3D global GRRMHD simulation to test stability of thin disk around black hole

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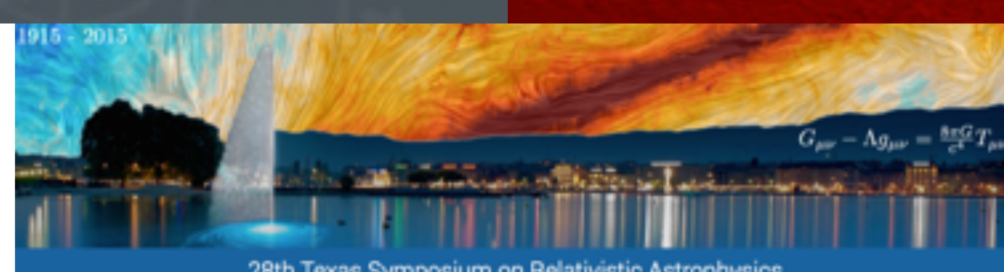
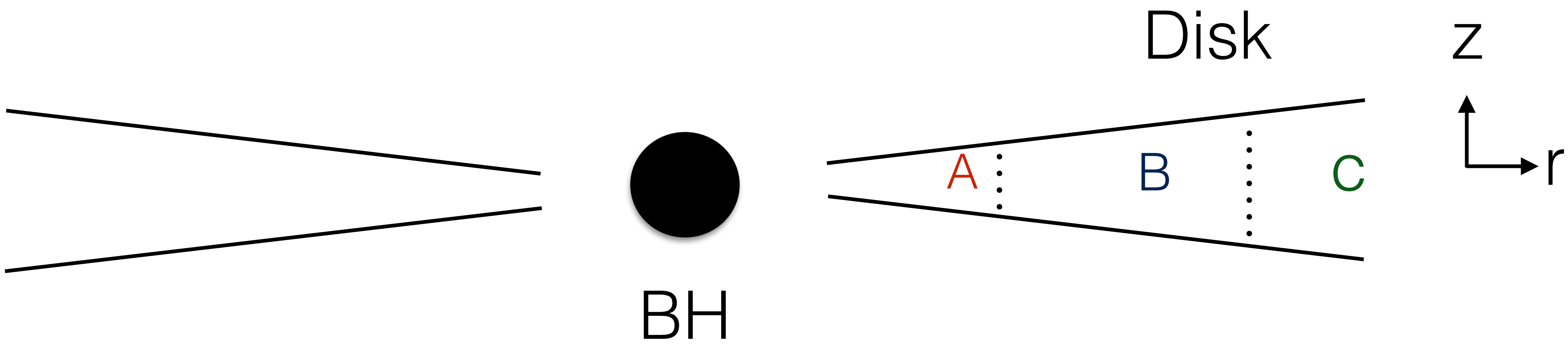


Thin disk



Region 'A' is radiation pressure dominated

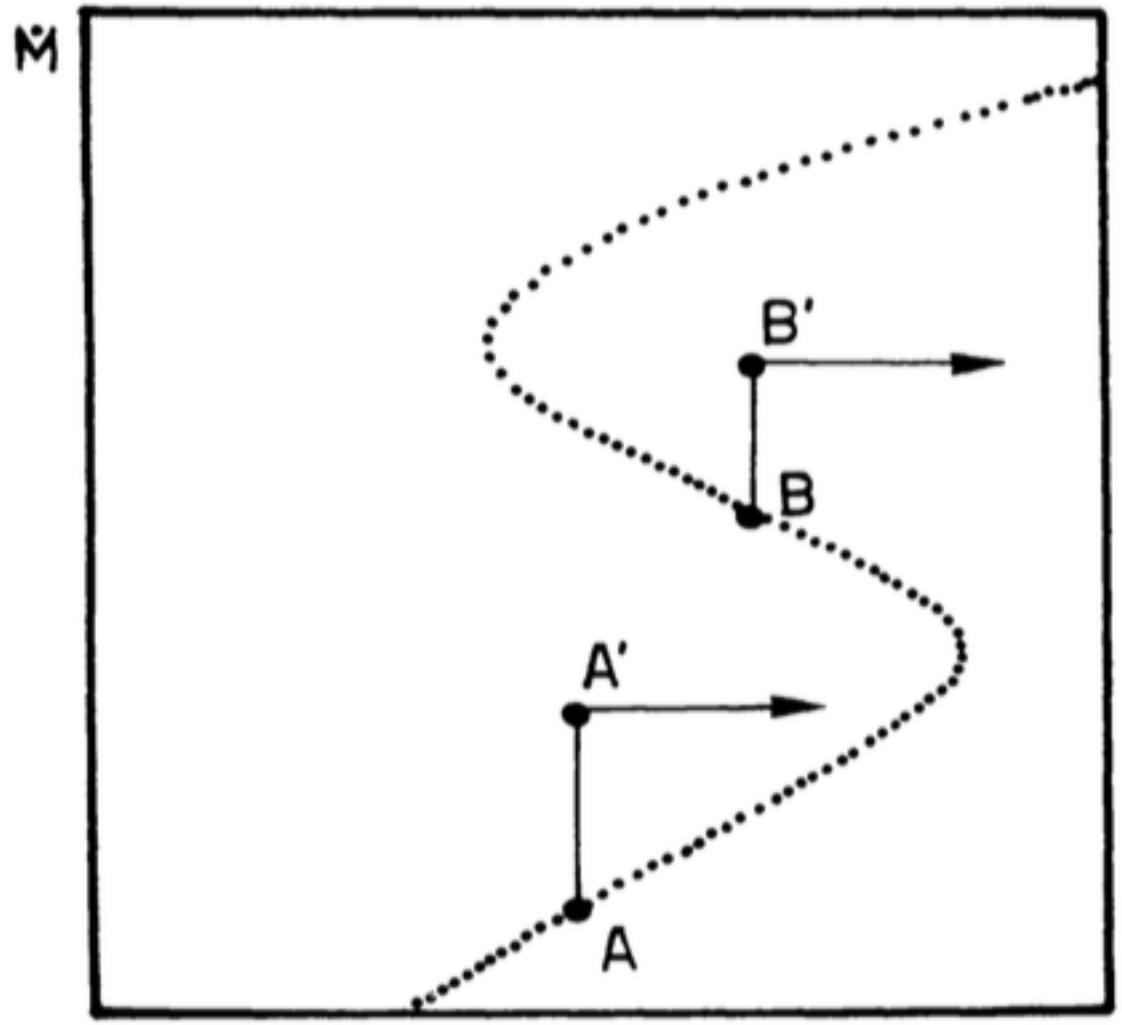
$$T_{r\phi} = \alpha \, P_t$$

Shakura and Sunyaev, 1973

Radiation pressure dominated disk is thermally unstable

Shakura and Sunyaev, 1976

S-curve



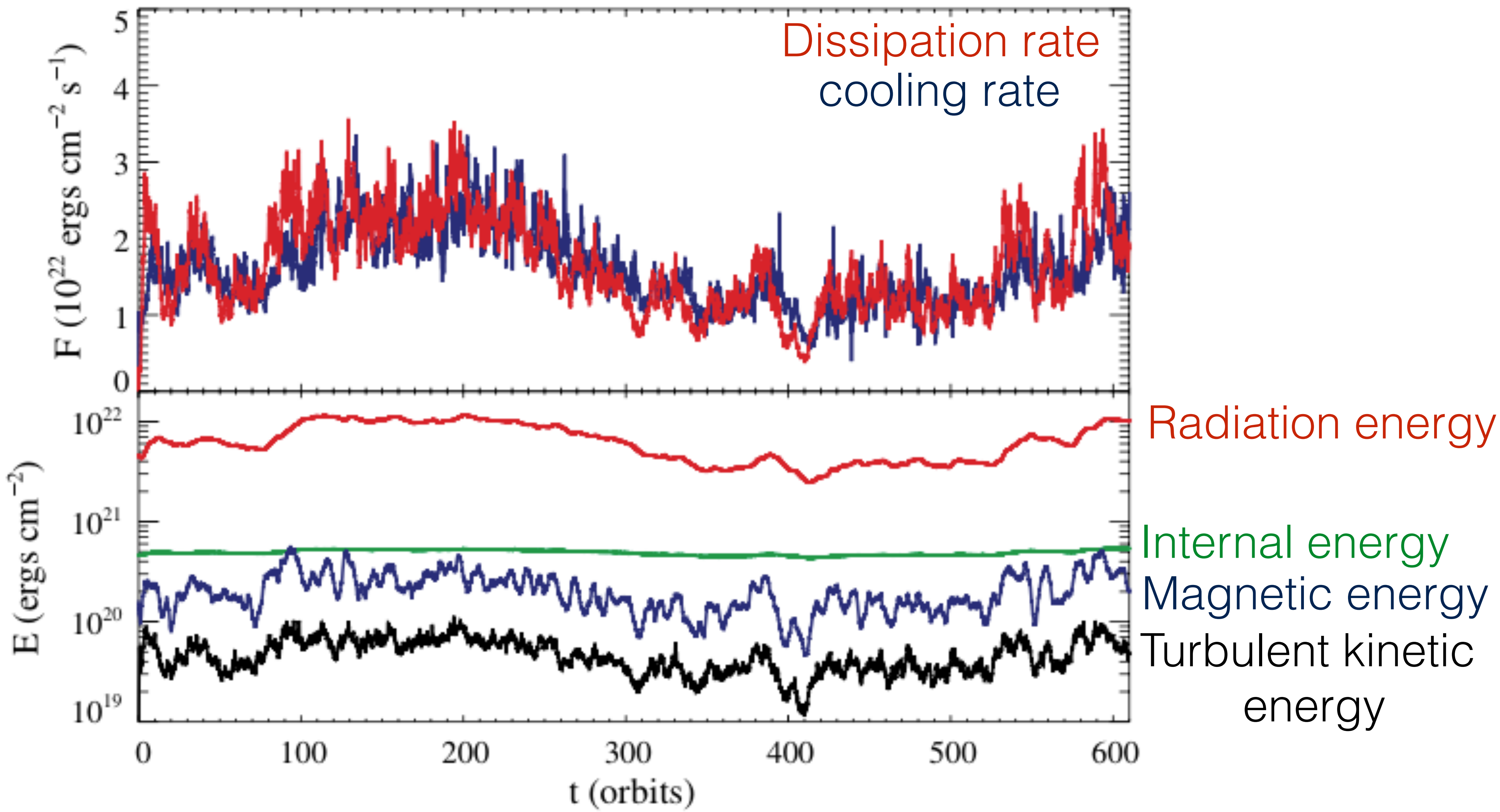
Σ (surface mass density)

Bath and Pringle, 1981

$$\left.\frac{\partial \ln Q^+}{\partial \ln P_t}\right|_\Sigma > \left.\frac{\partial \ln Q^-}{\partial \ln P_t}\right|_\Sigma$$

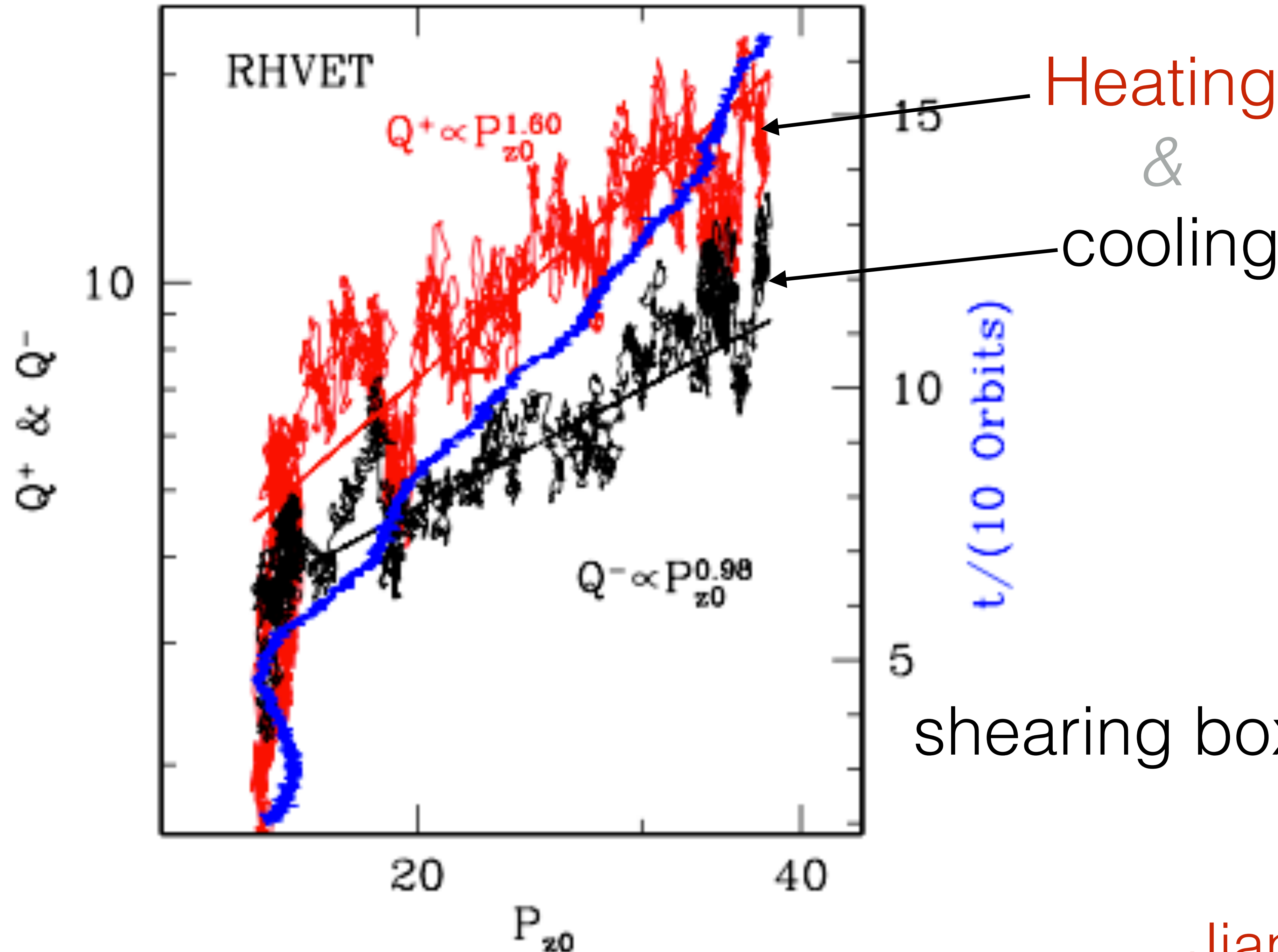
Piran, 1978

Thermal stability ?



Hirose et al 2009

Thermal instability



shearing box simulations

Jiang et al 2013

Global simulation setup

- Weakly magnetized thin disk (around non-rotating black hole)
- Opacity (absorption, scattering, thermal comptonization)
- M1 closure scheme *Sádowski et al 2013*
- Evolve GRRMHD equations

Global simulations

* Two resolutions with radiation pressure dominated disk

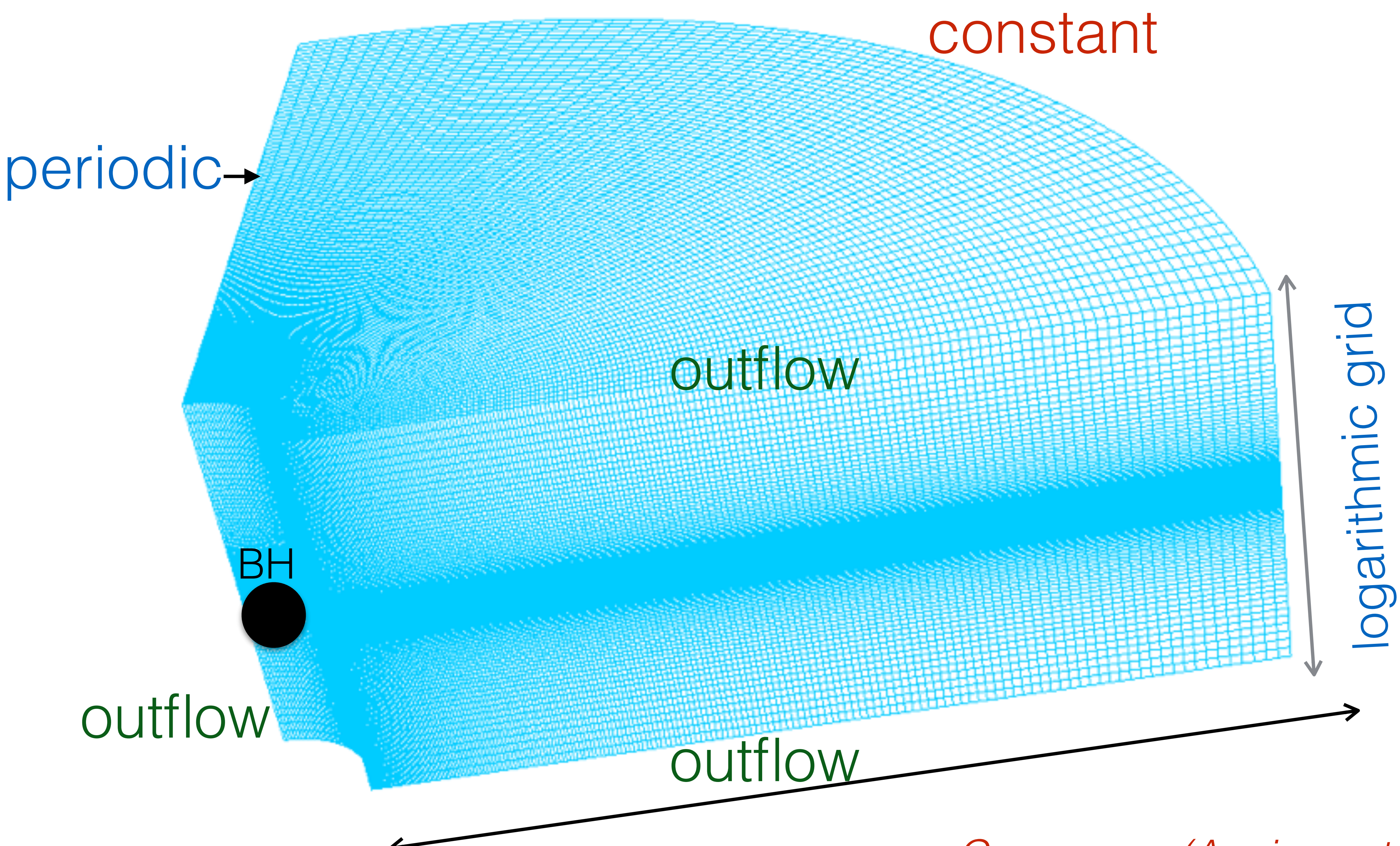
Mid plane density, $\rho_0 = 10^{-3}\mathrm{g\,cm}^{-3}$
RADPLR $(n_r, n_\phi, n_z) = (192 \times 32 \times 160)$
RADPHR $(n_r, n_\phi, n_z) = (192 \times 64 \times 160)$

Radiation pressure dominated disk $\longrightarrow$ Collapses

Mishra et al (in preparation)

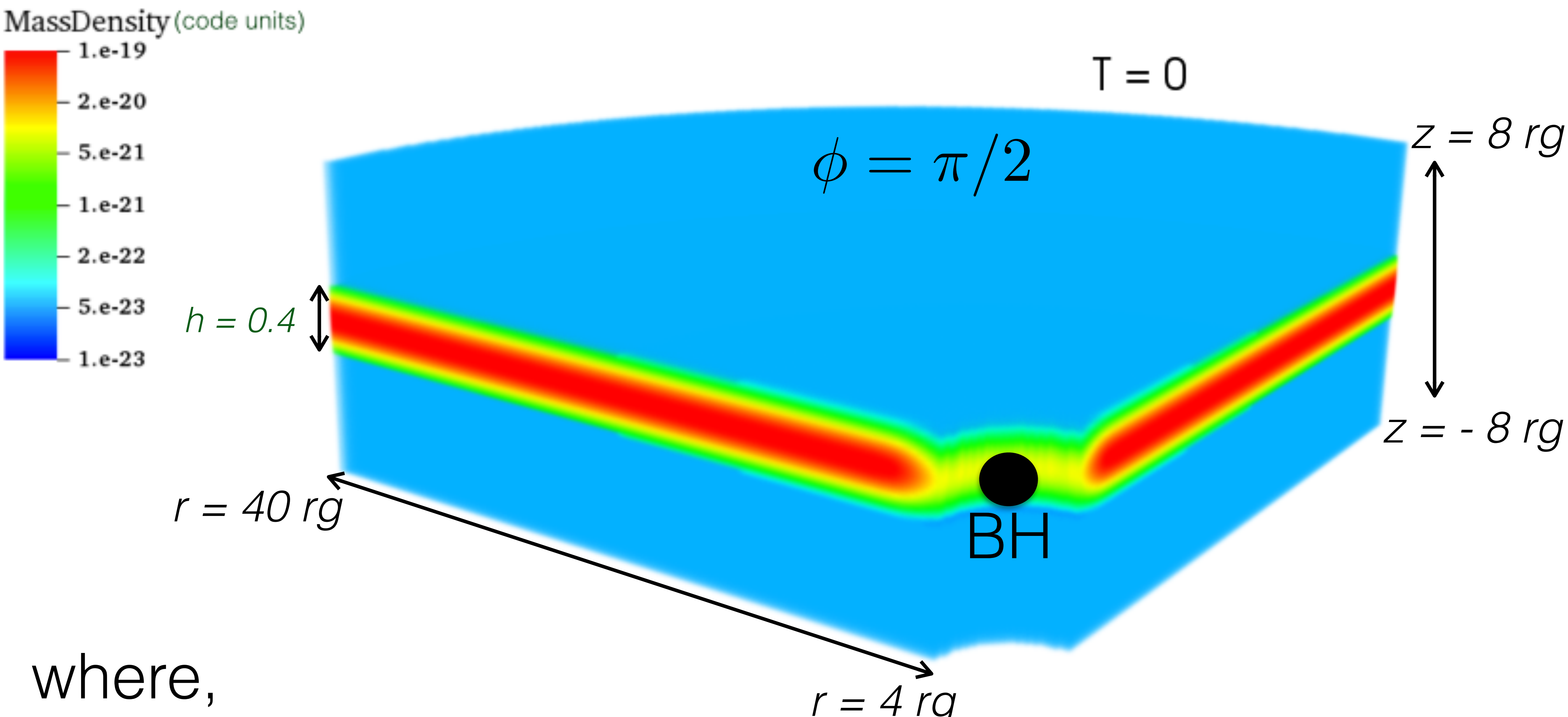
Grid and Boundary conditions

Cylindrical coordinate in KS metric



Cosmos++ (Anninos et al 2005)

Disk setup



where,

$$r_g = \frac{GM}{c^2}$$

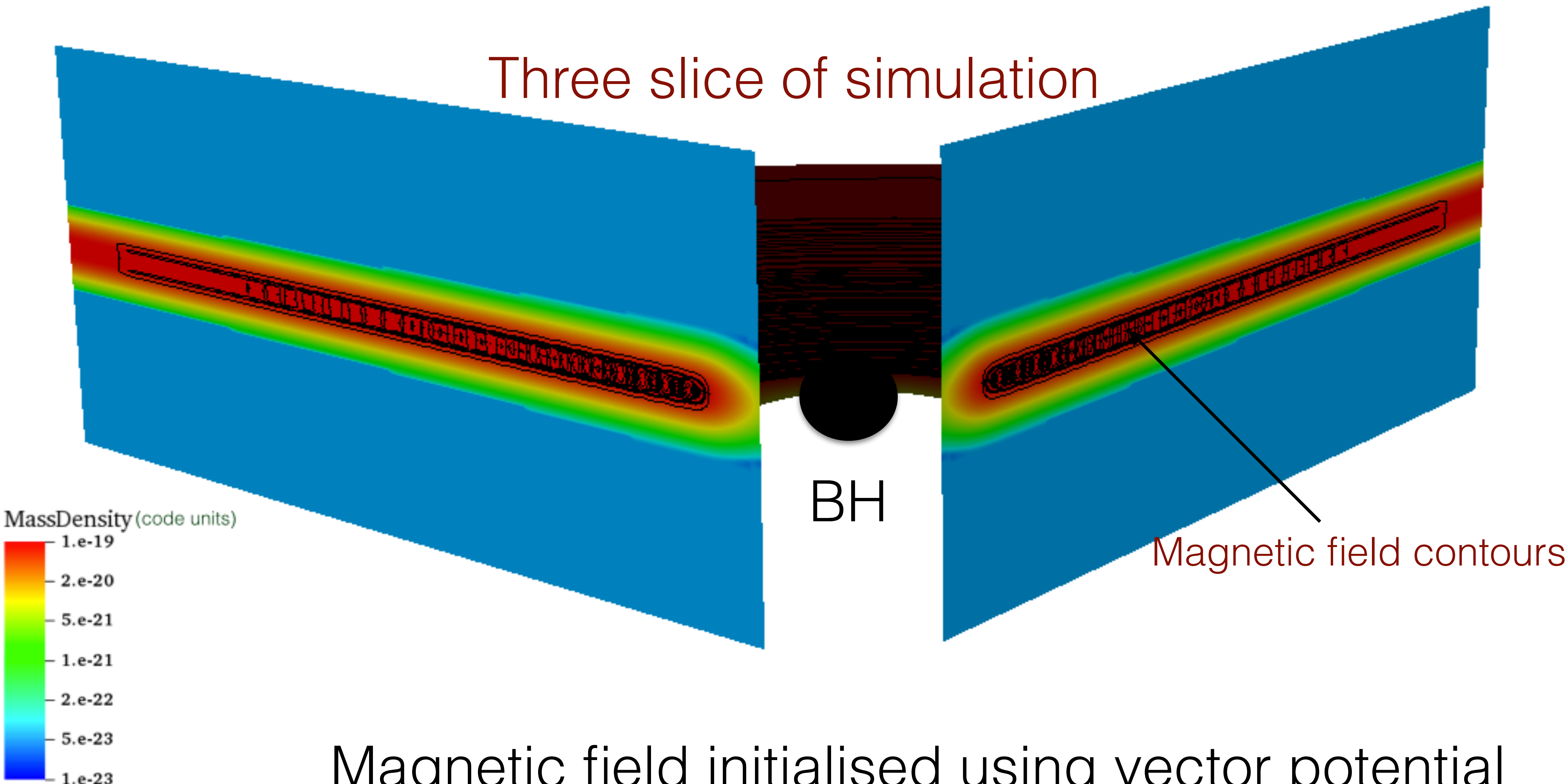
$$M_{\rm BH} = 6.67 M_\odot$$

$$\rho_0 = 10^{-3} \mathrm{g\,cm^{-3}}$$

$$\rho(r,z) = \frac{\rho_0 e^{-z^2/2h^2}\left(1 + e^{(r-r_o)/h^2}\right)}{1 + e^{(r_i - r)/h^2}}$$

Reynolds & Miller 2009

Magnetic field



Magnetic field initialised using vector potential
Constrained transport method to keep it divergence free

GRMHD+Radiation

$$T^{\alpha\beta} = \left(\rho + \rho\varepsilon + P_{\rm gas} + b^2\right) u^\alpha u^\beta + \left(P_{\rm gas} + P_b\right) g^{\alpha\beta} - b^\alpha b^\beta$$

$$R^{\alpha\beta} = E u^\alpha u^\beta + F^\alpha u^\beta + F^\beta u^\alpha + \frac{E}{3}\left(g^{\alpha\beta} + u^\alpha u^\beta\right)$$

The gas temperature has been calculated using LTE equation

$$P_{\rm tot} = p_{\rm gas} + p_{\rm rad} = \frac{k_b \rho T_{\rm gas}}{\mu} + \frac{1}{3} a_R T_{\rm gas}^4$$

$$E = a_R T_{gas}^4$$

$$R^{\alpha\beta} = \frac{4}{3} E_R u_R^\alpha u_R^\beta + \frac{1}{3} E_R g^{\alpha\beta}$$

GRMHD+Radiation

Hybrid explicit-implicit scheme

↓

1. Explicit HRSC method to update set of conserved variables

↓

2. Implicit scheme to complete update accounting radiation source terms

↓

$$A\,x = b$$

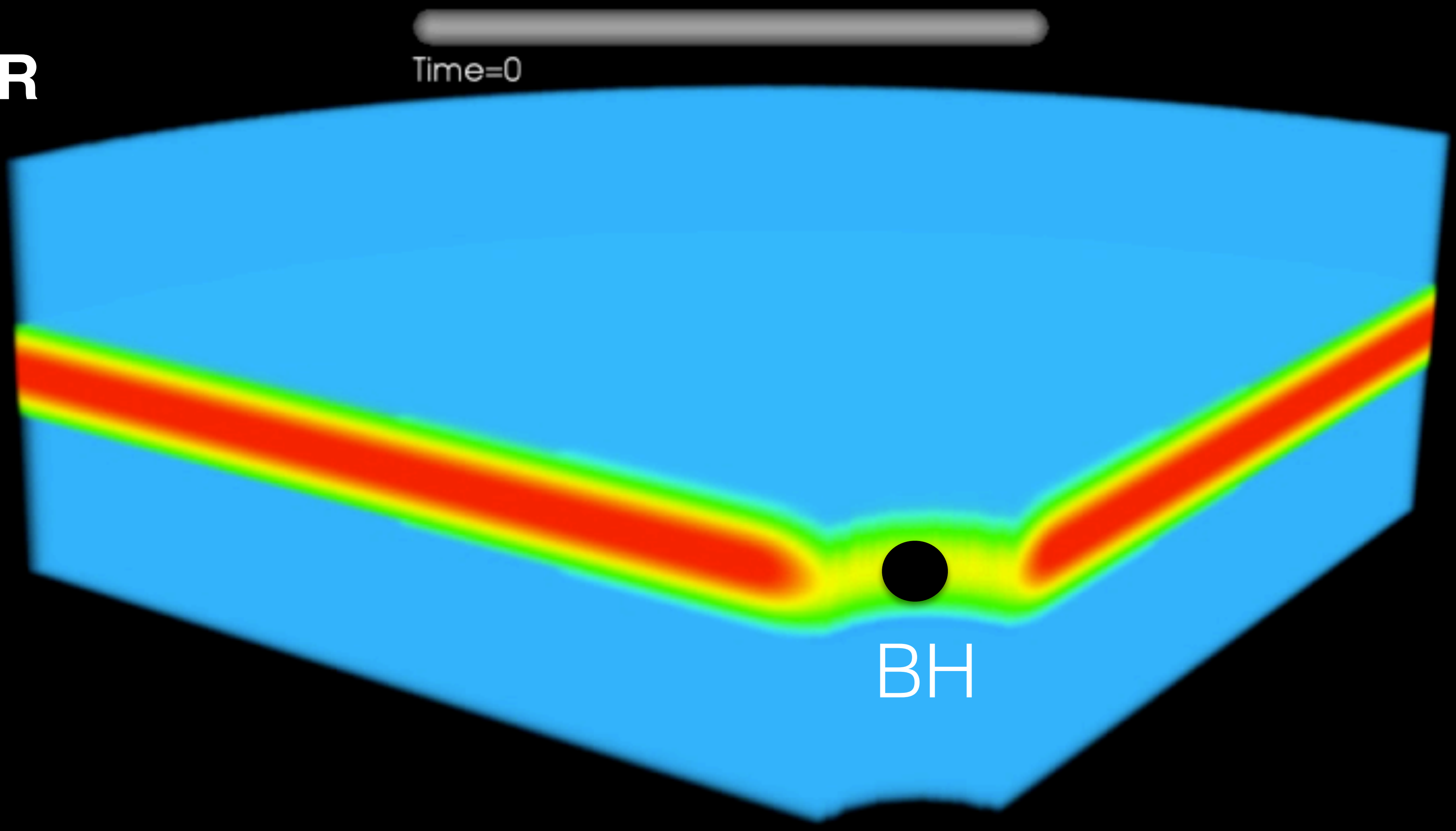
(equations for set of primitive fields)

A is a 12x12 matrix

'*x*' and '*b*' are 12-dimensional vectors

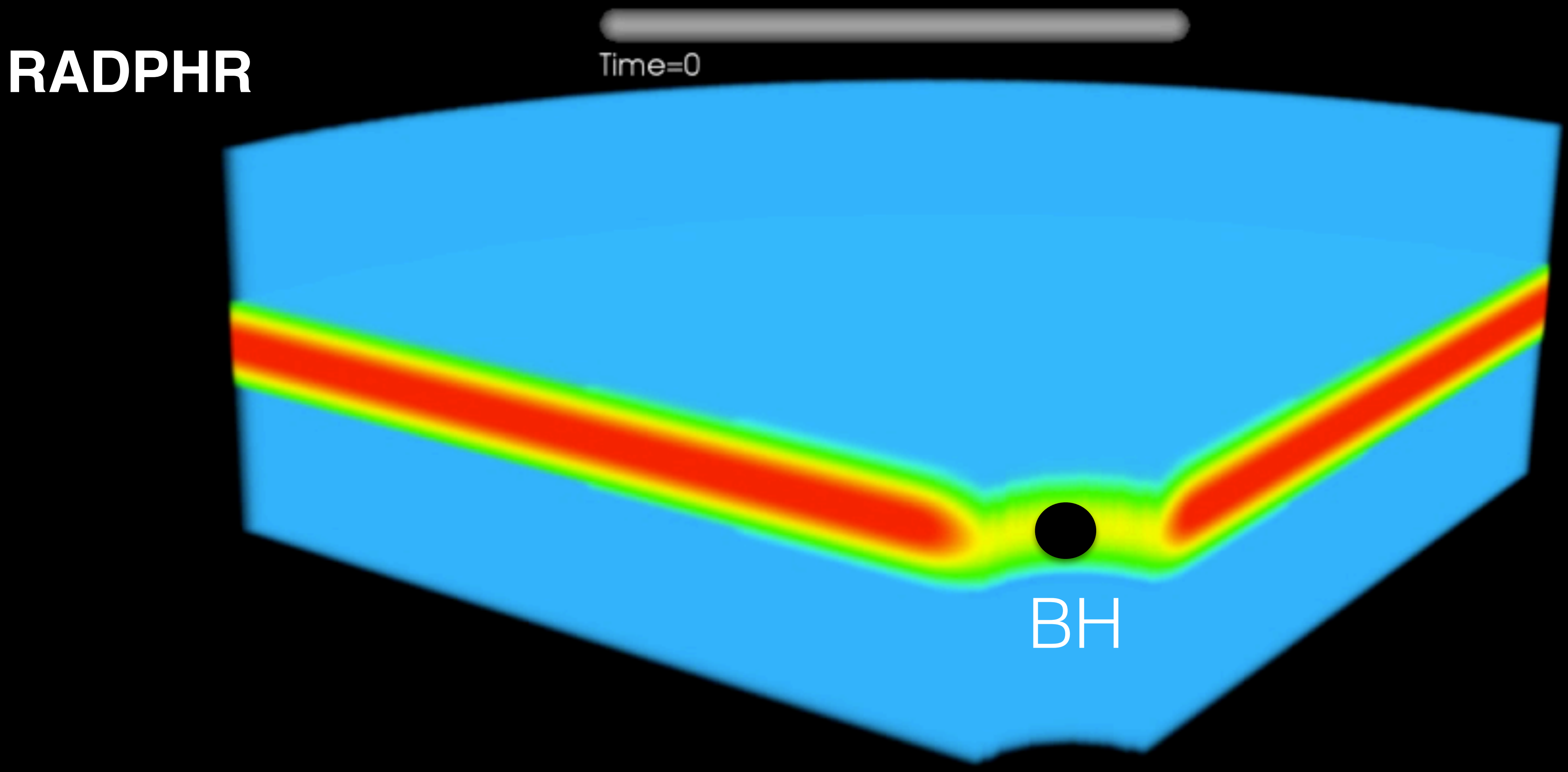
Unstable disk

RADPHR



Radiation pressure dominated simulation

Unstable disk



Radiation pressure dominated simulation

Collapsing disk

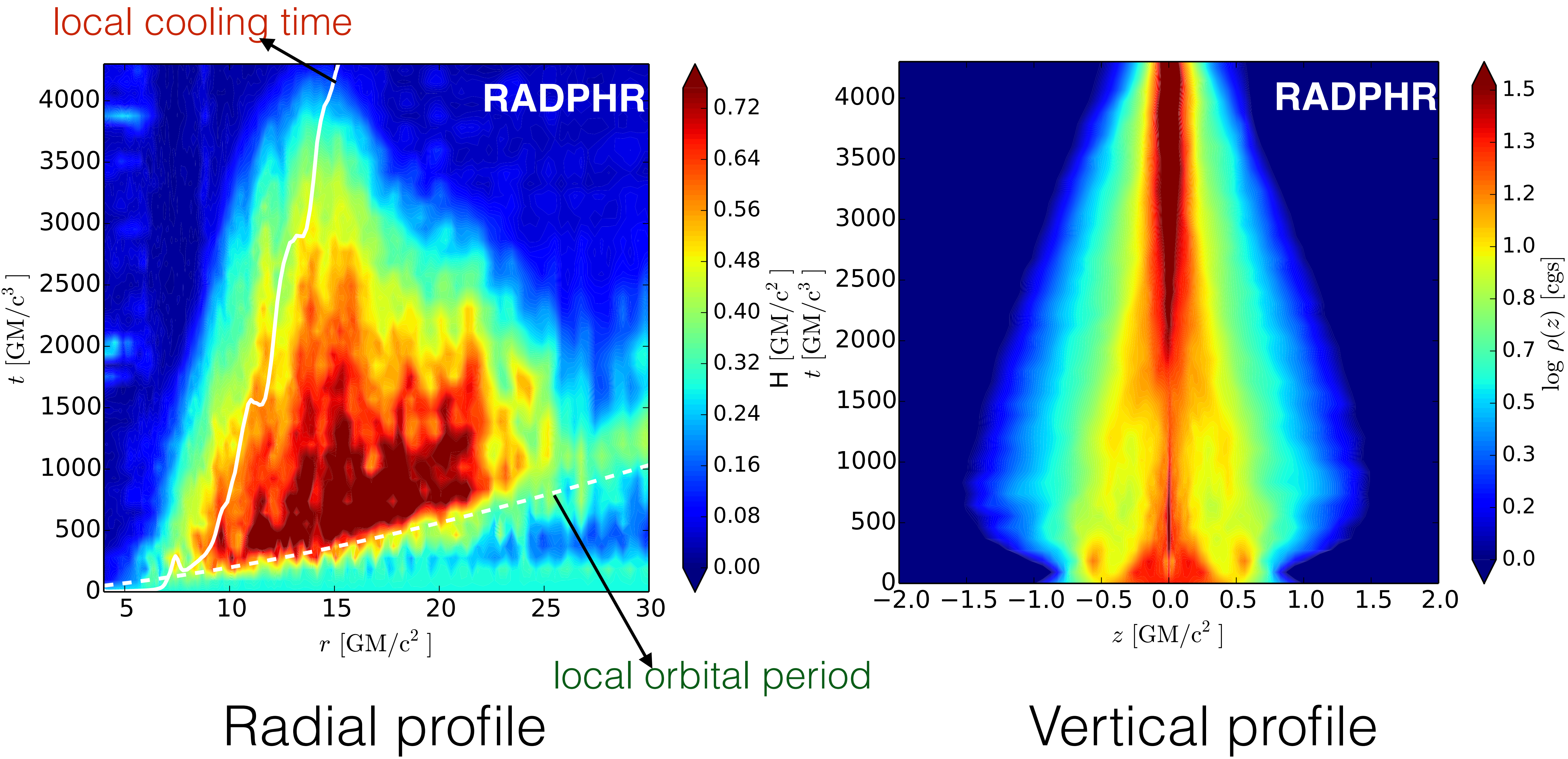
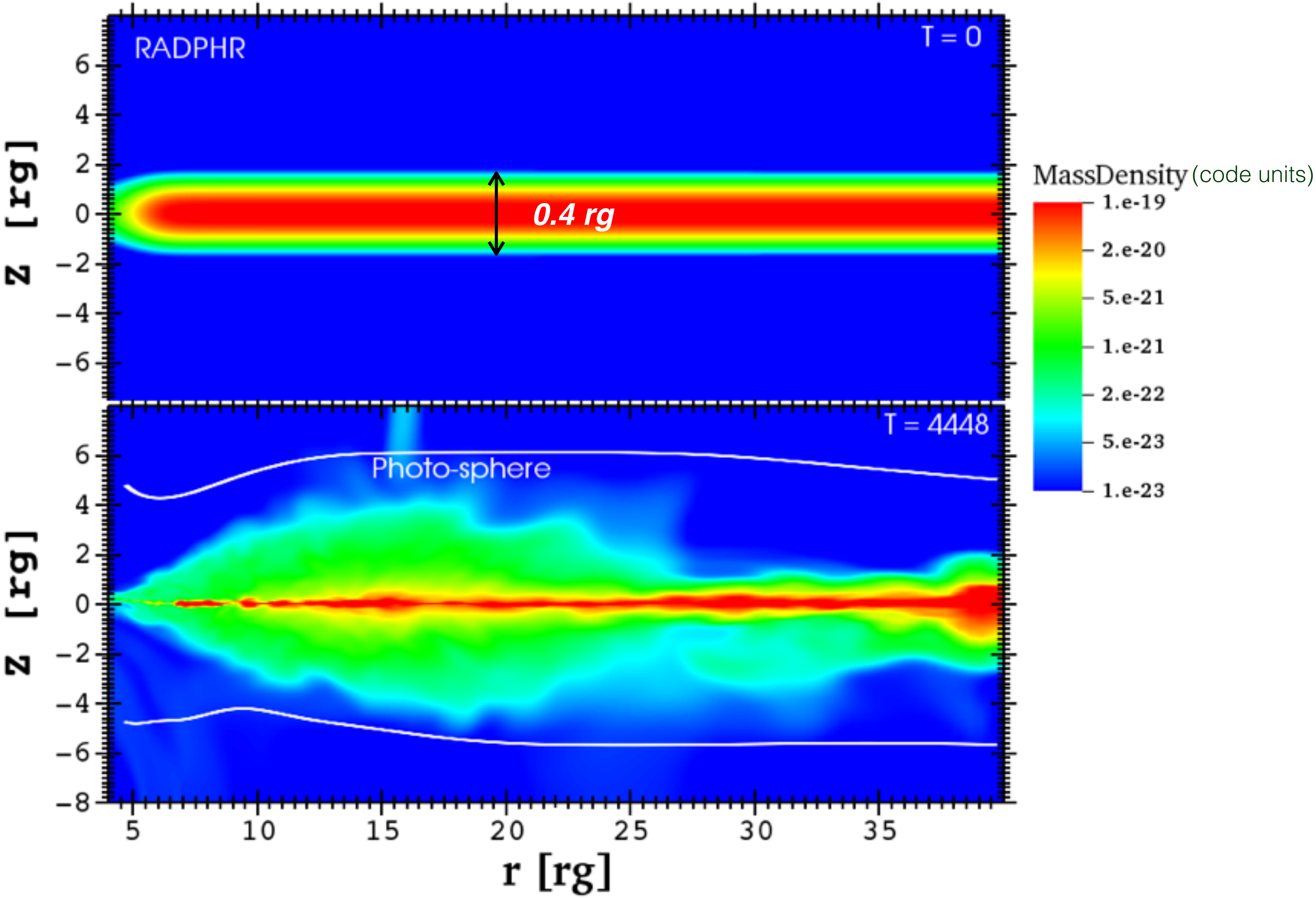
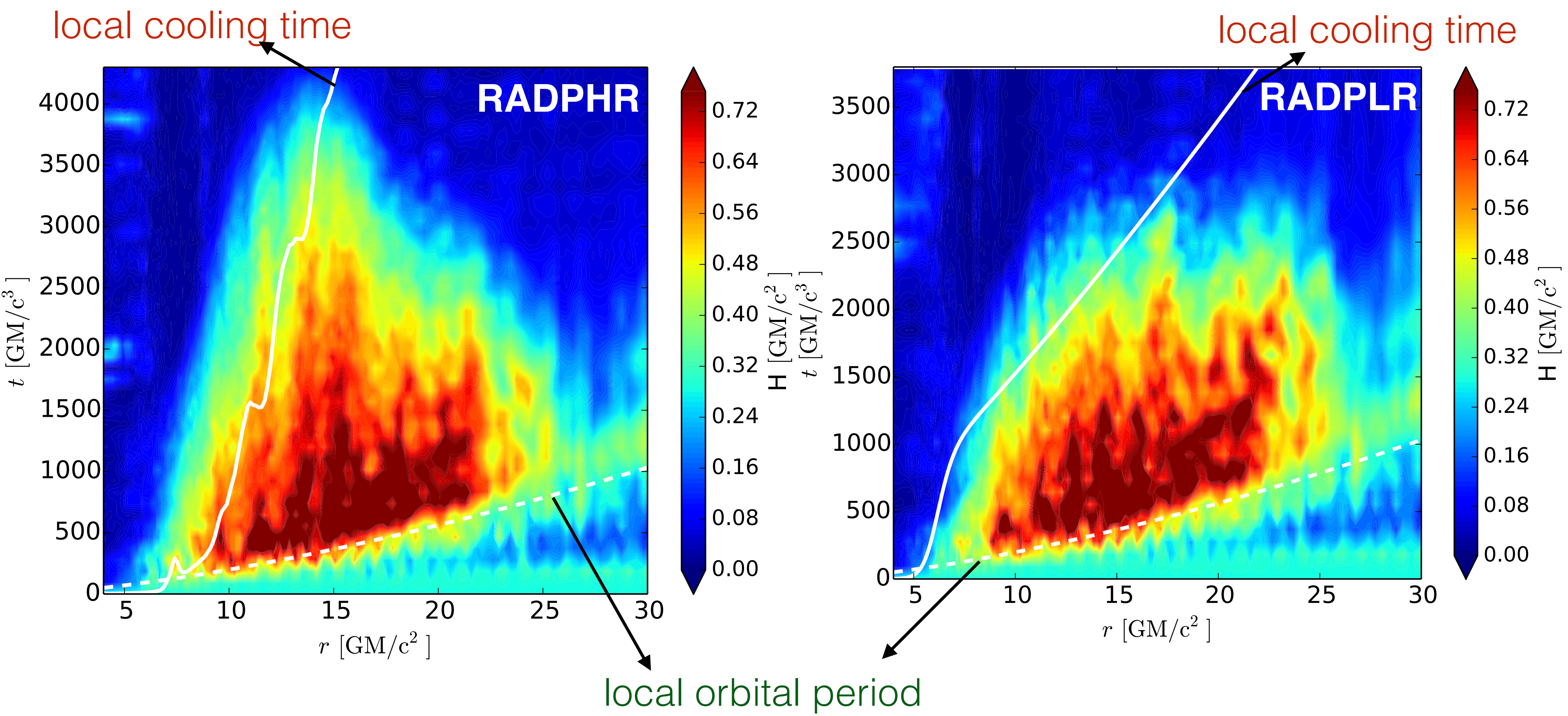


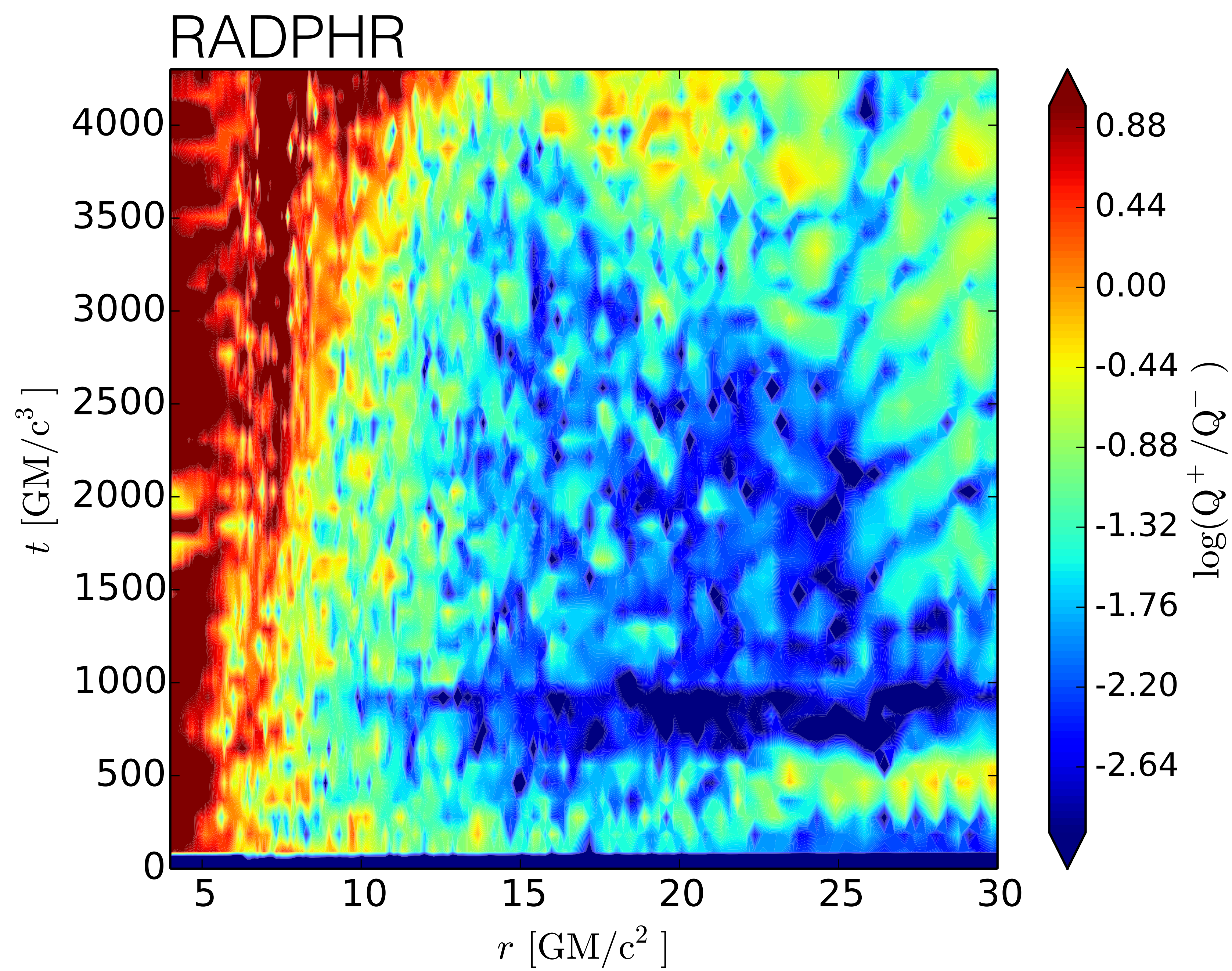
Photo-sphere



RADPHR *vs* RADPLR

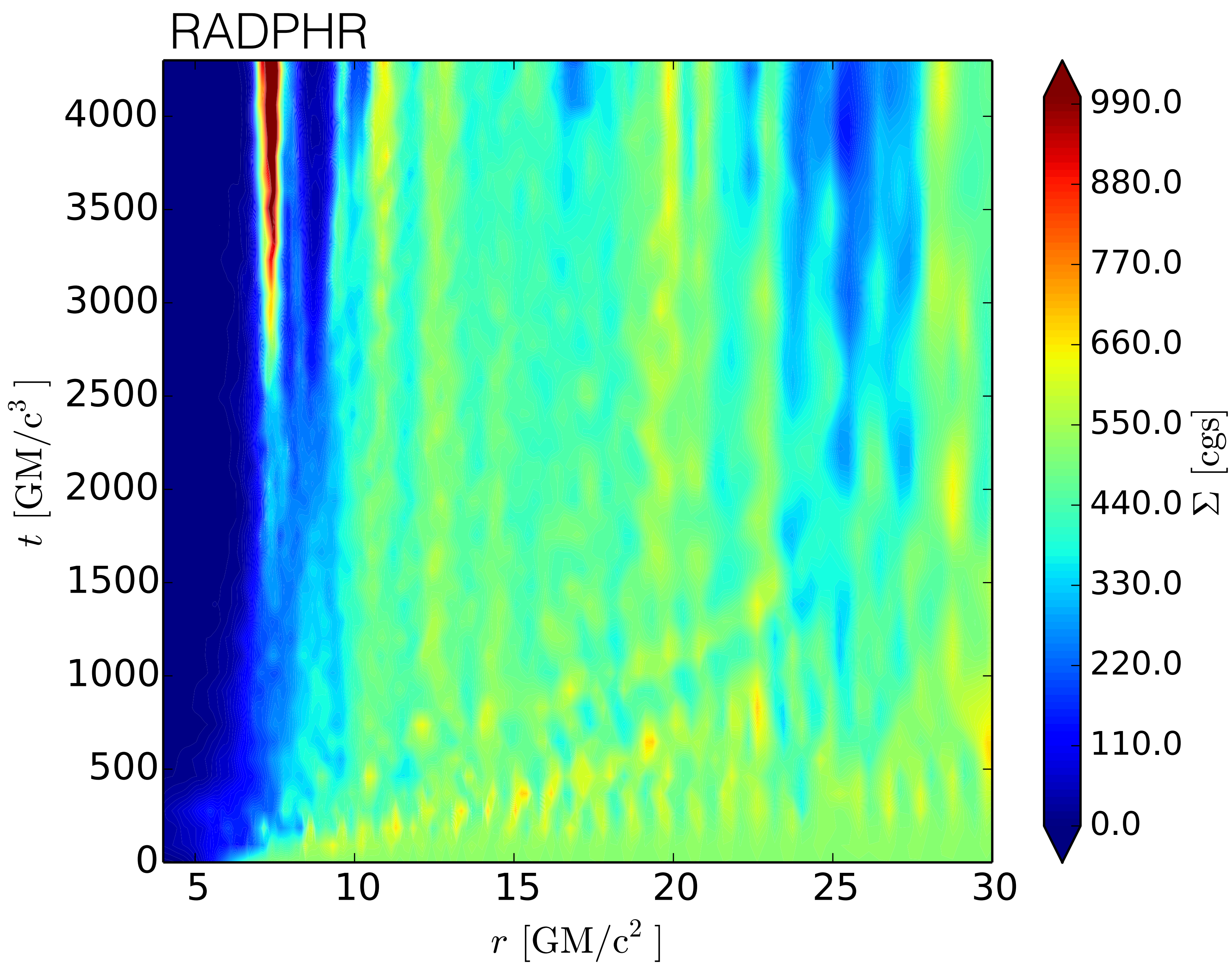


Heating *vs* cooling



Cooling dominates over heating

Surface density



Collapse is not due to significant mass loss from disk

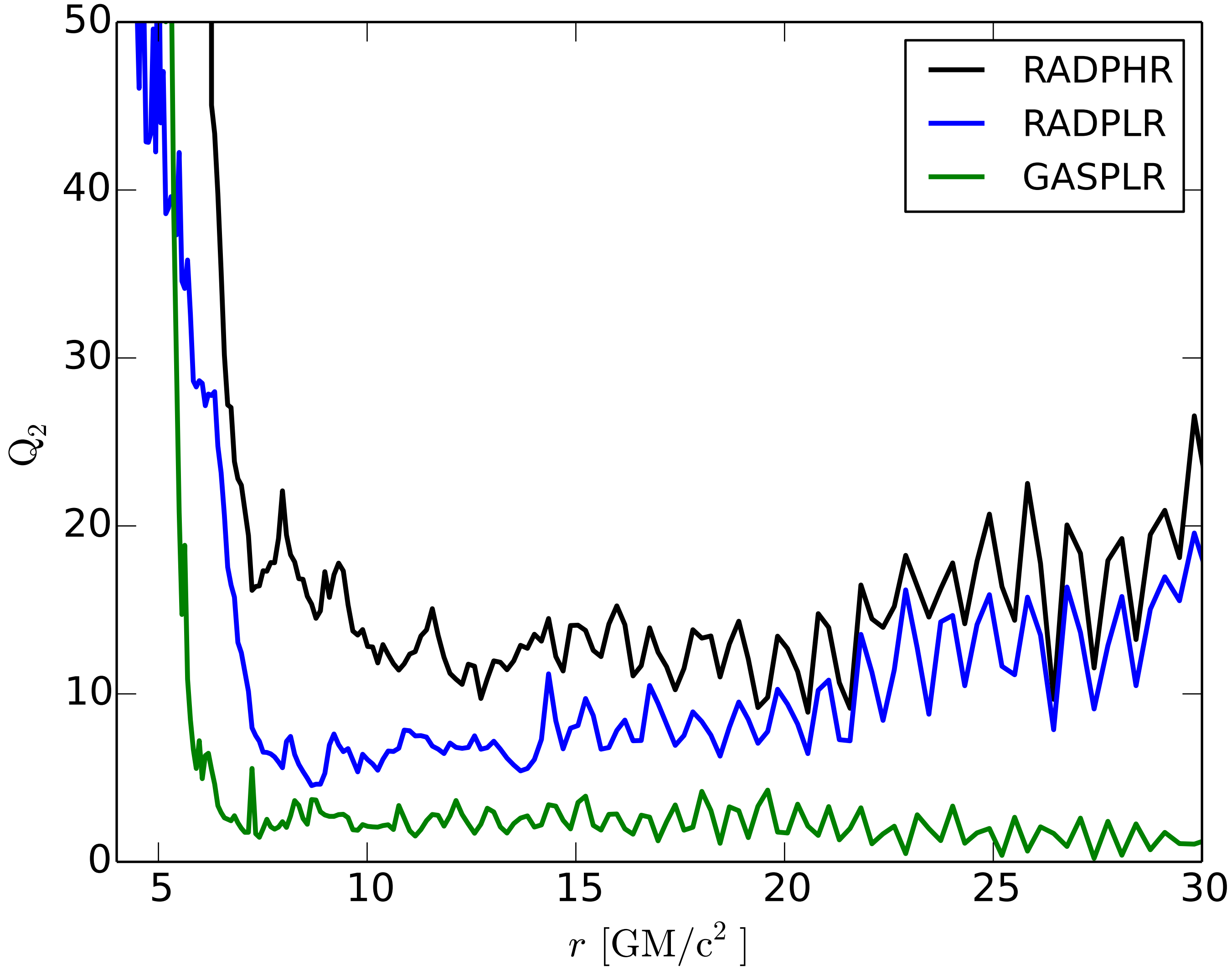
Conclusion

- Radiation pressure dominated geometrically thin and optically thick disks are thermally unstable

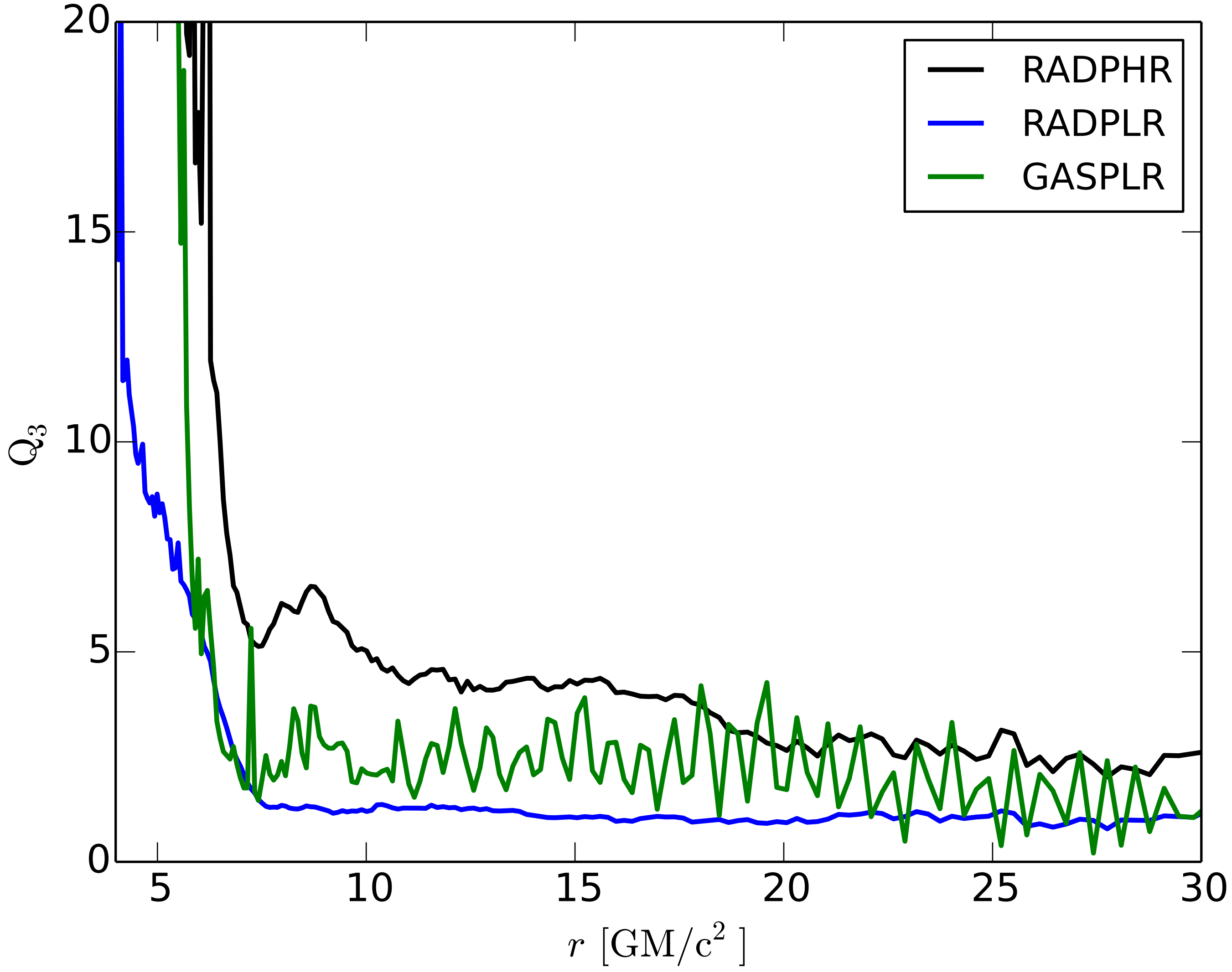
Merci !

Merci !

MRI Q values



Vertical



Azimuthal

GR Radiative MHD Equations

$$g_{\mu\nu} R^{t\mu} R^{t\nu} = -\frac{8}{9} E_R^2 \left(u_R^t\right)^2 + \frac{1}{9} E_R^2 g^{tt}$$

$$R^{tt} = \frac{4}{3} E_R \left(u_R^t\right)^2 + \frac{1}{3} E_R g^{tt}$$

Radiation energy density in radiation rest frame

Four velocity of radiation rest frame

The radiation and fluid four velocity are projected into the space of normal observer

GR Radiative MHD Equations

$$G^{\mu} = -\rho\left(\kappa_R^{\mathrm{a}} + \kappa^{\mathrm{s}}\right) R^{\mu\nu} u_{\nu} - \rho \left\{ \left[\kappa^{\mathrm{s}} + 4\kappa^{\mathrm{s}} \left(\frac{T_{\mathrm{gas}} - T_{\mathrm{rad}}}{m_e} \right) + \kappa_R^{\mathrm{a}} - \kappa_{\mathrm{J}}^{\mathrm{a}} \right] R^{\alpha\beta} u_{\alpha} u_{\beta} + \kappa_{\mathrm{P}}^{\mathrm{a}} a_R T_{\mathrm{gas}}^4 \right\} u^{\mu}$$

$$\partial_t D + \partial_i (D V^i) = 0$$

$$\partial_t \mathcal{E} + \partial_i \left(-\sqrt{-g}\; T^i_t \right) = -\sqrt{-g}\; T^{\alpha}_{\beta}\; \Gamma^{\beta}_{t\alpha} - \sqrt{-g}\; G_t$$

$$\partial_t \mathcal{S}_j + \partial_i \left(\sqrt{-g}\; T^i_j \right) = \sqrt{-g}\; T^{\alpha}_{\beta}\; \Gamma^{\beta}_{j\alpha} + \sqrt{-g}\; G_j$$

$$\partial_t \mathcal{R} + \partial_i \left(\sqrt{-g}\; R^i_t \right) = \sqrt{-g}\; R^{\alpha}_{\beta}\; \Gamma^{\beta}_{t\alpha} - \sqrt{-g}\; G_t$$

$$\partial_t \mathcal{R}_j + \partial_i \left(\sqrt{-g}\; R^i_j \right) = \sqrt{-g}\; R^{\alpha}_{\beta}\; \Gamma^{\beta}_{j\alpha} - \sqrt{-g}\; G_j$$

$$\partial_t \mathcal{B}^j + \partial_i (\mathcal{B}^j V^i - \mathcal{B}^i V^j) = 0$$

vector potential

$$A_\phi = \frac{\sqrt{P_{\rm gas}}\sin\left(\frac{2\pi r_{\rm cyl}}{5h}\right)}{1+e^\Delta}\ ,$$

where

$$\Delta = 10\left\{\frac{z^2}{h^2}+\left(\frac{h}{R-r_{\rm ms}}\right)^2+-1\right\}\ ,$$