Spiral-arm instability: Magnetic destabilization

Shigeki Inoue

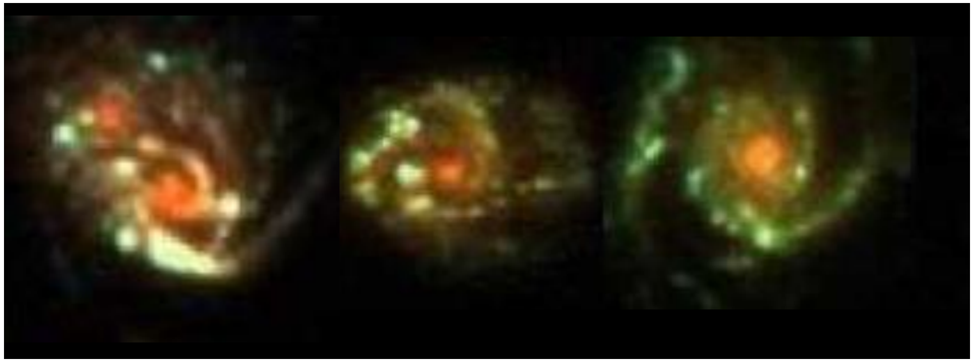
Naoki Yoshida

(Kavli IPMU / U.Tokyo)

Clumpy galaxies

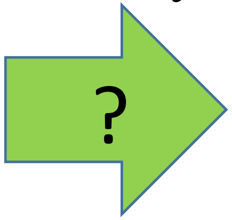
- Observed in the high-z universe（z > 1）
  - clump clusters / chain galaxies

in the high-z

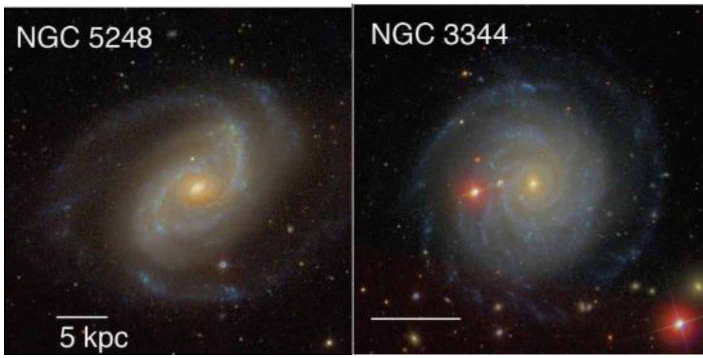


with HST　Guo et al. (2014)

$\sim 10^9$ yr



in the local universe

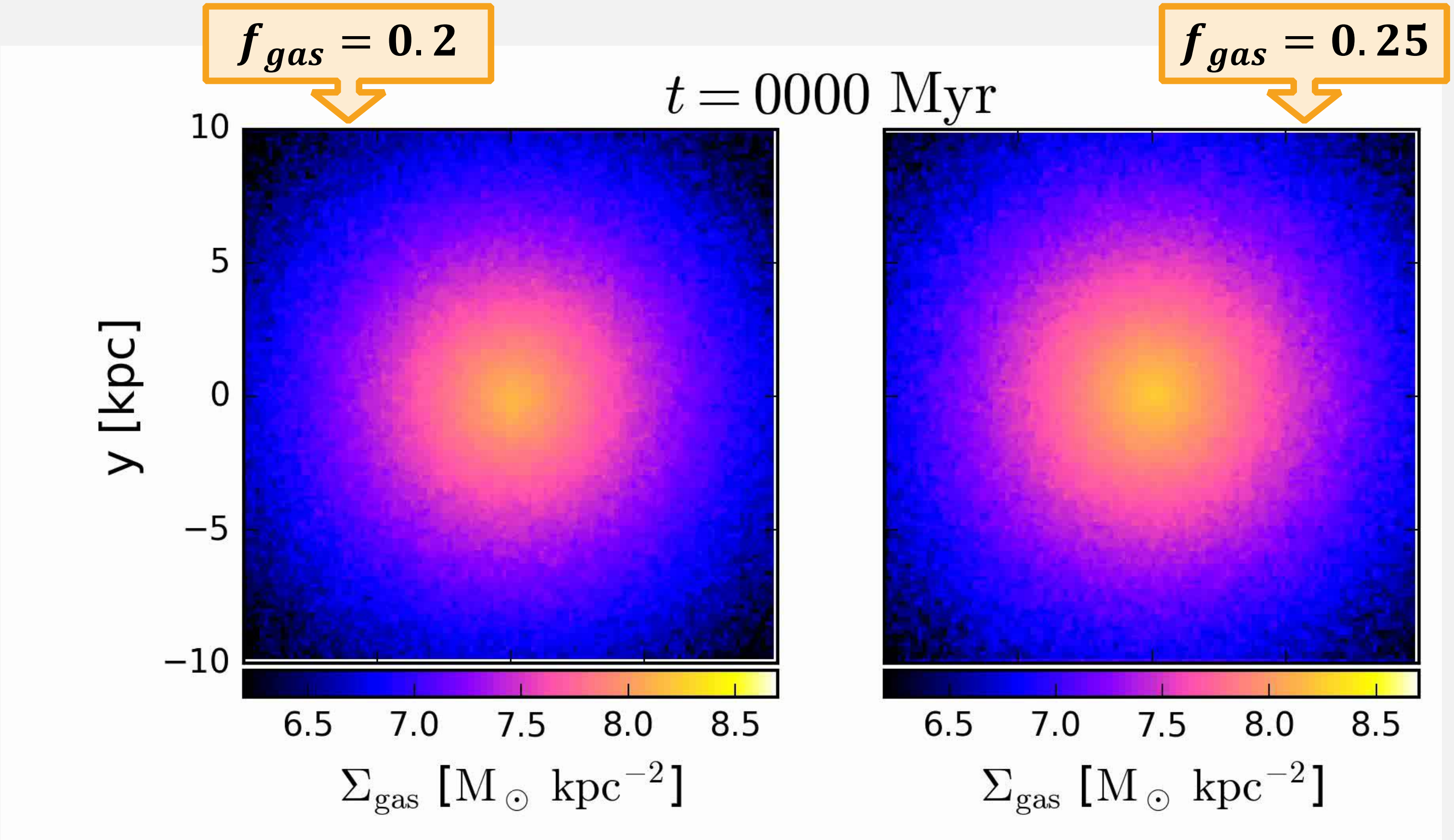


Elmegreen et al. (2013)

- \`Clumpy’ galaxies can be formative stages of spiral galaxies.
  - \`Giant clumps’ (~ $10^{8\text{-}9}$ $M_\odot$ at the largest)
  - Clumpy galaxies account for ~ 30-50 % at z=1-3
    - Tadaki+14, Livermore+15, Guo+15

In this workshop last year…

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



$f_{gas} = 0.2$

$f_{gas} = 0.25$

In this workshop last year...

- One can obtain the dispersion relation for the perturbations,

$$\omega^2 = \Big(\underbrace{c_s^2}_{\text{Pressure}} - \underbrace{\pi G f(kW)\Upsilon}_{\text{Self-gravity}}\Big) k^2 + \underbrace{4\Omega^2}_{\text{Coriolis force}}.$$

(cf. Takahashi et al. 2016)

- When $\omega^2 < 0$, the spiral is unstable.

- Considering this in the boundary case $\omega^2 = 0$, the instability criterion can be defined as

- ***Spiral-arm instability***

  (Inoue & Yoshida 2018)

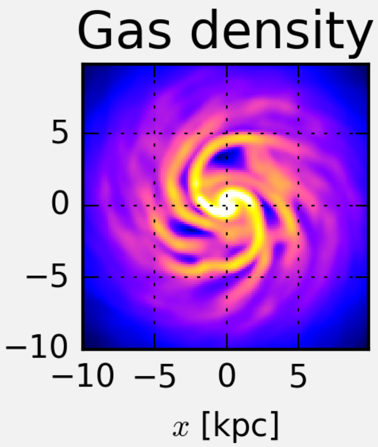
$$\boxed{S \equiv \frac{c_s^2 k^2 + 4\Omega^2}{\pi G f(kW)\Upsilon k^2} < 1.}$$

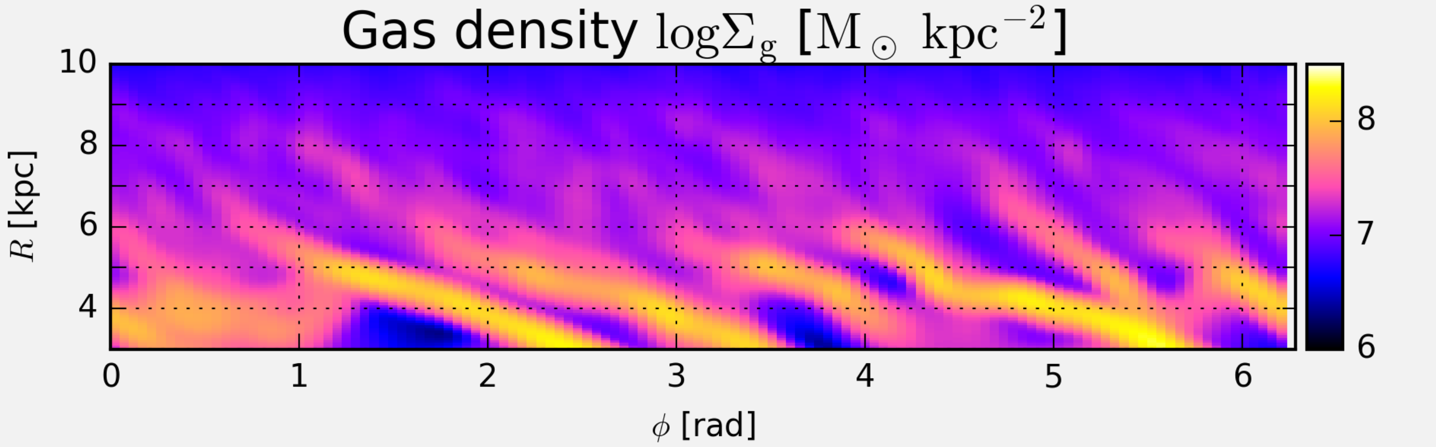
Line-mass: $\Upsilon \equiv 1.41\Sigma W,$ Half-width of spiral arm: W

$$f(kW) \equiv [K_0(kW)L_{-1}(kW) + K_1(kW)L_0(kW)],$$

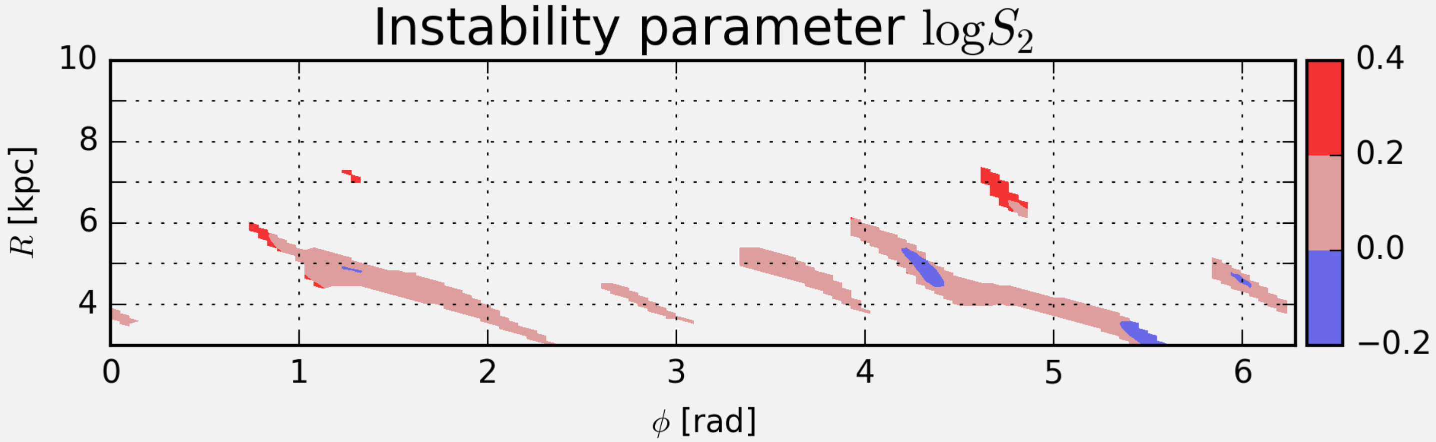
Demonstration

The fragmenting case


Gas density


Gas density $\log\Sigma_{\rm g}$ $[\rm M_\odot\ kpc^{-2}]$

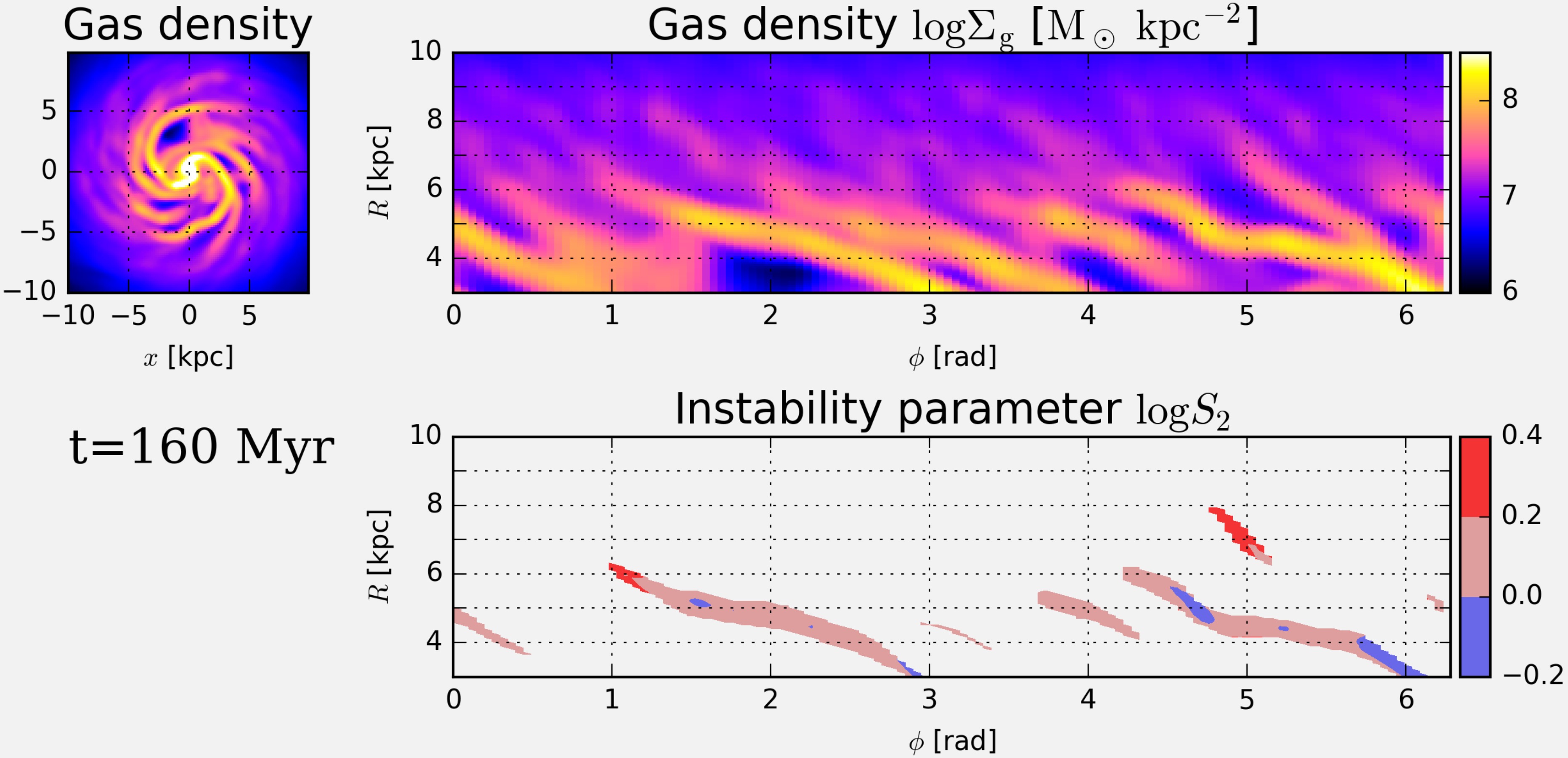
t=150 Myr


Instability parameter $\log S_2$

Inoue & Yoshida (2018)

Demonstration

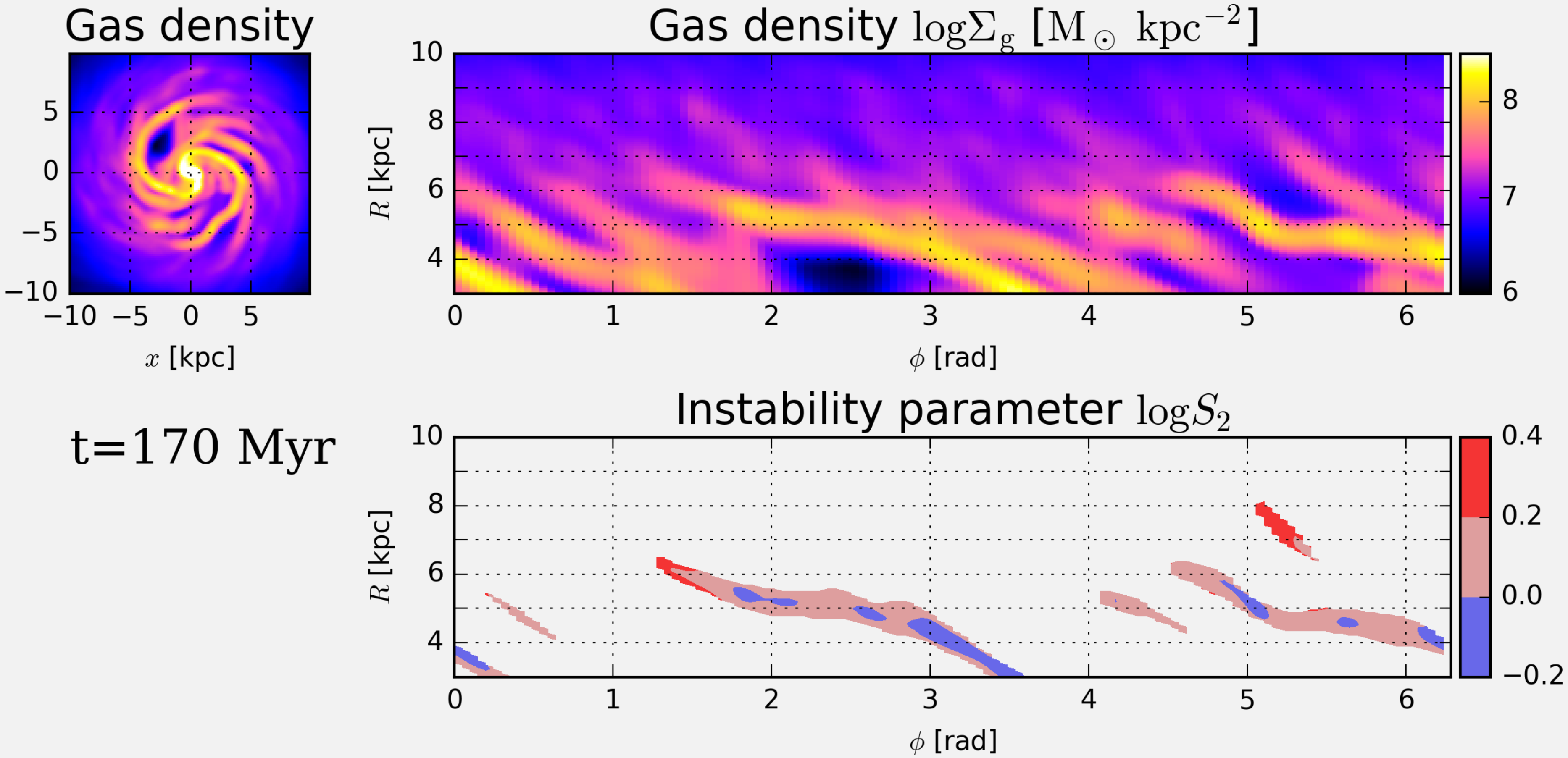
The fragmenting case



Inoue & Yoshida (2018)

Demonstration

The fragmenting case

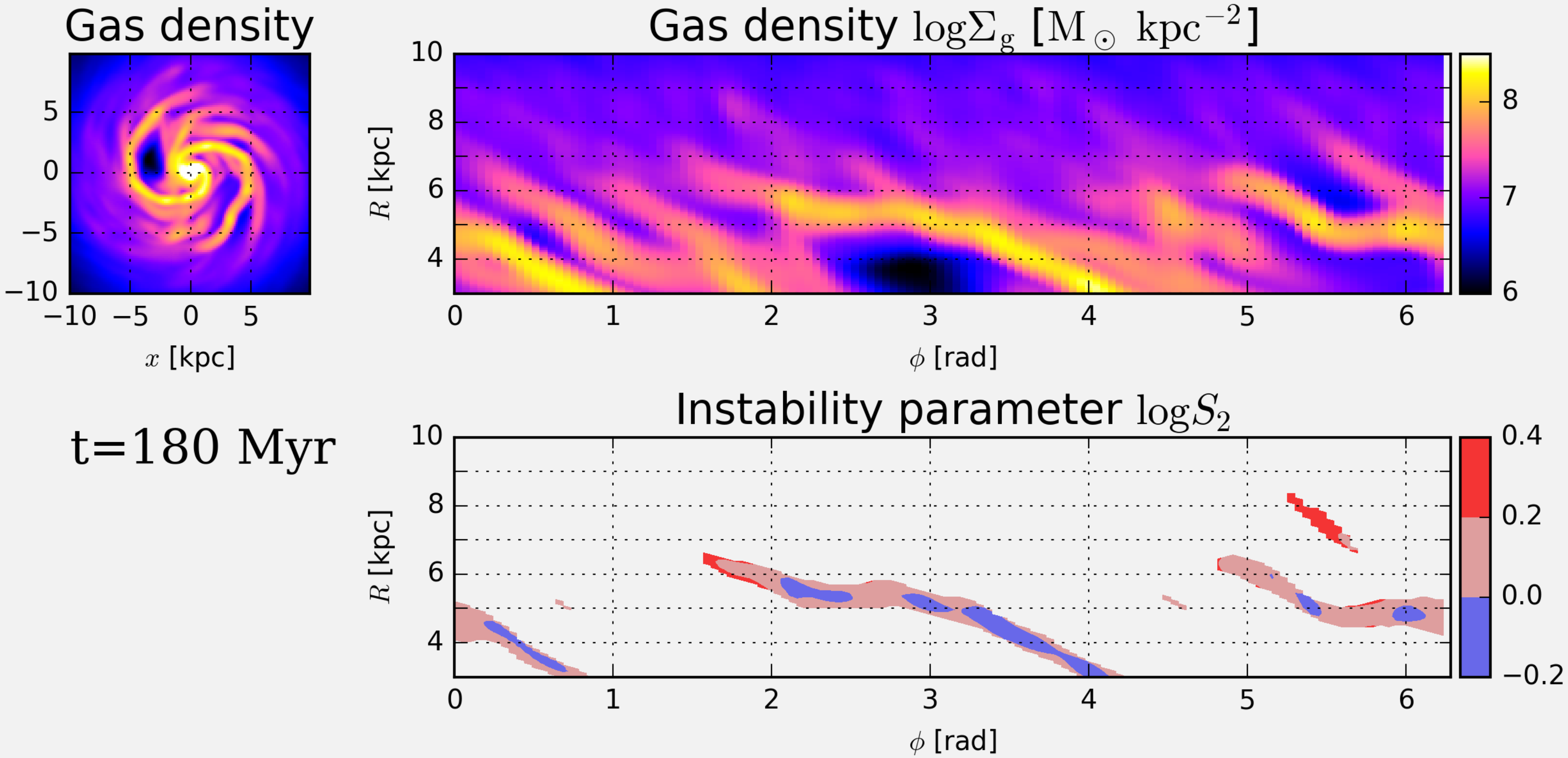


t=170 Myr

Inoue & Yoshida (2018)

Demonstration

The fragmenting case

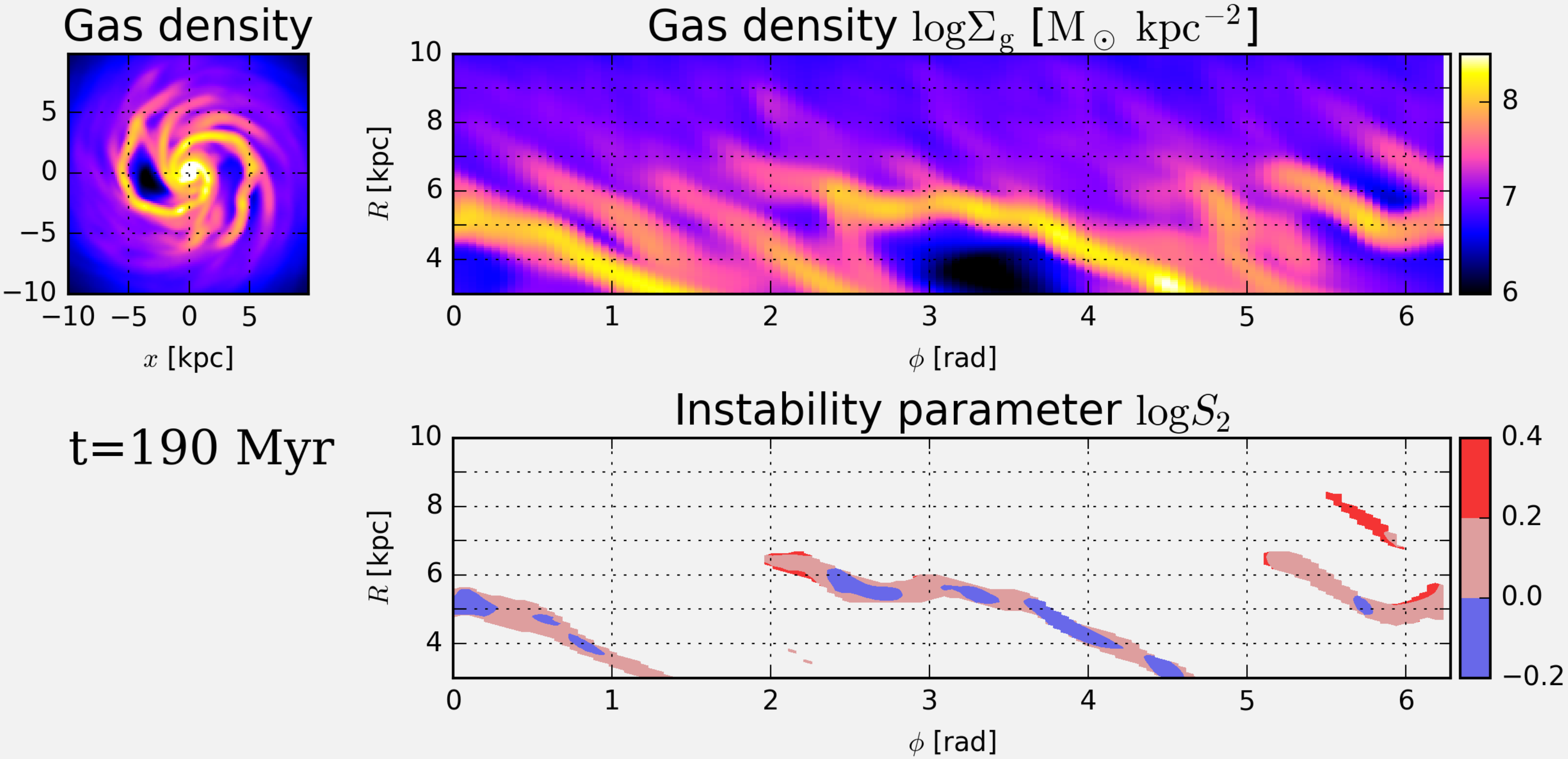


t=180 Myr

Inoue & Yoshida (2018)

Demonstration

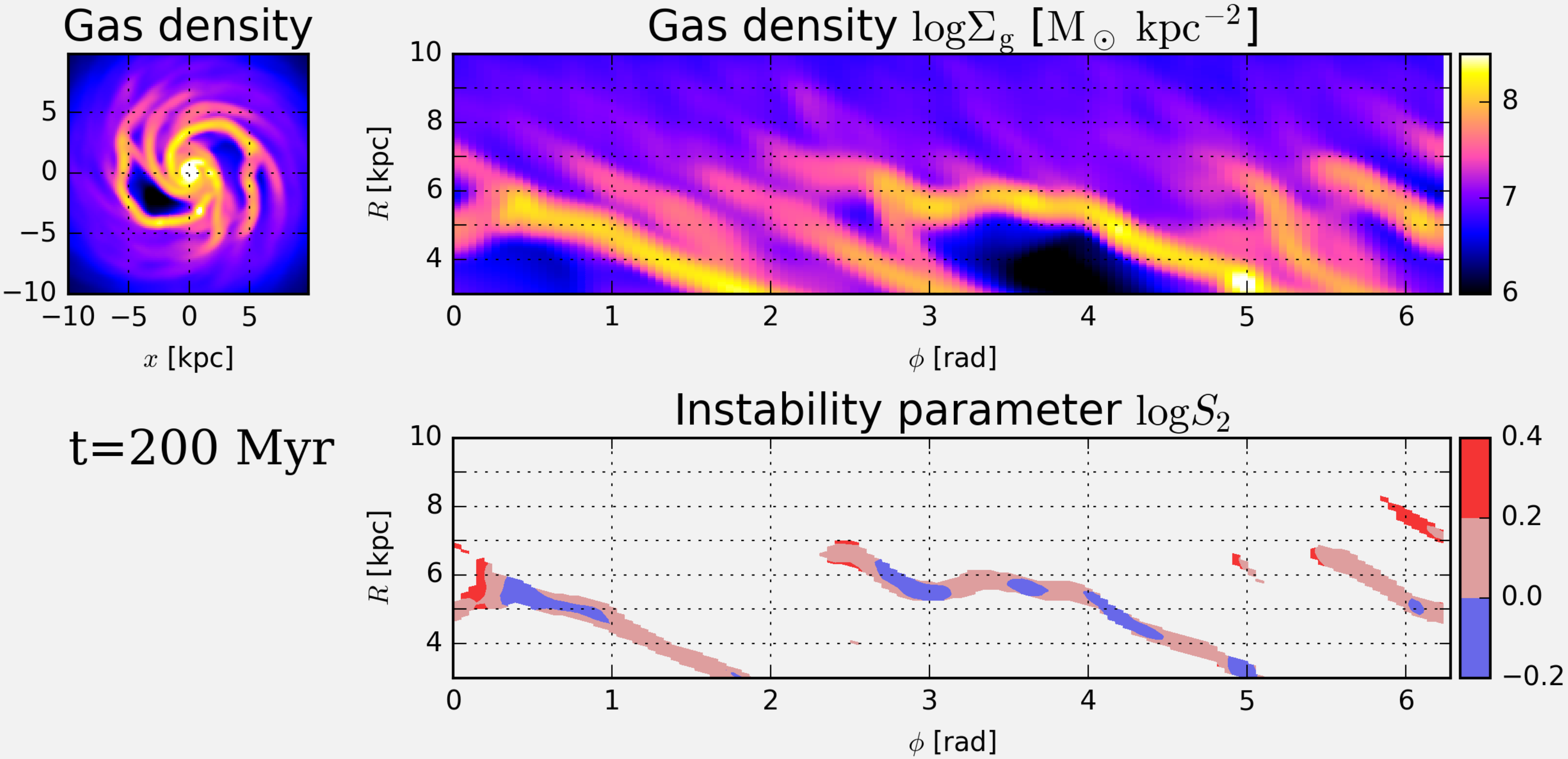
The fragmenting case



Inoue & Yoshida (2018)

Demonstration

The fragmenting case



Gas density

Gas density $\log \Sigma_g$ $[\mathrm{M}_\odot\ \mathrm{kpc}^{-2}]$

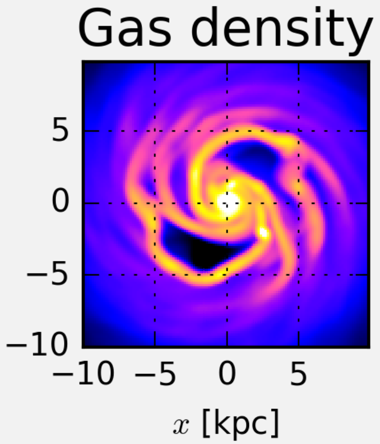
Instability parameter $\log S_2$

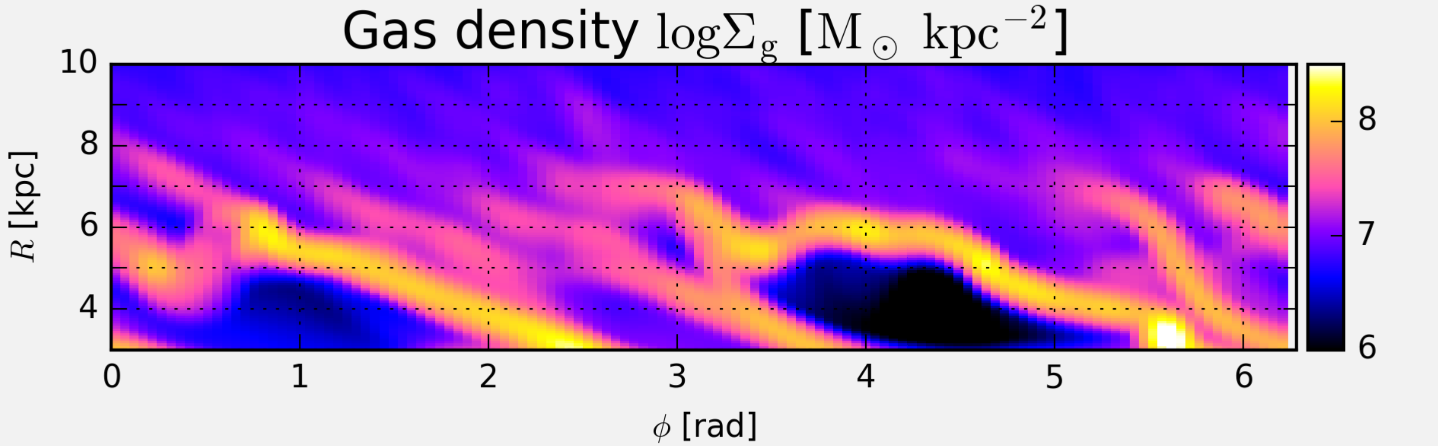
t=200 Myr

Inoue & Yoshida (2018)

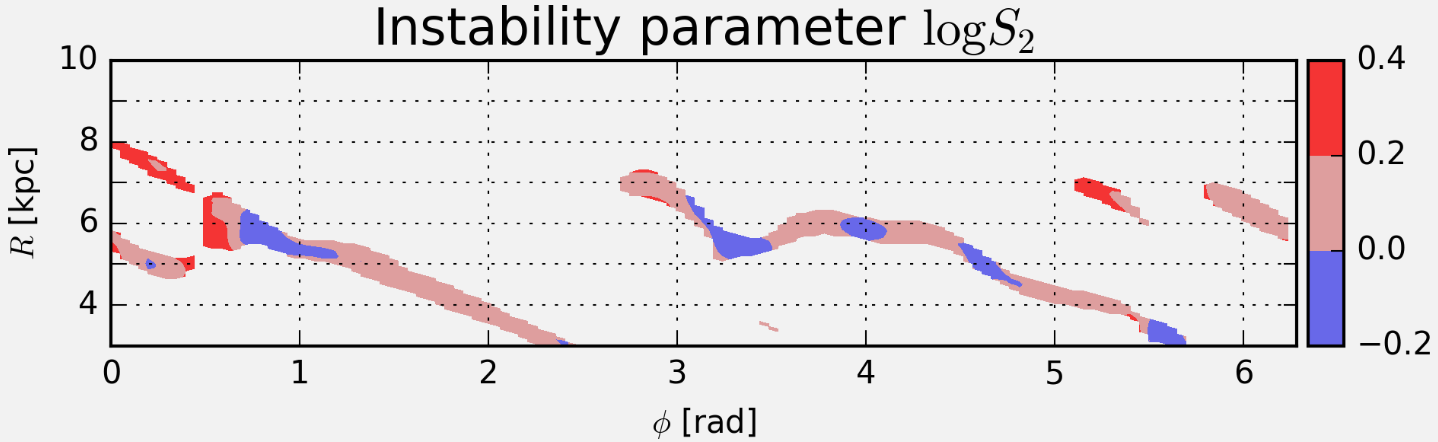
Demonstration

The fragmenting case





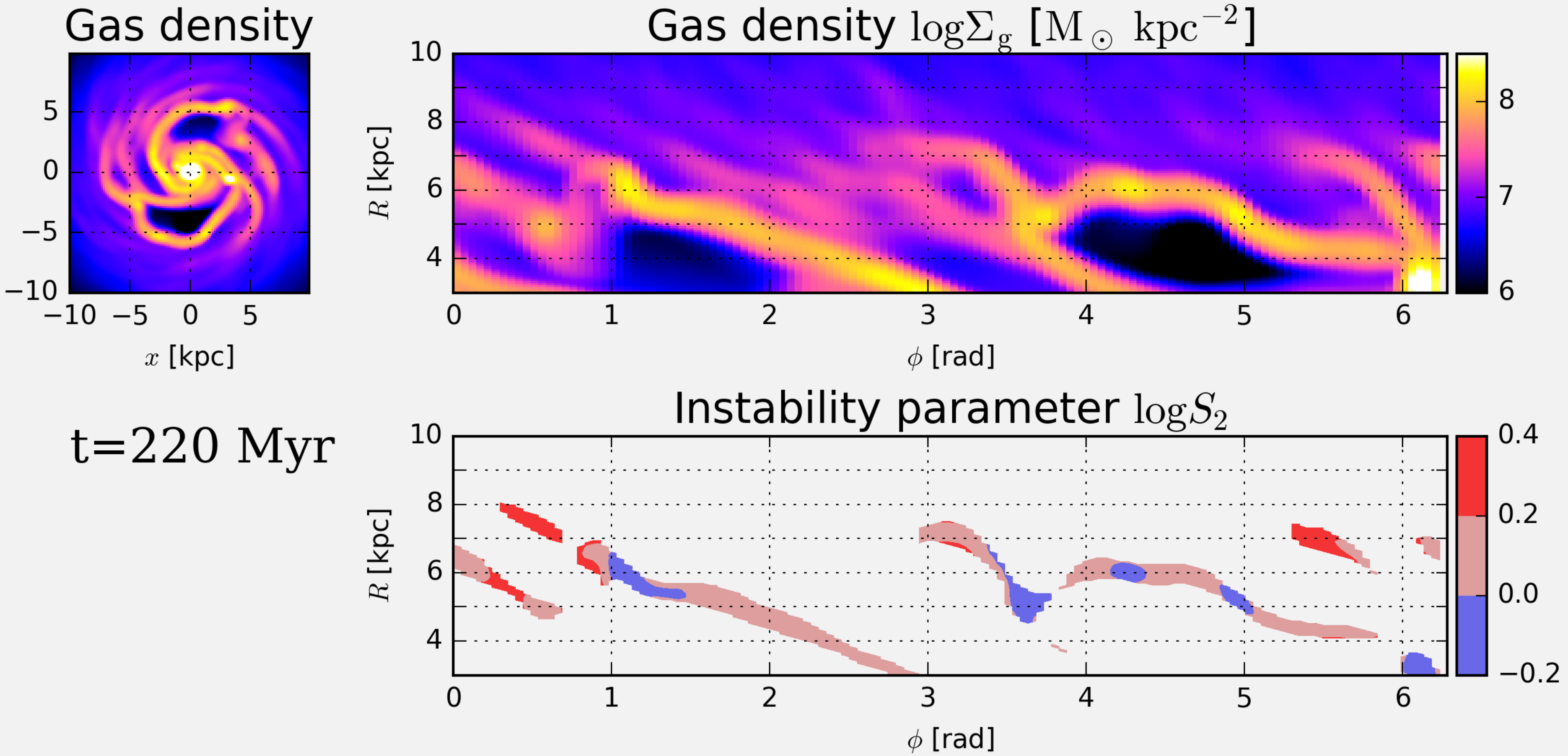
t=210 Myr



Inoue & Yoshida (2018)

Demonstration

The fragmenting case

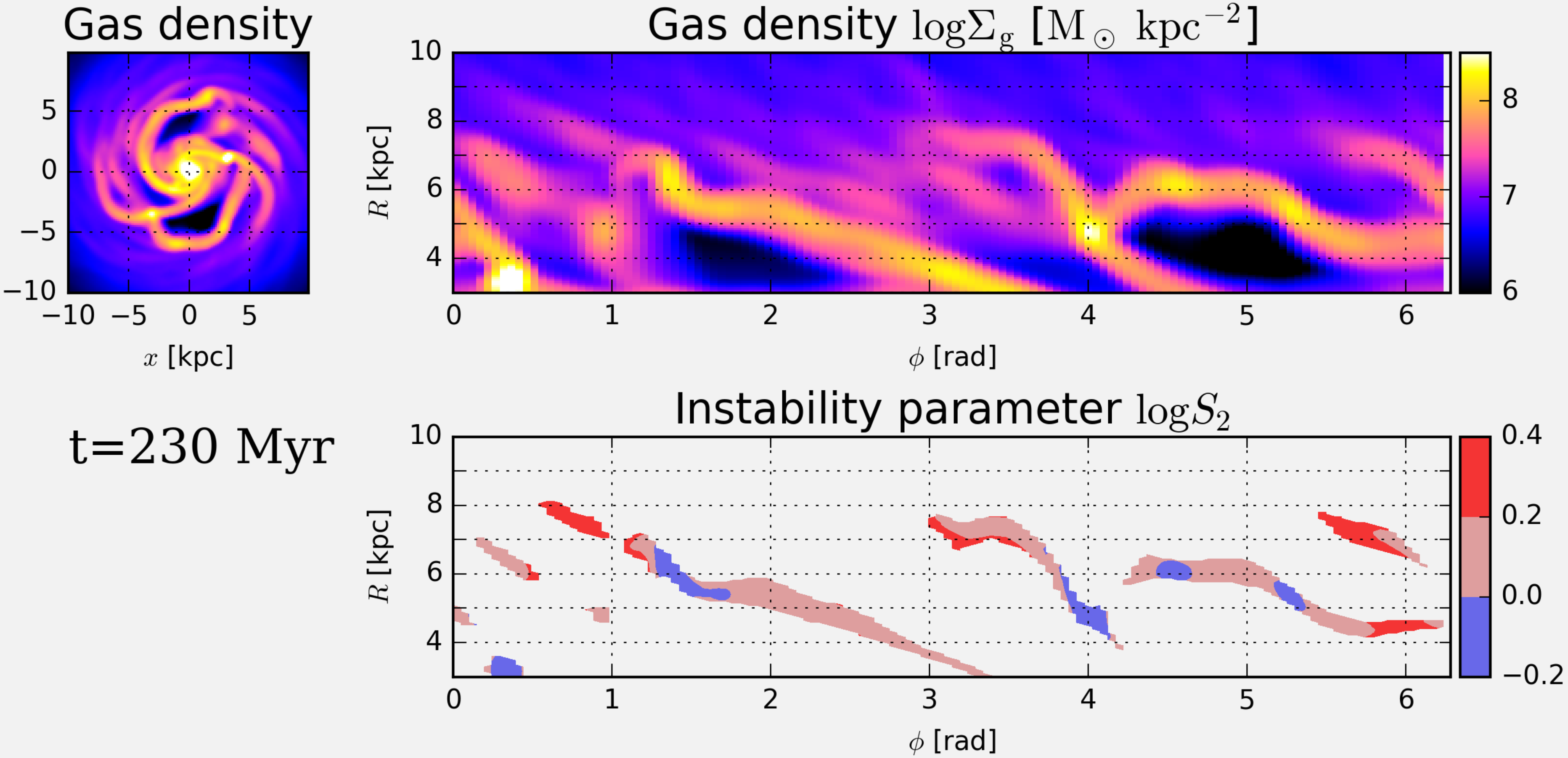


t=220 Myr

Inoue & Yoshida (2018)

Demonstration

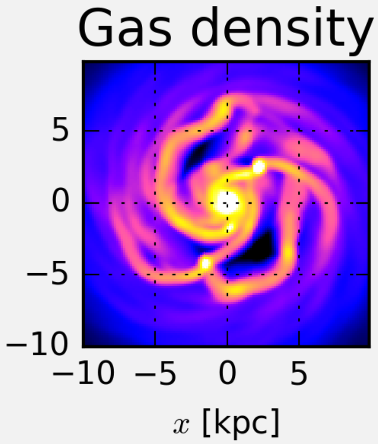
The fragmenting case

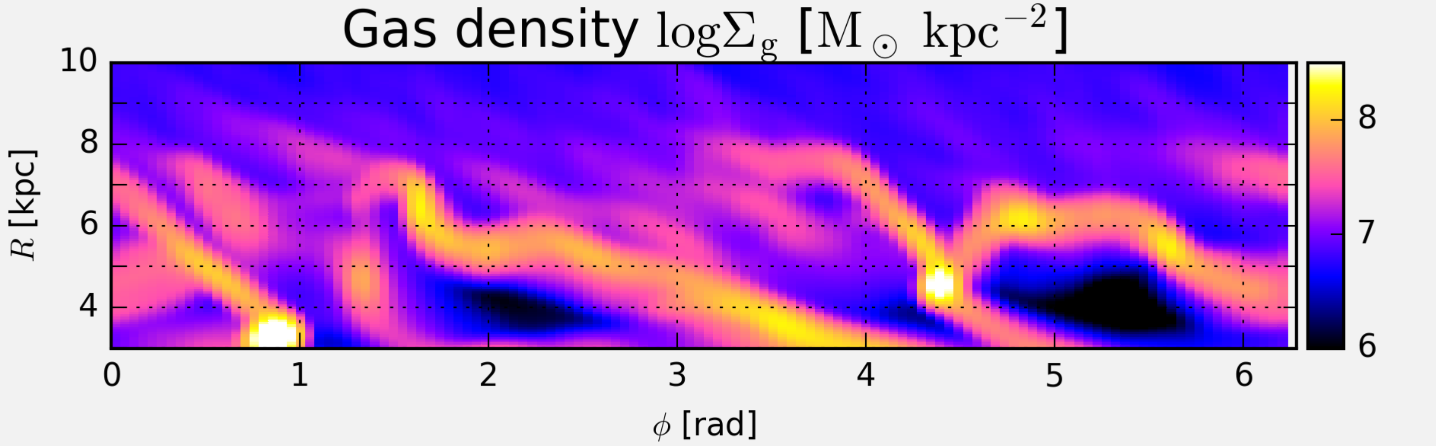


Inoue & Yoshida (2018)

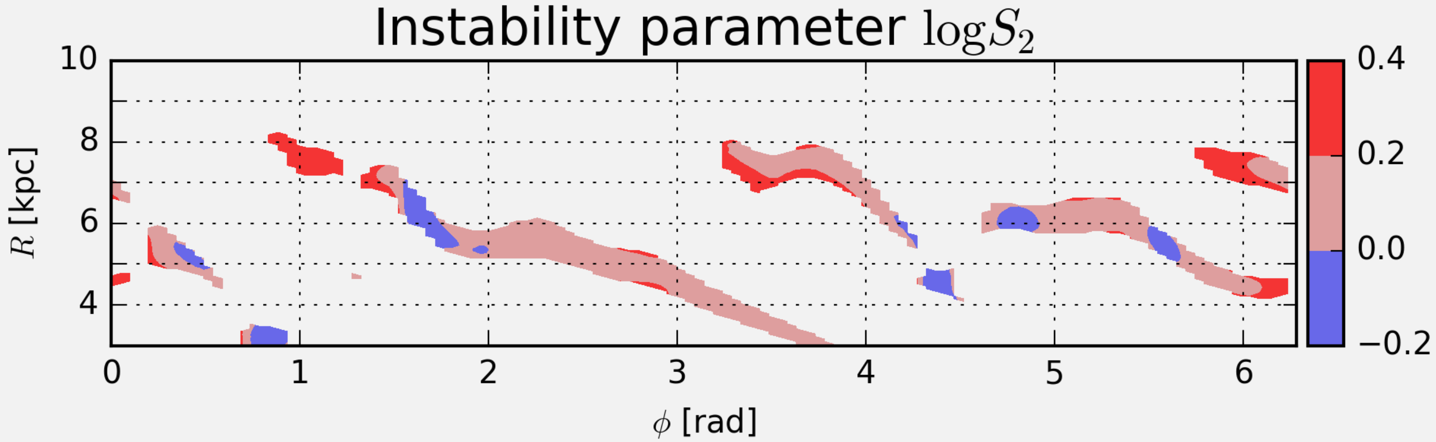
Demonstration

The fragmenting case


Gas density


Gas density $\log\Sigma_{\rm g}$ $[{\rm M}_\odot\ {\rm kpc}^{-2}]$

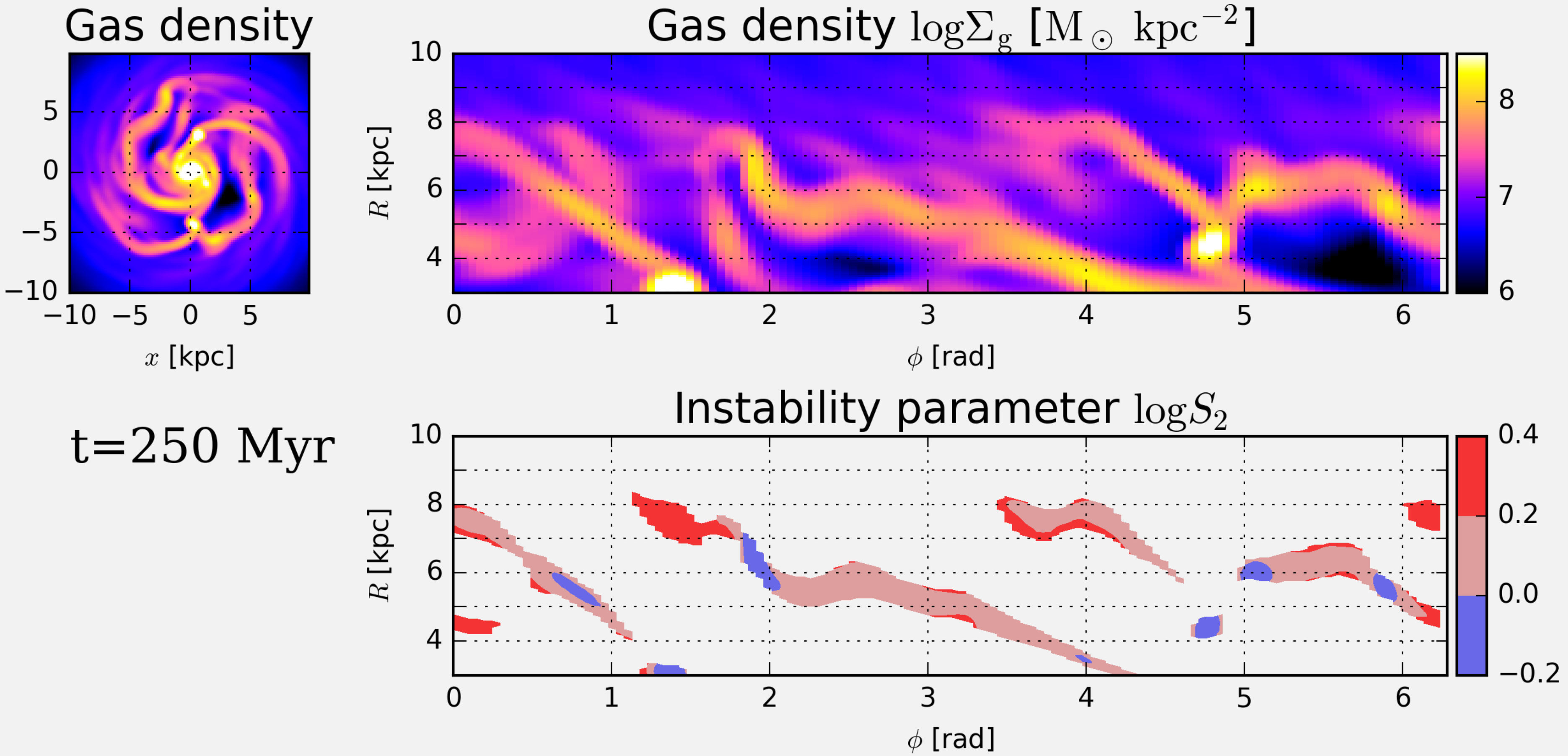
t=240 Myr


Instability parameter $\log S_2$

Inoue & Yoshida (2018)

Demonstration

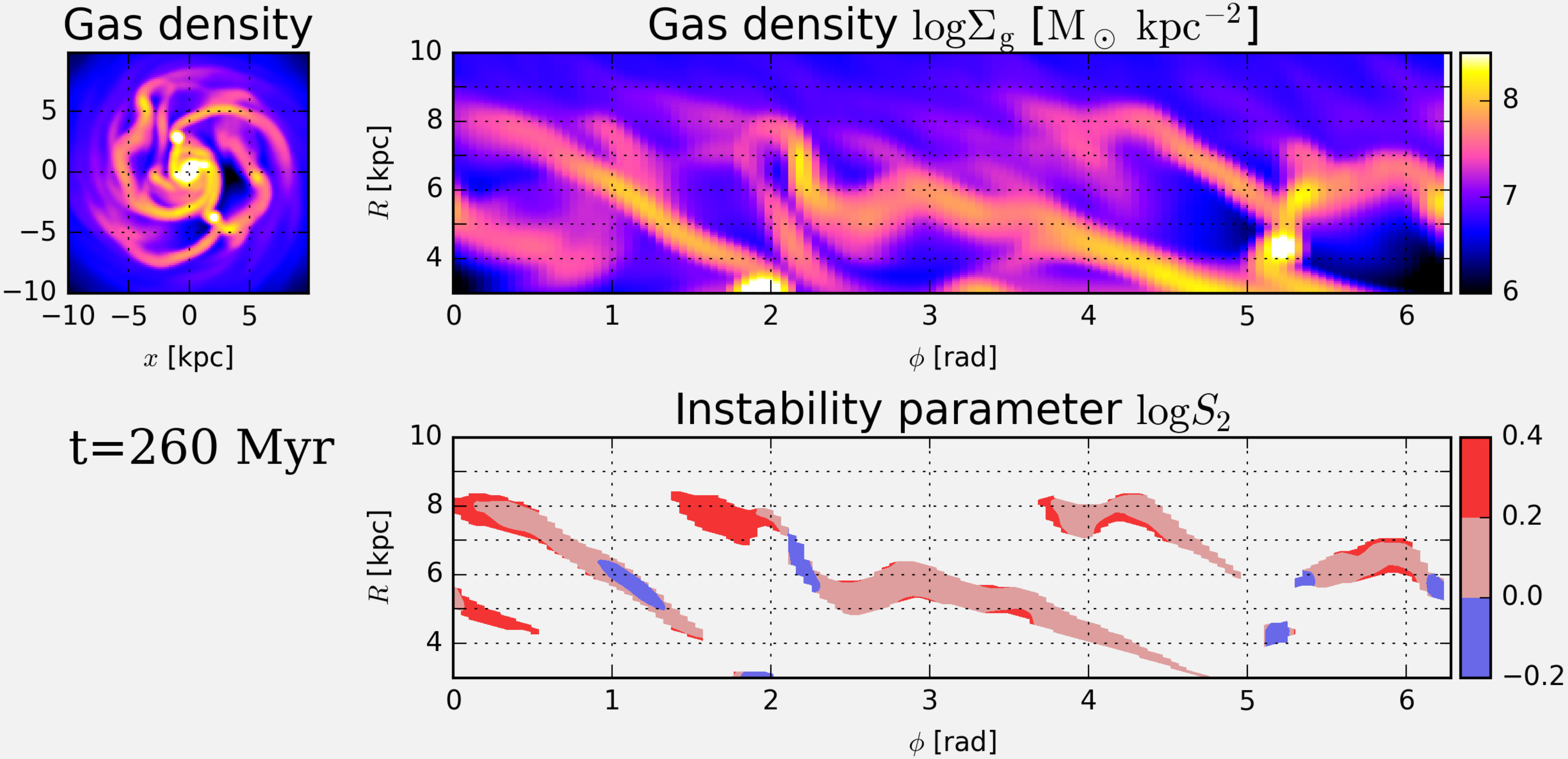
The fragmenting case



Inoue & Yoshida (2018)

Demonstration

The fragmenting case



t=260 Myr

Inoue & Yoshida (2018)

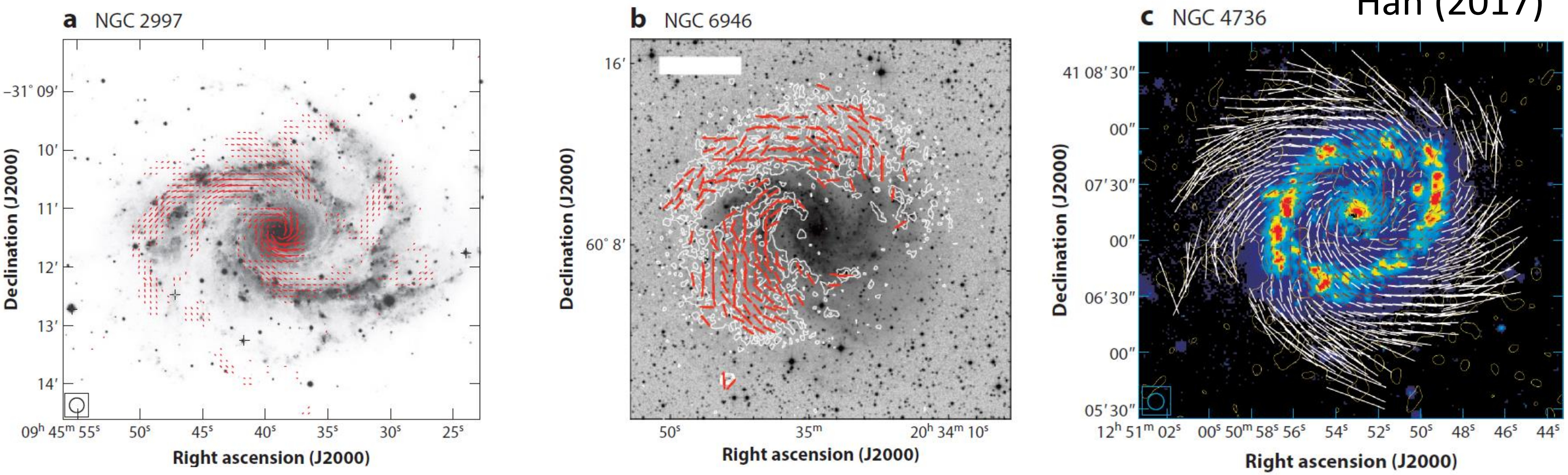
How does magnetic field affect spiral arm?

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

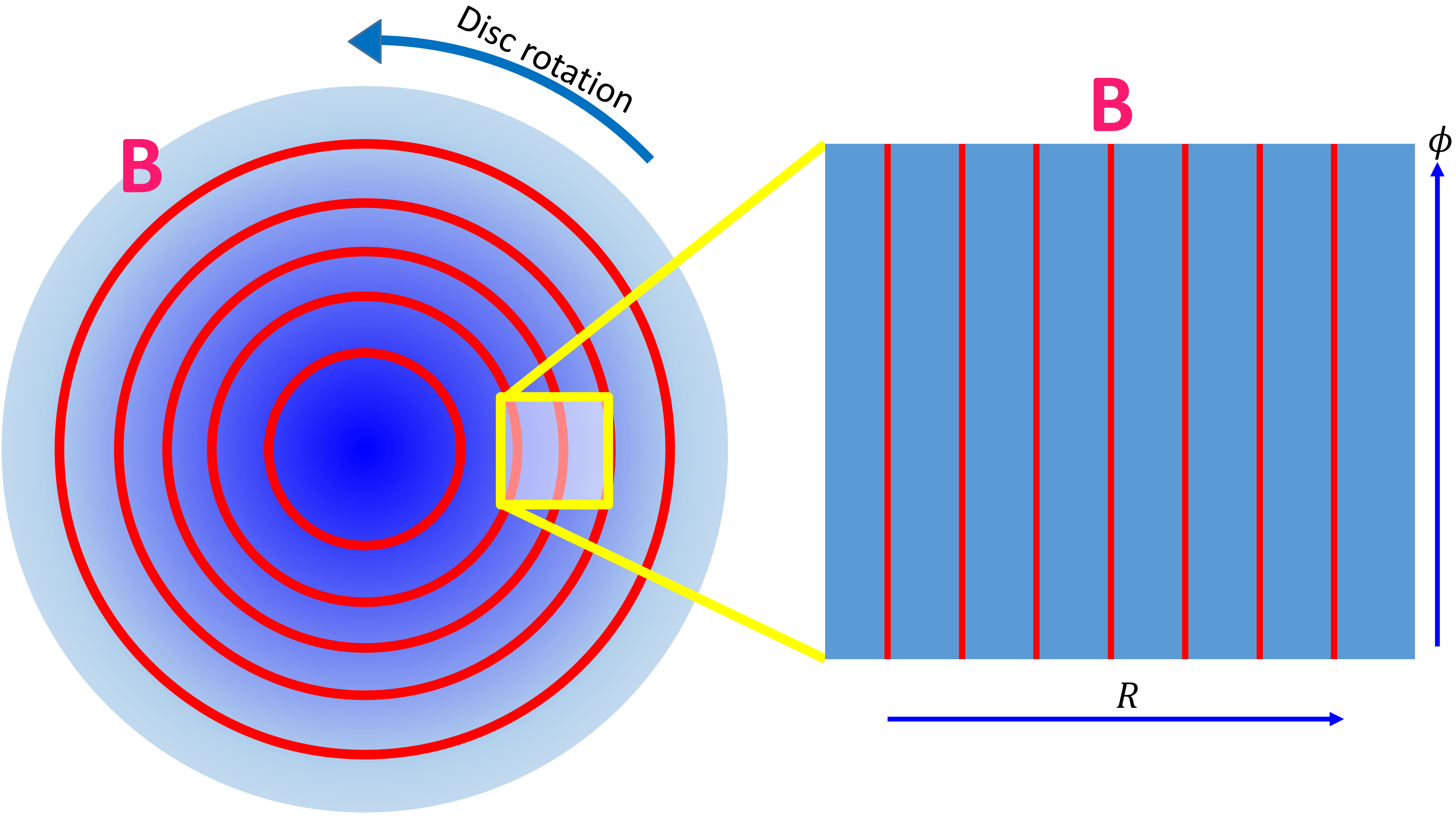
- Galactic B-fields are approximately toroidal and/or following spiral arms.
- $B_\theta \sim 1\ \mu$G around the sun (e.g. Inoue & Tabara 1981, Mouschovias 1983).



Han (2017)

Toroidal magnetic fields in a disc galaxy

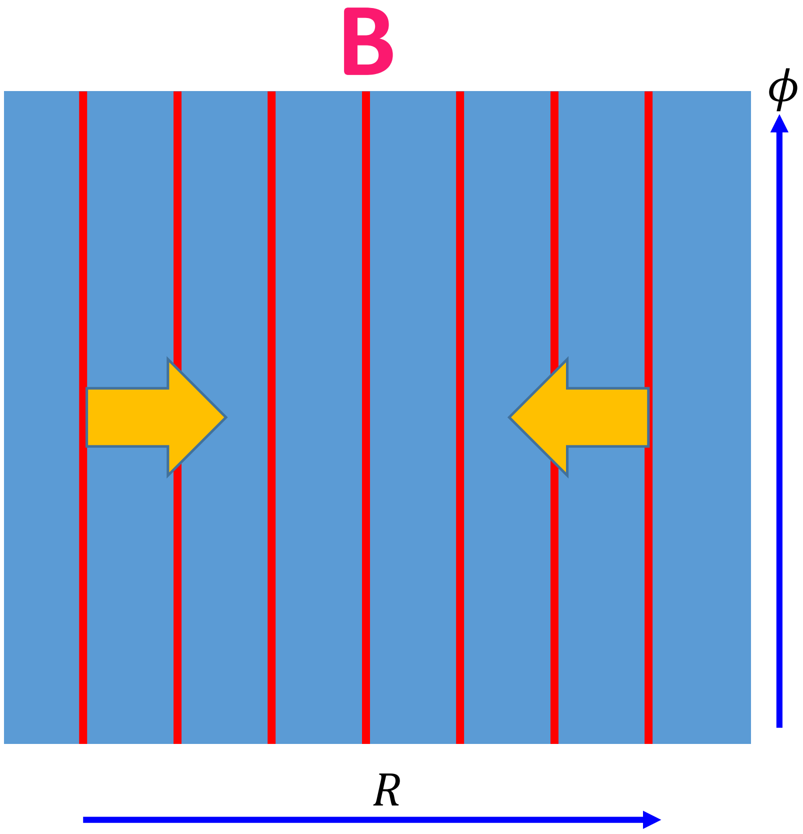
- Galactic B-fields are approximately toroidal and/or following spiral arms.



Toroidal magnetic fields in a disc galaxy

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

- Radial perturbations



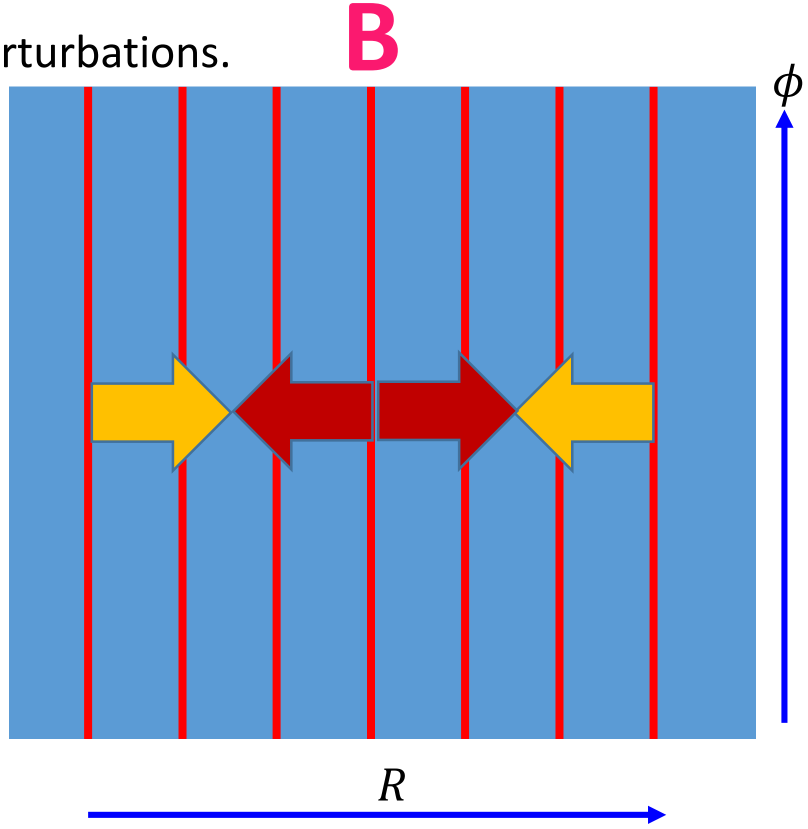
cf. Elmegreen (1987, 1991), Kim & Ostriker (2001)

Toroidal magnetic fields in a disc galaxy

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

- Radial perturbations
  - The magnetic pressure work against the perturbations.

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



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

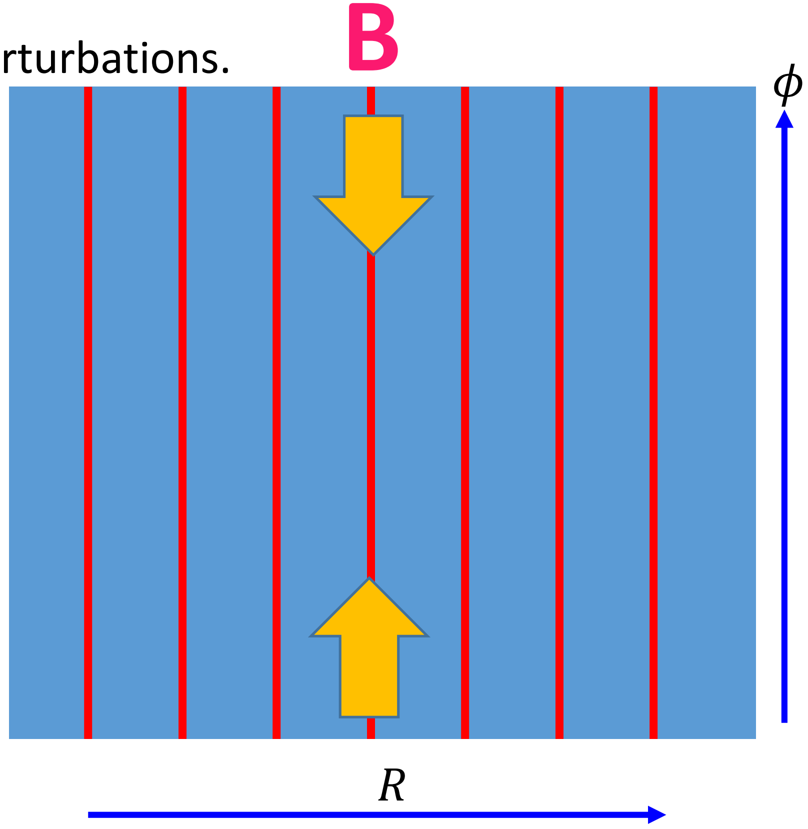
Toroidal magnetic fields in a disc galaxy

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

- Radial perturbations
  - The magnetic pressure work against the perturbations.

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

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



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

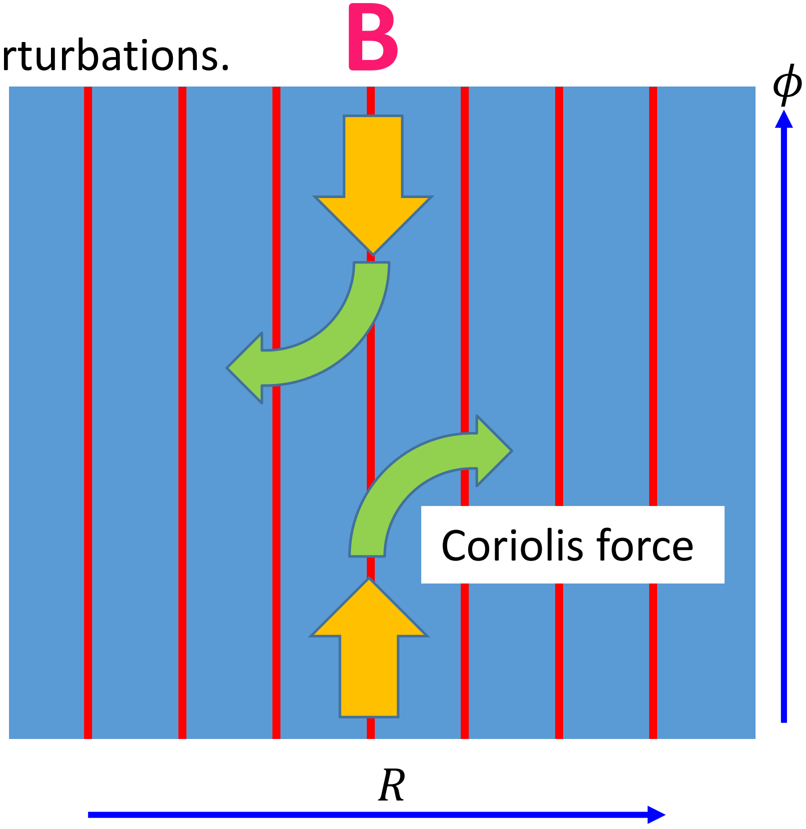
Toroidal magnetic fields in a disc galaxy

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

- Radial perturbations
  - The magnetic pressure work against the perturbations.

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

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



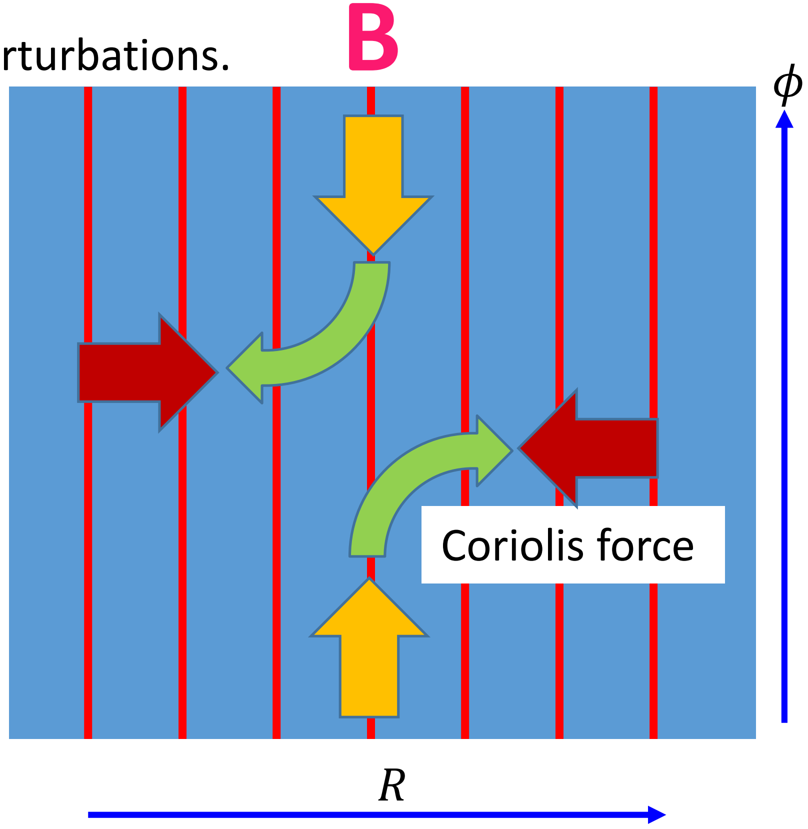
cf. Elmegreen (1987, 1991), Kim & Ostriker (2001)

Toroidal magnetic fields in a disc galaxy

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

- Radial perturbations
  - The magnetic pressure work against the perturbations.

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



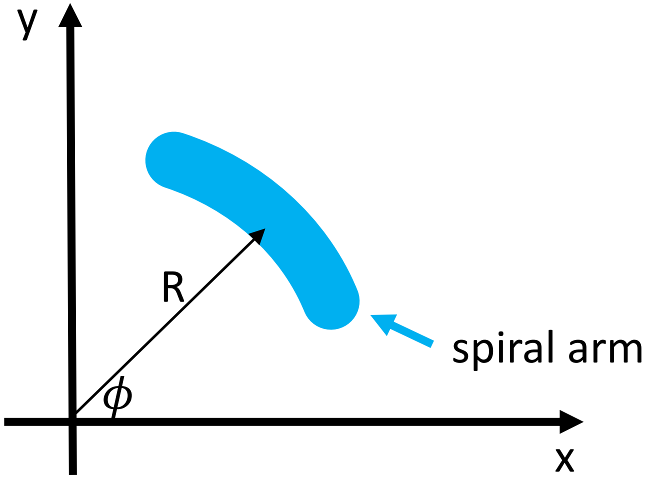
- Azimuthal perturbations
  - The B-fields do nothing in ϕ-direction..
  - But, work against Coriolis force.

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

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

Set-up for the linear perturbation theory

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



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

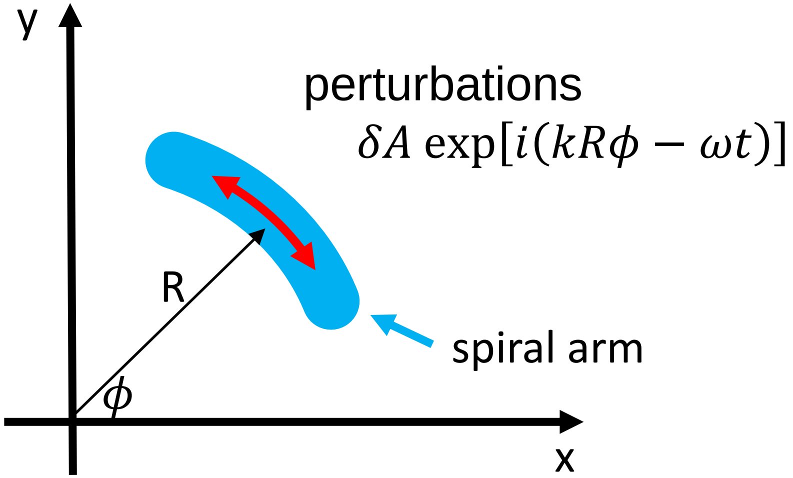
continuity: $$\frac{\partial}{\partial t}\Sigma + \nabla \cdot (\Sigma \mathbf{v}) = 0,$$

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

(**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…
  - 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**).

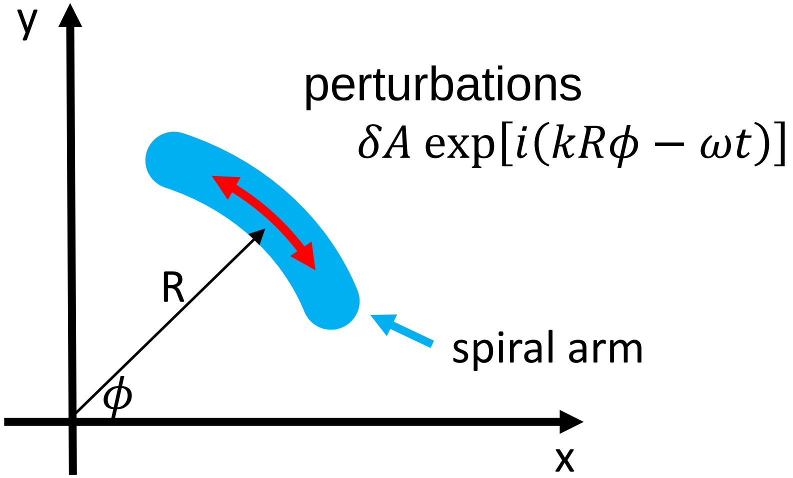
continuity: $$\frac{\partial}{\partial t}\Sigma + \nabla \cdot (\Sigma \mathbf{v}) = 0,$$

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…
  - 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: $\omega\delta\Upsilon = k\Upsilon\delta v_\phi,$

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

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,

$$\omega^2 = \left[\underbrace{c_s^2}_{\text{Thermal pressure}} - \underbrace{\pi G \Upsilon f(kW)}_{\text{Self-gravity}}\right] k^2 + \frac{4\Omega^2\omega^2}{\underbrace{\omega^2 + \boxed{k^2 v_{\mathrm{A}}^2}}_{\text{Coriolis force}}}. \quad \text{Magnetics}$$

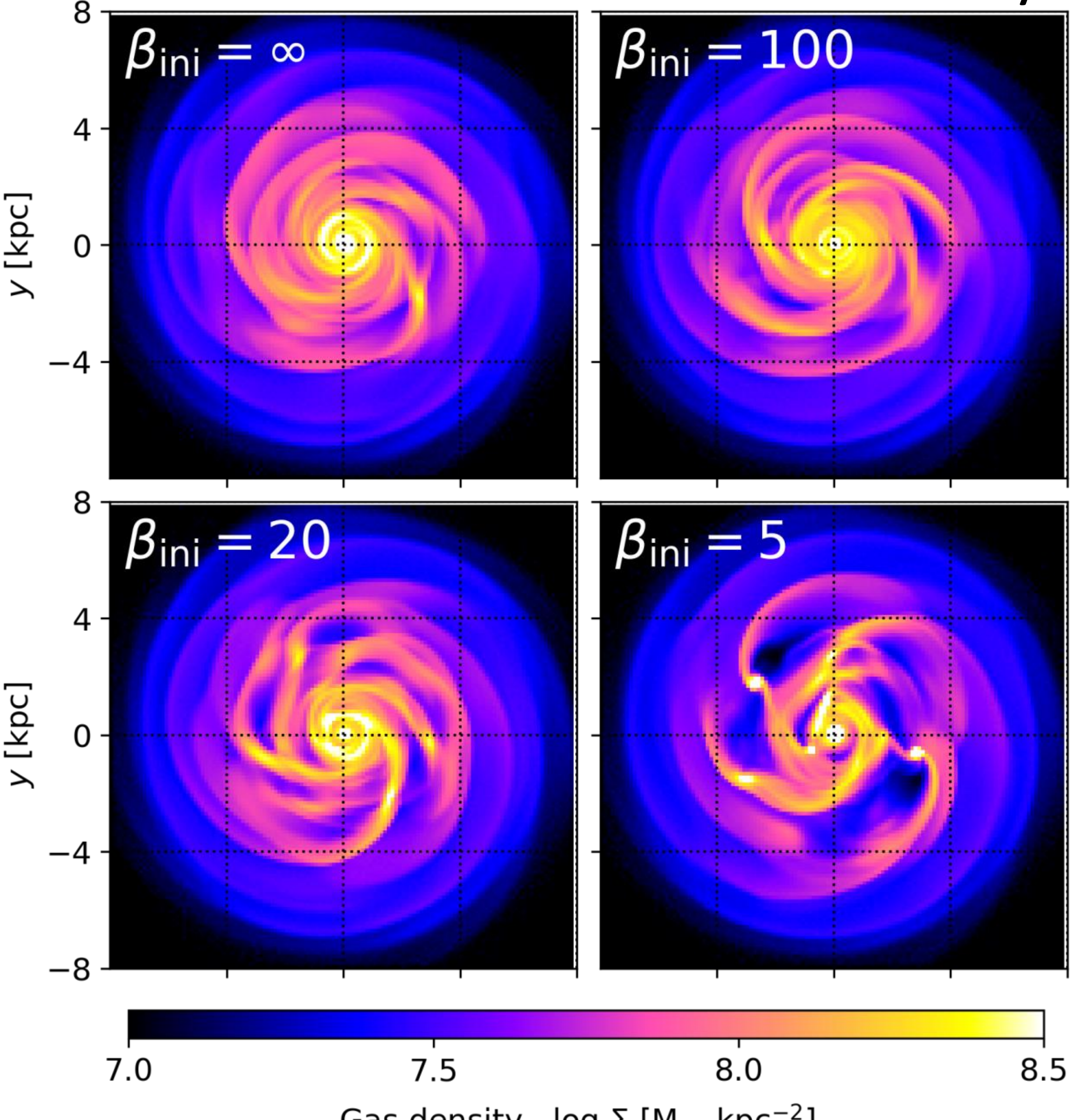
Basically, a high ω^2 means a stable state.

- Strong magnetic field (large v_A) cancels Coriolis force.
  - Coriolis force has a stabilizing effect.
    - **Canceling the stabilizing effect is a destabilizing effect.**

- Toroidal magnetic fields can drive spiral-arm fragmentation.

Ideal MHD simulations

at t=400 Myr



How can we predict the spiral-arm instability

- One can obtain the dispersion relation for the perturbations,

$$\omega^2 = \Big[\underbrace{c_s^2}_{\text{Pressure}} - \underbrace{\pi G \Upsilon f(kW)}_{\text{Self-gravity}}\Big] k^2 + \frac{4\Omega^2\omega^2}{\underbrace{\omega^2 + \boxed{k^2 v_{\mathrm{A}}^2}}_{\text{Coriolis force}}}. \quad \text{Magnetics}$$

  - If $\omega^2 > 0$ for all wavenumbers k, the arm is stable.
  - If $\omega^2 < 0$ for some wavenumbers k, the arm is unstable.
  - If ω^2 is complex for some wavenumbers k, the arm is unstable.

- Growth rates of perturbations can be computed as

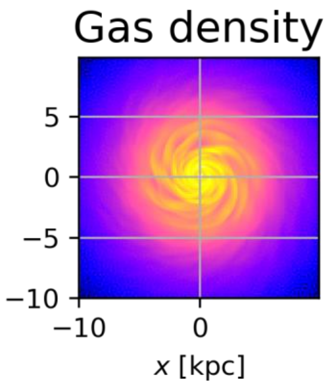
$$\omega_{\mathrm{grow}} = \left[\frac{-\mathrm{Re}(\omega^2) + \sqrt{\mathrm{Re}^2(\omega^2) + \mathrm{Im}^2(\omega^2)}}{2}\right]^{\frac{1}{2}} .$$

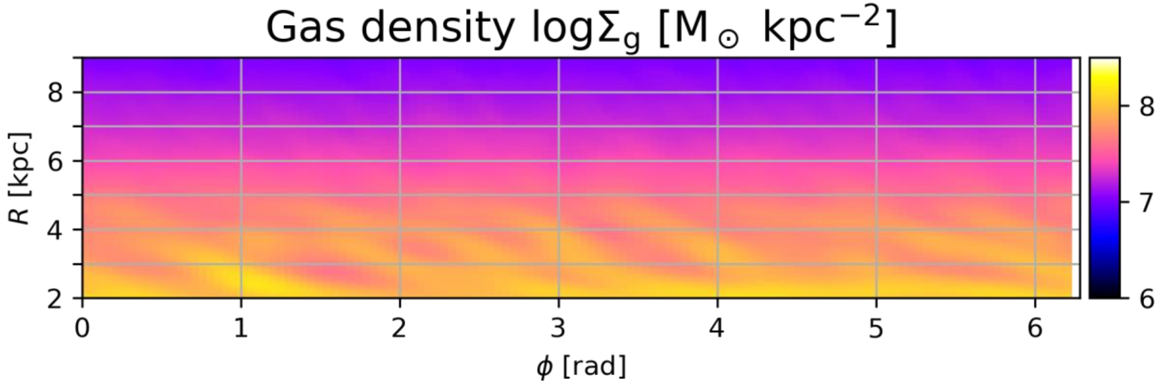
- $\omega_{\mathrm{grow}} = 0$ for stable perturbations.
- $\omega_{\mathrm{grow}} > 0$ for unstable perturbations.

Demonstration

The fragmenting case

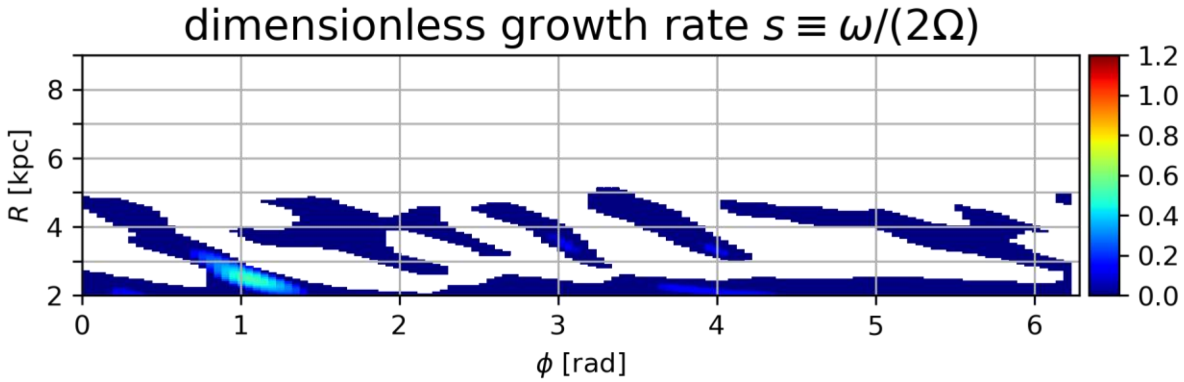
$\beta_{ini} = 5$


Gas density

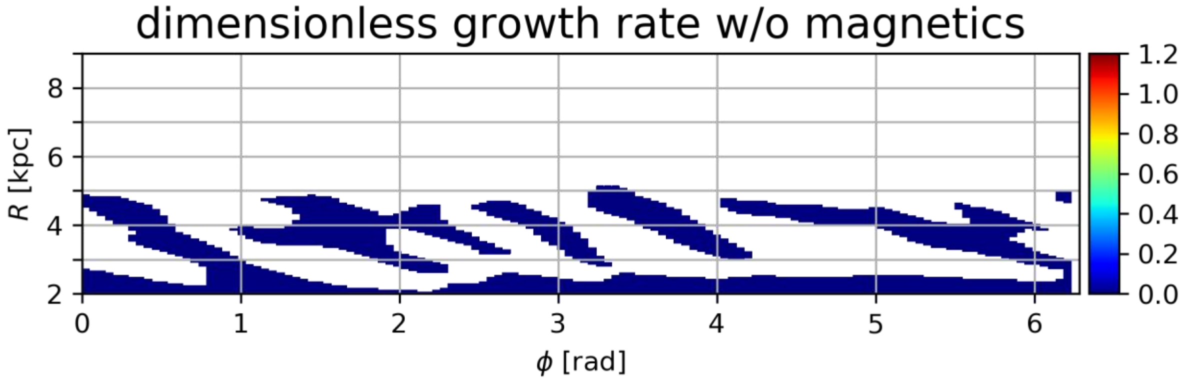

Gas density $\log\Sigma_g$ [$M_\odot$ kpc^{-2}]

t=140 Myr

Including B-field


dimensionless growth rate $s \equiv \omega/(2\Omega)$

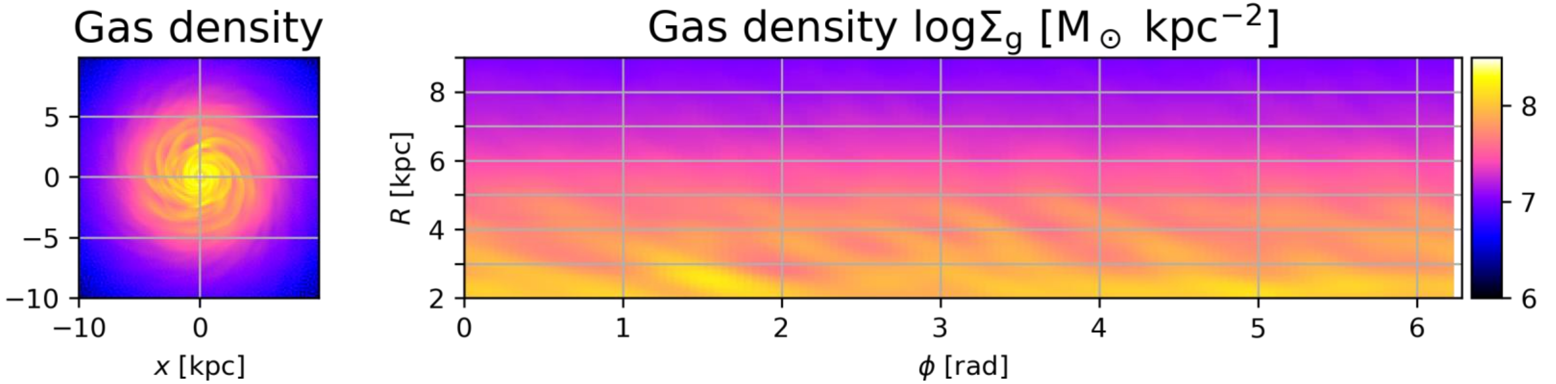
Ignoring B-field


dimensionless growth rate w/o magnetics

Demonstration

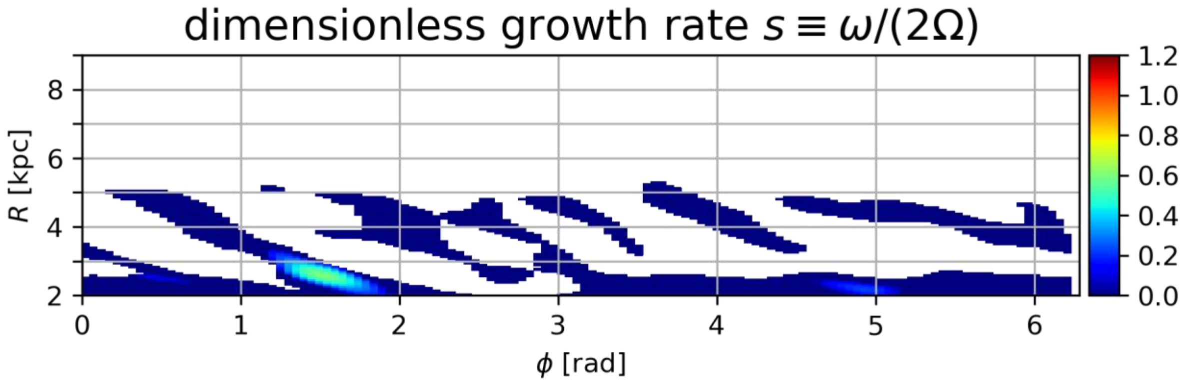
The fragmenting case

$\beta_{ini} = 5$

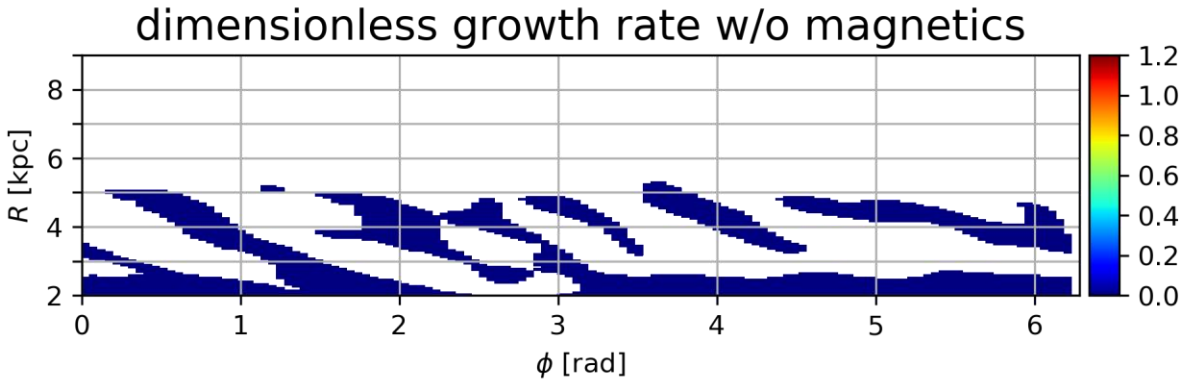


t=150 Myr

Including B-field



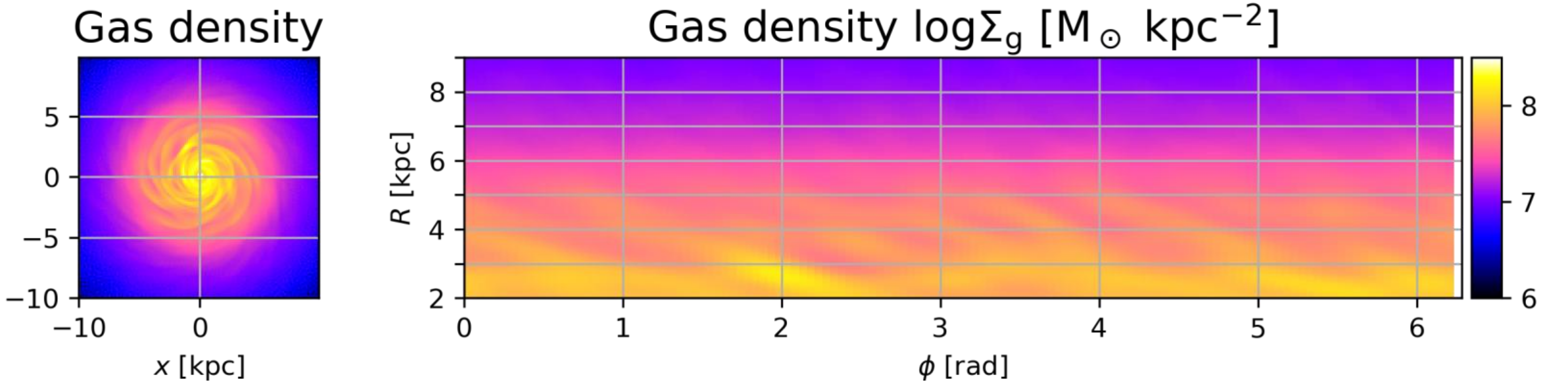
Ignoring B-field



Demonstration

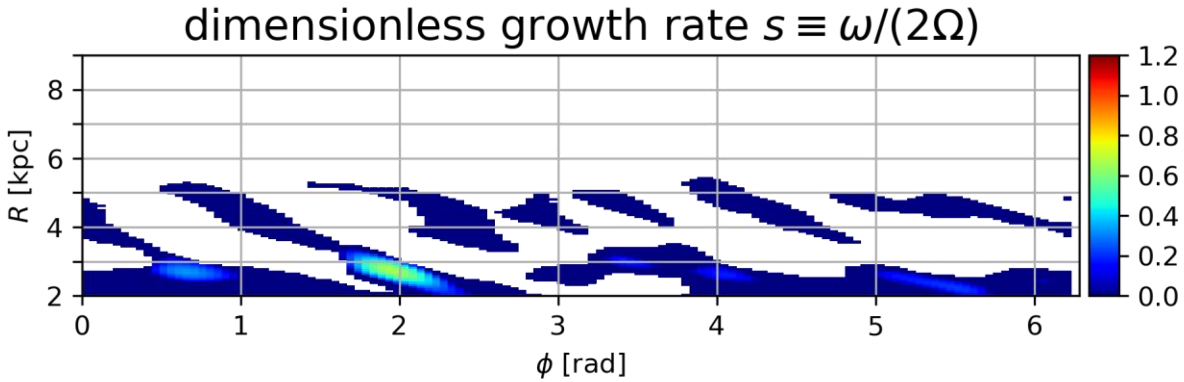
The fragmenting case

$\beta_{ini} = 5$

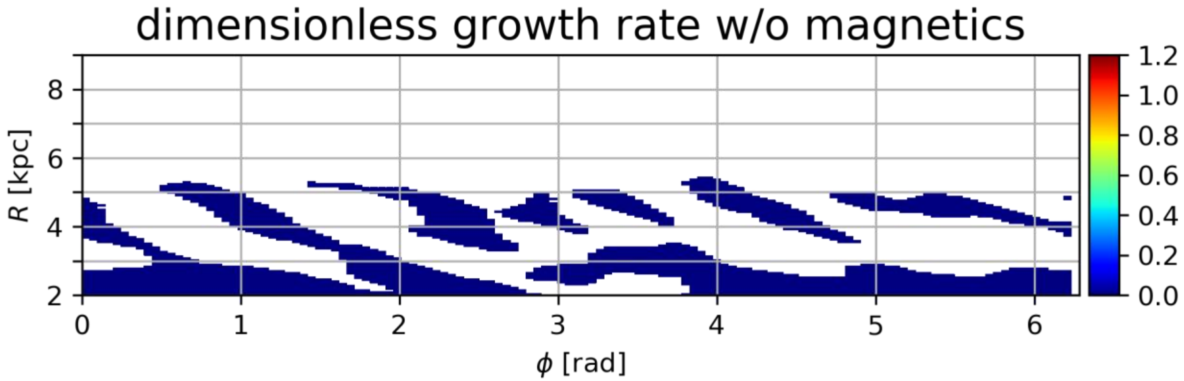


t=160 Myr

Including B-field



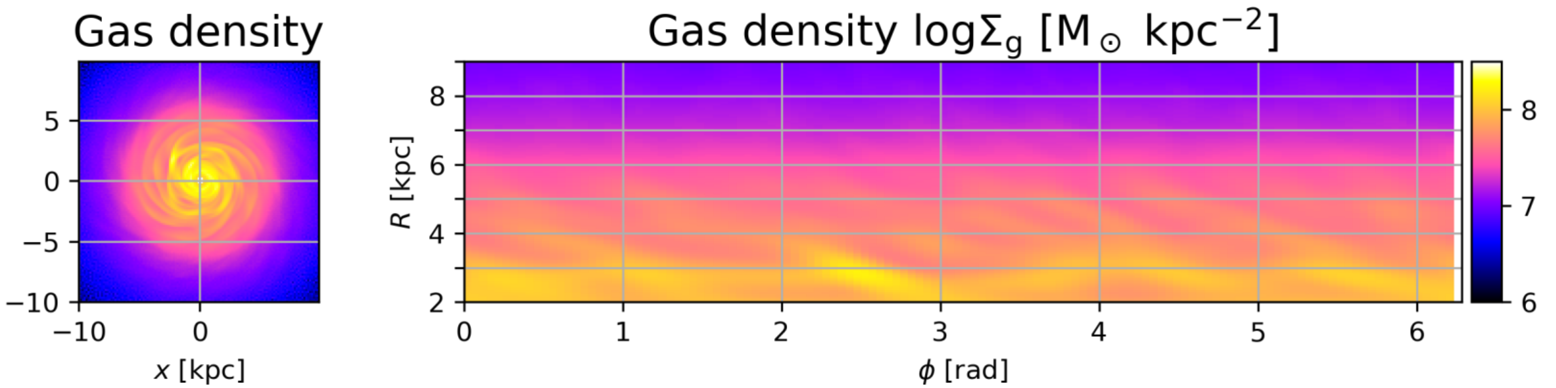
Ignoring B-field



Demonstration

The fragmenting case

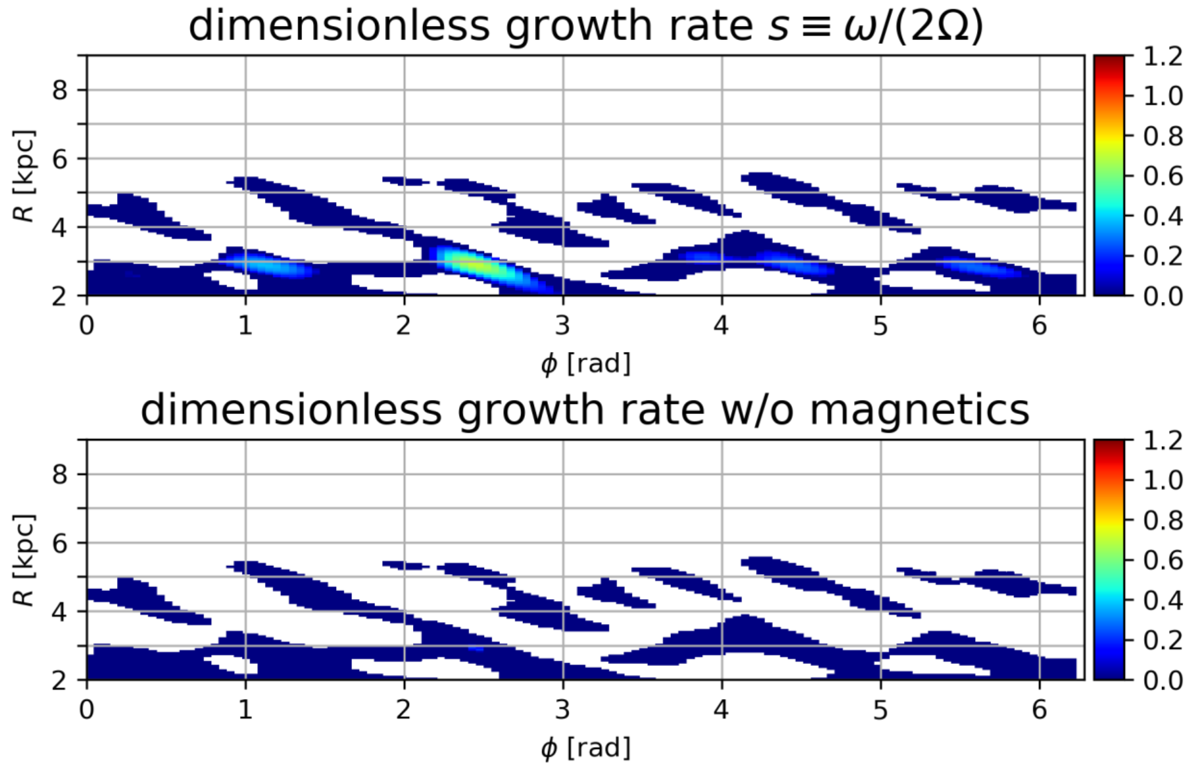
$\beta_{ini} = 5$



t=170 Myr

Including B-field

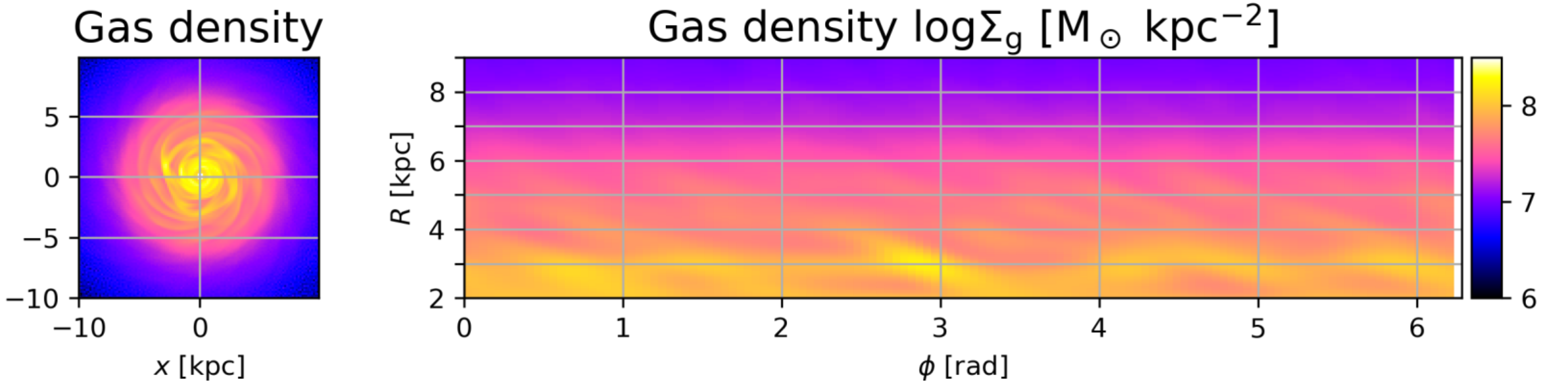
Ignoring B-field



Demonstration

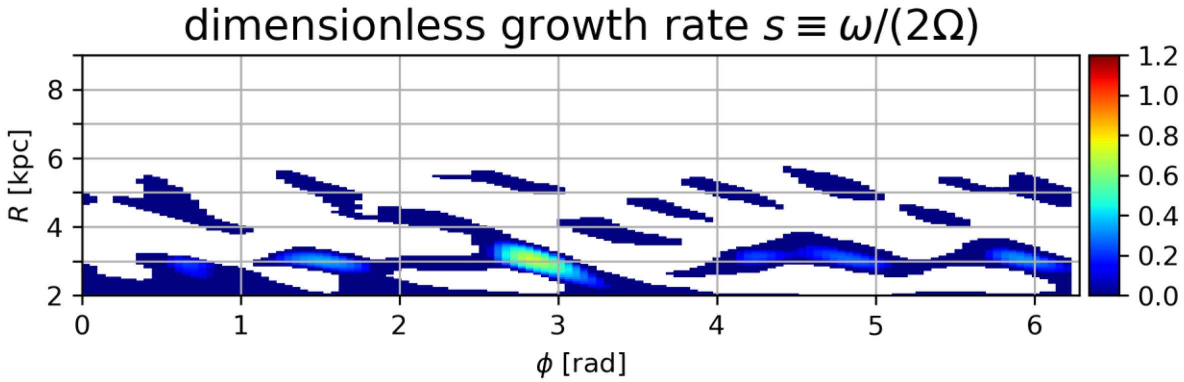
The fragmenting case

$\beta_{ini} = 5$

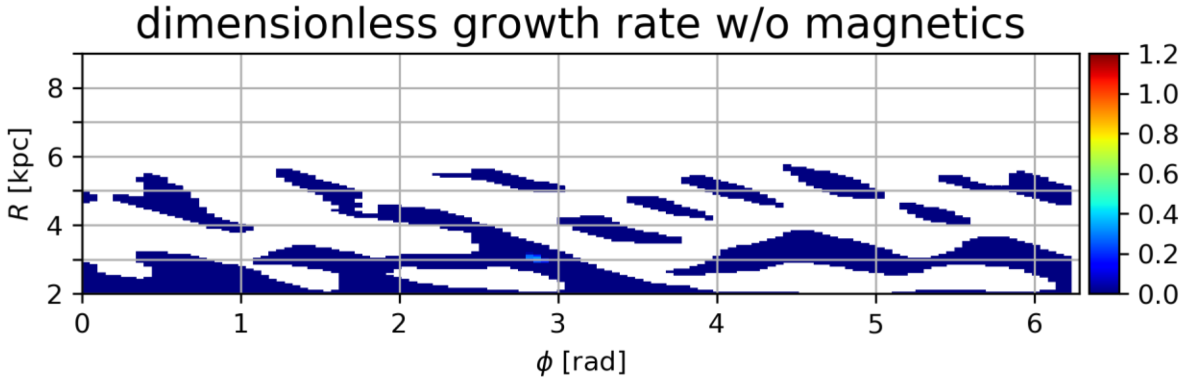


t=180 Myr

Including B-field



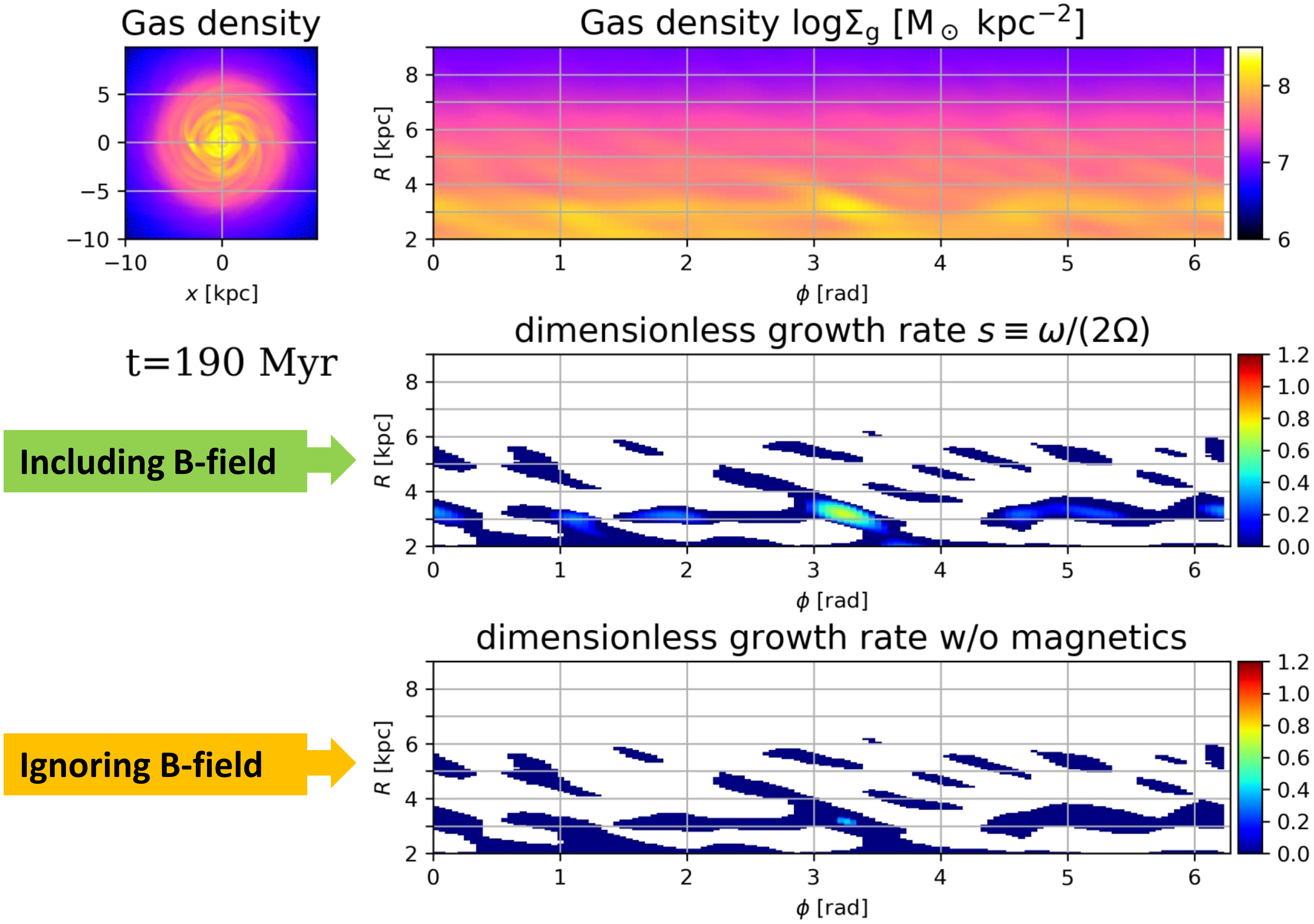
Ignoring B-field



Demonstration

The fragmenting case

$\beta_{ini} = 5$



t=190 Myr

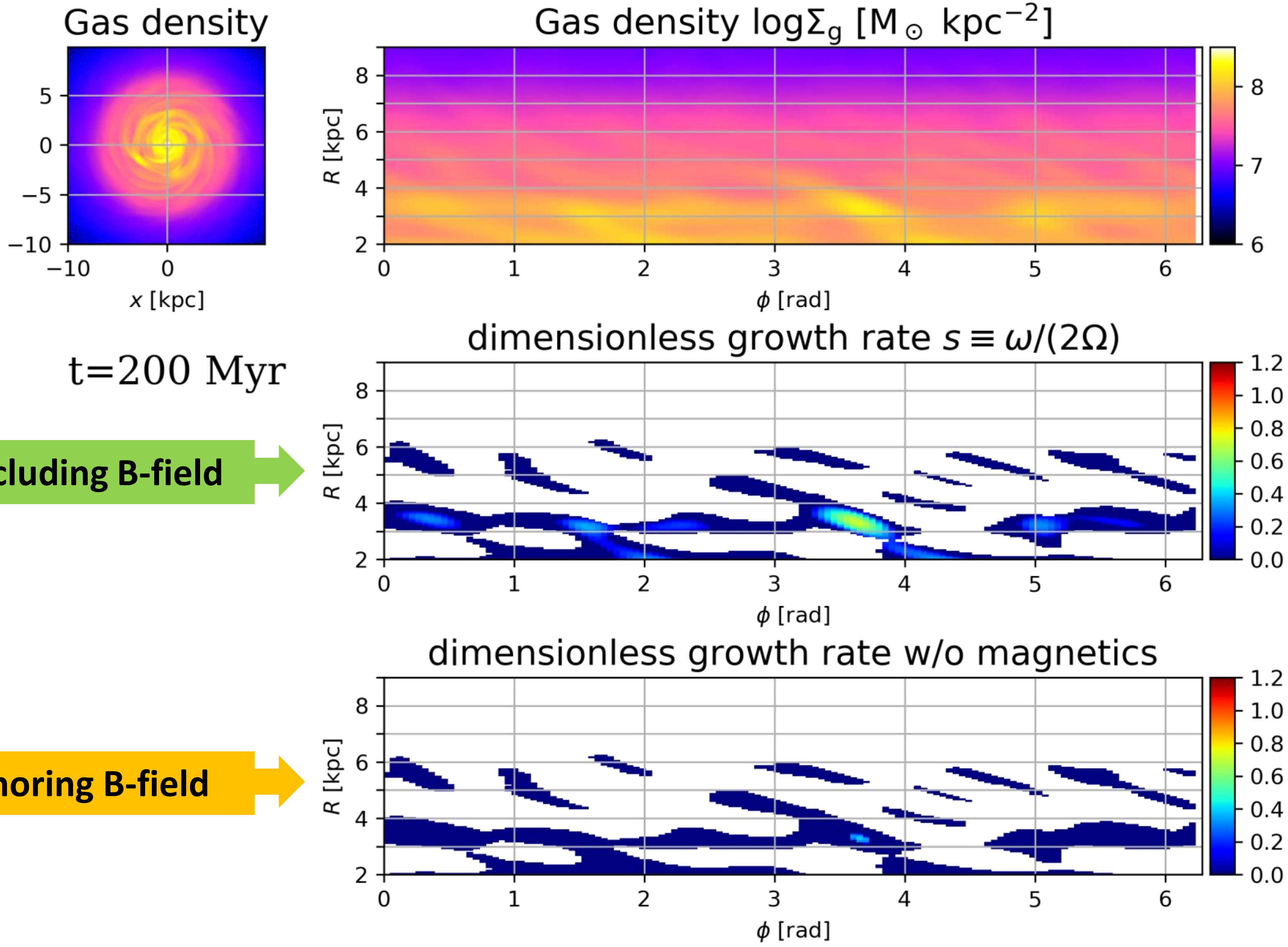
Including B-field

Ignoring B-field

Demonstration

The fragmenting case

$\beta_{ini} = 5$



t=200 Myr

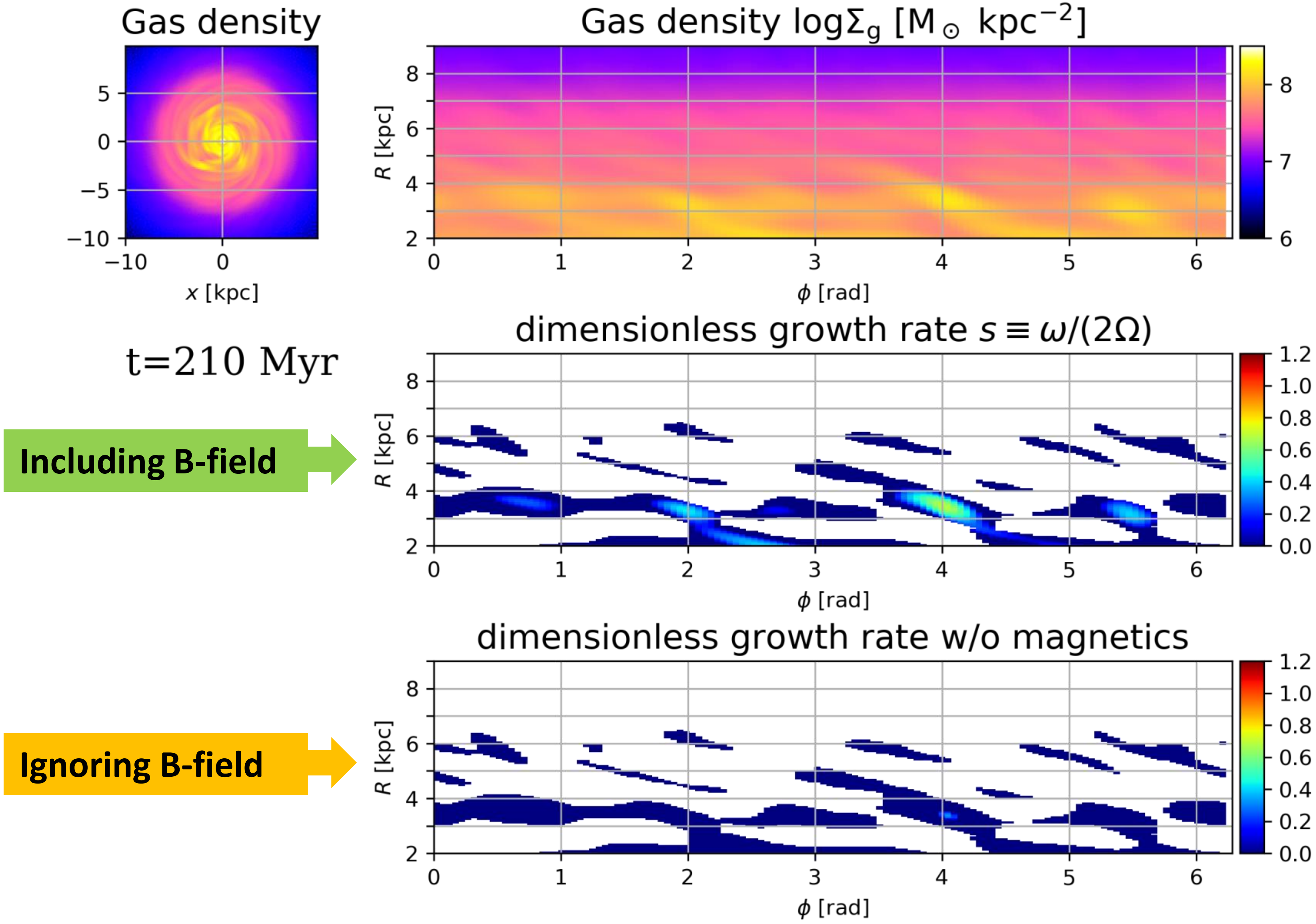
Including B-field

Ignoring B-field

Demonstration

The fragmenting case

$\beta_{ini} = 5$



Gas density

Gas density $\log\Sigma_g$ [$M_\odot$ kpc^{-2}]

t=210 Myr

dimensionless growth rate $s \equiv \omega/(2\Omega)$

Including B-field

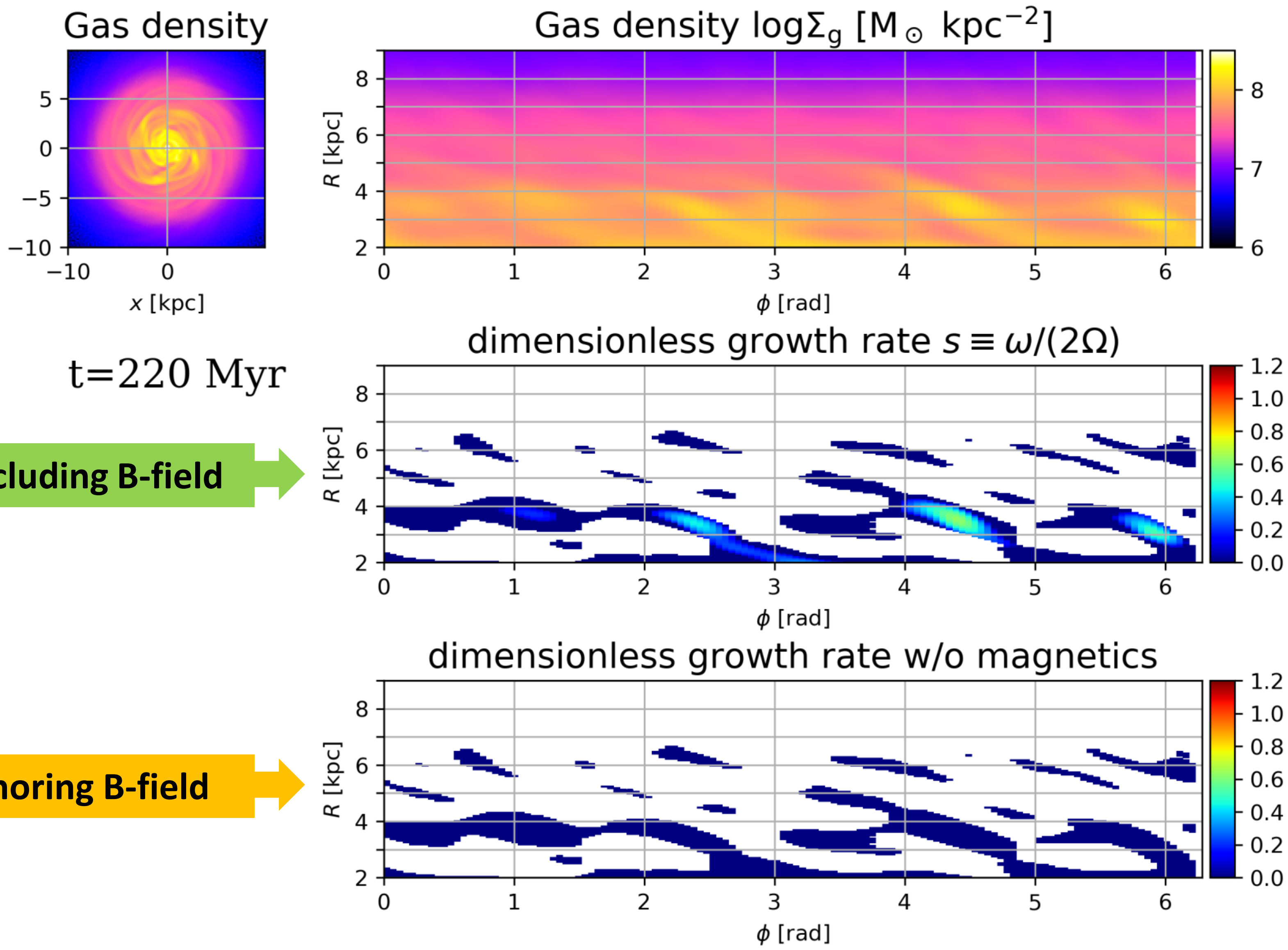
dimensionless growth rate w/o magnetics

Ignoring B-field

Demonstration

The fragmenting case

$\beta_{ini} = 5$



t=220 Myr

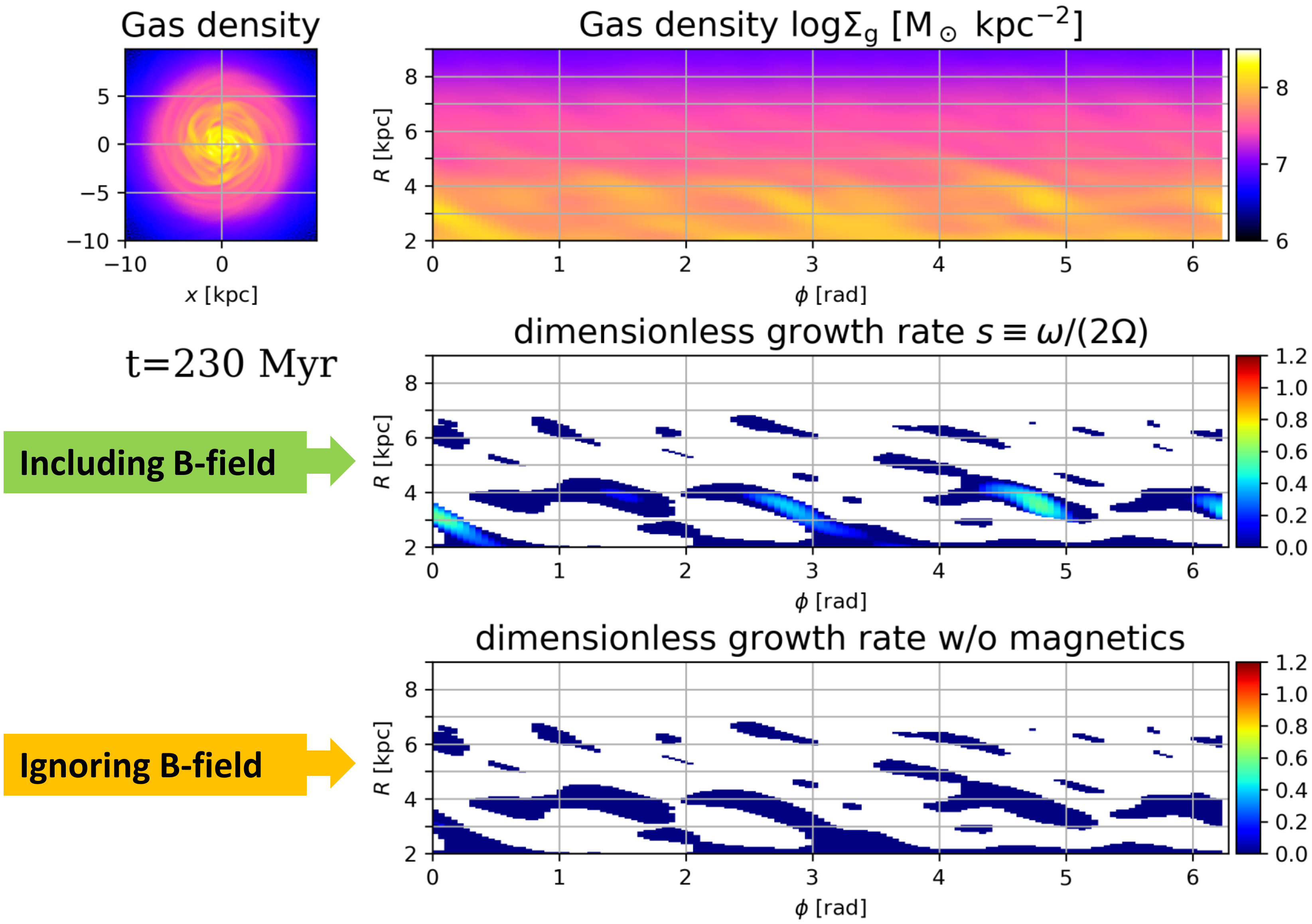
Including B-field

Ignoring B-field

Demonstration

The fragmenting case

$\beta_{ini} = 5$



t=230 Myr

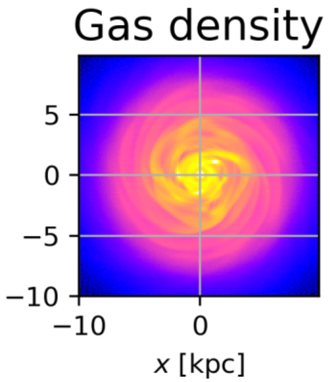
Including B-field

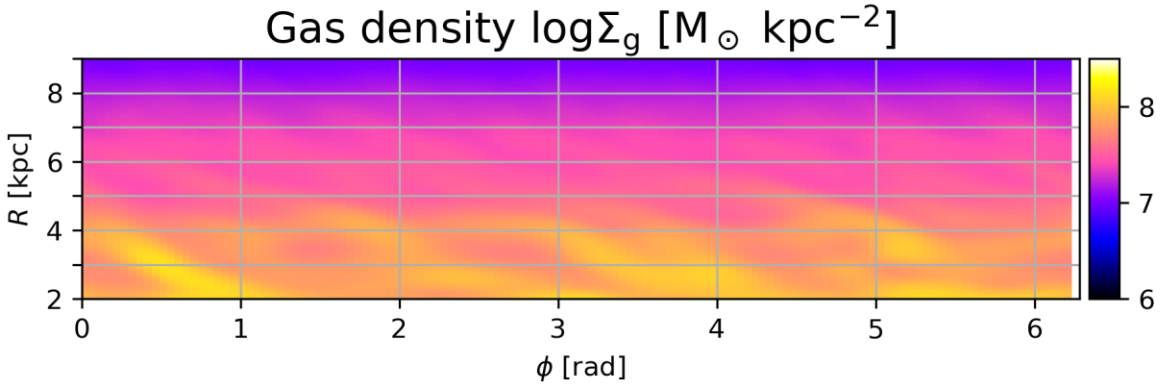
Ignoring B-field

Demonstration

The fragmenting case

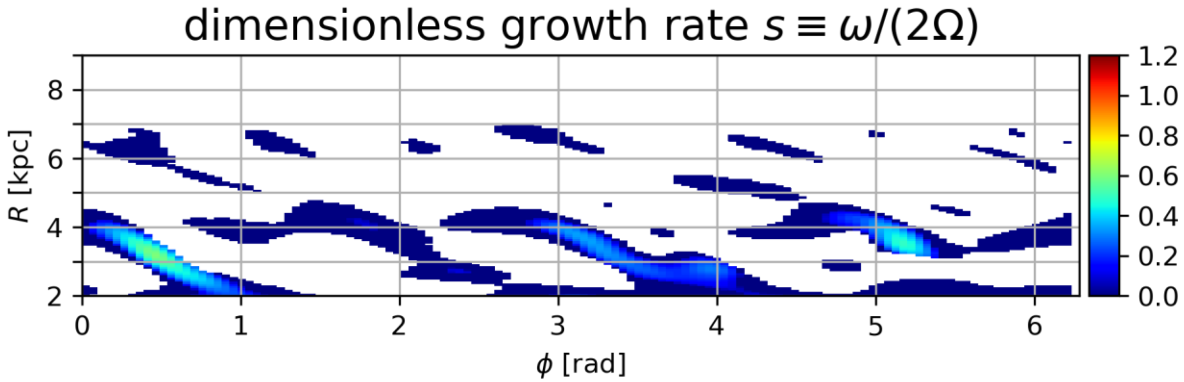
$\beta_{ini} = 5$


Gas density

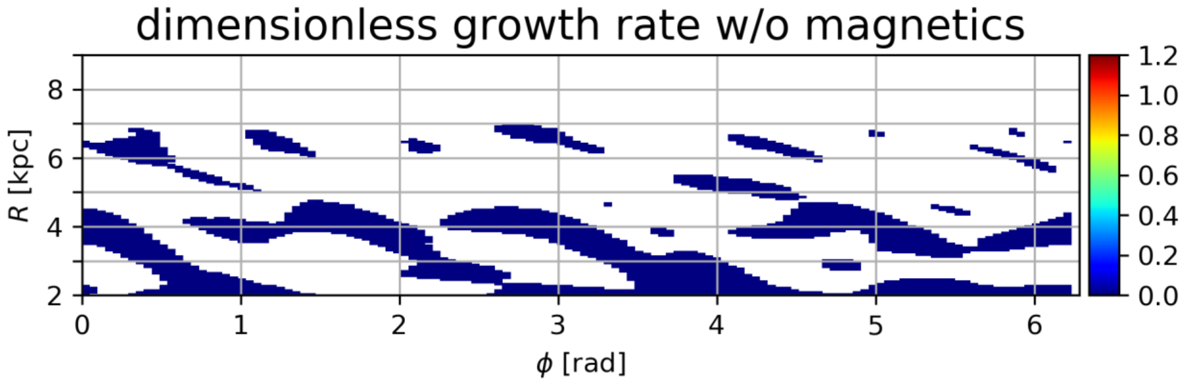

Gas density $\log\Sigma_g$ [$M_\odot$ kpc^{-2}]

t=240 Myr

Including B-field


dimensionless growth rate $s \equiv \omega/(2\Omega)$

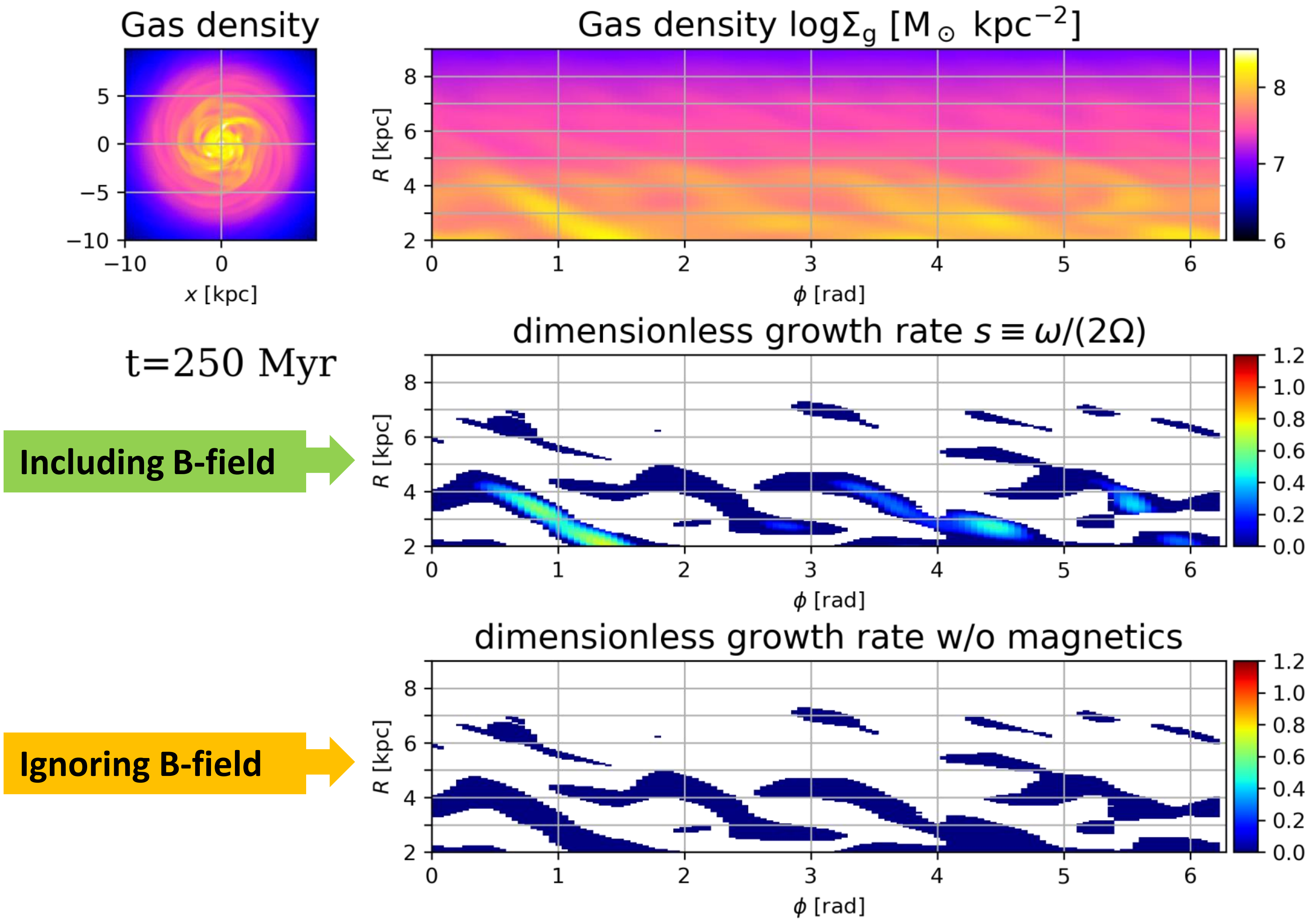
Ignoring B-field


dimensionless growth rate w/o magnetics

Demonstration

The fragmenting case

$\beta_{ini} = 5$



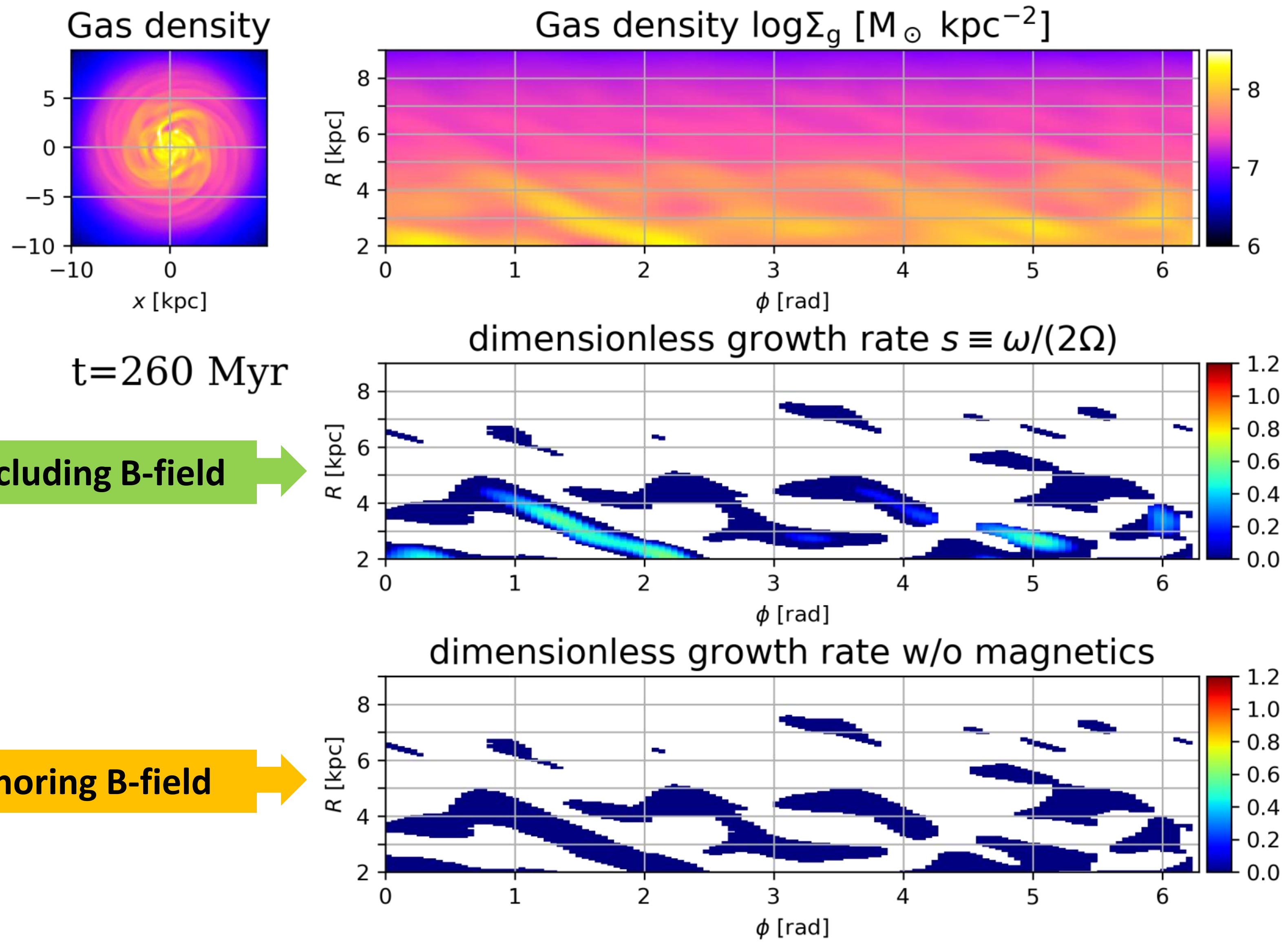
Including B-field

Ignoring B-field

Demonstration

The fragmenting case

$\beta_{ini} = 5$



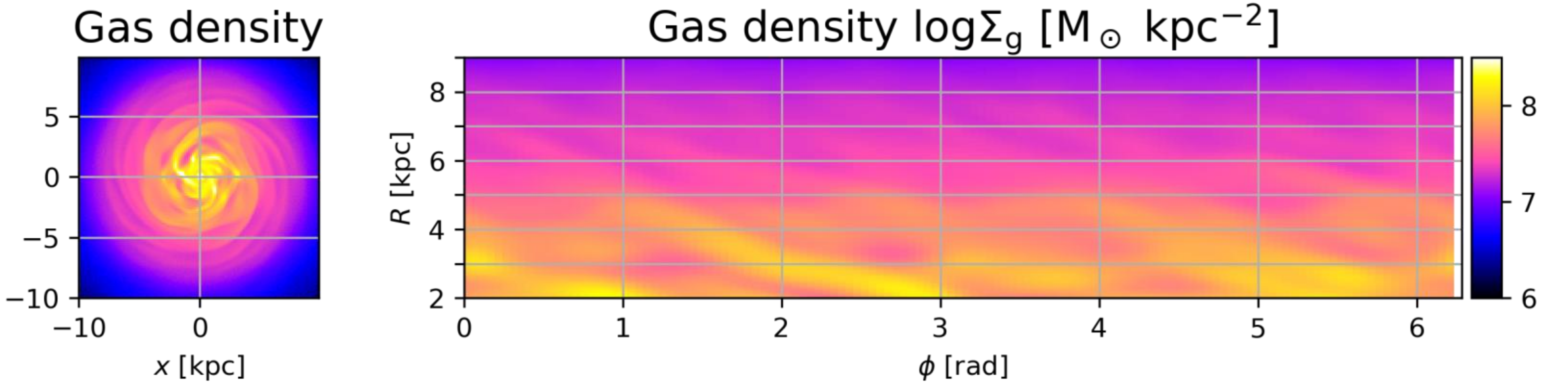
Including B-field

Ignoring B-field

Demonstration

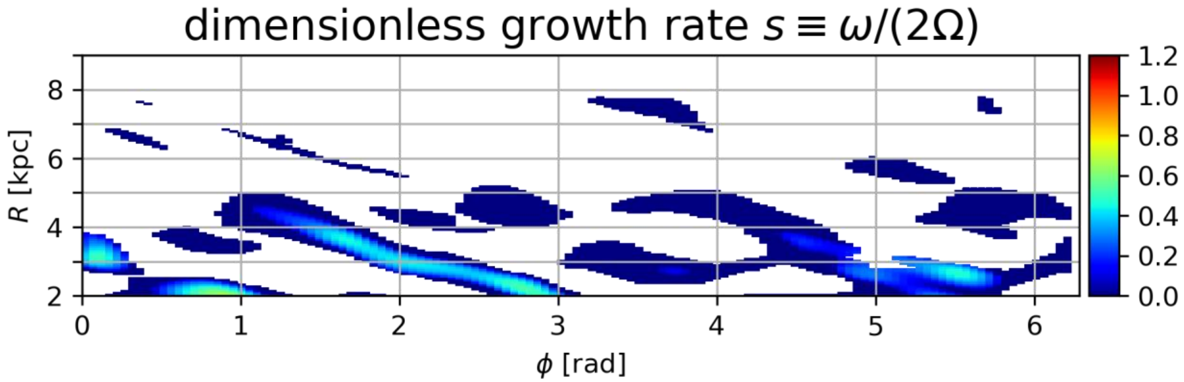
The fragmenting case

$\beta_{ini} = 5$

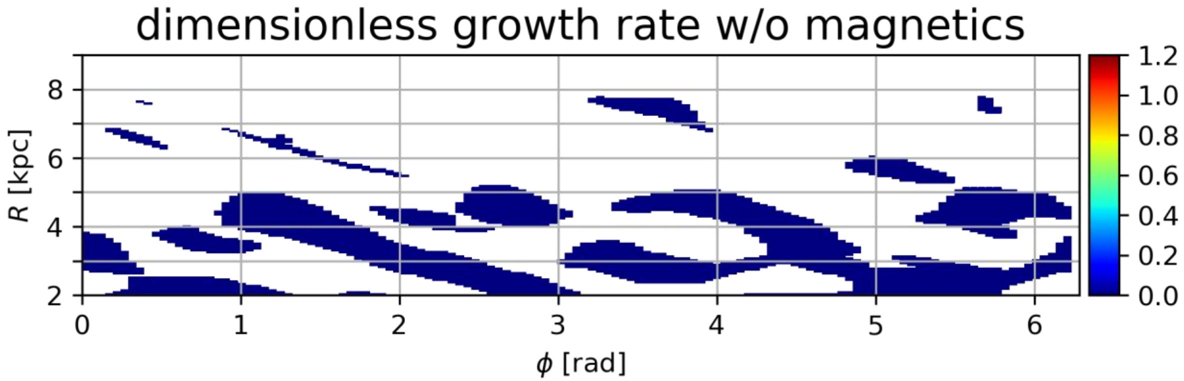


t=270 Myr

Including B-field



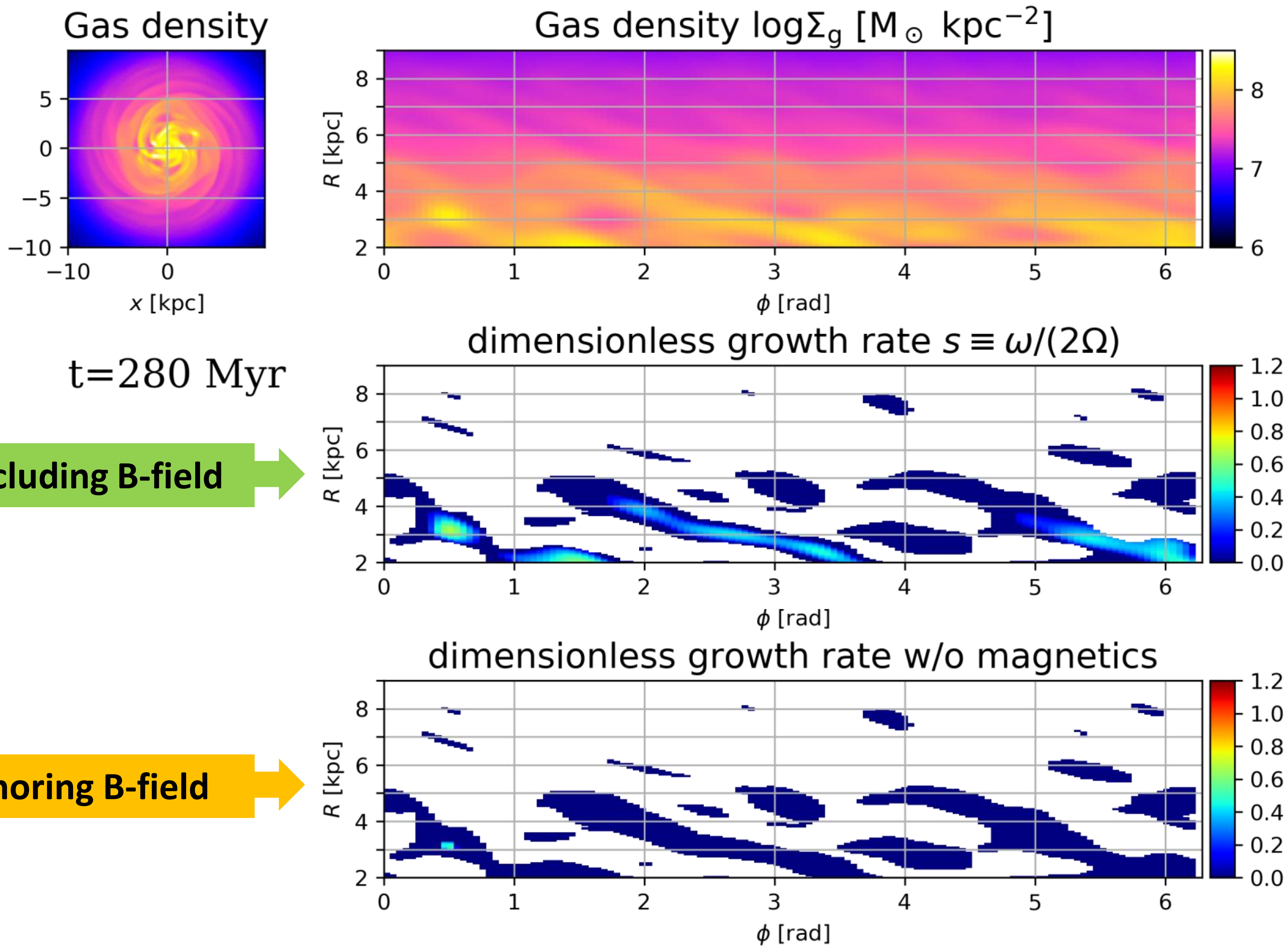
Ignoring B-field



Demonstration

The fragmenting case

$\beta_{ini} = 5$



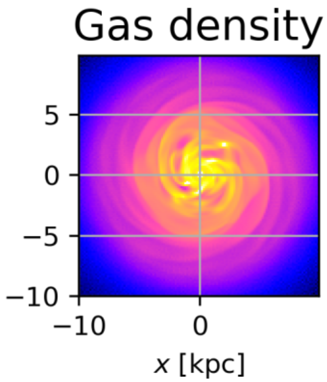
Including B-field

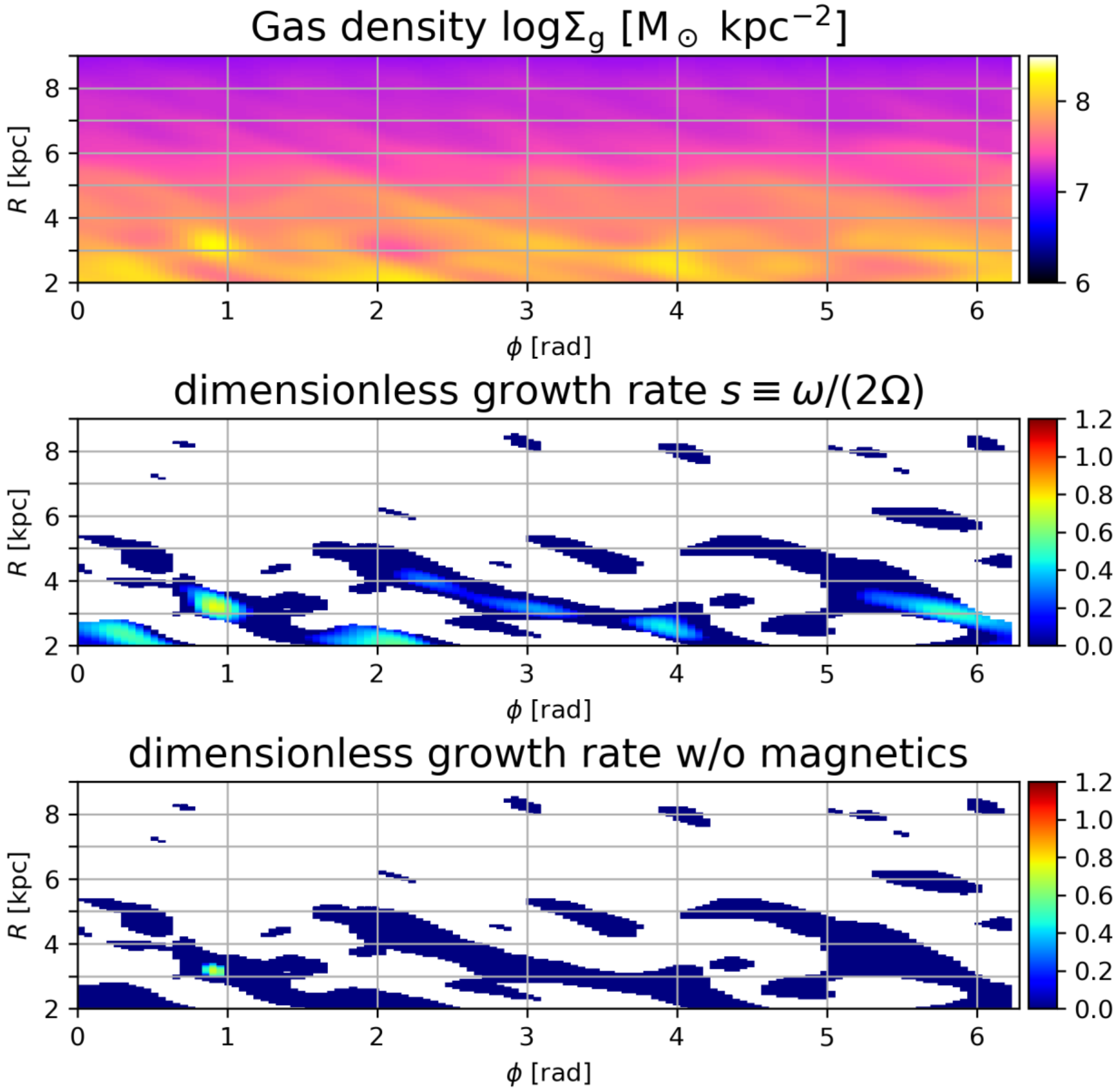
Ignoring B-field

Demonstration

The fragmenting case

$\beta_{ini} = 5$





t=290 Myr

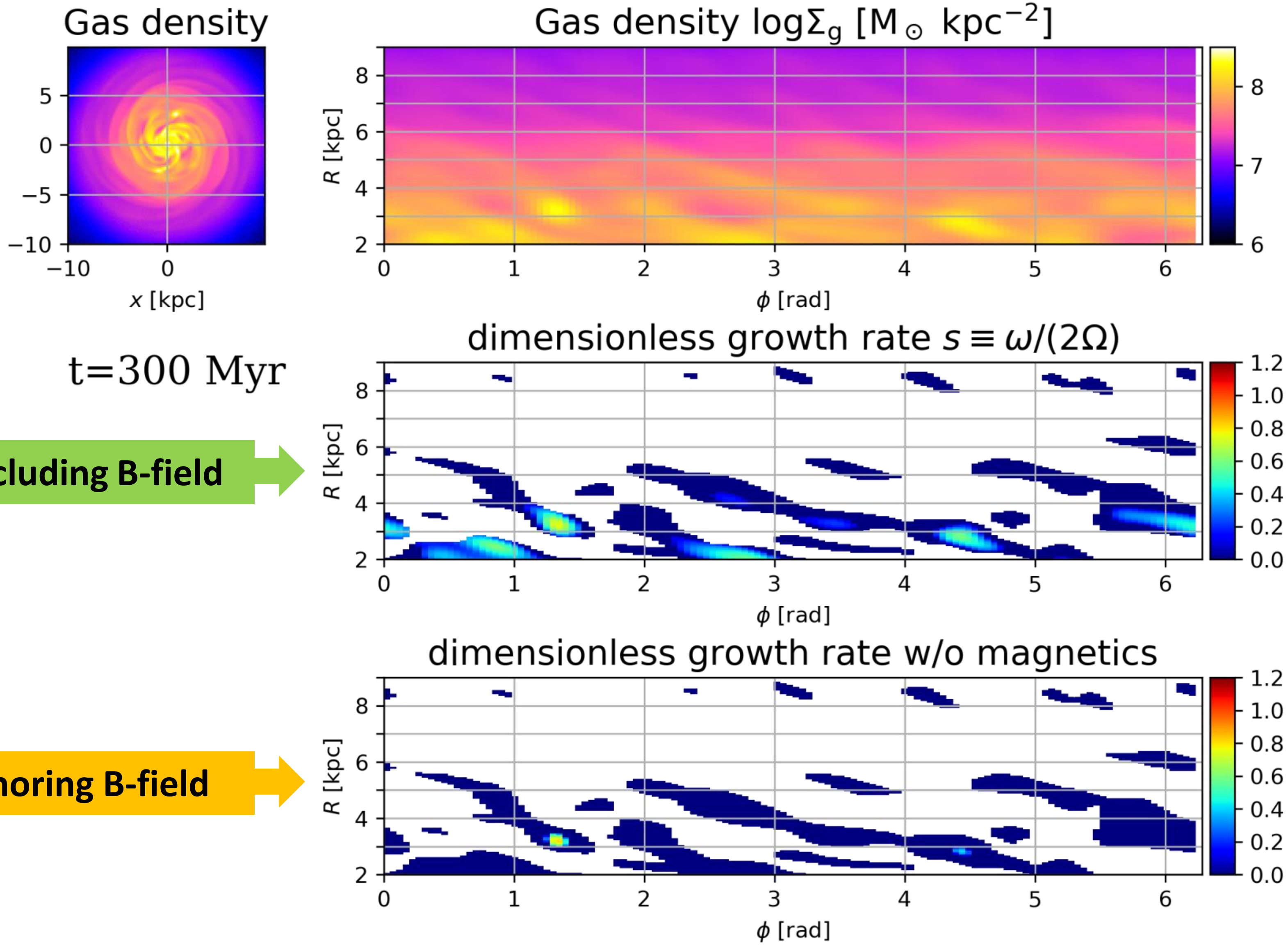
Including B-field

Ignoring B-field

Demonstration

The fragmenting case

$\beta_{ini} = 5$



t=300 Myr

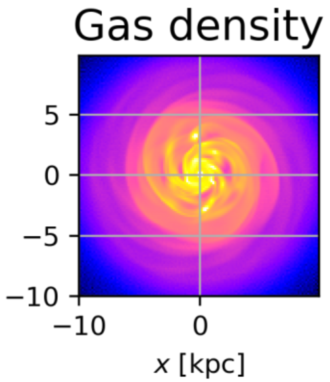
Including B-field

Ignoring B-field

Demonstration

The fragmenting case

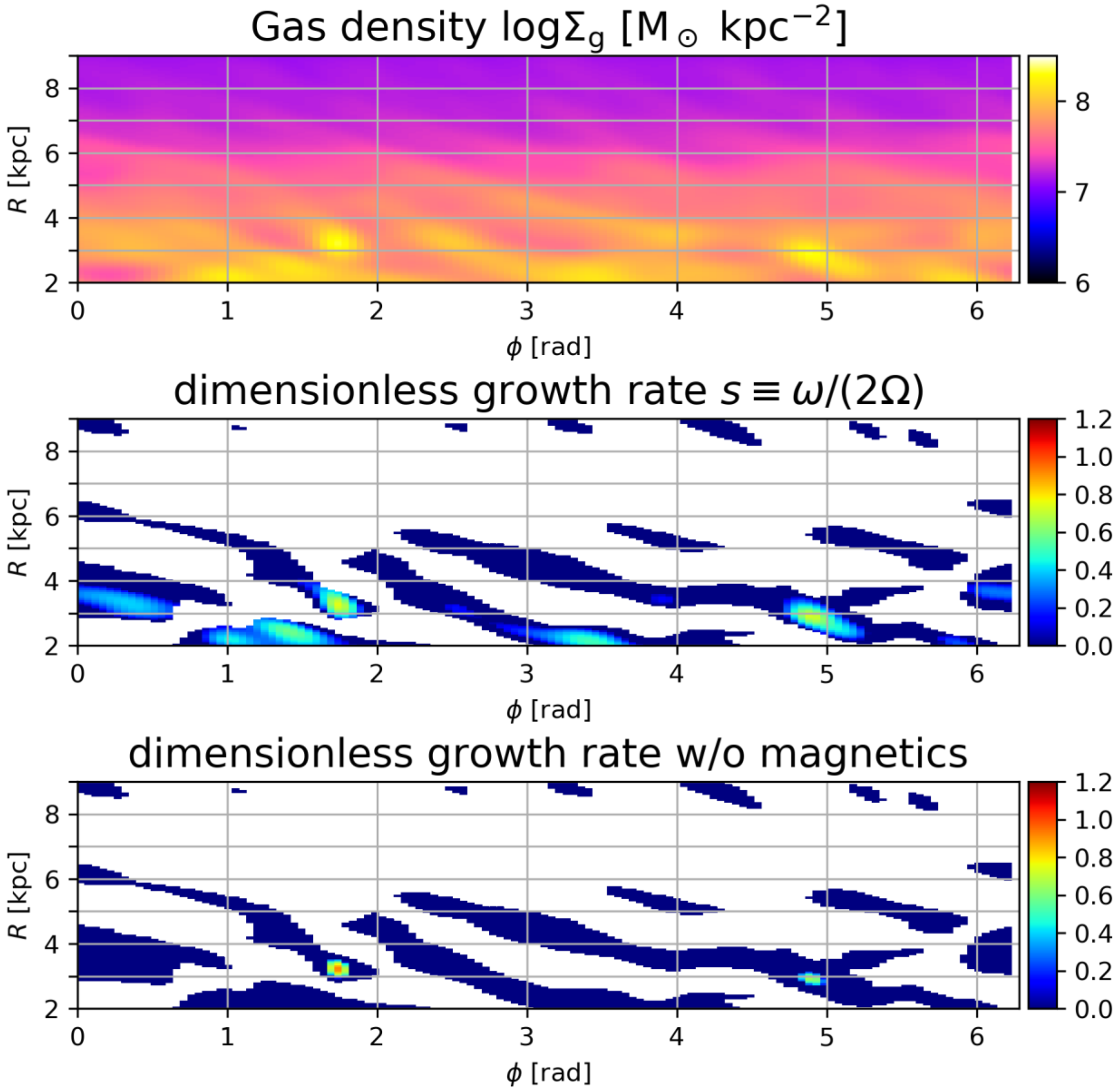
$\beta_{ini} = 5$



t=310 Myr

Including B-field

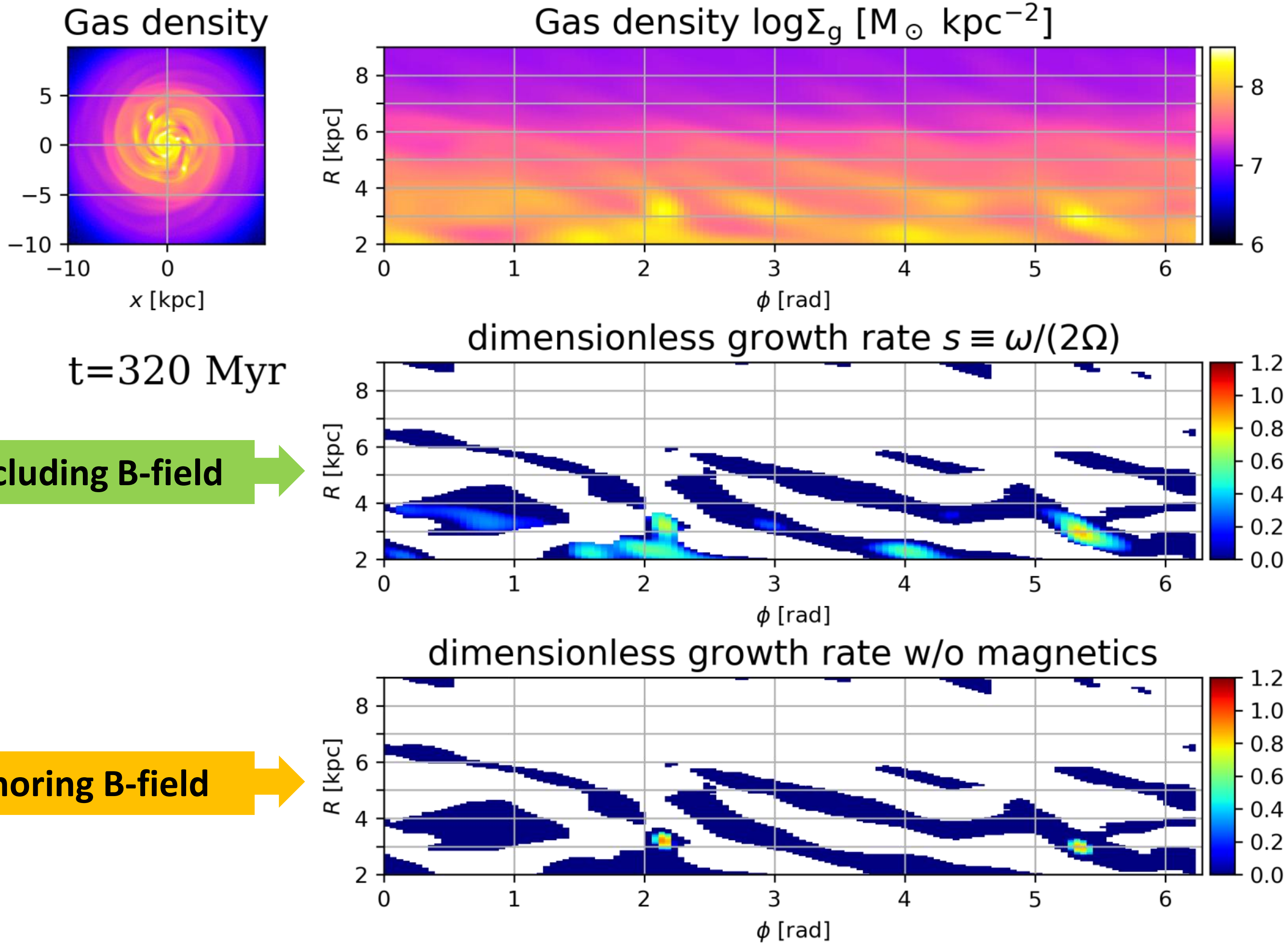
Ignoring B-field



Demonstration

The fragmenting case

$\beta_{ini} = 5$



t=320 Myr

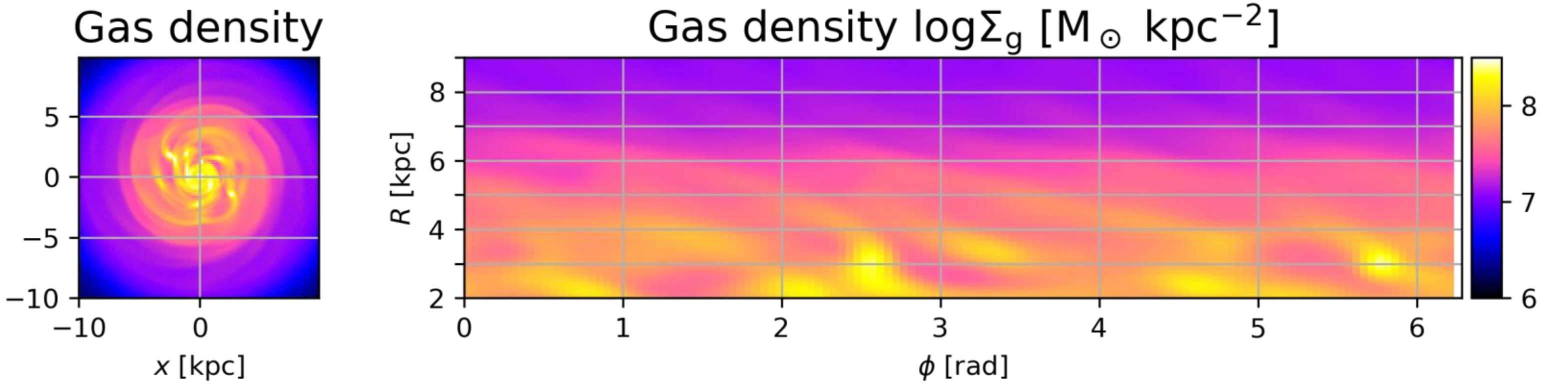
Including B-field

Ignoring B-field

Demonstration

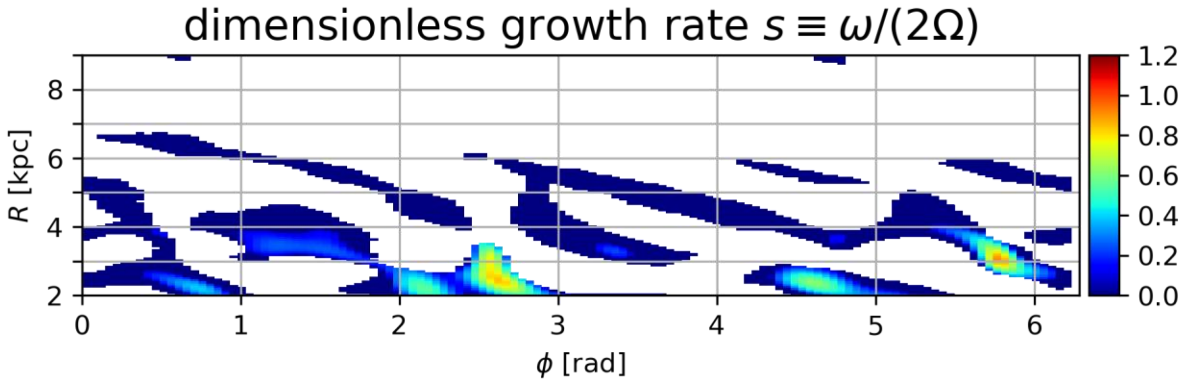
The fragmenting case

$\beta_{ini} = 5$

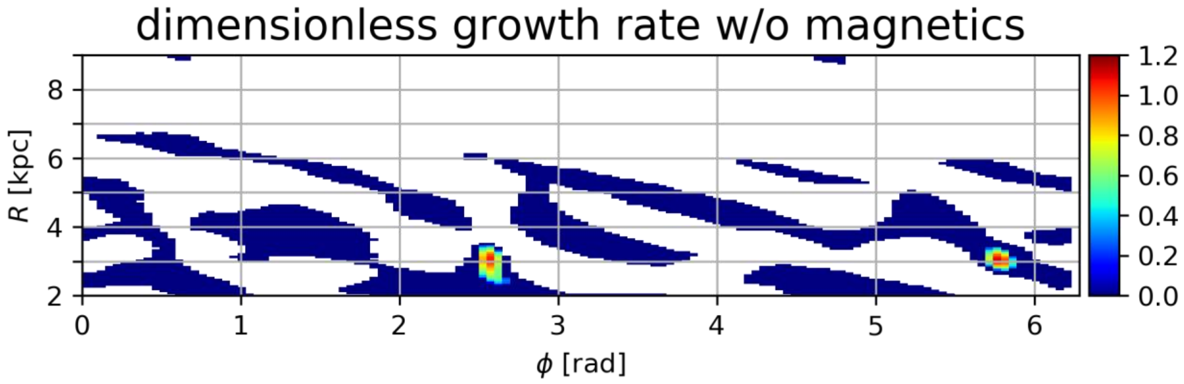


t=330 Myr

Including B-field



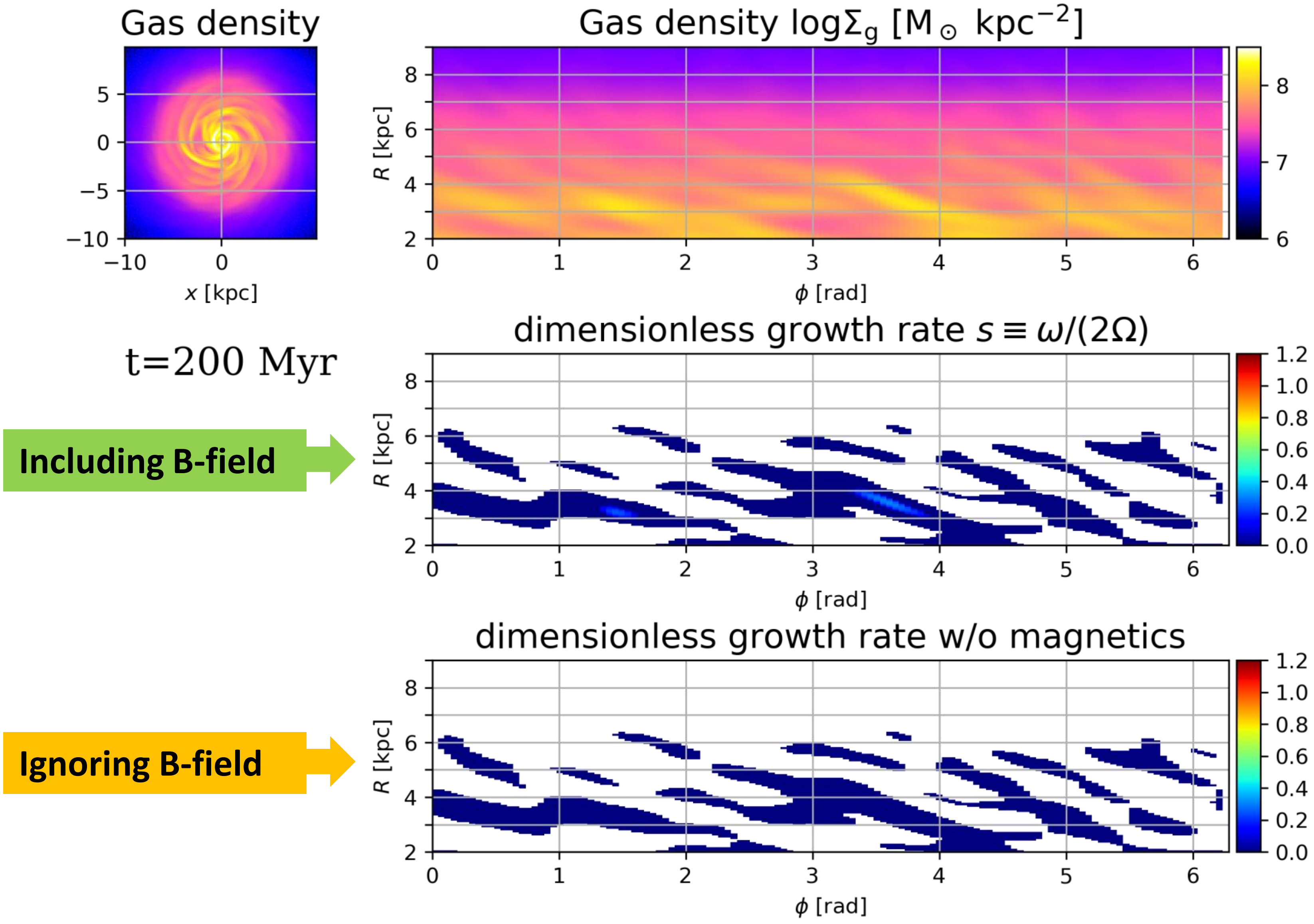
Ignoring B-field



Demonstration

The stable case

$\beta_{ini} = 100$



t=200 Myr

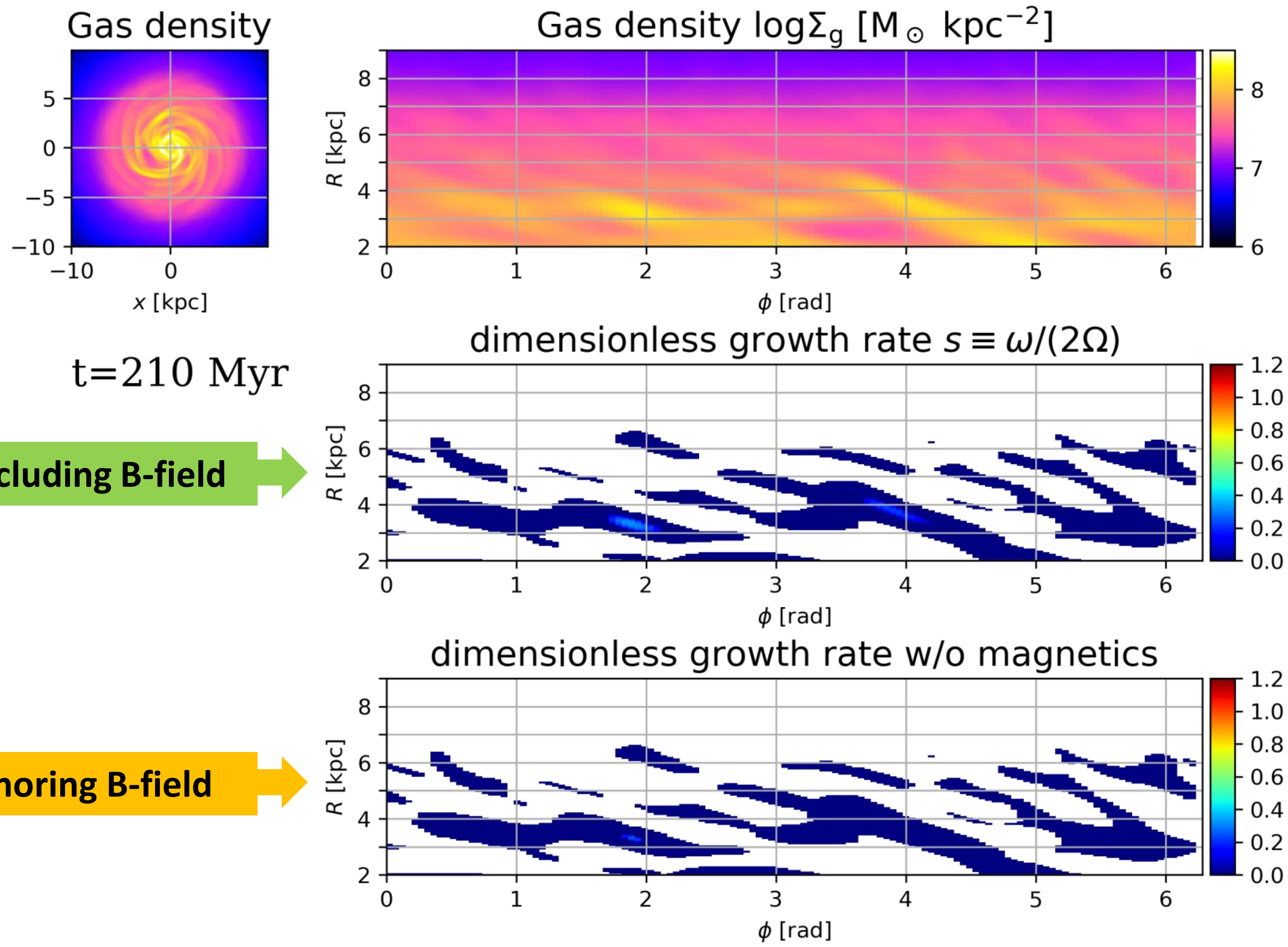
Including B-field

Ignoring B-field

Demonstration

The stable case

$\beta_{ini} = 100$



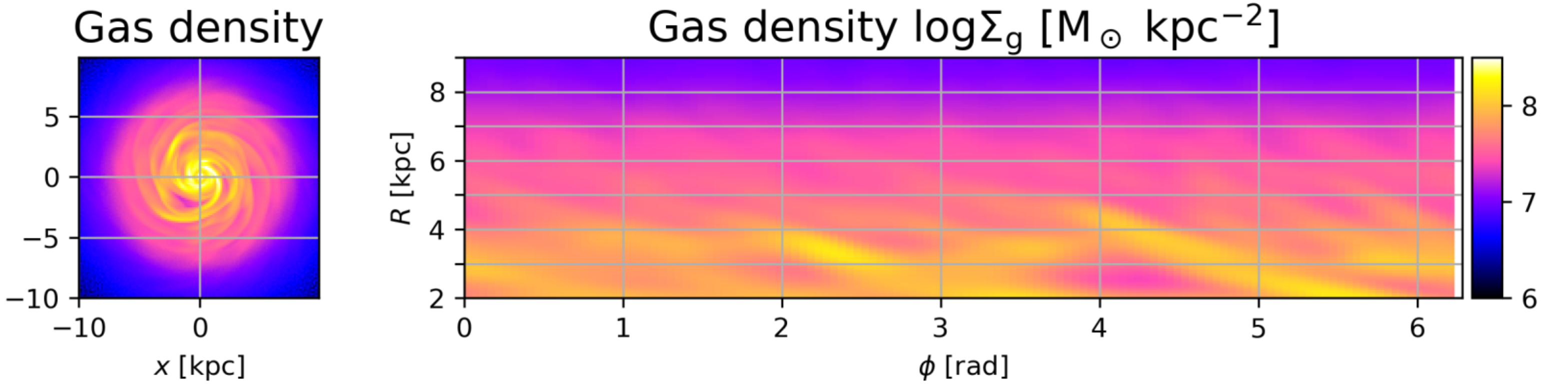
Including B-field

Ignoring B-field

Demonstration

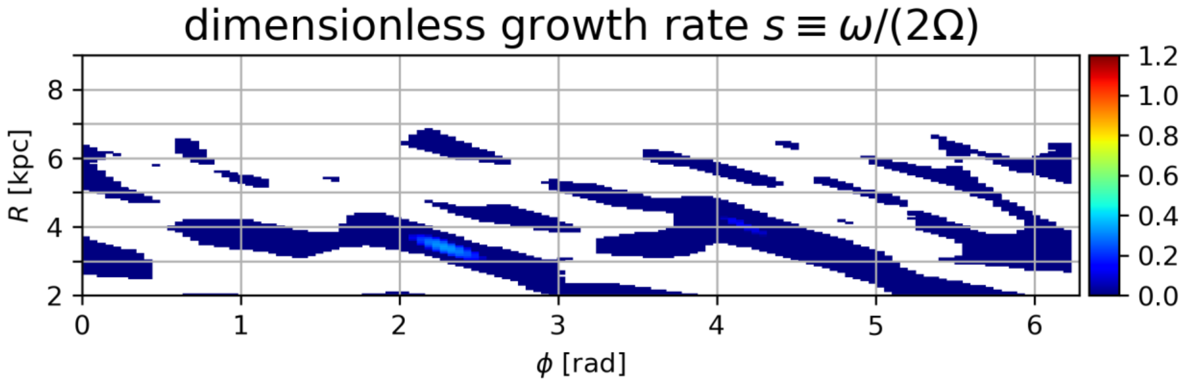
The stable case

$\beta_{ini} = 100$

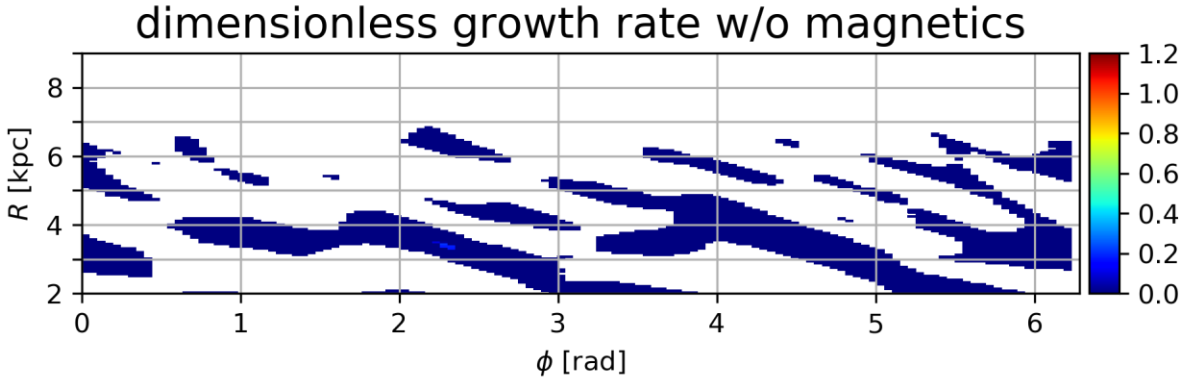


t=220 Myr

Including B-field



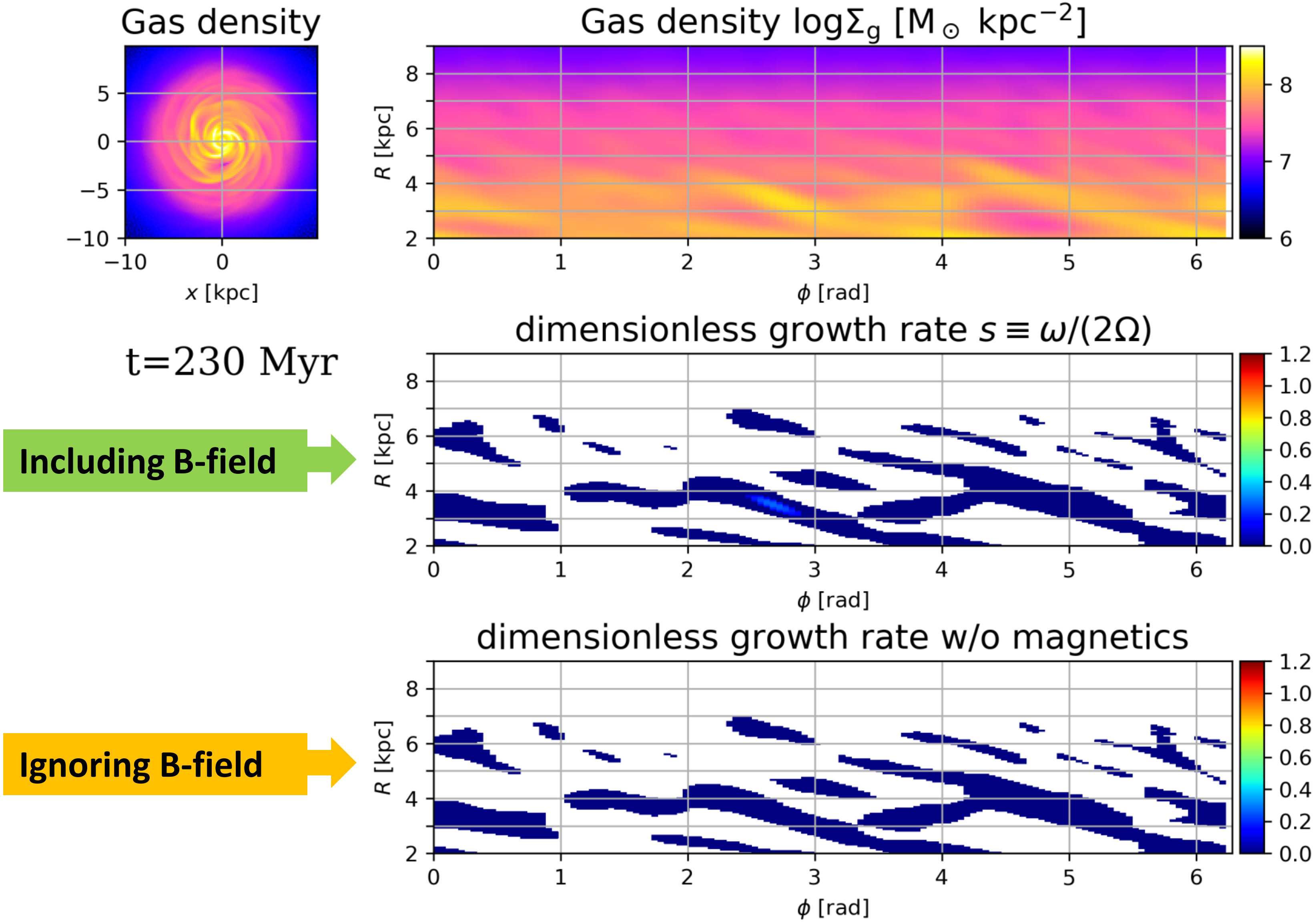
Ignoring B-field



Demonstration

The stable case

$\beta_{ini} = 100$



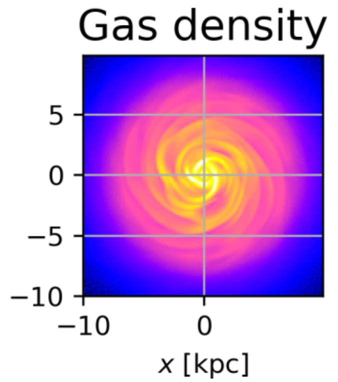
Including B-field

Ignoring B-field

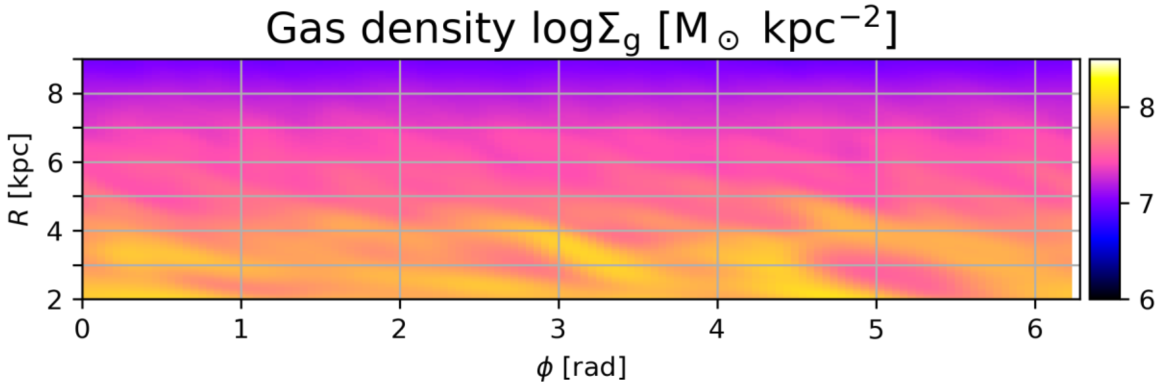
Demonstration

The stable case

$\beta_{ini} = 100$



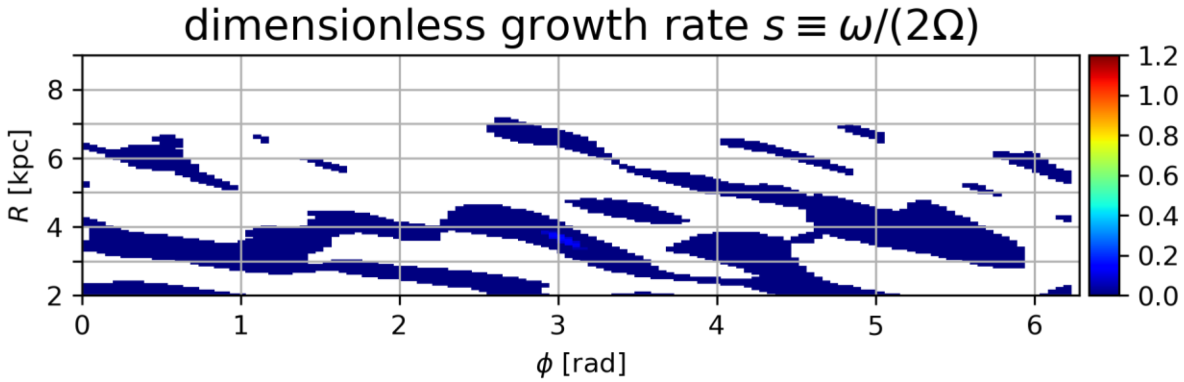
Gas density



Gas density $\log\Sigma_g$ [$M_\odot$ kpc^{-2}]

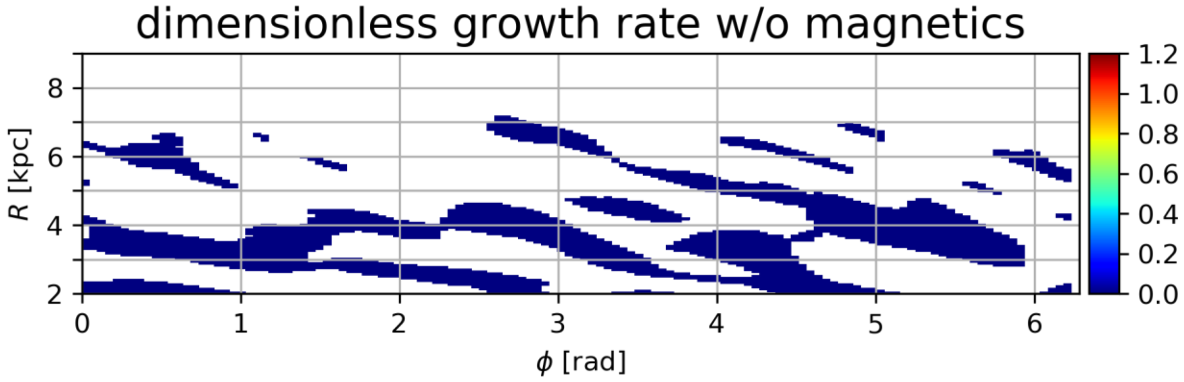
t=240 Myr

Including B-field



dimensionless growth rate $s \equiv \omega/(2\Omega)$

Ignoring B-field

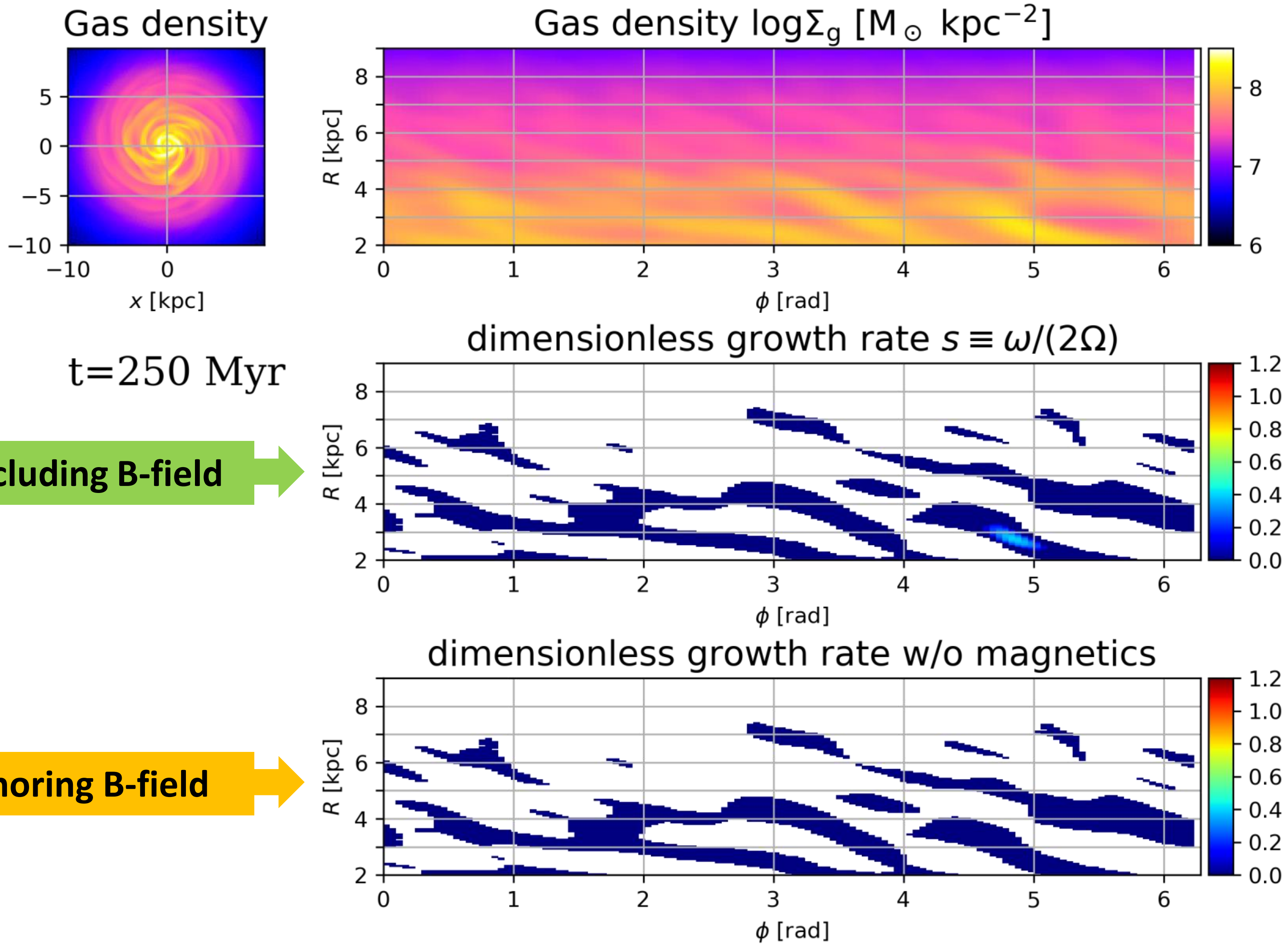


dimensionless growth rate w/o magnetics

Demonstration

The stable case

$\beta_{ini} = 100$



t=250 Myr

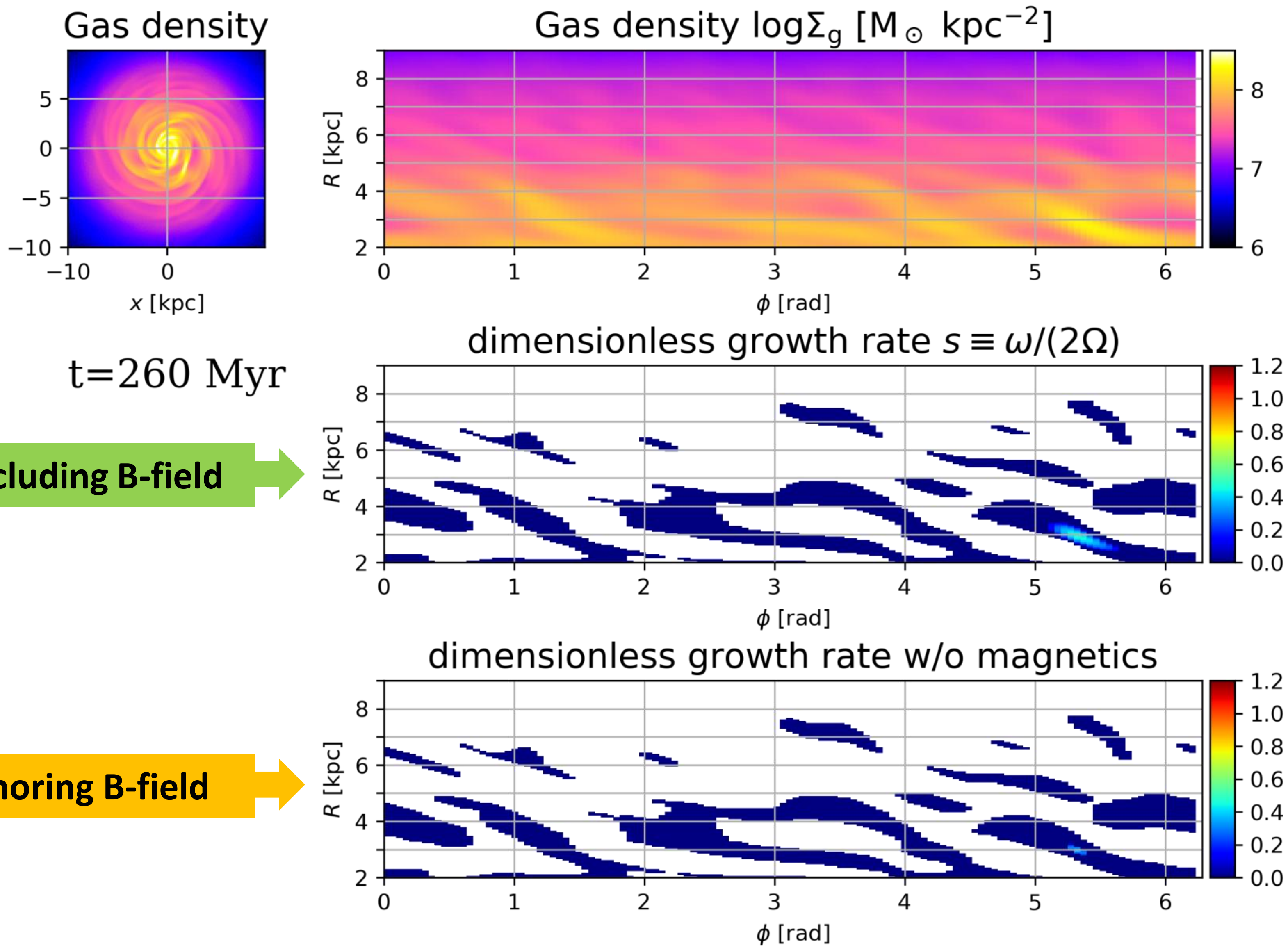
Including B-field

Ignoring B-field

Demonstration

The stable case

$\beta_{ini} = 100$



t=260 Myr

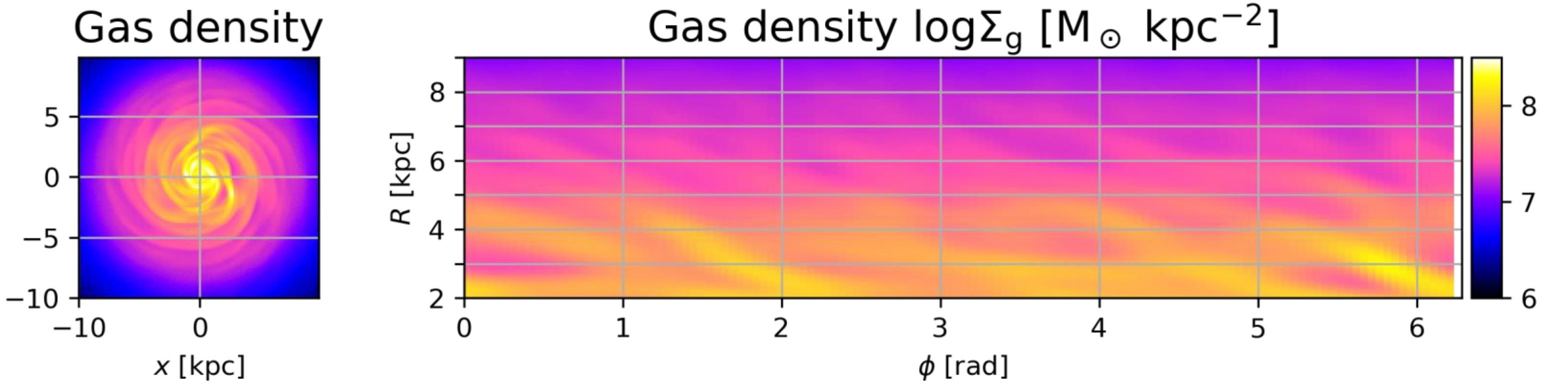
Including B-field

Ignoring B-field

Demonstration

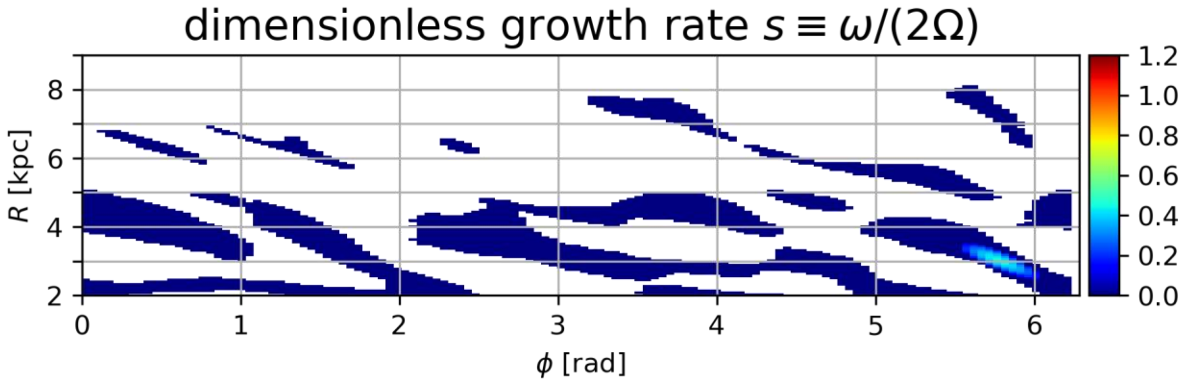
The stable case

$\beta_{ini} = 100$

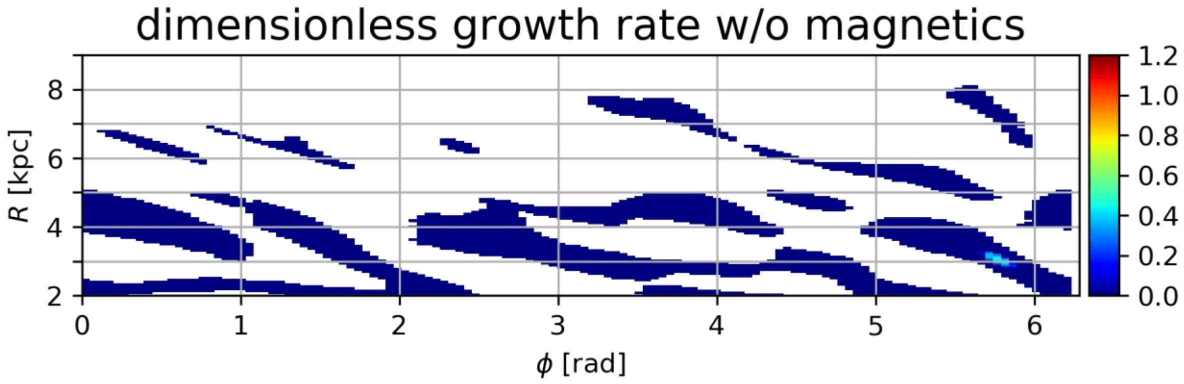


t=270 Myr

Including B-field



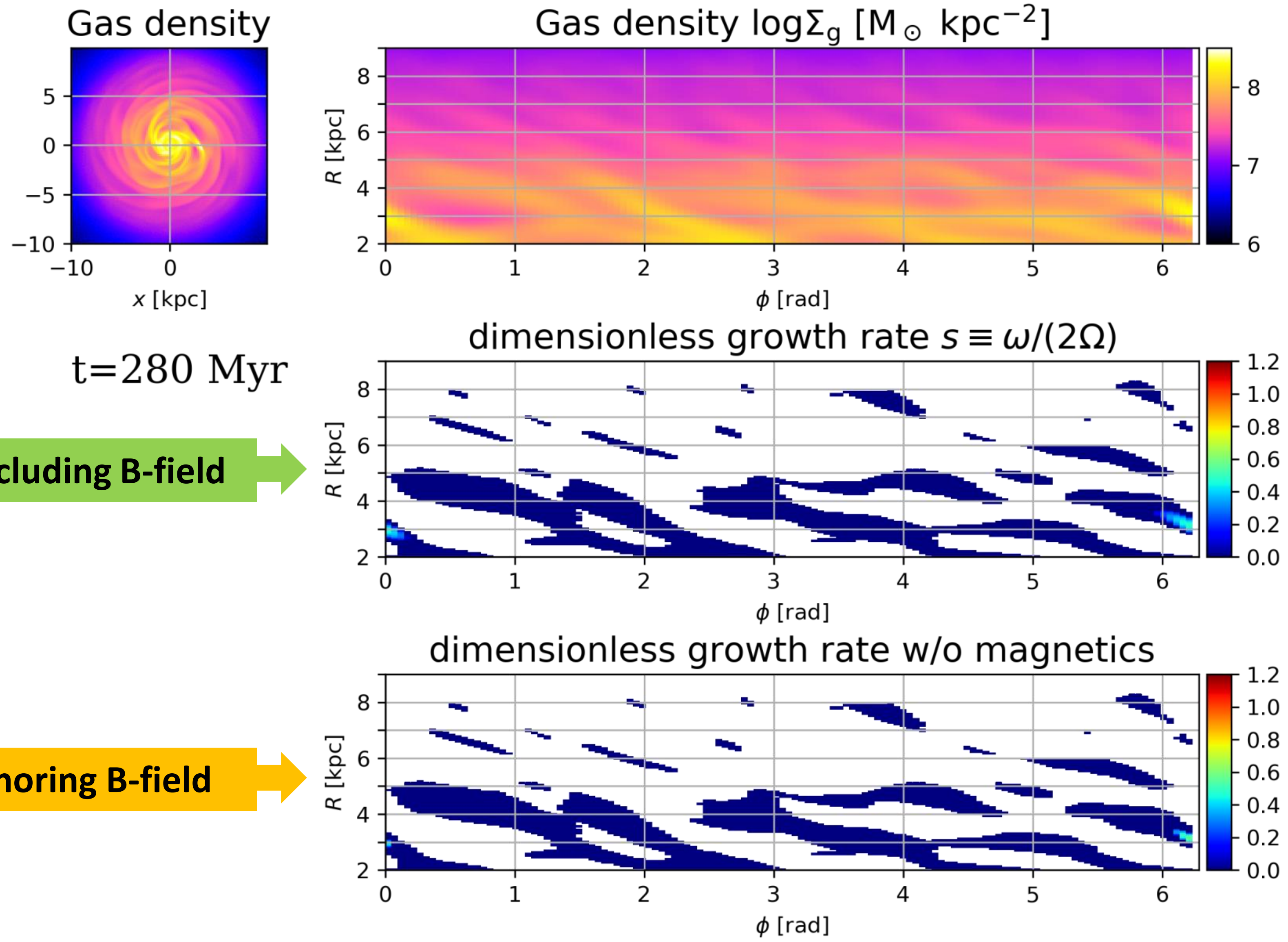
Ignoring B-field



Demonstration

The stable case

$\beta_{ini} = 100$



t=280 Myr

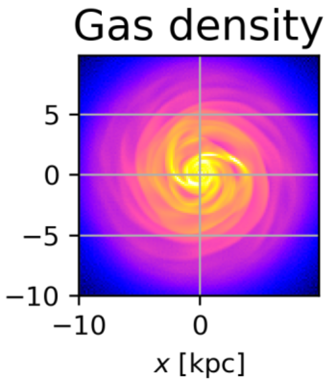
Including B-field

Ignoring B-field

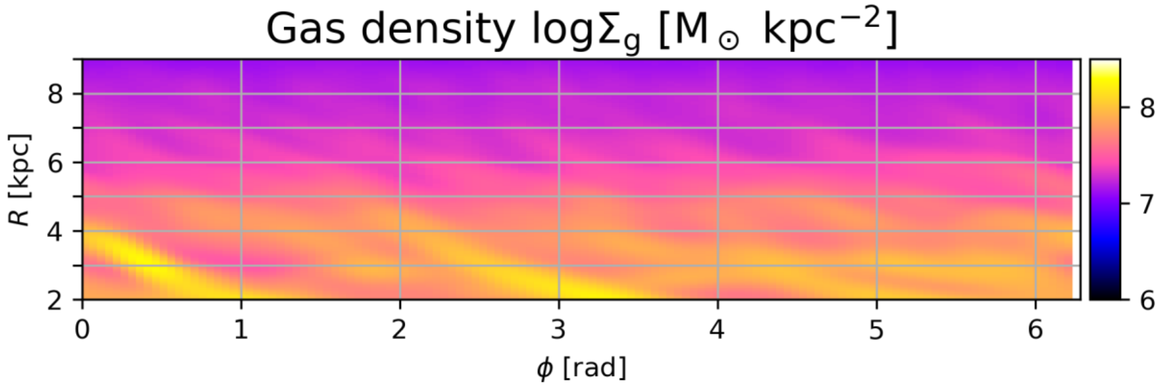
Demonstration

The stable case

$\beta_{ini} = 100$



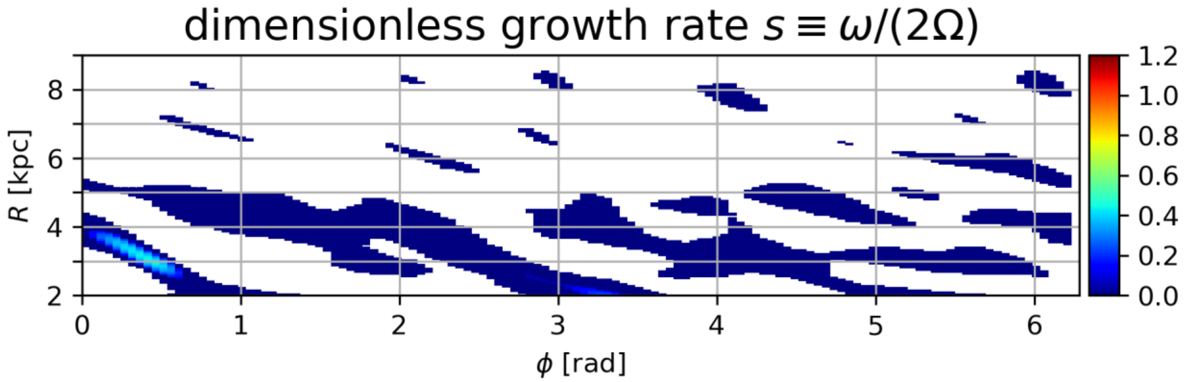
Gas density



Gas density $\log\Sigma_g$ [$M_\odot$ kpc^{-2}]

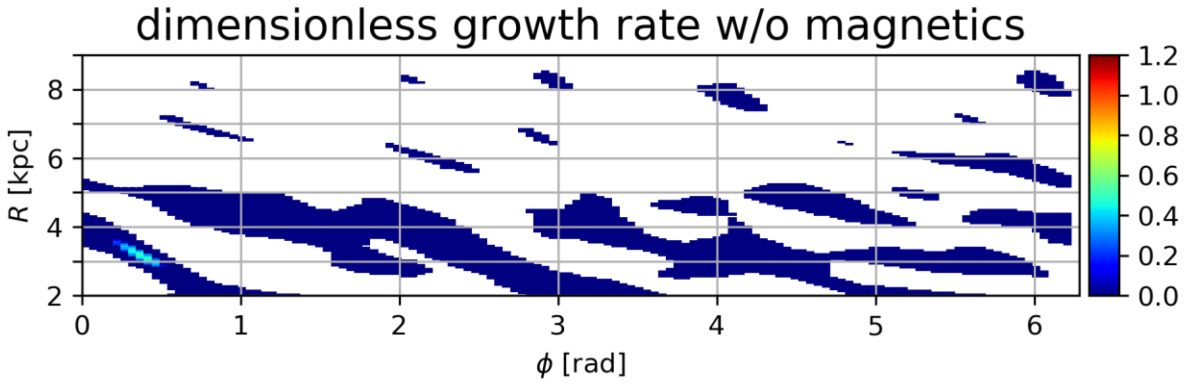
t=290 Myr

Including B-field



dimensionless growth rate $s \equiv \omega/(2\Omega)$

Ignoring B-field

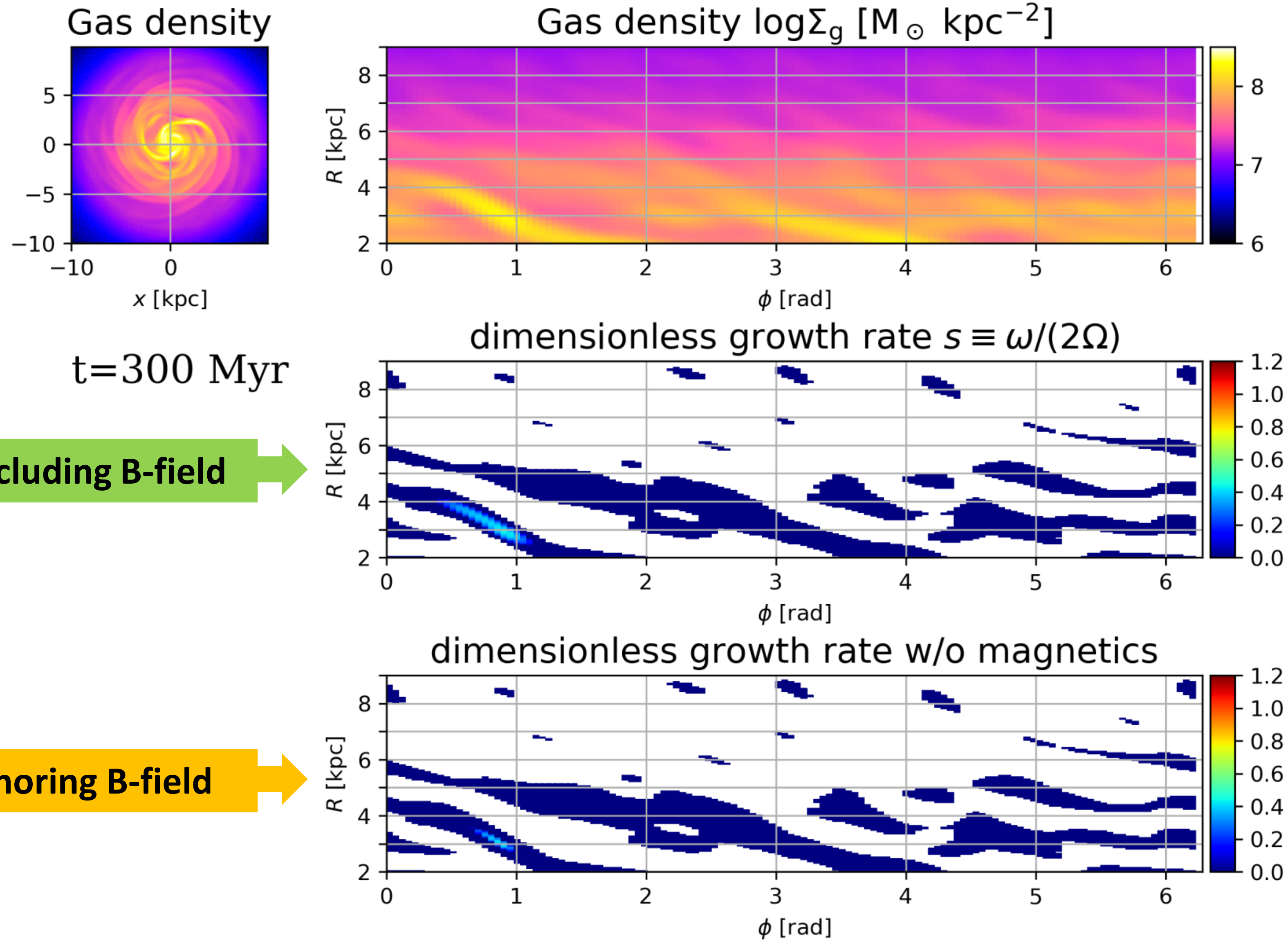


dimensionless growth rate w/o magnetics

Demonstration

The stable case

$\beta_{ini} = 100$



t=300 Myr

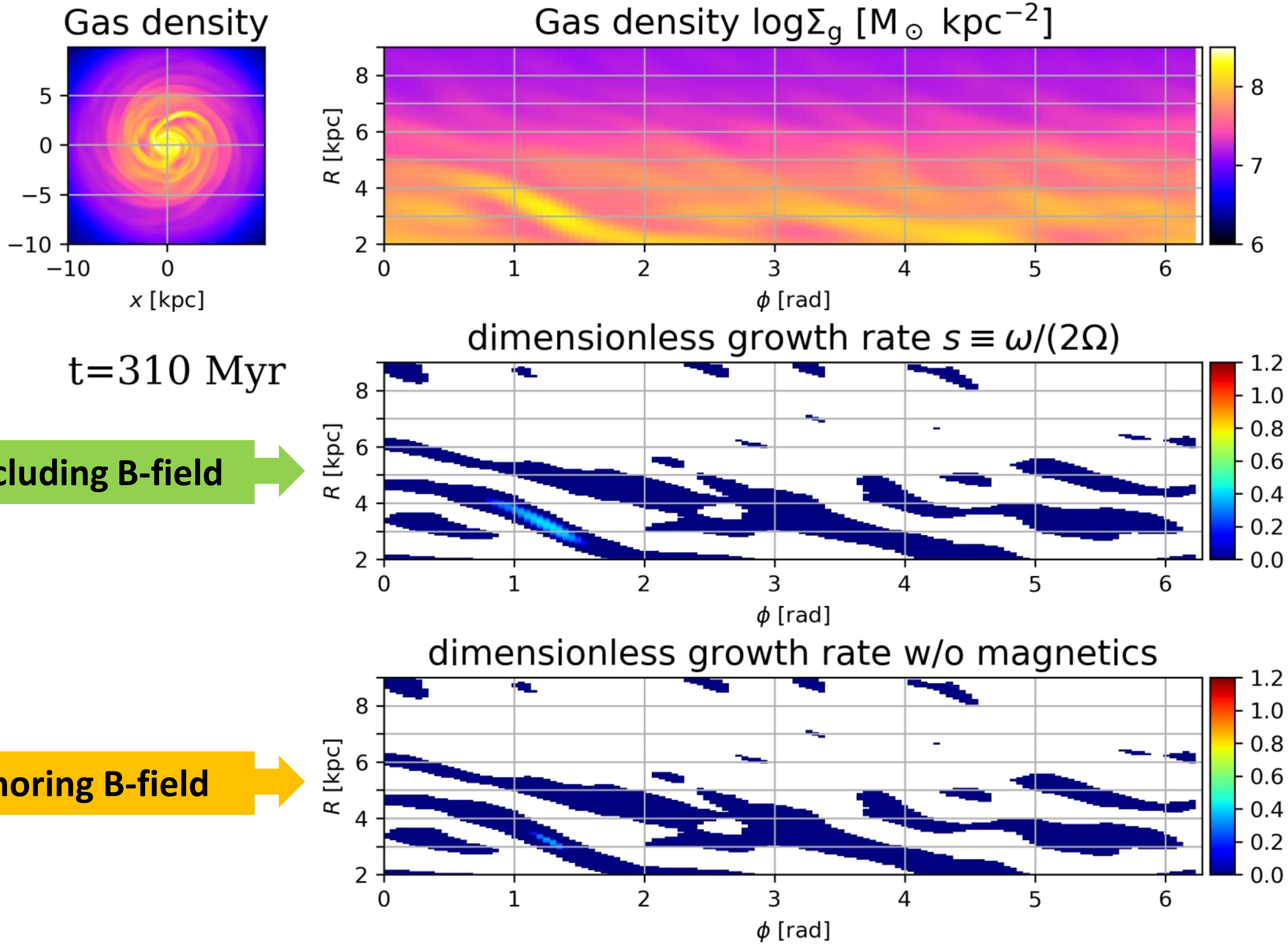
Including B-field

Ignoring B-field

Demonstration

The stable case

$\beta_{ini} = 100$



t=310 Myr

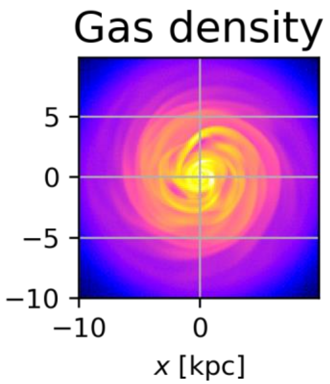
Including B-field

Ignoring B-field

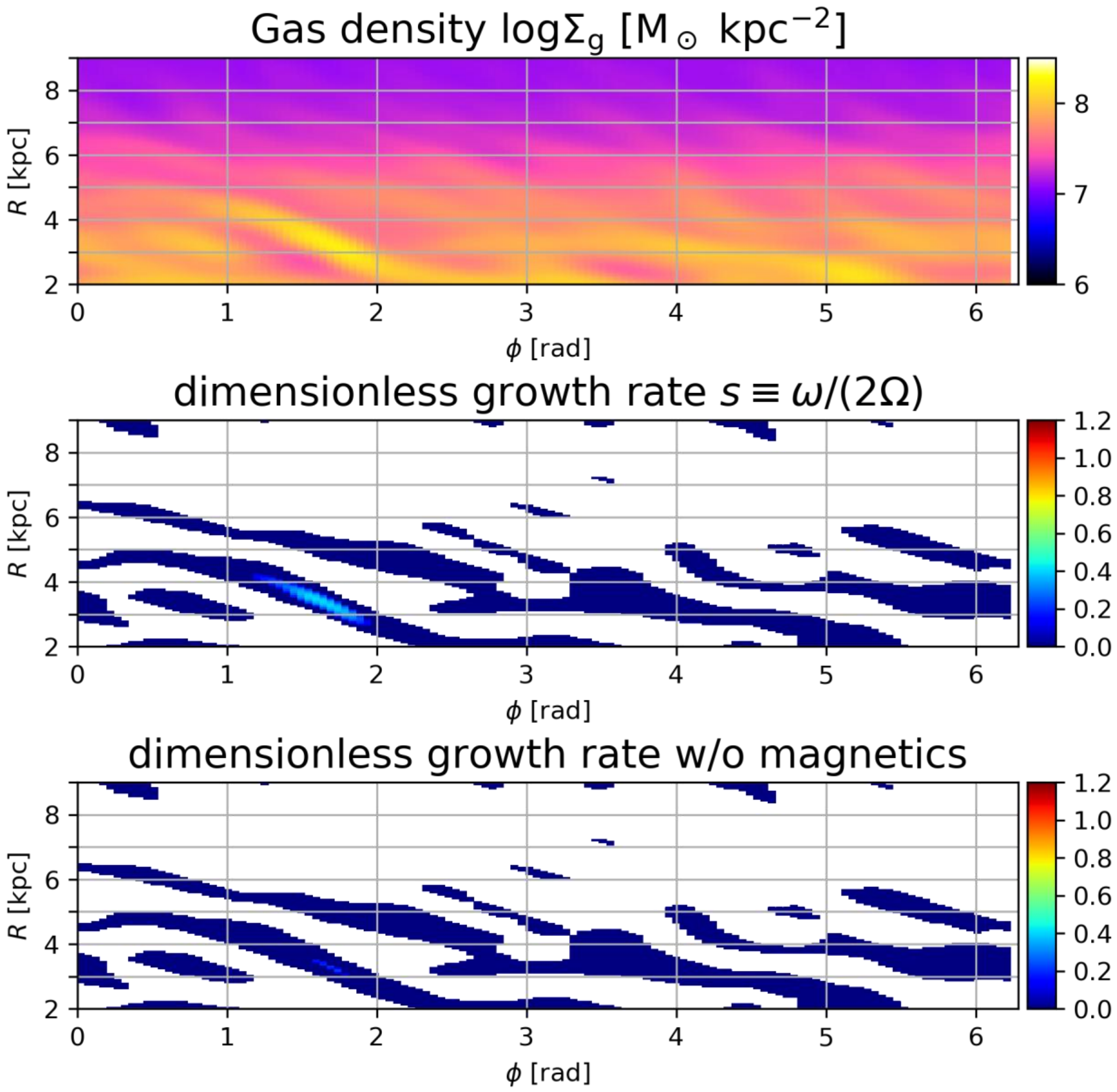
Demonstration

The stable case

$\beta_{ini} = 100$



t=320 Myr



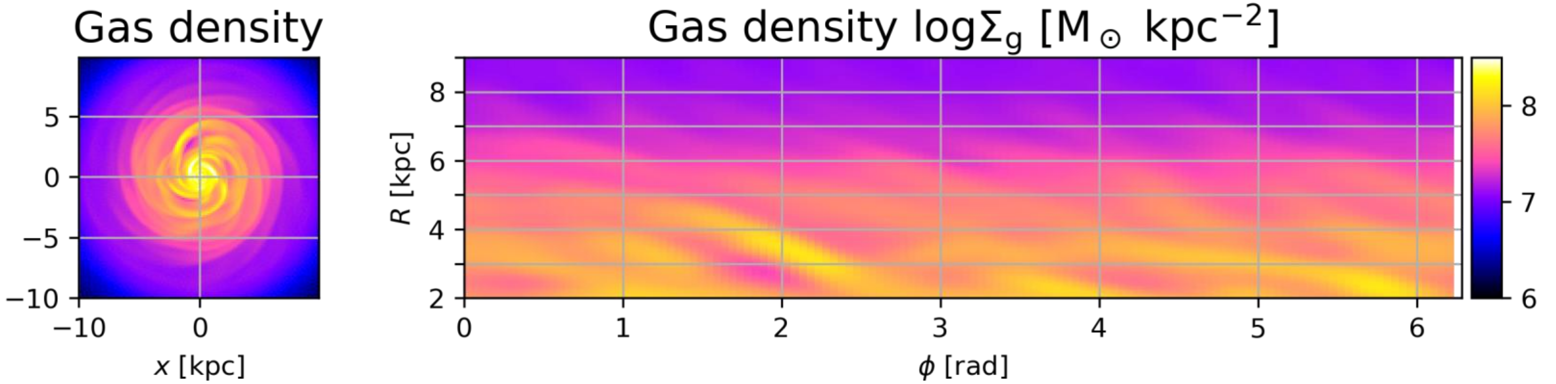
Including B-field

Ignoring B-field

Demonstration

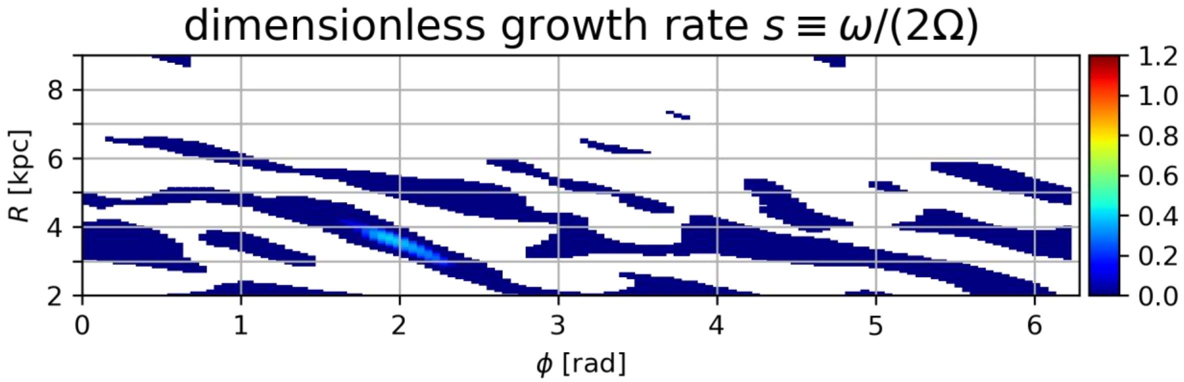
The stable case

$\beta_{ini} = 100$

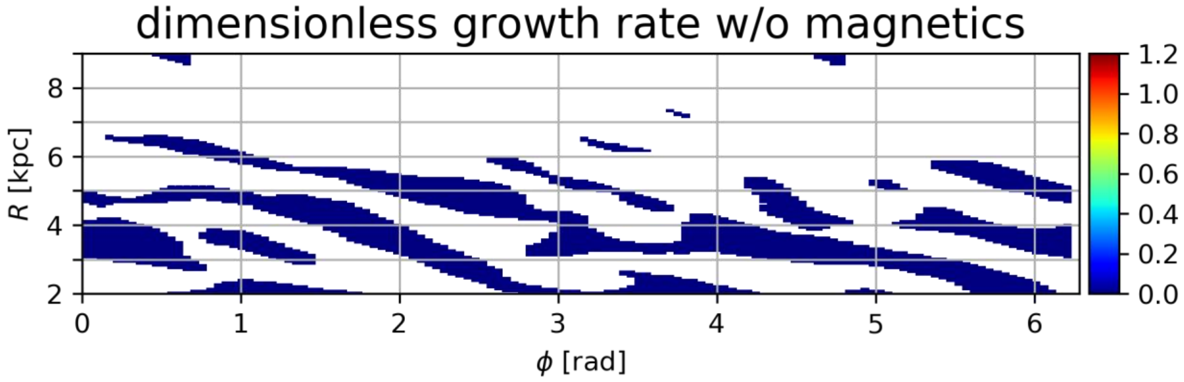


t=330 Myr

Including B-field



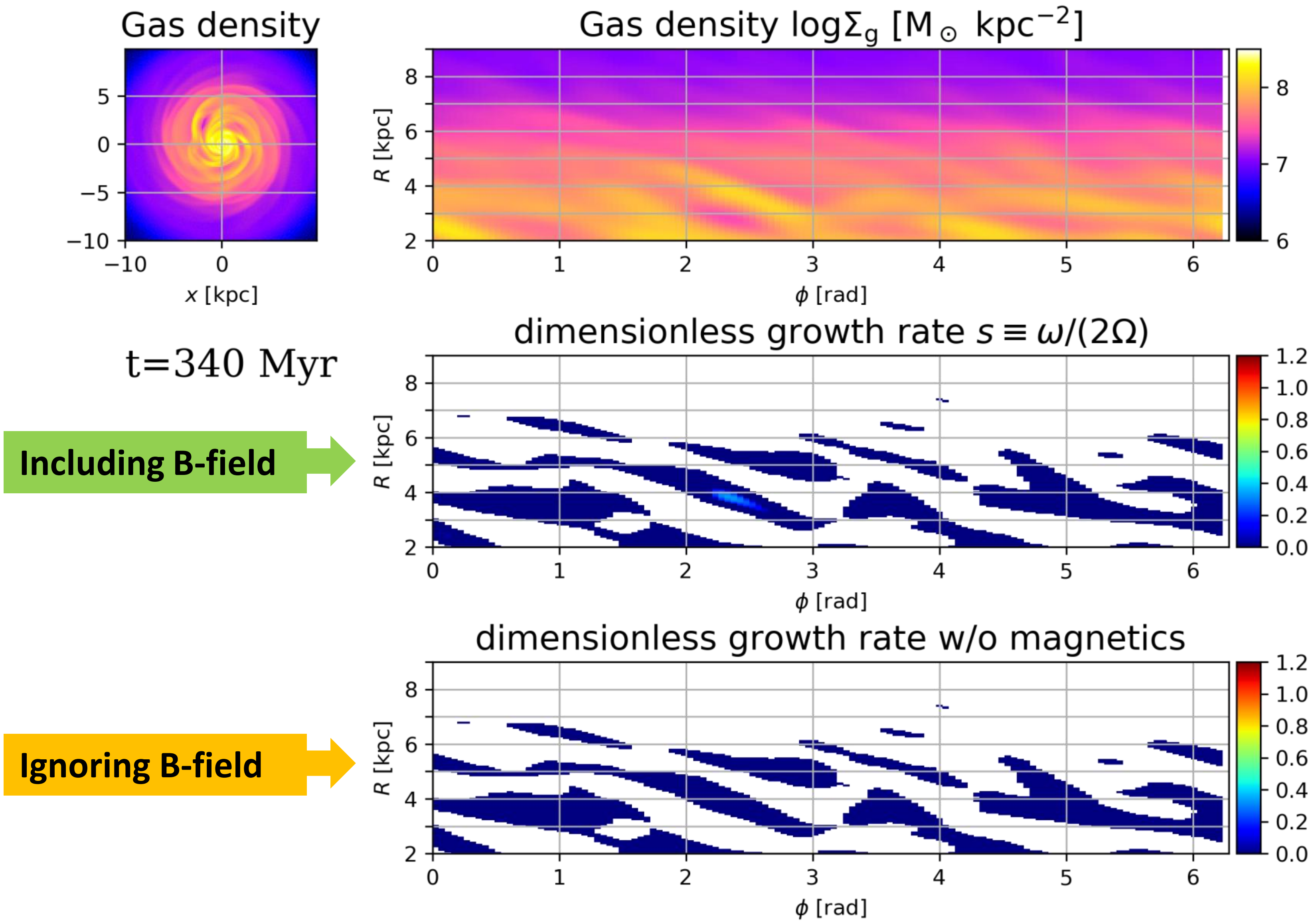
Ignoring B-field



Demonstration

The stable case

$\beta_{ini} = 100$



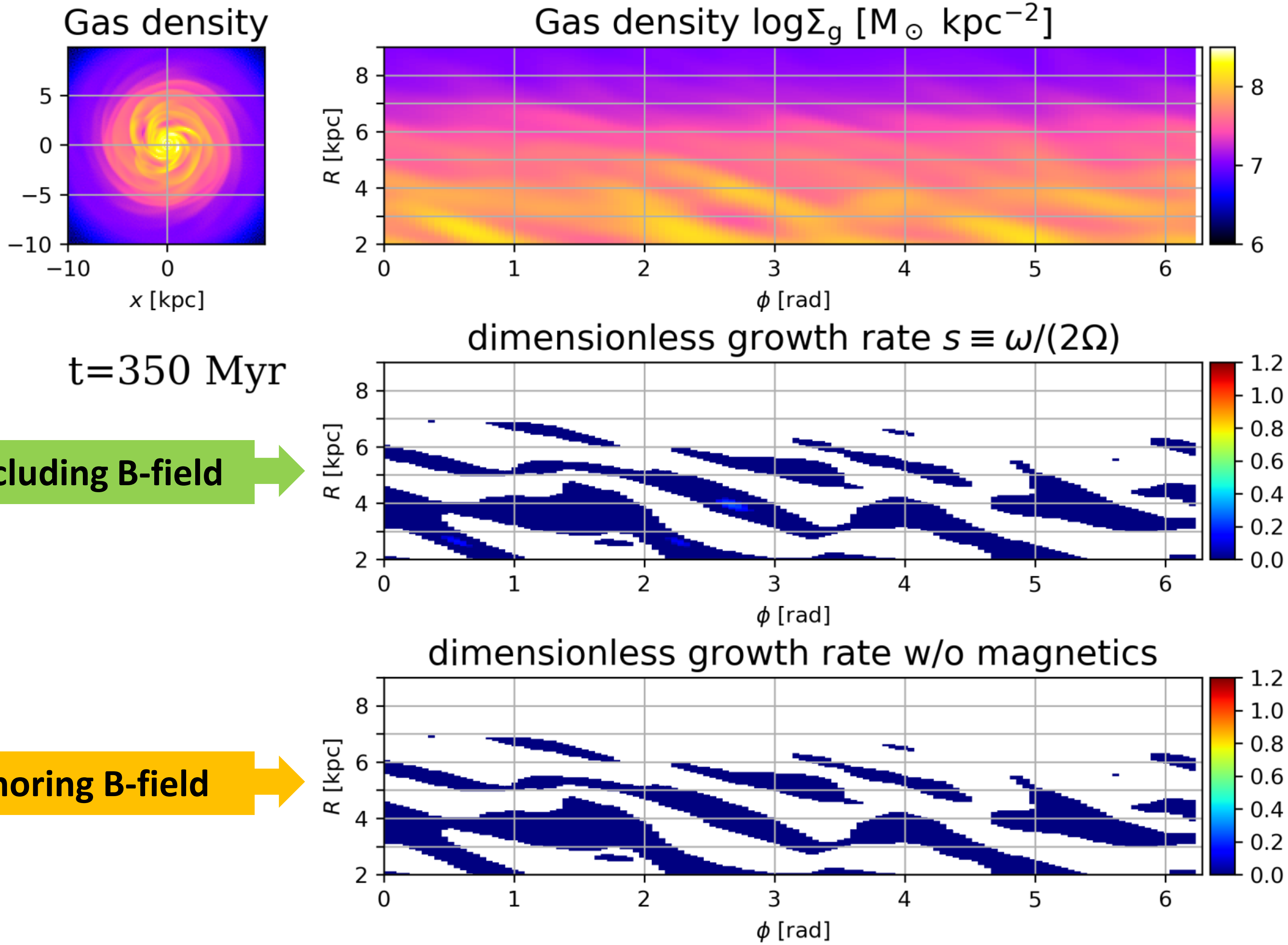
Including B-field

Ignoring B-field

Demonstration

The stable case

$\beta_{ini} = 100$



t=350 Myr

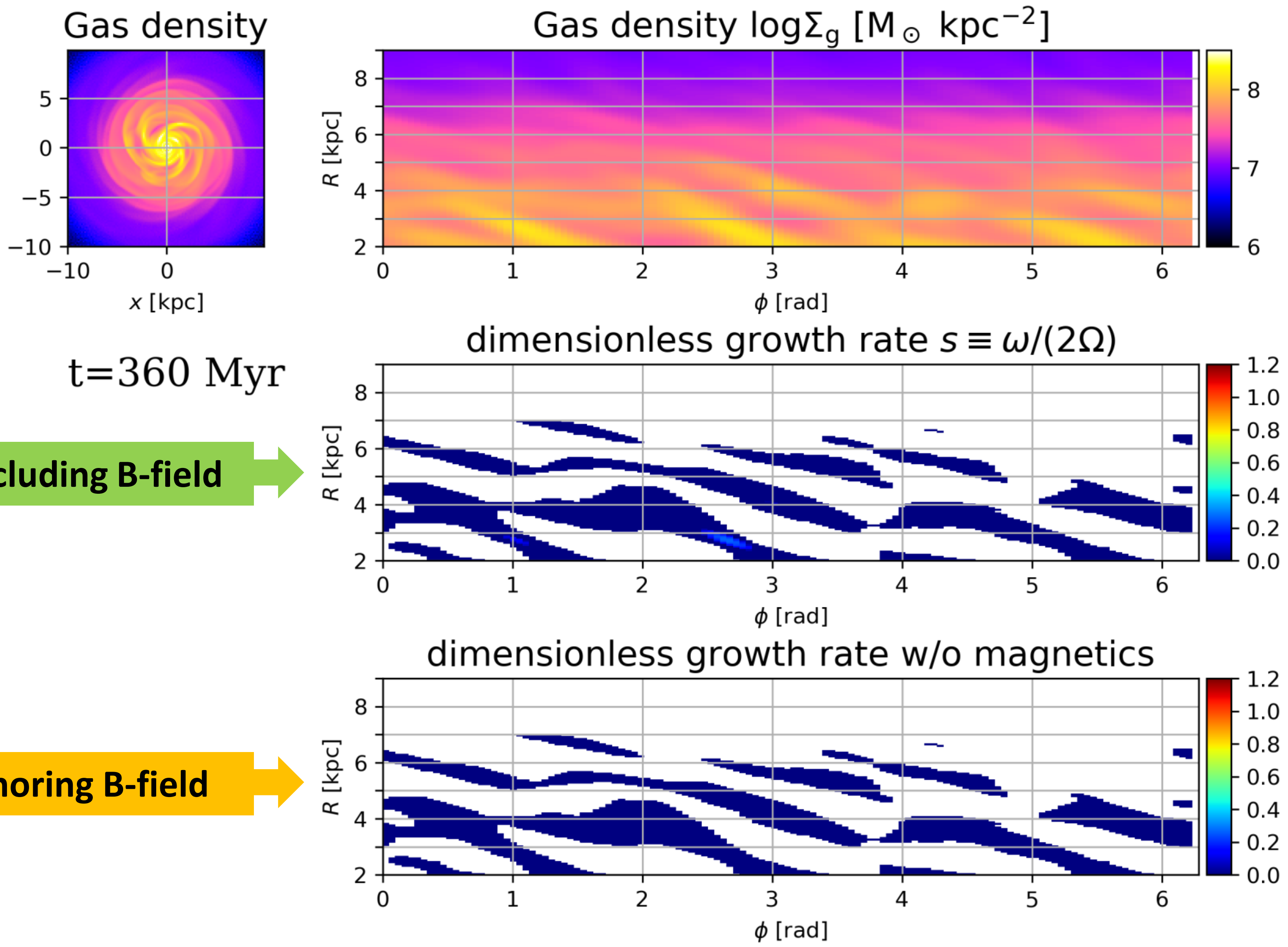
Including B-field

Ignoring B-field

Demonstration

The stable case

$\beta_{ini} = 100$



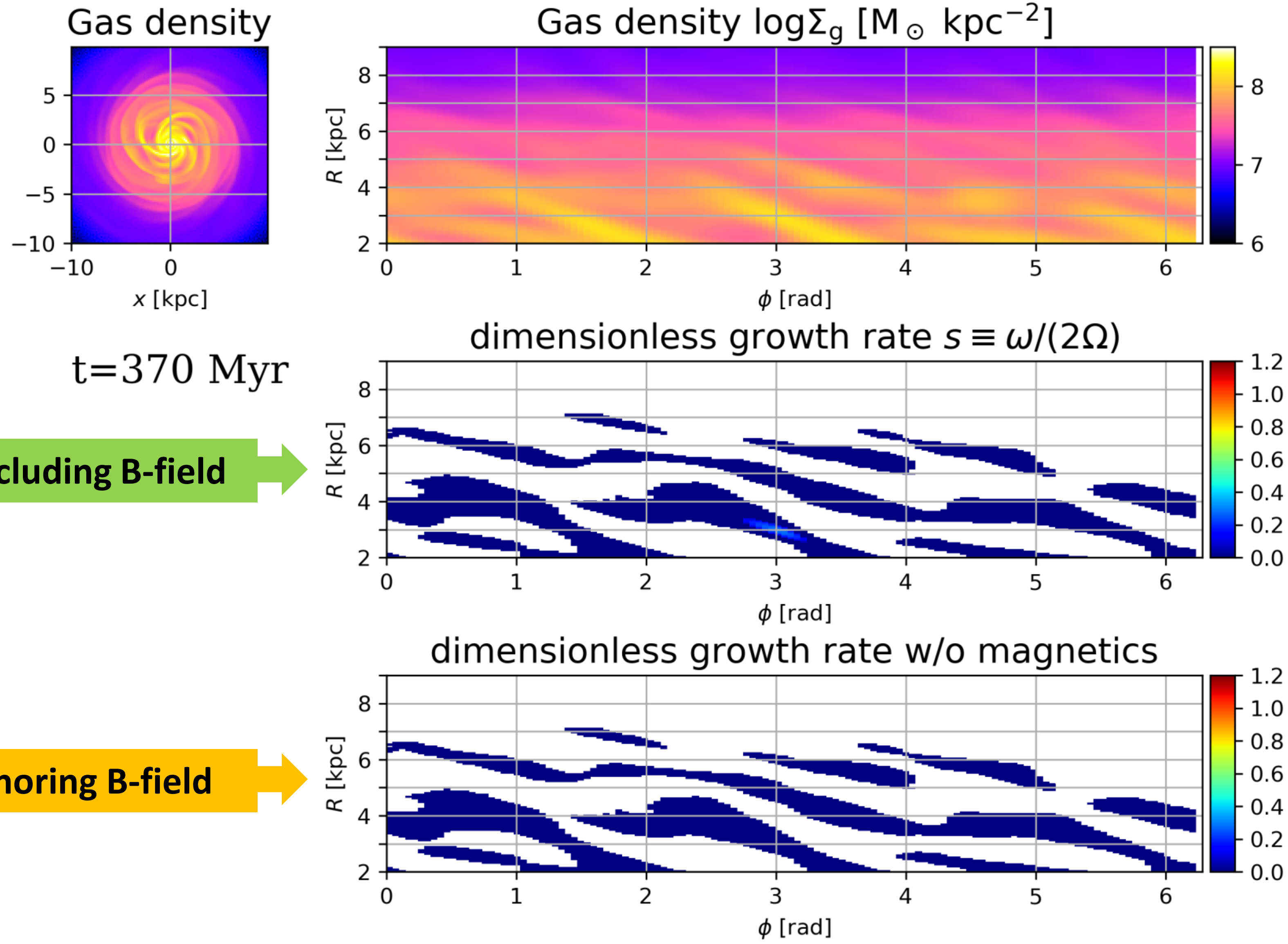
Including B-field

Ignoring B-field

Demonstration

The stable case

$\beta_{ini} = 100$



t=370 Myr

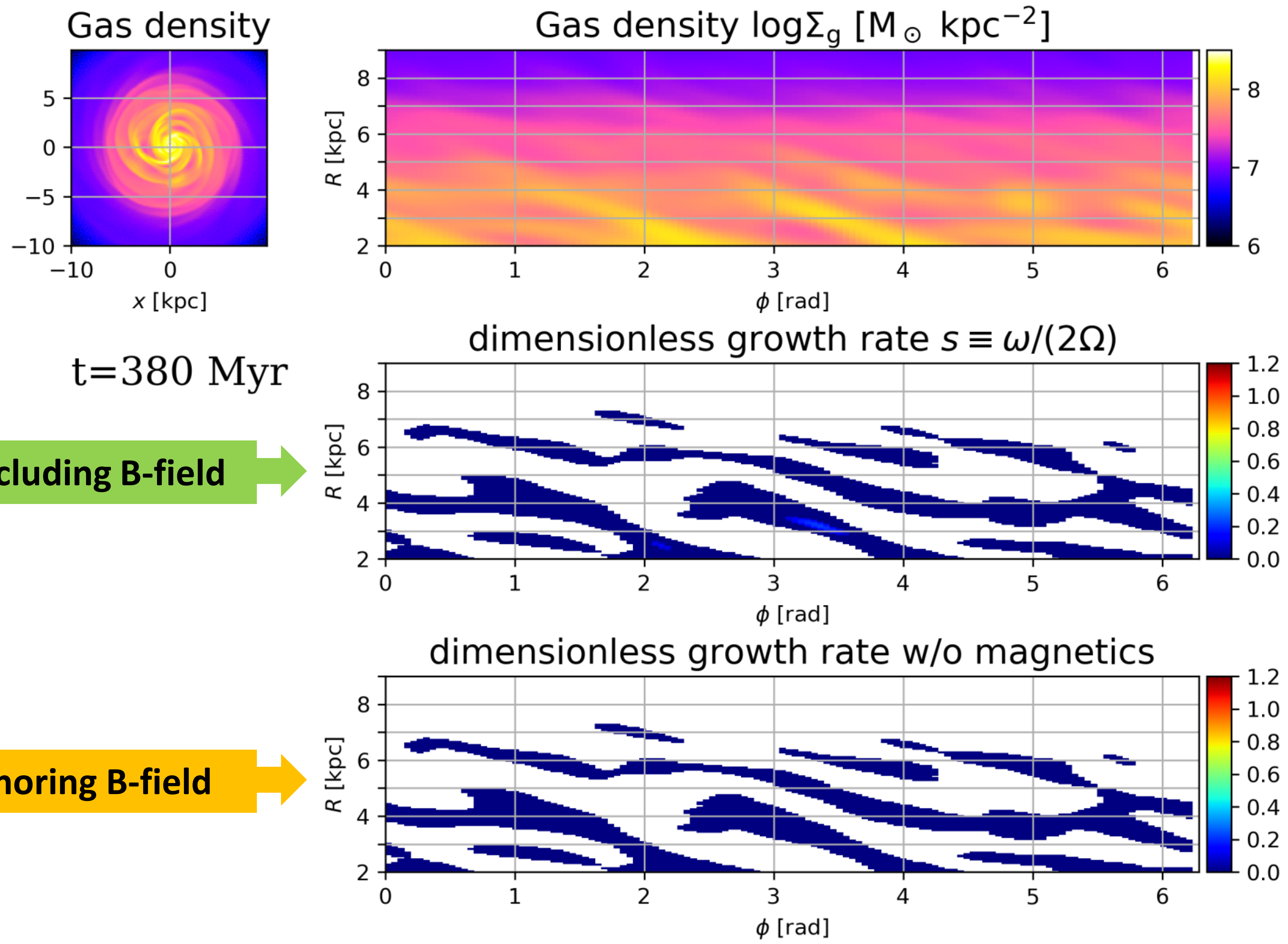
Including B-field

Ignoring B-field

Demonstration

The stable case

$\beta_{ini} = 100$



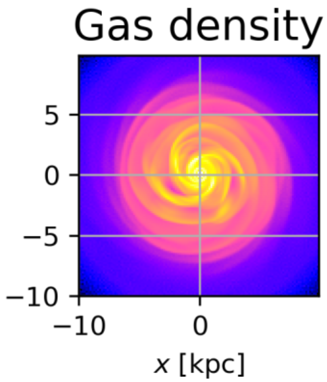
Including B-field

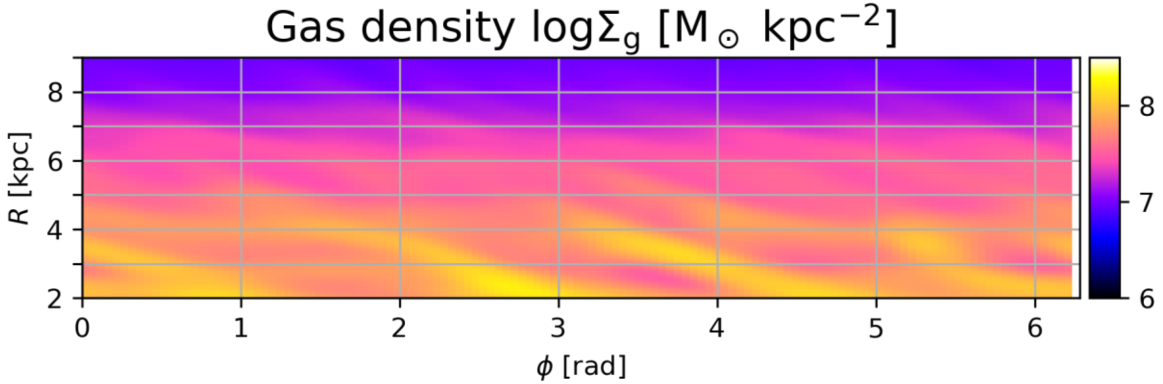
Ignoring B-field

Demonstration

The stable case

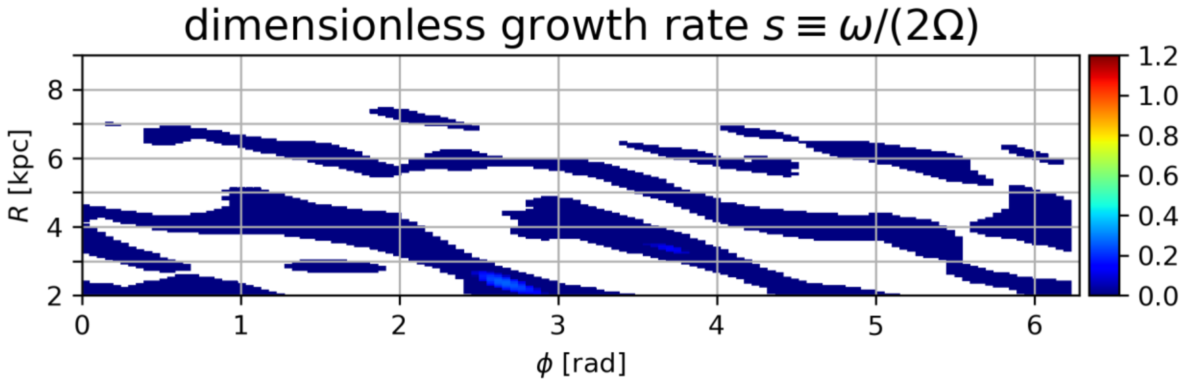
$\beta_{ini} = 100$


Gas density

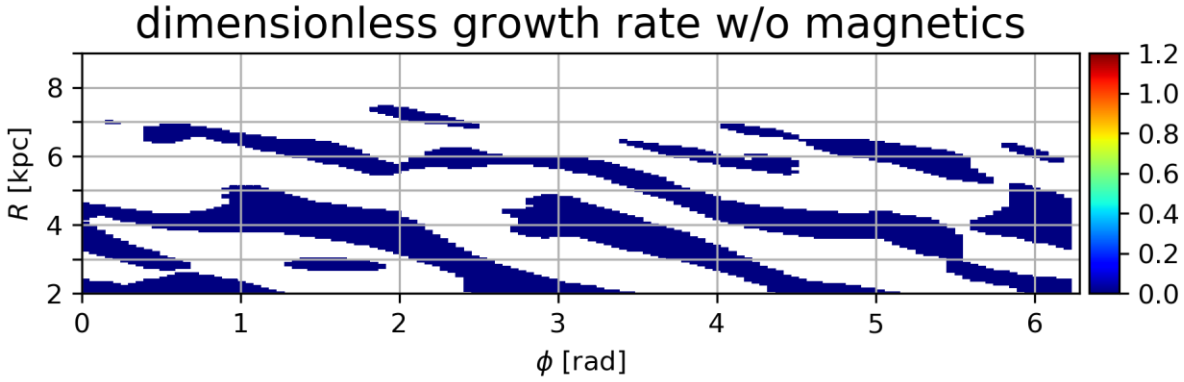

Gas density $\log\Sigma_g$ [$M_\odot$ kpc^{-2}]

t=390 Myr

Including B-field


dimensionless growth rate $s \equiv \omega/(2\Omega)$

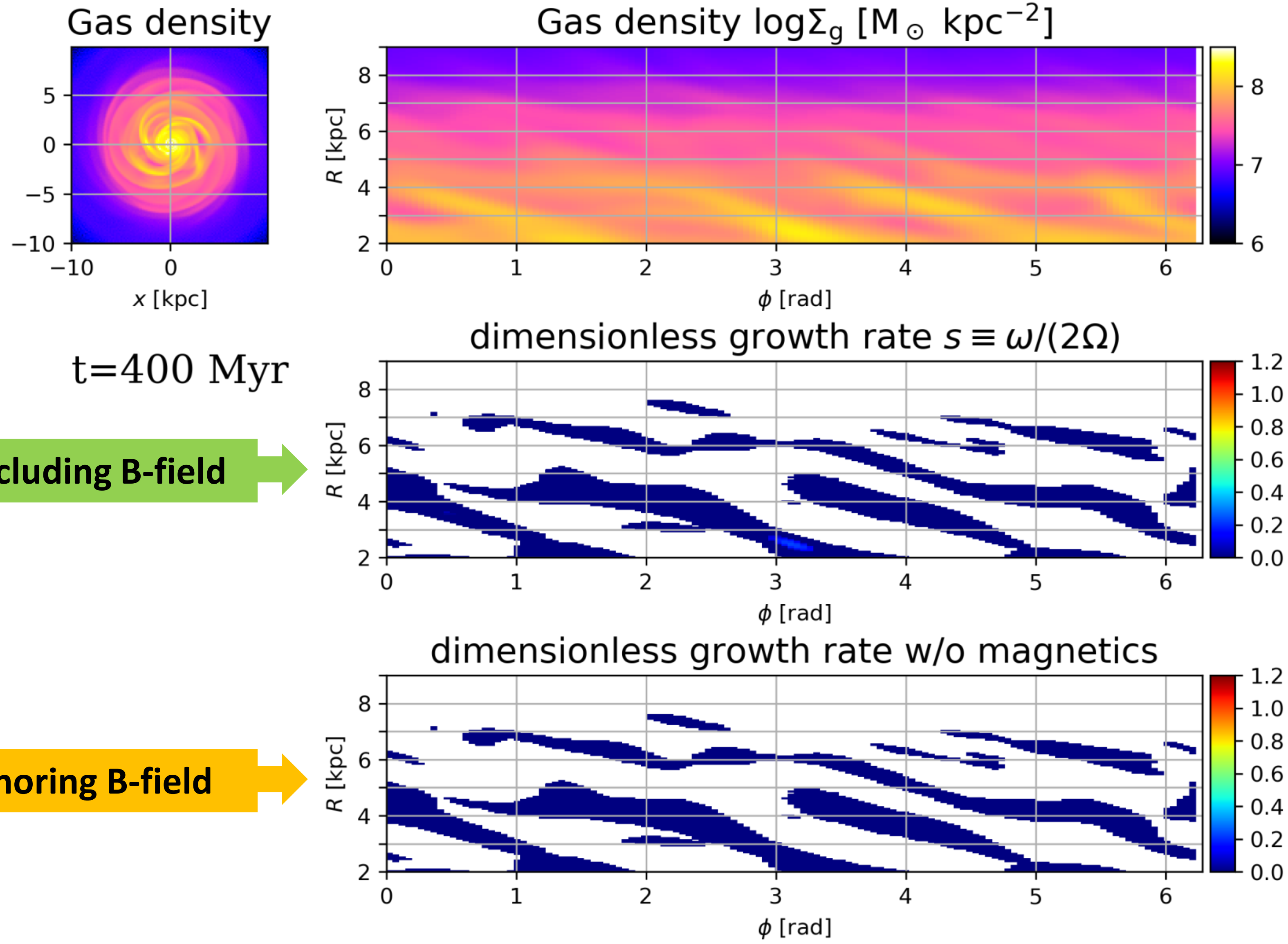
Ignoring B-field


dimensionless growth rate w/o magnetics

Demonstration

The stable case

$\beta_{ini} = 100$



t=400 Myr

Including B-field

Ignoring B-field

Two-component model: gas and stars

- This analysis can be applied to a multi-component model
  - Stars are not affected by magnetic fields.

- However, the dispersion relation becomes very complicated…
  - The two-component dispersion relation is

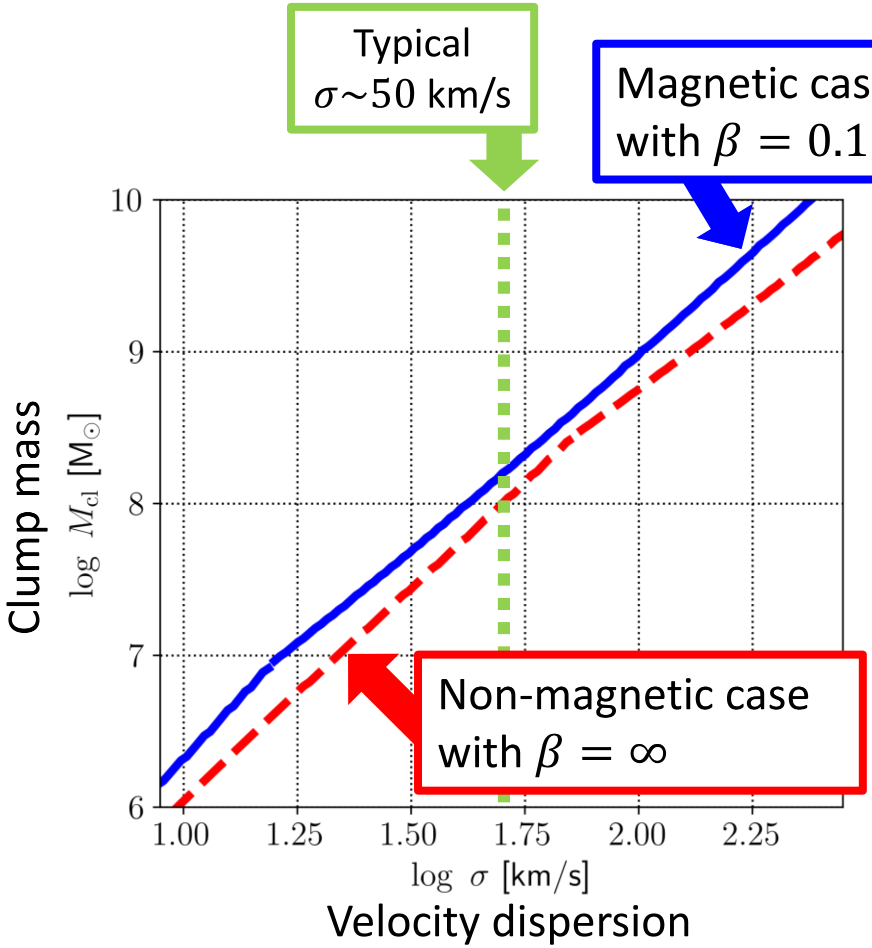
$$\underbrace{\frac{\pi G k^2 \Upsilon_{\mathrm{g}} f(kW_{\mathrm{g}})}{\sigma_{\mathrm{g}}^2 k^2 + \frac{4\Omega^2\omega^2}{\omega^2+k^2v_{\mathrm{A}}^2} - \omega^2}}_{\text{Gas}} + \underbrace{\frac{\pi G k^2 \Upsilon_{\mathrm{s}} f(kW_{\mathrm{s}})}{\sigma_{\mathrm{s}}^2 k^2 + 4\Omega^2 - \omega^2}}_{\text{Stars}} = 1.$$

  - This is reduced to a sixth-order (bi-cubic) equation of ω

$$\begin{aligned} s^6 &+ \left(\beta^{-1} q_{\mathrm{g}}^2 x_{\mathrm{g}}^2 - \alpha_{\mathrm{s}} - \alpha_{\mathrm{g}} - 1\right) s^4 \\ &+ \left[\alpha_{\mathrm{s}}\alpha_{\mathrm{g}} - \beta^{-1} q_{\mathrm{g}}^2 x_{\mathrm{g}}^2 \left(\alpha_{\mathrm{s}} + \alpha_{\mathrm{g}}\right) + \alpha_{\mathrm{s}} - \gamma_{\mathrm{s}}\gamma_{\mathrm{g}}\right] s^2 \\ &+ \beta^{-1} q_{\mathrm{g}}^2 x_{\mathrm{g}}^2 \left(\alpha_{\mathrm{s}}\alpha_{\mathrm{g}} - \gamma_{\mathrm{s}}\gamma_{\mathrm{g}}\right) = 0. \end{aligned}$$

Clump mass estimate

- A clump mass can be estimated from our linear analysis.
  - Assuming typical values of clumpy disc galaxies
    - Disc rotation velocity $V_\phi = 200$ km/s
    - Spiral arm width $W = 0.5$ kpc
    - Clump formation radius $R = 5$ kpc
    - High turbulence $\sigma \sim 50$ km/s


Typical $\sigma \sim 50$ km/s

Magnetic case with $\beta = 0.1$

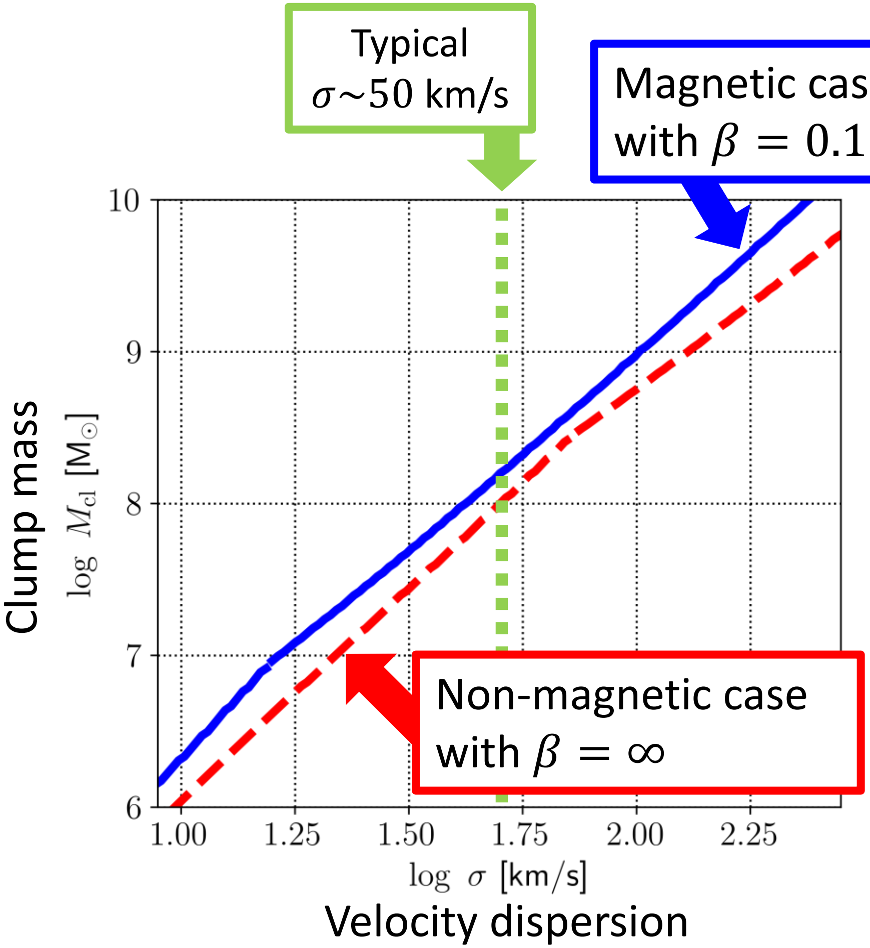
Non-magnetic case with $\beta = \infty$

- **The estimated mass $M_{cl} \sim 10^8$ $M_\odot$**
  - **Consistent with observed clumps**

- **The estimated mass is almost independent from magnetic fields.**

Clump mass estimate

- A clump mass can be estimated from our linear analysis.
  - Assuming typical values of clumpy disc galaxies
    - Disc rotation velocity $V_\phi = 200$ km/s
    - Clump formation radius $R = 5$ kpc
    - Spiral arm width $W = 0.5$ kpc

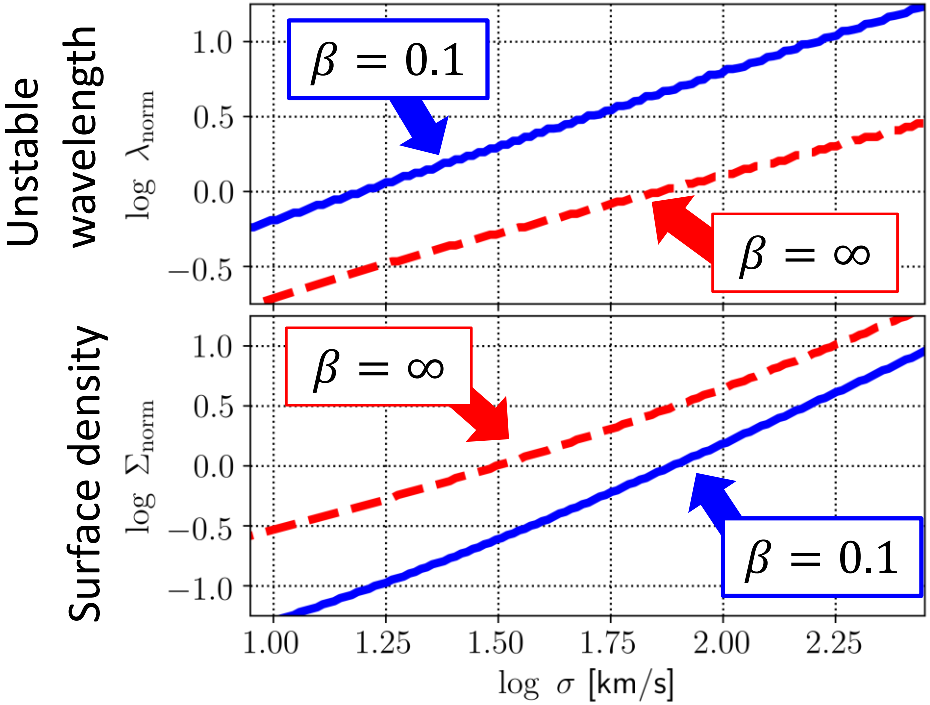


Typical σ~50 km/s

Magnetic case with $\beta = 0.1$

Non-magnetic case with $\beta = \infty$

- **The estimated mass M_{cl}~10^8 M$_\odot$**
  - **Consistent with observed clumps**



$\beta = 0.1$

$\beta = \infty$

$\beta = \infty$

$\beta = 0.1$

Summary

- **Toroidal magnetic fields can destabilize spiral arms and drive the formation of giant clumps.**
    - By canceling Coriolis force.
    - Presence of magnetic fields may induce clump formation and stimulate star formation in spiral galaxies.

- In MHD simulations, our linear analysis can characterize fragmentation of spiral arms and predict giant clump formation.
    - This implies that spiral-arm fragmentation is basically a linear process.
    - The analysis becomes inaccurate if the magnetic field is ignored.
    - Our analysis can also be applied to multi-component models.

- From our analysis, a typical clump mass is almost independent from strength of magnetic fields.
    - The toroidal fields causes a wide and low-density region to collapse.
    - The long wavelength and the low density compensate the dependence on B-fields, and result in formation of clumps with similar masses.