The Puzzle of Star Formation

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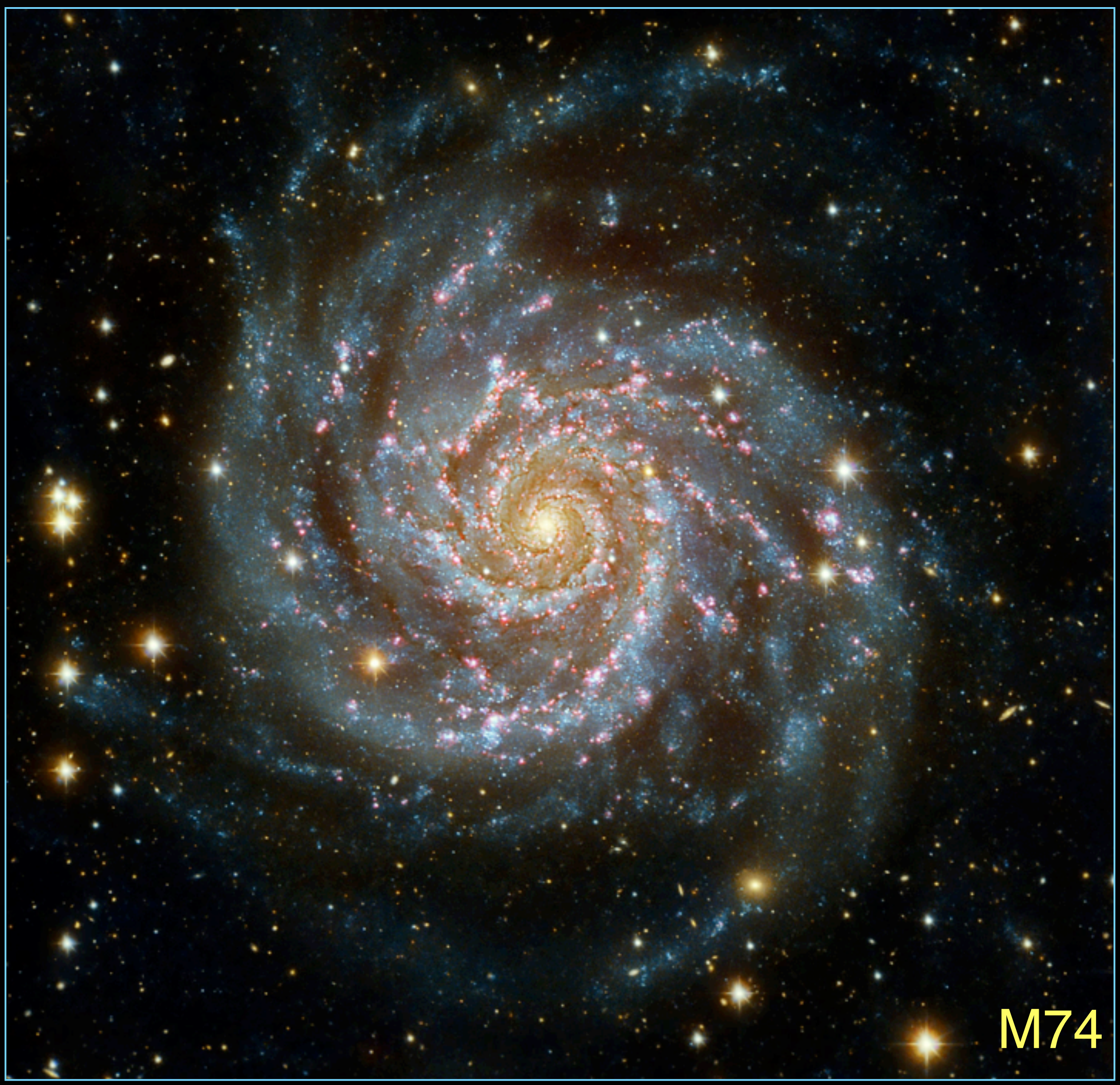
&
Andreas Burkert



Can we explain M74's star formation rate?

Can we explain M74's gas mass?

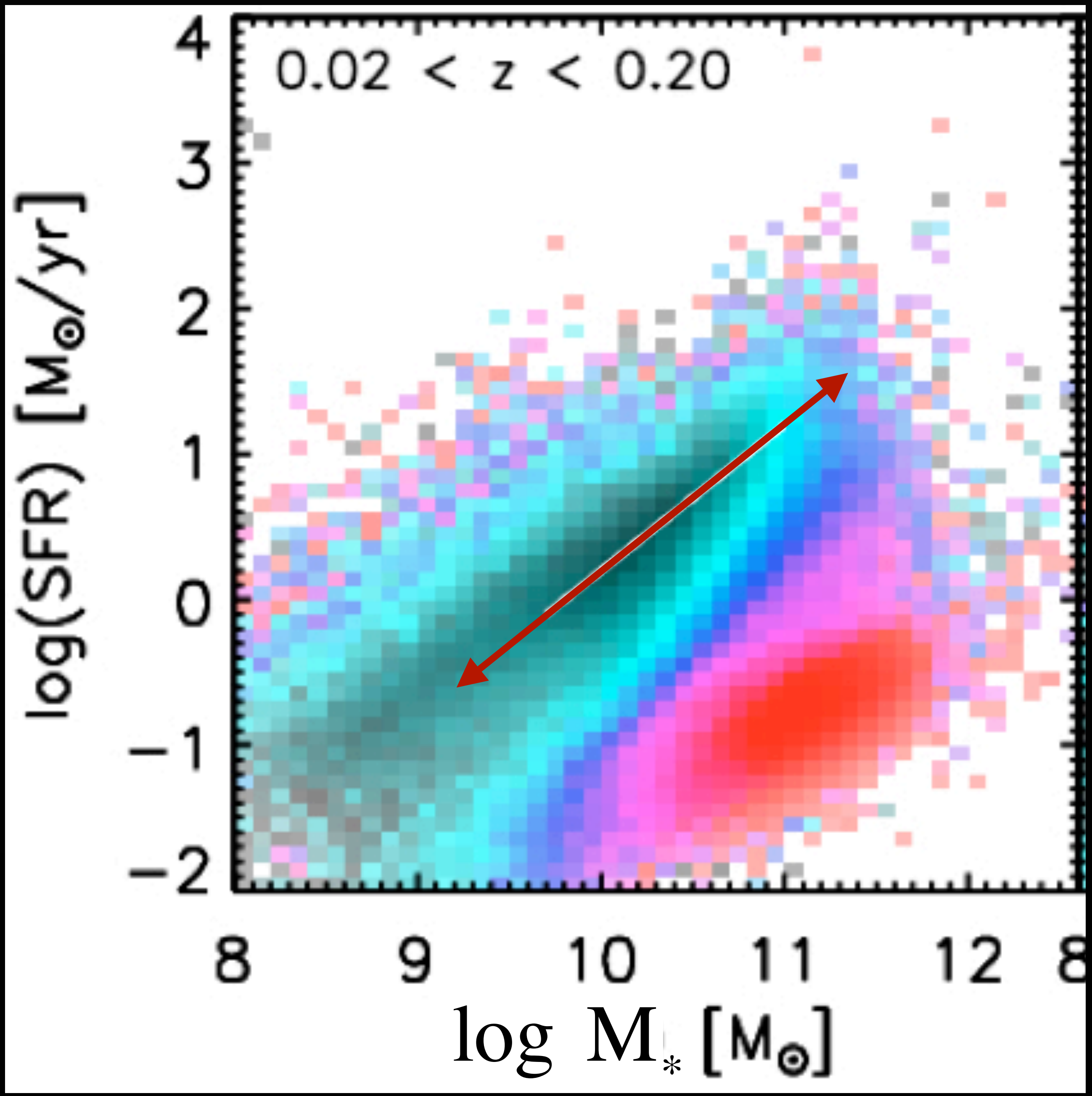
or

?

Why are star-forming galaxies gas-rich?

The Fundamental Plane of Star-Forming Galaxies

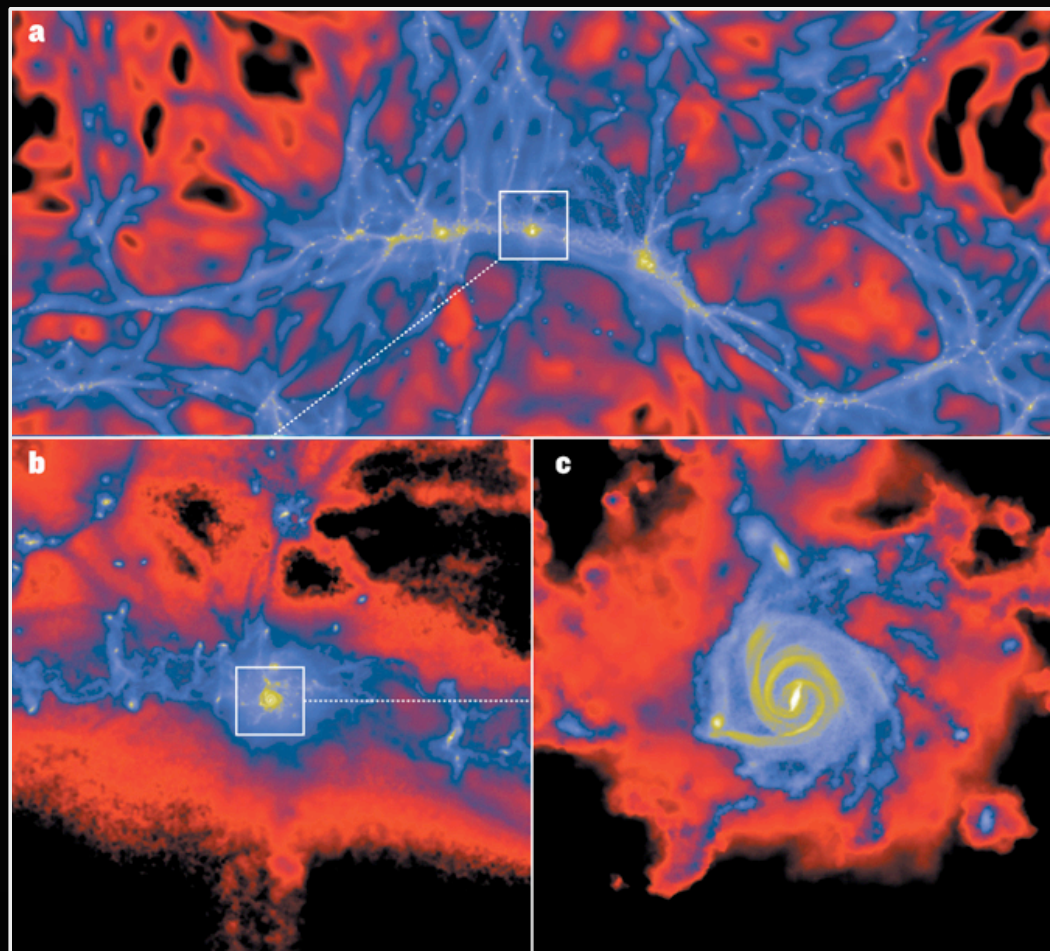
Rudnick+03,06; Adelberger+04; Noeske+07; Elbaz+07; Daddi+07; Marchesini+09; Shankar+09; Ilbert+10,13; Genzel+10; Peng+10; Brammer+11; Rodighiero+11,14; Caputi+11; Gonzalez+11; Magnelli+11,13; Whitaker+12,14; Muzzin+13; Stark+13; Speagle+14; Renzini&Peng15; Brinchmann+04; Schreiber+15, Tacconi+17 ...

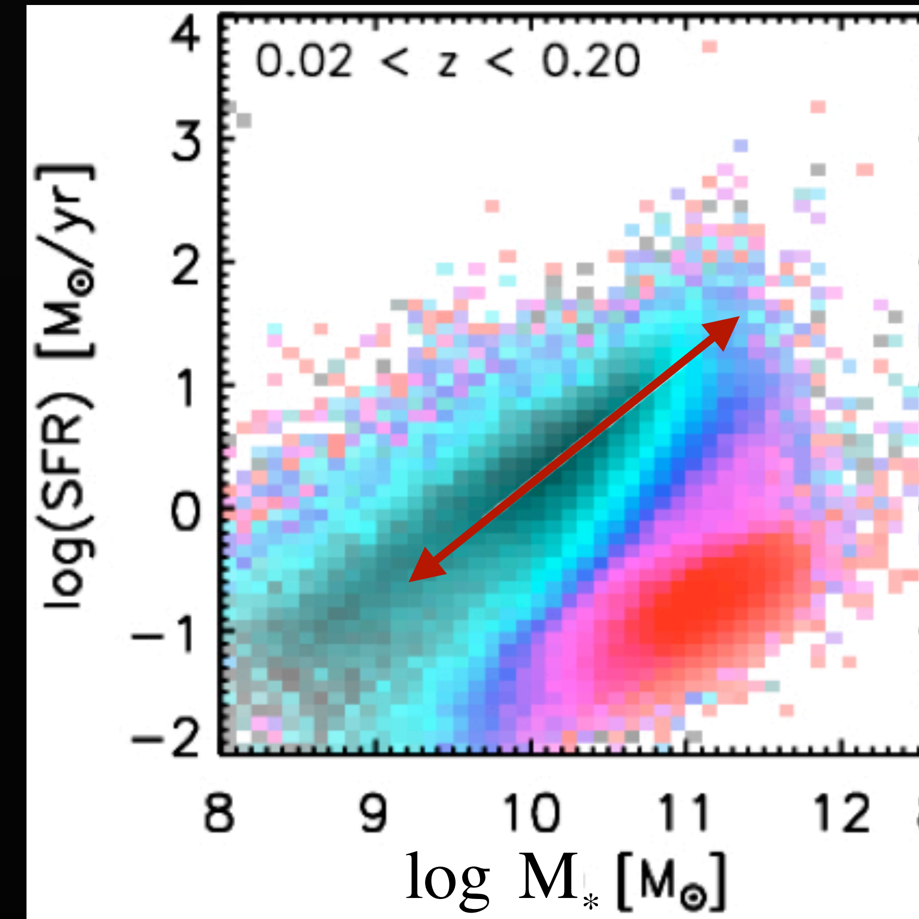


- Tight relation: 0.3 dex
- 90% of the cosmic SFR is on the MS

Cosmic accretion

(Bouche+10, Davé+11a,b, Lilly+13; Forbes+13)



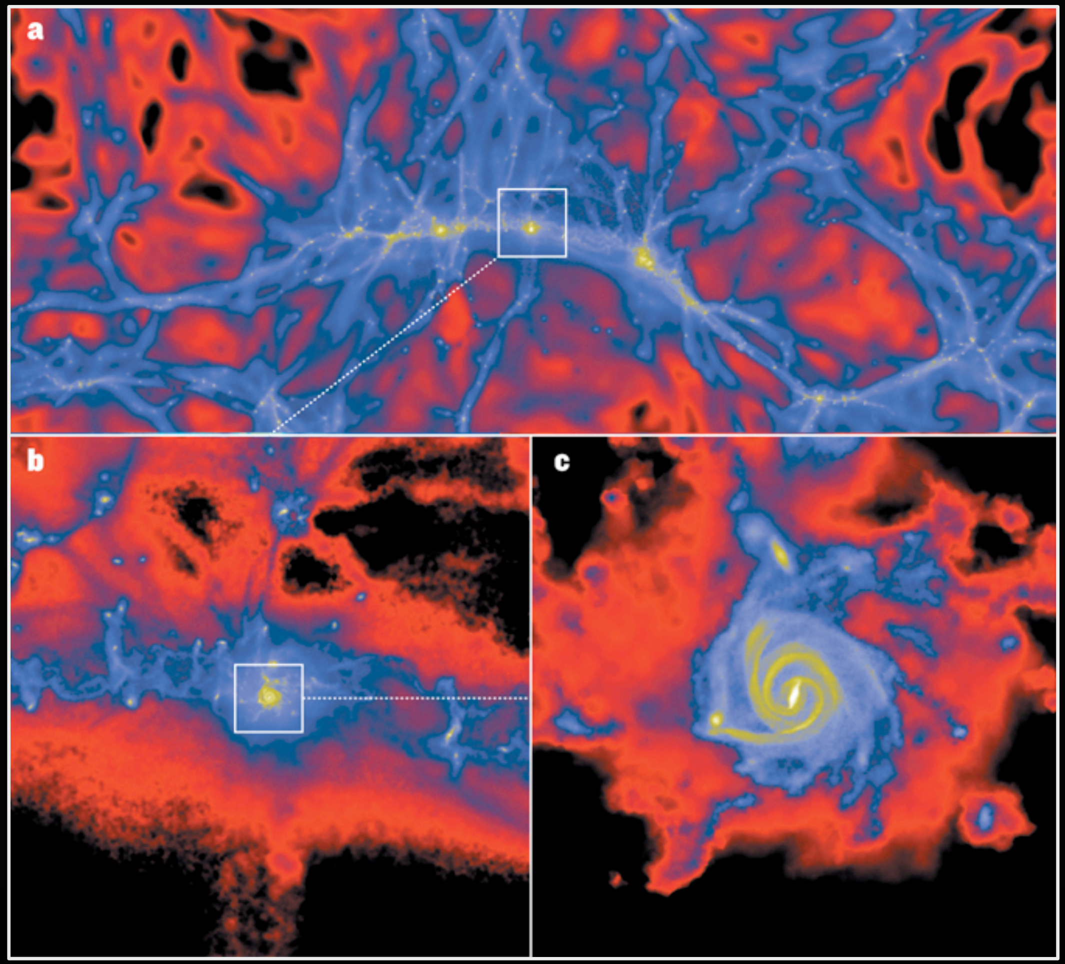


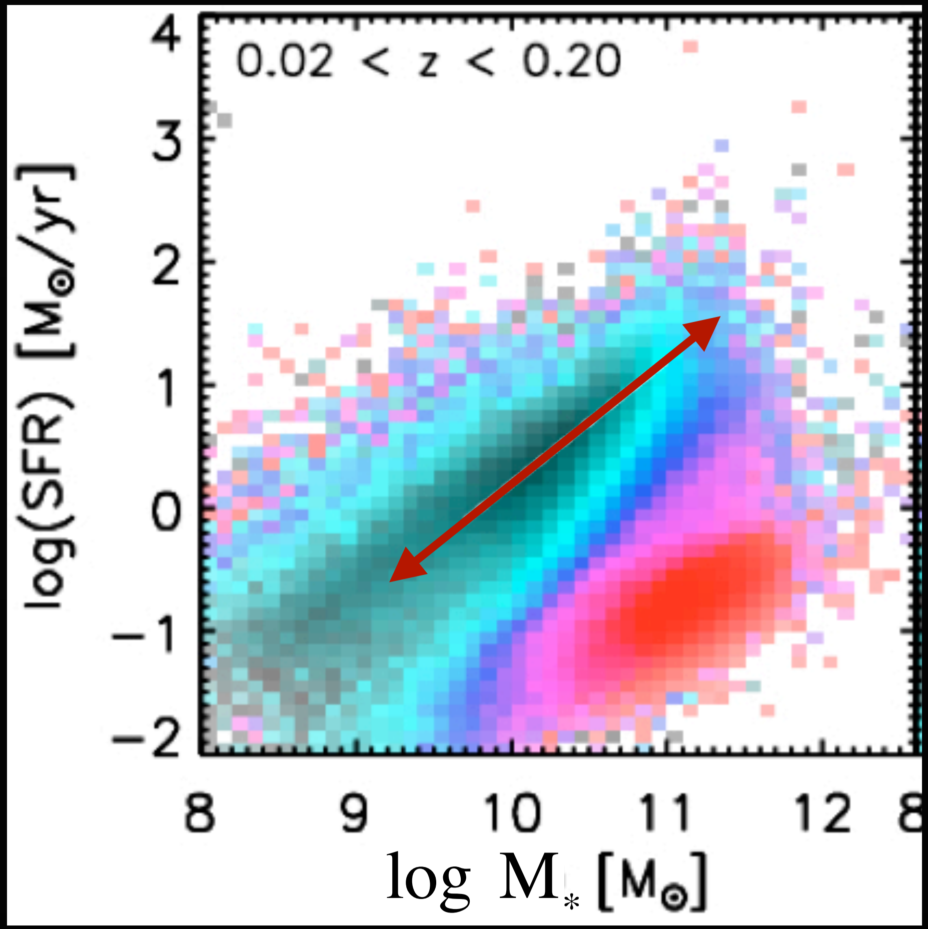
$$\dot{M}_g = \dot{M}_{acc} - SFR \cdot \left(1 - r + \alpha_{wind}\right) \approx \dot{M}_{acc} - 1.5 \cdot SFR$$

Equilibrium:

$$\dot{M}_g = 0 \quad \longrightarrow \quad SFR = \frac{2}{3}\dot{M}_{acc}$$

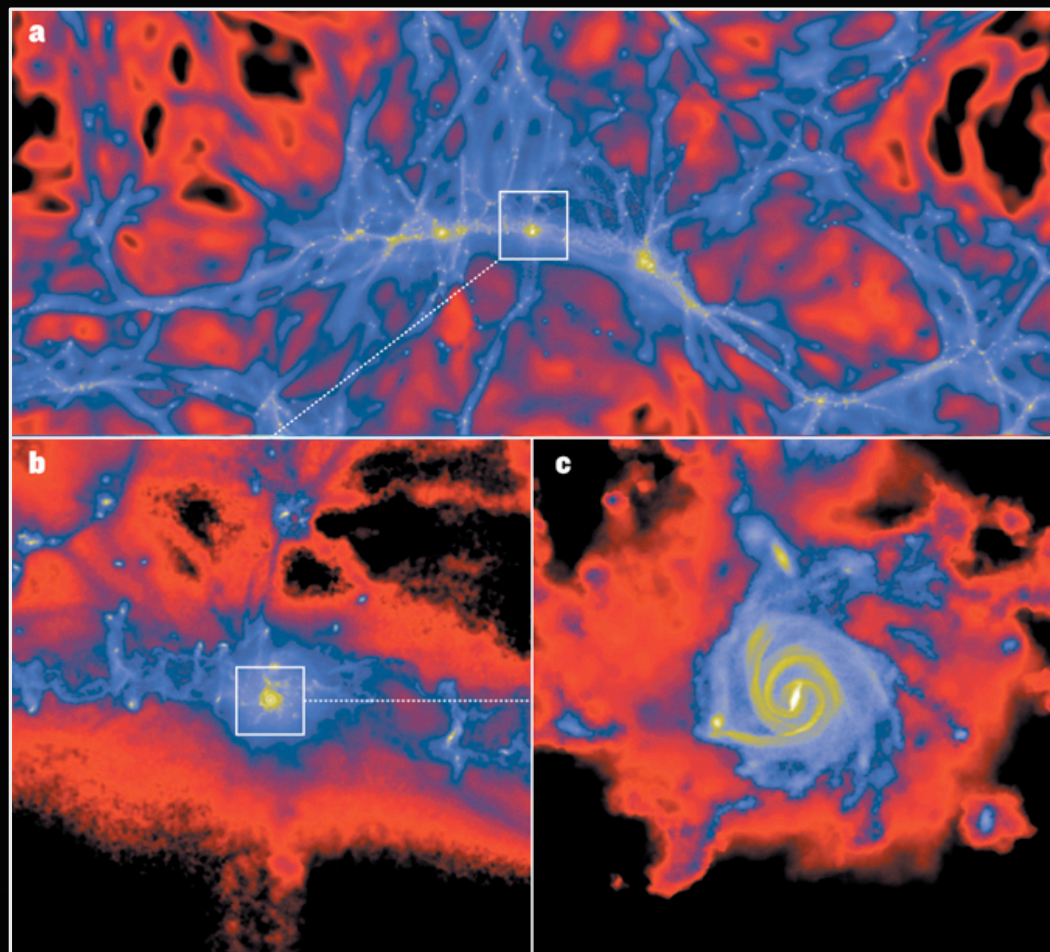
Why are galaxies gas rich?

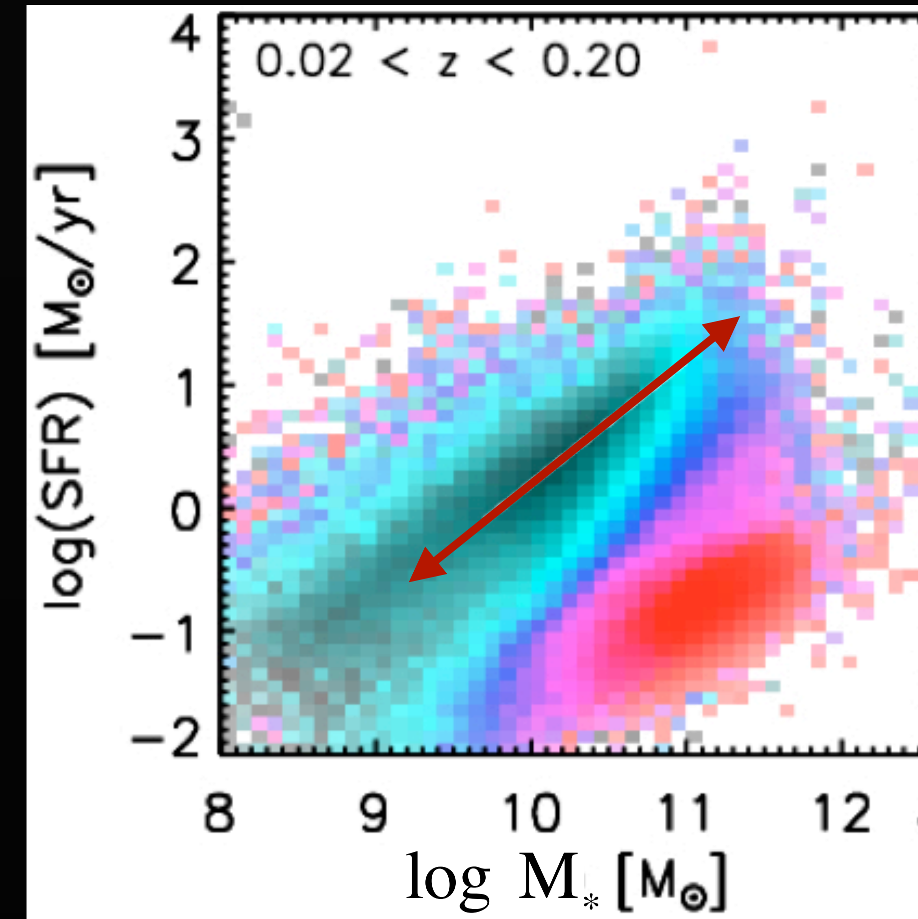




$$SFR = \frac{M_{H_2}}{\tau_{depl}} = \frac{2}{3}\dot{M}_{acc}$$

Why are galaxies gas rich?

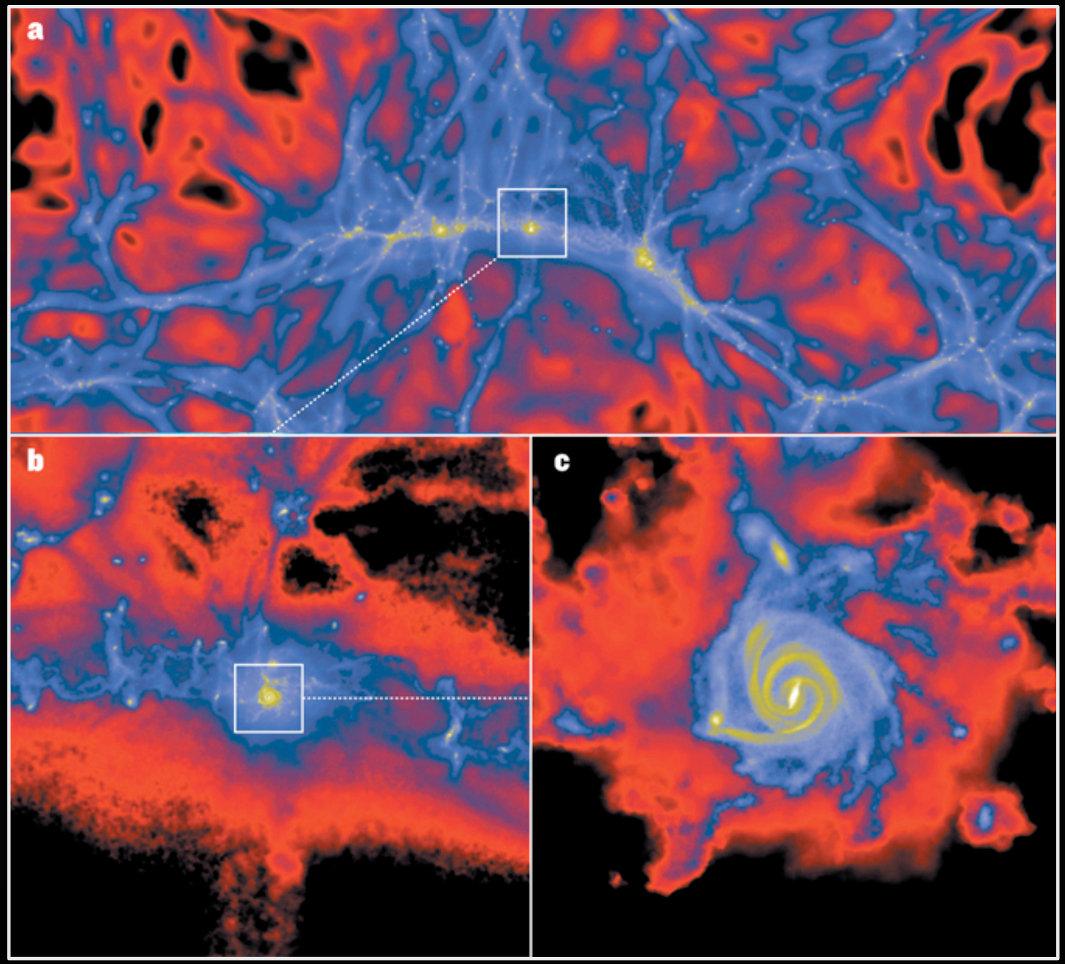




$$SFR = \frac{M_{H_2}}{\tau_{depl}} = \frac{2}{3}\dot{M}_{acc} \longrightarrow$$

$$M_{H_2} = \frac{2}{3}\dot{M}_{acc} \times \tau_{depl}$$

Why are galaxies gas rich?



Example

$$SFR = 2M_\odot/yr$$

$$\dot{M}_{acc} = 3M_\odot/yr$$

$$\tau_{depl} = 10^7 yrs$$

$$\longrightarrow M_{H_2} = 2 \times 10^7 M_\odot$$

$$\tau_{depl} = 10^9 yrs$$

$$\longrightarrow M_{H_2} = 2 \times 10^9 M_\odot$$

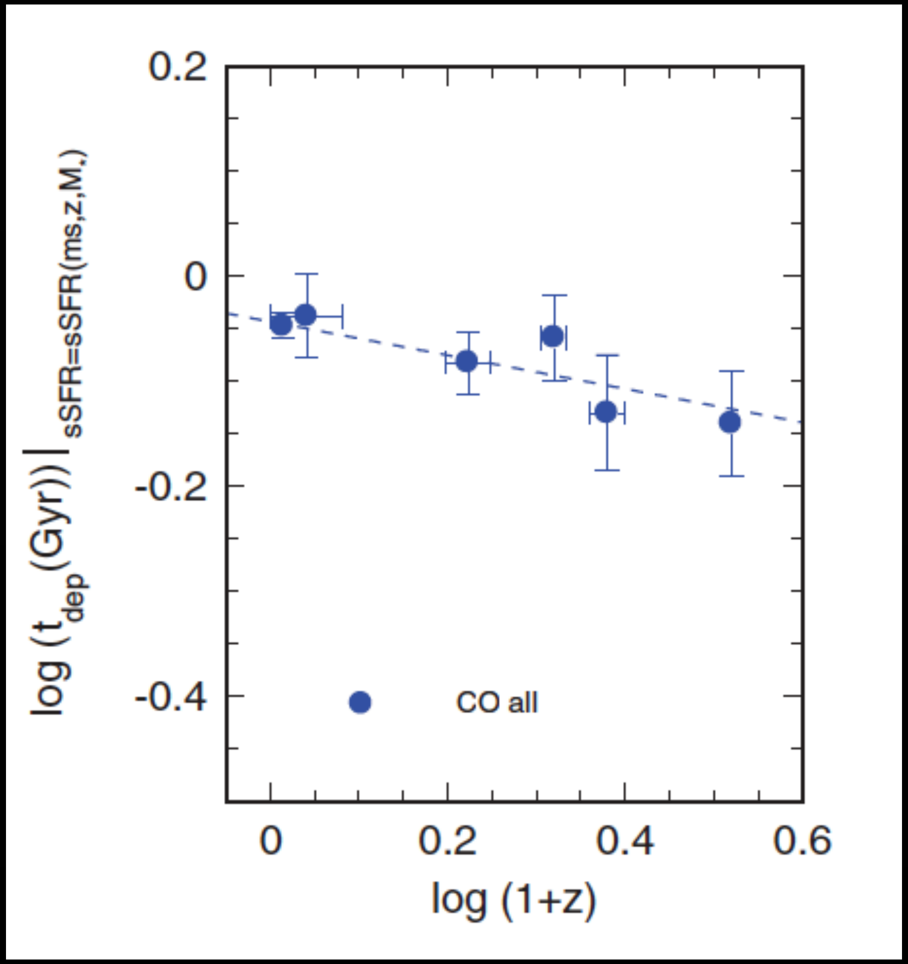
$$SFR = \frac{M_{H_2}}{\tau_{depl}} = \frac{2}{3}\dot{M}_{acc} \longrightarrow M_{H_2} = \frac{2}{3}\dot{M}_{acc} \times \tau_{depl}$$

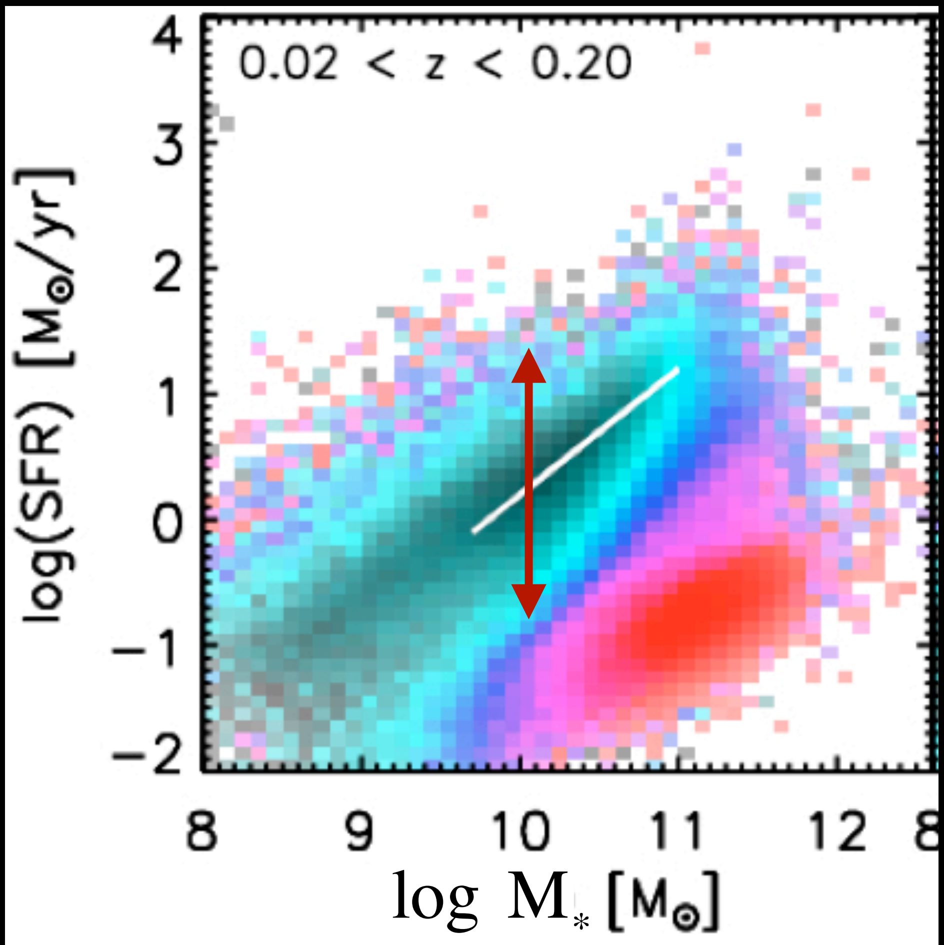
What determines the gas depletion timescale?

The surprising inefficiency of star formation

(Tacconi, Genzel & Sternberg 20)

$$\tau_{depl} = 1.6 \times 10^9 yrs \overset{?}{\times} \left(\frac{SFR}{SFR_{MS}}\right)^{-0.5} \overset{?}{\times} \left(\frac{1}{1+z}\right)$$





Star Formation per Free Fall Time

$$SFR = \epsilon_{ff} \frac{M_{H_2}}{\tau_{ff}} \longrightarrow \tau_{depl} = \frac{\tau_{ff}}{\epsilon_{ff}}$$

$1.6 \times 10^9 yrs$ $4 \times 10^6 yrs$

$$\epsilon_{ff} = 0.0025$$

Is this reasonable?

$$\tau_{depl} = \frac{\tau_{collapse}}{\epsilon_{sf}} = 1.6 \times 10^9 yrs$$

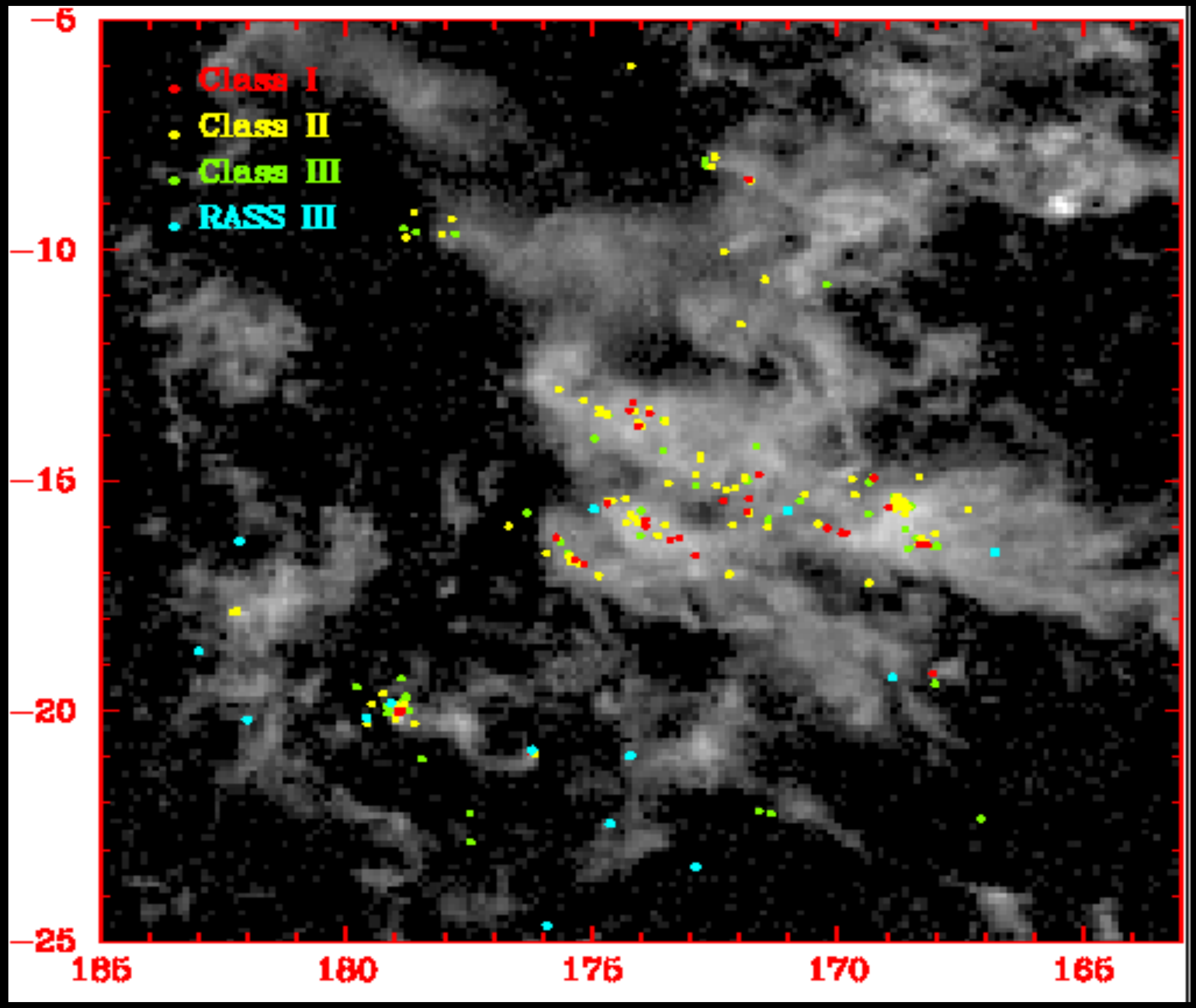
$\epsilon_{sf} = 0.1$ $\longrightarrow$ $\tau_{collapse} = 1.6 \times 10^8 yrs$

Could a large fraction of the molecular gas be stable against gravitational collapse?

How efficient is stellar feedback in dispersing molecular gas?

The post T-Tauri problem

Taurus



(Hartmann 2000, 2001)

Age spread of stars in Taurus:

1 - 3 Myrs

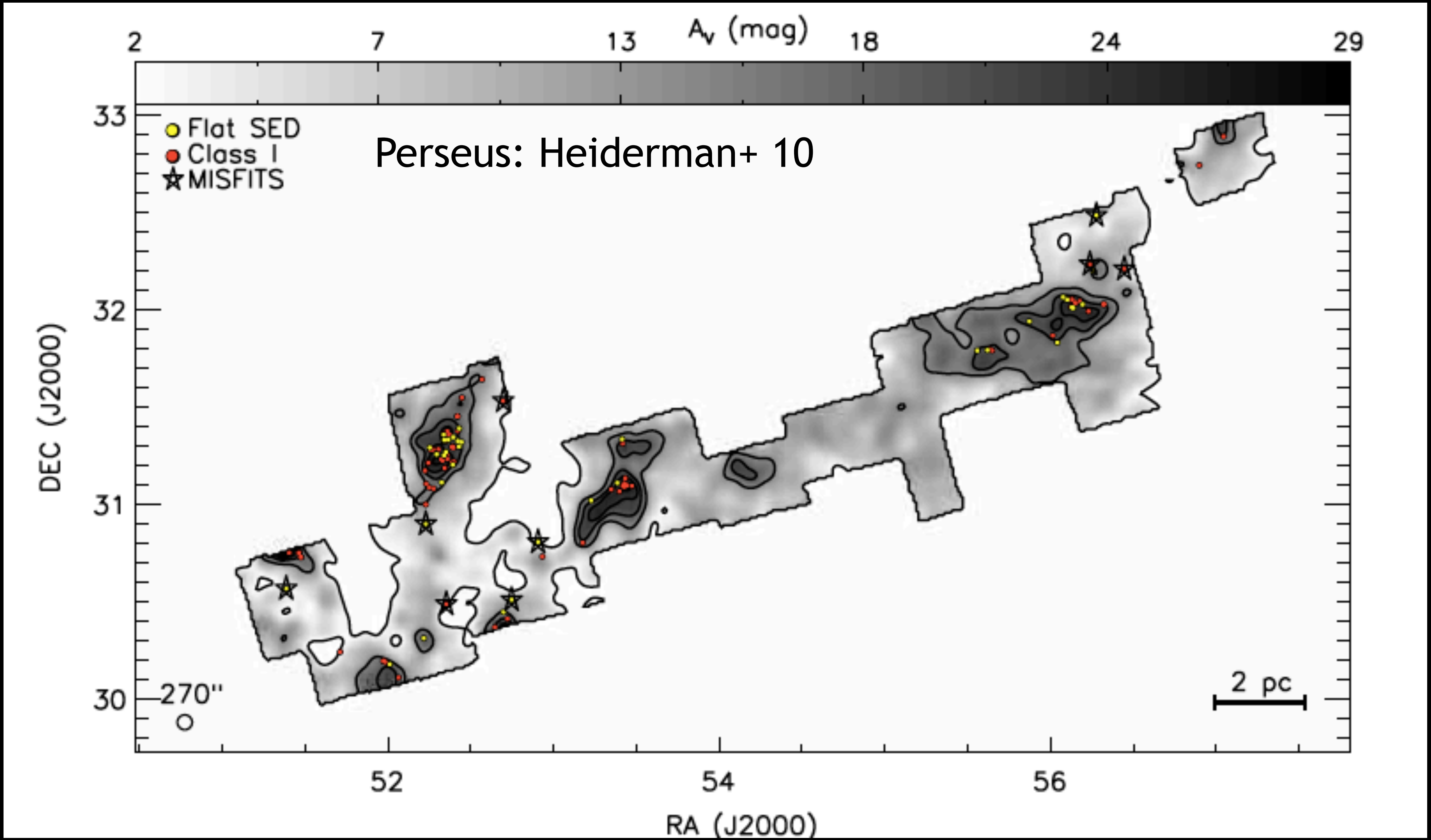
Almost **all** GMCs show **star formation.**

⟶ **GMC lifetimes are a few Myrs**

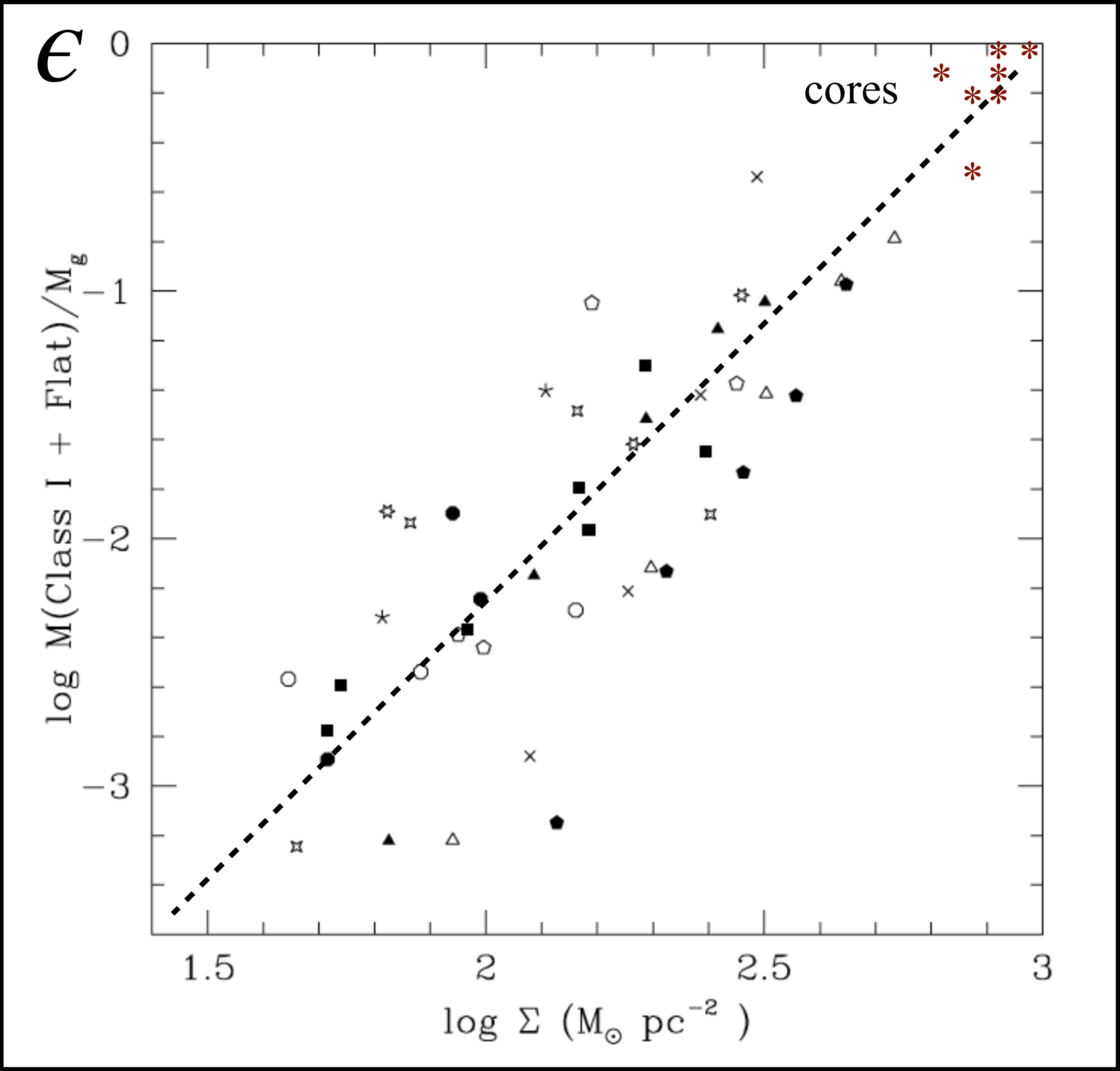
The star formation efficiency is a matter of definition?

(Burkert & Hartmann 2013)

Of course, **stars** always form in small dense pockets of **molecular gas**.
There the **efficiency** is quite large.



Dependence of SFE on gas surface density



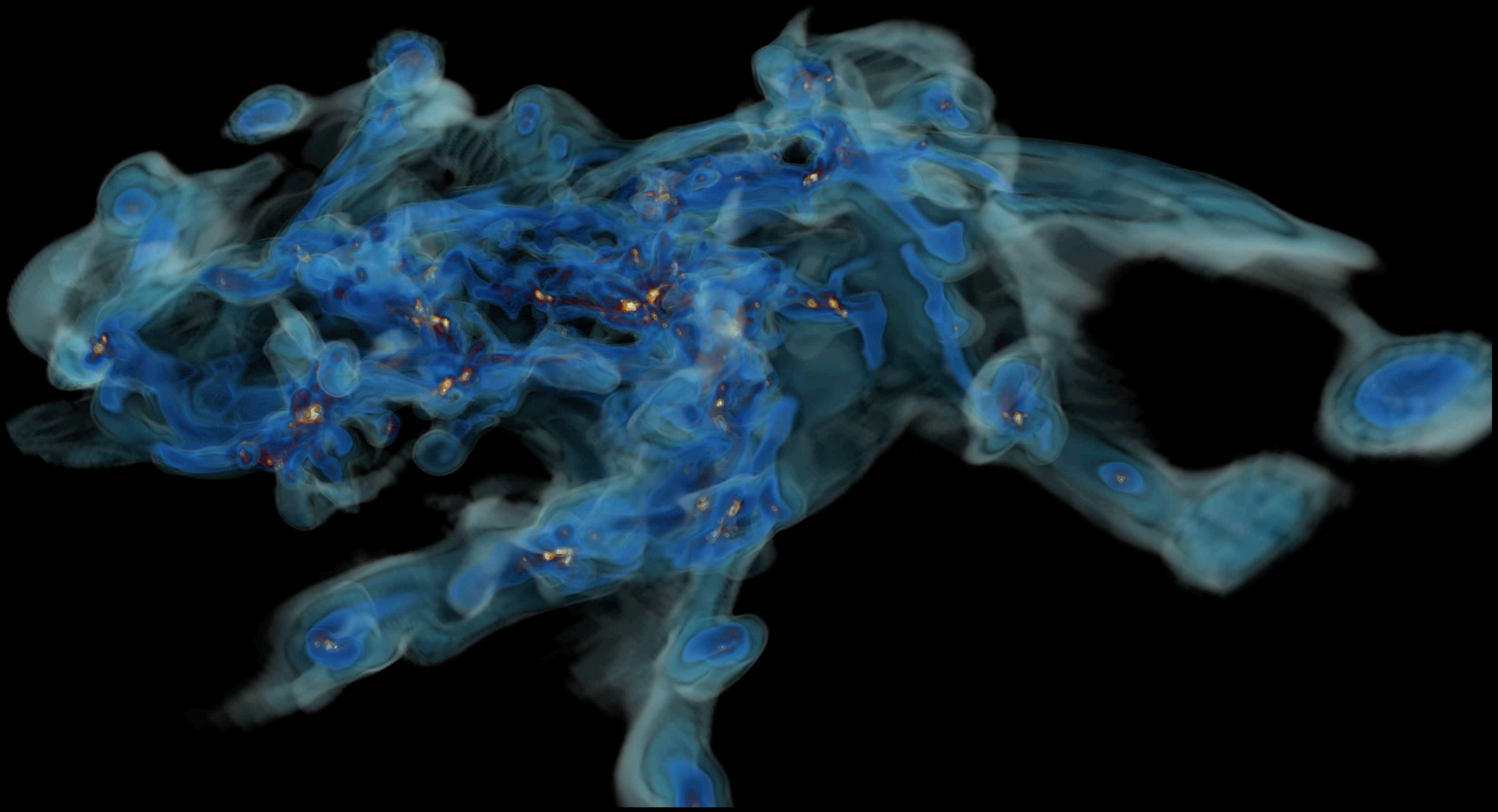
$$\epsilon = 0.01 \frac{\Sigma_{H_2}}{120 M_{\odot} pc^{-2}}$$

Maybe a large fraction of molecular gas is stable against gravitational collapse?

How can we quantify that observationally?

Irregular/Clumpy Galaxies at High-z

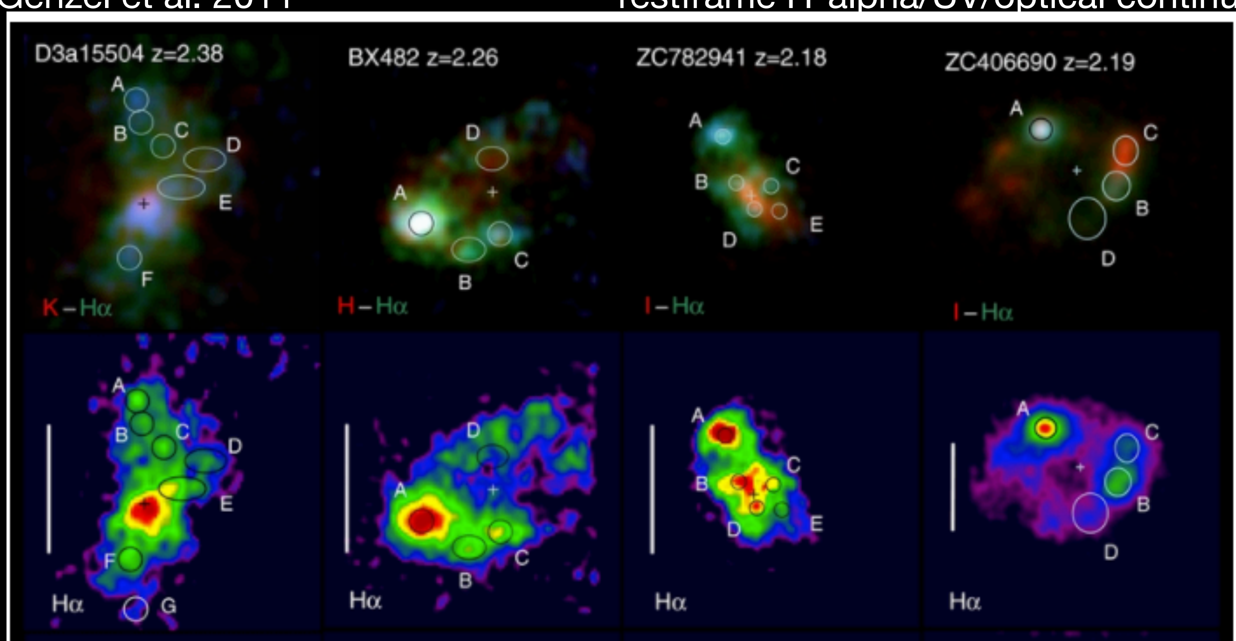
What is the Life-Time of Clumps?



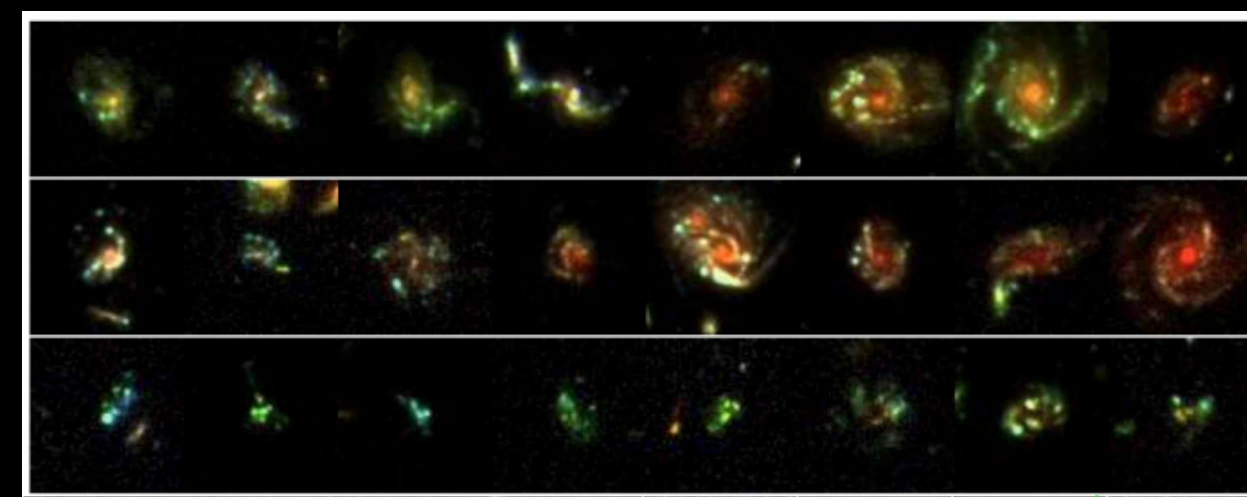
Irregular/Clumpy Galaxies at High-z

z~1-3

Genzel et al. 2011 restframe H-alpha/UV/optical continuum



Guo et al. 2018 RGB Bands - Restframe UV



- irregular and clumpy morphology
- large mol. gas fractions 30-80 %
- high σ ~20-100 km/s (ionized/molecular)
- rotating disks (M⁎ >10^9.5 M⊙)
- high SFR ~10-100 higher

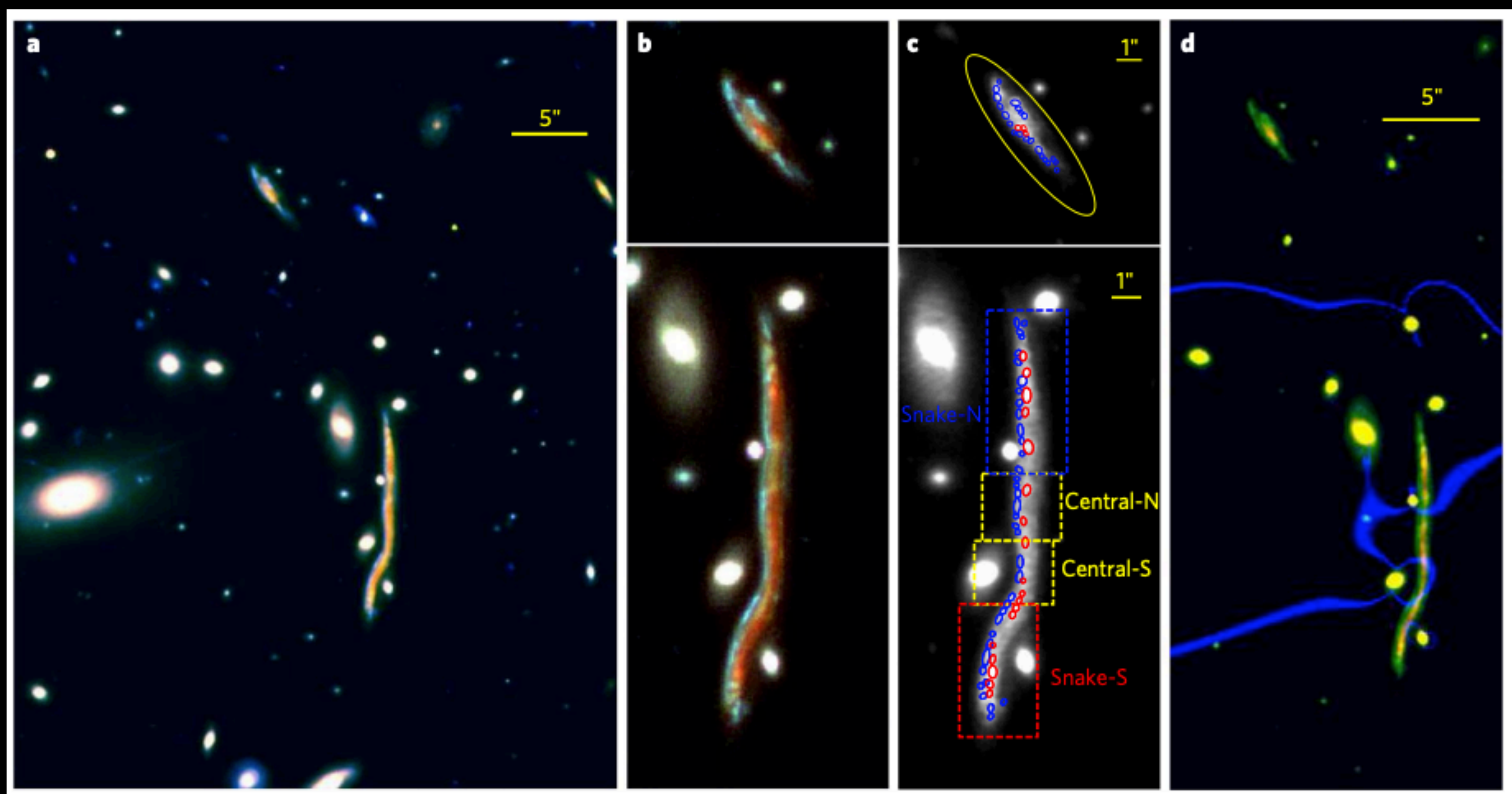
- clumps origin: disc instability?
Mclump ~10^8 - 10^9.5 M⊙
Rclump ~0.5 - 1.5 kpc

- observational resolution ~1-2 kpc

Giant Clump Substructure?

Strongly lensed

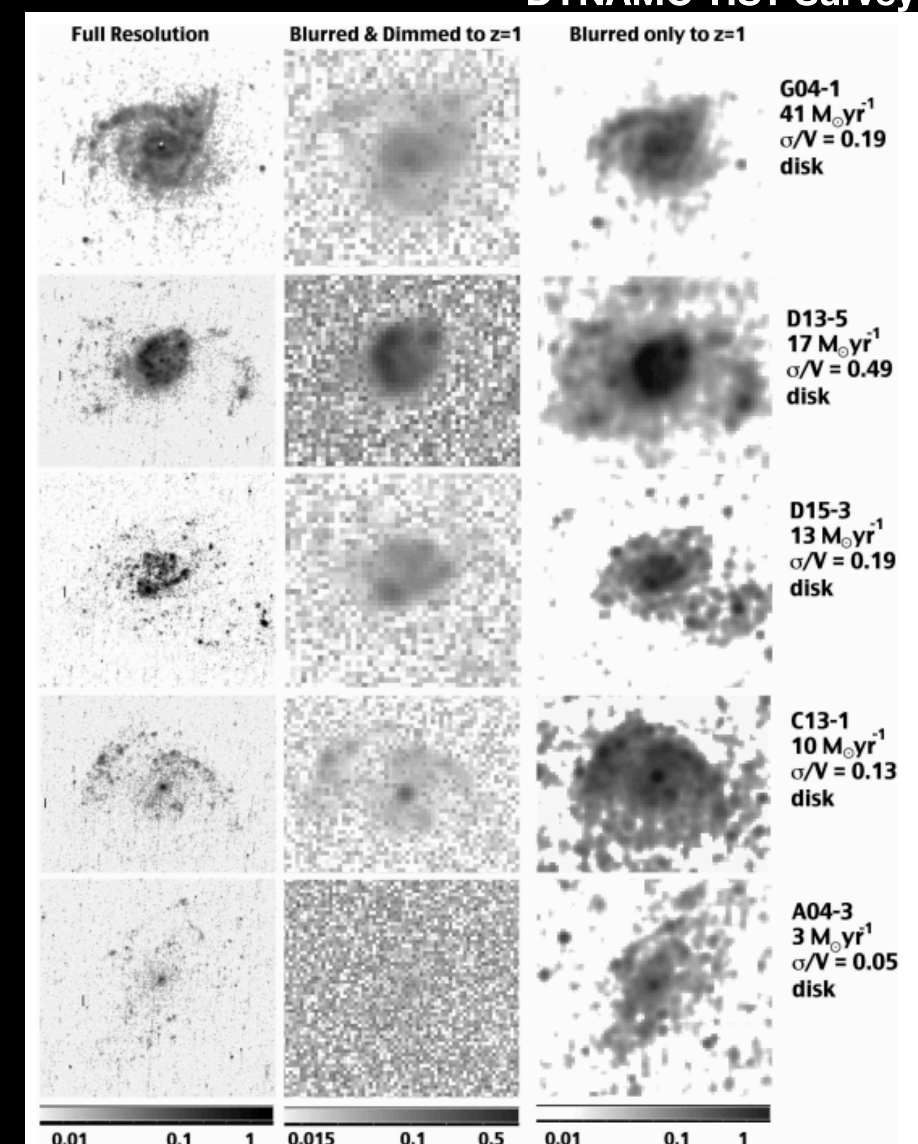
Cosmic Snake



Cava et al. 2017

Local Analogues

DYNAMO-HST Survey



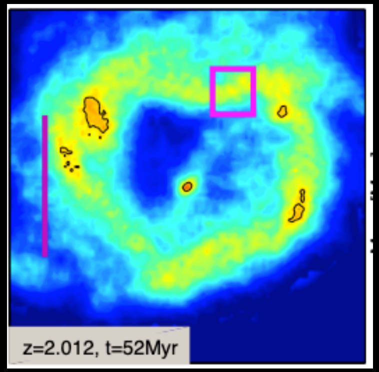
Fisher et al. 2017

Tuned Simulations to get SFR

Short Lived

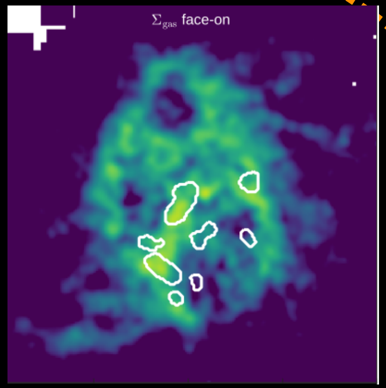
~ 50 Myr

Cosmological Zoom-In



Genel et al. 2011

Cosmological Simulations



Buck et al. 2016

Resolution dependence

- low -> lower densities

-> more fluffy

Tuned Simulations to get SFR

Short Lived

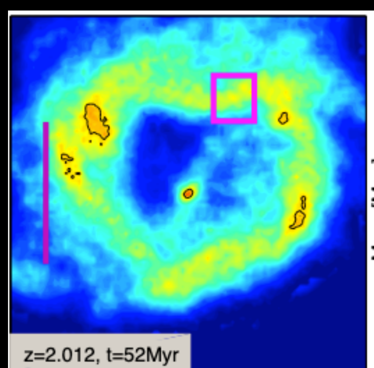
~ 50 Myr

Long Lived

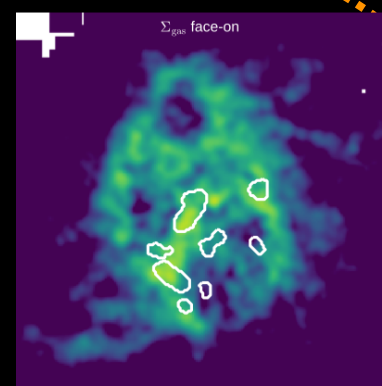
Several 100 Myrs

Cosmological Simulations

Cosmological Zoom-In



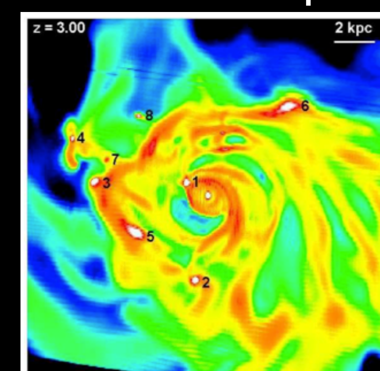
Genel et al. 2011



Buck et al. 2016

Cosmological Zoom-In

res ~ 70 pc



Ceverino et al. 2011

Resolution dependence

- low -> lower densities
-> more fluffy

- high -> higher densities
-> more compact -> less vulnerable to stellar feedback

Lifetime affects morphology

often preferred:

long-lived clumps can migrate to the center -> contribute to a bulge or feed AGN

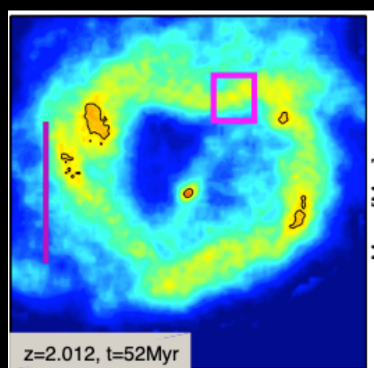
Tuned Simulations to get SFR

Short Lived

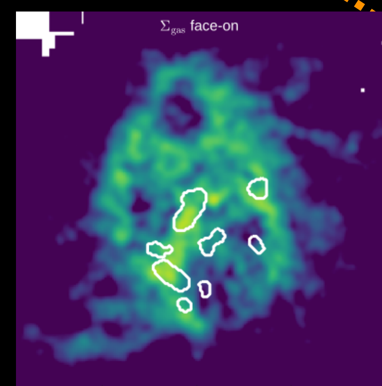
~ 50 Myr

Cosmological Simulations

Cosmological Zoom-In



Genel et al. 2011



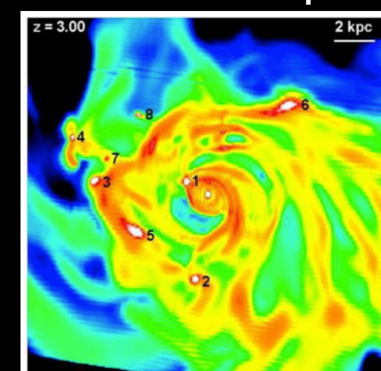
Buck et al. 2016

Long Lived

Several 100 Myrs

Cosmological Zoom-In

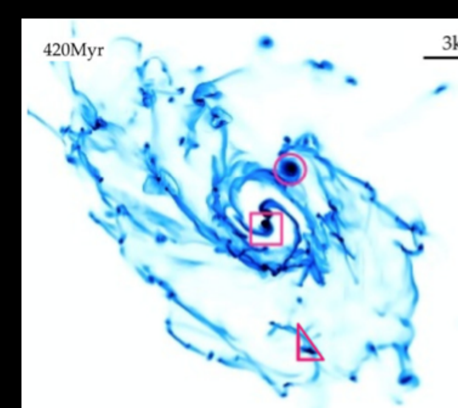
res ~ 70 pc



Ceverino et al. 2011

Isolated Galaxy

res ~ 3.5 pc



Bournaud et al. 2014

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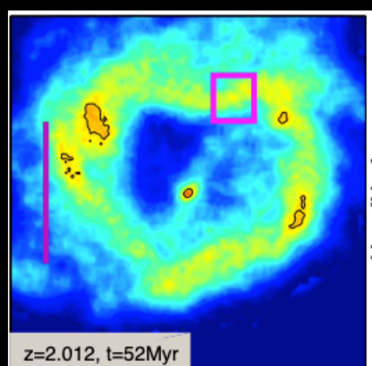
Cosmological Zoom-In



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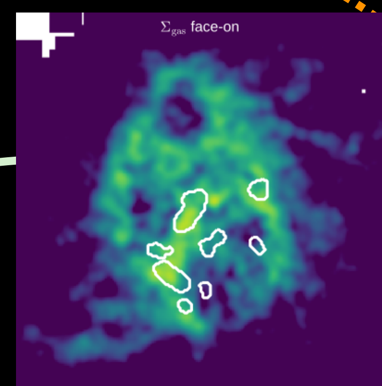

Buck et al. 2016

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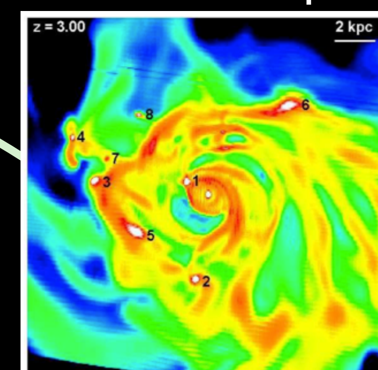

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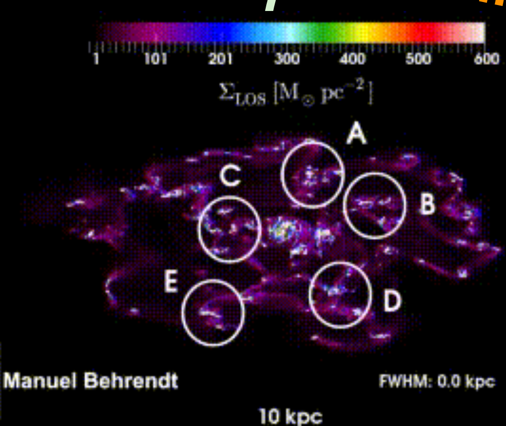
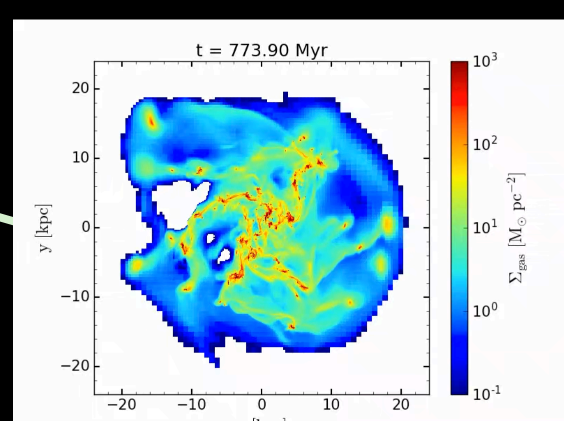


Isolated Galaxy

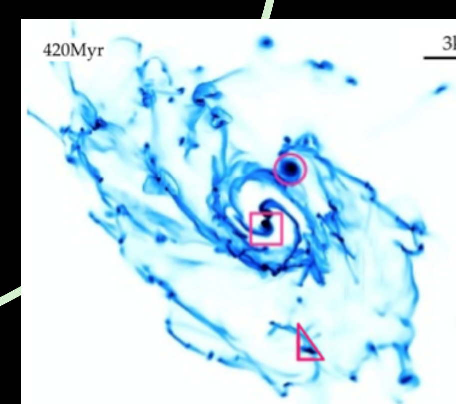
res ~ 3 pc



Behrendt et al.

Isolated Galaxy

res ~ 3.5 pc



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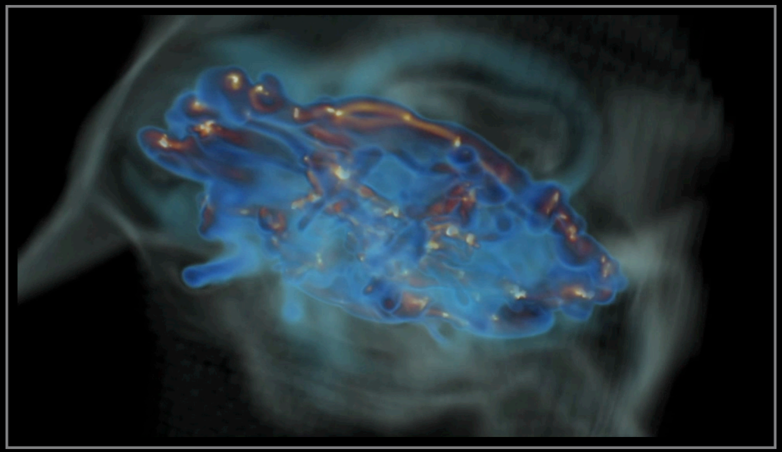
All Simulations can explain certain aspects of observations if you do mock observations (morphology, kinematics, SF,…)

Tuning

- SF efficiency/depletion
- Sn destructive nature (efficiency to supress SF) and move mass outwards
- At which densities stars form

Questions



Could a large fraction of the molecular gas be stable against gravitational collapse?

How efficient is stellar feedback in dispersing molecular gas?

Is there a dependence of the cloud lifetimes on their mass?

Is there an upper molecular cloud mass limit?

Do current simulations of gas-rich clumpy disks provide insight into massive clumps or do we need to wait for better resolved observations to understand their nature?