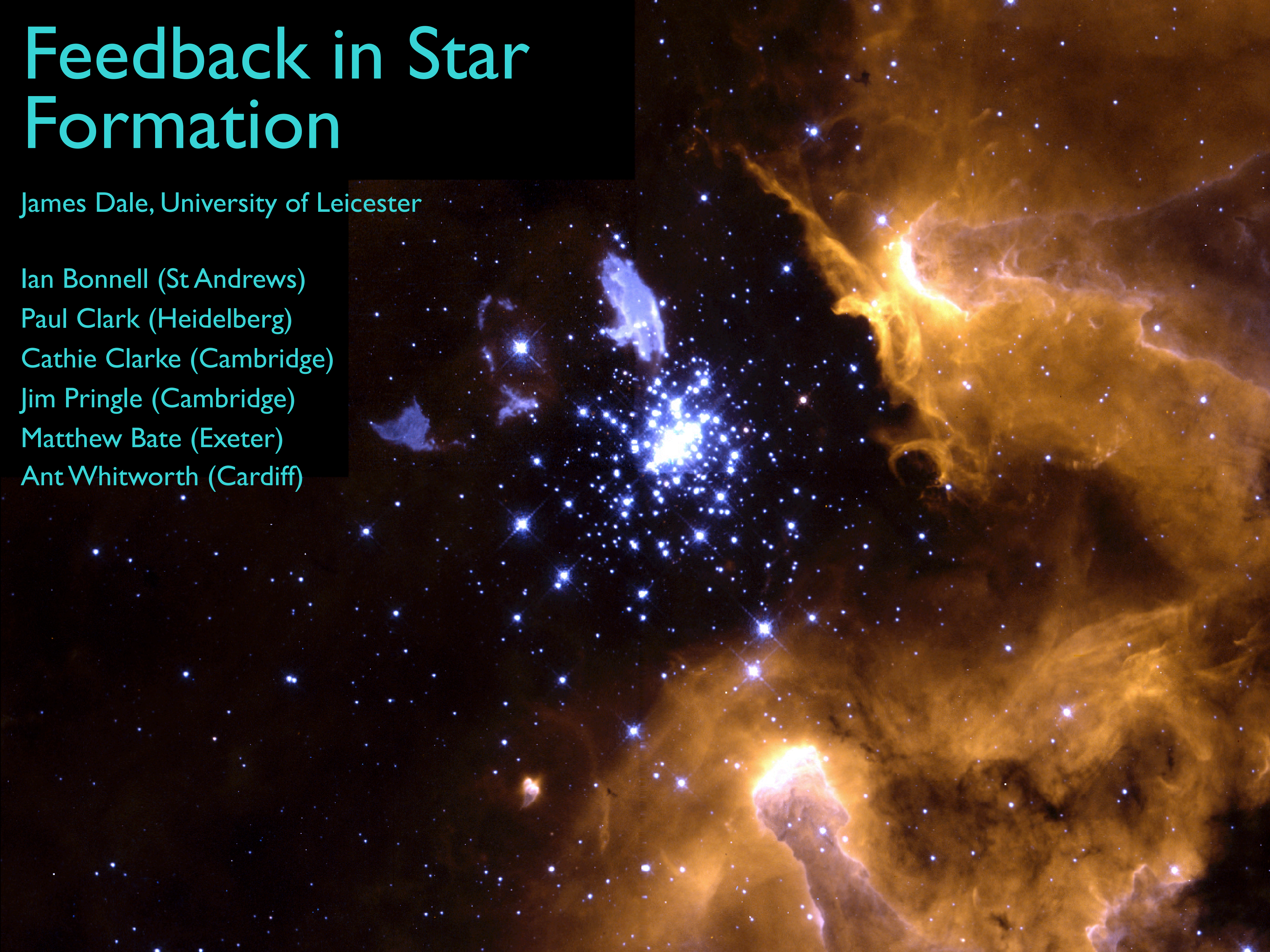
Feedback in Star Formation

James Dale, University of Leicester

Ian Bonnell (St Andrews)
Paul Clark (Heidelberg)
Cathie Clarke (Cambridge)
Jim Pringle (Cambridge)
Matthew Bate (Exeter)
Ant Whitworth (Cardiff)



Outline:

I will present 3-D SPH simulations of star cluster formation including the effects of radiative feedback from massive stars.

I will examine the effects of feedback on cluster dynamics, particularly with regard to disrupting clusters.

I will show two different simulations where I investigate the potential of feedback to induce or accelerate star formation.

Why do we need to understand feedback?

- ★ Birthrate of embedded clusters ~10x the birthrate of open clusters (Lada & Lada, 2003)
- ★ The Milky Way is forming stars at only a few percent of the rate implied by freefall collapse of its population of molecular clouds (Zuckerman & Evans, 1974)

⇒ something destroys most clusters at a young age
⇒ star formation is very slow...

...or star formation is very inefficient (Elmegreen, 2000)

Feedback could potentially solve both problems:

- Rapid expulsion of >50% of a cluster's mass can lead to the cluster's disruption (Hills, 1980). For feedback to do this, gas:stars mass ratio must be >1.
- Dispersal of gas would also terminate star formation before all the gas has been converted to stars.

Principal feedback mechanisms acting on the scale of clusters (~pc) are photoionisation, winds, supernovae.

We have a difficult problem on our hands:

- Complex 3-D gas dynamics
- Large numbers of stars (i.e. an N-body problem)
- Radiation and momentum input from some stars

Already have a hybrid SPH/N-body code

Have modified it to simulate (crudely!) photoionisation. In the process of doing winds (have not gotten around to doing SNe yet...)

The Strongren volume method

- determines volume of ionised gas by locating the Stromgren radius in all directions from a point source
- in gas of number density n, ion-electron recombination rate per unit volume is:

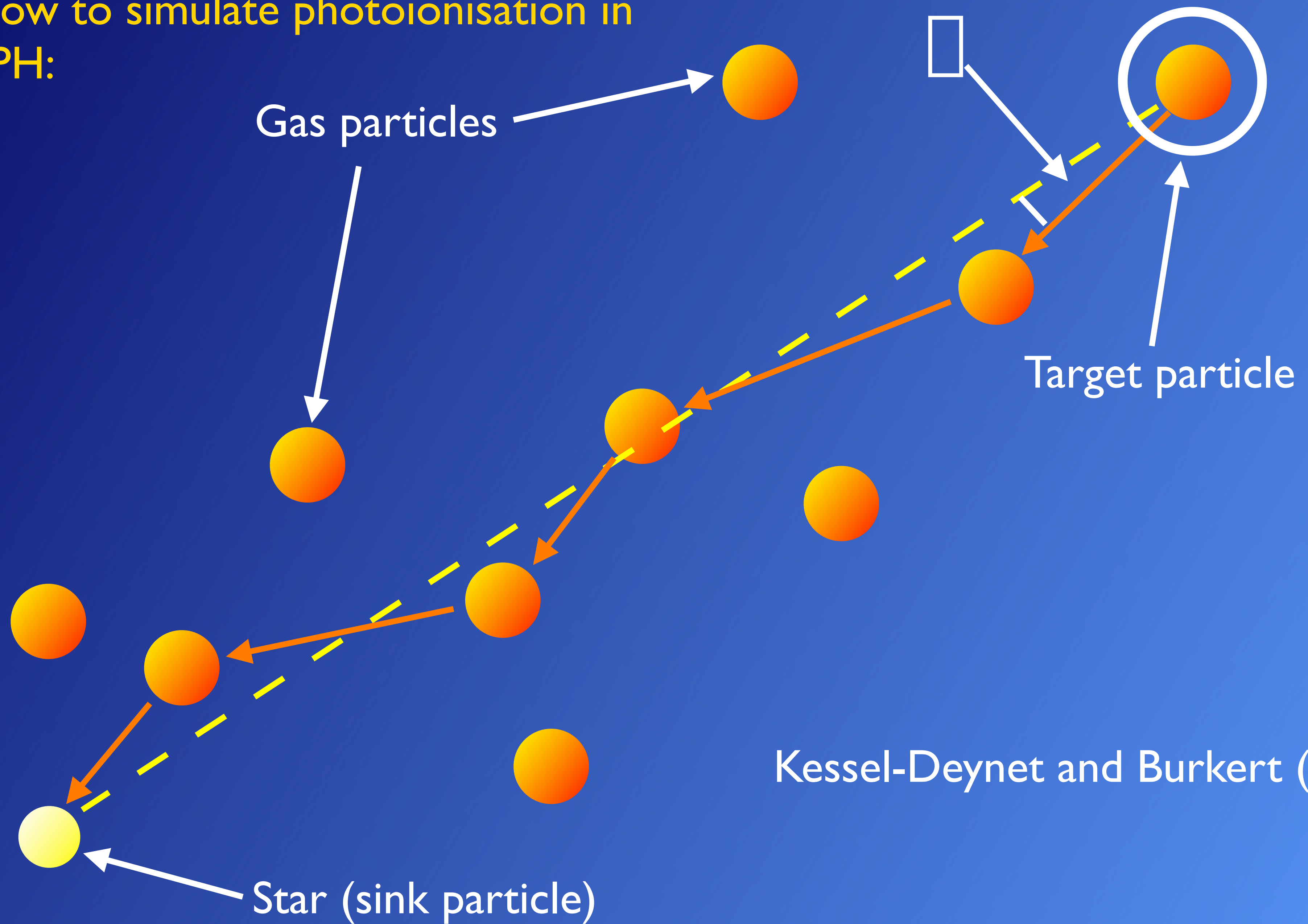
$$\alpha n^2$$

$$L* = \int_0^{R_s} 4\pi\alpha n^2 r^2 dr$$

- in non-uniform gas, if all directions are independent

$$\frac{L_*}{4\pi} = \int_0^{R_s(\theta,\phi)} \alpha n(r,\theta,\phi)^2 r^2 dr$$

How to simulate photoionisation in SPH:



Kessel-Deynet and Burkert (2000)

I have conducted a simulation of the effect of photoionisation on a protocluster.

Initial Conditions:

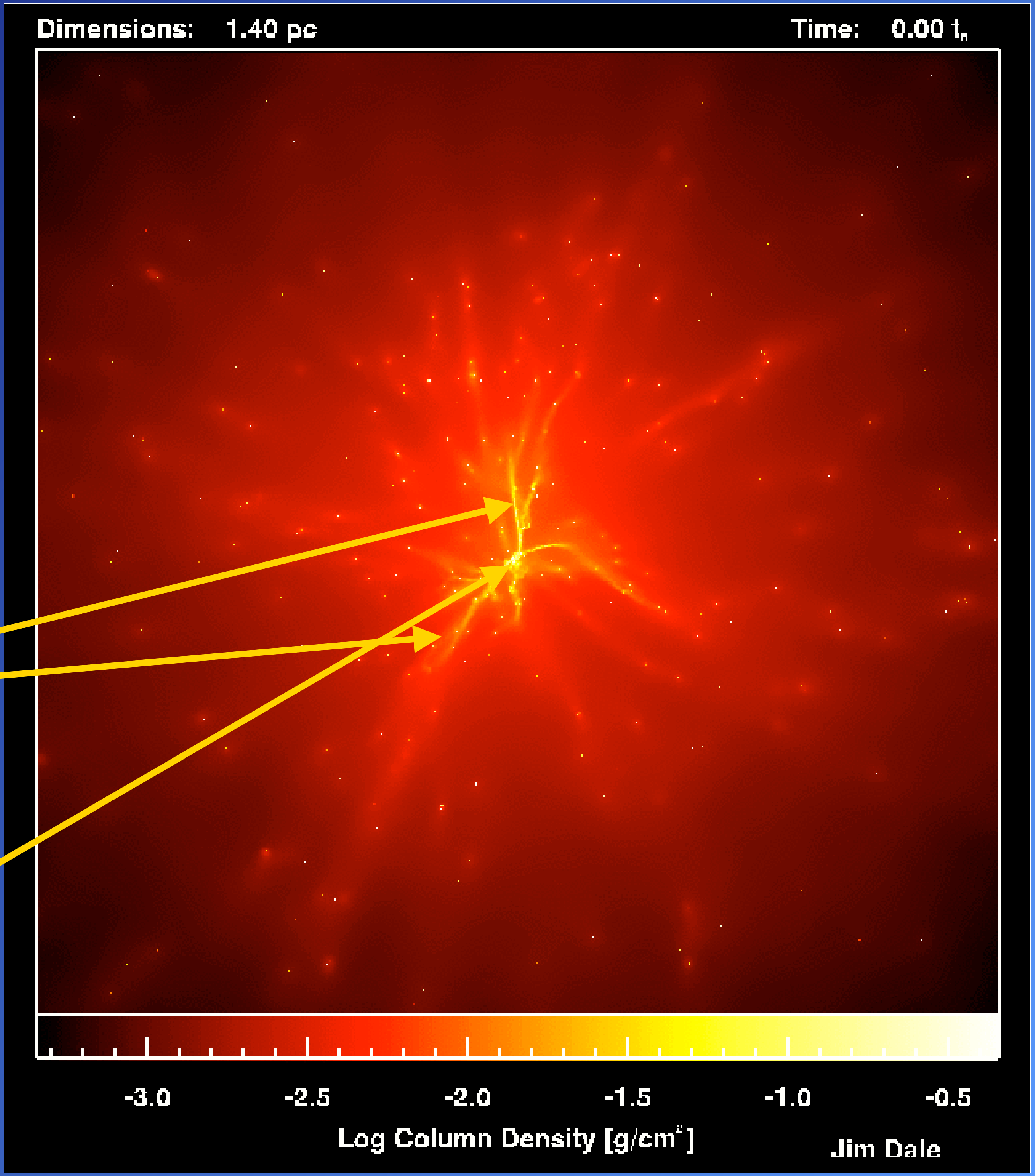
- Mass: ~750$M_\odot$, ~525$M_\odot$ gas, ~225$M_\odot$ stars - gas:stars mass ratio ≈2.5:1
- Radius: ~1.4pc
- Gas density: ~10^9 cm^{-3} (peak, in the core), ~10^4 cm^{-3} (mean)
- Initially bound - KE:|PE|<0.5

What does the cluster look like?

Complex filamentary structure

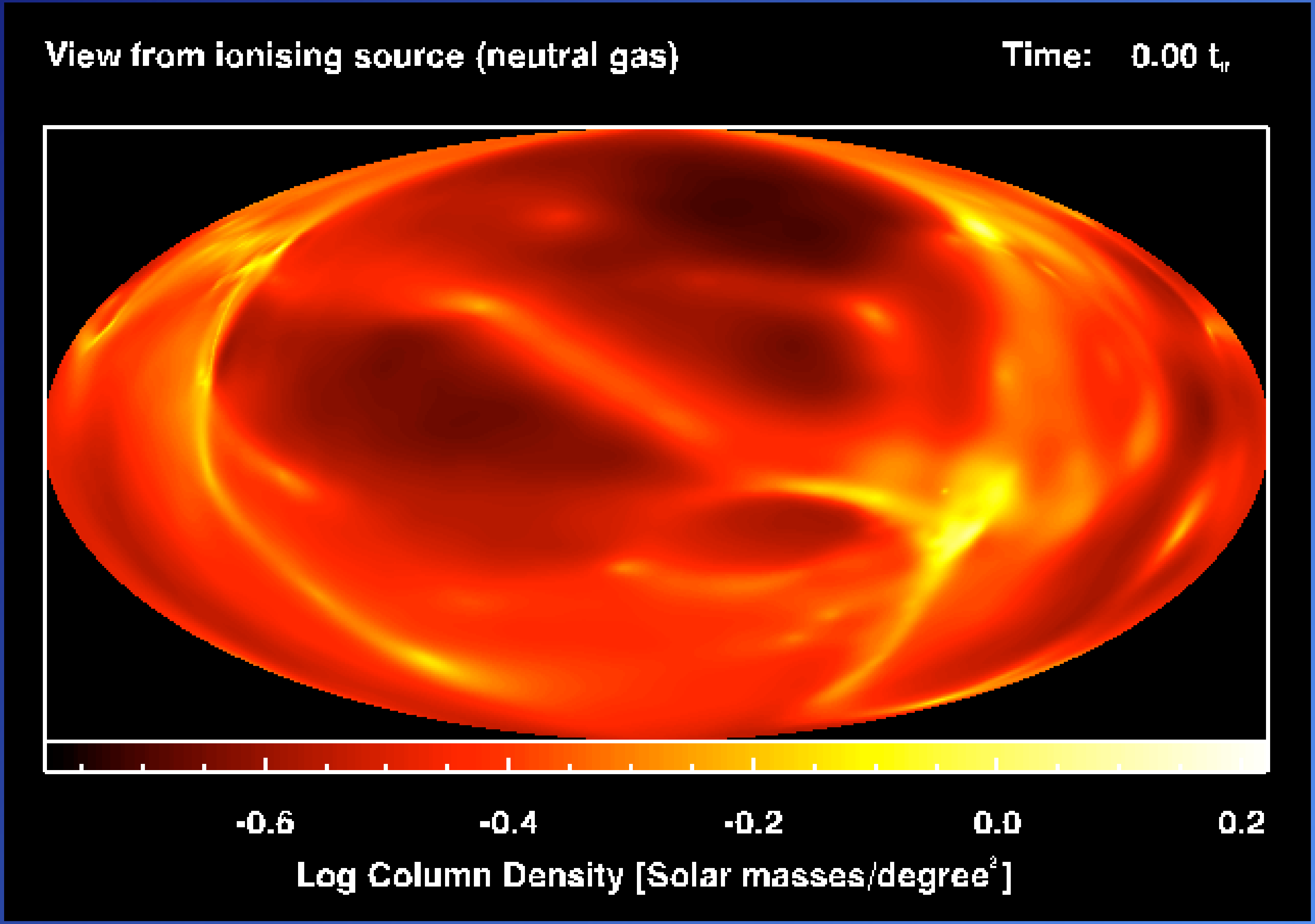
Strong accretion flows

O-star (~30$M_\odot$)



Cluster highly anisotropic...

A (θ,φ) column-density map as seen by the O-star:



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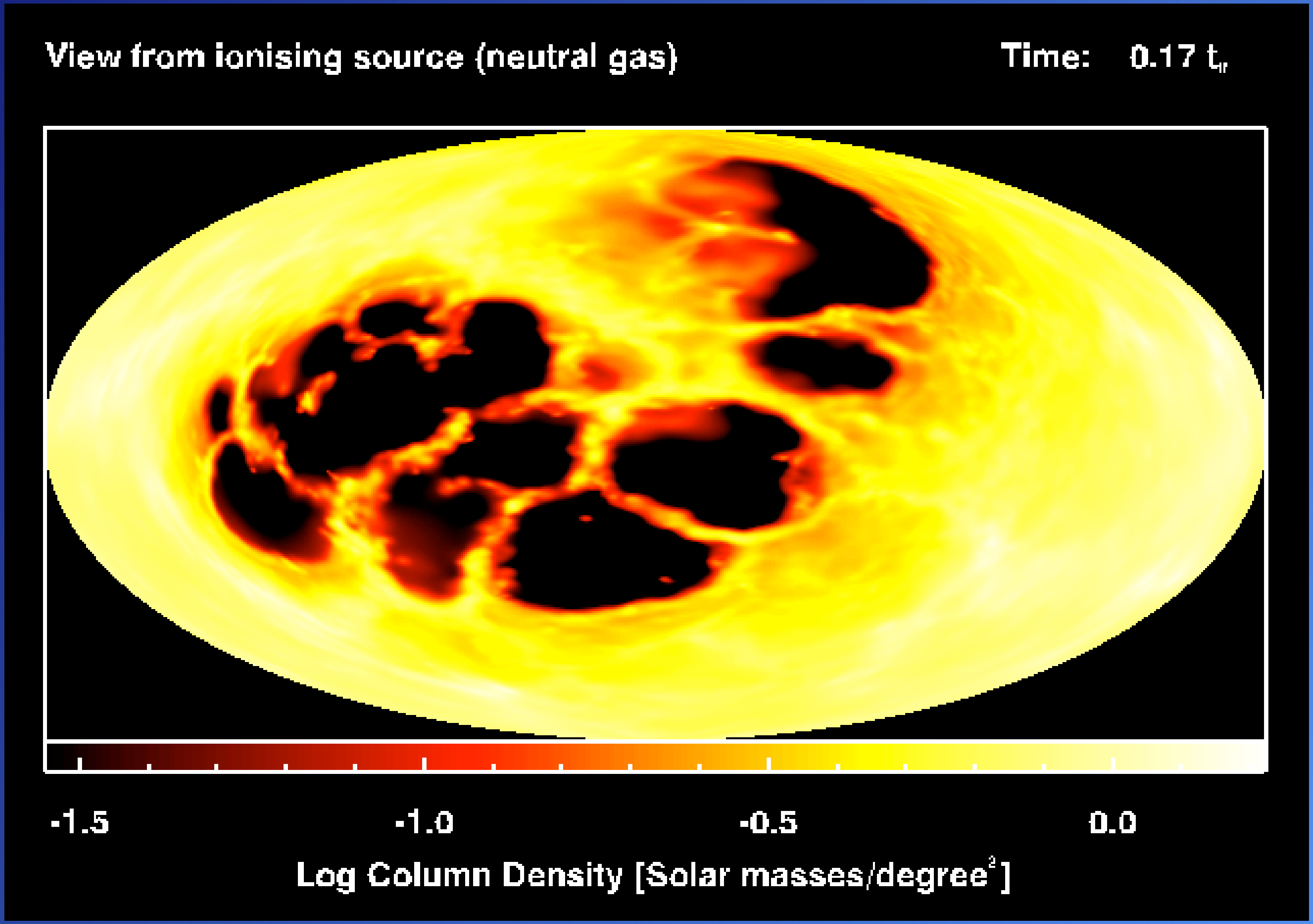
The HII region:

- Flickering
- Multi-lobed structure

Why does the HII region flicker?

- Accretion of neutral gas into the core region still vigorous and unsteady
- Sometimes, sufficient gas arrives in the core to swamp the radiation source
- Ionised gas cut off from its photon supply, and recombines
- Gas in core accreted - optical depth drops
- Ionisation begins afresh

Multi-lobed outflow/HII region structure:
A second (θ,φ) column-density map:



Artwork courtesy Ian Bonnell

What about long-term dynamical effects?

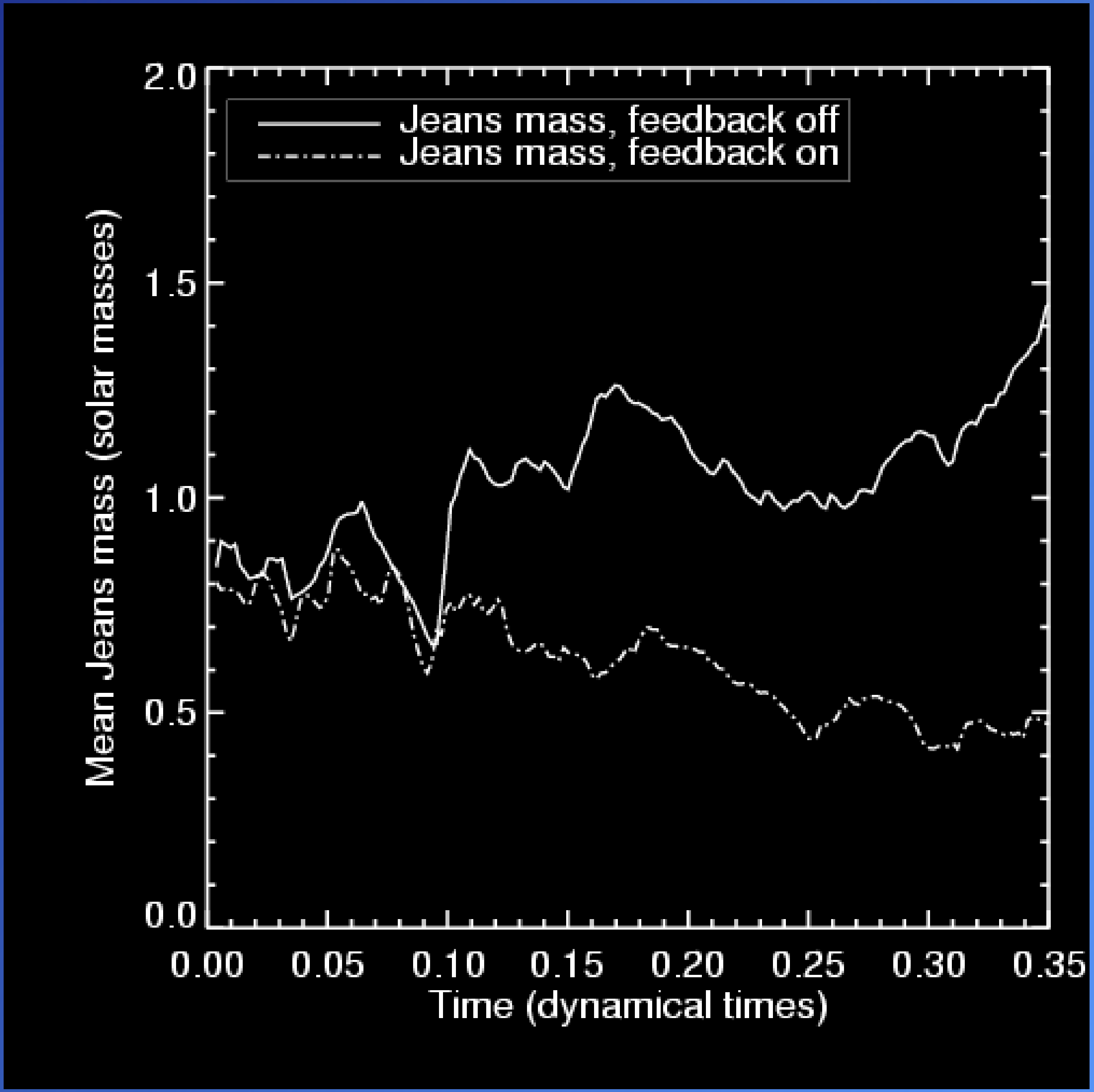
Simulation repeated for longer integration time at lower resolution on a *SUN* workstation. We seek the answers to two questions:

- What effect does the fragmentation of the cloud have on star-formation?
- Do the outflows expel enough mass on a short enough timescale to unbind the cluster?

Star formation - the mean Jeans mass:

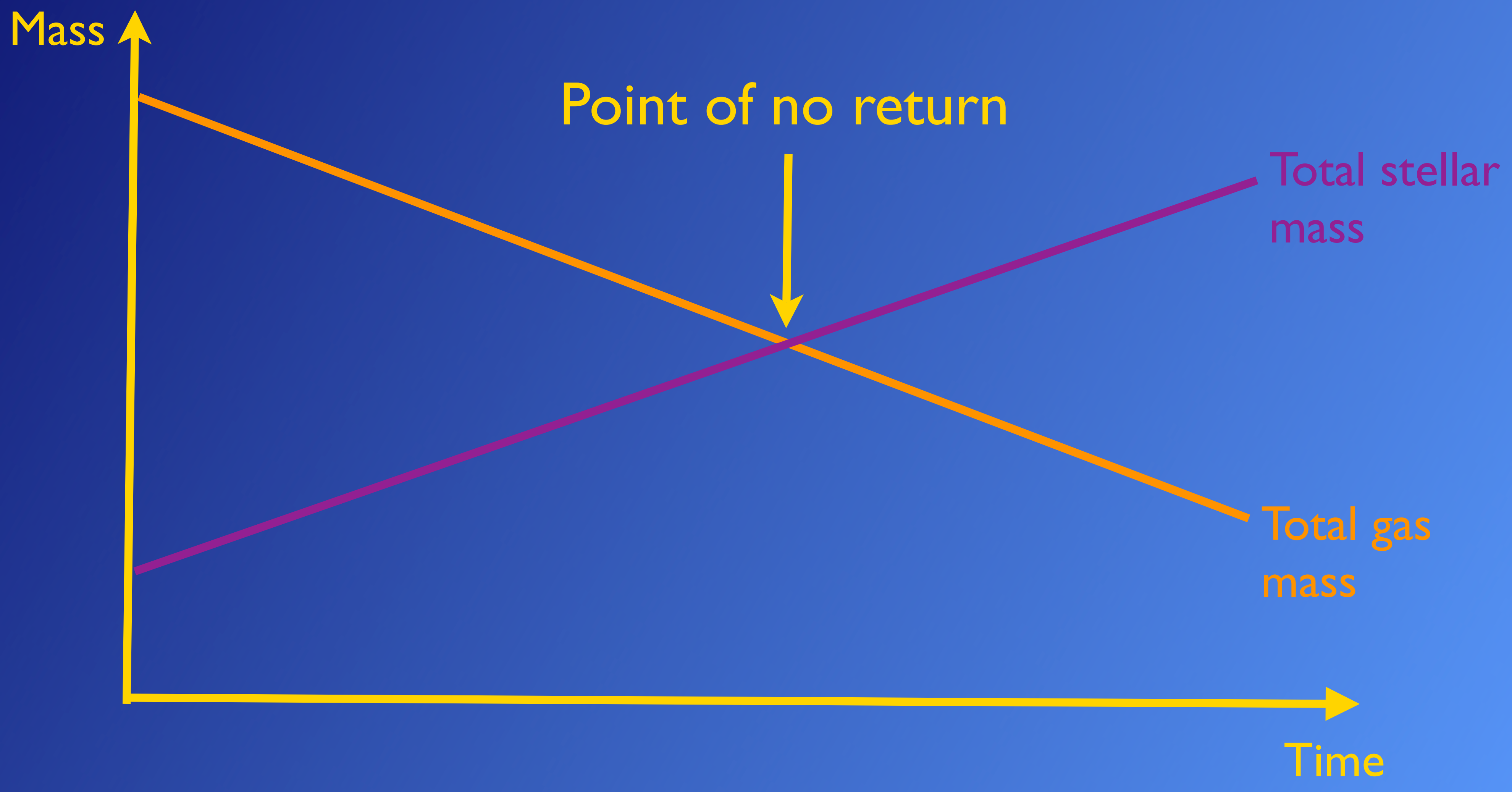
Drops by a factor of ~2 over 1/3 of a dynamical time (cold neutral gas compressed by hot ionised gas)

Feedback has stimulated further fragmentation.



But does the cluster become unbound?

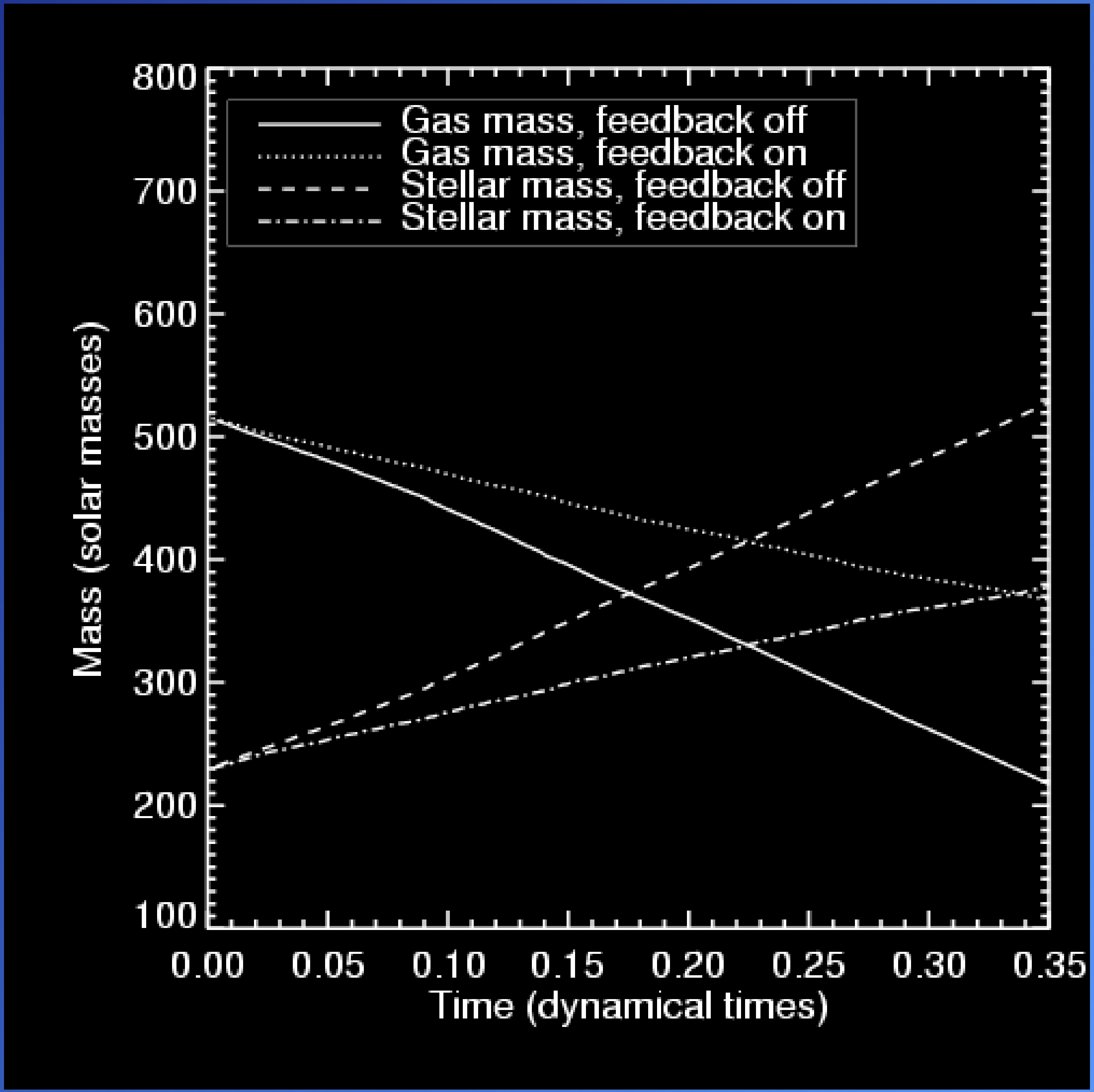
Need to expel the gas before gas:stars mass ratio reaches unity



Does the cluster become unbound?

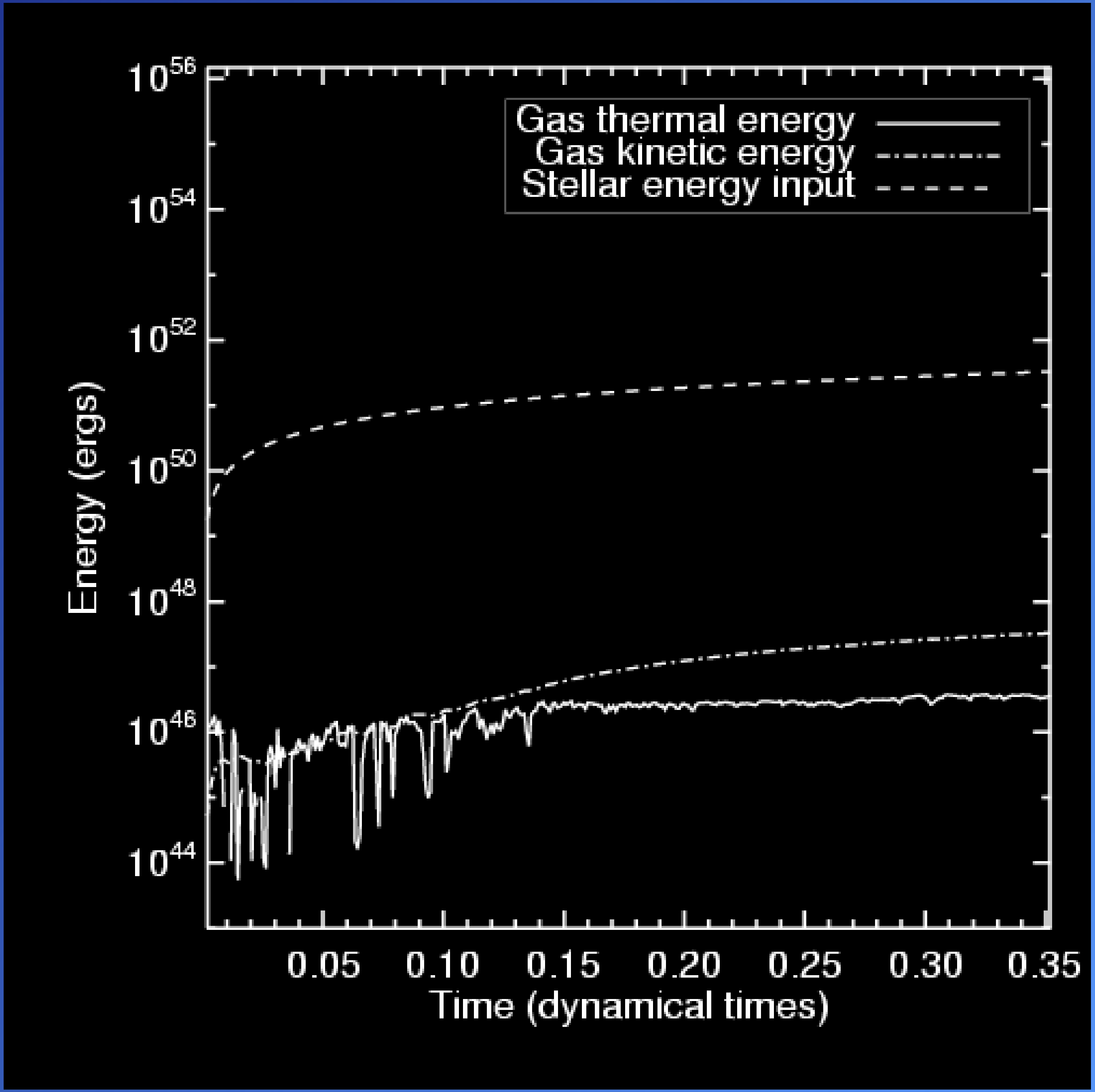
No.

Cluster still bound when it reaches the point of no return



Why feedback fails to do the job:

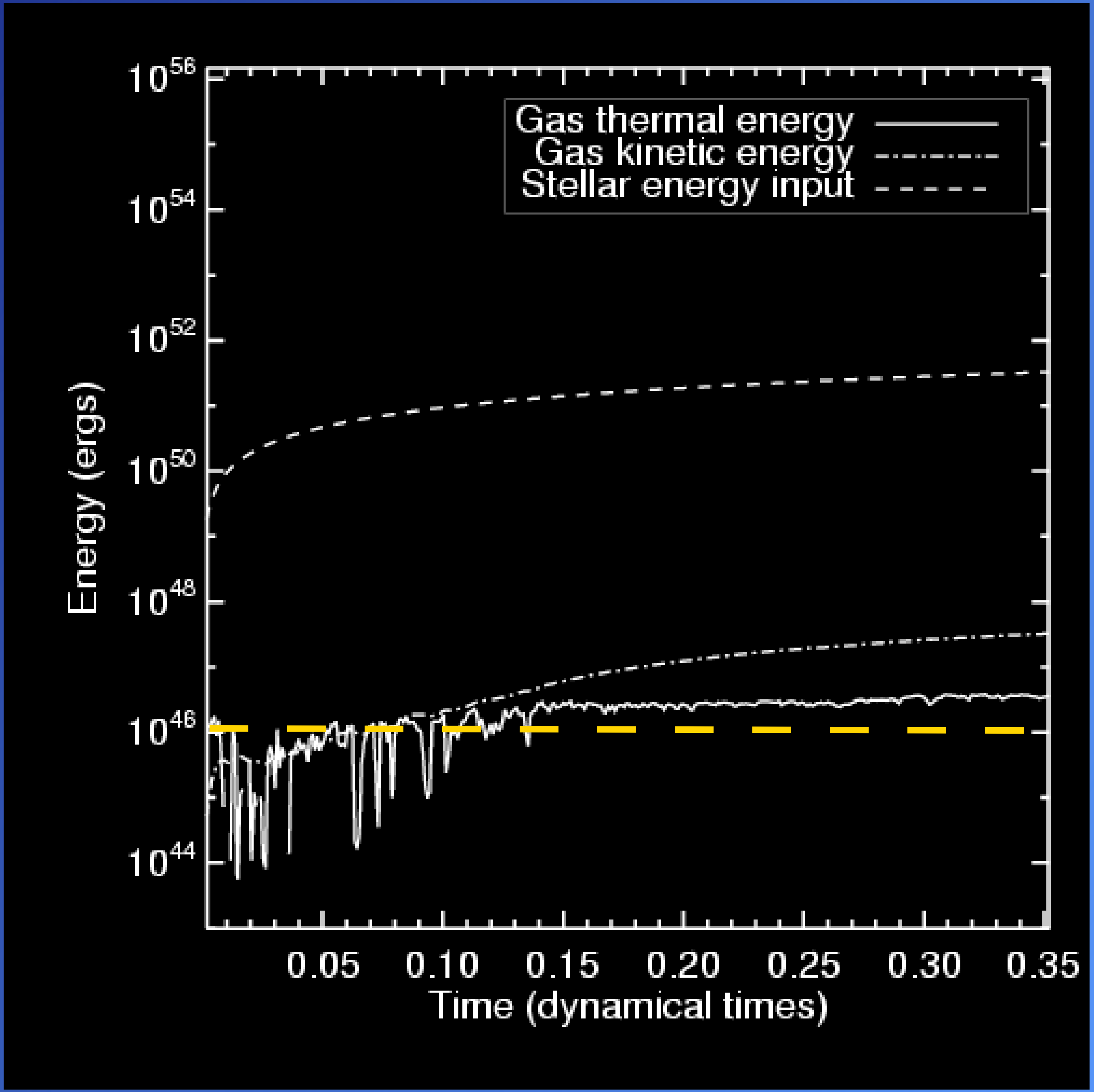
Most of the energy the O-star is pumping into the cloud is being wasted



But it's not as simple as that...

Gravitational binding energy of cluster:

$$\approx \frac{GM_{clus}^2}{R_{clus}}$$



Despite the inefficient energy uptake, the O-star has apparently managed to feed enough energy into the protocluster to unbind it.

So, why isn't the cluster unbound?

- almost all the thermal and kinetic energy injected by the star resides in the outflows
- outflows occupy fairly small solid angle - don't sweep up much gas
- outflows are transporting all the energy out of the cloud

Conclusions:

- The geometry of the HII regions and outflows generated by O-stars is strongly influenced by the structure of the protoclusters in which they form.
- Photoionisation produces positive and negative feedback effects, enhancing fragmentation but slowing accretion.
- The deposition of thermal/kinetic energy numerically in excess of a cluster’s binding energy is *not* a sufficient condition for unbinding the cluster.

Induced star formation?

-hinted at in previous calculation, but not enough resolution to follow star formation properly

-what does it mean to 'induce' star formation anyway?

-do we mean 'accelerate star formation that was already happening'?

-or do we mean 'force a molecular cloud to form more stars than it otherwise wants to'?

How do you actually get molecular gas to start making stars (if it isn't doing it already)?

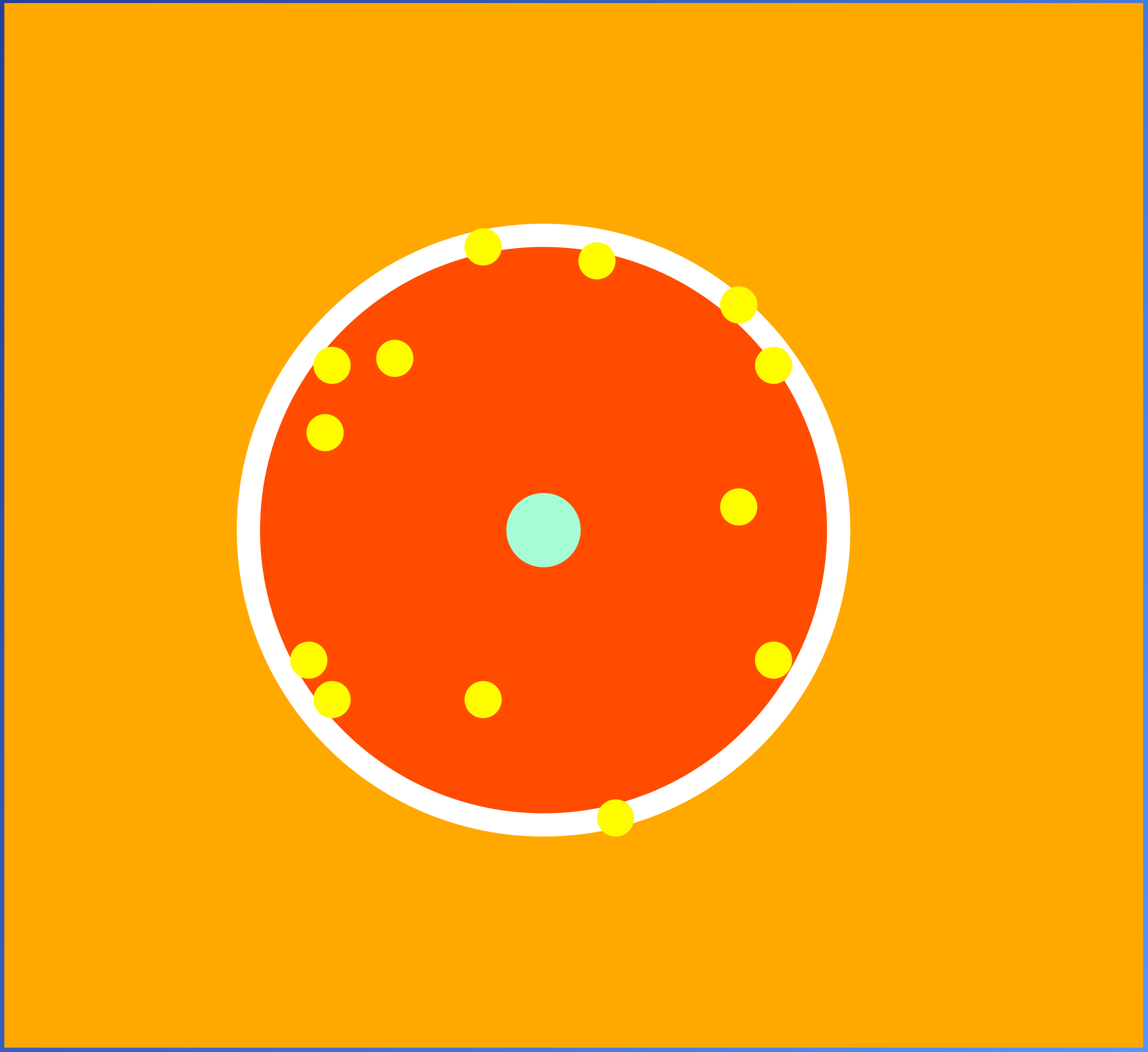
- Mergers/tidal interactions between galaxies
- Galactic spiral arms
- Collisions between GMCs
- Feedback from O-stars (ionisation, winds, SNe)

Last option raises an interesting question - might star-formation be a self-propagating, self-regulating process?

I have been looking at the problem of whether ionising radiation from O-stars can trigger star formation

Let's start with a simple problem...

- -Imagine a cloud of neutral gas in which an O-star is born
- -HII region quickly grows until all photons absorbed by recombinations
- -HII region expands, driving a shock in front of it
- -If shock becomes self-gravitating, get stars



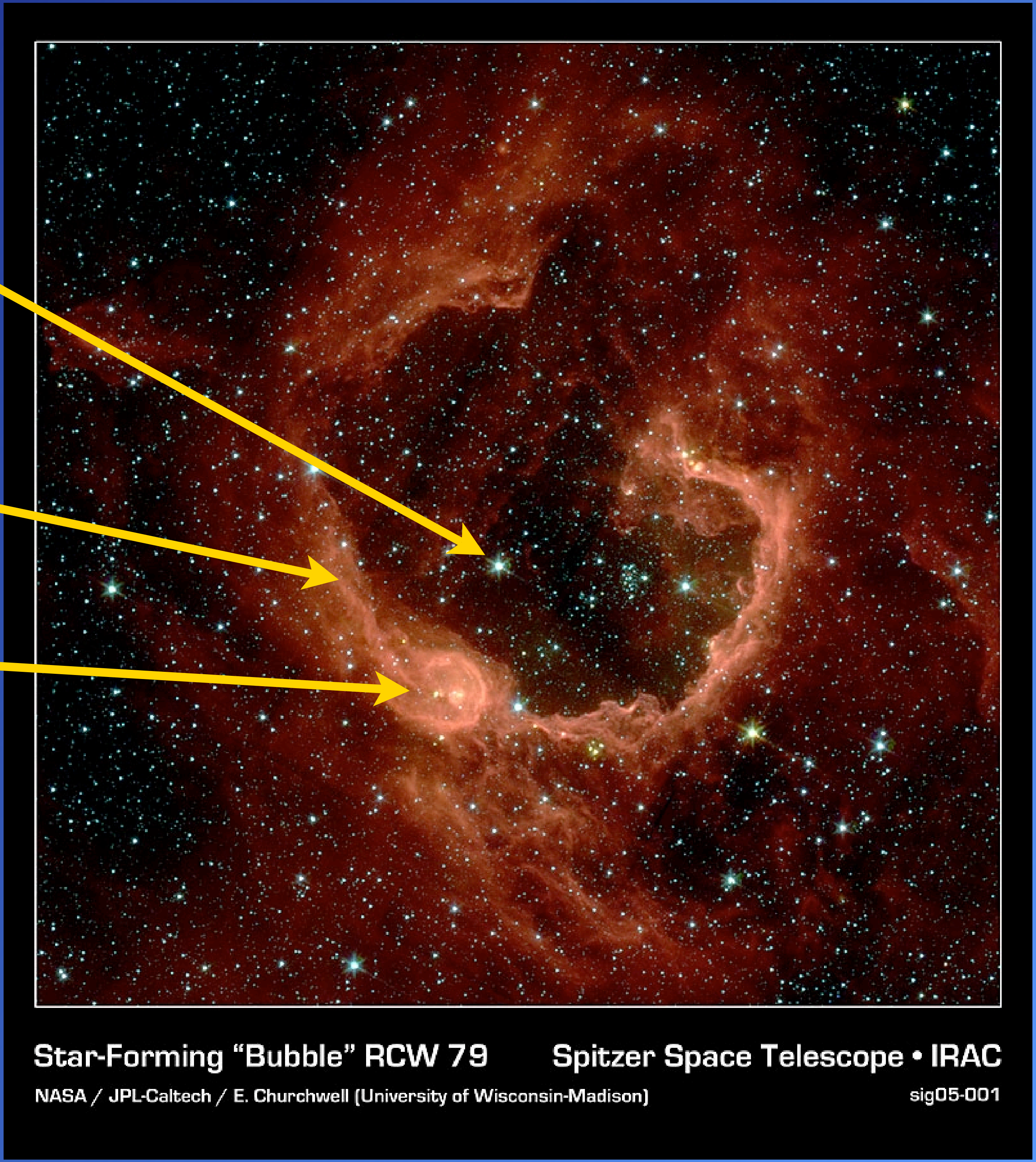
Sounds simple enough - does it ever happen?

RCW 79 HII region

O-star (O8V - Cohen et al 2002)

Molecular ring

MSX mid-IR source Another HII region, powered by an O9.5V star



A bit more theory...

Whitworth et al, 1994 looked at this analytically

- considered an infinite uniform cloud (typical theorists...)
- imagined an HII region expanding inside the cloud so that

$$R(t) = Kt^{\alpha}$$

- for an HII region expanding in a uniform medium,

$$K = f(L_*, n_0), \alpha = \frac{4}{7}$$

- can then calculate surface density of the shocked shell and ask when it becomes self-gravitating
- finally can actually calculate something useful:

(i) How long before the shell fragments?

(ii) What is the shell's radius when it breaks up?

(iii) How big are the fragments?

SPH simulations of collect-and-collapse

Uniform cloud:

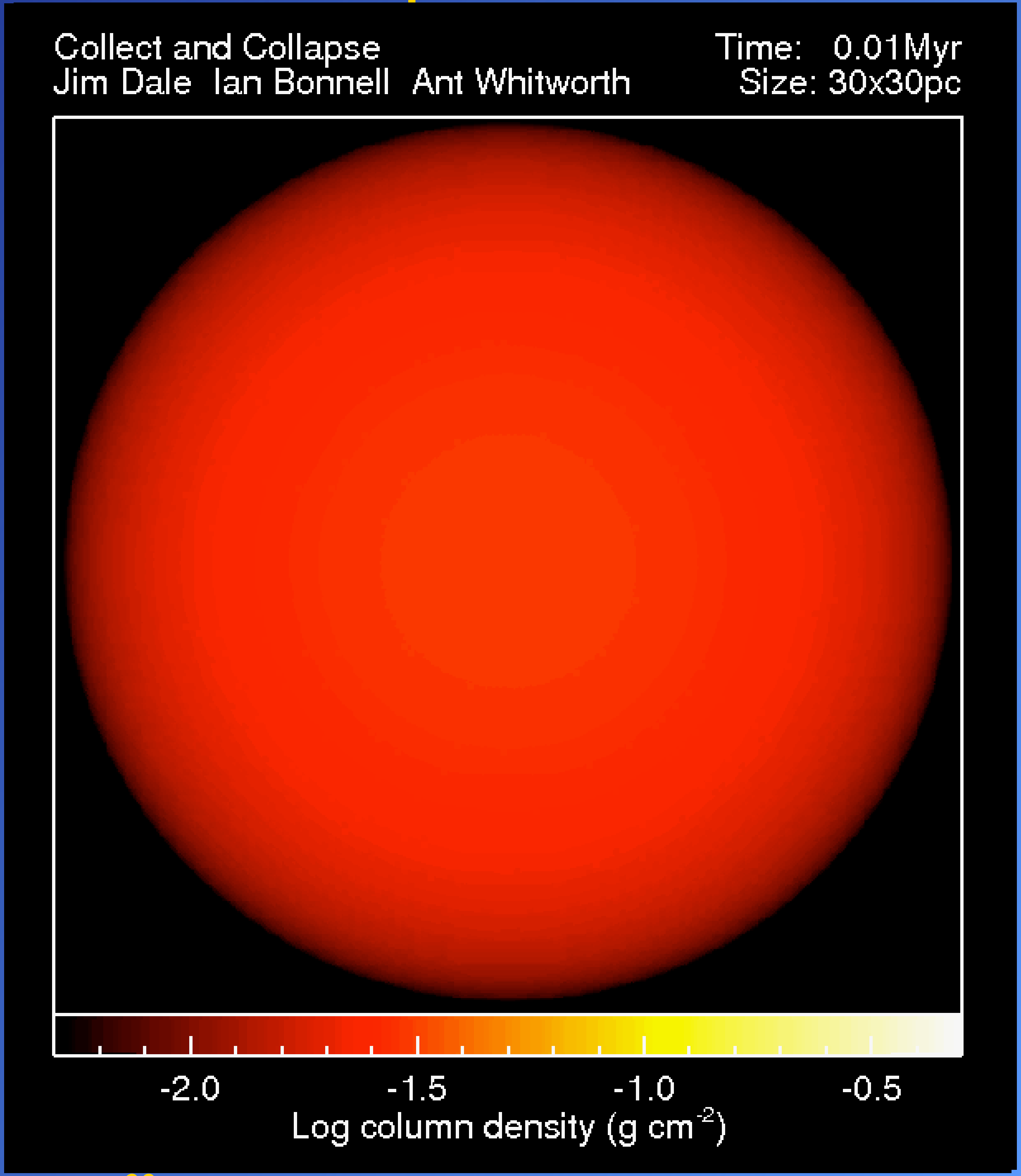
Mass: $6.4\times10^4 M_\odot$

Radius: ~15pc

$n=200cm^{-3}$

$L_*=10^{49}s^{-1}$

According to Whitworth et al, shell should fragment after 3.3Myr at a radius of about 14pc and produce $50M_\odot$ fragments



Collect and collapse results - did it work?

Actually did four simulations at different resolutions to check that we obtained convergence

We did :-)

Did a fifth to see if random noise in the particle distribution affects the results

It doesn't

- measured fragmentation time and radius by time and position of formation of first sink (lower limits)

- obtained 2.7 Myr (3.3Myr predicted) and 11pc (14pc predicted)

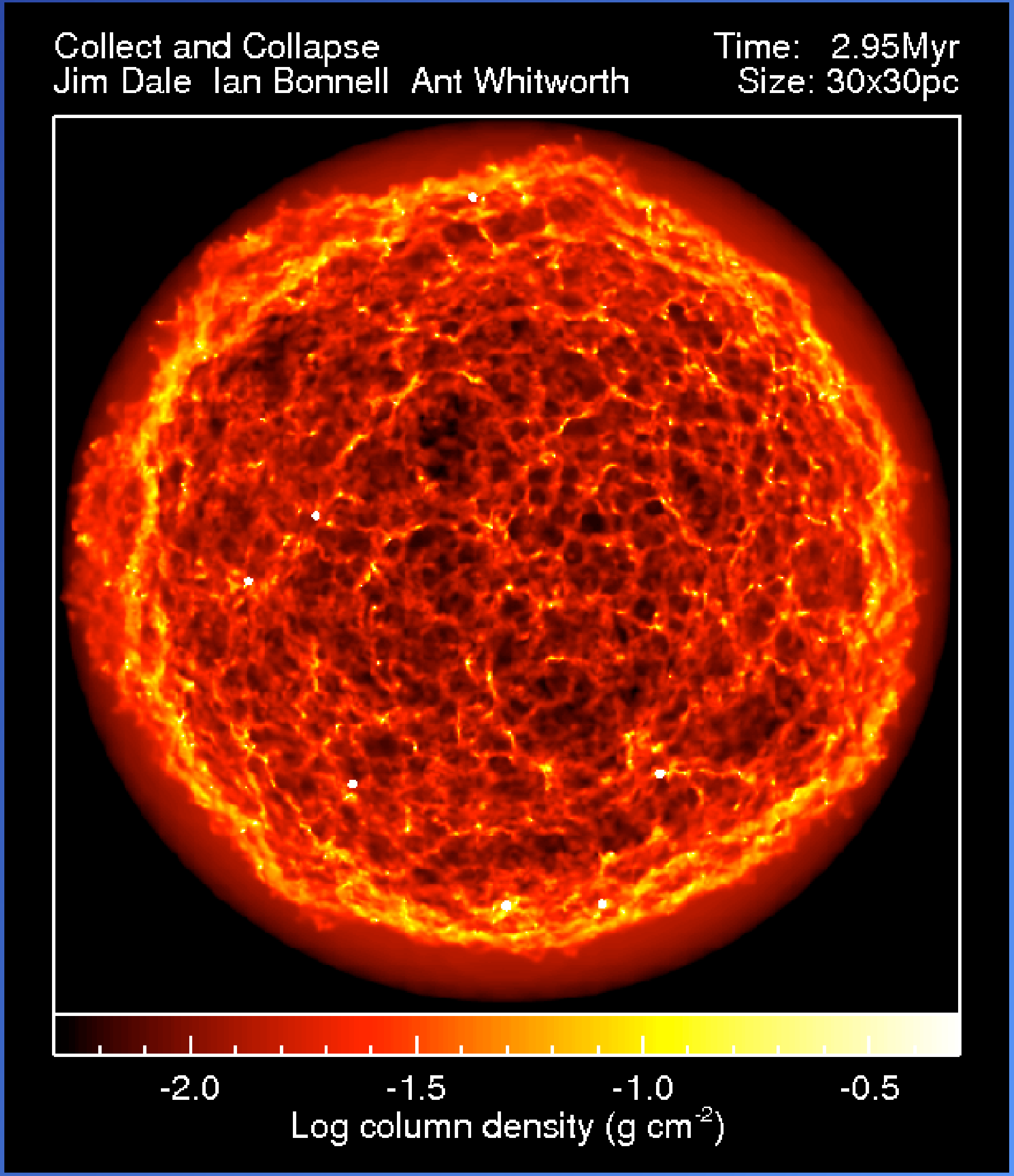
- fragment masses more difficult to measure...looked for self gravitating objects, found maximum masses of ~40$M_\odot$, mean masses of ~20$M_\odot$

What did we learn from this exercise?

- pretty good agreement between theory and simulations
- the collect-and-collapse model appears to be feasible
- implies that you can trigger star-formation even in uniform gas - can get stars to form anywhere, if you happen to have an O-star lying around
- a word of caution though...

Have we really got this right?

Spot the difference:



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In simulations, see lots of structure (and protostars) *inside* the shocked shell (projection effect)

Don't see this in the real HII region - have we got the geometry wrong? Is it really a ring instead of a spherical shell?

Could always do some more simulations....

Maybe later....

How often do you see a uniform molecular cloud anyway?

A more typical molecular cloud:

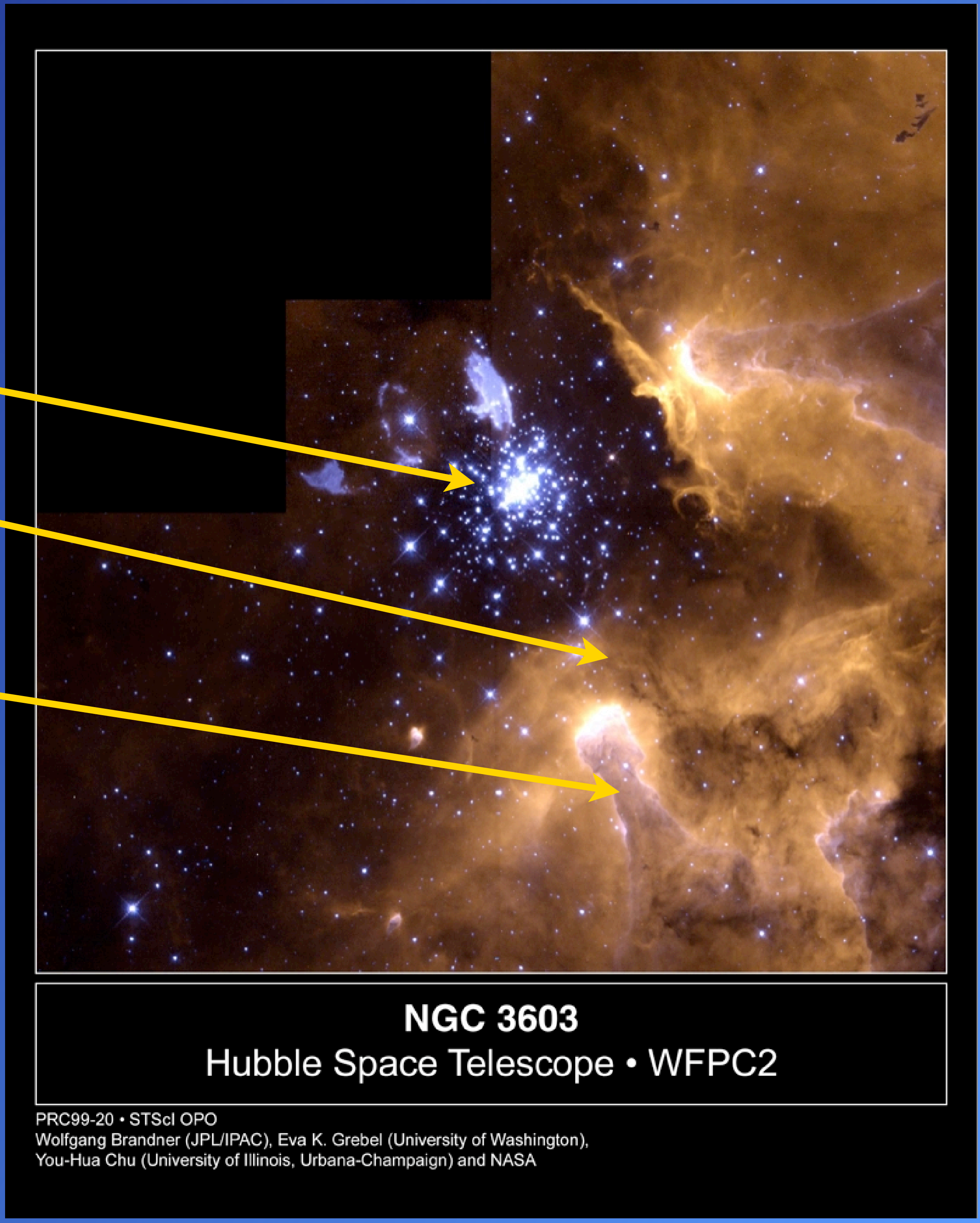
NGC 3603:
Galactic HII region

HD97950, central ionising cluster

Diffuse ionised gas

Denser pillars (elephants' trunks) of neutral gas

Several young OB stars reported near the tips of the pillars



Looks and sounds like induced star formation

...but how do we know those young O-stars weren't going to form anyway?

In fact, how do we know they hadn't already formed, and are now just being revealed as the gas around them is blown away?

We don't, of course - you can't tell by looking at one image. However, you could answer both of those questions if you could do a numerical simulation....

First, we need a molecular cloud...

Model obtained from Paul Clark

Mass: $10^4 M_\odot$

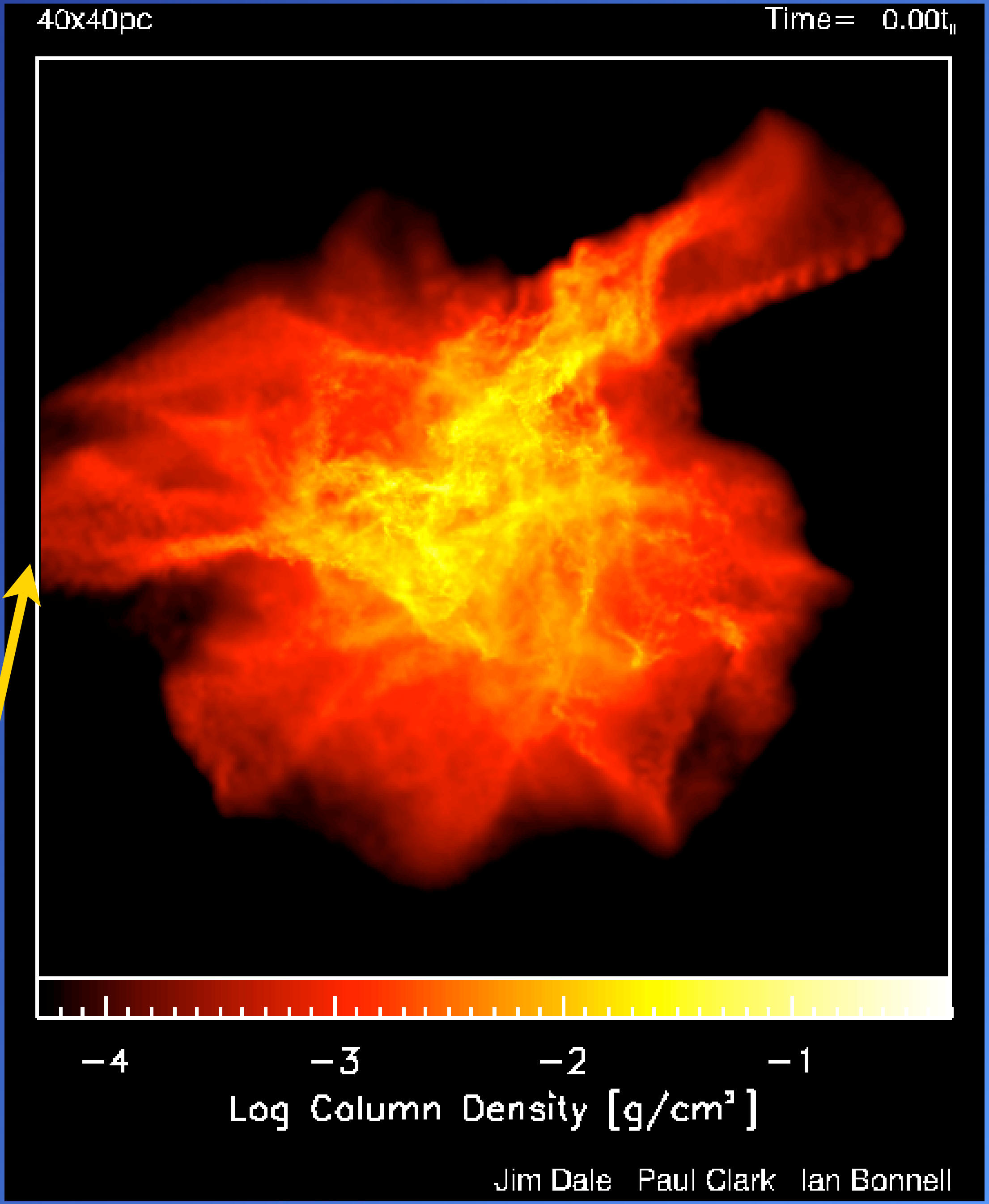
Radius: ~10pc

n~200cm^{-3}

Jeans mass~50$M_\odot$

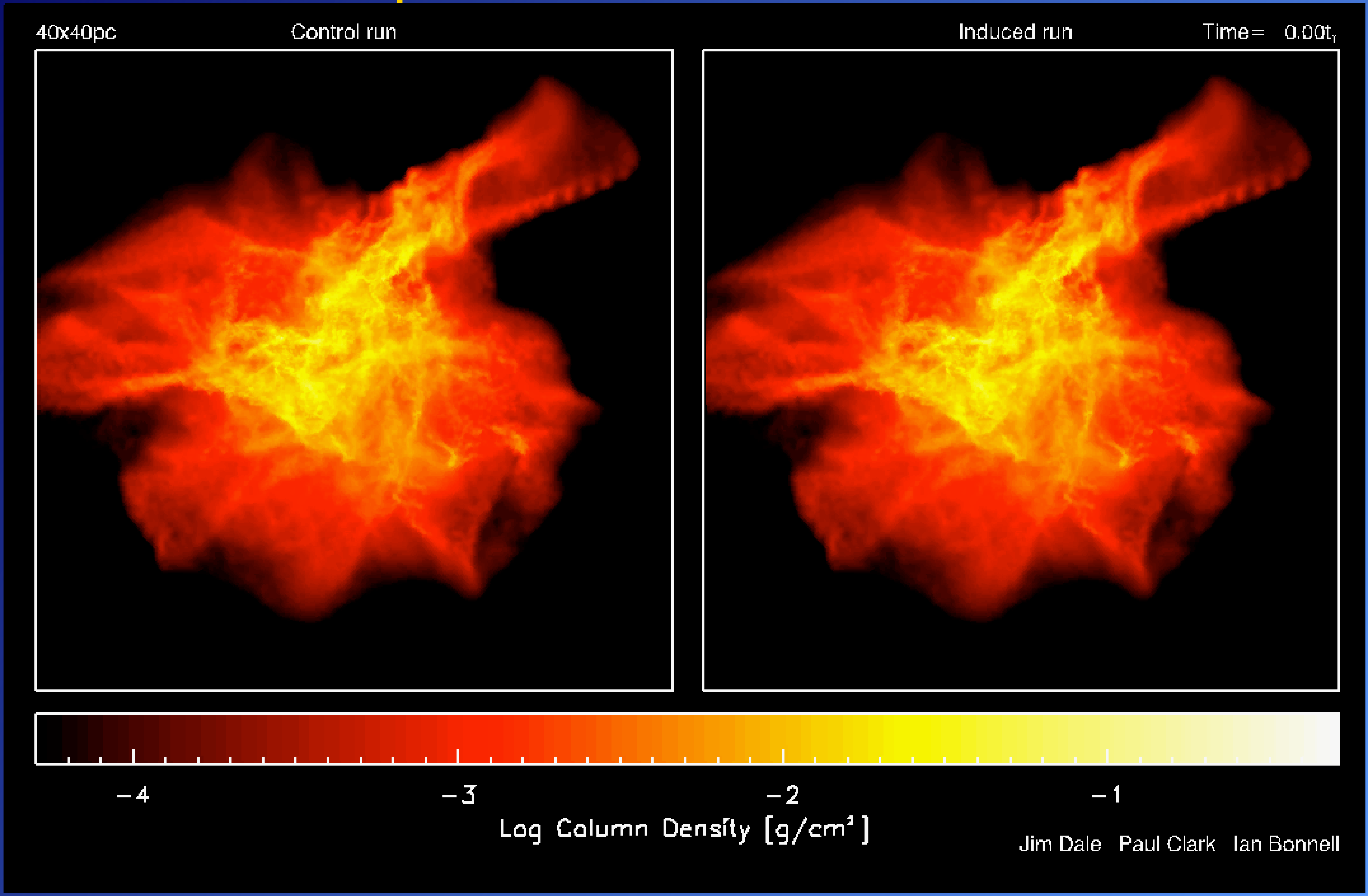
Globally unbound - KE=2PE

Turbulent velocity field



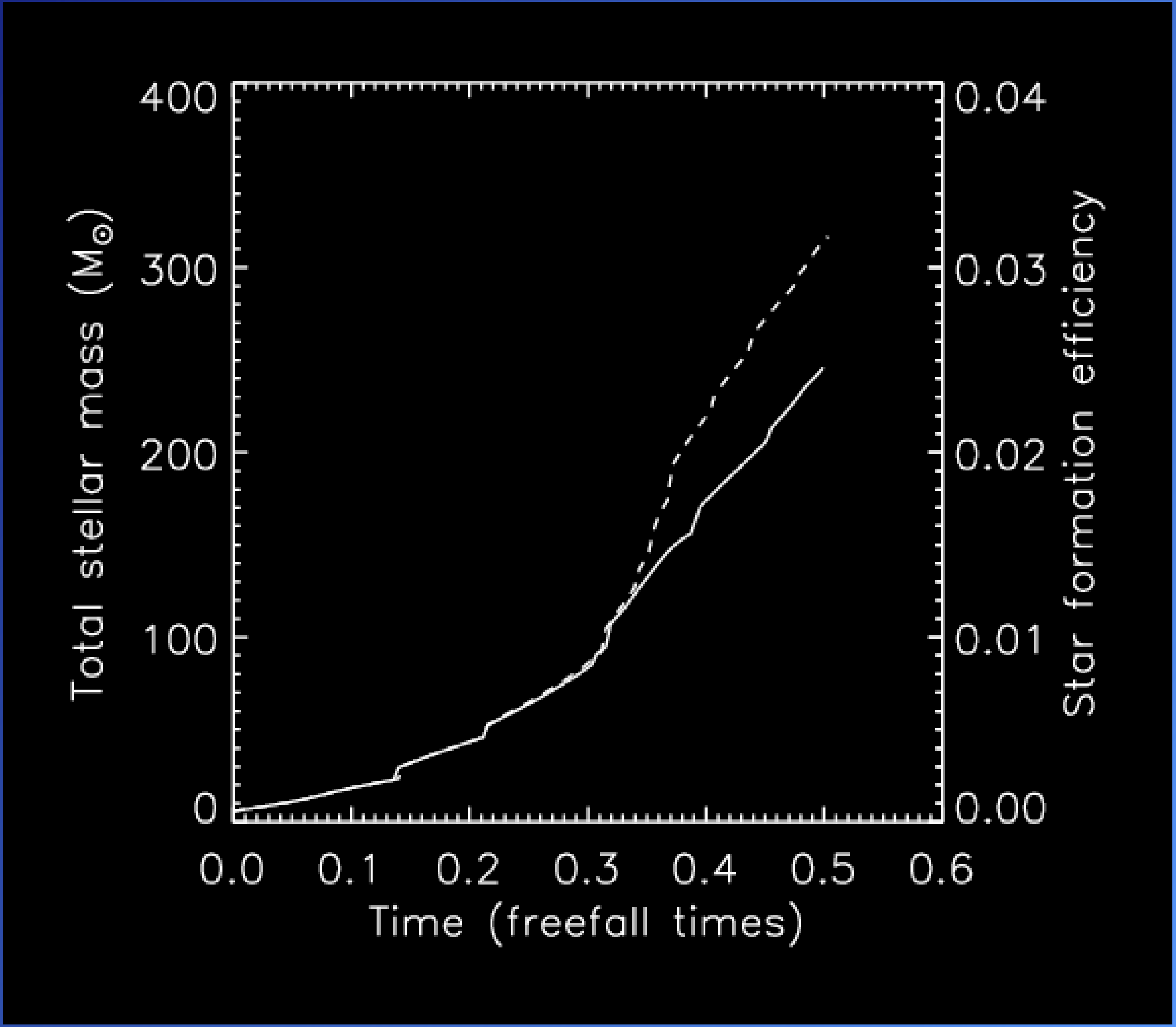
What happens if we place a radiation source ($L_{source}=10^{49}s^{-1}$) here?

A numerical experiment



Results

- Feedback run evidently forms more stars (12 as opposed to 8 clusters)
- Feedback run forms about 30% more stellar mass



Very important question:

Are we simply accelerating the formation of stars that were going to form anyway....

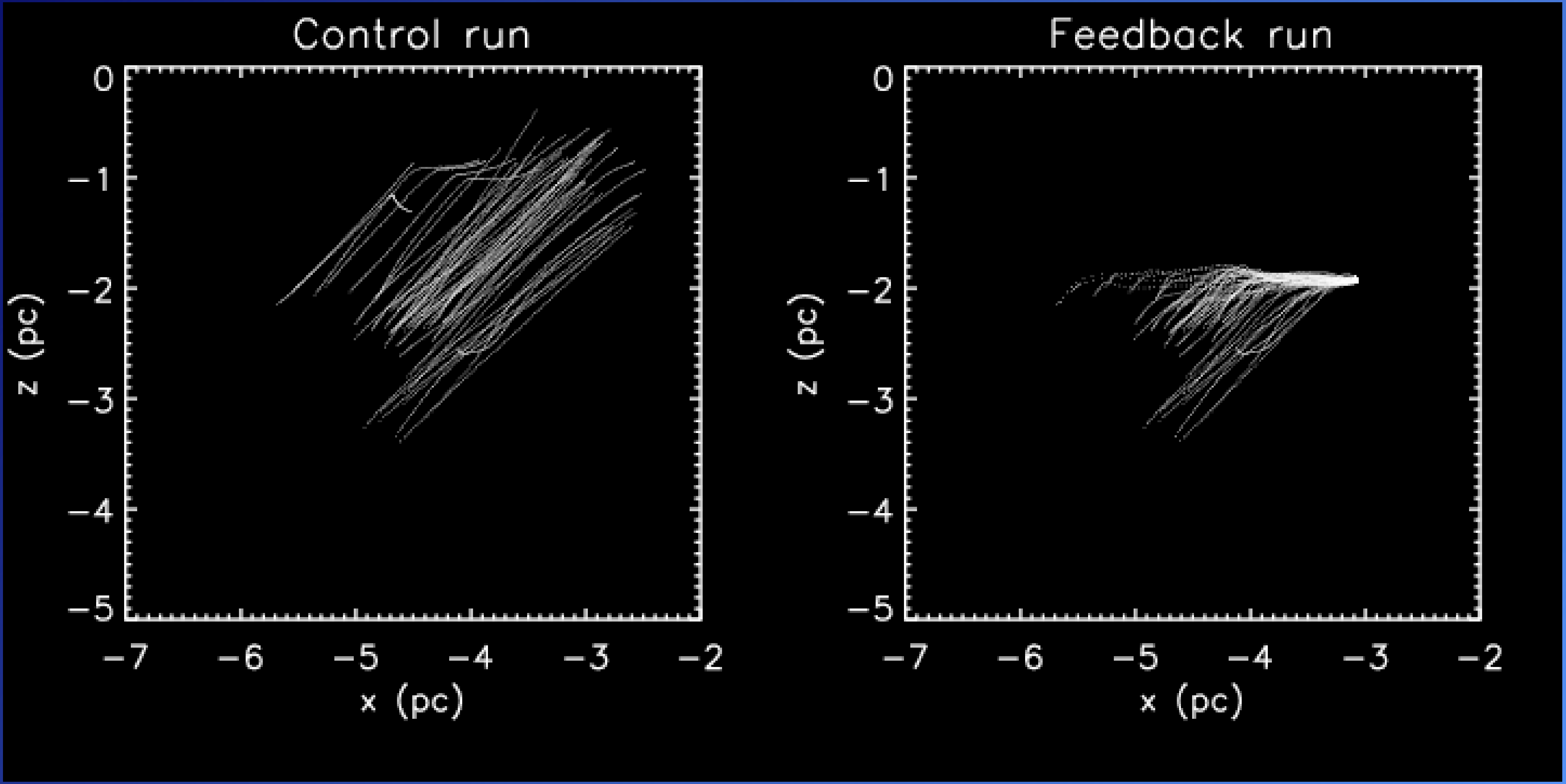
...or are we inducing the cloud to form stars that it would not otherwise have formed?

Same gas, different history...

SPH is a Lagrangian method - every particle has a unique and easily-traceable history

Can identify the groups of SPH particles from which cores formed and see what happened to those same particles in the other calculation

An example:



We are indeed genuinely inducing star formation

Results

- all 8 star-forming cores that form in the control also form in the feedback run, although some form earlier and some form later
- of the 4 extra cores in the feedback run, 2 look like they may eventually form in the control run...
- ...and 2 are clearly not going to form, so they have been induced

Final thoughts

- unbinding embedded stellar clusters with ionising radiation is harder than it looks - will winds help?
- the shocks driven by expanding HII regions can trigger star-formation in even perfectly uniform gas
- ionising radiation can induce molecular clouds to form stars that they would not otherwise form, and can increase the star-formation efficiency