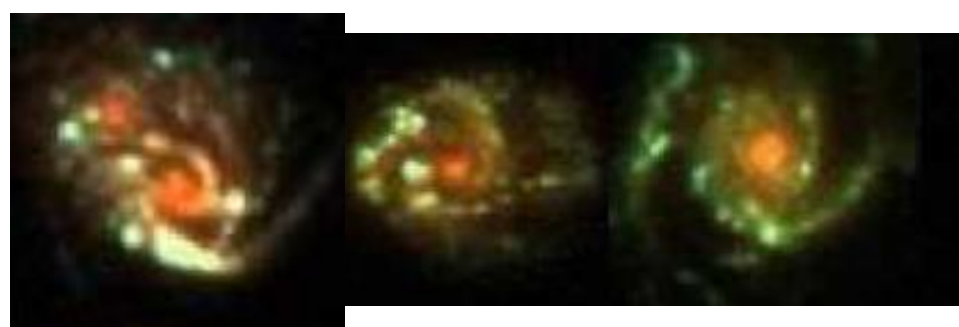
星形成銀河における円盤不安定性と星形成クランプの形成プロセス
Disc instability in star-forming galaxies and formation mechanisms of their giant clumps

井上 茂樹
カブリ数物連携宇宙研究機構 / 東京大学
Shigeki Inoue
Kavli IPMU / U Tokyo

I am going to talk about "giant clumps" in galaxies

- "clump"
  - is a very ambiguous word.
    - e.g. gas clouds, star cluster, dwarf galaxies etc.

- In this talk, "clump" I refer to as is
  - "giant clumps"
    - found in gas-rich galaxies (mainly in high-z galaxies)
    - massive star clusters containing much gas
    - $\sim 10^8\ M_\odot$ at the largest, $\sim$1 kpc in size.
    - actively star-forming



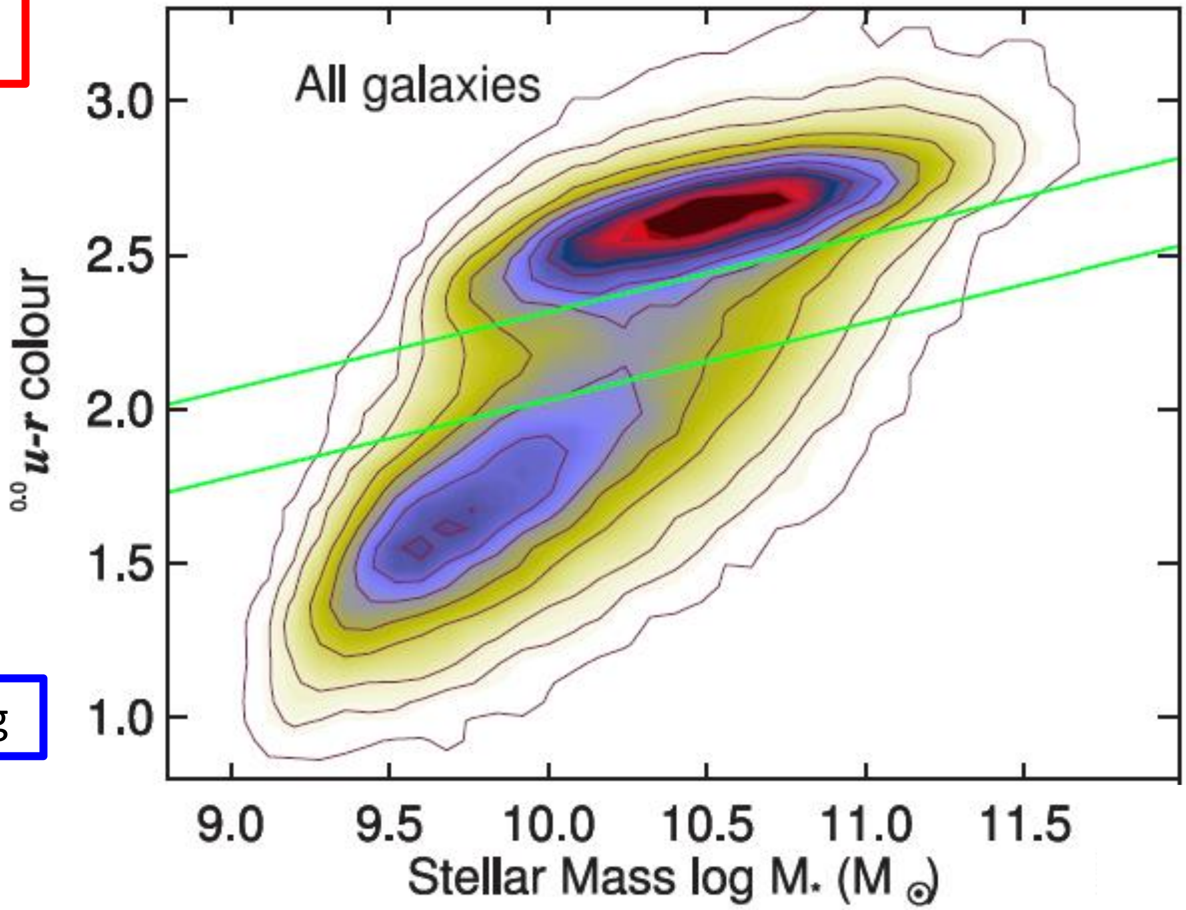
Star formation in galaxies

- Colour – stellar mass relation

Quiescent/ Quenched

Star-forming

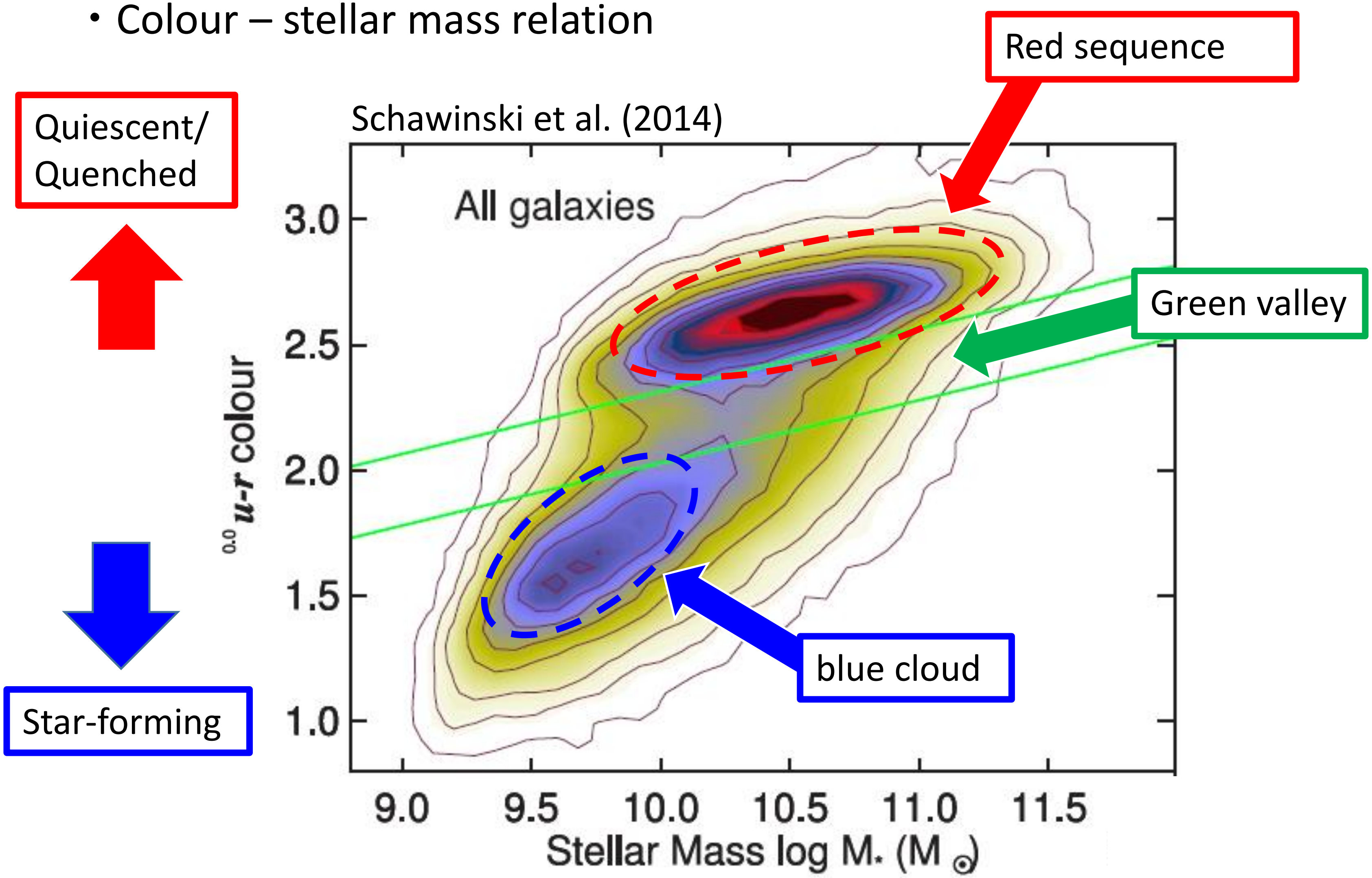
Schawinski et al. (2014)



Star formation in galaxies

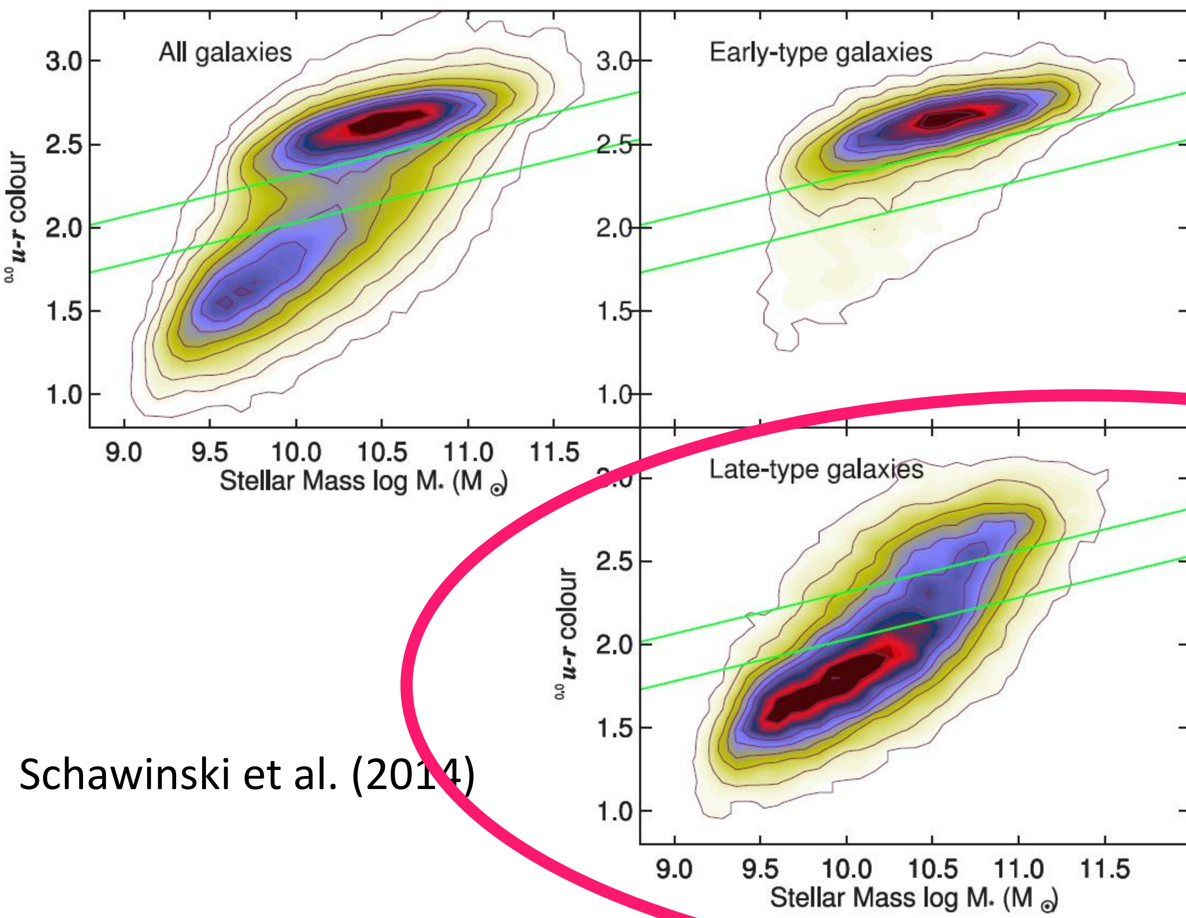
- Colour – stellar mass relation

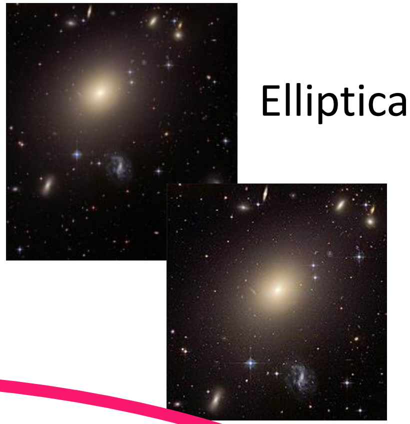
Schawinski et al. (2014)



Star formation in galaxies

- Colour – stellar mass relation





Ellipticals

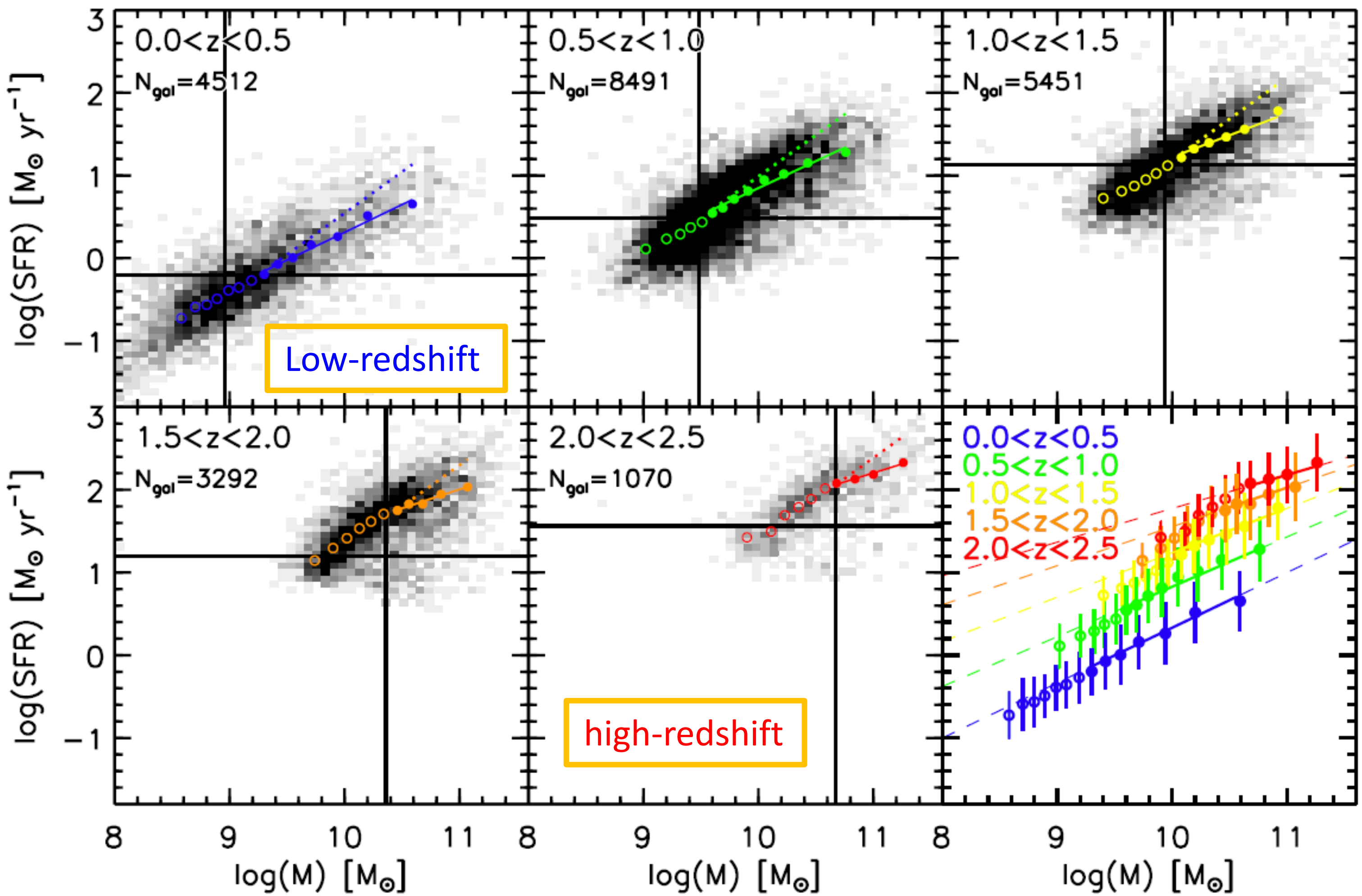
Discs

Schawinski et al. (2014)

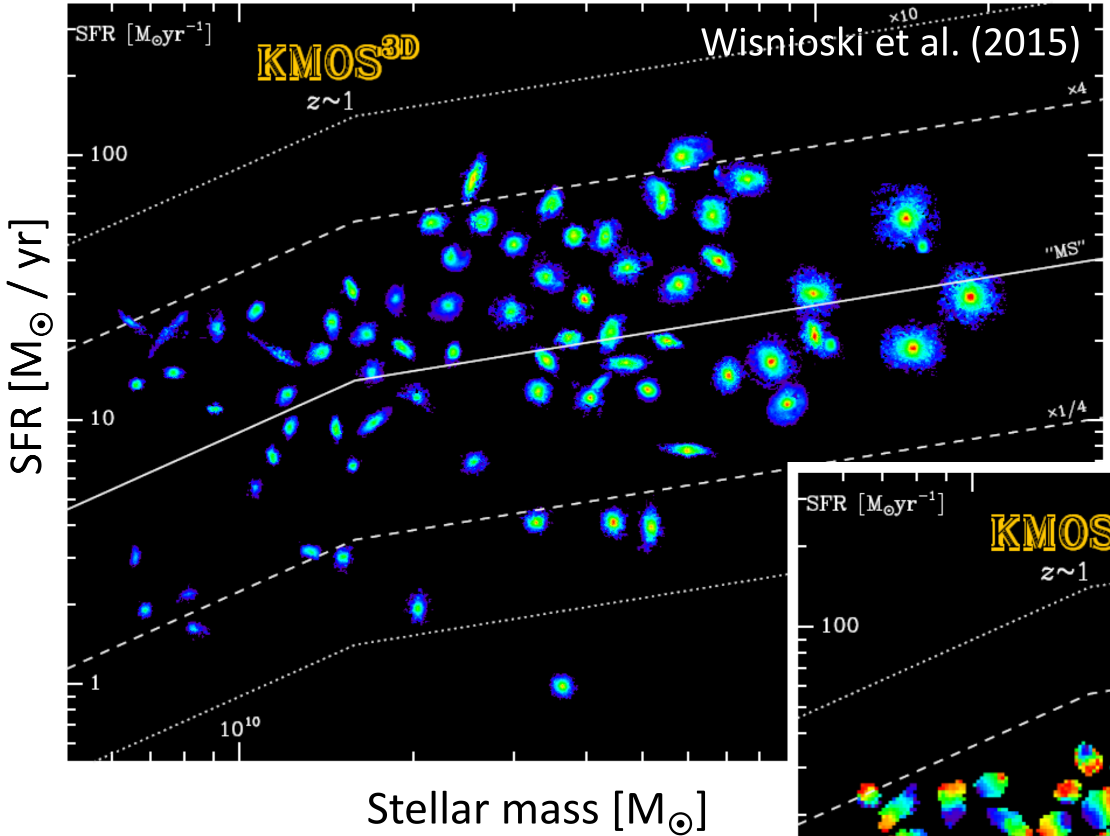
Star-formation "main sequence"

- Tight correlations between stellar mass and SFR
  - Evolving with redshifts
  - The origin is still a mystery

Whitaker et al. (2012)

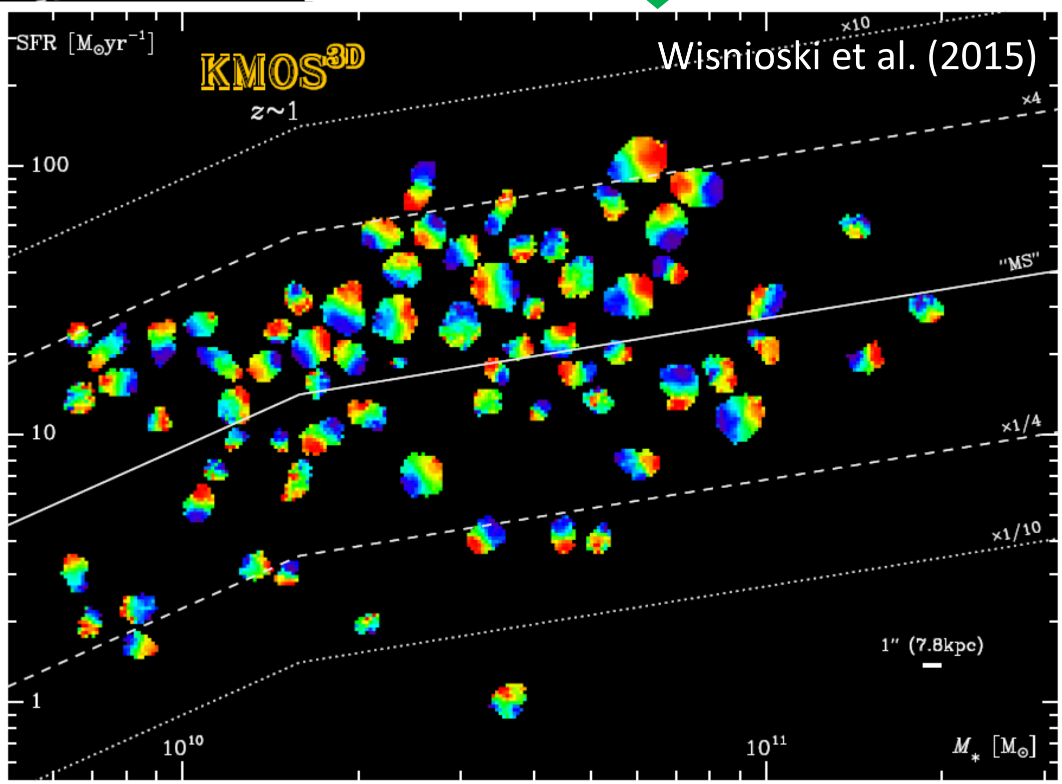


What do the “main-sequence” galaxies look like?



Stellar mass distributions

Line-of-sight velocity distributions

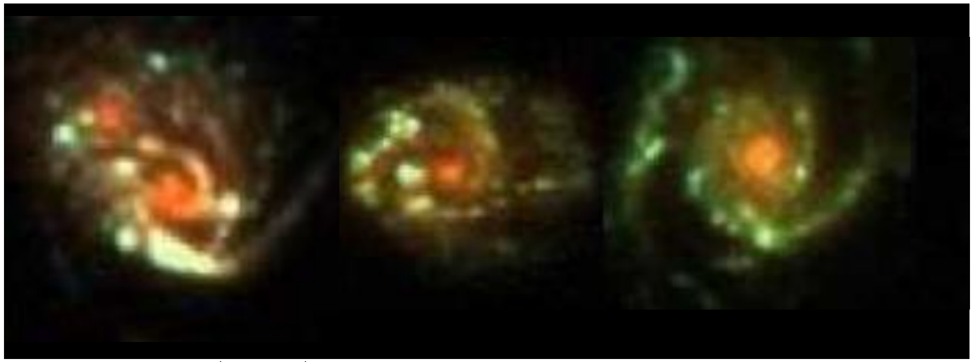


Most of star-forming galaxies are rotating discs.

Most of star formation takes place in disc galaxies.

Many of SF galaxies are clumpy

- Clumpy galaxies



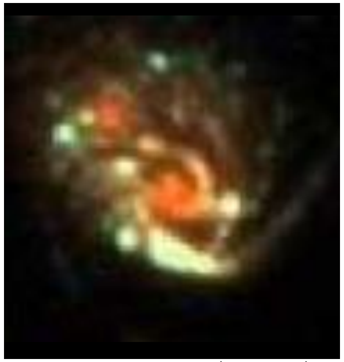
Guo et al. (2014)

- observed mainly at high redshifts z~2.
- Quite rare at low-redshifts.

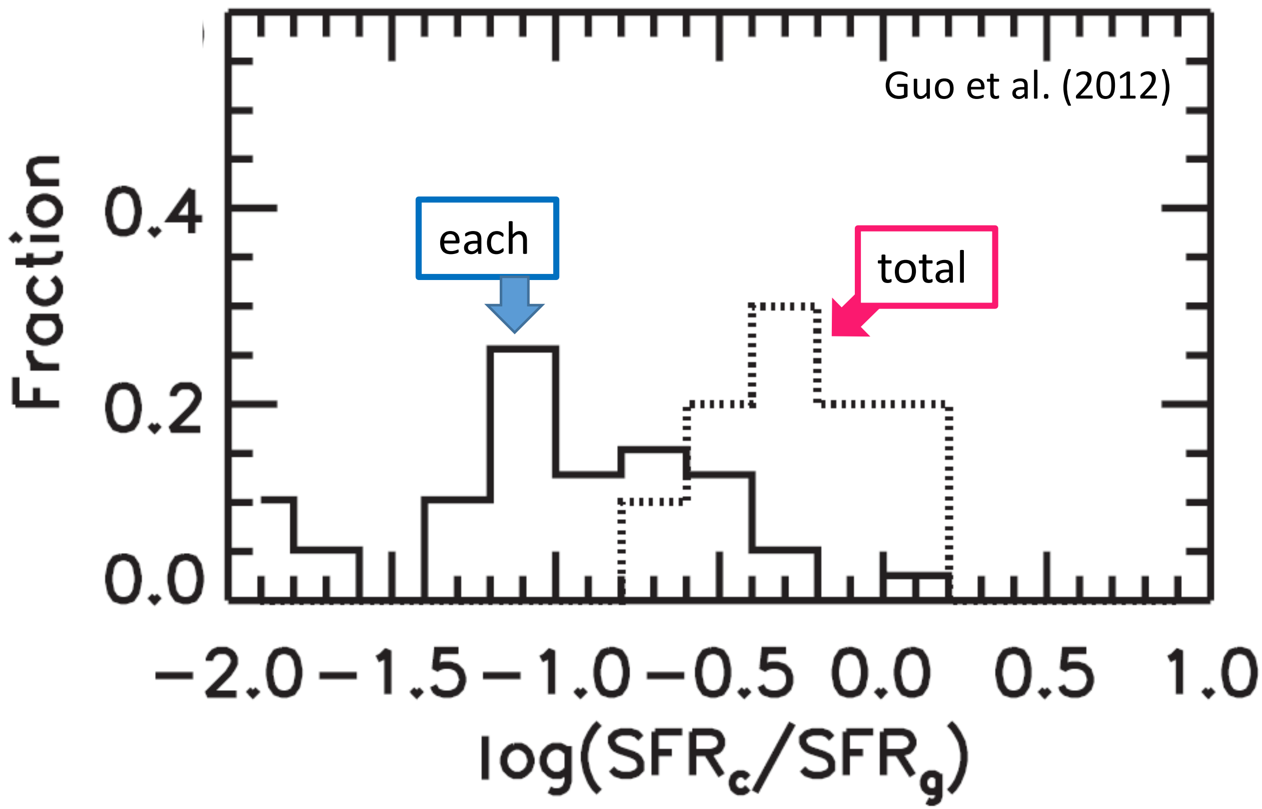
- The clumpy structures are detected with Hα and UV light.
  - They are star-forming clumps
  - $\sim 10^8\ M_\odot$ at the largest, $\sim$1 kpc in size

Many of SF galaxies are clumpy

- Clumpy galaxies



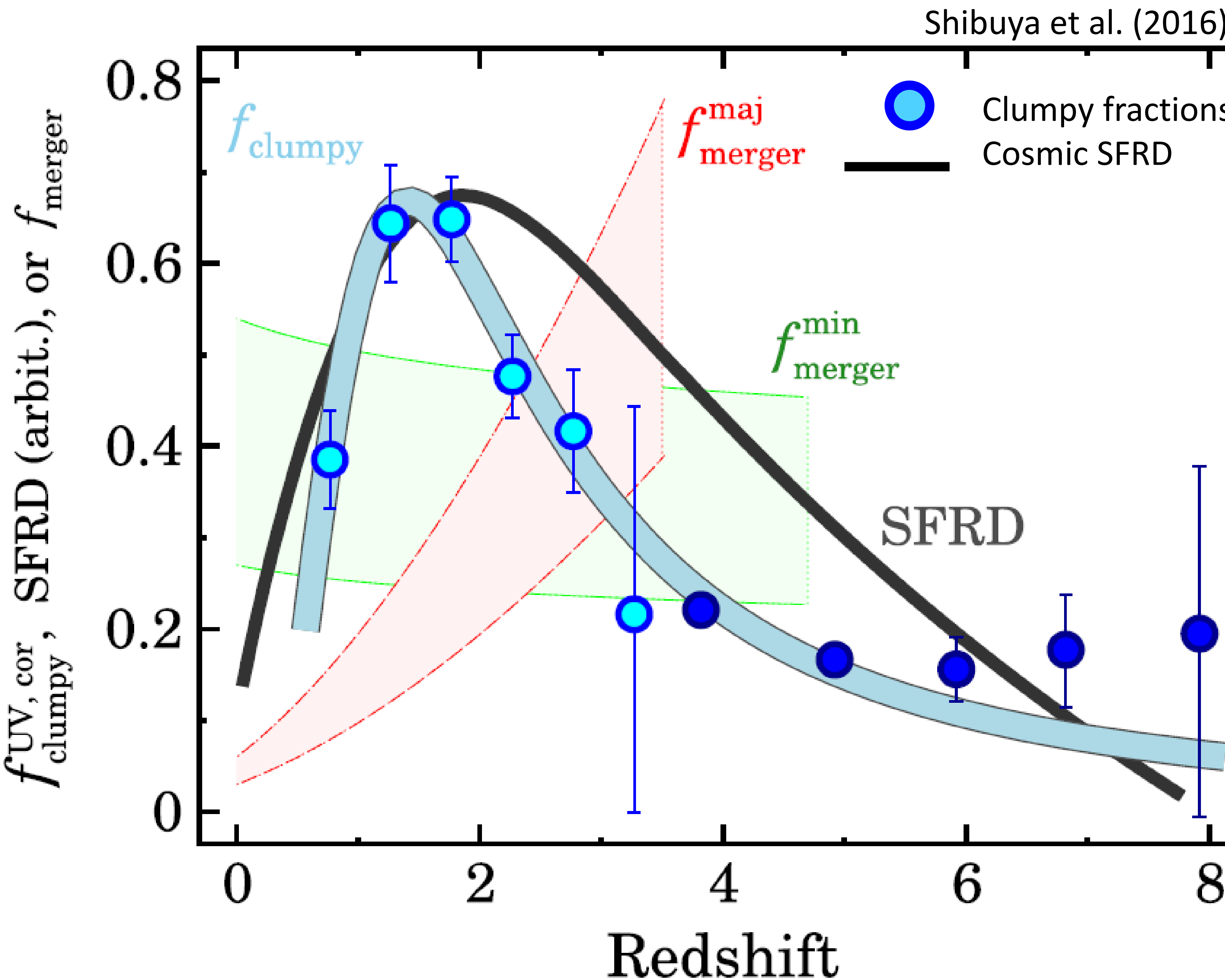
Guo et al. (2014)



- Each clump accounts for ～10% of the galactic total SFR.
- The total SFR in the clumps accounts for ～50% of the galactic SFR.
  - although the SFR fraction depends on spatial resolutions
    - see Dessauges-Zavadsky et al. 2016, Cava et al. 2017

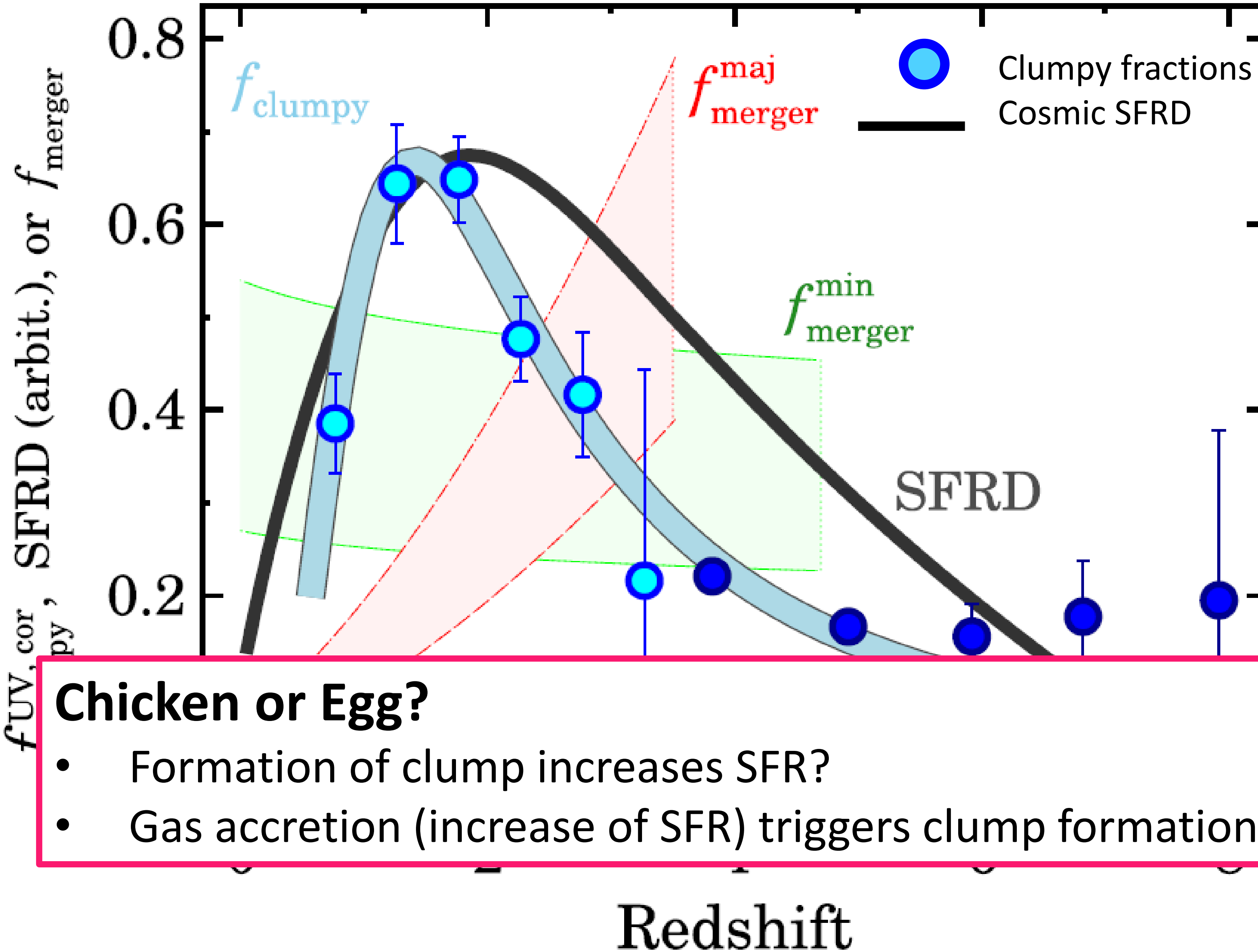
Giant clumps are the main SF sites in gas-rich clumpy galaxies.

Clumpy fraction and cosmic SFR



Clumpy fraction and cosmic SFR

Shibuya et al. (2016)



Chicken or Egg?

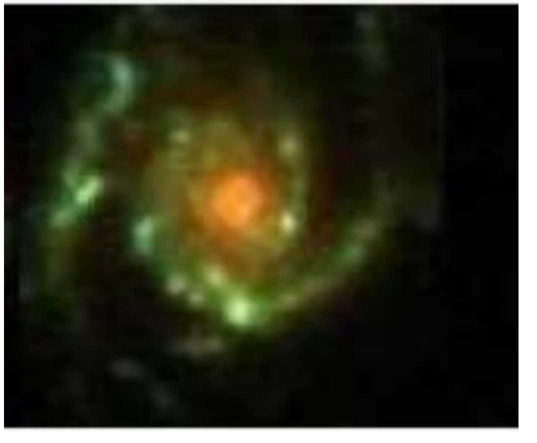
- Formation of clump increases SFR?
- Gas accretion (increase of SFR) triggers clump formation?

Fate of giant clumps: longevity or ephemerality?

- **The long-lived scenario**
    - Noguchi 98, 99; Immeli+ 04; Bournaud+ 06, 08, 14; Ceverino+ 10, 12; Inoue+ 11, 12, 14; Forbs+ 13; Moody+ 14
  - Observed giant clumps are gravitationally bound structures.
    - migrate to the galactic centres by dynamical friction and finally form bulges.
  - Possible if feedback processes are weak and/or clump masses are large.

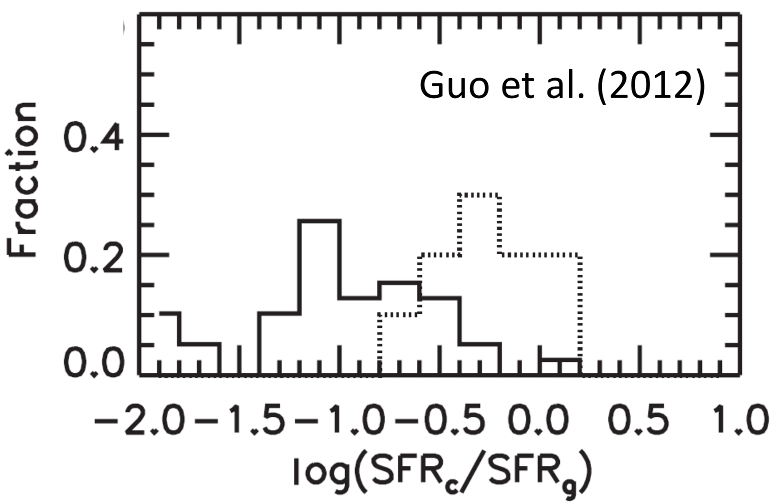
- **The short-lived scenario**
    - Genel+ 12; Hopkins+ 11; Buck+ 17; Oklopčić+ 17.
  - Observed giant clumps are less-bound and/or tidally disrupted soon.
    - cannot migrate to the galactic centres and are transient structures.
  - Possible if feedback processes are strong and/or clump masses are small.

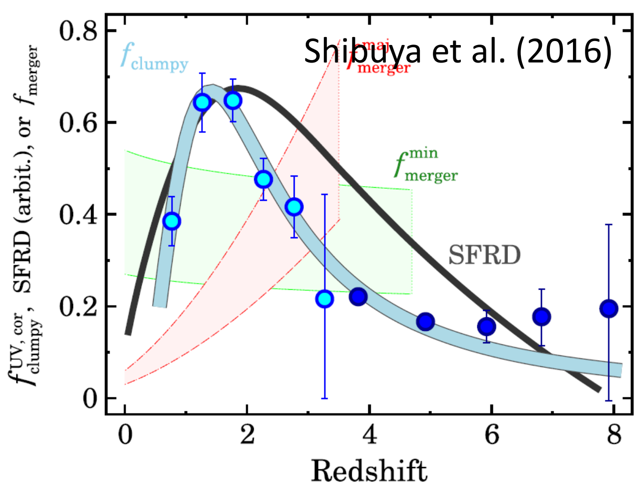
Still under debate



Clump formation and star formation

- **Thus, formation mechanisms of giant clumps are closely related to (global) physics of star formation in galaxies.**
  - What drives giant-clump formation?
    - Gravitational instability (GI)
    - Cosmological gas accretion
    - Galactic mergers
  - What suppress giant-clump formation? (why clumps disappear?)
    - Disc stabilization by gas consumption and/or heating
    - Growth of a massive bulge
    - Cessation of galactic mergers





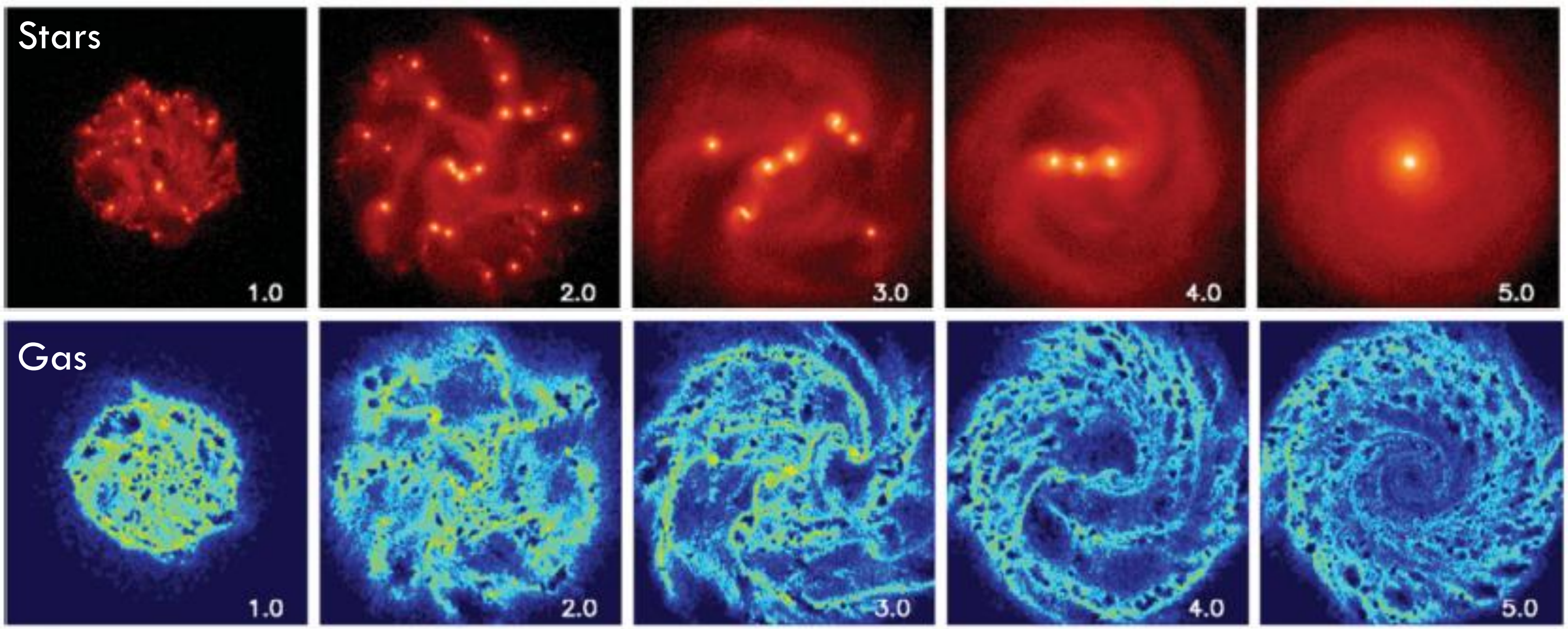
“Non-linear violent disc instability with high Toomre’s Q in high-redshift clumpy disc galaxies”

MNRAS, 456, 2052 (2016)

SI, Avishai Dekel, Nir Mandelker, Daniel Ceverino,
Frederic Bournaud, Joel Primack

Why are they clumpy?

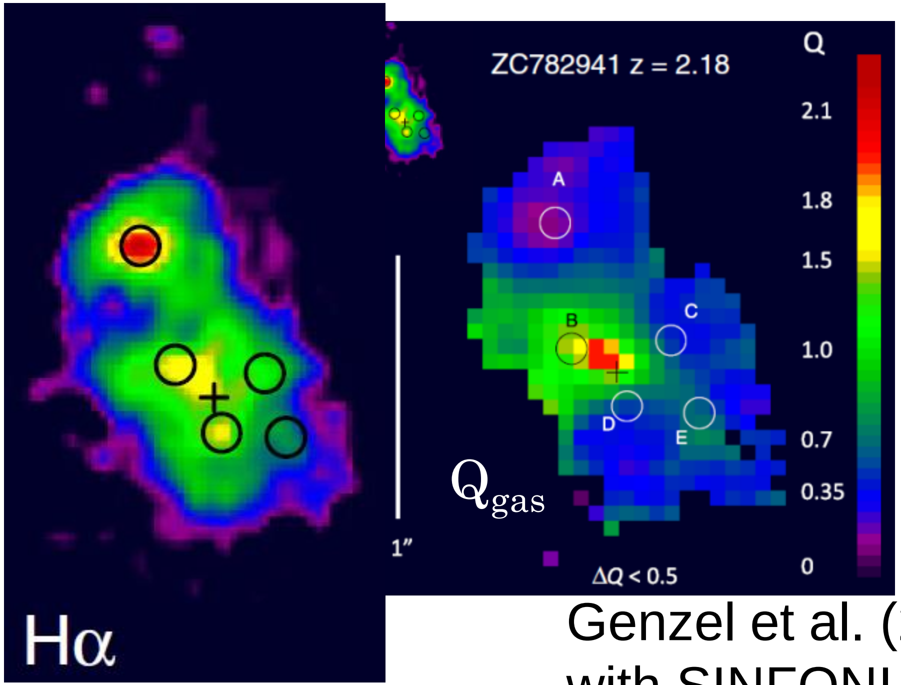
- It has been proposed;
  - Galaxies are highly gas-rich (stream-fed) in their early formation stages.
  - Cold gas discs in the galaxies are **Toomre unstable** (Noguchi 1998, 1999).
  - **Clump formation is caused by 'Toomre instability'**

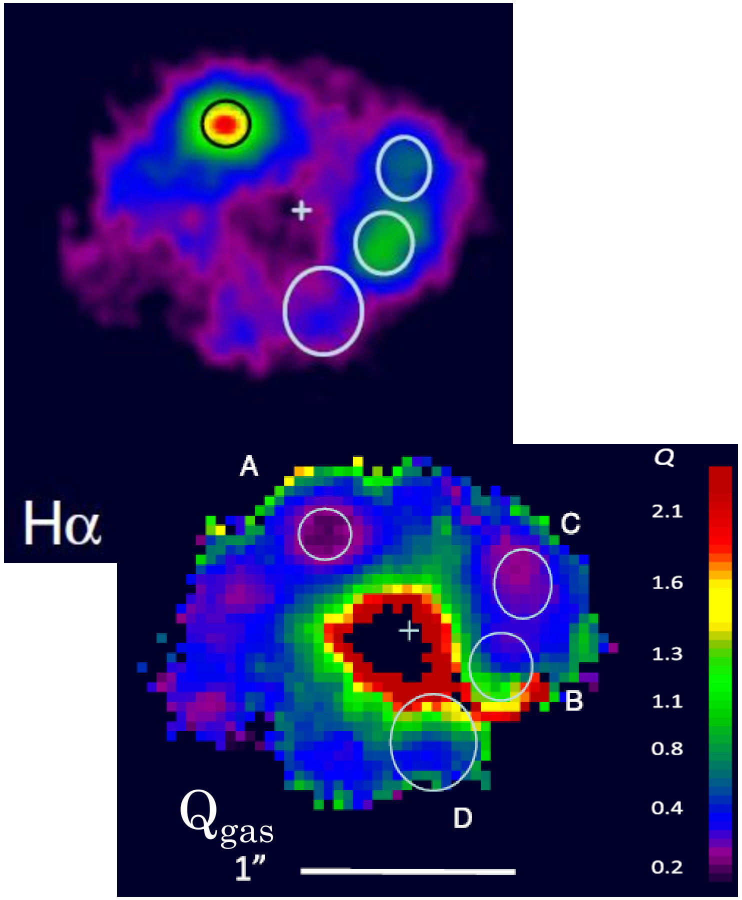


Inoue & Saitoh (2012)

Toomre instability

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





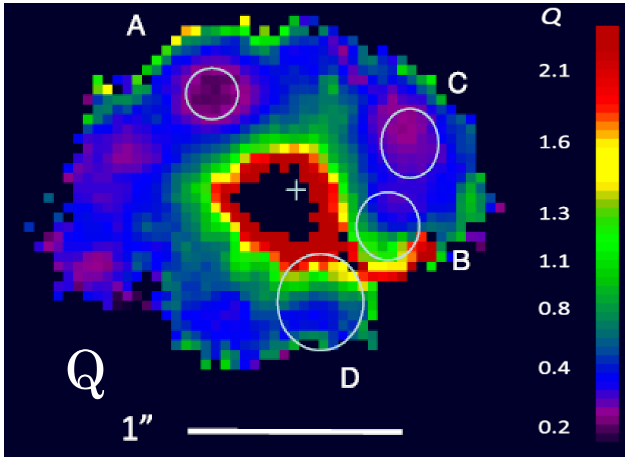
Genzel et al. (2011) with SINFONI

$Q \leq 1$ in observed clumpy discs.

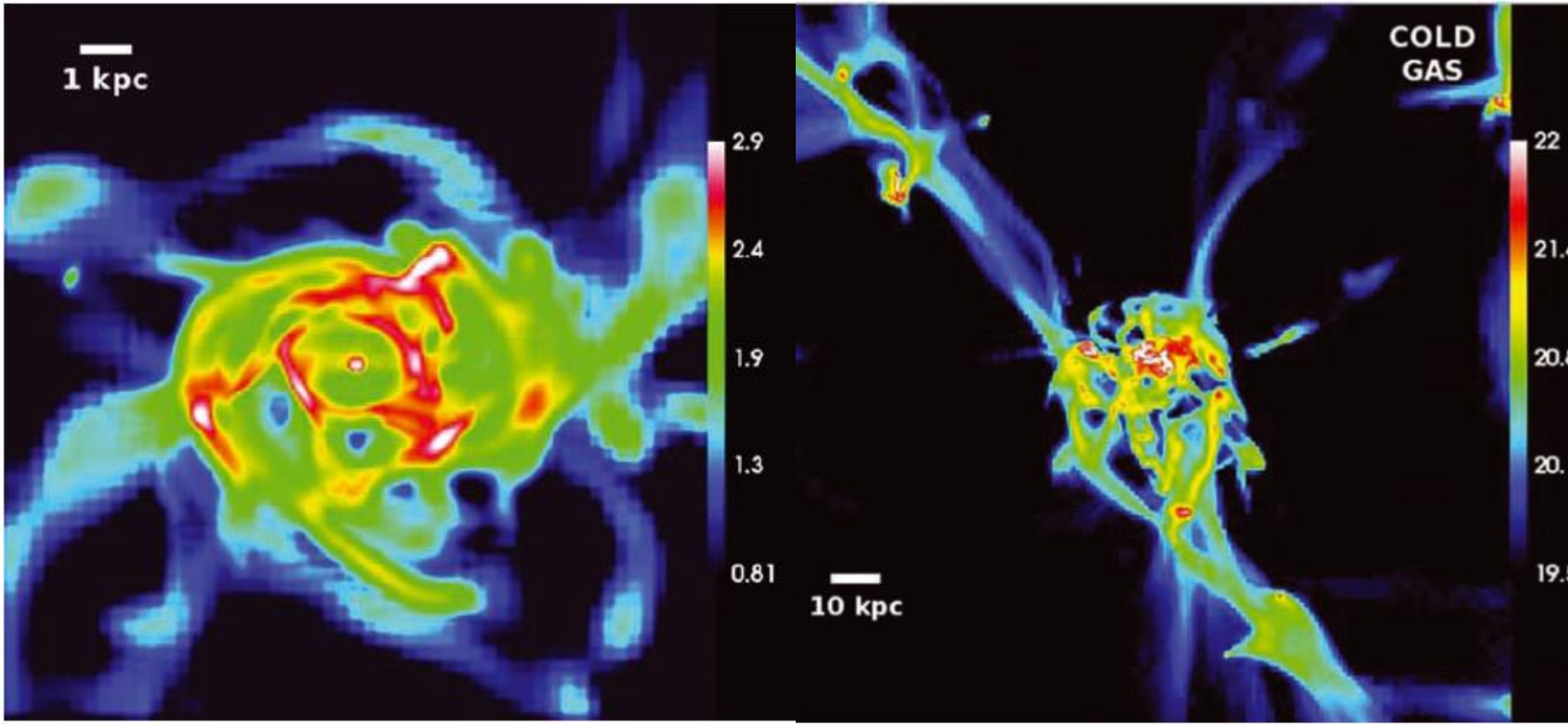
Toomre instability

- However, dynamically unstable states cannot be long-lasting.
  - The unstable regions will collapse soon, then their disc (inter-clump) regions turn over to stable states within the local dynamical time-scales.

The observation might be underestimating Toomre Q…



Toomre analysis in cosmological sims.



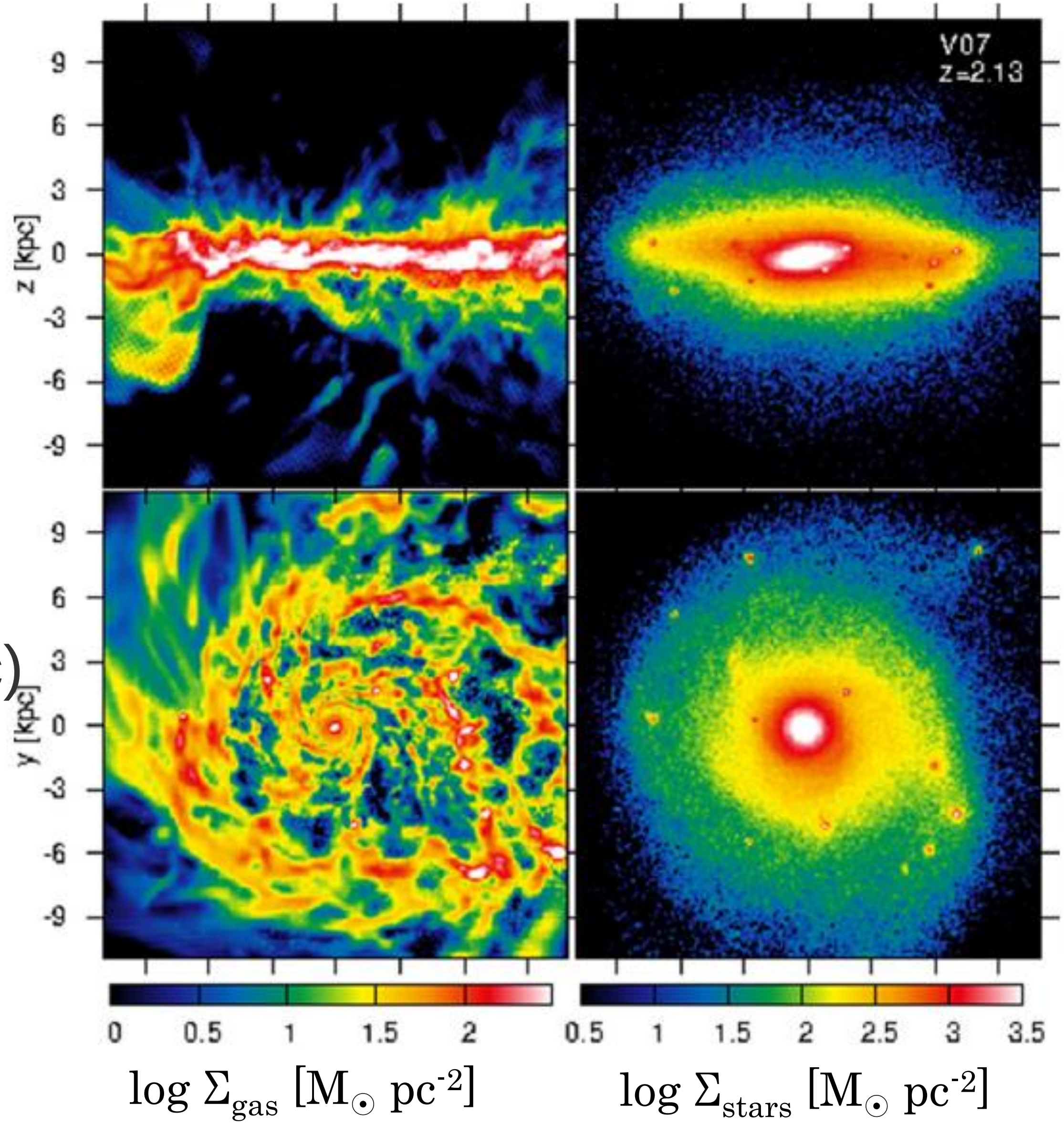
- Cosmological simulations
  - Ceverino et al. (2010, 2013) using ART code
    - 10pc-order resolution with radiation pressure.

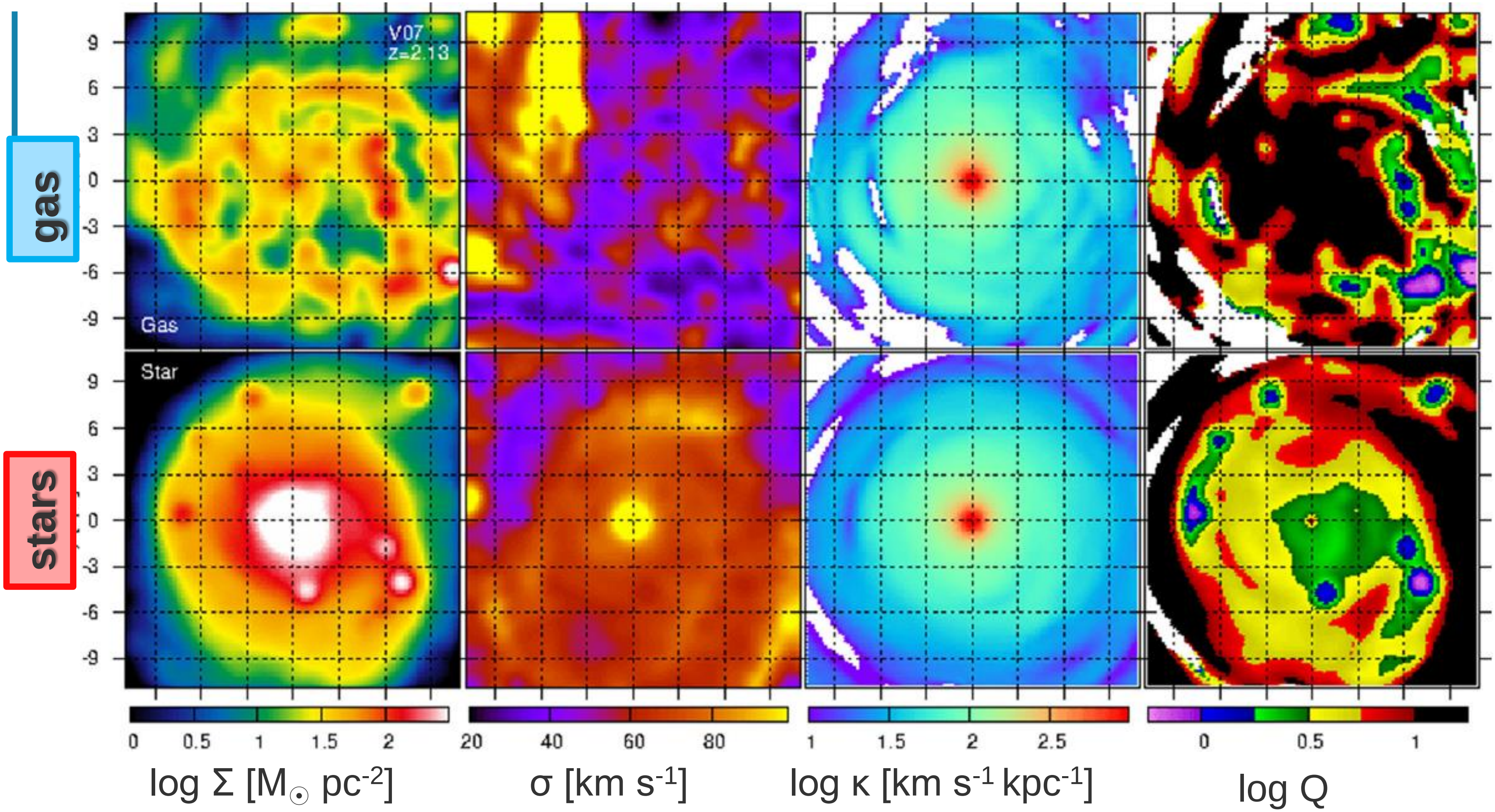
How to measure Q_{2comp}

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





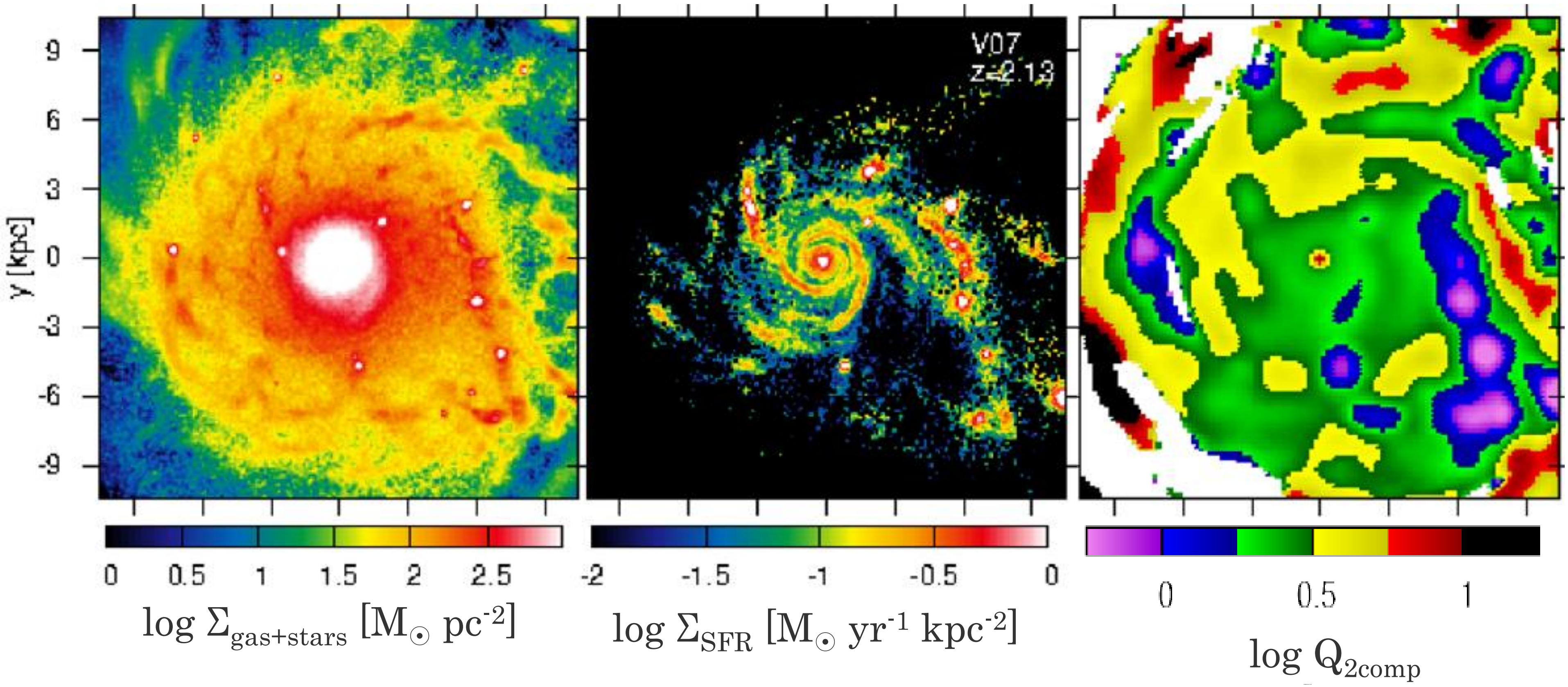
Purple Q<1: linear instability

Blue Q=1-1.8: non-linear instability

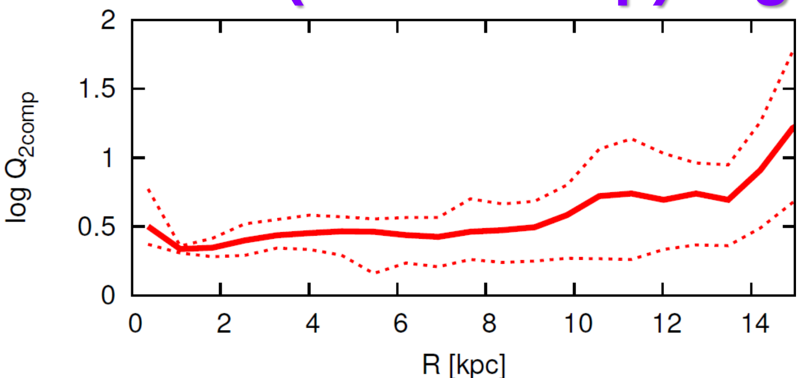
Green Q=1.8-3: dissipative instability

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).**



Purple Q<1: linear instability

Blue Q=1-1.8: non-linear instability

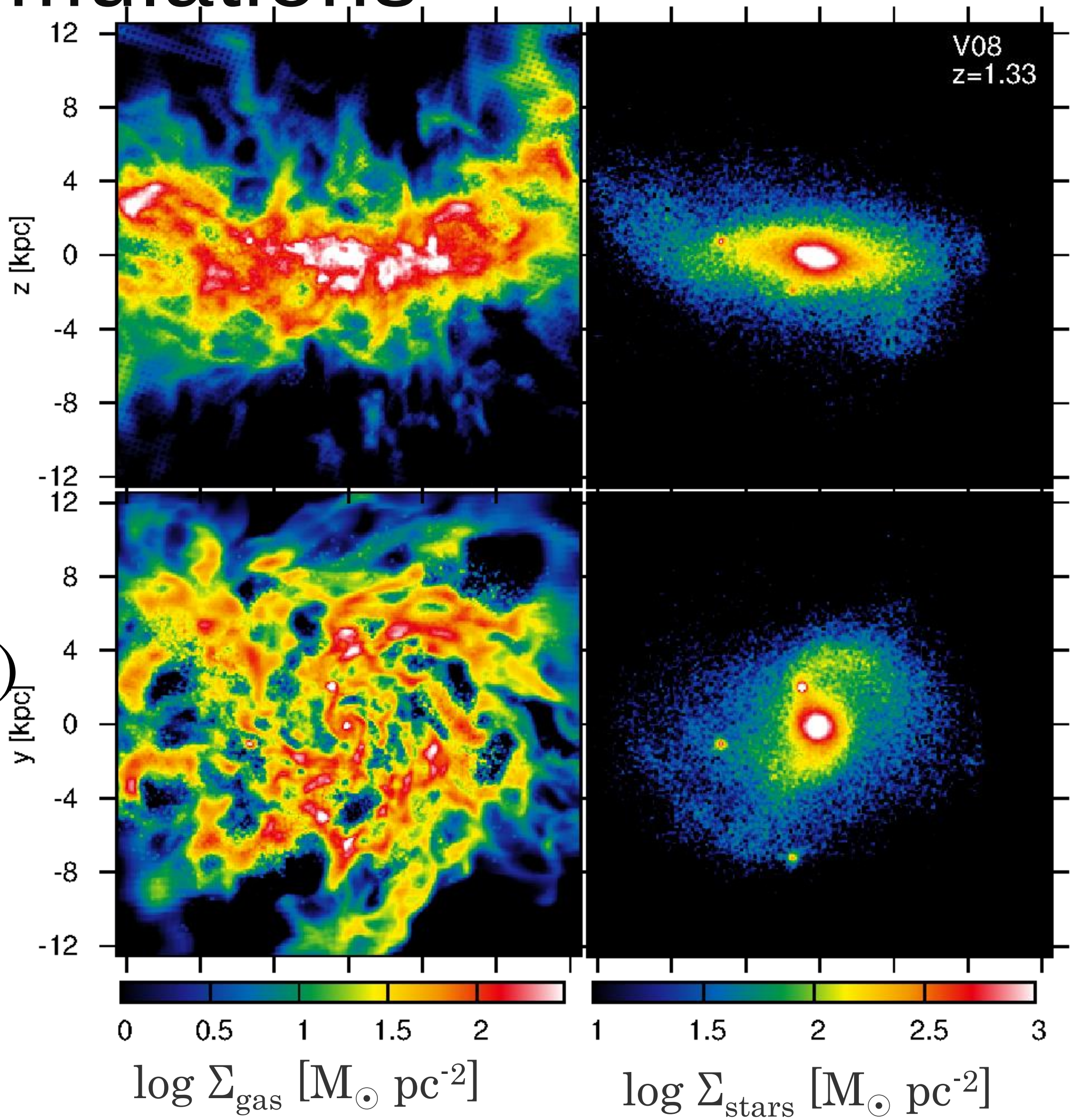
Green Q=1.8-3: dissipative instability

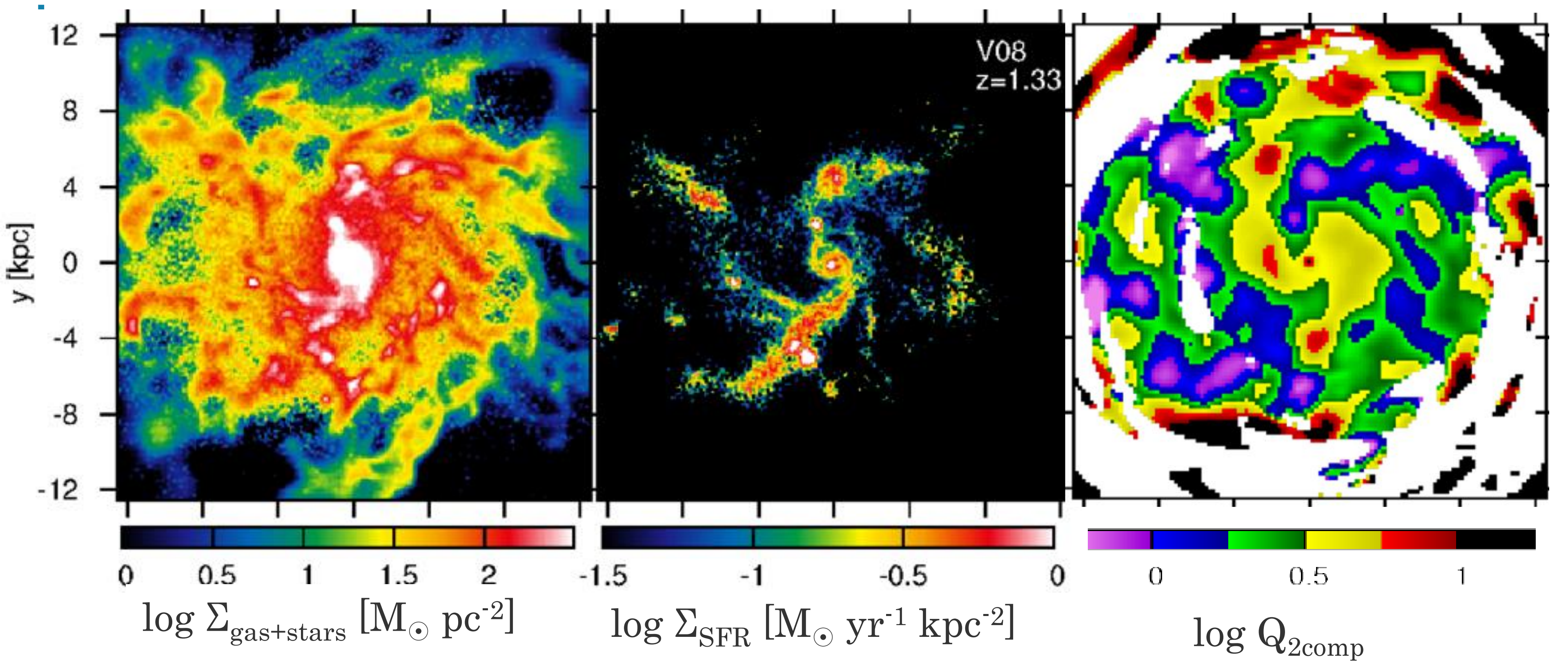
Yellow, Red, Black: Q>3: stable state

White: imaginary κ (Q cannot be defined)

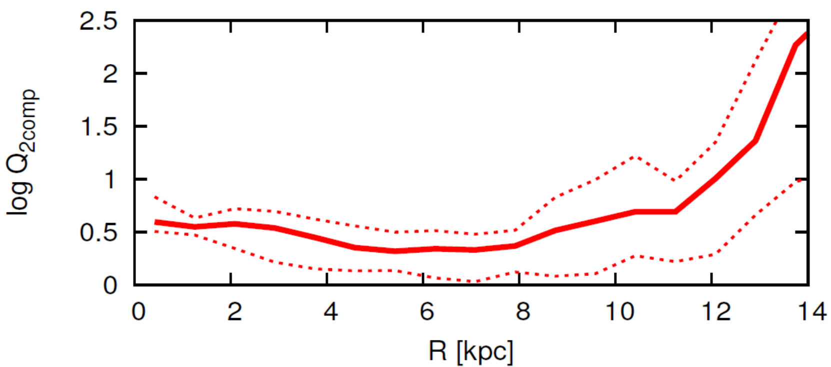
Cosmological simulations

- 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)
  - $SFR = 33.1\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$





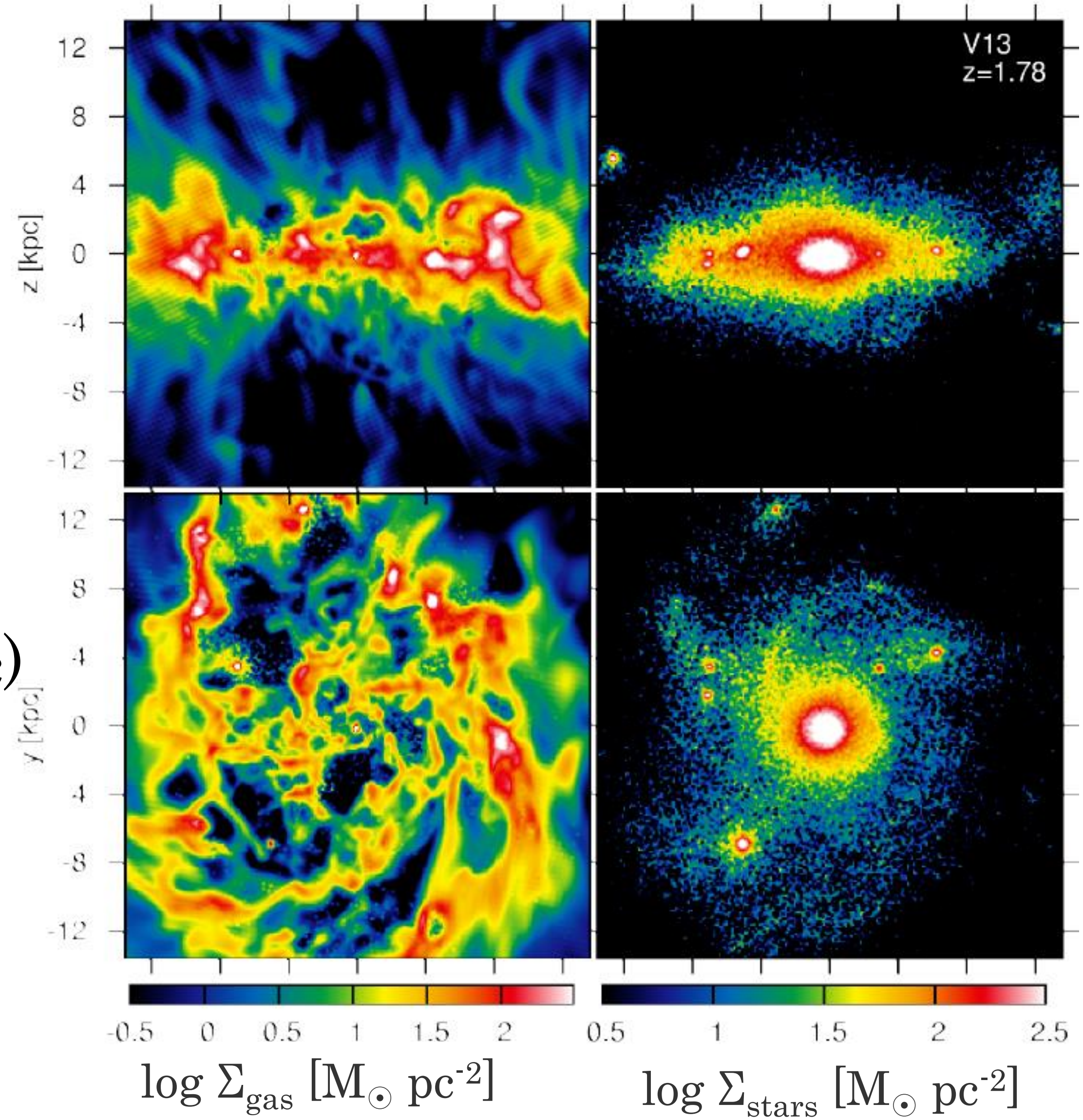
- **Instability (Q<1) can only be seen in/around the clumps.**
- **Disc (inter-clump) regions seem to be stable (Q>2).**

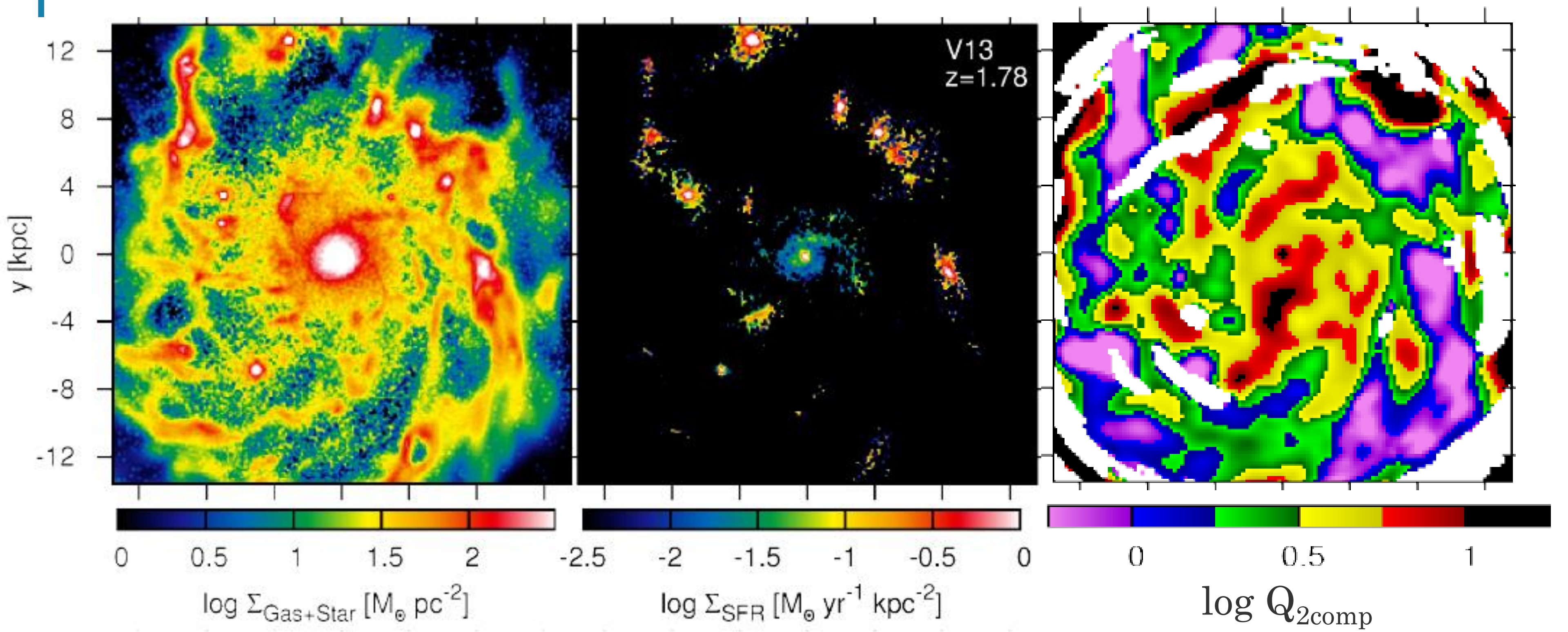


Purple Q<1: linear instability
Blue Q=1-1.8: non-linear instability
Green Q=1.8-3: dissipative instability
Yellow, Red, Black: Q>3: stable state
White: imaginary κ (Q cannot be defined)

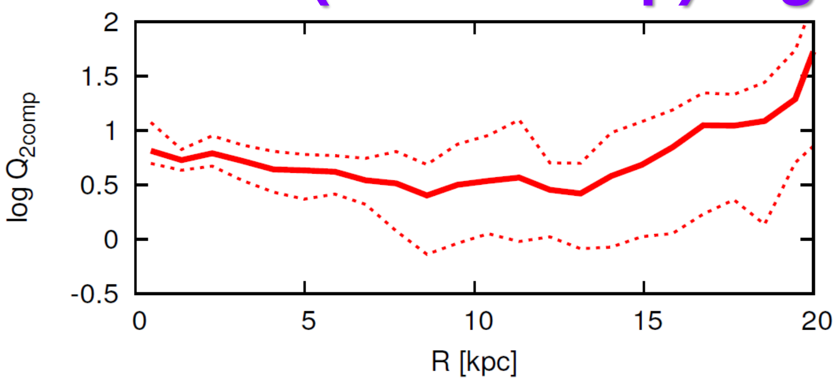
Cosmological simulations

- 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)
  - $SFR = 11.2\ \mathrm{M}_{\odot}\ \mathrm{yr}^{-1}$



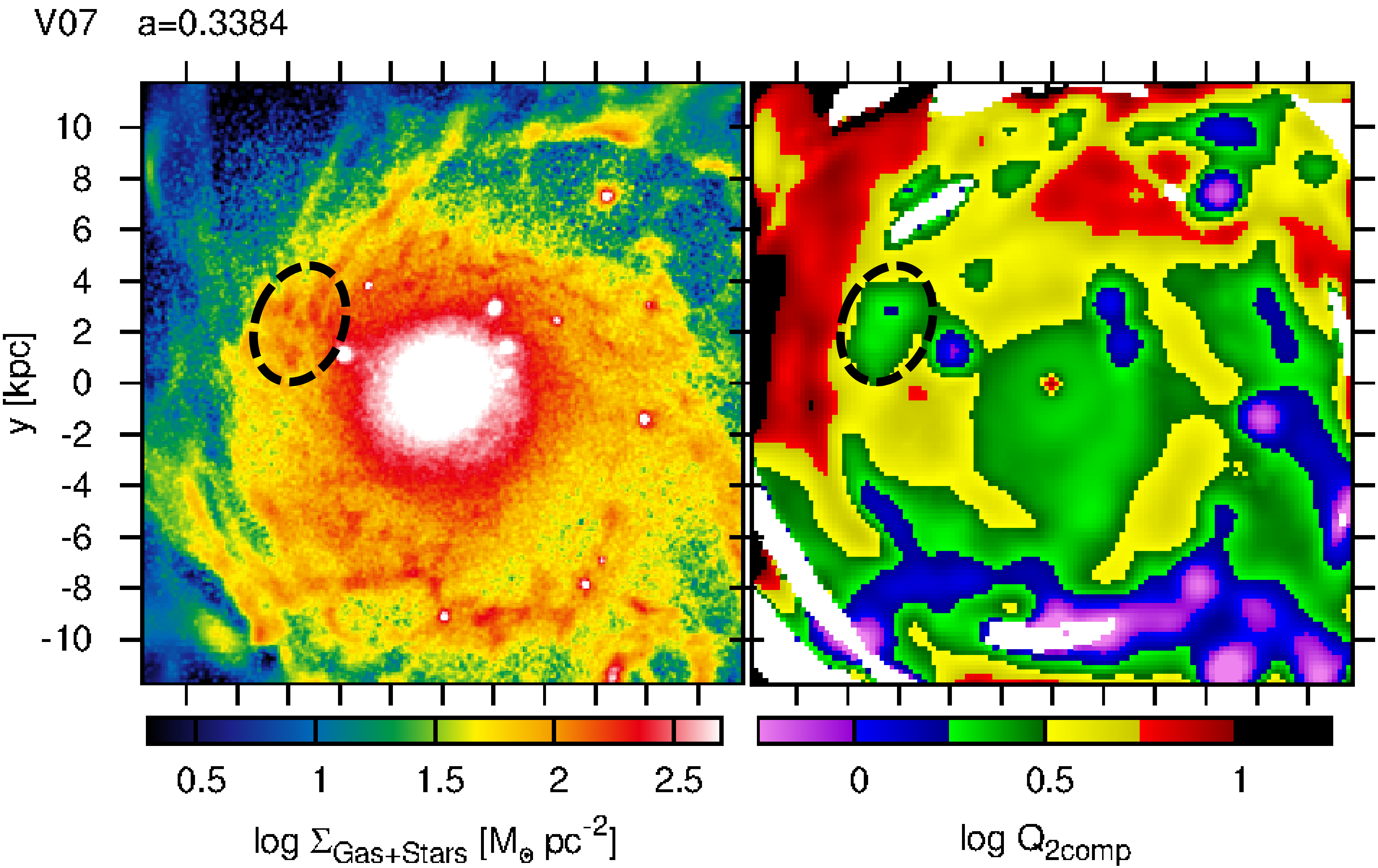


- **Instability (Q<1) can only be seen in/around the clumps.**
- **Disc (inter-clump) regions seem to be stable (Q>2).**

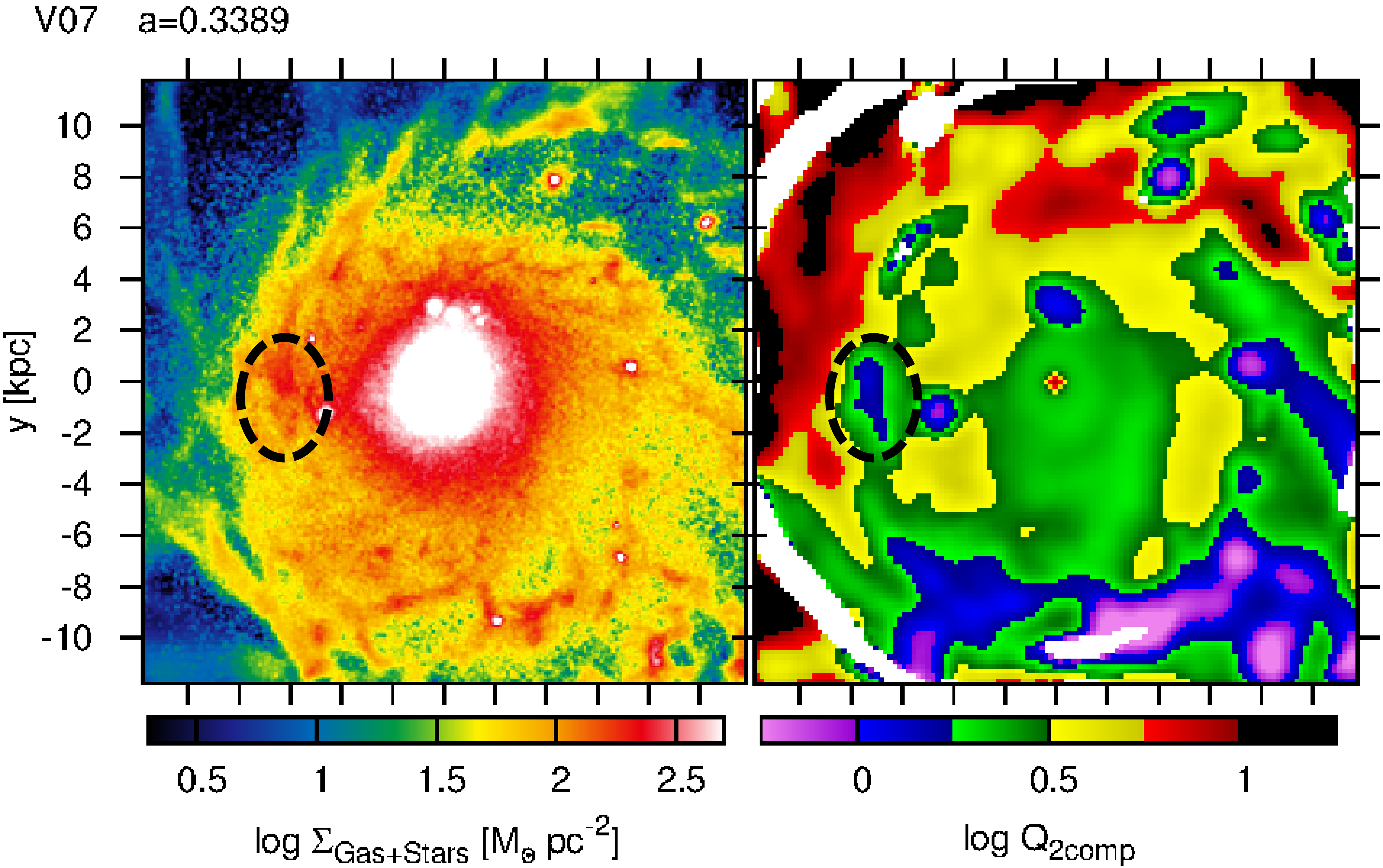


Purple Q<1: linear instability
Blue Q=1-1.8: non-linear instability
Green Q=1.8-3: dissipative instability
Yellow, Red, Black: Q>3: stable state
White: imaginary κ (Q cannot be defined)

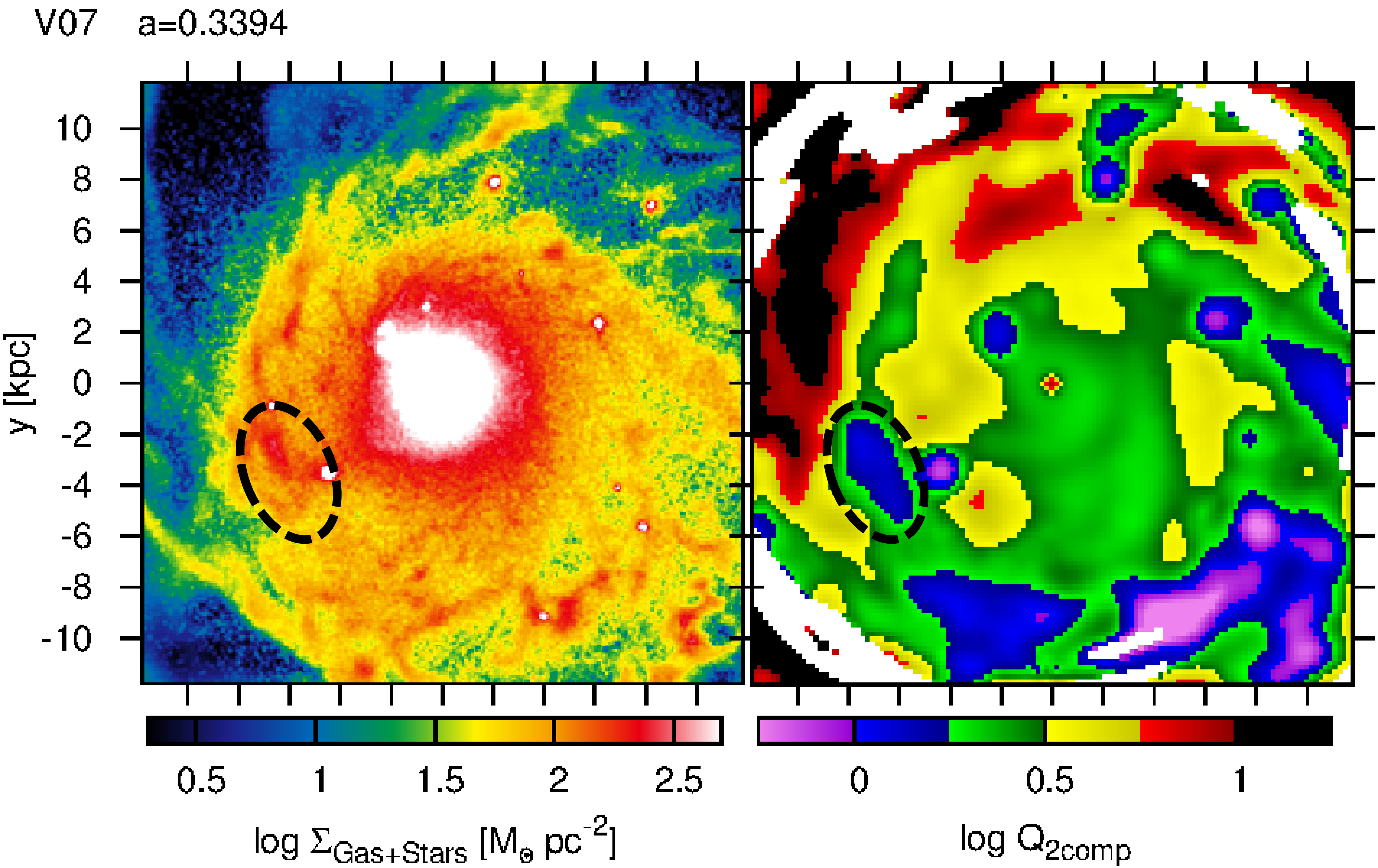
Non-linear formation of clumps



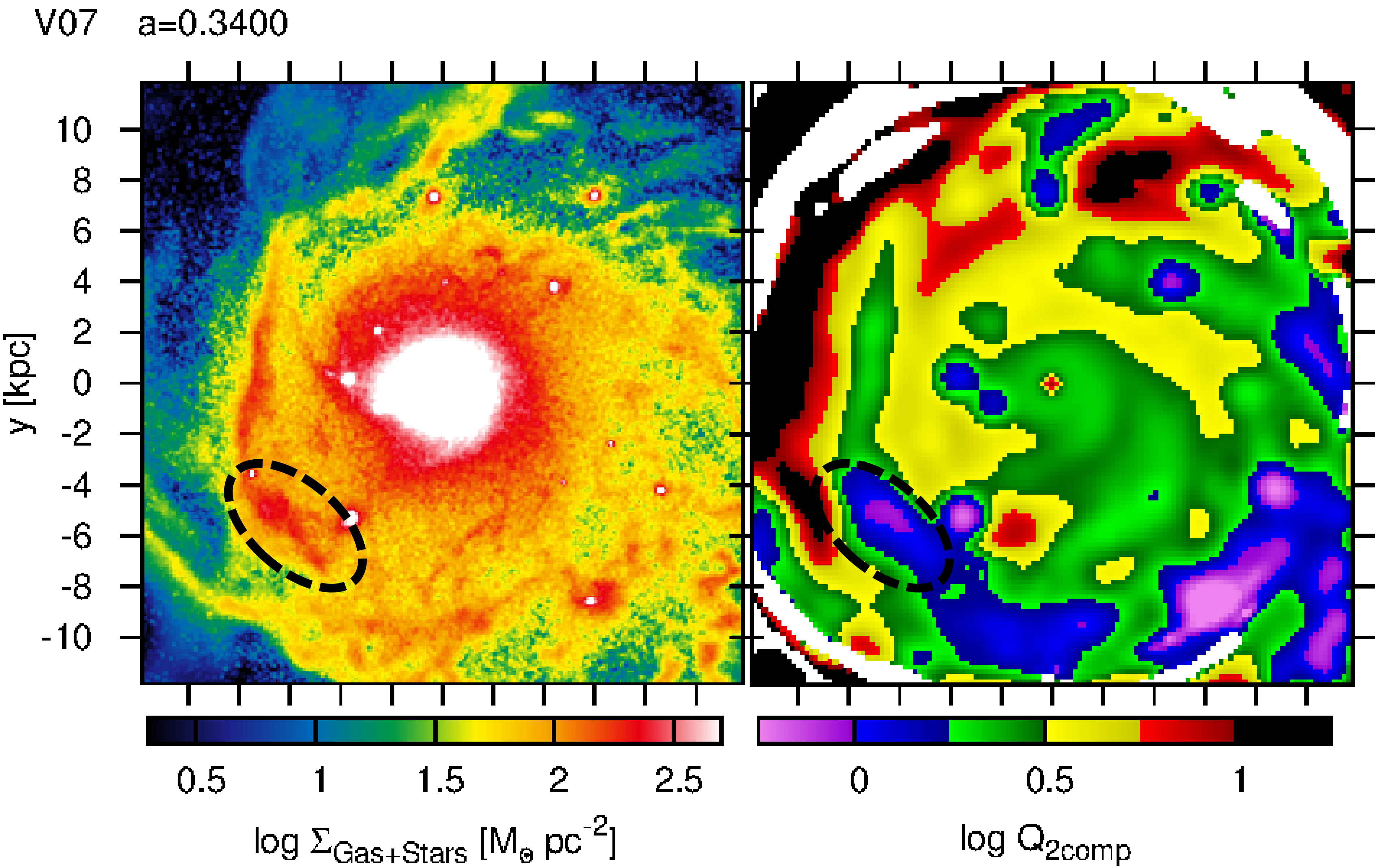
Non-linear formation of clumps



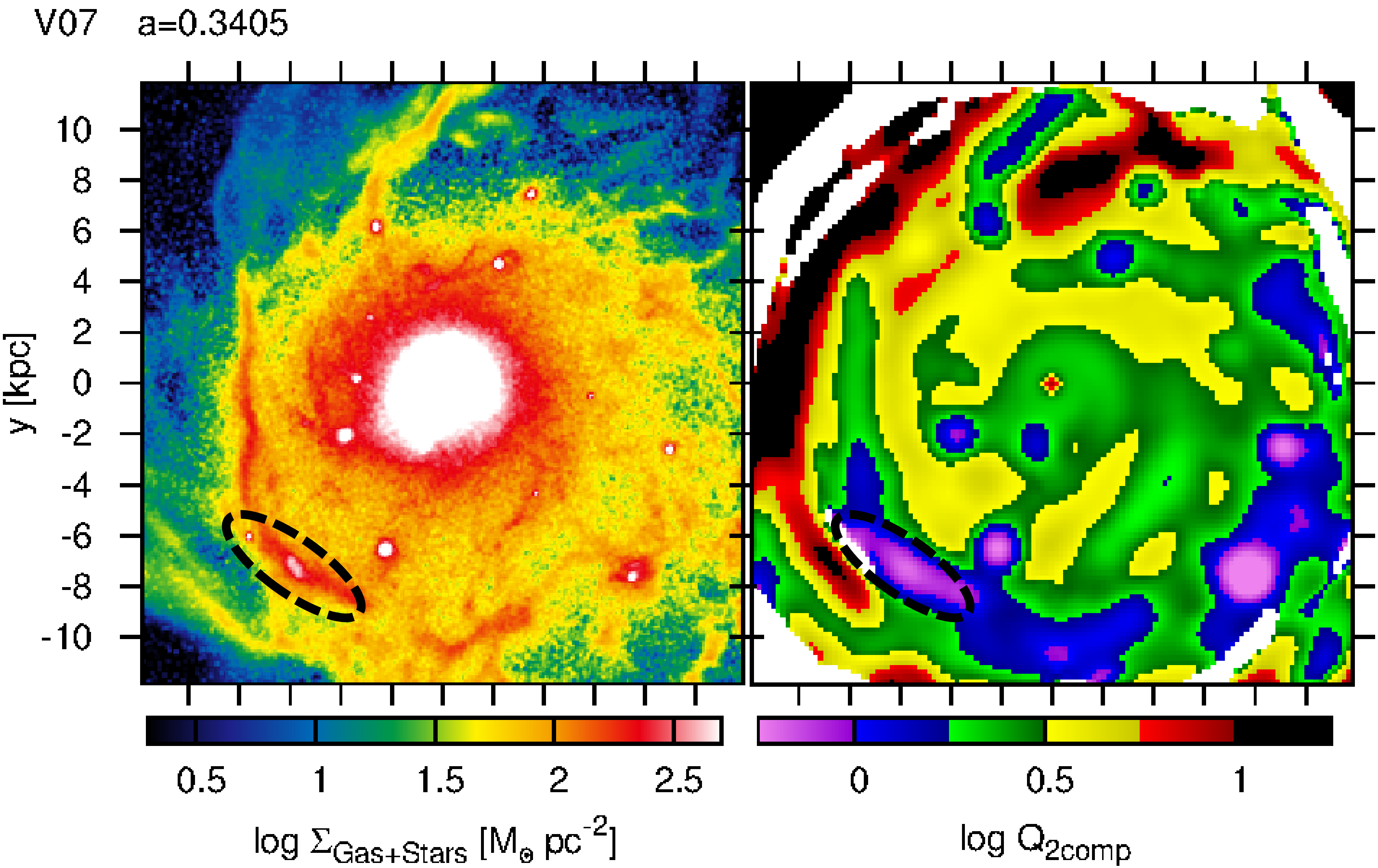
Non-linear formation of clumps



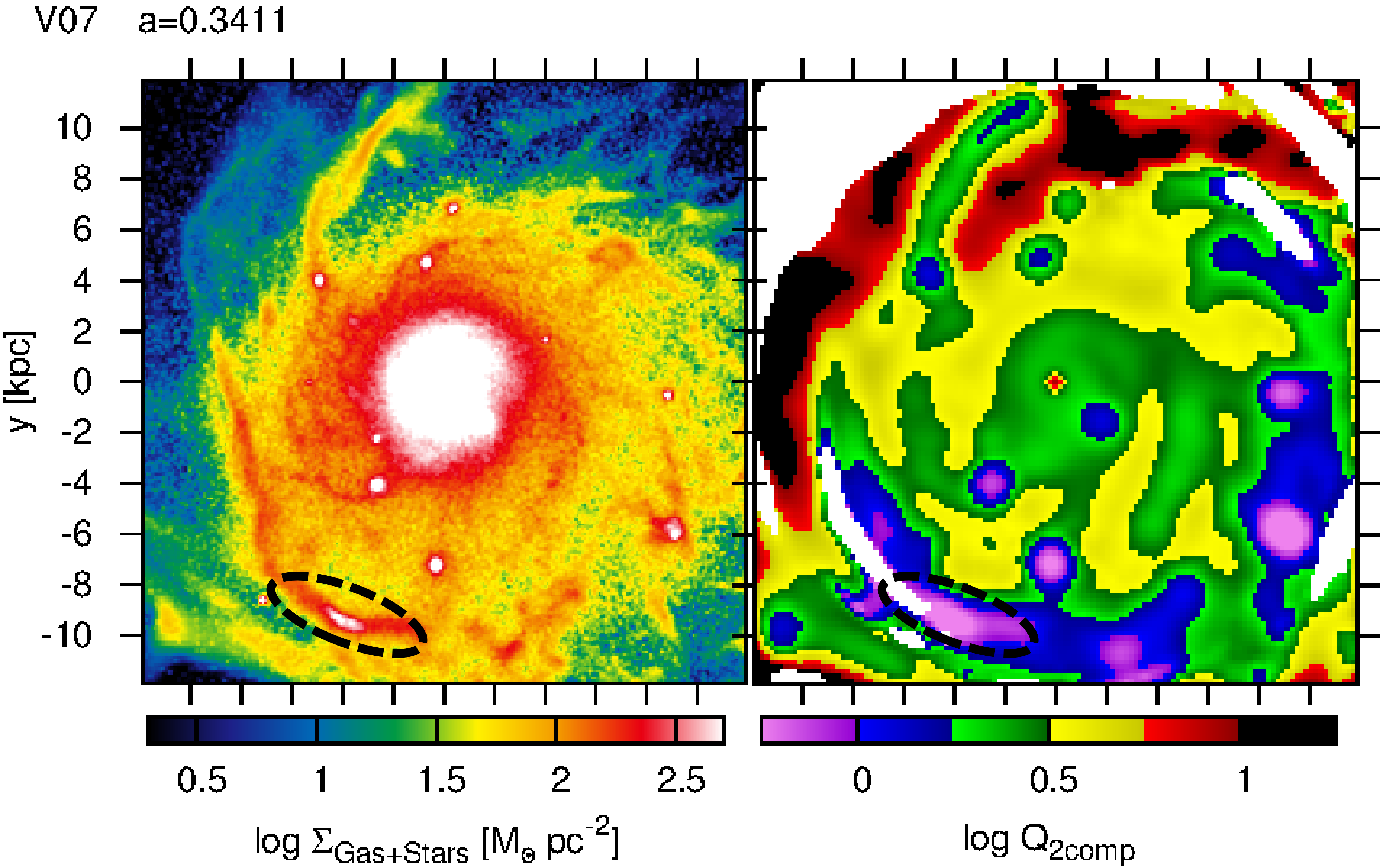
Non-linear formation of clumps



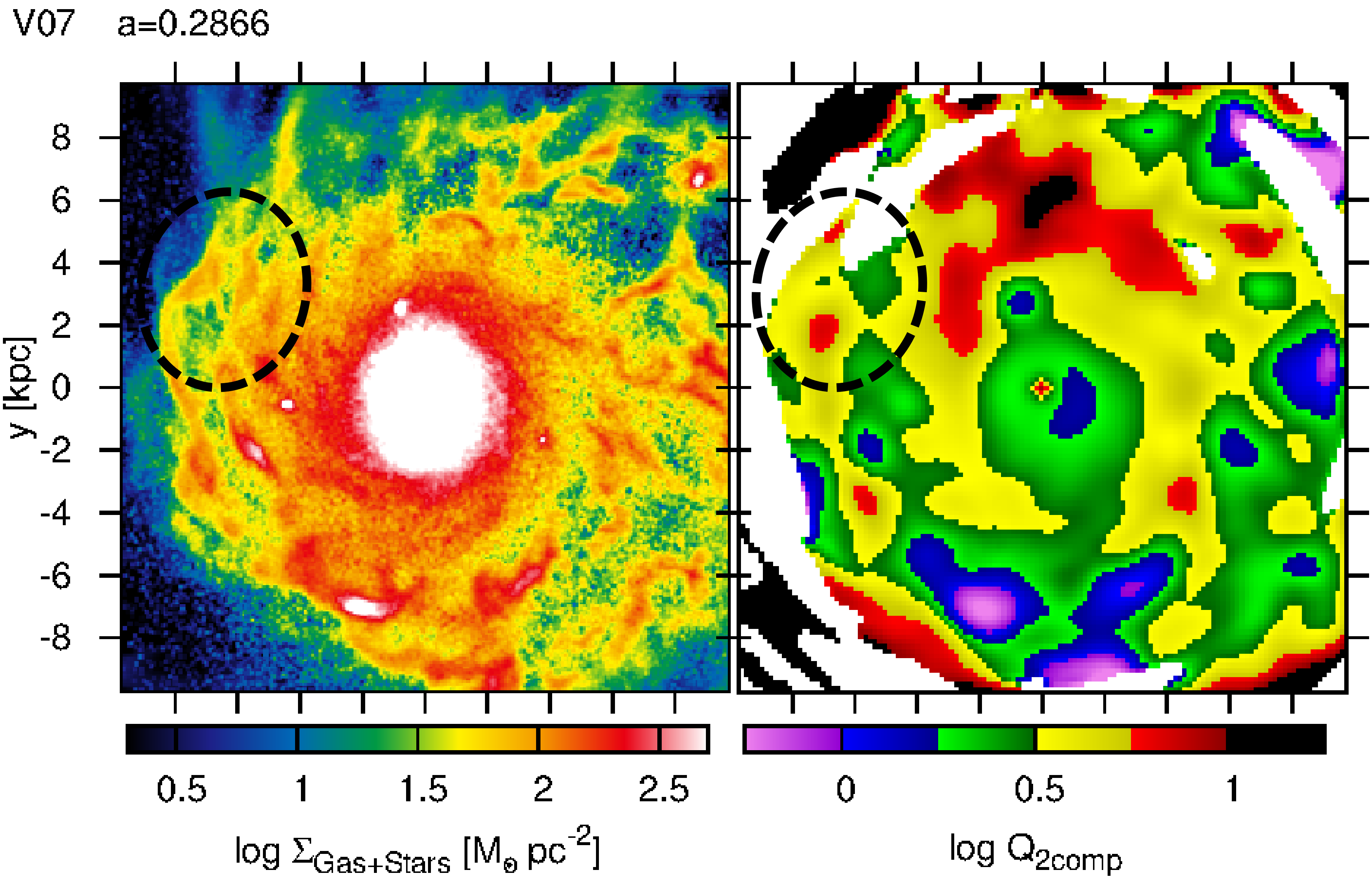
Non-linear formation of clumps



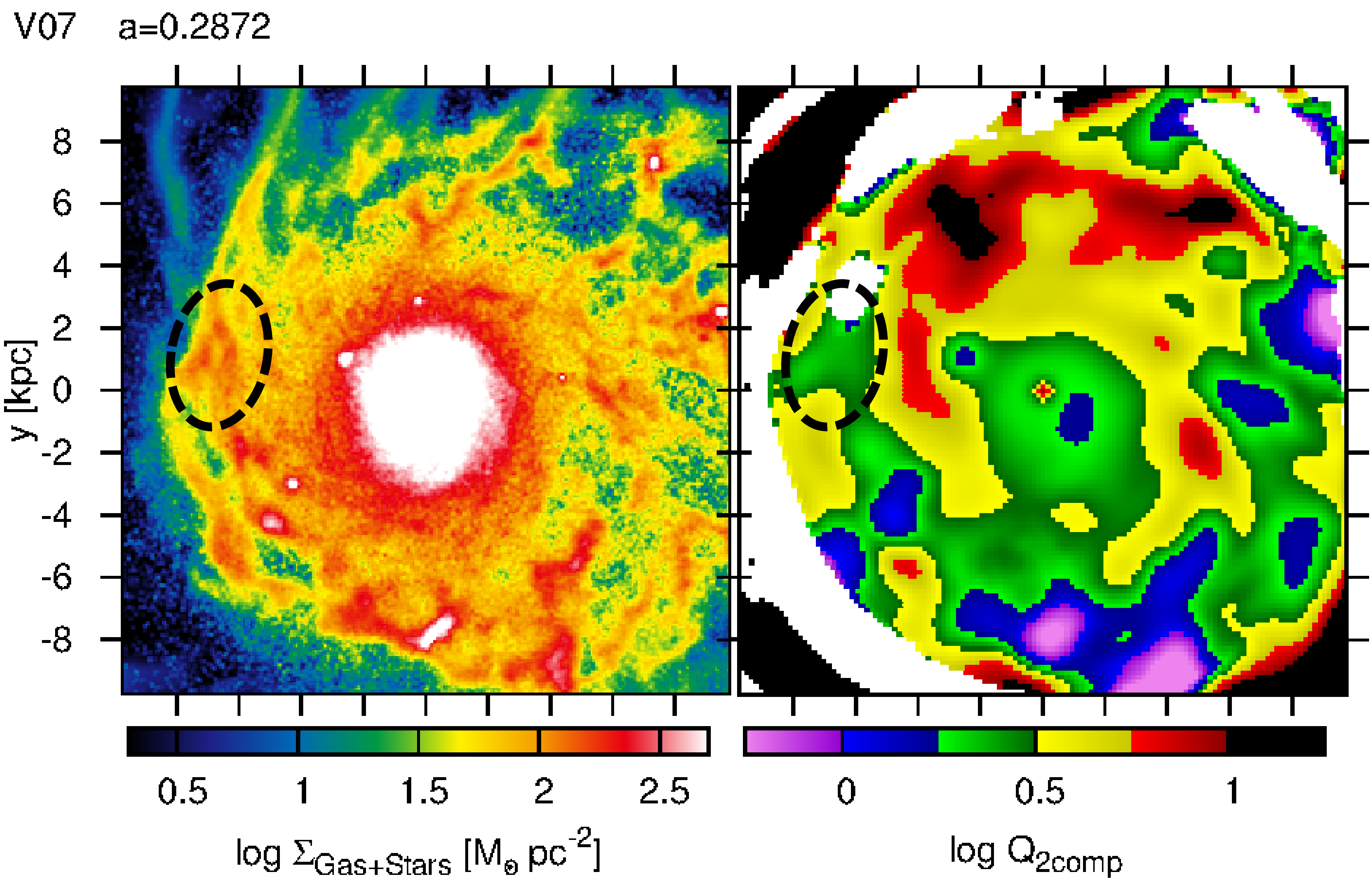
Non-linear formation of clumps



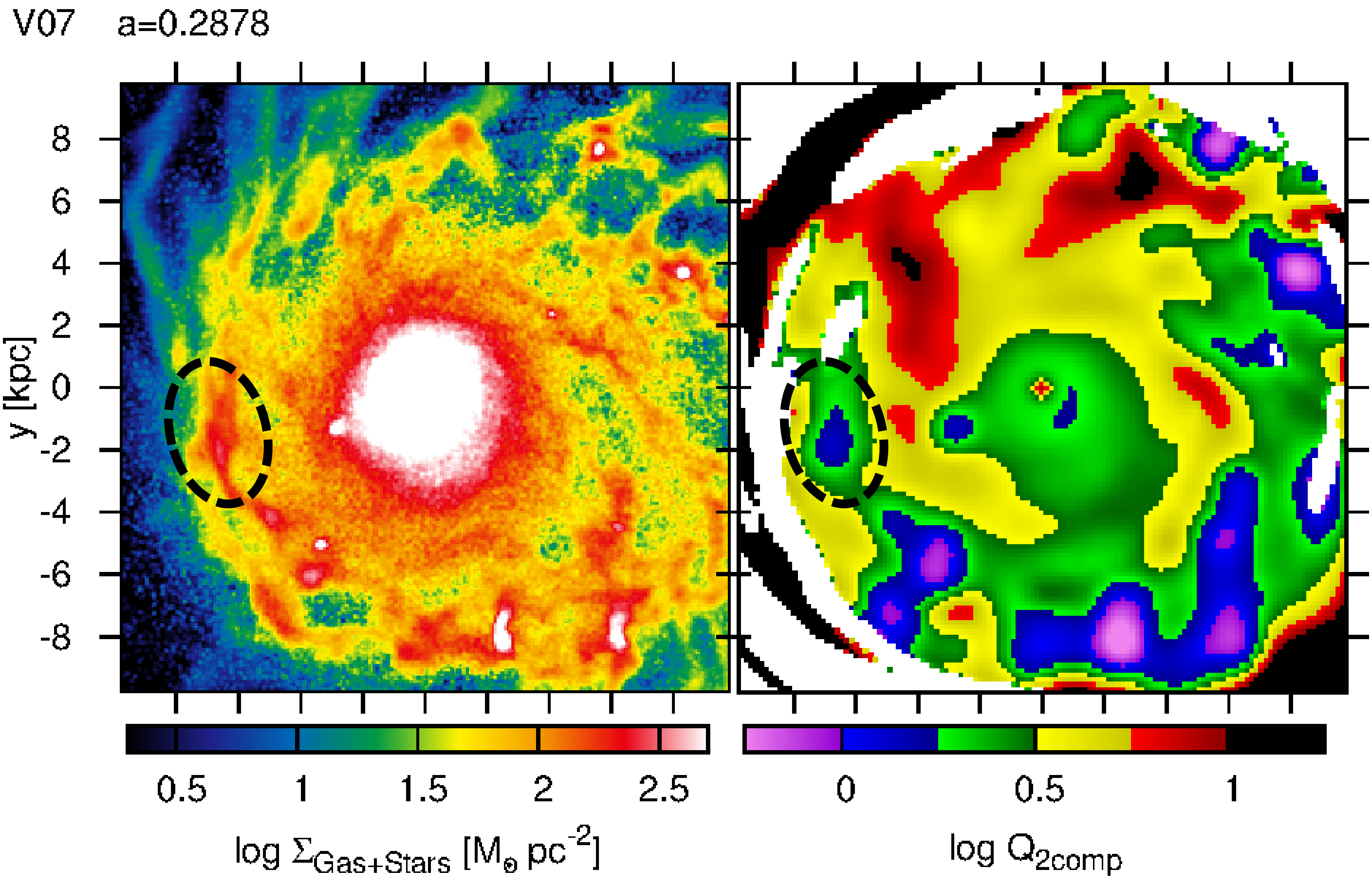
Non-linear formation of clumps



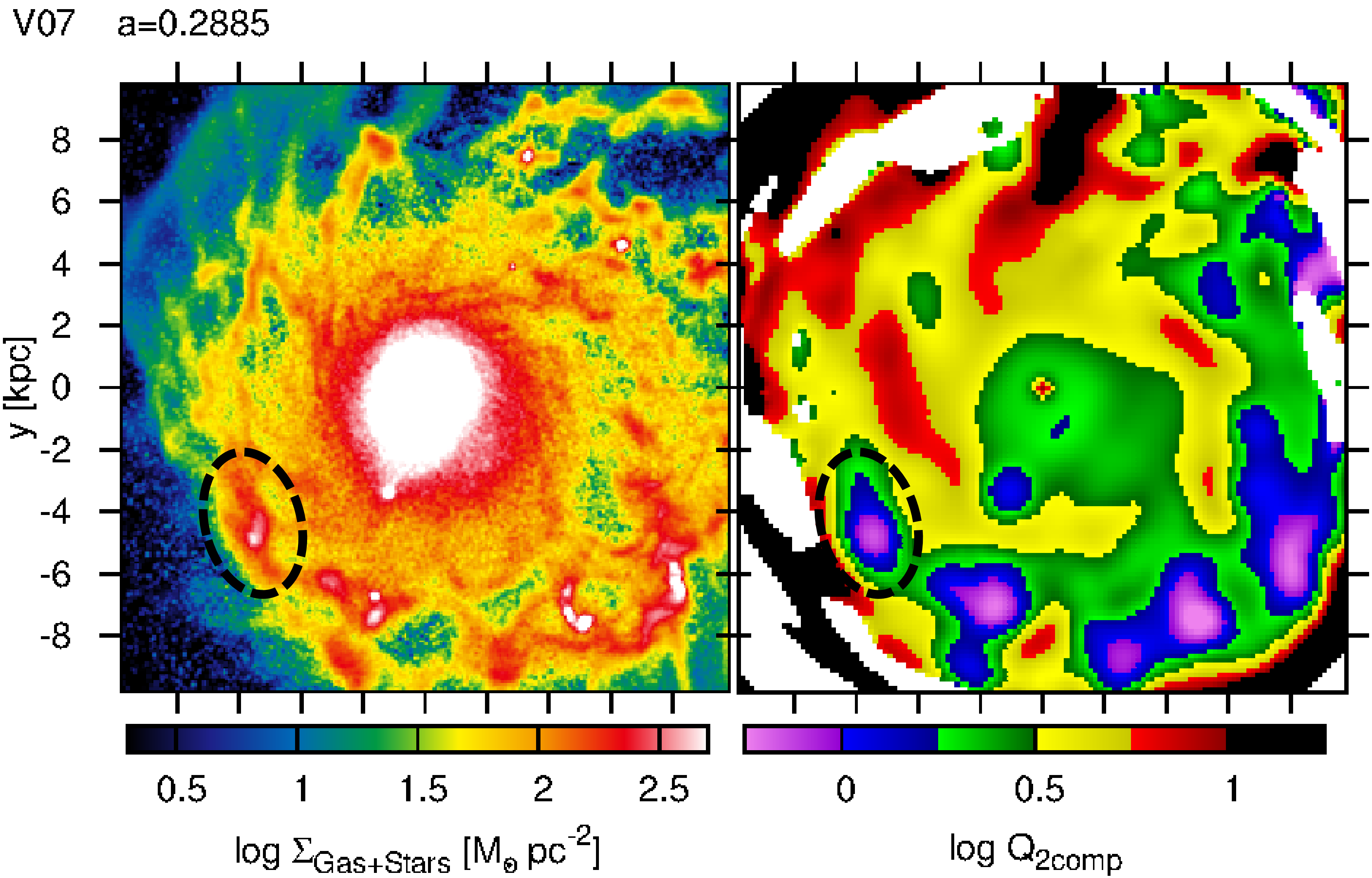
Non-linear formation of clumps



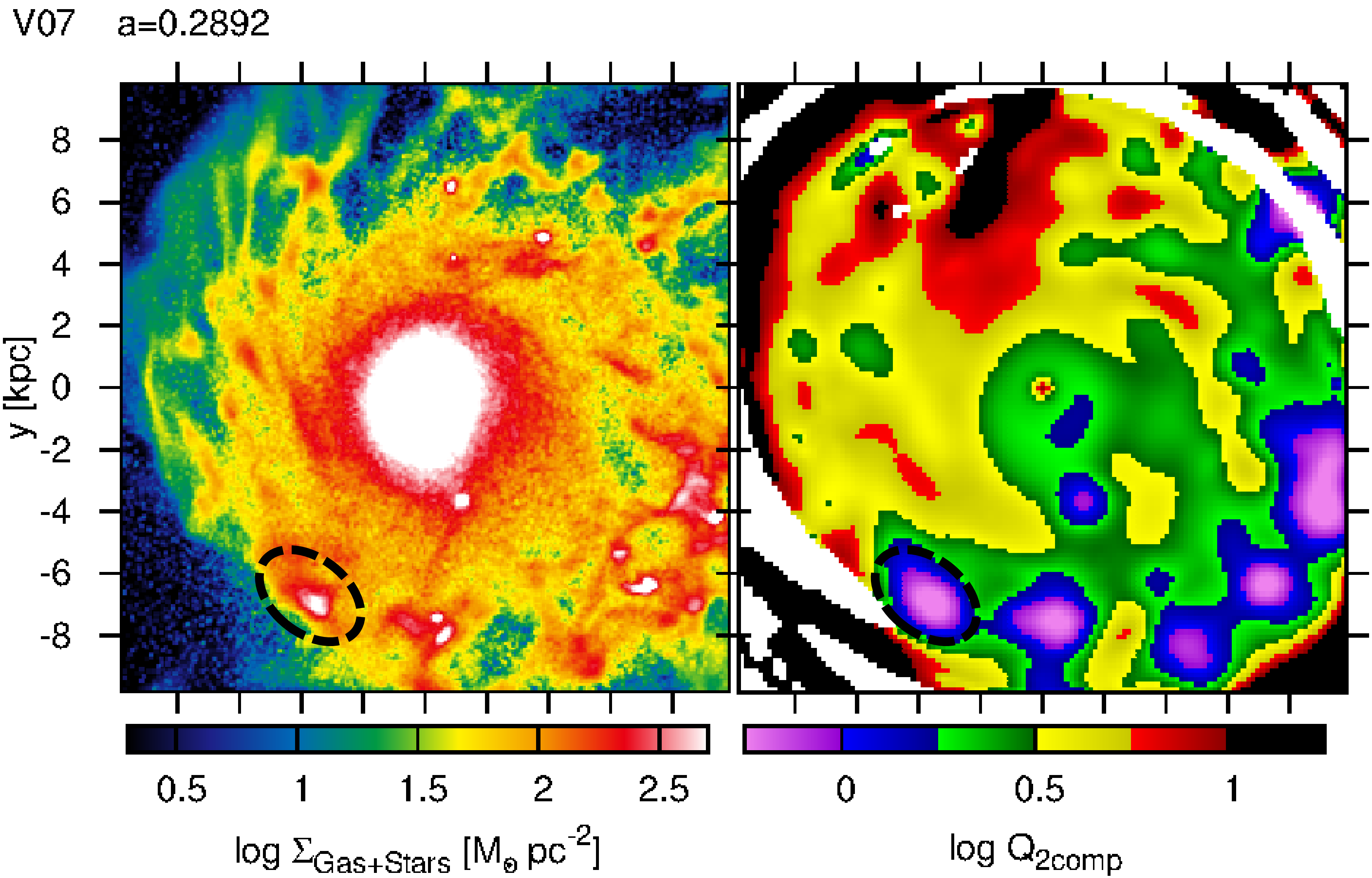
Non-linear formation of clumps



Non-linear formation of clumps



Non-linear formation of clumps

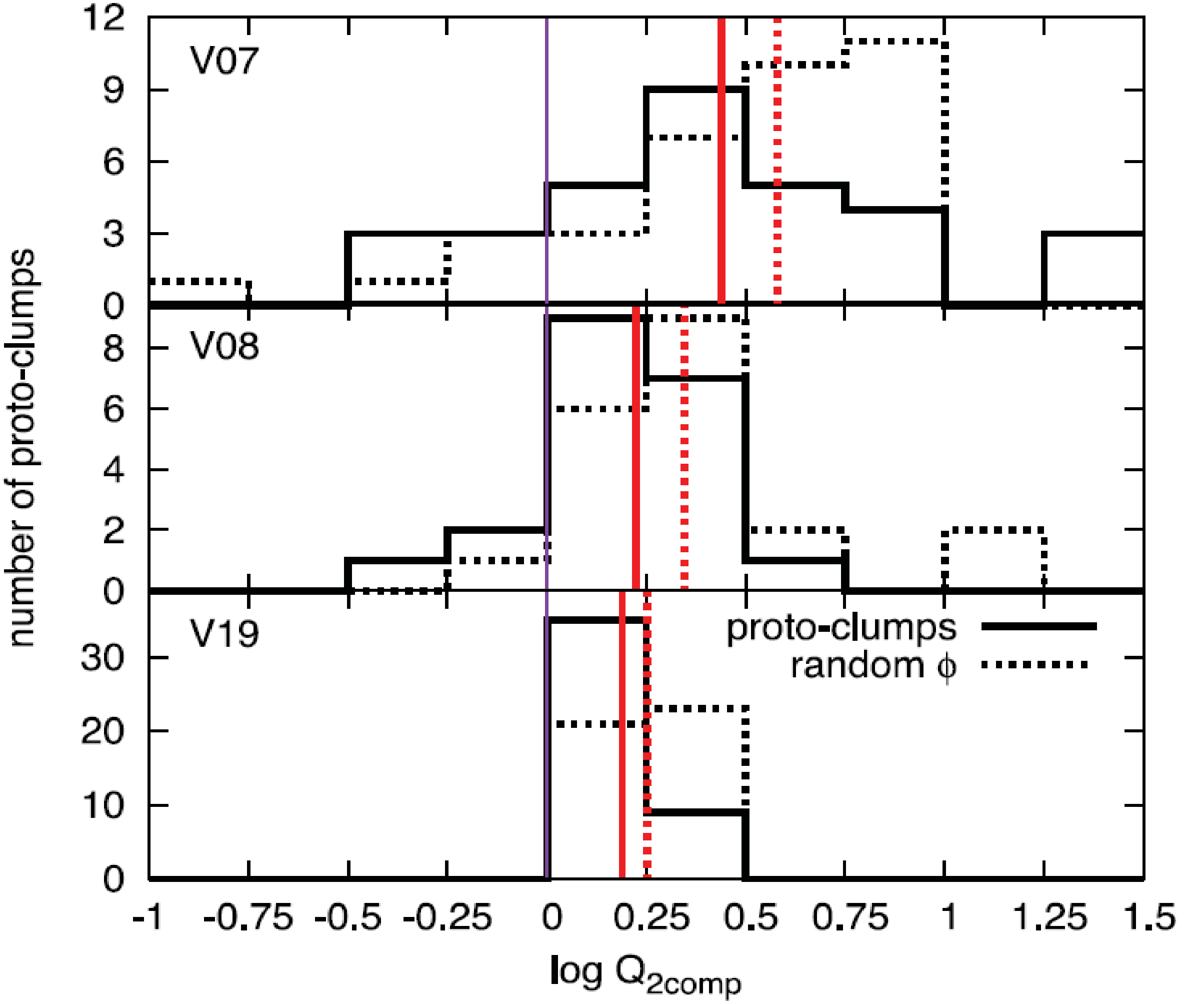


Non-linear formation of clumps

- 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.

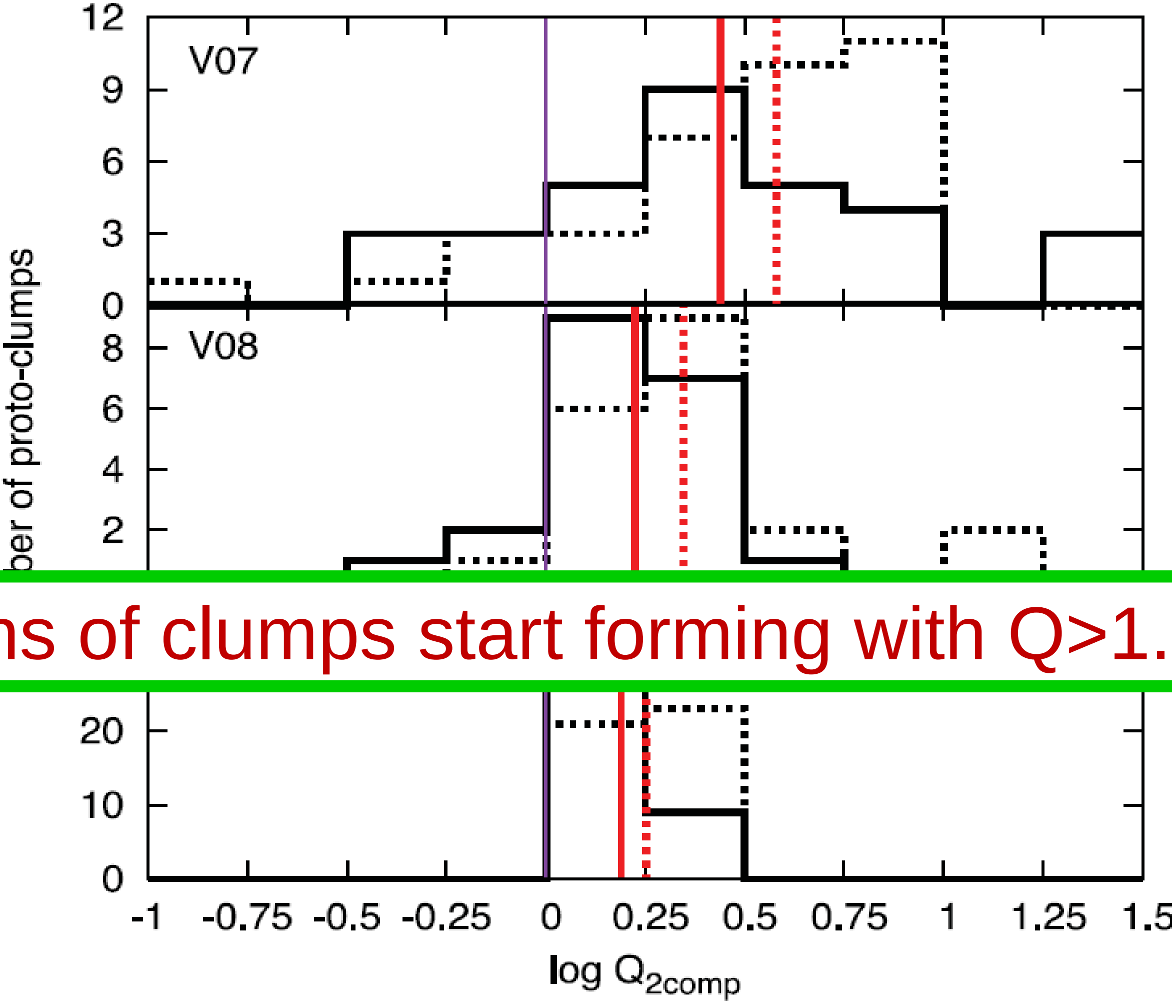


Non-linear formation of clumps

- 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



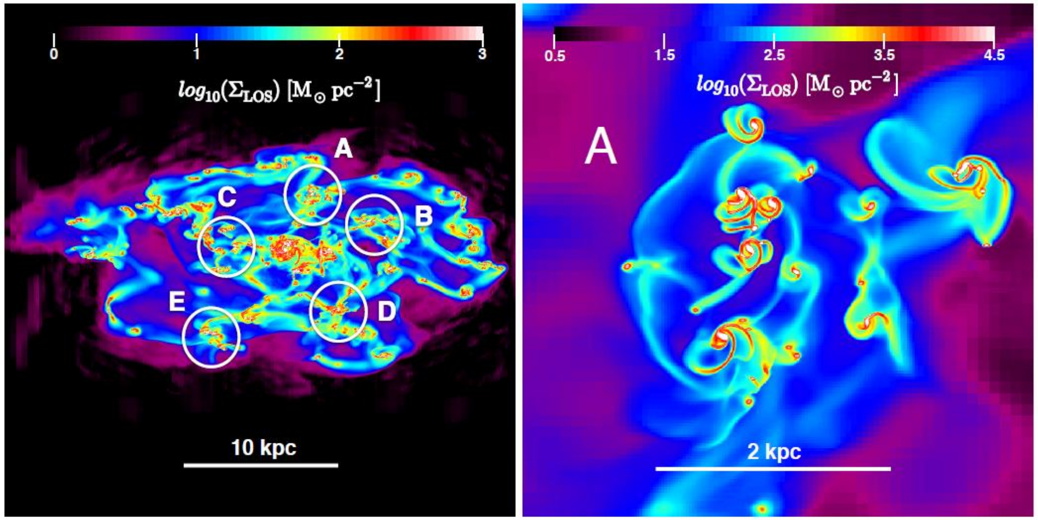
Significant fractions of clumps start forming with Q>1.8

How do giant clumps form?

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

How do giant clumps form?

- **Non-perturbative scenarios**
  - Gas dissipation
    - $Q_{crit} = 2 - 3$ if gas cooling is rapid. *(Elmegreen 2011)*
  - Small-scale formation and merger/accretion growth
    - Q can be <1 on small scales *(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)

How do giant clumps form?

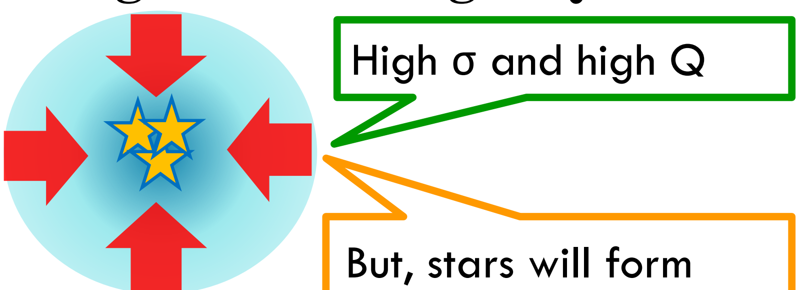
- Non-perturbative scenarios
  - Gas dissipation
    - $Q_{crit} = 2 - 3$ if gas cooling is rapid. *(Elmegreen 2011)*
  - Small-scale formation and merger/accretion growth
    - Q can be <1 on small scales *(e.g. Romeo et al 2010)*
  - Non-axisymmetric perturbation
    - $m \neq 0$ perturbations *(Griv & Gedalin 2012)*
      - unstable up to to $Q \cong 2$ for finite thickness.

How do giant clumps form?

- Perturbative scenarios
  - Minor mergers
    - Satellite accretion can disturb a disc.
  - Pre-existing clumps
    - Clumps also disturb a disc and stimulate formation of other clumps.
  - Cold stream flowing in a disc
    - Streams can join a disc with slow or counter rotation.
      - Slow rotation leads to low κ

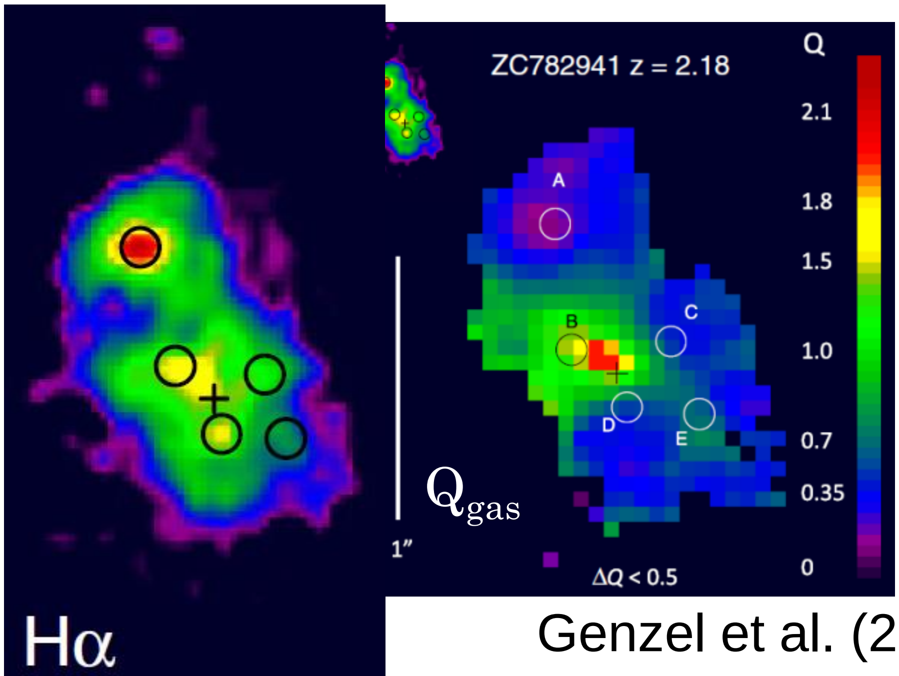
How do giant clumps form?

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

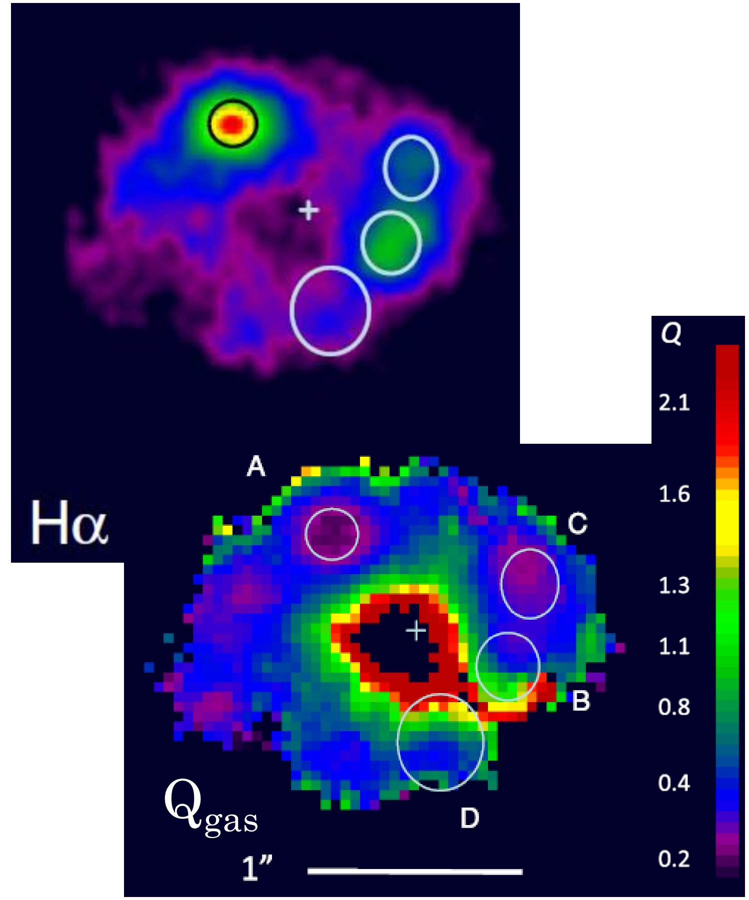


Toomre instability

- In observations,



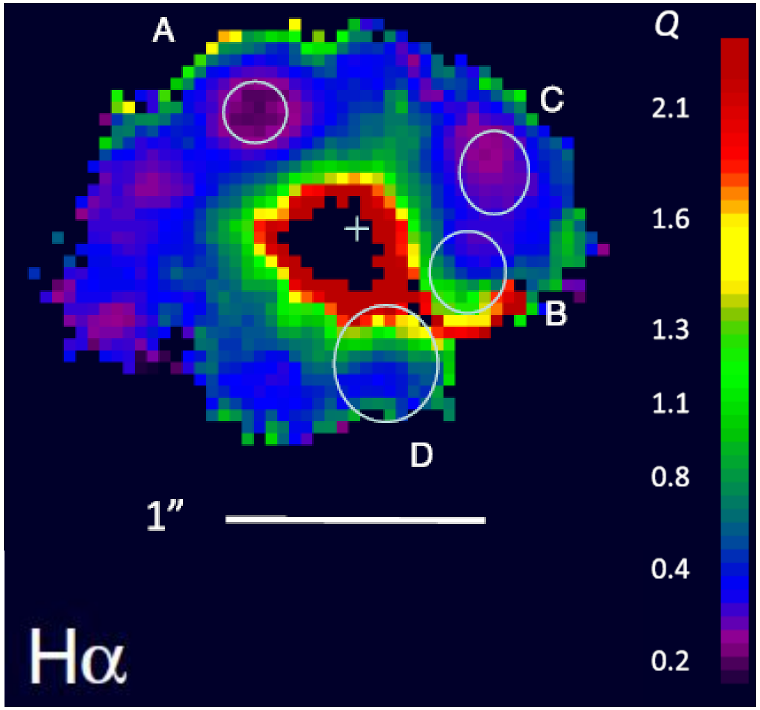
Genzel et al. (2011)
with SINFONI



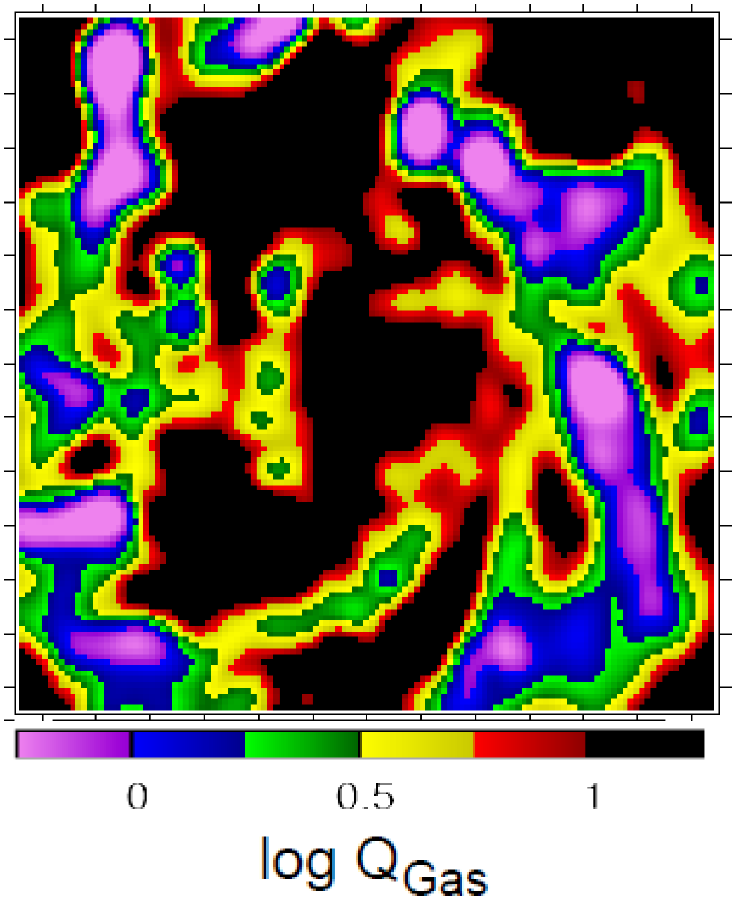
$Q \leq 1$ in the observations.
$Q > 1$ in our simulations.

Obs. vs. sims.

- Toomre Q of gas component.
- **Q ≤ 1 in the observations.**



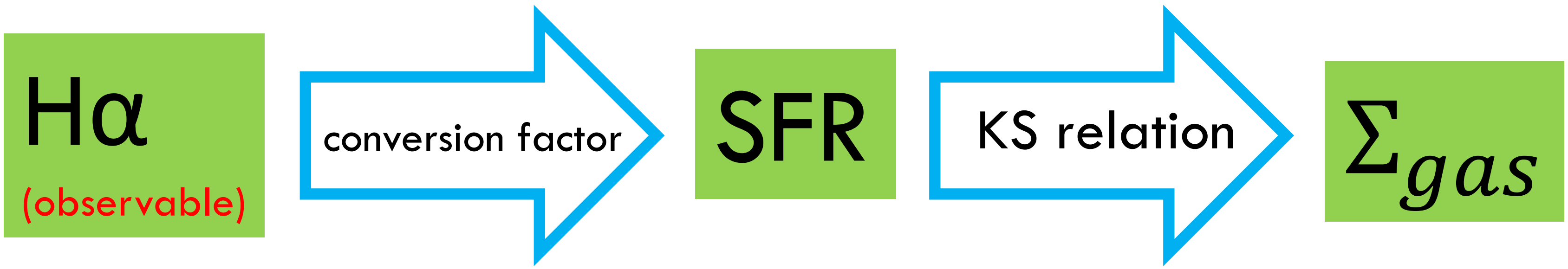
Genzel et al. (2011)



∼3-5 times lower in the obs.

Obs. vs. sims.

- Toomre Q of gas component.
- **Q ≤ 1 in the observations.**
  - <u>The observation might be underestimating Q.</u>
    - Perhaps, it might be die to overestimation of gas density.
      - **The gas density in obs. is measured from Hα luminosity.**



- **e.g.**
  - **KS relation may be different in high-z galaxies…?**
  - **Star-formation efficiency may be higher in high-z galaxies…?**

Summary

- **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..

- There is tension between our sims and IFS obs.
  - Gas density may be overestimated in IFS?

Transition of giant clump formation mechanisms at z~2: from Toomre to spiral-arm instabilities

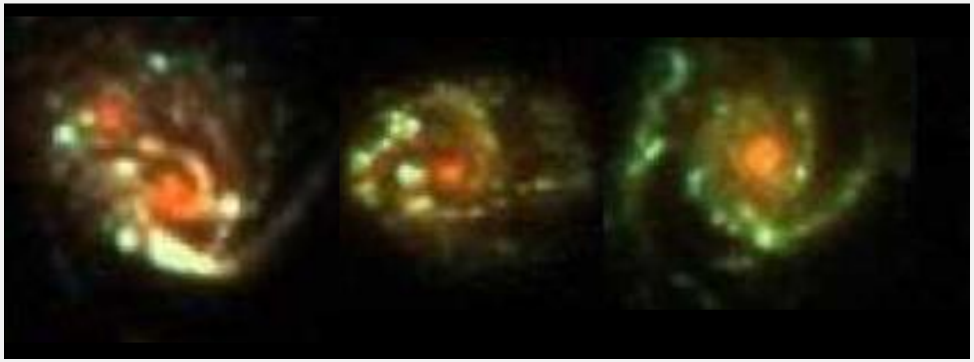
Beyond Toomre's Q

MNRAS in press
arXiv: 1706.01895

Shigeki Inoue (Kavli IPMU / U Tokyo)

w/ Naoki Yoshida, Takatoshi Shibuya

Spiral or Clumpy?

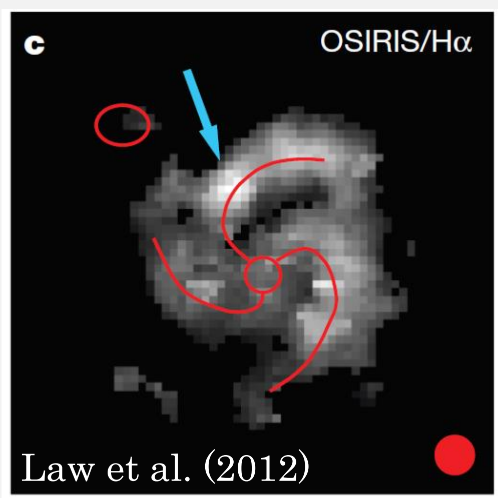


Guo et al. (2014)

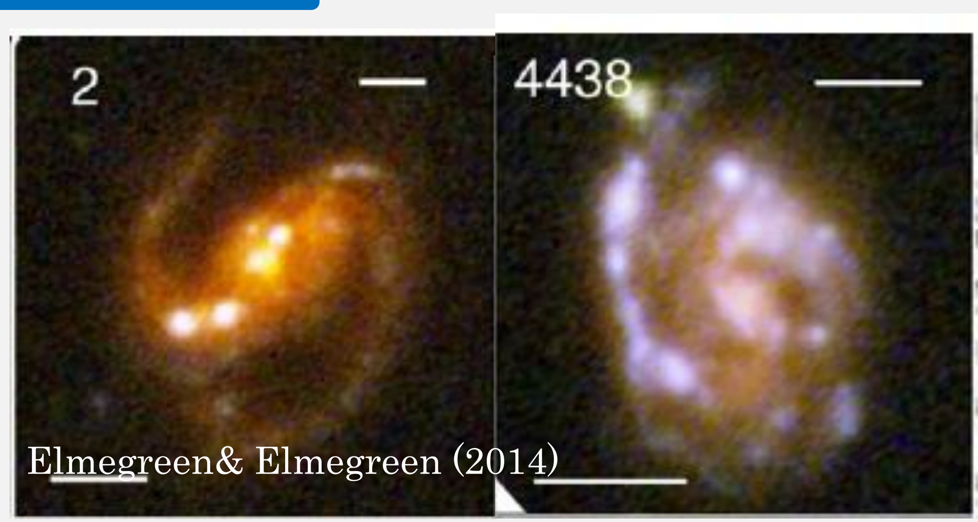
- Clumpy galaxies
  - **Giant clumps**
  - Gas-rich (f_{gas}>30%)

Spiral-arm fragmentation?

Spiral galaxies emerge at z<2 (Elmegeen+14)



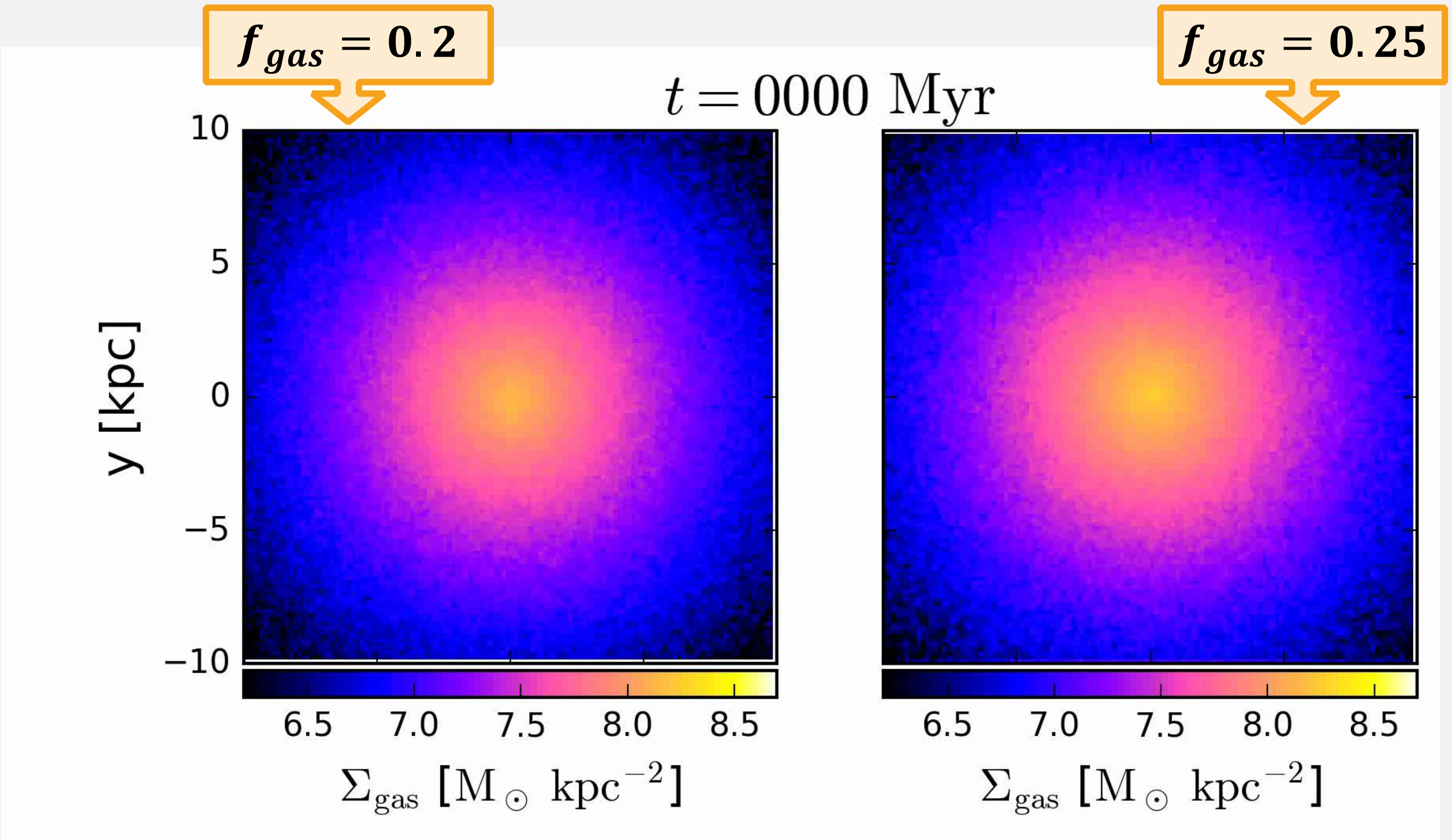
Law et al. (2012)



Elmegreen& Elmegreen (2014)

Spiral or Clumpy?

- Isolated disc galaxy simulations
  - Gas + stellar discs
  - Isothermal gas (no star formation, no feedback)
  - Moving-mesh code: Arepo



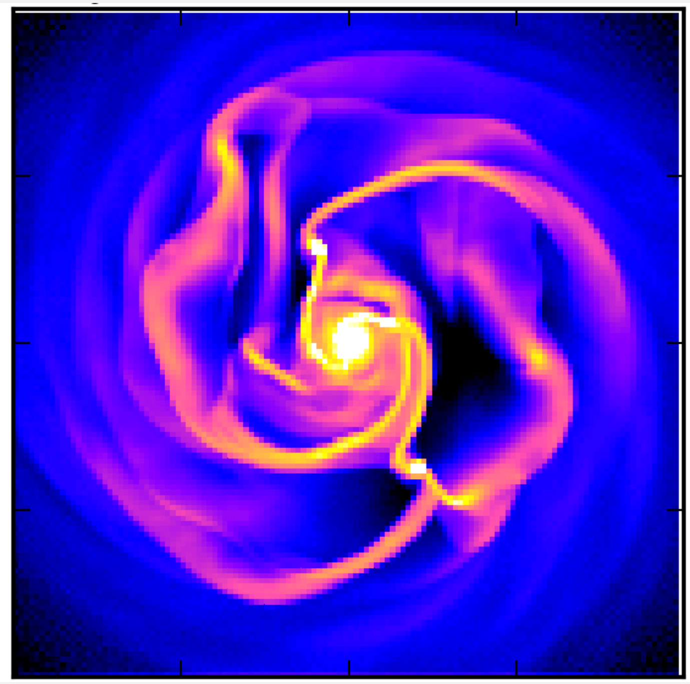
Spiral-arm fragmentation as a clump formation mechanism

- Spiral arms can fragment into clumps,
  - if the gas fraction is high and/or the disc is kinematically cold.
- **Spiral-arm fragmentation is not Toomre instability!**
- Spiral-arm fragmentation could be a possible mechanism of giant clump formation.

Beyond Toomre's Q

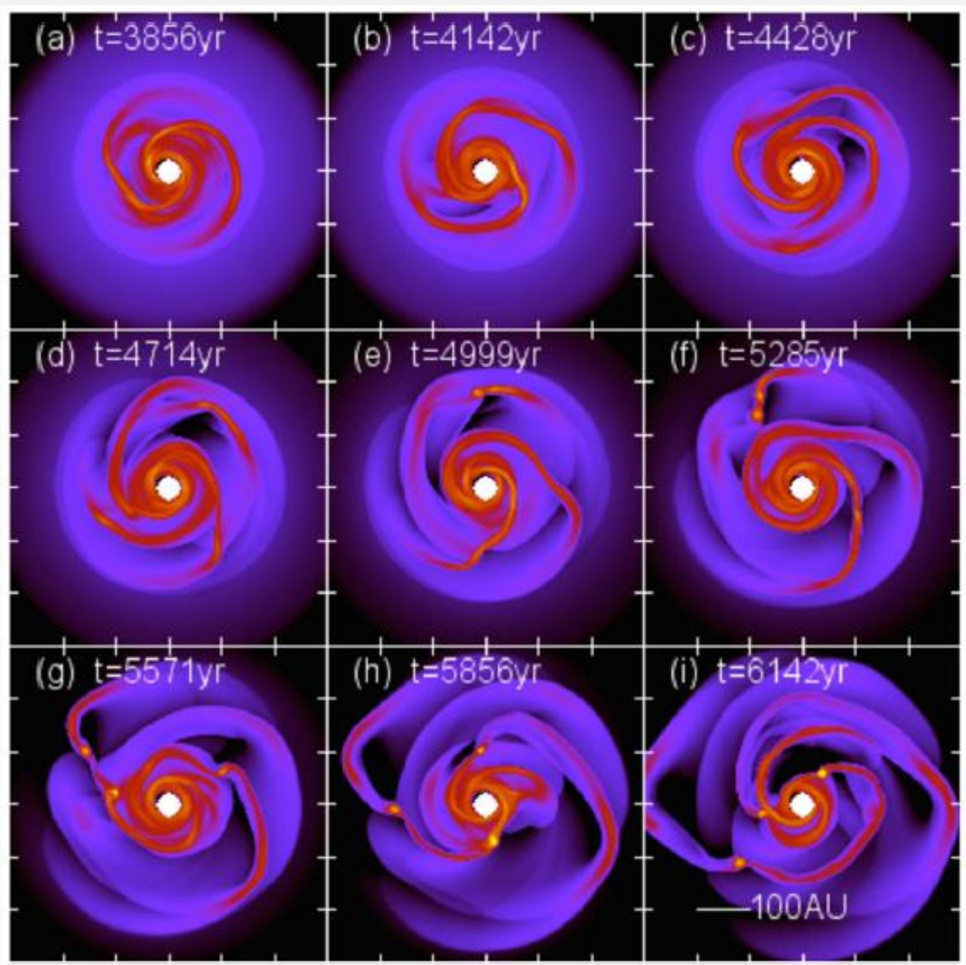
- The aims of this study:
  - How spiral-arm fragmentation occurs?
    - Derive **an instability parameter and its criterion**

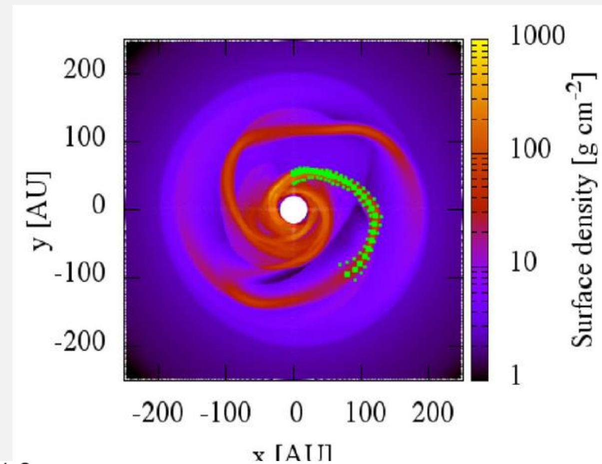
linear perturbation theory for a spiral arm

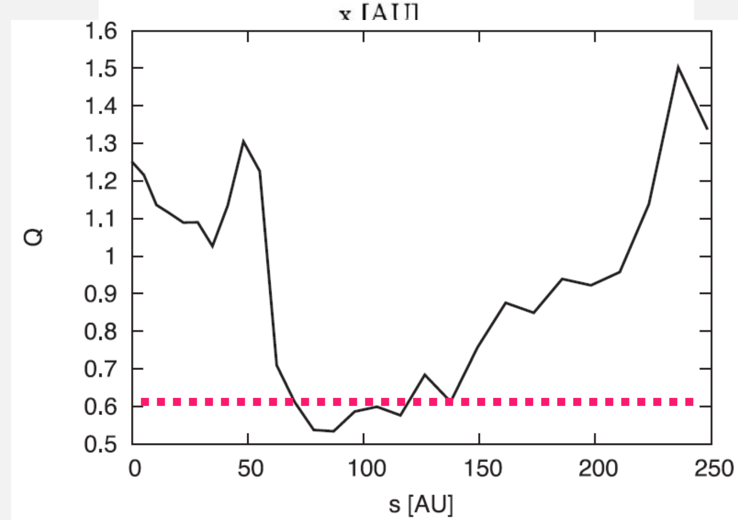


Takahashi, Tsukamoto & Inutsuka (2016)

- Proto-planetary discs
- *Spiral-arm fragmentation takes place only if $Q < 0.6$ on the spiral arm.*
- **Their linear perturbation analysis also supports this criterion.**

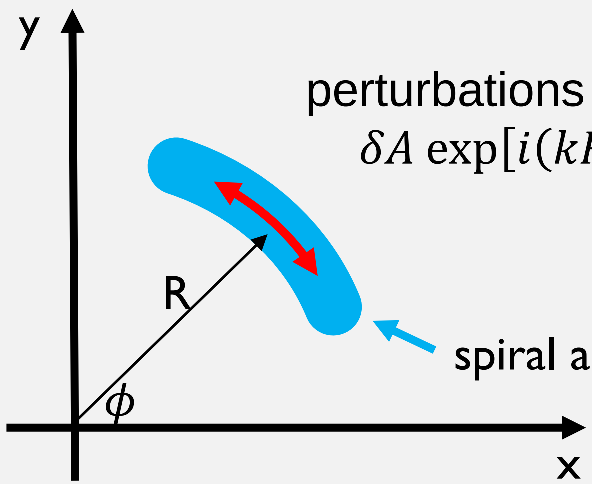






Set-up for the linear perturbation theory

- Now considering…
  - Gravitational instability for **azimuthal** perturbations on an **axisymmetric** spiral (ring).



Assuming:
- The spiral has **a rigid rotation** since self-gravitating.

$$\Omega = -B$$

- Replace surface density Σ with line-mass

$$\Upsilon = 1.4W\Sigma \quad (\textbf{Gaussian}).$$

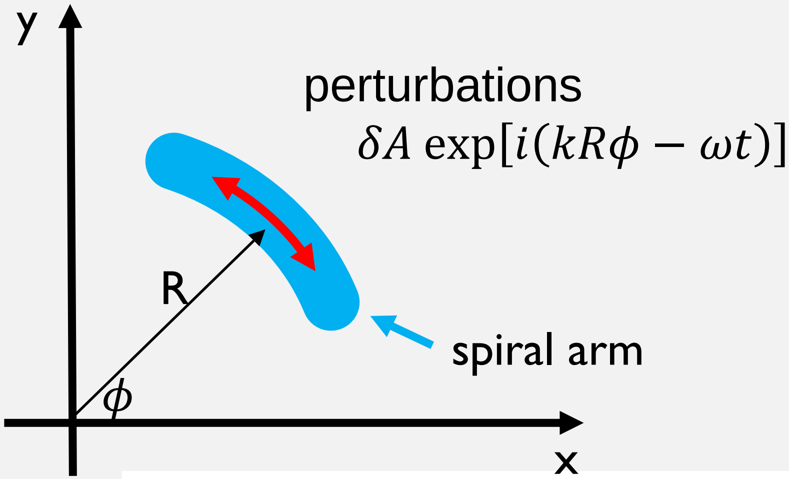
continuity: $$\frac{\partial}{\partial t}\delta\Sigma + \frac{1}{R}\frac{\partial}{\partial R}(R\Sigma_0\delta v_R) + \Omega\frac{\partial}{\partial\phi}\delta\Sigma + \frac{\Sigma_0}{R}\frac{\partial}{\partial\phi}\delta v_\phi = 0,$$

R-momentum: $$\frac{\partial}{\partial t}\delta v_R + v_R\frac{\partial}{\partial R}\delta v_R + \Omega\frac{\partial}{\partial\phi}\delta v_R - 2\Omega\delta v_\phi = -\frac{\partial}{\partial R}\left(c_s^2\frac{\delta\Sigma}{\Sigma_0} + \delta\Phi\right),$$

ϕ-momentum: $$\frac{\partial}{\partial t}\delta v_\phi + v_R\frac{\partial}{\partial R}\delta v_\phi + \Omega\frac{\partial}{\partial\phi}\delta v_\phi - 2B\delta v_R = -\frac{1}{R}\frac{\partial}{\partial\phi}\left(c_s^2\frac{\delta\Sigma}{\Sigma_0} + \delta\Phi\right).$$

Set-up for the linear perturbation theory

- Now considering…
  - Gravitational instability for **azimuthal** perturbations on an **axisymmetric** spiral (ring).



Assuming:
- The spiral has **a rigid rotation** since self-gravitating.

$$\Omega = -B$$

- Replace surface density Σ with line-mass

$$\Upsilon = 1.4 W \Sigma \quad (\textbf{Gaussian}).$$

continuity: $$\omega \delta \Upsilon = k \Upsilon \delta v_\phi,$$

R-momentum: $$-i\omega \delta v_R = 2\Omega \delta v_\phi,$$

ϕ-momentum: $$-i\omega \delta v_\phi = -2\Omega \delta v_R - ik \frac{c_s^2}{\Upsilon} \delta \Upsilon - ik \delta \Phi.$$

A dispersion relation for a single-component model

- One can obtain the dispersion relation for the perturbations,

$$\omega^2 = \left(c_s^2 + \frac{\Upsilon}{\delta\Upsilon}\delta\Phi \right) k^2 + 4\Omega^2.$$

- The Poisson equation for the perturbations is

$$\begin{aligned} \delta\Phi &= \int_{-W}^{W} -G\delta\Upsilon K_0(|kx|)/W \mathrm{d}x \\ &= -\pi G\delta\Upsilon \underbrace{\left[K_0(kW)L_{-1}(kW) + K_1(kW)L_0(kW)\right]}_{f(kW)} \end{aligned}$$

K : Bessel function
L : Struve function

W : half width of arm

A dispersion relation for a single-component model

- One can obtain the dispersion relation for the perturbations,

$$\omega^2 = \left(c_s^2 - \pi G f(kW)\Upsilon\right) k^2 + 4\Omega^2.$$

(cf. Takahashi, Tsukamoto & Inutsuka 2016)

- This can be transformed as

$$\frac{c_s^2 k^2 + 4\Omega^2 - \omega^2}{\pi G f(kW)\Upsilon k^2} = 1.$$

- When $\omega^2 < 0$, the spiral is unstable.
- Considering this in the boundary case $\omega^2 = 0$, the new instability parameter and its criterion can be defined as

$$S \equiv \frac{c_s^2 k^2 + 4\Omega^2}{\pi G f(kW)\Upsilon k^2} < 1.$$

A dispersion relation for a two-component model

- A galaxy usually has gas and stars. The dispersion relations of gas and stars are,

gas:

$$\omega^2 = \left(c_s^2 + \frac{\Upsilon_{\rm g}}{\delta\Upsilon_{\rm g}}\delta\Phi\right)k^2 + 4\Omega^2, \qquad \delta\Upsilon_{\rm g} = k^2 \frac{\Upsilon_{\rm g}}{\omega^2 - 4\Omega^2 - c_s^2 k^2}\delta\Phi,$$

stars:

$$\omega^2 = \left(\sigma_\phi^2 + \frac{\Upsilon_{\rm s}}{\delta\Upsilon_{\rm s}}\delta\Phi\right)k^2 + 4\Omega^2, \qquad \delta\Upsilon_{\rm s} = k^2 \frac{\Upsilon_{\rm s}}{\omega^2 - 4\Omega^2 - \sigma_\phi^2 k^2}\delta\Phi,$$

- Because gas and stars interact only through gravity, they are connected in the Poisson eq.,

$$\delta\Phi = -\pi G\left[\delta\Upsilon_{\rm g} f(kW_{\rm g}) + \delta\Upsilon_{\rm s} f(kW_{\rm s})\right]$$

- Then, one can obtain the two-component dispersion relation,

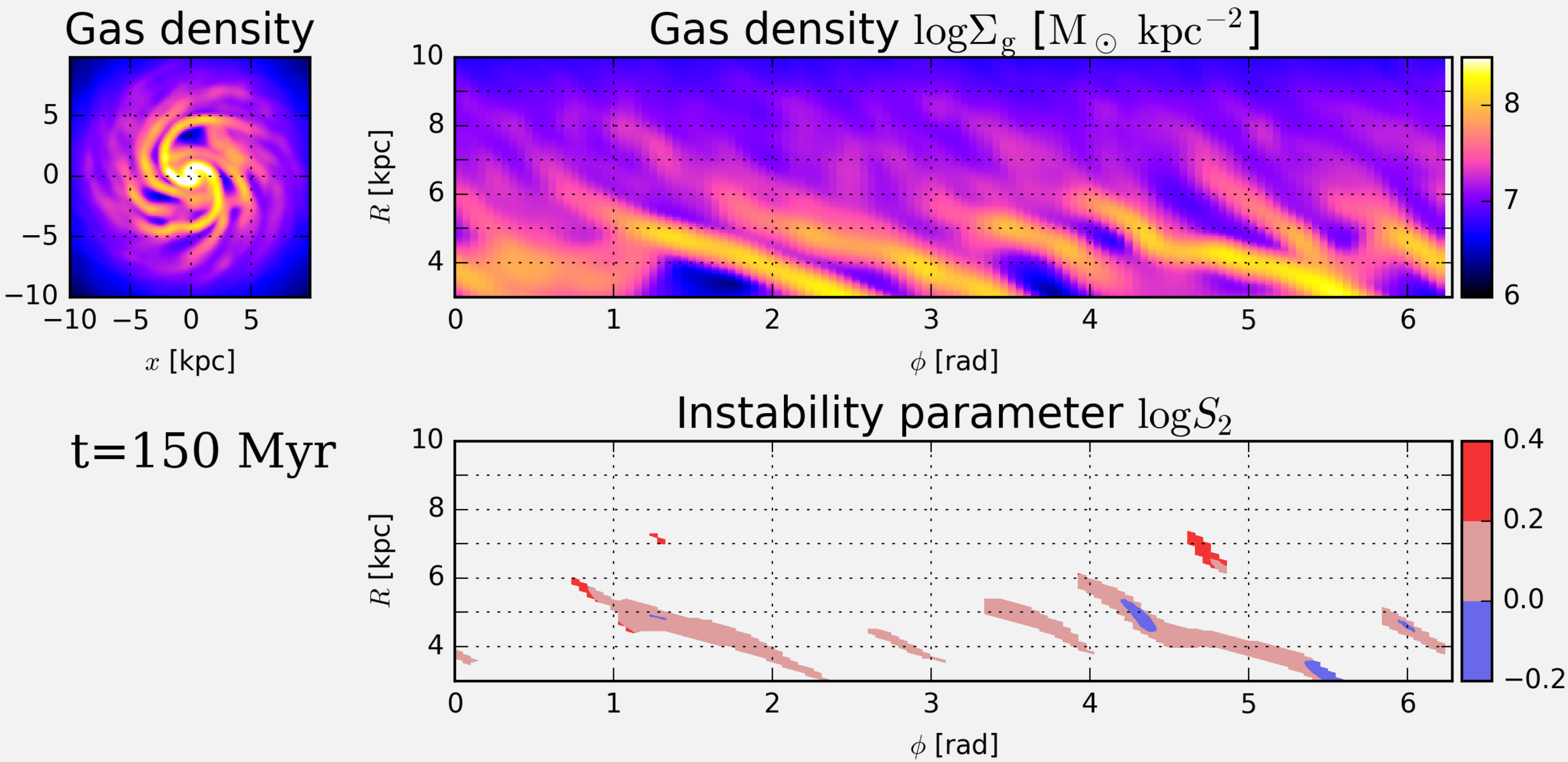
$$\left[\frac{\pi G k^2 \Upsilon_{\rm g} f(kW_{\rm g})}{c_s^2 k^2 + 4\Omega^2 - \omega^2} + \frac{\pi G k^2 \Upsilon_{\rm s} f(kW_{\rm s})}{\sigma_\phi^2 k^2 + 4\Omega^2 - \omega^2}\right] = 1,$$

- Finally, I obtain the new instability condition for 2-comp. models,

$$S_2 \equiv \frac{1}{\pi G k^2}\left[\frac{\Upsilon_{\rm g} f(kW_{\rm g})}{c_s^2 k^2 + 4\Omega_{\rm g}^2} + \frac{\Upsilon_{\rm s} f(kW_{\rm s})}{\sigma_\phi^2 k^2 + 4\Omega_{\rm s}^2}\right]^{-1} < 1.$$

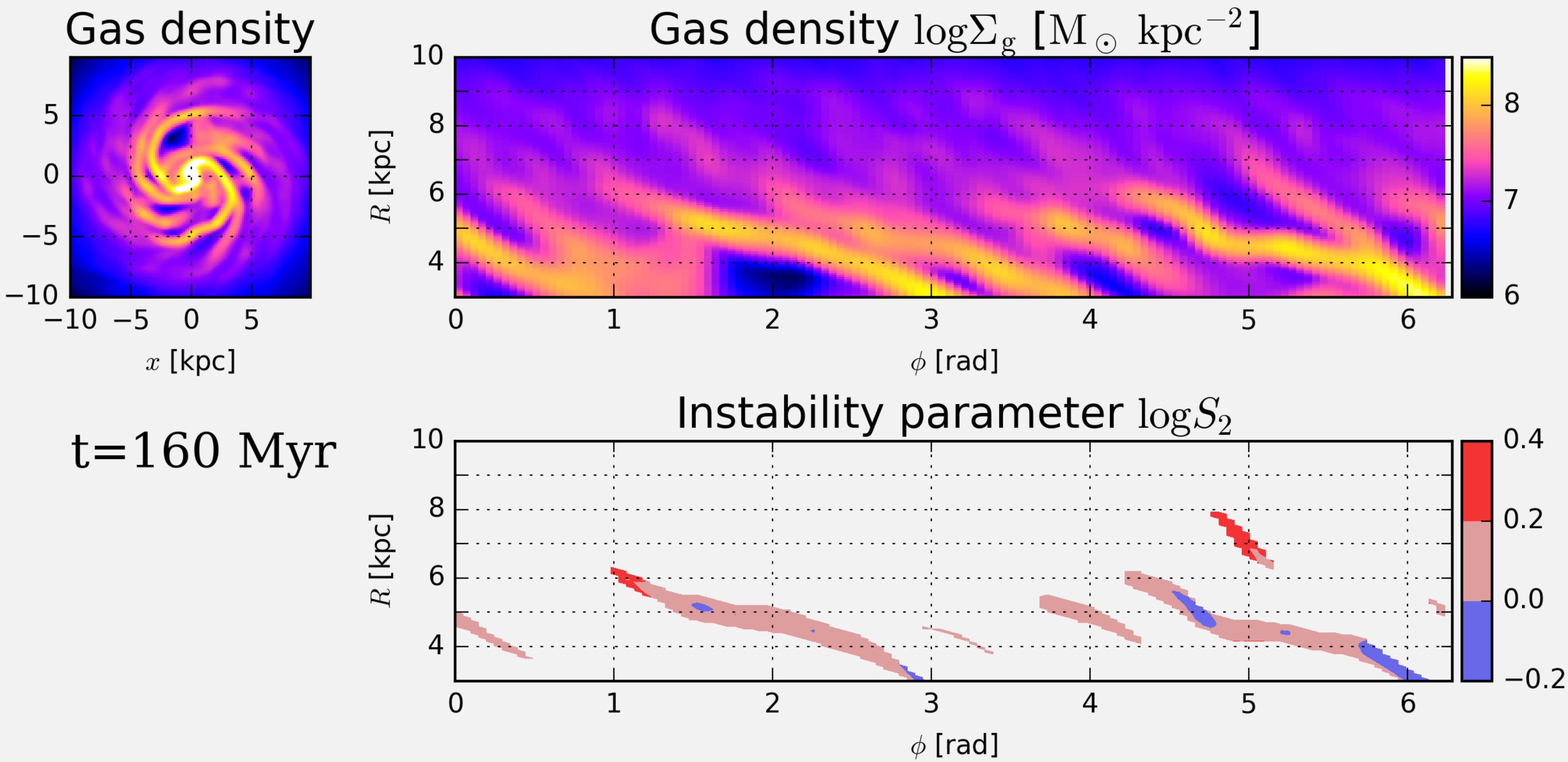
Demonstration

The fragmenting case



Demonstration

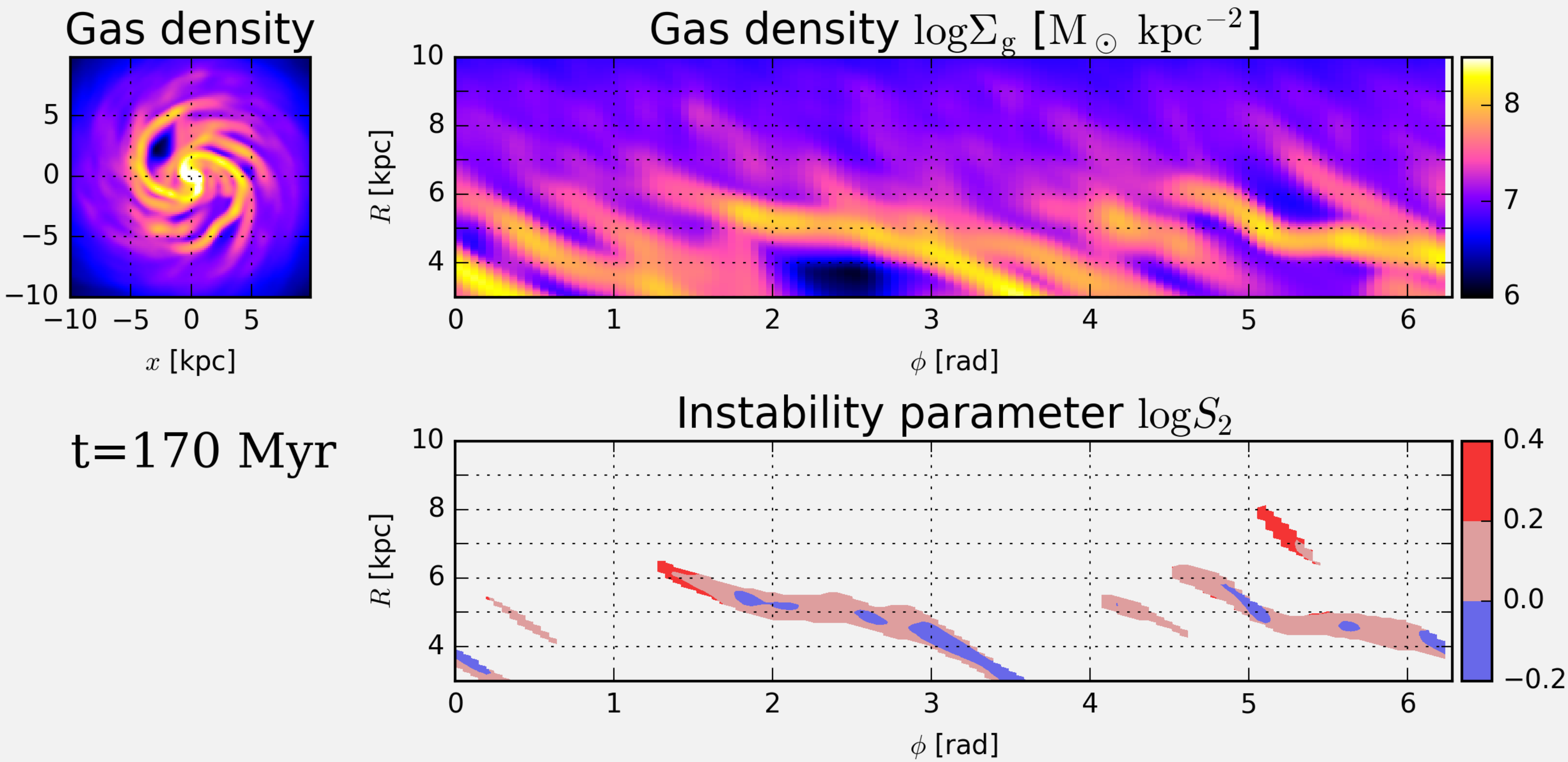
The fragmenting case



t=160 Myr

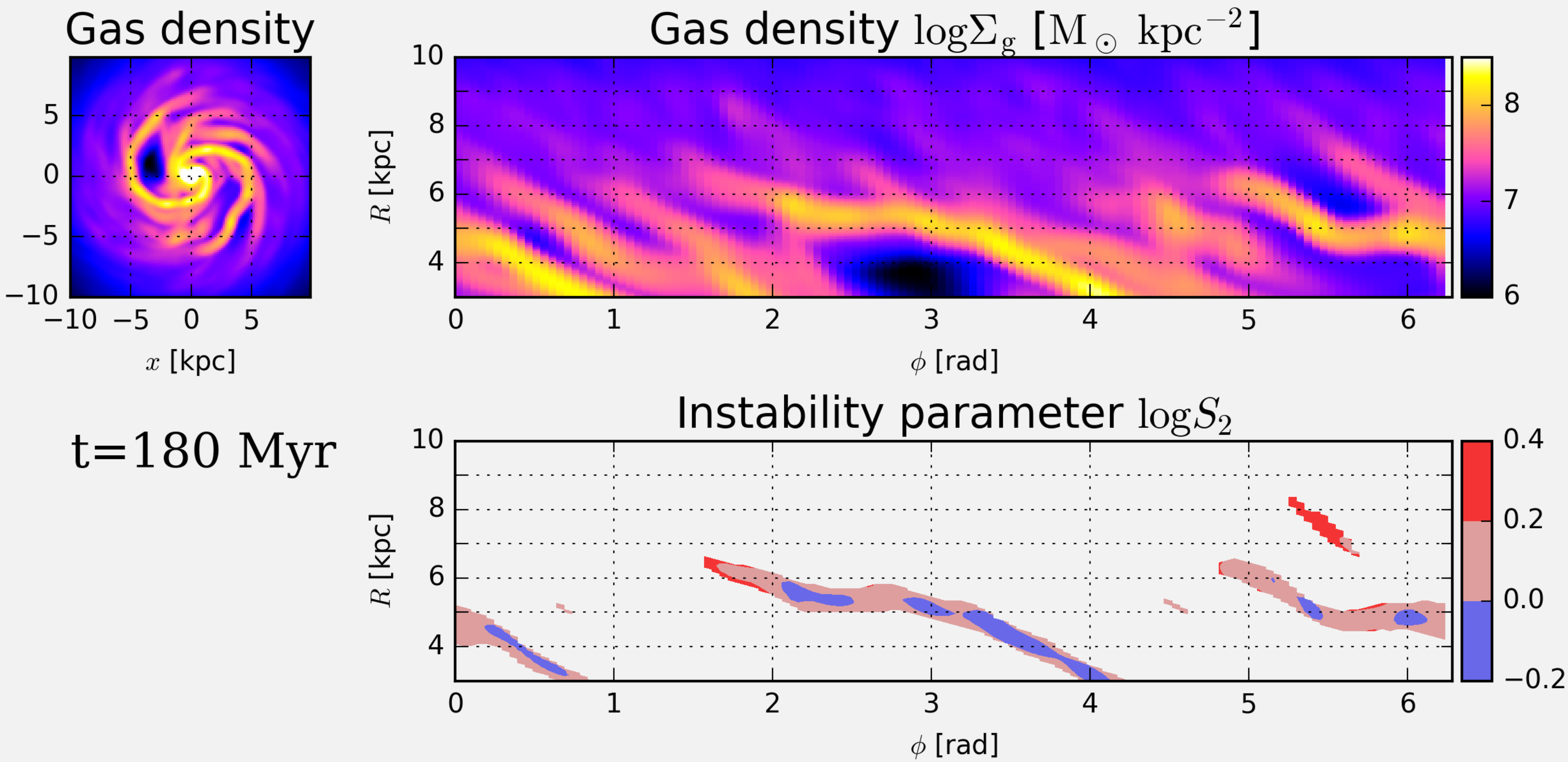
Demonstration

The fragmenting case



Demonstration

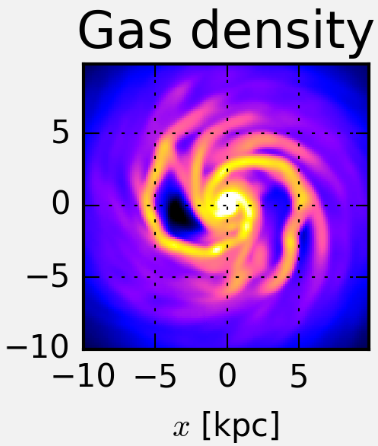
The fragmenting case

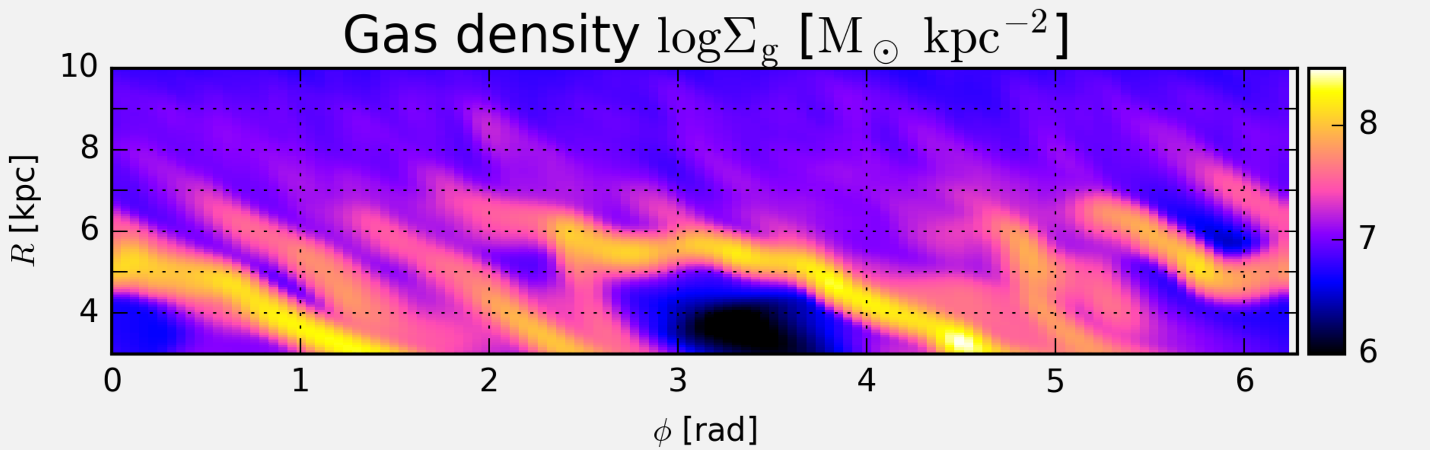


t=180 Myr

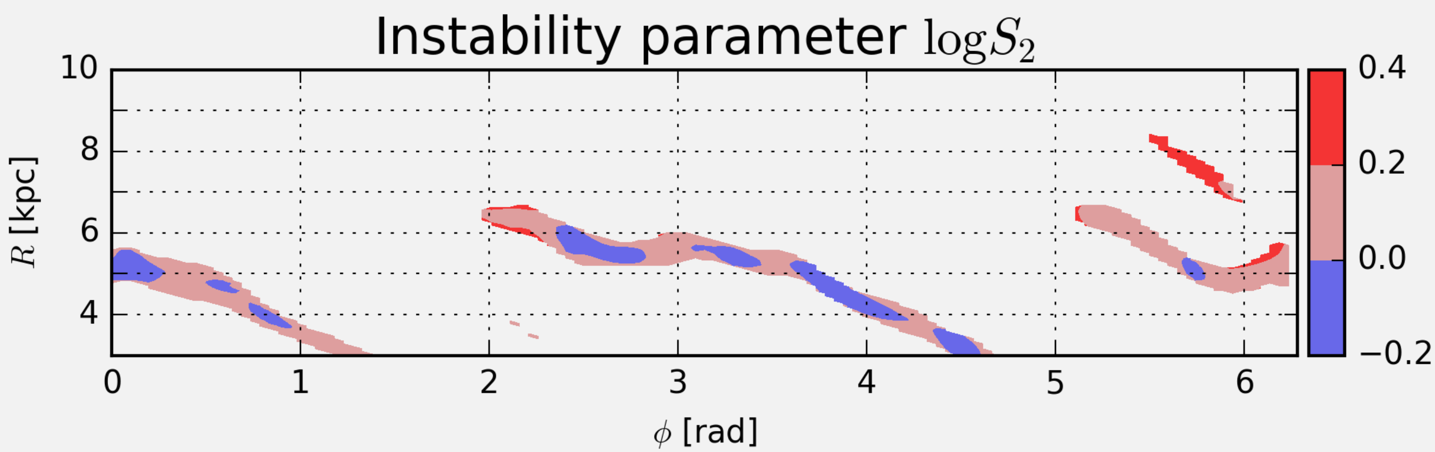
Demonstration

The fragmenting case



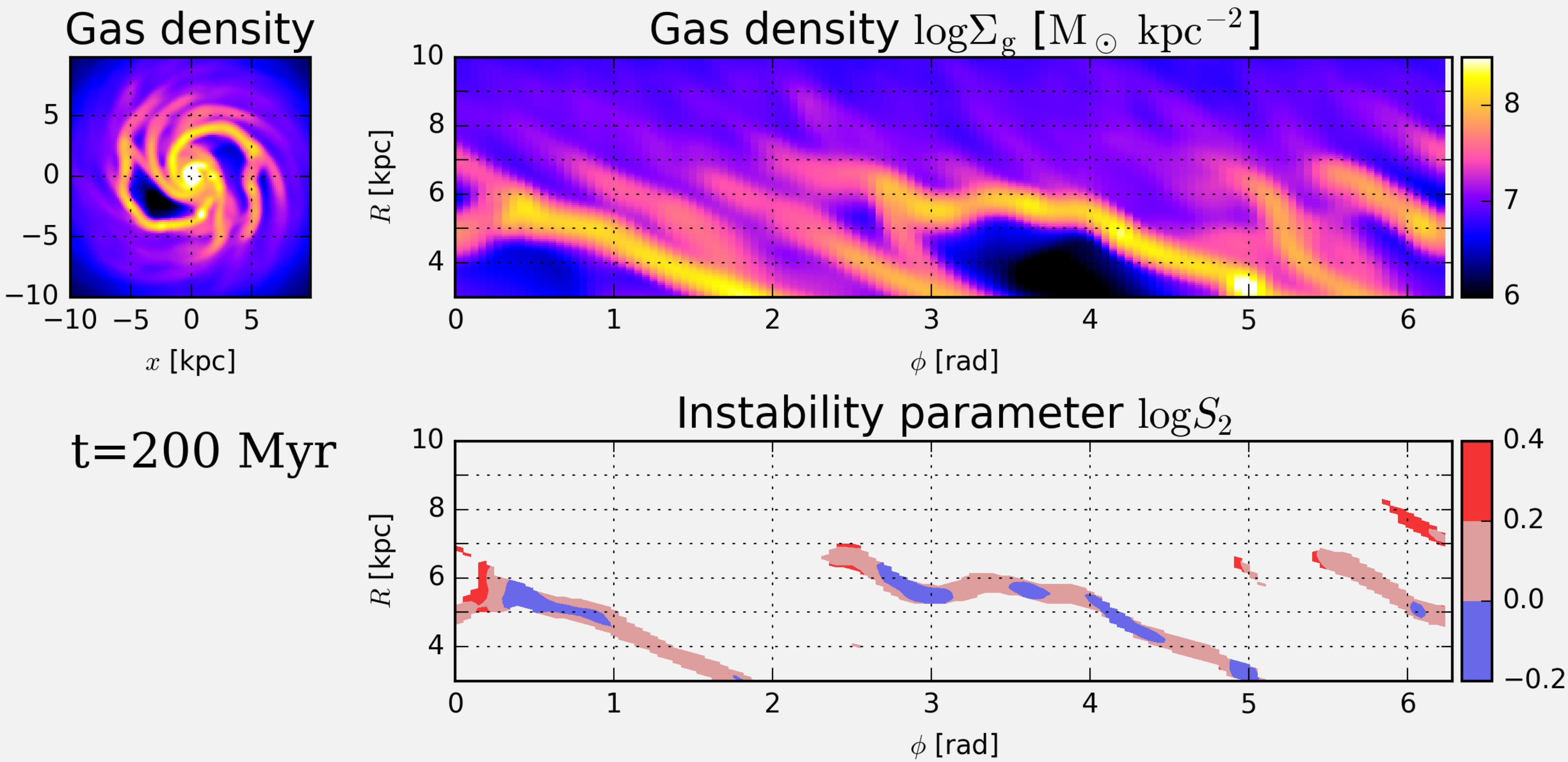


t=190 Myr



Demonstration

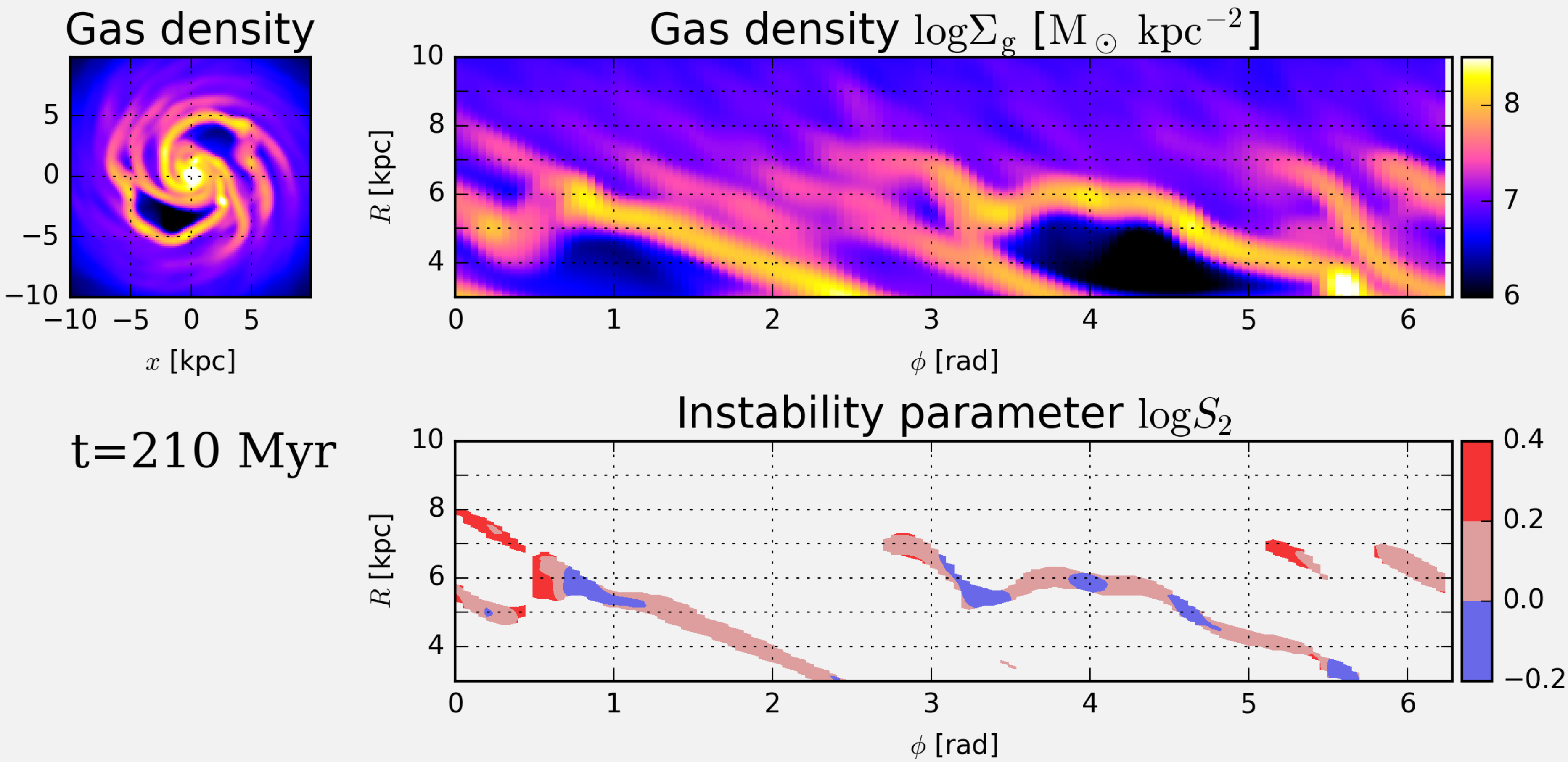
The fragmenting case



t=200 Myr

Demonstration

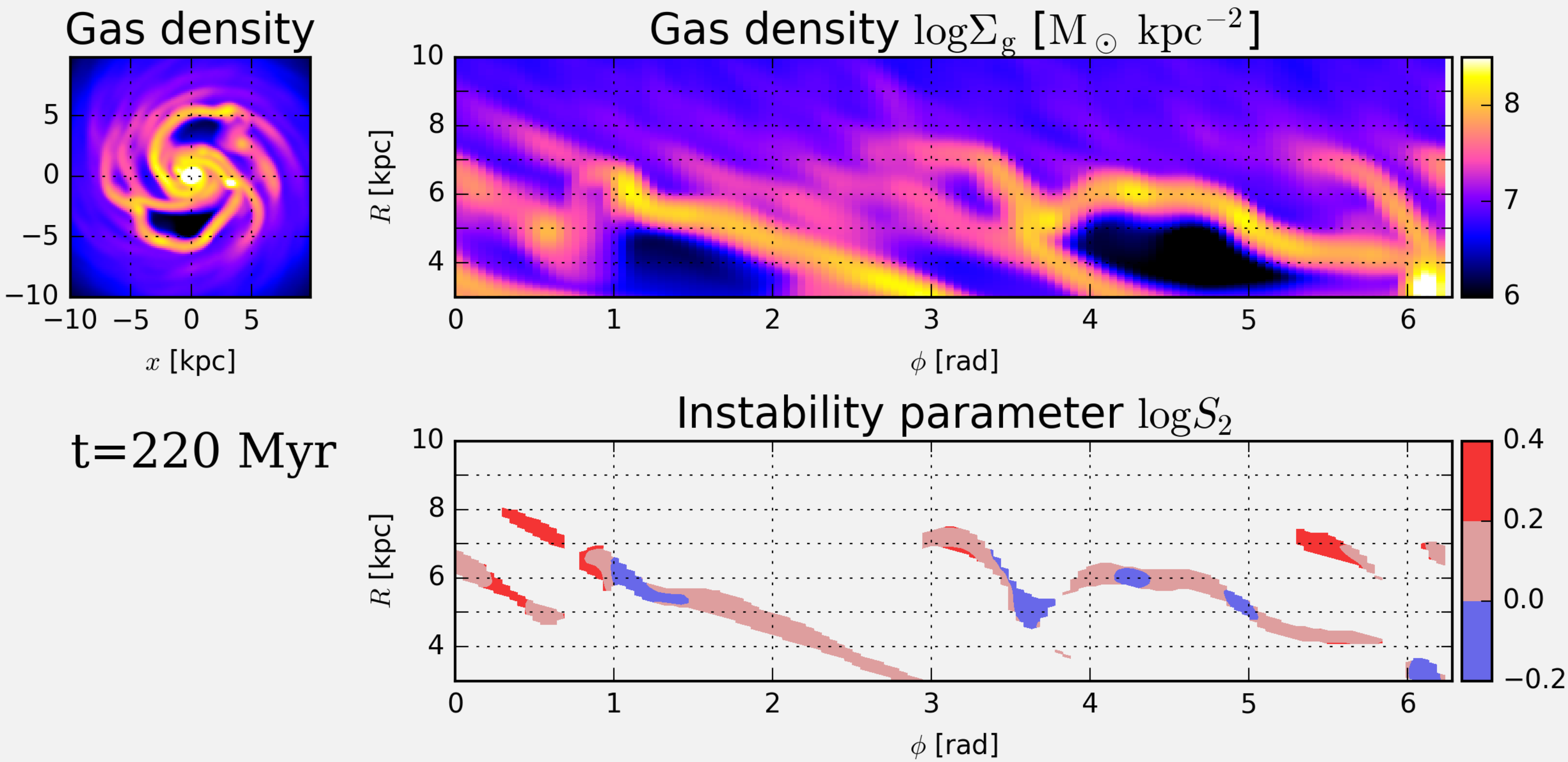
The fragmenting case



t=210 Myr

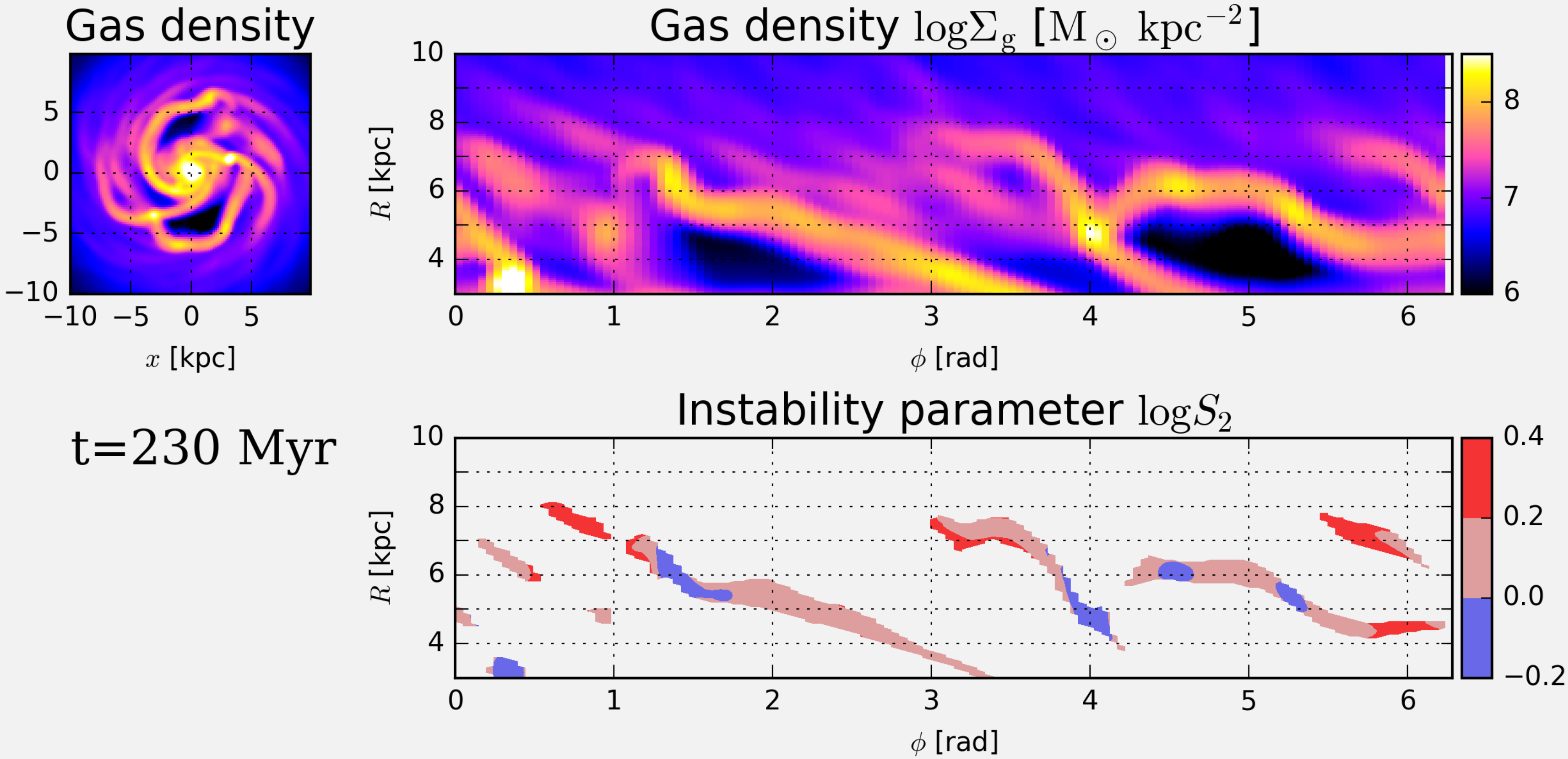
Demonstration

The fragmenting case



Demonstration

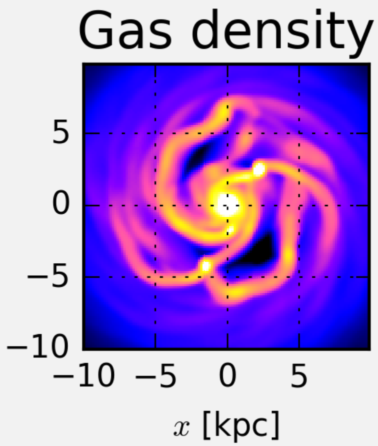
The fragmenting case

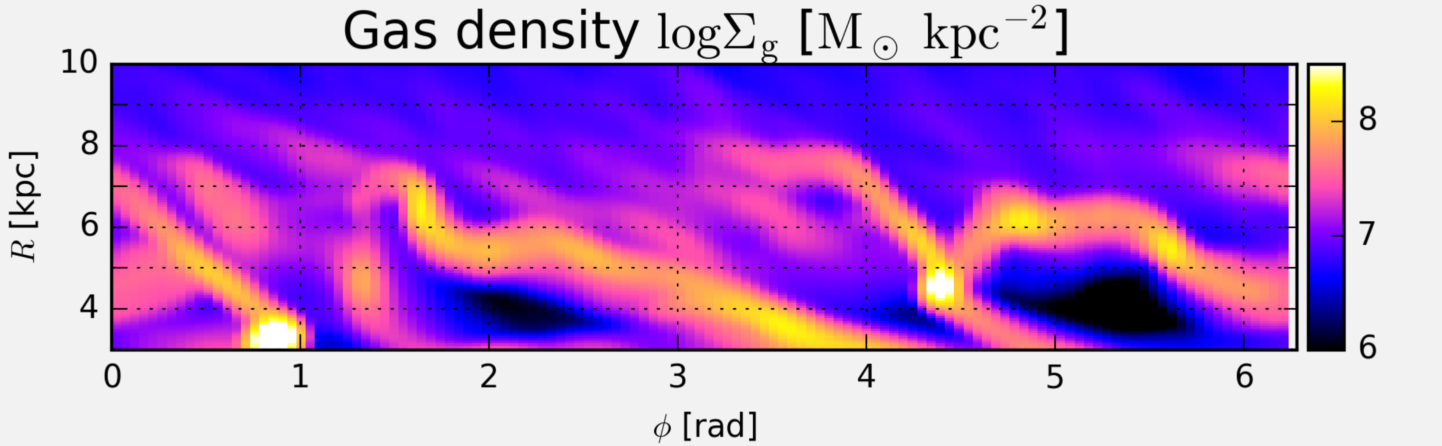


t=230 Myr

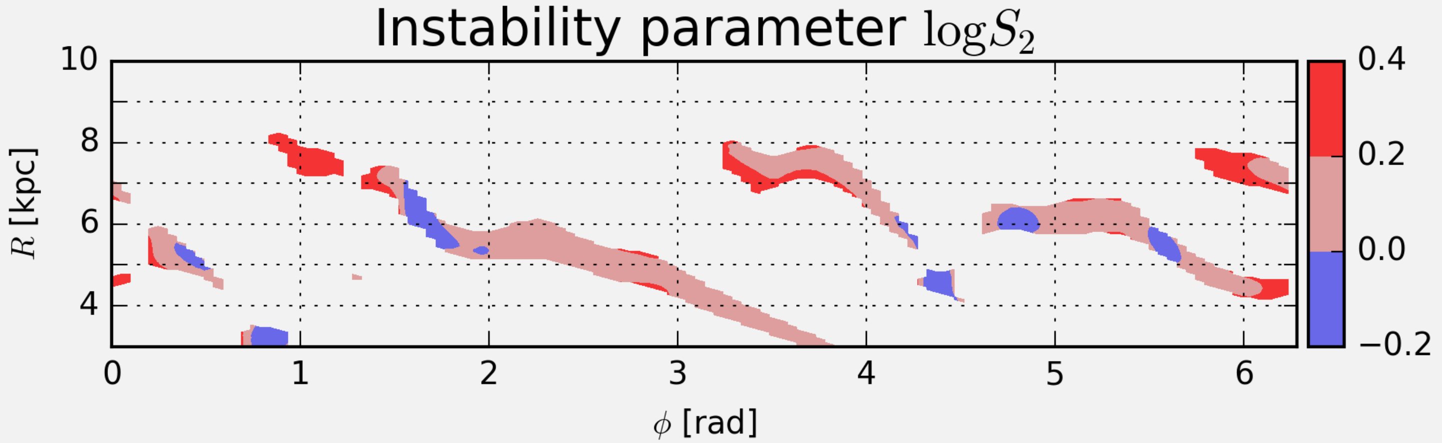
Demonstration

The fragmenting case



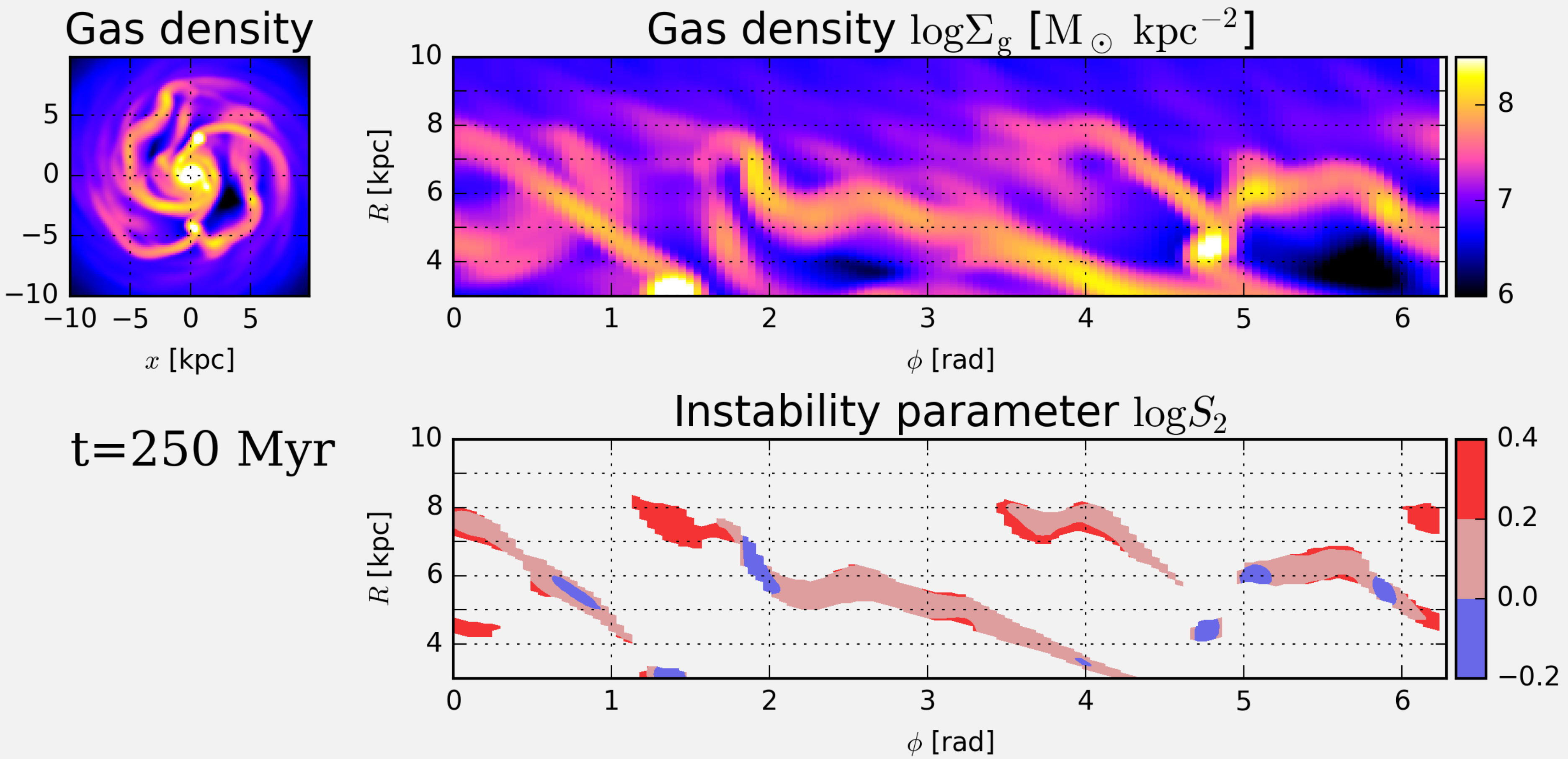


t=240 Myr



Demonstration

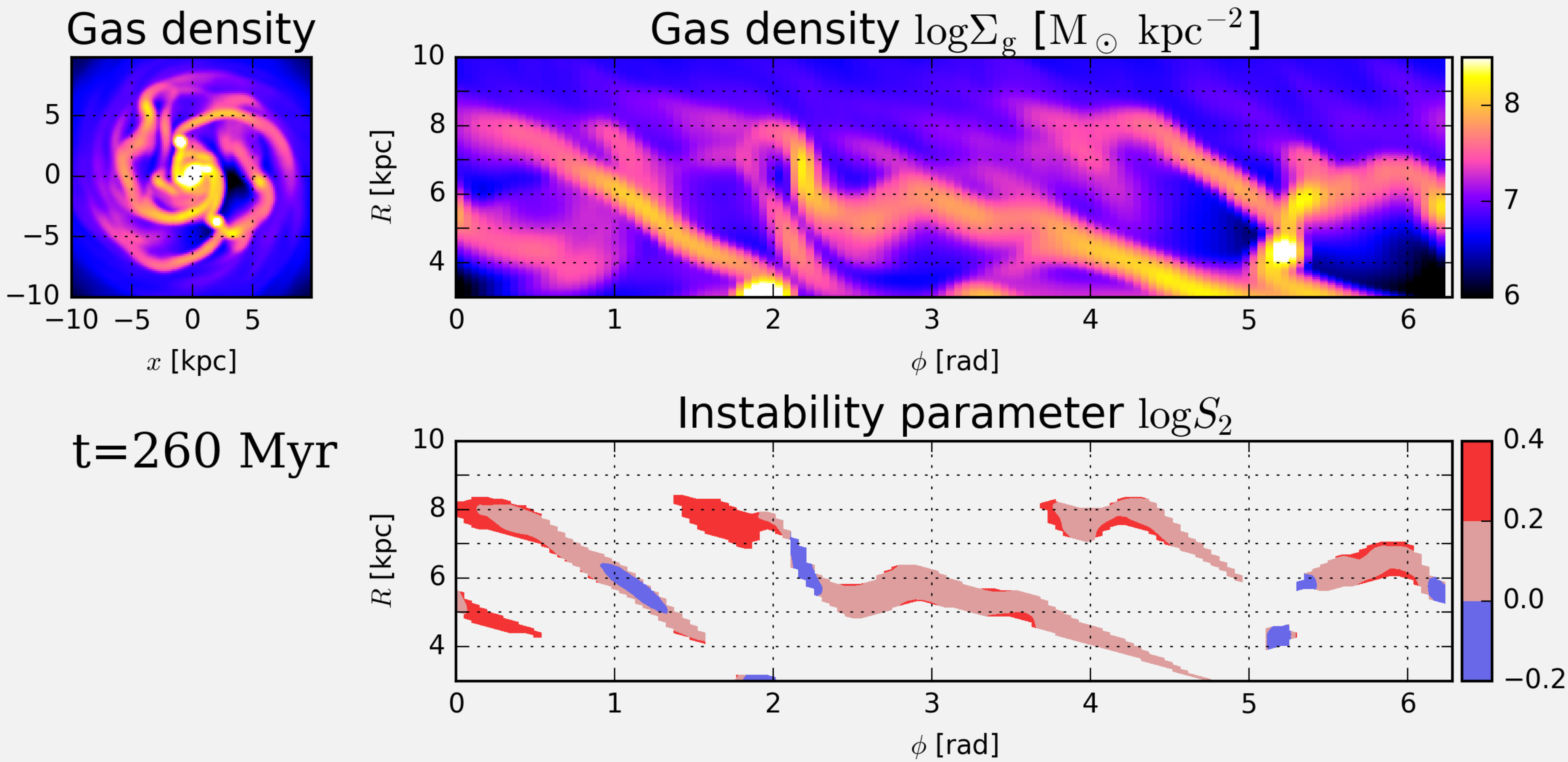
The fragmenting case



t=250 Myr

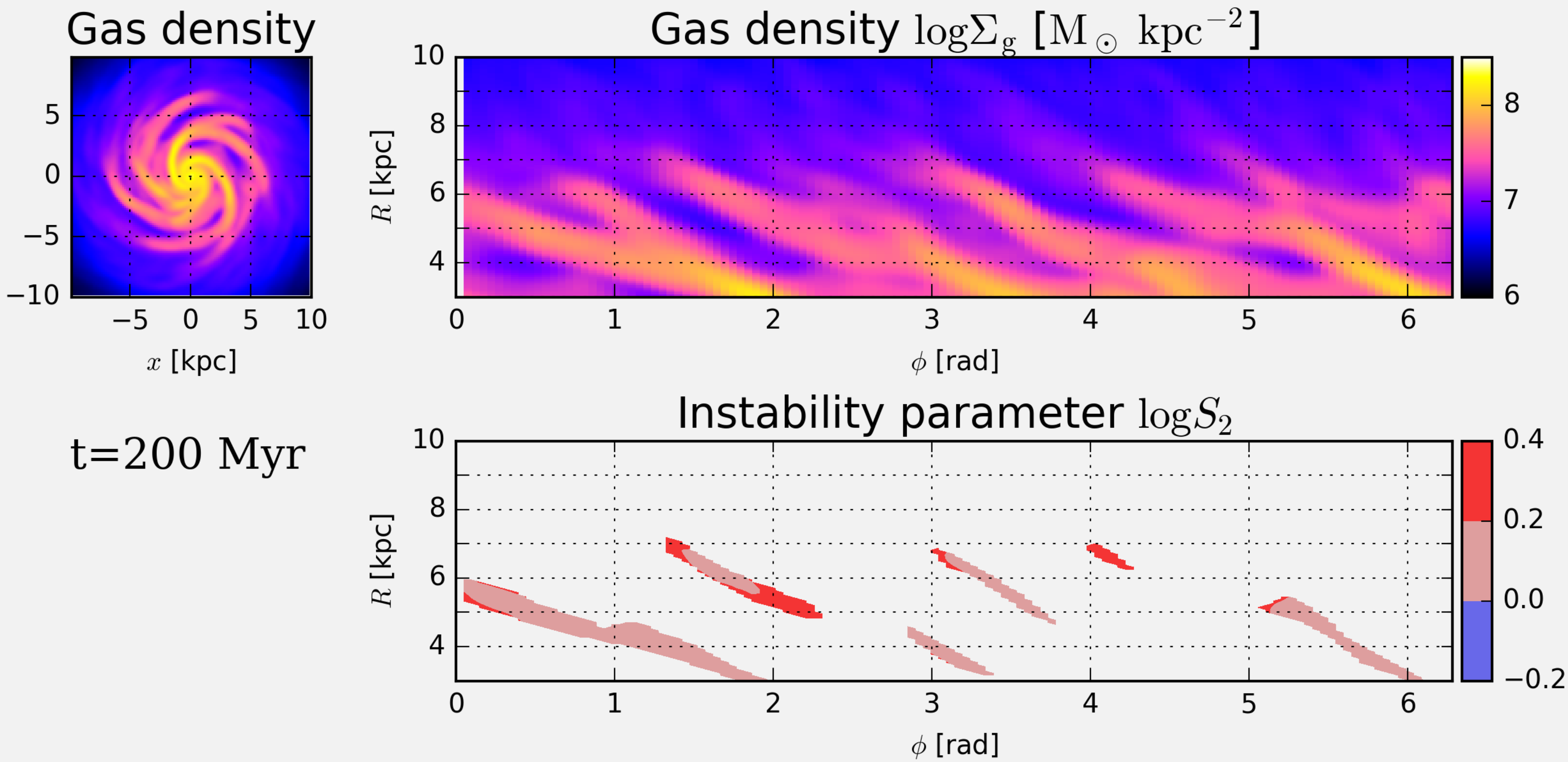
Demonstration

The fragmenting case



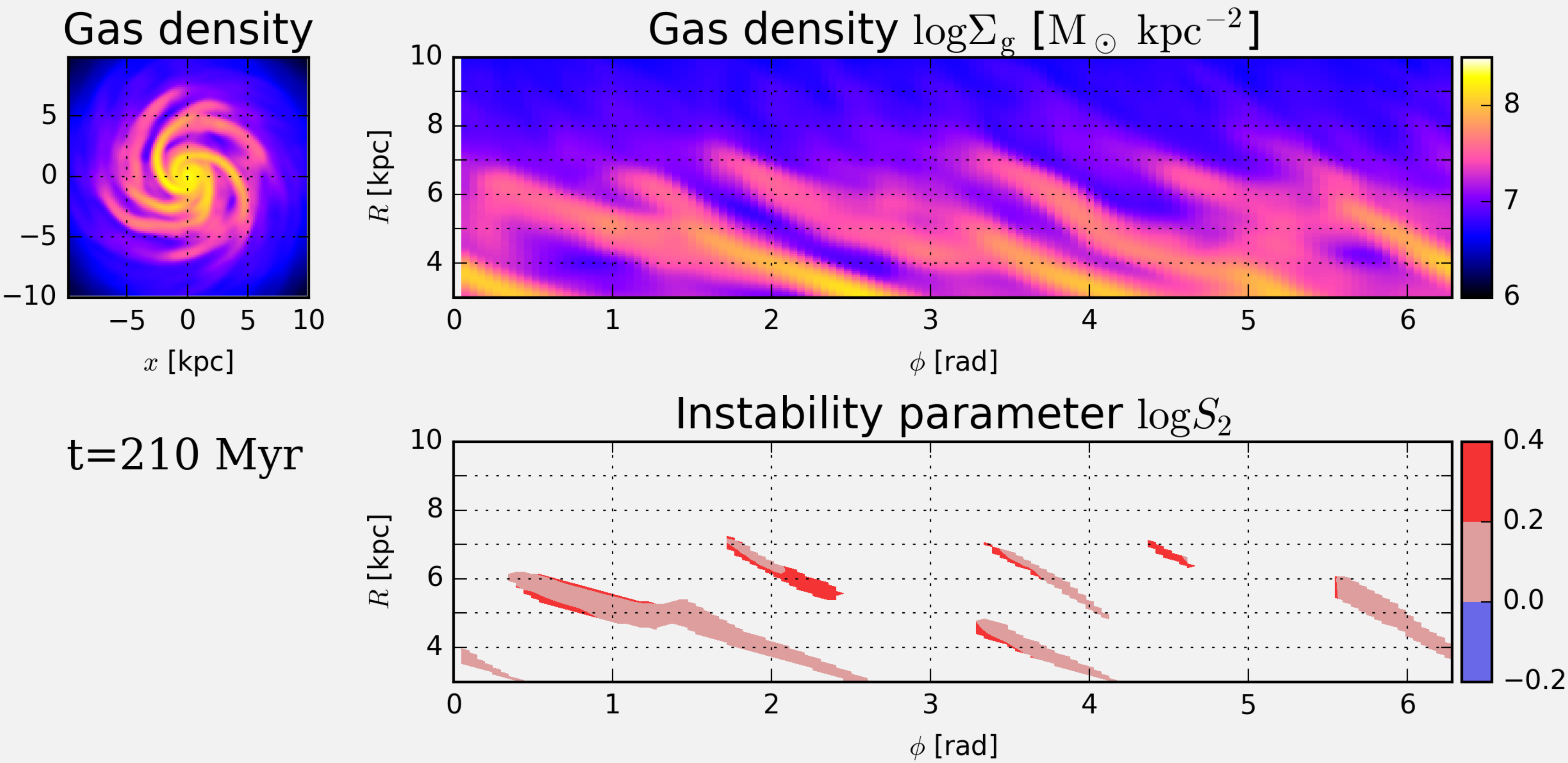
Demonstration

The stable case



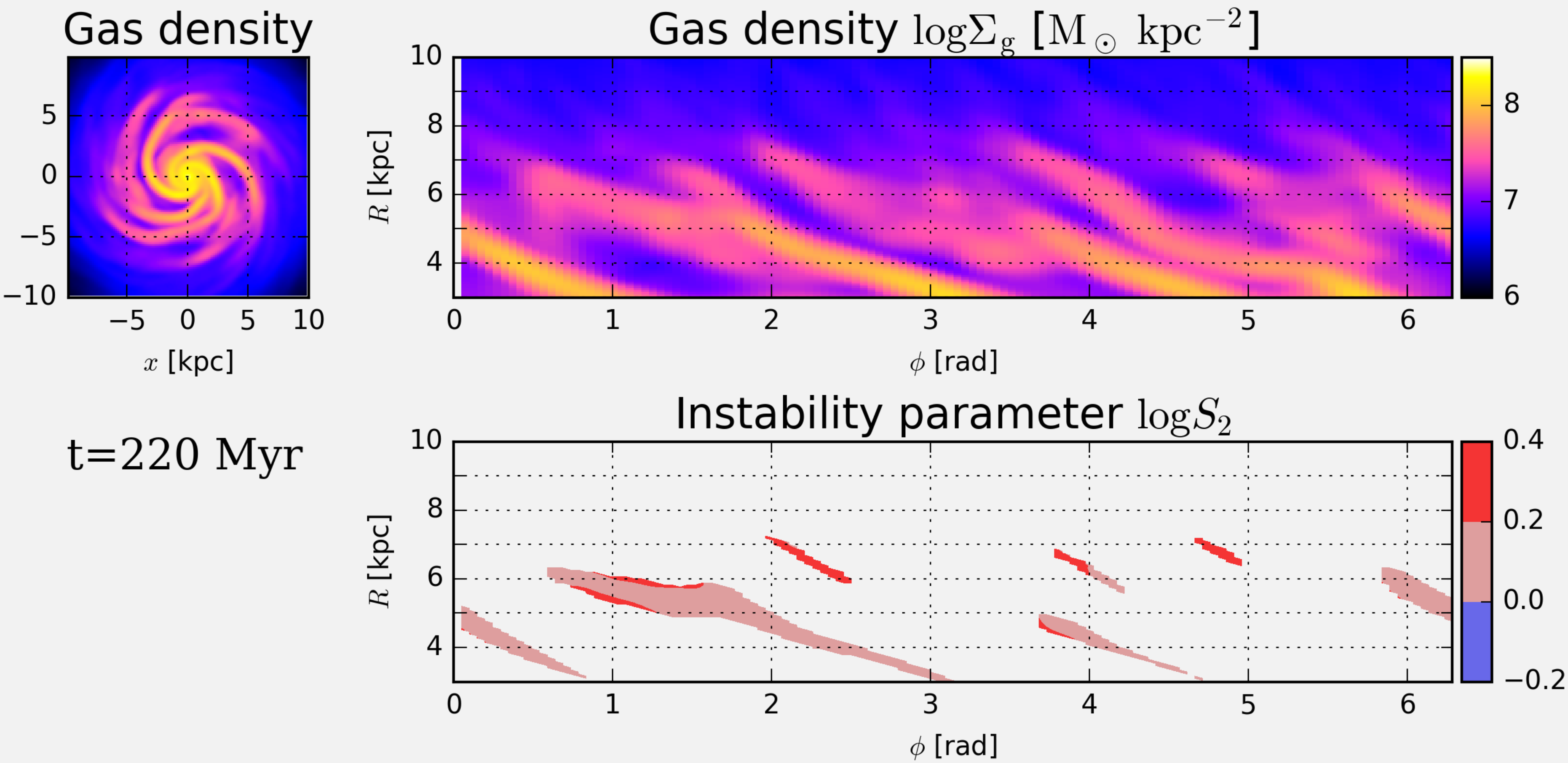
Demonstration

The stable case



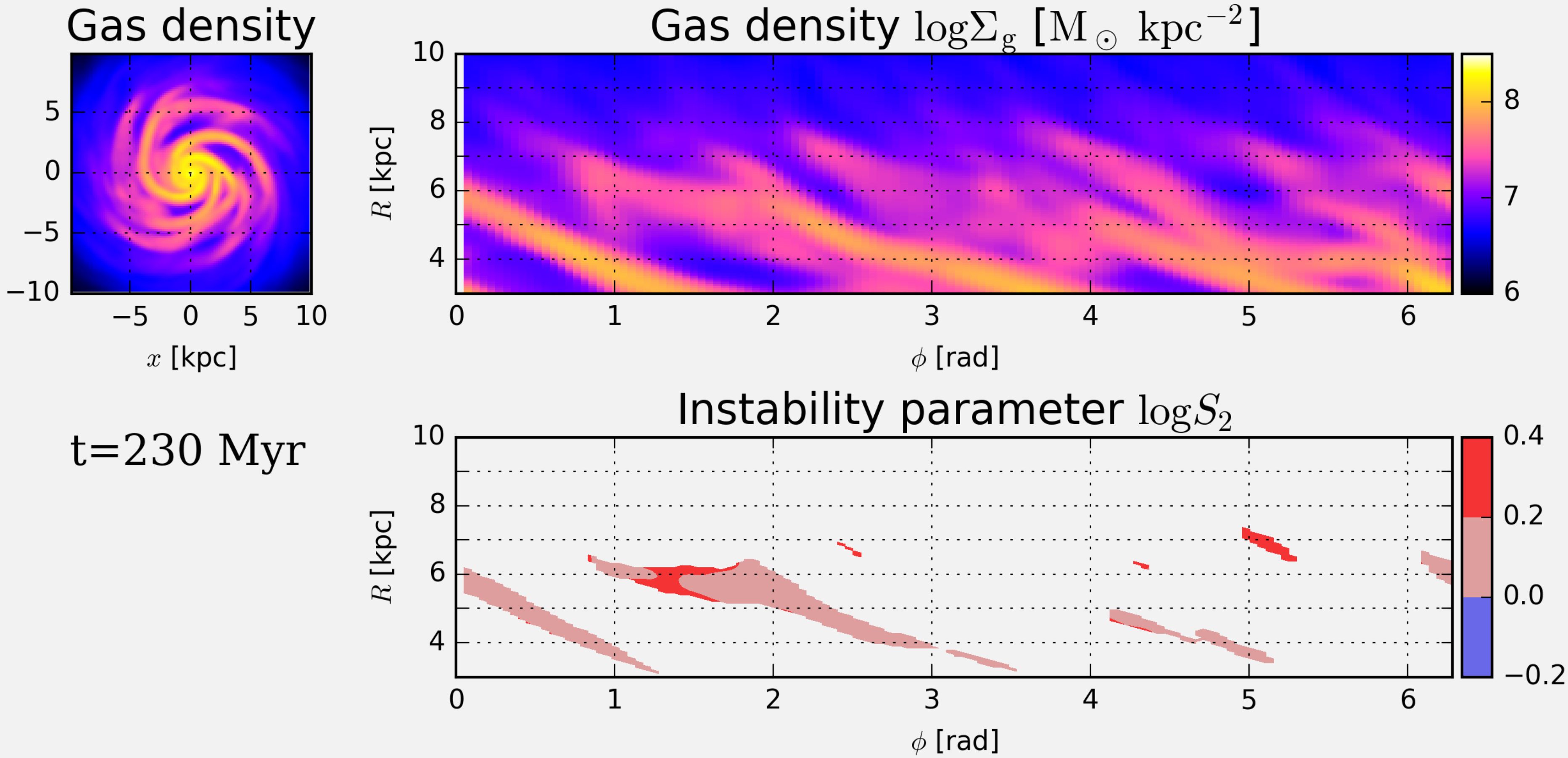
Demonstration

The stable case



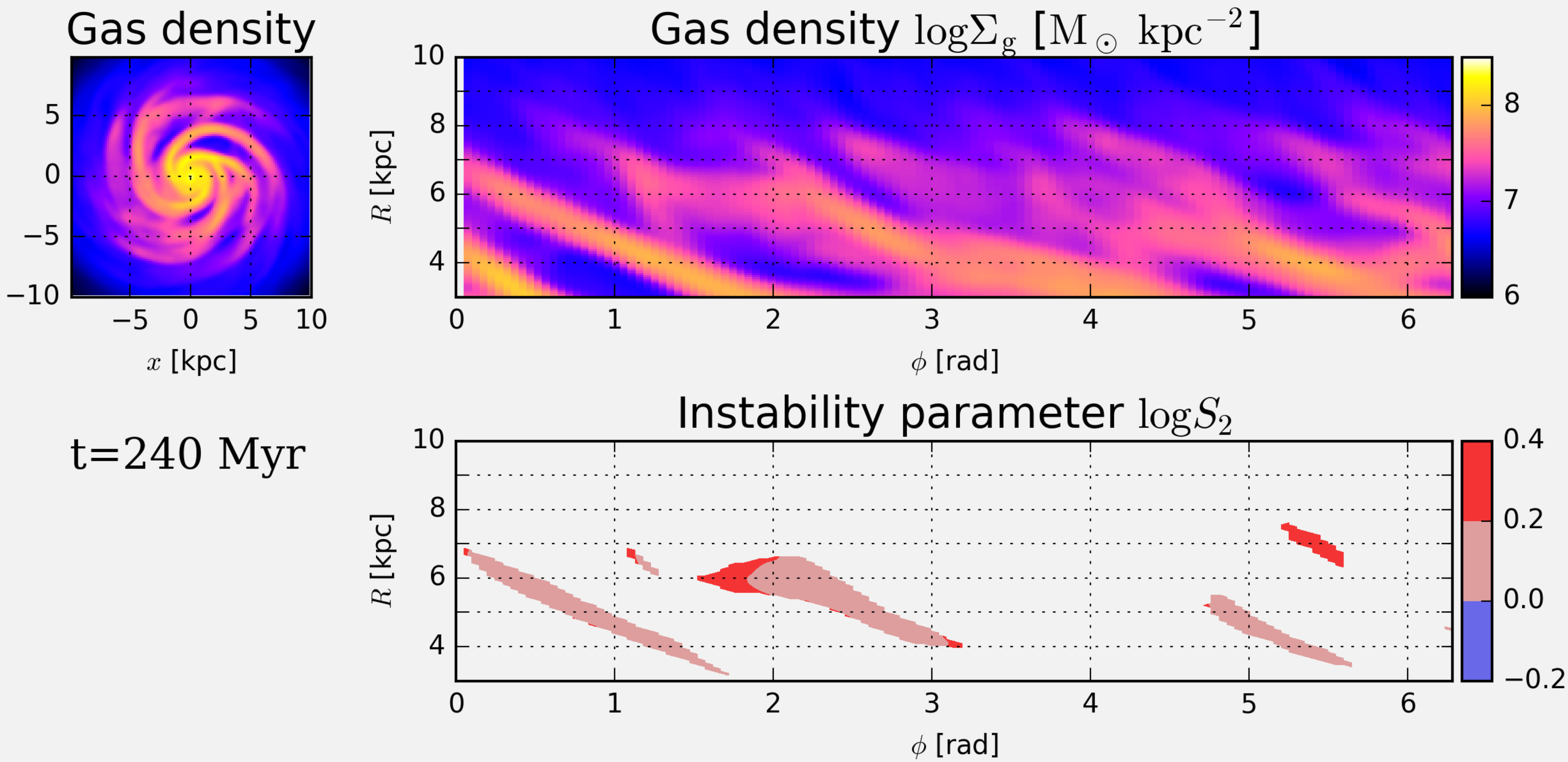
Demonstration

The stable case



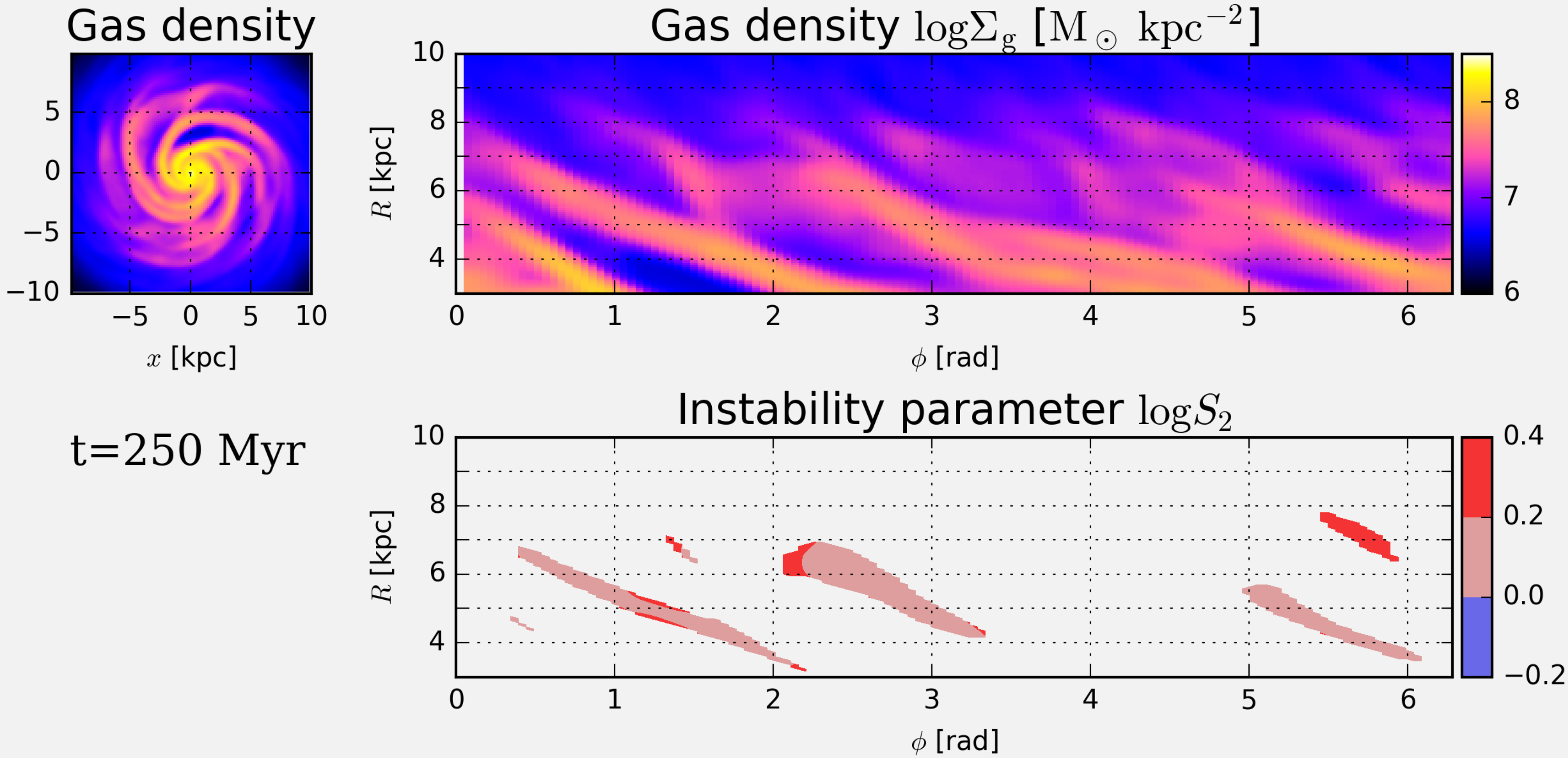
Demonstration

The stable case



Demonstration

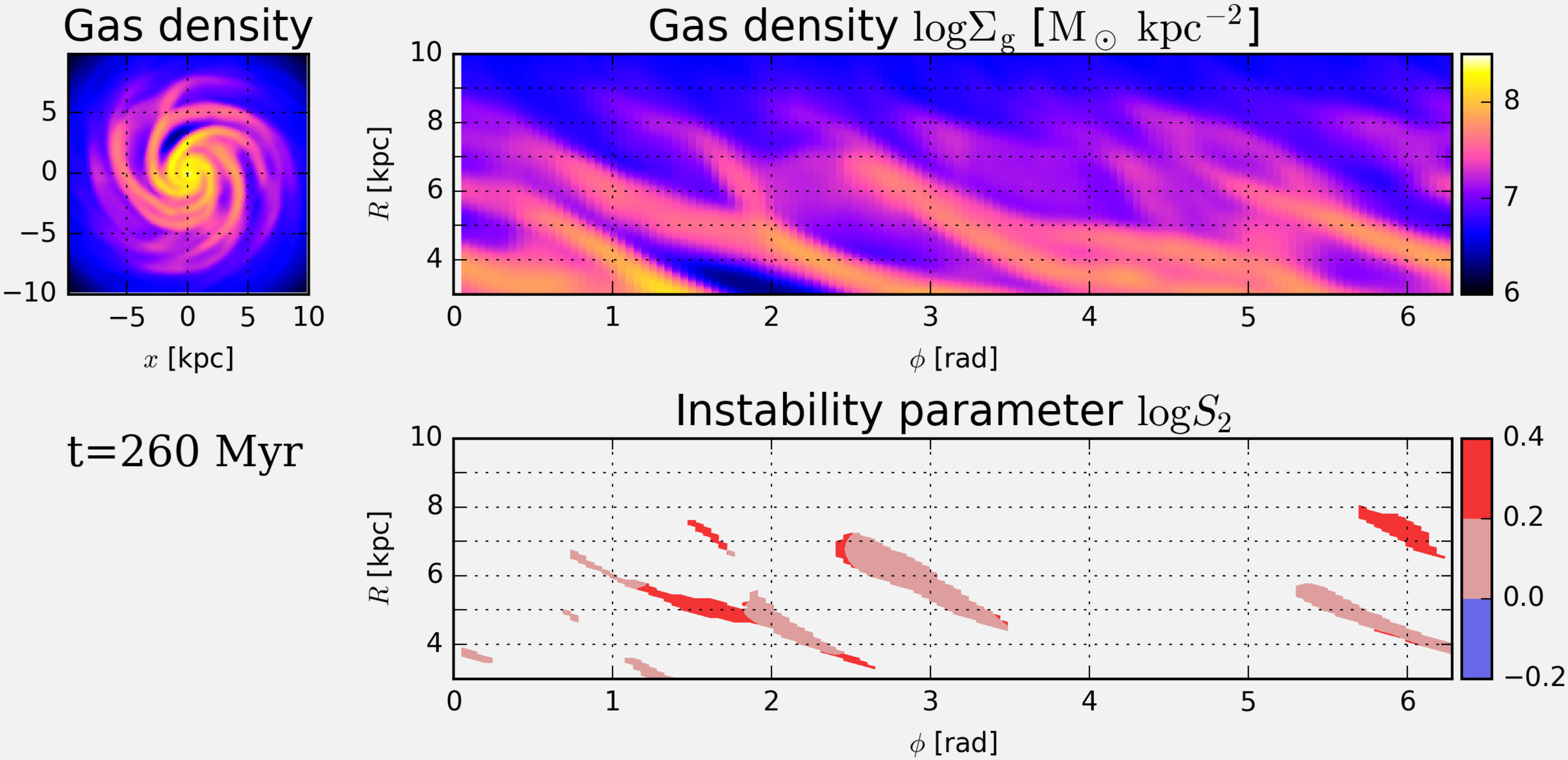
The stable case



t=250 Myr

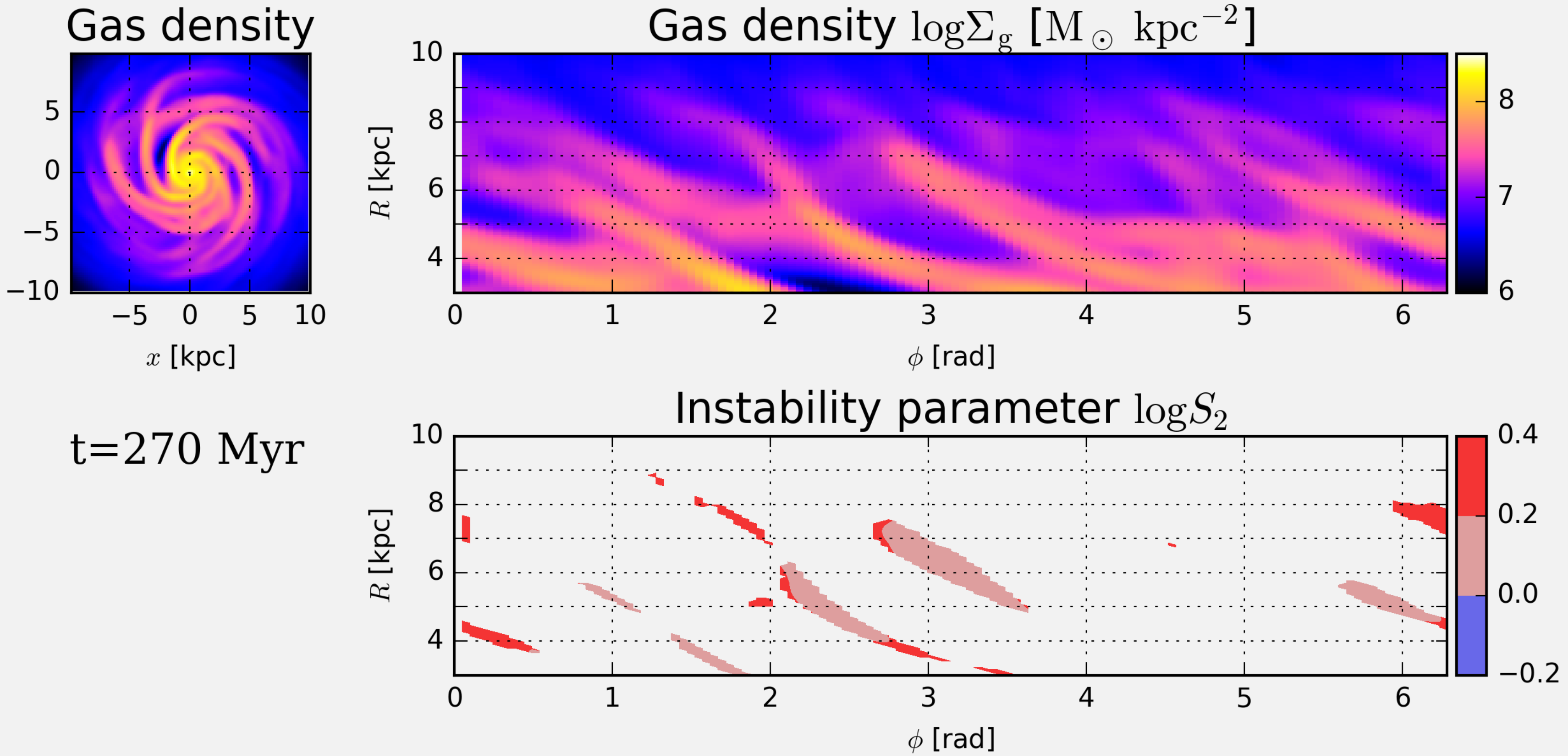
Demonstration

The stable case



Demonstration

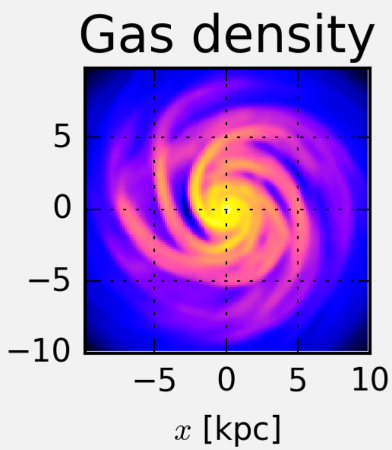
The stable case



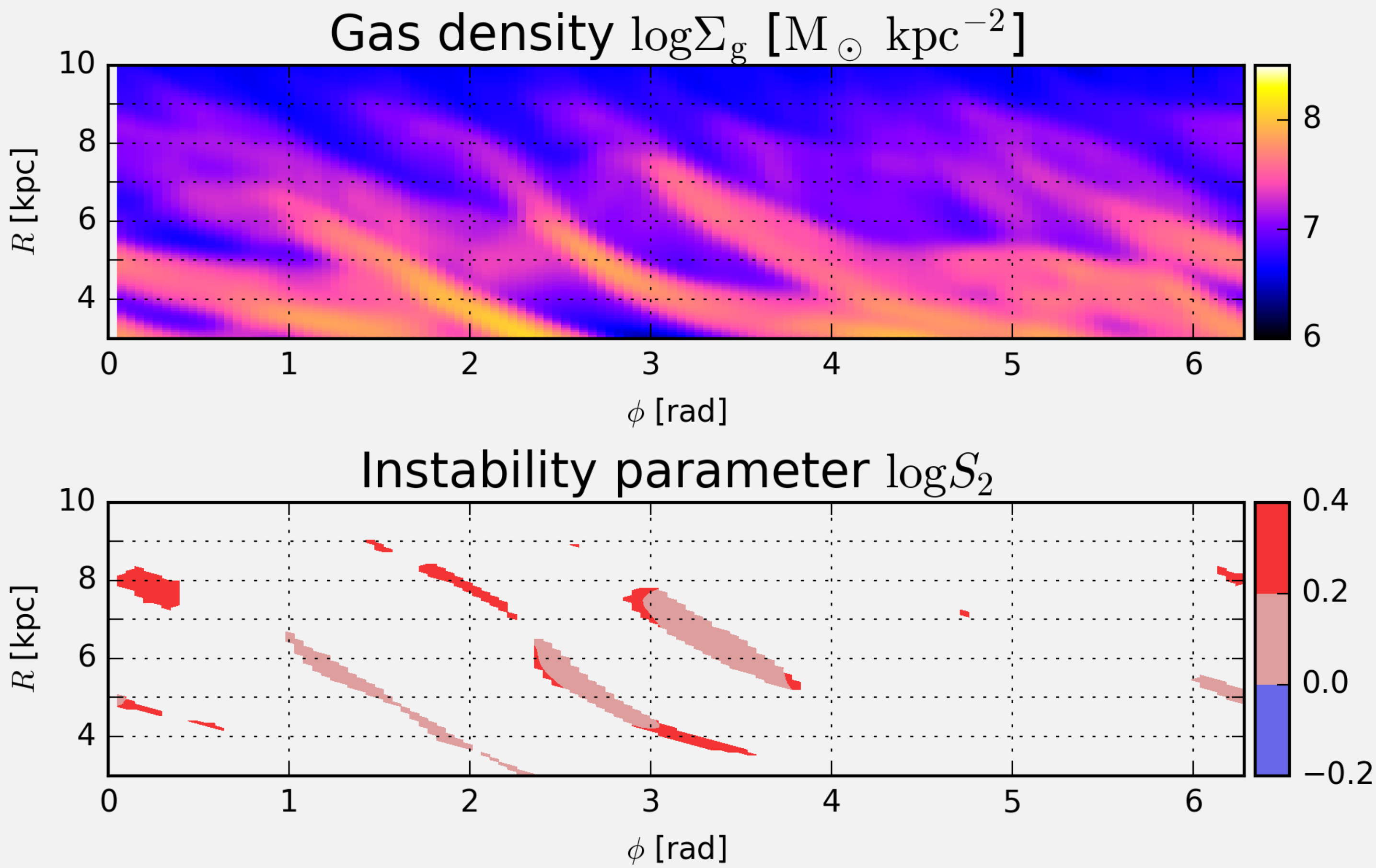
t=270 Myr

Demonstration

The stable case

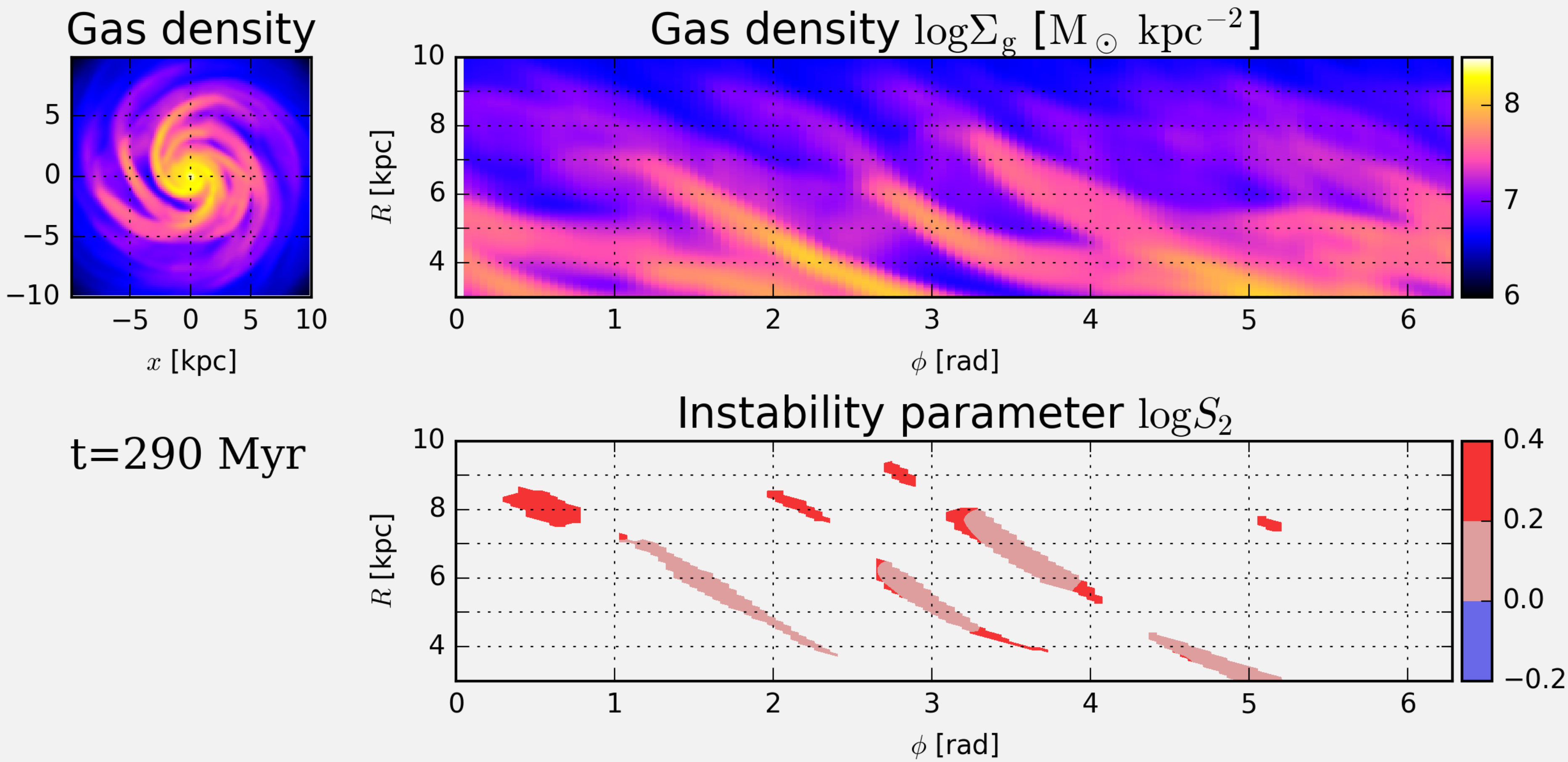


t=280 Myr



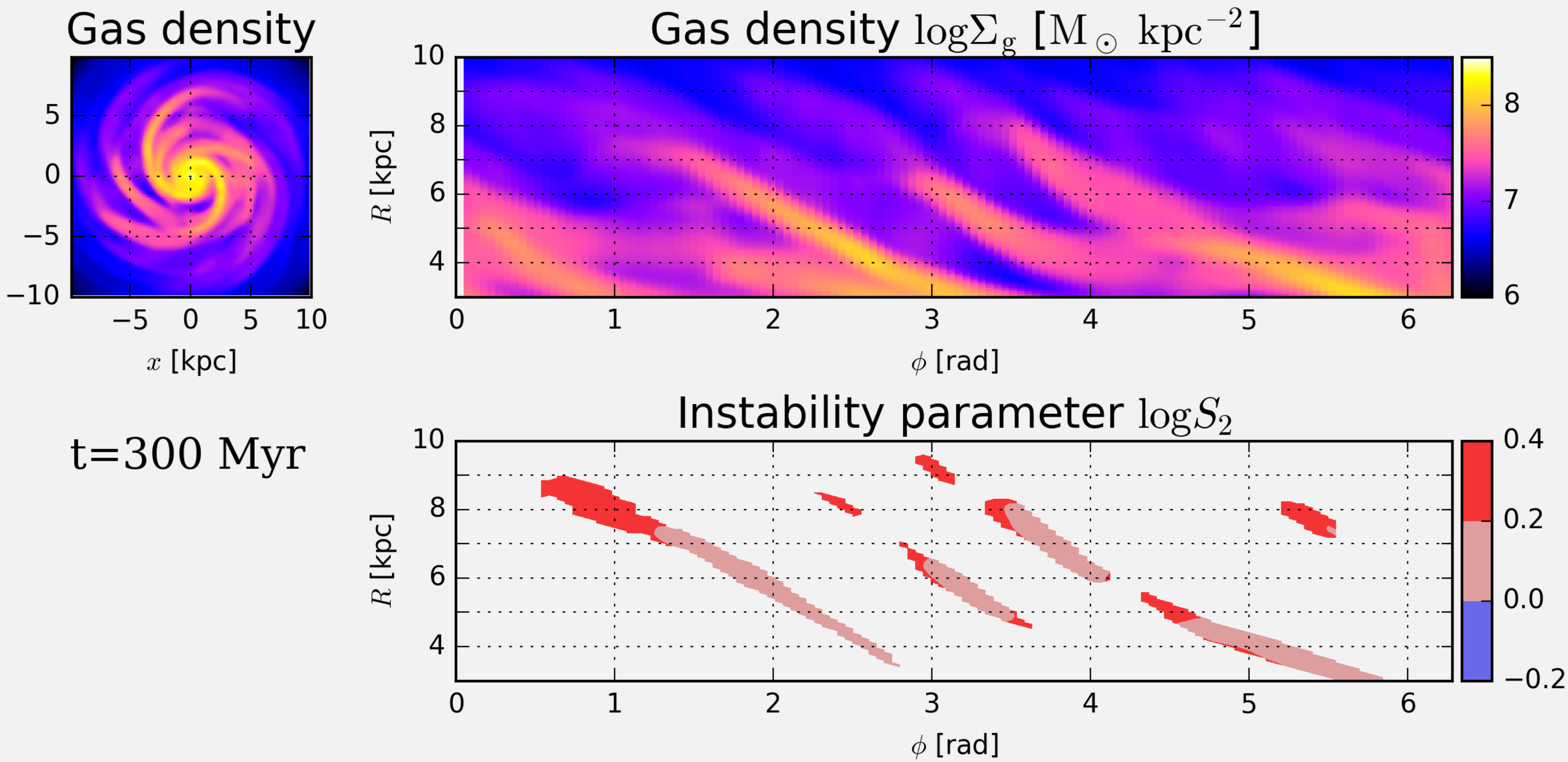
Demonstration

The stable case



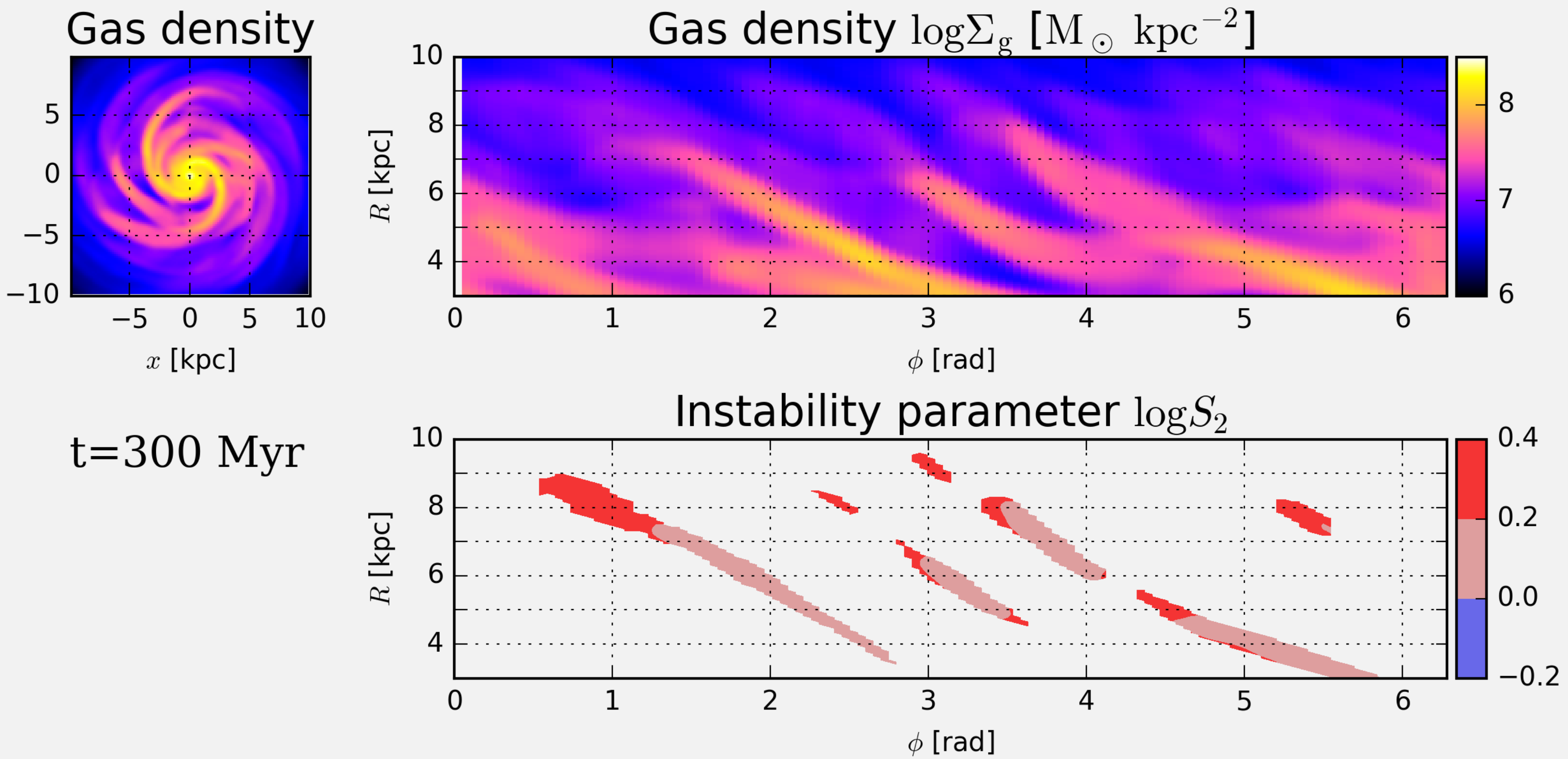
Demonstration

The stable case



Demonstration

The stable case

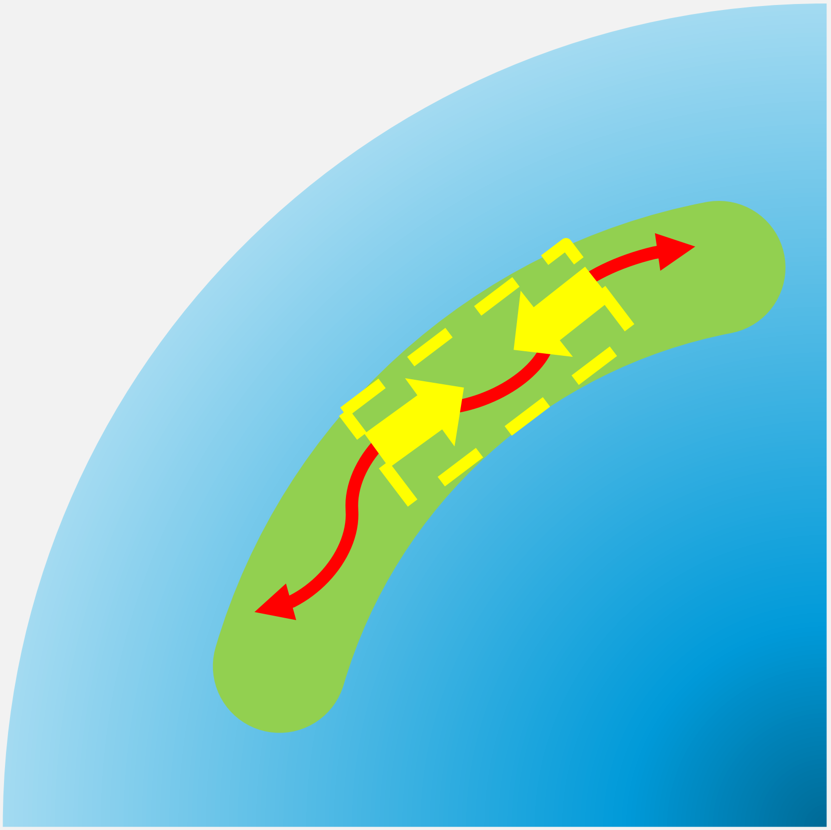


Clump mass estimation

- If the unstable wavelength is long, $\lambda \gg W$,
  - An unstable perturbation is expected to collapse along the arm (1D collapse)

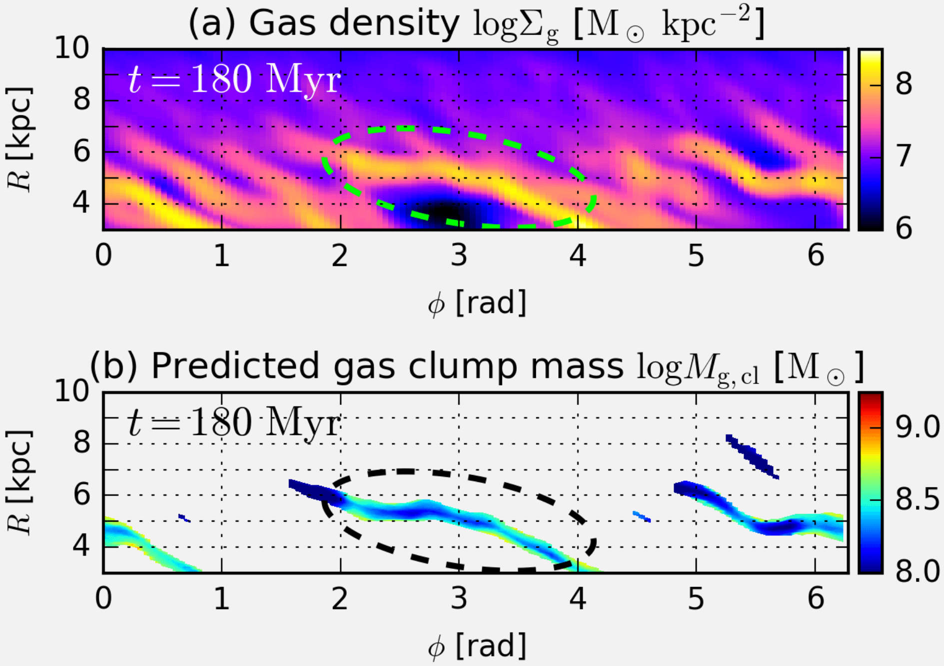
Clump mass estimation

- If the unstable wavelength is long, $\lambda \gg W$,
  - An unstable perturbation is expected to collapse along the arm (1D collapse)
- $M_{cl} \sim \Sigma W \lambda$



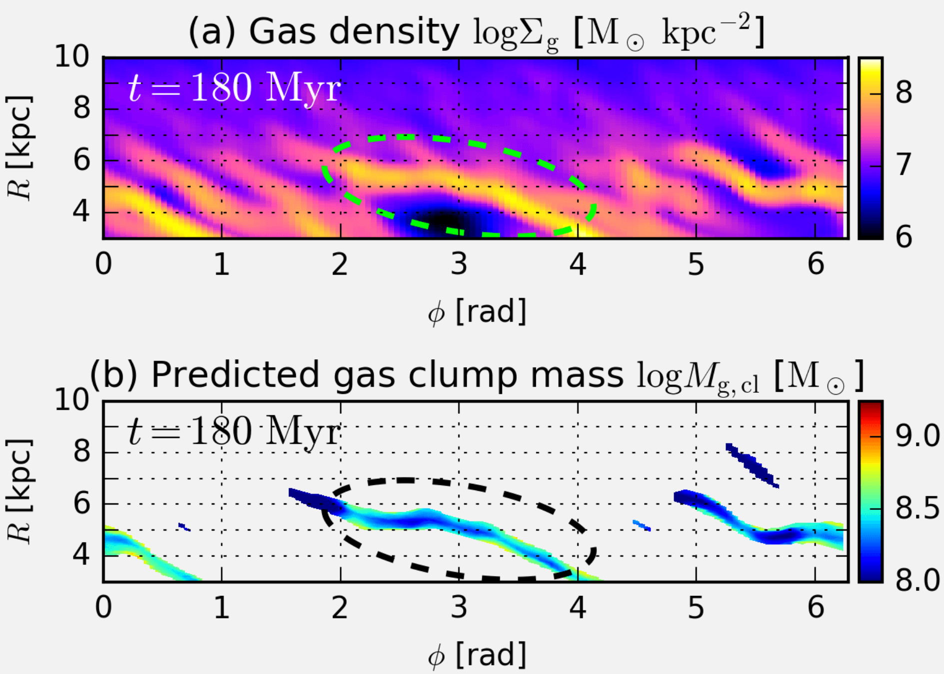
Clump-mass prediction

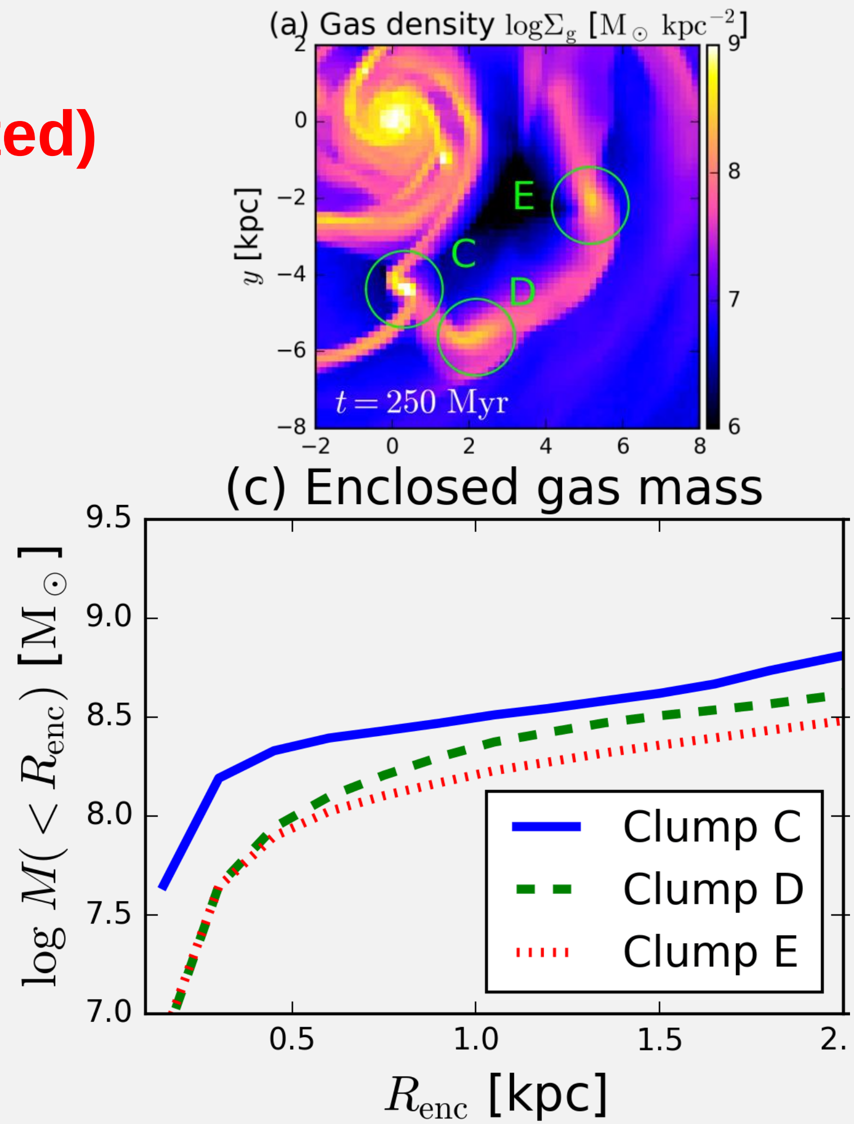
- $M_{cl} \sim \Sigma W \lambda$
- **$M_{cl} \sim 10^{8} - 10^{8.5}$ M$_\odot$ (predicted)**



Clump-mass prediction

- $M_{cl} \sim \Sigma W \lambda$
  - **$M_{cl} \sim 10^8 - 10^{8.5}$ $M_\odot$ (predicted)**





Toomre Instability (TI)

(e.g. Dekel et al. 2009)

v.s.

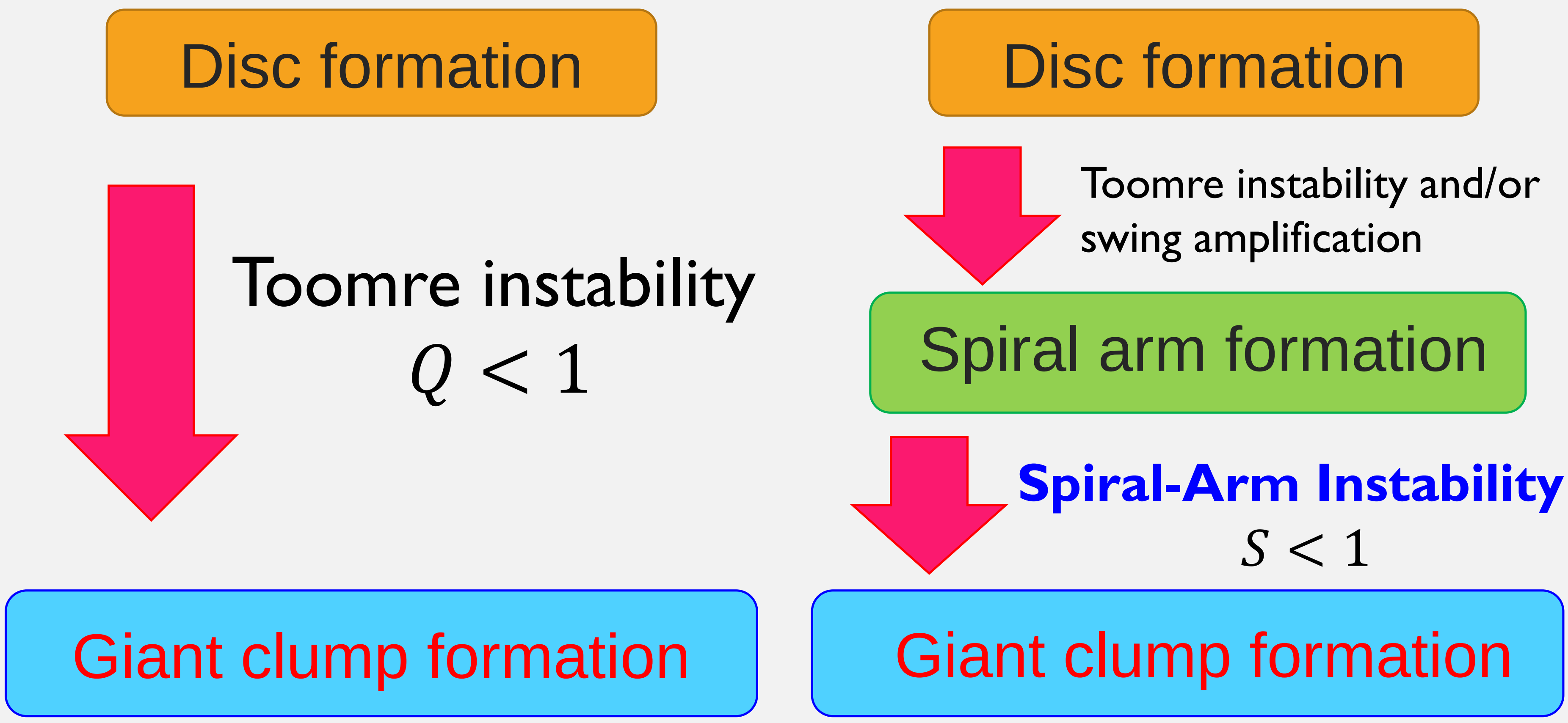
Spiral-Arm Instability (SAI)

(Inoue & Yoshida 2017)

For low-z clumpy galaxies

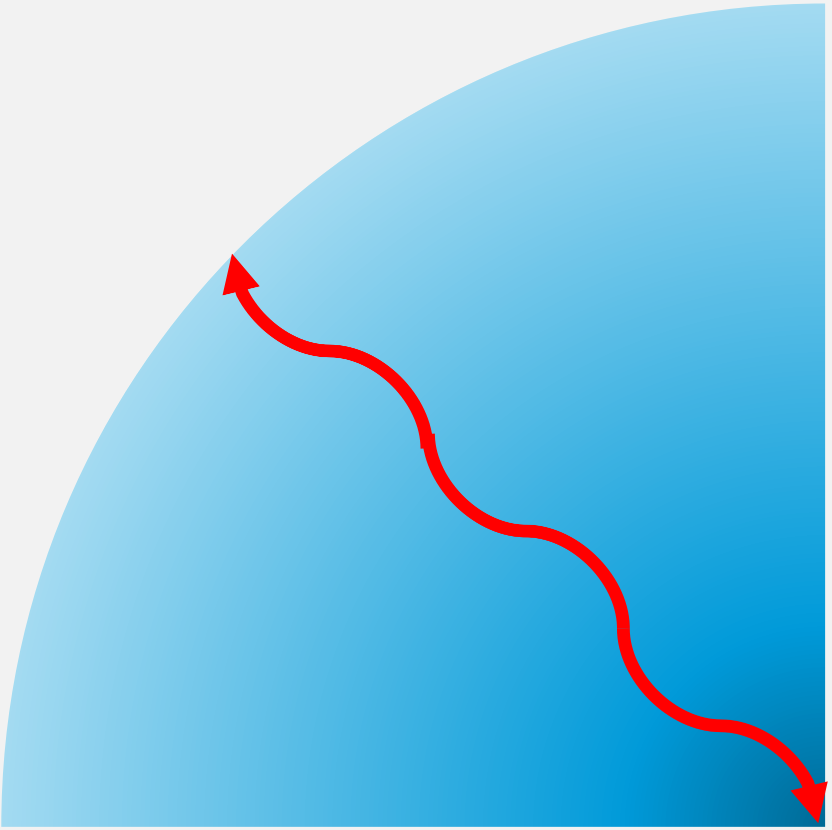
TI vs SAI

- Toomre Instability
- Spiral-Arm Instability



TI vs SAI

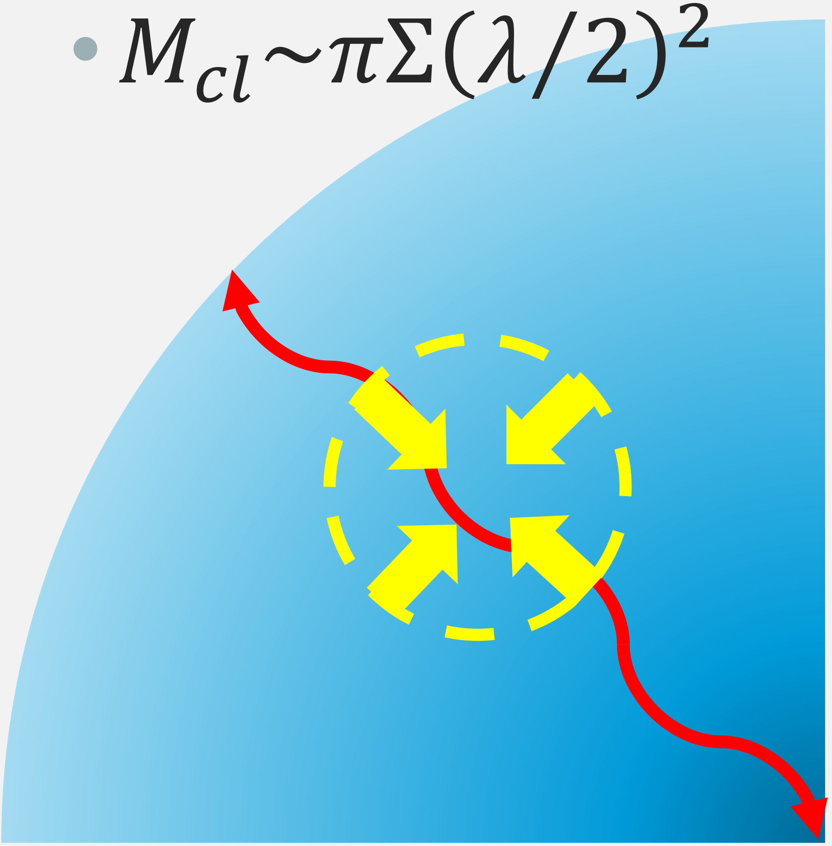
- Toomre Instability



- Spiral-Arm Instability

TI vs SAI

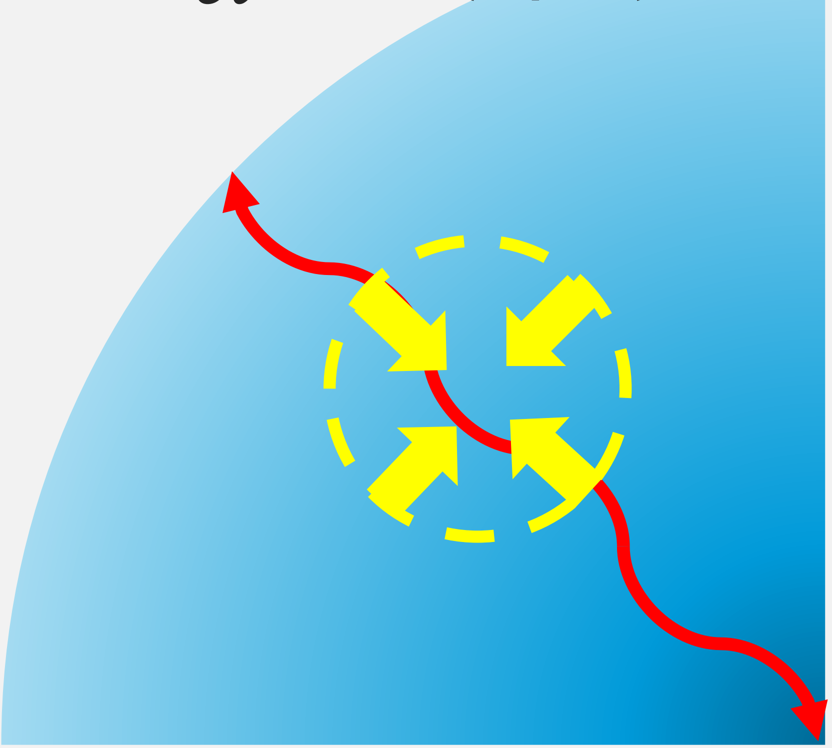
- Toomre Instability
  - **2D collapse**
  - $M_{cl} \sim \pi\Sigma(\lambda/2)^2$



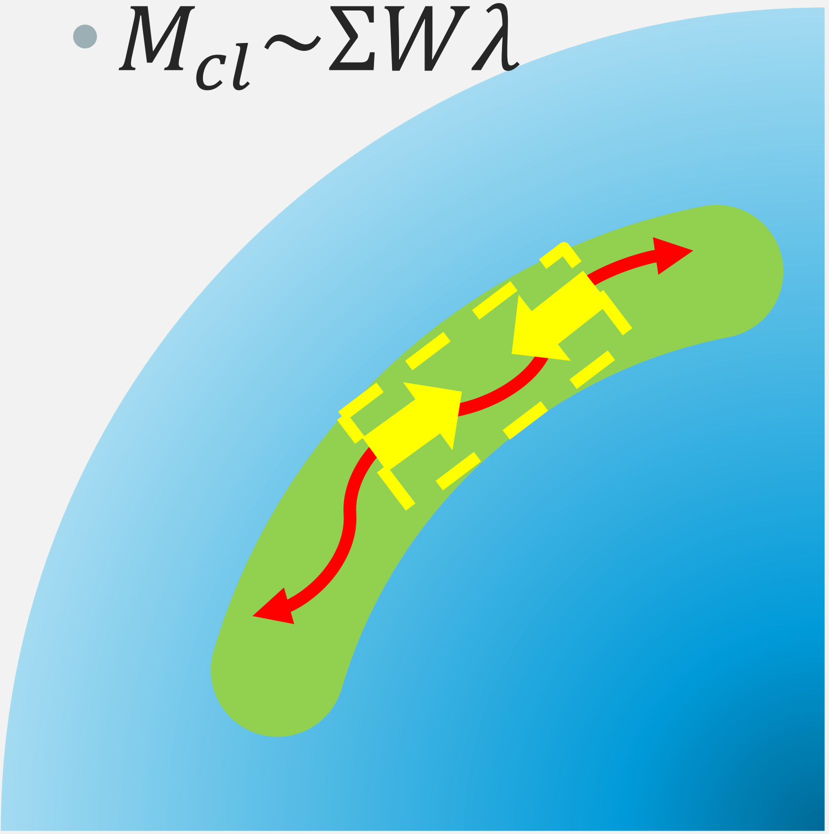
- Spiral-Arm Instability

TI vs SAI

- Toomre Instability
  - **2D collapse**
  - $M_{cl} \sim \pi\Sigma(\lambda/2)^2$

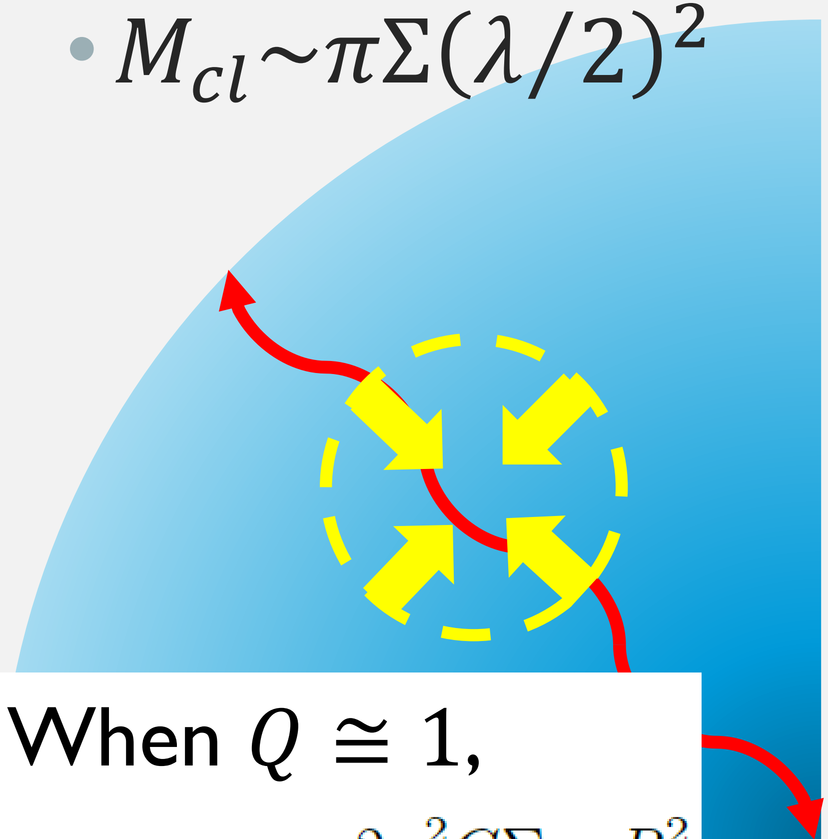


- Spiral-Arm Instability
  - **1D collapse**
  - $M_{cl} \sim \Sigma W \lambda$



TI vs SAI

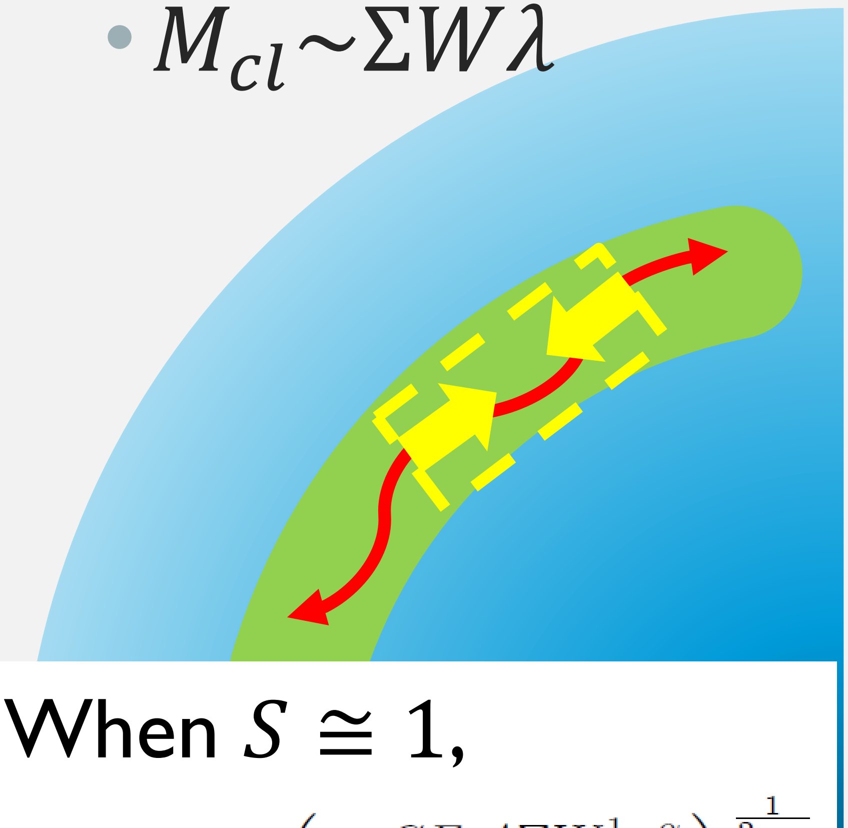
- Toomre Instability
  - **2D collapse**
  - $M_{cl} \sim \pi \Sigma (\lambda/2)^2$



When $Q \cong 1$,

$$\lambda_{\mathrm{MU}} \simeq \frac{2\pi^2 G \Sigma_{\mathrm{g,d}} R_{\mathrm{d}}^2}{a^2 V^2}$$

- Spiral-Arm Instability
  - **1D collapse**
  - $M_{cl} \sim \Sigma W \lambda$



When $S \cong 1$,

$$\lambda_{\mathrm{MU}} = 2\pi \left(\frac{\pi \alpha G F_0 A \Sigma W^{1-\alpha}}{8\Omega^2} \right)^{\frac{1}{2-\alpha}}$$

Scaling relations of high-z clumps

- From our analysis, we can obtain scaling relations of properties of giant clumps.

$$\sigma_{\rm cl}^2 \simeq \frac{16}{3}(\pi\epsilon)^{\alpha-3}(\alpha F_0 f_{\rm g})^{-1}\left(\frac{W^{\alpha/2}R_{\rm cl}^{1-\alpha/2}}{R_{\rm d}}V\right)^2.$$

Spiral-arm instability
expected scaling relation:

$$R_{\rm cl} \propto \left(\frac{\sigma_{\rm cl}}{V}R_{\rm d}\right)^{1.3}$$

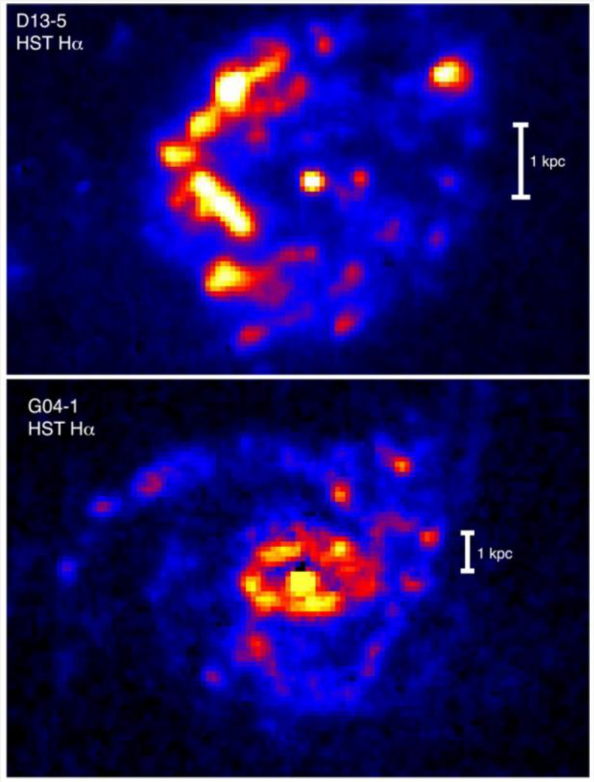
$$\sigma_{\rm cl}^2 \simeq \frac{a^2}{3\pi\epsilon^3 f_{\rm g}}V^2\left(\frac{R_{\rm cl}}{R_{\rm d}}\right)^2$$

Toomre instability
expected scaling relation:

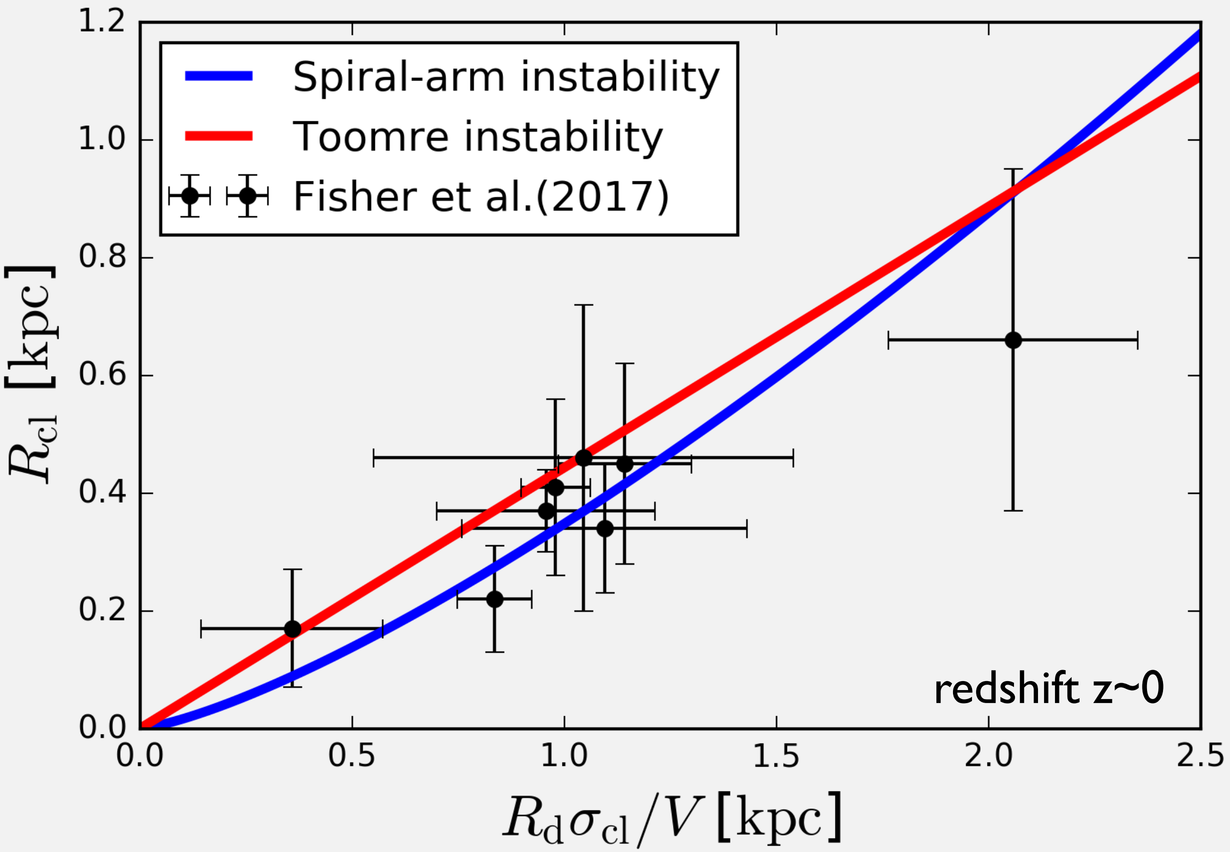
$$R_{\rm cl} \propto \frac{\sigma_{\rm cl}}{V}R_{\rm d}$$

$R_{\rm cl}$: clump radius, $\sigma_{\rm cl}$:vel. disp. with in clump, $R_{\rm d}$: disc radius, V: disc rot. vel.

Scaling relations of high-z clumps



Data from Fisher+17: DYNAMO



- Neither model is rejected by the observations.

Scaling relations of high-z clumps

- From our analysis, we can obtain scaling relations of properties of giant clumps.

$$\frac{M_{\rm cl}}{M_{\rm d,g+s}} \simeq 2\left[\frac{1}{8}\alpha F_0 \left(A\beta\right)^{3-\alpha}\eta\left(\frac{W}{R_{\rm d}}\right)^{3-2\alpha}\right]^{\frac{1}{2-\alpha}}$$

Spiral-arm instability

expected scaling relation:

$$\frac{M_{\rm g,cl}}{M_{\rm g,d}} \propto f_{\rm g}^{0.7} R_{\rm d}^{-1.3},$$

$$\frac{M_{\rm cl}}{M_{\rm d,g+s}} \simeq \pi^2 a^{-4} \eta^2.$$

$\eta \approx f_g$: gas fraction including DM

Toomre instability

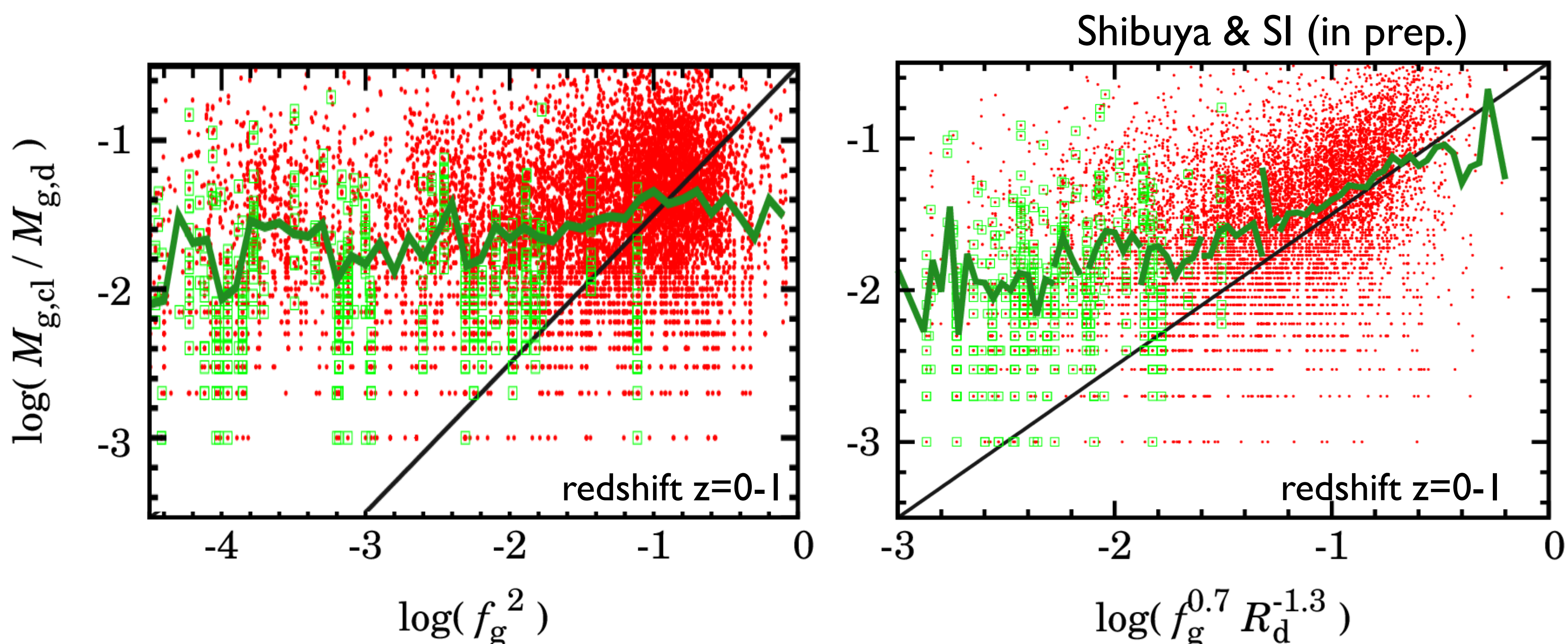
expected scaling relation:

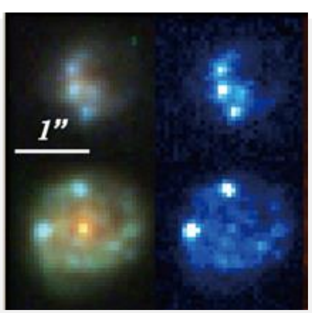
$$\frac{M_{\rm g,cl}}{M_{\rm g,d}} \propto f_{\rm g}^{2},$$

$R_{\rm cl}$: clump radius, $\sigma_{\rm cl}$:vel. disp. with in clump, $R_{\rm d}$: disc radius, V: disc rot. vel.

Scaling relations of high-z clumps

- Toomre Instability
- Spiral-Arm Instability





Data from Shibuya+16: HST @ z=0-1

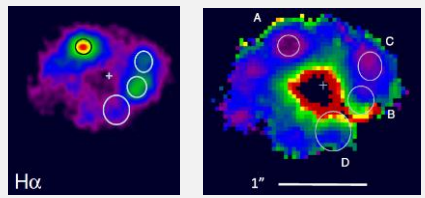
- Our SAI model appears better consistent with the observations of M_{cl}/M_d ~10% clumps.

Transition of the clump formation mechanisms

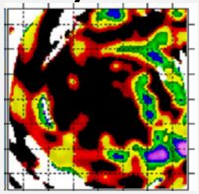
time

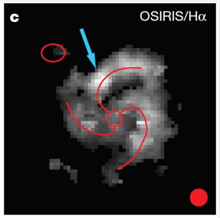
high z

Toomre instability: $Q < 1$



Possibly non-linear: $Q > 2-3$
(Inoue+ 2016)

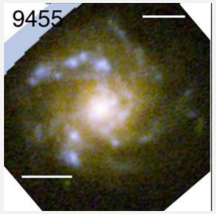




z~2

The onset of spiral galaxies

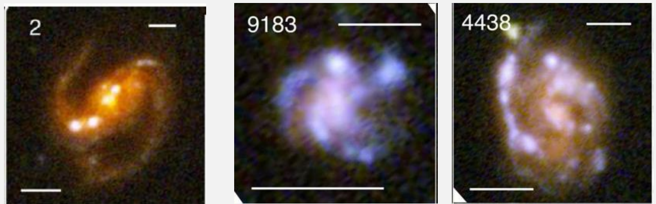
Low+12 @ z=2.1
Elmegreen+14 @ z~1.8



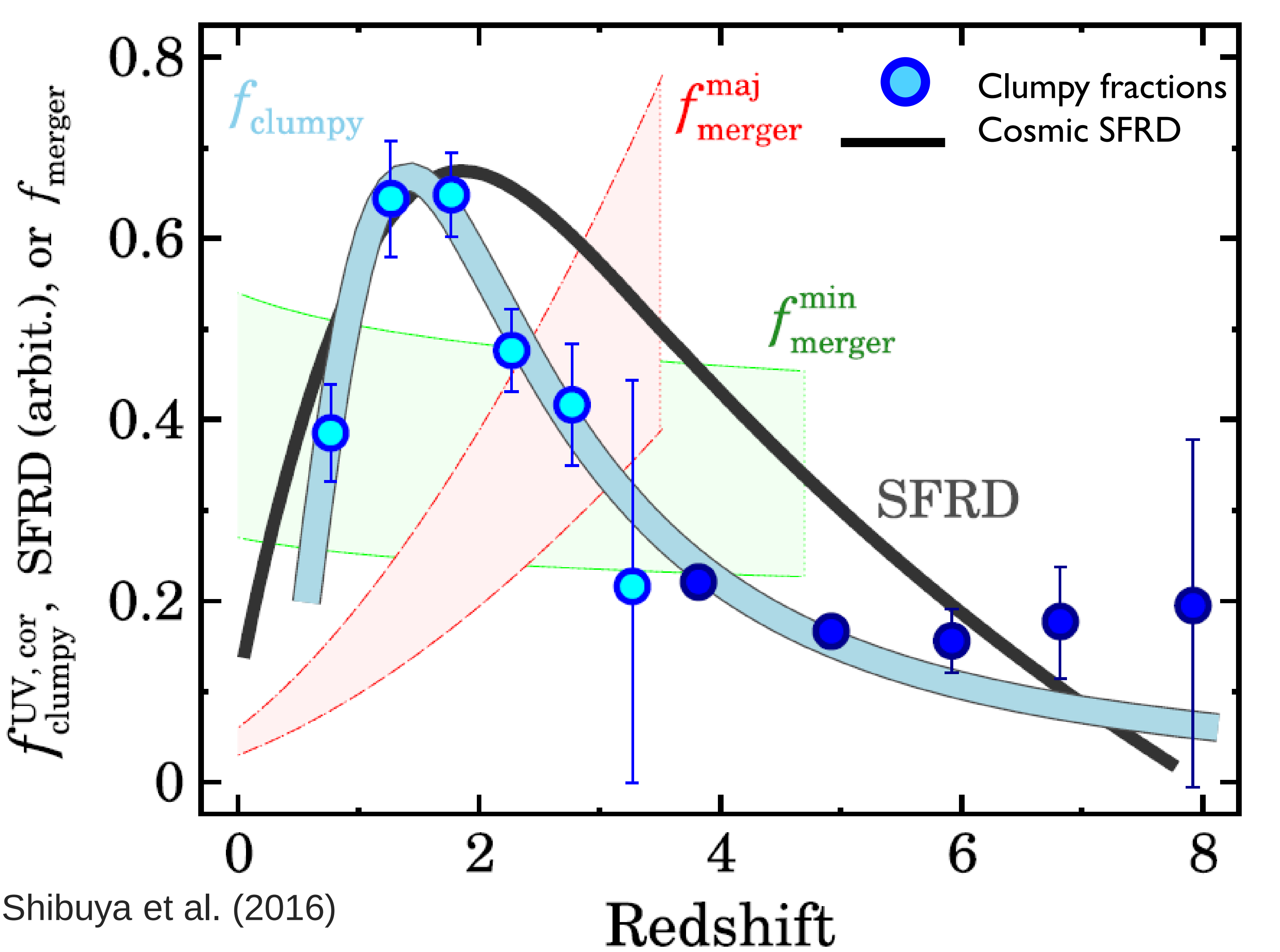
z~1

Spiral-arm instability: $S < 1$

z=0

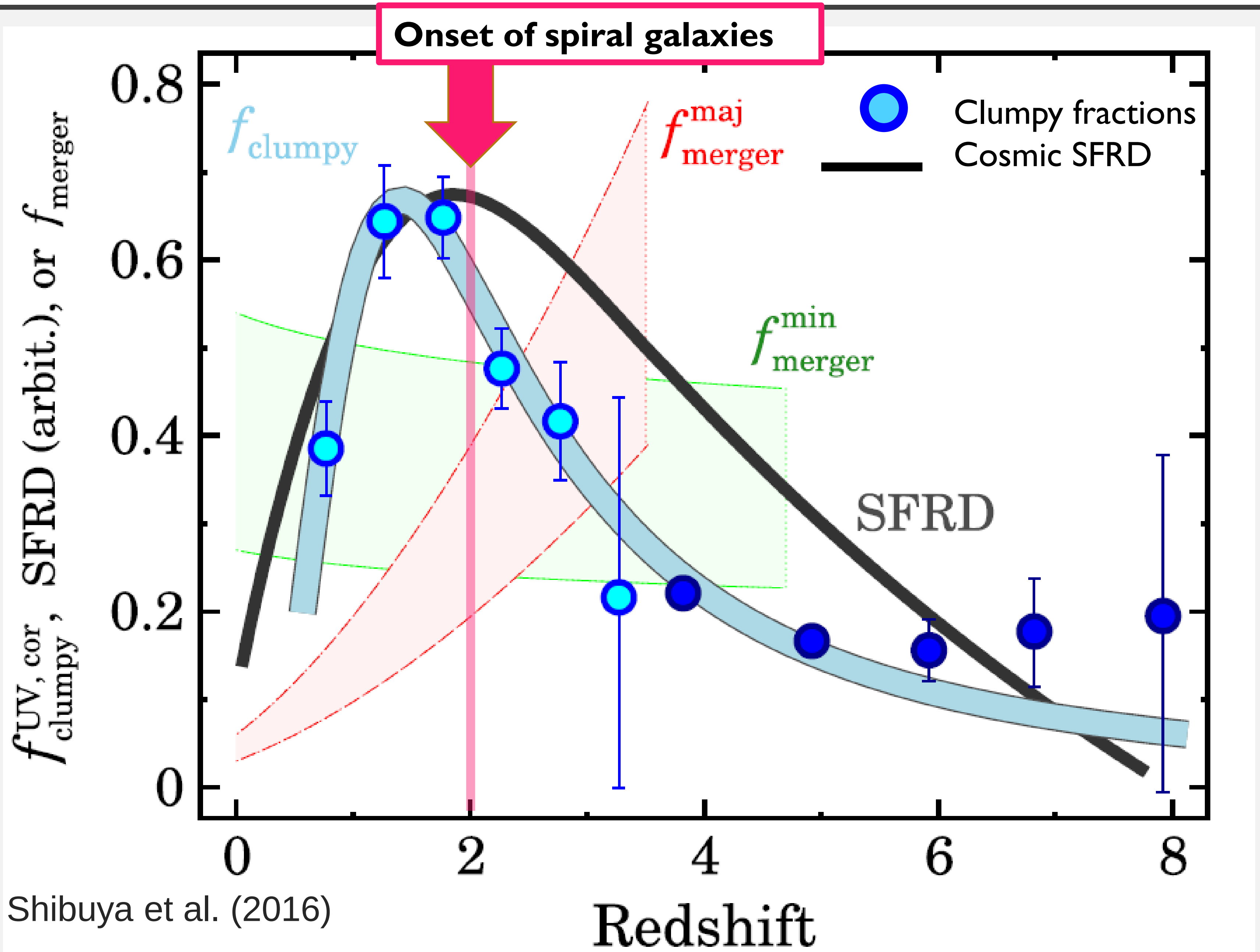


Clumpy fraction and cosmic SFR



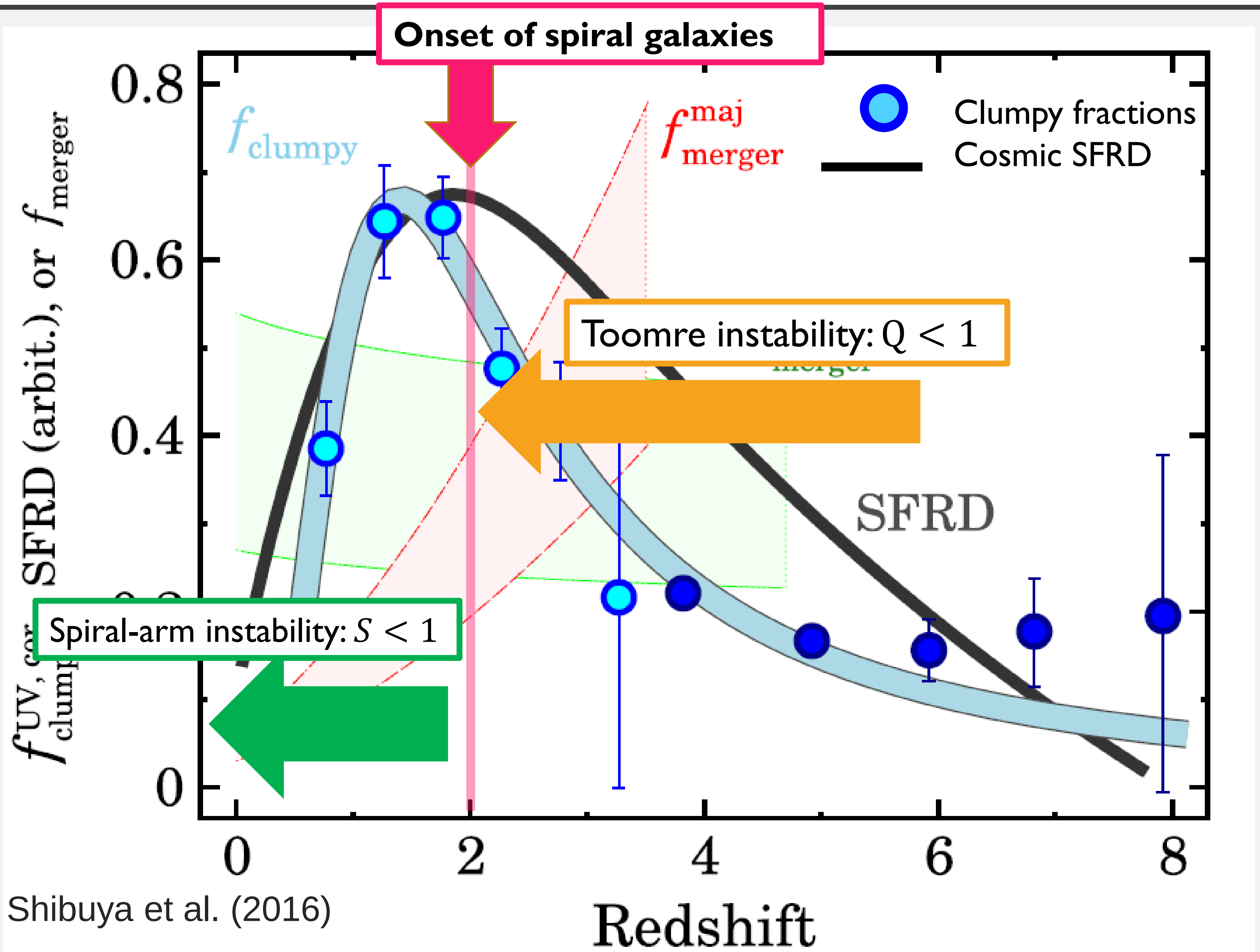
- Shibuya et al. (2016)

Clumpy fraction and cosmic SFR



- Shibuya et al. (2016)

Clumpy fraction and cosmic SFR



- Shibuya et al. (2016)

Summary

- Our SAI model appears better consistent with the low-z observations.

  - The TI model cannot reproduce the scaling relation of the observations despite that the TI model relays on fewer assumptions than our SAI model.

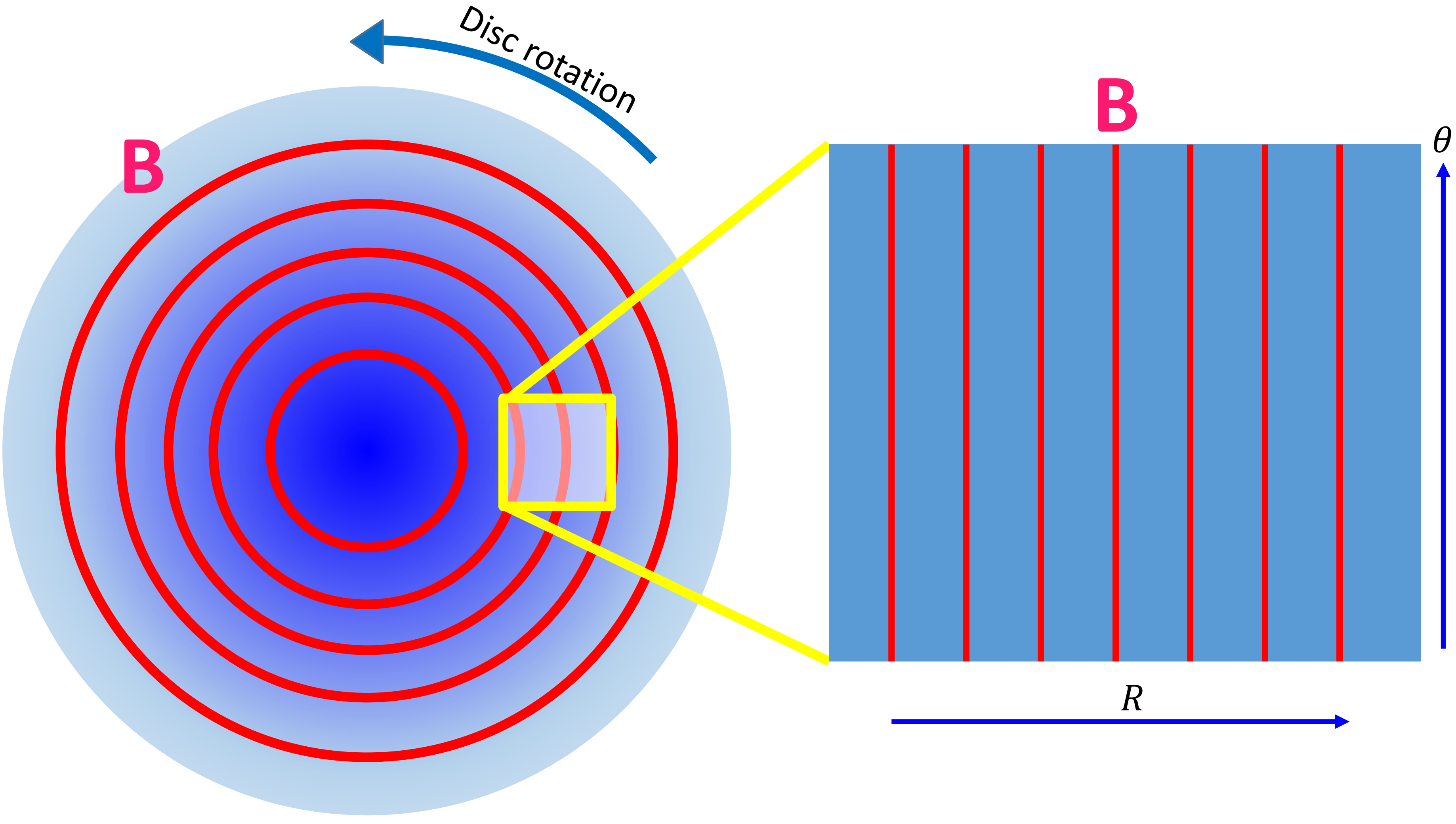
- There could be transition of clump formation mechanisms
  - @ z=2~1, from Toomre instability to spiral-arm instability

See arXiv: 1706.01895

A little about magnetic fields
for Toomre and spiral-arm instabilities

Toroidal magnetic fields in a disc galaxy

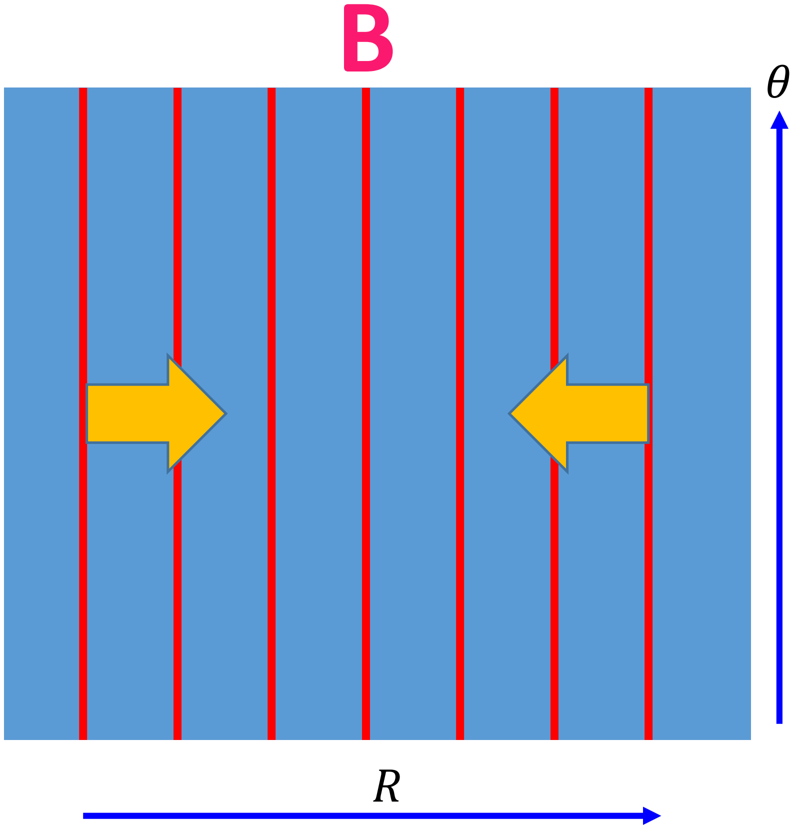
- The Galactic B-fields are approximately toroidal (Rand & Kulkarni 1989).
- $B_\theta \sim 1\ \mu$G (e.g. Inoue & Tabara 1981, Mouschovias 1983,).



Toroidal magnetic fields in a disc galaxy

- The Galactic B-fields are approximately toroidal (Rand & Kulkarni 1989).
- $B_\theta \sim 1\ \mu$G (e.g. Inoue & Tabara 1981, Mouschovias 1983,).

- Radial perturbations

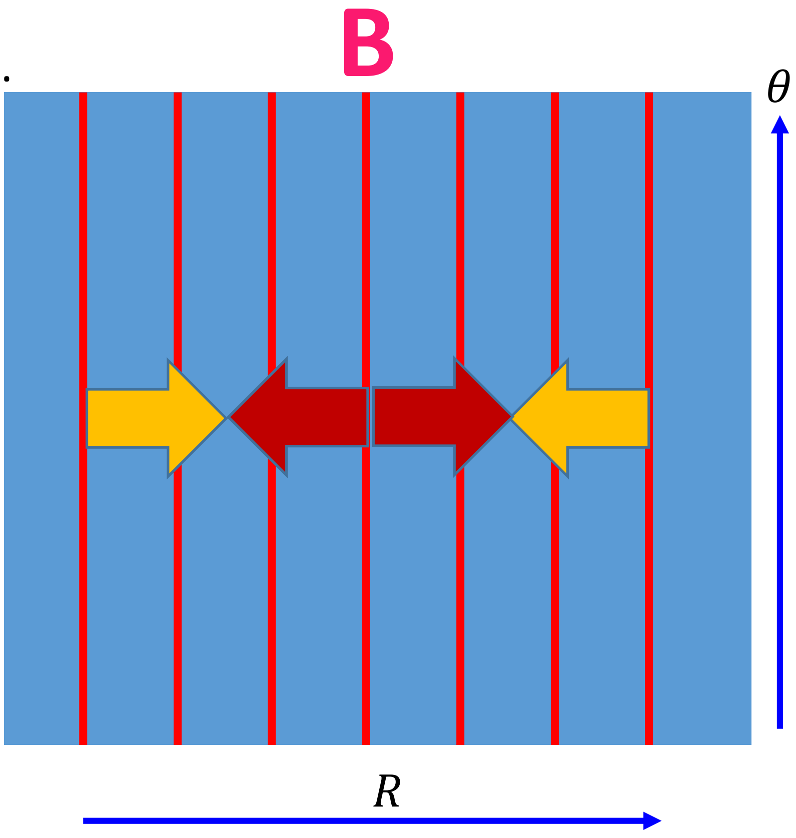


Toroidal magnetic fields in a disc galaxy

- The Galactic B-fields are approximately toroidal (Rand & Kulkarni 1989).
- $B_\theta \sim 1\ \mu$G (e.g. Inoue & Tabara 1981, Mouschovias 1983,).

- Radial perturbations
  - The B-fields work against the perturbations.

Azimuthal B-fields can stabilize azimuthal perturbations by magnetic pressure.



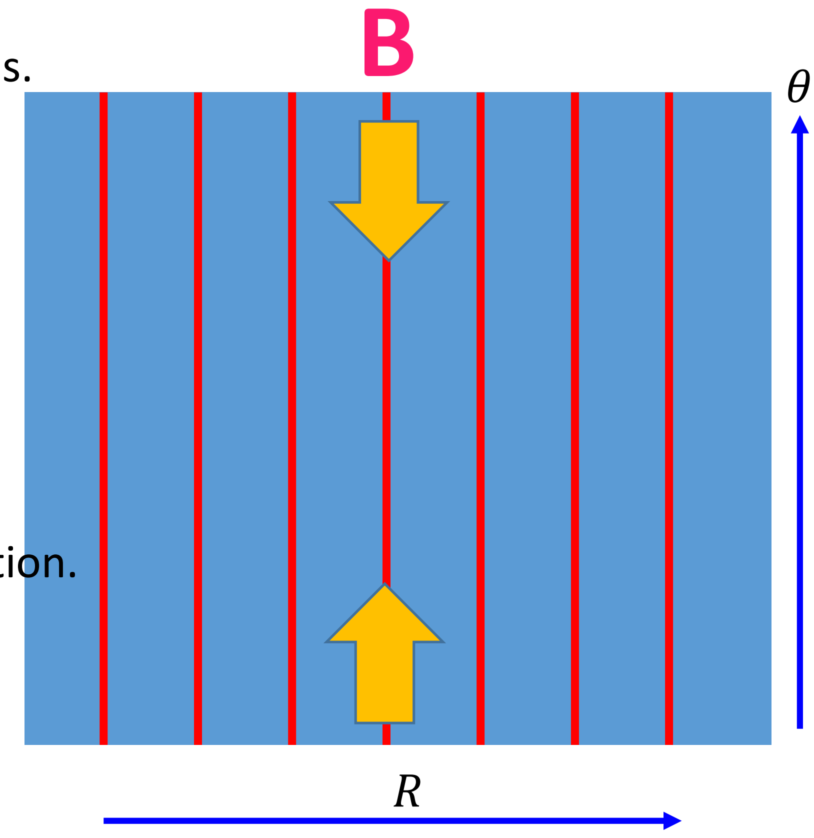
Toroidal magnetic fields in a disc galaxy

- The Galactic B-fields are approximately toroidal (Rand & Kulkarni 1989).
- $B_\theta \sim 1\ \mu$G (e.g. Inoue & Tabara 1981, Mouschovias 1983,).

- Radial perturbations
  - The B-fields work against the perturbations.

Azimuthal B-fields can stabilize azimuthal perturbations by magnetic pressure.

- Azimuthal perturbations
  - The B-fields do nothing in azimuthal direction.



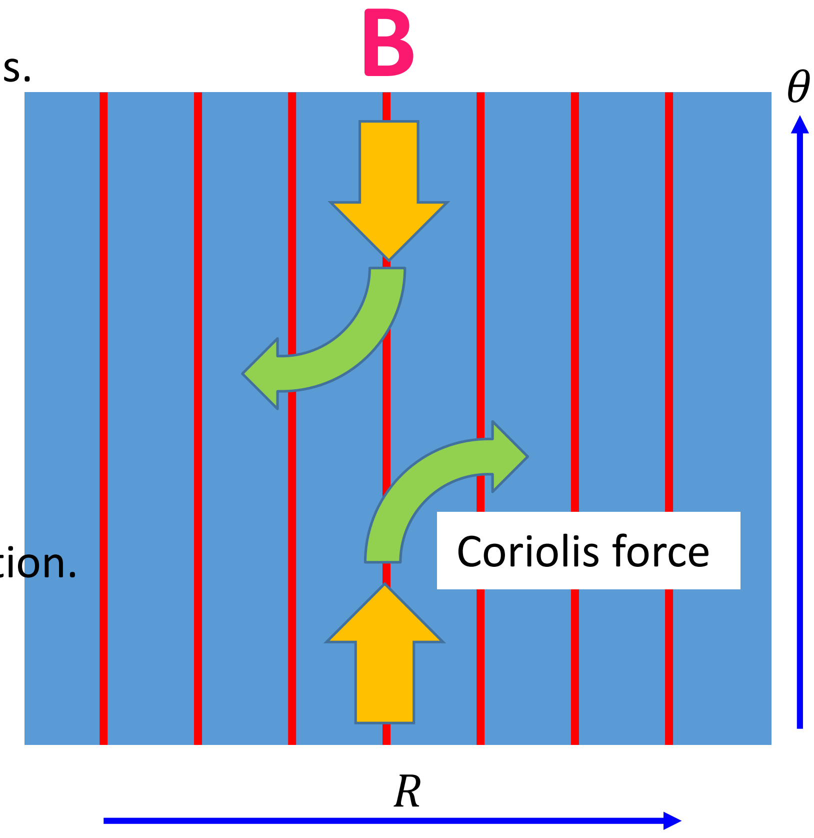
Toroidal magnetic fields in a disc galaxy

- The Galactic B-fields are approximately toroidal (Rand & Kulkarni 1989).
- $B_\theta \sim 1\ \mu$G (e.g. Inoue & Tabara 1981, Mouschovias 1983,).

- Radial perturbations
  - The B-fields work against the perturbations.

Azimuthal B-fields can stabilize azimuthal perturbations by magnetic pressure.

- Azimuthal perturbations
  - The B-fields do nothing in azimuthal direction.
  - But, work against Coriolis force.



Toroidal magnetic fields in a disc galaxy

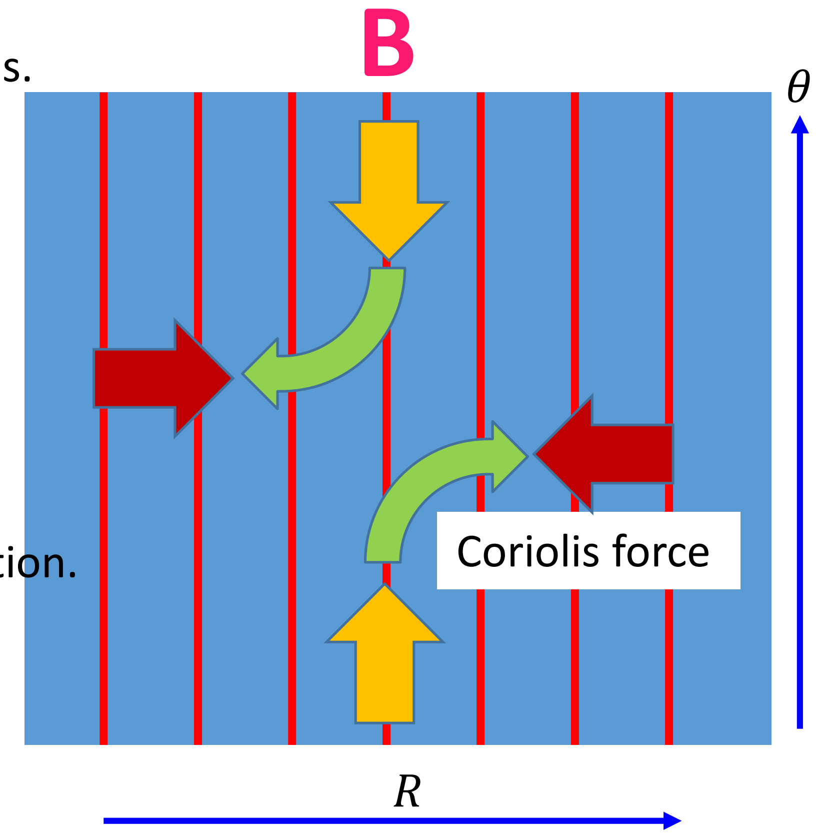
- The Galactic B-fields are approximately toroidal (Rand & Kulkarni 1989).
- $B_\theta \sim 1\ \mu$G (e.g. Inoue & Tabara 1981, Mouschovias 1983,).

- Radial perturbations
  - The B-fields work against the perturbations.

Azimuthal B-fields can stabilize azimuthal perturbations by magnetic pressure.

- Azimuthal perturbations
  - The B-fields do nothing in azimuthal direction.
  - But, work against Coriolis force.

Azimuthal B-fields can destabilize azimuthal perturbations by cancelling Coriolis force.



Toroidal magnetic fields in a disc galaxy

- The Galactic B-fields are approximately toroidal (Rand & Kulkarni 1989).
- $B_\theta \sim 1\ \mu$G (e.g. Inoue & Tabara 1981, Mouschovias 1983,).

- Radial perturbations: **Toomre instability**
  - The B-fields work against the perturbations.

Dispersion relation: $$\omega^2 = (c_s^2 + \underline{v_{\rm A}^2})k^2 - 2\pi G\Sigma k + \kappa^2.$$

(modified) Toomre Q: $$Q' = \frac{\kappa\sqrt{c_s^2 + v_{\rm A}^2}}{\pi G\Sigma}.$$

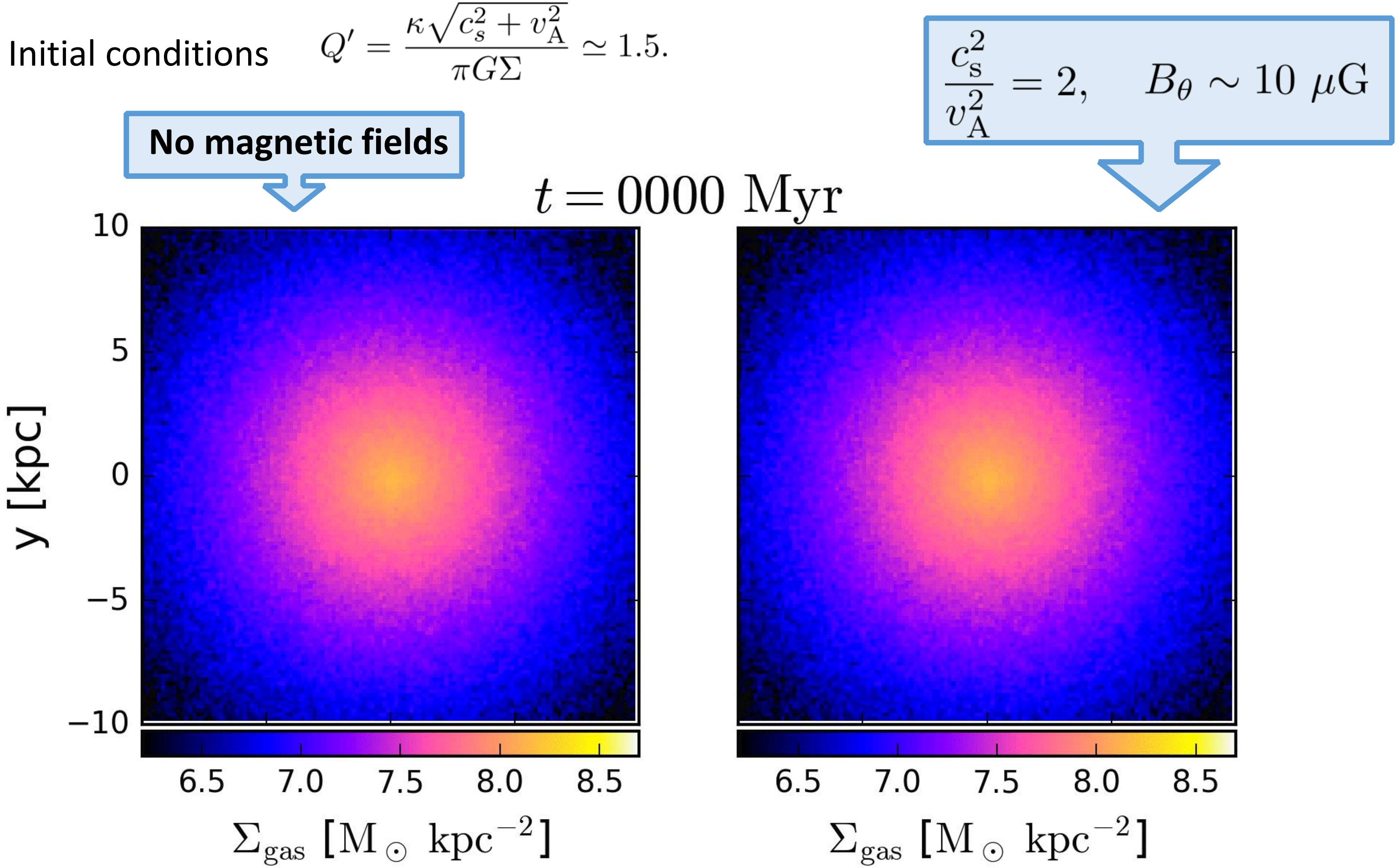
- Azimuthal perturbations: **Spiral-arm instability**
  - The B-fields do nothing in azimuthal direction.
  - But, work against Coriolis force.

Dispersion relation: $$\omega^2 = \left[c_s^2 - \pi G\delta\Upsilon f(kW)\right]k^2 + \frac{4\Omega^2\omega^2}{\omega^2 + k^2\underline{v_{\rm A}^2}}.$$

cf. Elmegreen (1987, 1991), Kim & Ostriker (2001)

Ideal MHD simulation

- Gas + stellar discs ($f_{gas} = 0.2$, isothermal gas)
- Initial conditions $Q' = \frac{\kappa\sqrt{c_s^2 + v_A^2}}{\pi G \Sigma} \simeq 1.5.$



Summary

- Assuming toroidal magnetic fields,
  - The magnetic fields can suppress growth of radial perturbations.
    - Toomre instability can be mitigated.
  - The magnetic fields can enhance growth of azimuthal perturbations.
    - By cancelling Coriolis force
    - Therefore, spiral-arms can be destabilized by the magnetic fields.
- **Giant-clump formation by spiral-arm fragmentation can be enhanced in toroidal magnetic fields in a spiral galaxy.**