Radiative Feedback and Cluster Formation Across the GMC Mass Spectrum

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Ralph E. Pudritz

Dept. of Physics and Astronomy, and

Origins Institute, McMaster University

Students, postdocs, and collaborators

McMaster: Corey Howard (Ph.D.), Mikhail Klassen (Ph.D.,
Helen Kirk (Banting Fellow, Herzberg Inst. for Astrophysics),
Bill Harris.

PPVI 2014, Andre et al team – filaments: (Philippe Andre, James de Francesco, Derek Ward-Thompson, Shu-ichiro Inutsuka, and Jaime Pineda)

Some basic questions:

- How do clusters form in filamentary GMCs?

- 90% of stars form in clusters… so cluster formation must dictate SFEs, SFRs, … What controls these? Feedback?

- Do cluster properties scale across GMC mass spectrum? Can we go from Orion to globular clusters with similar formation mechanism ?

I Observational Background

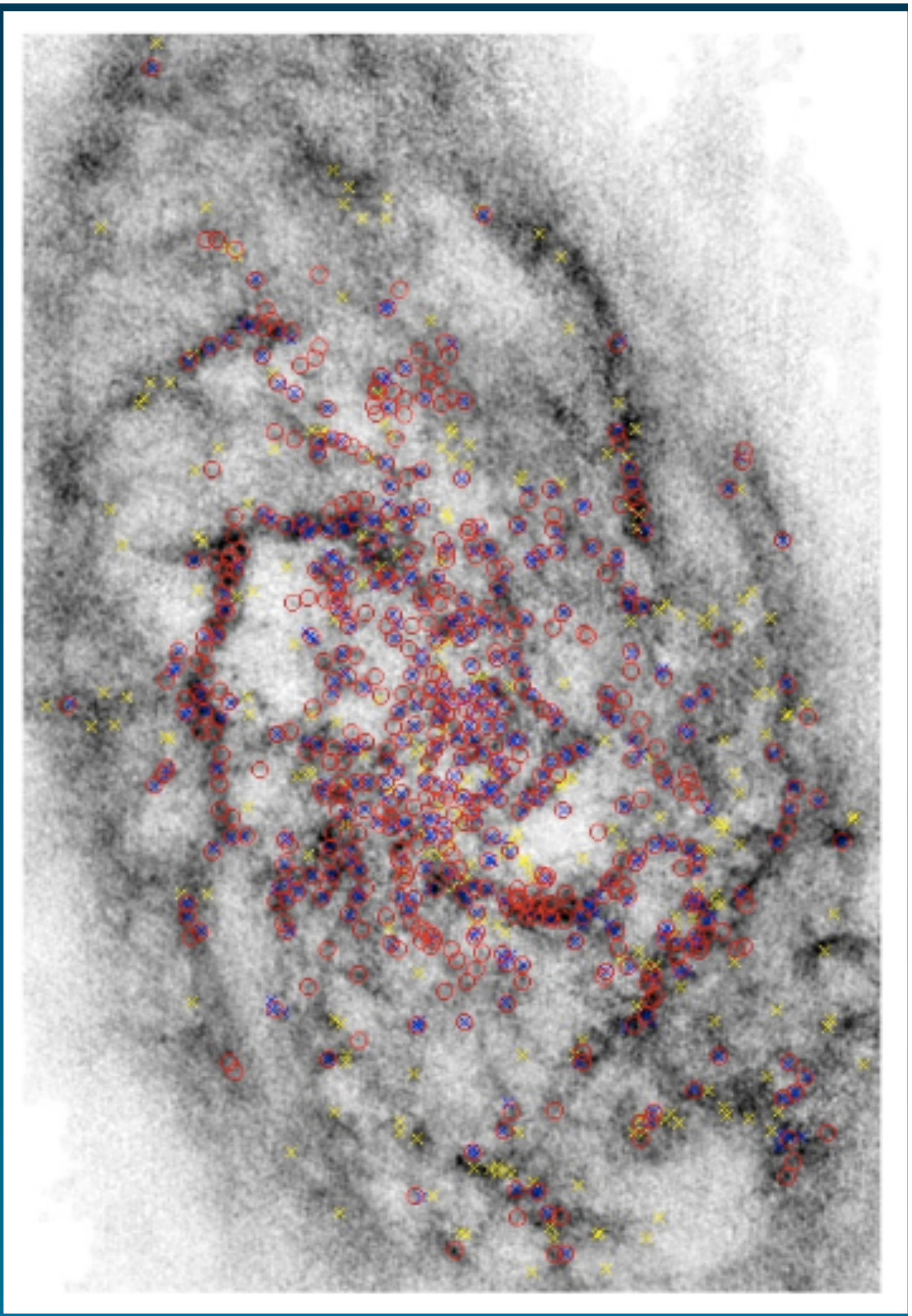
Galactic Scales: eg M33

Correspondence between:

- filamentary HI gas (grey) at 21cm (VLA, GBT)
- 566 giant molecular clouds (IRAM survey); $2 \times 10^4 - 2 \times 10^6$ M_{Sun}
- 630 young stellar clusters (Spitzer 24 µm, Galex UV- Sharma+2011); ages peak at 5 Myr

Clouds ages ~ 14 Myr (comparable to MW):

No clusters, 4Myr; embedded clusters, 2Myr; close association, clusters-GMCs.



GMCs (red) and clusters (yellow crosses) in M33 - Corbelli + 2017

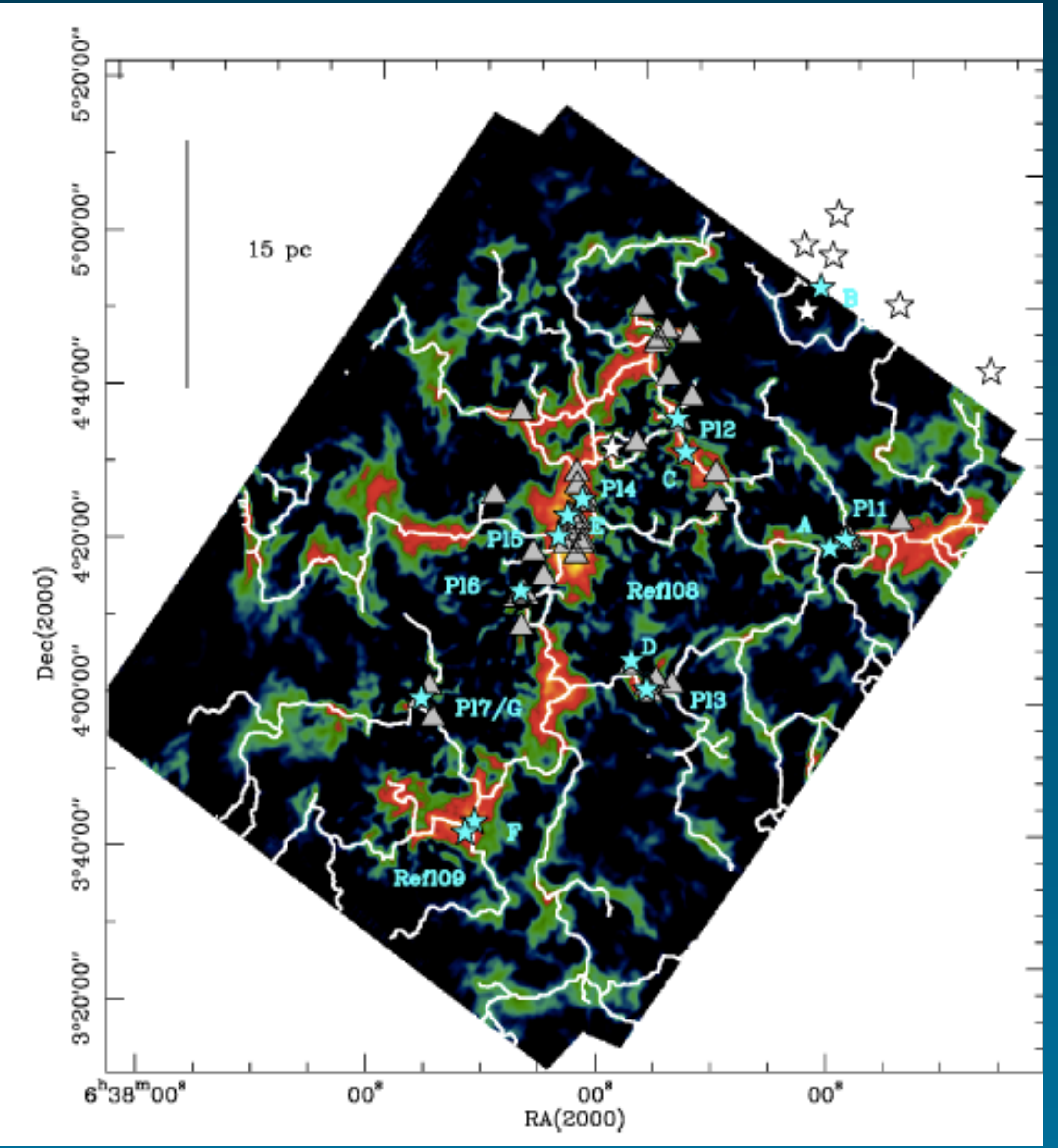
Clusters found at junctions of filaments

- Rosette illuminated by central OB cluster. GMC mass ~ 10^5 M_{sun}
- Clusters lie at filament intersections (eg. Myers 2009). Stellar cores occur in filaments

(simulations: Klessen & Hennebelle 2010, Vasquez-Semadeni + 2009)

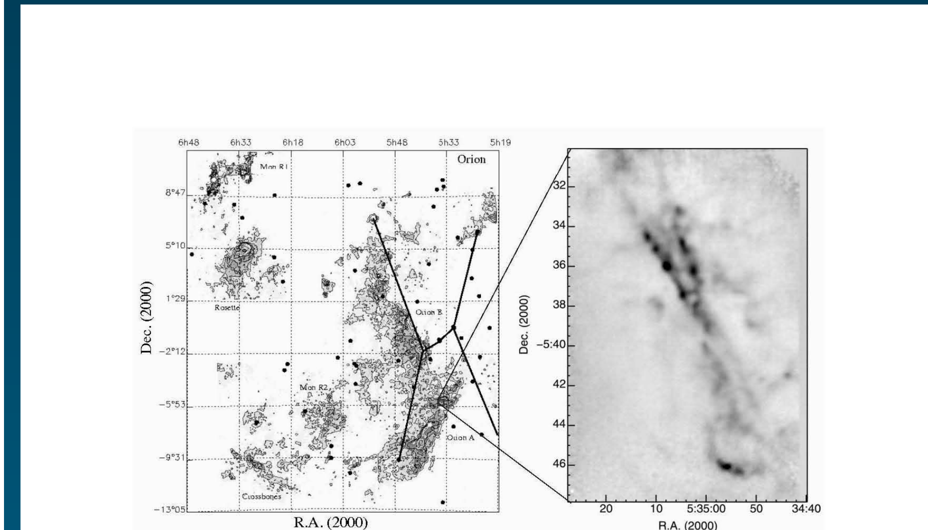
- Break in lognormal PDFs at A_v ~ 7-10 mag

- High mass and high accretion rates produce clusters



Clusters (blue stars) in Rosette Molecular Cloud: - Schneider + 2012

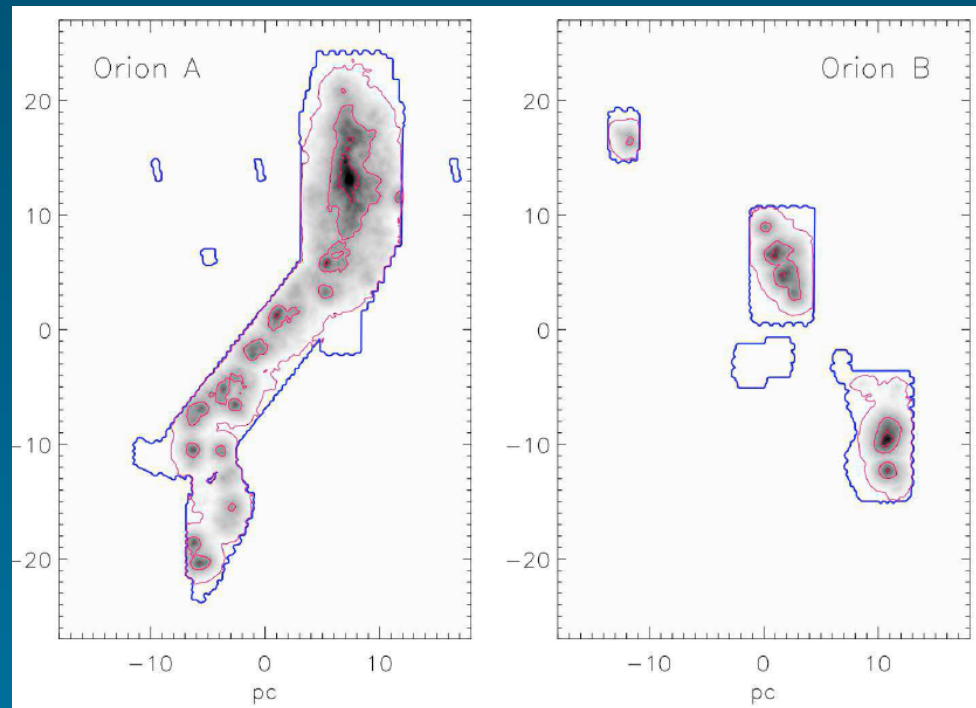
Clusters and filamentary clouds in the Milky Way; Orion



Left:
Extinction map of Orion and Mon molecular clouds (Cambresy 1998);
Right :
Scuba continuum 850 micron map of 10 pc portion of cloud (Johnstone & Bally 2006)

Clusters in Orion A and B clouds. Contours at 1, 10, and 100 pc^{-1} : (McGeath + 2016)

Suggests gravitational fragmentsion….



GMC Dynamics: Gravitational Boundedness

- Filaments & clumps
- Range of virial parameters

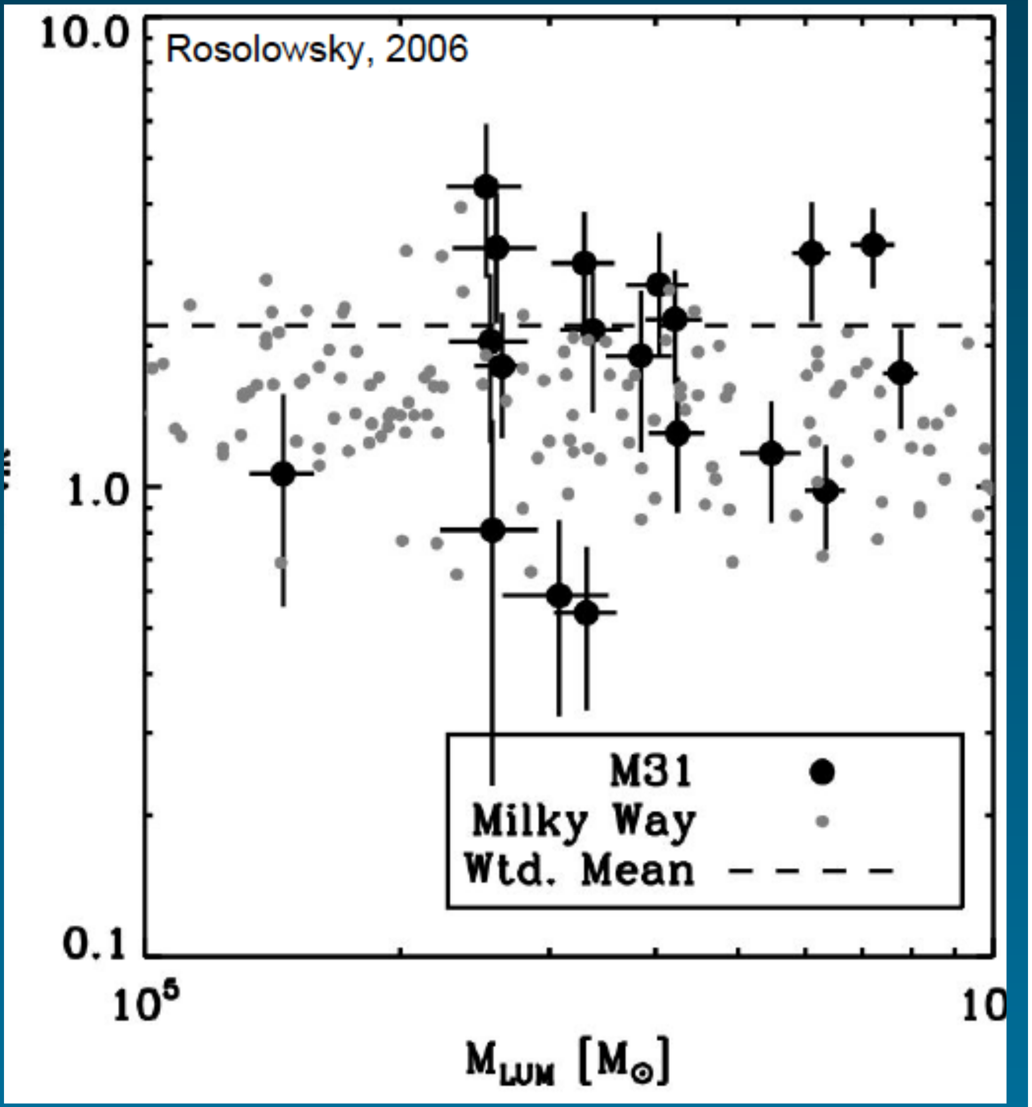
Observed clouds:

α from 0.5 – 5 (Rosolowsky2007, Hernandez & Tan 2015))

$$\alpha \approx \frac{5\sigma^2 R}{GM} = \frac{2E_{kin}}{|E_{grav}|}$$

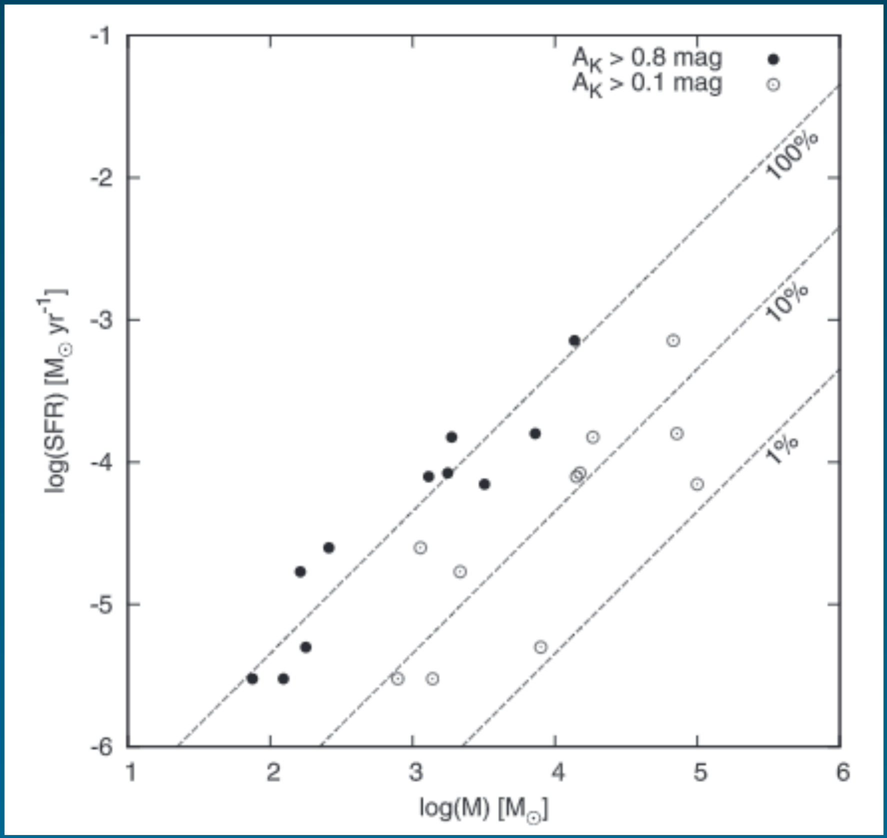
(Bertoldi & McKee, 1992)

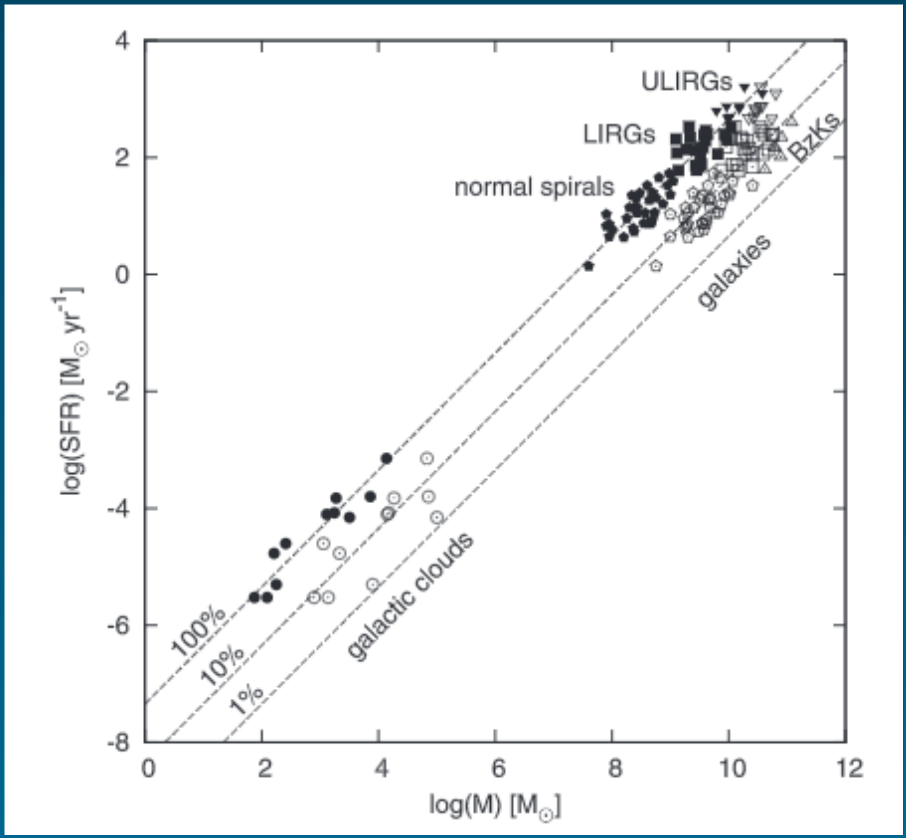
- Does this affect cluster formation? SFRs?



Star Formation Rates in Dense Gas: Multiscale Relation

Star formation rates correlate with the mass of dense gas in GMCs (n~ 10^4 cm^{-3} as measured by HCN)





Tight correlation above A_k~ 0.8 mag, over 9 decades!

(Lada + 2012; also Wu+2005, Gao & Solomon 2004)

$$SFR \equiv \dot{M}_* = 4.6 \times 10^{-8} f_{DG} M_G(M_\odot) \quad M_\odot \ yr^{-1}$$

Universal cluster scalings?

- Is there a higher density threshold in galactic CMZ? Why is star formation suppressed in dense clouds (Kruijssen+2014)?

- n_c / n_o = $x_{\rm turb} = A_x \alpha_{\rm vir} \mathcal{M}^2$; (Krumholz & McKee 2005, Padoan & Nordlund (2011)

If M = 10, and α_{vir} ~ A_x ~ 1 -> n_c ~ 10^2 n_o = 10^4 ✓

BUT; very sensitive to exact value of M… fine tuning?

Can have high virial parameters and M in more unbound systems…

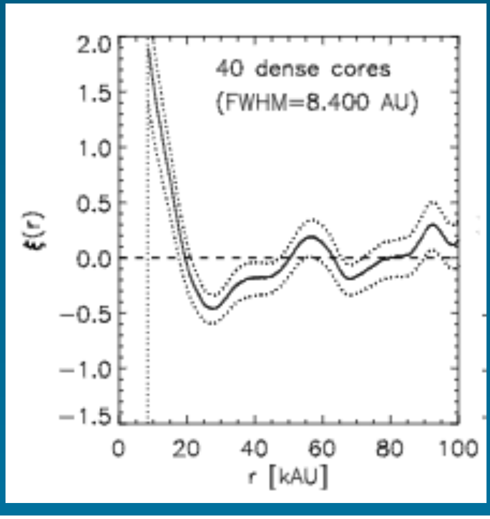
Gravitational Fragmentation of Filaments – the First Step? ALMA Observations of Orion A (Kainulainen+2016)

Multi-scale fragmentation

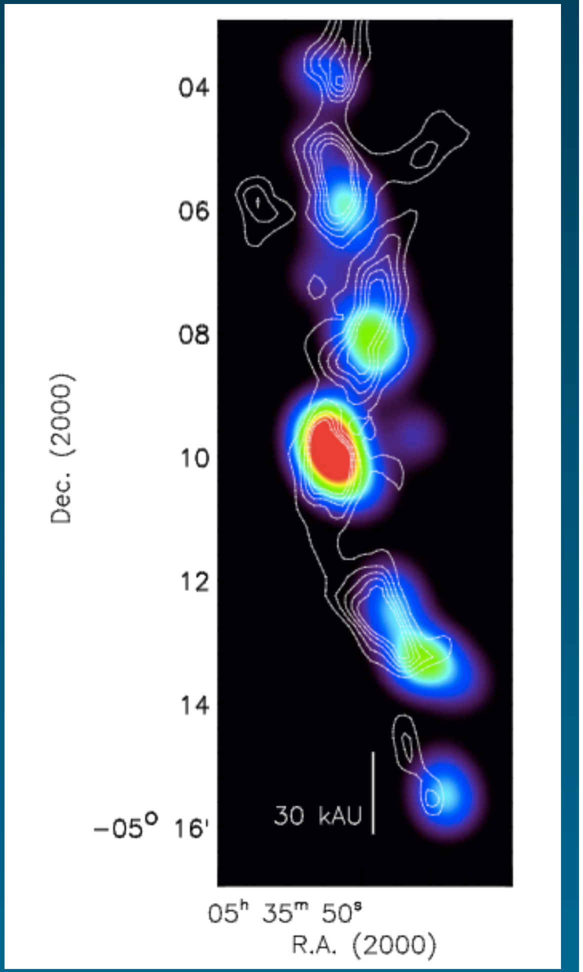
- Linear theory; periodic - fastest growing mode ~ several times filament width (eg. Larson.., Inutsuka * Miyama,..

Peak at 55,000 AU but growing power at spacings < 16,000 AU

- Periodic fragmentation for 55,000 AU (Fiege & Pudritz 2001a,b, Fischera & Martin 2012). Jeans type in spherical regions < 16,000 AU?



2 point correlation function of dense cores



Surface density of dense cores – contours at 60,80… 140 x 10^{21} cm^{-2}

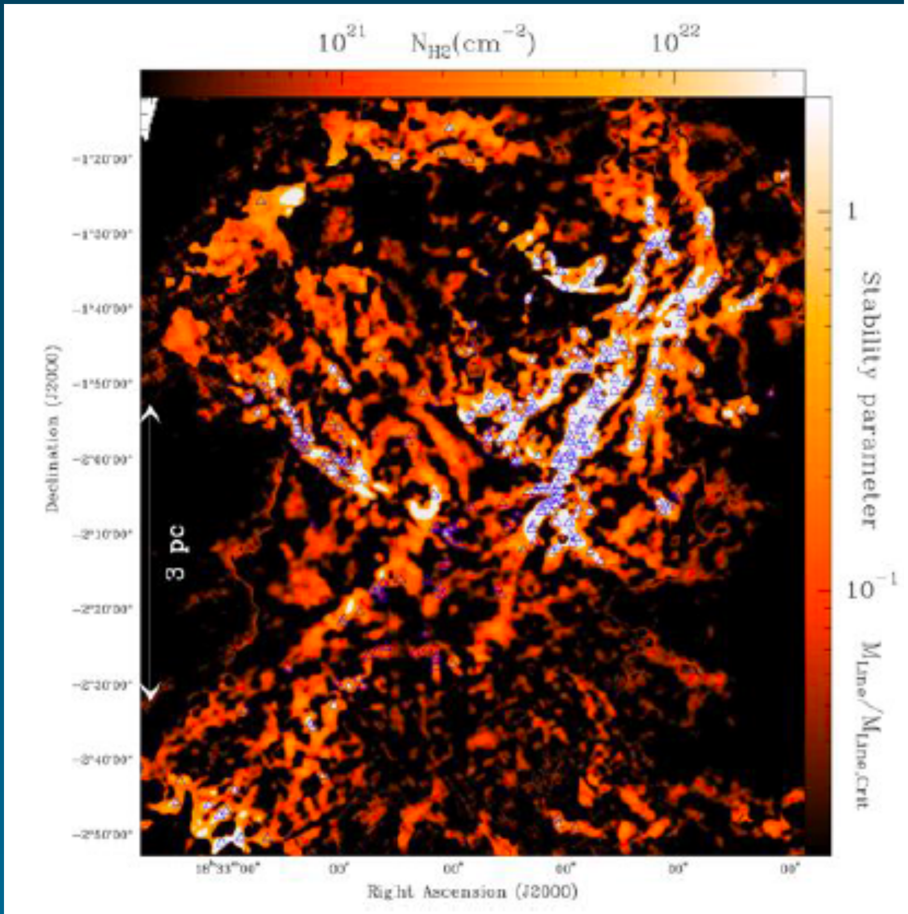
Evidence: core formation by gravitational instability….

Filaments: lengths 0.1 – 100 pc; masses 1 – 10^5 M_{sun} , line masses < 1000 M_{sun} pc^{-1} (Bally+ 1987, Hacar +2013, Kainulainen+2013,2016, .. Review: Andre +2014)

Herschel observations: clouds filamentary down to sub pc (Andre+ 2010, 2014 (PPVI), Menshchikov+2011, Henning+2010..)

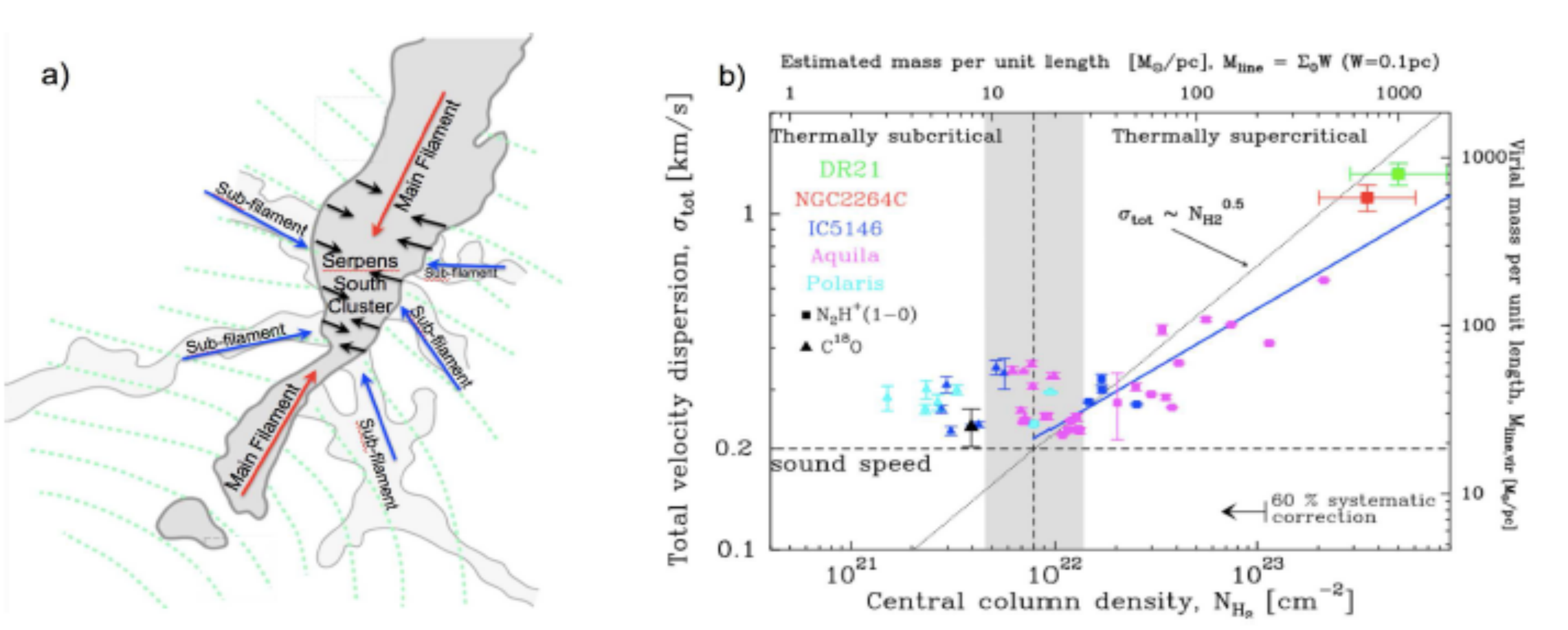
- Cores strongly associated with filaments > 70%; Polychroni+ 2013)

- GI? White = mass / length (T=10K): $m > m_{crit} = 2\, c_s^2 / G \sim 16\, M_{sun}\, pc^{-1}$



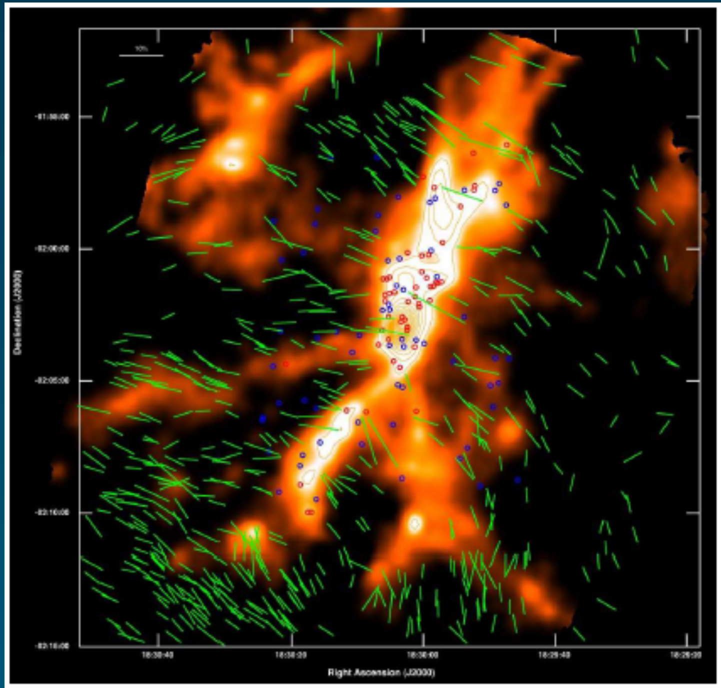
Aquila star forming cloud:
Andre+ 2010

Isolated clumps not enough!
filamentary flows gather cluster gas…



Accretion and filamentary flow:
sketch of velocity field around Serpens-South cluster (Kirk et al 2013)

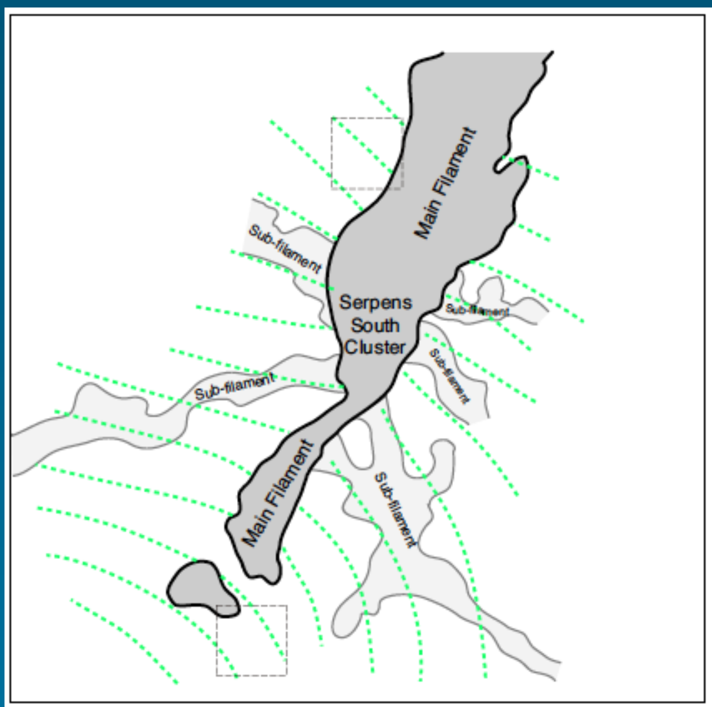
Total velocity dispersion vs central column density of filaments
(Arzoumanian et al 2013)



B fields - channeling gas onto filaments (review Hua-bai Li + 2014)

Infrared (H band) polarization overlaid on column density map + young stellar cluster

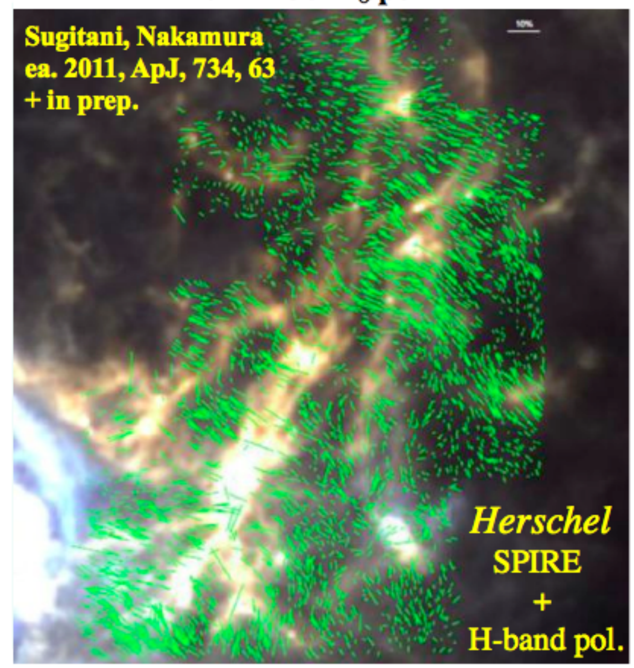
- Orientation – often perp to dense filament.
- Field strength ~ 100 μG



But.. this impedes filamentary flow! (gas doesn't like to cross field lines). Explanation?

Serpens South filament/protocluster:

M/L ~ 250 $M_\odot$/pc

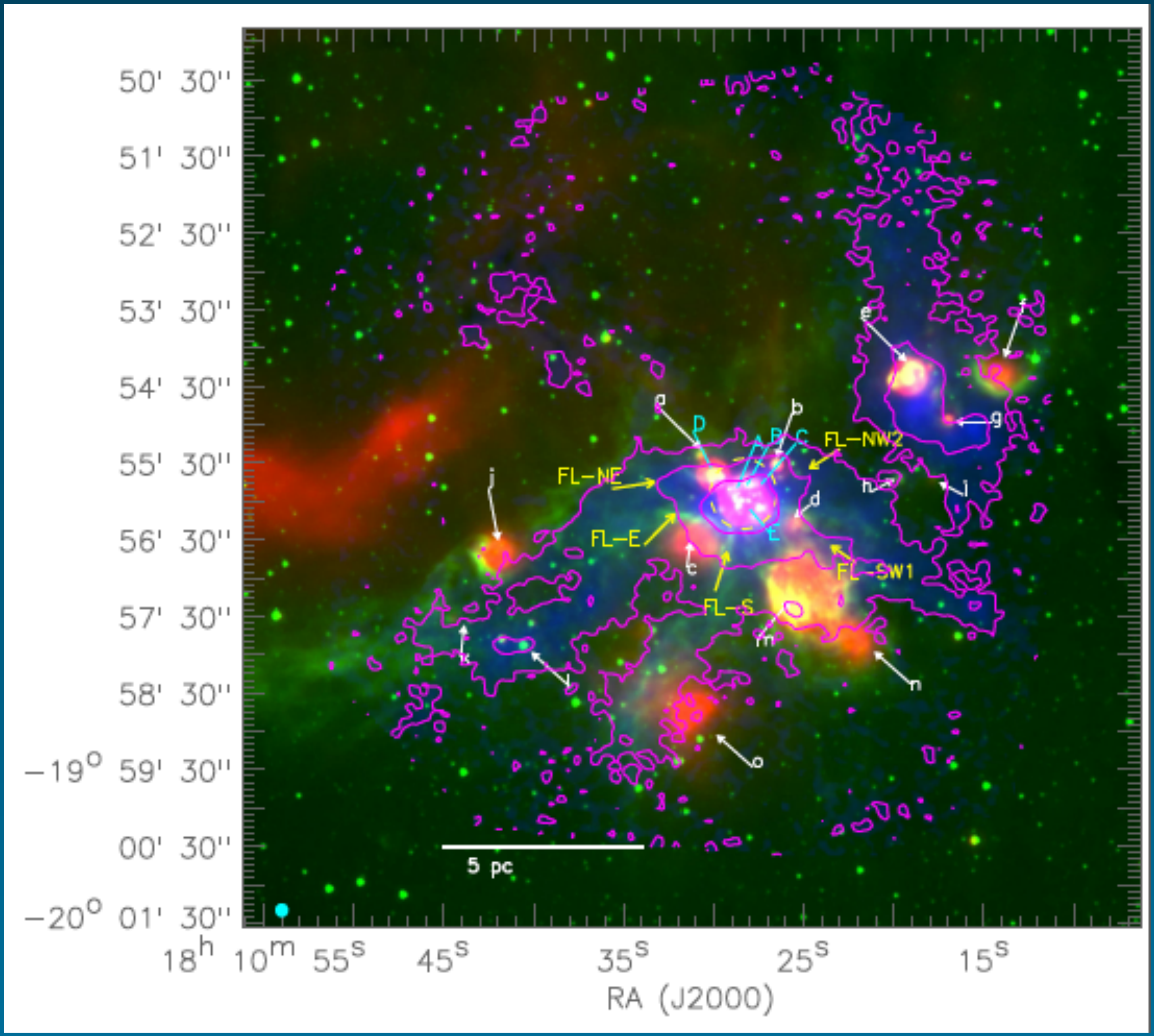


Ending cluster accretion?
radiative feedback from young clusters in filaments

Filaments and OB clusters, and HII regions in G10.6-0.4

(IRAM 30m MAMBO-2 bolometer array + SMA)

- 200 $M_{\odot}$ OB cluster
- Ultracompact HII regions: A-E



H.B. Liu et al 2011

IMF in star forming regions

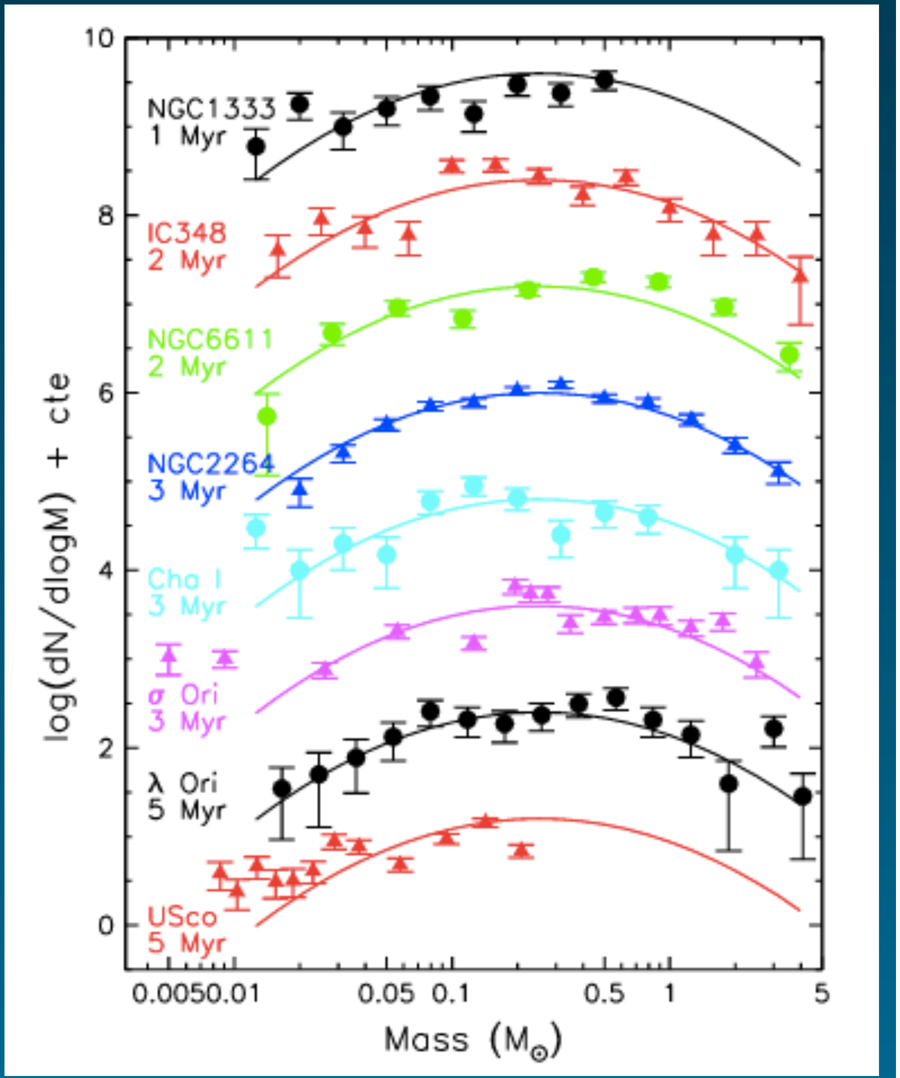
Remarkable agreement between different regions: with IMF Chabrier (2005):

lognormal - with peak 0.2-0.3 M_{sun} and $\sigma = 0.5$

(JWST will push down to 1 M_{jup} by observing in 3-10 μm)

Why? Properties of turbulence?

(Padoan+ 1997, Hennebelle & Chabrier 2008, Hopkins 2012, Offner+2014)



IMFs from 8 star forming regions. Data: Scholz+2012, Alves de Oliveira+2013, Oliveira+ 2009, Sung & Bessell 2010, Luhman+2007, Pena Ramirex+2012, Bayo +2011, Lodieu2013. Compiled by Offner+2014 (ppvi)

II Cluster formation: turbulence, feedback and B.

No feedback : turbulence, gravity and fragmentation

Turbulence, filaments, and turbulent fragmentation

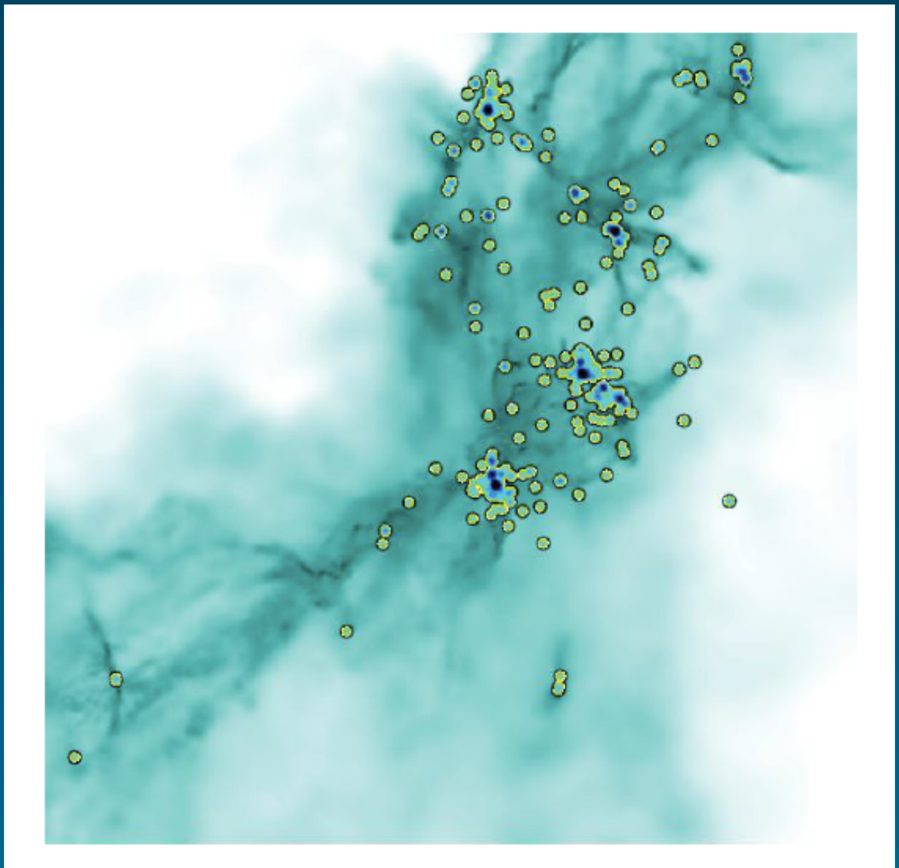
-Theory; eg. Larson 1981; Elmegreen & Scalo (2003)

-Reviews: eg. MacLow & Klessen 2004; McKee & Ostriker 2007; Bonnell et al 2007

- Simulations; Porter et al 1994; Vazquez-Semadeni et al 1995, Bate et al 1995, Klessen & Burkert 2001; Ostriker et al 1999, Padoan et al 2001; Tilley & Pudritz, 2004,2007; Krumholz et al 2007, Federrath et al 2010,…

Shocks dissipate turbulent support as t^{-1} (eg. Ostriker 2001)

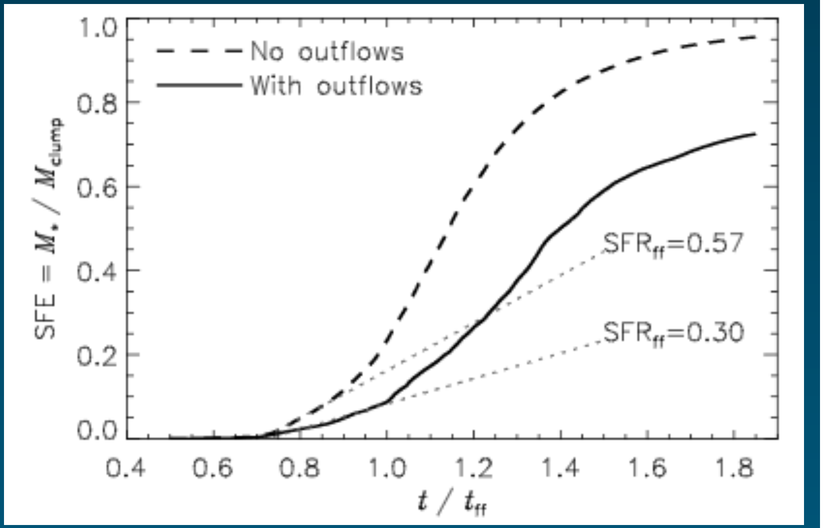
Figure: Subclusters, containing massive stars (blue), forming and accreting, and merging in turbulent cloud:



Bonnell, Vine, Bate (2004)

Feedback Effects

- radiative feedback: (thermal heating, radiation pressure, photo-ionization):
does not play a strong global role major accreting dense regions absorb most of the ionizing photons (Dale & Bonnell 2011, 2012)



- jets / outflows: drive small scale turbulence in clumps (Li & Nakamura 2006), Matzner (2007).

(Federrath+2014- winds, no rad.)

Simulations (Federrath + 2014) – reduce efficiencies by ~ 2

- stellar winds: perturbation on photionization effects – create spherical HII regions (Dale+ 2014).

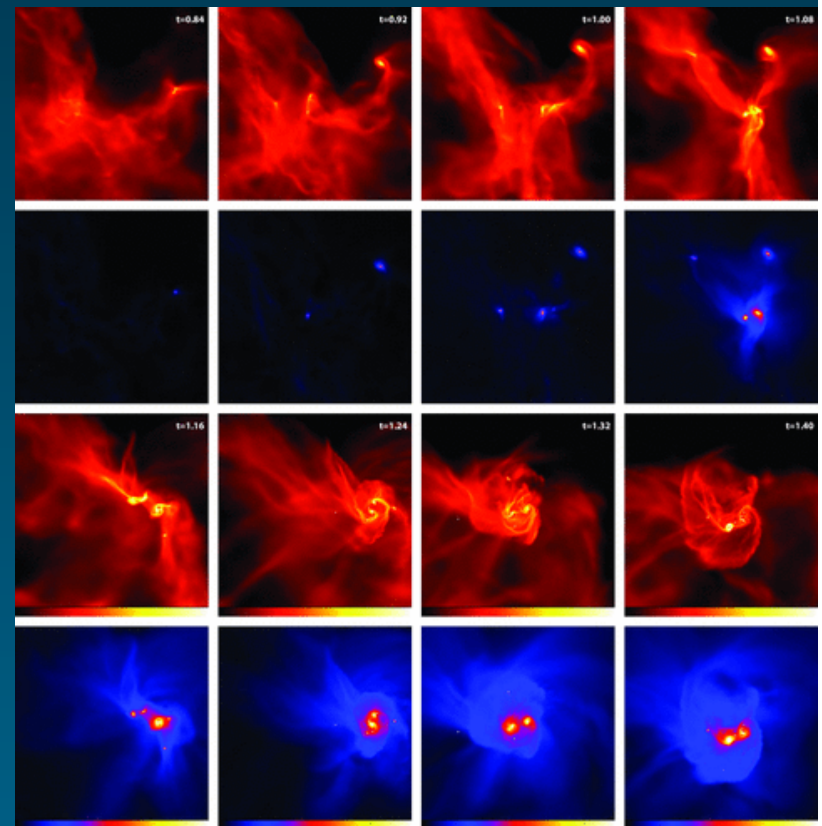
Break the filaments with outflows and cutoff gas flow? (eg. Wang + 2010)

- supernovae: too late: occur after winds/photoionization (> 4 Myr).

Cluster Formation Including Radiative Feedback

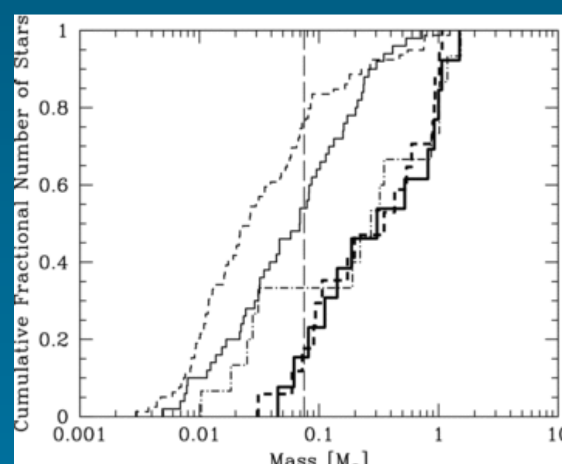
Radiative feedback from massive stars:
raises Jeans Mass $M_J \propto T^{3/2}$

- filaments don't fragment
- gas drains into primary and its disk (eg. Krumholz et al 2007)
- prevent fragmentation out to 1000 AU scales



Suppression of brown dwarfs:

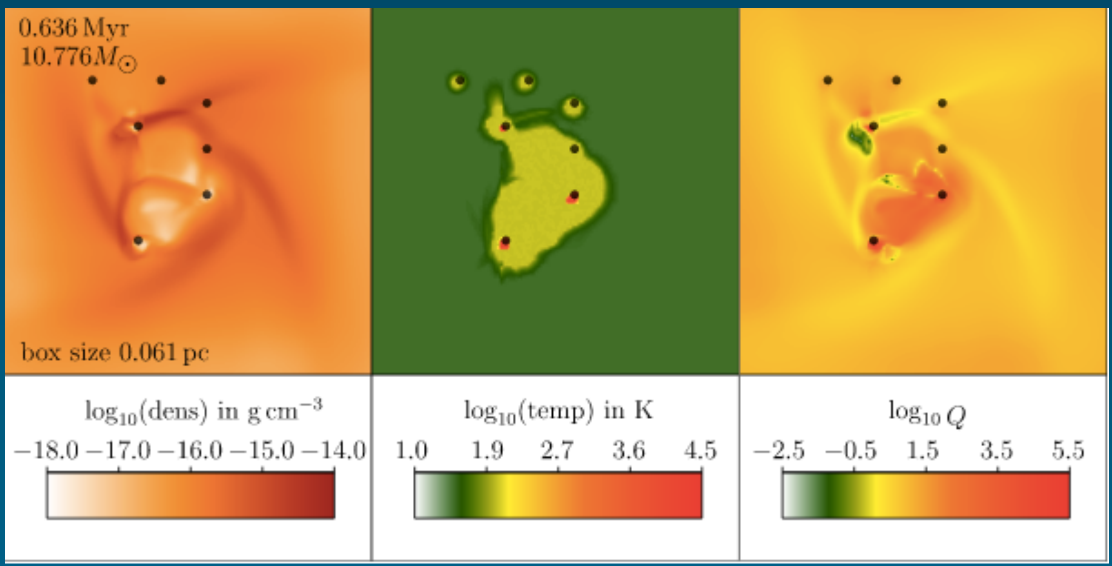
by factor 4 (Bate 2009): get robust low mass part of IMF…?

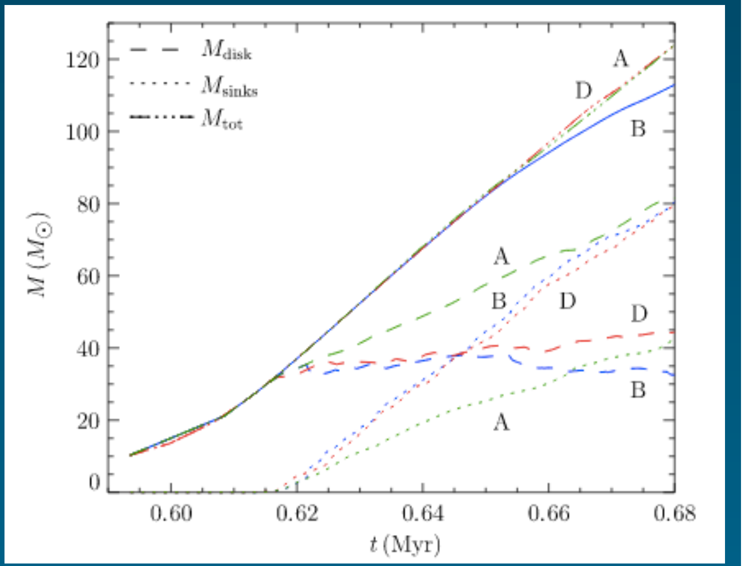


Bate (2009)

Mass limitation during cluster formation: fragmentation-induced starvation?

(Peters, Klessen, Mac Low, & Banerjee 2010)





Collapse into a disk of 1000 M_{sun} clump.
Ionization feedback.

- Fragments compete for gas in an unstable disk: muliplicity for O stars…
- Radiative heating -> larger Jeans mass
- (100 AU resolution)

Disk mass levels out..

Winds vs Photoionization

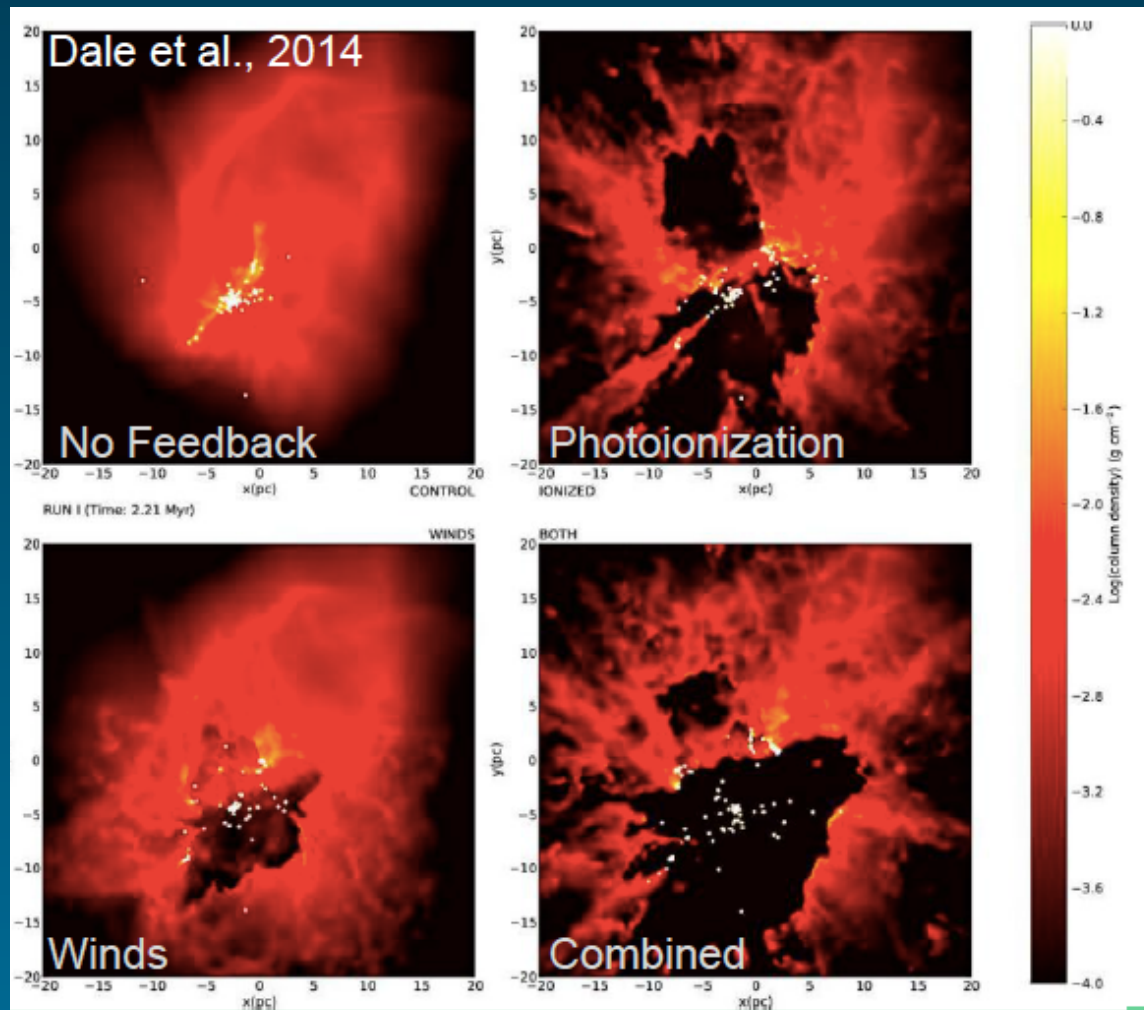
(eg. Dale + 2014)

- Winds most effective early – when massive stars deeply embedded

- Photoionization effects dominate at late times, when winds have cleared dense gas.

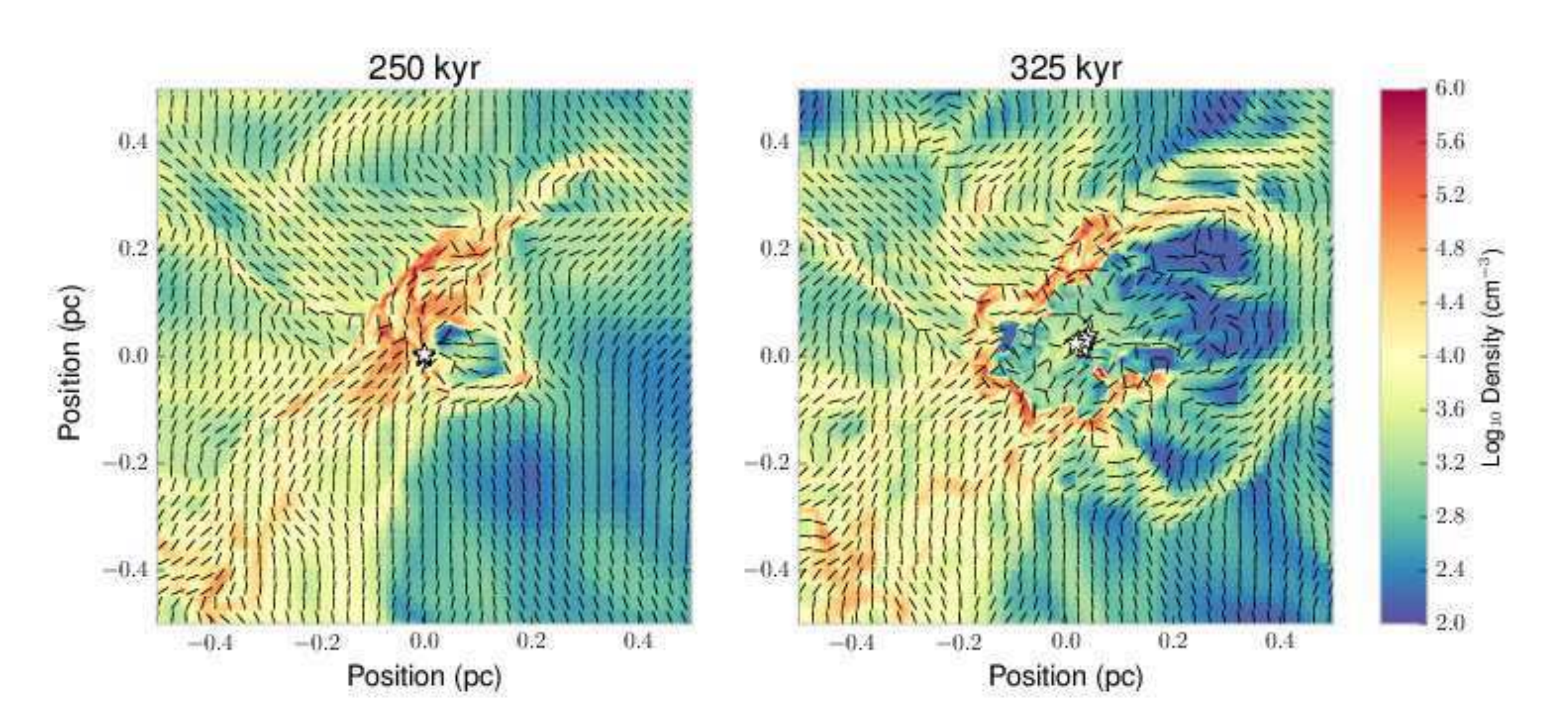
-Photoionization effects dominate. Biggest effect is on low mass clouds

(Also Murray+ 2010, Krumholz+2012..)



Gravity vs B in cluster building filaments:

Feedback in Serpens-like filamentary cloud: B and ρ in slice (Klassen, Pudritz & Kirk 2016) of gravitationally bound, 1200M_{Sun} cloud



- B II to filament within filament…perp outside: B dragged by gravitationally driven filamentary flow into cluster ..
- Bubble disrupts filament ending filamentary flow onto cluster

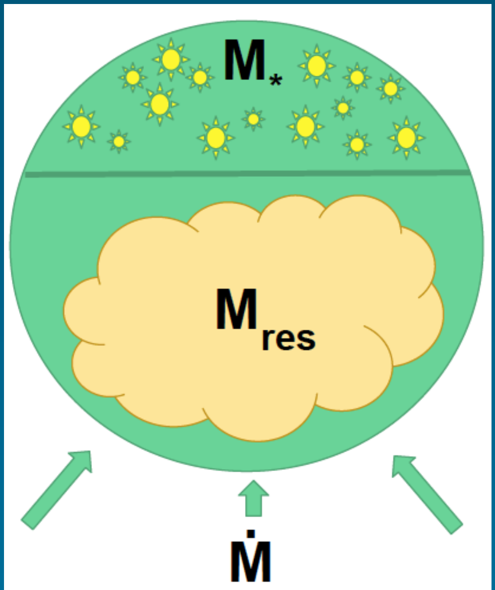
In cloud that forms a 16 M_{Sun} star and small cluster.

III. Radiative feedback and cluster formation

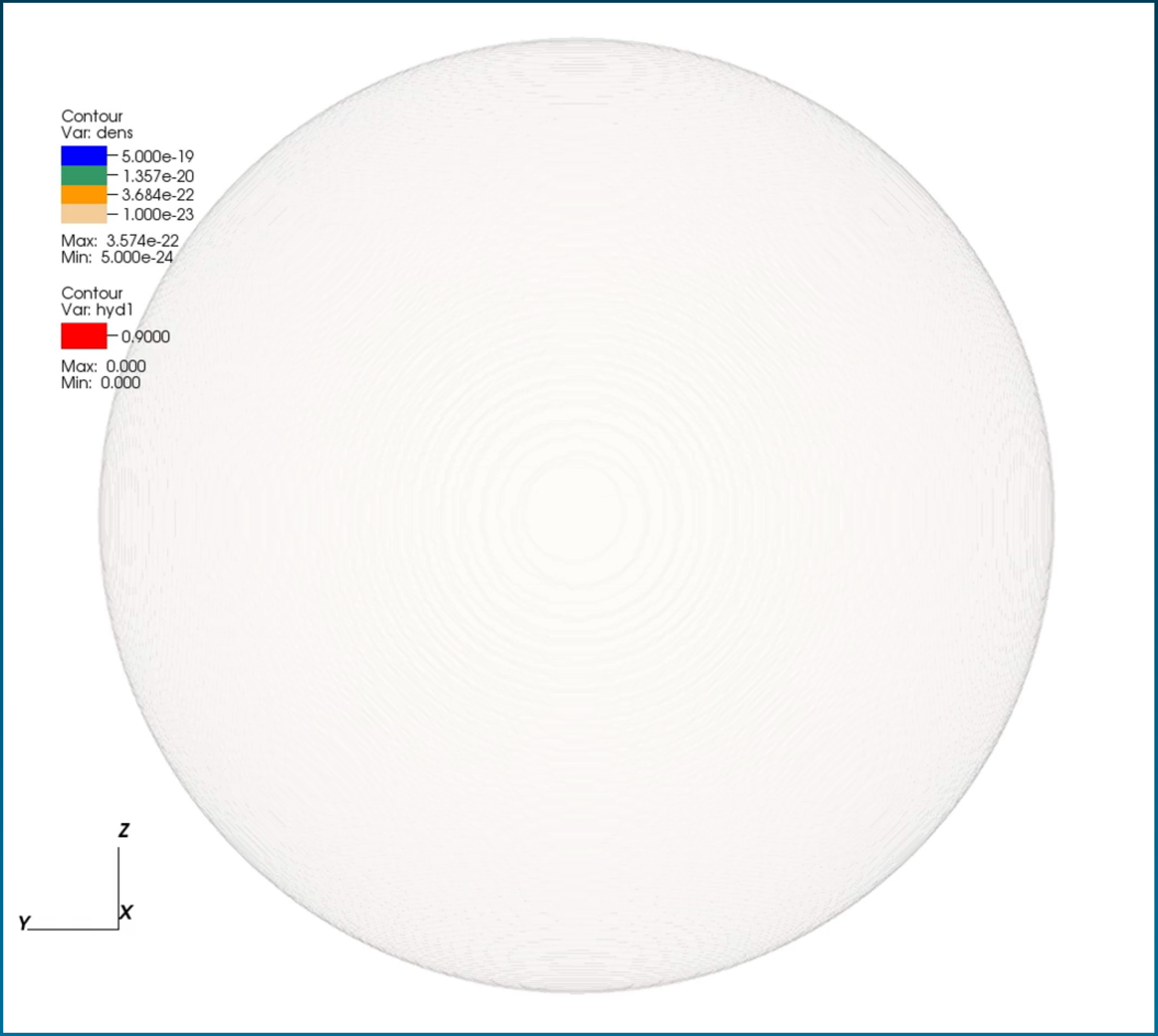
Simulating radiative feedback and cluster formation in GMCs (Howard, Pudritz, & Harris, 2016)

- Radiative feedback from evolving IMF in cluster sink particles – ray tracing from sources (Peters + 2010).
- Ionization, thermal heating, rad. pressure
- Clouds isolated: initial n=100 cm^{-3}, box 32- 80 pc, flattop + $r^{-3/2}$ density profile; low rotation (2 %);

  initial Burgers turbulence,
- Subgrid model: (Howard, Pudritz, Harris 2014)



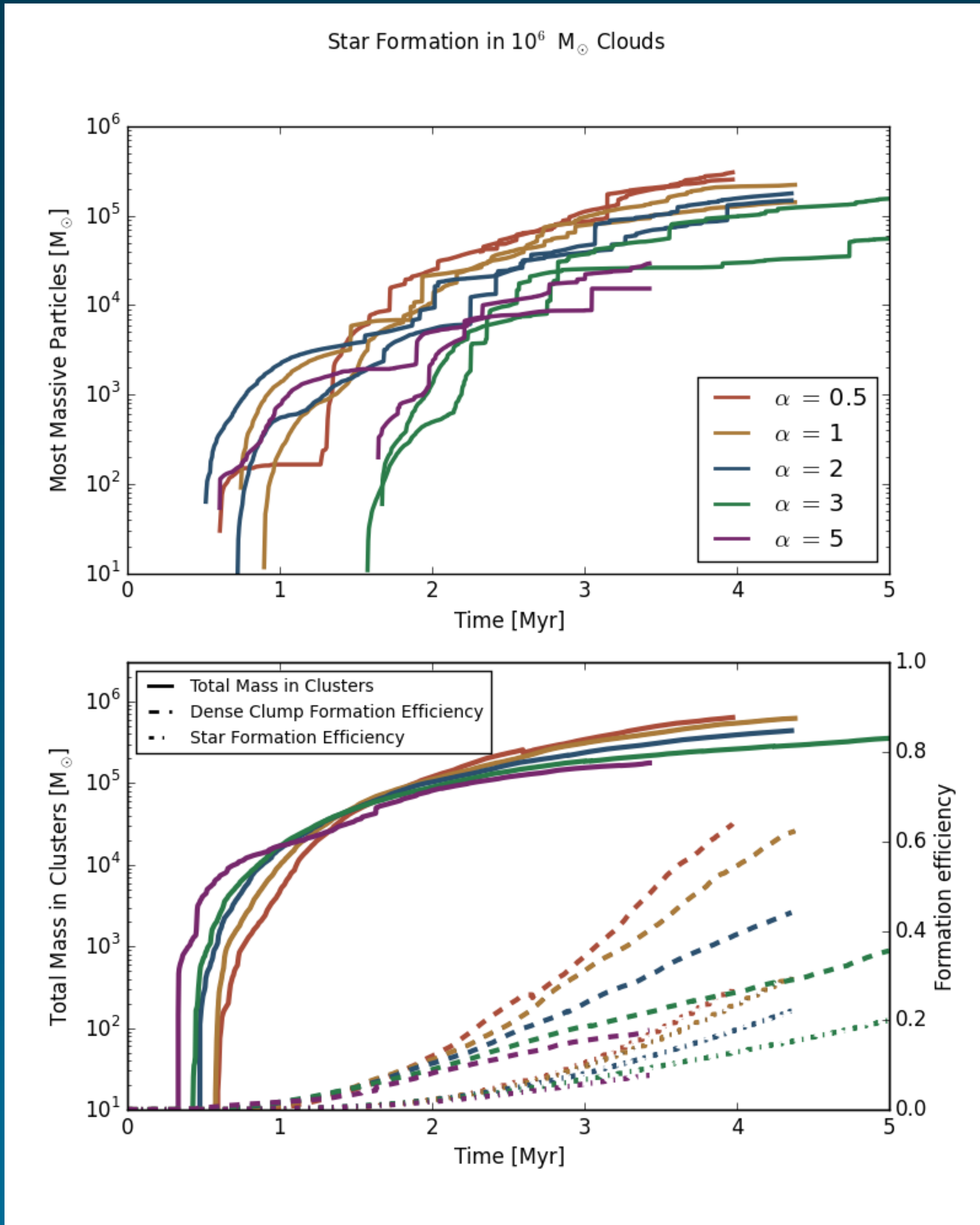
- Cluster particle forms in GMC
  (n=10^4 cm^{-3} threshold, Lada 2010)
- Divide gas into gas for star formation (20% per free fall)
  and reservoir
- Randomly draw stellar masses from IMF (Chabrier 2005)



M = 10^6 M_{sol}, α = 0.25, flatop,..

Cluster formation: initially poorly bound (α = 3), 10^6 M_{sun} GMC

Virial parameter: controls cluster formation, SFE…



Top: Stellar mass evolution of most massive star clusters – most massive clusters form in most bound clouds

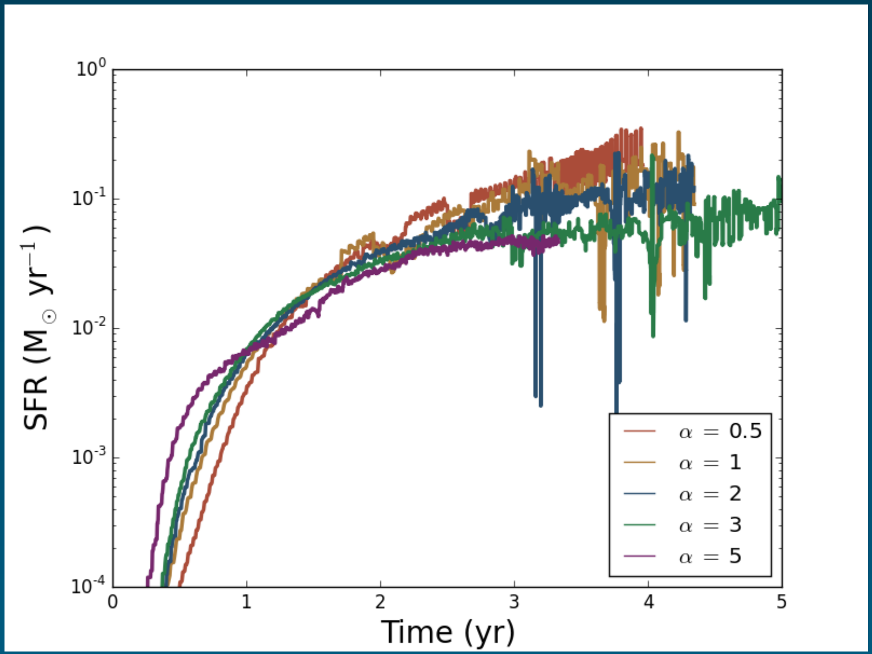
Bottom: clump and star formation efficiencies

Wide range in star formation efficiencies 20%-40%

Radiative feedback effects negligible for 10^6 M_{Sun}

POINT: low SFE requires initially unbound clouds… radiative feedback not so effective

SFR(M_{cl}) scales with M_{cl} : obs. vs theory



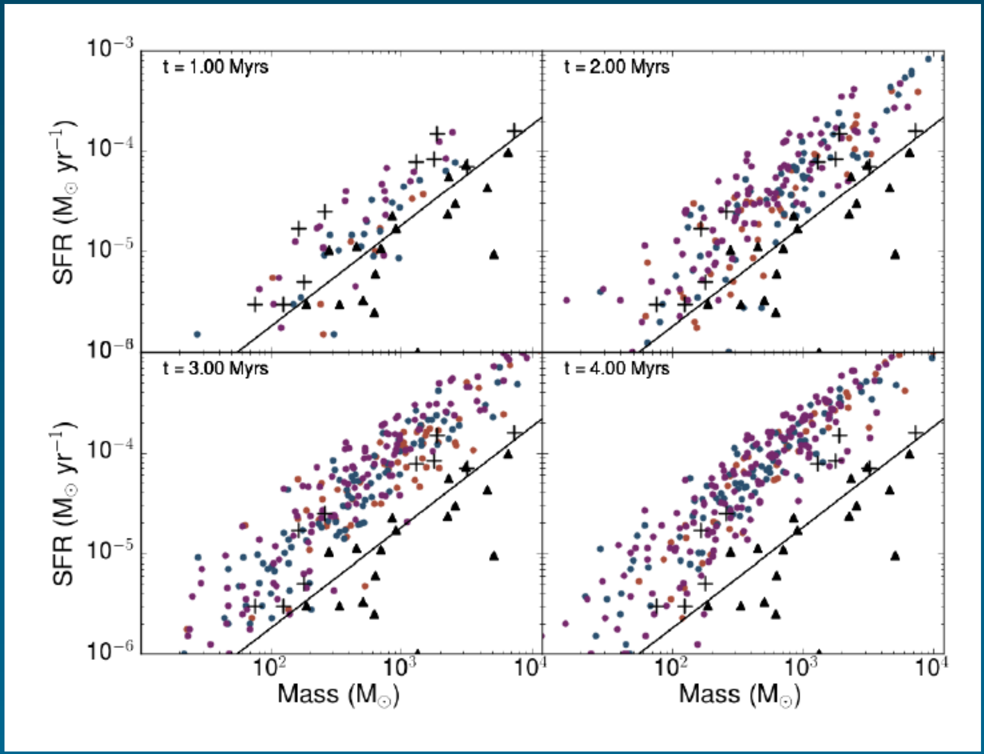
SFR – molecular mass diagram

(C. Lada + 2012)

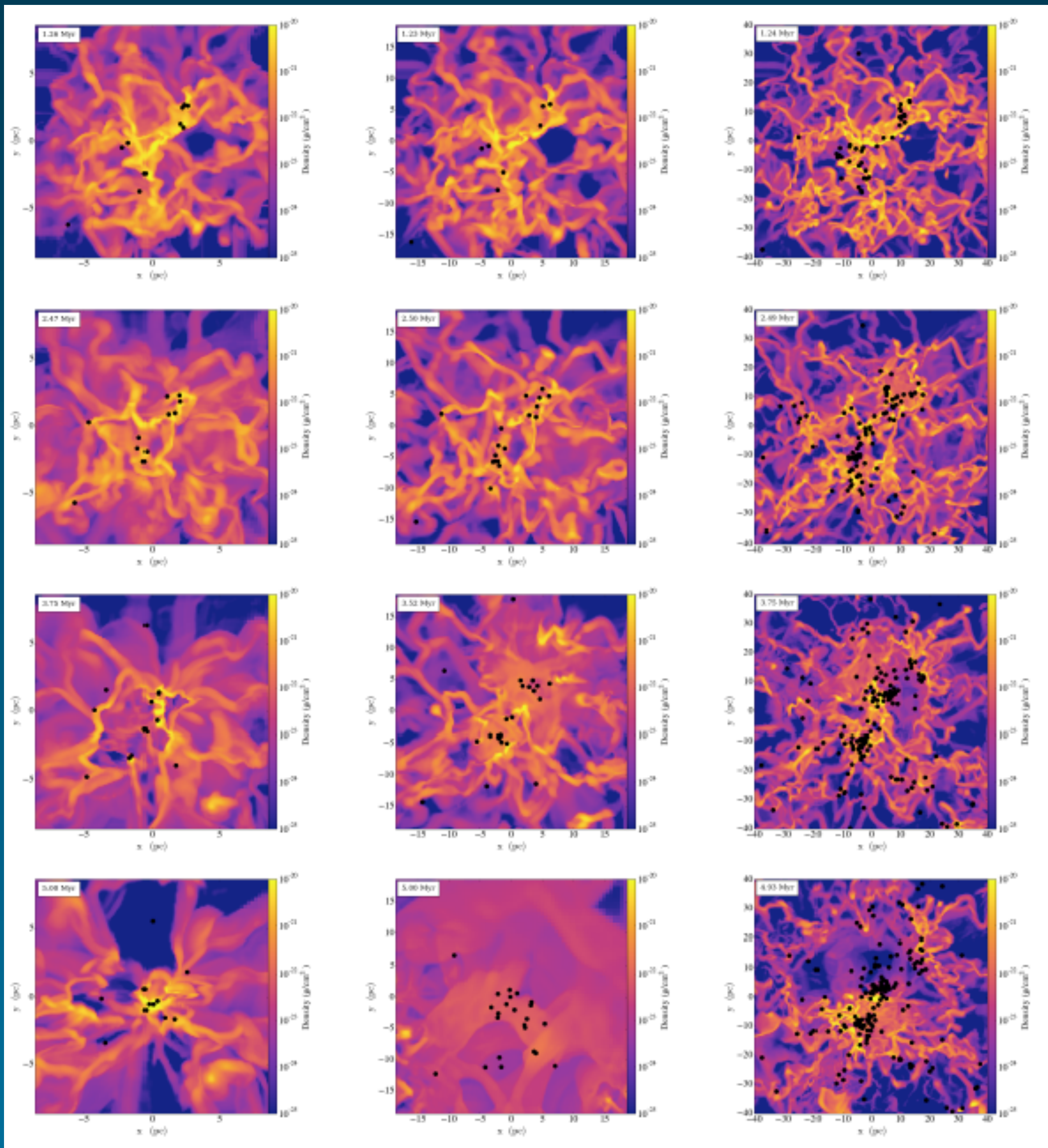
Lines: dense gas fractions

Dark (open) circles:

A_K > 0.8 (> 0.1) mag



Same trend with mass – but higher SFE with time. Additional feedback needed.



2. Mass sequence of GMCs: (Howard, Pudritz & Harris 2017)

- 10^4, 10^5, 10^6 M_{sun} (columns) @ 4 different times

- 20^2 , 40^2 , 80^2 pc^2

- 10^5 M_{sun} clouds dispersed in 5 Myr.. 10^6 M_{sun} live longer…

Low number of O stars in 10^4, , large gravity in 10^6 M_{Sun}

Cluster Mass Function

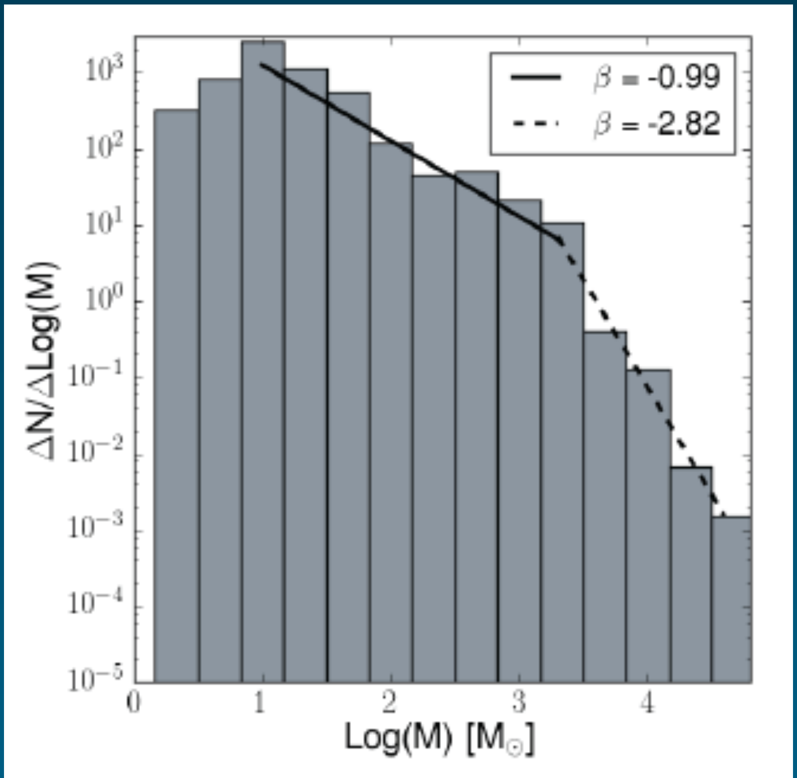
Observations of embedded cluster mass function in nearby regions:

dlog N / dlog M ~ M^{β} ; β_{obs} ~ -1

(Lada & Lada 2003)

- External galaxies show similar relation (Fall & Chandar 2012)

- Summing up over clouds $10^4 – 10^6$ using observed GMC spectrum.. we find:
- β_{HD} ~ - 0.83
- β_{RHD} ~ - 0.99 .. Agreement..



Howard, Pudritz, Harris 2017

Radiation feedback shapes the CMF for clusters… reduces the number of high mass clusters that would form in purely hydro simulation…

!V. Cluster Mass- Cloud Scaling

… and the Formation of Globular Clusters

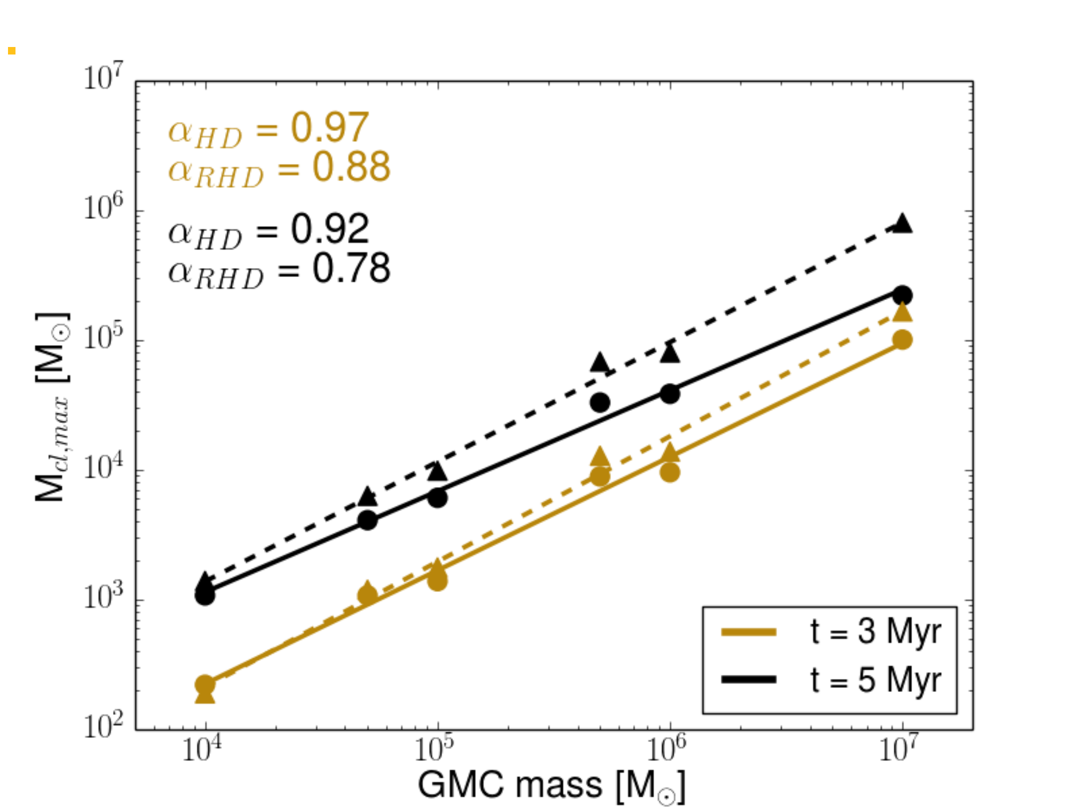
Maximum mass of cluster scales with cloud mass… into globular cluster regime….

Young Massive Clusters form in GMCs….of up to 10^5 M_{sun}

Globular clusters proposed to form in Supergiant Molecular Clouds (Harris & Pudritz 1994) (10^7 M_{Sun})

May also need high pressure environments (Kruijssen 2015)

Add simulations of Supergiant clouds….



(Howard+ 2017, in prep)

$M_{cluster,\ max} \sim M^{\alpha}_{cloud}$

Linear for pure hydro…, radiative feedback makes it shallower as massive clusters reduced… but get globular cluster masses…

Trends with metallicity:

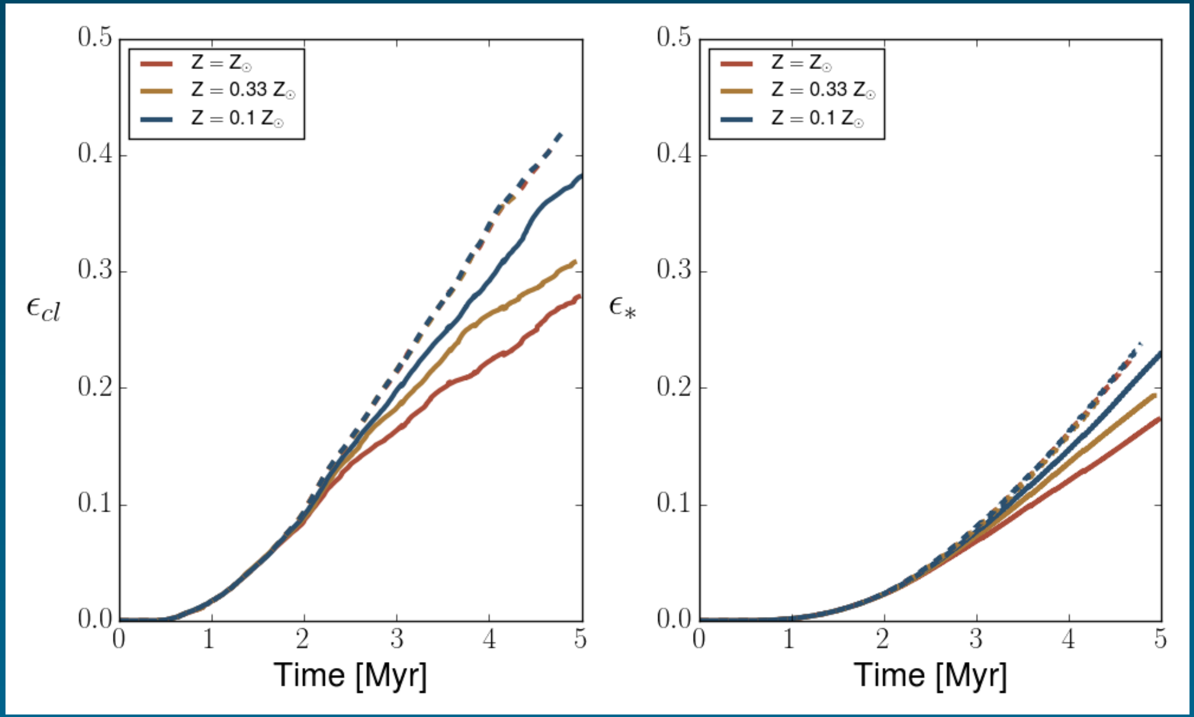
- higher star formation efficiency as gas gets more metal poor

Gas opacity is reduced (less dust) making feedback less efficient.

SFE approaches hydro limit as

$Z \sim 0.1 Z_{Sun}$

Early universe should be building more massive clusters – more efficiently…



SUMMARY

An emerging picture:

- filaments formed by turbulence… clusters form by gravitationally driven processes within them.

- rad feedback destructive to intermediate mass clouds ~ 10^5 M_{Sun}. More massive clouds survive and continue to produce the more massive clusters.

- gravitational boundedness more important for SFE than radiation field - too late to affect very dense gas….

- max cluster masses obey powerlaw scalings with cloud mass. These are not affected by radiation feedback in metal poor gas…