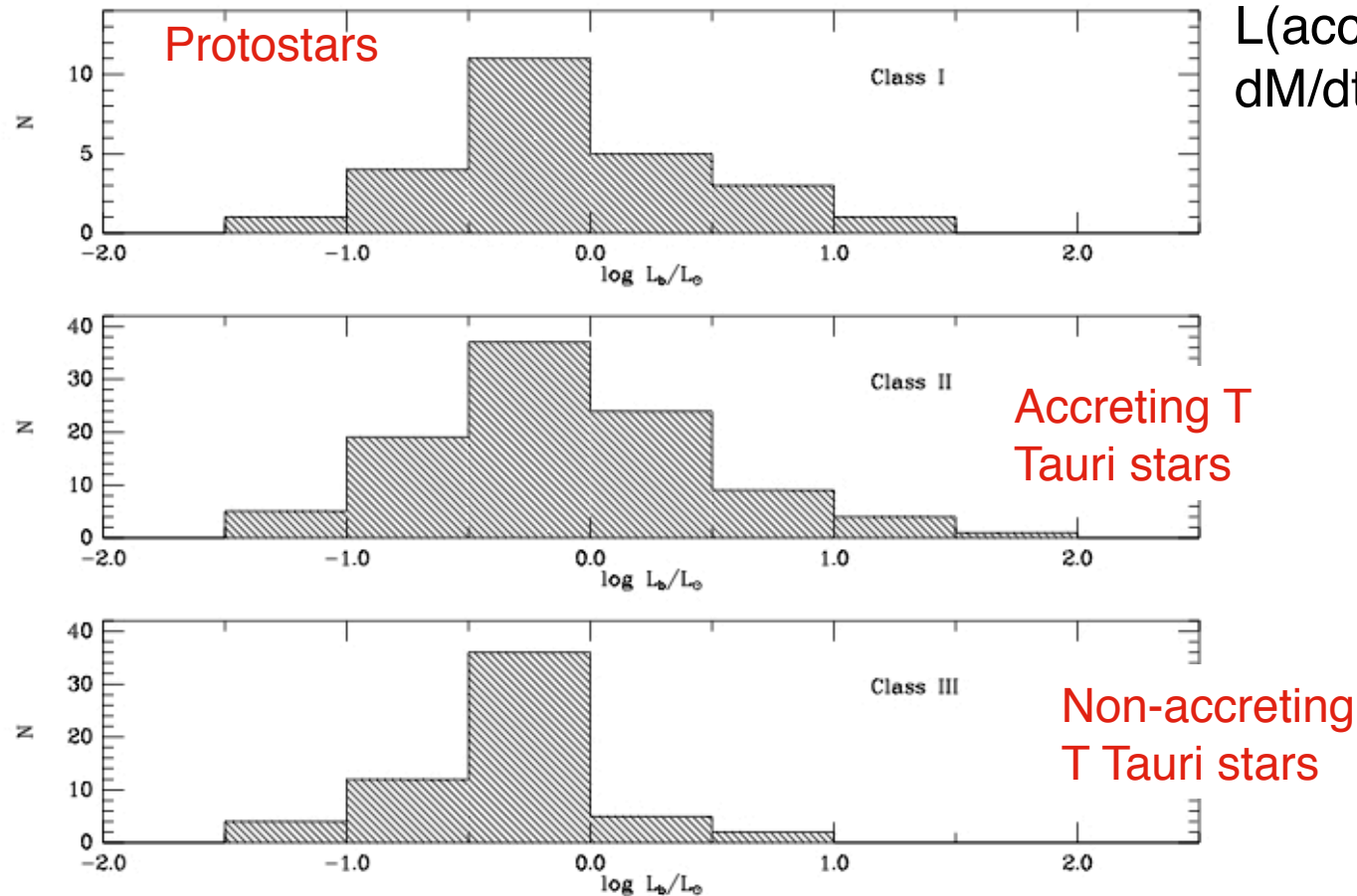
reasonably consistent with observations suggesting $\sim 0.3 - 0.5\text{ Myr}$ infall phase (e.g., Evans et al. 2009).

However, only works for cores which are roughly thermally supported at the time of collapse

This WON'T work to make high-mass stars; need much higher dM/dt

\Rightarrow infall from $r \gg r_j \Rightarrow$ closer to pressure-free (free-fall) collapse, more mass falls in at same time

“Luminosity problem” (Kenyon et al. 1990, 94).
Must lose energy to make star.

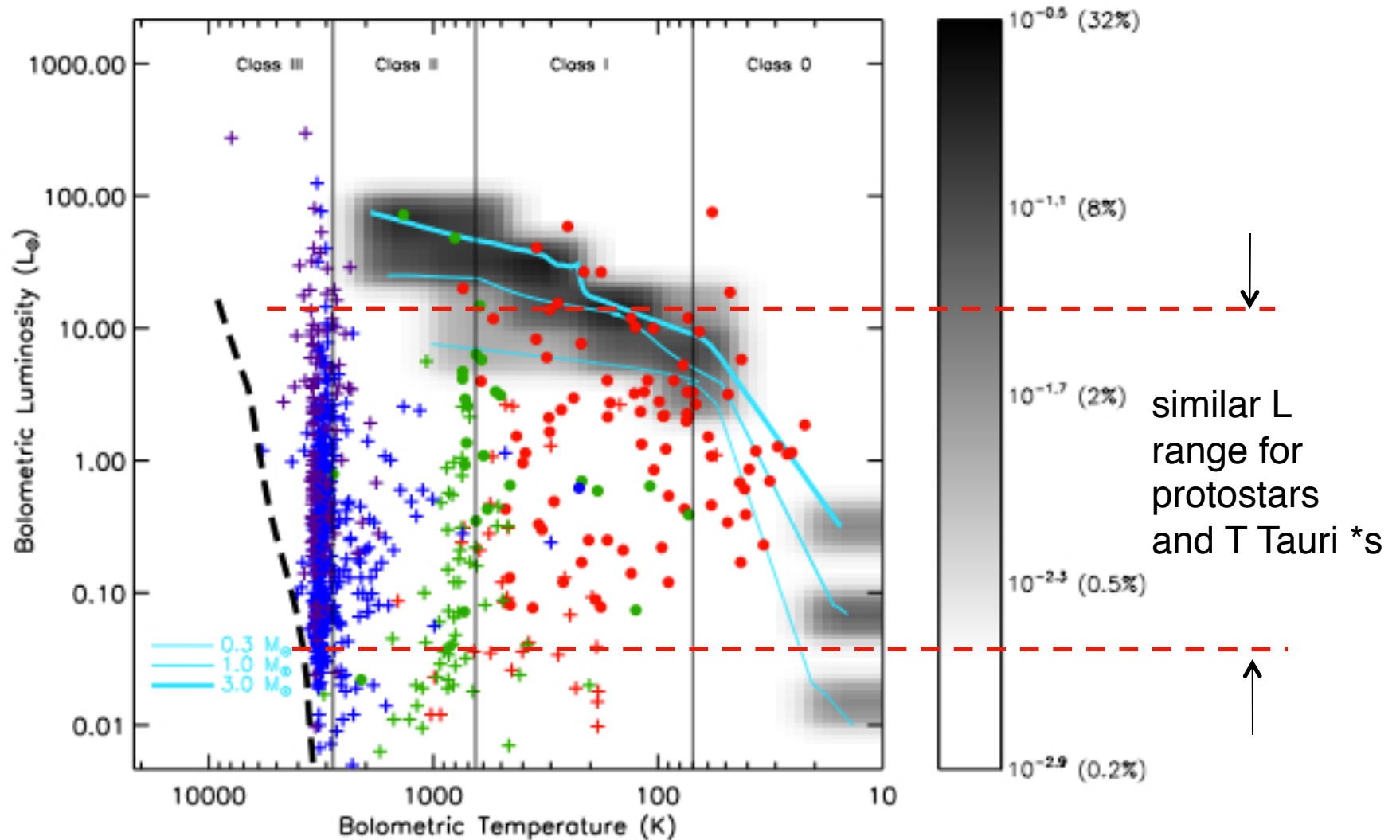


$L(\text{acc}) \sim 10 - 20 L(\text{sun})$ for
 $dM/dt \sim 2 \times 10^{-6} M(\text{sun})/\text{yr}$;

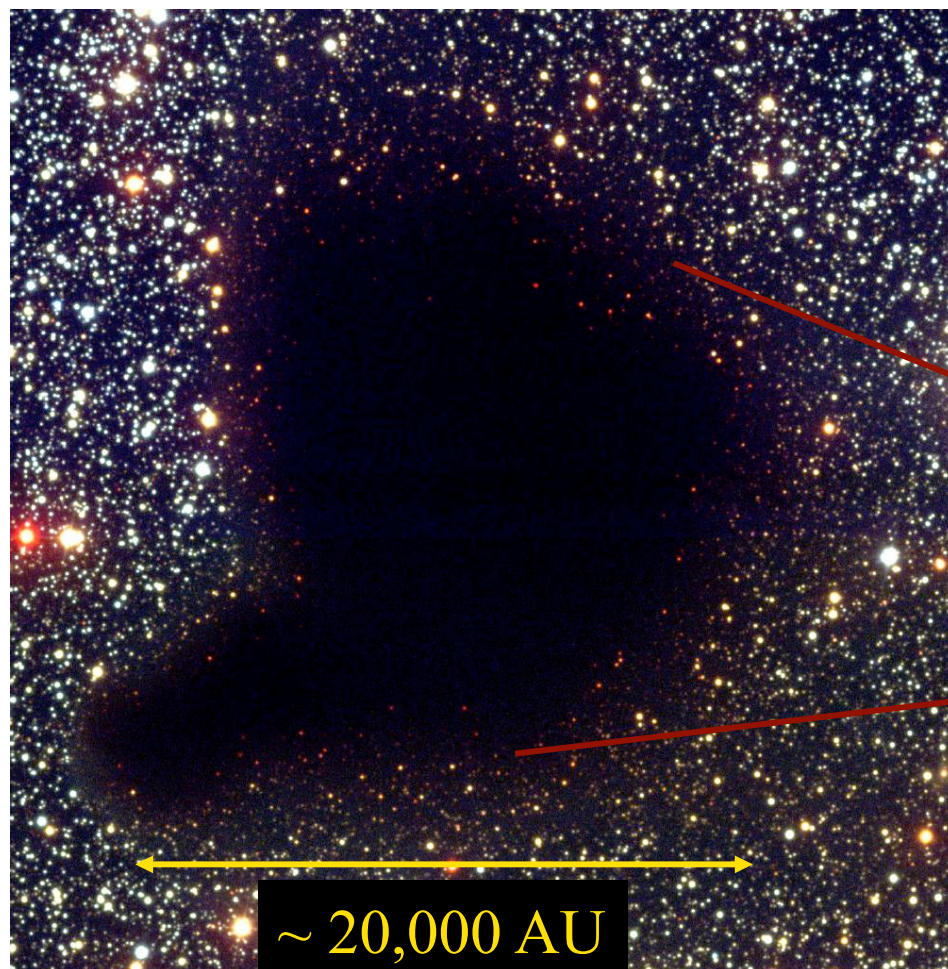
?
what's
wrong
?

Fig. 5.1. Luminosity distributions of Class I, II, and III sources in Taurus.

recent Spitzer results seem to confirm missing
accretion luminosity



Dunham, Evans et al. 2009



angular momentum
must come into play...

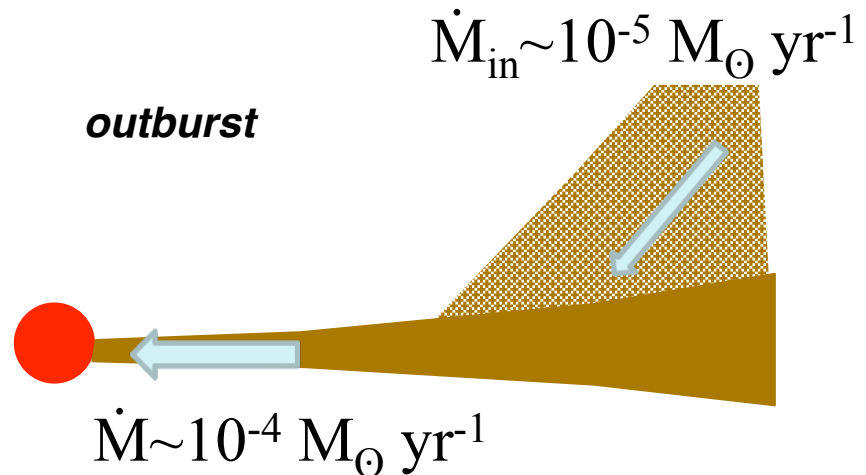
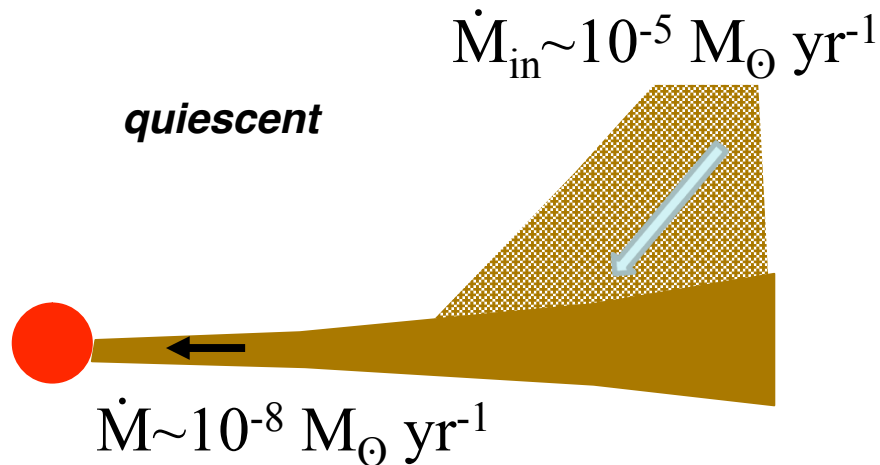
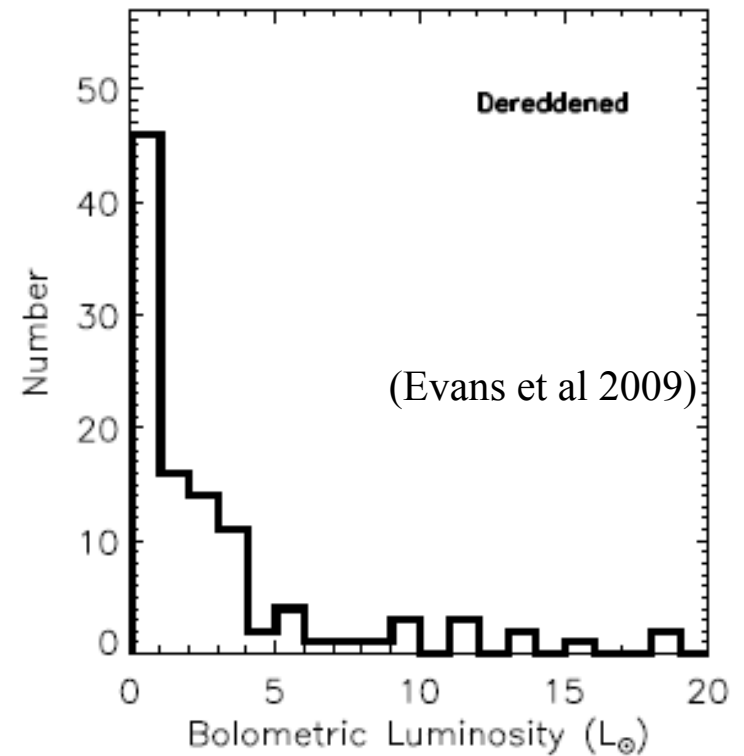
0.01 AU (*),
500AU (disk)

Alves, Lada & Lada 2001

Solutions: dM/dt not steady;

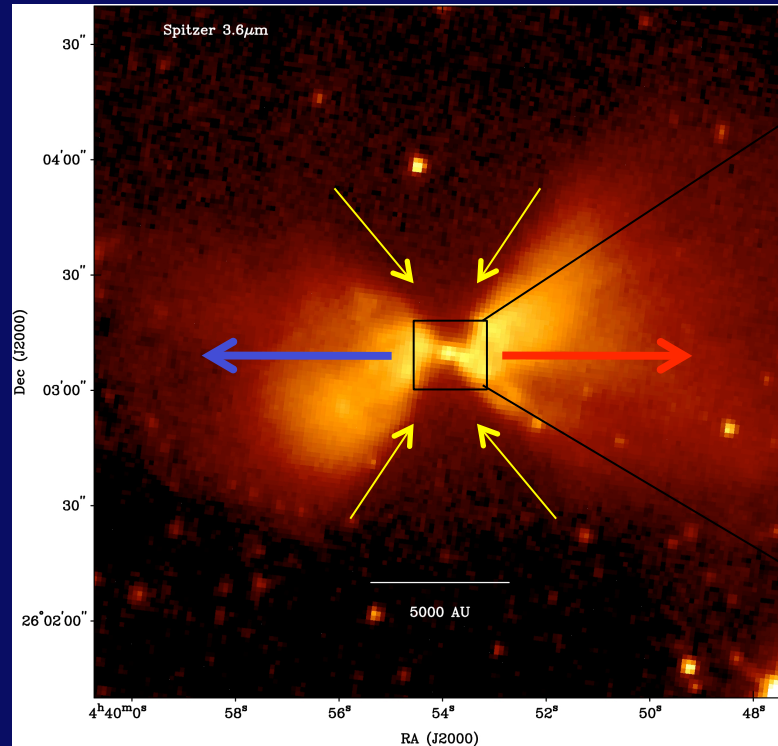
- Class I too late- “Class 0” short-lived, rapid accretion... but not obvious Class 0 are that much more luminous.

- Episodic accretion; first to disk, then in short-lived disk accretion outbursts?

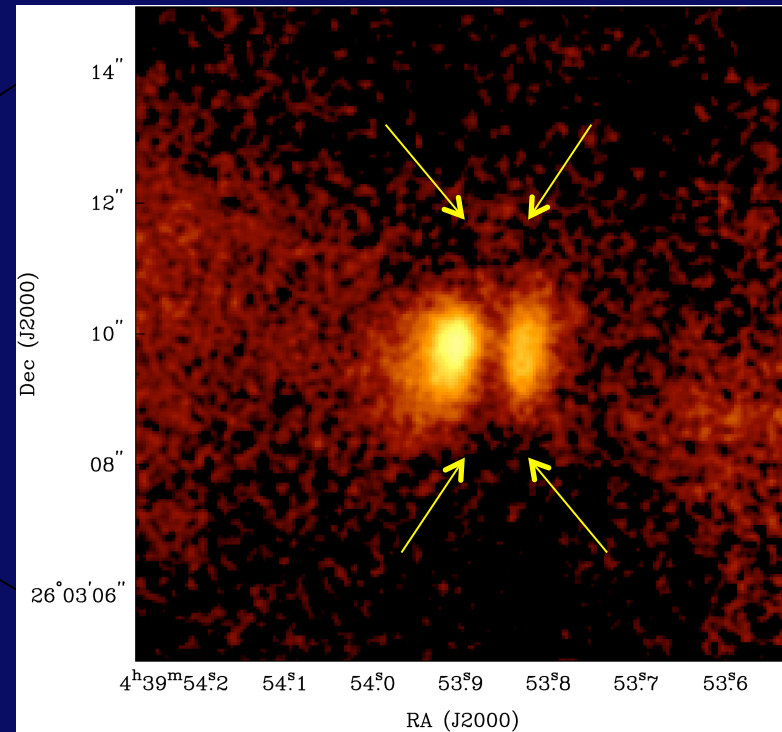


Disk formation by infalling, rotating cloud

L1527 Spitzer 3.6 micron

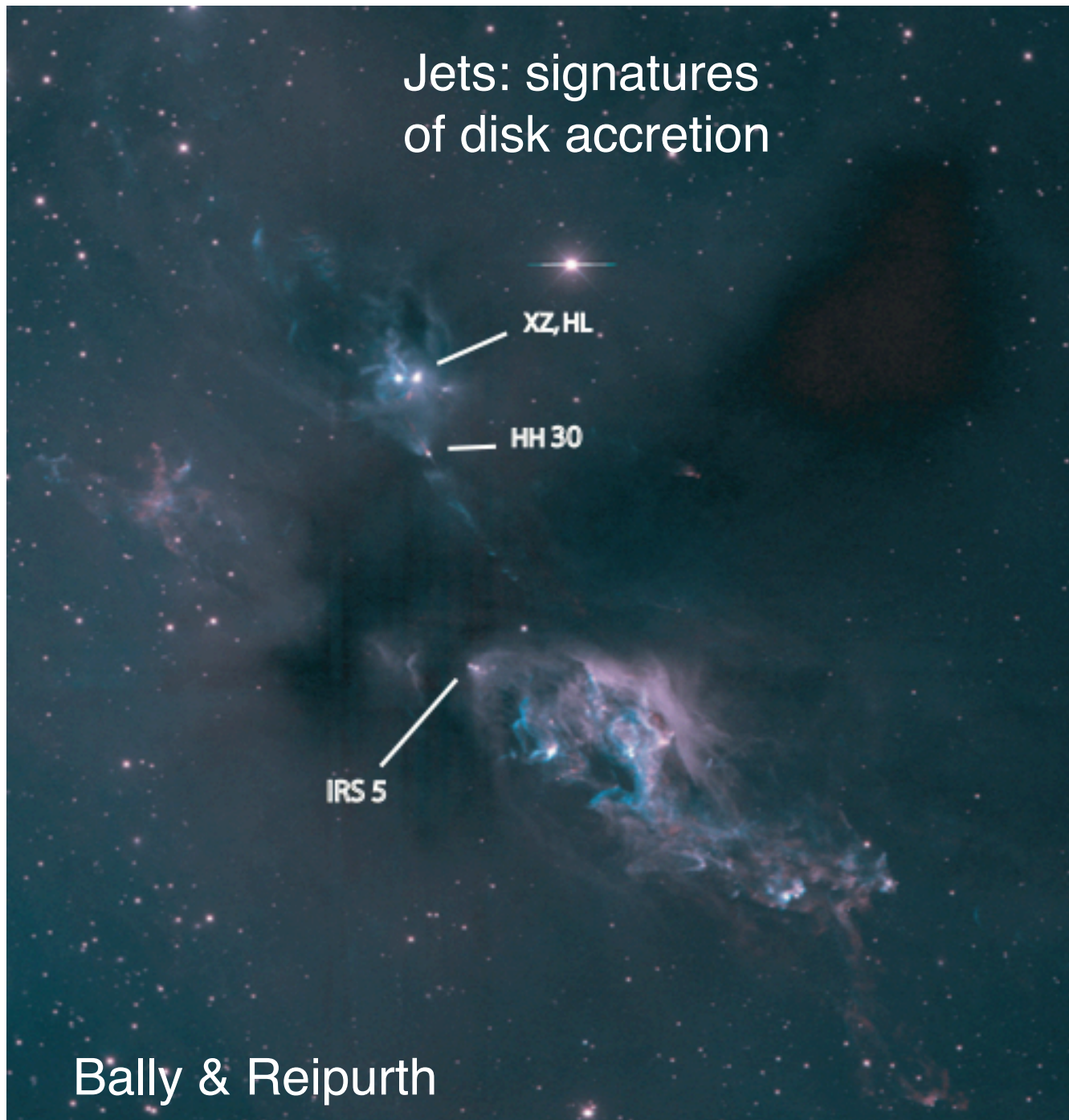


Gemini 3.8 micron



scattered light images of bipolar outflow cavities and upper and lower surfaces of edge-on circumstellar disk; Tobin et al. 2010, ApJL

Jets: signatures
of disk accretion



Bally & Reipurth

Supplemental material

Assuming spherical geometry and no magnetic pressure,

$$\frac{dP}{dr} = -\rho \frac{GM_r}{r^2}, \quad \frac{dM_r}{dr} = 4\pi r^2 \rho. \quad (1)$$

For an isothermal cloud, these equations can be combined to yield

$$\frac{1}{r^2} \frac{d}{dr} r^2 c_s^2 \frac{d \ln \rho}{dr} = -4\pi G \rho. \quad (2)$$

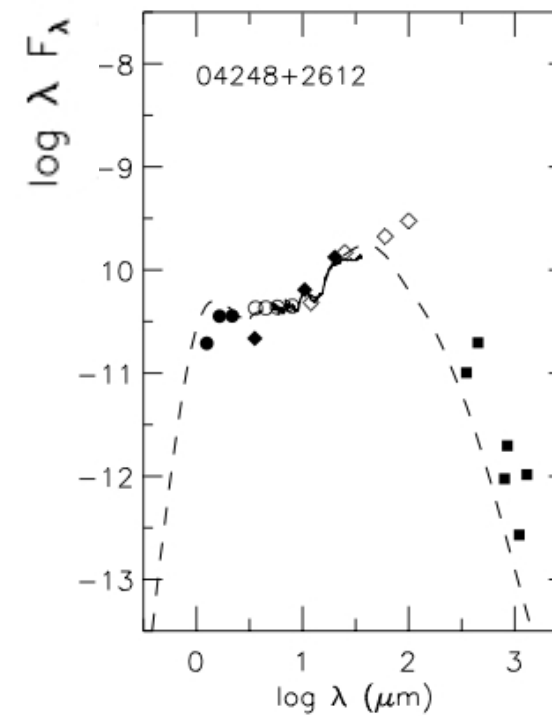
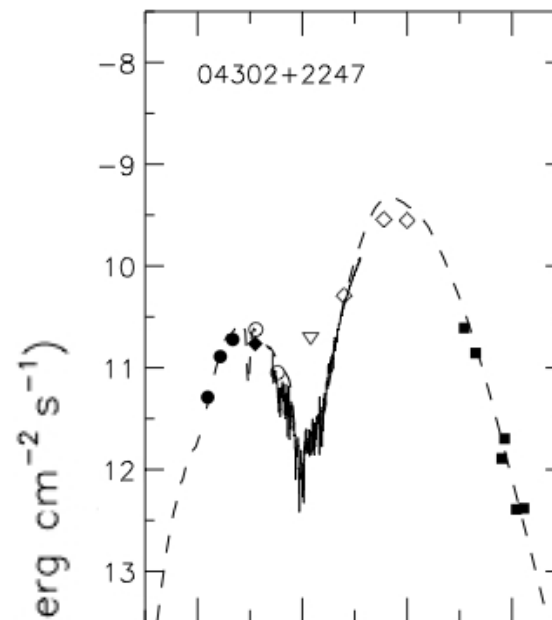
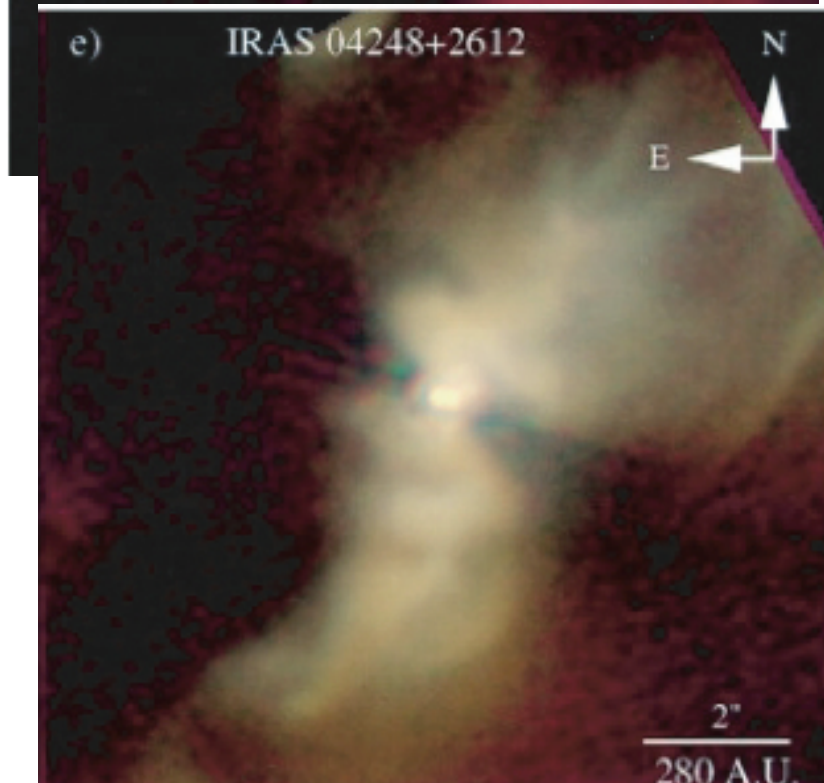
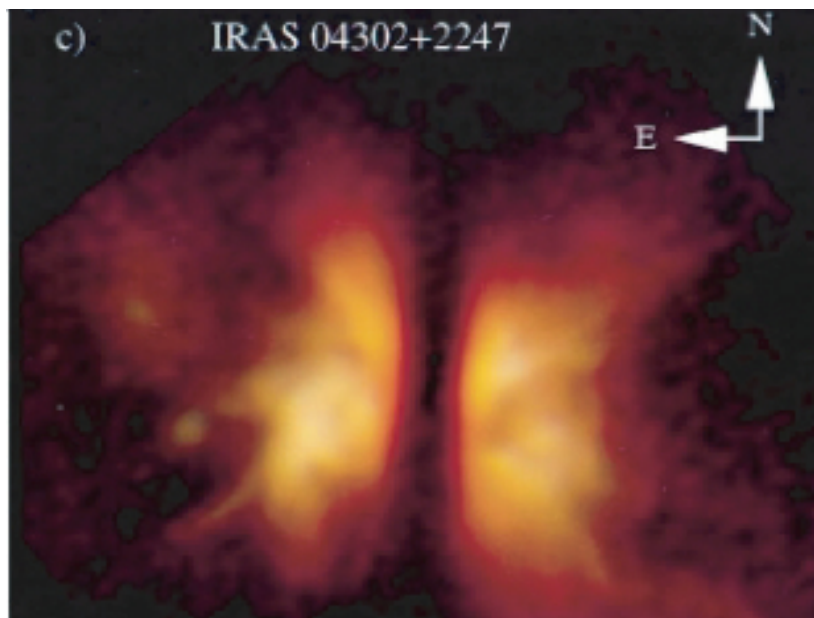
Making the substitution $\ln(\rho/\rho_c) \equiv -u$, one arrives at the Lane-Emden equation

$$\frac{1}{\xi^2} \frac{d}{d\xi} \xi^2 \frac{du}{d\xi} = e^{-u}, \quad (3)$$

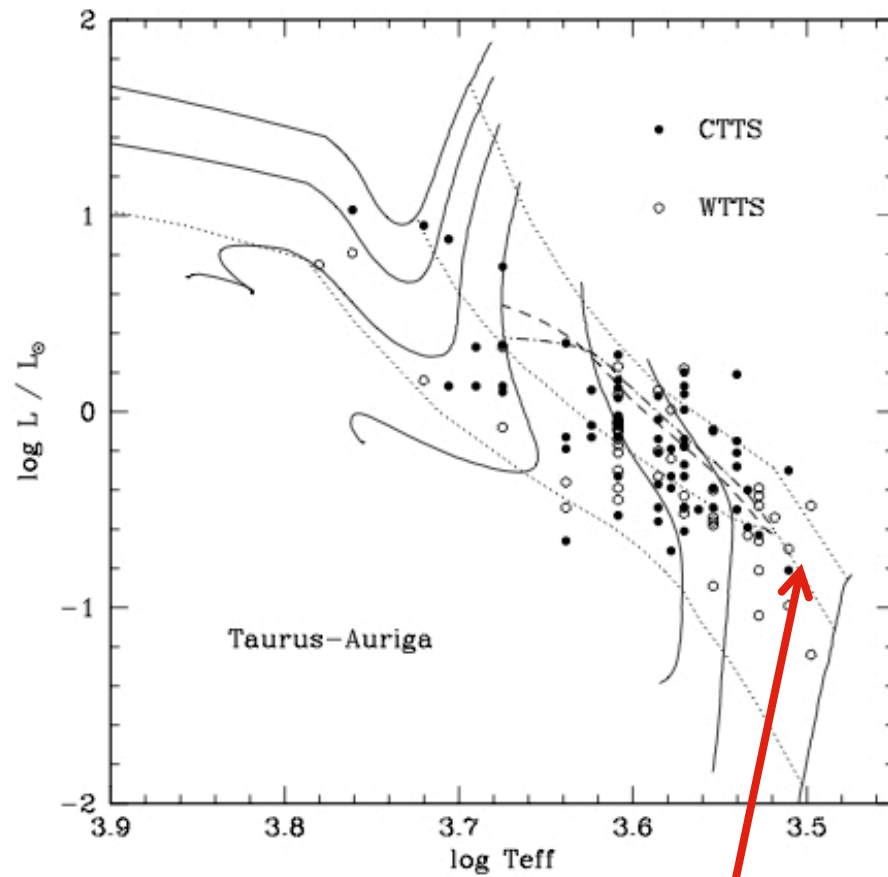
where $\xi = r/(c_s^2/4\pi G \rho_c)^{1/2}$ is the non-dimensional radial coordinate.

If ρ_c is taken to be the central density, then the boundary conditions are $u(0) = 0$ and $du/d\xi|_0 = 0$ (by symmetry). There is a family of solutions to this equation, known as Bonnor–Ebert spheres. The limiting case, where $\xi_1 \rightarrow \infty$, is that of the singular isothermal sphere,

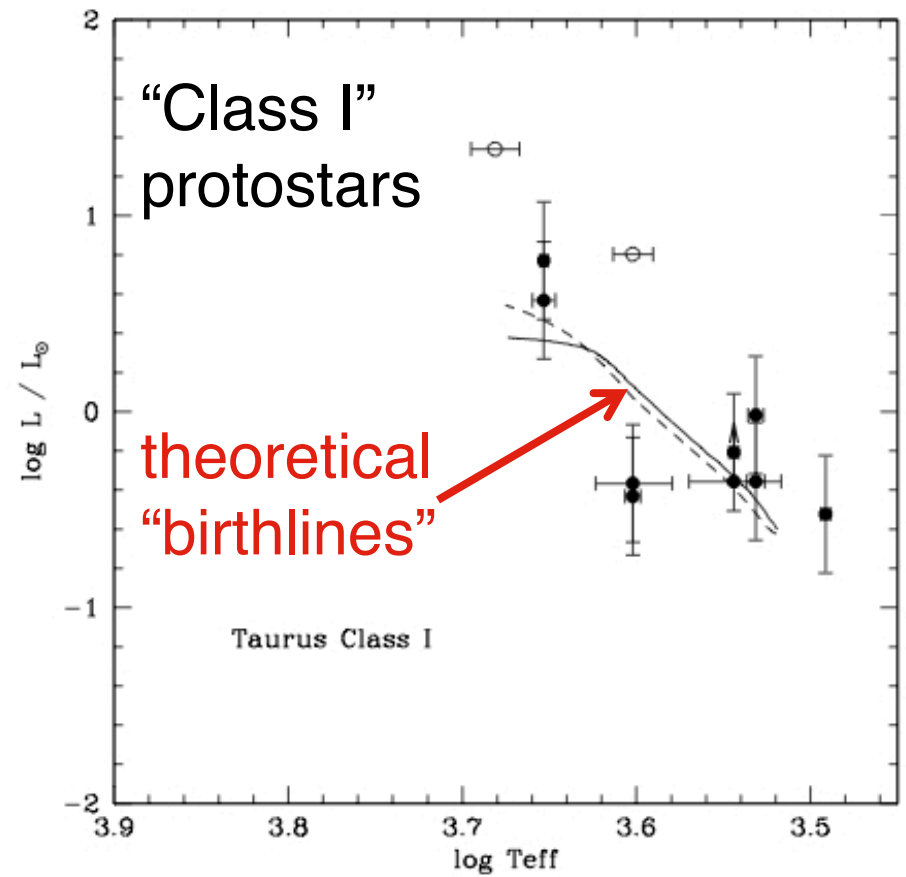
$$\rho = \frac{c_s^2}{2\pi G} r^{-2}. \quad (4)$$

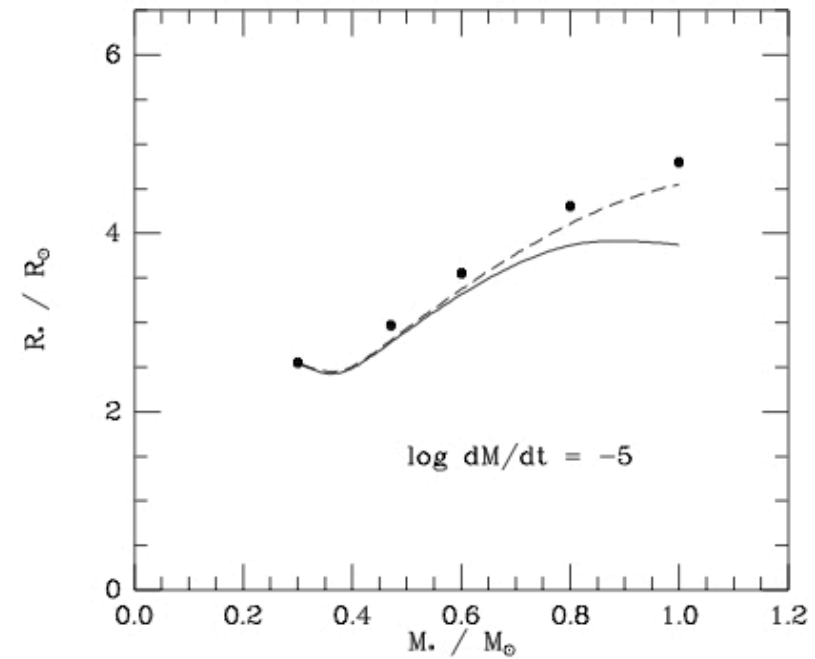
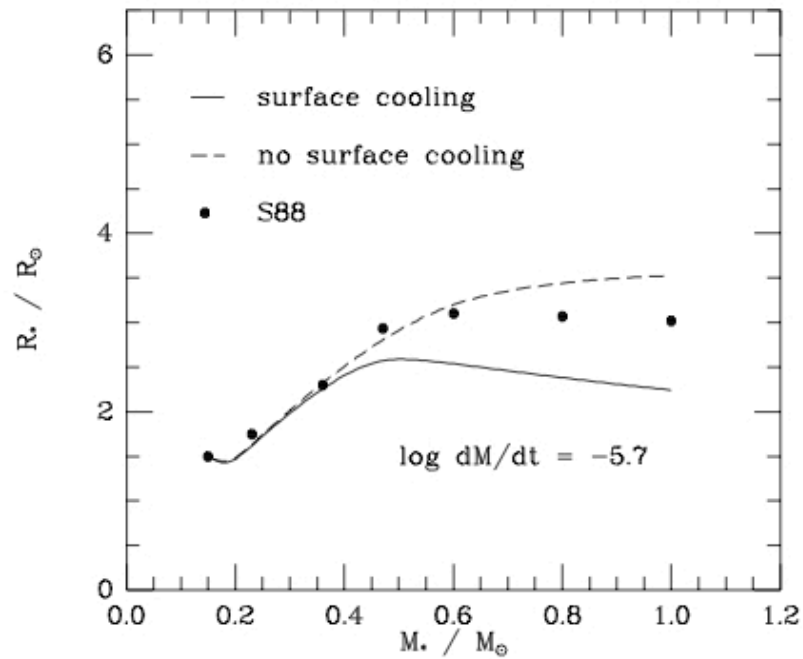


Protostellar
2 micron
images and
SEDs (FIR
emission
from dusty
envelopes)



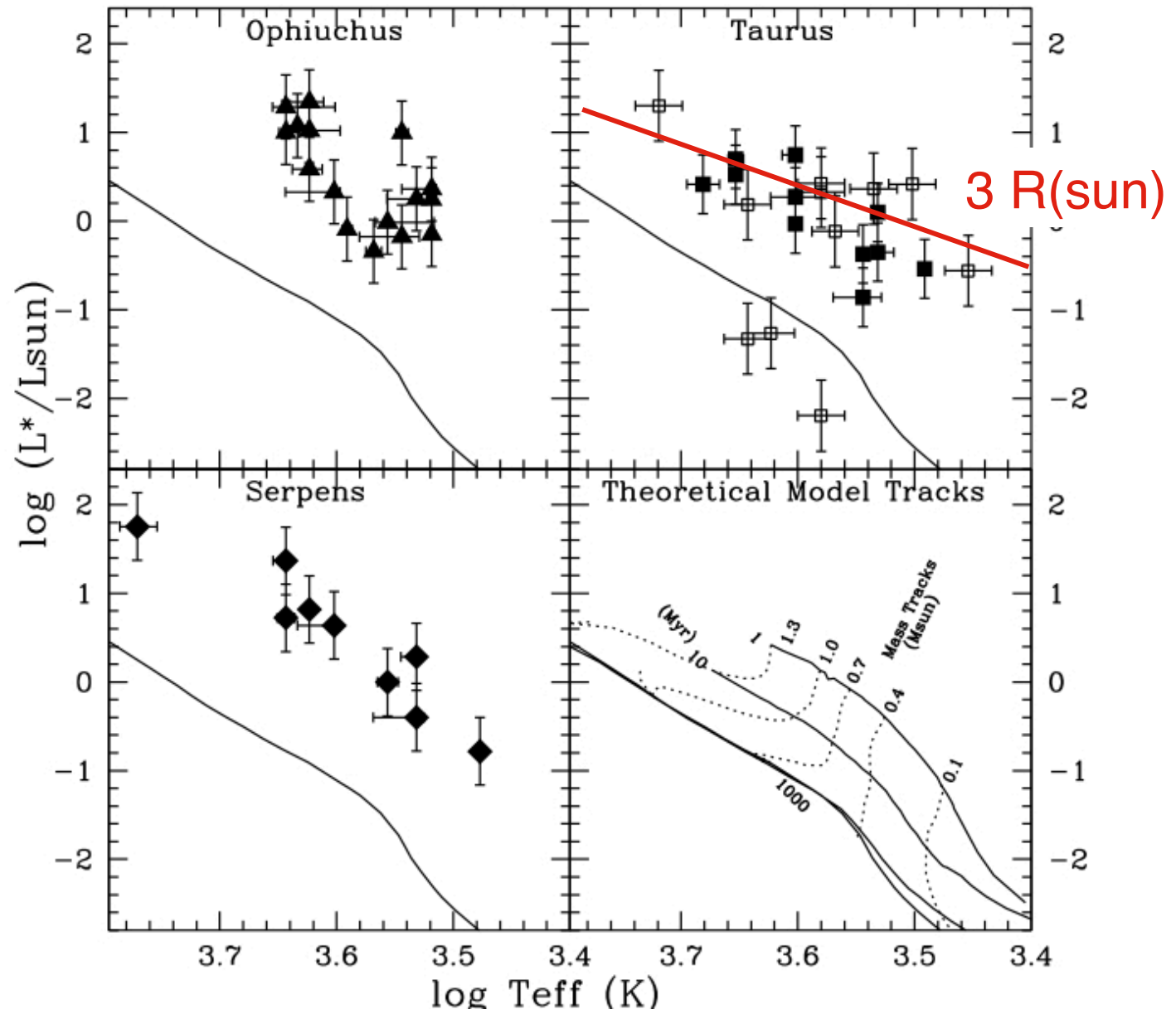
~ 1 Myr "isochrone"





Typical predicted (low-mass) protostellar properties at the end of infall; $R/M \sim 3\text{-}6 \text{ R}(\text{sun})/\text{M}(\text{sun})$

“Class I”
protostars



White et al. 2007

Many protostellar evolutionary calculations lead to estimates of $R_*/M_* \sim 6 R_\odot / M_\odot$ at the end of (major) accretion (especially if D fusion plays a significant role). The Kelvin-Helmholtz (contraction) timescale is the stellar energy content divided by the luminosity. For completely convective stars,

$$\tau_{KH} = \frac{3 G M_*^2}{7 R_* L_*}. \quad (1)$$

Low-mass, completely convective stars contract at nearly constant effective temperature; you can show that this results in contraction such that the luminosity varies as

$$L_* = L_\odot \left(\frac{3t}{\tau_{KH}} \right)^{-2/3}. \quad (2)$$

If the star had contracted from infinite radius (which they don't), then the age (really an upper limit) would be

$$t \sim \tau_{KH}/3. \quad (3)$$

Using $R_*/M_* \sim 6 R_\odot / M_\odot$ and a typical relation $L_* \sim (M_*/M_\odot)^2 L_\odot$,

$$t \sim 0.7 (M_*/M_\odot)^{-1} \text{Myr}, \quad (4)$$

which reasonably suggests a protostellar “age” of the same order as the expected collapse timescale.