RAGTIME

24th Relativistic Astrophysics Group Meeting

Resolution Study of an accretion disk initialized by an equilibrium torus.

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GRRMHD code KORAL

- Sądowski et al. (2013, 2014)
- Physics: **G**eneral **R**elativistic **R**adiation **M**agnetohydrodynamics

Comptonization, Bremmstrahlung, Synchrotron, Coulomb coupling

$(\rho u^\mu)_{;\mu} = 0$, mass conservations

$(T^\mu{}_\nu + R^\mu{}_\nu)_{;\mu} = 0$, energy conservation

$(T^\mu{}_\nu)_{;\mu} = G_\nu$,

$(R^\mu{}_\nu)_{;\mu} = -G_\nu$

$$T^\mu{}_\nu = (\rho + p + u_{\rm int} + b^2)u^\mu u_\nu + (p + b^2/2)\delta^\mu_\nu - b^\mu b_\nu$$

$$p = (\gamma - 1)u_{int}$$

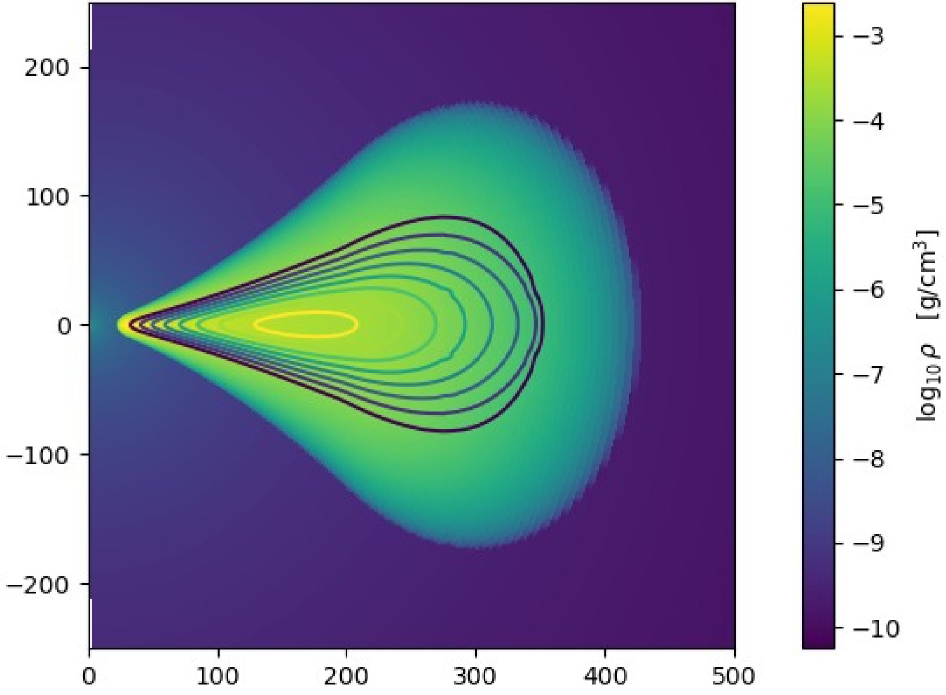
Resolution study

- Magnetorotational instability (MRI):
  - Triggered by a weak poloidal magnetic field
  - provides a convincing mechanism for the transport of angular momentum.
- MRI produces turbulence.
- Inadequate resolution may cause a number of numerical artifacts.
  - too low resolution may distort the properties of that turbulence.
- Conduct a series of accretion simulations with different resolutions.
- Examine how different resolutions affect accretion flow and various quantitative values.

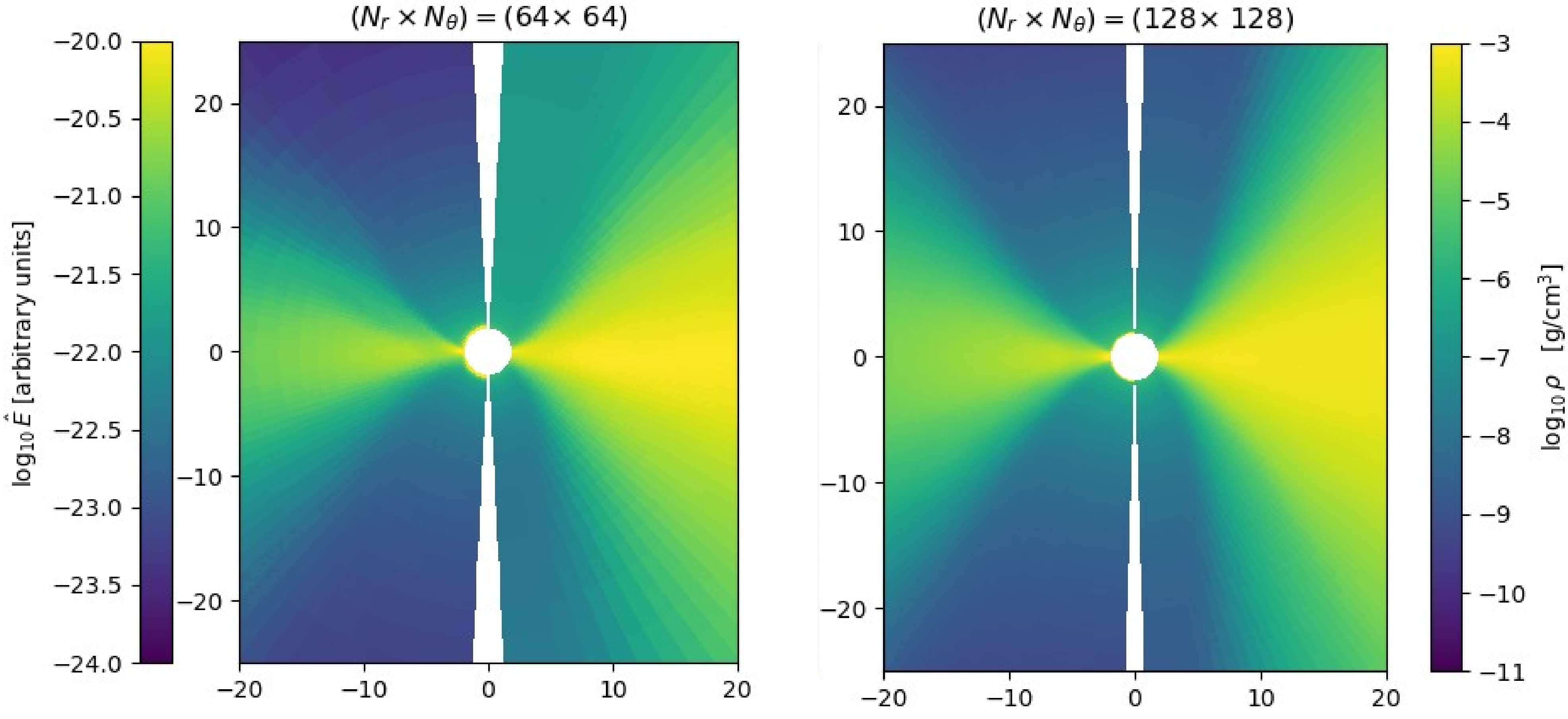
(R, θ)
64x64
128x128
256x256
512x512

Initial set-up

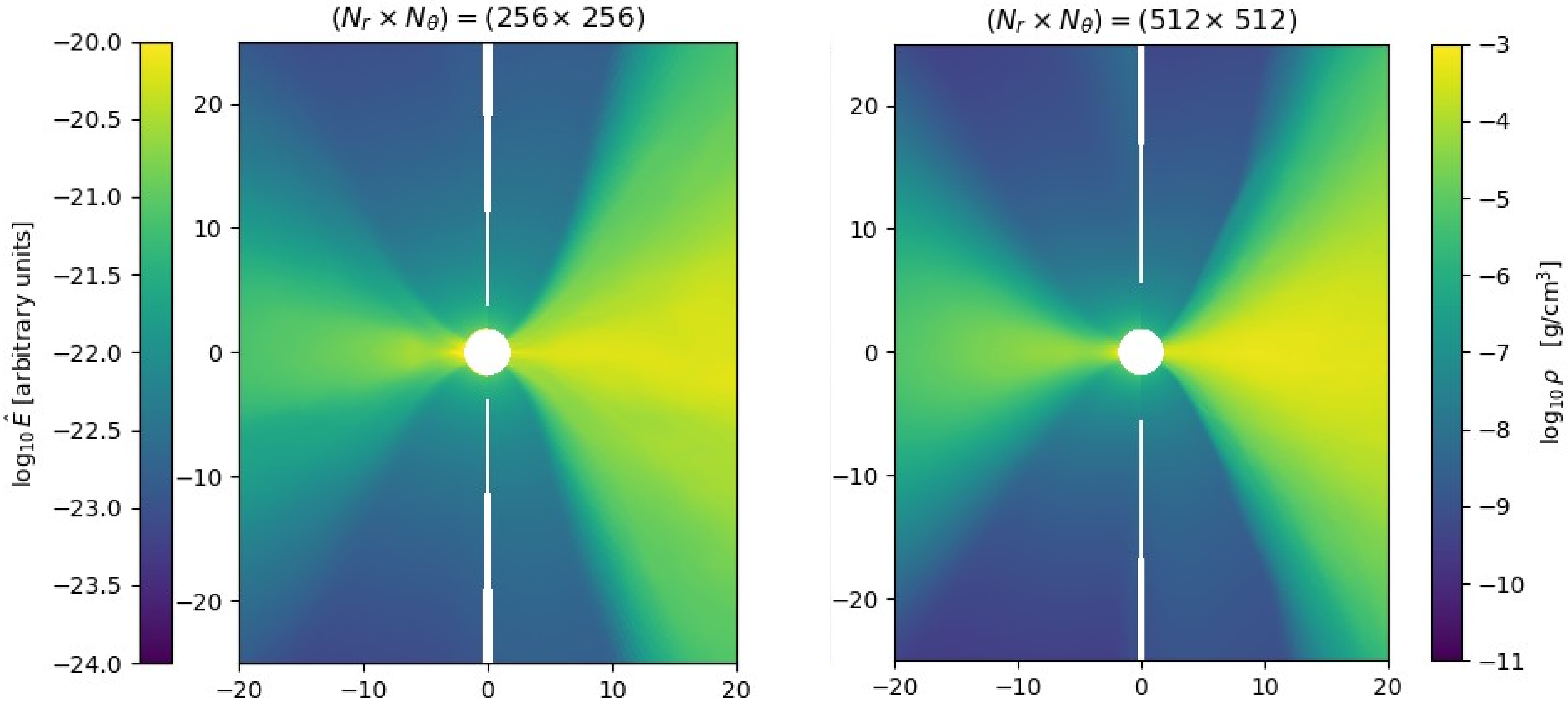
- Hydrodynamical equilibrium torus: Penna, Kulkani & Narayan (2013)
- Non-rotating BH of $10M_\odot$.
- Initial state:
  - $R_{in} = 22\ GM/c^2$
  - $p = K\rho^\gamma$, $\gamma = 4/3$, $K = 600$
  - $\beta_{max} = 20$, $\beta = p_{tot}/p_{mag}$



- Initial velocity:
  - Constant angular momentum for $R < R_1 = 30\ GM/c^2$
  - Keplerian multiplied by a factor $\xi = 0.975$ for $R > R_1$.



$(N_r \times N_\theta) = (64\times\ 64)$
$(N_r \times N_\theta) = (128\times\ 128)$
$\log_{10}\hat{E}$ [arbitrary units]
$\log_{10}\rho$ [g/cm^3]
−20.0
−20.5
−21.0
−21.5
−22.0
−22.5
−23.0
−23.5
−24.0
−3
−4
−5
−6
−7
−8
−9
−10
−11
20
10
0
−10
−20



$(N_r \times N_\theta) = (256\times\ 256)$
$(N_r \times N_\theta) = (512\times\ 512)$
$\log_{10}\hat{E}$ [arbitrary units]
$\log_{10}\rho$ [g/cm^3]
−20.0
−20.5
−21.0
−21.5
−22.0
−22.5
−23.0
−23.5
−24.0
−3
−4
−5
−6
−7
−8
−9
−10
−11
20
10
0
−10
−20

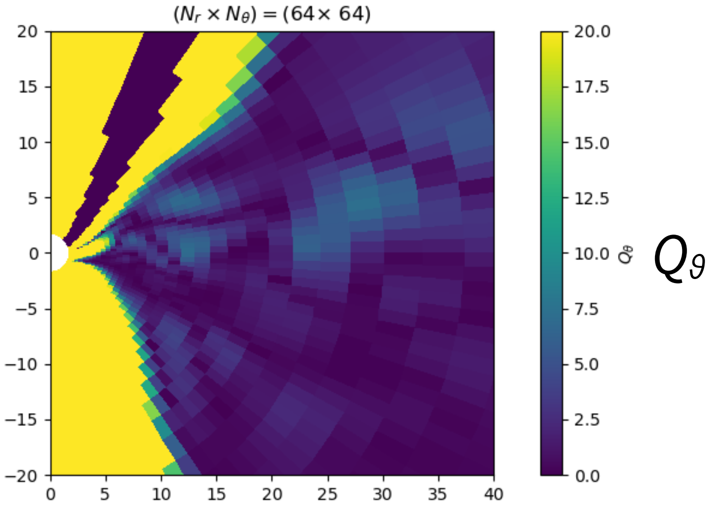
MRI quality parameter Q

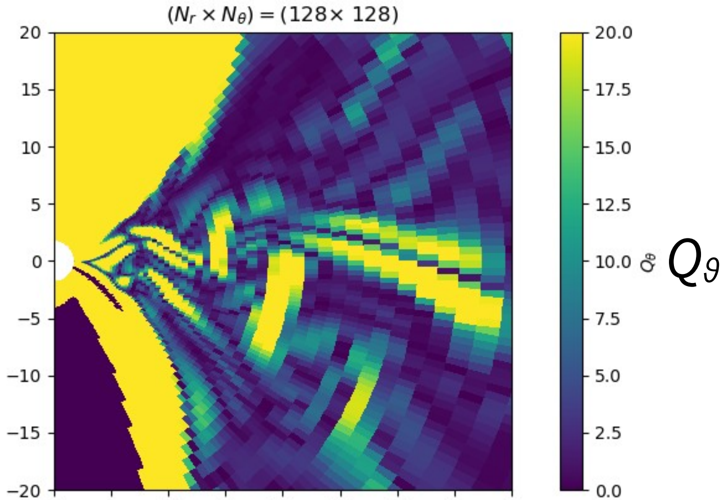
- To quantify the quality of resolution of MRI, one can evaluate the parameter $Q \equiv \lambda_{MRI} / \Delta x, \ \lambda_{MRI} = 2\pi u_A / \Omega$

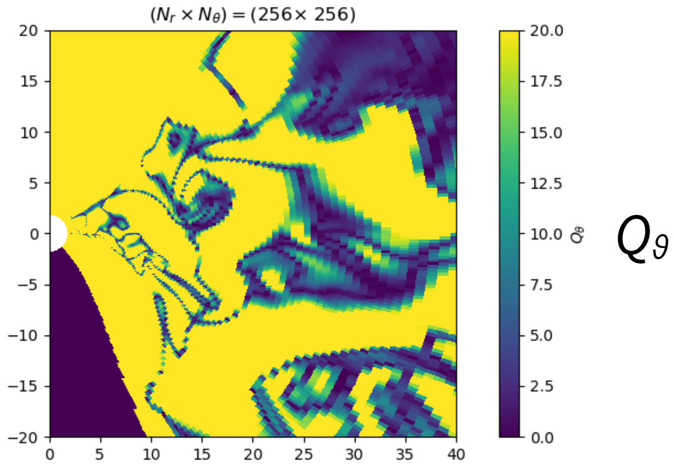
  $$Q_\theta = \frac{2\pi |u_{A\theta}|}{\Omega \Delta\theta}, \text{ where,}$$

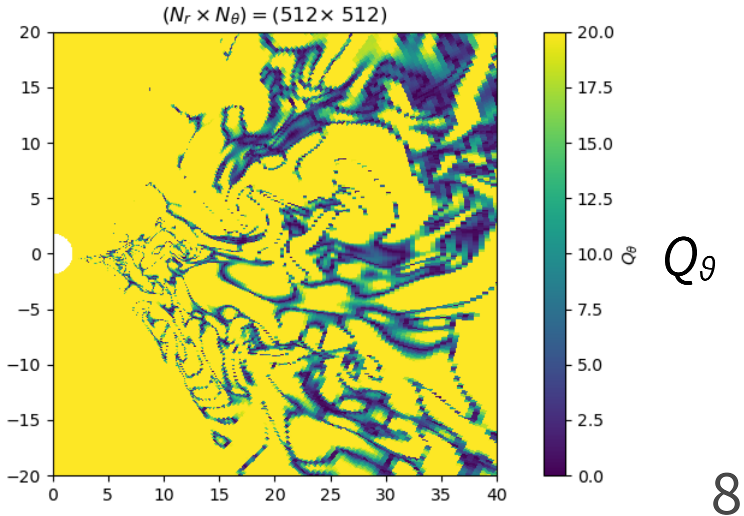
  $u_{A\theta}$ is the ϑ component of Alfven velocity and Ω is the rotation rate of the fluid

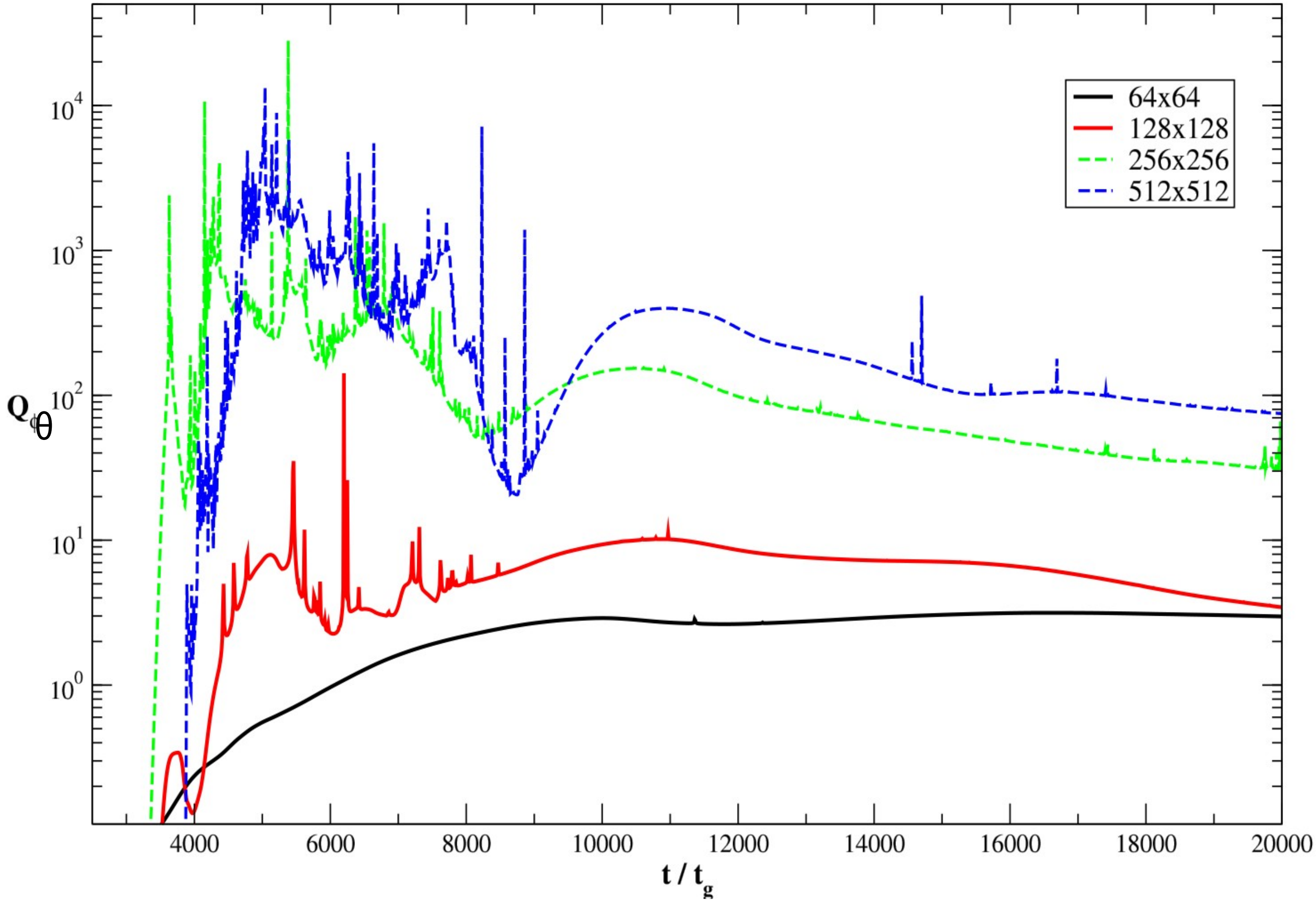
- Noble et al. (2010), Hawley et al. (2011; 2013)
  - Condition for adequate resolution $Q_\theta \gtrsim 20$


$(N_r \times N_\theta) = (64\times 64)$
20
15
10
5
0
−5
−10
−15
−20
0
5
10
15
20
25
30
35
40
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
Q_ϑ
Q_ϑ

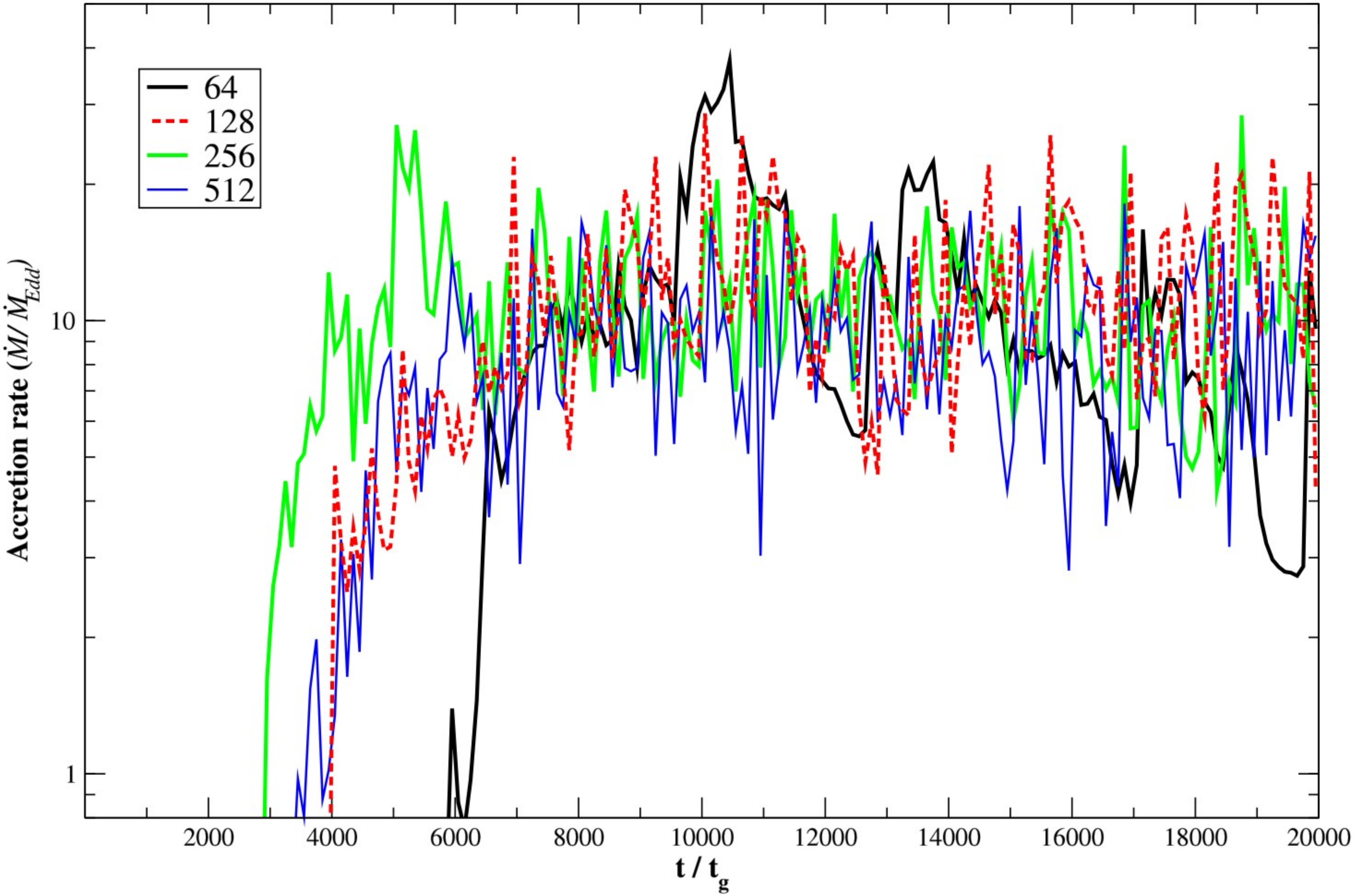

$(N_r \times N_\theta) = (128\times 128)$
20
15
10
5
0
−5
−10
−15
−20
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
Q_ϑ
Q_ϑ


$(N_r \times N_\theta) = (256\times 256)$
20
15
10
5
0
−5
−10
−15
−20
0
5
10
15
20
25
30
35
40
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
Q_ϑ
Q_ϑ

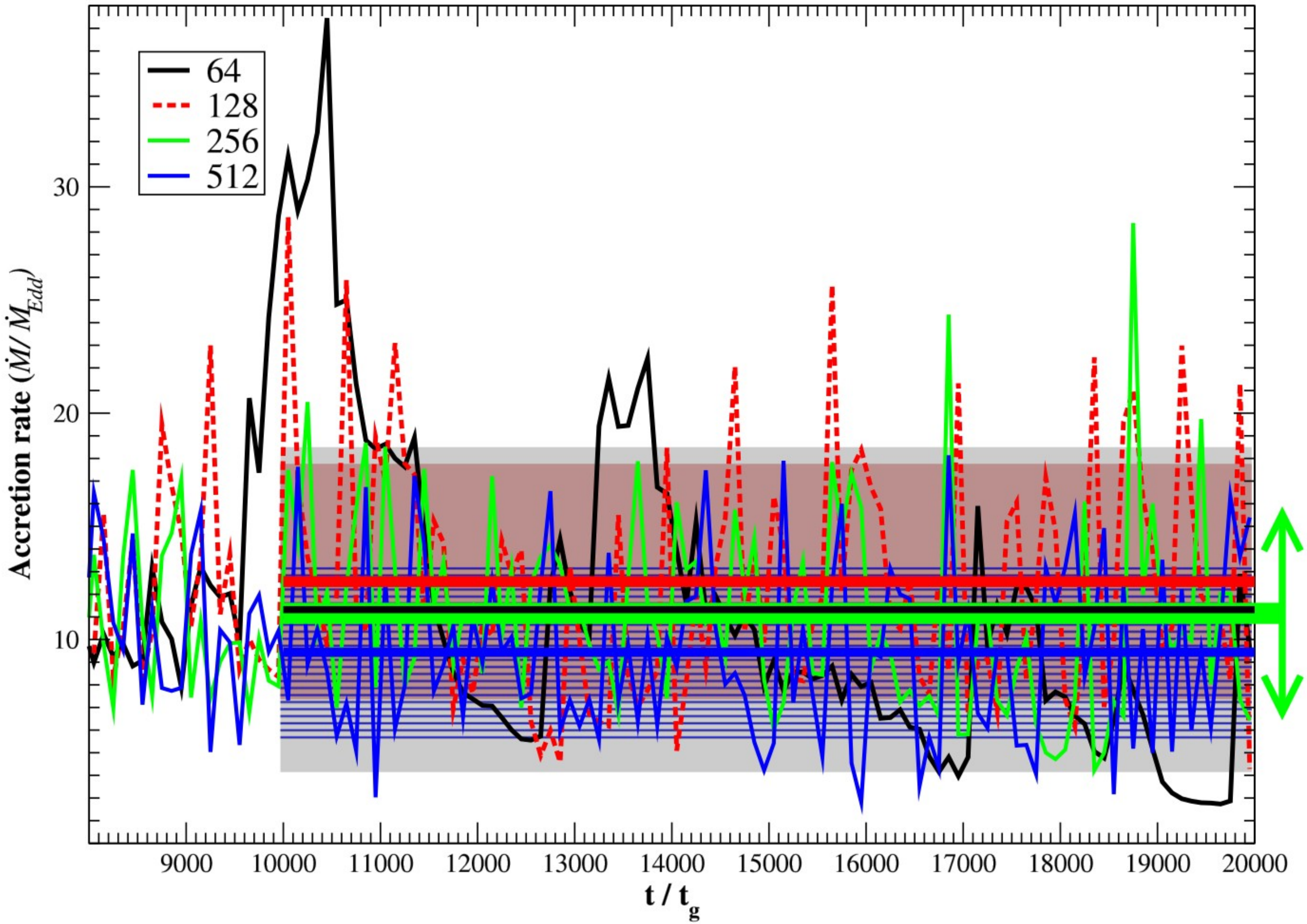

$(N_r \times N_\theta) = (512\times 512)$
20
15
10
5
0
−5
−10
−15
−20
0
5
10
15
20
25
30
35
40
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
Q_ϑ
Q_ϑ



64x64
128x128
256x256
512x512
10^4
10^3
10^2
10^1
10^0
Q
θ
4000
6000
8000
10000
12000
14000
16000
18000
20000
t / t_g



64
128
256
512
Accretion rate ($\dot{M}/\dot{M}_{Edd}$)
10
1
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
t / t_g

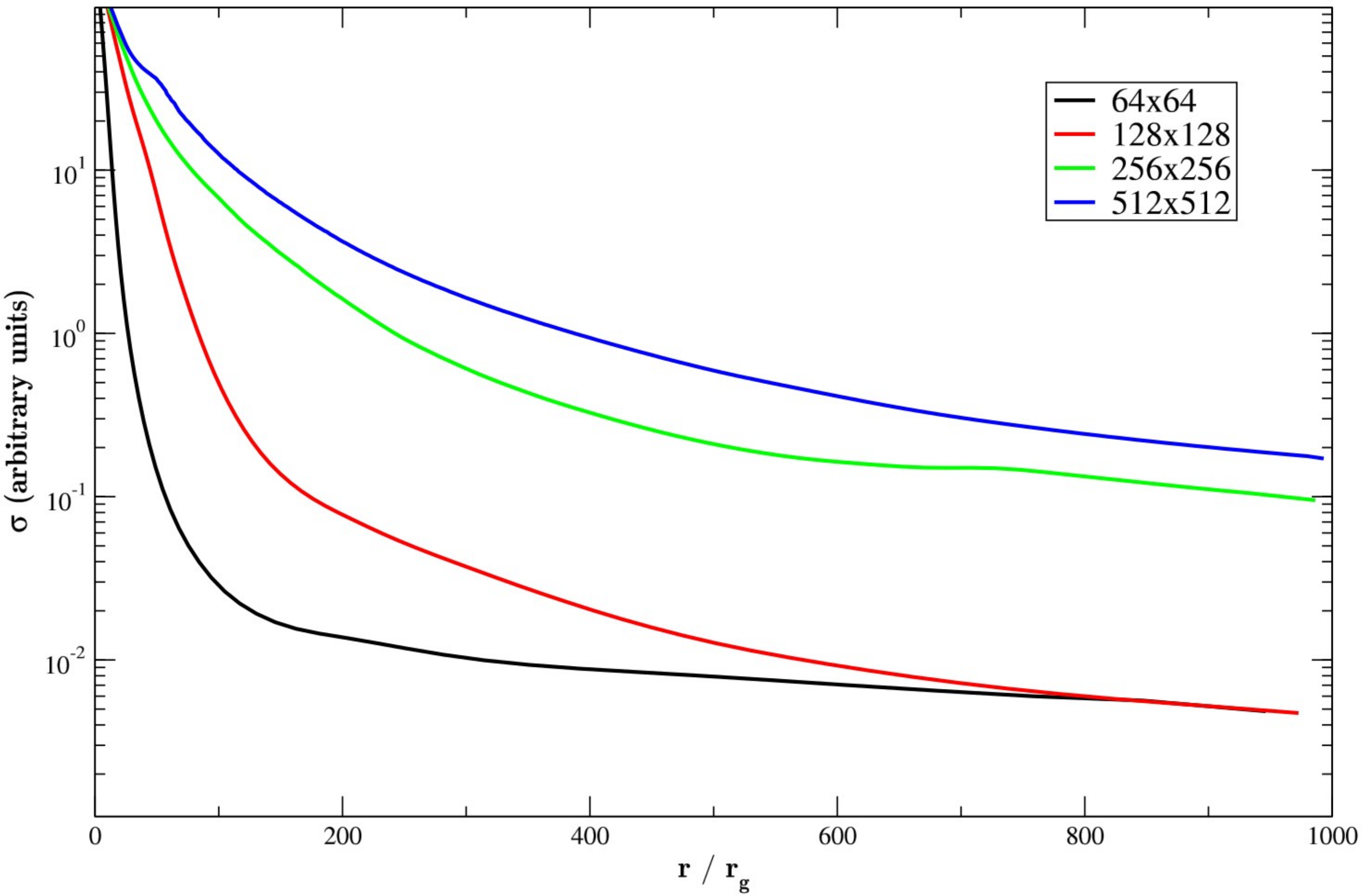


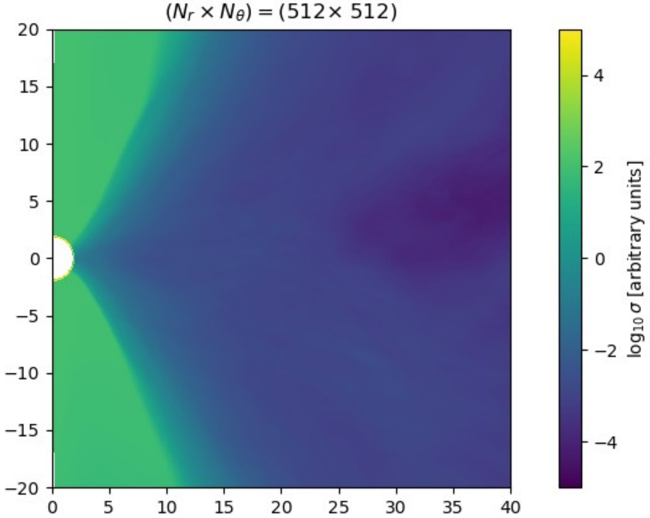
$(N_R \times N_\theta)$	Average ($\dot{M}_{Edd}$)
64x64	11.3 ± 7.2
128x128	12.6 ± 5.2
256x256	11.2 ± 4.4
512x512	9.4 ± 3.8

Horizontal lines show the average and color boxes indicate the stdev of the accretion rate.

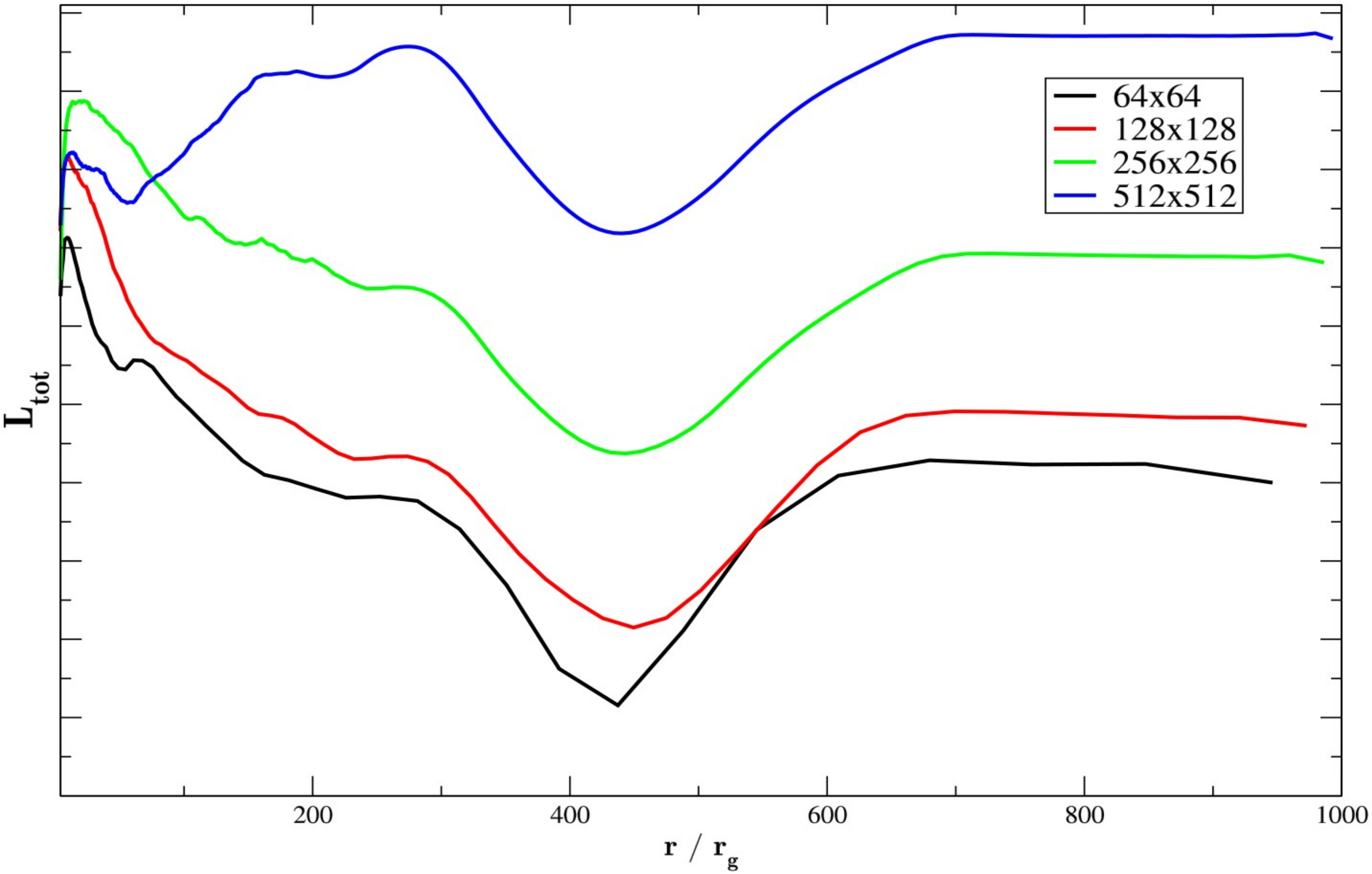
Grey box => (64x64)
Red => (128x128)
Green arrow (256x256)
Blue stripes (512x512)

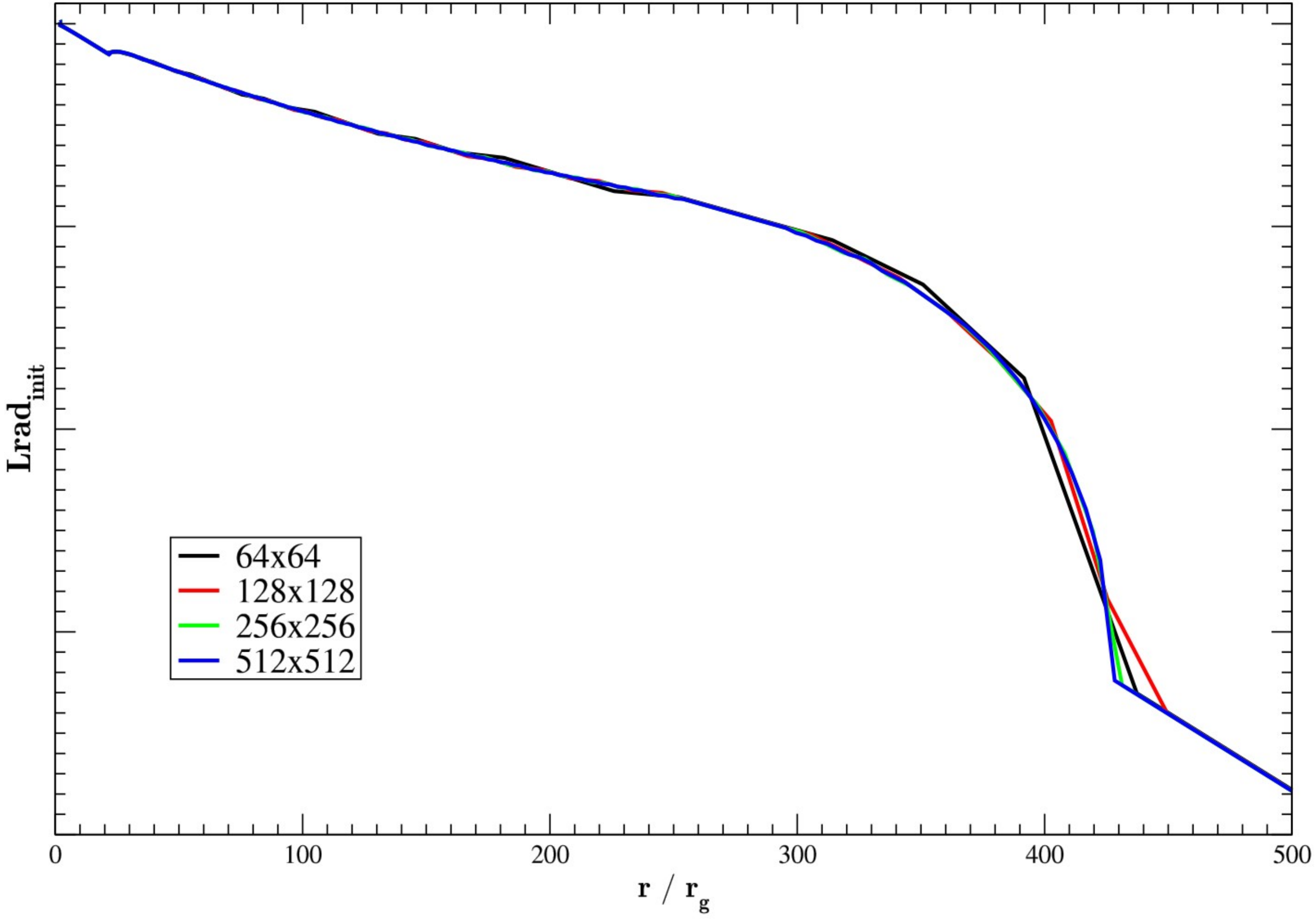
$$\sigma = \frac{B^2}{4\pi\rho c^2}$$



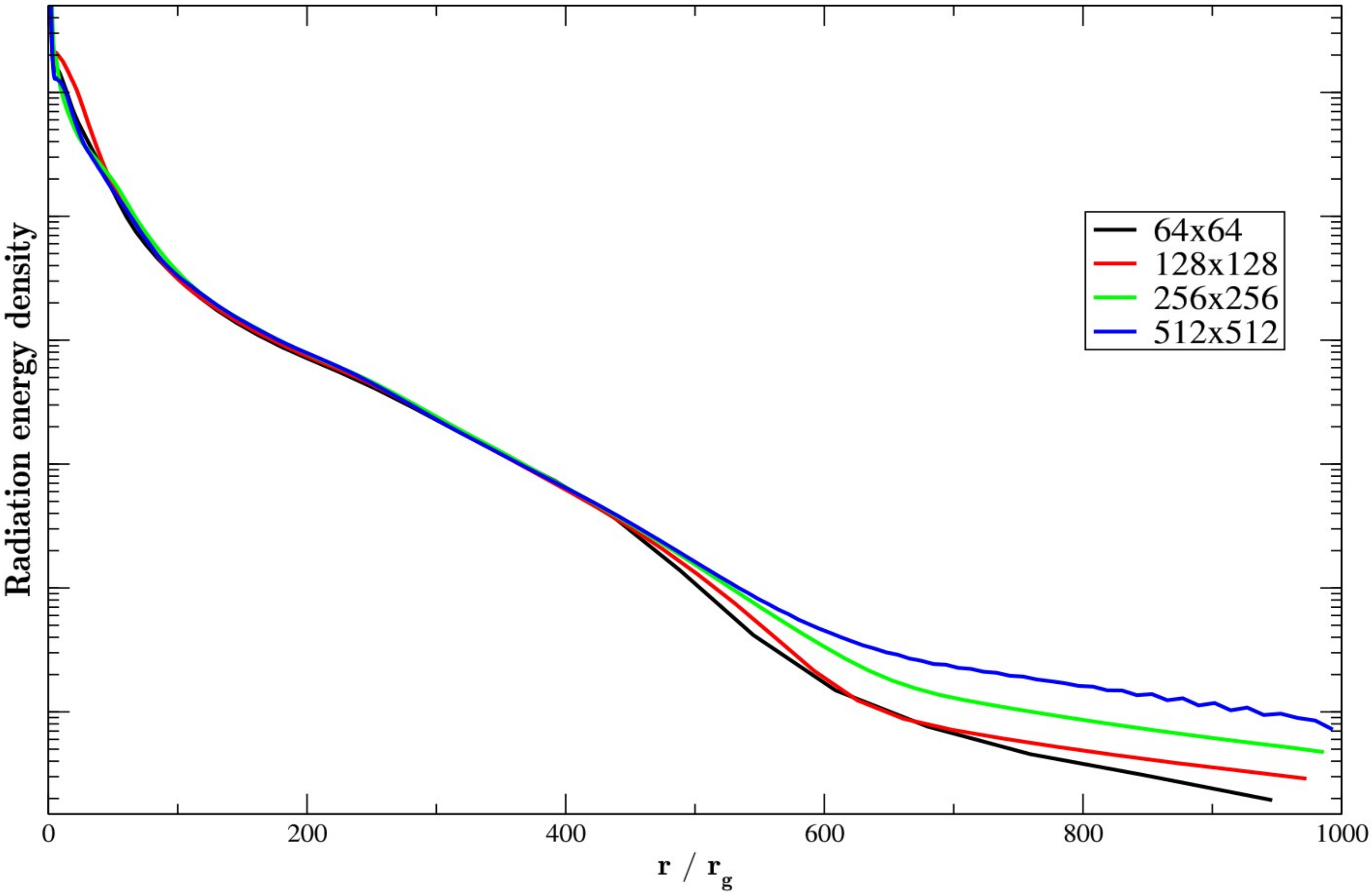


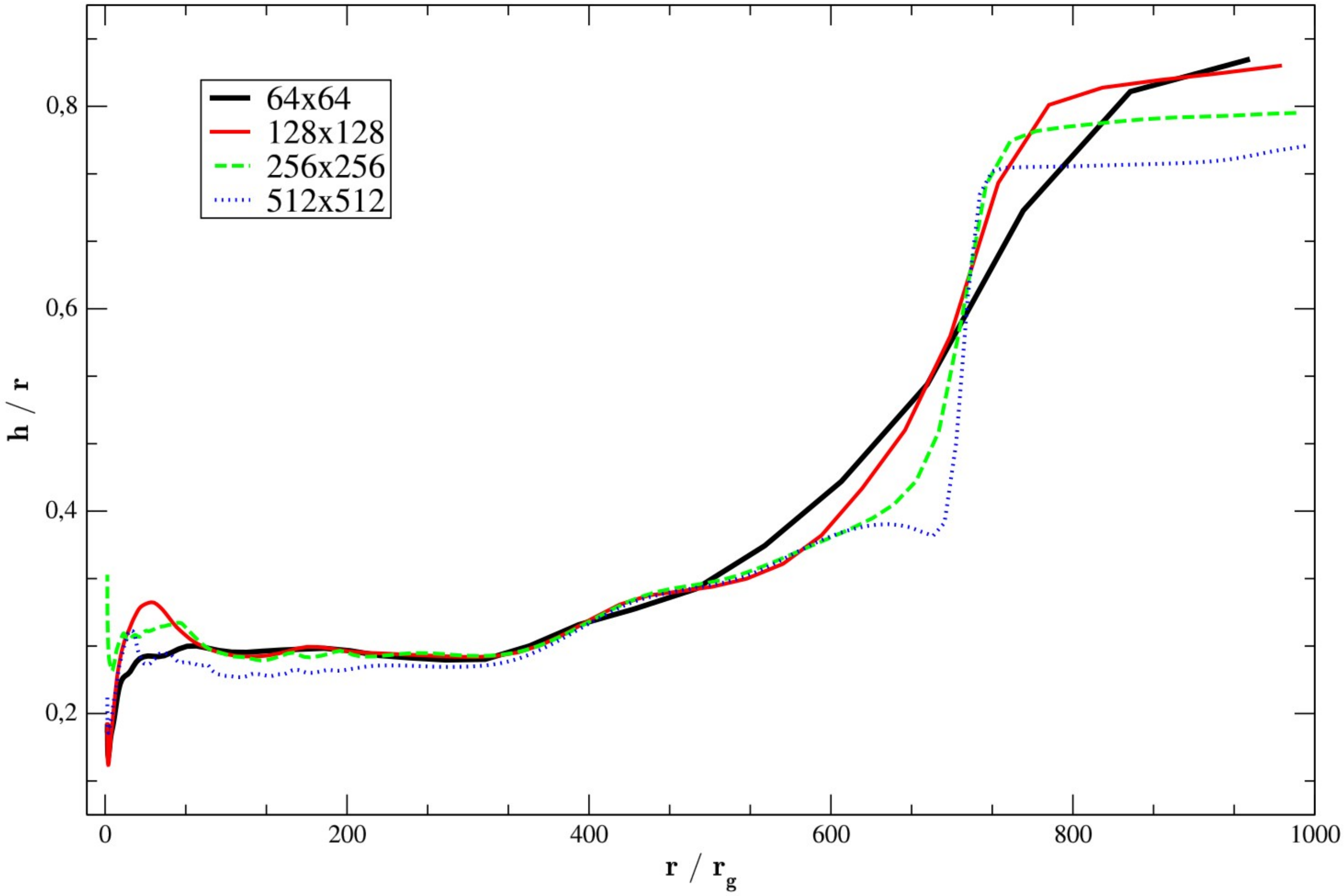
$T^r_t + R^r_t + \rho u^r$

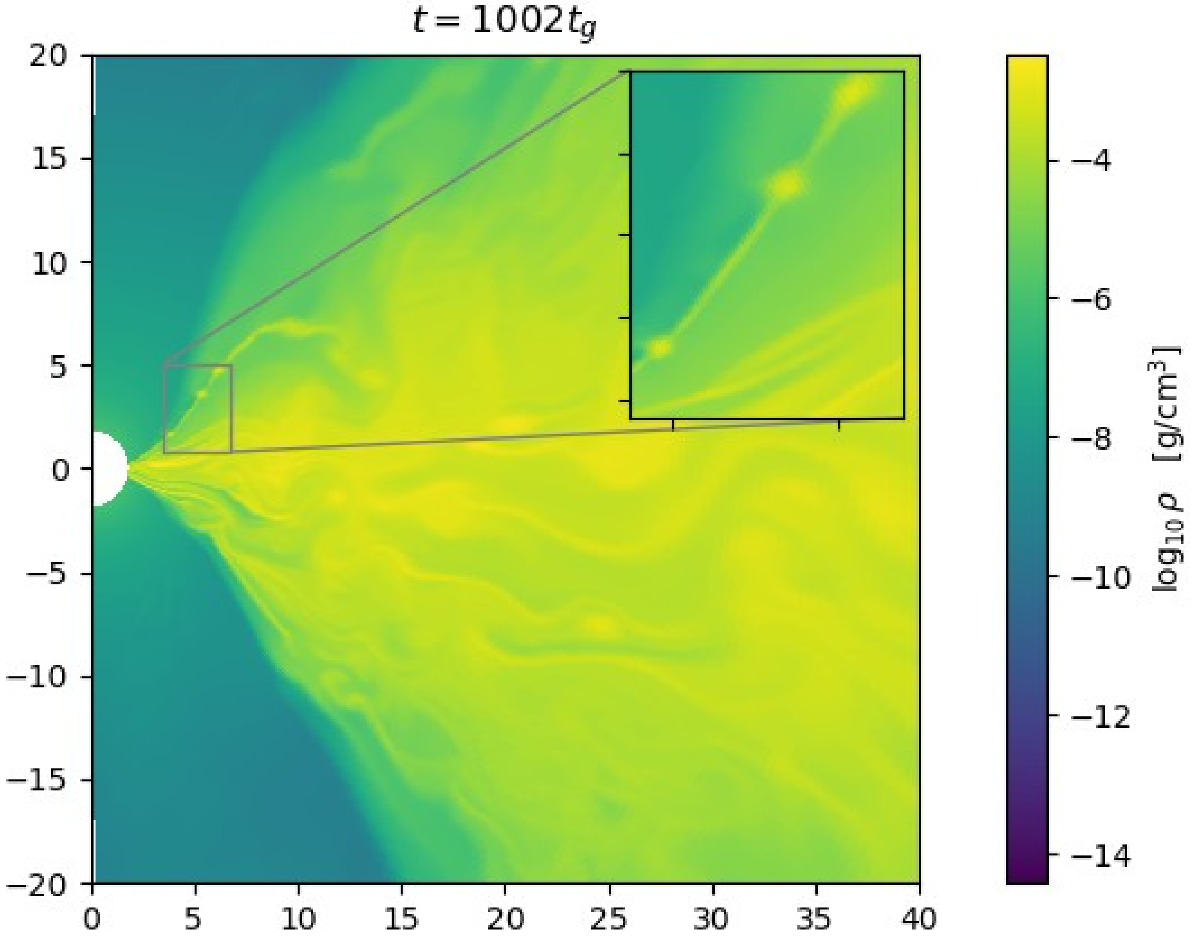




Lrad$_{init}$
r / r$_g$
0
100
200
300
400
500
64x64
128x128
256x256
512x512


Radiation energy density
r / r_g
0
200
400
600
800
1000
64x64
128x128
256x256
512x512


64x64
128x128
256x256
512x512
0,2
0,4
0,6
0,8
h / r
0
200
400
600
800
1000
r / r_g



$t = 1002 t_g$
20
15
10
5
0
−5
−10
−15
−20
0
5
10
15
20
25
30
35
40
−4
−6
−8
−10
−12
−14
$\log_{10} \rho$ [g/cm^3]

Conclusions

- Accretion rate is stable when MRI is properly resolved at $t > 3 \times 10^3 t_g$.
- Resolutions lower than 128x128 are inadequate to capture MRI.
- A resolution of 128x128 might be adequate.
- Quantitative values related to radiation are not affected by resolution.
- Low resolution cannot resolve the fine structure of blobs, plasmoids are only appear in the highest resolution.
- Next: Non-square resolution grid, non-radiative simulations