Stellar dynamics and radial gas flows in disk galaxies

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Chemical and Dynamical evolution of the MW and LG galaxies
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1. Radial gas flows: basic physics
2. External or internal origin?
3. Stellar evolution meets stellar dynamics
4. An unavoidable mechanism?

1. RADIAL GAS FLOWS: BASIC PHYSICS

Relevant for galaxy formation and evolution
Redistribution of chemical elements in disk galaxies
Cosmological implications, hot coronae

…

…

…

Physical aspect of the problem: angular momentum Jz

No radial flows are possible if angular momentum is conserved

Jz is conserved in axisymmetric systems

Gas dissipates and settles at radius R where the galaxy circular velocity Vc(R) corresponds to

Jz=Jc(R)=R Vc(R)

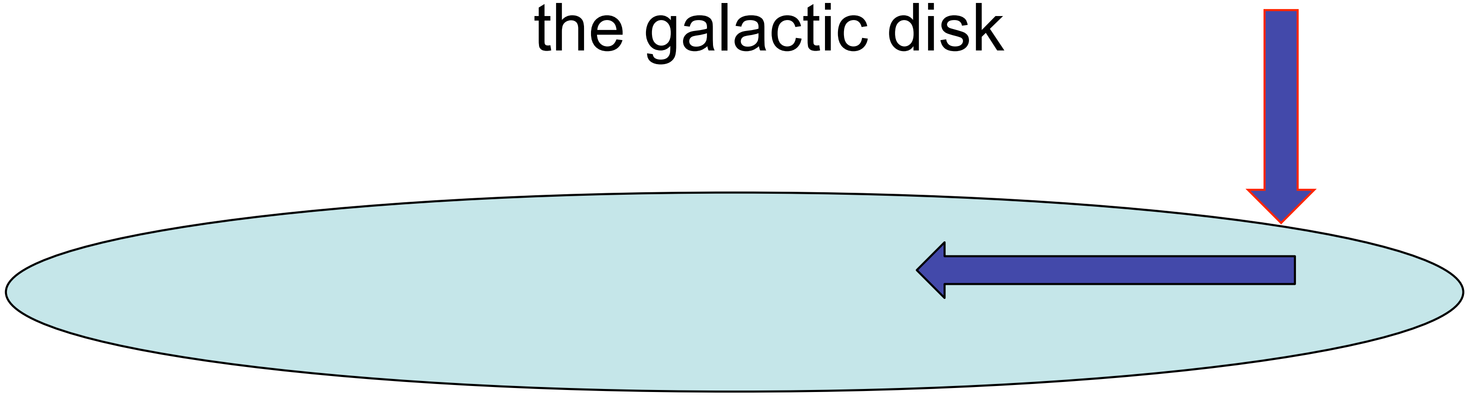
Jz of circular orbits - Jc(R) - increases with R for stable systems (Lord Rayleigh - e.g., Solar System, Third Kepler Law: Vc decreases but Jc increases)

THEREFORE: CONDITION FOR RADIAL FLOWS

Jz of ISM at R must be reduced below the value of Jc(R) at the corresponding galactocentric distance

2. EXTERNAL OR INTERNAL ORIGIN ?

EXTERNAL: accretion of low Jz material from above and below the galactic disk



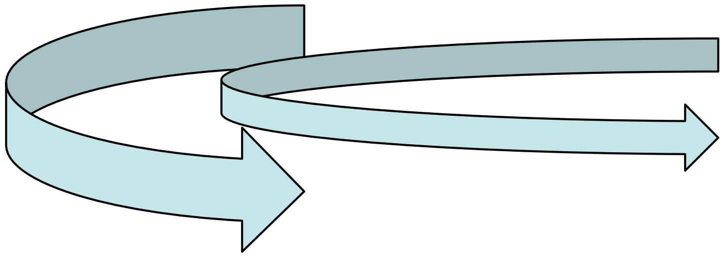
Material mixes with local ISM, reduces the specific Jz, and the resulting ISM drifts towards the center

PRO: accretion of fresh material is needed to sustain the observed star formation rates in disk galaxies

CONS: accretion rates, associated J_z, etc. will in general change from time to time and from galaxy to galaxy. Unclear how accretion of coronal material proceeds

INTERNAL (1): viscosity

Jz is tranferred from inner to outer gaseous rings, due to the radial trend of vc(R) and Jc(R)



Mass flows from outer to inner regions

Similar to AGN accretion (alpha) disks

PRO: independent of cosmological accretion

CONS: uncertain physical origin of viscosity: Kinetic (Maxwell)?, MRI ? …?

INTERNAL (2): large scale asymmetries

E.g.: Spiral arms, Bars, triaxiality of Dark Matter Halo

Main effect: J_z conservation breaks down (also for stars, “radial migration”)

PRO: independent of cosmological accretion, certainly present

CONS: difficult to quantify

INTERNAL 3: THIS WORK

STELLAR EVOLUTION
(stellar mass losses)
links

STELLAR DYNAMICS FLUIDODYNAMICS

then ISM knows stars are lagging with respect Vc(R)
(Asymmetric Drift)

PRO: all natural ingredients, quantitative predictions,
acts automatically in the right direction,
the phenomenon is necessarily present

CONS: may be it is irrelevant (?), need serious
observational/modelistic work

3. STELLAR EVOLUTION MEETS STELLAR DYNAMICS

Stellar Evolution ➔
INTERNAL MASS SOURCES

Mass

$$\dot{M}_*(t) \simeq 1.5 \times 10^{-11} L_{\rm B} t_{15}^{-1.3} \quad M_\odot {\rm yr}^{-1}$$

(ETGs)

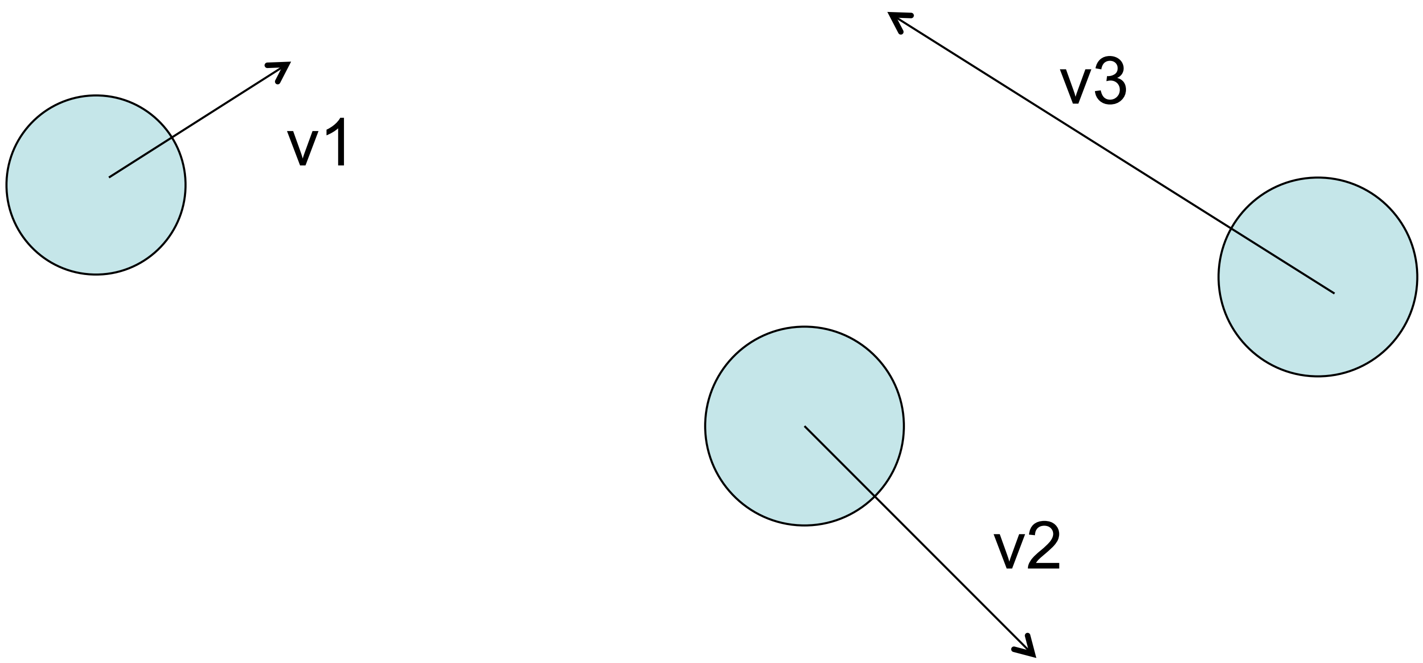
$$\Delta M_* \approx 0.1 - 0.3 M_*$$

- The rate decline with population age
- The total mass injection scales LINEARLY with M*

Interaction

The interaction of stellar winds and pre-existing ISM can be formalized rigorously as follows

Phase-space based (Jeans-like) approach PLUS hydrodynamics: consider a few stars in a small galaxy volume



We will consider phase-space averages over the DF of the injected quantities

In principle (not needed in practice!) from the phase-space DF f we can write the smoothed fields of stellar DENSITY, STREAMING VELOCITY, and VELOCITY DISPERSION in each point of the galaxy

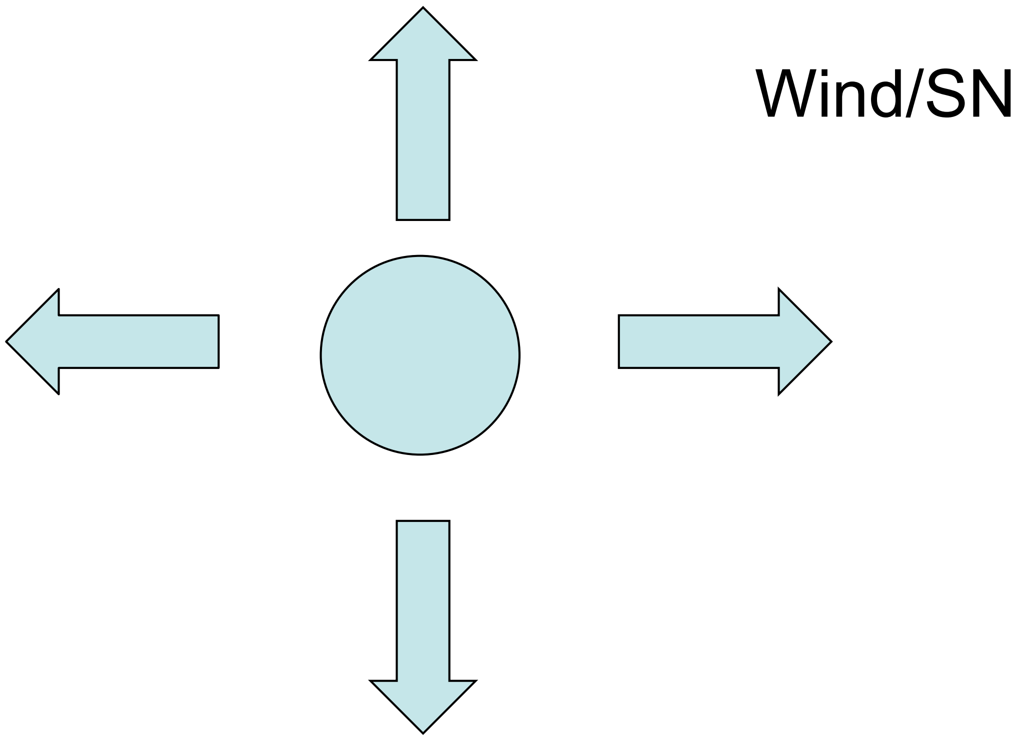
$$f = f(\boldsymbol{x}, \boldsymbol{v};\ t) \qquad\qquad n(\boldsymbol{x};\ t) = \int_{\Re^3} f\, d^3\boldsymbol{v}$$

$$n(\boldsymbol{x};\ t)\overline{\boldsymbol{v}}(\boldsymbol{x};\ t) = \int_{\Re^3} \boldsymbol{v} f\, d^3\boldsymbol{v}$$

"galaxy rotational field"

$$n(\boldsymbol{x};\ t)\sigma_{ij}^2(\boldsymbol{x};\ t) = \int_{\Re^3} (v_i - \overline{v}_i)(v_j - \overline{v}_j) f\, d^3\boldsymbol{v}$$

Each star produces a wind of given mass rate and velocity with respect to the star



These inject MASS, MOMENTUM, ENERGY in the ISM

Mass sources

Most general mass return, single star $m = m(\boldsymbol{x}, \boldsymbol{v}, \boldsymbol{n}; t)$

$$\mu(\boldsymbol{x}, \boldsymbol{n}; t) = \int_{\Re^3} mf d^3\boldsymbol{v}$$

$$\mathscr{M}(\boldsymbol{x}; t) = \int_{4\pi} \mu \, d^2\boldsymbol{n}$$

For isotropic mass return $\mathscr{M}(\boldsymbol{x}; t) = 4\pi nm$

Momentum sources

General

$$\boldsymbol{p} = m(\boldsymbol{x}, \boldsymbol{v}, \boldsymbol{n}; t)[\boldsymbol{v} + u_s(\boldsymbol{x}, \boldsymbol{v}, \boldsymbol{n}; t)\boldsymbol{n}]$$

$$\boldsymbol{\pi}(\boldsymbol{x}, \boldsymbol{n}; t) = \int_{\mathfrak{R}^3} \boldsymbol{p} f \, d^3\boldsymbol{v}$$

$$\boldsymbol{P}(\boldsymbol{x}; t) = \int_{4\pi} \boldsymbol{\pi} \, d^2\boldsymbol{n}$$

For isotropic mass return

$$\boldsymbol{P}(\boldsymbol{x}; t) = \mathscr{M}\bar{\boldsymbol{v}}$$

i.e. the velocity of the ejecta CANCELS rigorously and the injected momentum is just the injection mass rate times galaxy local streaming velocity

Energy sources

Internal + kinetic energy of the ejecta

$$e = e(\boldsymbol{x}, \boldsymbol{v}, \boldsymbol{n}; t) \quad k = \tfrac{1}{2} m(\boldsymbol{x}, \boldsymbol{v}, \boldsymbol{n}; t) || \boldsymbol{v} + u_s(\boldsymbol{x}, \boldsymbol{v}, \boldsymbol{n}; t) \boldsymbol{n} ||^2$$

$$\epsilon(\boldsymbol{x}, \boldsymbol{n}; t) = \int_{\mathfrak{R}^3} mef \, d^3\boldsymbol{v} \qquad \kappa(\boldsymbol{x}, \boldsymbol{n}; t) = \int_{\mathfrak{R}^3} kf \, d^3\boldsymbol{v}$$

$$\mathscr{E}(\boldsymbol{x}; t) = \int_{4\pi} \epsilon \, d^2\boldsymbol{n} \qquad \mathscr{K}(\boldsymbol{x}; t) = \int_{4\pi} \kappa \, d^2\boldsymbol{n}$$

For isotropic mass sources

$$\mathscr{E}(\boldsymbol{x}; t) = \mathscr{M} e$$

$$\mathscr{K}(\boldsymbol{x}; t) = \mathscr{M}[||\bar{\boldsymbol{v}}||^2 + u_s^2 + \mathrm{Tr}(\sigma^2)]/2$$

Hydrodynamical equations
for
phase-space
averaged sources

$$\frac{D\rho}{Dt} + \rho \boldsymbol{\nabla}_{\boldsymbol{x}} \cdot \boldsymbol{u} = \mathscr{M}$$

$$\rho \, \frac{D\boldsymbol{u}}{Dt} = \rho \boldsymbol{g} - \boldsymbol{\nabla}_{\boldsymbol{x}} p + \mathscr{M}(\overline{\boldsymbol{v}} - \boldsymbol{u}) \, ,$$

$$\frac{DE}{Dt} + (E + p)\boldsymbol{\nabla}_{\boldsymbol{x}} \cdot \boldsymbol{u} = \frac{\mathscr{M}}{2} \, || \boldsymbol{u} - \bar{\boldsymbol{v}} ||^2 + \mathscr{M}\left[e + \frac{u_{\mathrm{s}}^2}{2} + \frac{\mathrm{Tr}(\sigma^2)}{2} \right] - \mathscr{L}$$

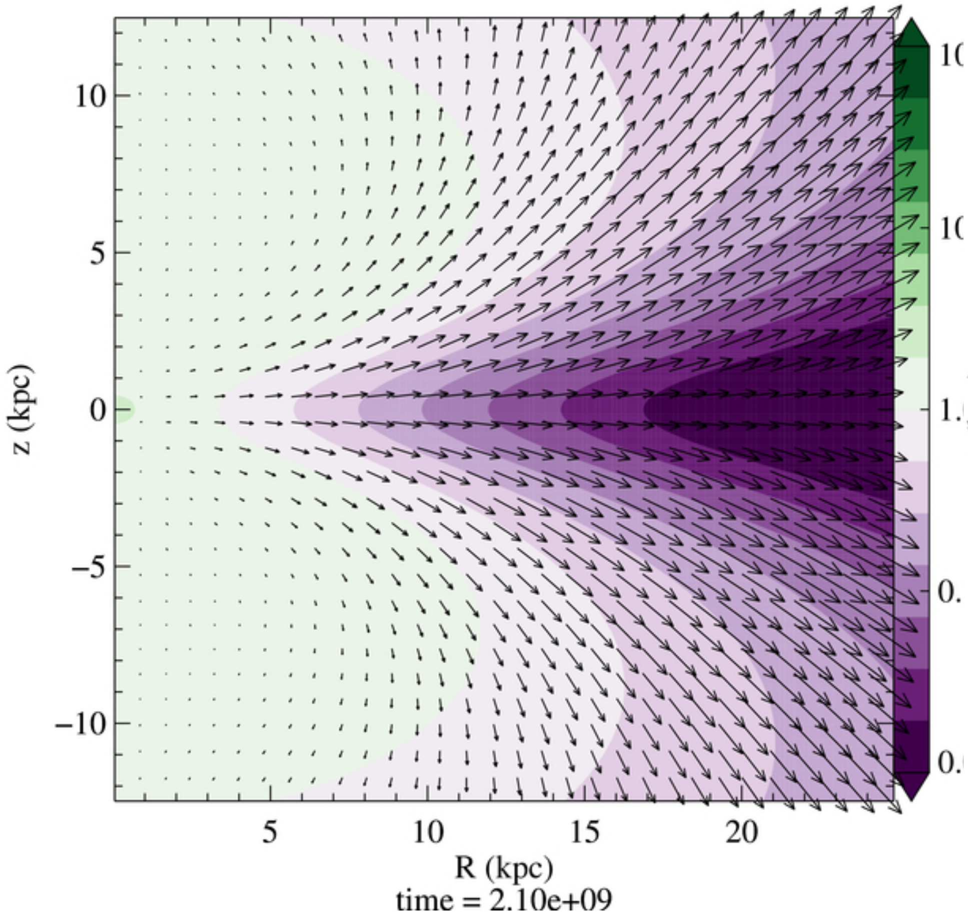
VELOCITY TERM in MOMENTUM EQUATION

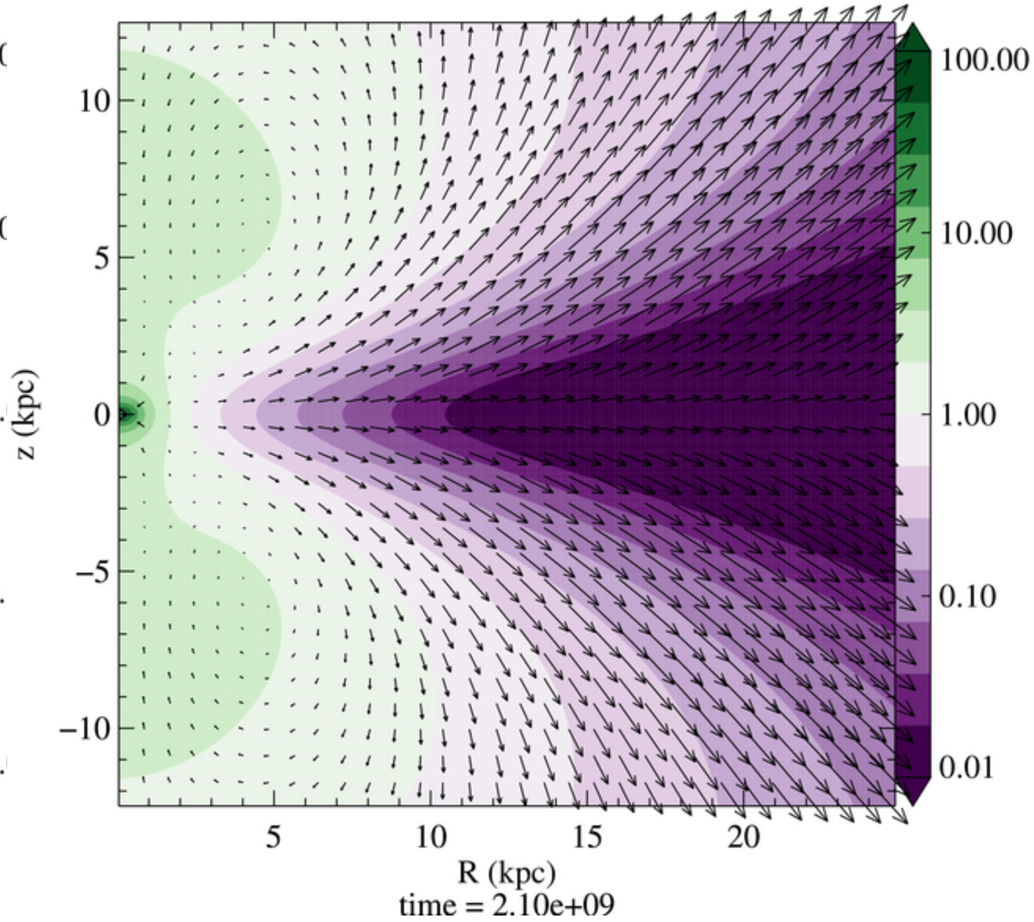
Examples of ISM evolution in a realistic S0/E4 galaxy with different internal dynamics: Jz effects

Posacki, Pellegrini, Ciotti (MNRAS, 2013): theoretical models for X-ray halos Lx and Tx as a function of ETGs shape and internal kinematics

Negri, Ciotti, Pellegrini (MNRAS, 2013);
Negri, Posacki, Pellegrini, Ciotti (MNRAS, 2014):
Negri, Pellegrini, Ciotti (MNRAS 2015): 2D hydro models for the models above.

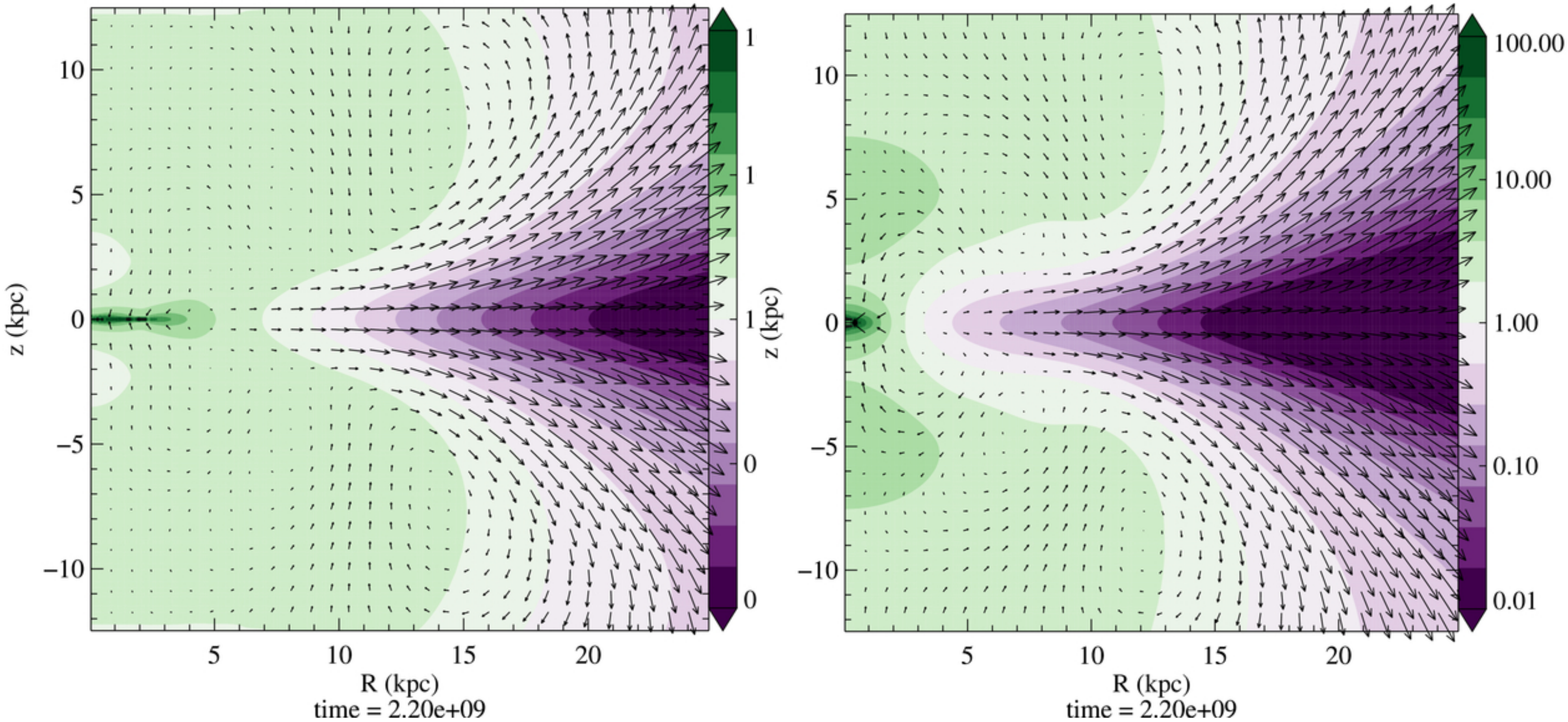
In the following, IDENTICAL galaxy models EXCEPT for the internal kinematics





Isotropic rotator

Velocity dispersion supported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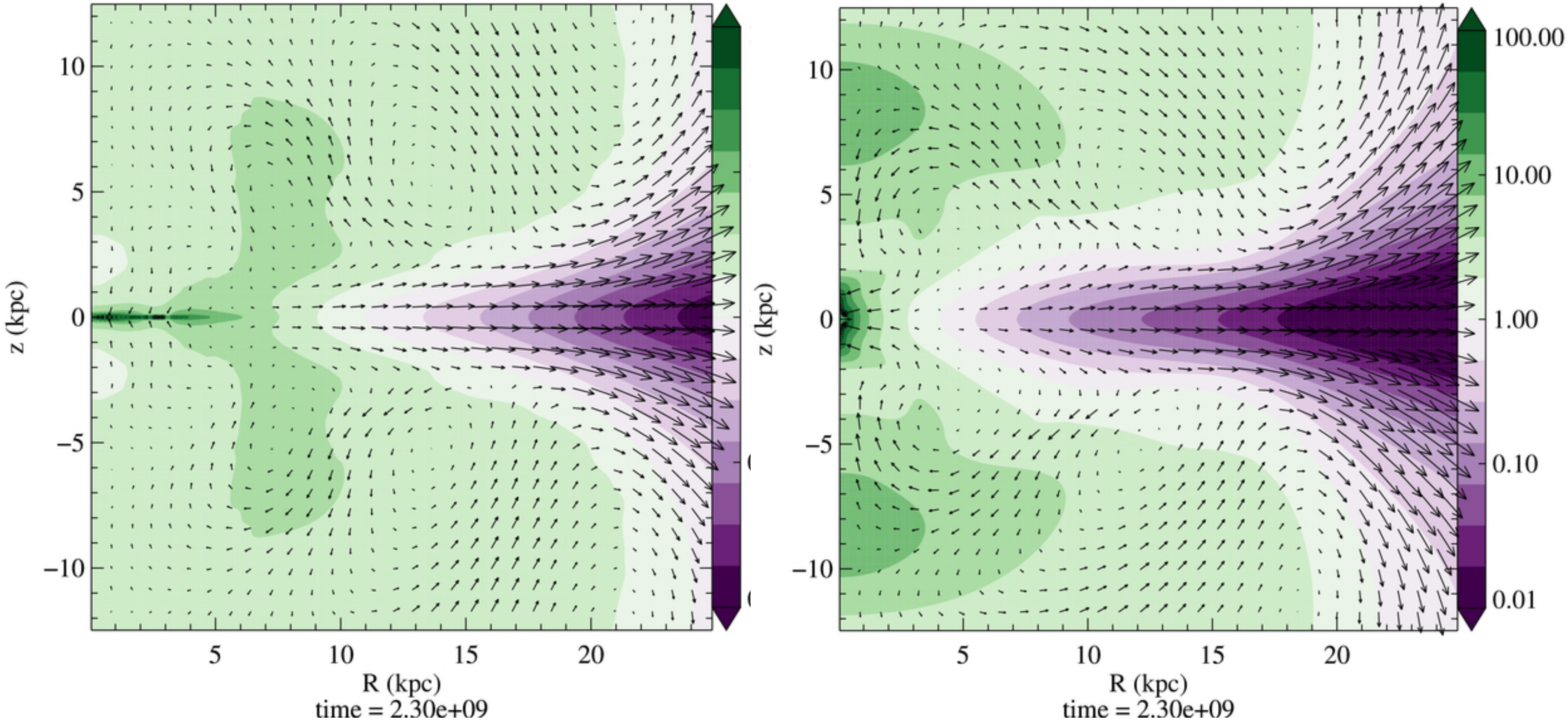
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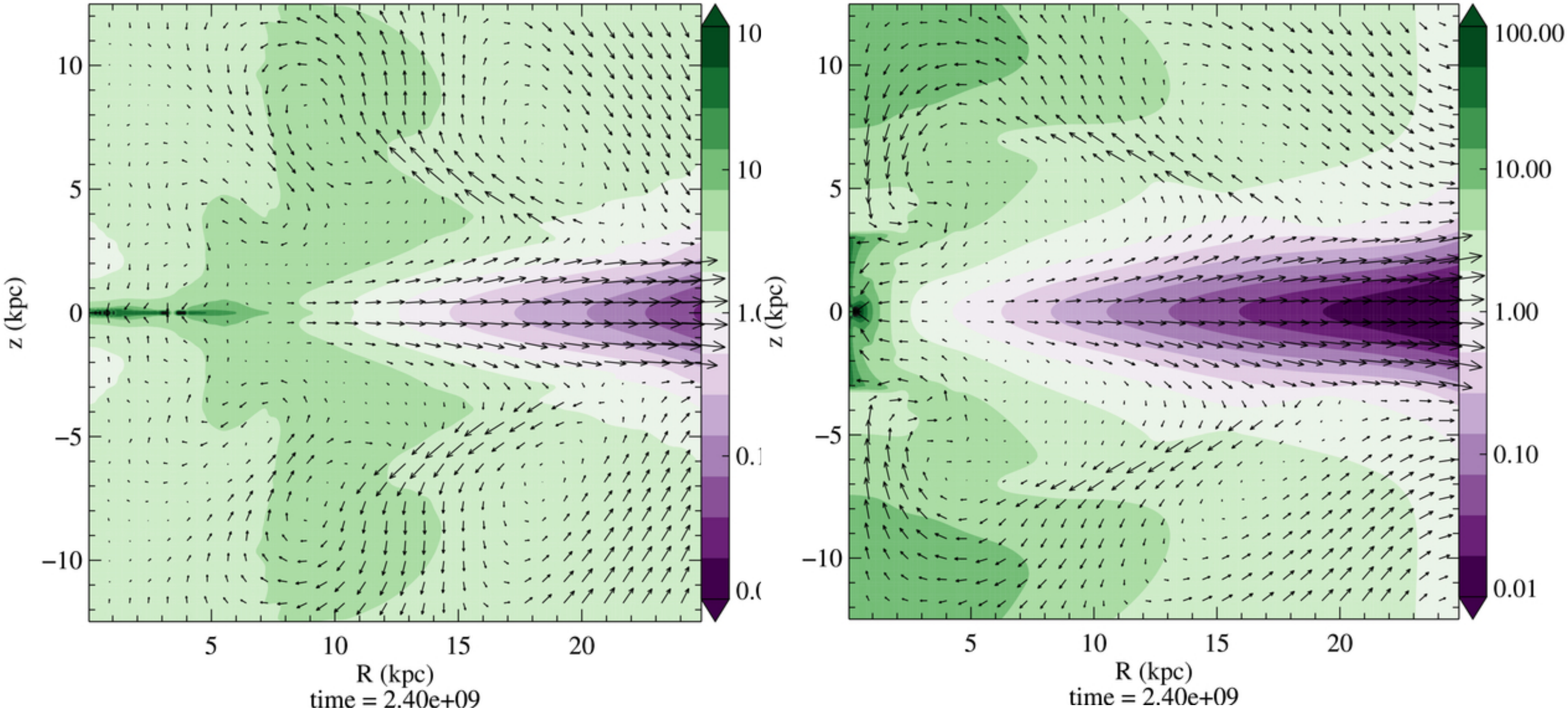

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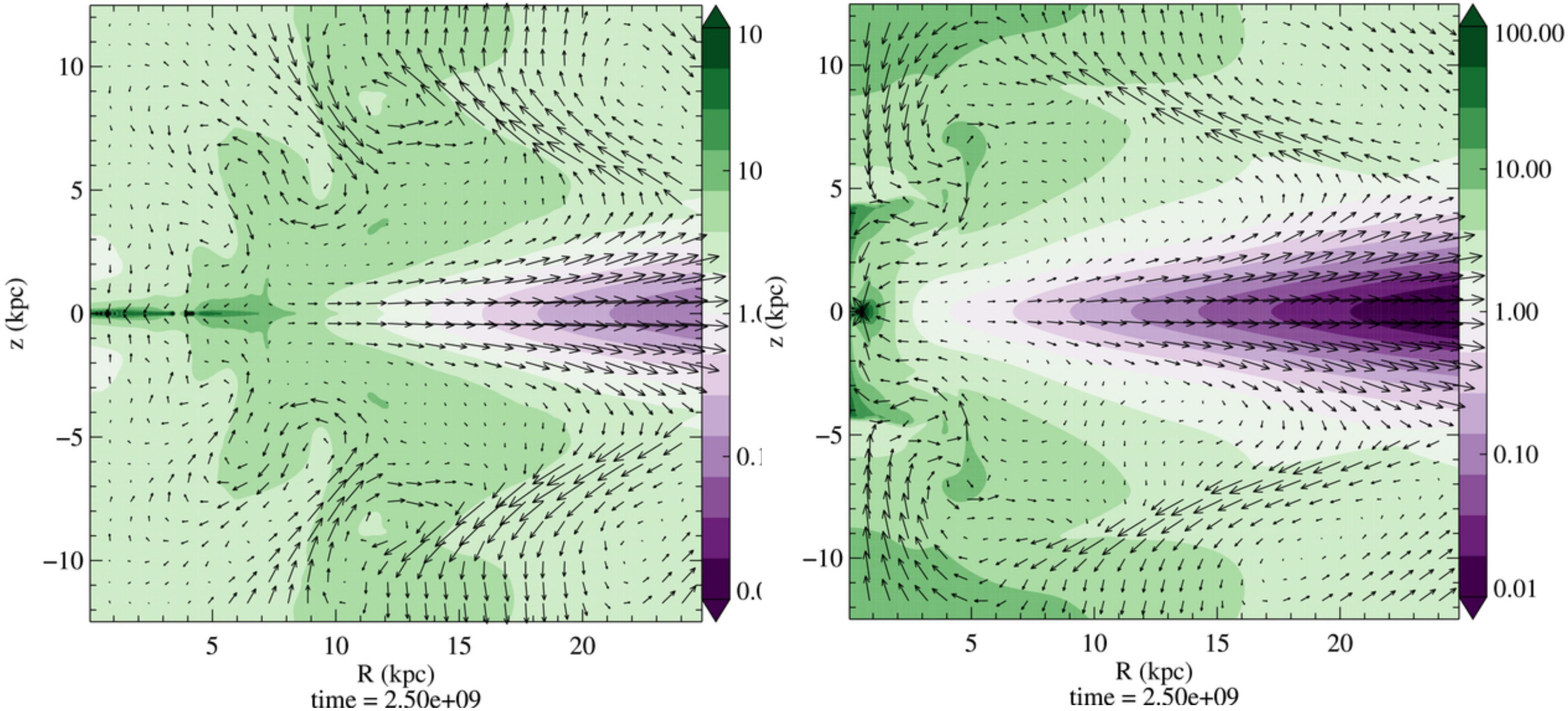
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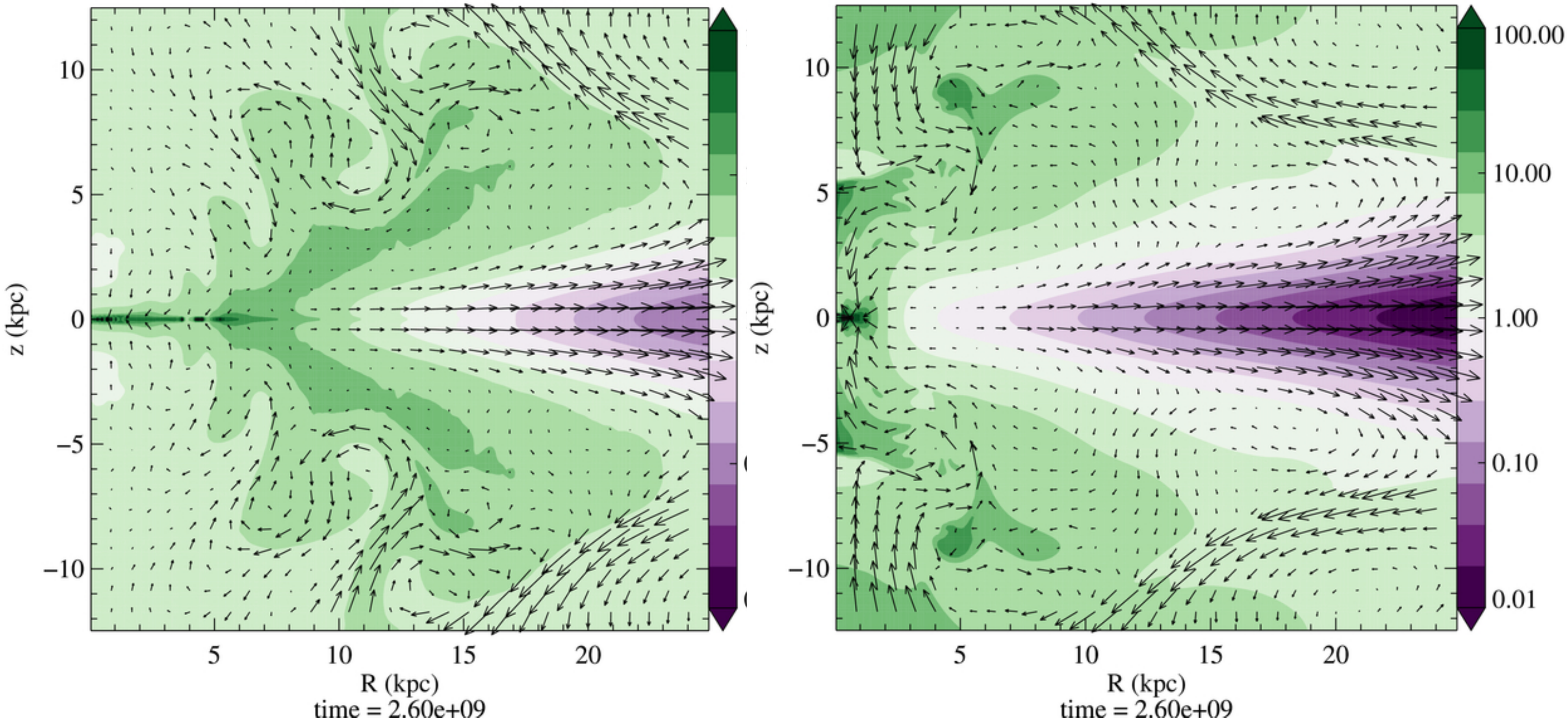

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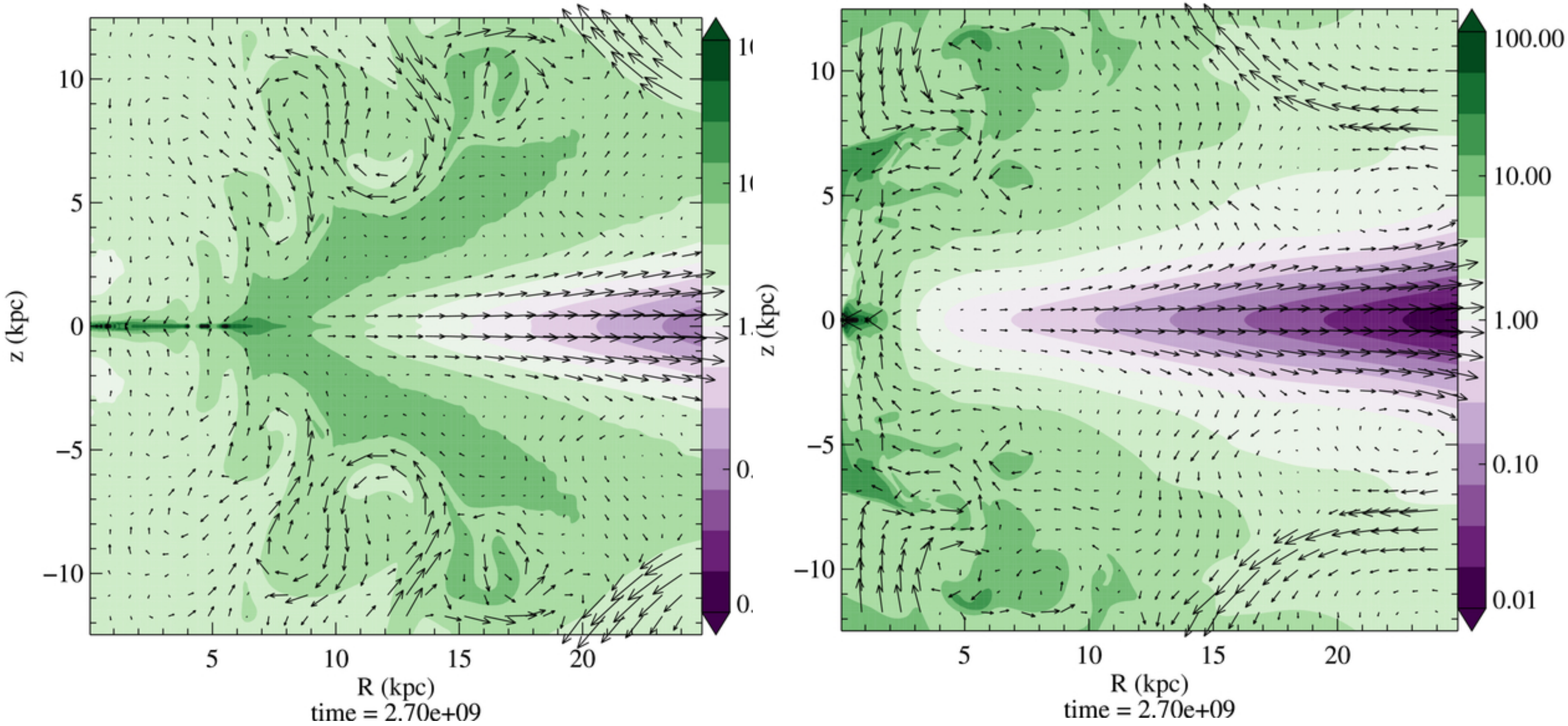

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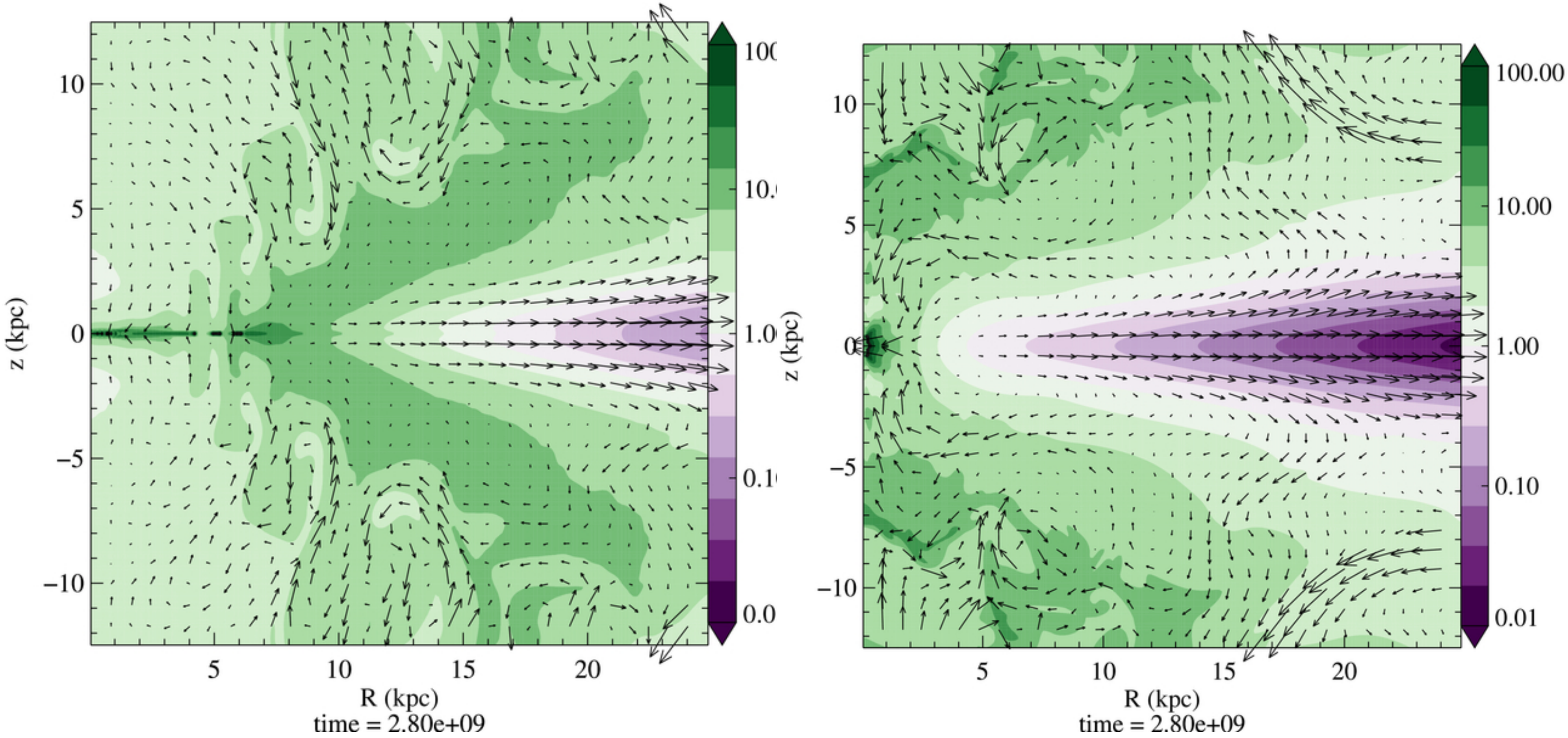
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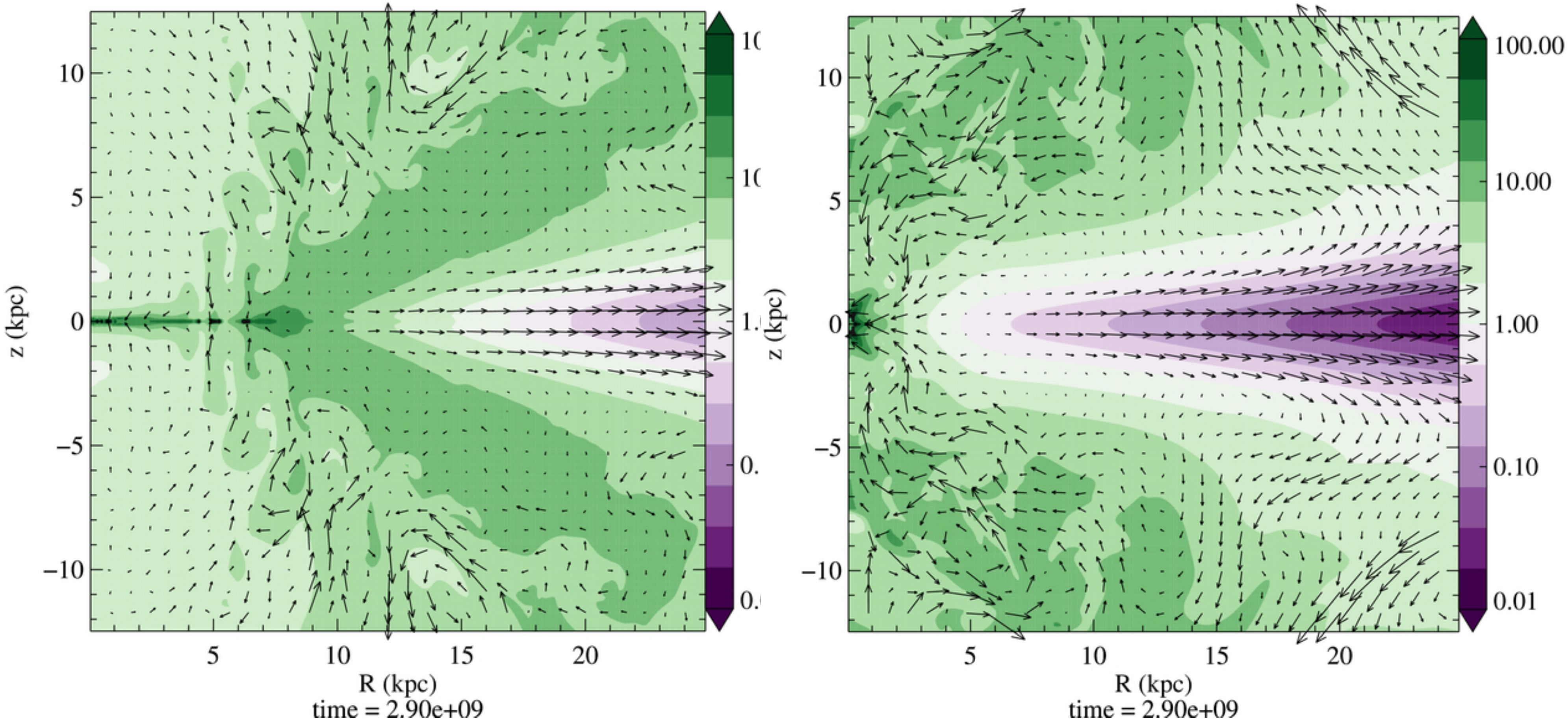

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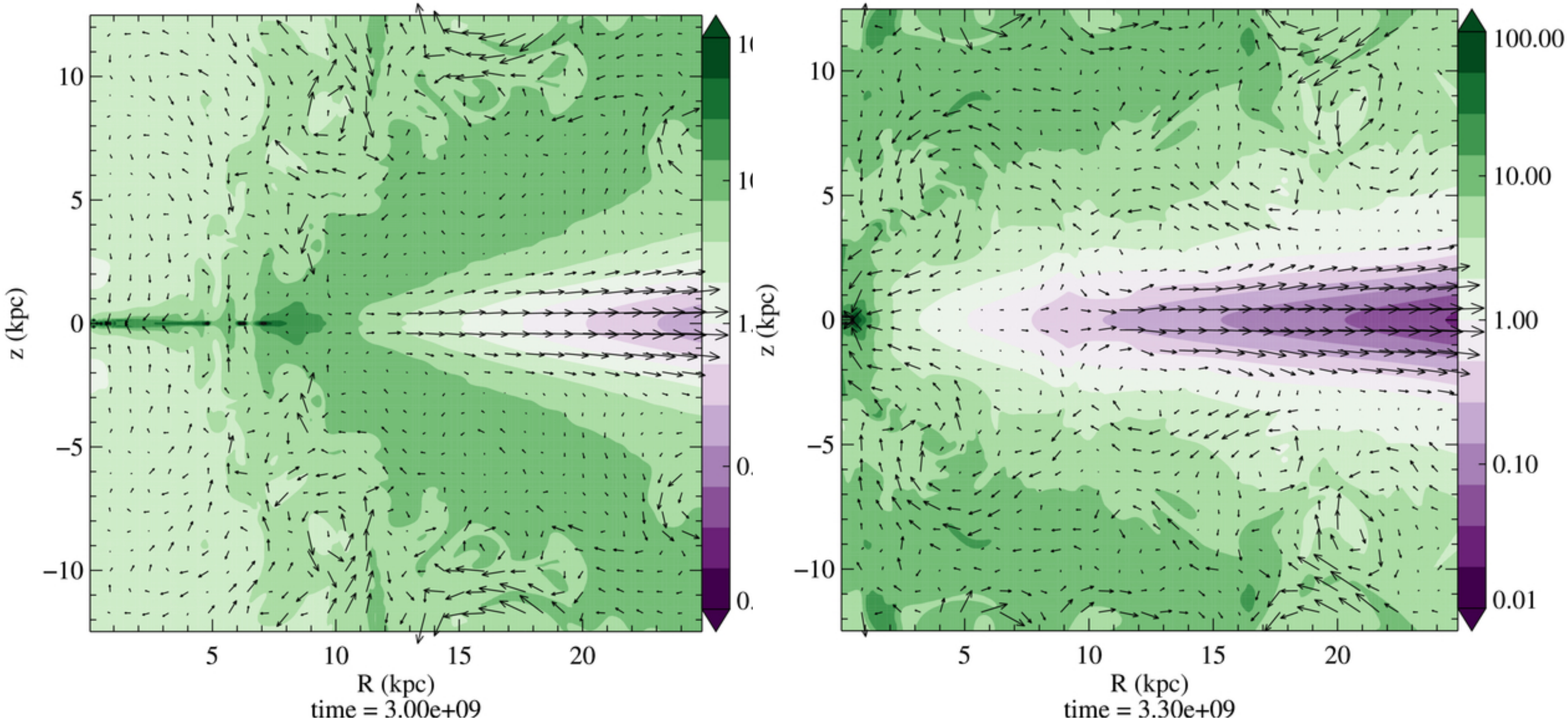
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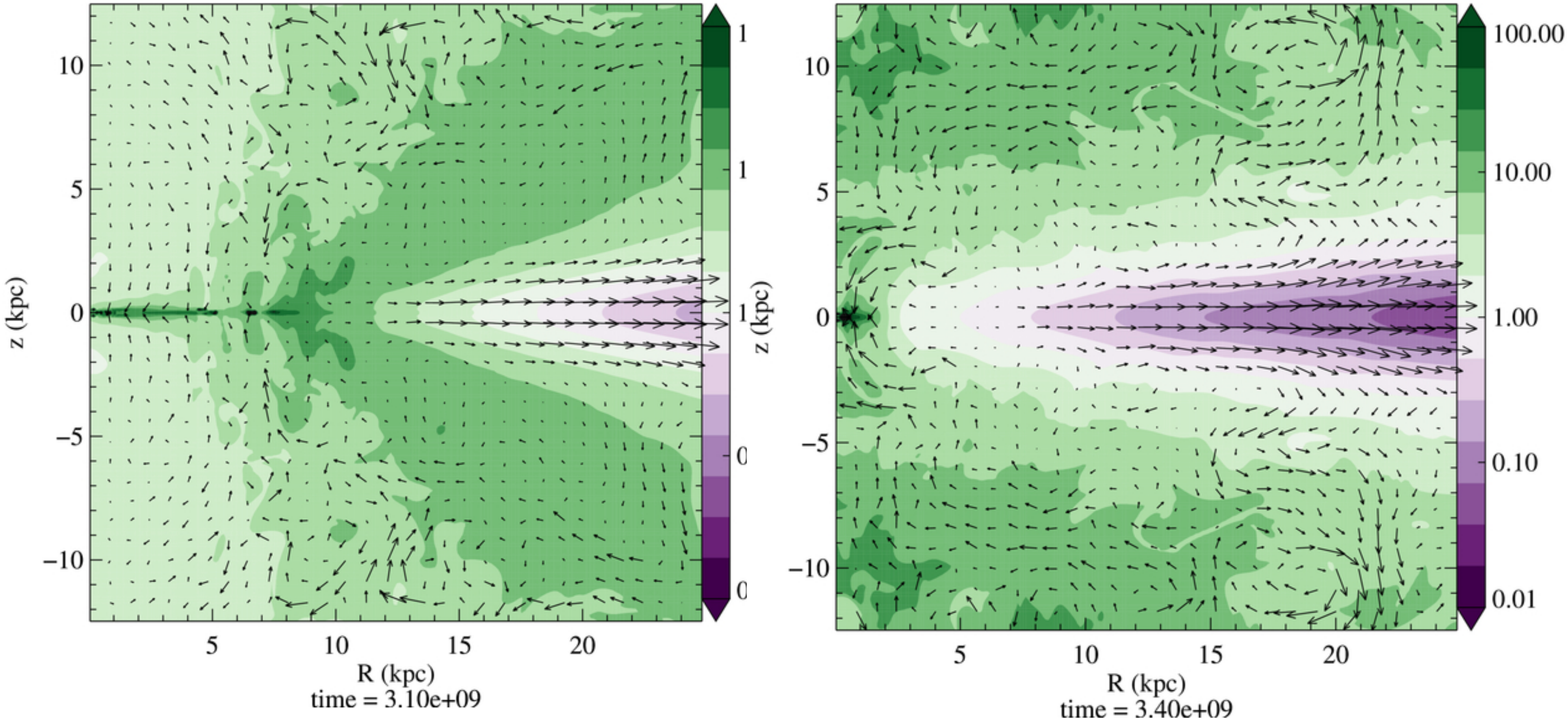

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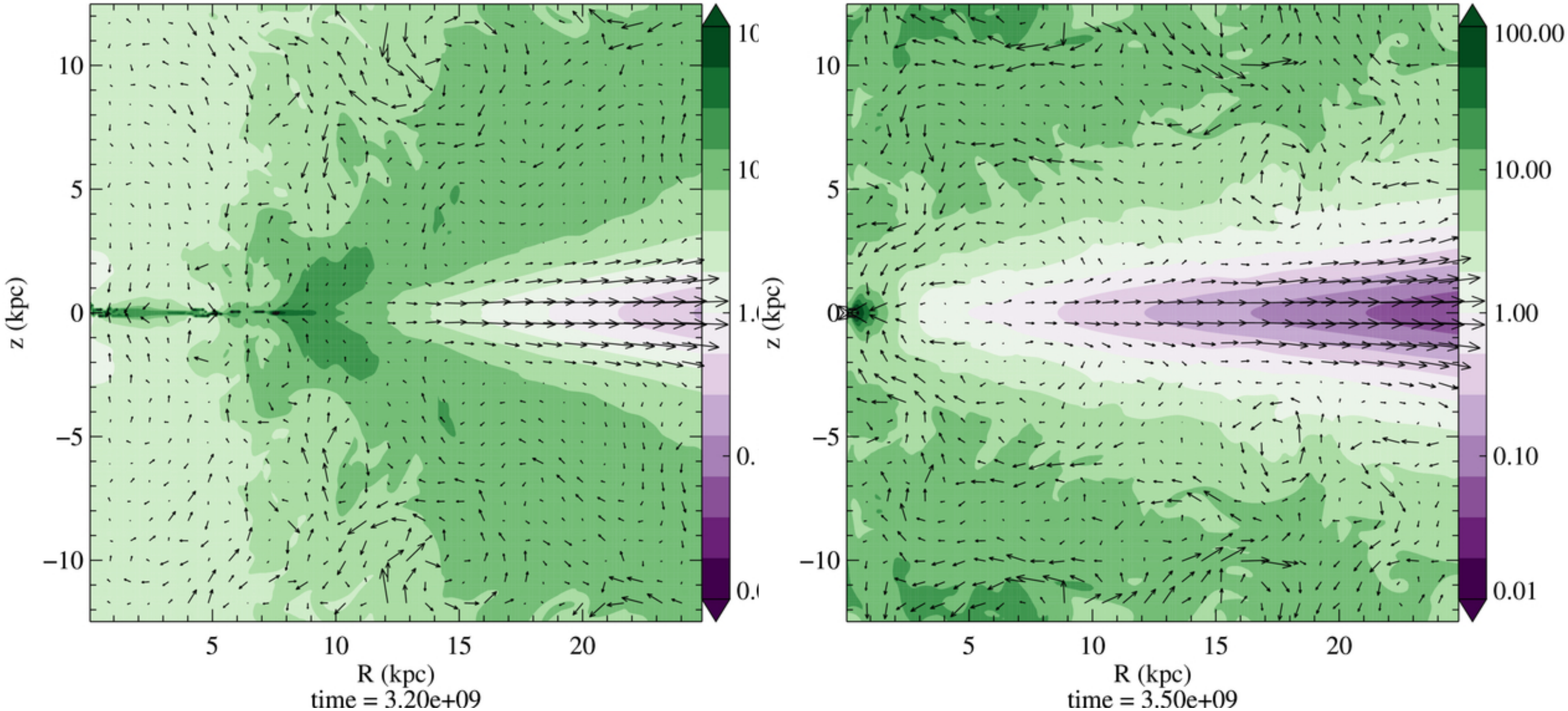

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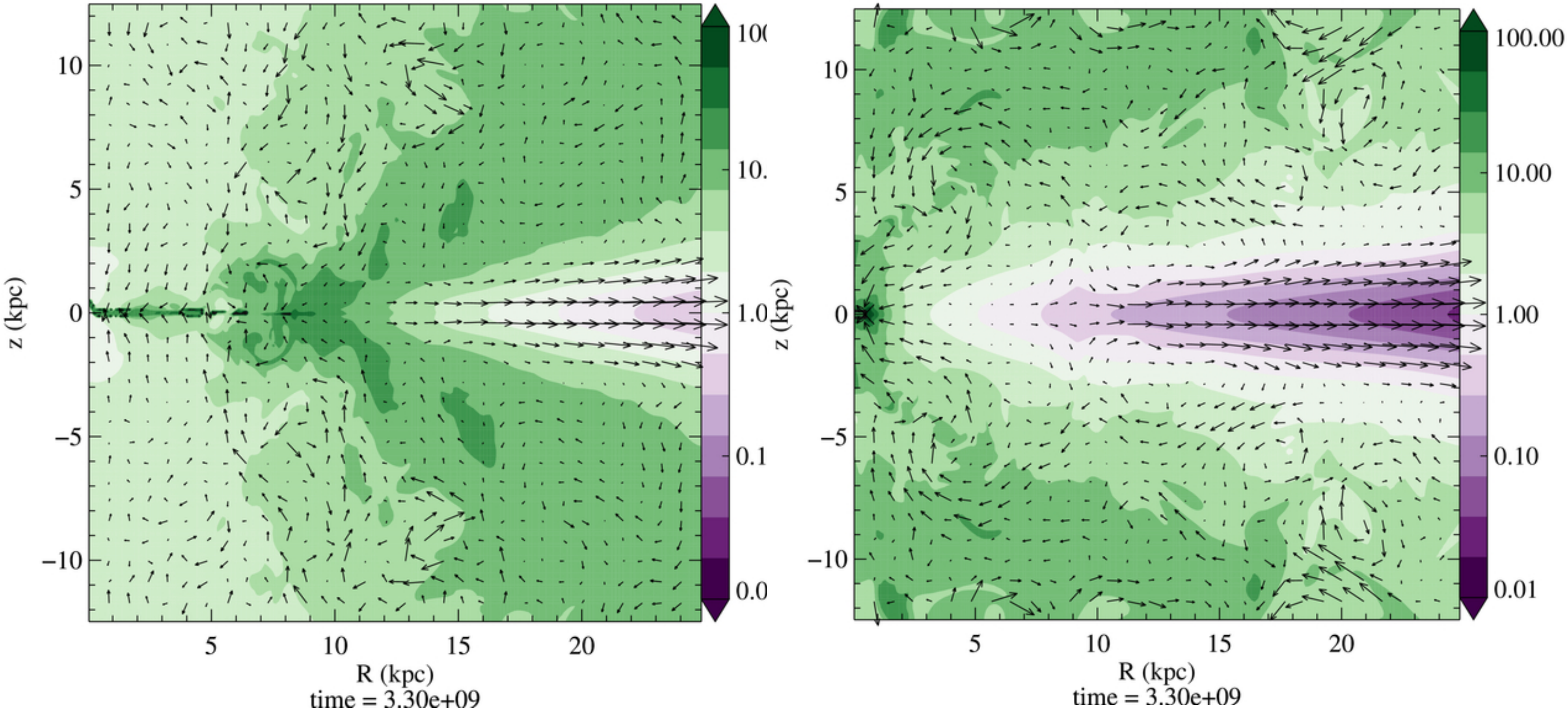
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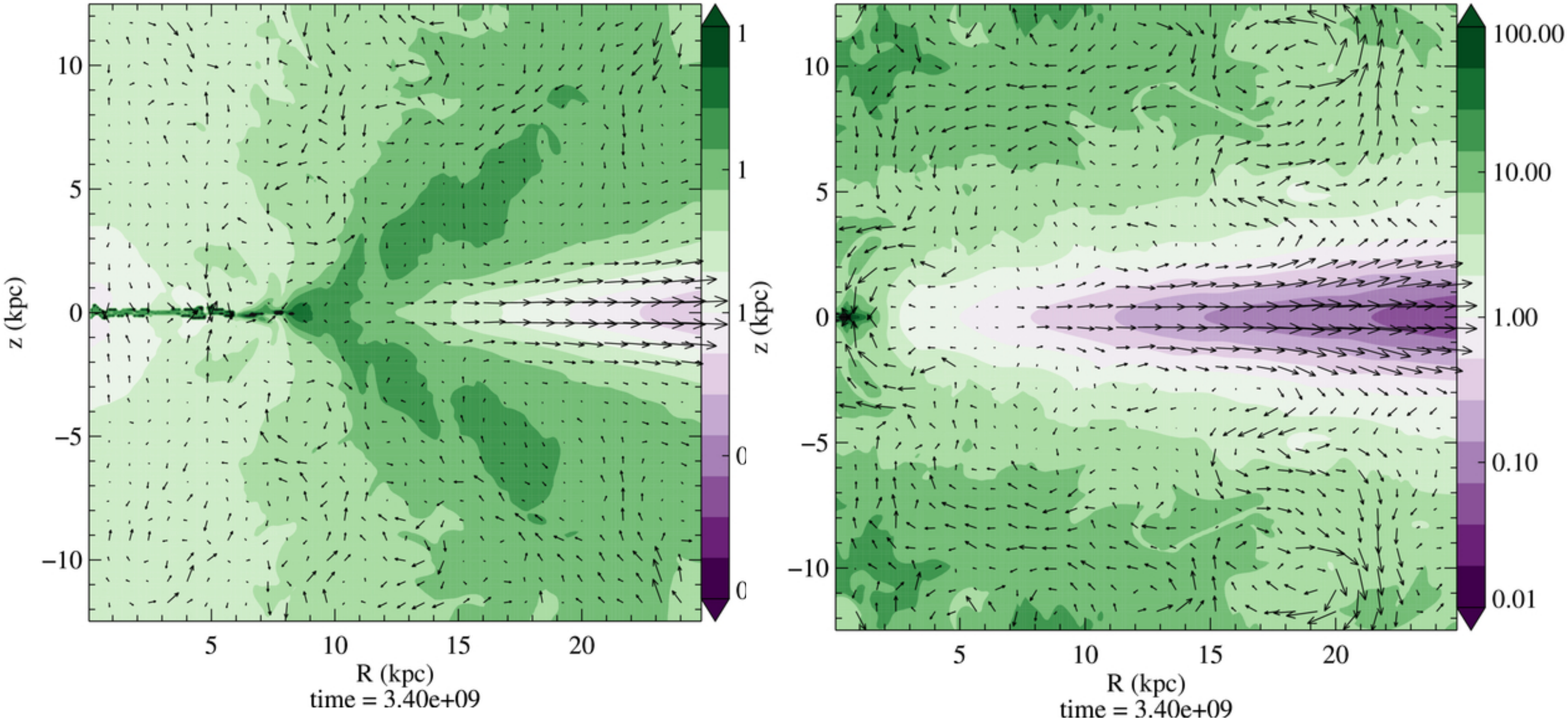
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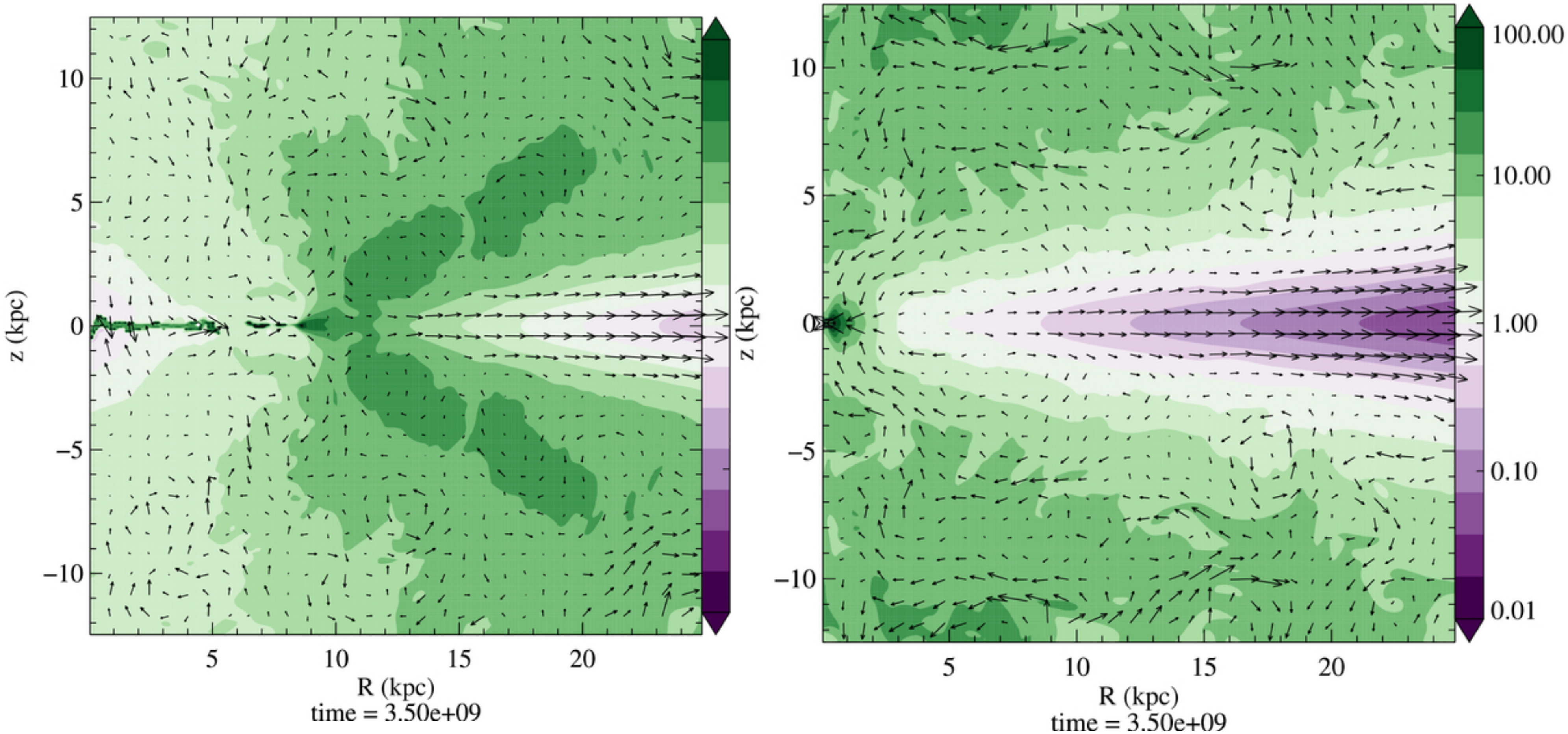

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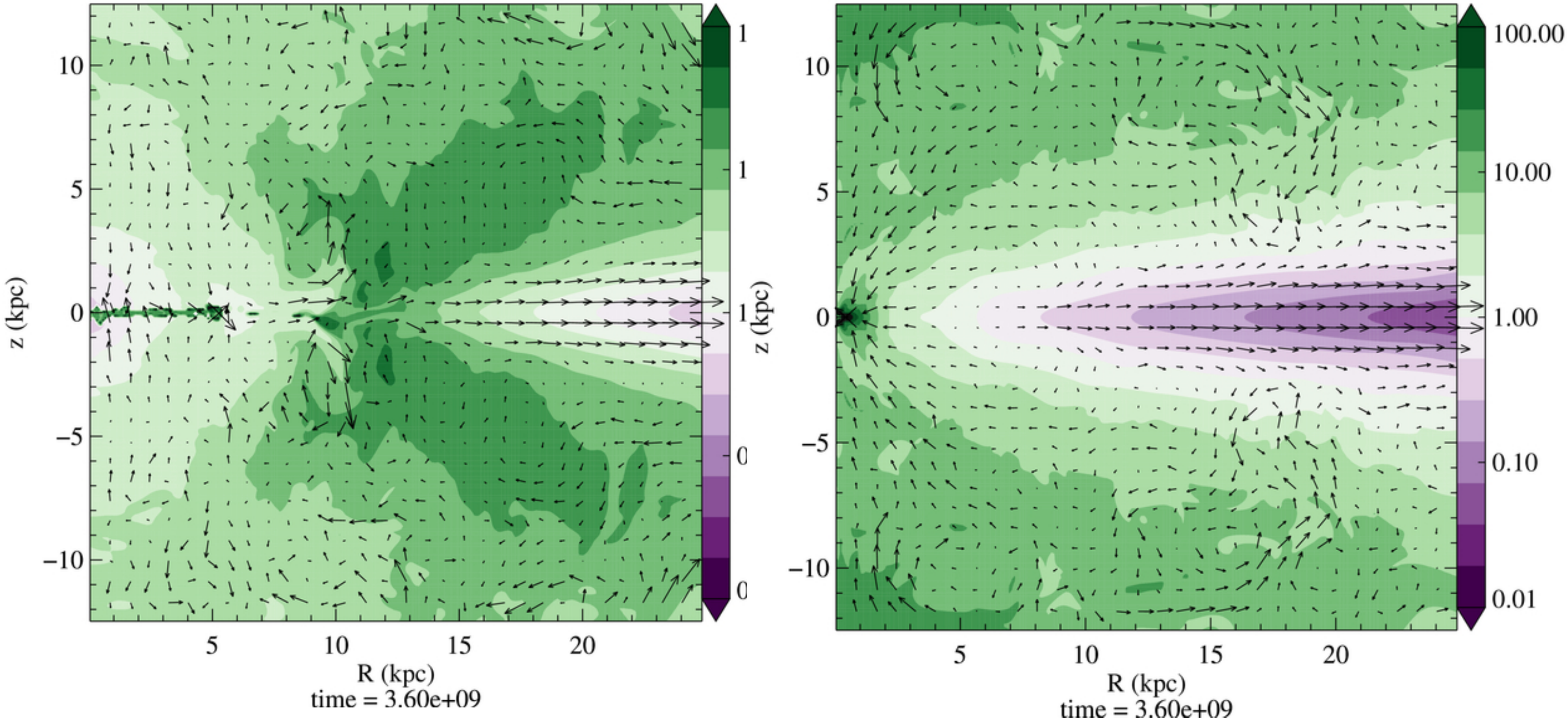

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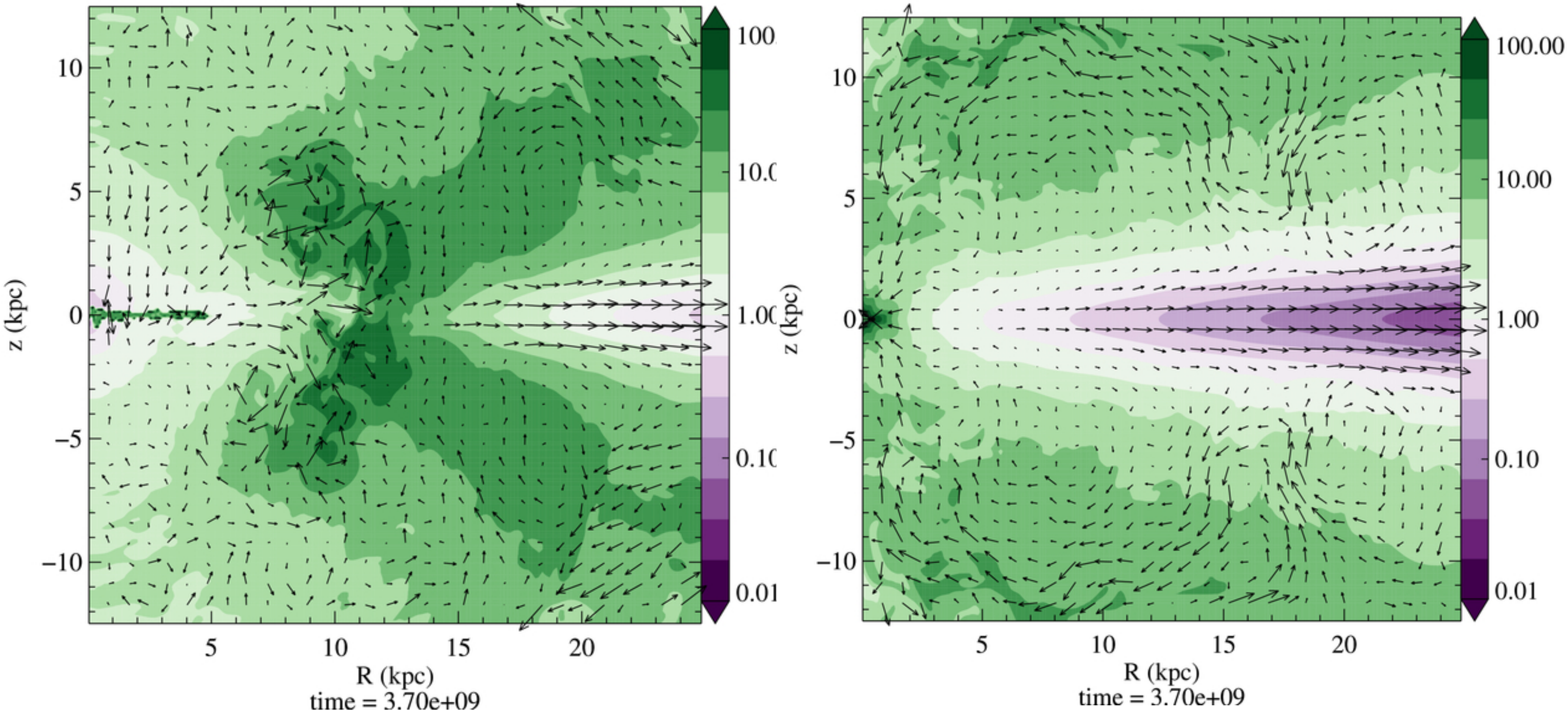

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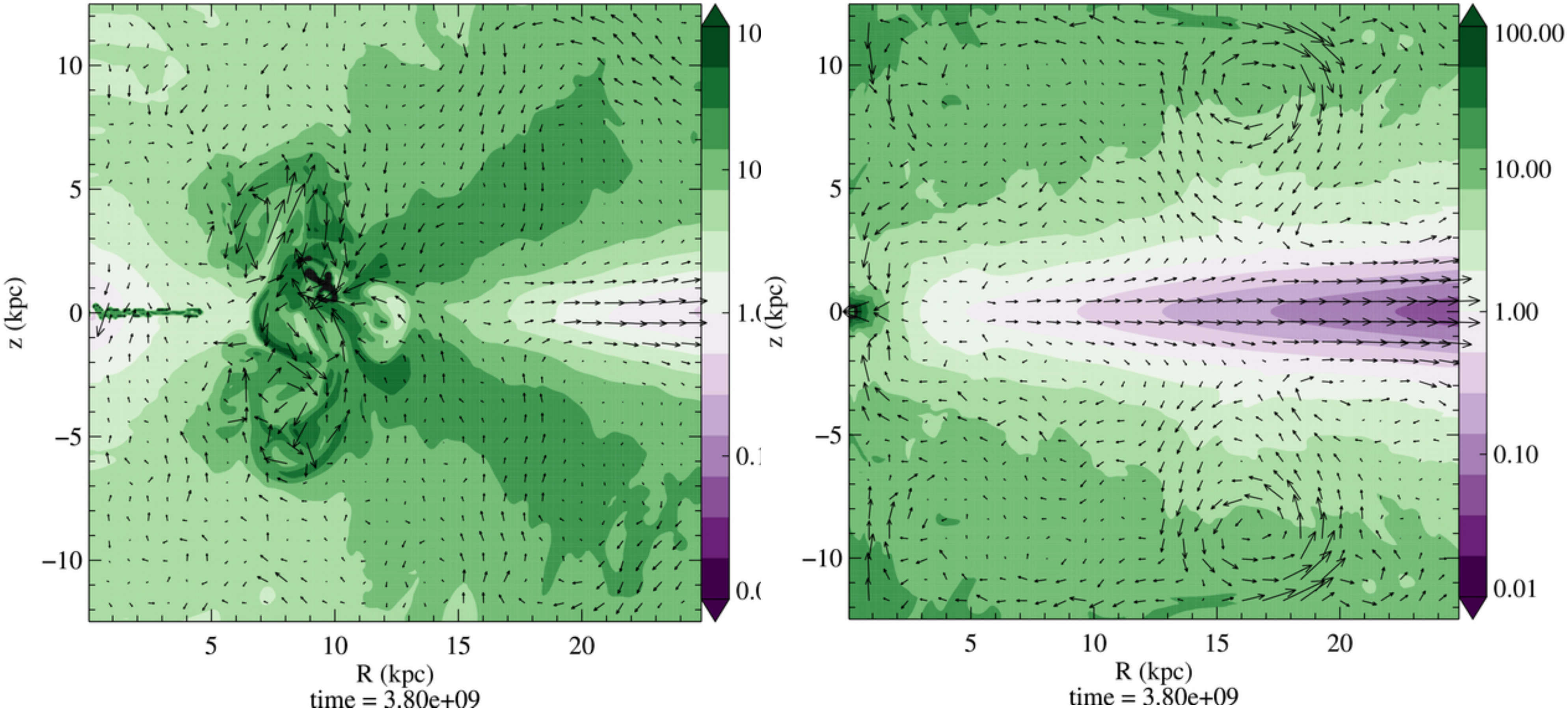

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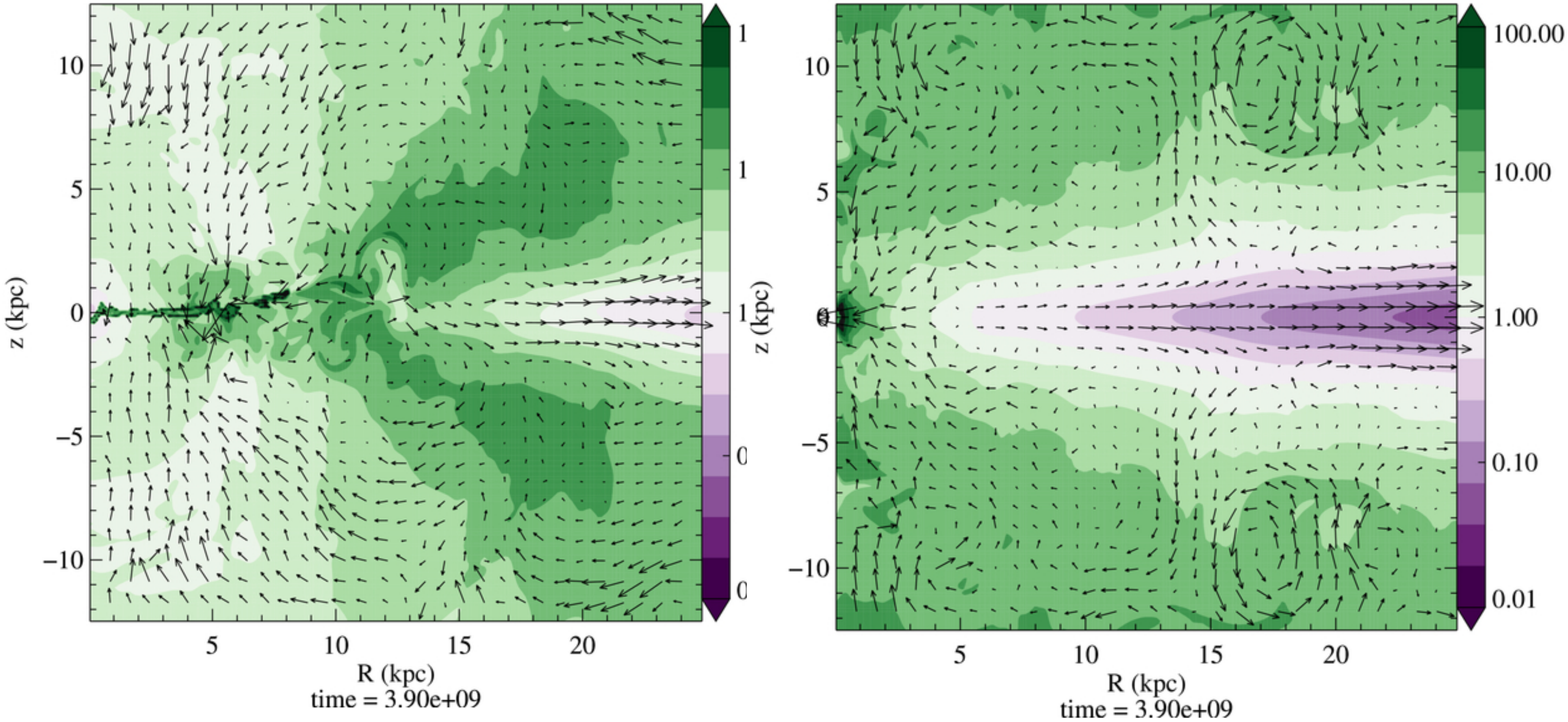
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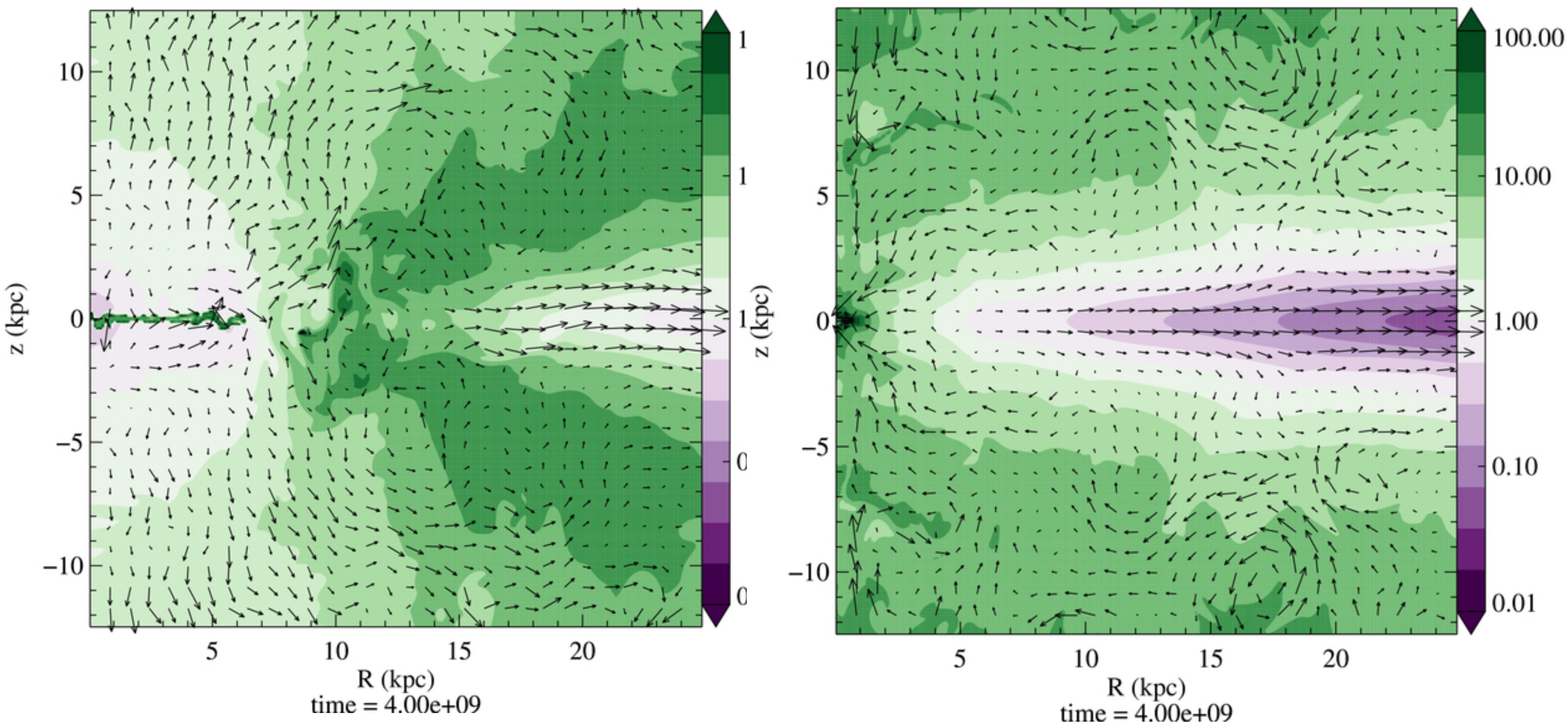

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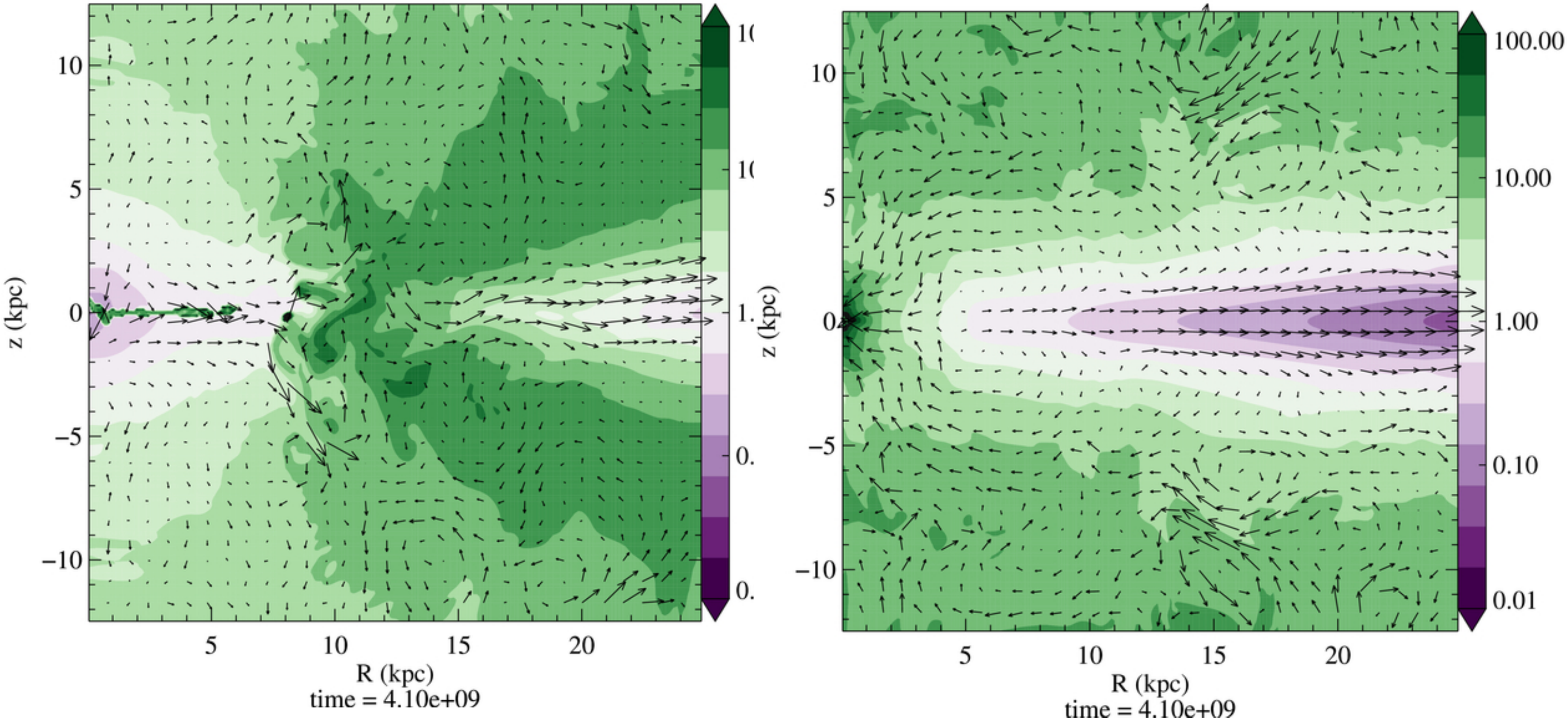
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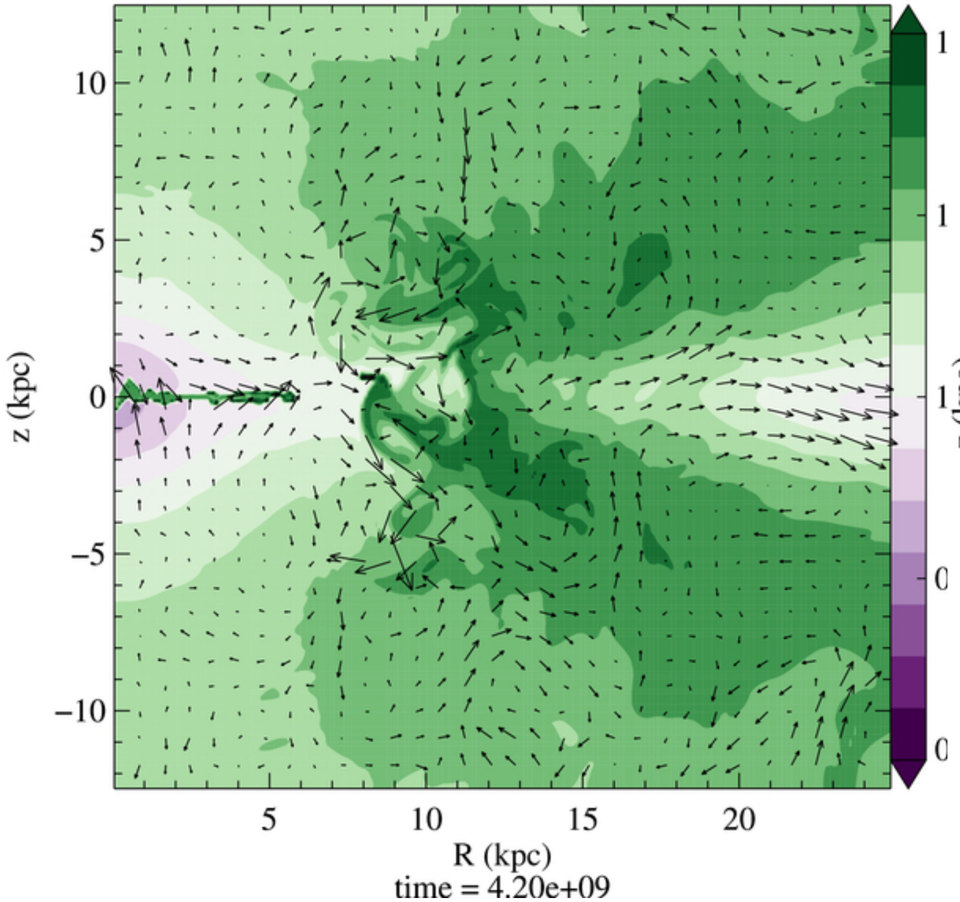

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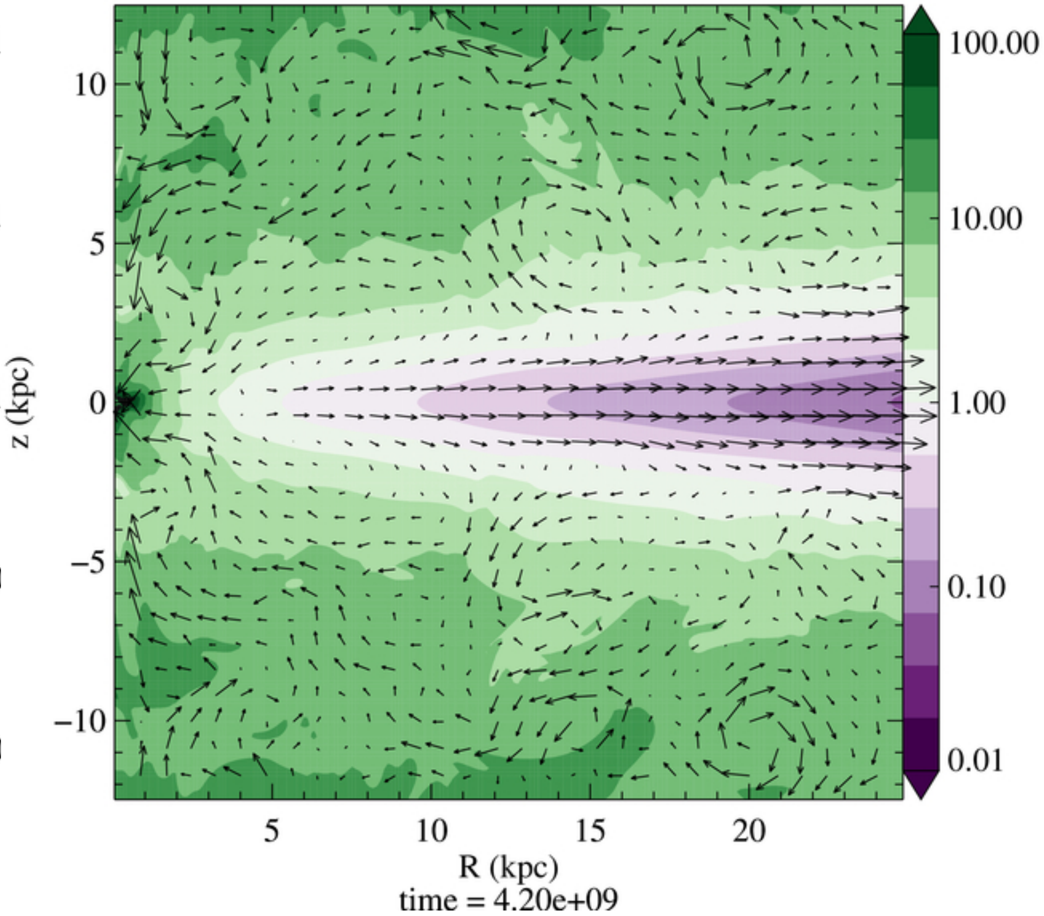

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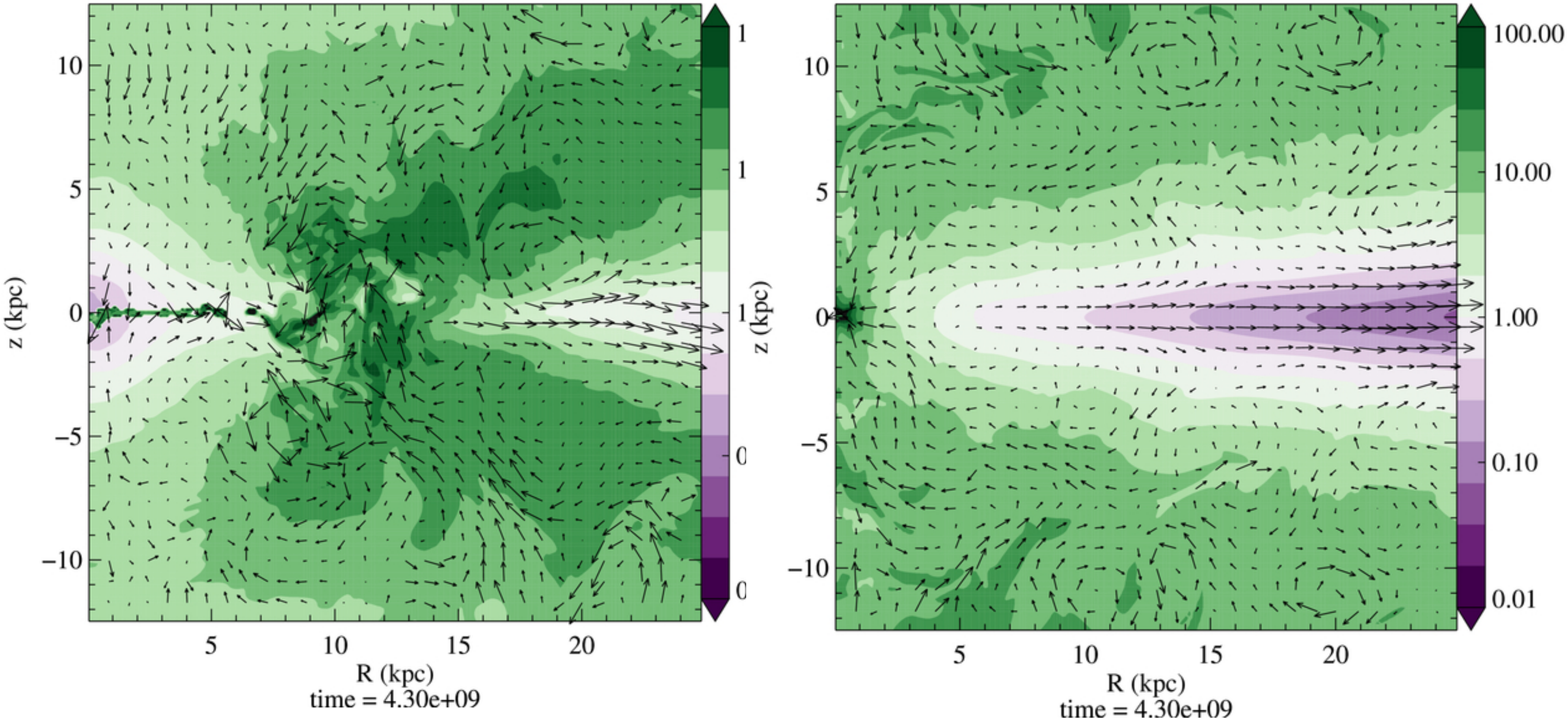

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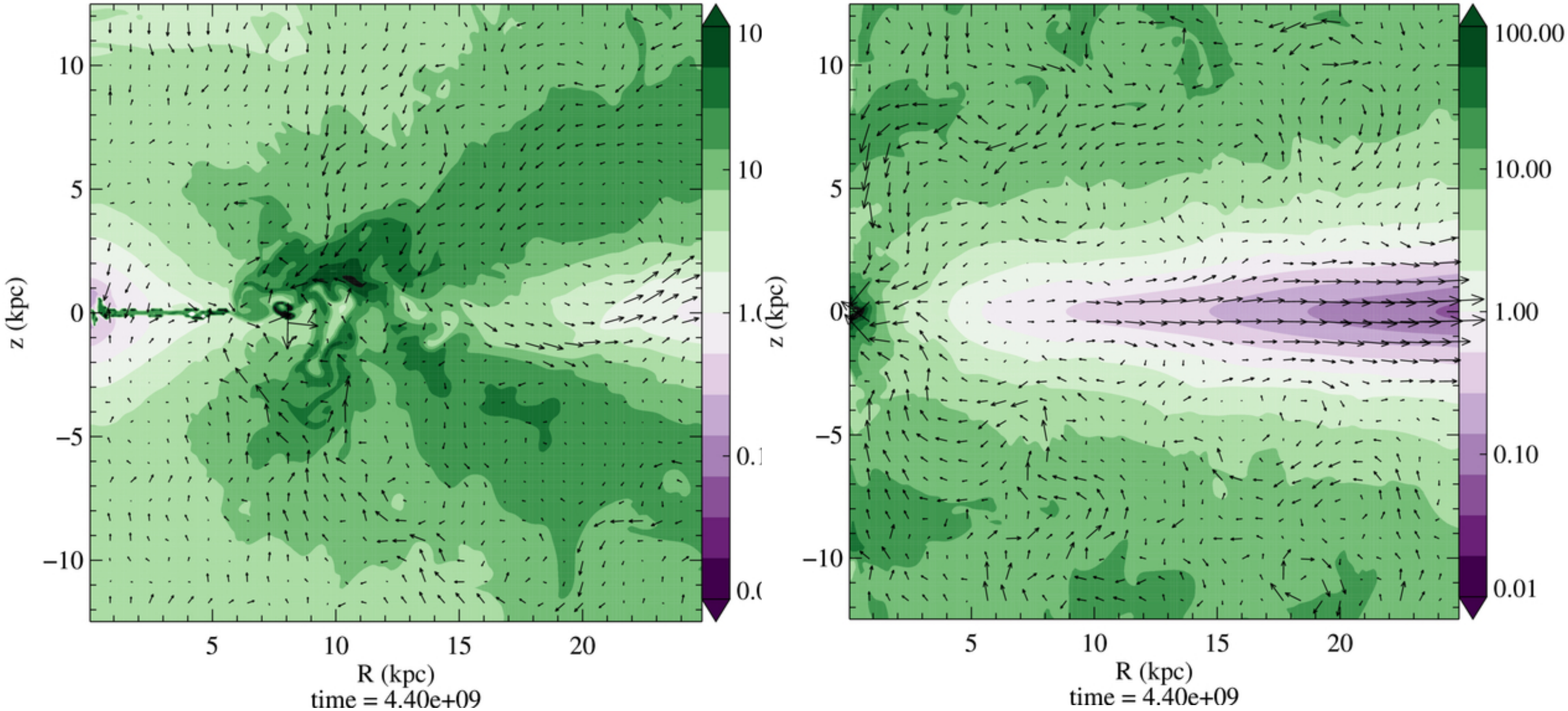

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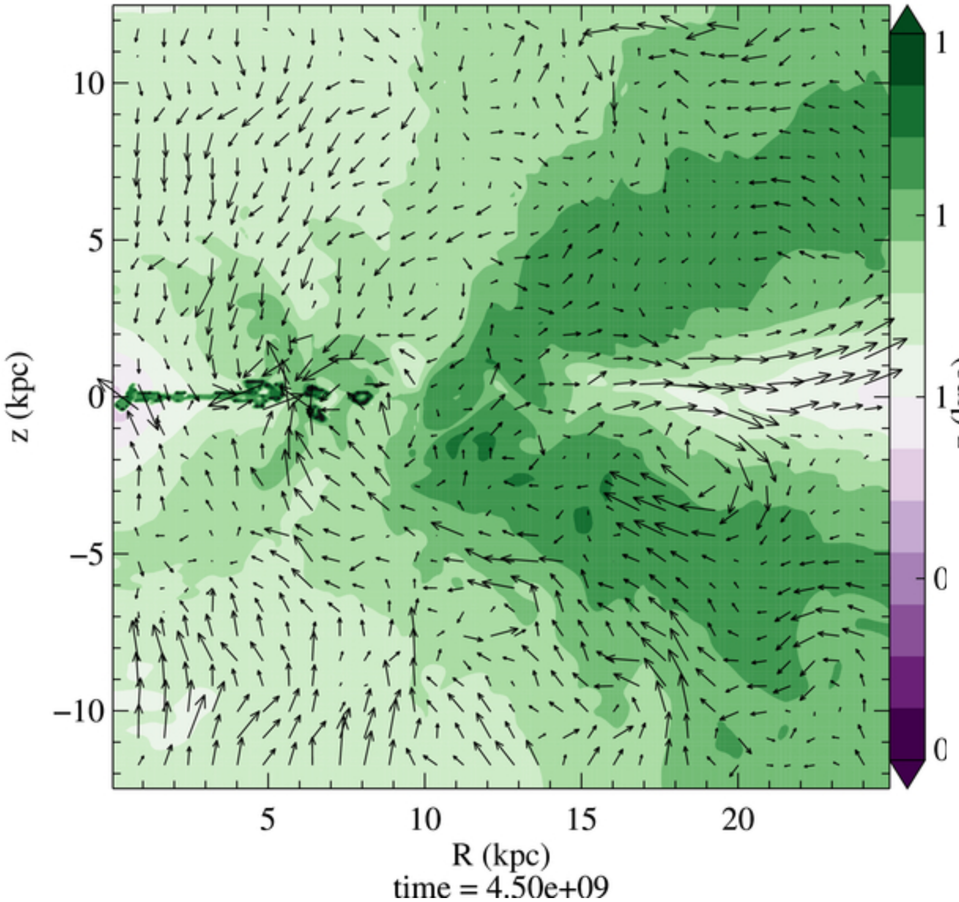

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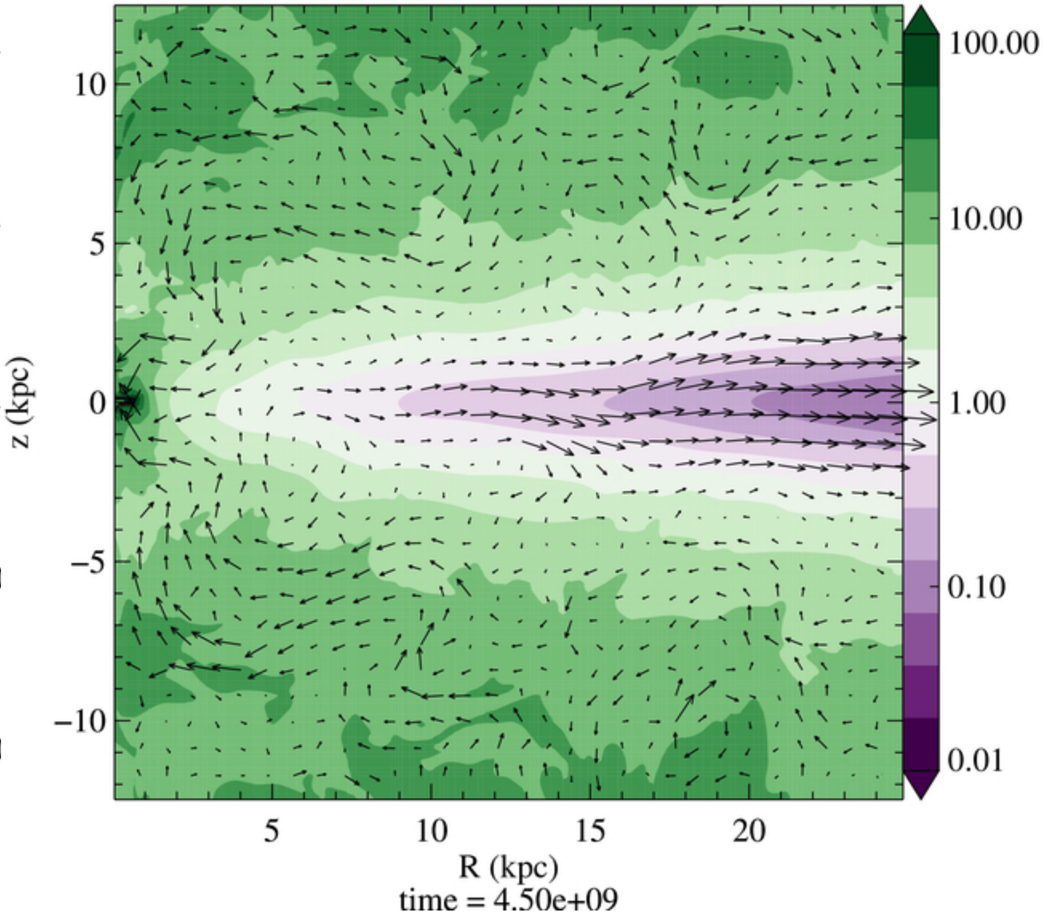

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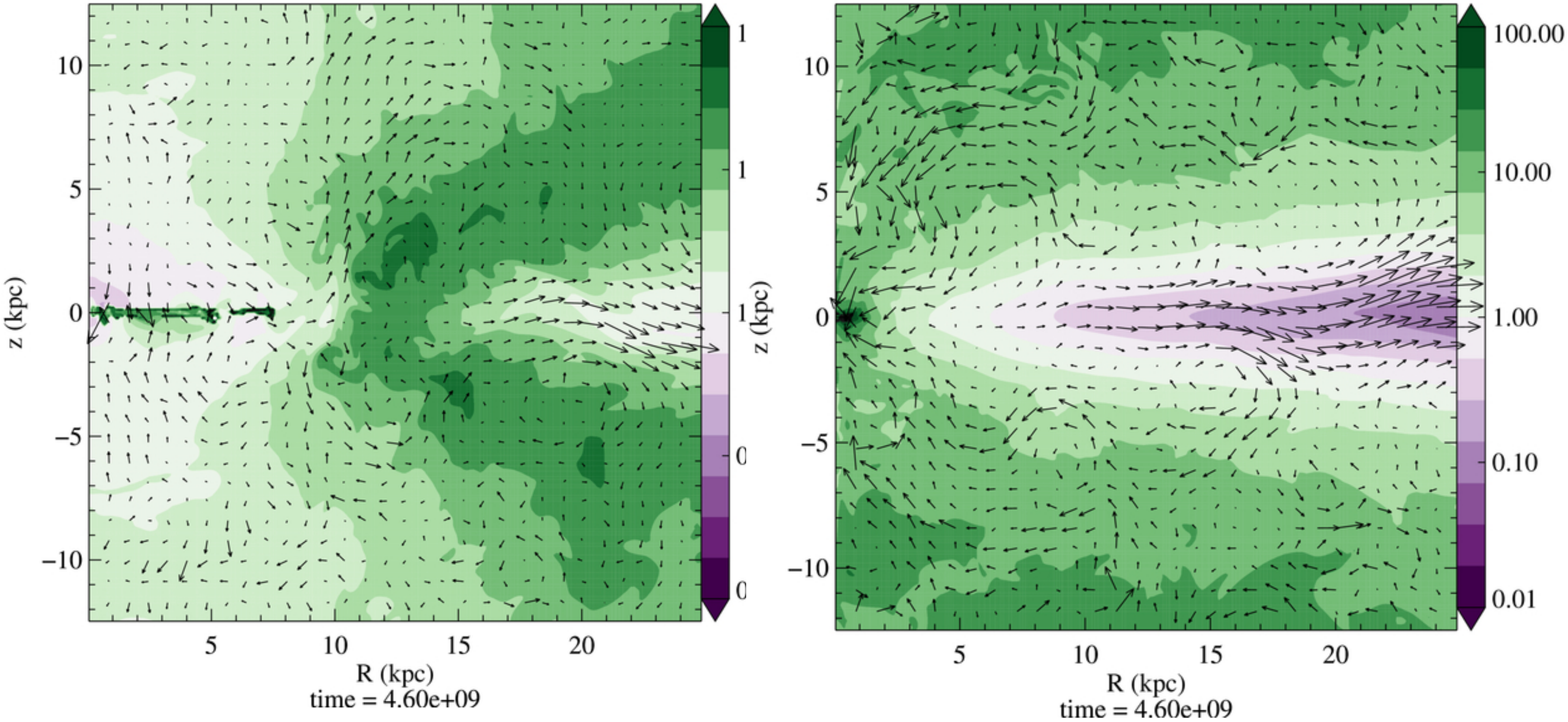
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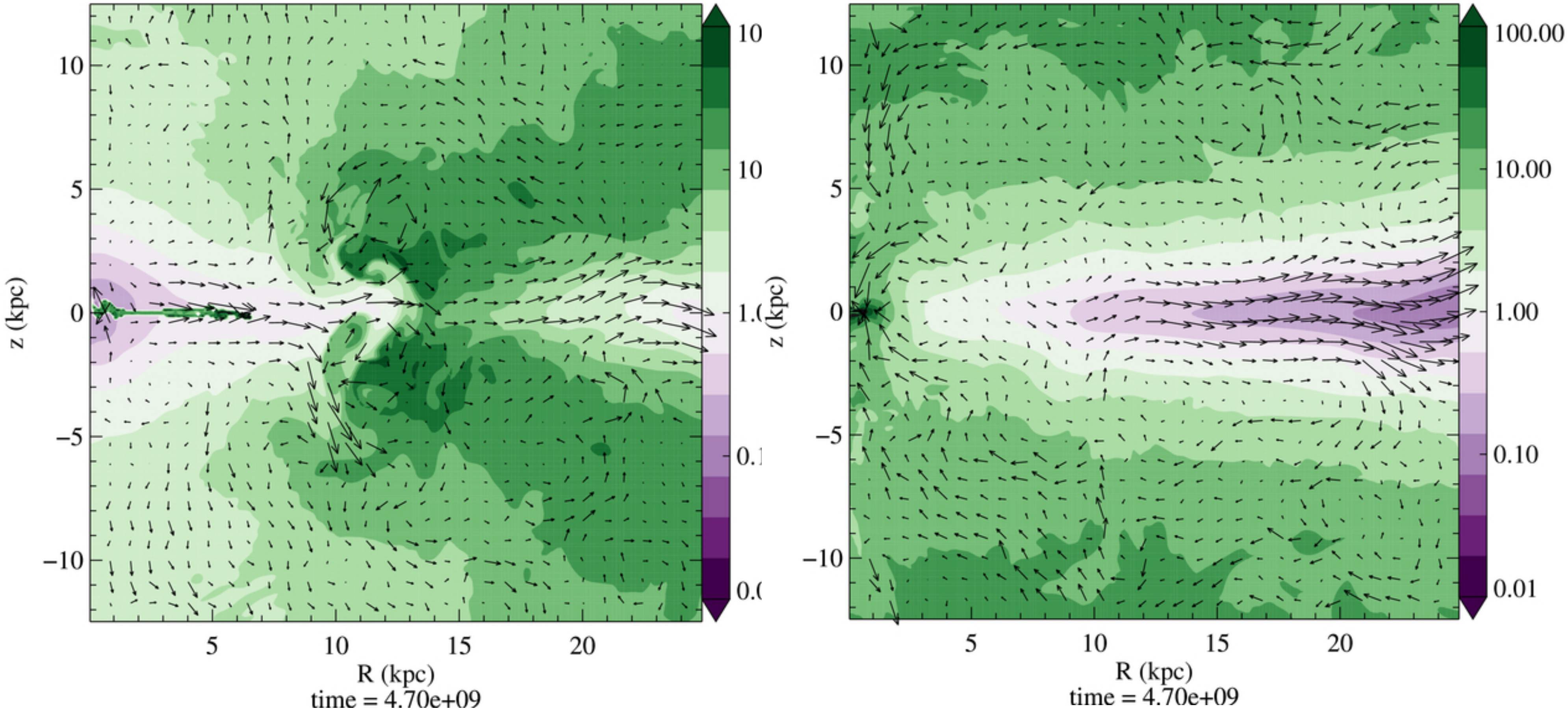
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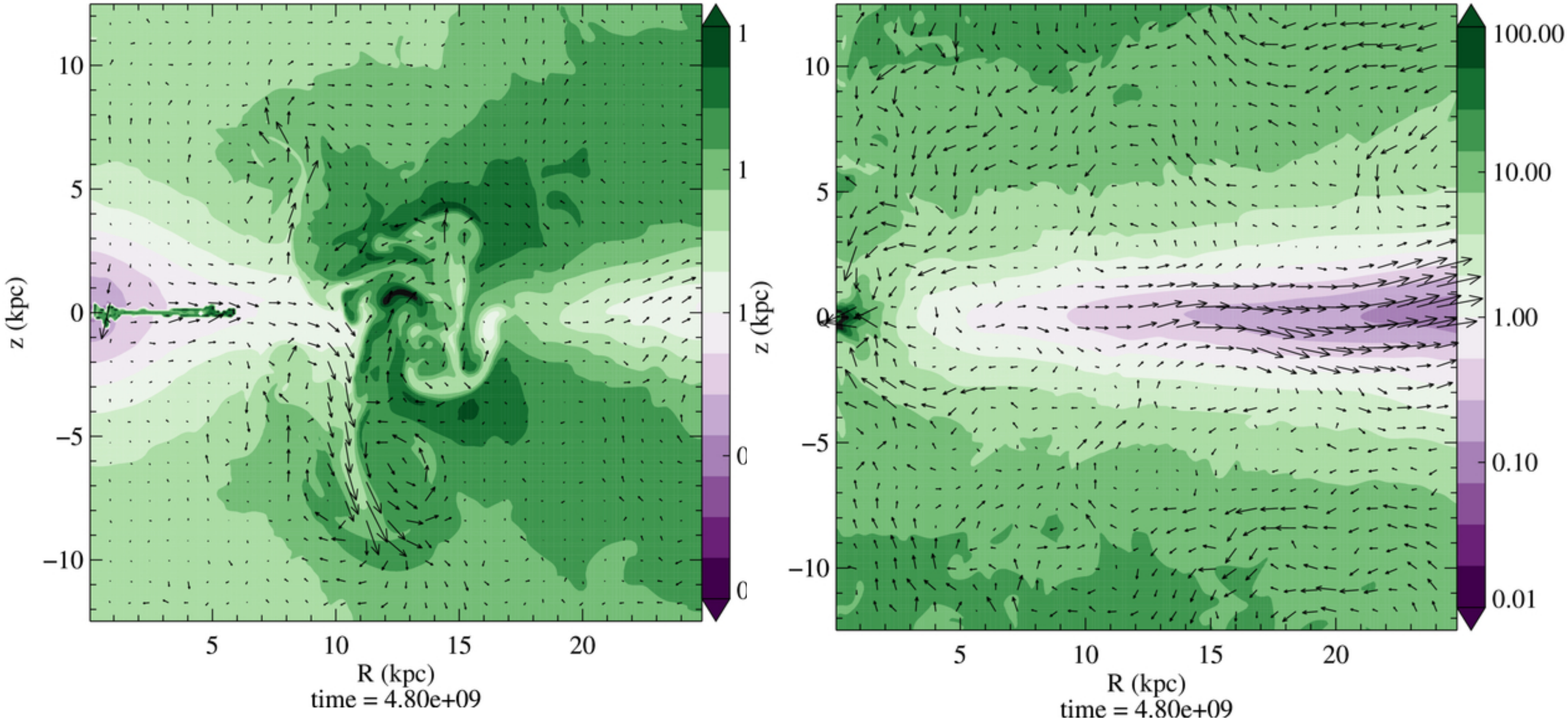
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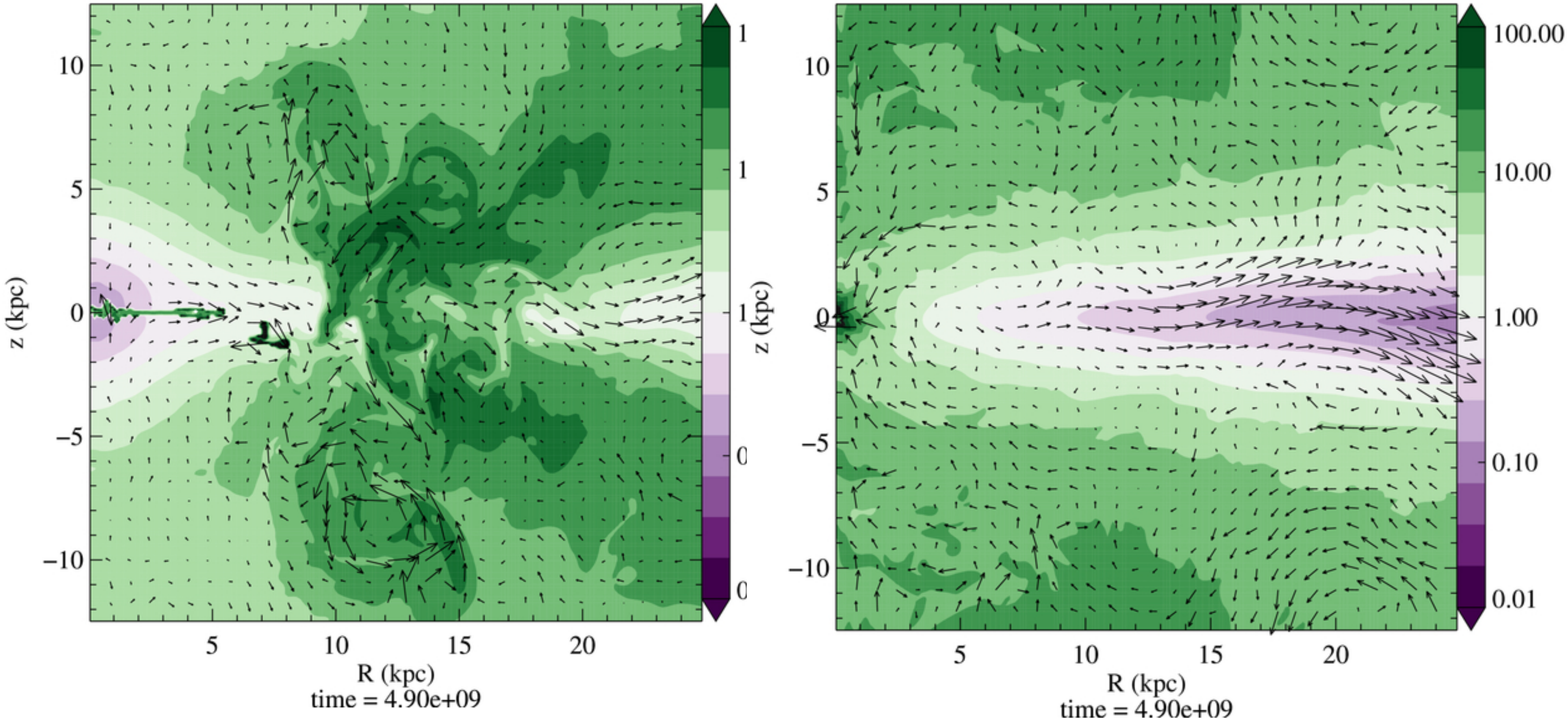

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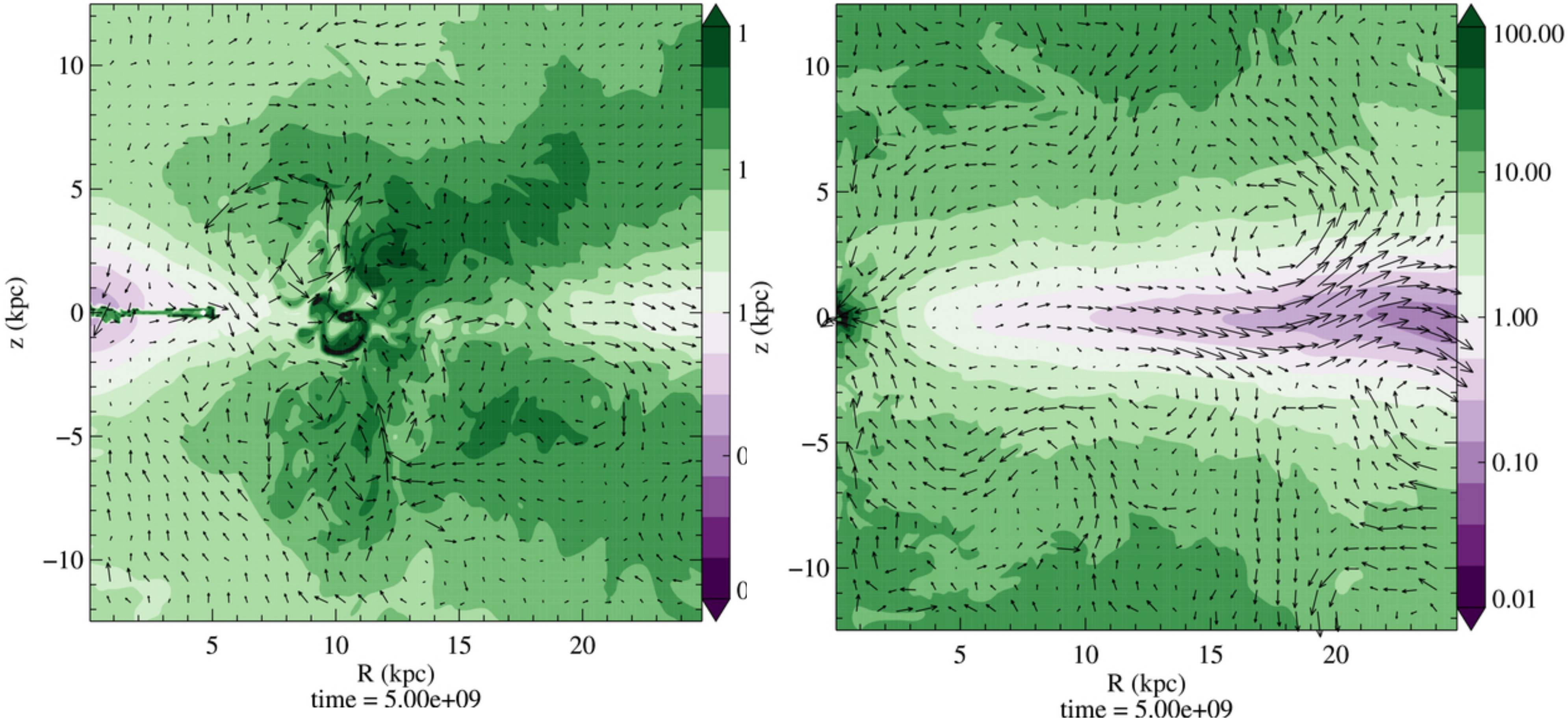
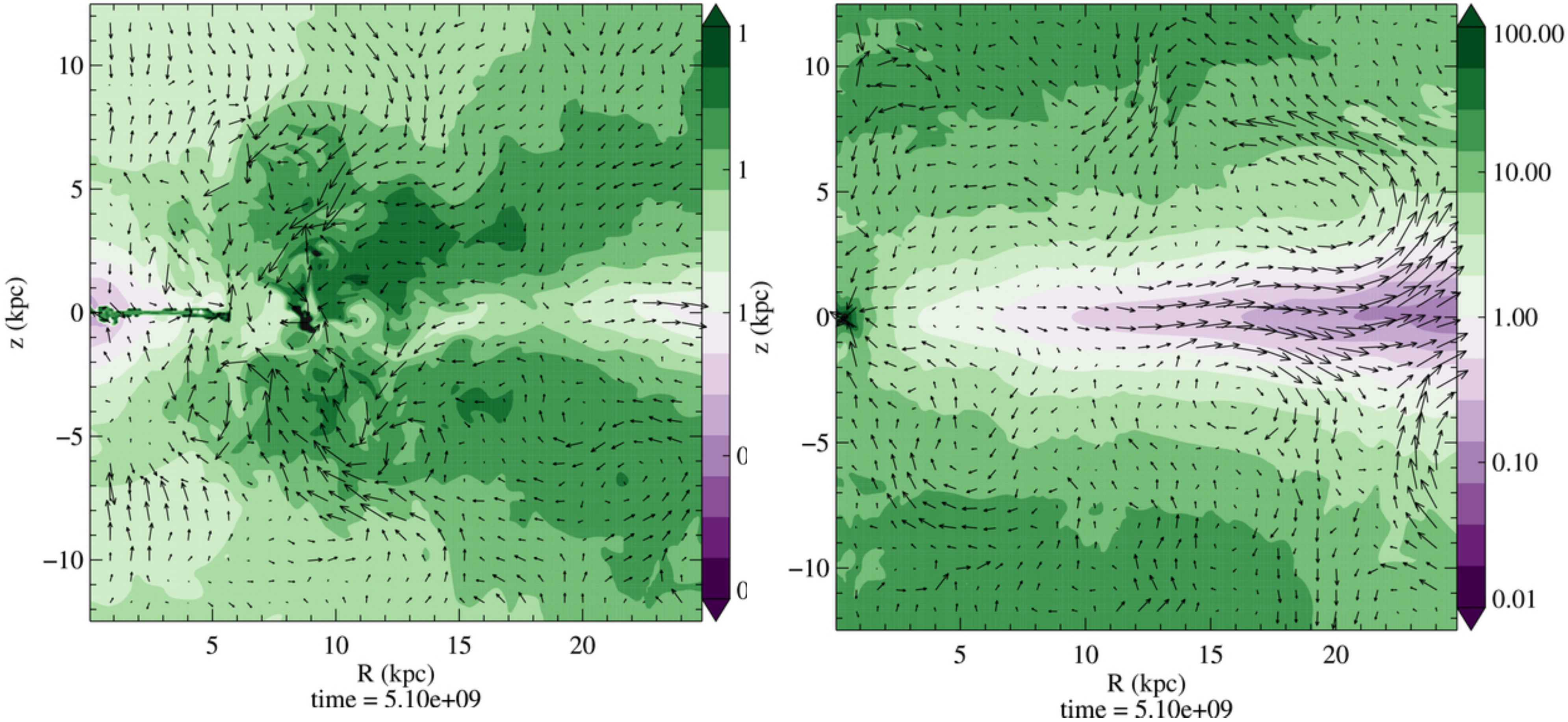
R (kpc)
time = 4.90e+09
z (kpc)
R (kpc)
time = 4.90e+09
100.00
10.00
1.00
0.10
0.01


z (kpc)
R (kpc)
time = 5.00e+09
z (kpc)
R (kpc)
time = 5.00e+09
100.00
10.00
1.00
0.10
0.01



z (kpc)
R (kpc)
time = 5.10e+09
z (kpc)
R (kpc)
time = 5.10e+09
100.00
10.00
1.00
0.10
0.01

4. AN UNAVOIDABLE MECHANISM?

Mass return happens

Momentum is injected with the ordered rotational velocity of the stellar component

NOW, STELLAR DYNAMICS SHOWS THAT THE STELLAR POPULATION AT R ROTATES LESS THEN Vc: "ASYMMETRIC DRIFT"

Jeans Equations for (two-integrals) axysimmetric systems

$$\frac{\partial \rho_* \sigma_*^2}{\partial z} = -\rho_* \frac{\partial \Phi_{\rm t}}{\partial z},$$

$$\frac{\partial \rho_* \sigma_*^2}{\partial R} - \rho_* \frac{\overline{v_\varphi^2} - \sigma_*^2}{R} = -\rho_* \frac{\partial \Phi_{\rm t}}{\partial R},$$

For simplicity, for an isotropic rotator

$$v_{\rm circ}^2 - \overline{v}_\varphi^2 = -\frac{R}{\rho_*}\frac{\partial \rho_* \sigma^2}{\partial R}, \quad > 0$$

Asymmetric Drift

Physical reason: vertical support of the stellar population reflects also on radial direction.

↓

Part of the centrifugal support is provided by “pressure” (vel. disp.)

↓

Less room for ordered rotation at fixed galaxy potential

Miyamoto-Nagai discs embedded in the Binney logarithmic potential: analytical solution of the two-integrals Jeans equations

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Department of Physics and Astronomy, University of Bologna, viale Berti Pichat 6/2, 40127 Bologna, Italy

$$J_0(R) = 2\pi R^2 \Delta R \, \Sigma(R) \, v_{\mathrm{circ}}(R). \tag{40}$$

In a time interval δt the evolving stars inject new material at a rate $\dot{\Sigma}(R)$, for an amount of mass

$$\Delta M_{\mathrm{inj}} = 2\pi R \, \Delta R \, \dot{\Sigma}(R) \, \delta t, \tag{41}$$

and angular momentum

$$\Delta J_{\mathrm{inj}} = 2\pi R^2 \Delta R \, \dot{\Sigma}(R) \, \delta t \, \overline{v}_{\varphi}. \tag{42}$$

The angular momentum per unit time after the mixing of the new material with the pre-existing one is given by

$$j(R) = \frac{R(\Sigma\, v_{\rm circ} + \dot{\Sigma}\,\delta t\,\overline{v}_\varphi)}{\Sigma + \dot{\Sigma}\,\delta t} \simeq j_0(R) - R\,{\rm AD}\,\delta t \times \frac{\dot{\Sigma}}{\Sigma}, \quad (43)$$

where $j_0(R) = Rv_{\rm circ}(R)$ is the specific angular momentum of the cold gas before injection. Since ${\rm AD} > 0$, there is a net radial inflow of gas to the radius $R+\delta R$, defined by the condition $j_0(R+\delta R) = j(R)$. Assuming a slow evolution (i.e., long characteristic times $\Sigma/\dot{\Sigma}$), and retaining linear order terms in δt and δR, one obtains an expression for the inflow velocity as

$$v_{\rm in}(R) = -\frac{R\,{\rm AD}(R)}{j_0'(R)} \times \frac{\dot{\Sigma}(R)}{\Sigma(R)}, \qquad j_0' = \frac{{\rm d}j_0}{{\rm d}R}, \quad (44)$$

DYNAMICAL FUNCTION times EVOLUTIONARY FUNCTION

Example of the dynamical radial function

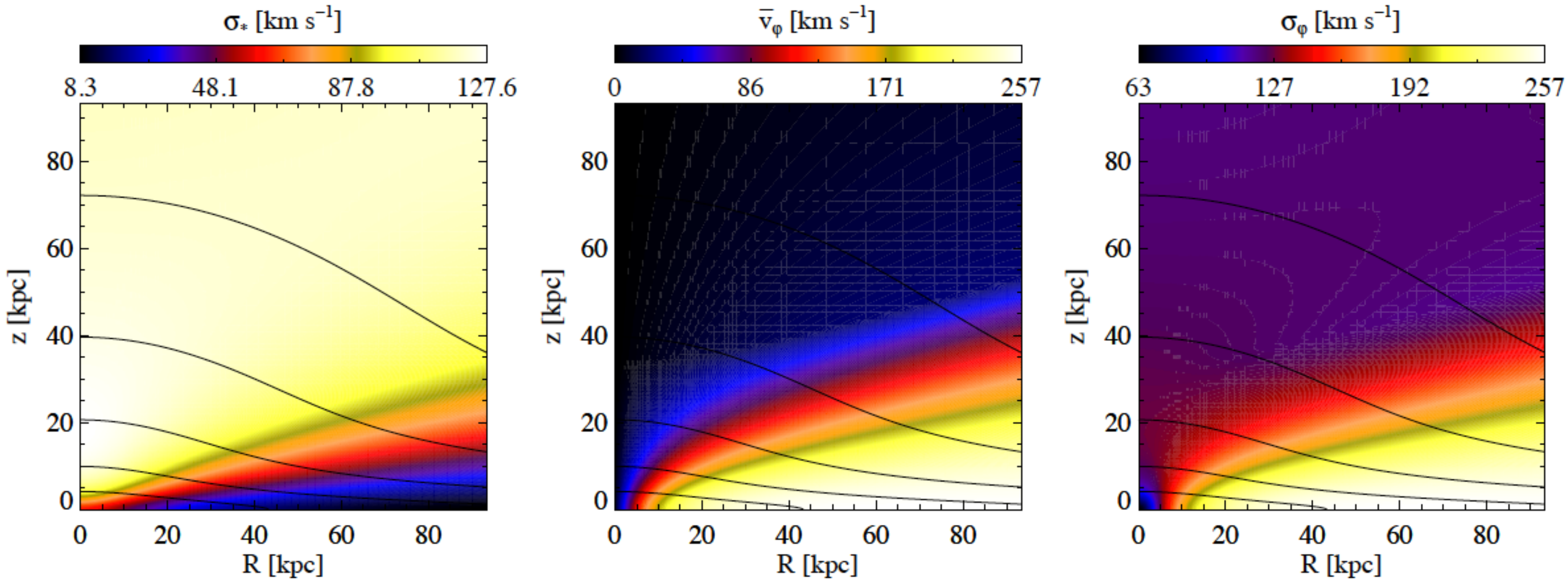
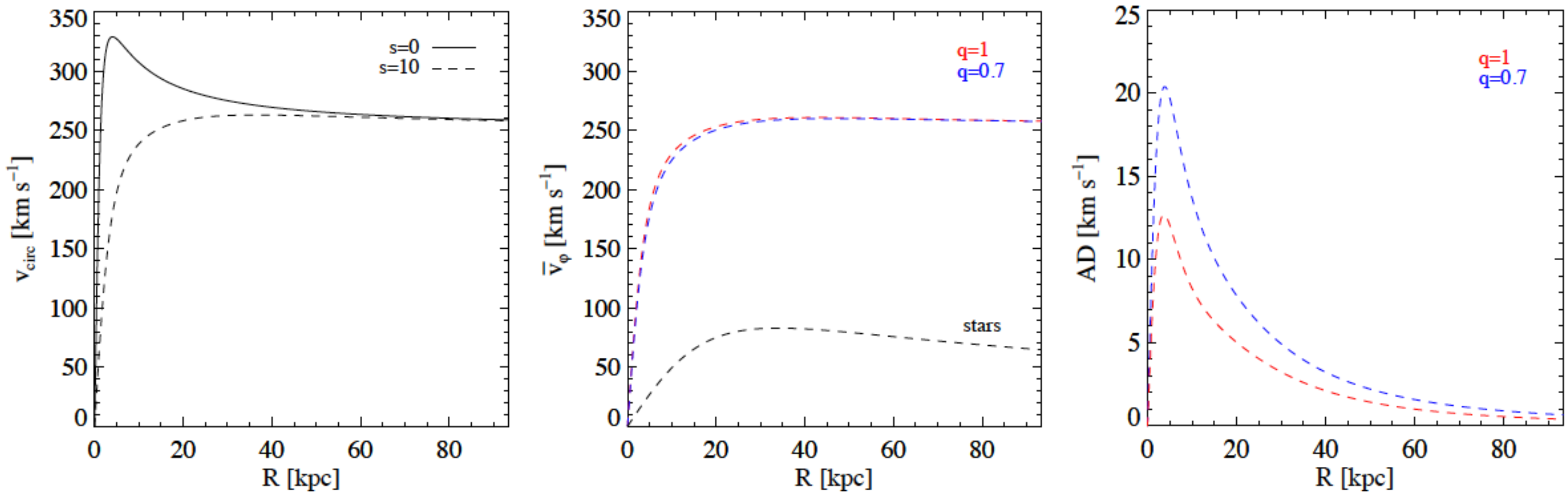
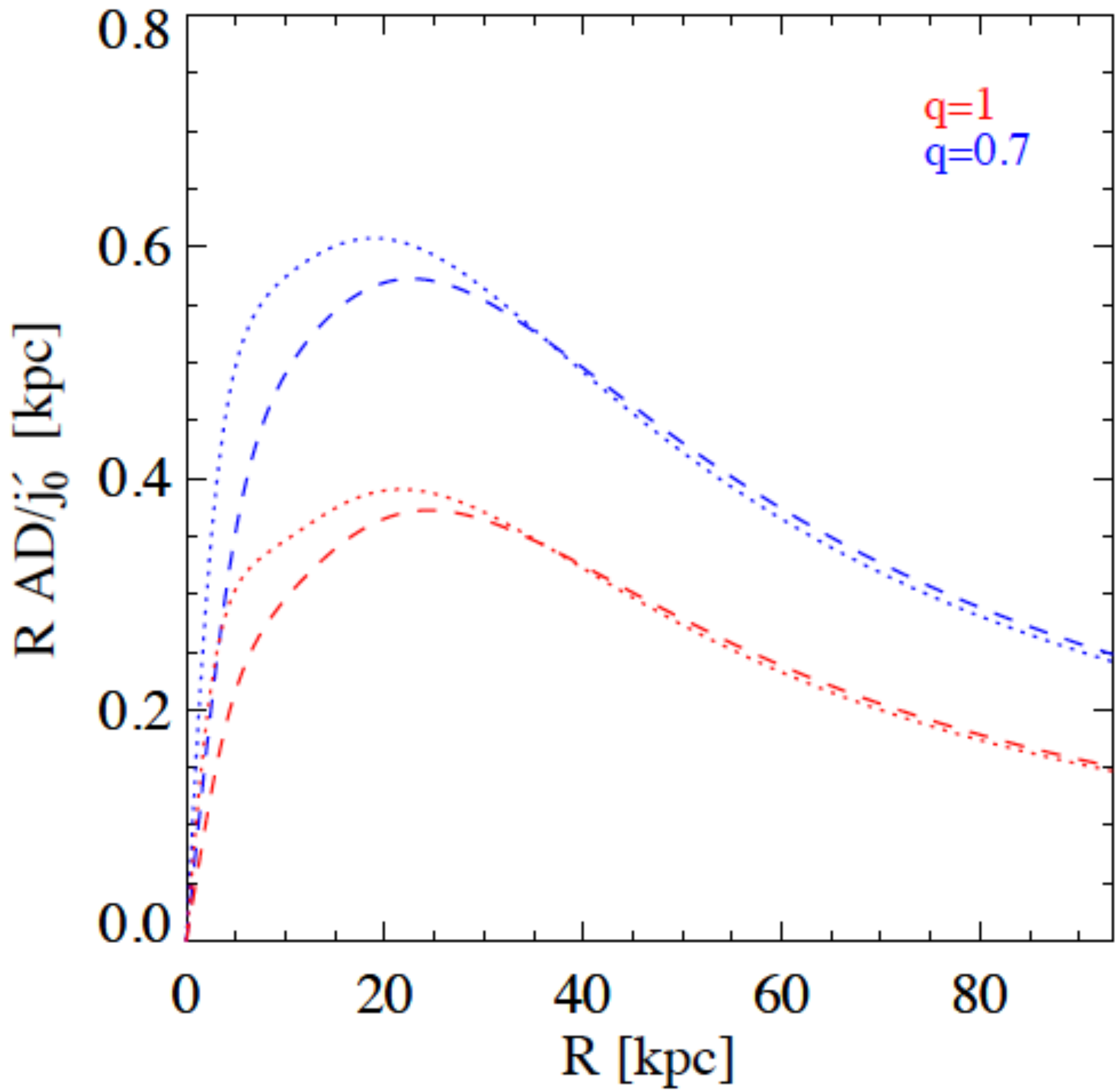


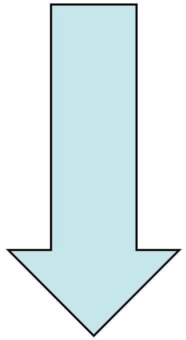
Figure 2. Two-dimensional maps in the meridional plane of the vertical and radial velocity dispersion $\sigma_* = \sqrt{\sigma_{**}^2 + \sigma_{*h}^2}$ (left panel), of the ordered azimuthal velocity $\overline{v}_\varphi$ in the isotropic case ($k = 1$, central panel), and of the azimuthal velocity dispersion σ_φ in the fully velocity dispersion supported case ($k = 0$, right panel). The structural parameters of the model are $M_* = 10^{11} M_\odot$, $b = 2$ kpc, $s = 10$, $v_h = 250\,\mathrm{km\,s^{-1}}$, $R_h = 5b$, and $q = 0.7$. Solid lines represent isodensity contours of the stellar distribution.

Miyamoto-Nagai disks + Binney's Log halo



s=0
s=10
v_{circ} [km s^{-1}]
R [kpc]
q=1
q=0.7
stars
$\overline{v}_{\varphi}$ [km s^{-1}]
R [kpc]
q=1
q=0.7
AD [km s^{-1}]
R [kpc]





Need of robust estimates for

$$\frac{\dot{\Sigma}(R)}{\Sigma(R)}$$

Can be in the range -1 km/s

5. CONCLUSIONS

Importance to know

1. the radial trend of the mass injection rate vs the local gas density in the disk

2. The radial trend of Asymmetric Drift

Then we have a simple recipe that can be used to compute the CONTRIBUTION of internal dynamics to RADIAL GAS FLOWS