Gas fraction of galaxies and impact of mergers across cosmic times

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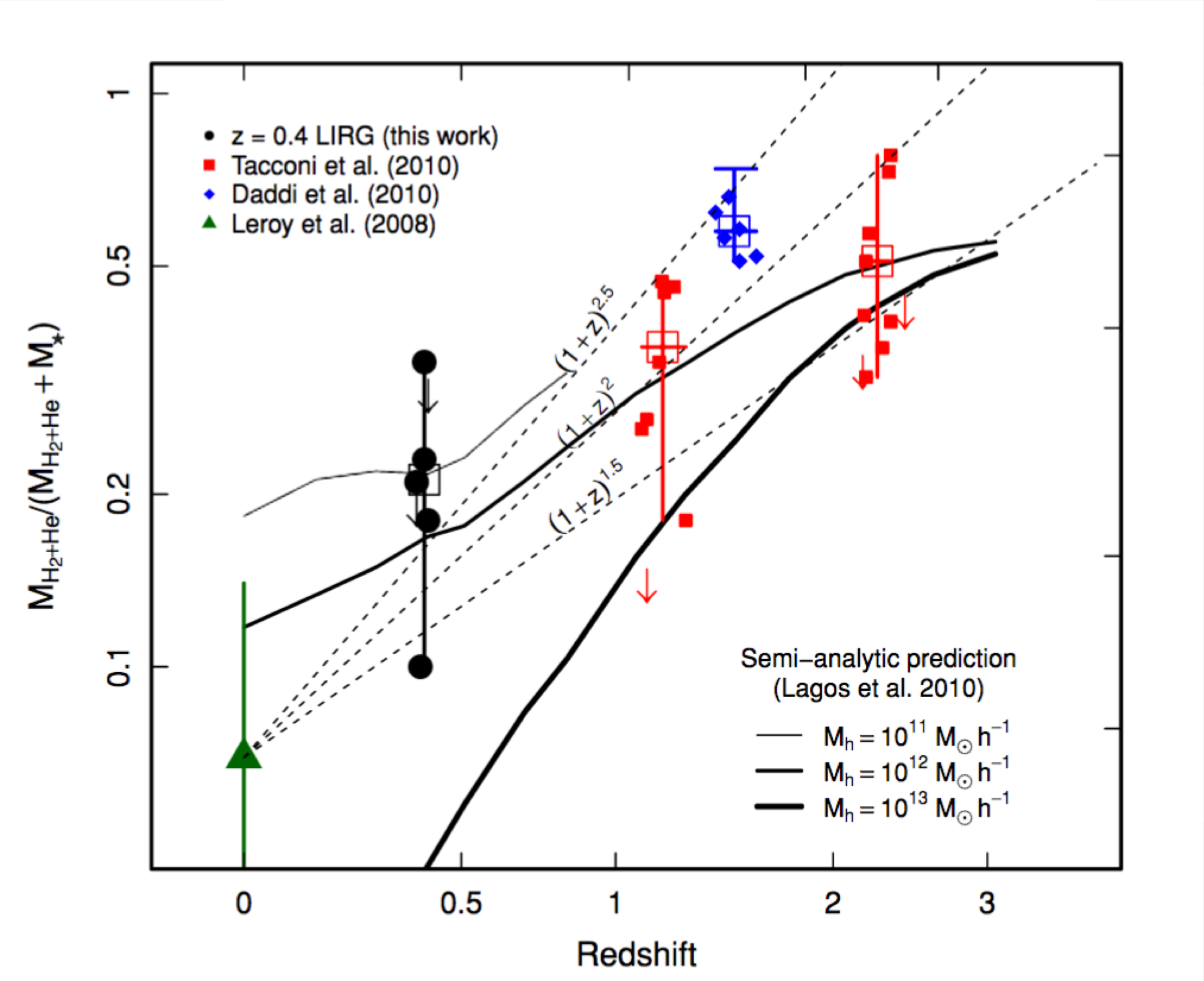
Gas fractions across cosmic time

Geach et al., 2011

see also Combes et al., 2013; Genzel et al., 2015



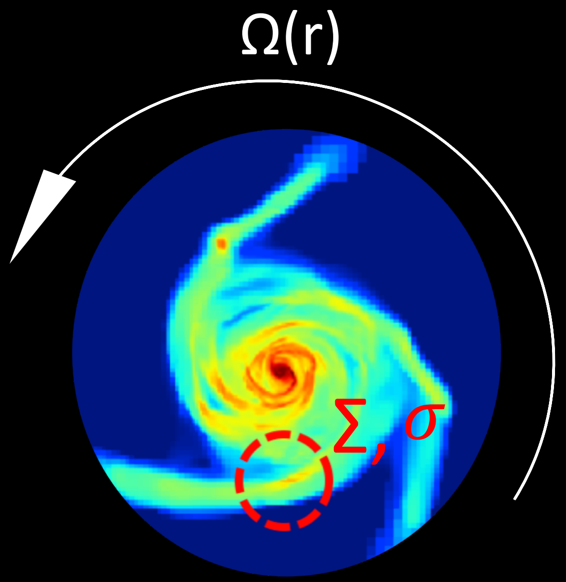
$$f_{\rm gas} = \frac{M_{\rm gas}}{M_{\rm star} + M_{\rm gas}}$$

"proxy for cosmic time"

How does this high gas fraction impacts disk stability ?

See e.g. Dekel et al., 2009, Elmegreen 2011

Disk stability and gas fraction:



Uniform, rotating disk

- angular velocity $\Omega(r)$
- surface density Σ
- velocity dispersion (turbulence) σ

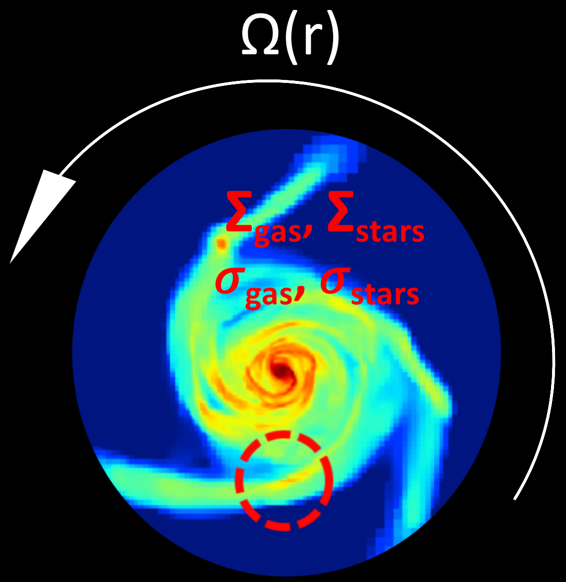
Shear → Turbulent support →

Local perturbation grows if : $$Q = \frac{\kappa c_s}{\pi G \Sigma} < 1$$

↑ Gravity

Toomre (1964)

Disk stability and gas fraction



<u>Two components,</u> rotating disk

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

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

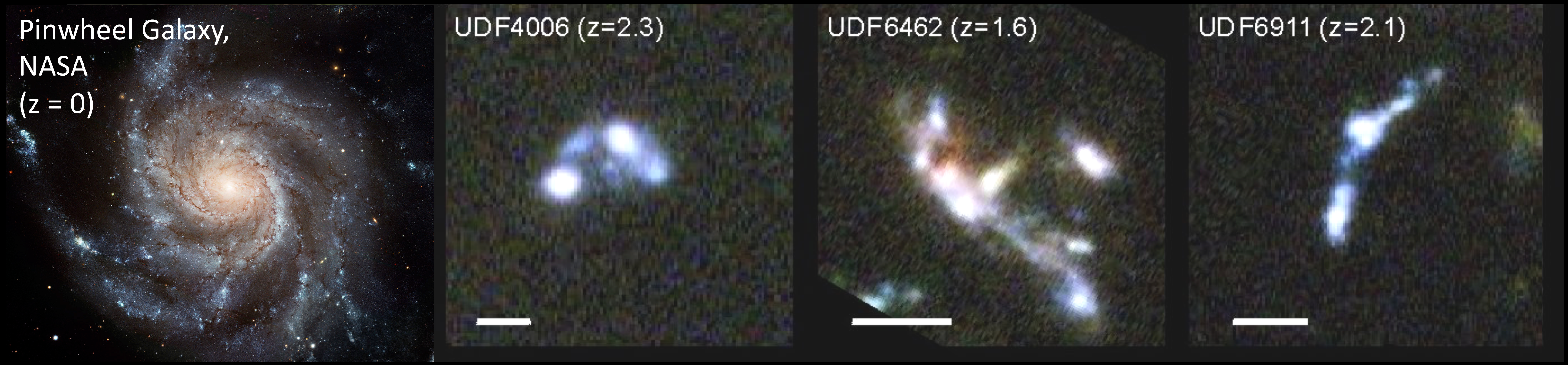
Jog & Solomon 1984
Elmegreen, 1995

Stars are non-dissipative : $\sigma_{gas} < \sigma_{stars}$

Transfer mass star -> gas : Q ↘

Increasing the gas fraction destabilizes the disk

Star forming galaxies at z=1-3: gas-rich clumpy disks



	z = 0 (now)	z = 2
Gas Fraction	10%	60%
Star Form. Rate	1-5 Msun / yr	50-80 Msun / yr
Turbulence	10 km/s	40 km/s

Cowie et al., 1996, Elmegreen et al. 2007

They are not ongoing mergers.
They are disks !

Clumpy morphology:

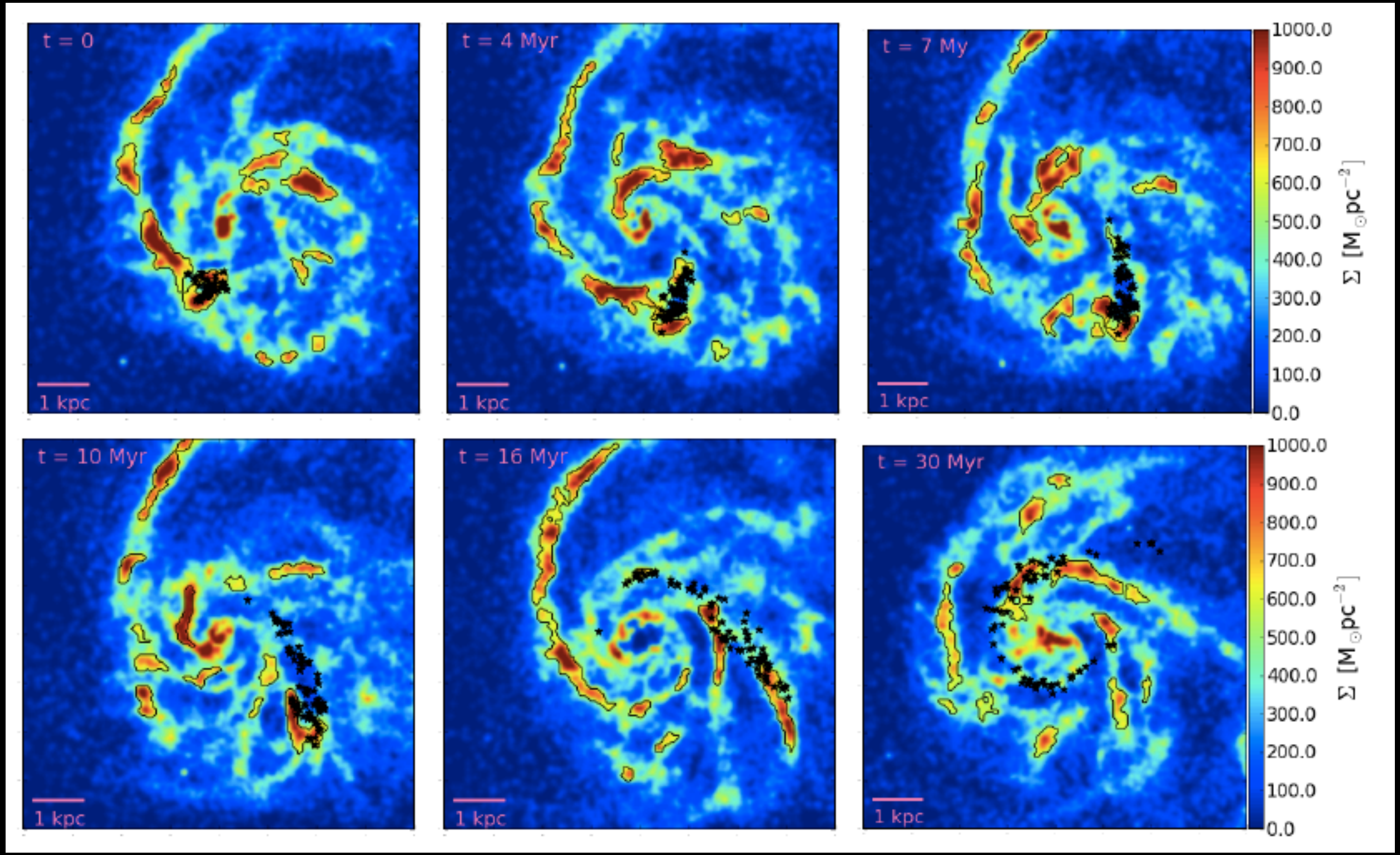
Mass ~ 10^{8-9} $M_\odot$

Size ~ 100-1000 pc

Genzel et al., 2008, Förster-Schreiber et al., 2011
Newman et al., 2012

Clump lifetime?

In some cosmological simulations, clumps are only short-lived.



Here FIRE simulation at z = 1.5.

Oklopčic et al., 2017

Gas mass fraction

20-25%

It is too low at z~2

-> 50-60% of gas

(Tacconi et al., 2010, Genzel et al., 2015)

Common issue, gas consumption is too fast … (see MacLow 2013; Dekel & Mandelker 2014)

Disk instabilities

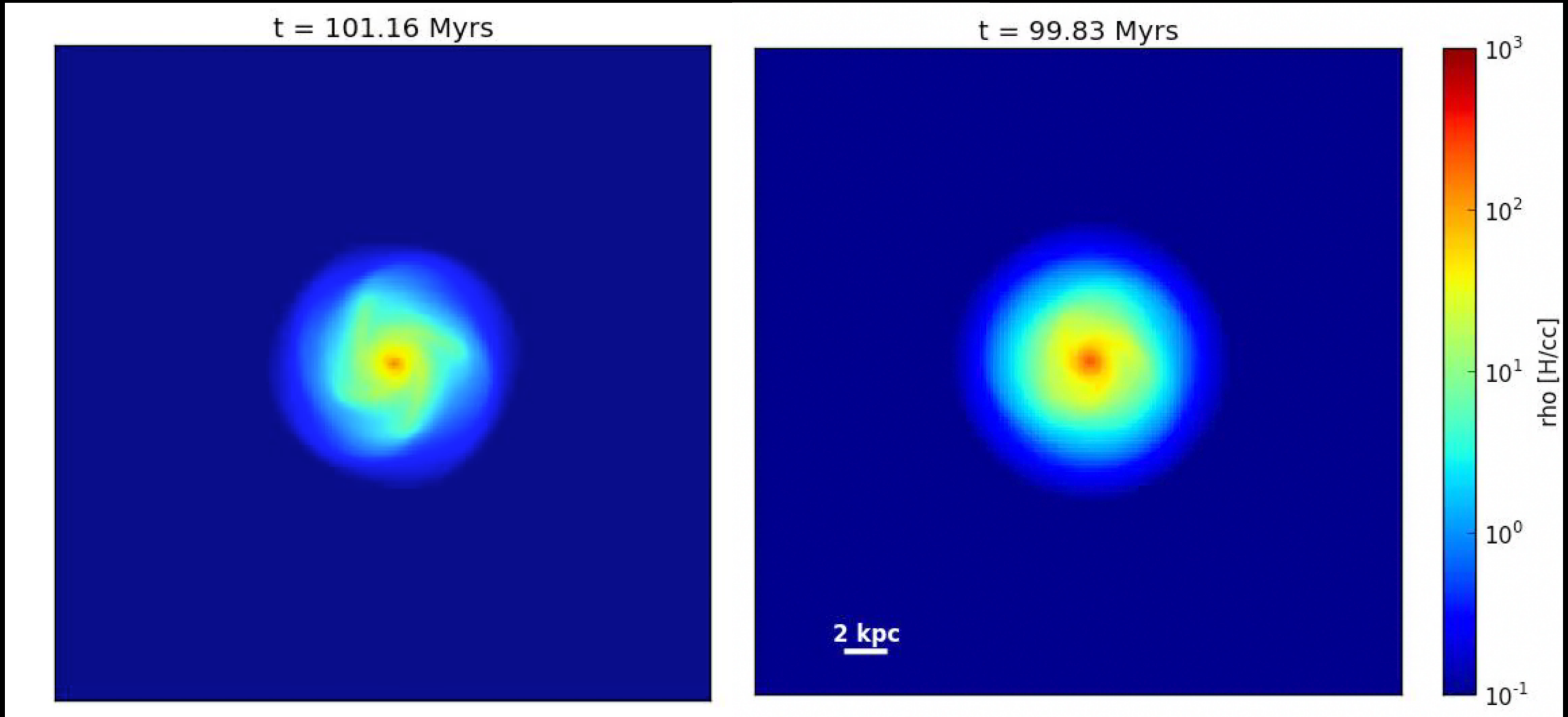
Bournaud & Fensch, 2018 (in prep.)

Test the impact of the gas fraction:

→ Total mass and mass distribution and ***resolution*** (20pc) from Oklopčic et al., 2017 (O17)

→ Same DM halo, same rotation curve

F_{gas} = 25% (O17) 50%



We test different types of feedback:

photon trapping factor: 2 -> 7

HII region temperature: $5x10^4$ -> $2x10^5$K

Thermal SN -> Kinetic SN

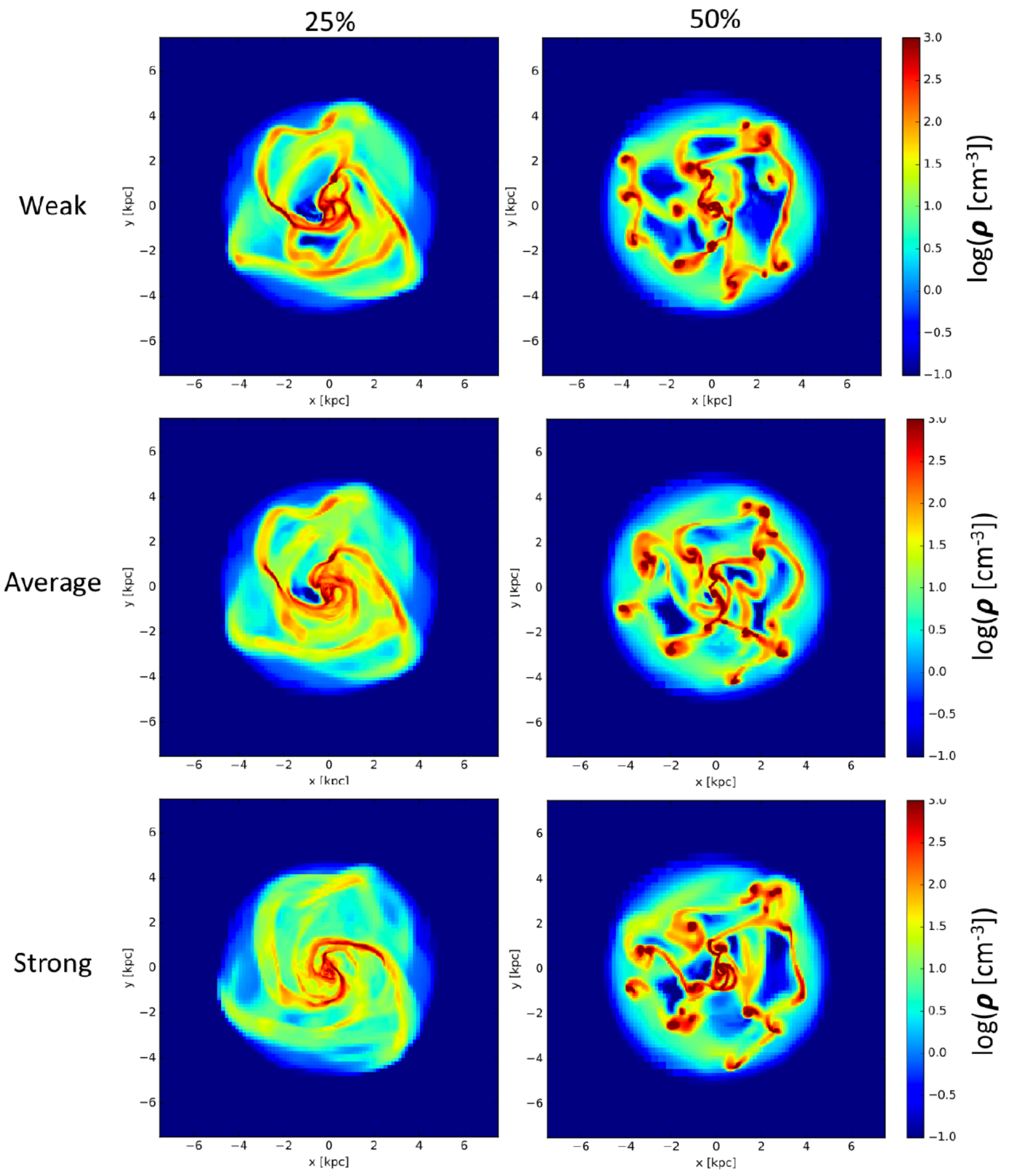
Virial parameter (Bertoldi&McKee, 1992):

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

	F20-F25	F50-F60
Weak	2.3	0.6
Average	2.5	0.9
Strong	2.9	1.1

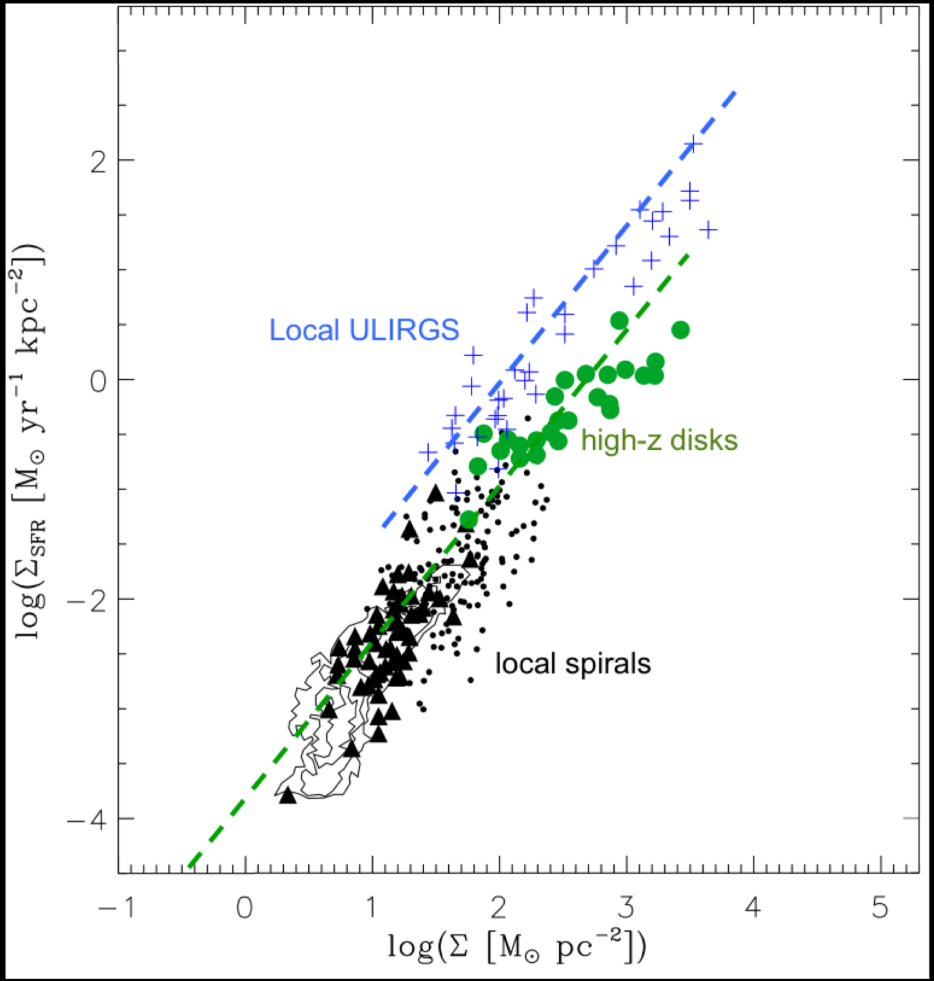
In O17: α ~ 3

Clumps in the 50% case are bound and long-lived on average.



What we know at low-redshift (f_gas = 10%):

Interactions *can* trigger starbursts.

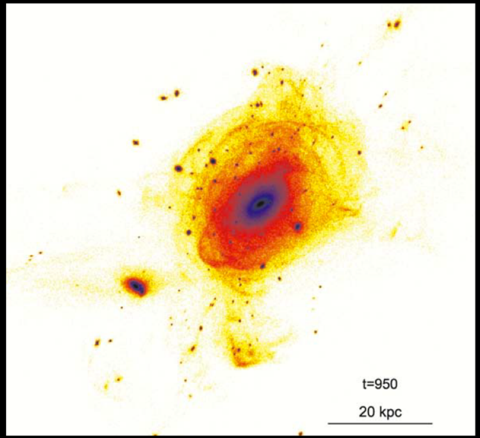


Renaud+12
Kraljic+14

Observations from Kennicutt et al. (1998, 2007), Bigiel et al. (2008), Tacconi et al. (2010), Daddi et al. (2010)

Interactions *can* trigger star cluster formation.

Whitmore et al. (1995, 2010)



Bournaud et al., 2008

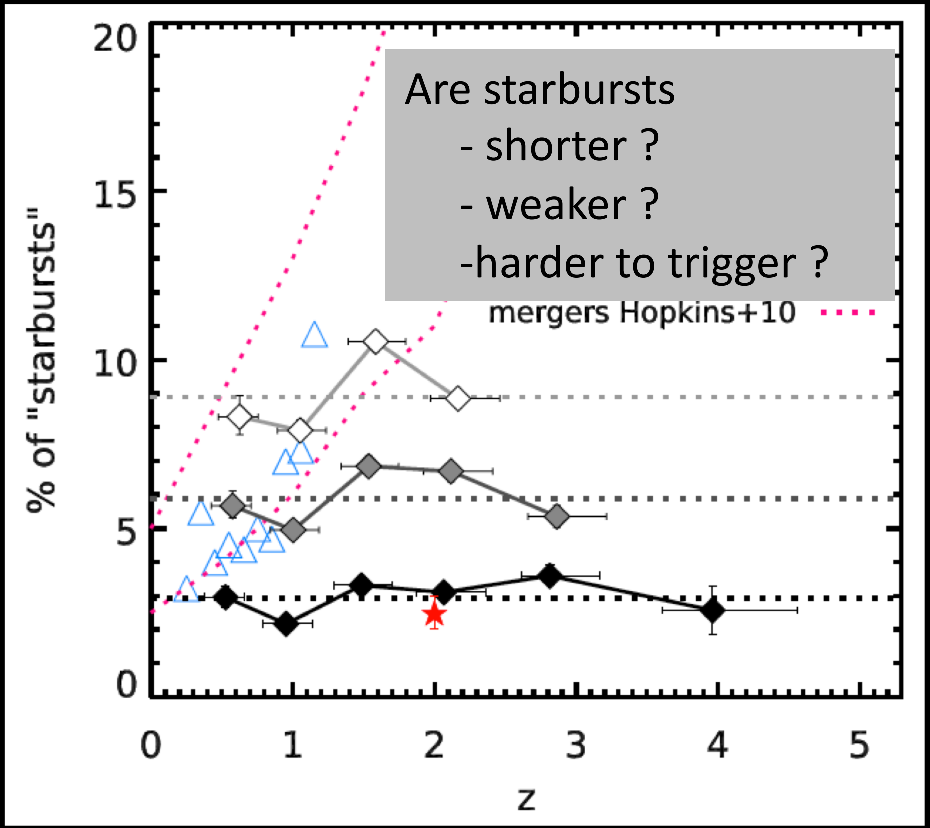
Young Massive Clusters

Similar in mass and size to Globular Clusters.

(10^4-10^6 Msun) (1-3 pc)

And at higher redshift (z=2, f_gas = 50%)?

Can interactions trigger strong starbursts?

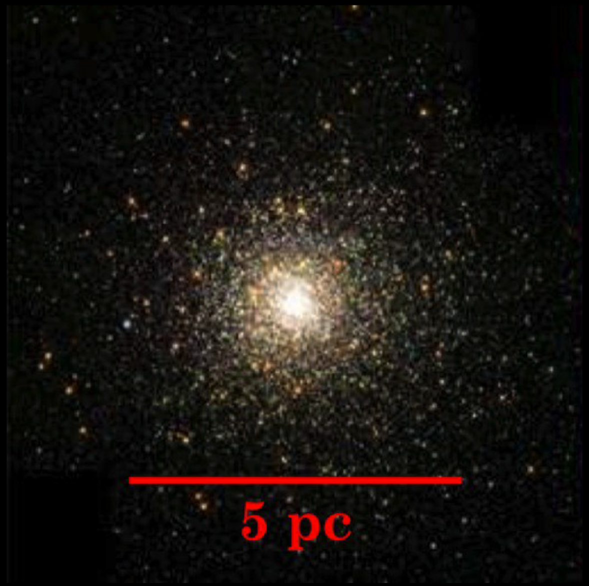


Schreiber et al., 2015

See also Rodighiero+11 and Lofthouse+17, Martin+17

Can interactions trigger star cluster formation?

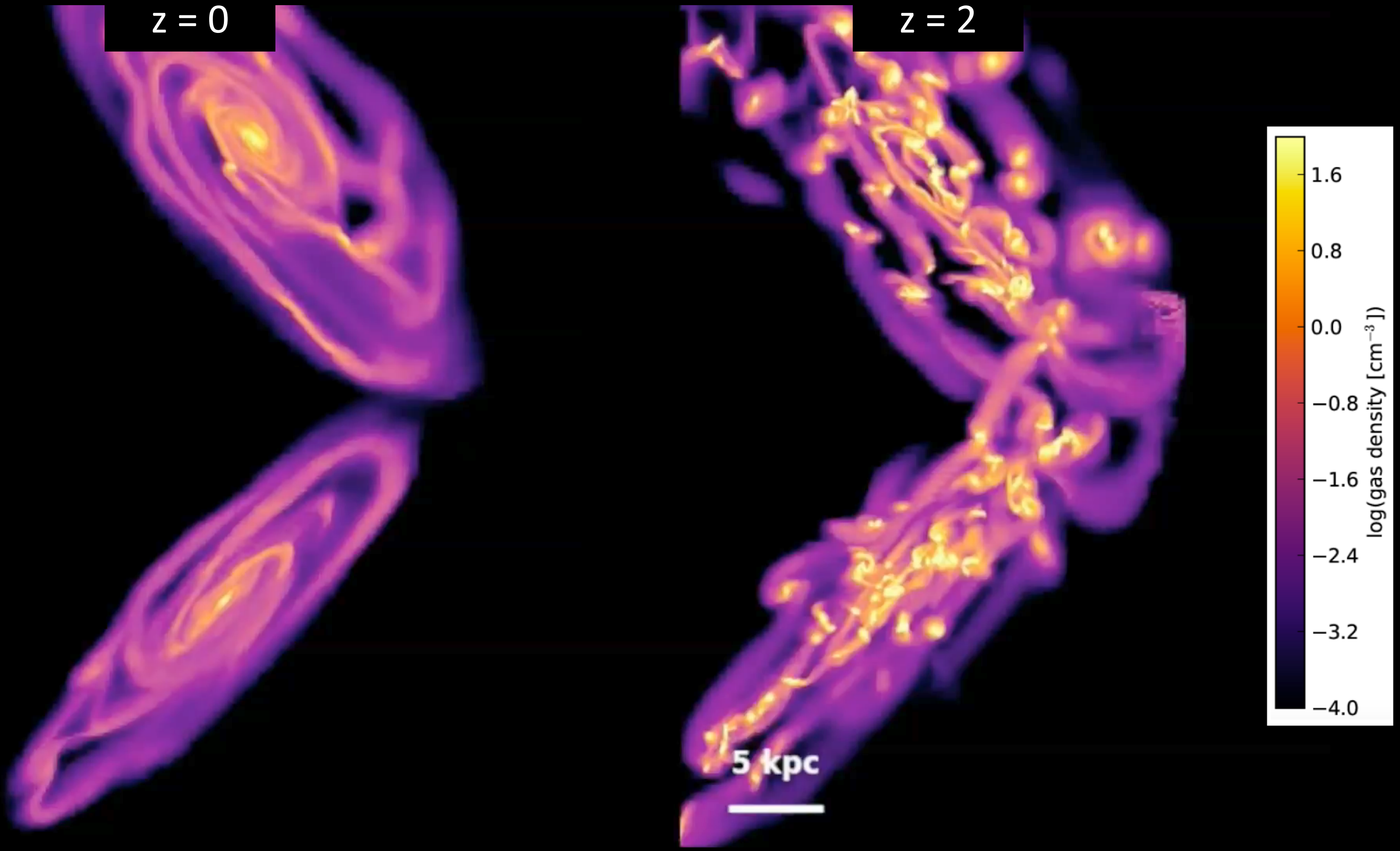
Could metal-rich GCs be produced by interactions?



Ashman & Zepf, 1992, 2001

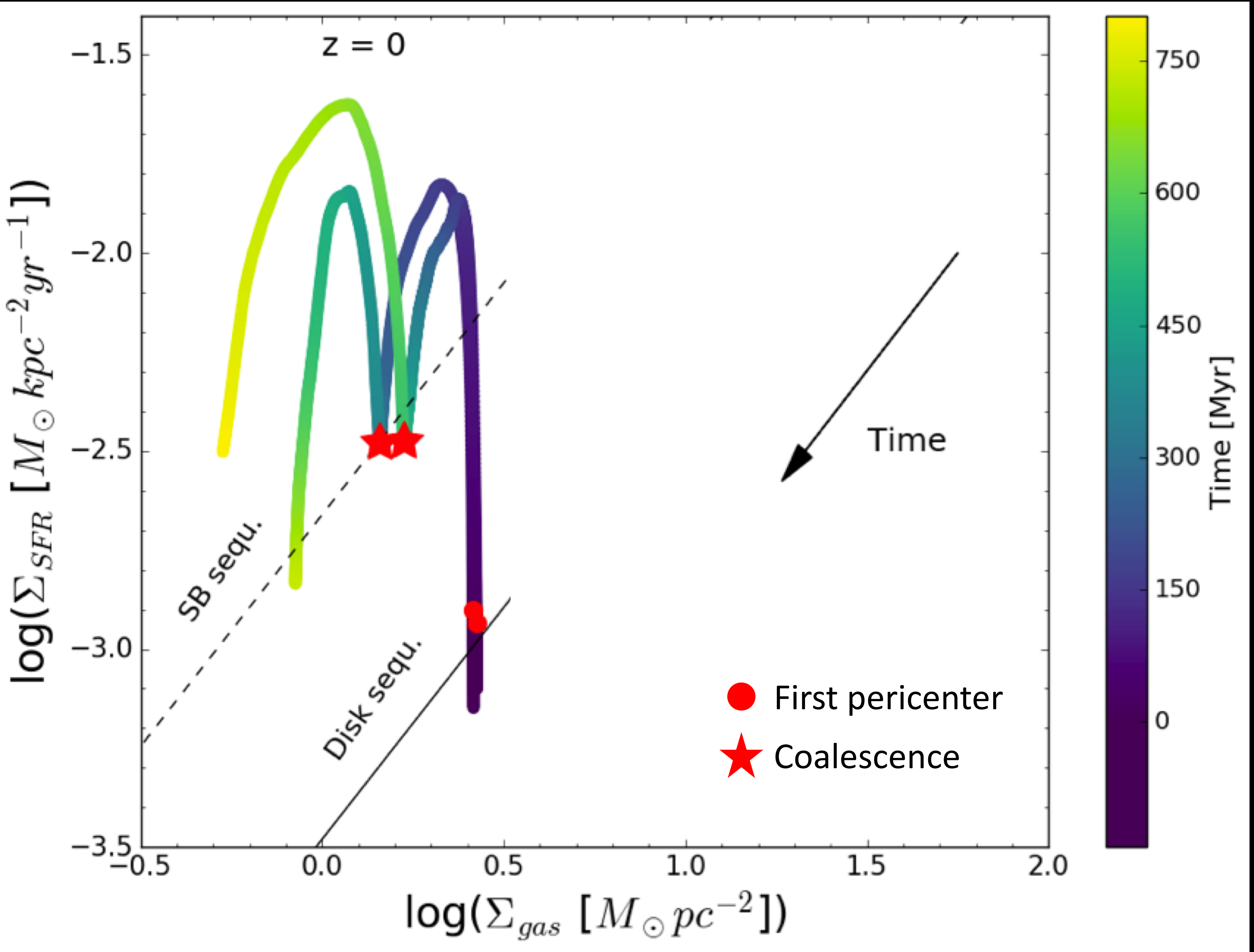
Bekki et al., 2002

Numerical Set:



Fensch et al., 2017

Results:



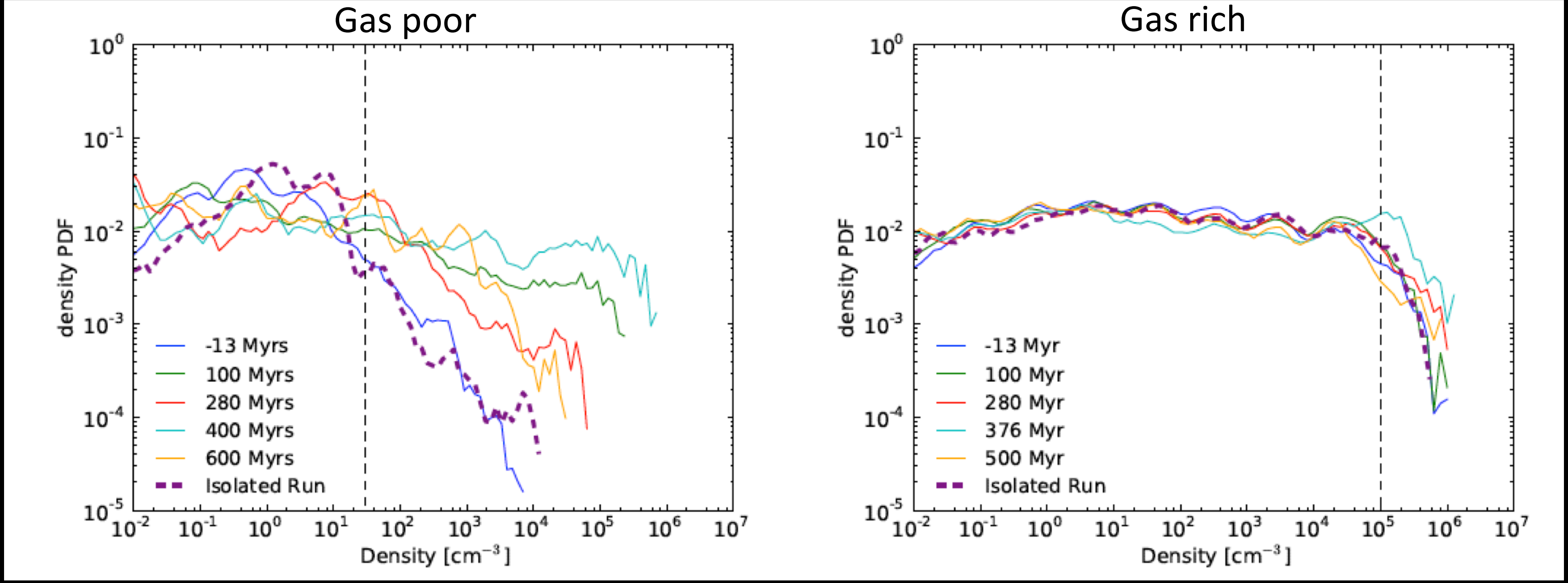
Merger-induced starbursts are:

- harder to trigger
- weaker
- shorter

See also Bournaud et al., 2011 , Hopkins et al., 2013
Perret et al., 2014

Density PDFs

No change at all
during the interaction !



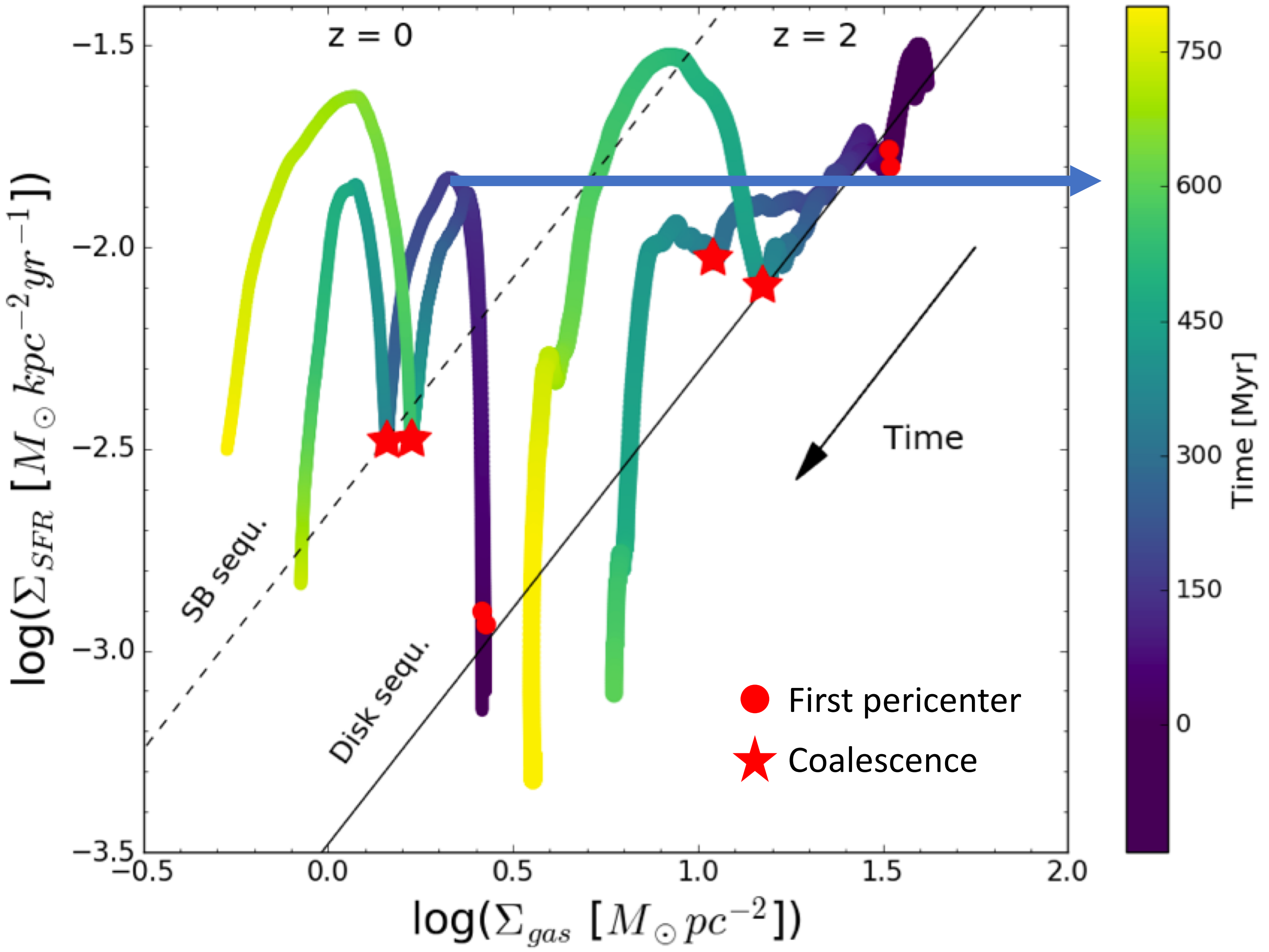
For isolated galaxies, log-normal distribution of width

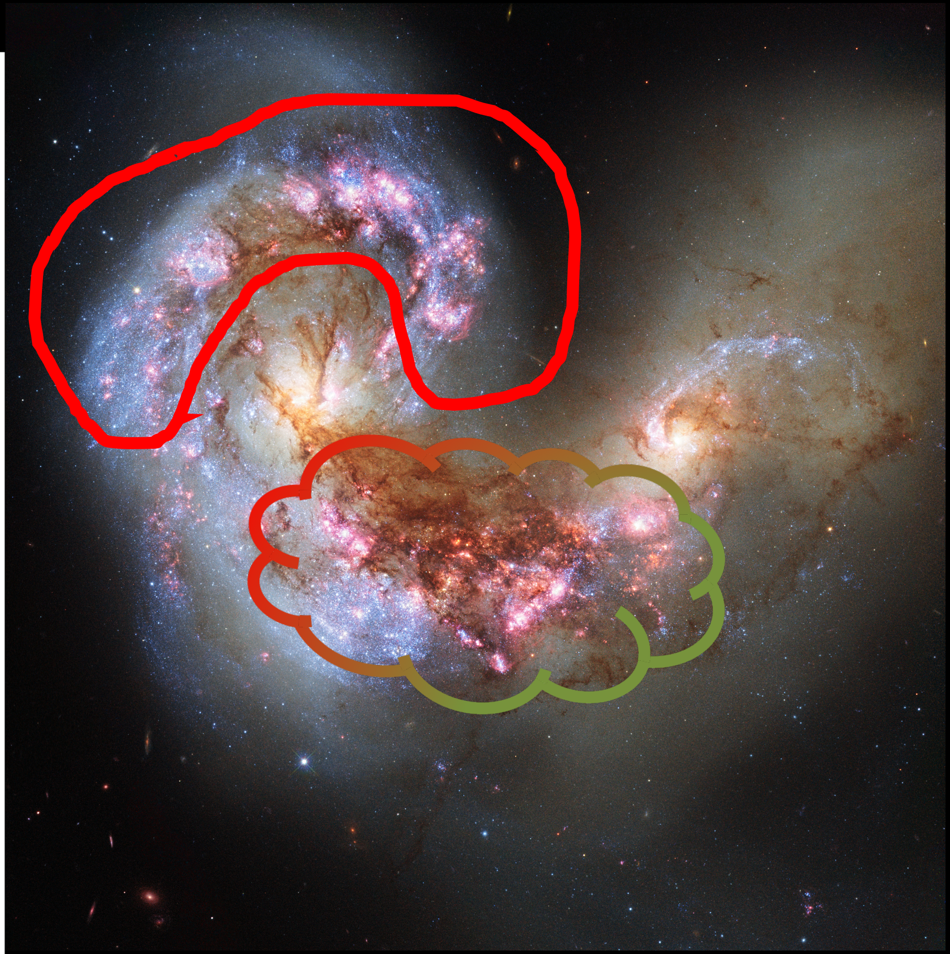
$$\omega^2 \propto \ln(1 + M^2)$$

e.g., Nordlund and Padoan, 1999

Fensch et al., 2017

Results:





Fensch et al., 2017

Physical processes:

<u>1/ Compressive turbulence:</u> *compression of the gas on pc scales*

Interaction

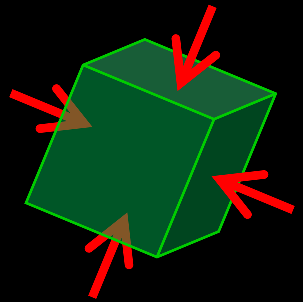
DRIVES

- compressive tides

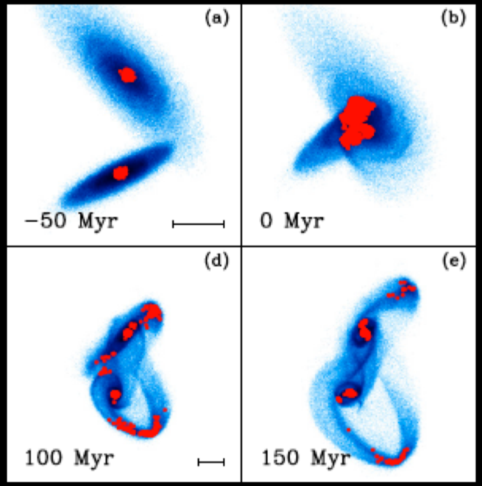
- turbulence

INDUCE

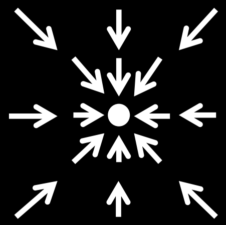
Increase of ***compressive*** turbulence



Renaud+08



$\nabla \times \sigma = 0$



See Renaud et al., 2014

Saturation effect I

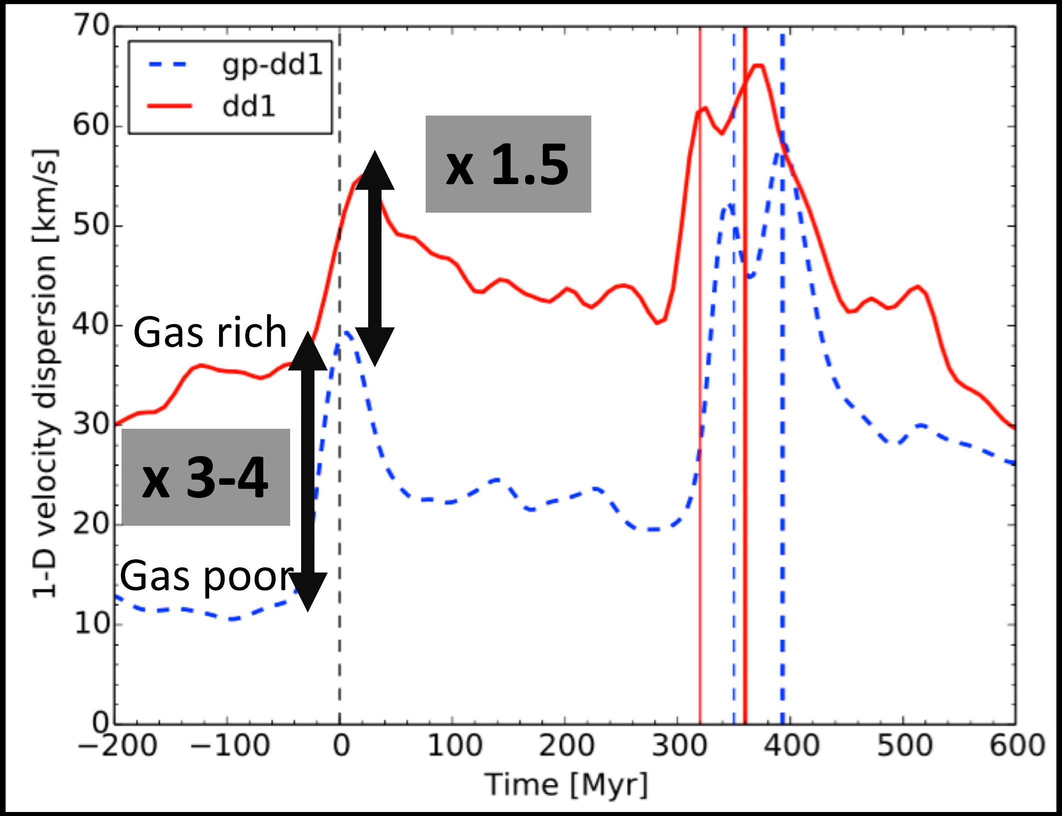
Turbulence is already high in gas-rich galaxies:

Fgas = 10% : σ = 10km/s

see e.g. Epinat et al., 2008

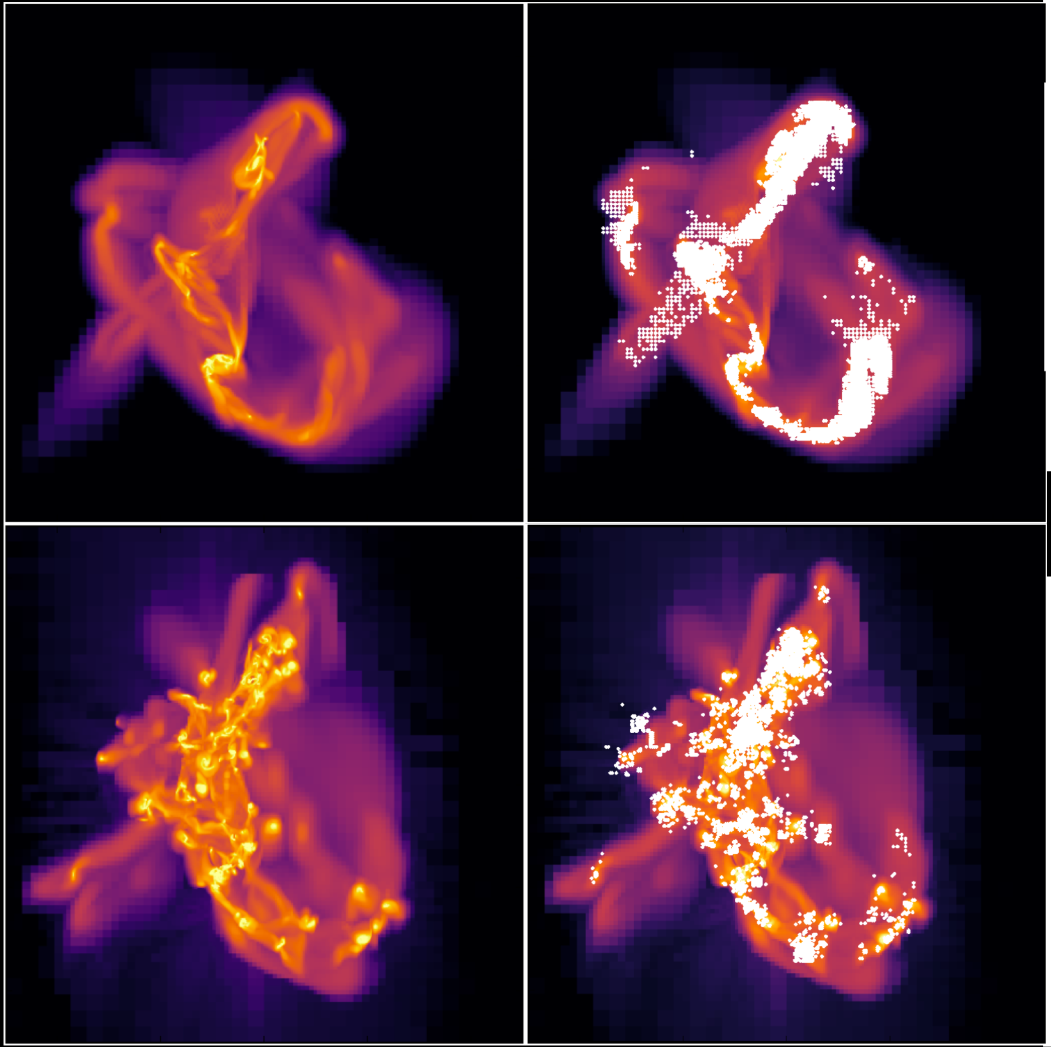
Fgas = 50% : σ = 40-50 km/s

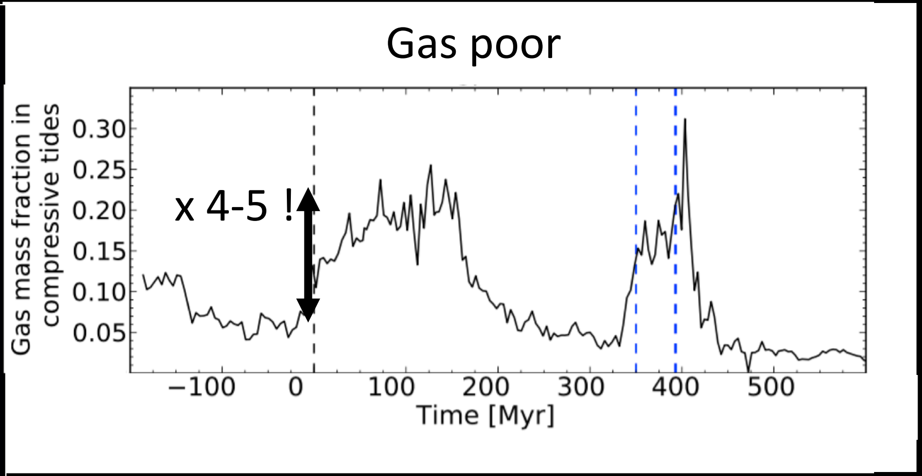
see e.g. Förster-Schreiber et al., 2011



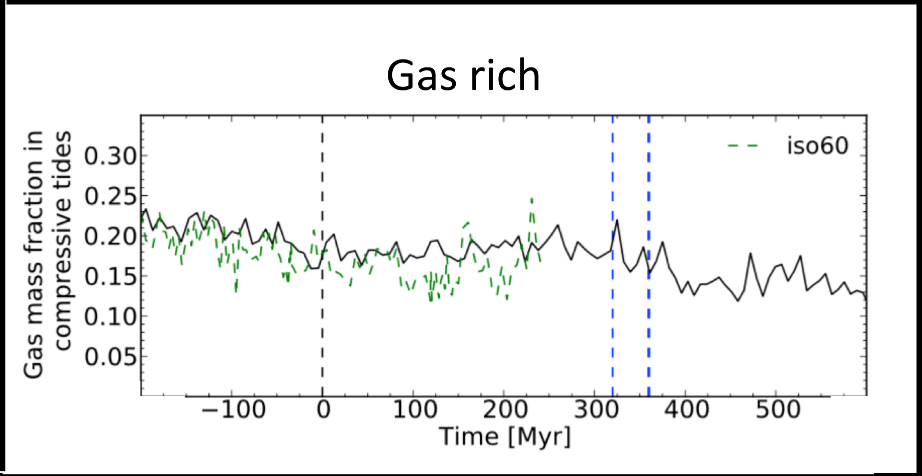
Fensch et al., 2017

Saturation effect II





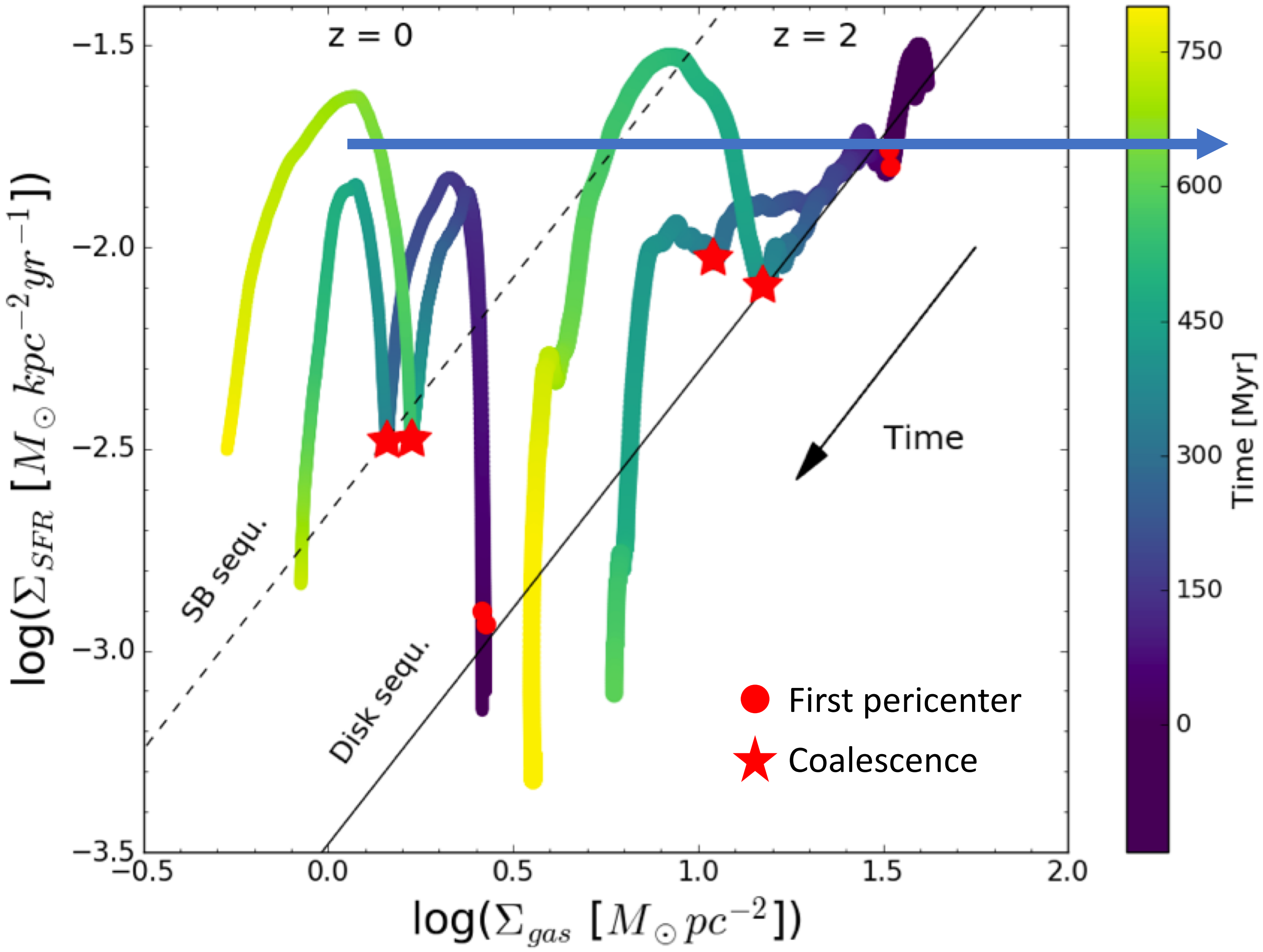
See also Renaud+08,+09

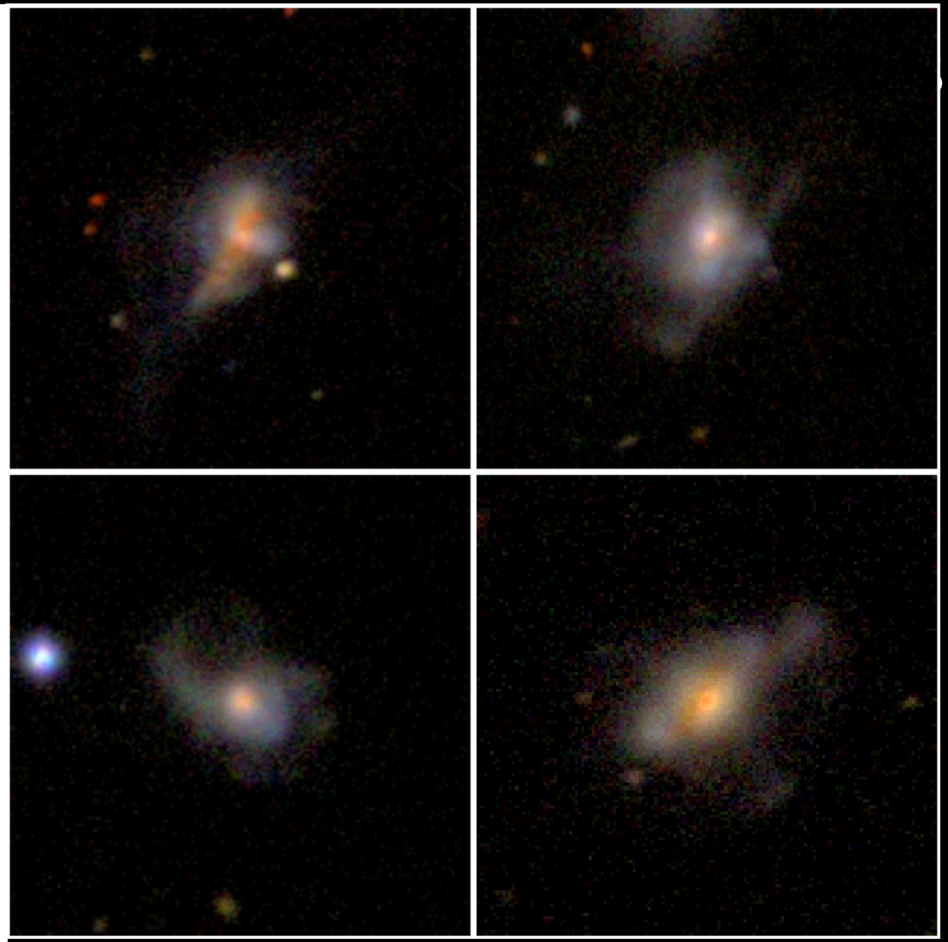


Compressive tides are already in place in gas-rich galaxies

Fensch et al., 2017

Results:



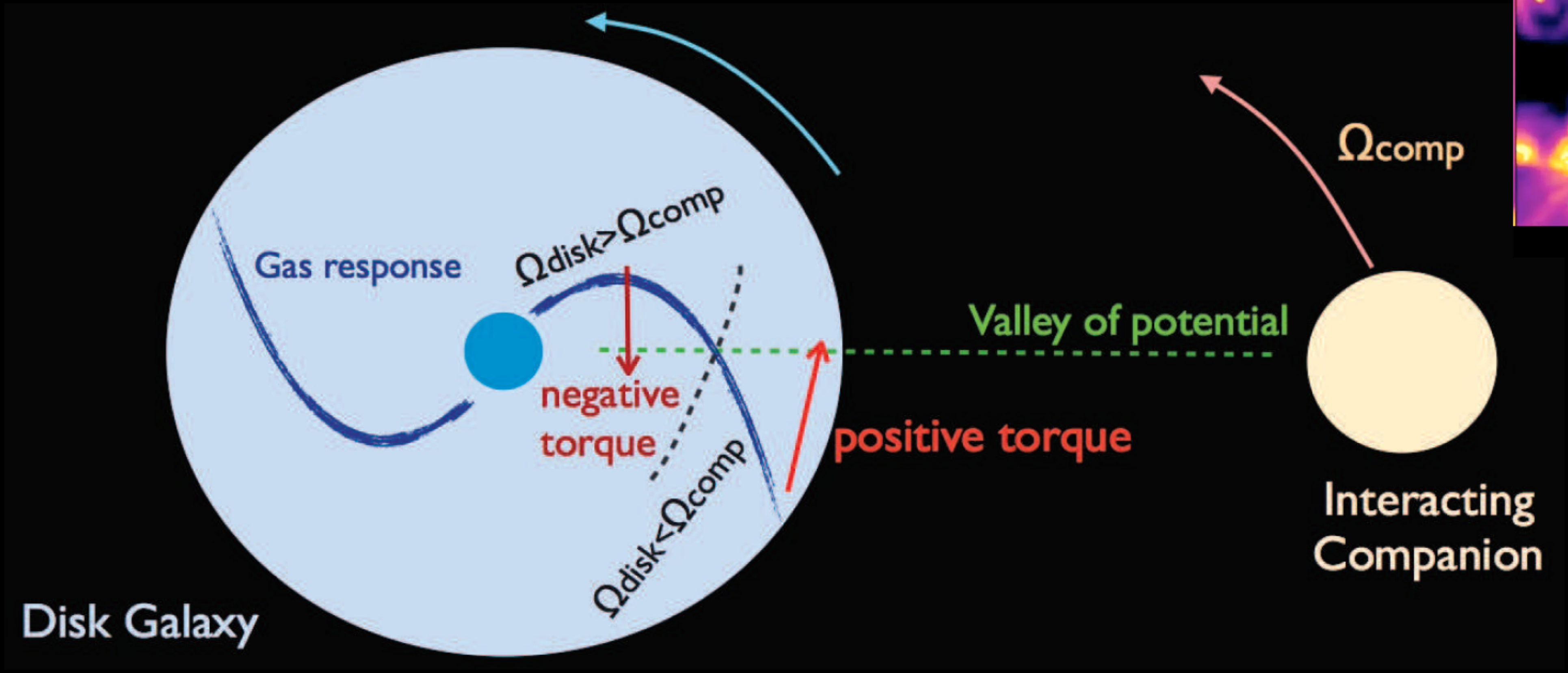


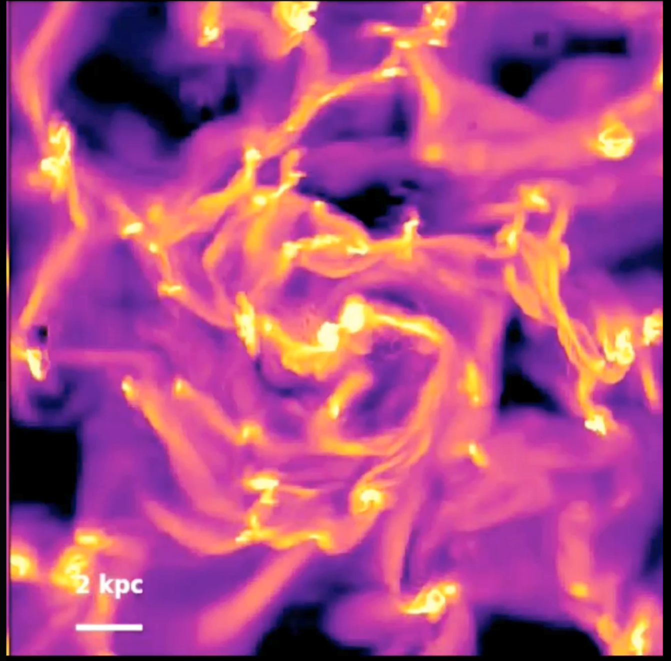
Nuclear starbursts

Fensch et al., 2017

Physical processes:

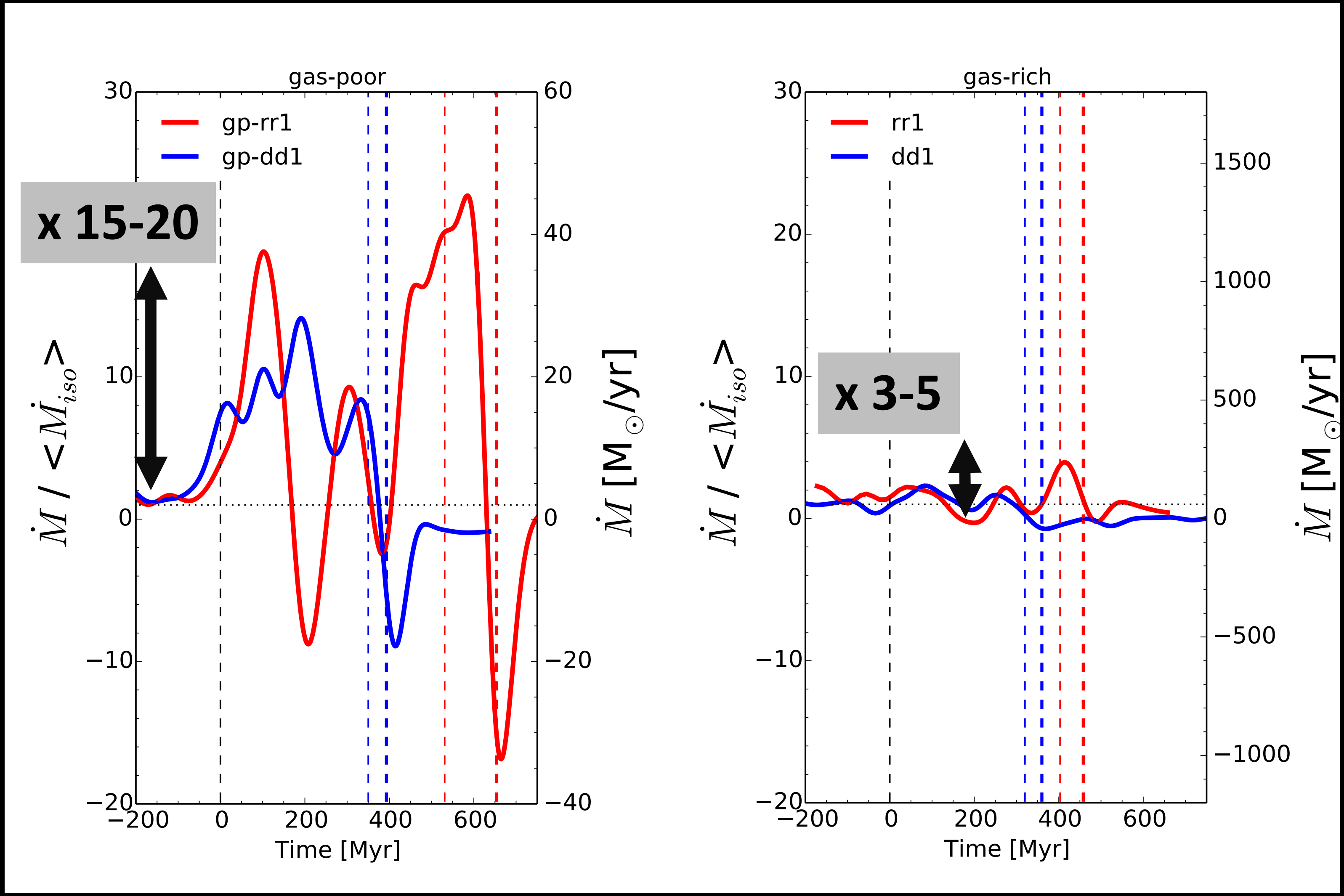
2/ Gas inflows : *compression of the gas on kpc scales*





See Barnes & Hernquist 1991
and reviews by Bournaud 2010; Duc & Renaud 2013

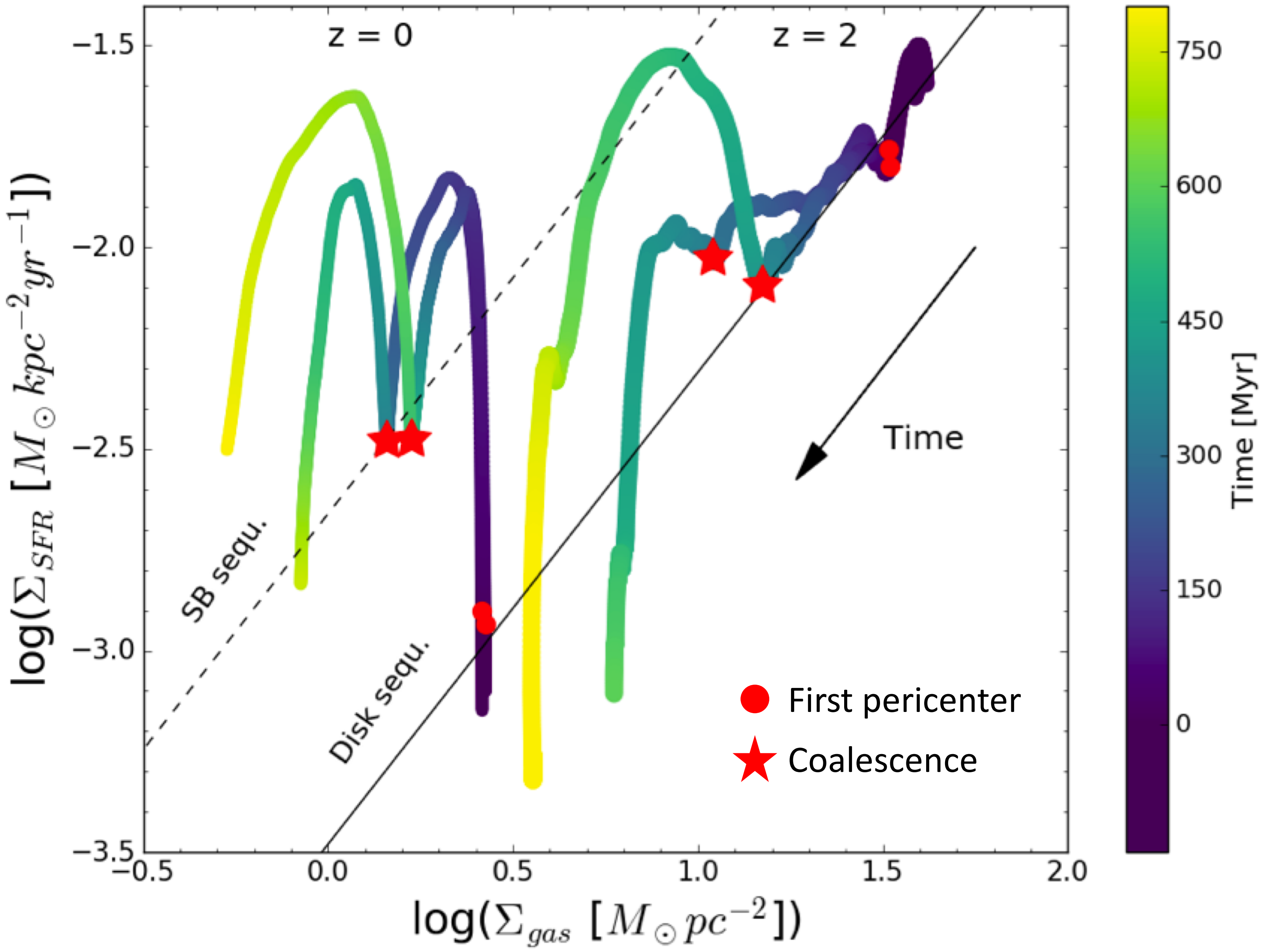
Physical processes III: Inflows



*Weaker **relative** increase of gas inflows.*

Fensch et al., 2017

Results:



Merger-induced starbursts are:

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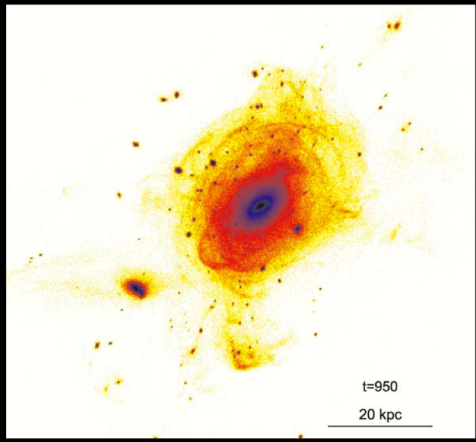
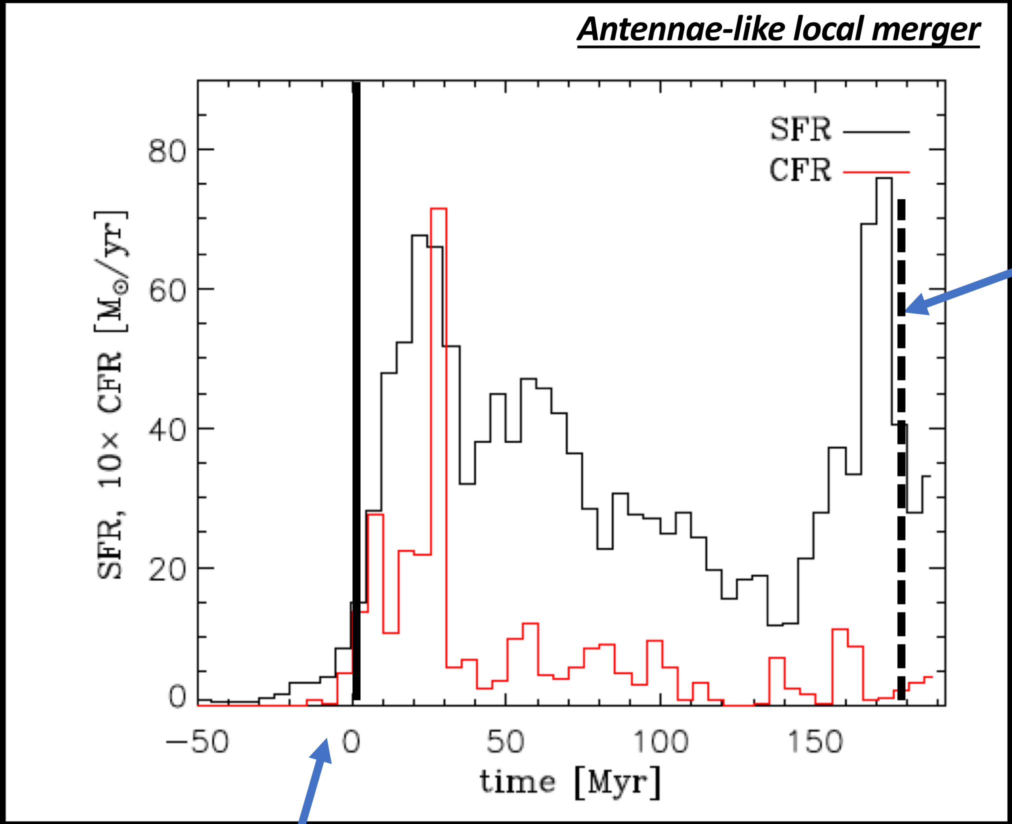


What about star clusters?

Fensch et al., 2017

Stellar cluster formation: z = 0 case

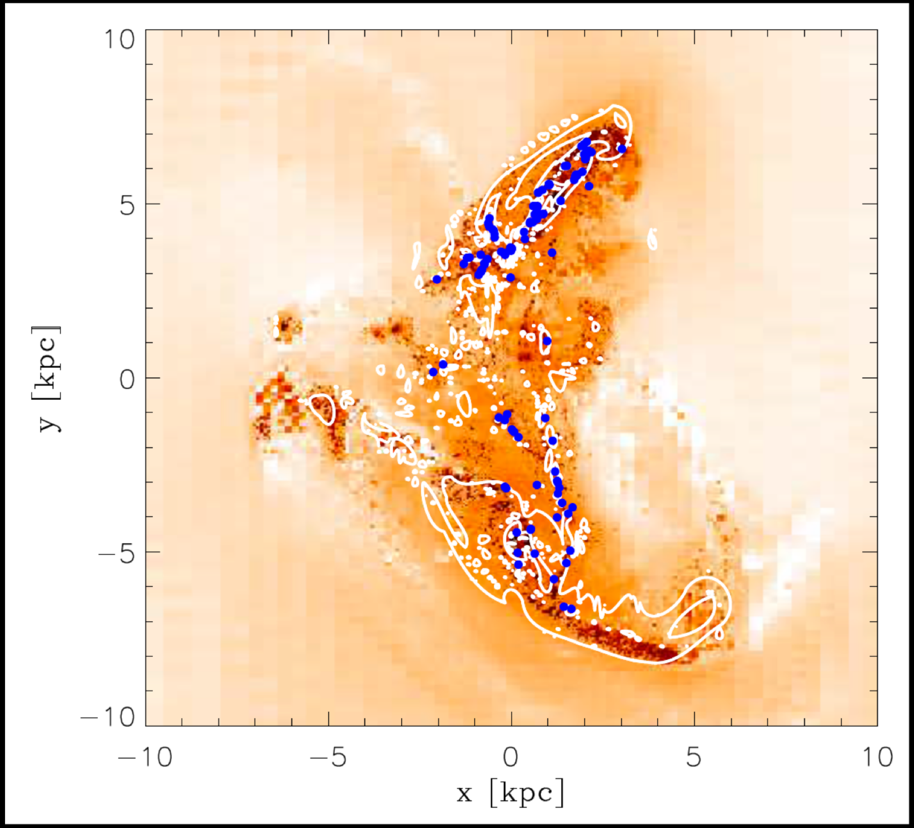


Nuclear starburst

Not much cluster formation

Tidal compression, cluster formation

Renaud et al., 2015

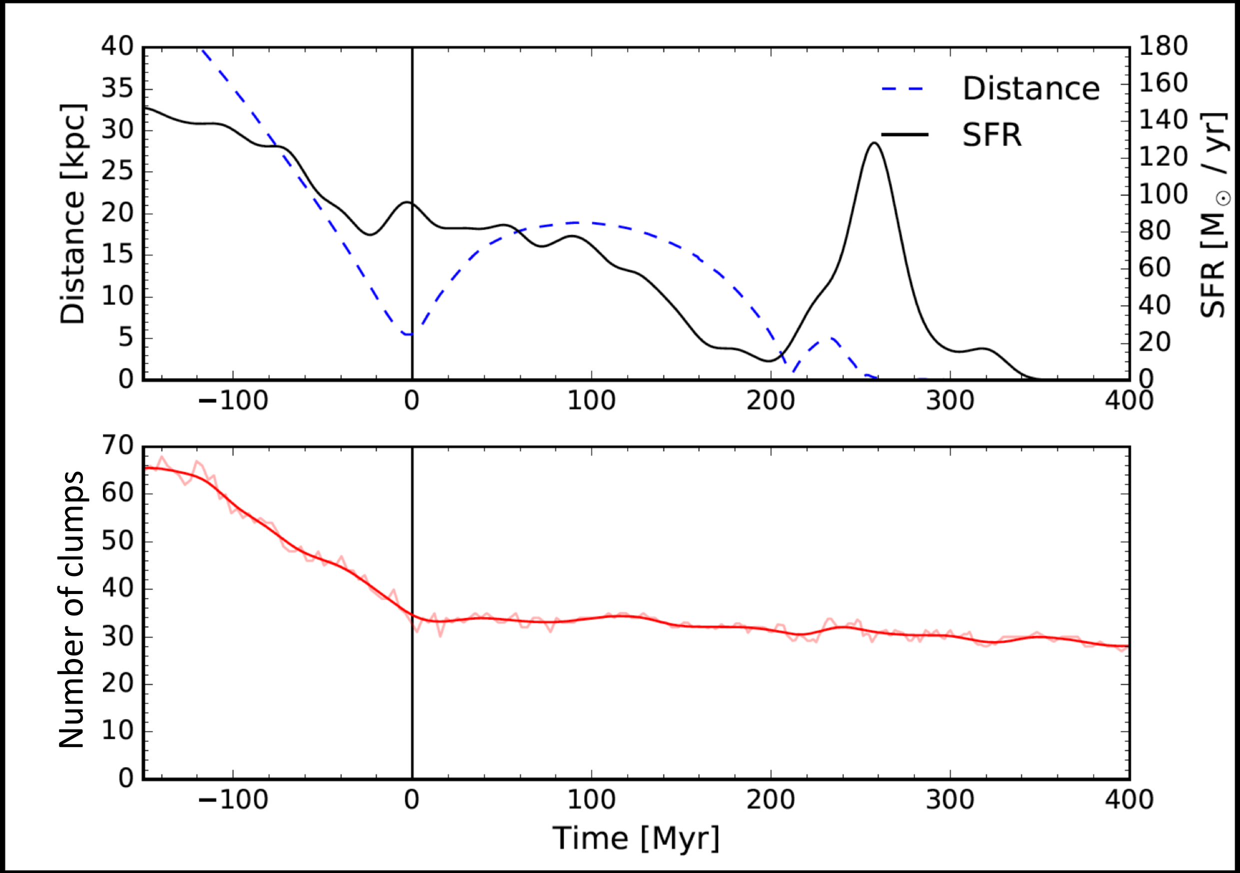


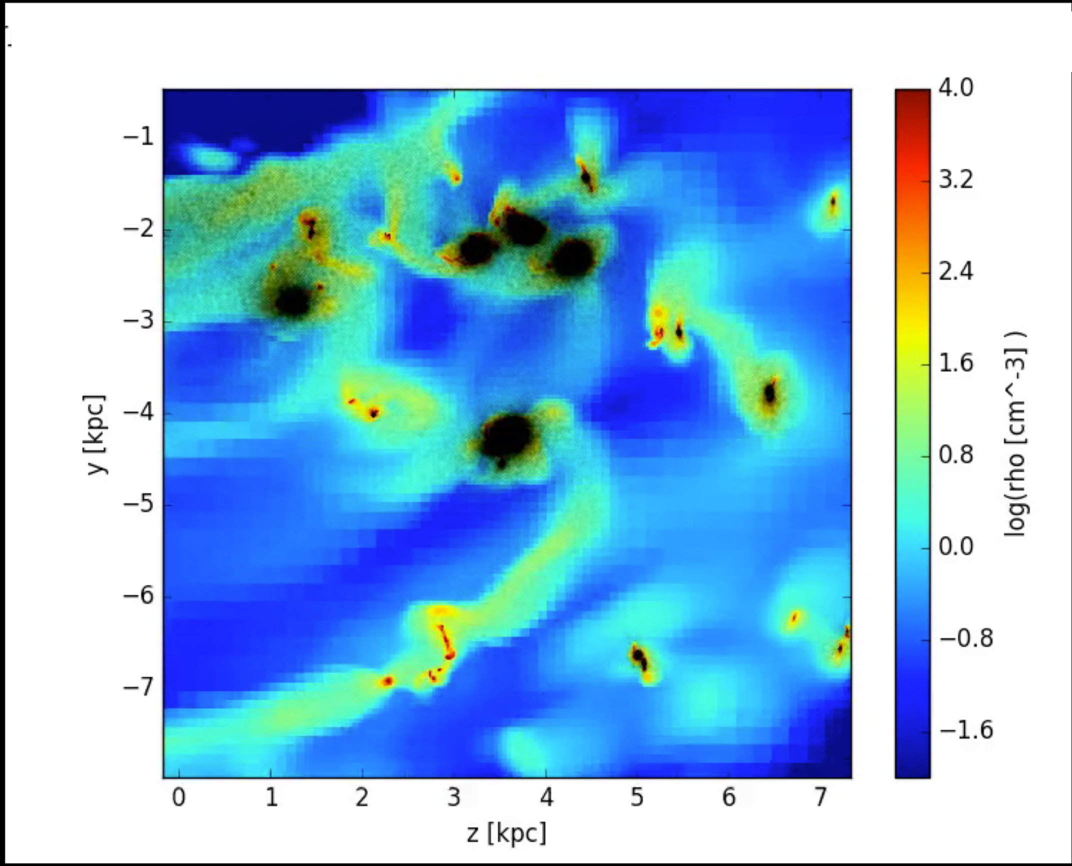
Red: compressive tidal field

White: compressive turbulence

Blue: stellar clusters

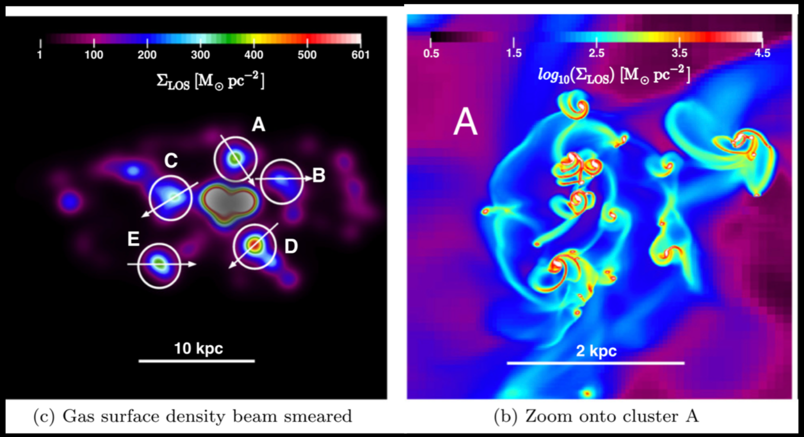
For clumpy galaxies,
mergers have barely any effect on gas fragmentation.





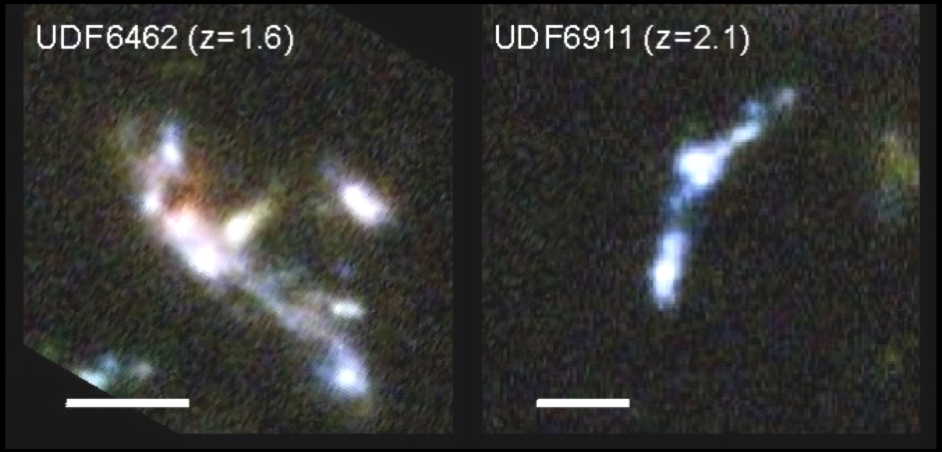
Fensch et al., 2018 (in prep.)

Clump properties:



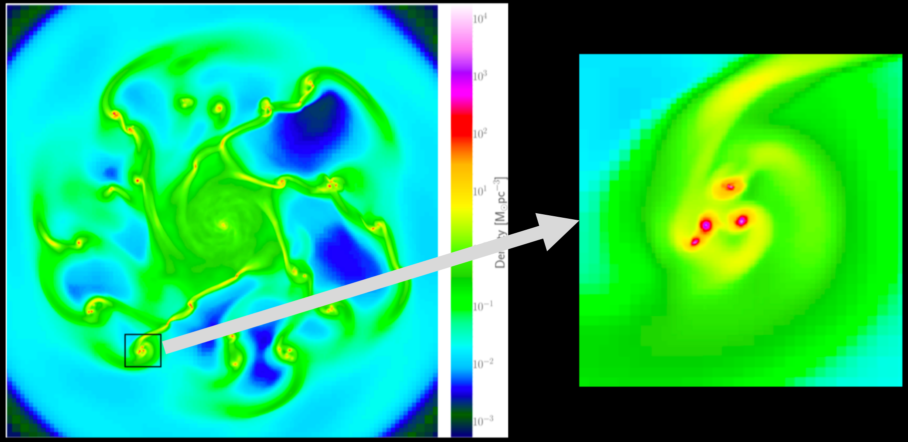
(c) Gas surface density beam smeared (b) Zoom onto cluster A

Behrendt et al., 2016: simulation without star formation
See Manuel's talk for simulations with feedback



Mass ~ $10^{8\text{-}9}$ $M_\odot$
Size ~ 100-1000 pc

Substructures ?

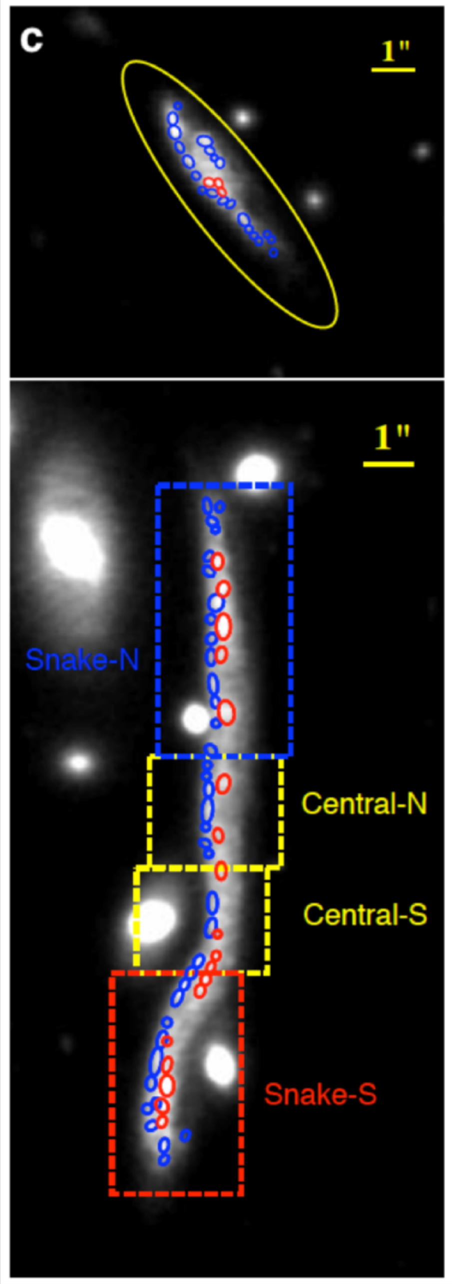


Baptiste Faure, starting his PhD with F. Bournaud

Enough mass in stellar clumps to account for all metal-rich GCs ?

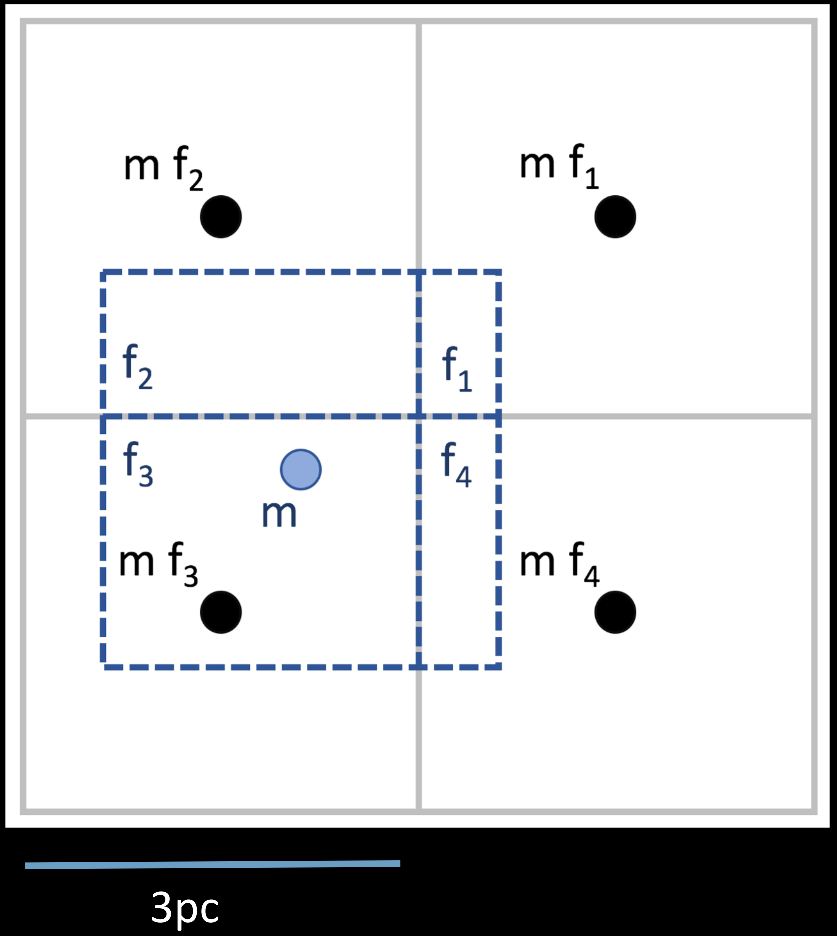
Shapiro+10

Not enough resolution
to probe single clusters:
need to go to ~ 0.1 pc resolution



Cava et al., 2018

Disclaimer: "Particle-mesh" method



Each star is 800 $M_\odot$

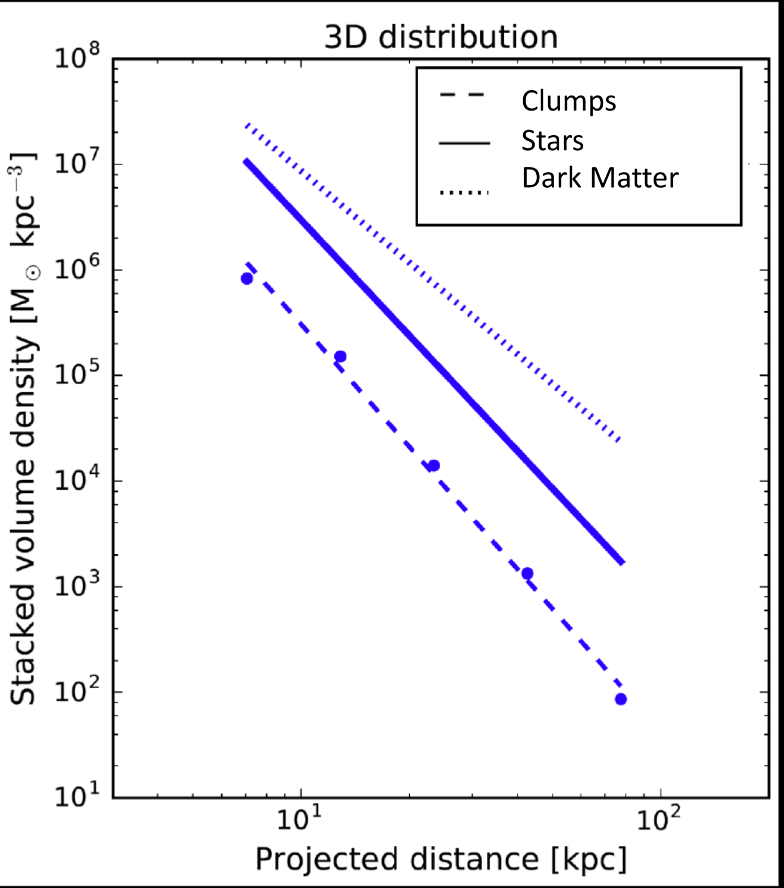
What do we NOT resolve ? Internal dynamics

- mass loss (see e.g. Kruijssen 2008, Lamers et al., 2017)
- size evolution (see e.g. Gieles et al., 2010)
- fractal stellar structure (see e.g. Bekki 2017)

What do we resolve ?
formation region and trajectory

Alternative : post-process using NBODY code (see e.g. Renaud & Gieles, 2013, 2015)

Ejection of stellar clumps into the halo



Fensch et al., 2018 (in prep.)

Distribution is similar to red globular clusters

see e.g. Forbes et al., 2012

They would have similar metallicity as red GCs

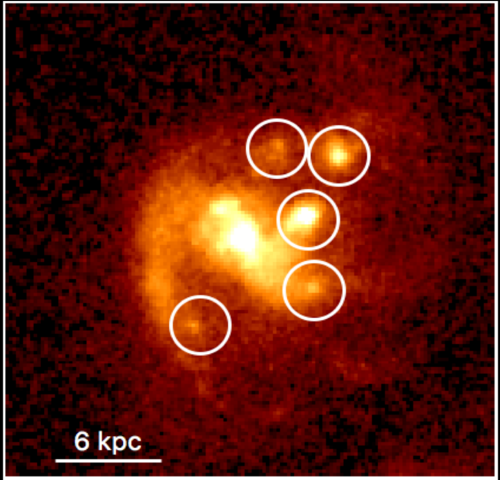
see e.g. Erb et al., 2006

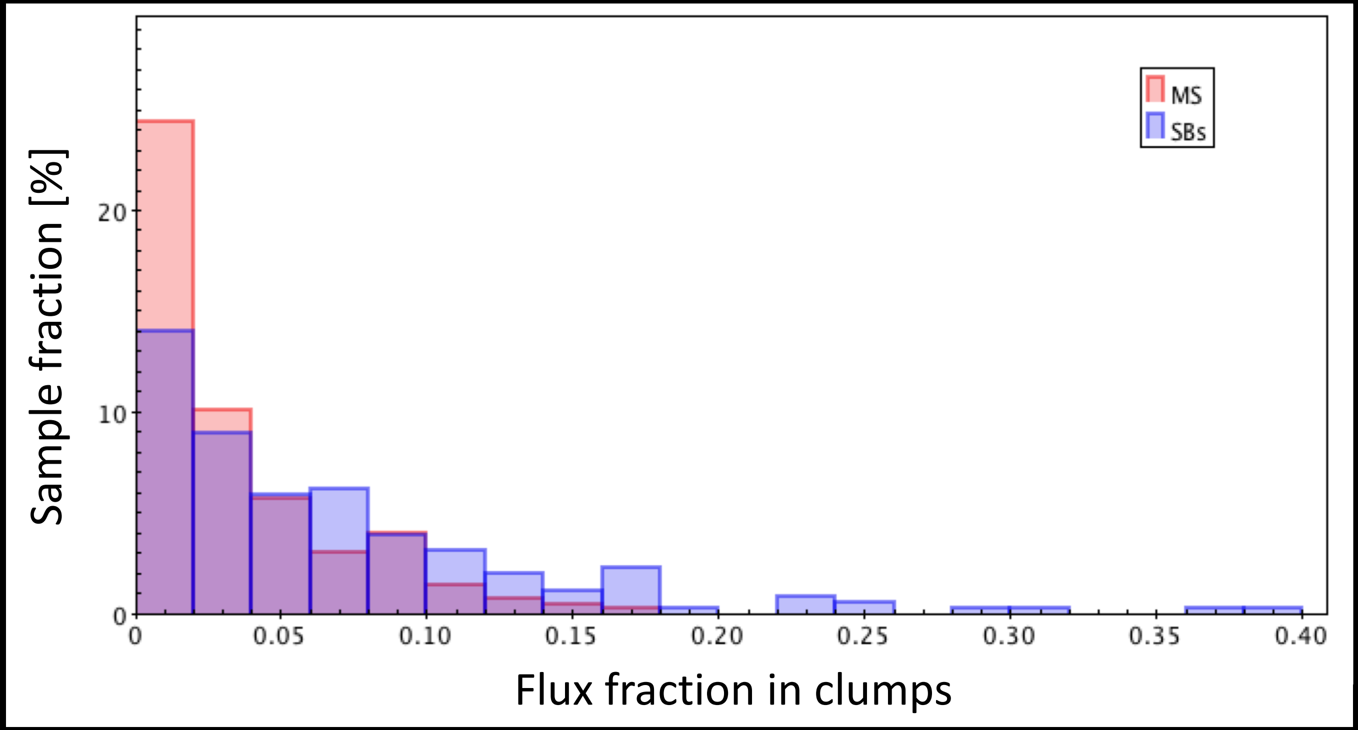
Clumps could be sufficient to form all red GCs

Shapiro et al., 2010

Next step:
resolve cluster formation in the clumps

Intermediate gas fractions? (30%, typical of z = 0.7)





Mergers seem to trigger clump formation.

- What is the formation process?
- What is their fate?
  - -> lifetime
  - -> contribution to disk structure (bulge, thick disk)

Calabrò, Daddi, work in progress…

-> Problem:
we are looking for galaxy discs at the limit of stability

Gas

Mock F814W
Obs. at z=0.7 (no ext.)

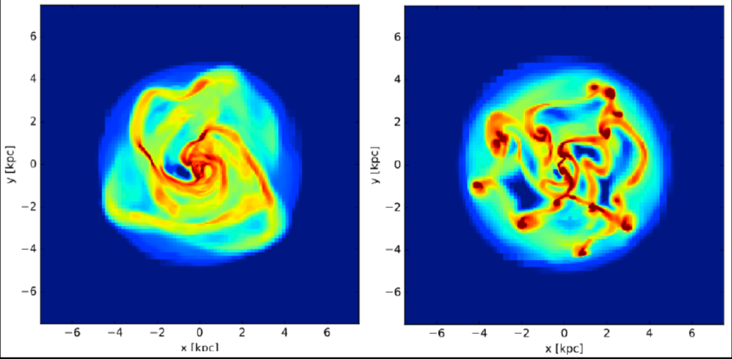
Our isolated disk models are too clumpy…
clumpiness of $\sim$25 %

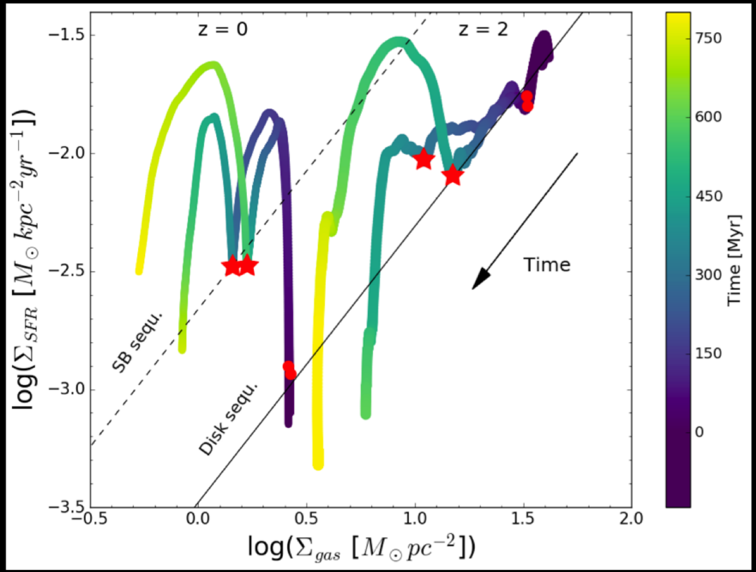
-> Testing the impact of isothermal relaxation
and start of SF

Fensch, Bournaud, work in progress …

Summary:

- ➢ <u>Gas fraction</u> is a driver of different internal instabilities
  - ➢ Clump formation
  - ➢ Strong inflows and turbulence





- Saturates the gas distribution:
  weak impact of mergers on star formation

- Clumps : birth nest of some
  metal-rich globular clusters?