How do protostars get their mass?

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Origin of Stellar Masses • Tenerife, Spain • October 18, 2010

Introduction

How does nature make…

a star?

a star of particular mass?

a star of particular mass in a cluster?

The cluster problem:

> 100 stars in ~ 1 pc in ~ 1 Myr

centrally condensed distribution

masses follow IMF

central massive stars

dense filamentary gas

Ser S cluster (Gutermuth et al 2008)

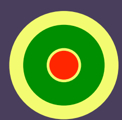
Outline

stars	origin models: stars, IMF, clusters
cores	cores and stars core boundaries core-clump accretion
infall	what stops infall distribution of durations
models	core-clump accretion, equally likely stopping filamentary cluster
summary	

Models of stellar mass origin

gravitational infall
What limits infall?

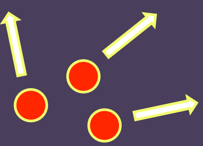
well-studied versions of basic process (geometry, eqn of state, B, J)
leading candidates:



initial structure

core boundary
$n \sim r^{-p}$, $p > 3$
B tension , AD
thermal BE sphere
turbulent core

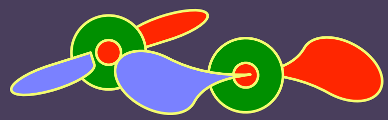
gravitational competition
neighbor stars, cores



stellar dynamics

ejection

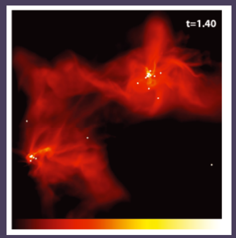
moving accretion
("competitive accretion")



gas dispersal

stellar feedback
outflows
ionization
rad heating

large scale flows



combination

turb fragmentation
ejection
moving accretion
(Bate 09)

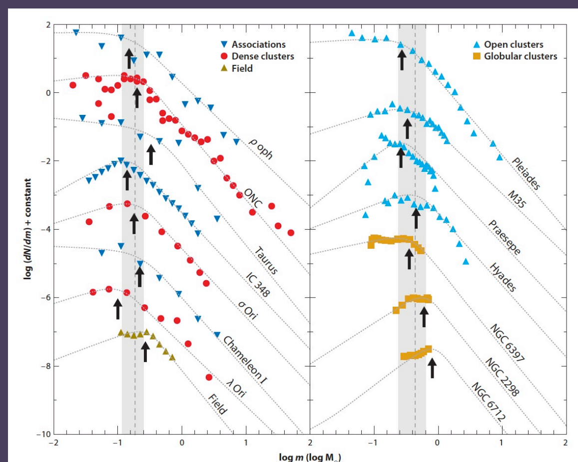
Basu, Nakamura, Glover, Bate talks

Larson 69, Shu 77, Foster & Chevalier 93, Bonnell et al 97, Reipurth & Clarke 01, McKee & Tan 03, Shu, Lizano & Adams 04, Myers 08, Bate 09

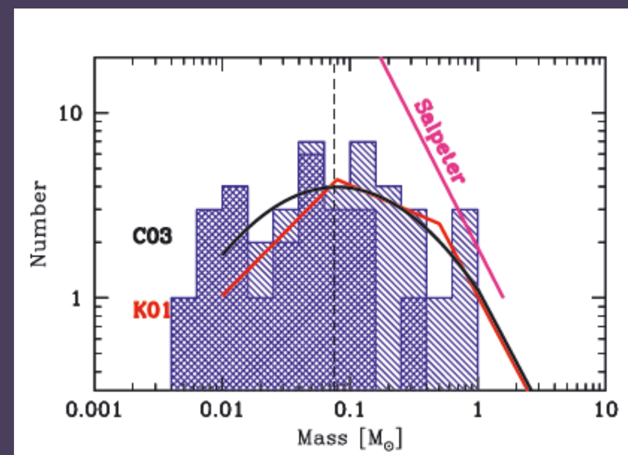
Stellar mass and the IMF

Mass fundamental property of stellar evolution. Early models – “low” and “high”

IMF a major property of star formation, clusters, seen in many settings (Kroupa 02, Chabrier 05, Bastian, Covey & Meyer 10); log-normal + Salpeter power-law



BCM 10



Bate 09

IMF Models *cores:* ambipolar diffusion; gravoturbulent fragmentation (HD, MHD) *protostars:* collapse of bounded or unstable region; accretion of seed or sink cell

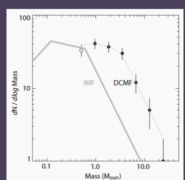
Bouvier, Lodieu, Luhman, Chabrier, Kroupa, Hartmann talks, Dib poster

Zinnecker 82, Adams & Fatuzzo 96, Elmegreen 97, Padoan & Nordlund 02, Larson 03, Shu et al 04, Klessen et al 04, Bonnell et al 06, Elmegreen 08, Hennebelle & Chabrier 08, Kunz & Mouschovias 09, Bate 09

Does core mass set star mass?

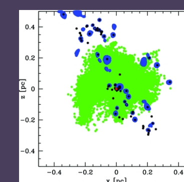
*Stars are **born** in collapsing cores*

core = local max of n, N, with $M \approx M_\star$
protostars are associated with cores



Y

N



core boundary limits accretion
one core, one star
core density profile ~ BES
CMF ~ IMF
massive stars - turbulent cores

?

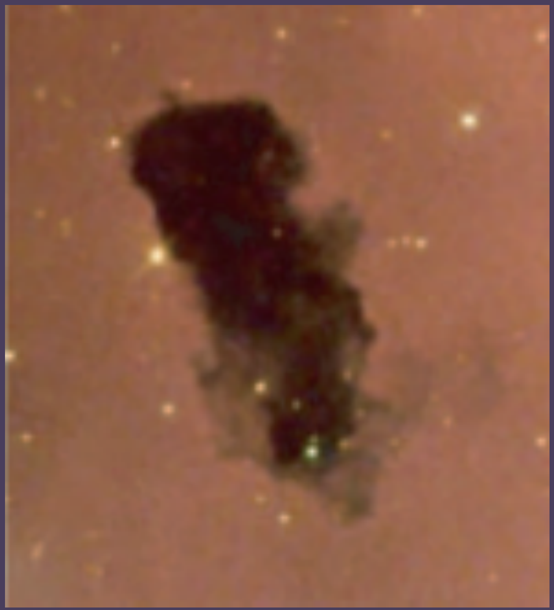
accretion from beyond core
one clump, many cores, many stars
turbulent fragmentation
competitive accretion

André, Ward-Thompson, Chabrier, Peretto, Clark, Moeckel talks, Smith poster

Alves, Lombardi & Lada 07, Bacmann et al 00, Beichmann et al 86, Bonnell, Bate, & Vine 03, Bonnell, Vine & Bate 04, Larson 69, McKee & Tan 2003, Motte, Andre & Neri 98, Myers & Benson 83, Shu 77, Smith, Longmore & Bonnell 10, Wang, Li, Abel & Nakamura 10

Cores with boundaries

cold dense globules bounded by transition to hot rarefied medium



Reipurth 03

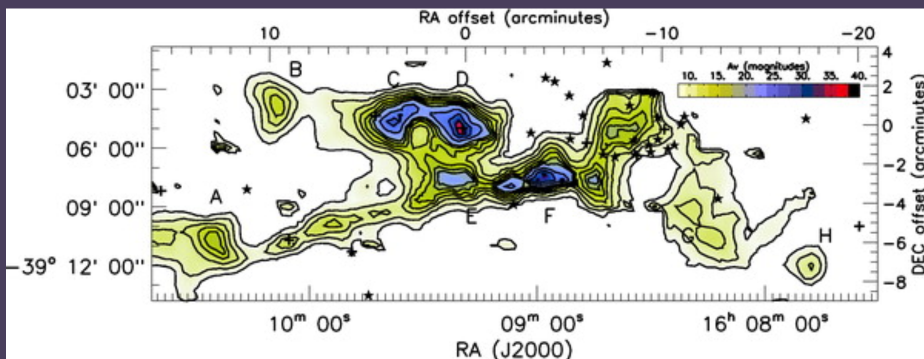
Thackeray 3 in H II region IC2944

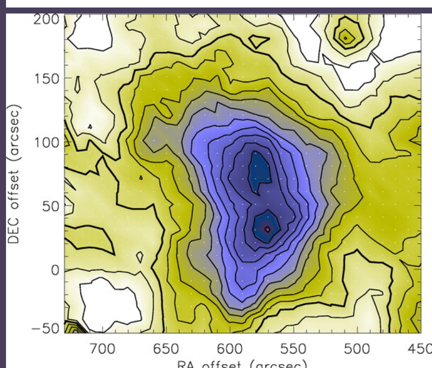
Alves, Lada & Lada 01

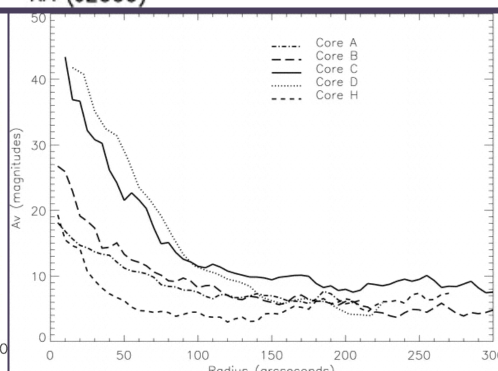
Barnard 68 in Loop I superbubble from Sco-Cen OB Association

Cores without boundaries

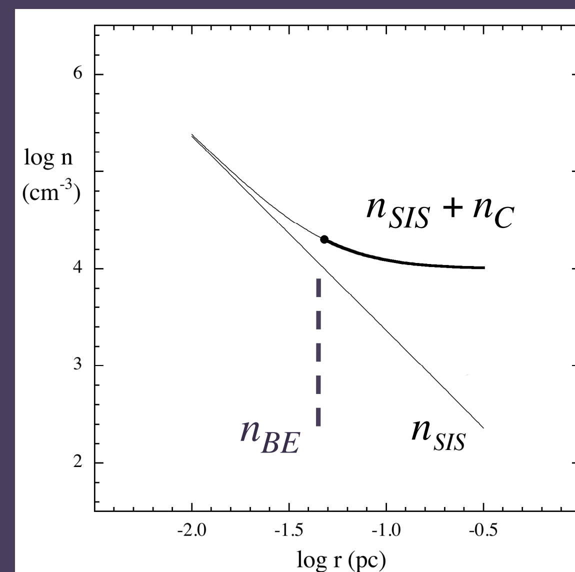
Steep-slope cores in shallow-slope clump
No mass boundary as in BE model







Model: core in clump
Clump = core environment
No unique free-fall time



Lupus Teixeira, Lada & Alves 05
Perseus Kirk, Johnstone & Di Francesco 06

Myers 09

Cores without boundaries

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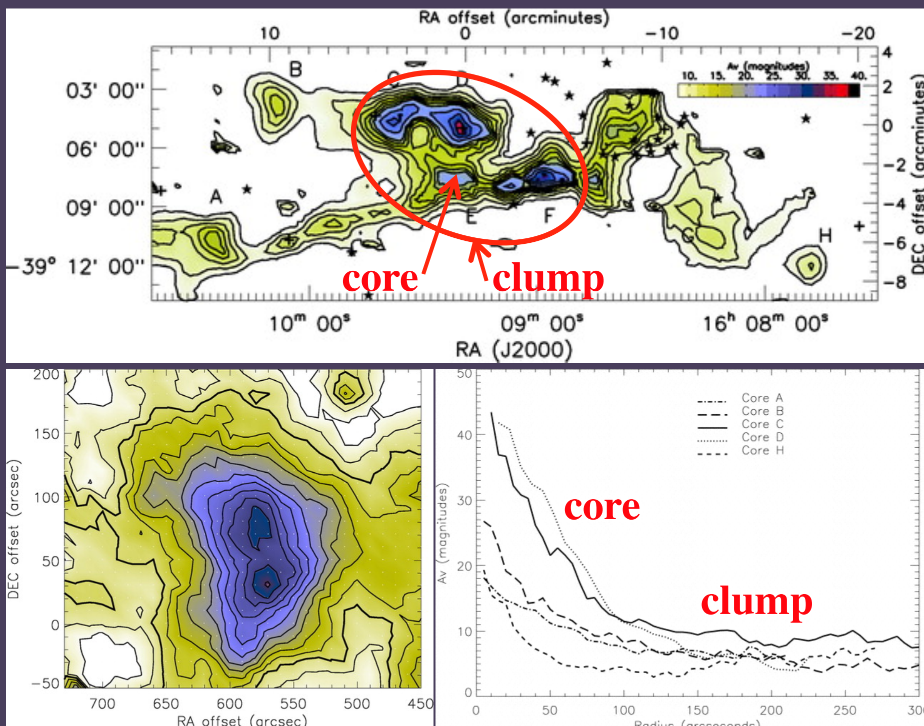

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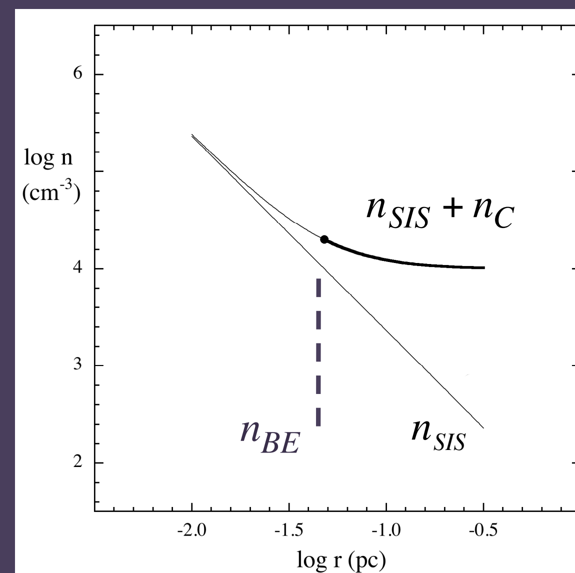
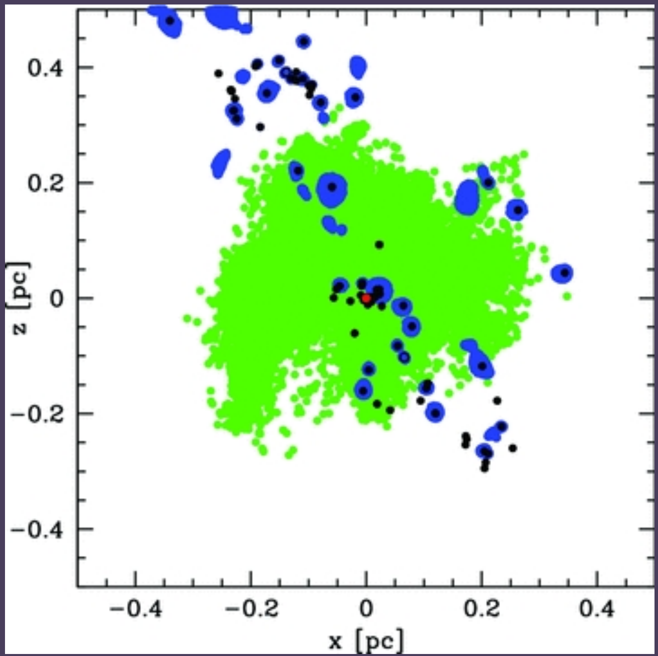


Myers 09

Do massive stars exceed their core mass?

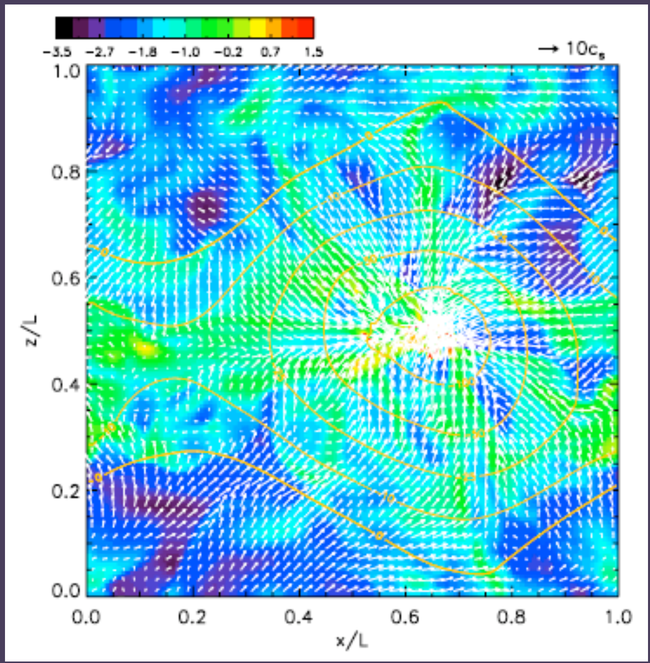
simulations

massive star originates in clump



Smith, Longmore & Bonnell 10

at center of clump potential well



Wang et al 10

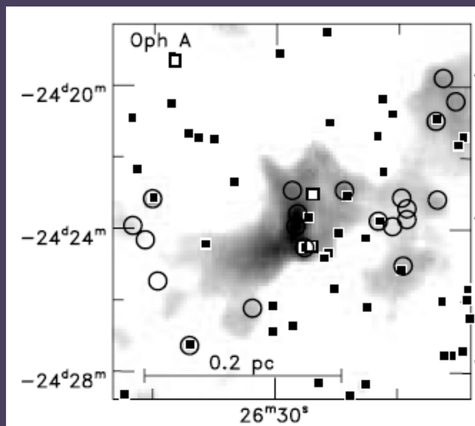
observations

“Monolithic” massive cores break into many smaller units, in high-resolution SMA observations: G28.34+0.06 (Zhang et al 09), NGC6334 I(N) (Brogan et al 09)

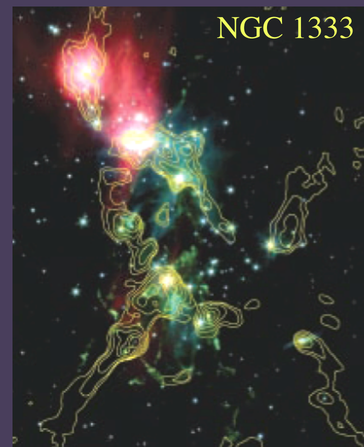
Bontemps, Tan, Csengeri talks

What stops infall?

We know infall stops…



Cores disappear after << 1 Myr
Jørgensen et al 08



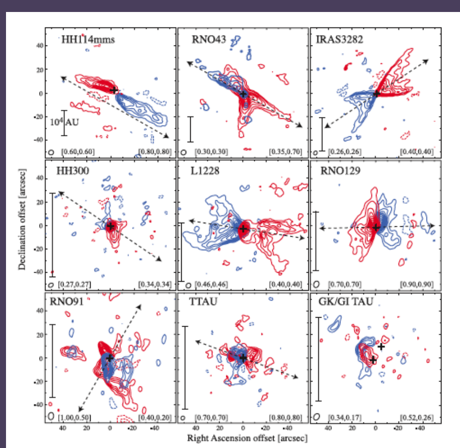
Cluster partly revealed after
~ 1 Myr Walawender et al 08

But we don't know how

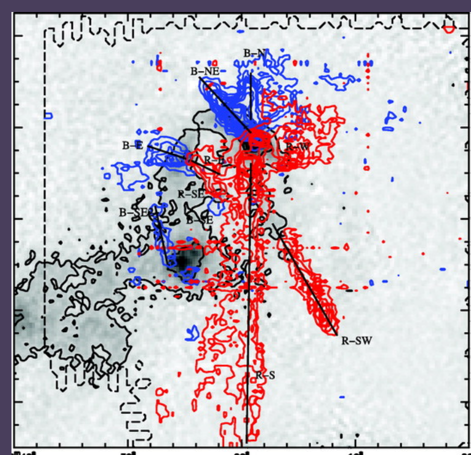
Stellar feedback: outflows
massive star rad'n, winds
ionization, evaporation

dynamical ejection
competitive accretion
combination of effects
key problem (SAL 87)

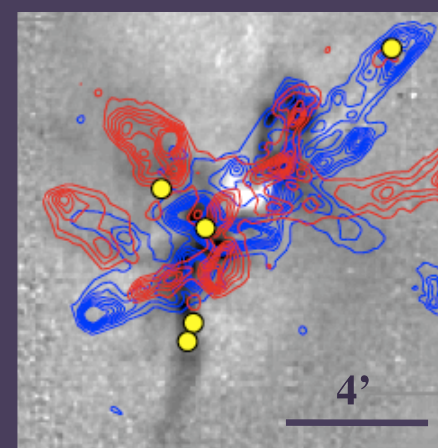
Phan-Bao, Stamatellos talks



Outflow lobes broaden over time
Arce & Sargent 06



Multiple outflows disrupt
L1641-N Stanke & Williams 07



Serpens Greaves et al 10

How are infall durations distributed?

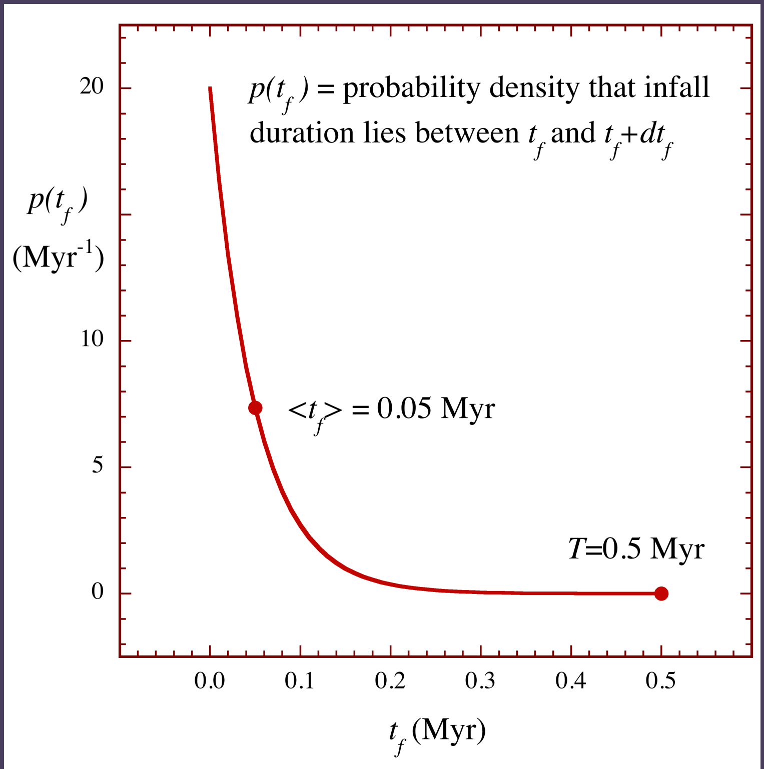
Infall duration

No unique free-fall time
Ejection, dispersal, competition stop infall
Agents act asynchronously
True distribution? ***key problem***

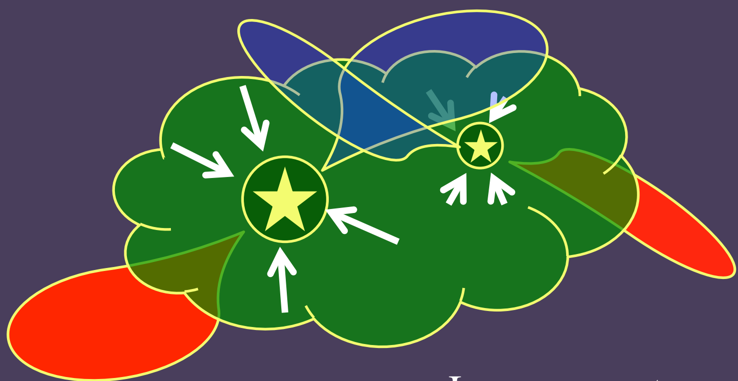
Simplest possible model: equally likely infall stopping (ELS) (Basu & Jones 04)

$$p(t_f) \sim \exp(-t_f/\langle t_f \rangle)$$

A given condensation can form a low-mass or high-mass star, depending on when its infall stops.



Model: core-clump accretion with ELS



Low-mass stars
short infall core-dominated

"High"-mass stars < 10 $M_\odot$ no H II
long infall   clump-dominated

Same basic process makes low- and high-mass stars

Analytic model
Pro: simple, gives insight
Con: too idealized

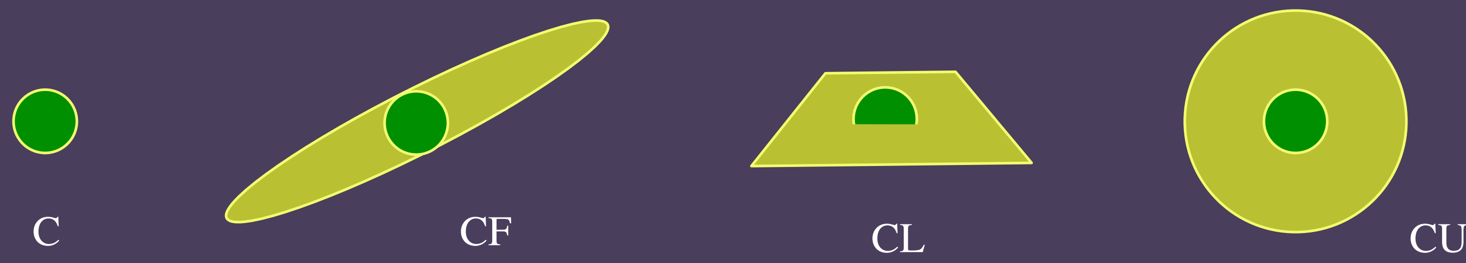
Stationary accretion competes with ELS

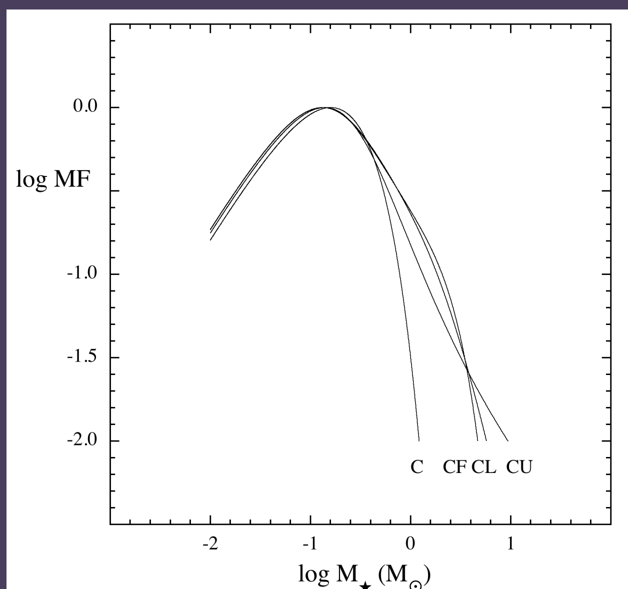
Accretion is steady, duration t_f
More realistic: intermittent (Vorobyov & Basu 05), gradually decreasing (Bontemps et al 96).

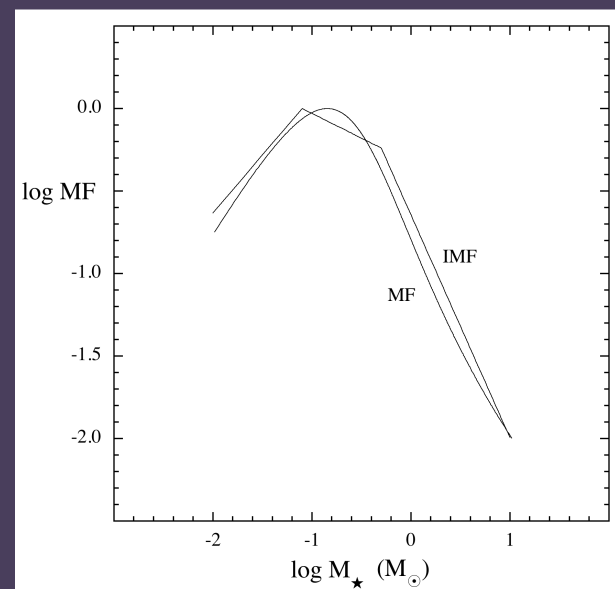
Accreted mass $M_\star \sim M_{gas}$ available for cold spherical infall from rest in time t_f More realistic: pressurized, magnetized, turbulent gas, complex disk geometry

Myers 09

Core-clump models approximate IMF



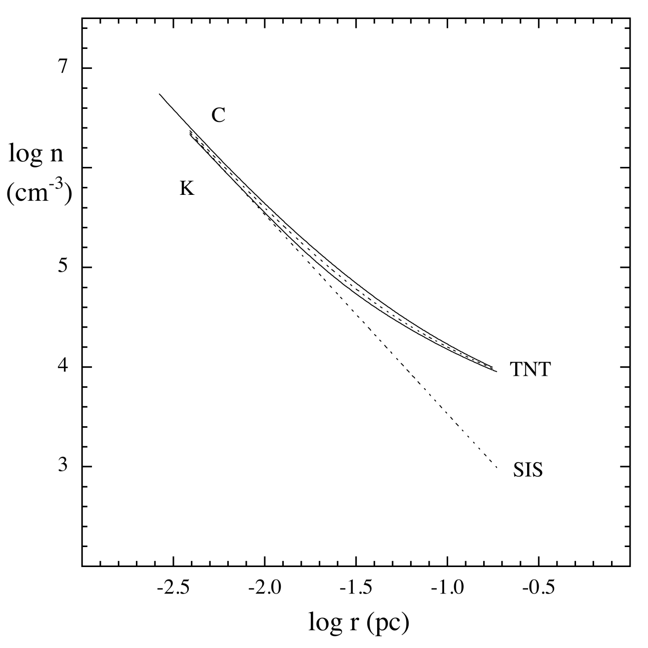




Myers 09

CU, CL, CF models approach IMF if peak environment density $n_E >\sim 10^4$ cm^{-3}.
High n_E needed to get massive stars (short t_f) and clustered stars (short λ_J)
Peak of MF $\sim (\sigma^3/G)\langle t_f \rangle$, less than Jeans mass *Smith poster*

Core-clump structure matches IMF



C Chabrier 05
K Kroupa 02

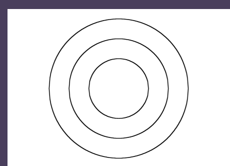
Myers 10

Get unique *n(r)* by assuming IMF and equally likely stopping
n(r) like thermal core in nonthermal clump $n(r) = Ar^{-2} + Br^{-2/3}$ like TNT, 2CTC models
Cluster conditions: ~20 K, 10^4 cm^{-3} like IRDCs; warmer, denser than isolated regions.

How do such core-clump condensations make a cluster?

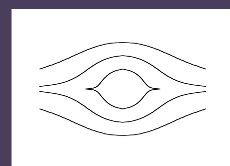
Core-clump structure in filaments

spherical core in spherical clump

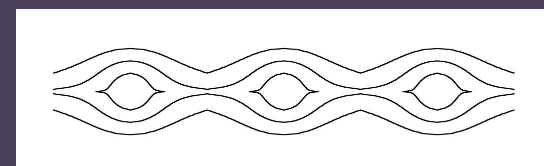


same $M(r)$ same MF

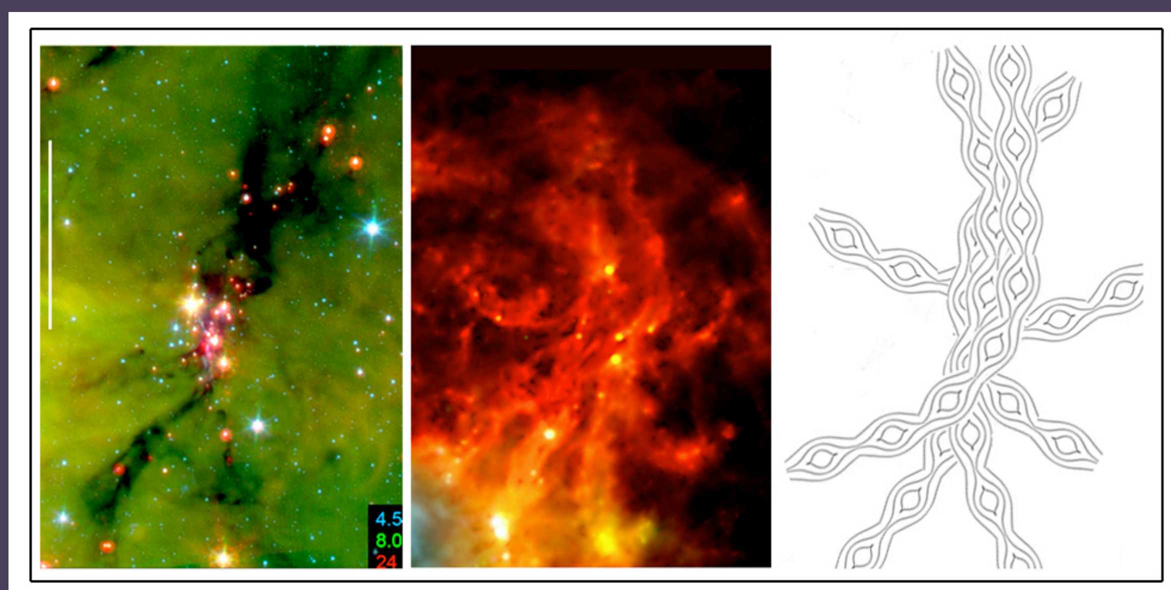
spherical core in cylindrical clump



equal spacing filamentary chain



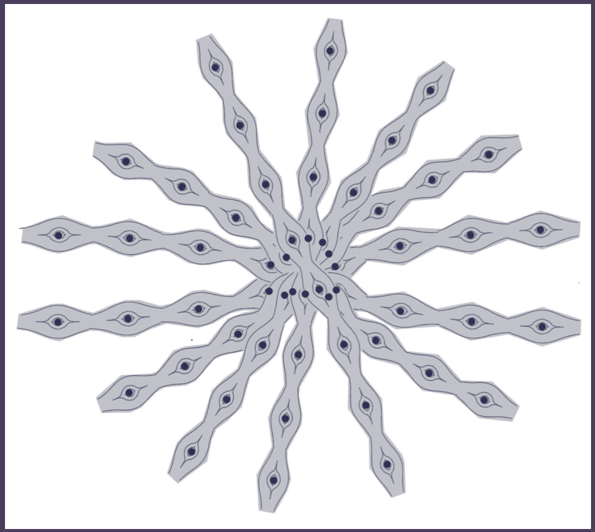
N_{21}=15, 20, 30 s = 0.2 pc

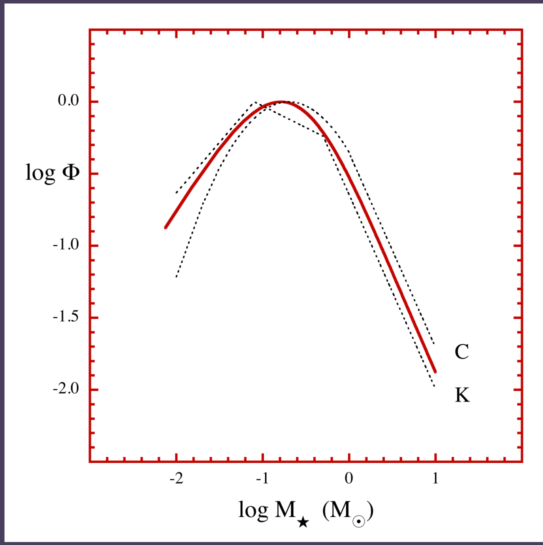


Myers 11

Ser South Gutermuth et al 09 André et al 10 converging filaments

Radial filaments cluster





Chabrier 05
Kroupa 02

Myers 11

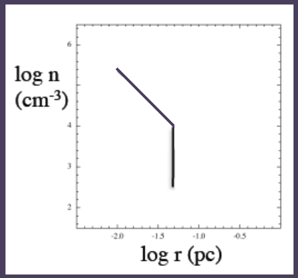
~ colliding flow simulations Vazquez-Semadeni et al 07, Banerjee et al 09

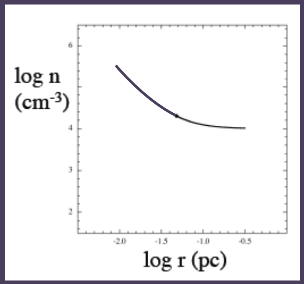
inputs	results	future
radial filaments	filamentary appearance	dynamics
equally spaced condensations	centrally condensed birthsites	mass segregation
core-clump structure	peak surface density ~N_{fil}/s^2	*see H. Kirk talk*
equally likely stopping	protostar MF matches IMF	

Summary

stellar mass	origin problem: IMF-clusters initial structure, infall stopping
star-forming condensations	cores in clumps
model of IMF-cluster	core-clump accretion equally likely stopping converging filaments
key problems	does core mass set star mass? what stops infall? what sets distribution of infall duration?

Core boundaries and the IMF





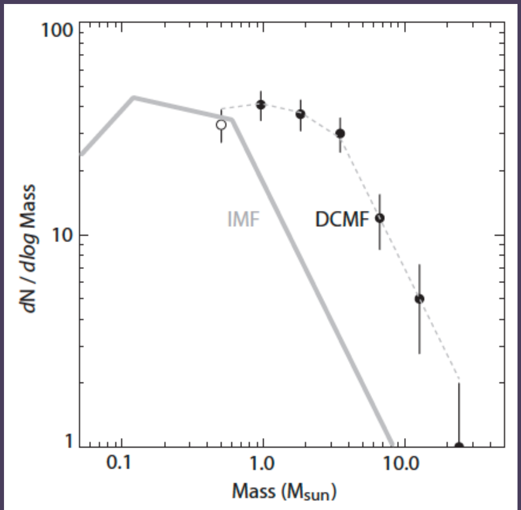
Do cores have mass flow boundaries?	**Yes**	**No**
Then star-forming infall stops because	*M(R)* is used up	infall-ready gas is dispersed
Infall duration is set by	free fall time t_f at R	dispersal time t_d
$M_\star$ is set by	$M(R)$ [M_{core}] --a *space* limit	$M(t_f = t_d)$ --a *time* limit
IMF is set by distribution of	M_{core} [CMF]	t_f and $\rho(r)$

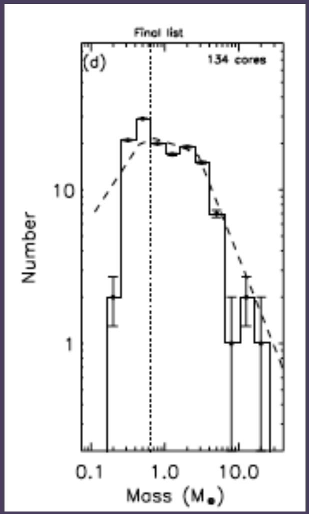
But doesn't the CMF ~ IMF?

Does the CMF resemble the IMF?

Many claims (Motte et al 98, Testi & Sargent 98, Johnstone et al 00, Alves et al 07…)

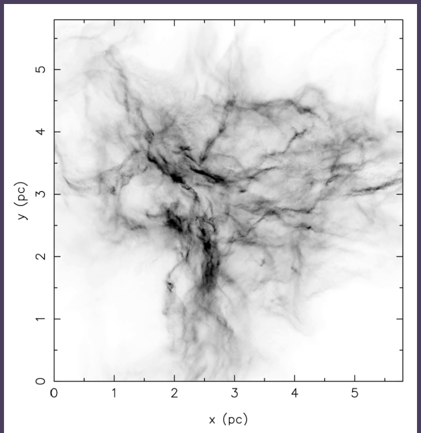
Pipe Nebula Alves et al 07 Rathborne et al 09

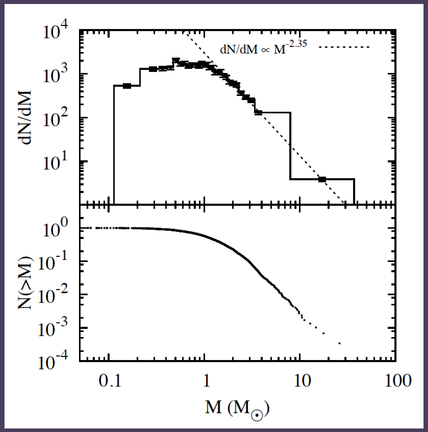




But the most careful study shows departures at low and high mass.
Such departures are expected if lowest-mass cores don't make stars, and if highest-mass cores fragment to make multiple stars (Hatchell & Fuller 08, Myers 09).

Should the CMF resemble the IMF?





Reid et al 10

Causal

CMF generates IMF
CMF from gravoturbulent or superAlfvenic turbulence

Hennebelle & Chabrier 08

Coincidental

Many indep. processes → log-normal distribution
clump-finding, noise, resolution changes number of members but preserves shape

Swift & Williams 08, Reid et al 10, Michel et al 11

In any case, it is necessary to explain both CMF and IMF