Thermal instability in 3D GRRMHD simulations of thin disks

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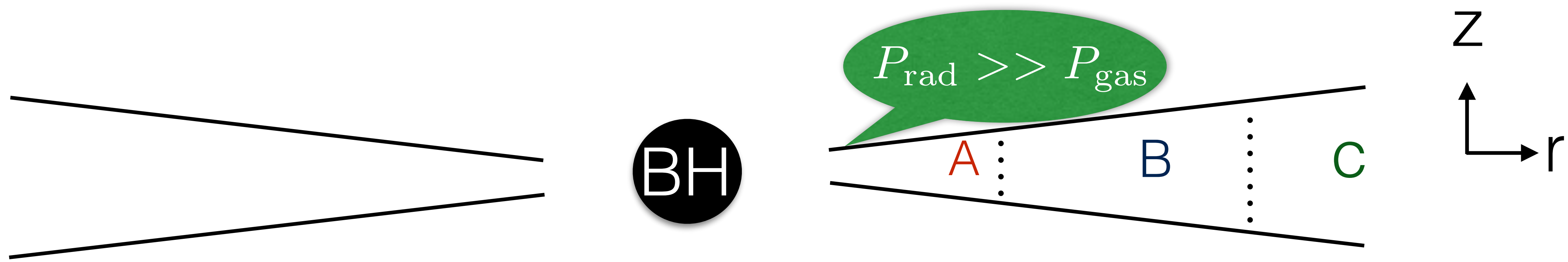
Geometrically thin disk

$H/r << 1 \longrightarrow$ challenging to simulate



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

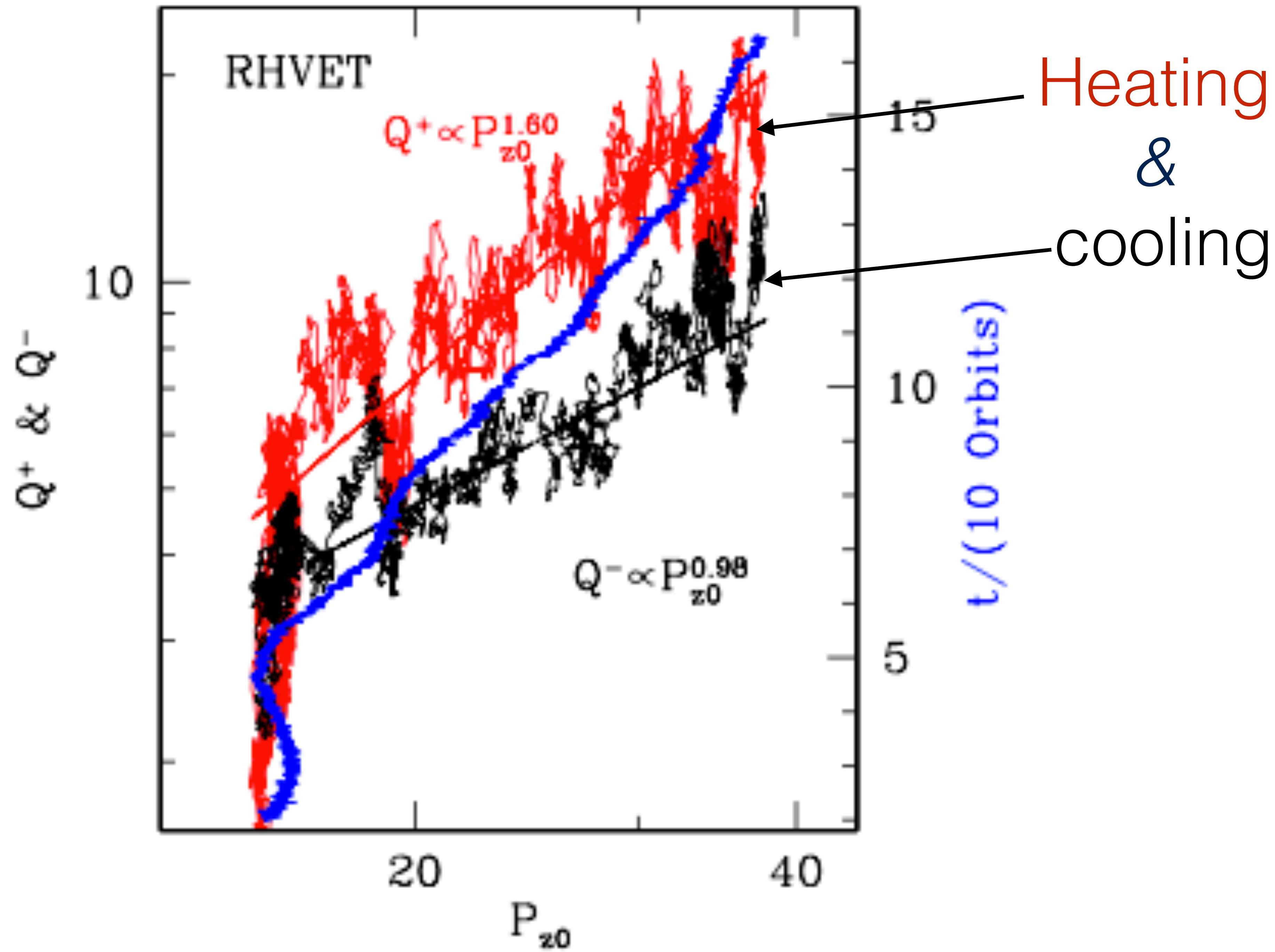
Shakura and Sunyaev, 1973

Hirose et al 2009

Radiation pressure dominated thin disk is thermally unstable

Shakura and Sunyaev, 1976, Piran 1978

Thermal instability



shearing box simulations *Jiang et al 2013*

Global disk setups

Radiation pressure dominated (RADP) $P_{\rm rad} >> P_{\rm gas}$

Gas pressure dominated (GASP) $P_{\rm rad} << P_{\rm gas}$

RADP → $\rho_0 = 10^{-3} {\rm g\,cm^{-3}}$

GASP → $\rho_0 = 10^{-6} {\rm g\,cm^{-3}}$

RADPLR $(n_r, n_\phi, n_z) = (192 \times 32 \times 160)$

RADPHR $(n_r, n_\phi, n_z) = (192 \times 64 \times 160)$

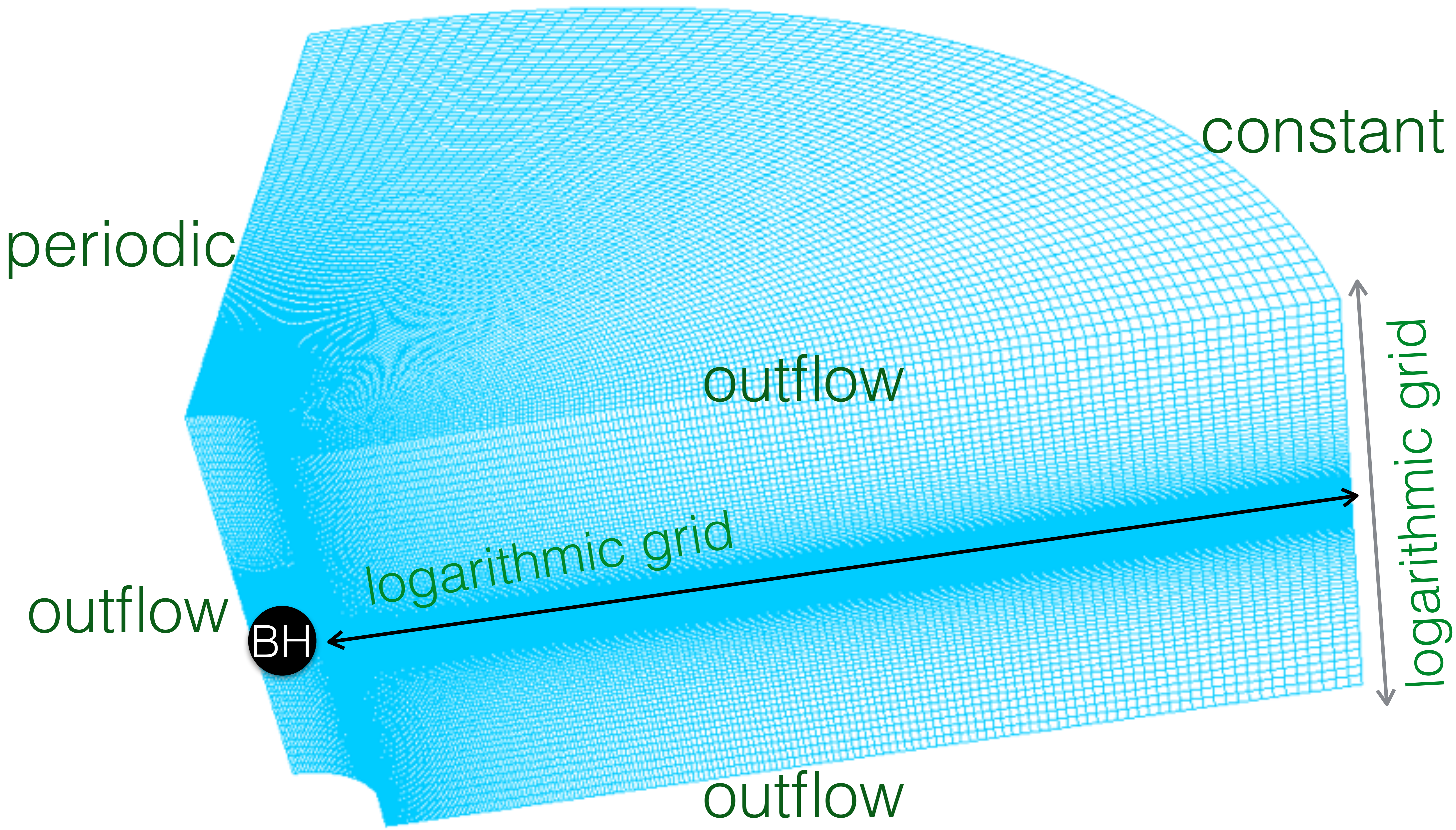
GASPLR $(n_r, n_\phi, n_z) = (192 \times 32 \times 160)$

GASPHR $(n_r, n_\phi, n_z) = (192 \times 64 \times 160)$

Radiation pressure dominated disk ⟶ Collapses

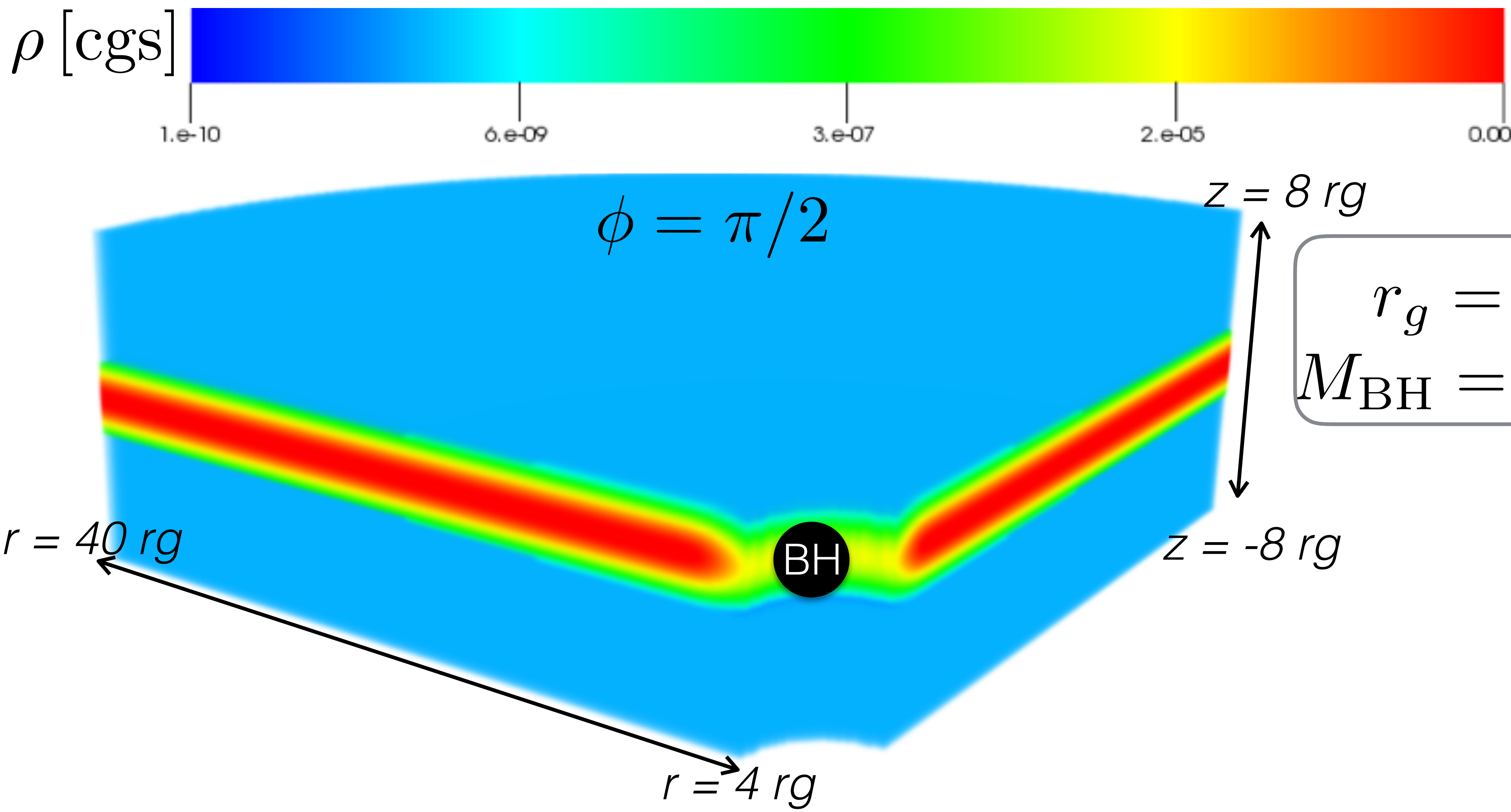
Mishra et al 16

Grid and Boundary conditions



Cosmos++ (Anninos et al 2005)

RADP setup



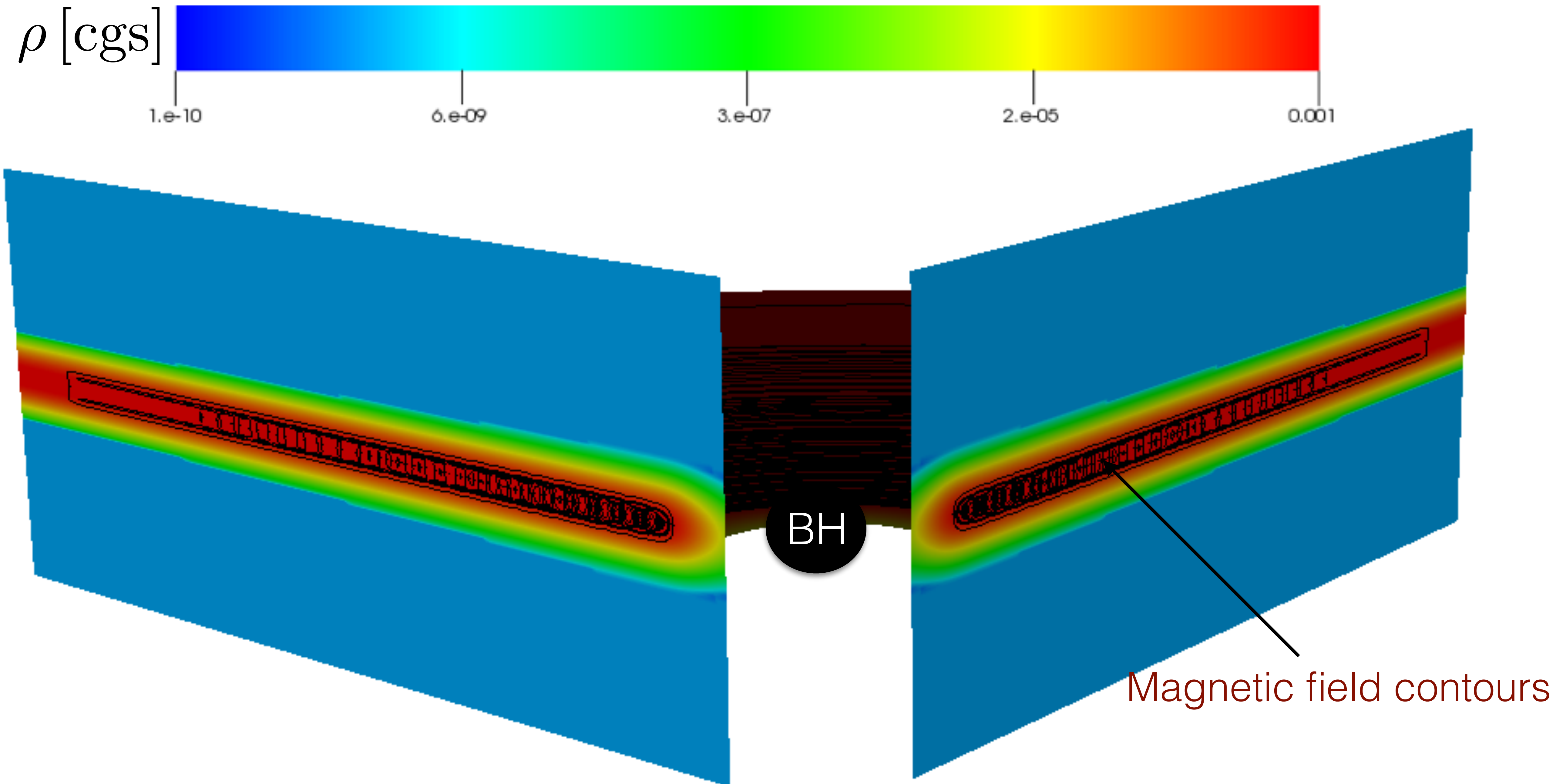
$$\phi = \pi/2$$

$$r_g = GM_{\rm BH}/c^2$$
$$M_{\rm BH} = 6.62 M_\odot$$

$$\rho(r,z) = \frac{\rho_0 e^{-z^2/2h^2}(1 + e^{(r-r_o)/h^2})}{1 + e^{(r_i - r)/h^2}}, \quad \rho_0 = 10^{-3} \mathrm{g\,cm}^{-3}$$

Reynolds & Miller 2009

Magnetic field



$$\beta = \frac{P_{\rm gas}}{P_{\rm mag}}$$

$$\beta = 10$$

Closure scheme

- M1 closure scheme
- Radiation rest frame: Radiation flux vanishes
- Satisfying Eddington approximation in radiation rest frame

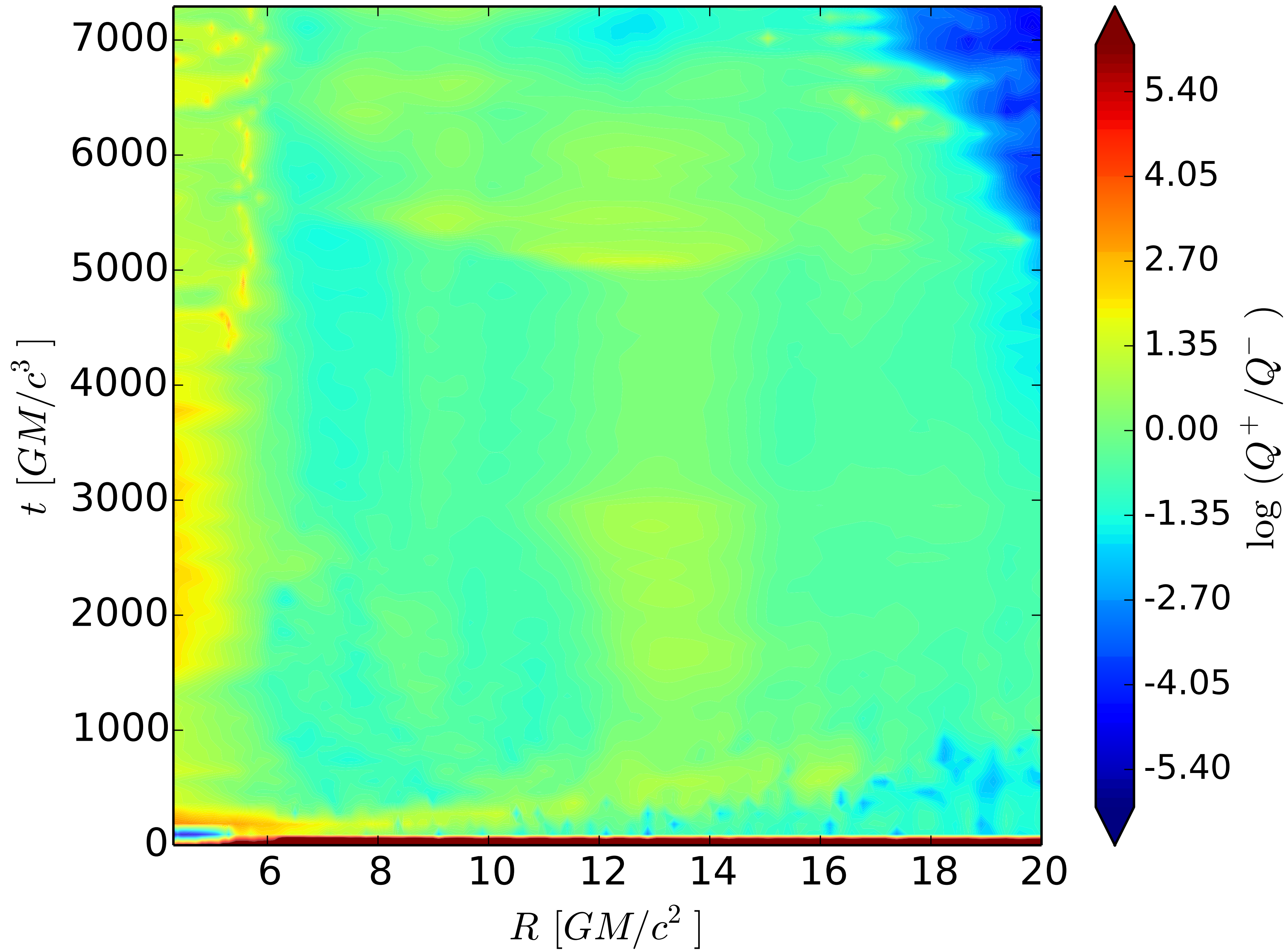
Sądowski et al 14

Opacity

- Electron scattering
- Absorption (Rosseland mean opacity)
- Thermal Comptonization (without relativistic corrections)

Gas pressure dominated disk

Heating vs cooling (GASPLR)

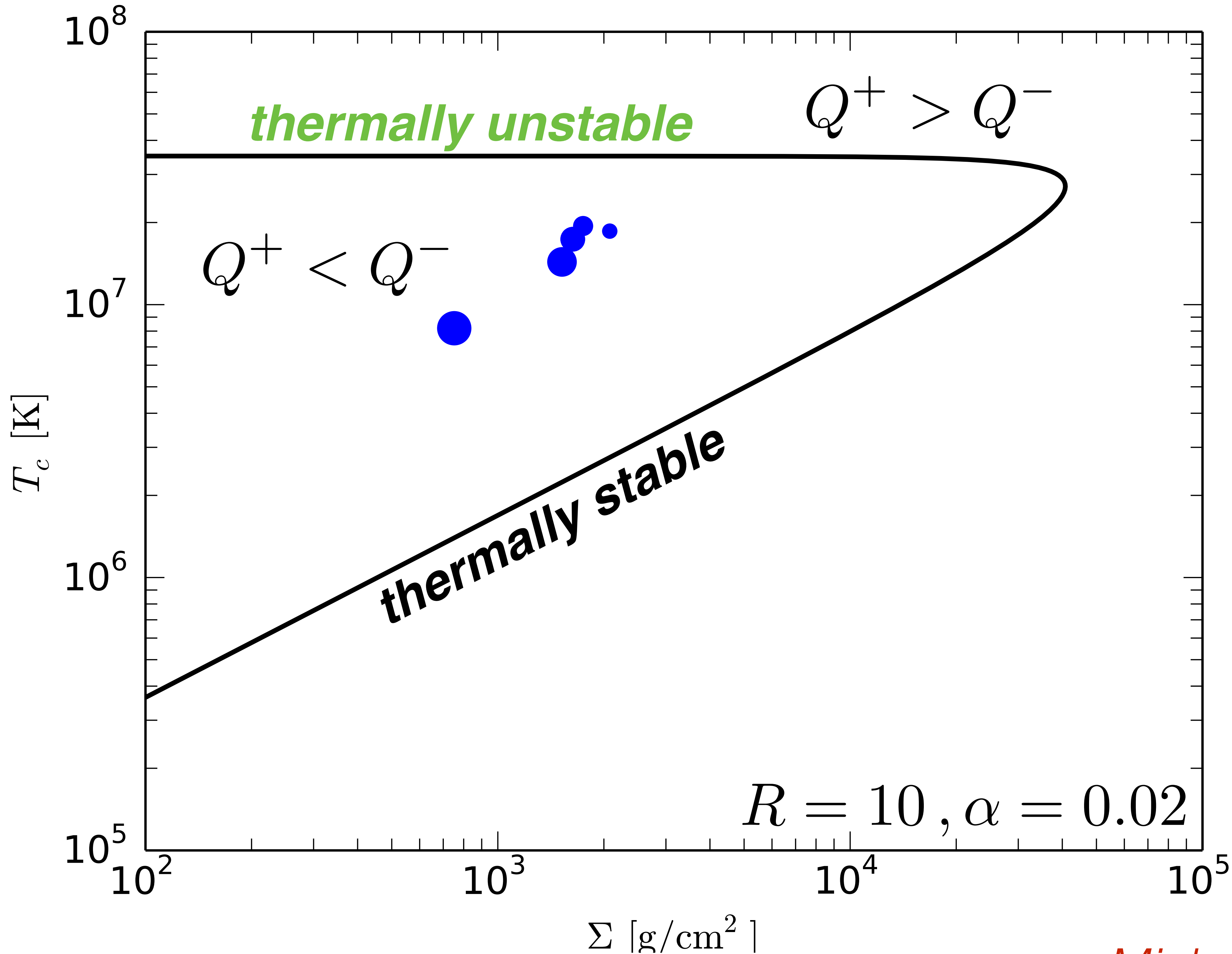


$$Q^+ = 1.5(z_t - z_b)V^\phi T^{r\phi} \quad \& \quad Q^- = L_{photo}$$

The heating and cooling are in balance

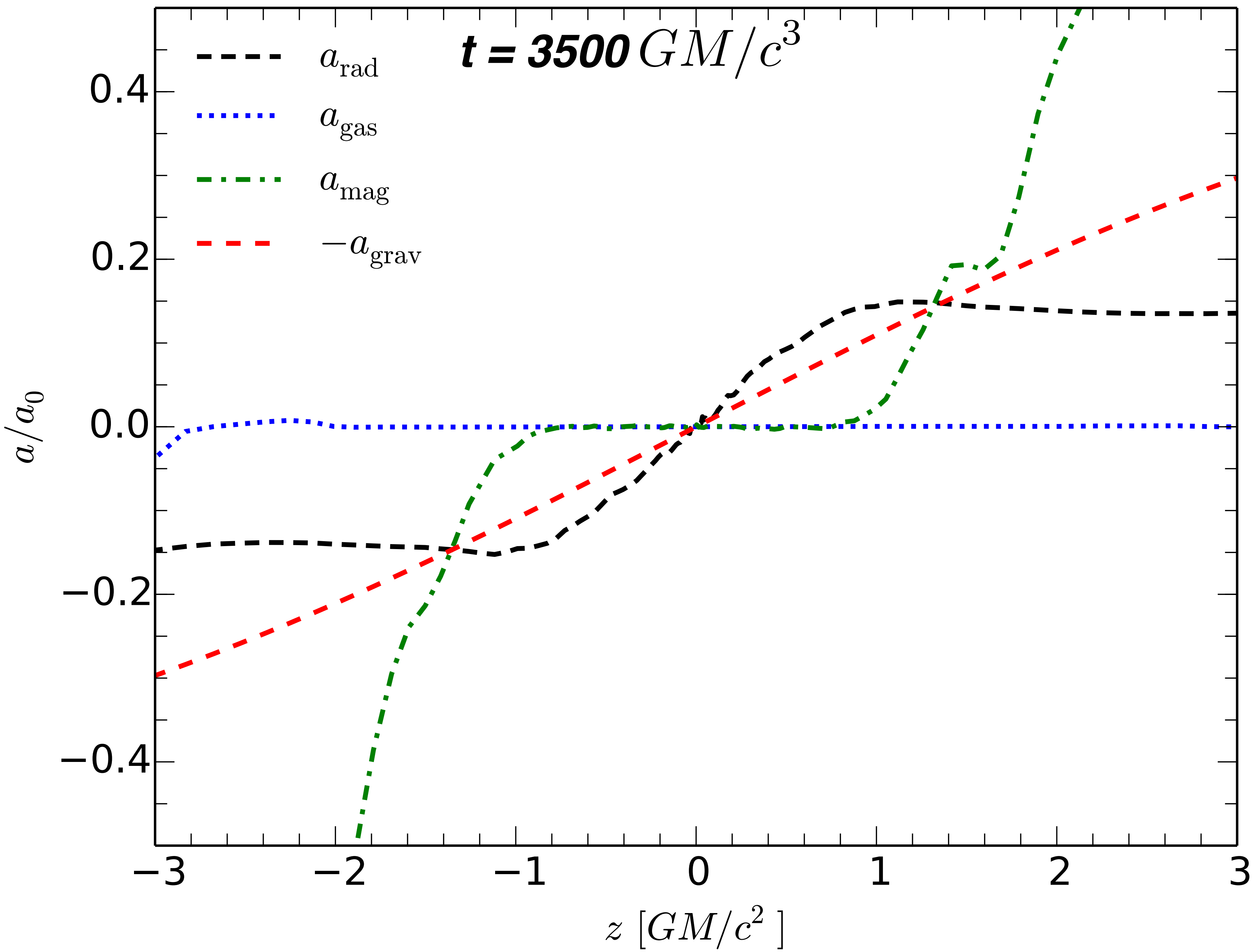
Radiation pressure dominated disk

Stability curve



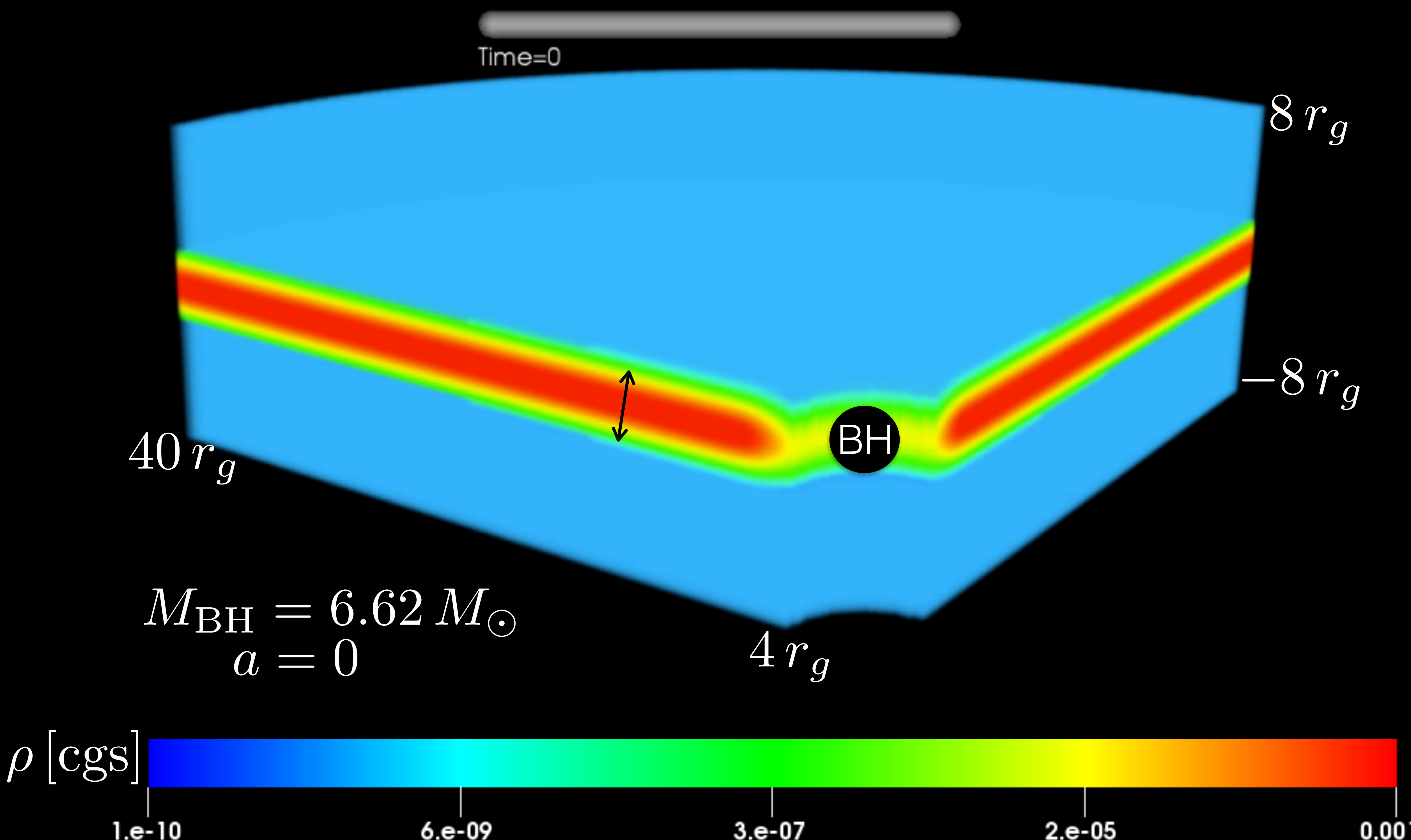
Mishra et al 16

Hydrostatic balance

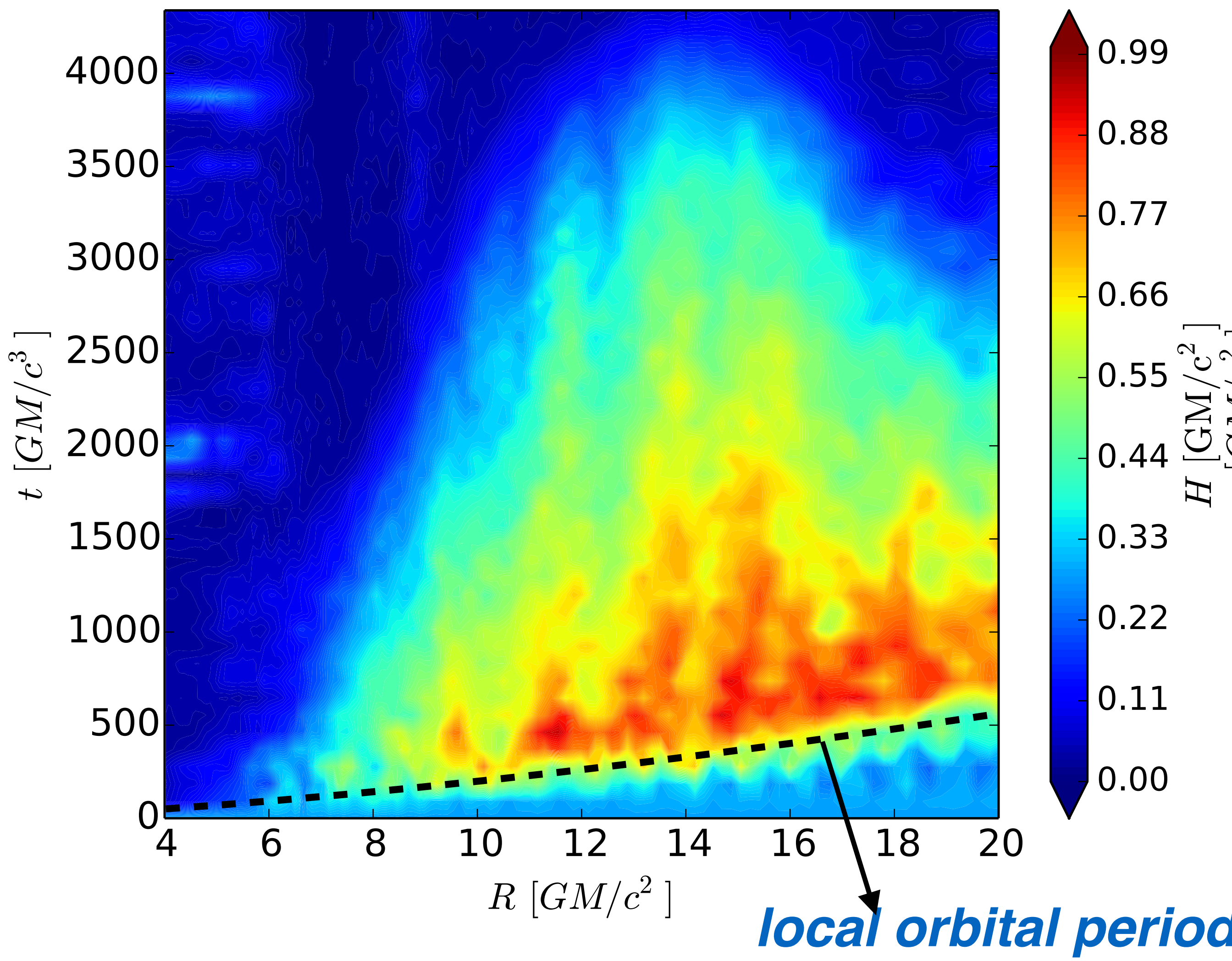


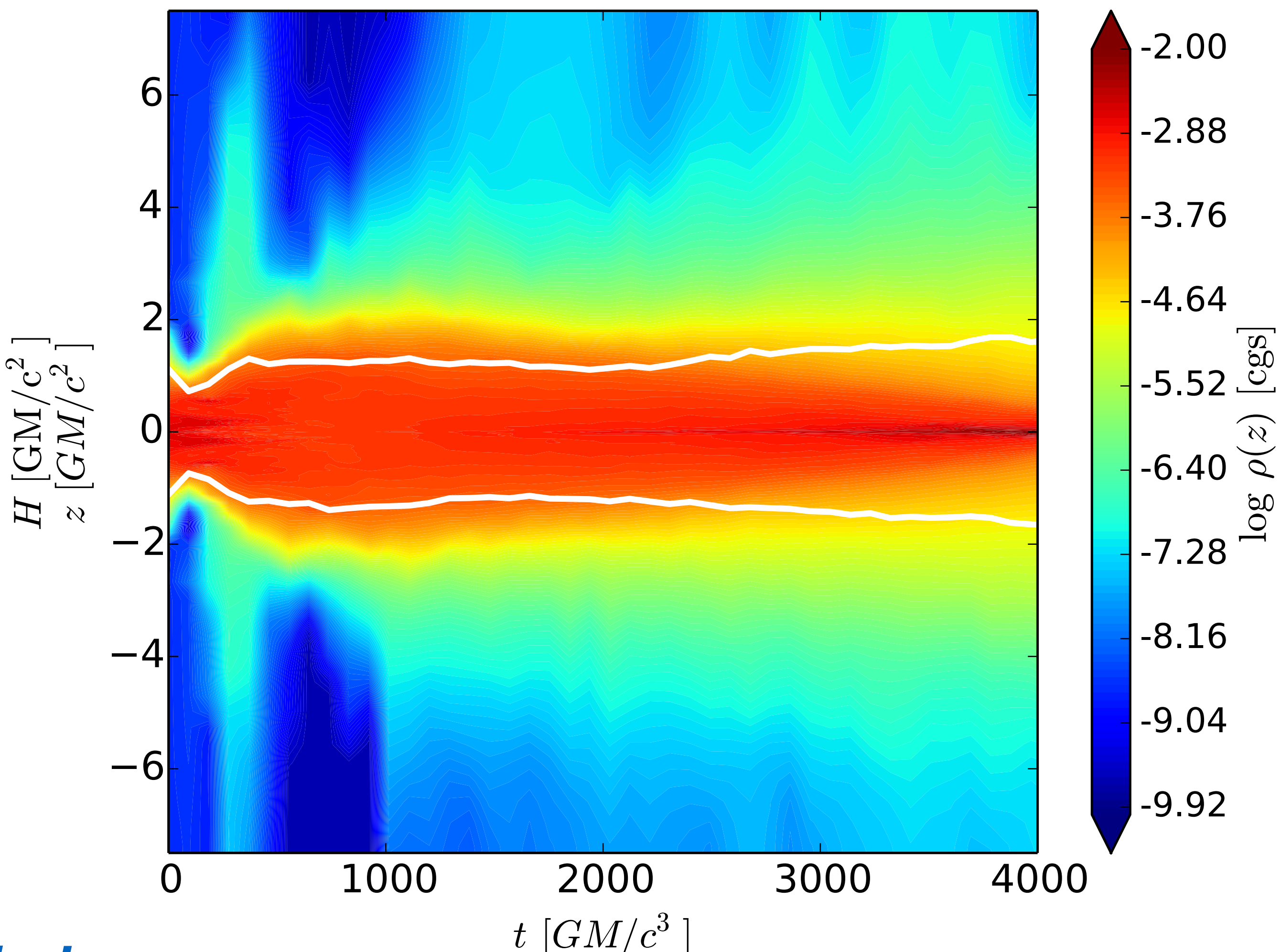
Unstable disk

RADPHR



RADPHR, disk collapse

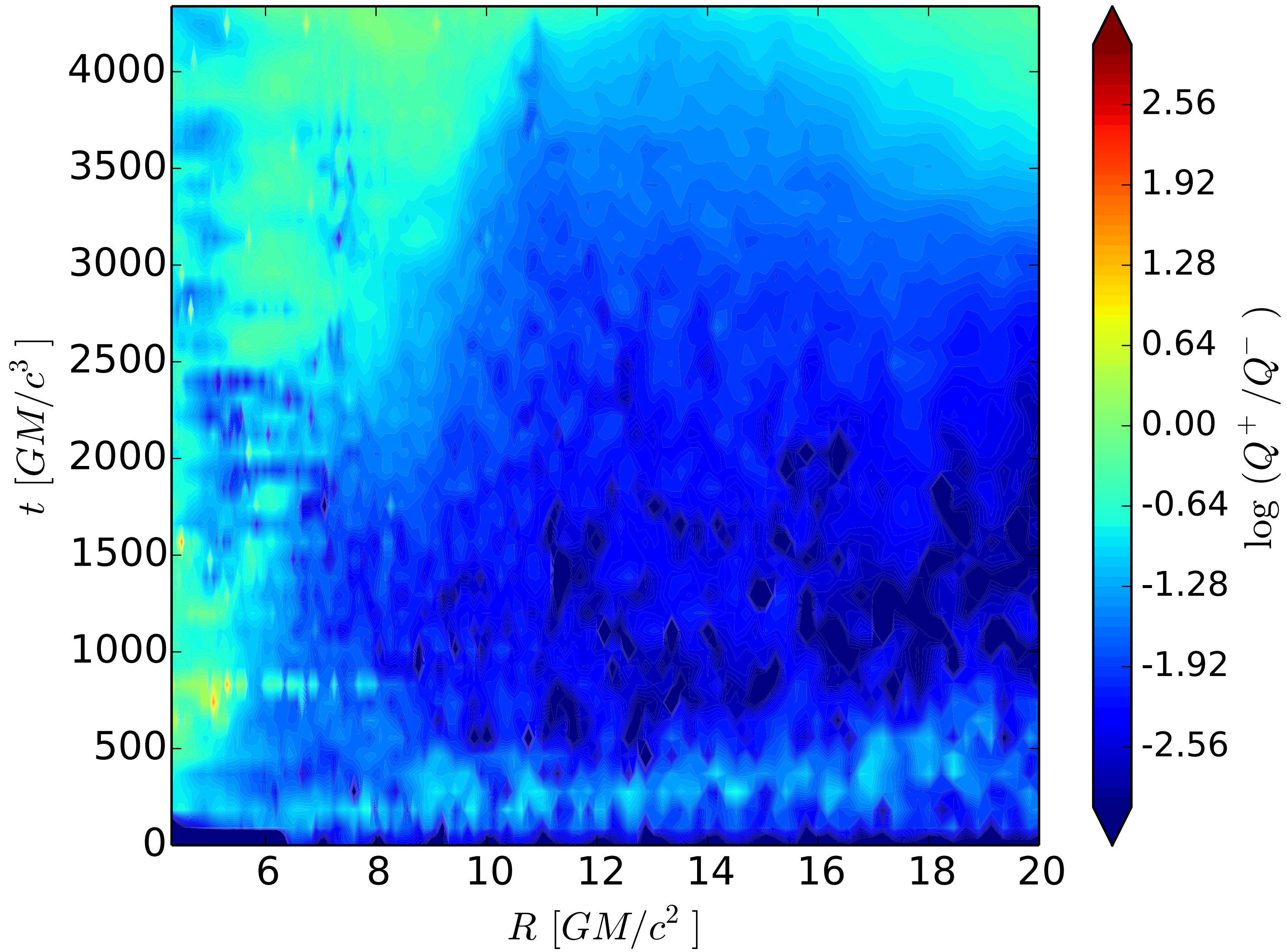




Radial profile of Height

Vertical density profile

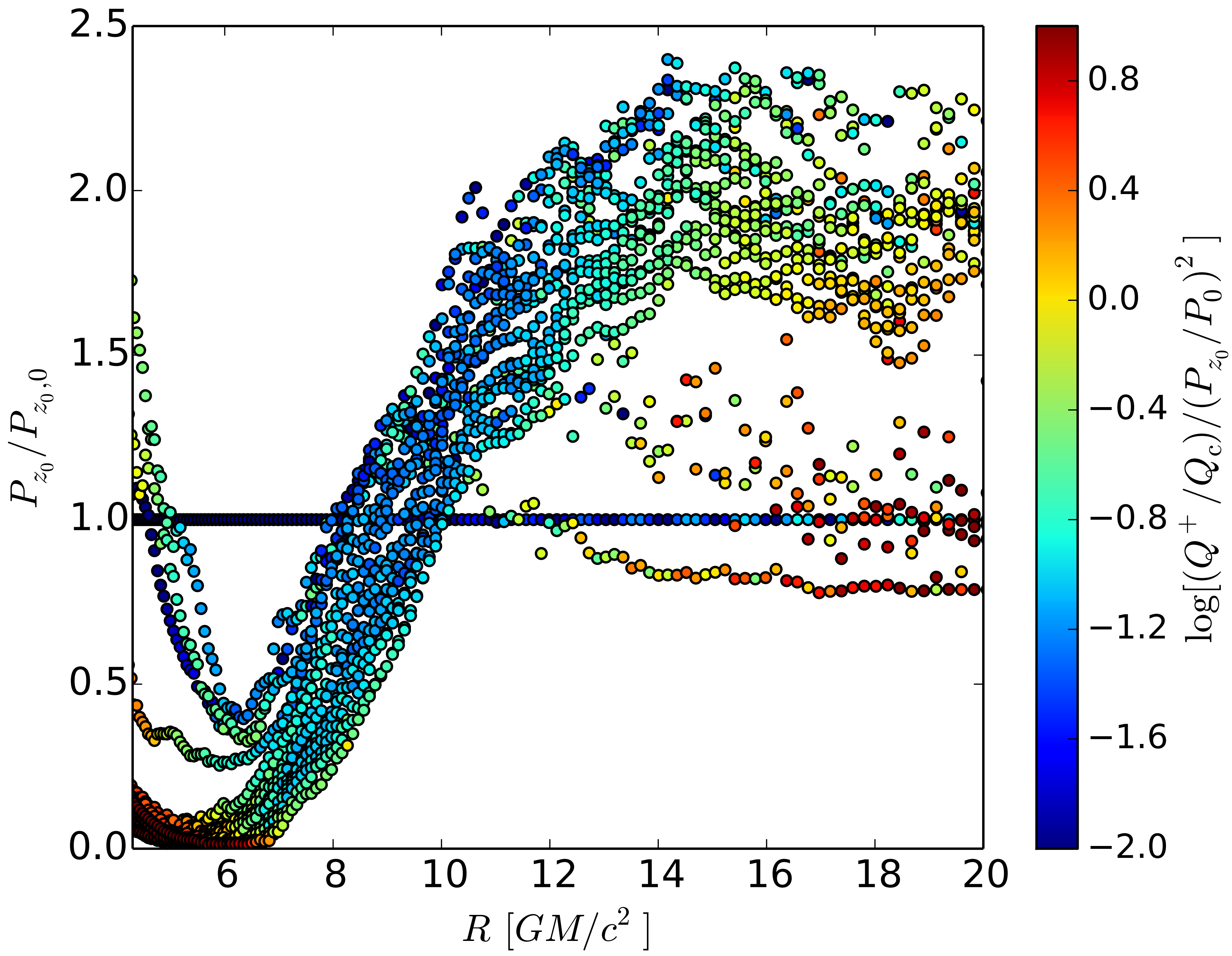
Heating vs cooling (RADPHR)



$$Q^{+}(R) = \frac{3}{2}\int < V^{\phi} W_{\hat{r}\hat{\phi}} >_{\phi} dz$$

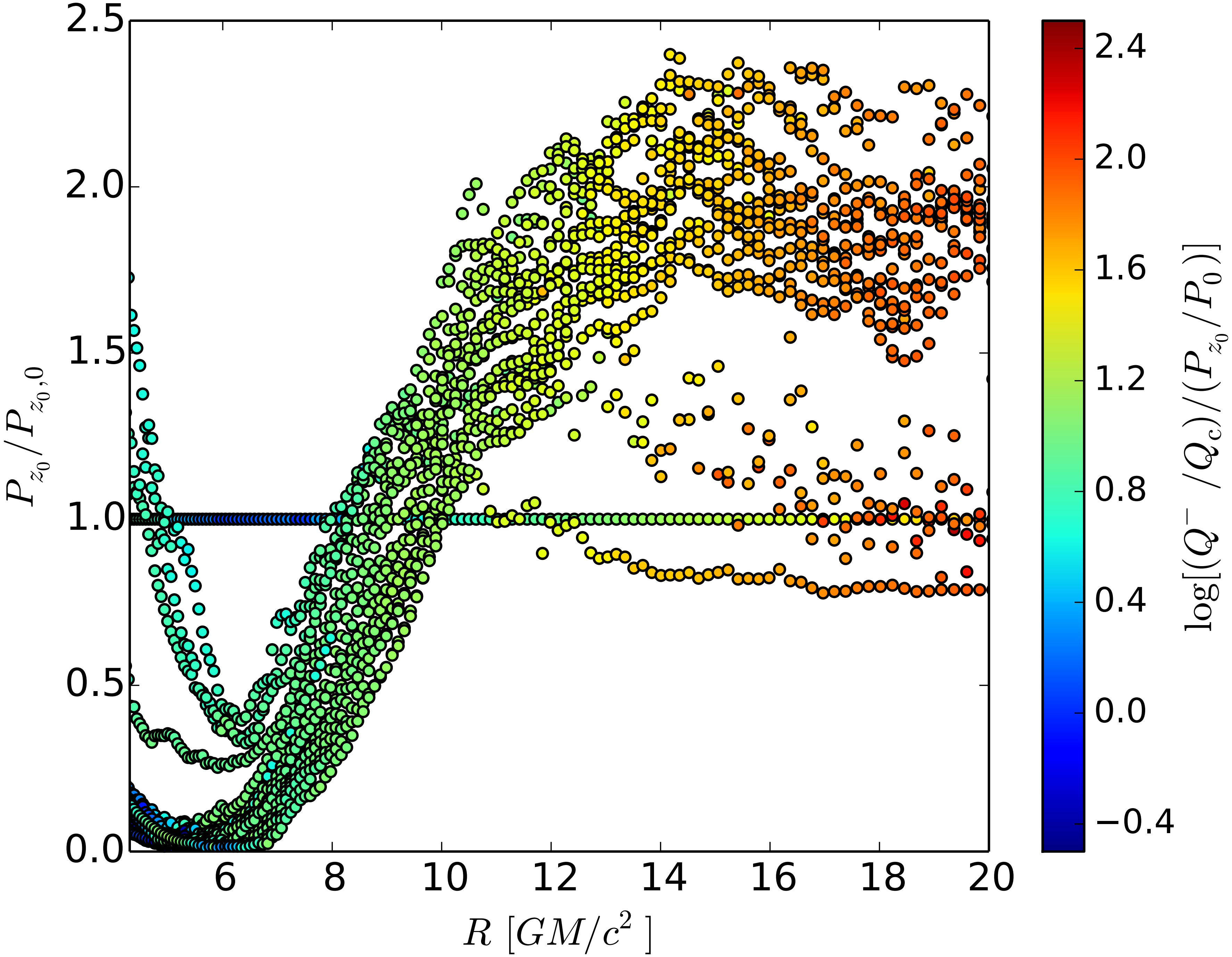
$$Q^{-}(R) = < F^{z}_{\mathrm{photo}+}(R) >_{\phi} - < F^{z}_{\mathrm{photo}-}(R) >_{\phi}$$

*Heating **vs** mid-plane total pressure*



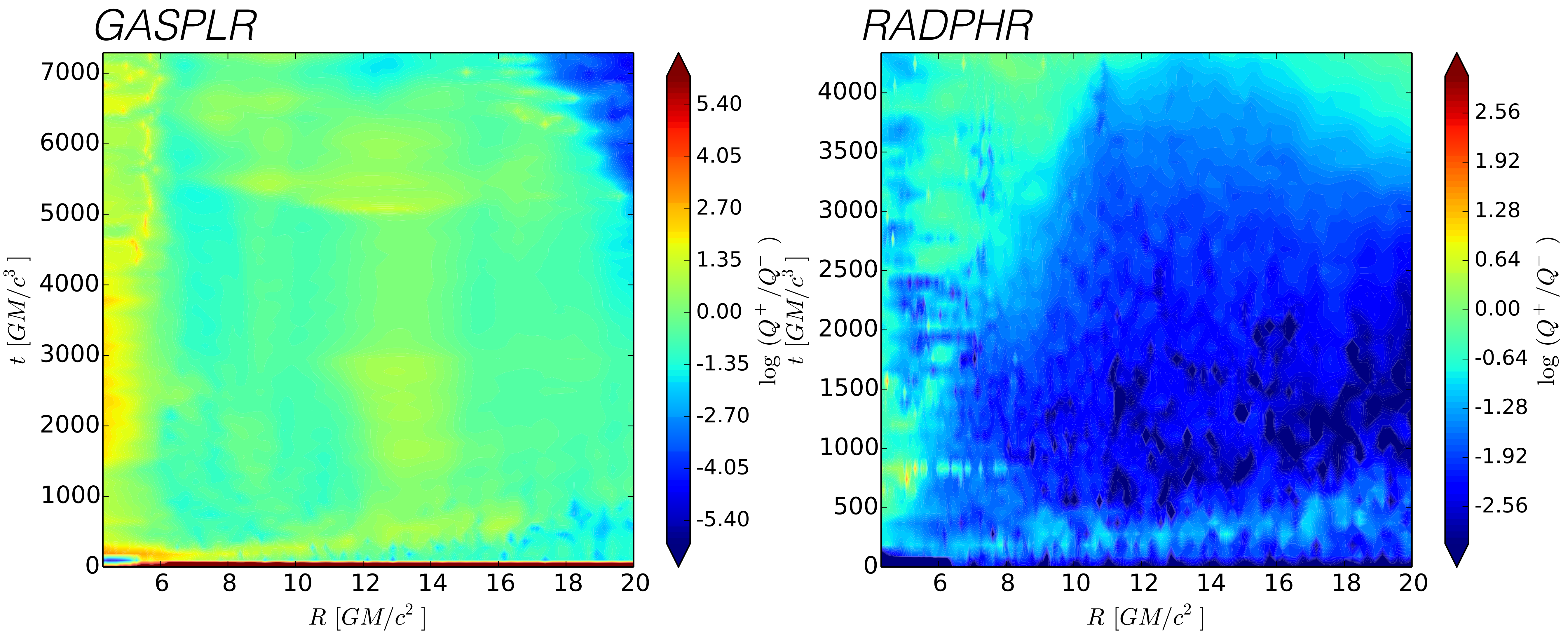
$$Q_c = c\Omega^2 H/\kappa_s$$

Cooling ***vs*** *mid-plane pressure*



$$Q_c = c\Omega^2 H/\kappa_s$$

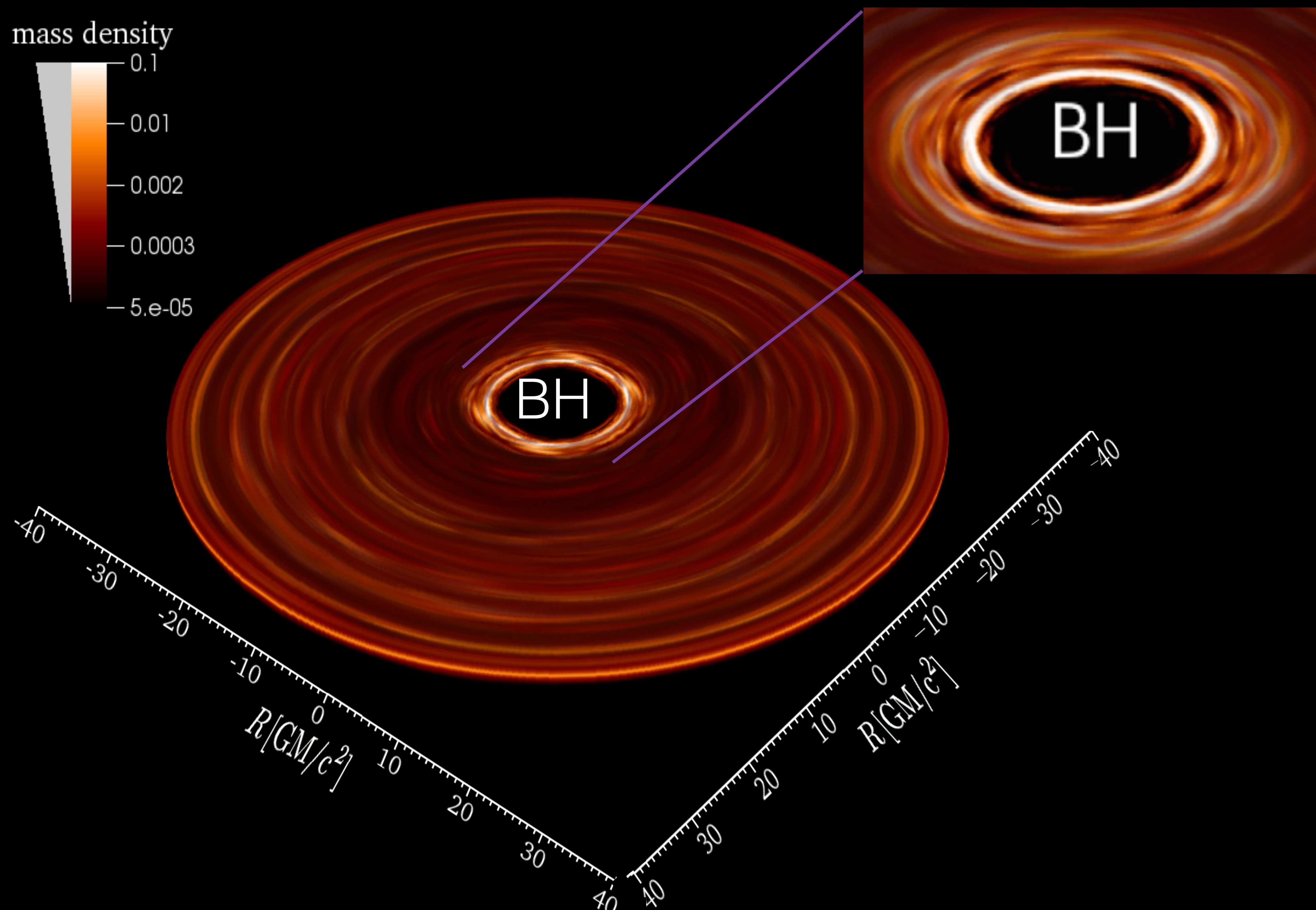
GASP vs RADP



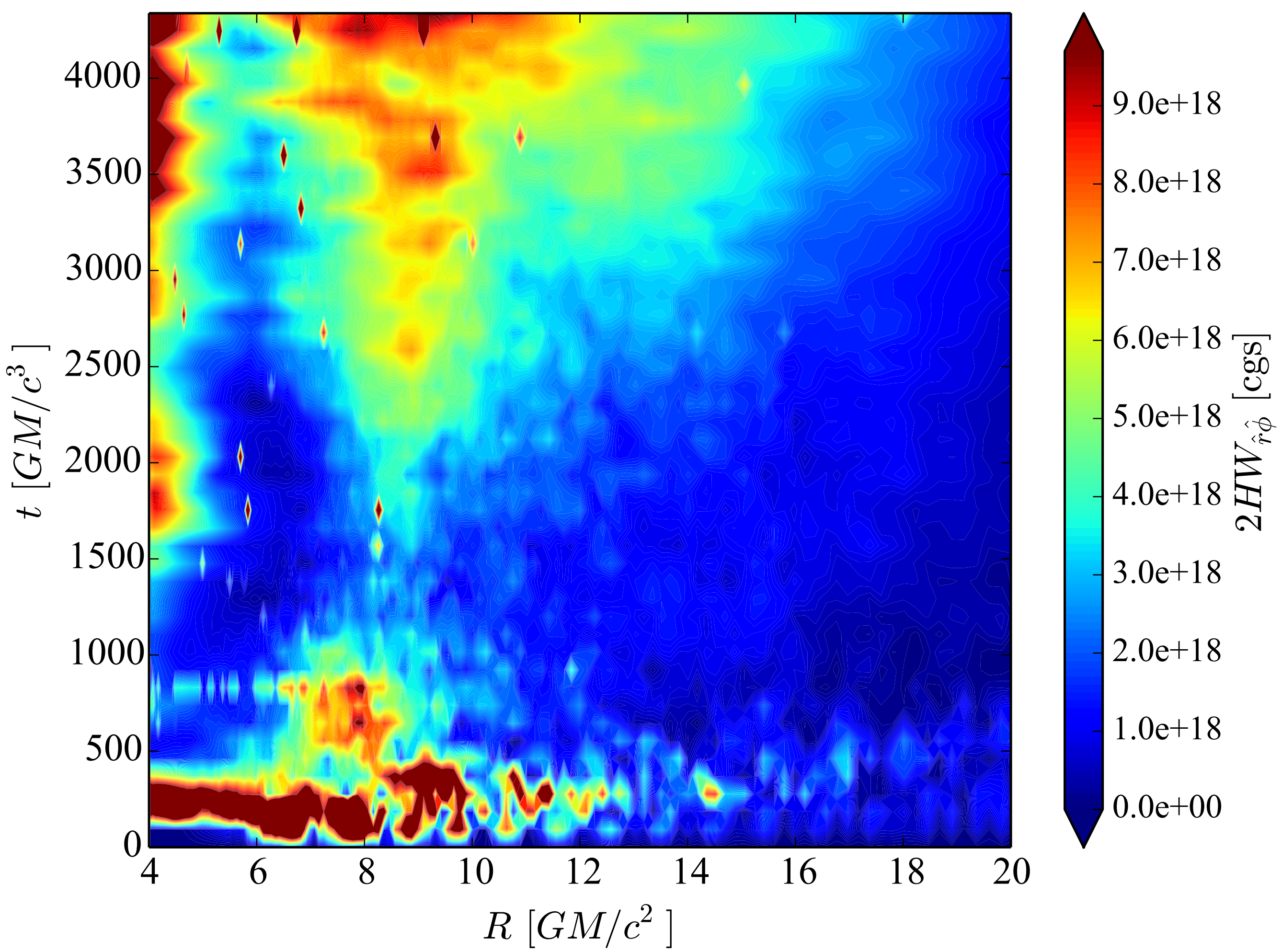
Stable

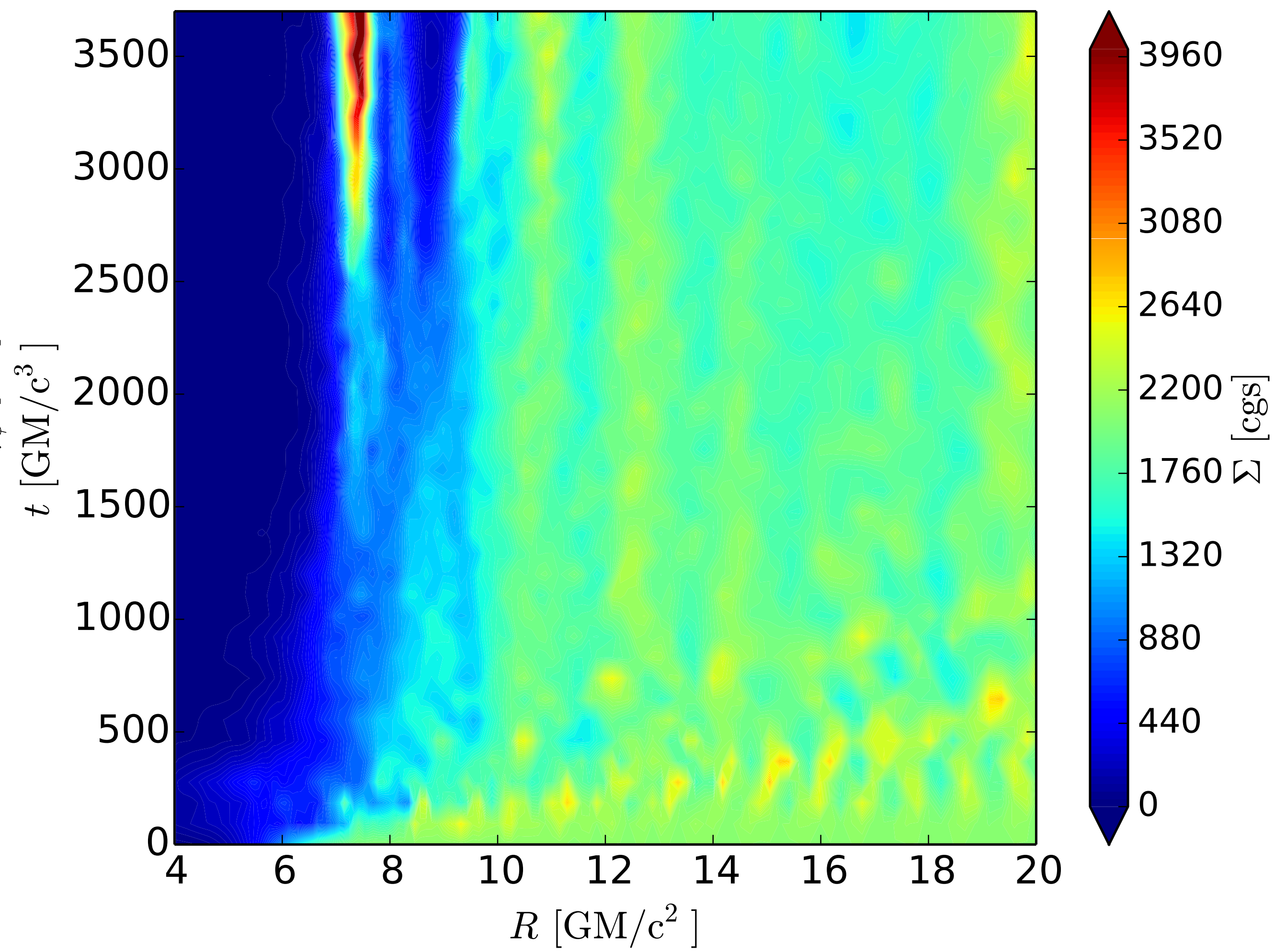
Unstable

Viscous Instability

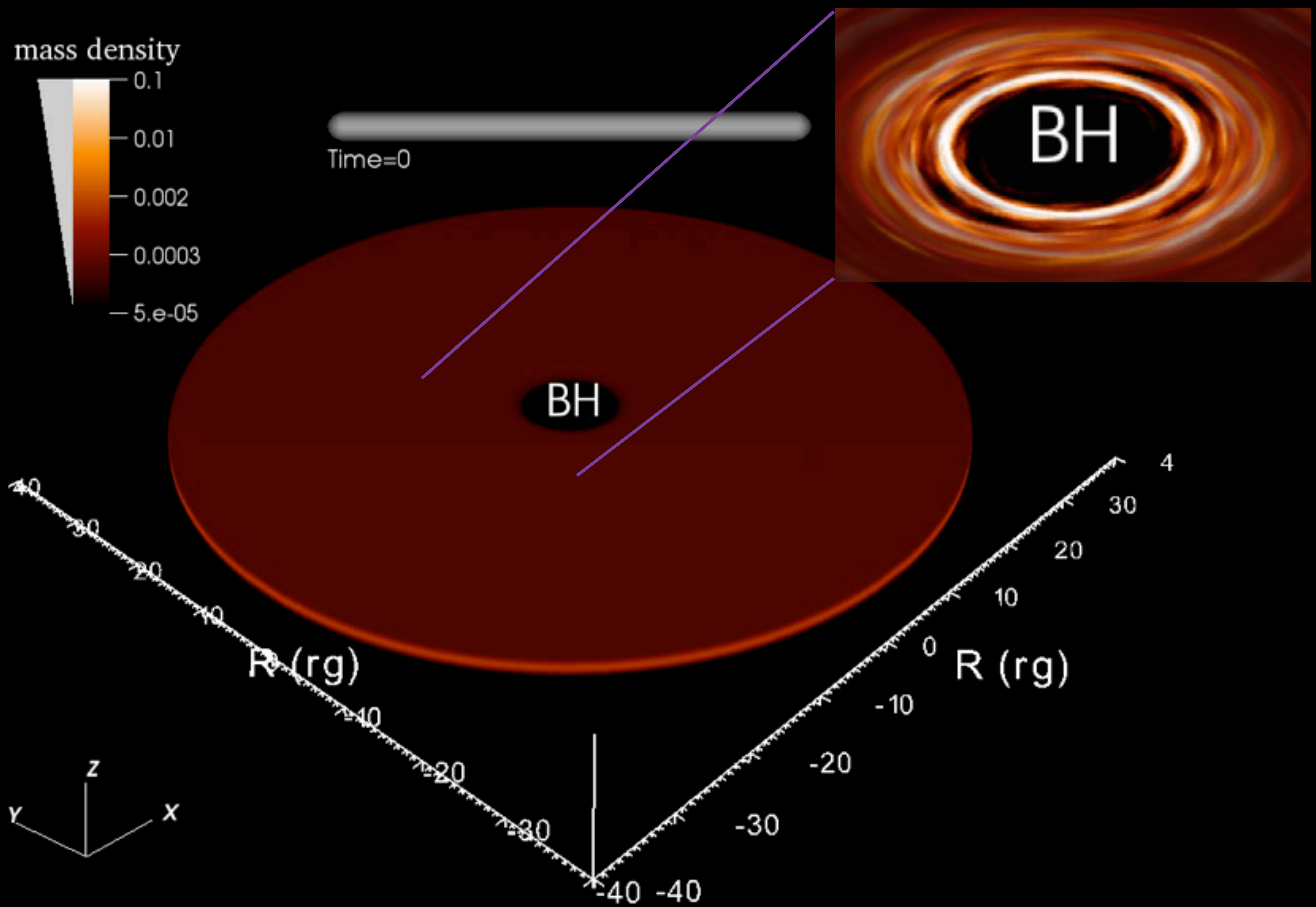


Viscous Instability





Viscous Instability



Conclusions

- Radiation pressure dominated disks are thermally unstable
- Still need more computational power to well resolve these simulations
- In my knowledge, first evidences of viscous instability in numerical simulations

Thank you !