Disc instability analyses for high-z clumpy galaxies in simulations

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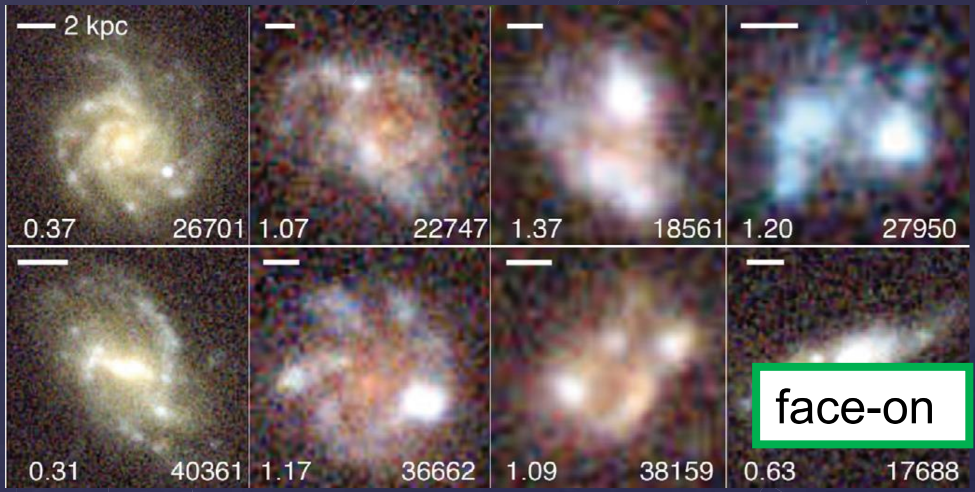
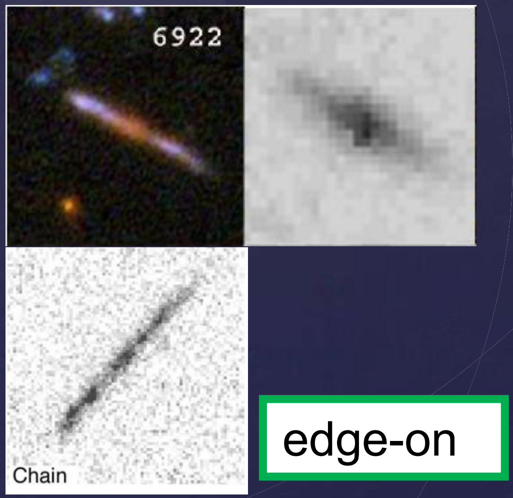
Clumpy disc galaxies

- Observed in the high-z universe (z > 1)
  - clump clusters / chain galaxies



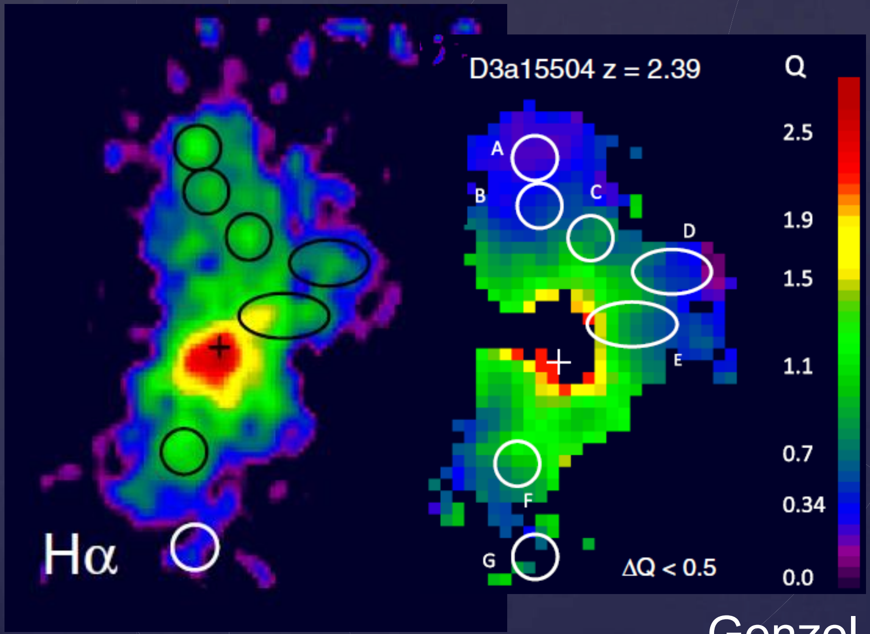
Elmegreen et al. (2009)

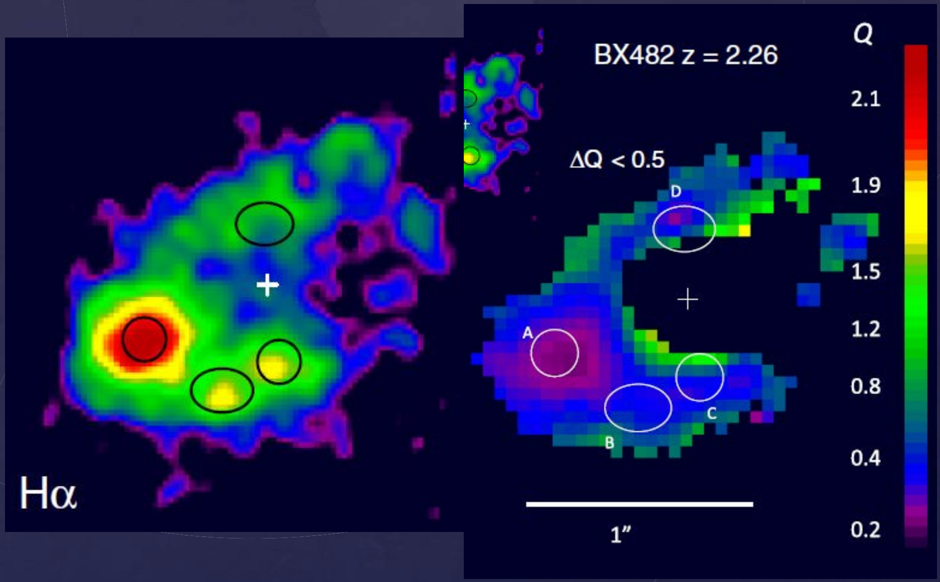


- **`Clumpy' galaxies are discs in their formation stages.**
  - `Giant clumps' (massive star clusters) in discs.
  - Clump mass ~ $10^9\ M_\odot$ at the largest.

Toomre instability in high-z discs

- Toomre instability criterion
  - $Q \equiv \frac{\sigma\kappa}{\pi G \Sigma} < 1$





Genzel et al. (2011)

Toomre instability in high-z discs

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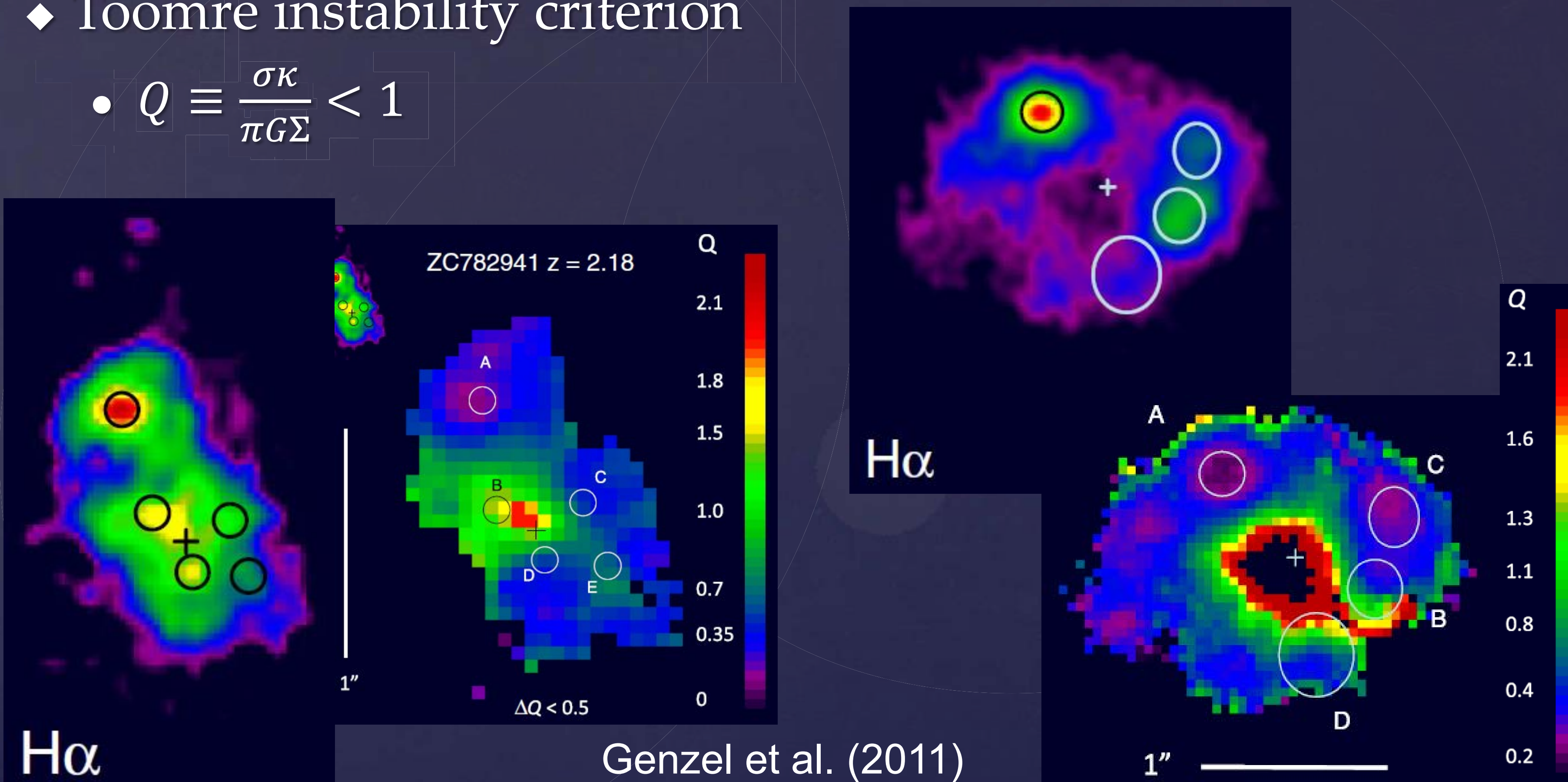
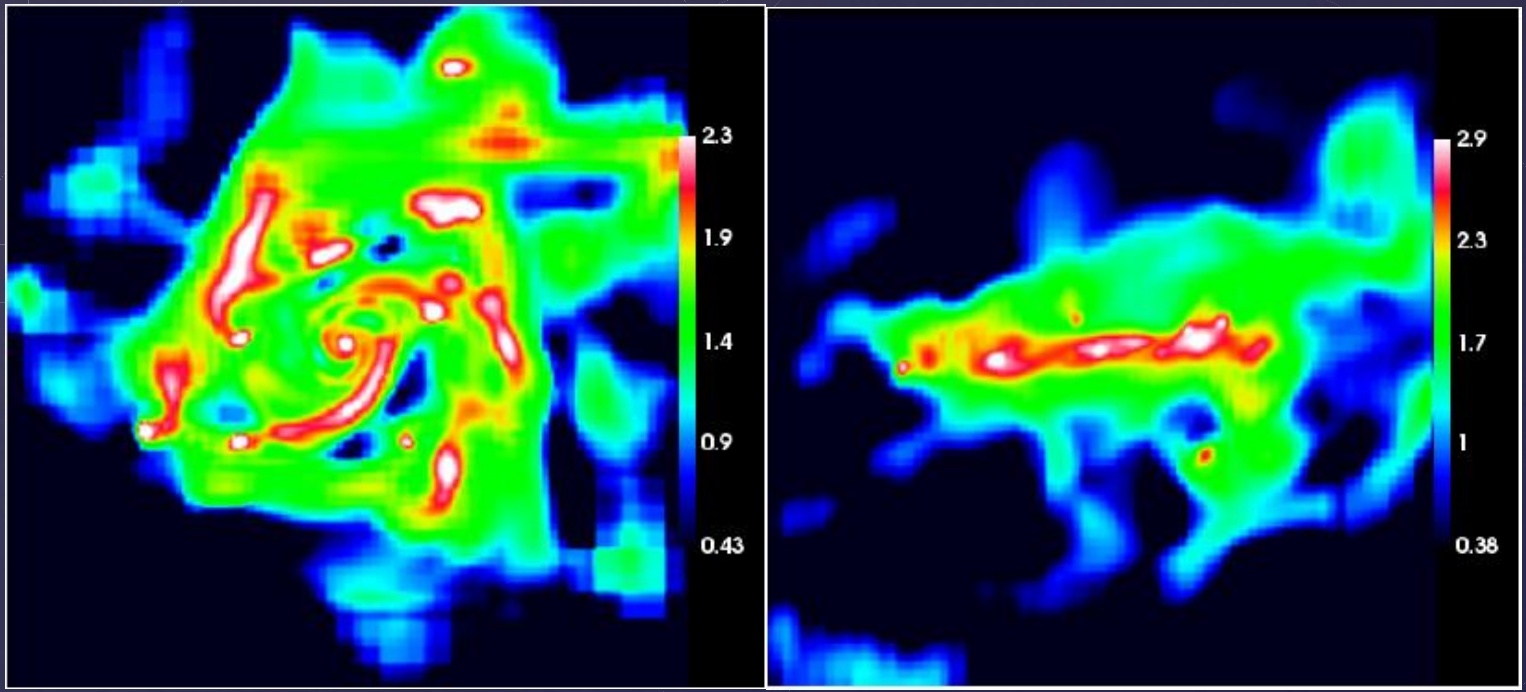


Genzel et al. (2011)

- In observations, high-z galaxies indicate Q<1 in entire disc regions.
  - **Toomre instability gives birth to clumps.**

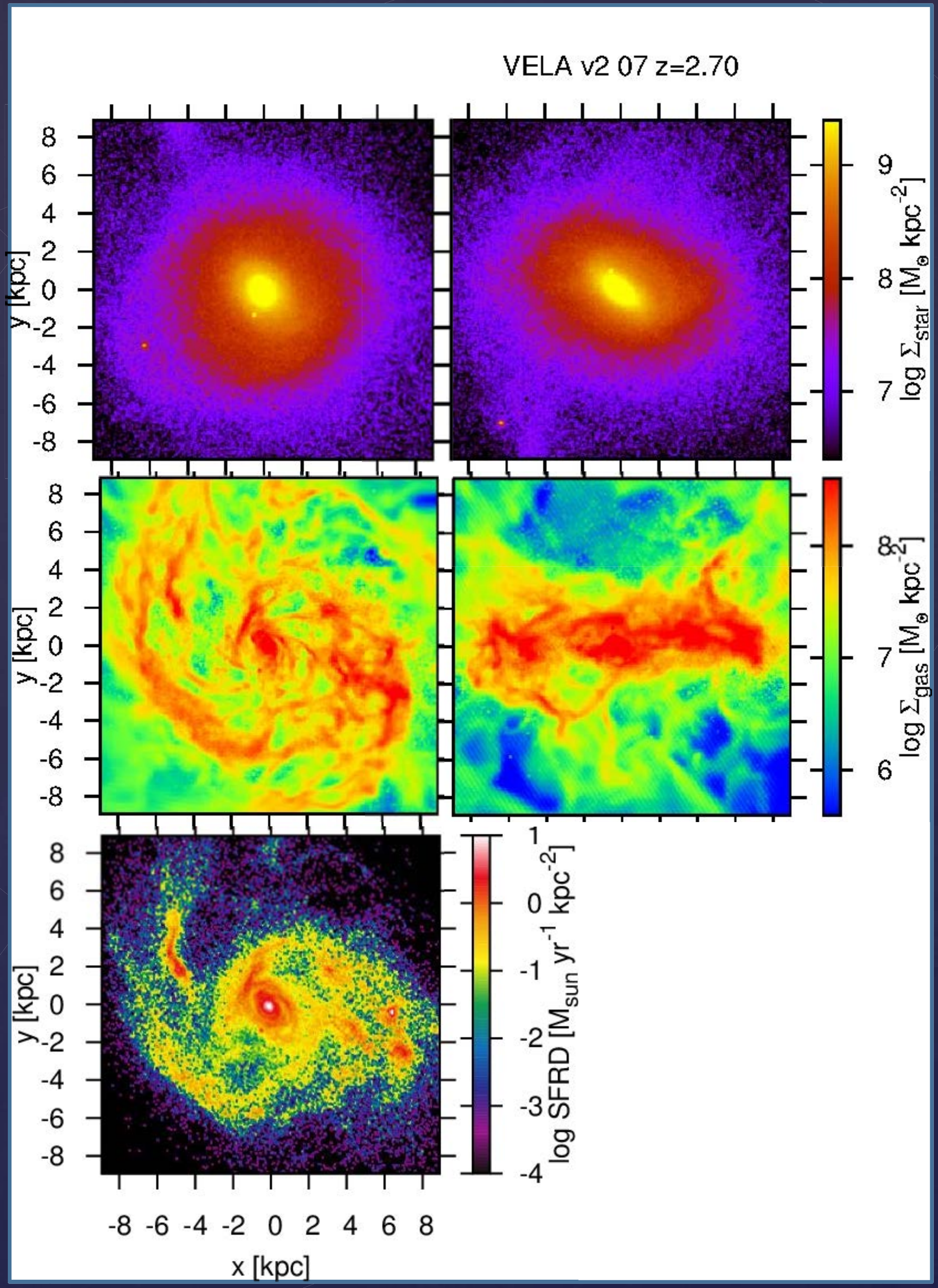
- What about Toomre Q in simulations?



Dekel, Sari & Ceverino (2009)

- from the cosmological simulations
  - Ceverino et al. (2010, 2013) using ART code
    - 10pc-order resolution with radiation pressure.
- Cosmological simulations are always non-linear.

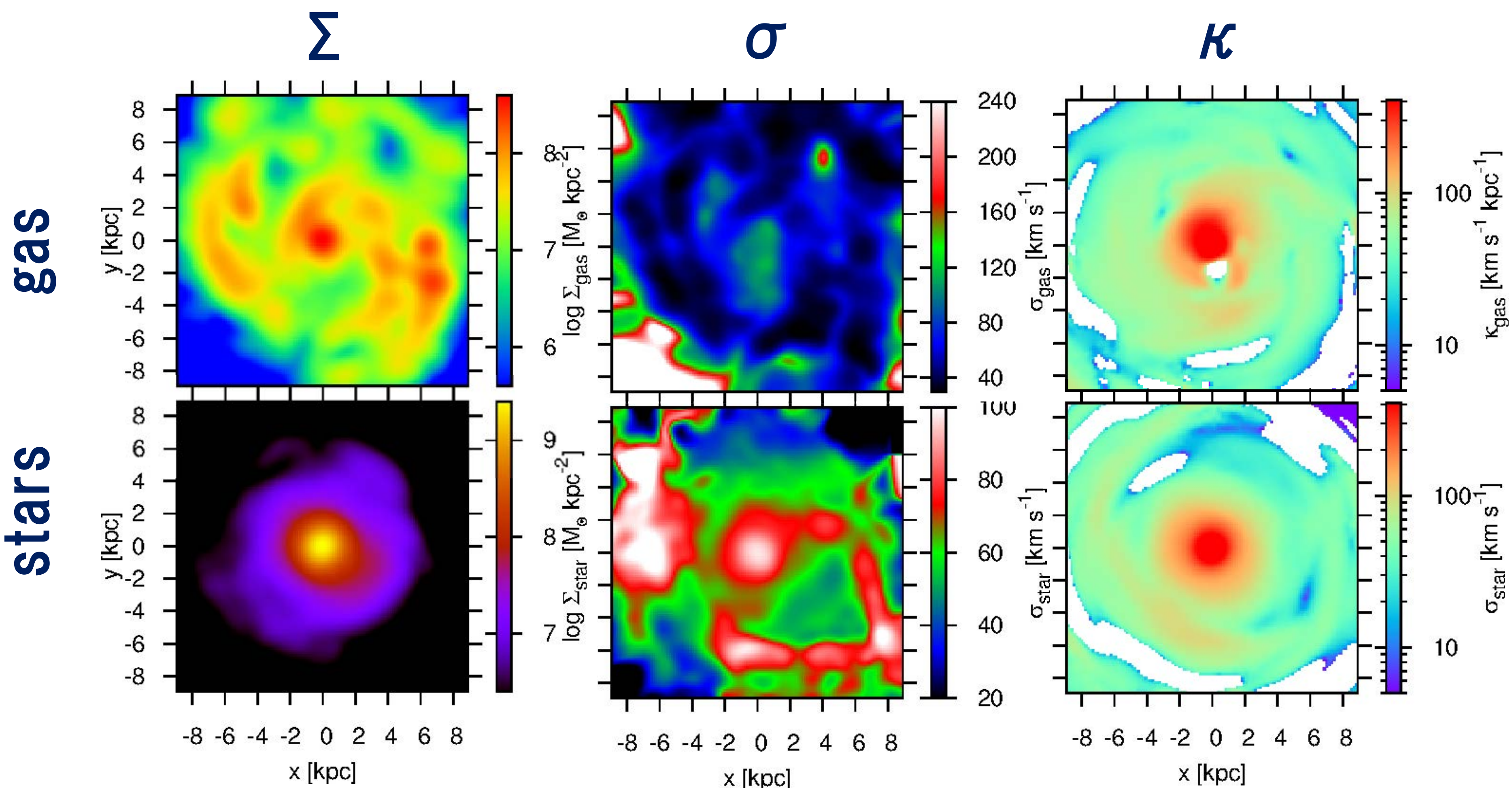
- $M_{vir} = 1.1x\ 10^{12}\ M_{\odot}$
- $M_{star} = 7.7x\ 10^{9}\ M_{\odot}$
- red-shift z = 2.7



How to compute Toomre's Q

- 2-component model (Romeo & Wiegert 2011)
  - $Q_{gas} = \frac{\kappa_{gas}\sigma_{gas}}{\pi G \Sigma_{gas}}$, $Q_{star} = \frac{\kappa_{star}\sigma_{star}}{3.36 G \Sigma_{star}}$
  - $\begin{cases} {Q_{2comp}}^{-1} = W{Q_{gas}}^{-1} + {Q_{star}}^{-1} & (if \quad Q_{gas} > Q_{star}) \\ {Q_{2comp}}^{-1} = {Q_{gas}}^{-1} + W{Q_{star}}^{-1} & (if \quad Q_{gas} < Q_{star}) \end{cases}$
    - $W \equiv \frac{\sigma_{gas}\sigma_{star}}{{\sigma_{gas}}^2 + {\sigma_{star}}^2}$
  - σ is radial velocity dispersions of gas/star.
  - κ is calculated from mean velocity fields of gas/star.
    - $\kappa \equiv \sqrt{2\frac{<v_\phi>}{R}\left(\frac{d<v_\phi>}{dR} + \frac{<v_\phi>}{R}\right)}$
  - Stars younger than 100 Myr are considered to be "gas "

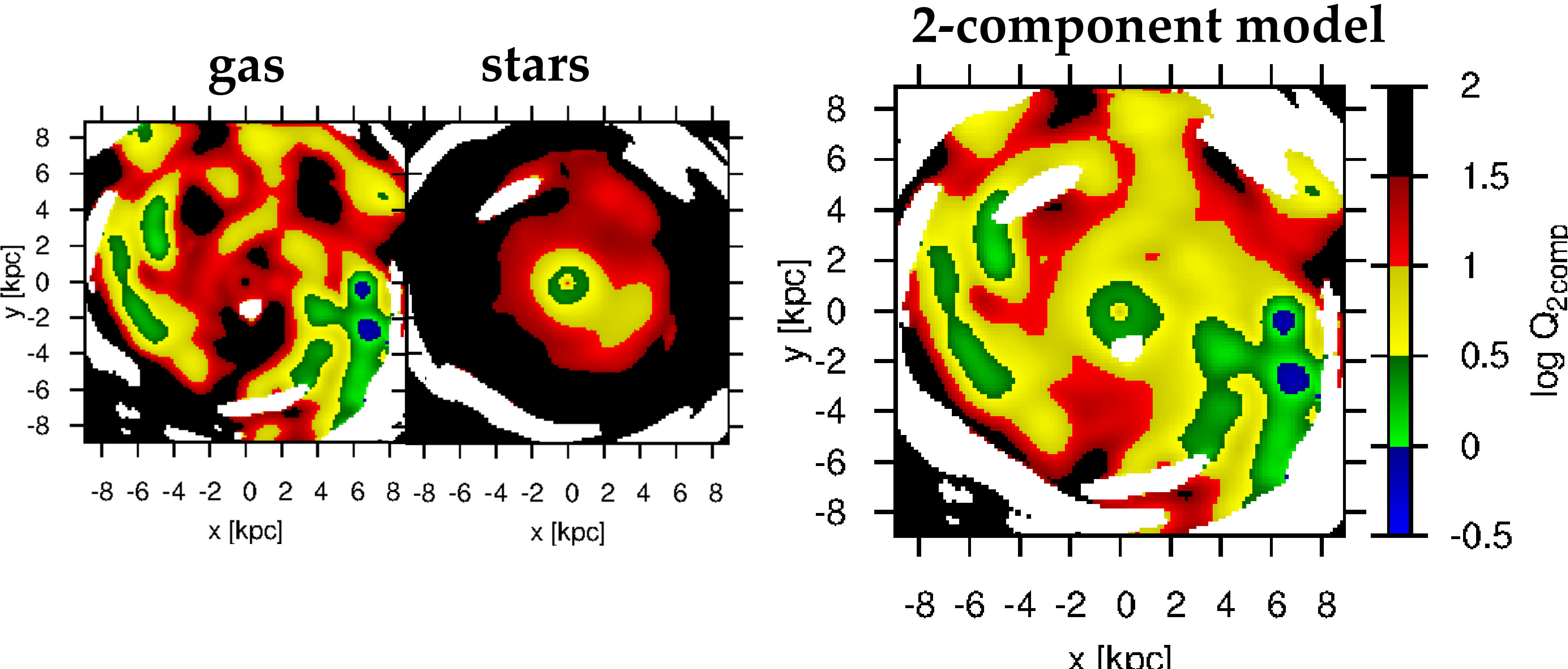
- Bulge stars are removed ; $\frac{v_\phi}{|v|} < 0.8$
- Gaussian smoothing is applied to all physical quantities.
  - with FWHM of 1.2 kpc



Results

The clumpy disc seems stable against Toomre instability…

- Q maps



Blue Q<1: linear instability, **Green** Q=1-3: non-linear and/or dissipative instability

Yellow, Red, Black: Q>3: stable state

White: imaginary κ (Q cannot be defined)

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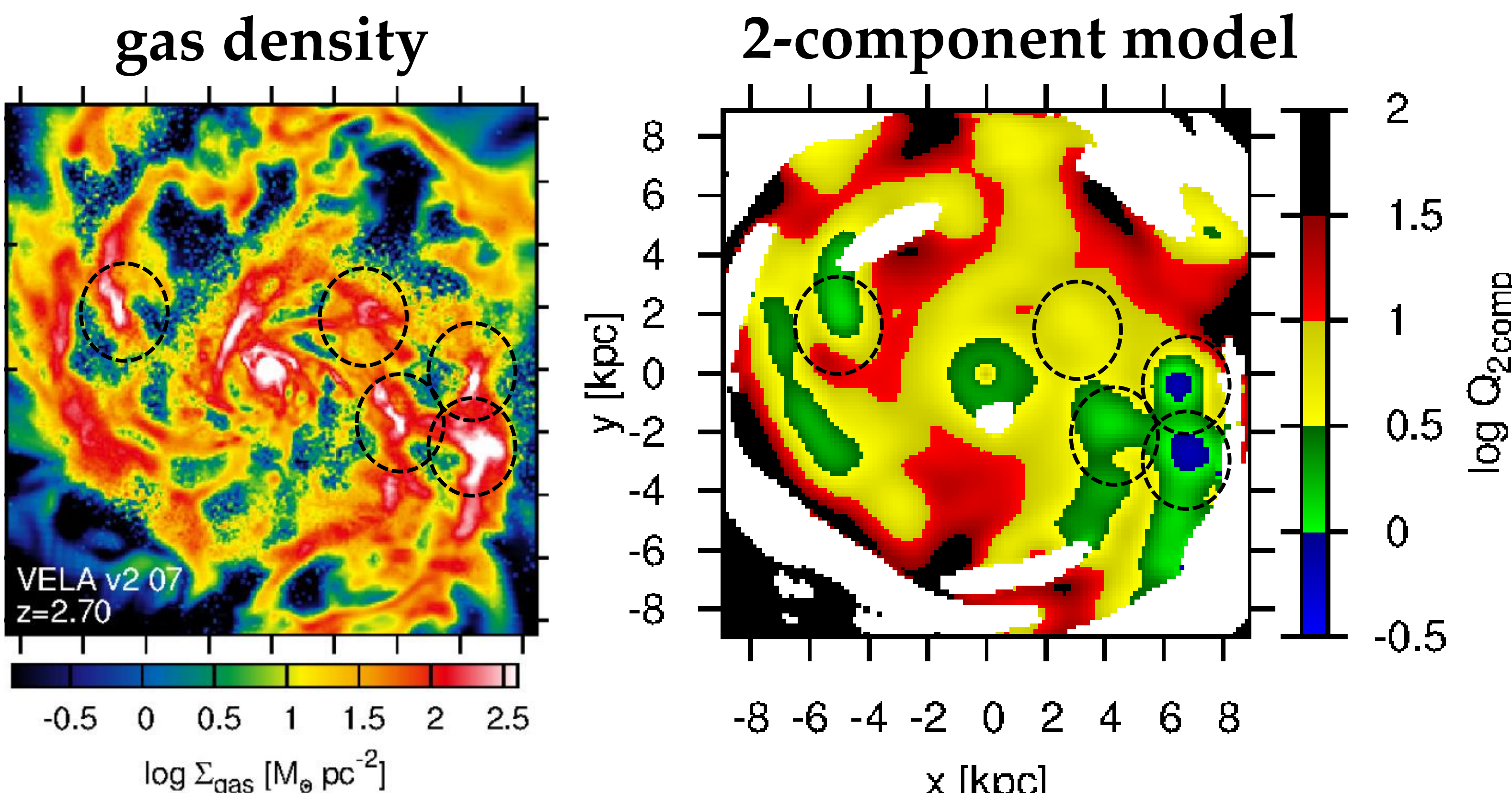

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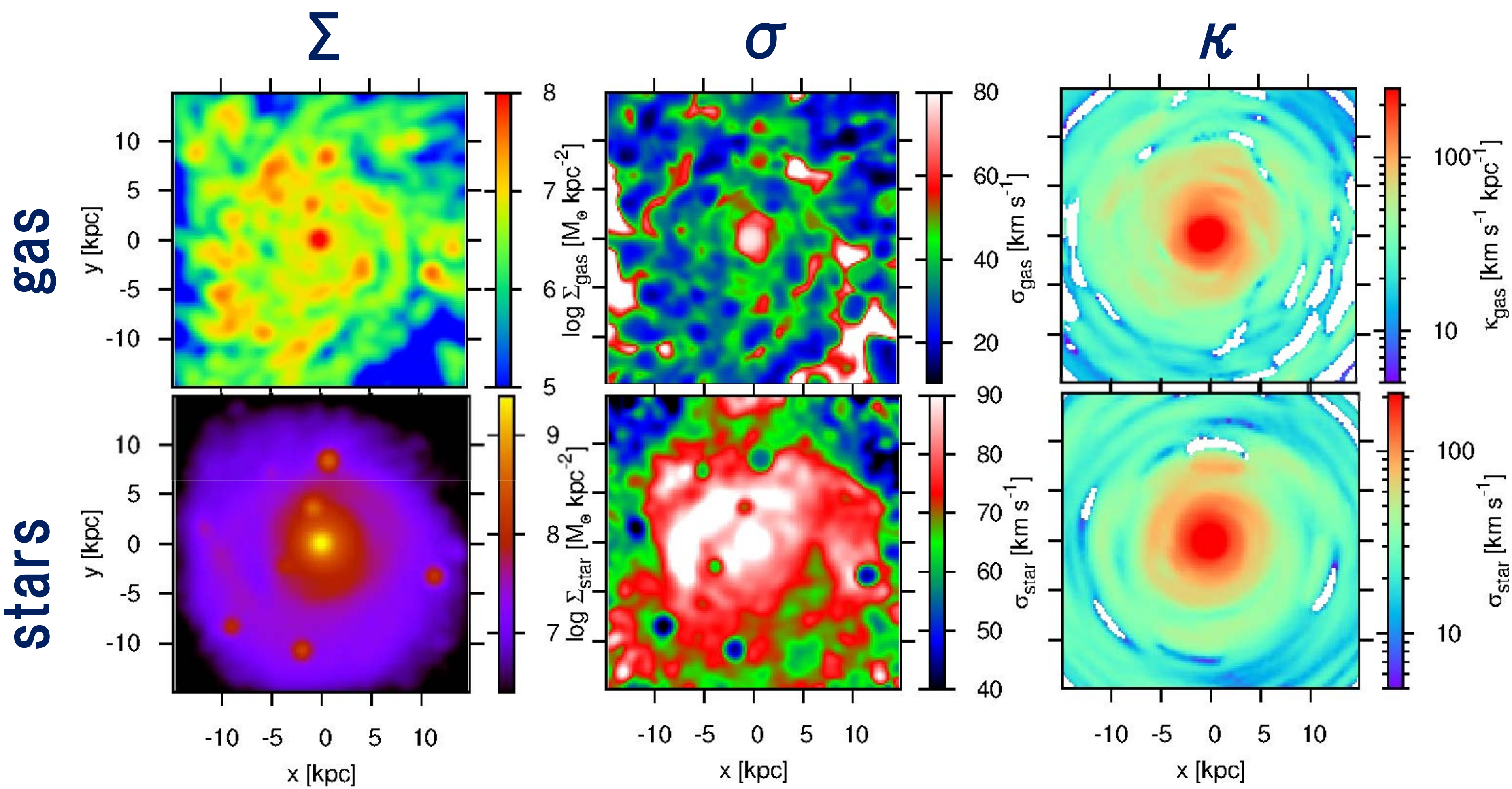
- the same galaxy
- at redshift z=1.13



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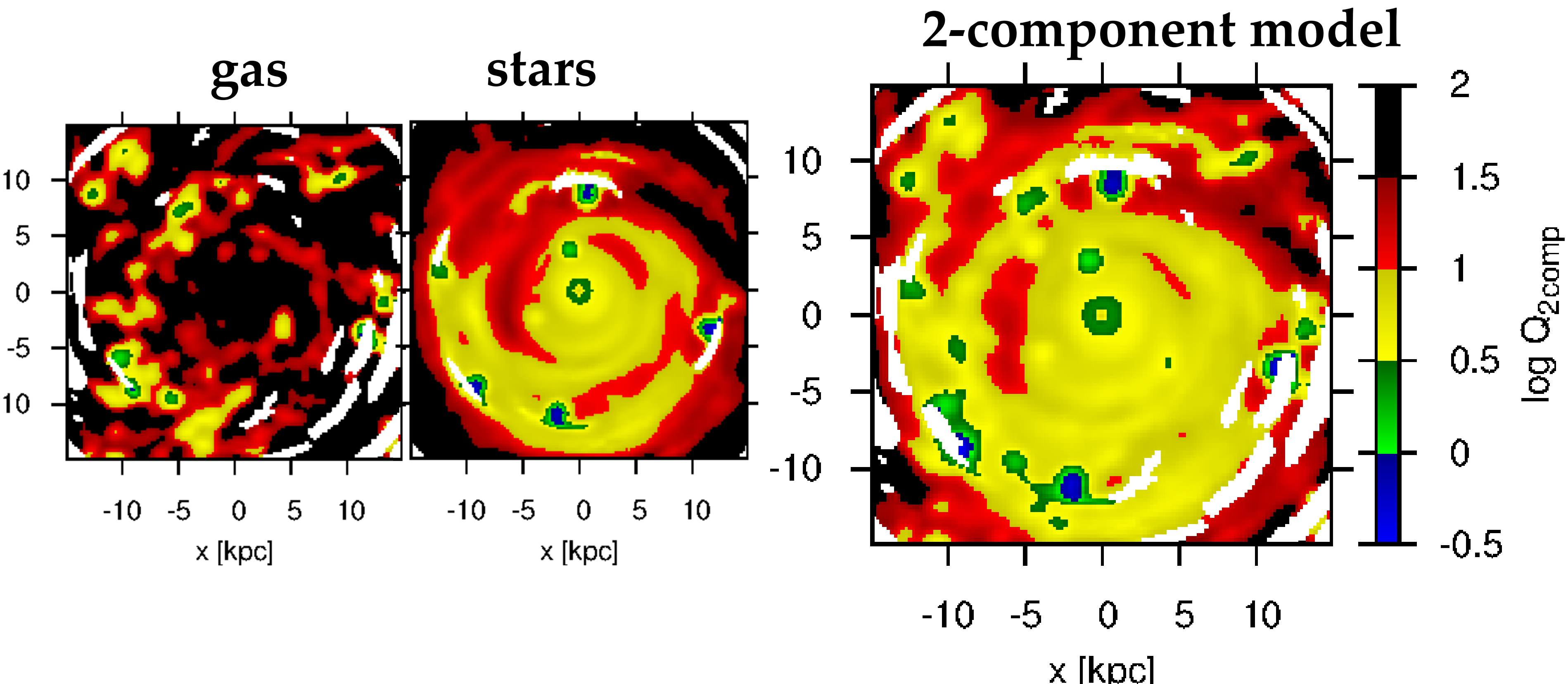

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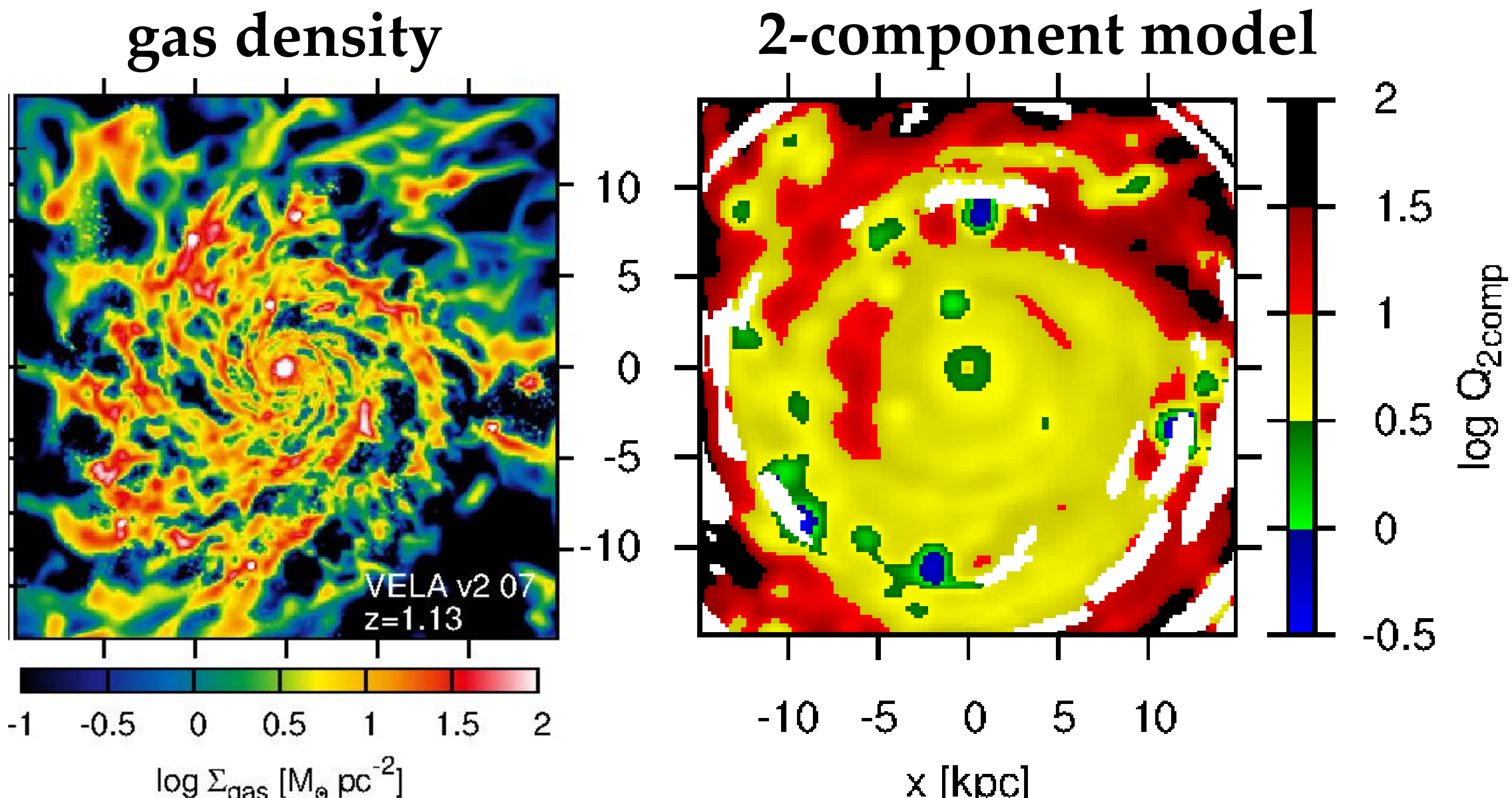

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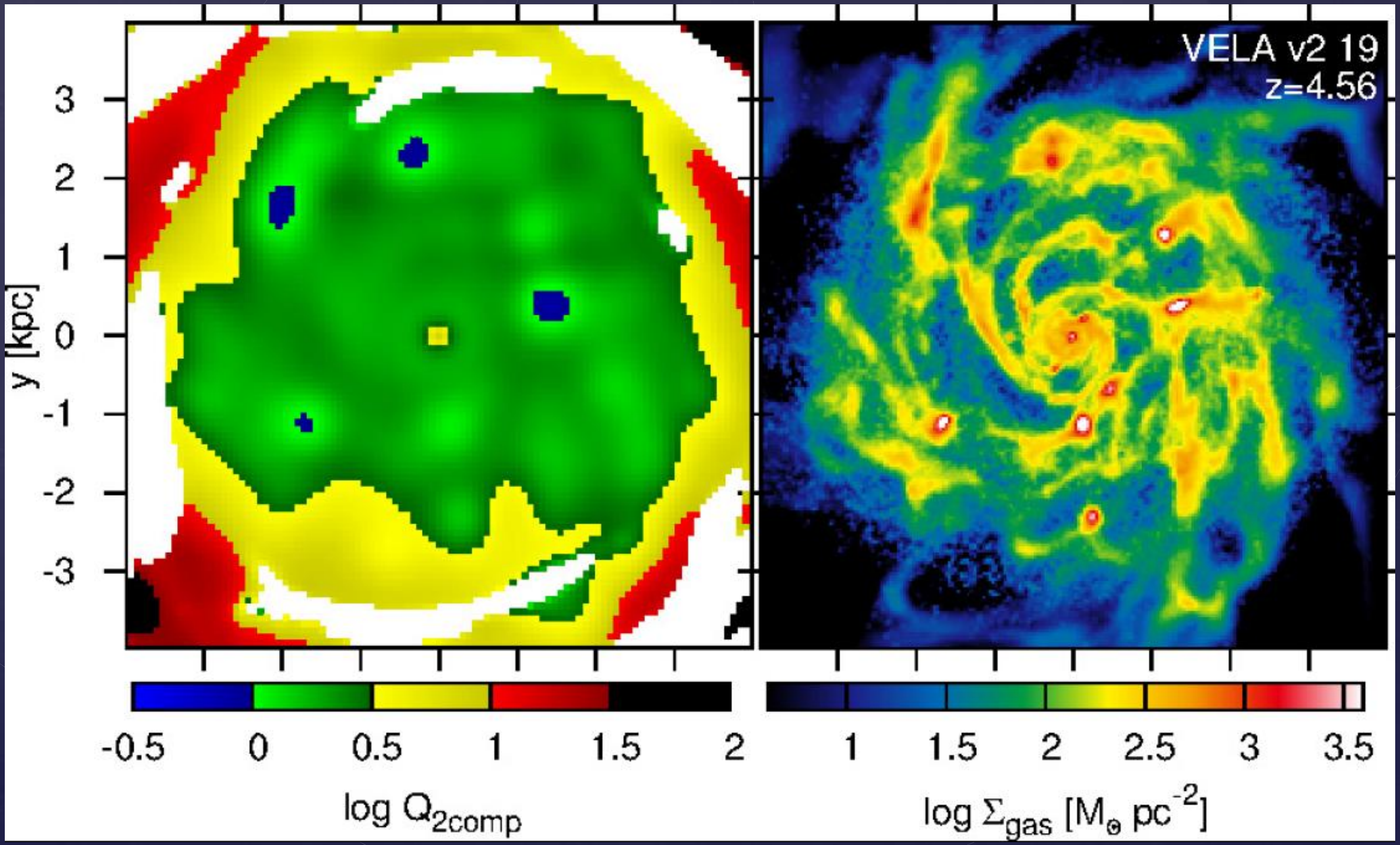
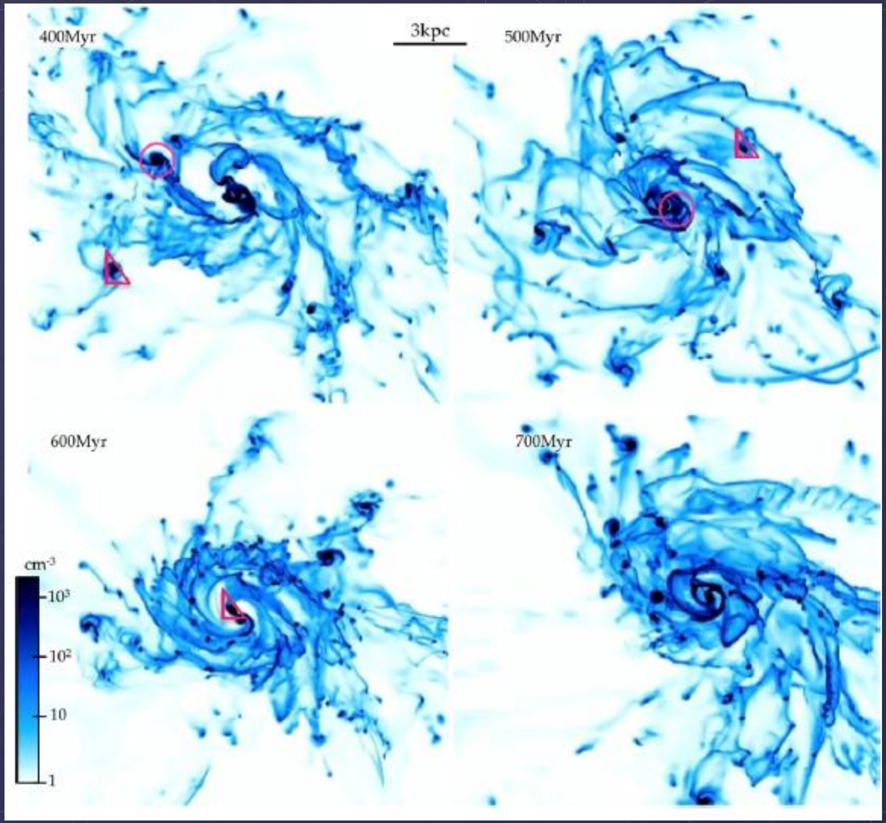
A case of the lowest Q

- at z=4.56
- disc size = 1-2 kpc



- What about Toomre Q in isolated simulations?



Bournaud et al. (2014)

- from the isolated simulations
  - Bournaud et al. (2014) using RAMSES code
    - 1pc-order resolution with radiation pressure.
    - Inititially, an exponential disc with a bulge in a halo.

- the isolated galaxy

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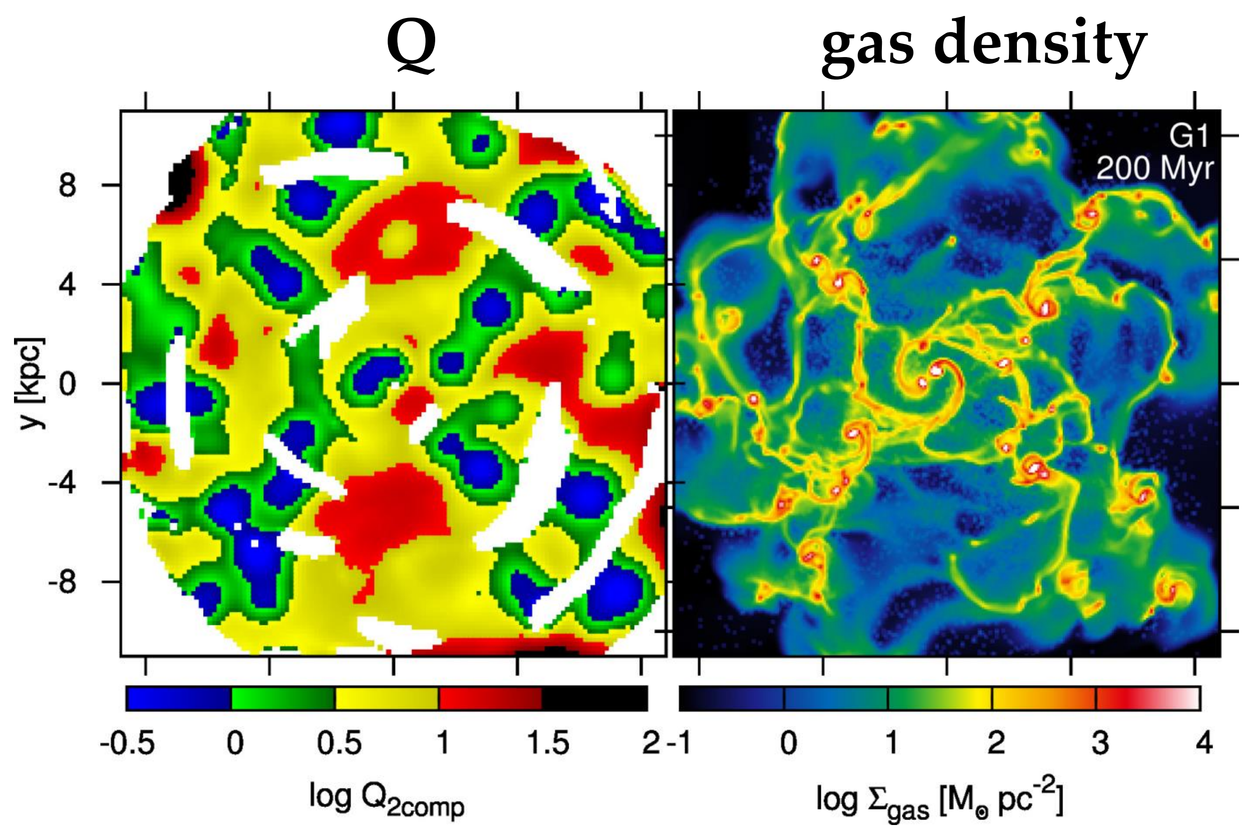

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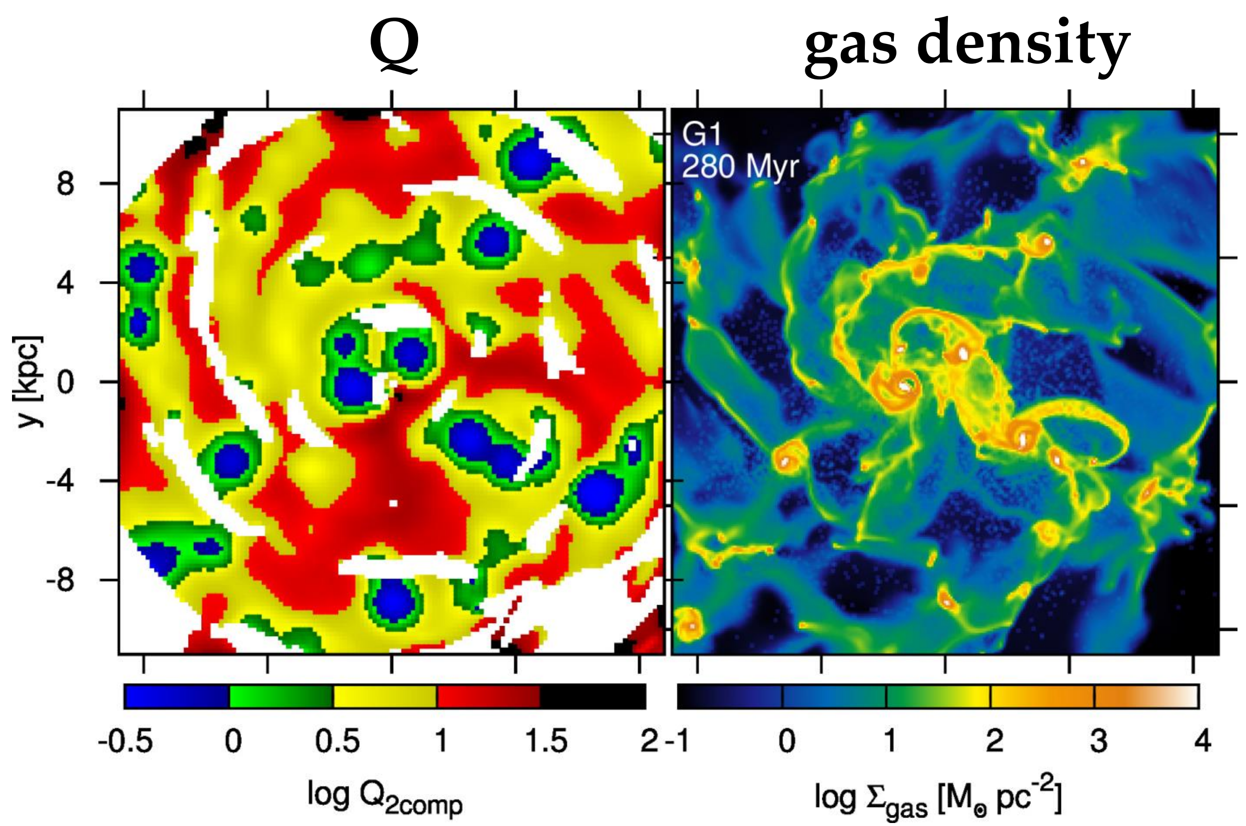

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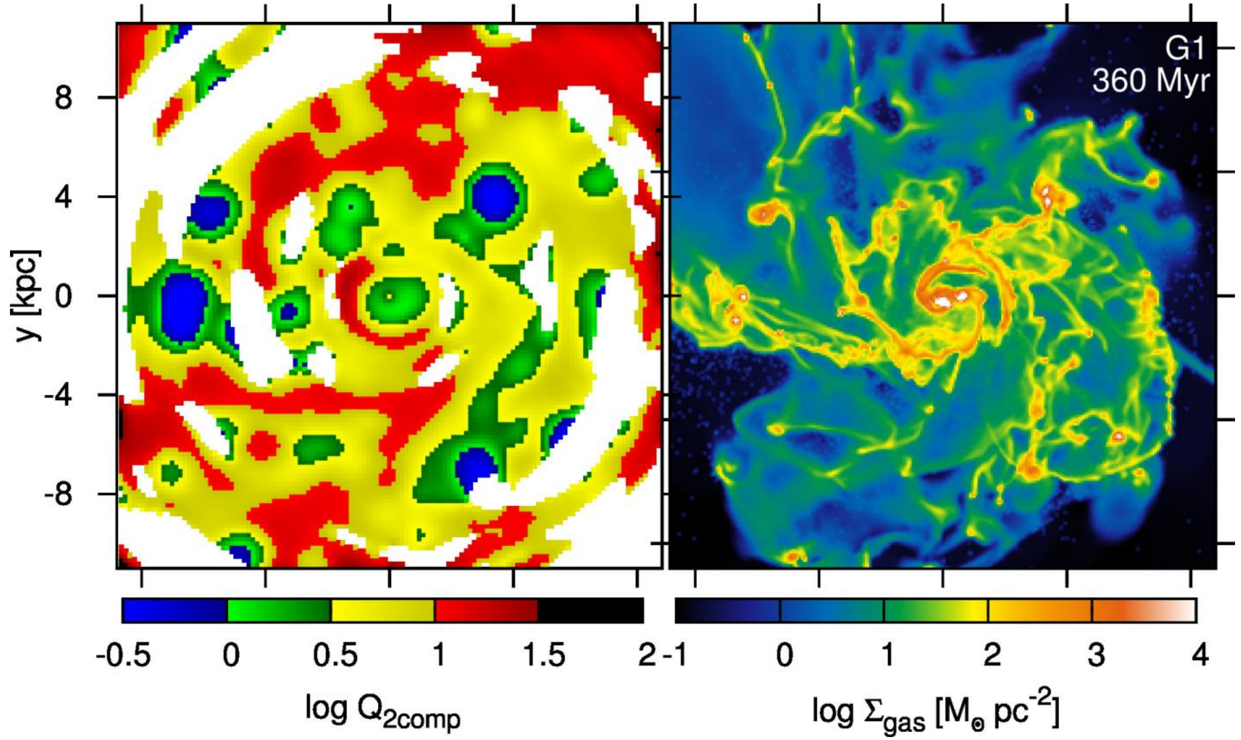
Q **gas density**



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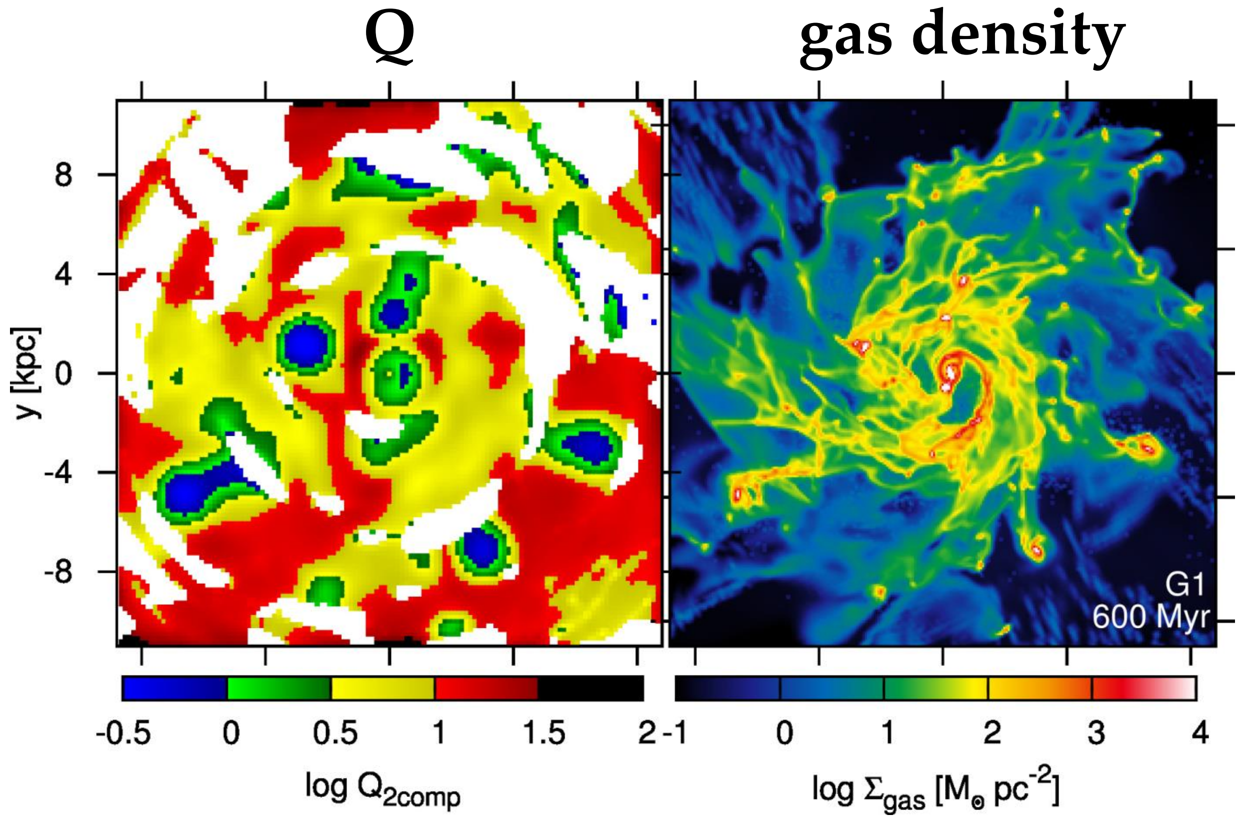

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Overestimate?

- **Disc thickness?**
  - Thickness can stabilize a disc, but we did not apply thickness correction.
  - So, our results would still be **underestimating** Q.
- **How to determine κ ?**
  - κ was determined from mean rotation vel. of star/gas.
  - Circular vel. is also often used.
  - But, generally the mean rotation leads to **lower Q**.
- **How does a bulge affect?**
  - Bulge stars were removed from our analyses.
  - Inclusion of the bulge can increase Q by **～30% at the largest.**

Conclusion 1

- High-z observations for clumpy discs have shown Q<1.
- However, numerical simulations indicate typically Q>1.

- Probably…
  - **Observations are overestimating gas density…?**
    - Gas density was converted from Hα in Genzel et al. (2011,2014)

and/or

  - **Simulations are not compatible with the real galaxies…?**
    - The simulations have lower gas fraction and SFR than the observations.

Conclusion 2

- Clumpy discs indicate Q>1 in our simulations.
- But, actually clumps are forming in the discs.
  - regardless of cosmological/isolated simulations

- Probably…
  - **The criterion of Q=1 may not be accurate.**
    - For example, Toomre analysis assumes axisymmetric perturbation.

and/or

  - **Clump formation may be triggered by external stimuli.**
    - due to tidal force and/or turbulence, etc…?

Summary

- The clumpy nature and formation of giant clumps in high-z disc galaxies have been thought to be triggered by Toomre instability ($Q \lesssim 1$).
- Current observations support $Q<1$.

- In simulations, however, $Q>1$ in disc regions.
  - Observations may be overestimating gas densities?
  - Simulations still cannot reproduce real galaxies?

  - In the sims, $Q<1$ can be seen only inside and around clumps.
  - The criterion of $Q=1$ may not be accurate.
  - Formation of giant clumps may not be purely due to Toomre instability.
    - Maybe due to tidal force and/or turbulence, etc…