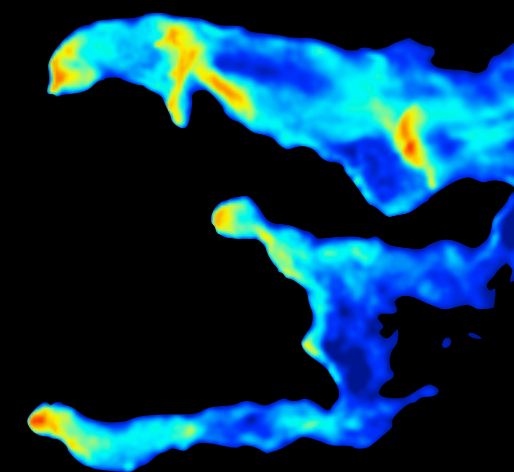
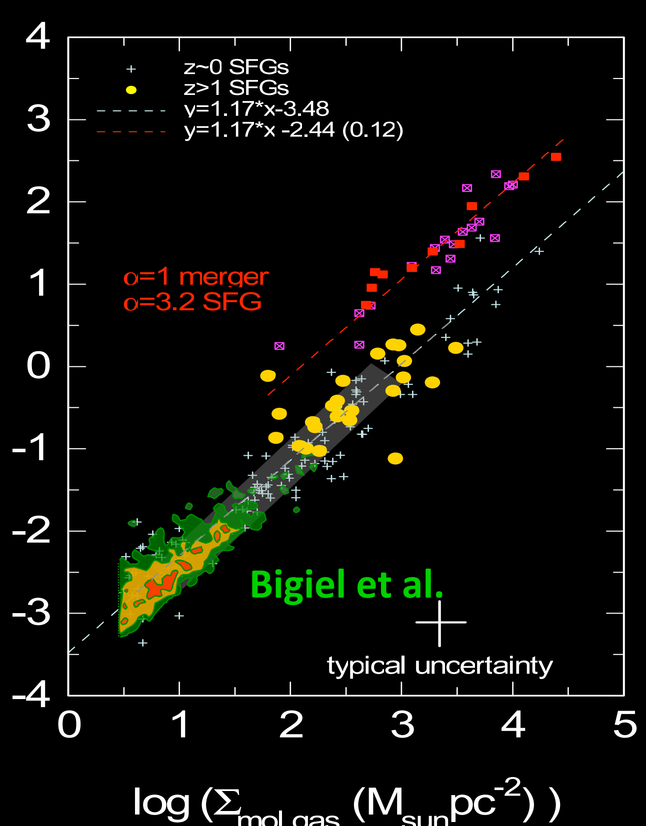
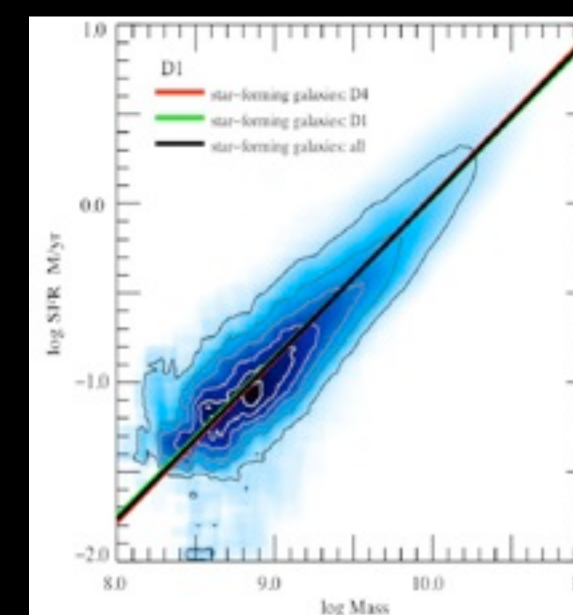
Self-regulated star formation

Andreas Burkert







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

Munich University Observatory
CAST
Computational Astrophysics Group

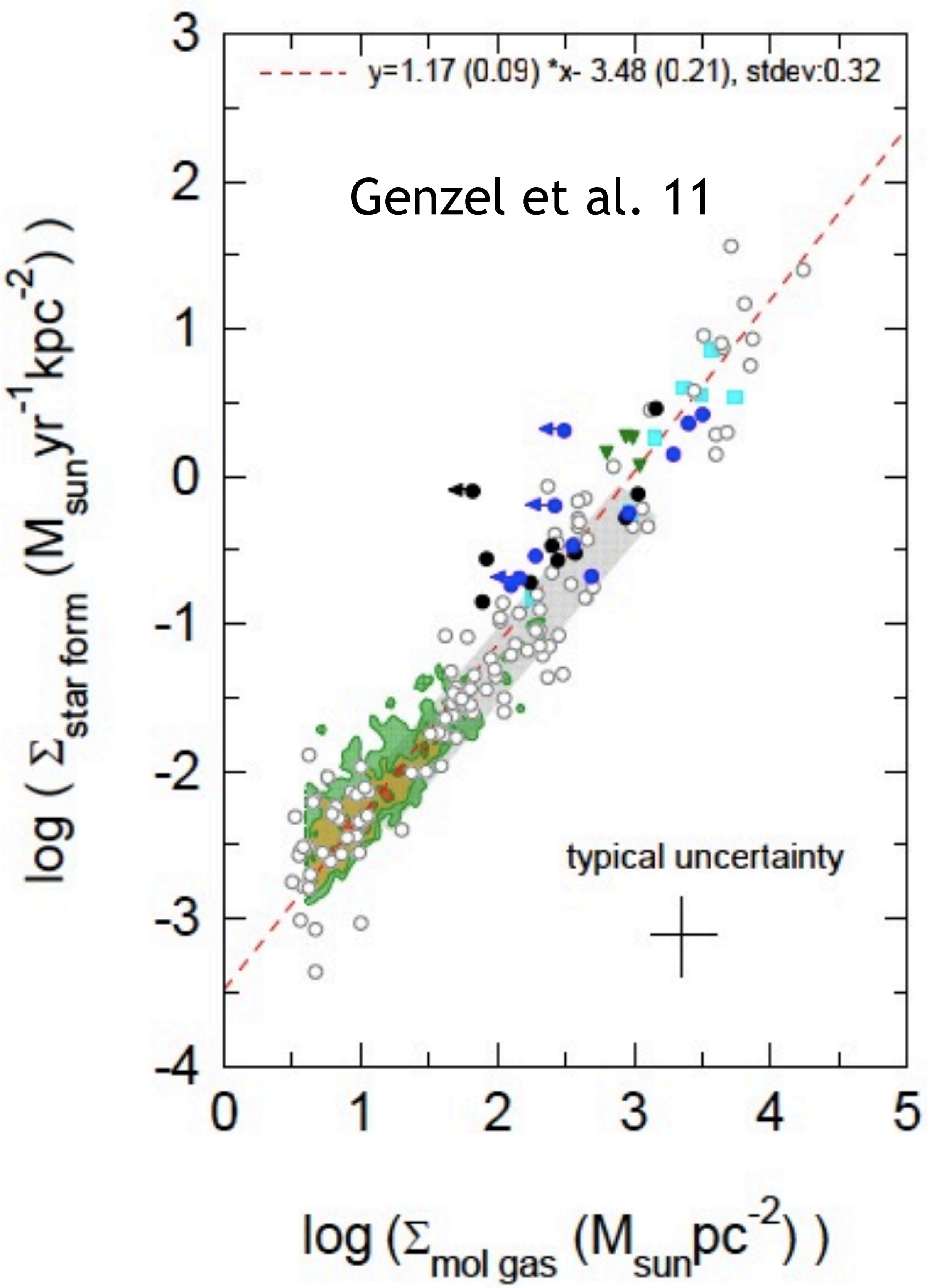
Munich

Today Aug 9	Mi 10	Do 11	Fr 12	Sa 13	So 14	Mo 15	Di 16	Mi 17	Do 18
Nachm. Schauer	Vorm. Schauer	L. Bewölkt	L. Bewölkt	L. Bewölkt	Sonnig	Nachm. Schauer	Regen	L. Bewölkt	Sonnig
65°F High	66°	72°	74°	77°	81°	80°	72°	73°	73°
49° Low	48°	49°	56°	58°	59°	59°	57°	52°	52°

Santa Cruz

Tonight ago 8	mar 9	mer 10	gio 11	ven 12	sab 13	dom 14	lun 15	mar 16	mer 17
Partly Cloudy	Partly Cloudy	Partly Cloudy	Mostly Sunny	Partly Cloudy	Partly Cloudy	AM Clouds / PM Sun	AM Clouds / PM Sun	Sunny	Sunny
-- High	65°	68°	65°	65°	67°	67°	66°	64°	64°
52° Low	53°	54°	53°	53°	54°	55°	54°	54°	53°

Evidence for self-regulation



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

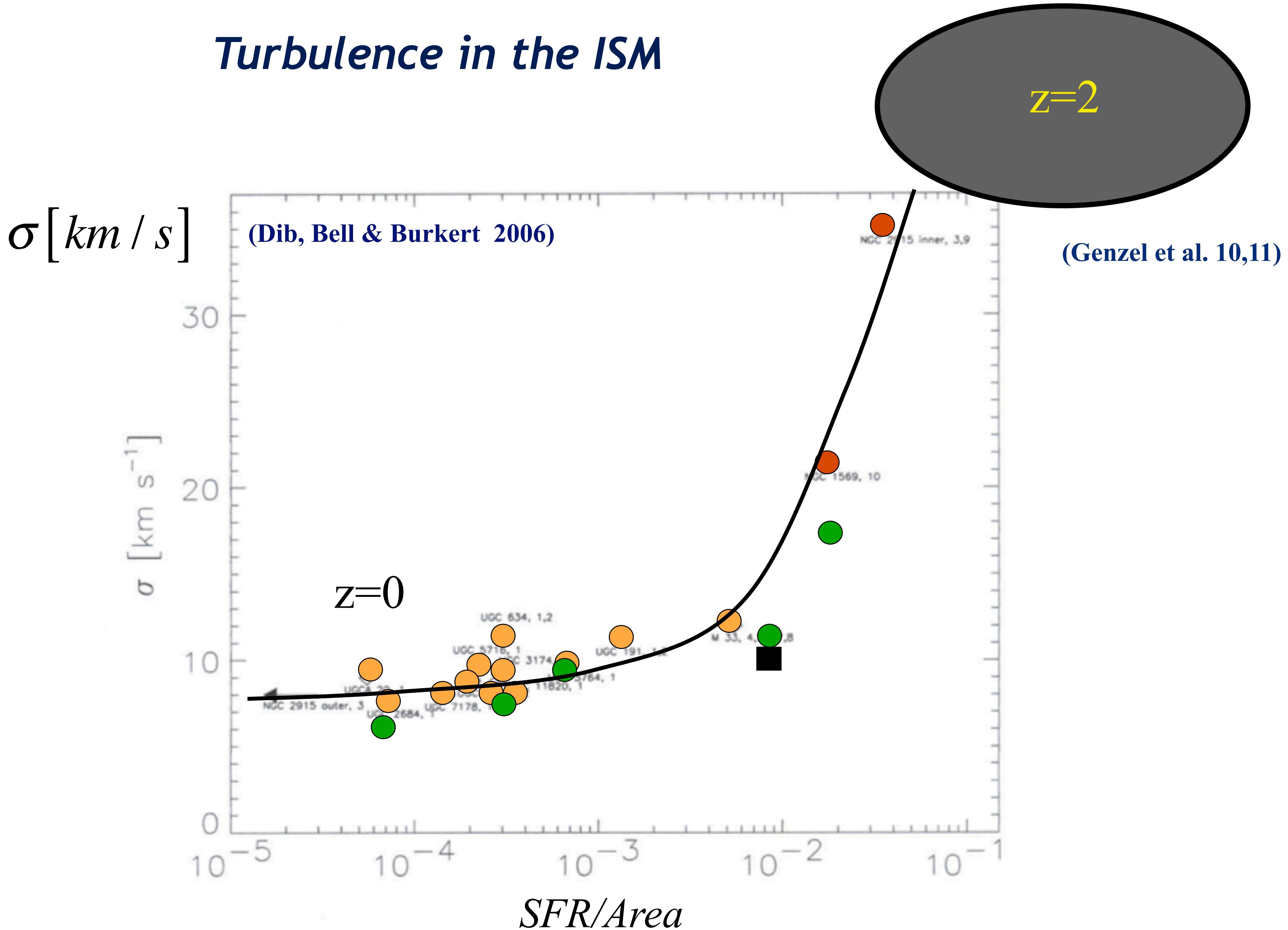
- τ_{sf} is almost independent of redshift
- Gas depletion timescale **50 times** greater than local free-fall timescale.

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

→ continuous replenishment

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

Turbulence in the ISM



Numerical simulations of the molecular web

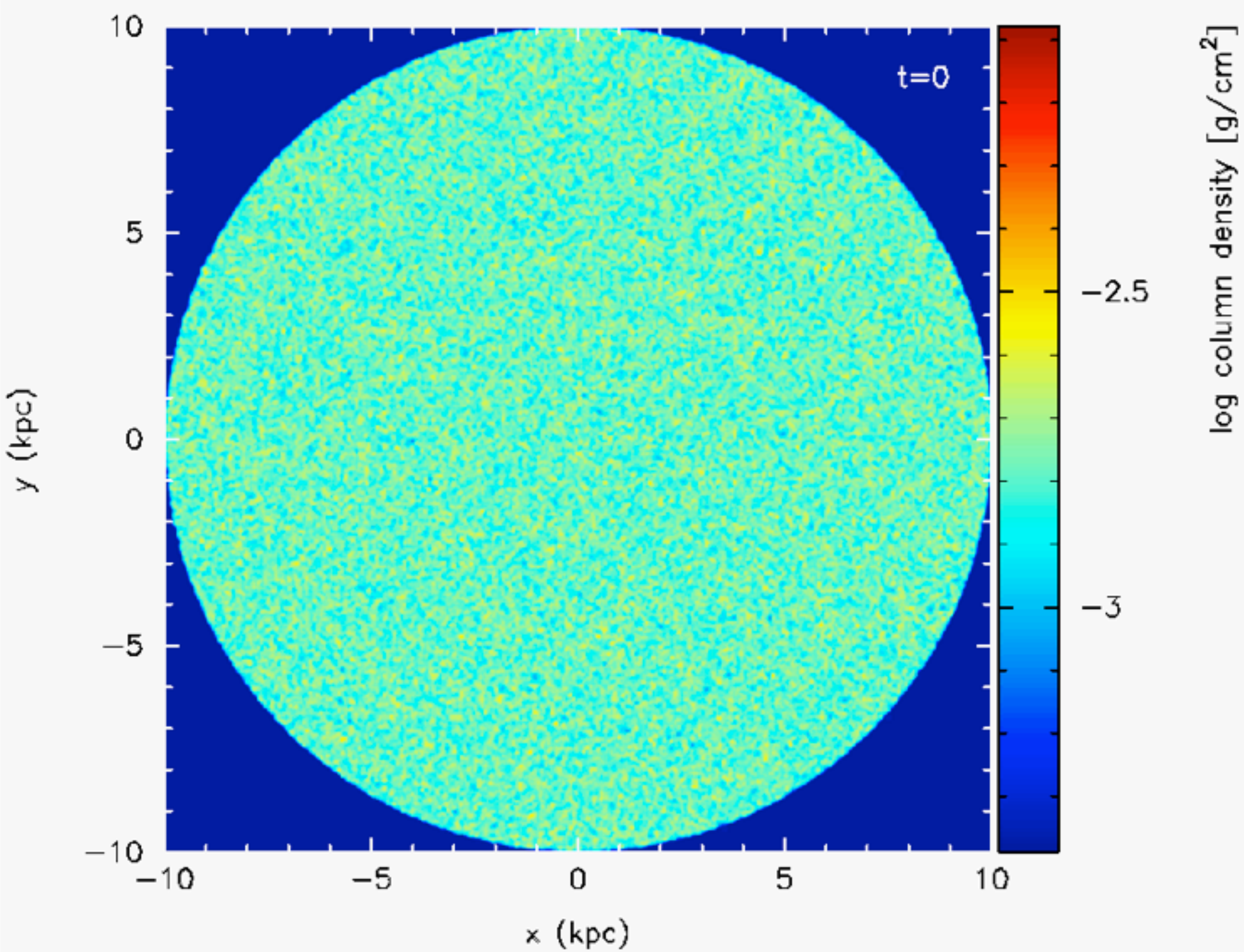
(Dobbs, Burkert & Pringle 11a,b)

- **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 **2 or 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

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

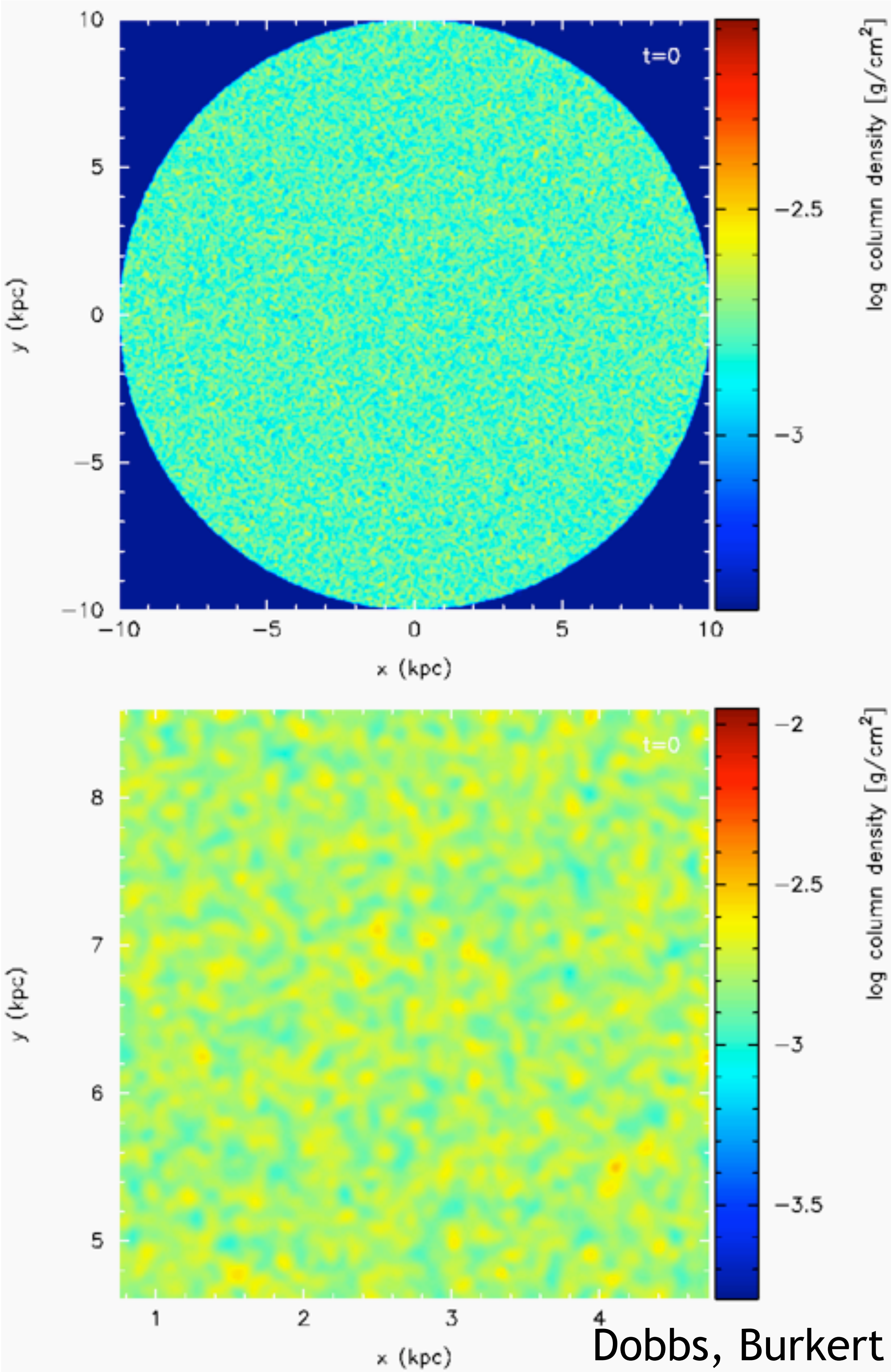
$$\varepsilon \approx 2 - 5\%$$

Calculation with 5 % efficiency



Dobbs, Burkert & Pringle 11a,b

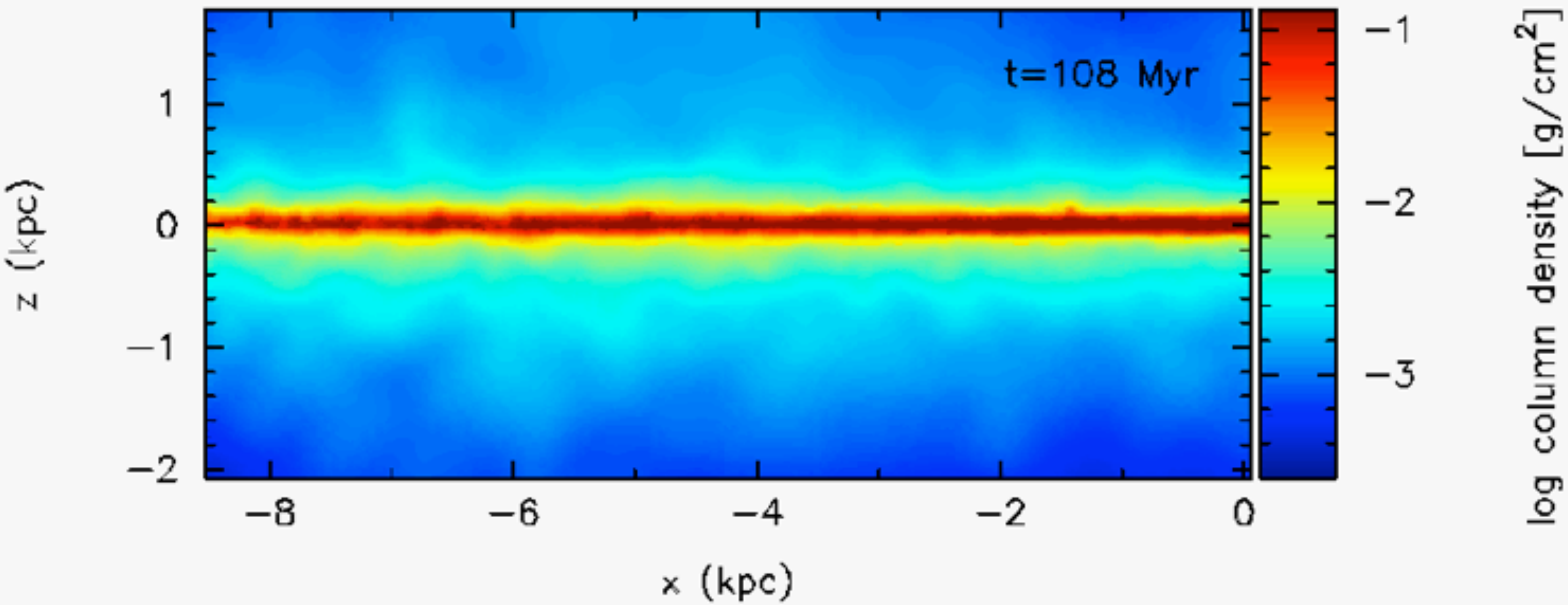
Filamentary interarm features (spurs)

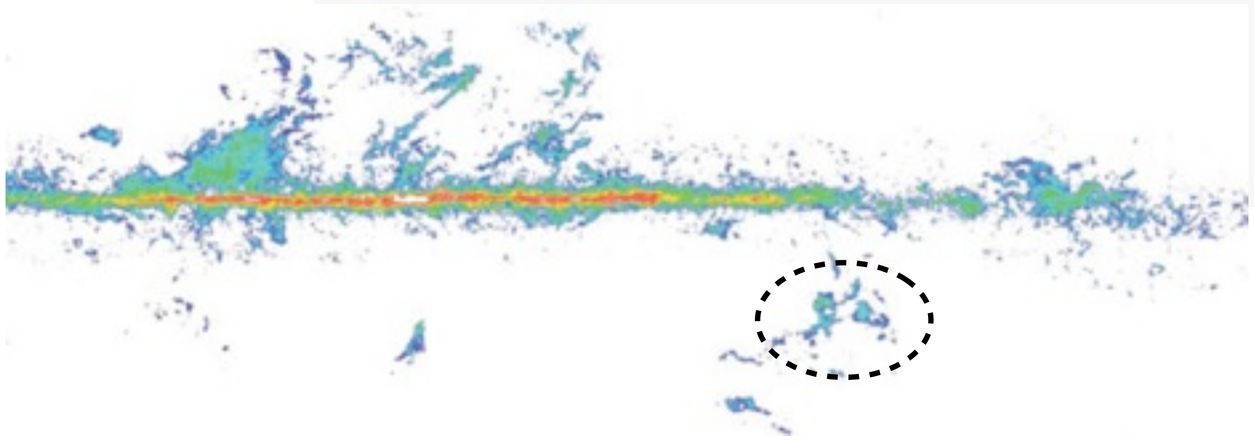


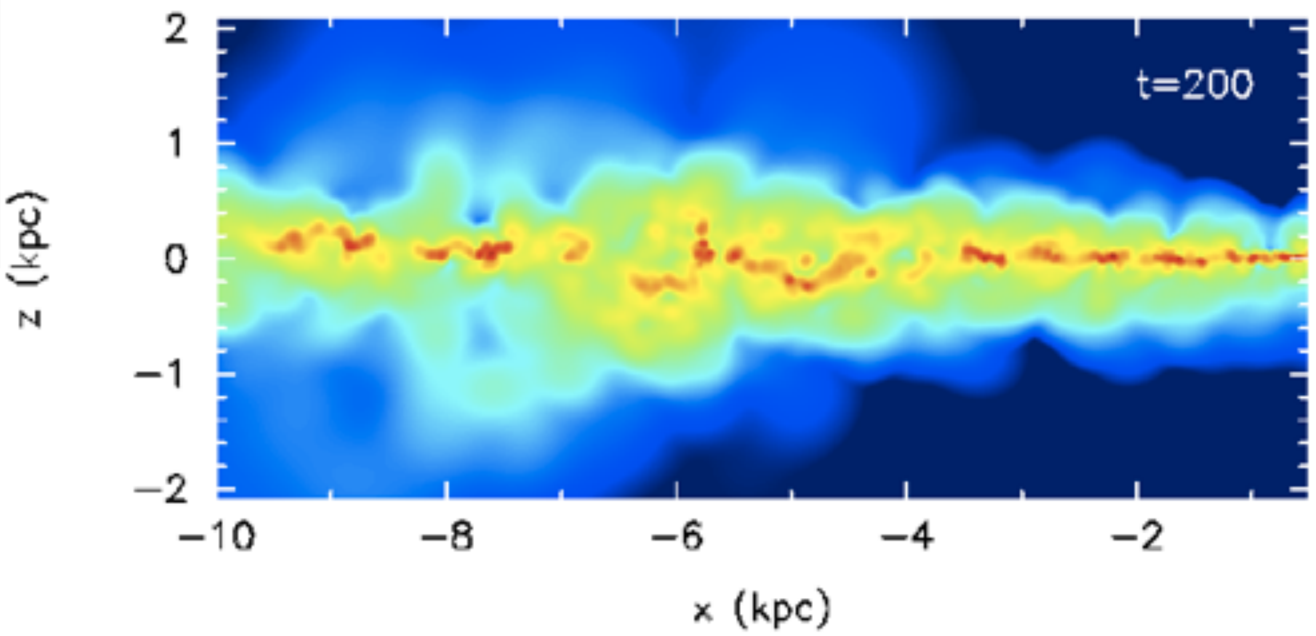
Dobbs, Burkert & Pringle 11a,b

Feedback puffs up disks

Dobbs, Burkert & Pringle 11a,b

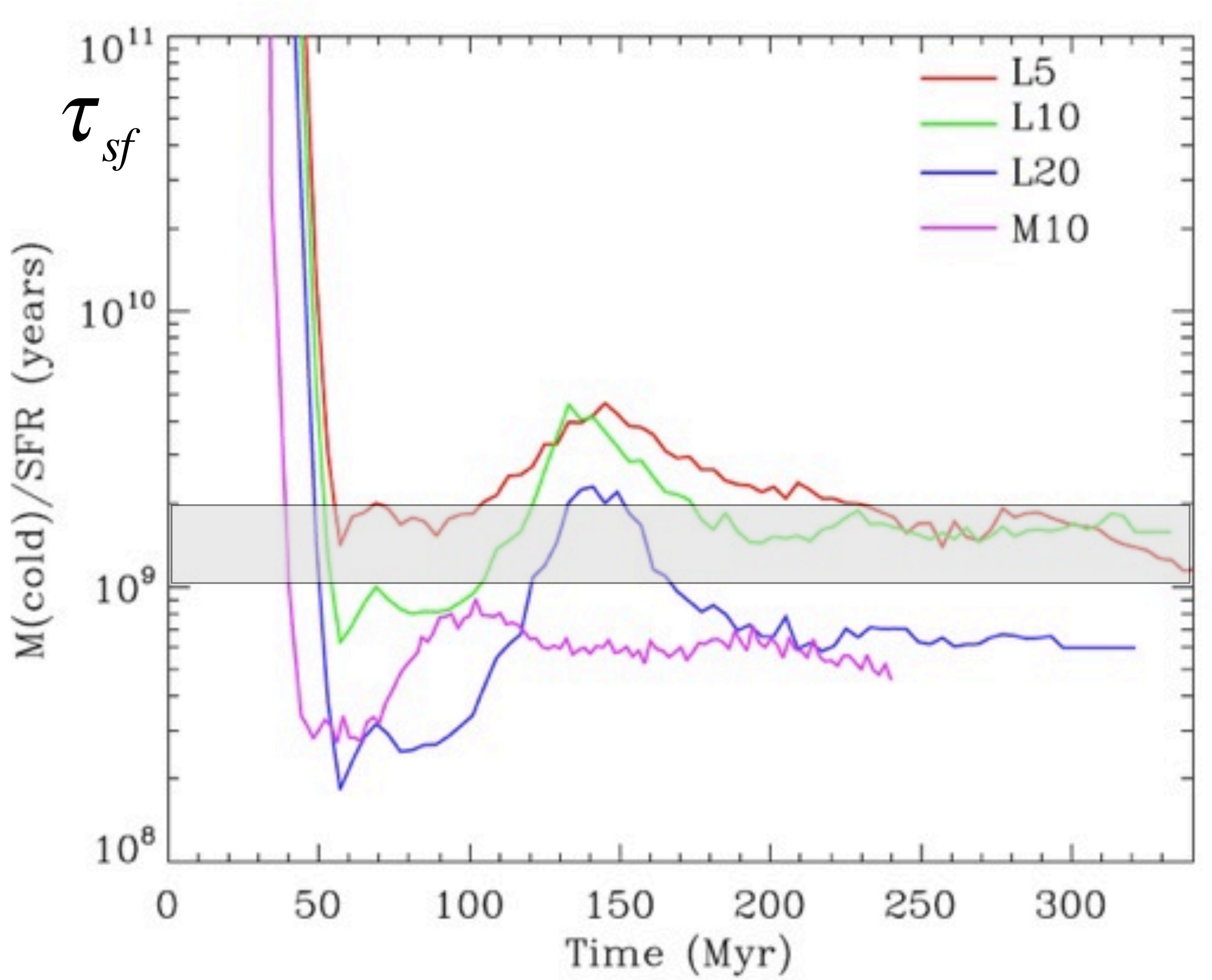




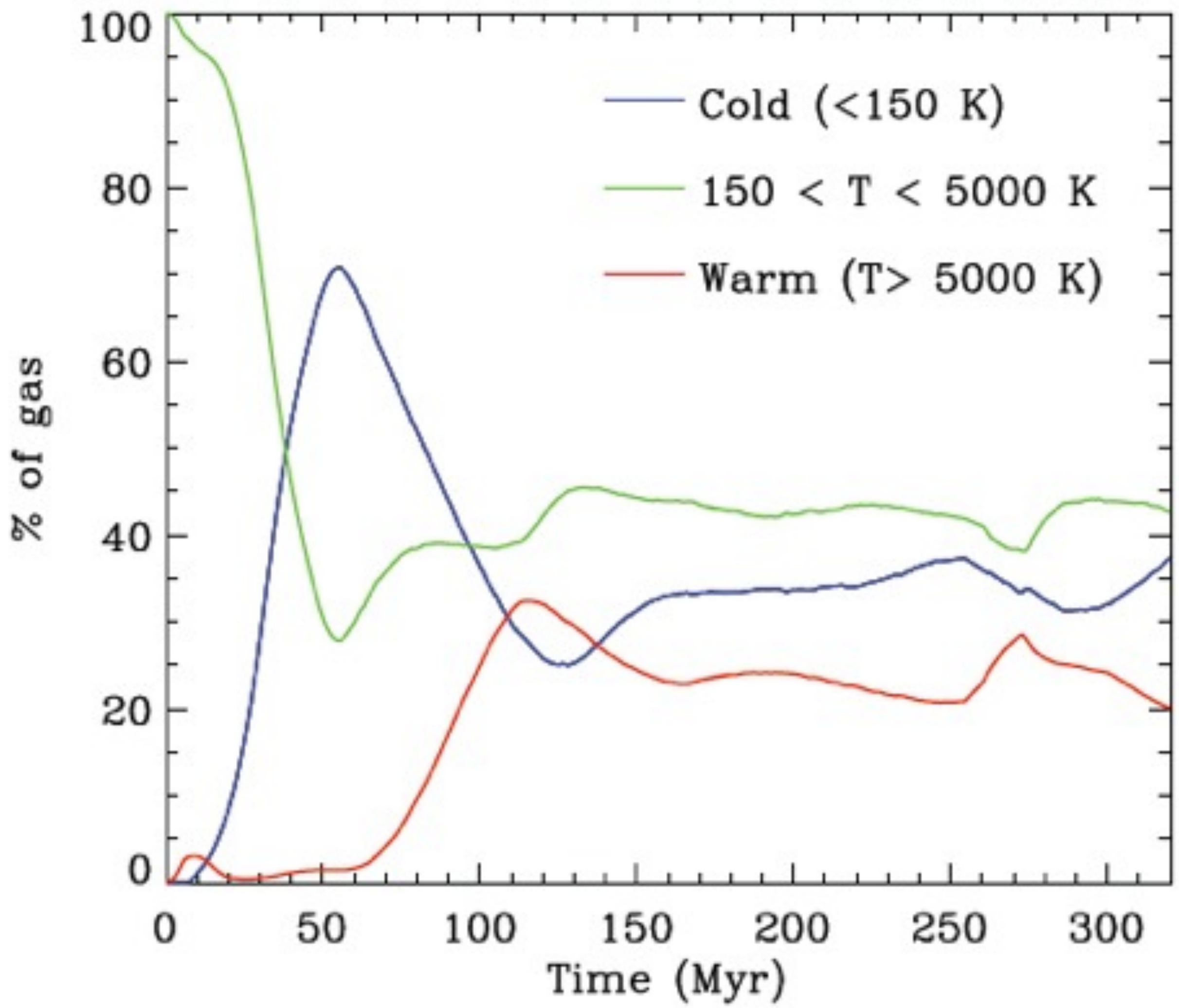


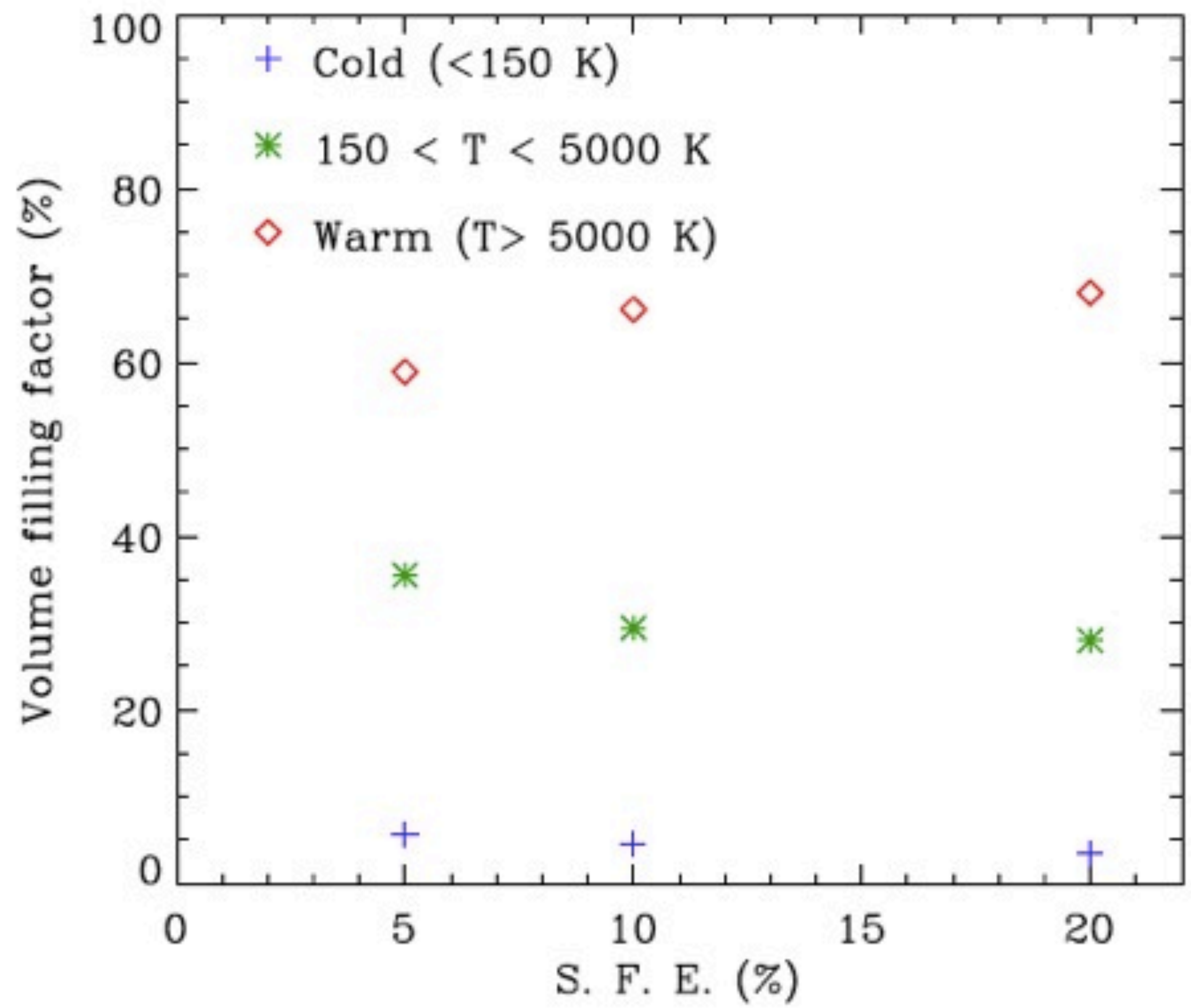
Star formation timescale

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

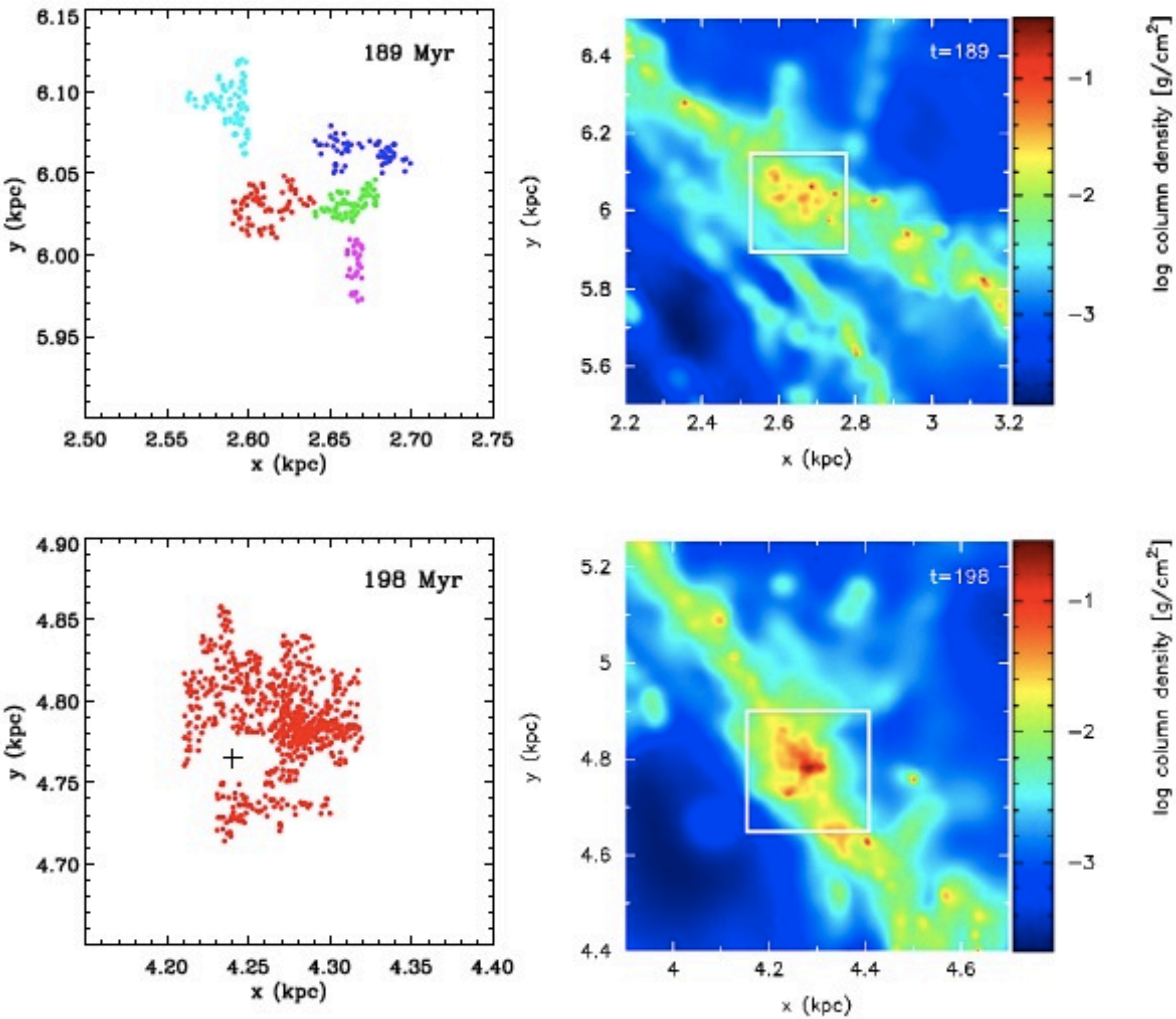


Gas mass fraction and volume filling factor: 5% efficiency

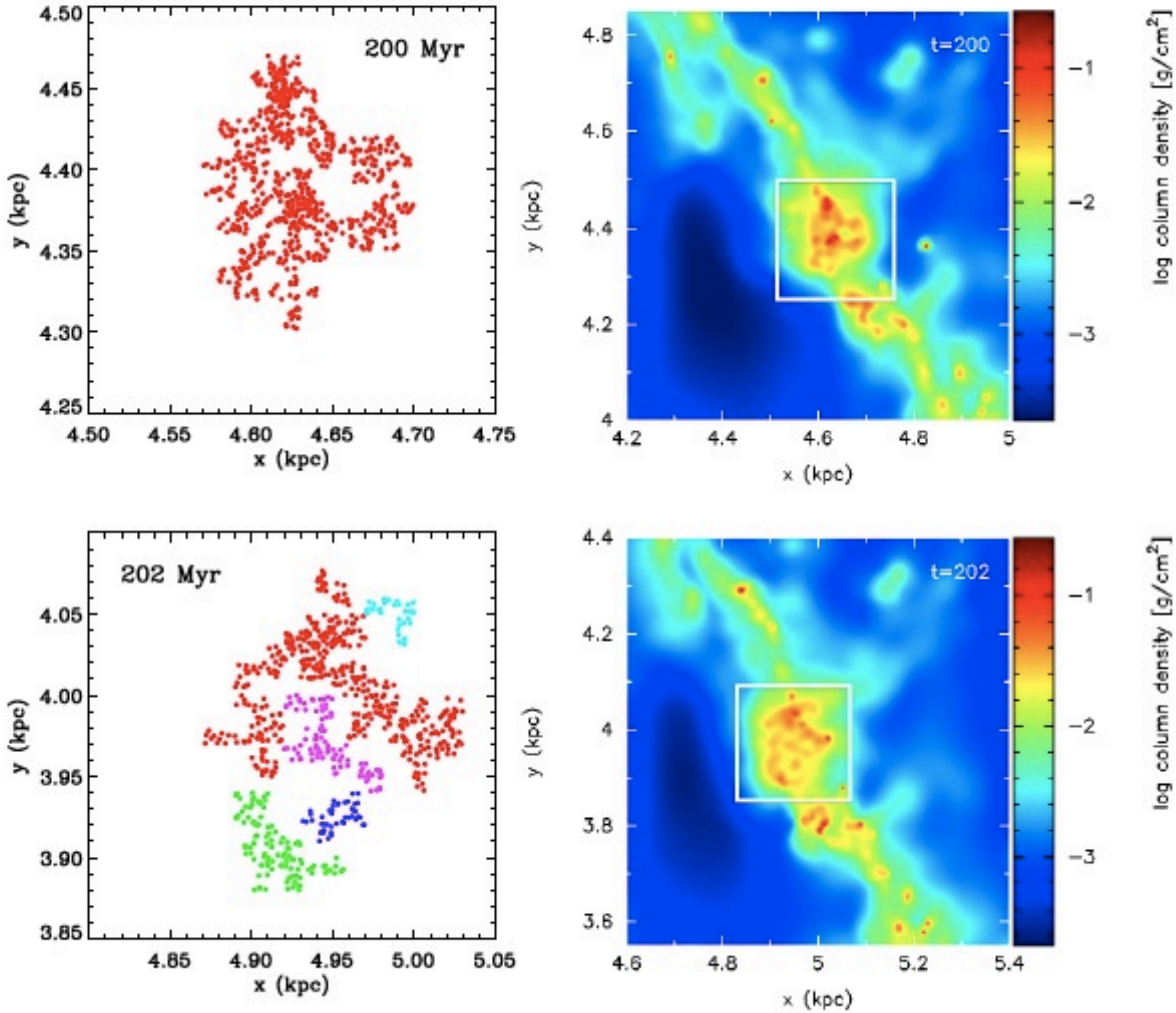




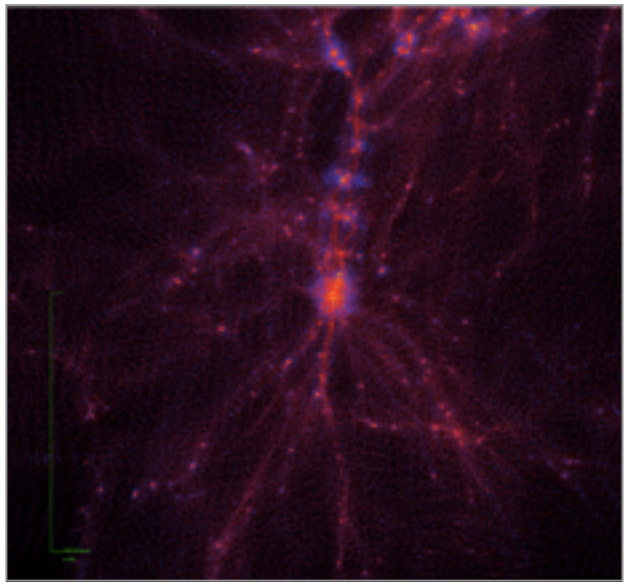
1. Collisions by local gravitational instability and irregular gas motions generate massive clouds and drive internal turbulence



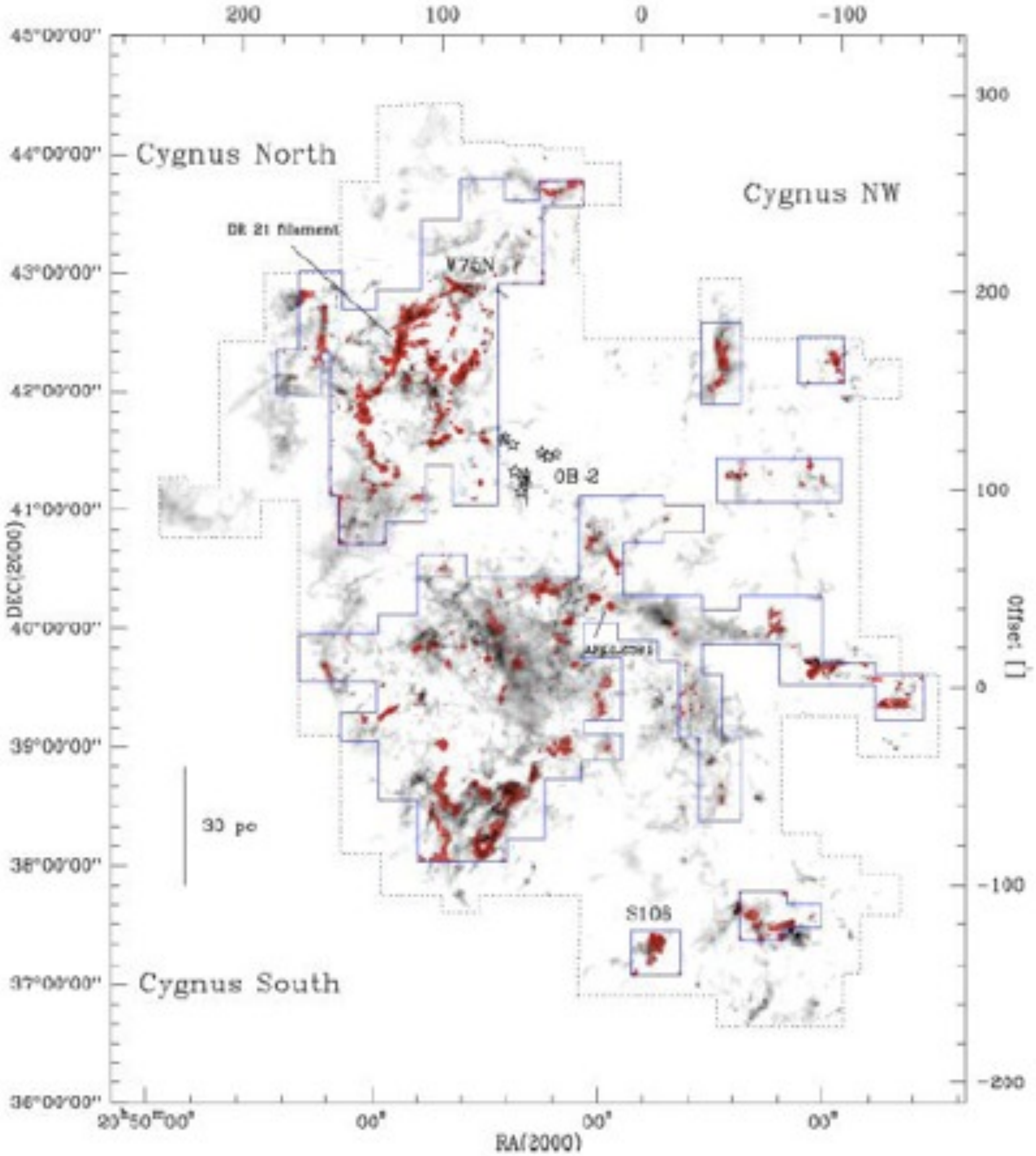
2. Stellar feedback disperses clouds and drives irregular gas motions in the molecular web.

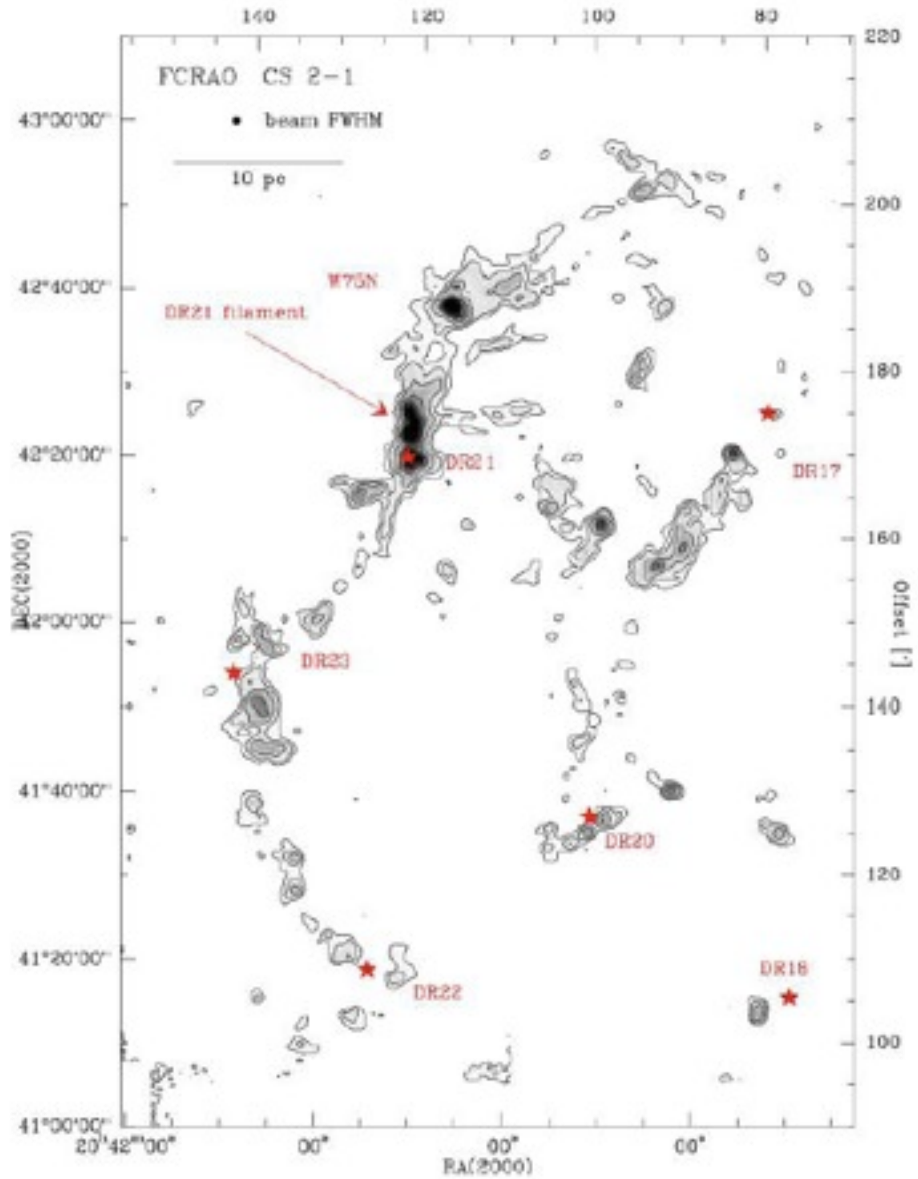


The molecular web

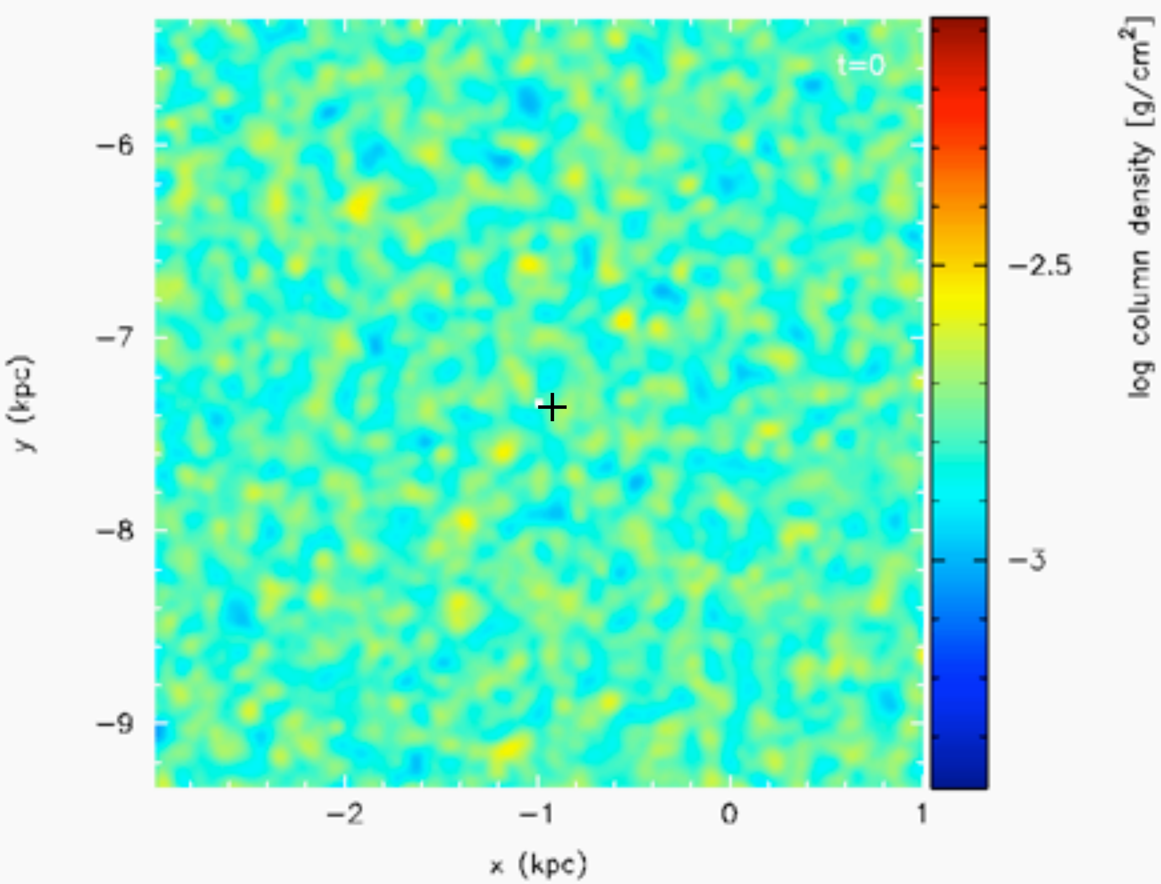


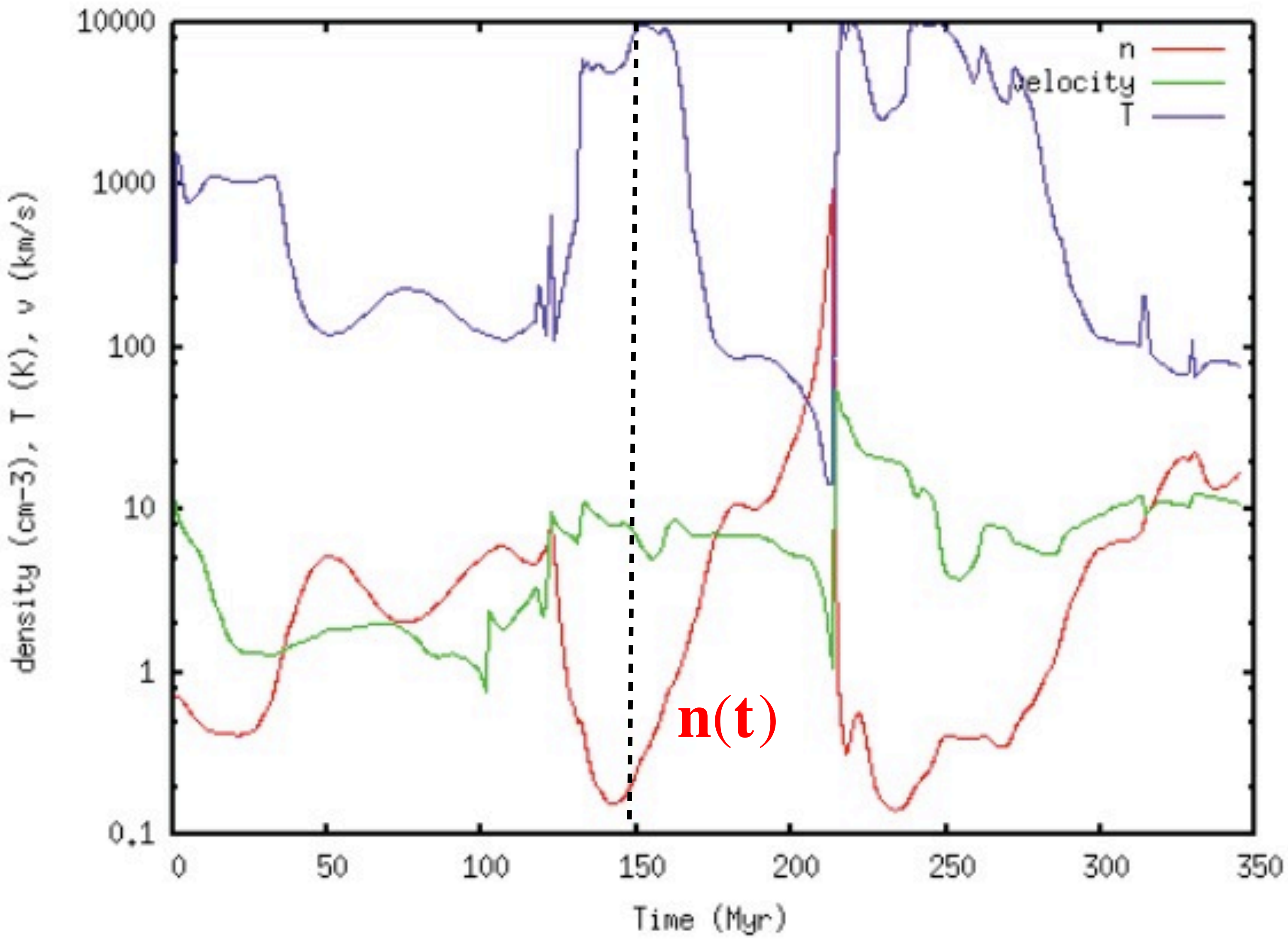
Schneider et al. 2010



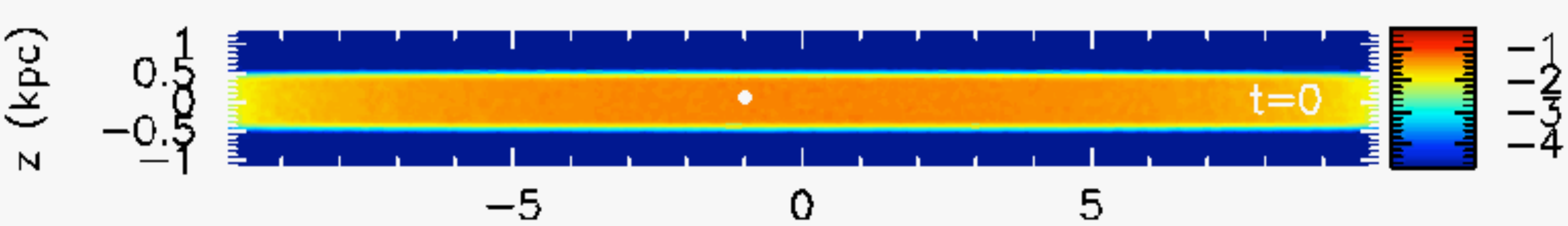


Gravitational instabilities and star formation timescale





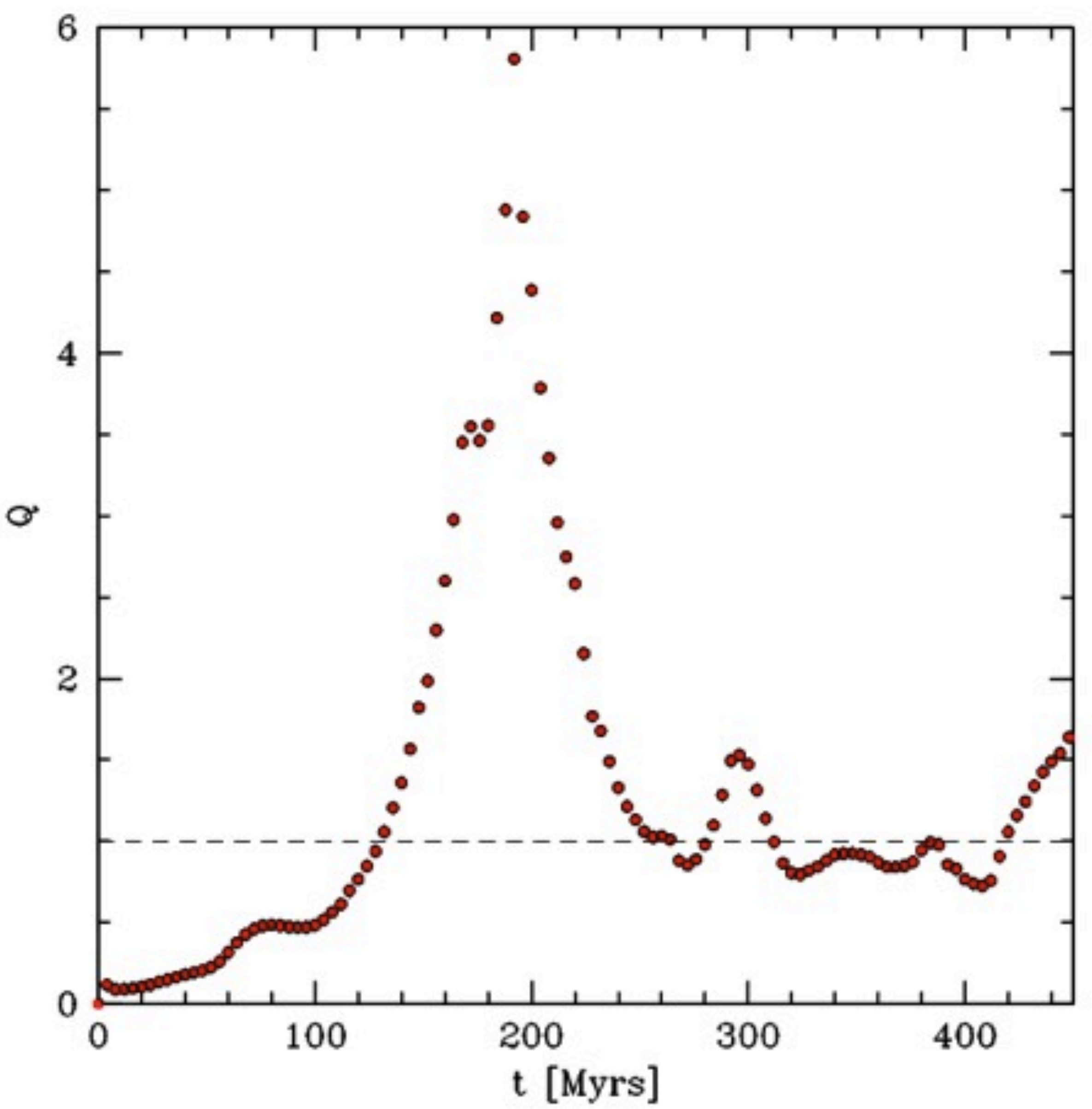
$$\rho \sim \rho_0 \exp(t/\tau) \text{ with } \tau = 2 \cdot 10^7 yrs$$

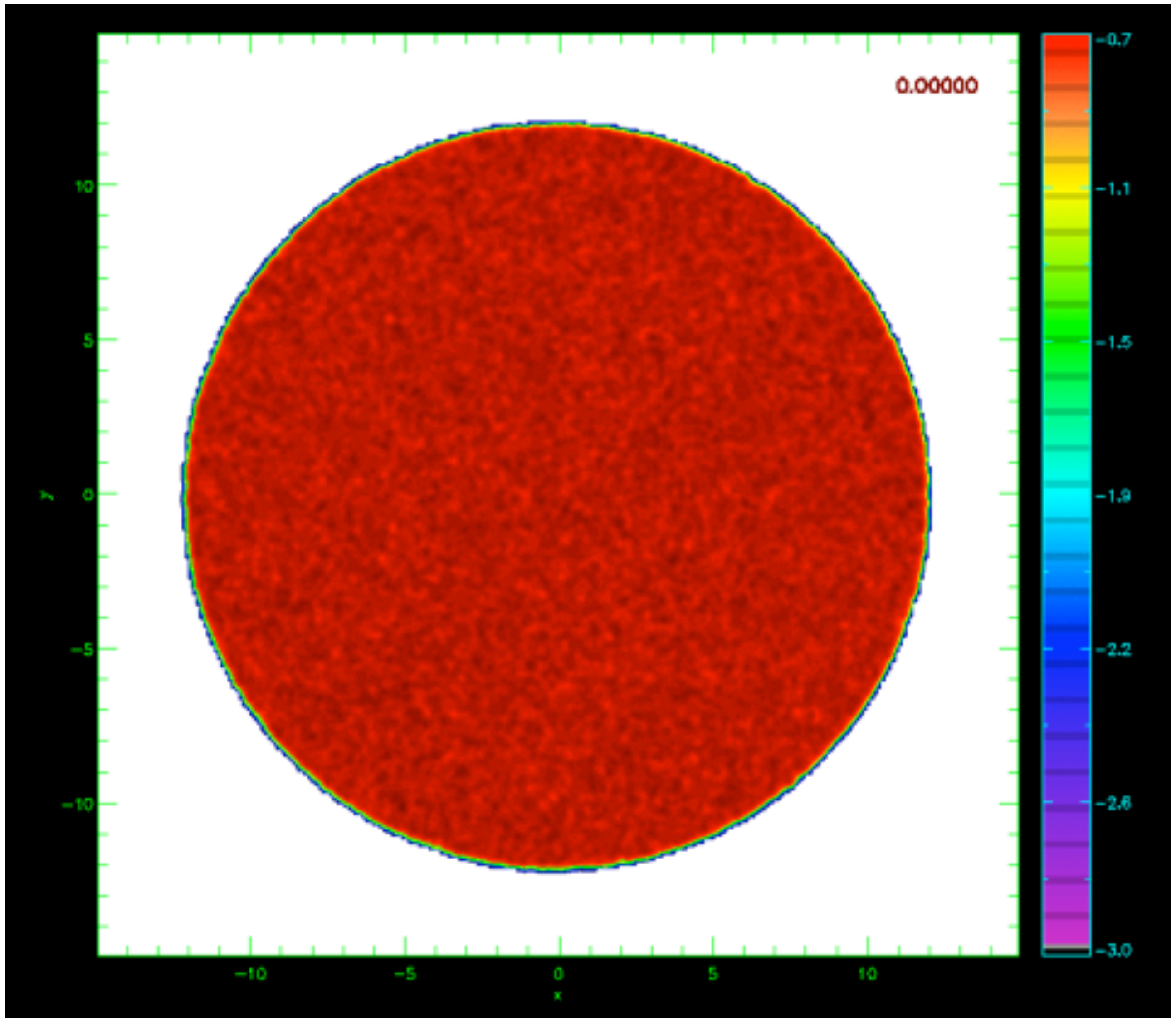


Gravitational disk instabilities

(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:

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

$$Q = 1$$

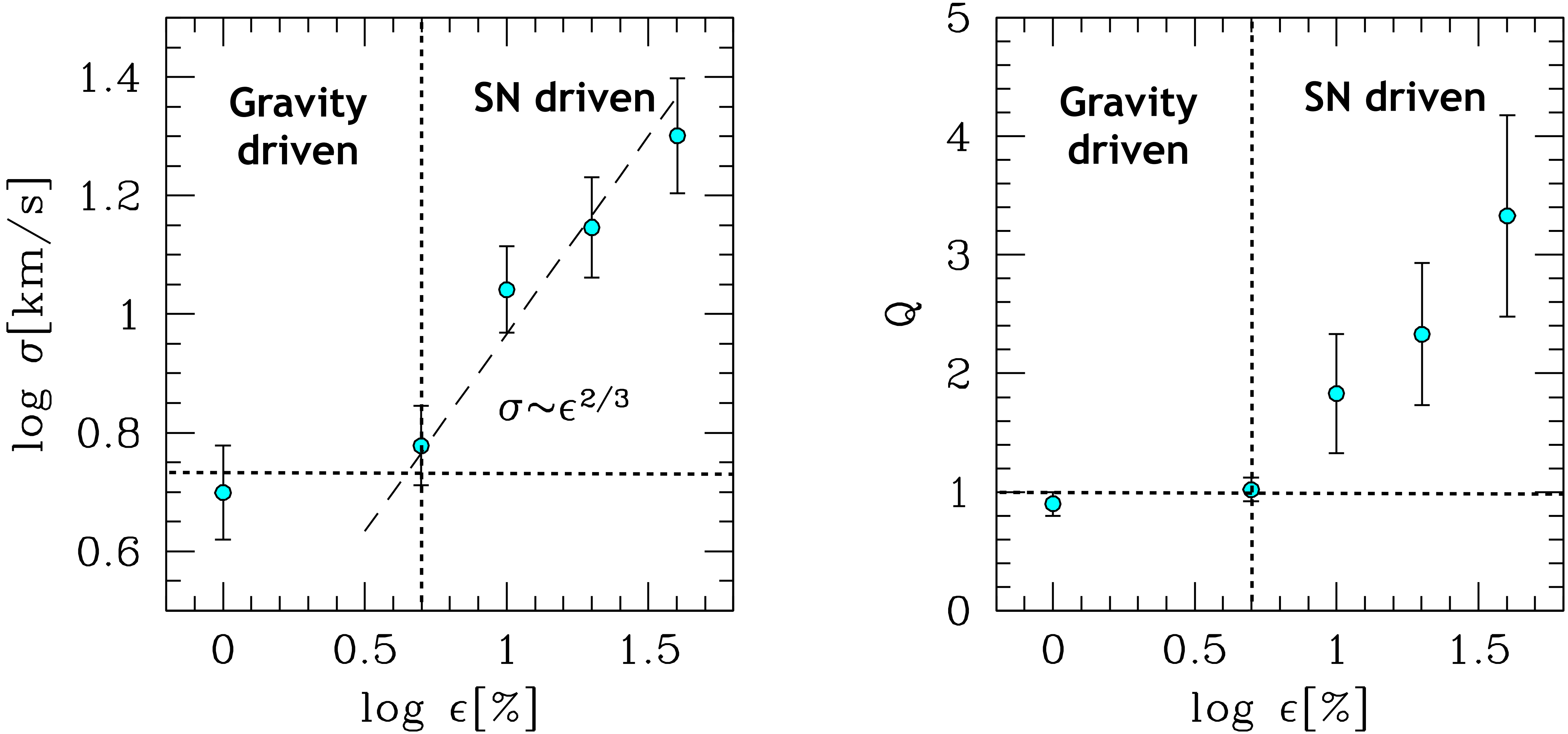
$$\tau_{orb} \sim \frac{R_{vir}}{V_{vir}} \sim H^{-1}$$

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

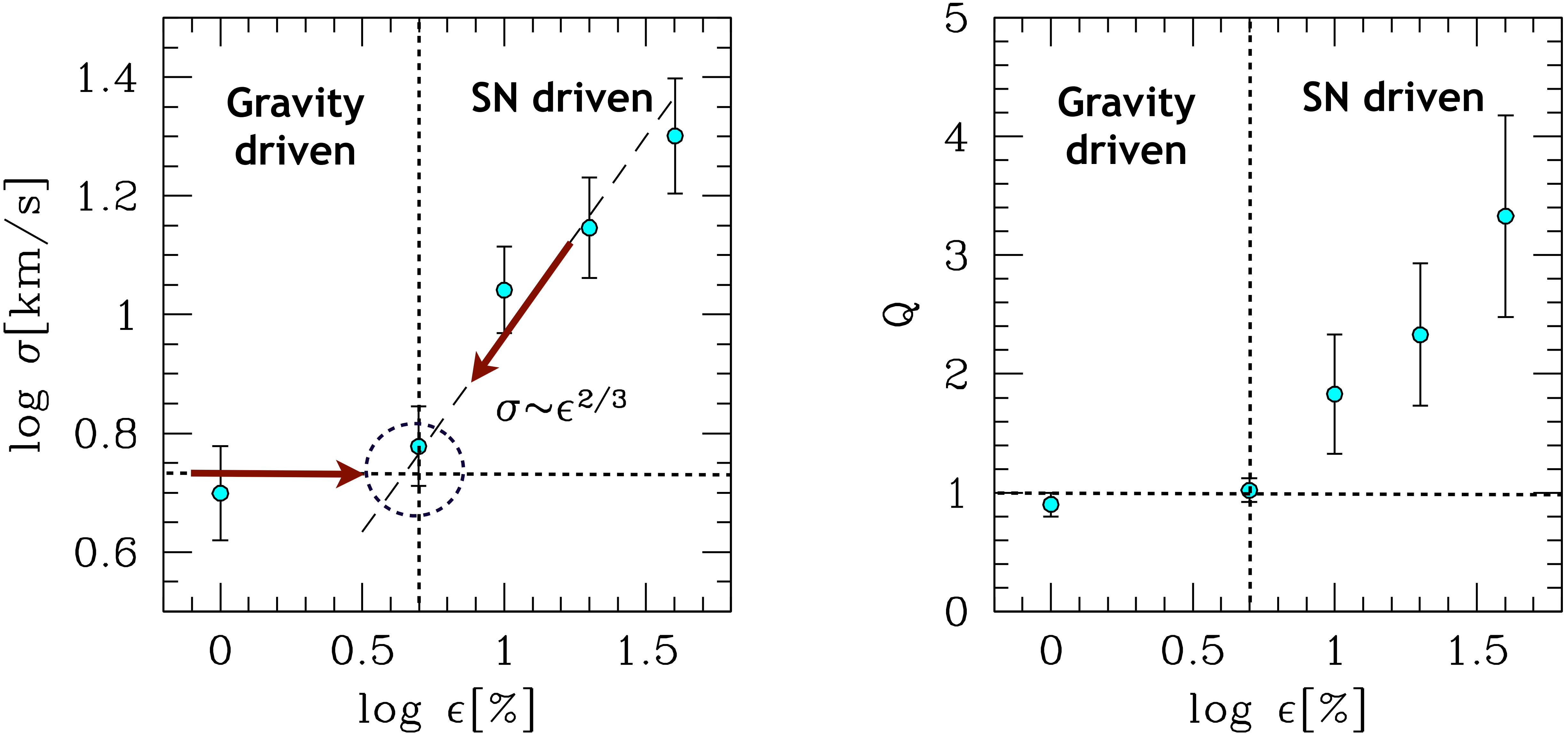
Gravitational instabilities affect galactic disk evolution

What determines the star formation efficiency?

Gas velocity dispersion

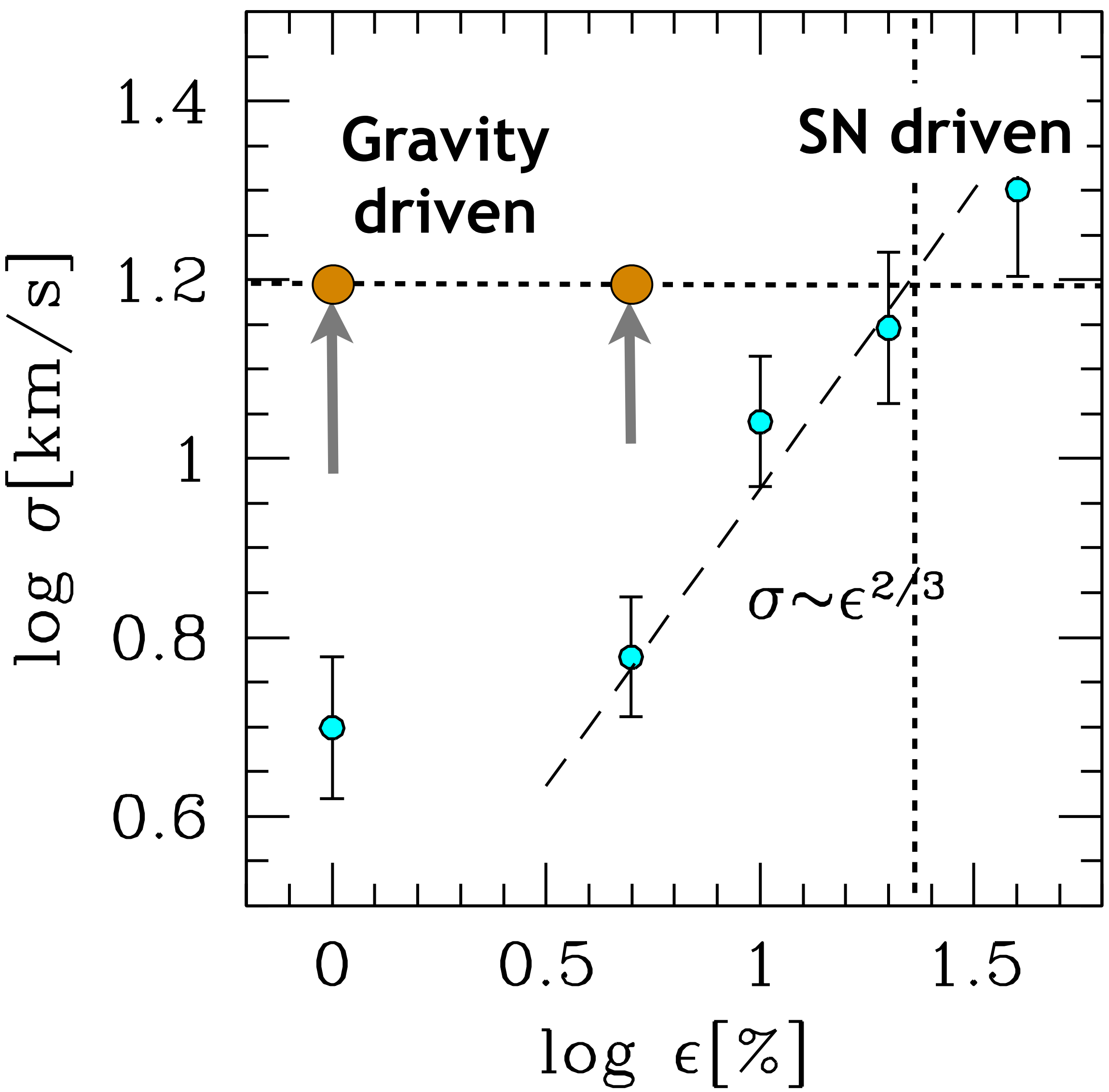


What determines the star formation efficiency?



Higher gas surface densities/gas fractions

$$Q = 1 \rightarrow \sigma / v_{rot} \sim f_{gas}$$

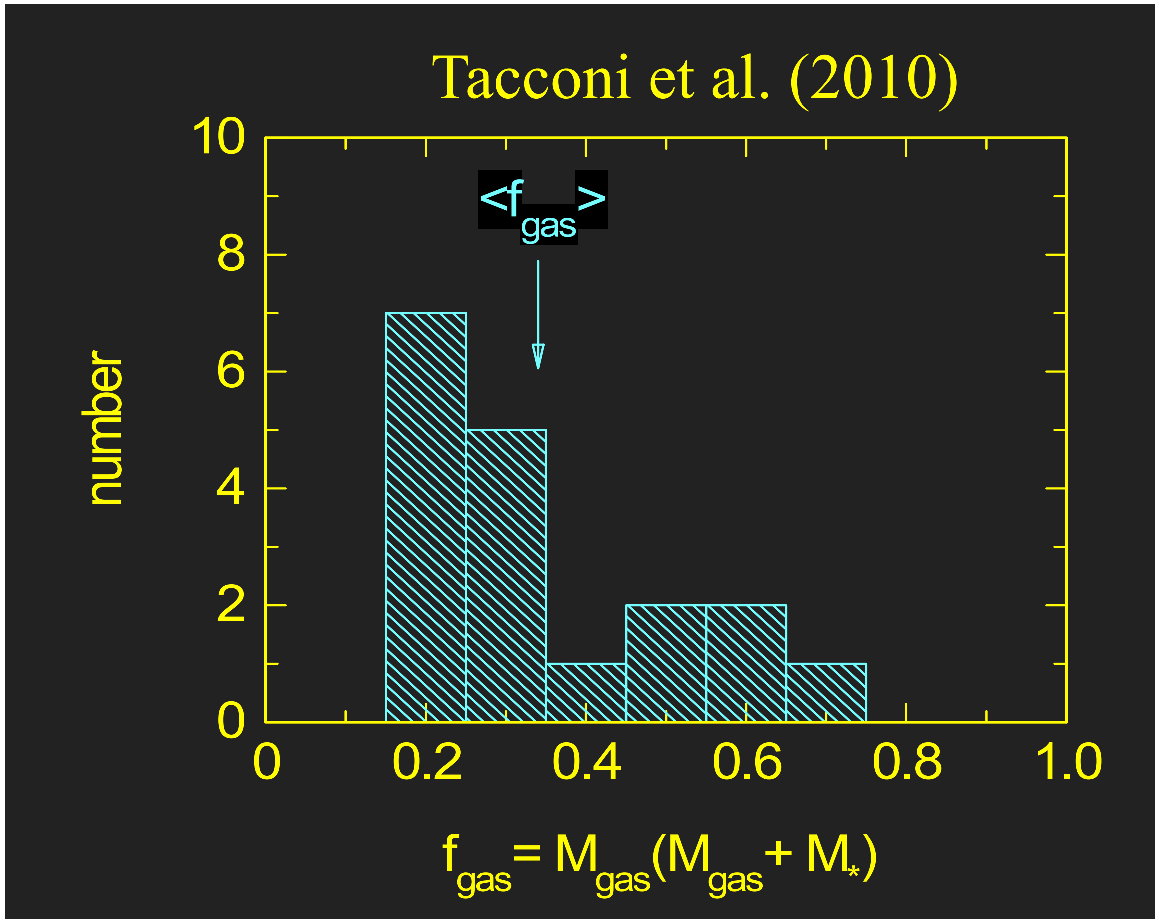


The **gravity driven mode** becomes more dominant for higher gas fractions.

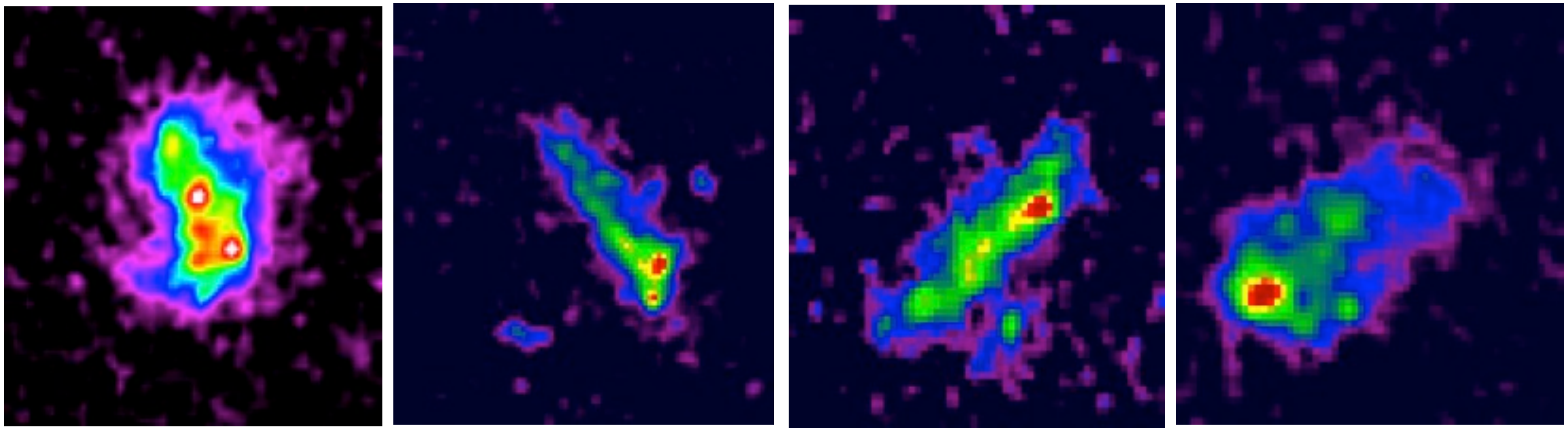
Properties of z=2 fast rotating disk galaxies

- **Very high molecular gas fractions**

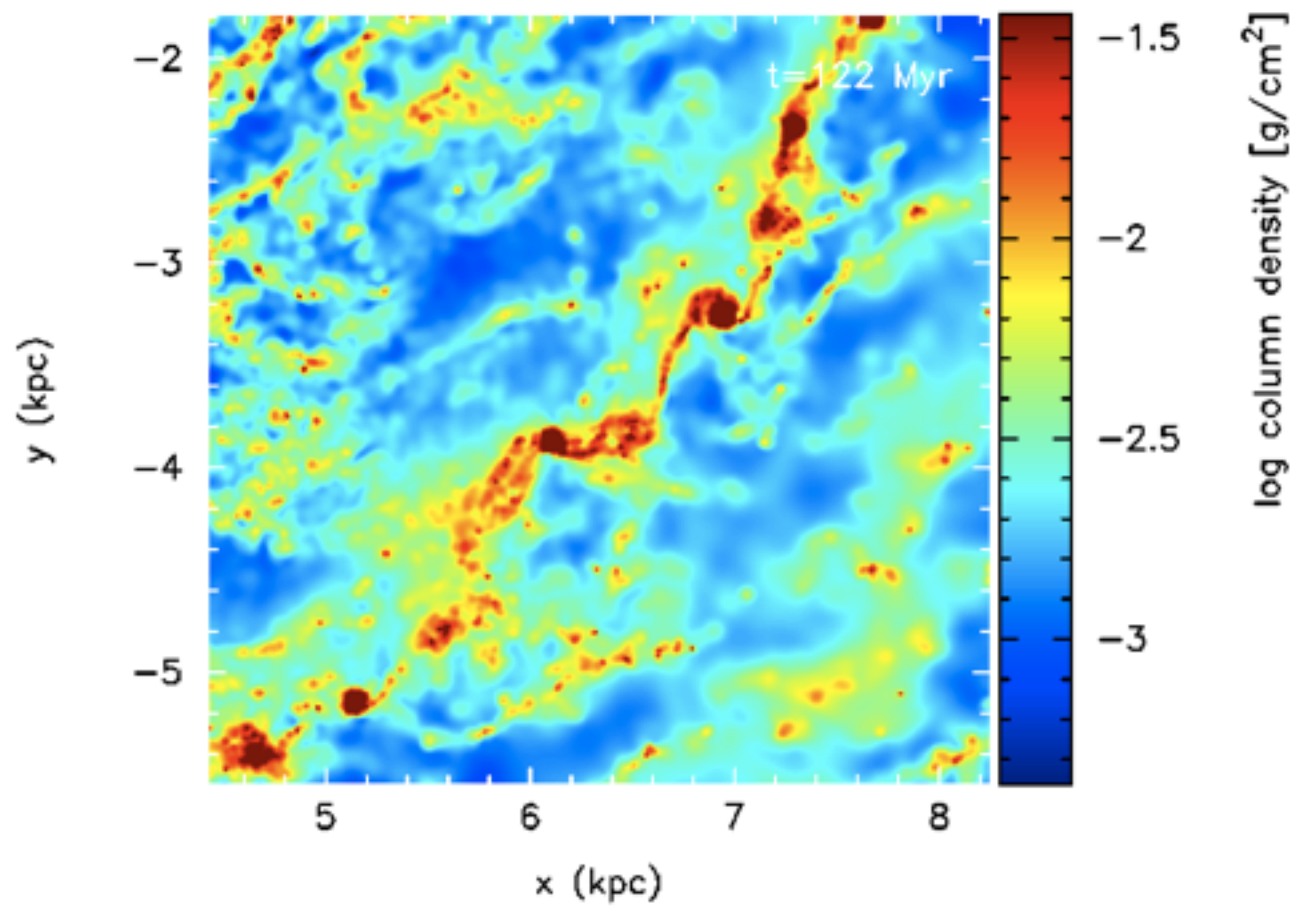
- **High velocity dispersions**

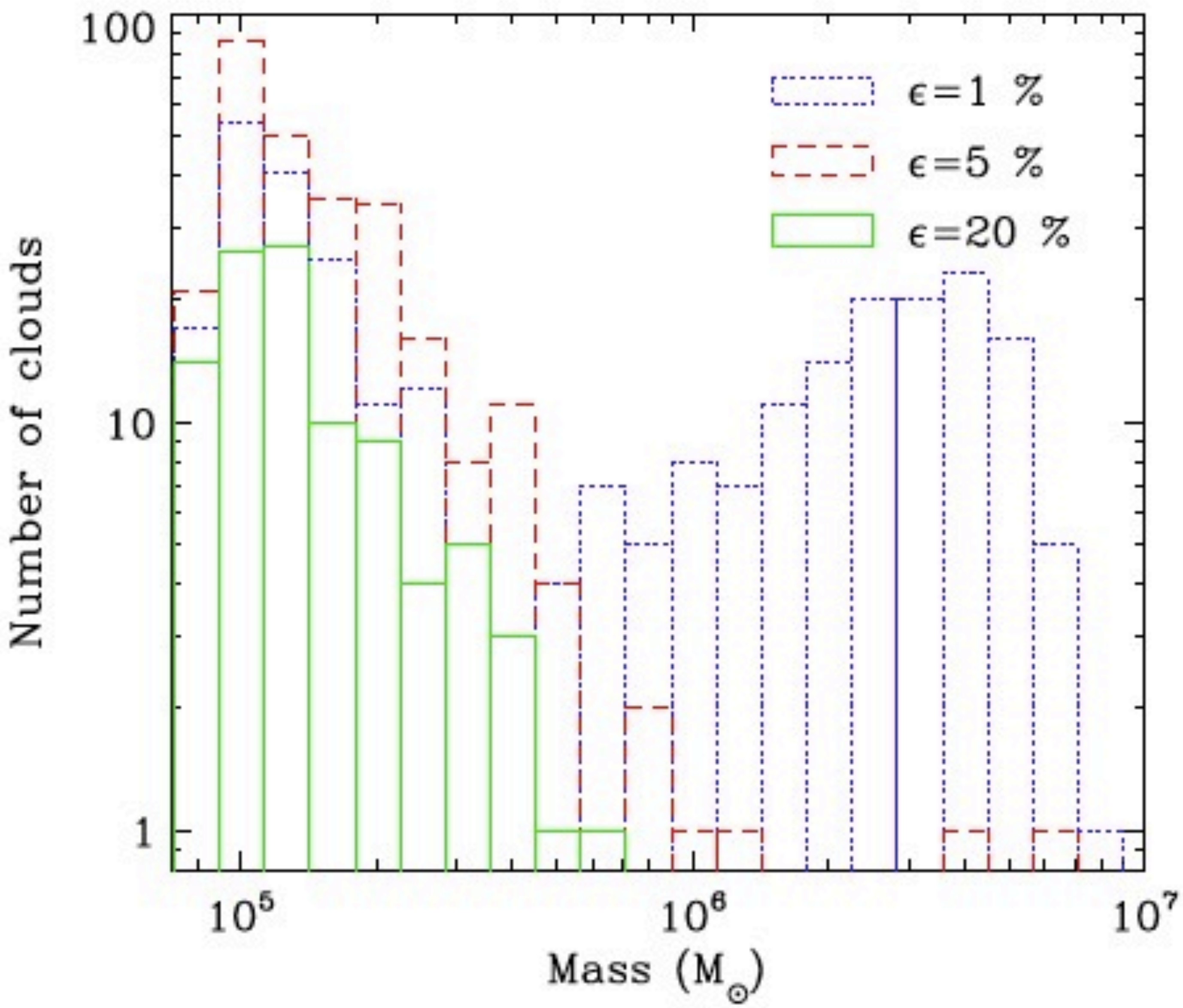


- **Dominated by massive clumps**

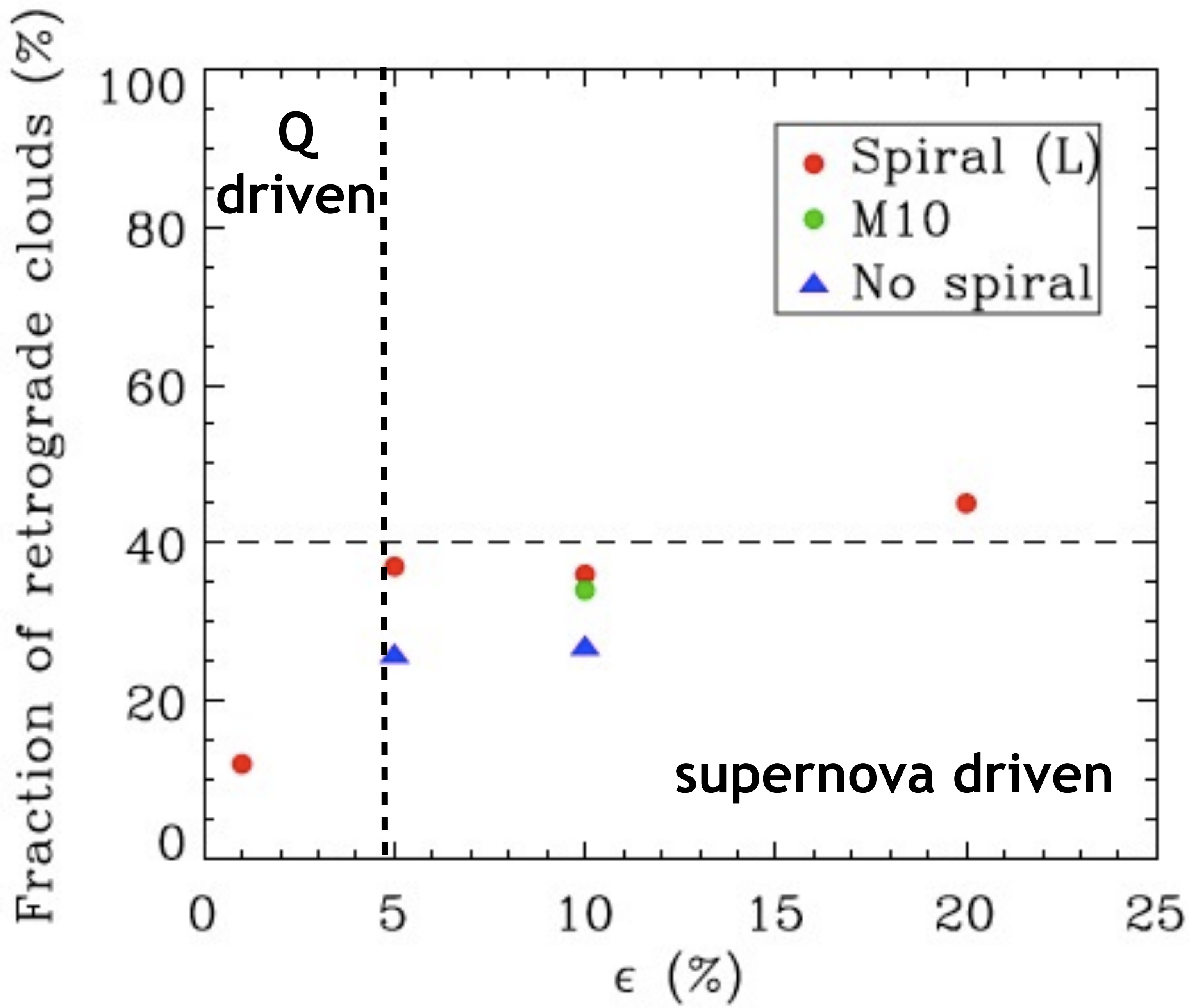


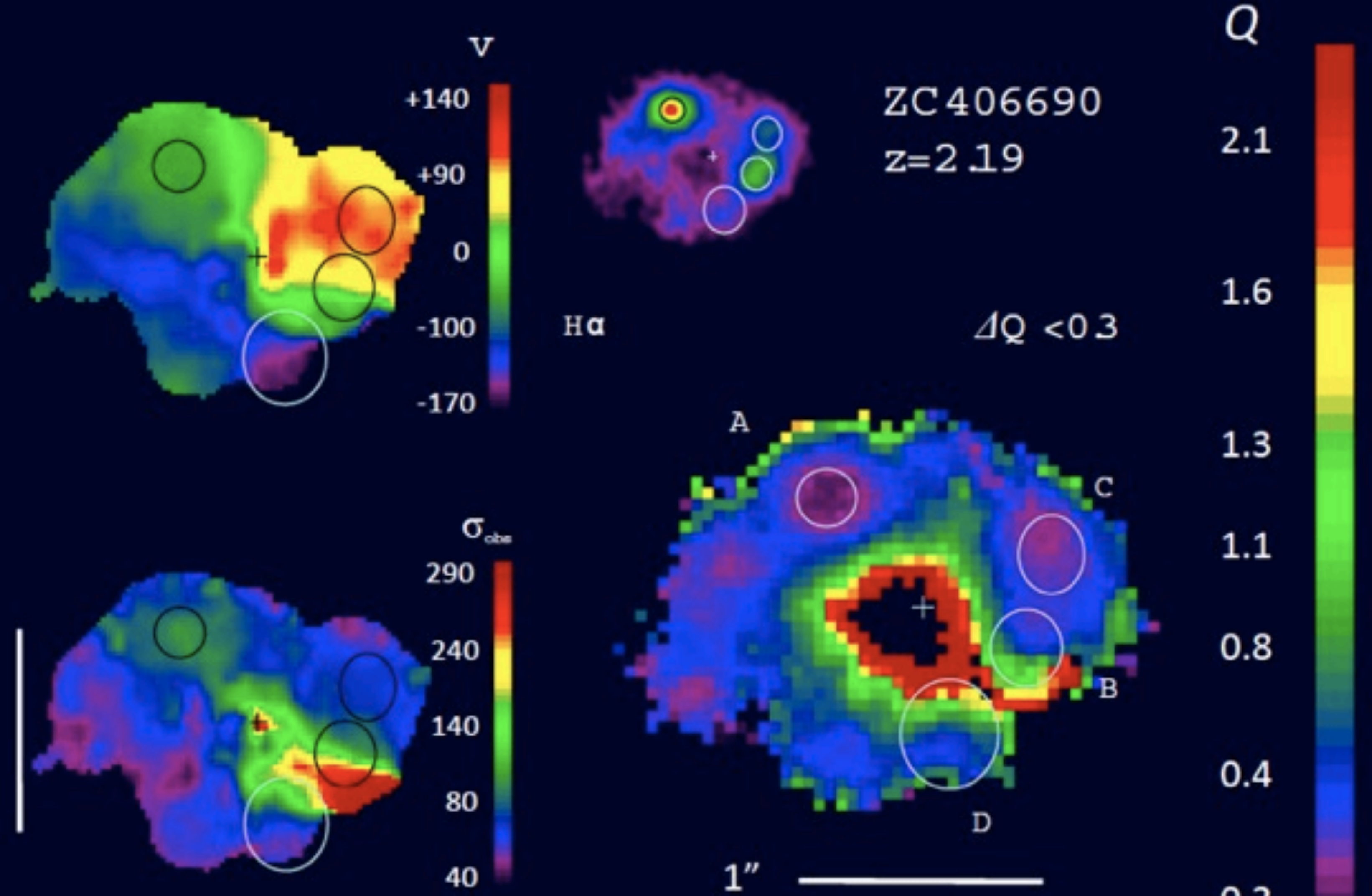
Gravity driven mode: formation of giant clumps



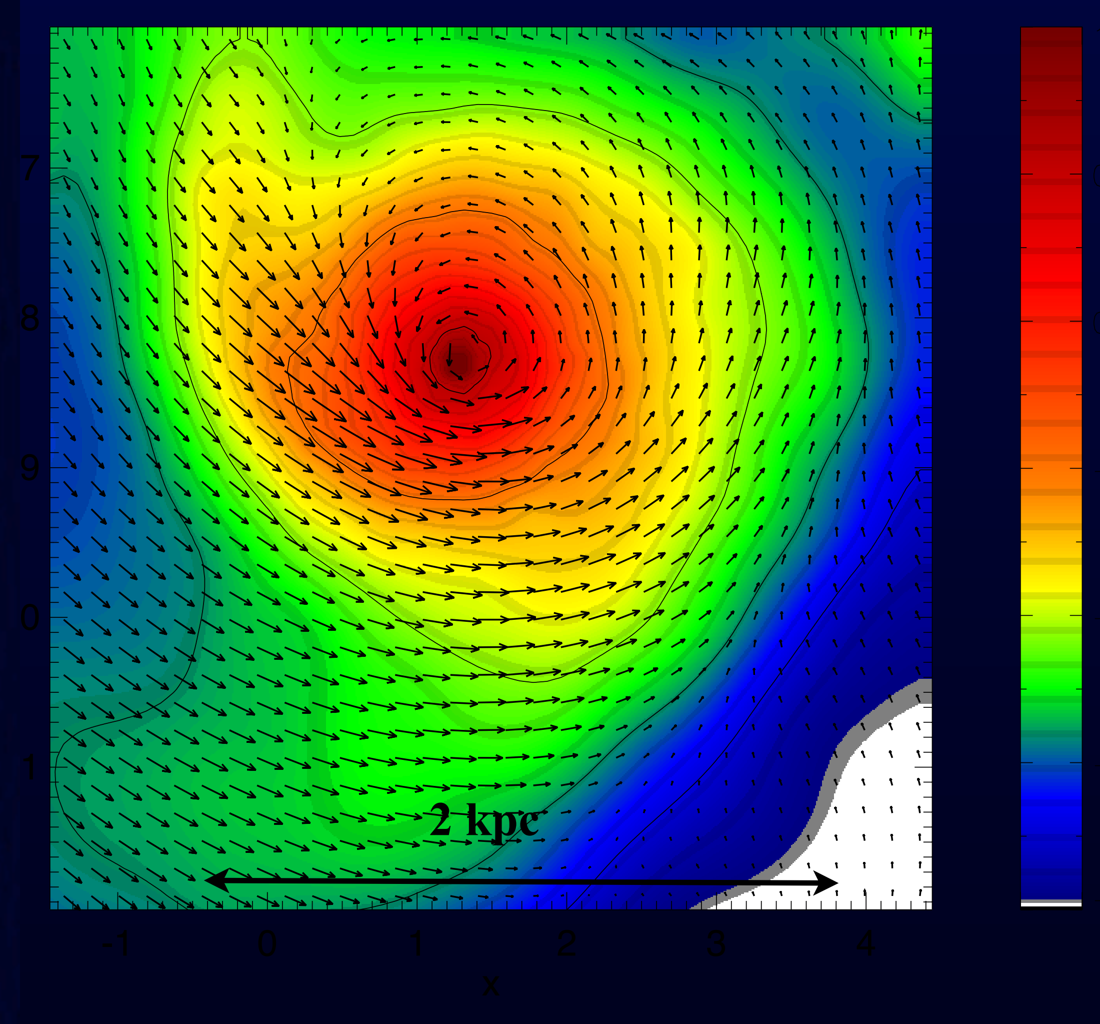


Fraction of retrograde clouds

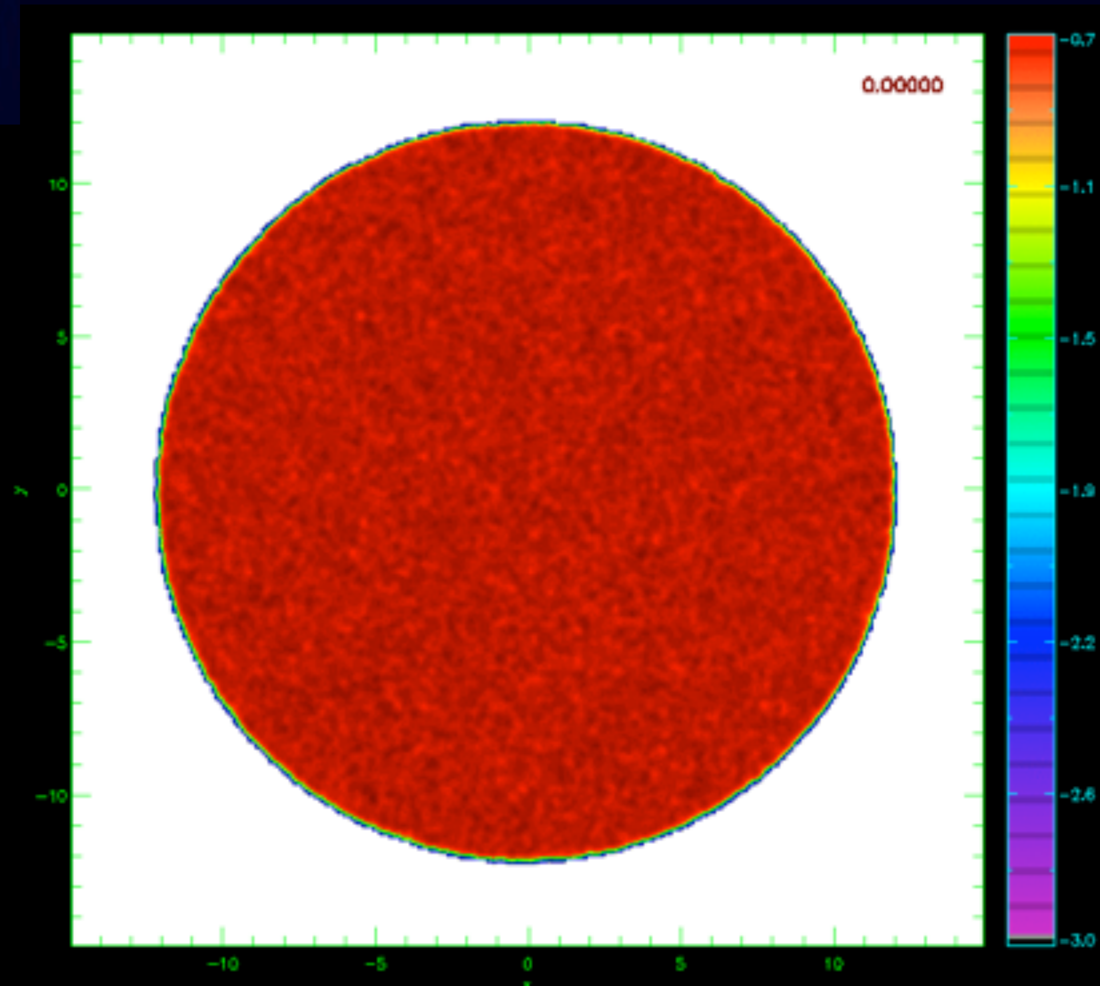


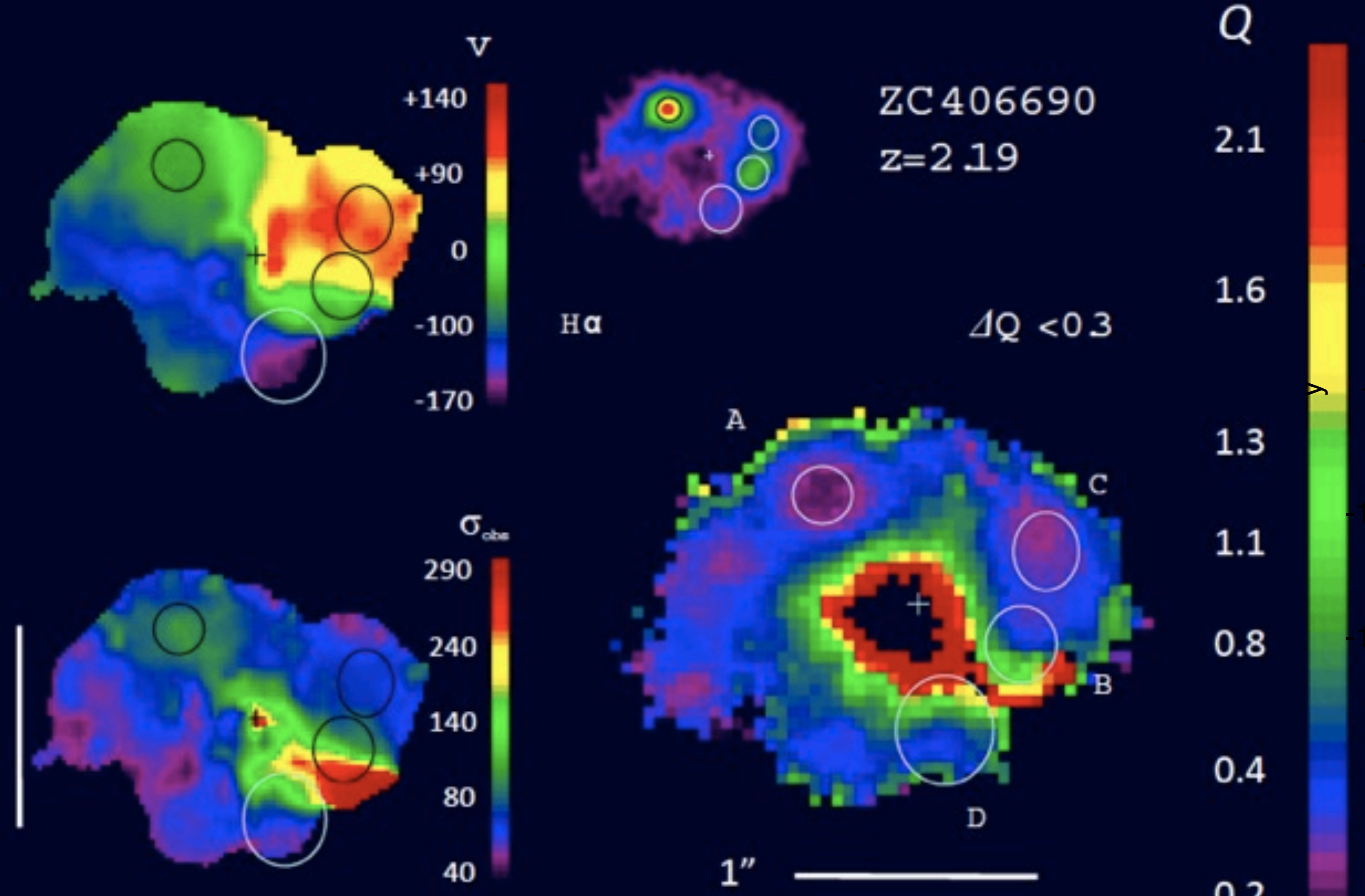


Genzel et al. (2011)

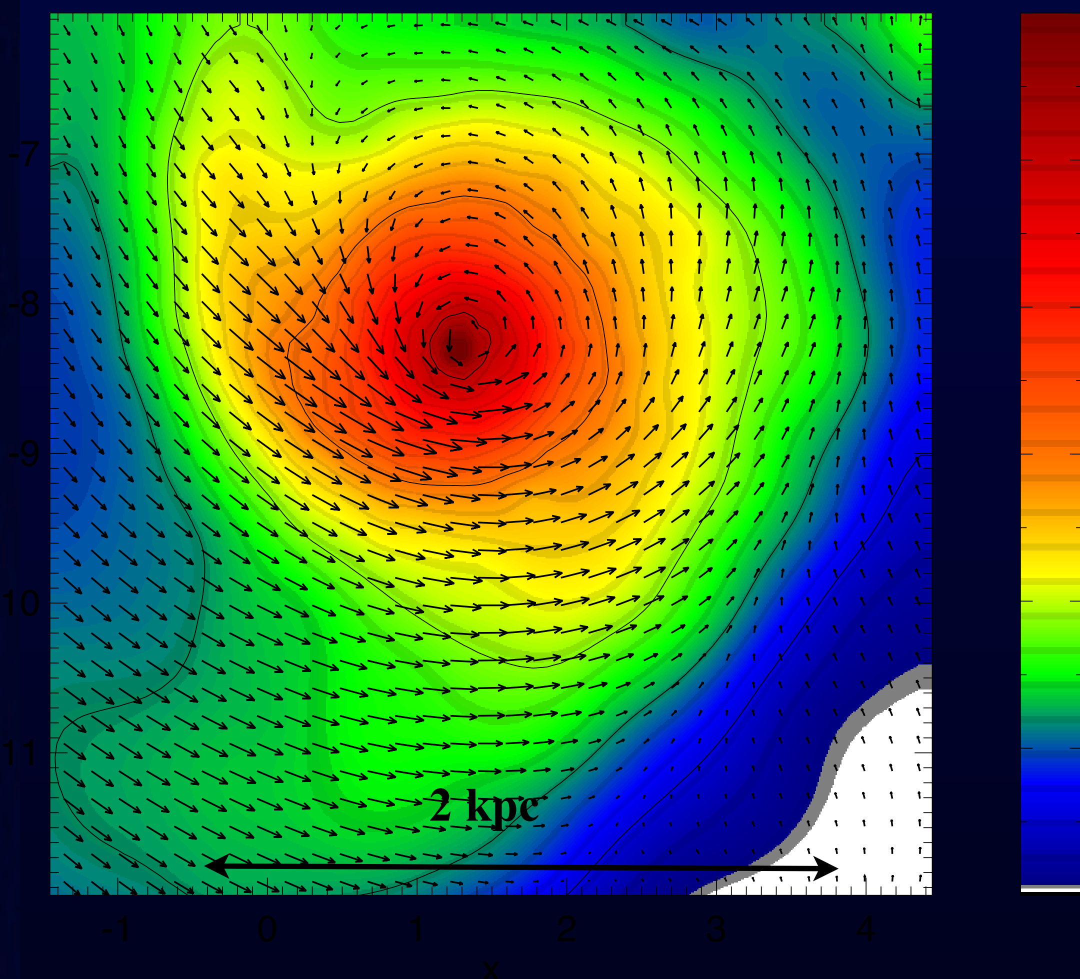


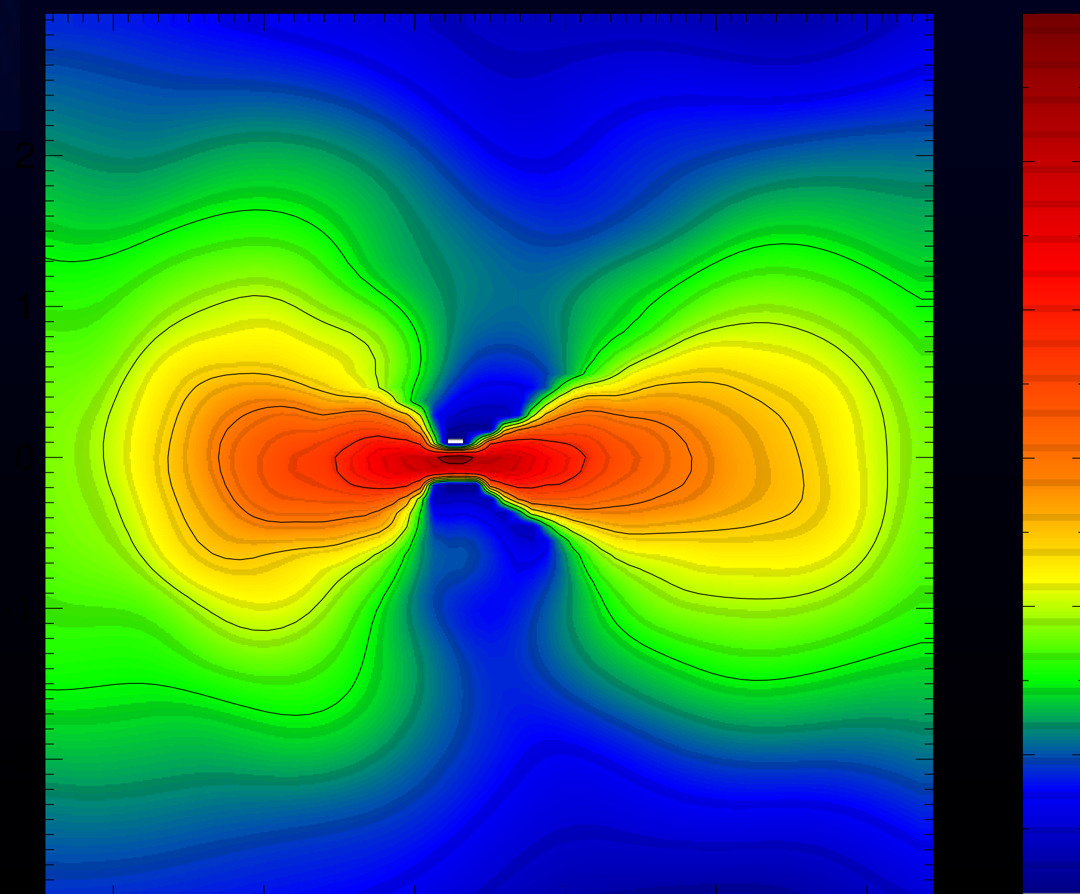
High-z disks: Q-driven mode?





Genzel et al. (2011)





High-z disks: Q-driven mode?

<u>Rotationally supported minidisks</u>

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

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

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.
- In the **gravity-driven mode** turbulence is regulated by **$Q \approx 1$** 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