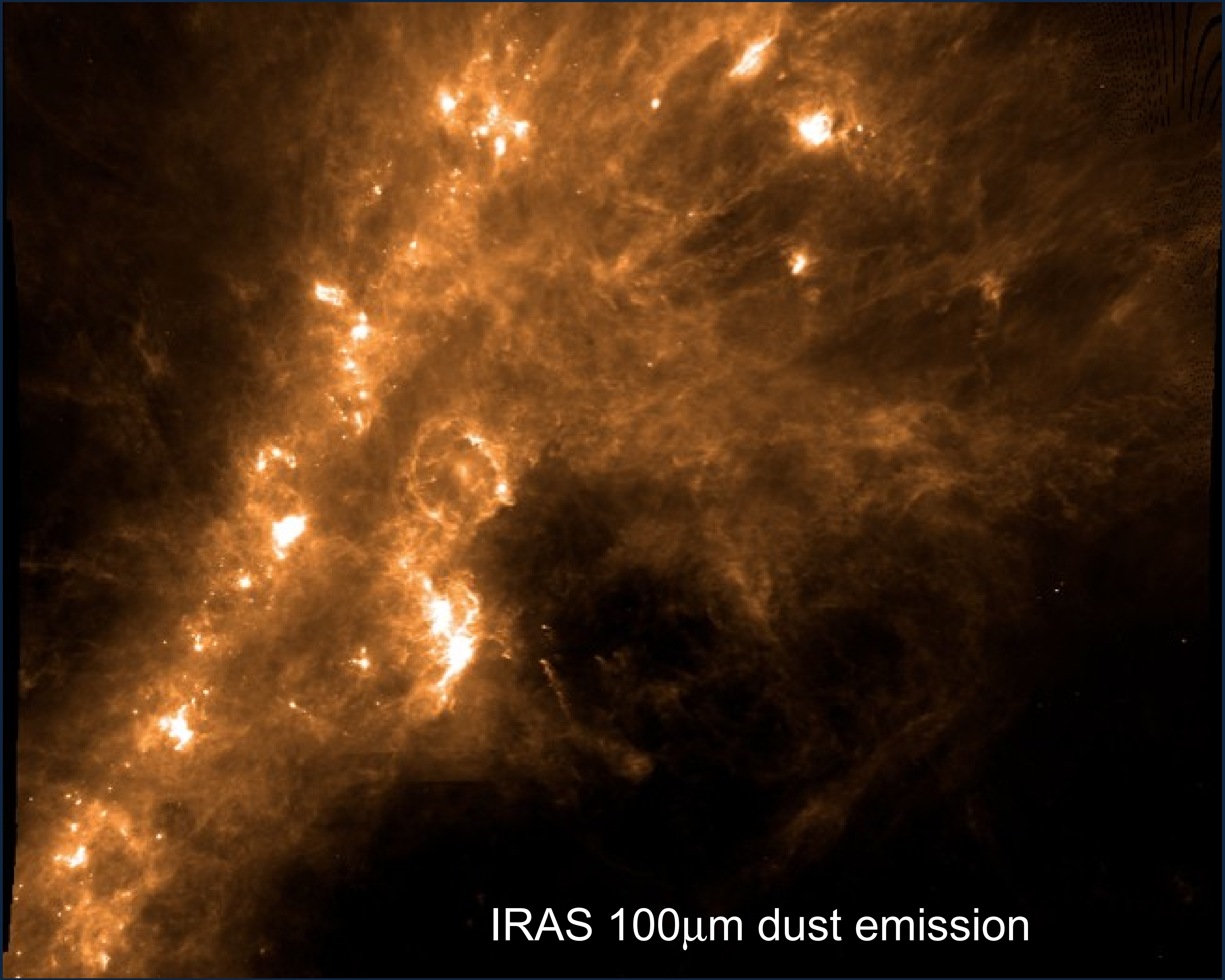
Star formation up close

Lee Hartmann, University of Michigan

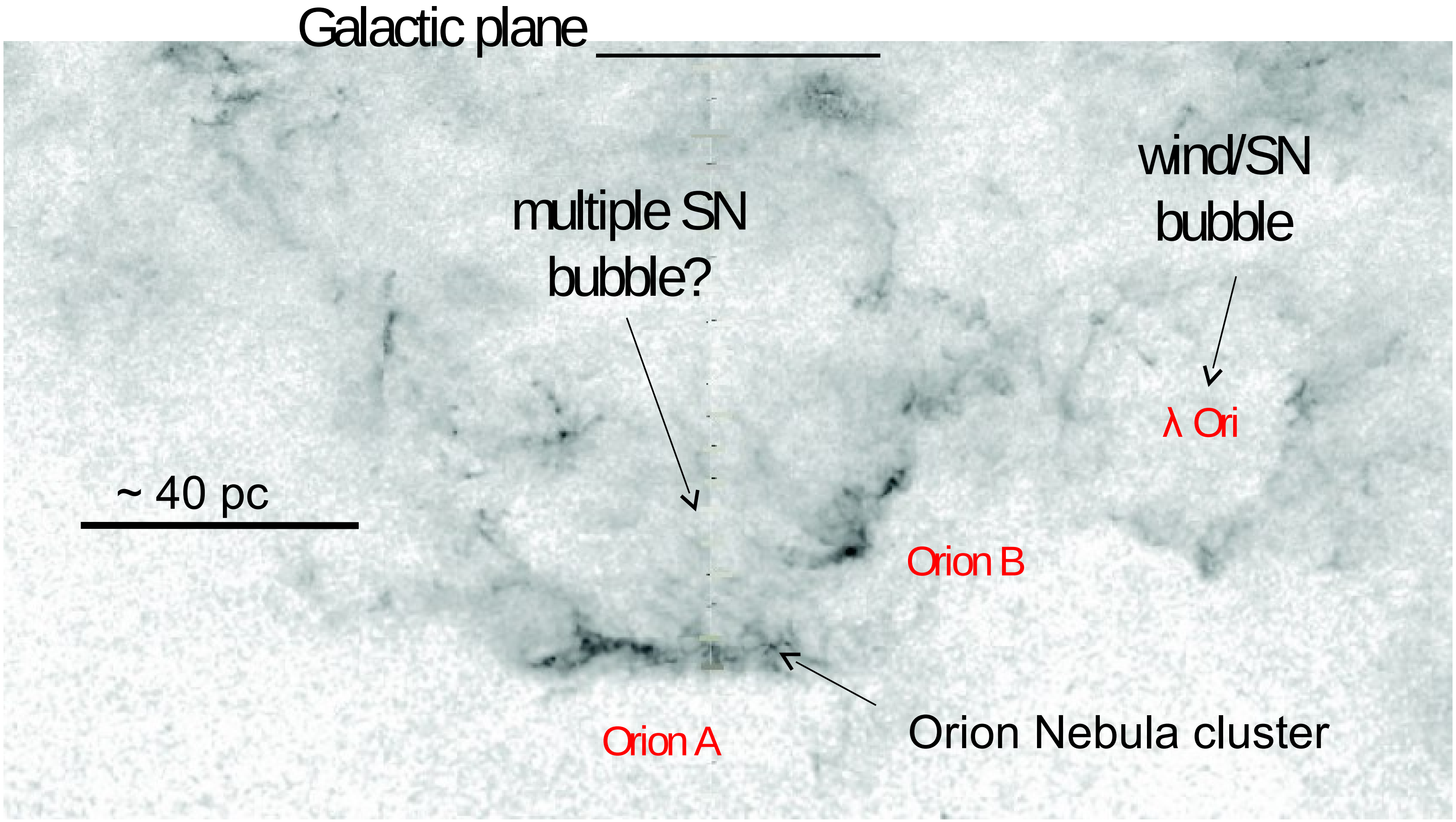
Andi Burkert, Javier Ballesteros-Paredes, Fabian Heitsch, Tina Hsu

Michigan Star and Planet Formation

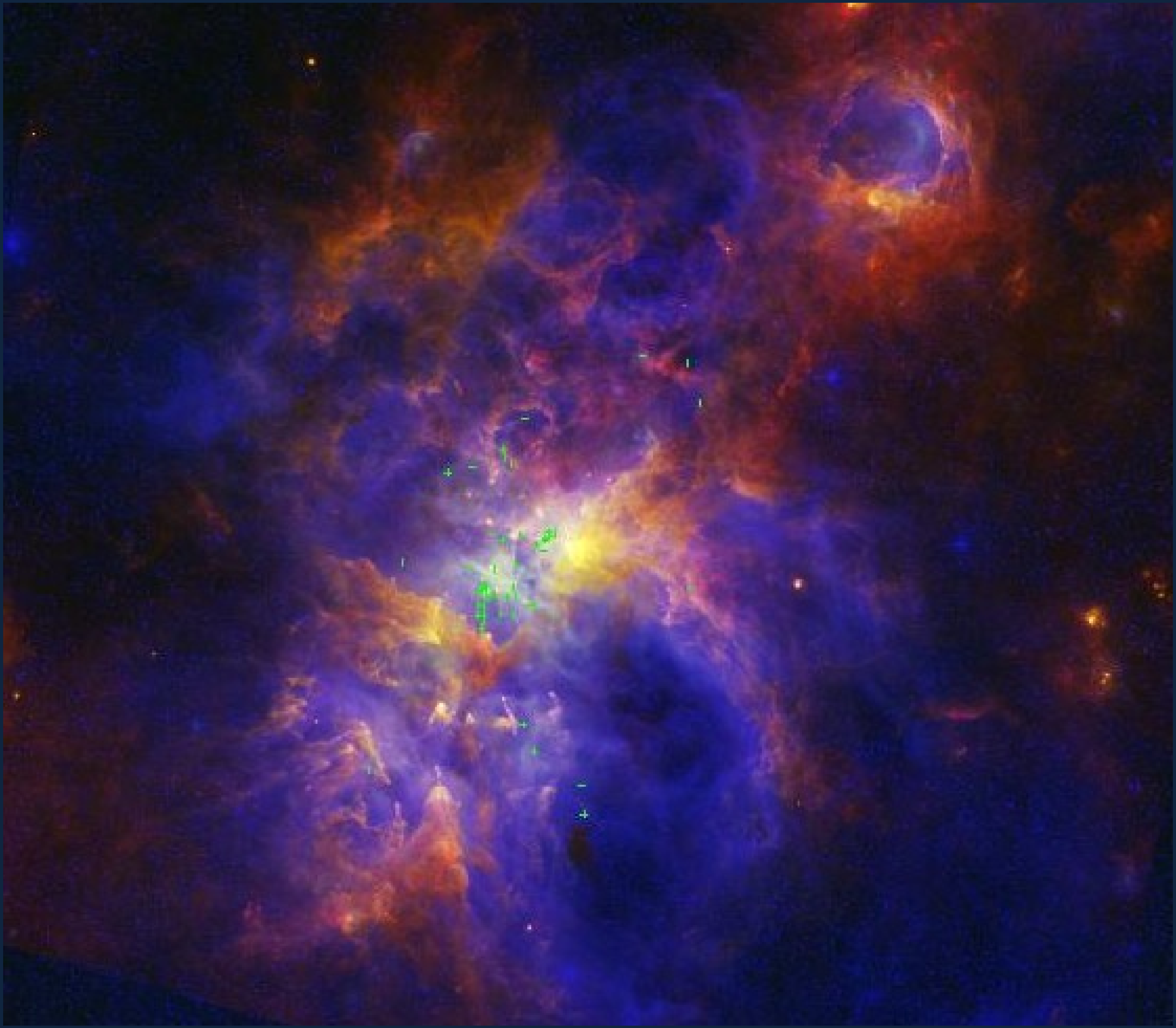
1. Bubbles: the end and the beginning



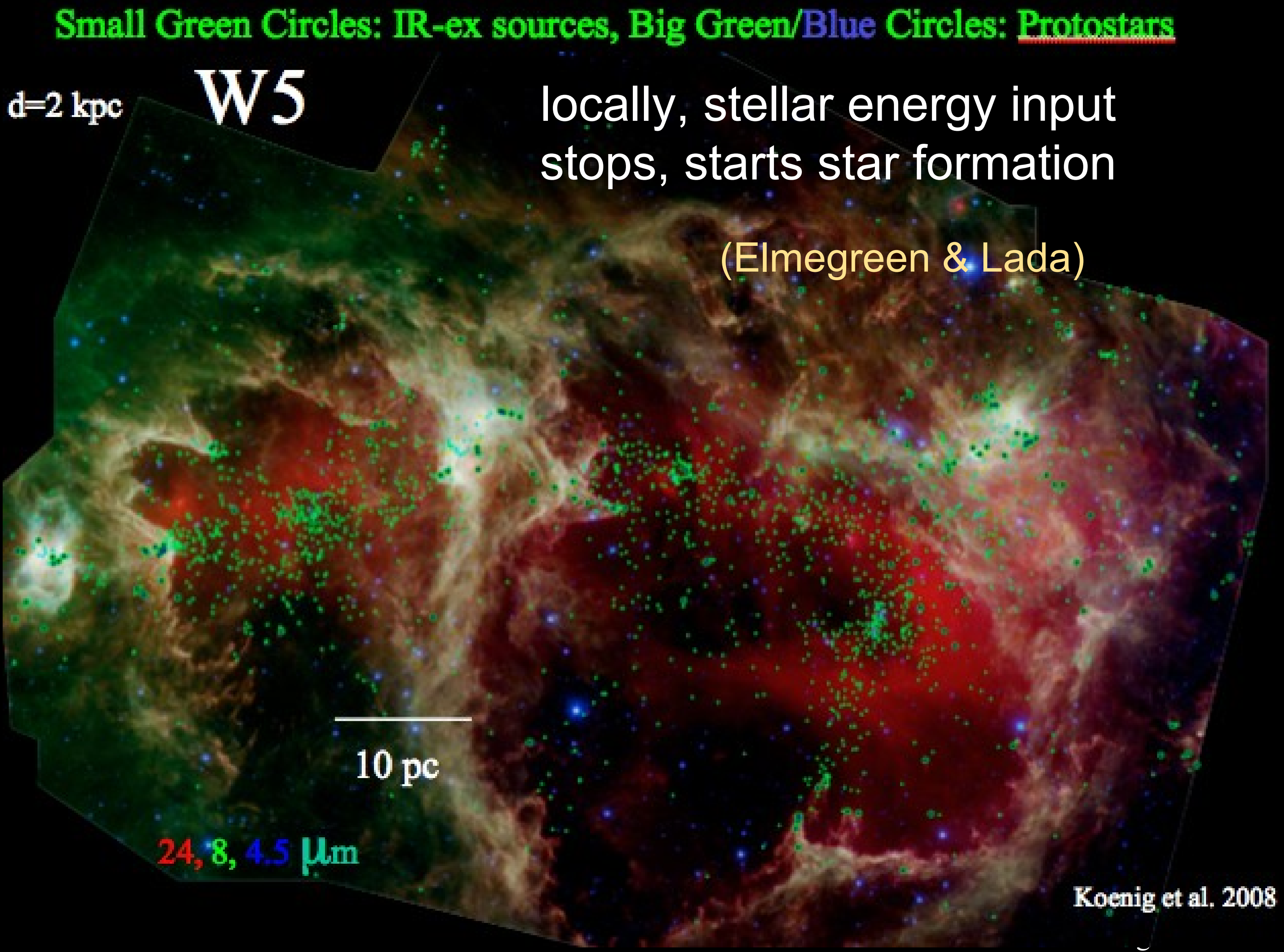
IRAS 100μm dust emission



Froebrich & Rowles 2010, A_V map



Preibisch et al. 2012, Carina



Koenig et al. 2008

locally, stellar energy input stops, starts star formation

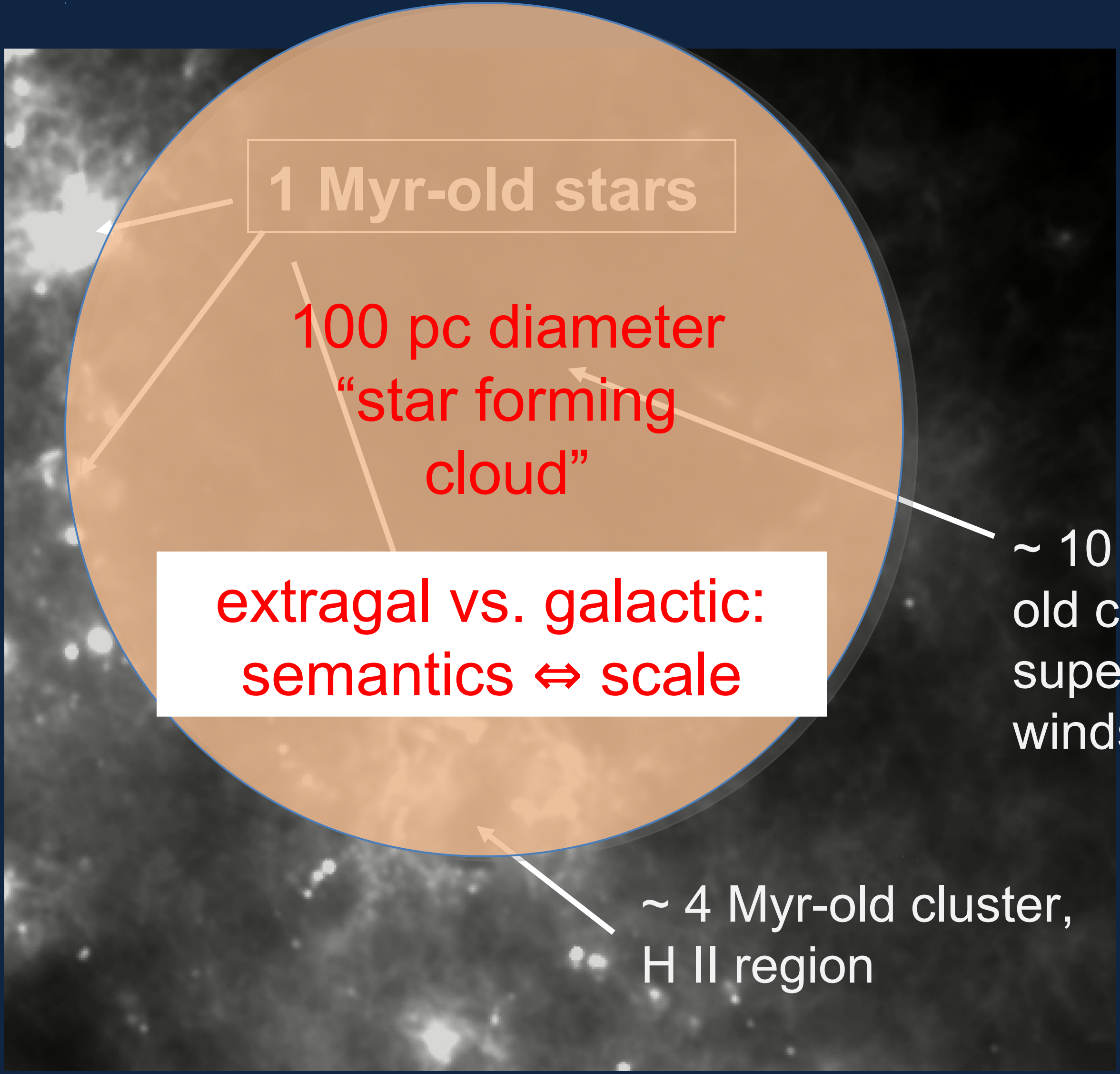
(Elmegreen & Lada)

more star-forming bubbles

Cep OB2

50 pc

100 µm IRAS
dust emission



1 Myr-old stars

100 pc diameter
“star forming
cloud”

extragal vs. galactic:
semantics ⇔ scale

~ 10 Myr-
old cluster:
supernova/
winds

~ 4 Myr-old cluster,
H II region

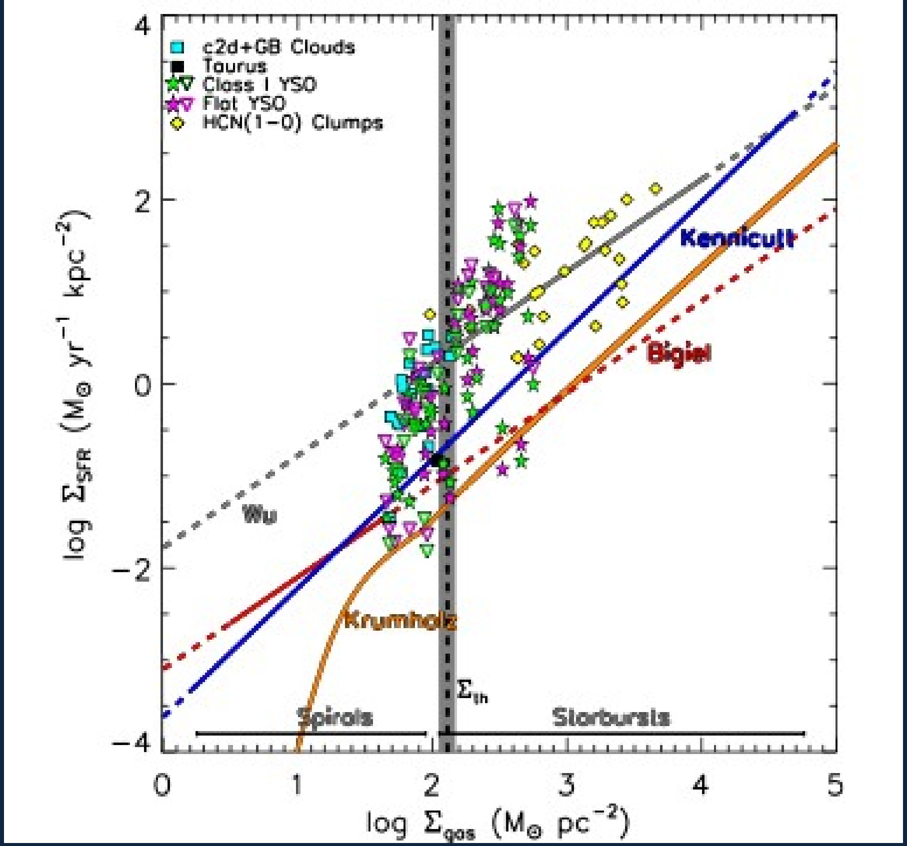
Spiral arms collect gas, shock; but each H II region is the site of molecular gas destruction, halting star formation locally and triggering it nearby

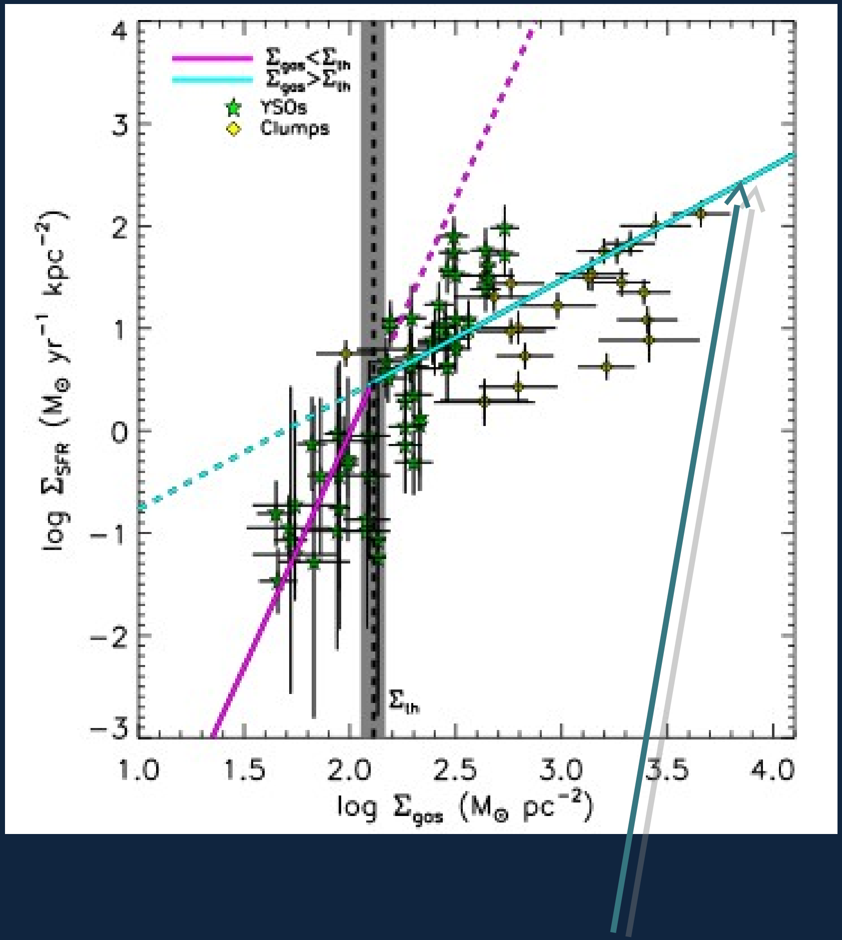
This “churning” is part of the reason it is so difficult to estimate star formation efficiencies

2. Density “thresholds” for star formation and linear gas-SFR relations

Surface density threshold for star formation?

Heiderman et al. 2010; Lada et al. 2010





Σ (th) ~ 120 Msun/pc^2 ~ A_V ~ 7; n > 10^4 cm$^{-2;}$ linear SFR above?

Lada et al. 2010:

stars / dense gas ~ constant (same t)

stars/(same t_{cloud}) / dense gas

= SFR/ dense gas ~ constant

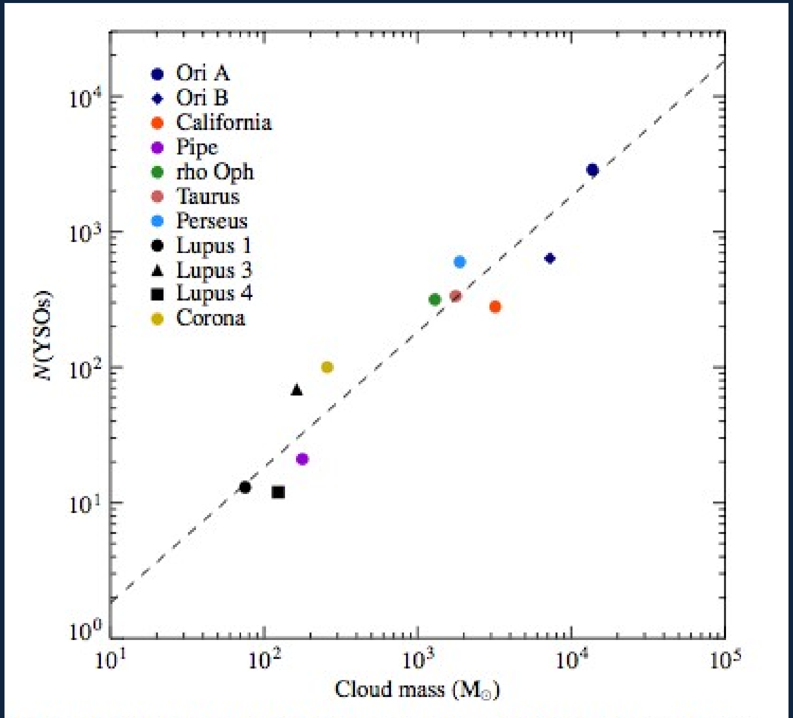


Figure 4. Relation between N(YSOs), the number of YSOs in a cloud, and $M_{0.8}$, the integrated cloud mass above the threshold extinction of $A_{K0} = 0.8$ mag. For

First conclusion*:* because stars continue to form, *dense gas mass must increase with time!*

Continued input from lower-density cloud regions

(Burkert & Hartmann 2012)

Second conclusion: constant ratio of stars to gas means *dense gas mass increases NON-LINEARLY with time!*

For example:

$$M_g(t) = qM_*(t) = q\epsilon M_g(t - \tau_{ff}) \, , \;\; q = \text{constant}$$

$$\epsilon = \text{efficiency}/\tau_{ff} \sim \text{const.}$$

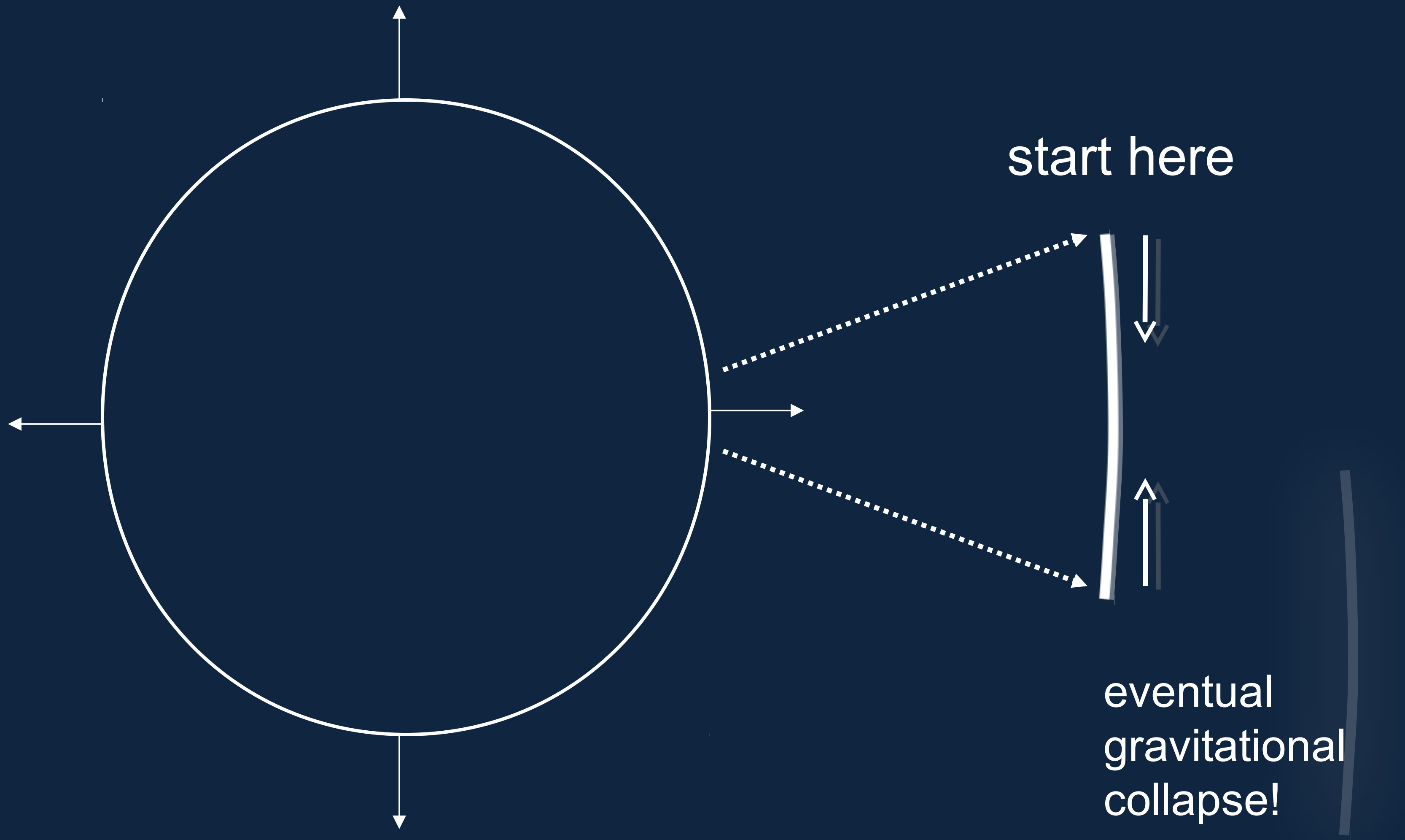
$$M_g(t) = M_g(0) \exp(t/t_0) \, , \;\; t_0 = \frac{\tau_{ff}}{\ln(q\epsilon)}$$

This non-linear increase with t is seen in many simulations with “global” gravitational collapse.

(Burkert & Hartmann 2012)

Toy model of finite sheet evolution with gravity

Burkert & Hartmann 04; piece of bubble wall ≈ sheet



start here

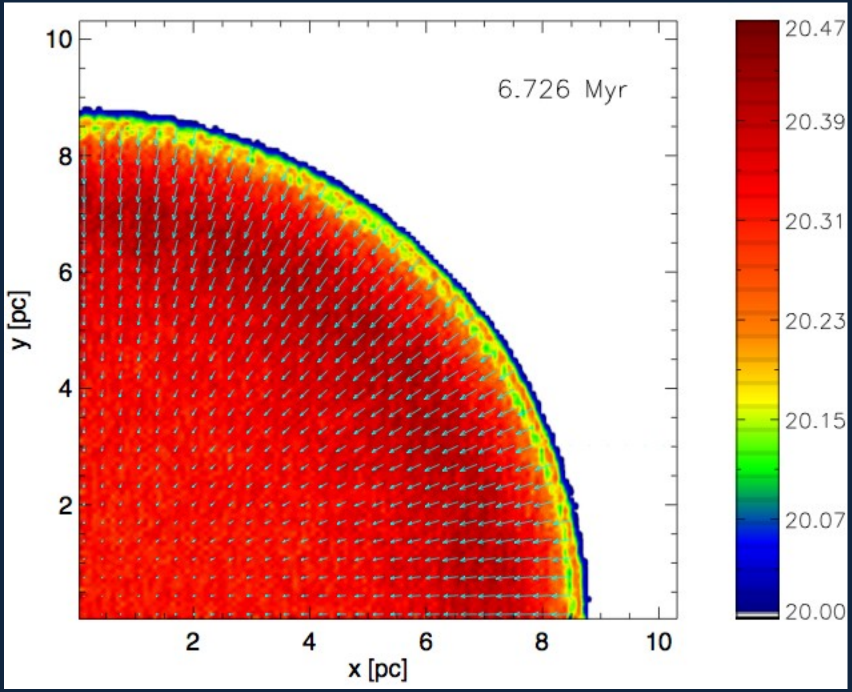
eventual gravitational collapse!

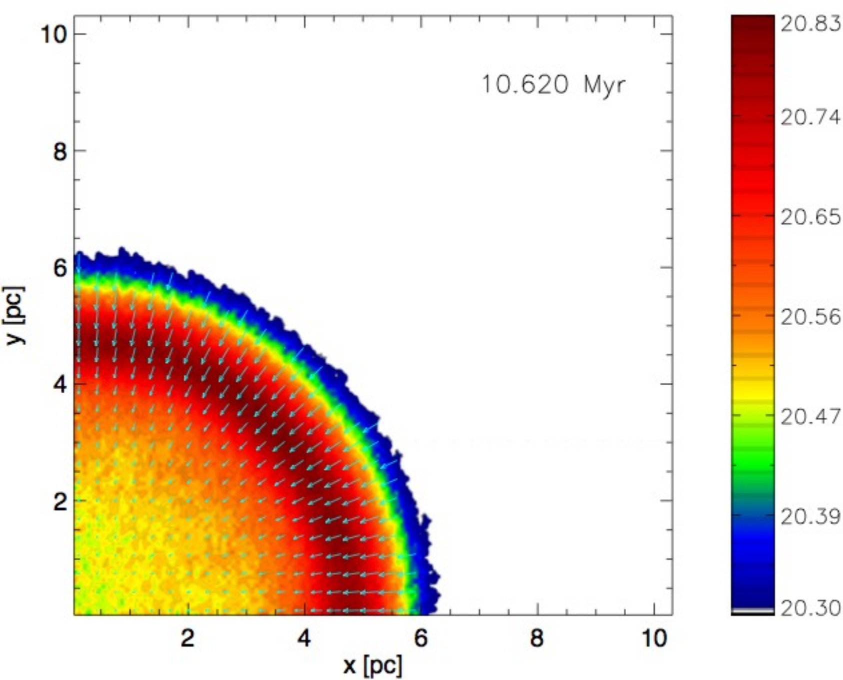
Finite sheet evolution with gravity

uniform surface density Σ, isothermal, circular sheet:

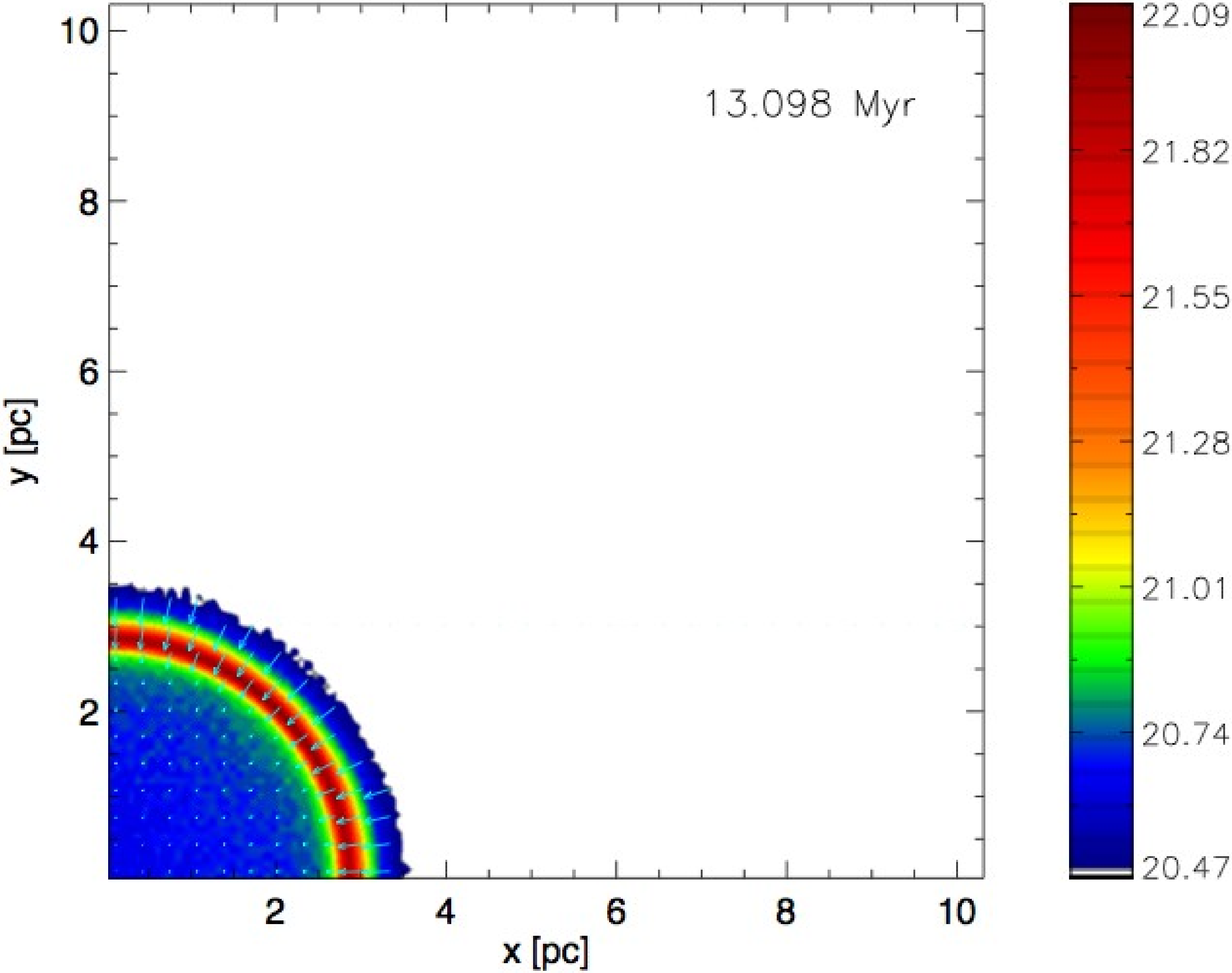
⇒ pileup of material at edge!

(simple way to make a filament without making "clusters" at filament ends; see later)

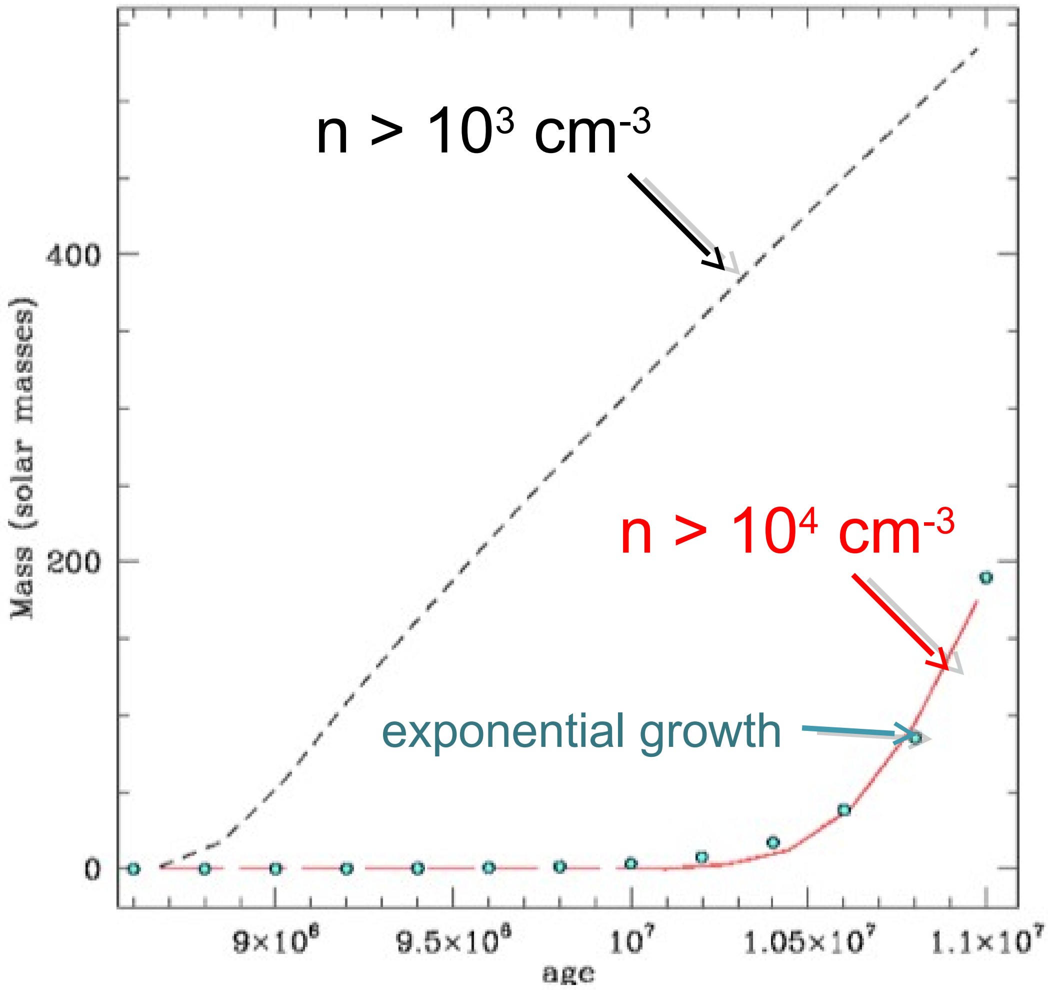




(Burkert & Hartmann 2012)


13.098 Myr
y [pc]
x [pc]
2
4
6
8
10
2
4
6
8
10
22.09
21.82
21.55
21.28
21.01
20.74
20.47

Global collapse of circular sheet:



n > 10^3 cm^{-3}

n > 10^4 cm^{-3}

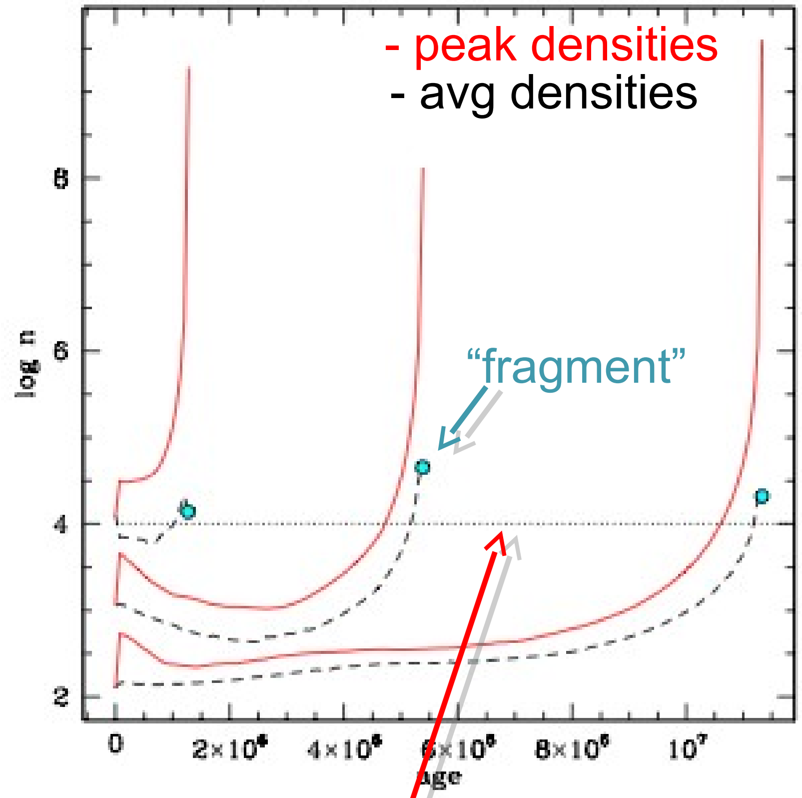
exponential growth

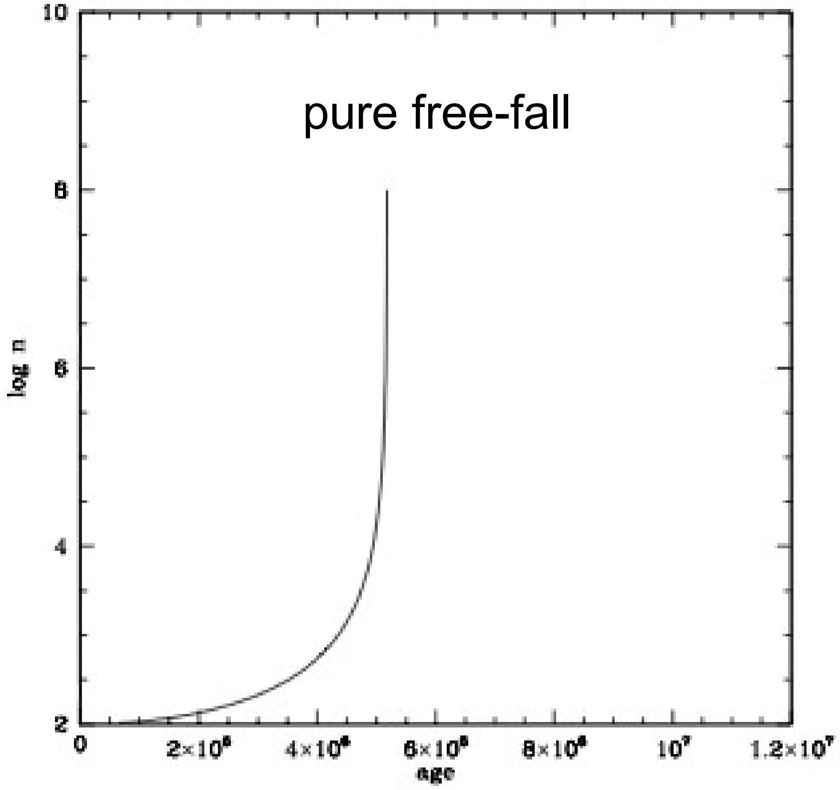
exponential growth at high densities fits the simulation remarkably well

Burkert & Hartmann 2012

Global collapse of circular sheet:

dense gas mass naturally increases non-linearly with time

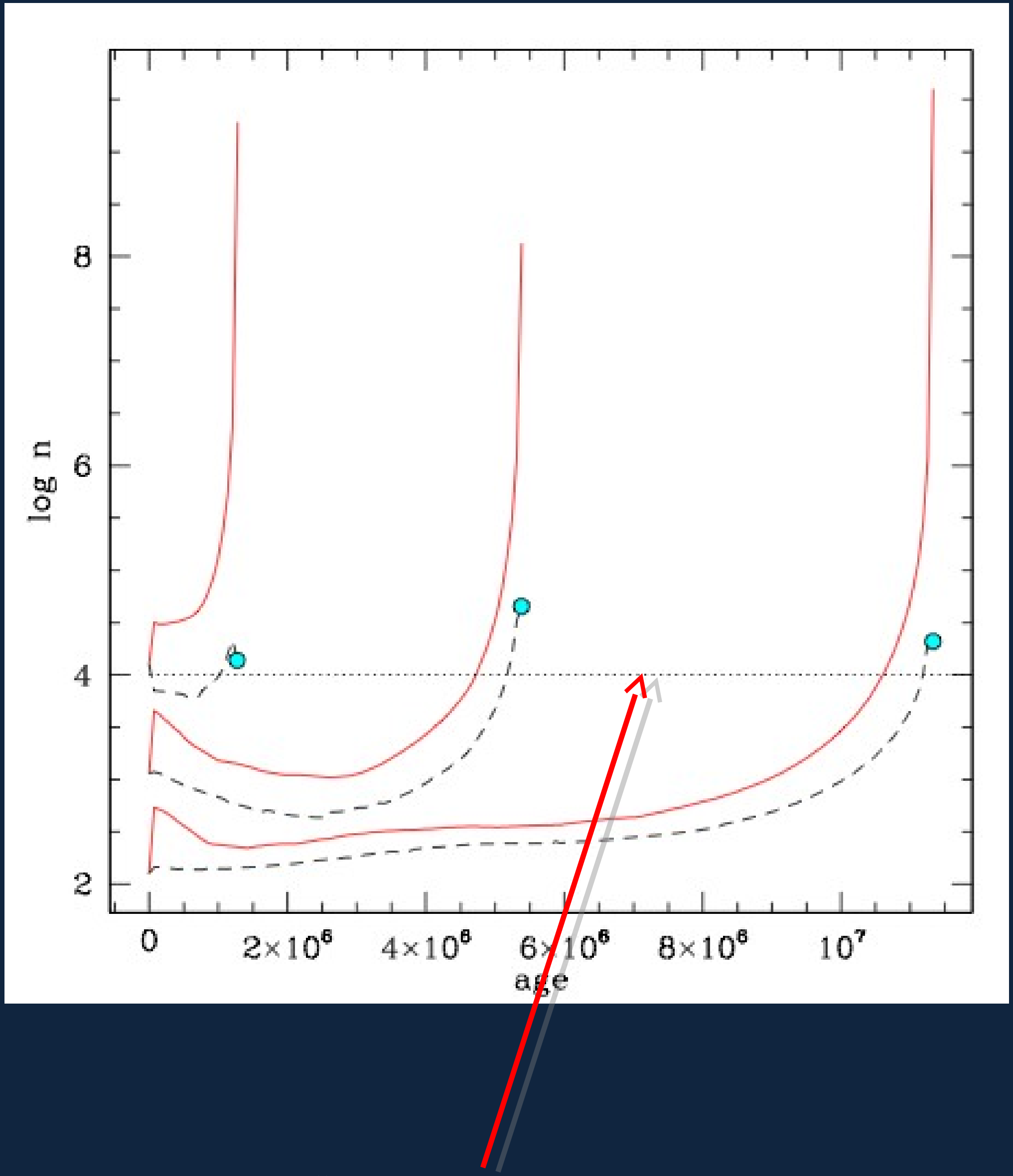




approx threshold density

Burkert & Hartmann 2012

Global collapse under gravity:



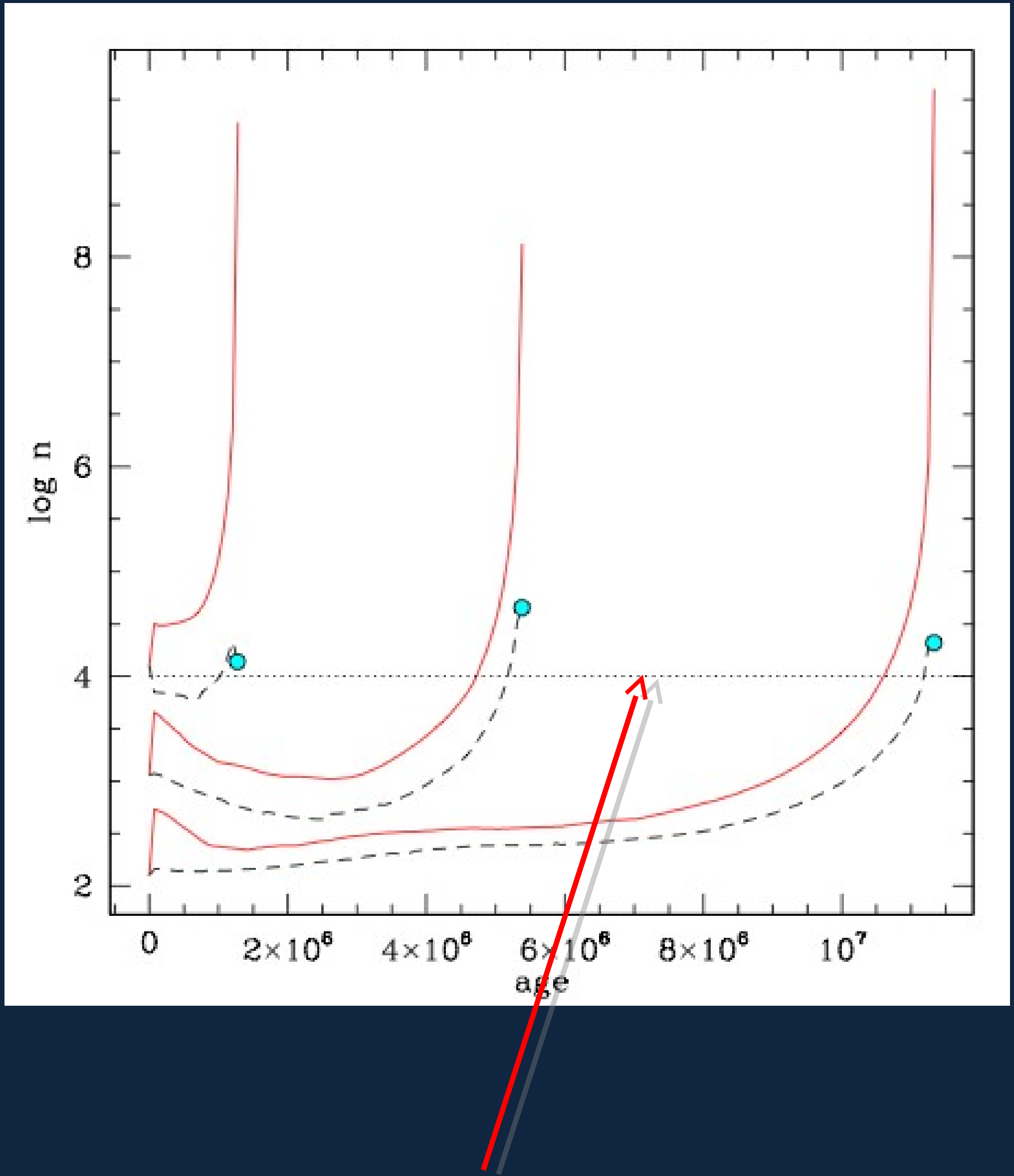
approx “threshold” density

There is NOT a specific magic density or Σ above which stars form;

the observational “threshold” ~ where evolution becomes ≈ 10x faster than the global cloud evolutionary time of a few Myr

Burkert & Hartmann 2012

Global collapse under gravity:



approx “threshold” density

But why ~ 10^4 cm^{-3}?
or Σ ~ 100 Msun/pc^2 ?

At this surface density, the pressure P(grav) = $\pi G \Sigma^2/2$ > 300x typical P(ISM)
⇒ gravity dominates

⇒ most of the cloud is at lower Σ because it was formed by lower- pressure ISM flows

Need low Σ cloud to form the impression of a “threshold”

Burkert & Hartmann 2012

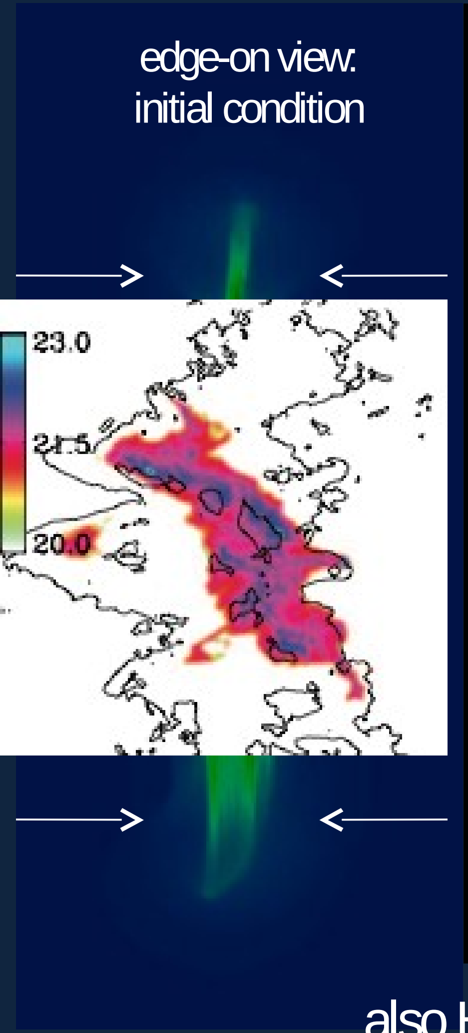
3. This is too simple! No turbulence!...

Sheet made by uniform inflows with cooling;

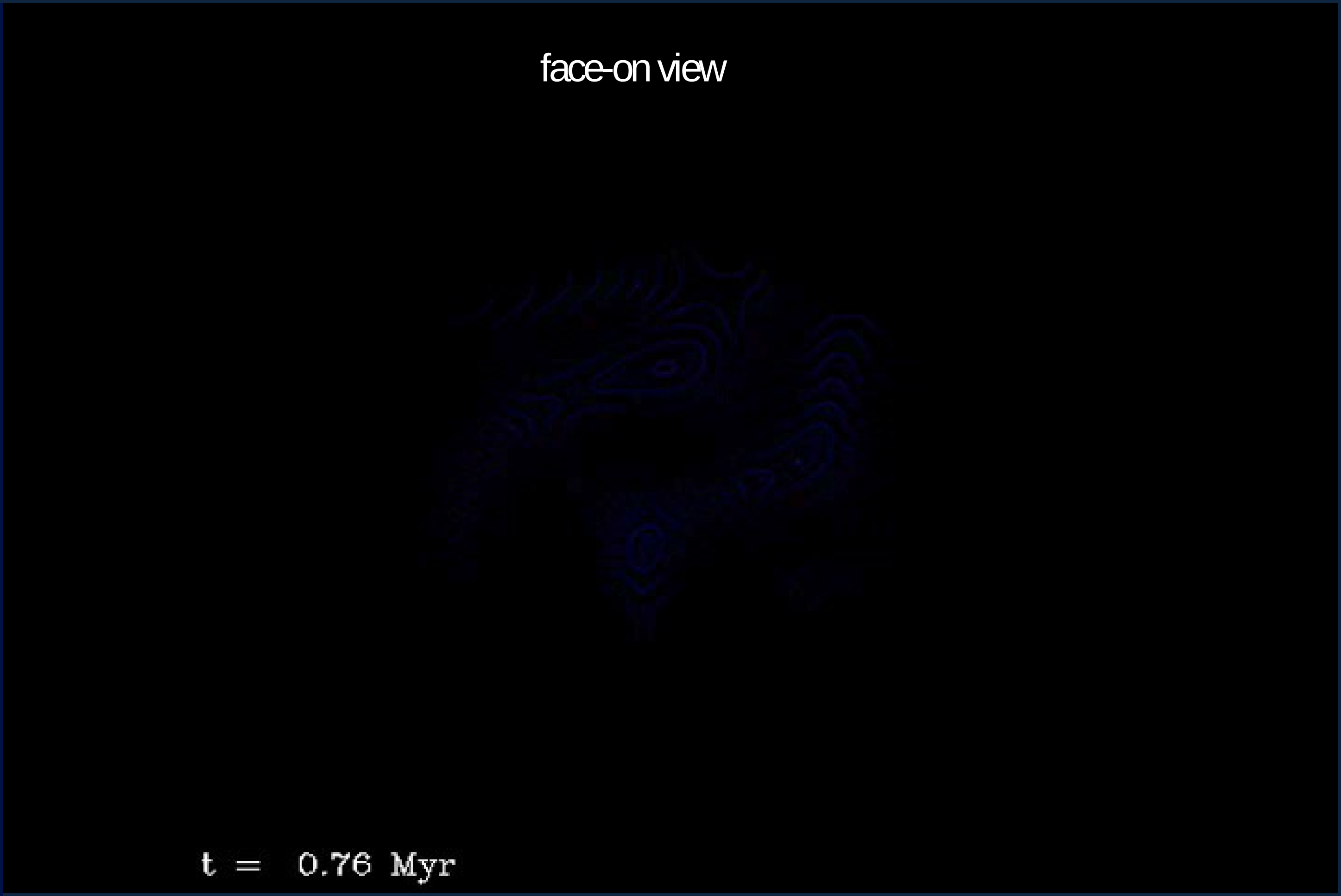
instability ⇒ turbulence + cooling ⇒ density fluctuations;

then gravity wins!

Heitsch+ 2007, 2008



edge-on view:
initial condition



face-on view

also Hennebelle; Vazquez-Semadeni+ 2007, 2010; Clark & Glover

Simulations of cloud flow with gravity show accelerating collapse

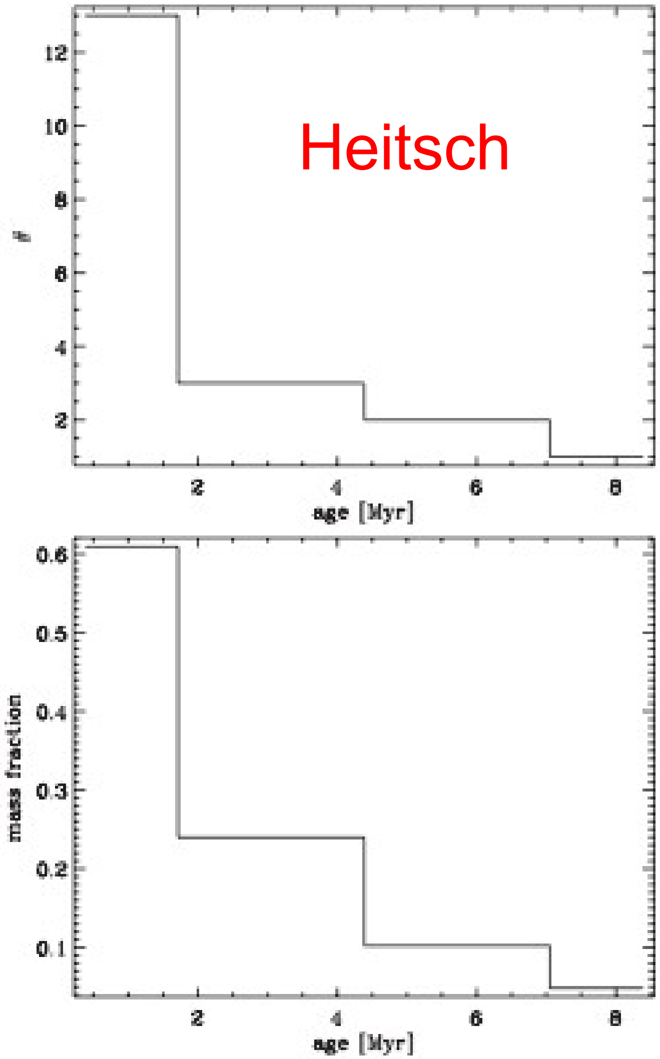


Figure 2. History of massive core formation in the simulation Gs of Heitsch et al. (2008), plotted as a function of time prior to the end of the simulation (see text).

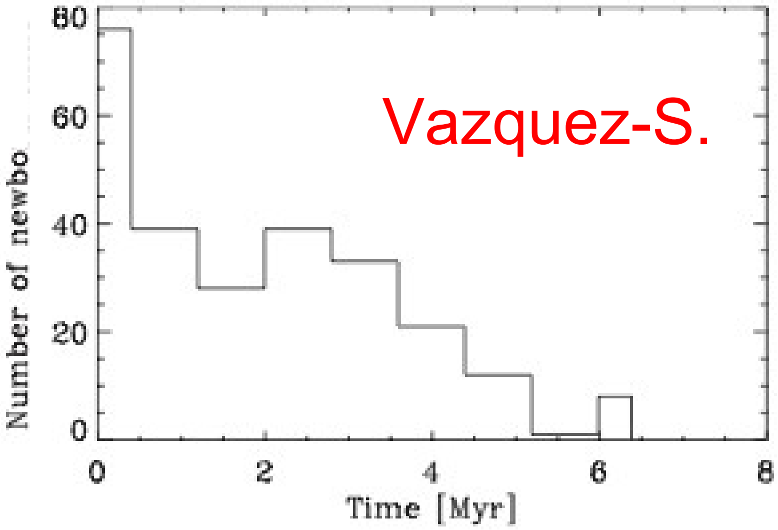
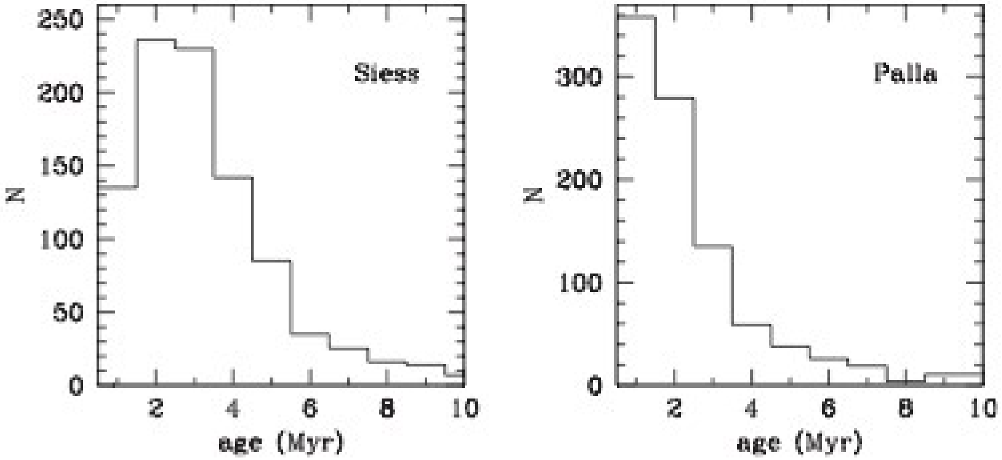
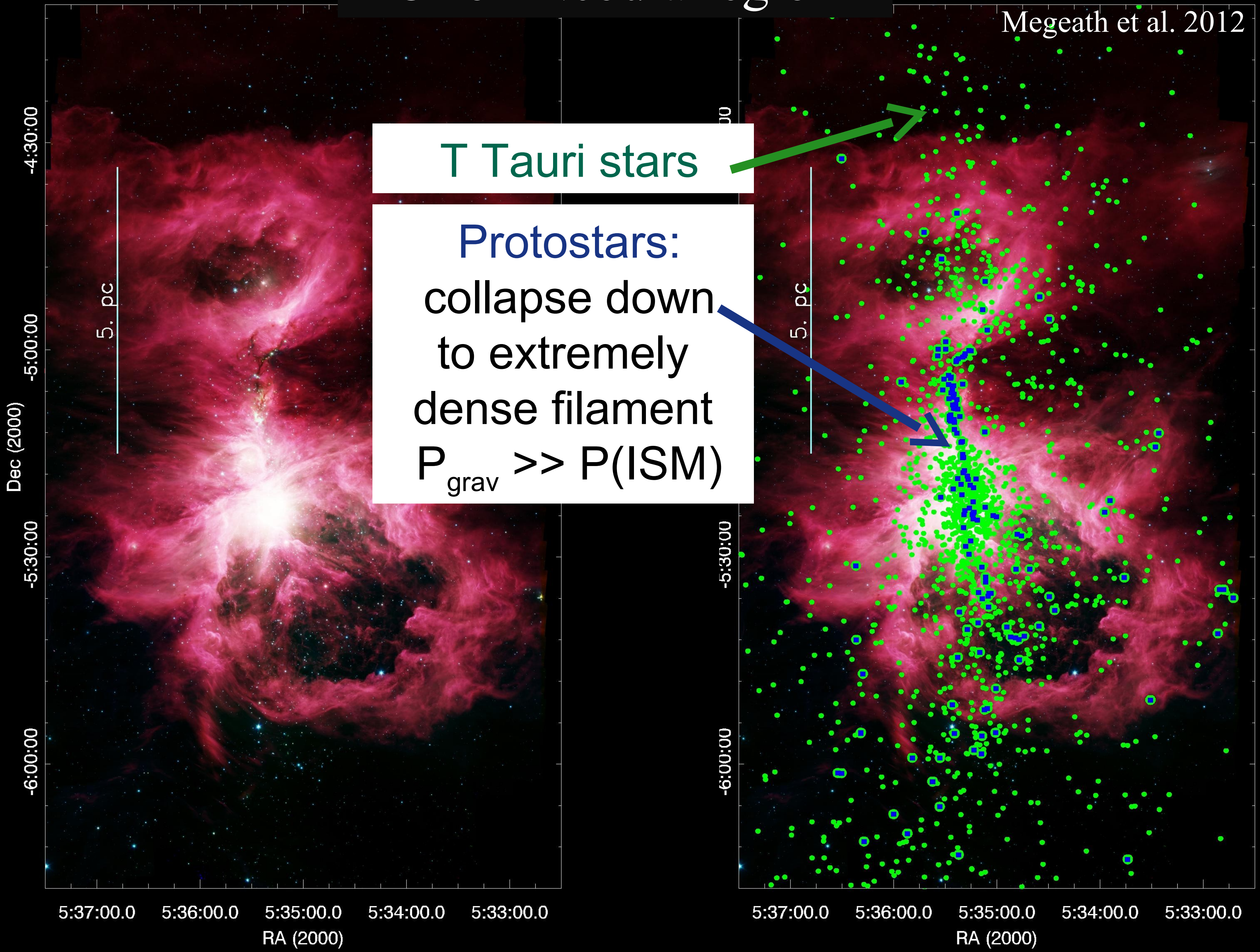


Figure 4. Histograms of the newborn sink particles as a function of time for run 20 in Vázquez-Semadeni et al. (2007). The number of newborn sink



ages of ONC stars??

Orion Nebula region

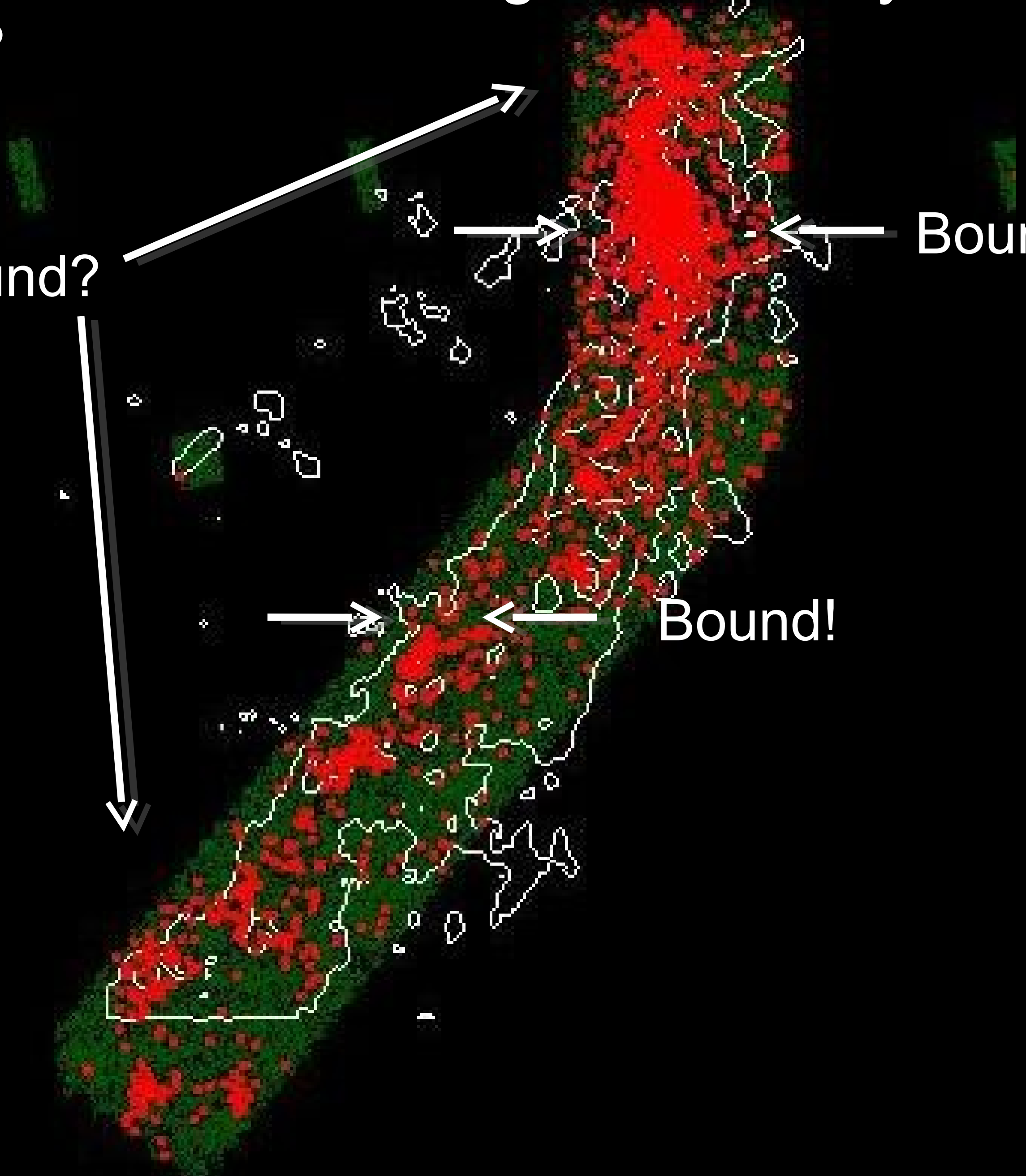


Megeath et al. 2012

T Tauri stars

Protostars: collapse down to extremely dense filament $P_{grav} >> P(ISM)$

4. Are molecular clouds gravitationally bound?

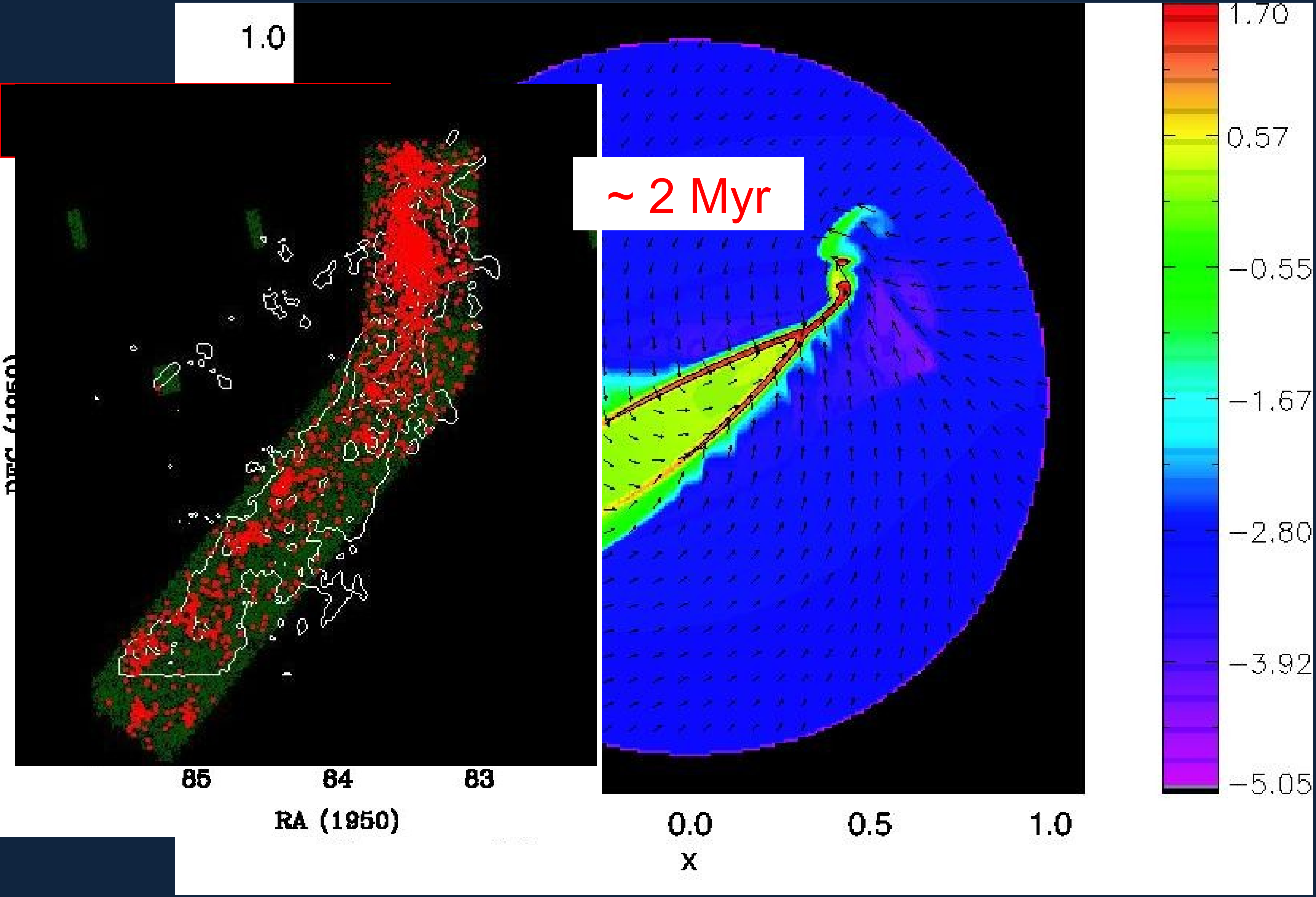


Bound?

Bound!

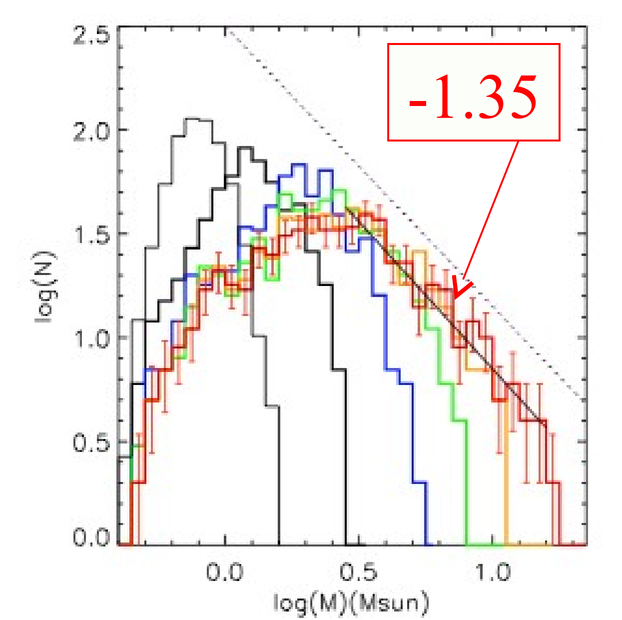
Bound!

Orion A (Hartmann & Burkert 2007): rotating oval sheet with a surface density gradient



~ 2 Myr

Upper mass IMF: “competitive accretion” (Bonnell, Bate); essentially Bondi-Hoyle accretion (Zinnecker 1982)

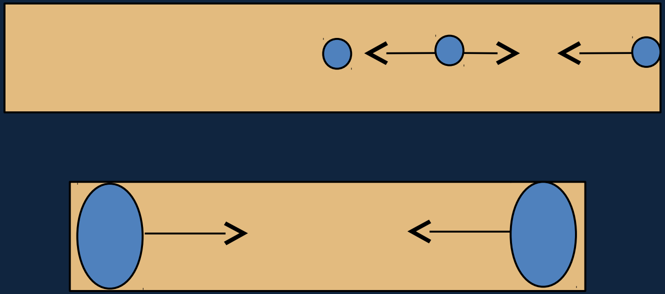


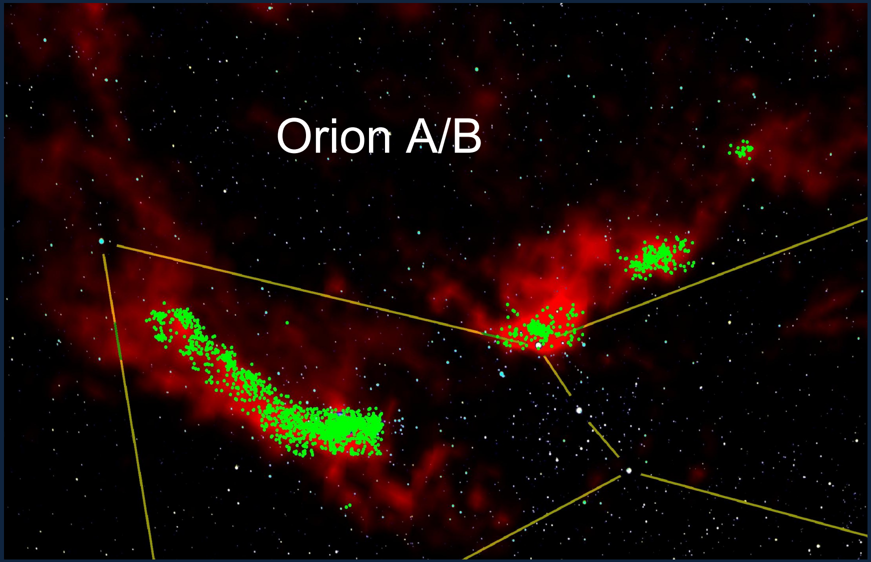
Hsu+ 2010 simulation “turbulence” is only density, not velocity fluctuations; result is evolution toward Salpeter purely due to gravity

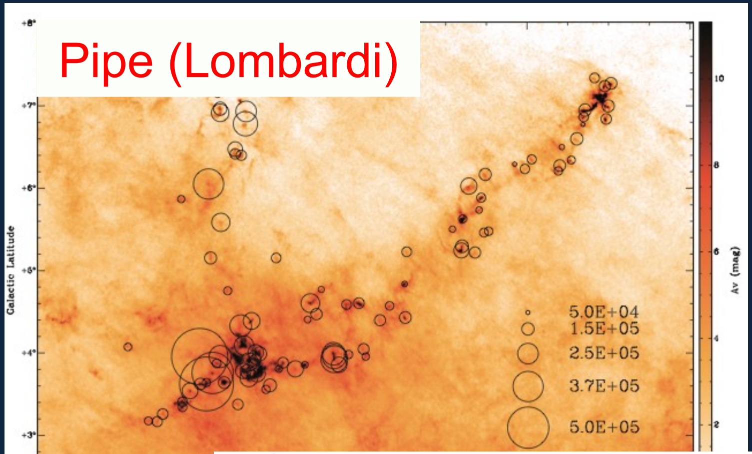
implies non-universal IMF; consistent with fewer high-M stars in lower-ρ environments (less gas to accrete) (Hsu talk)

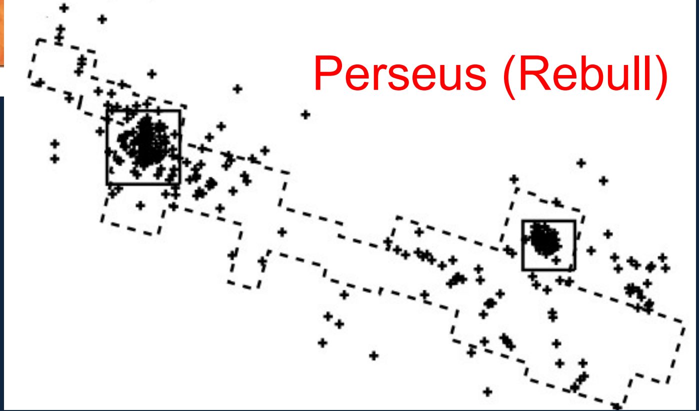
Upper IMF similar to star cluster IMF (Lada^2, Fall, Chandar); gravitational focusing to make clusters?

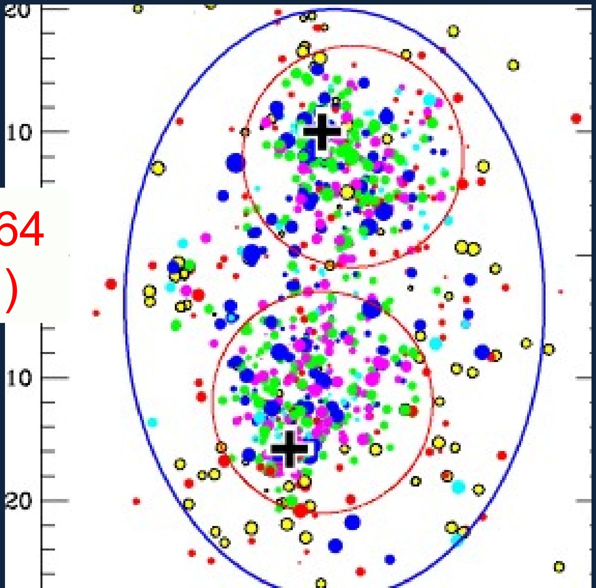
Evidence for large-scale gravity; focusing in elongated clouds causes clusters to form preferentially at ends (Bonnell; Burkert & LH, “focal points”)




Orion A/B


Pipe (Lombardi)


Perseus (Rebull)


NGC 2264
(Sung+)

Summary

1. Star formation is dynamic: locally, strongly driven by stellar energy input; dispersal and formation on 10s of pc scales
2. Star-forming molecular clouds are dynamically evolving with long-range gravitational collapse continually producing dense gas at an increasing rate
3. Long-range gravity ⇒ Upper-mass stellar IMF, clusters