科研費
KAKENHI

渦状腕の線形摂動理論：
渦状腕分裂によるクランプ形成

Beyond Toomre's Q

MNRAS submitted
arXiv: 1706.01895 （←昨日！！）

井上 茂樹 (CREST/SPPEXA fellow)
カブリ数物連携宇宙研究機構 / 東京大学

w/ **吉田 直紀 (東京大学)**

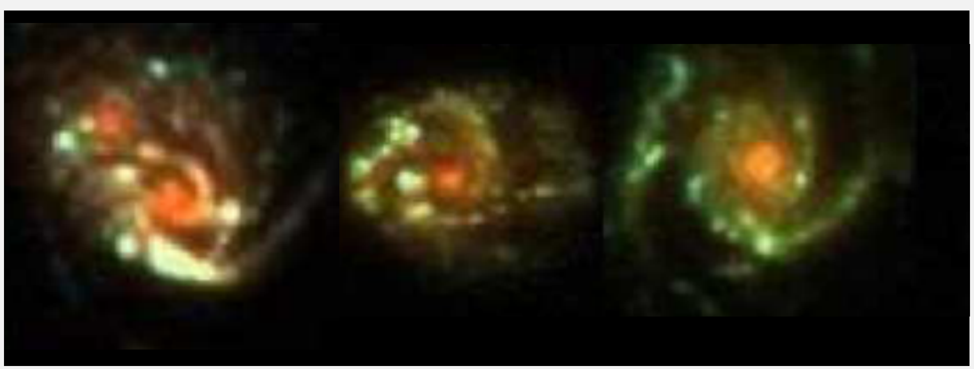
Spiral or Clumpy?

at low-z

- Spiral galaxies
  - Low redshifts
  - Gas-rich (f_{gas}~10%)

Toomre instability

at high-z



with HST Guo et al. (2014)

- Clumpy galaxies
  - **Giant clumps**
  - High redshifts (mainly)
  - Gas-rich (f_{gas}~30%)

Toomre instability

really…?

What was Toomre instability???

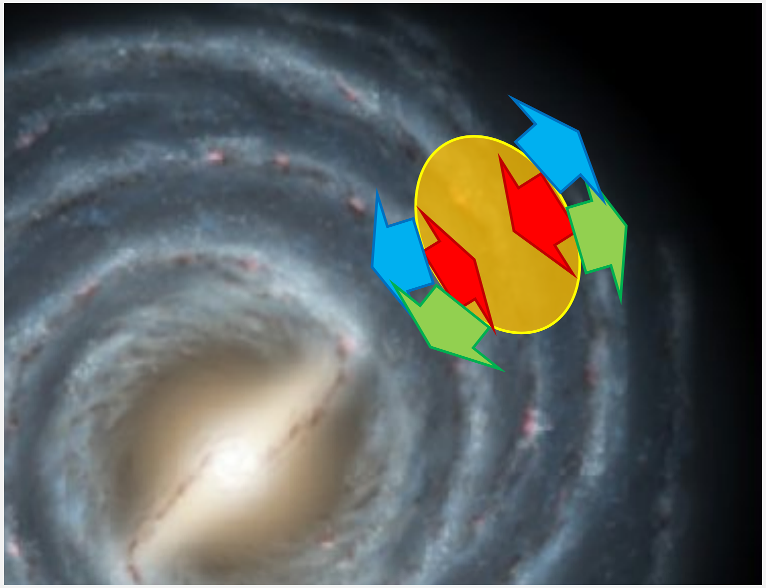
- From **local** and **linear** perturbation theory for **axisymmetric** perturbations in **smooth discs**,

Velocity dispersion or sound speed (pressure)

Epicyclic frequency (Coriolis force)

The stability condition: $Q \equiv \dfrac{\sigma\kappa}{\pi G \Sigma} > 1$

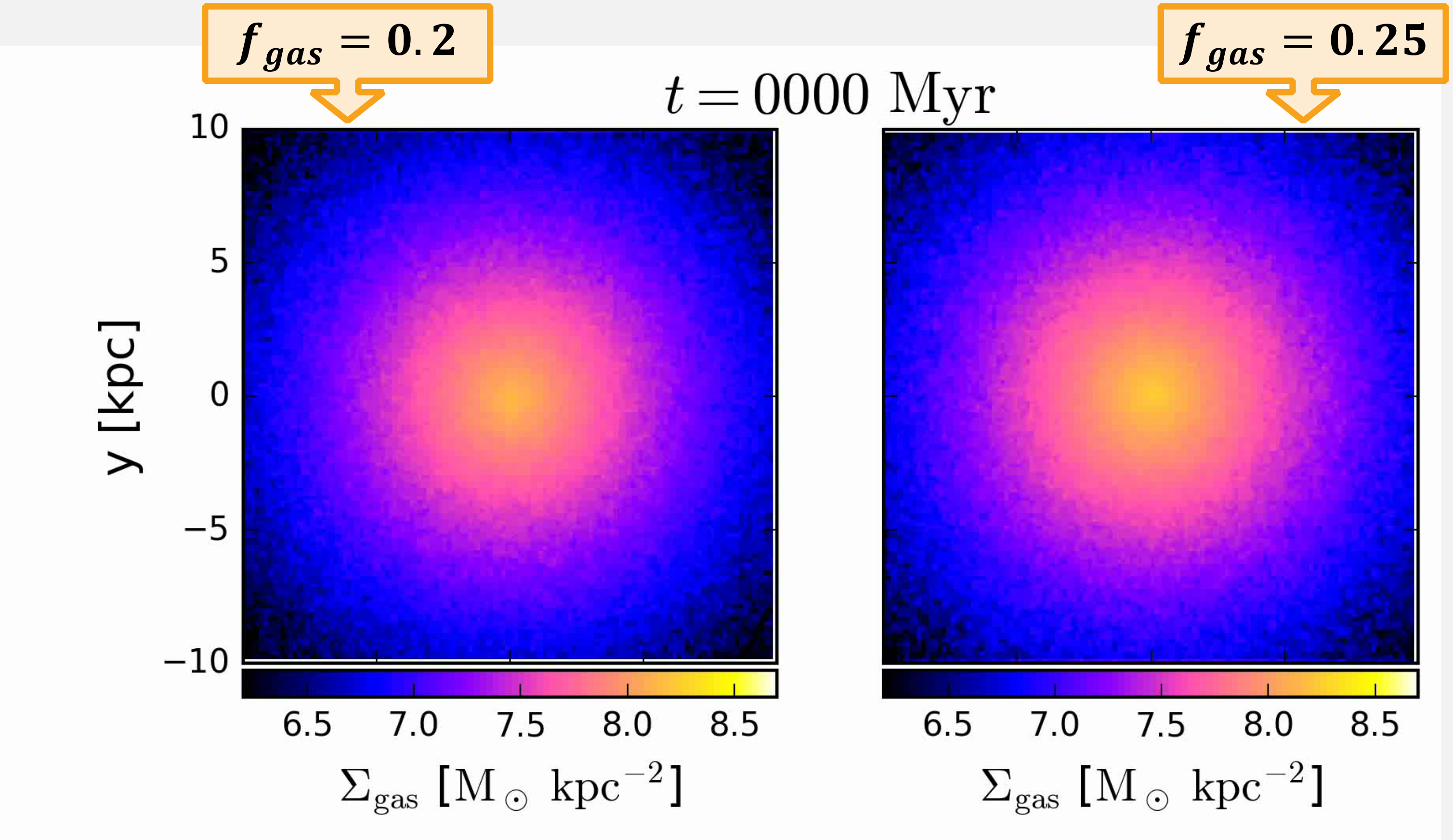
Surface density (self-gravity)



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

Spiral or Clumpy?

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

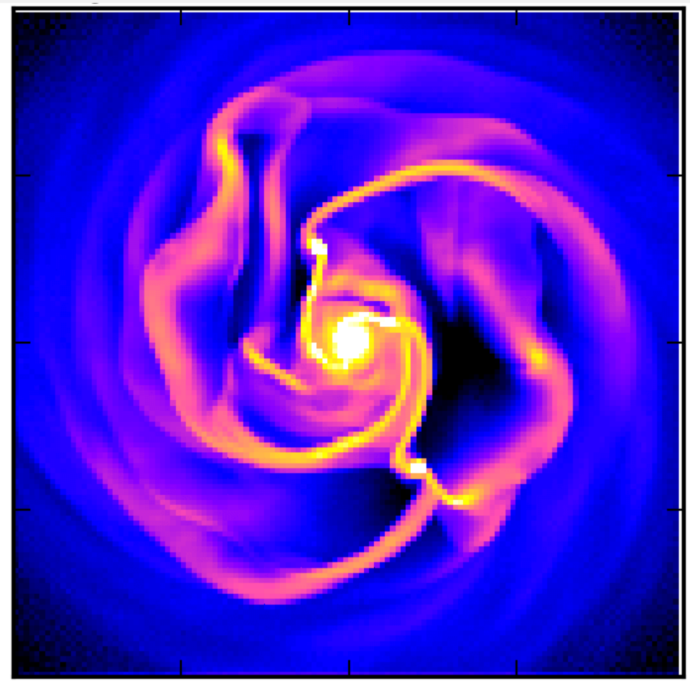


Spiral-arm fragmentation as a clump formation mechanism

- Spiral arms can fragment into clumps,
  - if a gas fraction is high and/or a 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

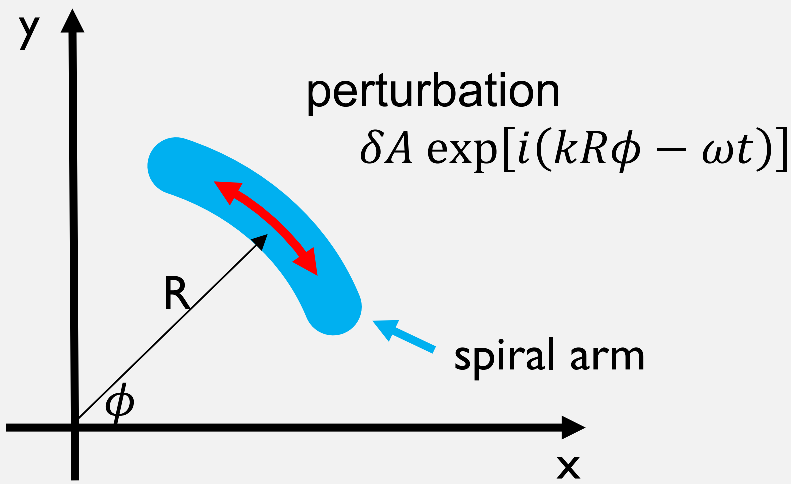
- The aims of this study:
  - How spiral-arm fragmentation occurs?
    - Derive **an instability parameter and its criterion**
  - Discuss **if the fragmentation can form high-z clumps**



Let's go to linear perturbation theory for a spiral arm!!
(線形摂動理論)

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

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

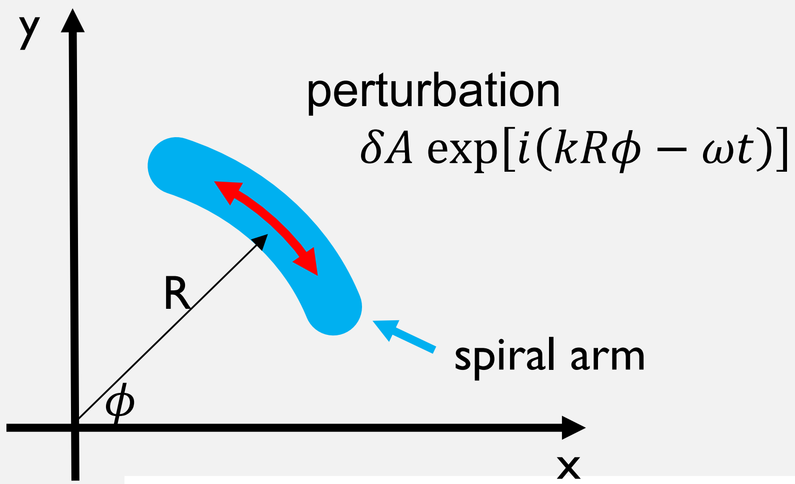
continuity:
$$\frac{\partial}{\partial t}\delta\Sigma + \frac{1}{R}\frac{\partial}{\partial R}\left(R\Sigma_0 \delta v_R\right) + \Omega\frac{\partial}{\partial \phi}\delta\Sigma + \frac{\Sigma_0}{R}\frac{\partial}{\partial \phi}\delta v_\phi = 0,$$

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 $\Upsilon = 1.4W\Sigma$ (**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.
- Hence, 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:
$$\omega^2 = \left(c_s^2 + \frac{\Upsilon_{\rm g}}{\delta\Upsilon_{\rm g}}\delta\Phi\right)k^2 + 4\Omega^2, \qquad \delta\Upsilon_{\rm g} = k^2\frac{\Upsilon_{\rm g}}{\omega^2 - 4\Omega^2 - c_s^2k^2}\delta\Phi,$$

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

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

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

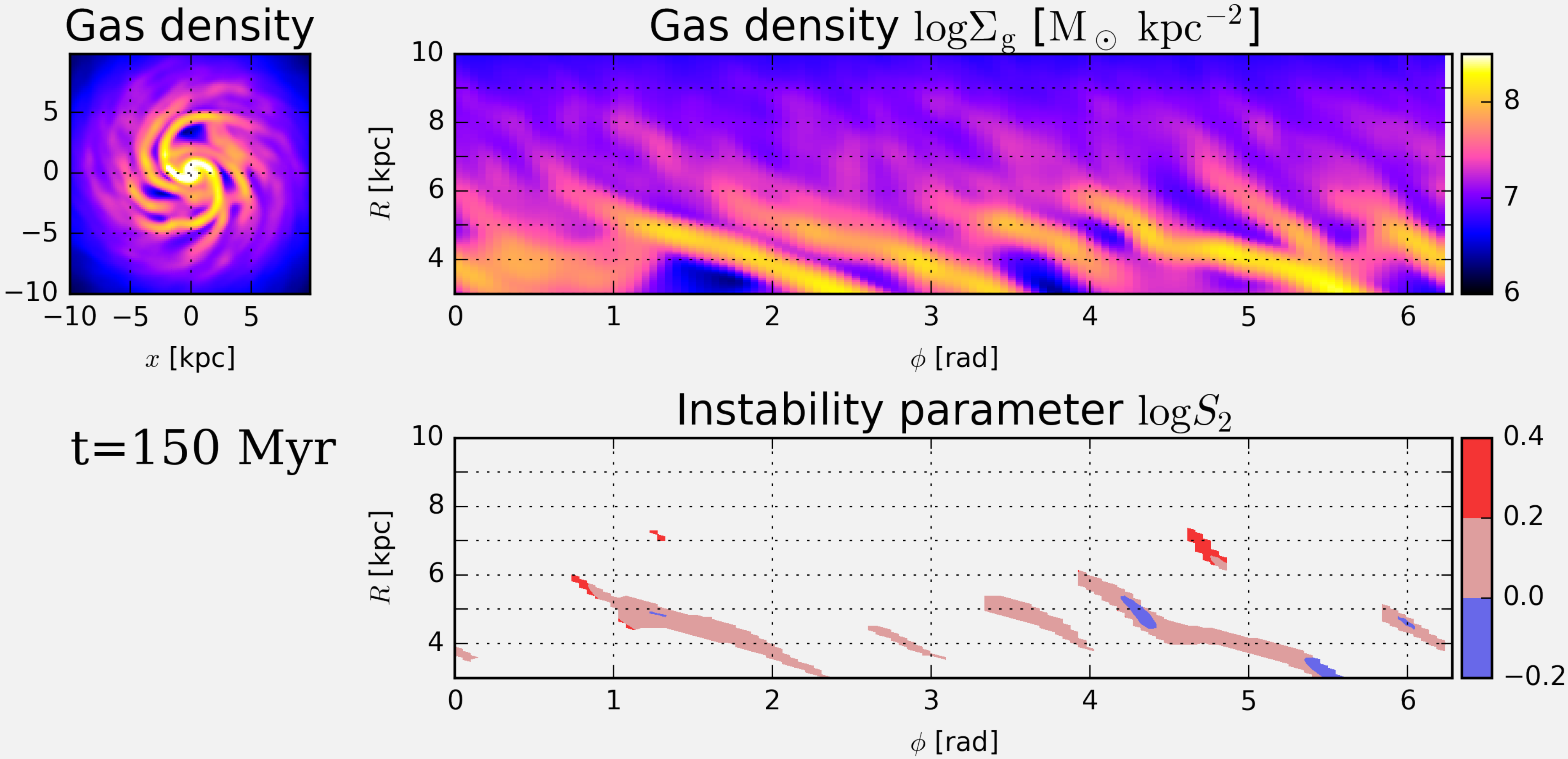
- Then, one can obtain the two-component dispersion relation,

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

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

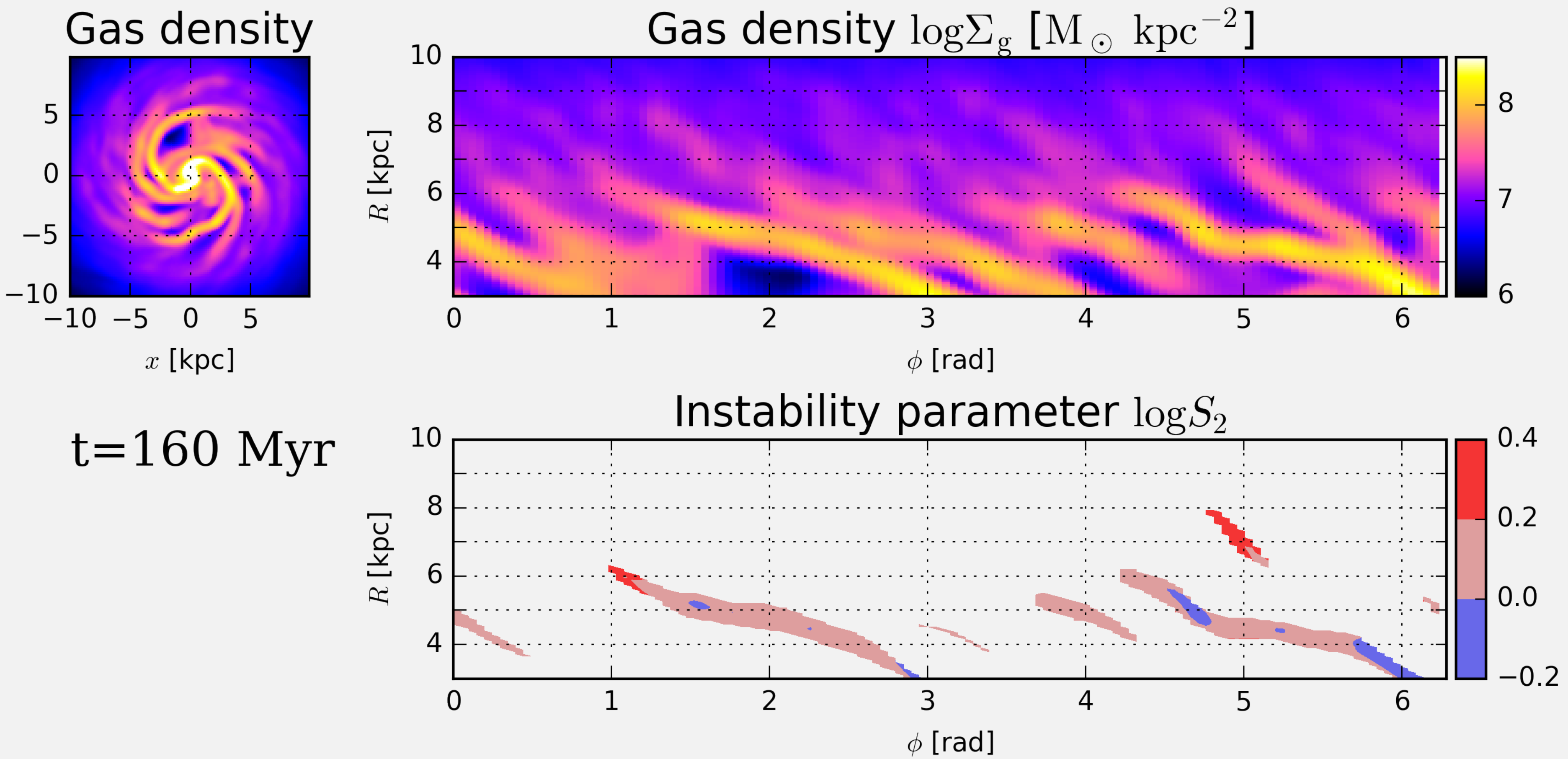
$$S \equiv \frac{1}{\pi G k^2}\left[\frac{\Upsilon_{\rm g} f(kW_{\rm g})}{c_s^2k^2 + 4\Omega_{\rm g}^2} + \frac{\Upsilon_{\rm s} f(kW_{\rm s})}{\sigma_\phi^2k^2 + 4\Omega_{\rm s}^2}\right]^{-1} < 1.$$

Demonstration



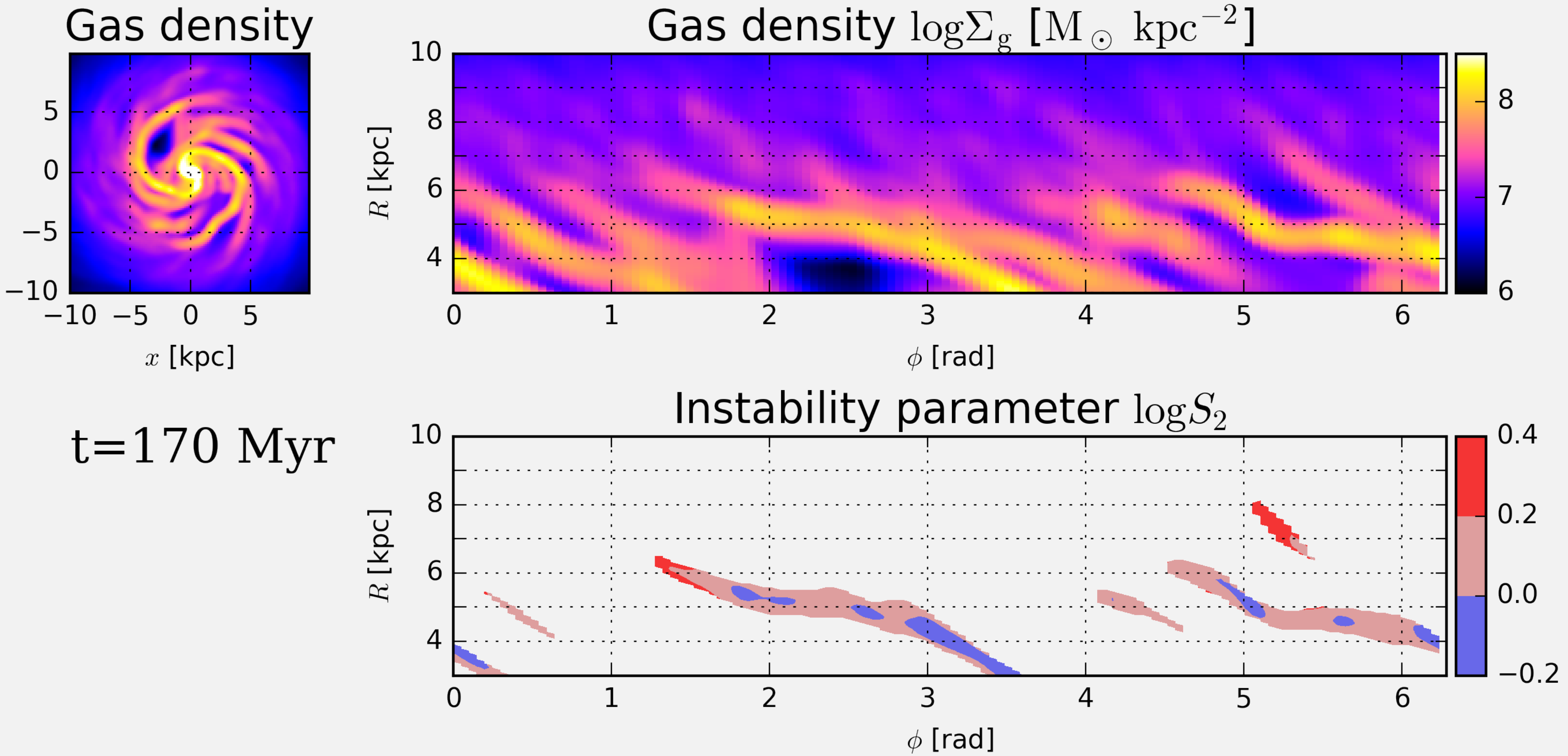
t=150 Myr

Demonstration



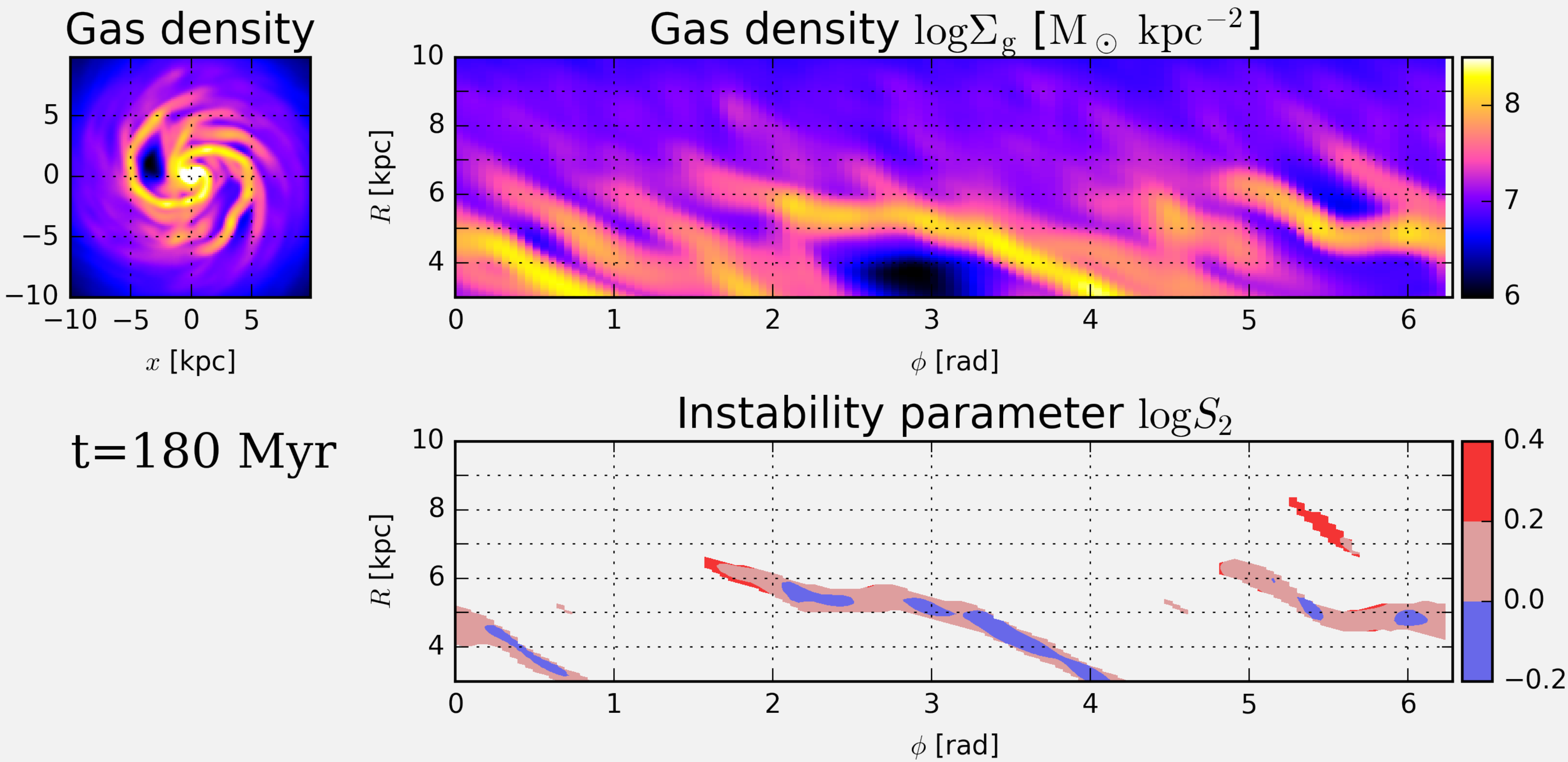
t=160 Myr

Demonstration

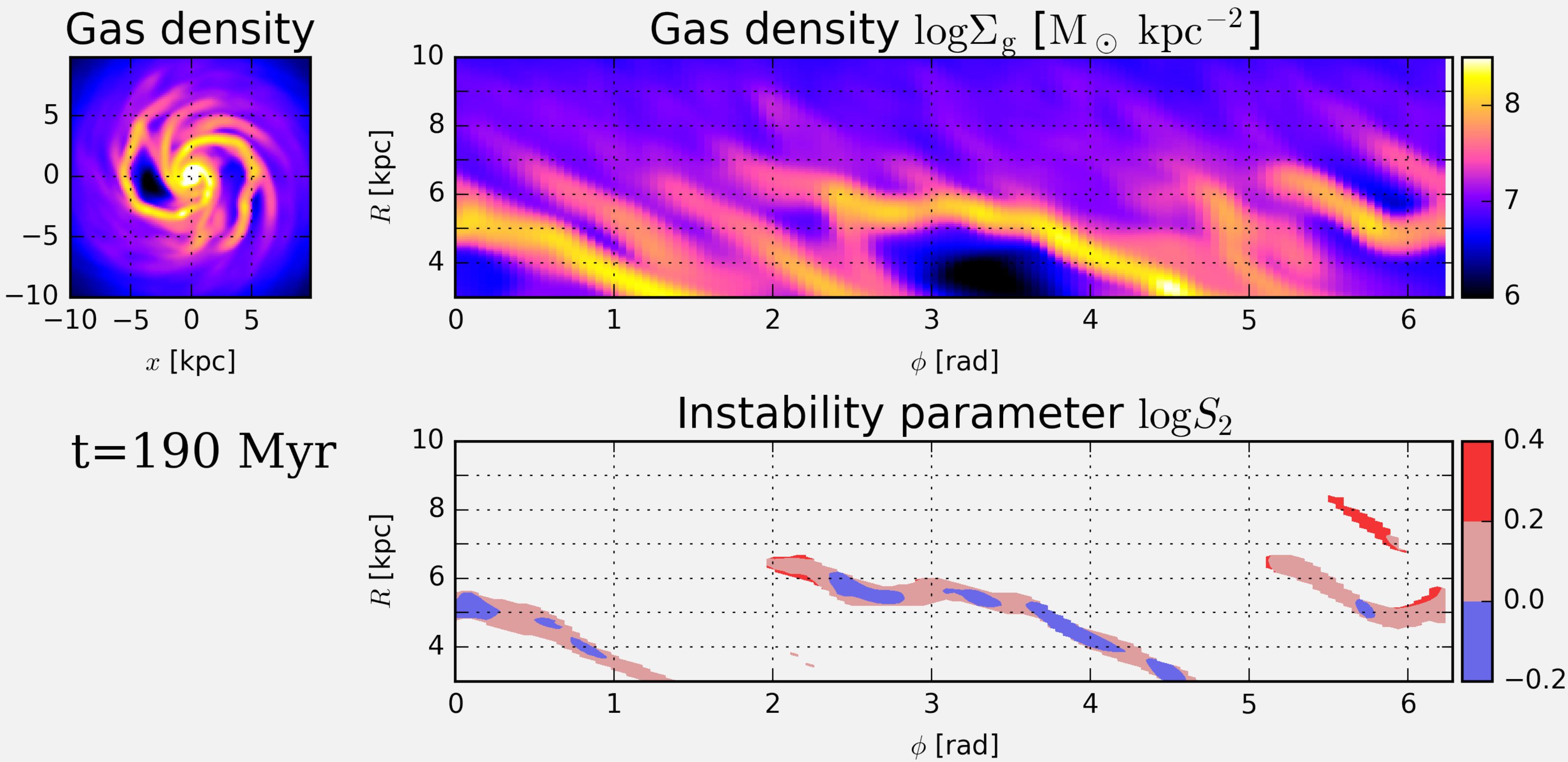


t=170 Myr

Demonstration

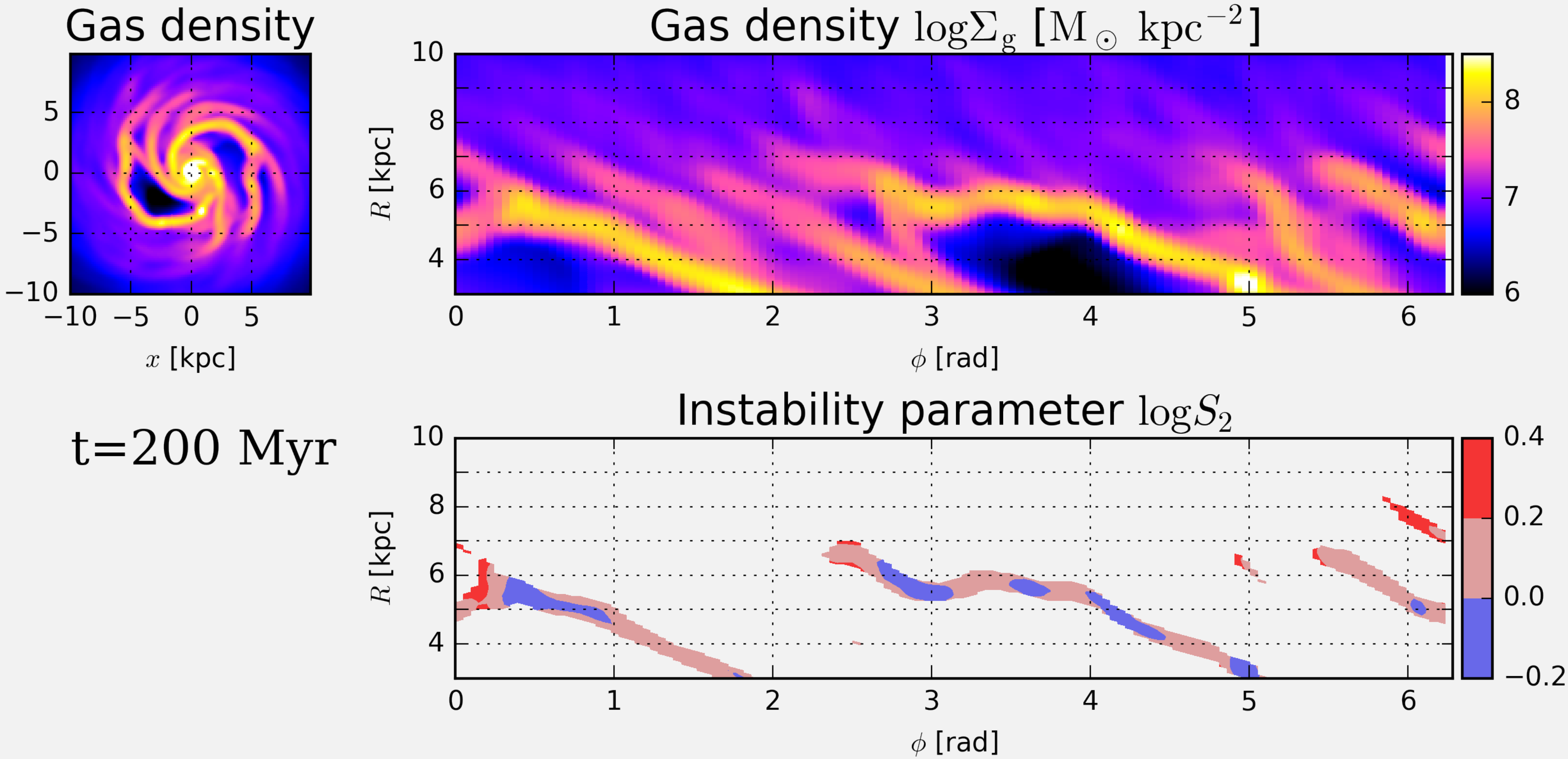


Demonstration

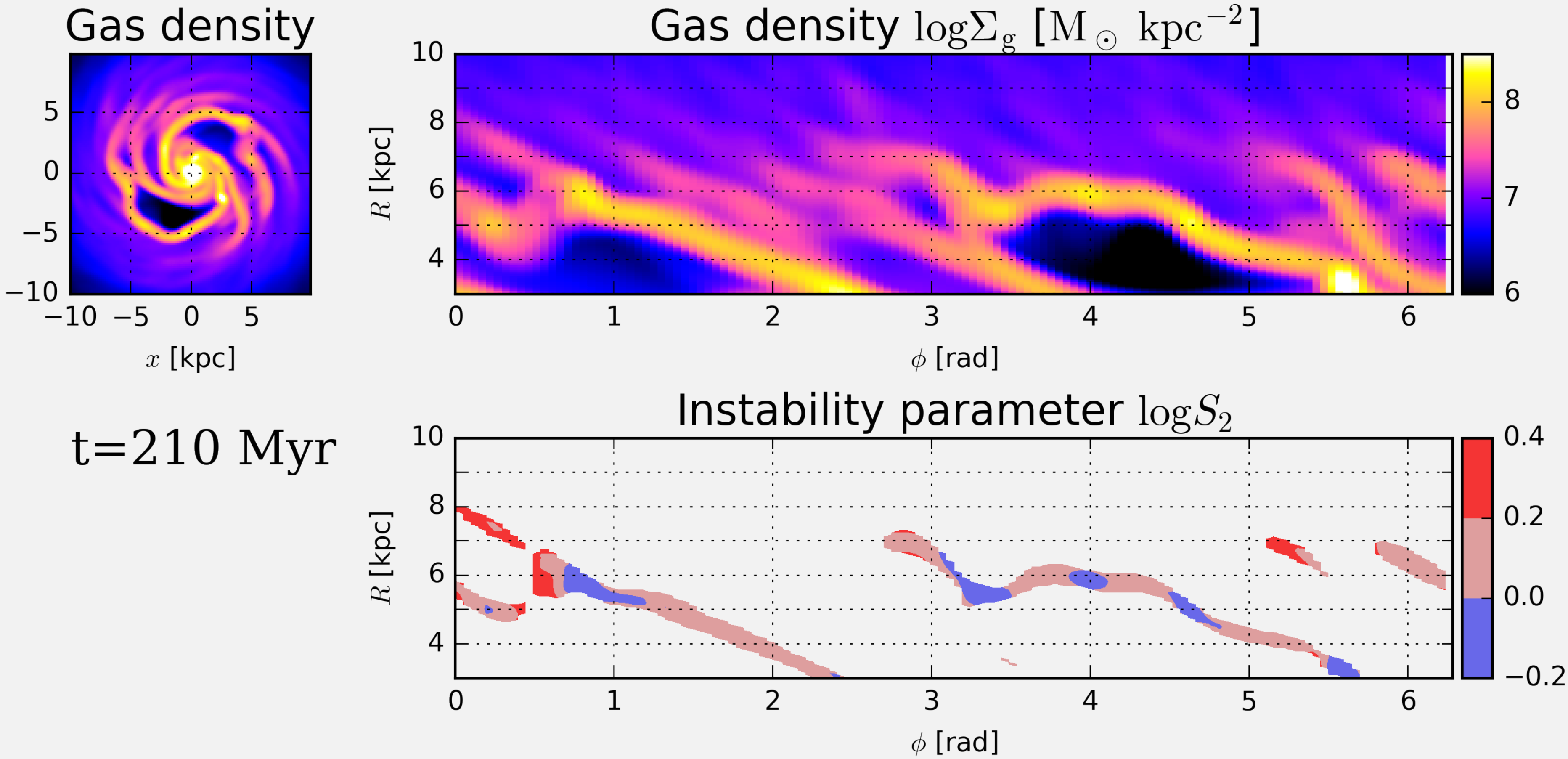


t=190 Myr

Demonstration

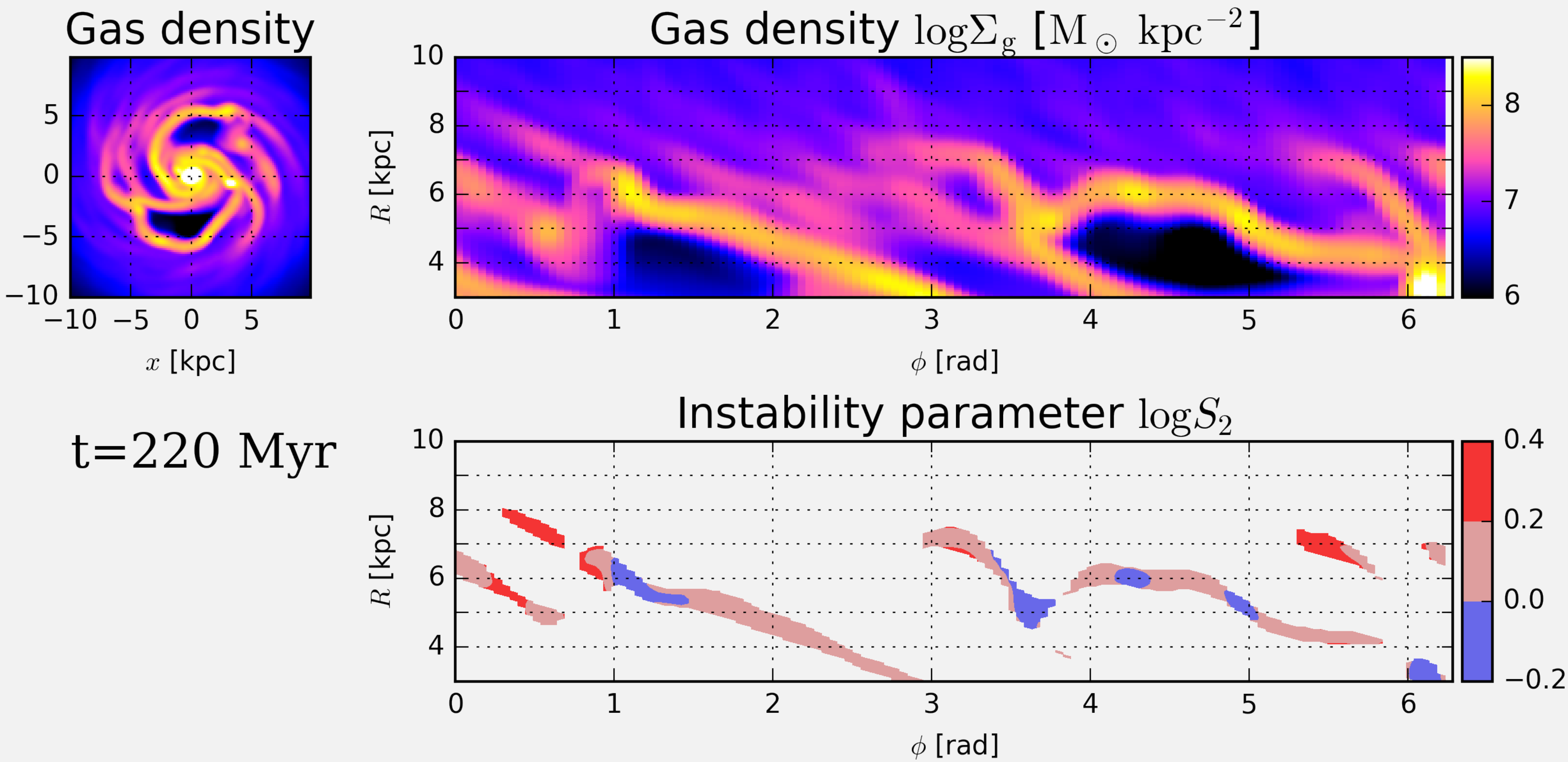


Demonstration

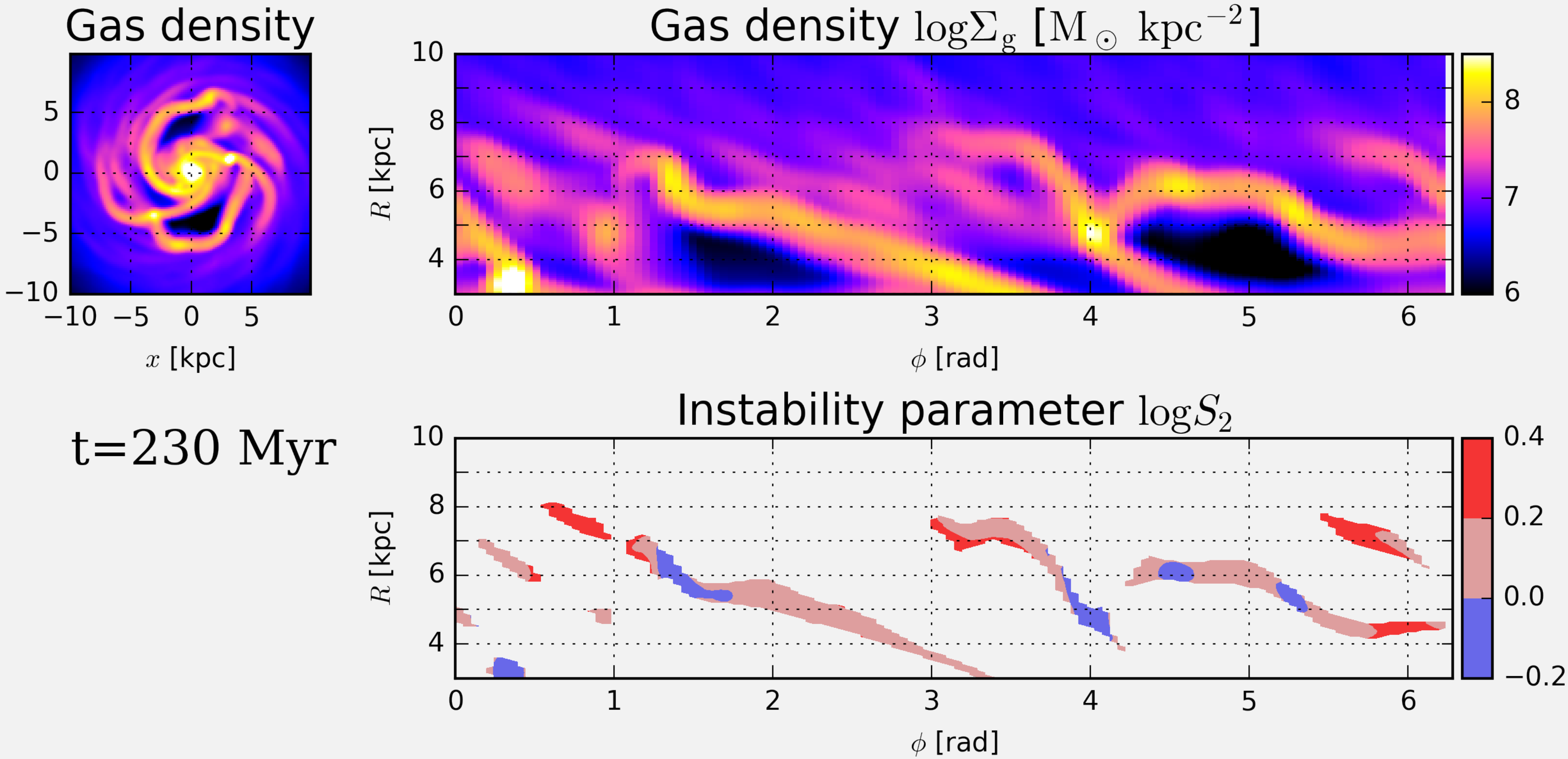


t=210 Myr

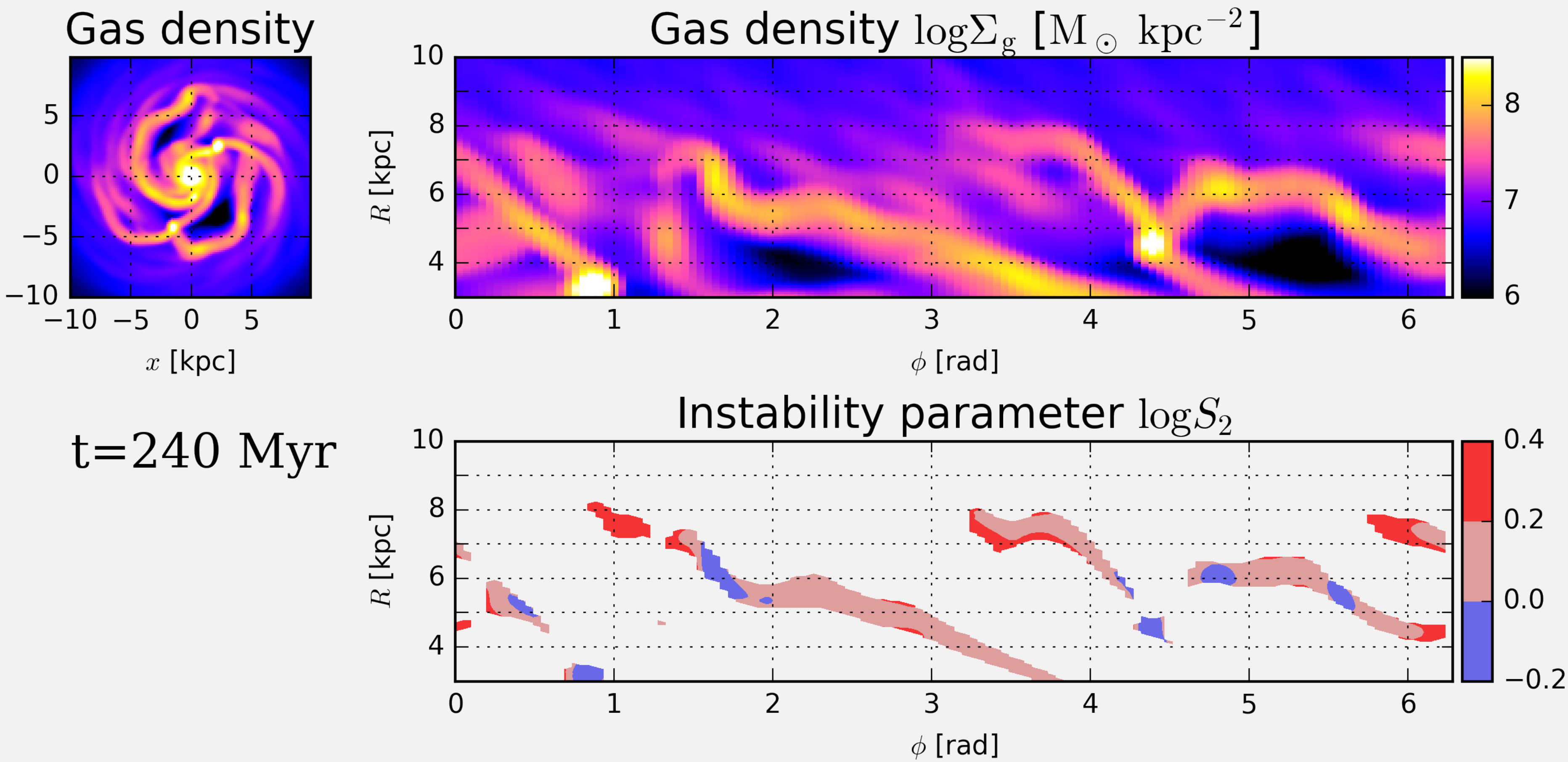
Demonstration



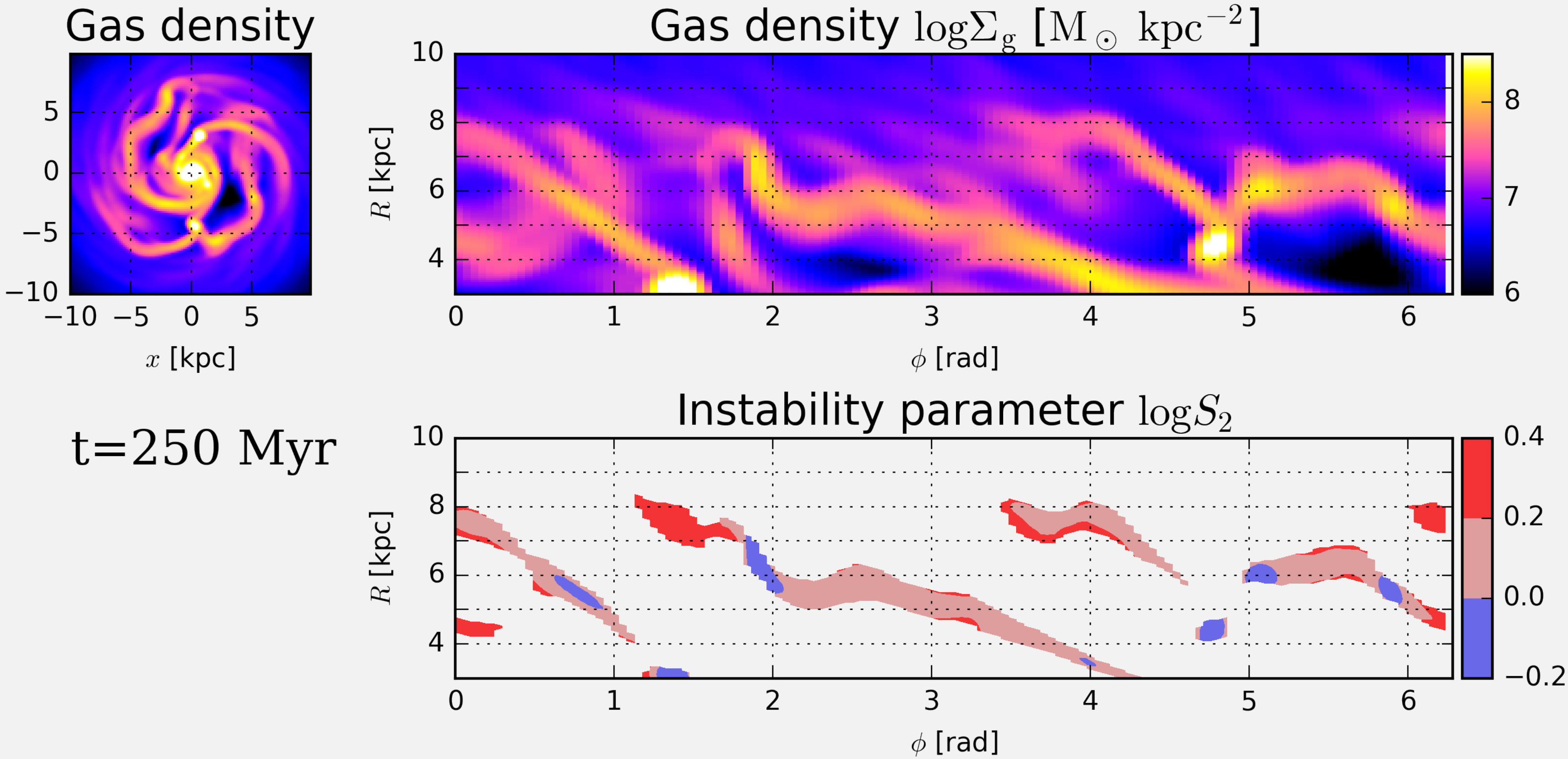
Demonstration



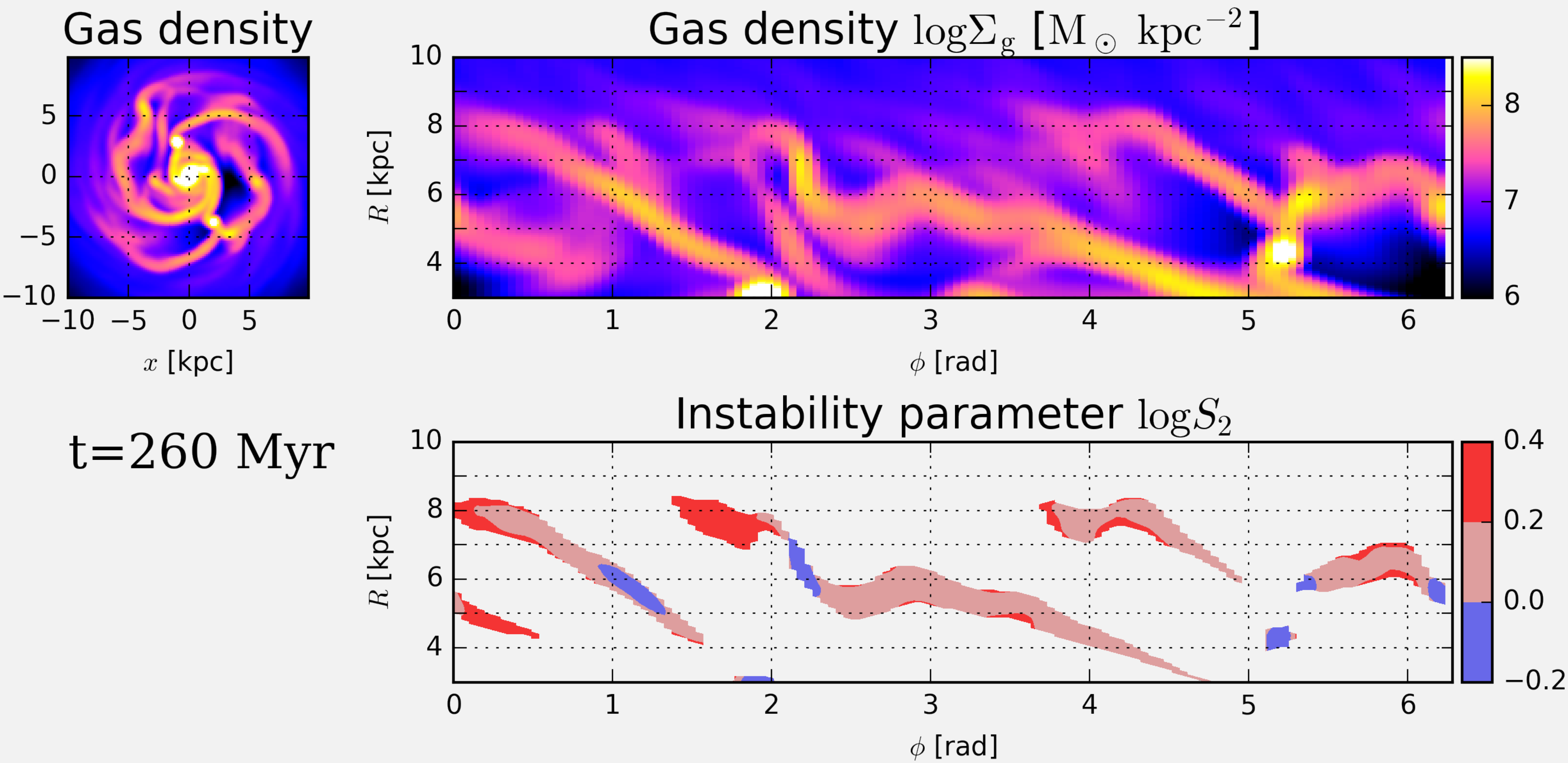
Demonstration



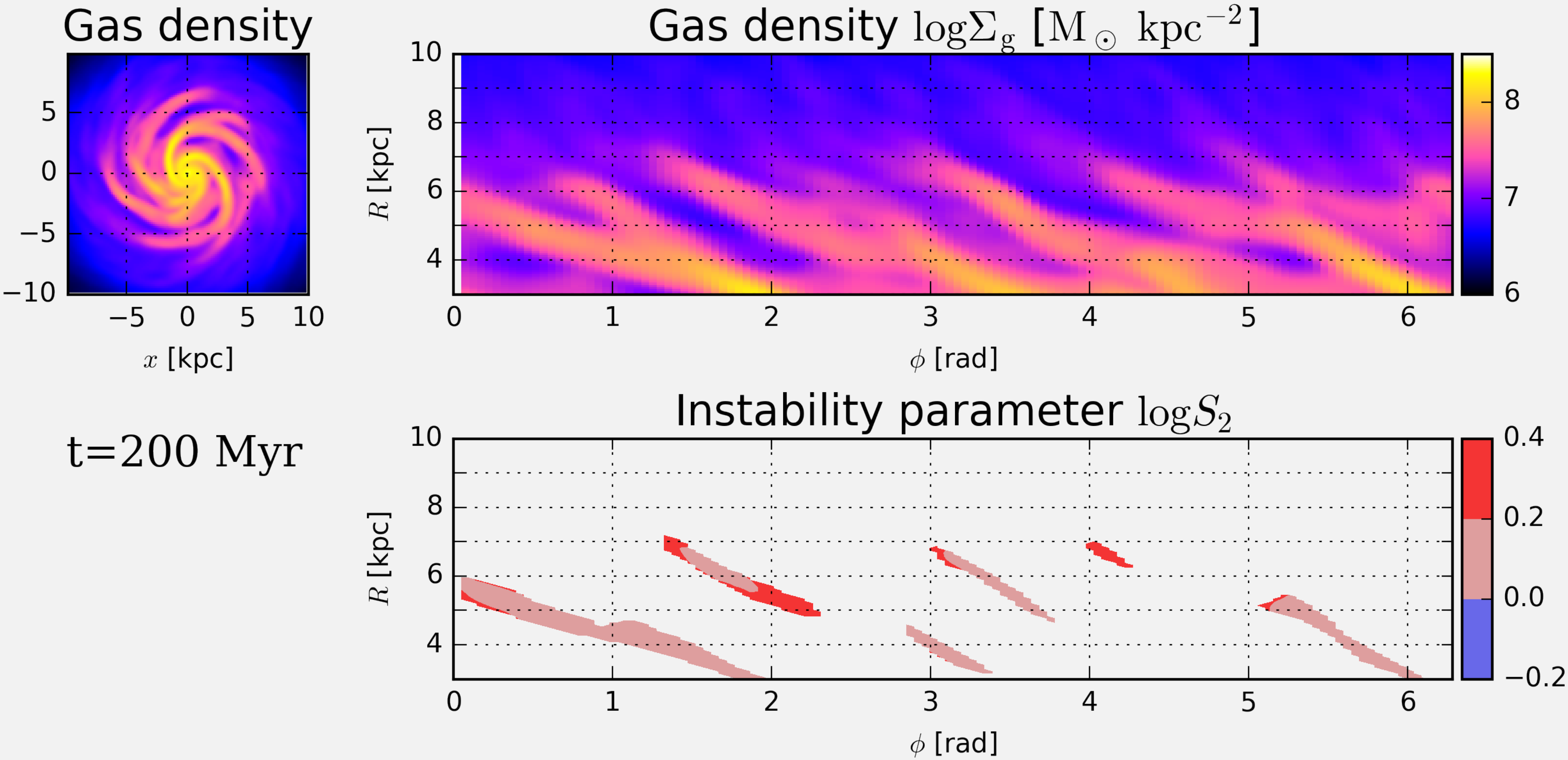
Demonstration



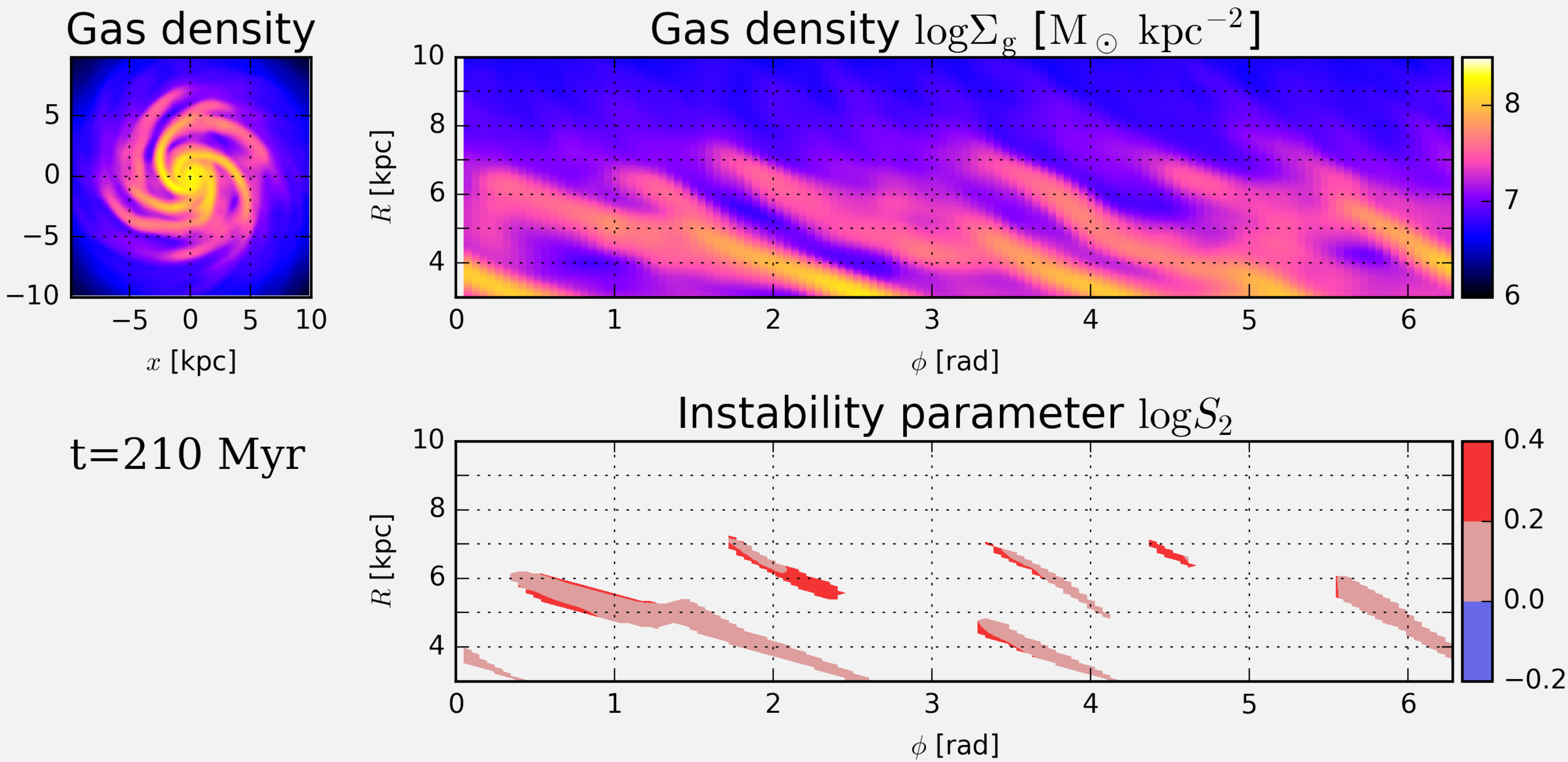
Demonstration



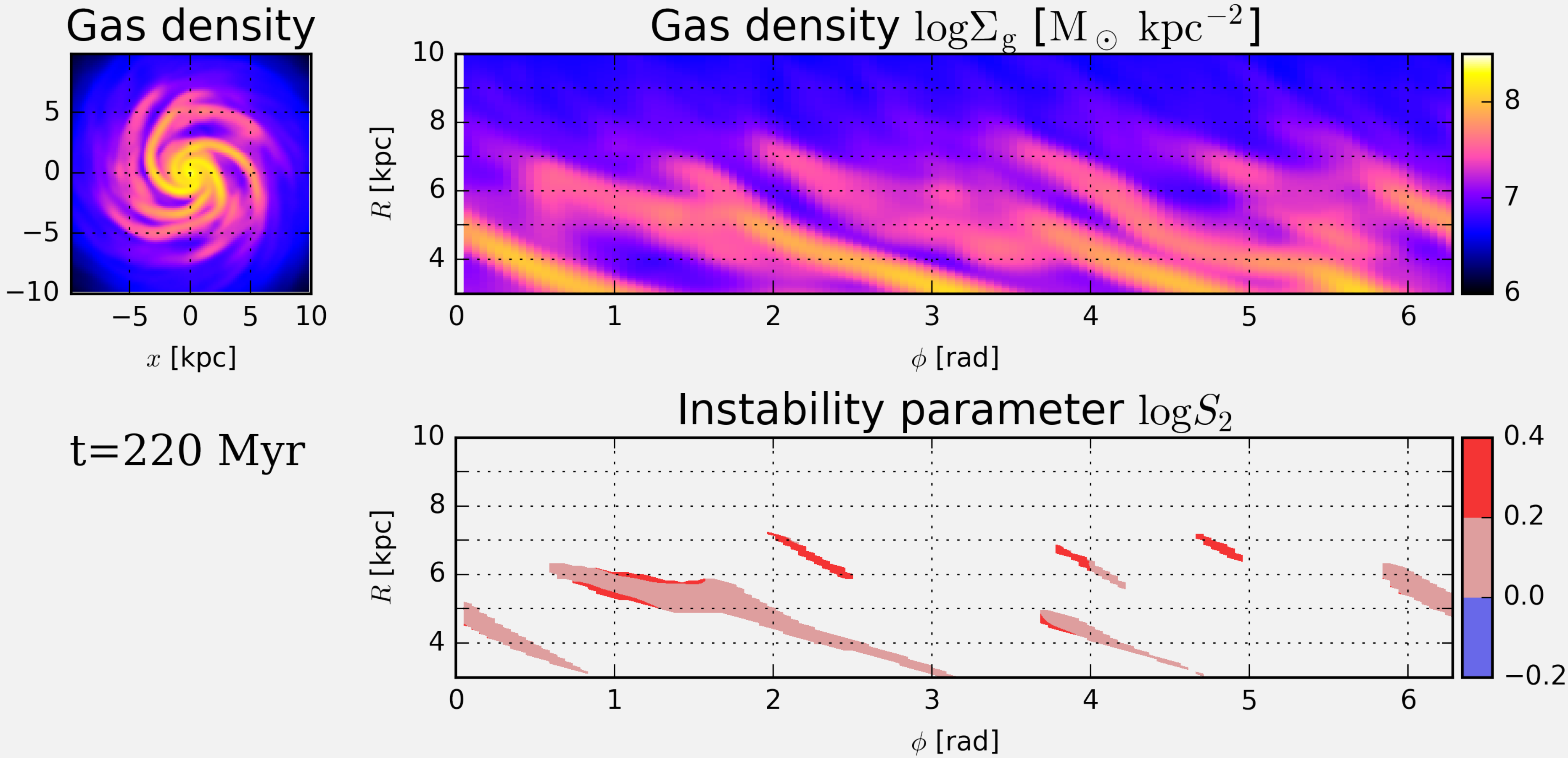
Demonstration



Demonstration

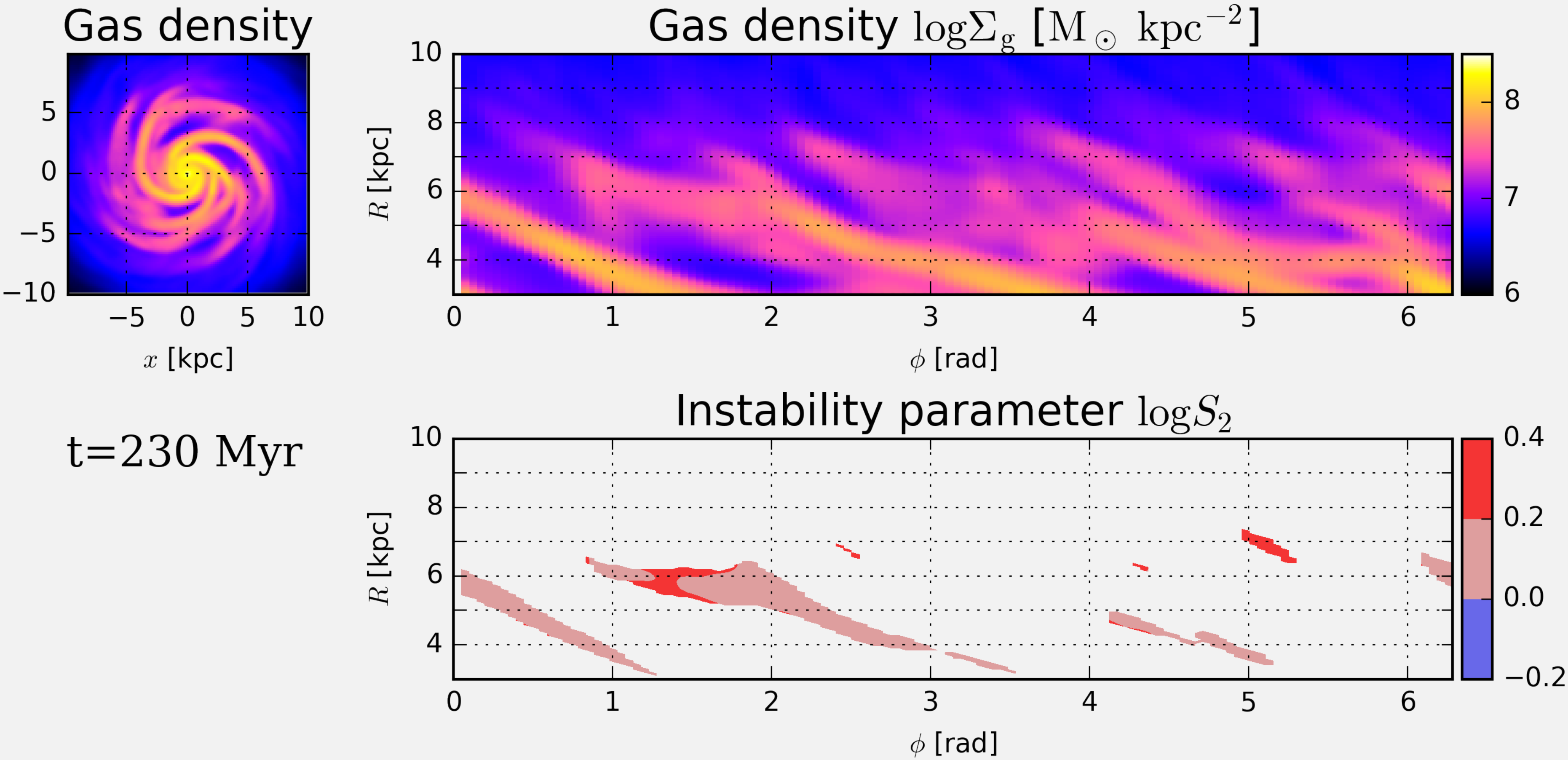


Demonstration

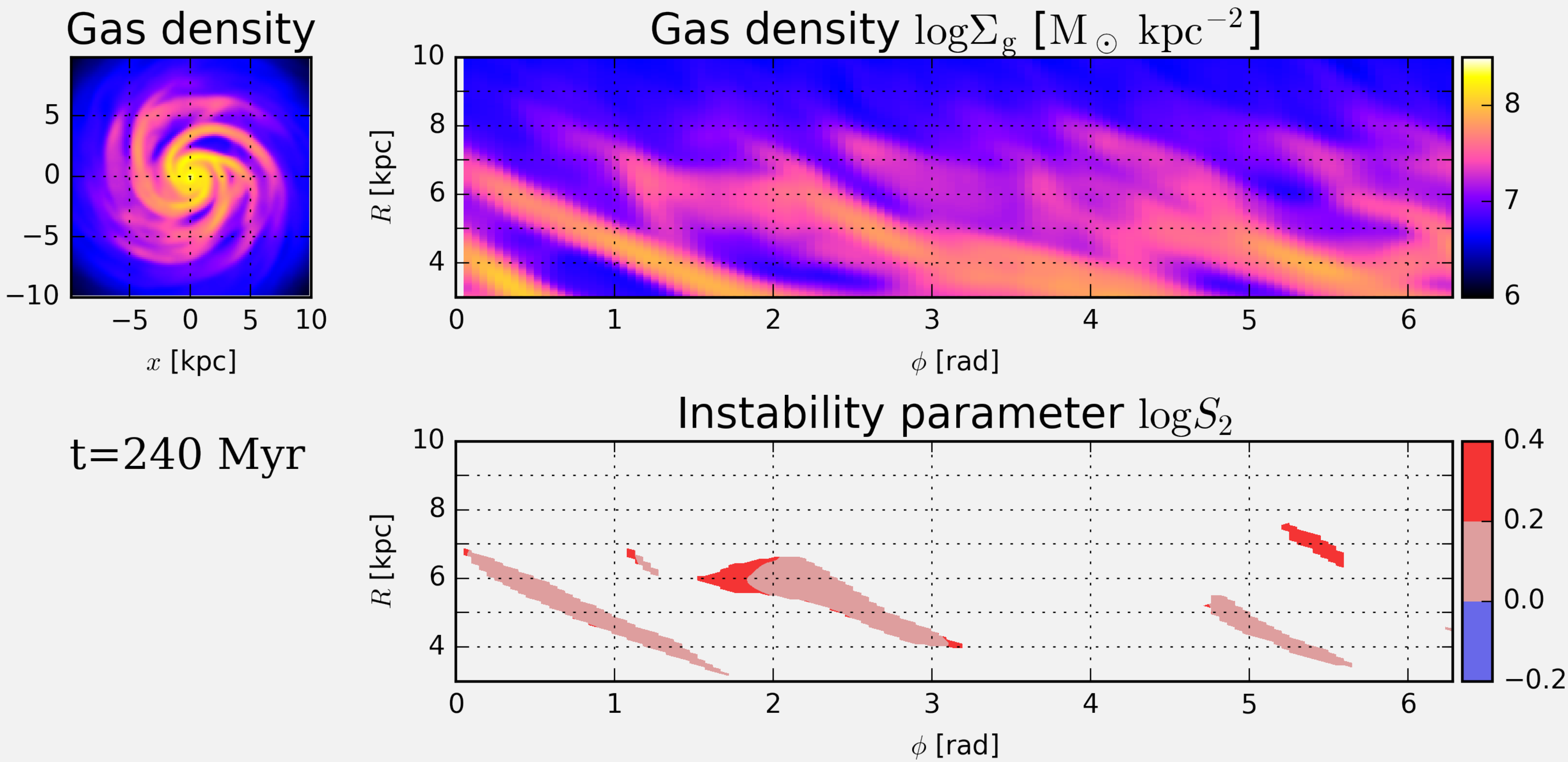


t=220 Myr

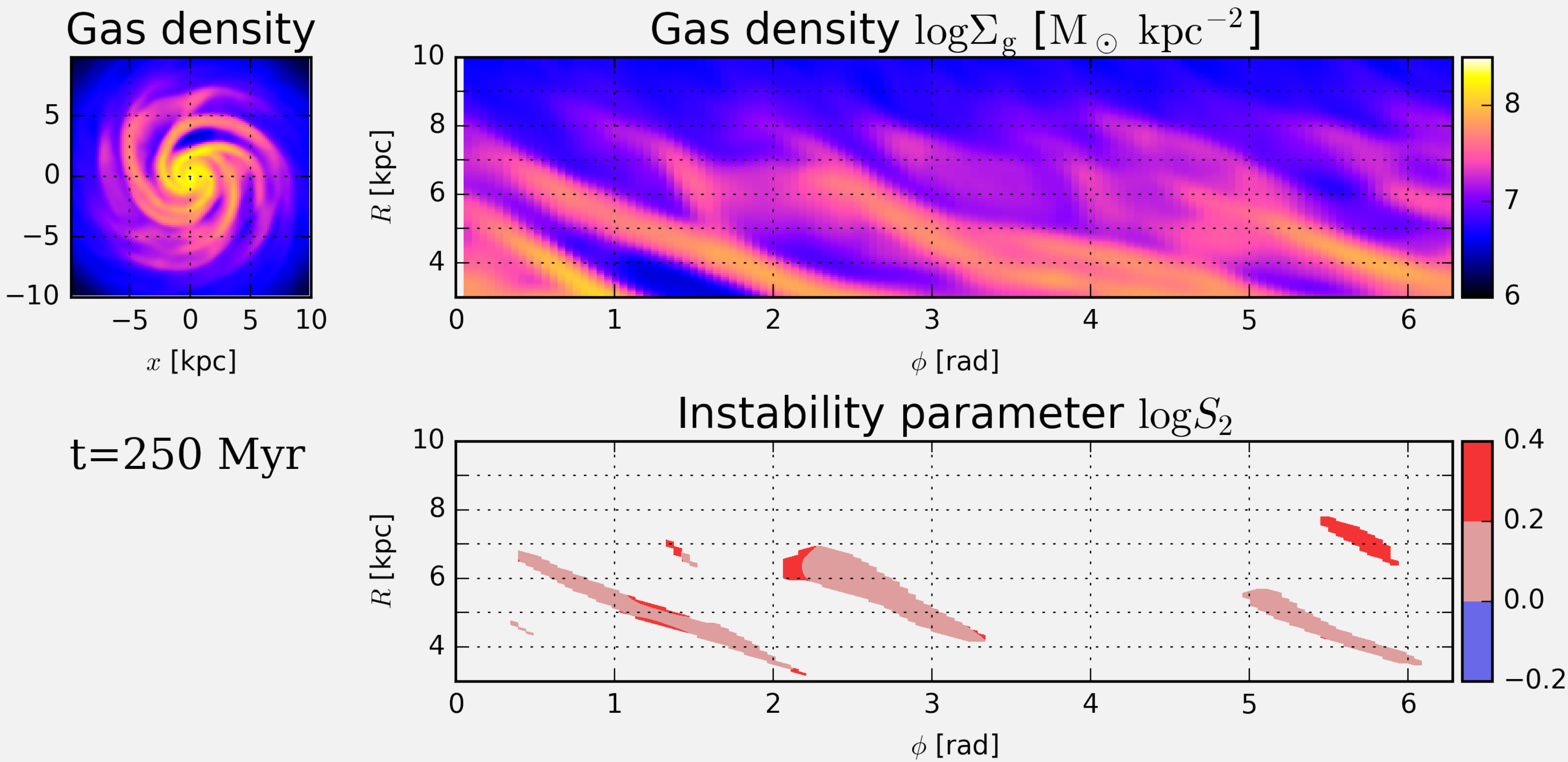
Demonstration



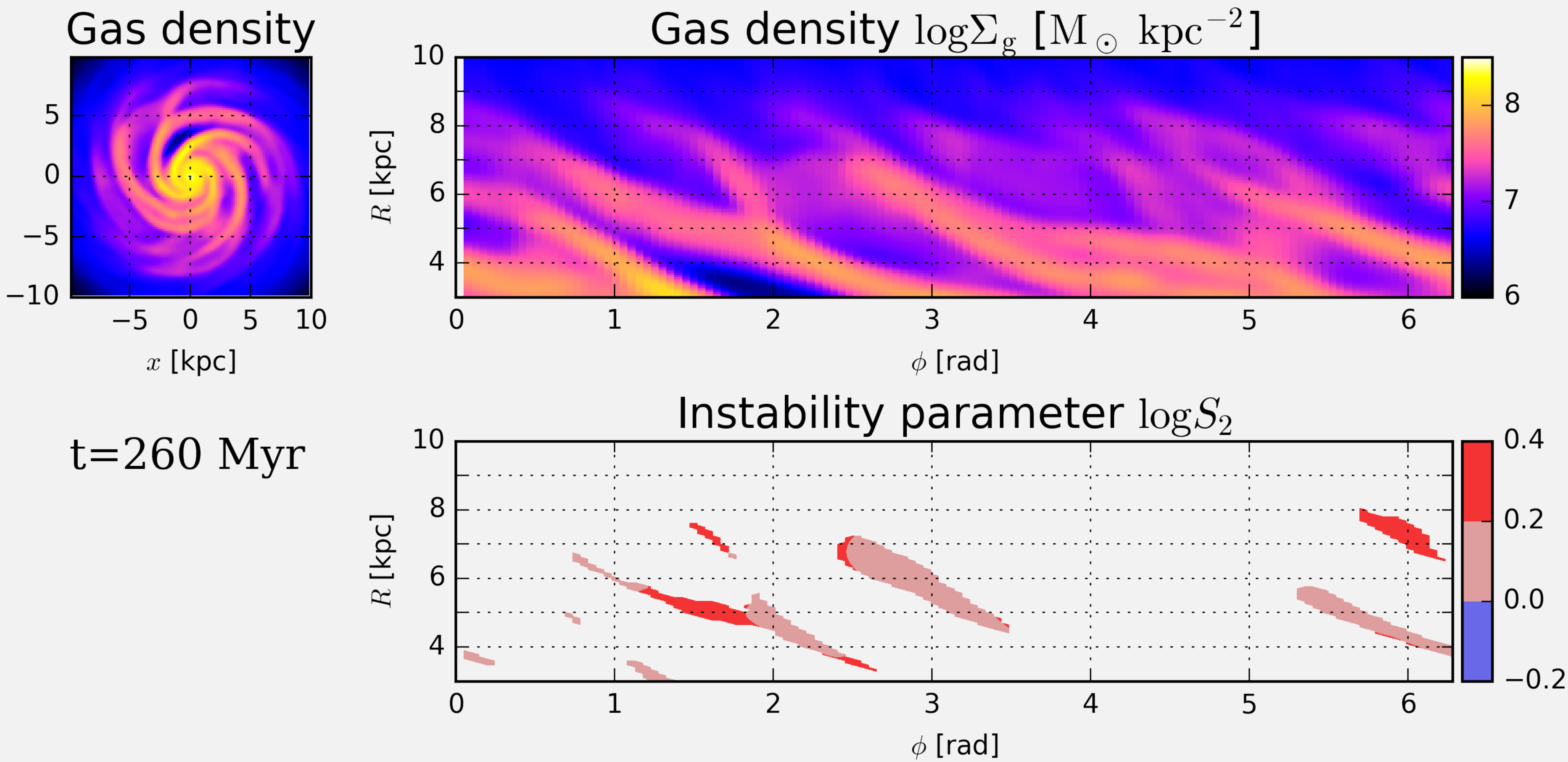
Demonstration



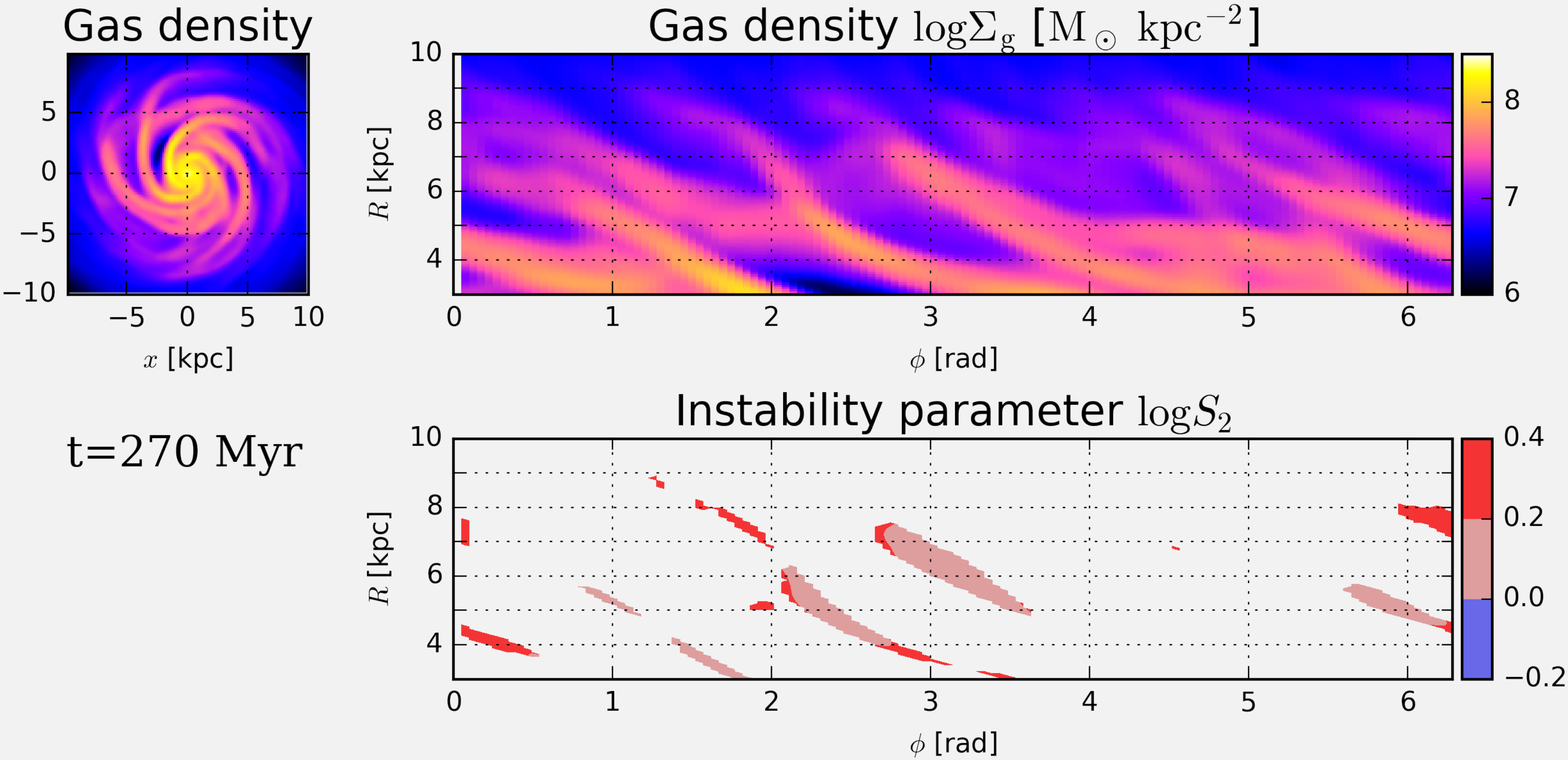
Demonstration



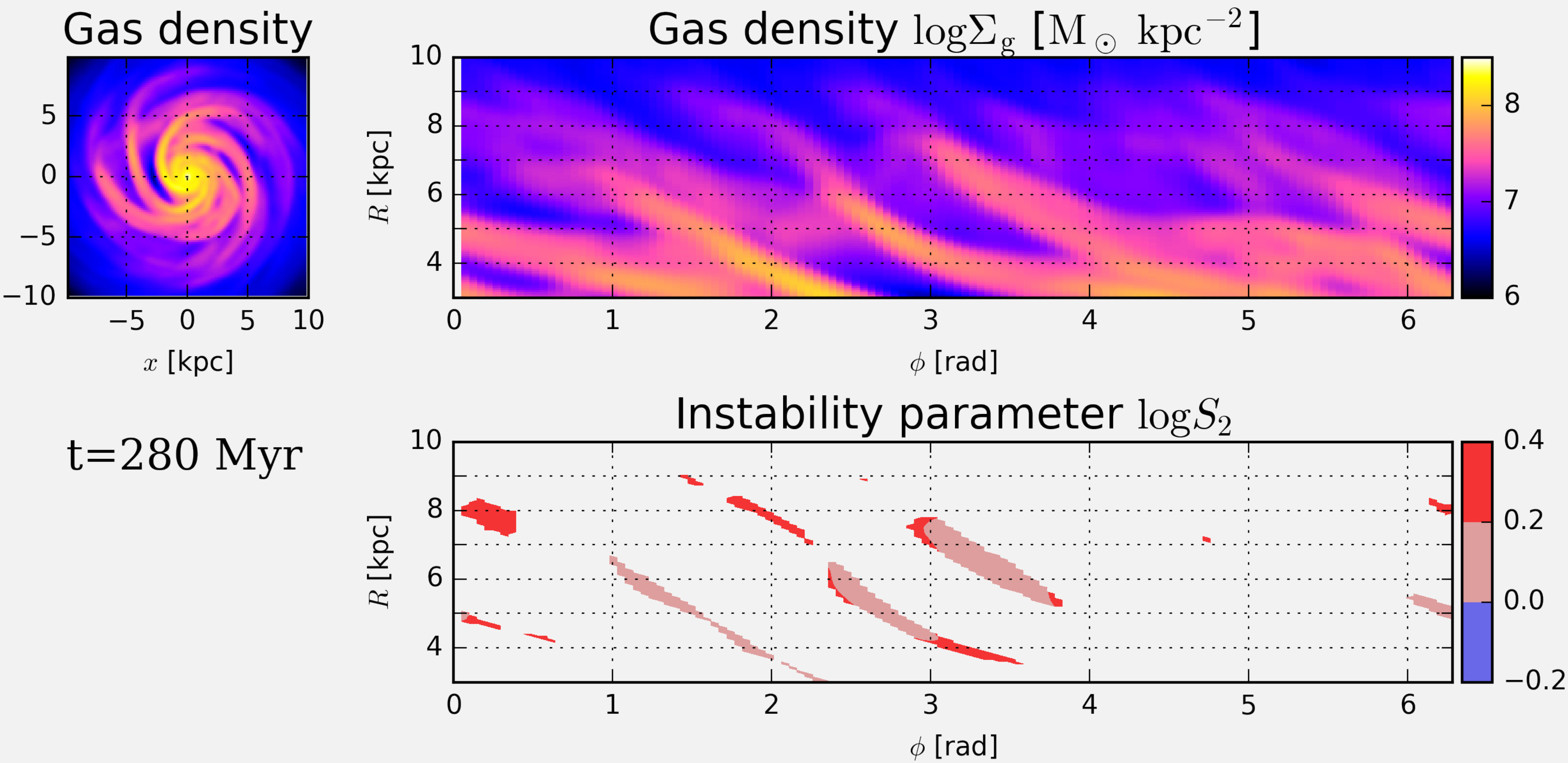
Demonstration



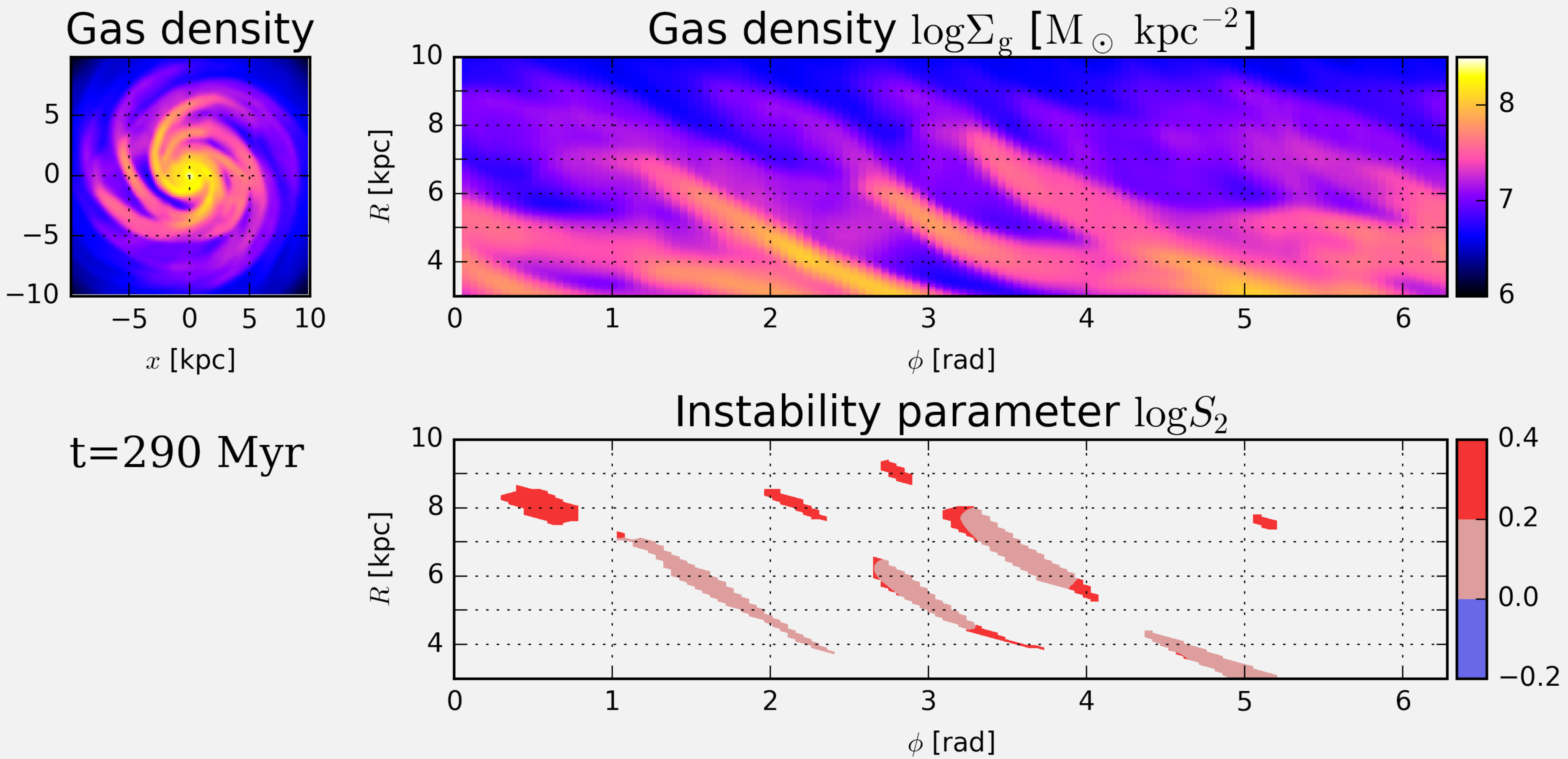
Demonstration



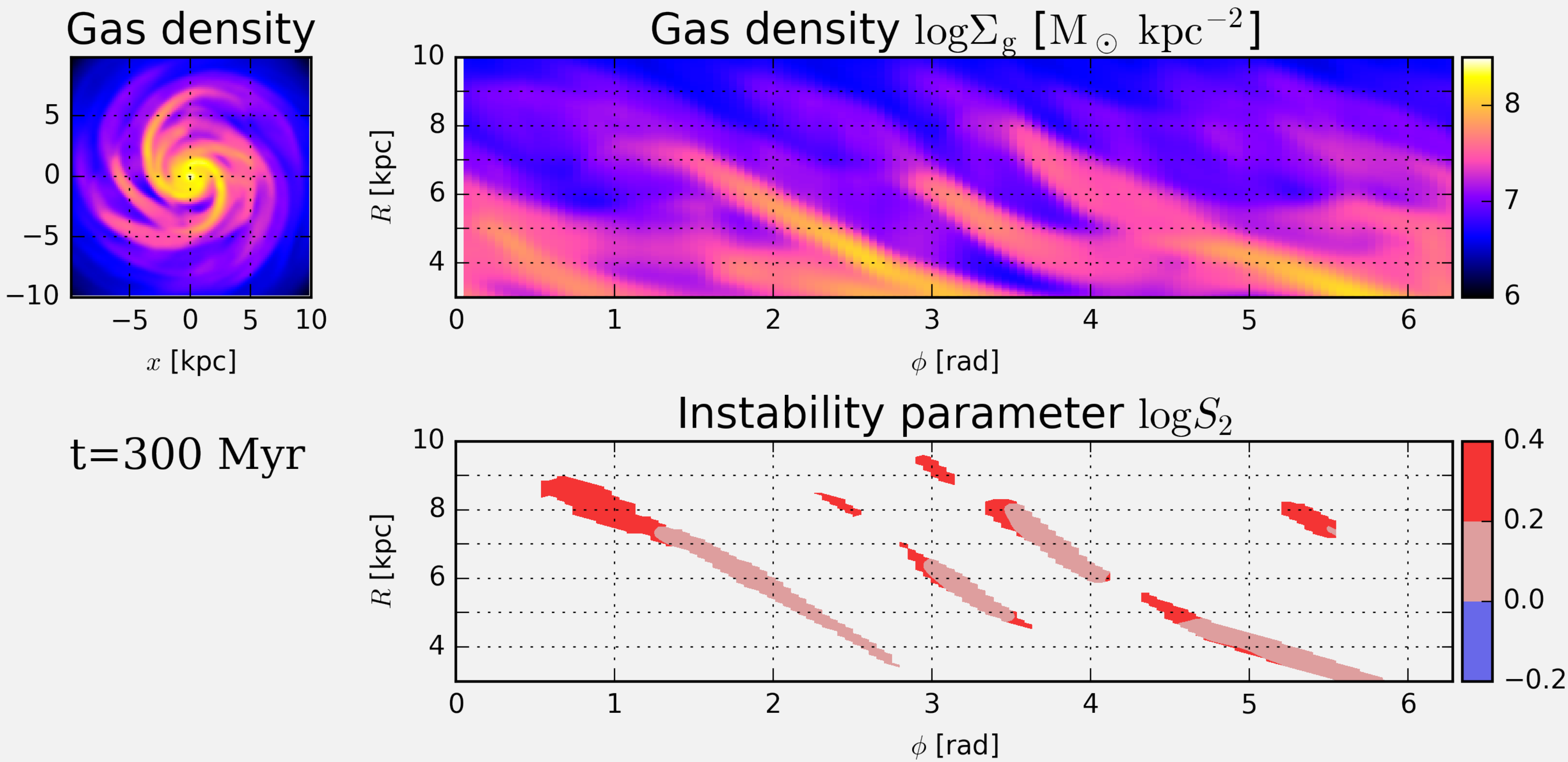
Demonstration



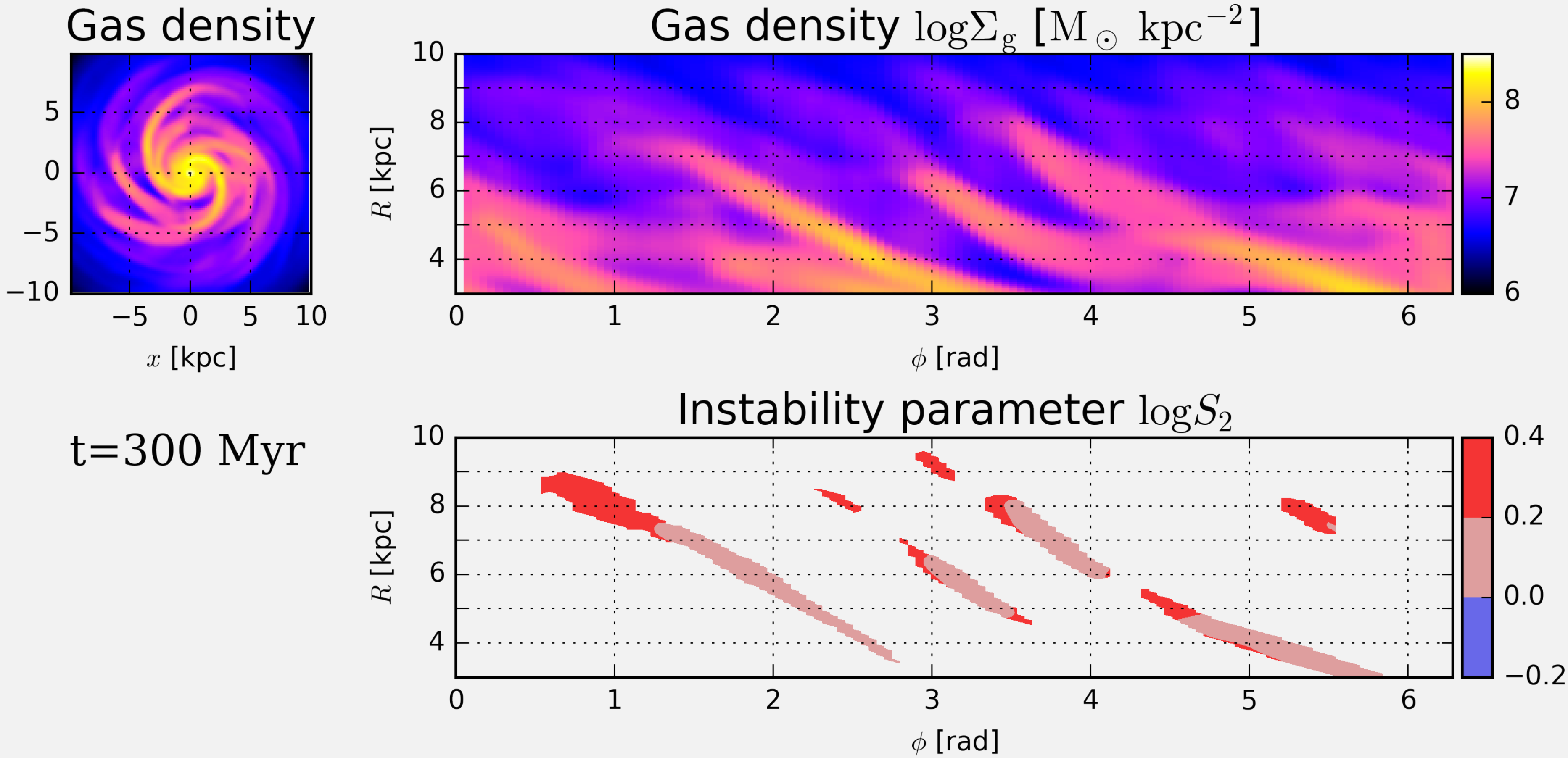
Demonstration



Demonstration



Demonstration

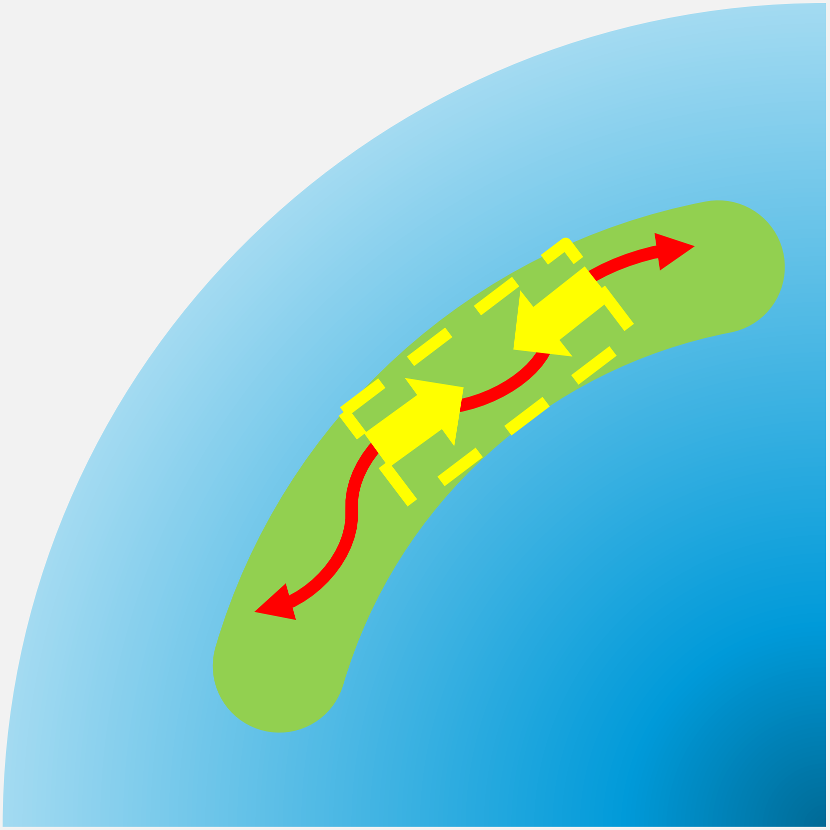


Clump mass estimation

- An unstable perturbation is expected to collapse along the arm (1D collapse)

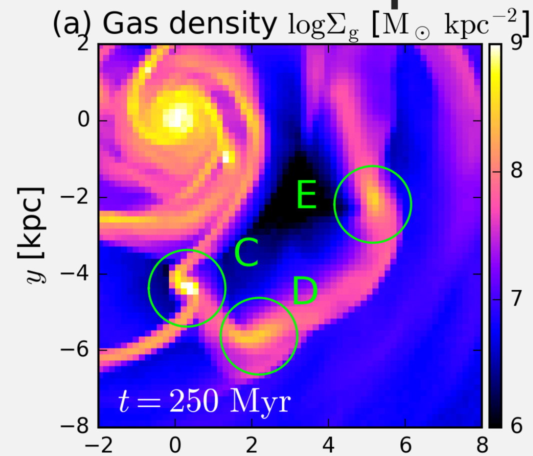
Clump mass estimation

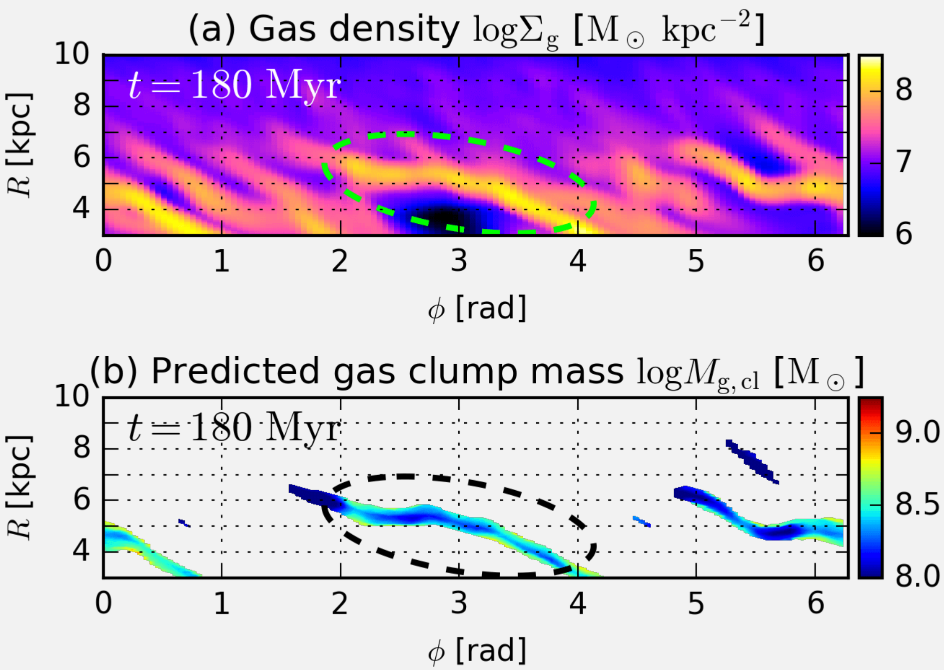
- An unstable perturbation is expected to collapse along the arm (1D collapse)
- $M_{cl} \sim \Sigma W \lambda$

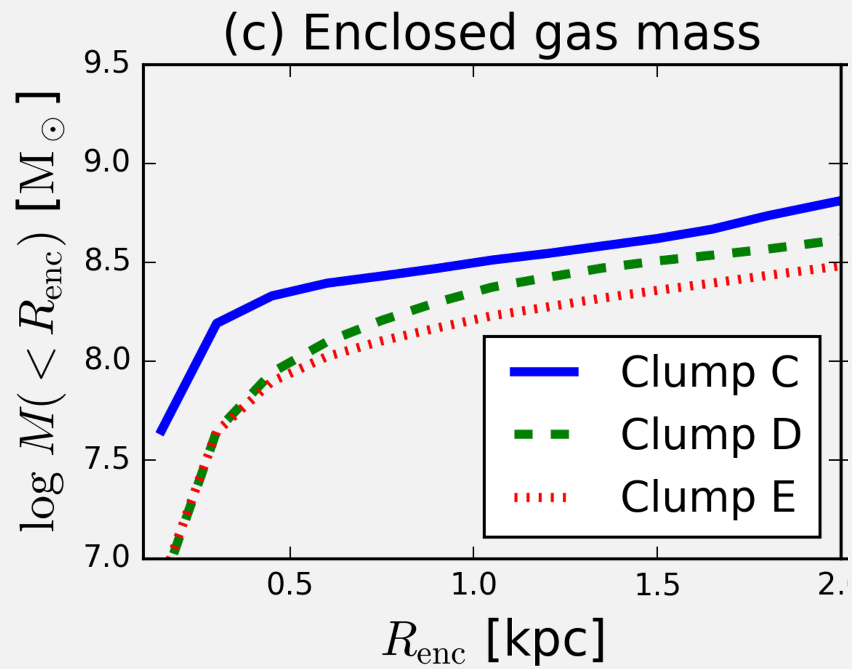


Clump-mass prediction

- An unstable perturbation is expected to collapse along the arm (1D collapse)
- $M_{cl} \sim \Sigma W \lambda$
- **$M_{cl} \sim 10^{8} - 10^{8.5}$ $M_{\odot}$ (predicted)**







Limitations of our models

- Our simulations are ideal
  - Isolated models
  - Isothermal gas
  - No star formation or stellar feedback
  - Very thin discs

- Our analytic model is also ideal
  - Razor-thin spiral arms
  - Tight-winding approximation
  - Equilibrium for spiral arms
  - Gaussian density distribution assumed

- We also find a few non-linear fragmentation
  - Clump formation can occur even if the instability condition is not satisfied.
    - But, non-linear fragmentation is quite rare in our simulations.

Violent Disc Instability (VDI)

(based on Toomre instability; Dekel et al. 2009)

v.s.

Spiral-Arm Instability (SAI)

VDI vs SAI

- Violent Disc Instability

Disc formation

↓ Toomre instability $Q < 1$

Giant clump formation

- Spiral-Arm Instability

Disc formation

↓ Toomre instability and/or swing amplification

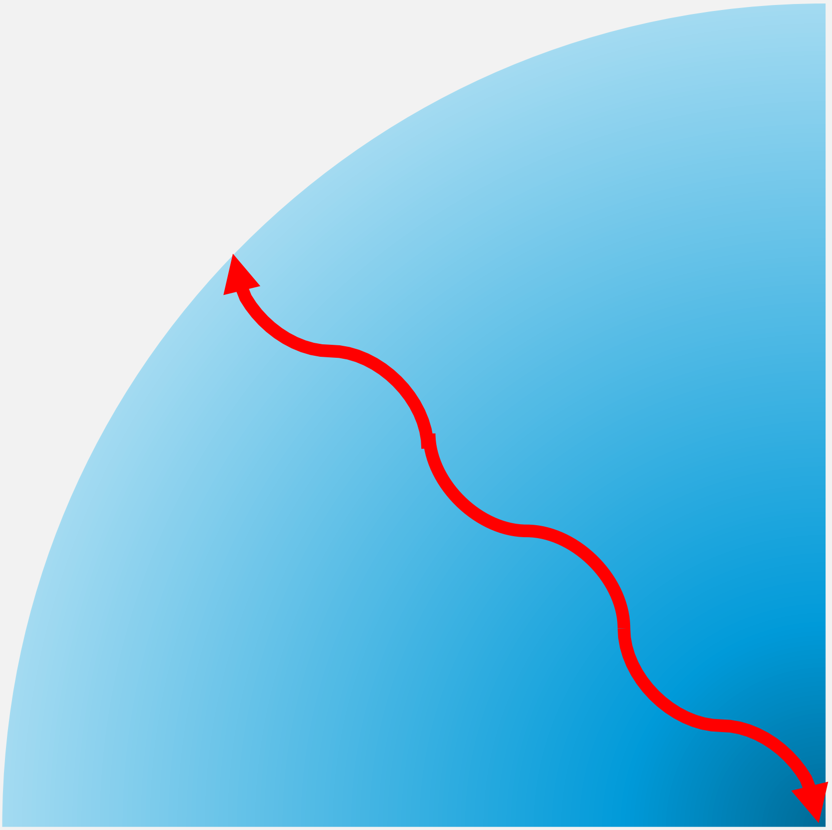
Spiral arm formation

↓ **Spiral-Arm Instability** $S < 1$

Giant clump formation

VDI vs SAI

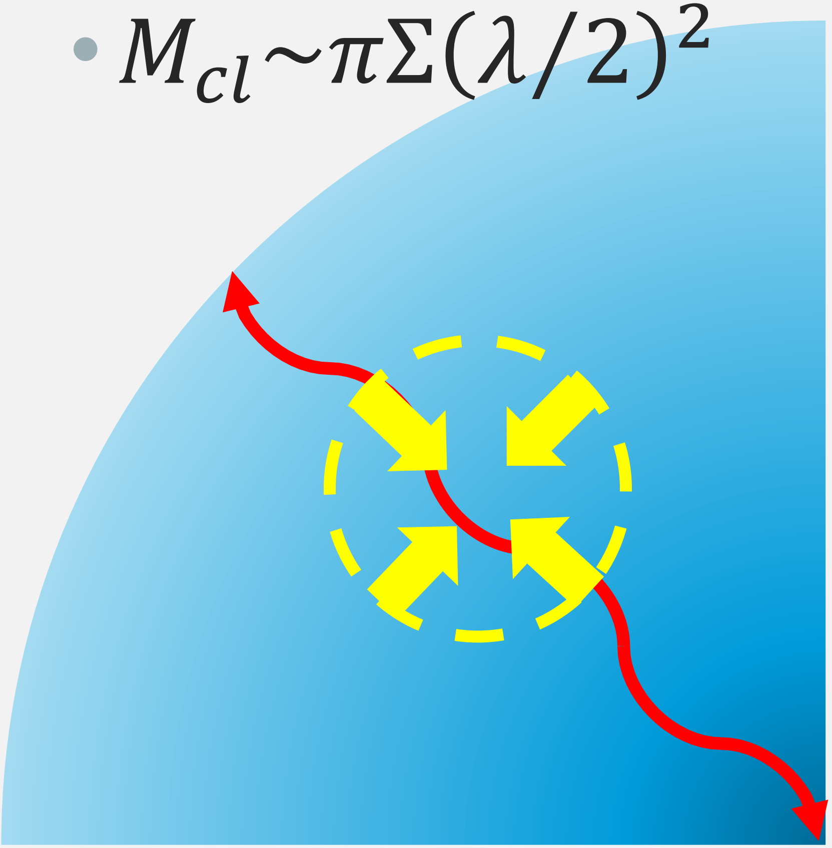
- Violent Disc Instability



- Spiral-Arm Instability

VDI vs SAI

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



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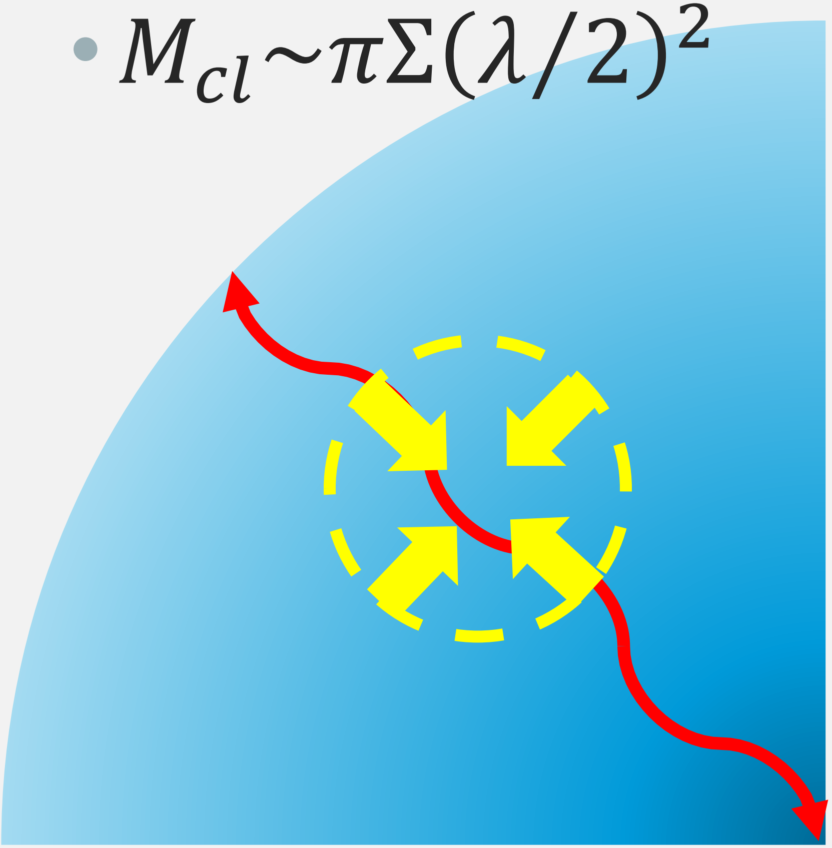
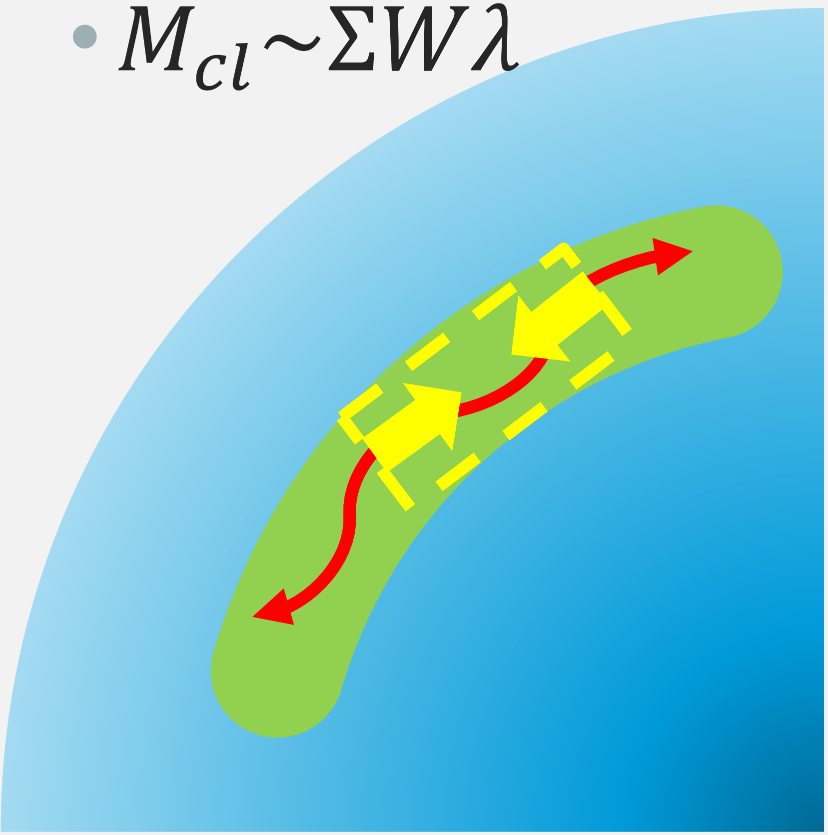


- Spiral-Arm Instability
  - **1D collapse**
  - $M_{cl} \sim \Sigma W \lambda$



Scaling relations of high-z clumps

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

the most unstable wavelength: $$\lambda_{\rm MU} = 2\pi \left(\frac{\pi \alpha G F_0 A \Sigma W^{1-\alpha}}{8\Omega^2} \right)^{\frac{1}{2-\alpha}}.$$

expected clump mass: $$M_{\rm cl} \sim \lambda_{\rm MU} \frac{\Upsilon}{f_{\rm g}} = \lambda_{\rm MU} A \frac{\Sigma}{f_{\rm g}} W.$$

expected velocity dispersion within a clump: $$\sigma_{\rm cl}^2 \simeq \frac{1}{3} \frac{G M_{\rm cl}}{R_{\rm cl}} = \frac{2}{3} G \frac{\Sigma}{\varepsilon f_{\rm g}} W A \simeq \frac{2}{3\pi} \eta \beta A \left(\varepsilon f_{\rm g} \right)^{-1} \frac{W}{R_{\rm d}} V^2.$$

Spiral-arm instability

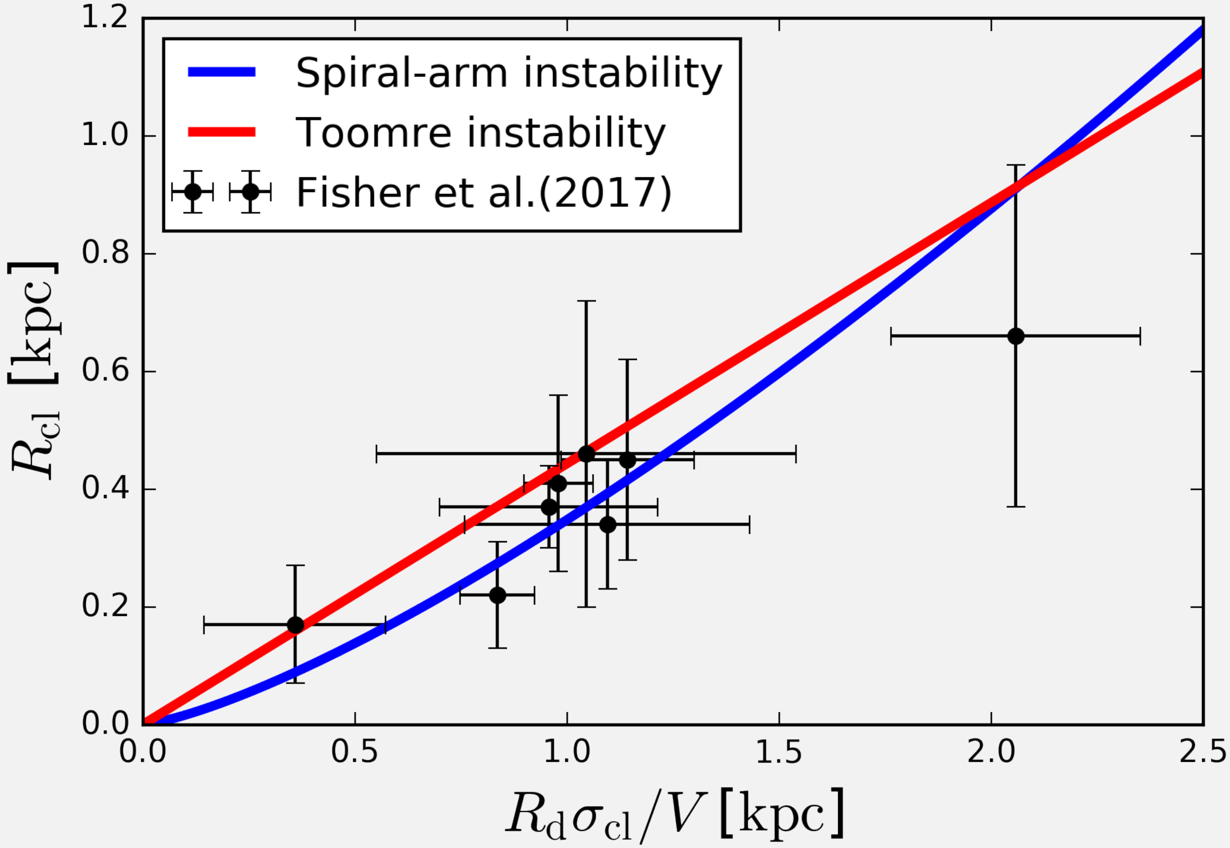
expected scaling relation: $$R_{\rm cl} \propto \left(\frac{\sigma_{\rm cl}}{V} R_{\rm d} \right)^{1.3}$$

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



- Both models of the spiral-arm and Toomre instability can explain the observations.
  - Neither is rejected by the observations.

- Our spiral-arm instability theory can be a possible mechanism of giant clump formation in high-z galaxies.

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:

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

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

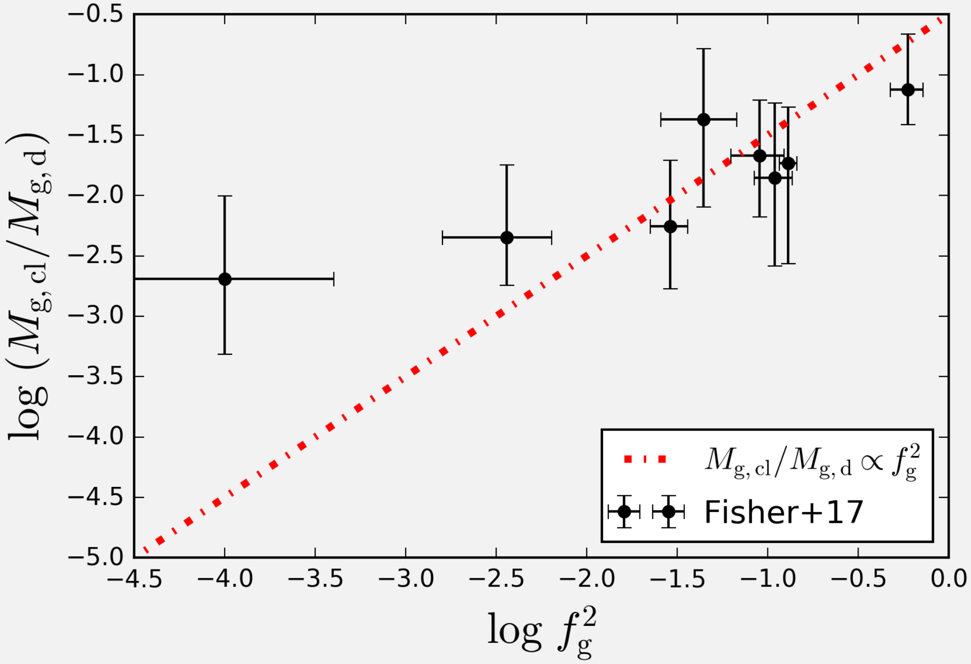
Toomre instability
expected scaling relation:

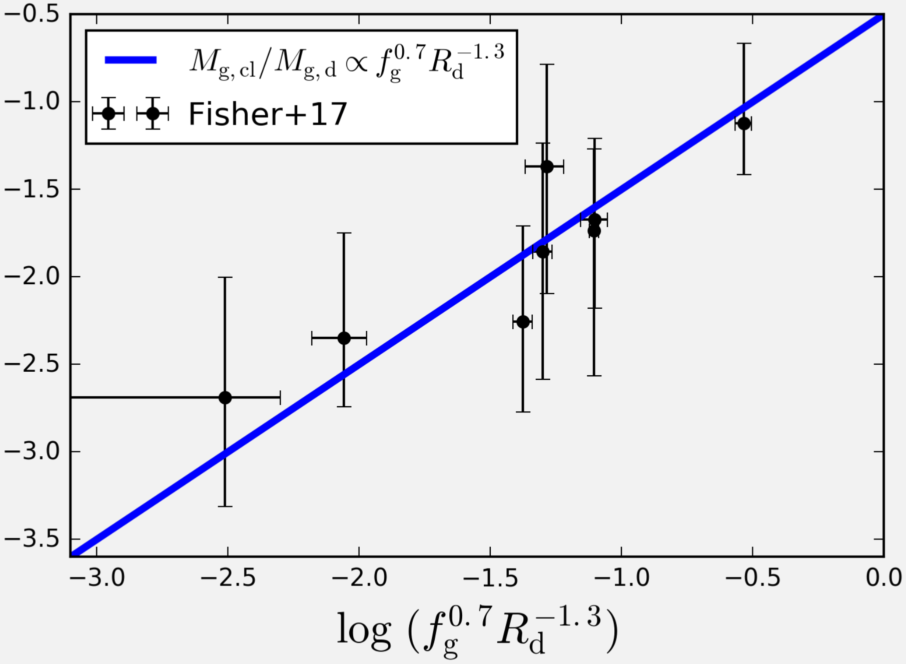
$$\frac{M_{\rm g,cl}}{M_{\rm g,d}} \propto f_{\rm g}^2,$$

$R_{\rm cl}$: 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

- Violent Disc Instability
- Spiral-Arm Instability





- The observations may prefer our SAI model.
  - But, the sample size is too small.
  - If the most gas-poor one is excluded, the fittings become comparable in both models.

Summary

- We analytically derived an instability parameter and its criterion for spiral-arm fragmentation.

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

- Our novel instability parameter can characterize remarkably well fragmentation of spiral arms and clump formation following.

- Neither model of our spiral-arm nor Toomre instability is inconsistent with current observations.
  - **The spiral-arm instability could be a possible mechanism of giant clump formation in high-redshift galaxies.**

- **It is also interesting to adopt our instability analysis to local spiral galaxies.**