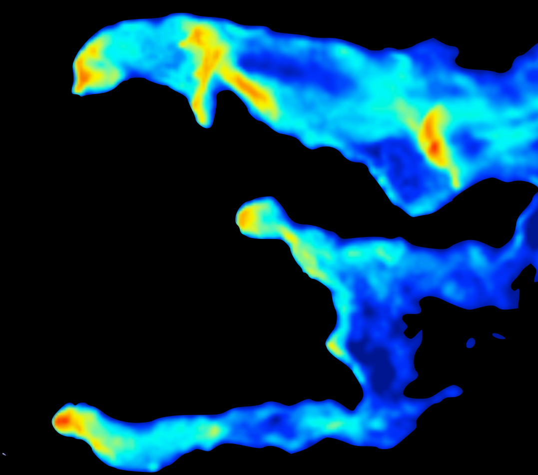
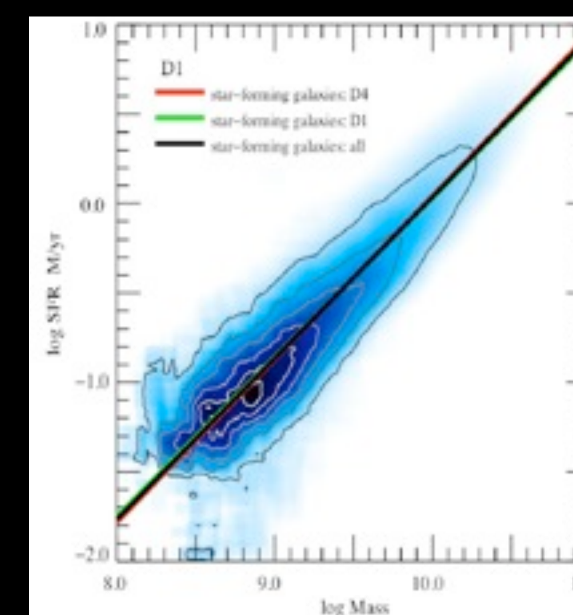
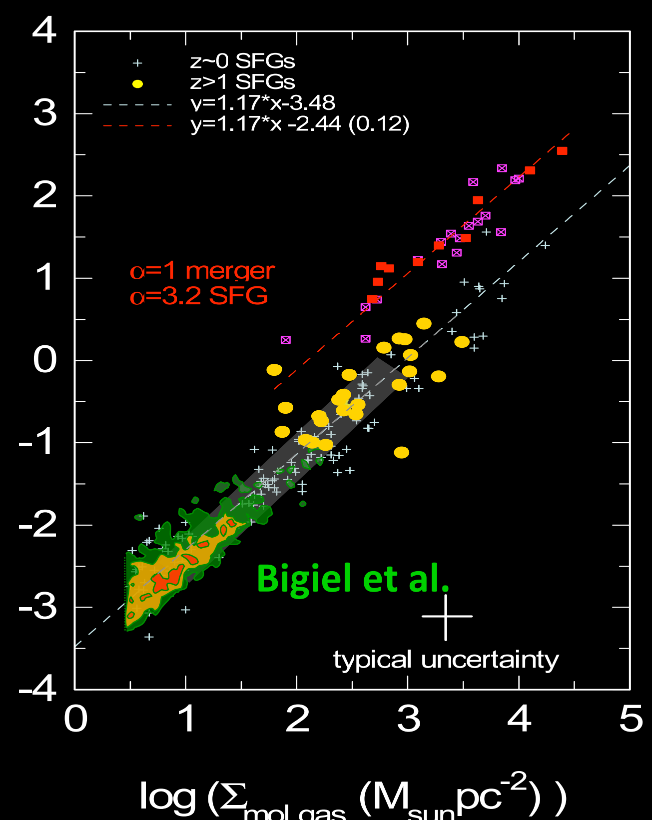
Self-regulated star formation

Andreas Burkert



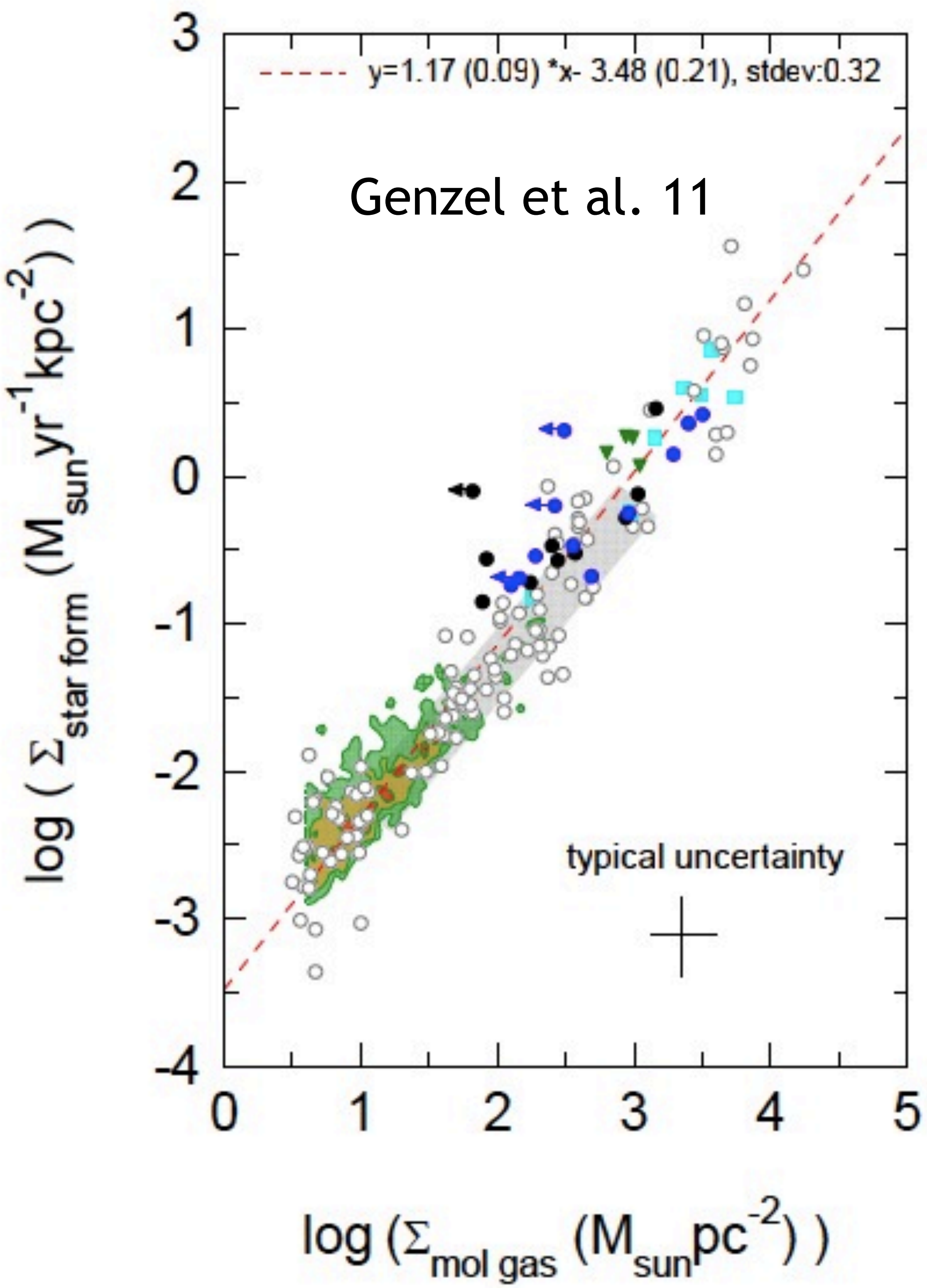




C. Dobbs, E. Ntormousi, K. Fierlinger, J. Ngoumou, J. Pringle, S. Walch

Munich University Observatory
CAST
Computational Astrophysics Group

Evidence for self-regulation



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

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

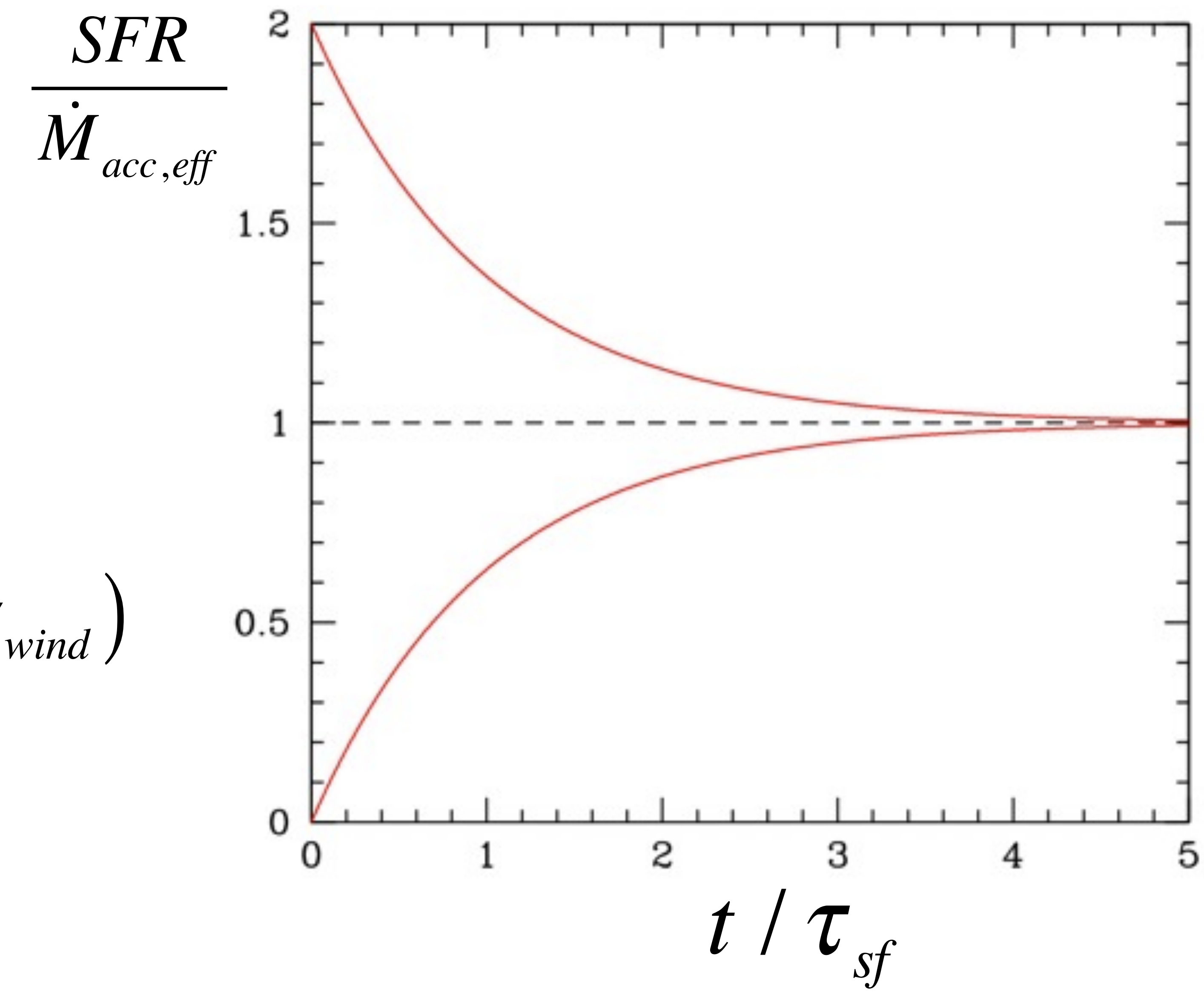
$$\tau_{ff} \ll \tau_{sf} < \tau_{\mathrm{Hubble}}$$

→ continuous replenishment

Bouché et al. 07, McKee & Ostriker 08, Genzel et al. 10,11, Daddi et al. 10

What determines SFR?

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



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

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

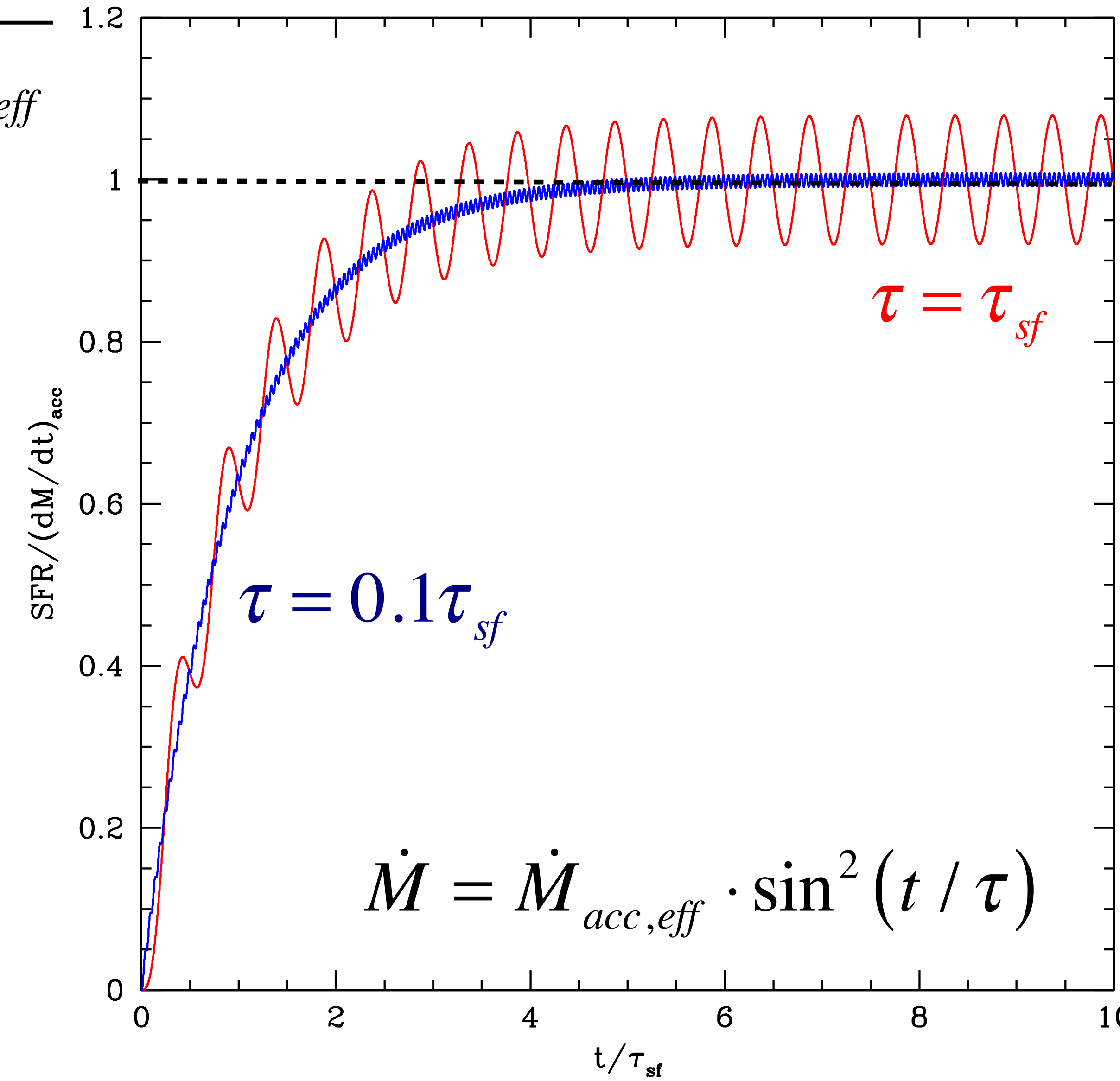
$$SFR = \frac{M_g}{\tau_{sf}} = \frac{1}{1 - R + \alpha_{wind}}\left(\frac{dM_g}{dt}\right)_{acc}\left(1 - \exp\left(-\frac{t}{\tau_{sf}}\right)\right)$$

→ $SFR = \dot{M}_{acc,eff}$

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**

What determines the gas mass?

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

- τ_{sf} determines the gas mass

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

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

Numerical simulations of the molecular web

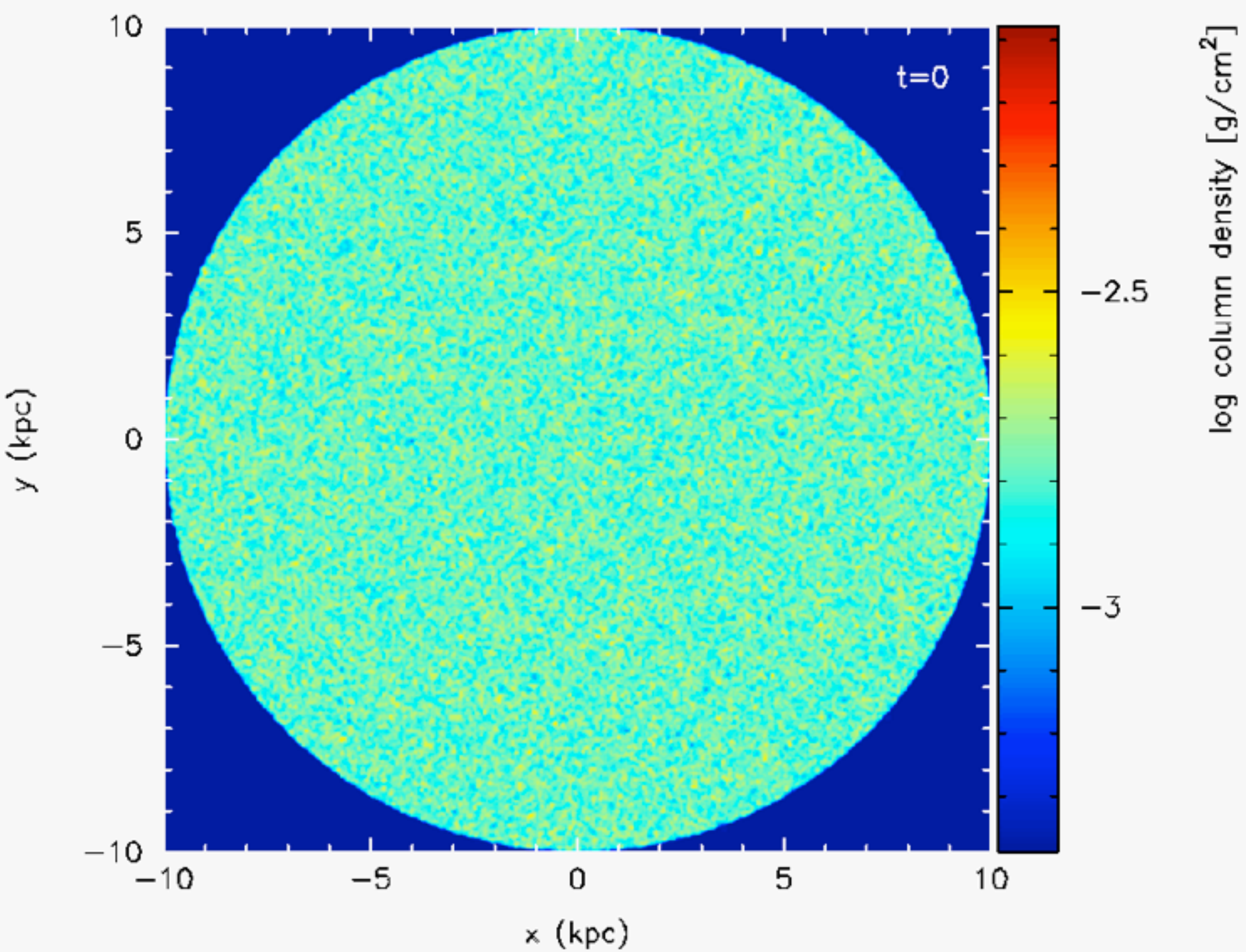
(Dobbs, Burkert & Pringle 11a,b)

- **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

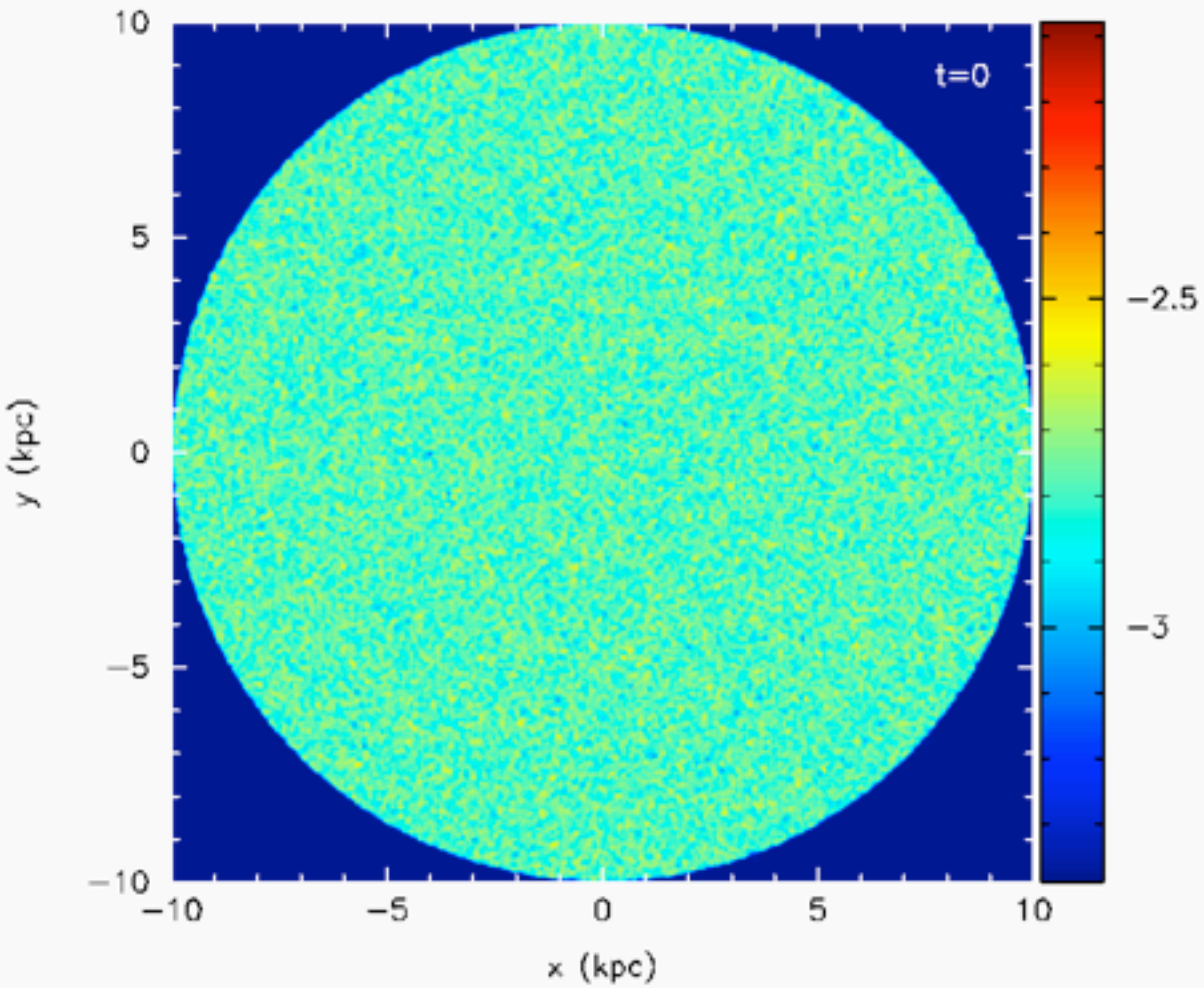
$$E_{SN} = \varepsilon \frac{M_{dense}}{160 M_{\odot}} \cdot 10^{51} ergs$$

$$\varepsilon \approx 2 - 5\%$$

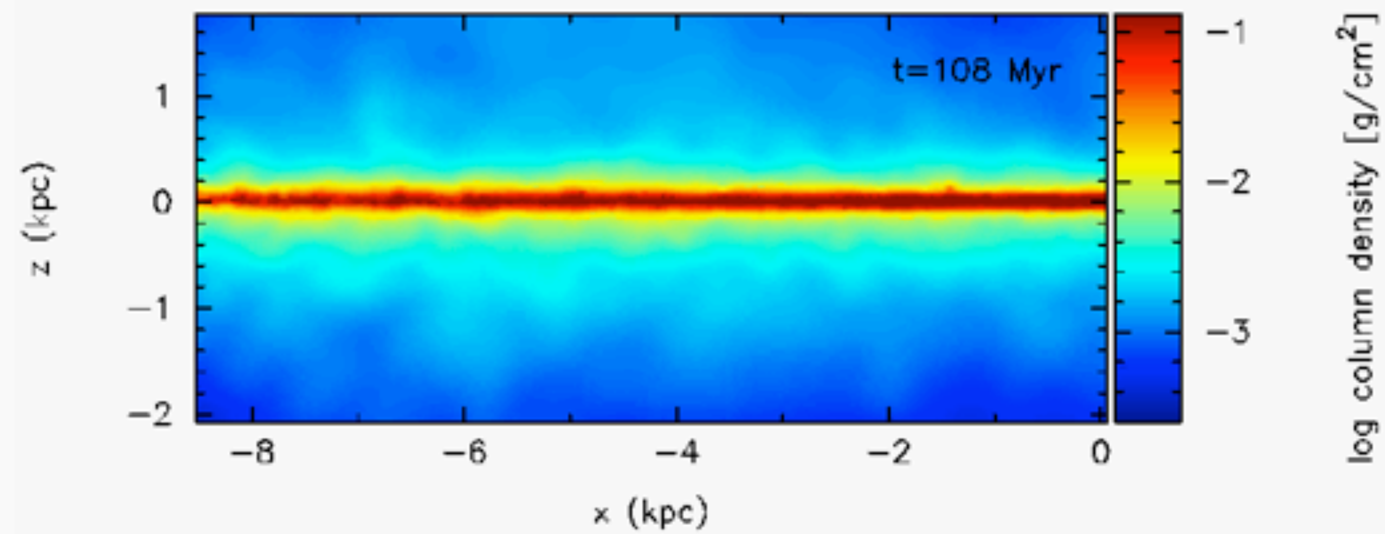
Calculation with 5 % efficiency

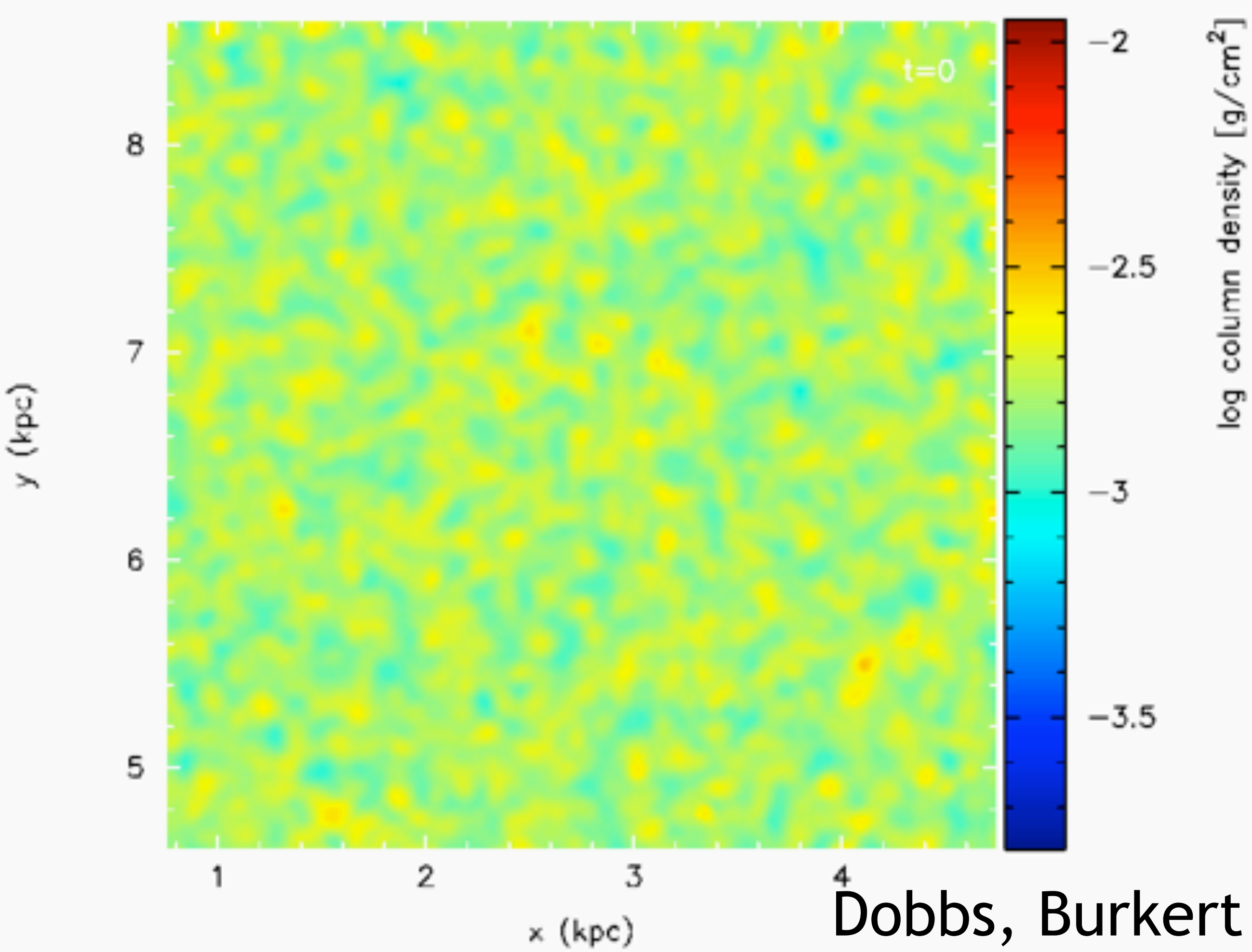


Dobbs, Burkert & Pringle 11a,b



Feedback puffs up disk

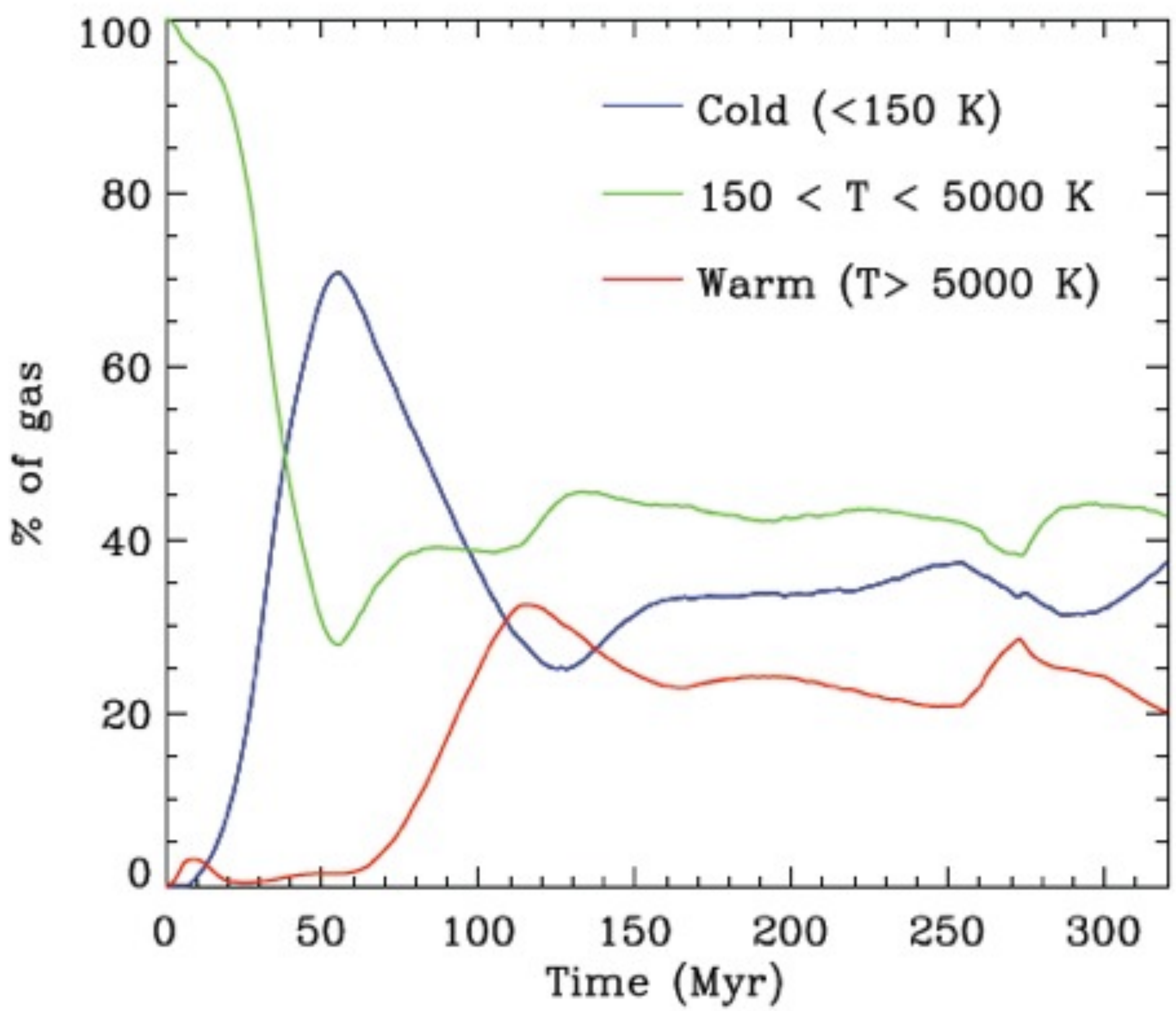


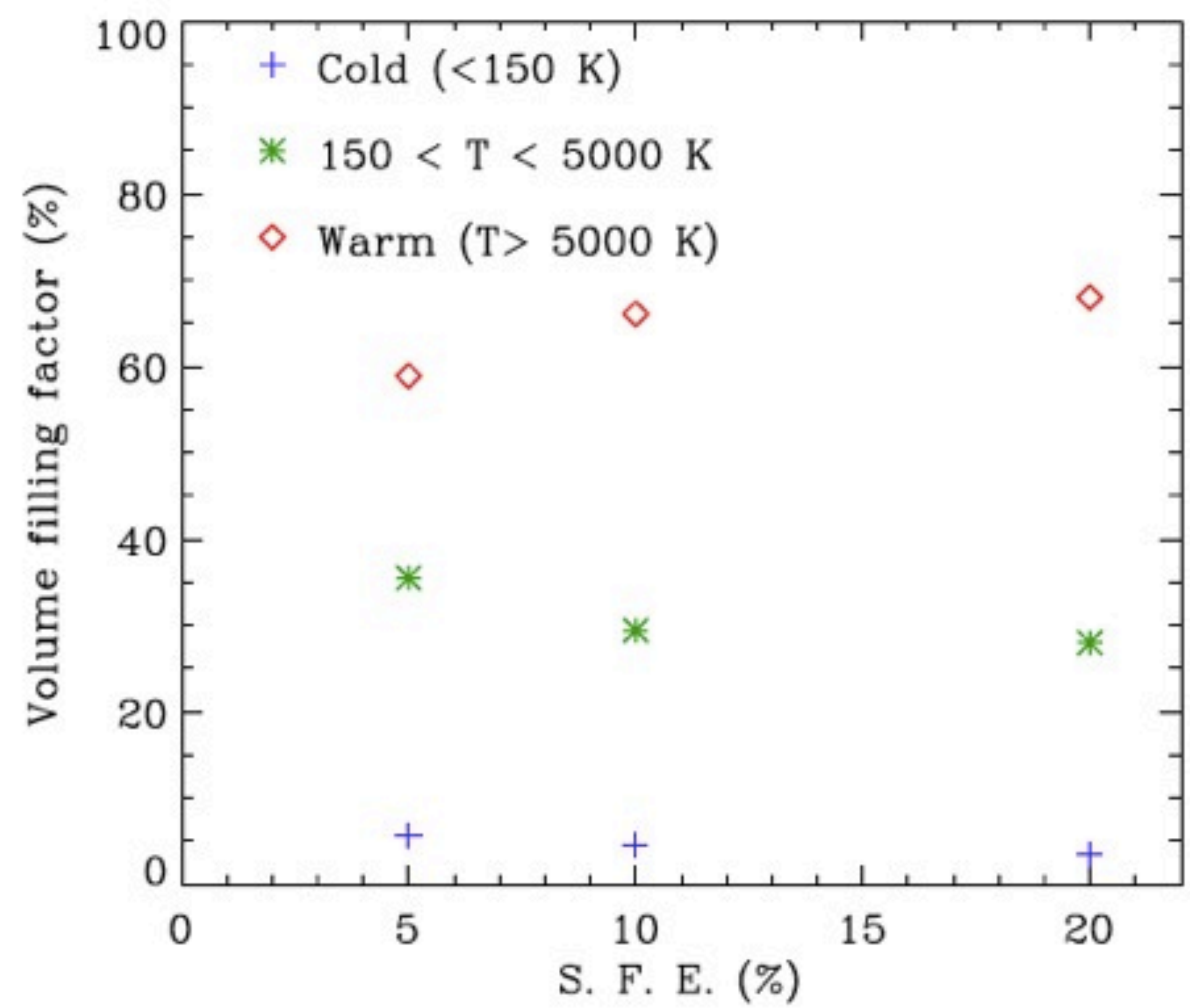


Filamentary interarm features (spurs)

Dobbs, Burkert & Pringle 11a,b

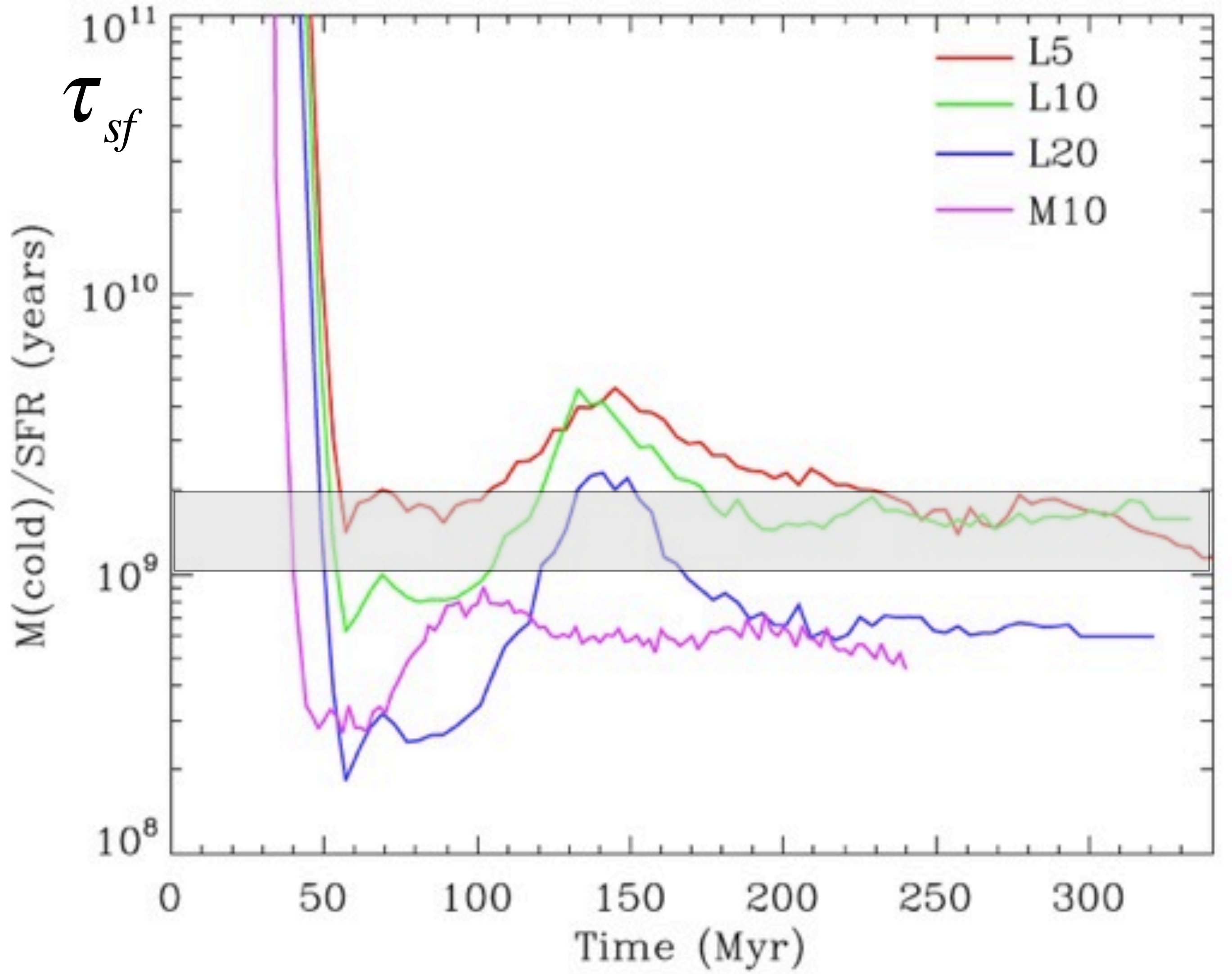
Gas mass fraction and volume filling factor: 5% efficiency





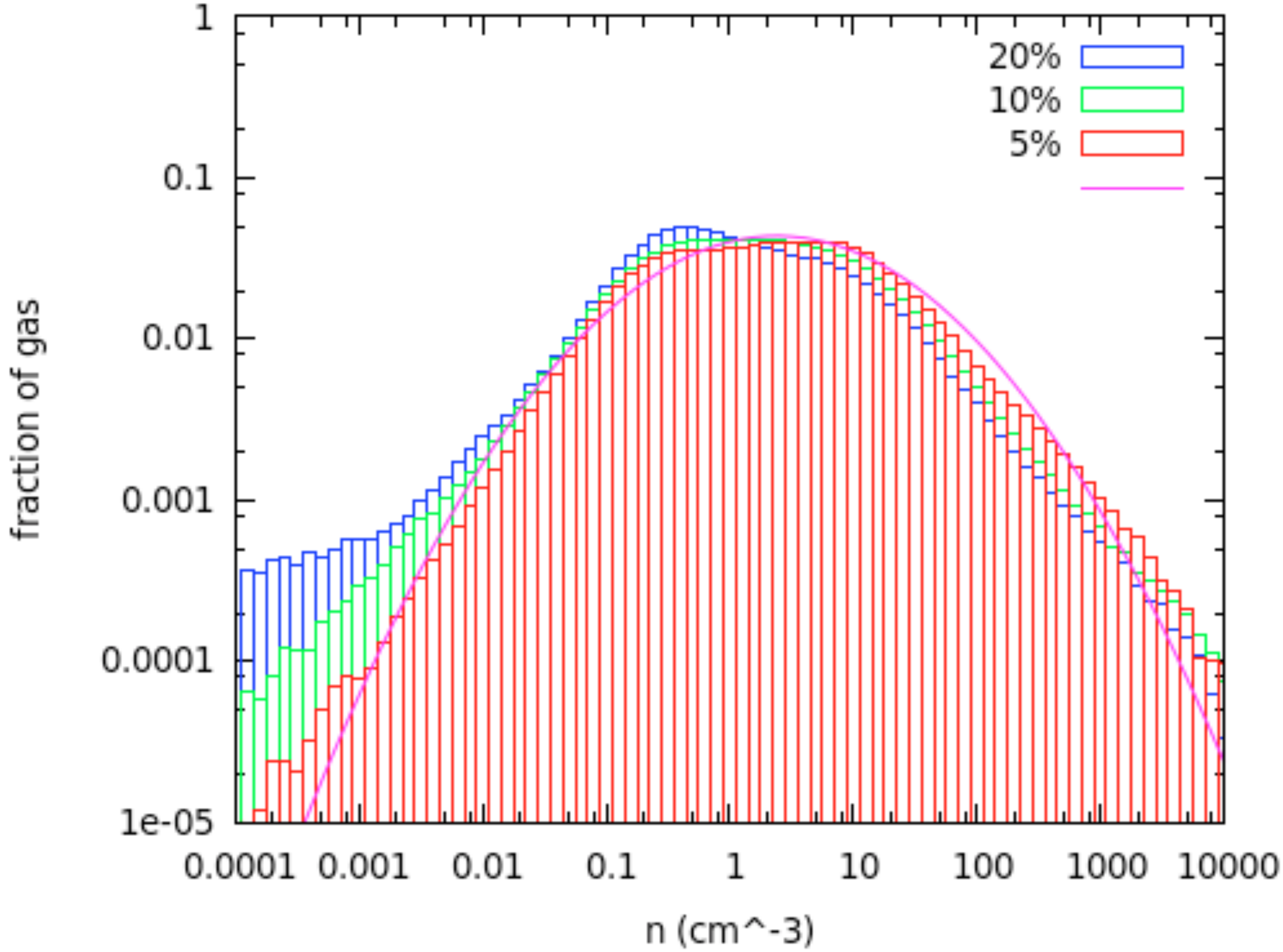
Star formation timescale

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

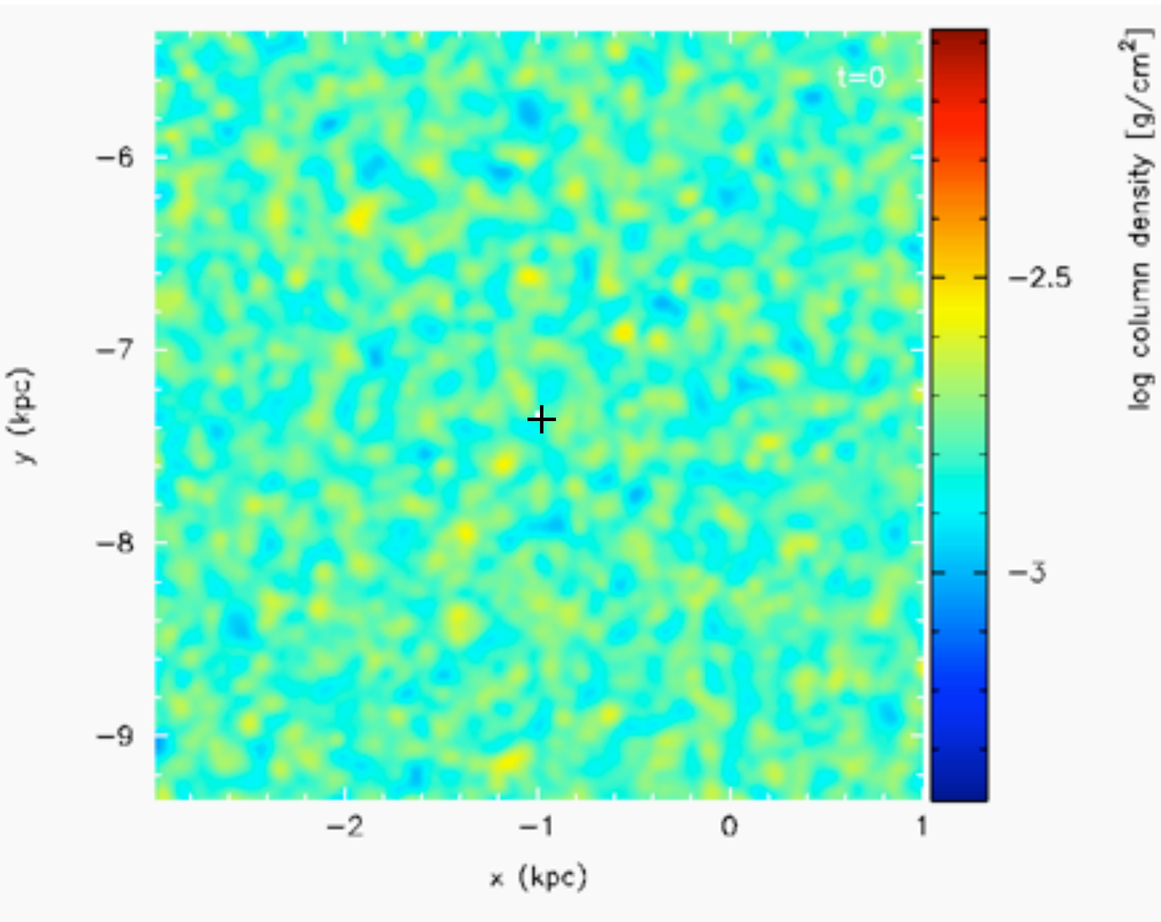


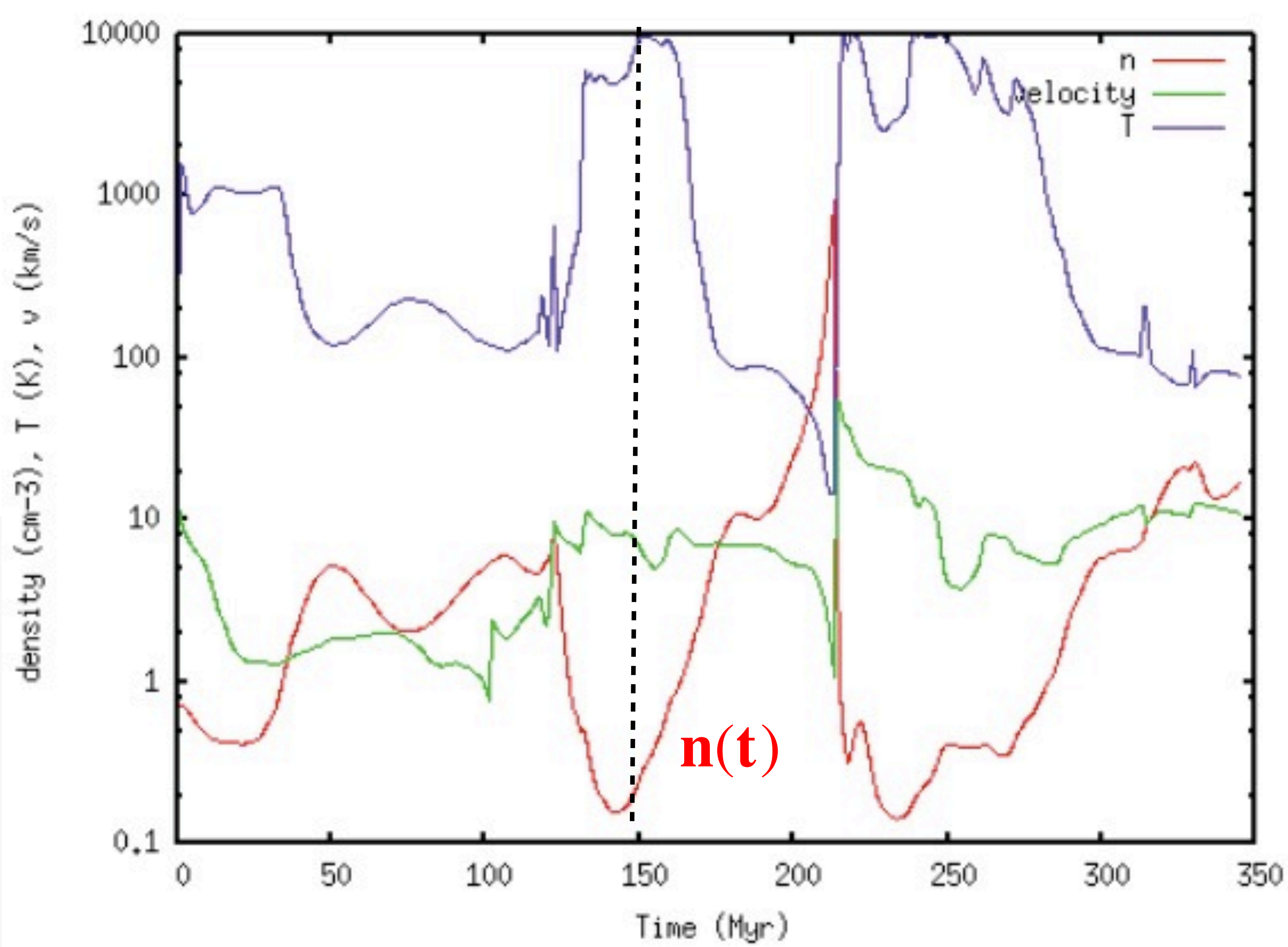
Density Probability Distribution Function

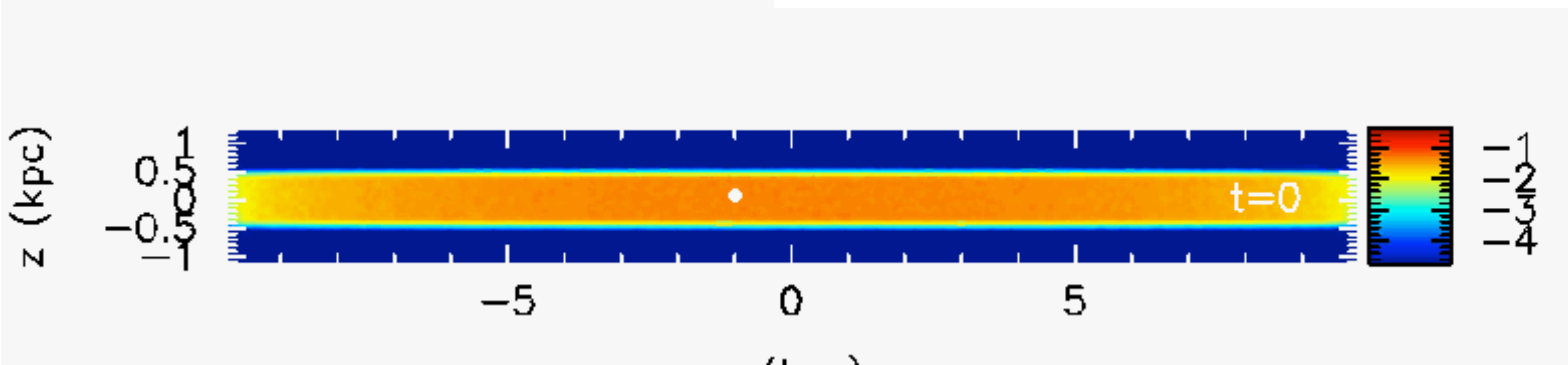
(Elmegreen 02; Krumholz & McKee 05; Wada & Norman 07)



Gravitational instabilities and star formation timescale







Growth rate of gravitational instabilities:

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

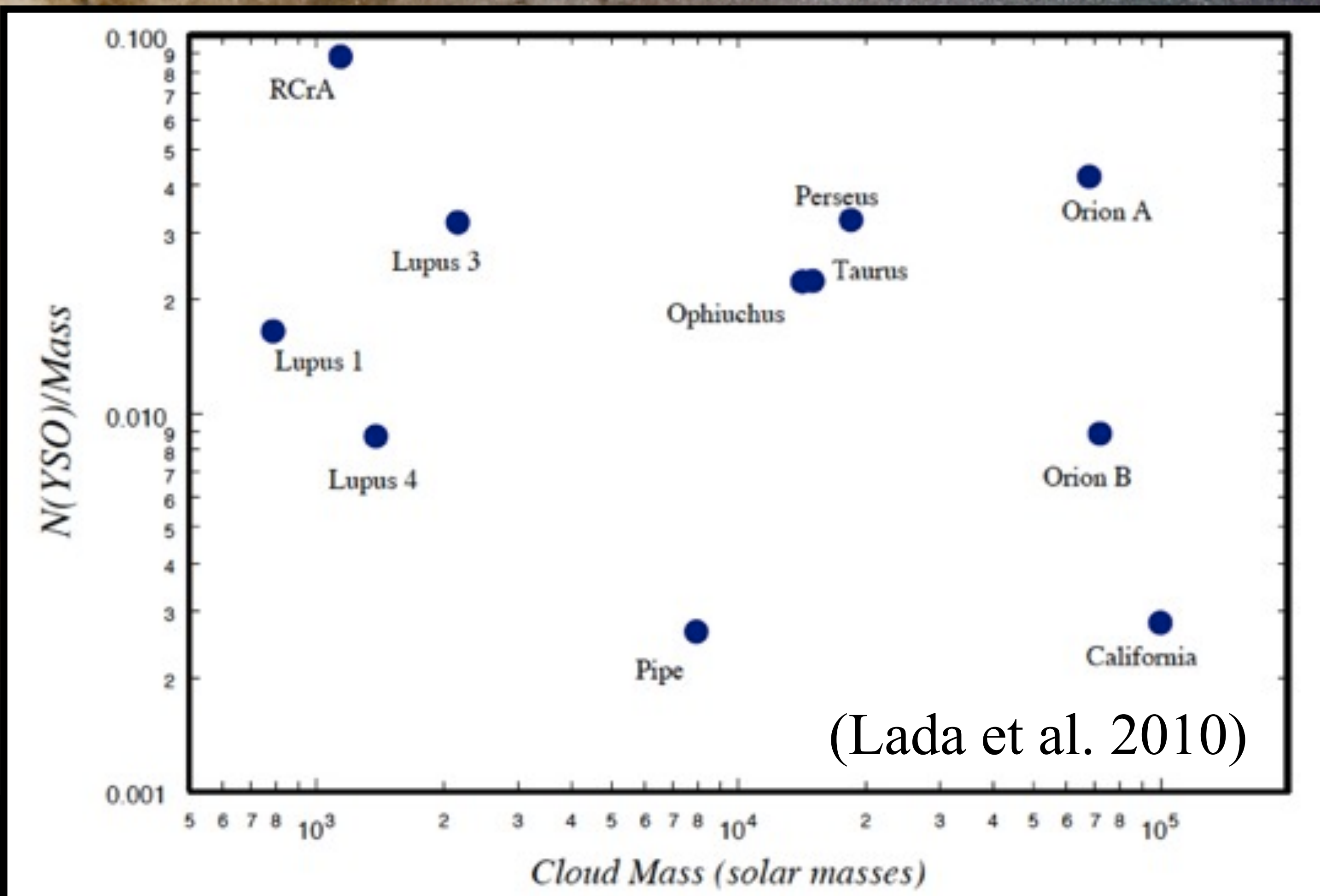
$$Q = 1$$

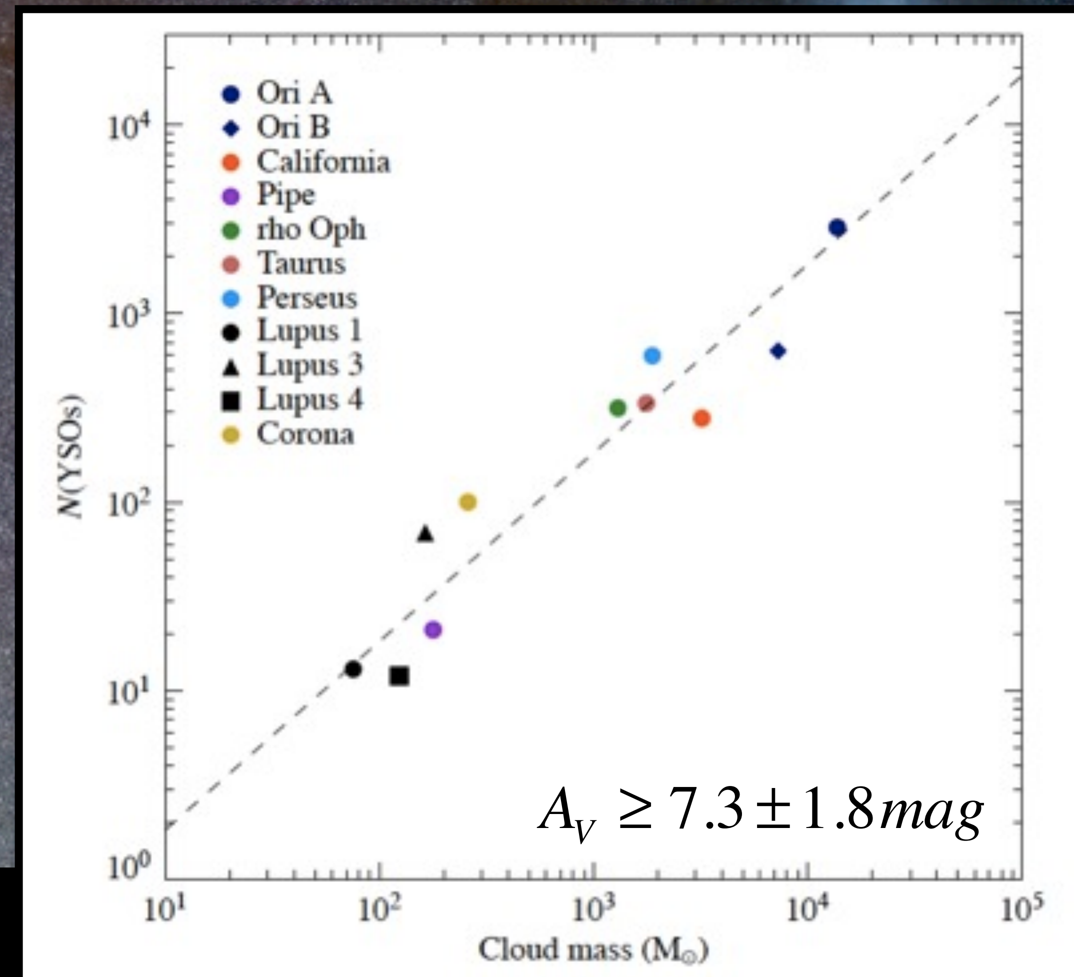
$$\tau_{orb} \sim \frac{R_{vir}}{V_{vir}} \sim H^{-1}$$

$$\tau_{SF} \approx 10^{9}\, yrs \approx 50 \cdot \tau_{Toomre} \approx \tau_{Toomre} / \varepsilon$$

$$SFR = 0.02 \frac{M_{H_2}}{\tau_{Toomre}}$$

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



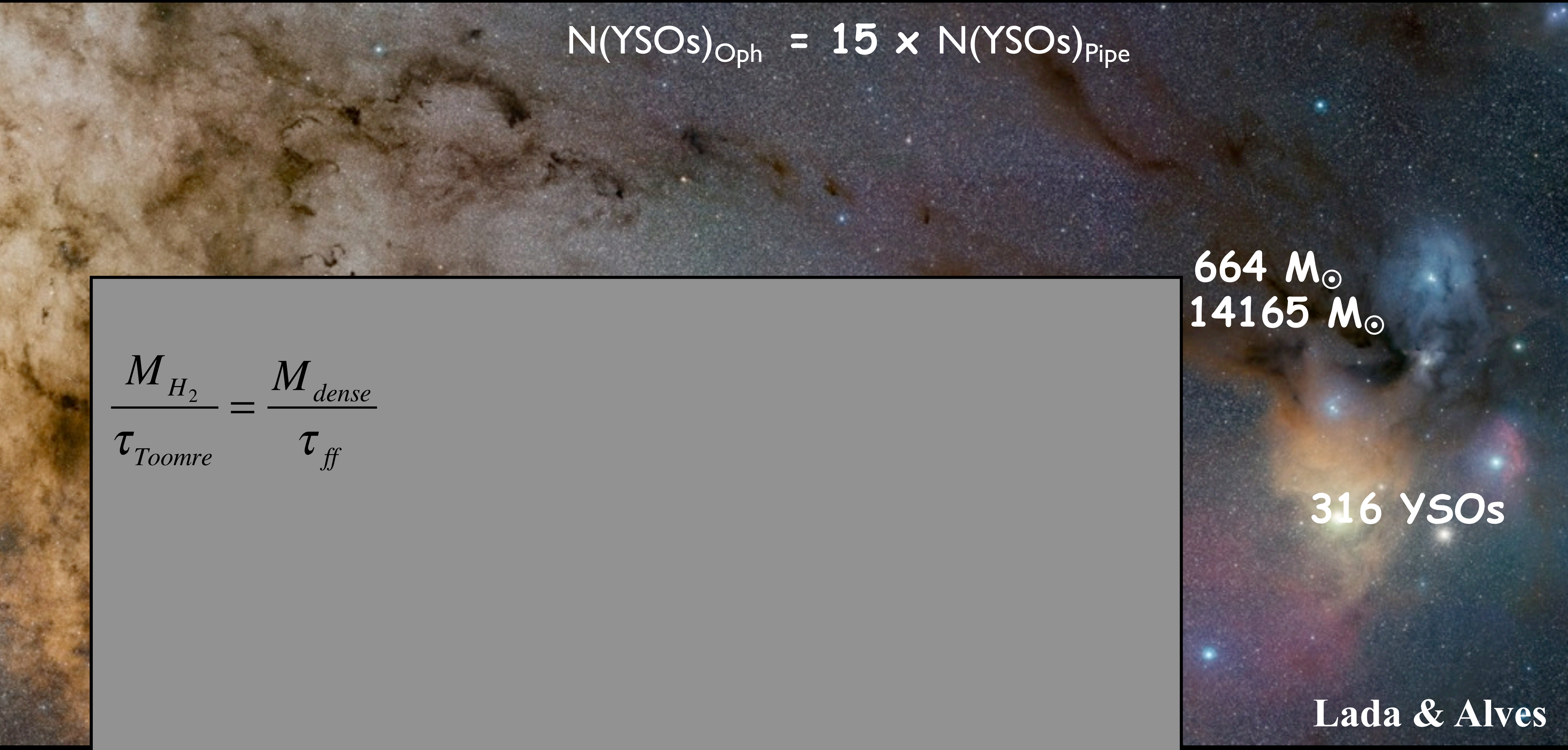


$$n_{A_V=7.3} \approx 10^4\, cm^{-3} \rightarrow \tau_{ff} \approx 3.5 \cdot 10^5\, yrs \longrightarrow SFR \approx 0.02 \frac{M_{dense}}{\tau_{ff}}$$

Large scales:

$$SFR \approx \frac{M_{H_2}}{10^9\, yrs} \approx 0.02 \frac{M_{H_2}}{\tau_{dyn}}$$

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



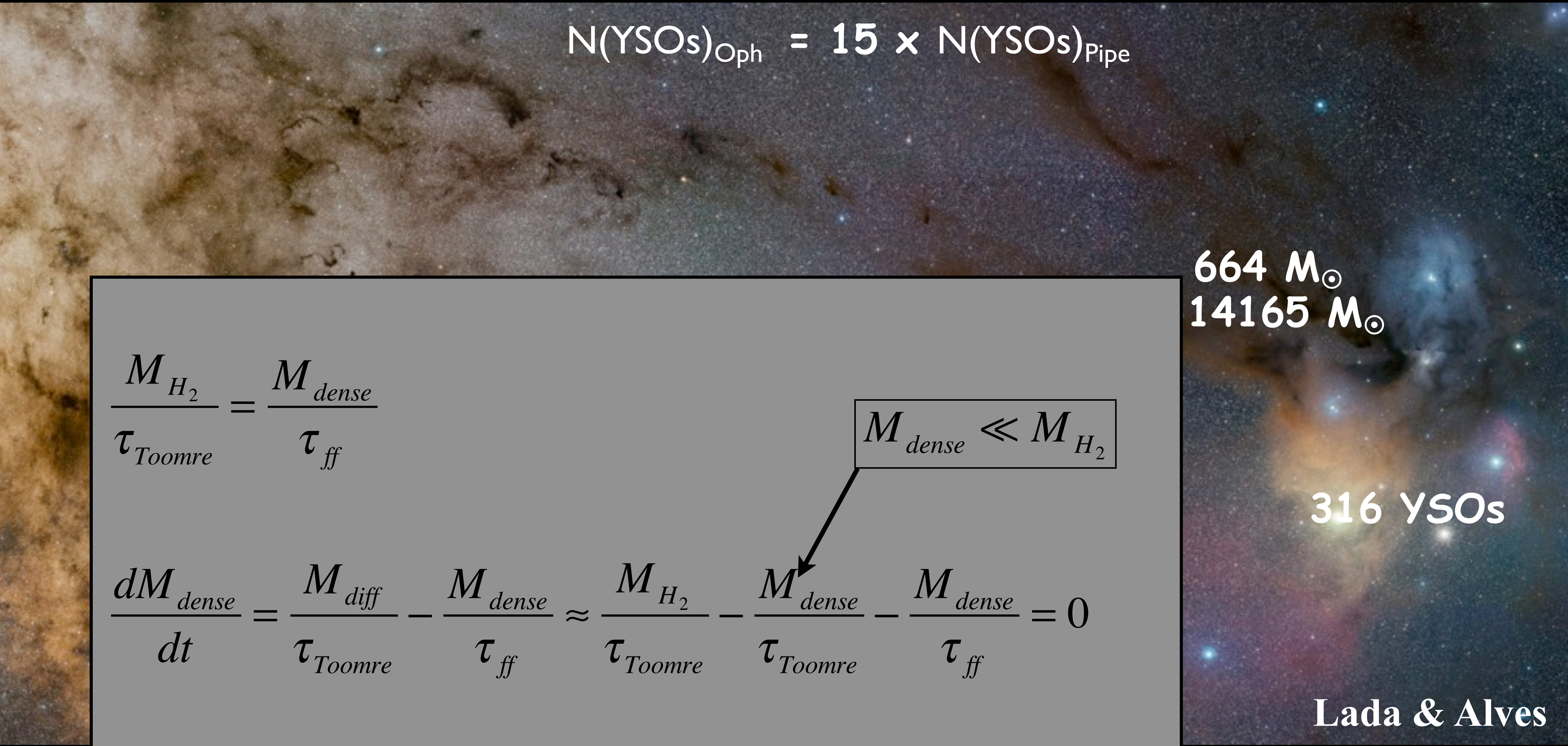
$$\frac{M_{H_2}}{\tau_{Toomre}} = \frac{M_{dense}}{\tau_{ff}}$$

$$n_{A_V=7.3} \approx 10^4\, cm^{-3} \rightarrow \tau_{ff} \approx 3.5 \cdot 10^5\, yrs \longrightarrow SFR \approx 0.02 \frac{M_{dense}}{\tau_{ff}}$$

Large scales:

$$SFR \approx \frac{M_{H_2}}{10^9\, yrs} \approx 0.02 \frac{M_{H_2}}{\tau_{Toomre}}$$

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



$$\frac{M_{H_2}}{\tau_{Toomre}} = \frac{M_{dense}}{\tau_{ff}}$$

$$M_{dense} \ll M_{H_2}$$

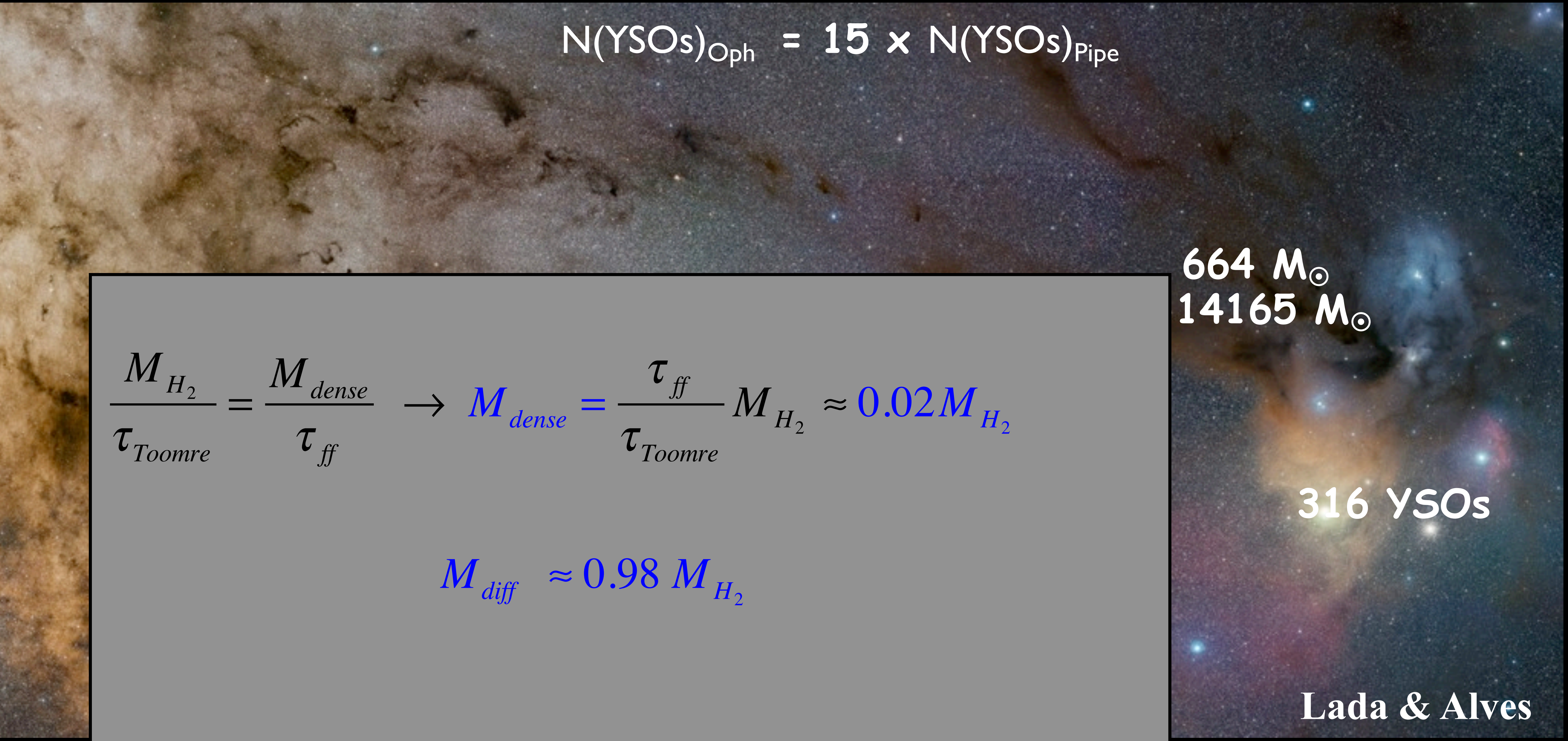
$$\frac{dM_{dense}}{dt} = \frac{M_{diff}}{\tau_{Toomre}} - \frac{M_{dense}}{\tau_{ff}} \approx \frac{M_{H_2}}{\tau_{Toomre}} - \frac{M_{dense}}{\tau_{Toomre}} - \frac{M_{dense}}{\tau_{ff}} = 0$$

$$n_{A_V=7.3} \approx 10^4\,cm^{-3} \rightarrow \tau_{ff} \approx 3.5 \cdot 10^5\,yrs \longrightarrow SFR \approx 0.02\frac{M_{dense}}{\tau_{ff}}$$

Large scales:

$$SFR \approx \frac{M_{H_2}}{10^9\,yrs} \approx 0.02\frac{M_{H_2}}{\tau_{Toomre}}$$

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



$$\frac{M_{H_2}}{\tau_{Toomre}} = \frac{M_{dense}}{\tau_{ff}} \rightarrow M_{dense} = \frac{\tau_{ff}}{\tau_{Toomre}} M_{H_2} \approx 0.02 M_{H_2}$$

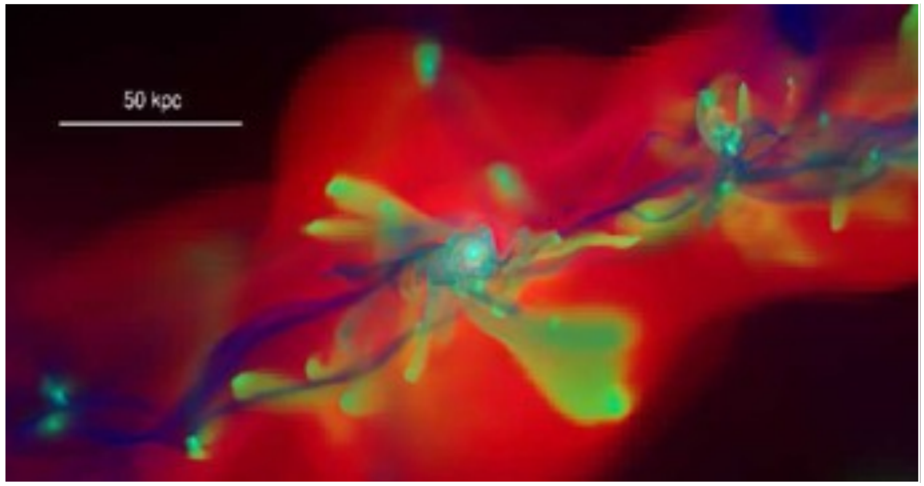
$$M_{diff} \approx 0.98\, M_{H_2}$$

$$n_{A_V=7.3} \approx 10^4\, cm^{-3} \rightarrow \tau_{ff} \approx 3.5 \cdot 10^5\, yrs \quad \rightarrow \quad SFR \approx 0.02 \frac{M_{dense}}{\tau_{ff}}$$

Large scales:

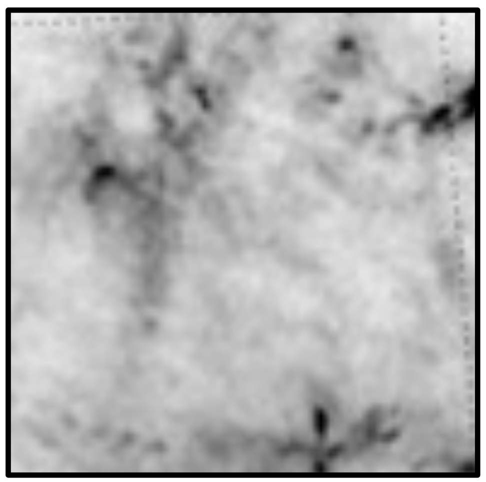
$$SFR \approx \frac{M_{H_2}}{10^9\, yrs} \approx 0.02 \frac{M_{H_2}}{\tau_{Toomre}}$$

Self-regulated star formation



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

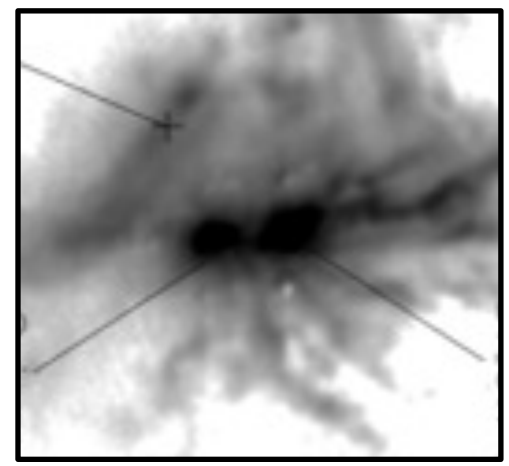
$\dot{M}_{acc}$



98%

$$0.98\,\frac{M_{dense,H_2}}{\tau_{ff}}$$

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

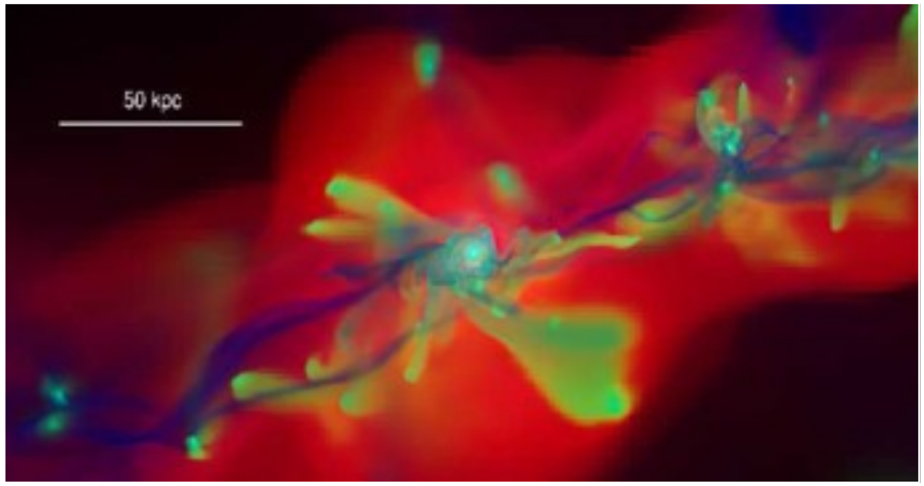


2%

$$0.02\,\frac{M_{dense,H_2}}{\tau_{ff}} = \dot{M}_{acc}$$

$$\tau_{sf} = 50 \cdot \tau_{Toomre} = \frac{1}{\varepsilon \cdot \kappa}$$

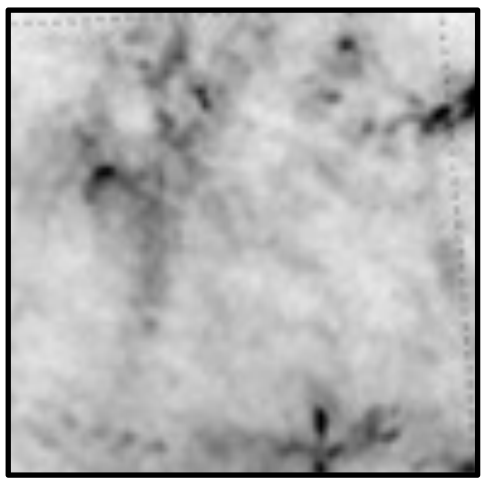
Self-regulated star formation



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

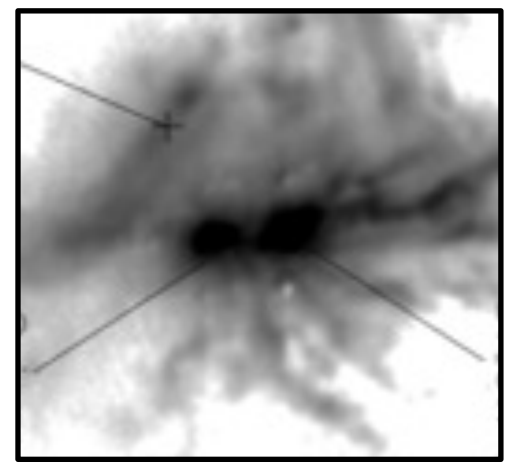
$\dot{M}_{acc}$

98%



$0.98 \frac{M_{dense,H_2}}{\tau_{ff}}$

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



$$2\% = \frac{\tau_{ff}}{\tau_{Toomre}}$$

?

$$0.02 \frac{M_{dense,H_2}}{\tau_{ff}} = \dot{M}_{acc}$$

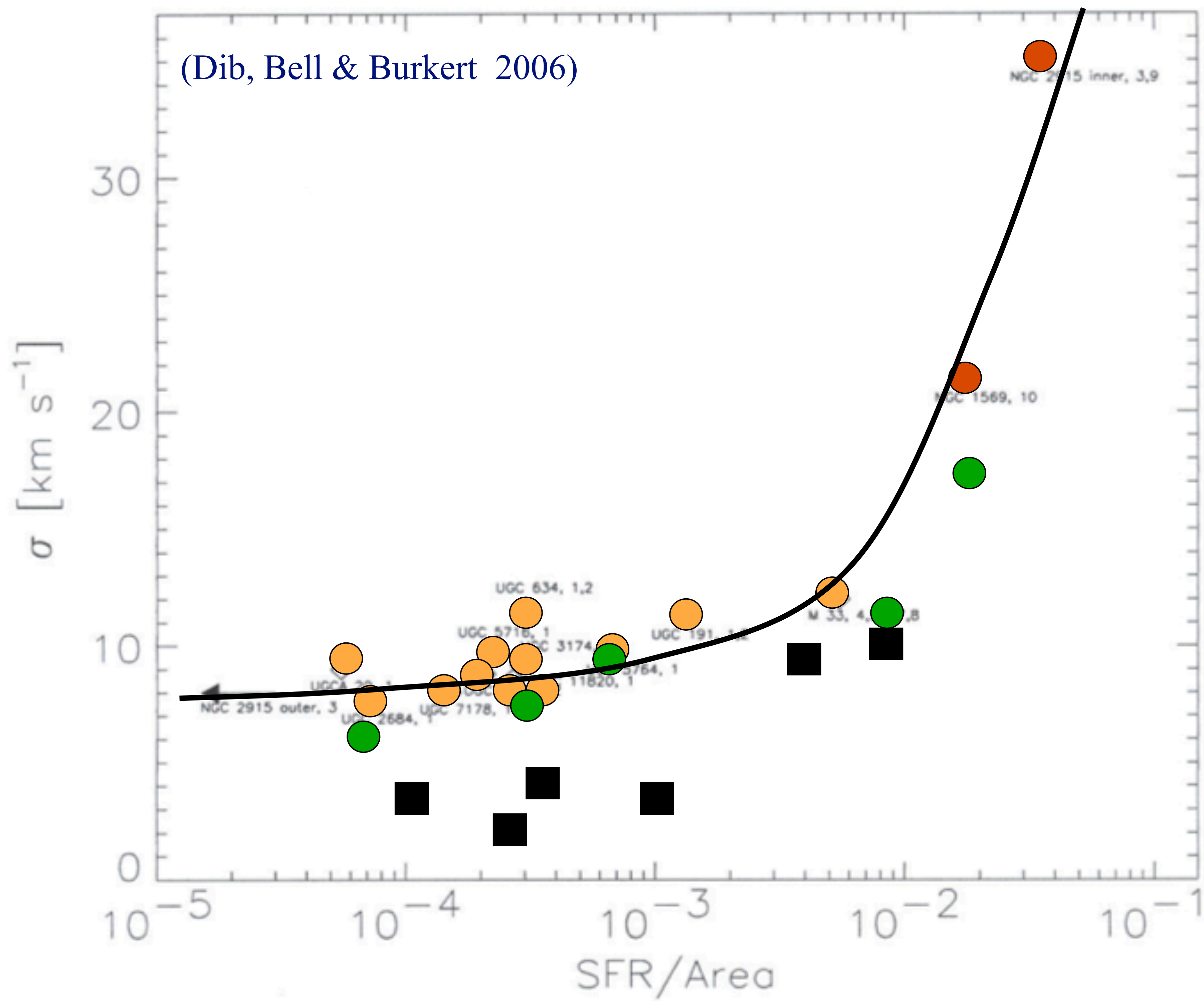
$$\tau_{sf} = 50 \cdot \tau_{Toomre} = \frac{1}{\varepsilon \cdot \kappa}$$

$$SFR \approx \varepsilon \frac{M_{H_2}}{\tau_{Toomre}} \approx \frac{M_{H_2}}{10^9\, yrs}$$

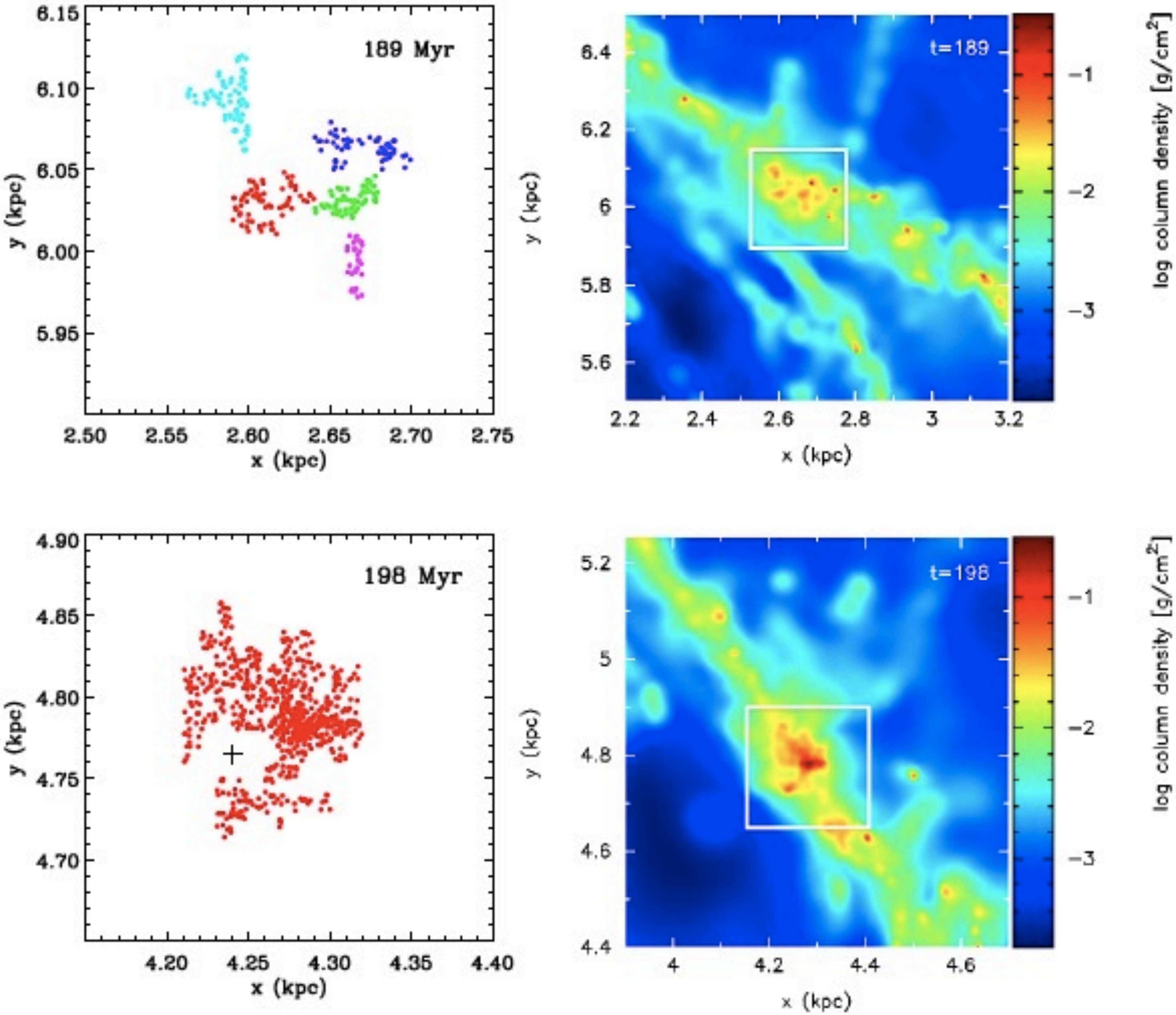
$\varepsilon \approx 0.02$

What determines the star formation efficiency?

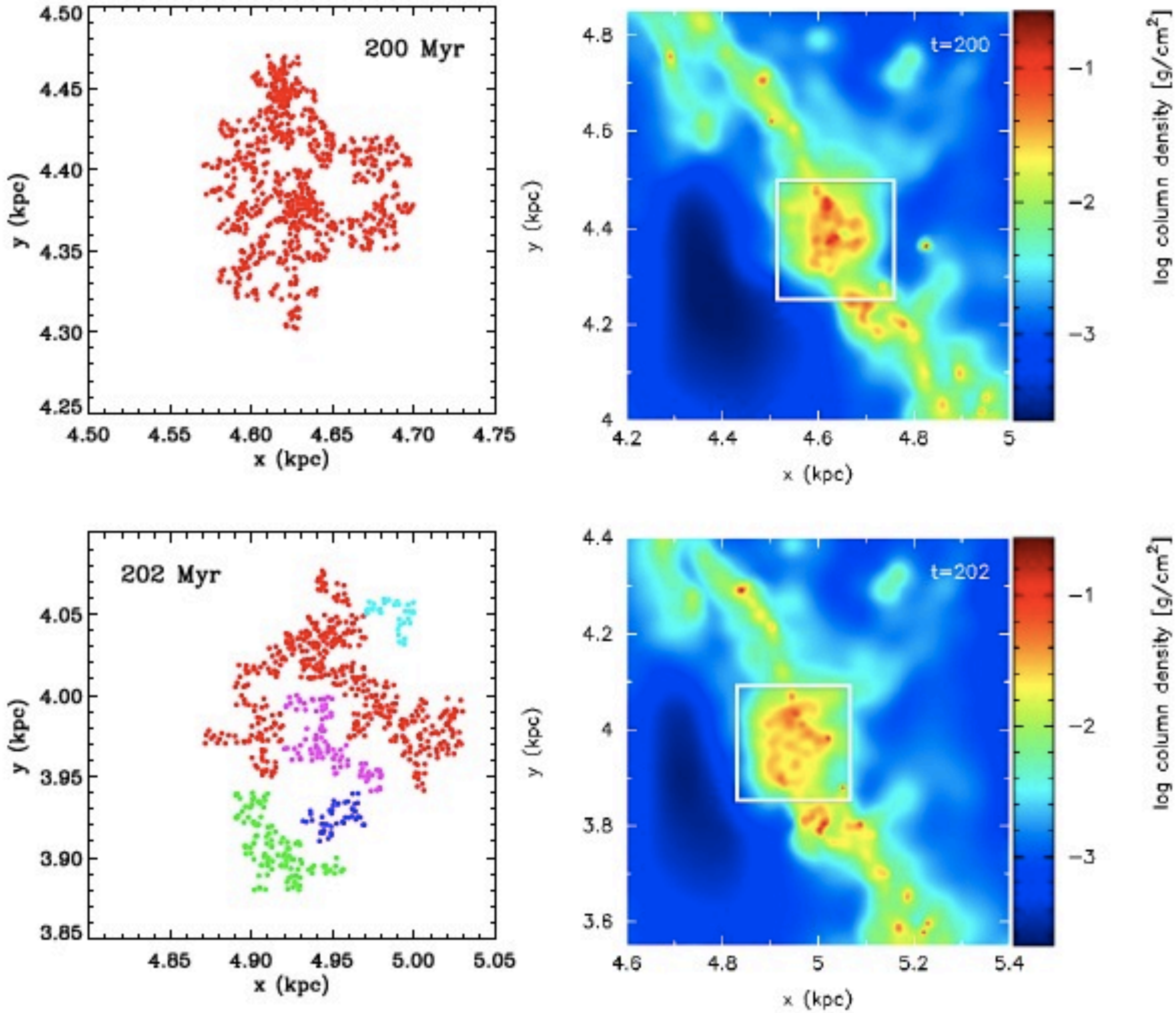
Turbulence in the ISM



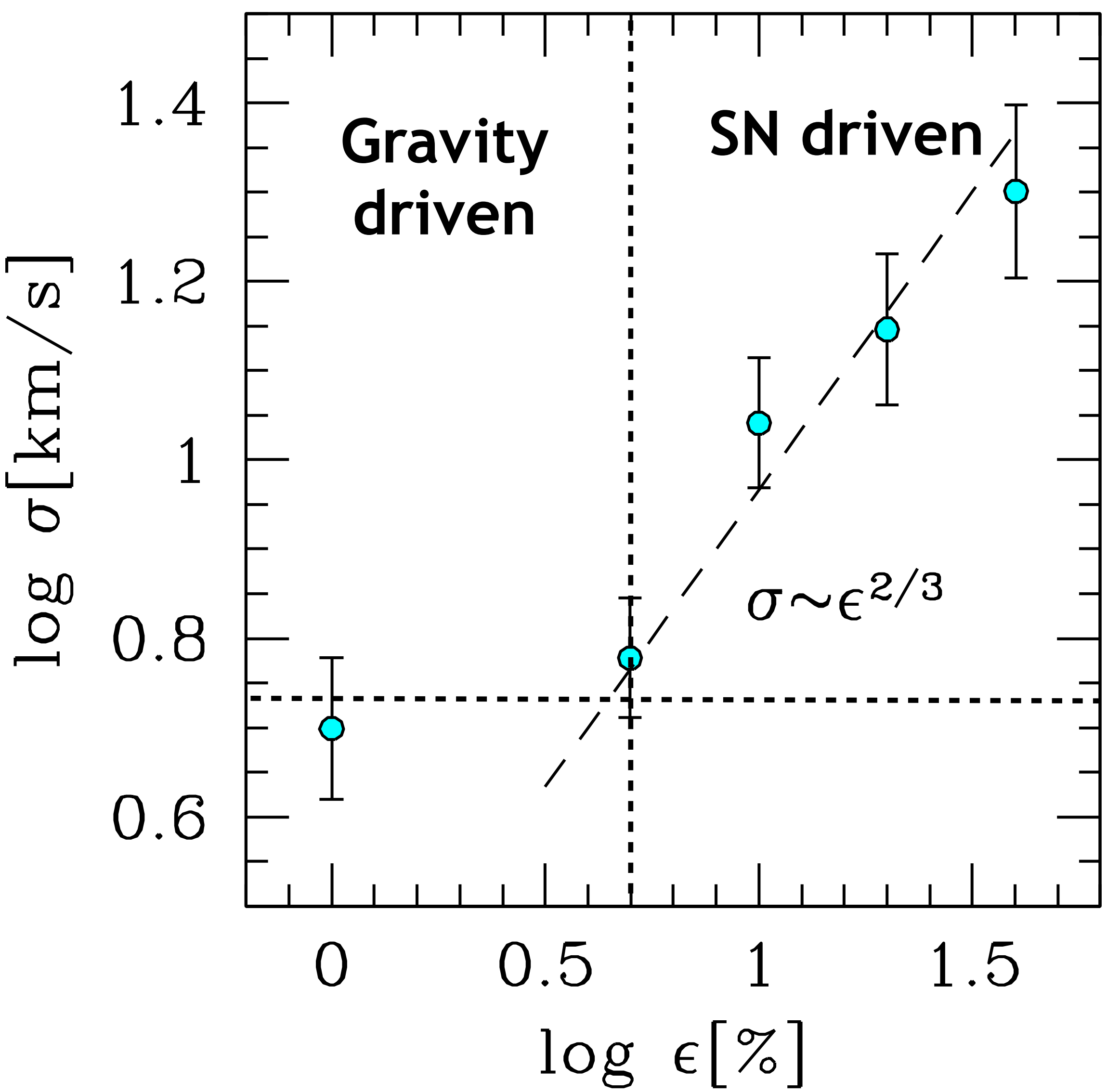
1. Collisions by local gravitational instability and irregular gas motions generate massive clouds and drive internal turbulence

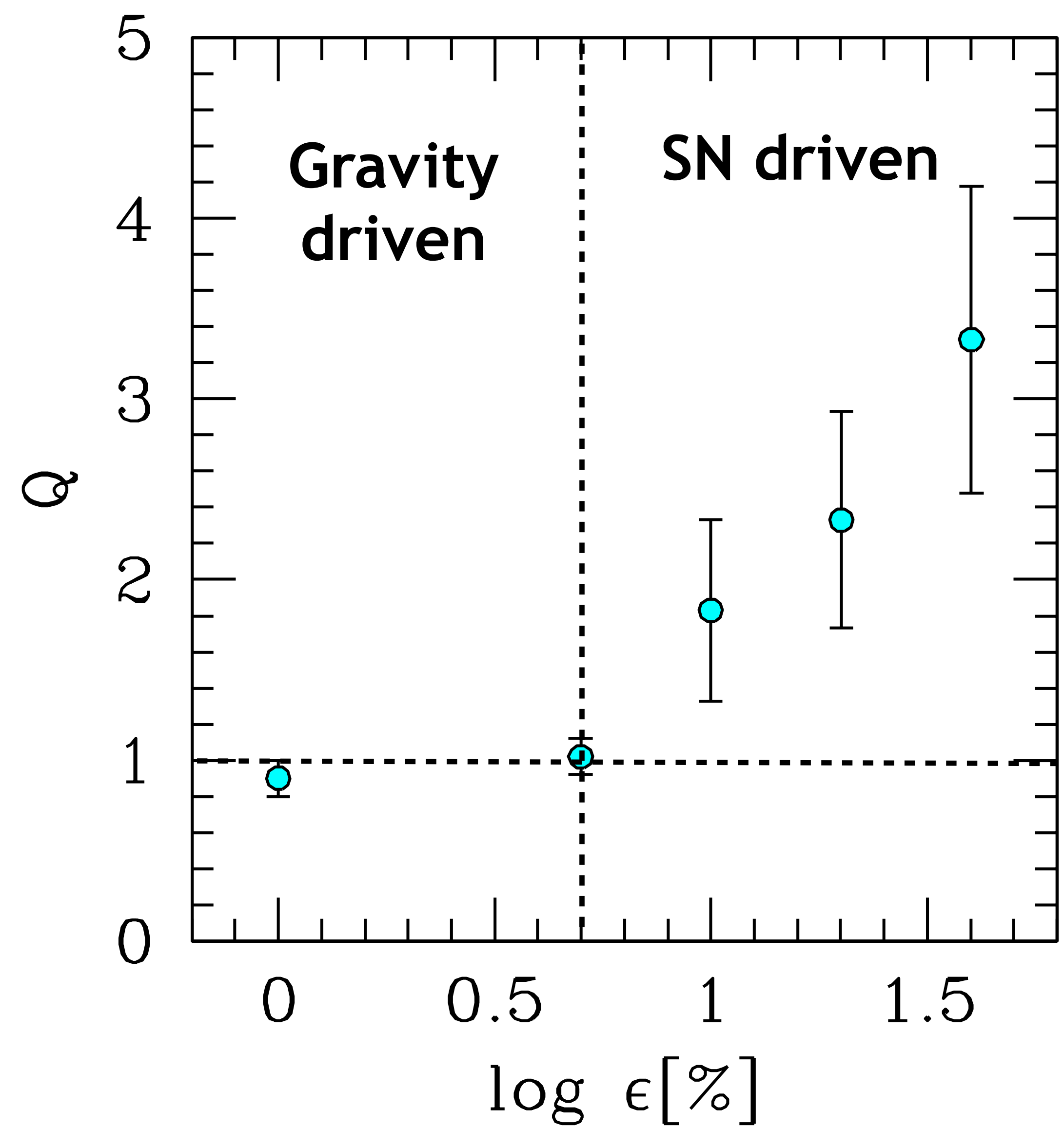


2. *Stellar feedback disperses clouds and drives irregular gas motions in the molecular web.*



Gas velocity dispersion



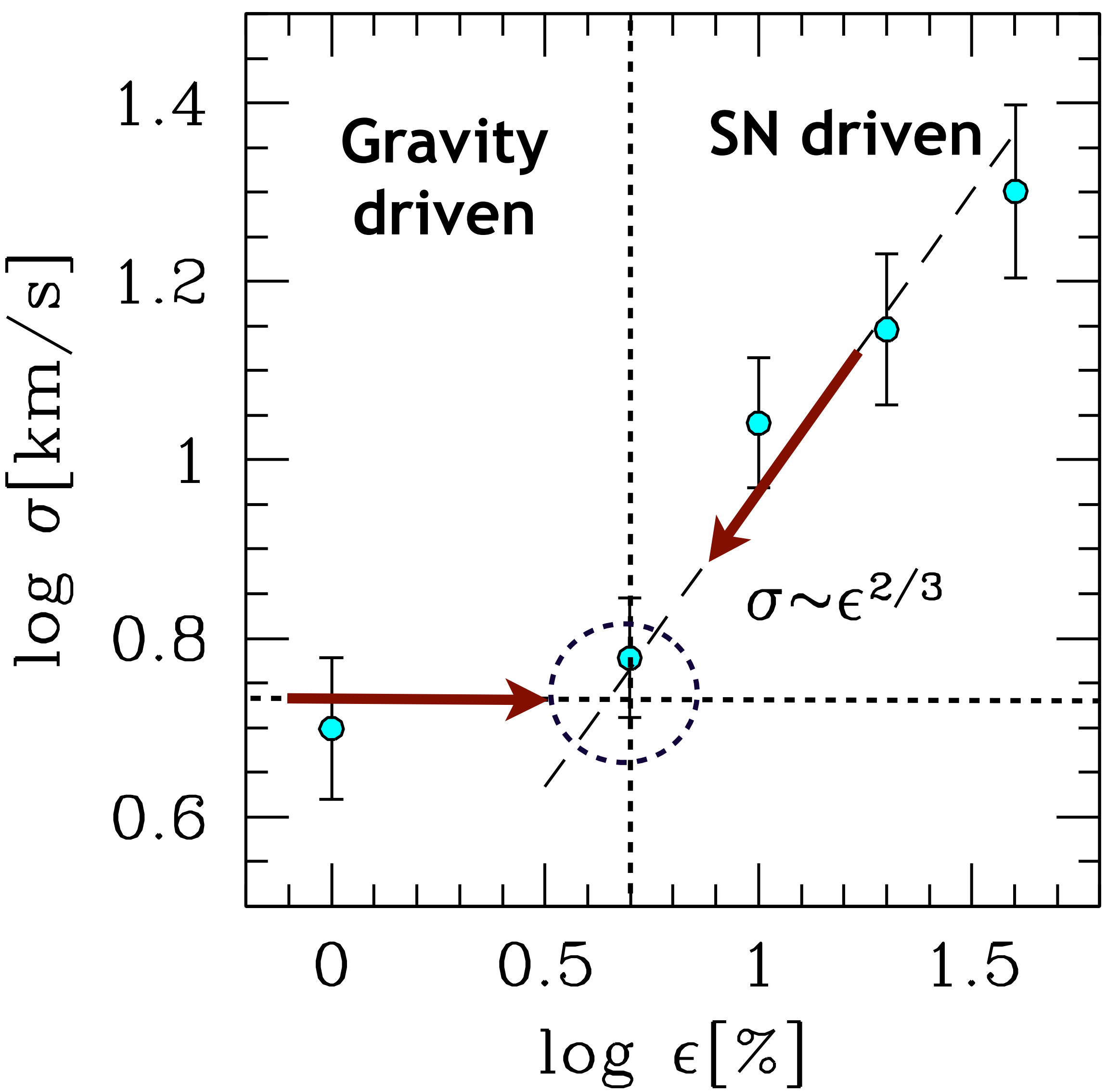


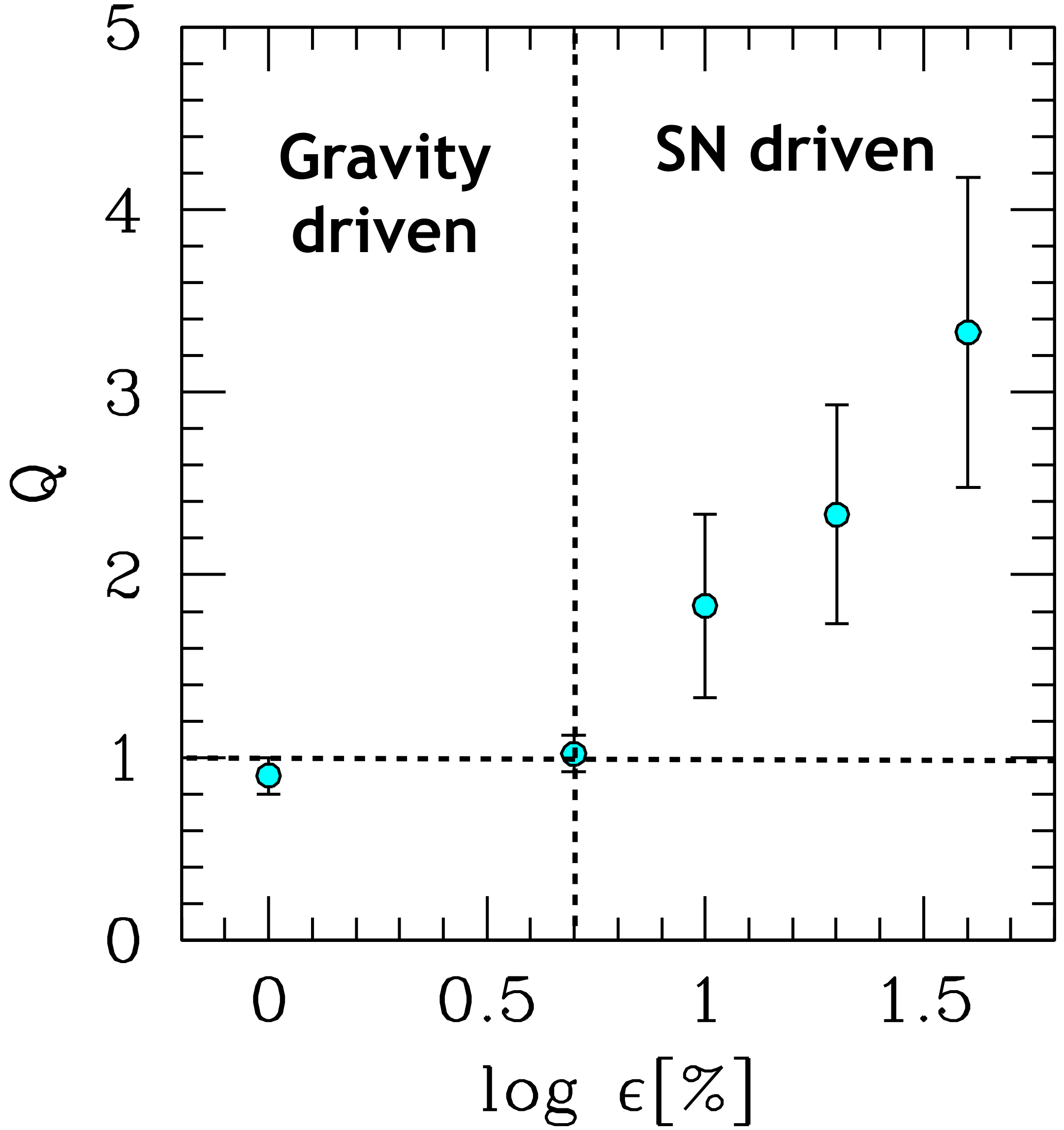
Summary

- The **molecular web** is regulated by **gravitational instabilities** and **stellar feedback.**
- The **star formation timescale** is set by the timescale of global **disk instabilities** and the **efficiency** of star formation.
- Molecular clouds are **transient structures** in the **molecular web**
    - **Stellar feedback** disrupts bound cloud regions and drives **turbulence** in the molecular web
    - **Cloud-cloud collisions** drive internal cloud turbulence, **stabilising** clouds against gravitational collapse
- In the **gravity-driven mode** turbulence is regulated by **Q≈1** leading to **massive**, **rotating cloud complexes** and **massive star clusters**
- In the **feedback-driven mode** turbulence is regulated by **stellar feedback** leading to **Q>1** and a **power-spectrum** of cloud masses, with highly turbulent clouds and **negligible rotation**.

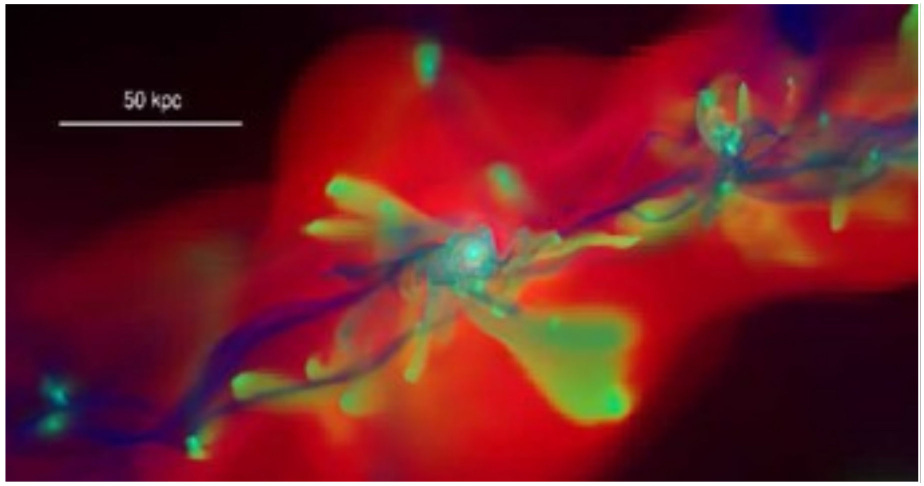
Galaxies might prefer to live in the transition region from gravity-driven to stellar feedback driven turbulence → star formation efficiency

What determines the star formation efficiency?





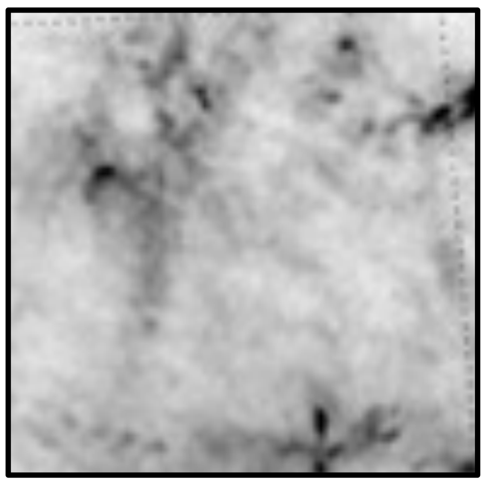
Self-regulated star formation



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

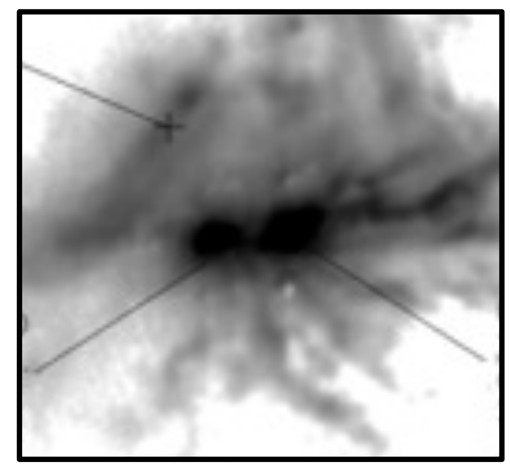
$\dot{M}_{acc}$

98%



$$0.98 \frac{M_{dense,H_2}}{\tau_{ff}}$$

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

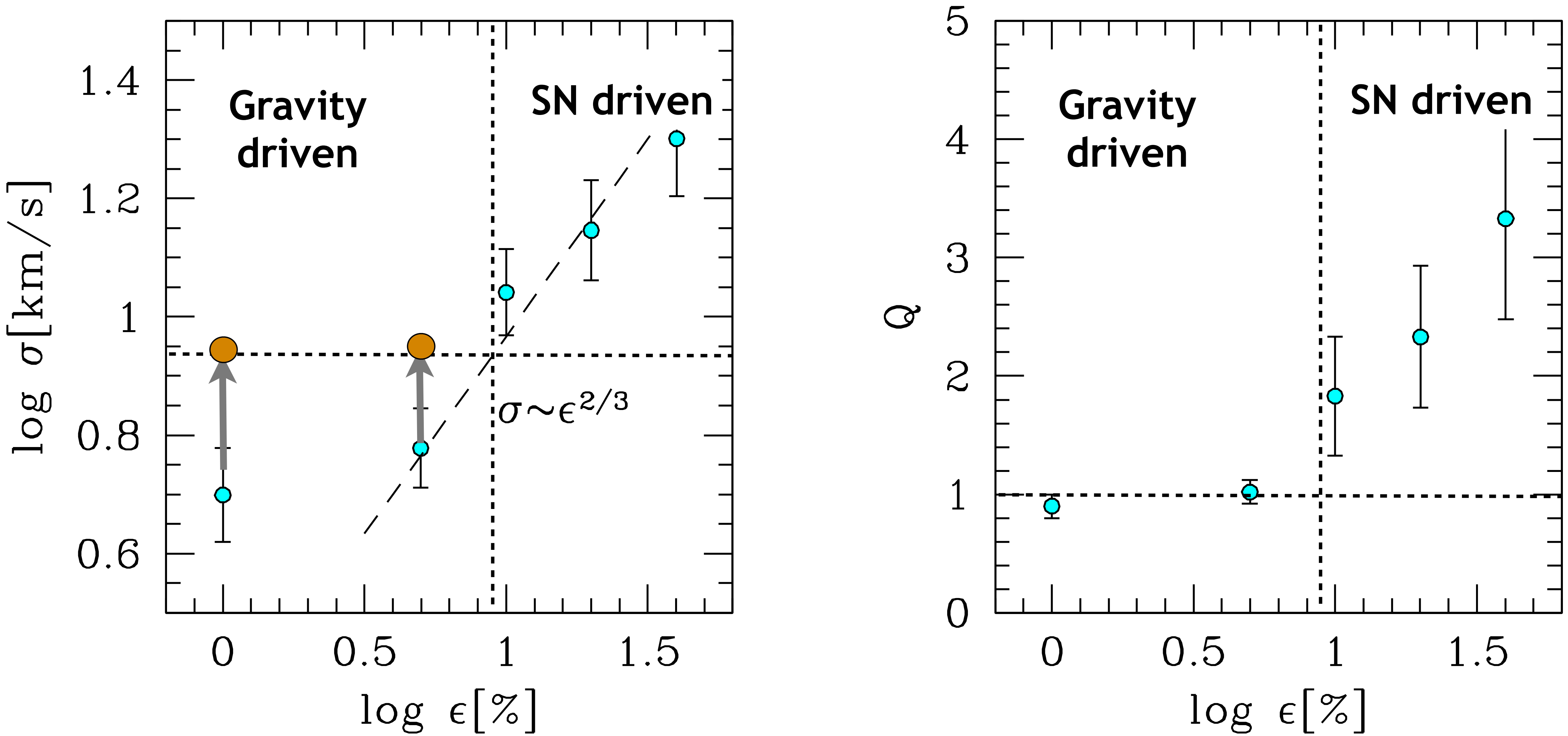


2%

$$0.02 \frac{M_{dense,H_2}}{\tau_{ff}} = \dot{M}_{acc}$$

$$\tau_{sf} = 50 \cdot \tau_{Toomre} = \frac{1}{\varepsilon \cdot \kappa}$$

Higher gas surface densities



The **gravity driven mode** becomes more dominant for higher gas surface densities.

Growth rate of gravitational instabilities:

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

$$Q = 1$$

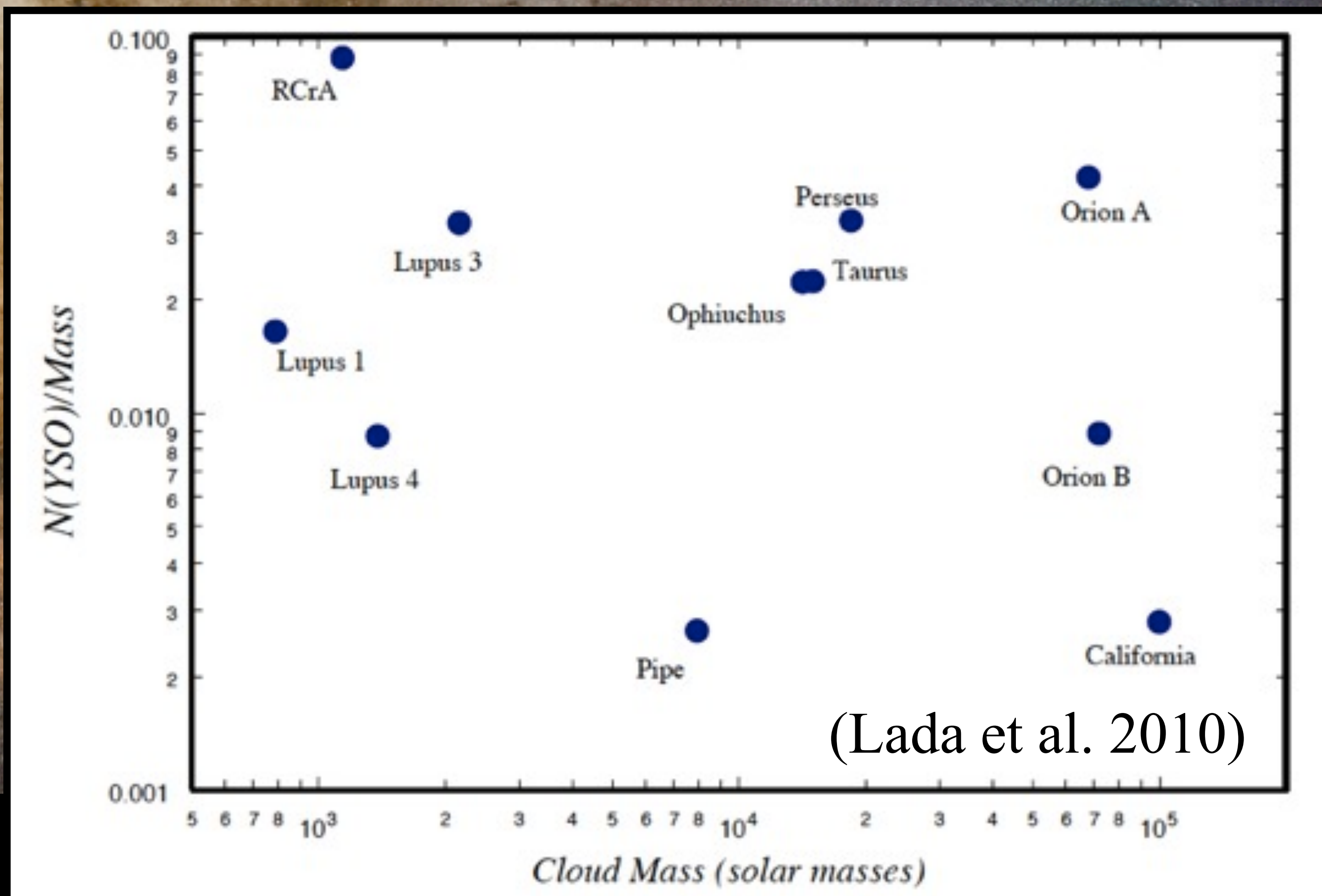
$$\tau_{orb} \sim \frac{R_{vir}}{V_{vir}} \sim H^{-1}$$

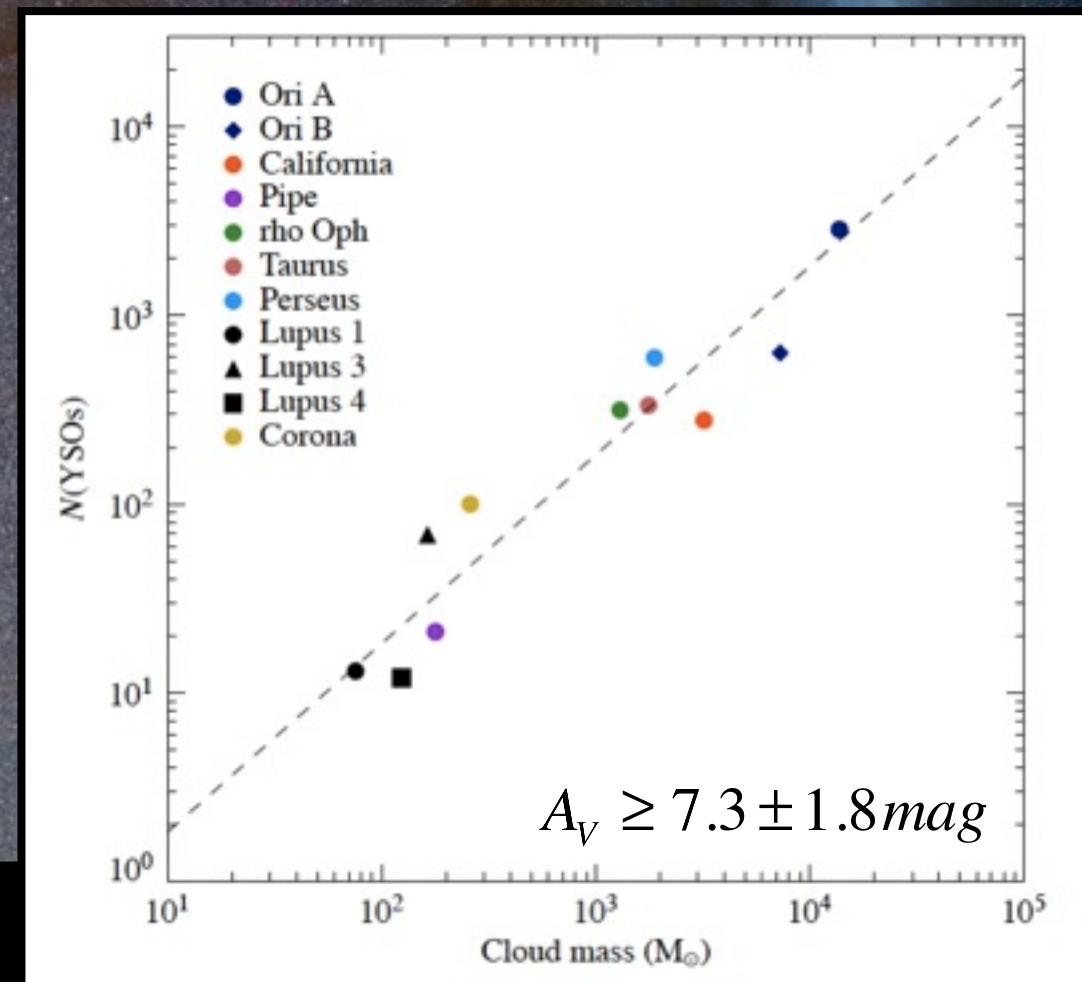
$$SFR \approx \varepsilon \frac{M_{H_2}}{\tau_{Toomre}} \approx \frac{M_{H_2}}{10^{9}\, yrs}$$

$$\varepsilon \approx 0.02$$

What determines the star formation efficiency?

$N(YSOs)_{Oph} = 10 \times N(YSOs)_{Pipe}$

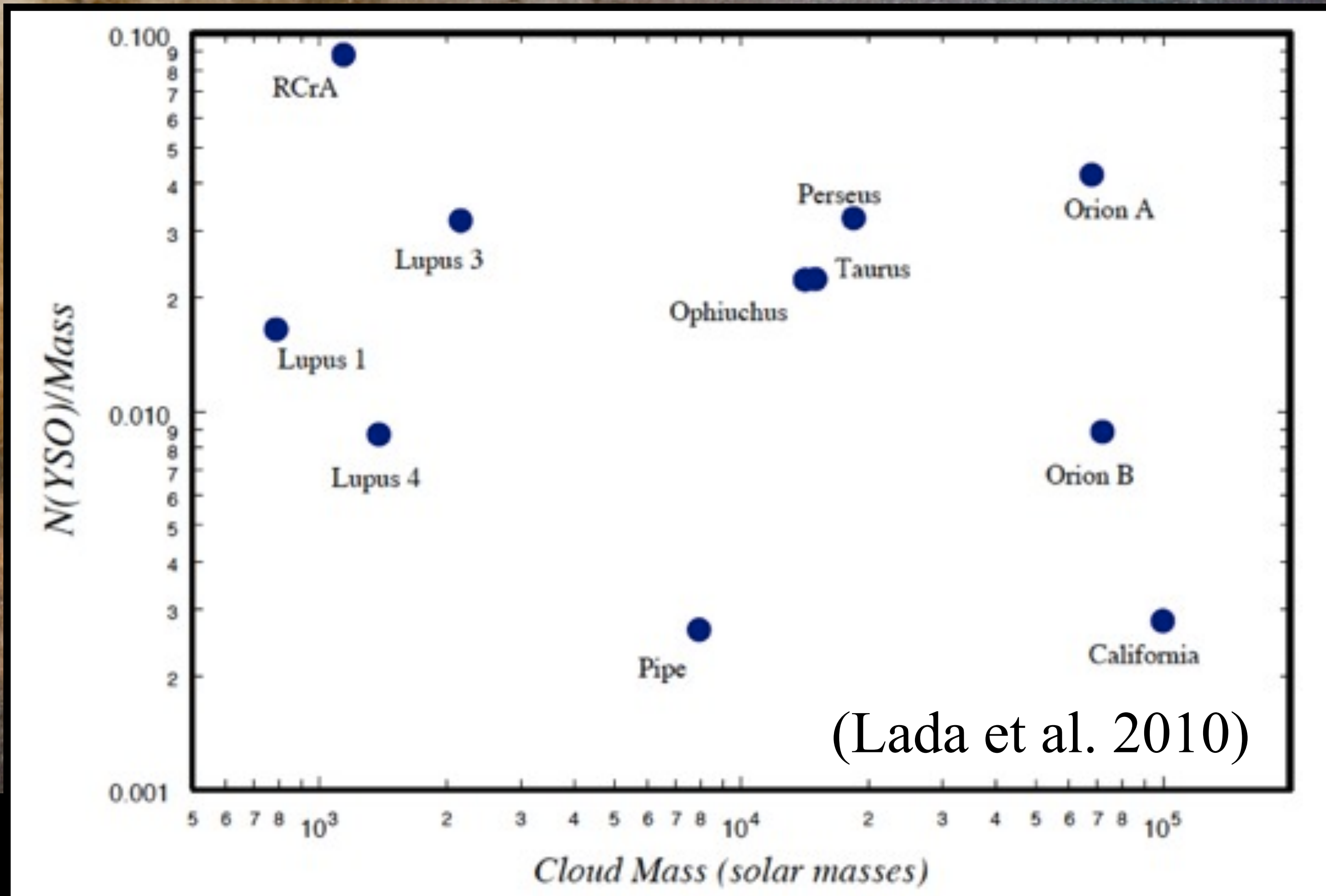


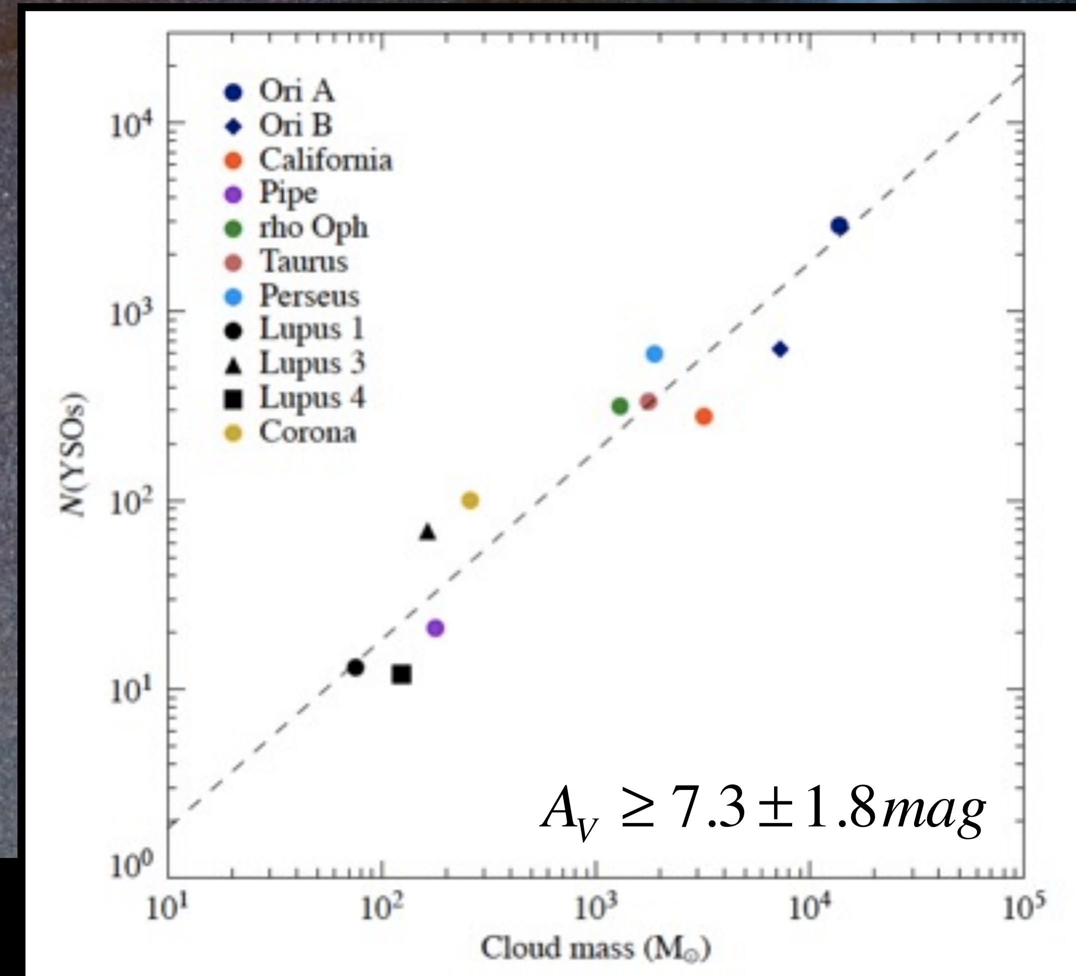


$$n_{A_V = 7.3} \approx 10^4 \, cm^{-3} \rightarrow \tau_{ff} \approx 4 \cdot 10^5 \, yrs$$

$$\longrightarrow \quad SFR \approx 0.02 \frac{M_{dense,H_2}}{\tau_{ff}}$$

$N(YSOs)_{Oph} = 10 \times N(YSOs)_{Pipe}$

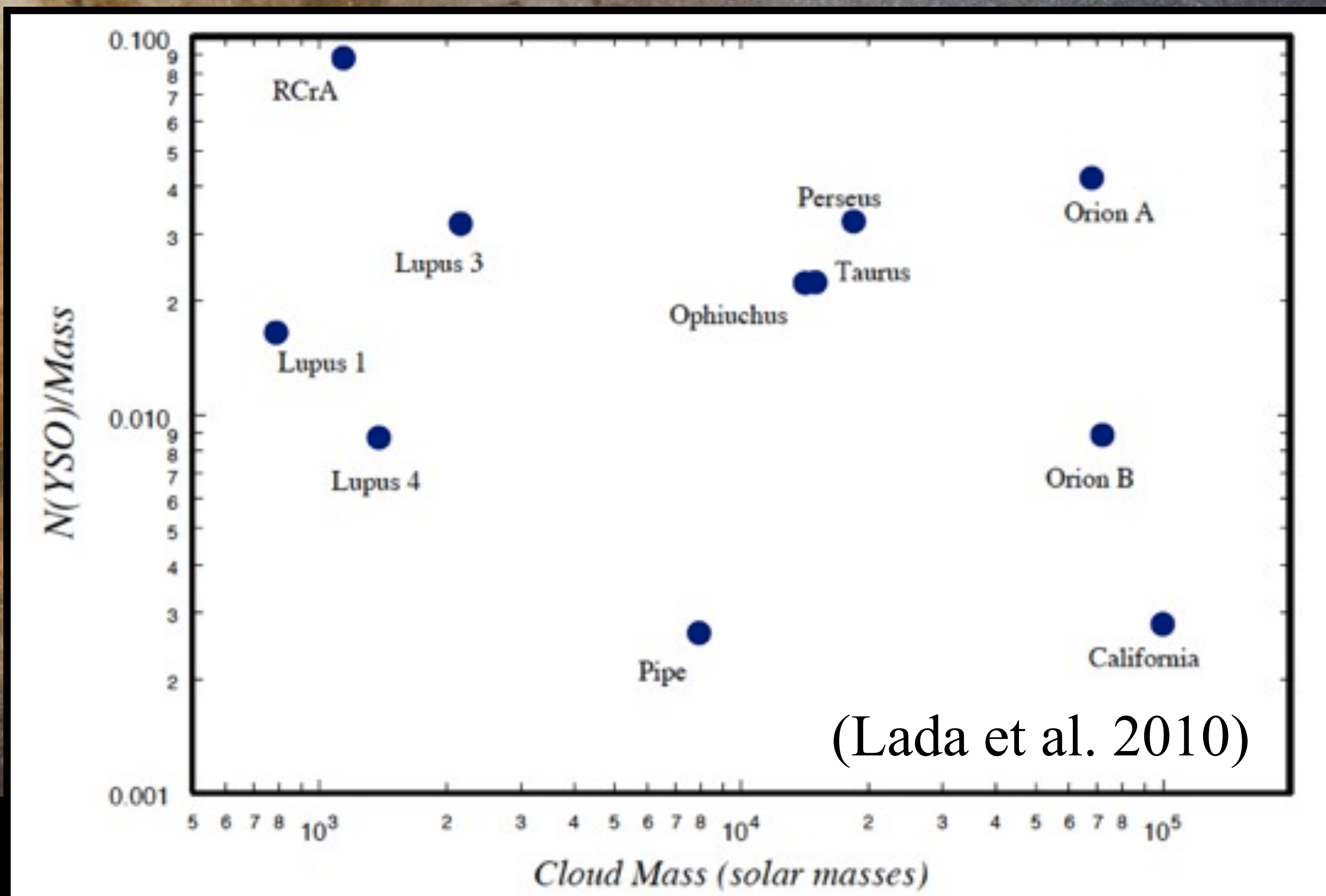


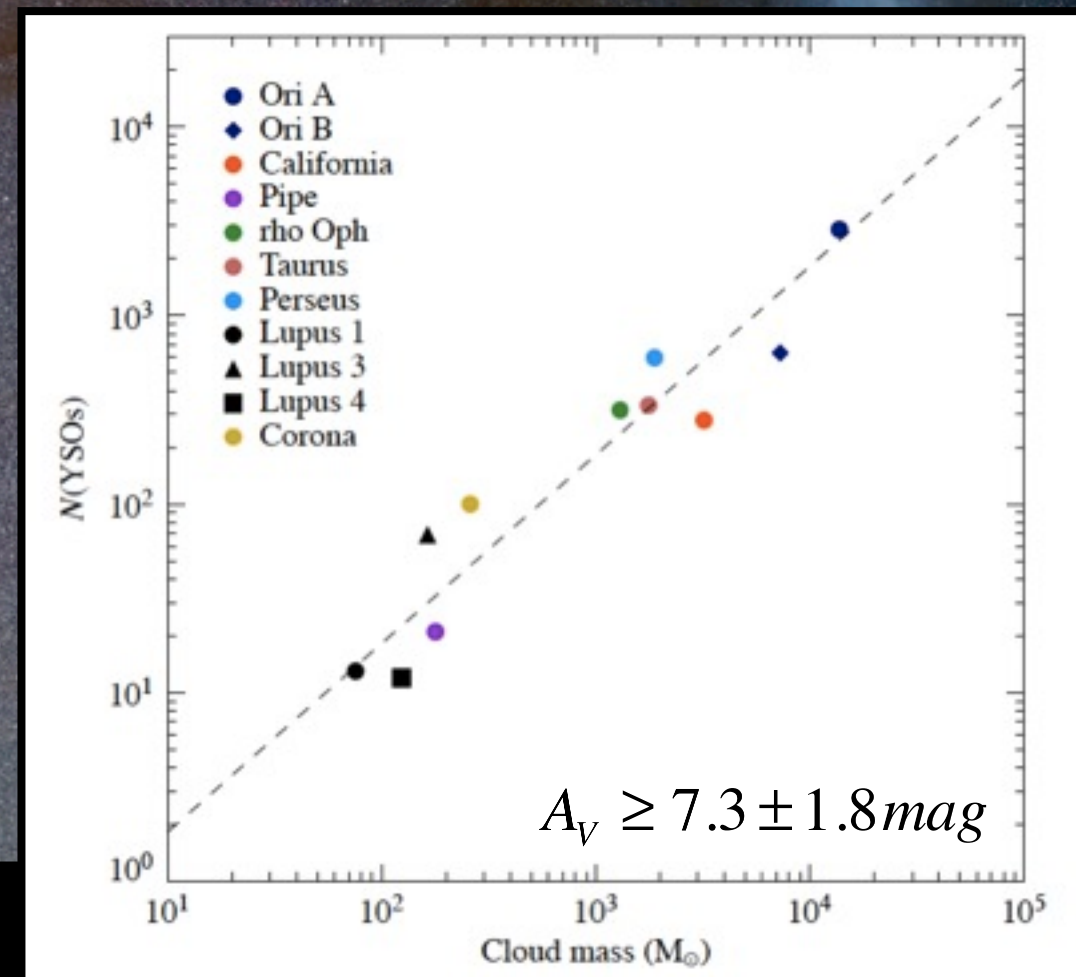


$$n_{A_V=7.3} \approx 10^4\, cm^{-3} \rightarrow \tau_{ff} \approx 4 \cdot 10^5\, yrs$$

$$\longrightarrow \quad SFR \approx 0.02 \frac{M_{dense,H_2}}{\tau_{ff}} \equiv \frac{M_{dense,H_2}}{\tau_{sf,dense}}$$

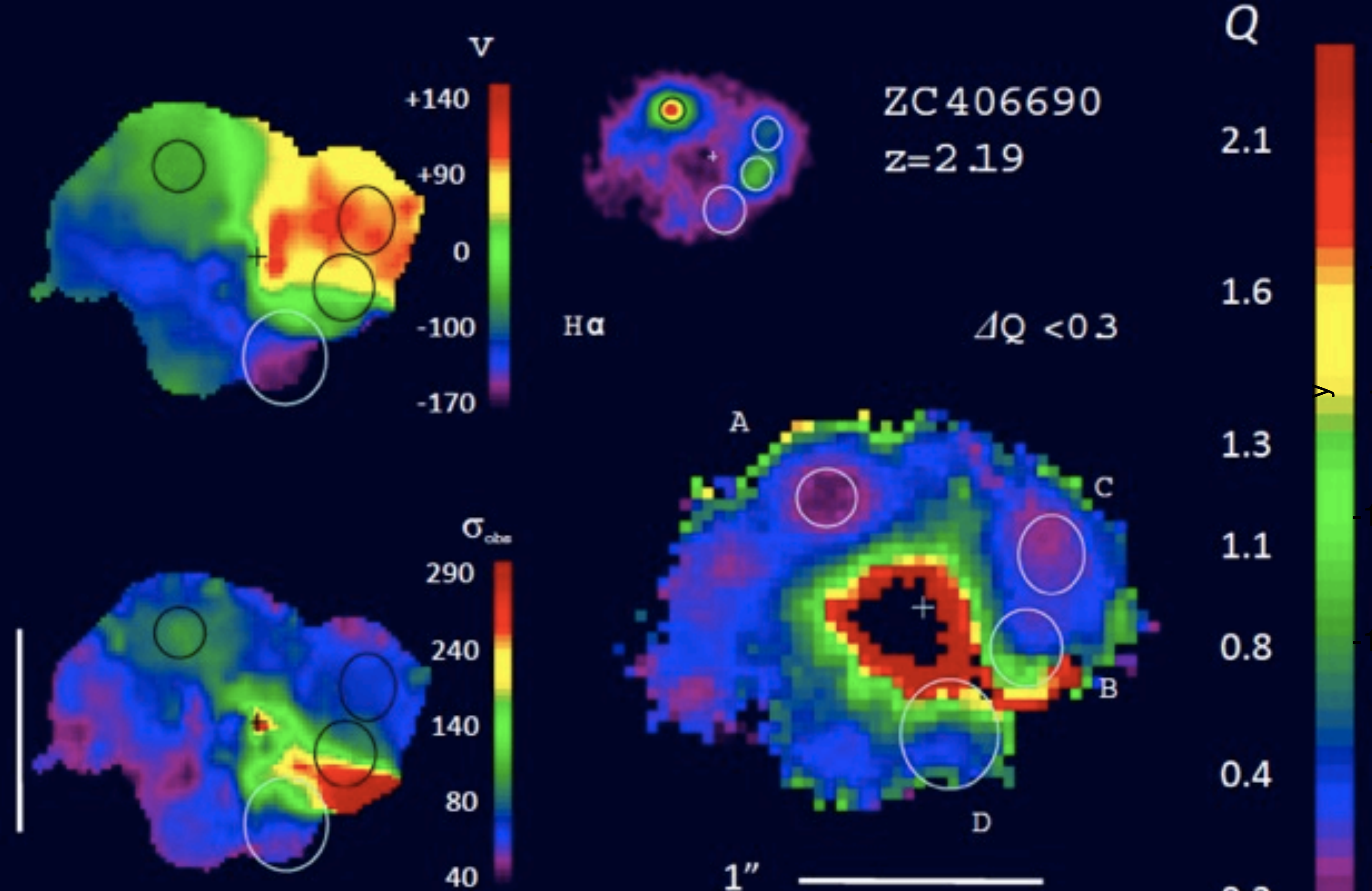
$N(YSOs)_{Oph} = 10 \times N(YSOs)_{Pipe}$



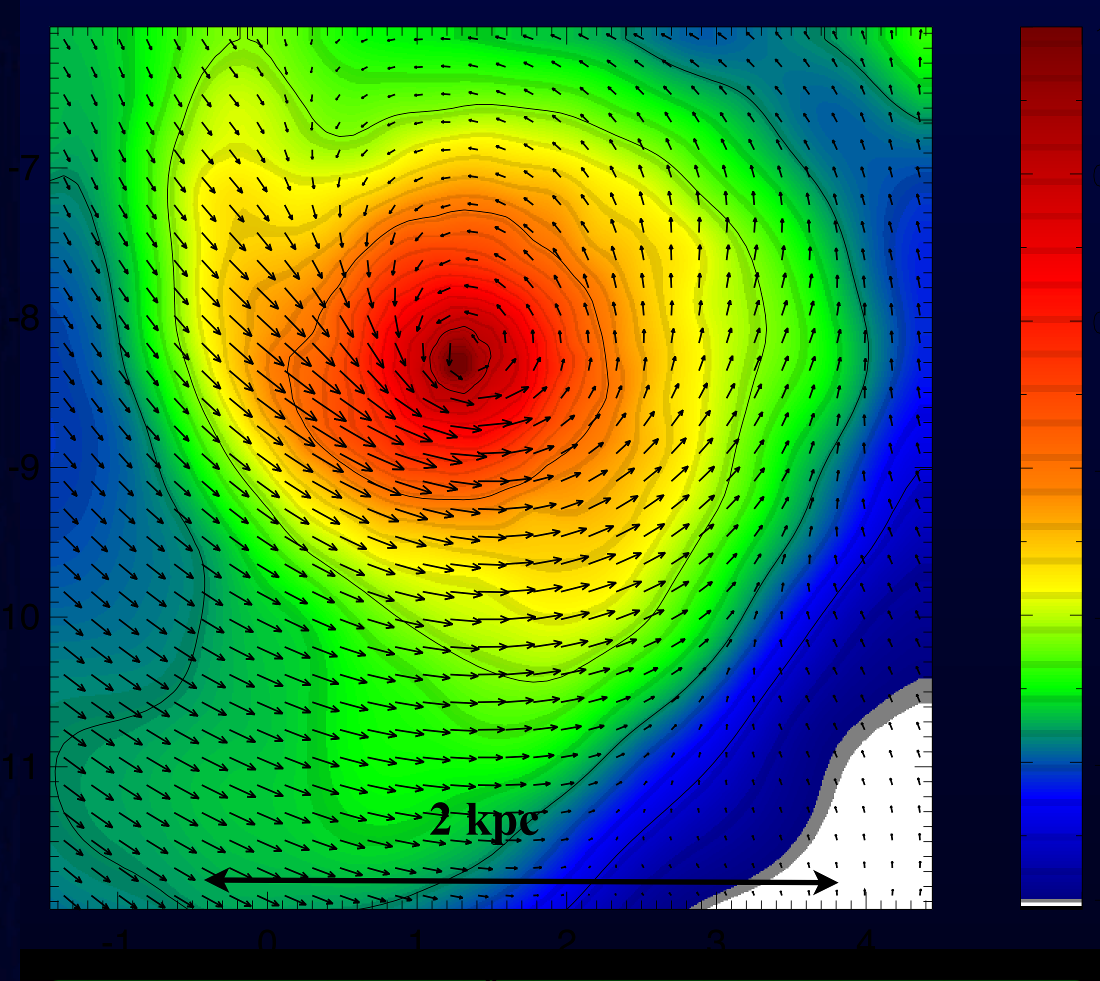


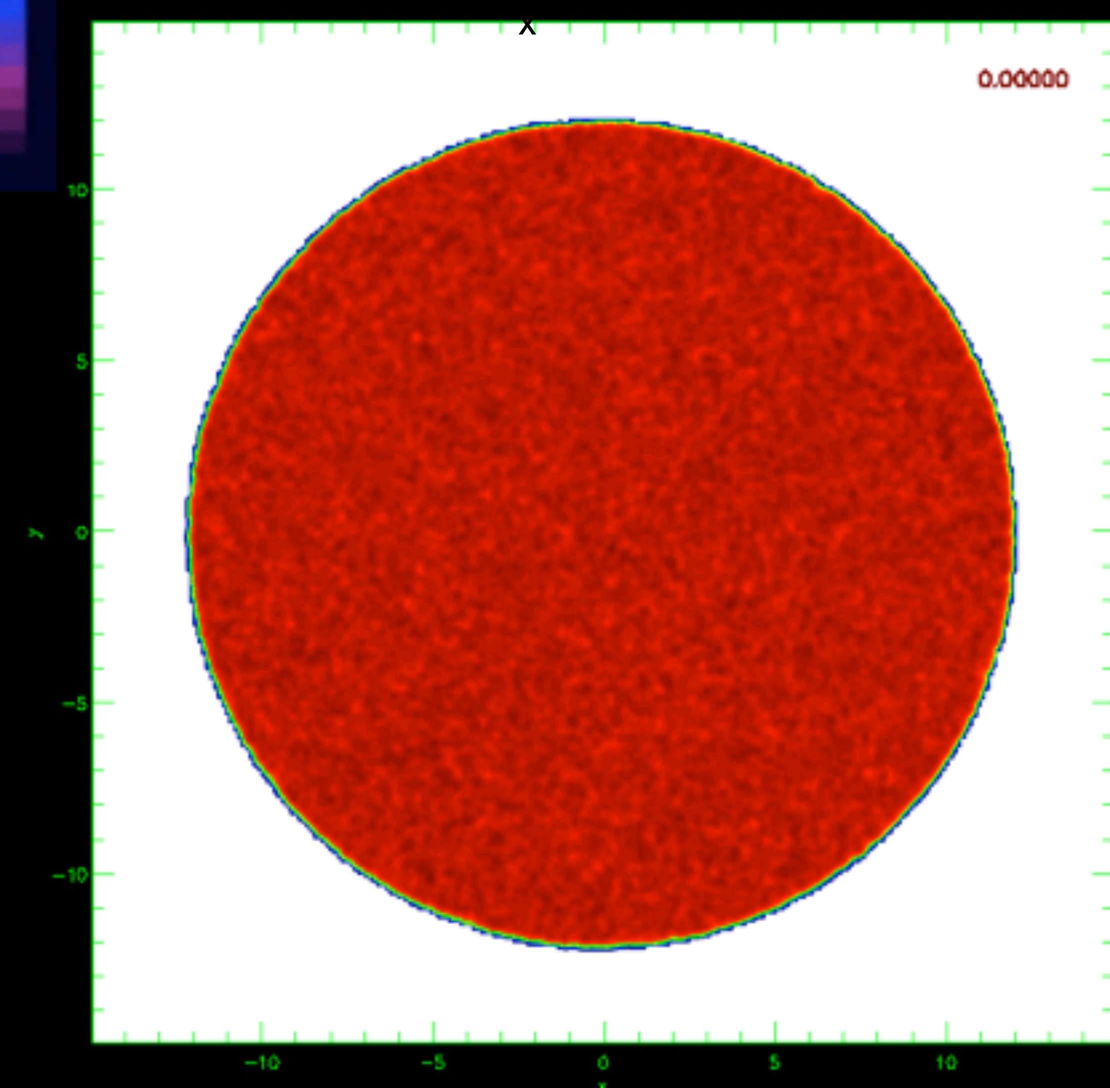
$$n_{A_V=7.3} \approx 10^4\,cm^{-3} \rightarrow \tau_{ff} \approx 4 \cdot 10^5\,yrs$$

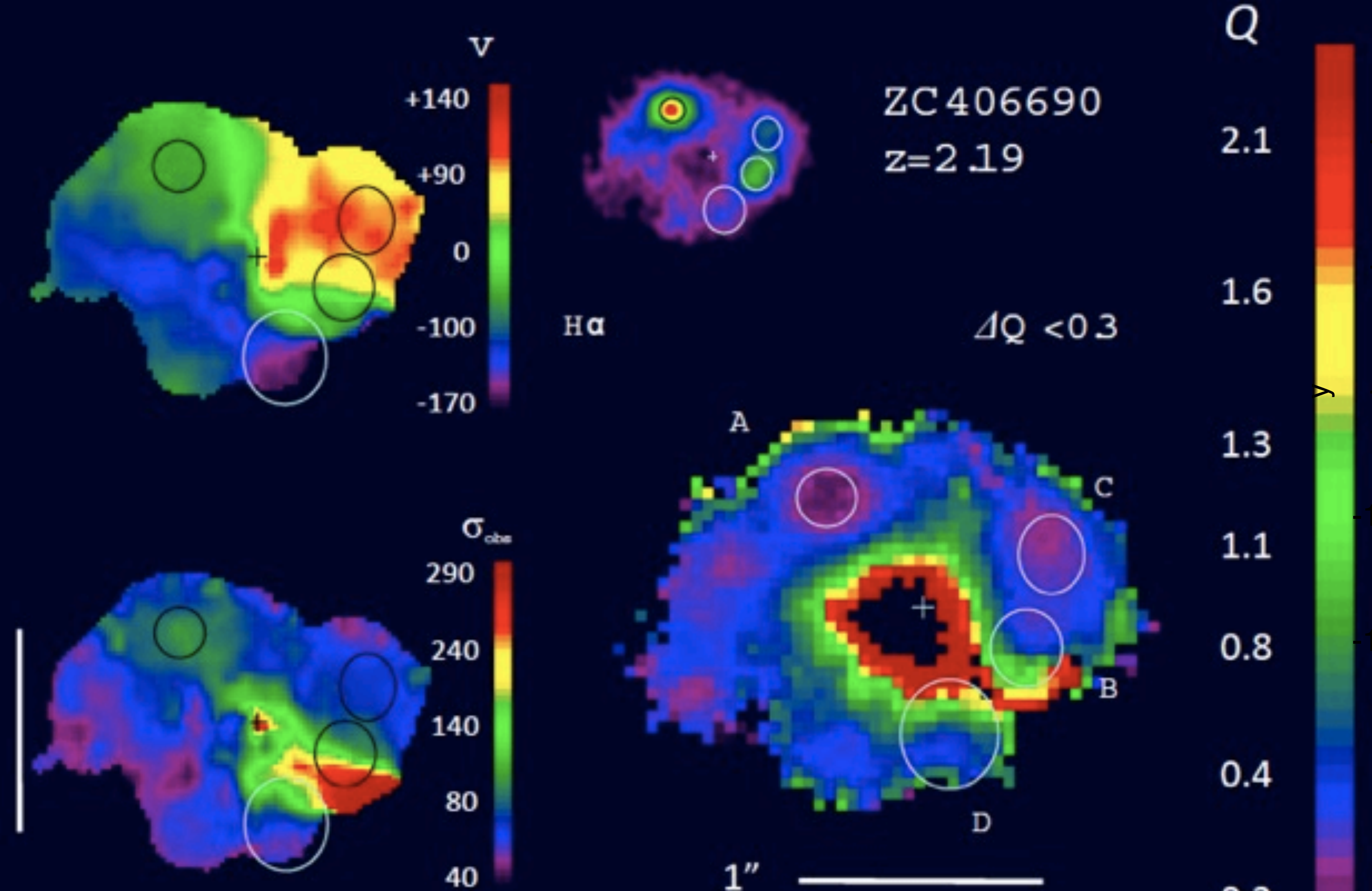
$$\rightarrow \quad SFR \approx 0.02 \frac{M_{dense,H_2}}{\tau_{ff}} \quad \rightarrow \quad \tau_{sf,dense} \approx 2 \cdot 10^7\,yrs$$



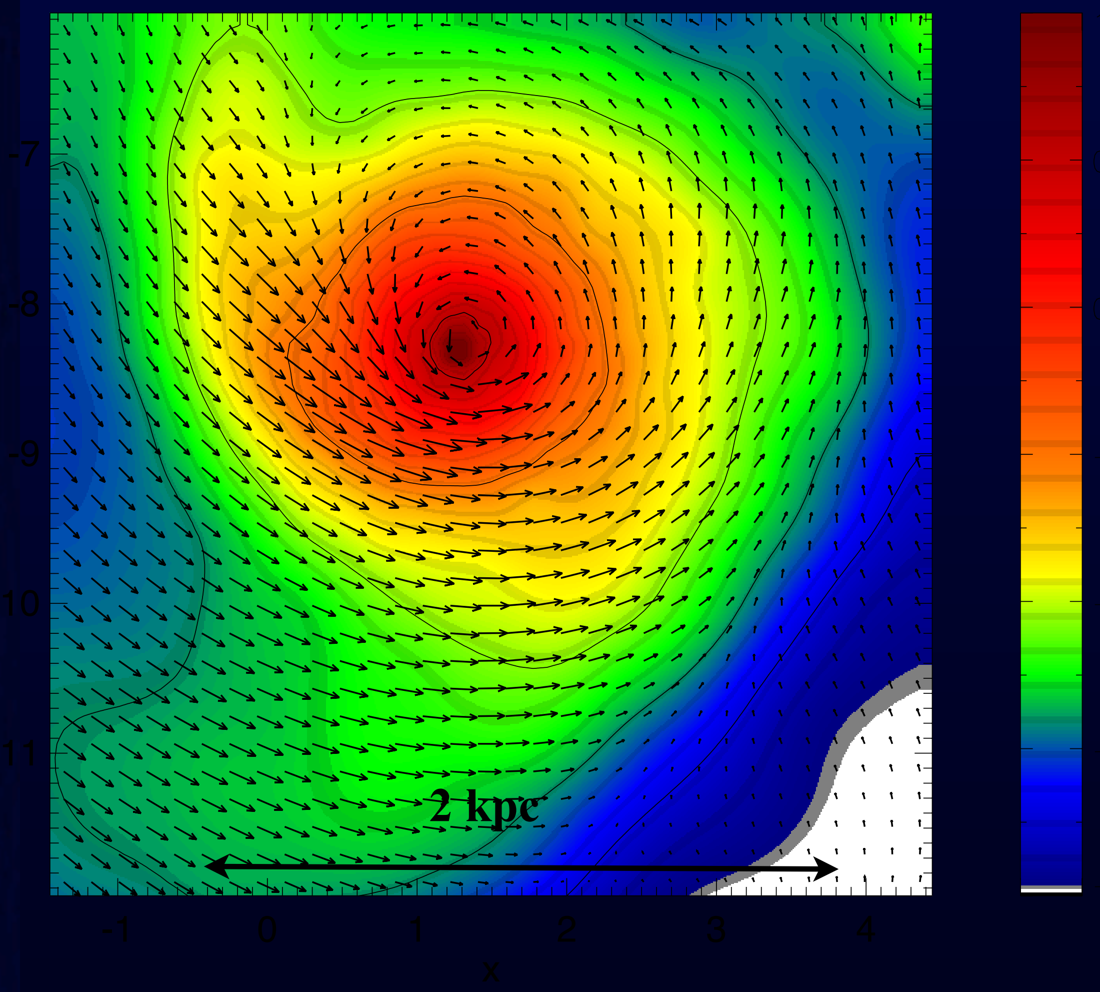
Genzel et al. (2011)

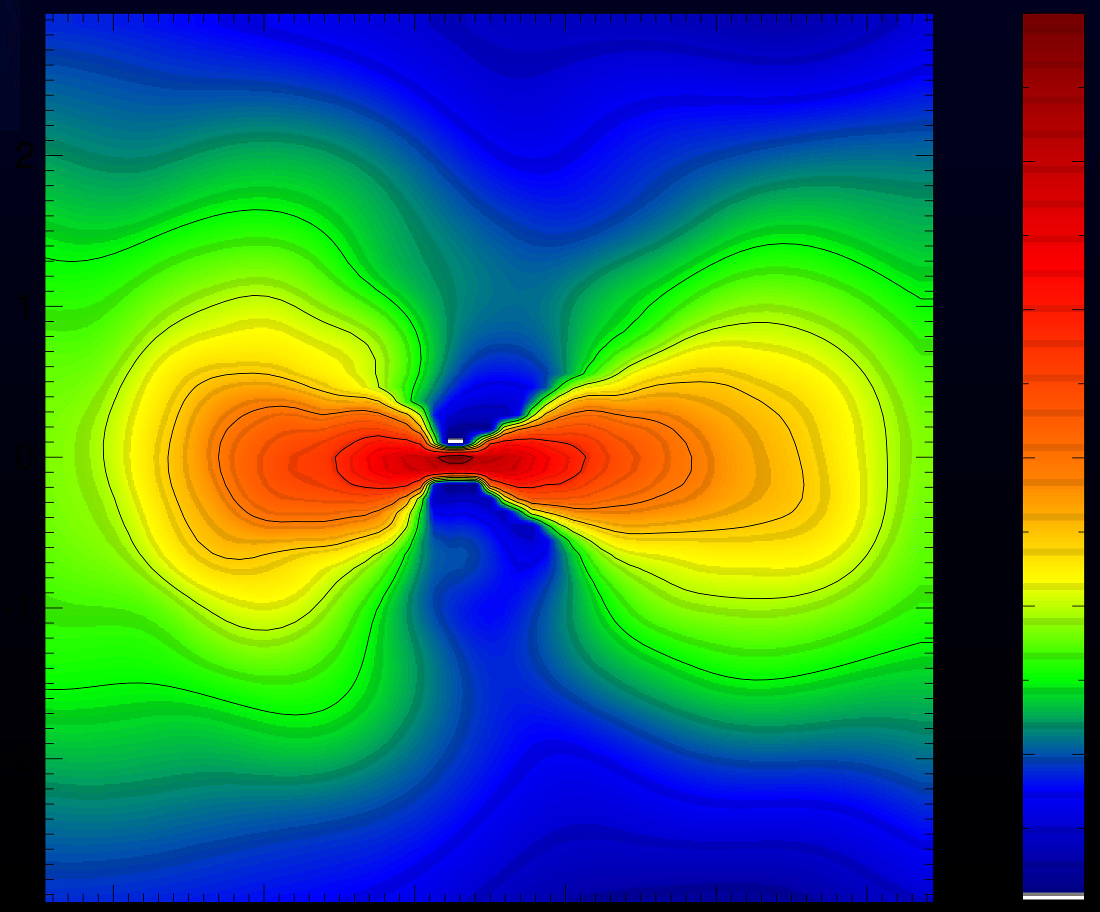






Genzel et al. (2011)



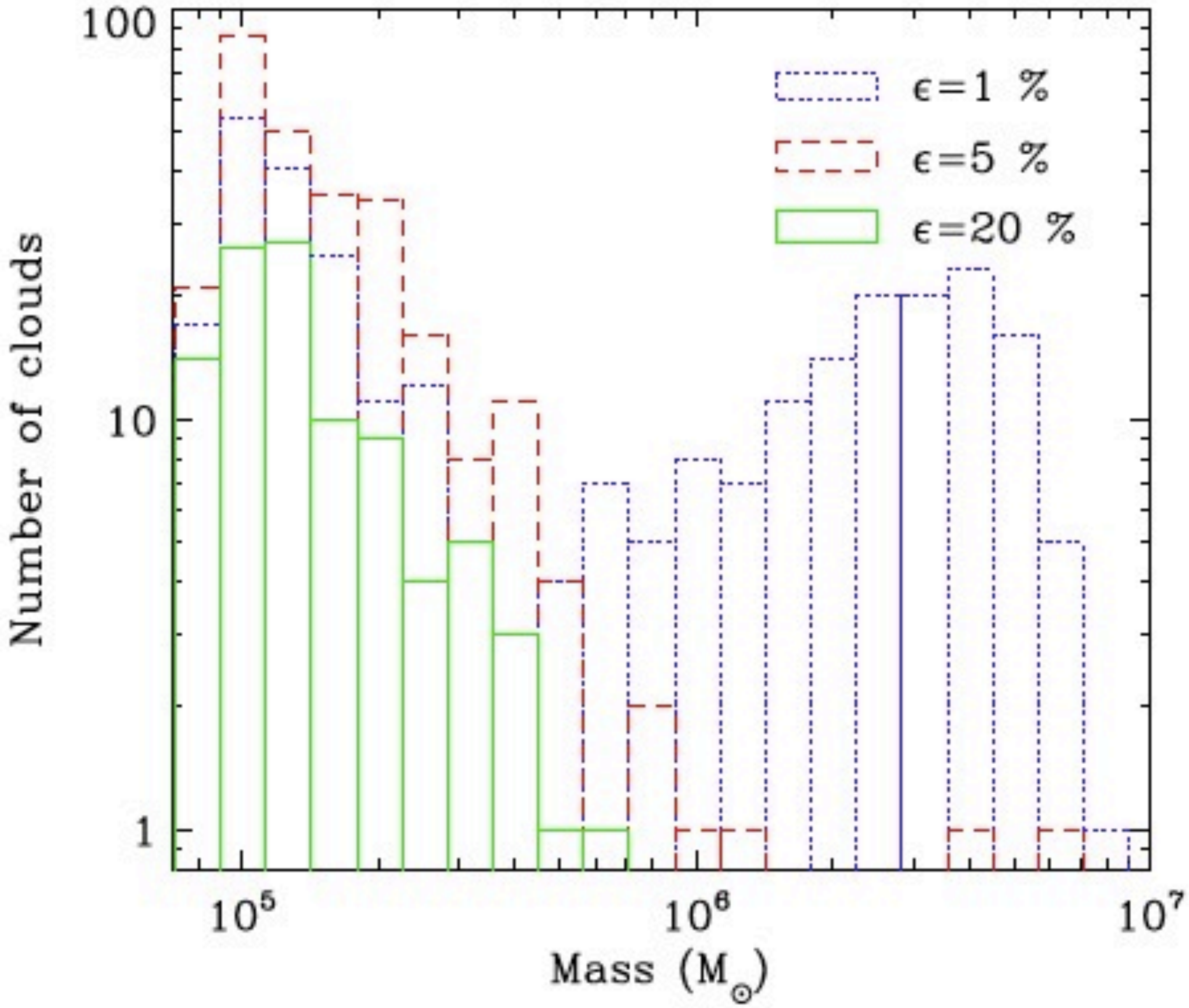


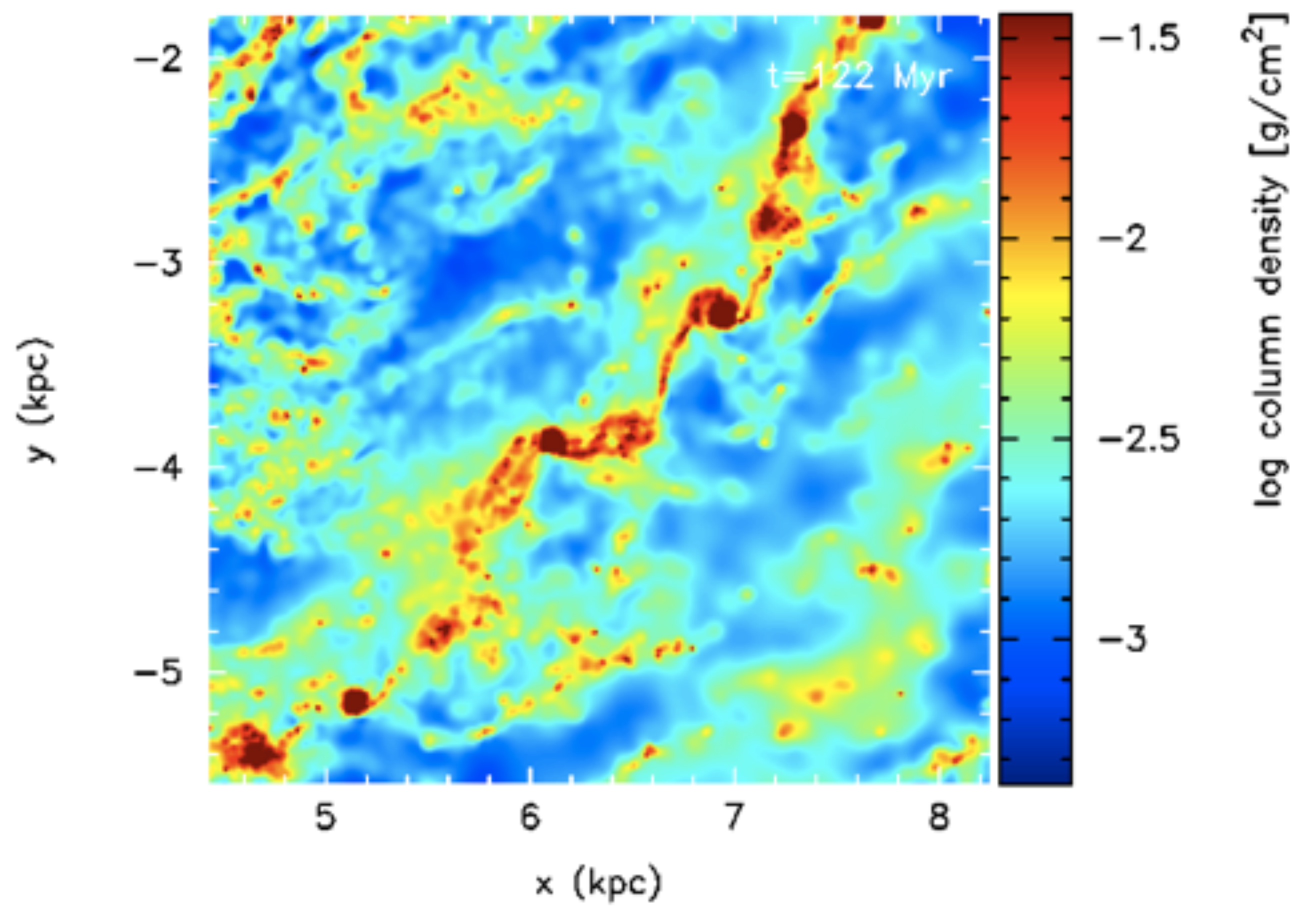
<u>Rotationally supported minidisks</u>

Expected: $v_{rot} \approx 200 km / s$

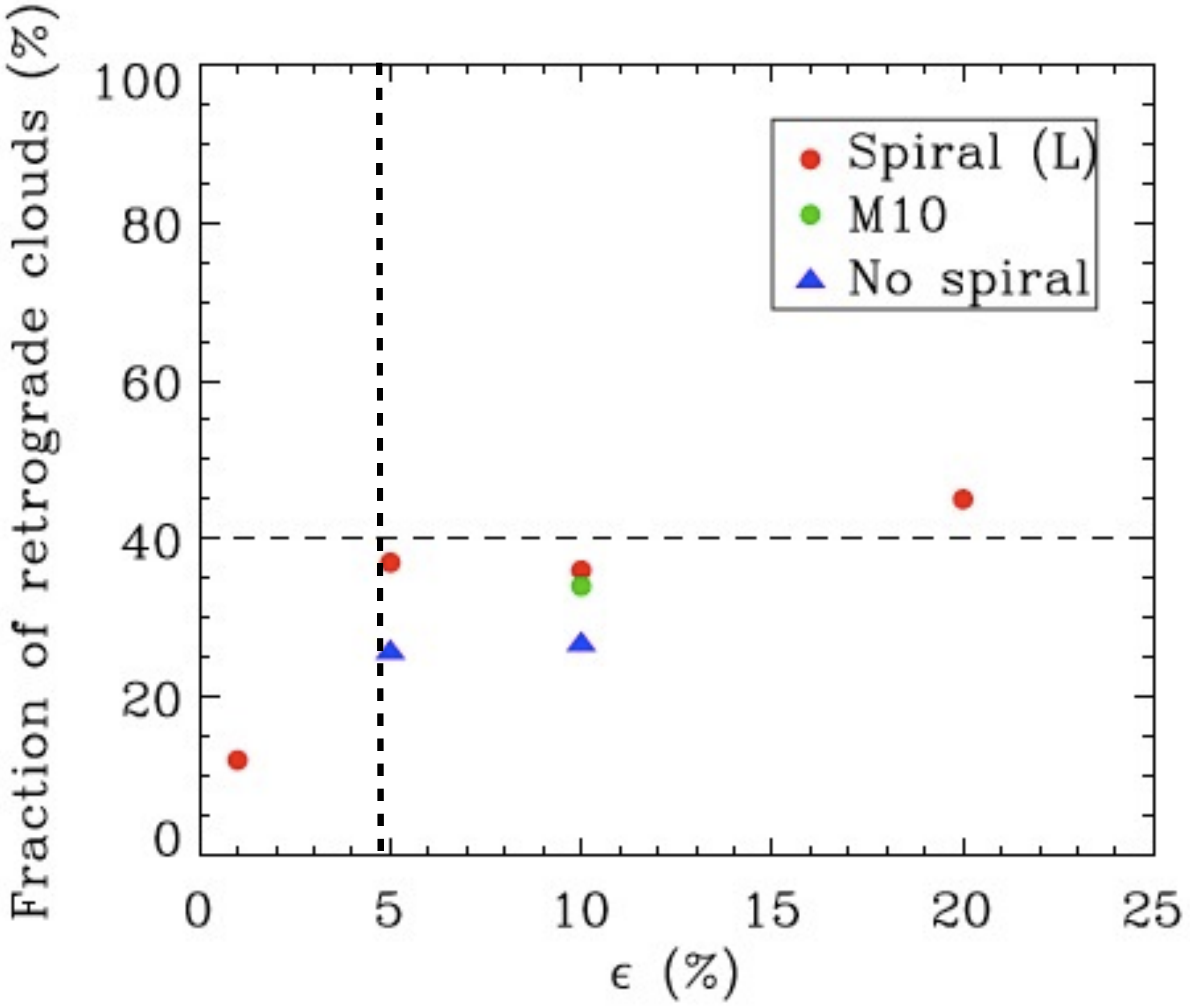
Observed: $v_{rot} \approx 10 - 40 km / s$

Gravity driven mode: formation of giant clumps





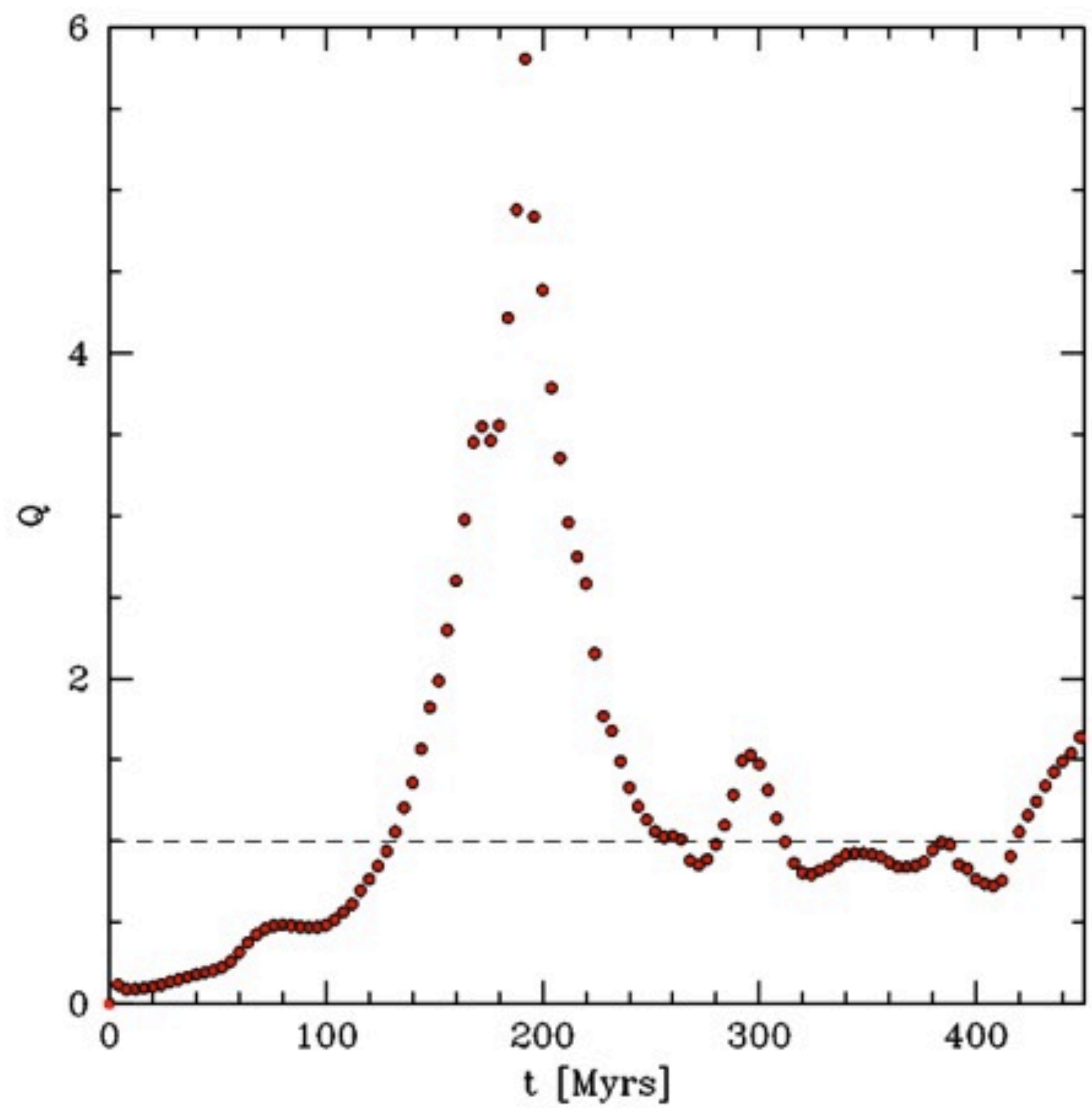
Fraction of retrograde clouds

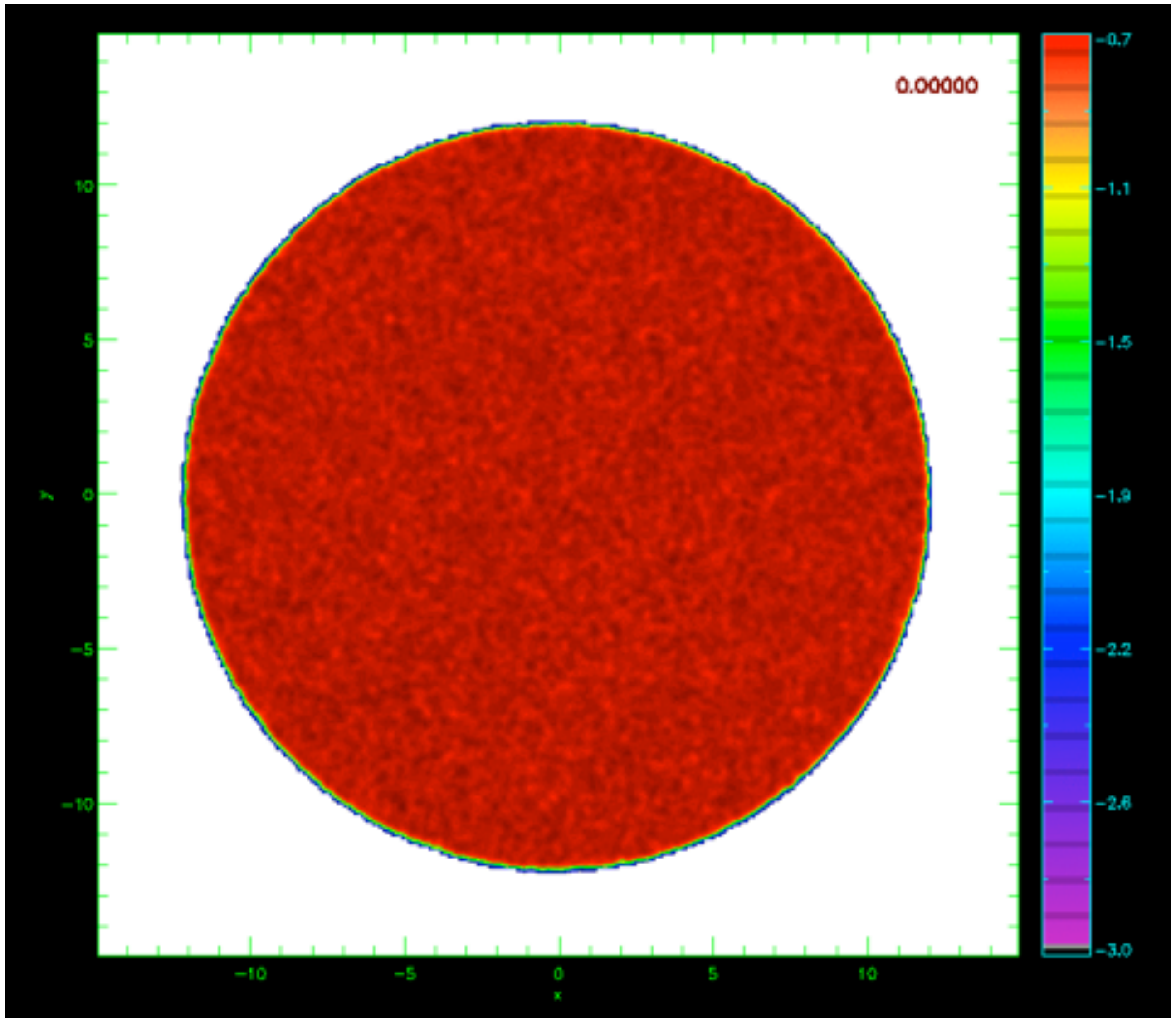


Gravitational disk instabilities

(Toomre 1964; Goldreich & Lynden-Bell 65; Elmegreen 94; Kim & Ostriker 01, 06)

Gaseous disks will **self-regulate** themselves into a state of **marginal stability**
(Dekel et al. 09; Bournaud et al. 09; Krumholz & Burkert 10; Elmegreen & Burkert 10; Genzel et al. 10, Burkert et al. 11; Dobbs et al. 11a,b)





Growth rate of gravitational instabilities:

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

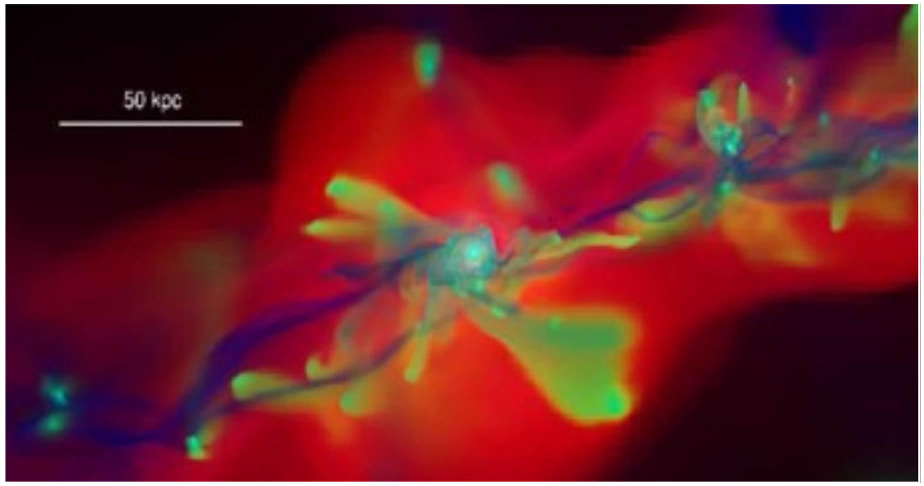
$$Q = 1$$

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

$$\tau_{Toomre} \approx \tau_{sf,dense}$$

$$\frac{M_{diff,H_2}}{\tau_{Toomre}} \approx \frac{M_{dense,H_2}}{\tau_{ff}} \longrightarrow \frac{M_{dense,H_2}}{M_{diff,H_2}} = 0.02$$

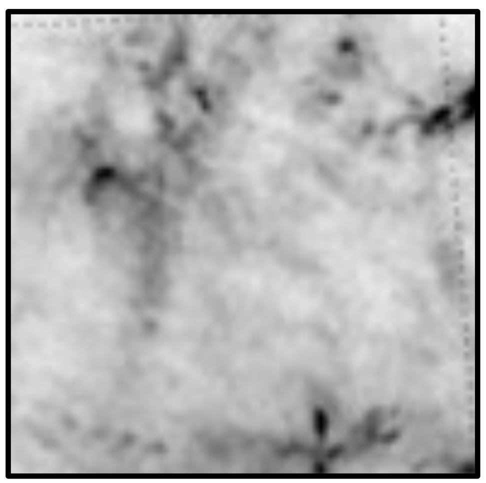
Self-regulated star formation



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

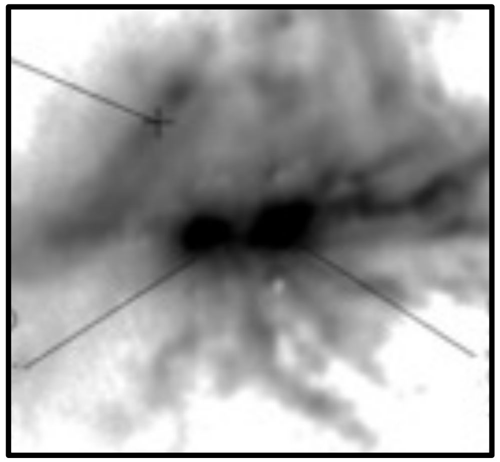
$\dot{M}_{acc}$

98%



$0.98 \frac{M_{dense,H_2}}{\tau_{ff}}$

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

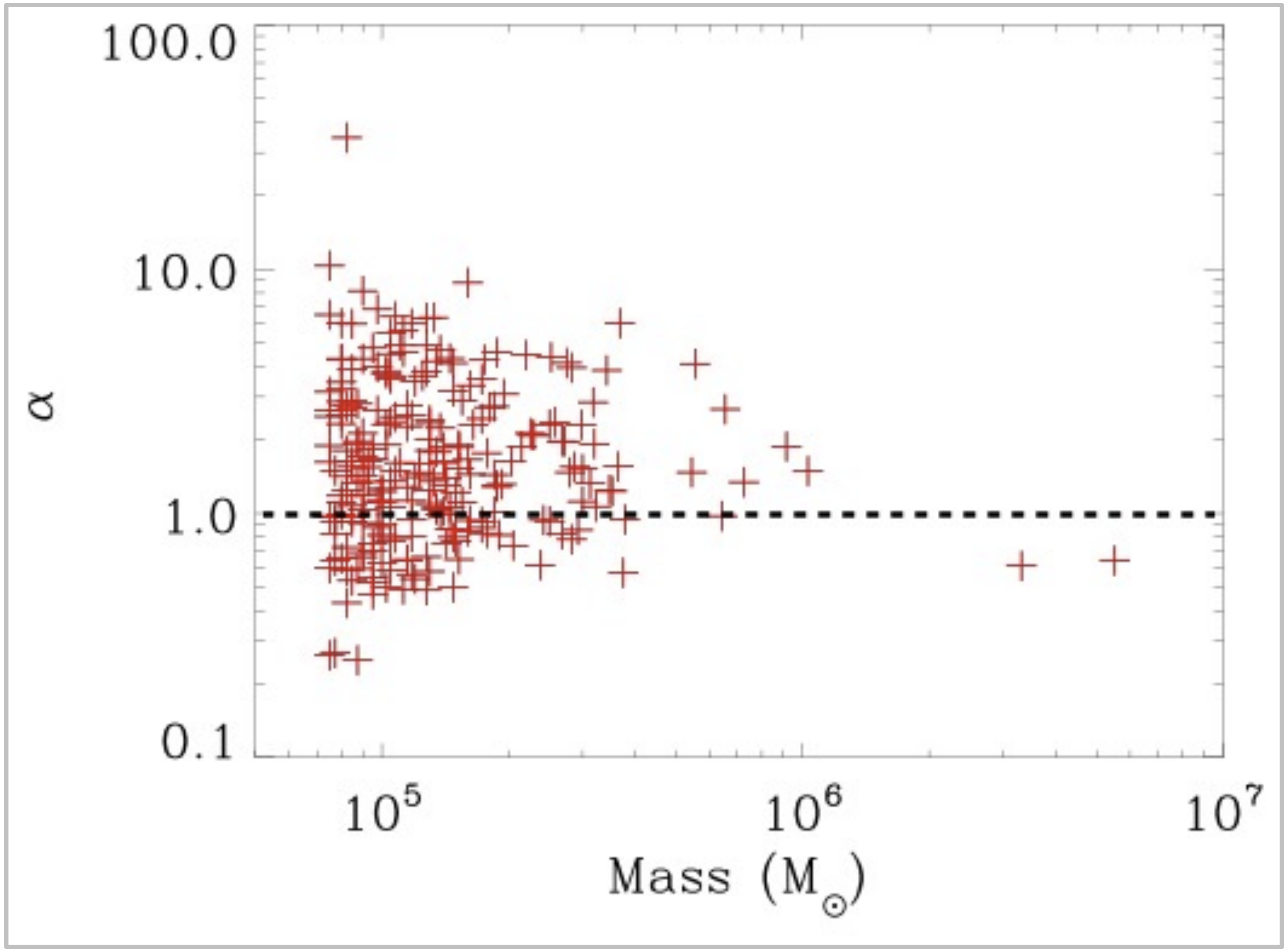


2%

$0.02 \frac{M_{dense,H_2}}{\tau_{ff}} = \dot{M}_{acc}$

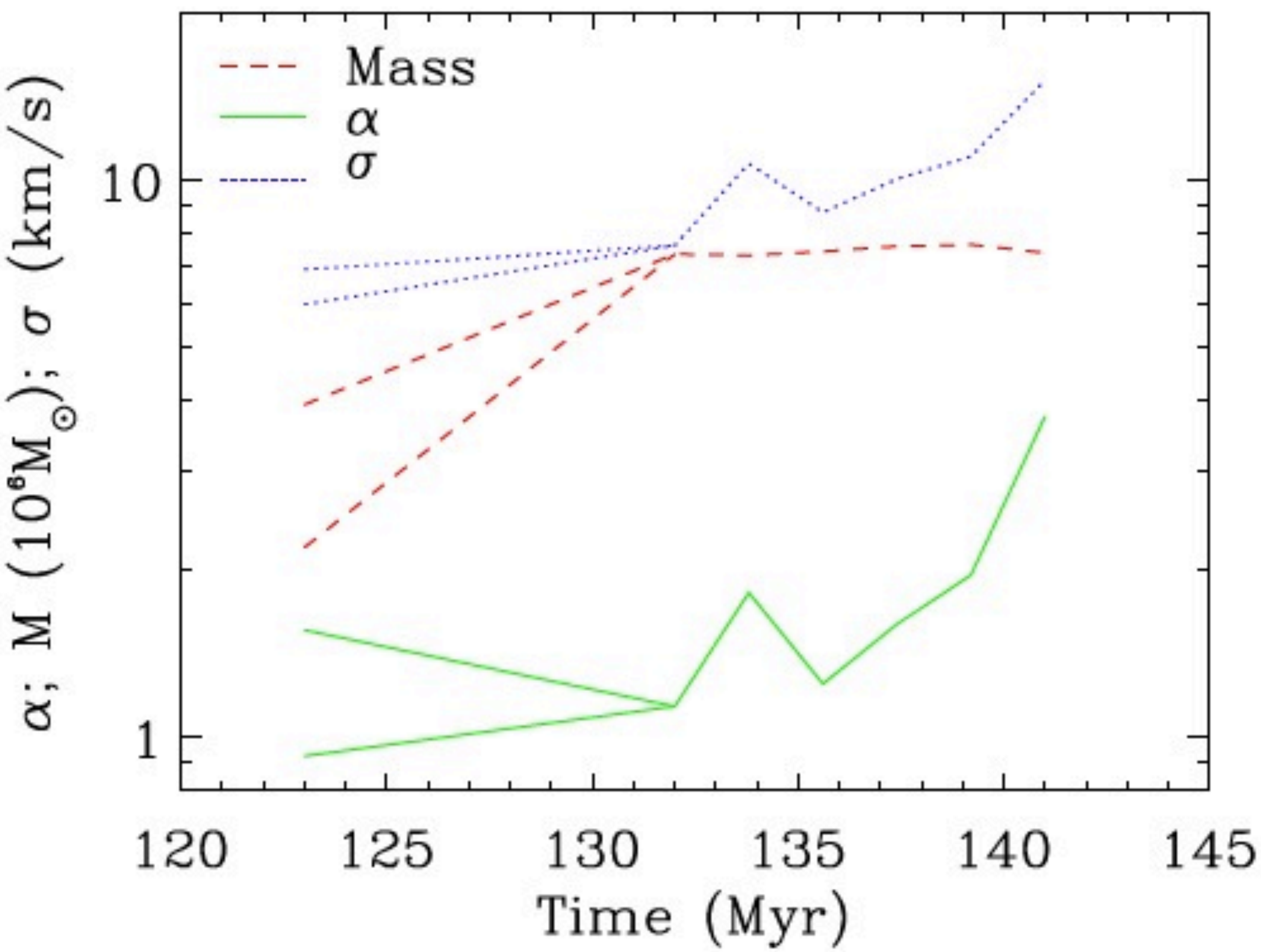
Most clouds are gravitationally unbound!

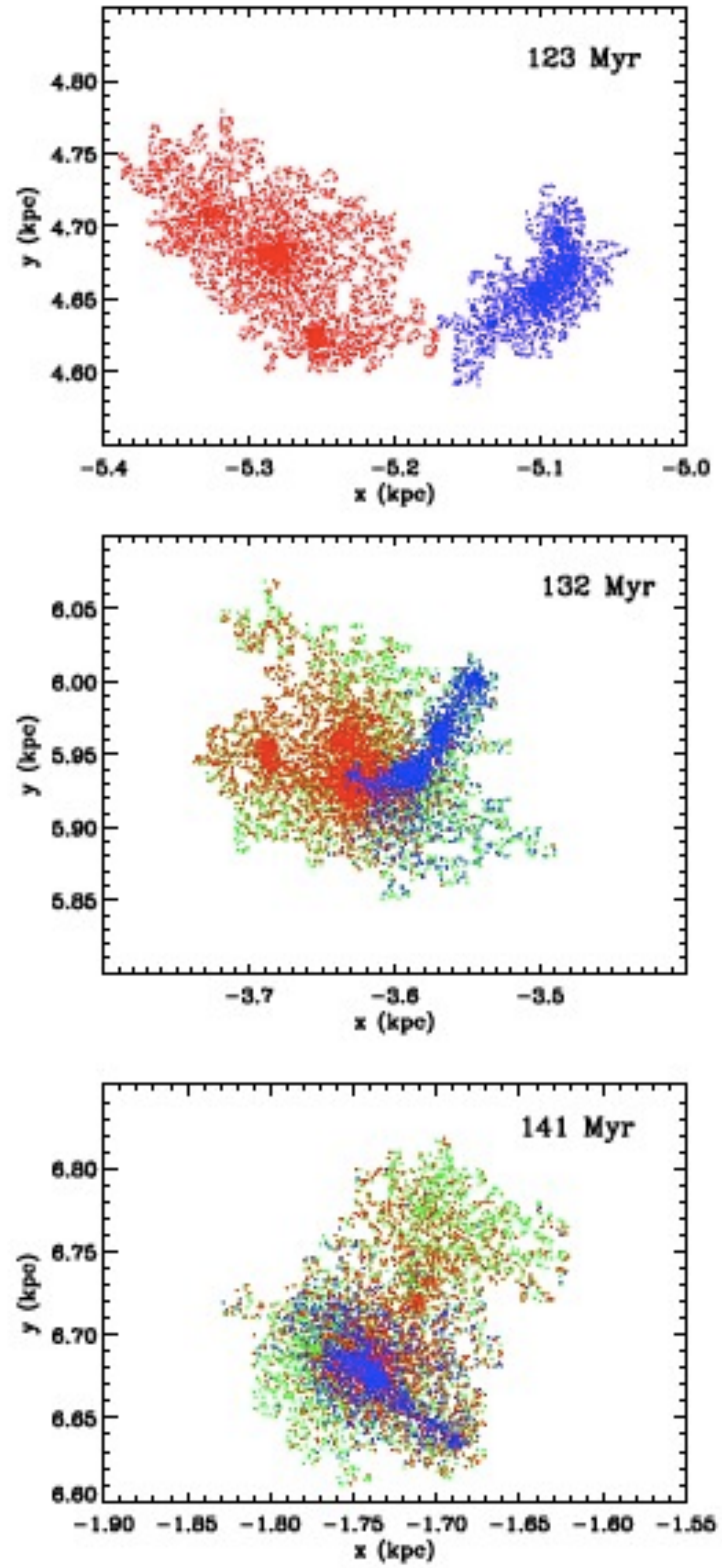
$$\alpha = \frac{5\sigma_v^2 R}{GM}$$



Why are most clouds gravitationally unbound?

1. Collisions drive internal turbulence



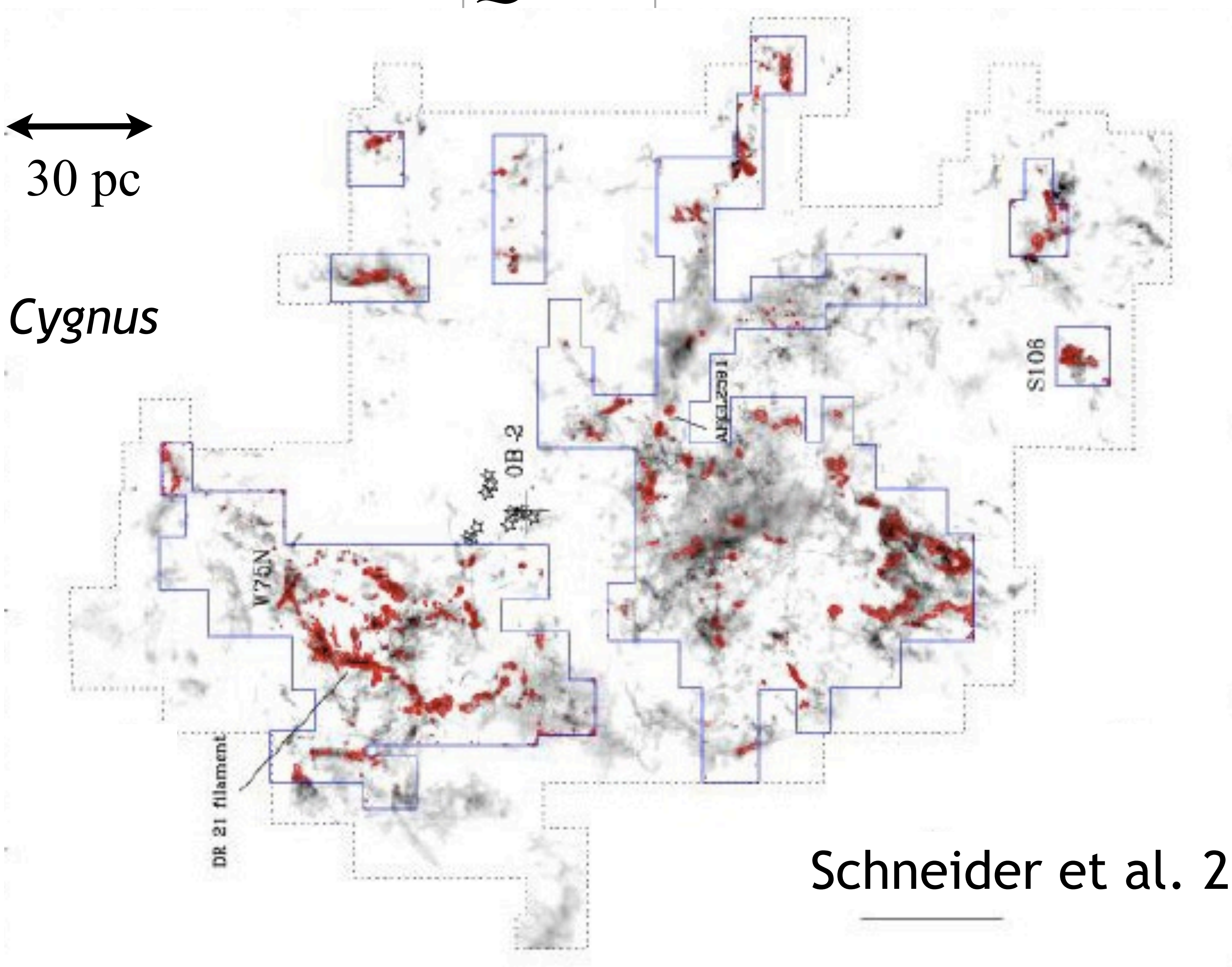


Growth rate of gravitational instabilities: (Silk 01; Silk&Norman 09)

$$\tau_{Toomre} = \frac{\sigma}{\pi G \Sigma} = \kappa^{-1} = \left(\sqrt{2}\Omega\right)^{-1} \rightarrow \tau_{\mathrm{Toomre}} = 0.1 \cdot \tau_{orb} \approx 2 - 5 \cdot 10^{7}\, yrs$$

$$Q = 1$$

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

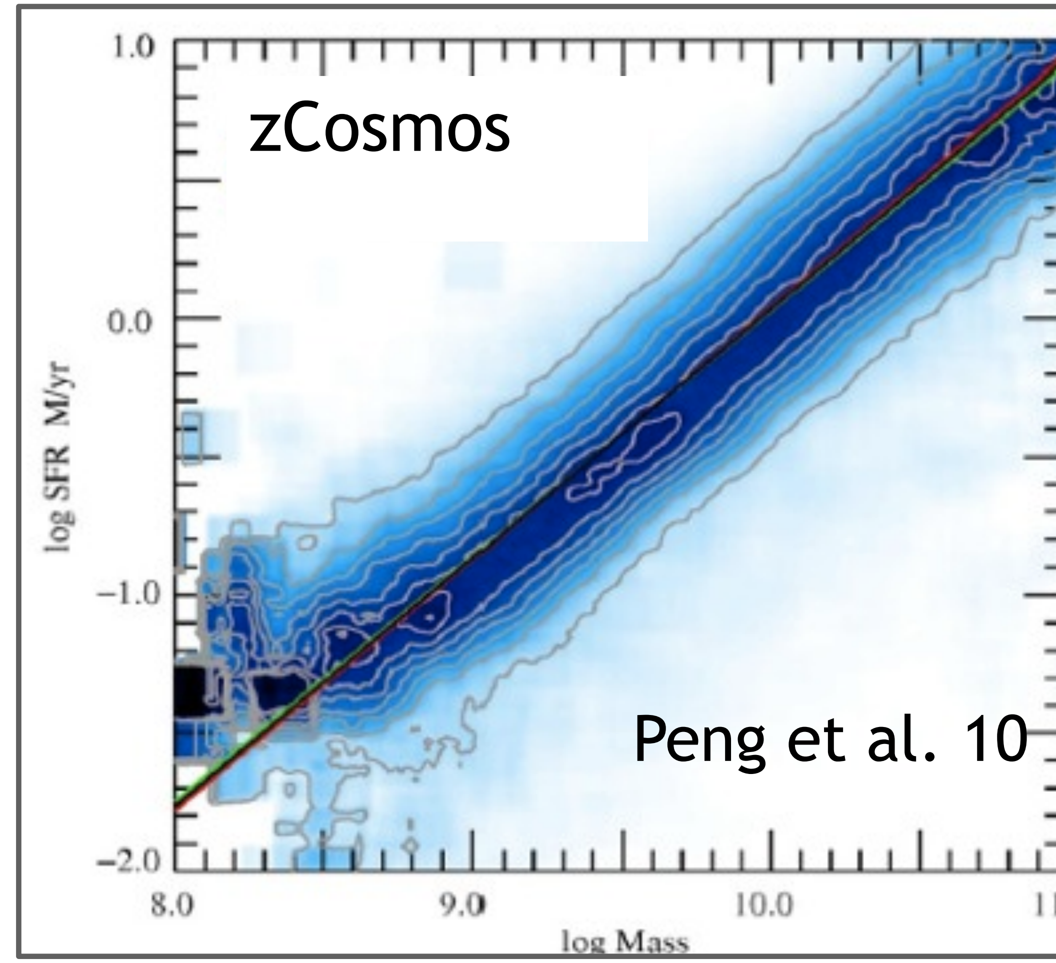


The molecular web

Schneider et al. 2010

What determines the SFR?

$\log \mathrm{SFR}\ [M_\odot / yr]$



$\log \mathrm{M}_*\ [\mathrm{M}_\odot]$

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

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

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

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