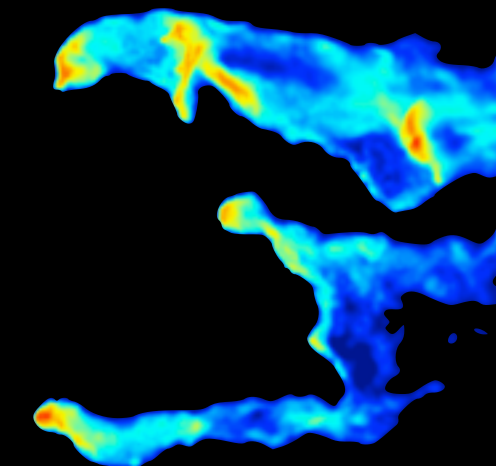
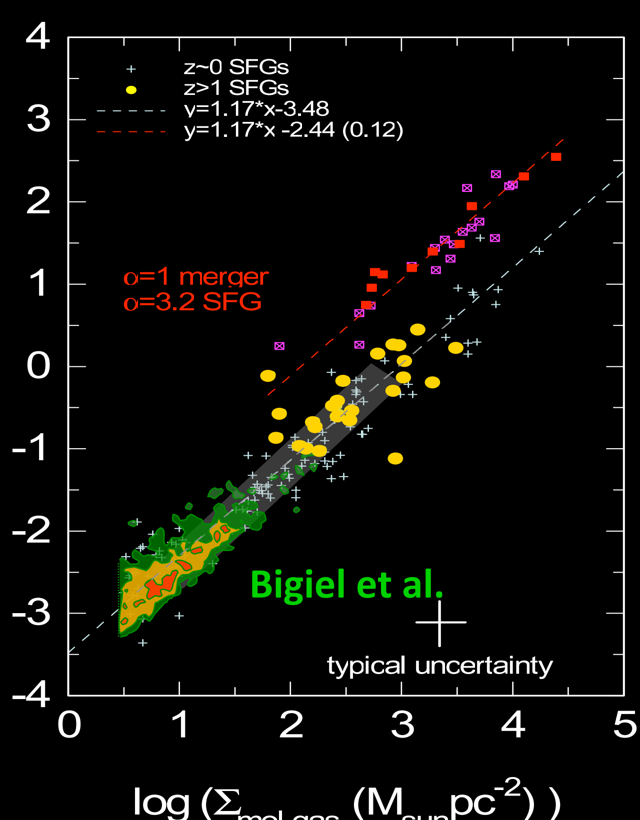
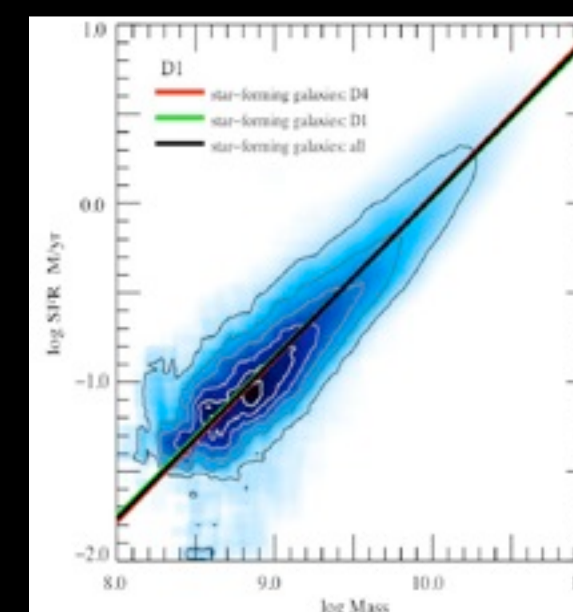
Self-regulated star formation

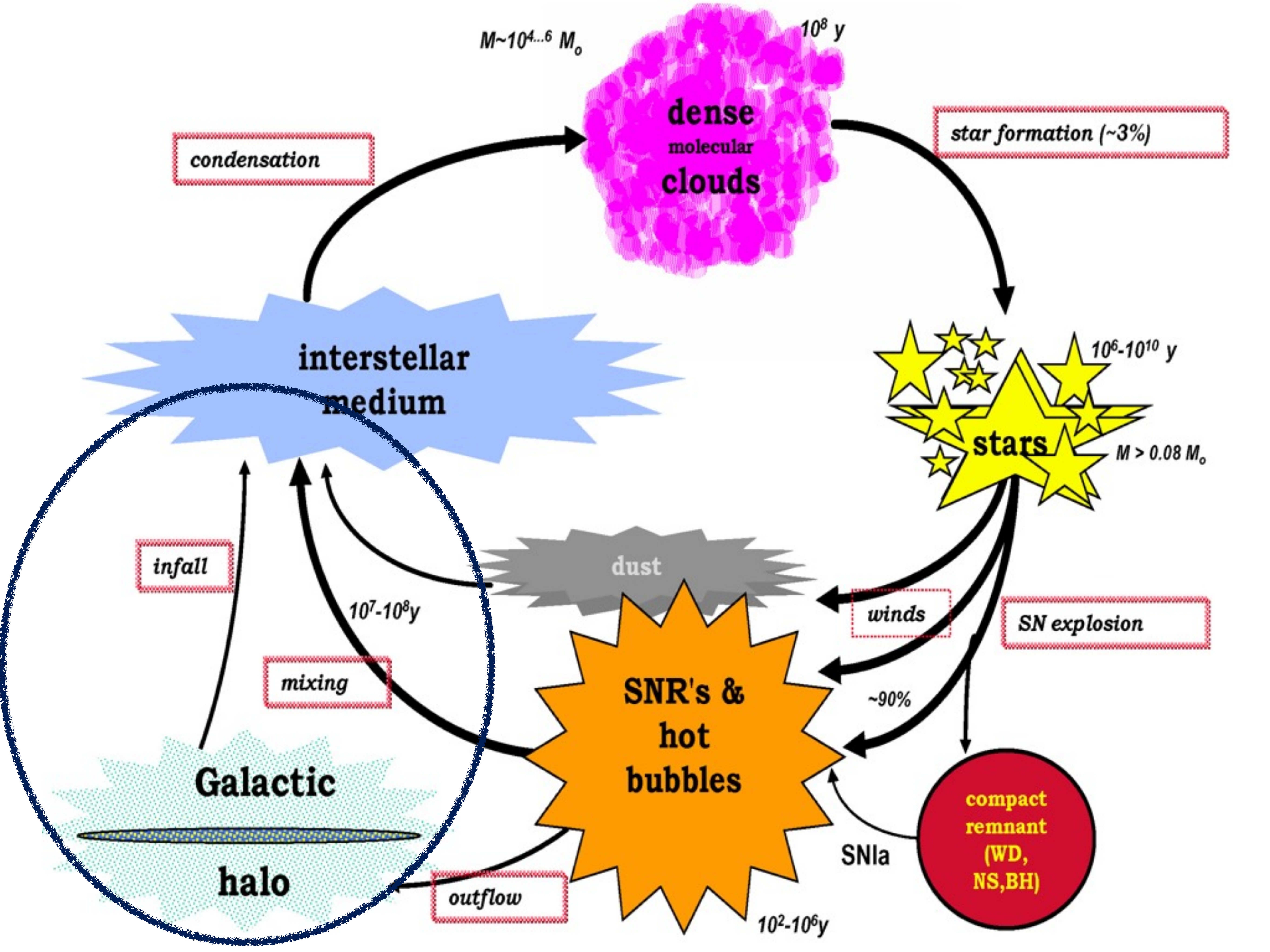
Andreas Burkert





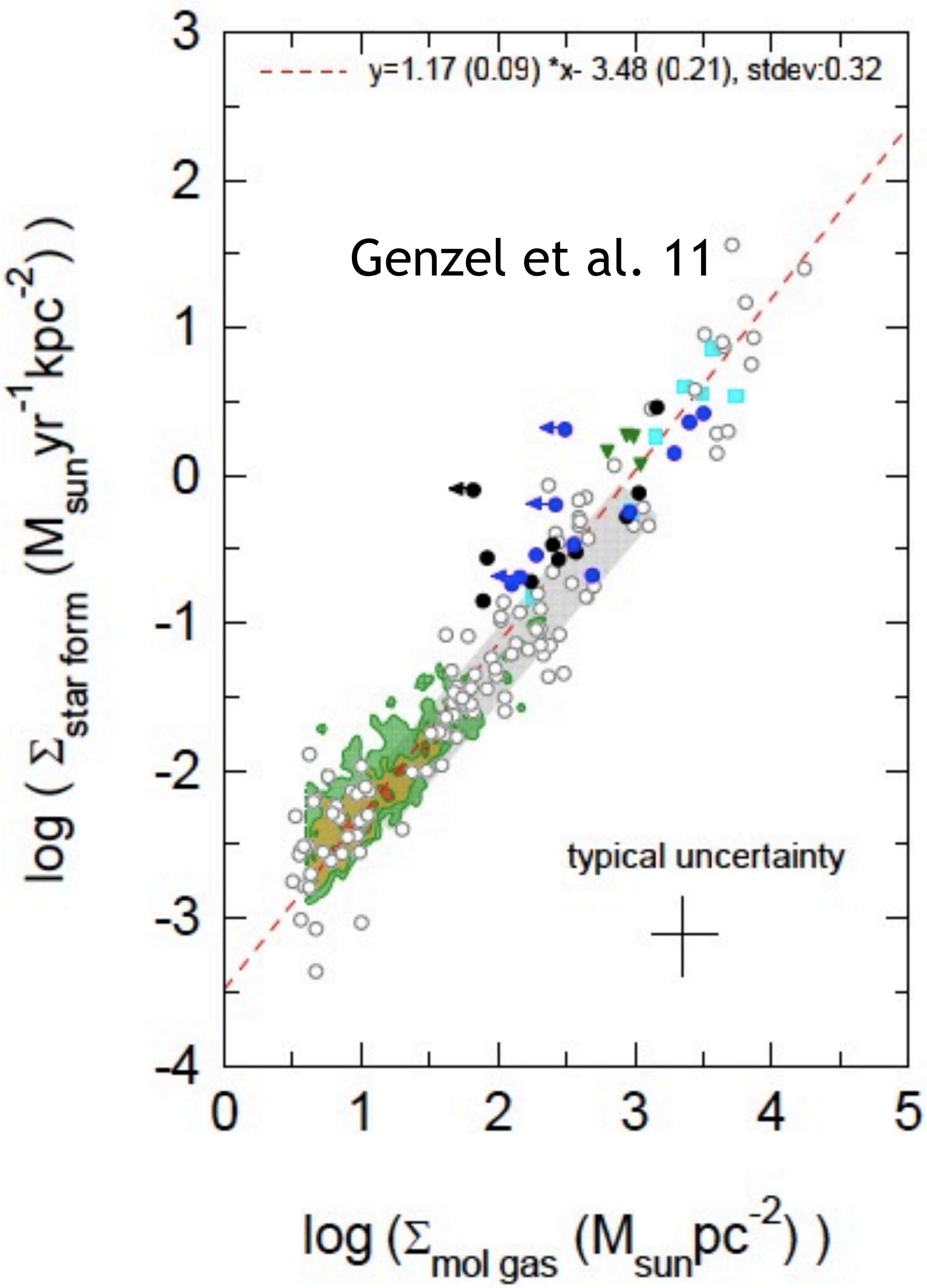


C. Dobbs, E. Ntormousi, K. Fierlinger,
J. Ngoumou, J. Pringle, L. Hartmann,
S. Walch, T. Preibisch, J. Dale



M~10^4...6 M_o
10^8 y
dense
molecular
clouds
condensation
star formation (~3%)
interstellar
medium
10^6-10^10 y
stars
M > 0.08 M_o
dust
infall
winds
SN explosion
10^7-10^8y
mixing
~90%
SNR's &
hot
bubbles
Galactic
halo
compact
remnant
(WD,
NS,BH)
SNIa
outflow
10^2-10^6y

Evidence for self-regulated star formation



$$SFR = \frac{M_{H_2}}{\tau_{sf}} \text{ with } \tau_{sf} \approx 1 - 2 \cdot 10^9\, yrs$$

- τ_{sf} is almost independent of redshift
- Gas depletion timescale **50 times** greater than local free-fall timescale.

$$\tau_{ff} \ll \tau_{sf} < \tau_{\text{Hubble}}$$

→ continuous replenishment

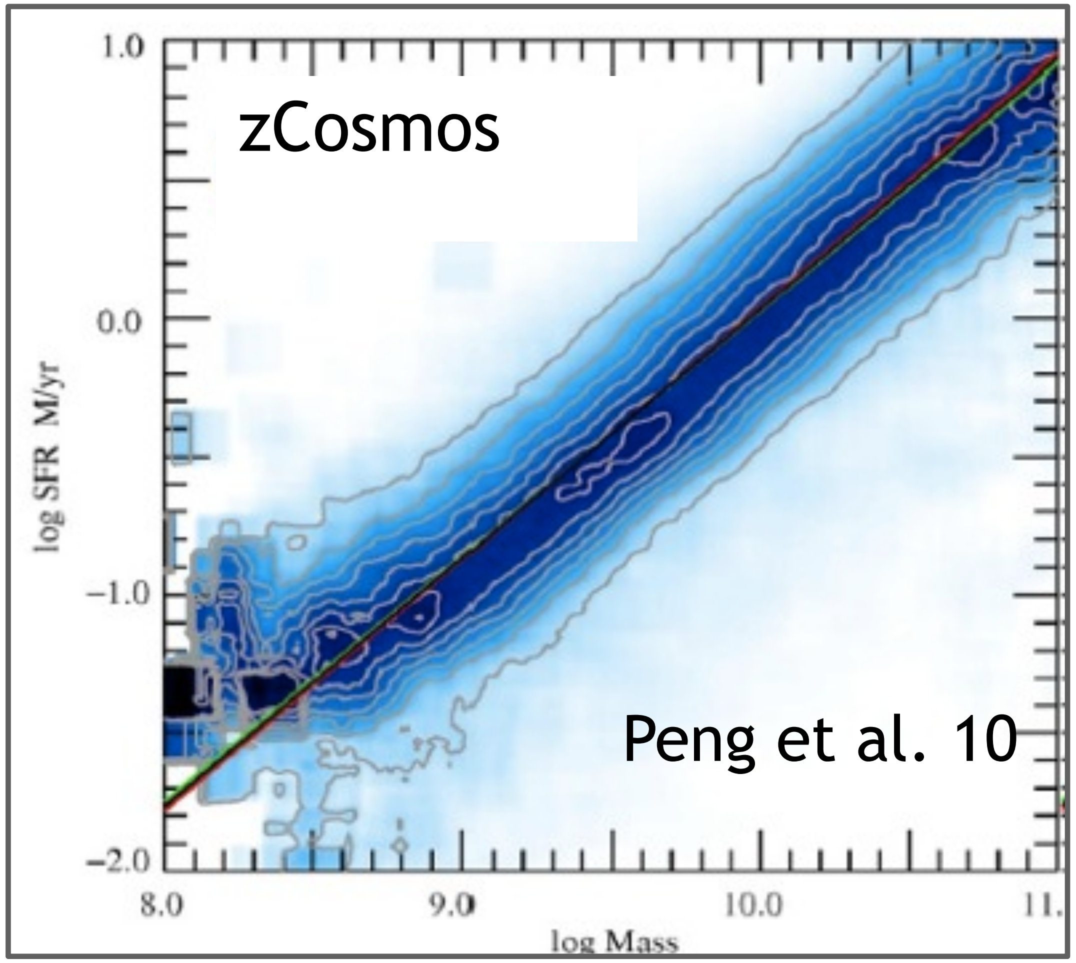
Bouché et al. 07, McKee & Ostriker 08, Genzel et al. 10,11, Daddi et al. 10, Dave 11a,b, Krumholz+ 12

What determines the SFR?

Star formation main sequence (Noeske et al. 07; Daddi et al. 07, Peng et al. 10, Bouche et al. 10):

$$SFR \approx 6 \left(\frac{M_*}{10^{11} M_\odot} \right)^{0.8..1} (1+z)^{2.5} \frac{M_\odot}{yr}$$

log SFR $[M_\odot / yr]$



log M_* $[M_\odot]$

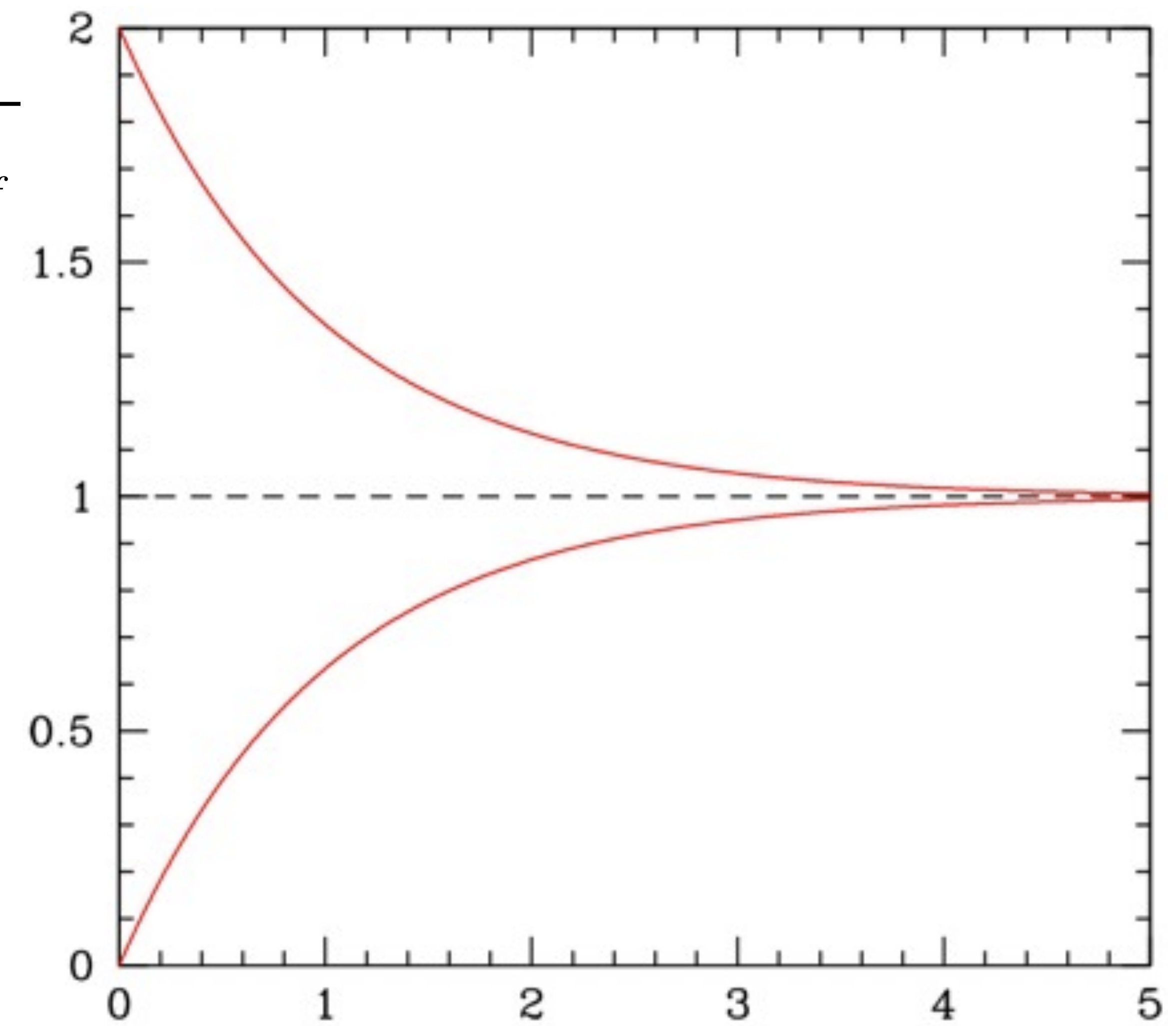
Cosmic baryonic **accretion rate** (Neistein & Dekel 08):

$$\left(\frac{dM_g}{dt} \right)_{acc} \approx 7 \cdot \varepsilon_g \left(\frac{M_{DM}}{10^{12} M_\odot} \right)^{1.1} (1+z)^{2.2} \frac{M_\odot}{yr}$$

What determines SFR?

(Bouche et al. 10; Davé et al. 11a,b)

$$\frac{SFR}{\dot{M}_{acc,eff}}$$



$$t / \tau_{sf}$$

$$\frac{dM_g}{dt} = \left(\frac{dM_g}{dt}\right)_{acc} - \frac{M_g}{\tau_{sf}}\left(1 - R + \alpha_{wind}\right)$$

$\dot{M}_{acc,eff}$

$$SFR = \frac{M_g}{\tau_{sf}} = \frac{1}{1 - R + \alpha_{wind}}\left(\frac{dM_g}{dt}\right)_{acc}\left(1 - \exp\left(-\frac{t}{\tau_{sf}}\right)\right)$$

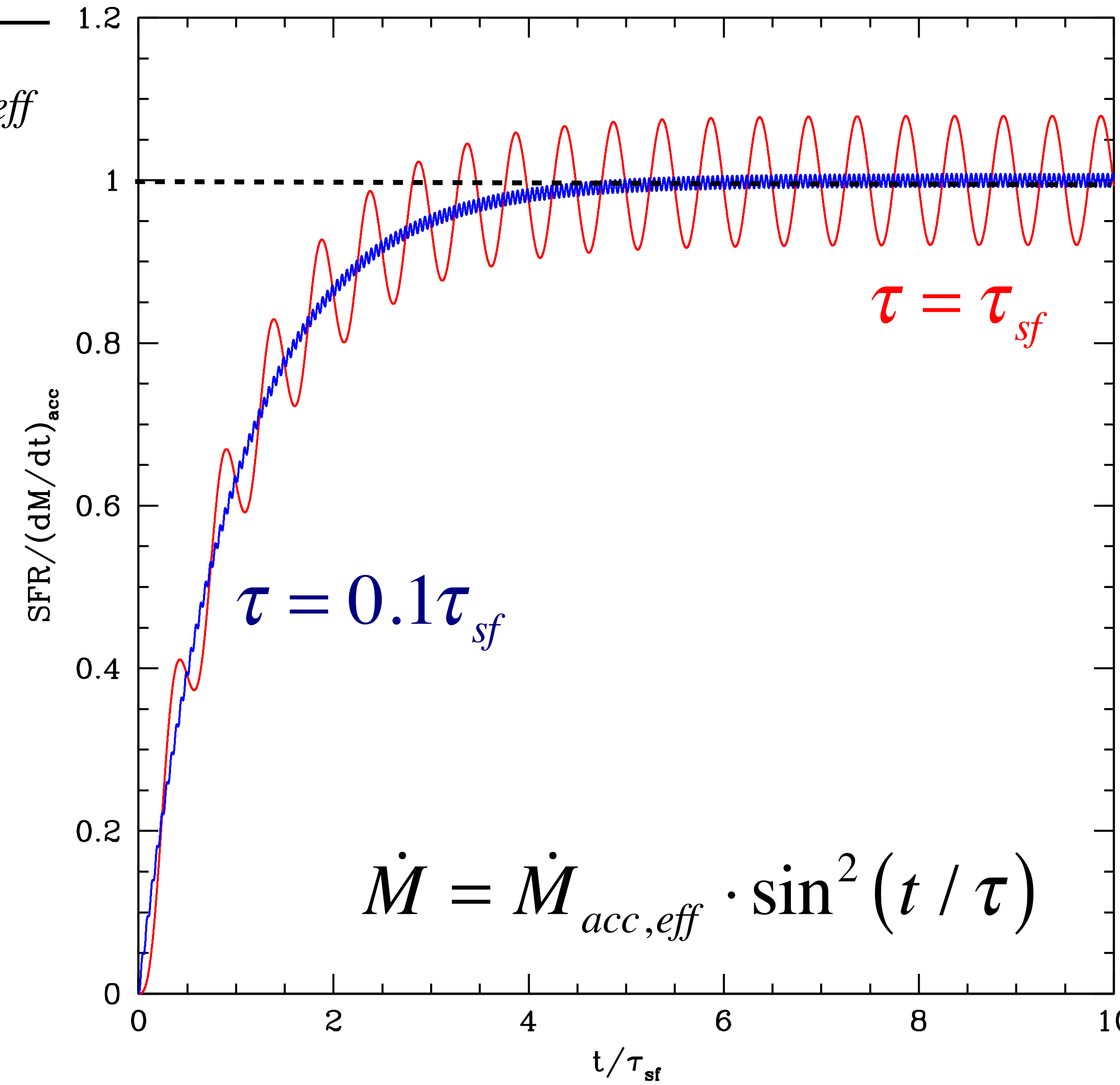
→ $SFR = \dot{M}_{acc,eff}$

- τ_{sf} **does not determine SFR**

What determines SFR?

(Bouche et al. 10; R. Davé et al. 11a,b)

$$\frac{SFR}{\dot{M}_{acc,eff}}$$



$$t \,/\, \tau_{sf}$$

$$\frac{dM_g}{dt} = \left(\frac{dM_g}{dt}\right)_{acc} - \frac{M_g}{\tau_{sf}}\left(1 - R + \alpha_{wind}\right)$$

$$\dot{M}_{acc,eff}$$

$$SFR = \frac{M_g}{\tau_{sf}} = \frac{1}{1 - R + \alpha_{wind}}\left(\frac{dM_g}{dt}\right)_{acc} \left(1 - \exp\left(-\frac{t}{\tau_{sf}}\right)\right)$$

→ $$SFR = \dot{M}_{acc,eff}$$

- τ_{sf} **does not determine SFR**

And what's about self-regulation?

$$SFR = \dot{M}_{acc,eff} = M_g / \tau_{sf}$$

- τ_{sf} determines the gas mass

$$\boxed{M_g = \dot{M}_{acc,eff} \cdot \tau_{sf}}$$

Why is $\tau_{sf} \approx 10^9\, yrs$?

The OML 10 self-regulation model

(Ostriker, McKee & Leroy 2010)

- The **diffuse HI gas** in the ISM provides its pressure P
- P is set by the **weight** of overlying material in galactic disks
- The diffuse gas is in **equilibrium** between UV heating by massive stars (star formation rate) and cooling.
- The **star formation rate** is linearly proportional to the amount of molecular gas in the galaxy.

$$P = \int_0^{z_{\max}} \rho_{diff} \left(\frac{d\Phi_{diff}}{dz} + \frac{d\Phi_{GMC}}{dz} + \frac{d\Phi_{star}}{dz} + \frac{d\Phi_{DM}}{dz} \right) dz$$

$$P = \frac{\pi G \Sigma_{diff}^2}{2} + \pi G \Sigma_{GMC} \Sigma_{diff} + 2\pi G \left(\frac{\rho_{star+DM}}{\rho_{diff}} \right)_{z=0} \Sigma_{diff}^2$$

$$P = \frac{\pi G \Sigma_{diff}^2}{2} + \pi G \Sigma_{GMC} \Sigma_{diff} + 2\pi G \left(\frac{\rho_{star+DM}}{\rho_{diff}} \right)_{z=0} \Sigma_{diff}^2 = n_{diff} kT \sim n_{diff}$$

$T \approx 10^4 K$

$$\Sigma_{GMC} = \Sigma_{total} - \Sigma_{diff}$$

This leads to an **equilibrium** because

Σ_{diff} too high → ... ng > heating

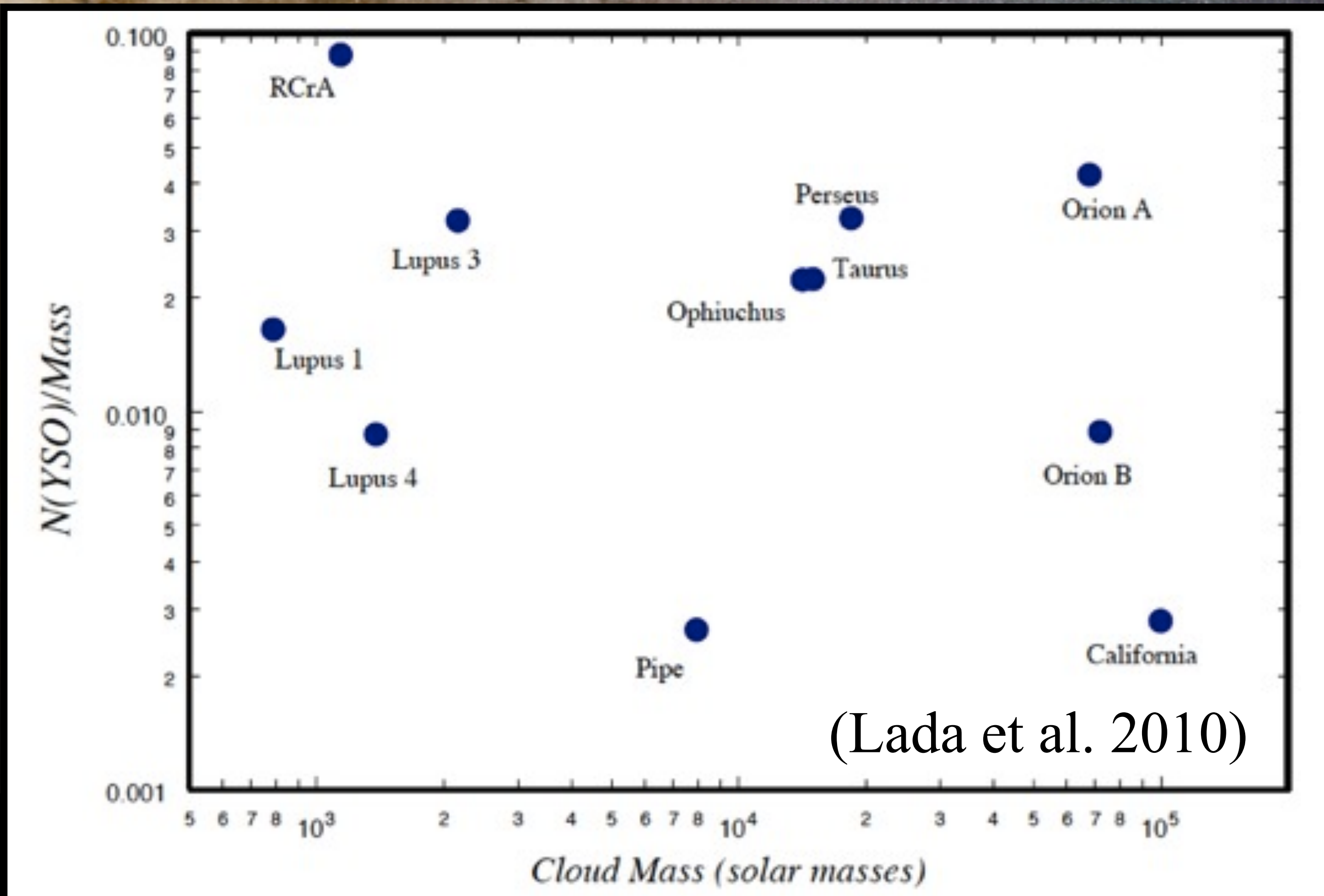
Why is $\tau_{sf} = 10^9\, yrs$?

Σ_{diff} too low → n_{diff} low and Σ_{GMC} high → cooling < heating

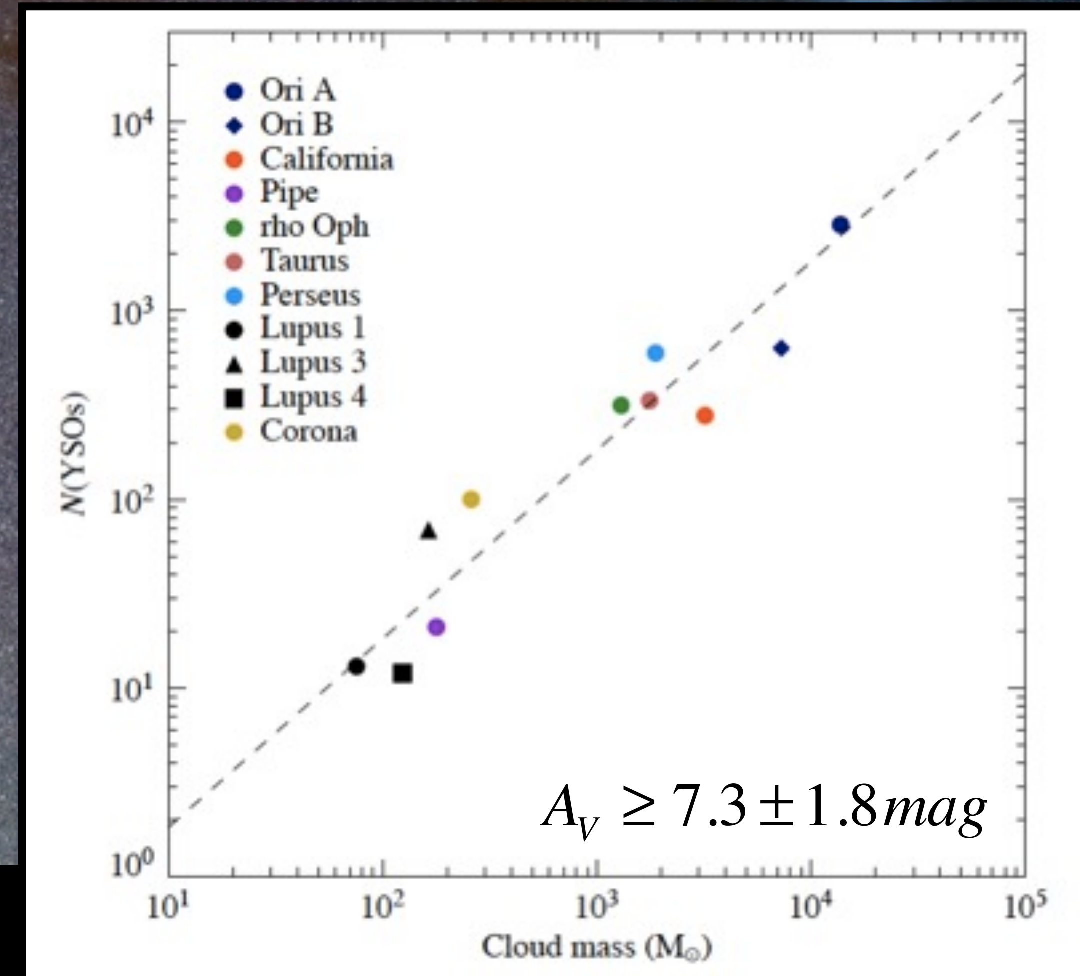
The equilibrium condition requires a certain **SFR**.
But the SFR and Σ_{total} is given by the accretion rate.

→ M_{HI}, M_{H_2} and *SFR* are determined by the accretion rate.

$N(YSOs)_{Oph} = 15 \times N(YSOs)_{Pipe}$



(Lada et al. 2010)



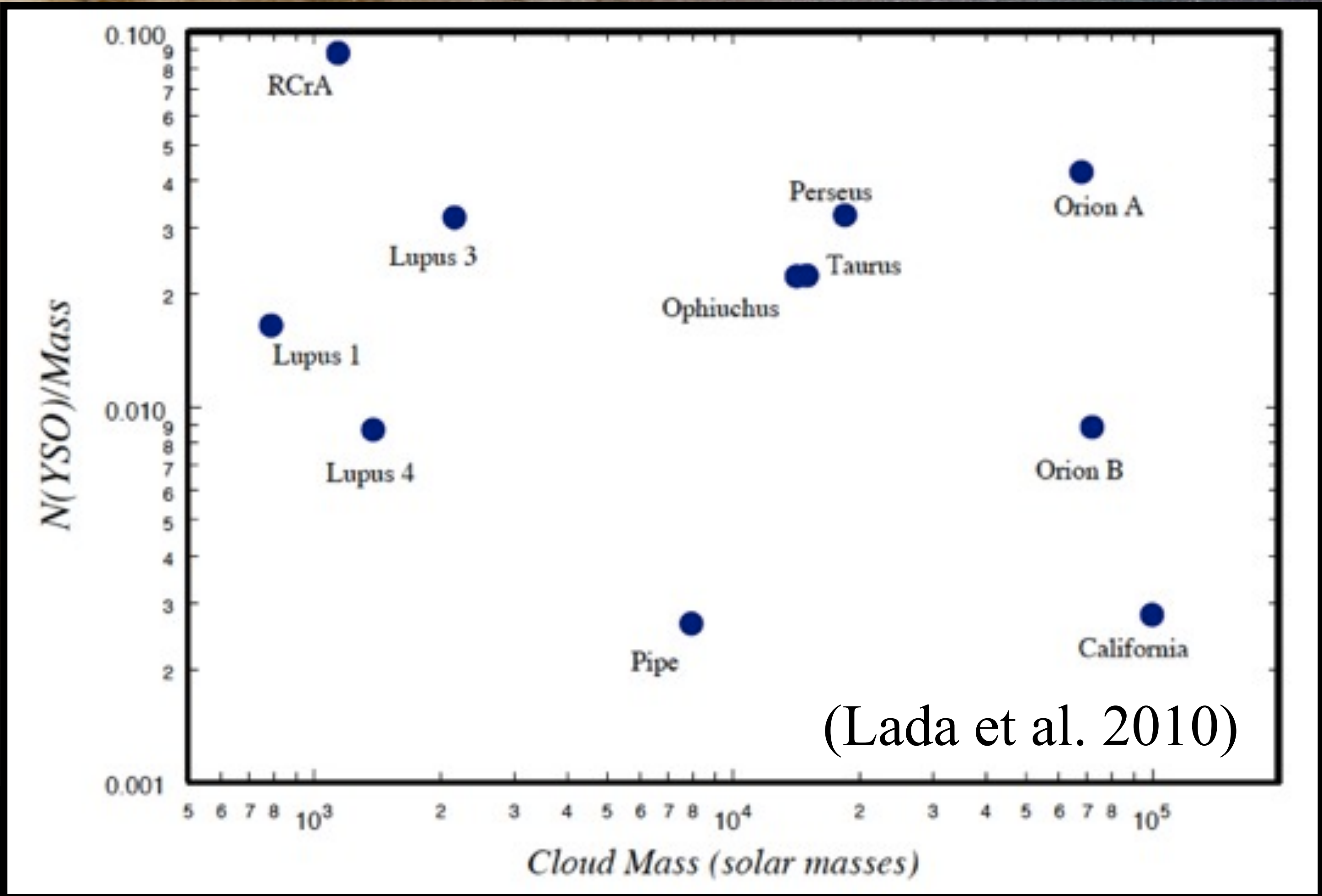
$$n_{A_V=7.3} \approx 10^4 \, cm^{-3}$$

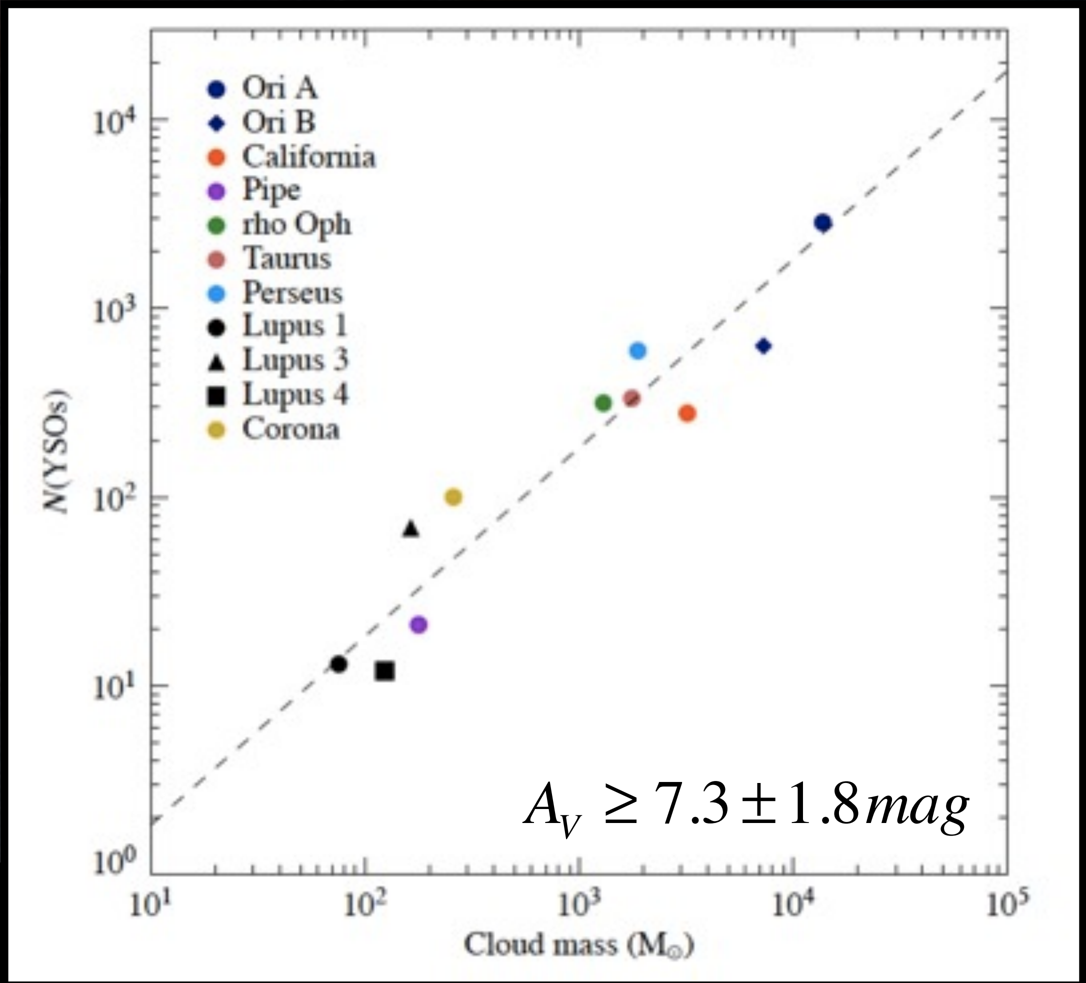
Star formation history of molecular clouds

$$SFR \sim M_{dense} \sim \exp\left(t / \tau_{ff} \right)$$

(Burkert & Hartmann 12)

$N(YSOs)_{Oph} = 15 \times N(YSOs)_{Pipe}$

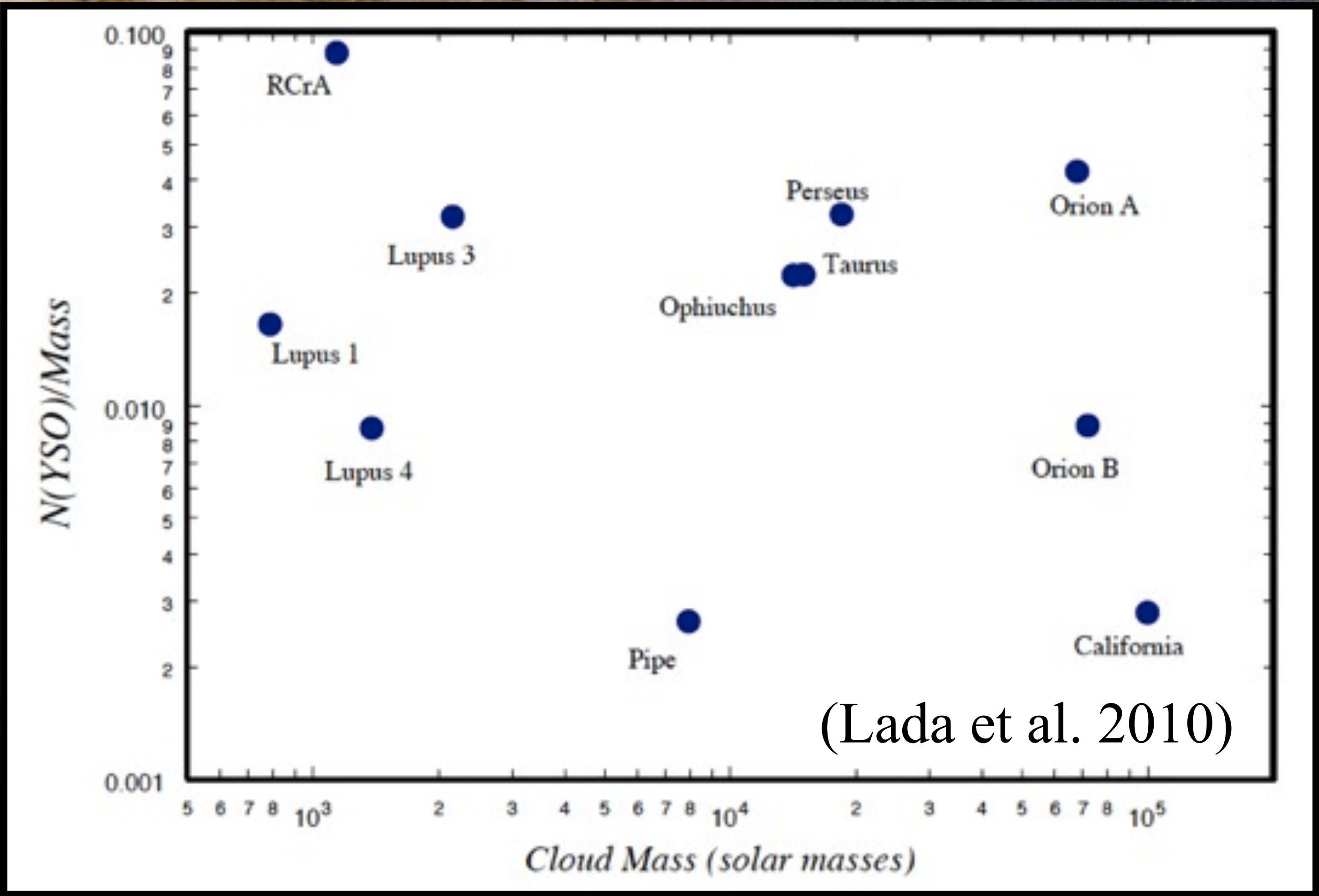


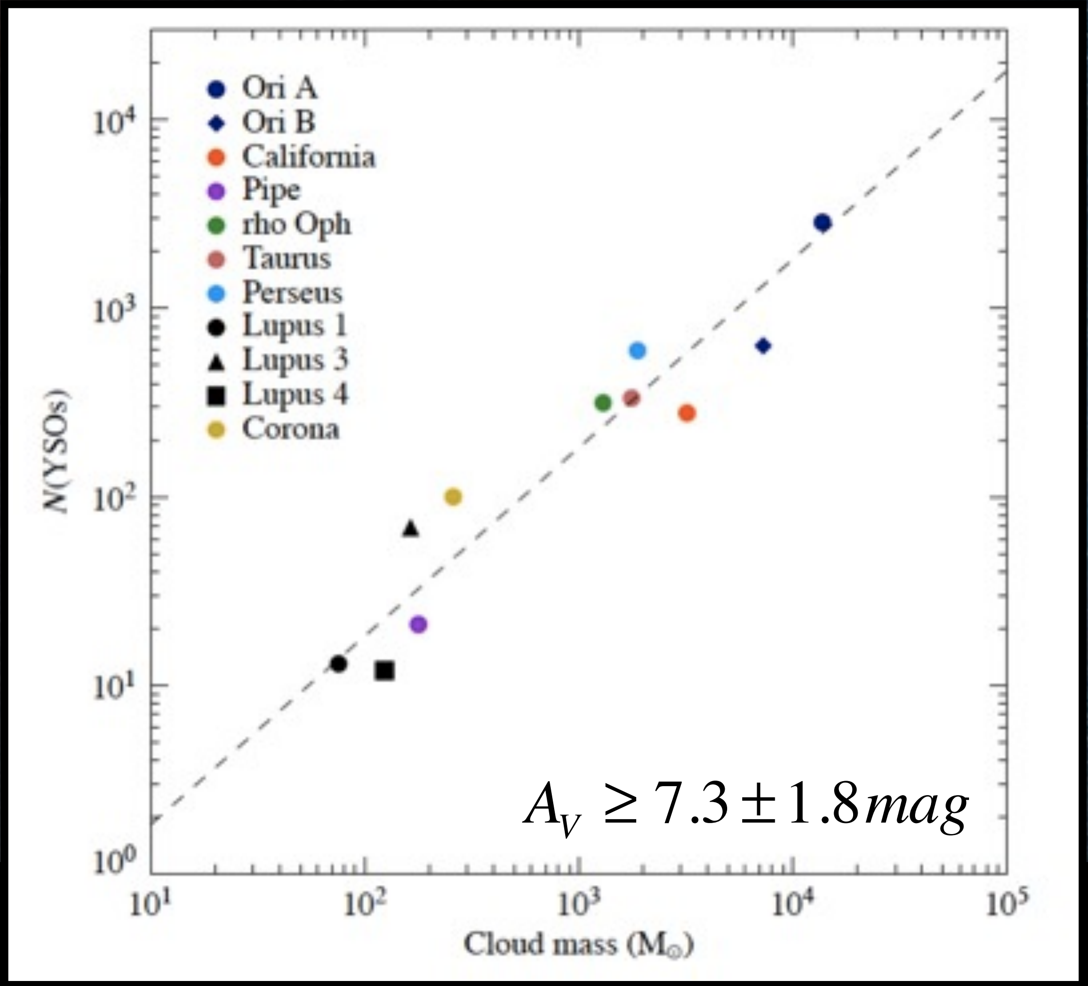


Galactic scales:

$$SFR \approx \frac{M_{H_2}}{10^9\ yrs}$$

$N(YSOs)_{Oph} = 15 \times N(YSOs)_{Pipe}$

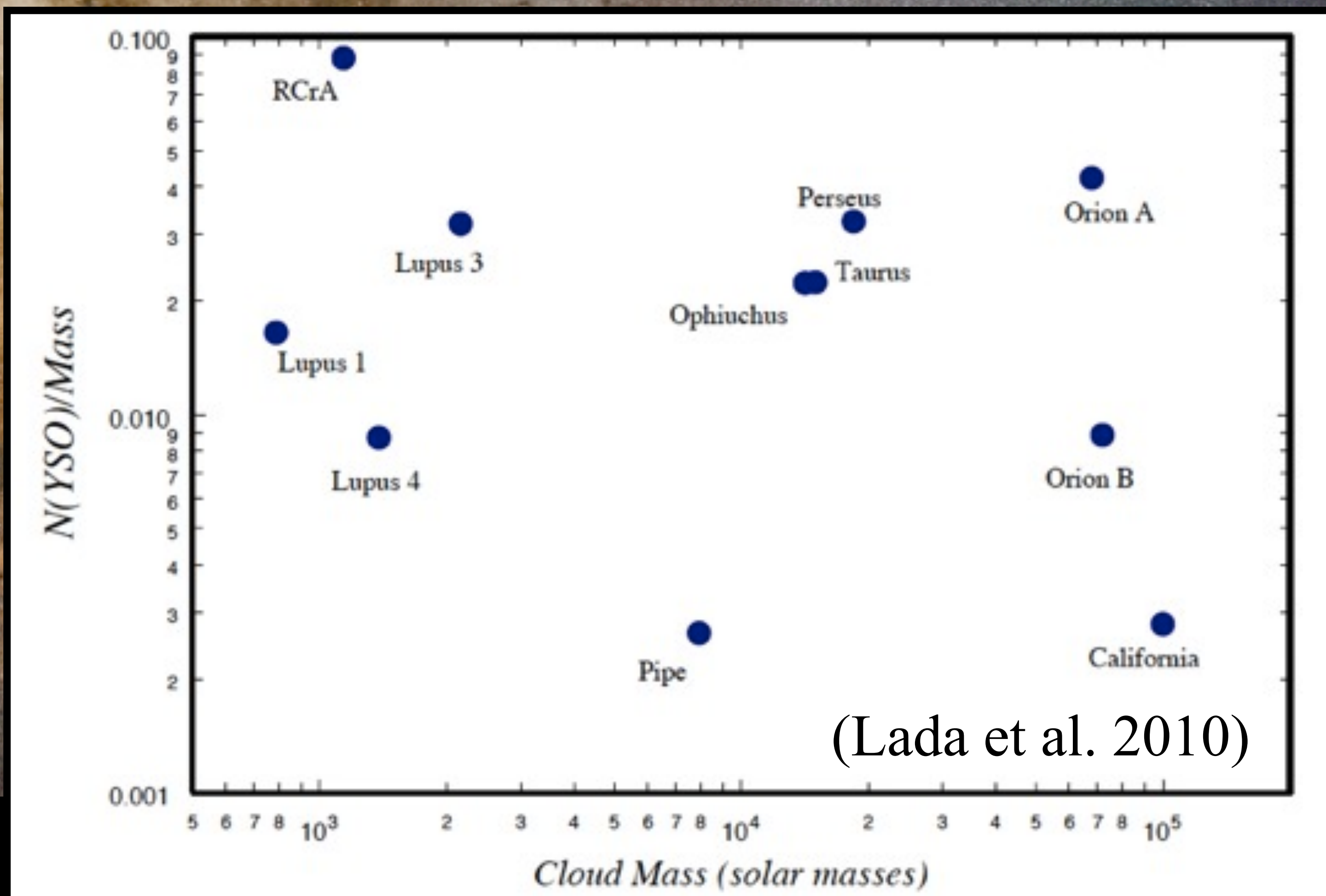


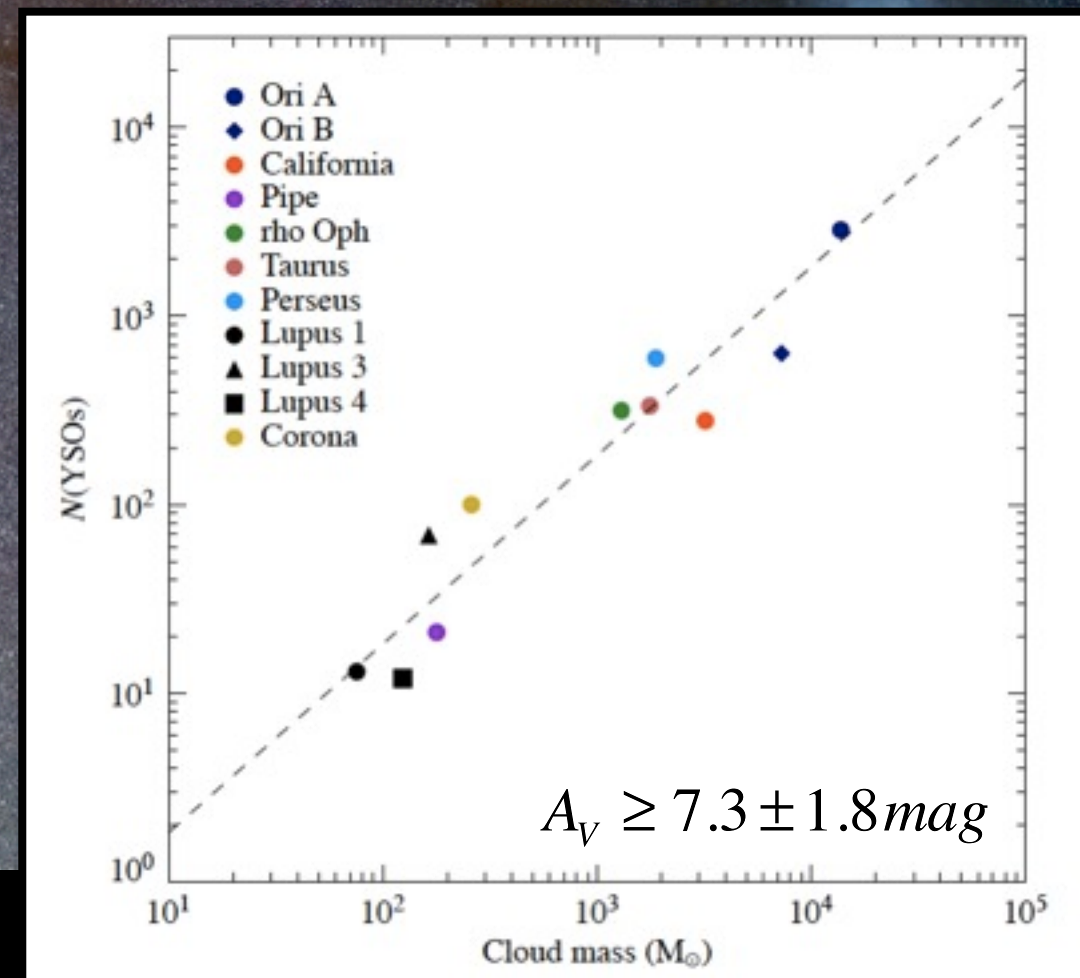


Galactic scales:

$$SFR \approx \frac{M_{H_2}}{10^9 yrs} \approx \frac{M_{dense}}{10^8 yrs}$$

$N(YSOs)_{Oph} = 15 \times N(YSOs)_{Pipe}$





Galactic scales: **self-regulation** $\varepsilon = 0.1$ (Krause+ 12; Fierlinger+ 12)

$$SFR \approx \frac{M_{H_2}}{10^9\,yrs} \approx \frac{M_{dense}}{10^8\,yrs} \approx \varepsilon \frac{M_{dense}}{10^7\,yrs}$$

$$\tau_{ff} = 3.5 \cdot 10^5\,yrs$$

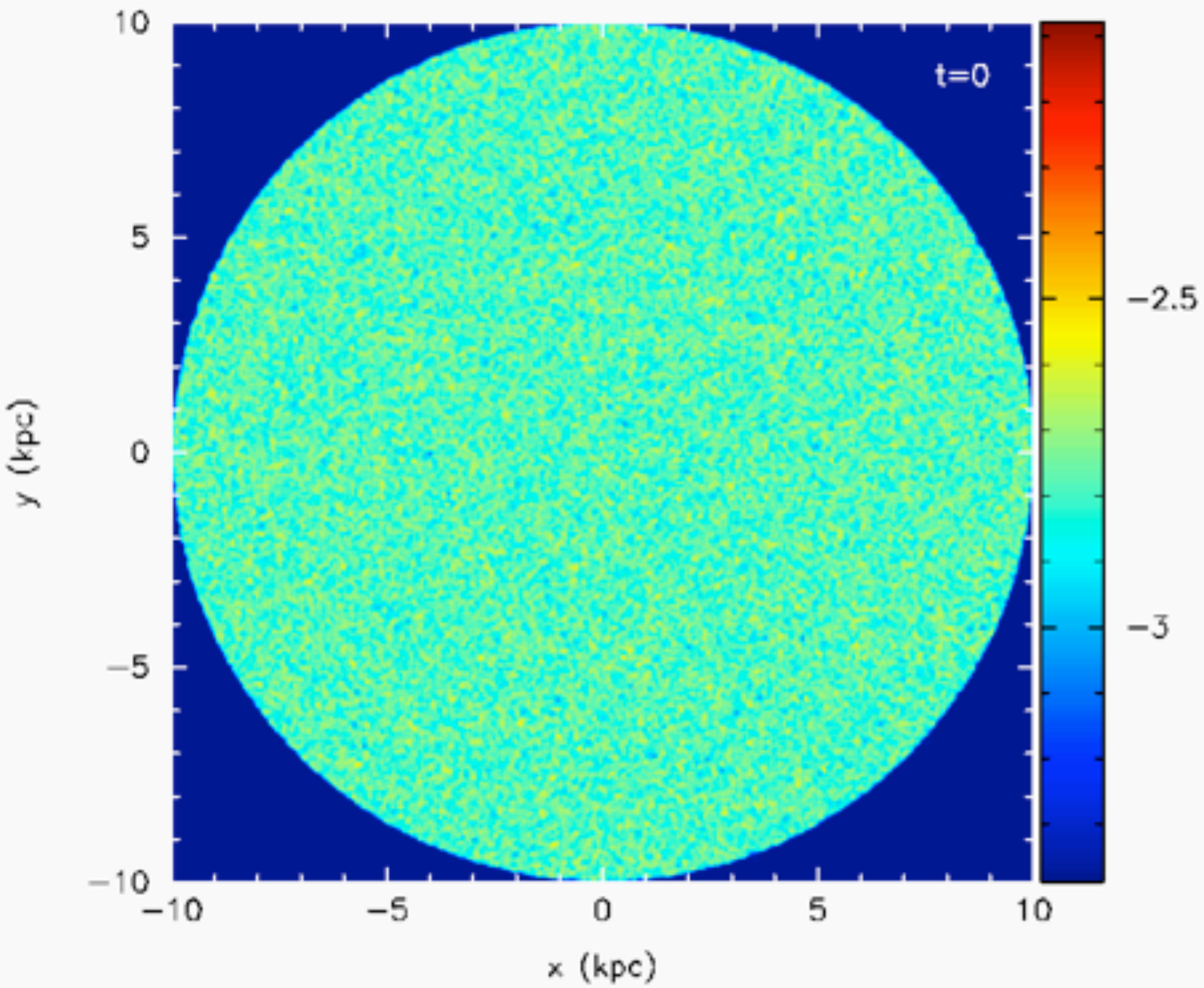
Numerical simulations of the molecular web

(Dobbs, Burkert & Pringle 11a,b, 12a,b)

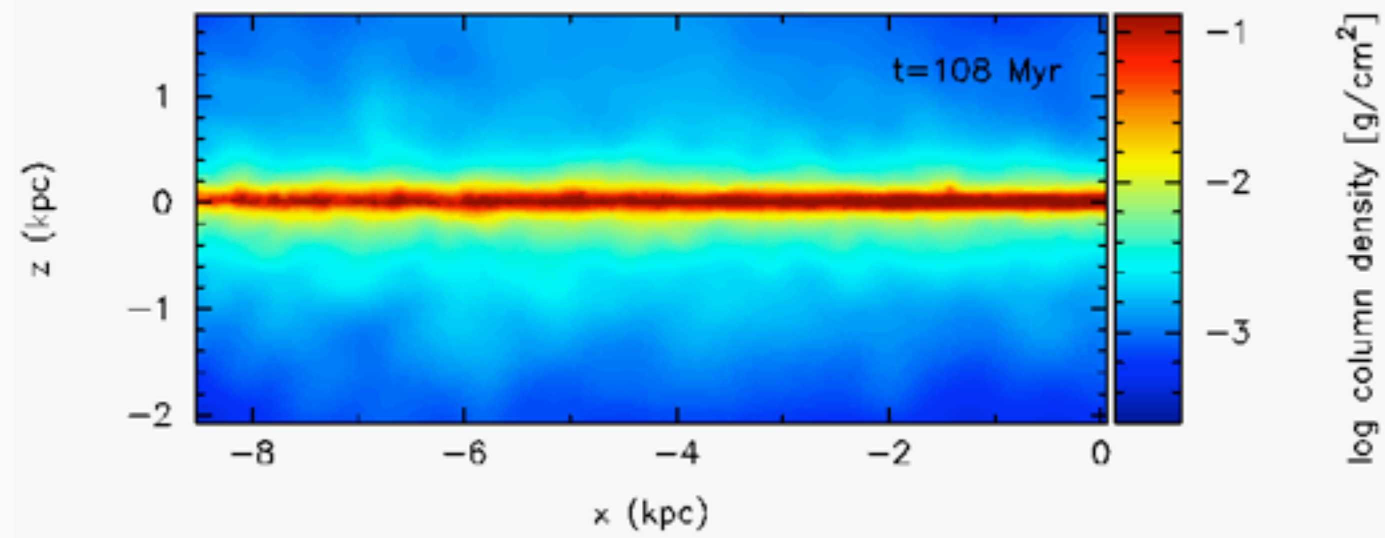
- **3d SPH** simulations (Bate et al. 95)
- Fixed **galactic gravitational potential** (stellar disk + halo)
- **Self-gravity** of the gas component included
- Calculations with and without an additional **4 armed spiral potential**
- **Heating** (supernovae + FUV background)
- **Cooling:** radiative + gas-grain energy transfer + recombination on grains
- **Stars form** when a local molecular region collapses
  and its density exceeds $n_{crit} = 250 cm^{-3}$
- A fraction ε of the gas is assumed to turn into stars that
  heat the environment with an energy (winds and SN) of

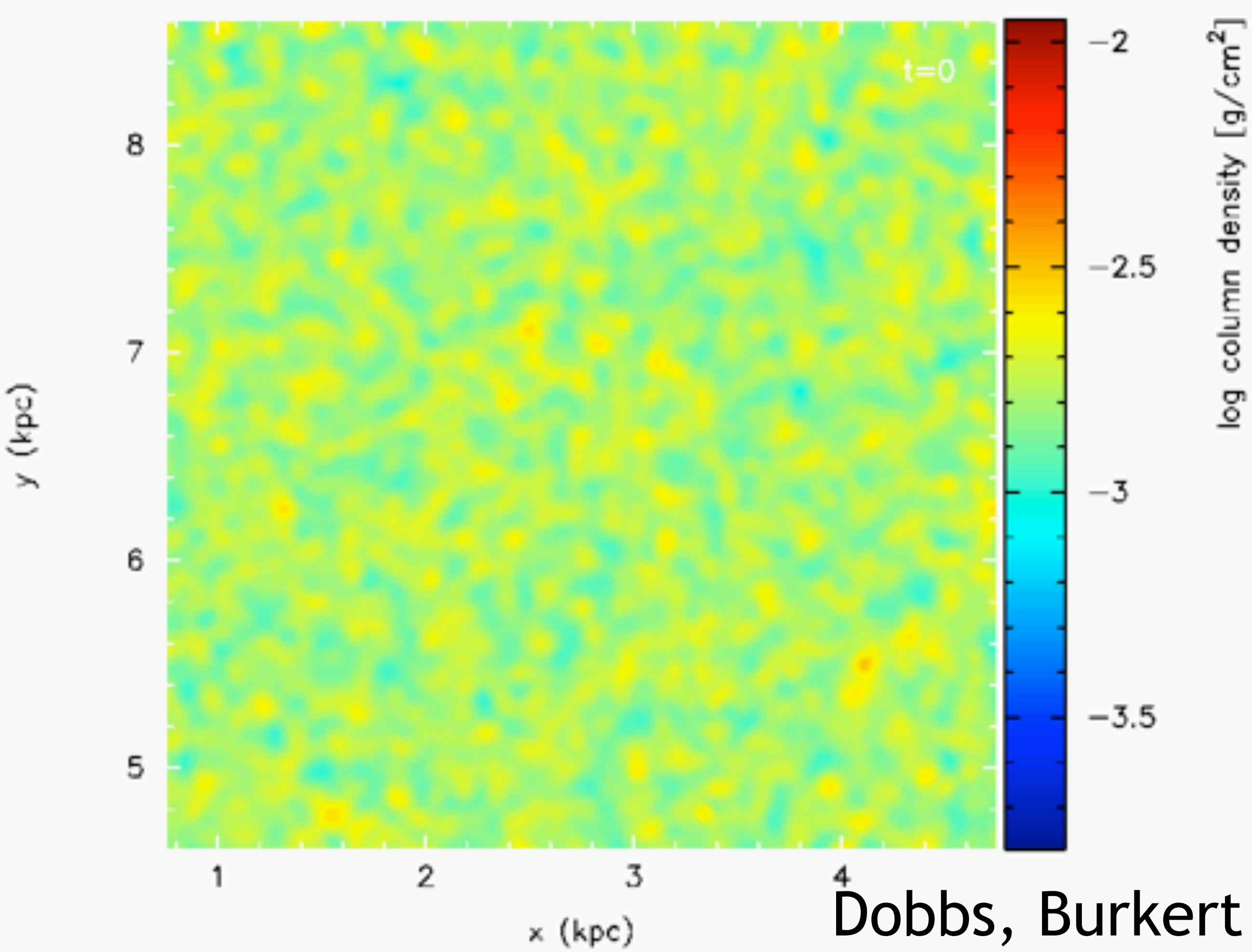
$$E_{SN} = \varepsilon \frac{M_{dense}}{160 M_{\odot}} \cdot 10^{51} ergs$$

$$\boxed{\varepsilon \approx 2 - 5\%}$$



Feedback puffs up disk

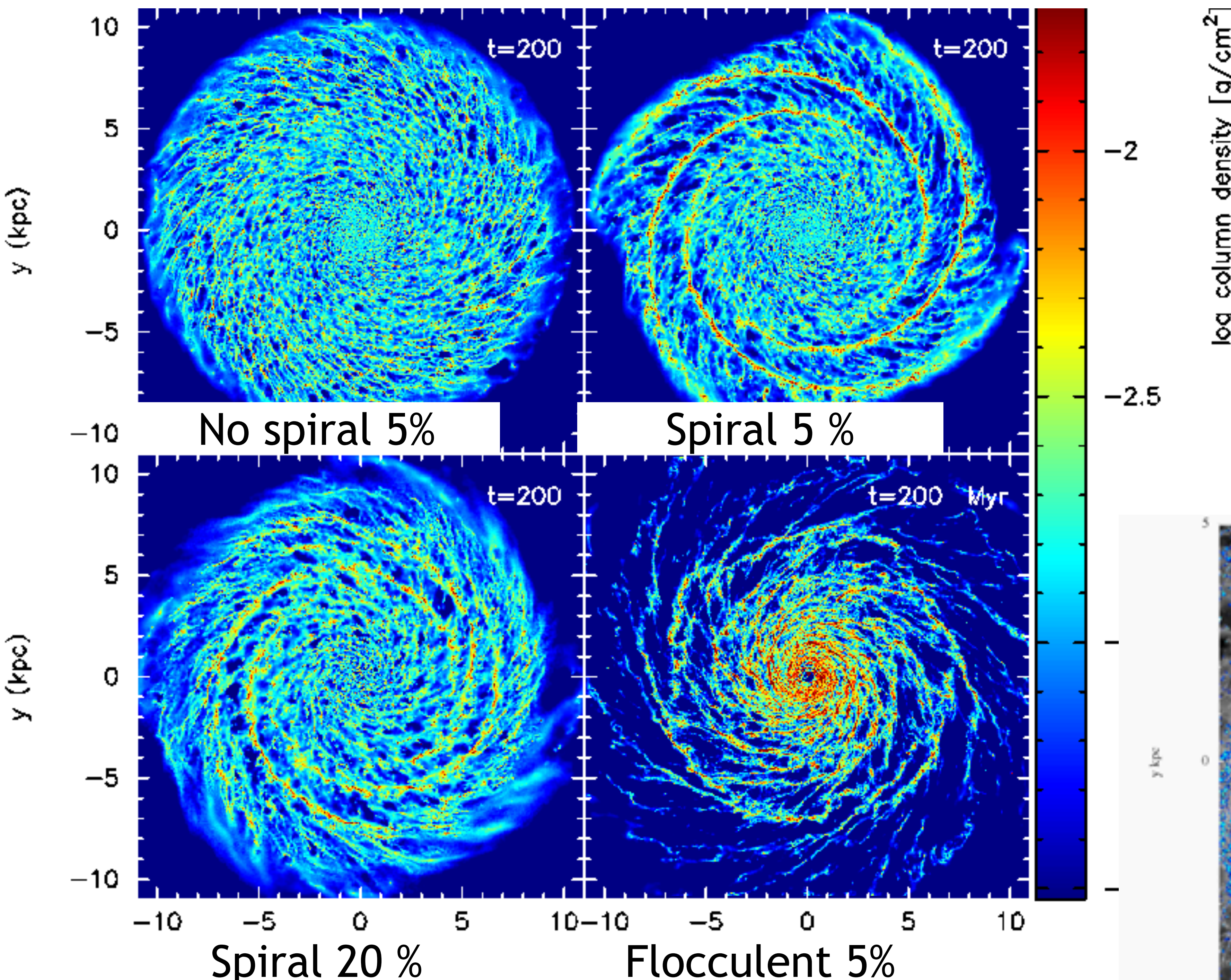


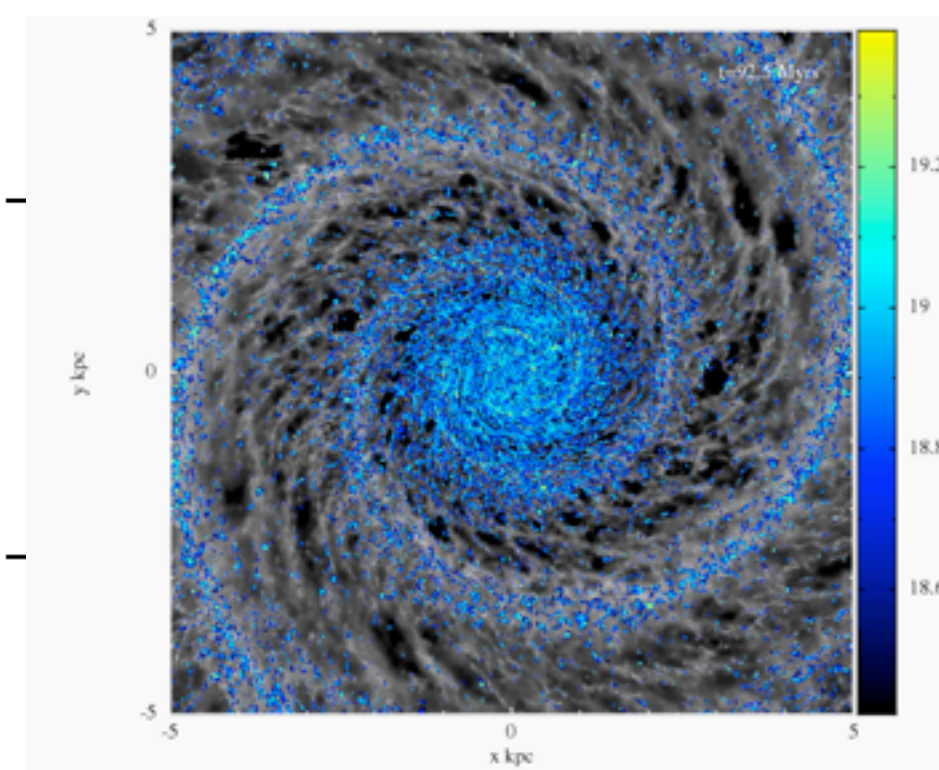


Filamentary interarm features (spurs)

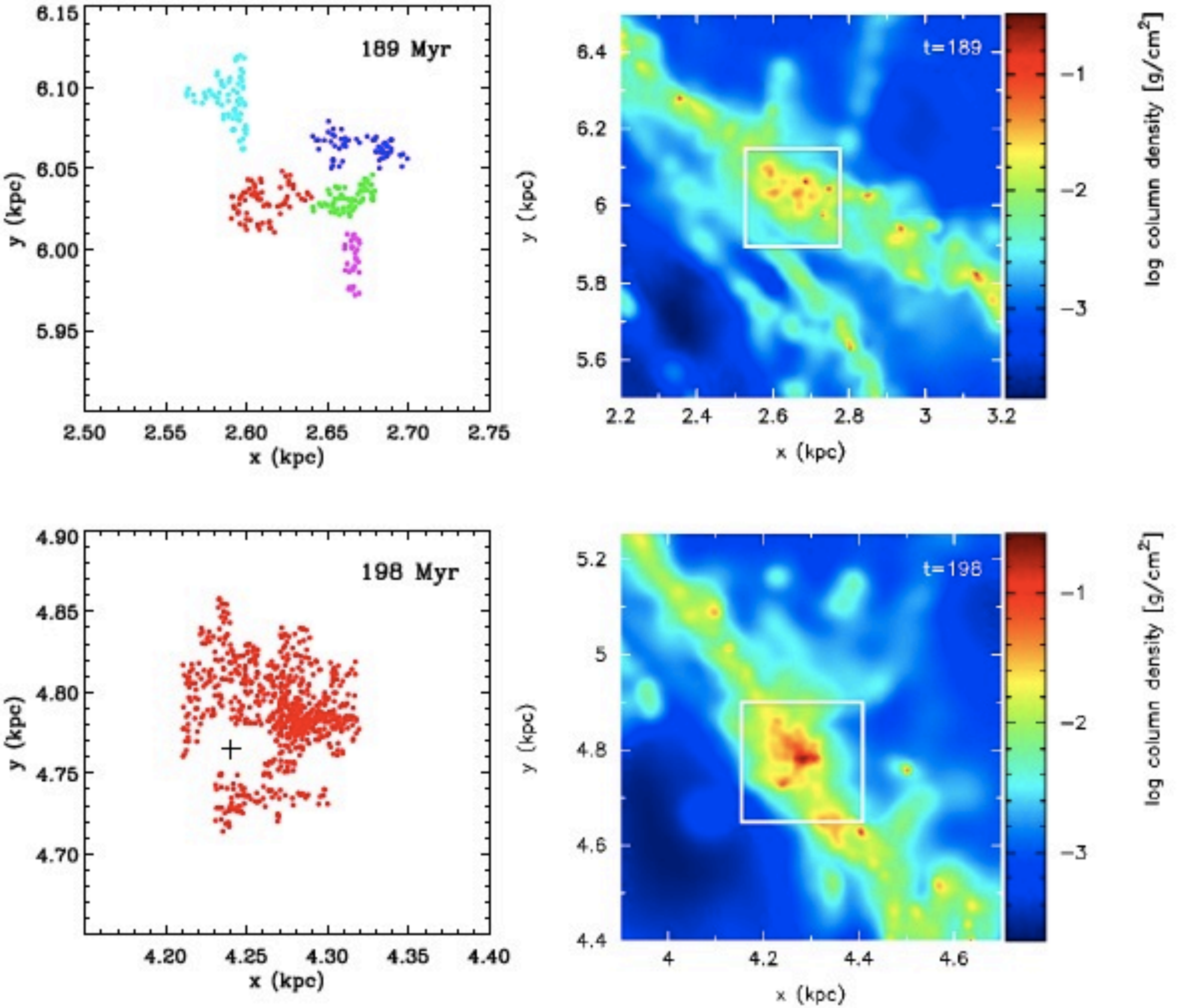
Dobbs, Burkert & Pringle 11a,b, 12a,b

Gas flows in galaxies - 4 examples

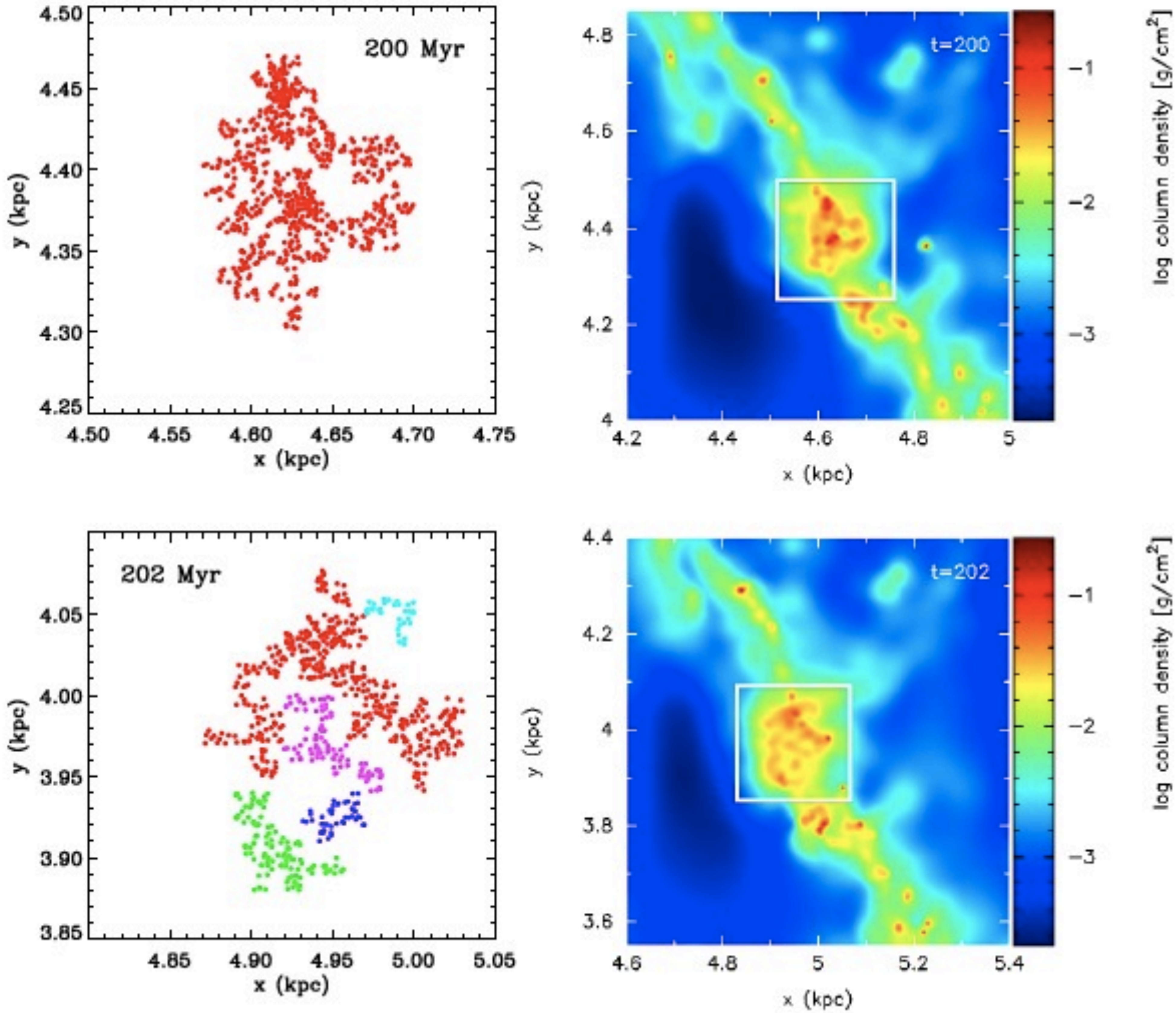




1. Collisions by local gravitational instability and irregular gas motions generate massive clouds and drive internal turbulence



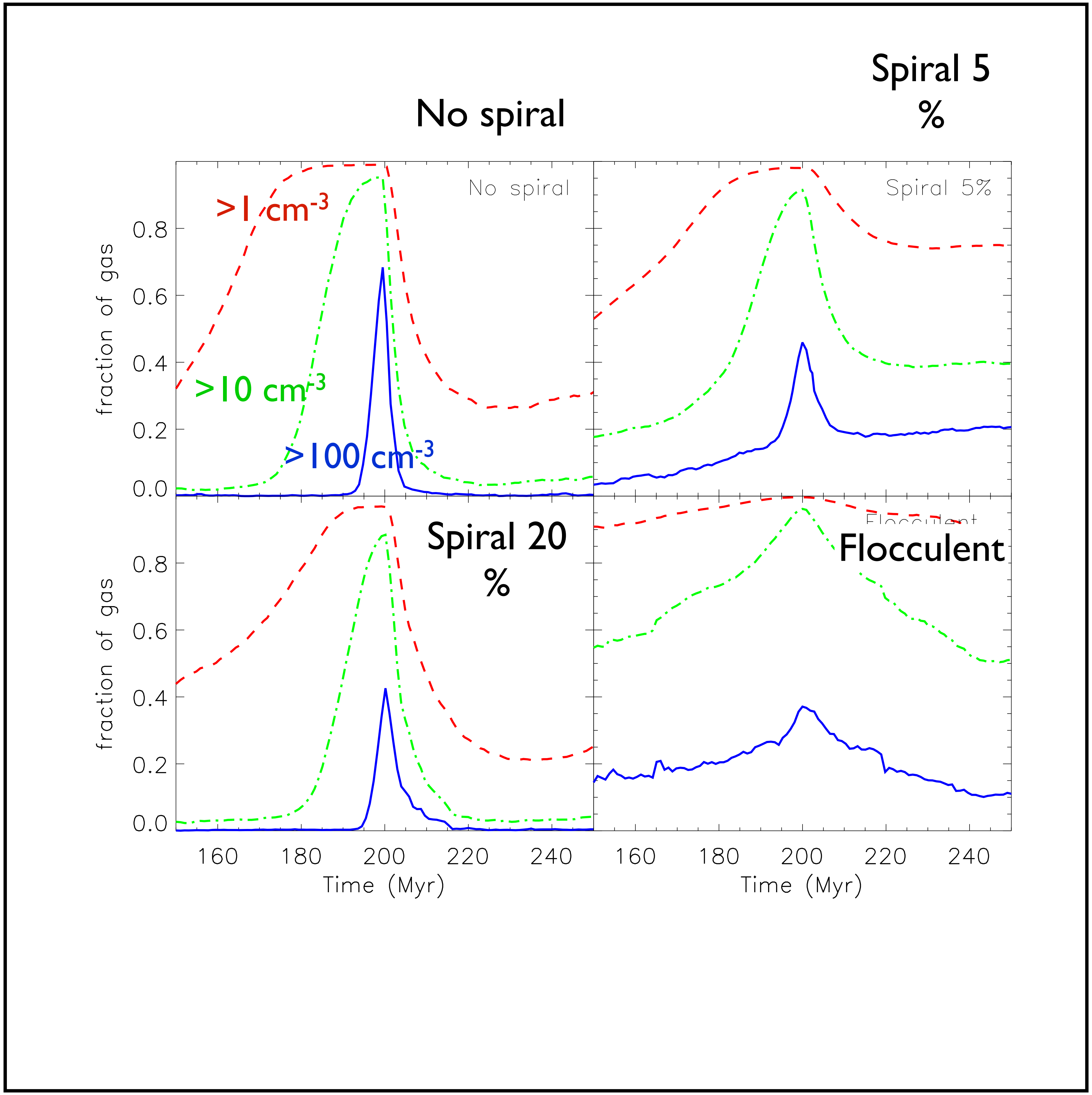
2. Stellar feedback disperses clouds and drives irregular gas motions in the molecular web.



How long is gas in GMCs?

Very dense gas occurs 5-10 Myr around star formation

Moderately dense gas exists for much longer



Growth rate of gravitational instabilities in galaxies:

$$\tau_{Toomre} = \frac{\sigma}{\pi G \Sigma} = \kappa^{-1} = \left(\sqrt{2}\Omega\right)^{-1} \rightarrow \tau_{\rm Toomre} = 0.1 \cdot \tau_{orb} \approx 1-2 \cdot 10^{7}\, yrs$$

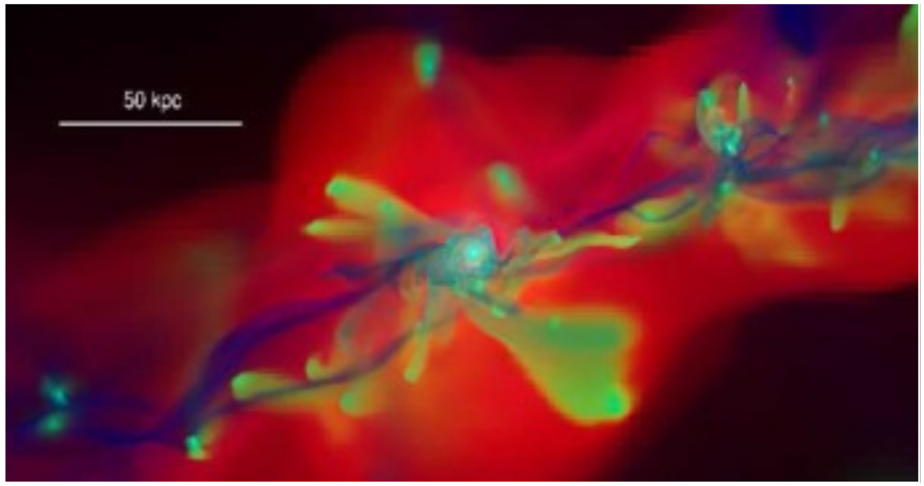
$$Q = 1$$

$$\tau_{orb} \sim \frac{R_{vir}}{V_{vir}} \sim H^{-1}$$

$$SFR \approx \frac{M_{H_2}}{10^9\, yrs} \approx \varepsilon_{sf} \cdot \frac{M_{dense}}{M_{H_2}} \cdot \frac{M_{H_2}}{\tau_{Toomre}}$$

$$\varepsilon_{sf} \approx 0.1$$

Self-regulated star formation

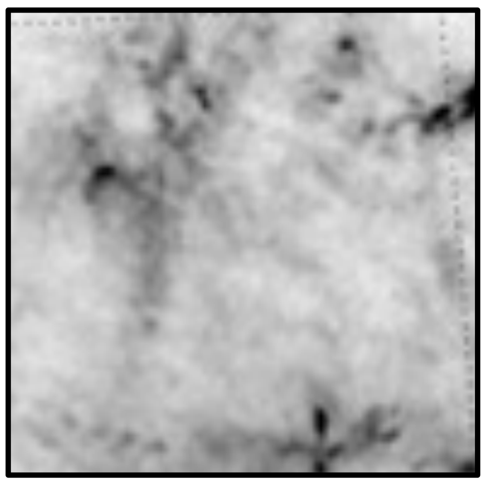


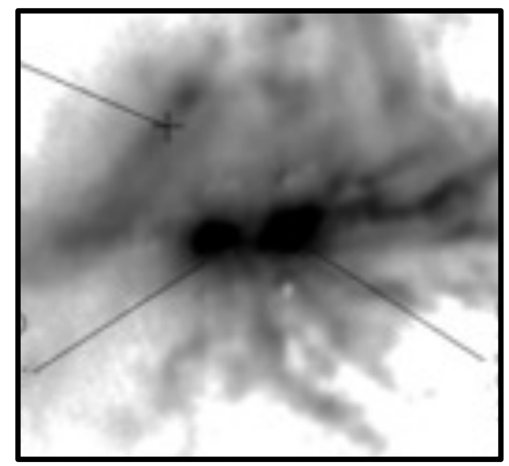
$$M_{H_2} = \dot{M}_{acc} \cdot \tau_{sf}$$

$\dot{M}_{acc}$

$0.9 \frac{M_{dense,H_2}}{\tau_{Toomre}}$

90%





10%

$M_{diff,H_2} / \tau_{Toomre}$

$0.1 \frac{M_{dense,H_2}}{\tau_{Toomre}} = \dot{M}_{acc}$

$$\tau_{sf} = 100 \cdot \tau_{Toomre} = \frac{M_{diff} / M_{dense}}{\varepsilon \cdot \kappa}$$