Spiral shocks and the triggering of star formation

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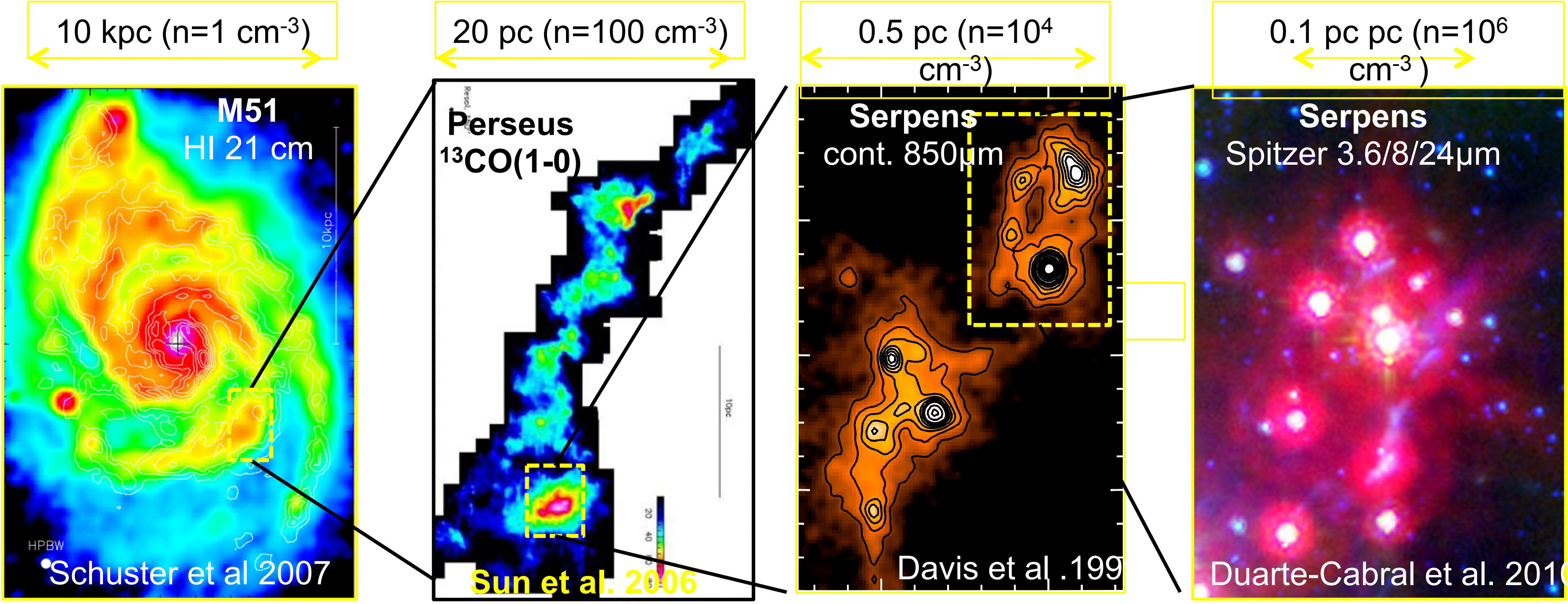
Modeling Star Formation in a Galactic Context



Transformation of ISM to GMCs

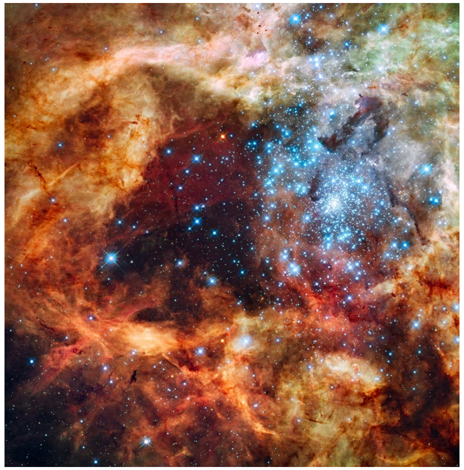
Resolve star formation

SPH: sink-particles

100+ self-gravitating particles

Include feedback from high-mass stars into GMC and ISM

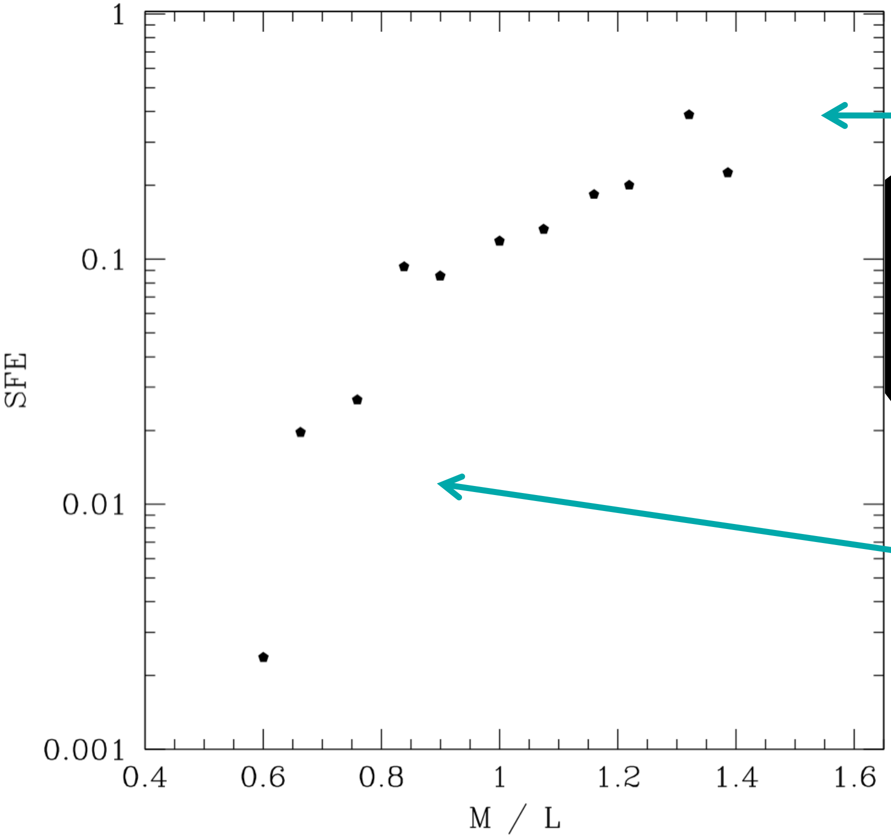
Magnetic fields (later)

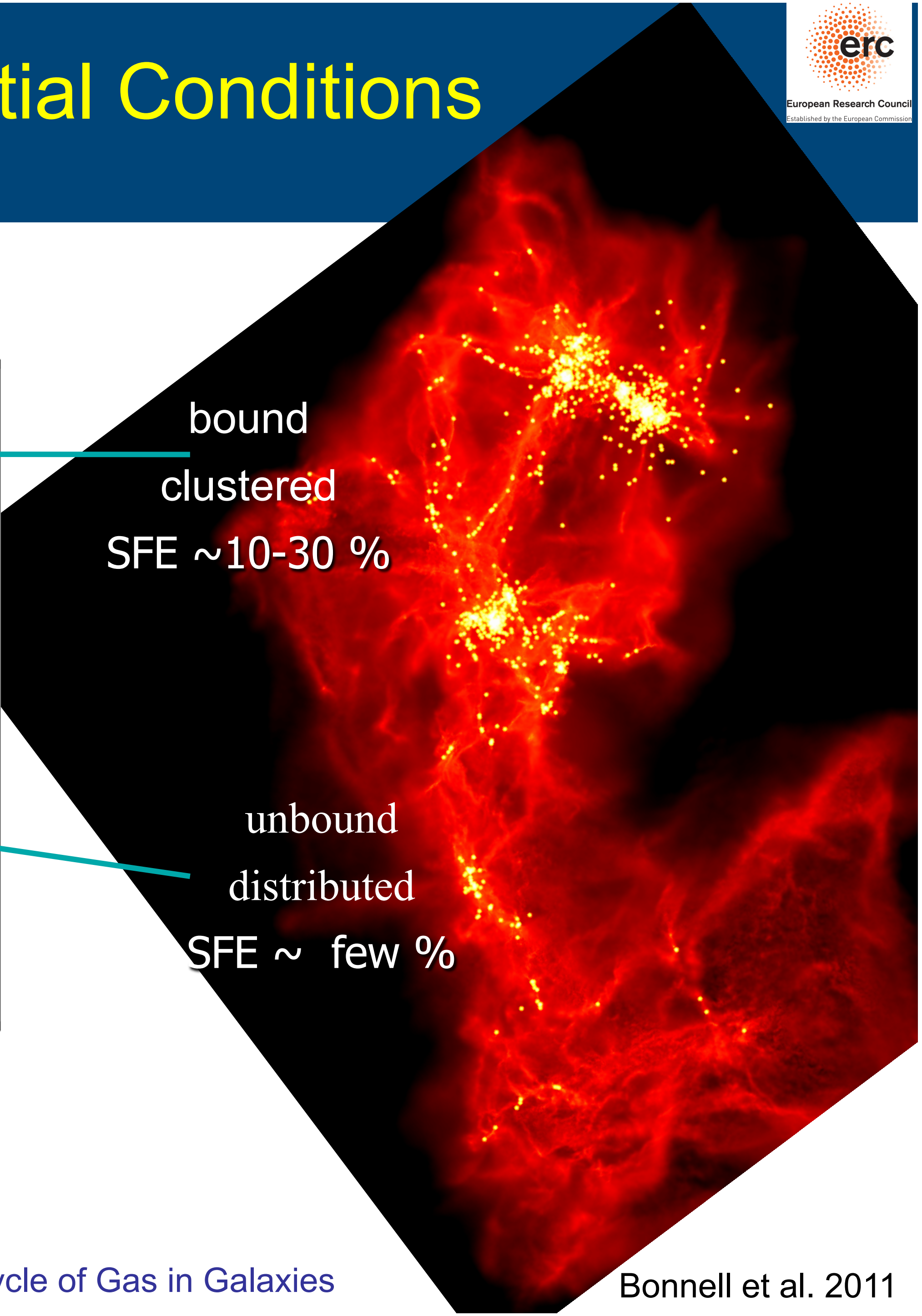


Life Cycle of Gas in Galaxies

Importance of Initial Conditions

- Bound conditions produce stellar clusters and full IMF





Bonnell et al. 2011

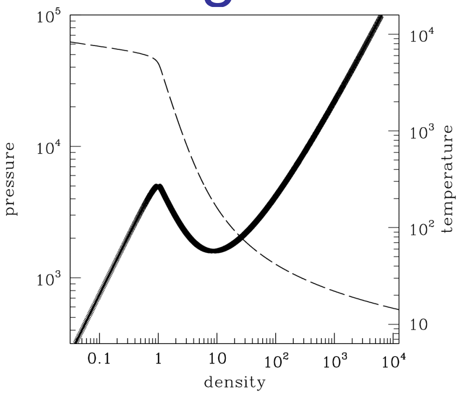
- Unbound regions produce
  - Low SF efficiencies , peaked IMF
  - See Clark et al 2008

Realistic initial conditions for star formation

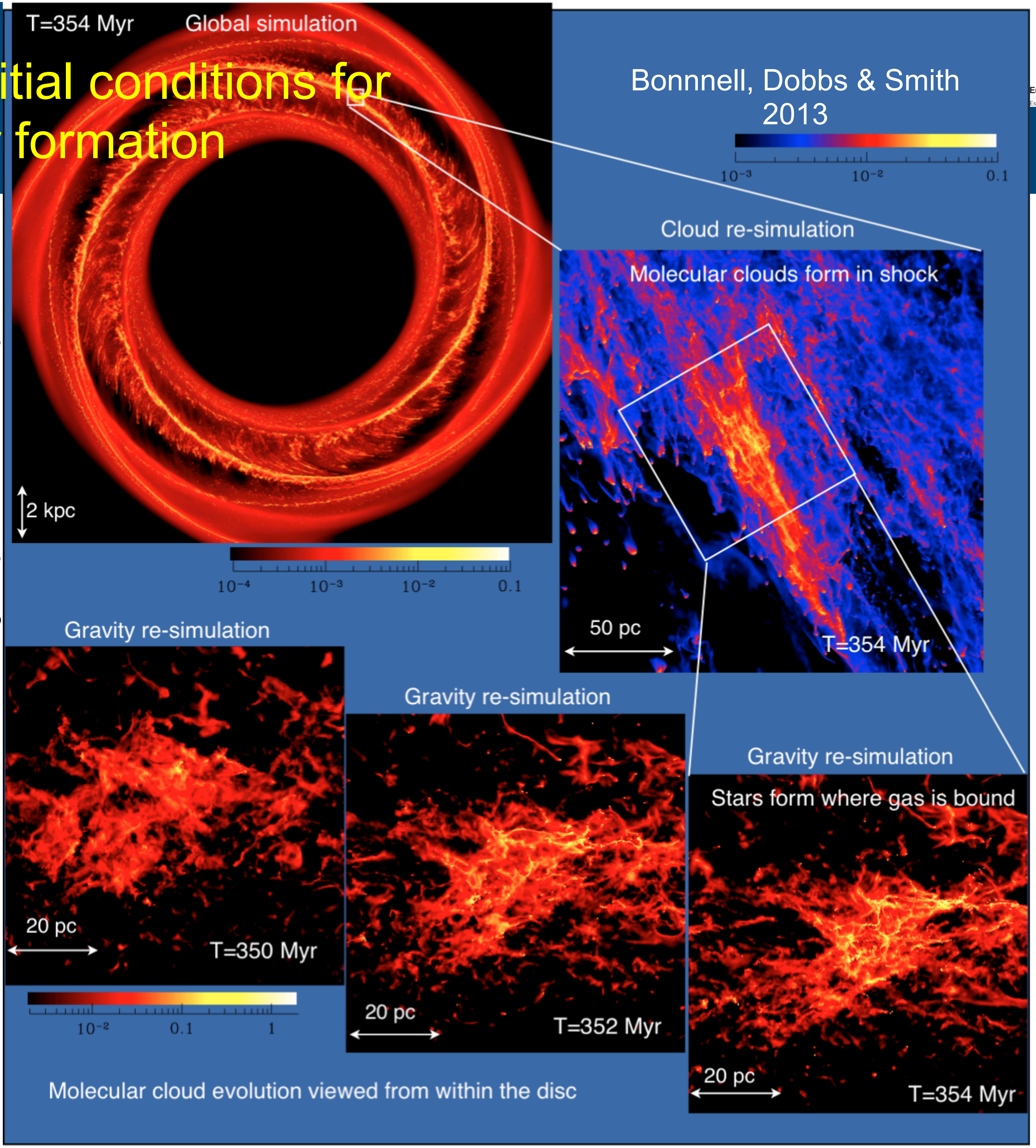
Global disc
2.5 x 10^7 particles
2 x 10^9 M_{sun} gas

Cloud
1.1 x 10^7 particles
1.7 x 10^6 M_{sun} gas

Cooling curve:

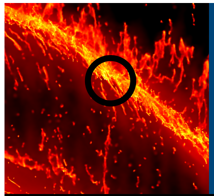


T: 10 to ~10^4 K

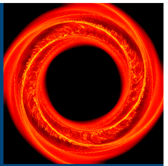


Bonnnell, Dobbs & Smith 2013

Molecular cloud evolution viewed from within the disc



Galactic triggering of star formation



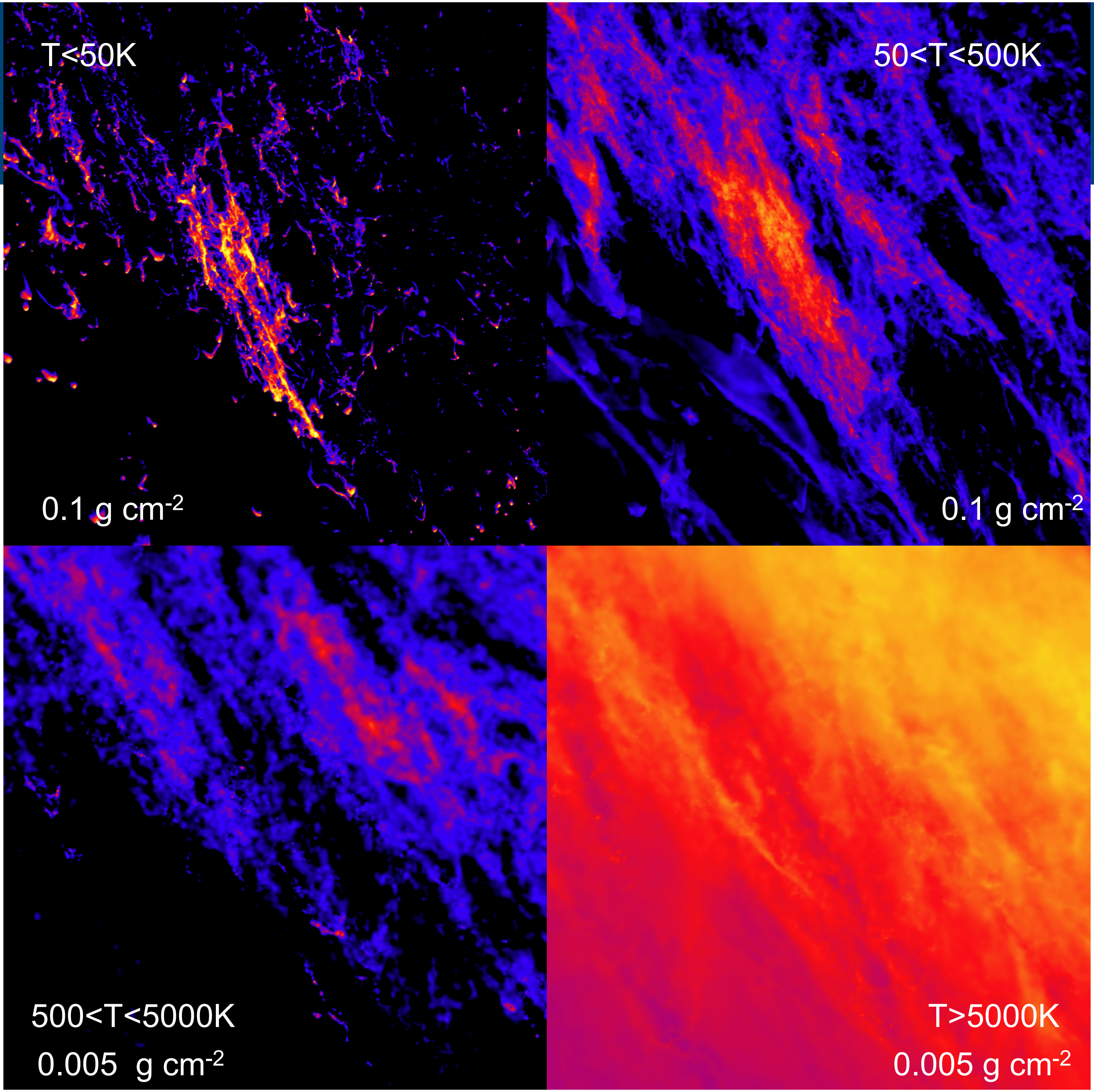
Face on view

Galactic plane view

High resolution region 200x200pc

Cold gas 1.7 x 10^6 M_o gas

Resolution ~ 10 M_o , 0.05 pc

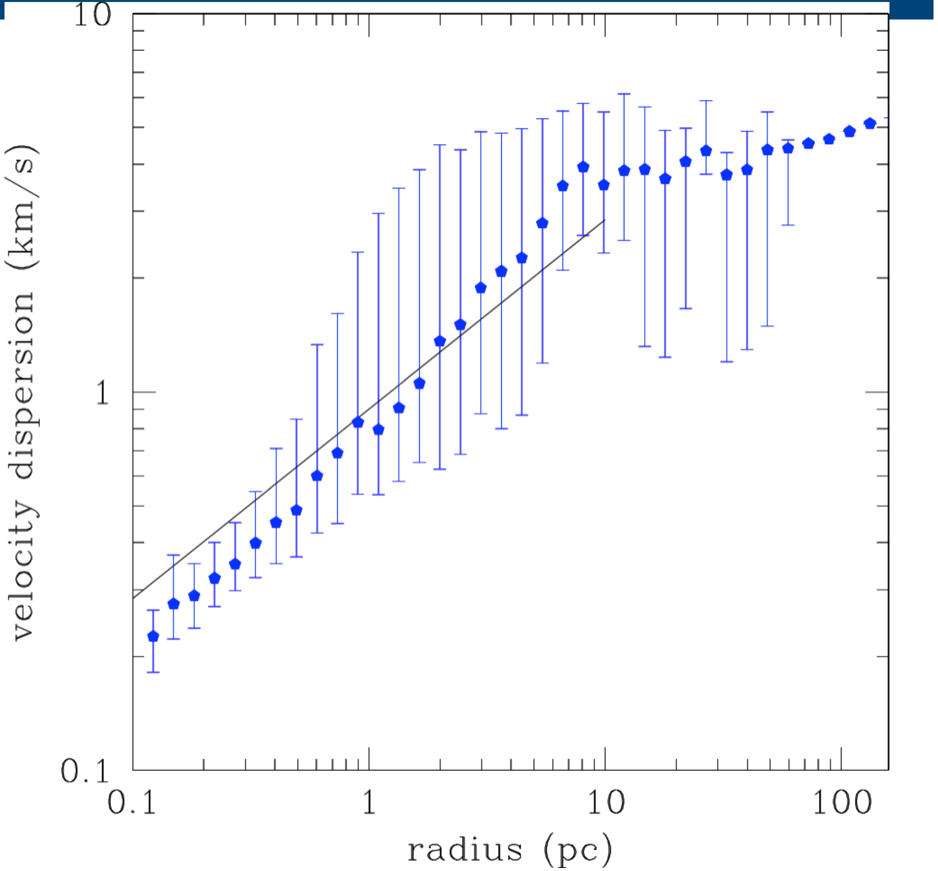

T<50K
0.1 g cm-2
50<T<500K
0.1 g cm-2
500<T<5000K
0.005 g cm-2
T>5000K
0.005 g cm-2

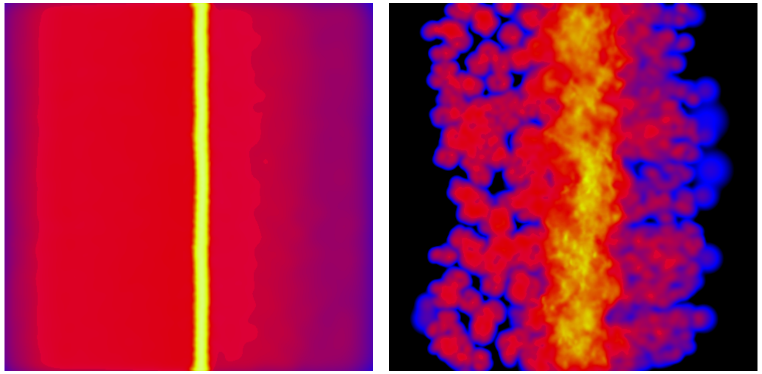
GMC Kinematics

- Convergent gas streams
  - Clumpy gas
  - generates velocity dispersion

  - Thermal instability

- Turbulence driving on ~10 pc scales



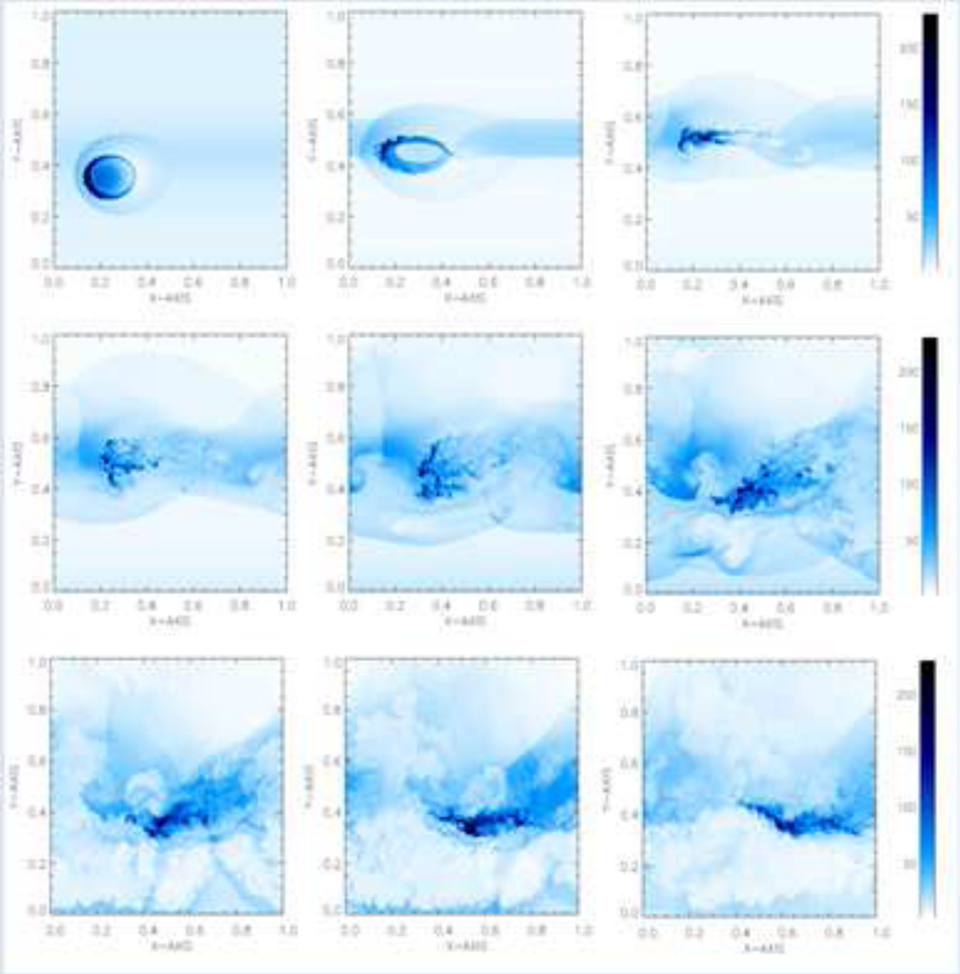


Bonnell, Dobbs & Smith 2013

Dobbs & Bonnell 2007

Falceta-Goncalves et al 2014

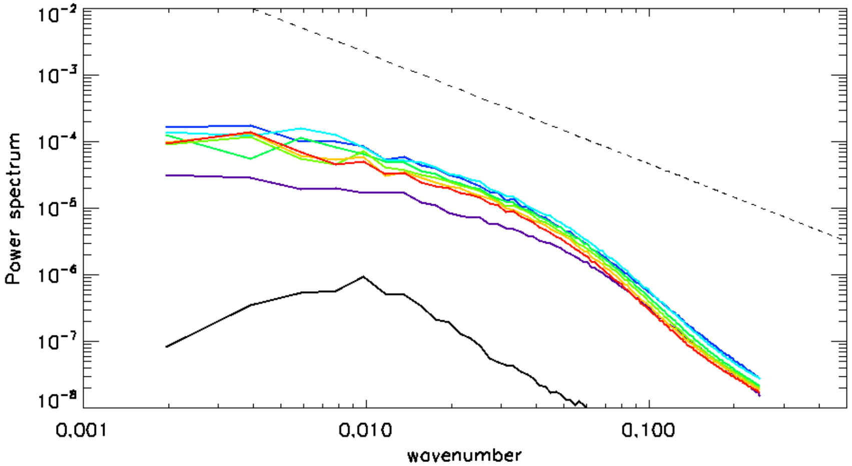
Spiral arm driven turbulence

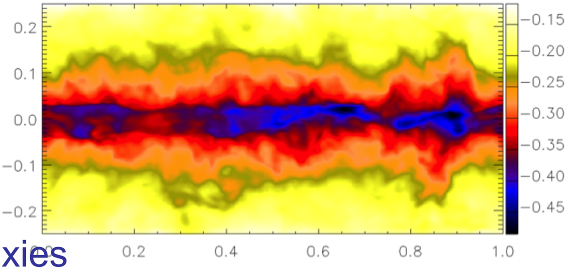


Single cloud-arm interaction

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

Drives turbulence



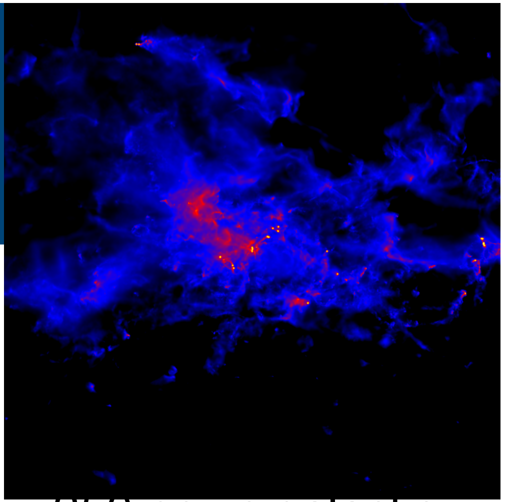


Falceta-Goncalves et al 2014

Initial Conditions for Star Formation

~ 10^6 M_o at molecular cloud densities

in ~ 100 pc, With self-gravity



250 pc, in galactic plane

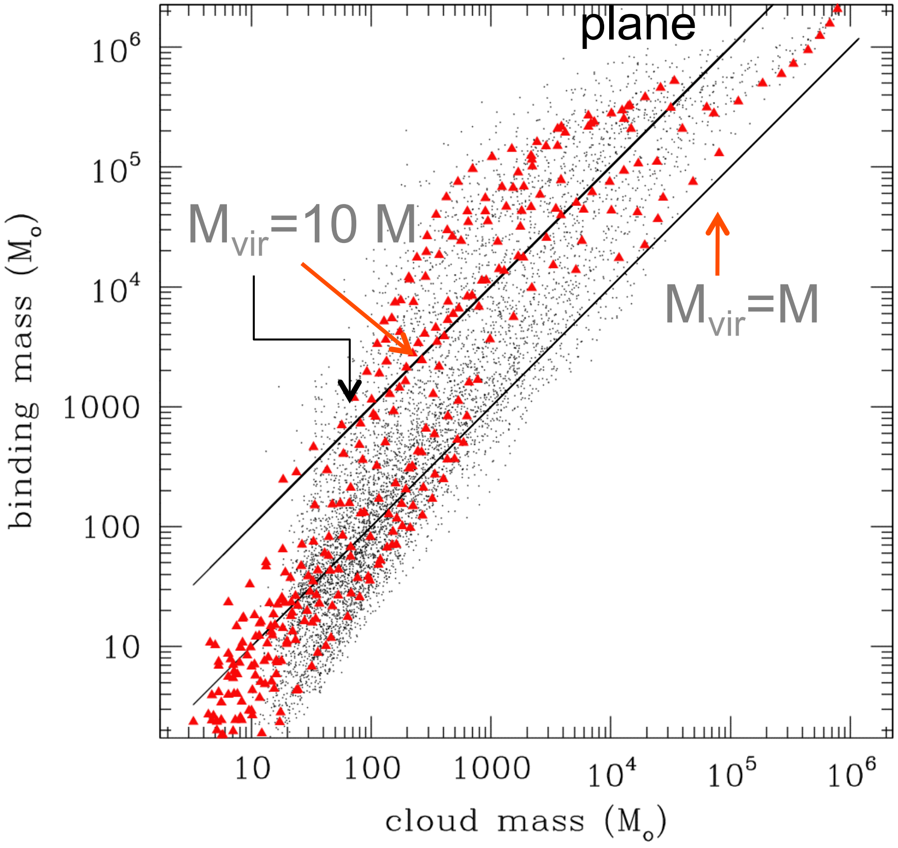
- Clouds globally unbound
  - Formed by spiral shock

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

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

highly structured

Cooler inside / warmer outside



Star Formation Rates

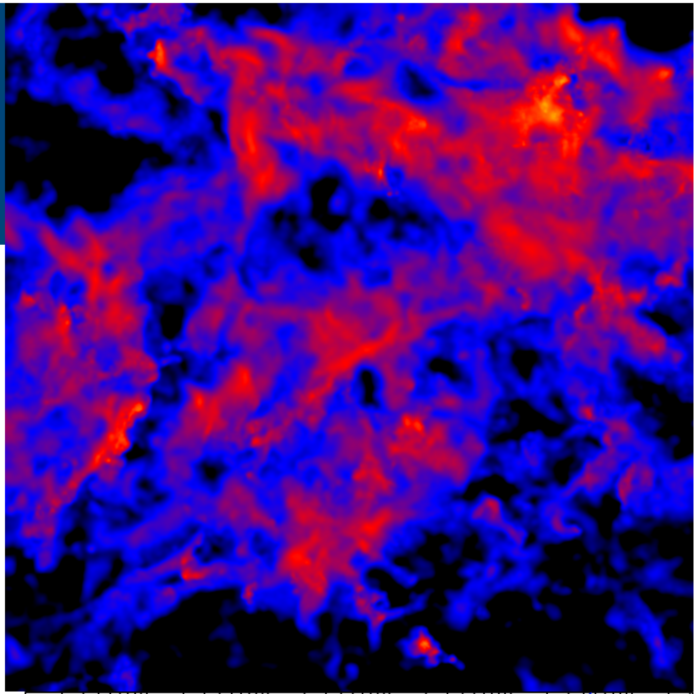
Local estimates of star formation rates

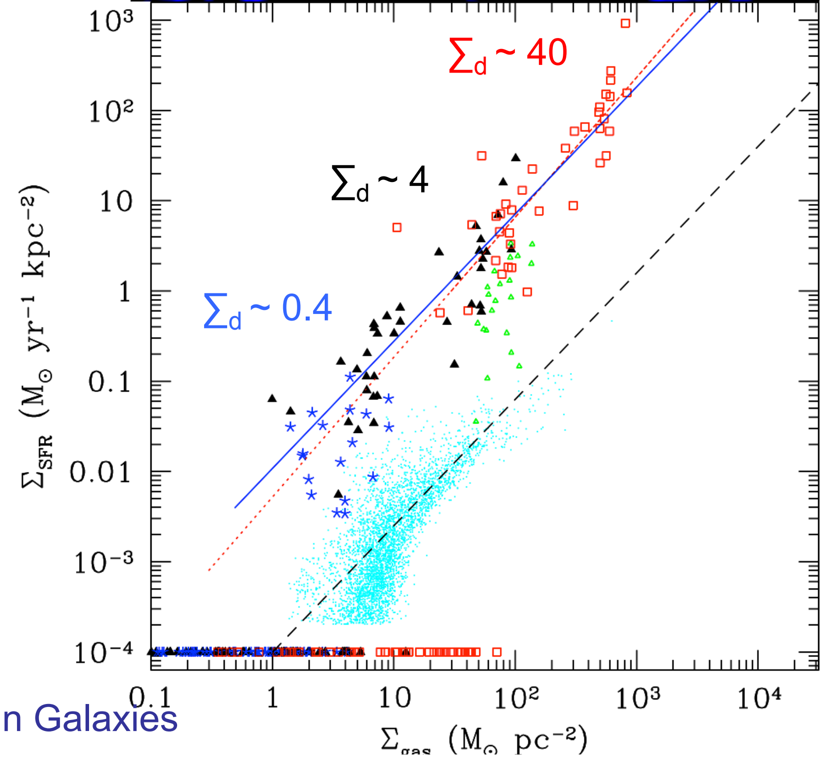
- After t=3.5 Myr
- Grid, sizes of 50x50 pc

- Over 3 simulations with
  $\Sigma_{gas} = 0.4$, 4 and 40 $M_o\ pc^{-2}$
  - S-K power law, but higher, closer to nearby GMCs (Heiderman et al 2011)
  - Critical step : formation of dense cold gas

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

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





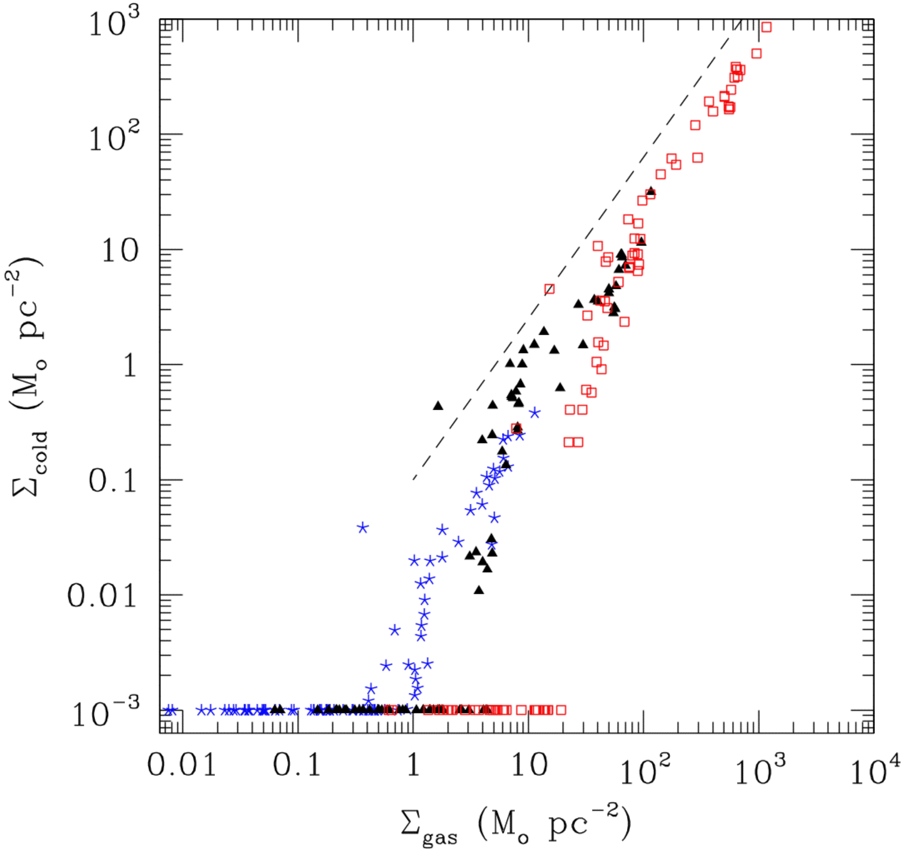
Dense gas: precursor for star formation

- Cold, dense gas follows same relation

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

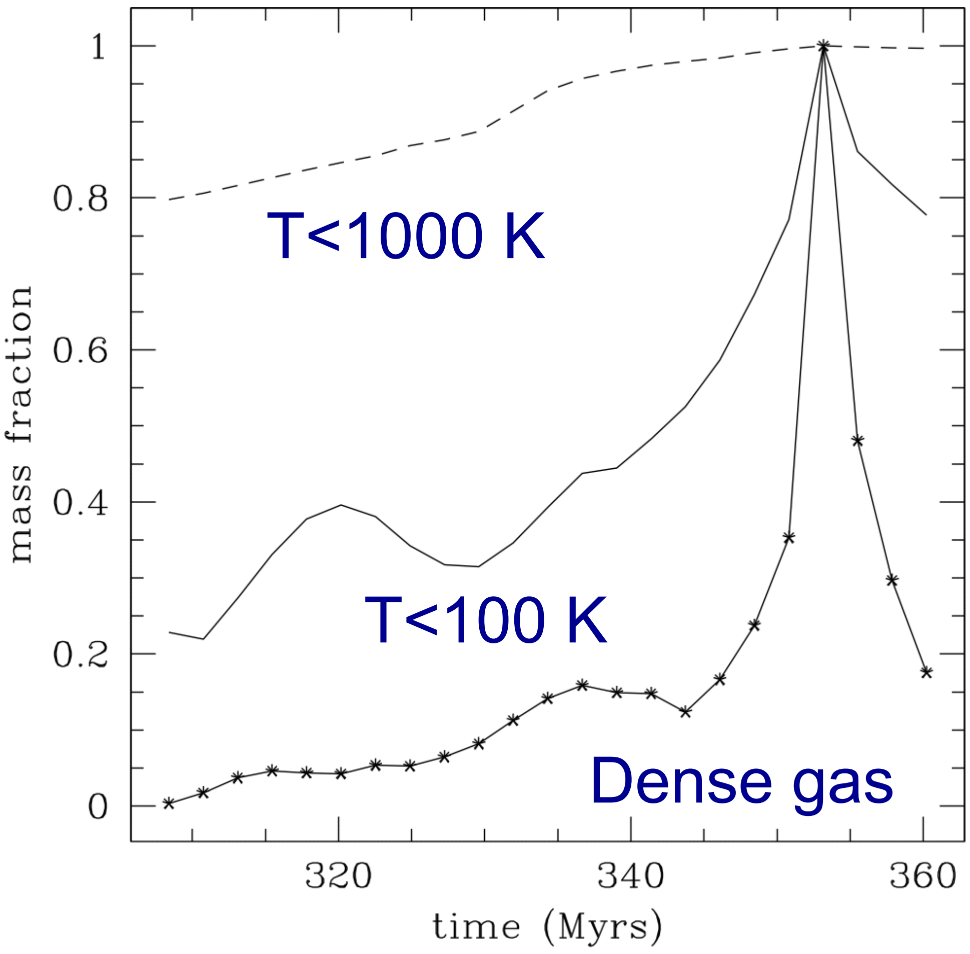
- Even without self-gravity
  - Due to shock and cooling

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



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
  - $\rho > 10\ M_{sun}\ pc^{-3}$
  - lifetimes ~ 5 Myr
  - Easier to compress cool gas



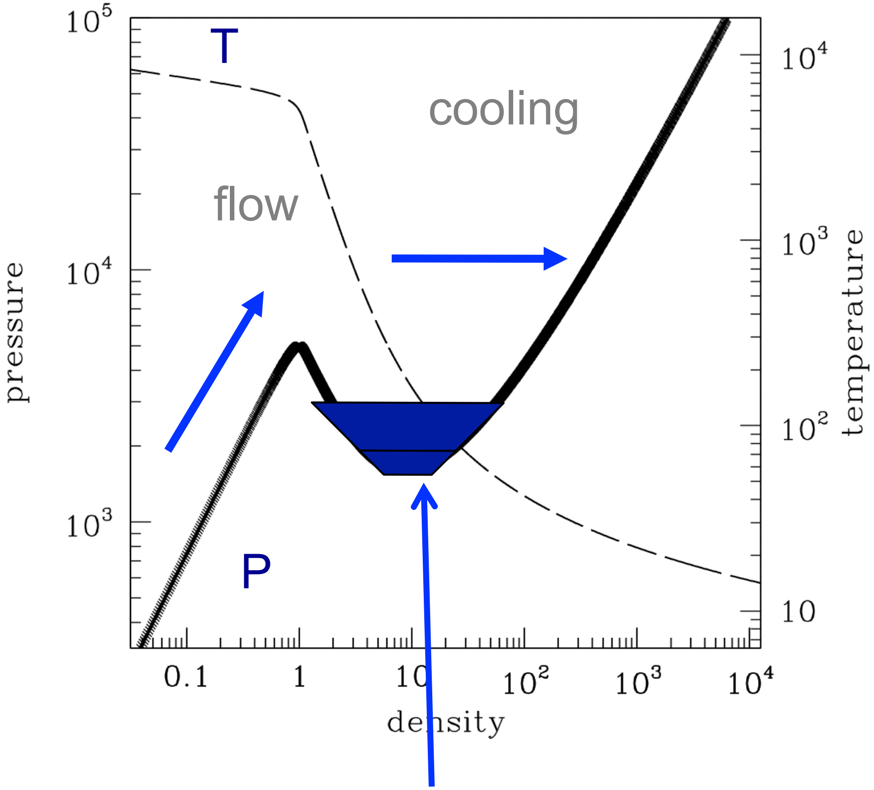
SF rates : cooling

- Dense clouds formed
  - from multiple shocks
  - Involve cool gas

- Higher Σ:
  - higher pressure
    - Gas can stay cool

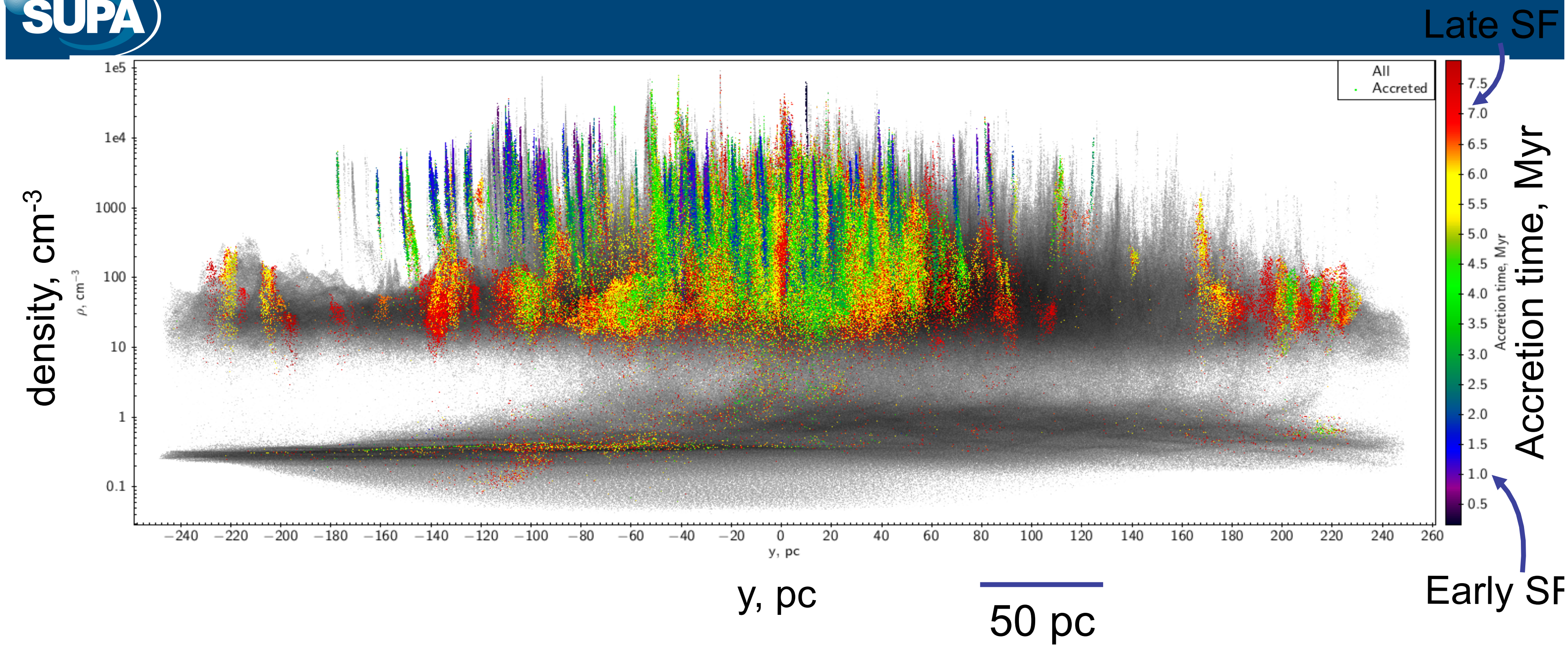
$$\rho_s \propto \left(v_s / c_s \right)^2$$

- shocks are stronger
- more gas attains high densities
- gravitationally bound
- Increased star formation rates



Cool gas between shocks

Initial conditions for star formation



- 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 2015

Cluster Formation

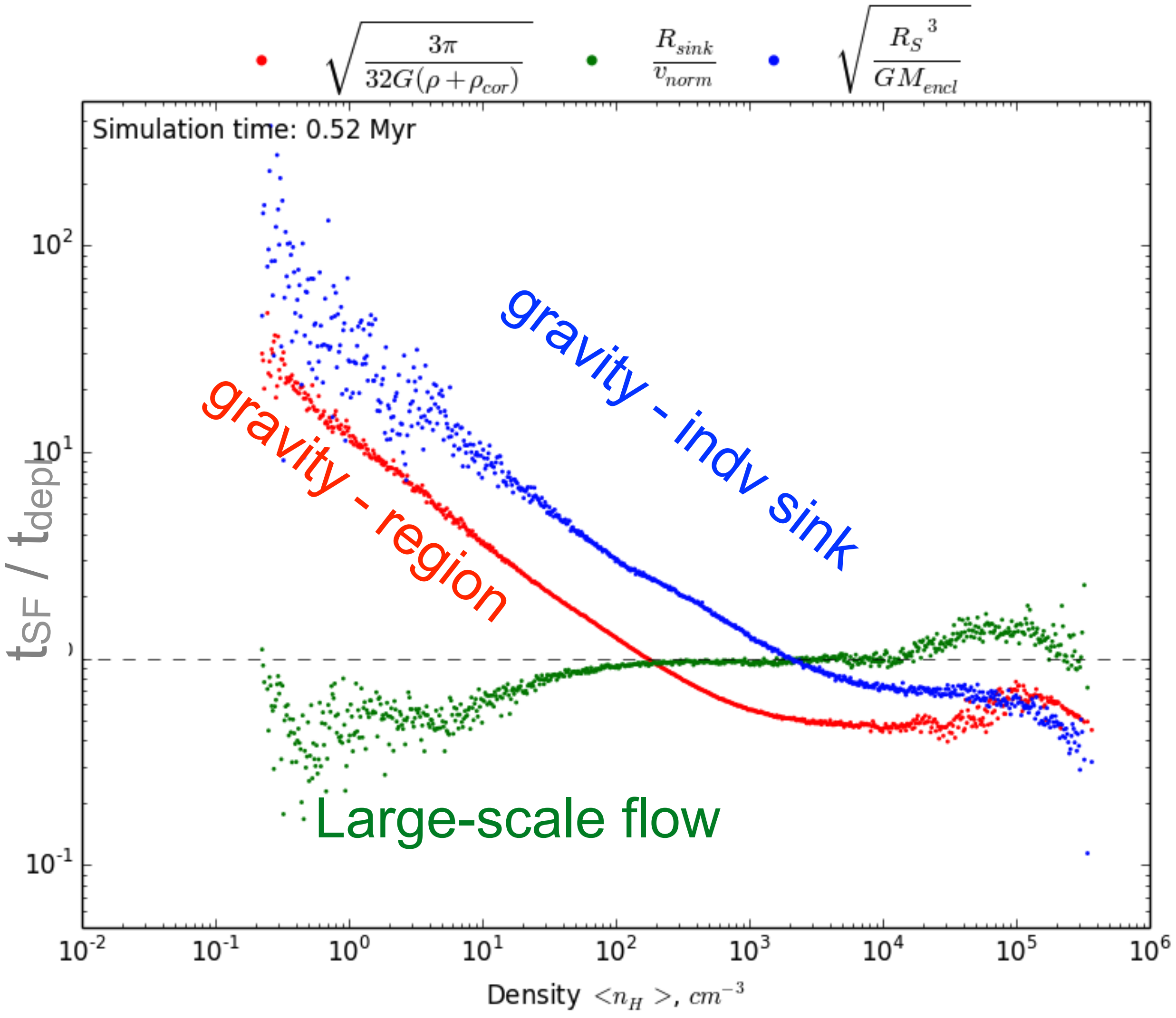
What drives star formation ?

Compare theoretical timescales with simulated SF times

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

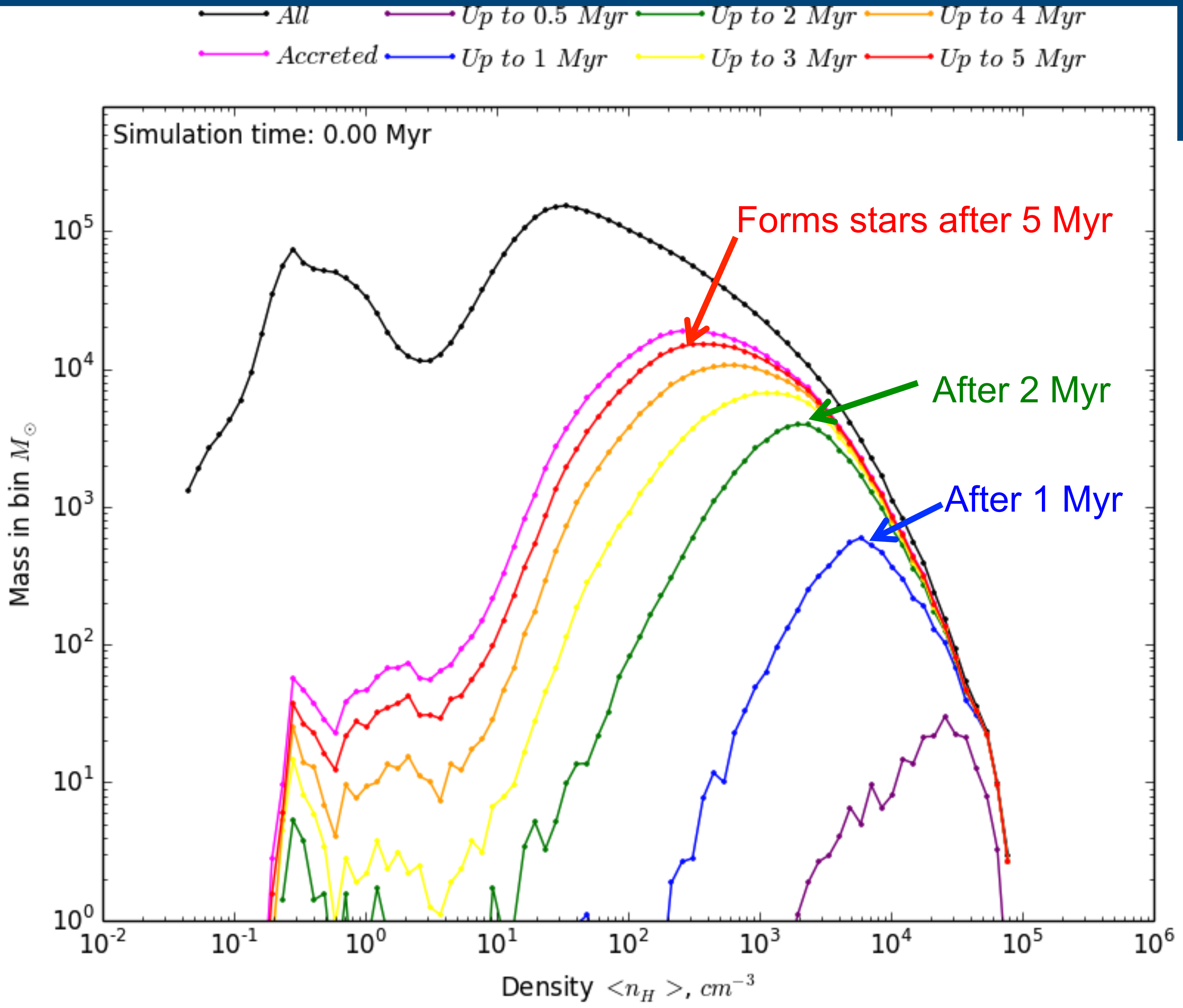
2) Self-gravity of forming cluster dominates on smaller scales,

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



Need $t_{sf} < t_{depl}$

Smilgys & Bonnell 2015

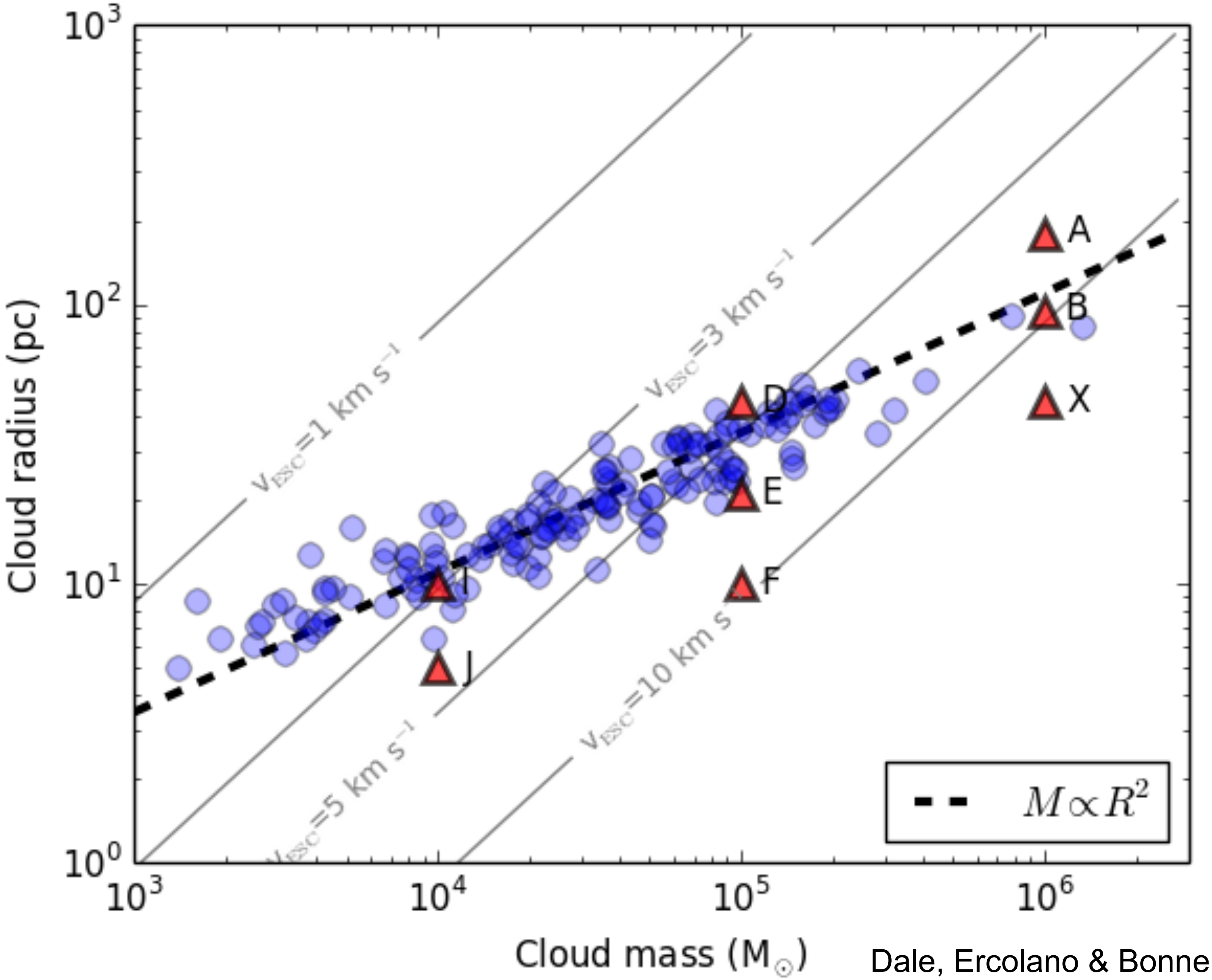


Forms stars after 5 Myr

After 2 Myr

After 1 Myr

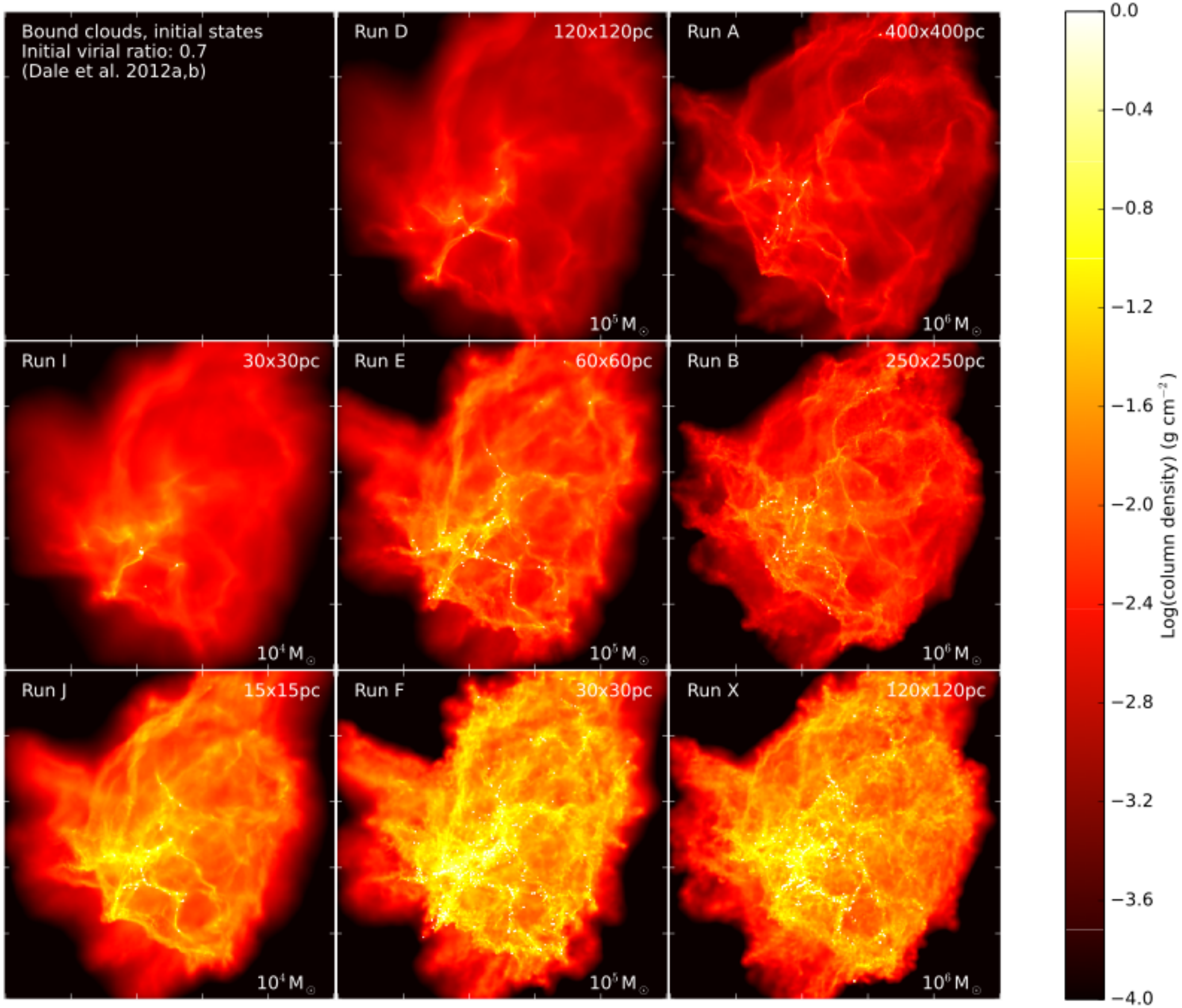
Feedback from high-mass stars



Dale, Ercolano & Bonnell 2012, 2014

Initial Conditions

Dale, Ercolano & Bonnell 2012, 2014



Ionisation and stellar winds

Dale, Ercolano & Bonnell 2012, 2014

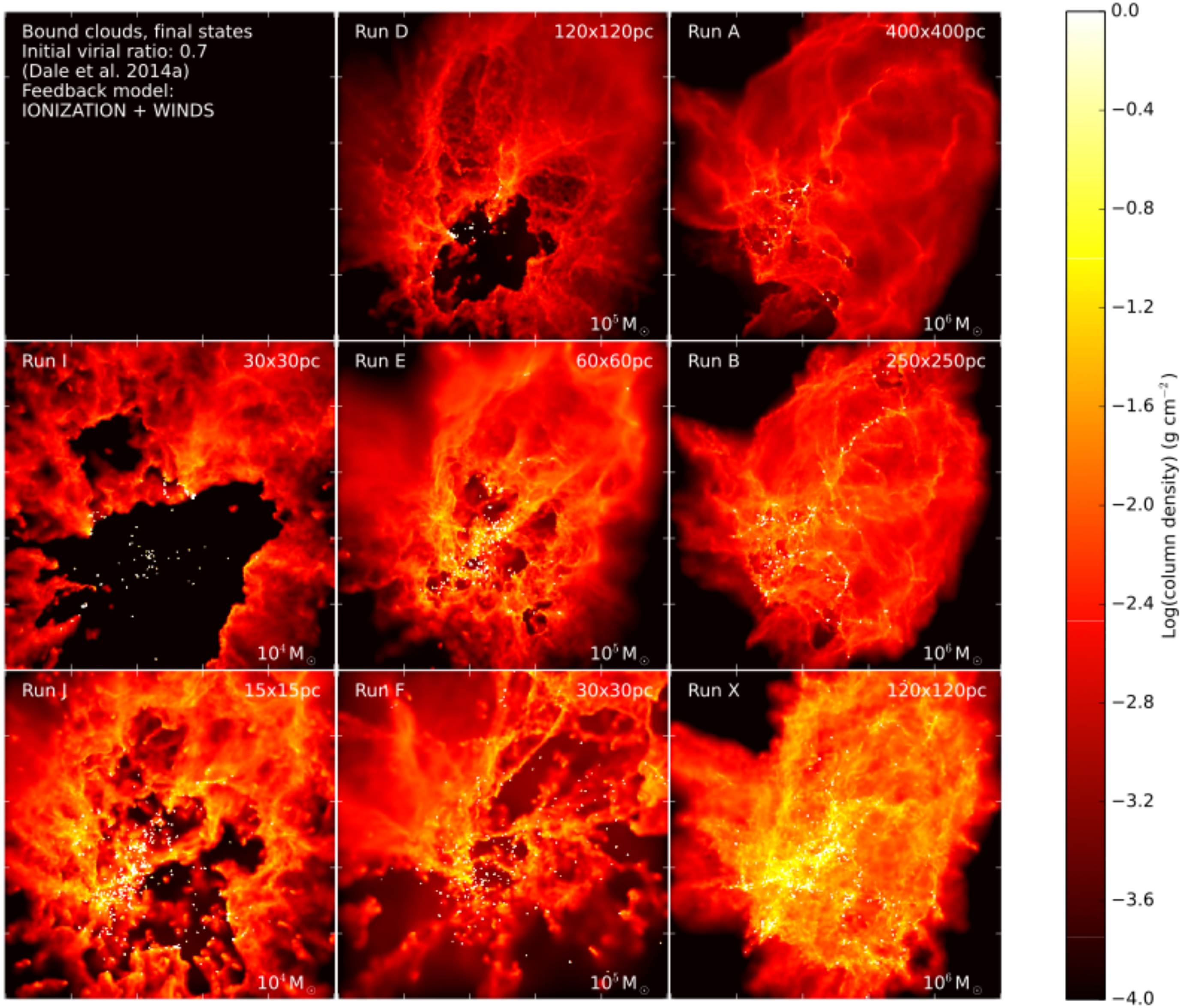
Lower density clouds affected

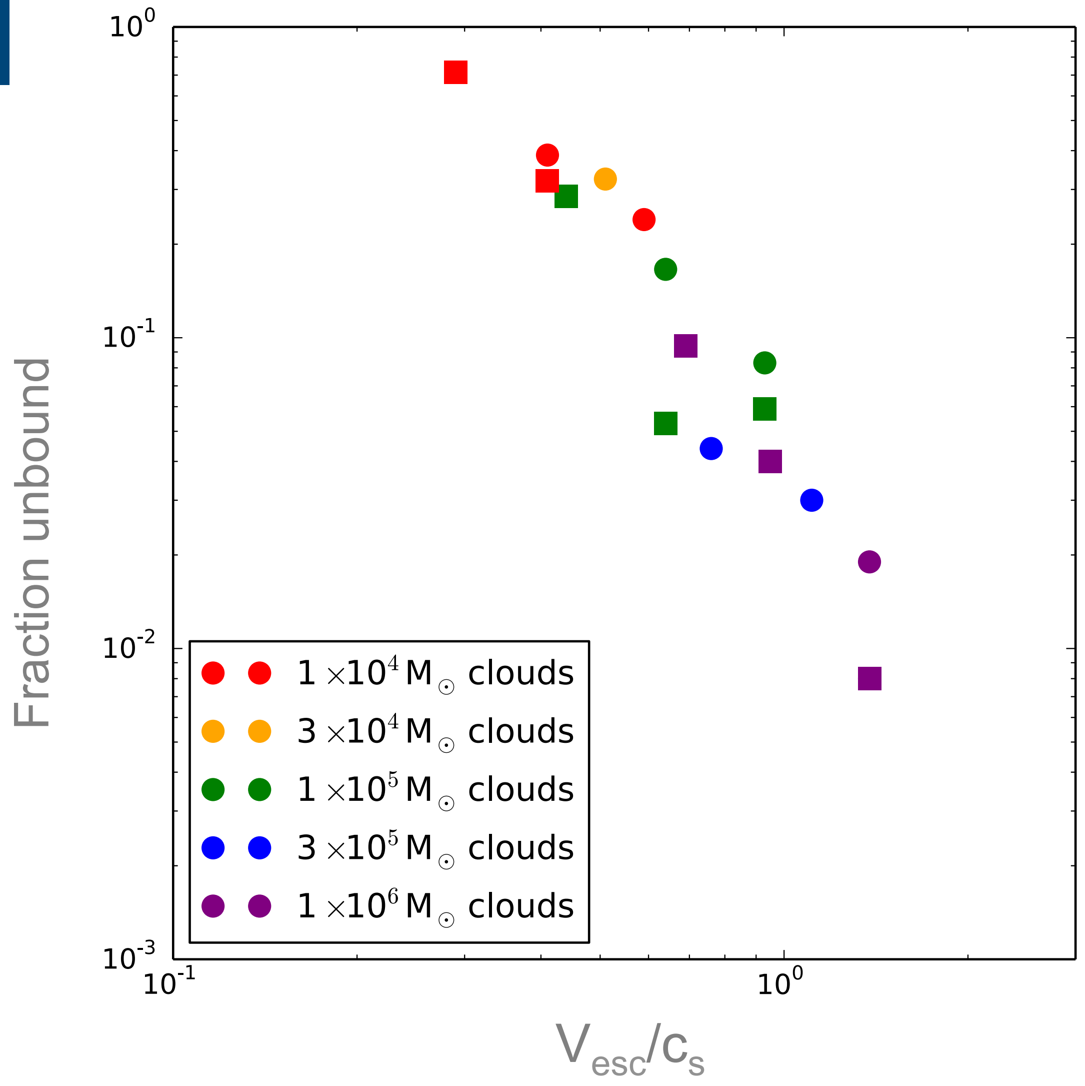
But none are destroyed outright?

Radiation leaks out through cloud

Can unbind gas in clouds with

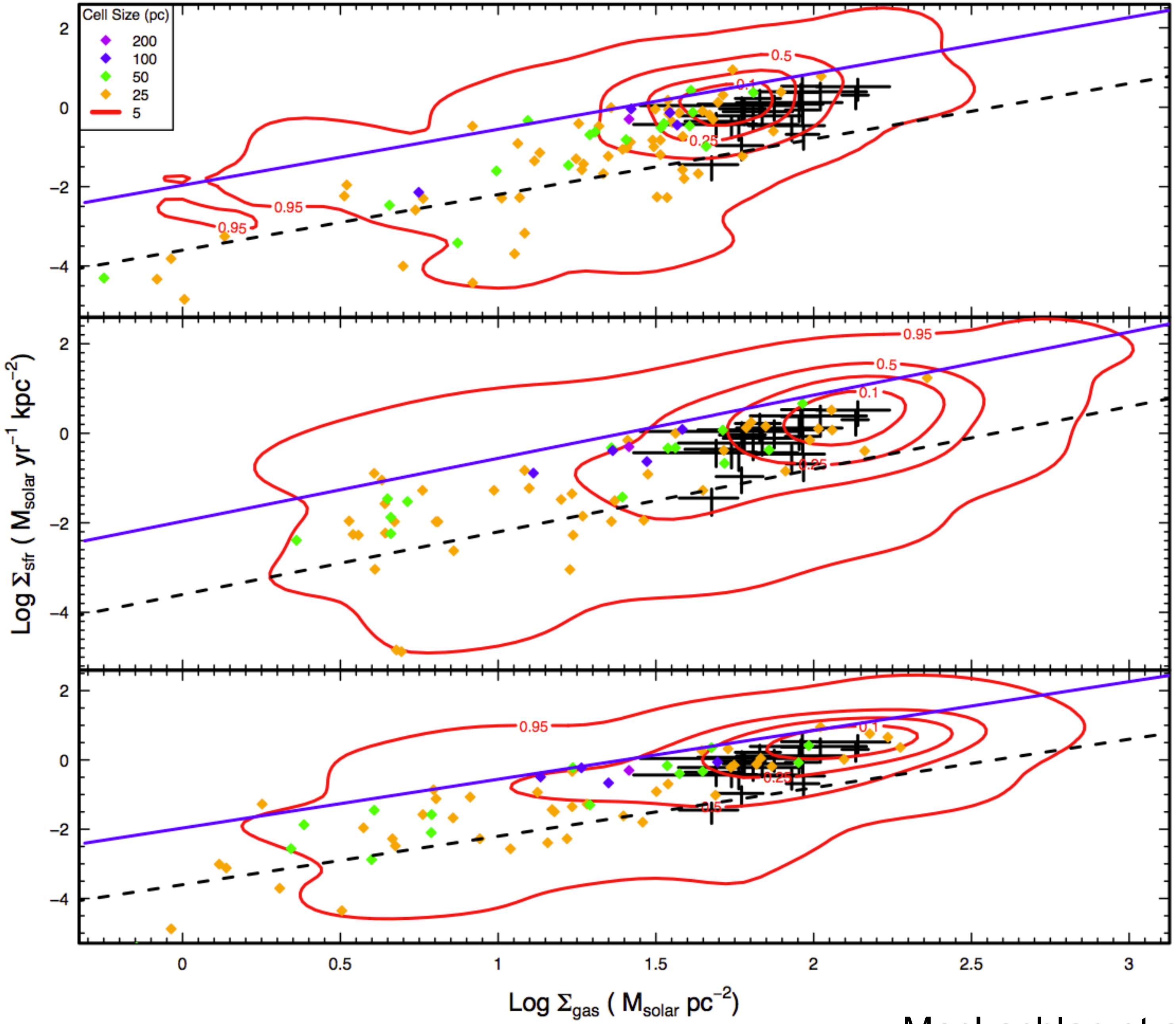
$v_{esc} << c_s$ (HII)





(a) Gas

Dale et al 2014



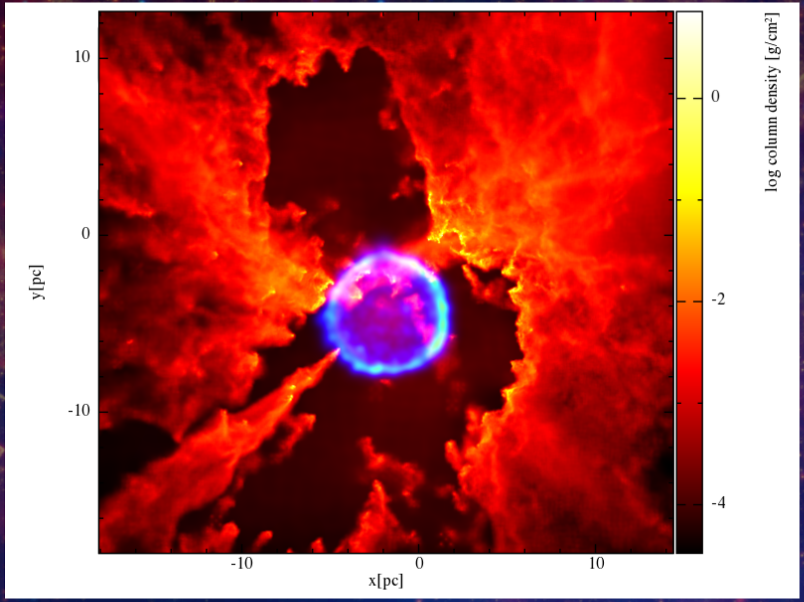
MacLachlan et al 2014

Lucas, Bonnell & Dale, 2015

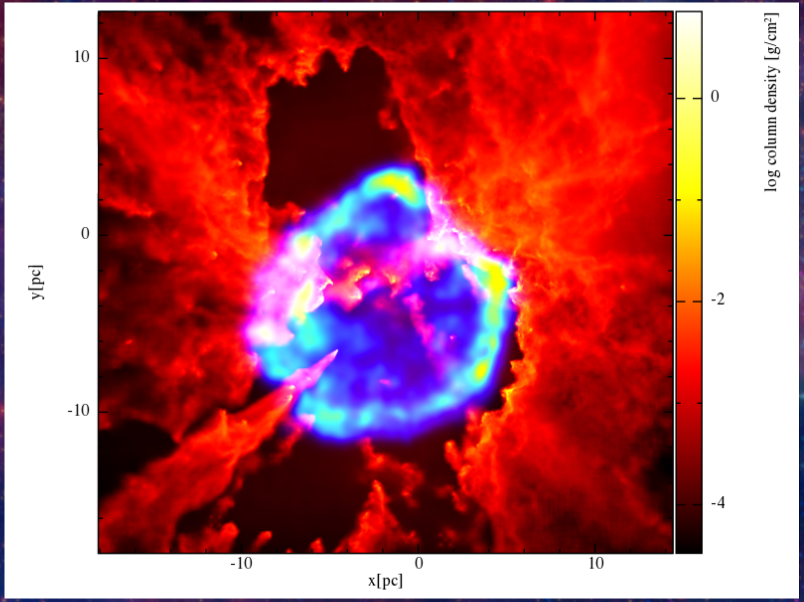
Supernova feedback

Simulation of ionising feedback from young massive stars in a molecular cloud (Dale et al. 2012). Then take the most massive star – blow it up!

t = 1118 yrs

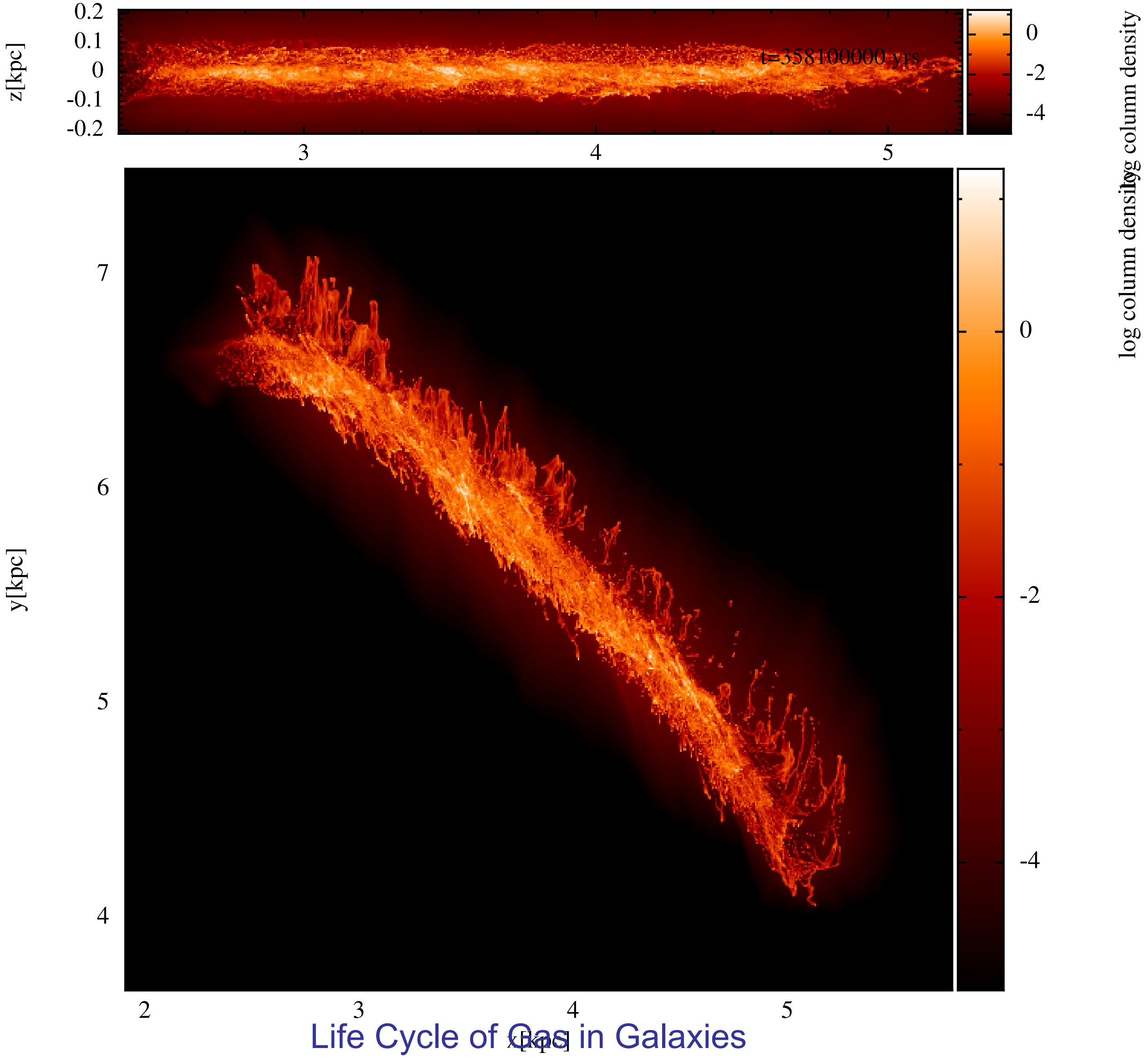


t = 3354 yrs

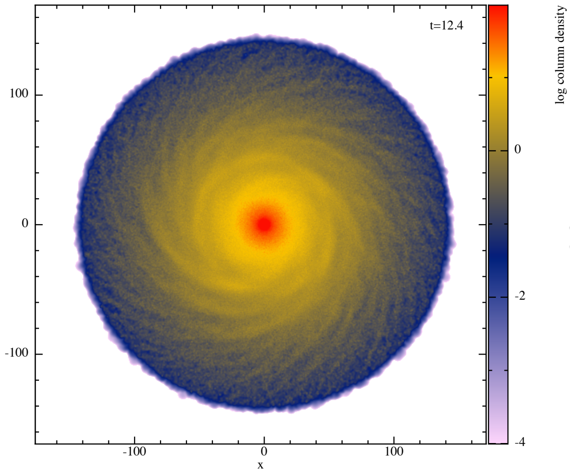


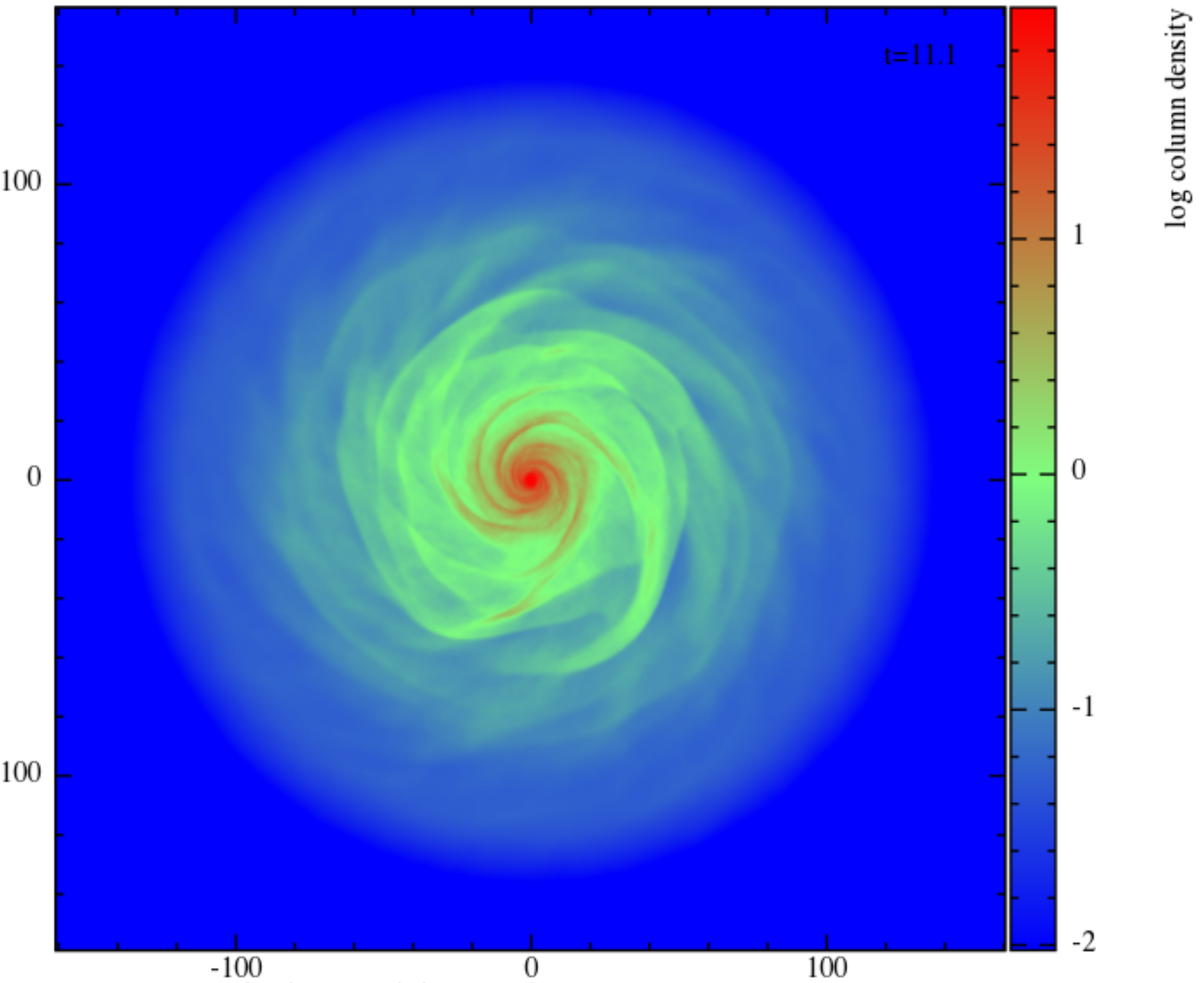
SN ejecta easily escapes through low density channels – only small regions of compression, otherwise very little effect on the cloud.

Towards full galaxy simulations



Gas dynamics in flocculent spirals





Provide laboratory for high resolution studies of GMC formation and triggering of star formation

Ramon-Fox et al

Summary

- Large scale flows can trigger star formation
  - – ISM pressure (inc ram pressure)
  - – Compression of cool gas
  - – Drive internal turbulence
  - – No need for self gravity until star formation
    - Lower star formation efficiencies
- Feedback has moderate effects on star formation
  - – ~ factor 2 reduction in SFR in dense gas
  - – Magnetic fields