The Simultaneous Formation of Massive Stars and Stellar Clusters

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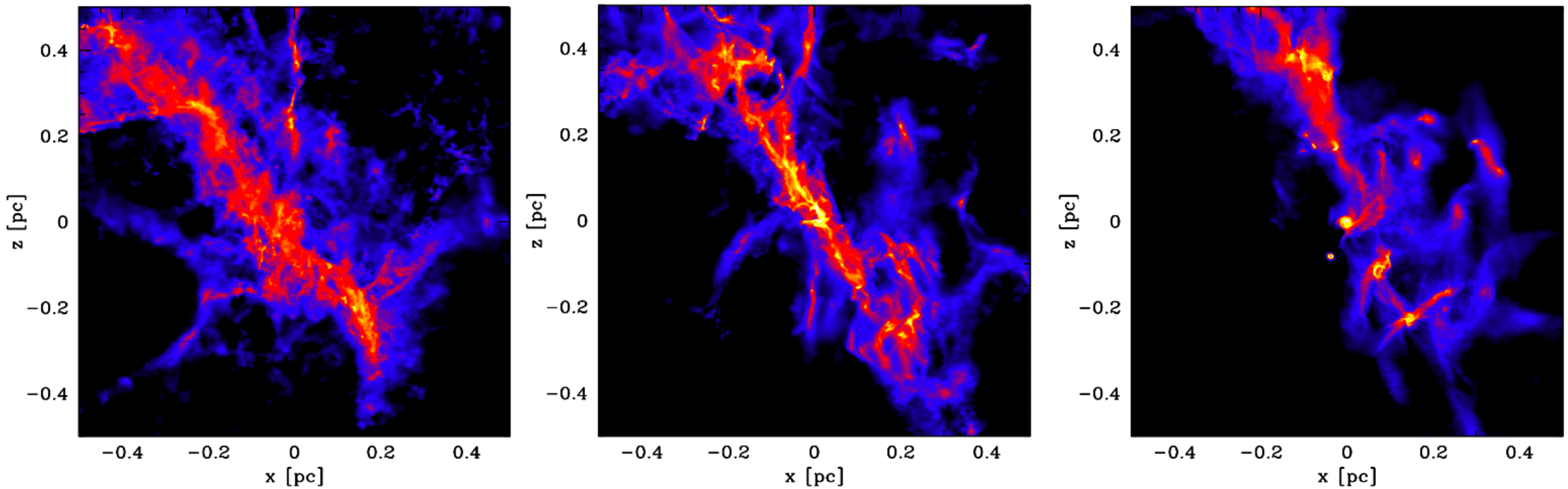
Steven Longmore & Ian Bonnell



Summary

1. Massive star forming clumps evolve from diffuse filamentary structures to more compact ones.
2. Collapse consistent with interferometry observations.
3. Most massive star and greatest total stellar mass formed in the most bound clump.
4. Collapse continuously channels material to the cluster centre where it can be accreted.
5. Original core of massive star only intermediate mass.
6. Most of the mass for the massive star came from the diffuse clump gas between the cores.

Motivation

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Massive Star Forming Clusters

Massive Stars almost universally formed in star clusters

(Lada & Lada 2003)

Physical processes that form clusters linked to MSF

- dynamic chaotic environment
- levels of structure
- often global collapse

Q. When is the mass for a massive star gathered?

- before, during or after cluster formation?

Clusters, Clumps & Cores

	Cloud	Clump	Core
Size (pc)	$2-15$	$0.3-3$	$0.03-0.2$
Mass ($M_\odot$)	10^3-10^4	$50-500$	$0.5-5$
Mean density (cm^{-3})	$50-500$	10^3-10^4	10^4-10^5
Velocity Extent (kms^{-1})	$2-5$	$0.3-3$	$0.1-0.3$
Gas Temperature (K)	~ 10	$10-20$	$8-12$

clump - enhanced density region

- will form a stellar cluster

core - smaller condensation

- potential well distinct from environment
- contains no bound substructure

Clump Observations

•Motte et. al. 2007

pre-stellar massive cores either extremely short lived or don't exist

•Beuther et. al. 2002

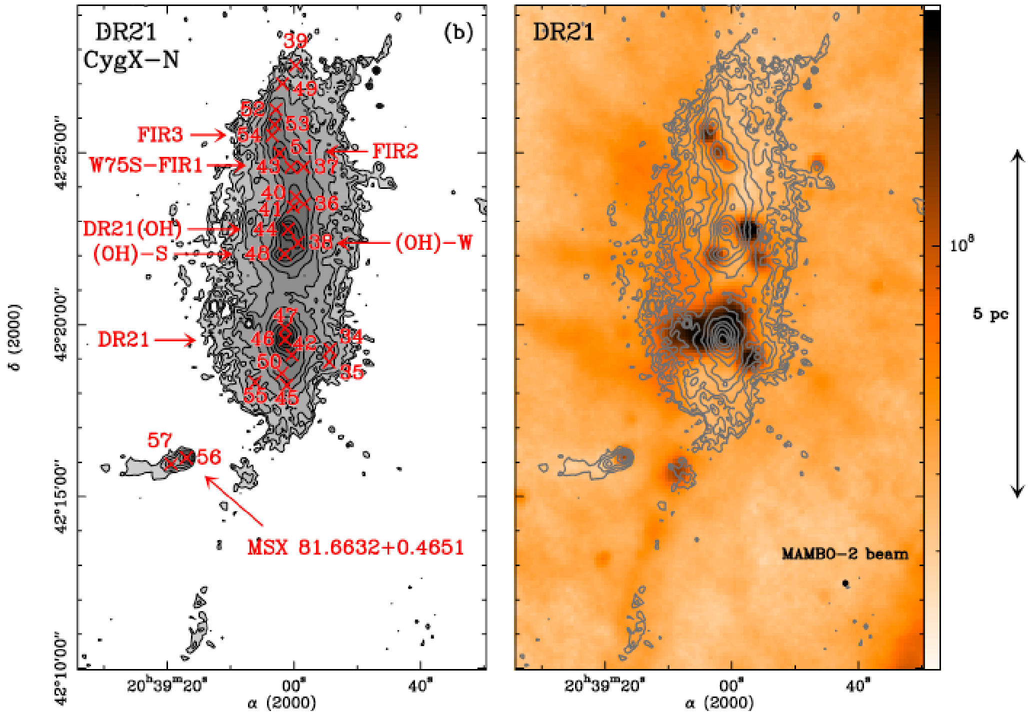
linewidths of HMPO's can be explained by dynamic collapse

•Peretto et al 2006/2007

NGC 264-C collapsing along its axis

• Furesz et. al. 2008

velocity gradients in Orion nebula suggest it is in a state of dynamic collapse



(Motte et al 2007)

Massive Star Formation

Molecular Clouds	Massive Stars
Stable, long lived MC's (~ 10 t_{cross}) Tan et. al. 2006	Massive cores supported by turbulence McKee & Tan 2003
Short lived MC's (~t_{cross}) Elmegreen 2000	Accretion Zinnecker 1982, Bonnell et. al. 2001, Keto 2007

The Simulation

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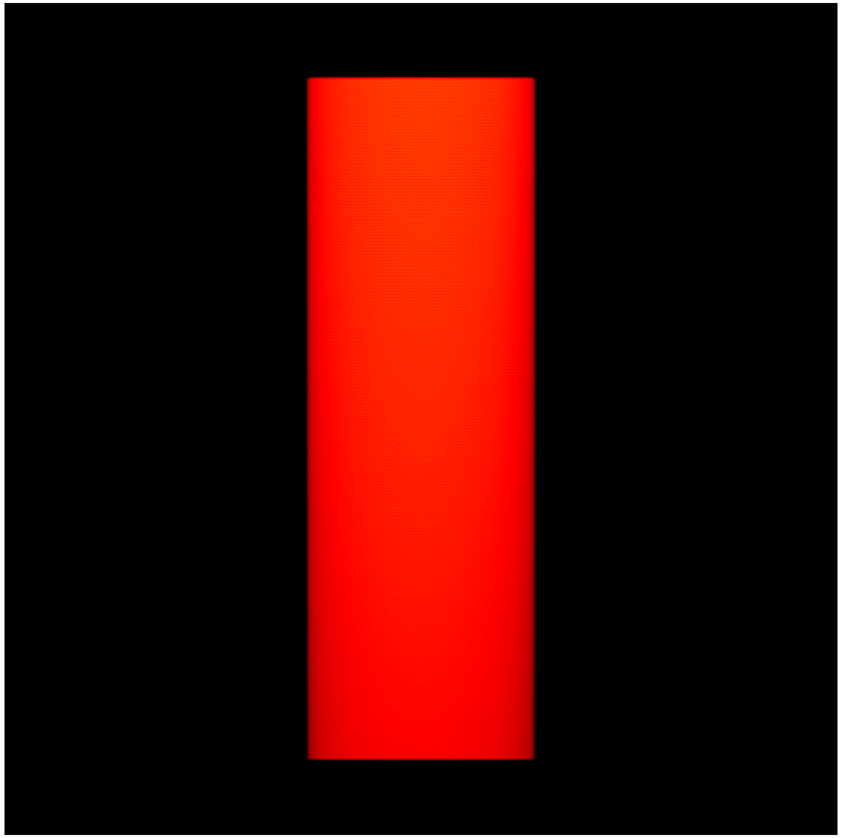
The Simulation

Loosely based on Orion A

- 10 000 M_{sol}
- Smooth Particle Hydrodynamics
- 15.5 million particles
  - particle splitting
- Barytropic equation of state
- Sink particles for star formation
- Heating from sinks
- Self gravity
- Decaying turbulence
- No magnetic fields



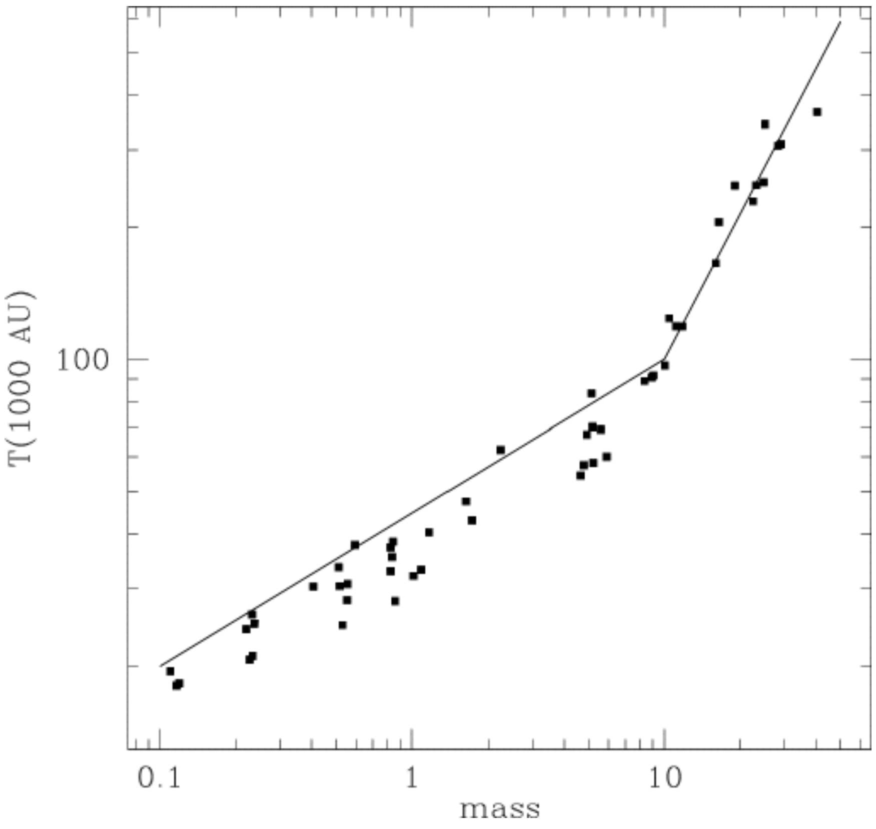
Sink Heating

Basic fit to MC models

Robitaille et. al. 2006

$$T = 100K \left(\frac{M}{10 M_o} \right)^a \left(\frac{R}{1000 AU} \right)^q$$

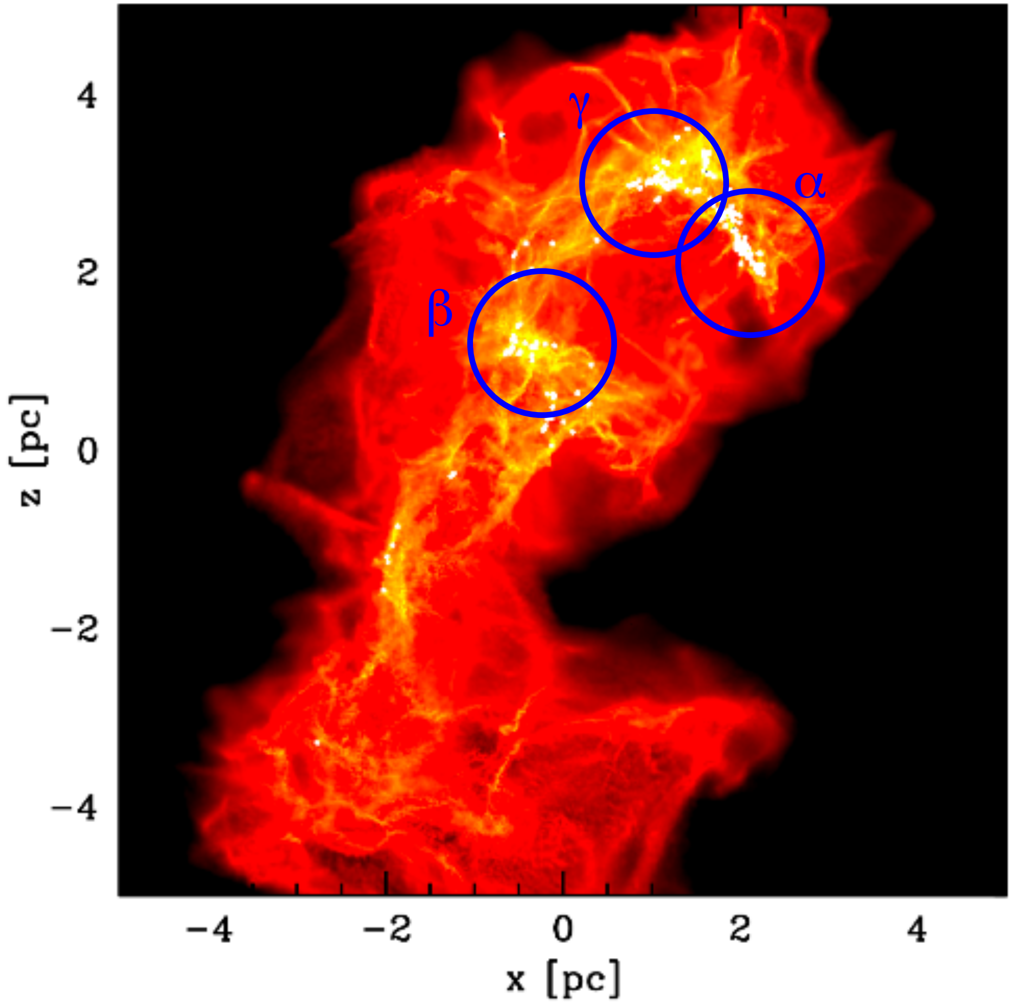
- a: 0.33 M < 10
- a: 1.1 M > 10
- q: -0.4 to -0.5



Overestimates feedback

- Spherical symmetric
- Isolated
- Underestimates column densities
- Ignores cluster structure, discs etc

Clump Selection



- From the global simulation three **clumps** are arbitrarily assigned.

- Each forms a star cluster.

- Consists of all the mass within 1pc of the precursor of the most massive sink.

Global Evolution of Star Forming Clumps

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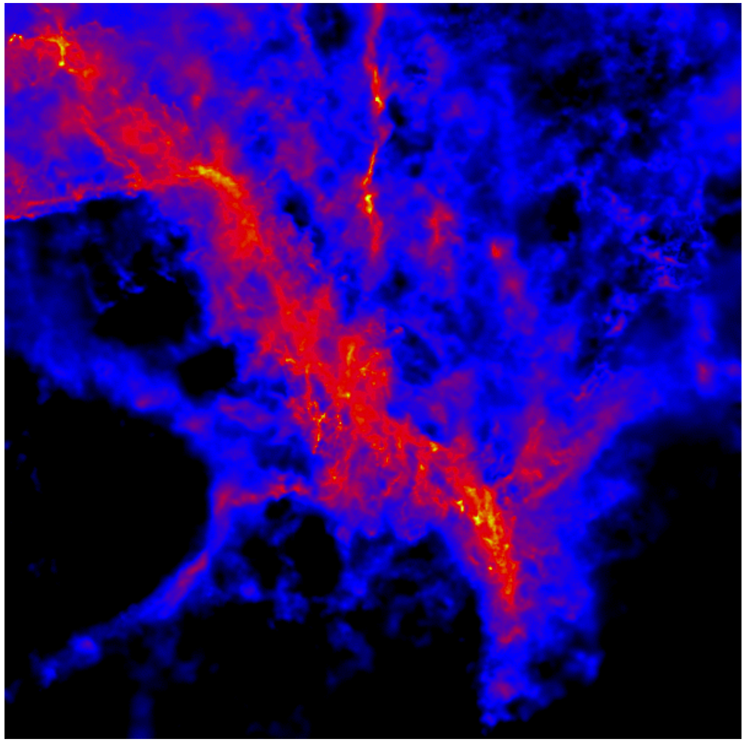
Time Evolution



Clump Alpha

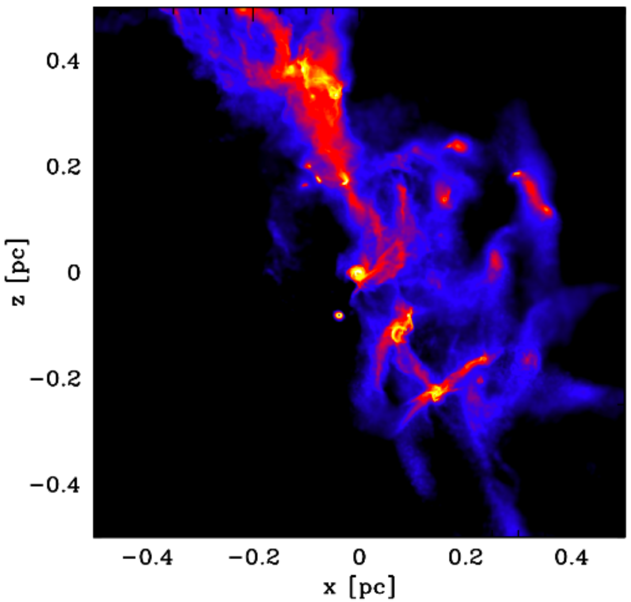
in column density

blue: 0.05 gcm^{-2} yellow: 5 gcm^{-2}

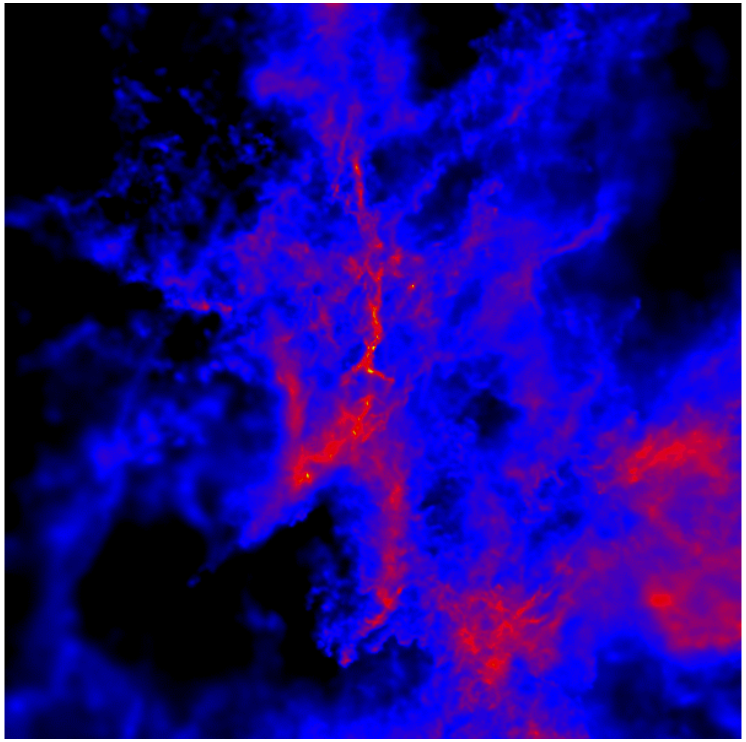
Filament collapsing along its axis

- evolves to a more compact state with less sub-structure

2.4 x 10^5 yrs



Time Evolution



Clump Beta

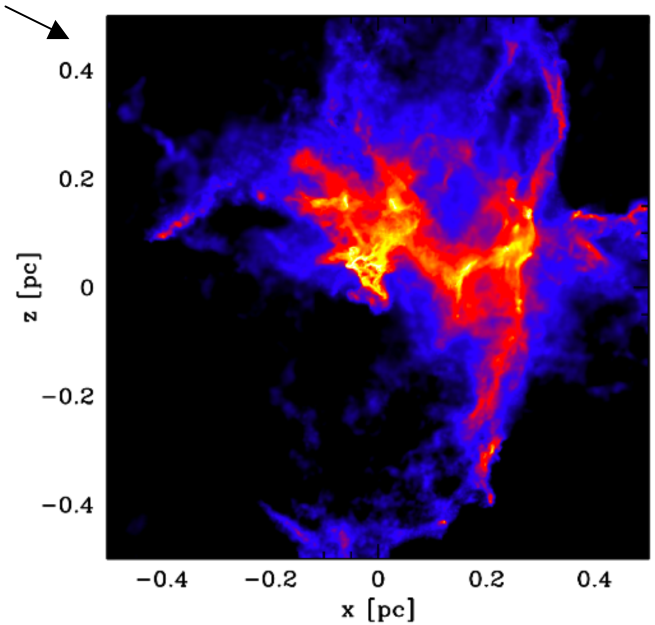
in column density

blue: 0.05 gcm^{-2} yellow: 5 gcm^{-2}

Region formed by converging shocks

- evolves to a more compact state with enhanced densities

2.4 x 10^5 yrs



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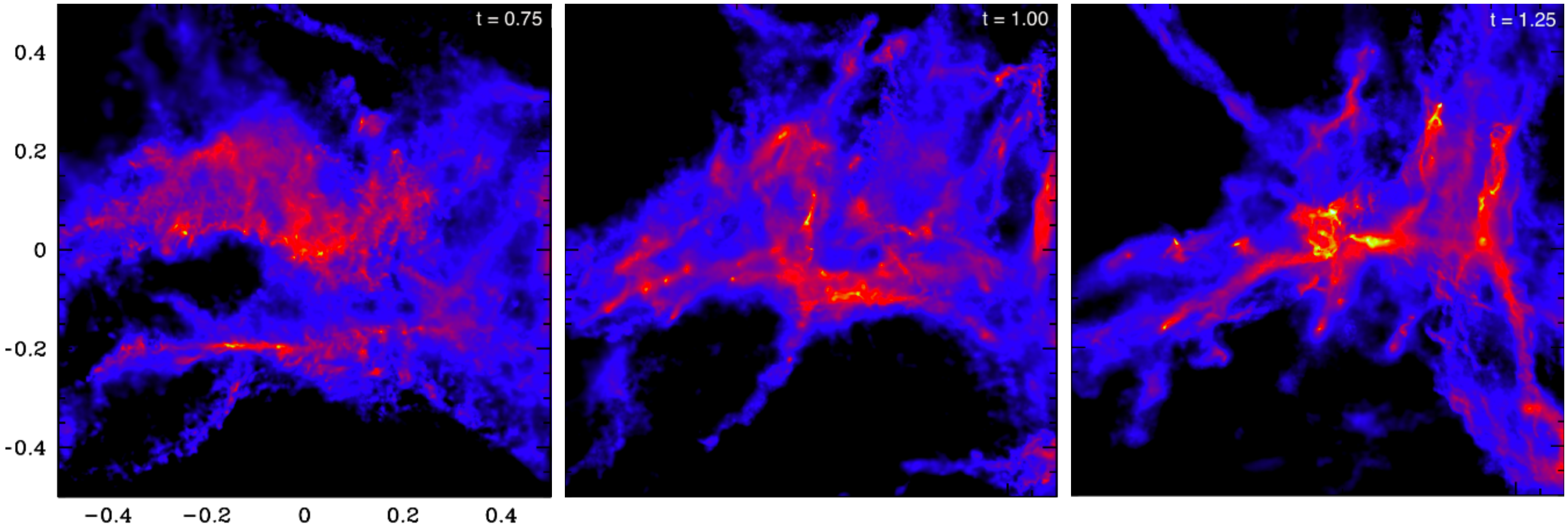


Clump Gamma

in column density

blue: 0.05 gcm^{-2} yellow: 5 gcm^{-2}

Mass Evolution

Clump	M [$M_\odot$]	M_{2D} [$M_\odot$]	$\bar{\rho_g}$ [gcm^{-3}]	max. M_s [$M_\odot$]	tot. M_s [$M_\odot$]
beginning					
Alpha	893	1528	1.1×10^{-18}	0.85	3.10
Beta	882	1516	4.0×10^{-19}	1.11	2.24
Gamma	1034	1985	7.6×10^{-19}	0.58	1.84
end					
Alpha	987	1412	8.0×10^{-18}	29.2	361.4
Beta	995	1882	8.8×10^{-18}	11.3	189.2
Gamma	1127	1993	5.0×10^{-18}	12.6	243.9

- Mass & mean density increases.
- Most massive star not found in most massive clump.

Energy Evolution

Clump	$\bar{v_r}$ [kms^{-1}]	E_{rat}	E_{rat2}	E_p [erg]
beginning				
Alpha	-0.45	3.4	18.8	$1.26 \times 10^{+47}$
Beta	-0.62	0.8	4.6	$8.64 \times 10^{+46}$
Gamma	-0.44	1.8	11.1	$1.08 \times 10^{+47}$
end				
Alpha	-1.62	1.09	3.0	$4.78 \times 10^{+47}$
Beta	-1.16	0.57	3.0	$2.49 \times 10^{+47}$
Gamma	-0.19	1.61	4.5	$2.64 \times 10^{+47}$

- Supersonic infall (c ~ 0.2 kms^{-1})
- Most massive sink & greatest stellar mass are formed in the initially most bound clump.

Dispersion

To quantify the collapse of the clump the dispersion :

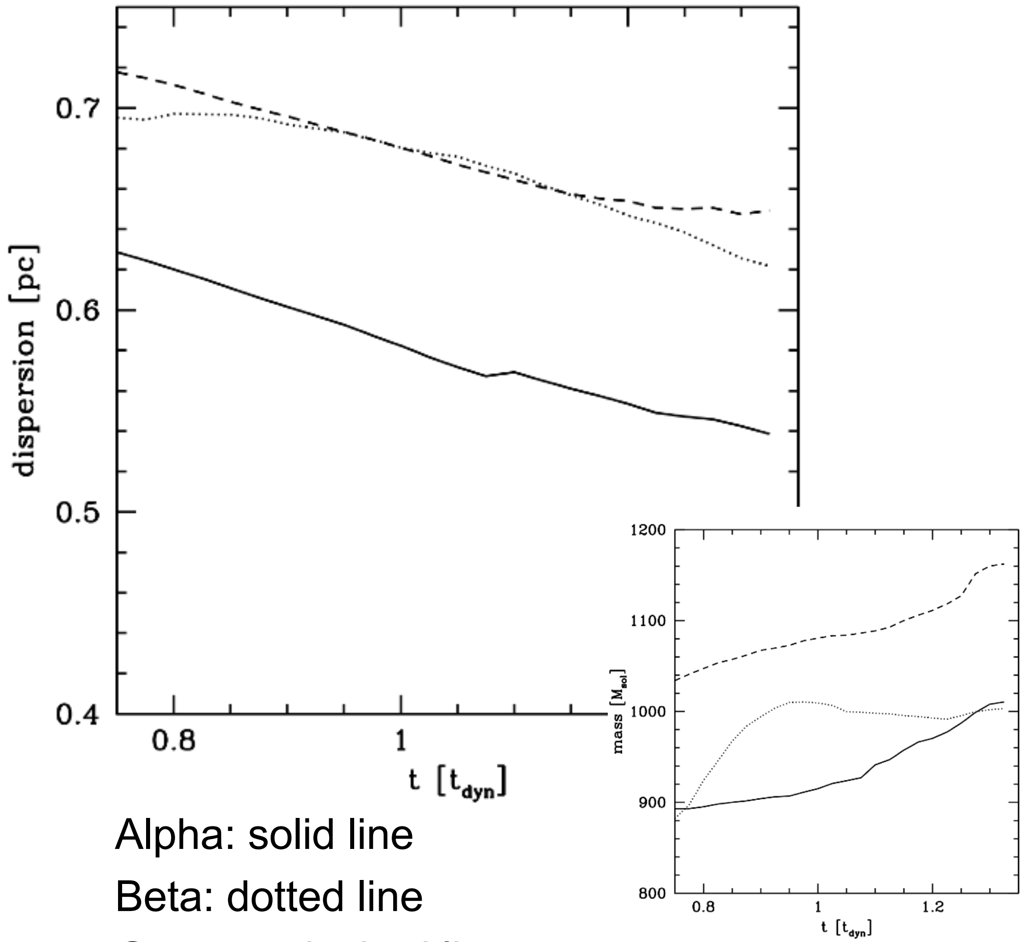
$$\sigma(r)_{3D} = \sqrt{\frac{\sum m_i (r_i - \bar{r})^2}{\sum m_i}}$$

is calculated.

Least dispersed clump

=

Most massive sink



Alpha: solid line

Beta: dotted line

Gamma: dashed line

Comparison to Observations

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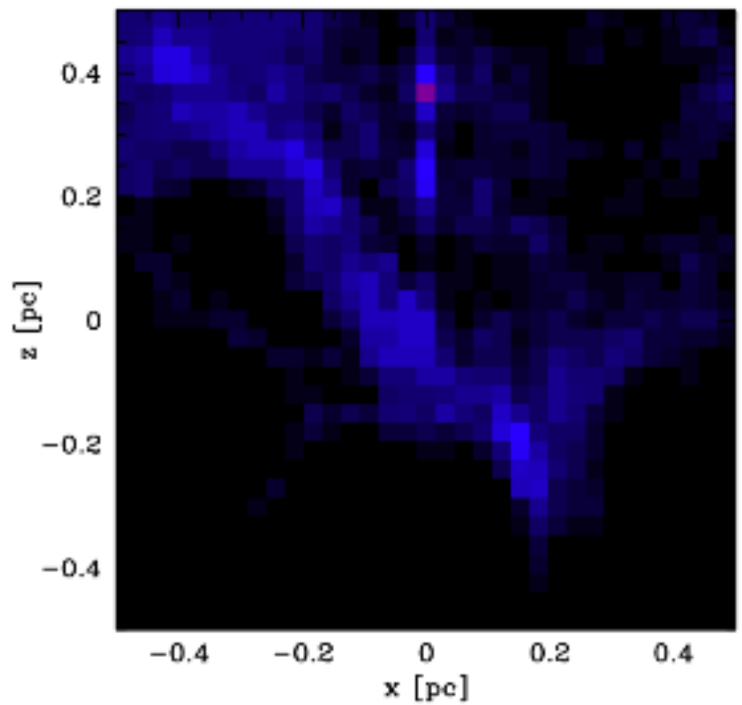
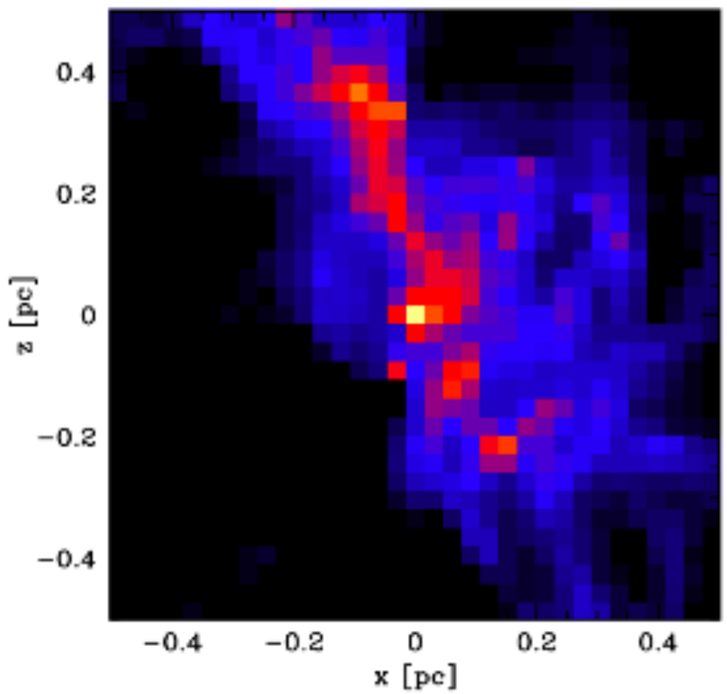
In Dust Emission

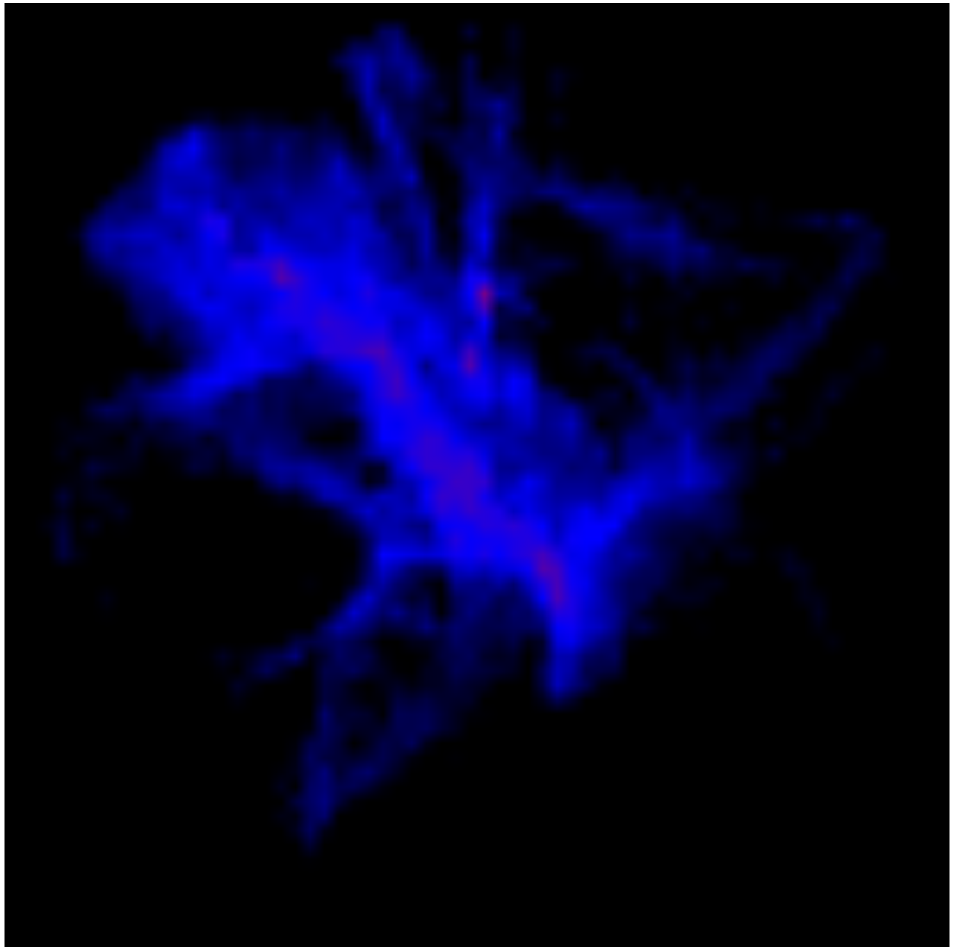
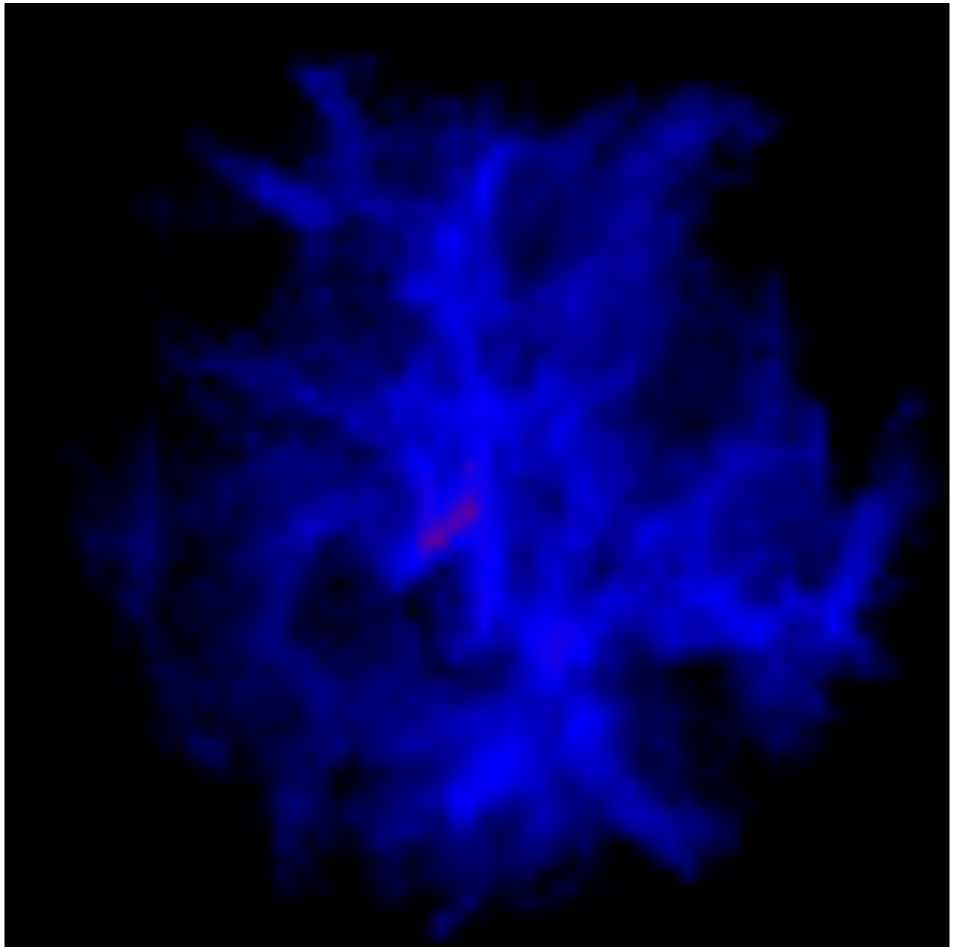




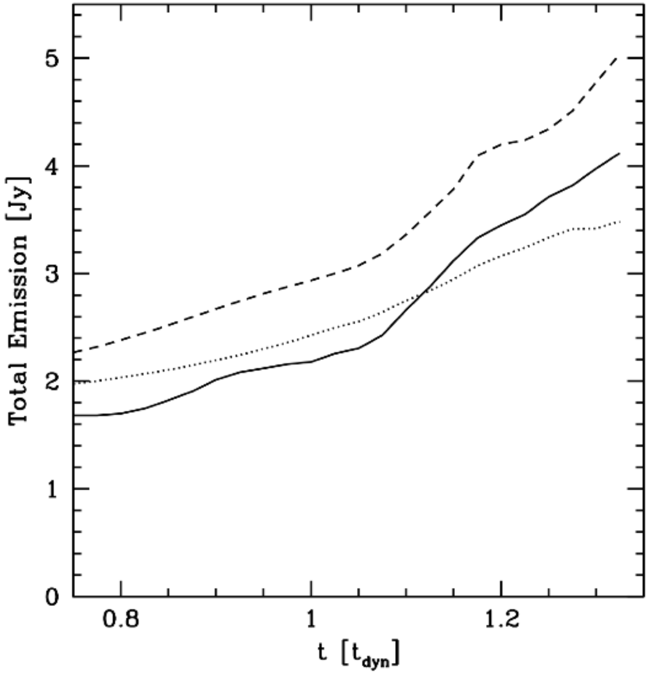
Interpolate to a grid and calculate flux using:

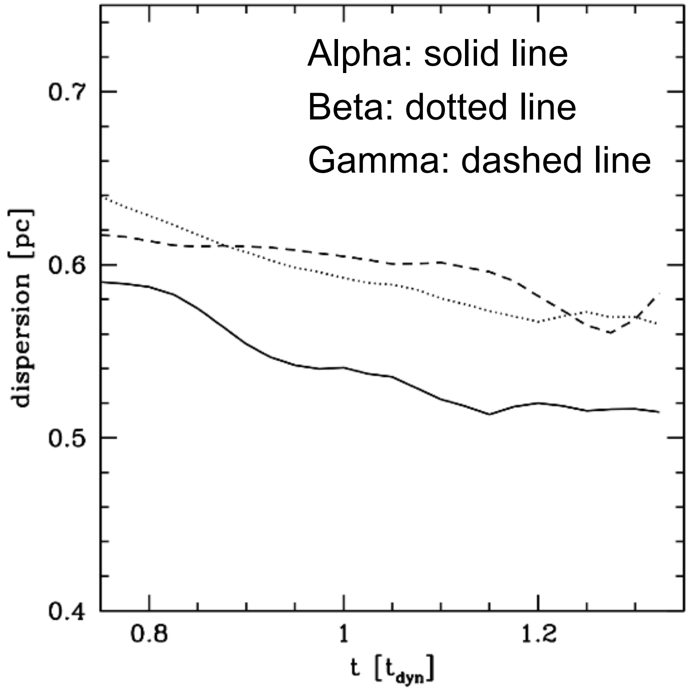
$$F(\nu) = \sum_{i=1,n} \frac{m_i g \kappa_\nu B_\nu(T_i)}{d^2}$$

Movies

Evolution

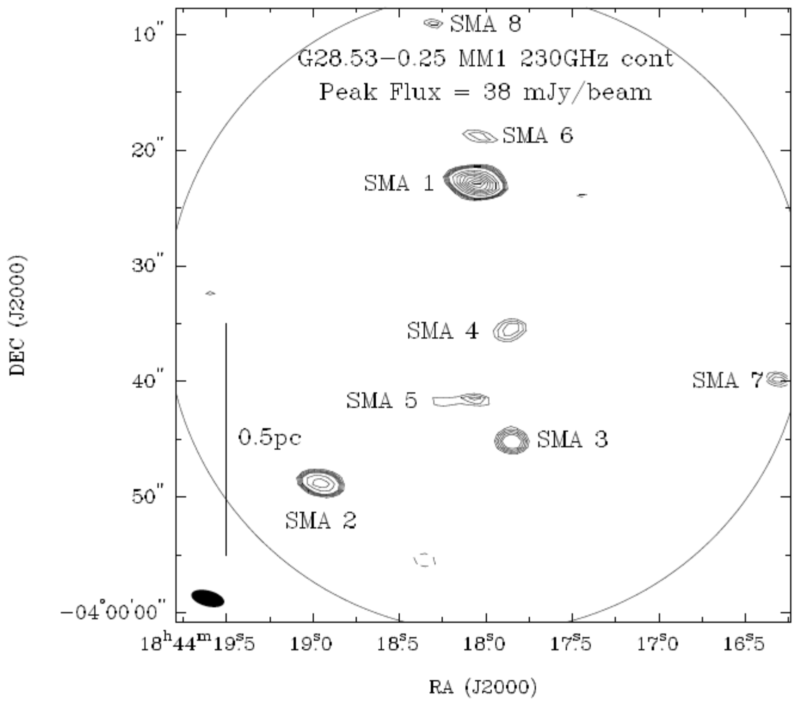




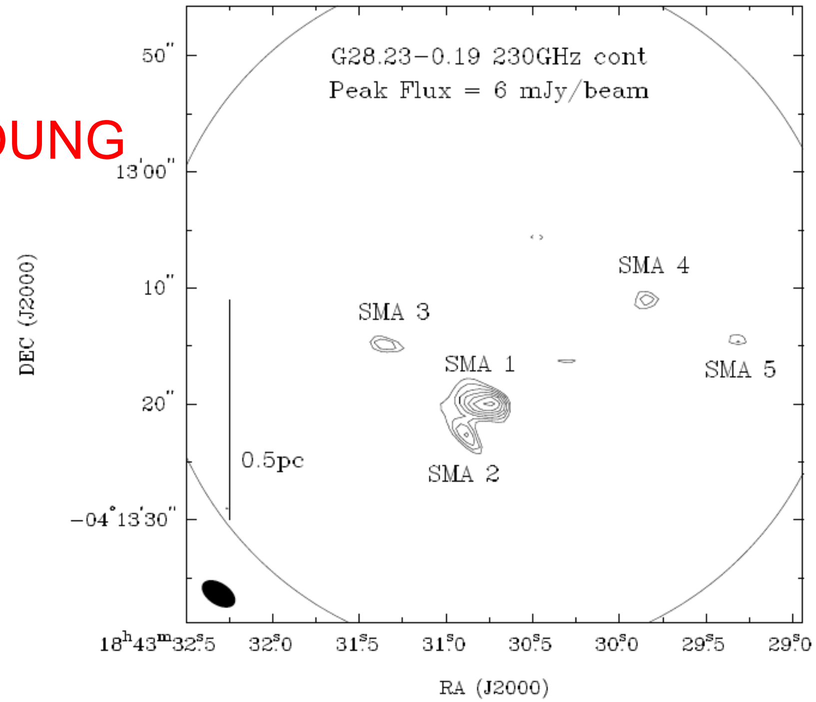
Emission increases due to increasing mass and temperature.

Dispersion decreases, but less obvious in 2D.

Interferometry Observations



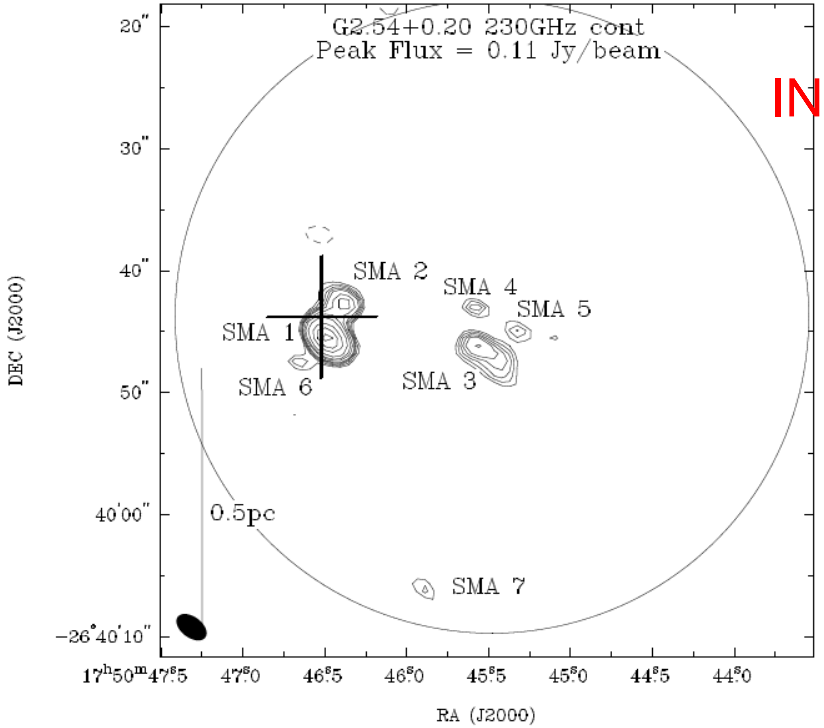
YOUNG



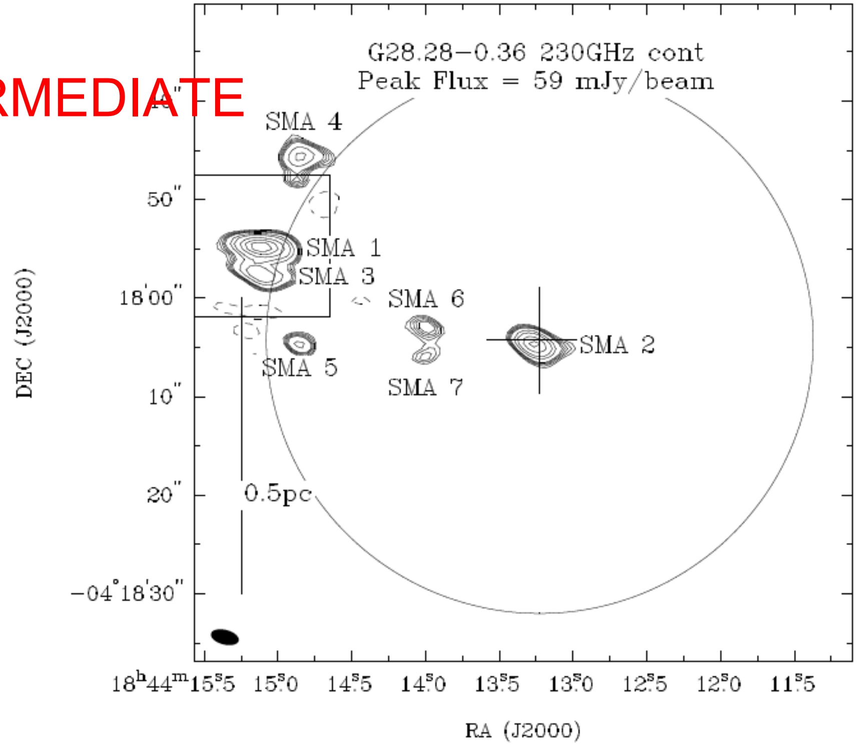
Longmore et. al. 2009 observed clumps of gas where massive stars were thought to be forming.

Used maser emission and chemical tracers to estimate their relative ages.

Interferometry Observations



INTERMEDIATE



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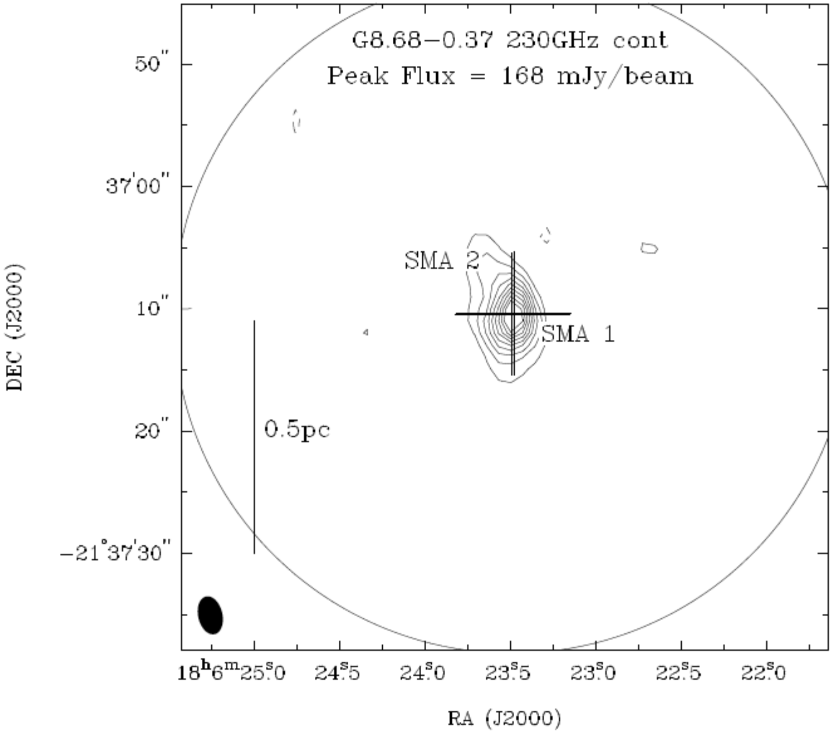
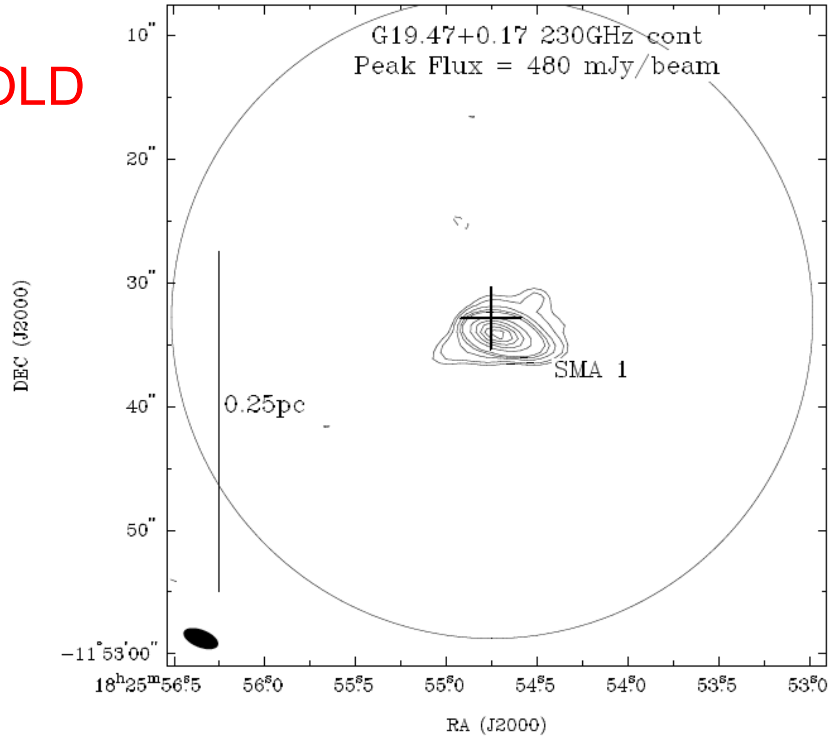
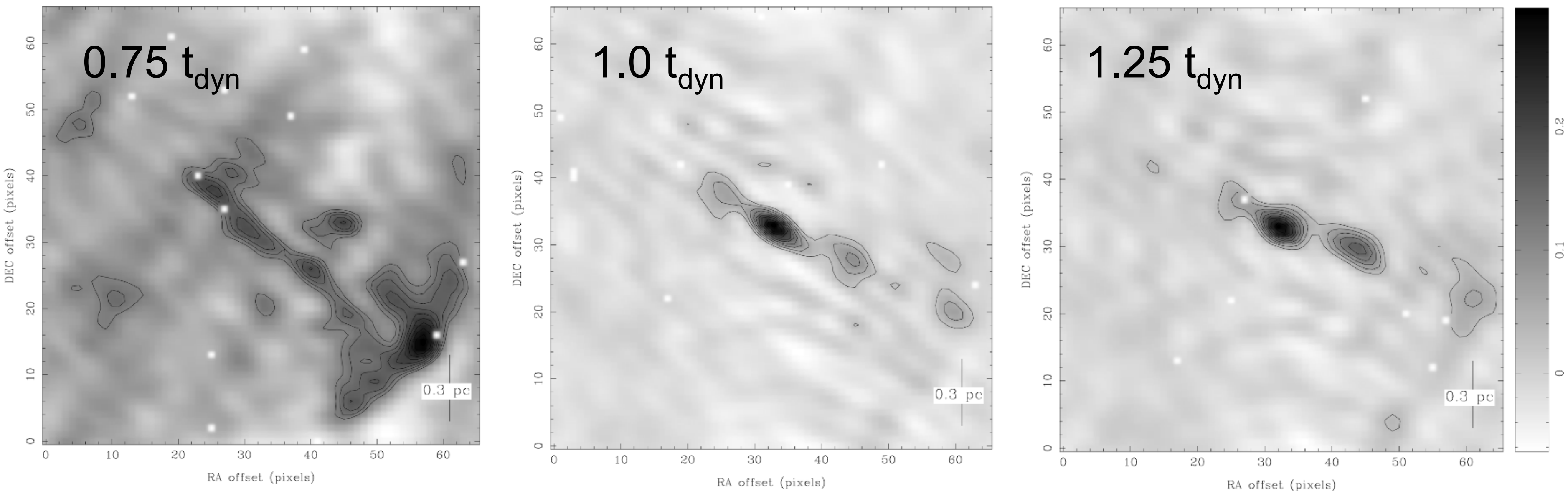


OLD



Older clumps have less sub-structure.

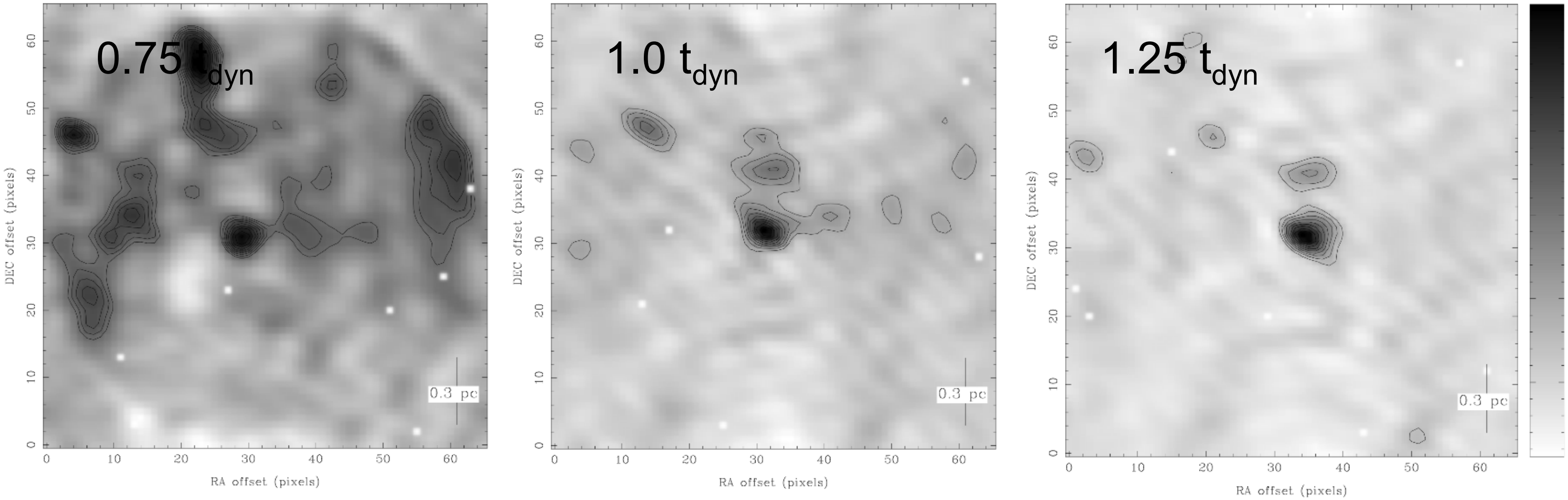
Interferrometry



Clump Alpha

Synthetic flux image sampled with the same uv-coverage as the previous observations.

Interferometry



•Large scale emission filtered out.

•At early times: low density contrast between centre and outer regions, see significant substructure.

•At later times: higher density contrast and emission from forming massive stars, dominated by a few sources.

Collapse and Accretion

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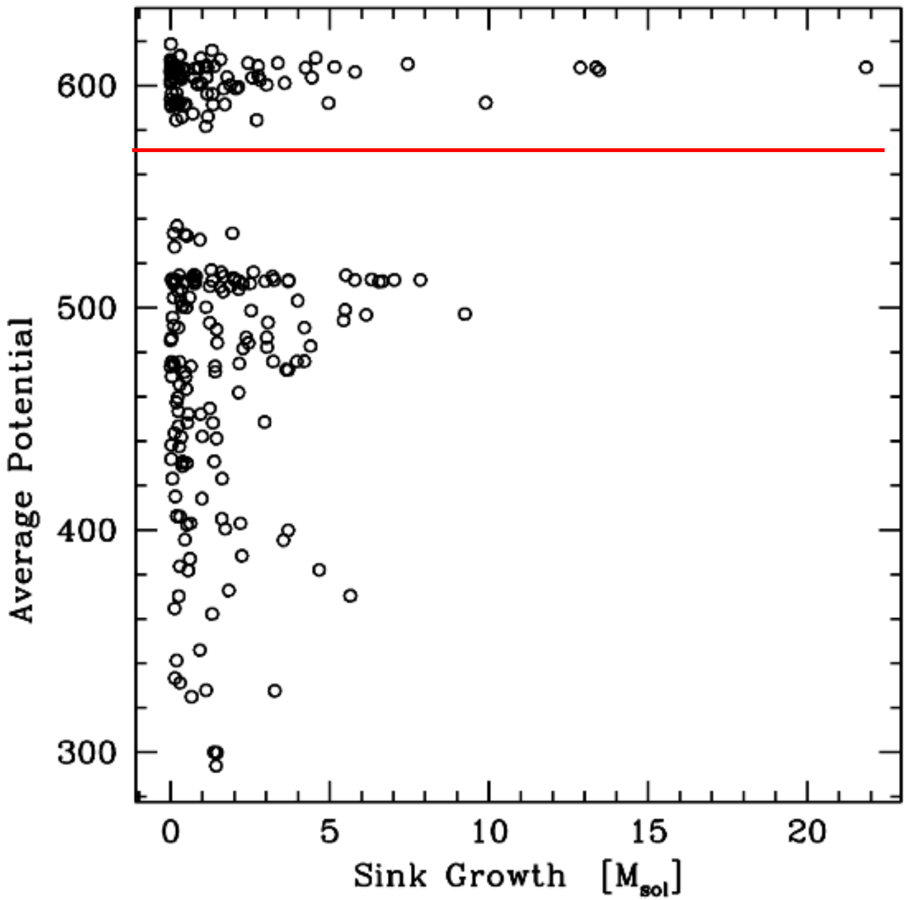
Sink Growth

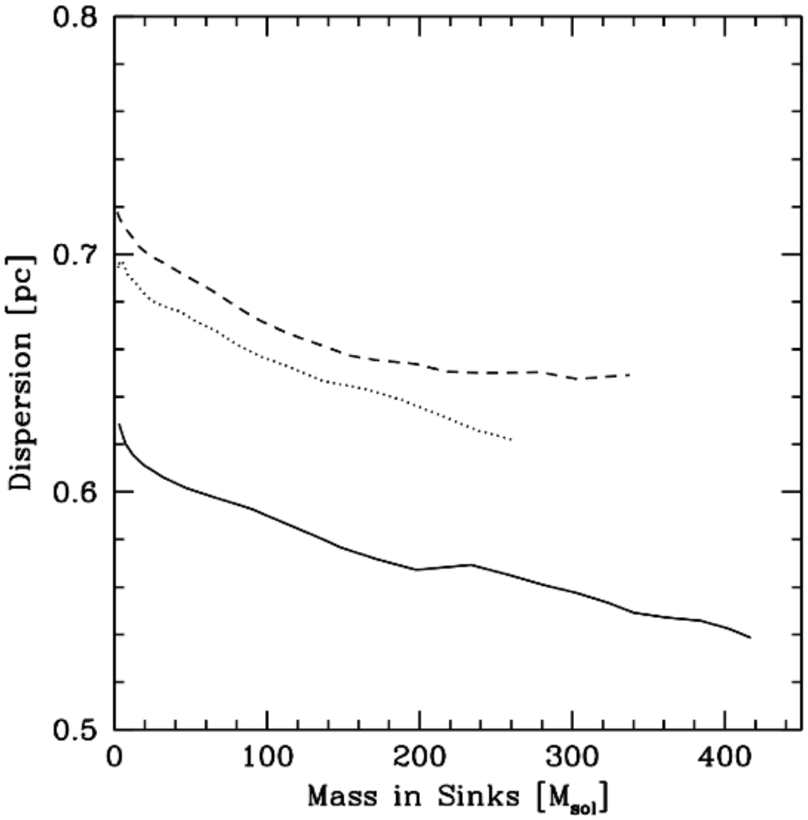
Clump Alpha



Average potential of the matter within 1 pc of each individual sink.

- Greatest growth by sinks in the deepest potential.
- however most sinks still remain at low masses.

Sink Growth



Mass in sinks is increasing as the clump contracts.

In Competitive Accretion the tidal radius should be used instead of the Bondi-Hoyle radius.

$$R_{acc} = C_{tidal}\left(\frac{M_*}{M_{enc}}\right)^{1/3} r_* \qquad \dot{M}_* \approx \pi\rho v_{rel} R_{acc}^2$$

Both the potential of the cluster and that of the proto-star gather mass for accretion.

Clump-Core Interaction

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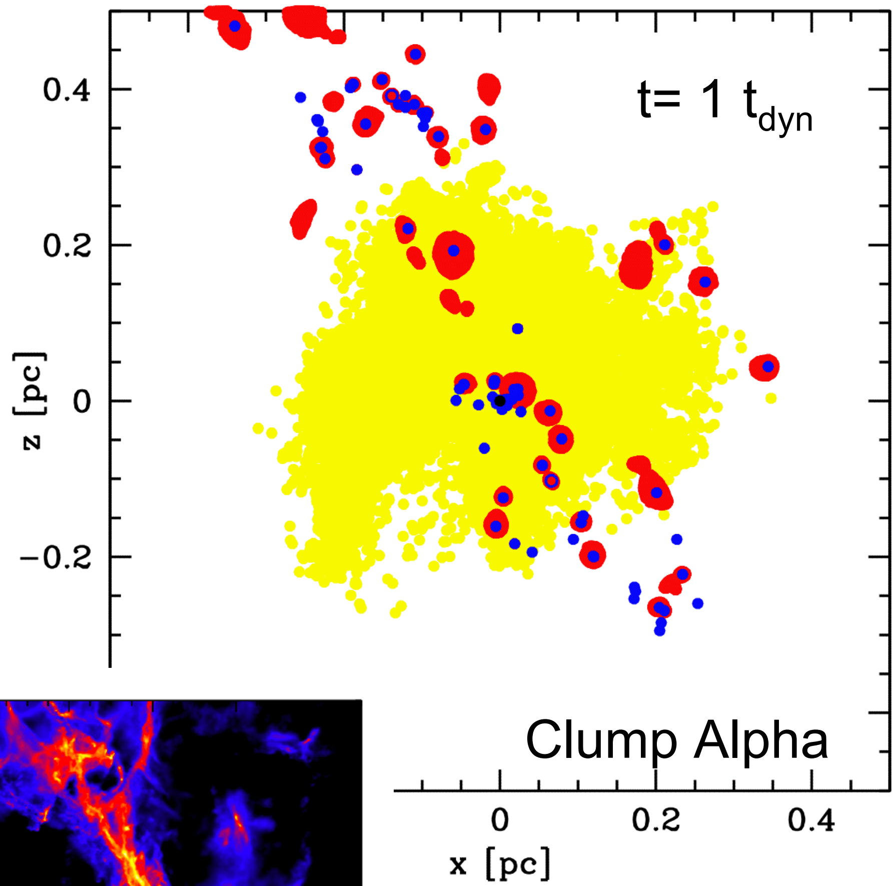
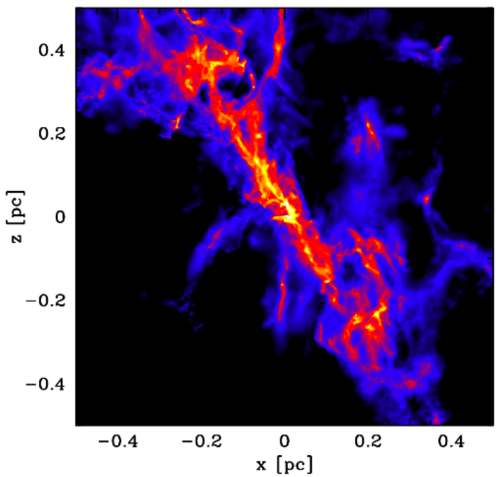
Fate





Red = p-cores

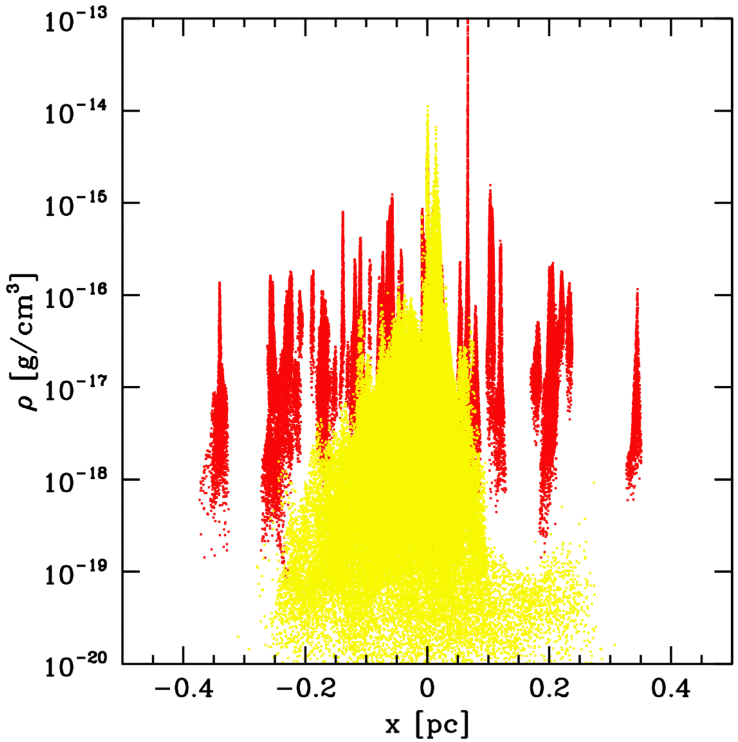
Solid blue = sinks

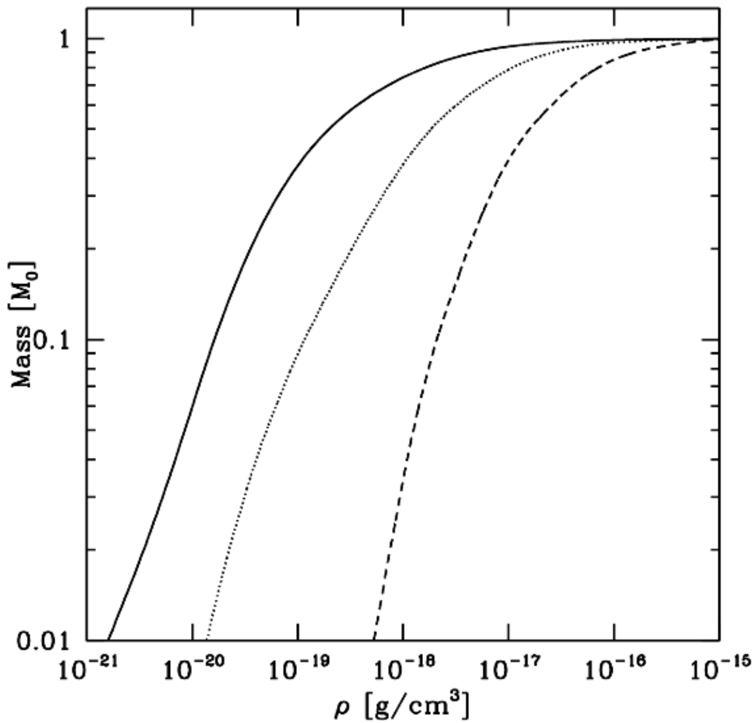
Hollow blue= pre-stellar

Yellow = mass which will be accreted by the most massive sink within 0.25 t_{dyn}

Surrounding p-cores unaffected by the accretion process.

Density & Accretion





Accreted gas has a lower density and hence a longer free fall time.

- needs a long free fall time to reach the central sink.

Massive Star Progenitor

The bound pre-stellar core which evolves into the most massive star, has a mass of only 0.67 M_{sol}

At the end of the simulation it has a mass of 29.2 M_{sol}

Mass which formed the massive star comes from the larger clump rather than a single well defined core.

Conclusions

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Conclusions

1. Massive star forming clumps evolve from diffuse filamentary structures to more compact ones.
2. Collapse consistent with interferometry observations.
3. Most massive star and greatest total stellar mass formed in the most bound clump.
4. Collapse continuously channels material to the cluster centre where it can be accreted.
5. Original core of massive star only intermediate mass.
6. Most of the mass for the massive star came from the diffuse clump gas between the cores.

Overview

1. Massive Star Forming Clusters
2. The Simulation
3. Global Evolution of Star Forming Clump
4. Comparison to Observations
5. Collapse & Accretion
6. Clump-Core Interaction
7. Conclusions