Radiation MHD Simulation of Super-Eddington Accretion Disks

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Super-Eddington Accretion Disks

- Growth of supermassive black hole seeds in early universe (Mortlock et al. 2011, Volonteri & Silk 2014)
- Tidal Disruption Events (Rees 1988)
- Ultraluminous X-ray (ULX) sources (e.g., Colbert & Mushotzky 1999)

Questions:

- What the super-Eddington disks look like?
- What is the radiative efficiency?
- What the spectrum looks like?

ULX

- Beaming cannot be very strong (King et al. 2001, Pakull & Mirioni 2002, Moon et al. 2011)
    - The observed X-rays are "seen" by the sounding nebulae
- Binaries are very hard to provide the required mass supply if radiation efficiency is low (Rappaport et al. 2005)
- Need to increase the radiative efficiency
    - But optically thin Photon Bubbles probably do not exist (Begelman 2002)

Slim Disk Model

Abramowicz et al. (1988)

- Photon Trapping
  - Optical depth is so large that photon diffusion time is very long
  - Photon Trapping radius
- Radiative Efficiency
  - Radiative efficiency decreases with accretion rate

$$R_{\rm tr} = \dot{m} R_s$$

$$\frac{L}{L_{\rm Edd}} \sim 2\left[1+\ln\left(\frac{\dot{m}}{50}\right)\right],$$

Sadowski et al. (2014)
McKinney et al. (2014)

Minimum Physics Required for First Principle Calculations

- Magneto-rotational Instability (MRI)
  - Angular Momentum Transfer
  - Dissipation
- Radiative Transfer
  - Radiation pressure supported disks
  - Angular distribution of the intensity
- 3D Calculations
  - Self-consistent dynamo and turbulence only exists in 3D

Ideal MHD with Time-dependent Transfer Equation

Jiang et al. (2014)

Ideal MHD

photon momentum

$$\frac{\partial\rho}{\partial t} + \boldsymbol{\nabla}\cdot(\rho\boldsymbol{v}) = 0,$$
$$\frac{\partial(\rho\boldsymbol{v})}{\partial t} + \boldsymbol{\nabla}\cdot(\rho\boldsymbol{v}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B} + \mathsf{P}^*) = -\boldsymbol{S_r}(\boldsymbol{P}) - \rho\boldsymbol{\nabla}\phi,$$
$$\frac{\partial E}{\partial t} + \boldsymbol{\nabla}\cdot[(E + P^*)\boldsymbol{v} - \boldsymbol{B}(\boldsymbol{B}\cdot\boldsymbol{v})] = -cS_r(E) - \rho\boldsymbol{v}\cdot\boldsymbol{\nabla}\phi,$$
$$\frac{\partial\boldsymbol{B}}{\partial t} - \boldsymbol{\nabla}\times(\boldsymbol{v}\times\boldsymbol{B}) = 0. \qquad (1)$$

radiation energy

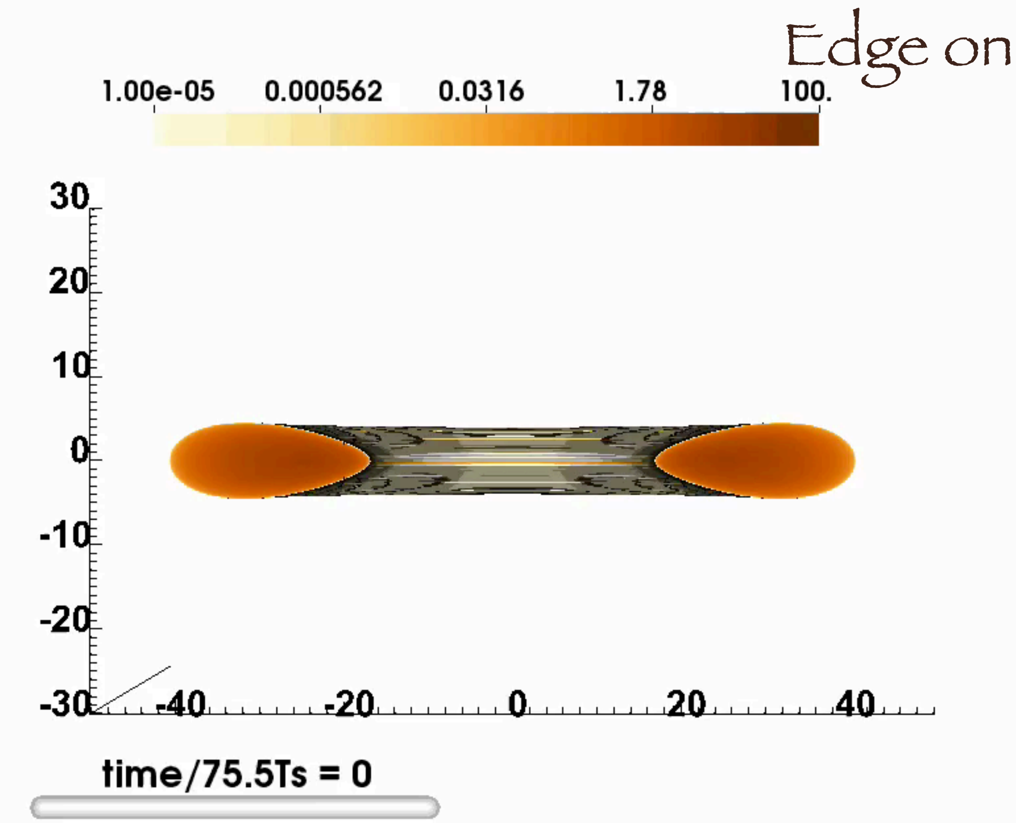
Radiative Transfer

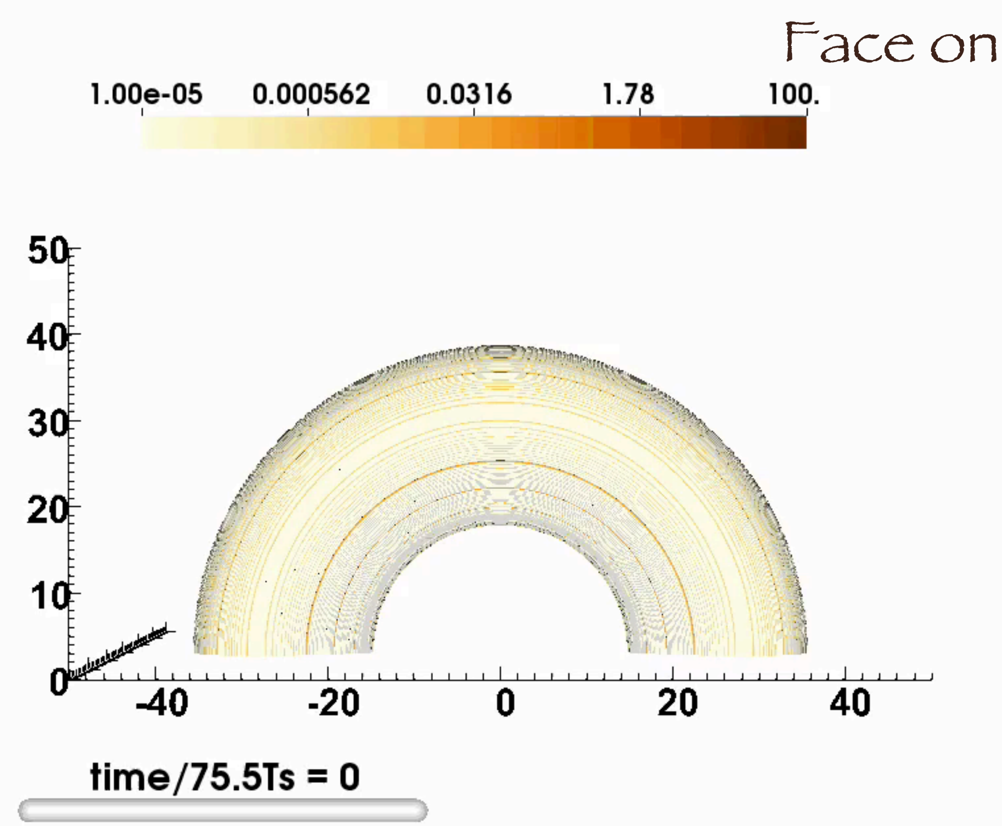
$$\frac{\partial I}{\partial t} + c\boldsymbol{n}\cdot\boldsymbol{\nabla}I = c\sigma_a\left(\frac{a_rT^4}{4\pi} - I\right) + c\sigma_s(J - I)$$
$$+ 3\boldsymbol{n}\cdot\boldsymbol{v}\sigma_a\left(\frac{a_rT^4}{4\pi} - J\right)$$
$$+ \boldsymbol{n}\cdot\boldsymbol{v}(\sigma_a + \sigma_s)(I + 3J) - 2\sigma_s\boldsymbol{v}\cdot\boldsymbol{H}$$
$$- (\sigma_a - \sigma_s)\frac{\boldsymbol{v}\cdot\boldsymbol{v}}{c}J - (\sigma_a - \sigma_s)\frac{\boldsymbol{v}\cdot(\boldsymbol{v}\cdot\mathsf{K})}{c}.$$

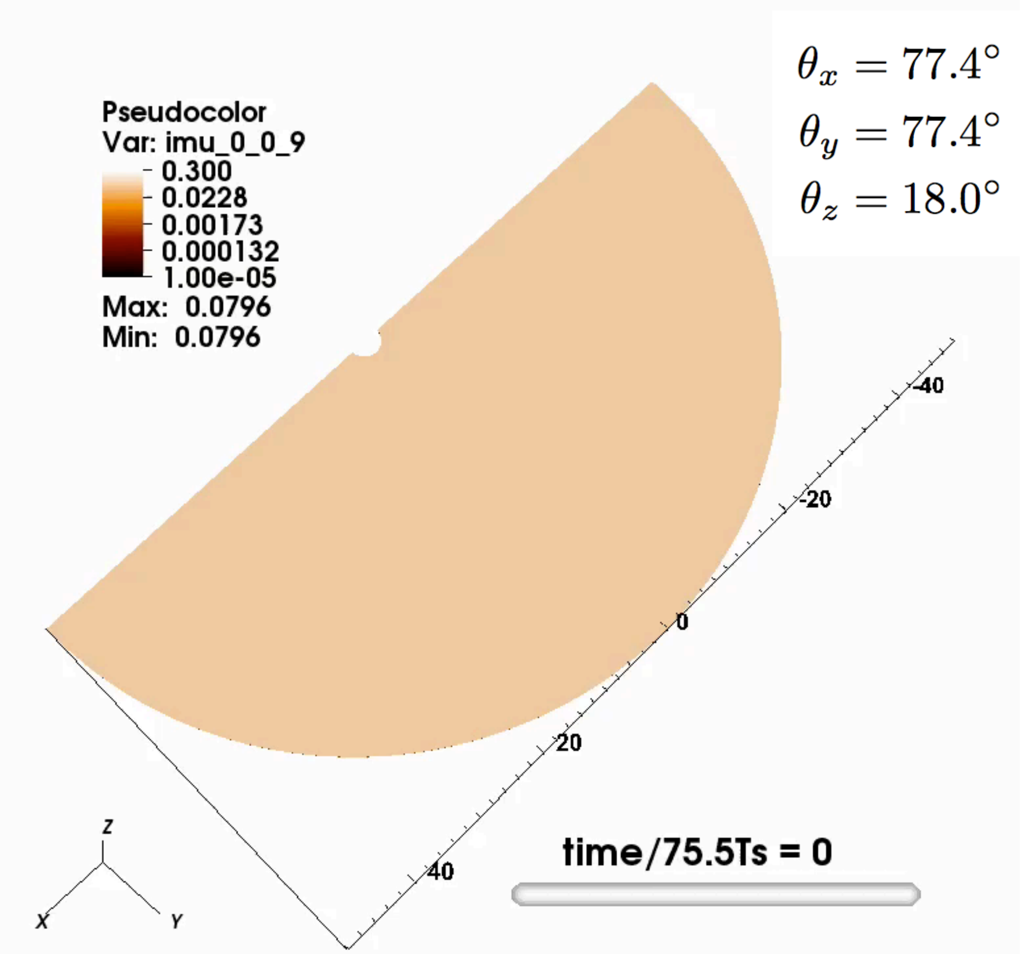
$$J \equiv \int I d\Omega, \boldsymbol{H} \equiv \int \boldsymbol{n} I d\Omega, \mathsf{K} \equiv \int \boldsymbol{n}\boldsymbol{n} I d\Omega.$$

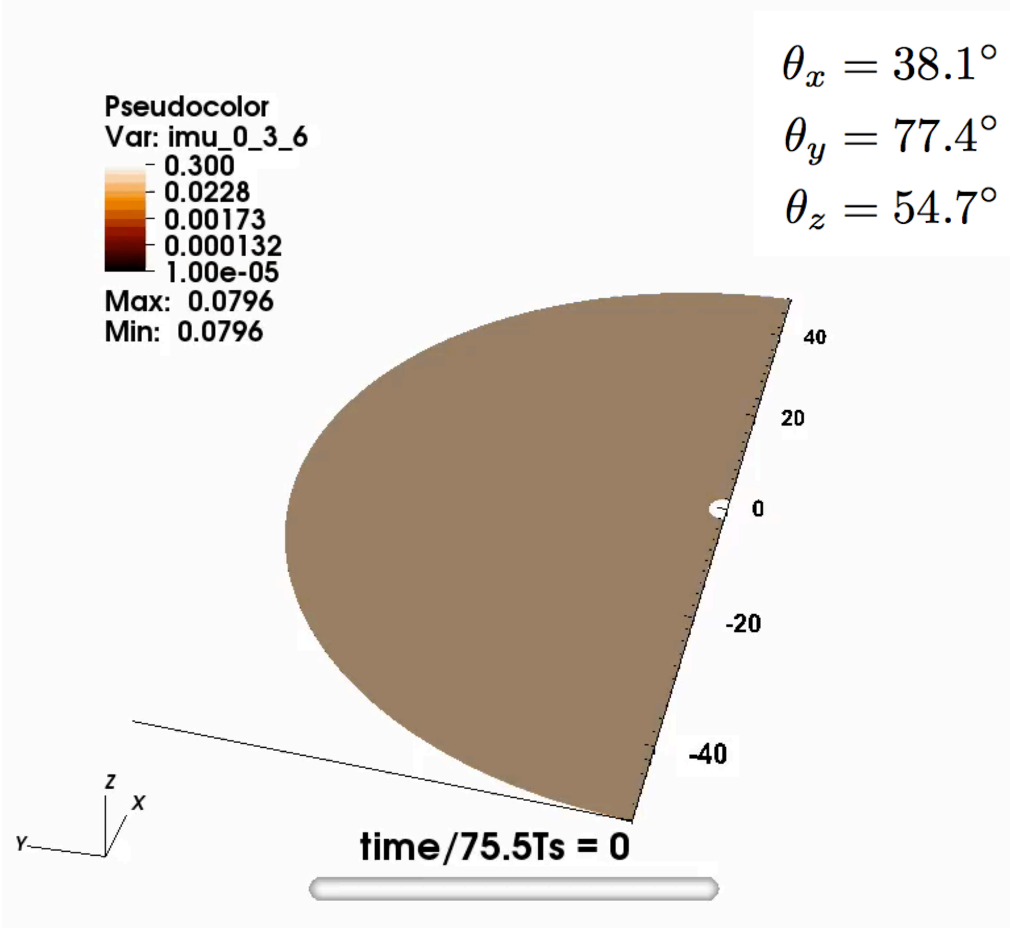
Density and Specific Intensity

$$
\begin{aligned}
r &\in (2, 50)r_g \\
\phi &\in (0, \pi) \\
z &\in (-30, 30)r_g \\
N_r &= 512 \\
N_\phi &= 128 \\
N_z &= 1024 \\
N_n &= 80
\end{aligned}
$$





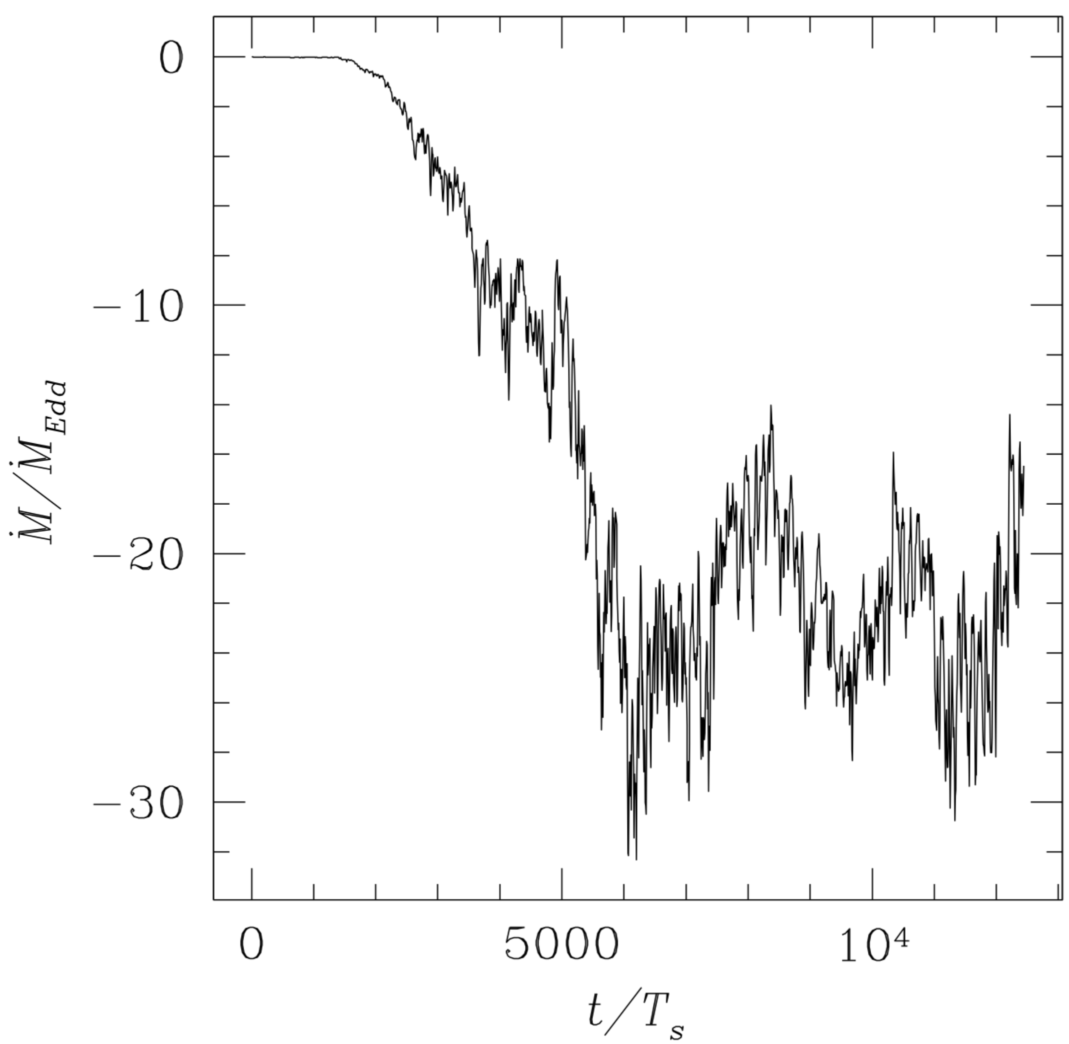


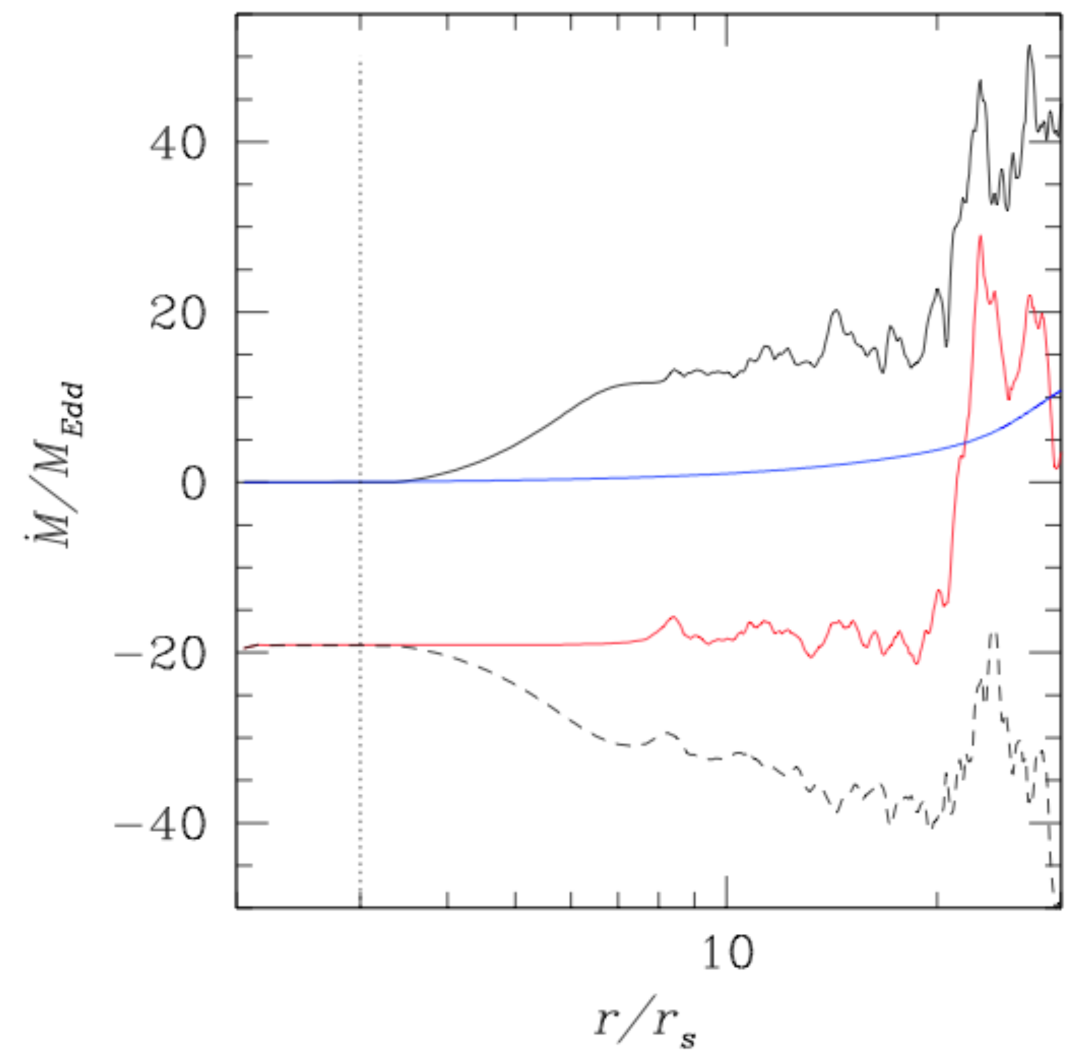


Accretion Rate

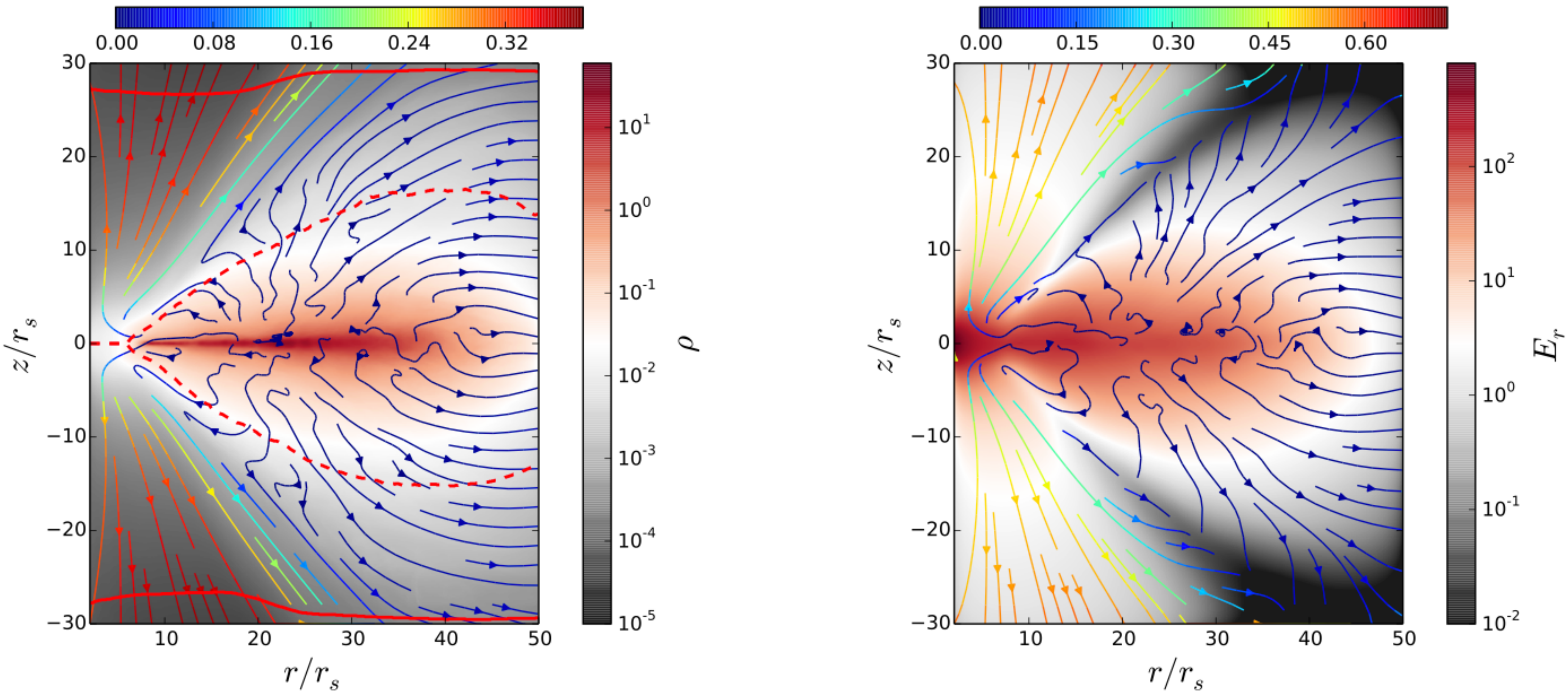
$$L_{\rm edd} = \frac{4\pi G M_{\rm BH} c}{\kappa_{\rm es}},$$

$$M_{\rm edd} = \frac{L_{\rm edd}}{0.1c^2} = \frac{40\pi G M_{\rm BH}}{\kappa_{\rm es} c}.$$



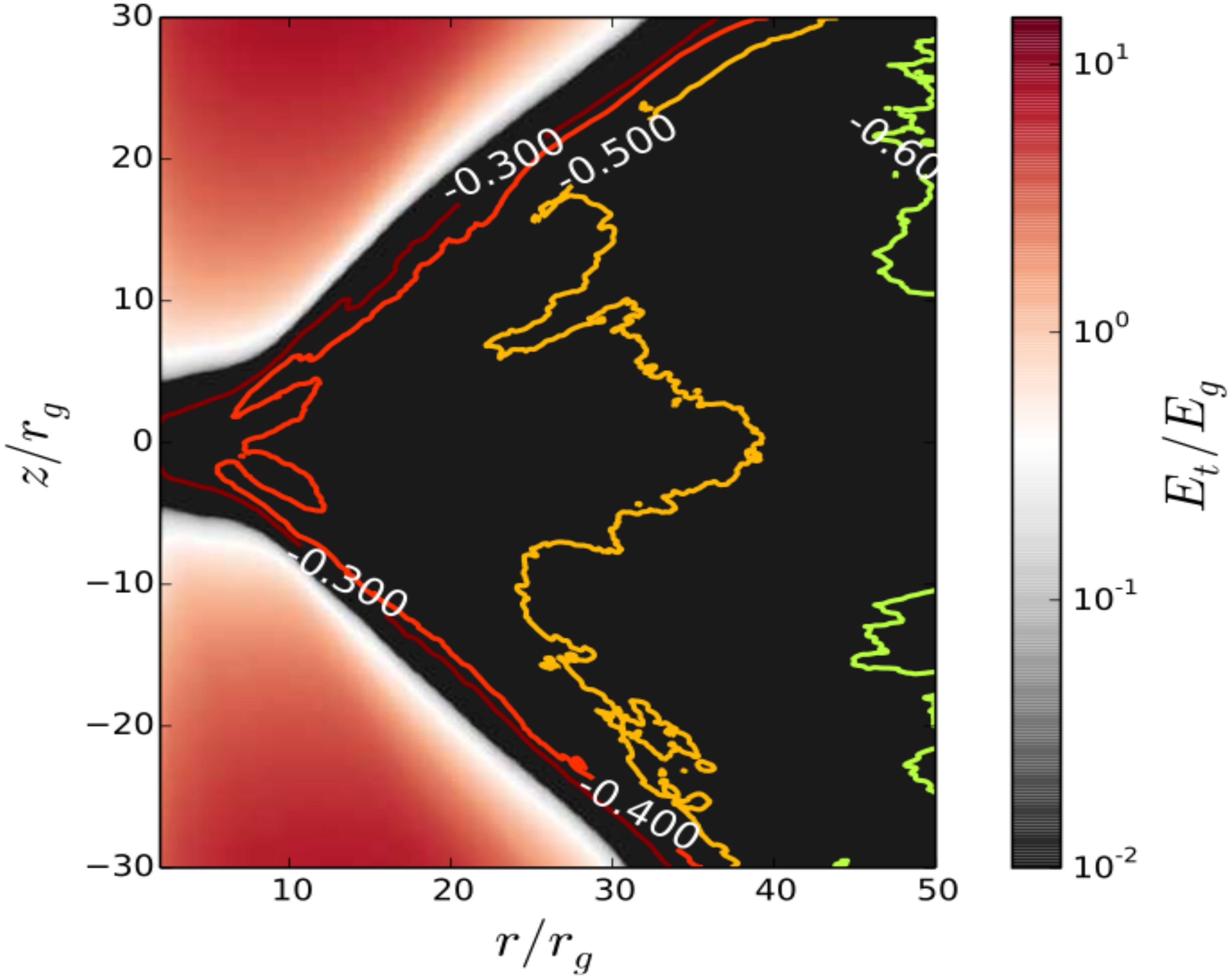


Radiation Driven Outflow



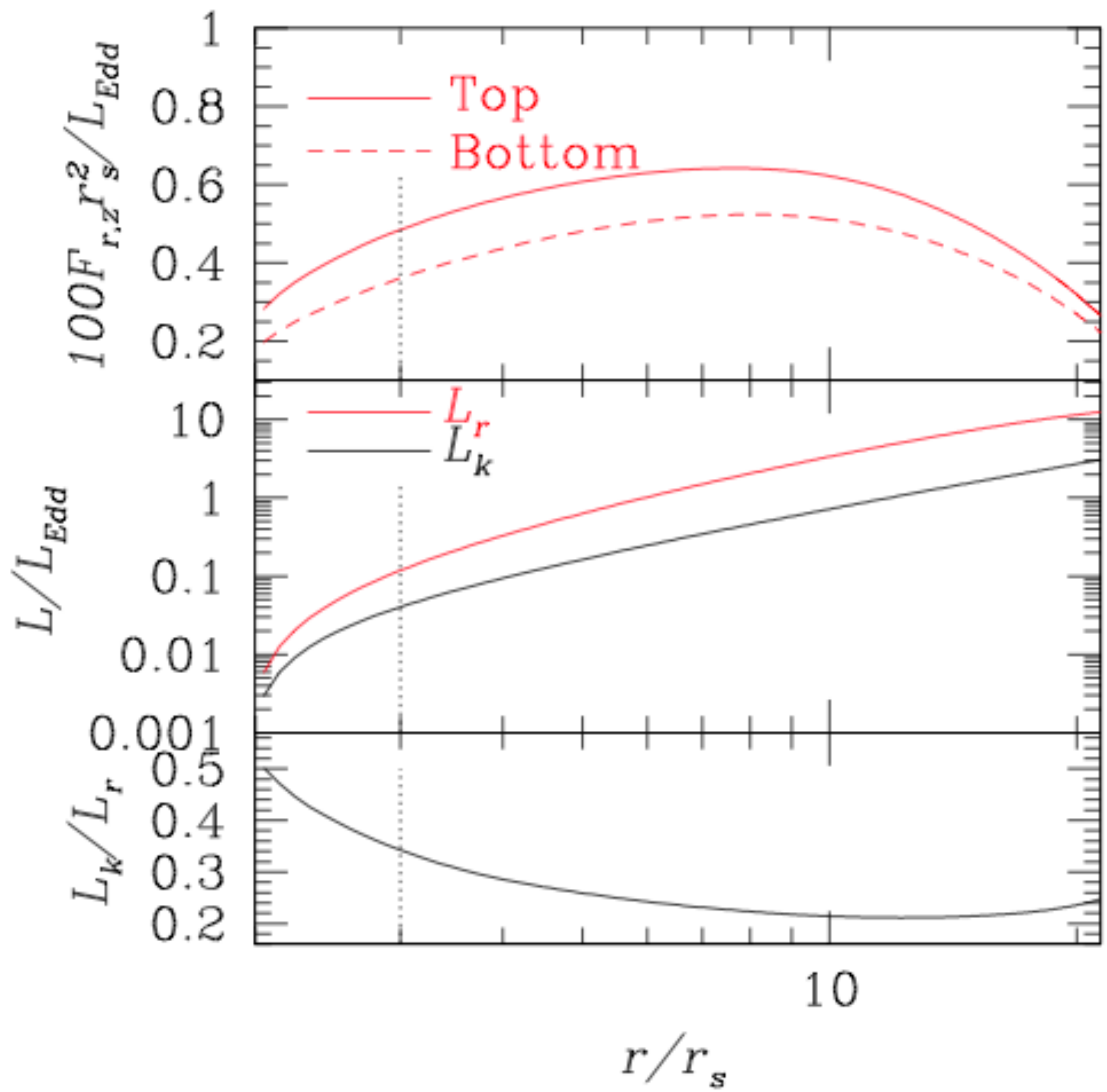
- Strong outflow with a large open angle

Radiation Driven Outflow



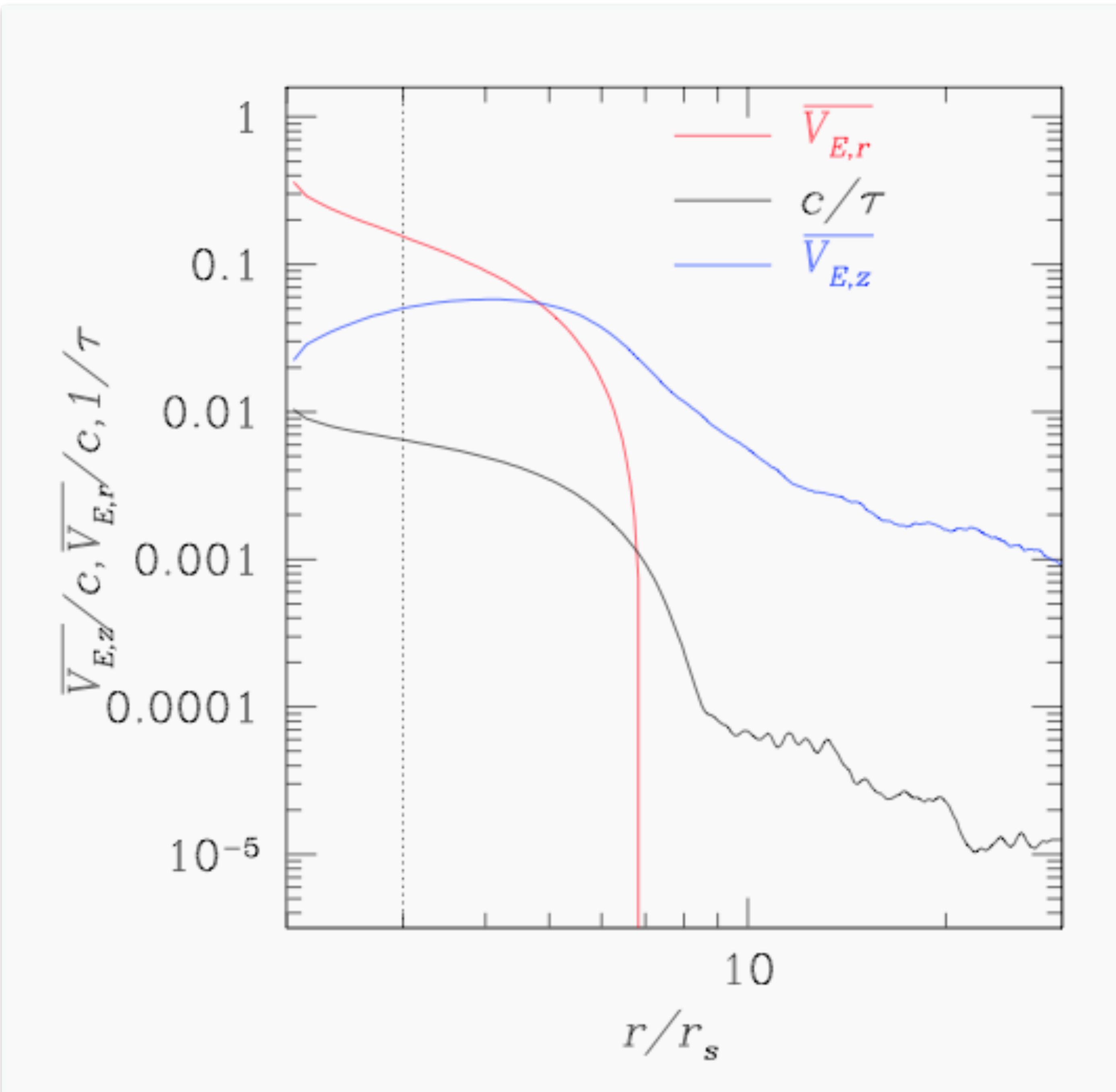
- total energy is positive in the outflow region

Radiative and Kinetic Energy Flux



Energy Transport Velocity

- Diffusive Energy Transport Speed $c/\tau,\ \tau \sim 10^4$
- Advective Energy Transport Speed v

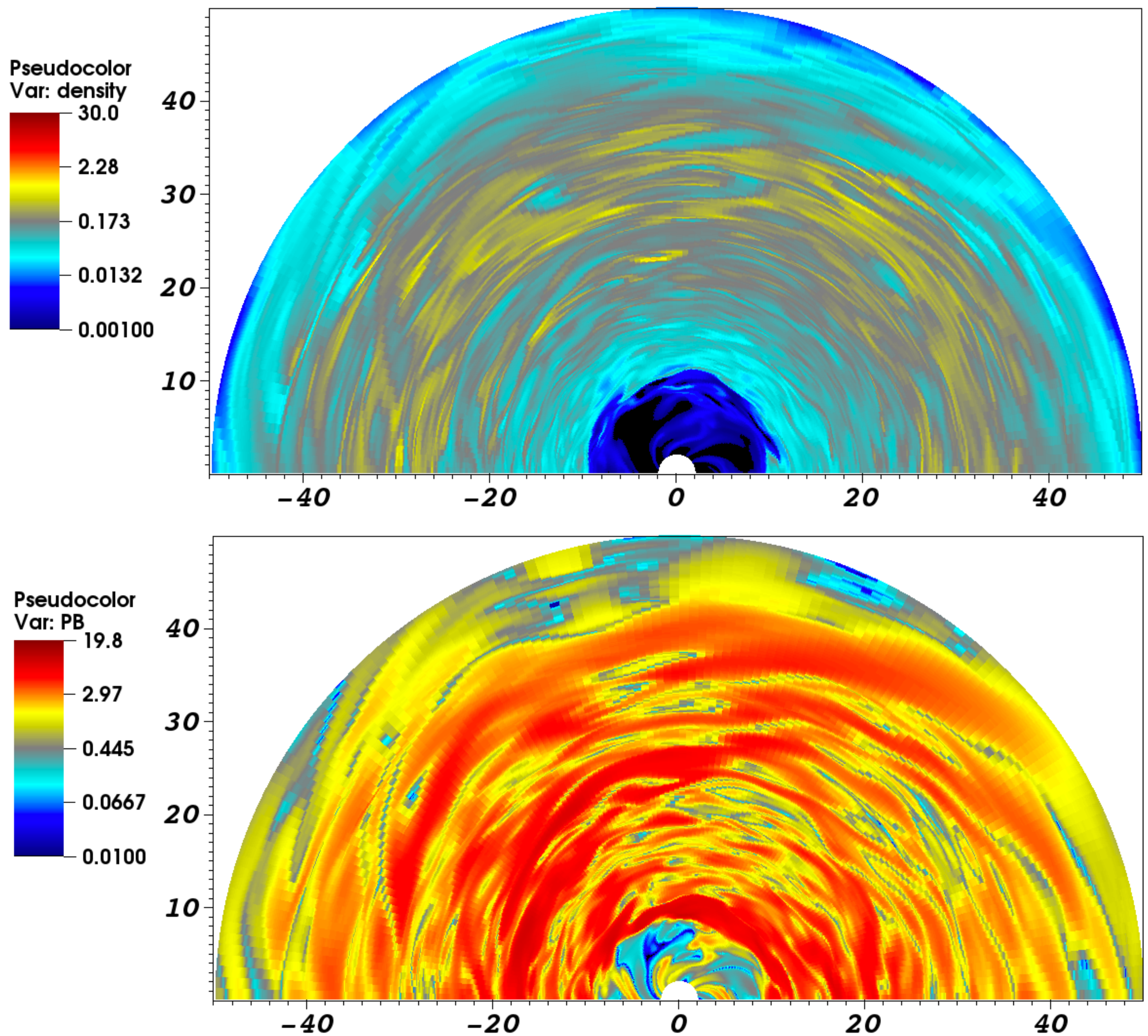


- Advective photons are released near the photosphere
- Scale height is reduced
- Dissipation is moved away from the disk mid-plane
- Luminosity is increased

Vertical Advective Energy Transport due to Magnetic Buoyancy

Snapshot (z=5r_s)

Blaes et al. (2011)
Jiang et al. (2013)

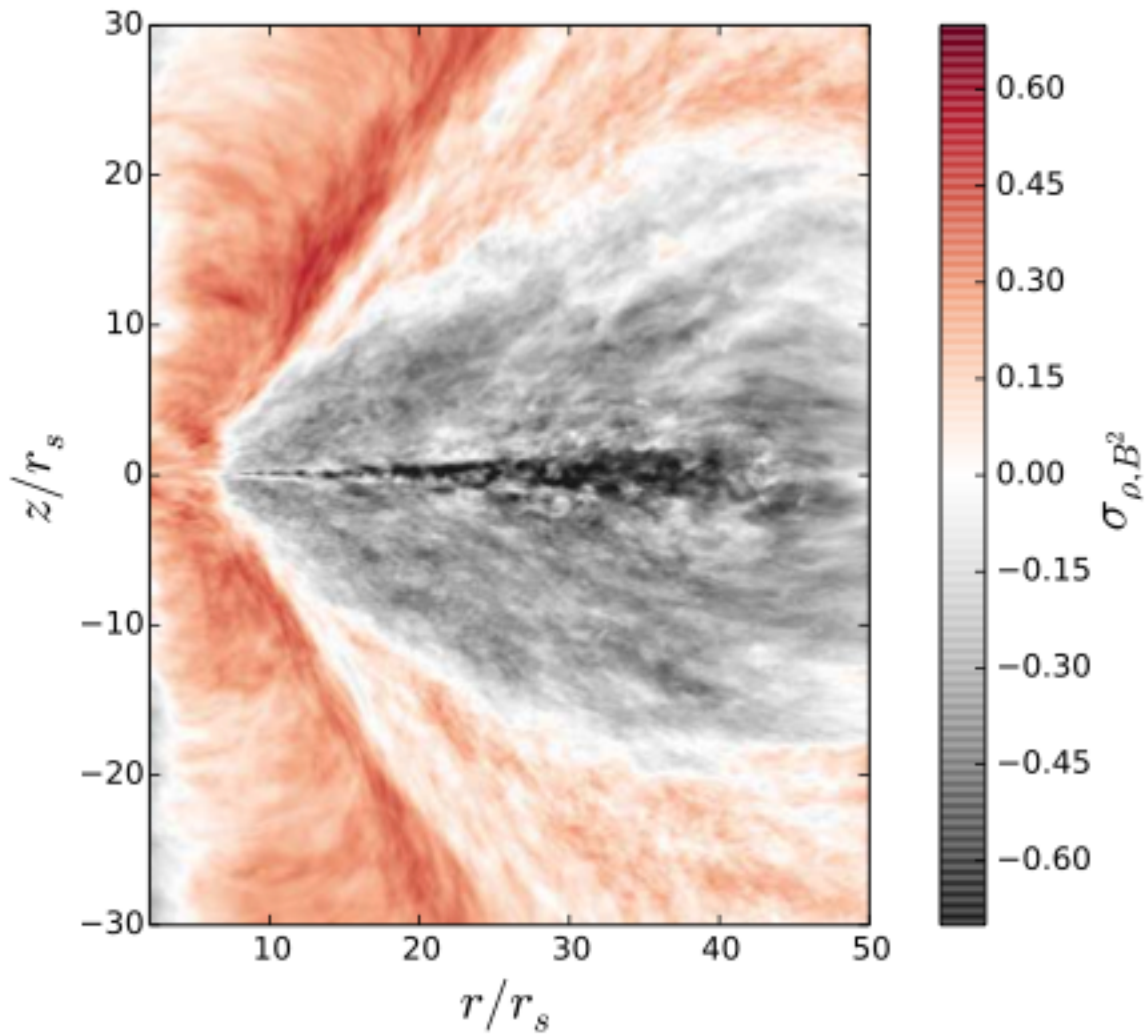


Vertical Advective Energy Transport due to Magnetic Buoyancy

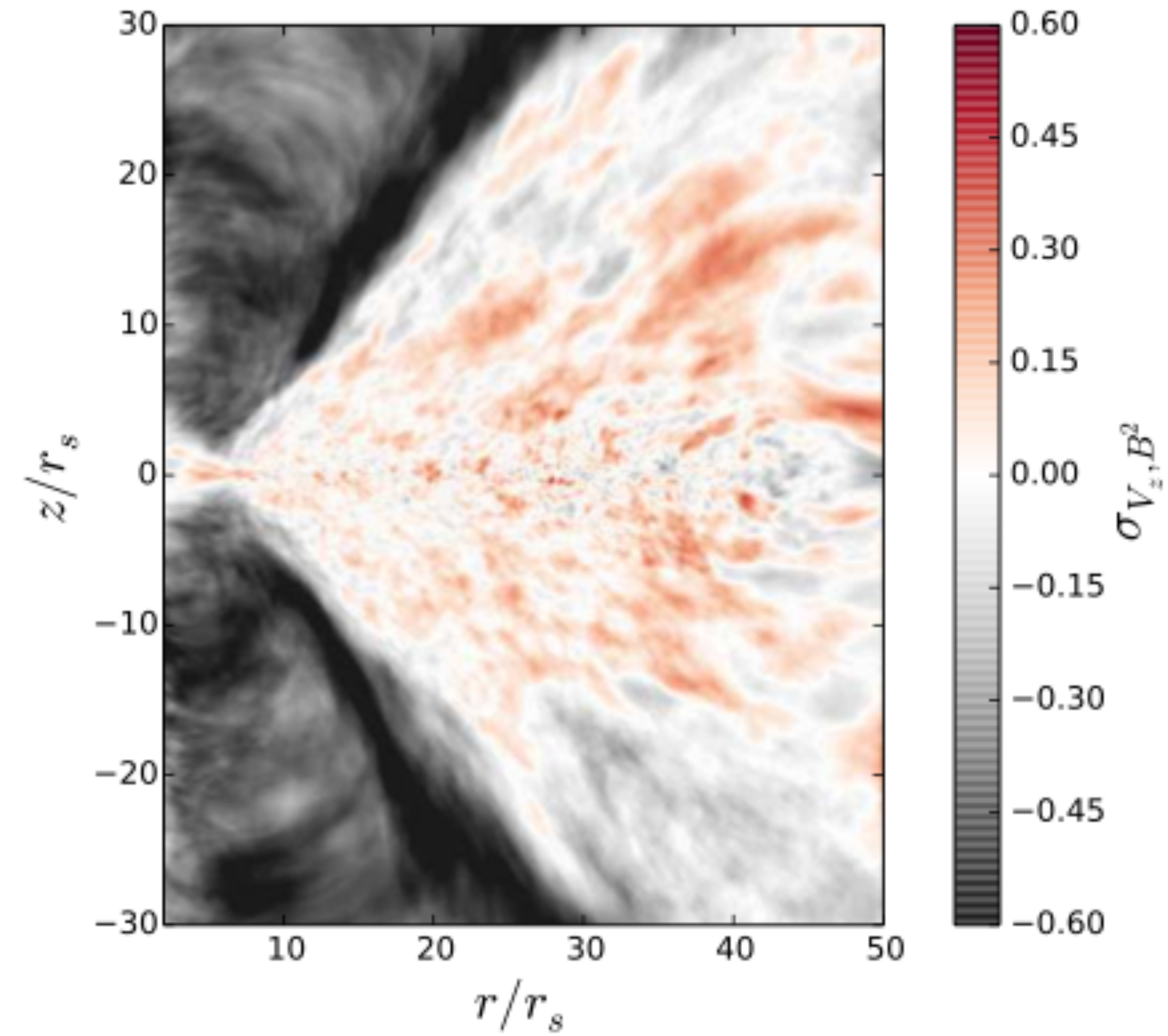
$$\sigma_{\rho,B^2} = \frac{\langle(\rho-\overline{\rho})(B^2-\overline{B^2})\rangle}{\sigma_\rho\sigma_{B^2}},$$

$$\sigma_{V_z,B^2} = \frac{\langle(|v_z|-\overline{|v_z|})(B^2-\overline{B^2})\rangle}{\sigma_{v_z}\sigma_{B^2}},$$

- Density, magnetic pressure, vertical velocity correlations for the global simulations along the azimuthal direction (3D)

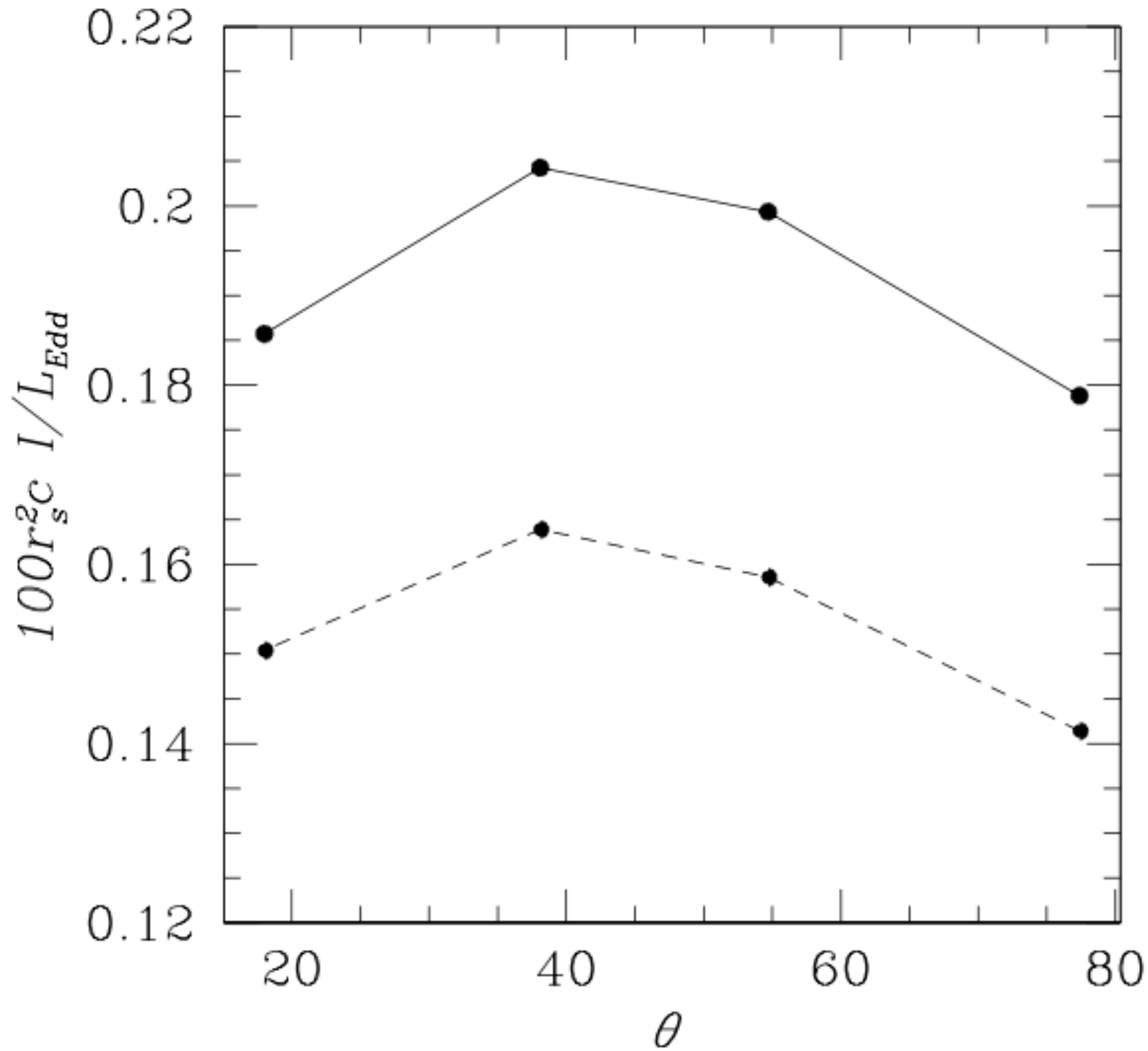


Density - Magnetic pressure



Magnetic Pressure - Vertical Motion

Angular Distribution



Beaming is not very strong.

Conclusion

- It is possible to solve the full radiative transfer equation for MHD simulations.
- Advection caused by magnetic buoyancy can help increase the radiative efficiency of super-Eddington accretion disks (we do not need Photon bubbles)
- Radiation coming from the disk is not very strongly beamed