“Non-linear violent disc instability with high Toomre’s Q in high-redshift clumpy disc galaxies”

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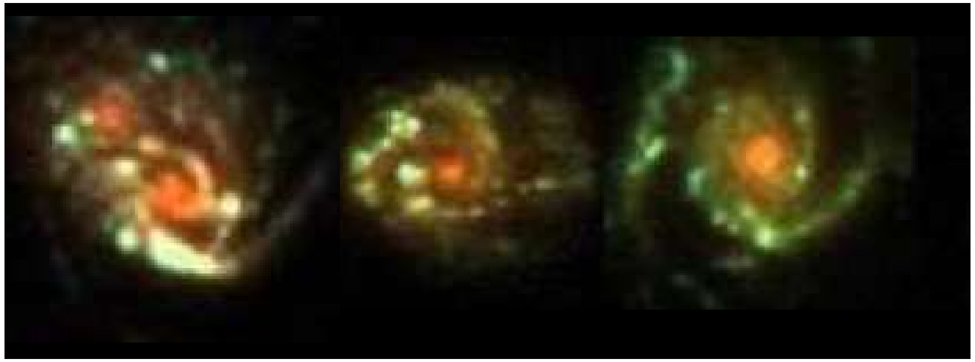
w/ Avishai Dekel, Nir Mandelker, Daniel Ceverino,

Frederic Bournaud, Joel Primack

Clumpy galaxies

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

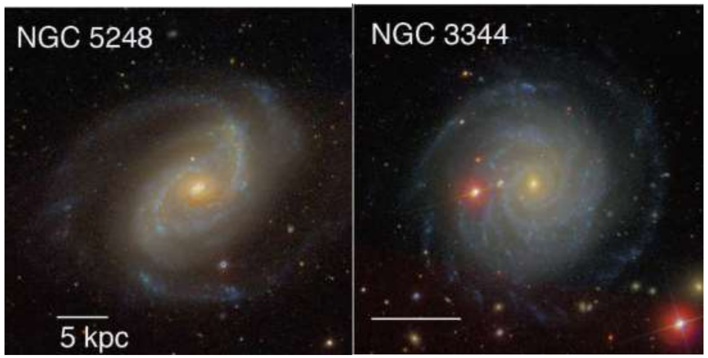
in the high-z



with HST Guo et al. (2014)

$\sim 10^9$ yr

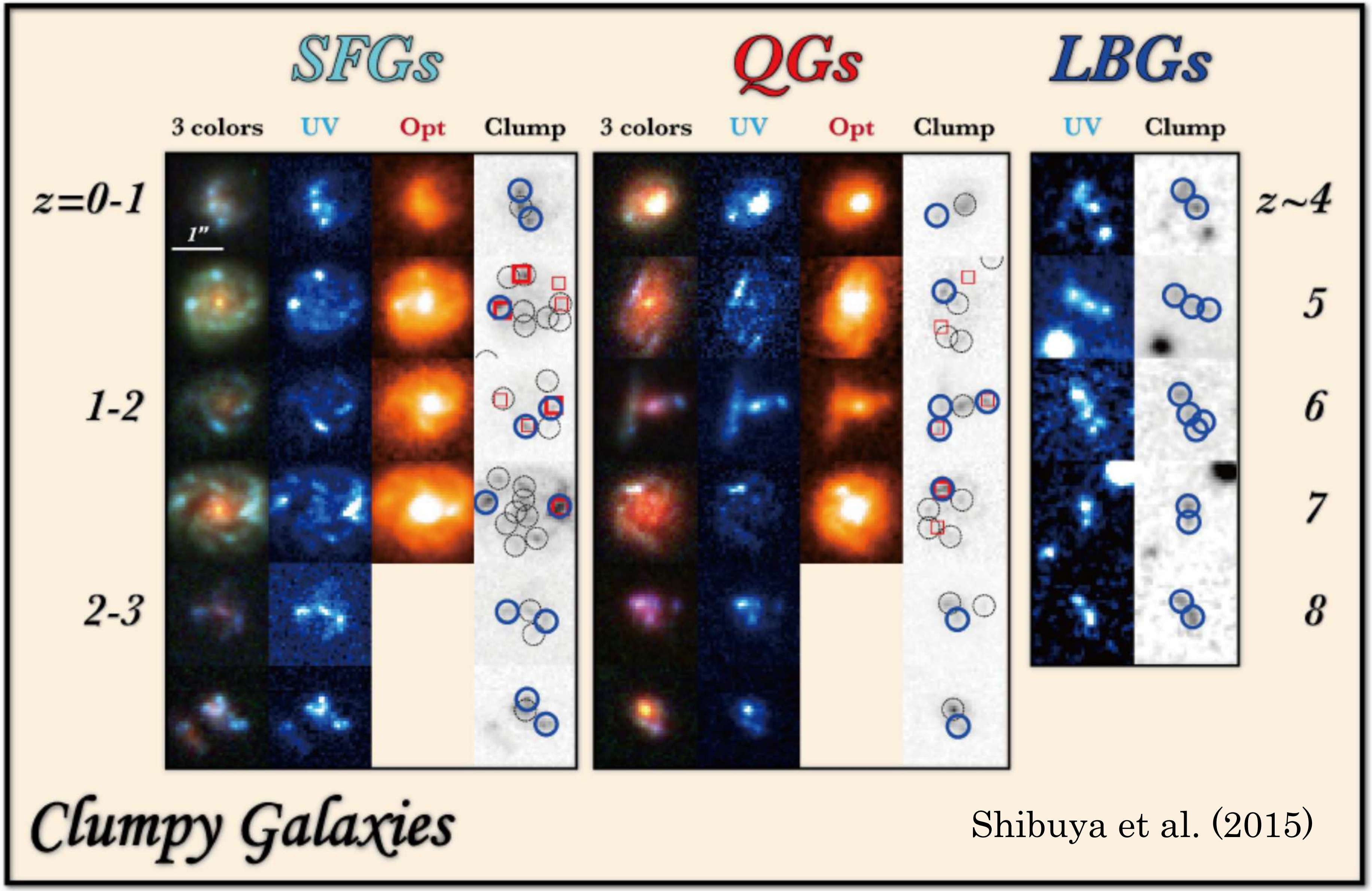
in the local universe



Elmegreen et al. (2013)

- \`Clumpy' galaxies are formation stages of disc galaxies.
  - \`Giant clumps' (~ 10^9 $M_\odot$ at the largest)
  - Clumpy galaxies account for ~ 30-60 % in z=1-3
    - Tadaki+14, Murata+14, Livermore+15, Guo+15, Shibuya+15

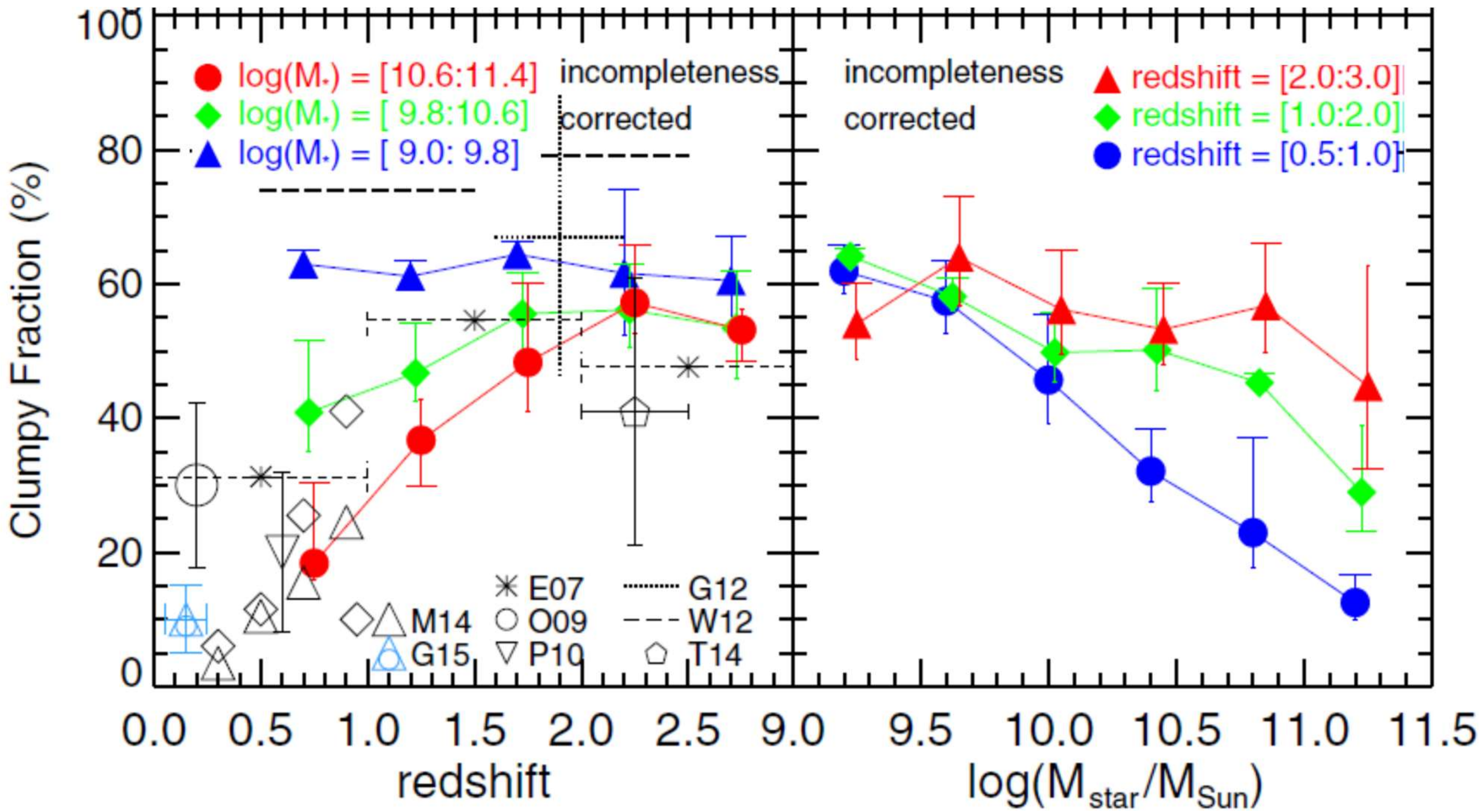
Clumpy galaxies



Clumpy fraction of galaxies

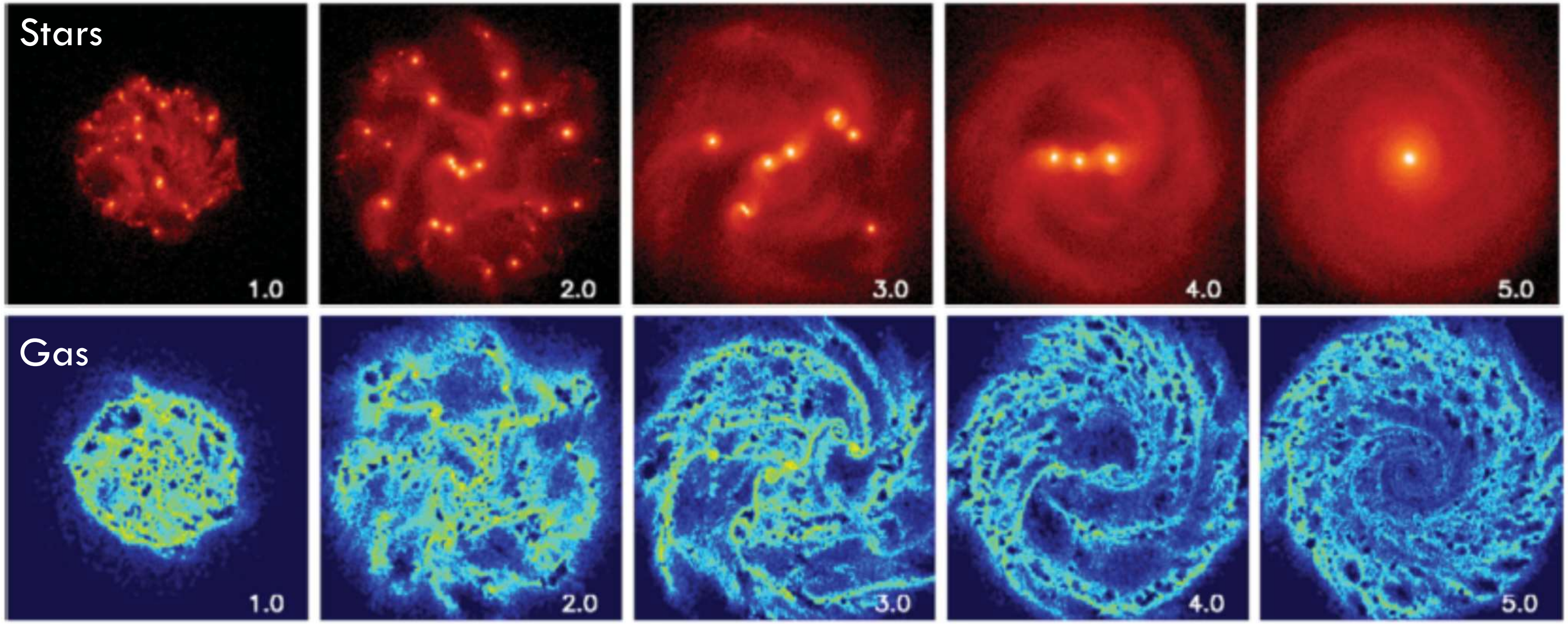
- Clumpy galaxies account for ~ 30-50 % in z=1-3
  - Tadaki+14, Livermore+15, Guo+15, Shibuya+15

Guo et al. (2015)



Why are they clumpy?

- It has been proposed;
  - Galaxies are highly gas-rich (stream-fed) in their early formation stages.
  - Cold gas discs in the galaxies are Toomre unstable (Noguchi 1998, 1999).
  - <u>Clump formation is caused by 'Toomre instability'</u>



Inoue & Saitoh (2012)

Toomre instability

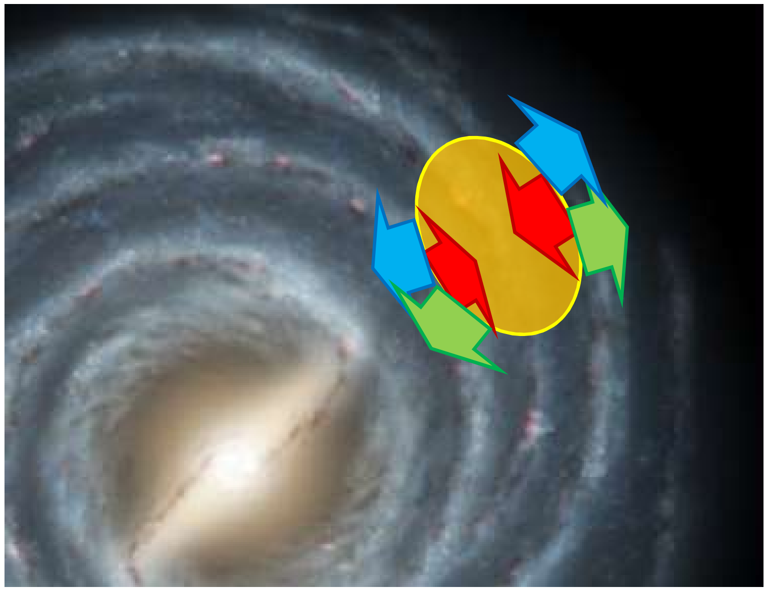
- From a local and linear perturbation theory for axisymmetric perturbations,

Velocity dispersion or sound speed (pressure)

Epicyclic frequency (Coriolis force)

<u>The stability condition</u>: $$Q \equiv \frac{\sigma \kappa}{\pi G \Sigma} > 1$$

Surface density (gravity)



If Q<1, the local region is gravitationally unstable, going to collapse.

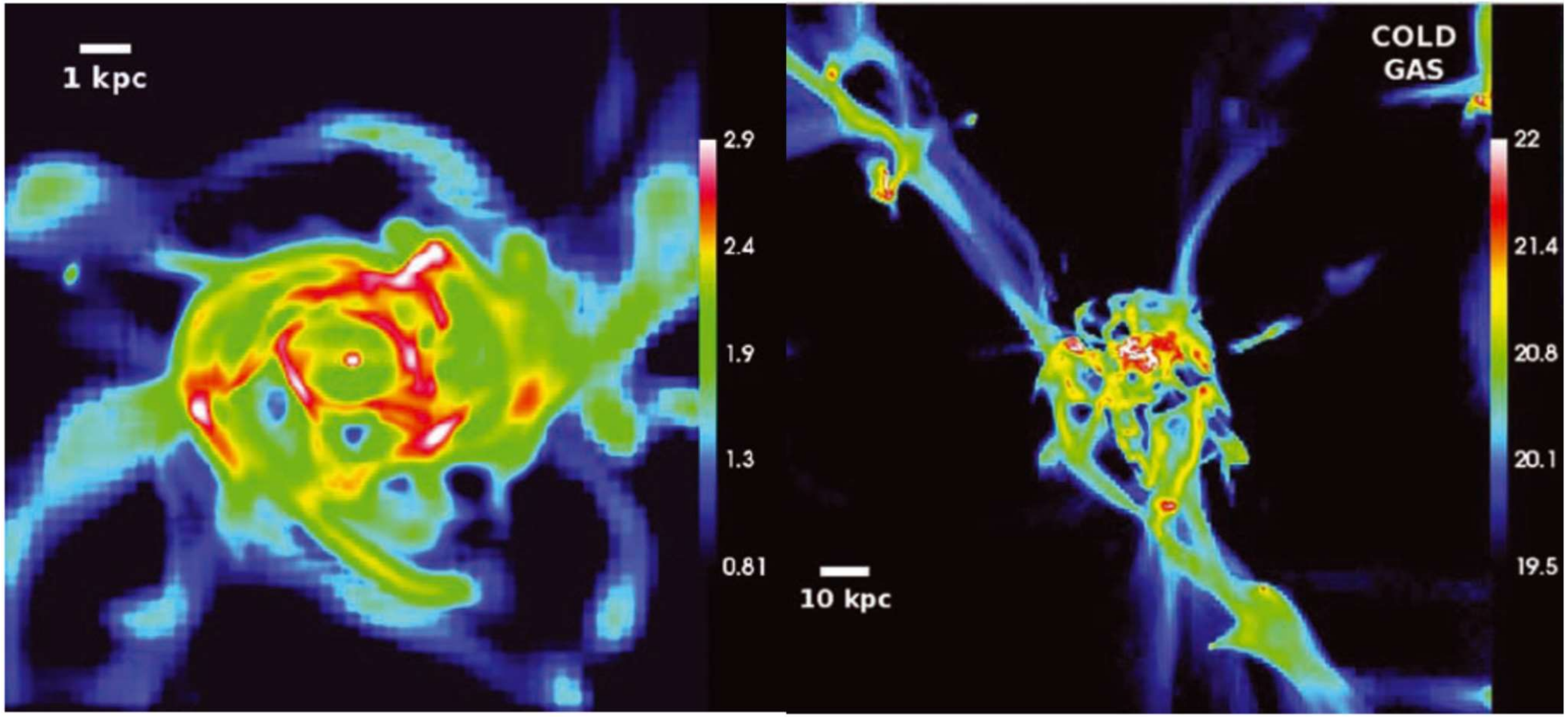
Toomre instability

- From a **local** and **linear** perturbation theory for **axisymmetric** perturbations

- But, actually
  - Global effect may work for instability.
  - Perturbations may grow non-linearly.
  - Perturbations may be non-axisymmetric.

- Galaxies in cosmological context may deviate from the “idealized” situation.

Toomre analysis in cosmological sims.



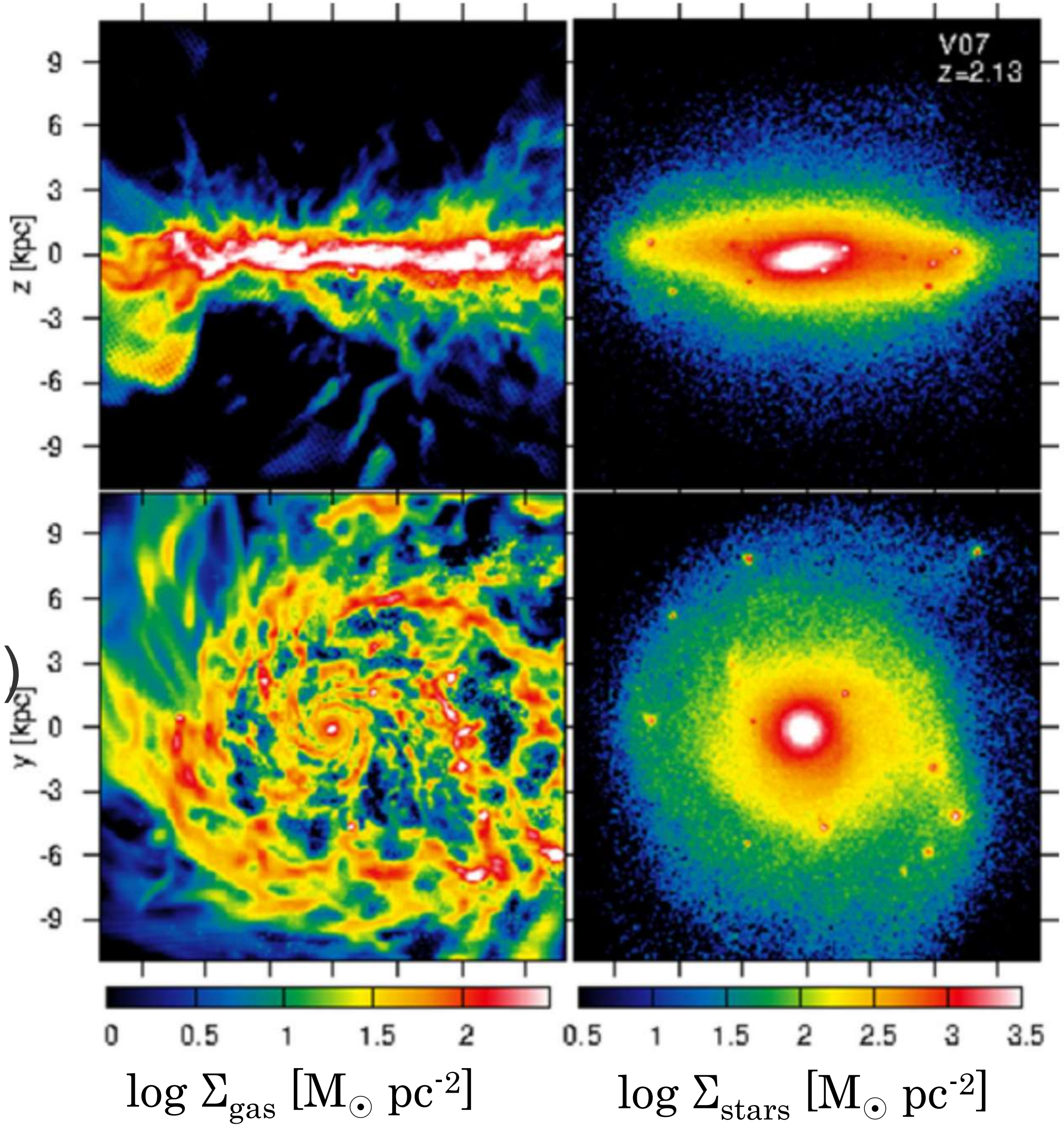
- Cosmological simulations
  - Ceverino et al. (2010, 2013) using ART code
    - 10pc-order resolution with radiation pressure.

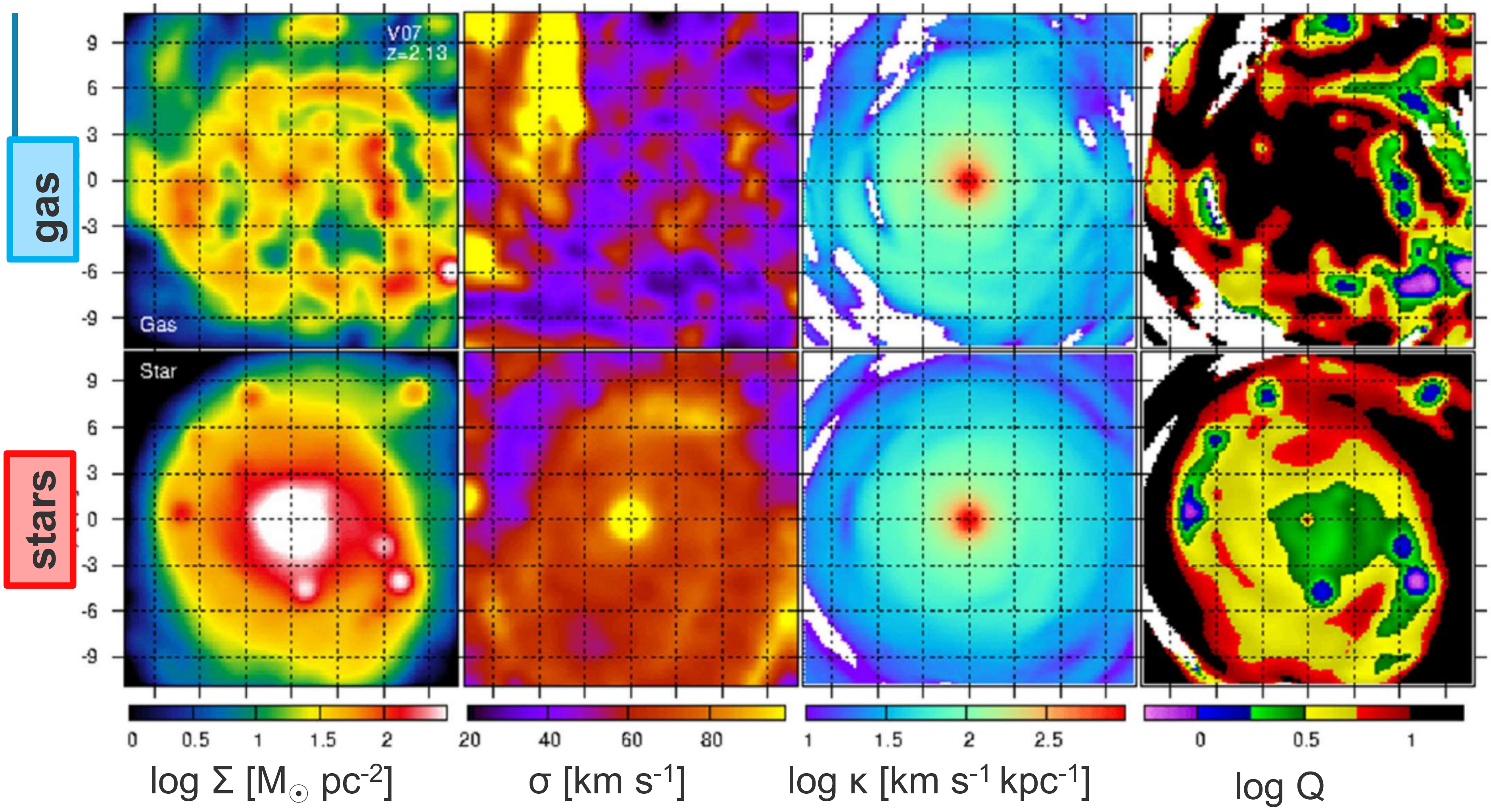
How to measure Q_{2comp}

- <u>2-component model</u> (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 velocity dispersion (not sound speed).
  - κ is calculated from mean velocity fields of gas/star.
    - $\kappa \equiv \sqrt{2\frac{<v_\phi>}{R}\left(\frac{d<v_\phi>}{dR} + \frac{<v_\phi>}{R}\right)}$
  - Young stars (age<100 Myr) are considered to be "gas "
  - Bulge stars are removed ; $j_z/j_{max} < 0.7$
  - Gaussian smoothing with FWHM=1.2 kpc
    - to focus on $M_{clump} = 10^{8-9}$ $M_\odot$
  - A razor-thin disc model (which gives lower limits)

Cosmological simulations

- V07
  - $z = 2.13$
  - $M_{vir} = 8.8 \times 10^{11}$ $M_{\odot}$
  - $M_{star} = 5.6 \times 10^{10}$ $M_{\odot}$
  - $f_{gas} = 0.18$
  - $B/T = 0.37$ (kinematic)
  - $SFR = 27.5$ $M_{\odot}$ yr^{-1}





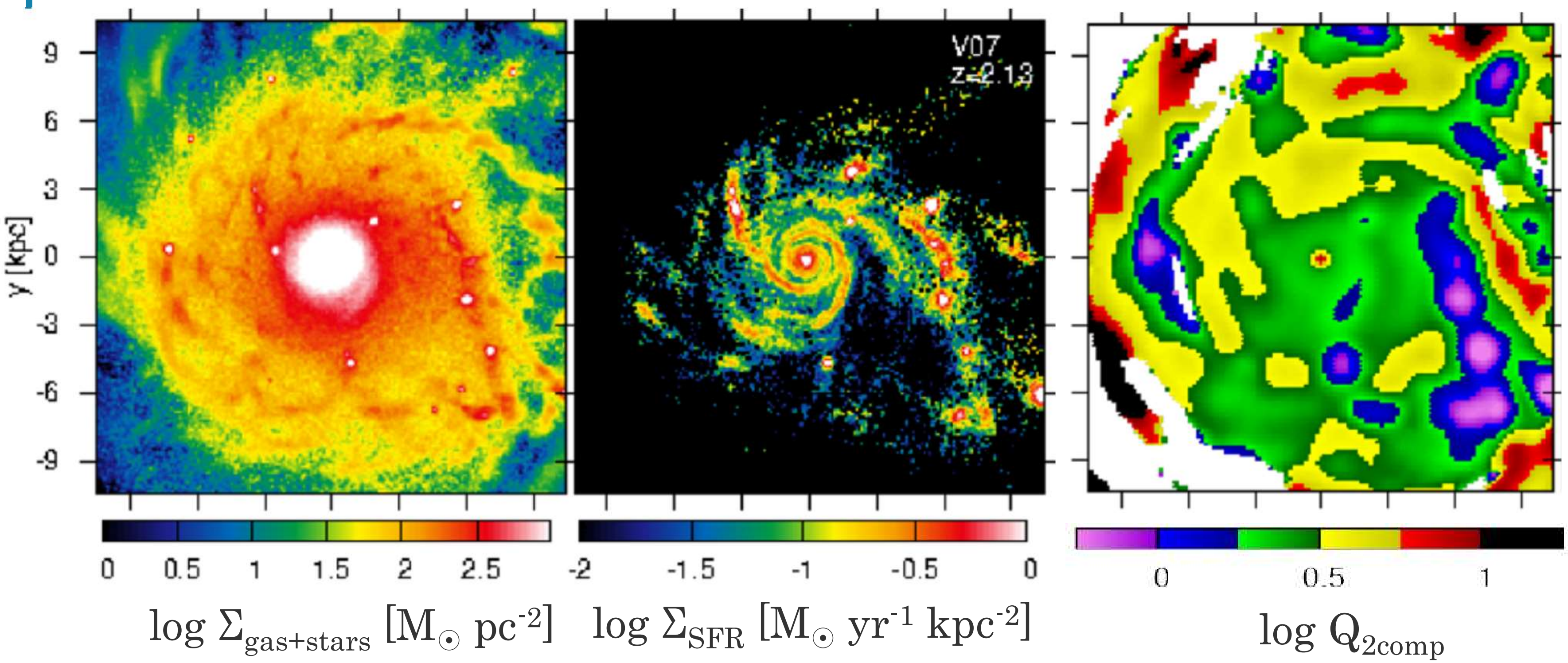
Purple Q<1: linear instability

Blue Q=1-1.8: non-linear instability

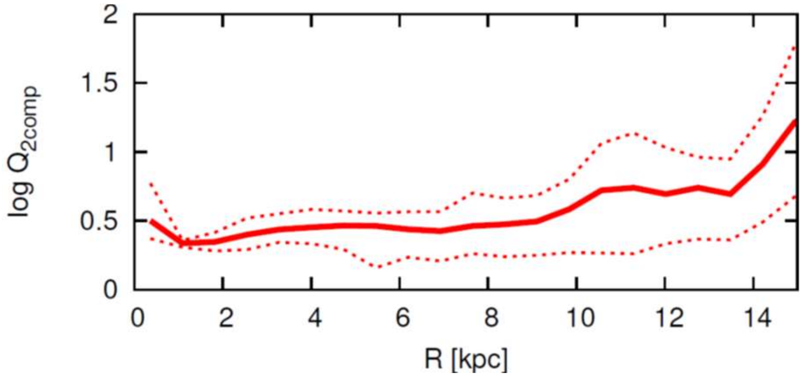
Green Q=1.8-3: dissipative instability

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

White: imaginary κ (Q cannot be defined)



- **Instability (Q<1) can only be seen in/around the clumps.**
- **Disc (inter-clump) regions seem to be stable (Q>2).**



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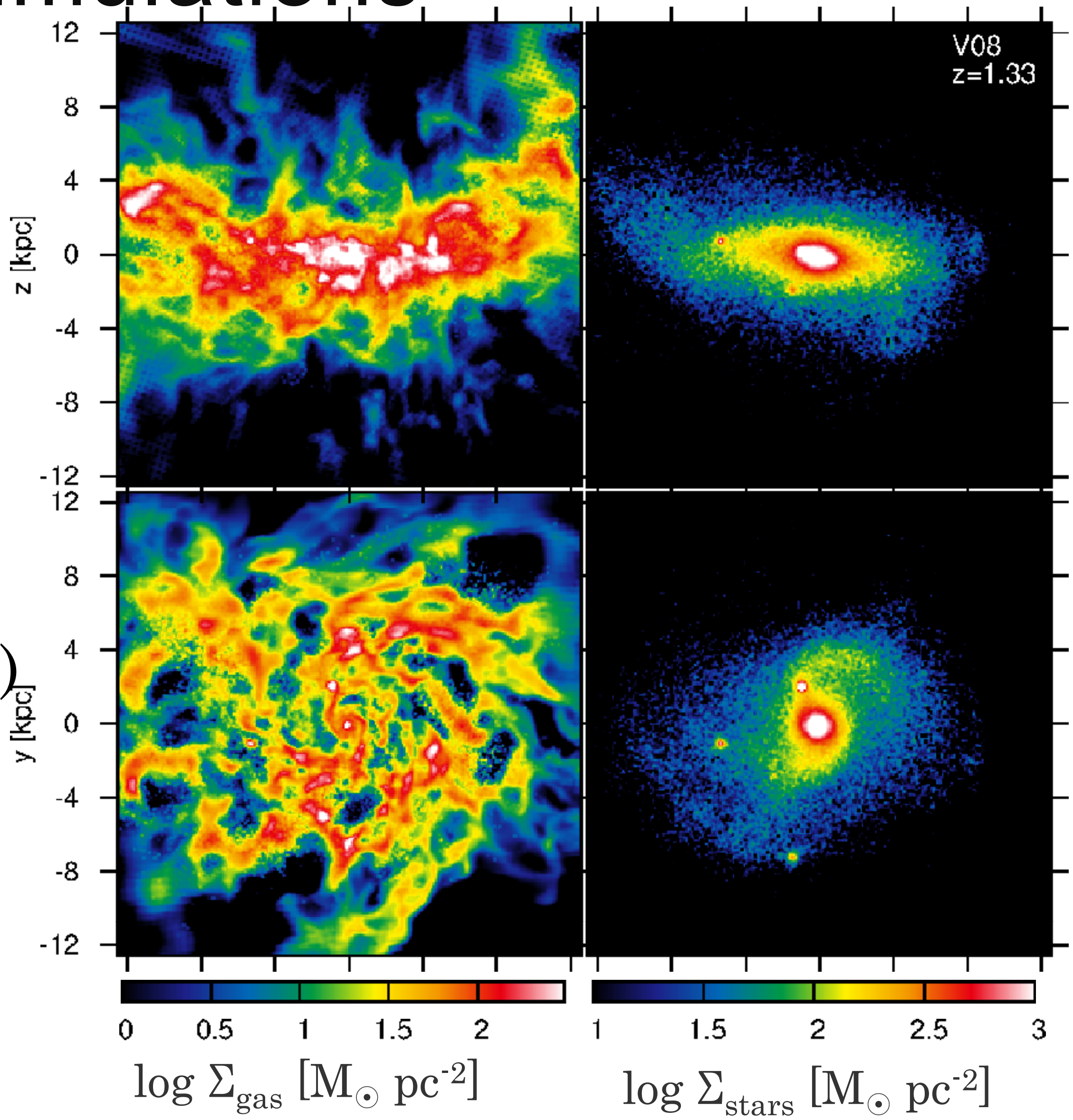
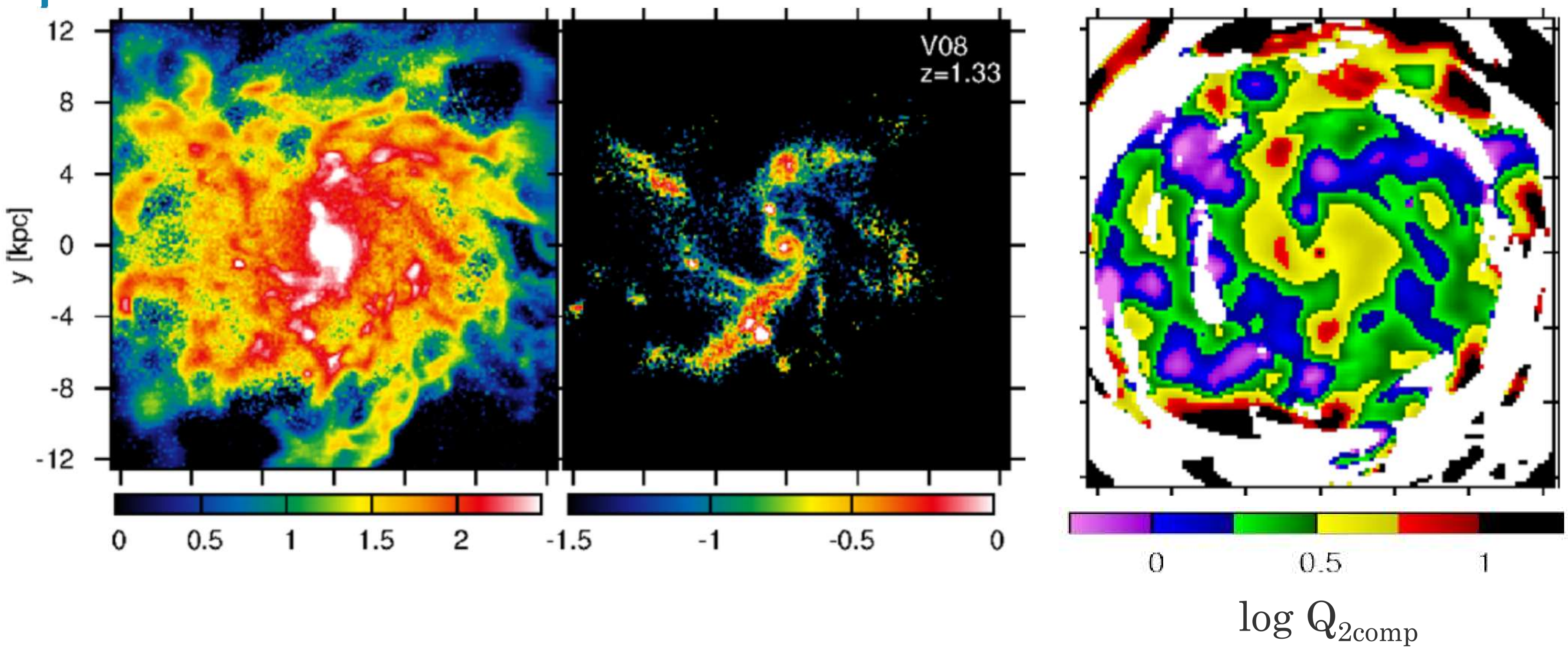
Cosmological simulations

- V08
  - $z = 1.33$
  - $M_{vir} = 6.0 \times 10^{11}\ \mathrm{M}_\odot$
  - $M_{star} = 1.9 \times 10^{10}\ \mathrm{M}_\odot$
  - $f_{gas} = 0.42$
  - $B/T = 0.45$ (kinematic)
  - $SFR = 33.1\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$





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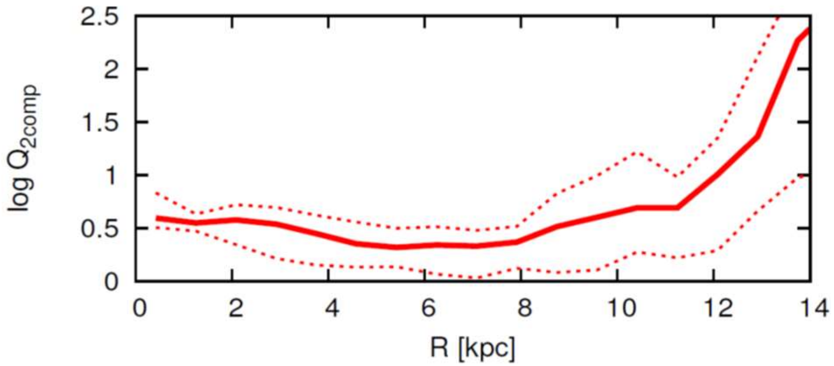

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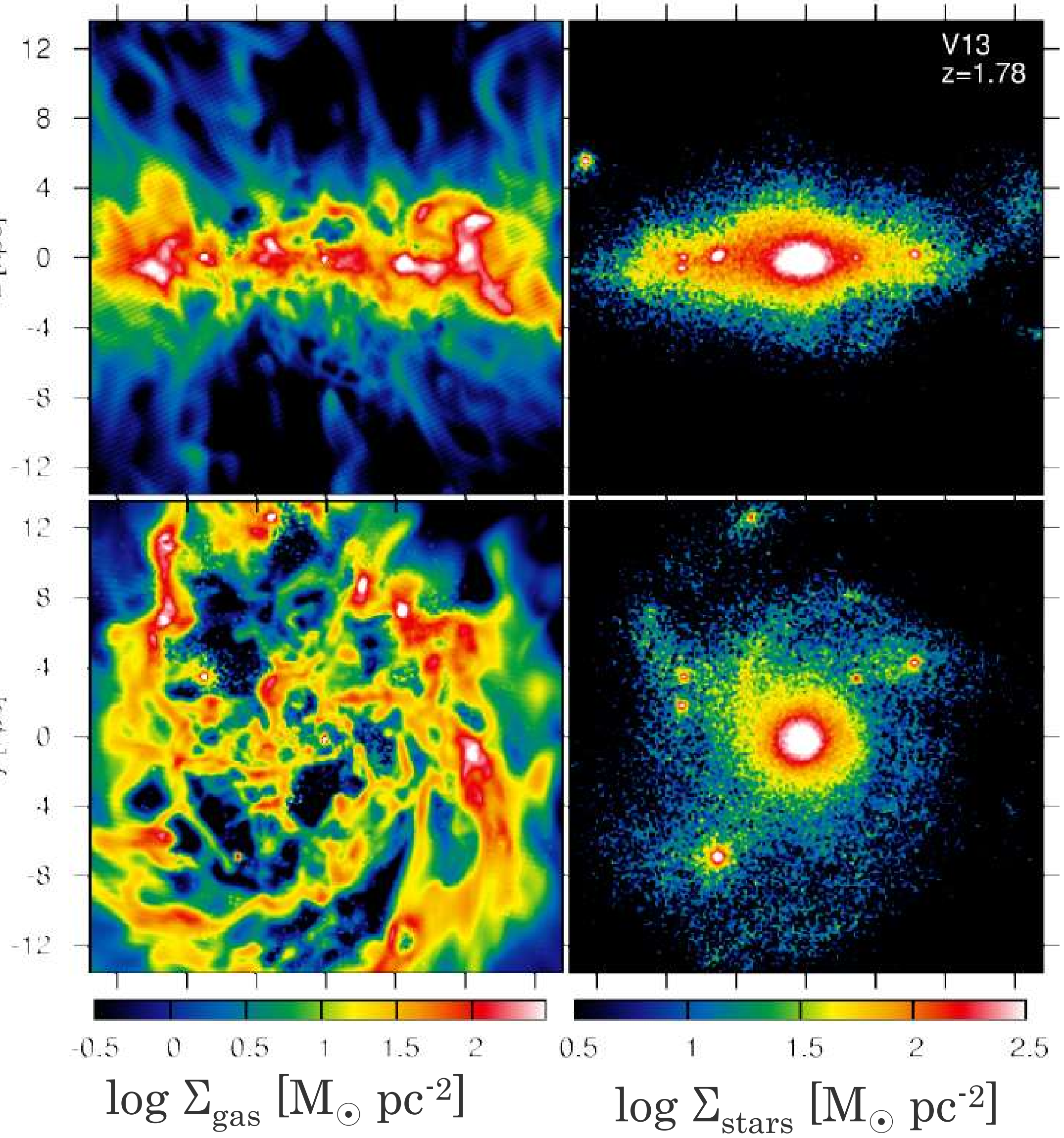
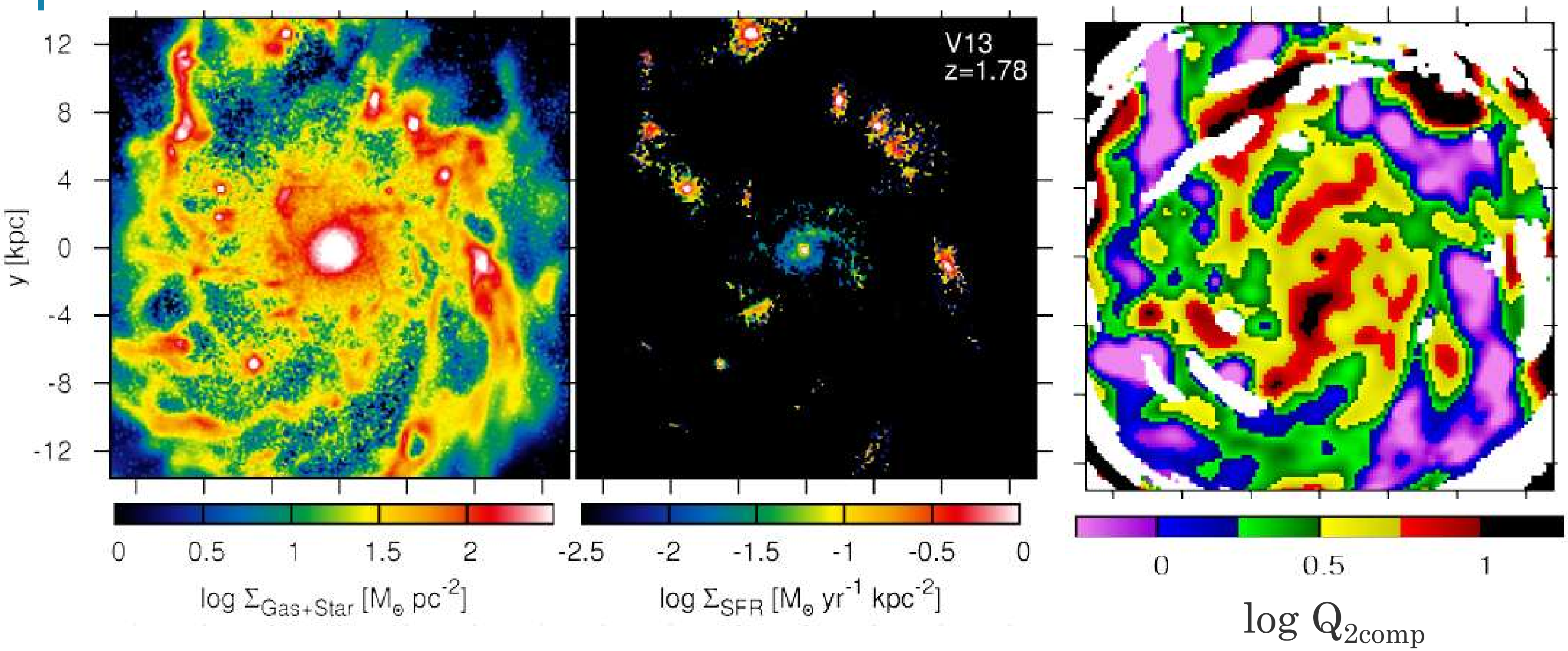
Cosmological simulations

- V13
  - $z = 1.78$
  - $M_{vir} = 3.4 \times 10^{11}\ \mathrm{M}_\odot$
  - $M_{star} = 1.2 \times 10^{10}\ \mathrm{M}_\odot$
  - $f_{gas} = 0.40$
  - $B/T = 0.46$ (kinematic)
  - $SFR = 11.2\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$





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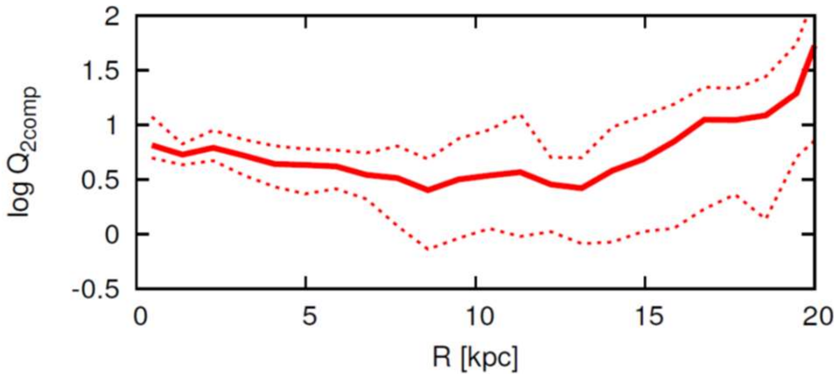

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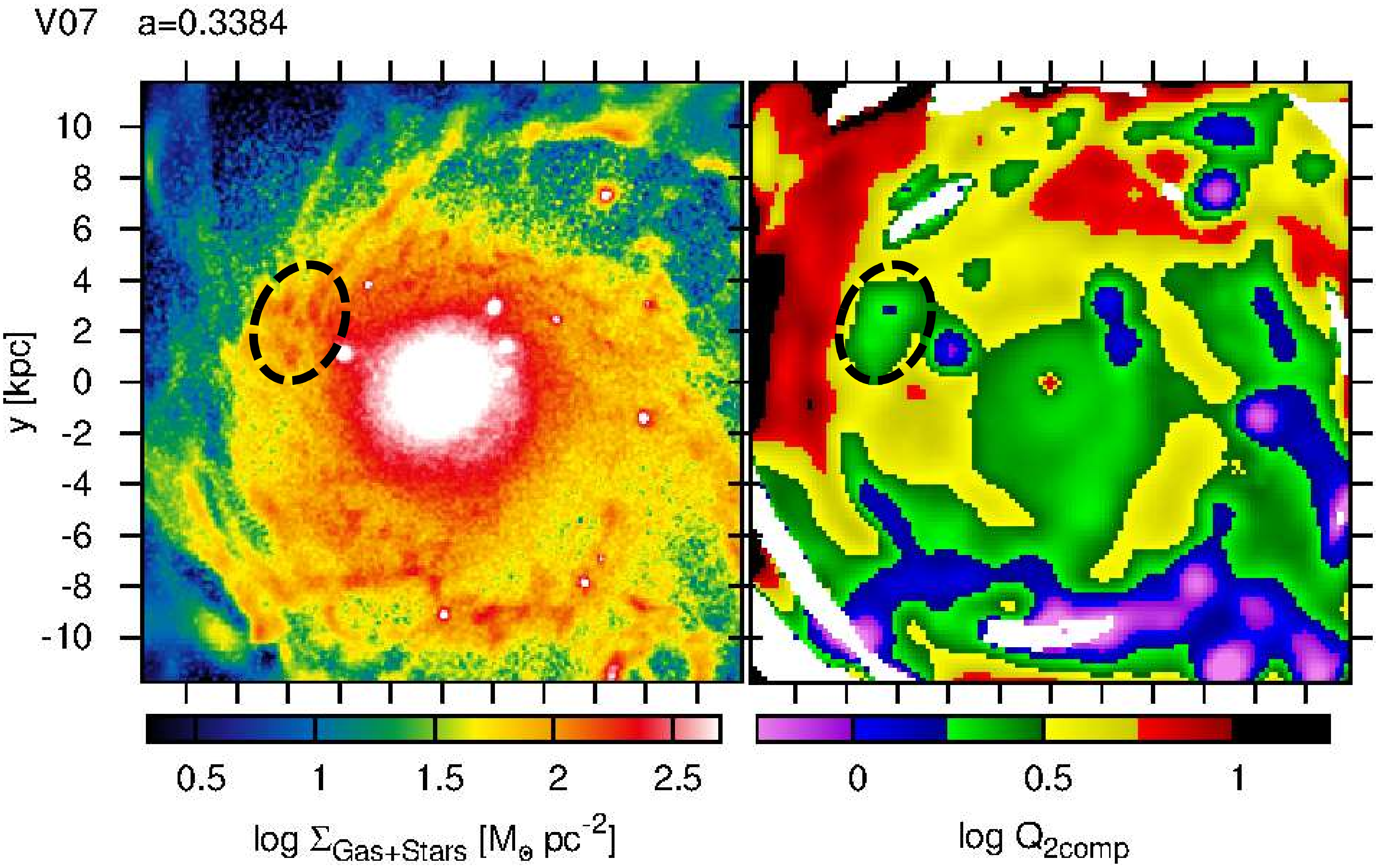
Non-linear formation of clumps



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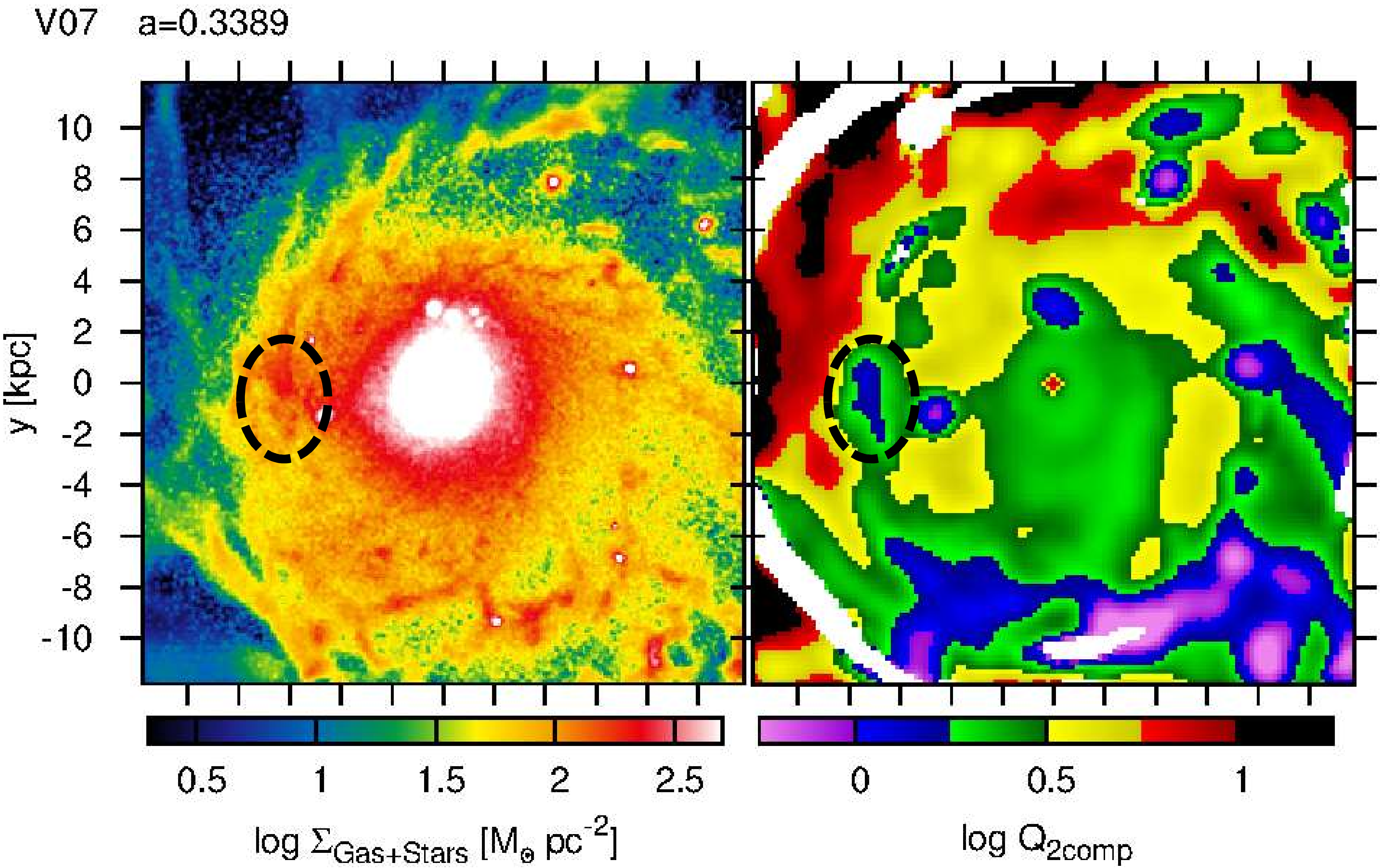

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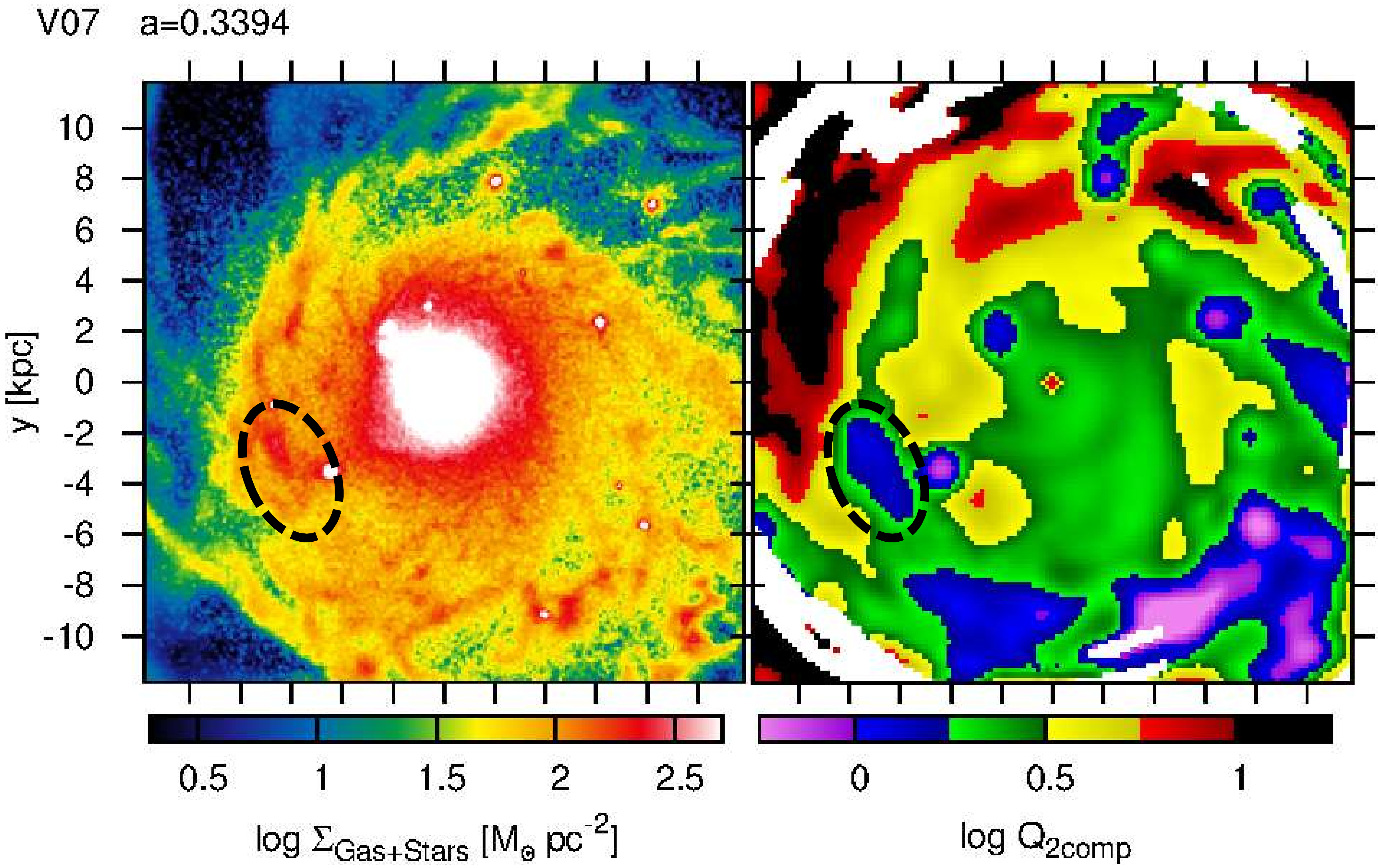

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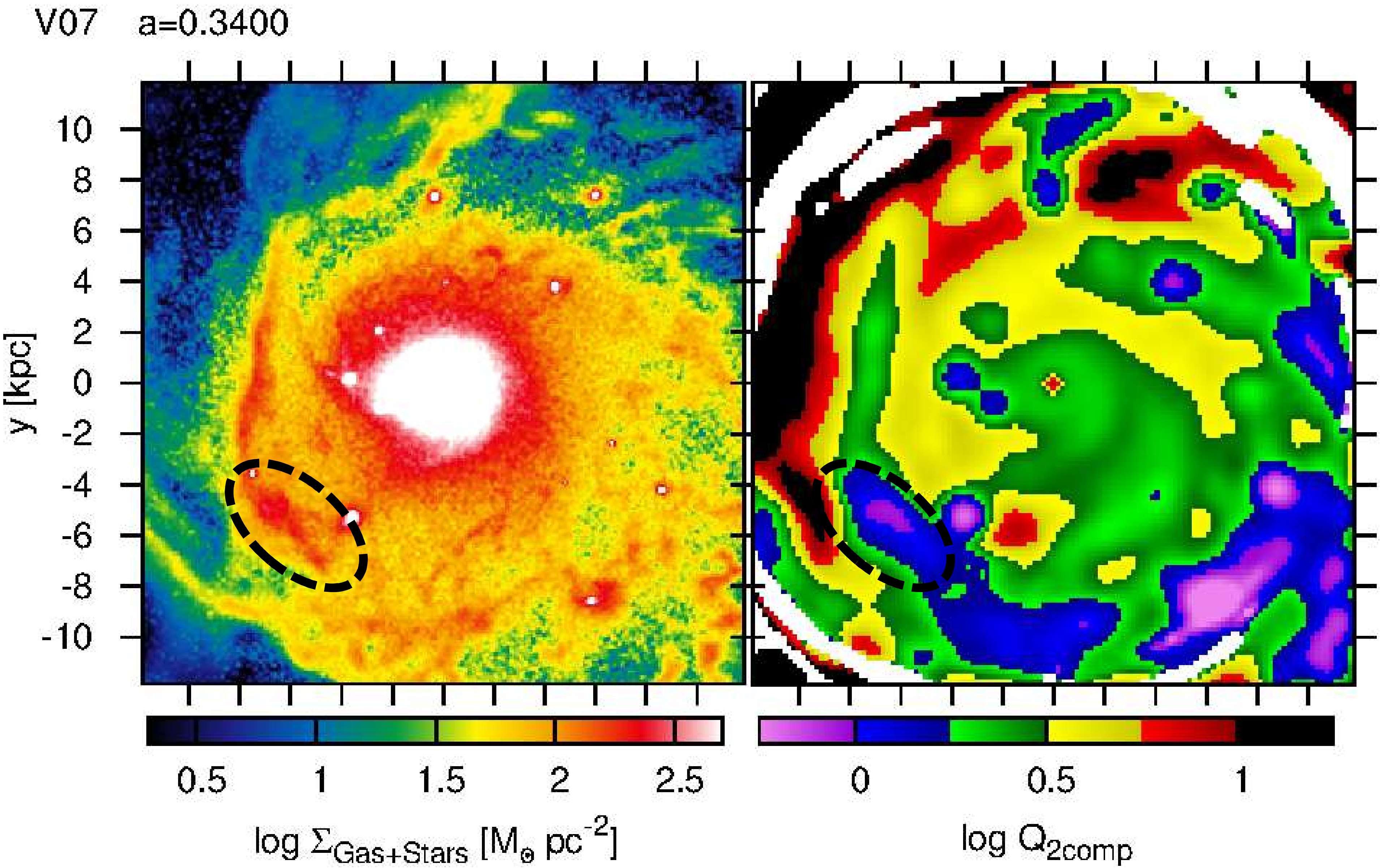

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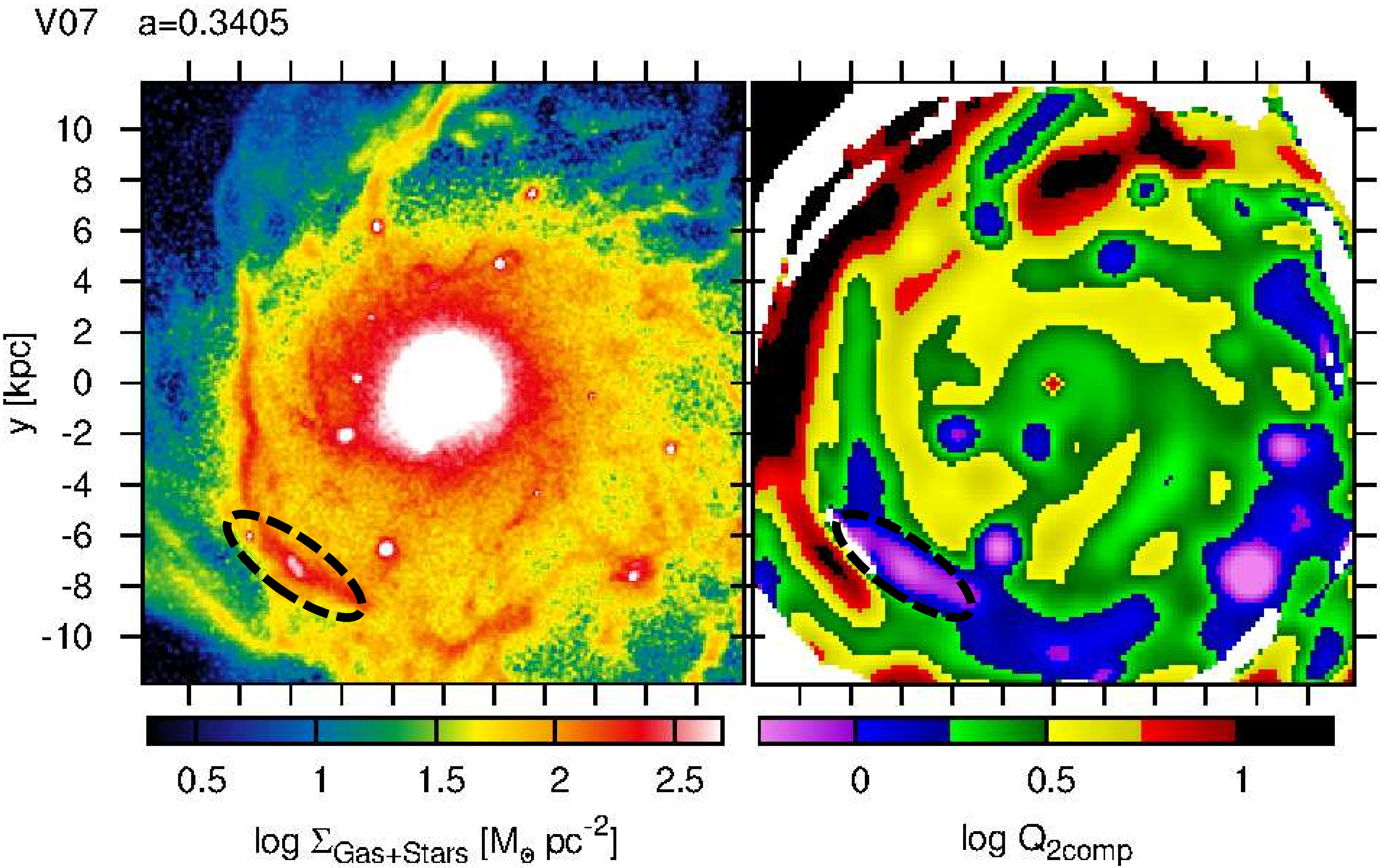

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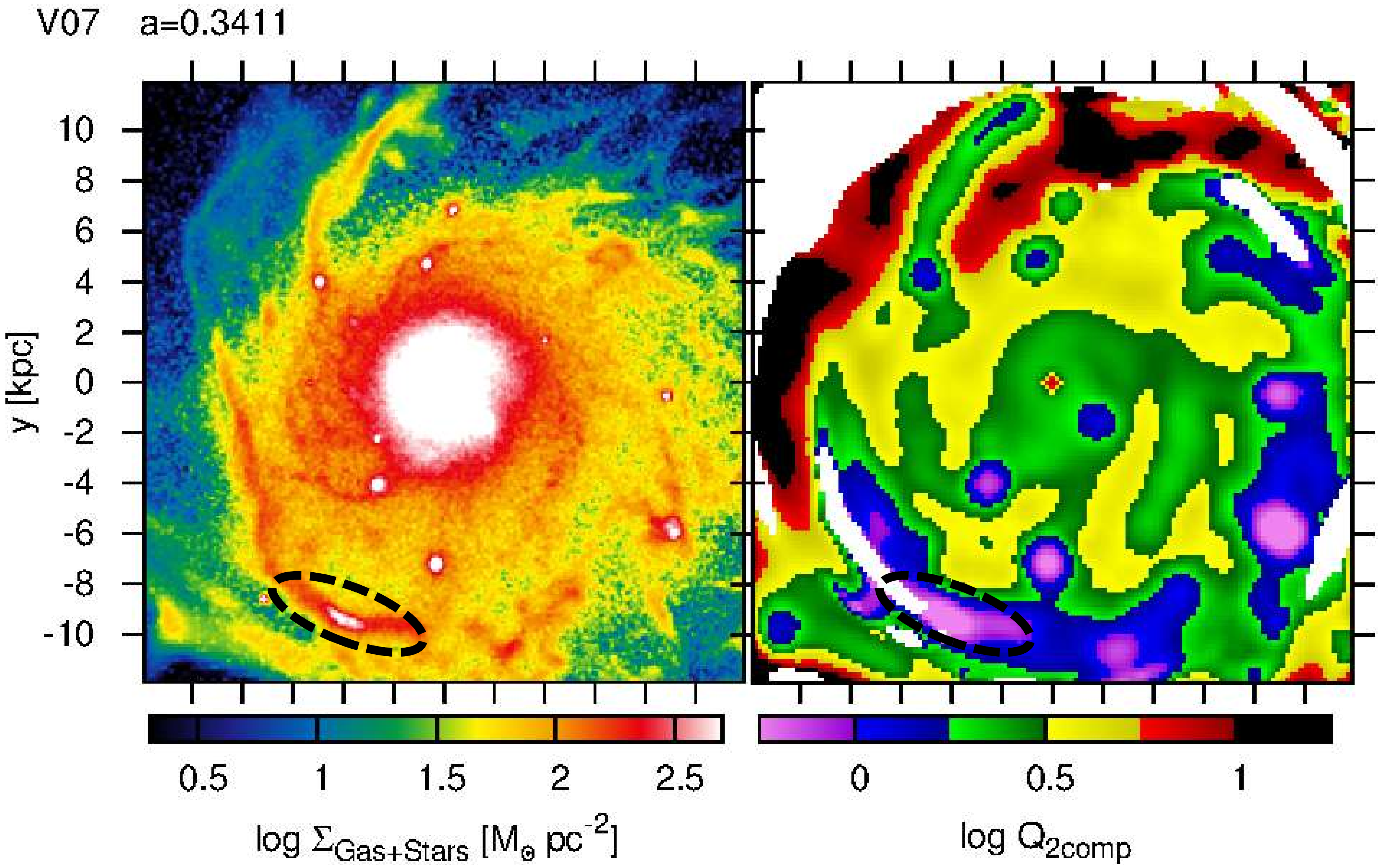

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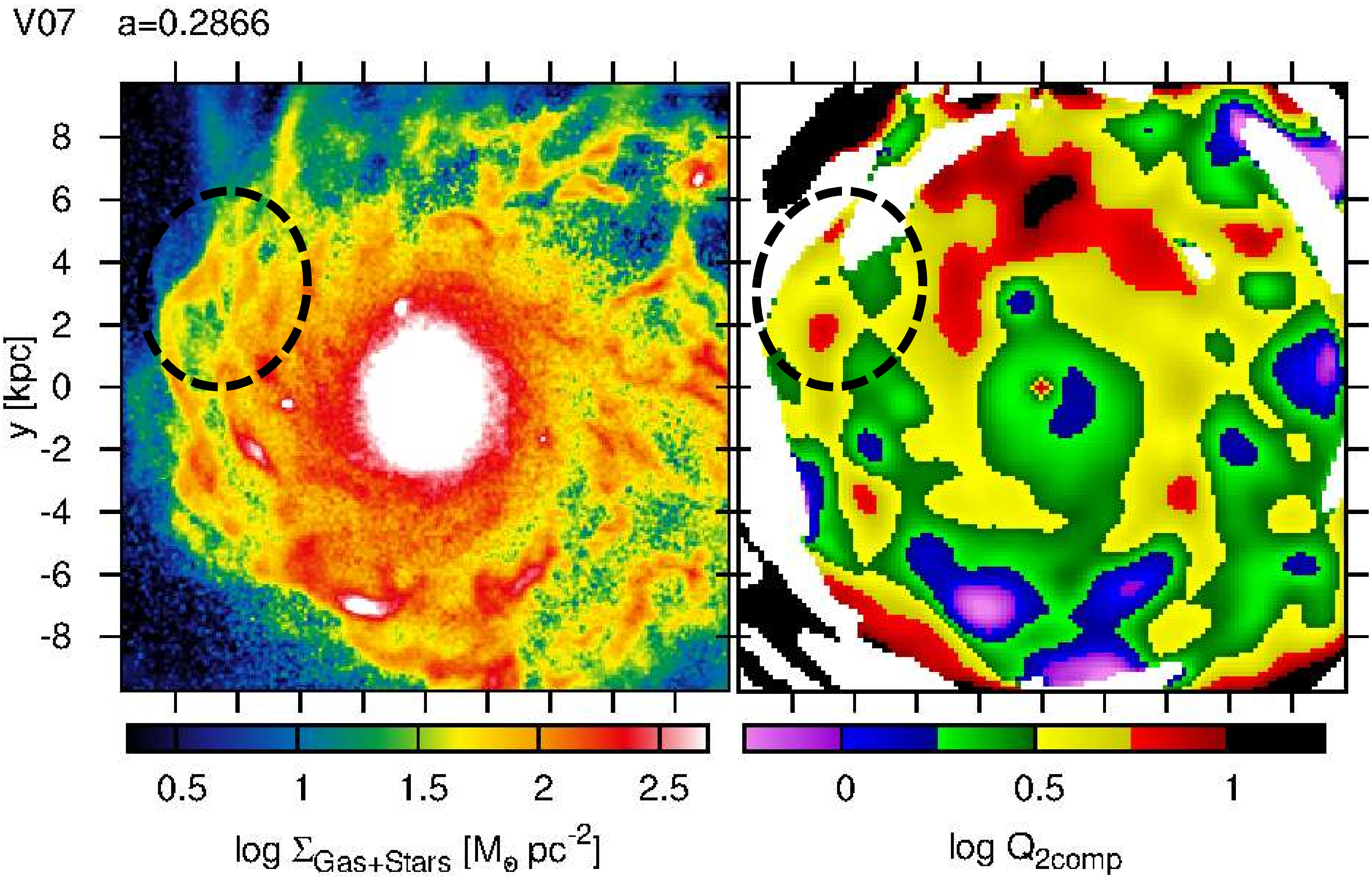

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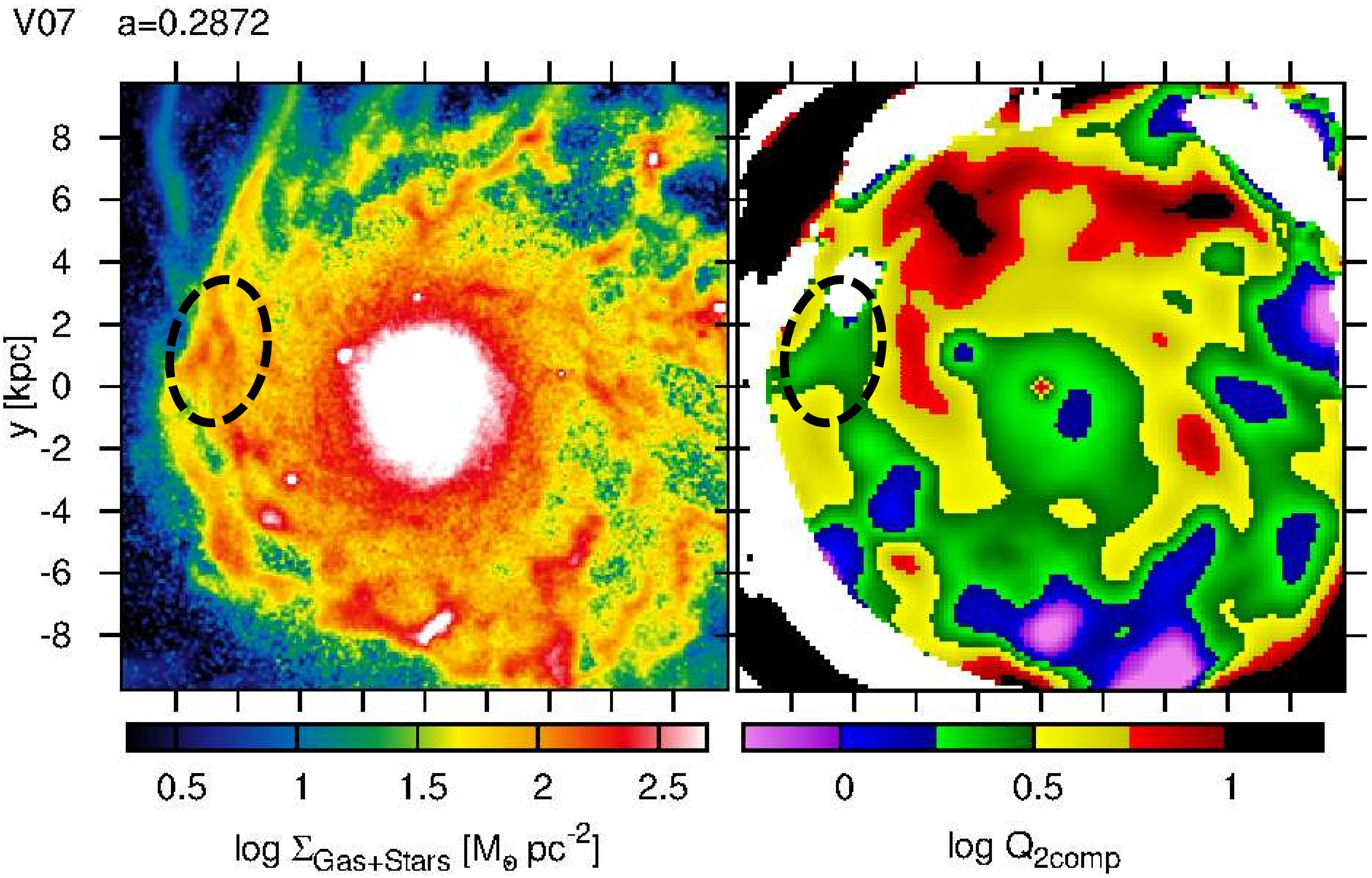

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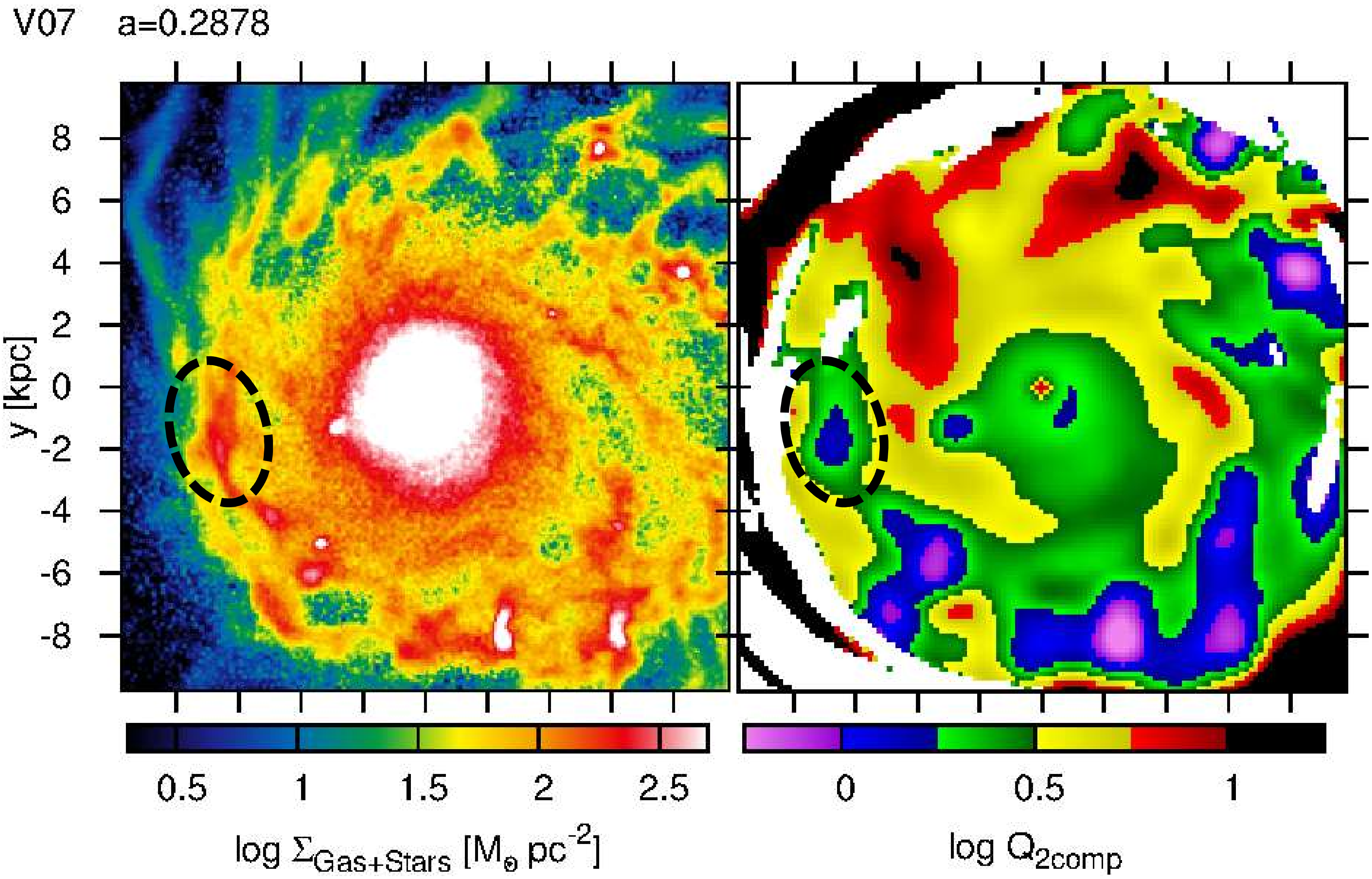

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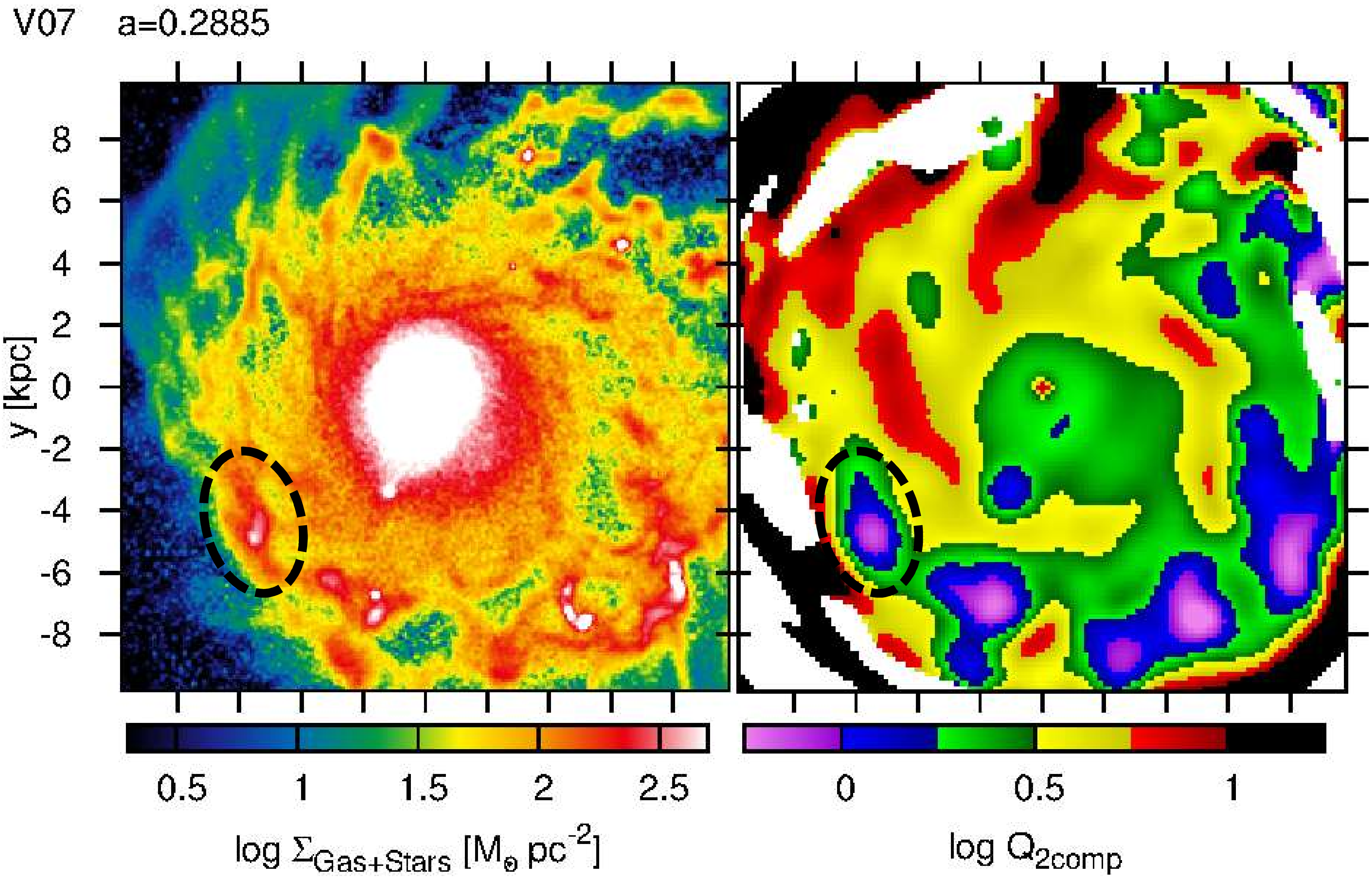

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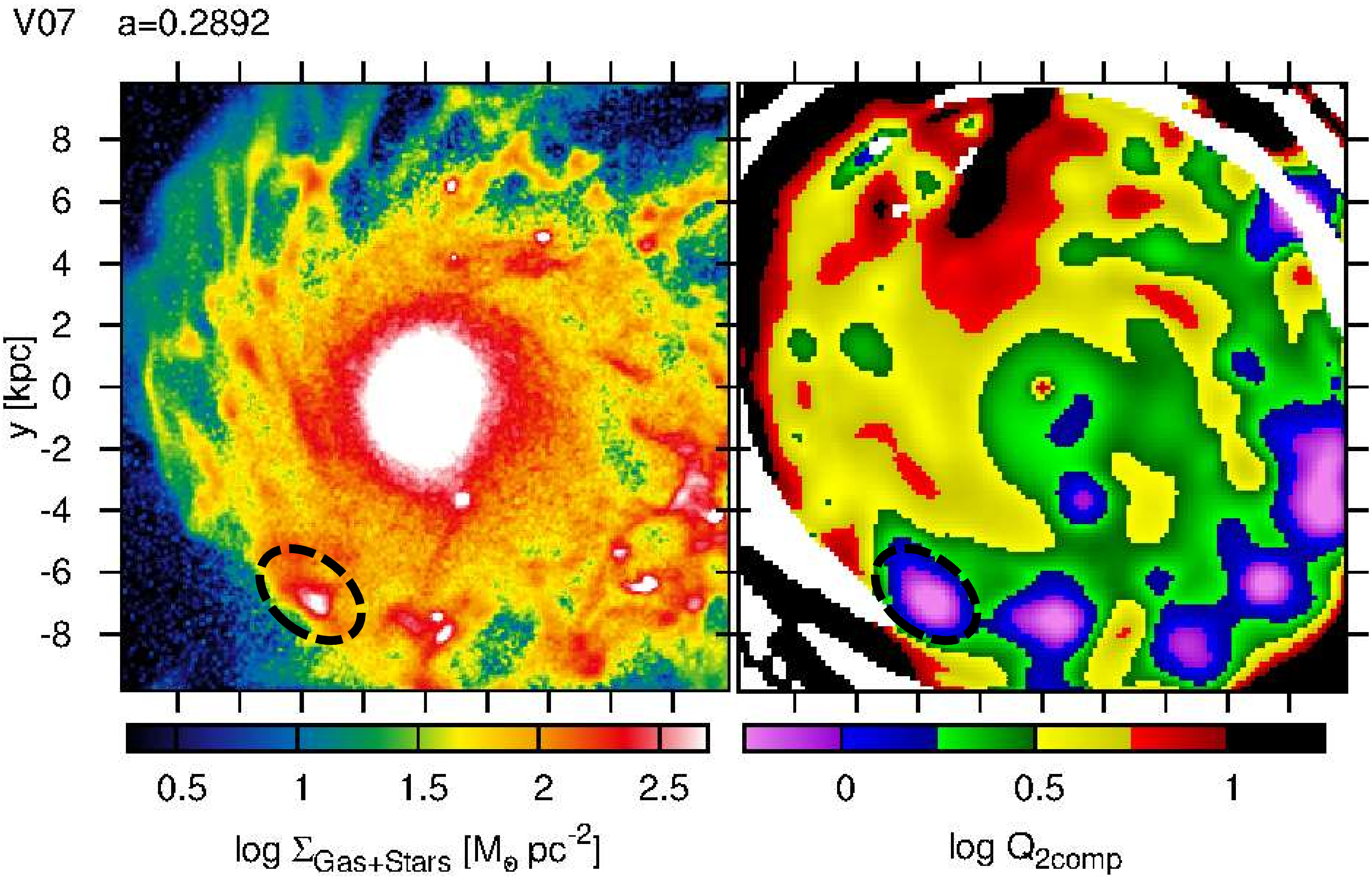
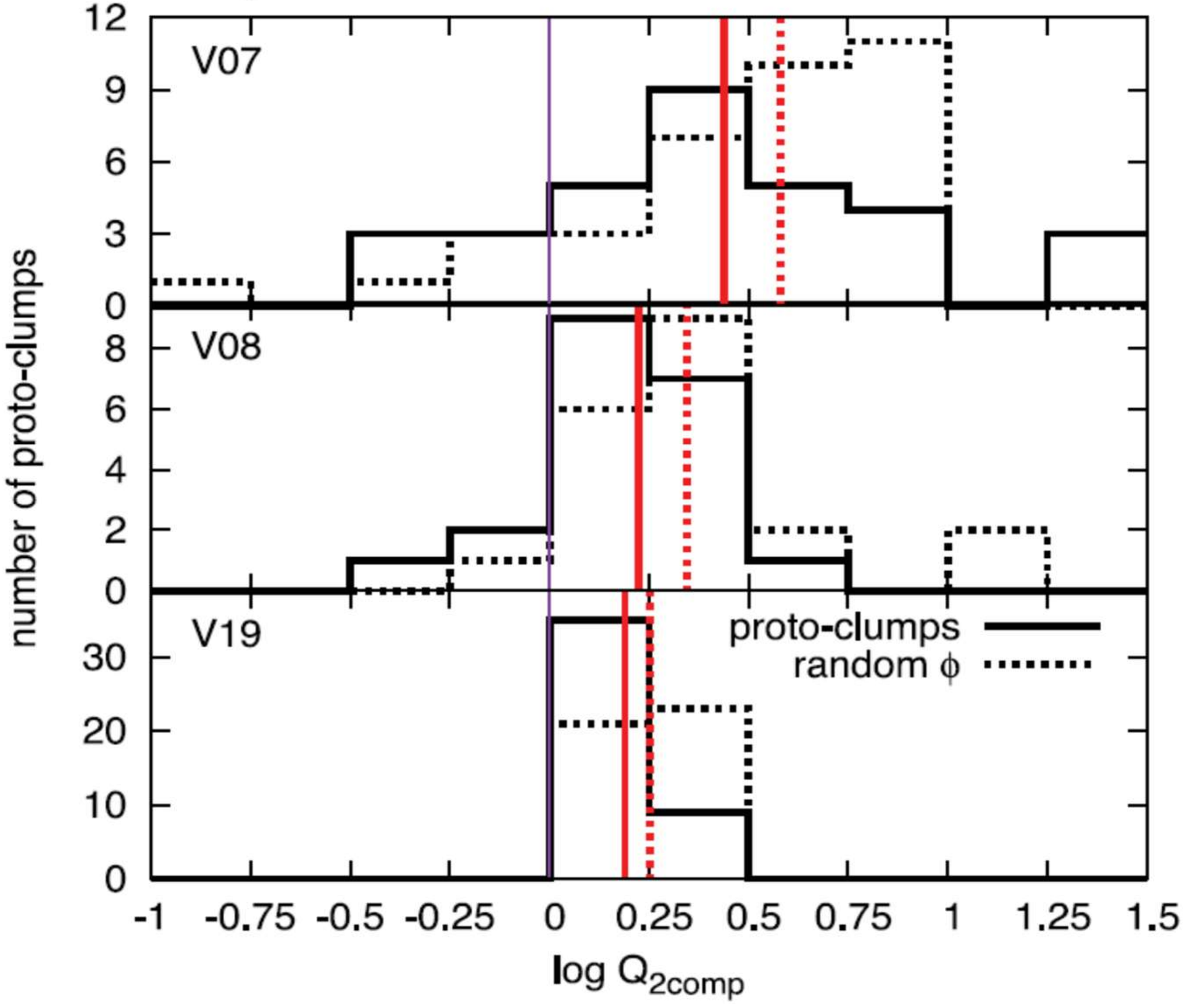


Non-linear formation of clumps

- Distributions of Q on proto-clumps.
  - The initial masses $M_{clump} > 10^8\ M_{\odot}$

Clump detection scheme
(Mandelker+ 2014)

We trace clumps back in time and space, and then we look into proto-clumps which are detected for the first time.



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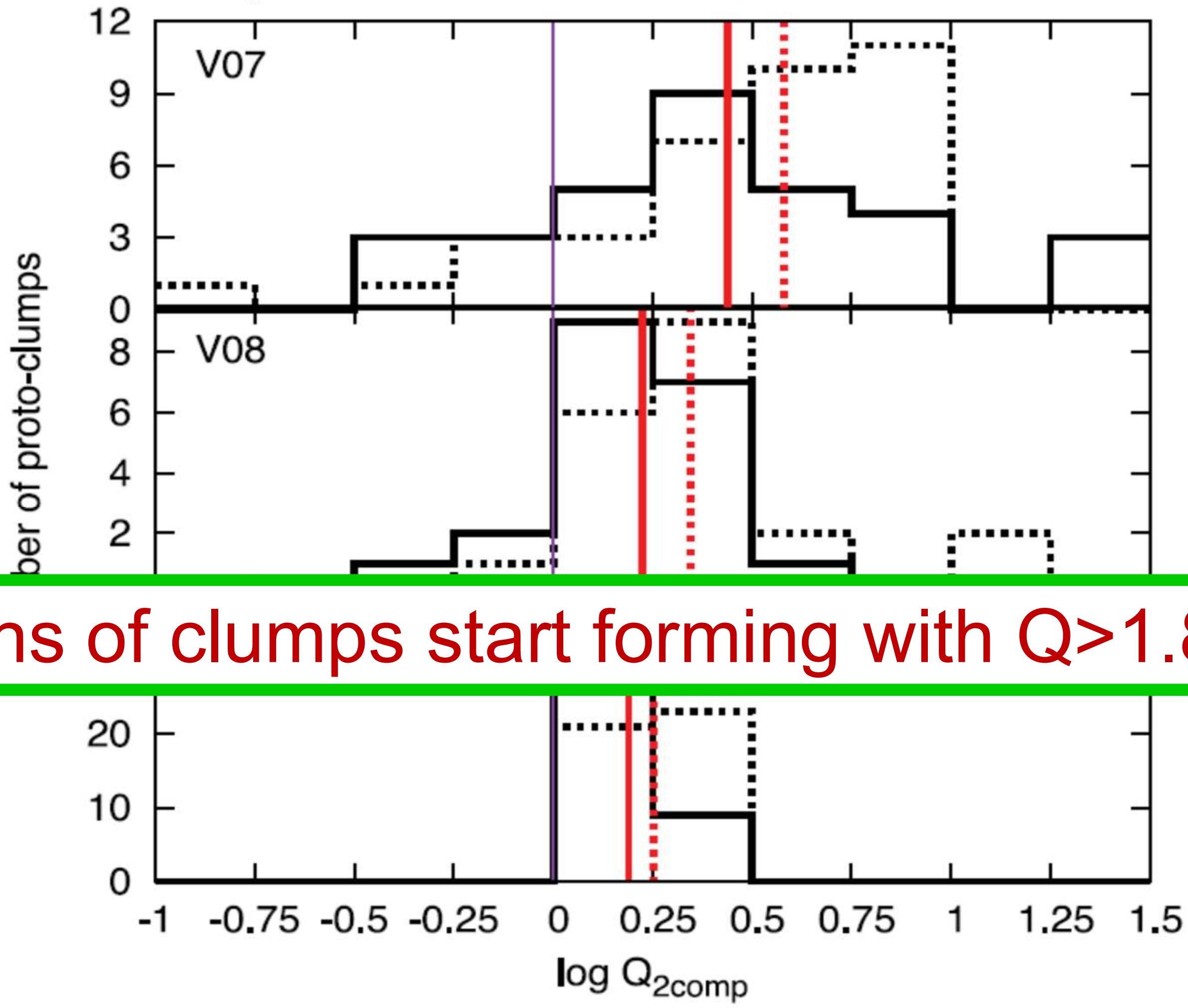

Significant fractions of clumps start forming with Q>1.8

How do giant clumps form?

- Non-perturbative scenarios
  - Gas dissipation
    - $Q_{crit} = 2 - 3$ if gas cooling is rapid. *(Elmegreen 2011)*

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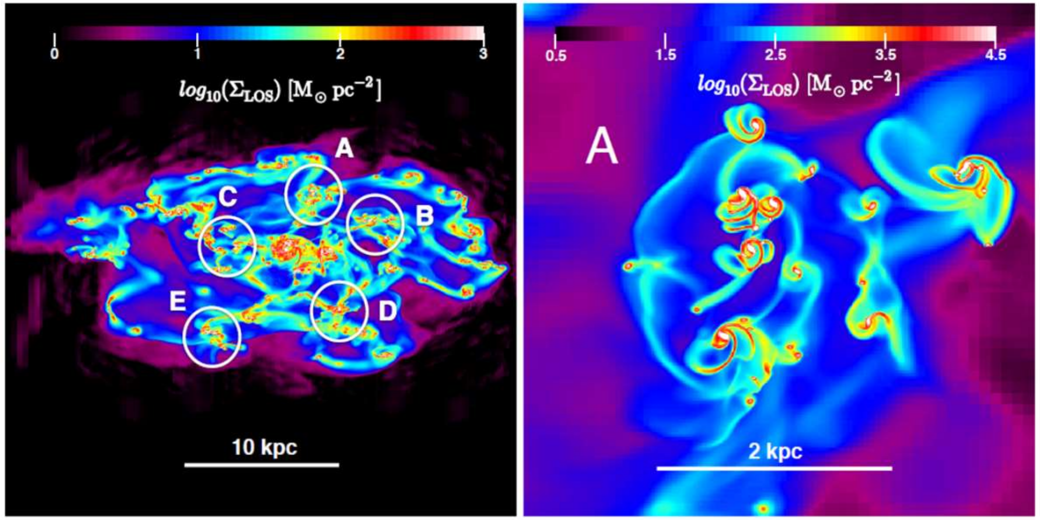
  - Small-scale formation and growth following
    - Q can be <1 on small scale *(e.g. Romeo et al 2010)*
      - Q-measurement can depend on physical scales, e.g. Larson low
      - We applied the Gaussian smoothing with FWHM=1.2 kpc



(a) Gas surface density (b) Zoom onto cluster A

A giant clump may form by mergers of small clumps. (Behrendt et al. 2015)

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    - $Q_{crit} = 2 - 3$ if gas cooling is rapid. *(Elmegreen 2011)*
  - Small-scale formation and growth following
    - Q can be <1 on small scale *(e.g. Romeo et al 2010)*
  - Non-axisymmetric perturbation
    - Rossby wave instability *(Lovelace & Hohlfeld 1978)*
      - A ring structure can break up into clumps
    - $m \neq 0$ perturbations *(Griv & Gedalin 2012)*
      - unstable up to $Q \cong 2$.

How do giant clumps form?

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  - Minor mergers
    - Satellite accretion can disturb a disc.
  - Pre-existing clumps
    - Clumps also disturb a disc and stimulate formation of other clumps.

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  - Cold stream flowing in a disc
    - Streams can join a disc with slow or counter rotation.
      - Slow rotation leads to low κ

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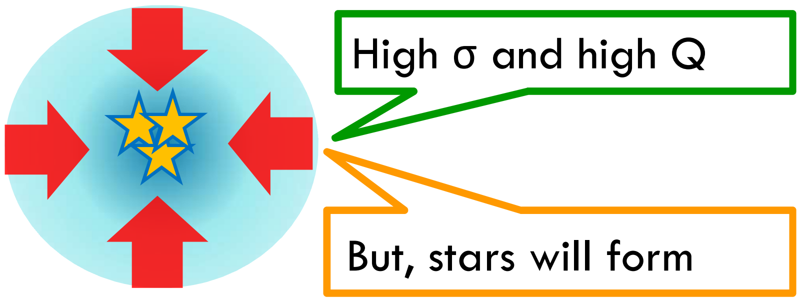
  - Cold stream flowing in a disc
    - Streams can join a disc with slow or counter rotation.
  - Compressive turbulence
    - Compressing gas can indicate a high σ (i.e. high Q)
      - But a clump will form there



Summary

- We utilized the cosmological simulations and performed the Toomre analysis for high-z disc galaxies.
  - Focusing on massive clumps of $M_{clump} \cong 10^{8-9}$ $M_\odot$ on ~1kpc scale.

- **Q>2-3 in disc (inter-clump) regions,**
- **Q<1 inside/around giant clumps.**

- **Formation of new clumps can start with Q>2-3.**

- **Clump formation is NOT NECESSARILY due to the (standard) Toomre instability.**

- Maybe induced by other mechanisms.
  - minor mergers, pre-existing clumps, cold streams, etc..

最近知りたいこと

- 遠方円盤銀河のクランプは、
  - 必ずしもトゥームレ不安定のせいというわけではなさそう。
  - では、どういう物理でクランプを作るのか？

- なぜ力学不安定性の結果が違うのか？
  - 近傍の円盤では 渦状腕
  - 遠方銀河では クランプ

- しかし、両方ともトゥームレ不安定の結果とされている。
  - 同じ不安定性ならば、なぜ結果がちがっているのか？