Florent Renaud
Lund Observatory

Knut and Alice Wallenberg Foundation

# When (and why) has the Milky Way stopped forming massive clusters?

WITH


FLOOR VAN DONKELAAR, LUND → ZÜRICH

TIMMY EJDETJÄRN, LUND → STOCKHOLM

ÁLVARO SEGOVIA OTERO, LUND

OSCAR AGERTZ, LUND

ALESSANDRO ROMEO, CHALMERS

AND THE VINTERGATAN TEAM

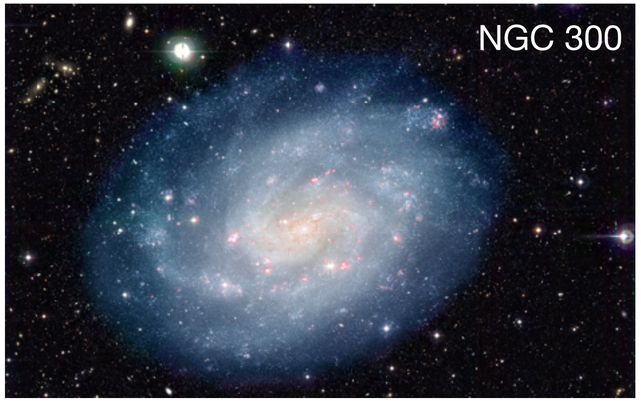
JUSTIN READ, NILS RYDE, ERIC ANDERSSON, THOMAS BENSBY, MARTIN REY, DIANE FEUILLET

# Where are the young massive clusters?

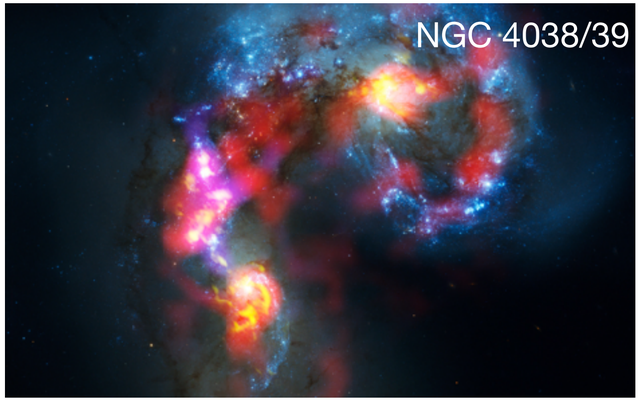
*Florent Renaud*
@renaudflo

*in the local Universe*

Galactic centers
e.g. Neumayer et al. (2020)




Starbursts
e.g. Adamo et al. (2011)




Gas-rich dwarf galaxies
e.g. Hunter et al. (2016), Cook et al. (2019)

# Where are the young massive clusters?

*Florent Renaud*
@renaudflo

*in the Milky Way*

# Where are the young massive clusters?

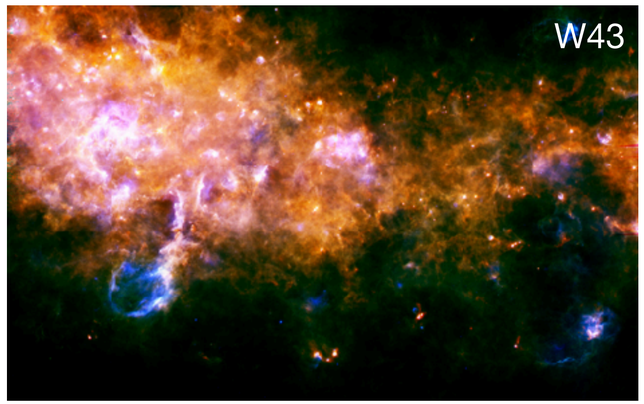
*Florent Renaud*
@renaudflo

*in the Milky Way*

Galactic center
e.g. Bland-Hawthorn & Gerhard (2016)

Infalling dwarf satellites
e.g. Minniti et al. (2021), Piatti et al. (2021)


Tip of the bar?
Nguyen-Luong et al. (2013)



# In which conditions do massive clusters form?

*Florent Renaud*
@renaudflo

*in the local Universe*




repeated fueling of gas and stars
e.g. Guillard et al. (2016)

shocks + tidal compression
Jog & Solomon (1992), Renaud et al. (2014)

galaxy-driven over-densities
e.g. Renaud et al. (2015)

*in the Milky Way*




The Milky Way is not an efficient factory of massive clusters
anymore...

# Then, where do the 150+ (old) globular clusters come from?

*Florent Renaud*
@renaudflo

Accretion
e.g. Renaud et al. (2017), Li et al. (2017), Reinas-Campos et al. (2019)

In situ formation at high redshift

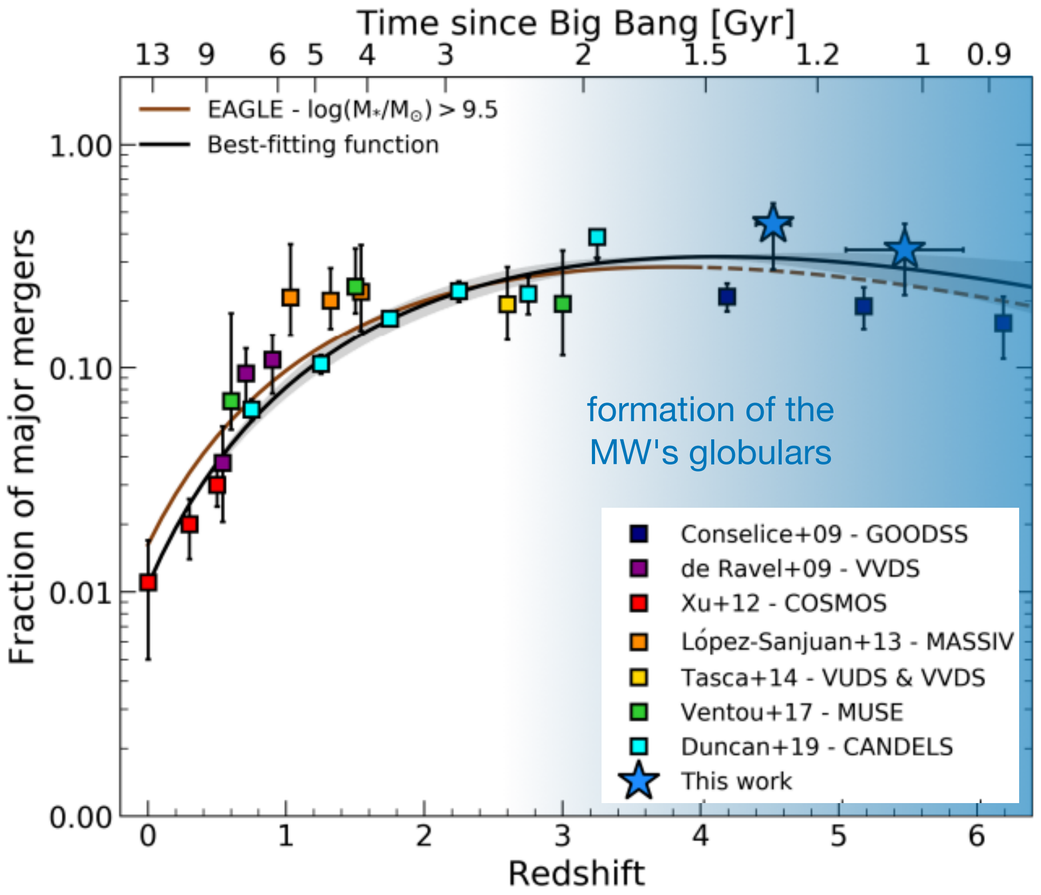
- more frequent mergers

  ... but not necessarily more starbursts
  e.g. Lofthouse et al. (2017)

- early phase of galaxy formation

  - higher gas fraction
  - stronger turbulence
  - higher (but steady) SFR

Romano et al. (2021)



# CLUMPY GALAXIES

*Florent Renaud*
@renaudflo

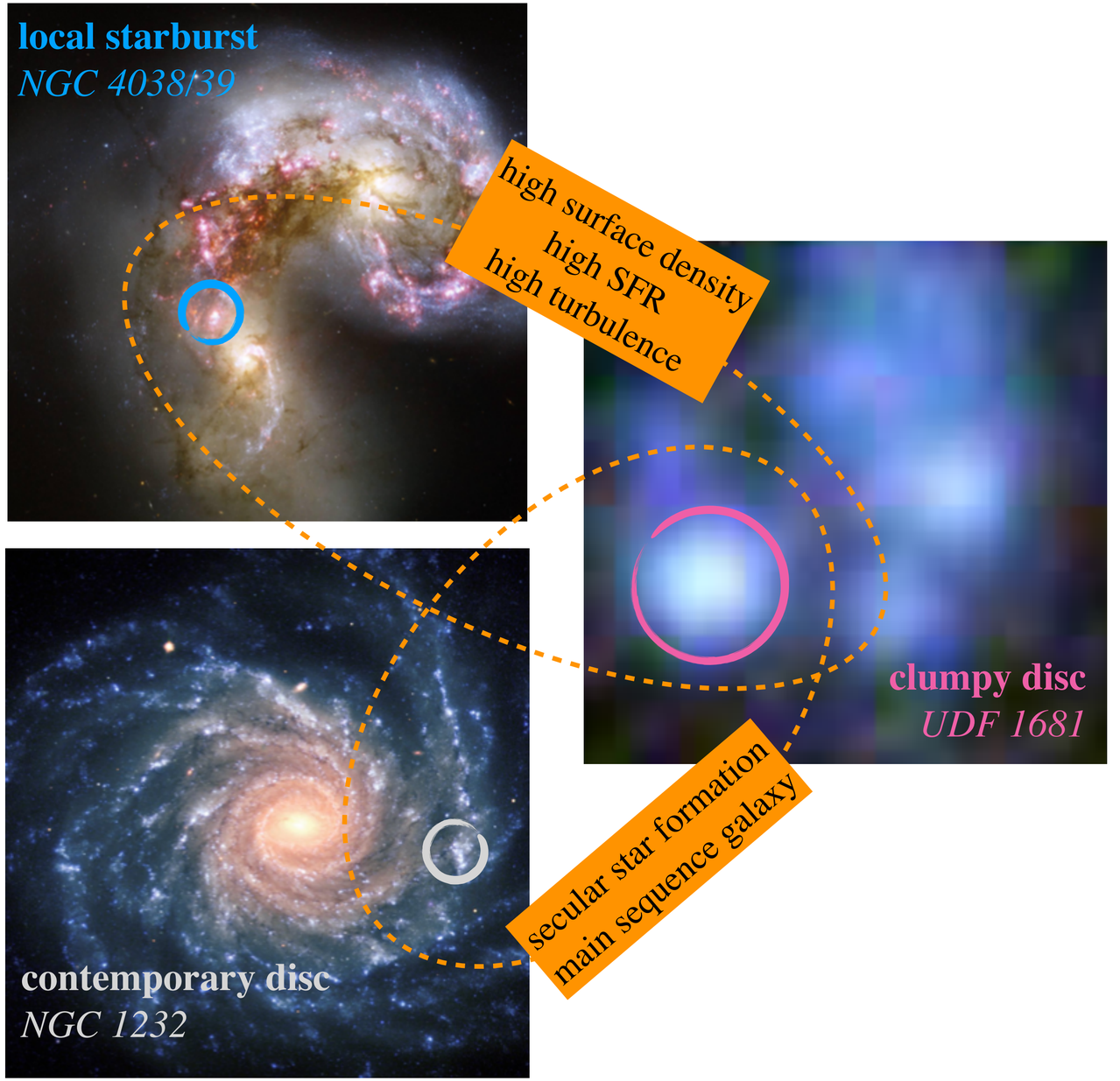
Most of disc galaxies at $z \gtrsim 1$ have
huge star forming gas clumps ( $\sim 10^{8-9}\,\mathrm{M}_\odot$)

Guo et al. (2015)
but see Huertas-Company (2020) about sub-clumps

Clumps are found in galaxies with
high gas fractions:

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

see also Wuyts et al. (2012), Zanella et al. (2015), Dessauges-Zavadsky et al. (2019), Huertas-Company (2020), and many more...



# GAS-RICH GALAXIES

*Florent Renaud*
@renaudflo

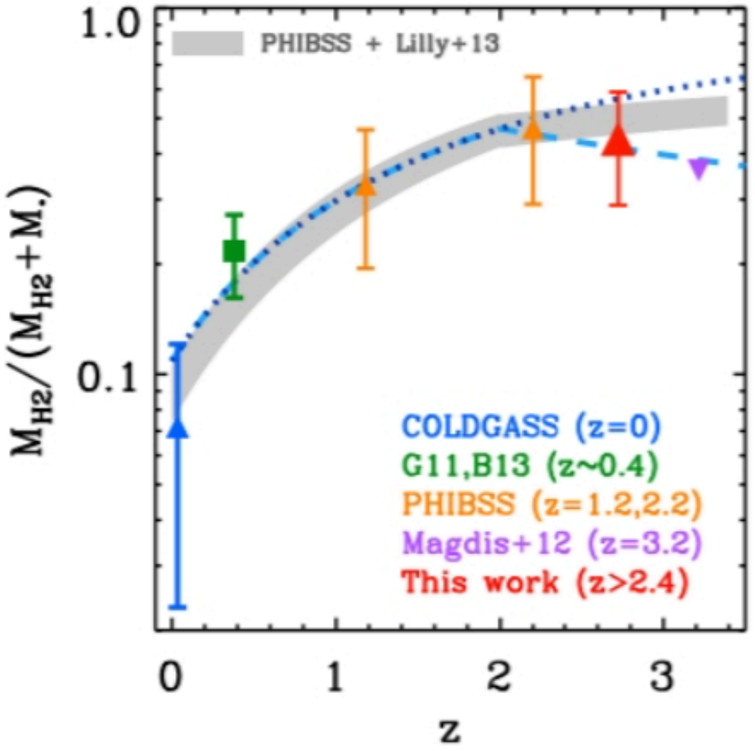
The gas fraction in discs evolves with redshift

Most (if not all) Milky Way-likes have had a clumpy phase
Guo et al. (2015)

Massive clumps are natural sites for
the formation of massive clusters

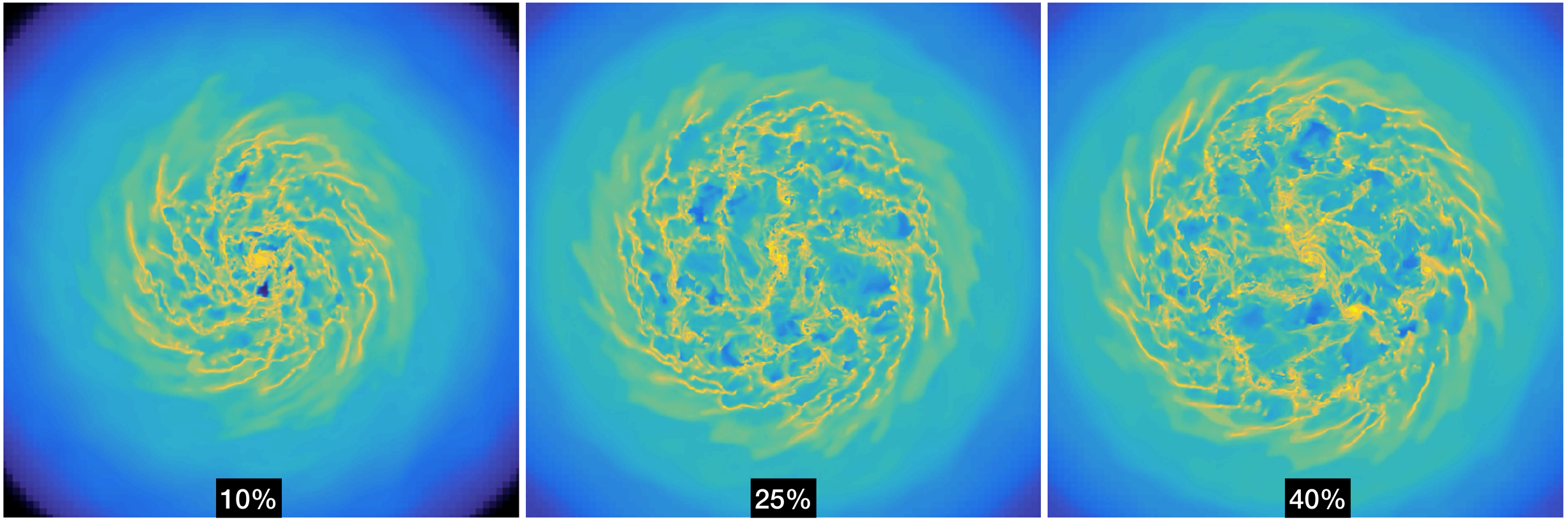
- massive
- large
- turbulent
- could be dynamically ejected in a thick disc / spheroid

Saintonge et al. (2013)



# Varying the Gas Fraction

*Florent Renaud*




Simulation suite of isolated galaxies

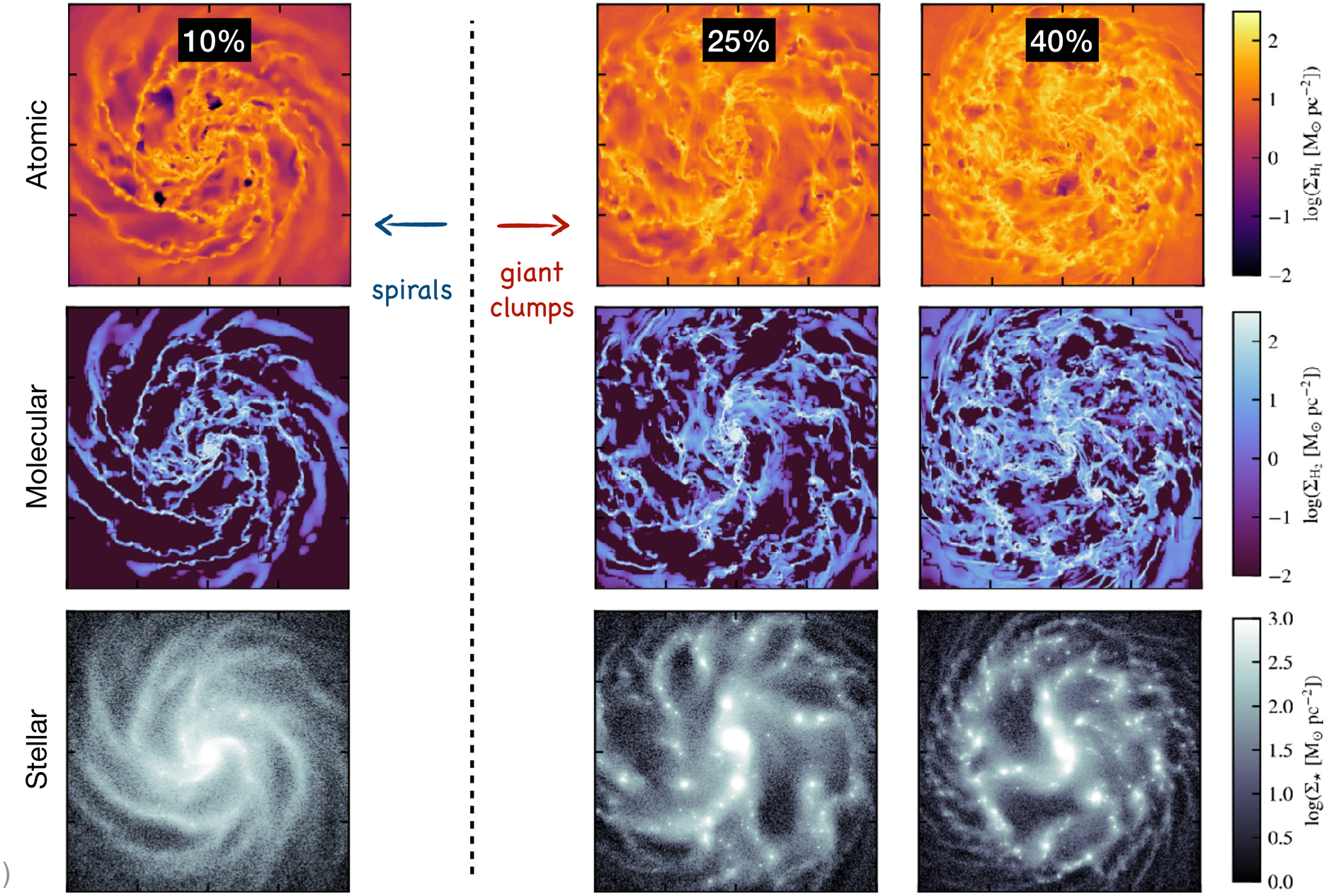
RAMSES, 12 pc resolution, heating, cooling, star formation, winds, radiative feedback, SNe Ia + II
Teyssier (2002), Agertz et al. (2021)

Several models, exact same initial conditions, except the gas fraction

# MORPHOLOGY

*Florent Renaud*

Structure changes
at $f_{\rm gas} \approx 20\,\%$




Renaud, Romeo & Agertz (2021)

# THE TRANSITION AT 20% IS ALSO SEEN IN KINEMATICS!

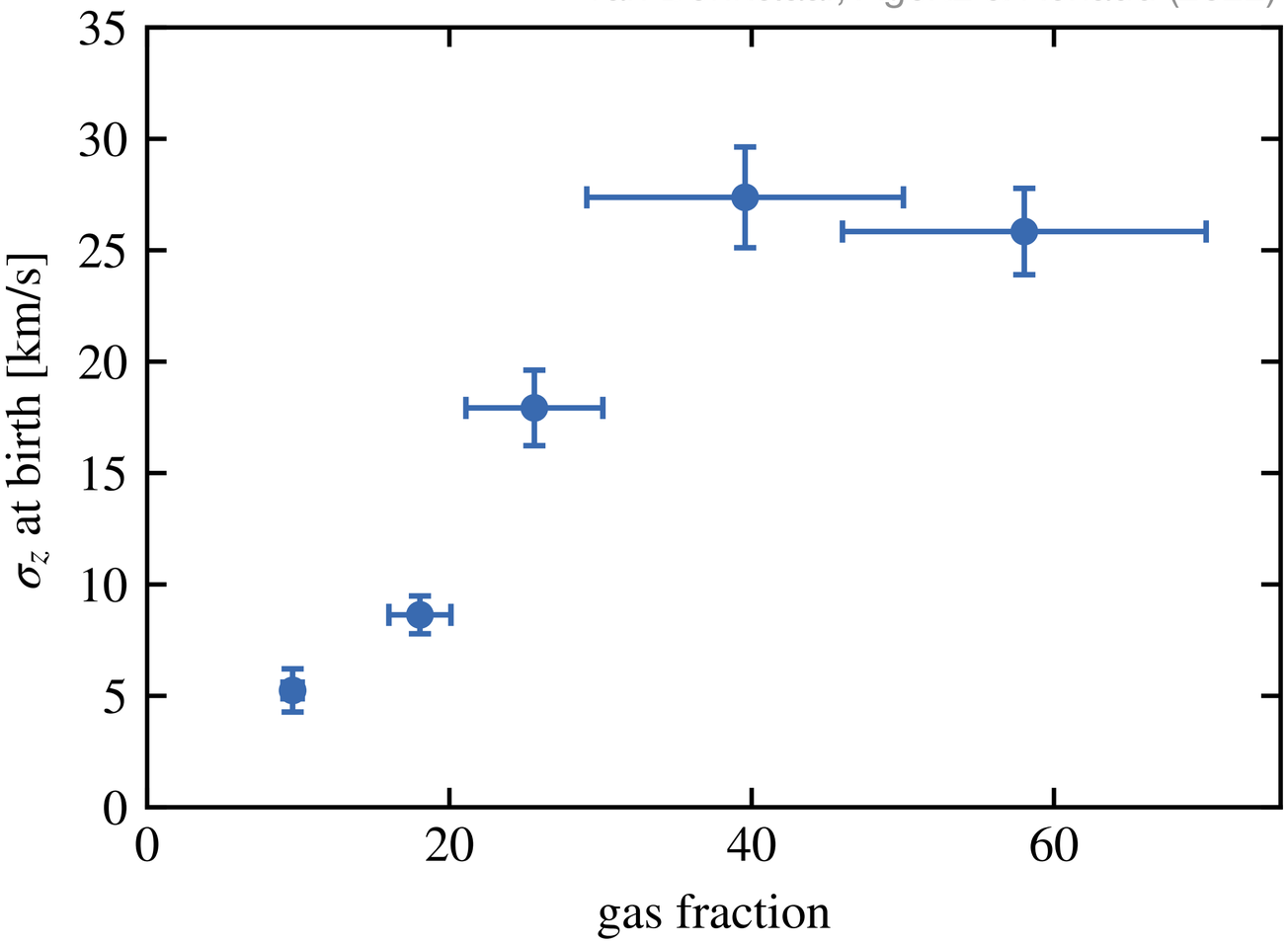
*Florent Renaud*
@renaudflo

Gas rich (clumpy) discs provide a high velocity dispersion to young stars...

...but only at $f_{\rm gas} \gtrsim 20\,\%$

**see Floor's talk on Friday**

van Donkelaar, Agertz & Renaud (2022)



# Driver of instabilities

*Florent Renaud*
@renaudflo

Using the Romeo & Falstad (2013) framework

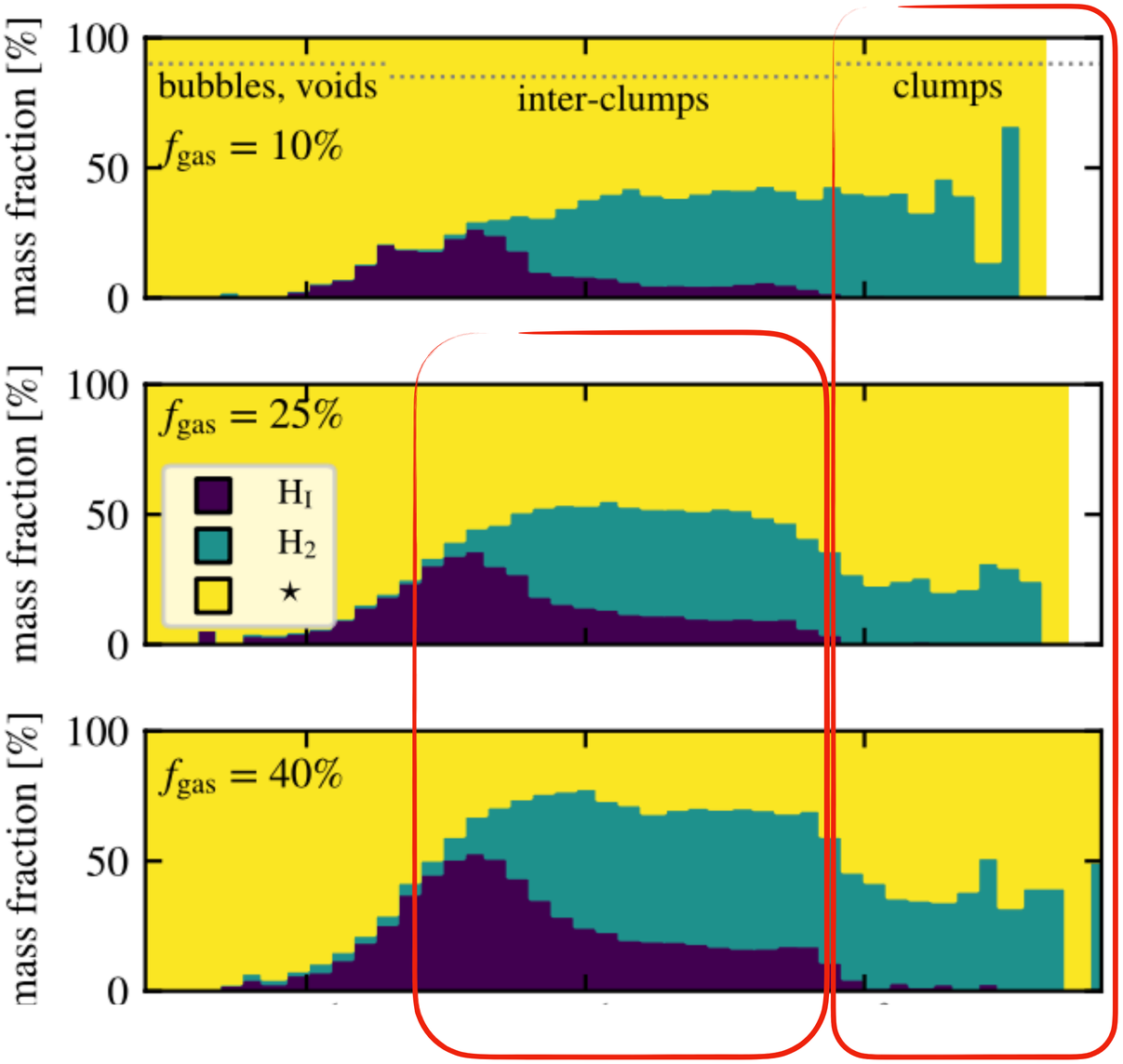
Gas takes the dominant role in the inter-clump medium
i.e. for the assembly of the clumps

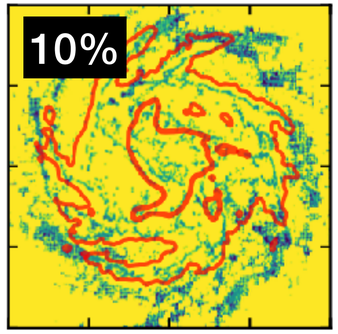
The gaseous phase sets the formation of the clumps

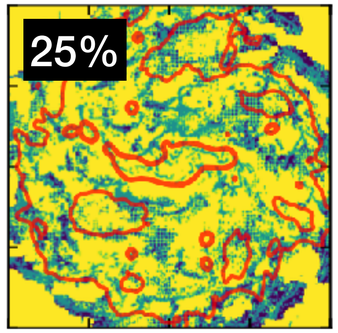
Stars dominate *within* clumps

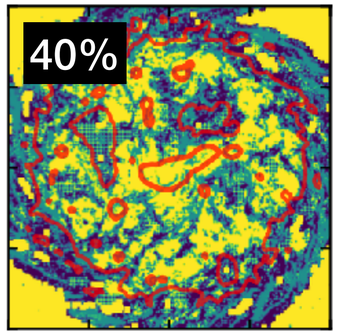
Stellar feedback increases the turbulence support
(doesn't affect the stars much)

Renaud, Romeo & Agertz (2021)



# ISM PSD WTF (Interstellar Medium's Power Spectrum Density: a Wonderful Theoretical Function)

*Florent Renaud*
@renaudflo

Change of slope at ~ 100 - 200 pc

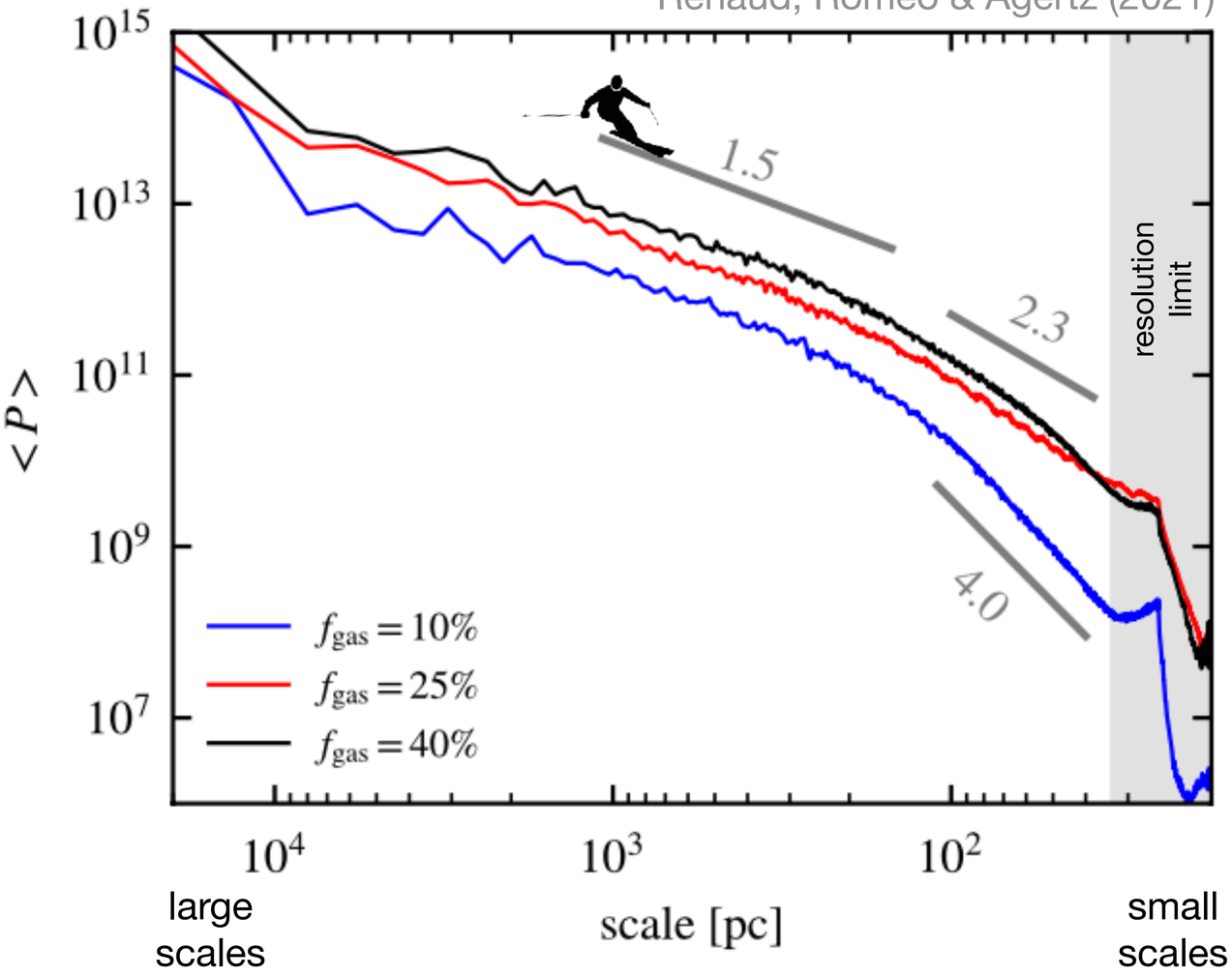
Partly caused by the transition
from 2D to 3D turbulence
(i.e. within the disc scaleheight)
Dutta et al. (2009), Renaud et al. (2013)

But divergence between the 3 cases...

Transition from disc-instabilities (Toomre-like)
to clump-instabilities, but only at high $f_{\rm gas}$

Ask me for details

Renaud, Romeo & Agertz (2021)



# Intrinsic evolution of the Milky Way

- Gas plays a less and less important role in disc dynamics
- The regime of instabilities shifts from clump-dominated to disc-dominated
- The star formation activity calms down

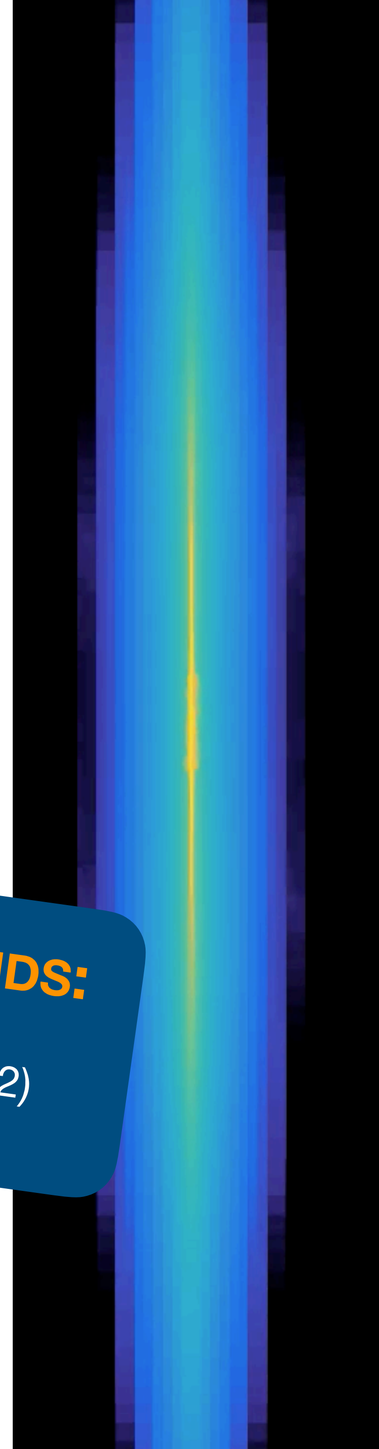
  see also Clarke et al. (2019), Khoperskov et al. (2021)

- Massive clumps stop being formed
  → no more formation sites for massive clusters

**in an isolated galaxy**

but ... the Milky Way is not isolated ...

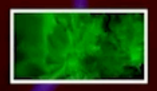
**From Giant Clumps to Clouds:**
I: Renaud, Romeo & Agertz (2021)
II: van Donkelaar, Agertz & Renaud (2022)
III: Ejdetjärn et al. (2022)



# VINTERGATAN

Agertz, Renaud et al. (2021)
Renaud, Agertz et al. (2021a,b)

MILKY WAY


IRON


STARS


GAS


DARK MATTER

Z = 6

12.9 GYR AGO

# The end of the merger phase

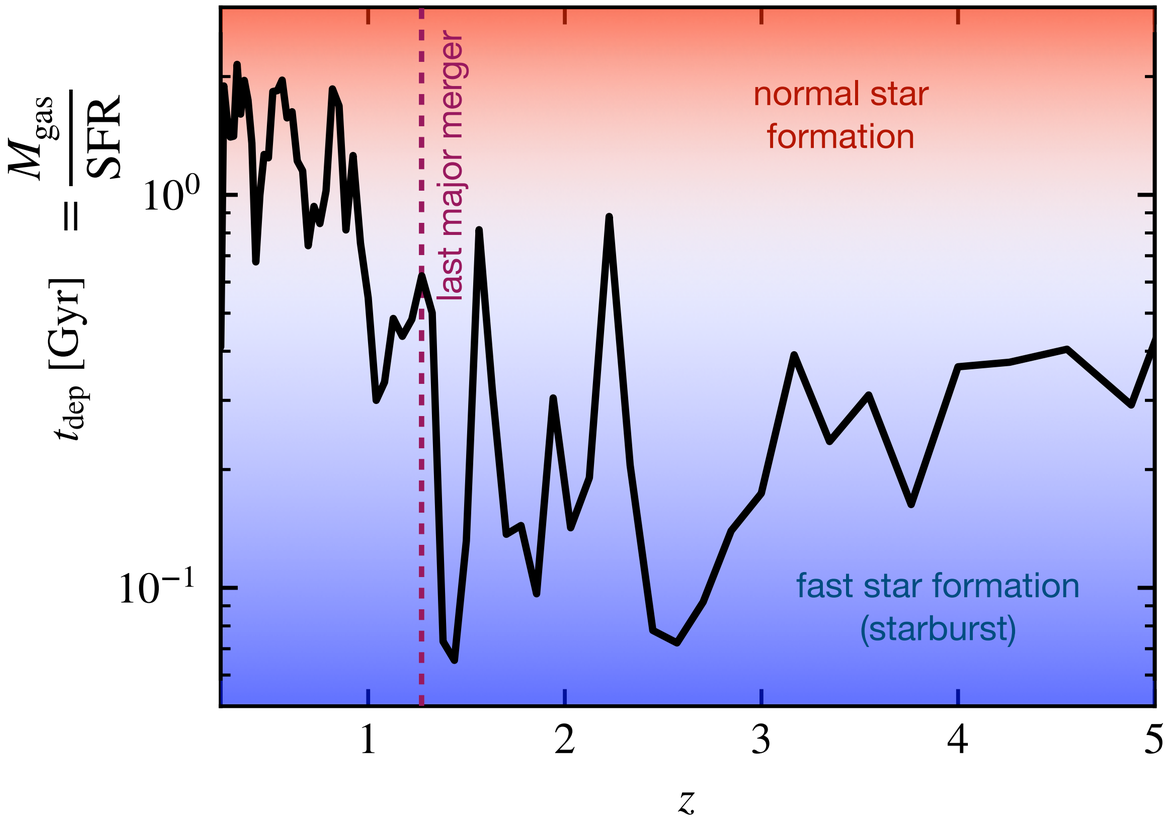
*Florent Renaud*
@renaudflo

After the last major merger:

- less tidal stirring
- less large-scale injection of turbulence

- less star formation
- slower star formation (longer depletion times)
- slower replenishment of the gas reservoir

Segovia Otero et al. (submitted)



# Conclusion

The Milky Way stopped hosting the conditions for the formation of massive clusters because of the decrease of its gas fraction, *and* the end of the merger phase.

For details, see:

- isolated galaxies: From Clumps To Clouds
  Renaud, Romeo & Agertz (2021)
  van Donkelaar, Agertz & Renaud (2022)
  Ejdetjärn et al. (2022)
- in cosmological context: Vintergatan
  Agertz, Renaud et al. (2021)
  Renaud, Agertz et al. (2021a,b)
  Segovia Otero, Agertz & Renaud (2022)