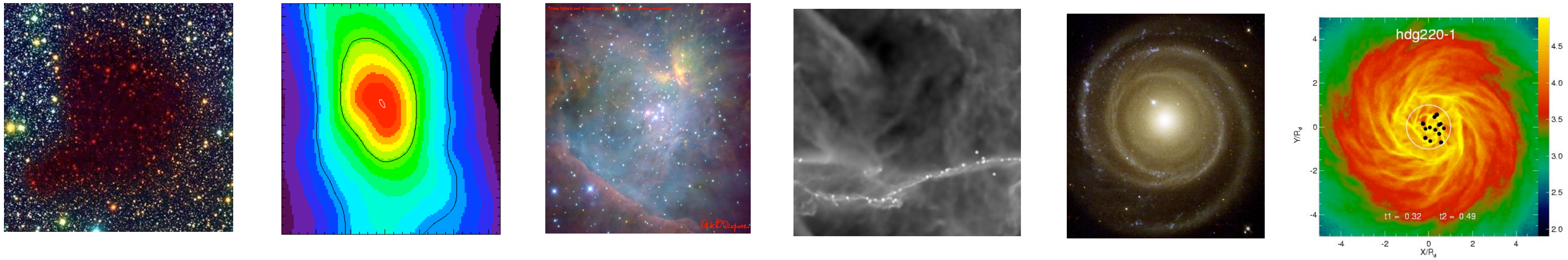
From clouds to stars



Ralf Klessen

Zentrum für Astronomie der Universität Heidelberg
Institut für Theoretische Astrophysik

ISM fragmentation:
from clouds to stars

- more on gravoturbulent cloud fragmentation and star formation
- IMF (mass spectrum of collapsing objects)
- from prestellar cores to stars

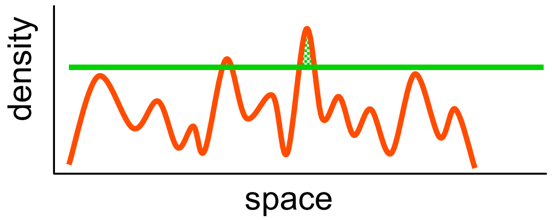
Literature (update)

- Star Formation:
  - Stahler, S., & Palla, F., 2004, "The Formation of Stars" (Weinheim: Wiley-VCH)
  - Osterbrock, D., & Farland, G., 2006, Astrophysics of Gaseous Nebulae & Active Galactic Nuclei, 2nd ed. (Sausalito: Univ. Science Books)
  - Lada, C. F., & Kylafis, N. D. 1999, "The Origin of Stars and Planetary Systems", NATO ASI Series 540 (Kluwer Academic Publisher)
  - Mannings, V., Boss, A. P., & Russell, S. S. 2000, "Protostars and Planets IV" (University of Arizona Press, Tucson)
- Review articles:
  - Mac Low, M.-M., Klessen, R.S., 2004, "The control of star formation by supersonic turbulence", Rev. Mod. Phys., 76, 125 - 194·
  - Bromm, V., Larson, R.B., 2004, "The first stars", ARAA, 42, 79 - 118
  - Larson, R.B., 2003, "The physics of star formation", Rep. Prog. Phys, 66, 1651 - 1697
  - Shu, F.H, Adams, F.C., Lizano, S., 1987, "Star formation in molecular clouds: Observations and theory", ARAA, 25, 23 - 81
  - Protostars and Planets V (new review book): articles at

    http://www2.ifa.hawaii.edu/cspf/ppv/ppv.html

gravoturbulent SF

Gravoturbulent star formation



- interstellar gas is highly *inhomogeneous*
  - *thermal instability*
  - *gravitational instability*
  - *turbulent compression* (in shocks $\delta\rho/\rho \propto \mathcal{M}^2$; in atomic gas: $\mathcal{M} \approx 1...3$)
- cold *molecular clouds* can form rapidly in high-density regions at *stagnation points* of *convergent large-scale flows*
  - chemical *phase transition*: atomic → molecular
  - process is *modulated* by large-scale *dynamics* in the galaxy
- inside *cold clouds:* turbulence is highly supersonic ($\mathcal{M} \approx 1...20$)
  → *turbulence* creates large density contrast,
  gravity selects for collapse

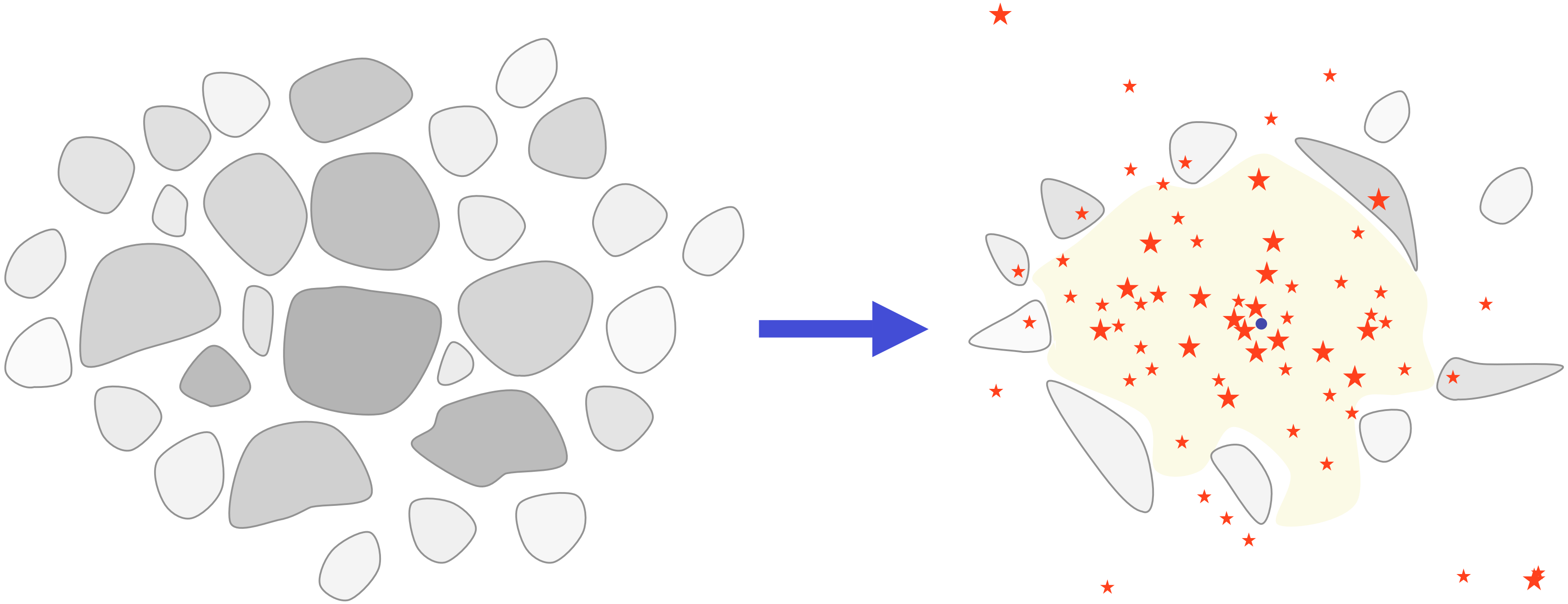
⟶ ***GRAVOTUBULENT FRAGMENTATION***

- *turbulent cascade:* local compression *within* a cloud provokes collapse
  → formation of individual *stars* and *star clusters*

(e.g. Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

star-cluster formation

Star cluster formation



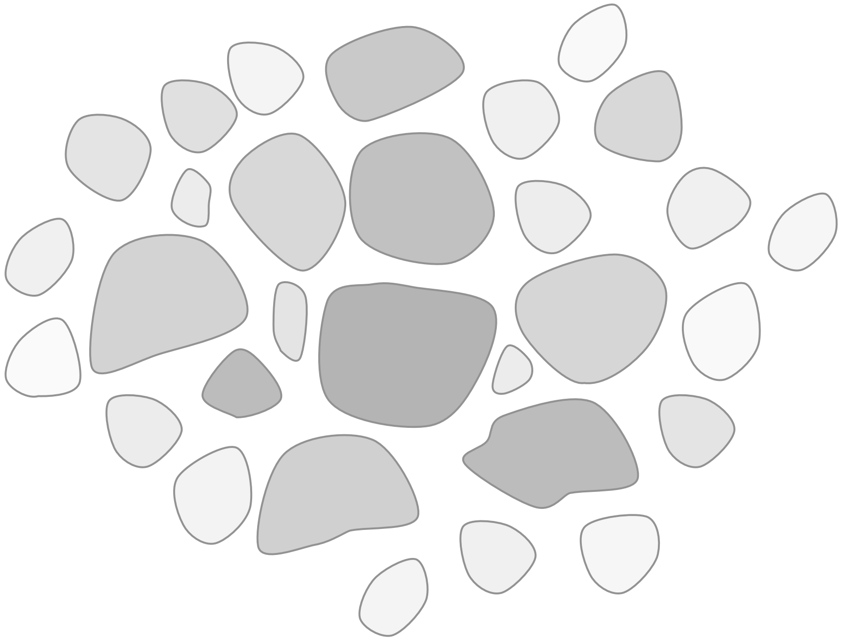
How to get from cloud cores to star clusters?

How do the stars acquire mass?

(e.g. Larson 2003, Prog. Rep. Phys.; Mac Low & Klessen, 2004, Rev. Mod. Phys, 76, 125 - 194)

Formation and evolution of cores

What happens to distribution of cloud cores?



Two exteme cases:

(1) turbulence decays, i.e. gravity dominates: $\alpha = E_{kin}/|E_{pot}| < 1$
--> *global contraction*
--> core do *interact* while collapsing
--> *competition* influences *mass growth*
--> *dense cluster with high-mass stars*

(2) turbulence dominates energy budget: $\alpha = E_{kin}/|E_{pot}| > 1$
--> individual cores do *not* interact
--> *collapse* of *individual* cores dominates *stellar mass growth*
--> *loose cluster of low-mass stars*

predictions

Predictions of gravoturbulent theory

- *global properties* (statistical properties)
  - SF efficiency and timescale
  - stellar mass function -- IMF
  - dynamics of young star clusters
  - description of self-gravitating turbulent systems (pdf's, Δ-*var.)*
  - chemical mixing properties
- *local properties* (properties of individual objects)
  - properties of individual clumps (e.g. shape, radial profile, lifetimes)
  - accretion history of individual protostars (dM/dt vs. t, j vs. t)
  - binary (proto)stars (eccentricity, mass ratio, etc.)
  - SED's of individual protostars
  - dynamic PMS tracks: T_{bol}-L_{bol} evolution

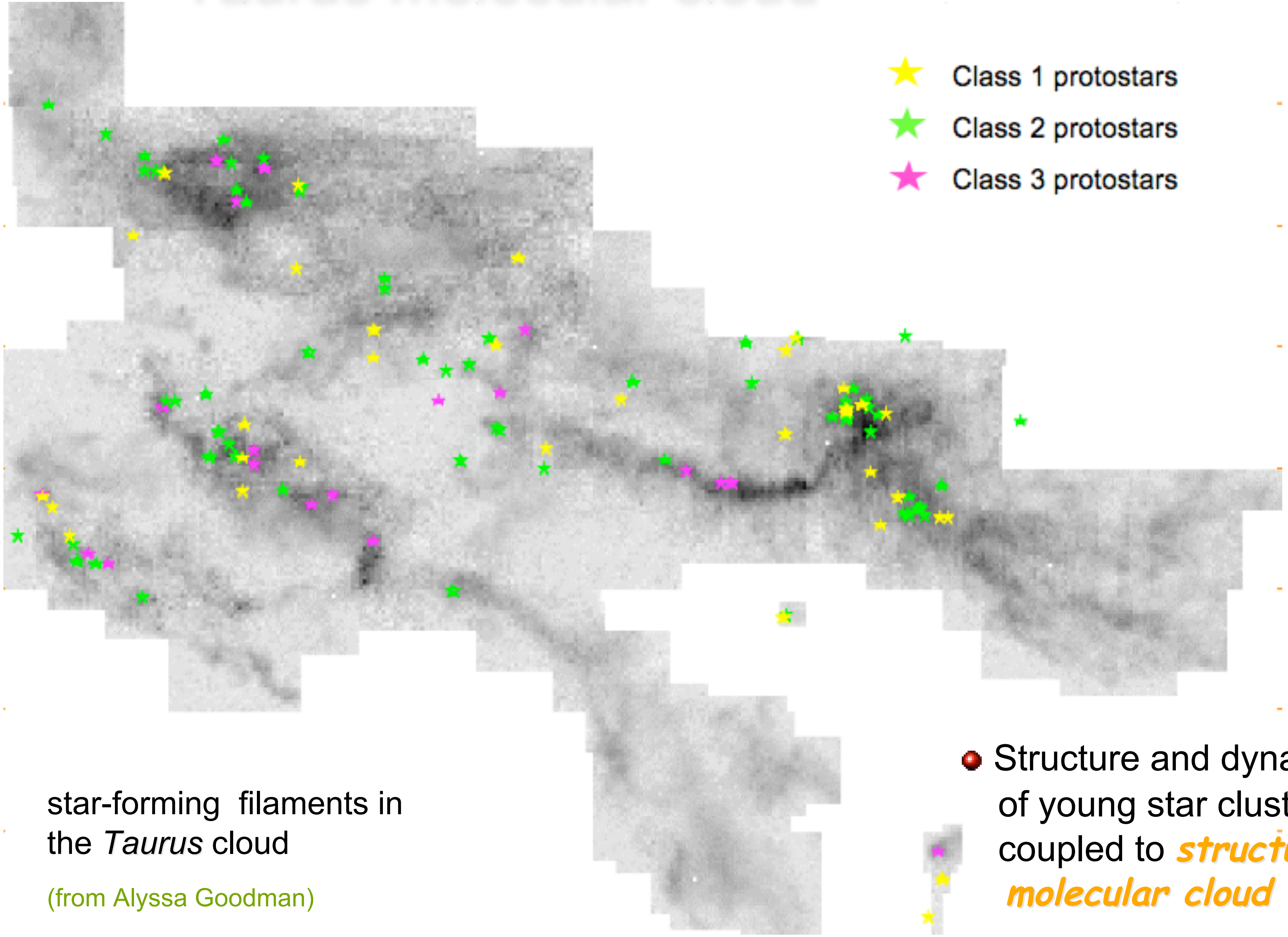
Examples

example 1: (numerical) models of gravoturbulent fragmentation and subsequent formation of star clusters

example 2: speculations on the origin of the stellar mass spectrum (IMF)

example 1

Taurus molecular cloud

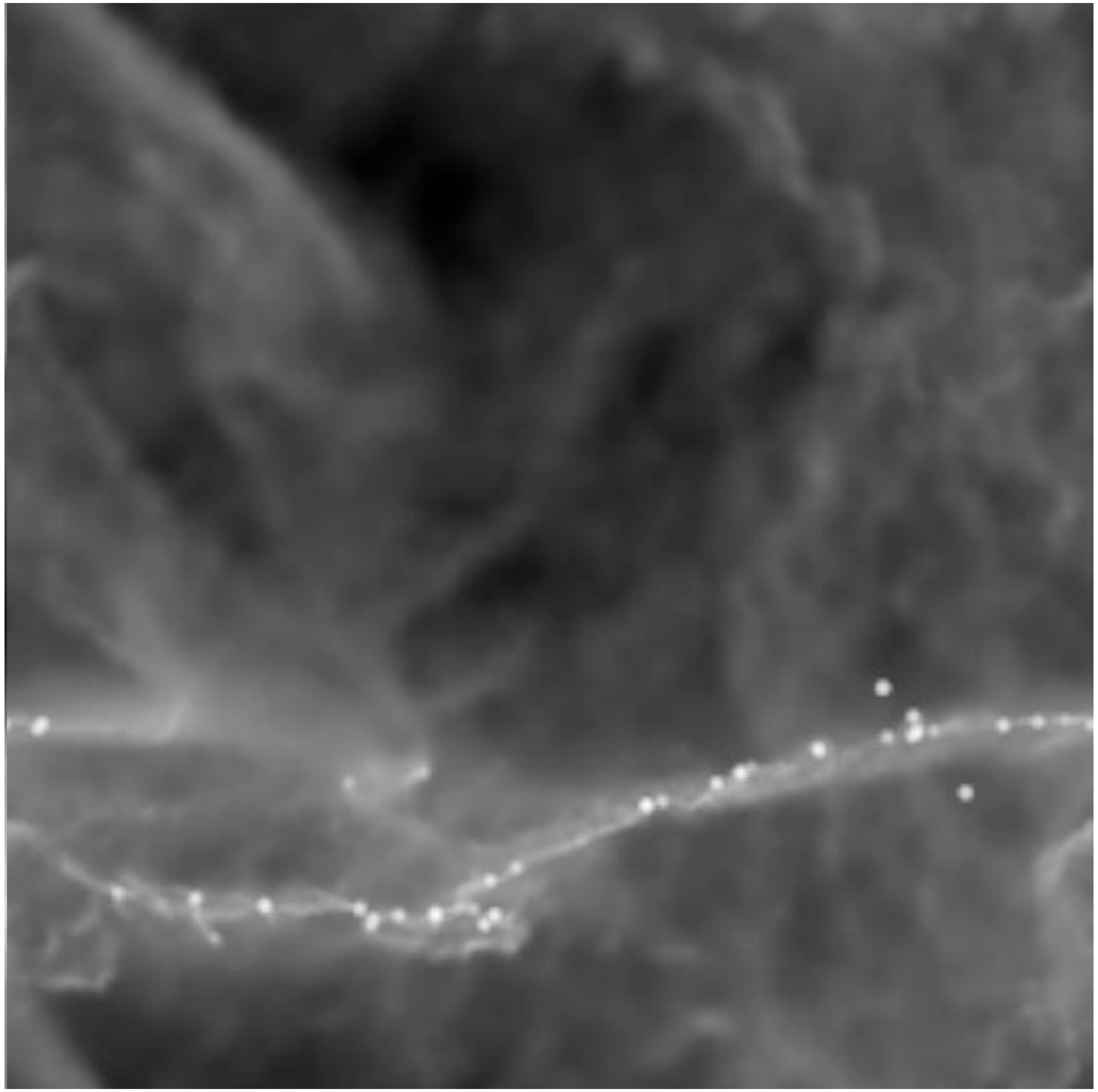


star-forming filaments in the *Taurus* cloud

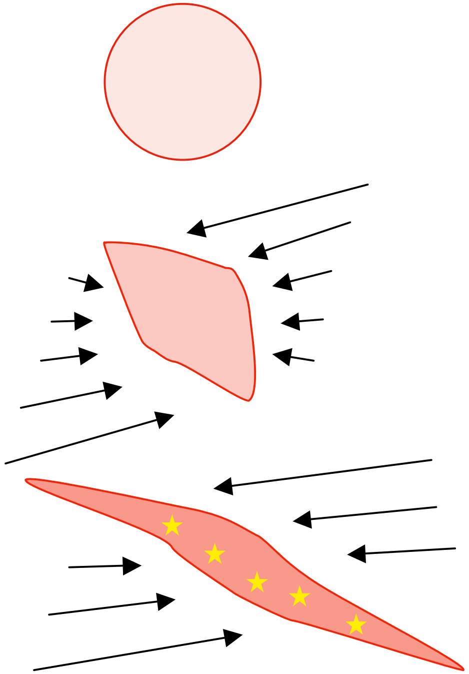
(from Alyssa Goodman)

- Structure and dynamics of young star clusters is coupled to **structure of molecular cloud**

Gravoturbulent fragmentation



Filament generated by combination of compression and local shear:



"Taurus":

→ density $n(H_2) \approx 10^2\,\mathrm{cm}^{-3}$

→ $L = 6\,\mathrm{pc}$, $M = 5000\,M_\odot$

Goal

- We want to understand the formation of star clusters in turbulent interstellar gas clouds.

--> We want to describe the transition from a hydrodynamic system (the self-gravitating gas cloud) to one that is dominated by (collisional) stellar dynamics (the final star cluster).

- How can we do that?

Numerical approach I

- Problem of star formation is very complex. It involves many scales (10^7 in length, and 10^{20} in density) and many physical processes
  → *NO* analytic solution
  → NUMERICAL APPROACH

- BUT, we need to…
  - solve the MHD equations in 3 dimensions
  - solve Poisson's equation (self-gravity)
  - follow the full turbulent cascade (in the ISM + in stellar interior)
  - include heating and cooling processes (EOS)
  - treat radiation transfer
  - describe energy production by nuclear burning processes

IMPOSSIBLE

Numerical approach II

- Simplify!
  Divide problem into little bits and pieces….
- **GRAVOTURBULENT CLOUD FRAGMENTATION**
- We try to…
  - solve the HD equations in 3 dimensions
  - solve Poisson's equation (self-gravity)
  - include a (humble) approach to supersonic turbulence
  - describe perfect gas (with polytropic EOS)
  - follow collapse: include "sink particles"
    (this will "handle" our subgrid-scale physics)

LARGE-EDDY SIMULATIONS

Large-eddy simulations

- We use ***LES*** to models the large-scale dynamics
- Principal problem: only large scale flow properties
  - Reynolds number: $Re = LV/\nu$ ***($Re_{nature} >> Re_{model}$)***
  - dynamic range much smaller than true physical one
  - need ***subgrid model*** (in our case simple: only dissipation) more complex when processes (chemical reactions, nuclear burning, etc) on subgrid scale determine large-scale dynamics
- Also: stochasticity of the flow ⇒ unpredictable when and where “interesting things” happen
  - occurance of localized collapse
  - location and strength of shock fronts
  - etc.

LES with SPH

- For self-gravitating gases SPH is probably okay …
  - fully Lagrangian (particles are free to move where needed)
  - good resolution in high-density regions (in collapse)
  - particle based --> good for transition from hydrodynamics to stellar dynamics
- BUT:
  - low resolution in low-density region
  - difficult to reach very high levels of refinement (however, particle splitting may be promising path)
  - dissipative and need for artificial viscosity
  - how to handle subgrid scales?

Particle-based vs. grid-based

- Each group strongly favors their own method!
- Comparison between particle-based and grid-based methods:
  SPH vs. ZEUS / GADGET vs. ENZO

Klessen, Heitsch, Mac Low (2000)	O'Shea et al. (2005)
Heitsch, Mac Low, Klessen (2001)	Agertz et al. (2006)
Ossenkopf, Klessen, Heitsch (2001)	

- Both methods are complementary…

⟶ Bracketing reality!

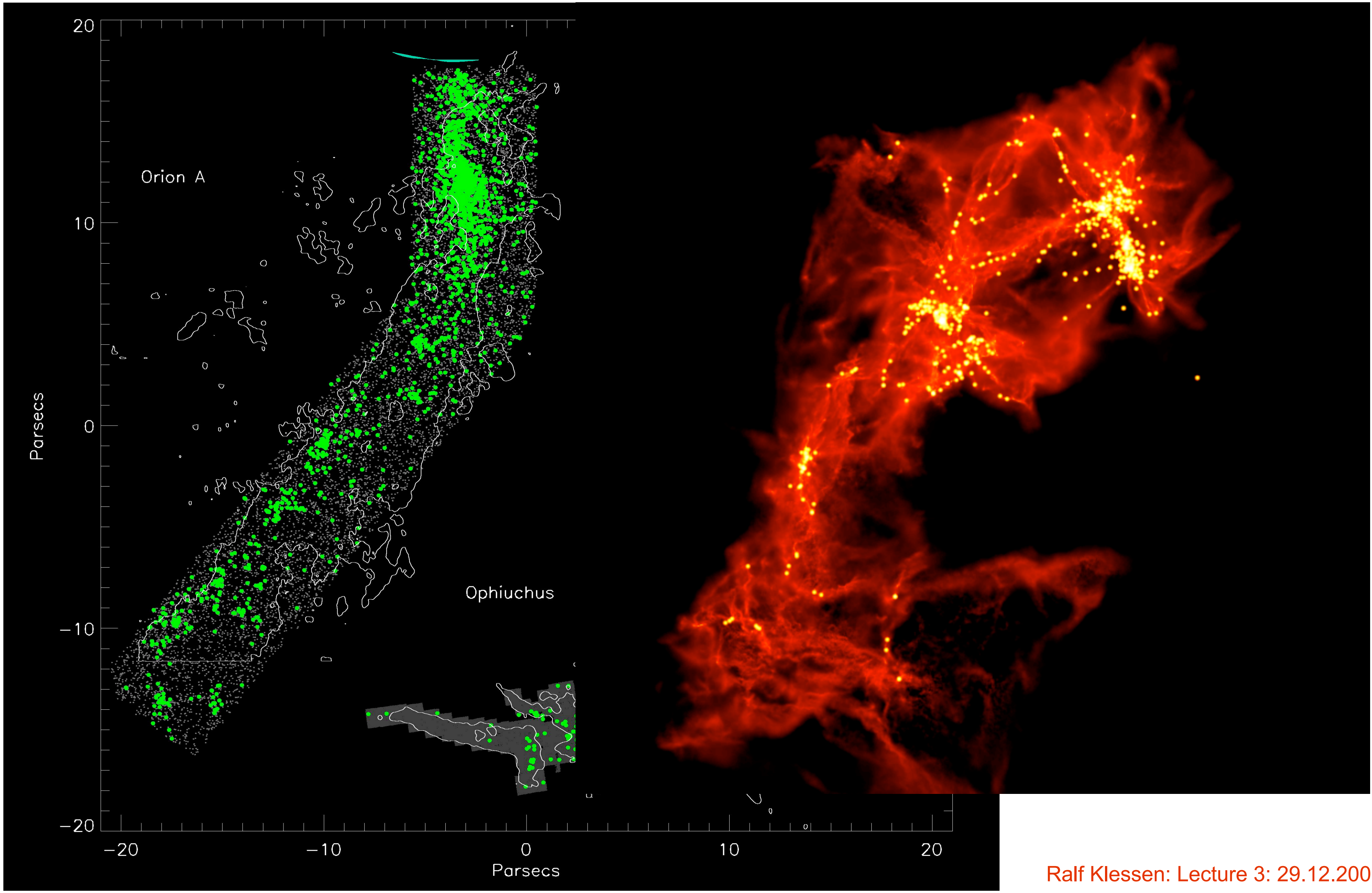
- As a crude estimage:

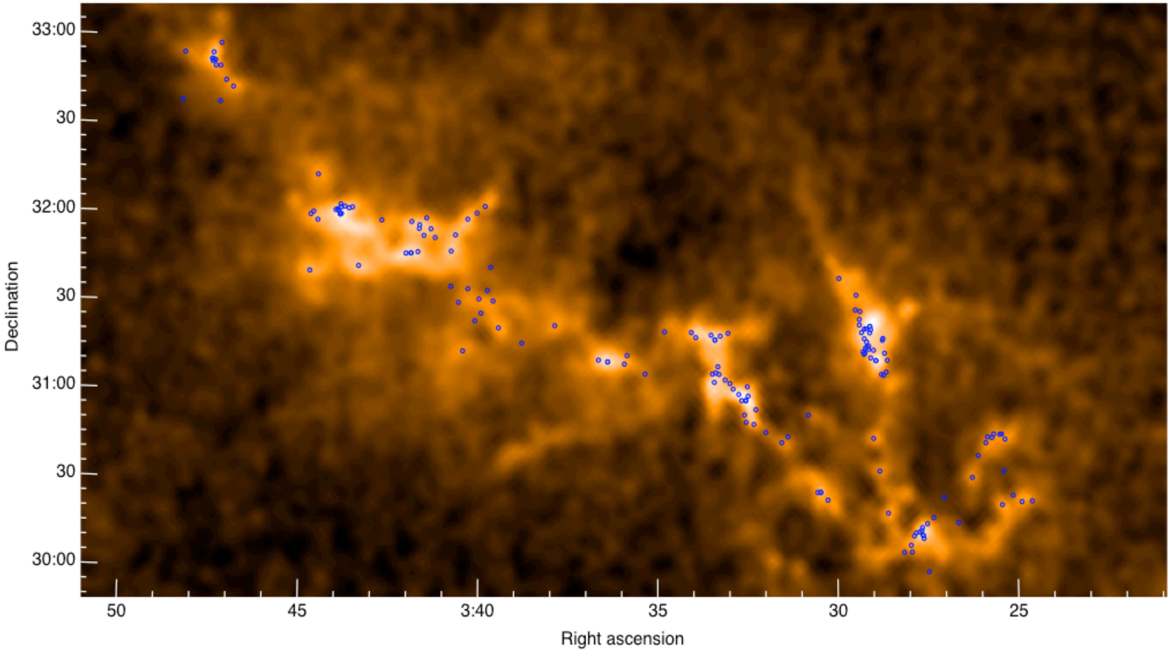
particle-based: better in high-density regions

grid-based: better in low-density regions

- future: GPM / AMR / ???

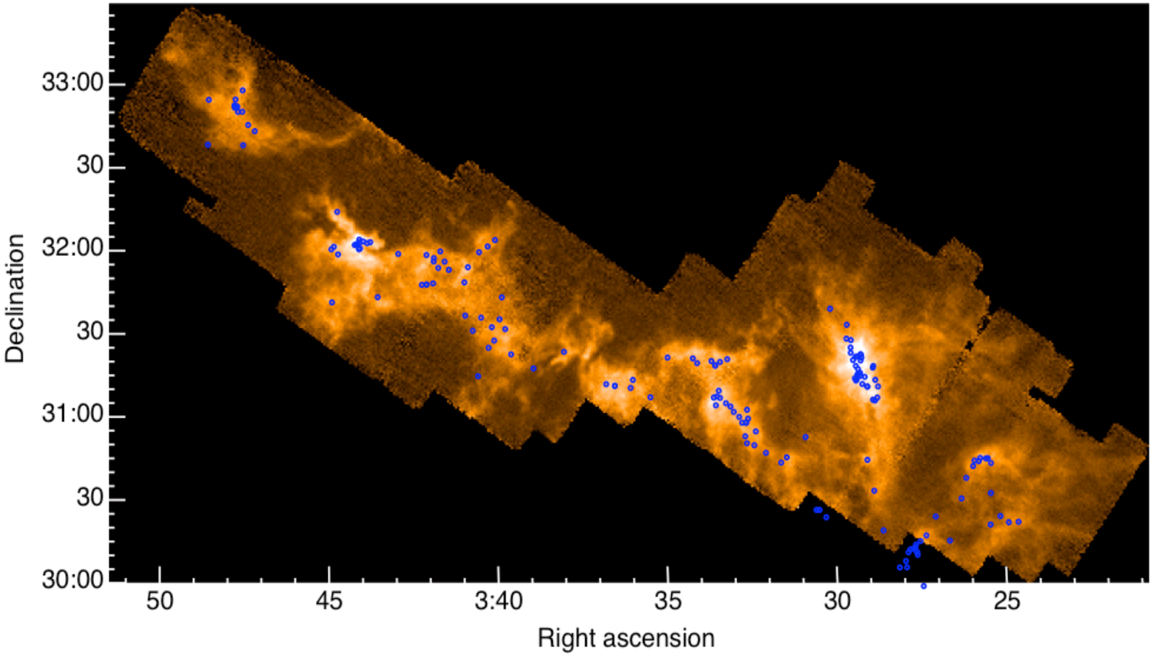
young stars in Orion cloud





IRAM Observations

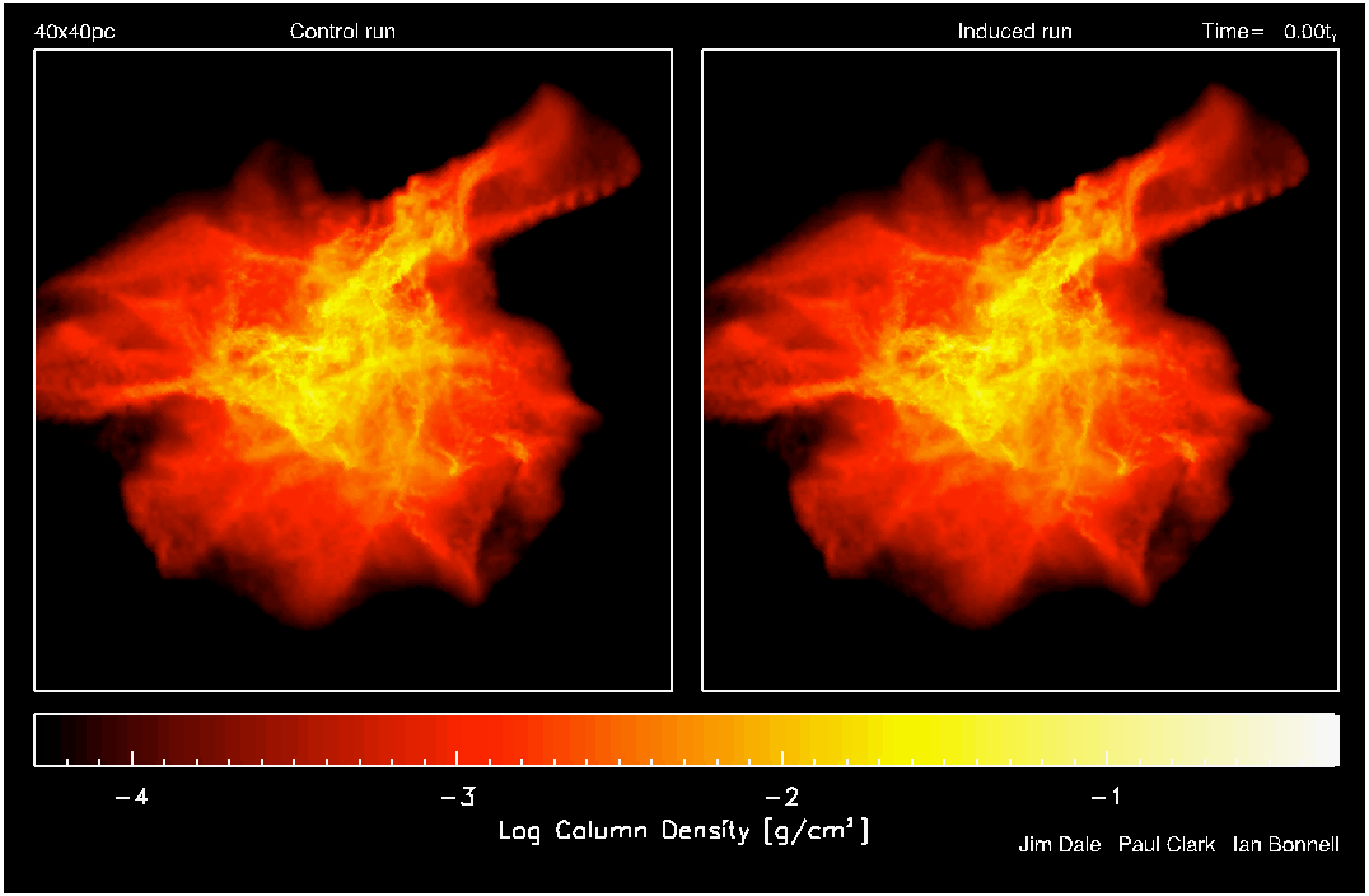
- N_2H^+ and $C^{18}O$
- 15 arcsecond res.
  - ~3000 AU
- N_2H^+ dense gas tracer
  - Most SCUBA
  - Few extinction!



(Perseus: Johnstone et al.)

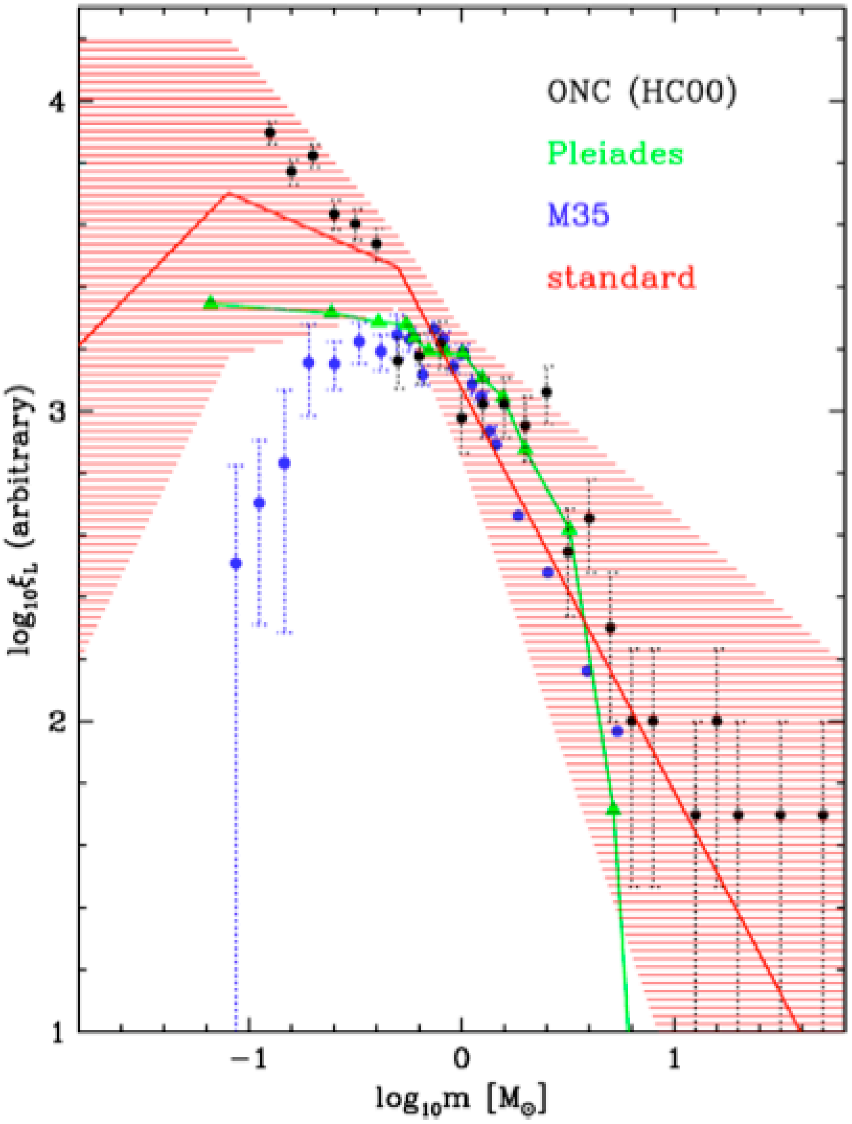
including more physics

immediate future: SPH with radiation feedback (first validation runs)



example 2

IMF: observations I



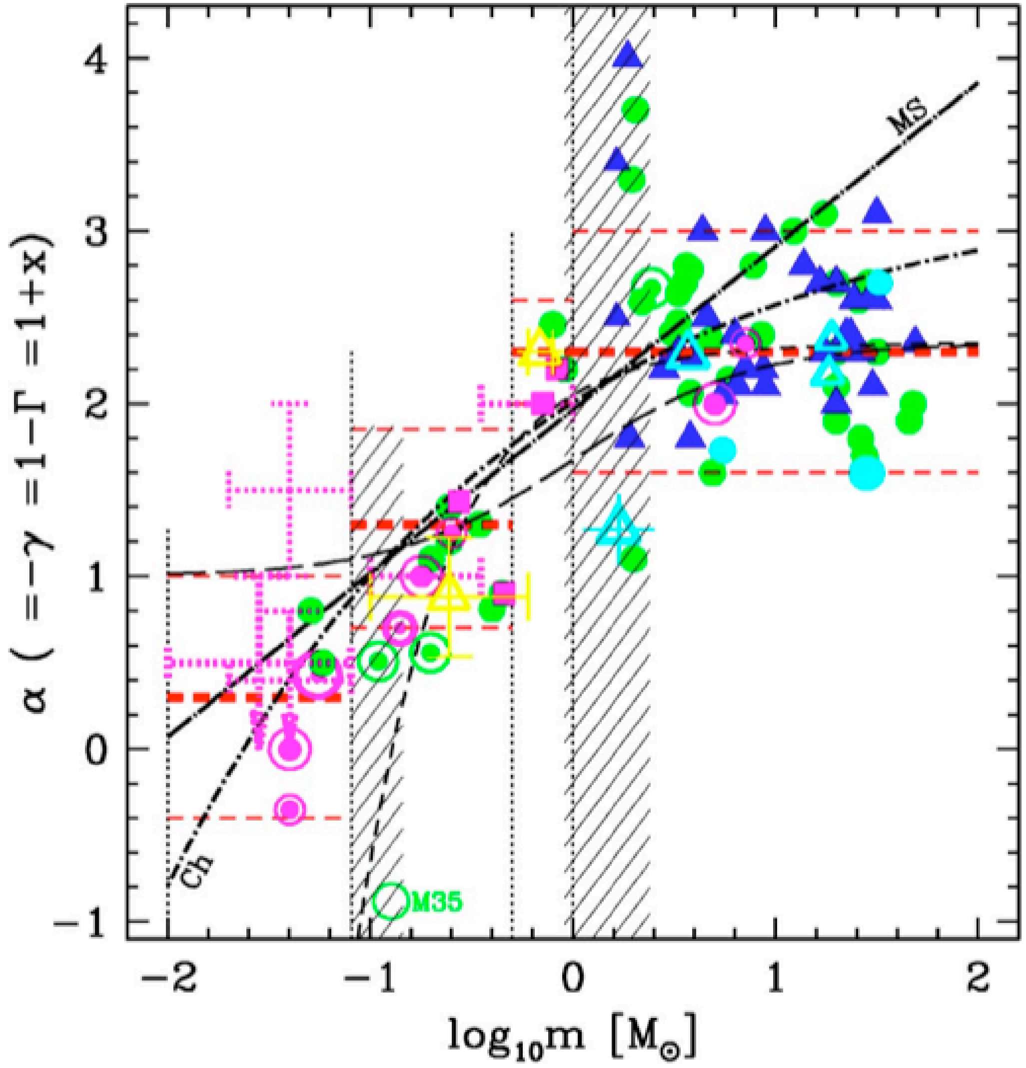
(Kroupa 2002)

power-law approximation to the IMF (Kroupa, Tout, Gillmore 1993, Kroupa 2002)

$$\xi(m)\,dm \propto m^{-\alpha}\,dm,$$

$$\xi(m)=\begin{cases} 0.26\ m^{-0.3} & \text{for } 0.01 \leqslant m < 0.08 \\ 0.035\ m^{-1.3} & \text{for } 0.08 \leqslant m < 0.5 \\ 0.019\ m^{-2.3} & \text{for } 0.5 \leqslant m < \infty. \end{cases}$$

IMF: observations II



but notice possible influence of dynamical evolution in star cluster on tranformation from present-day mass function (PDMF) to IMF.

(Kroupa 2002)

IMF: observations III

notice alternative functional forms for the IMF

- log-normal form (Miller & Scalo 1979):

$$\log_{10}\xi(\log_{10}m)=A-\frac{1}{2(\log_{10}\sigma)^2}\left[\log_{10}\left(\frac{m}{m_0}\right)\right]^2.$$

with $m_0=0.23, \quad \sigma=0.42, \quad A=0.1.$

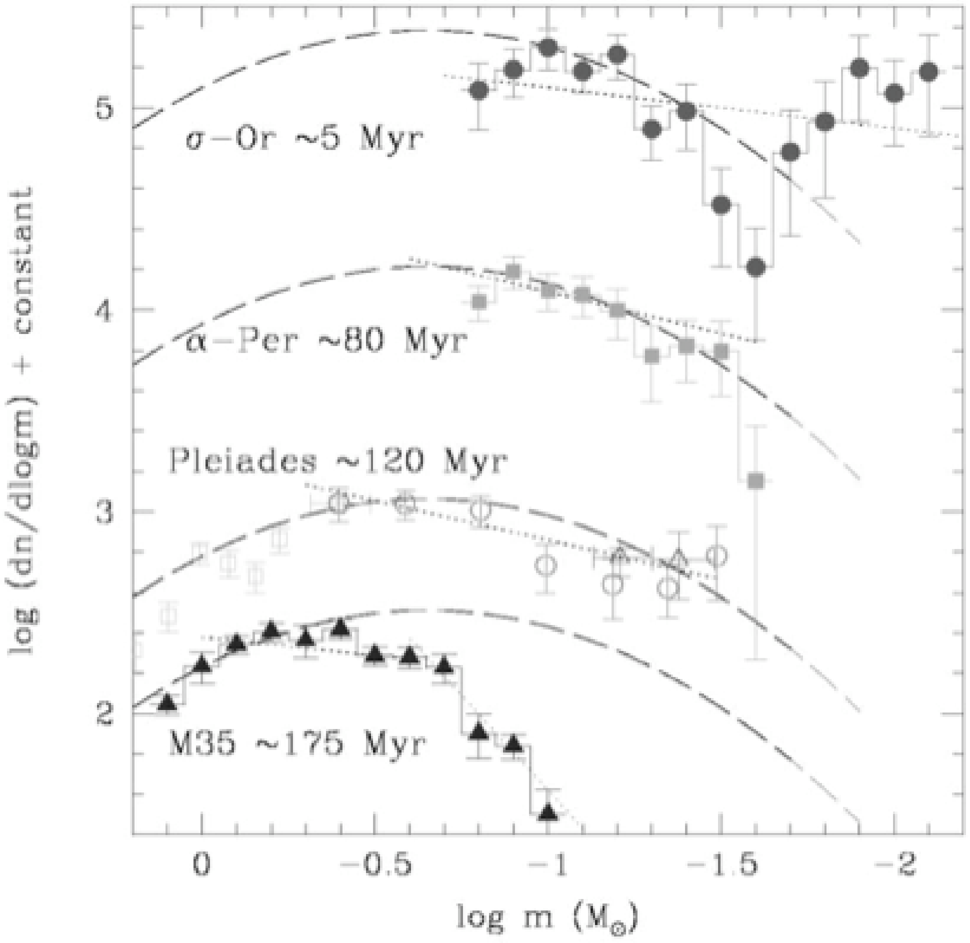
- combined log-normal & power-law (Chabrier 2003):

$$m\leq 1.0\ M_\odot,\ \xi(\log m)\ =\ A\exp\left[-(\log m-\log m_c)^2/2\sigma^2\right]$$

$$m>1.0\ M_\odot,\ \xi(\log m)\ =\ Am^{-x}$$

A	$0.158^{+0.051}_{-0.046}$	A	4.43×10^{-2}
m_c	$0.079^{-0.016}_{+0.021}$	x	1.3 ± 0.3
σ	$0.69^{-0.01}_{+0.05}$		

IMF: observations IV



comparison at low-mass end

(Chabrier 2003)

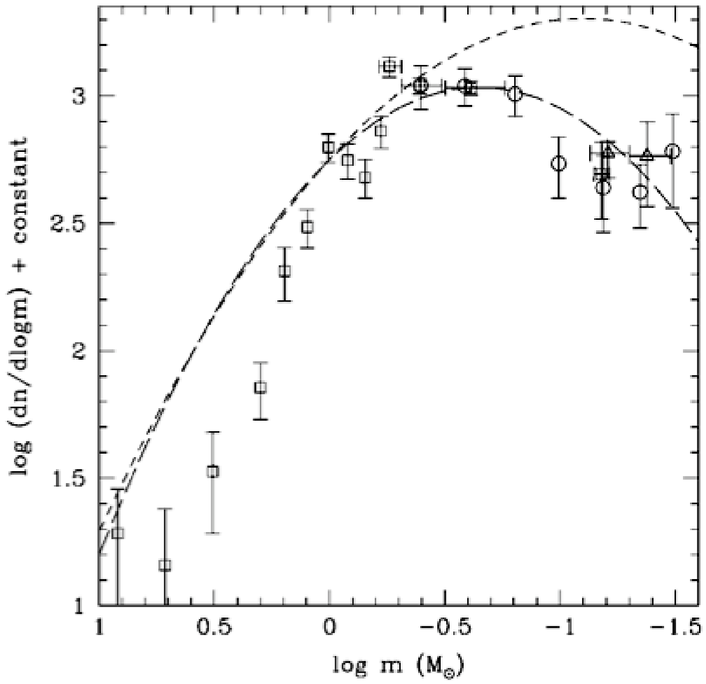


FIG. 4.—Pleiades mass function calculated with the BCAH98 and Chabrier et al. (2000a) MMRs from various observations. *Squares:* Hambly et al. (1999); *triangles:* Dobbie et al. (2002b); *circles:* Moraux et al. (2003). The short-dashed and long-dashed lines display the single (eq. [17]) and system (eq. [18]) field MFs, respectively, arbitrarily normalized to the present data.

system vs. single-star IMF

IMF

- distribution of stellar masses depends on
  - turbulent initial conditions
    --> mass spectrum of prestellar cloud cores
  - collapse and interaction of prestellar cores
    --> competitive accretion and *N*-body effects
  - thermodynamic properties of gas
    --> balance between heating and cooling
    --> EOS (determines which cores go into collapse)
  - (proto) stellar feedback terminates star formation
    ionizing radiation, bipolar outflows, winds, SN

(e.g. Larson 2003, Prog. Rep. Phys.; Mac Low & Klessen, 2004, Rev. Mod. Phys, 76, 125 - 194)

IMF

- many approaches give the „right“ IMF
  - IMF from random sampling of fractal clouds (Elmegreem: quasi-static approach)
  - IMF from stellar feedback (Adams & Fatuzzo)
  - IMF as closest packing problem (Richtler)
  - IMF from ambipolar diffusion in magnetically dominated clouds (Shu, Li, Allen)
  - IMF from competitive accretion (Bonnell, Bate)
  - IMF from turbulent fragmentation (Padoan & Nordlund)
  - IMF from gravoturbulent fragmentation (Ballesteros-Paredes, Heitsch, Klessen, Li, Nakamura, Mac Low, Pudritz, Vazquez-Semadeni, etc.)
  - etc...

beyond the IMF

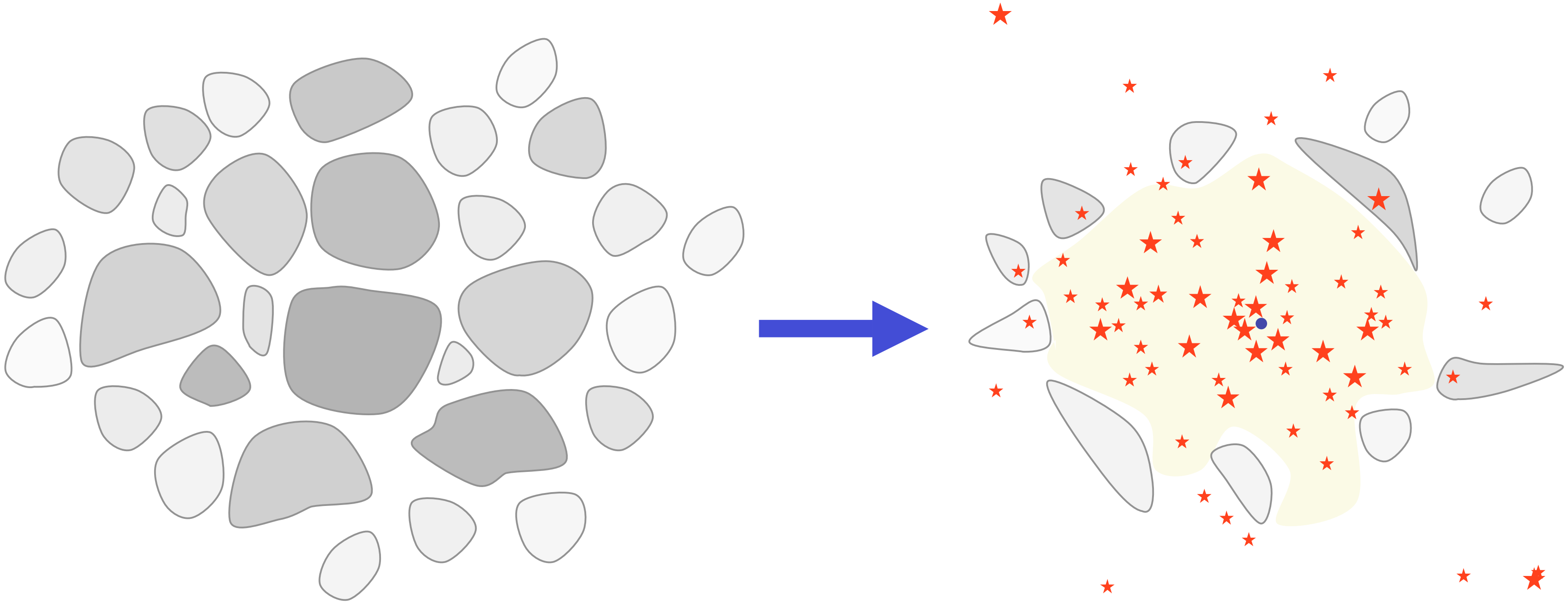
- many approaches give the „right“ IMF

therefore, we may need to look for „secondary“ parameters which could act as better discriminants

  - chemical composition (mixing)
  - binarity (separation, mass ratio, etc.)
  - disks, rotational properties
  - dynamics
    (correlation between young stars and parental gas)

Gravoturbulent approach

Most stars form in clusters → *star formation = cluster formation*



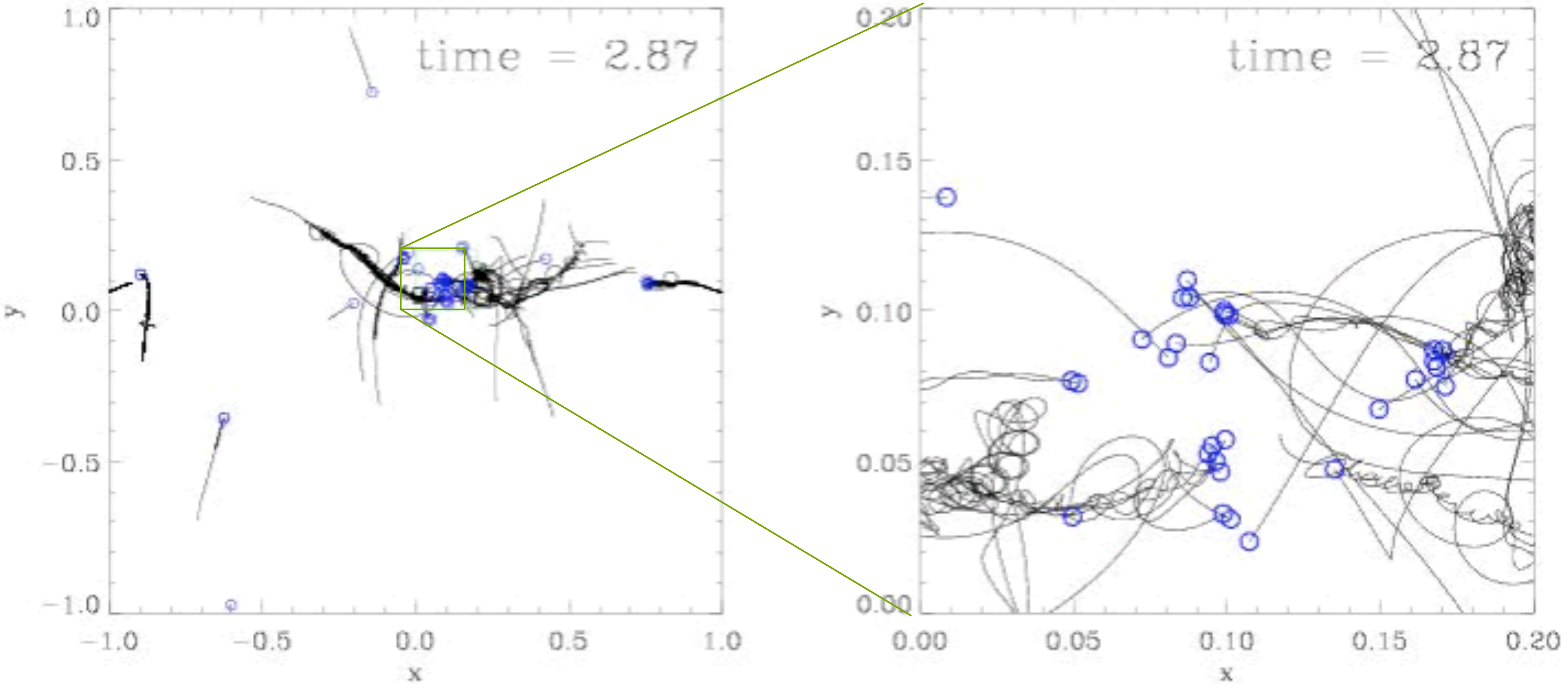
How to get from cloud cores to star clusters?

How do the stars acquire mass?

(e.g. Larson 2003, Prog. Rep. Phys.; Mac Low & Klessen, 2004, Rev. Mod. Phys, 76, 125 - 194)

Star cluster formation

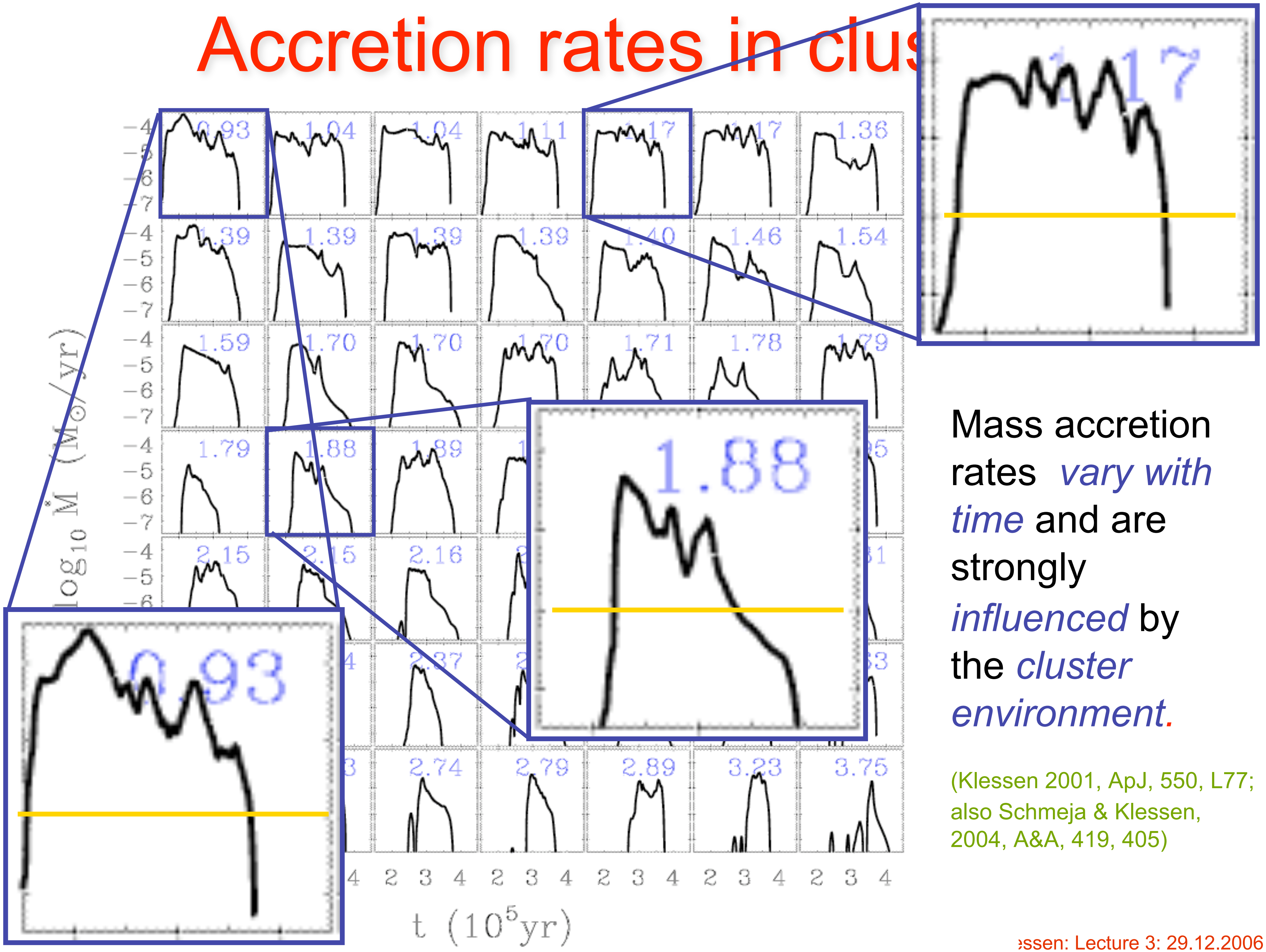
Most stars form in clusters → *star formation = cluster formation*



Trajectories of protostars in a nascent dense cluster created by gravoturbulent fragmentation

(from Klessen & Burkert 2000, ApJS, 128, 287)

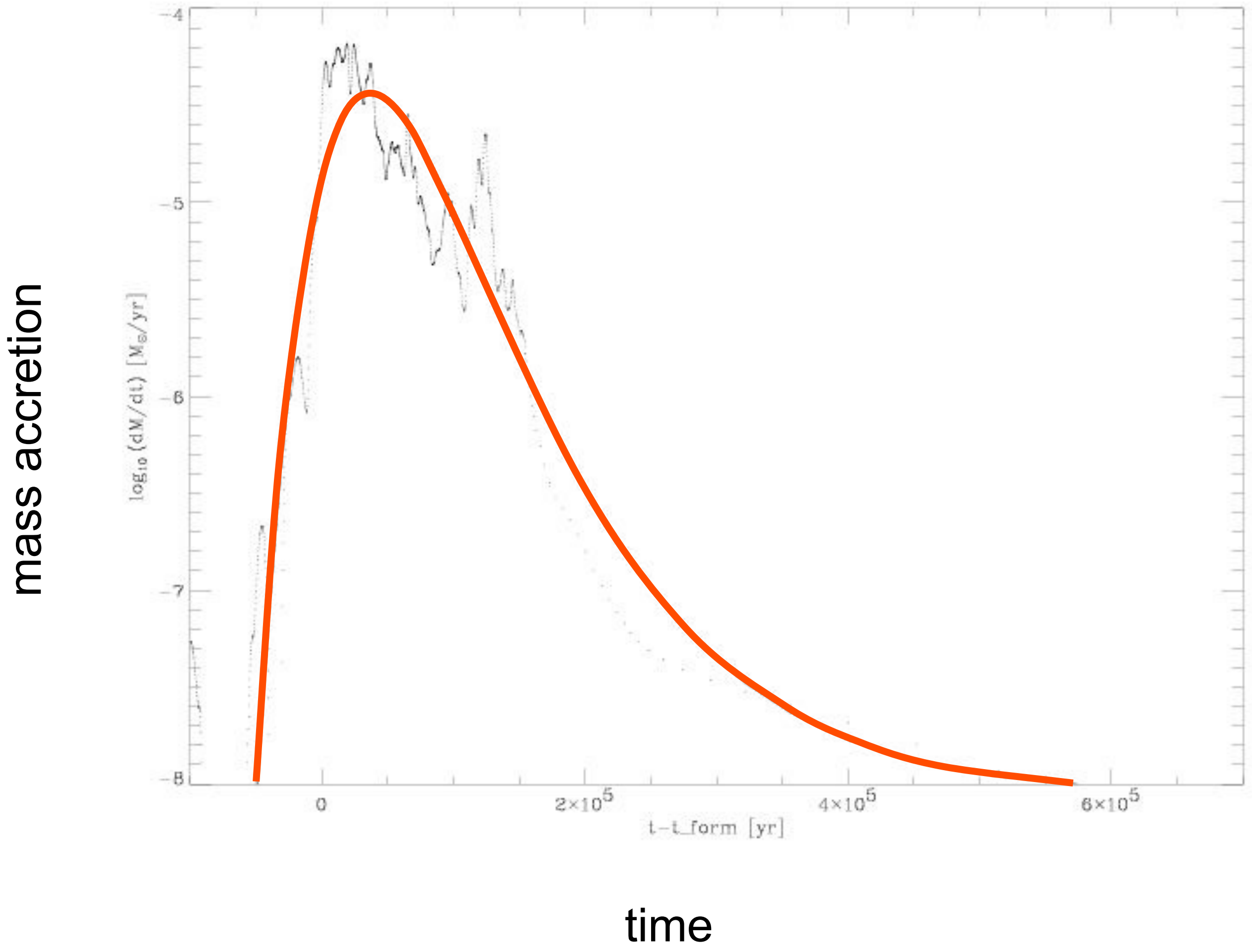
Accretion rates in clus



Mass accretion rates *vary with time* and are strongly *influenced* by the *cluster environment*.

(Klessen 2001, ApJ, 550, L77; also Schmeja & Klessen, 2004, A&A, 419, 405)

“Empirical” mass accretion law



Simple analytic formula for individual mass accretion rates: $\boxed{dM/dt = At \cdot \exp(-t/\tau)}$

(Schmeja & Klessen, 2004 -- A&A, 419, 405 - 417)

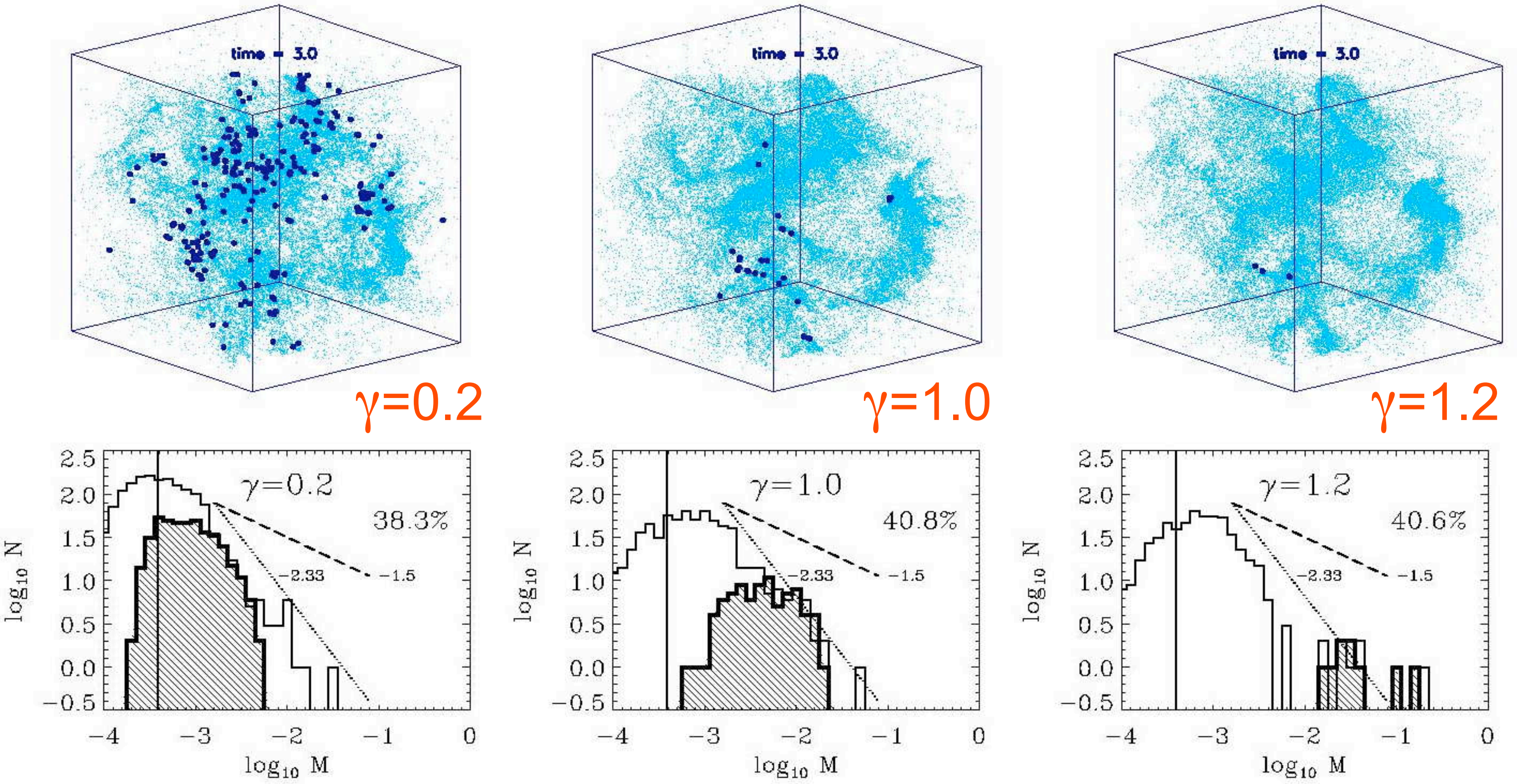
Dependency on EOS

- degree of fragmentation depends on *EOS!*

- polytropic EOS: $p \propto \rho^{\gamma}$
- $\gamma<1$: dense cluster of low-mass stars
- $\gamma>1$: isolated high-mass stars

(see Li, Klessen, & Mac Low 2003, ApJ, 592, 975; also Kawachi & Hanawa 1998, Larson 2003)

Dependency on EOS



for γ<1 fragmentation is enhanced → *cluster of low-mass stars*

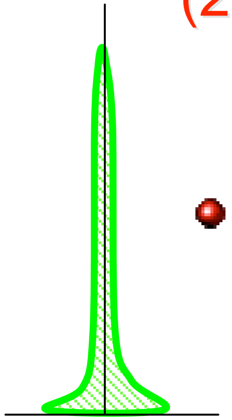
for γ>1 it is suppressed → formation of *isolated massive stars*

(from Li, Klessen, & Mac Low 2003, ApJ, 592, 975)

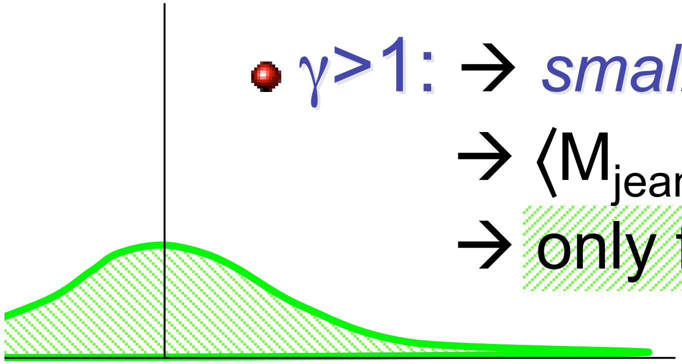
How does that work?

(1) $\mathbf{p \propto \rho^{\gamma}} \quad \rightarrow \quad \mathbf{\rho \propto p^{1/\gamma}}$

(2) $\mathbf{M_{jeans} \propto \gamma^{3/2} \rho^{(3\gamma-4)/2}}$



- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ becomes small
  → number of fluctuations with $M > M_{jeans}$ is large



- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

Implications

- degree of fragmentation depends on *EOS!*

- polytropic EOS: $p \propto \rho^{\gamma}$
- $\gamma<1$: dense cluster of low-mass stars
- $\gamma>1$: isolated high-mass stars

(see Li, Klessen, & Mac Low 2003, ApJ, 592, 975; Kawachi & Hanawa 1998; Larson 2003; also Jappsen, Klessen, Larson, Li, Mac Low, 2005, 435, 611)

- implications for extreme environmental conditions

  - expect Pop III stars to be massive and form in isolation
  - expect IMF variations in warm & dusty starburst regions

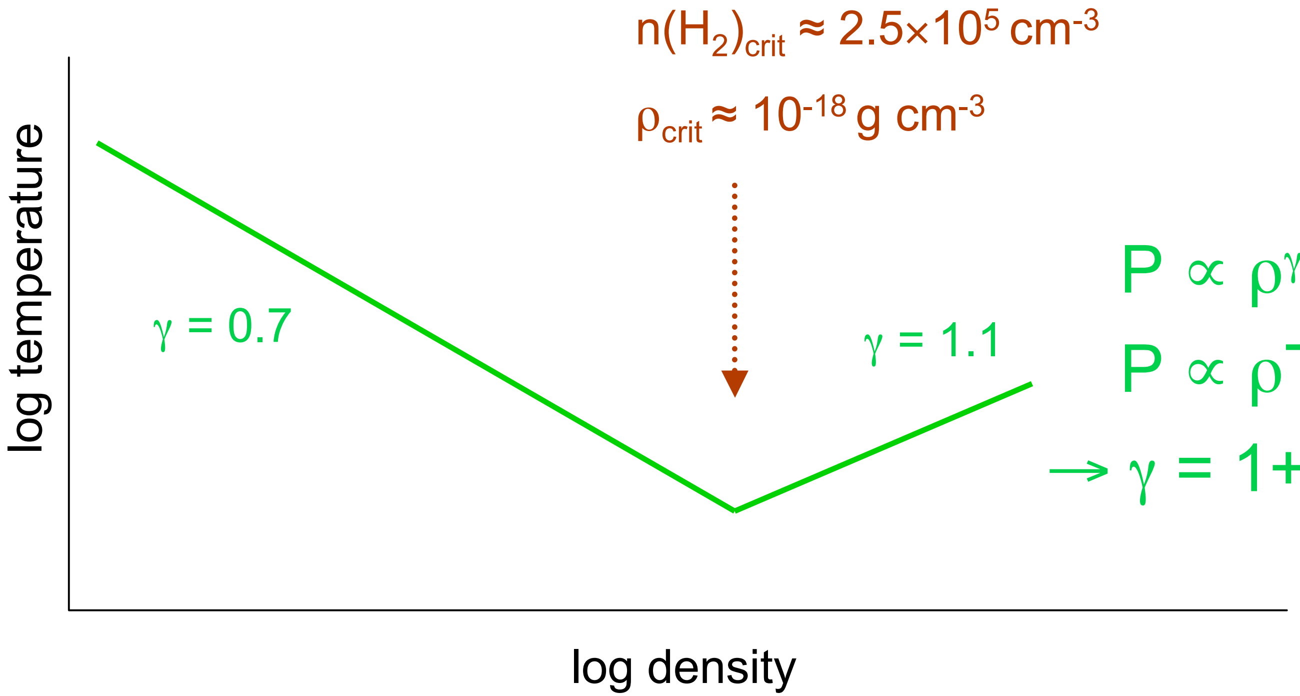
  (Spaans & Silk 2005; Klessen, Spaans, & Jappsen 2006)

- Observational findings: isolated O stars in LMC (and M51)?

  (Lamers et al. 2002, Massey 2002; see however, de Witt et al. 2005 for Galaxy)

More realistic EOS

- But EOS depends on *chemical state*, on *balance* between *heating* and *cooling*



$P \propto \rho^\gamma$

$P \propto \rho T$

$\rightarrow \gamma = 1 + d\log T / d\log\rho$

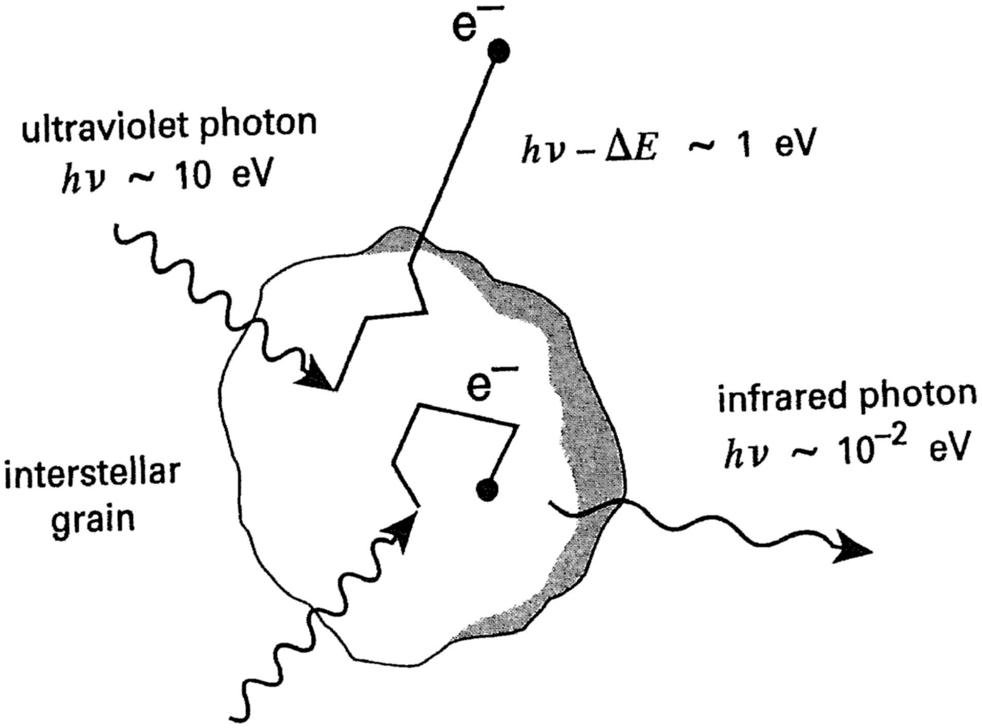
(Larson 2005; Jappsen et al. 2005, A&A, 435, 611)

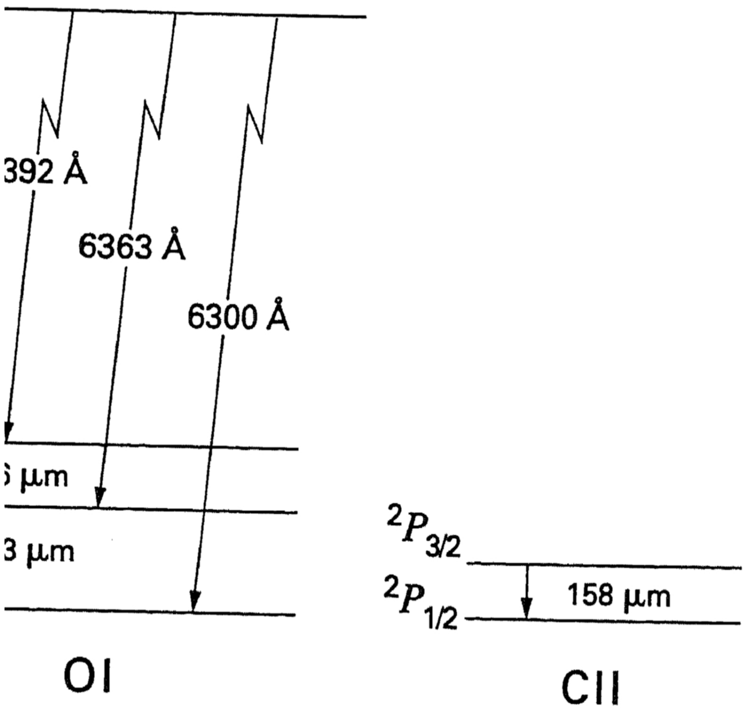
Heating and Cooling Processes

$n < 10^4\ \mathrm{cm}^{-3}$

- photoelectric emission from dust grains

- collisionally excited line emission from OI and CII



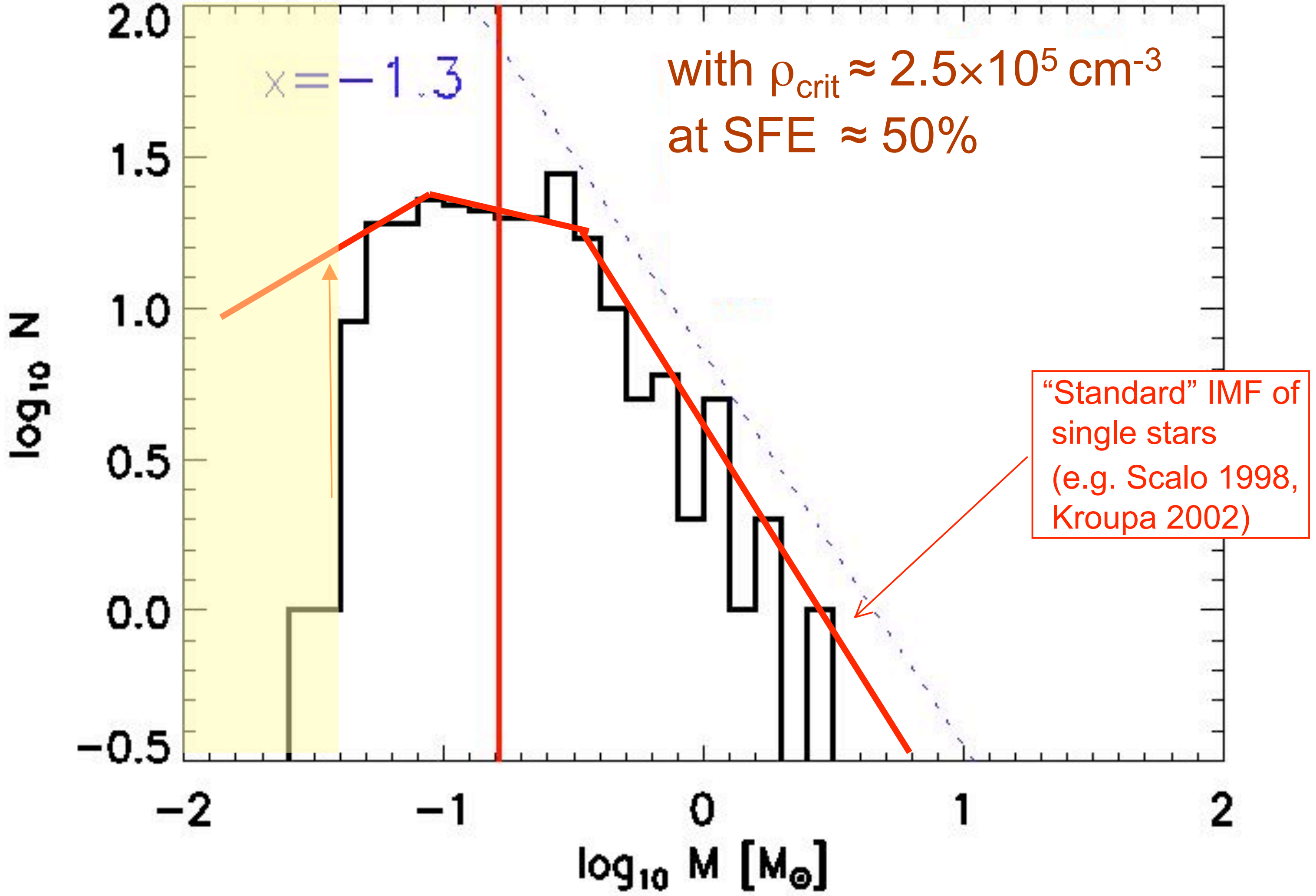


Heating and Cooling Processes

$n > 10^4\ \mathrm{cm}^{-3}$

- cloud cores optically thick to heating radiation and atomic line emission
- cooling by molecules limited because of freeze out on the surface of dust grains

IMF in nearby molecular clouds

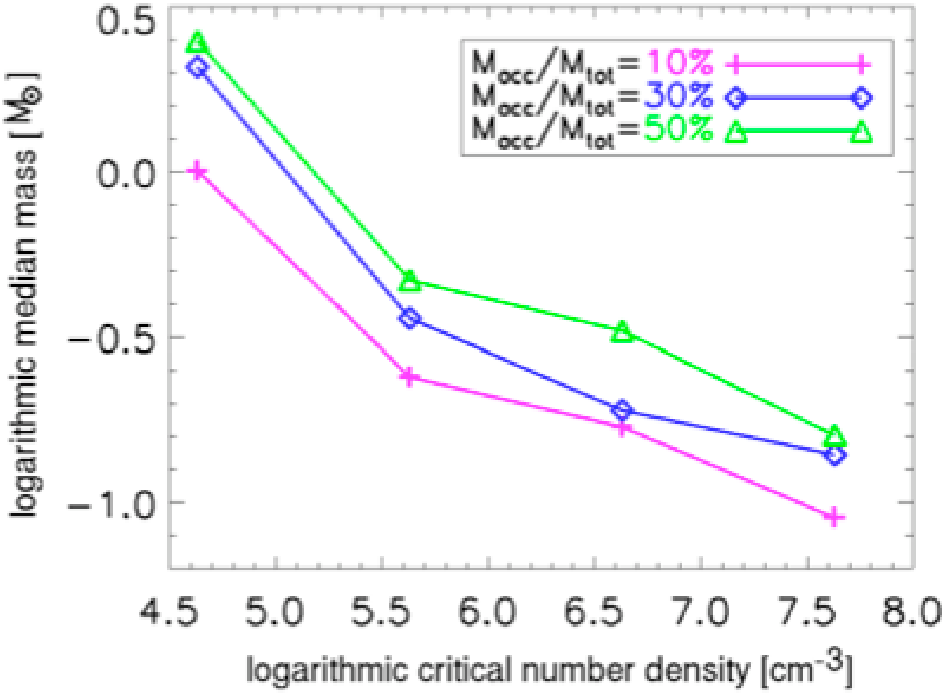


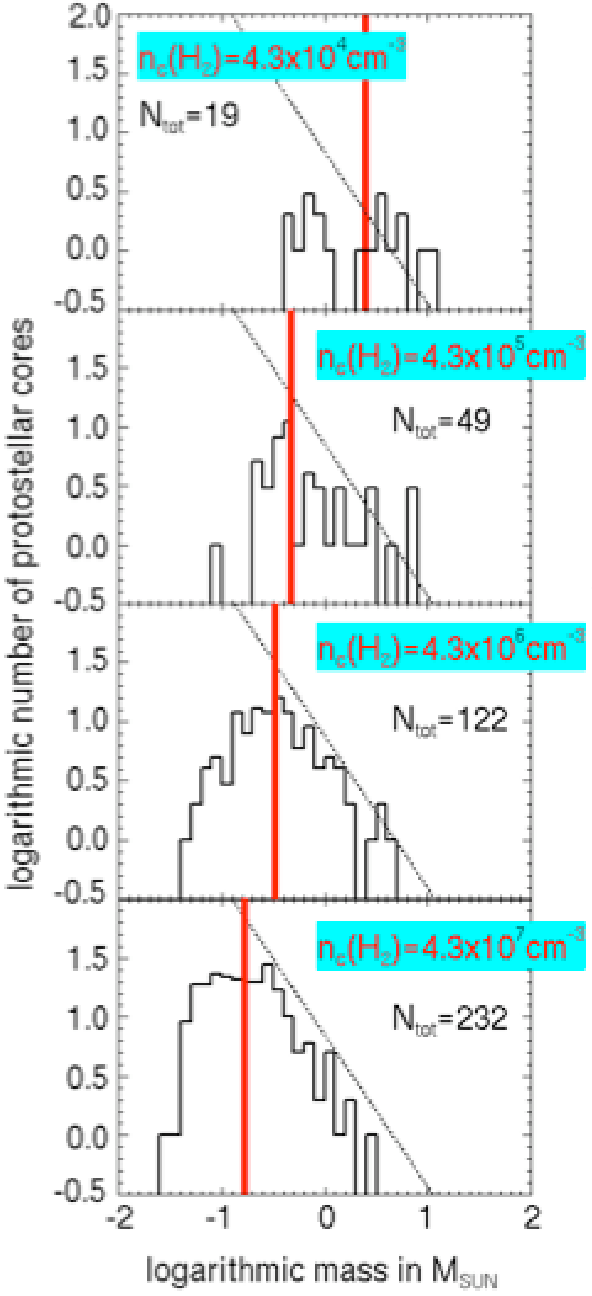
with $\rho_{crit} \approx 2.5\times10^5$ cm^{-3}
at SFE ≈ 50%

"Standard" IMF of single stars (e.g. Scalo 1998, Kroupa 2002)

(Jappsen et al. 2005, A&A, 435, 611)c

peak of mass spectrum
depends on EOS details





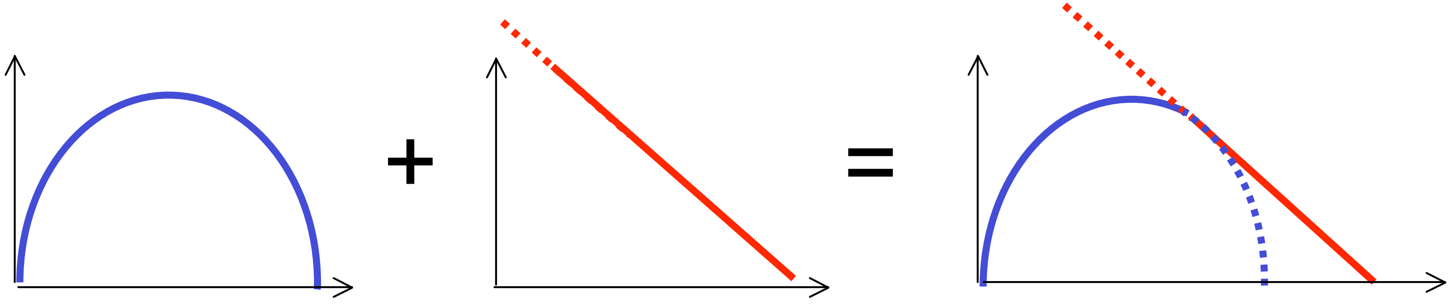
peak of mass spectrum
depends on EOS details

- we can relate stellar mass spectrum to *universal quantities*
  - atomic and molecular parameters for balance of heating and cooling &
  - universal scaling relations for supersonic interstellar turbulence and gravity

cause of universal IMF?

what about extreme environmental cond.?

Plausibility argument for shape



- Supersonic turbulence is scale free process

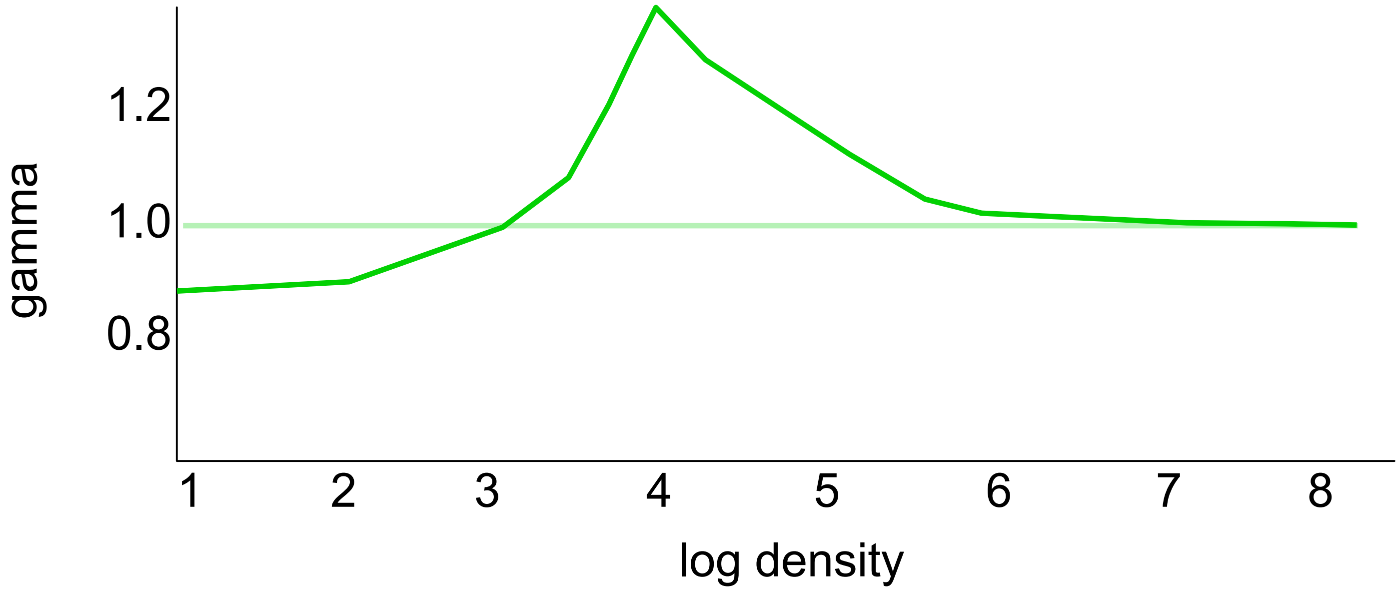
  → *POWER LAW BEHAVIOR*

- *But also:* turbulence and fragmentation are highly stochastic processes → central limit theorem

  → *GAUSSIAN DISTRIBUTION*

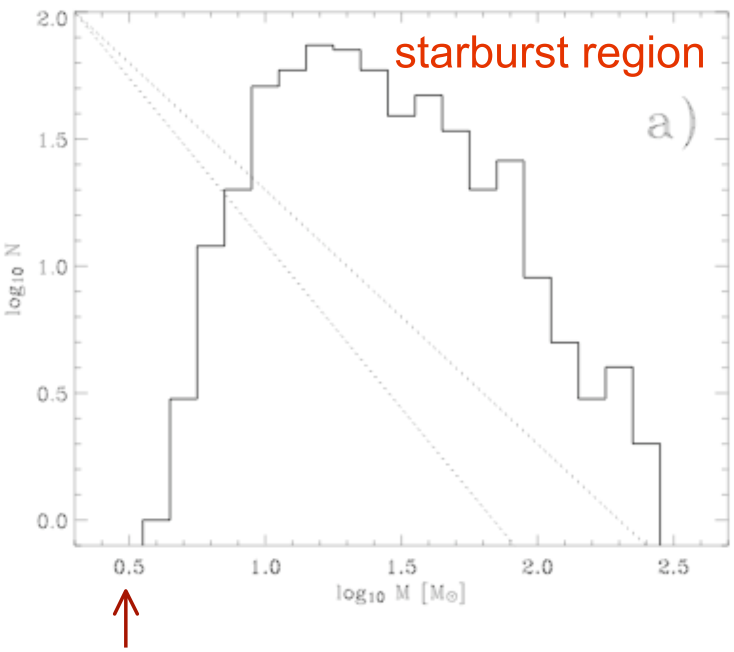
IMF in starburst galaxies

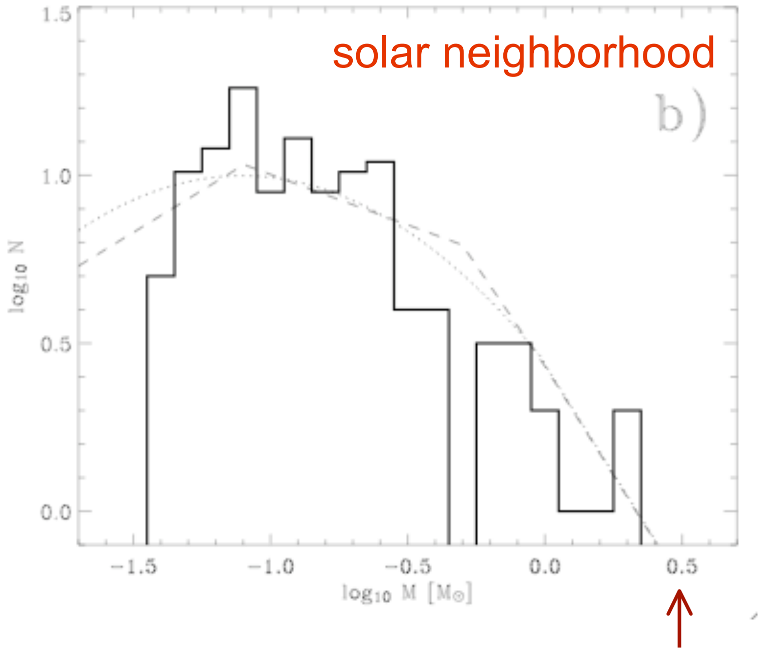
- Nuclear regions of starburst galaxies are extreme:
  - hot dust, large densities, strong radiation, etc.
- Thermodynamic properties of star-forming gas differ from Milky Way --> Different EOS!
  (see Spaans & Silk 2005)



IMF in starburst galaxies

- Different EOS --> different IMF
  (see Klessen, Spaans, Jappsen, in prep.)





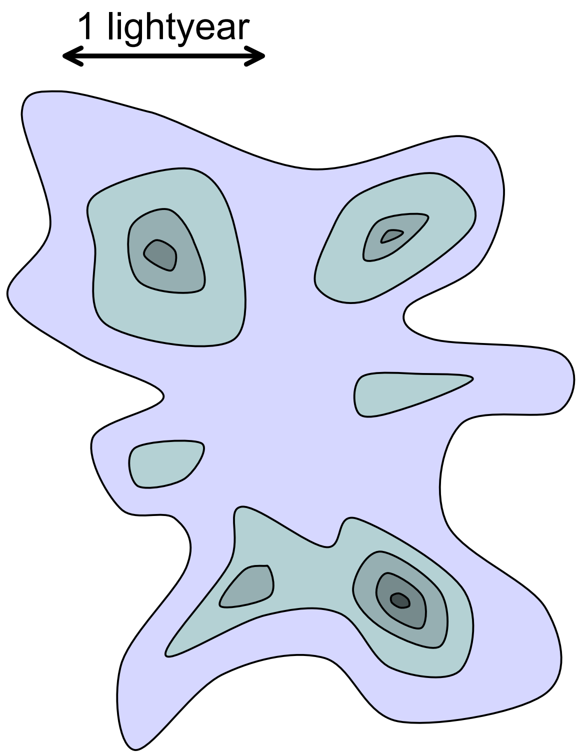
note the different mass scale...

Remarks

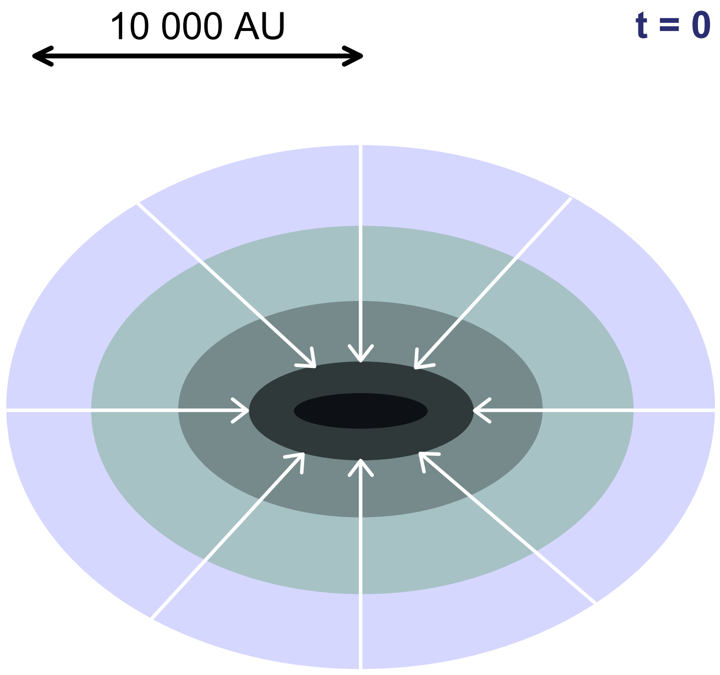
- What is the lowest mass in IMF?
- How do you get it? Do BD‘s form just like stars?
  - „normal“ gravoturbulent fragmentation?
    (opacity limit)
  - disk fragmentation?
  - failed stars (say by ejection in dense clusters or by external irradiation)?

ang. mom.
& binaries

Phases of star formation

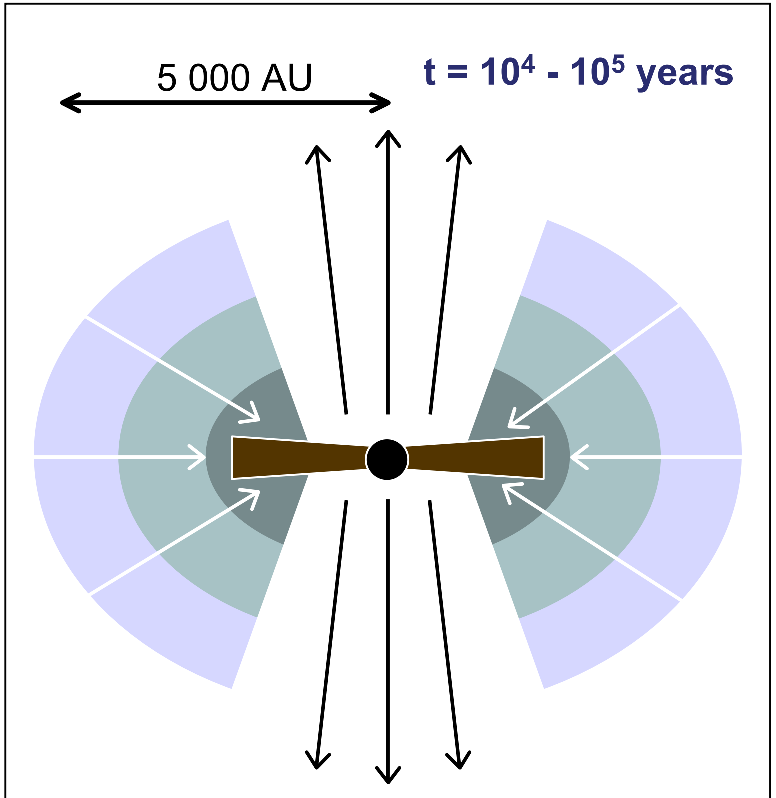


prestellar cores in dark clouds



gravitational collapse: class 0 object

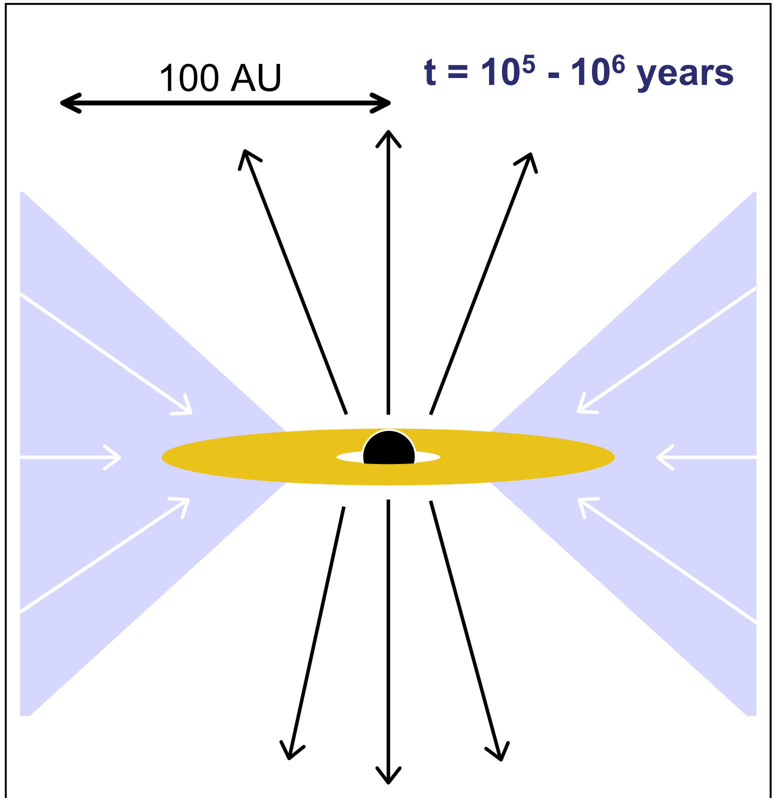
Phases of star formation



5 000 AU

$t = 10^4 - 10^5$ years

embedded protostar: class 1



100 AU

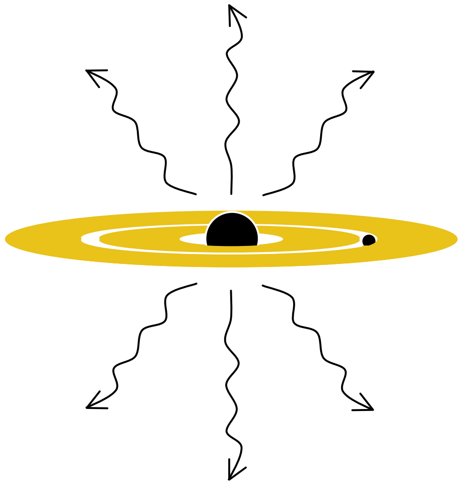
$t = 10^5 - 10^6$ years

classical T Tauri star: class 2

Phases of star formation

100 AU

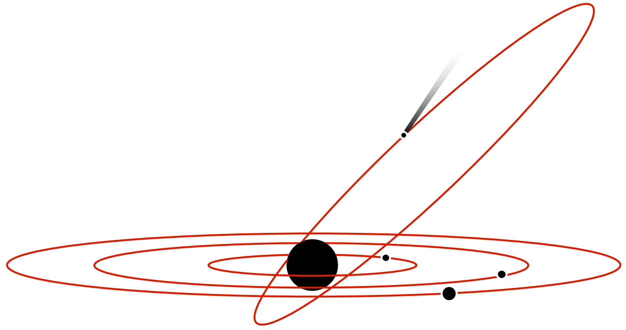
t = 10^6 - 10^7 years



pre-main sequence star, debris disks, visible at optical wavelengths

50 AU

t > 10^7 years

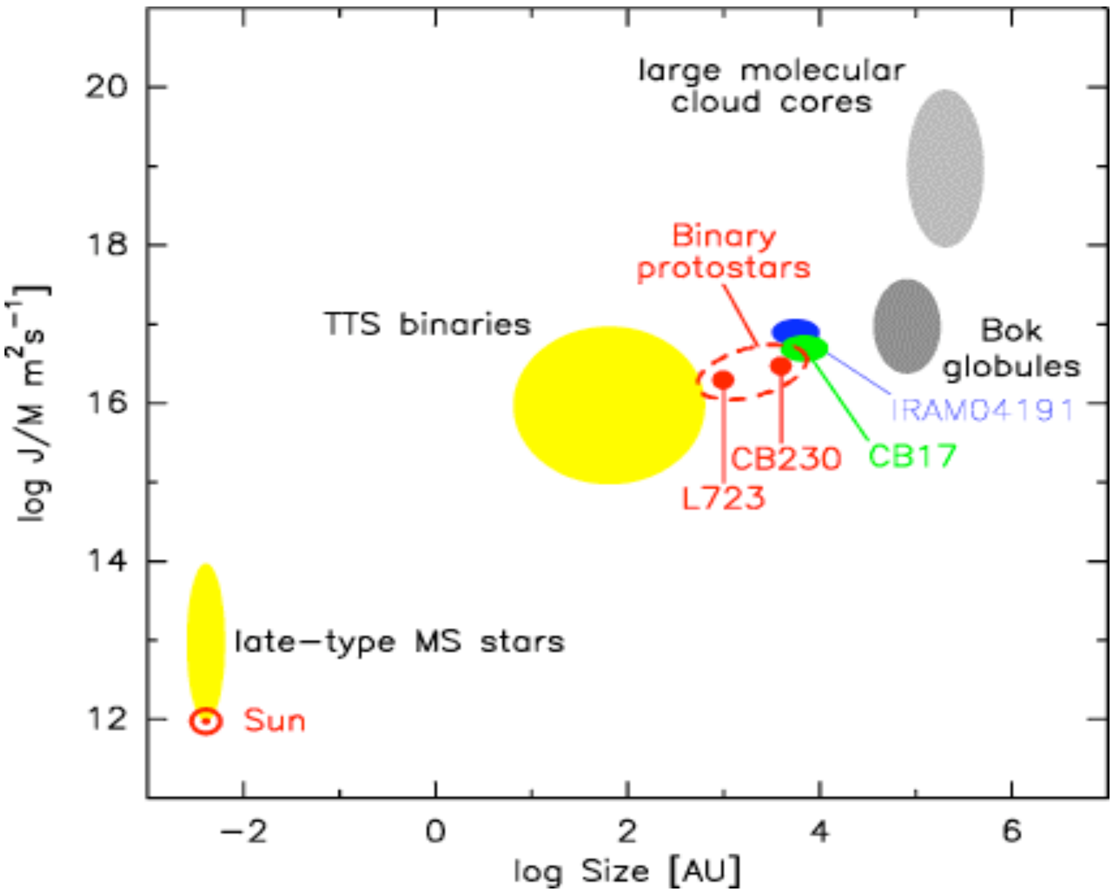


star on main sequence (nuclear fusion) with planetary system ang. mom.

loss

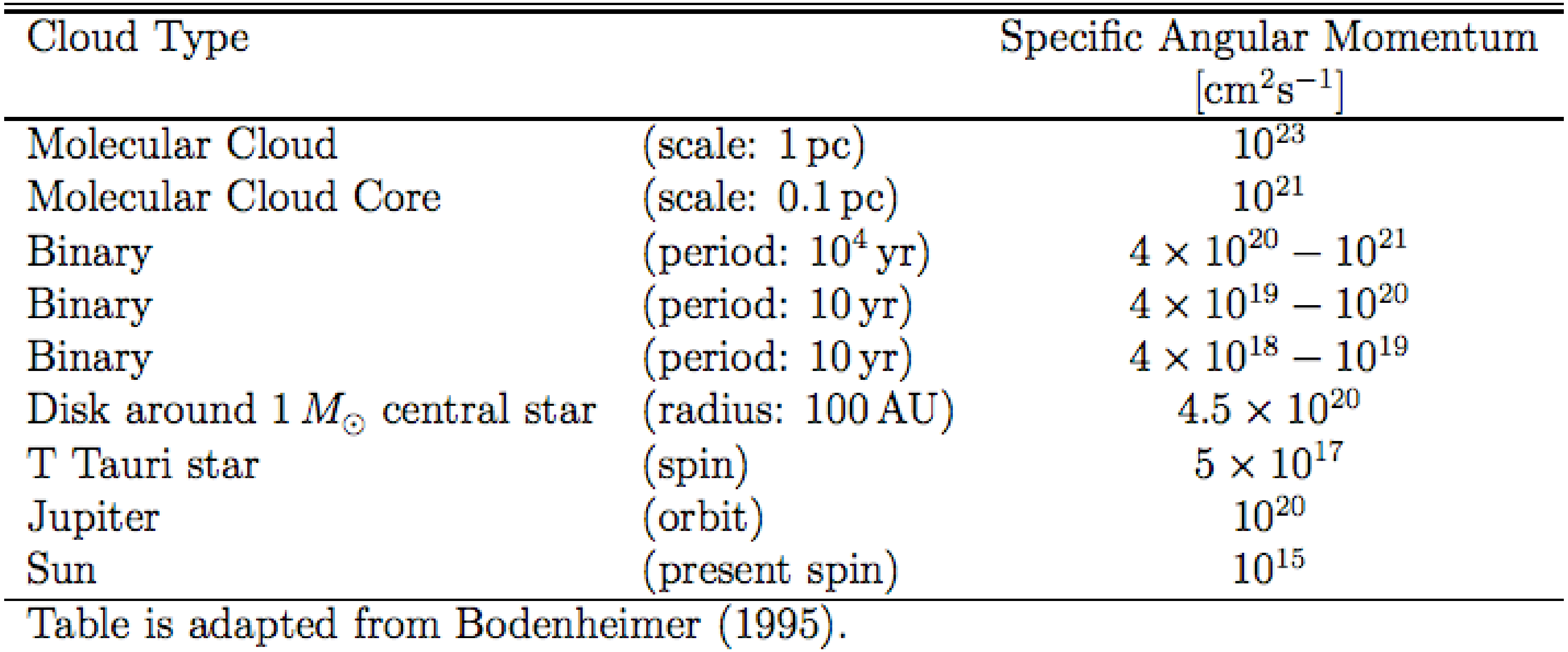
Angular momentum problem

Specific angular momentum vs. Size scale



(from R. Launhardt, see also Bodenheimer 2000)

Angular momentum problem



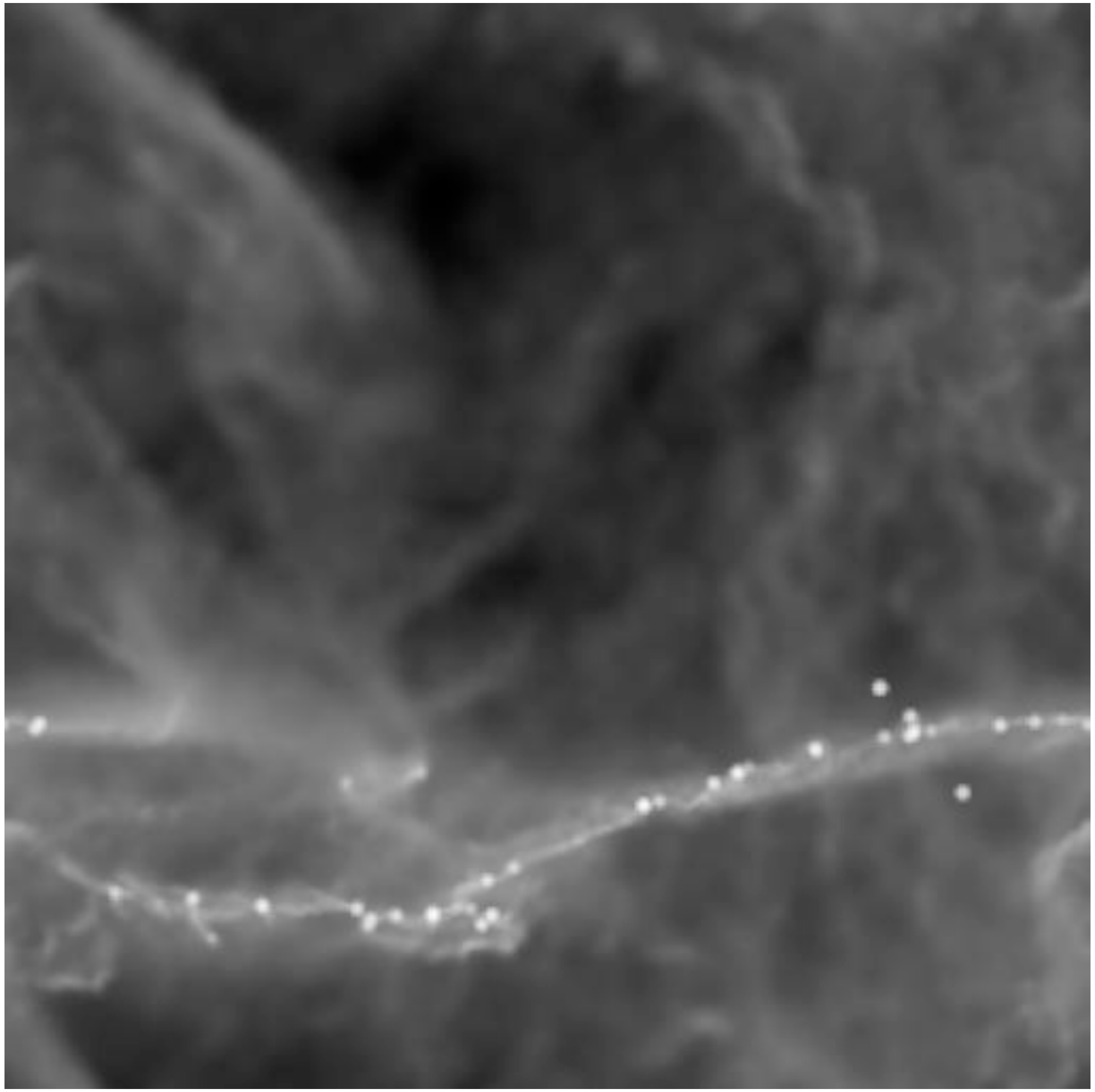
Cloud Type		Specific Angular Momentum $[\mathrm{cm^2 s^{-1}}]$
Molecular Cloud	(scale: 1 pc)	10^{23}
Molecular Cloud Core	(scale: 0.1 pc)	10^{21}
Binary	(period: 10^4 yr)	$4 \times 10^{20} - 10^{21}$
Binary	(period: 10 yr)	$4 \times 10^{19} - 10^{20}$
Binary	(period: 10 yr)	$4 \times 10^{18} - 10^{19}$
Disk around 1 $M_\odot$ central star	(radius: 100 AU)	4.5×10^{20}
T Tauri star	(spin)	5×10^{17}
Jupiter	(orbit)	10^{20}
Sun	(present spin)	10^{15}

Table is adapted from Bodenheimer (1995).

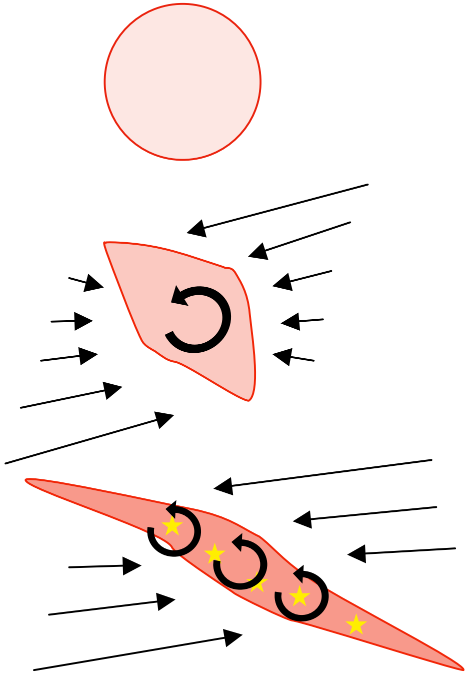
Question

- How does the system loose angular momentum during collapse and star formation?
  - from clouds to cores:
    - magnetic breaking
    - tidal angular momentum redistribution
  - from cores to disks
    - outflows / winds
    - spreading of disk (and possible truncation in cluster)
  - from disk to star(s)
    - binary formation / planet formation
    - disk locking

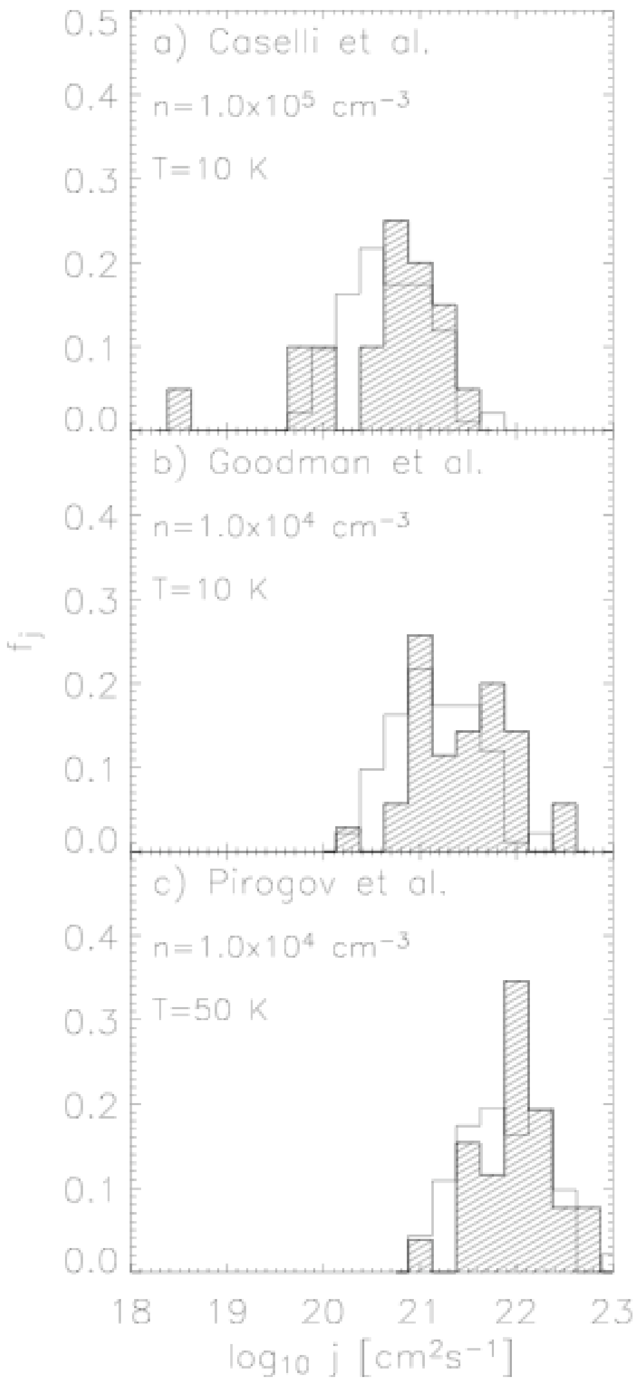
Distribution of ang. mom.



generation of local vorticity
in oblique shocks:



Example

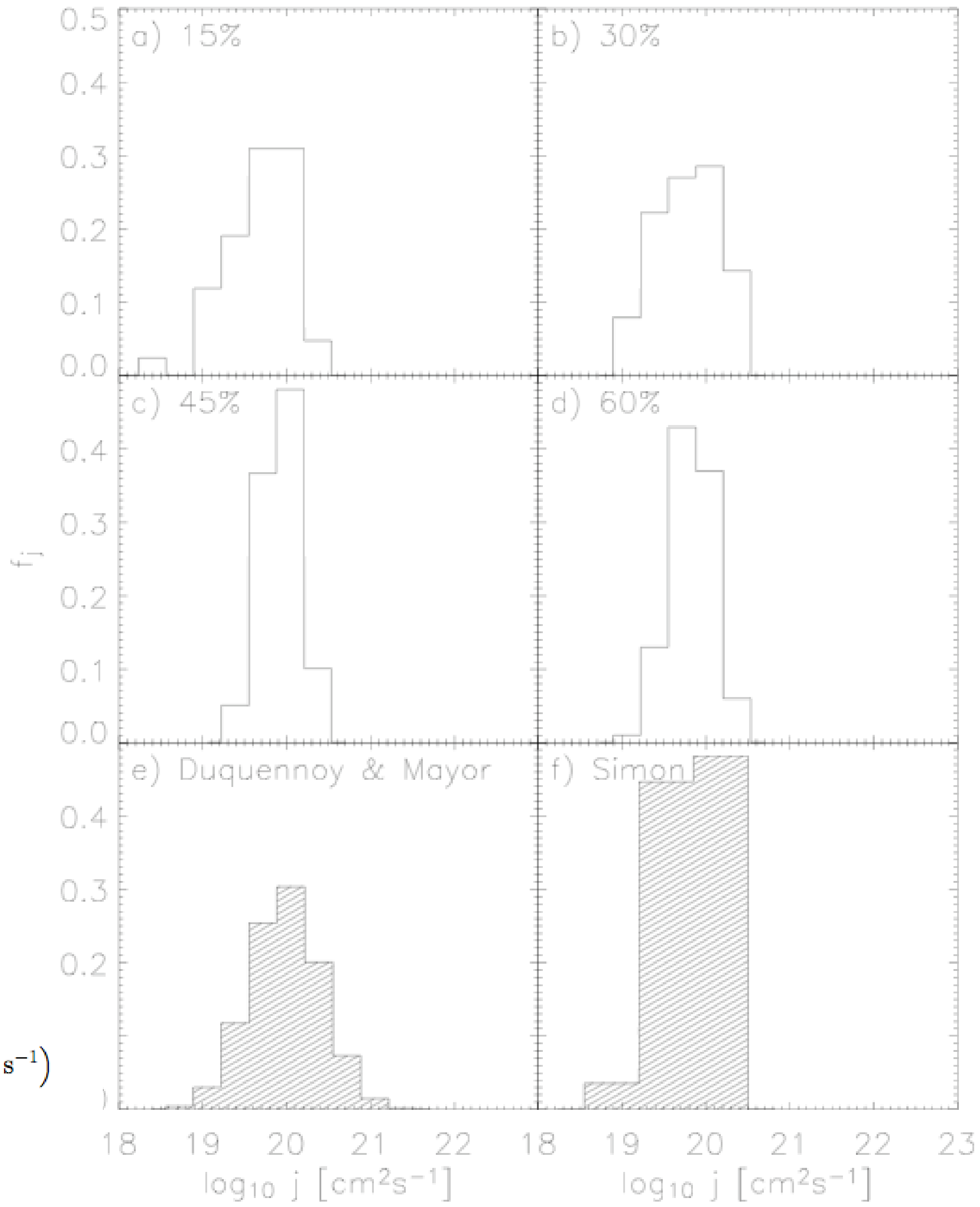


distribution of specific angular momentum in observed cloud cores

Example

distribution of specific angular momentum of protostars and protostellar systems in gravoturbulent models, compared to j distribution of binaries in nearby G dwarves.

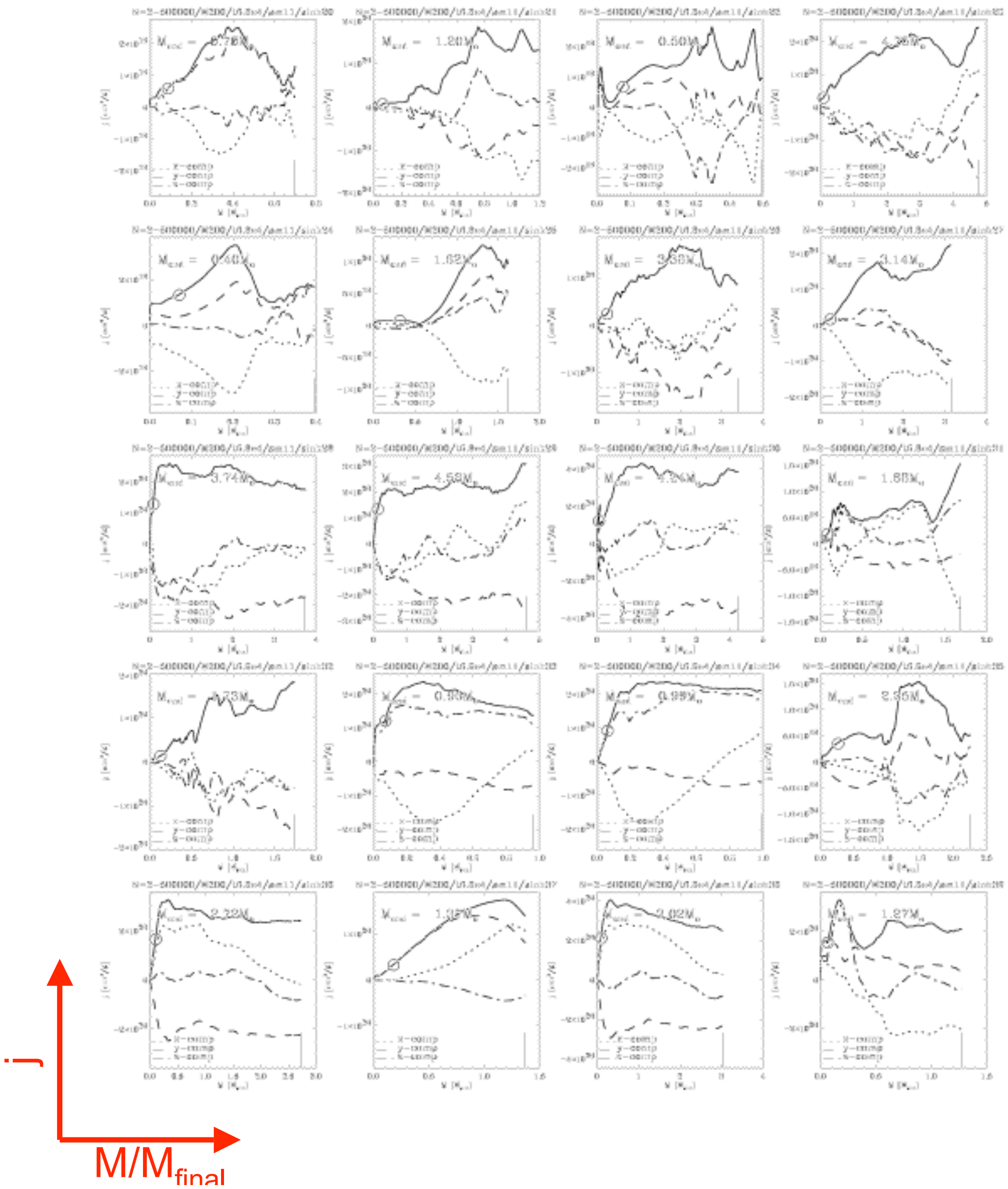
(from Jappsen & Klessen 2004)



conversion used:

$$j = 6.23 \times 10^{18} \left(1 - e^2\right)^{1/2} P^{1/3} \frac{m_1 m_2}{(m_1 + m_2)^{4/3}} \left(\mathrm{cm}^2\,\mathrm{s}^{-1}\right)$$

Angular momentum evolution



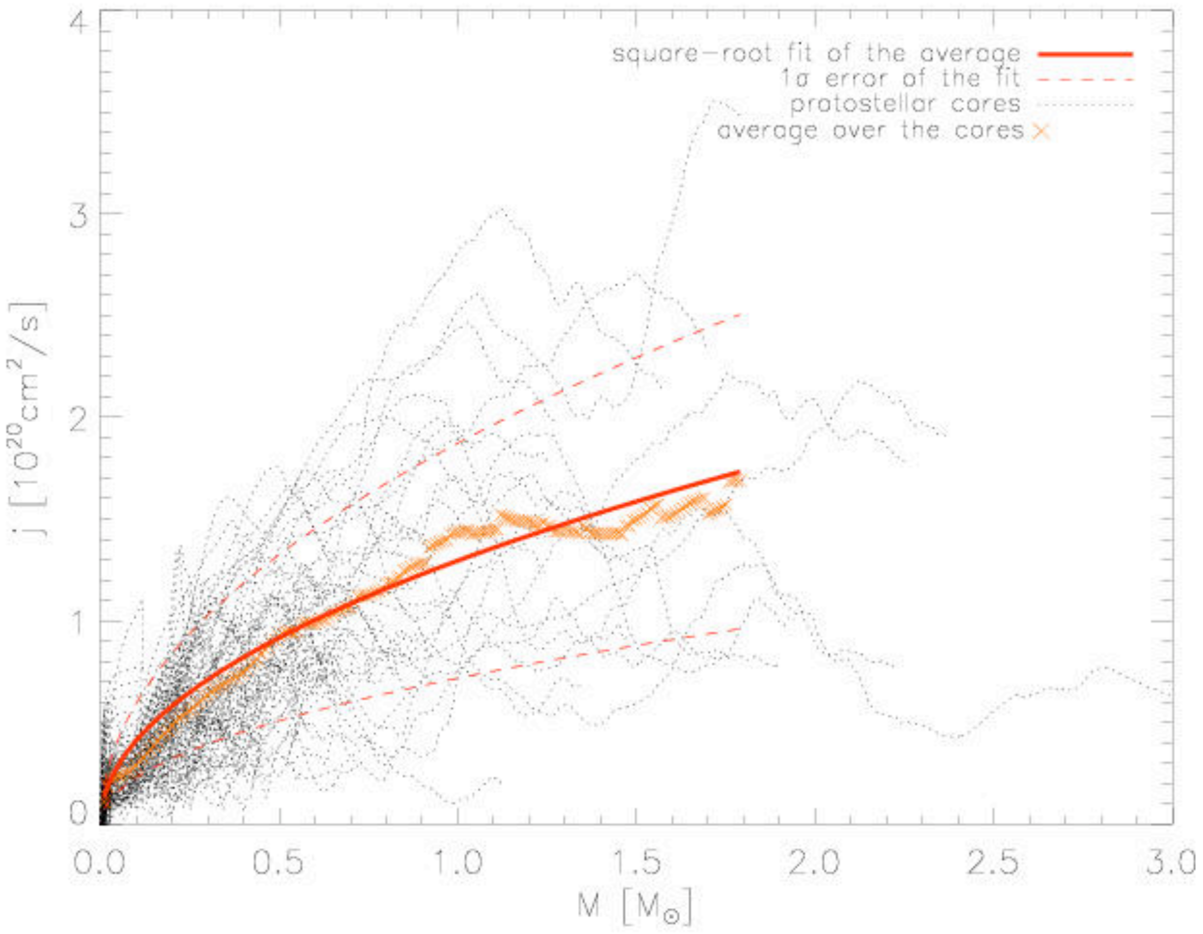
- *Angular momentum evolution* during protostellar collapse determines *disk sizes* (and possible *binary fraction*)

Examples of the time evolution of *j* (actual plot j vs. M)

(Jappsen & Klessen, 2004)

Angular momentum evolution

- Statistical dependence of *ang. mom.* on *mass*



$j \propto M^{2/3}$

corresponds to rigid rotation of homogeneous sphere ...

(Jappsen & Klessen, 2004)

we adopt rigid body rotation with constant angular velocity Ω and uniform core density ρ. With these assumptions the specific angular momentum j can be written as

$$j = p\Omega R^2. \tag{5.2}$$

For a uniform density sphere $p = \frac{2}{5}$. The mass M of a sphere with constant density ρ_0 is related to the radius R via

$$M = \frac{4\pi}{3}\rho_0 R^3. \tag{5.3}$$

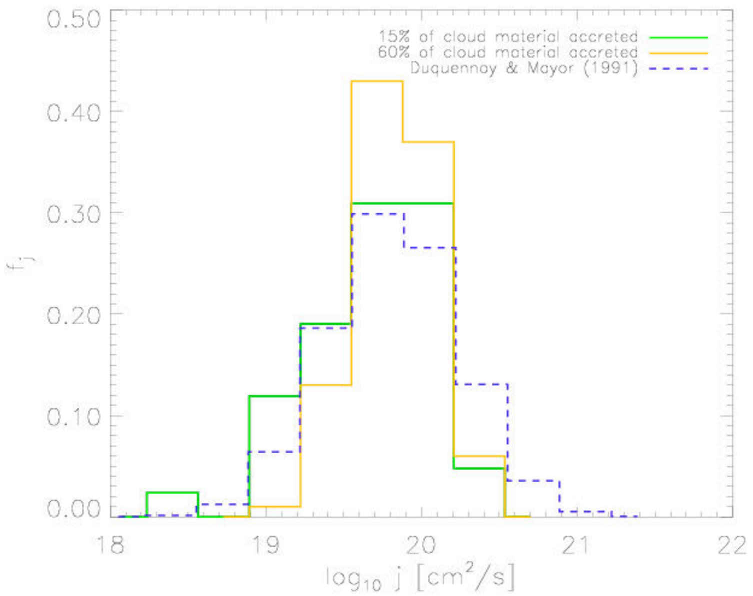
From Equations 5.2 and 5.3 follows that j can be expressed as:

$$j = p\Omega \left(\frac{3}{4\pi\rho_0}\right)^{2/3} M^{2/3}. \tag{5.4}$$

Therefore we fit the average angular momentum with a function of the form

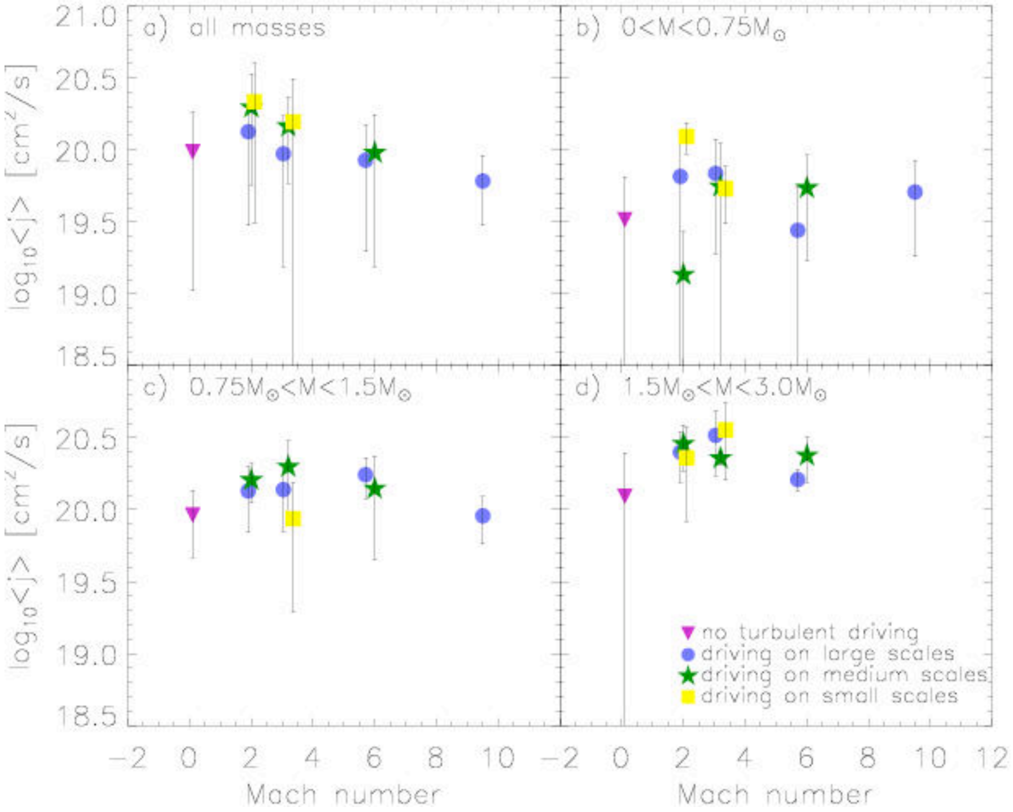
$$j = \mathcal{A}(M/M_\odot)^{2/3}, \tag{5.5}$$

Angular momentum evolution



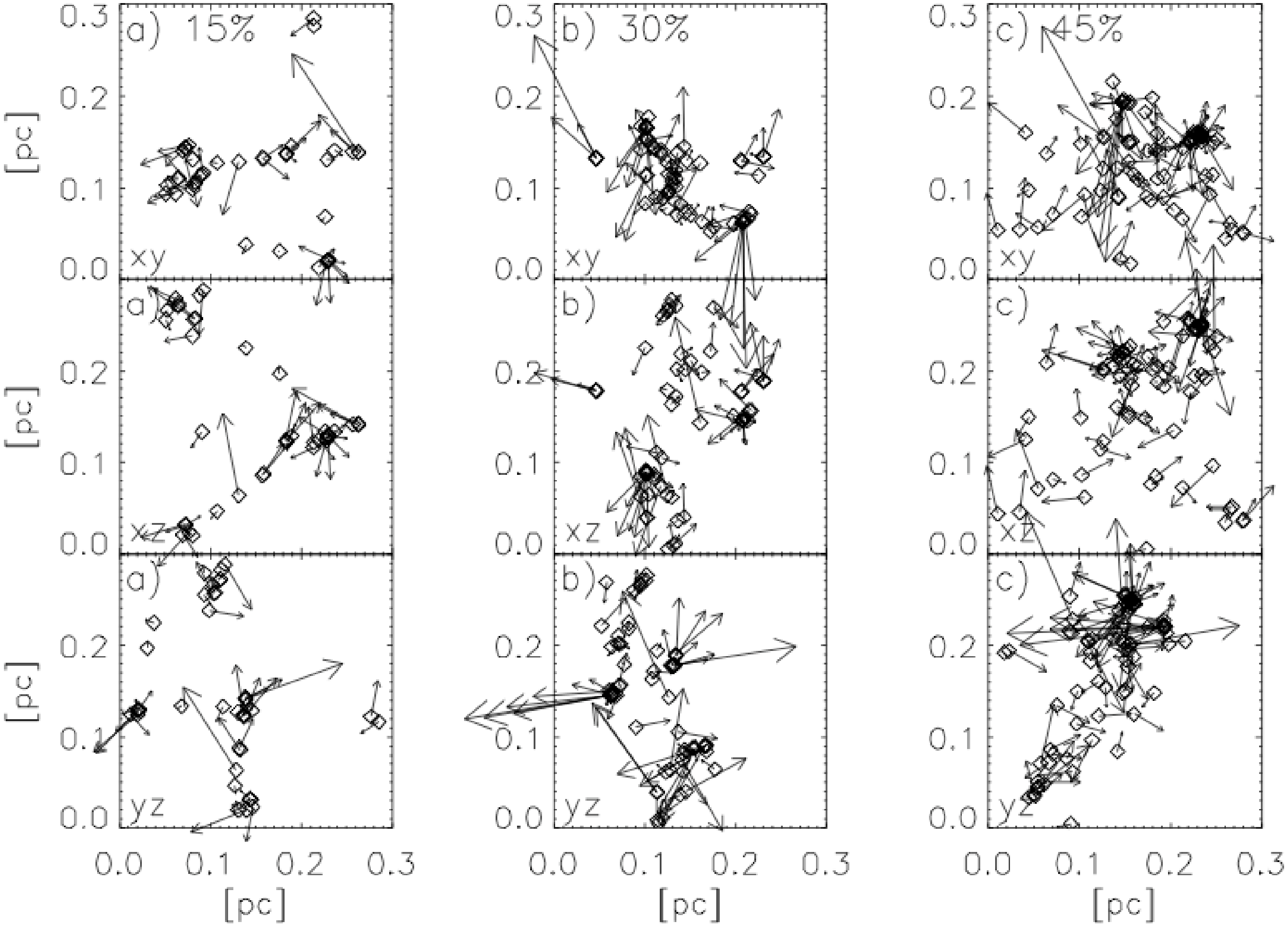
Distribution of *j* similar to that of observed G-dwarf binaries

Angular momentum loss by gravitational torques in turbulent environment



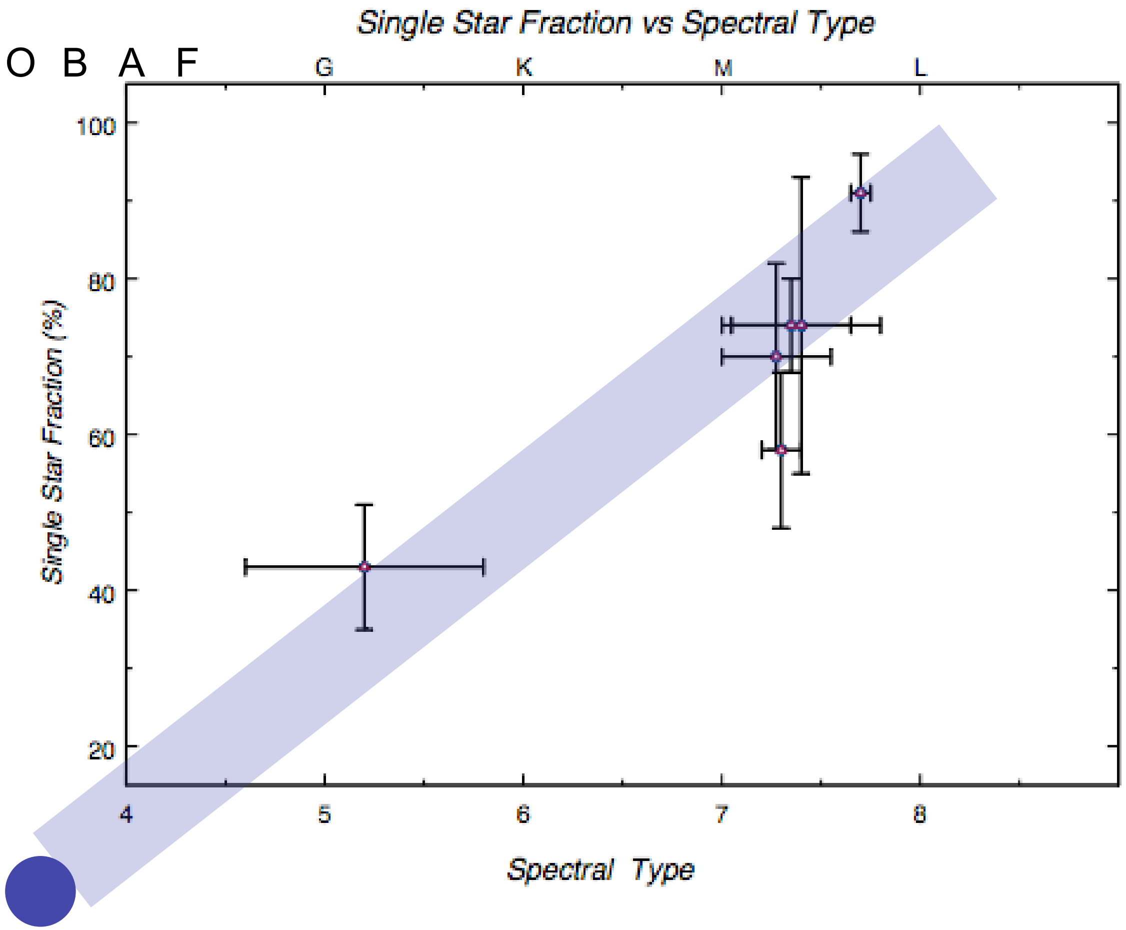
Weak dependency of *j* on Mach number

(Jappsen & Klessen, 2004, A&A, in press) correlation of ang. mom. vectors at different times (obs.: look for outflow alignment in multiple systems)



binarity

Stellar multiplicity

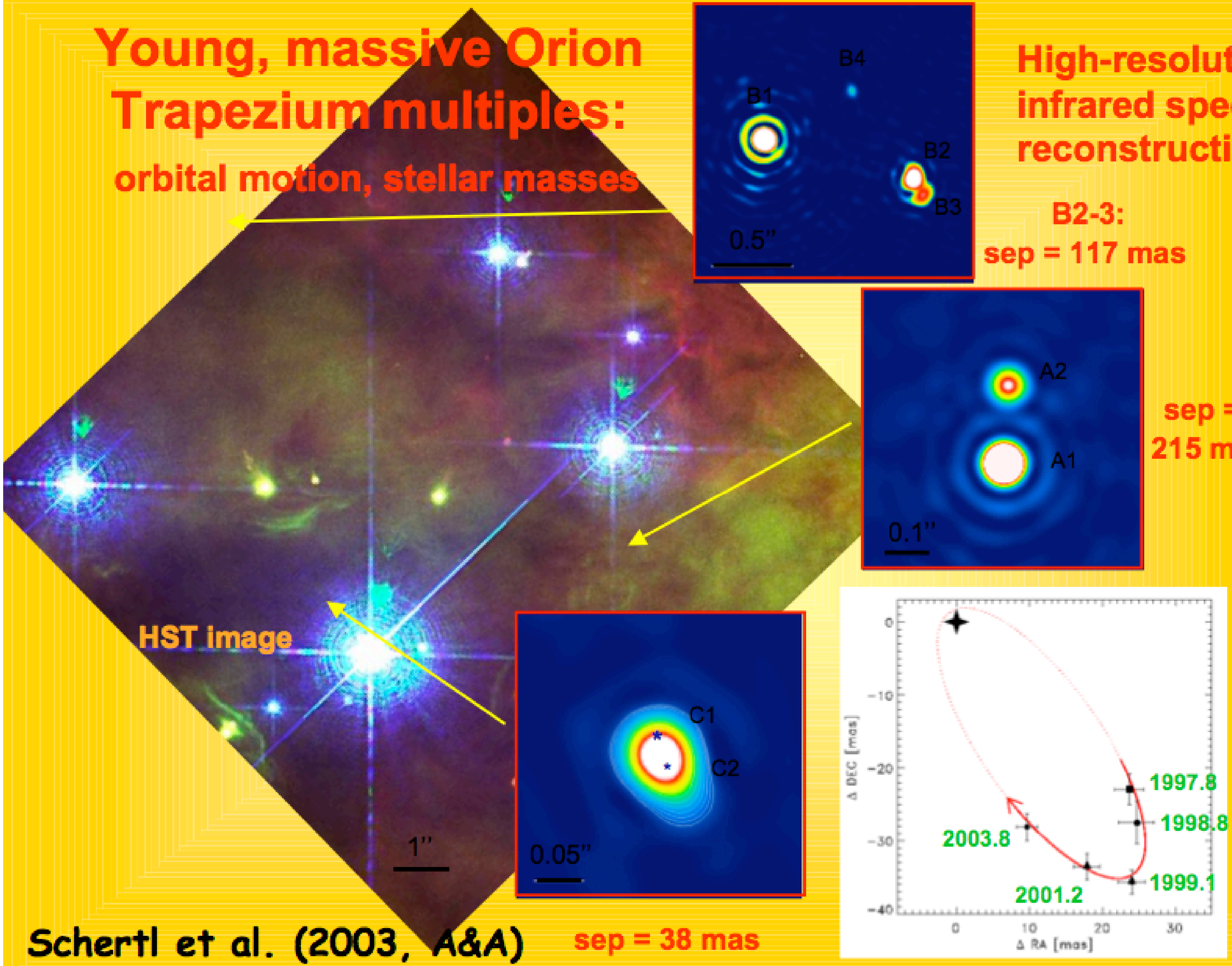


(Lada 2006)

Young, massive Orion Trapezium multiples:

orbital motion, stellar masses

High-resolution infrared speckle reconstruction



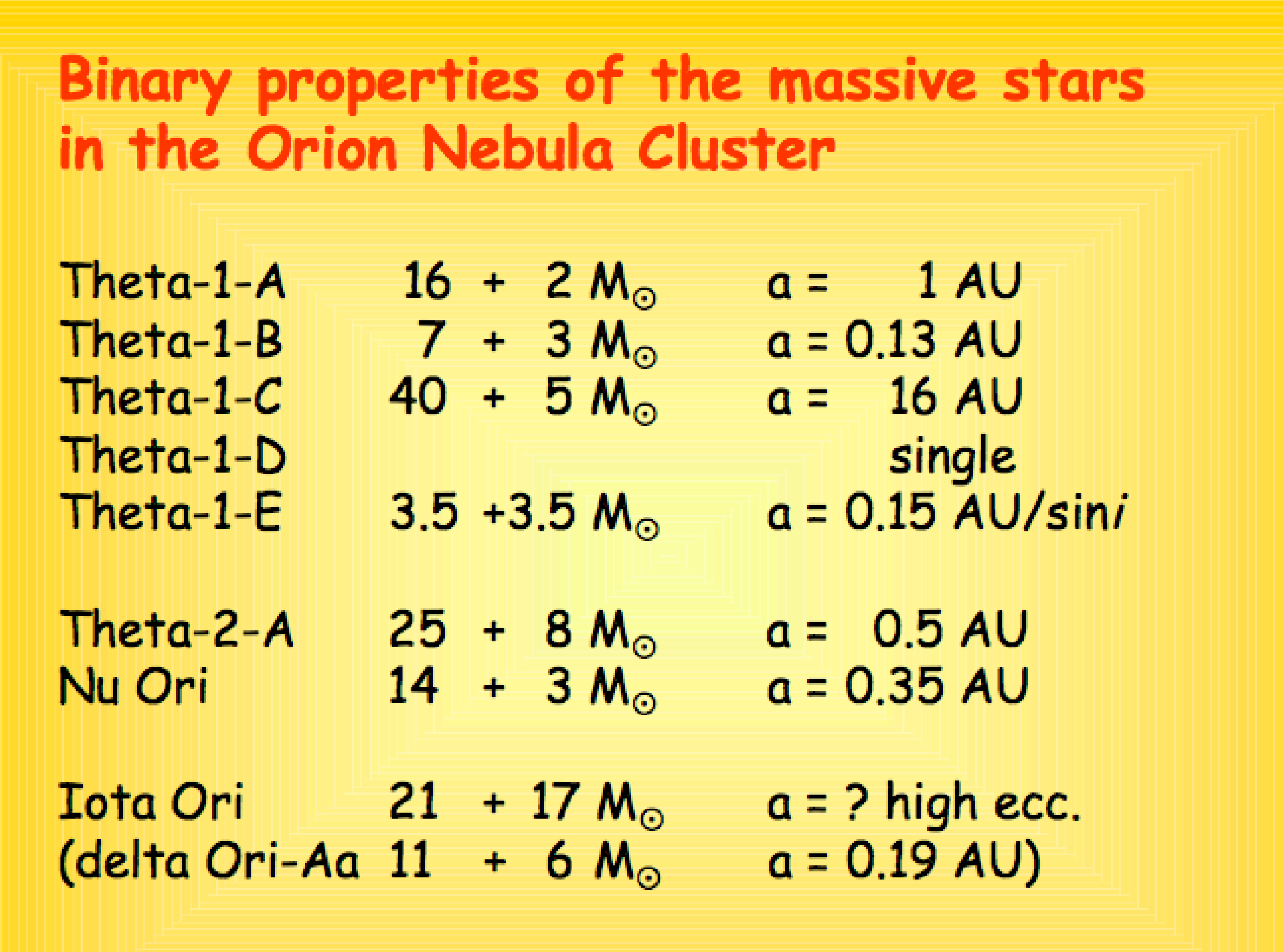
HST image

B2-3:
sep = 117 mas

sep = 215 mas

sep = 38 mas

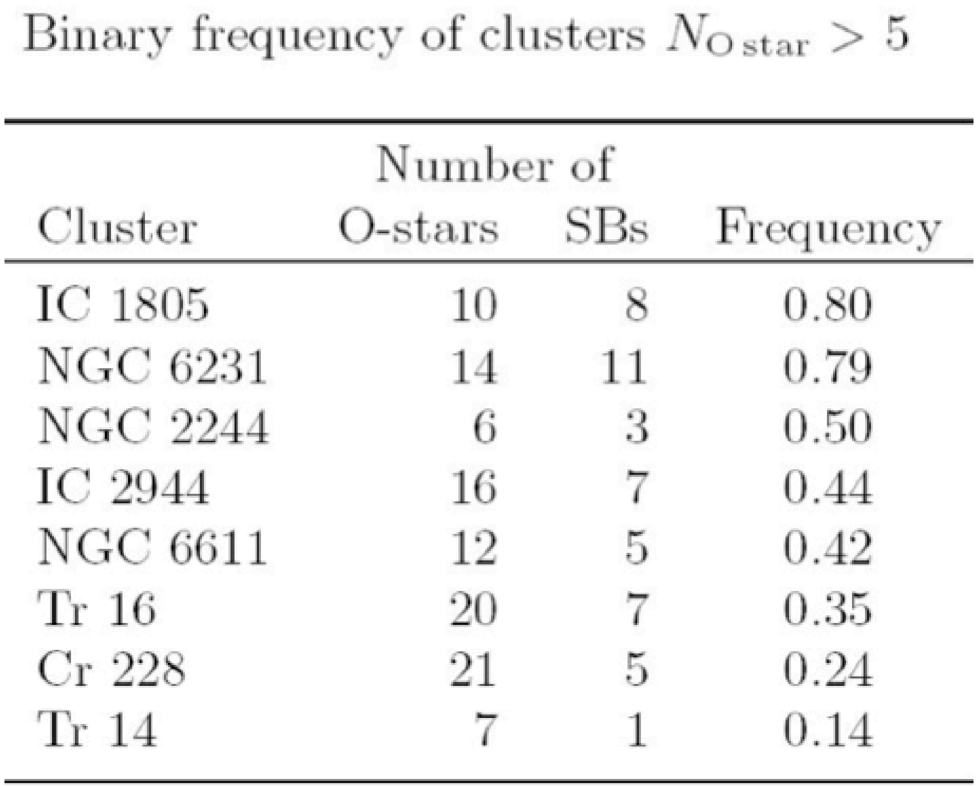
Schertl et al. (2003, A&A)



Binary properties of the massive stars in the Orion Nebula Cluster

Theta-1-A	$16 + 2\ M_\odot$	a = 1 AU
Theta-1-B	$7 + 3\ M_\odot$	a = 0.13 AU
Theta-1-C	$40 + 5\ M_\odot$	a = 16 AU
Theta-1-D		single
Theta-1-E	$3.5 + 3.5\ M_\odot$	a = 0.15 AU/sin*i*
Theta-2-A	$25 + 8\ M_\odot$	a = 0.5 AU
Nu Ori	$14 + 3\ M_\odot$	a = 0.35 AU
Iota Ori	$21 + 17\ M_\odot$	a = ? high ecc.
(delta Ori-Aa	$11 + 6\ M_\odot$	a = 0.19 AU)

(Preibisch et al. 1999, Harvin et al. 2002)



Binary frequency of clusters $N_{\mathrm{O\,star}} > 5$

Cluster	Number of O-stars	SBs	Frequency
IC 1805	10	8	0.80
NGC 6231	14	11	0.79
NGC 2244	6	3	0.50
IC 2944	16	7	0.44
NGC 6611	12	5	0.42
Tr 16	20	7	0.35
Cr 228	21	5	0.24
Tr 14	7	1	0.14

(Garcia & Mermilliod 2001)

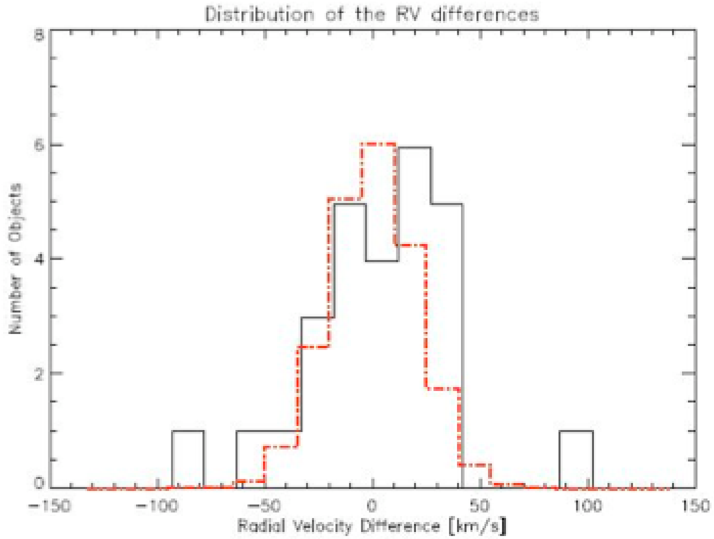


Fig. 3.— Histogram of the observed radial velocity differences of the systems at different epochs plotted with the solid black line. The two outliers are very good candidates for being close binary stars. The dot-dashed red line indicates a hypothetic distribution of a single star population observed with a normally distributed measurement error 20 km/s.

(Apai et al. 2007)

Massive binaries

1) multiplicity among massive stars higher than among low-mass (3x)

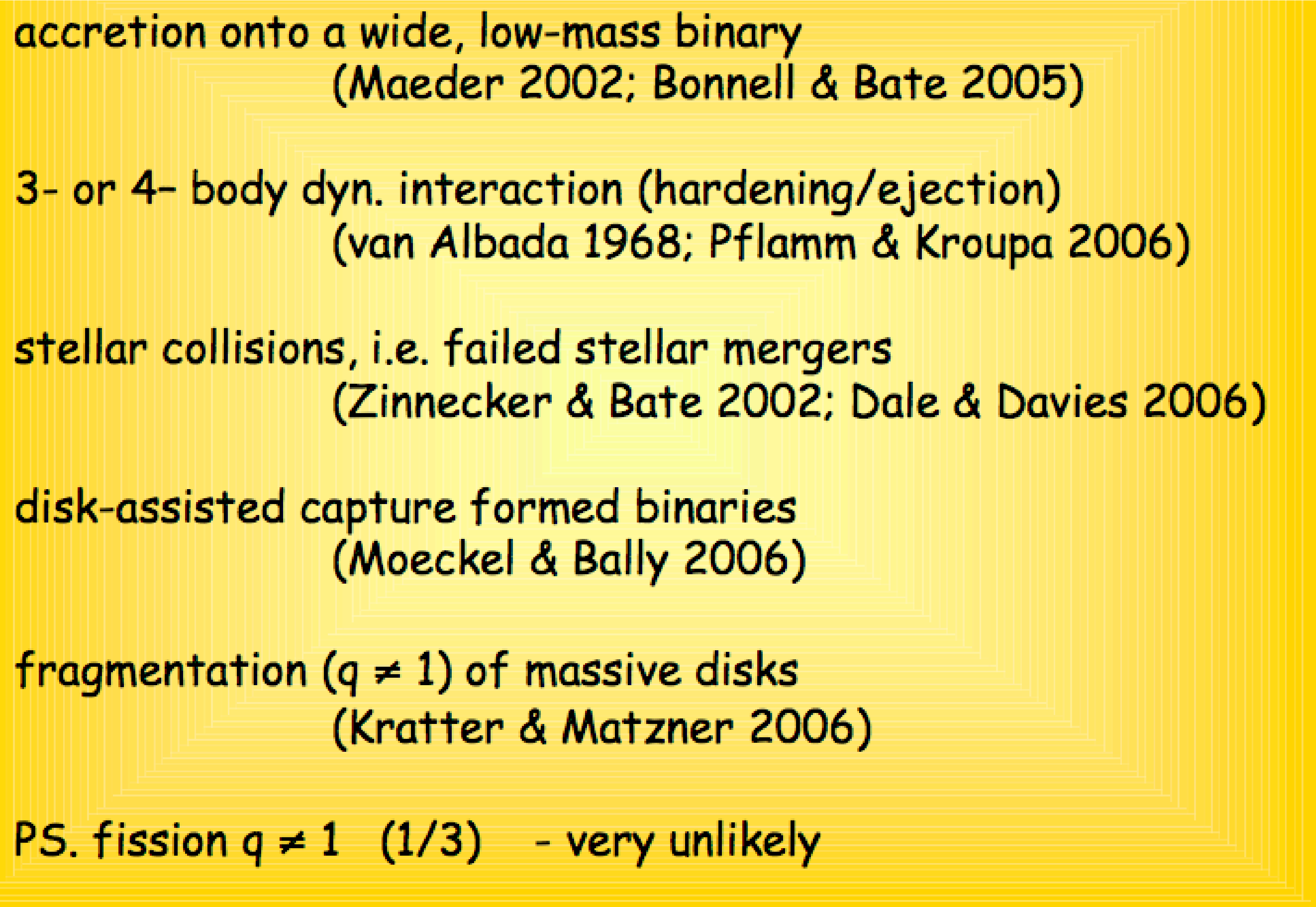
2) preponderance of tight binaries (SB2, sometimes highly eccentric)

3) 20 out of 25 O-stars are triple, consisting of SB + VB pairs (Mason et al. 1998)

4) runaway O-stars preferentially single (Mason et al. 1998)

5) Trapezia within Orion Trapezium

Theoretical models



accretion onto a wide, low-mass binary
(Maeder 2002; Bonnell & Bate 2005)

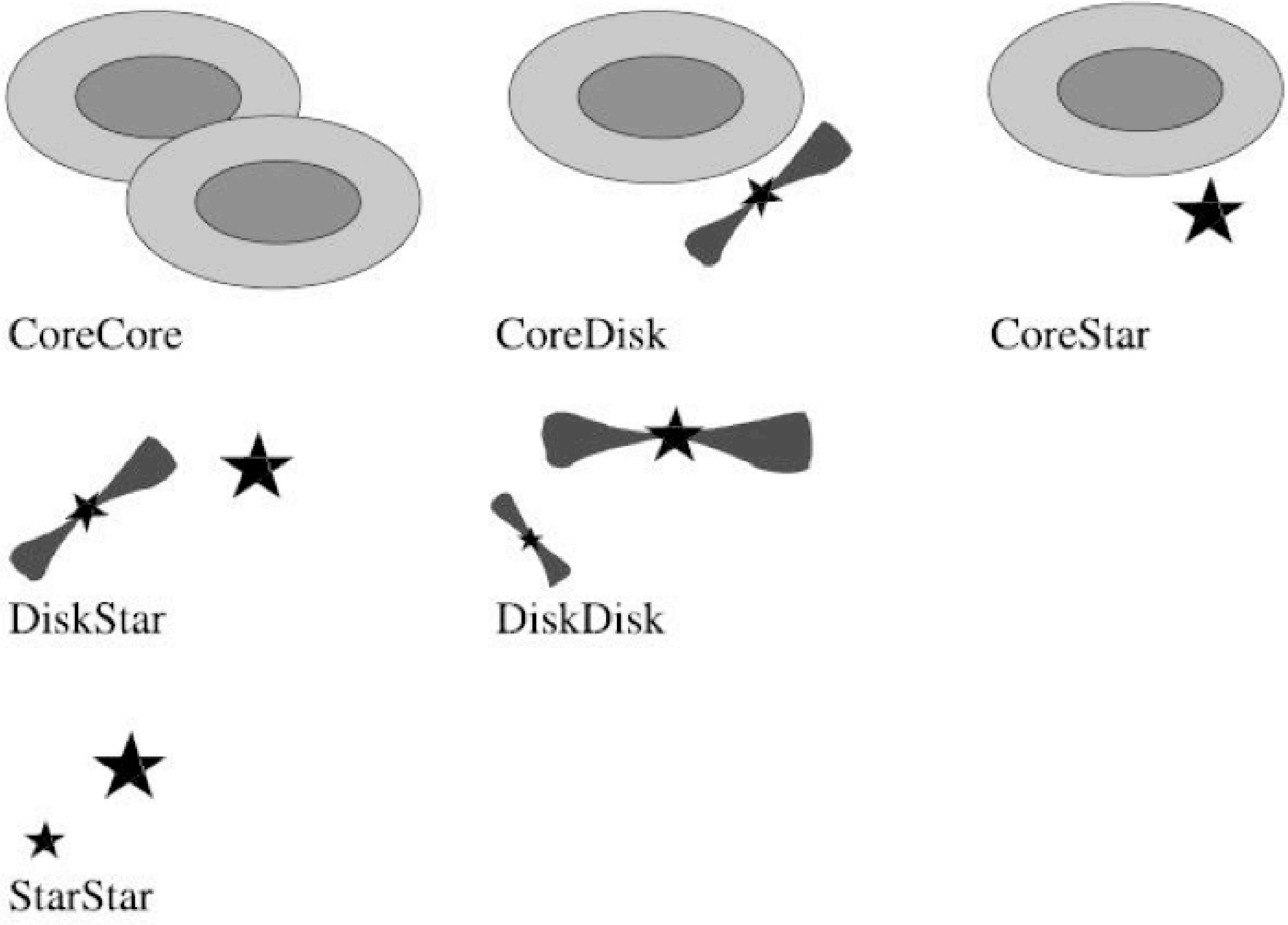
3- or 4- body dyn. interaction (hardening/ejection)
(van Albada 1968; Pflamm & Kroupa 2006)

stellar collisions, i.e. failed stellar mergers
(Zinnecker & Bate 2002; Dale & Davies 2006)

disk-assisted capture formed binaries
(Moeckel & Bally 2006)

fragmentation ($q \neq 1$) of massive disks
(Kratter & Matzner 2006)

PS. fission $q \neq 1$ (1/3) - very unlikely



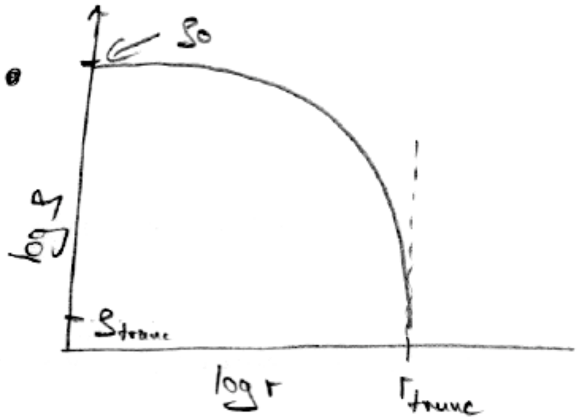
Interactions possible in a high density cluster environment leading to merging or capture-formed binaries.

(from Bally & Zinnecker 2005)

Bonnor-Ebert spheres

④ Isothermal equilibria of (pressure bounded) self-grav. spheres

- force balance → static sln → $\boxed{\vec{\nabla} p = -\rho \vec{\nabla} \Phi}$
- ideal gas: $p = c_s^2 \rho$ with isothermal sound speed $c_s^2 = \frac{R}{\mu} T$
- spherical symmetry: eqn. of motion $\frac{c_s^2}{\rho} \frac{d\rho}{dr} = - \frac{d\Phi}{dr}$
- $\longmapsto$ integration → $\boxed{\rho = \rho_0 \exp(-\Phi/c_s^2)}$ hydrostatic eqn.
- include Poisson's eqn: $\boxed{\frac{1}{r^2} \frac{d}{dr} \left(r^2 \frac{d\Phi}{dr} \right) = 4\pi G \rho = 4\pi G \rho_0 \exp\left(-\frac{\Phi}{c_s^2}\right)}$ *

  Lane-Emden equation
- regular sln's from $\Phi = 0$ & $\frac{d\Phi}{dr} = 0$ at $r = 0$
- 

if $\frac{\rho_0}{\rho_{trunc}} > 14$ only unstable equilibria possible!

- Singular isothermal sphere if $\rho_0/\rho_{trunc} \longrightarrow \infty$

(or equivalently, if outer edge $r_{trunc} \rightarrow \infty$; or $p_{ext} \rightarrow 0$)

↳ SIS: $\boxed{\rho = \frac{c_s^2}{4\pi G r^2} \quad \& \quad \frac{d\phi}{dr} = \frac{2c_s^2}{r}}$

Shu (1977) assumes SIS & $v=0$; but to reach SIS, system evolves throug a sequence of unstable equilibria

↳ collapse sets in much earlier → SIS with $v=0$ will never be reached.

- solving *): define $\xi = \frac{r}{c_s}\sqrt{4\pi G \rho_0}$ ρ_0 = core density

↳ $\boxed{\frac{d}{d\xi}\left(\xi^2 \frac{d\psi}{d\xi}\right) = \xi^2 e^{-\psi}}$ **) $\psi = \ln \rho/\rho_0$

sln of **) with $\psi(0) = 0$ & $\frac{d\psi(0)}{d\xi} = 0$ are finite at the center $\xi = 0$.

↳ further change of variables:

$$y_1 = \xi^2 \frac{d\psi}{d\xi}$$

$$y_2 = \psi$$

↳ coupled set of 1. order ODE's:

$$\frac{dy_1}{d\xi} = \frac{y_0}{\xi^2}$$

$$\frac{dy_0}{d\xi} = \xi^2 \exp(-y_1)$$

boundary conditions $y_0(0) = 0$ & $y_1(0) = 0$.

↳ ∃ family of solutions characterized by parameter

$$\boxed{\xi_{max} = \frac{r_{trunc}}{c_s}\sqrt{4\pi G \rho_0}}$$

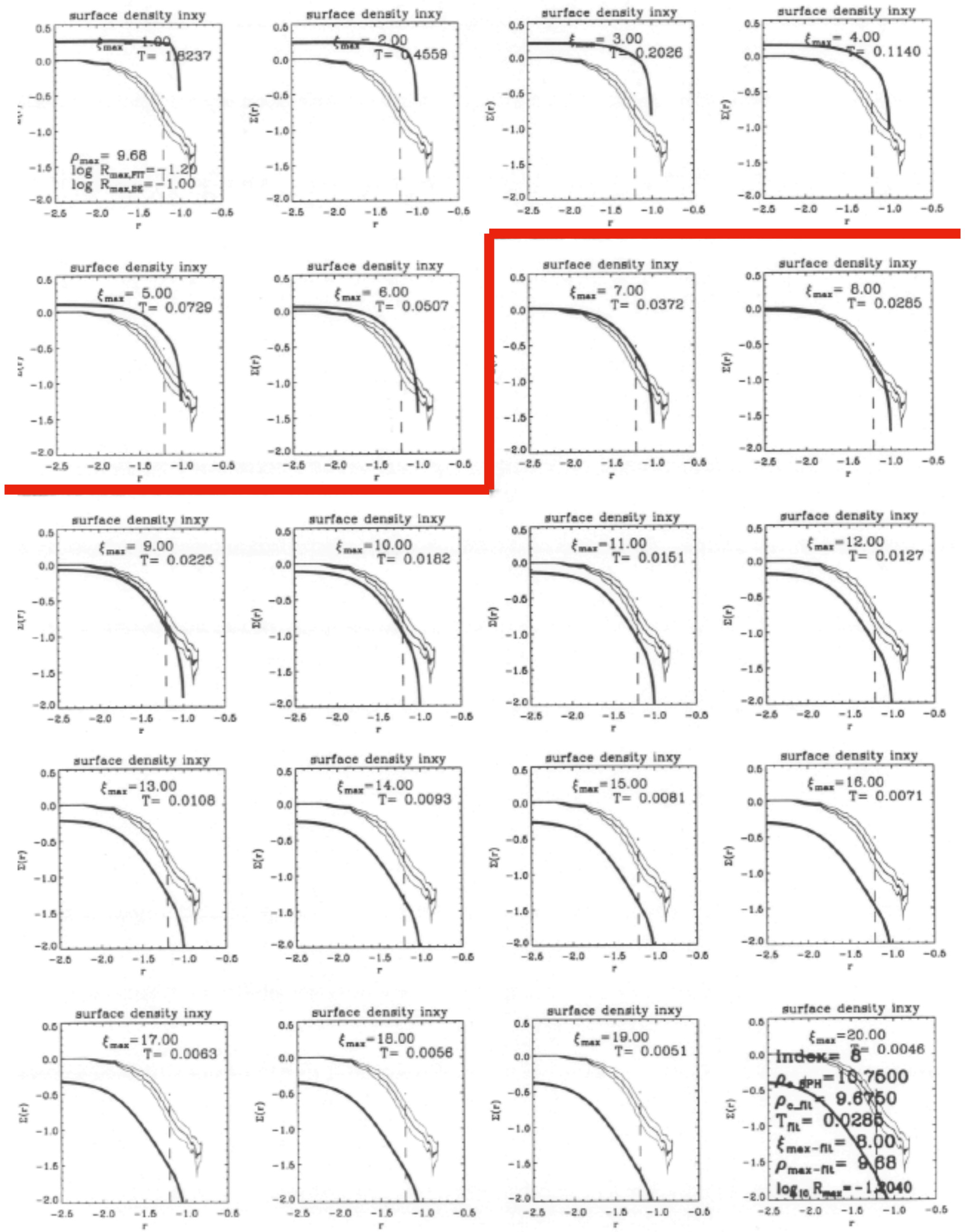
ξ_{max} = value of ξ at outer boundary r_{trunc}

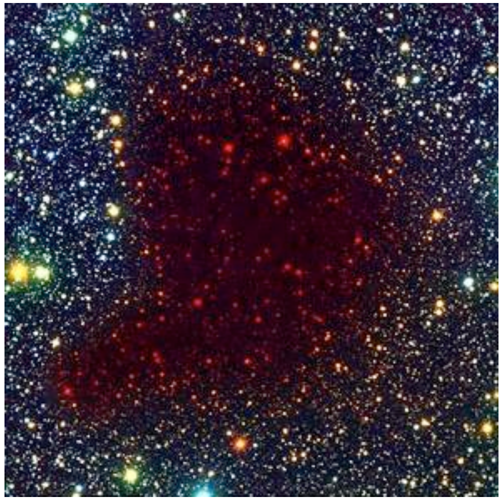
$\xi_{max} > 6,5$ unstable equilibria : collaps

$\xi_{max} < 6,5$ stable s/u

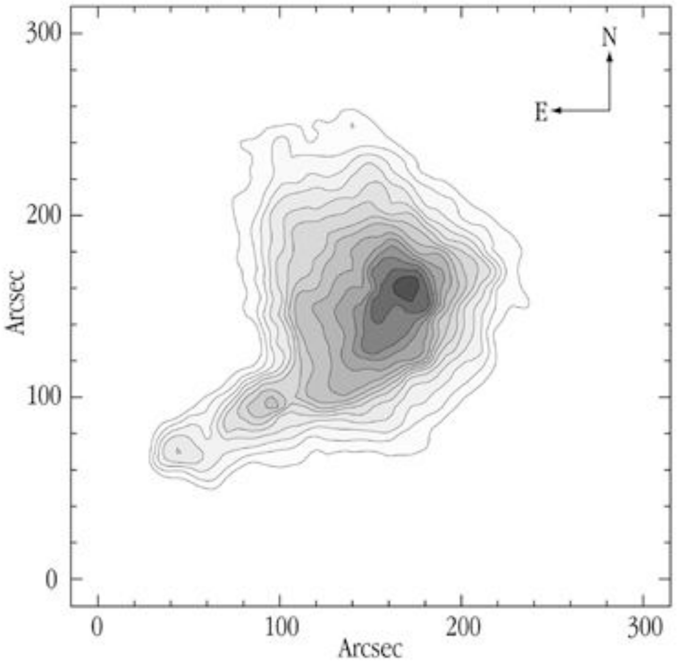
stable

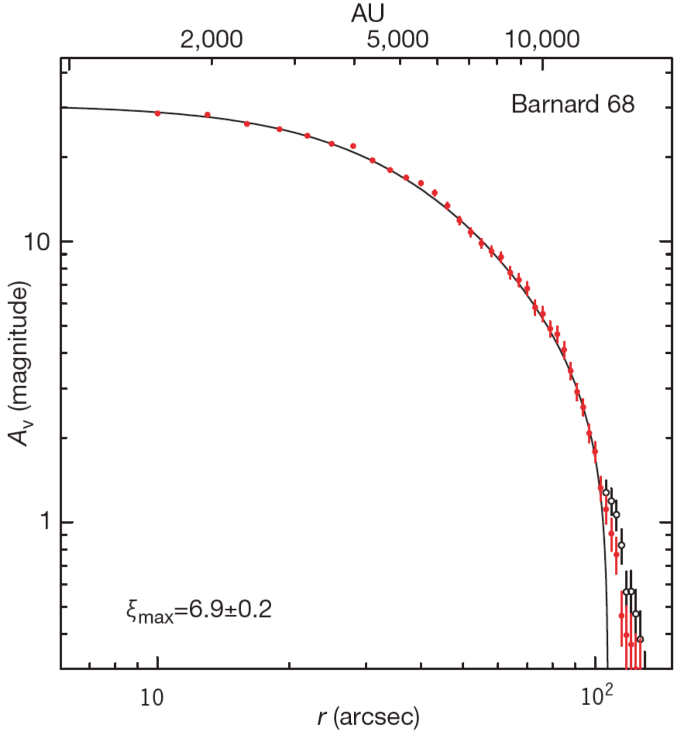
unstable

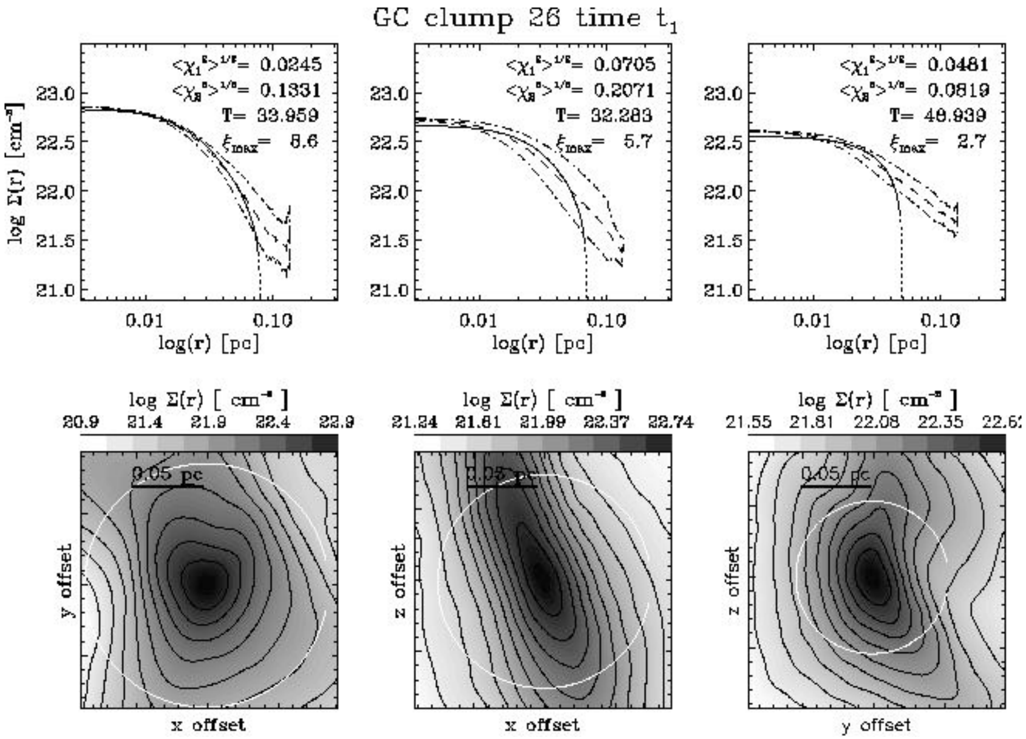


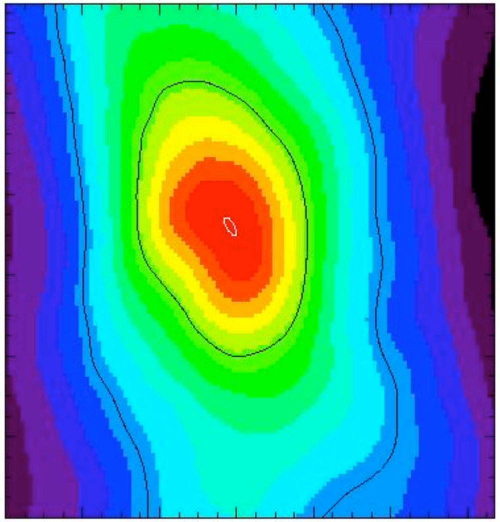


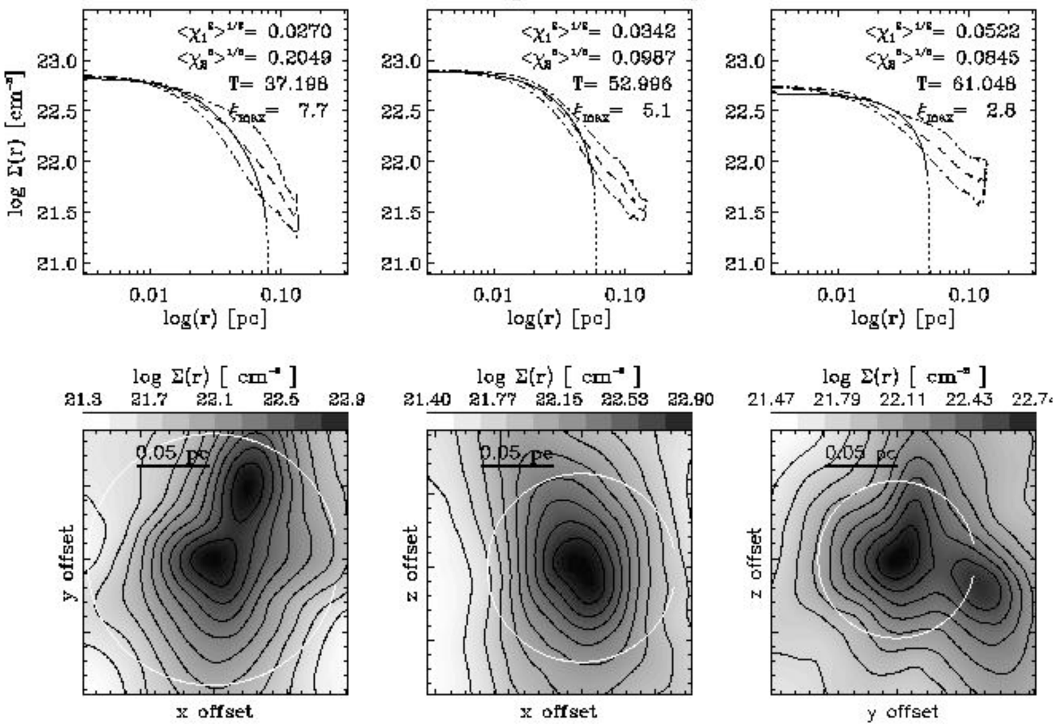
Alves, Lada, Lada (2001)






GC clump 26 time t_1
$<\chi_1^2>^{1/2}$= 0.0245
$<\chi_2^2>^{1/2}$= 0.1331
T= 33.959
ξ_{max}= 6.6
$<\chi_1^2>^{1/2}$= 0.0705
$<\chi_2^2>^{1/2}$= 0.2071
T= 32.283
ξ_{max}= 5.7
$<\chi_1^2>^{1/2}$= 0.0481
$<\chi_2^2>^{1/2}$= 0.0819
T= 46.939
ξ_{max}= 2.7
log Σ(r) [cm^{-2}]
23.0
22.5
22.0
21.5
21.0
0.01
0.10
log(r) [pc]
log Σ(r) [cm^{-2}]
20.9 21.4 21.9 22.4 22.9
21.24 21.61 21.99 22.37 22.74
21.55 21.81 22.08 22.35 22.6
0.05 pc
y offset
x offset
z offset
x offset
z offset
y offset

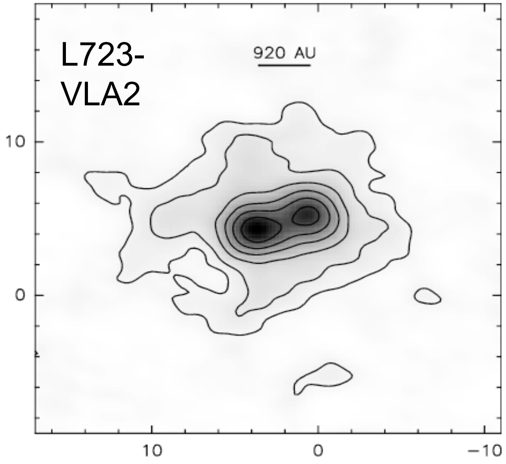


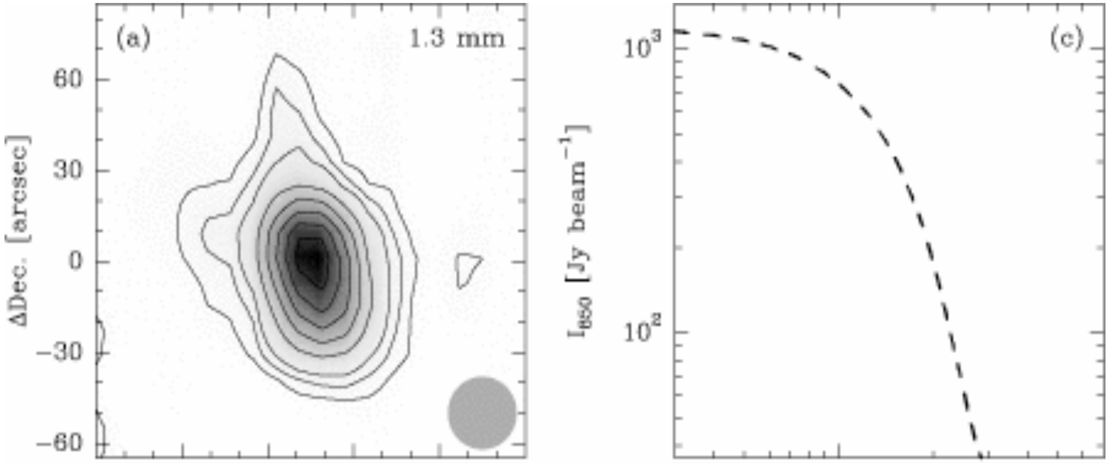

GC clump 04 time t_0
$<\chi_1^2>^{1/2}$= 0.0270
$<\chi_2^2>^{1/2}$= 0.2049
T= 37.198
ξ_{max}= 7.7
$<\chi_1^2>^{1/2}$= 0.0342
$<\chi_2^2>^{1/2}$= 0.0987
T= 52.996
ξ_{max}= 5.1
$<\chi_1^2>^{1/2}$= 0.0522
$<\chi_2^2>^{1/2}$= 0.0845
T= 61.048
ξ_{max}= 2.8
log Σ(r) [cm^{-2}]
23.0
22.5
22.0
21.5
21.0
0.01
0.10
log(r) [pc]
log Σ(r) [cm^{-2}]
21.3 21.7 22.1 22.5 22.9
21.40 21.77 22.15 22.53 22.90
21.47 21.79 22.11 22.43 22.7
0.05 pc
y offset
x offset
z offset
x offset
z offset
y offset

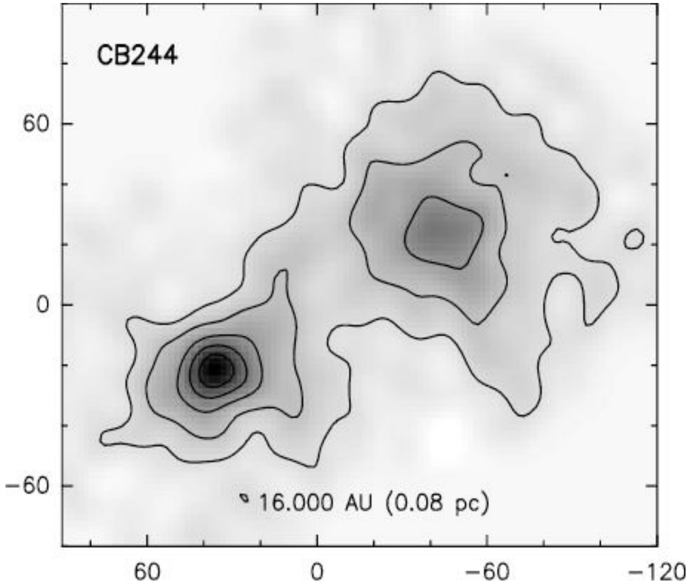
cores

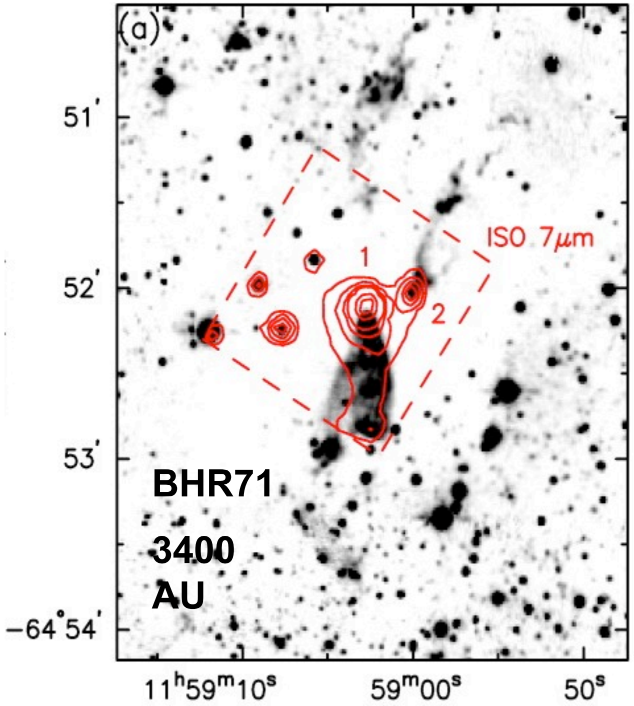
Prestellar cores

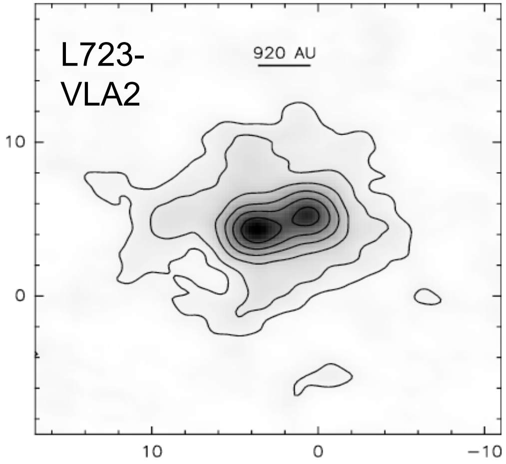
- Prestellar cores are the direct progenitors of individual star(s)

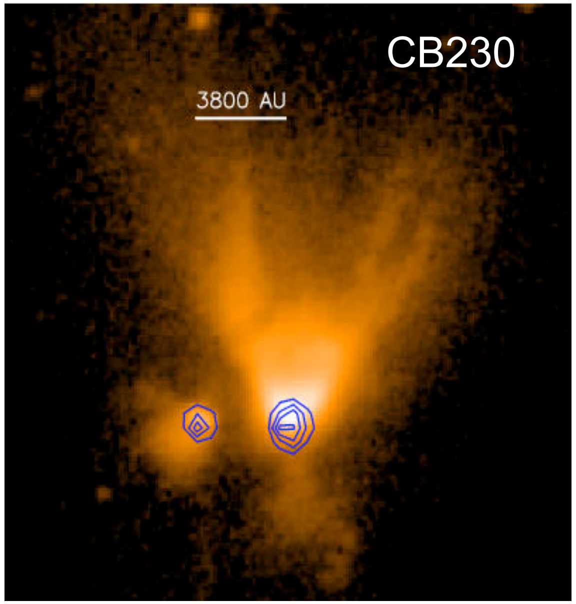






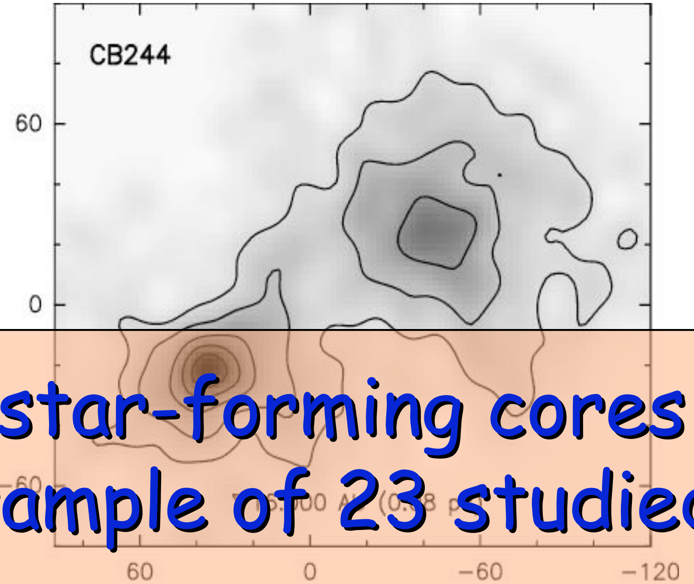


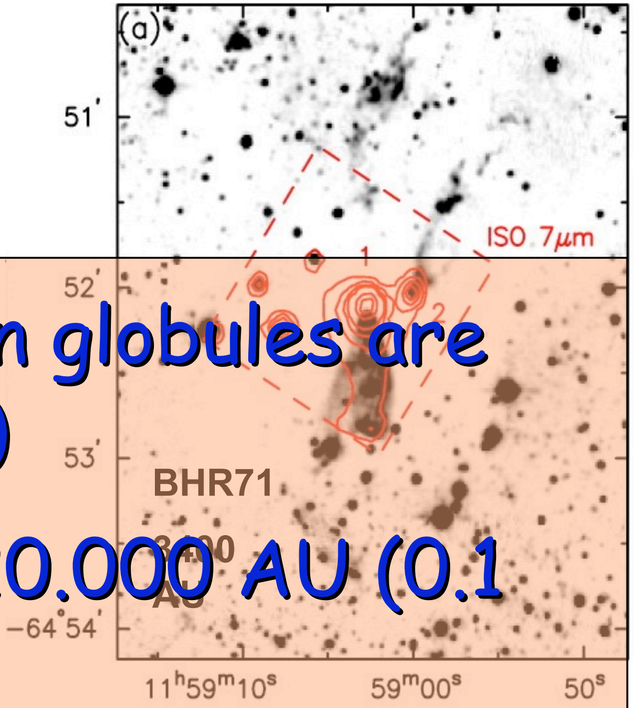


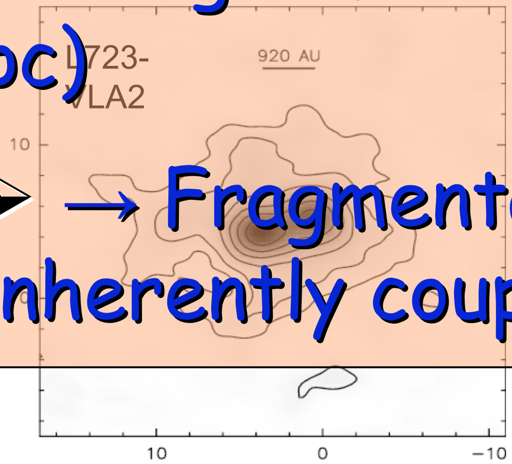


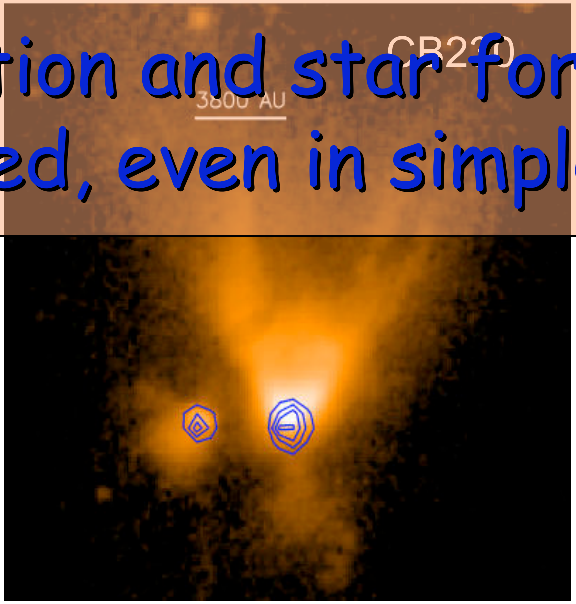
many multiple prestellar cores are discovered

(Launhardt et al.)









- ➢ 78% of star-forming cores in globules are multiple (sample of 23 studied)
- ➢ Range of scales: 500 AU - 20.000 AU (0.1 pc)
- ➢ → Fragmentation and star formation are inherently coupled, even in simple Bok globules!

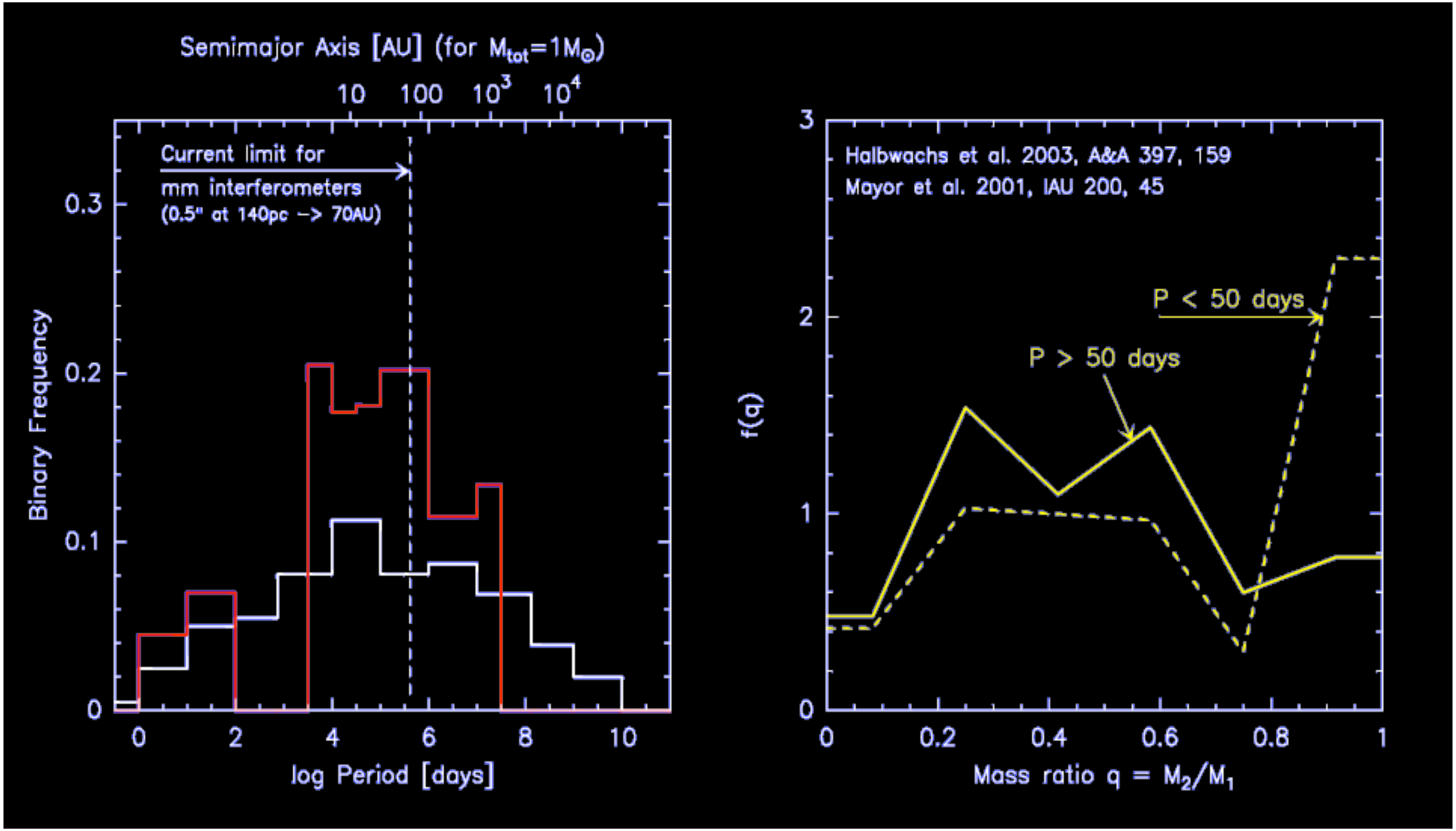
many multiple prestellar cores are observed!

(Launhardt et al.)

What do we know about binaries?

Separations:

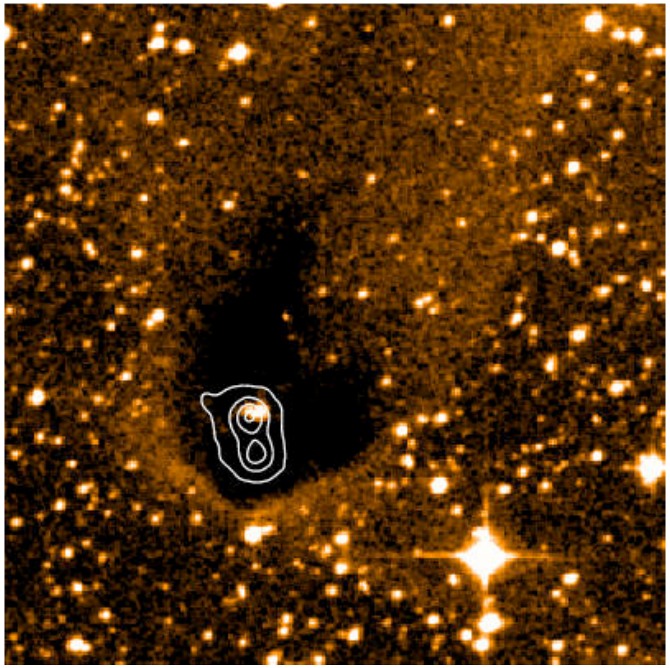
Mass ratios:

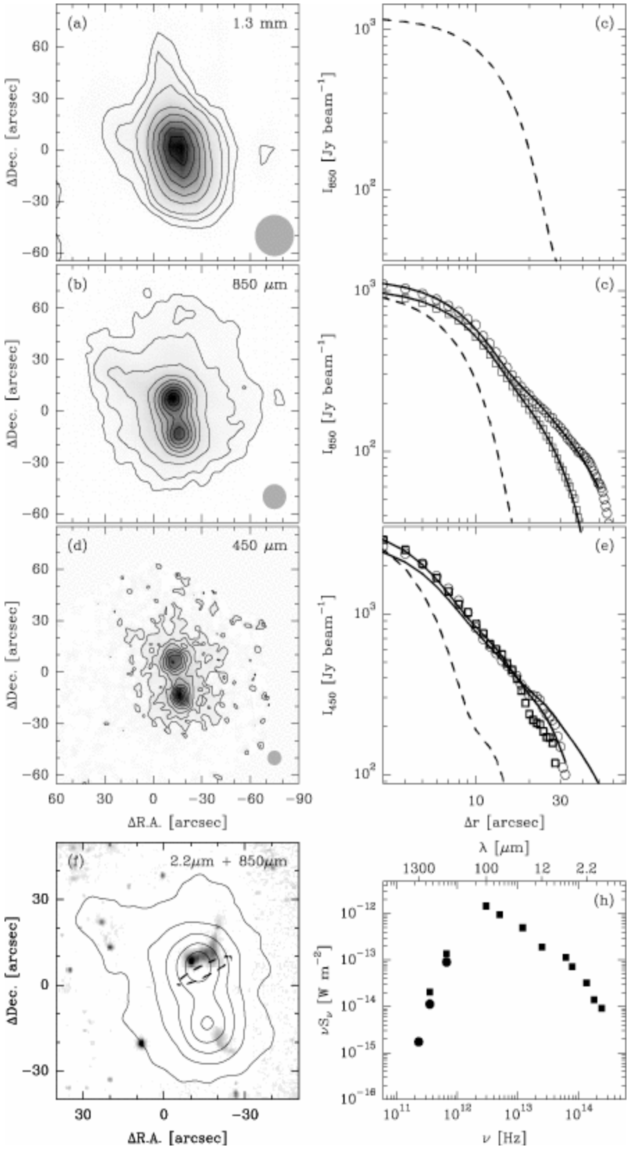


Real object 1: BHR12 (CG30)

- d = 200 pc
- λ = 0.85 mm
- HPBW = 14´´

- Separation ≈ 4000 AU
- Mass ratio ≈ 0.5
- *More massive component more evolved? (or projection effect?)*

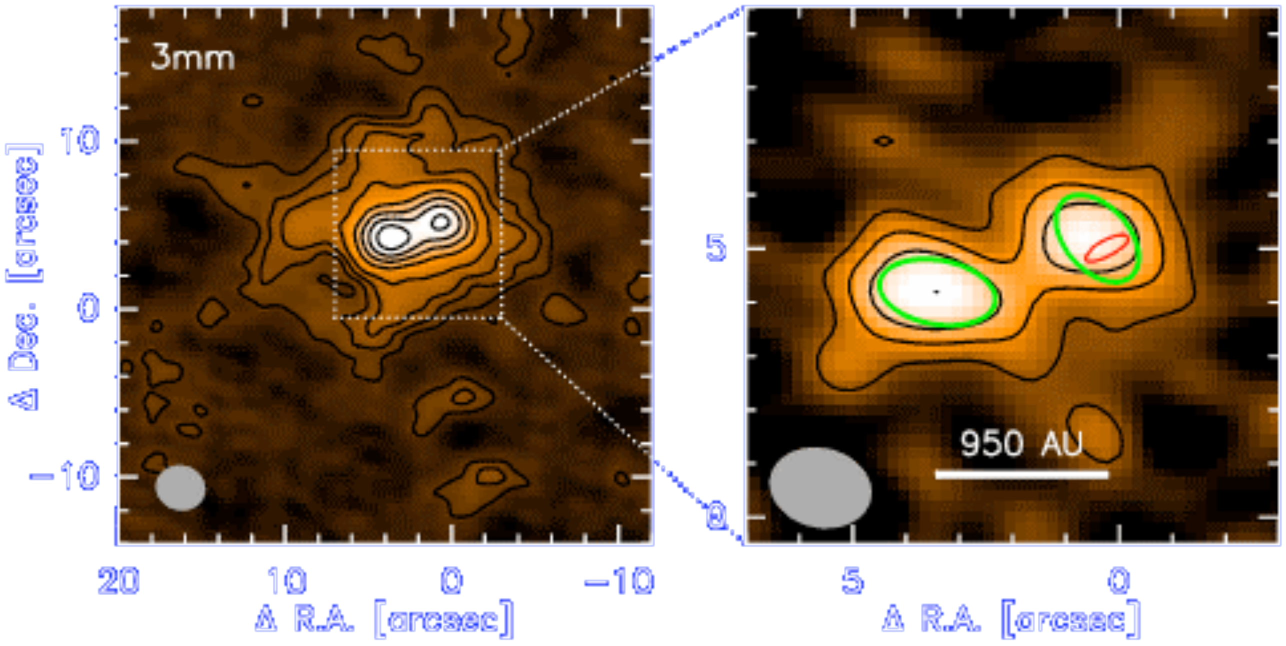




Real object 2: L723-VLA2

- d = 300 pc
- λ = 3mm
- HPBW = 1.7´´

- ➢ Separation = 950 AU
- ➢ Mass ratio ~ 0.8
- ➢ *Missaligned accretion disks*

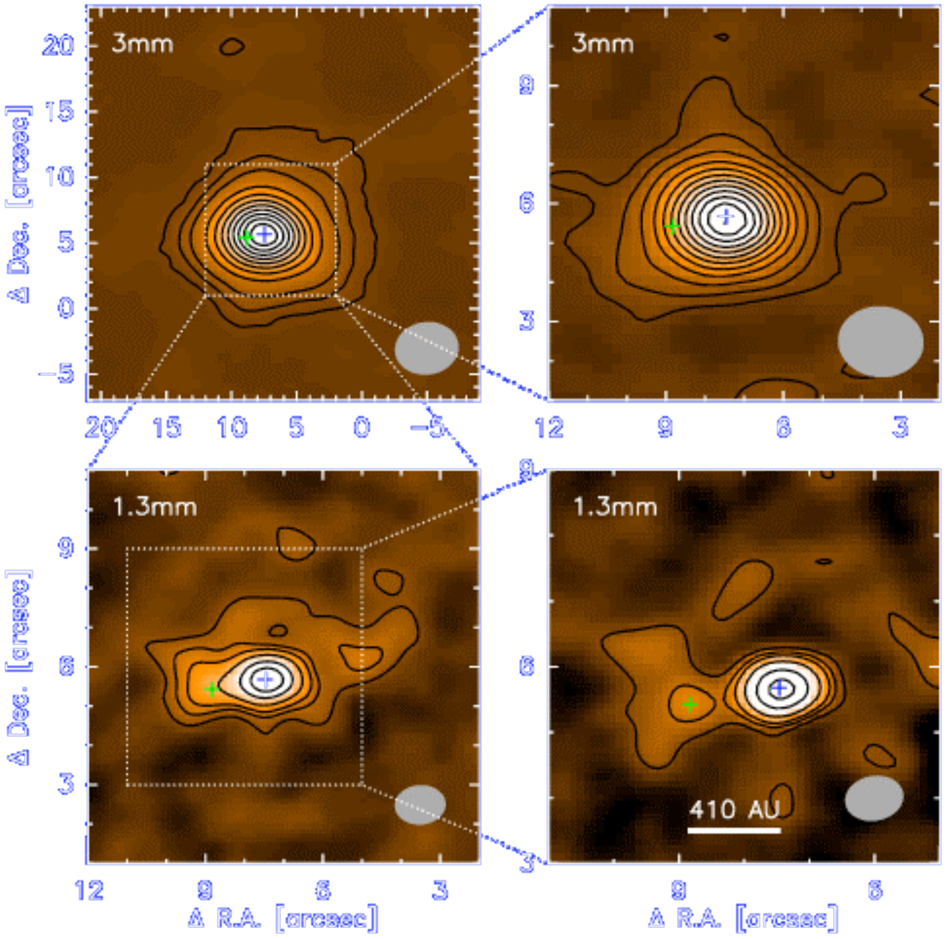


Real Object 3: IRAS 03282+3035

- d = 300 pc
- λ = 3 and 1.3mm
- HPBW = 2´´ and 0.7´´

- Separation = 420 AU
- Mass ratio ~ 0.2

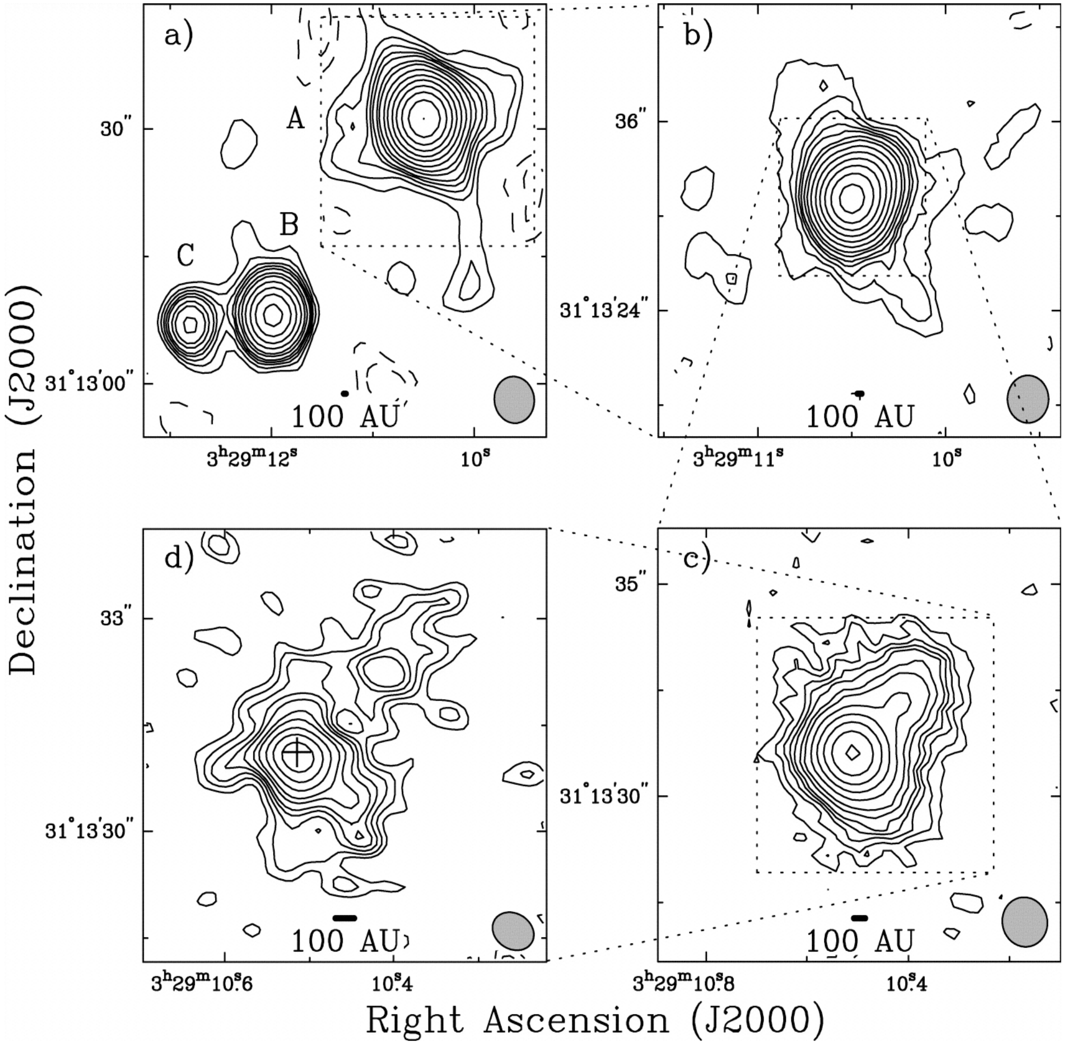
- *Unequal masses*



Real object 4: NGC1333 IRAS4A-C

- d = 350 pc
- λ = 3mm
- HPBW = 5...0.6´´

- Separation 10000 AU
  3700 AU
  600 AU
- Mass ratios ~ 0.3
  (~0.2)
- *Hierarchical system*



Looney et al. 2000

summary

Summary: MC fragmentation & SF

- interstellar gas is highly inhomogeneous
  - *thermal instability*
  - *gravitational instability*
  - *turbulent compression* (in shocks $\delta\rho/\rho \approx \mathcal{M}^2$; in atomic gas: $\mathcal{M} \approx 1...3$)
- cold *molecular clouds* form rapidly in high-density regions
  - chemical *phase transition*: atomic → molecular
  - process is *modulated* by large-scale *dynamics* in the galaxy
- inside *cold clouds:* turbulence is highly supersonic ($\mathcal{M} \approx 1...20$)
  → *turbulence* creates density structure, *gravity* selects for collapse

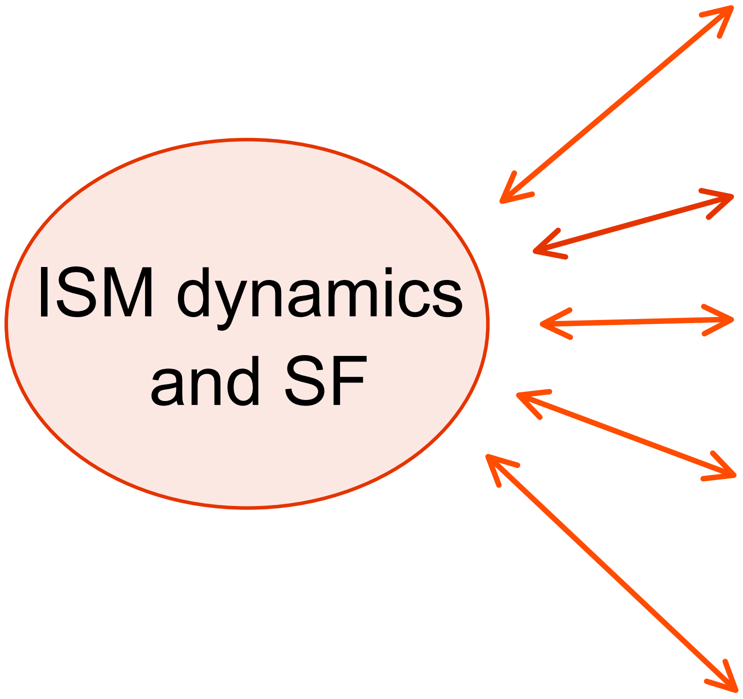
  ⟶ ***GRAVOTUBULENT FRAGMENTATION***
- *turbulent cascade:* local compression *within* a cloud provokes collapse
- individual *stars* and *star clusters* form through *sequence* of highly *stochastic* events:
  - *collapse* of cloud cores in turbulent cloud (cores change during collapse)
  - plus mutual *interaction* during collapse (importance depends on ratio of potential energy to turbulent energy) (buzz word: *competitive accretion*)

(Larson 2003, PRP; Mac Low & Klessen 2004, RMP, 76, 125-194, Ballesteros-Paresed et al. PPV)

Some further remarks…

- *GRAVOTURBULENT STAR FORMATION:*
  This dynamic theory can explain and reproduce many features of star-forming regions on small as well as on large galactic scales.
- Some open questions:
  - role of magnetic fields?
  - role of thermodynamic state of the gas?
  - what drives turbulence?
  - how are small scales (local molecular clouds) connected to large-scale dynamics?
  - what terminates star formation locally?

Where to go next?



ISM dynamics and SF

magneto-hydrodynamics
(multi-phase, non-ideal MHD,
turbulence)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

stellar dynamics
(collisional: star clusters,
collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

\+ **laboratory work**
(reaction rates, cross sections,
dust coagulation properties, etc.)

Where to go next?

- massive parallel codes
- particle-based: SPH with improved algorithms (XSPH with turb. subgrid model, GPM, particle splitting, MHD-SPH?)
- grid-based: AMR (FLASH, ENZO, RAMSES, Nirvana3, etc), subgrid-scale models (FEARLESS)
- BGK methods

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stellar evolution
(feedback: radiation, winds, SN)

Where to go next?

- ever increasing chemical networks
- working reduced networks for time-dependent chemistry in combination with hydrodynamics
- improved data on reaction rates (laboratory + quantum mechanical calculations)

magneto-hydrodynamics
(multi-phase, non-ideal MHD,
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Where to go next?

magneto-hydrodynamics
(multi-phase, non-ideal MHD,
turbulence)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

↔

- continuum vs. lines
- Monte Carlo, characteristics
- approximative methods
- combine with hydro

stellar dynamics
(collisional: star clusters,
collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

Where to go next?

magneto-hydrodynamics
(multi-phase, non-ideal MHD,
turbulence)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

stellar dynamics
(collisional: star clusters,
collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

- statistics: number of stars (collisional: 10^6, collisionless: 10^{10})
- transition from gas to stars
- binary orbits
- long-term integration

Where to go next?

magneto-hydrodynamics
(multi-phase, non-ideal MHD,
turbulence)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

stellar dynamics
(collisional: star clusters,
collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

- very early phases (pre main sequence tracks)
- massive stars at late phases
- role of rotation
- primordial star formation

Where to go next?

methods need to be combined!

magneto-hydrodynamics
(multi-phase, non-ideal MHD,
turbulence)

chemistry (gas + dust, heating + cooling)

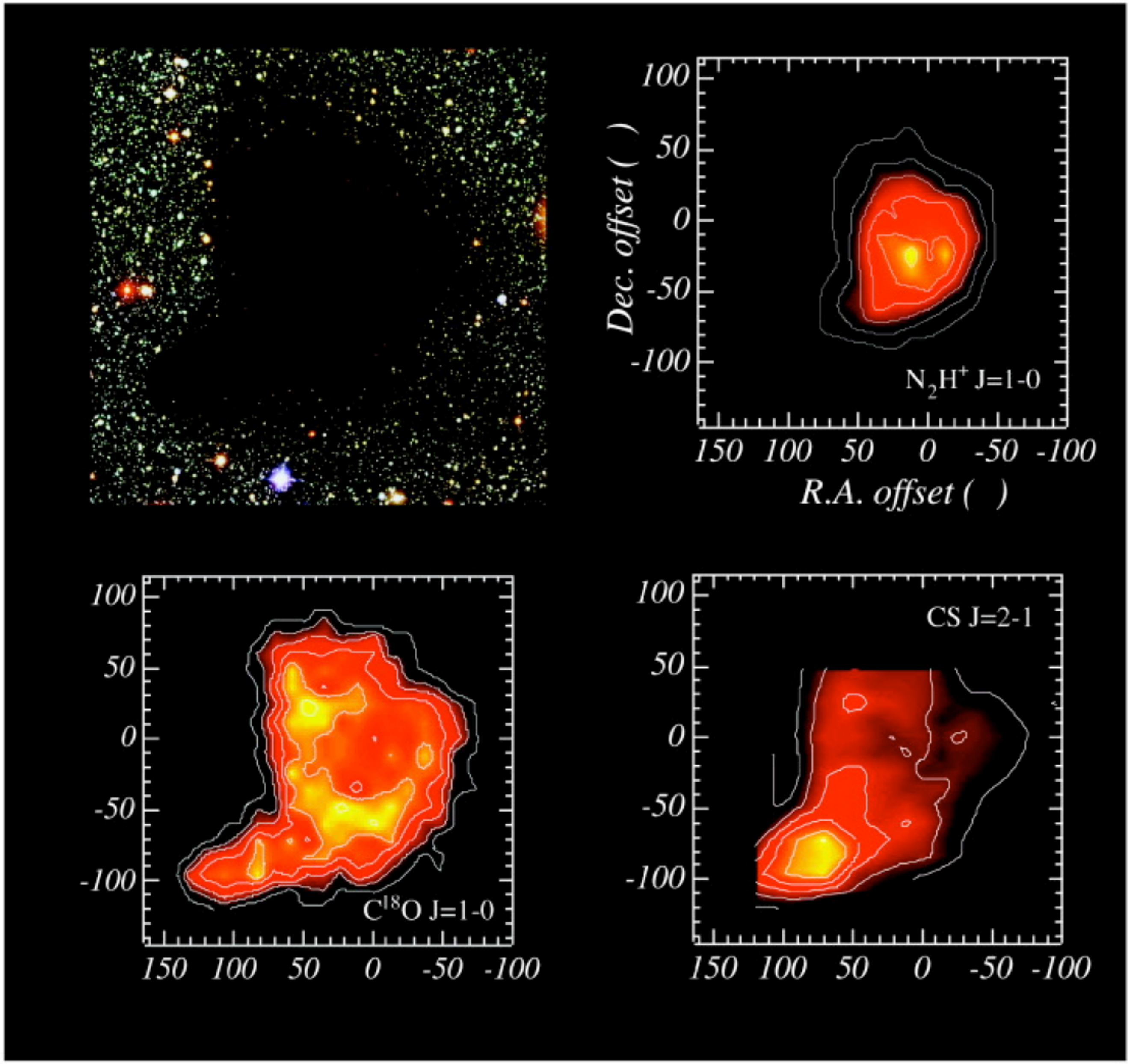
radiation (continuum + lines)

stellar dynamics
(collisional: star clusters,
collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

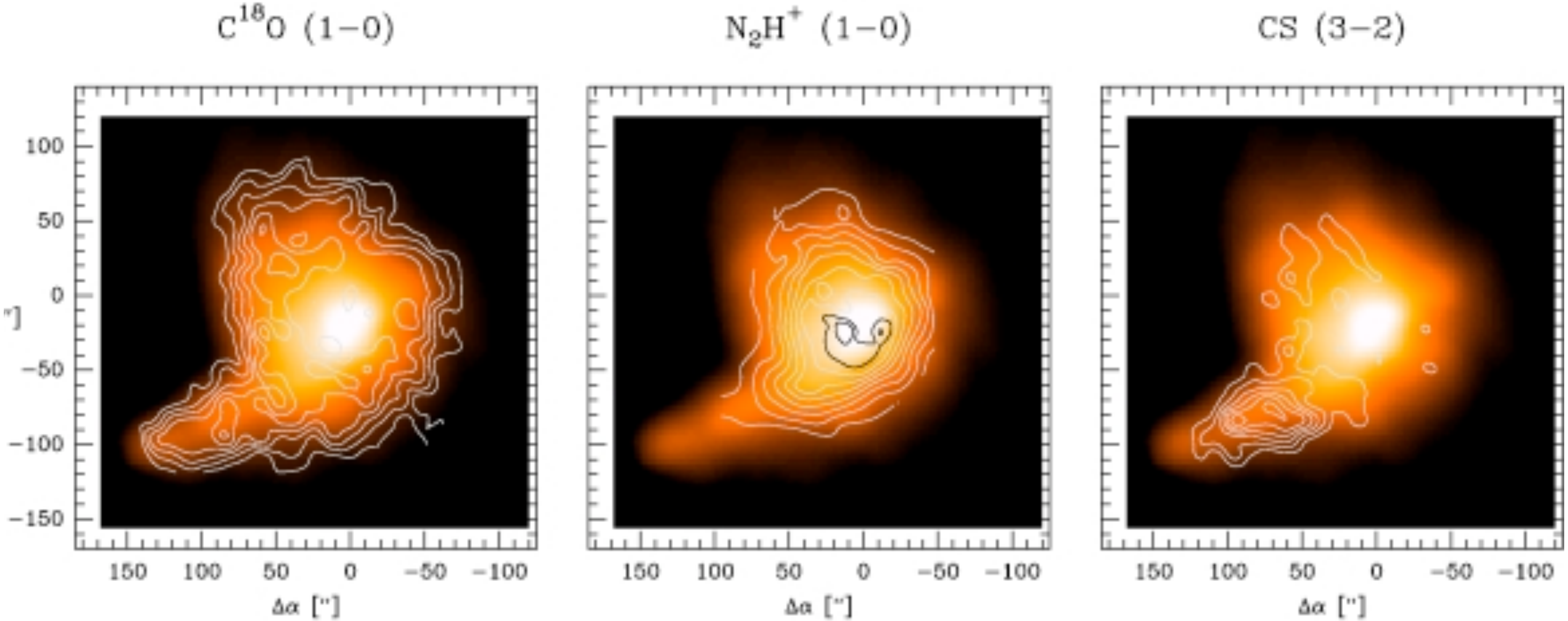
\+ **laboratory work**
(reaction rates, cross sections,
dust coagulation properties, etc.)

Barnard 68: a well-studied isolated prestellar core

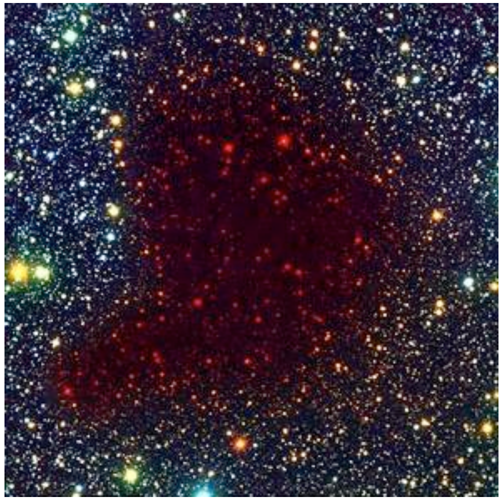


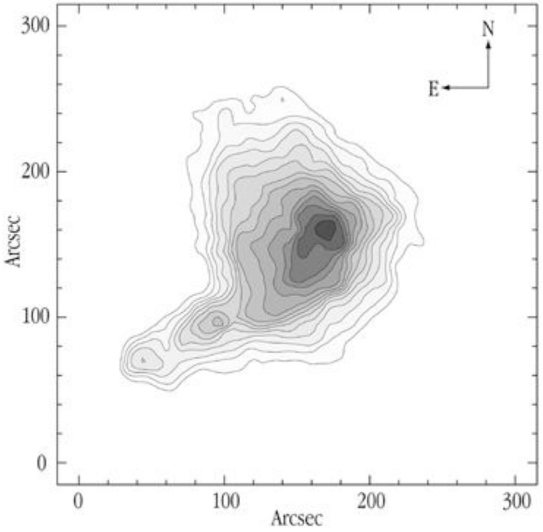
(Lada et al. 2003)

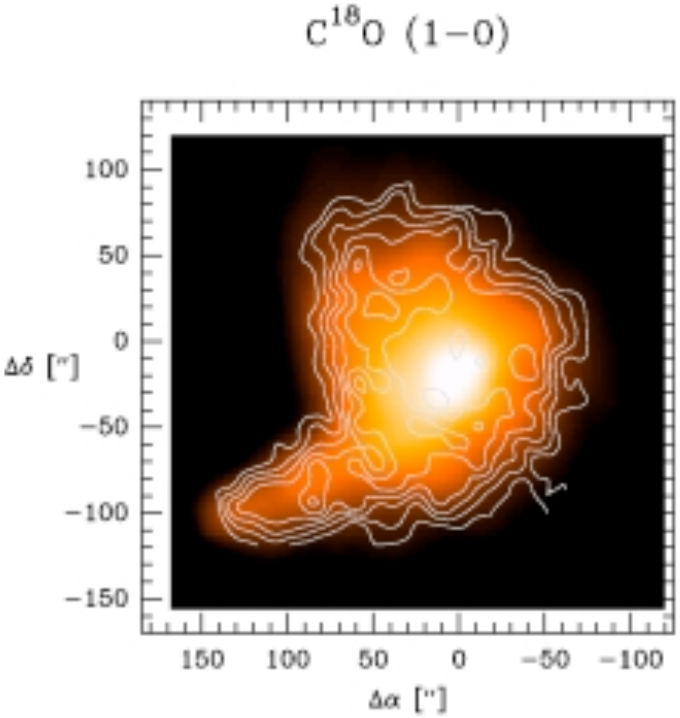
Barnard 68



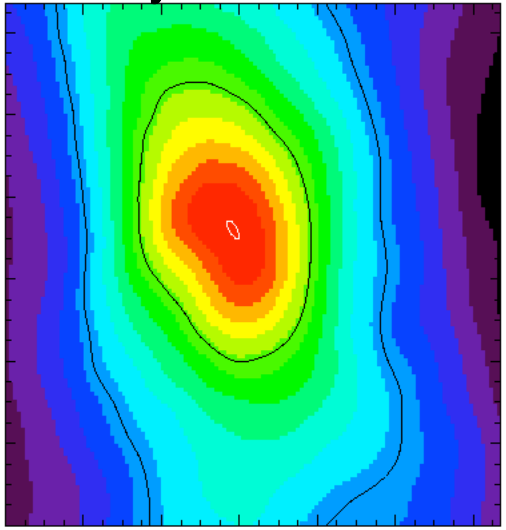
observations

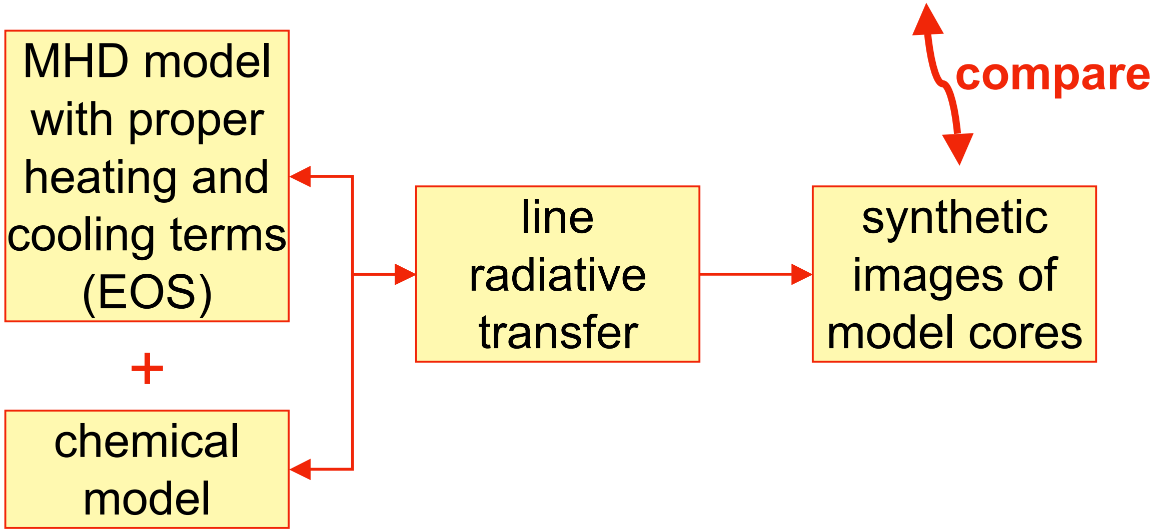






theory





compare

MHD model with proper heating and cooling terms (EOS)

+

chemical model

line radiative transfer

synthetic images of model cores

(e.g. Semenov & Pavlyuchenkov)

(3D core structure: Steinacker)

Thanks!