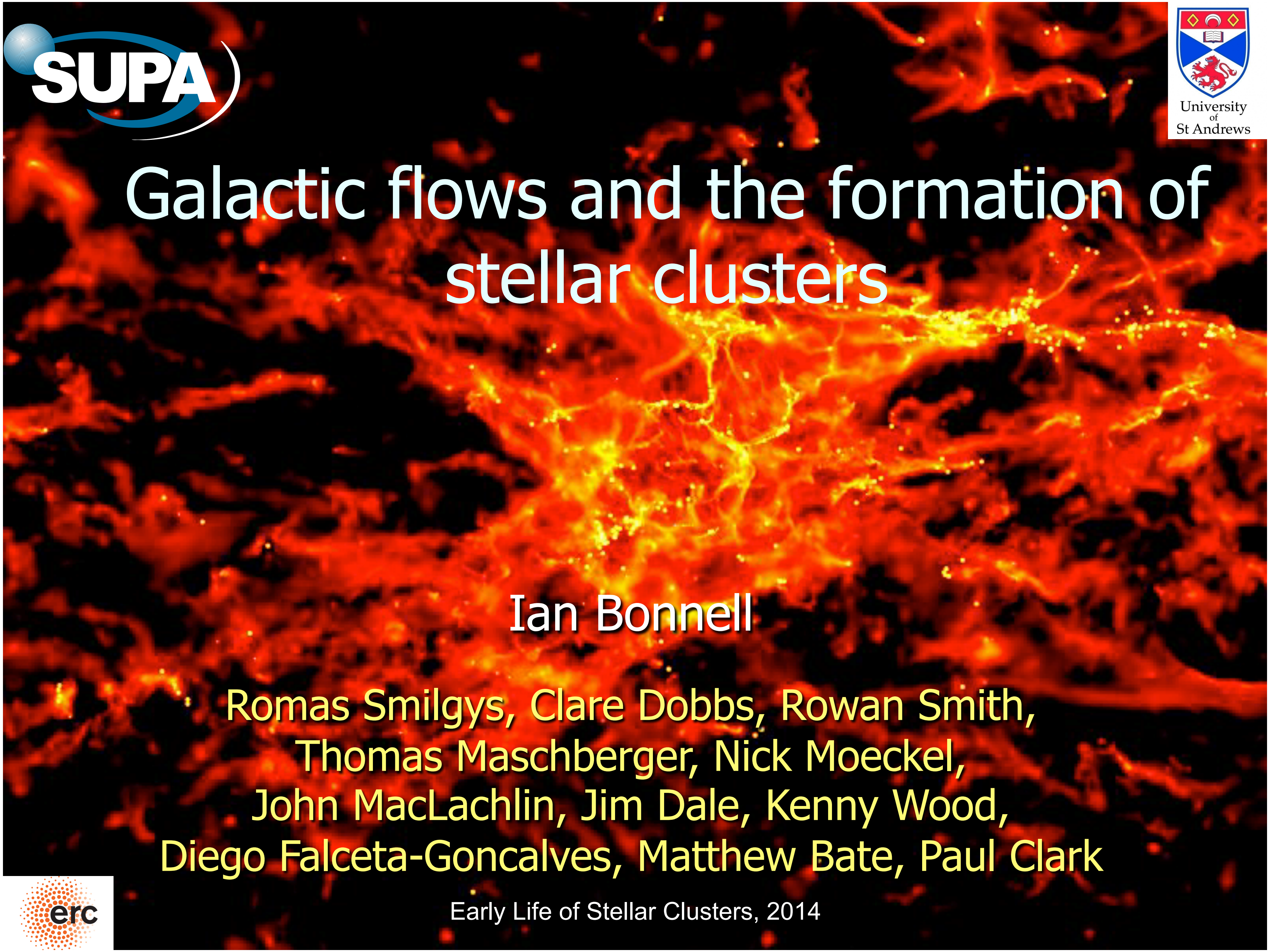


Galactic flows and the formation of stellar clusters

Ian Bonnell

Romas Smilgys, Clare Dobbs, Rowan Smith, Thomas Maschberger, Nick Moeckel, John MacLachlin, Jim Dale, Kenny Wood, Diego Falceta-Goncalves, Matthew Bate, Paul Clark

University of St Andrews

Early Life of Stellar Clusters, 2014

GMC scale star formation

- $10^4\ M_{sun}$ in 10 pc

  SPH : 1.5×10^7 particles

- Forms > 2500 stars

  in 6×10^5 years

  $\sim 1600\ M_{sun}$ ($\sim 0.003\ M_{sun}\ yr^{-1}$)

Mass resolution $\sim 0.02\ M_{sun}$

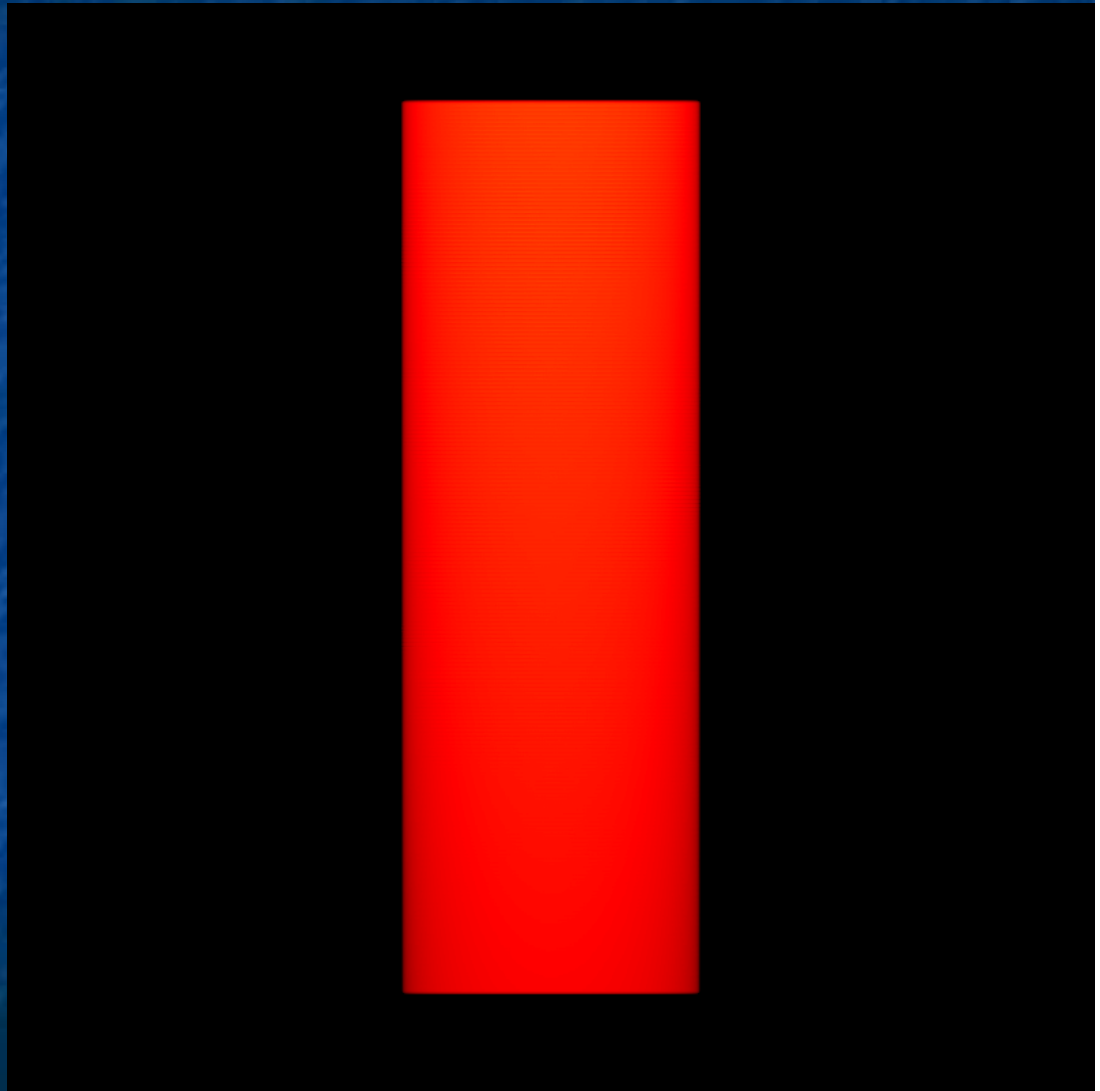
Sink radius: 200 AU

No MHD, feedback

Initial conditions:

Bound (top) and

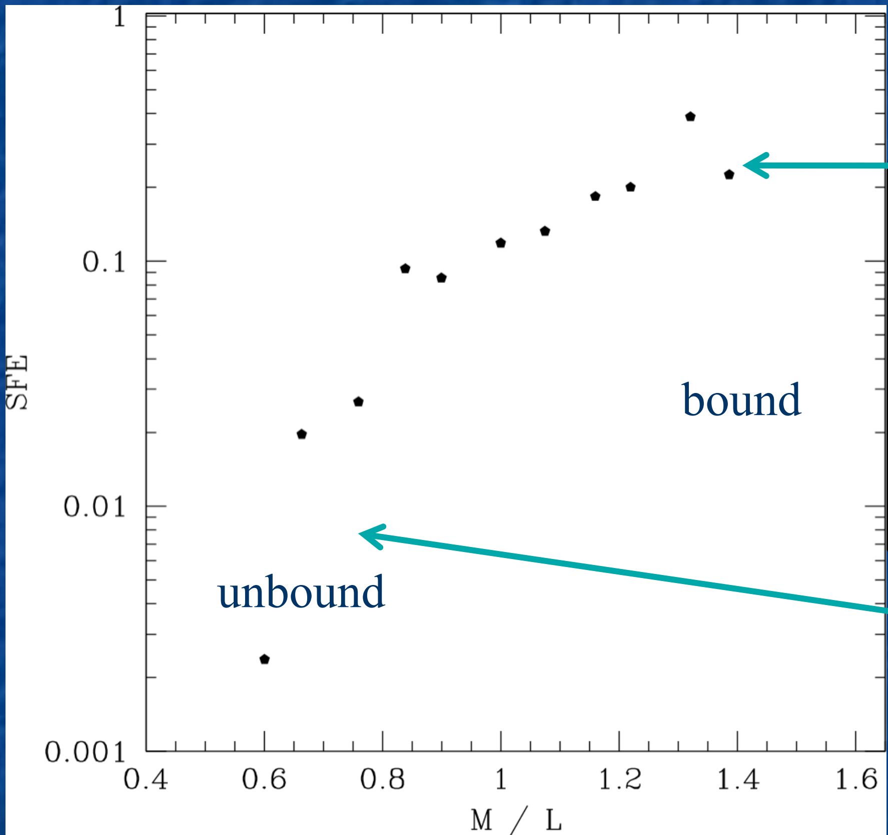
Unbound (bottom)

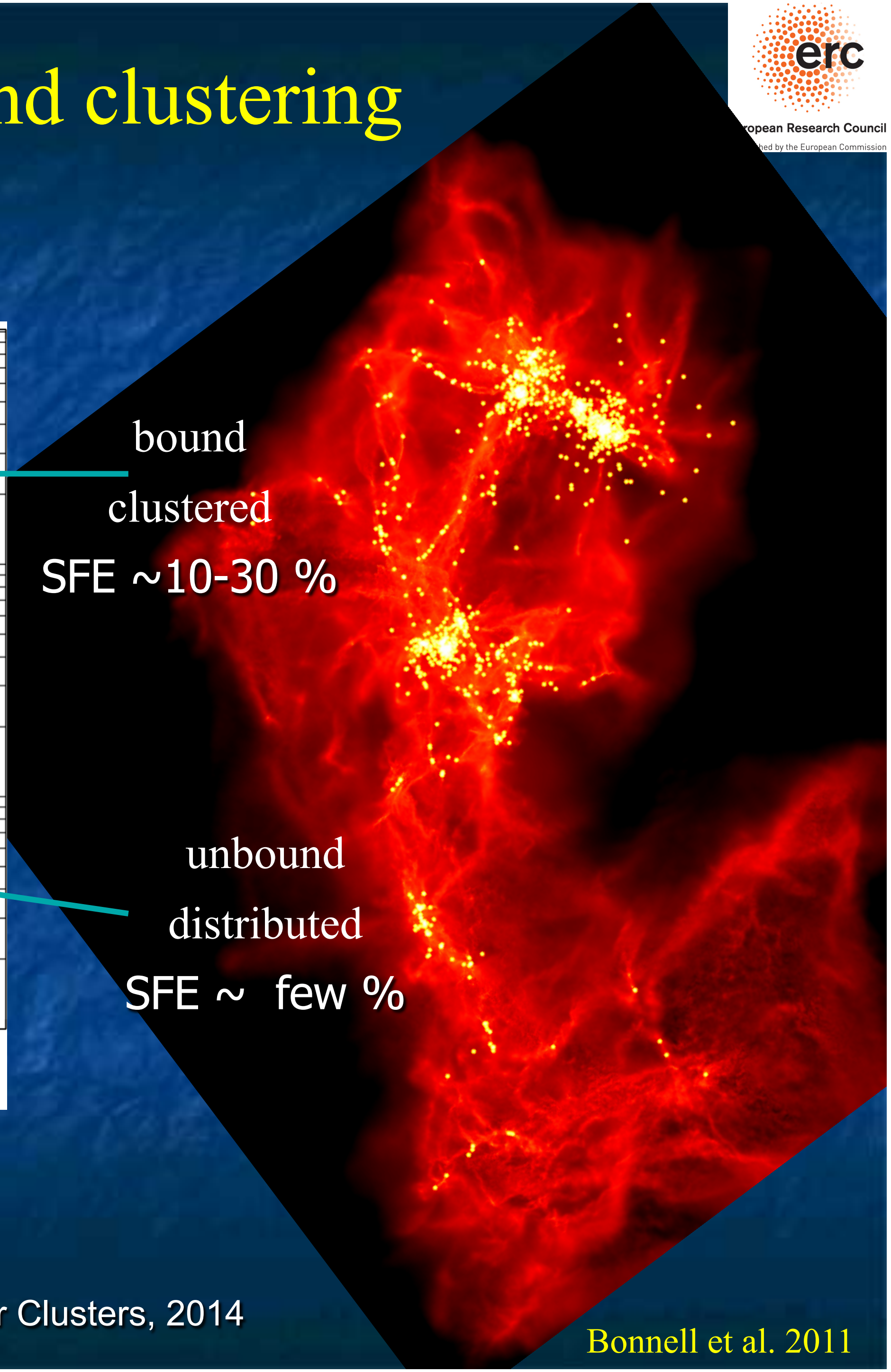


Bonnell, Smith, Clark, Bate 2011

SF efficiencies and clustering

- Bound conditions produce stellar clusters





- Unbound regions produce
  - Low SF efficiencies
  - See Clark et al 2008

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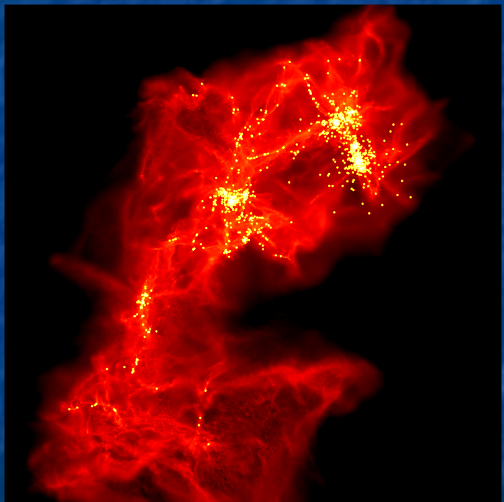
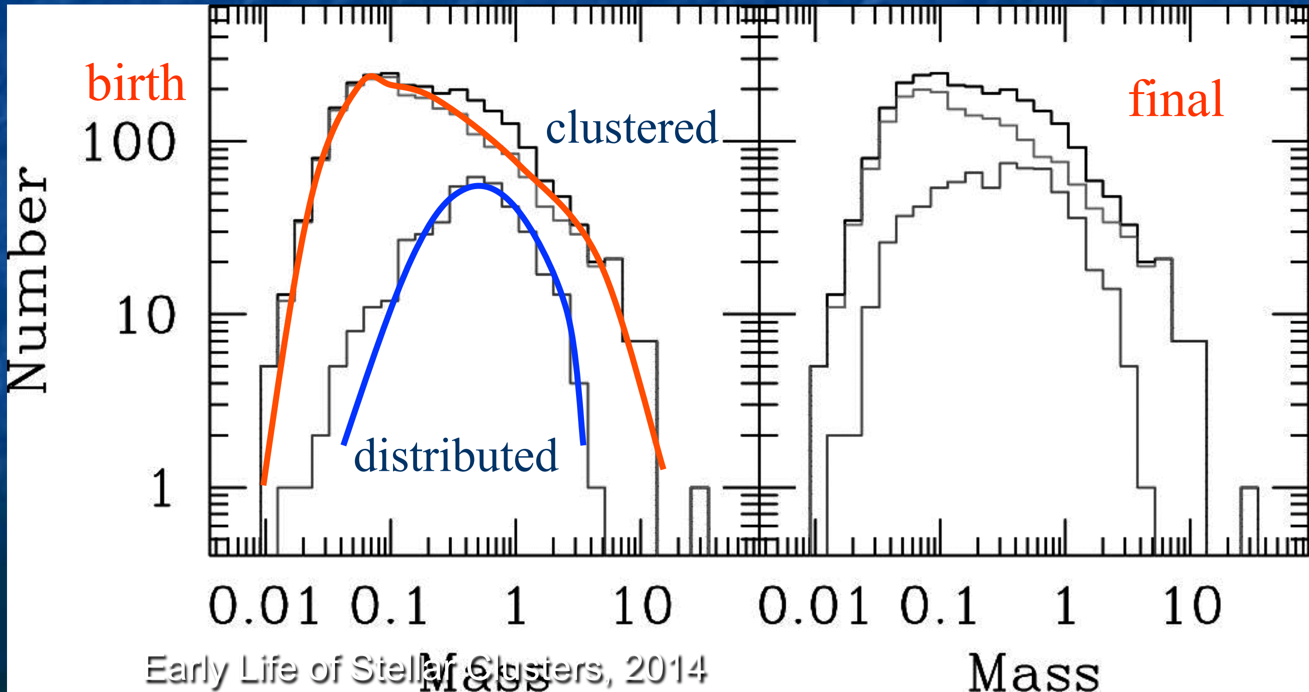
IMF depends on birth environment

- Stellar clusters
  - Full IMF
  - Form from Bound conditions SFE 20-40 %

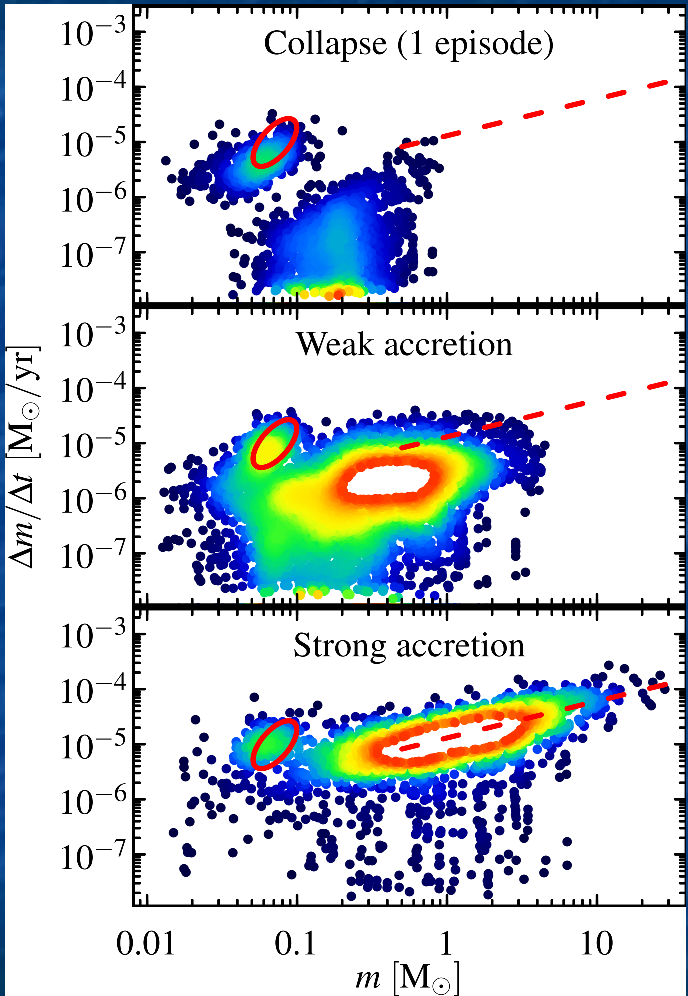
Clark et al 2007; Bonnell et al 2011

- Distributed SF
  - No high-mass, few low mass stars
  - Flat/Peaked IMF
  - Unbound regions
  - Low SF efficiencies





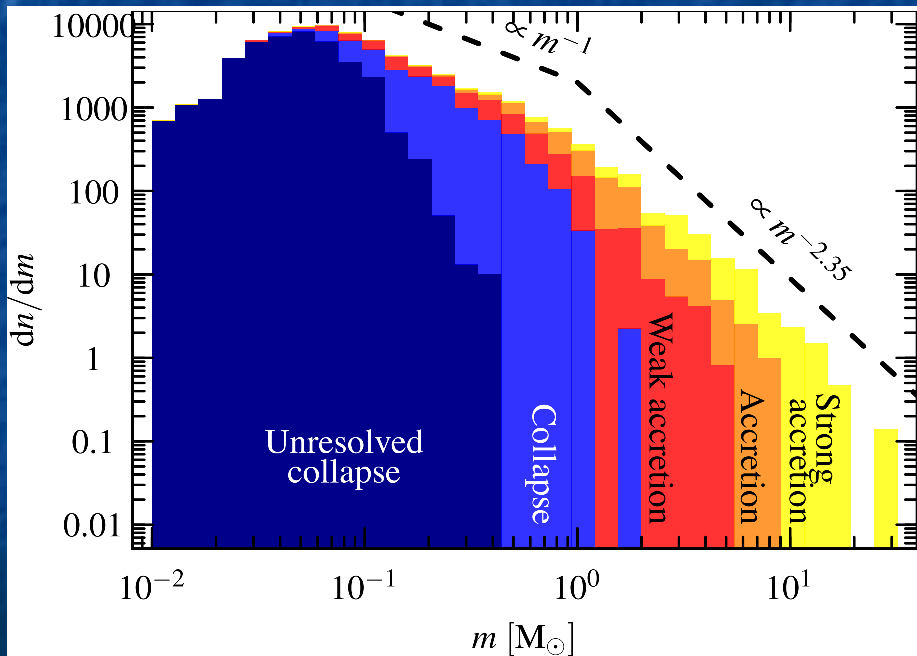
Accretion in Clusters



- Higher mass stars formed through accretion

$$\dot{M} \propto M^{2/3}$$

- Tidal radius accretion



Maschberger et al 2014

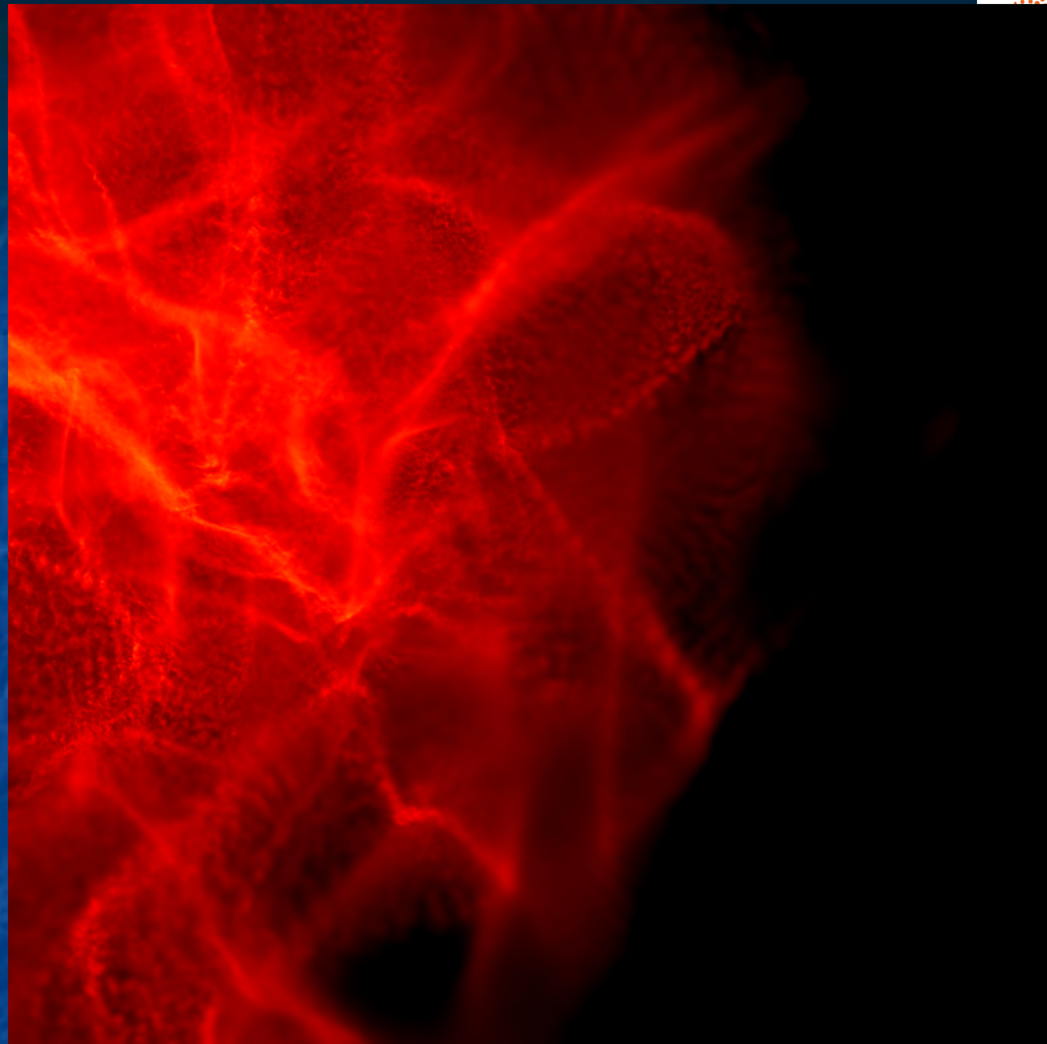
Formation of stellar clusters

Fragemntation in filaments

clusters grow at intersection of filaments

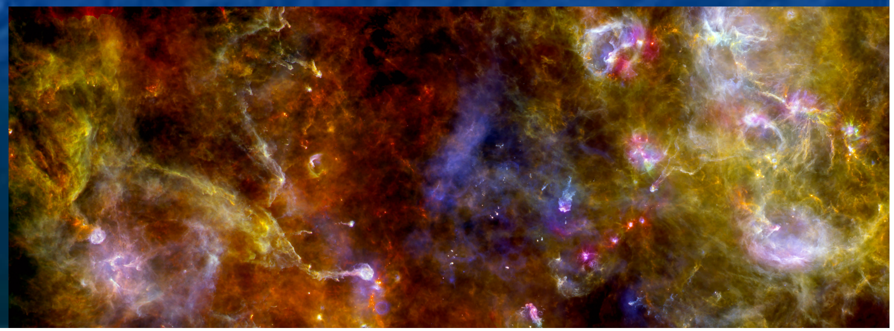
Filaments feed gas and stars into cluster

Clusters grow through Hierarchical mergers

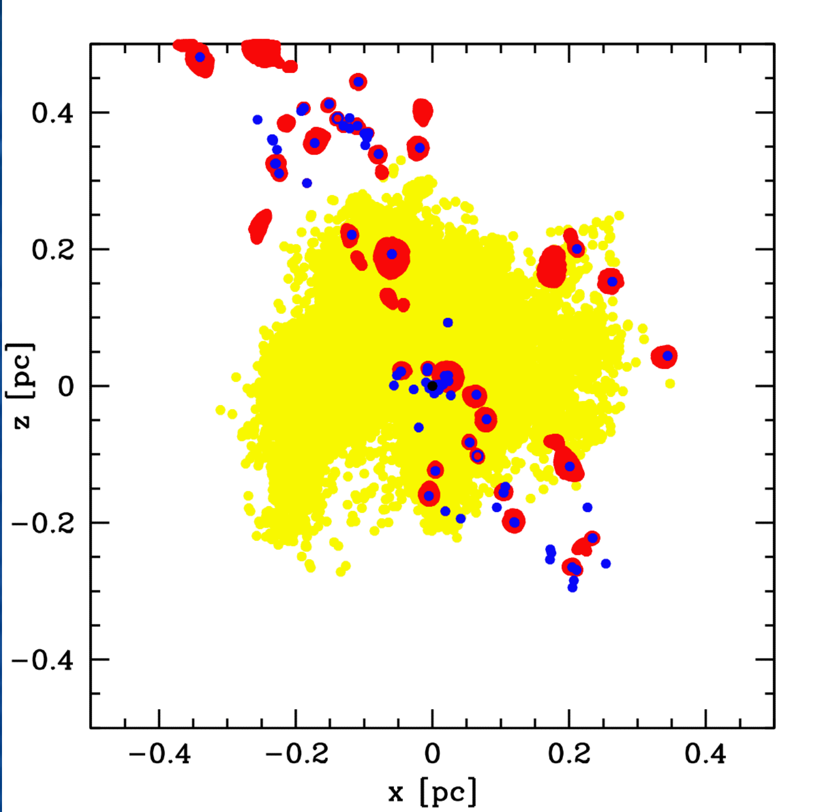


~ 2 pc

Bonnell et al 2011

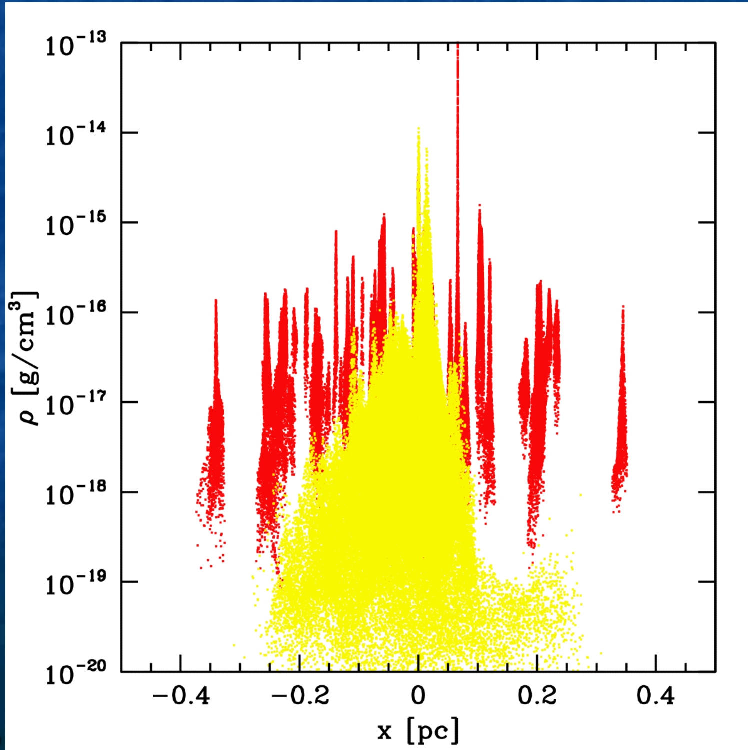


Accretion reservoirs



Accretion onto high-mass stars comes from cluster scale, lower density gas

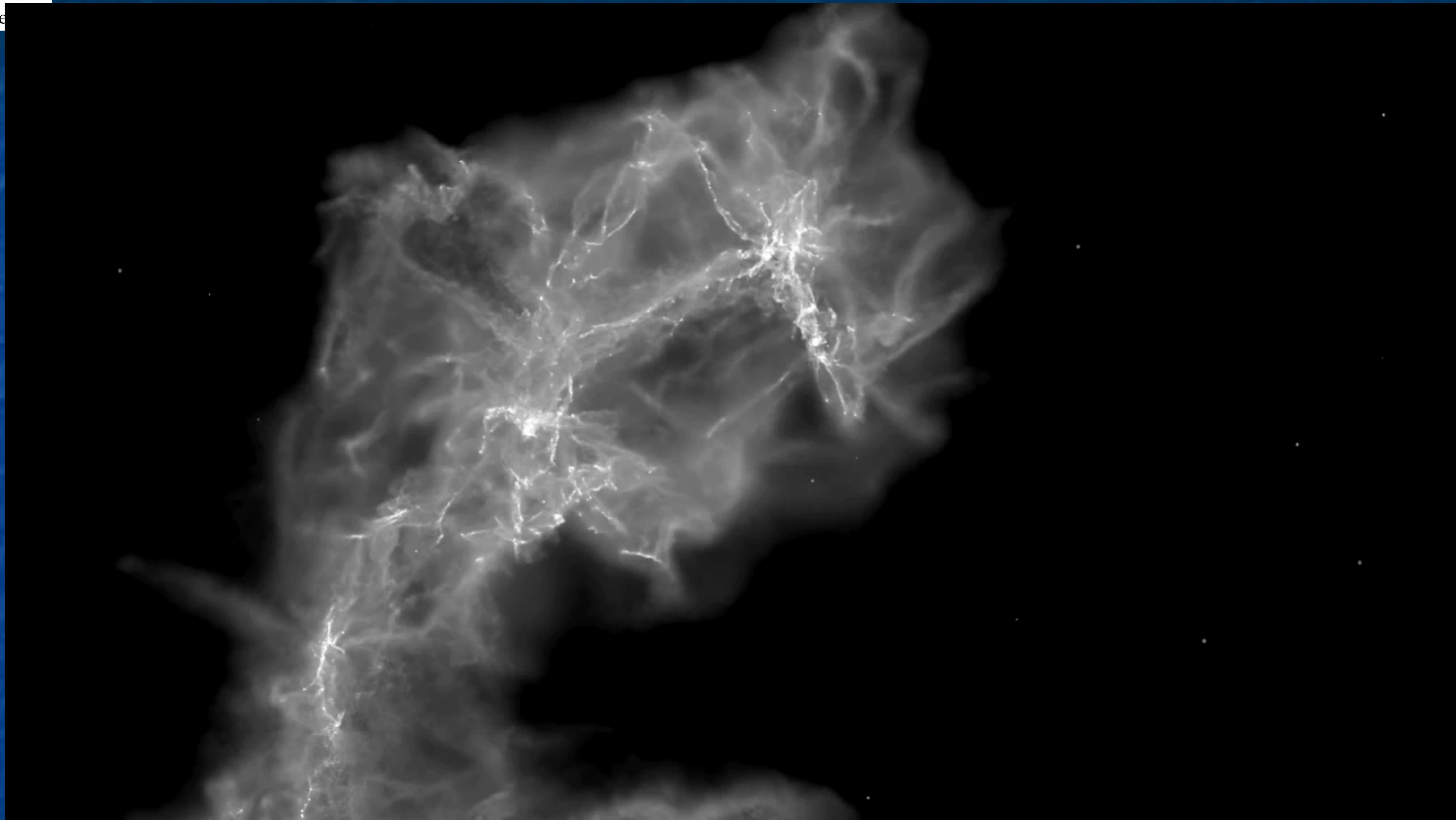
Yellow = mass which will be accreted by the most massive sink within 0.25 t_{dyn}



Infalling fragments (cores) form low-mass stars

Smith et al 2009

GMCs to associations



N-Body simulation following on from hydro

Cluster formation

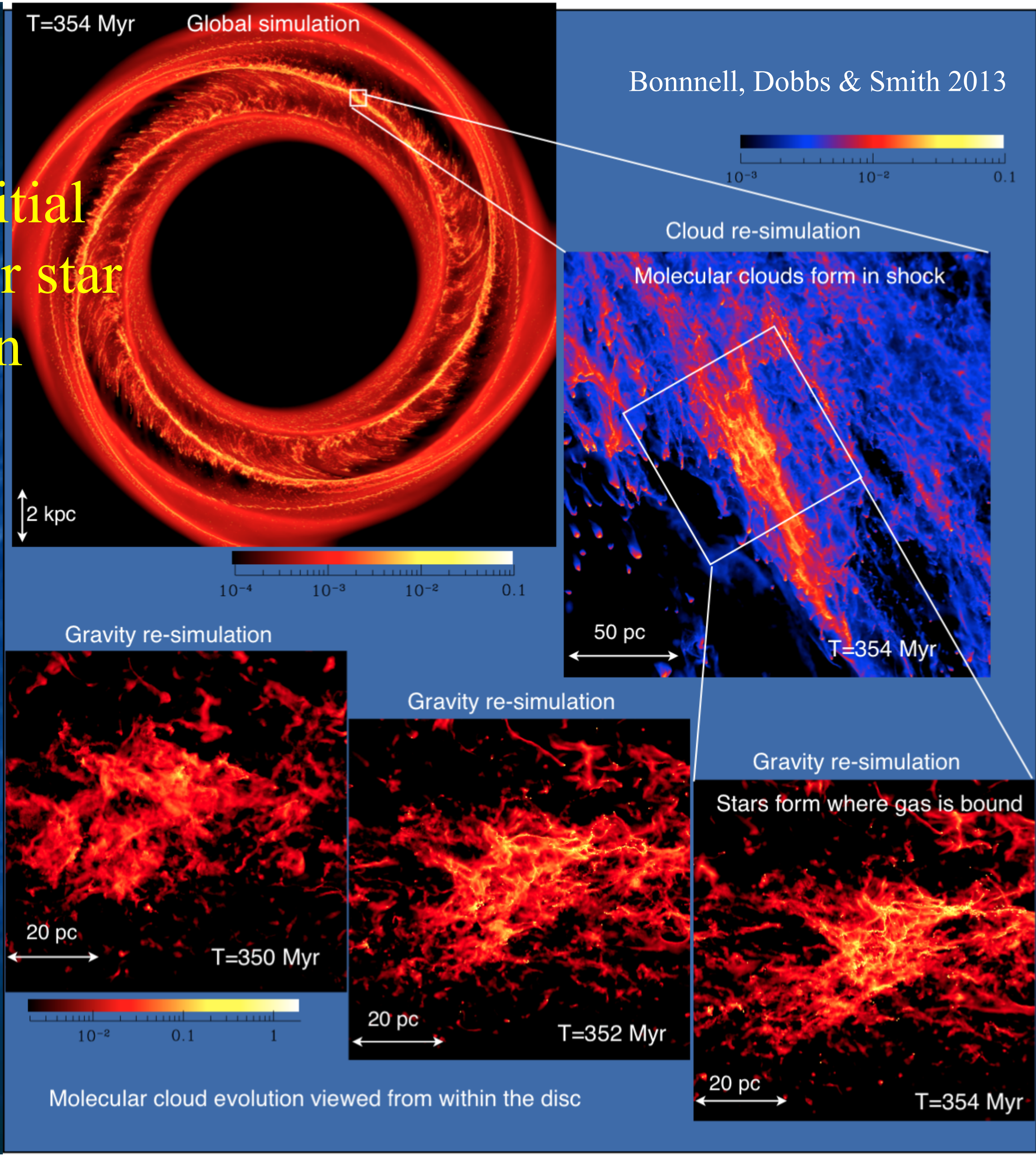
Moeckel et al 2012

Realistic initial conditions for star formation

Global disc simulation
25 million SPH particles
2 x 10^9 M_{sun} gas

Cooling curve:
(Koyama & Inutsuka 2002)
Smooth mixture of cold-dense gas and hot gas:

10 to ~10^4 K



Molecular cloud formation

- Clouds formed by shock
- Ram pressure from flow
  - At ~ 30 km/s

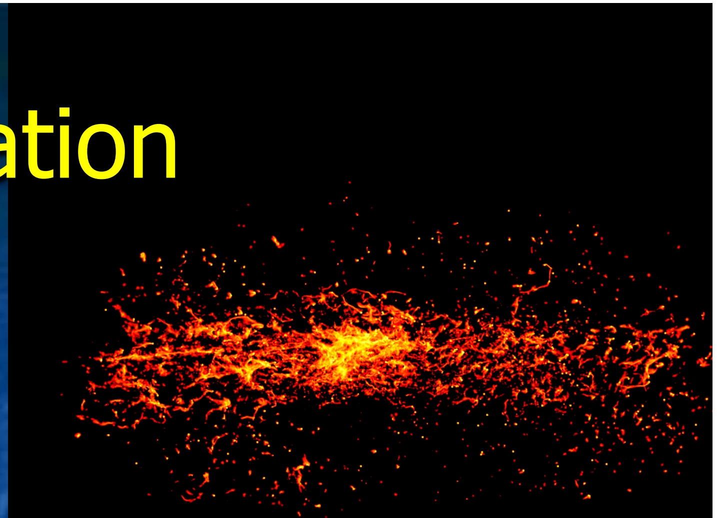
$$P_{ram} = \rho v_s^2$$

  - Compresses gas
  - Thermal instability and cooling
  - Generate internal turbulence

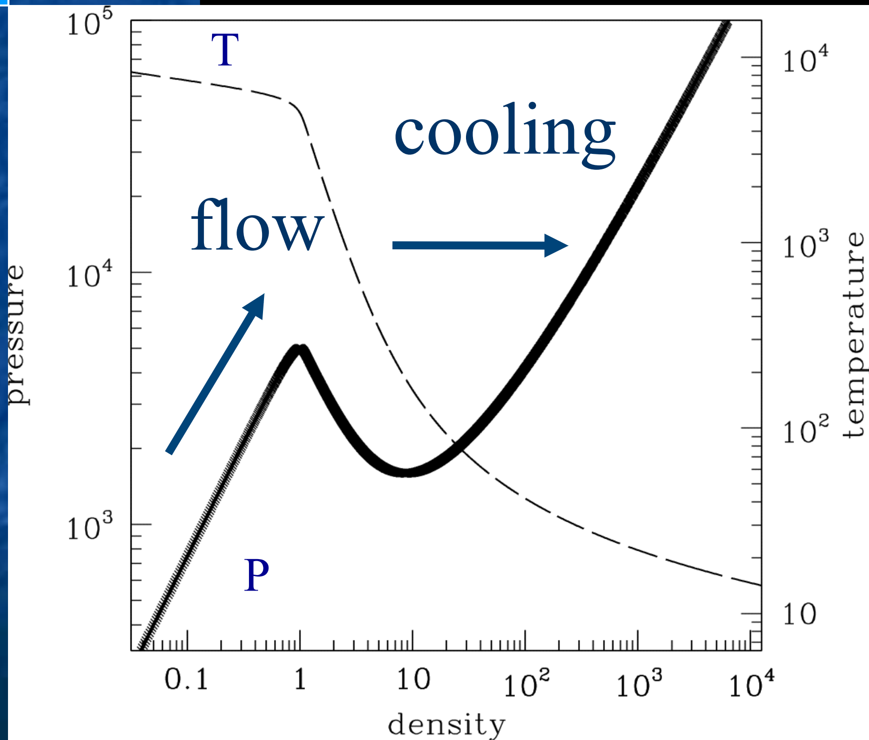
Bonnell et al 2006; Dobbs & Bonnell 2007
Bonnell, Dobbs & Smith 2013

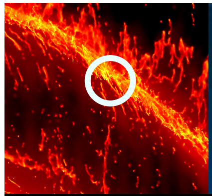
- Thermal pressure of hot gas

Can form without self-gravity

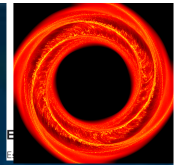


400 pc, in galactic plane





Galactic triggering of star formation



25 million SPH particles
Cooling curve
Smooth mixture of cold-dense gas and hot gas:
10 to ~10^4 K

High resolution region 200x200pc
Cold gas 1.7 x 10^6 M_o gas
Resolution ~ 10 M_o , 0.05 pc

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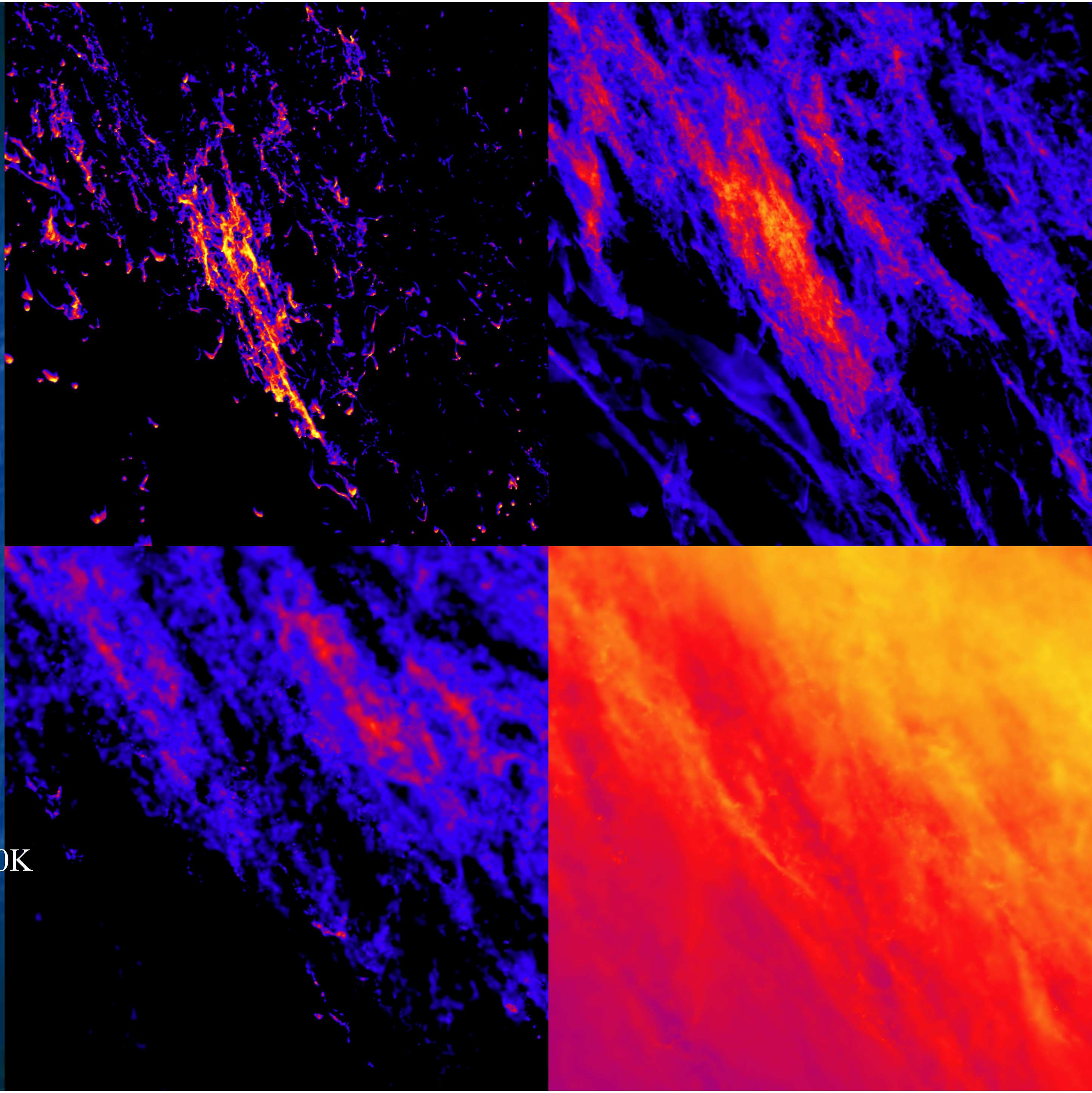
T<50K

0.1 g cm^{-2}

50<T<500K

0.1 g cm^{-2}



500<T<5000K

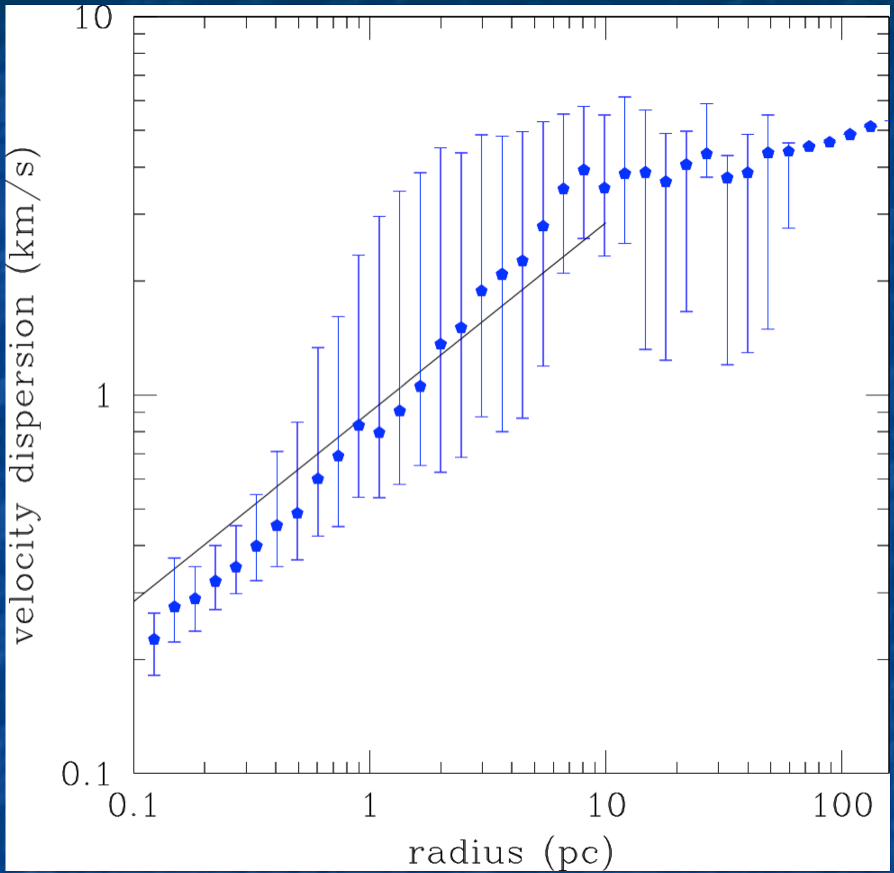
0.005 g cm^{-2}

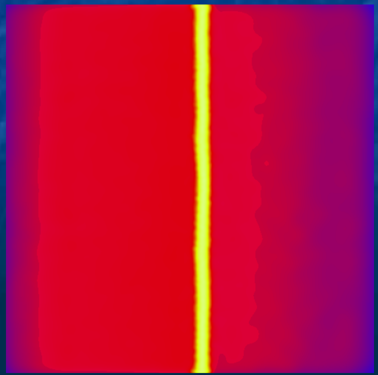
T>5000K

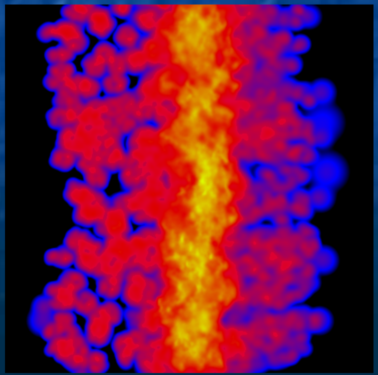
0.005 g cm^{-2}

GMC Kinematics

- Convergent gas streams
  - Clumpy gas
  - generates velocity dispersion
  - Thermal instability
- Turbulence driving on ~10 pc scales







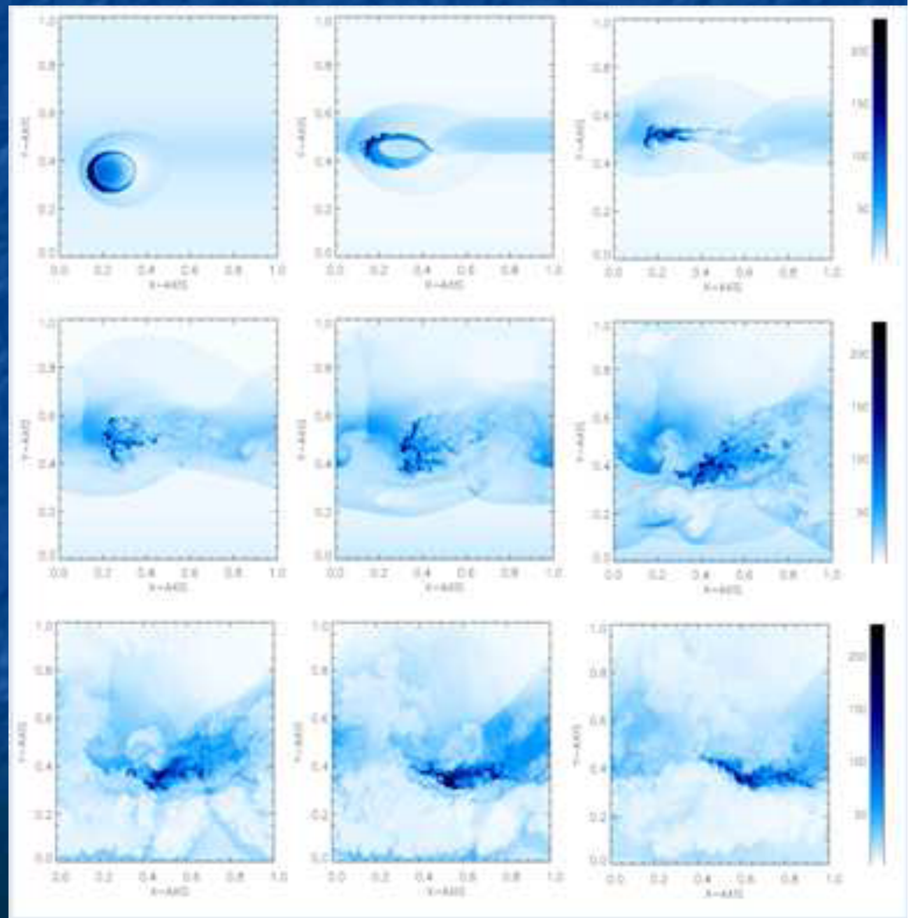
Bonnell, Dobbs & Smith 2013

Dobbs & Bonnell 2007

Falceta-Goncalves et al 2014

Spiral arm driven turbulence

Falceta-Goncalves et al 2014



Single cloud-arm interaction

100 cm^{-3} cloud self-shocking
cooling
KH-instabilities

Drives turbulence

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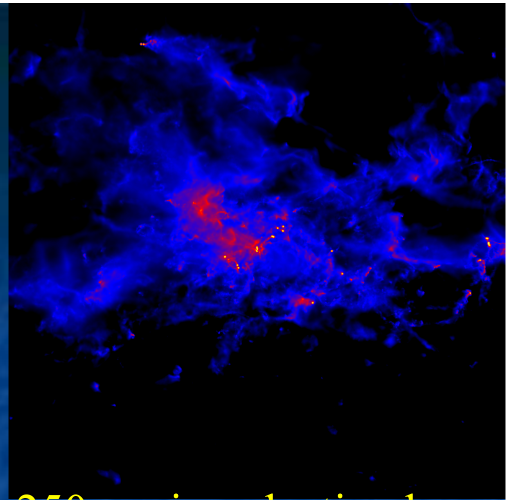
Initial Conditions for Star Formation



250 pc, in galactic plane

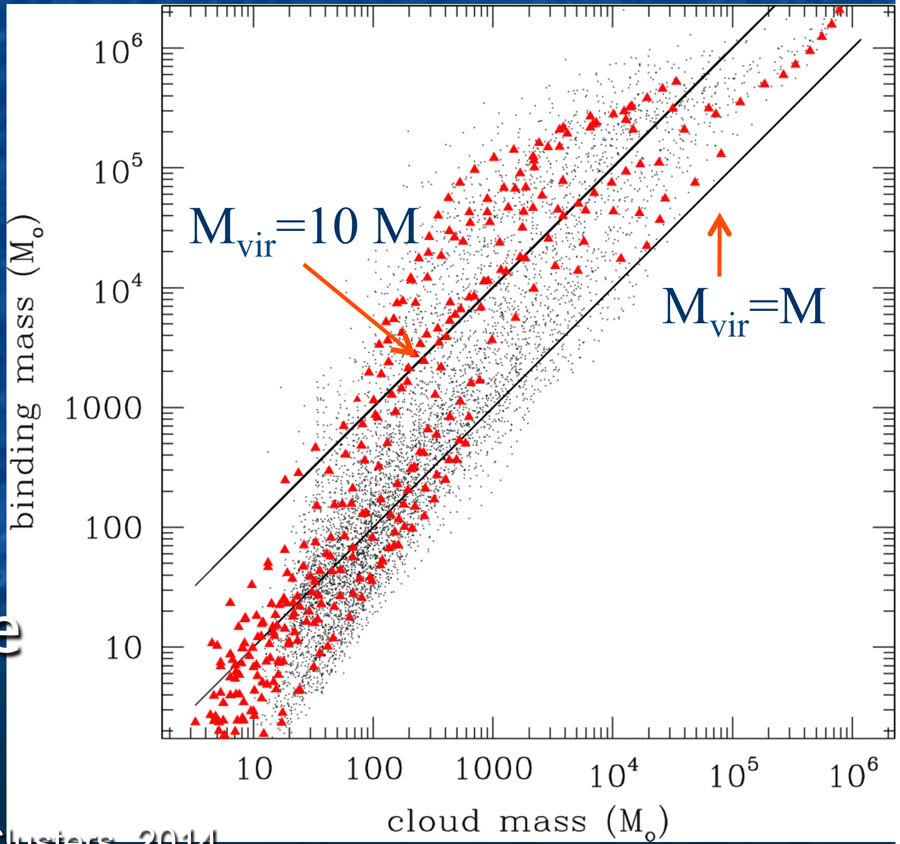
~ 10^6 M_o at molecular cloud densities
in ~ 100 pc, With self-gravity

- Clouds globally unbound
  - Formed by spiral shock

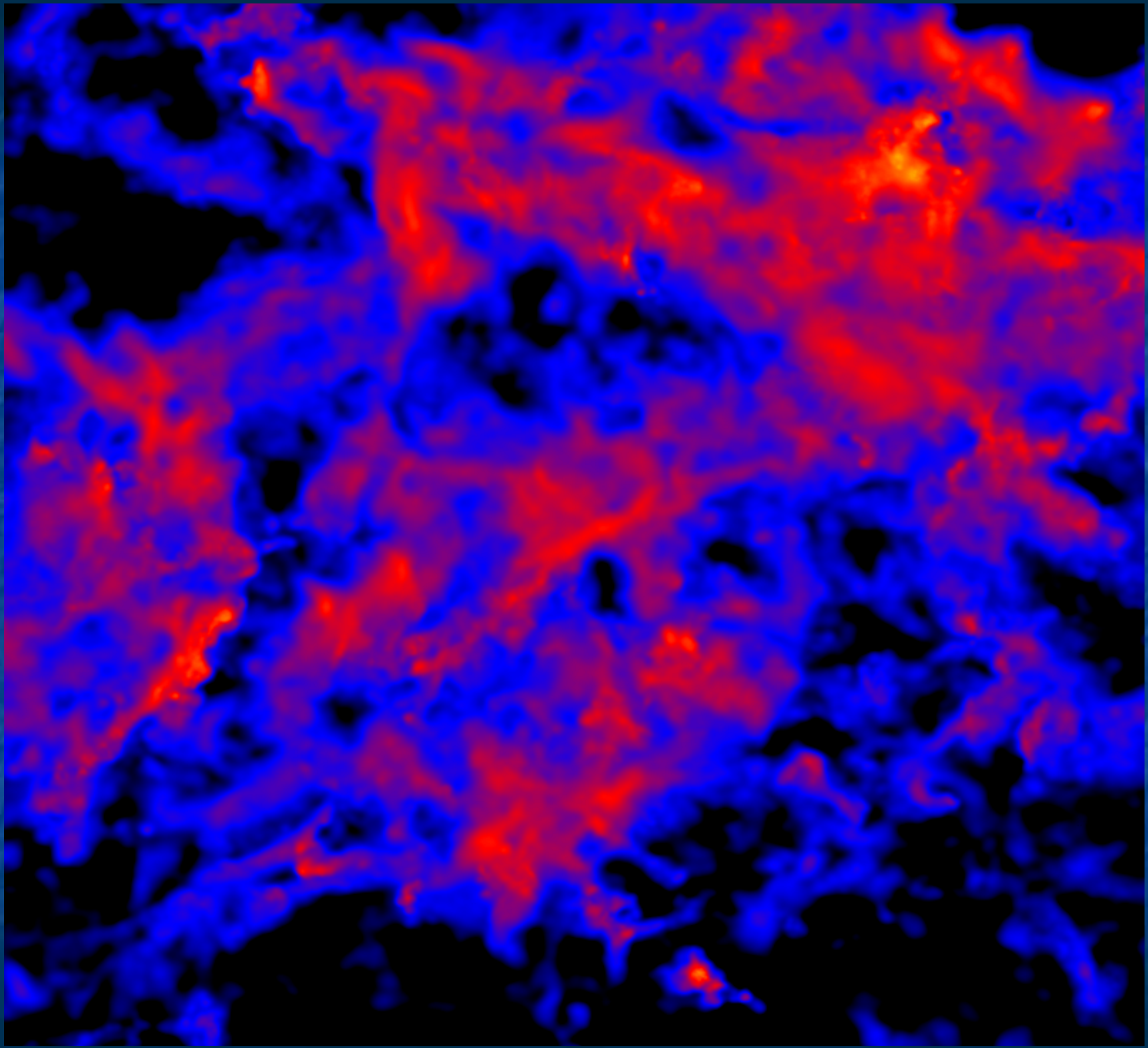
$$M_{cloud} < M_{vir} < 10\,M_{cloud}$$

- Locally: forms bound clumps
  - M ~ 1000 M_o ; R ~ few pc

highly structured
Cooler inside / warmer outside



With self-gravity:



Sink particles
0.25 pc
M> 10 M_o

>1000 sinks
not individual stars

~ 10^5 M_o
in 5 Myr

~100 pc

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Star Formation Rates

Local estimates of star formation rates

- After t=3.5 Myr
- Grid, sizes of 50x50 pc

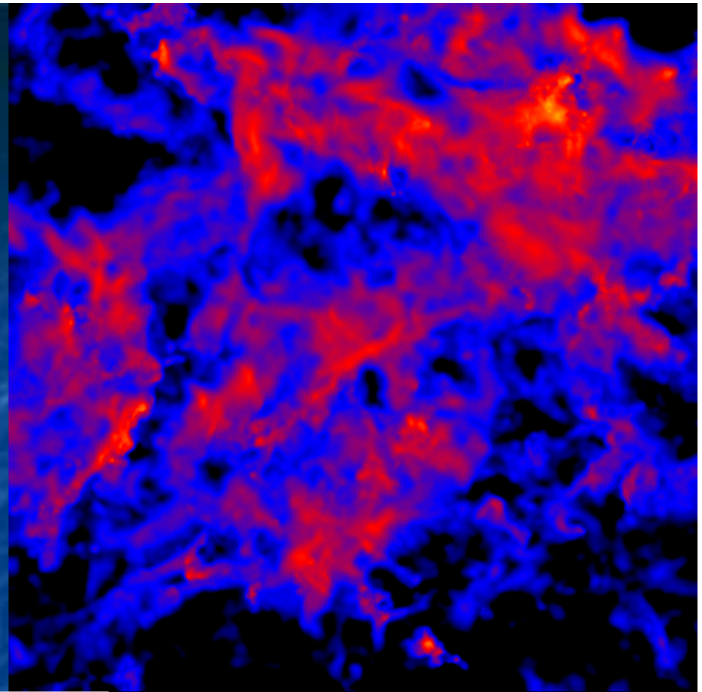
- Over 3 simulations with Σ_{gas} = 0.4, 4 and 40 M_o pc^{-2}

  - S-K power law, but higher, closer to nearby GMC (Heiderman et al 2011)

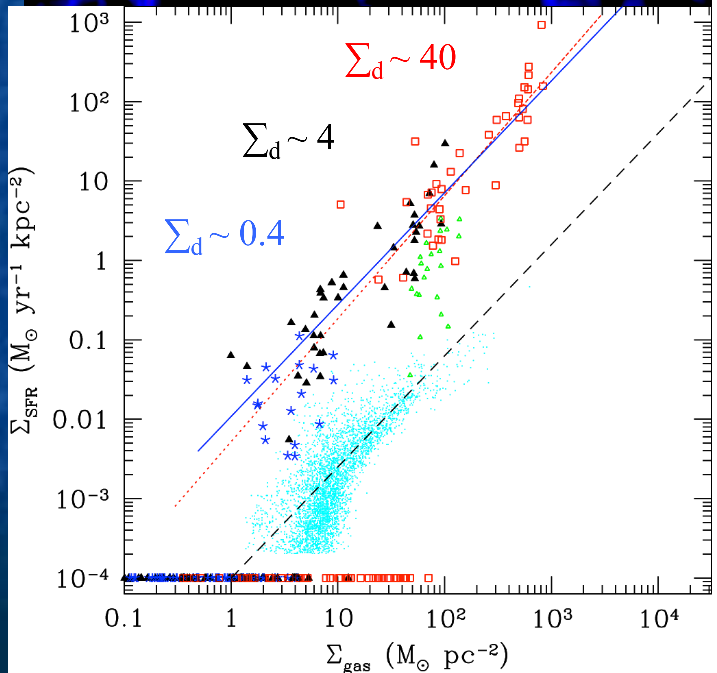
  - Critical step : formation of dense cold gas

$$\Sigma_{SFR} \propto \Sigma_{mol} \propto \Sigma_{gas}^{3/2}$$

- Upper limits on SFRs:
  - Magnetic fields
  - Feedback
  - Additional turbulence



Star Formation Rates



Surface density of gas

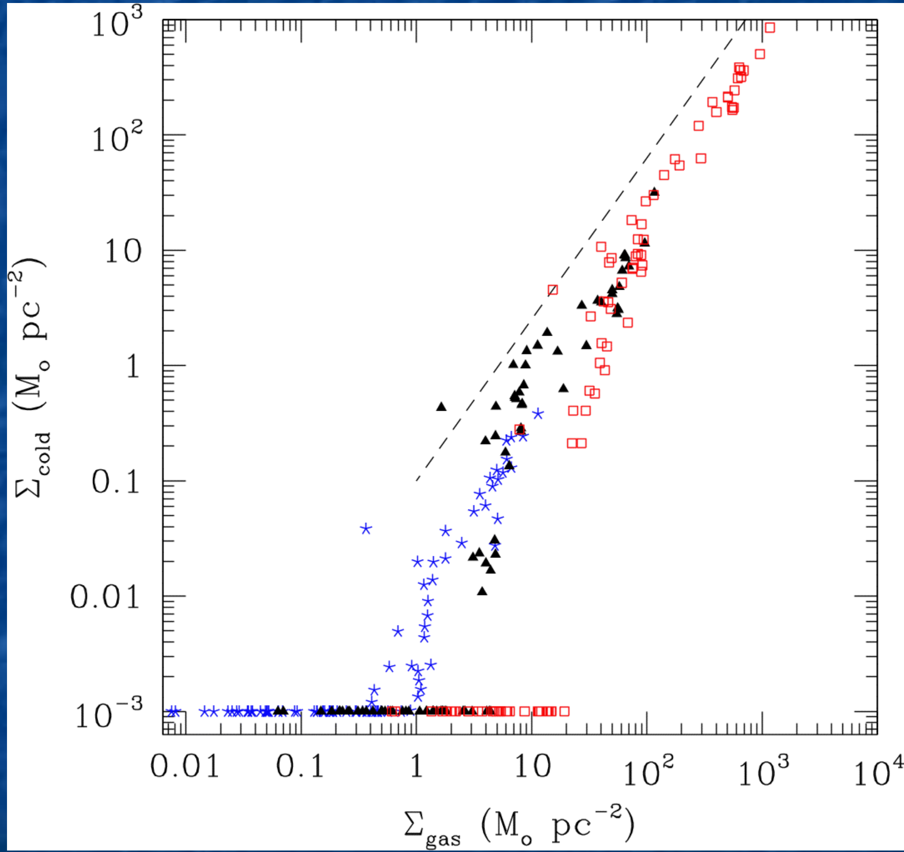
Dense gas: precursor for star formation

- Cold, dense gas follows same relation

$$\Sigma_{cold} \propto \Sigma_{gas}^{3/2}$$

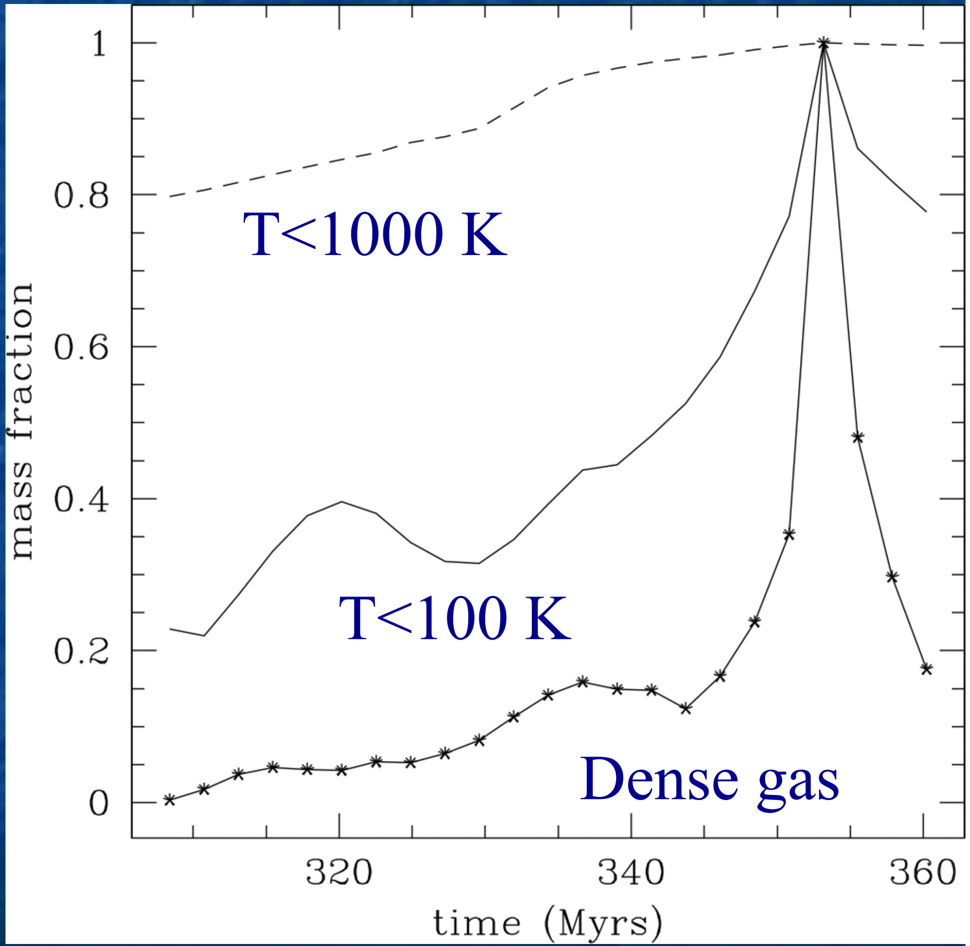
- Even without self-gravity
  - Due to shock and cooling

$$\Sigma_{SFR} \approx \Sigma_{cold} / t_{ff}$$



Where does the star forming gas come from?

- Cool gas, T<1000 K
- Cold gas, T<100 K
  - 10's of Myr
- From previous shocks
- Dense gas
  - $\rho > 10\ M_{sun}\ pc^{-3}$
  - ~ 5 Myr
  - Easier to compress cool gas



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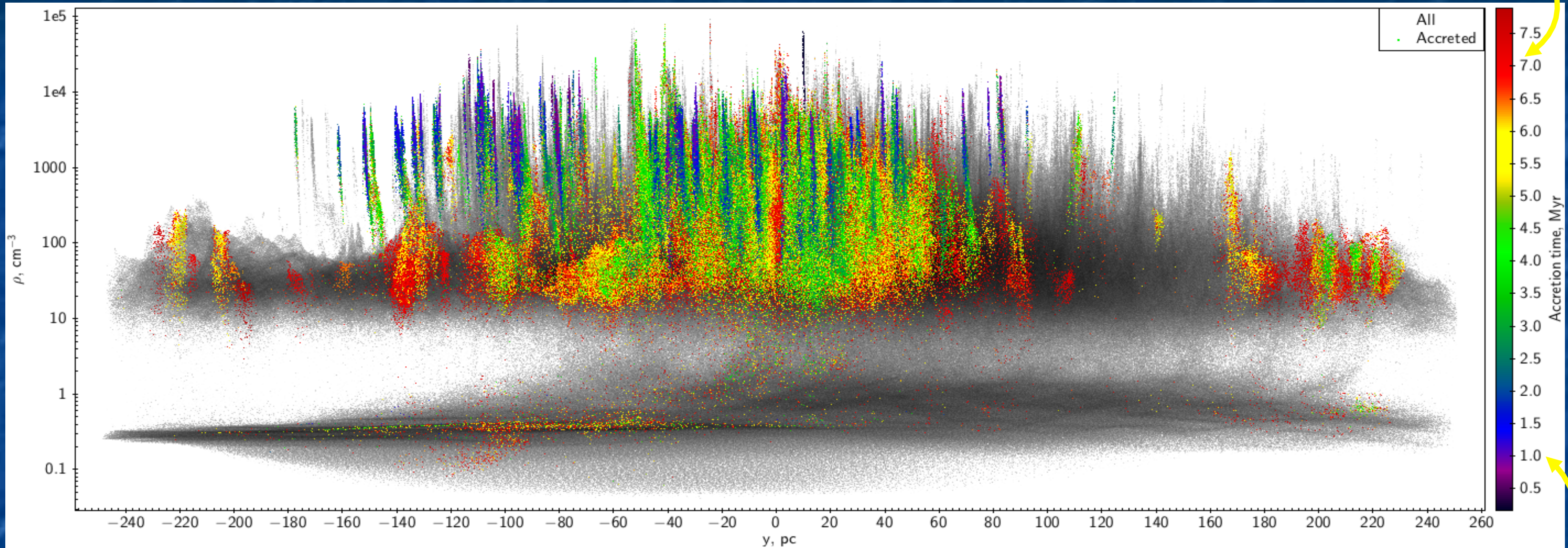
Initial conditions for star formation

Late SF

density, cm^{-3}



Accretion time, Myr

y, pc

50 pc

Early SF

- Two phases of gas: dense (cold) and less dense (hot)

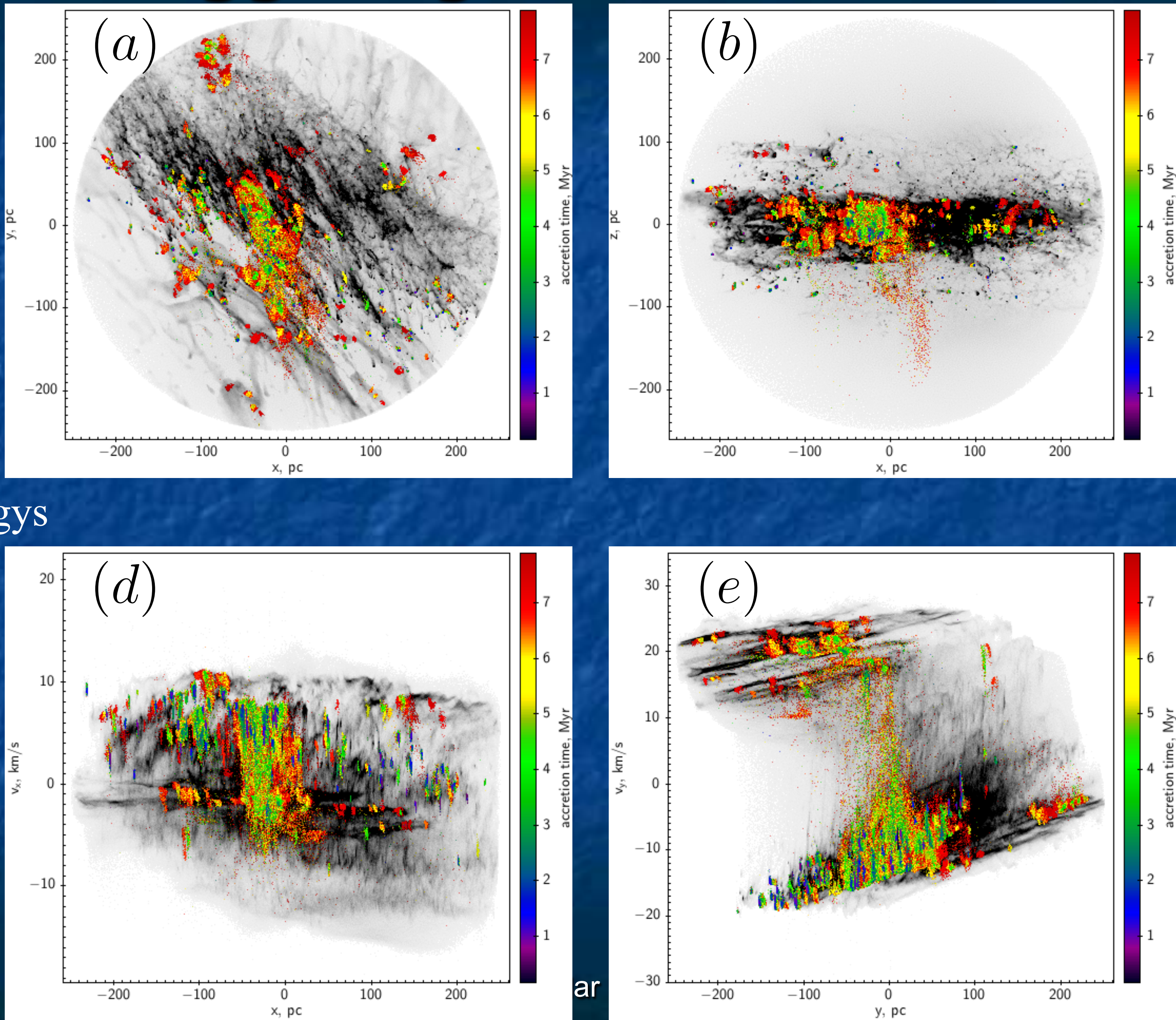
- Trace star forming gas through evolution
- Star forming gas (coloured) - located in dense gas regions
- Highest density gas undergoes star formation first (blue)

Smilgys & Bonnell 2014

Triggering Star Formation

R. Smilgys

velocities



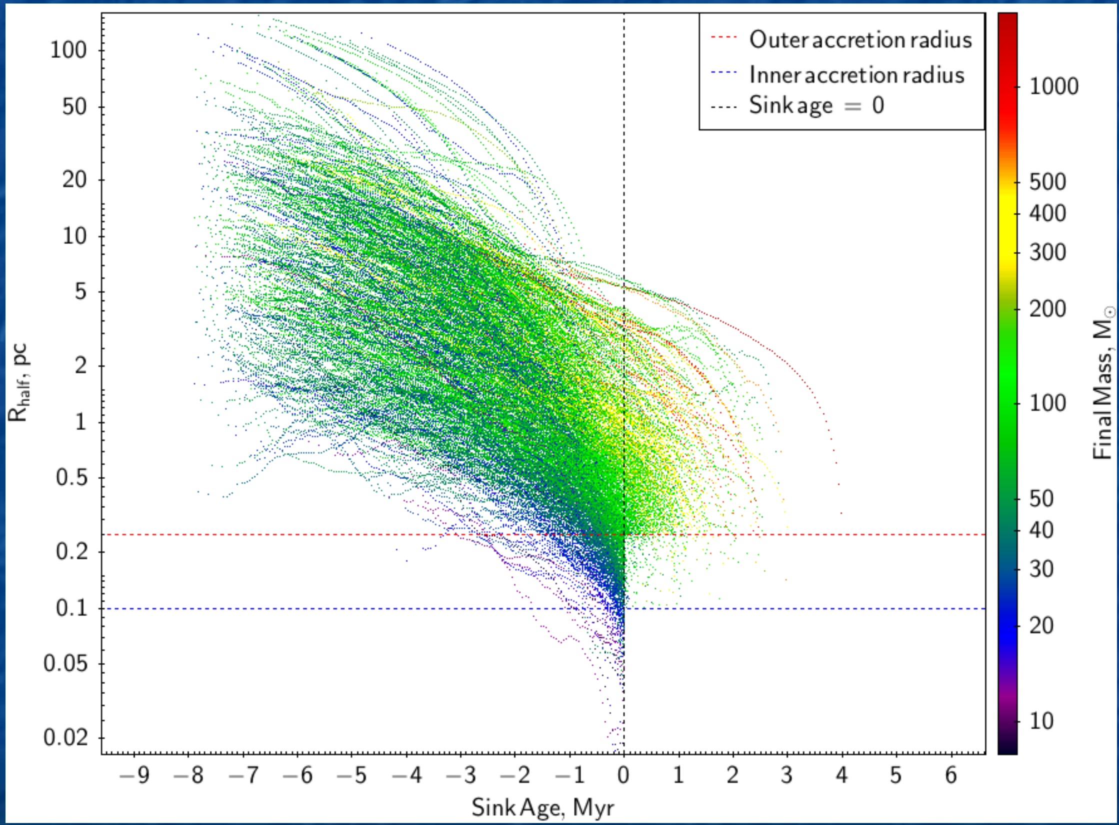
ar

Colours : Depletion times

Formation of Stellar Clusters

Stellar clusters gather gas from large distances

Small clusters < 5-10 pc
Large clusters ~10-100 pc



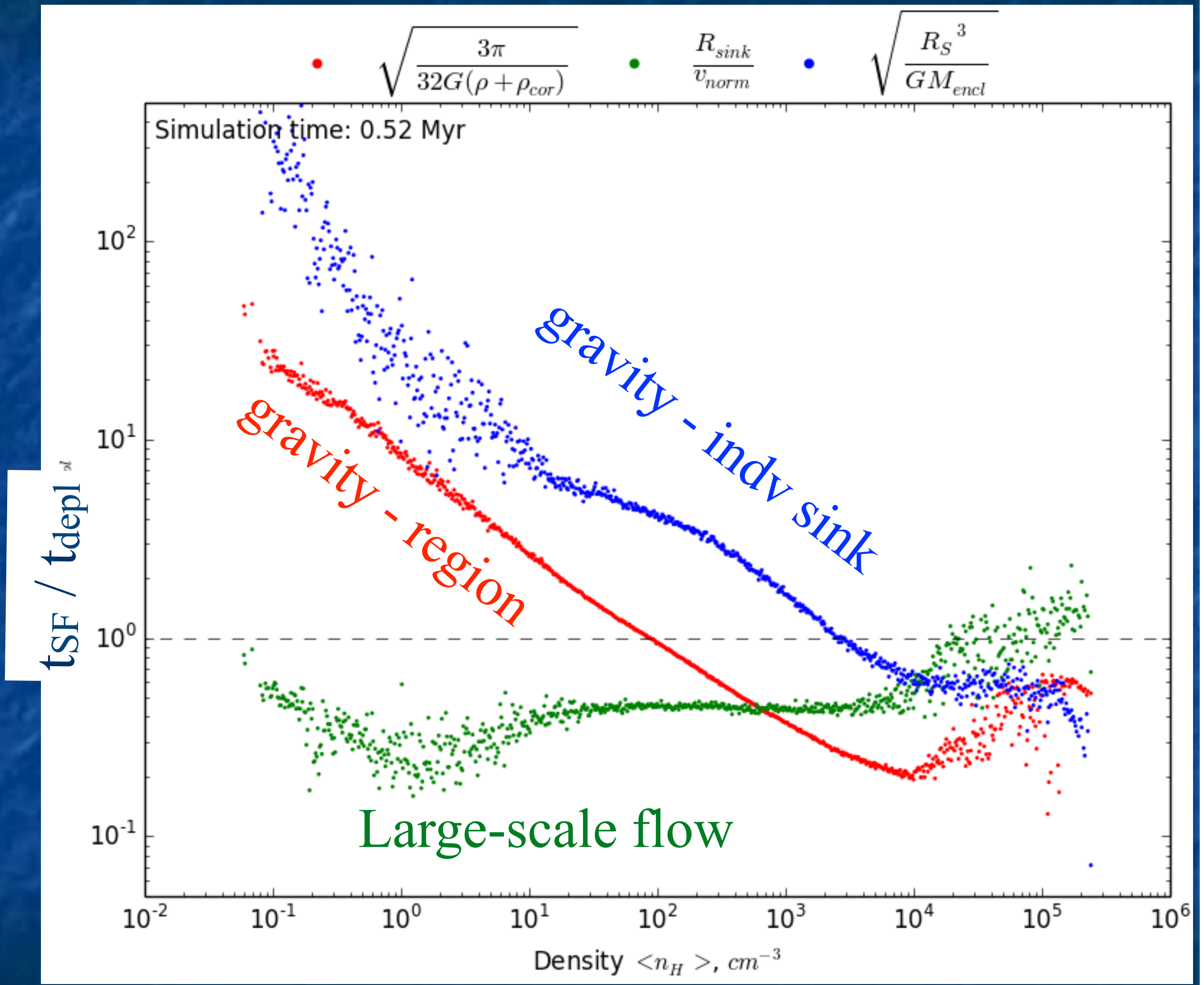
What drives star formation ?

Compare theoretical timescales with simulated SF times

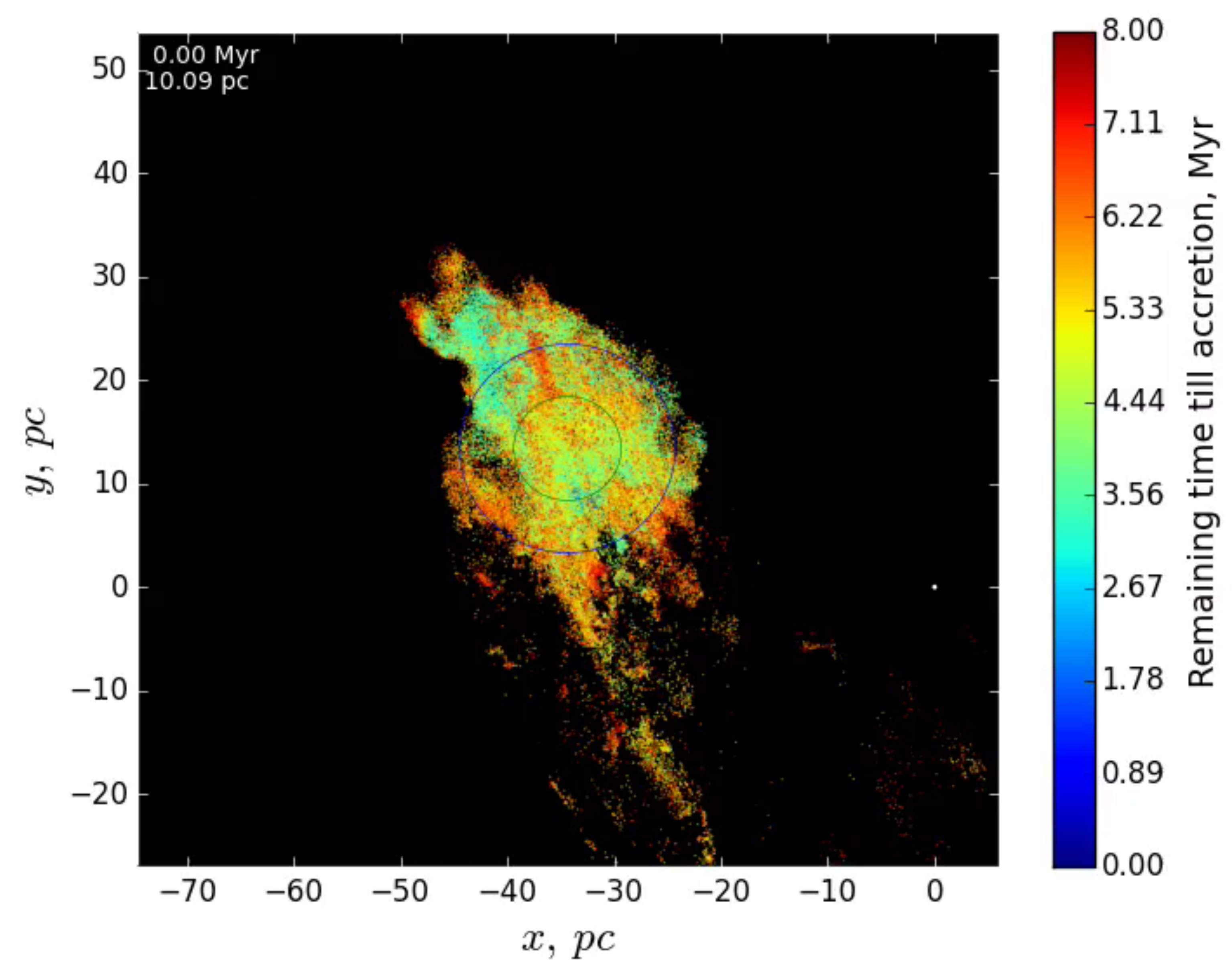
1) Galactic flows dominate on large scales (~10+ pc)

2) Self-gravity of forming cluster dominates on smaller scales,

3) For Densities > 10^3 cm^{-3}



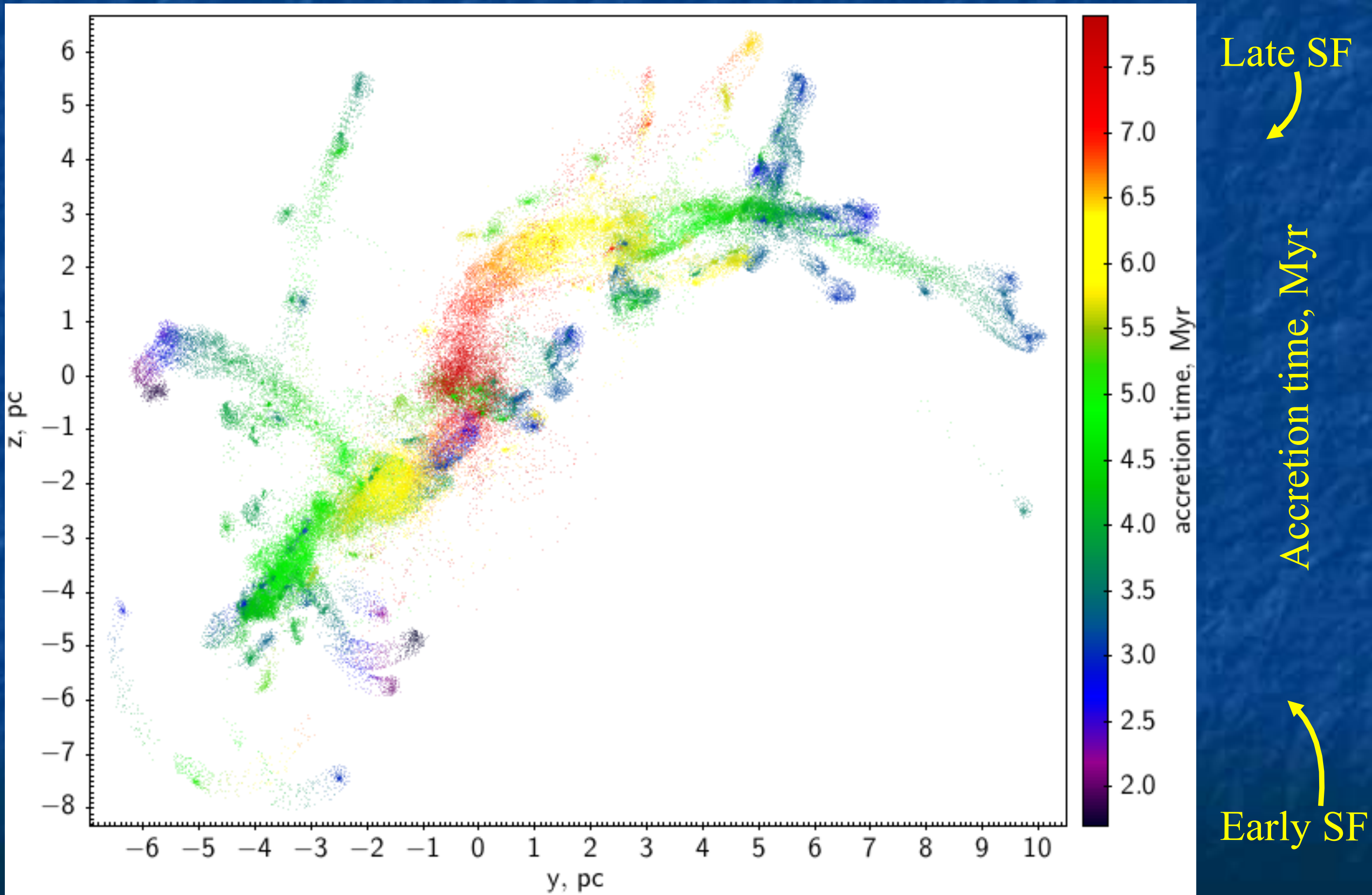
Cluster Formation



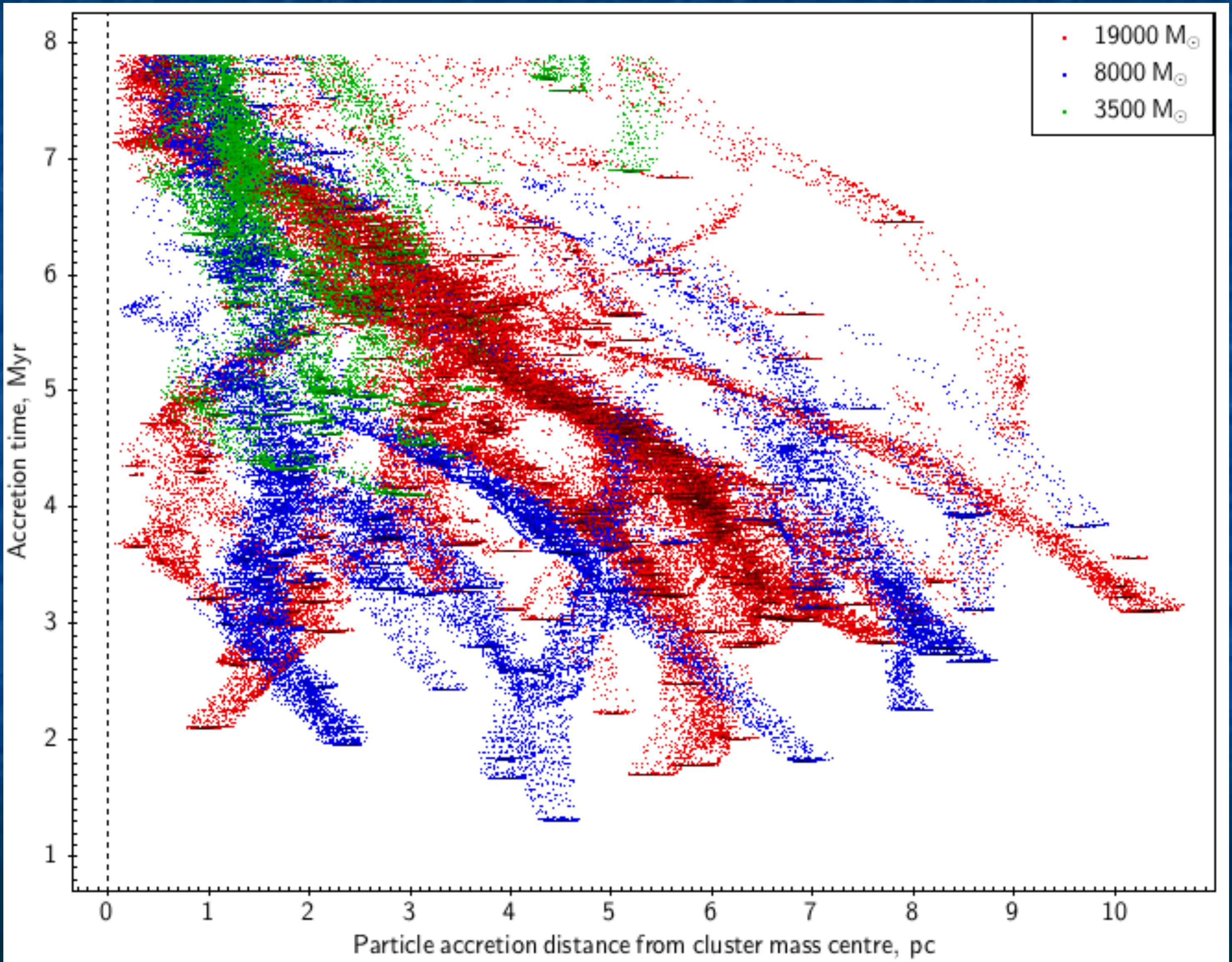
Early Life of Stellar Clusters, 2014

Tracks in the sand

Formation history of a 19000 M_o cluster



Age spreads

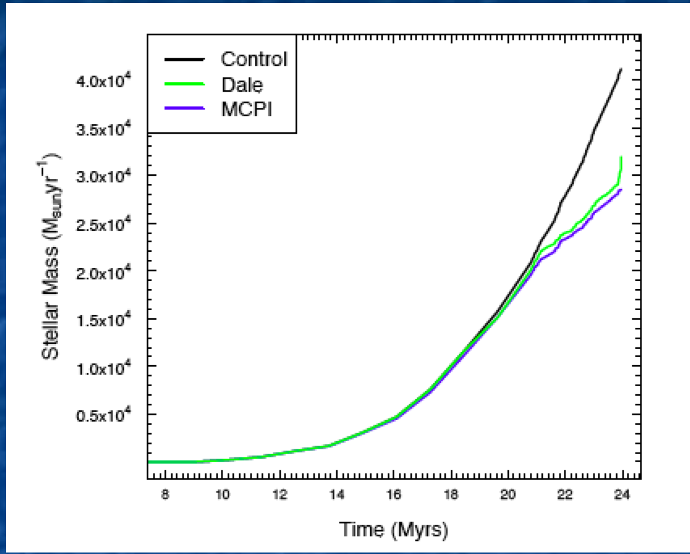


19000 M⊙
8000 M⊙
3500 M⊙
Accretion time, Myr
1
2
3
4
5
6
7
8
0
1
2
3
4
5
6
7
8
9
10
Particle accretion distance from cluster mass centre, pc

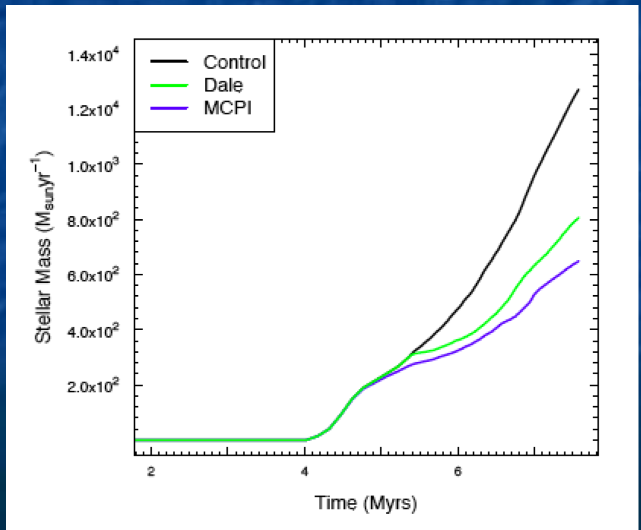
Feedback: Ionising Feedback

- Monte Carlo ionisation
- Post processed
  - No affect on dynamics

- Ionised gas removed from further star formation



Dale cloud A

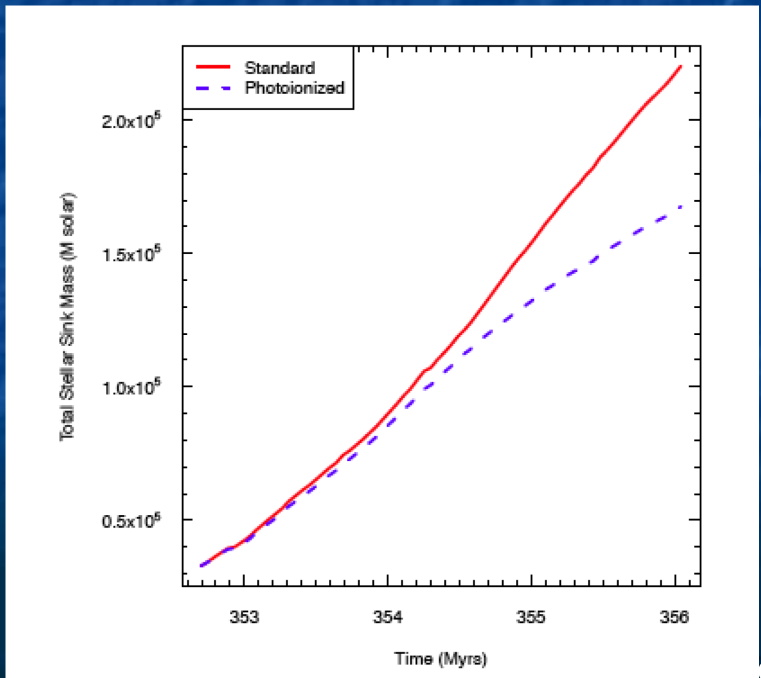


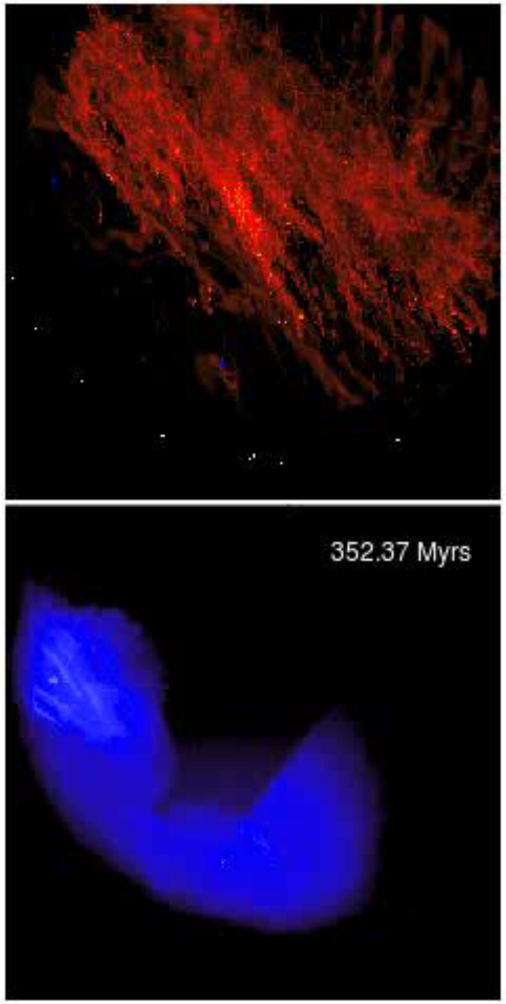
Dale cloud I

MacLachlin et al 2014

Feedback: Ionising Feedback

- Monte Carlo ionisation
- Ionised gas removed from any star formation
- Reduces star formation by at most ~2





McLaughlin et al 2013

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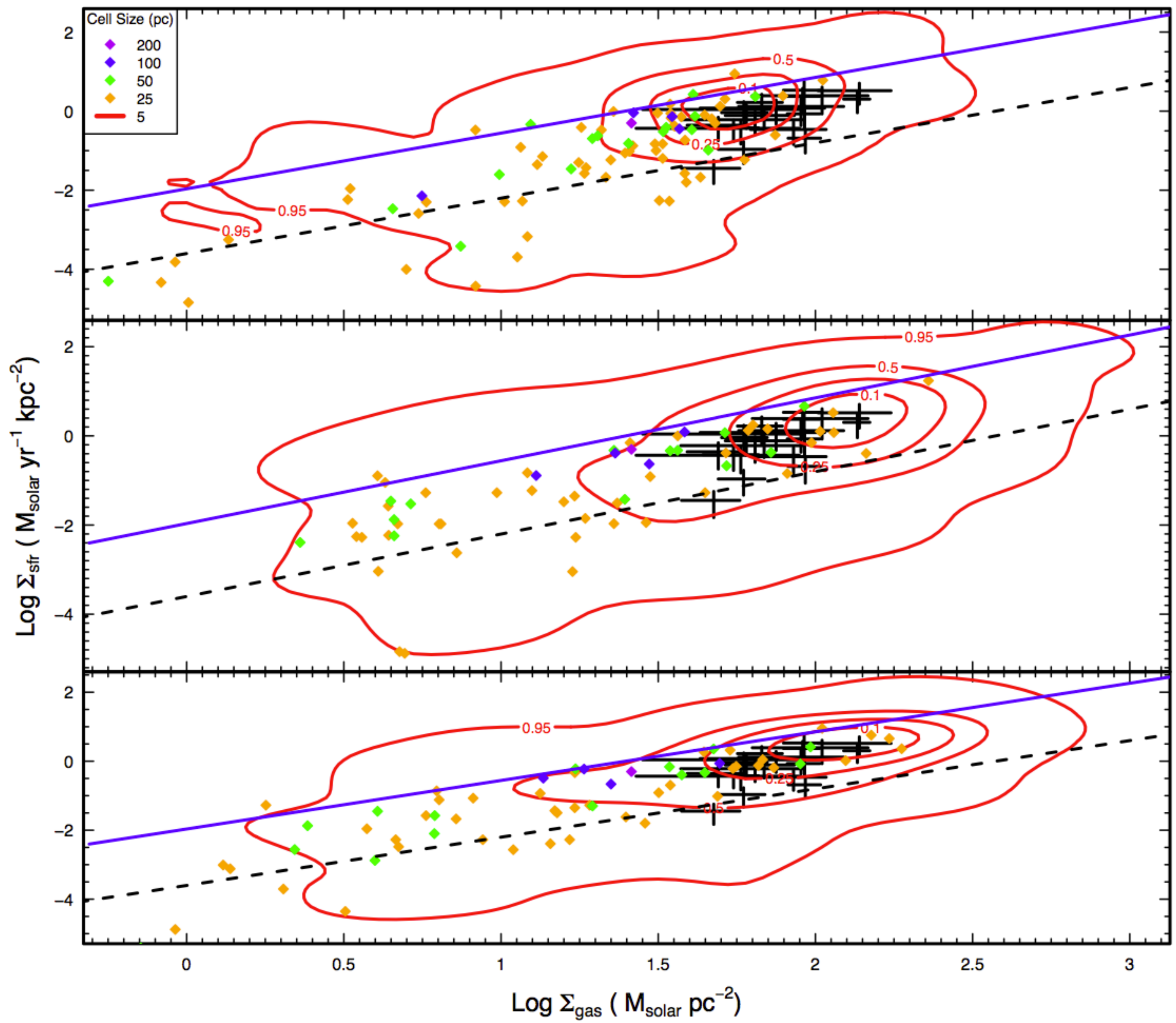

Summary

Large-scale Shocks and cooling can trigger star formation

- Realistic molecular clouds (structures/dynamics)?
  - Large scale turbulence driving
  - Need not be globally bound : low star formation efficiencies
- Schmidt-Kennicutt type SFR relations (but higher)
- Clusters form from several to 10's pc scales
  - Assembled by large scale flows
  - Clusters form in bound regions (global infall)
  - Age spreads up to several Myrs
  - Massive stars accrete as $\dot{M} \propto M^{2/3}$
- Ionising Feedback factor of 2 decrease n SFR