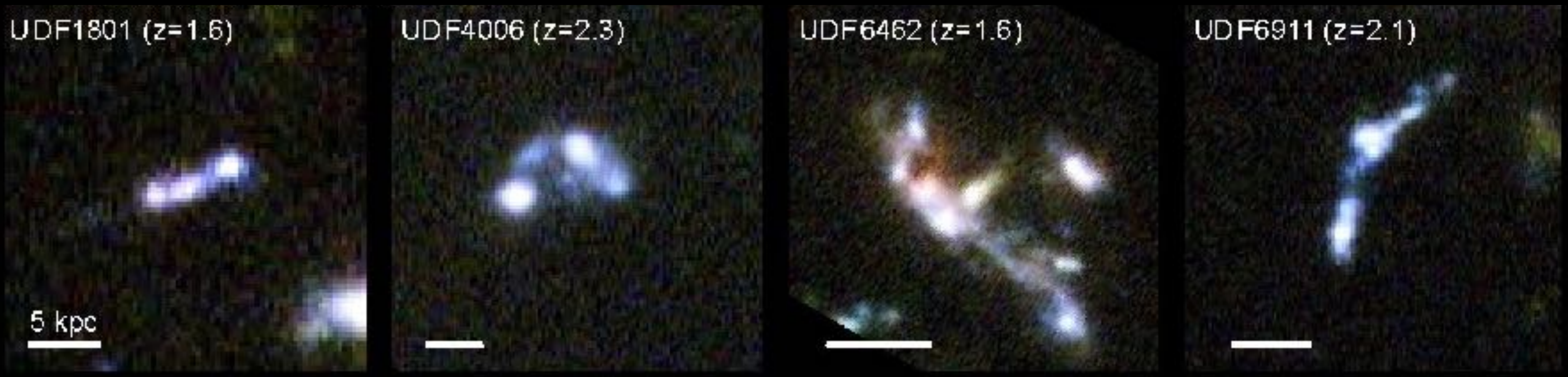
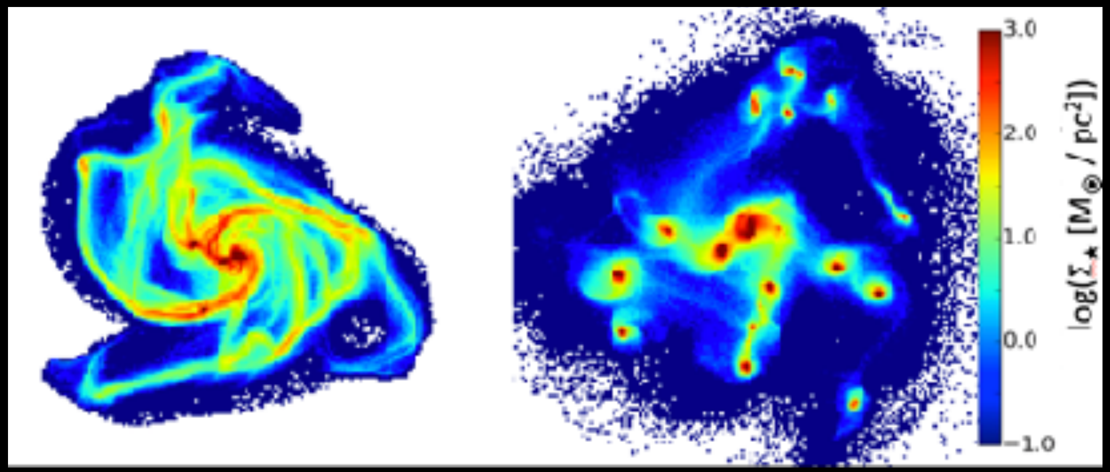


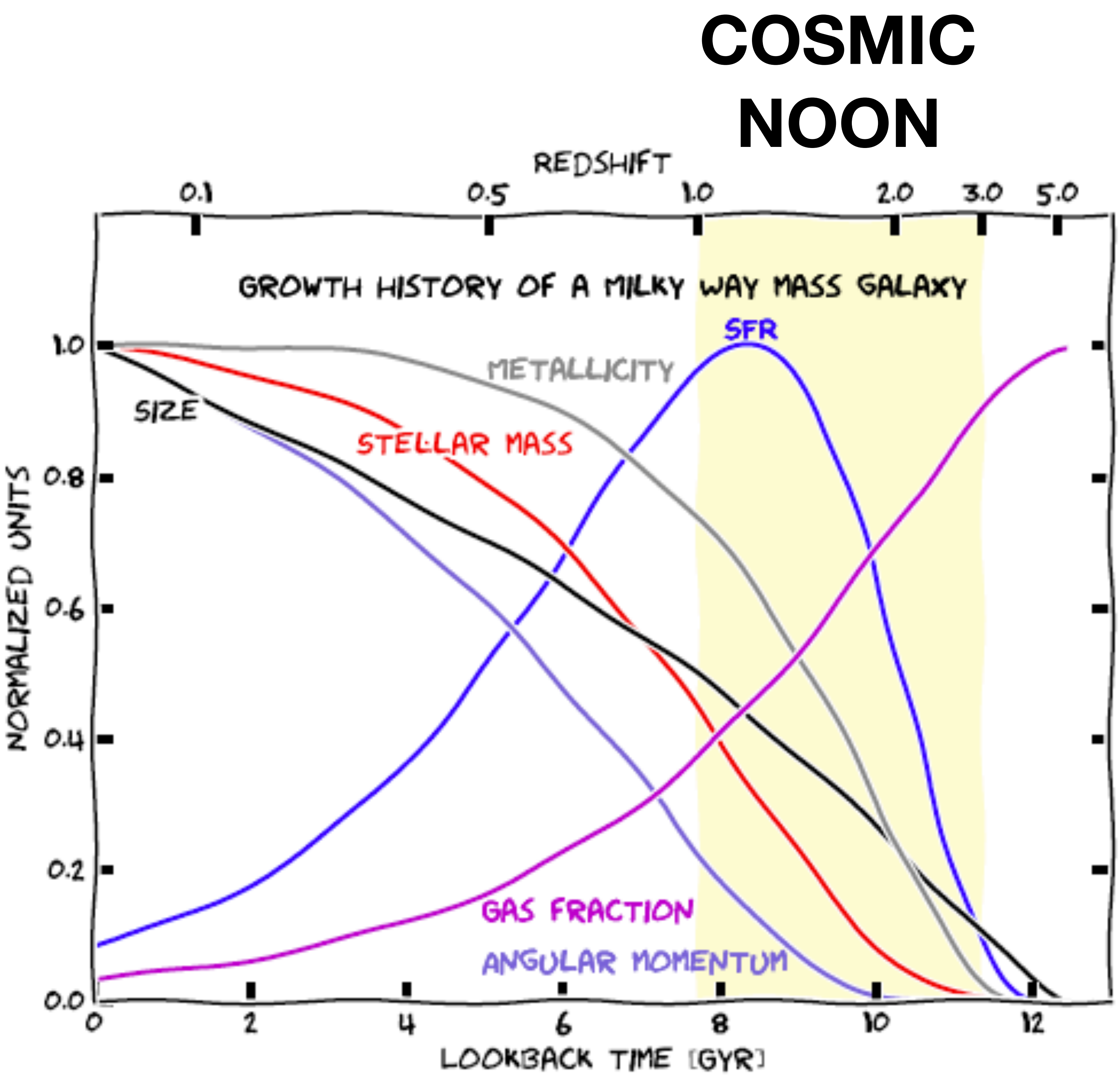
Star formation in cosmic-noon galaxies



ENS DE LYON
CRAL
CENTRE DE RECHERCHE ASTROPHYSIQUE DE LYON

Jérémy Fensch
& F. Bournaud, F. Renaud, P.-A. Duc, etc.

Galaxy Evolution in a nutshell



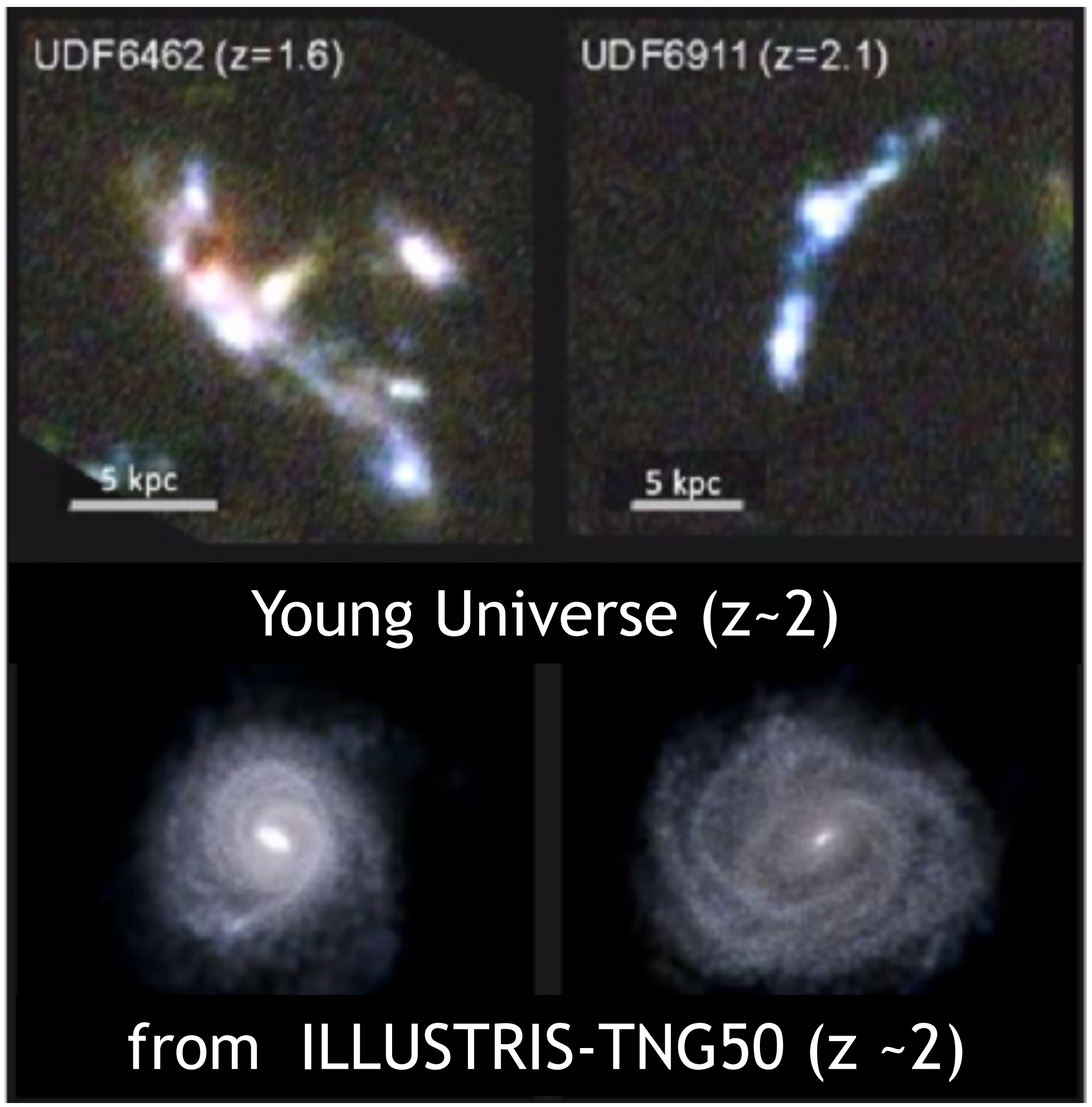
Looks straightforward,

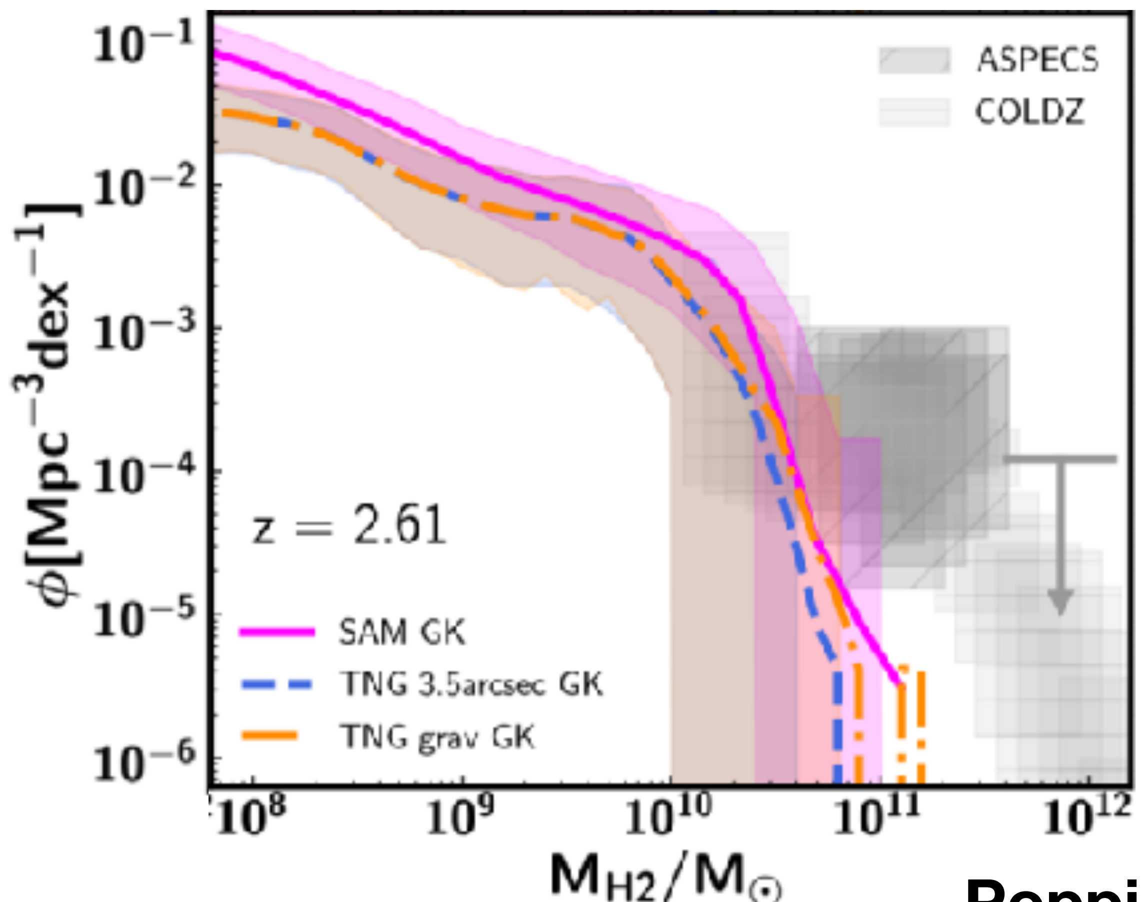
but not so easy to understand and model

Review by Förster-Schreiber & Wuyts 2020

Galaxy Evolution in a nutshell

In cosmological simulations:
(but also NIHAO, FIRE etc.)





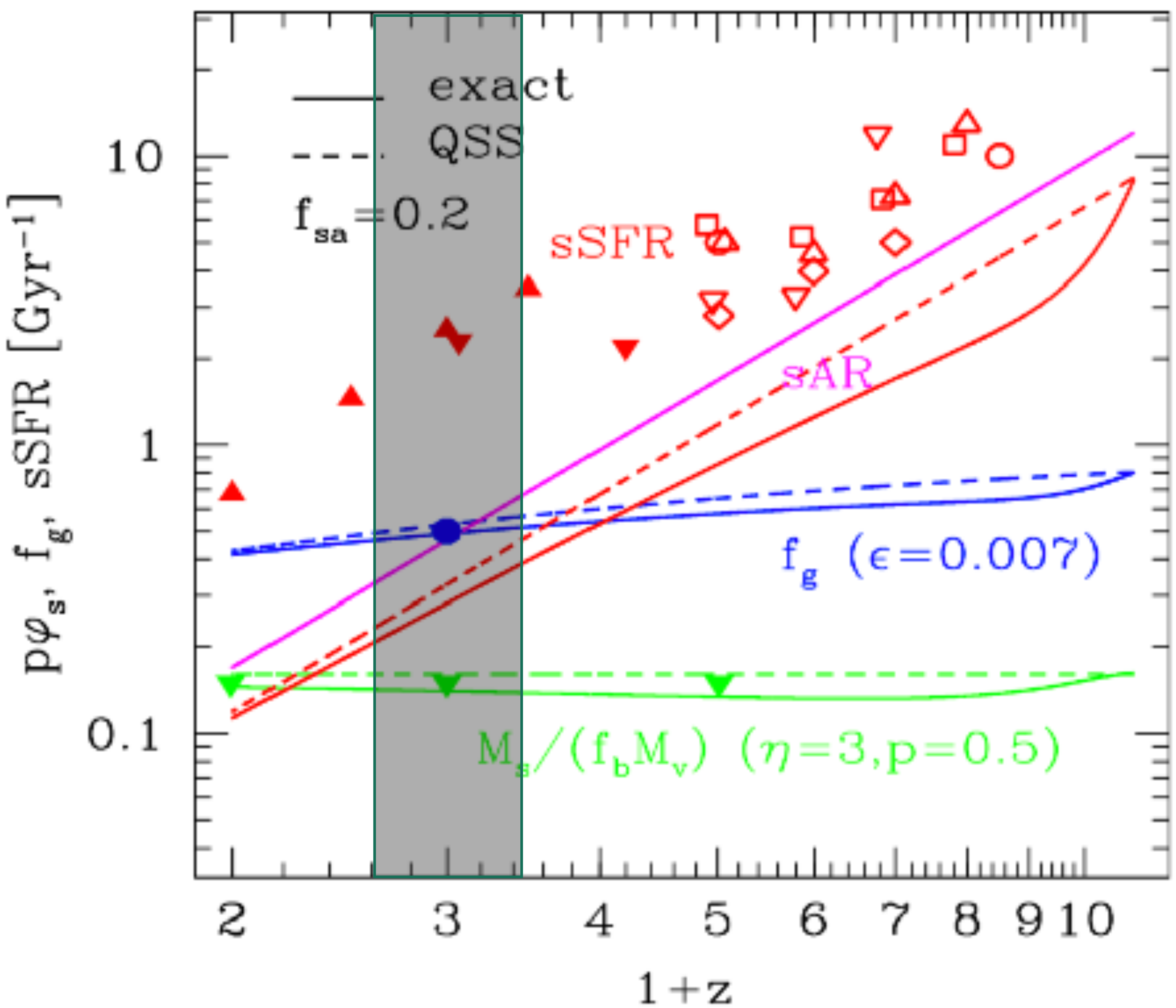
Popping et al., 2019

Pillepich et al., 2019

In (most) cosmological simulations,
galaxies have wrong morphologies and are not enough gas-rich.

Galaxy Evolution in a nutshell

Analytical model for star formation history



Dekel & Mandelker 2014

Gas fraction can be fine

but

star formation rate (SFR) underestimated by at least x3

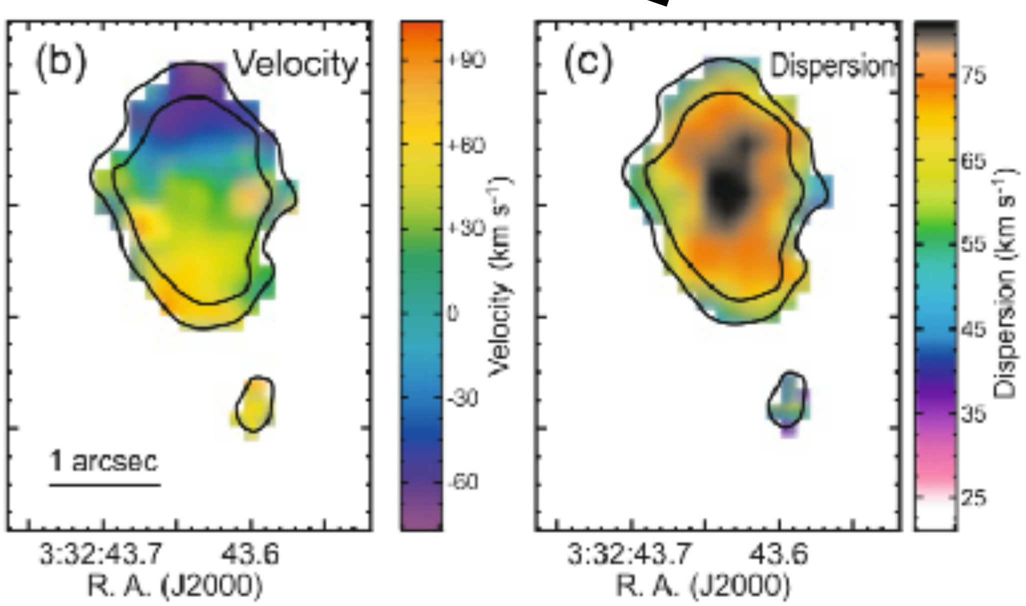
How do you regulate star formation without ejecting all your gas ?

What are we missing?

z~2 star-forming galaxies have:

1/ a high turbulence: ~ 40-75km/s

May have a huge role
in regulating star formation
for high surface densities

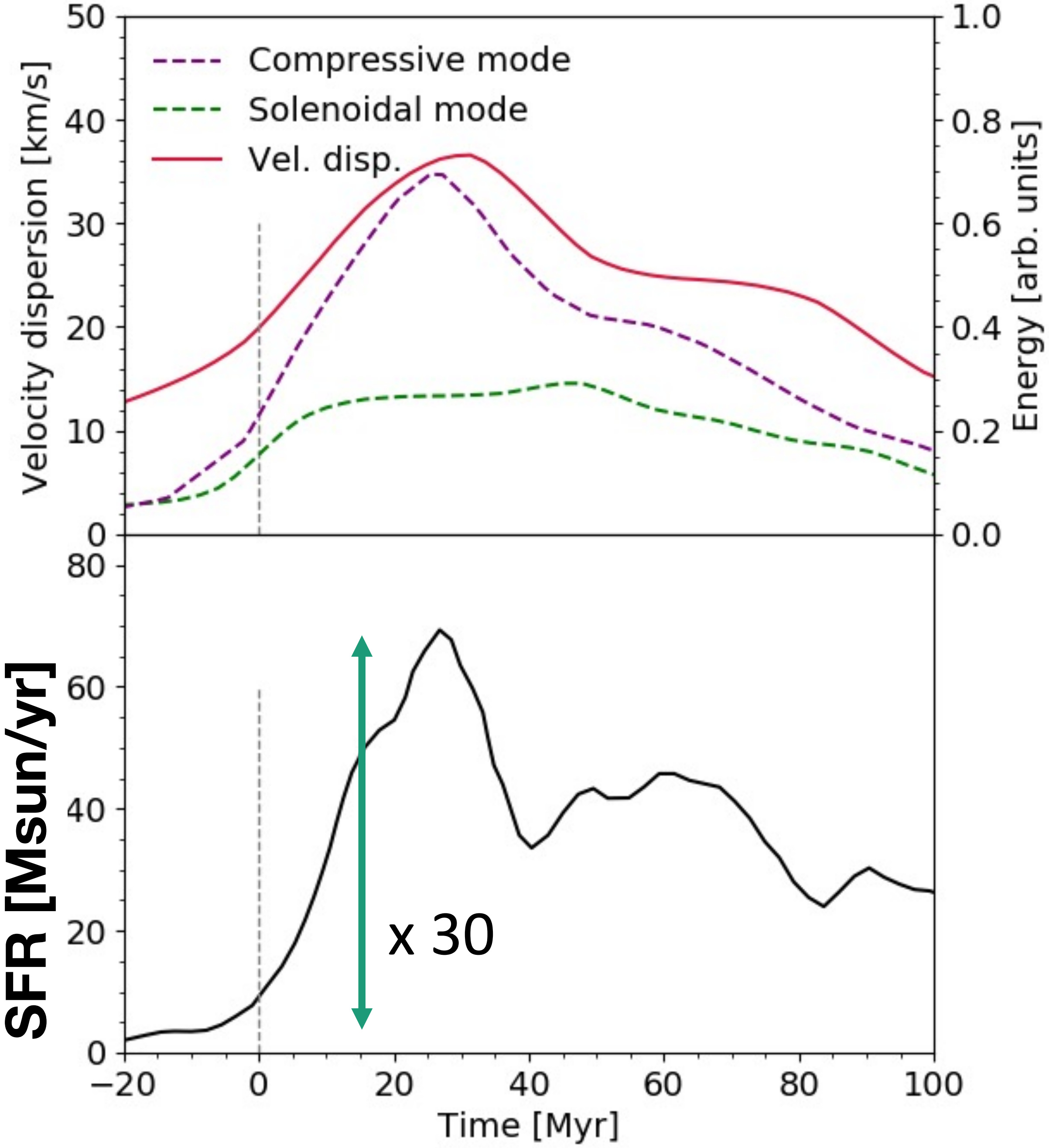


Bournaud et al., 2008,
see also SINS, KMOS3D survey

cf. talk from Noé Brucy (yesterday)

High turbulence may trigger unexpected behaviours
Example: mergers

Example: low-z starbursts

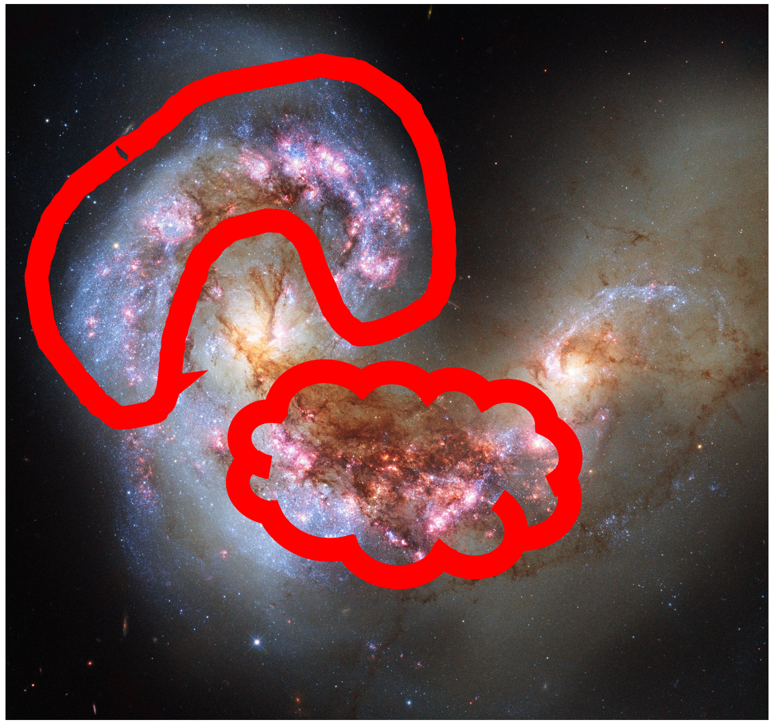


Renaud et al., 2014

Turbulent energy fed by gravitational energy liberation

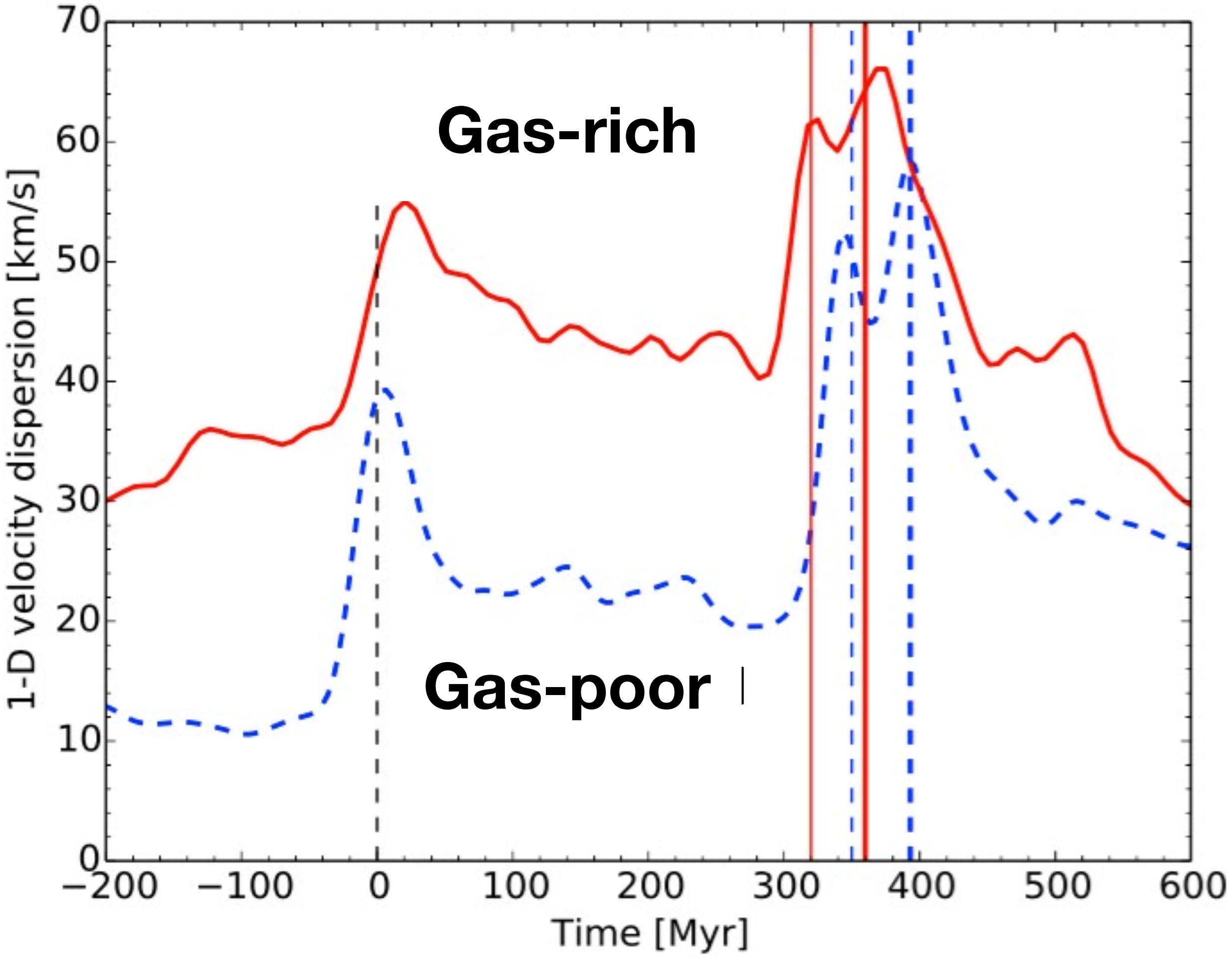
Preferential increase of energy in compressive mode of turbulence

Compressive: gas destabilization
Solenoidal: pressure/stabilization



Starburst triggered by compressive turbulence

Turbulence saturation



Fensch et al., 2017

Final turb. energy — **Initial turb. energy**

$$\frac{3}{2} M_{\rm gas} \sigma_{\rm f}^2 = \frac{3}{2} M_{\rm gas} \sigma_{\rm i}^2 + M_{\rm gas} f \Delta\phi$$

Grav. energy

$$\sigma_{\rm f} = \sqrt{\sigma_i^2 + \frac{2}{3} f \Delta\phi}$$

gas-poor : Mach 1 -> 5
gas-rich : Mach 4 -> 6

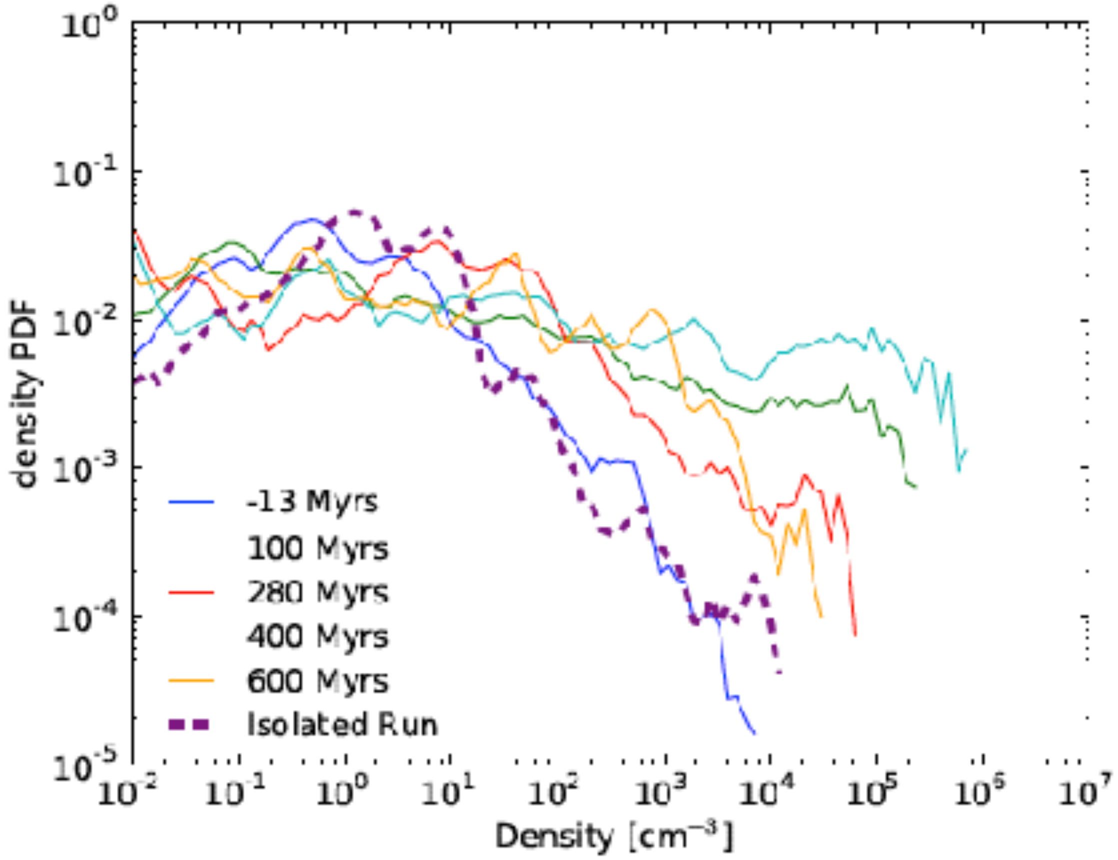
Sound speed:
~ 10 km/s for T = 10 000 K

Turbulence saturation:
weak compression augmentation

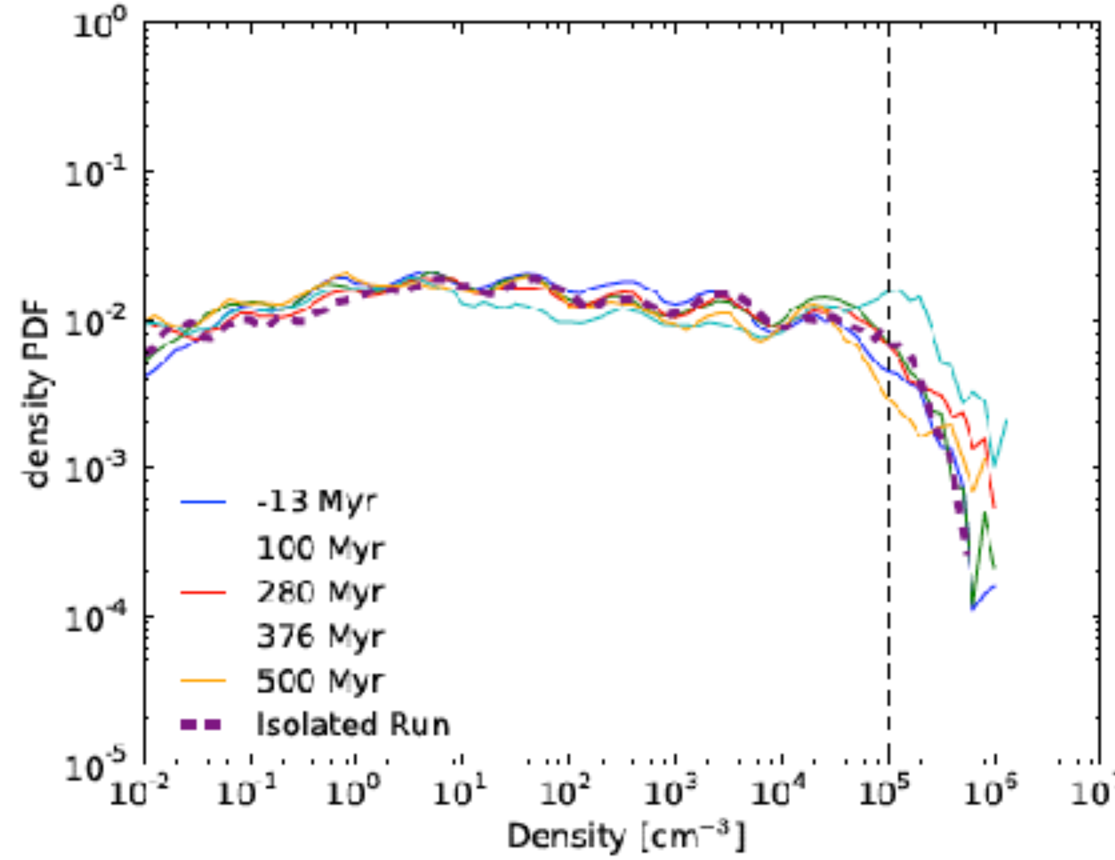
-> weak star formation increase

Turbulence saturation

gas-poor
z=0



gas-rich
z=2



For isolated galaxies, the width of the PDF is given by:

$$\omega^2 \propto \ln(1 + bM^2)$$

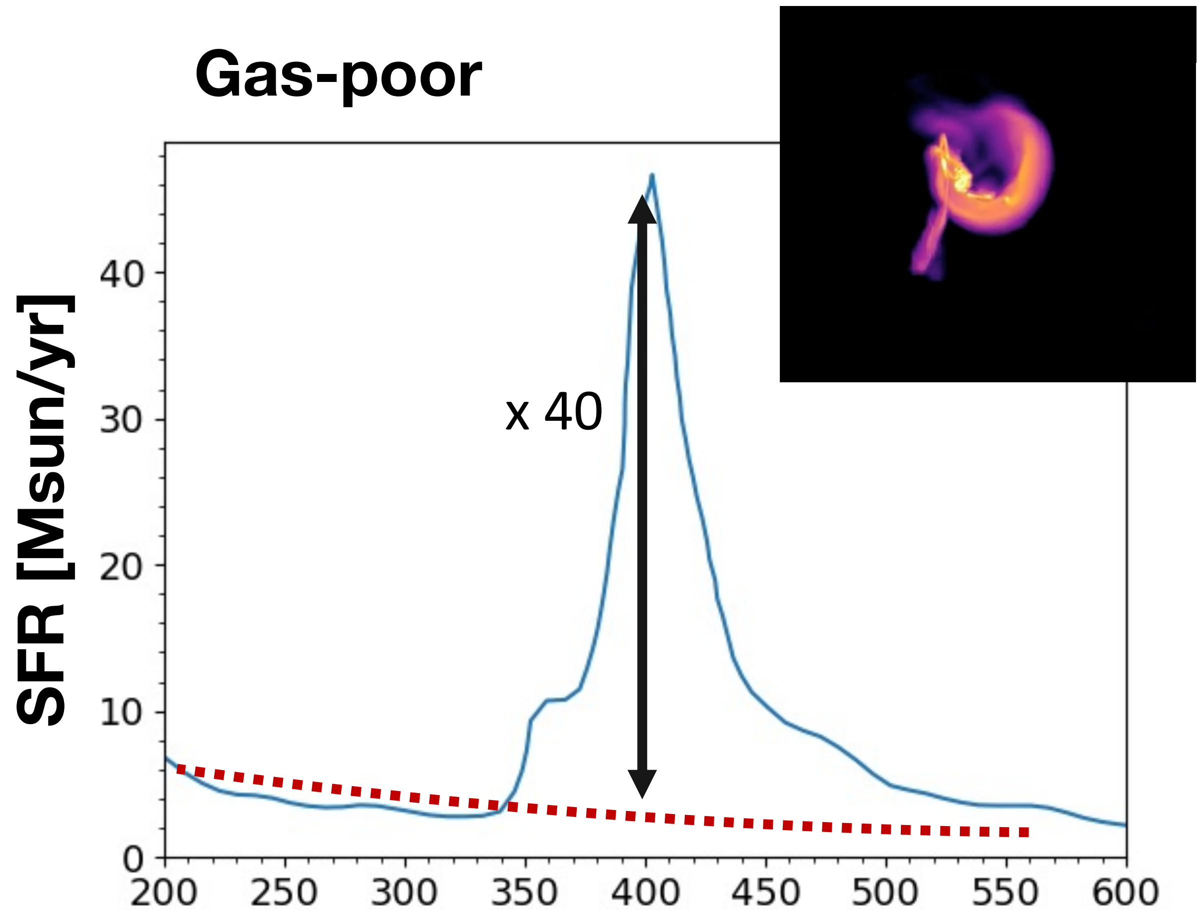
e.g., Nordlund and Padoan, 1999

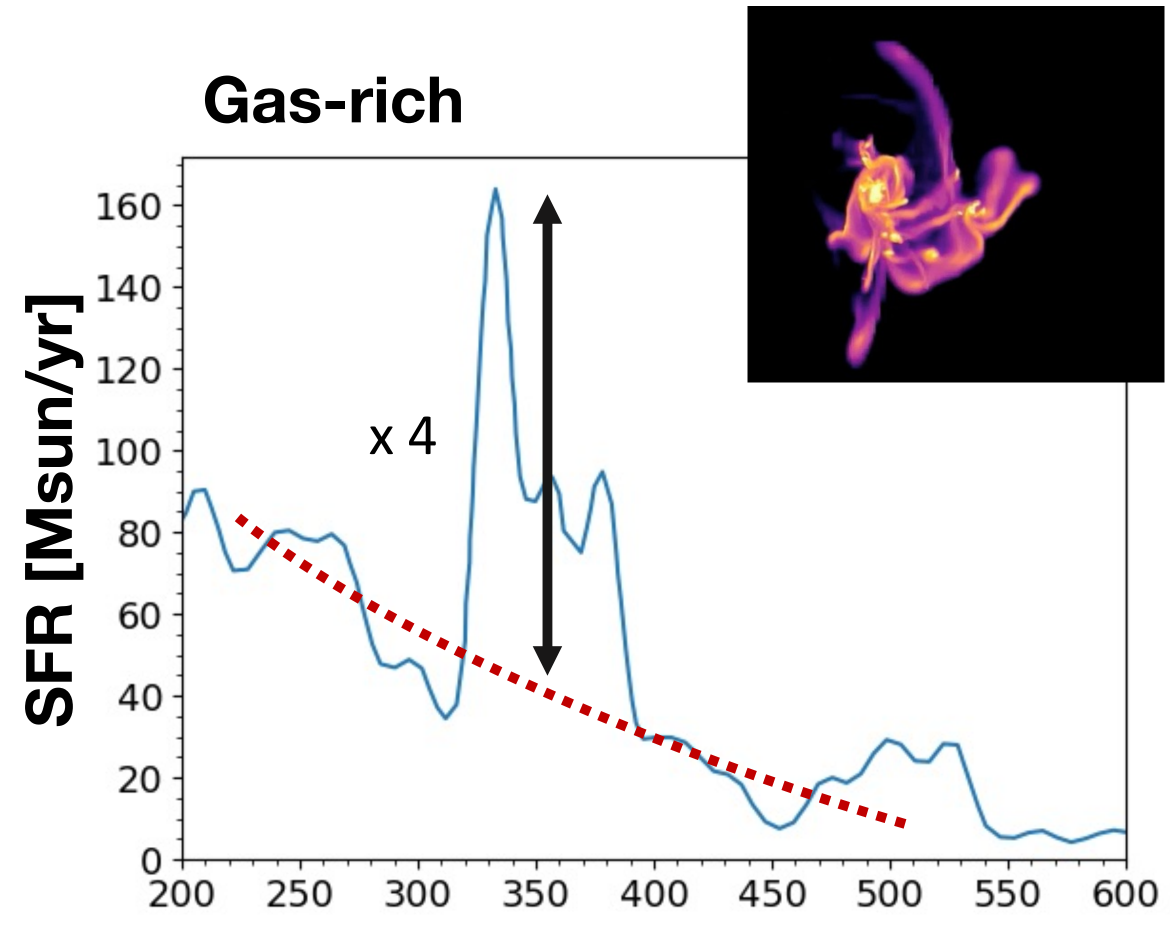
depends on turbulence modes

Mach number

Fensch et al., 2017

Turbulence saturation

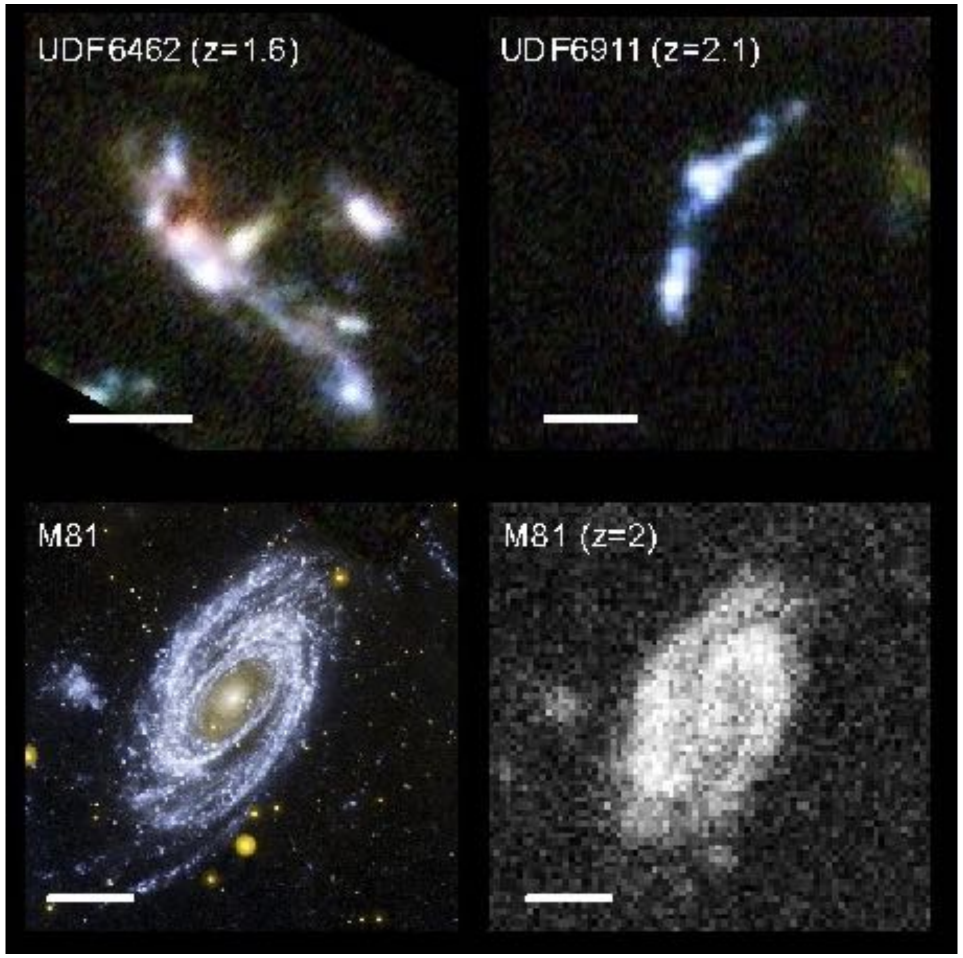




The high turbulence of young galaxies limits the efficiency of galaxy interactions of triggering starbursts

Fensch et al., 2017

What are we missing?

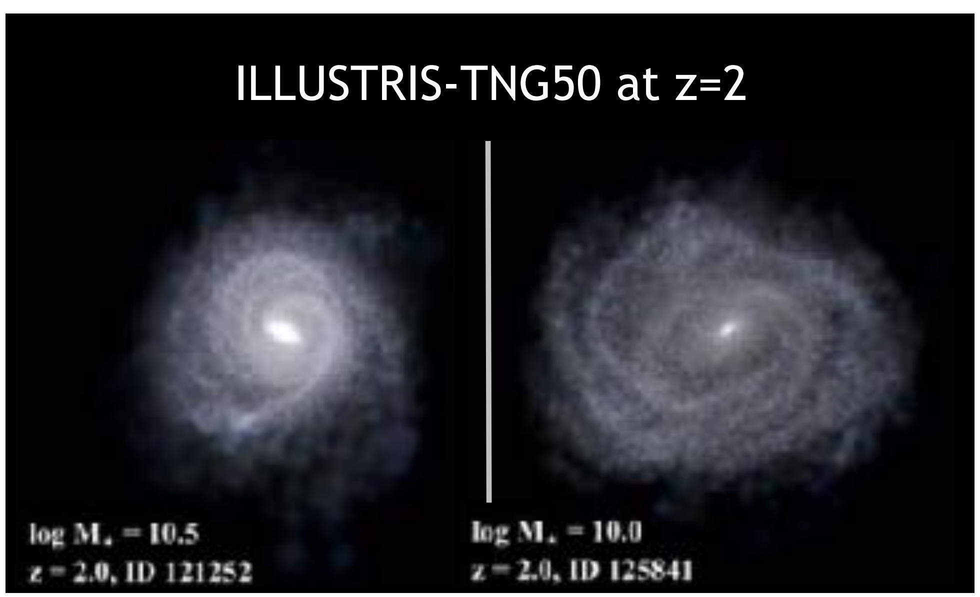


z~2 star-forming galaxies have:

1/ a high turbulence

2/ an UV-restframe clumpy structure

which is usually not reproduced!

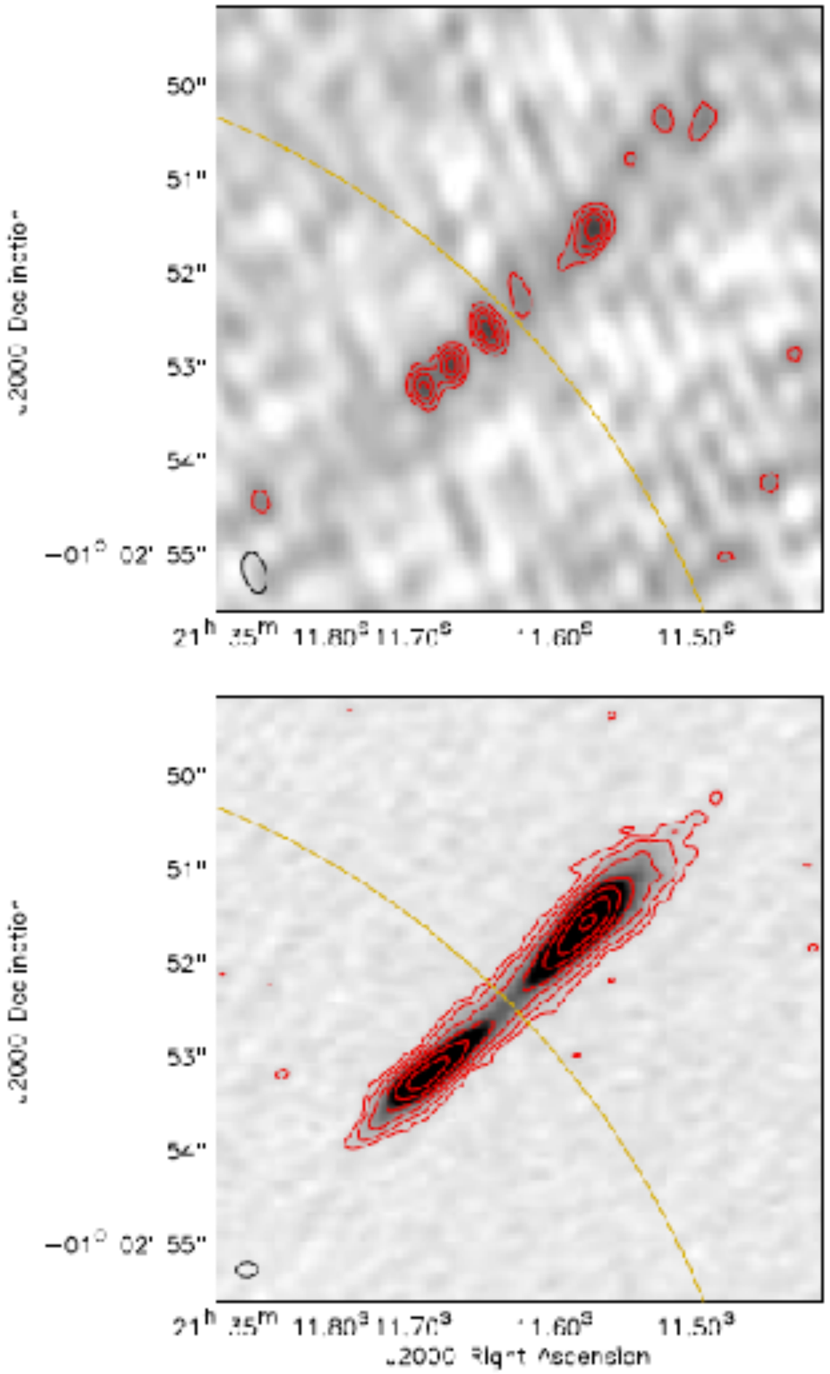


see also FIRE, NIHAO, etc.

but see VELA or Extreme HORIZON

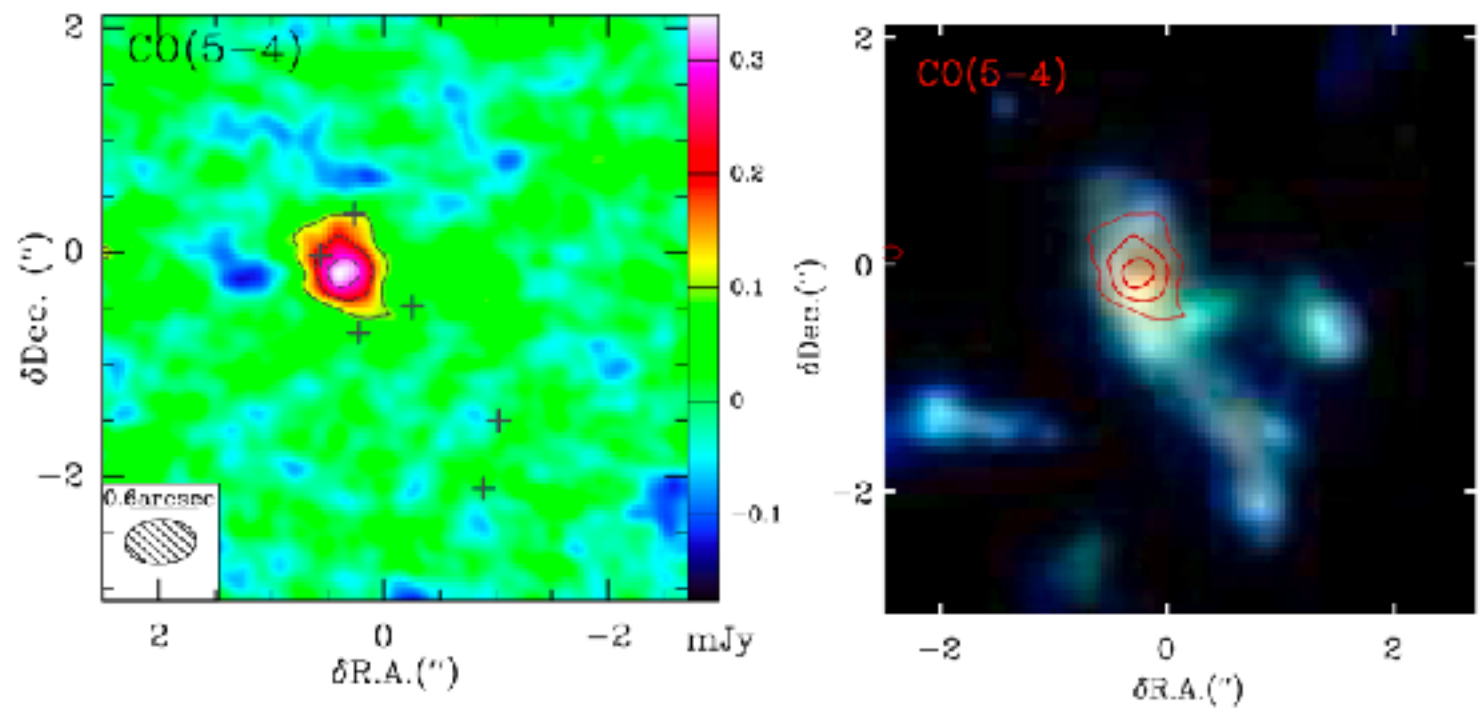
Giant clumps? Observational debate

Swinbank et al., 2010



Dust continuum
Ivison et al., 2020

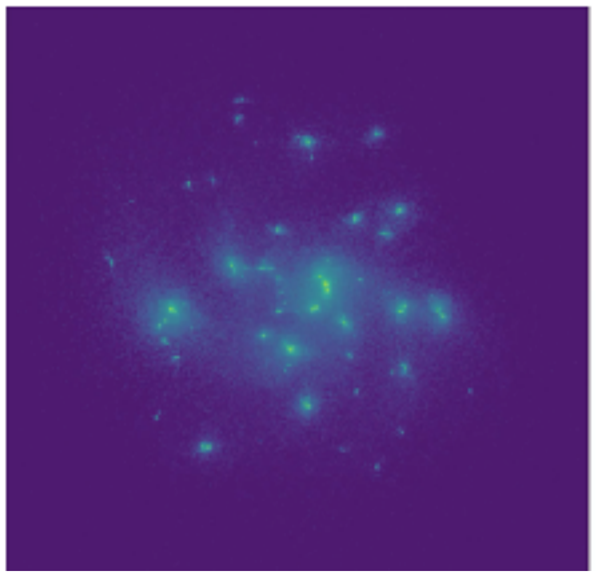
Clumpy UV morphology do not show in deep sub-mm data

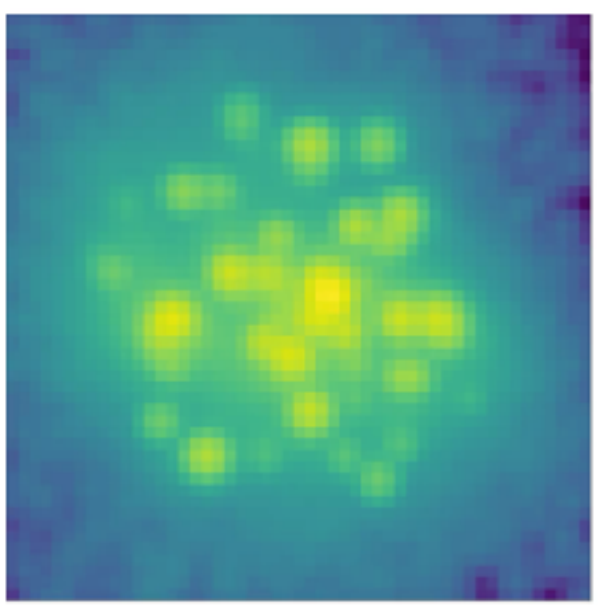


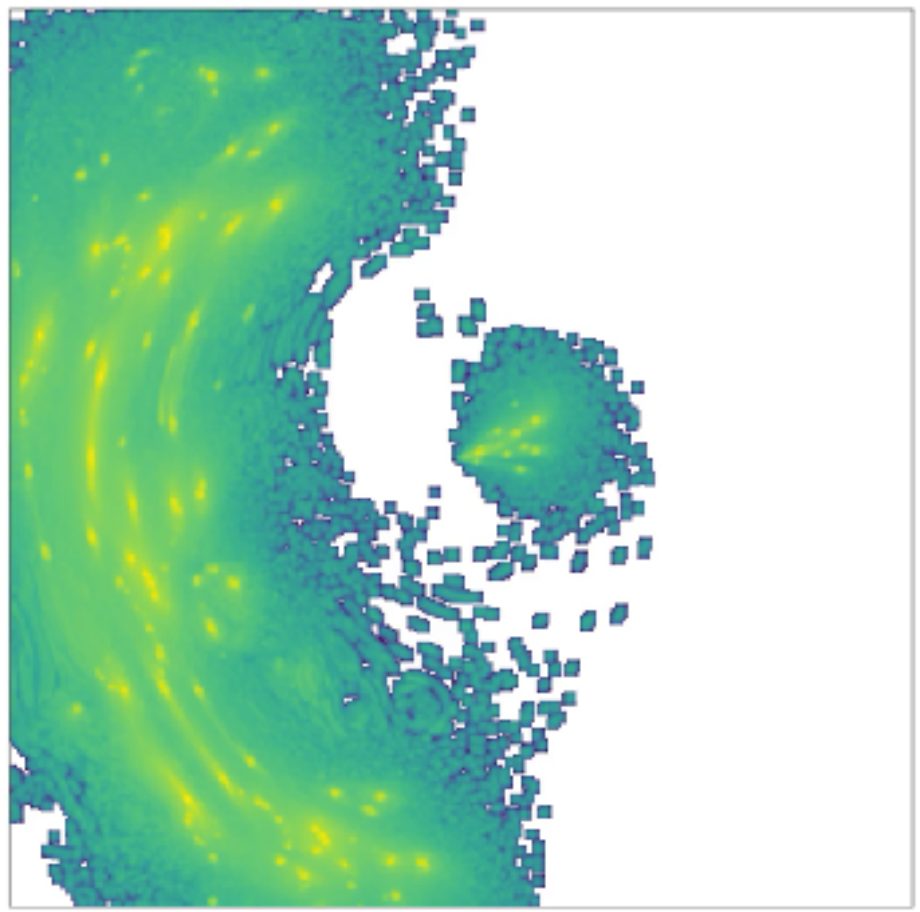
Dense gas CO transition
Cibinel et al., 2017

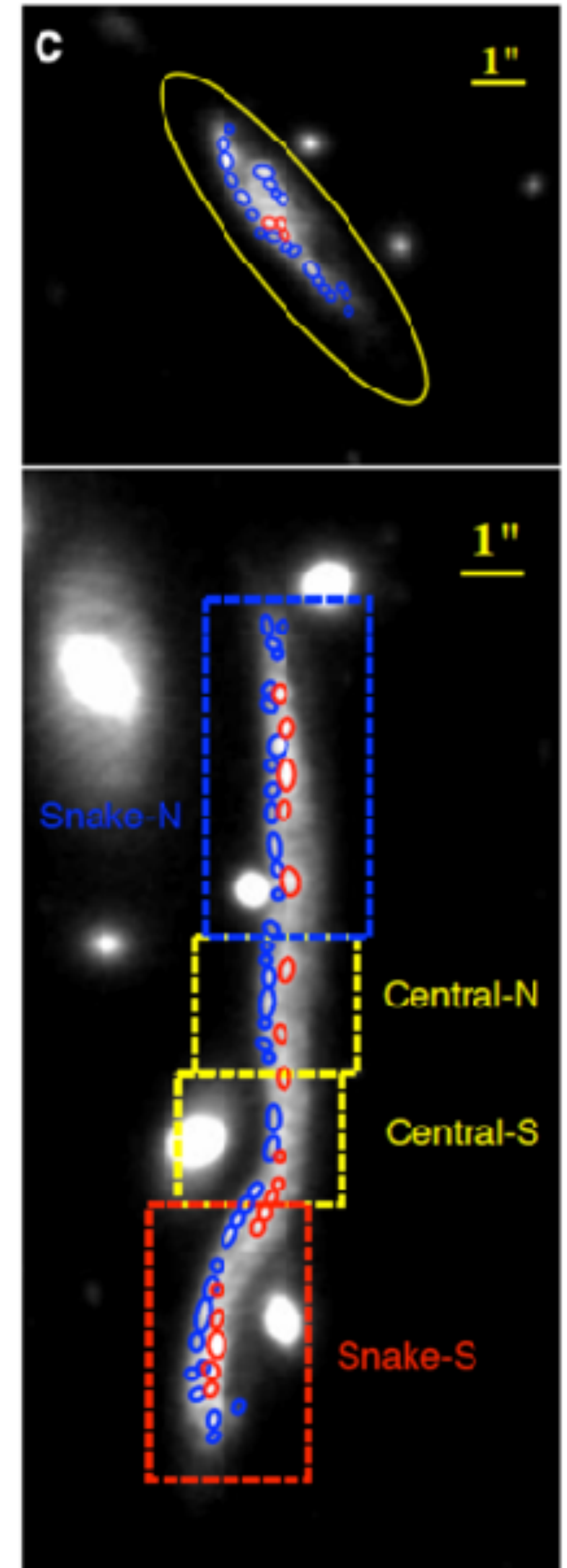
Giant clumps? Observational debate

**If too high resolution,
probing the sub-structure of clumps**





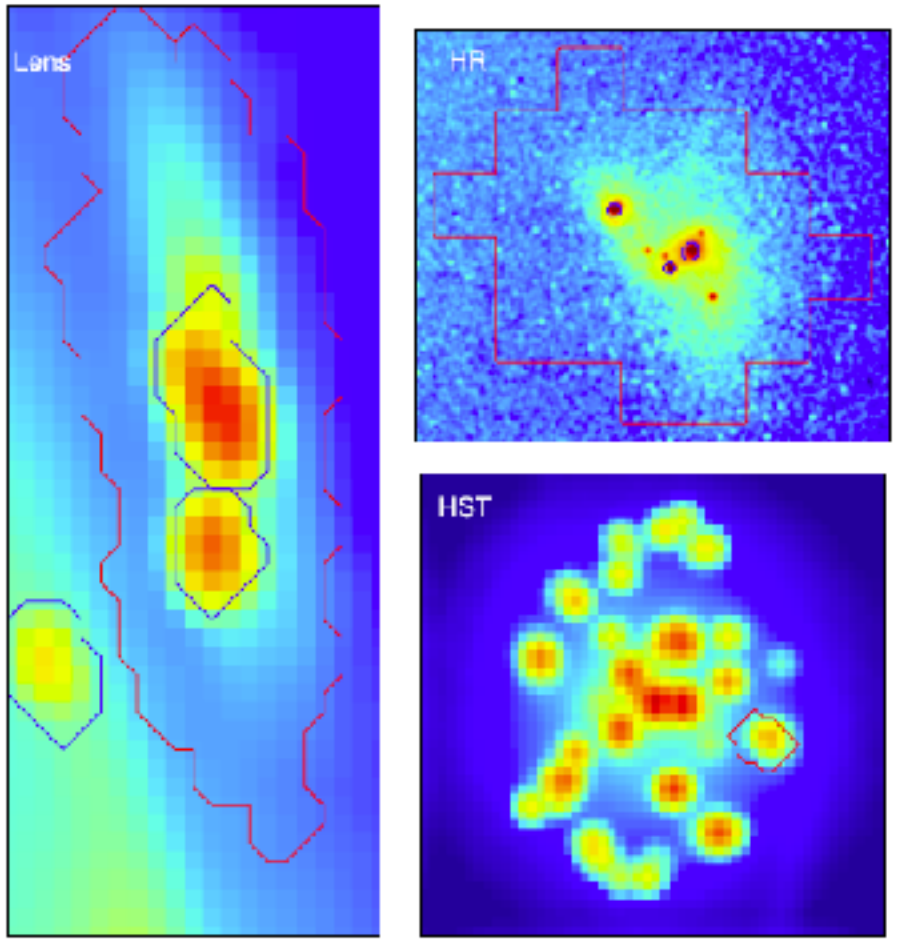




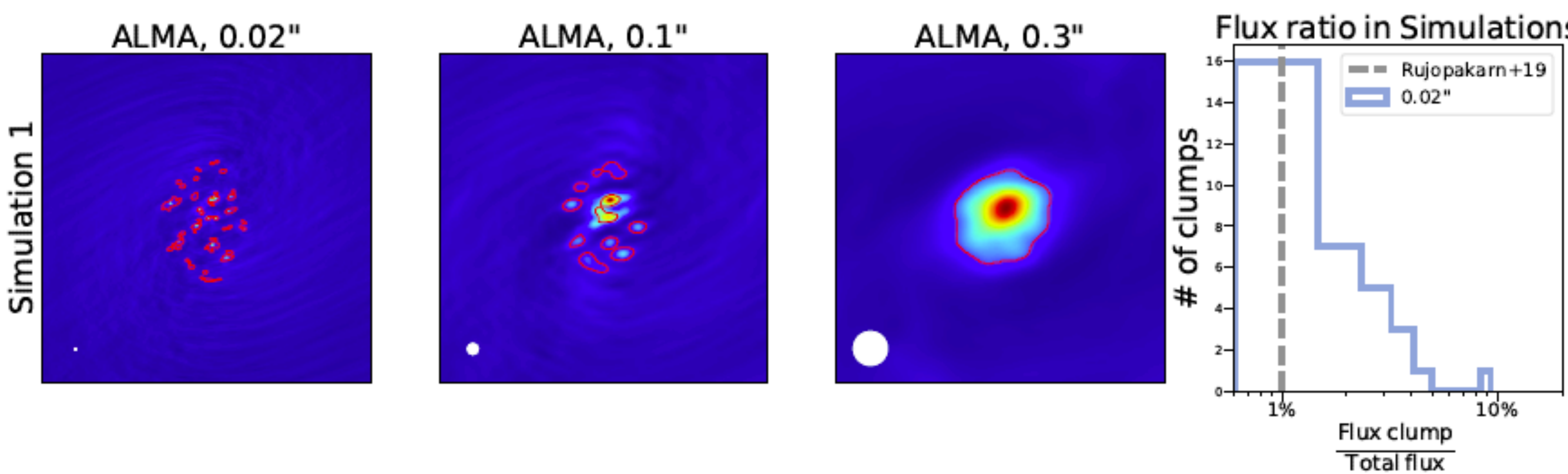
Faure, Bournaud, Fensch et al., 2021

Cava et al., 2018

Giant clumps? Observational debate



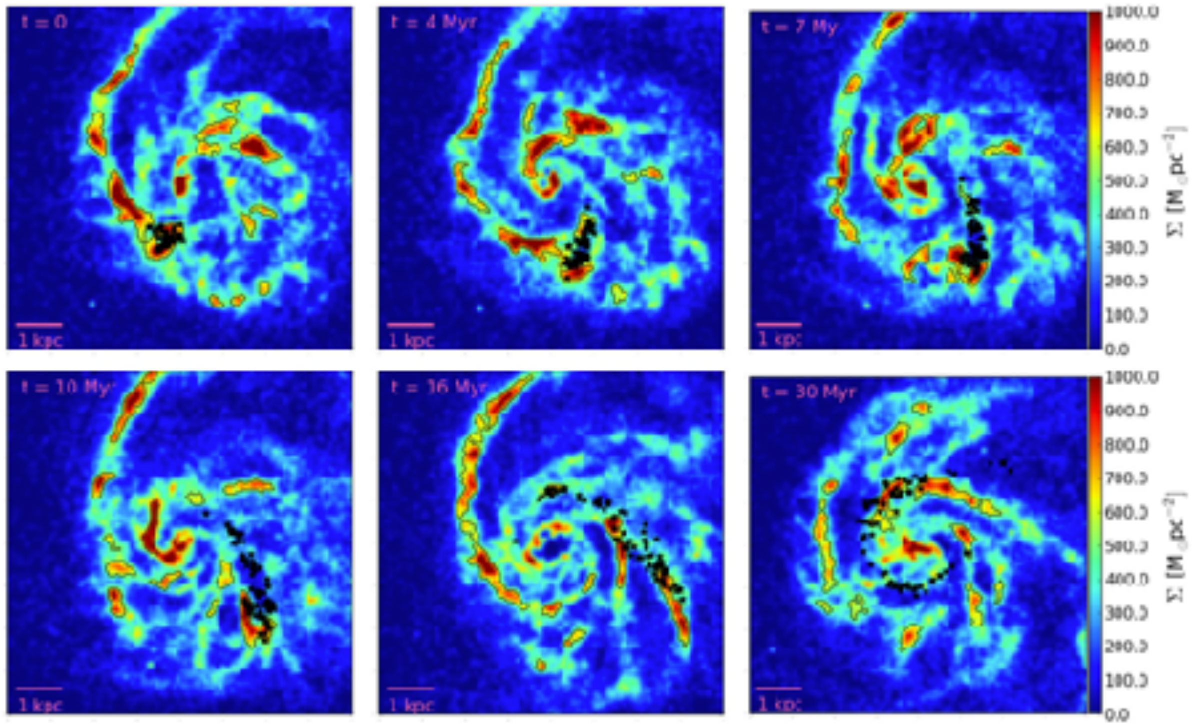
High-resolution observations
(via ALMA or lenses)
are sensitive to sub-structures of clumps



Faure, Bournaud, Fensch et al., 2021

Clumps in cosmological simulations

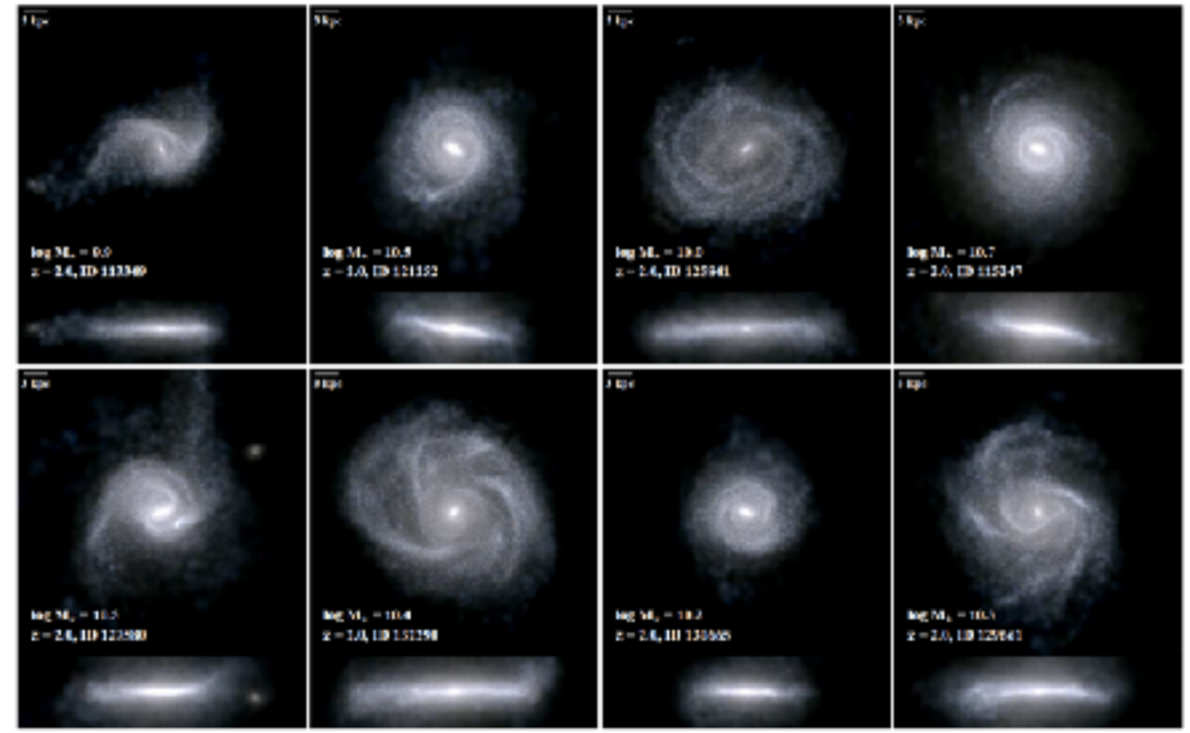
FIRE



Oklopčic et al., 2017

Short-lived: ~20 Myr

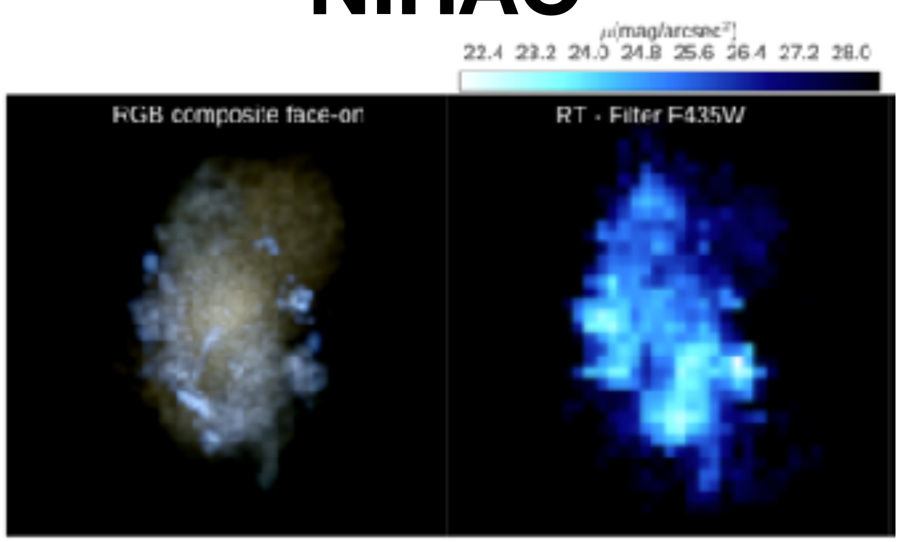
ILLUSTRIS-TNG



Pillepich et al., 2019

No clumps?

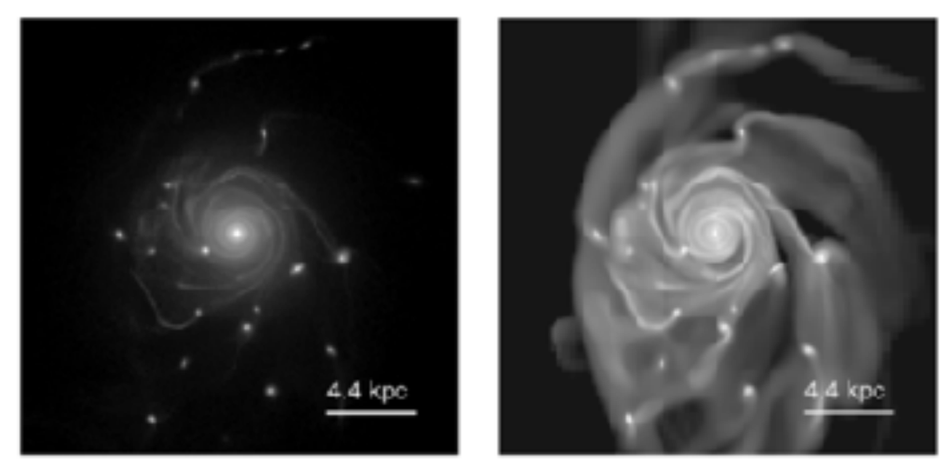
NIHAO



Buck et al., 2017

Patchy dust?

RAMSES (see also ART, VELA)

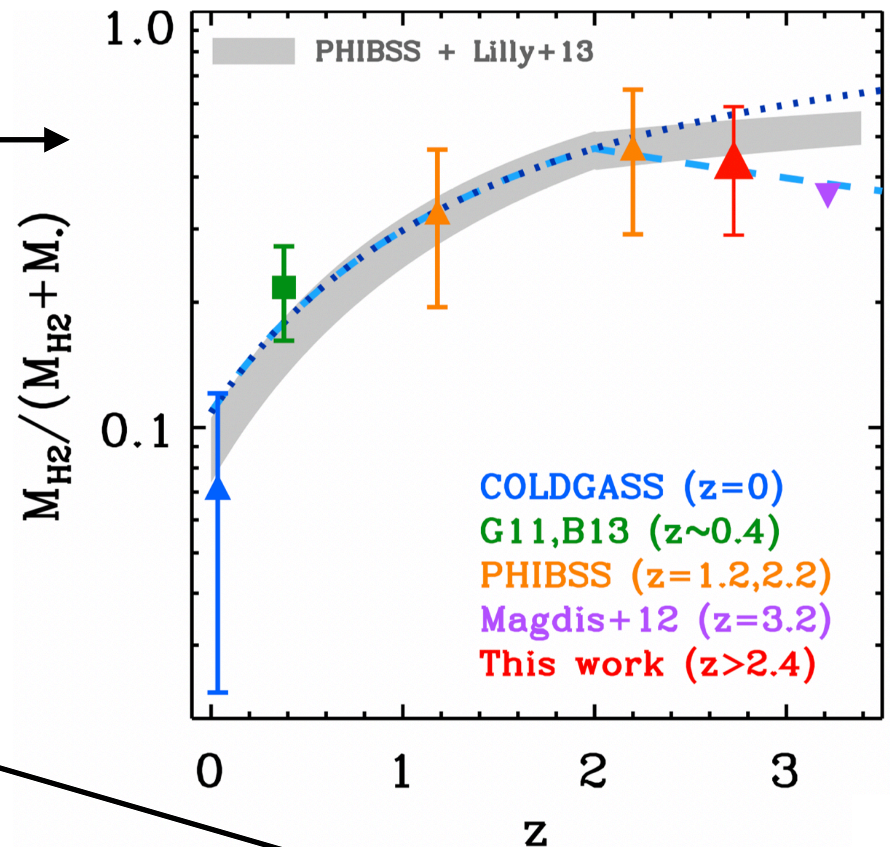


Agertz et al., 2009

Extended disk?

Gas mass fraction cosmological simulations

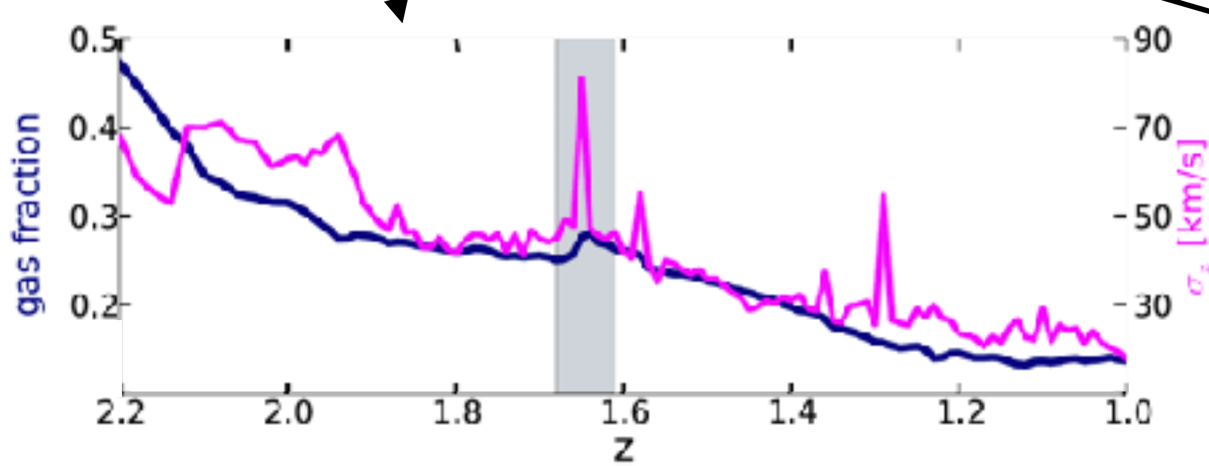
Observations



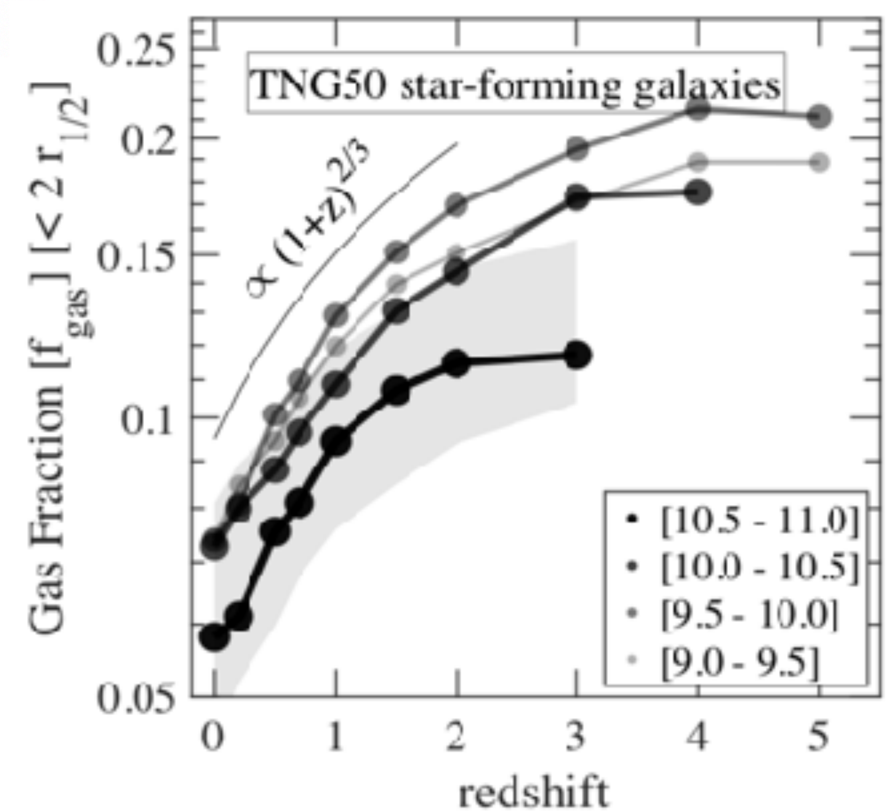
$$f_{\rm gas} = \frac{M_g}{M_g + M_\star}$$

Saintonge et al., 2013

Simulations



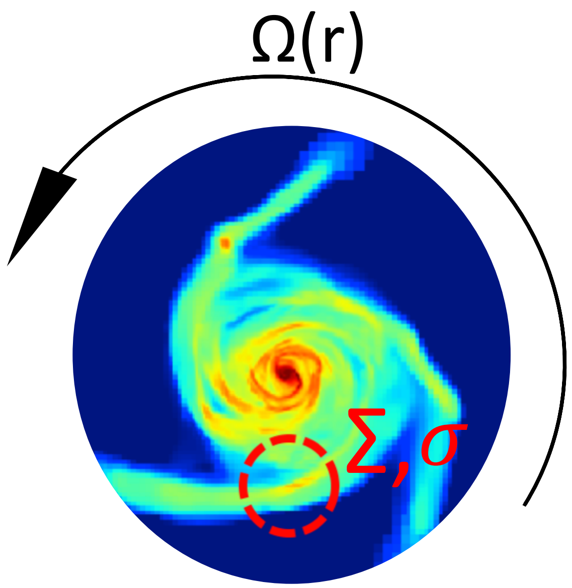
Oklopčic et al., 2017 (O17)



Modelled galaxies are gas-depleted at z ~ 2

Pillepich et al., 2019
also Popping et al., 2020

Gas mass fraction and disk instability

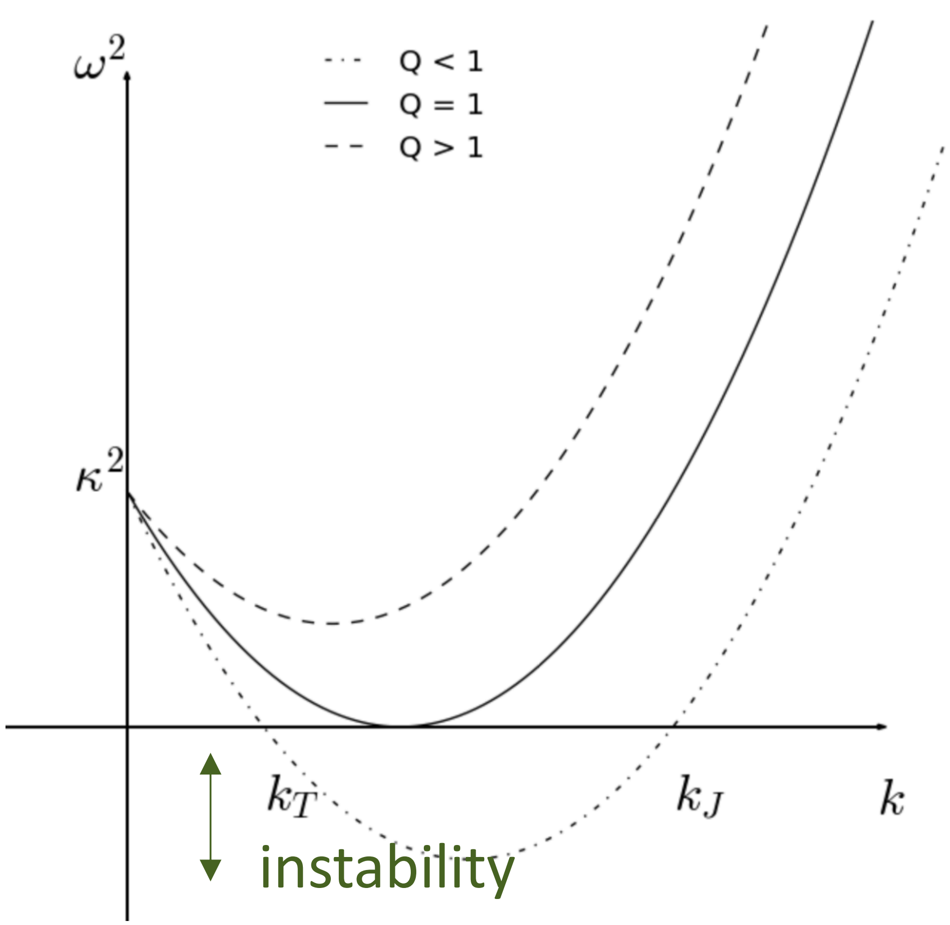


Uniform rotating disk:

- angular velocity Ω(r)
- surface density Σ
- velocity dispersion σ
- epicyclic frequency $\kappa \sim \Omega$

Dispersion relation for axisymmetric disturbances:

$$\omega^2 = k^2\sigma^2 - 2\pi G\Sigma_{\rm gas}|k| + \kappa^2$$



Instability if:

‘shear’

turbulent support

$$Q = \frac{\kappa\sigma}{\pi G\Sigma} < 1$$

Gravity

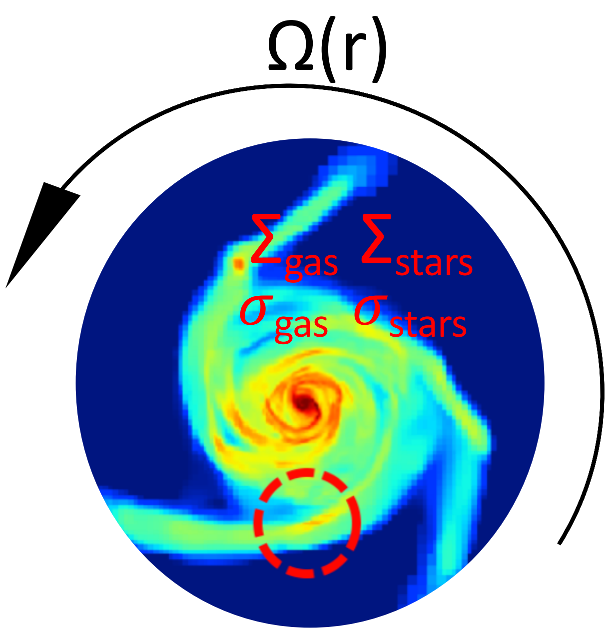
Toomre (1964)

(Rule of thumb: here no dissipation, disk ∞ thin...)

Gas mass fraction and disk instability

Two components

- angular velocity $\Omega(r)$
- surface density Σ_{gas}, Σ_{stars}
- velocity dispersion σ_{gas}, σ_{stars}



Jog & Solomon 1984
Elmegreen, 1995

$$\frac{1}{Q_{\mathrm{total}}} \sim \frac{\Sigma_{\mathrm{gas}}}{\sigma^2_{\mathrm{gas}}} + \frac{\Sigma_{\mathrm{stars}}}{\sigma^2_{\mathrm{stars}}}$$

Stars are not dissipative : $\sigma_{gas} < \sigma_{stars}$

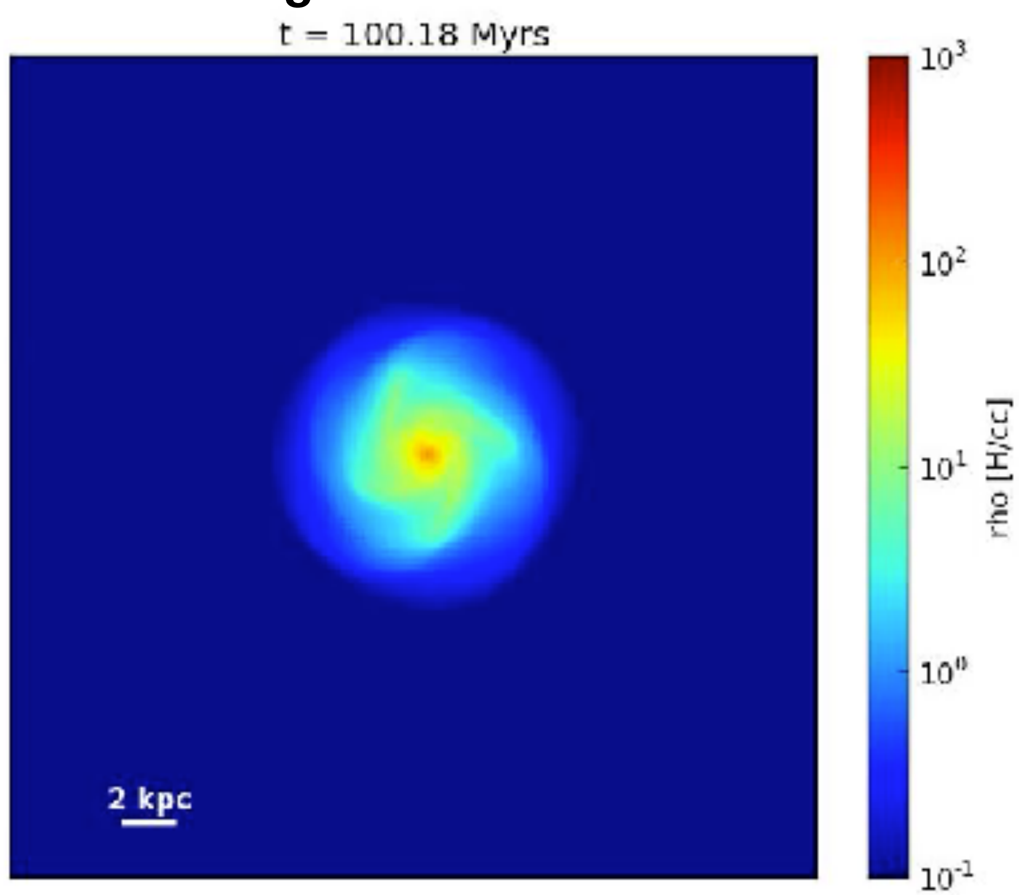
If one replace stars with gas: Q ↘

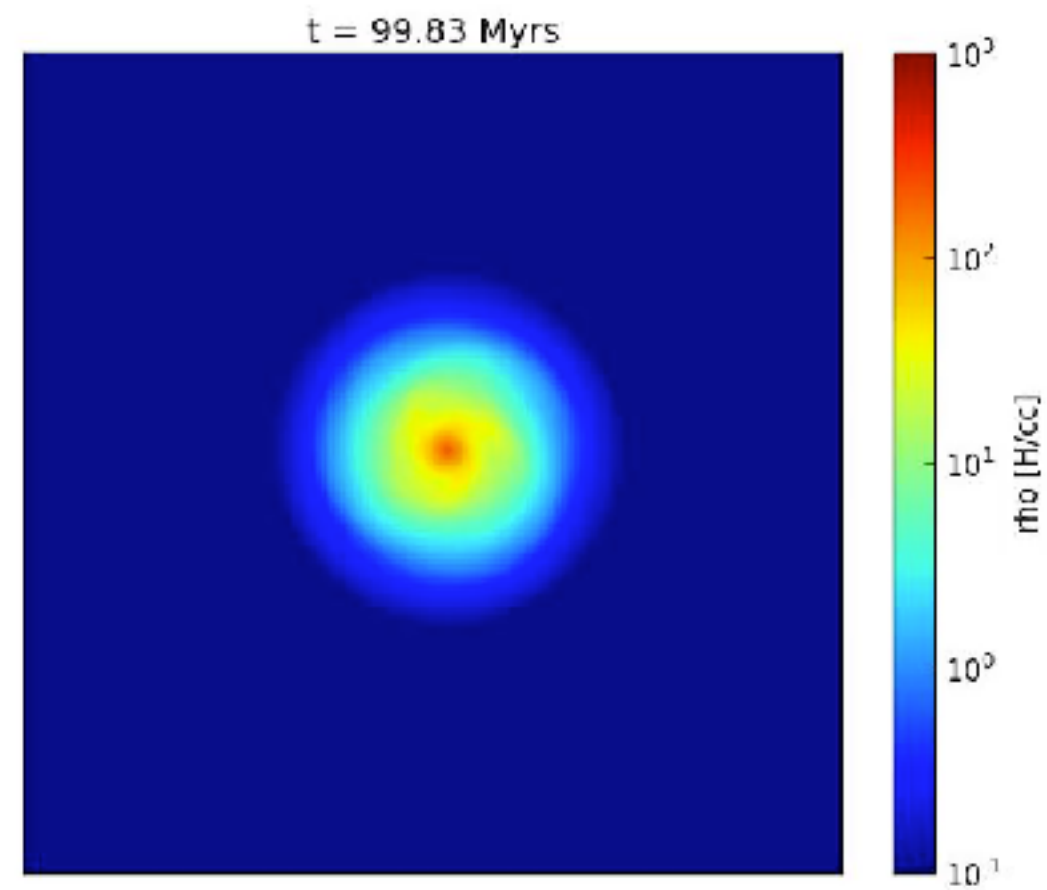
Higher gas fraction leads to violent instabilities

Disk stability: simulations

Same mass distribution:
same total mass distribution and rotation curve

z = 2 **gas fraction from cosmological simulations**	**z = 2** **realistic gas fraction**
F_{gas} = 25 %	**F_{gas} = 50 %**





Fensch & Bournaud 2021, see also Renaud et al., 2021

Question:

How do gas fraction and feedback impact disk stability?

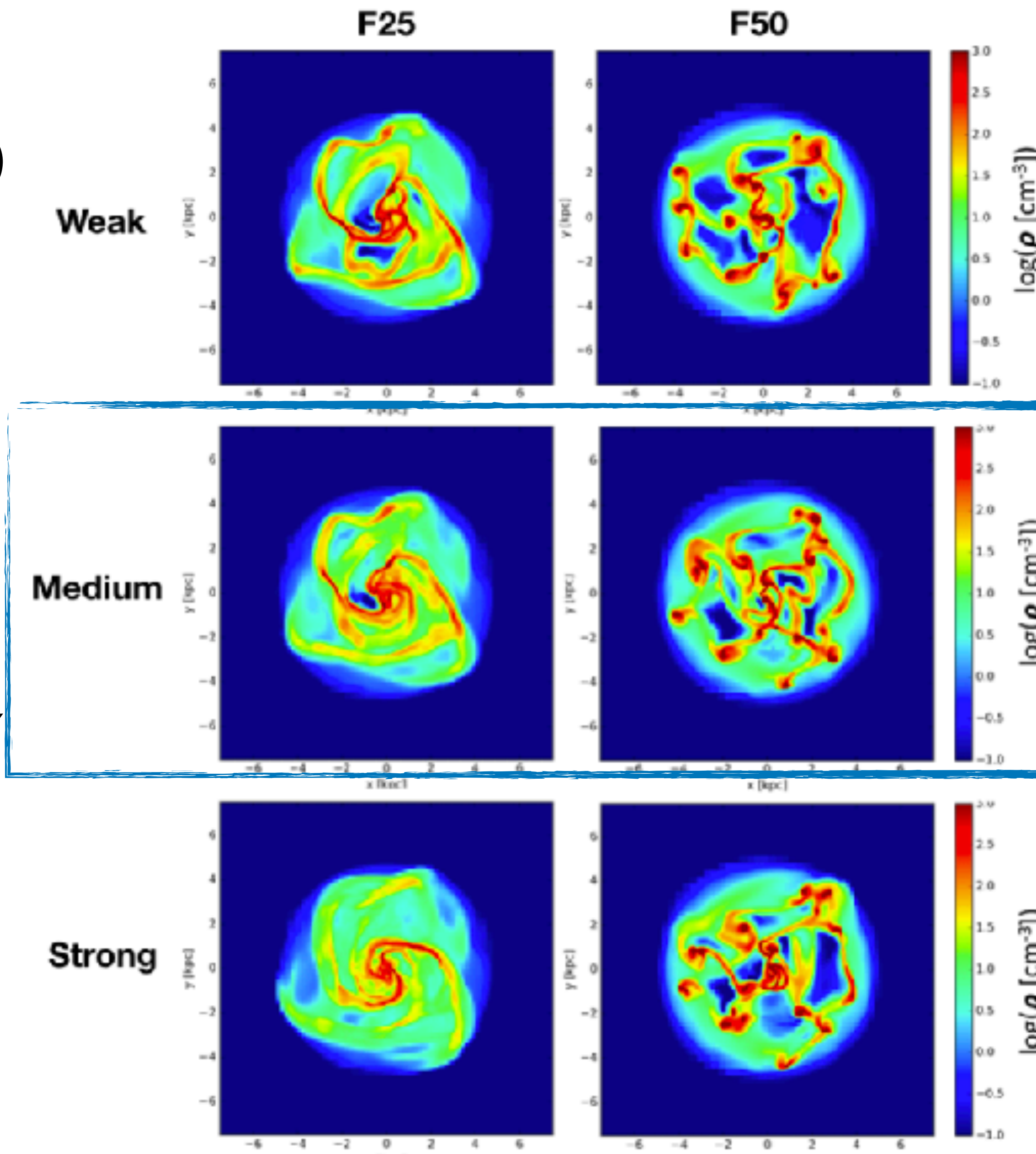
Numerical set with:

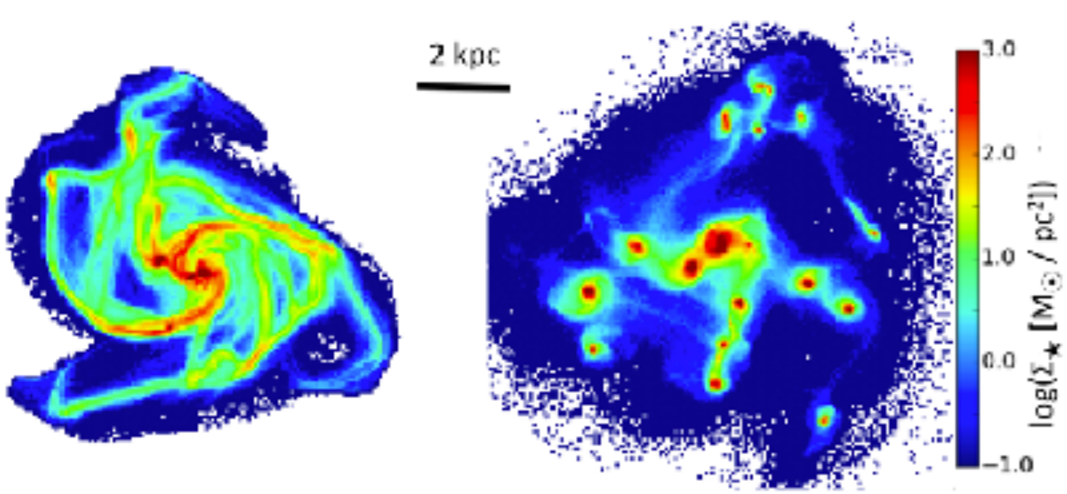
A. **2 gas fractions:**
   - **25% (like FIRE, ILLUSTRIS-TNG…)**
   - **50% (like obs.)**

B. **3 feedback calibrations:**
   - **HII region temperature**
   - **mix thermal/kinetic SN output**

And galaxy model of FIRE zoom-in galaxy.

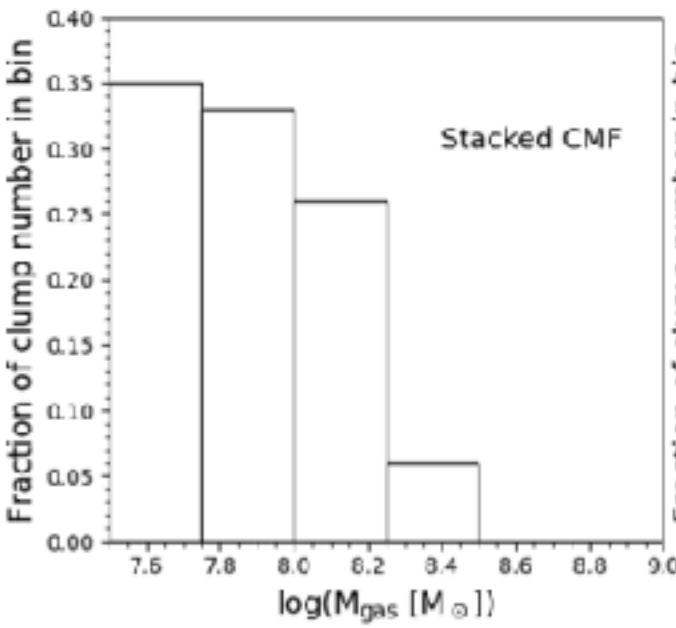
Galaxy-wide mass-loading factor ~1

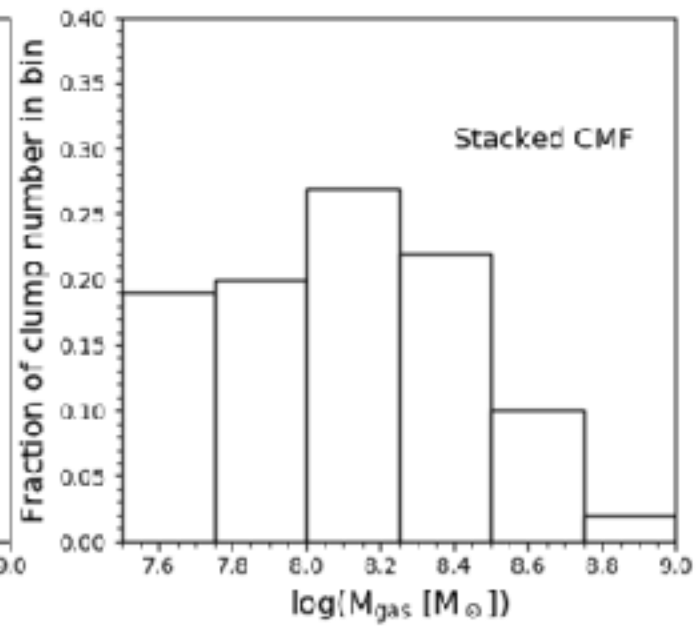




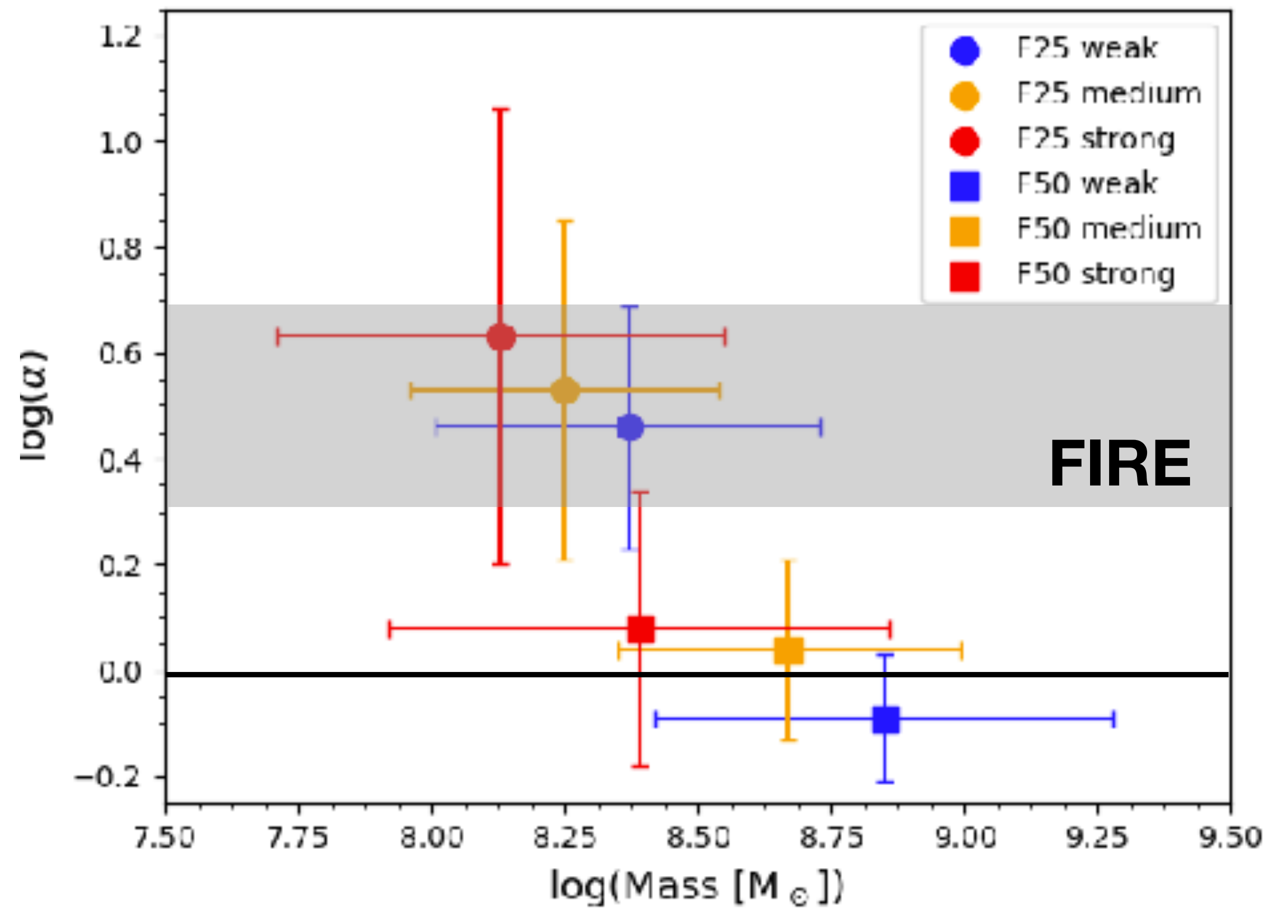
Fensch & Bournaud 2021

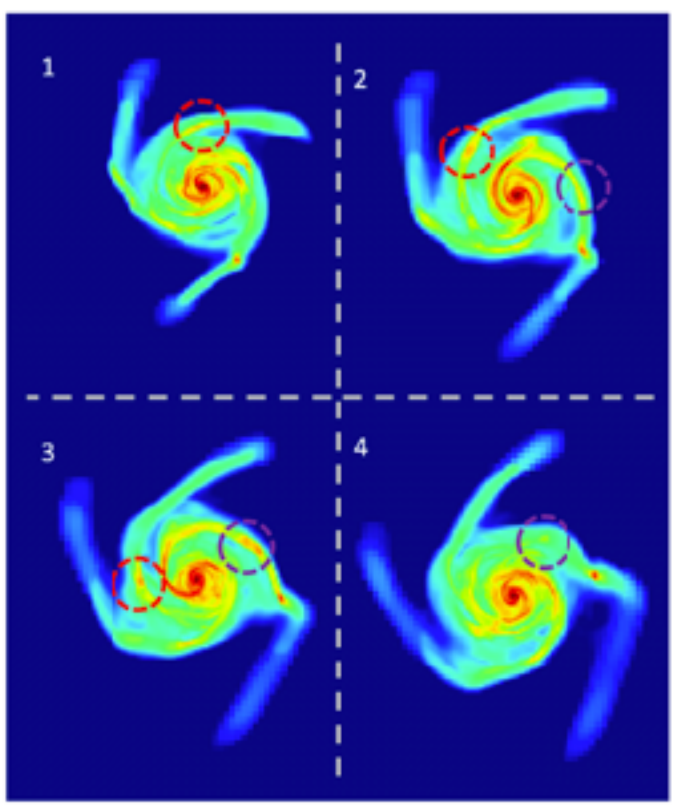
Gas mass fraction and disk instability





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





Over-densities are unbound for F25 (~ FIRE) and marginally bound for F50

Spans 36 Myr

Fensch & Bournaud 2021

Gas mass fraction and disk instability

Galaxy model Feedback model	F25 *medium*	F50 *medium*
Galaxy-wide mass loading factor of galactic winds η (Section 4.1)	1.13	0.96
Timescale for... [Myr] (Section 4.2)		
Gas removal *(by feedback/stripping)*	70 *(265/95)*	215 *(304/730)*
Gas (re-)accretion	405	195

RESULTS:

1/ **F25: Gas removal quicker than re-accretion (i.e unbound)**
F50: Gas removal as fast as gas re-accretion (i.e bound)

2/ **Feedback is playing a second order-role**

bonus/F25: Stripping more efficient than feedback in removing gas (because of spiral arms!)

Fensch & Bournaud 2021

Gas mass fraction and disk instability

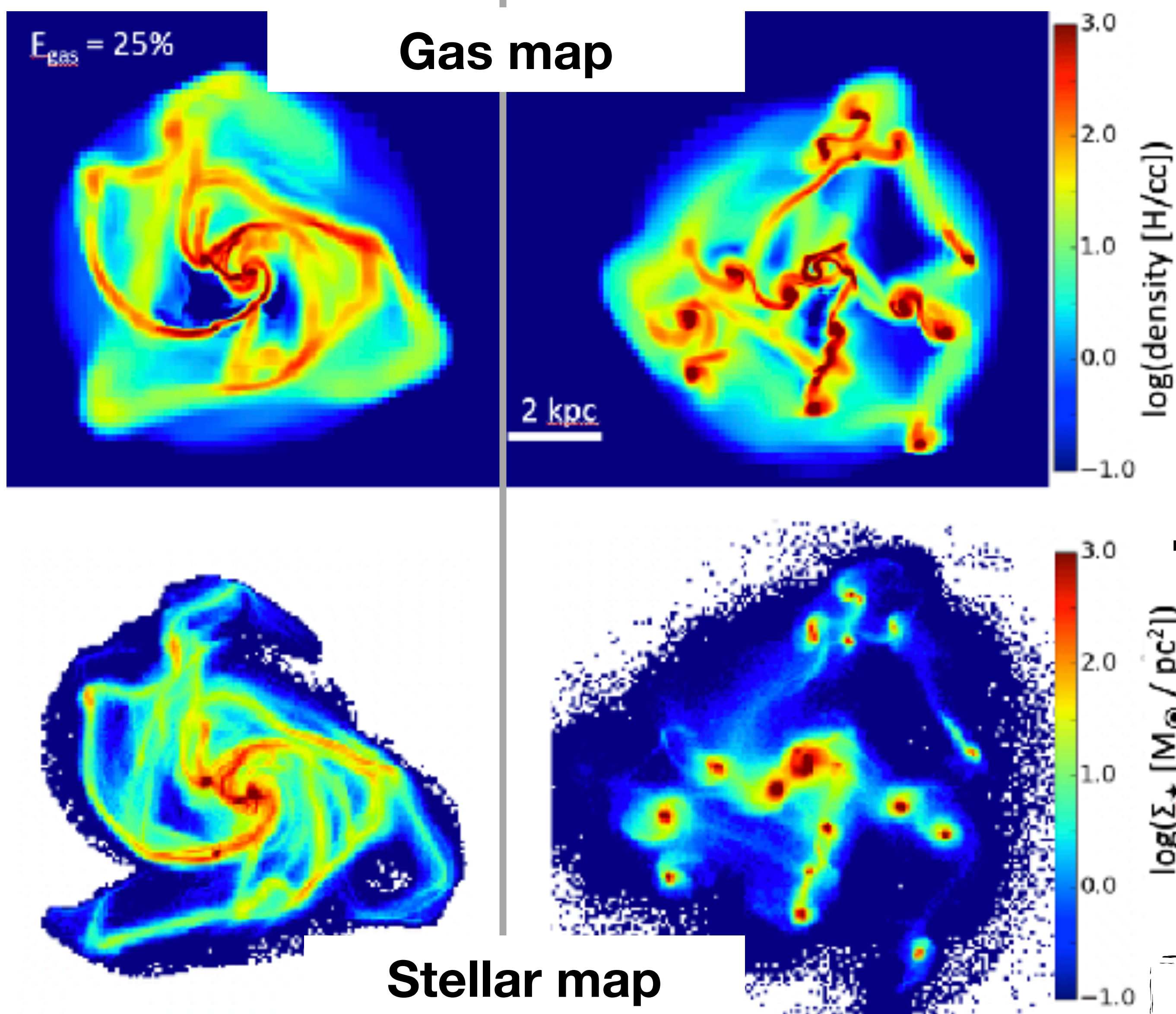
Galaxy model **Feedback model**	F25 *medium*	F50 *medium*
Galaxy-wide mass loading factor of galactic winds η (Section 4.1)	1.13	0.96
Timescale for... [Myr] (Section 4.2)		
Gas removal *(by feedback/stripping)*	70 *(265/95)*	215 *(304/730)*
Gas (re-)accretion	405	195
Gas inflow rate at 1 kpc [$M_\odot$ yr^{-1}] (Section 4.3)		
Normalized to F50 with medium feedback	3.1	6.8

Impact on the whole galaxy: nuclear inflow rate is much higher.
Impact on bulge / thick disk formation ?
(see e.g. Bournaud et al., 2016)

Morphology and gas fractions

Gas fraction

from cosmological simulations | realistic



Realistic gas fractions explain the irregular morphology.

In cosmological simulations, galaxies convert gas into star too efficiently

They stabilize a spiral structure too early in the history of the Universe.

How do you regulate SF without ejecting all your gas?

Fensch & Bournaud 2021

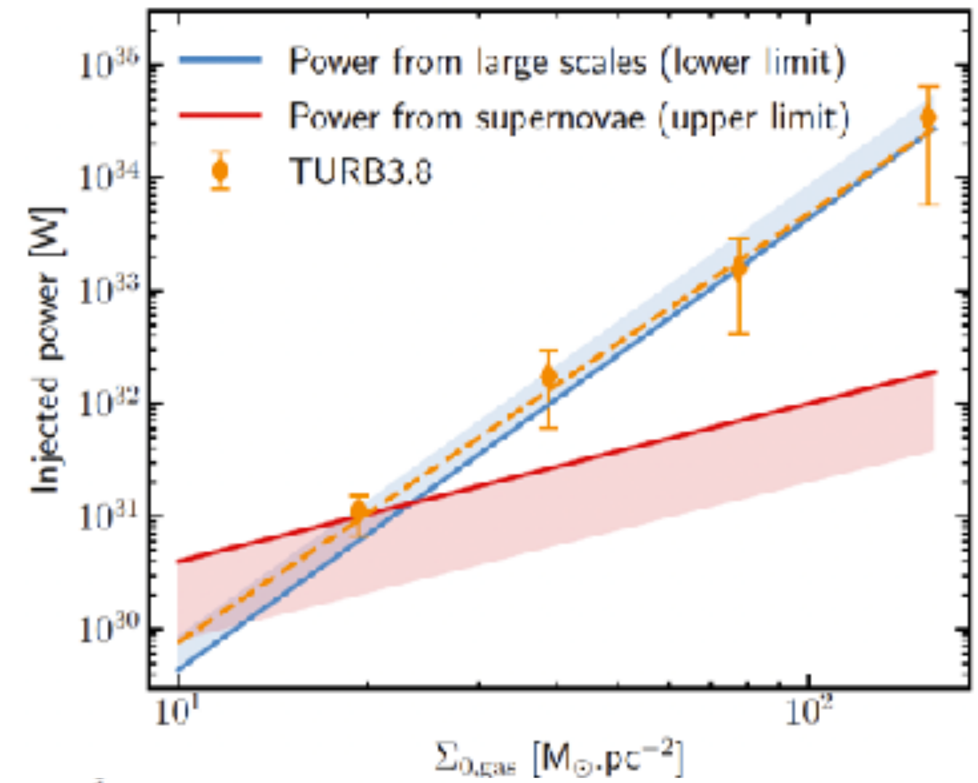
The case for zoom-in simulations

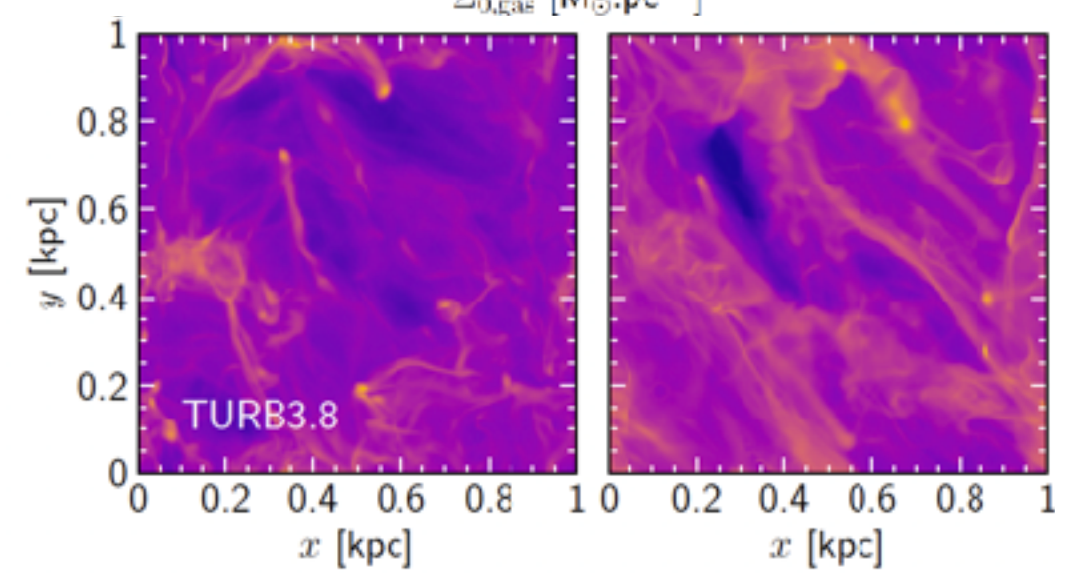
How do you regulate SF without ejecting all your gas ?

External turbulence forcing seems necessary to regulate SF in high density environment

Need to bridge the gap from galaxy to SF cloud scales

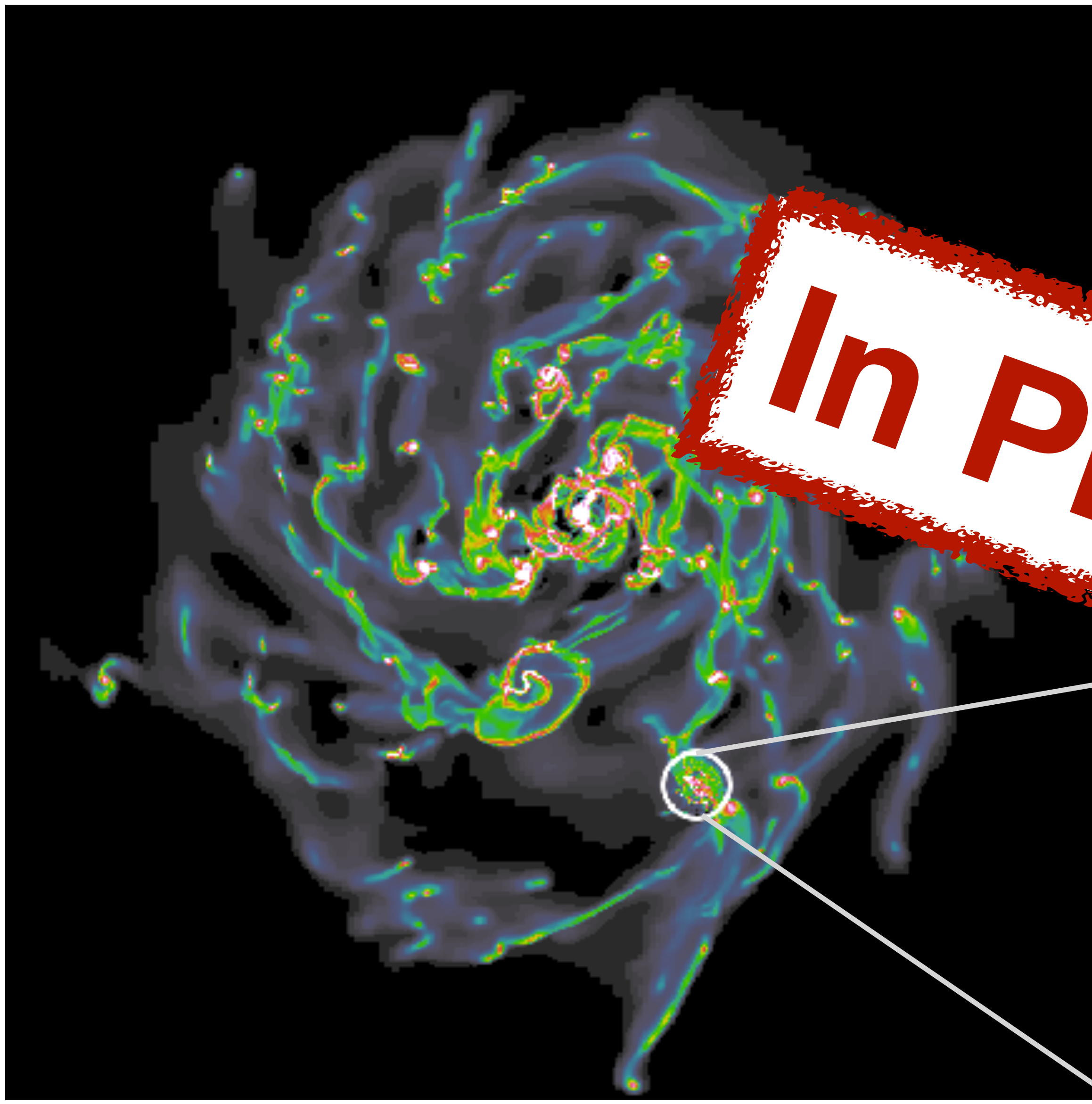
to compare effects of internal (feedback) vs. external (gravity) turbulence forcing





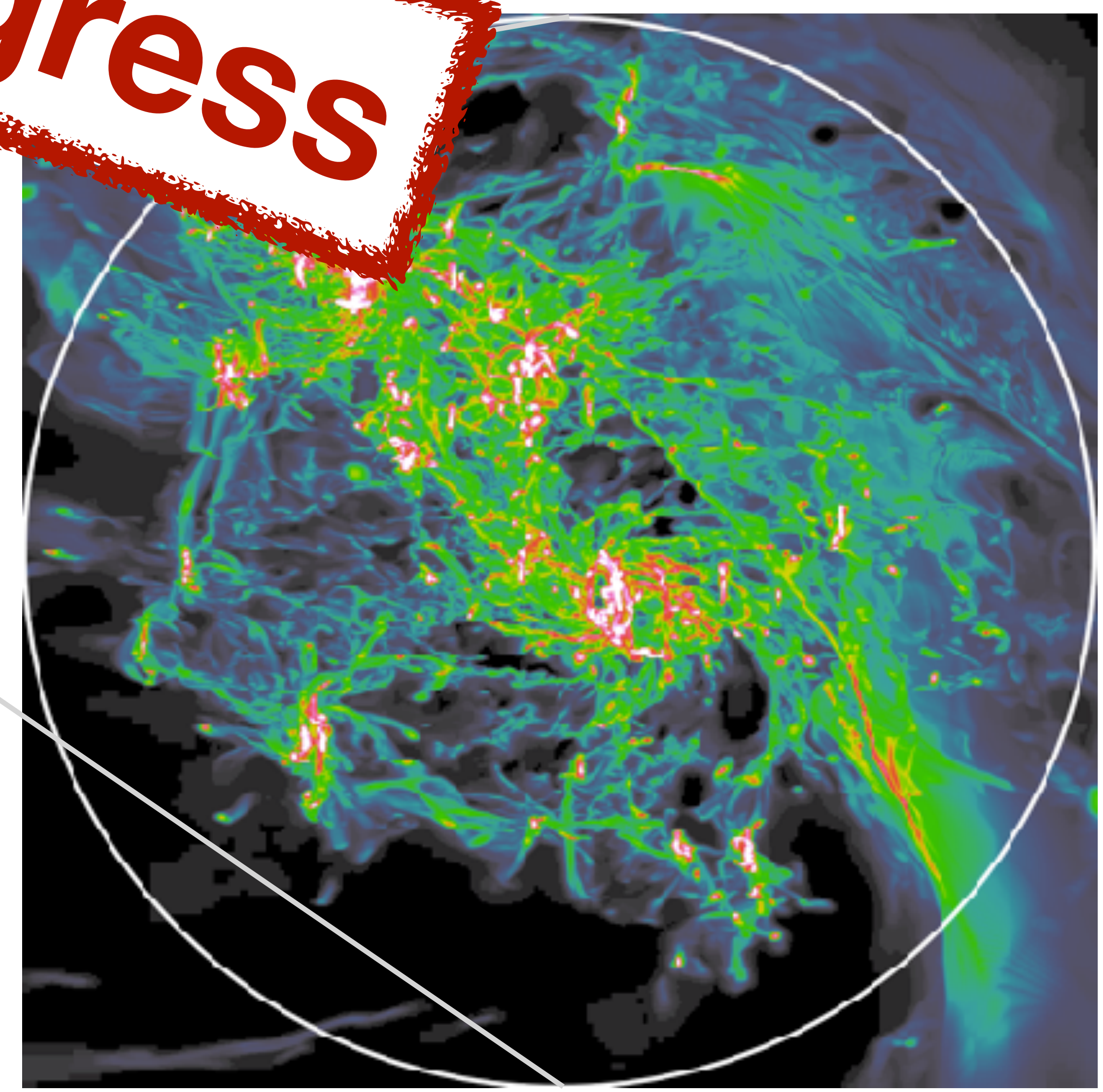
Brucy et al., 2020

The case for zoom-in simulations



In Progress

20 Mh, PI: FENSCH



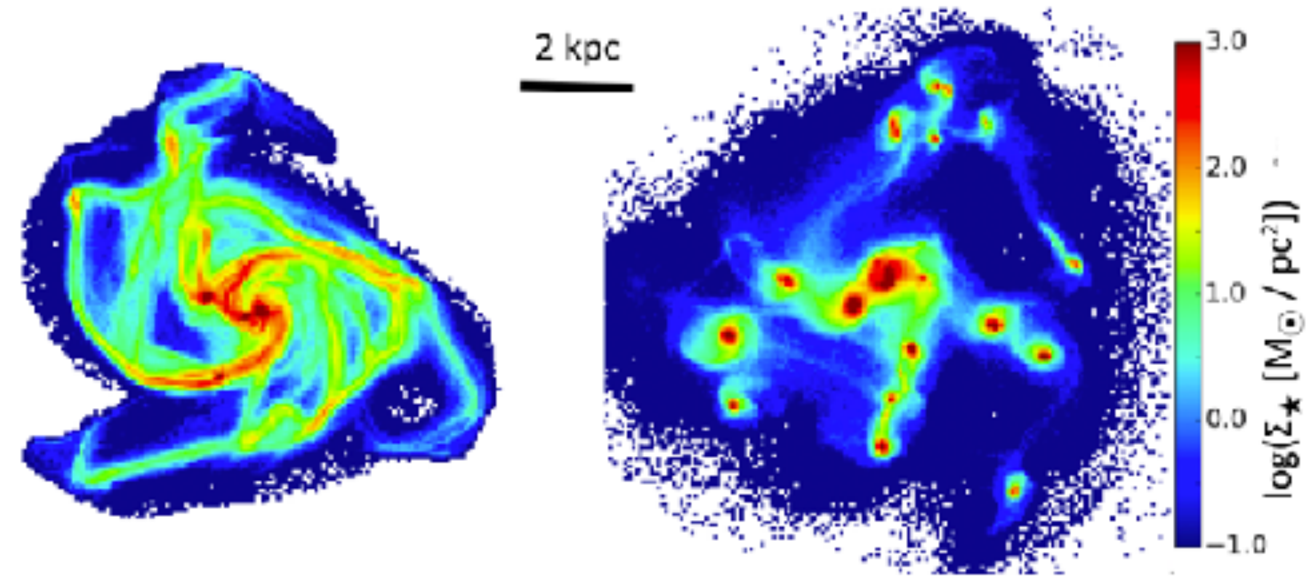
resolving Jeans length with 30 cells
run for 25 Myr

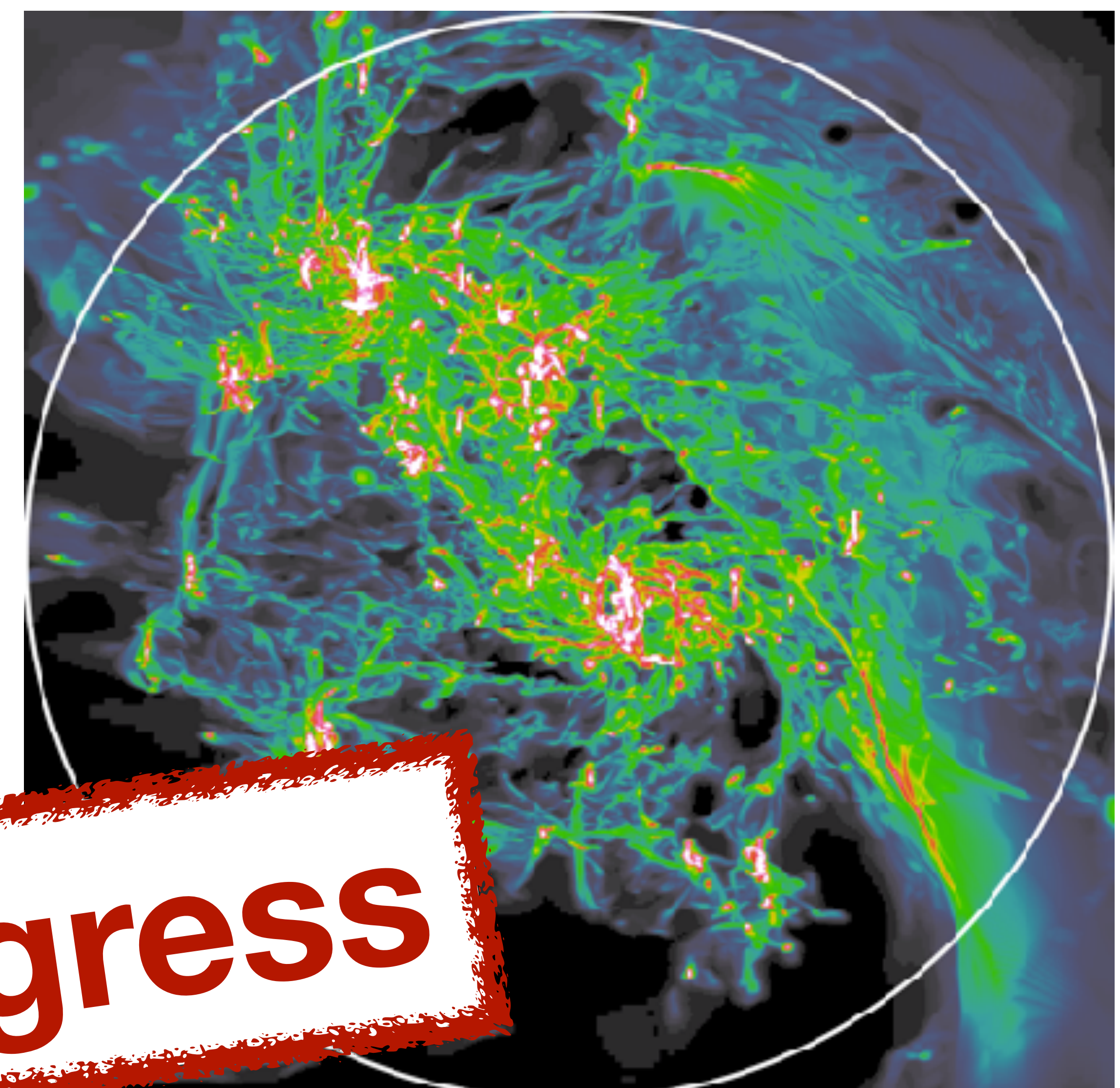
0.09 pc (level 20) resolution with
- only hydro and gravity

0.38 pc (level 18) resolution with
- Radiative transfer (M1)
- Mechanical feedback

Conclusion:

- Gas fraction rules disk stability
- Disk stability impacts galaxy assembly
- We need to understand how to maintain a high gas fraction in cosmological models.
- Need to bridge the scales between galaxy and GMC scales





In Progress