Cloud Structure and Star Formation

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Introduction

Star formation problem

How does nature make

>100 stars in ~ 1 pc in ~ 1 Myr
masses from <0.1 to > 100 M_{sun}
masses following IMF
stars centrally concentrated

from a complex network of filaments, clumps, and cores?

This talk

Filaments, clumps, cores, and their relation to star formation

Ser S cluster (Gutermuth et al 2008)

Outline

Filamentary clouds and formation models

Filaments and cores

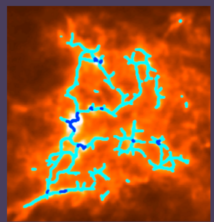
The role of cores in star formation

Accretion models

assumption: stars, VLMSs, and BDs are all born from clouds, cores, and disks (but not necessarily in the same way)

Big filamentary complexes

"Nessie" Jackson et al 10 ~80 pc



"South-Nest"

Vela C Hill et al 11 ~ 30 pc

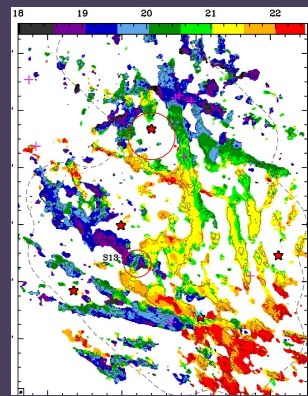
G345.00-022 ~20 pc

M09a

Oph ~20 pc

Cr Australis ~5 pc

www.panther-observatory.com



G14.2-0.5 ~ 5 pc

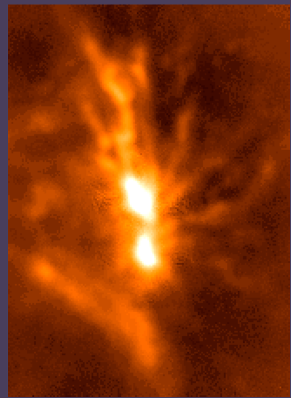
Busquet et al 11

Small filamentary complexes

Ser S ~ 2 pc

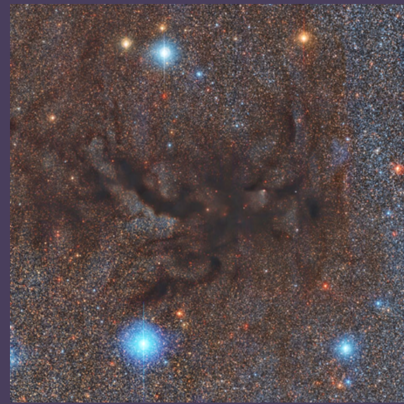
Gutermuth et al 08

Orion A ~1pc



Johnstone & Bally 99

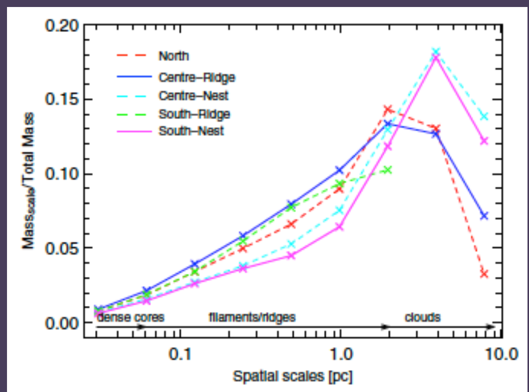
B59 ~1 pc



Alves et al 10

Morphological types--single filament (Nessie)
parallel filaments (G14.2-0.5)
network (Vela C South-Nest)
hub-filament (CrA).

Clusters often found in hubs (M 09a)



Mass distribution—mass in "cloud" gas on ~ pc scale, "filaments & ridges" on few 0.1 pc, "cores" < 0.1 pc

Massive filaments– A_V >100 "ridges" may form massive stars (Hill et al 11)

Filamentary models - overview

How to make a single filament

compress in 2D	shock in 2 directions	oblique colliding flows HD or MHD turbulence
	gravitational amplification of prolate cloud	
elongate in 1D	shearing motions	HD or MHD turbulence

How to make a system of filaments

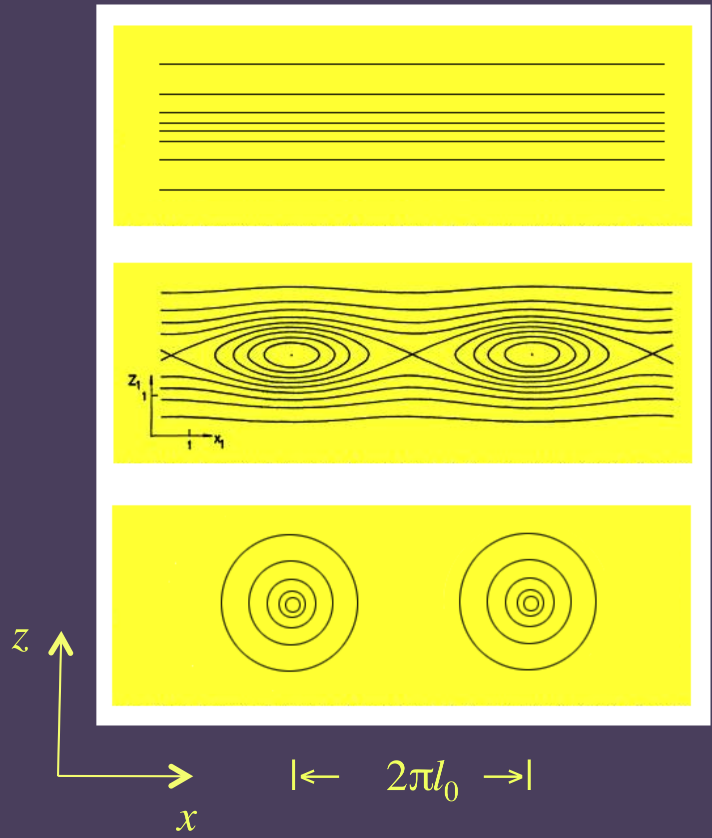
1. compress in 1D	single shock	head-on colliding flows swept-up shell
2. modulate	gravitational equilibrium gravitational fragmentation thin-shell and other instabilities	

Combination of large-scale flows, turbulence, magnetic field, gravity

Gravitational equilibrium

Infinitely extended, isothermal, self-gravitating equilibrium layer (Schmid-Burgk 67)

Constant density contours



$A = 0$ uniform
Spitzer 42

$A = 0.2$

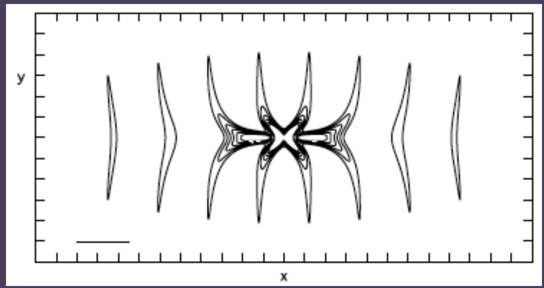
$A \rightarrow 1$ cylinders
Stodolkiewicz 63
Ostriker 64

$$\rho = \rho_0 \frac{1 - A^2}{\left[\cosh\left(\frac{z}{l_0}\right) - A\cos\left(\frac{x}{l_0}\right)\right]^2}$$

l_0 = thermal scale height
$= \sigma/(2\pi G\rho_0)$
ρ_0 = unmodulated midplane density

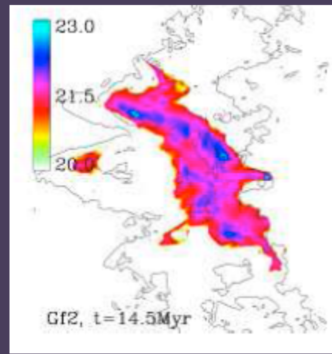
Limitations - infinite extent, no hub, no network

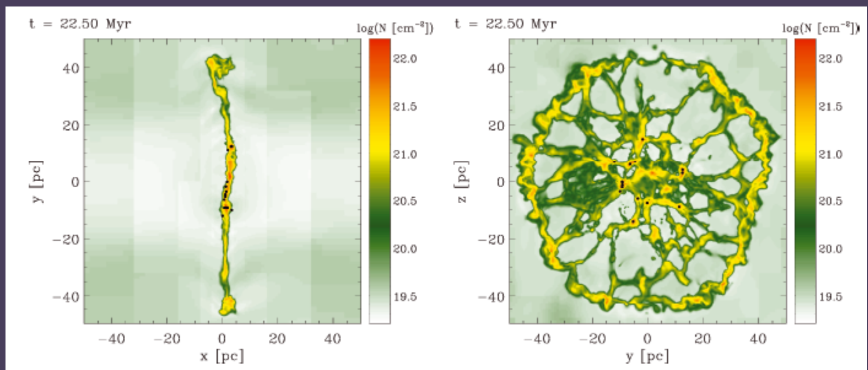
Flows make filamentary layers



clumpy medium compressed into layer with S-B modulation: outer equilibrium, inner collapse (M 09a)
(What sets modulation?)

Colliding atomic flows interface elongated 3:1
moderate perturbation of interface
global gravity creates main filament
no B, no stars (Heitsch & Hartmann 09)

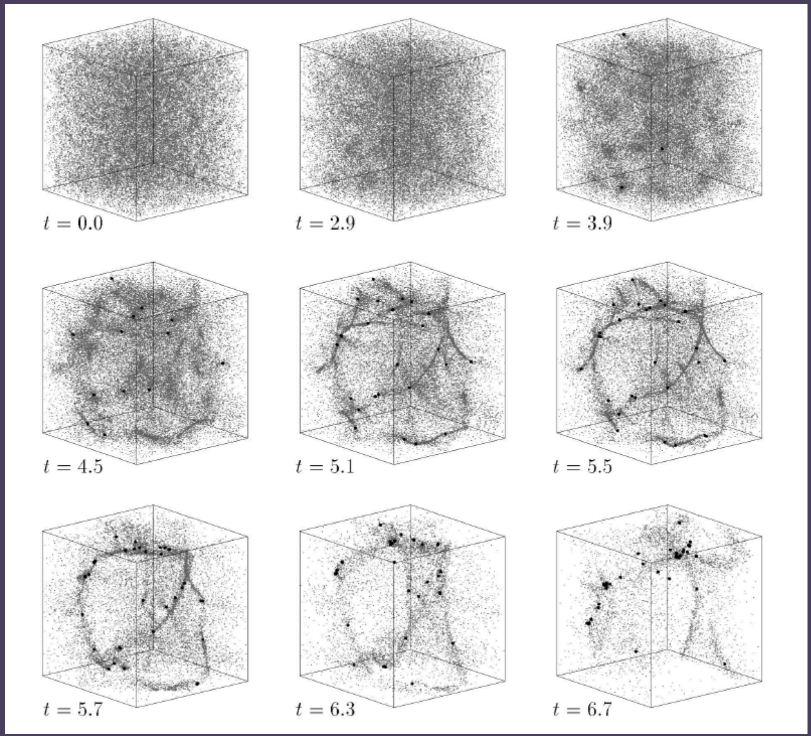


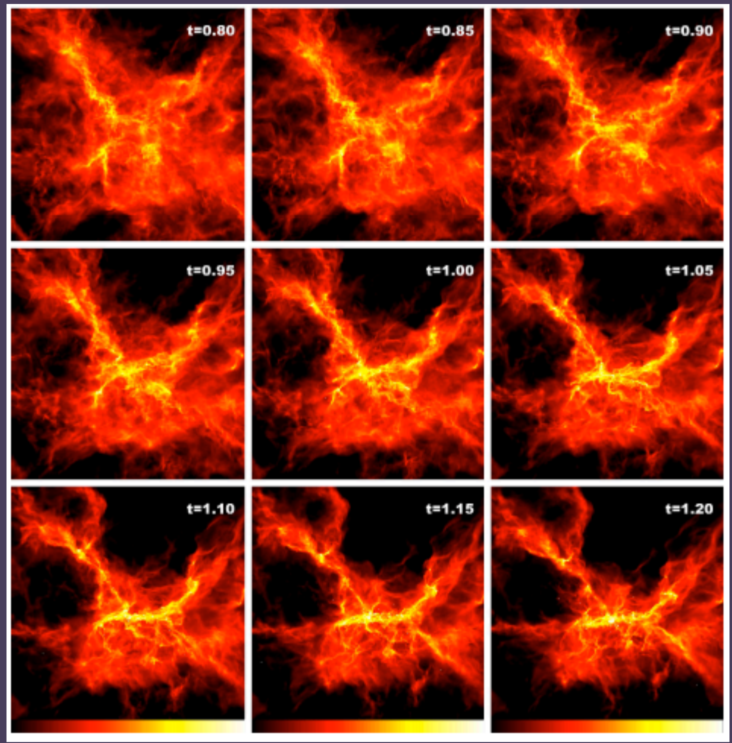


Colliding atomic flows circular interface
weak B along flow filamentary network
(Banerjee et al 09)

HD turbulence makes filaments

Turbulent stirring uniform cloud: shocks, filaments and cores. Gravity preserves denser structures.

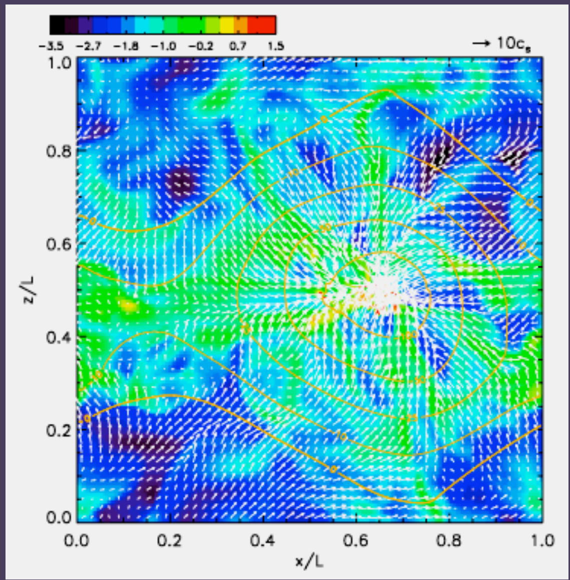




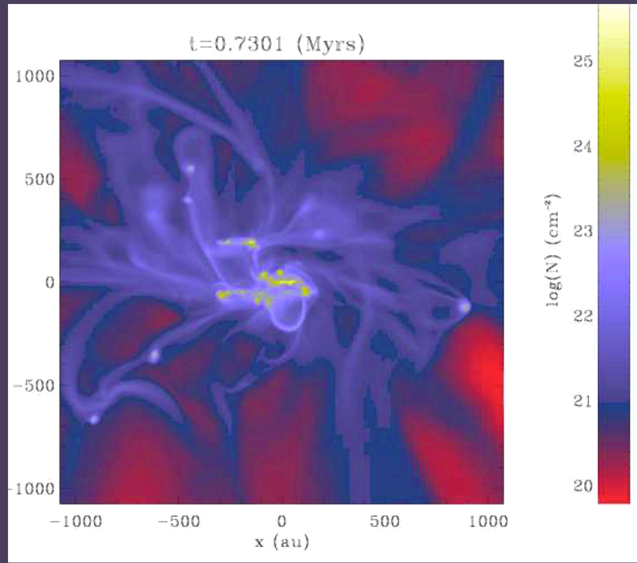
Klessen & Burkert 01 *Bate talk* Bate 11

Radiative feedback heats gas, makes fewer fragments, BDs, does not change SFR (Bate 11)

MHD turbulence makes filaments



Collapse of a magnetically supercritical 1600 M_{Sun} clump; massive sf is outflow-regulated, clump-fed (Wang et al 10)

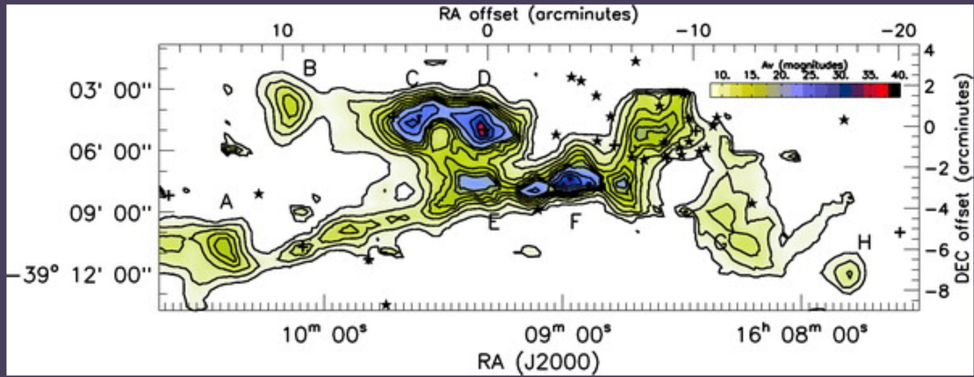


Collapse of a magnetically supercritical 100 M_{Sun} clump; ***B*** reduces inner ***J*** , helps launch outflows, reduces fragmentation (Hennebelle et al 11)

MHD turbulence channels flows, give less fragmentation, lower stellar masses than HD turbulence

Relation of clumps, filaments, and cores

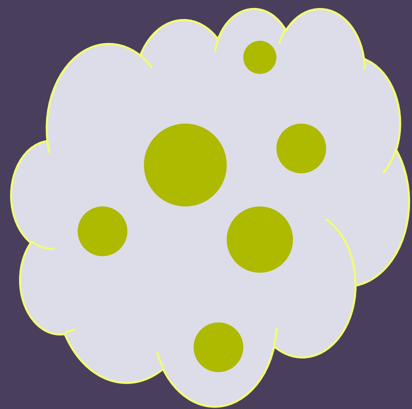
observed



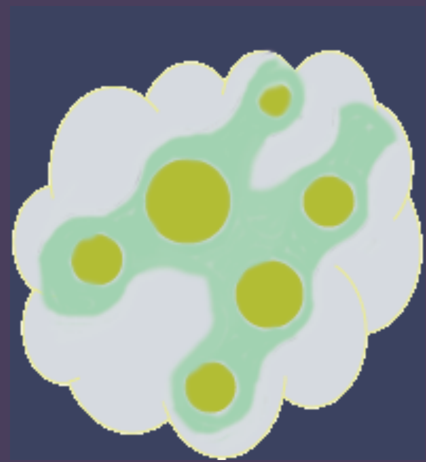
Cores in Lupus 3
Teixeira et al 06

models

Clump with isolated
core, mass boundary
isolated core collapse



Clump with cores
no mass boundaries
core-clump accretion

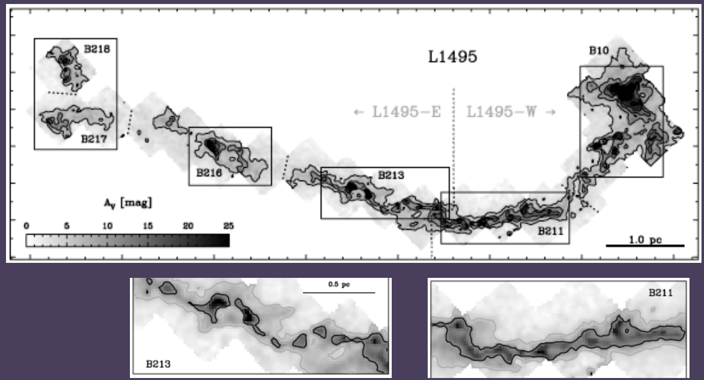


Clump with cores in
filaments, no mass boundary
filamentary core-clump accretion

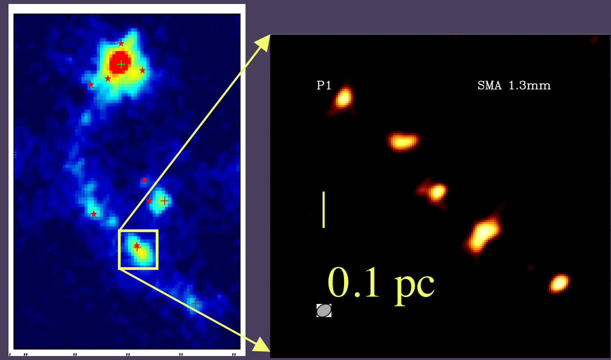
1 pc

Cores in filaments

multiple cores, ~ regular spacing, wide range of size scales

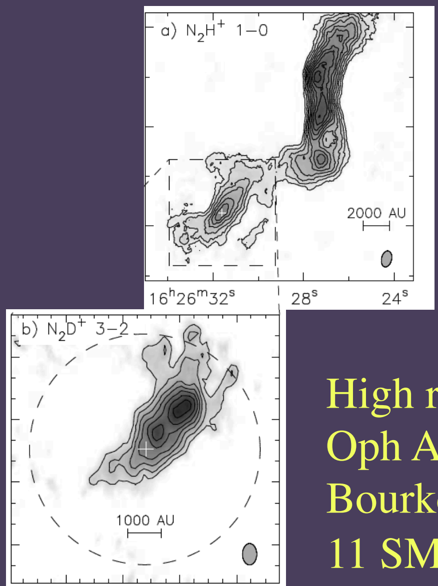


Taurus L1495 Schmalzl et al 10



IRDC G28.34 Zhang et al 09 SMA

André, Hacar, Teixeira talks



High resolution
Oph A N6
Bourke et al
11 SMA

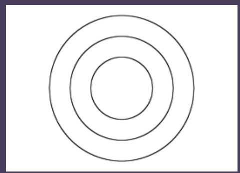
Models: similar to models of filament formation

Gravity	exact isothermal equilibrium	Curry 00
	Jeans fragmentation	Larson 85
	critically stable iso cylinder $M/L = 2\sigma^2/G$	
	Jeans spacing $\lambda \sim \sigma/(G\rho_0)^{1/2}$	
Turbulence	HD, MHD models match general structure, more studies are needed	

Are filaments isothermal?

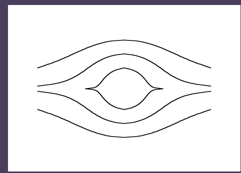
If filamentary chains make the IMF, their structure is not purely isothermal (M11a) *L977 Alves et al 98*
Herschel tests

core-clump
$n(r)$+ ELS
→IMF

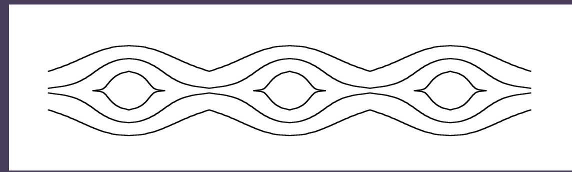


spherical core in
spherical envelope

same
$M(r)$
similar
MF



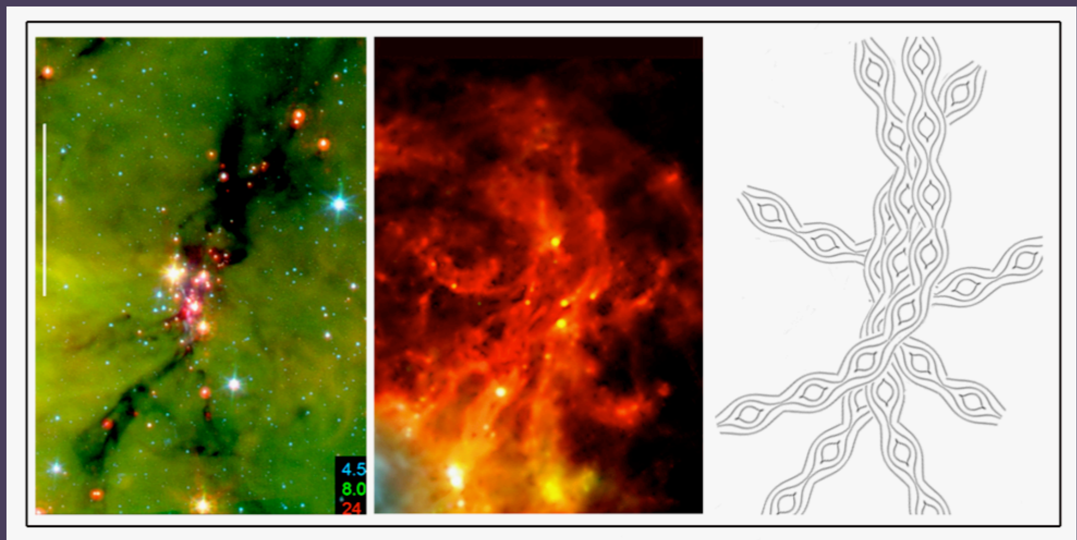
spherical core in
cylindrical envelope



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

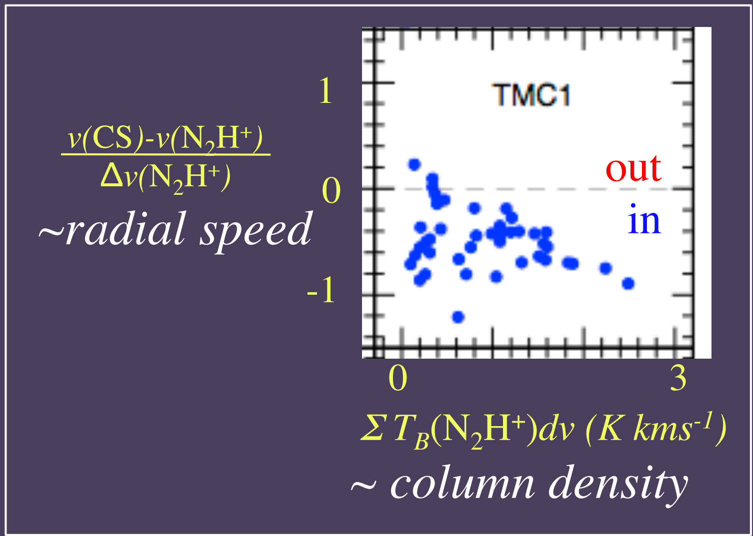
equal-spacing filamentary chain

Some clusters look like bundles of filamentary chains:



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

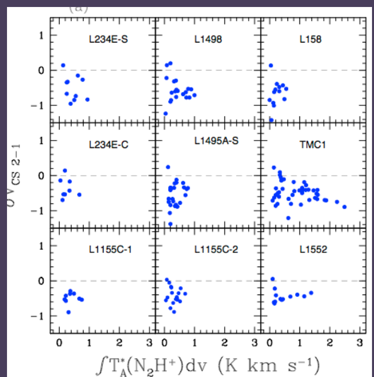
The role of cores: starless cores are contracting



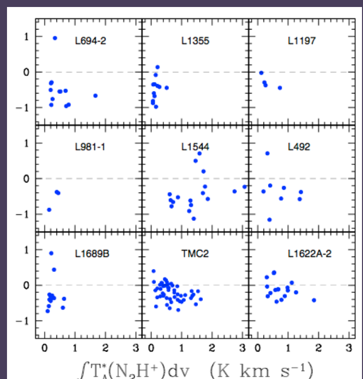
CS 2-1 line maps of
33 starless dense cores:

Most cores are contracting over ~0.1 pc at ~0.1 km s^{-1}
Denser cores are more likely to contract

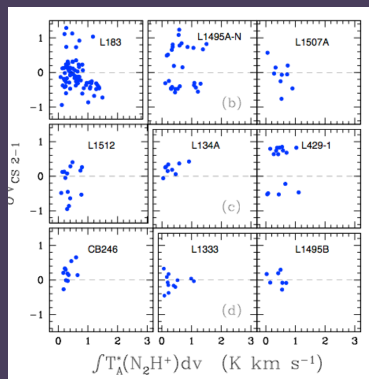
(Lee & Myers 11) *Lee poster*



19 contracting:
blue-skewed line profiles dominate



3 oscillating:
mix of red- and blue-skewed profiles



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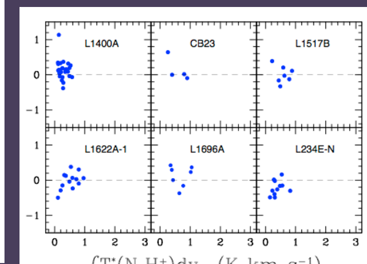
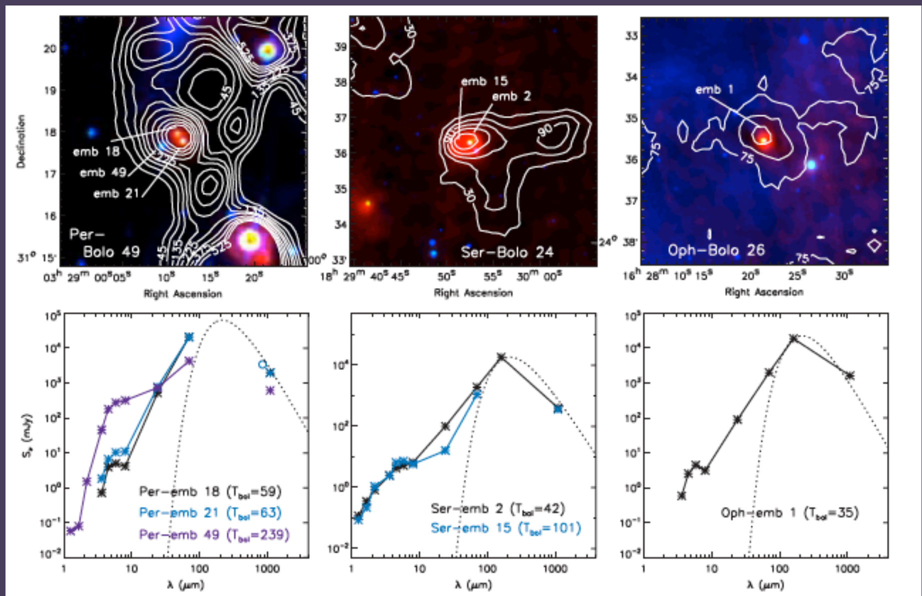


8 static:
no significant skewing of line profiles

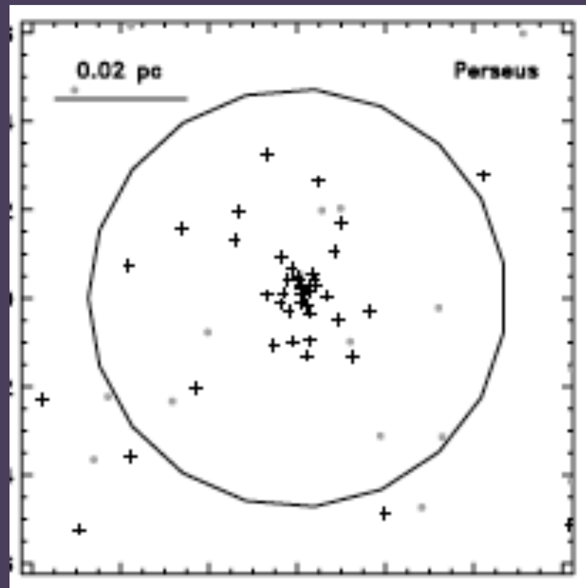
The role of cores: cores harbor protostars

Early: *IRAS* protostars in $C^{18}O$ and NH_3 line cores (Beichman et al 86)

Recent: *Spitzer* protostars in mm and submm dust continuum cores



Protostars projected on Bolocam cores   Enoch et al 09



Protostars centered in SCUBA cores
Jørgensen et al 08

The role of cores: do cores set star mass?

Stars are born in cores

core = local max of *n, N*
dense starless cores are contracting
protostars are associated with cores

Yes

boundary limits accretion
one core, one star

core density profile ~ BE sphere
CMF sets IMF
$M_{star} = \varepsilon M_{core}$

No

accretion from environment
one clump, many cores

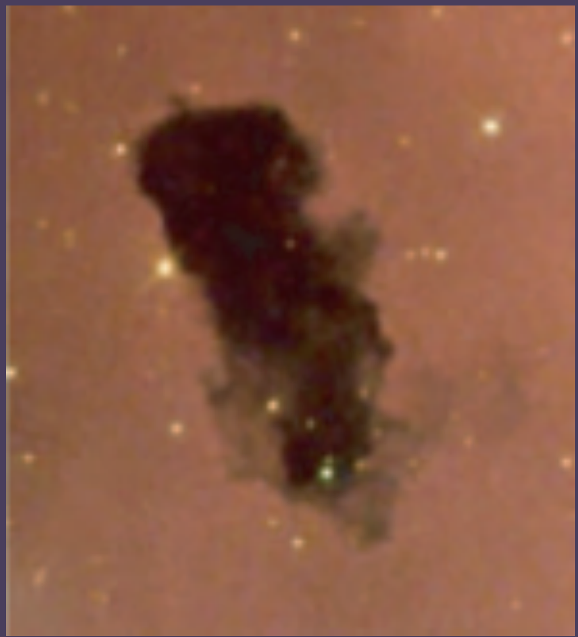
M_{star} increases with rate and duration of accretion
CMF does not set IMF

key problem: what sets CMF?

André, Bate, Boss, Chabrier, Commerçon, Duchene, Reipurth talks

Cores with boundaries

cold dense globules bounded by transition to hot rarefied medium



Reipurth 03

Alves, Lada & Lada 01

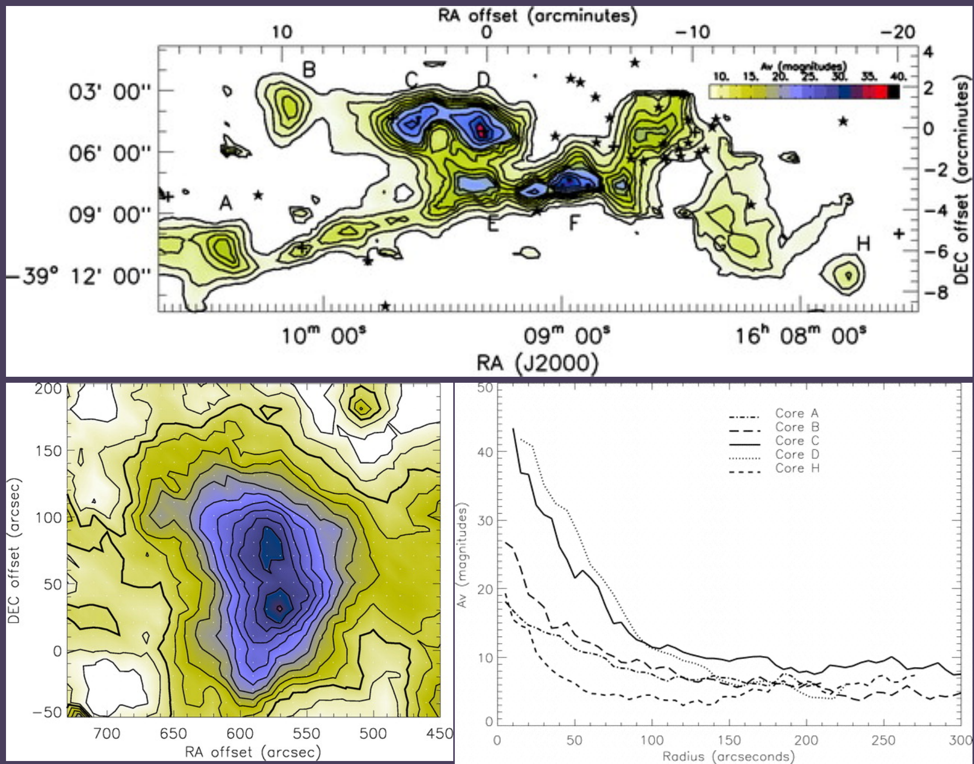
Thackeray 3 in H II region IC2944

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

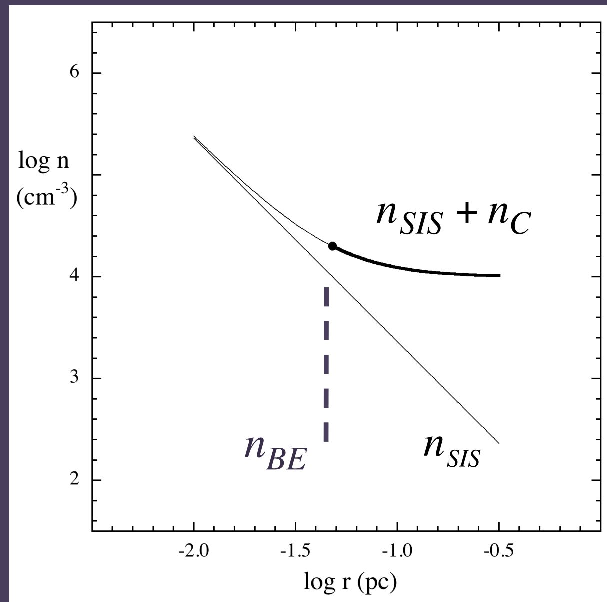
Mäkelä poster - globulettes

Cores without boundaries

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



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

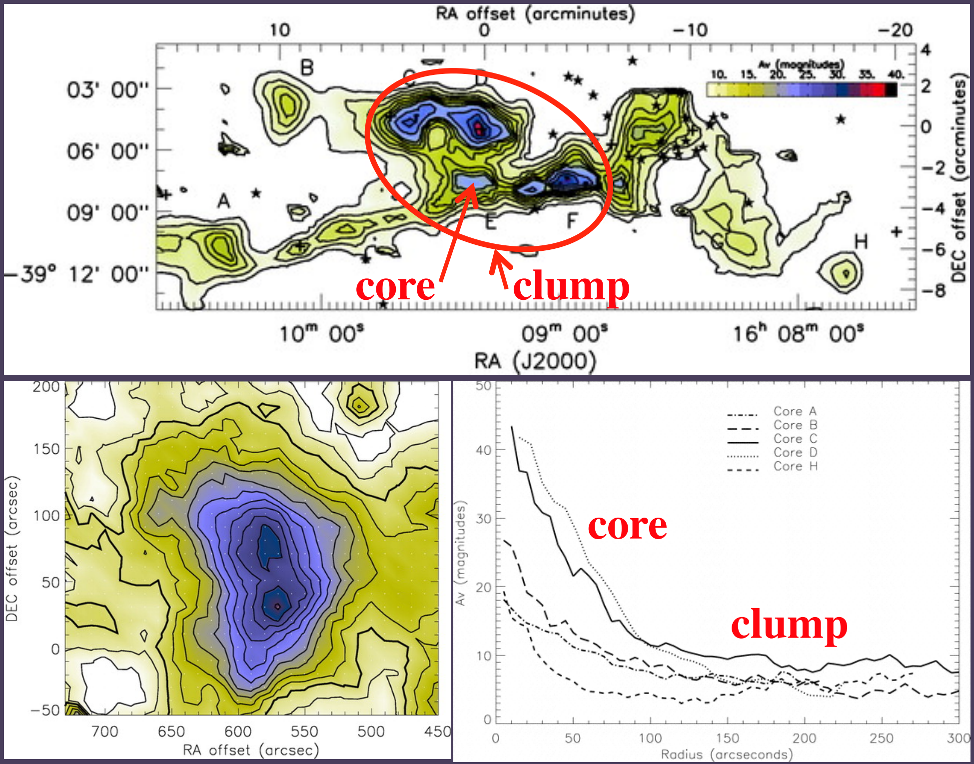


Lupus Teixeira, Lada & Alves 05
Perseus Kirk, Johnstone & Di Francesco 06

M 09b

Cores without boundaries

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



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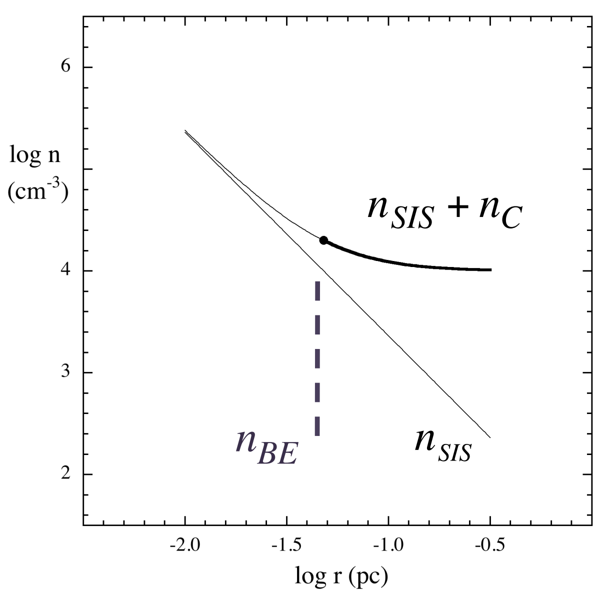


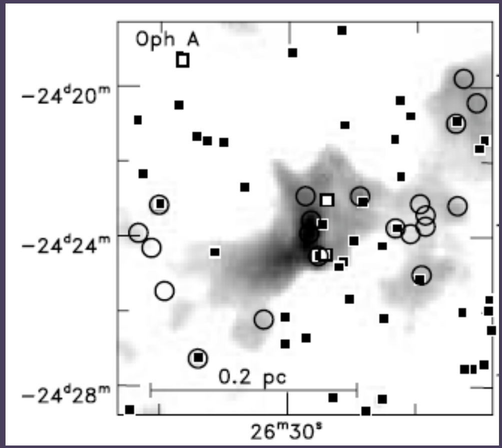
Lupus Teixeira, Lada & Alves 05
Perseus Kirk, Johnstone & Di Francesco 06

M 09b

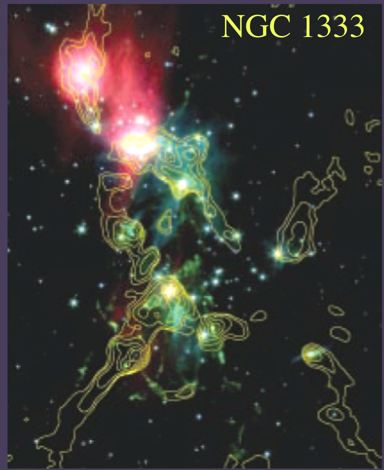
If no accretion boundary, what stops accretion?

What stops accretion?

We know accretion stops…



Cores disappear after << 1 Myr
Jørgensen et al 08



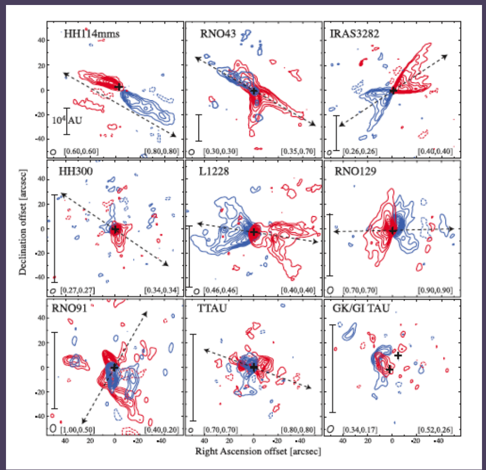
Cluster partly revealed after
~ 1 Myr Walawender et al 08

But we don't know how

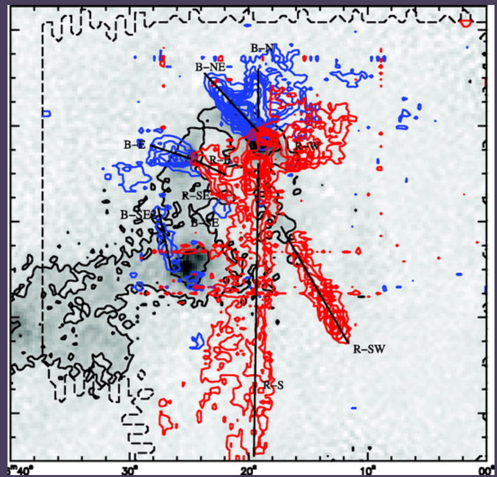
Stellar feedback: outflows
massive star rad'n, winds
ionization, evaporation

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

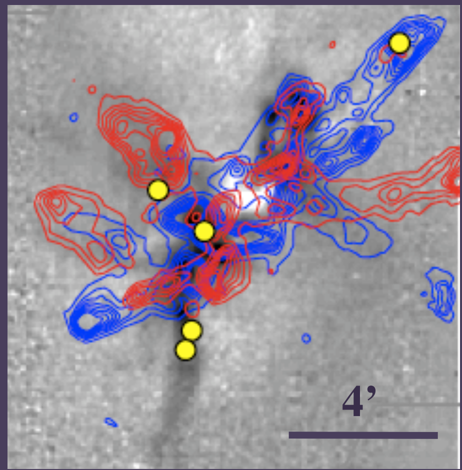
Hartmann, Natta, Reipurth talks



Outflow lobes broaden over time
Arce & Sargent 06



Multiple outflows disrupt
L1641-N Stanke & Williams 07



Serpens Greaves et al 10

How are accretion durations distributed?

Accretion durations are not all equal

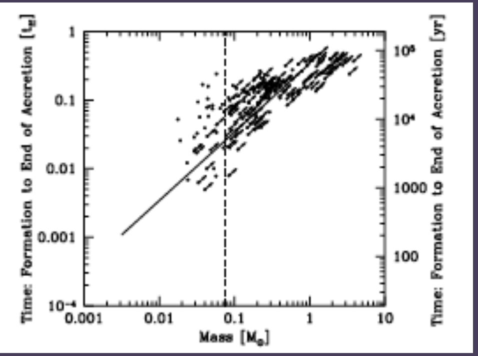
No unique free-fall time
Ejection, feedback, competition limit accretion
Simulations show broad distribution of t_f

Model: equally likely accretion stopping (ELS)

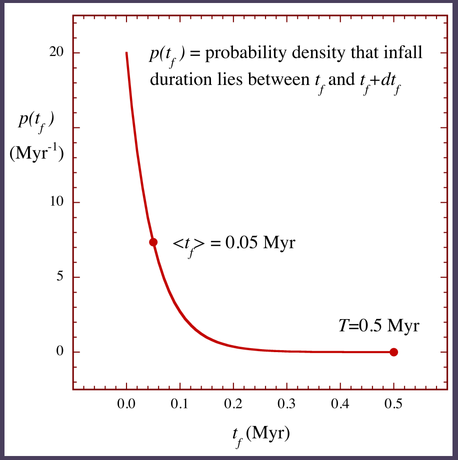
$$p(t_f) \sim \exp(-t_f/\langle t_f \rangle)$$

(Basu & Jones 04)

Basu, Bate, Dunham, Offner, Reipurth, Stamatellos talks



broad distributions of accretion duration and protostar mass Bate 11



ELS prob density of duration M09

Core-clump accretion models

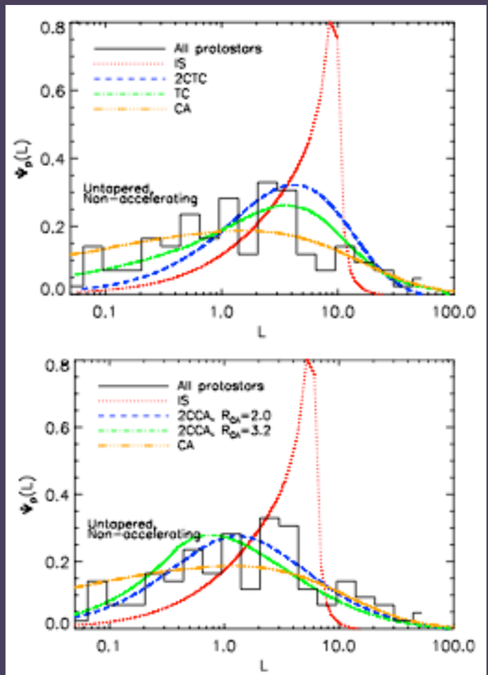
Complex 3D structure → model 1D accretion rate; match IMF and protostar luminosity function

Pure core collapse
doesn't make massive stars
in the available time

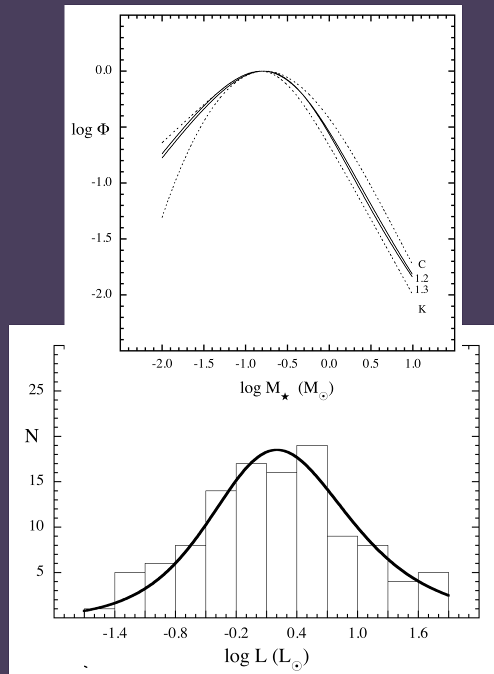
Core-clump accretion rate

$$\dot{m} = \dot{m}_{core} + \dot{m}_{core}\left(\frac{m}{\dot{m}_{core}\tau_{clump}}\right)^{p}$$

Pure clump accretion
requires seed masses
ignores protostars in cores



Offner talk



2CTC and 2CCA accretion rate +
IMF fits PLF   Offner & McKee 11

Core-clump accretion rate
+ ELS fit IMF, PLF   M11b

Summary

star-forming clouds are filamentary	one main filament parallel filaments network hub-filament system	colliding flows HD shocks MHD shocks gravity
filaments have multiple cores	models - similar to filament formation isothermal & gravity, MHD & HD turbulence	
role of cores	cores are birth sites	contraction protostars
set star mass?	*Yes:* isolated collapse bounded core	*No:* core-clump accretion, stop times distributed
key problems	do cores set star mass? what stops accretion? what sets the CMF?	

Thanks…to organizers for the invitation, to P. Hennebelle & Q. Zhang for recent results!