Magnetic Fields Evolution in Grand-design Spiral Galaxies with 3D MHD Simulations

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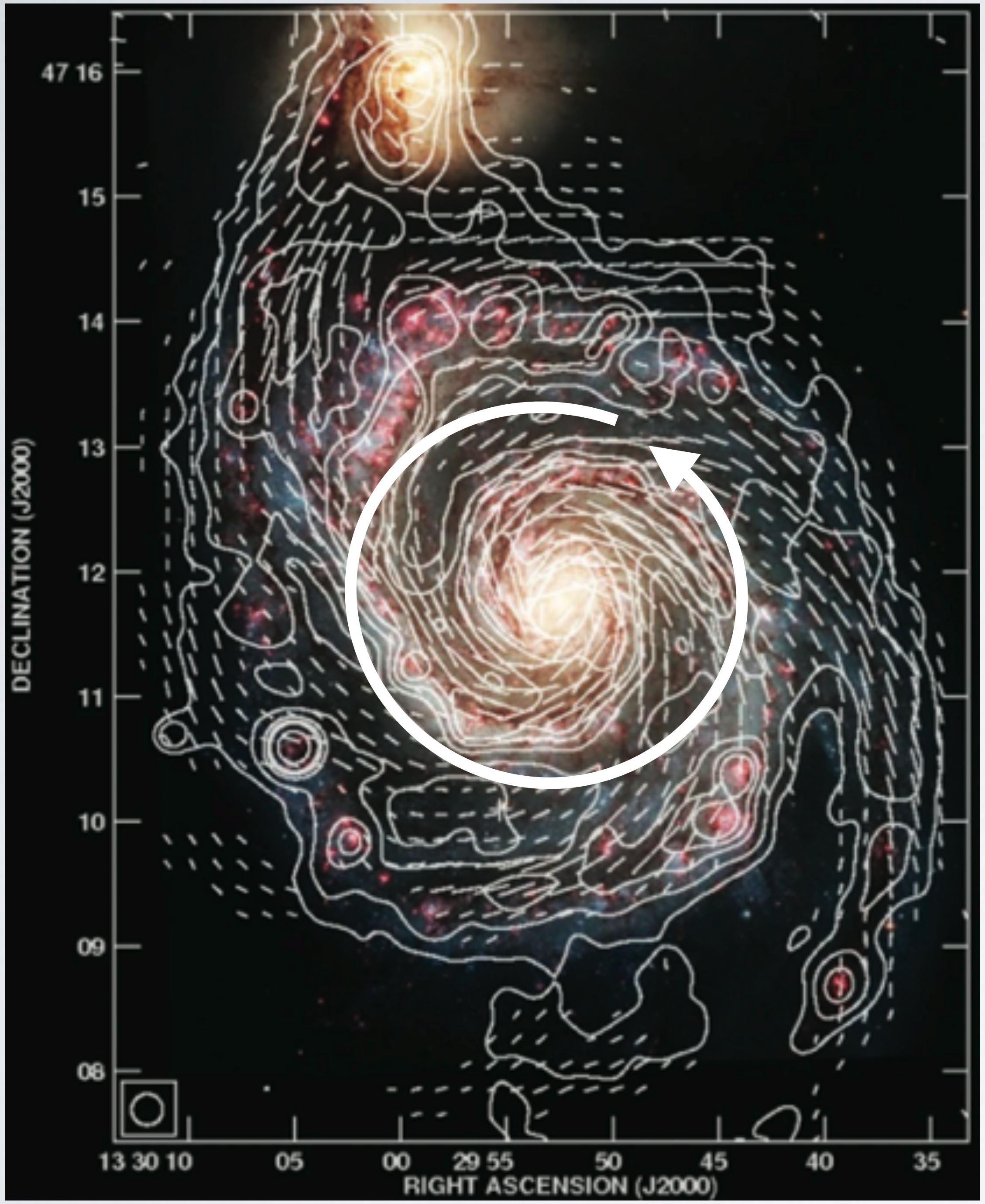
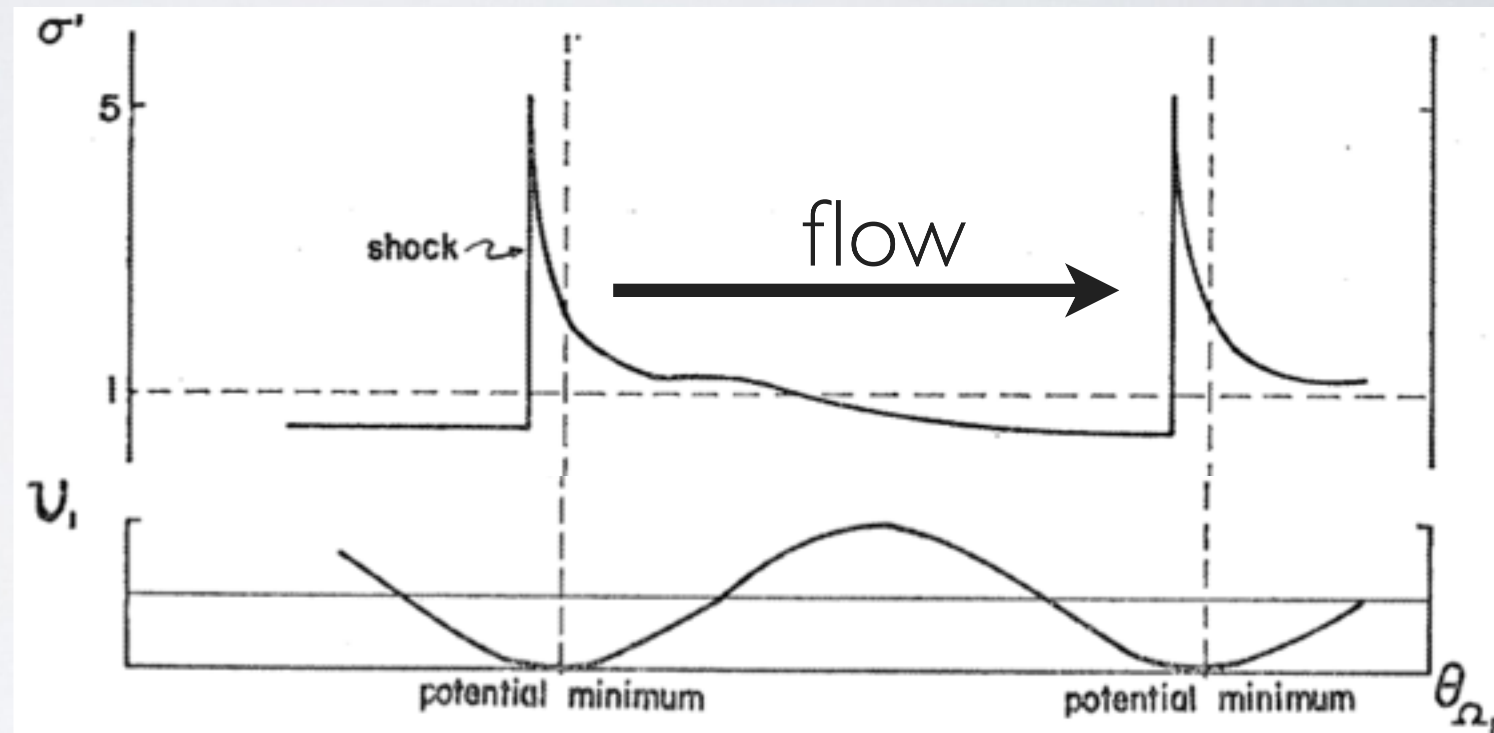
Introduction

Grand-design Spiral Galaxies



Fletcher+, 2011
(M51, λ=6cm)

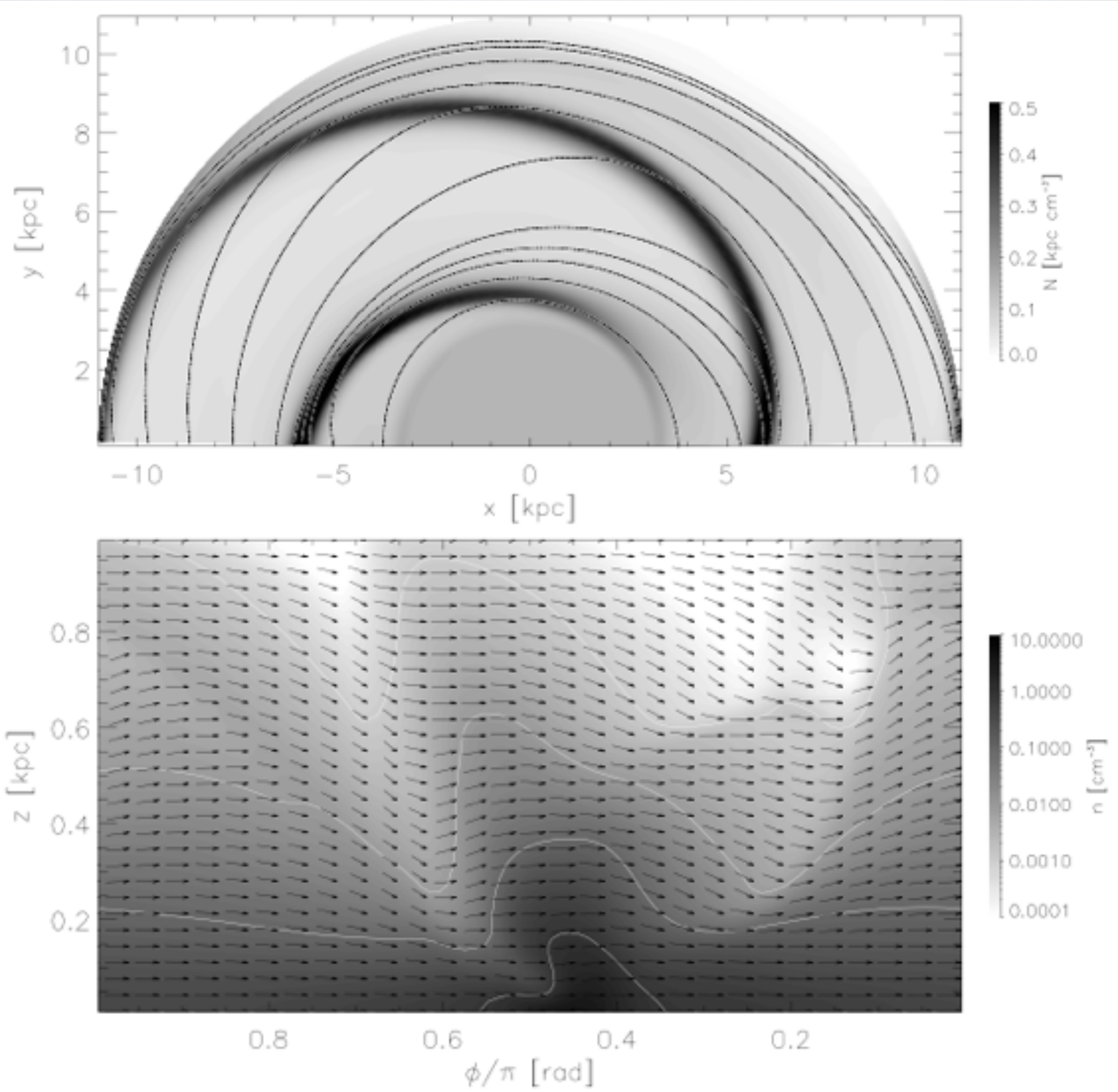


Roberts, 1969

Spiral galaxies have magnetic fields along the spiral arms
@ galactic plane.

Introduction
Previous Work

Previous Work



Gomez & Cox, 2002

isothermal, initial B ~ a few μG

Motivation

Motivation

Effects of a spiral potential on
1. gaseous structure
2. **magnetic field structure**

Model

&

Methods

Model: Basic Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot \left\{ \rho \mathbf{u}\mathbf{u} + \left(p_{\rm gas} + \frac{1}{8\pi} B^2 \right) \mathbf{I} - \frac{1}{4\pi} \mathbf{B}\mathbf{B} \right\} = -\rho \nabla \Phi + \rho \Omega_{\rm sp}^2 \mathbf{R} - 2\rho \boldsymbol{\Omega}_{\rm sp} \times \mathbf{u}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot \left[\left\{ e + \left(p_{\rm gas} + \frac{1}{8\pi} B^2 \right) \right\} \mathbf{u} - \frac{1}{4\pi} (\mathbf{B} \cdot \mathbf{u}) \mathbf{B} \right] = \mathbf{u} \cdot (-\rho \nabla \Phi + \rho \Omega_{\rm sp}^2 \mathbf{R}) - \rho^2 \Lambda(T_{\rm gas})$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \cdot (\mathbf{u}\mathbf{B} - \mathbf{B}\mathbf{u}) = \mathbf{0}$$

$$e_{\rm gas} = \frac{p_{\rm gas}}{\gamma_{\rm gas} - 1},\ \gamma_{\rm gas} = 5/3,\ e = \frac{1}{2}\rho u^2 + e_{\rm gas} + \frac{1}{8\pi} B^2,\ \mathbf{u} = \mathbf{v} - \Omega_{sp} R \mathbf{e}_\varphi$$

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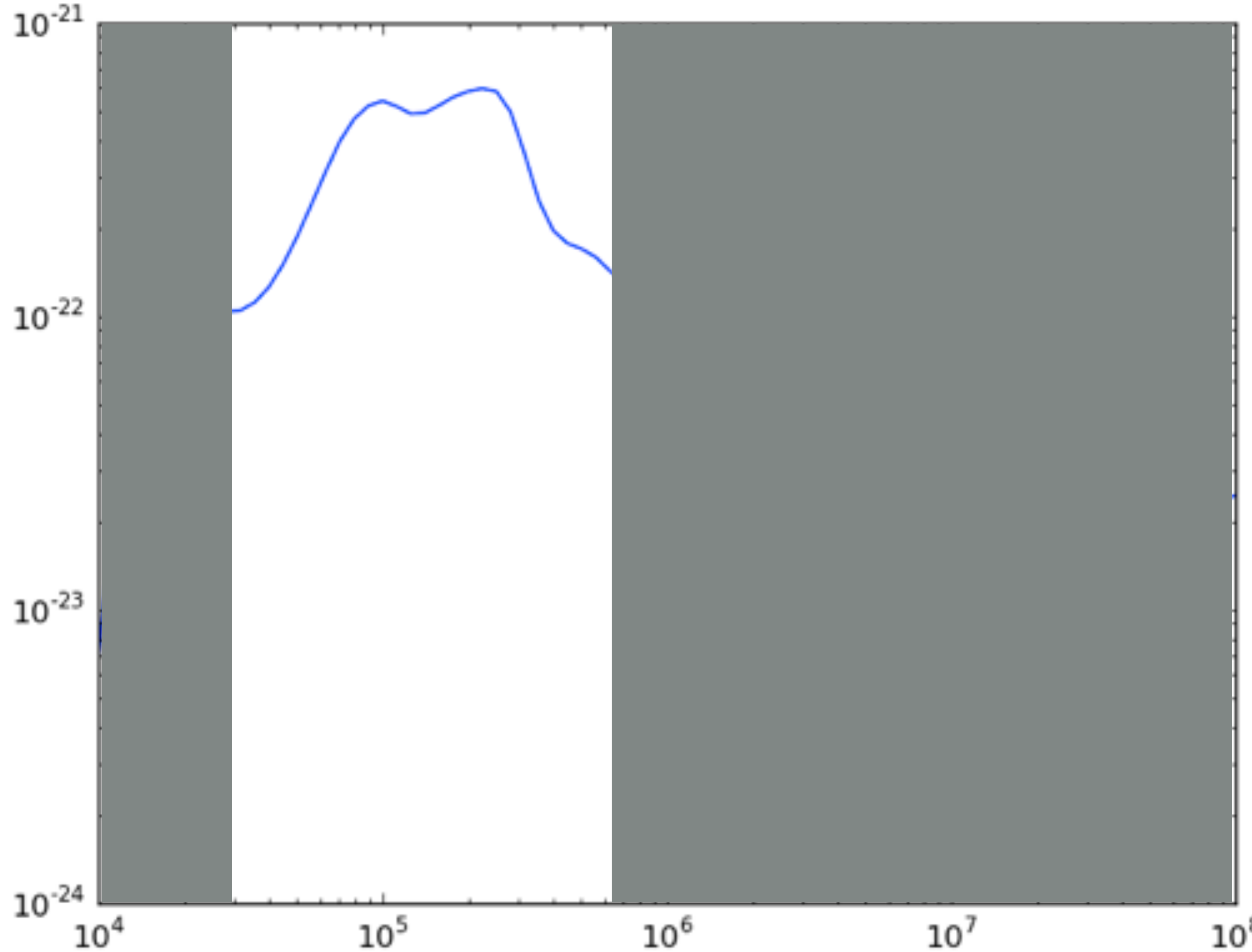
Radiative Loss Function



Raymond+, 1979

$$\Lambda(T_{\rm gas}) = \begin{cases} 0 & (T_{\rm gas} < 2\times10^4) \\ 10^{-21.85} & (2\times10^4 < T_{\rm gas} < 4\times10^4) \\ 10^{-31}T_{\rm gas}^2 & (4\times10^4 < T_{\rm gas} < 7.9\times10^4) \\ 10^{-21.2} & (7.9\times10^4 < T_{\rm gas} < 2.5\times10^5) \\ 10^{-10.4}T_{\rm gas}^{-2} & (2.5\times10^5 < T_{\rm gas} < 5.6\times10^5) \\ 0 & (5.6\times10^5 < T_{\rm gas}) \end{cases}$$

Rosner+, 1978

Model: Basic Equations

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Spiral Potential

$$\Phi(R,\varphi,z;t) = \Phi_{\rm bulge}(R,z) + \Phi_{\rm disc}(R,z) + \Phi_{\rm halo}(R,z) + \underline{\Phi_{\rm sp}(R,\varphi,z;t)}$$

non-axisymmetric potential

$$\Phi_{\rm sp}(R,\varphi,z;t) = \Phi_{\rm disc}(R,z)\epsilon_{\rm sp}\frac{(R/R_a)^2}{\{1+(R/R_a)^2\}^{3/2}}\frac{z_a}{\sqrt{z^2+z_a^2}} \times \cos\left[m\left\{\varphi - \Omega_{\rm sp}t + \cot i_{\rm sp}\ln\left(\frac{R}{R_{\rm phase}}\right)\right\}\right]$$

Wada+ 2004, Waba+ 2011

$$\epsilon_{\rm sp} = 0.025, R_{\rm a} = 7{\rm kpc}, z_{\rm a} = 0.3{\rm kpc}, m = 2, \Omega_{\rm sp} = 15{\rm kms^{-1}kpc^{-1}}, i_{\rm sp} = 15^\circ, R_{\rm phase} = 0.1{\rm kpc}$$

Model: Initial Condition

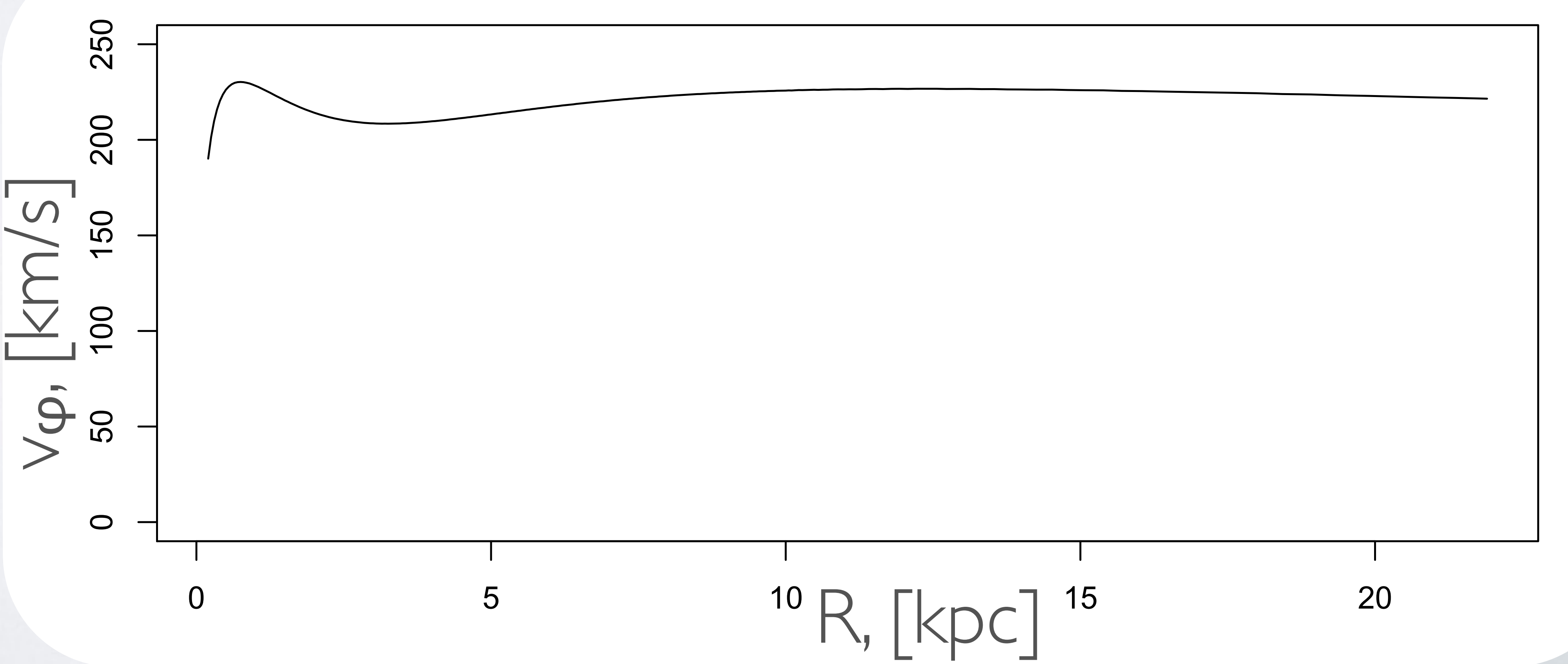
Initial gas distribution

$$\rho = \rho_{\rm disc} + \rho_{\rm halo}, \qquad \rho_{\rm disc} = \rho_{\rm disc,0} \exp\left(-\frac{R}{R_{\rm disc}}\right) \mathrm{sech}^2\left(\frac{z}{z_{\rm disc}}\right)$$

$$\rho_{\rm halo} = \rho_{\rm halo,0} \exp\left(-\frac{\Phi_{\rm axi}(R,z) - \Phi_{\rm axi}(0,0)}{Cs^2_{\rm halo}}\right)$$

$$R_{\rm disc} = 4{\rm kpc}, z_{\rm disc} = 0.3{\rm kpc}, T_{\rm disc} = 10^4{\rm K}, T_{\rm halo} = 10^6{\rm K}$$

Rotation curve



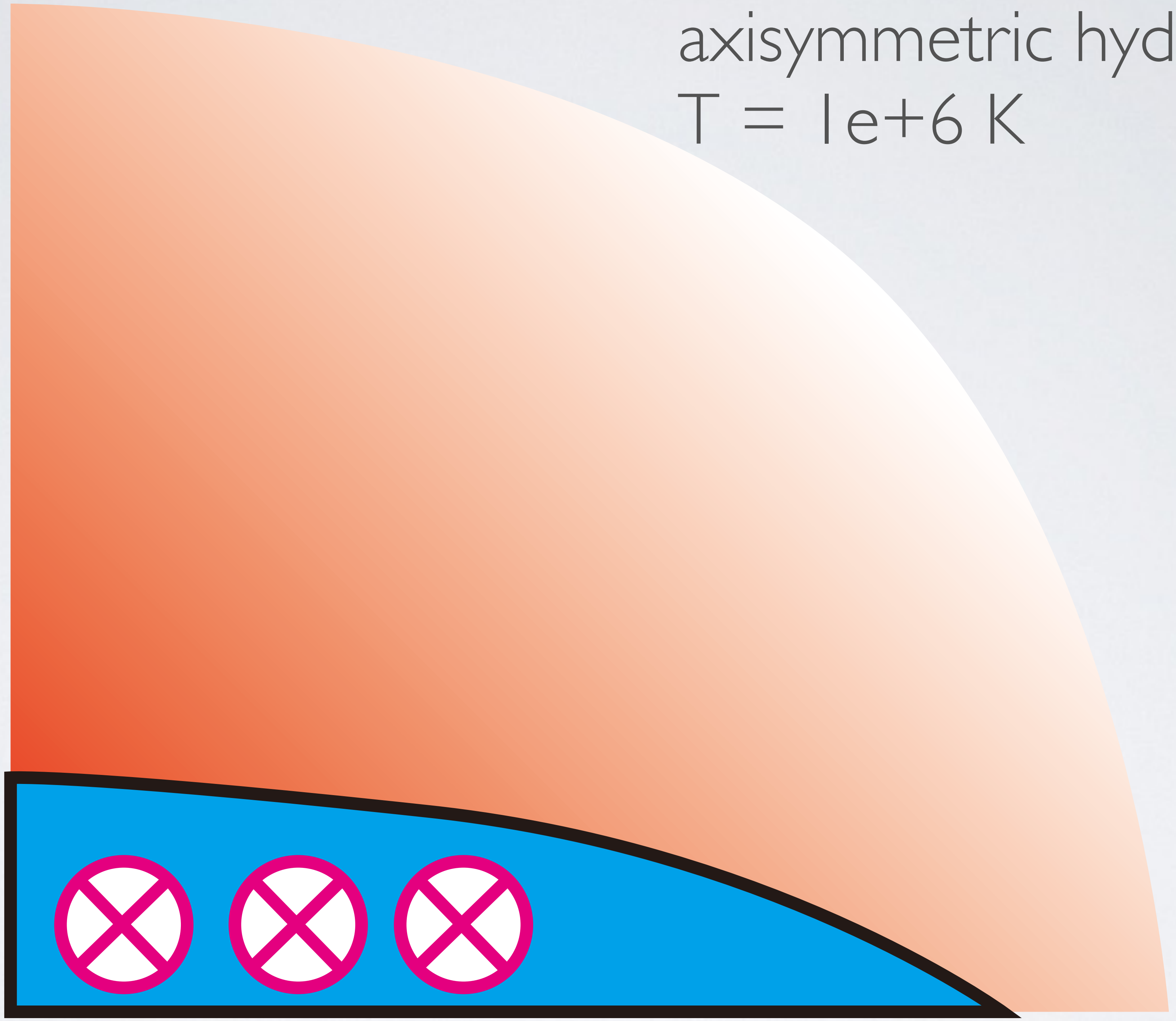
Model: Initial Condition

Initial magnetic field distribution

$$B_R = B_z = 0, B_\varphi = B_{\varphi,0} \exp\left(-\frac{R}{R_{\rm disc}}\right) \mathrm{sech}^2\left(\frac{z}{z_{\rm disc}}\right)$$

$$\beta = 10^4 \text{ @ } R = 0\mathrm{kpc} \implies B_{\varphi,0} \sim 0.1\mu\mathrm{G}$$

Model: Initial Condition



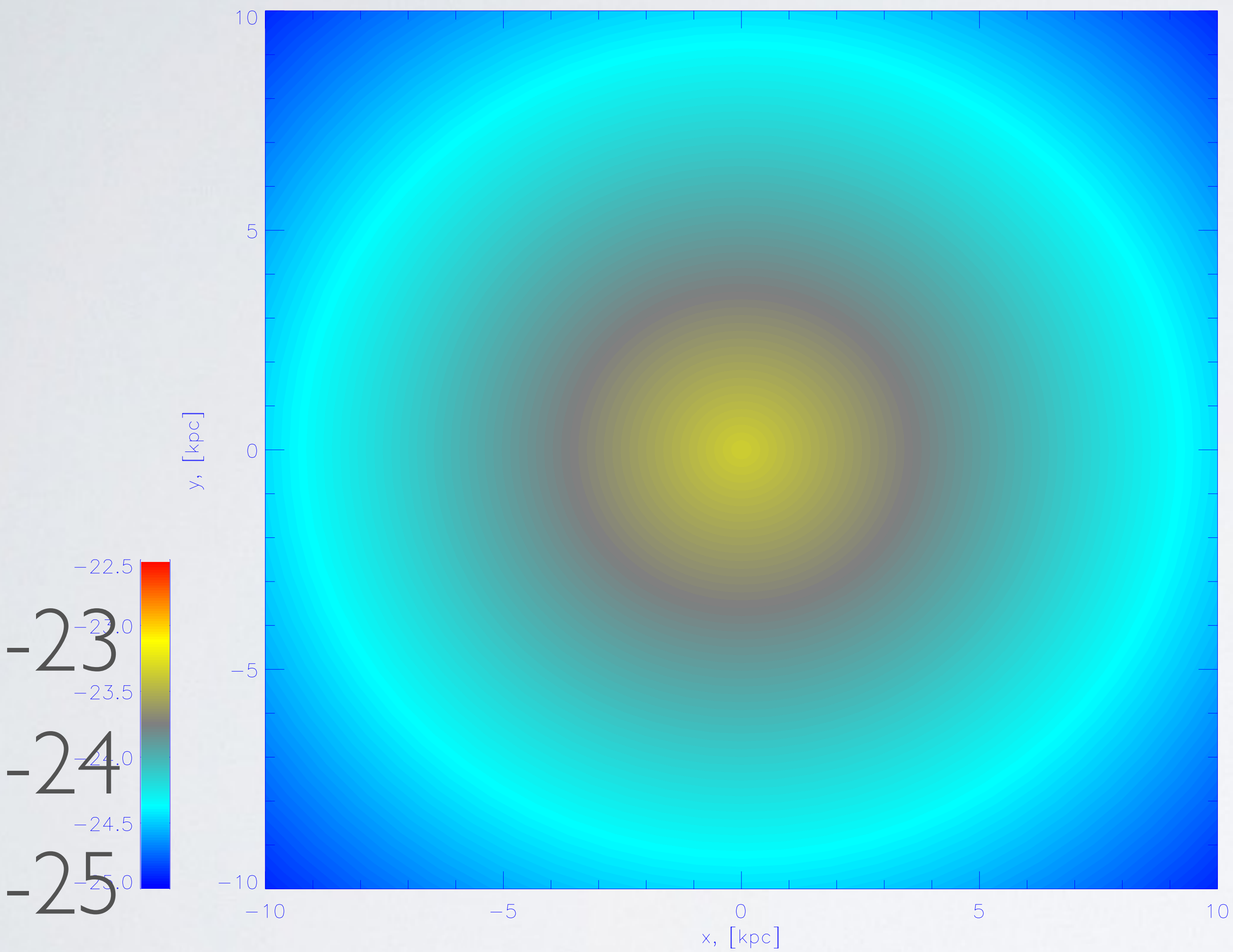
Methods

I. flux: HLLD (Miyoshi&Kusano 2005)
II. time & space: 2nd order accuracy
III. divergence constraint:
Hyperbolic Divergence Cleaning (Dedner+ 2002)
IV. cylindrical coordinate, $(N_R, N_\varphi, N_z)=(250, 64, 200)$
V. Simulation region & Boundary conditions (↓)

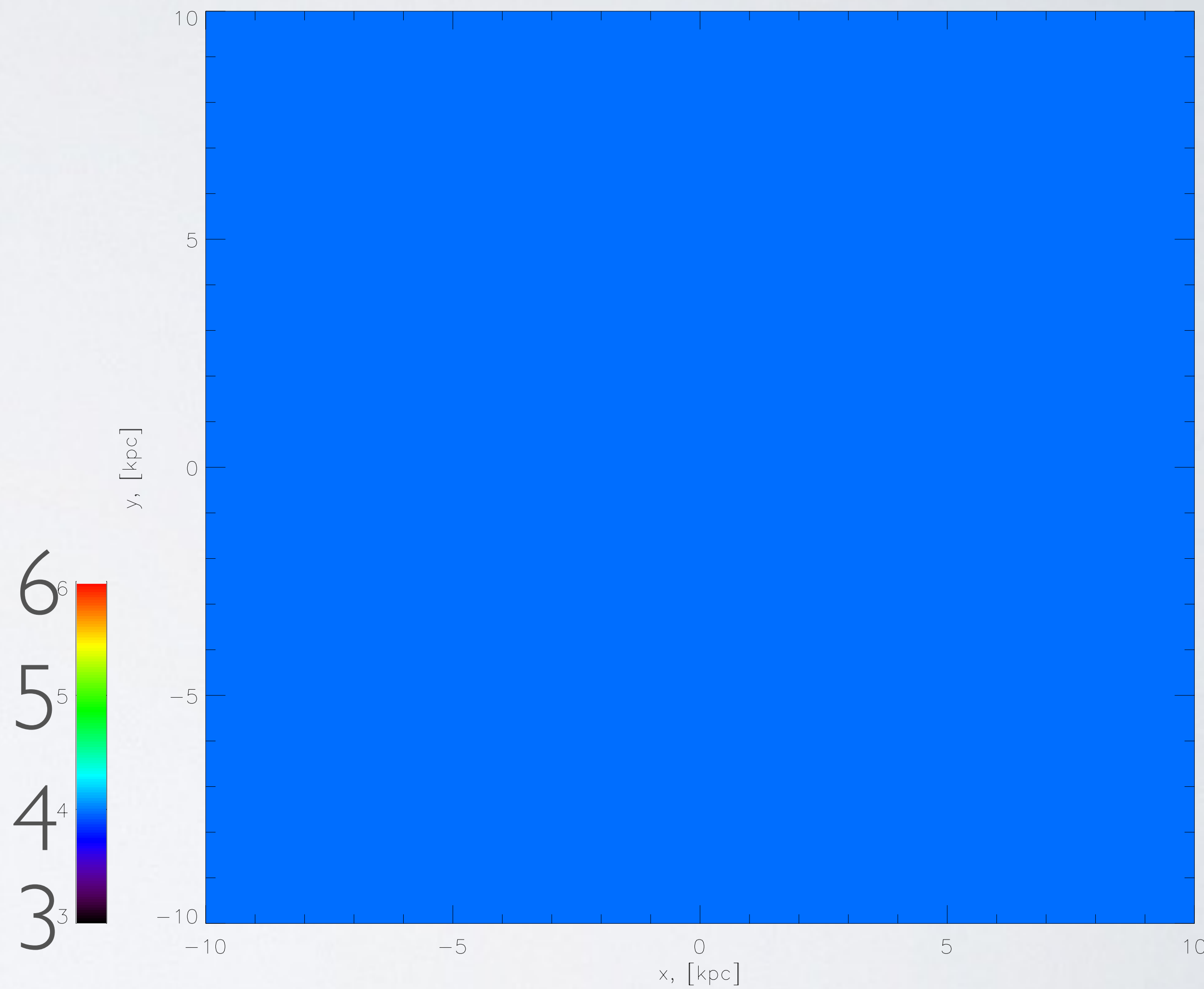
Results

Results

Log(density)

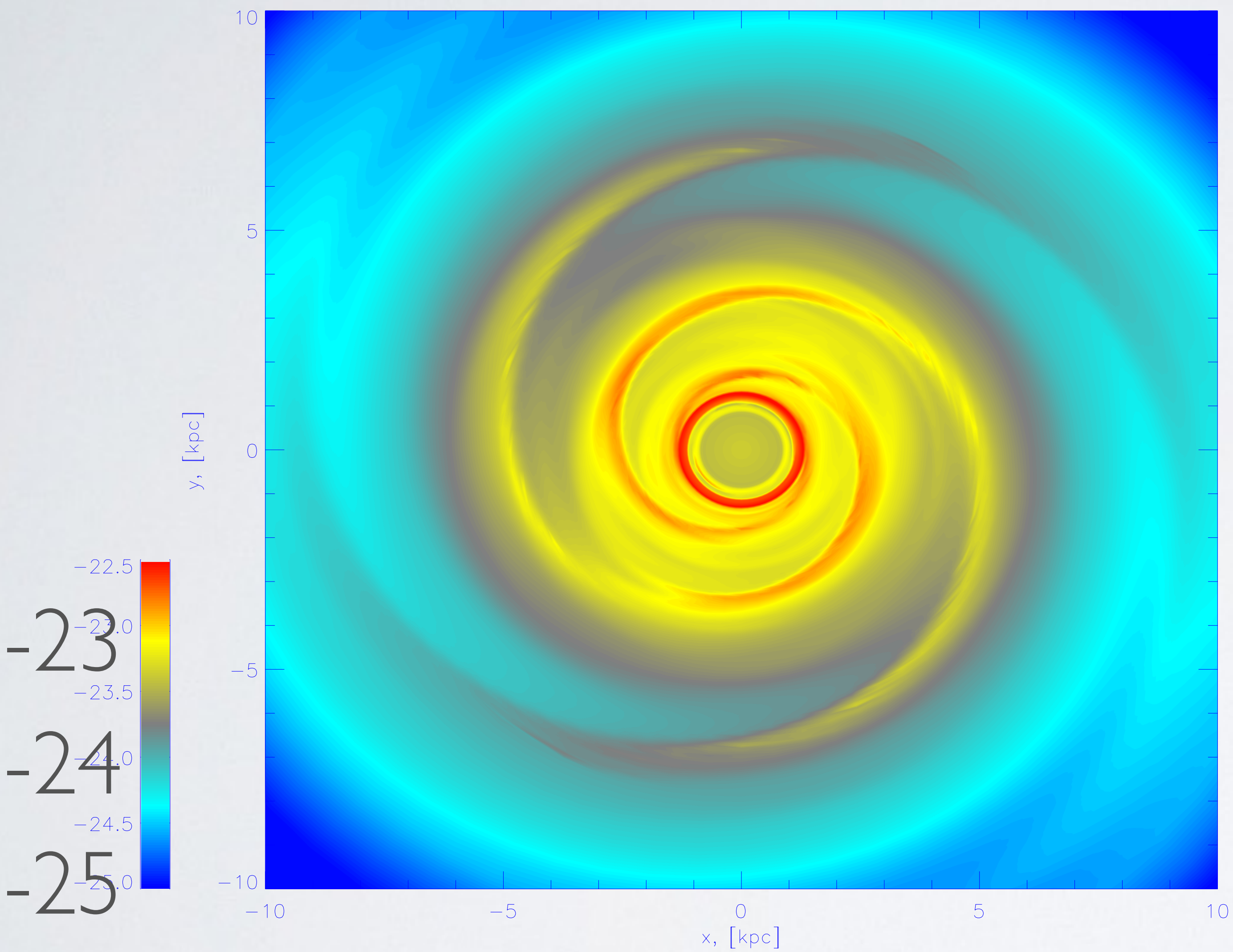


Log(temperature)

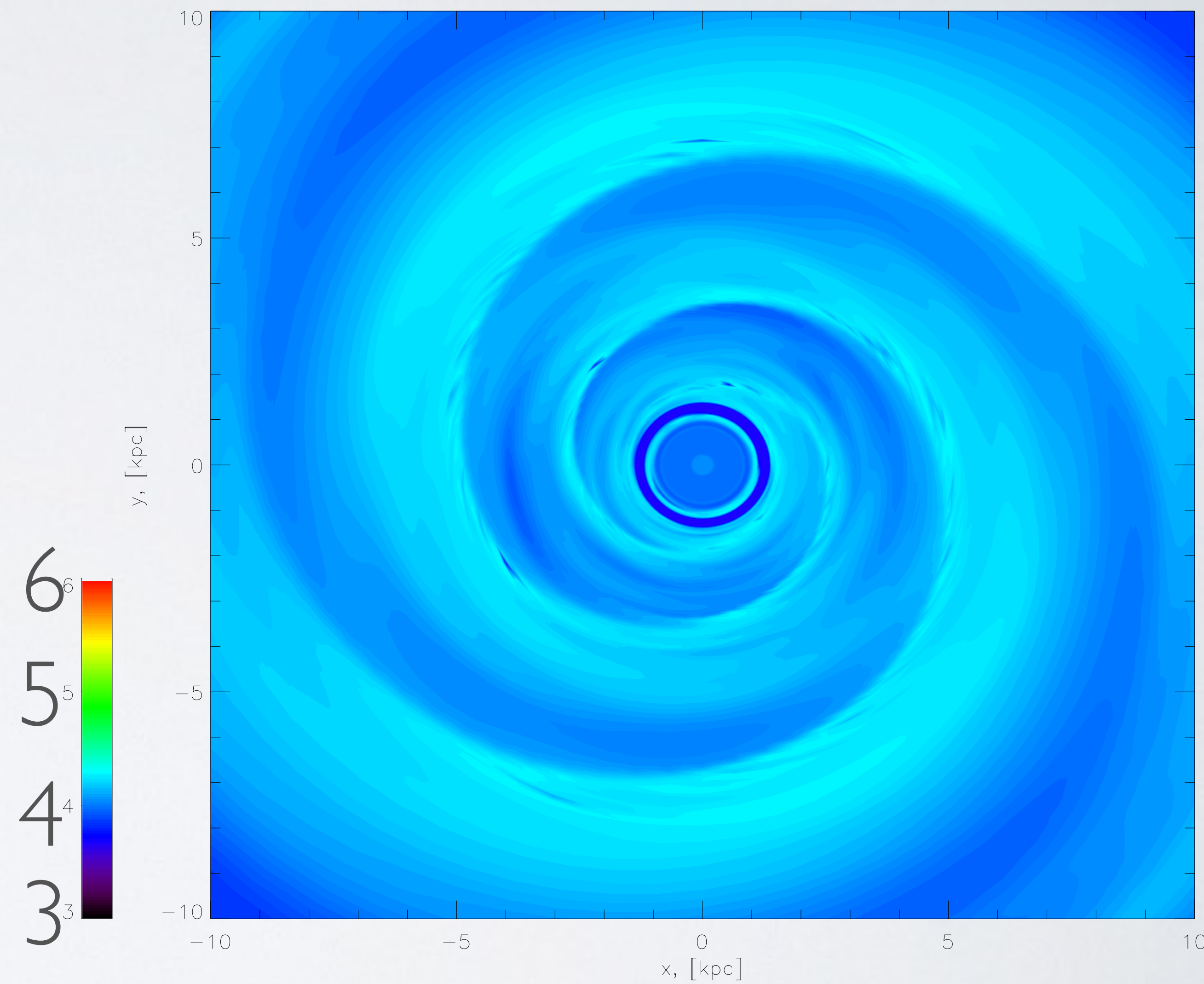


Results(t=800Myr)

Log(density)

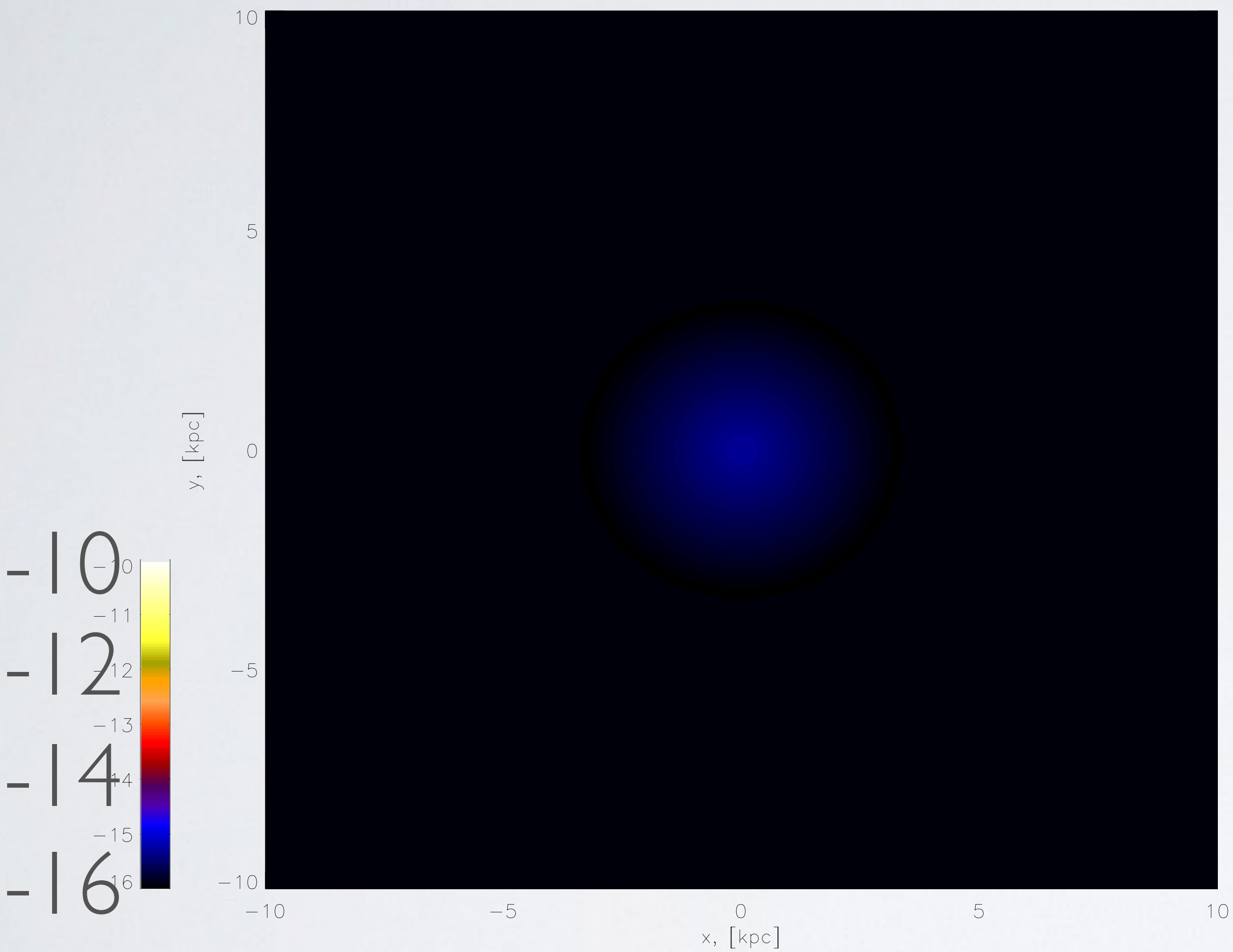


Log(temperature)

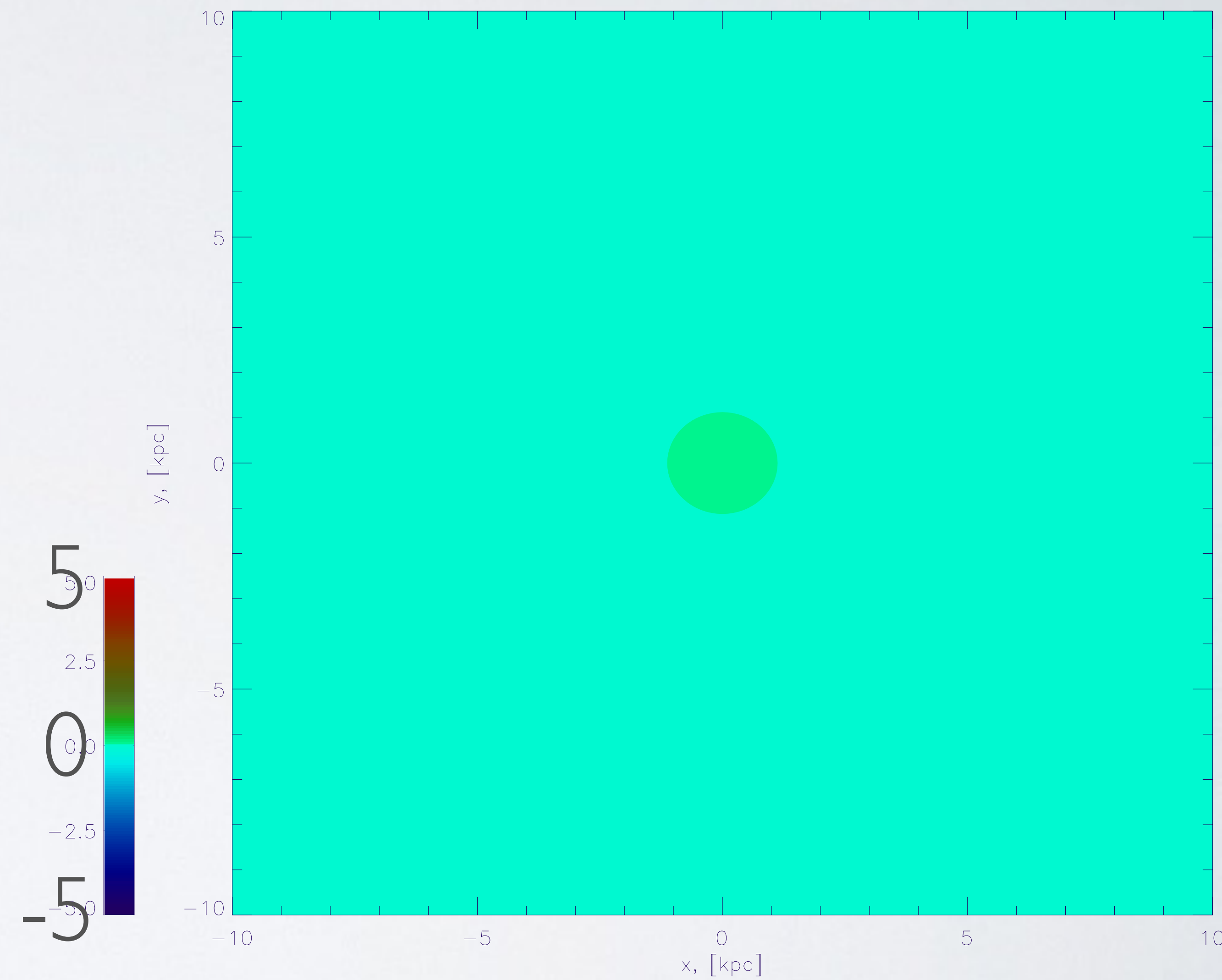


Results

$Log(B^2/8\pi)$

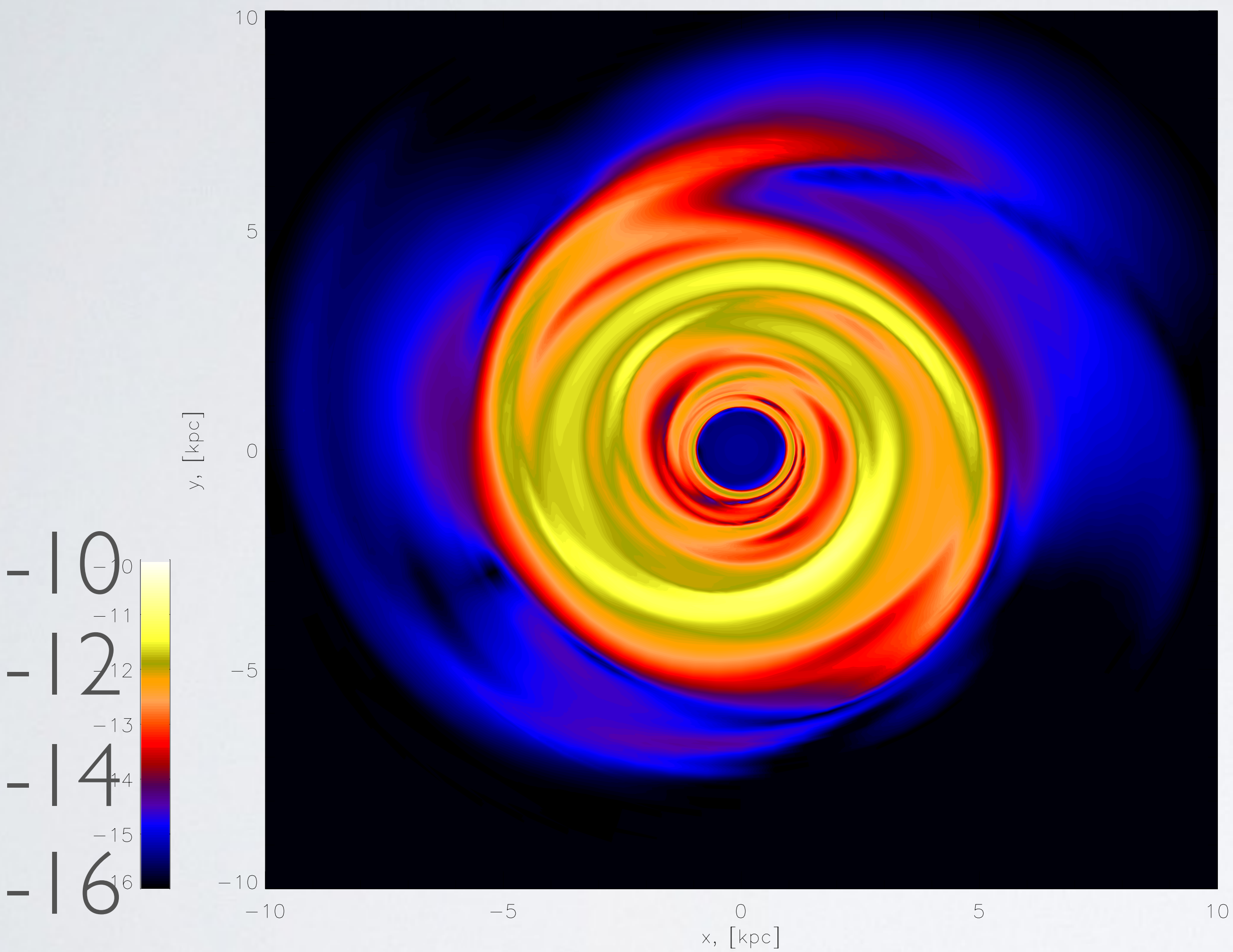


$B_{\varphi}(\mu G)$

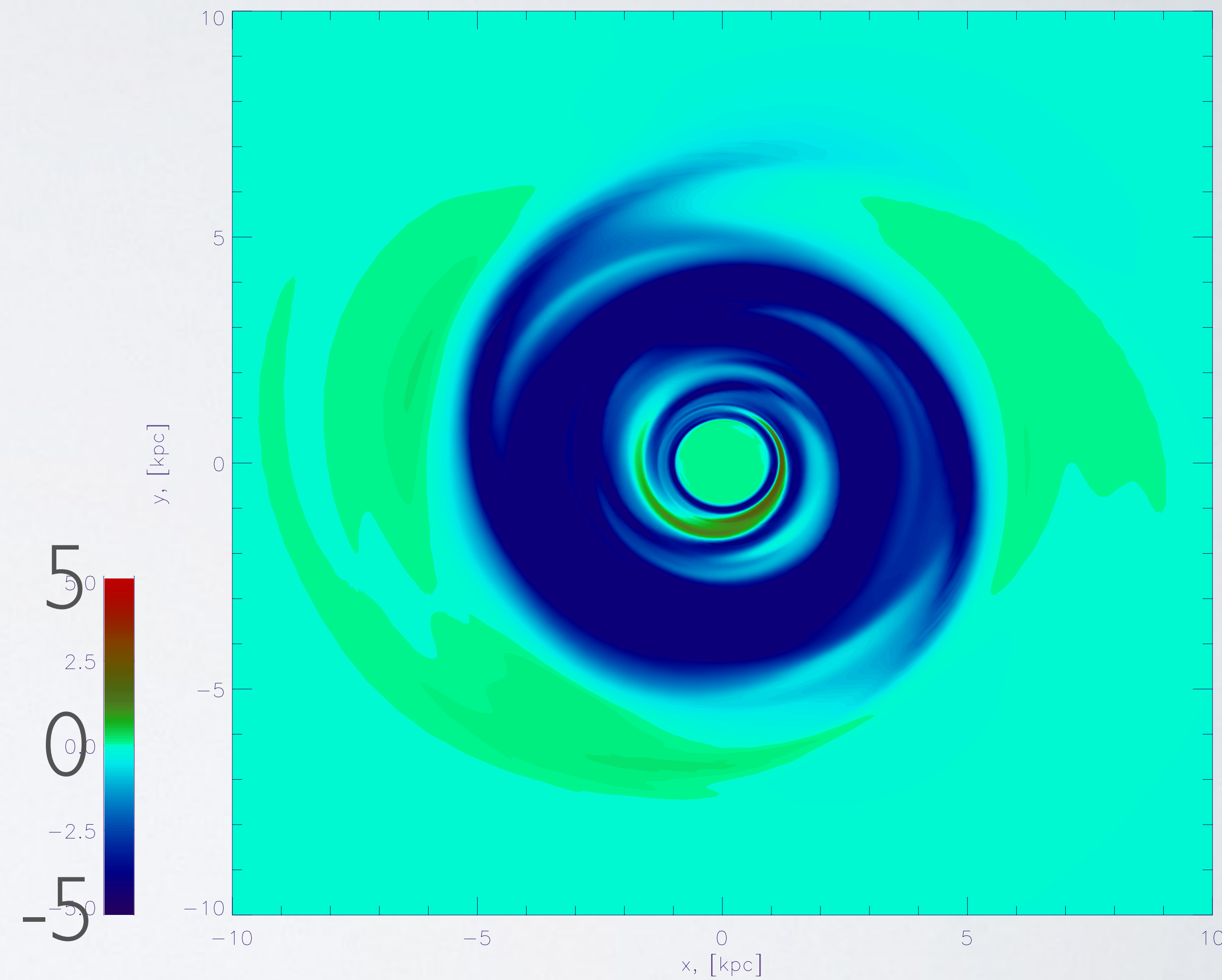


Results(t=800Myr)

Log($B^2/8\pi$)

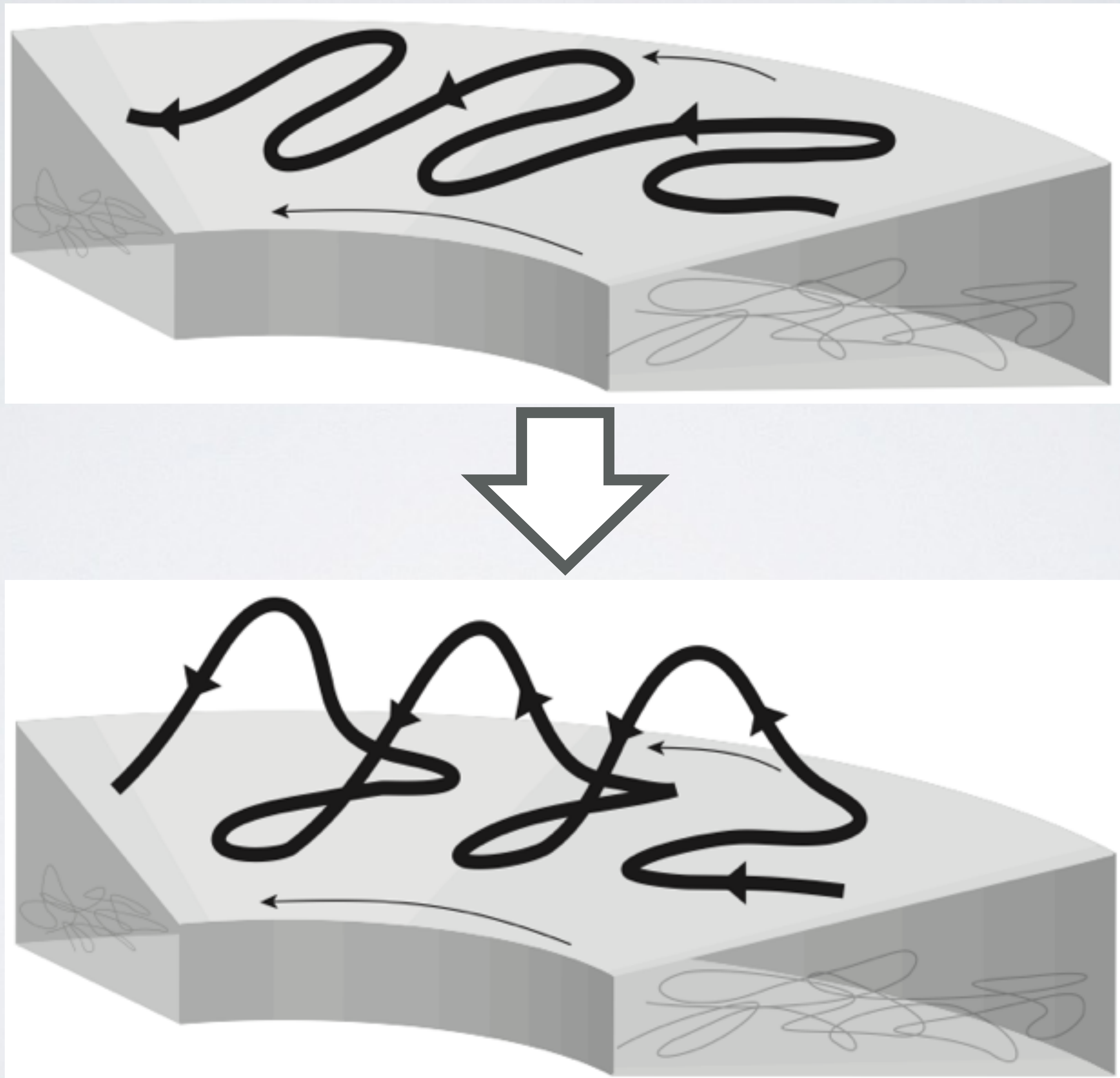


B_φ(μG)



?

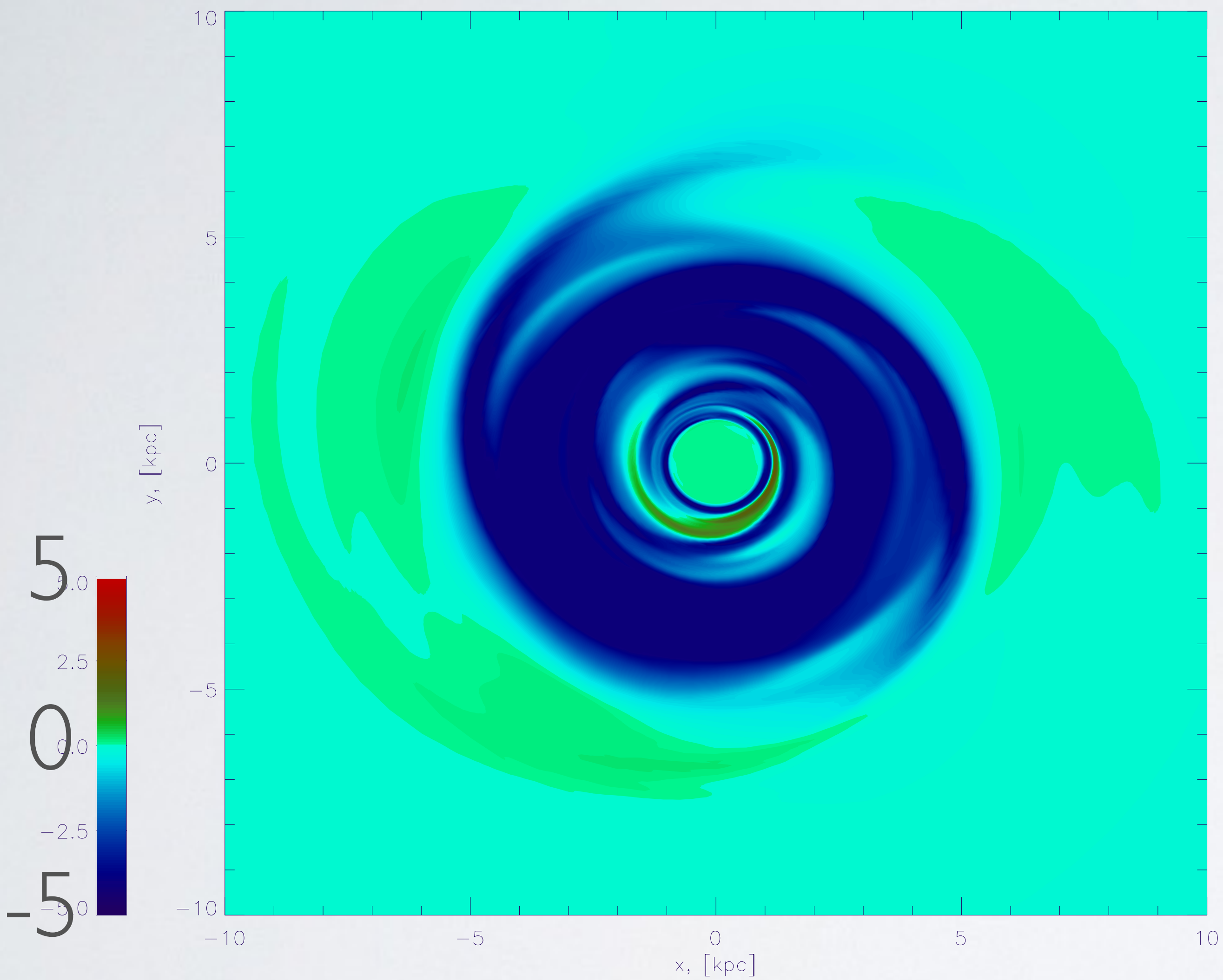
MRI-Parker dynamo



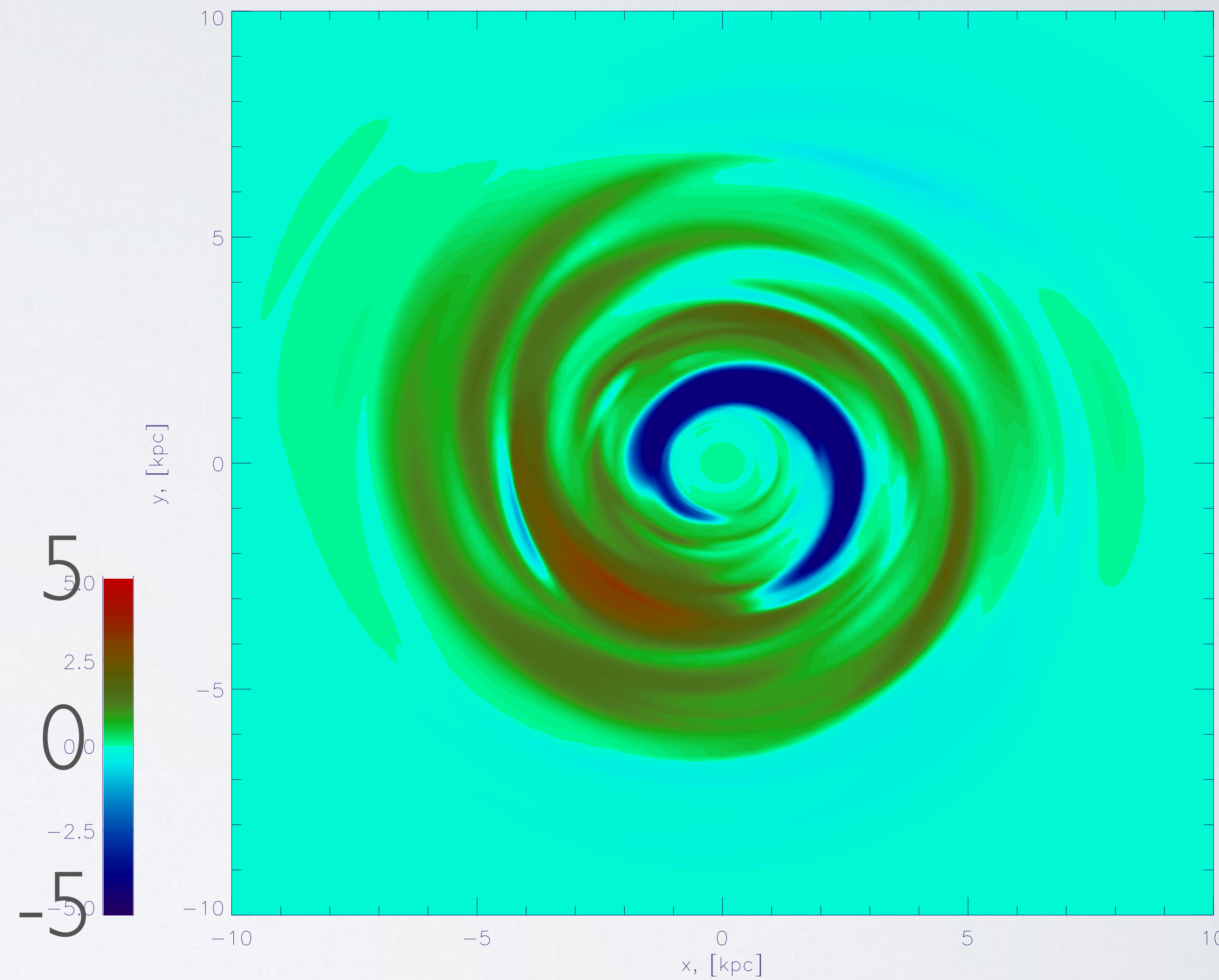
Nishikori+, 2006
Machida+, 2013

Results(t=800Myr)

$B_{\varphi}(z=0)$



$B_{\varphi}(z=0.3kpc)$

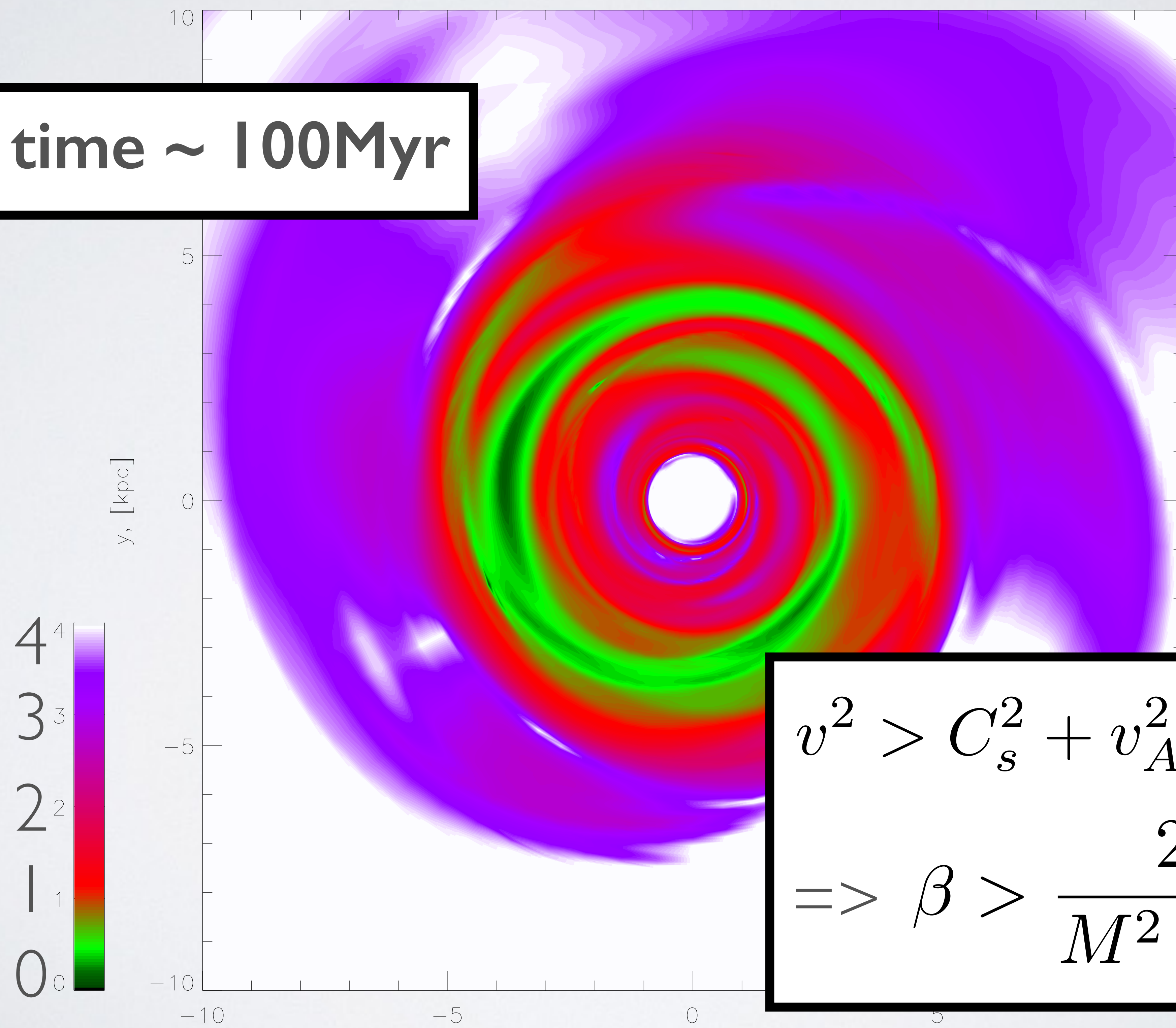


Results(t=800Myr)

plasma **β** @ z=0

Log(**β**)

e-folding time ~ 100Myr



$$v^2 > C_s^2 + v_A^2$$

$$\Rightarrow \ \beta > \frac{2}{M^2 - 1}$$ **~0.2**

Conclusion

Conclusion

1. We have shown that spiral arms rapidly amplify magnetic fields and escape magnetic fluxes from disc to halo.

Thank you
for your attention