軸対称磁場による銀河渦状腕の不安定化とクランプ形成

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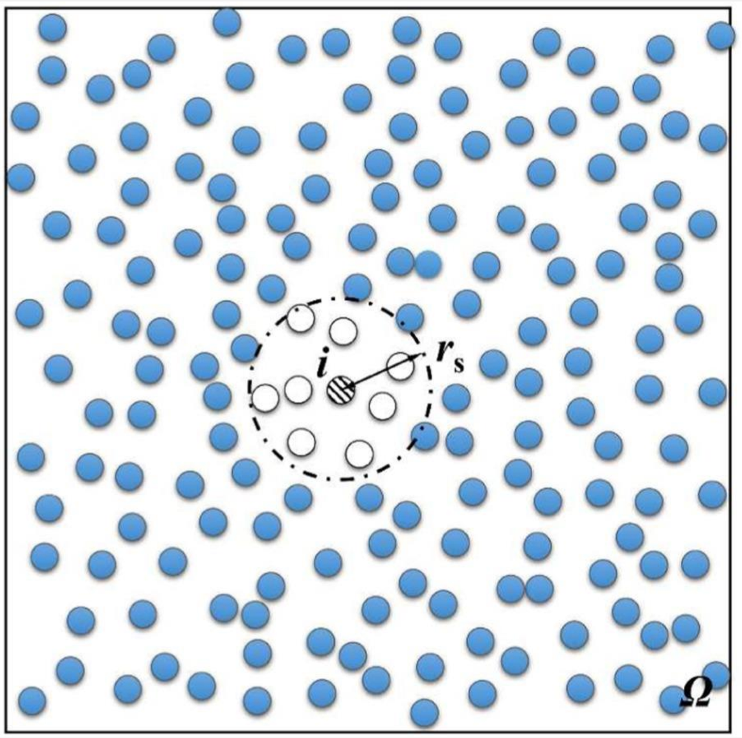
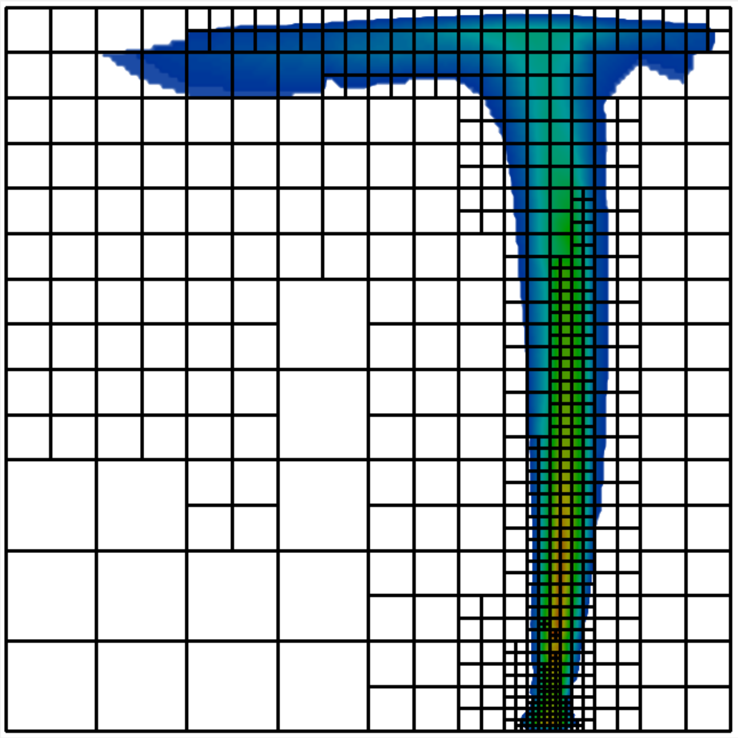
宇宙物理学における流体シミュレーション法

- SPH法 (平滑化粒子法)



- 高密度領域で自然に高解像度
- 人工的な表面張力、不連続面が苦手

- AMR法 (最適化格子法)

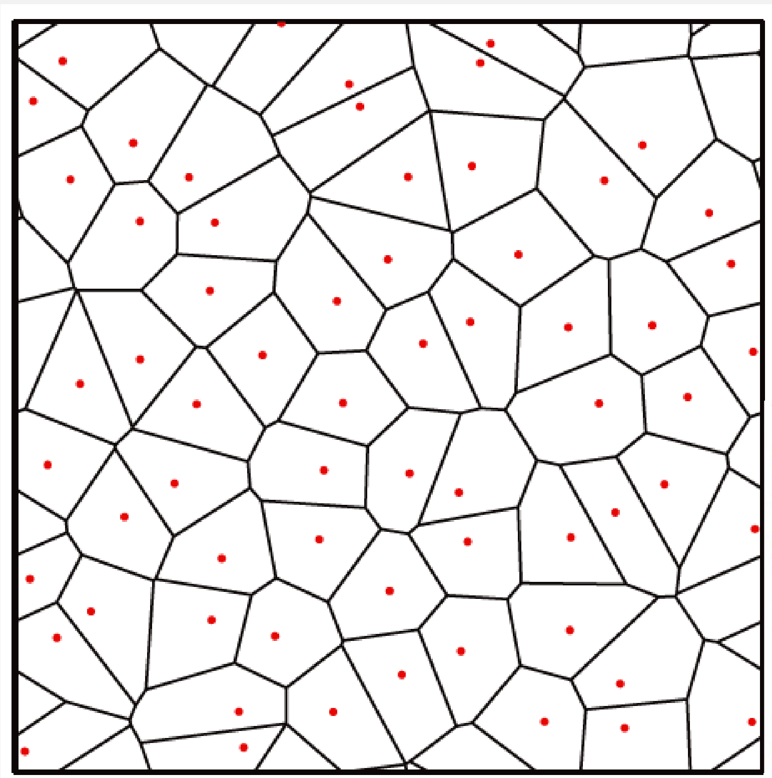


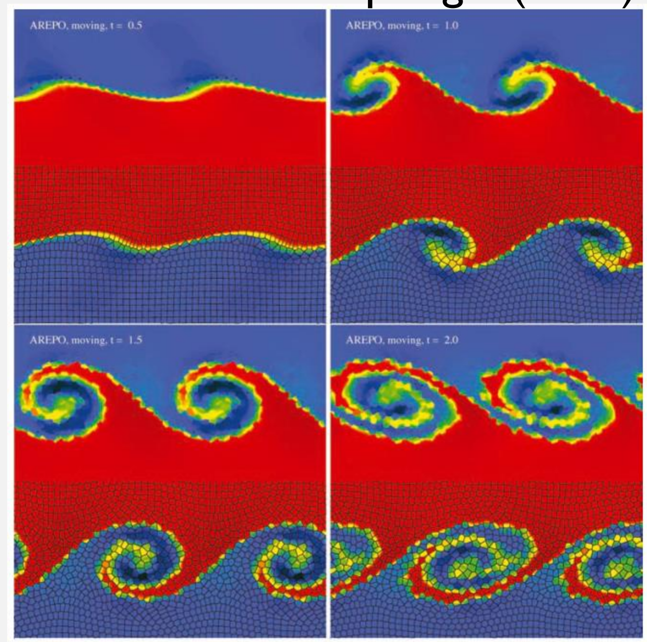
- 解像度が不連続に変わる
- ガリレイ不変ではない

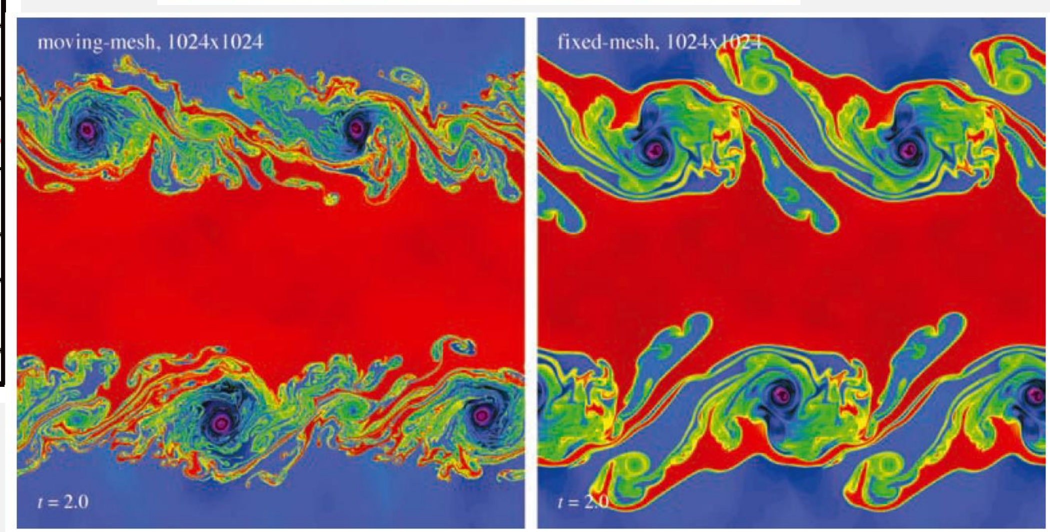
移動格子法流体シミュレーション

- ムービングメッシュ法
  - ボロノイ格子

Springel (2010)

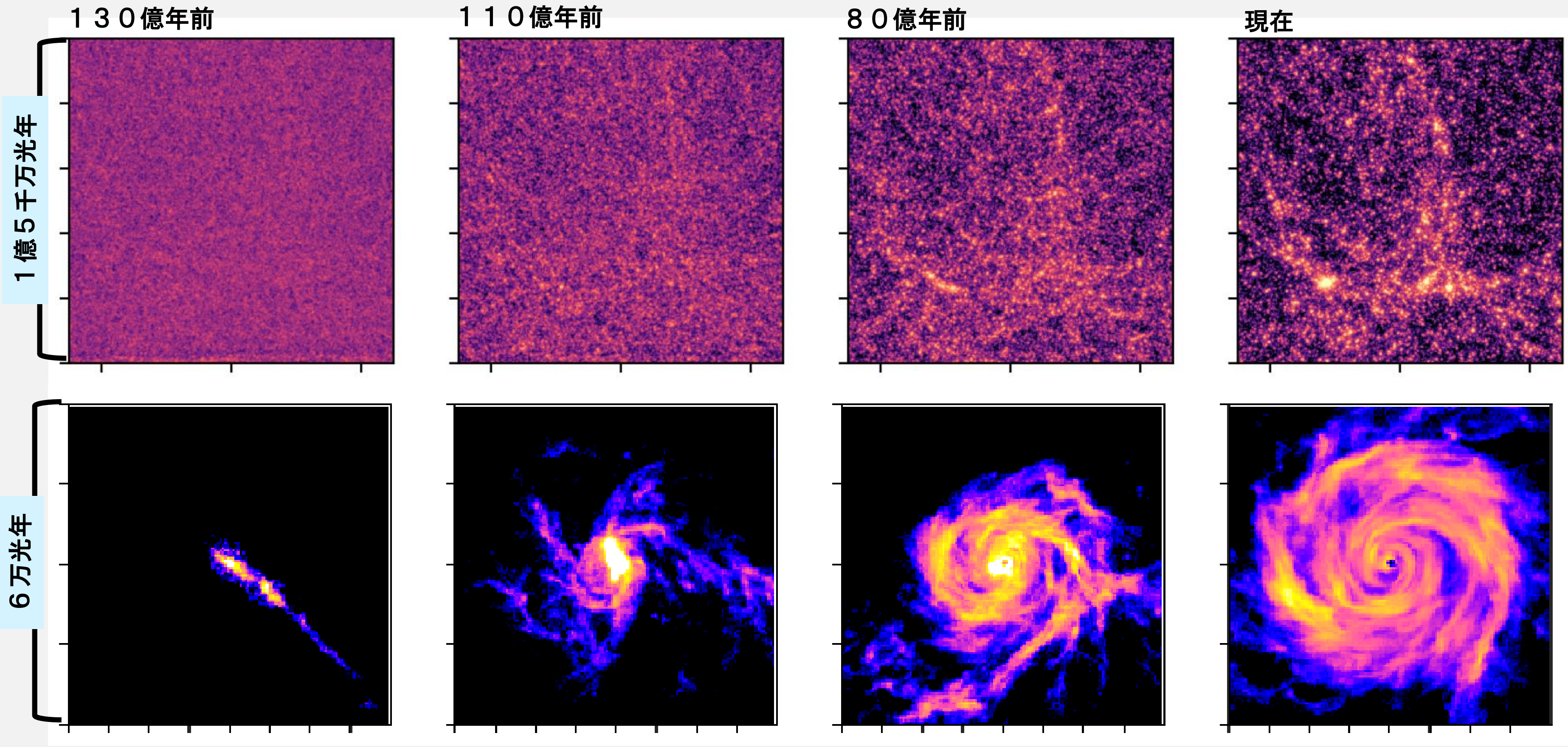






移動格子法流体シミュレーション

- Arepo code (Springel 2010)
  - 宇宙論的銀河形成シミュレーション



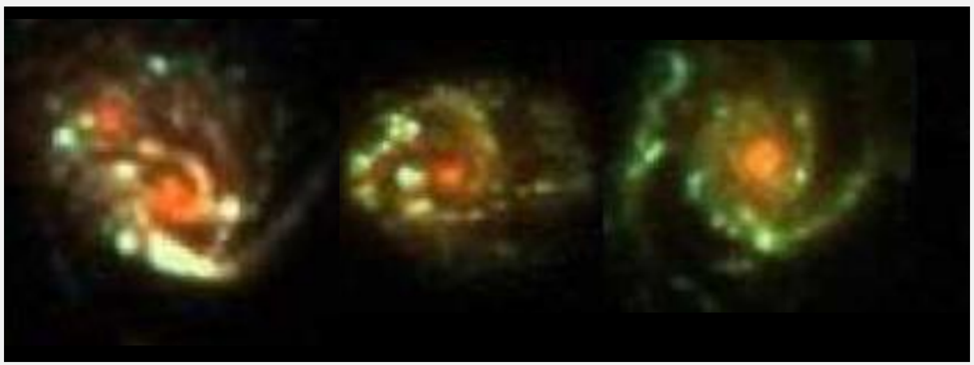
クランピー銀河について

- 円盤銀河の形成段階に相当すると考えられている銀河

Clumpy galaxies

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

in the high-z

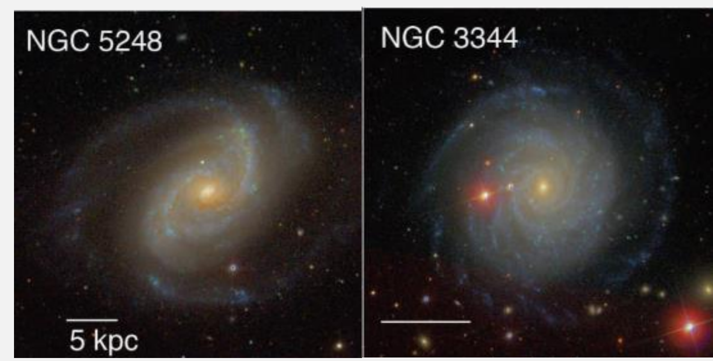


with HST Guo et al. (2014)

$\sim 10^9$ yr

?

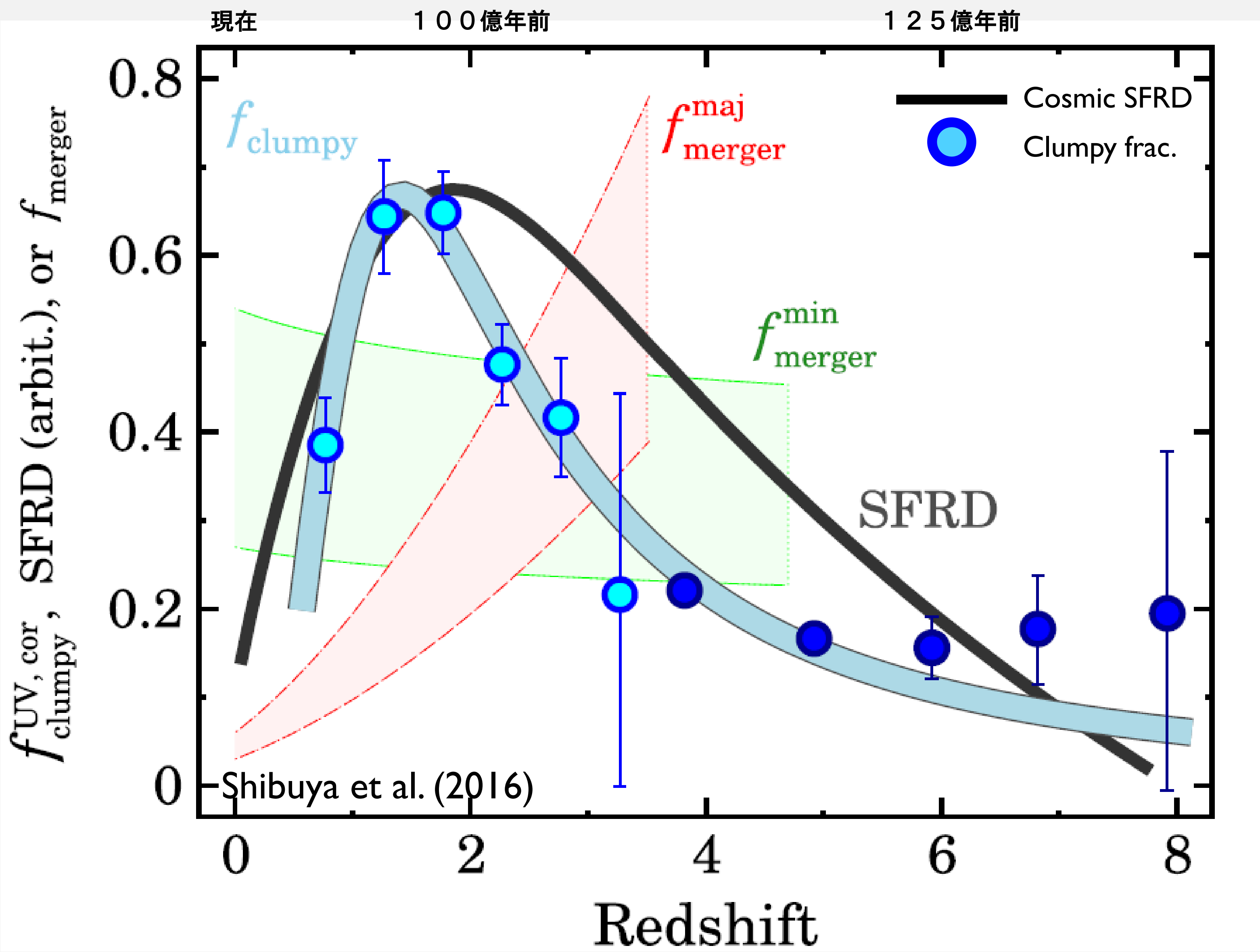
in the local universe



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 ~ 30-50 % in z=1-3
    - Tadaki+14, Livermore+15, Guo+15

Clumpy fraction and cosmic SFR



Clump formation and star formation

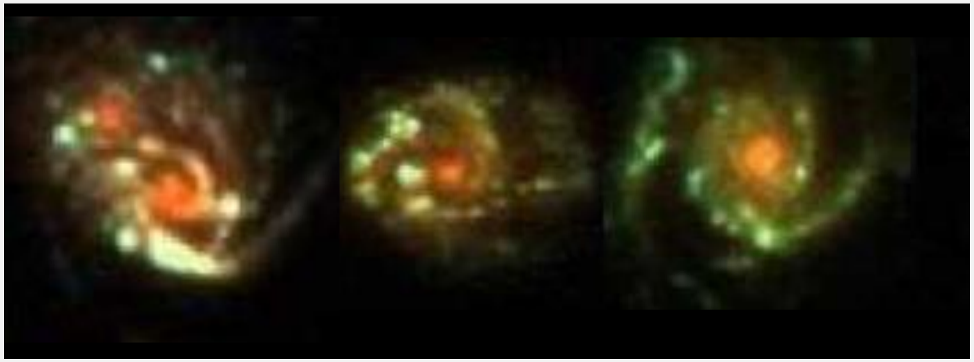
- **What yet to understand are:**
  - What drives giant-clump formation?
    - Gravitational instability (GI)
    - Cosmological gas accretion
    - Galactic mergers
  - What suppress giant-clump formation? (why clumps disappear?)
    - Disc stabilization by gas consumption and/or heating
    - Growth of a massive bulge
    - Cessation of galactic mergers

Spiral-arm instability: giant clump formation via fragmentation of a galactic spiral arm

Beyond Toomre's Q

MNRAS 474, 3466 (2018)

Spiral or Clumpy?

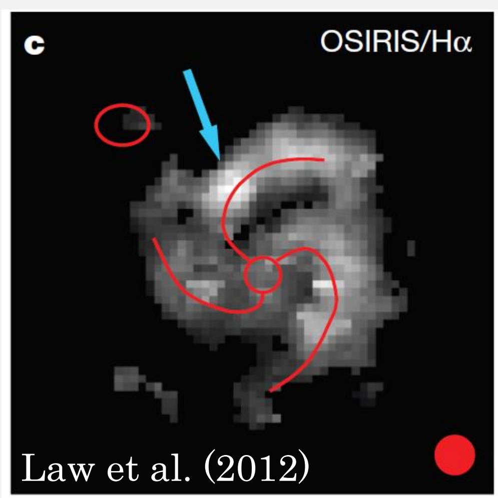


Guo et al. (2014)

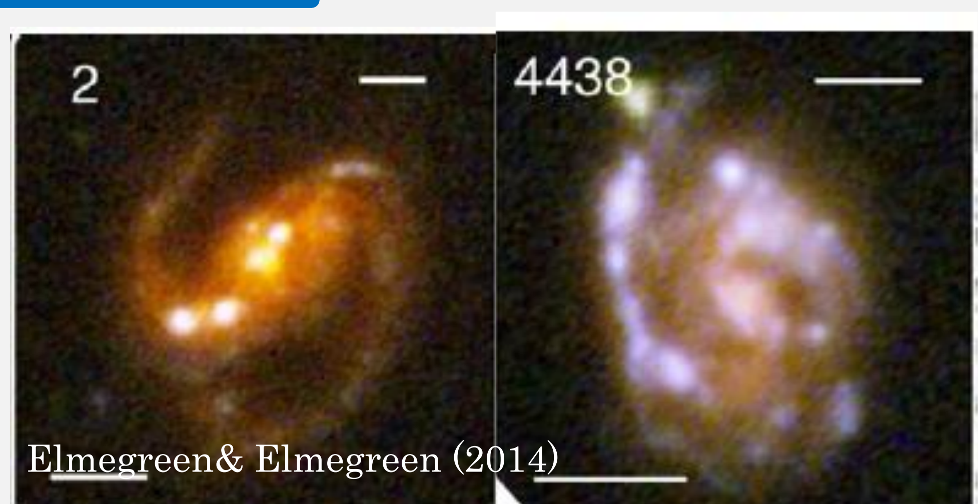
- Clumpy galaxies
  - **Giant clumps**
  - Gas-rich (f_{gas}>30%)
  - **Toomre instability?**

Spiral-arm fragmentation?

Spiral galaxies emerge at z<2-3 (Elmegeen+14)



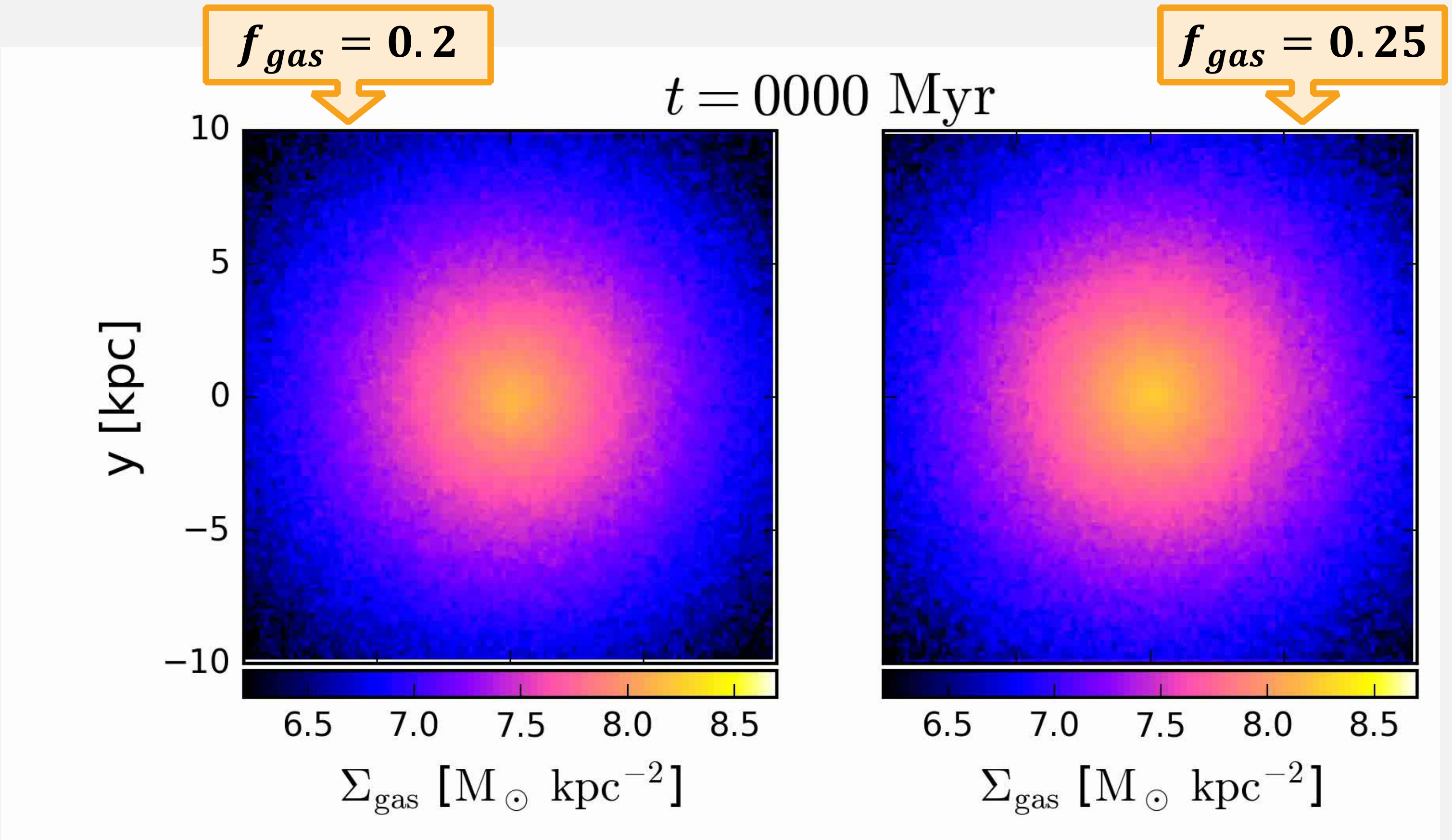
Law et al. (2012)



Elmegreen& Elmegreen (2014)

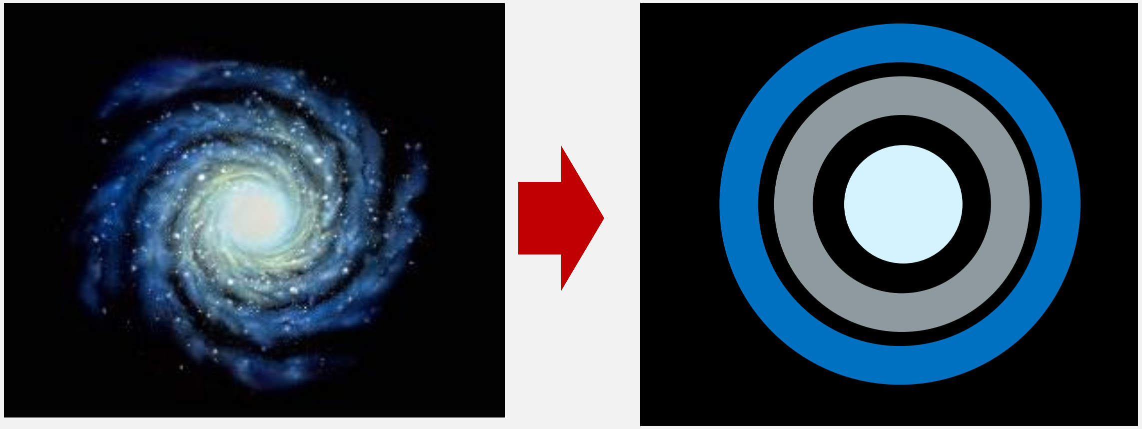
Spiral or Clumpy?

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



Set-up for the linear perturbation theory

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



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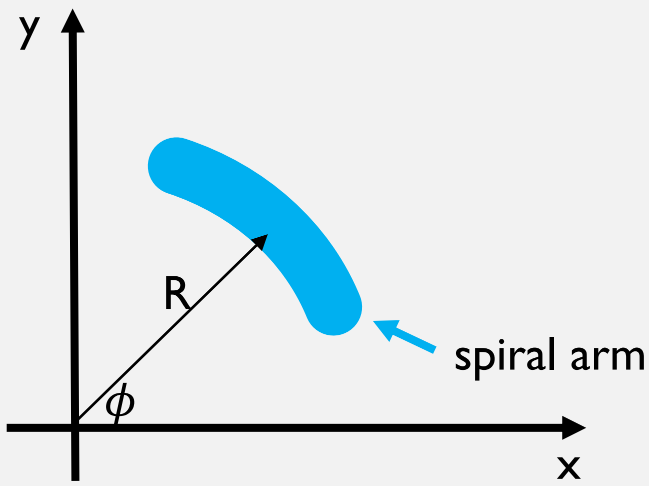

- *Linear perturbation equations*
  - $A \rightarrow A_0 + \delta A$
  - consider the first-order terms

continuity: $$\frac{\partial}{\partial t}\Sigma + \nabla \cdot (\Sigma \mathbf{v}) = 0,$$

R- and ϕ-momenta: $$\frac{\partial}{\partial t}\mathbf{v} + (\mathbf{v} \cdot \nabla)\,\mathbf{v} = -\frac{1}{\rho}\nabla p - \nabla \Phi.$$

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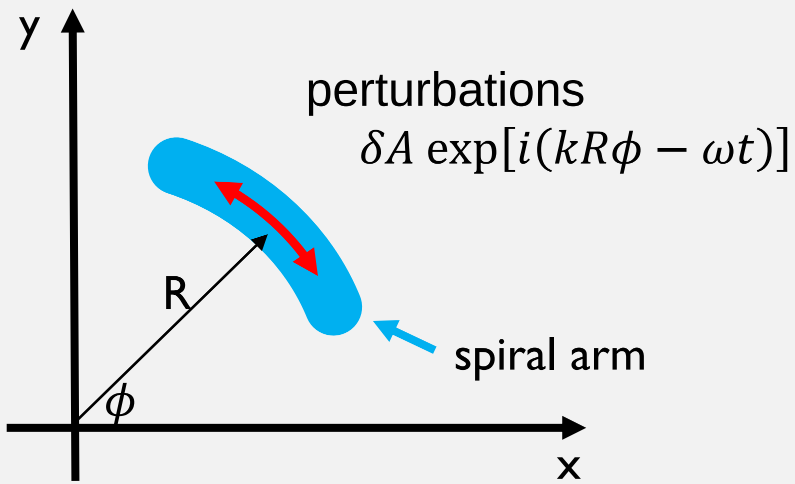


Assuming:

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

$$\Omega = -B$$

- Replace surface density Σ with line-mass

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

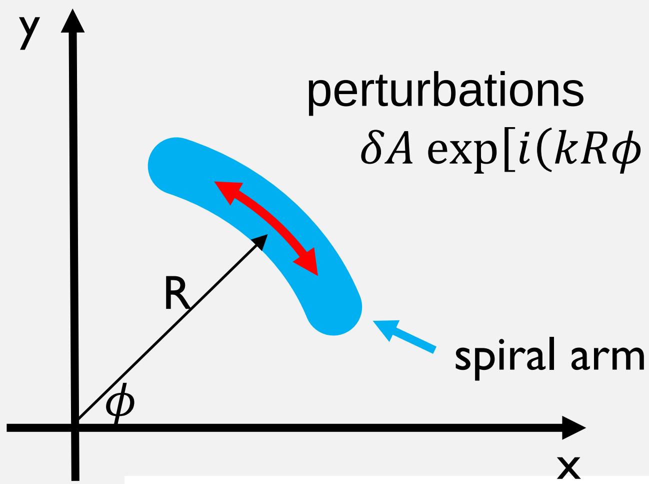
continuity:
$$\frac{\partial}{\partial t}\delta\Sigma + \frac{1}{R}\frac{\partial}{\partial R}(R\Sigma_0 \delta v_R) + \Omega\frac{\partial}{\partial\phi}\delta\Sigma + \frac{\Sigma_0}{R}\frac{\partial}{\partial\phi}\delta v_\phi = 0,$$

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).



perturbations
$\delta A \exp[i(kR\phi - \omega t)]$

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,

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

Pressure　　Self-gravity　　Coriolis force

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

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

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

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

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

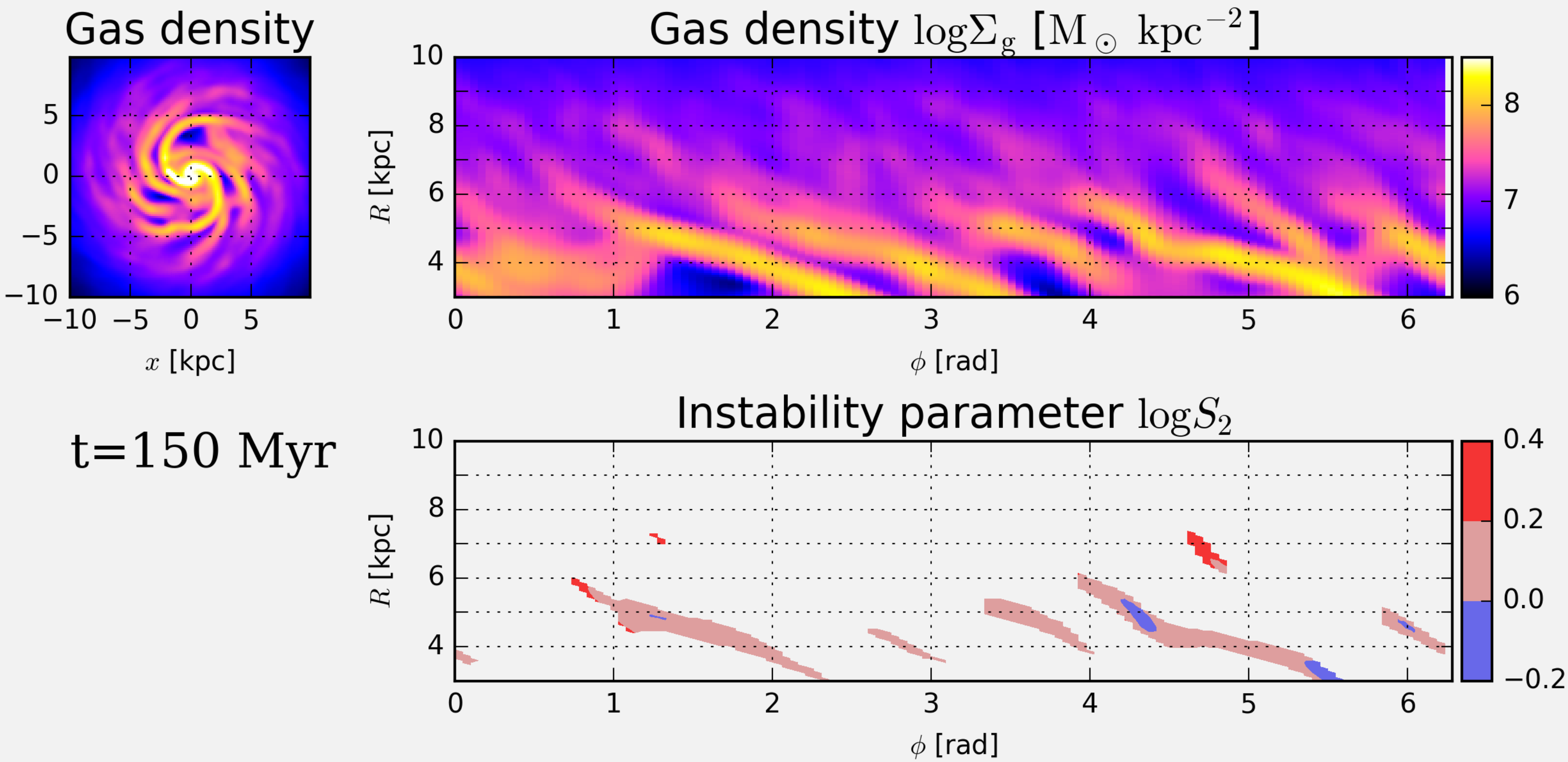
$$\left[\frac{\pi G k^2\Upsilon_\mathrm{g} f(kW_\mathrm{g})}{c_s^2k^2 + 4\Omega^2 - \omega^2} + \frac{\pi G k^2\Upsilon_\mathrm{s} f(kW_\mathrm{s})}{\sigma_\phi^2k^2 + 4\Omega^2 - \omega^2}\right] = 1,$$

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

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

Demonstration

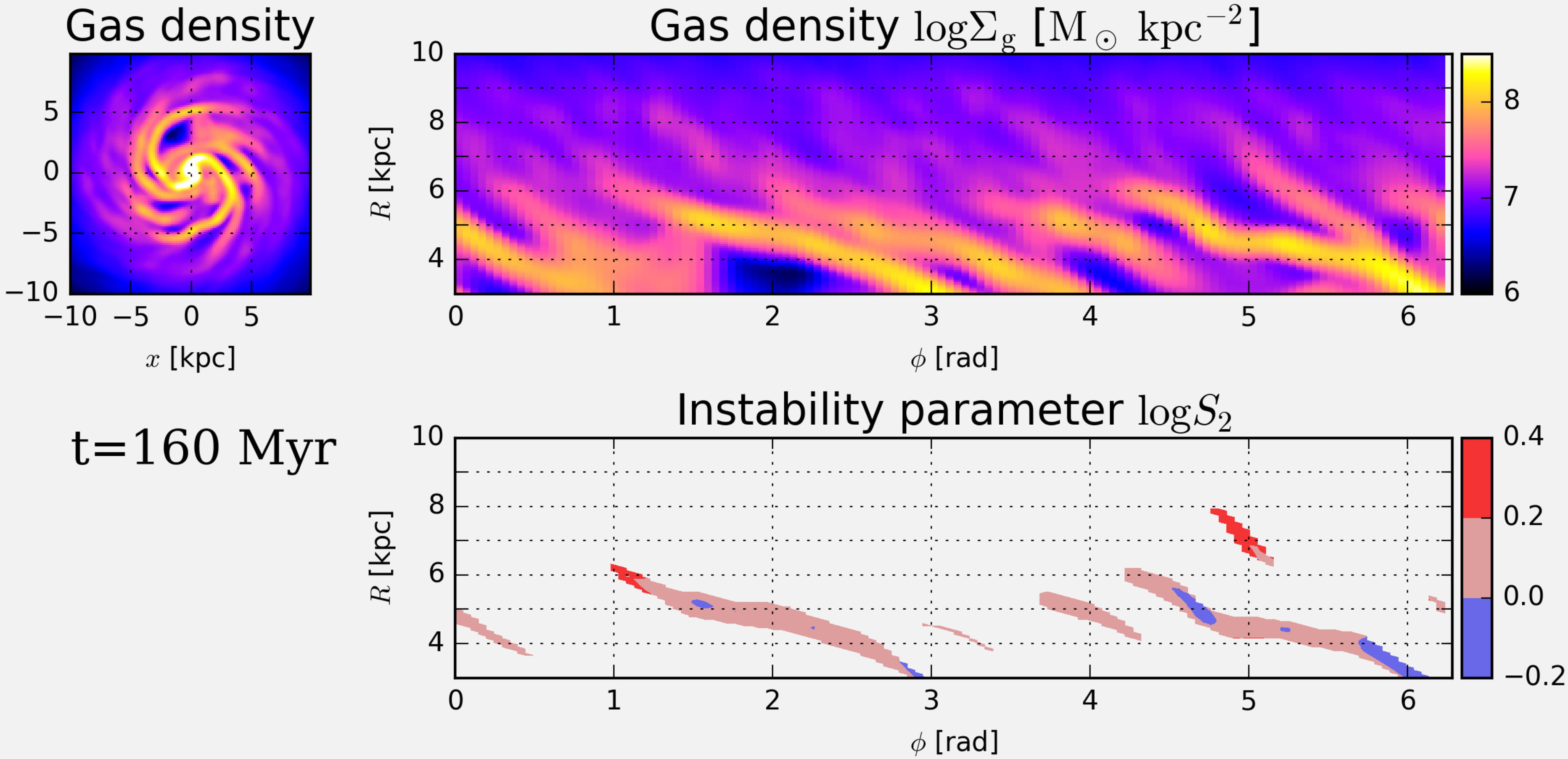
The fragmenting case



t=150 Myr

Demonstration

The fragmenting case



Demonstration

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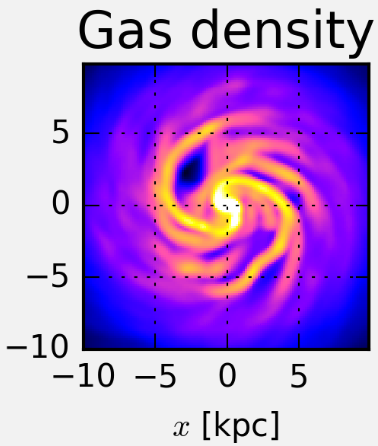
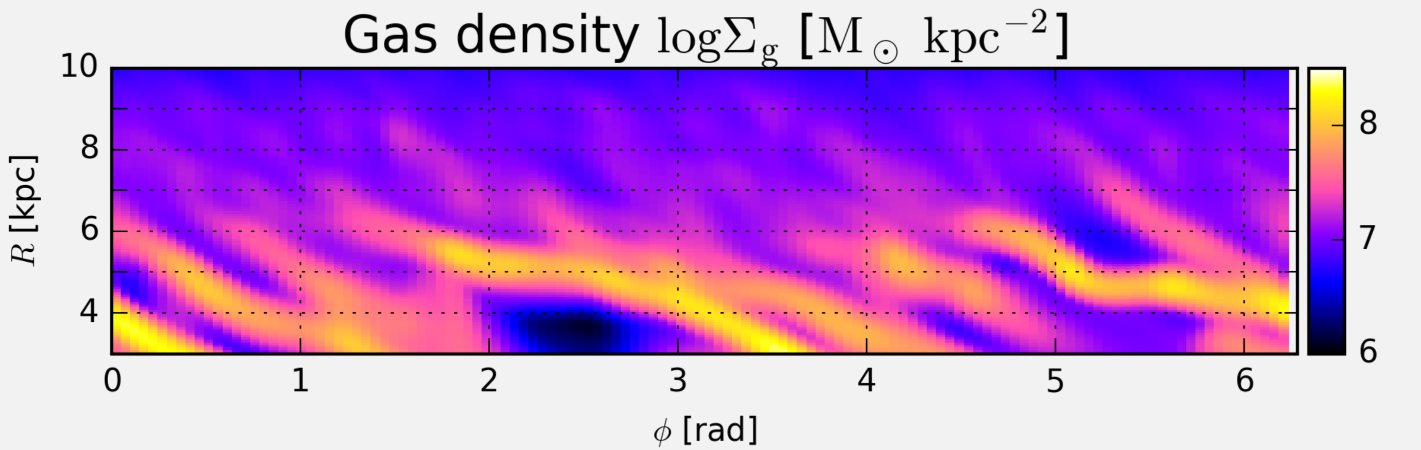
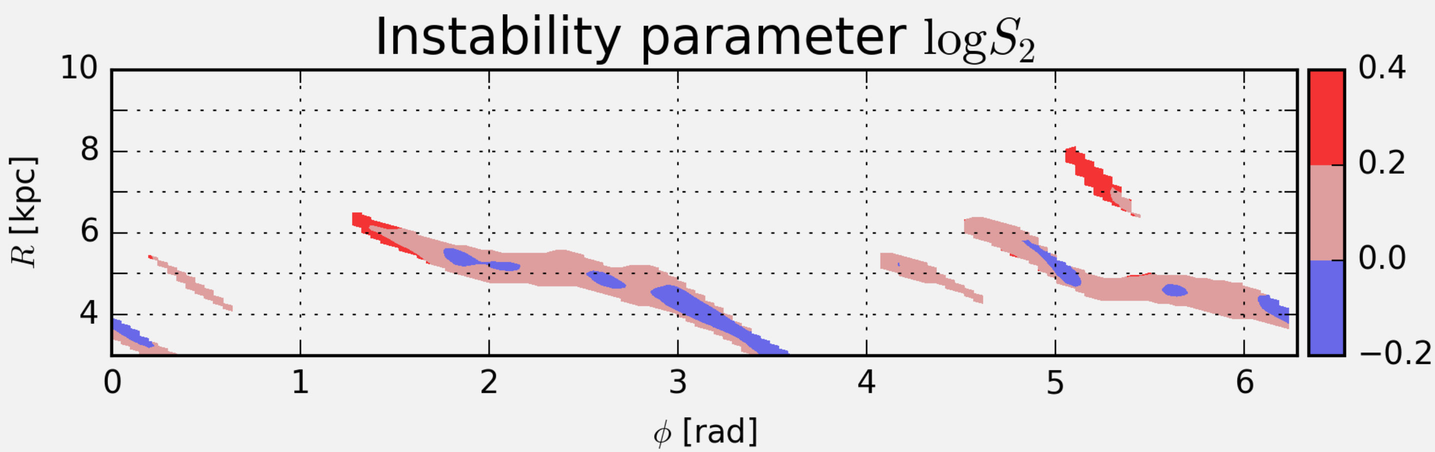


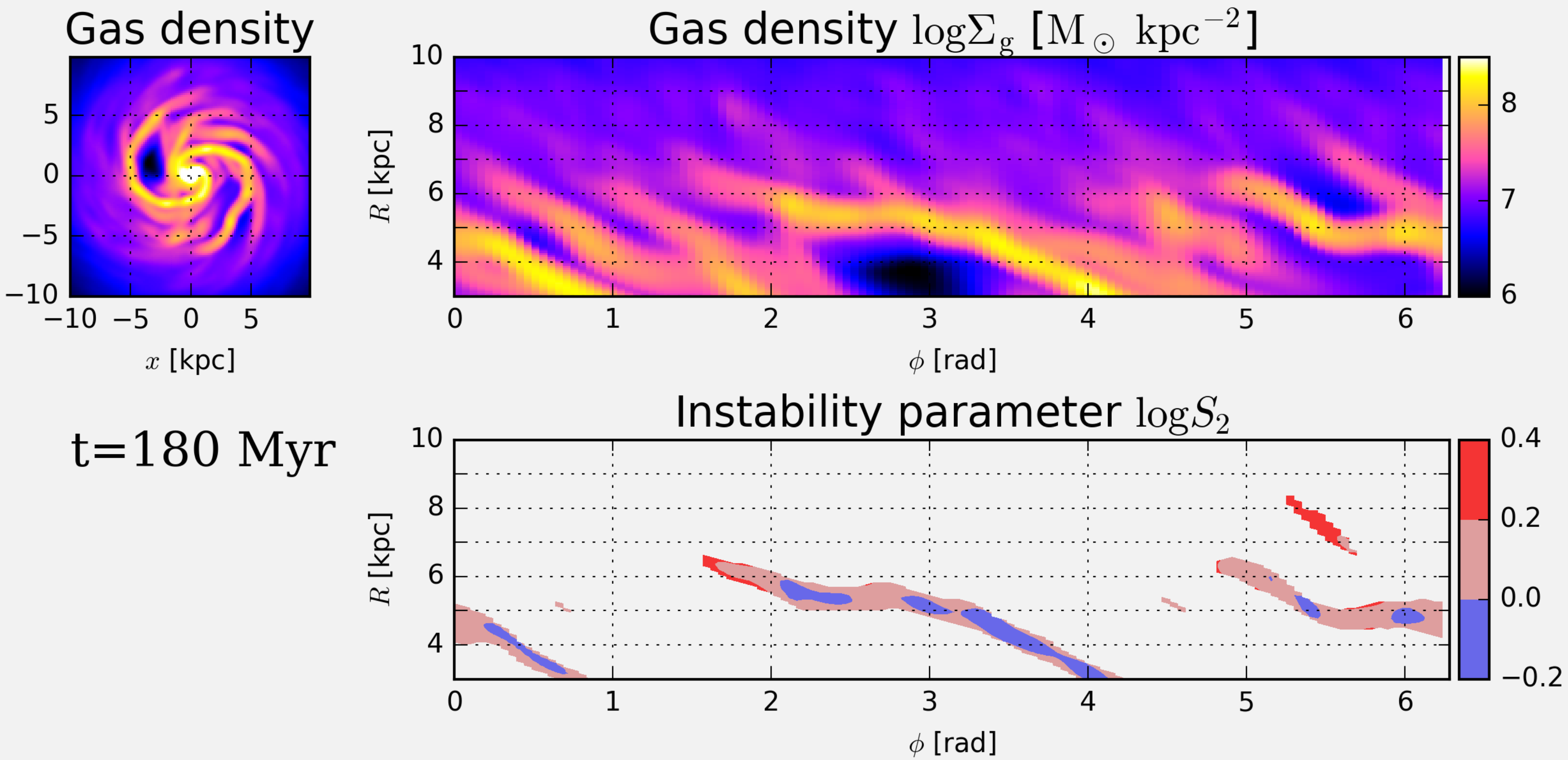


t=170 Myr



Demonstration

The fragmenting case



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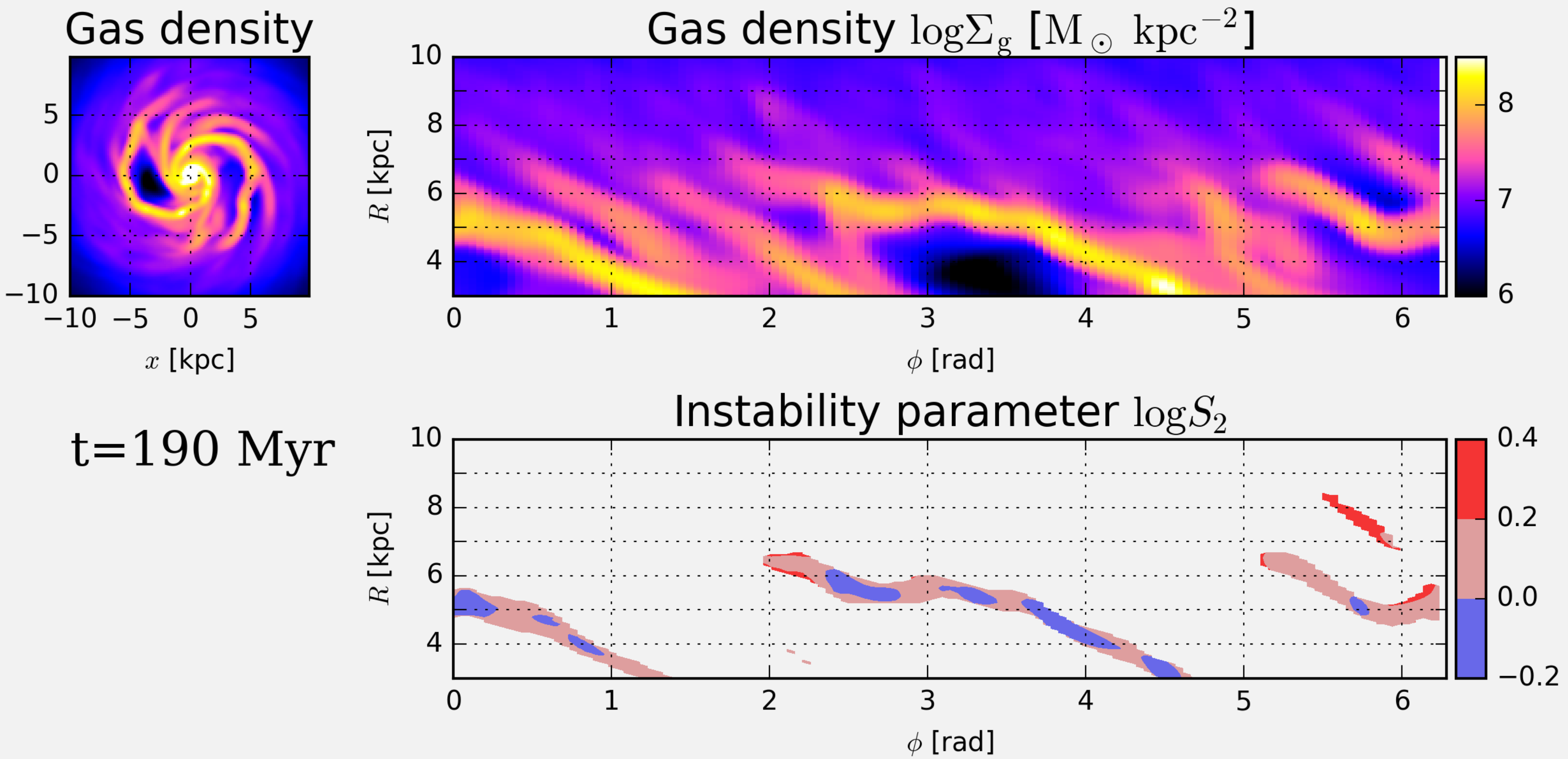

Demonstration

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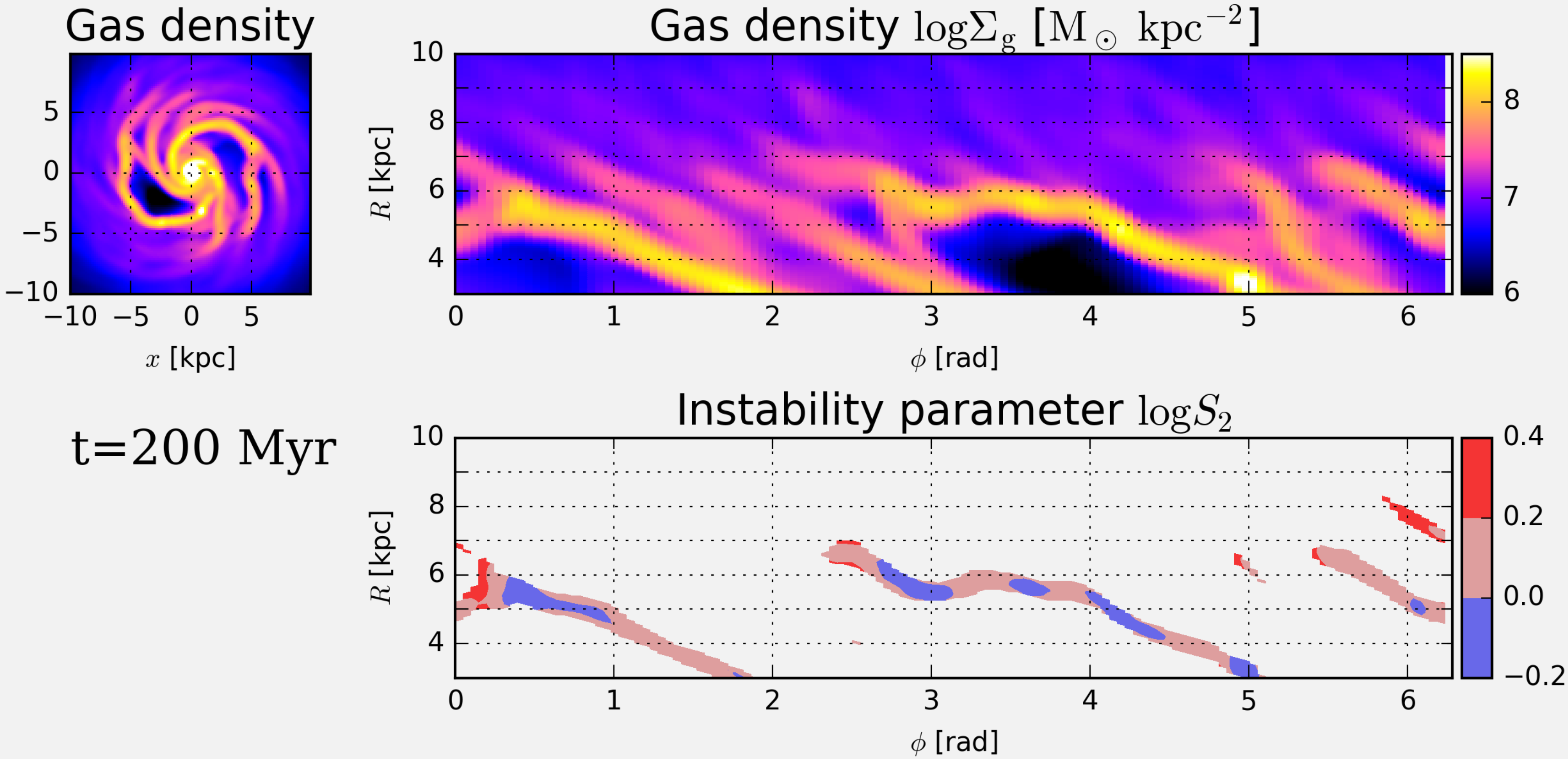
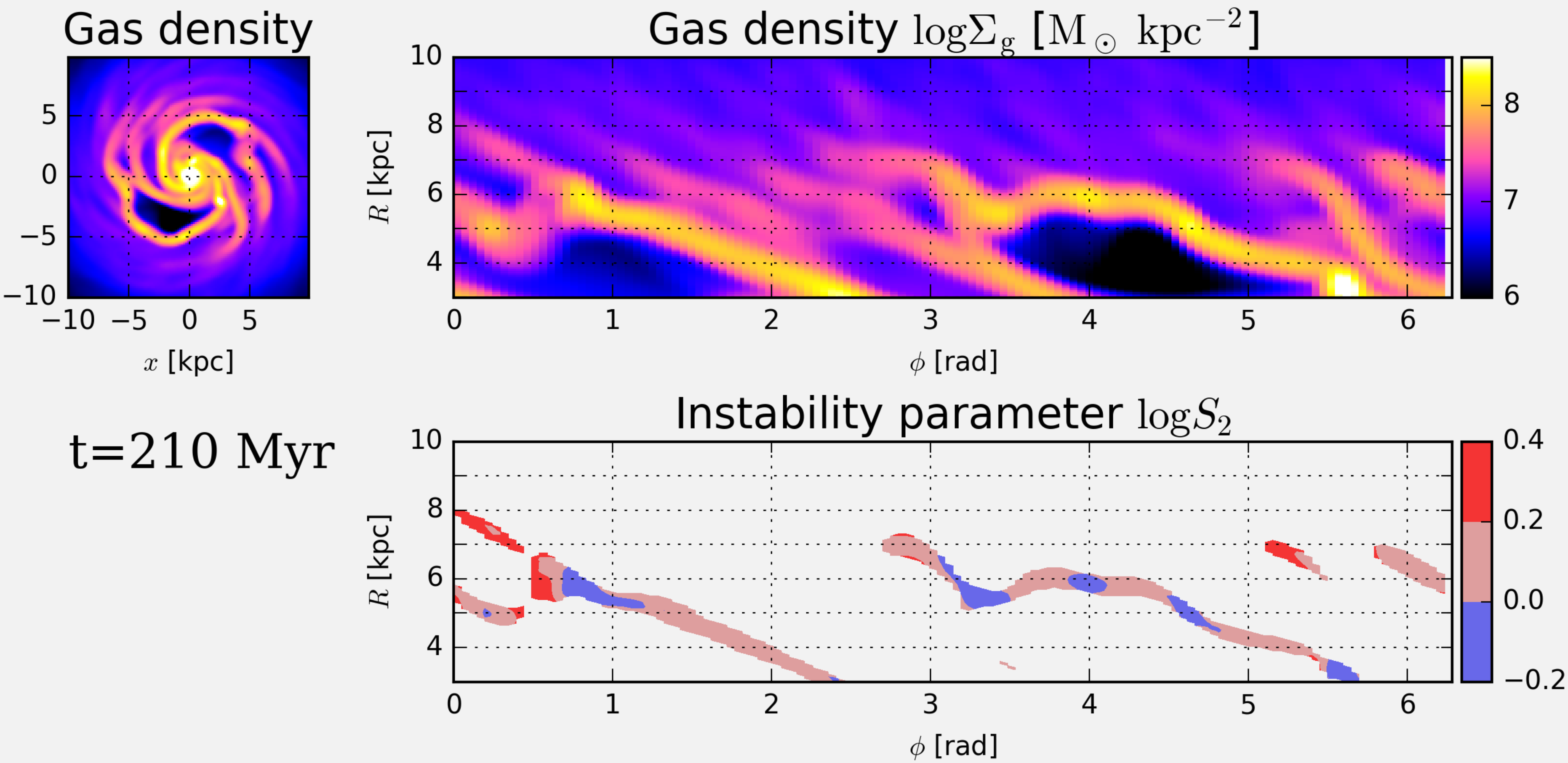


t=200 Myr

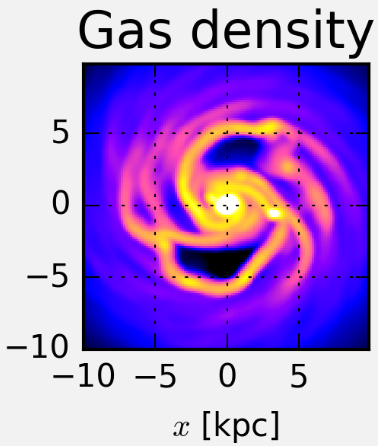
Demonstration

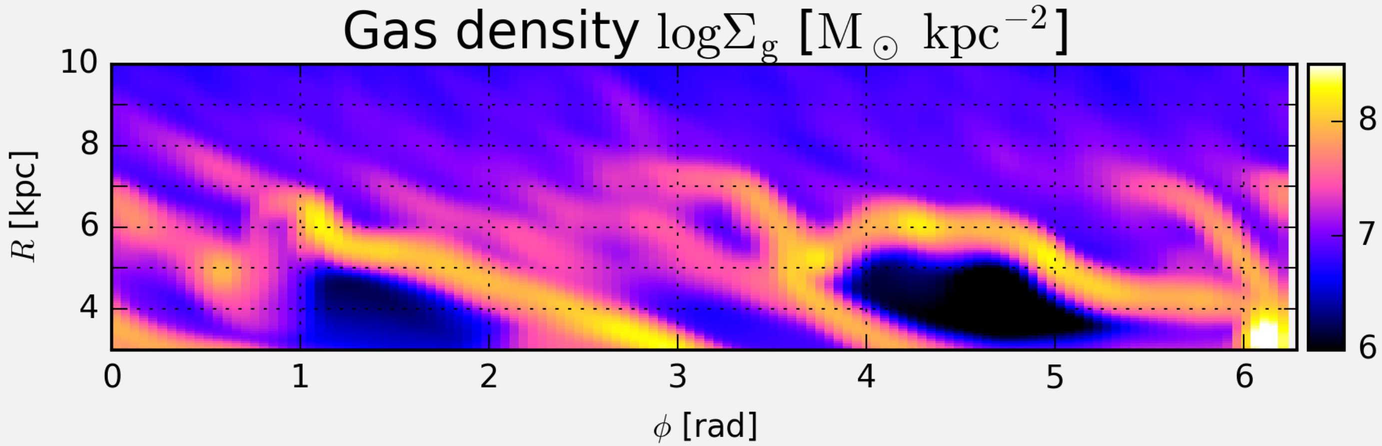
The fragmenting case



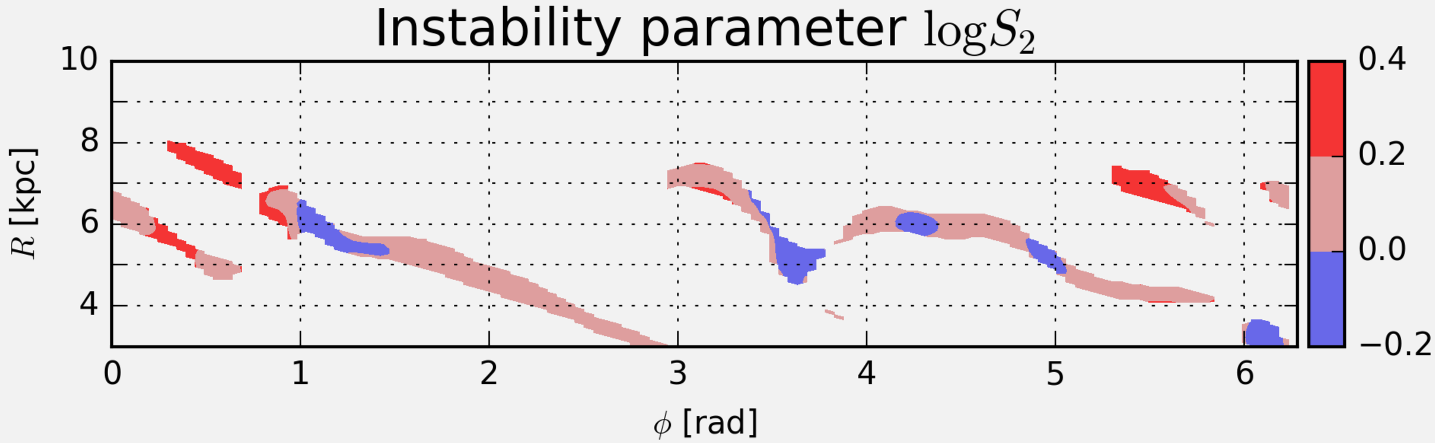
Demonstration

The fragmenting case



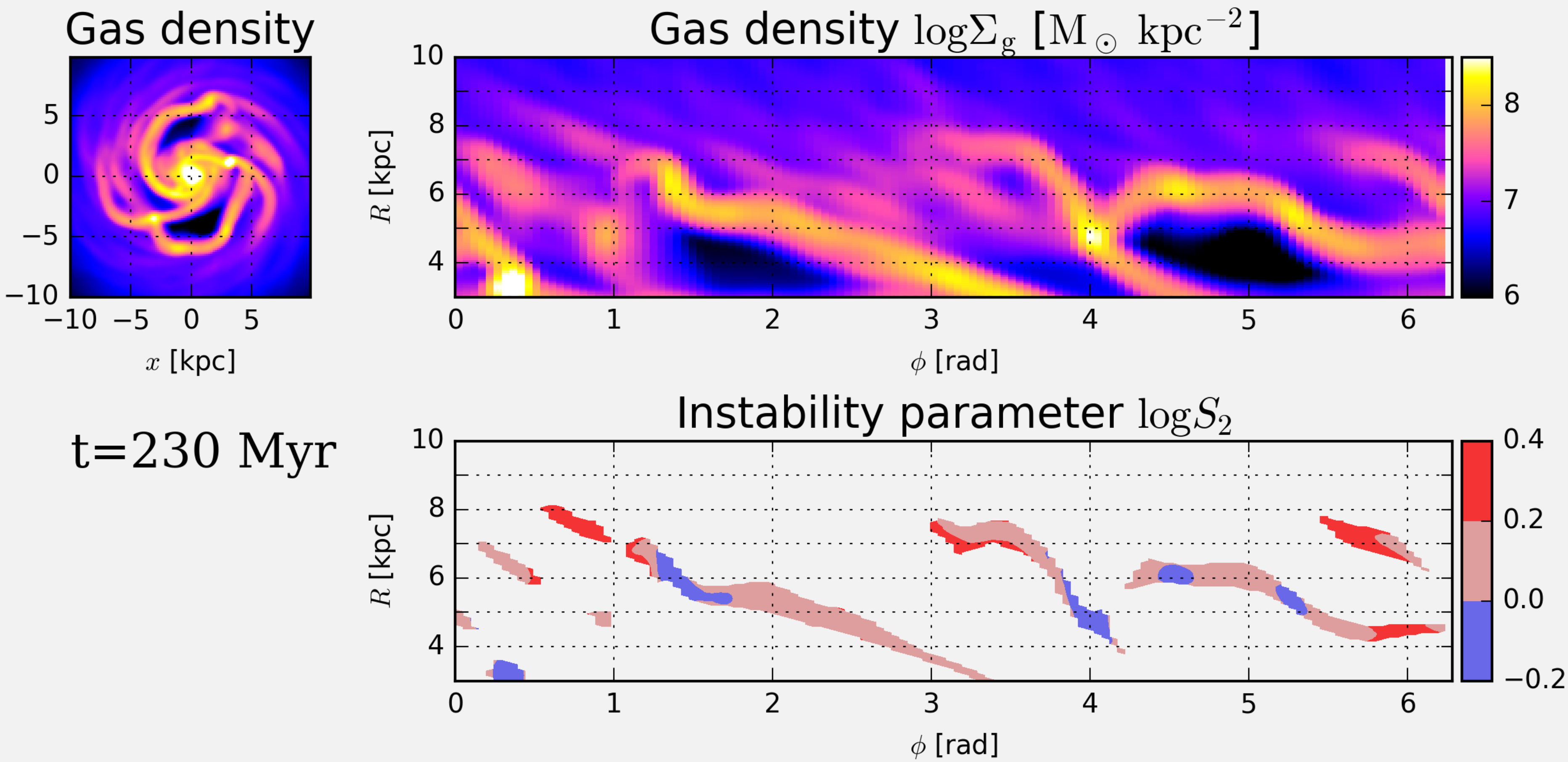


t=220 Myr



Demonstration

The fragmenting case



Demonstration

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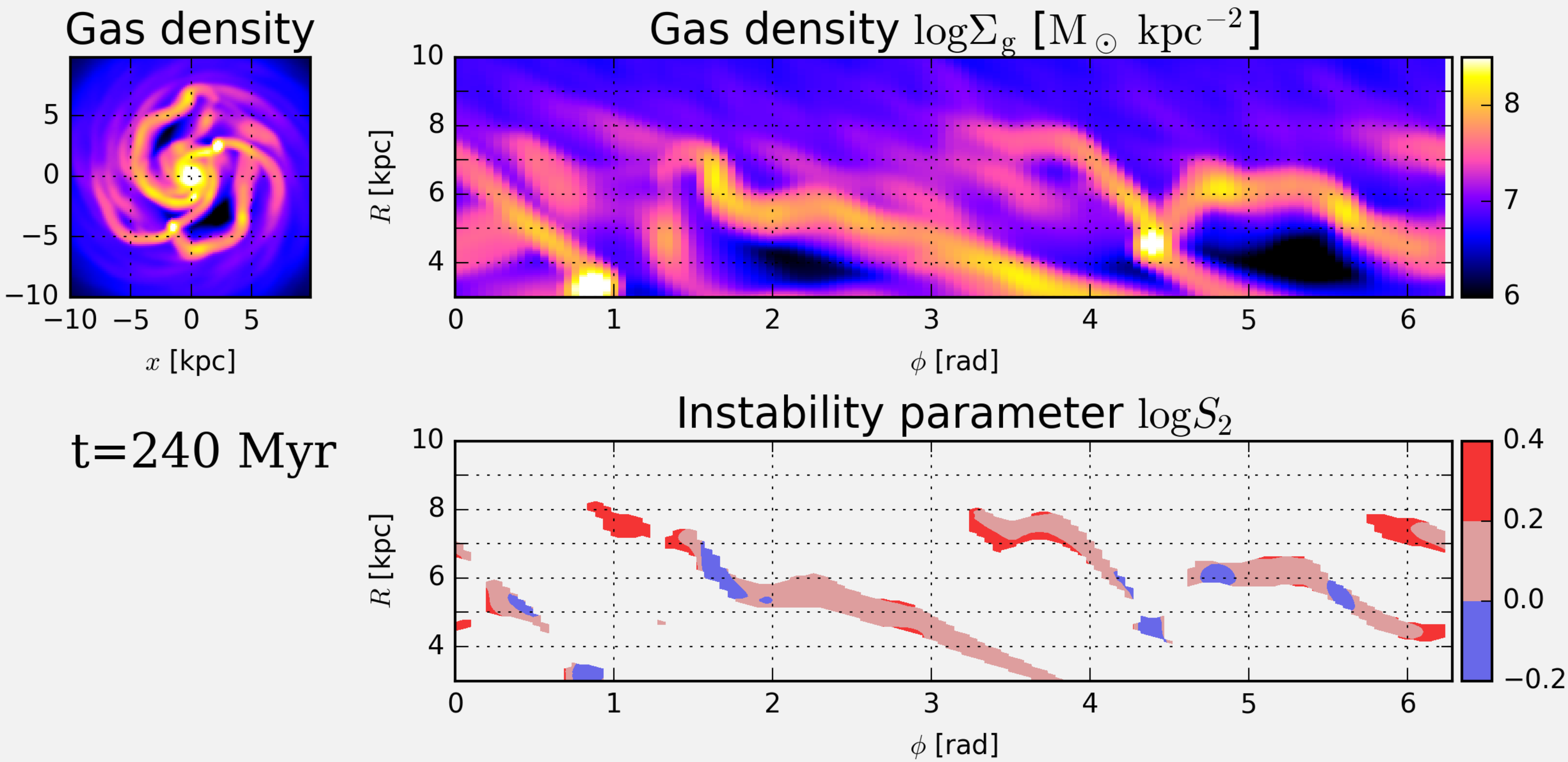
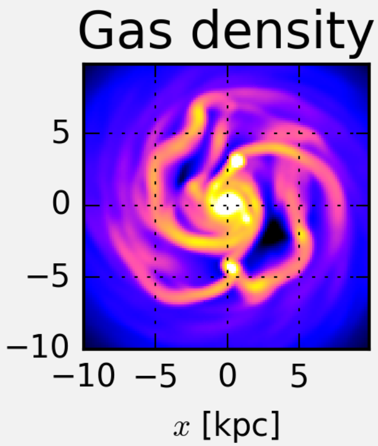
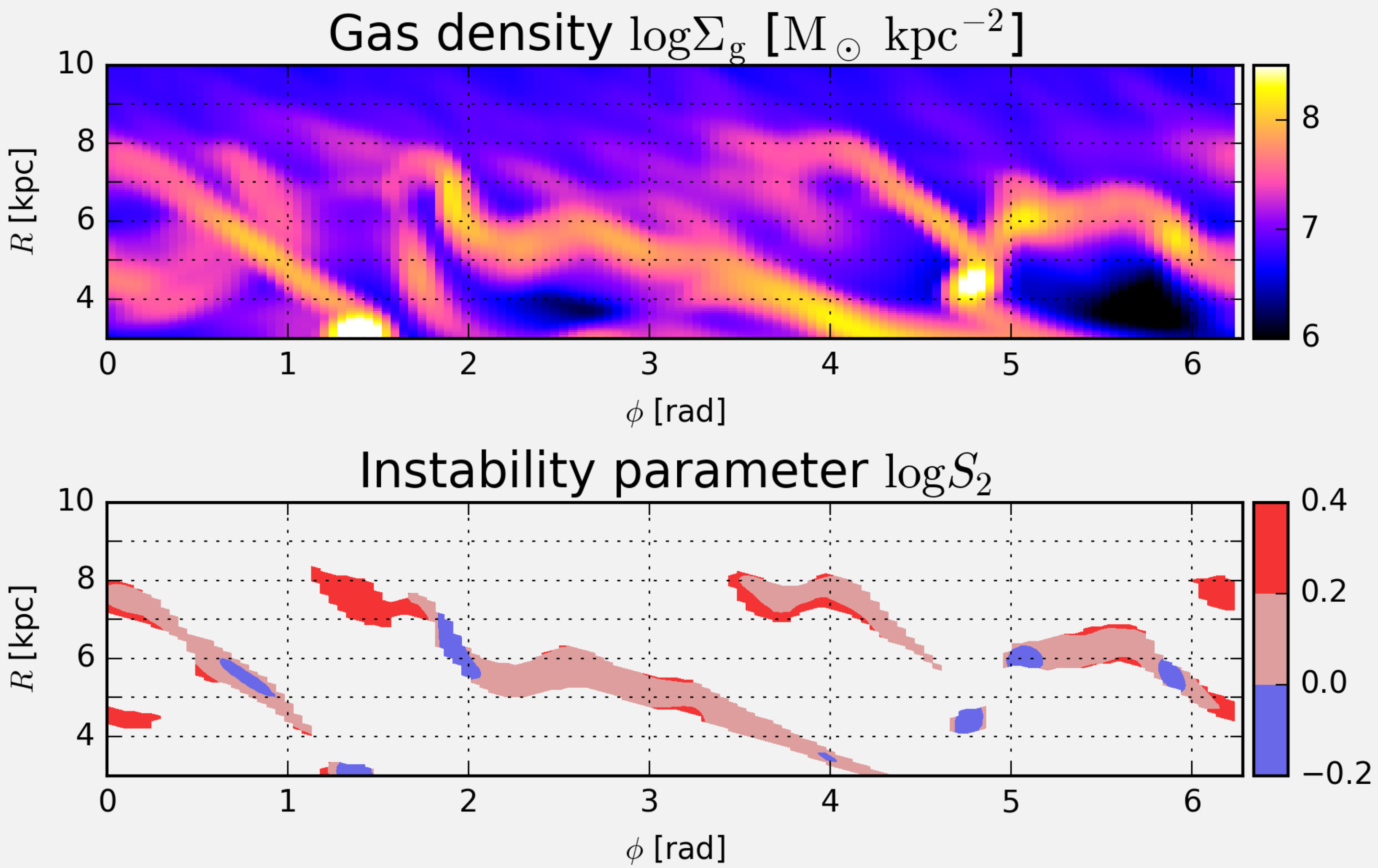


t=240 Myr

Demonstration

The fragmenting case





t=250 Myr

Demonstration

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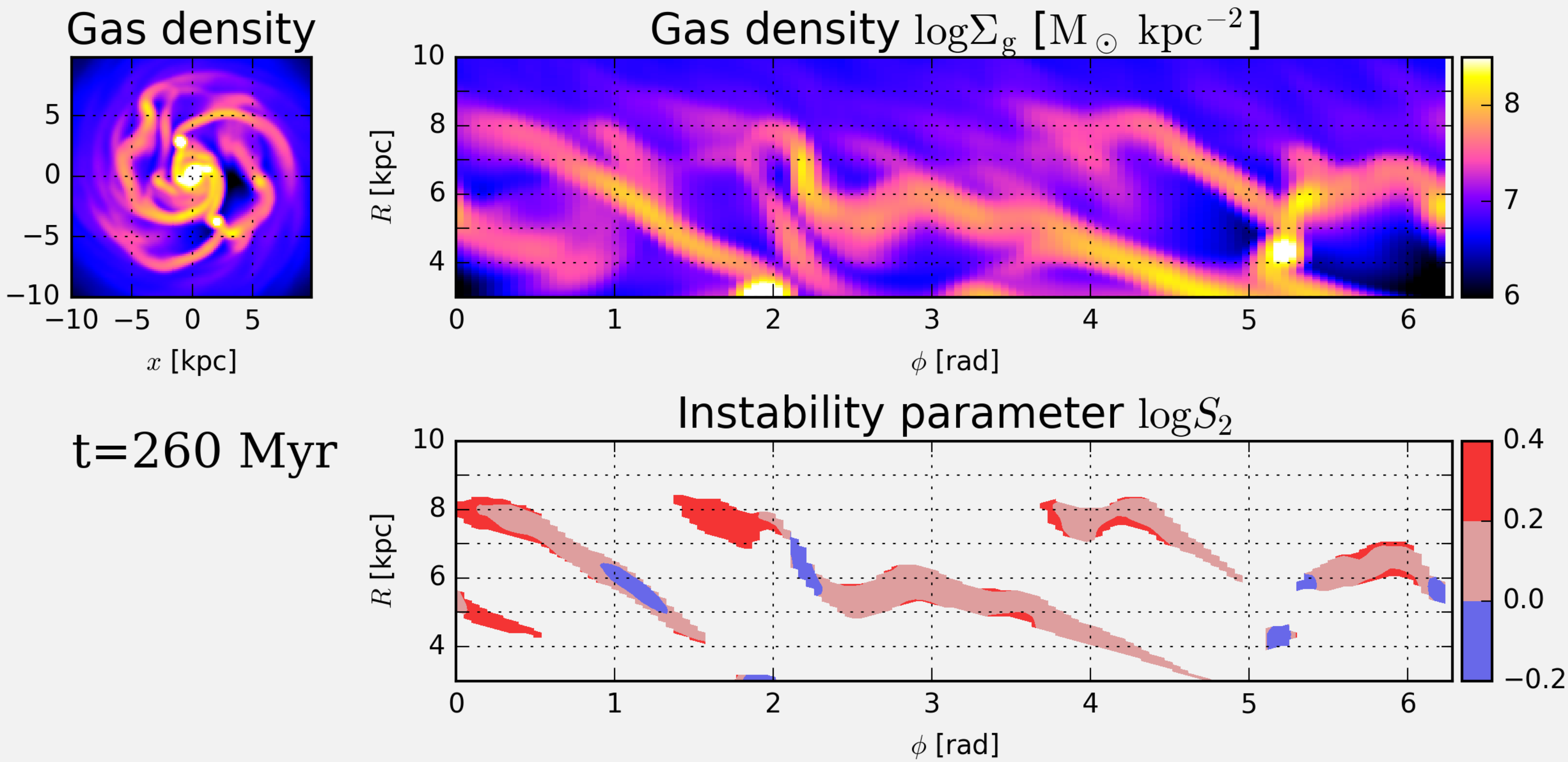
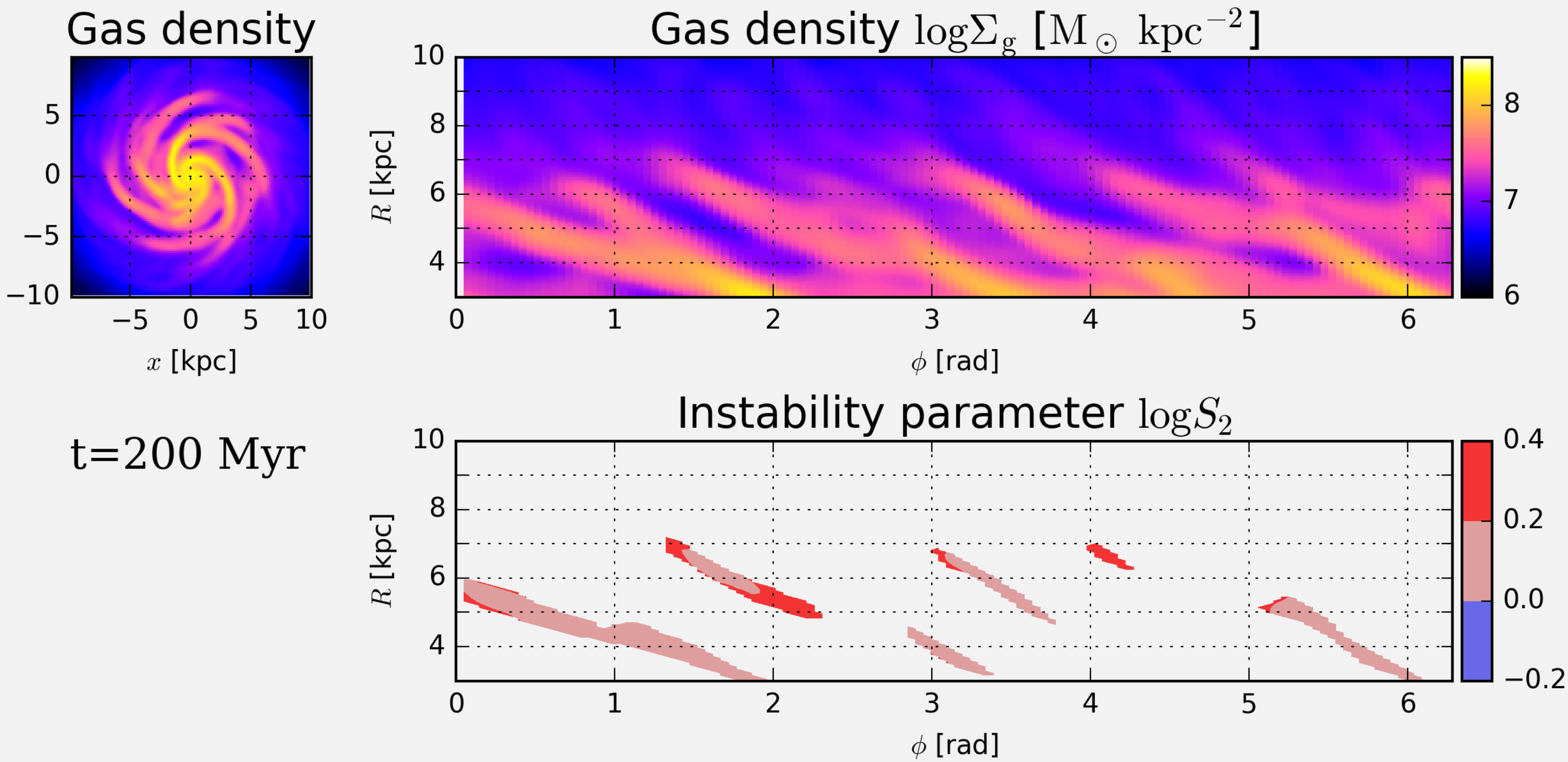


t=260 Myr

Demonstration

The stable case



Demonstration

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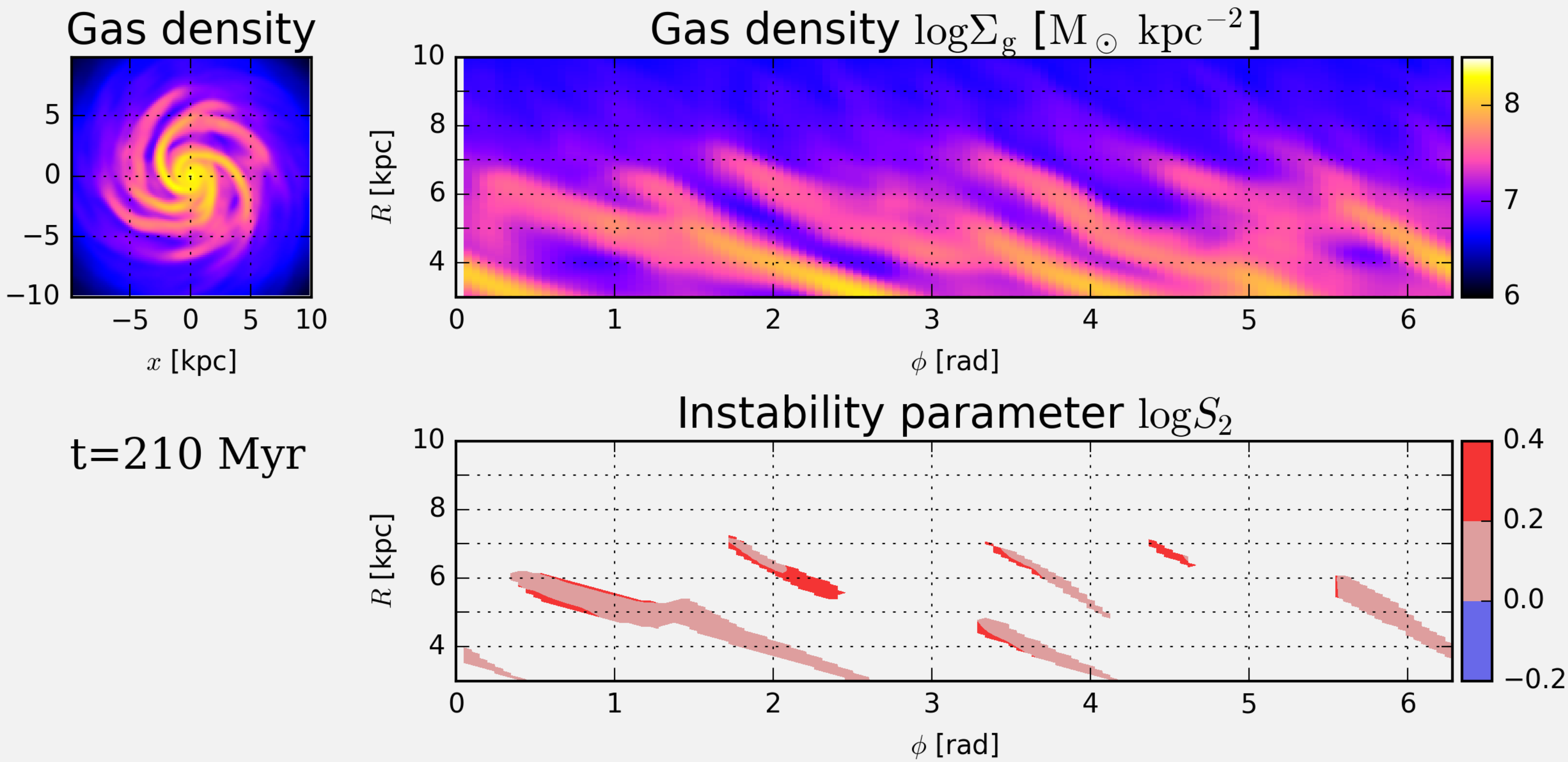

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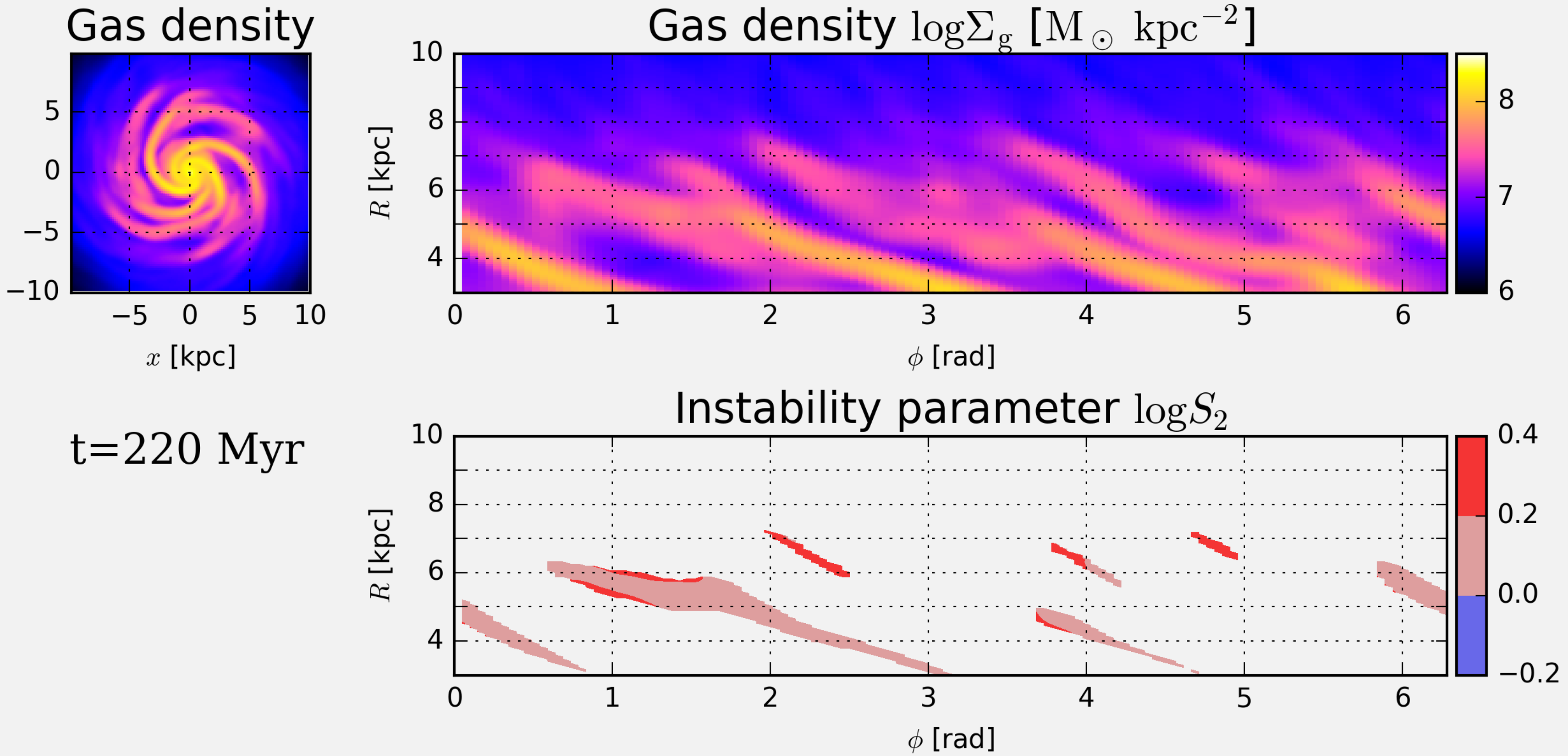

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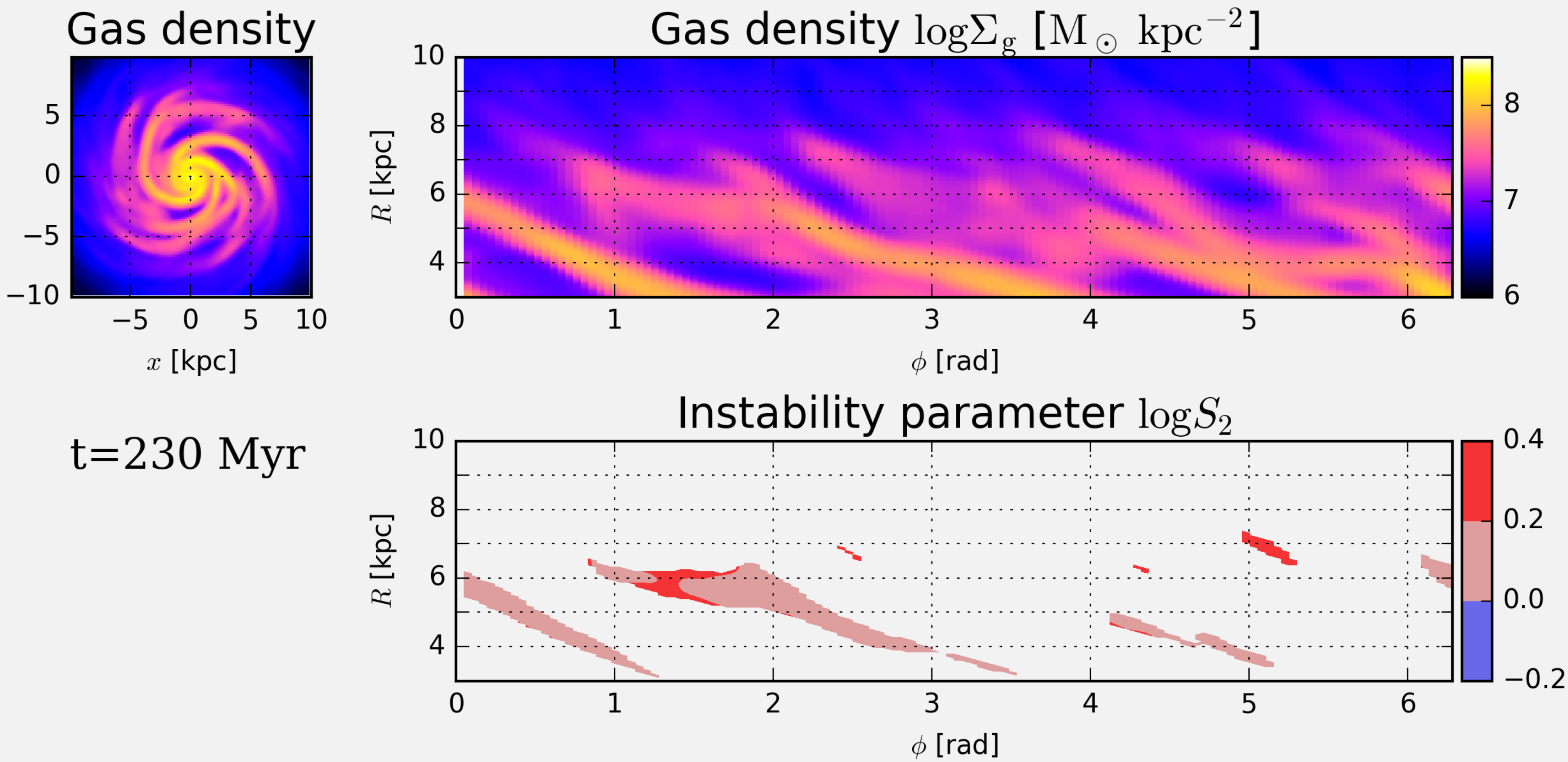
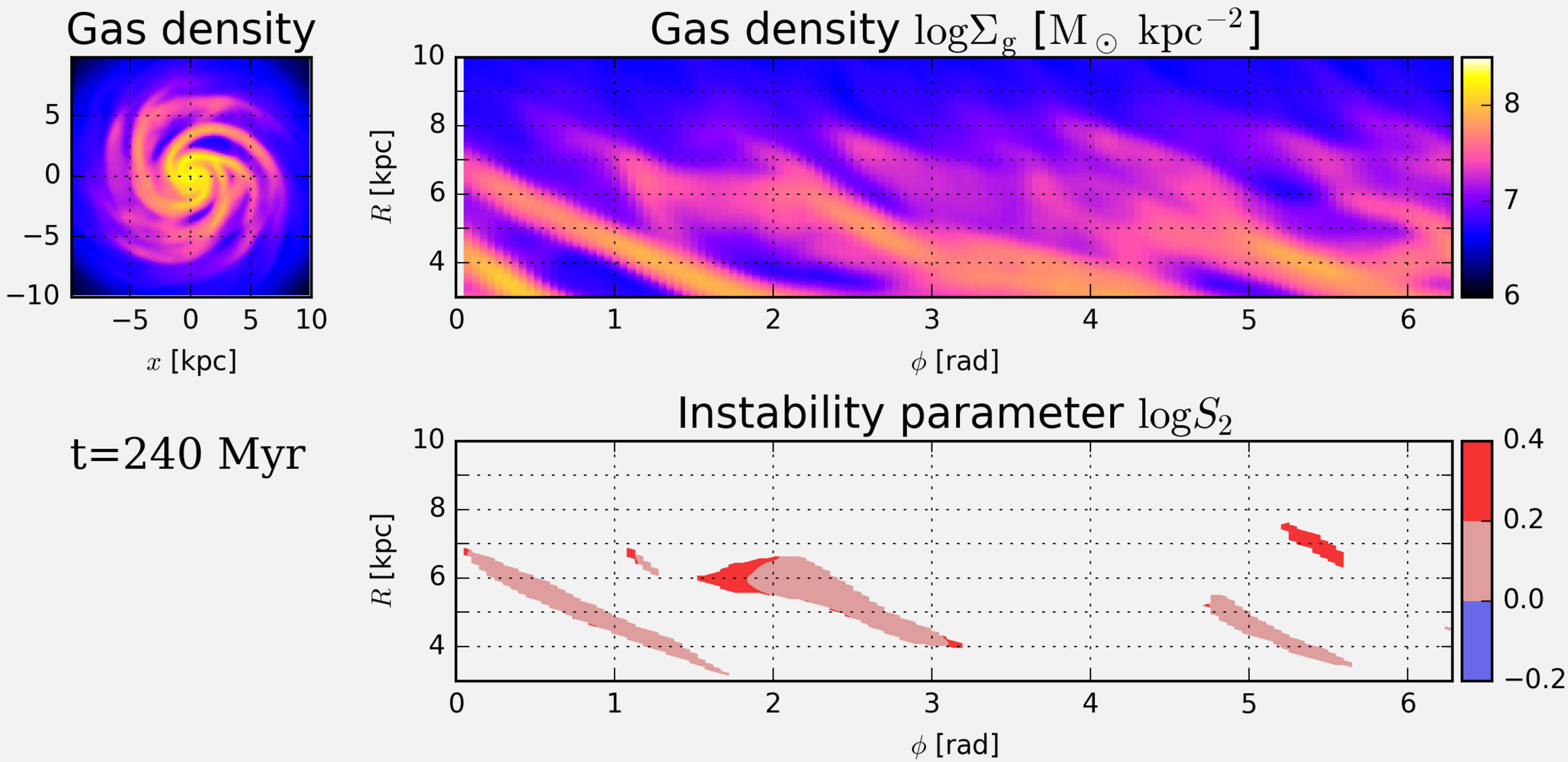


t=230 Myr

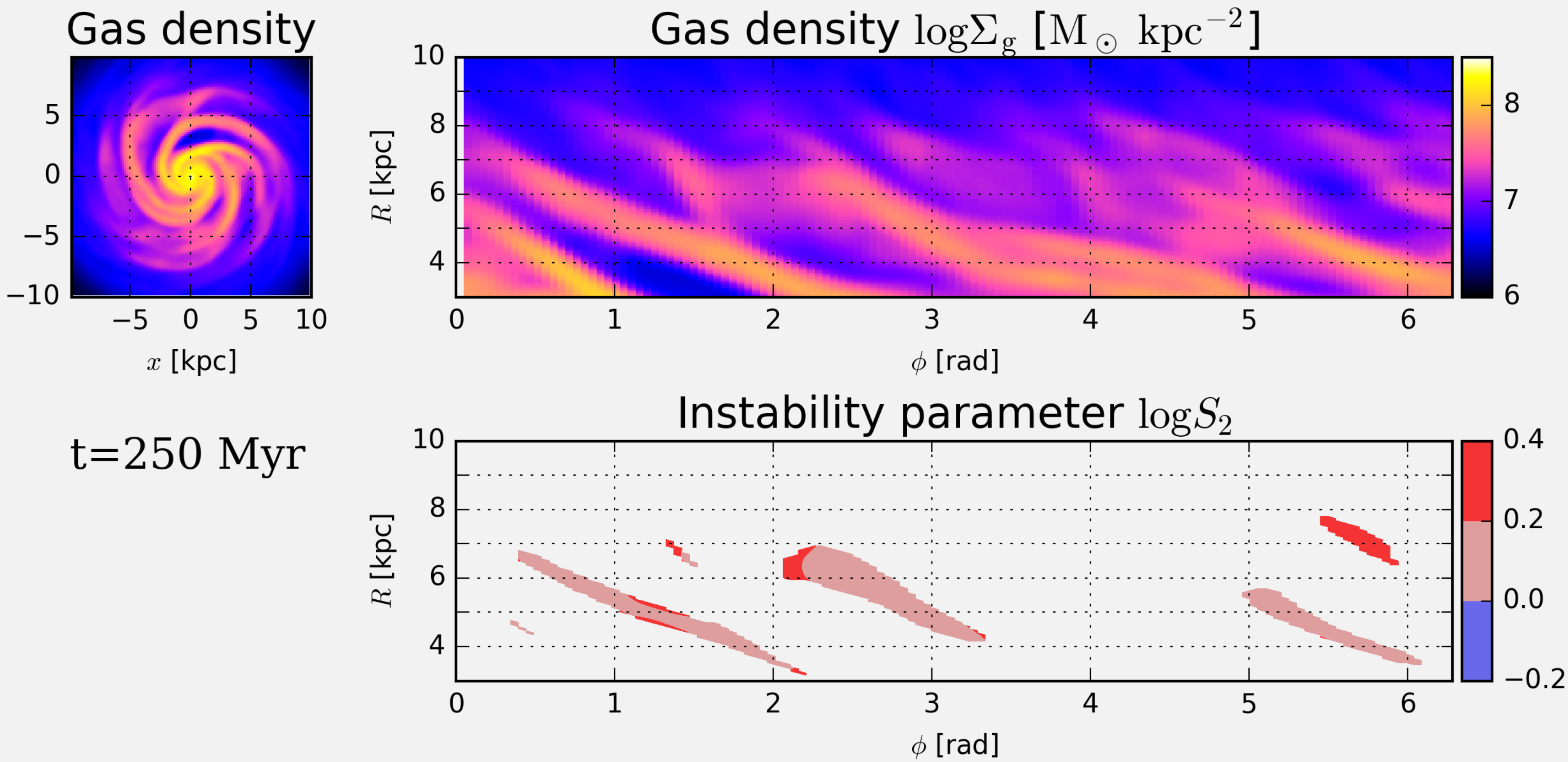
Demonstration

The stable case



Demonstration

The stable case



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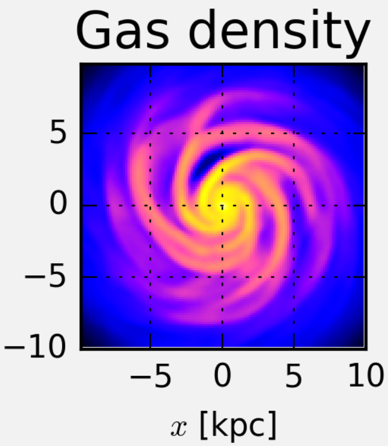

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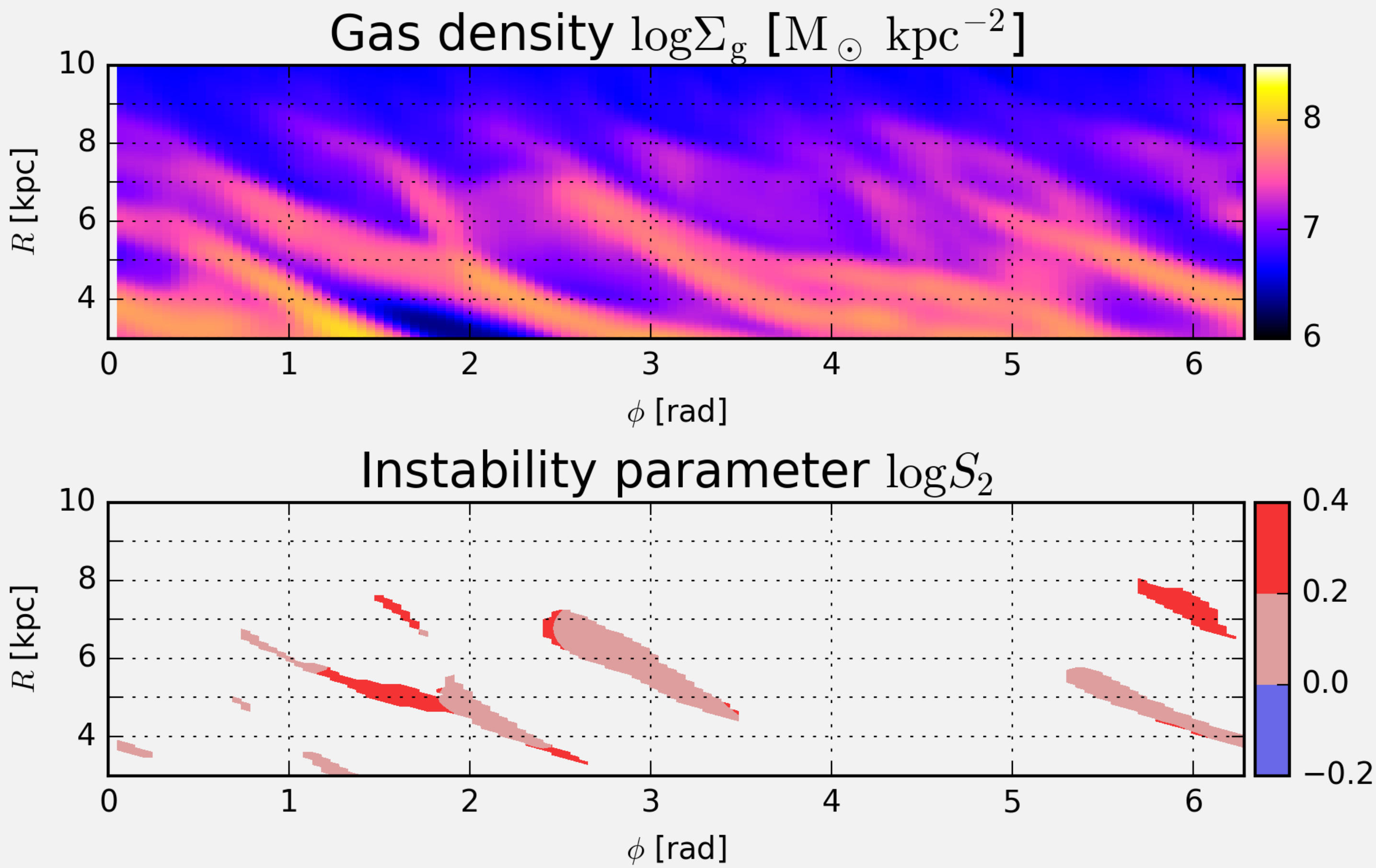

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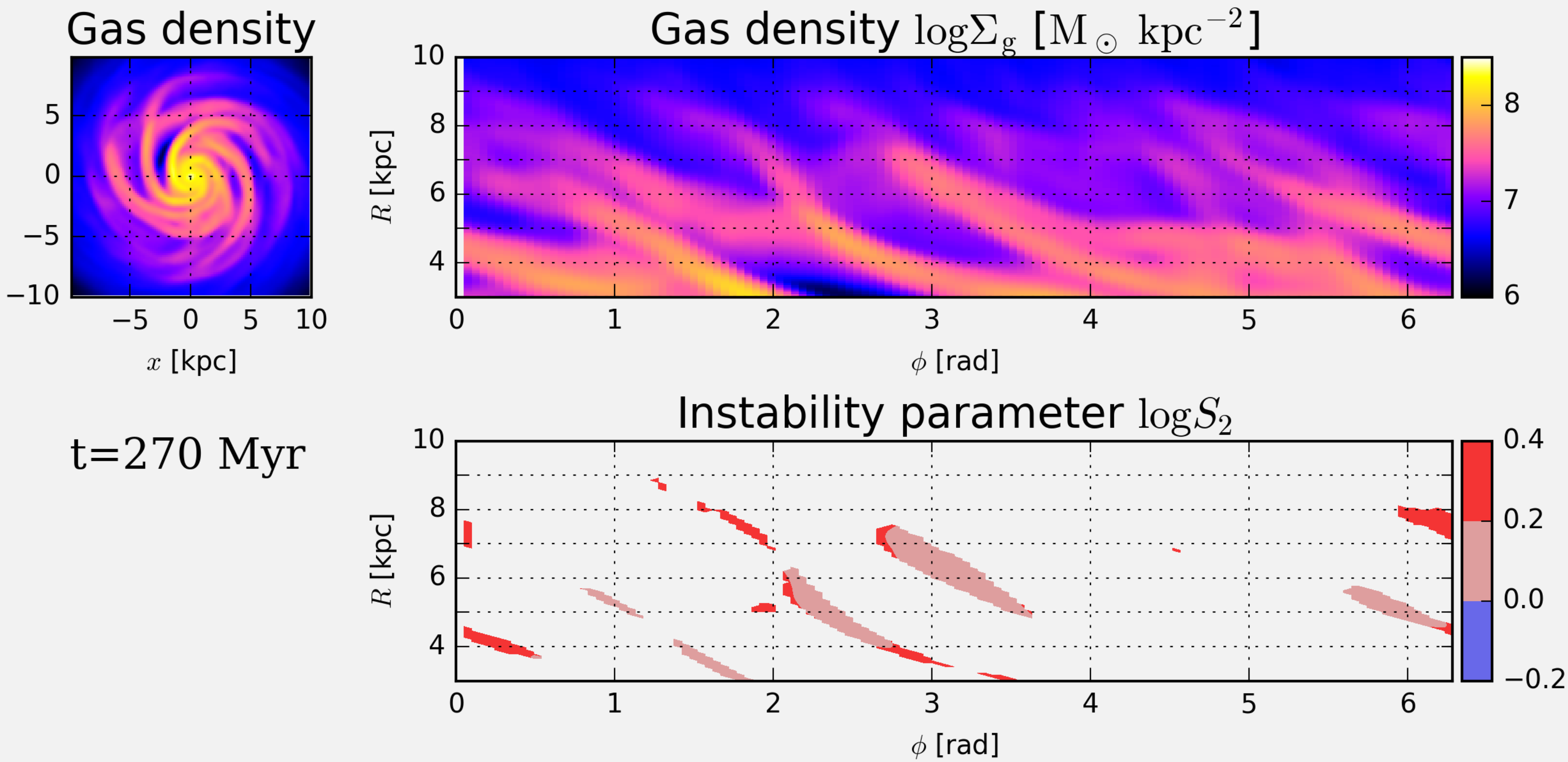

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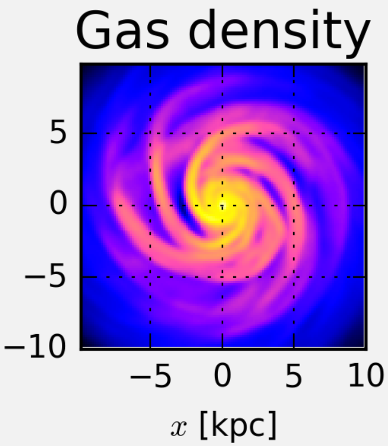
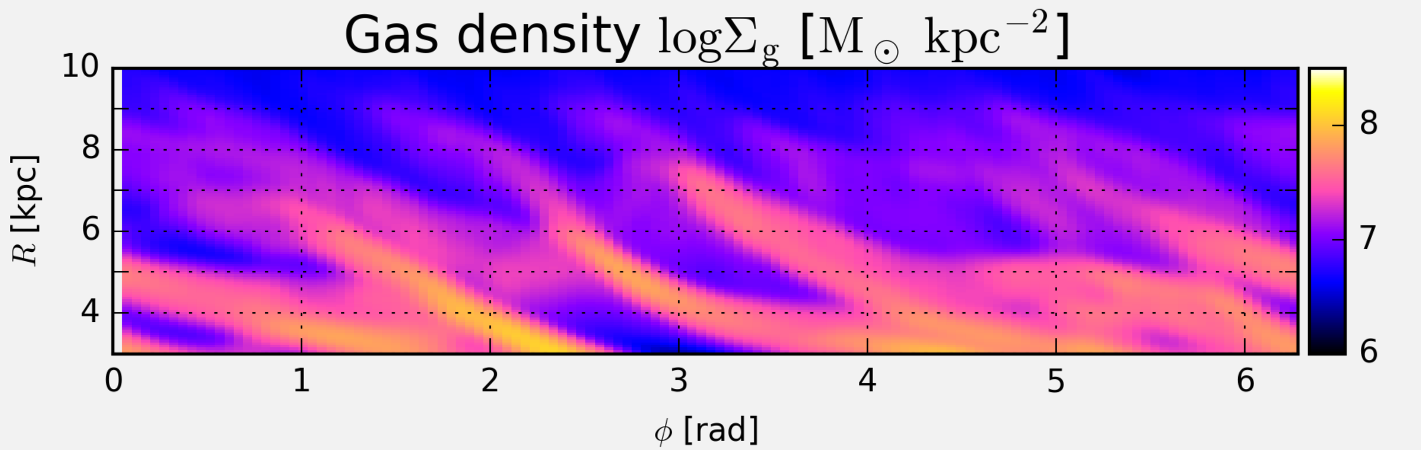
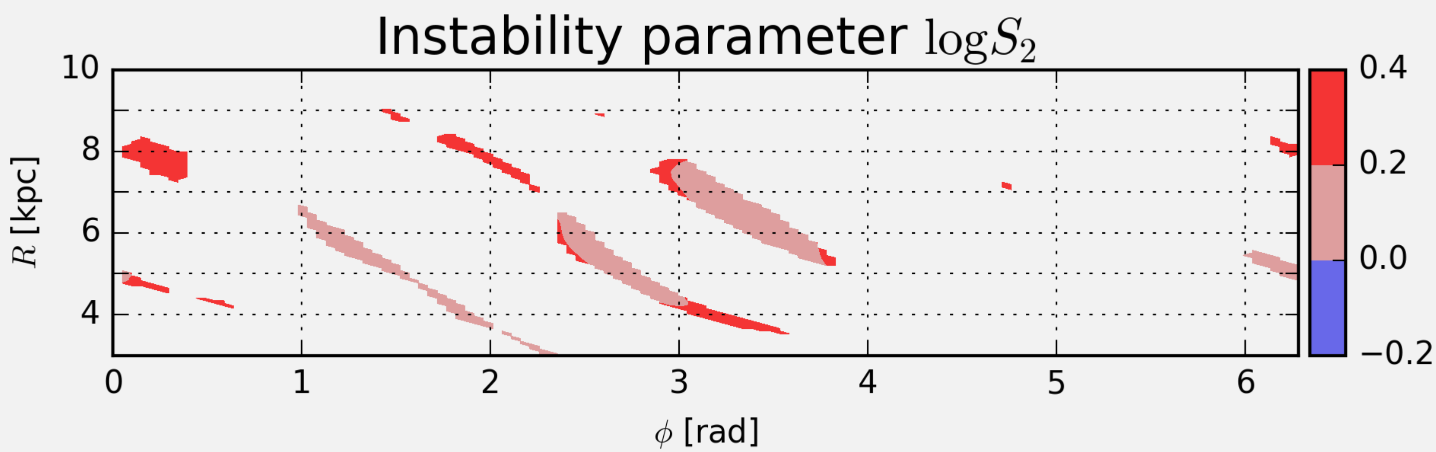




t=280 Myr



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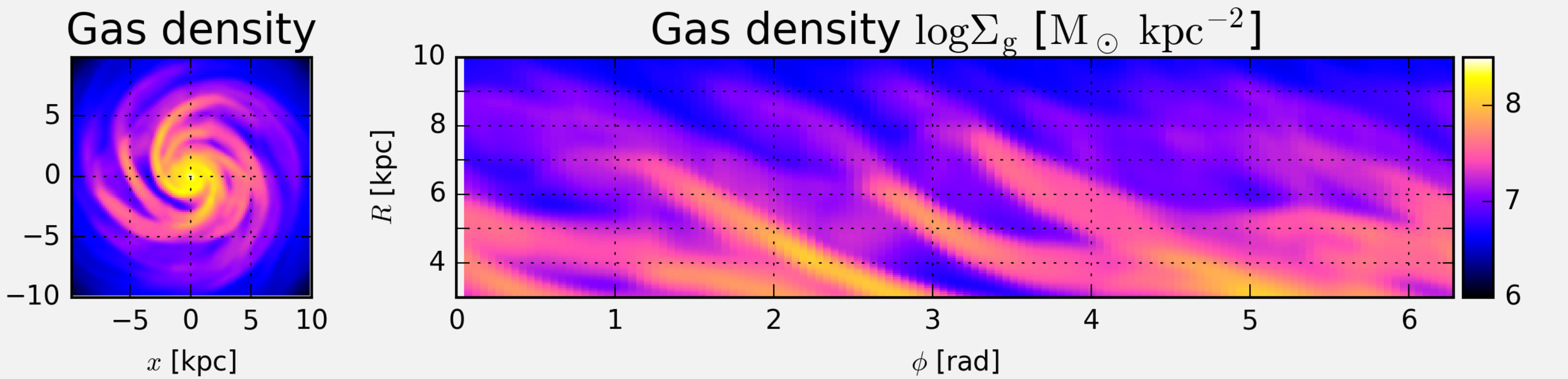
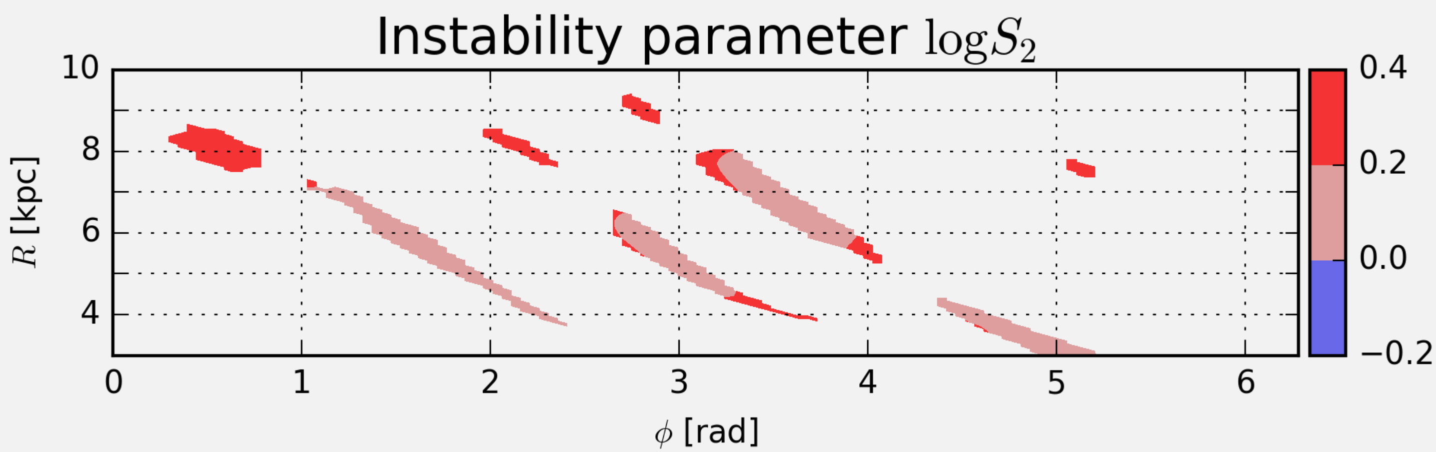


t=290 Myr



Demonstration

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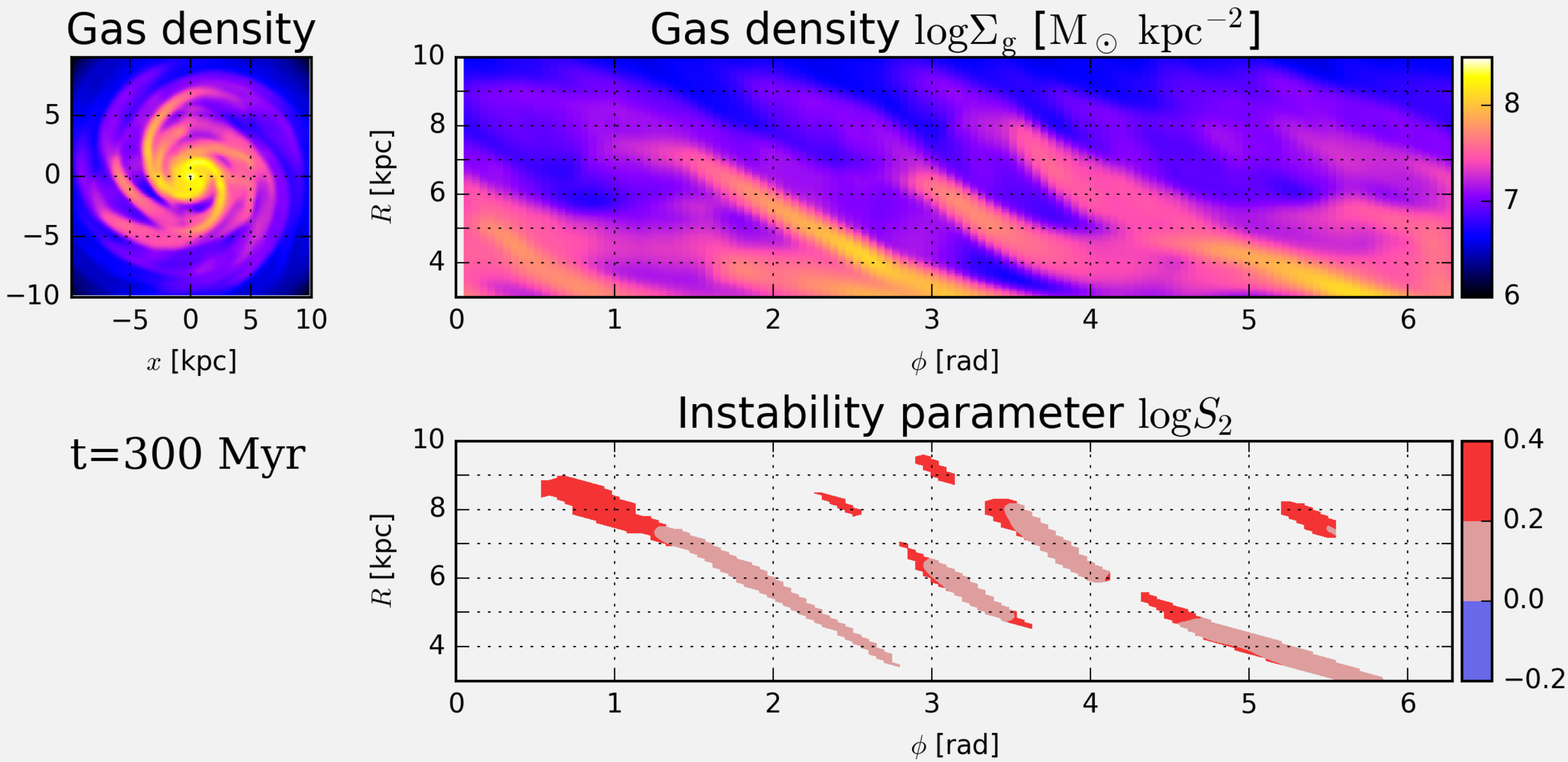

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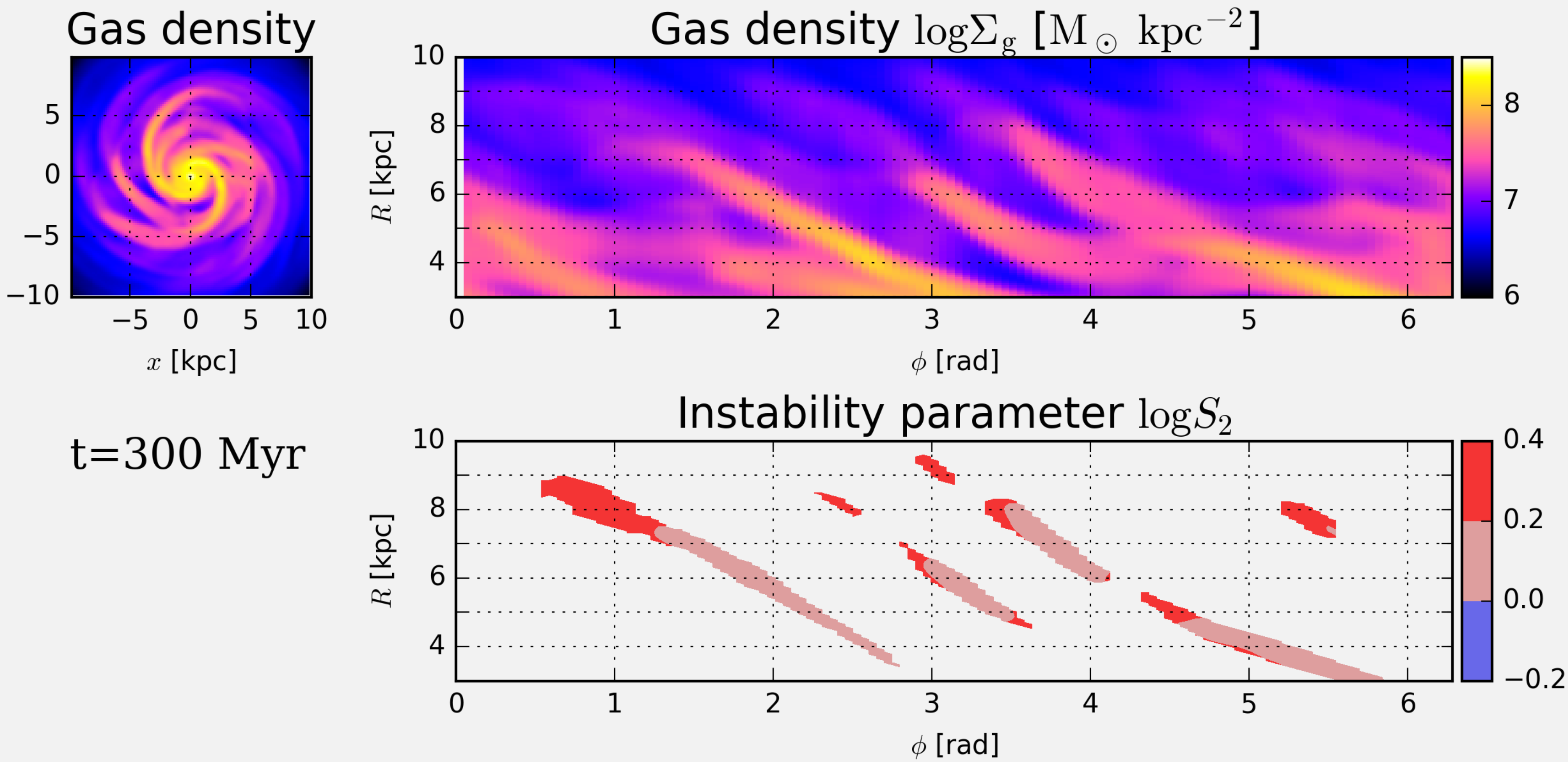


ここまでのまとめ

- 銀河の渦状腕の分裂は、線形摂動解析で非常にうまく記述できる。
  - 解析的に分裂不安定の物理条件を導出することに成功。
  - シミュレーションの結果に適用し、渦状腕の分裂を予測することができる。

➡ 今後実際の銀河の観測データに適用

- 渦状腕の分裂は、クランプの形成メカニズムの候補になりうる。

軸対称磁場による銀河渦状腕の不安定化とクランプ形成

井上 茂樹

吉田 直紀

(Kavli IPMU / U.Tokyo)

MNRAS 474, 3466 (2018)

arXiv:1807.02988

How does magnetic field affect spiral arm?

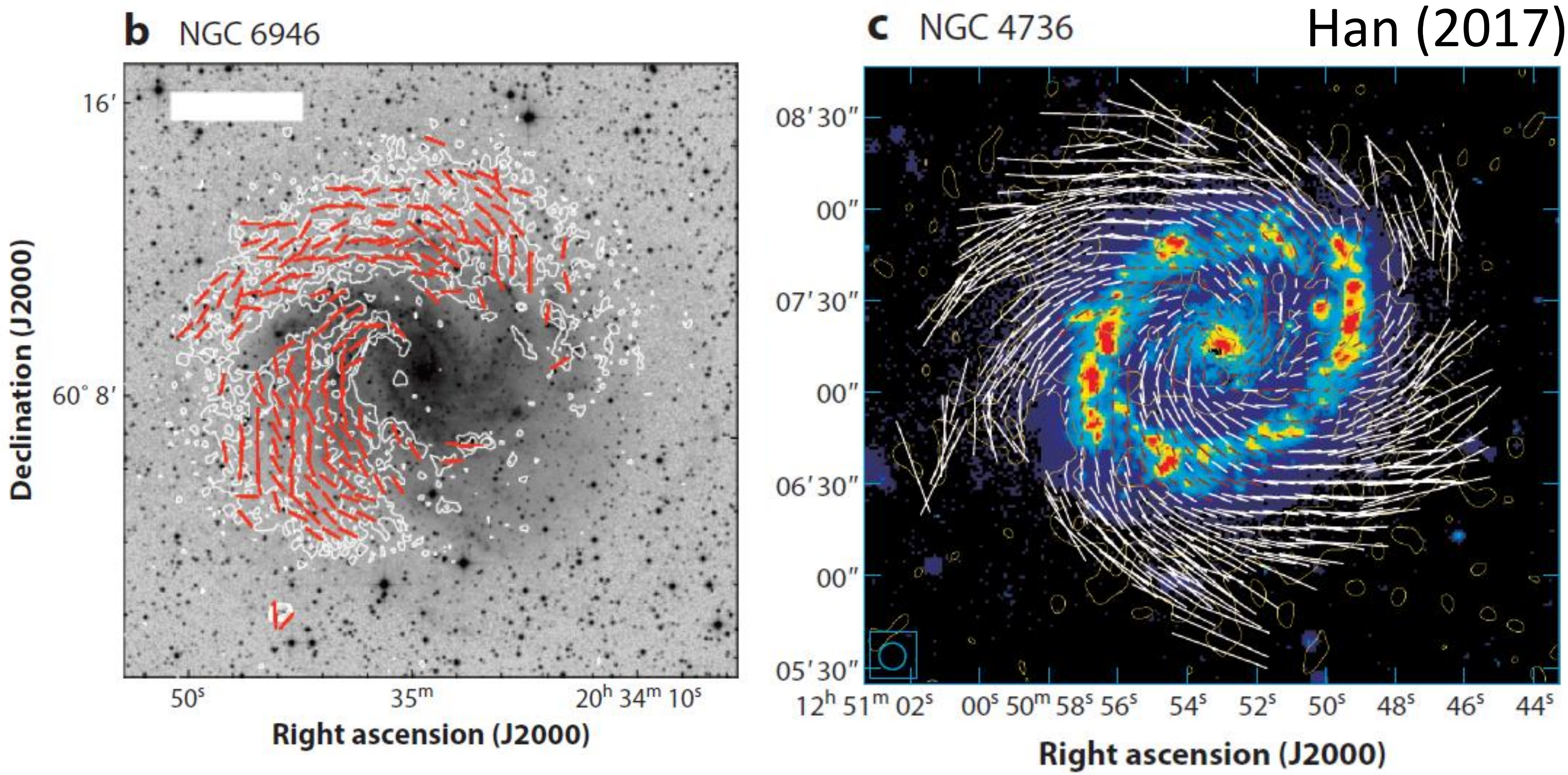
Does magnetic field stabilize or destabilize the arm?

If it destabilizes, it may drive clump formation with high SFR.

Toroidal magnetic fields in a disc galaxy

- Galactic B-fields are approximately toroidal and/or following spiral arms.
- $B_\theta \sim 1\ \mu$G around the sun (e.g. Inoue & Tabara 1981, Mouschovias 1983).

Han (2017)



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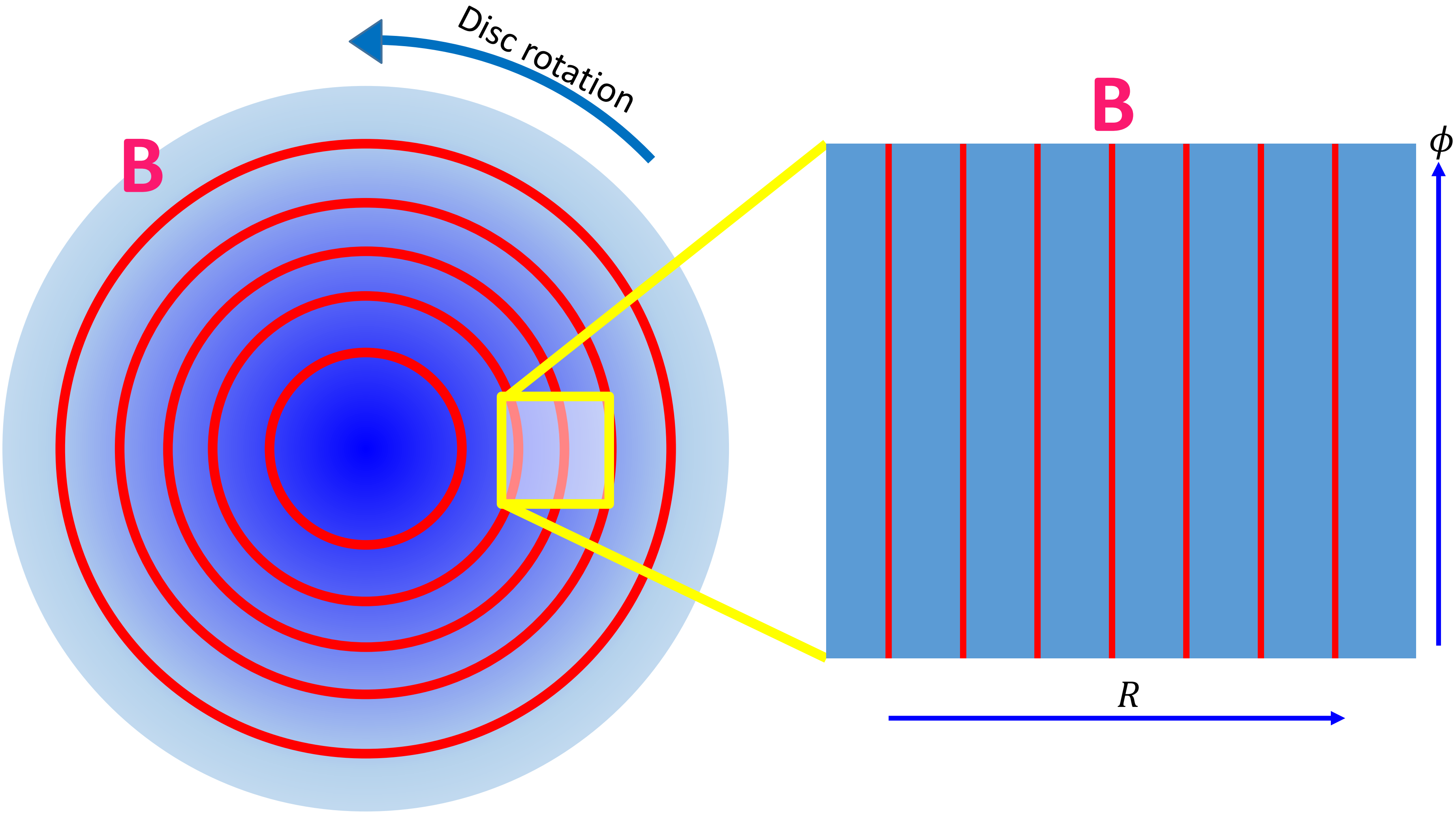
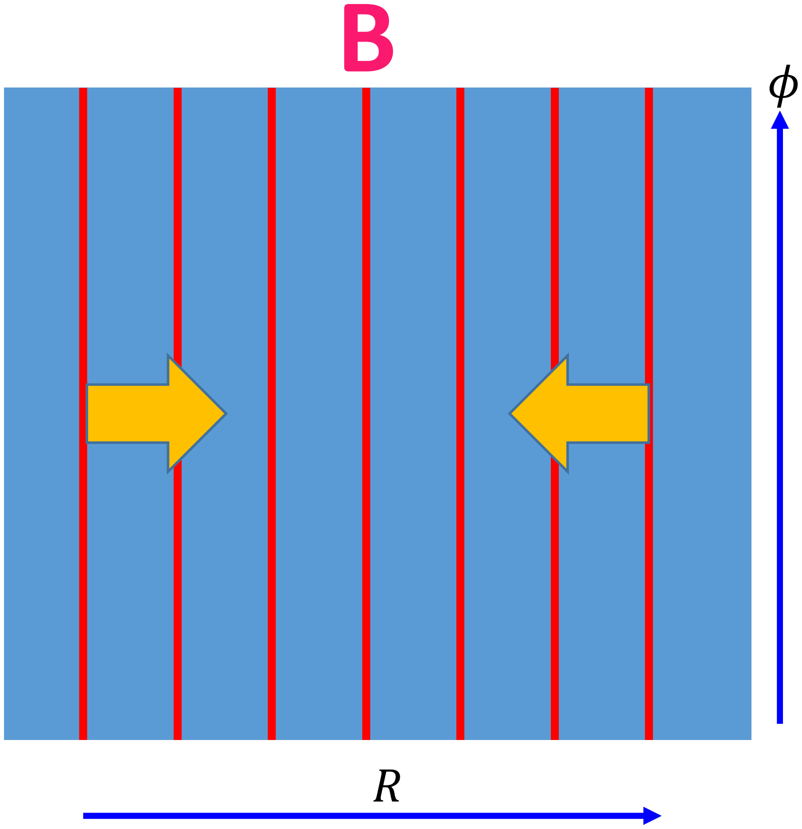


Toroidal magnetic fields in a disc galaxy

- Galactic B-fields are approximately toroidal and/or following spiral arms.

- Radial perturbations



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

Toroidal magnetic fields in a disc galaxy

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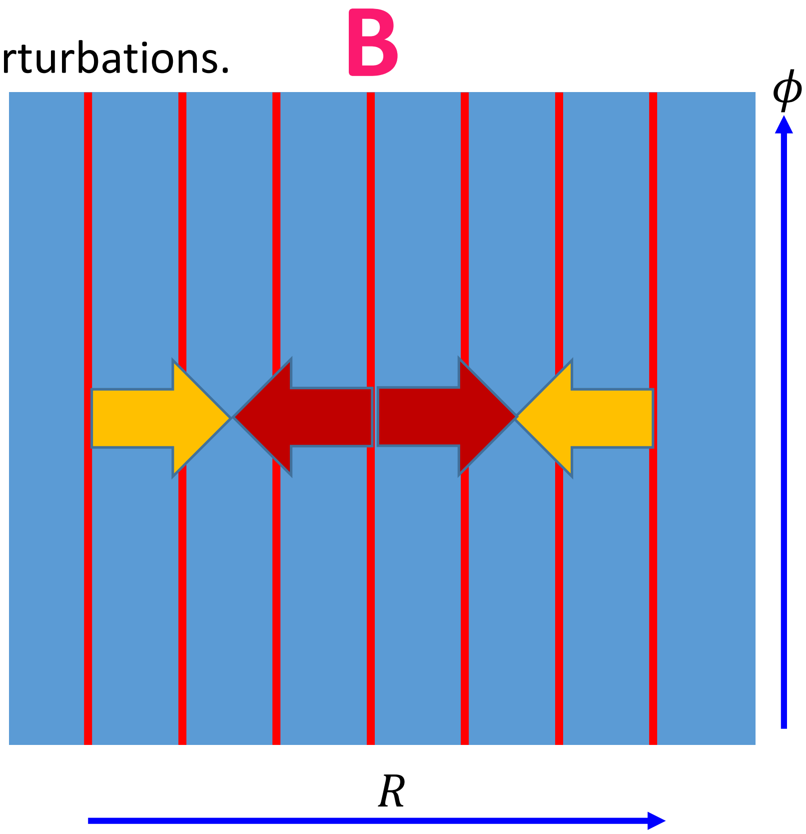
  - The magnetic pressure work against the perturbations.

Toroidal B-fields can stabilize radial perturbations by magnetic pressure.



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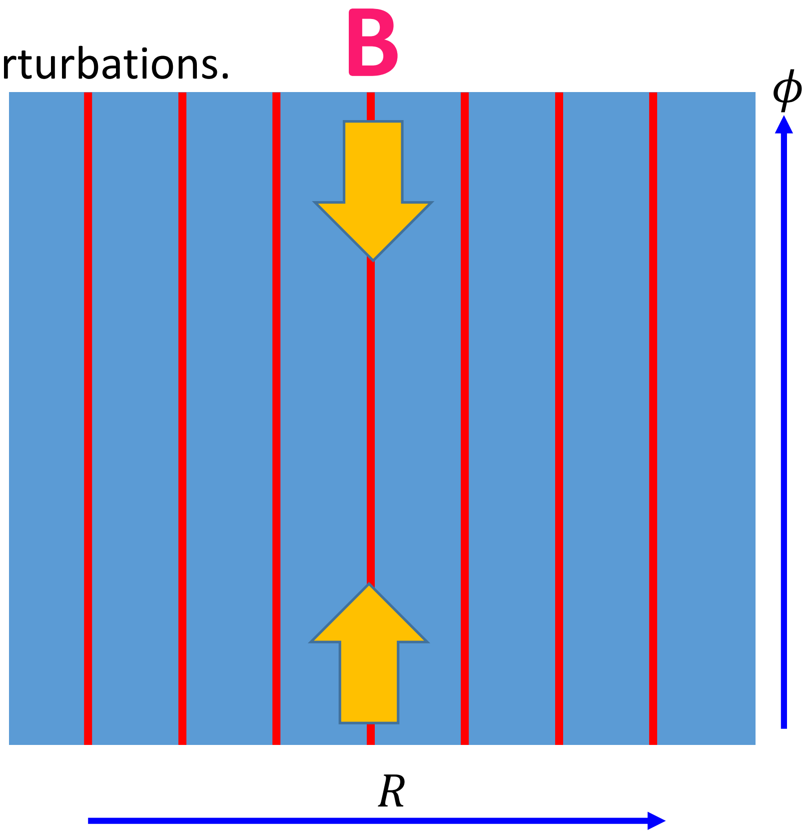
  - The B-fields do nothing in ϕ-direction.



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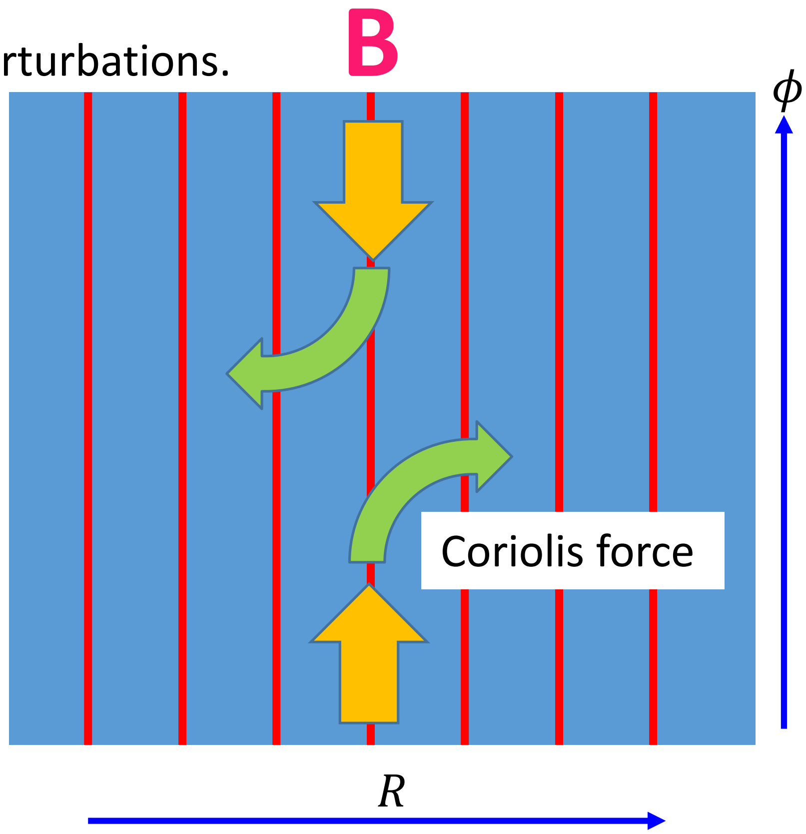

- Azimuthal perturbations
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Toroidal magnetic fields in a disc galaxy

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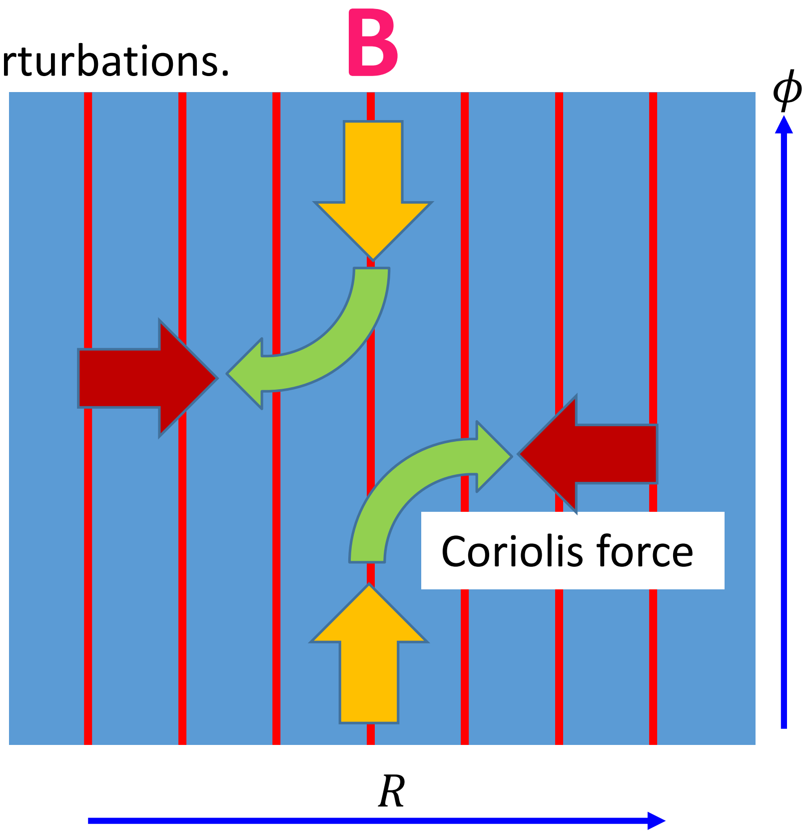
  - But, work against Coriolis force.

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



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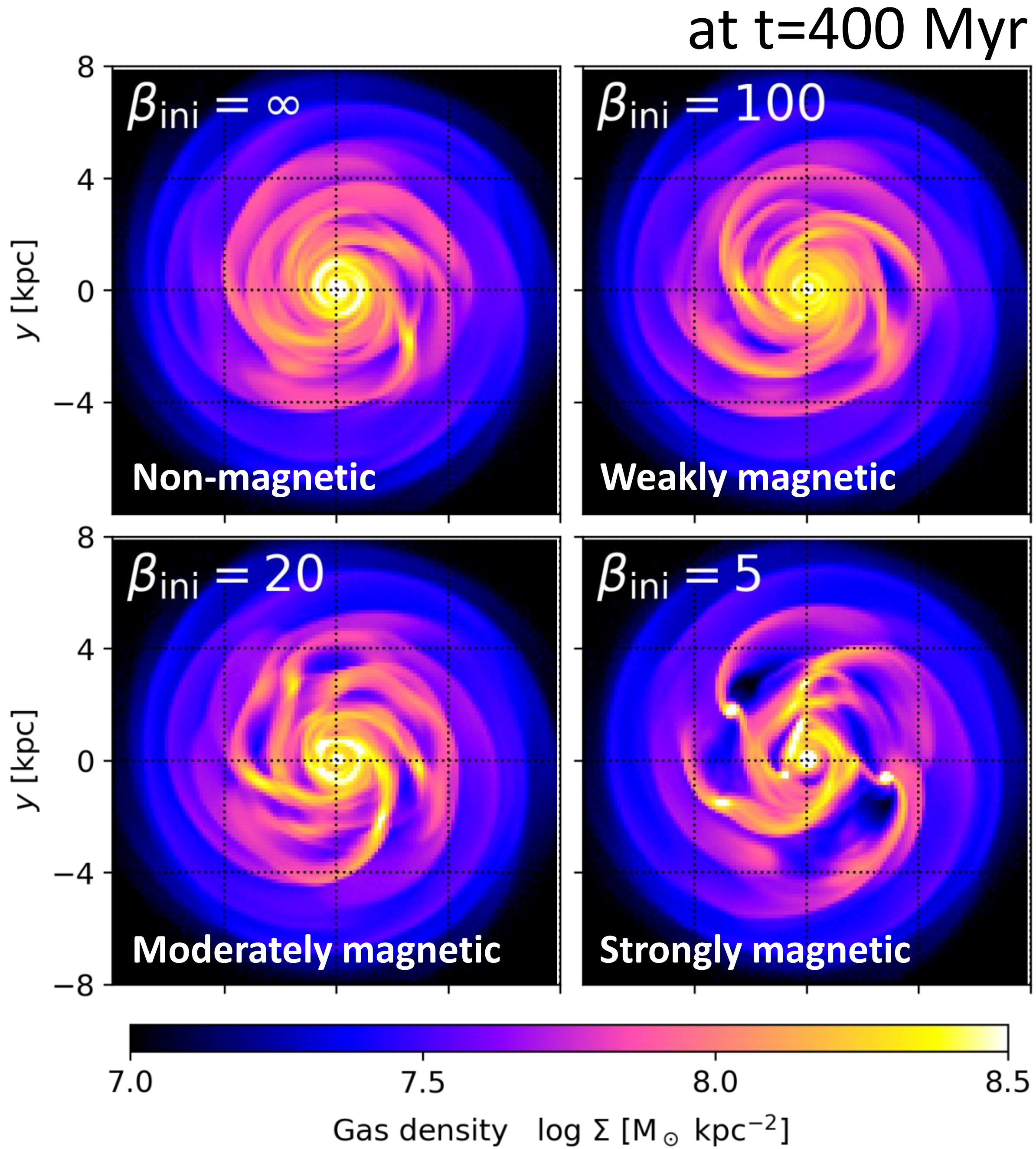
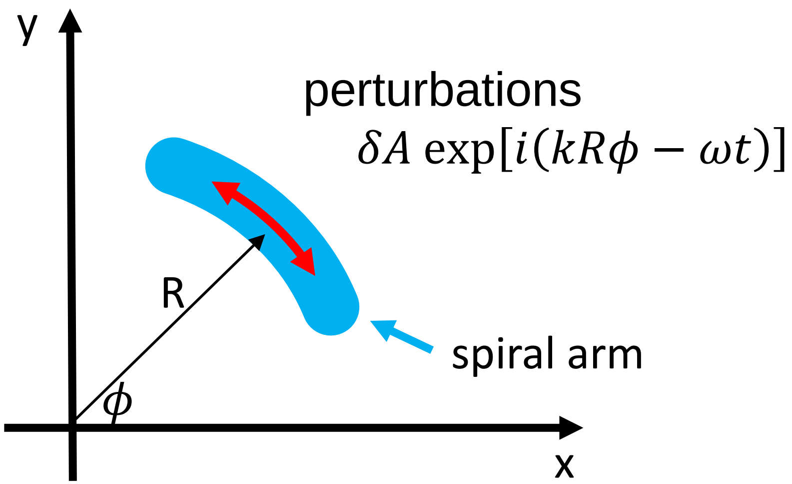
Ideal MHD simulations



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
  $\Upsilon = 1.4 W \Sigma$ (**Gaussian**).

continuity: $$\frac{\partial}{\partial t}\Sigma + \nabla \cdot (\Sigma \mathbf{v}) = 0,$$

R- and ϕ-momenta: $$\frac{\partial}{\partial t}\mathbf{v} + (\mathbf{v}\cdot\nabla)\,\mathbf{v} = -\frac{1}{\rho}\nabla p - \nabla\Phi - \frac{1}{4\pi\rho}\mathbf{B}\times(\nabla\times\mathbf{B})$$

(**ideal**) Faraday's law: $$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v}\times\mathbf{B})$$

Set-up for the linear perturbation theory

- Now considering…
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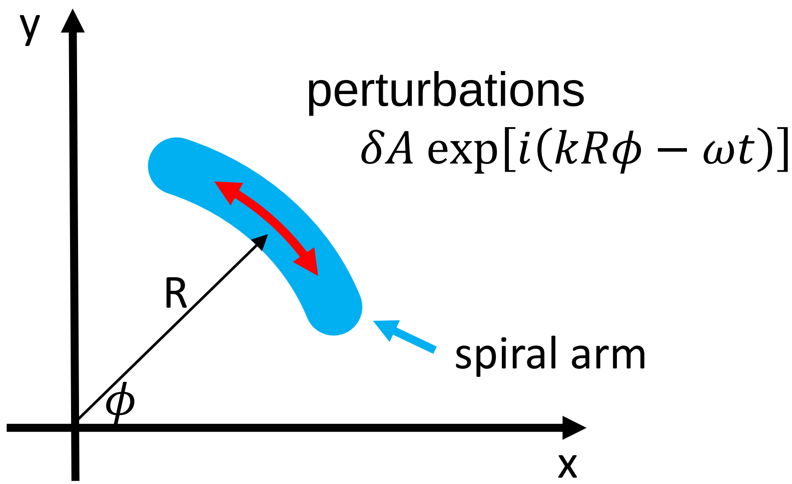

Assuming:

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

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- Replace surface density Σ with line-mass $\Upsilon = 1.4W\Sigma$ (**Gaussian**).

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

R-momentum: $$-i\omega\delta v_R = 2\Omega\delta v_\phi - i\frac{k^2}{\omega}v_\mathrm{A}^2\delta v_R,$$

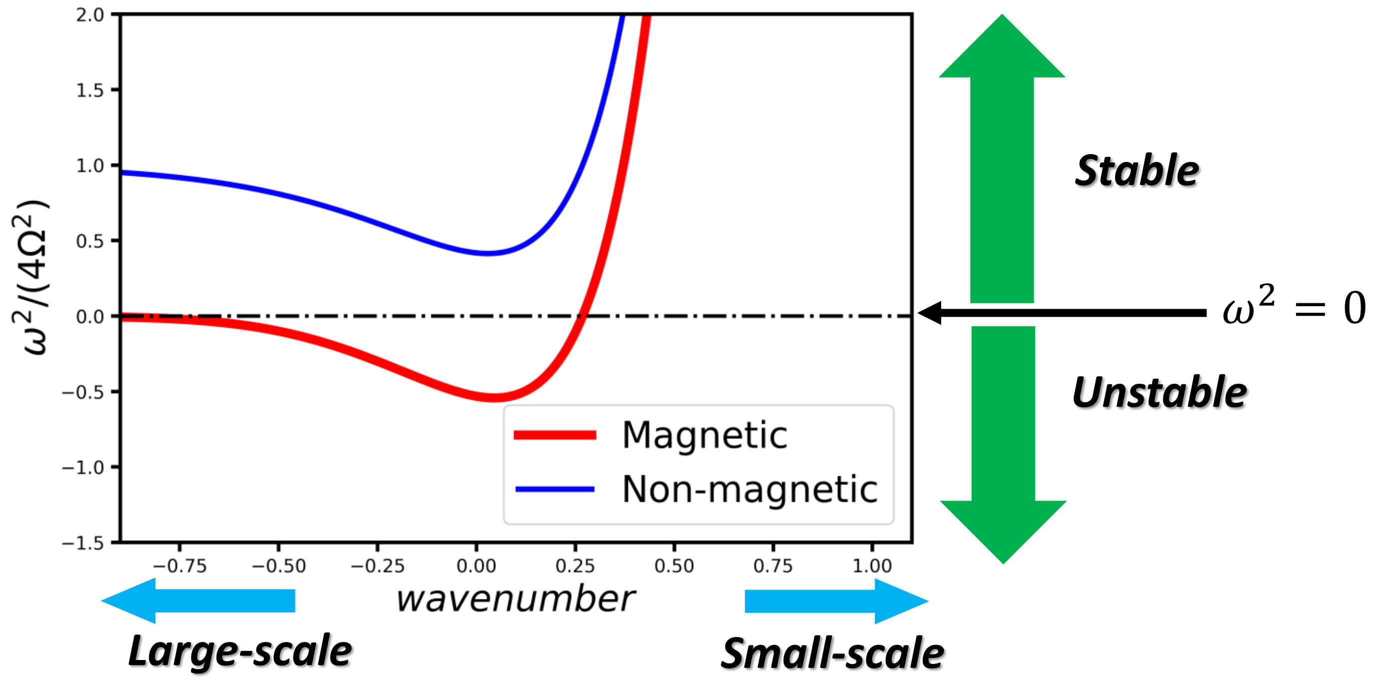
ϕ-momentum: $$-i\omega\delta v_\phi = -2\Omega\delta v_R - ik\frac{c_s^2}{\Upsilon}\delta\Upsilon - ik\delta\Phi.$$

The dispersion relation of MHD

- One can obtain the dispersion relation for the perturbations,

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

Thermal pressure — Self-gravity — Coriolis force — Magnetics



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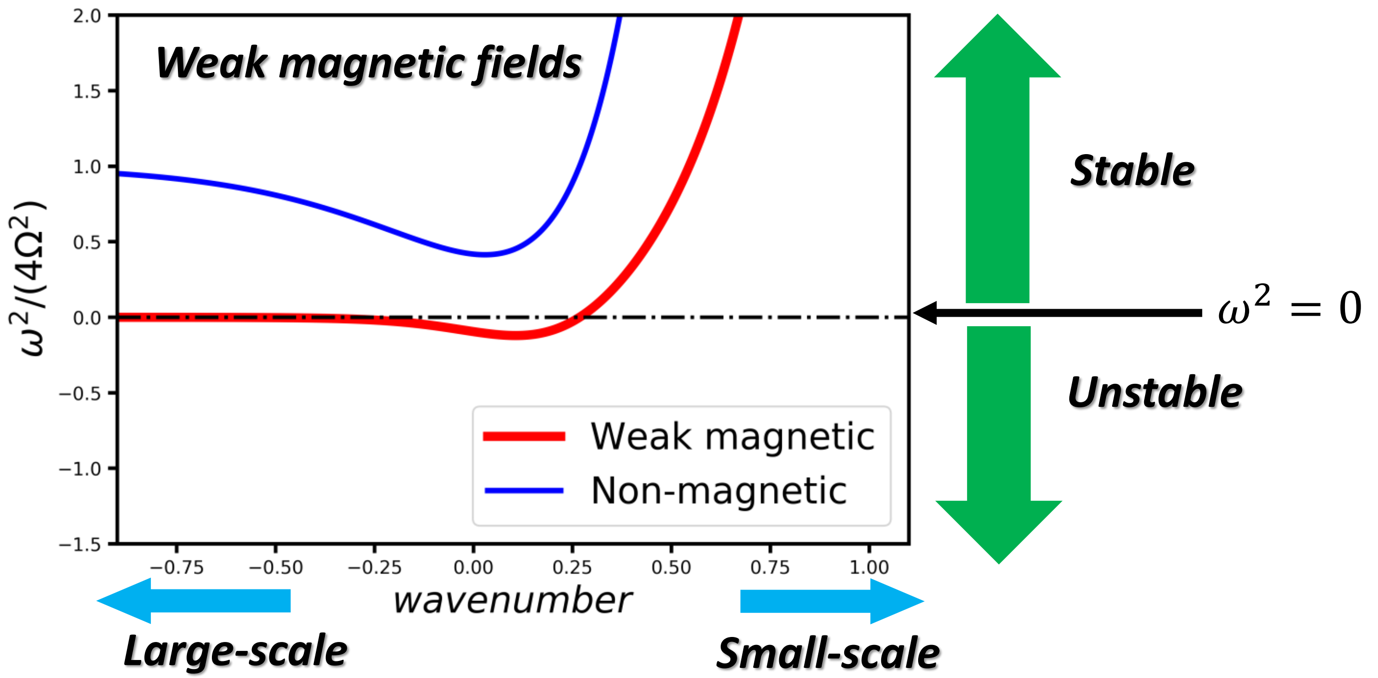

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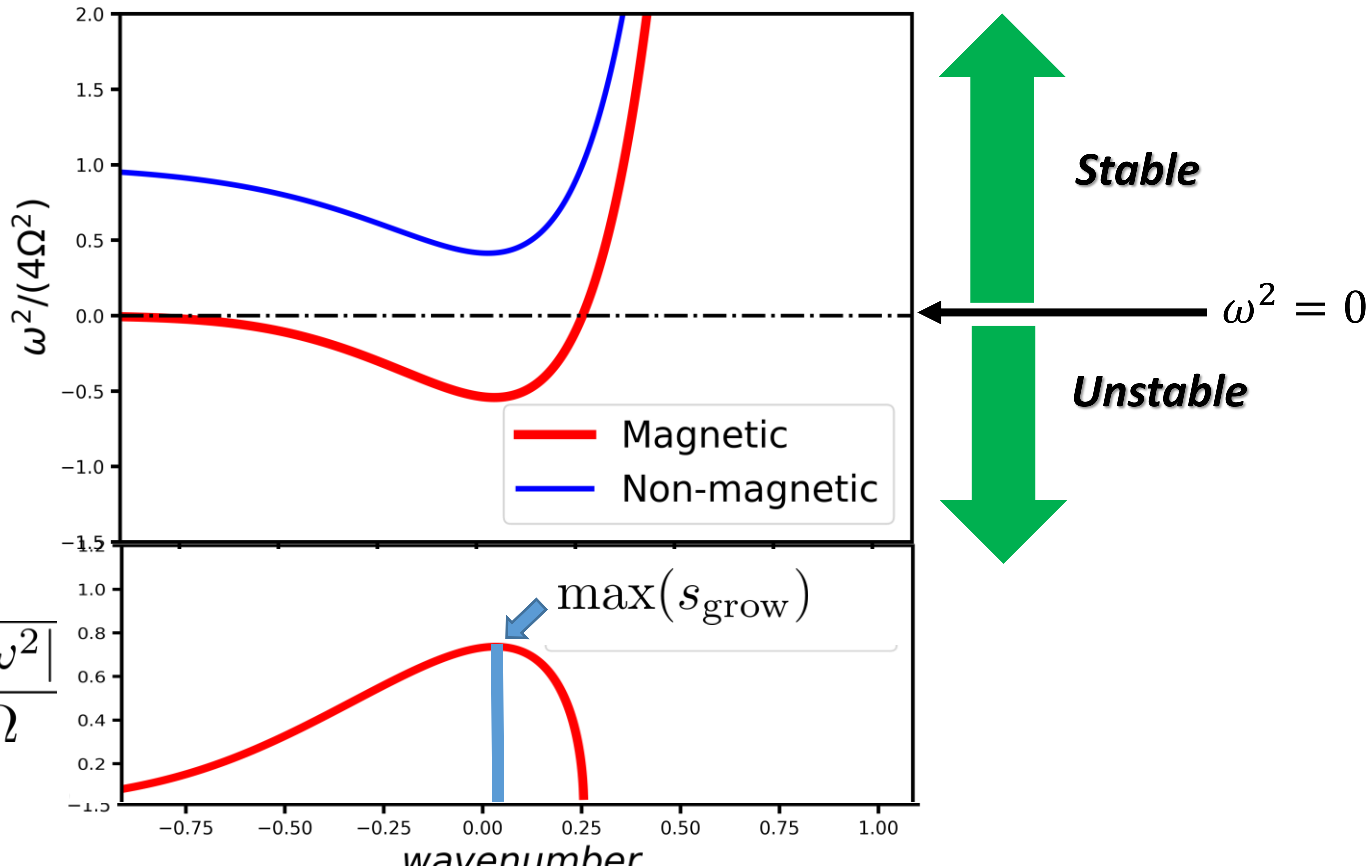
Thermal pressure (c_s^2) — Self-gravity ($\pi G \Upsilon f(kW)$) — Coriolis force ($\frac{4\Omega^2\omega^2}{\omega^2 - k^2 v_{\mathrm{A}}^2}$) — Magnetics ($k^2 v_{\mathrm{A}}^2$)

Growth rate

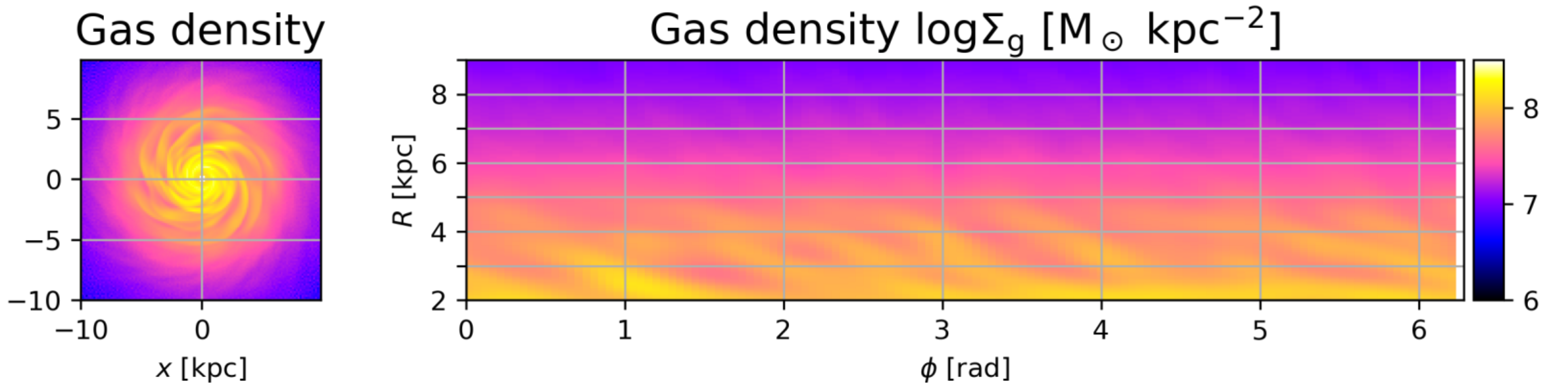
$$s_{\mathrm{grow}} = \frac{\sqrt{|\omega^2|}}{2\Omega}$$



Demonstration

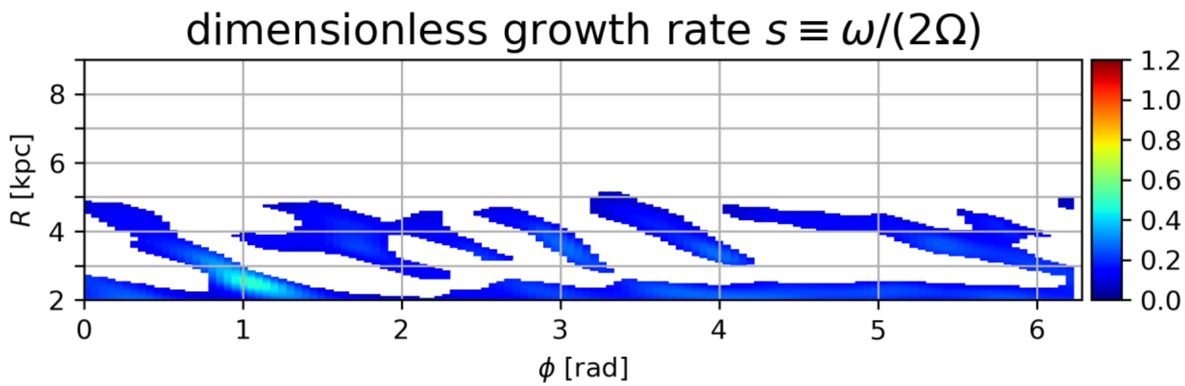
The fragmenting case

$\beta_{ini} = 5$

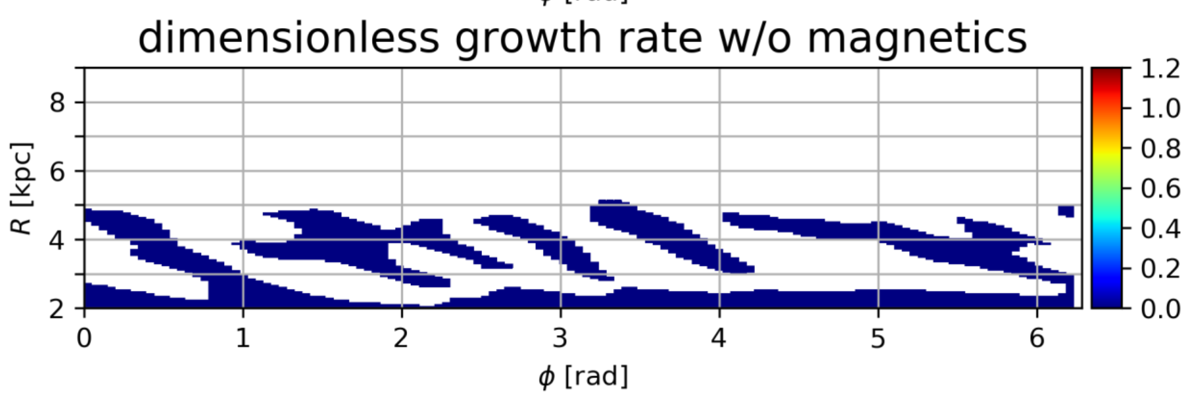


t=140 Myr

Including B-field



Ignoring B-field



Demonstration

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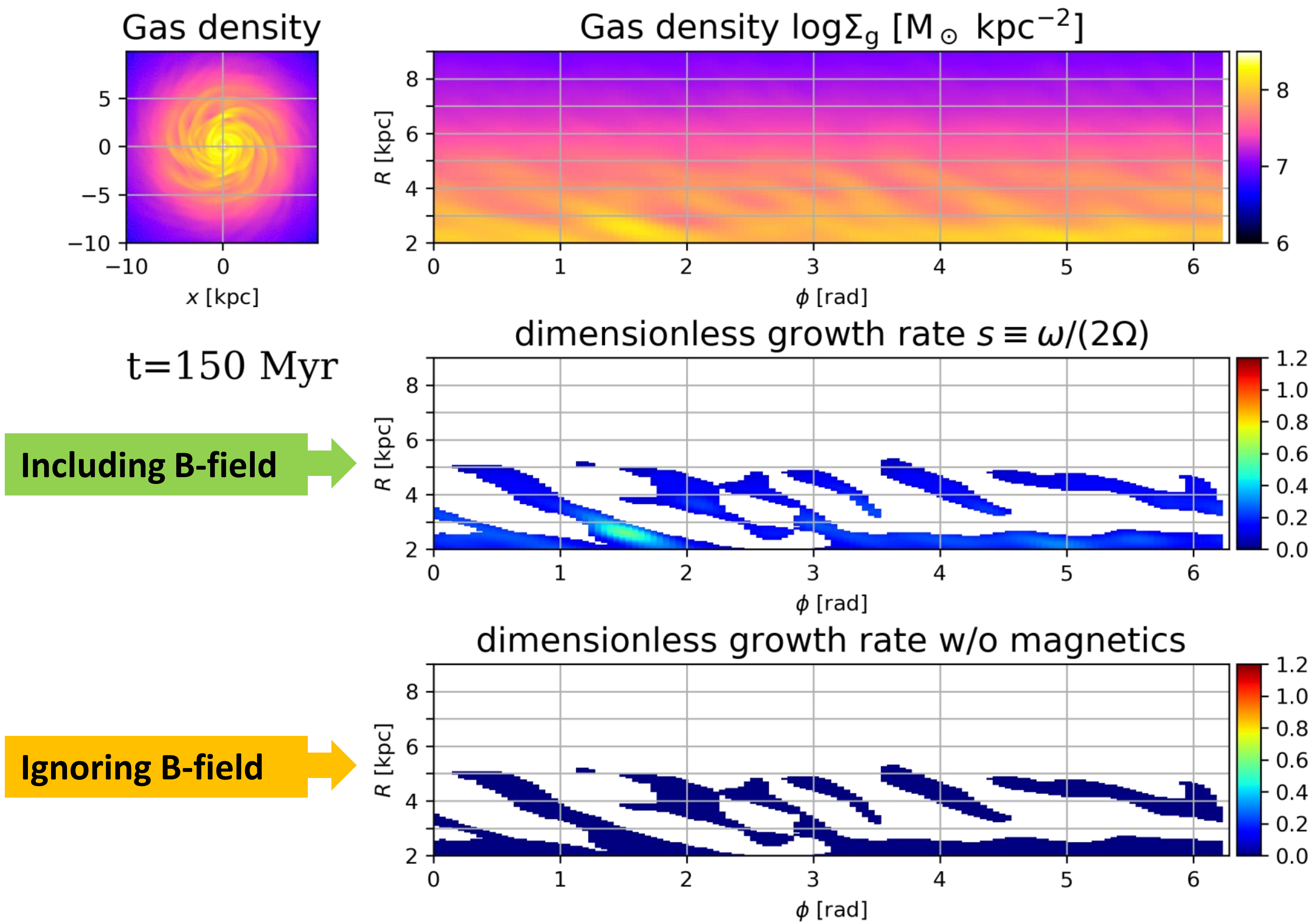

Demonstration

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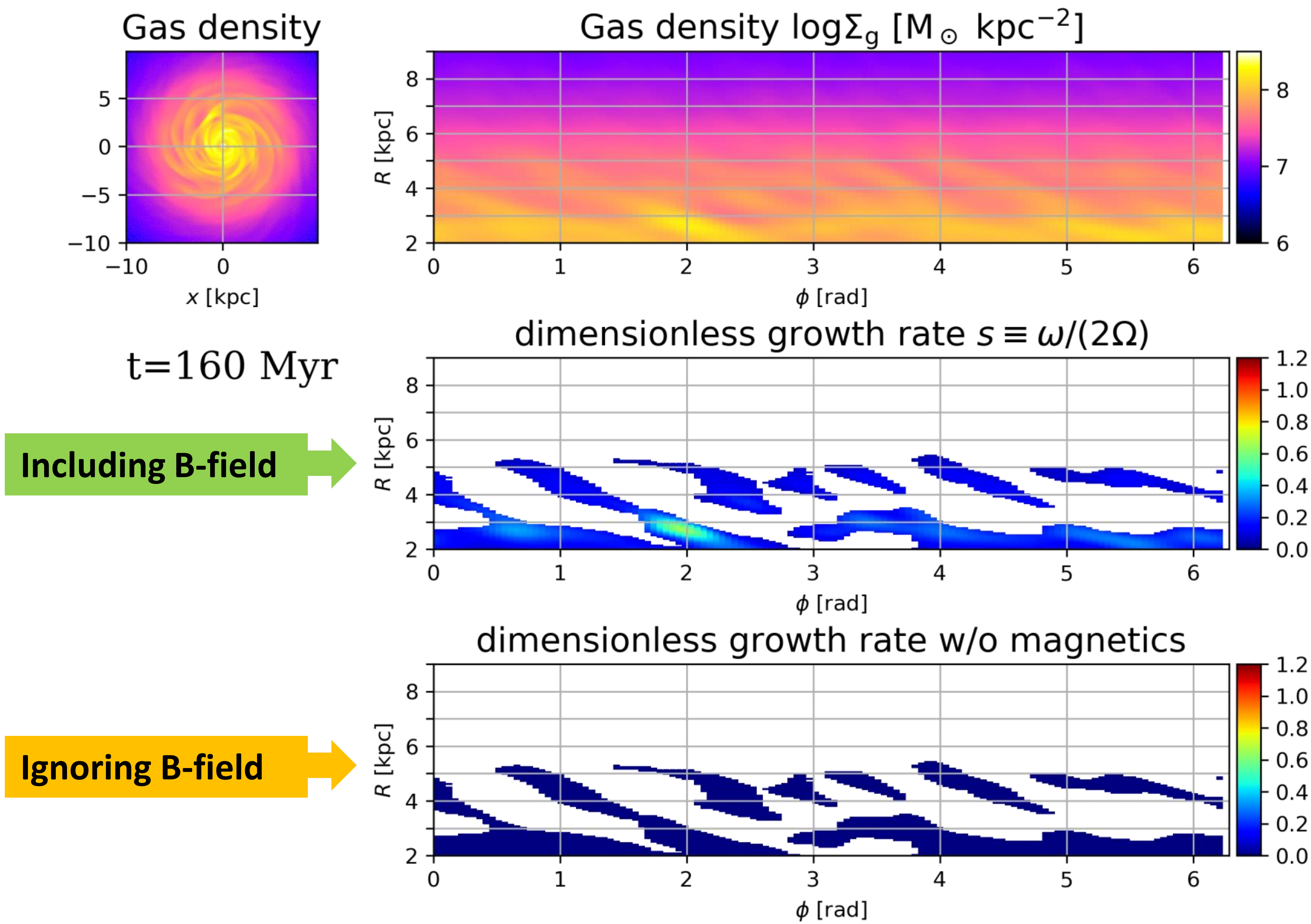


Demonstration

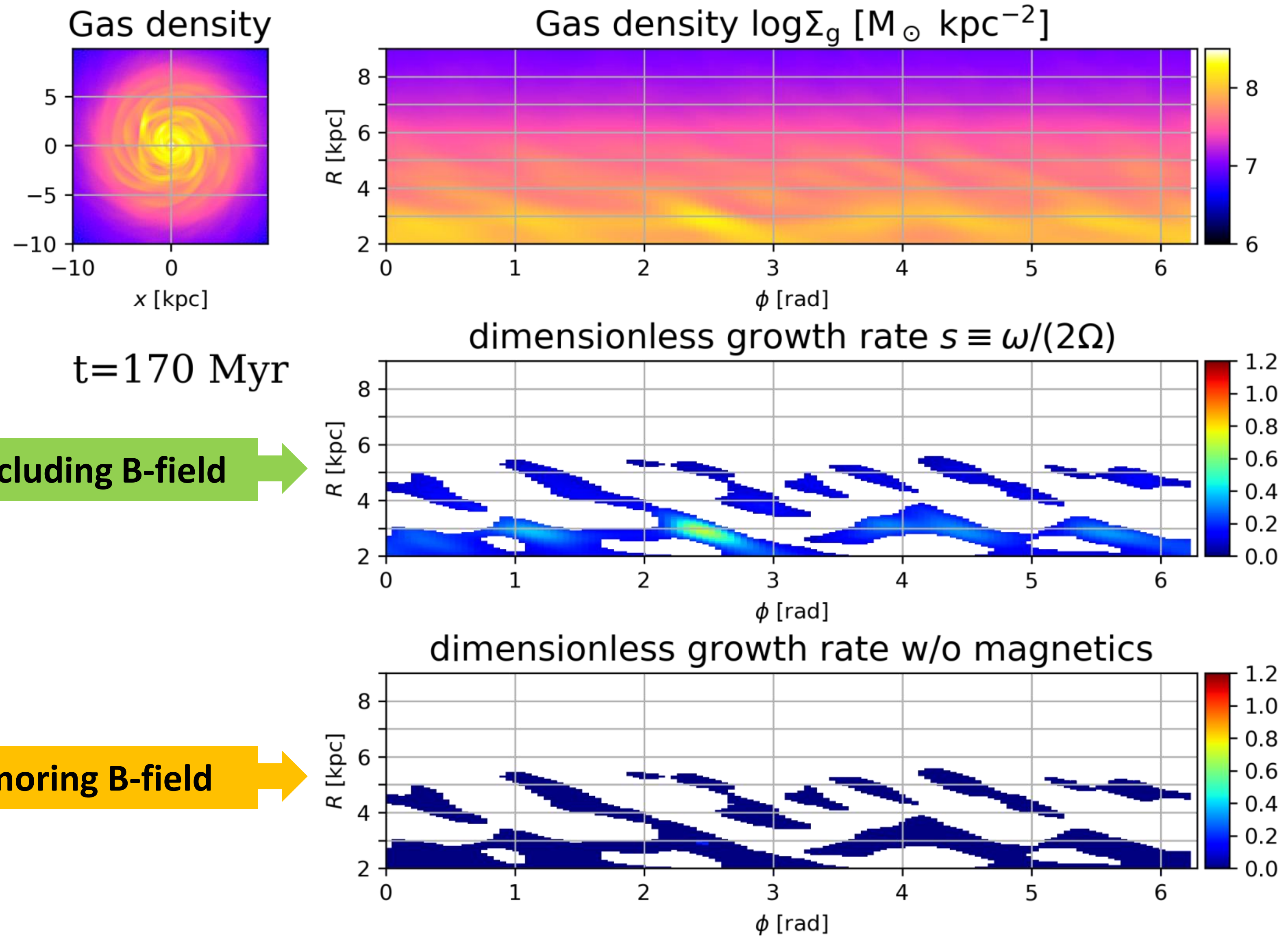
The fragmenting case

$\beta_{ini} = 5$

t=170 Myr

Including B-field

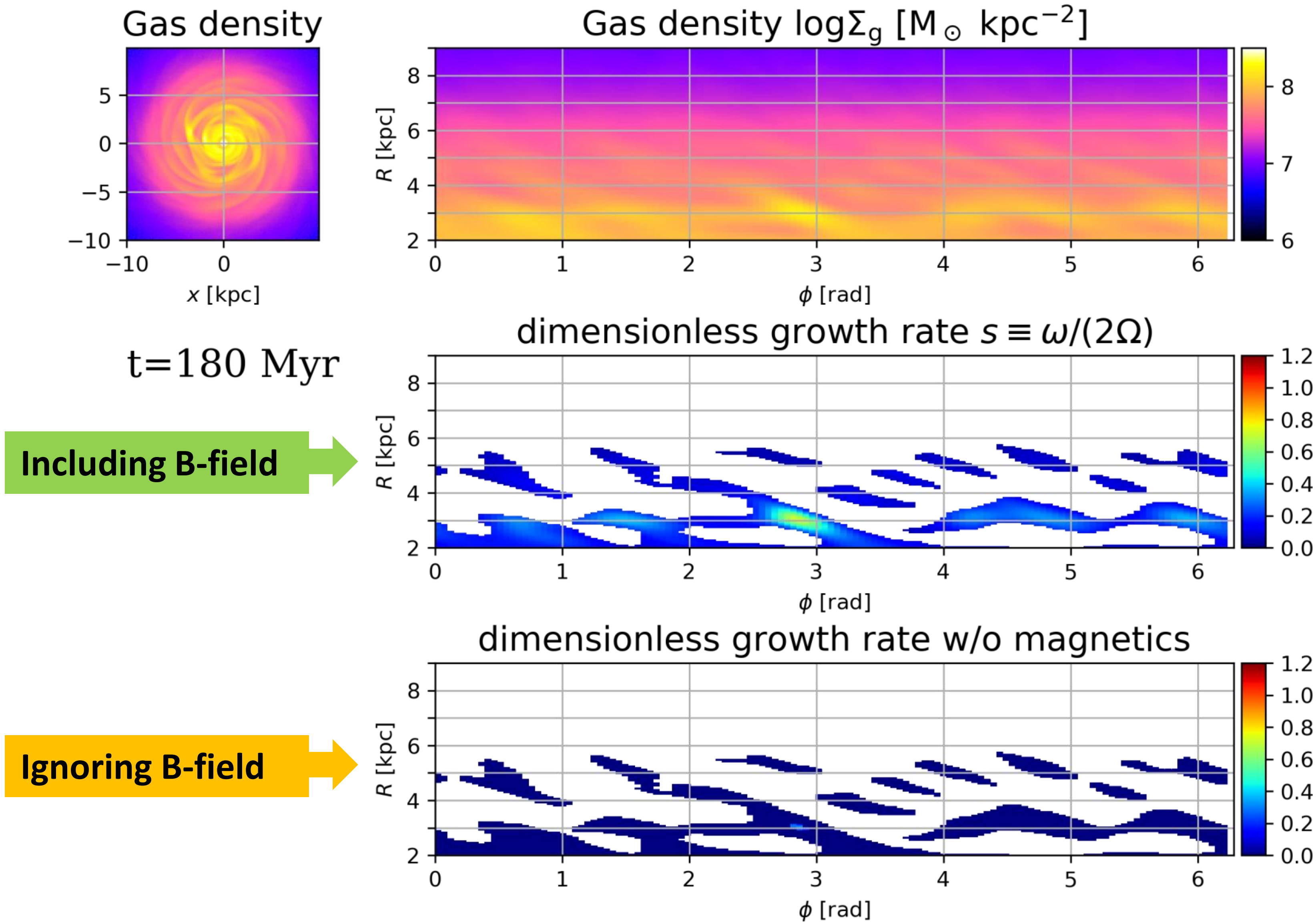
Ignoring B-field



Demonstration

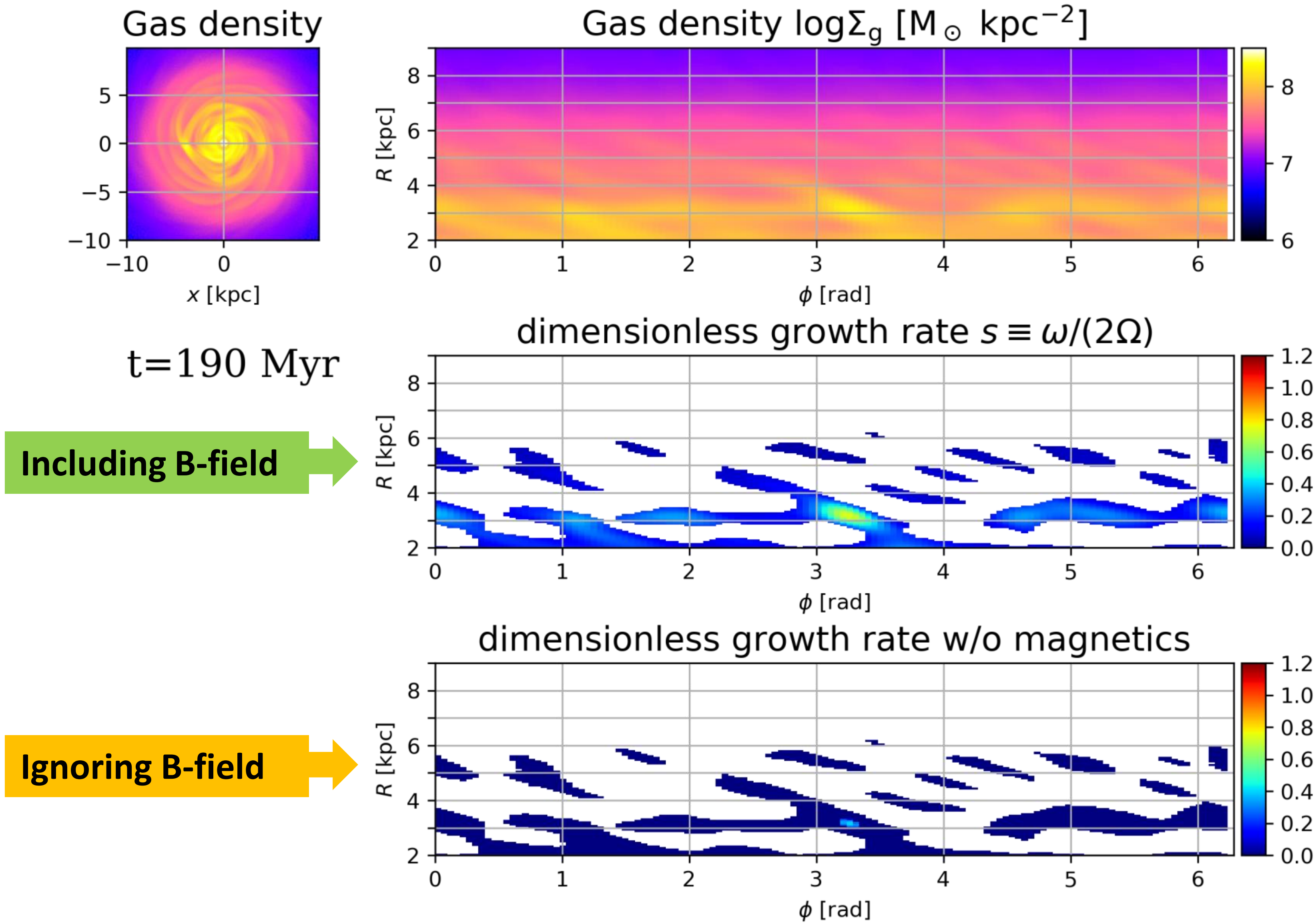
The fragmenting case

$\beta_{ini} = 5$



Demonstration

The fragmenting case $\beta_{ini} = 5$



Demonstration

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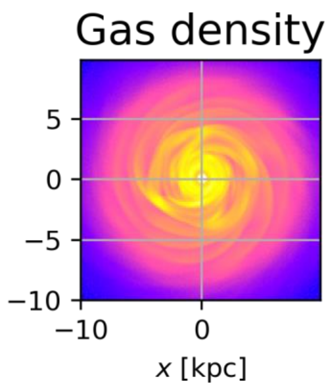
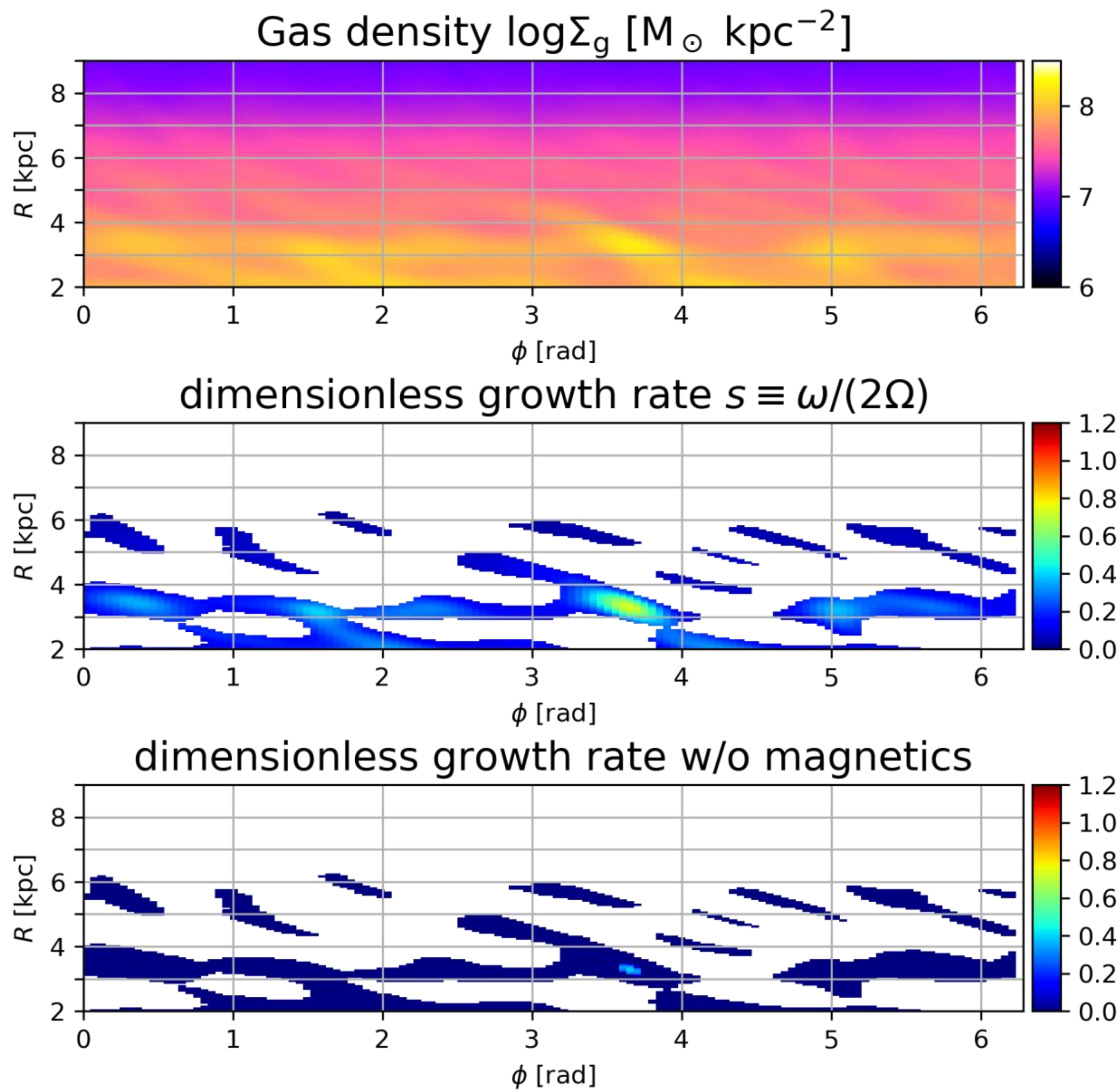


t=200 Myr

Including B-field

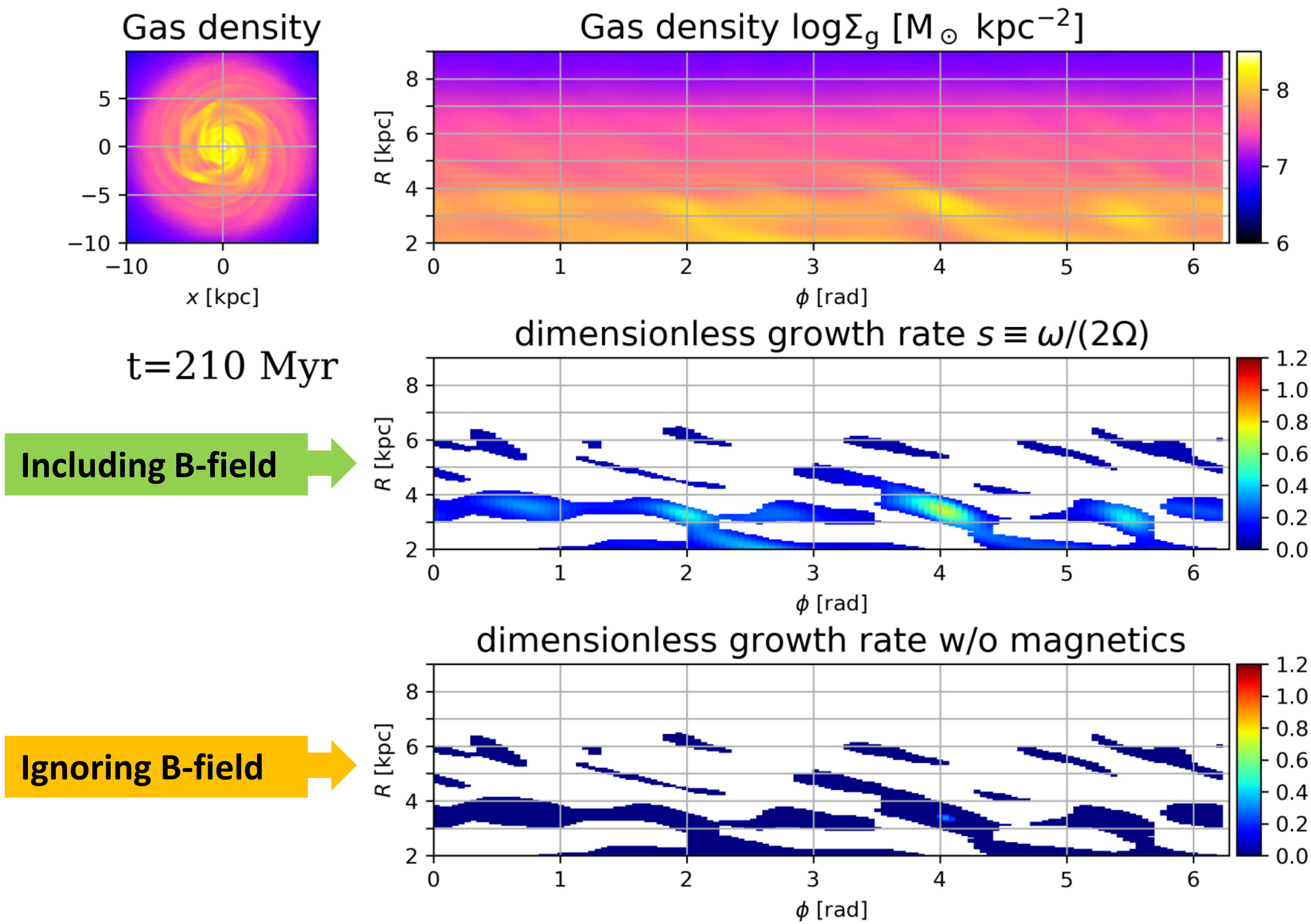
Ignoring B-field



Demonstration

The fragmenting case

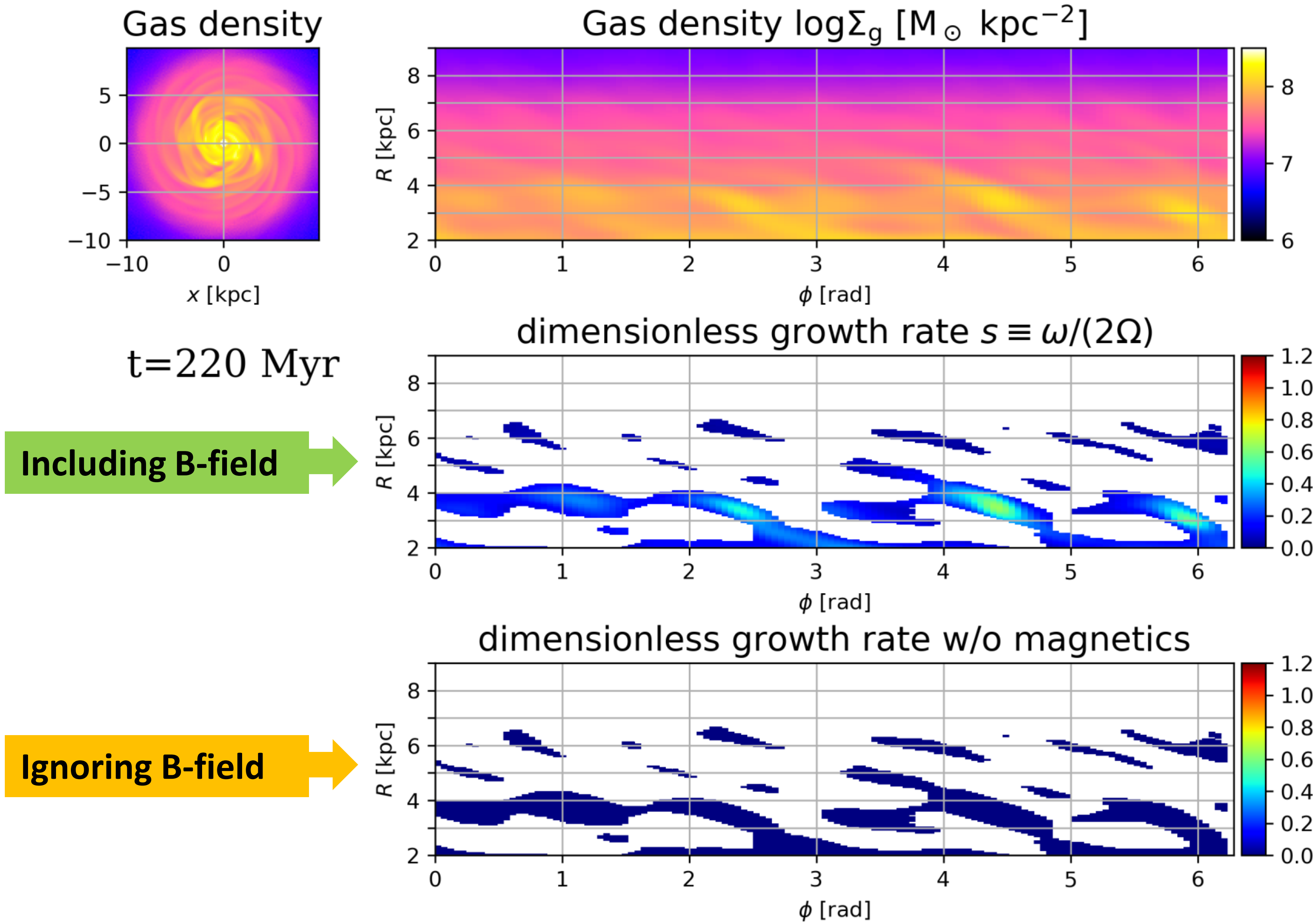
$\beta_{ini} = 5$



Demonstration

The fragmenting case

$\beta_{ini} = 5$



Demonstration

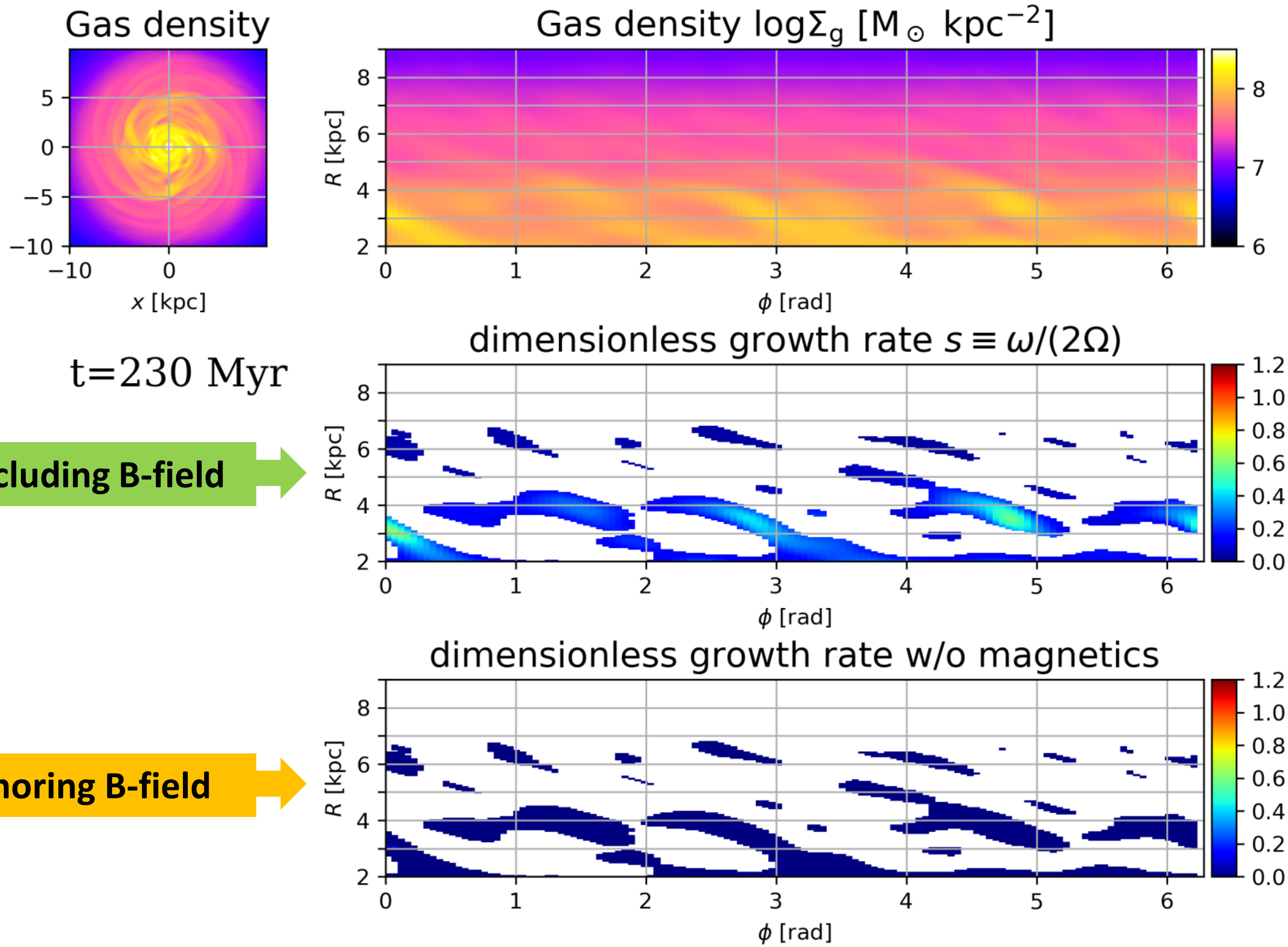
The fragmenting case

$\beta_{ini} = 5$

t=230 Myr

Including B-field

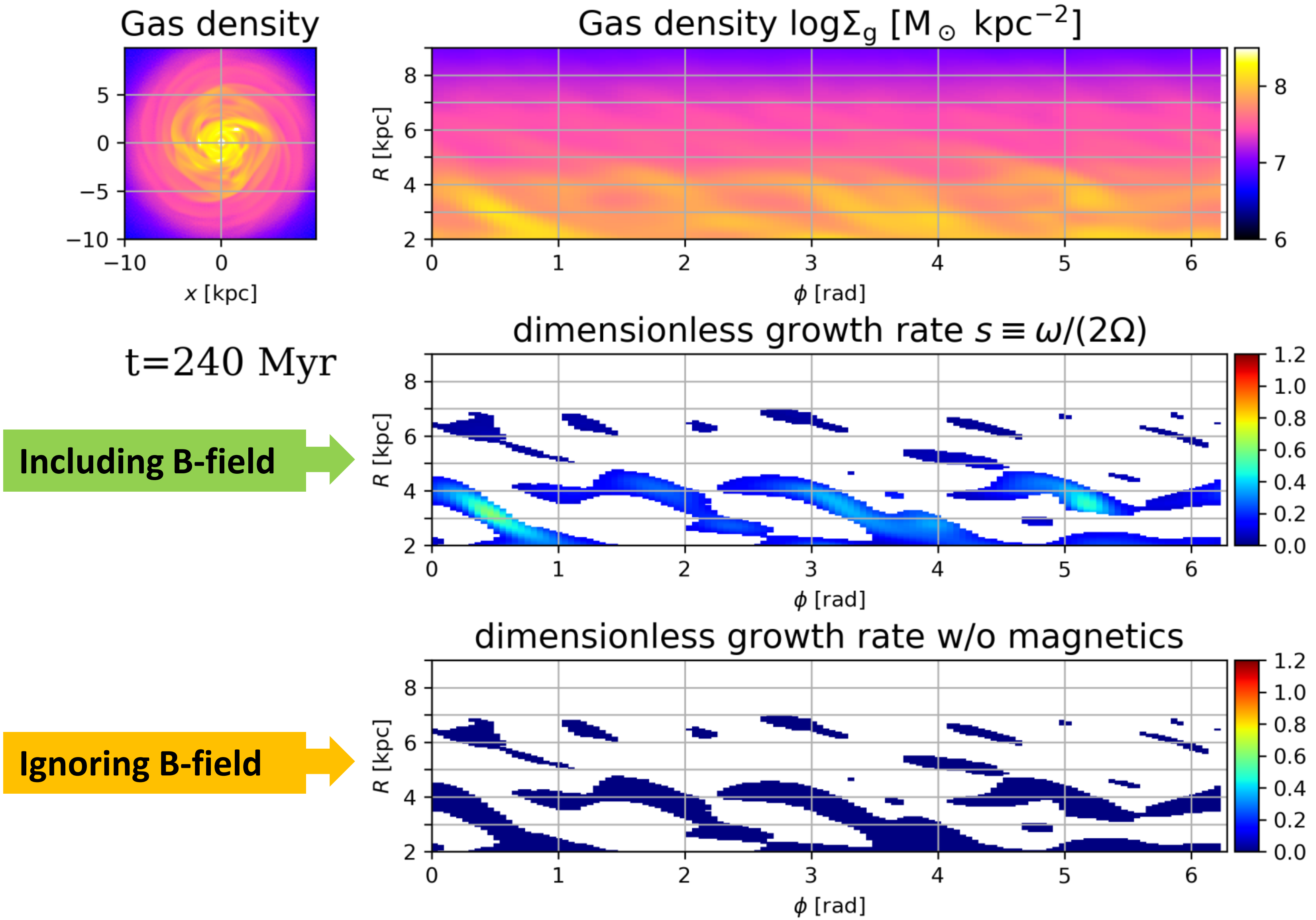
Ignoring B-field



Demonstration

The fragmenting case

$\beta_{ini} = 5$



Demonstration

The fragmenting case

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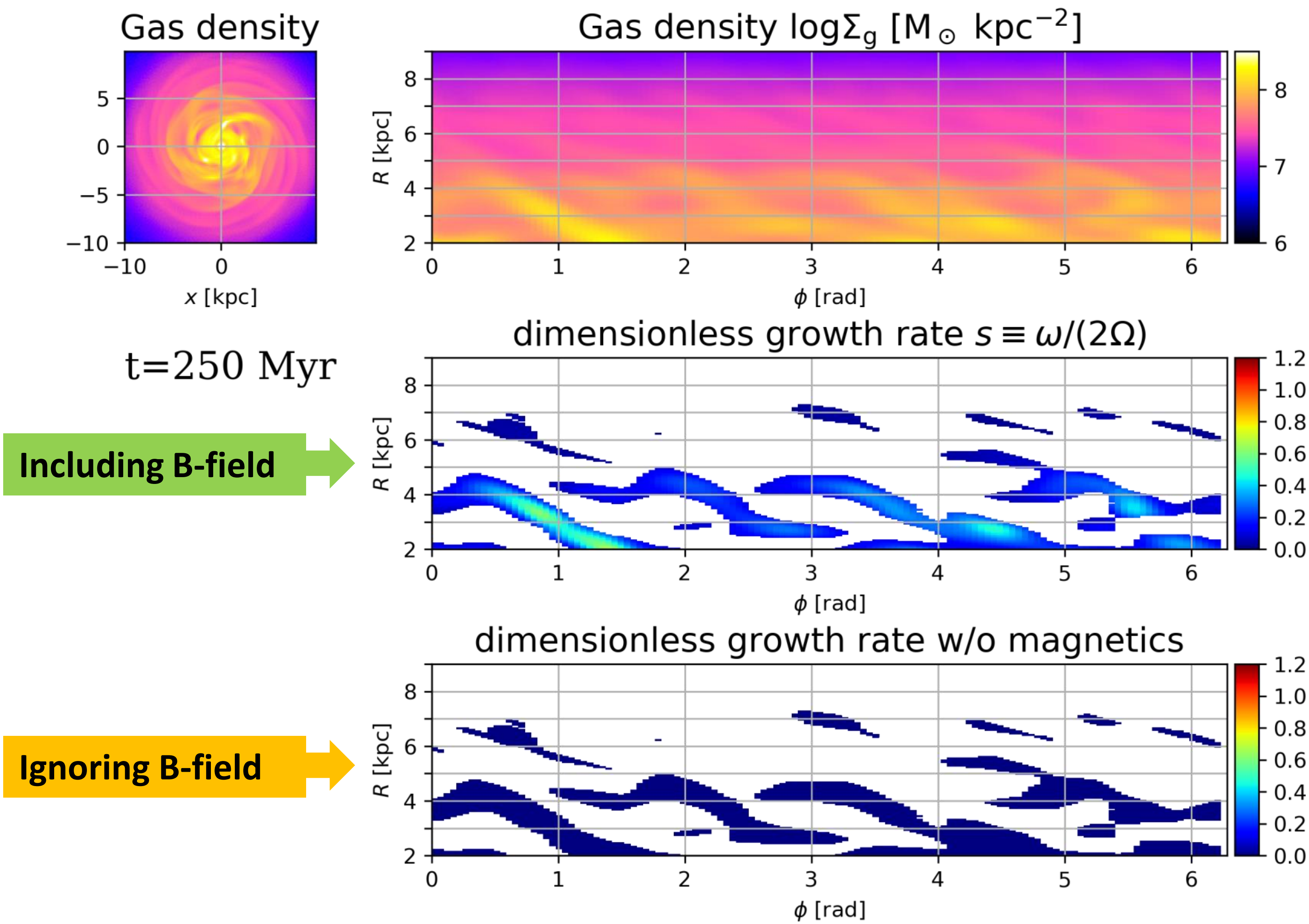

Demonstration

The fragmenting case

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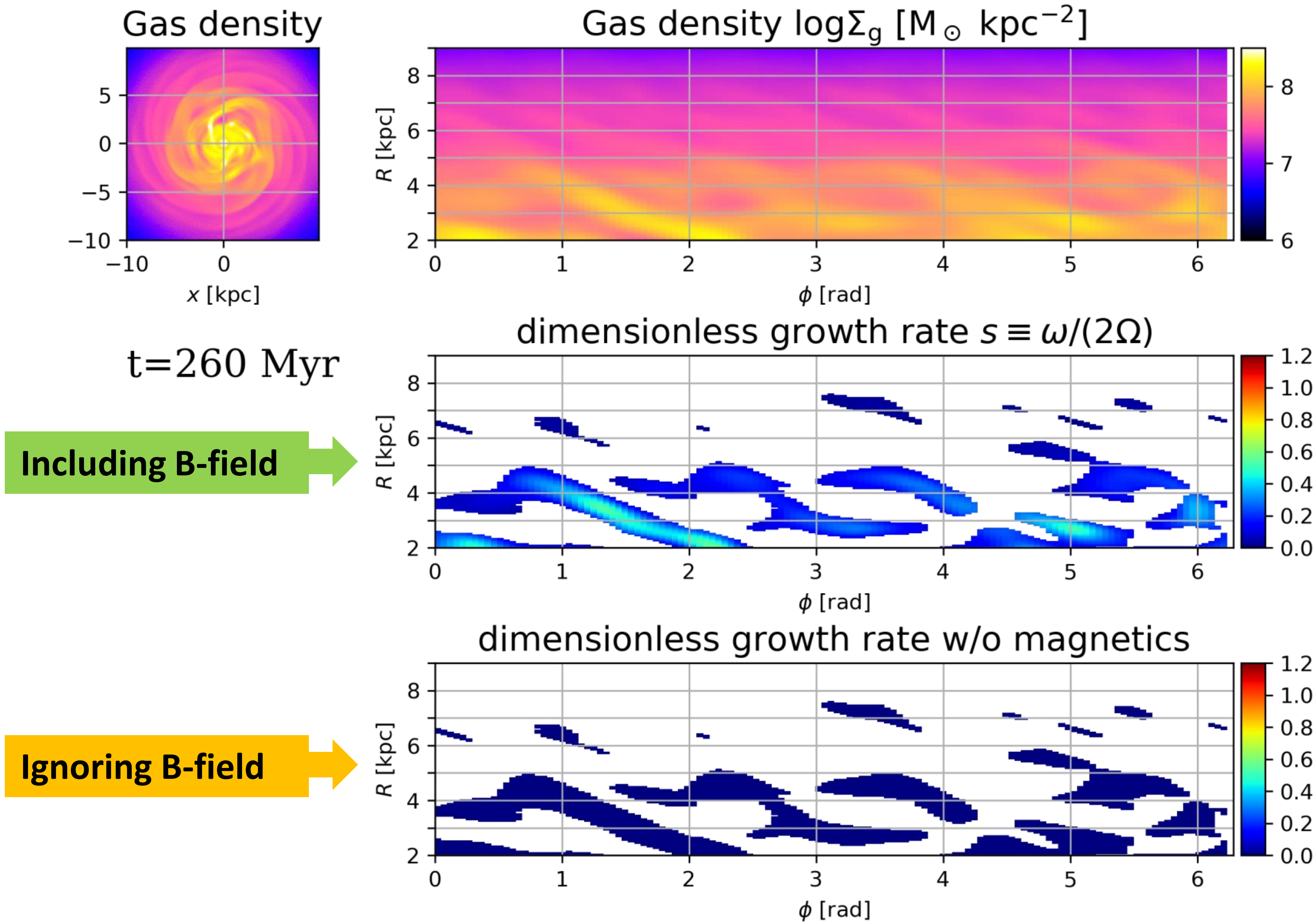

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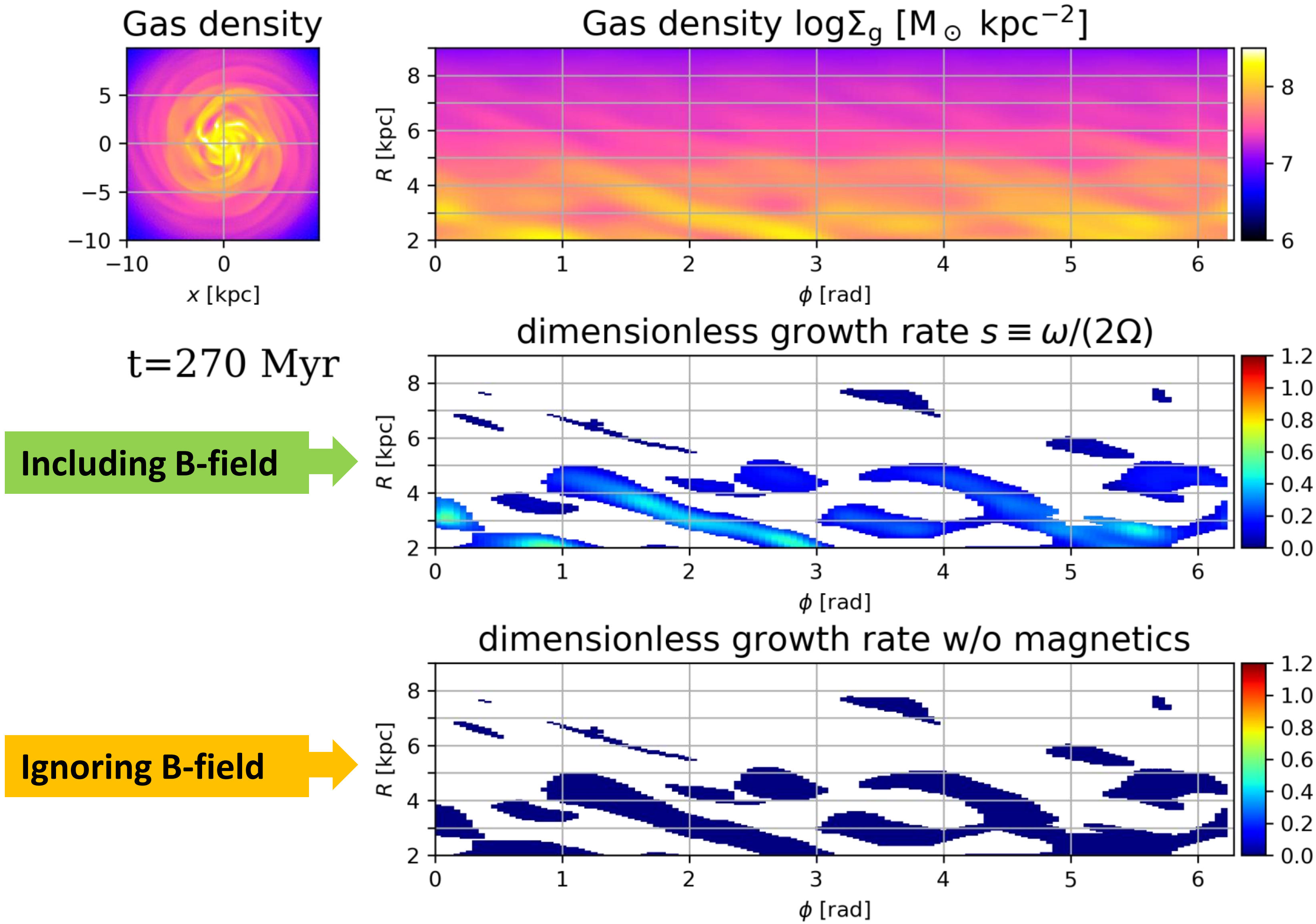

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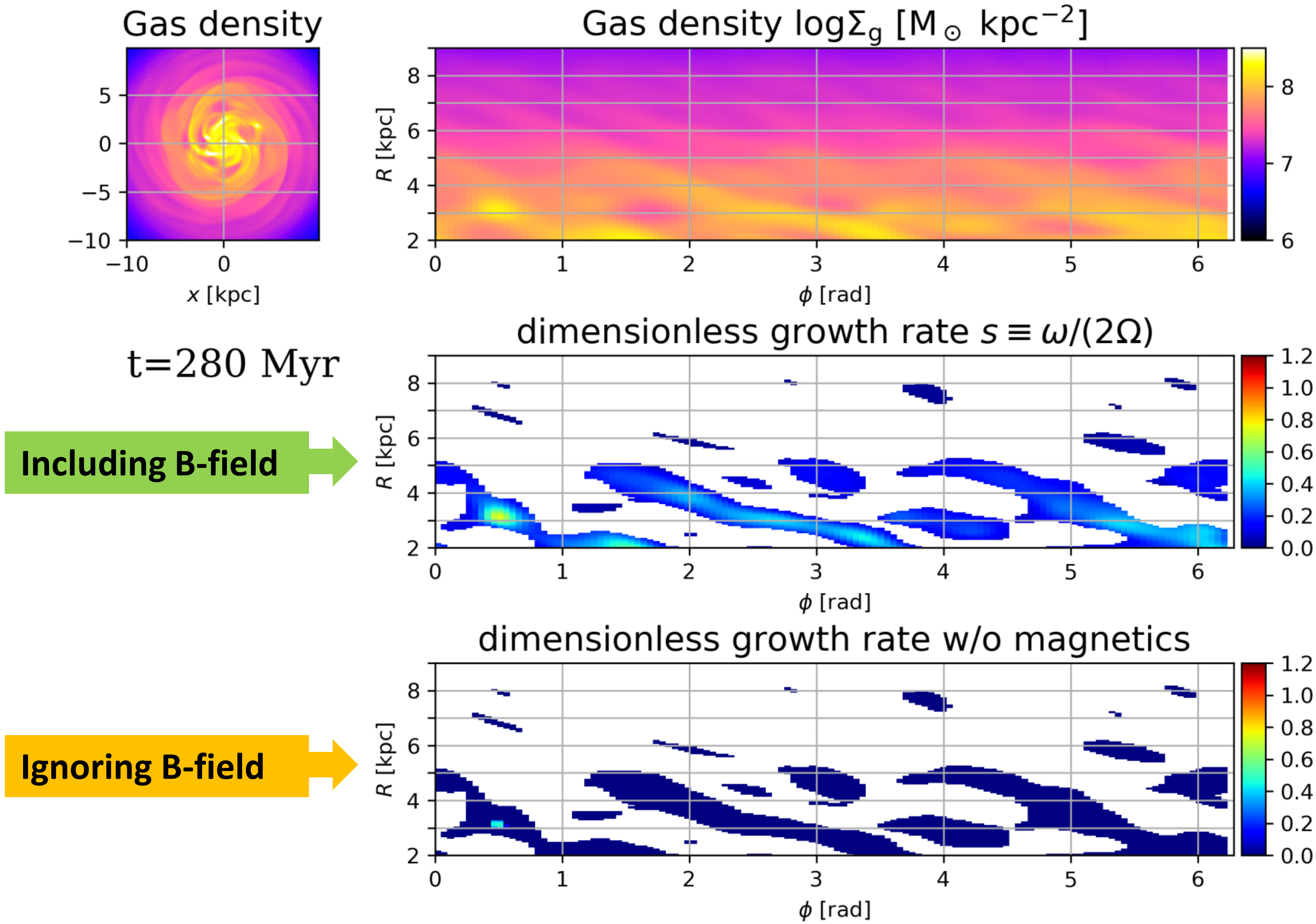

Demonstration

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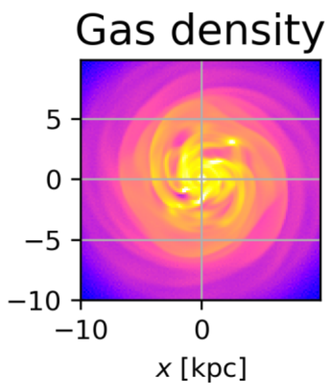
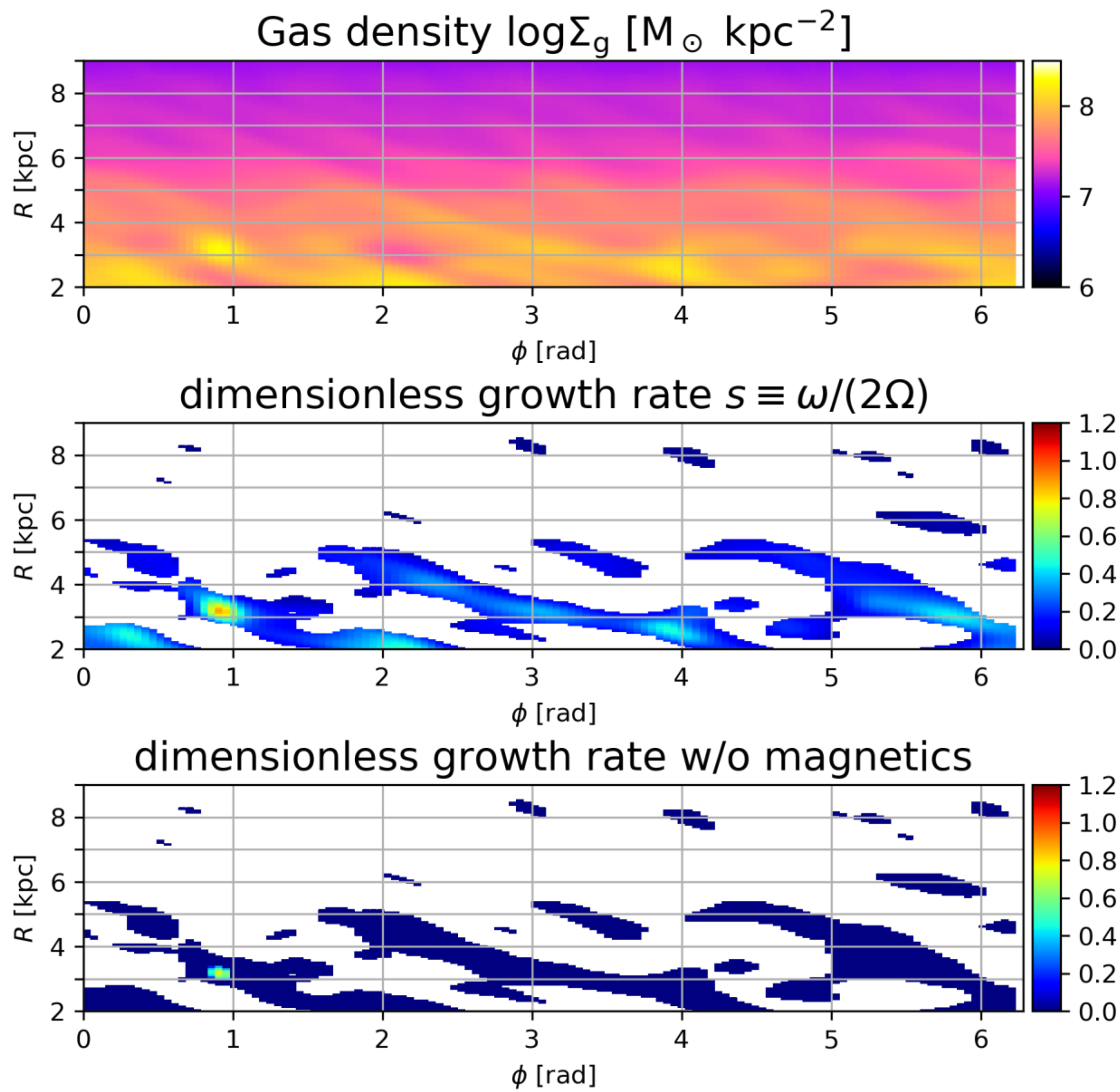


t=290 Myr

Including B-field

Ignoring B-field



Demonstration

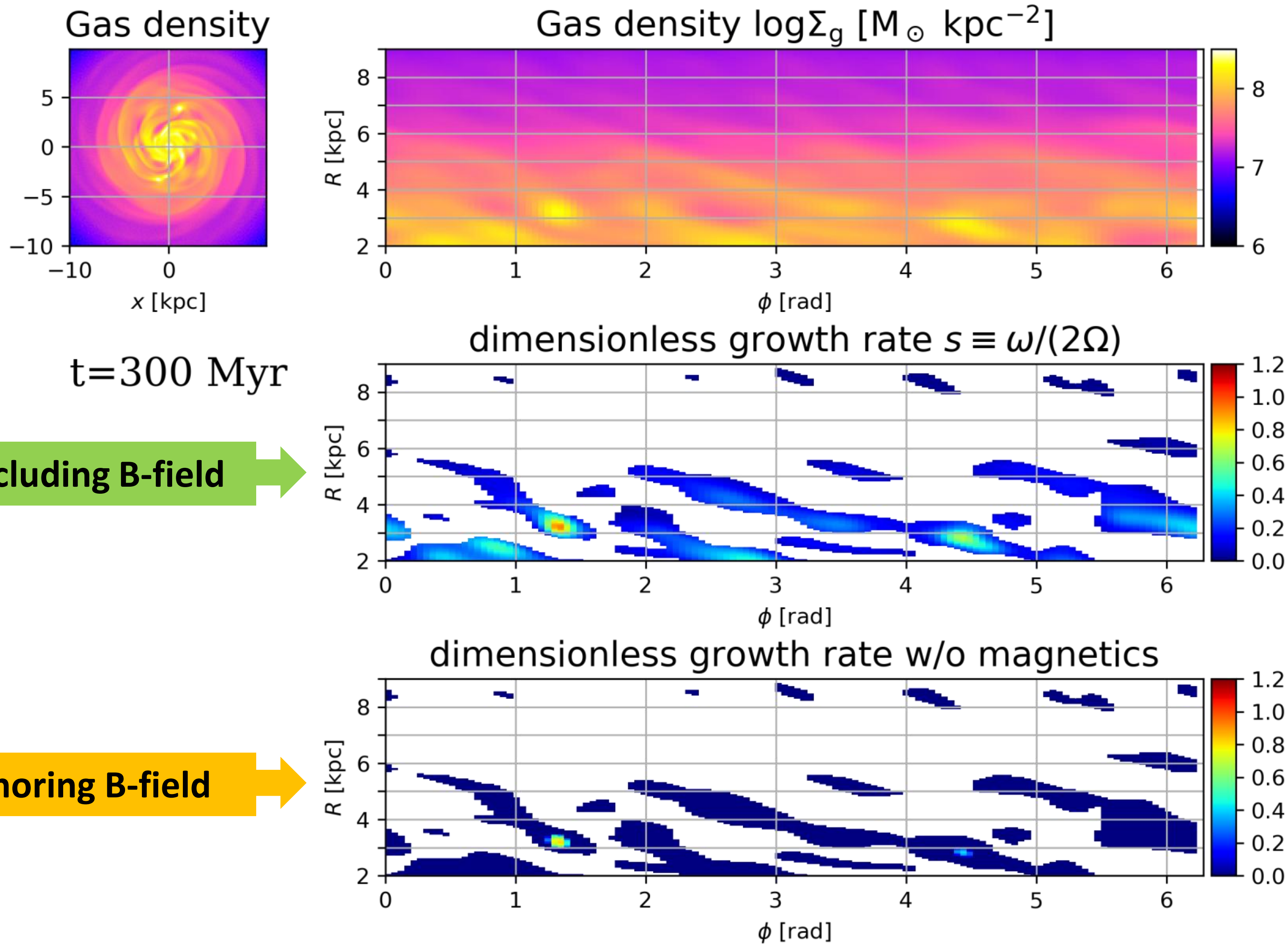
The fragmenting case

$\beta_{ini} = 5$

t=300 Myr

Including B-field

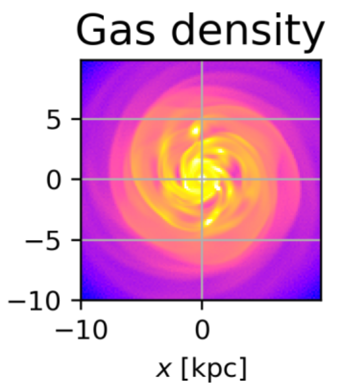
Ignoring B-field



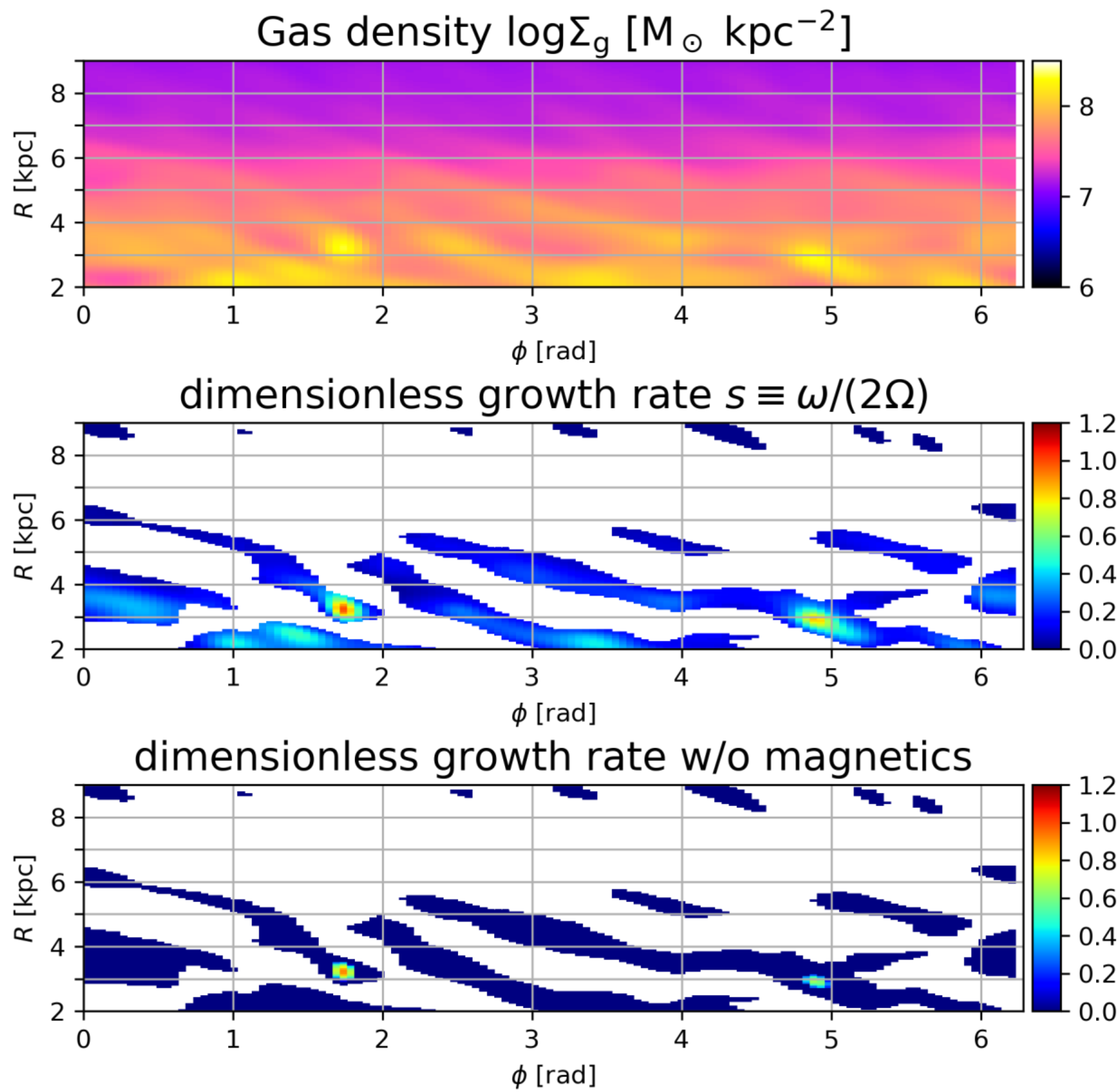
Demonstration

The fragmenting case

$\beta_{ini} = 5$



t=310 Myr



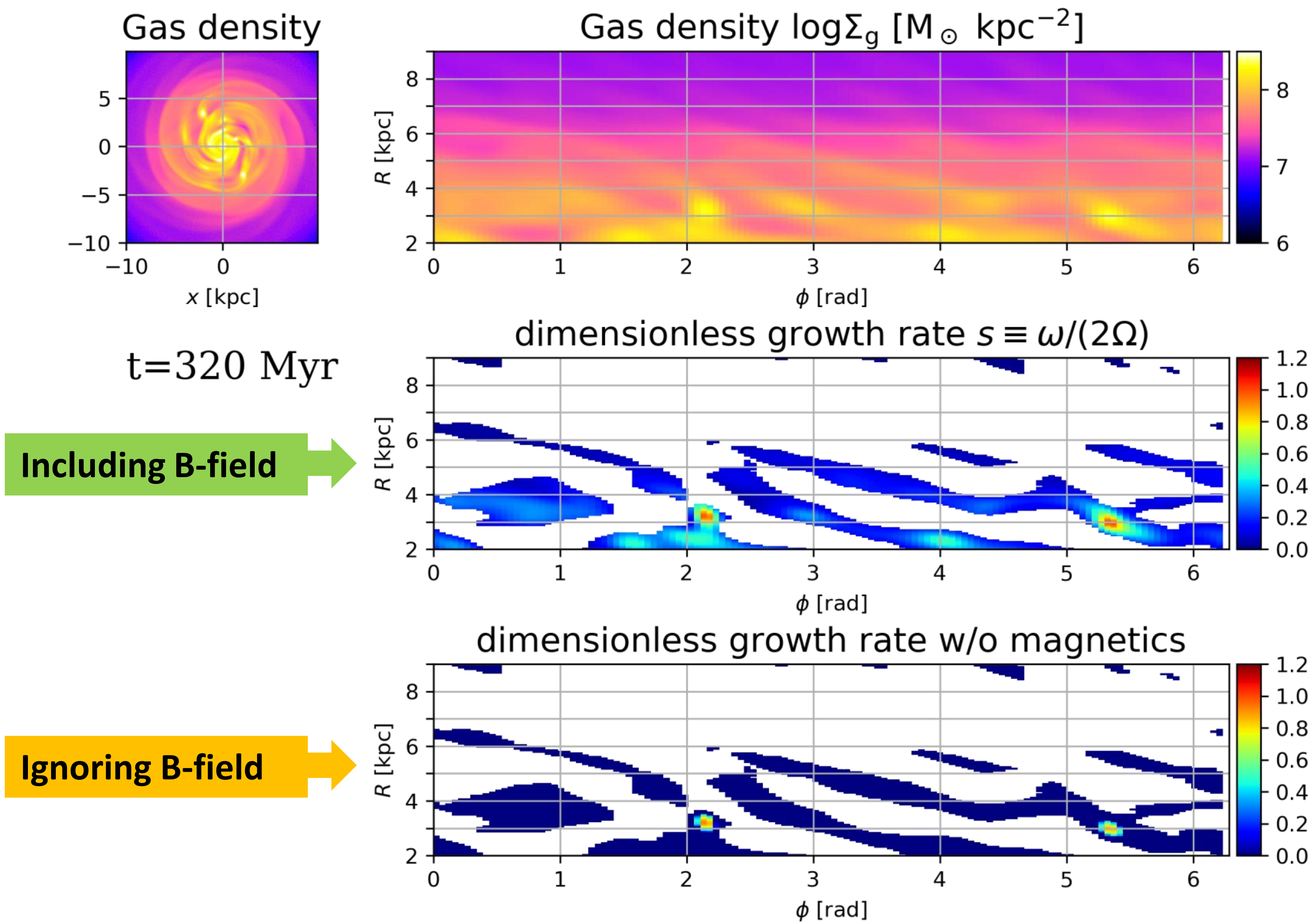
Including B-field

Ignoring B-field

Demonstration

The fragmenting case

$\beta_{ini} = 5$



Demonstration

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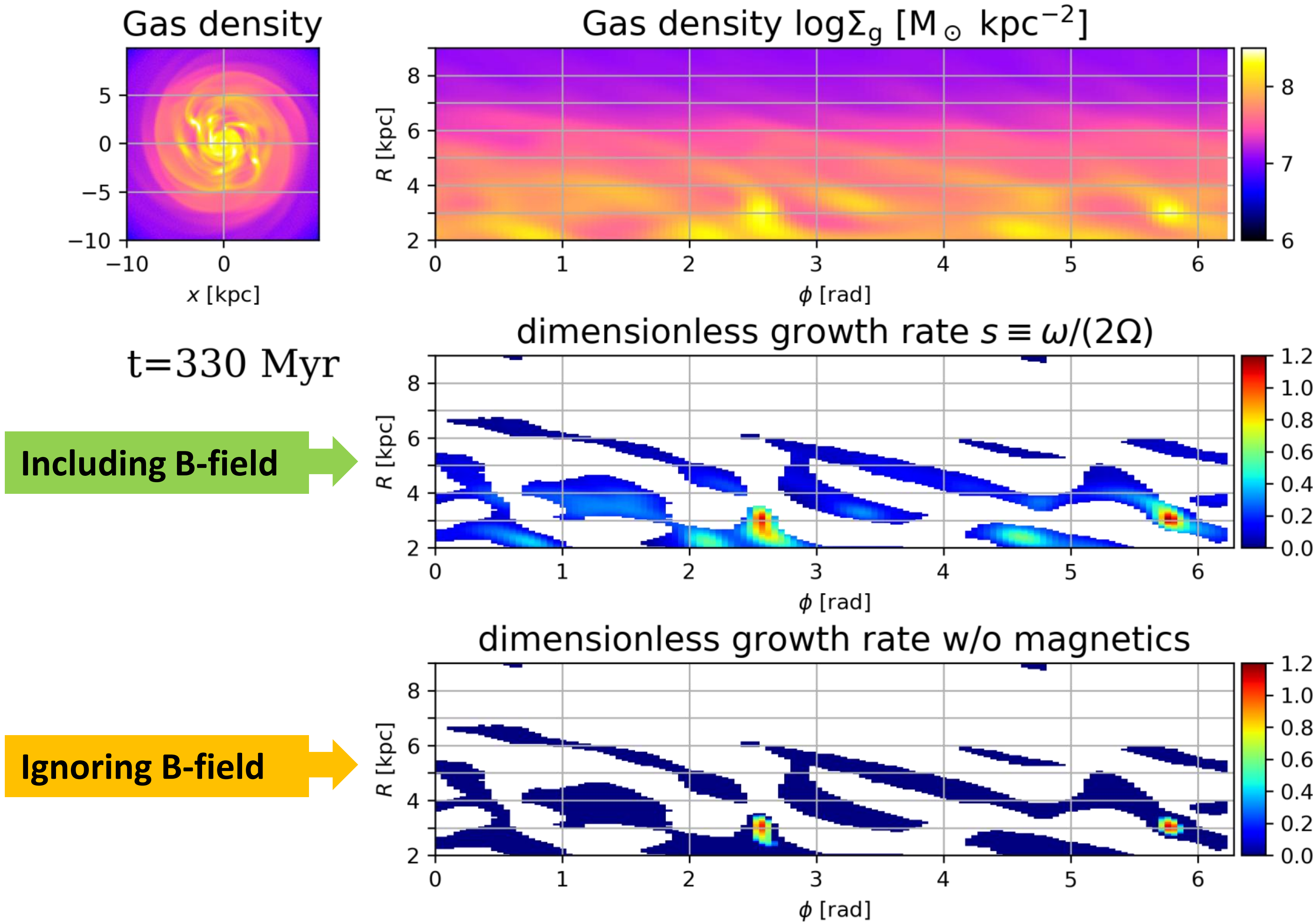


Demonstration

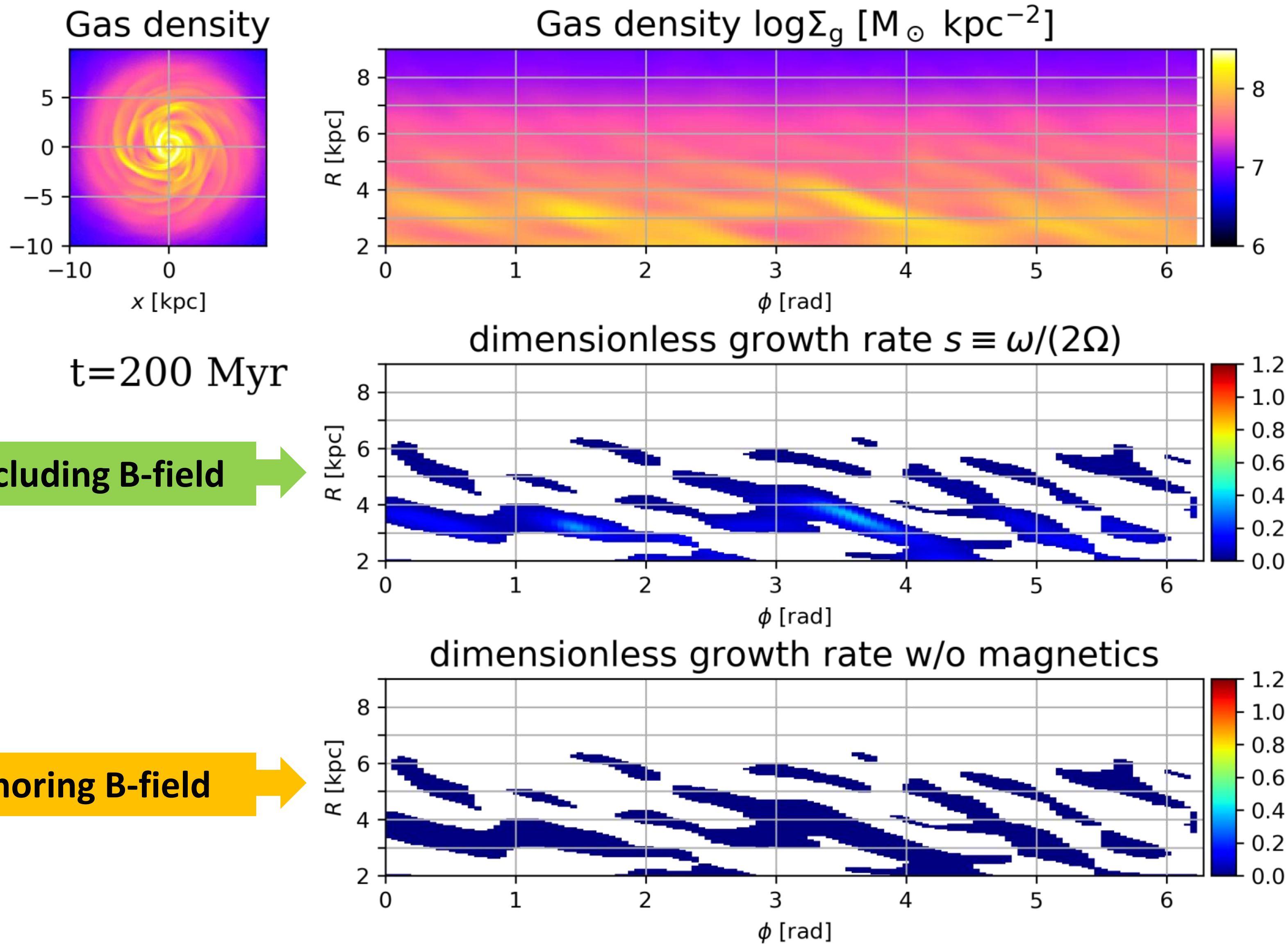
The stable case

$\beta_{ini} = 100$

t=200 Myr

Including B-field

Ignoring B-field



Demonstration

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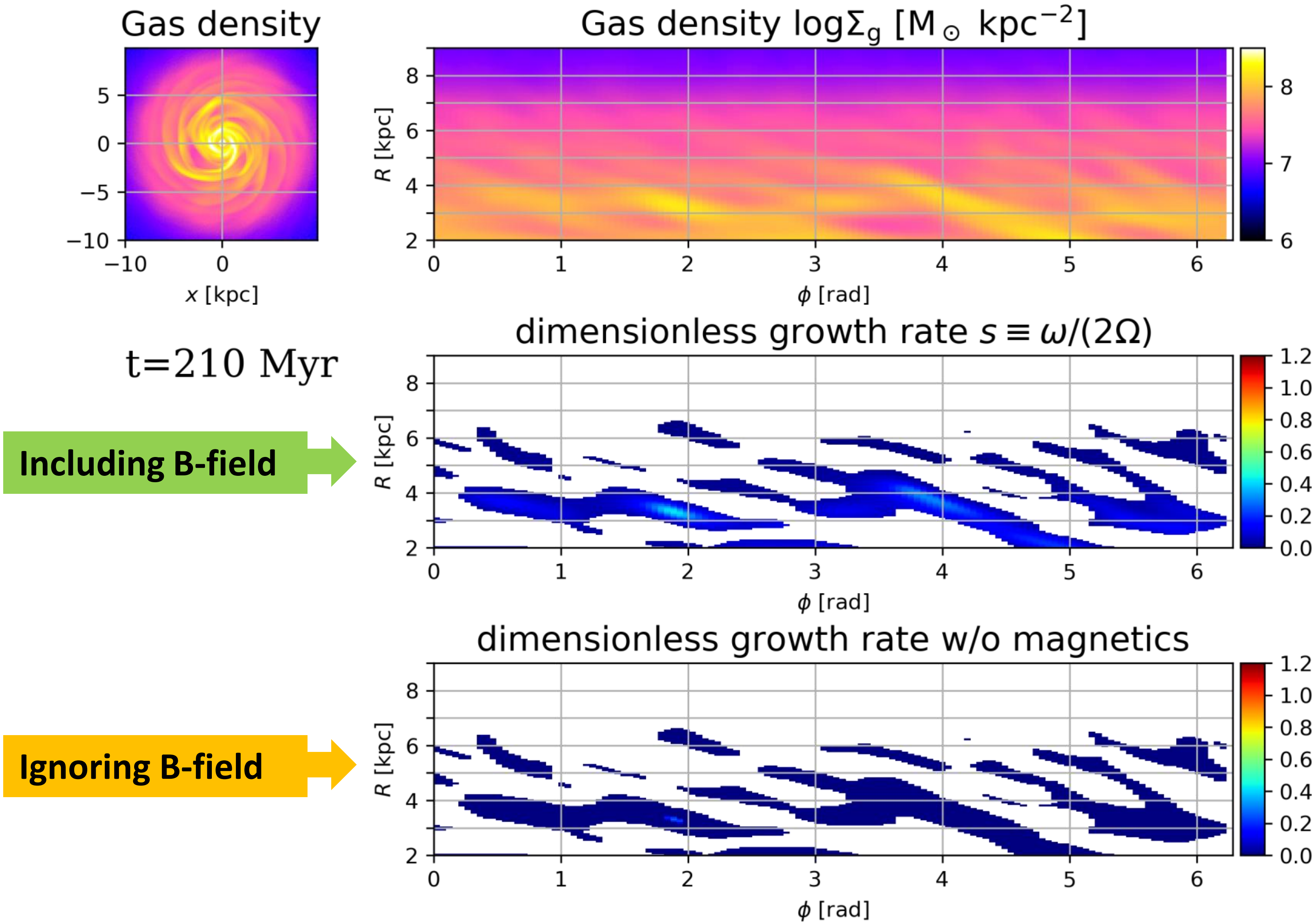

Demonstration

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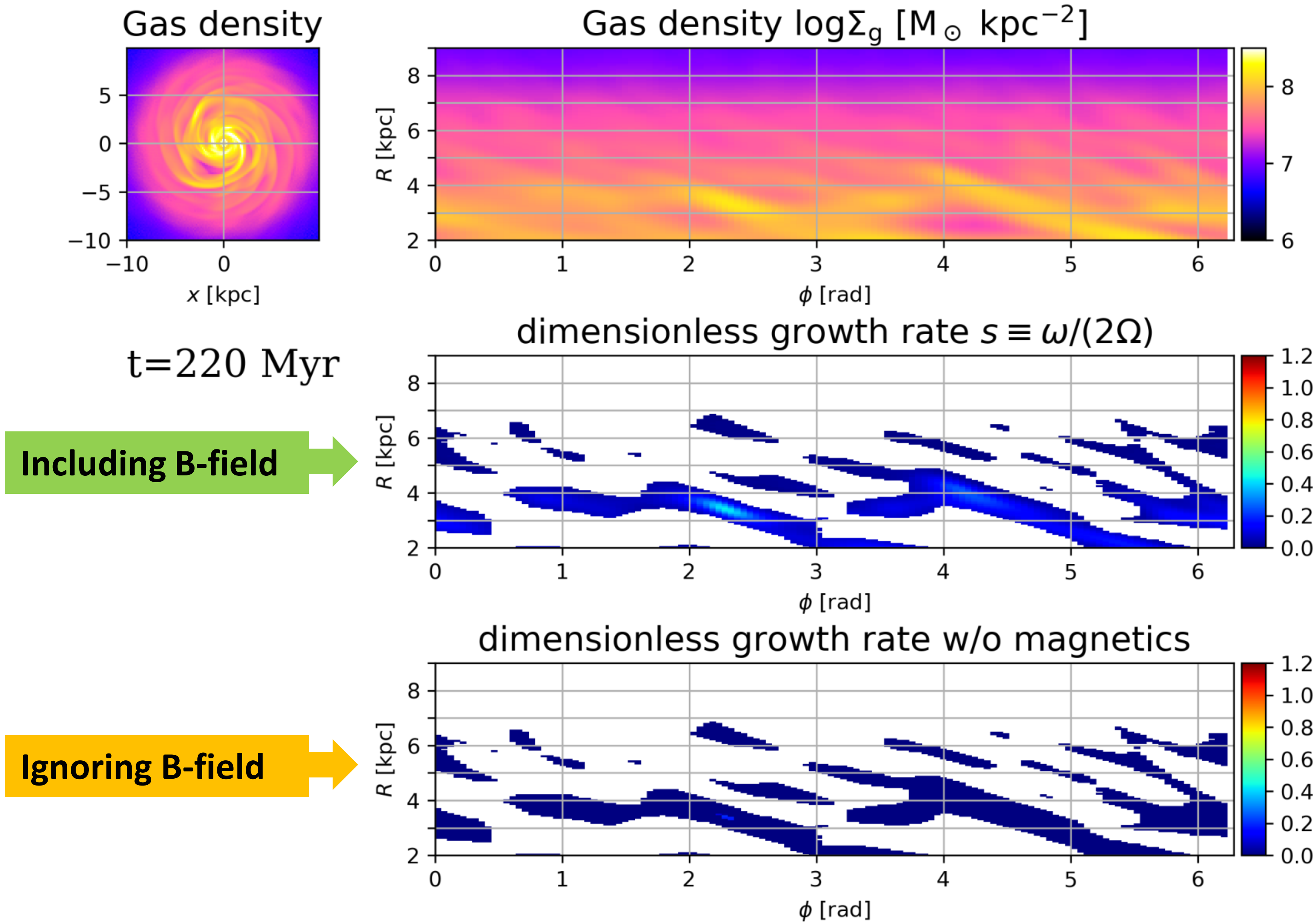

Demonstration

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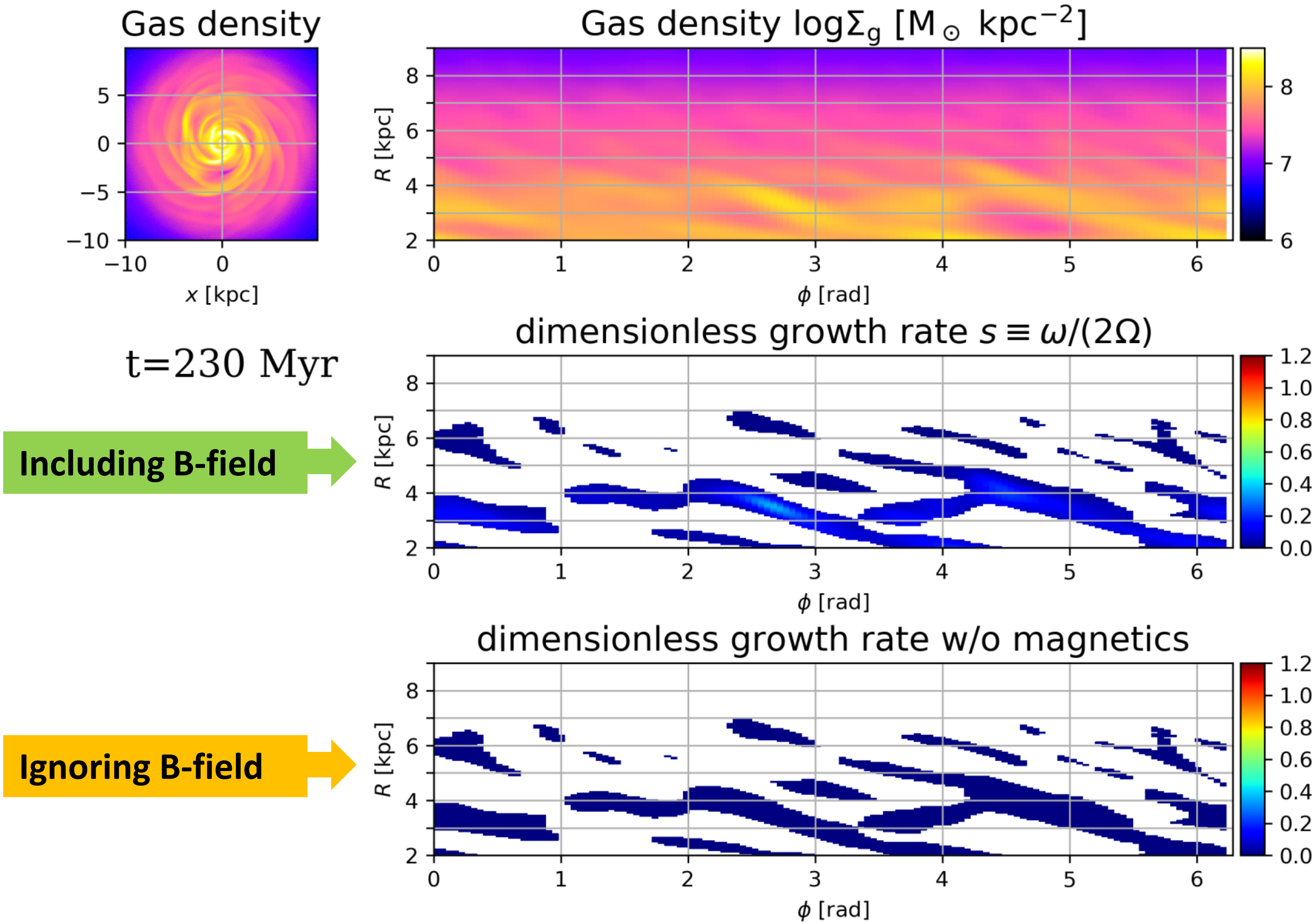

Demonstration

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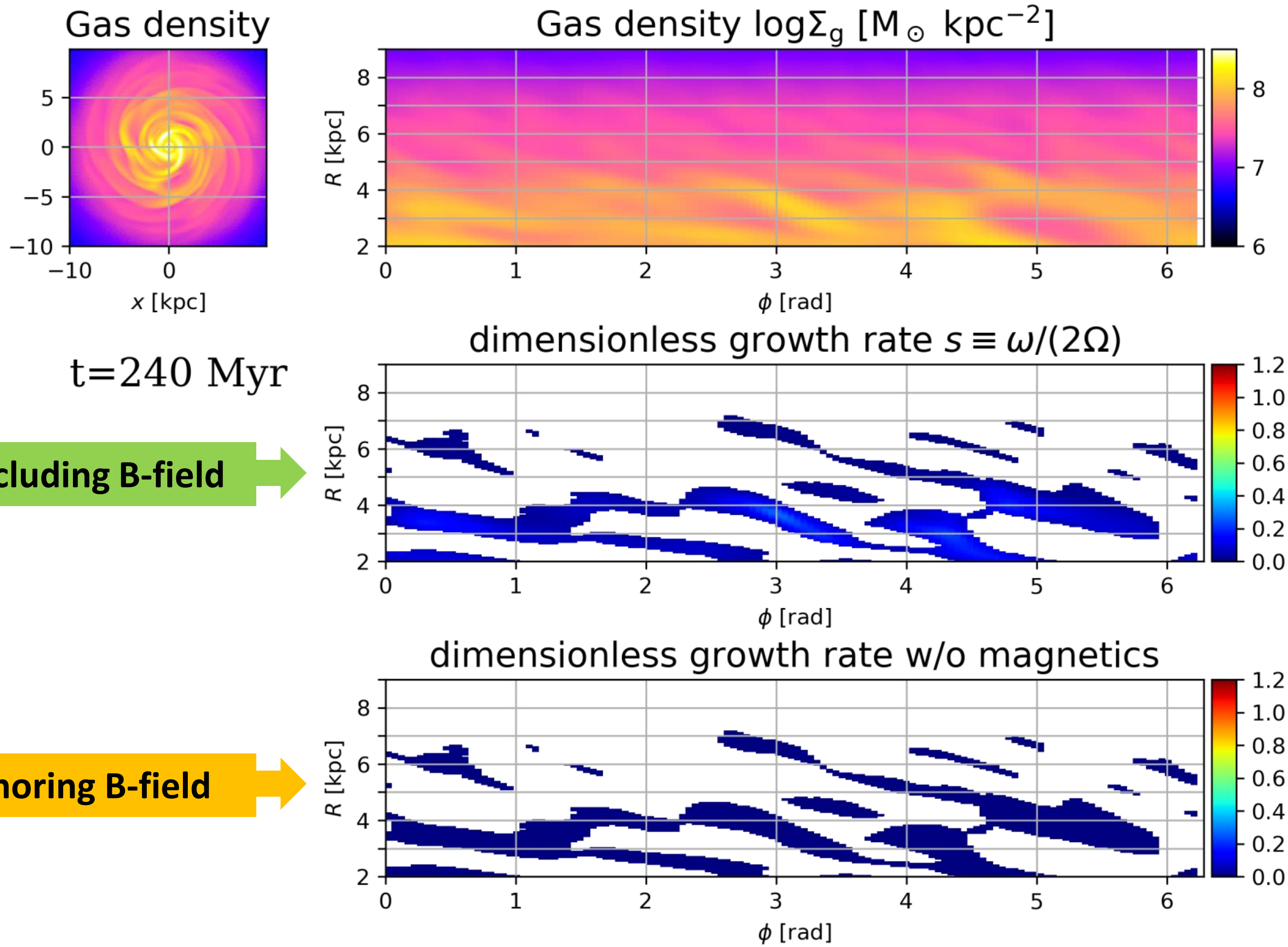


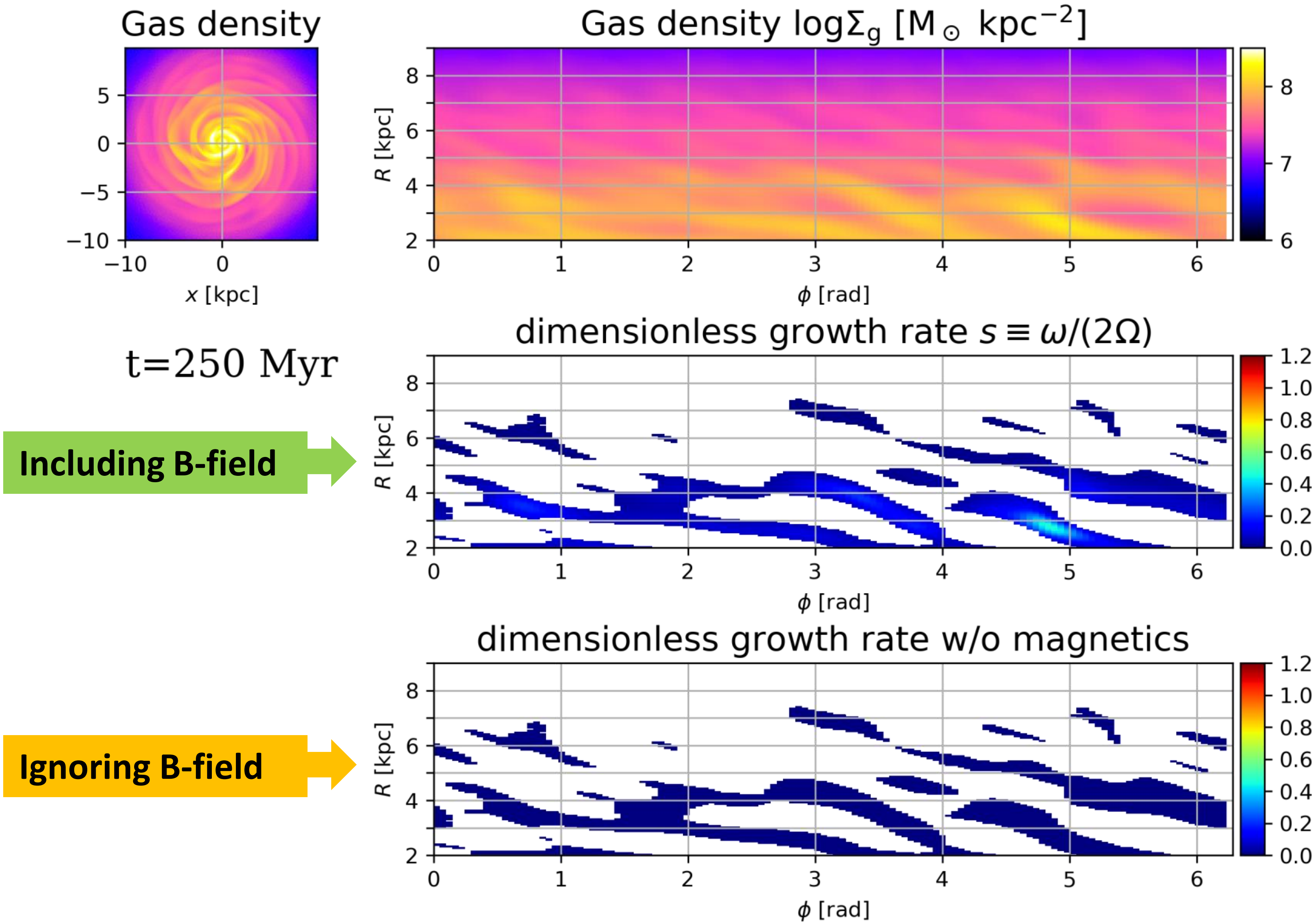
Including B-field

Ignoring B-field

Demonstration

The stable case

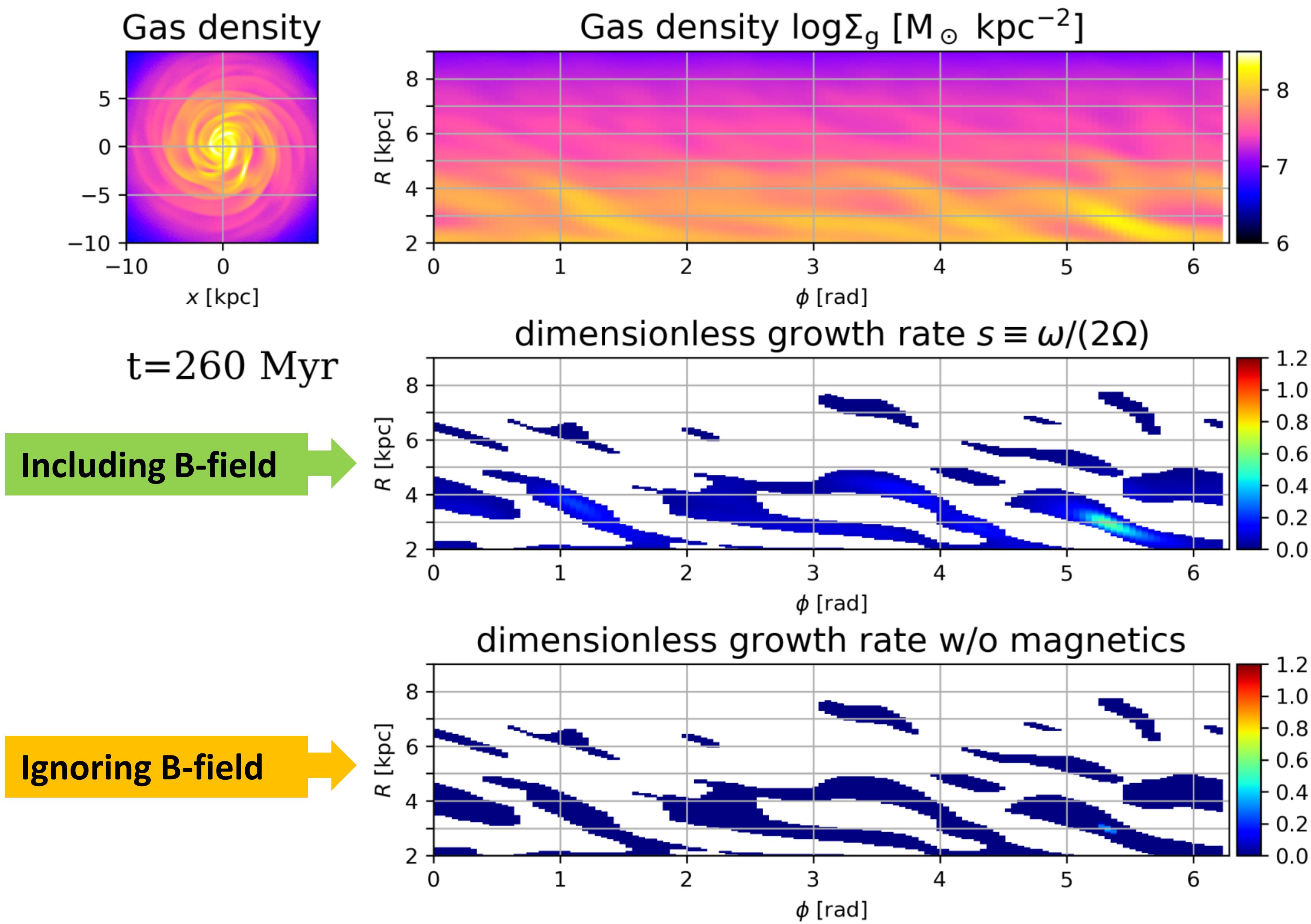
$\beta_{ini} = 100$



Demonstration

The stable case

$\beta_{ini} = 100$



Demonstration

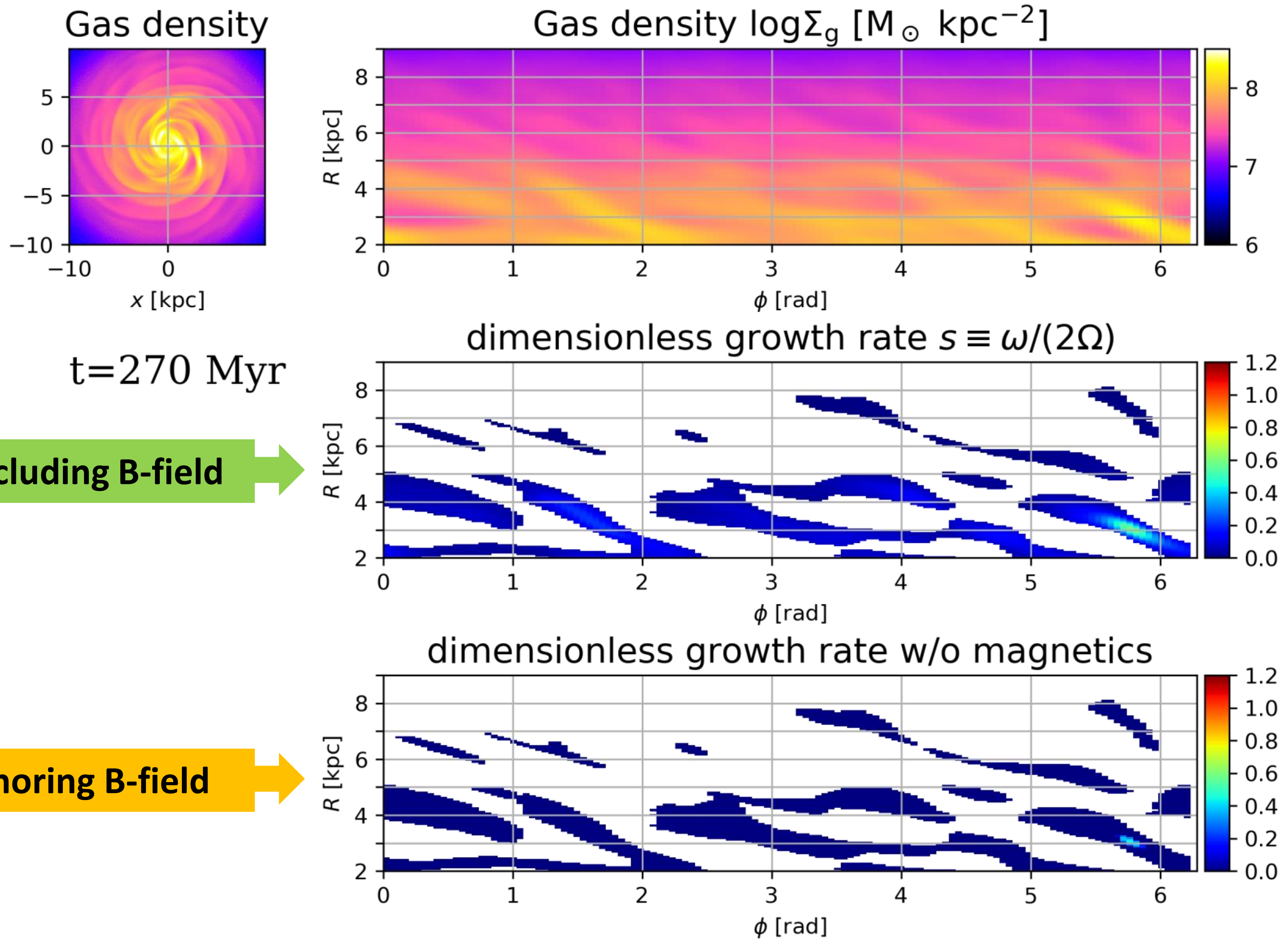
The stable case

$\beta_{ini} = 100$

t=270 Myr

Including B-field

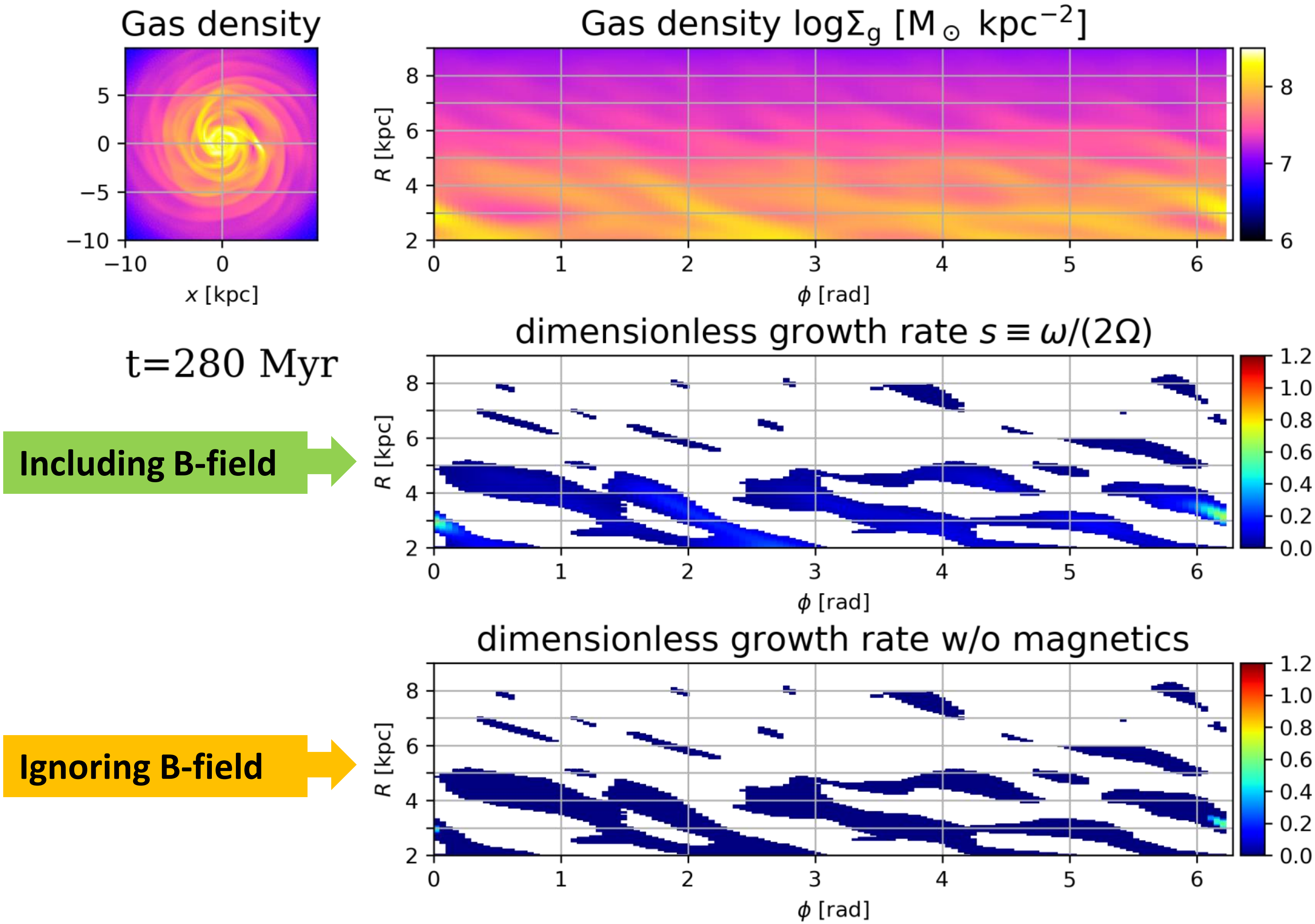
Ignoring B-field



Demonstration

The stable case

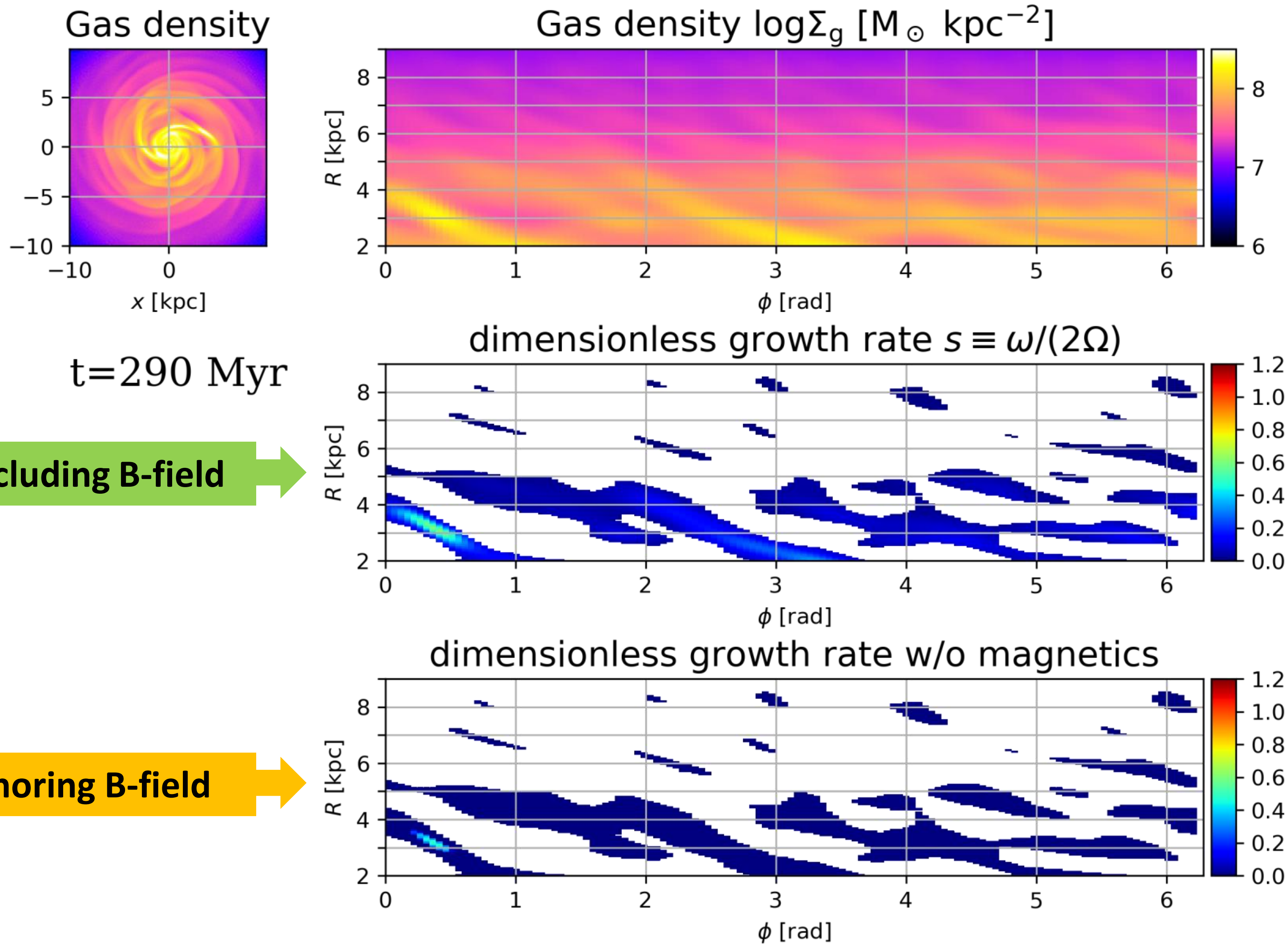
$\beta_{ini} = 100$



Demonstration

The stable case

$\beta_{ini} = 100$



t=290 Myr

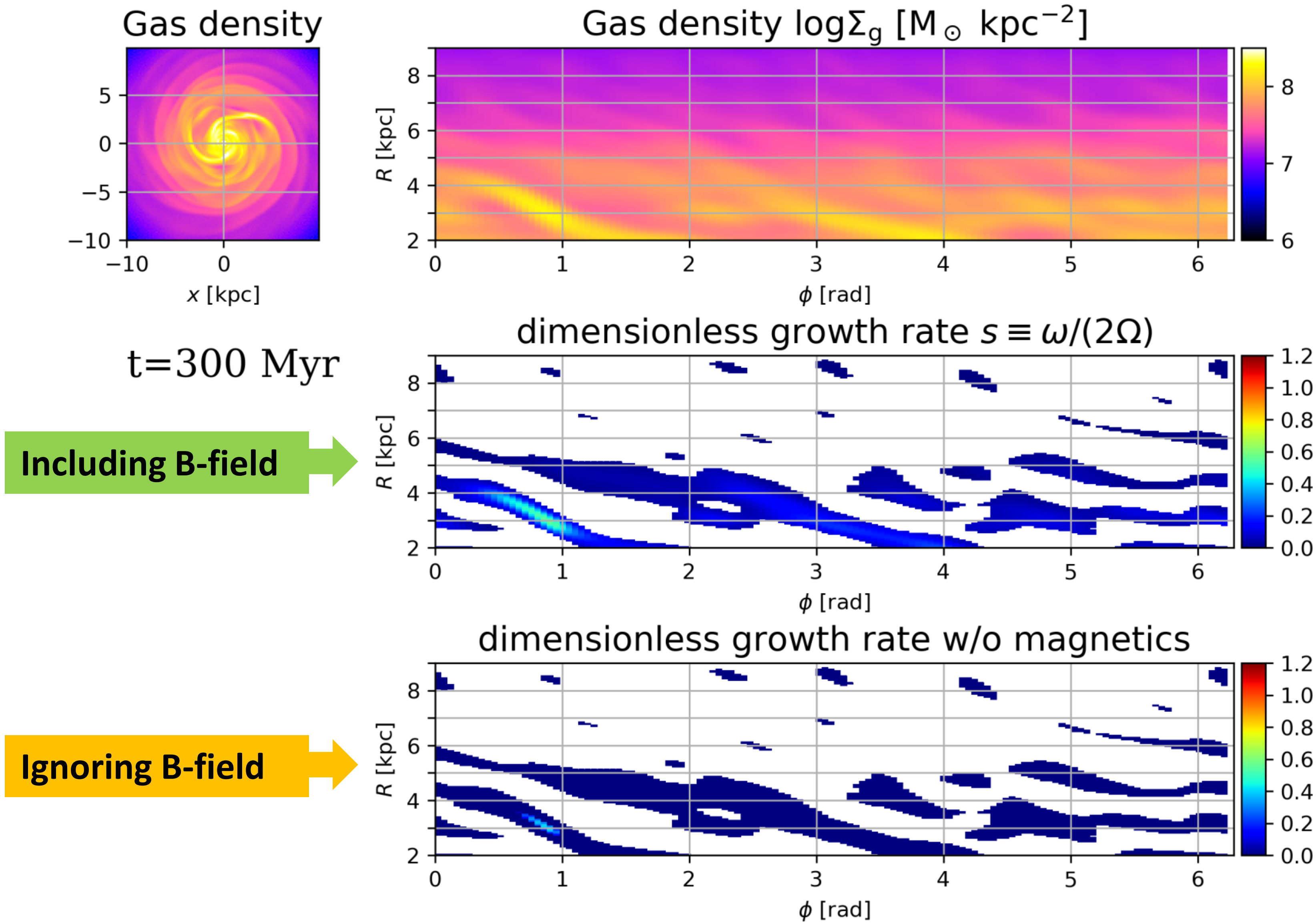
Including B-field

Ignoring B-field

Demonstration

The stable case

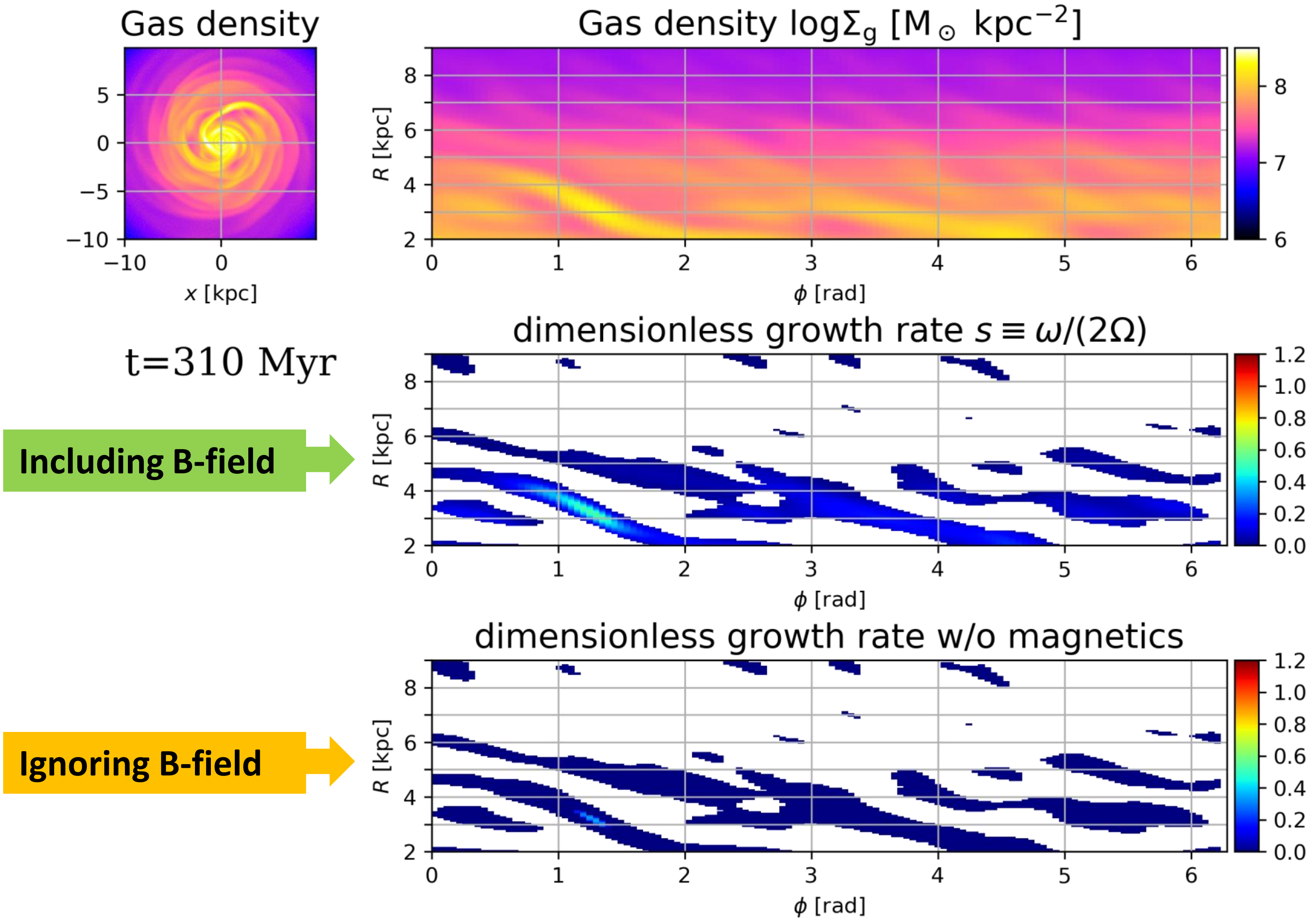
$\beta_{ini} = 100$



Demonstration

The stable case

$\beta_{ini} = 100$



Demonstration

The stable case

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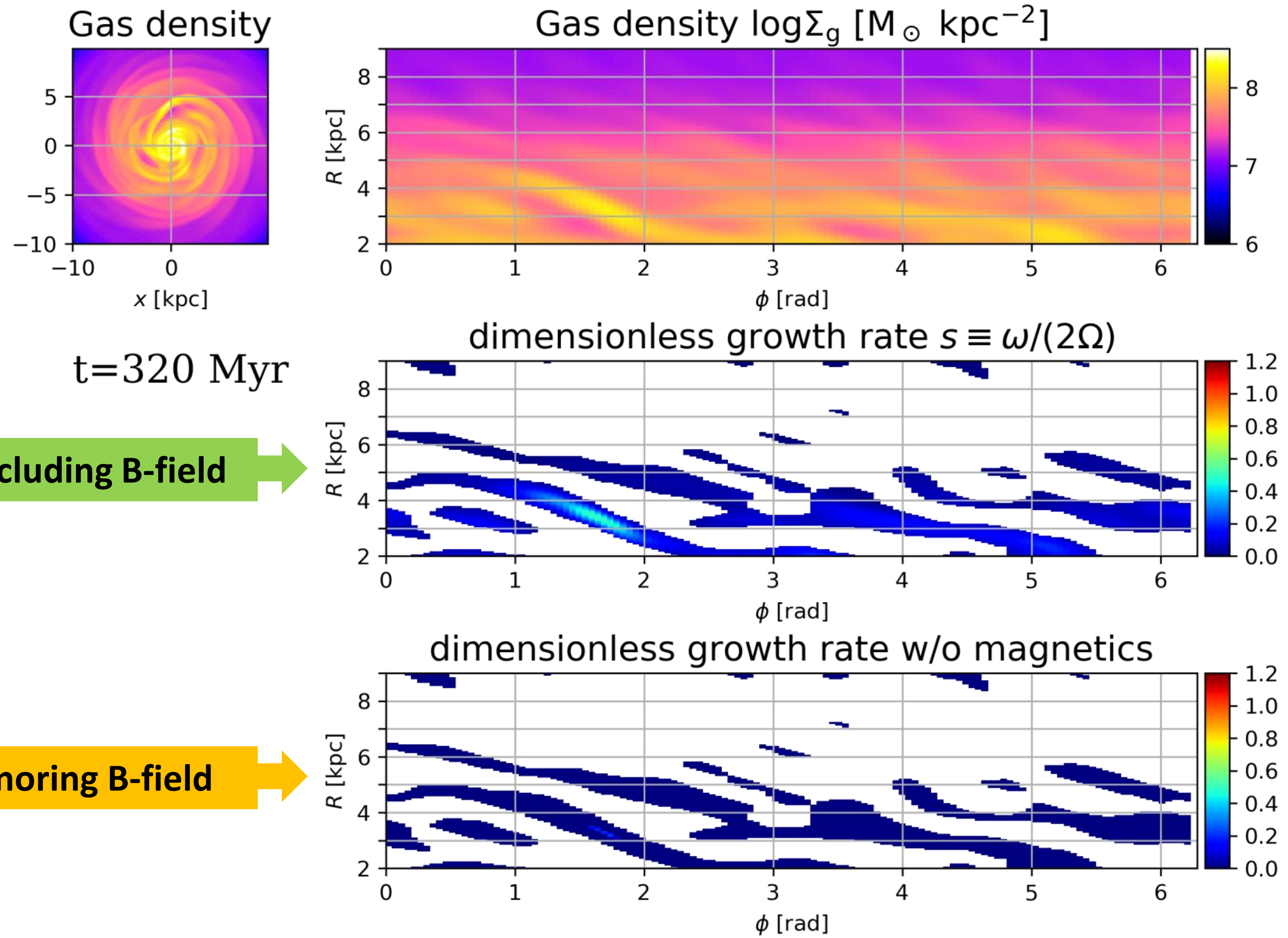


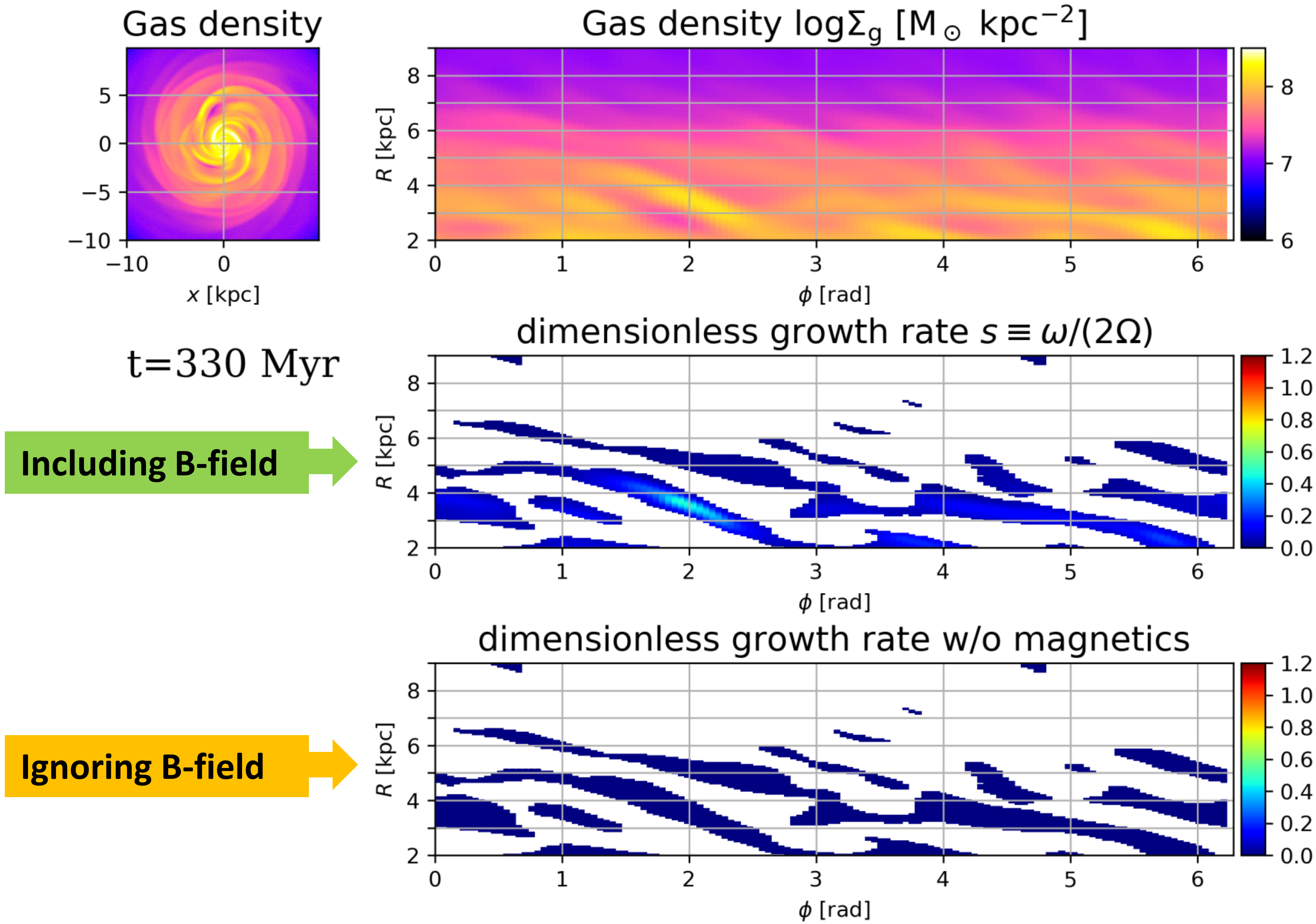
Including B-field

Ignoring B-field

Demonstration

The stable case

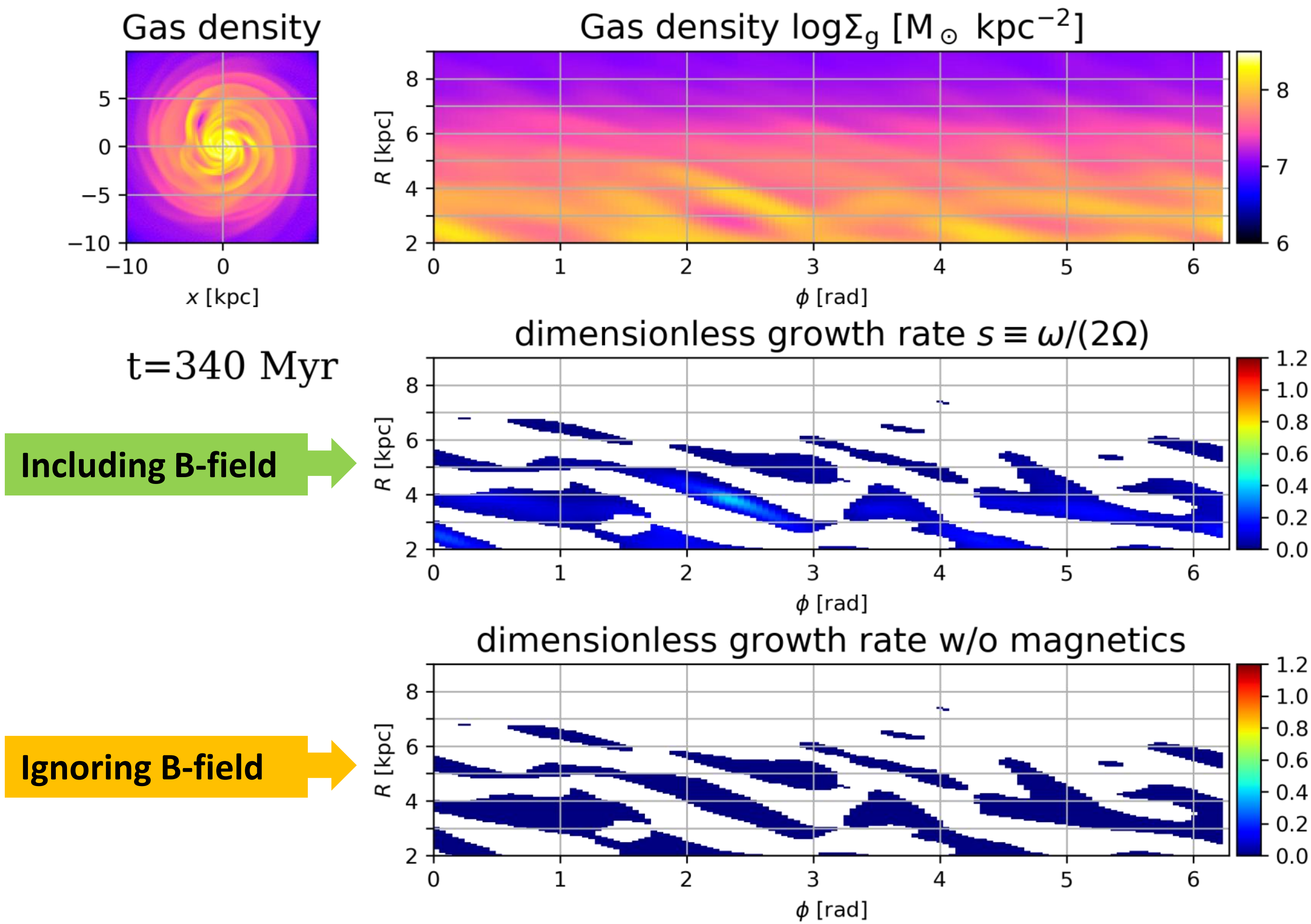
$\beta_{ini} = 100$



Demonstration

The stable case

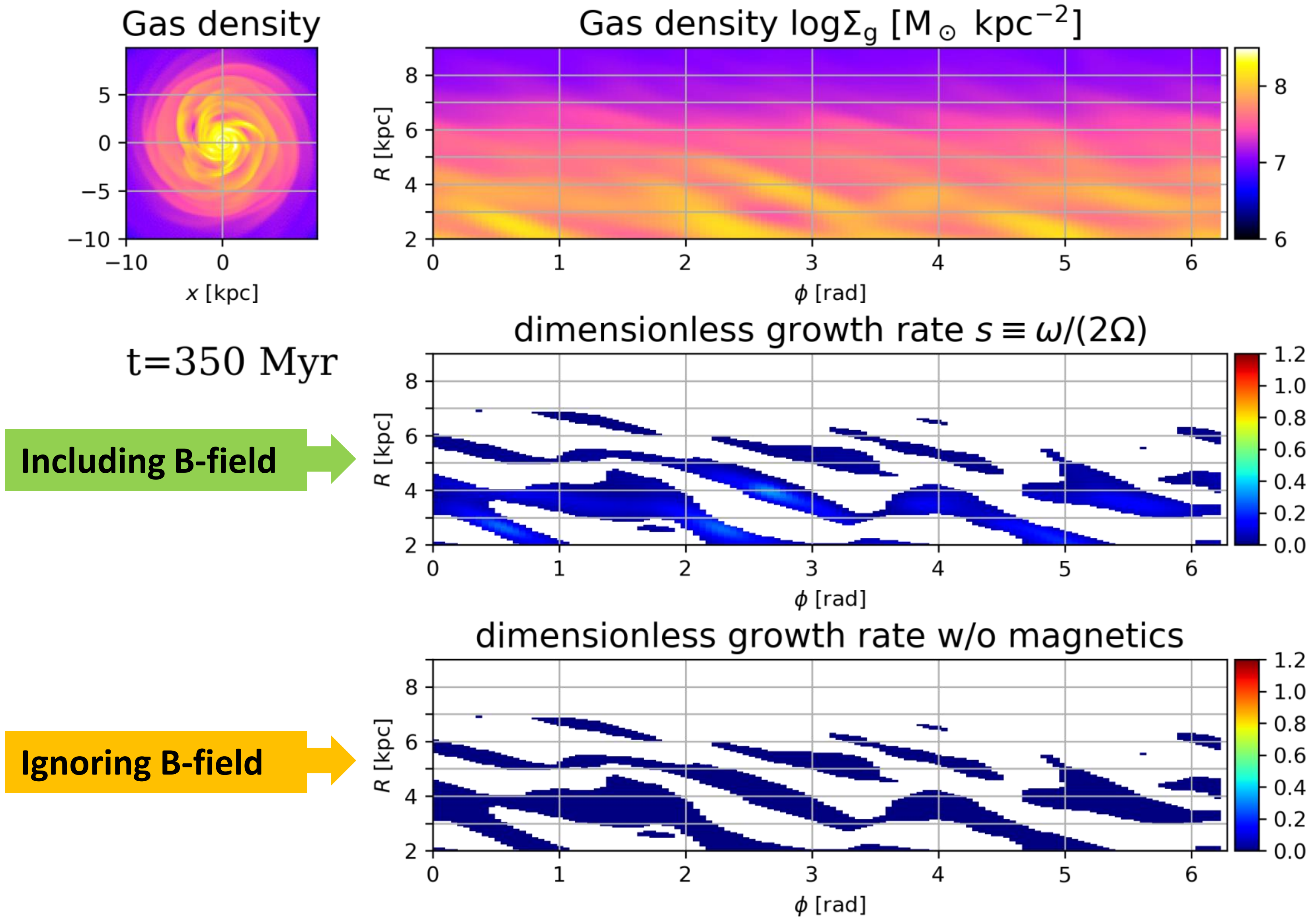
$\beta_{ini} = 100$



Demonstration

The stable case

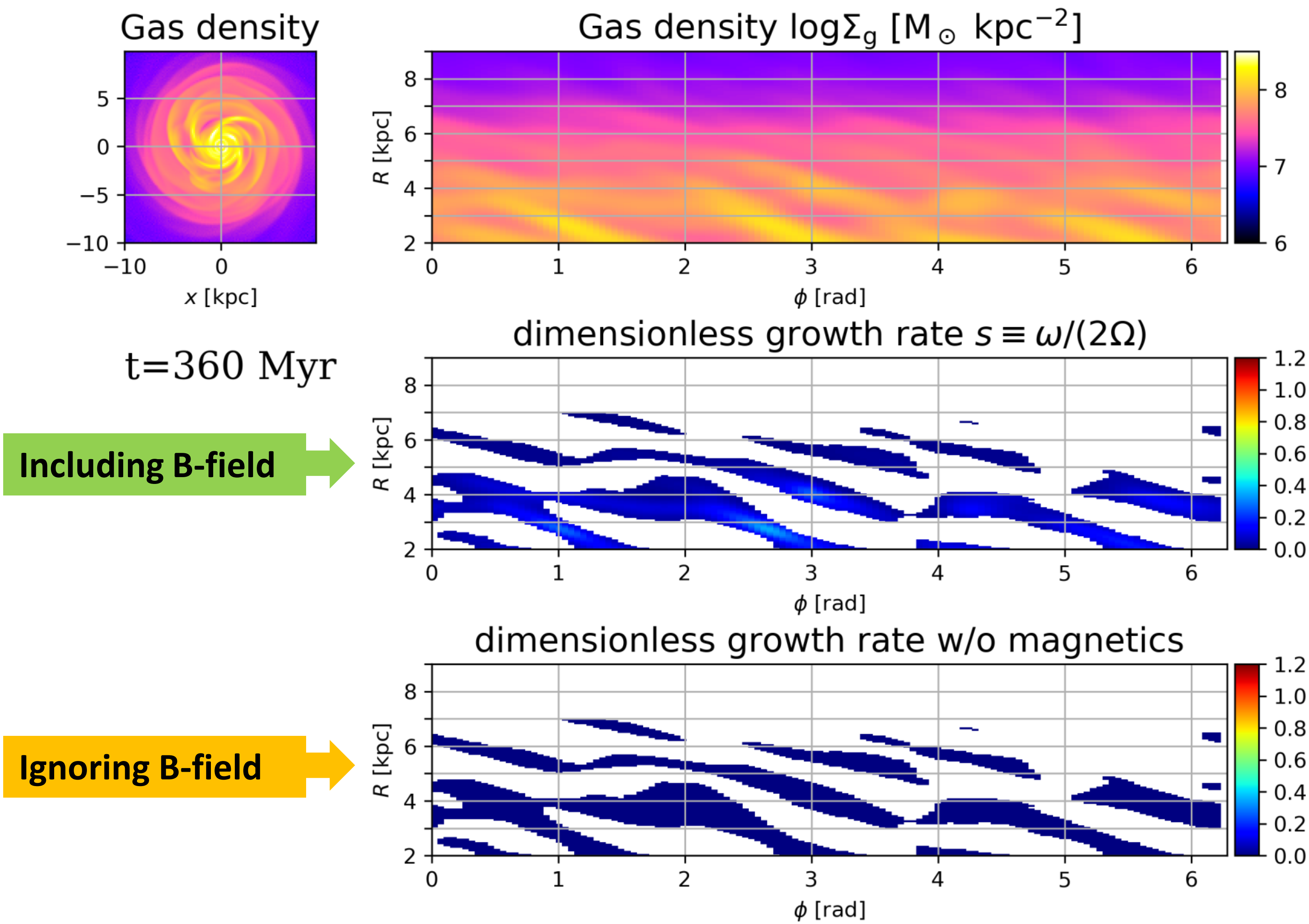
$\beta_{ini} = 100$



Demonstration

The stable case

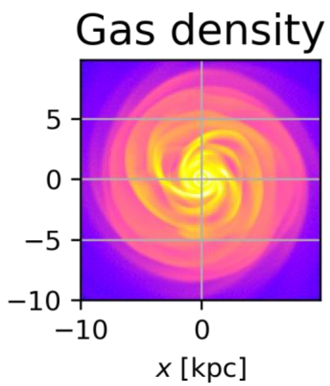
$\beta_{ini} = 100$

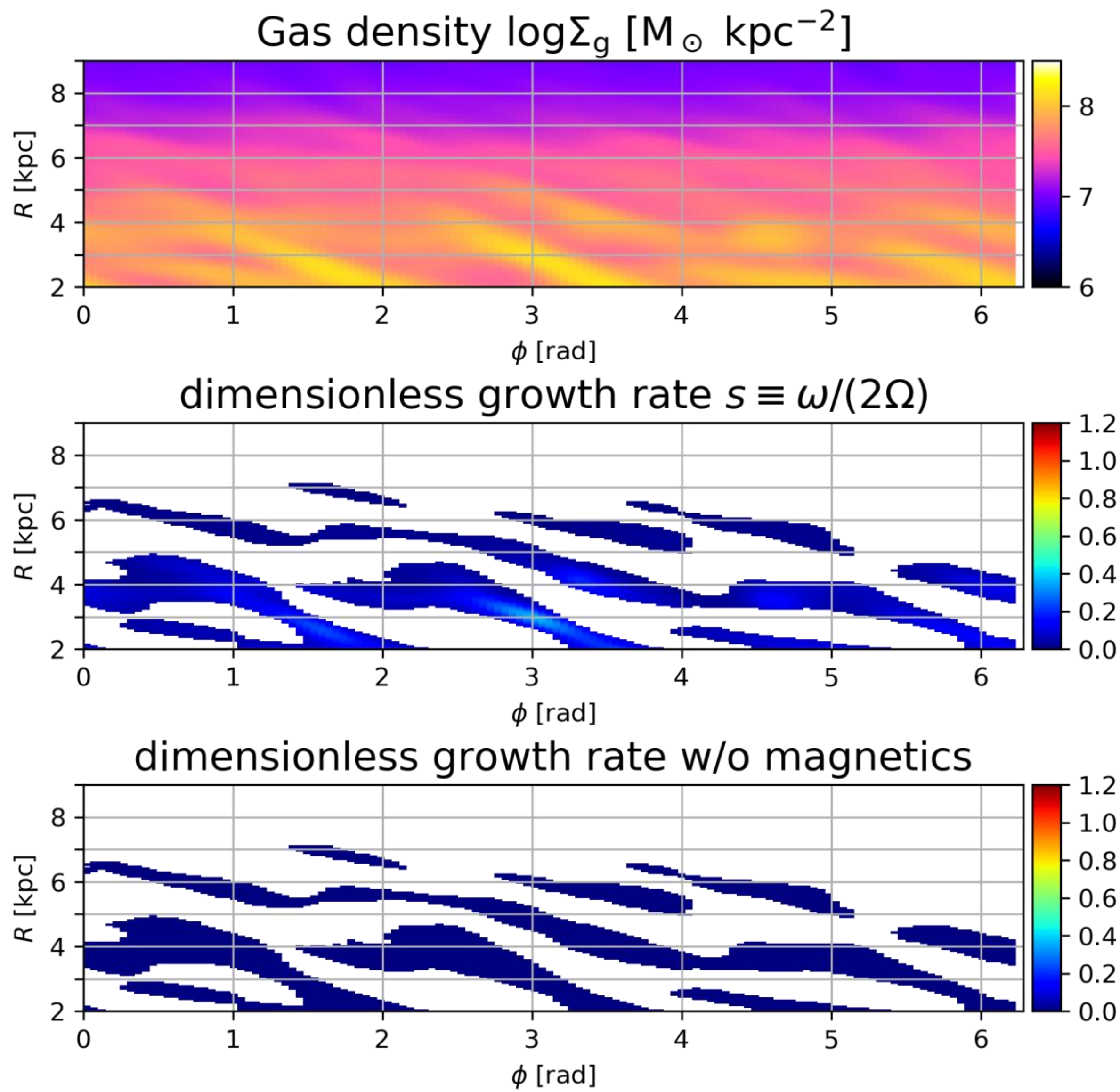


Demonstration

The stable case

$\beta_{ini} = 100$





t=370 Myr

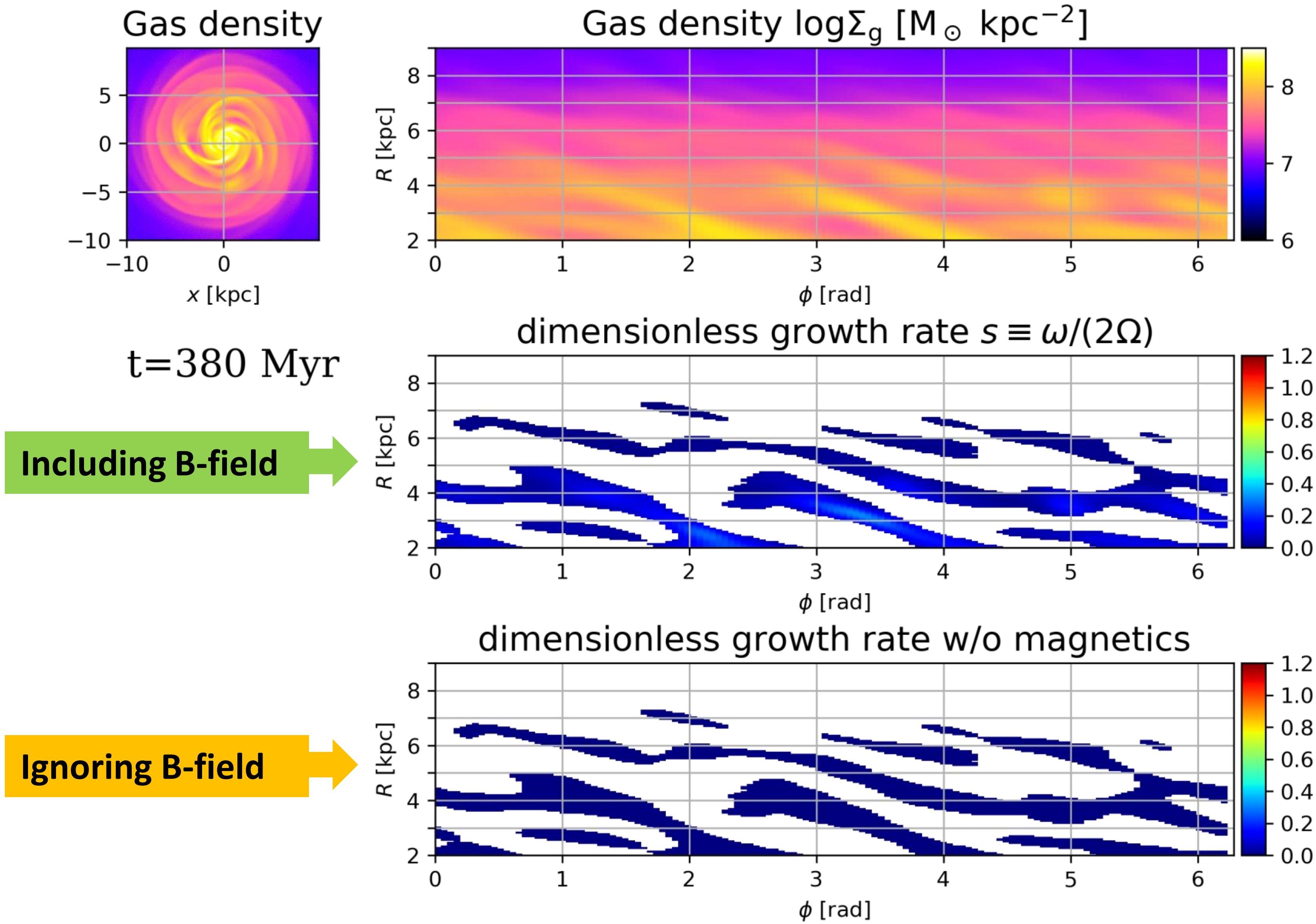
Including B-field

Ignoring B-field

Demonstration

The stable case

$\beta_{ini} = 100$



Demonstration

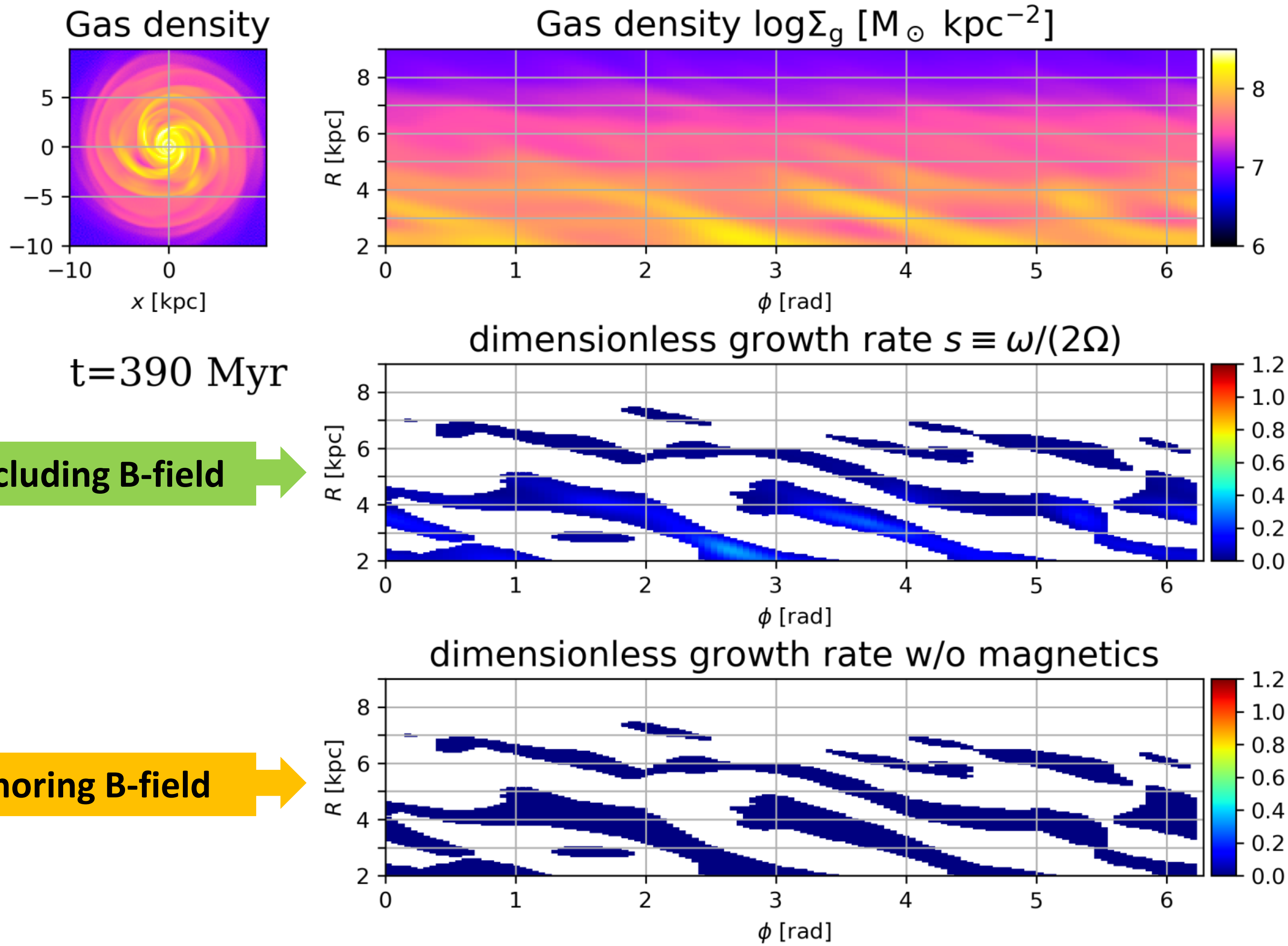
The stable case

$\beta_{ini} = 100$

t=390 Myr

Including B-field

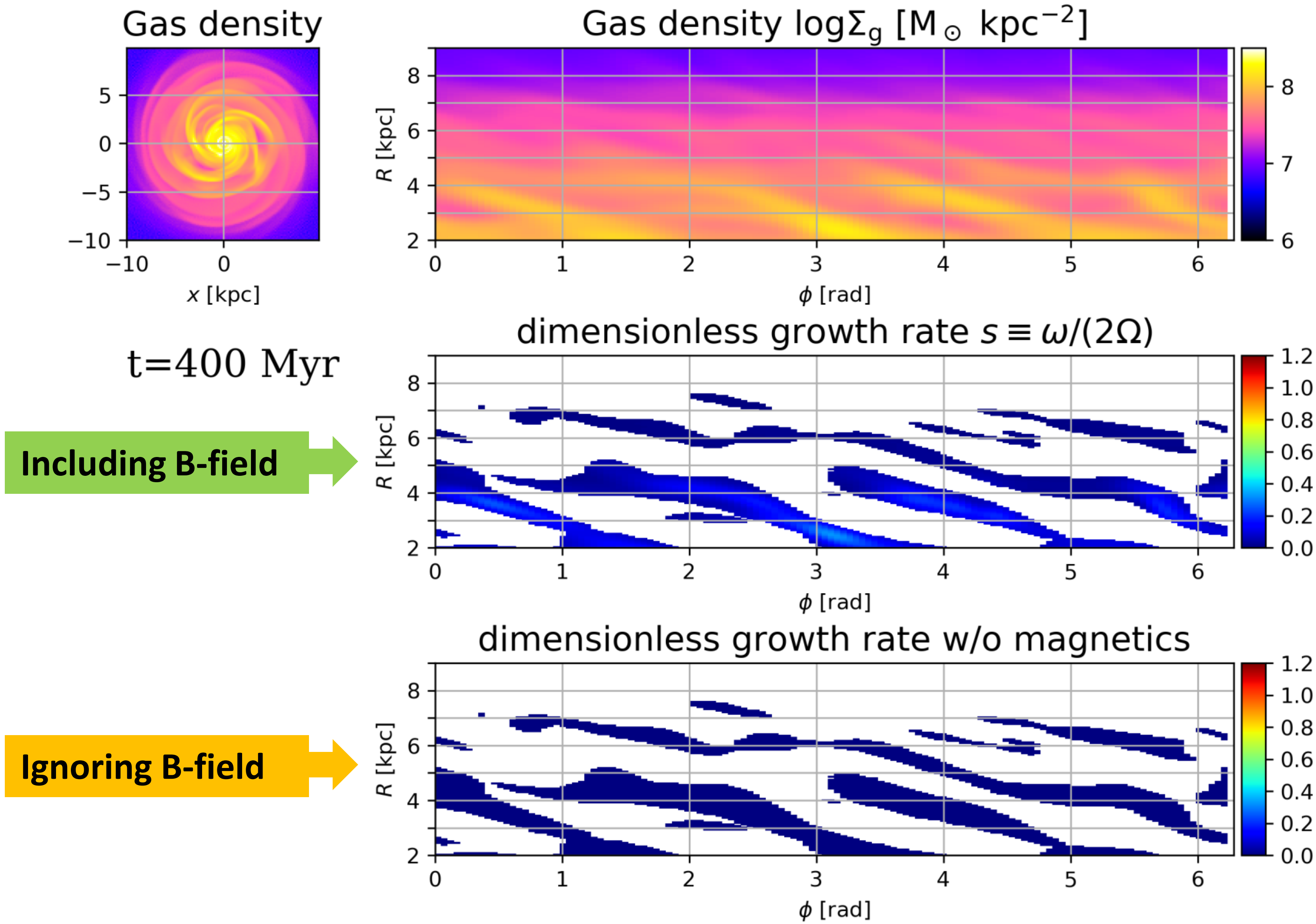
Ignoring B-field



Demonstration

The stable case

$\beta_{ini} = 100$



Toomre Instability (TI)

(e.g. Dekel et al. 2009)

v.s.

Spiral-Arm Instability (SAI)

(Inoue & Yoshida 2018a, 2018b)

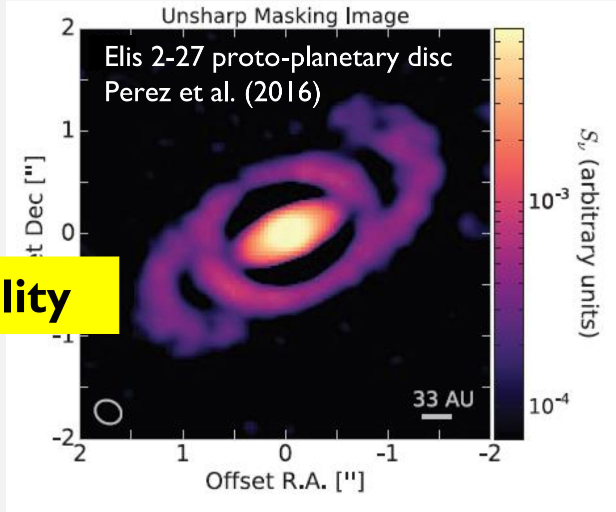
For low-z clumpy galaxies

Gravitational instability (GI) of discs

- GI can form structures in a disc.

Spiral arms

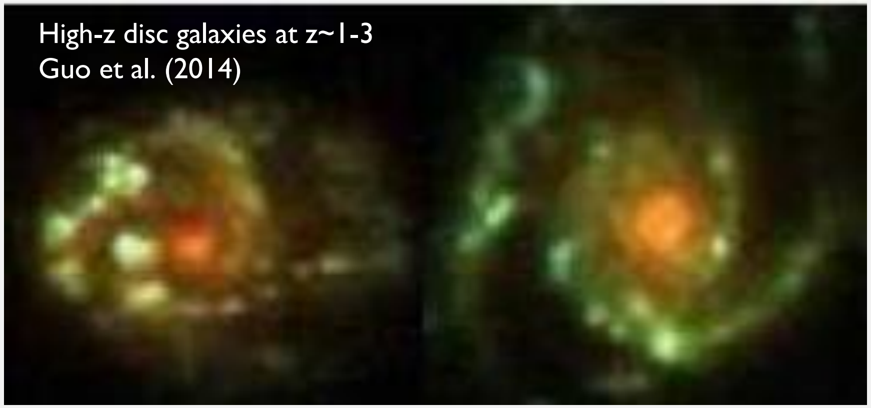
Toomre instbility



Proto-planets/
Giant clumps

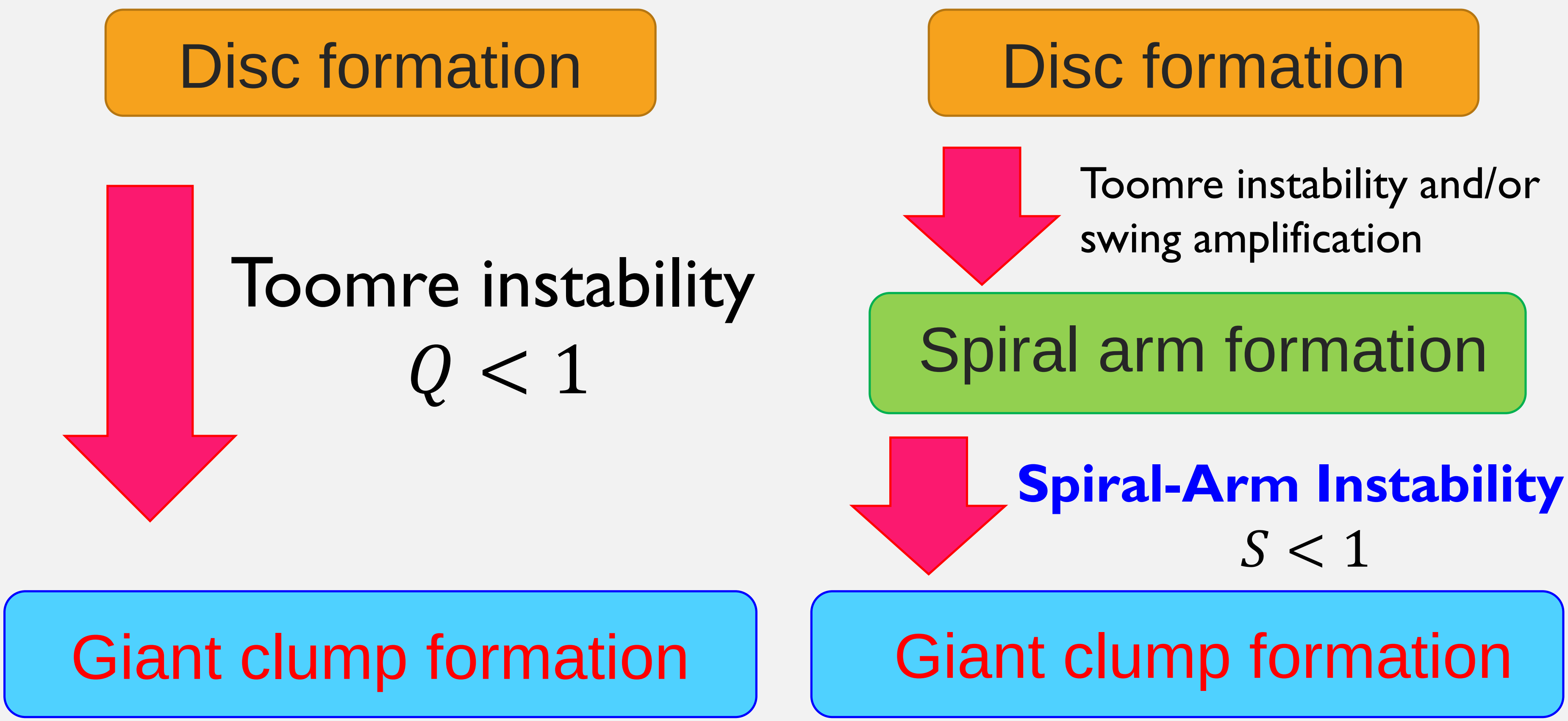
Toomre instability!!

Really??



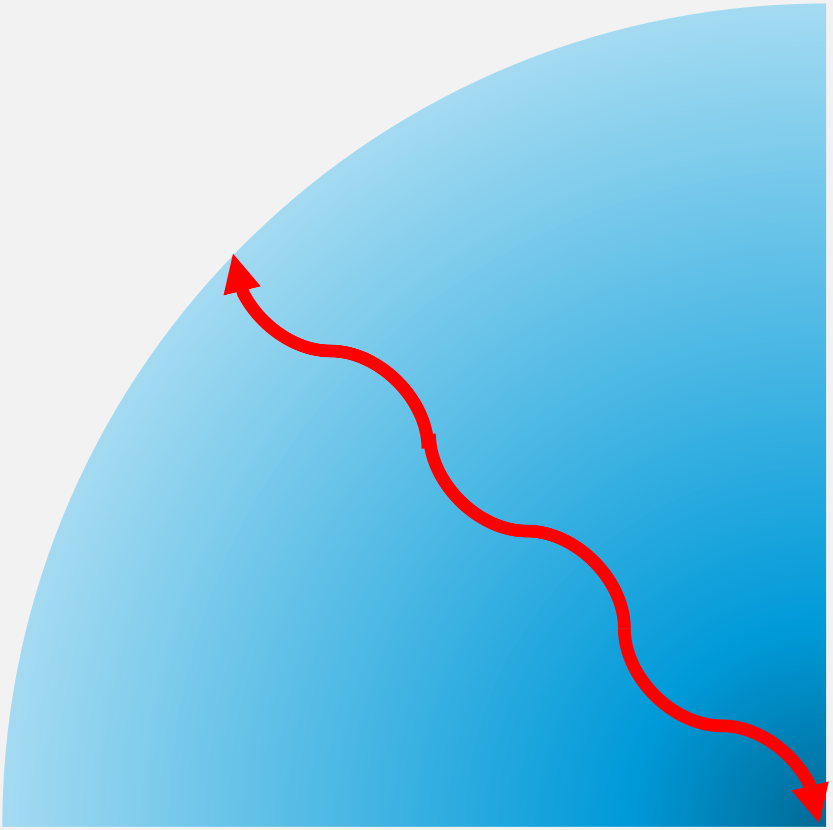
TI vs SAI

- Toomre Instability
- Spiral-Arm Instability



TI vs SAI

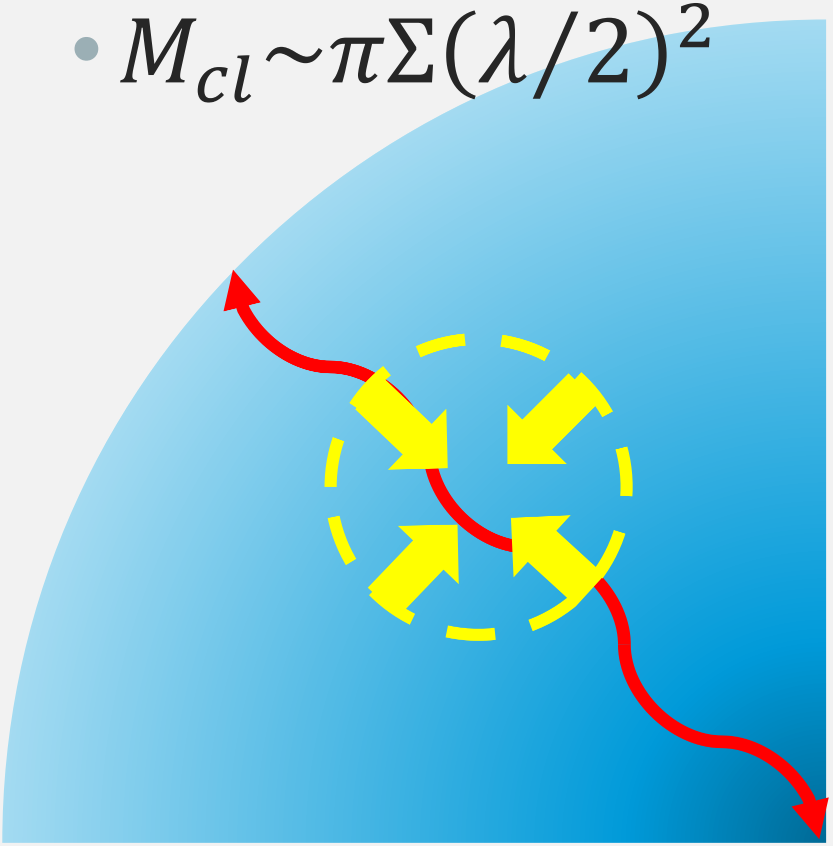
- Toomre Instability



- Spiral-Arm Instability

TI vs SAI

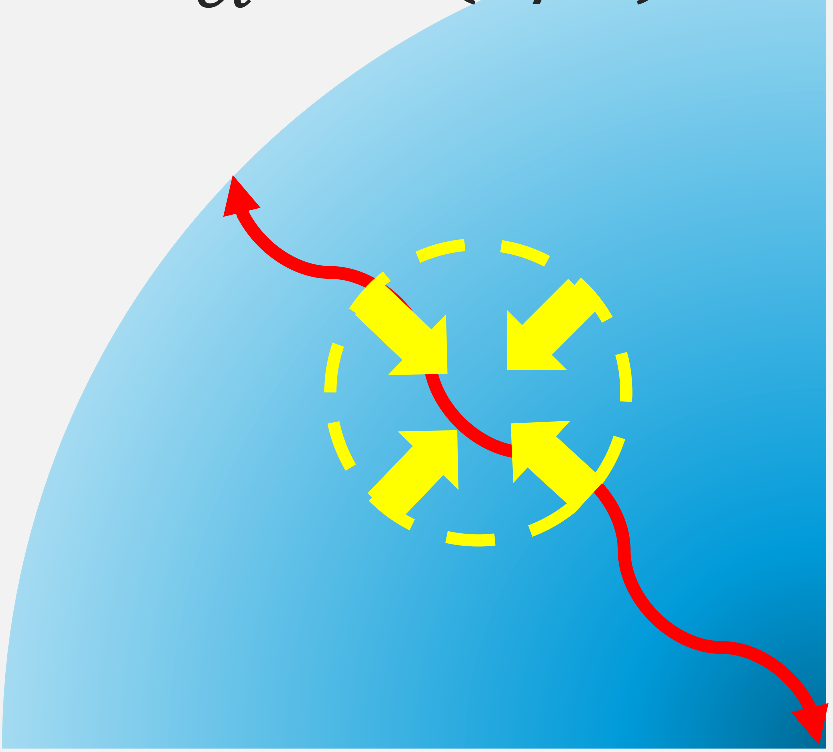
- Toomre Instability
  - **2D collapse**
  - $M_{cl} \sim \pi \Sigma (\lambda/2)^2$



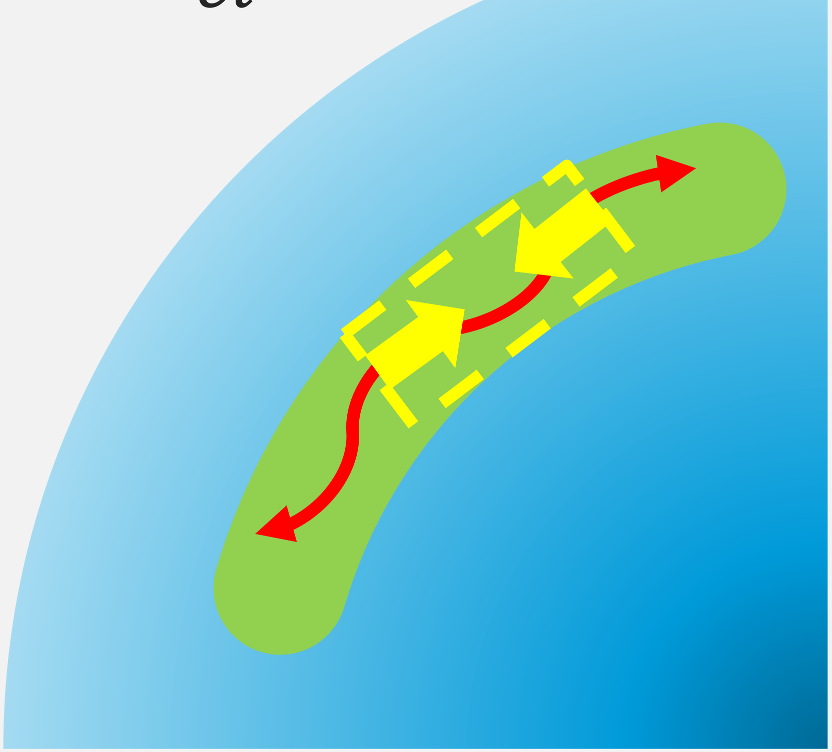
- Spiral-Arm Instability

TI vs SAI

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

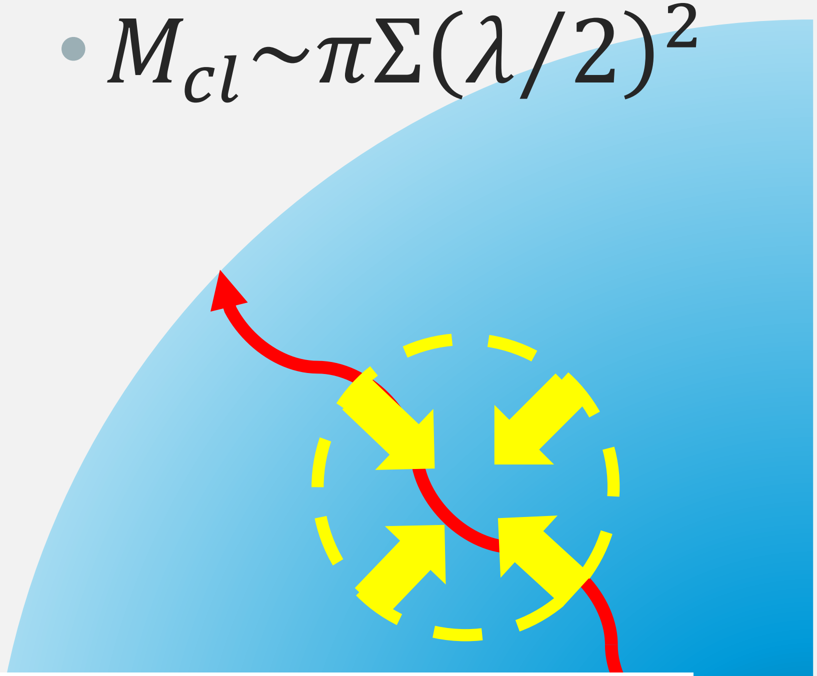


- Spiral-Arm Instability
  - **1D collapse**
  - $M_{cl} \sim \Sigma W \lambda$



TI vs SAI

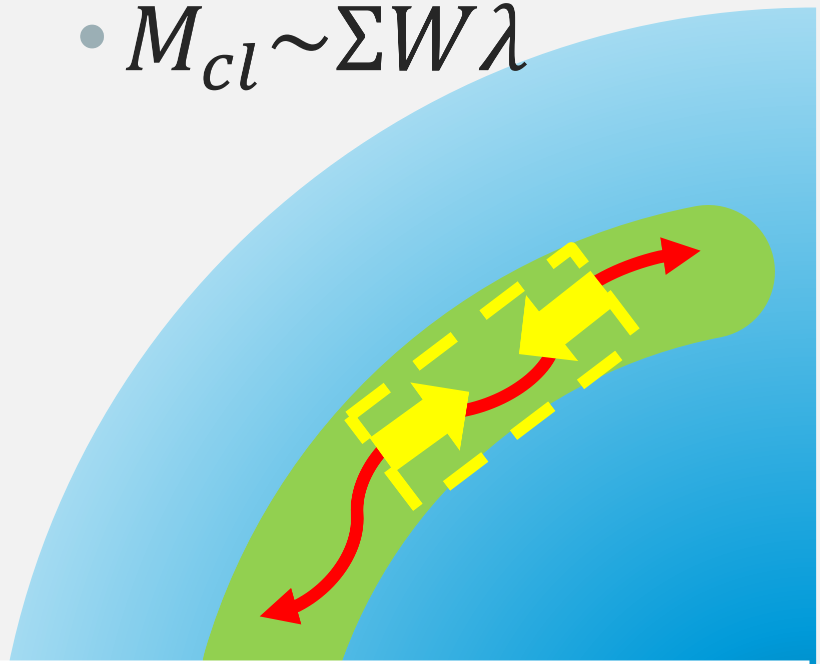
- Toomre Instability
  - **2D collapse**
  - $M_{cl} \sim \pi \Sigma (\lambda/2)^2$



When $Q \cong 1$,

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

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



When $S \cong 1$,

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

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:

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

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

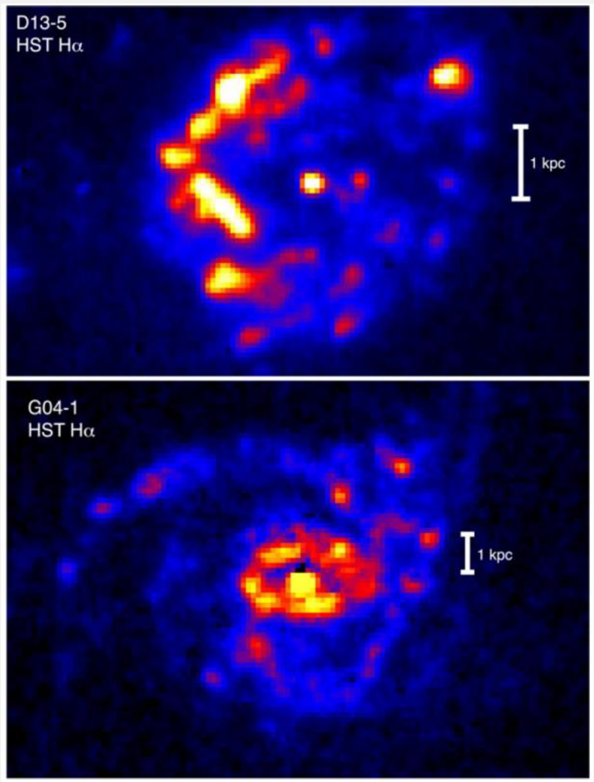
Toomre instability

expected scaling relation:

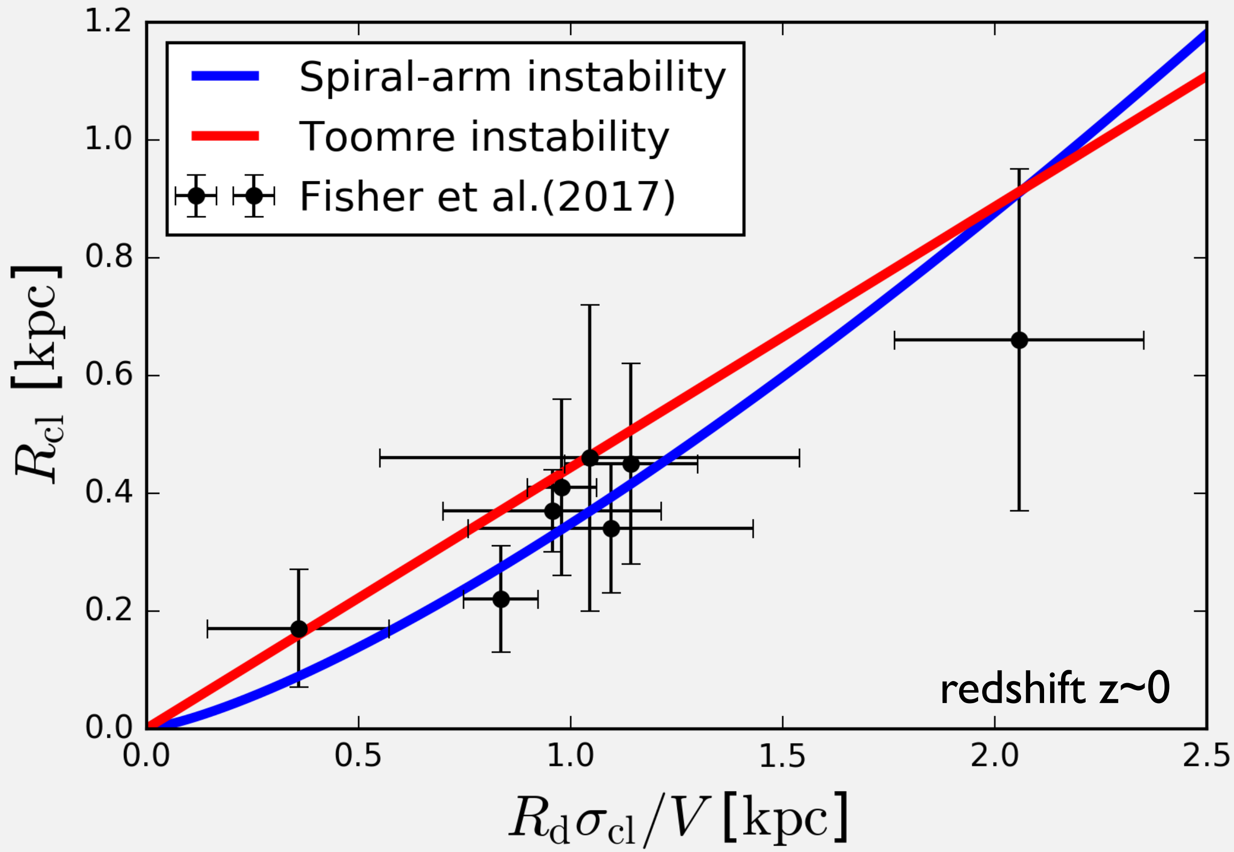
$$R_{\rm cl} \propto \frac{\sigma_{\rm cl}}{V} R_{\rm d}$$

$R_{\rm cl}$: 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.

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

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

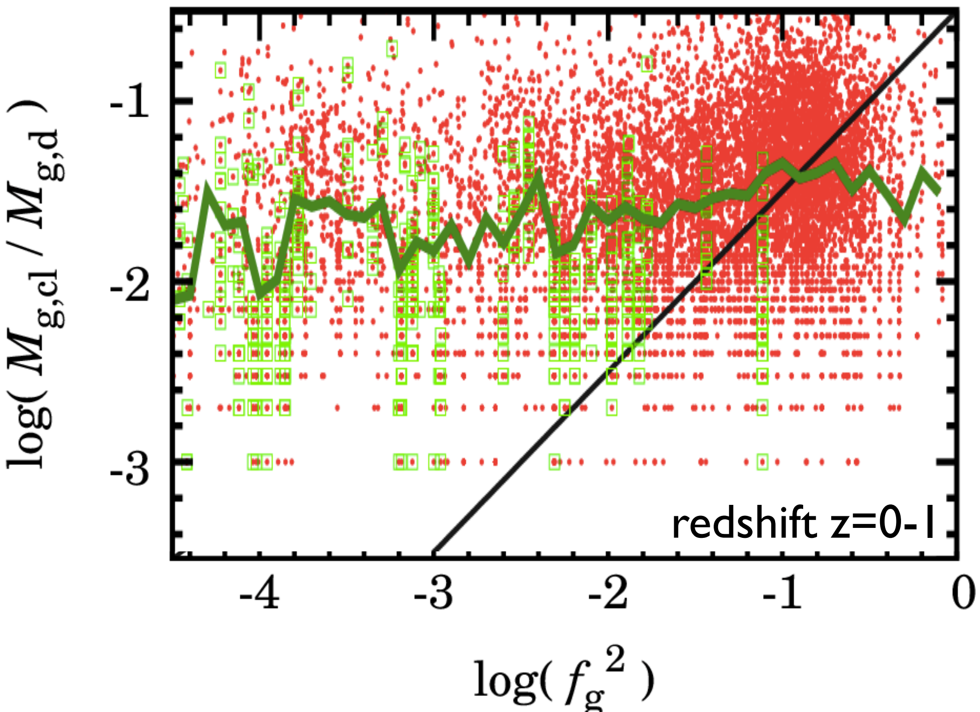
expected scaling relation:

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

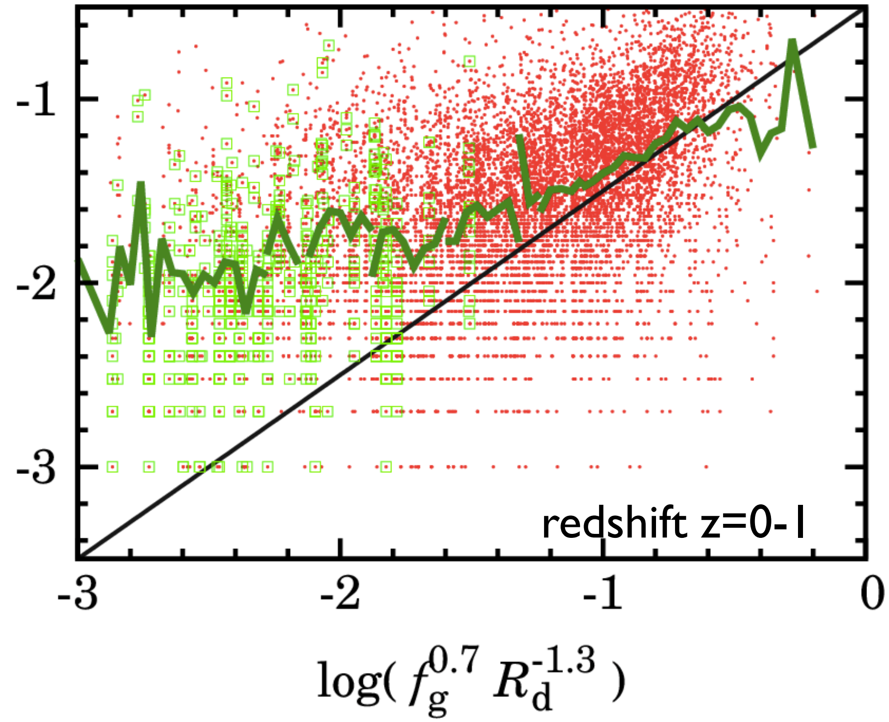
$R_{\rm cl}$: clump radius, $\sigma_{\rm cl}$:vel. disp. with in clump, $R_{\rm d}$: disc radius, V: disc rot. vel.

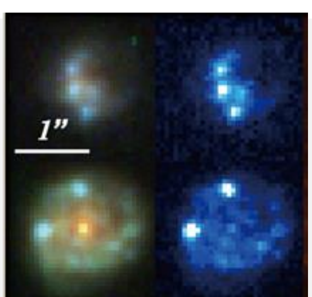
Scaling relations of high-z clumps

- Toomre Instability
- Spiral-Arm Instability



Shibuya & SI (in prep.)





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

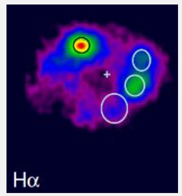
- Our SAI model appears better consistent with the observations of M_{cl}/M_d ~10% clumps.

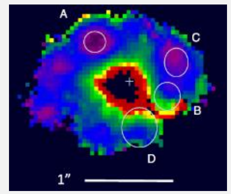
Transition of the clump formation mechanisms

time

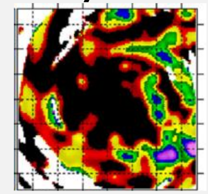
high z

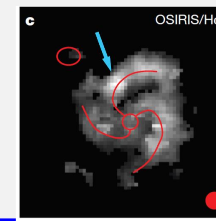
Toomre instability: $Q < 1$





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

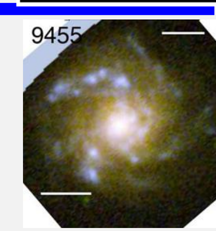




z~2-3

The onset of spiral galaxies

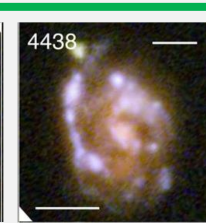
Low+12 @ z=2.1
Elmegreen+14 @ z~1.8
Yuan+17 @ z>2.5



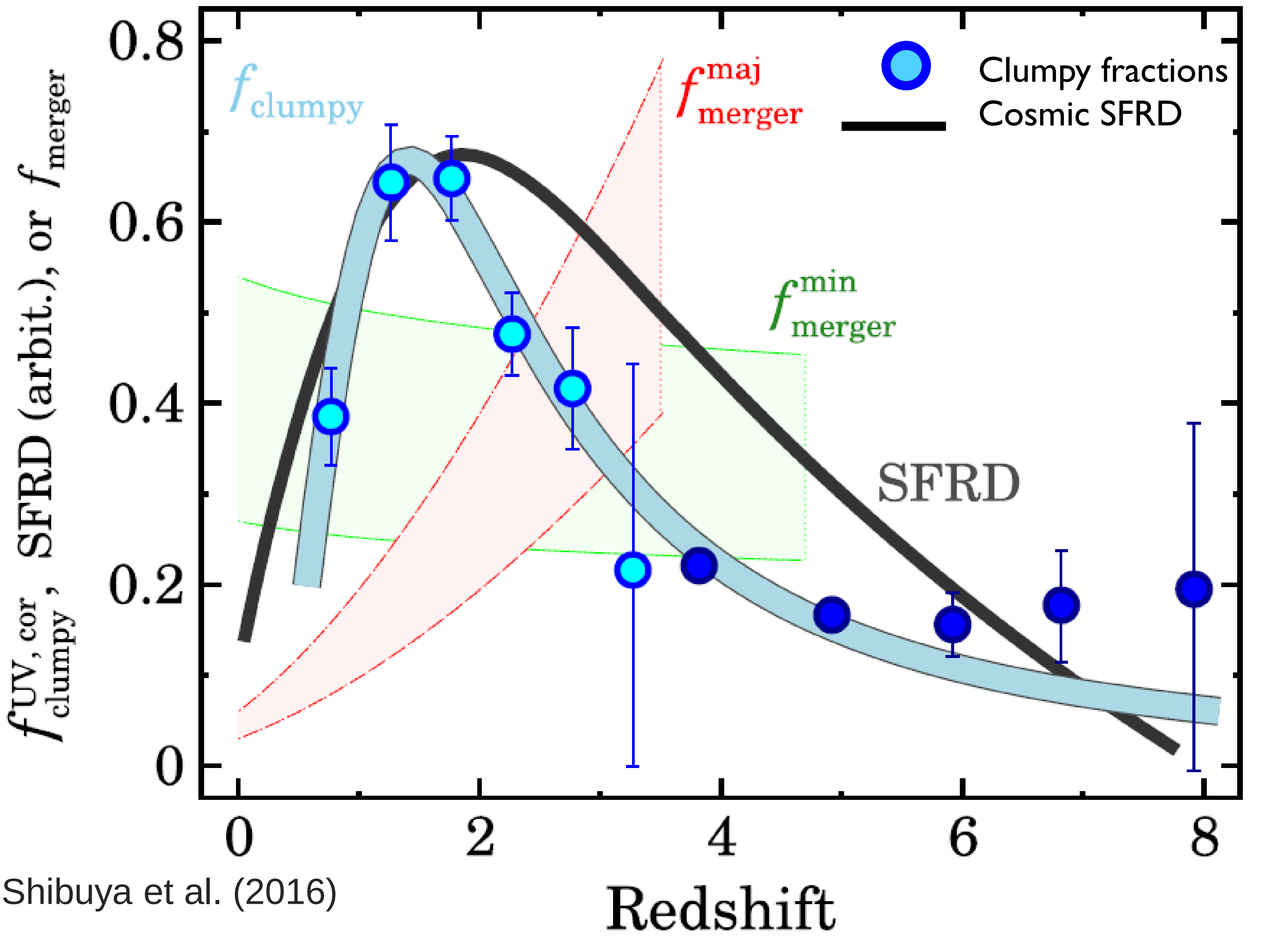
z~1

Spiral-arm instability: $S < 1$

z=0

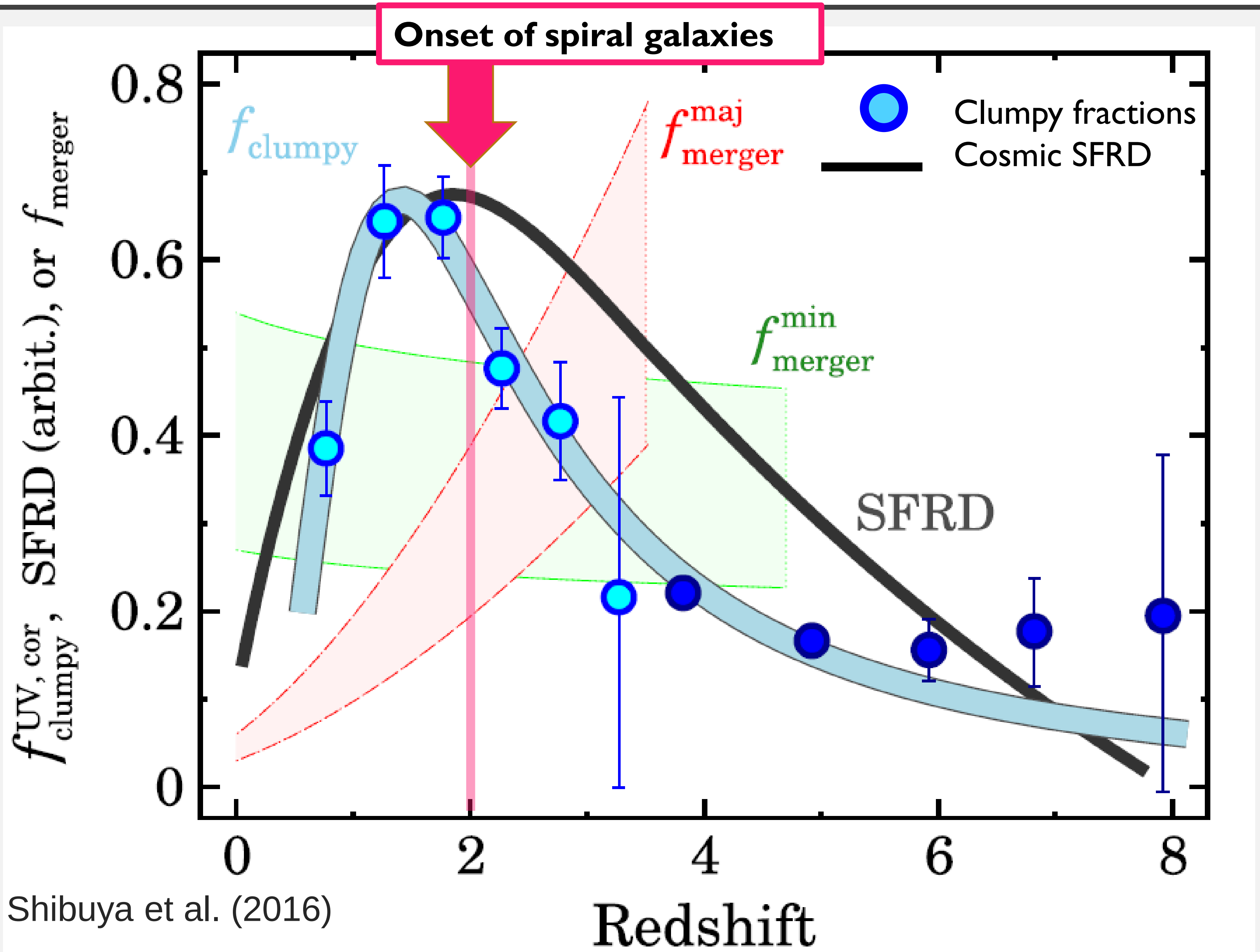


Clumpy fraction and cosmic SFR



- Shibuya et al. (2016)

Clumpy fraction and cosmic SFR



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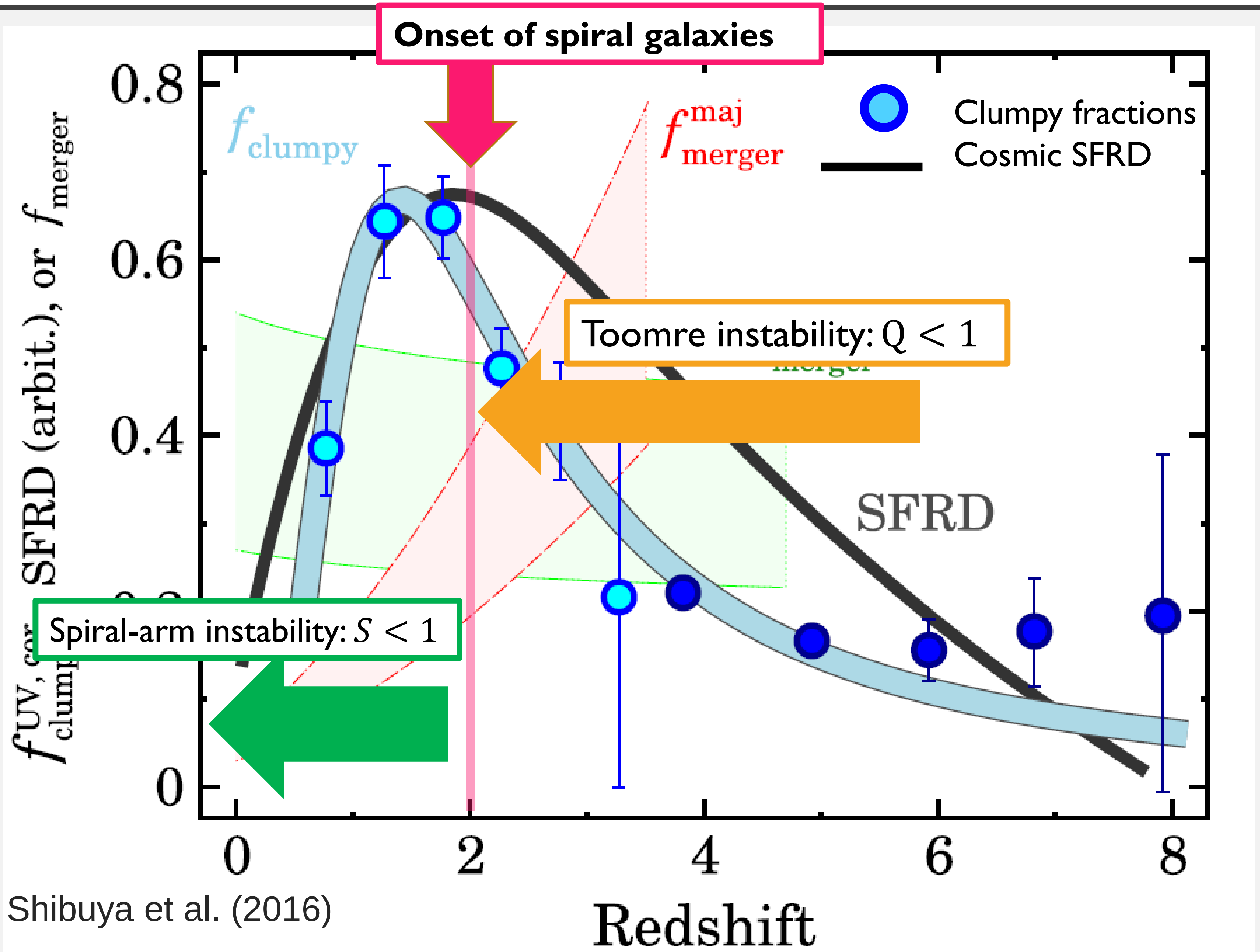
Clumpy fraction and cosmic SFR



- 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