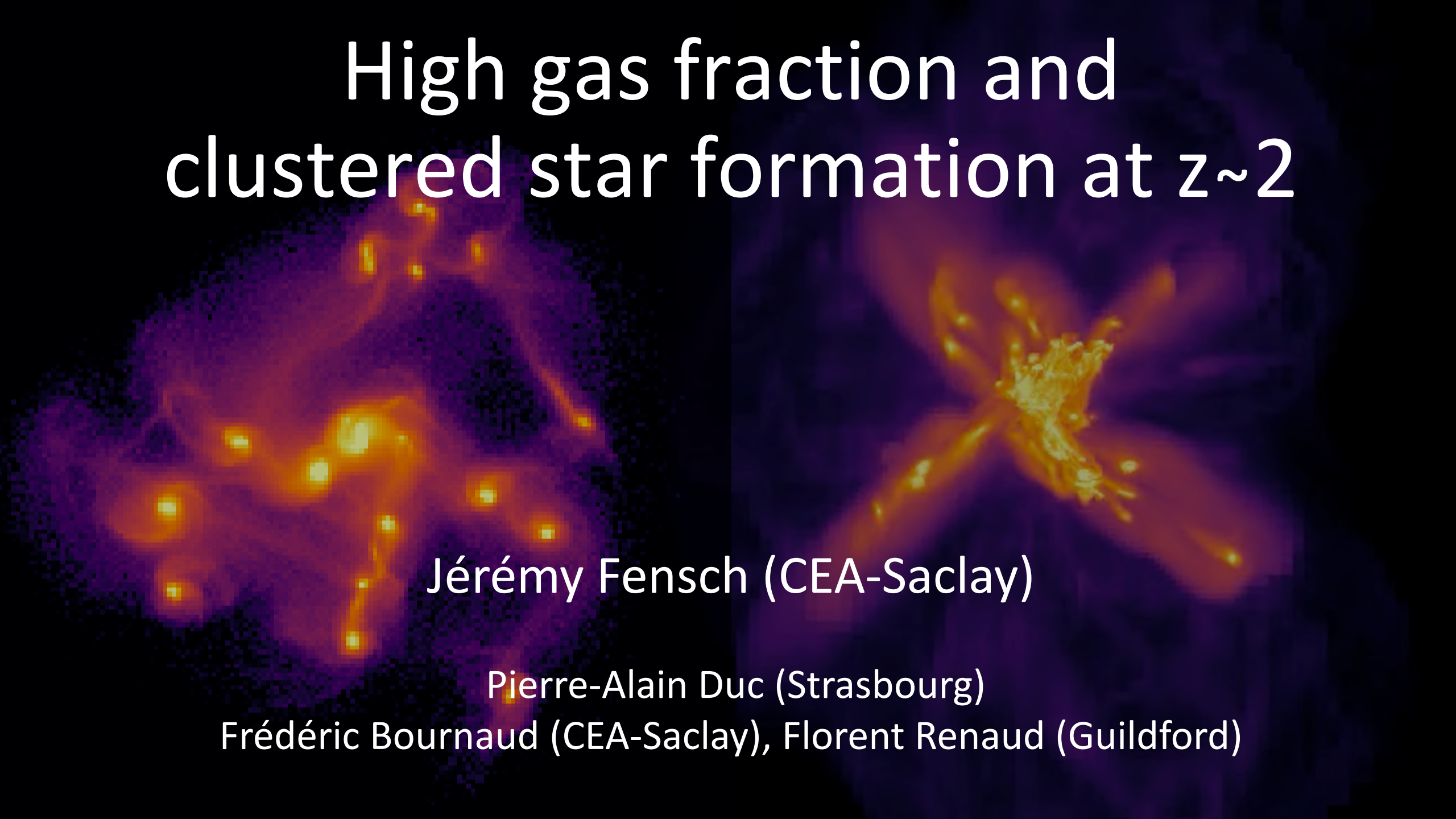
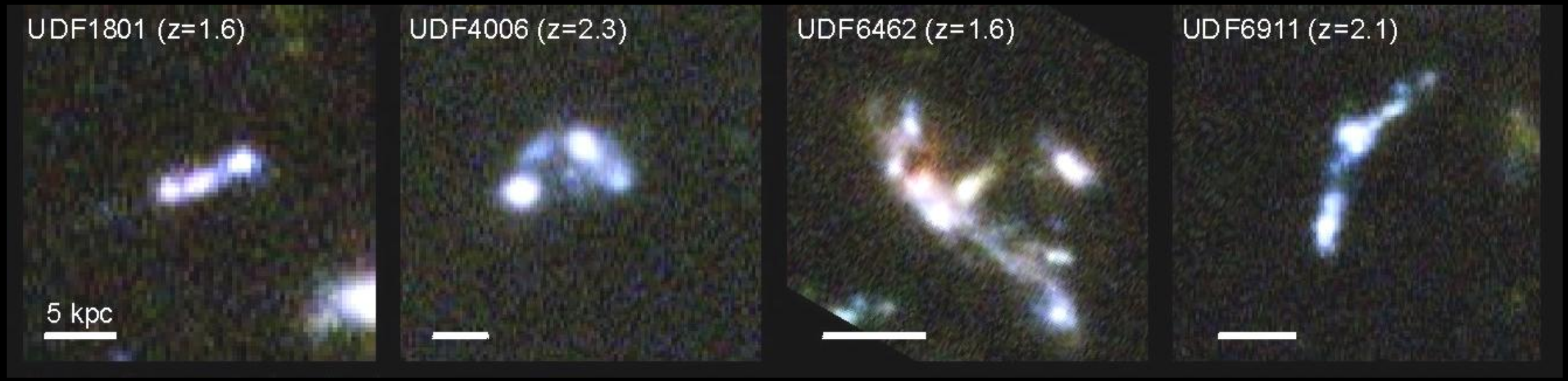
High gas fraction and clustered star formation at z~2



Jérémy Fensch (CEA-Saclay)

Pierre-Alain Duc (Strasbourg)
Frédéric Bournaud (CEA-Saclay), Florent Renaud (Guildford)

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



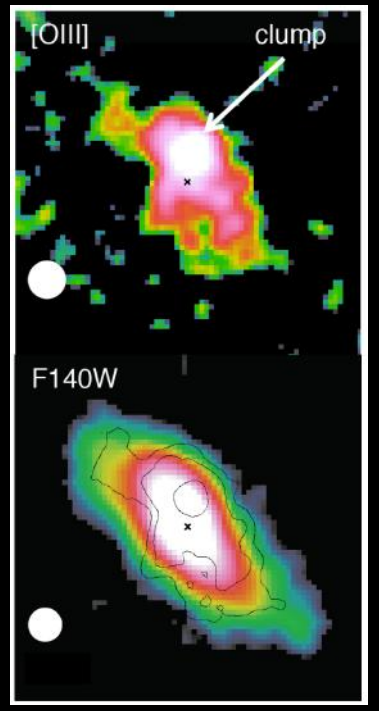
What is their origin?

In-situ or merging dwarfs?

What is their evolution?

Transient or long-lived?

Origin?

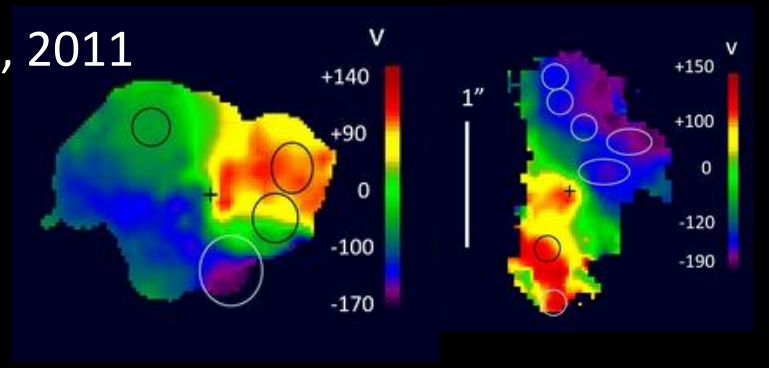


- Some clumps are observed very young : < 10Myr

Zanella et al., 2015, Nature

- Clump motions consistent with galaxy rotation

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



Around 80% of the clumps have formed in-situ

Mandelker et al., 2014

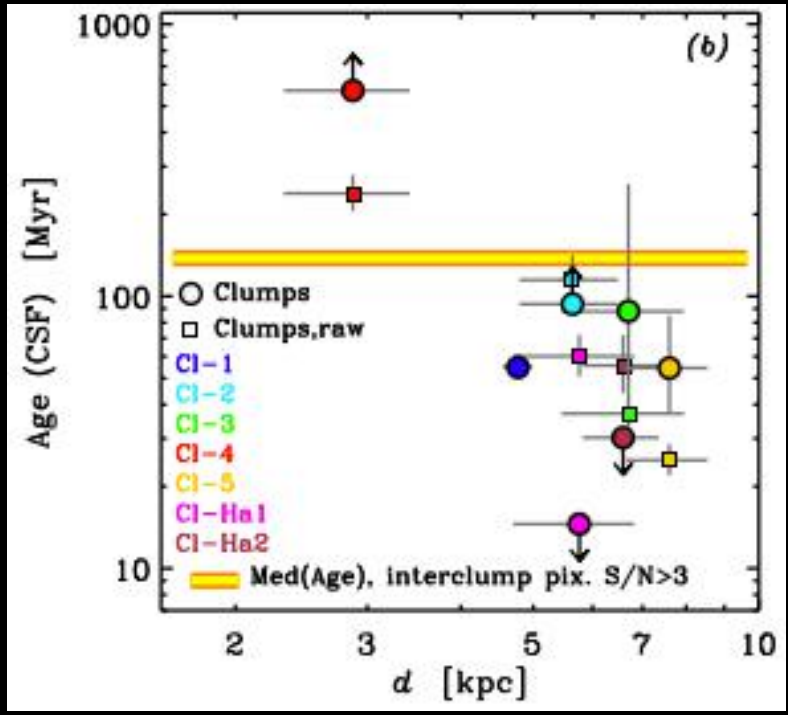
Transient or long-lived?

- Stellar age typically can reach 200 Myr
  -> Lower limit for clump age

Wuyts et al., 2012; Bournaud et al., 2014

- Inward positive age gradient
  -> clump migration?

Förster-Schreiber et al., 2011
Guo et al., 2012, 2014

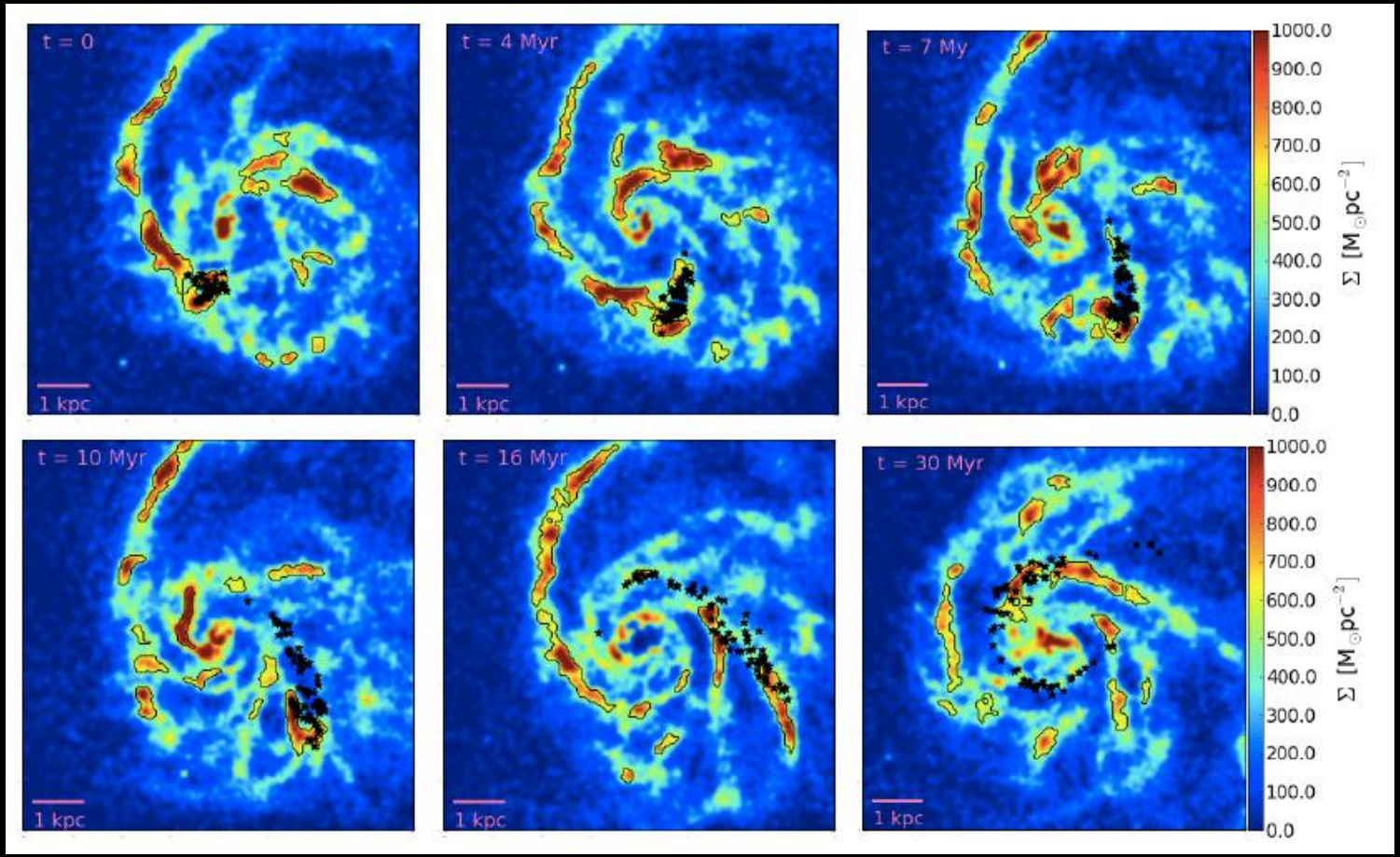


Förster-Schreiber et al., 2011

Tend to support long-lived clumps

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)

Disk instabilities

Bournaud & Fensch, 2017 (in prep.)

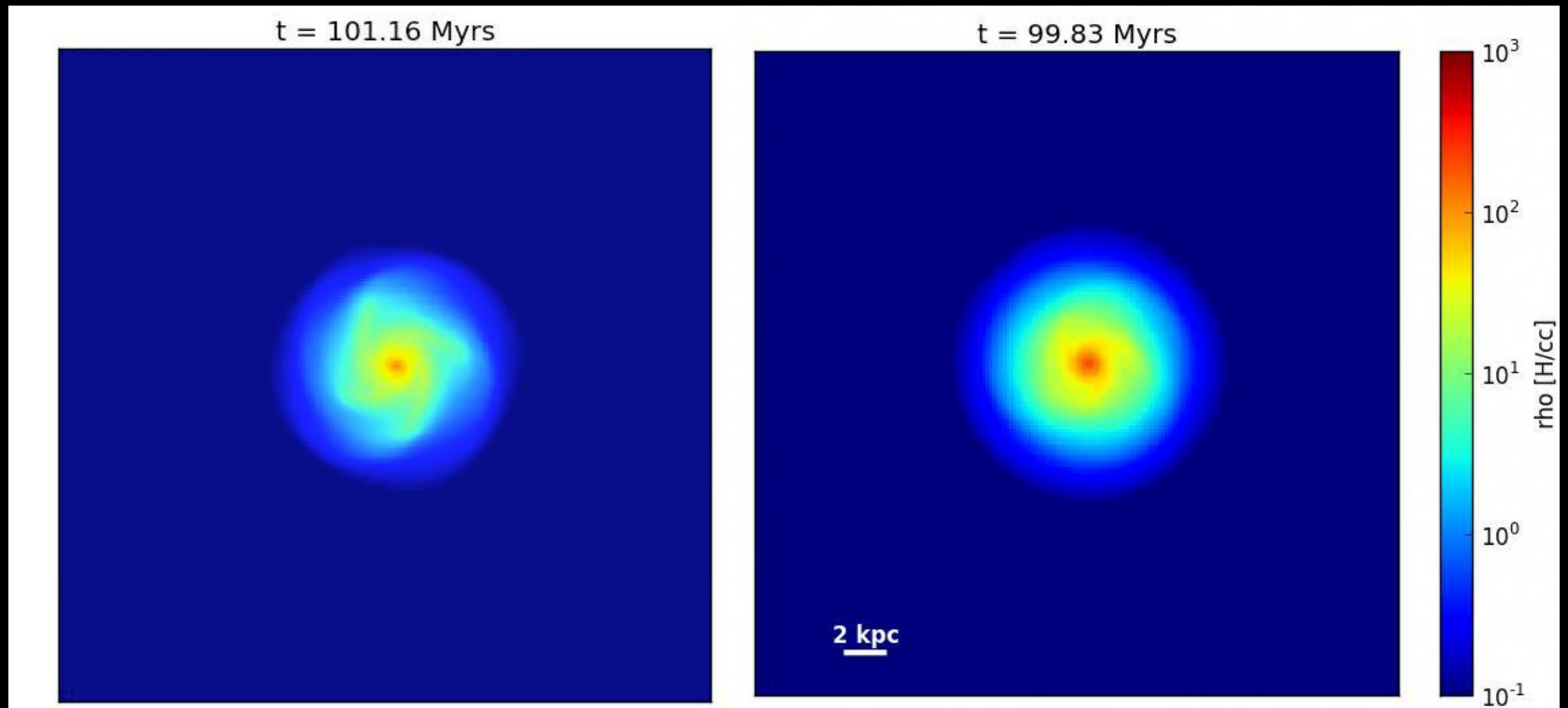
Test the impact of the gas fraction:

→ RAMSES code (Teyssier 2002)

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

→ Same DM halo, same rotation curve

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



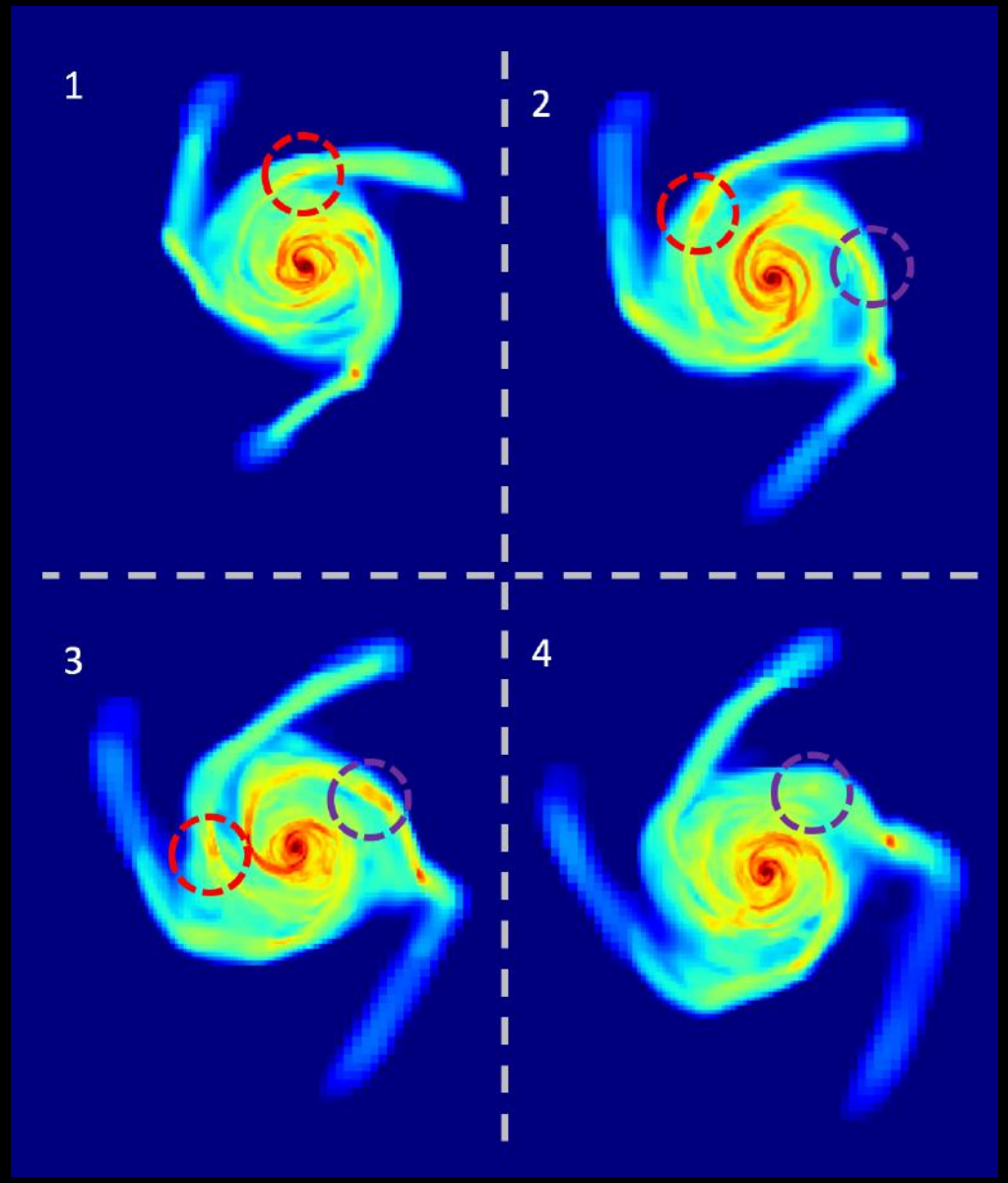
$$\alpha = \frac{5\sigma^2 r}{GM}$$

25% : 2.9 (in O17: α ~ 3)

50% : 0.9

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

Clump survival



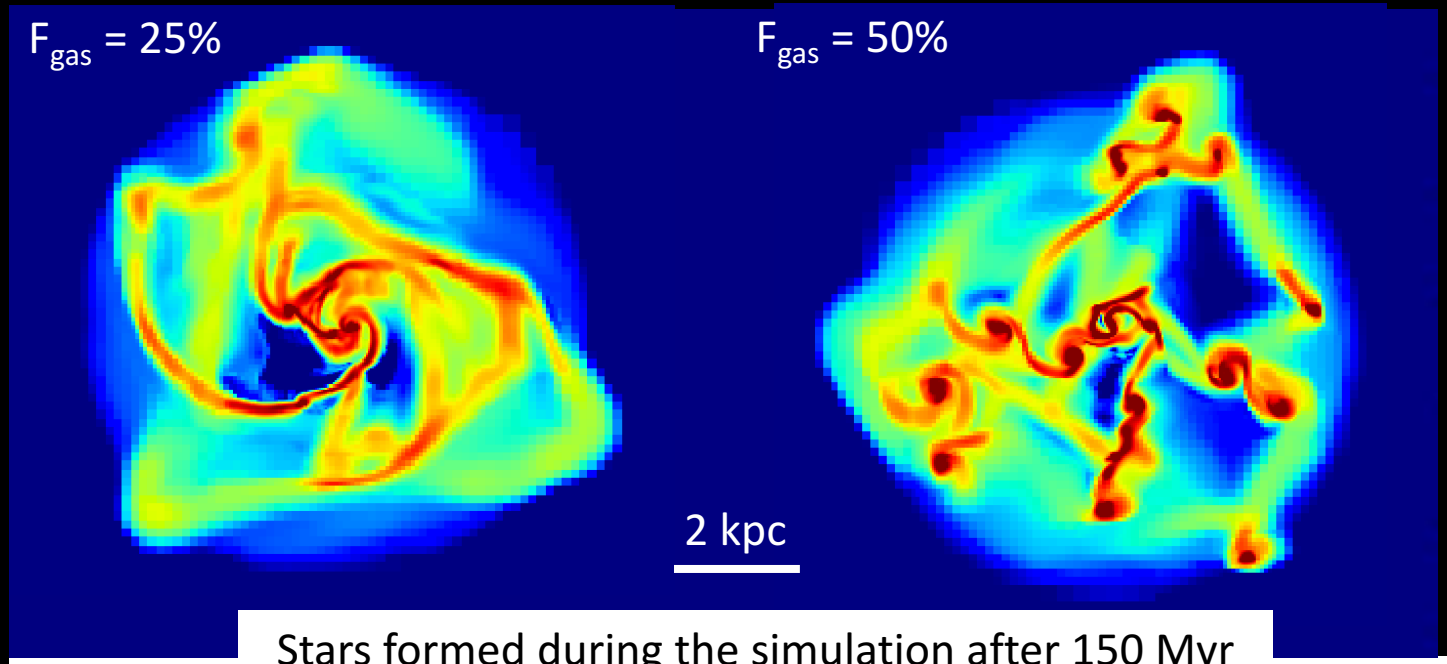
F_{gas} = 25% : clumps are sort-lived

located in spiral arms:
destroyed by shear more than feedback

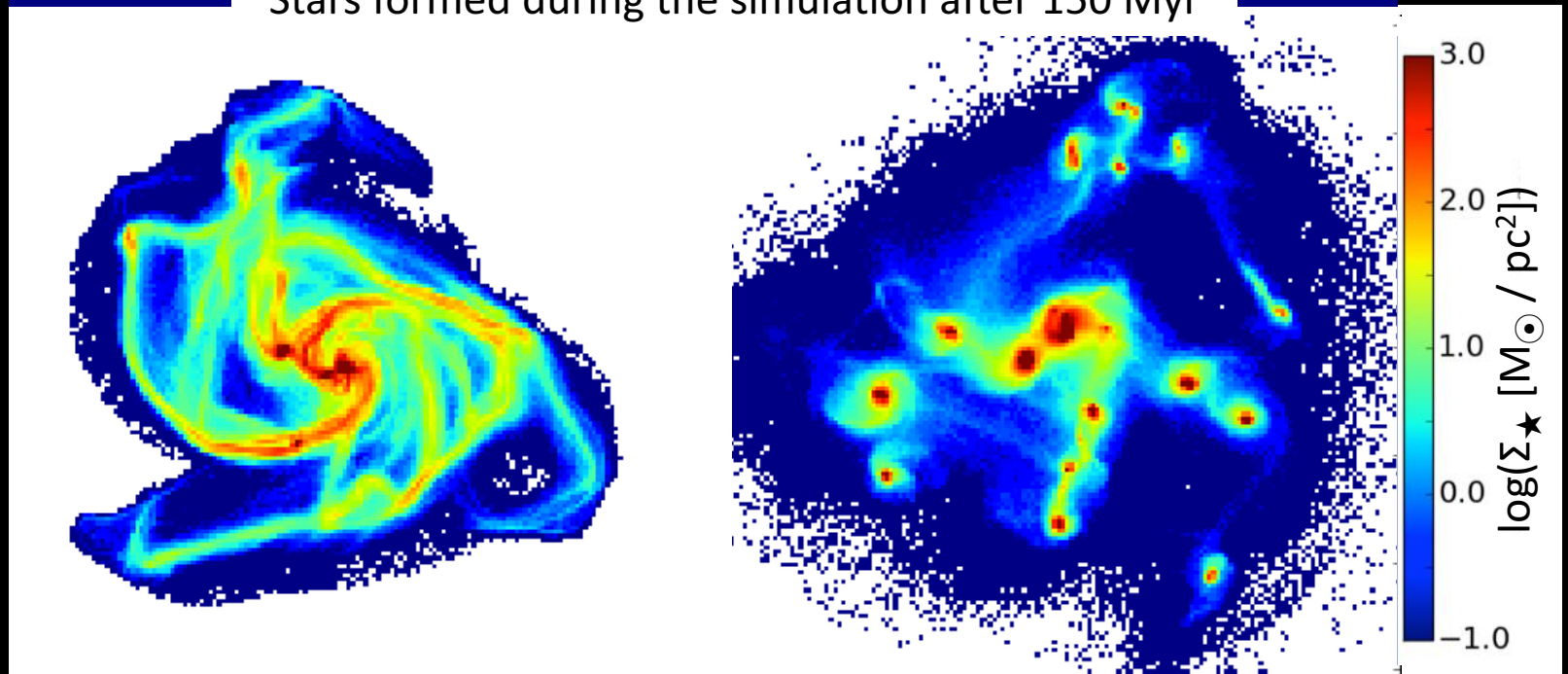
Timescale for … (in Myr)	25%	50%
Gas removal	**70**	**215**
By feedback	*265*	*304*
By stripping	*95*	*730*
Gas accretion	**405**	**195**

Bournaud & Fensch, 2017 (in prep.)

Higher gas fraction induces clustered star formation

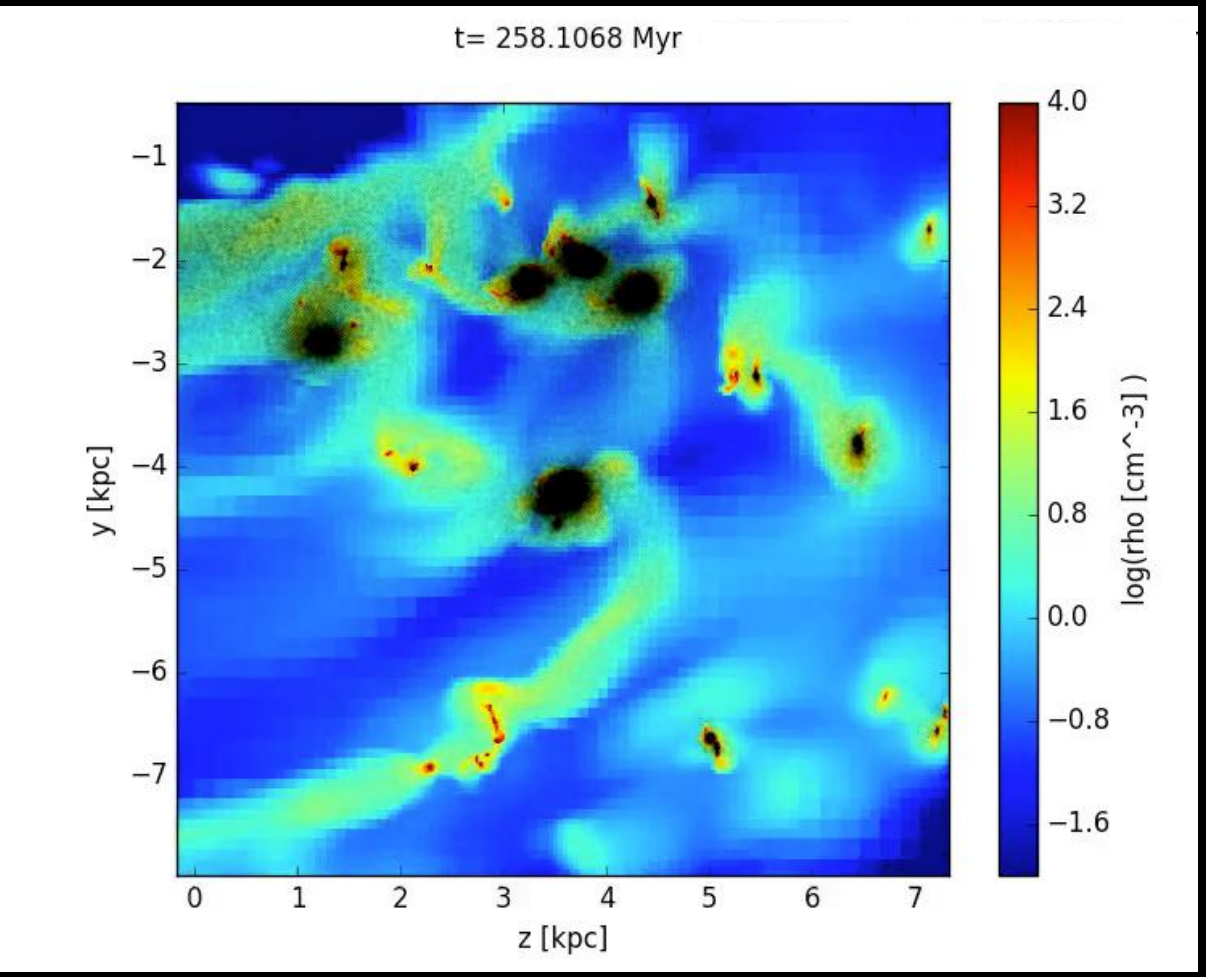


Stars formed during the simulation after 150 Myr



B&F (in prep.)

Evolution of stellar star clusters in the disk



→ Massive clusters clean their neighborhood and grow by merging of smaller clusters.

→ Massive clusters migrate towards the center ~ 0.5 Gyr

See Bournaud et al., 2009, Dekel et al., 2009, 2013)

→ Tidal field of the galaxy may disrupt them (not resolved in this simulation: *future work*)

Due to moderate resolution (3 pc) we do not resolve the internal structure !
Each clump may **be highly structured** (see e.g. Behrendt & Burkert 2016).

What about mergers ?

Merger rate is important at high-redshift

$$\propto (1+z)^{2.5}$$

Le Fèvre et al., 2000; Kartaltepe et al., 2007; Lotz et al., 2011

→Ejection of in-situ clusters?

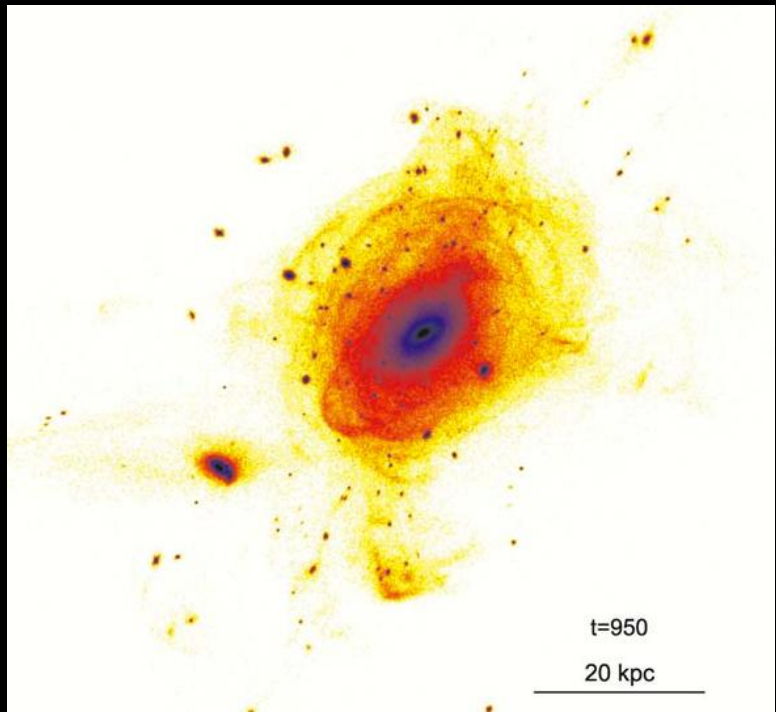
Kruijssen 2014

→Formation of clusters?

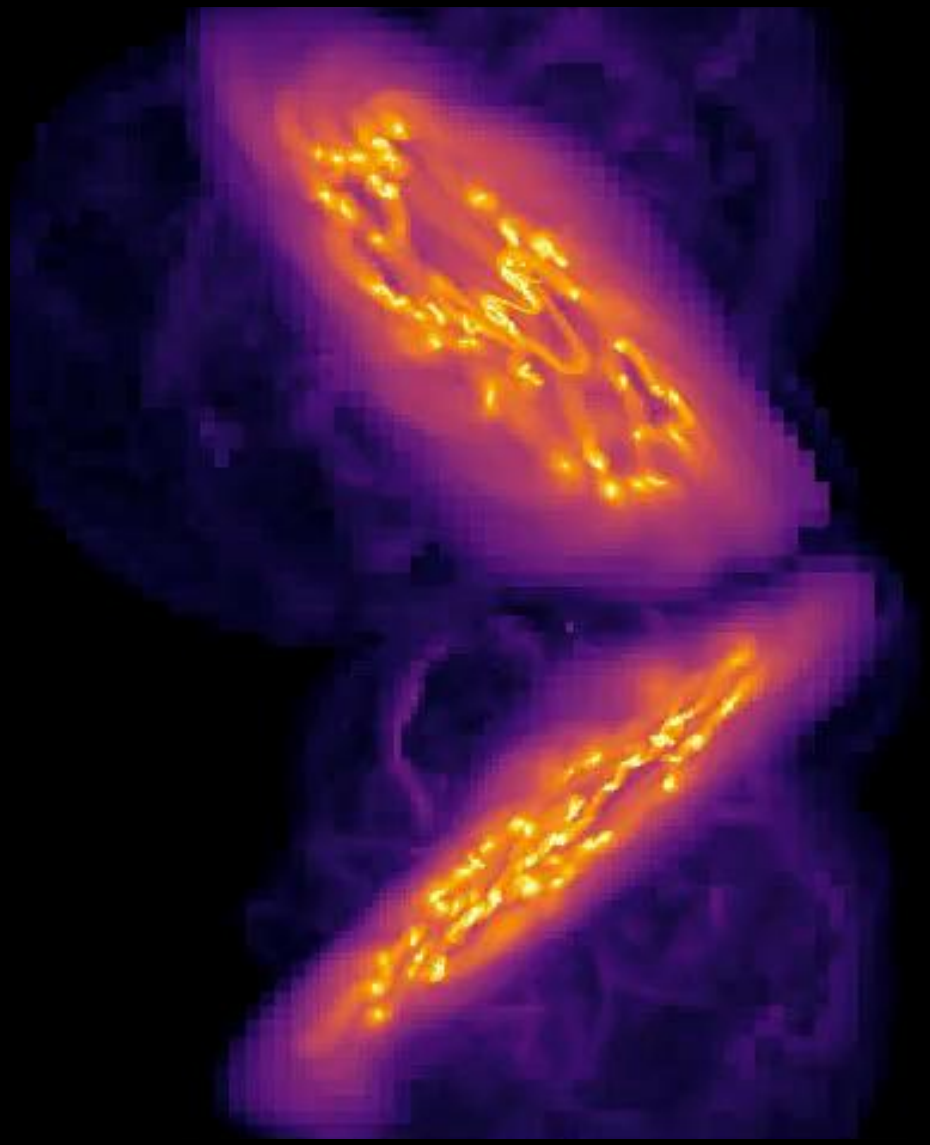
Theory: Ashman & Zepf, 1992

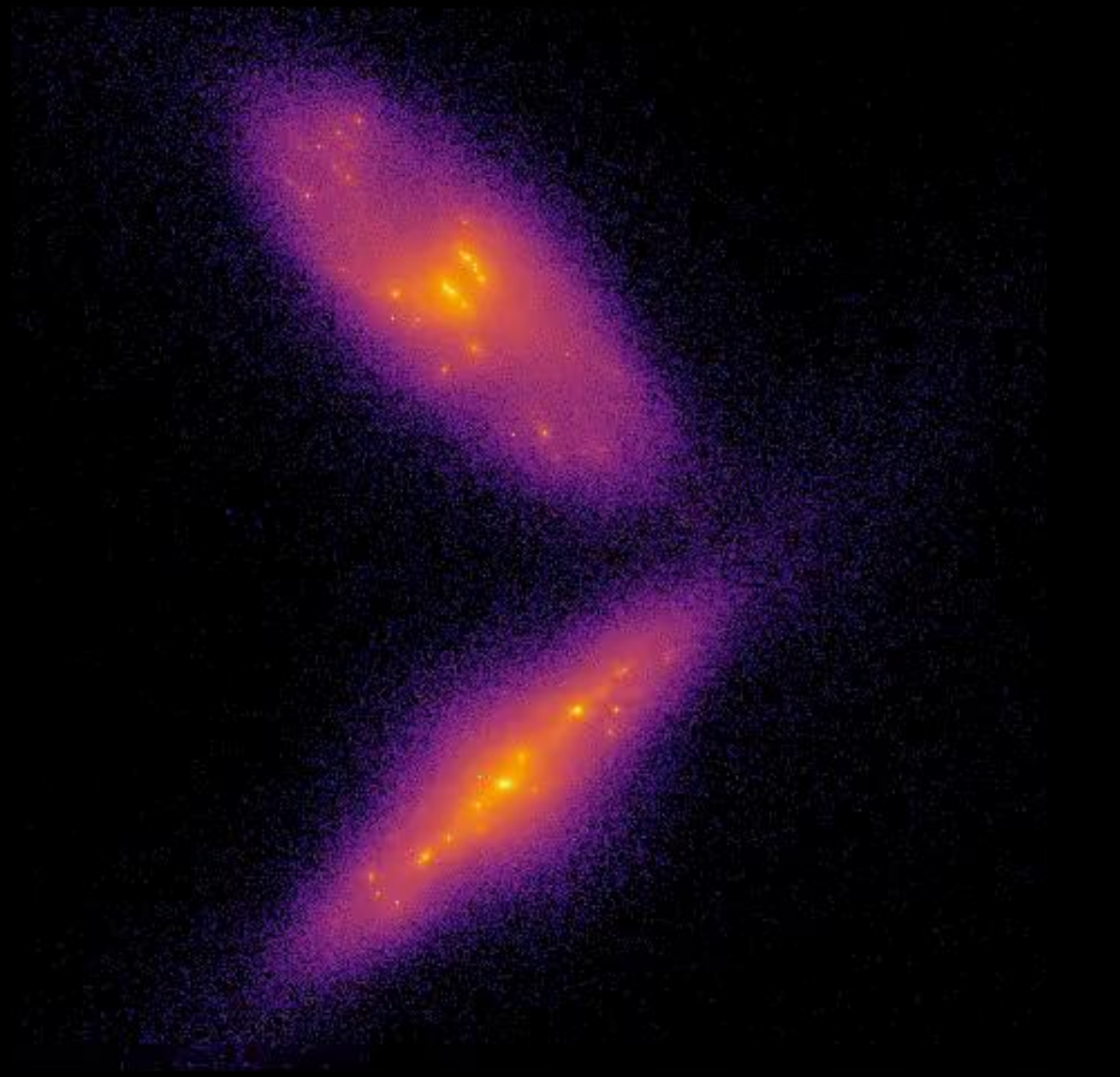
Observations: Whitmore et al., 2010
Herrera & Boulanger 2017

Simulations: Bournaud et al., 2008
Renaud et al., 2015

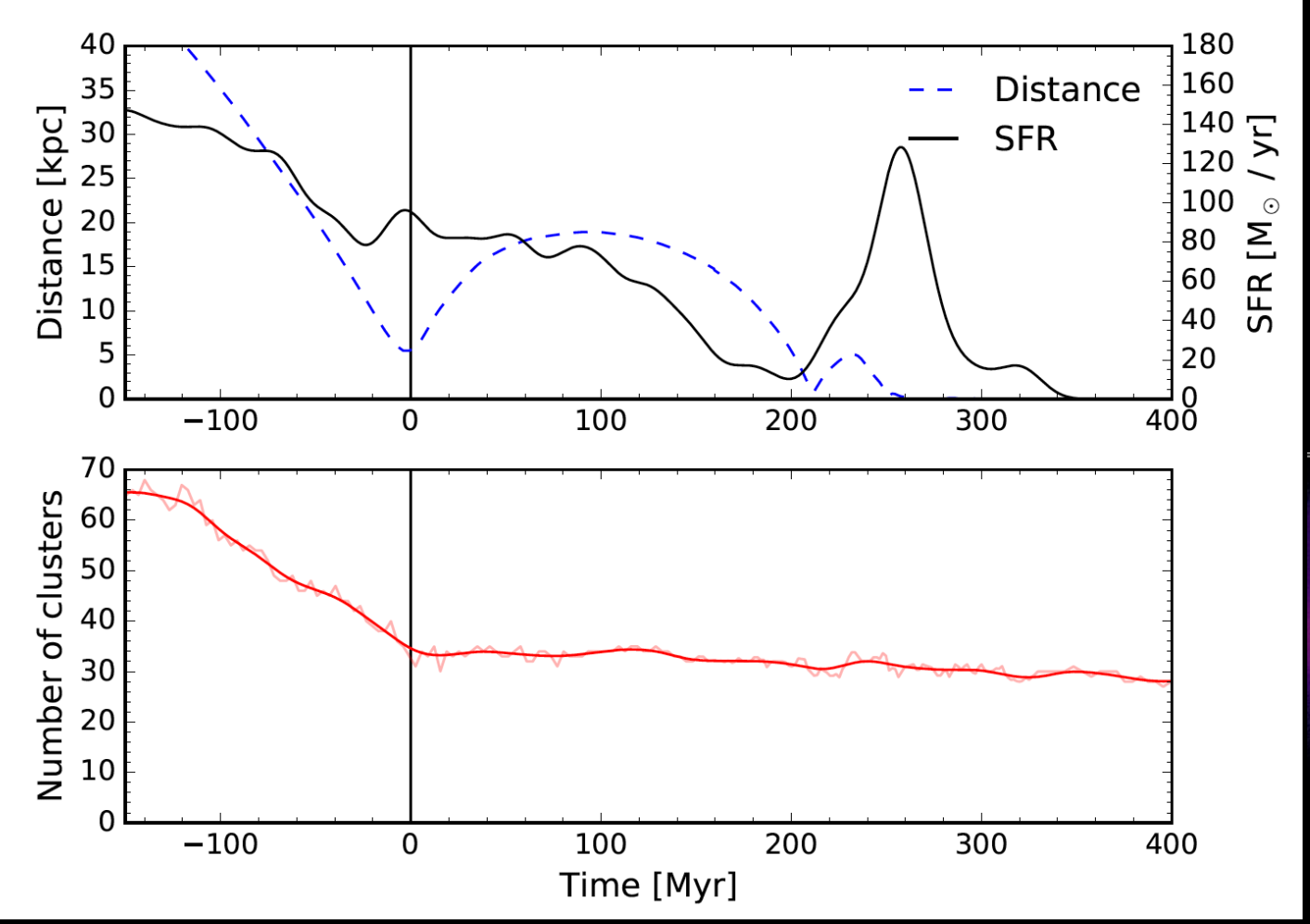


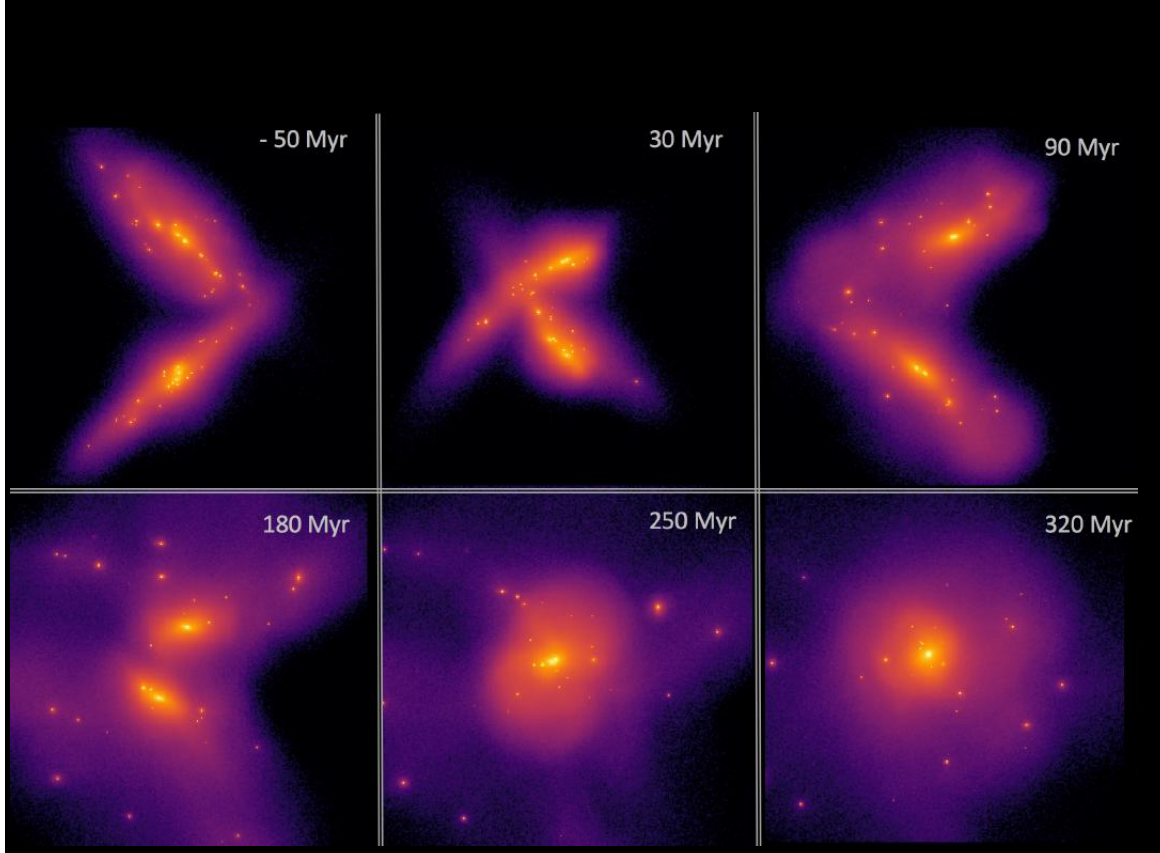
Merger of clumpy galaxies





Fensch et al., 2017b (in prep.)



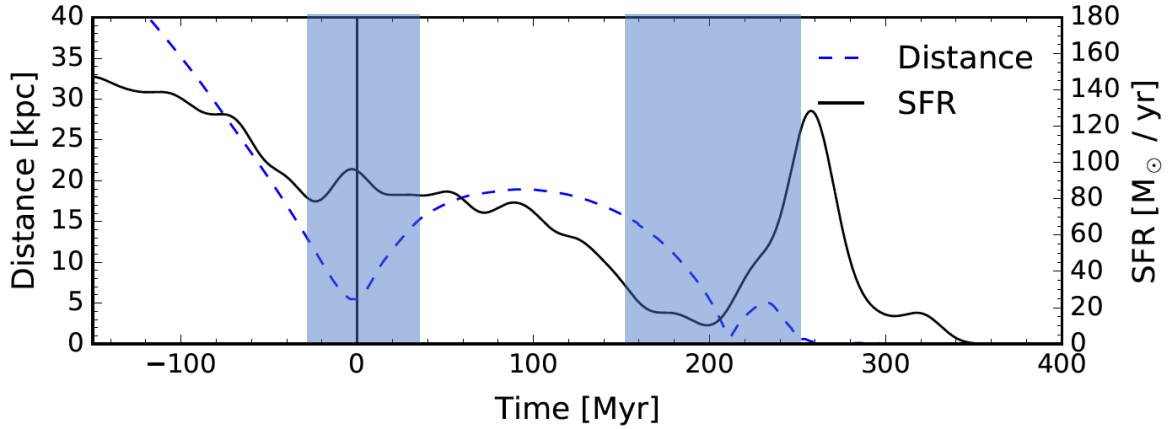


1/ No increase of star and stellar cluster formation

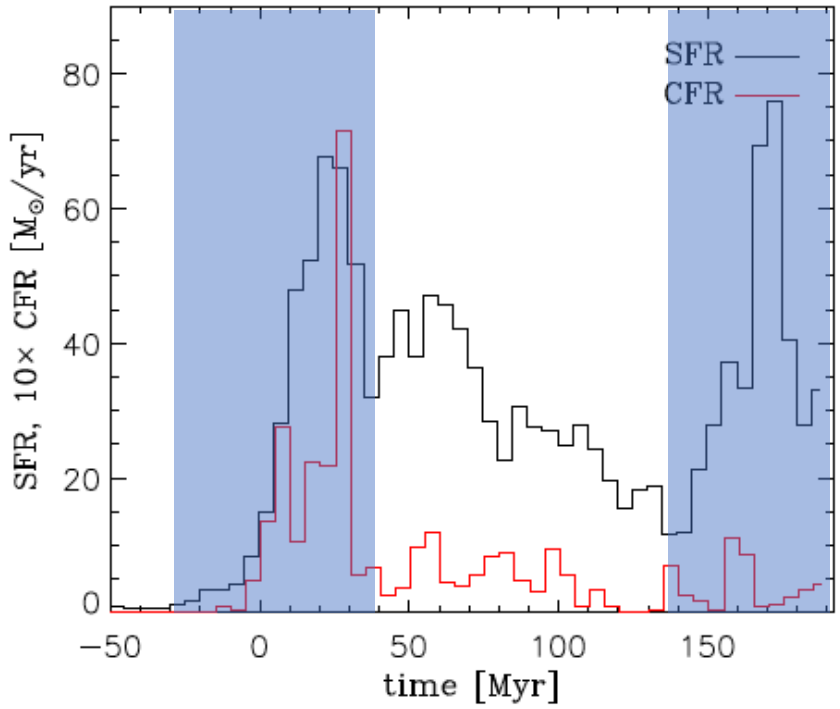
2/ Stabilization of the number of star clusters

Fensch et al., 2017b (in prep.)

1/ No increase of star and stellar cluster formation



Renaud et al., 2015 ***Antennae-like local merger***



No significant increase of SFR at first pericenter

Mild increase at coalescence

High-redshift major mergers weakly enhance star formation

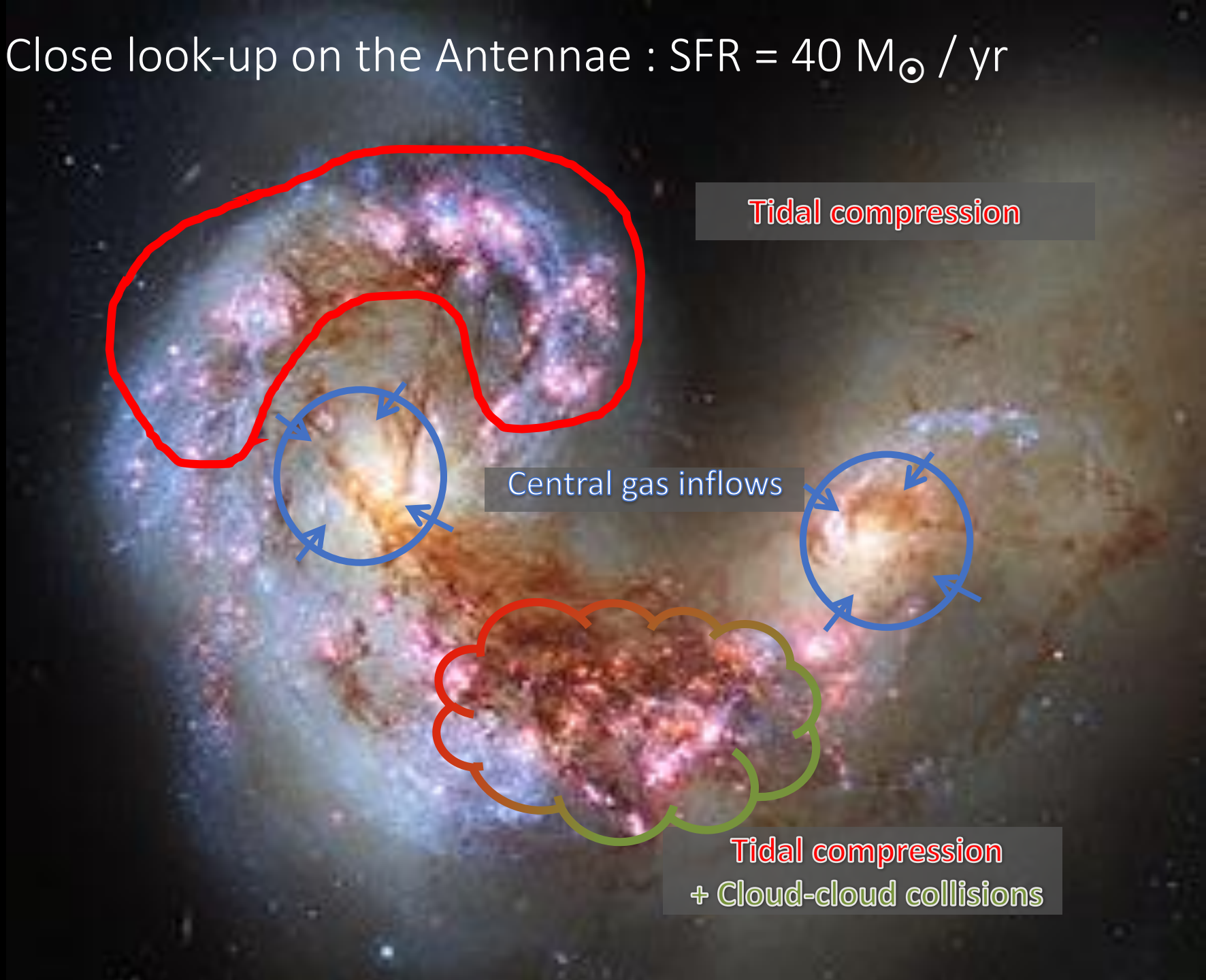
Fensch et al., 2017a, 1610:03877

see also Bournaud et al., 2011; Hopkins et al., 2013
Perret et al., 2014

Consistent with observations:
see Rodighiero et al., 2011
Kaviraj et al., 2013
Schreiber et al., 2015

This is very different from local galaxies !

Close look-up on the Antennae : SFR = 40 $M_\odot$ / yr



Physical processes

Gas fragmentation increase:

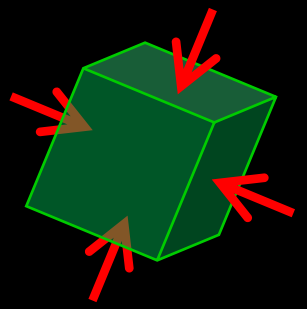
Interaction

DRIVES

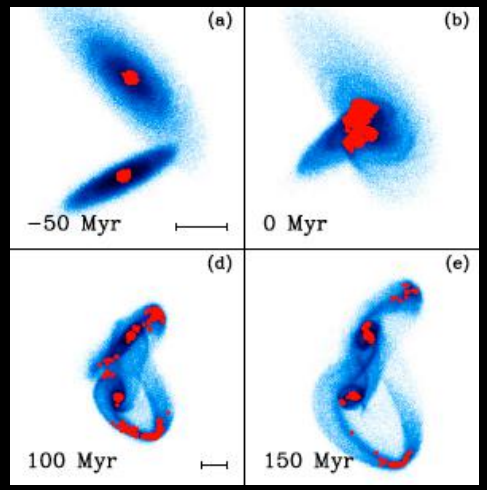
- compressive tides
- turbulence

INDUCE

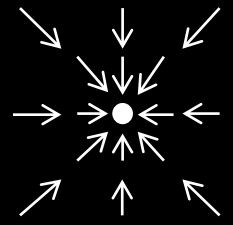
Increase of ***compressive*** turbulence



Renaud et al., 2008



$\nabla \times \sigma = 0$

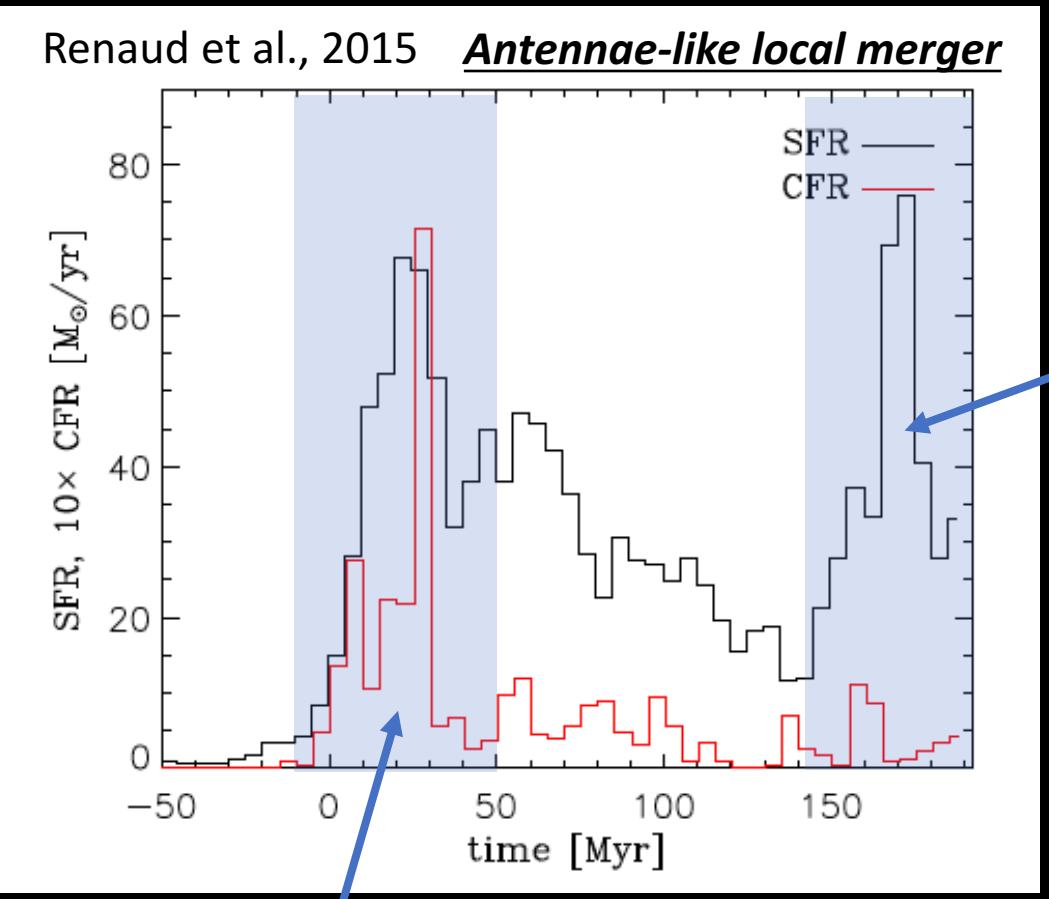


See Renaud et al, 2014

See Christoph's talk

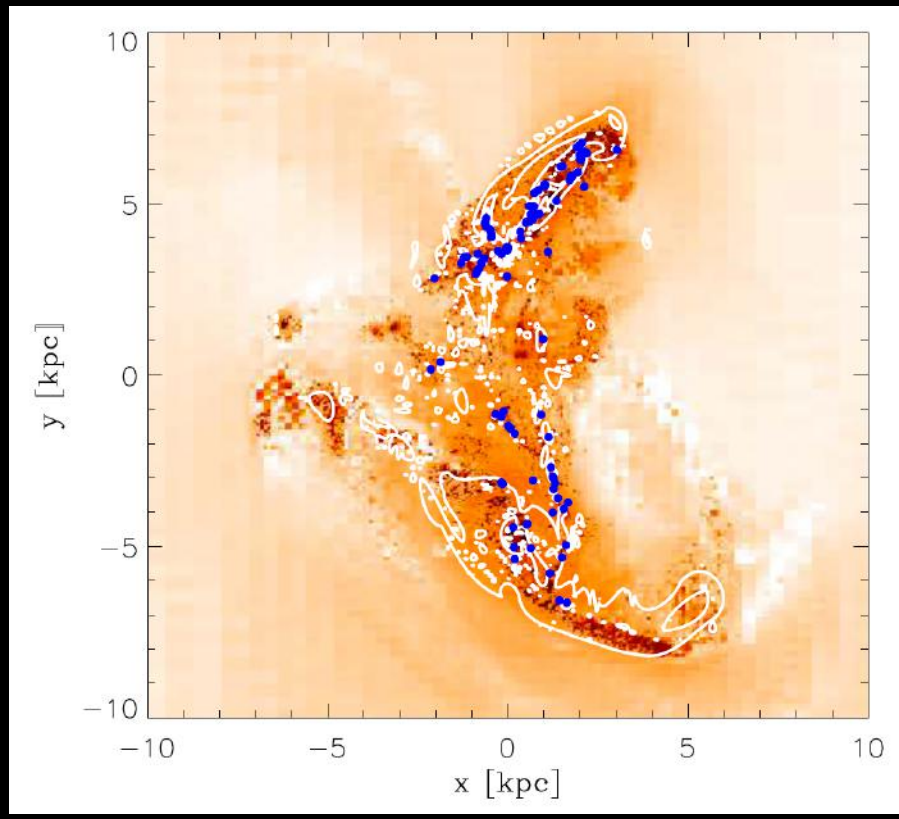
Formation of star clusters at the first pericenter passage

Renaud et al., 2015 ***Antennae-like local merger***



Nuclear starburst
few cluster formation

Tidal compression, cluster formation



Red: compressive tidal field

White: compressive turbulence

Blue: stellar clusters

Saturation effect I

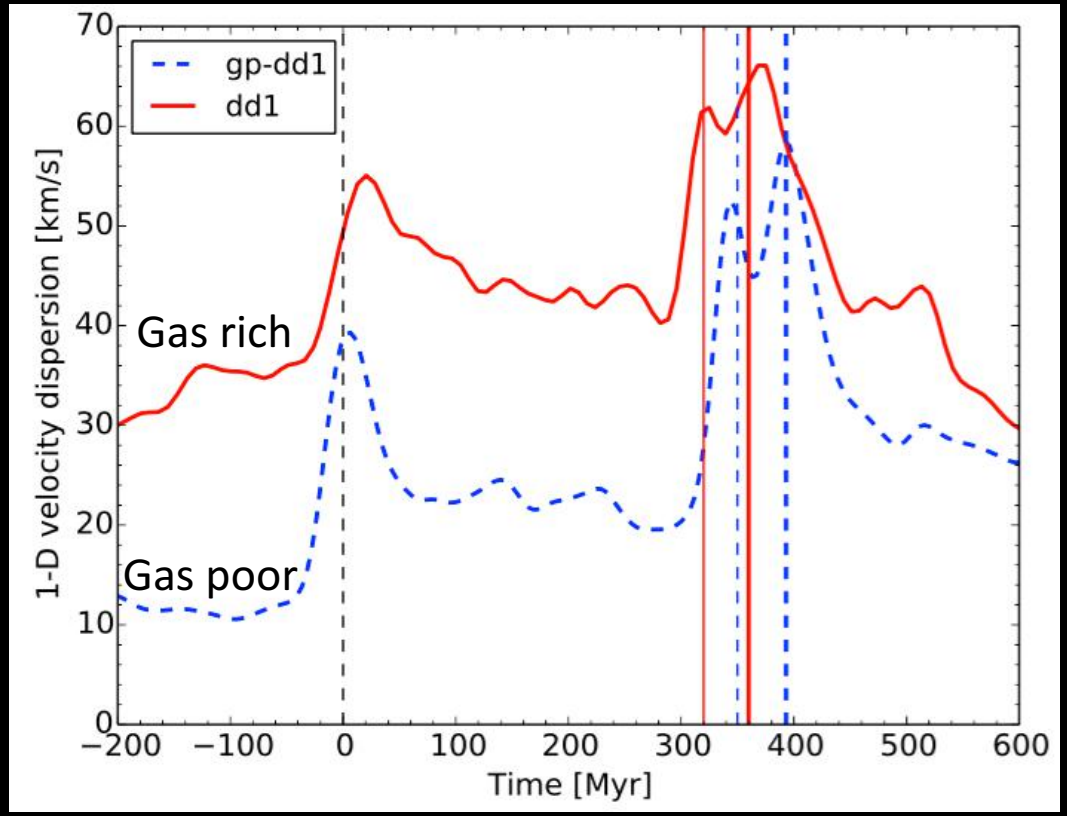
Turbulence is already high in gas-rich galaxies:

Fgas = 10% : σ = 10km/s

see e.g. Epinat et al., 2008

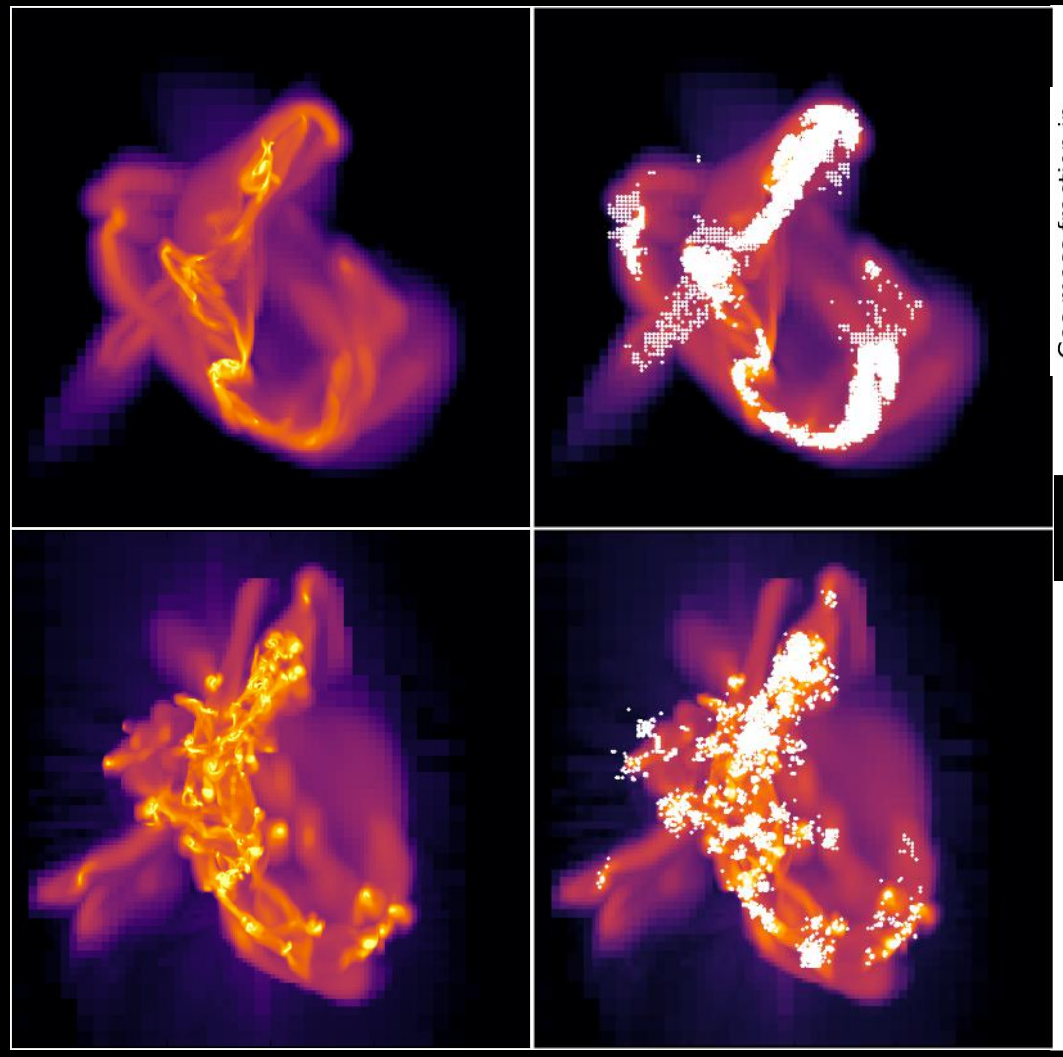
Fgas = 50% : σ = 40-50 km/s

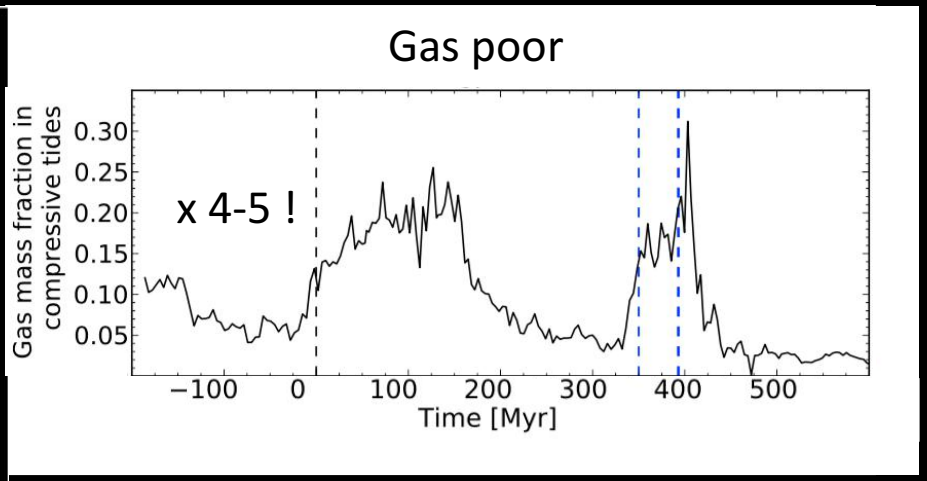
see e.g. Förster-Schreiber et al., 2011



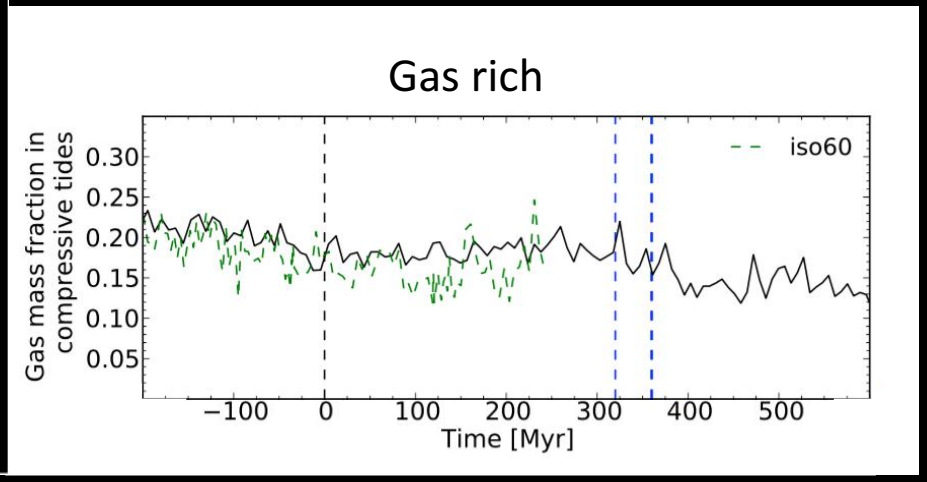
Fensch et al., 2017a

Saturation effect II





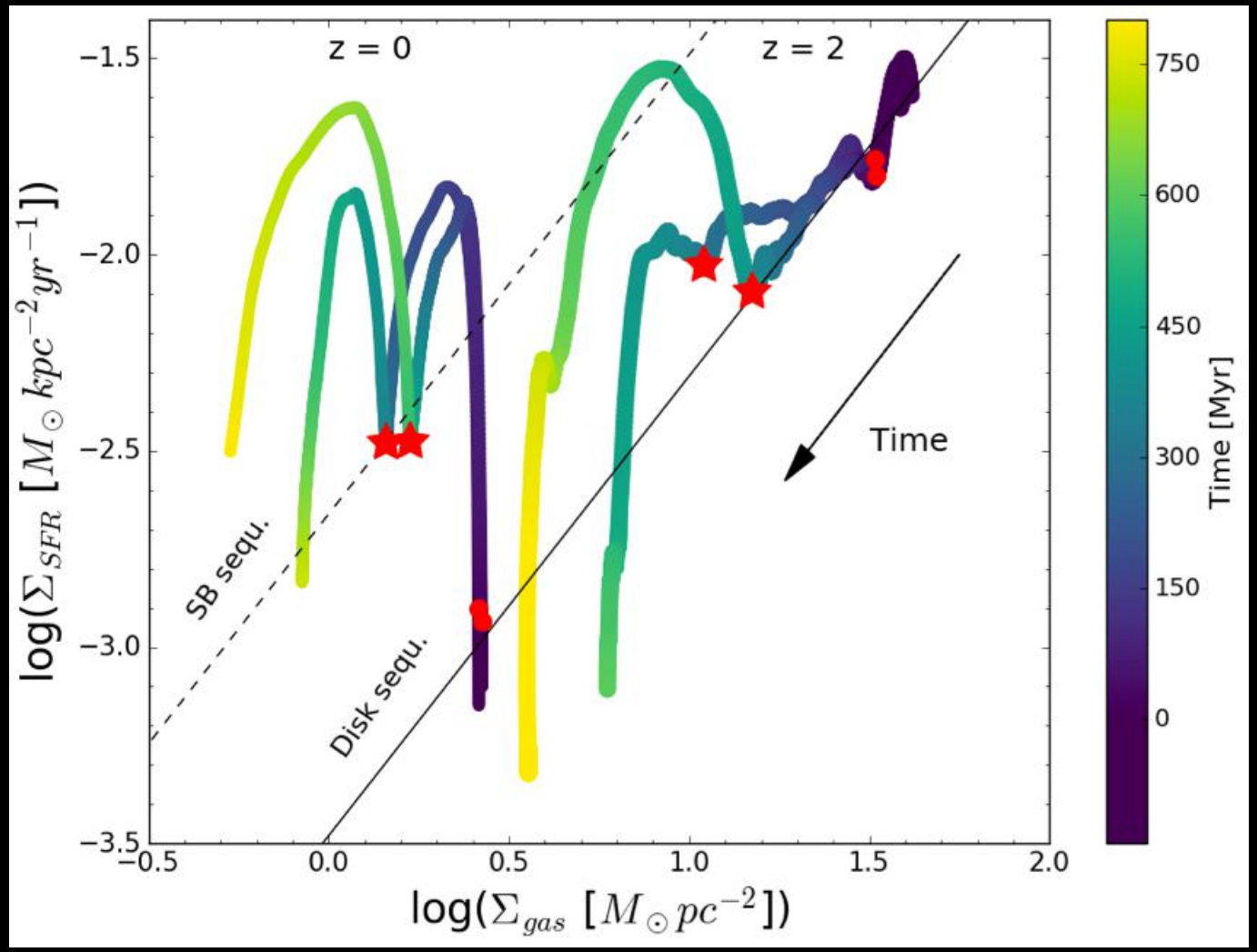
See also Renaud+08,+09



Compressive tides are already in place in gas-rich galaxies

Fensch et al., 2017a

Starbursts ?

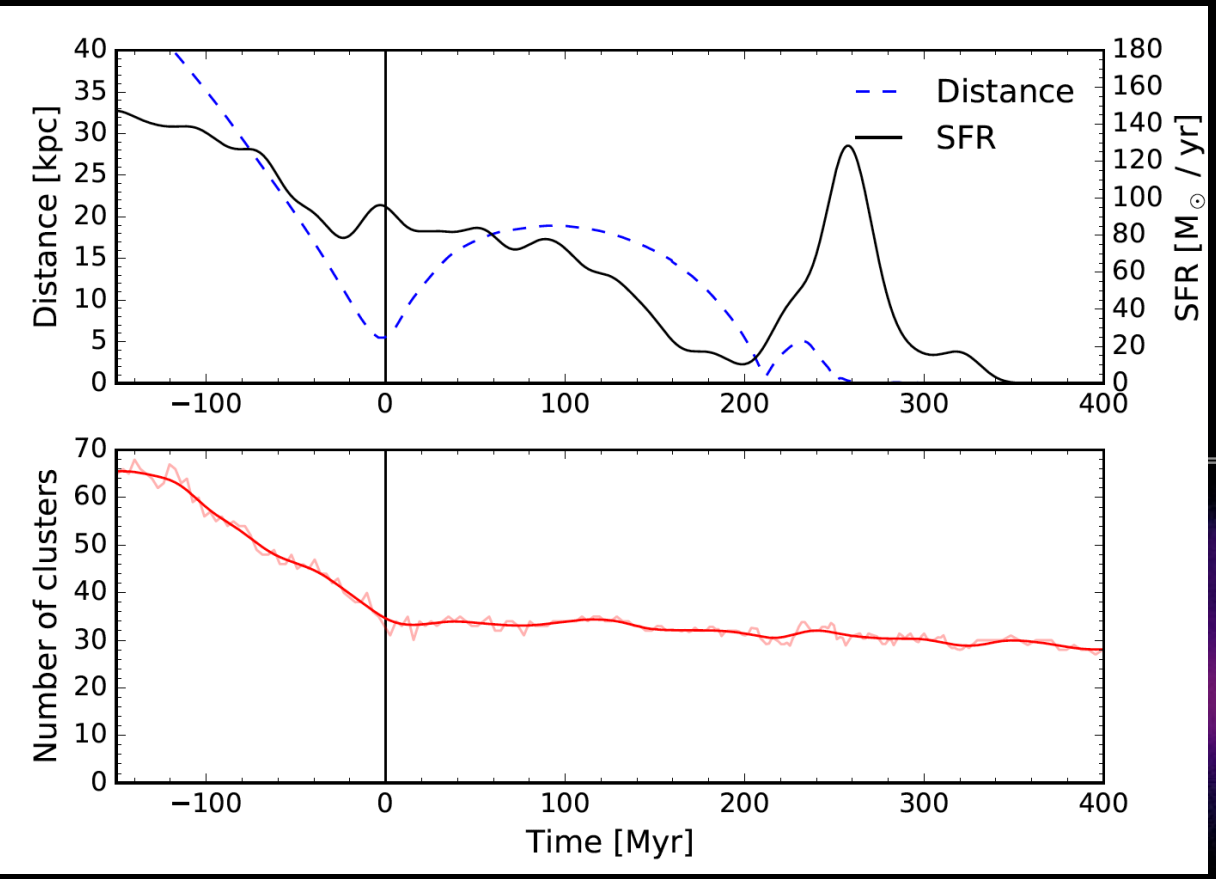


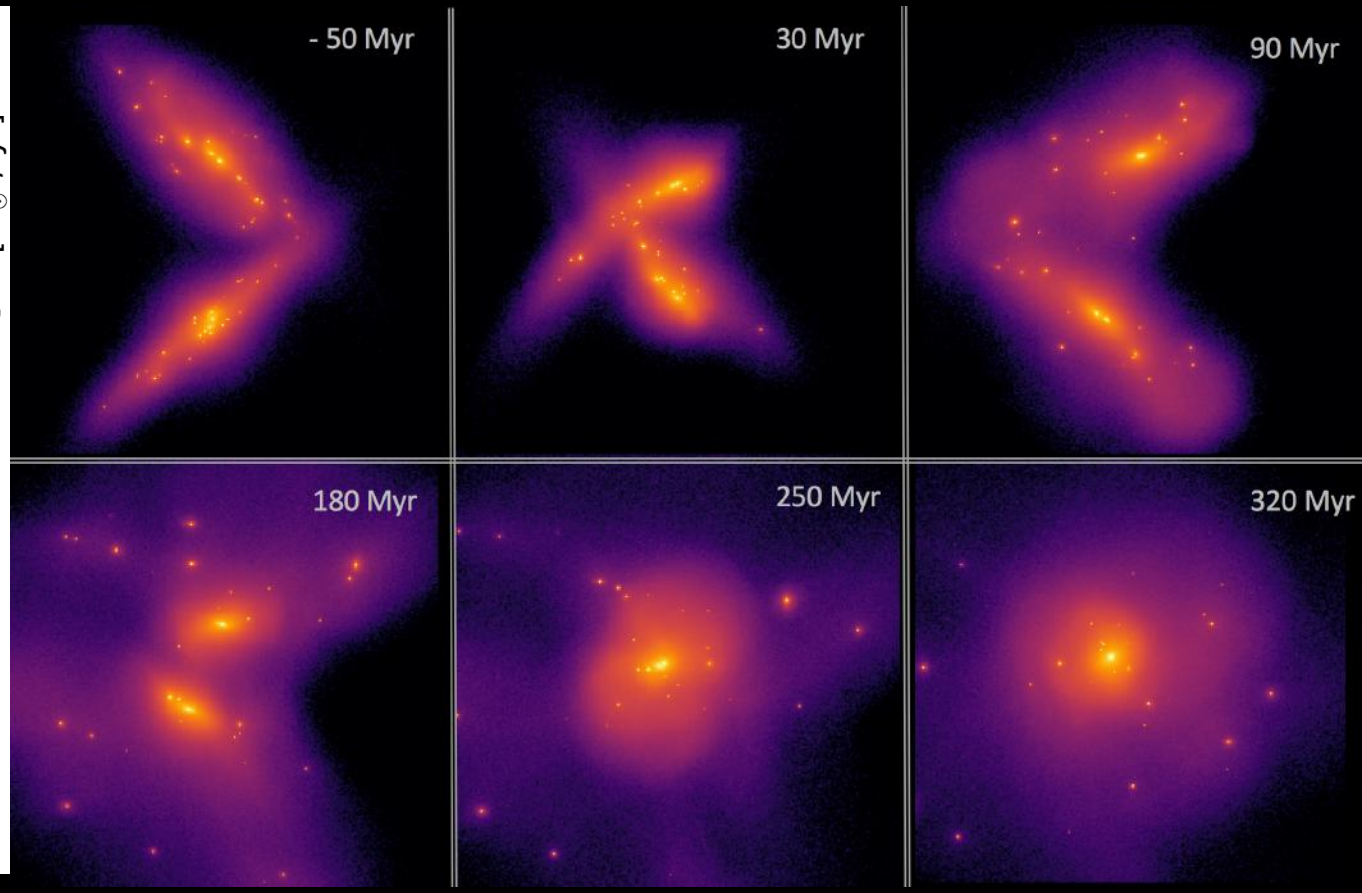
Galaxies are on the starburst sequence for a shorter amount of time.

Fensch et al., 2017a

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

No significant increase of star and stellar cluster formation

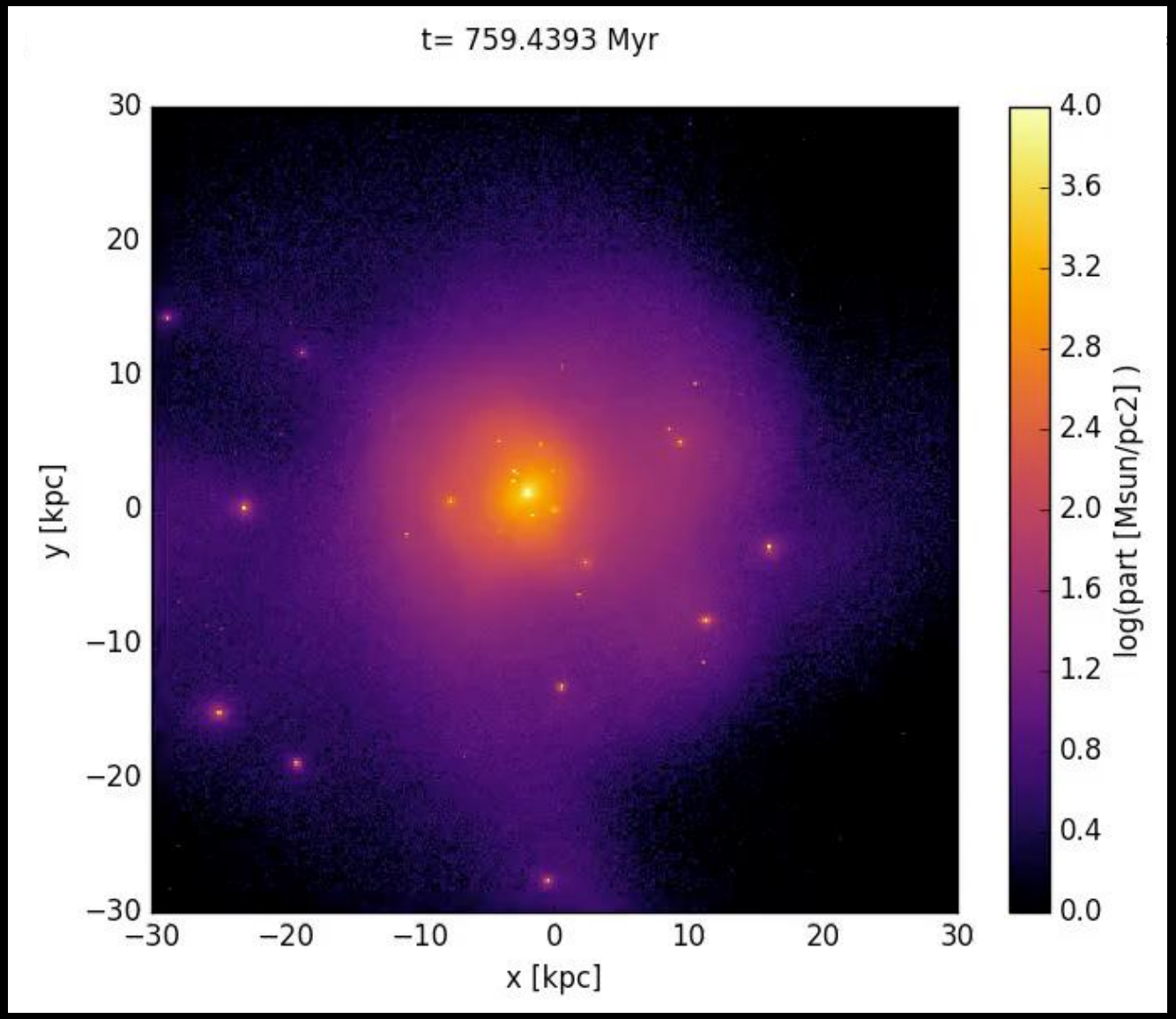




However, the merger seems to preserve the star clusters
by ejecting them out of the disks !

Fensch et al., 2017b (in prep.)

Ejection of clusters into the halo



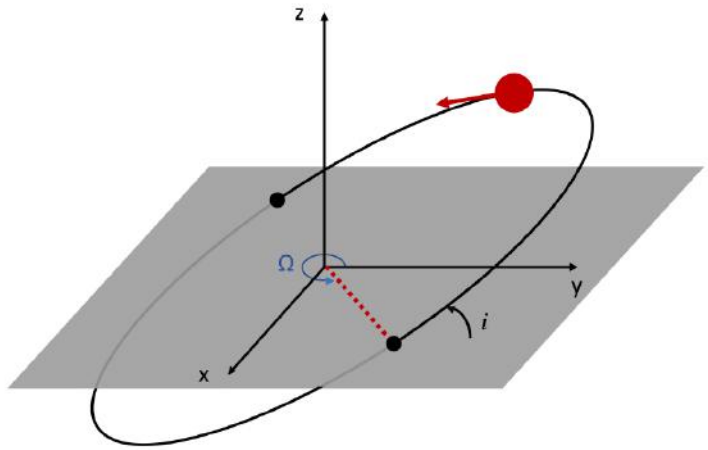
What are their orbits ?

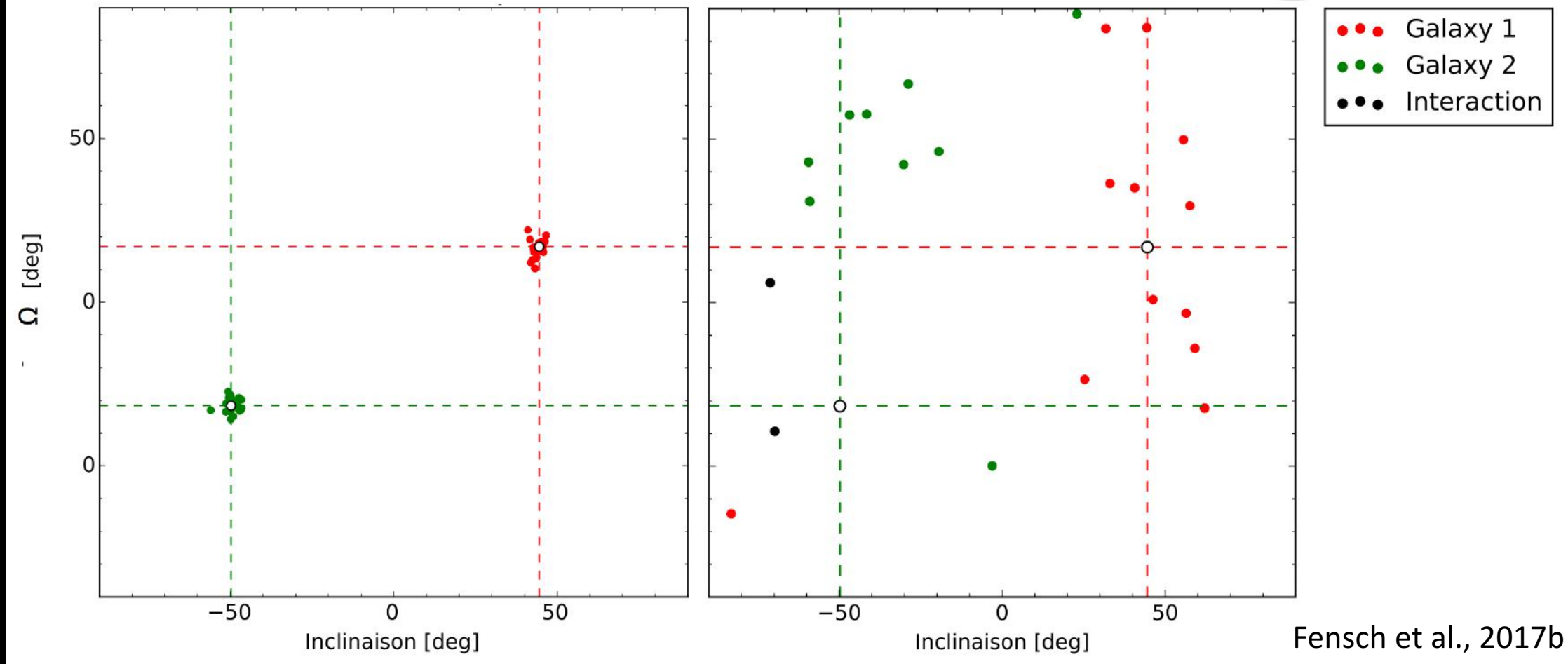
-planes ?
-distribution ?

Fensch et al., 2017b (in prep.)

Ejection of clusters into the halo

Galaxy planes are not conserved during the interaction.

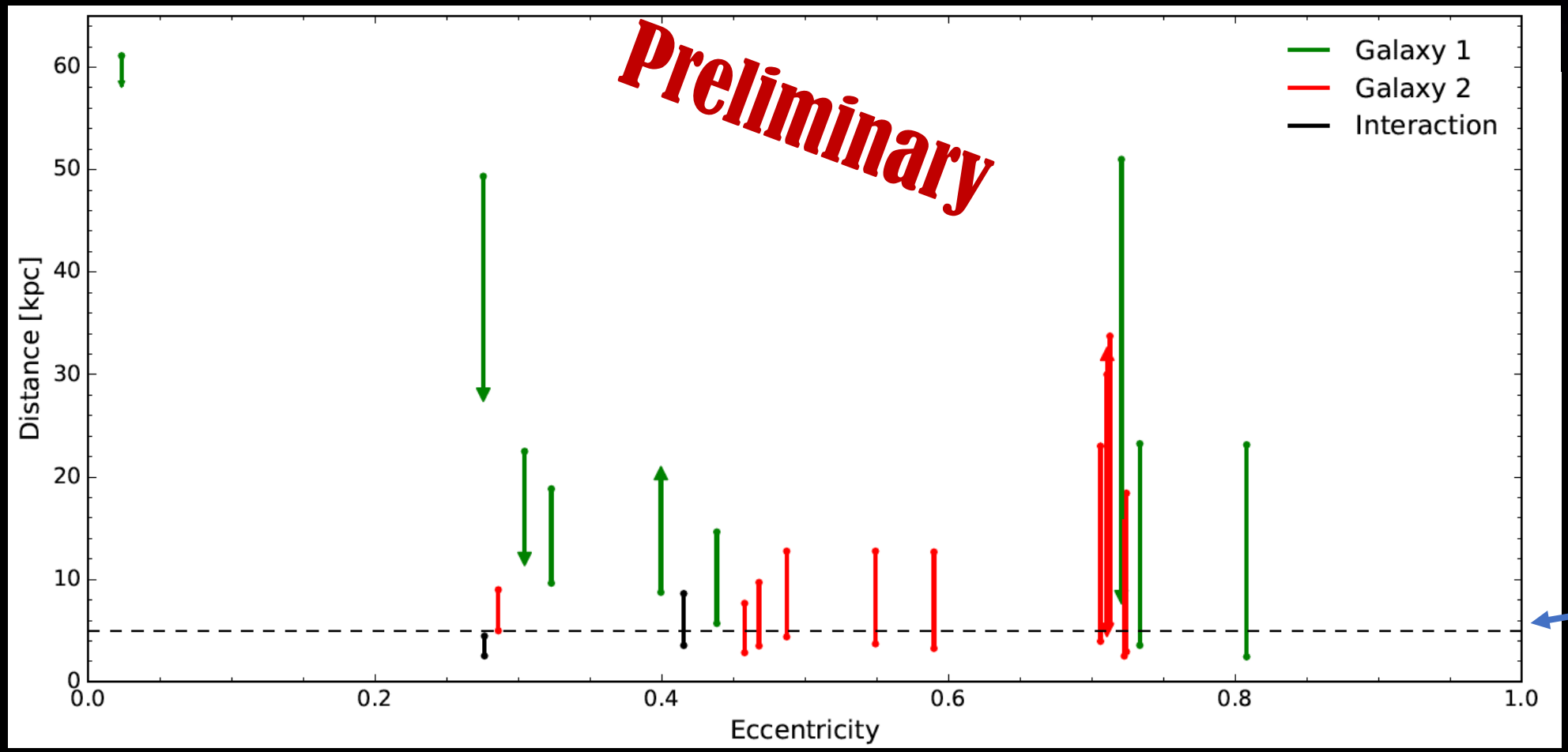




Fensch et al., 2017b

Ejection of clusters into the halo

Orbits can be quite eccentric :
pericenter quite close to the remnant center



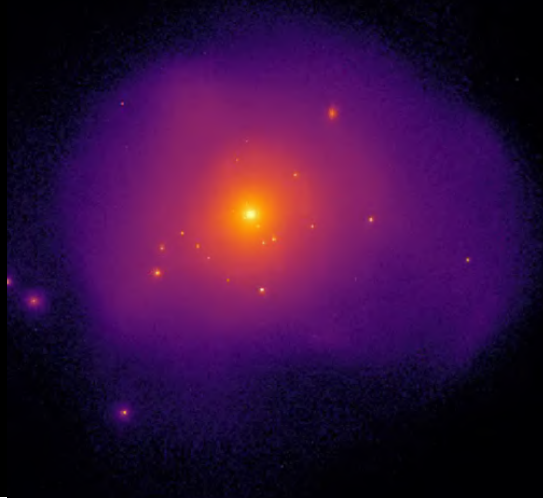
Tidal effects may be important !

R_{eff}

Fensch et al., 2017b (in prep.)

Ejection of clusters into the halo

Cluster spatial distribution follows that of the stars



Similar to red globular clusters

see e.g. Forbes et al., 2012

They would have similar metallicity as red GCs

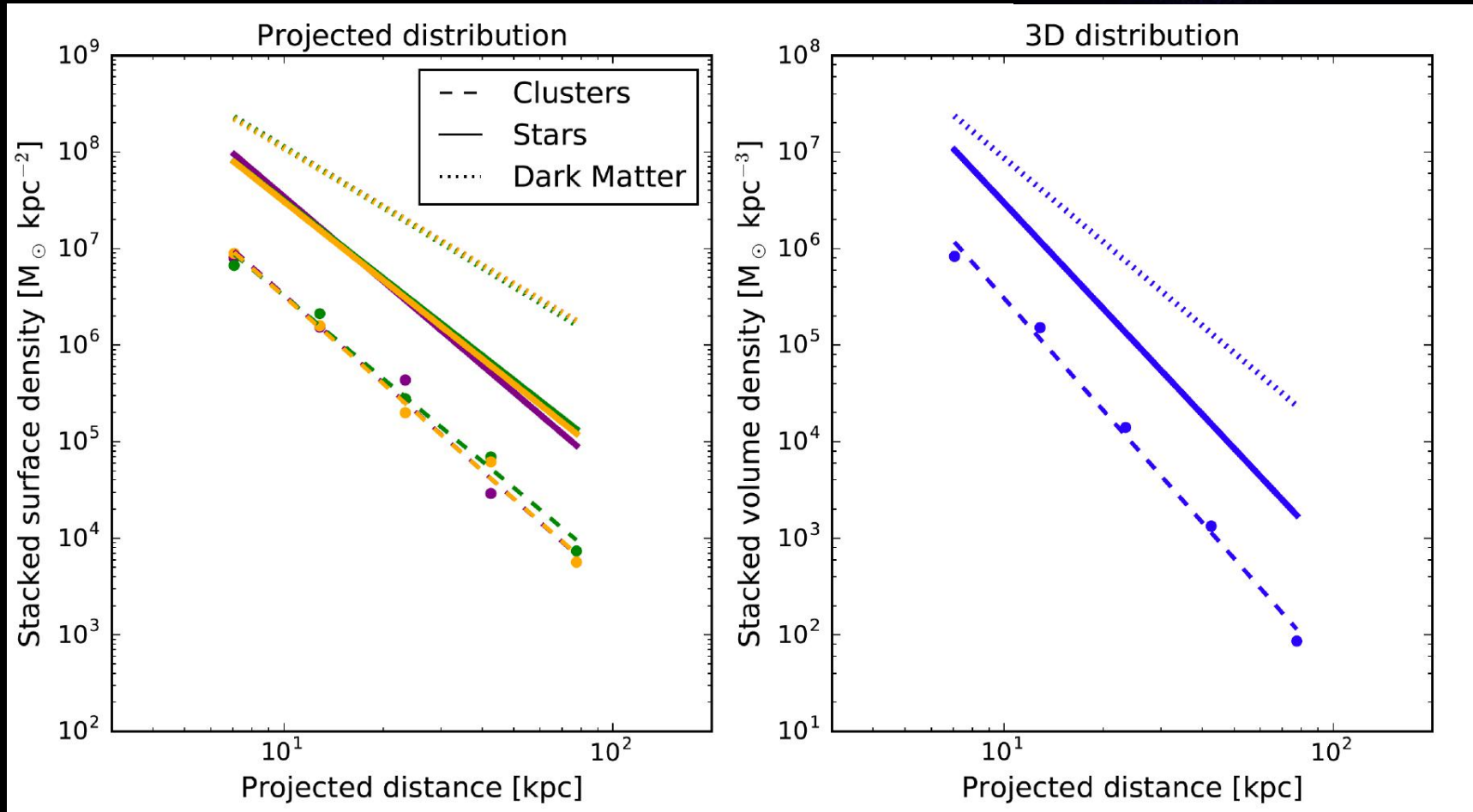
see e.g. Erb et al., 2006

Clumps could be sufficient to form all red GCs

Shapiro et al., 2010

Not resolved … ***yet*** !

Future work, stay tuned !



Conclusion

- Gas-rich disks at high-redshift naturally form bound stellar clusters.
- High-z major mergers do not appear to contribute to the formation of **stars and stellar clusters**.
- Major mergers expel these clusters into the halo of the remnant: progenitors of metal rich globular clusters ?