Theoretical Calculations of the Inner Disk’s Luminosity

Scott C. Noble, Julian H. Krolik (JHU)

(John F. Hawley, Charles F. Gammie)

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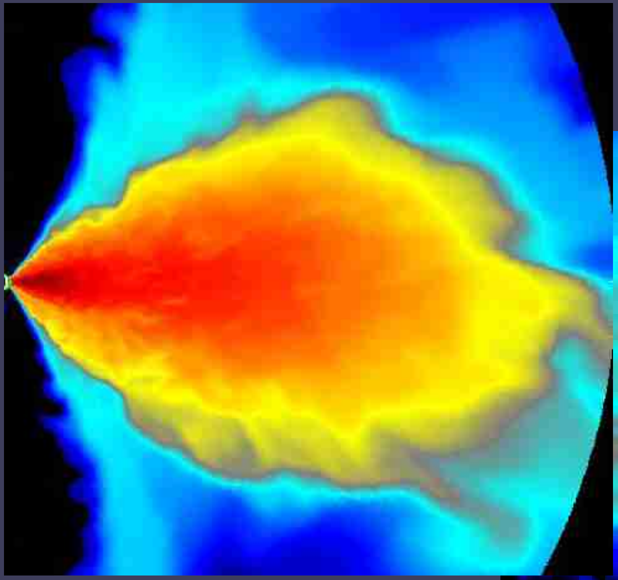
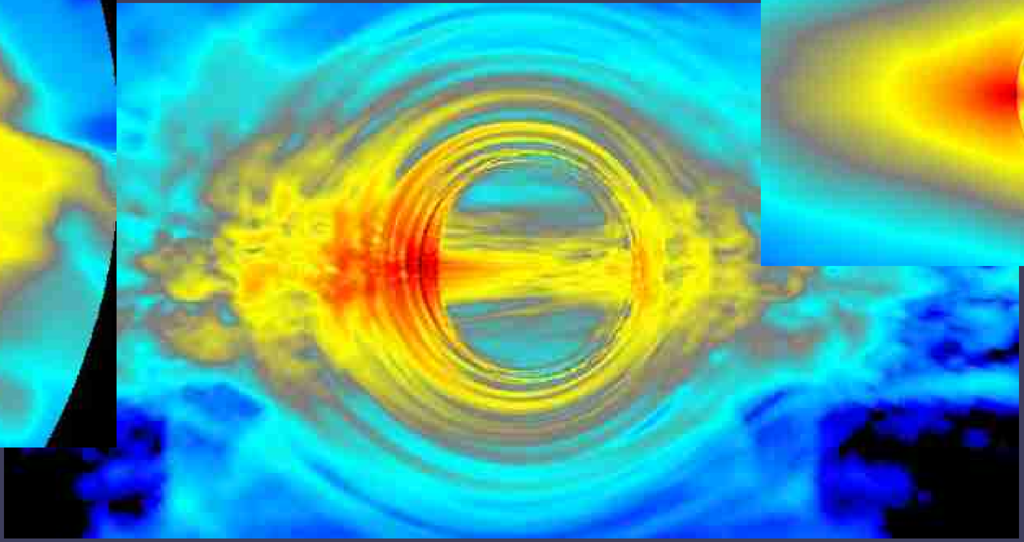
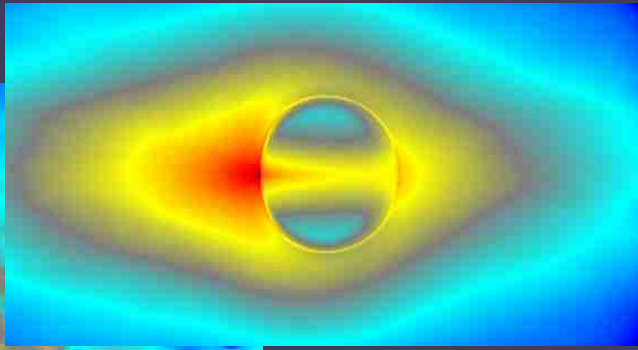
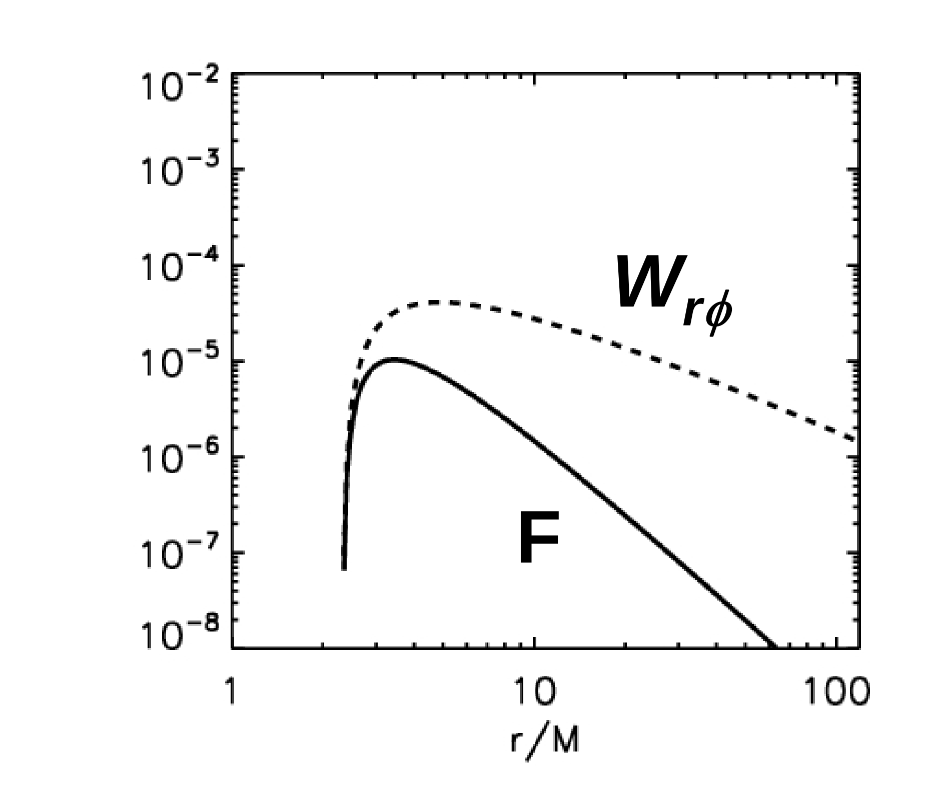






Steady-State Model: Novikov & Thorne (1973)

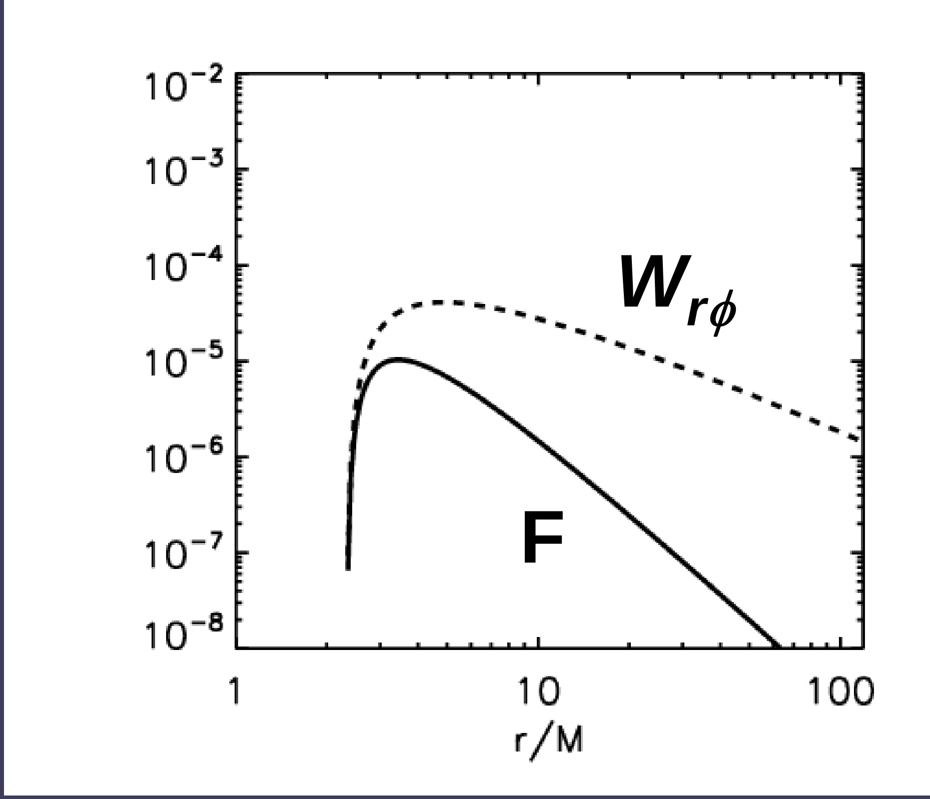
- GR model of radiatively efficient disks
- $F(r,a) \rightarrow T(r,a)$ and R_{in}
- Observations $\rightarrow M_{BH}$, a_{BH}



Steady-State Model: Novikov & Thorne (1973)

Assumptions:

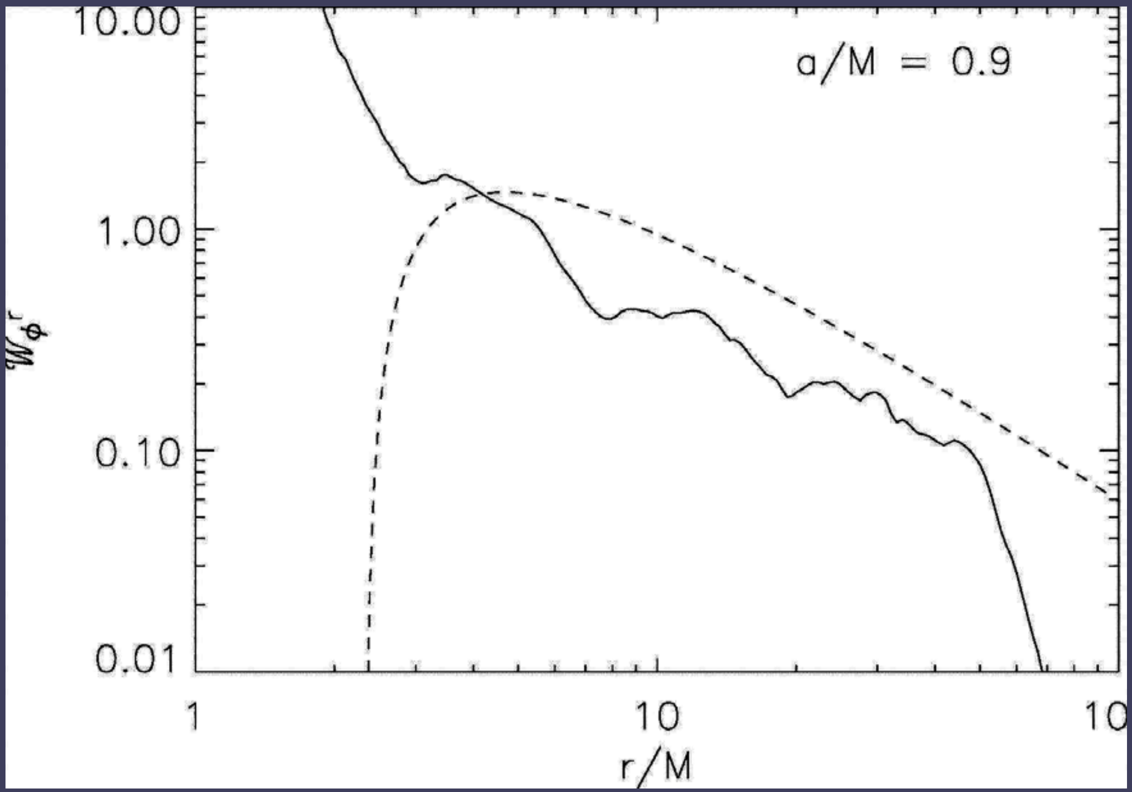
1) Stationary gravity
2) Equatorial Keplerian Flow
   - ➢ Thin, cold disks
   - o Tilted disks?
3) Time-independent
4) Prompt, local dissipation of stress to heat
5) Conservation of M, E, L
6) Zero Stress at ISCO
   - o Magnetic fields?
   - o Need dynamic simulations!



For steady-state model context:
Shafee, Narayan, McClintock (2008)

Previous Work

- De Villiers, Hawley, Hirose, Krolik (2003-2006)
  - MRI develops from weak initial field.
  - Significant field within ISCO up to the horizon
- Beckwith, Hawley, Krolik (2008)
  - Rad. Flux ~ Stress
  - Uncontrolled loss of dissipated energy



Krolik, Hawley, Hirose (2005)

Our Method: Simulations

- **HARM**:
  Gammie, McKinney, Toth (2003)
- Axisymmetric (2D)
- Total energy conserving
- Modern Shock Capturing techniques (greater accuracy)
- Improvements:
  - 3D
  - More accurate (higher effective resolution)
  - Stable low density flows

$$\nabla_\nu {}^*F^{\mu\nu} = 0$$

$$\nabla_\mu \left(\rho u^\mu\right) = 0$$

$$\nabla_\mu T^\mu{}_\nu = 0$$

Our Method: Simulations

- Improvements:
  - 3D
  - More accurate (higher effective resolution)
  - Stable low density flows

  - Cooling function:
    - Control energy loss rate
    - Parameterized by H/R
    - $t_{cool} \sim t_{orb}$
    - Only cool when $T > T_{target}$
    - Passive radiation
    - Radiative flux is stored for self-consistent post-simulation radiative transfer calculation

$$\nabla_\nu {}^*F^{\mu\nu} = 0$$

$$\nabla_\mu \left(\rho u^\mu\right) = 0$$

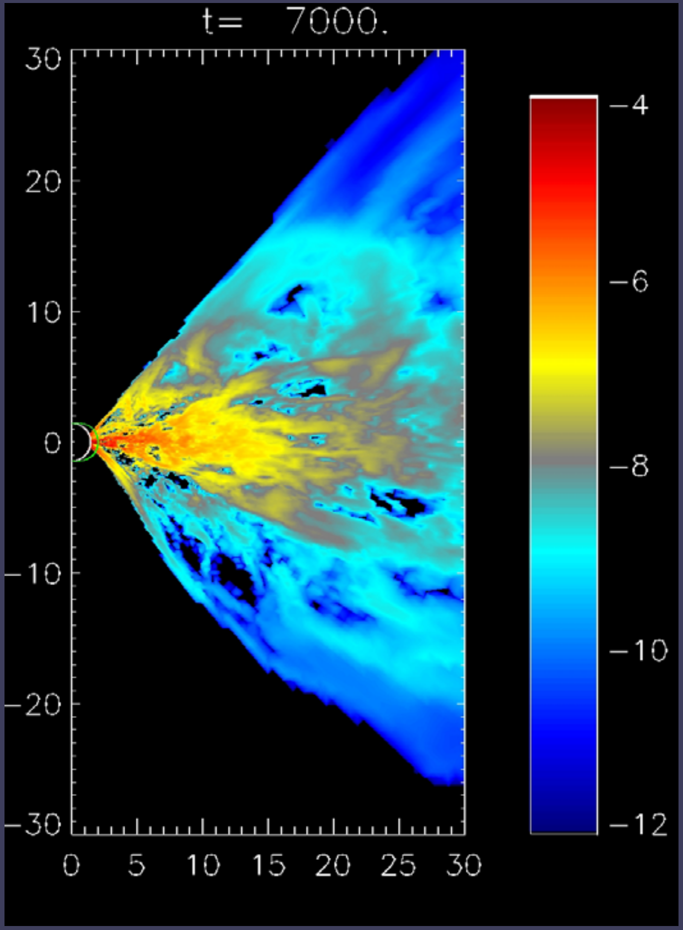
$$\nabla_\mu T^\mu{}_\nu = -\mathcal{F}_\mu$$

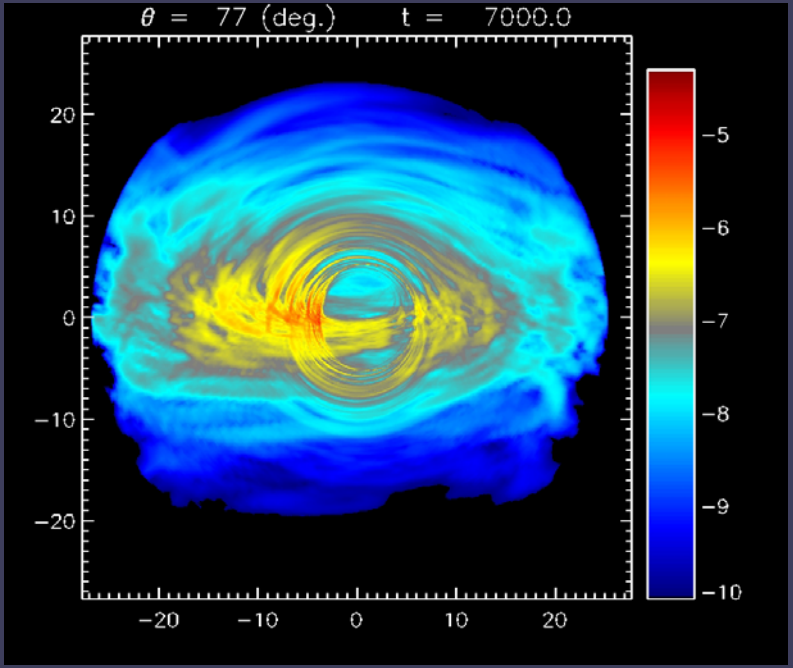
H/R ~ 0.1 $a_{BH} = 0.9$

Our Method: Radiative Transfer

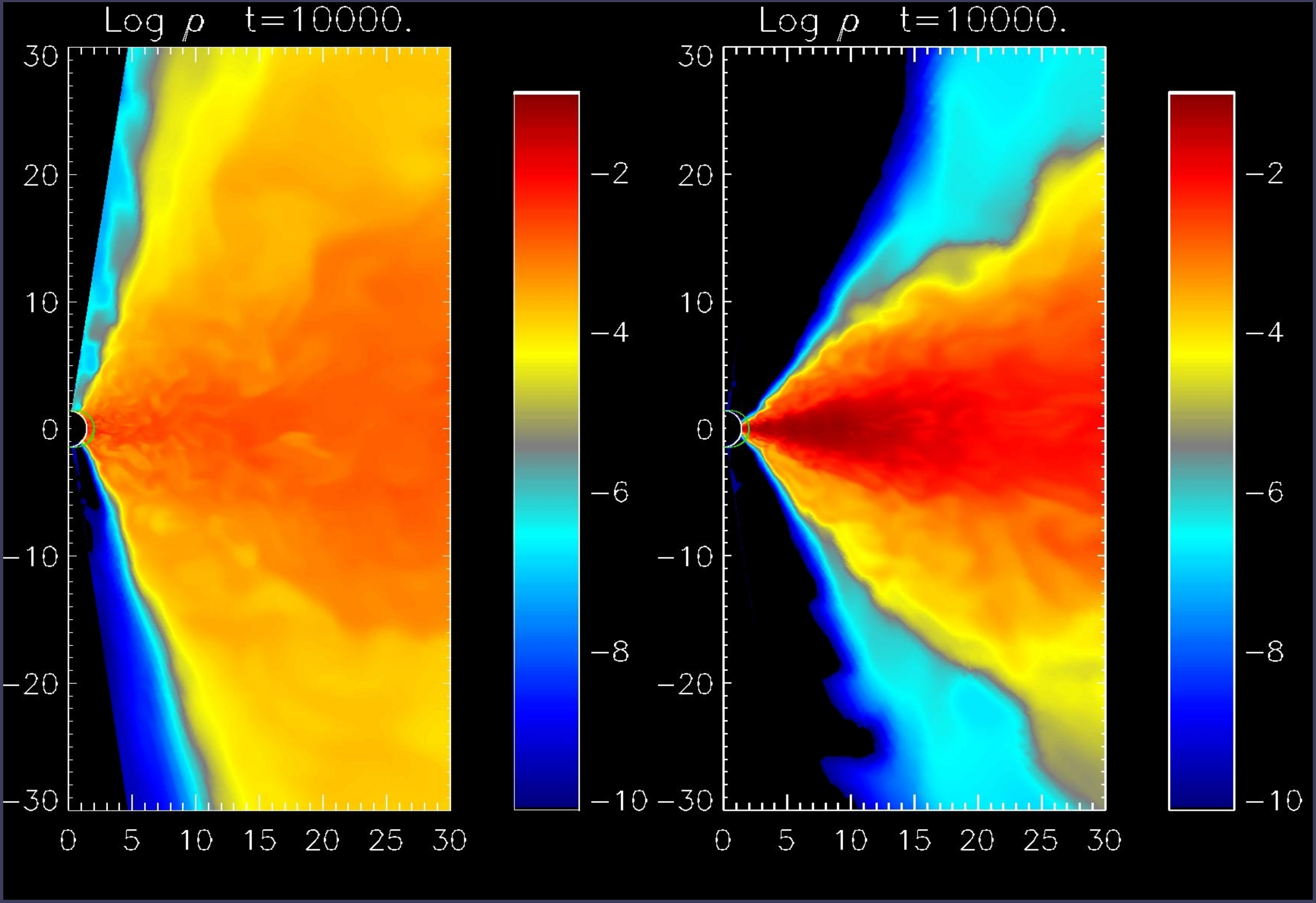
$$j \propto \mathcal{F}_\mu$$

- Full GR radiative transfer
  - GR geodesic integration
  - Doppler shifts
  - Gravitational redshift
  - Relativistic beaming
  - Uses simulation's fluid vel.
  - Inclination angle survey
  - Time domain survey

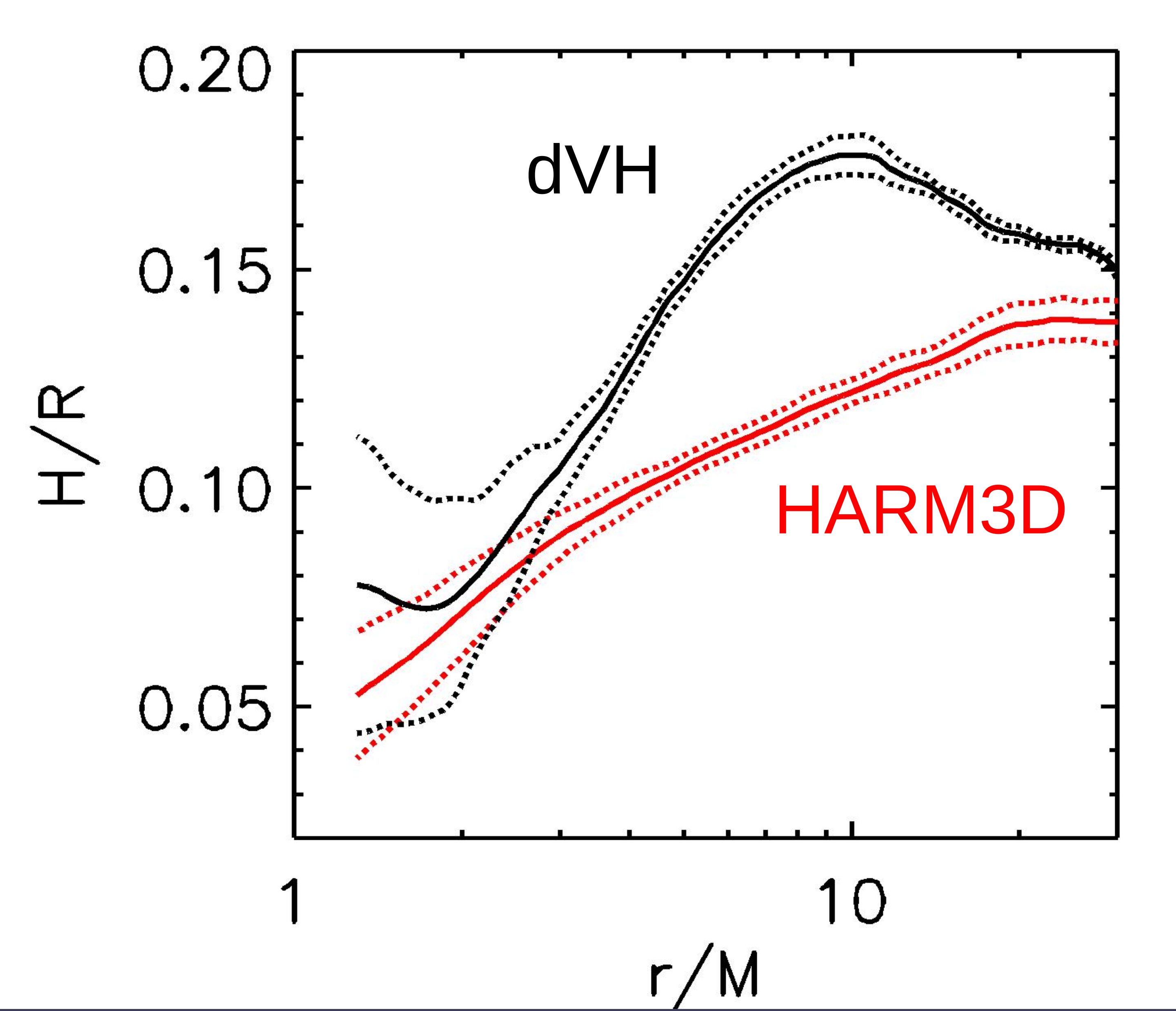




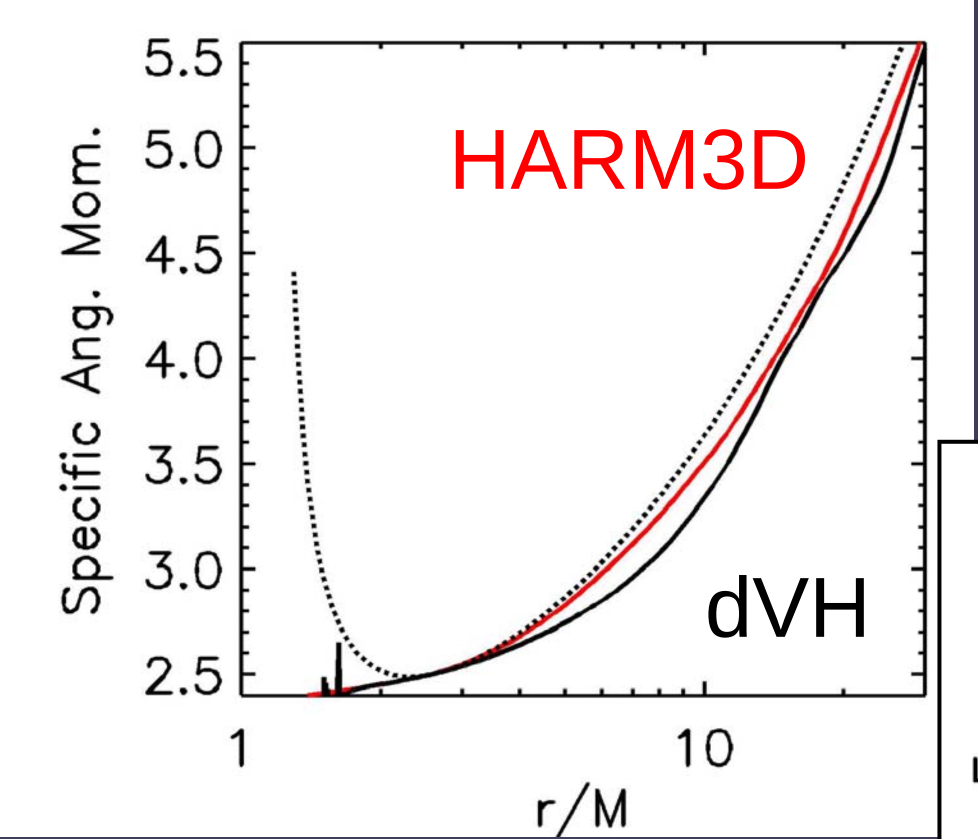
Disk Thermodynamics

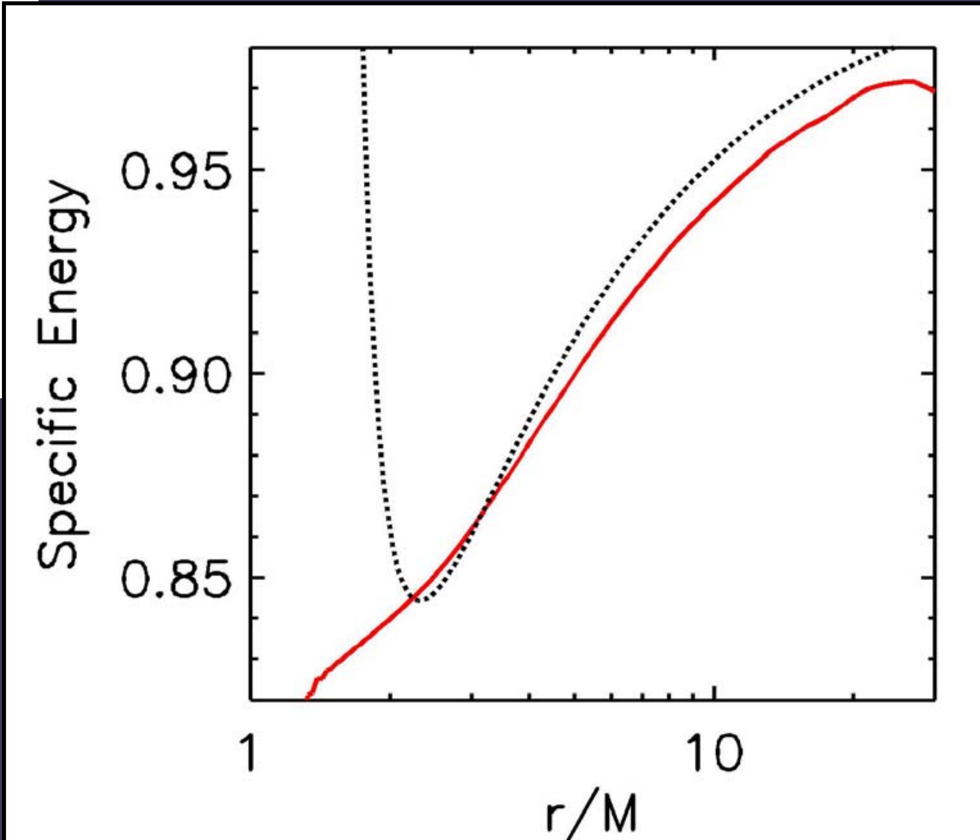


Disk Thickness

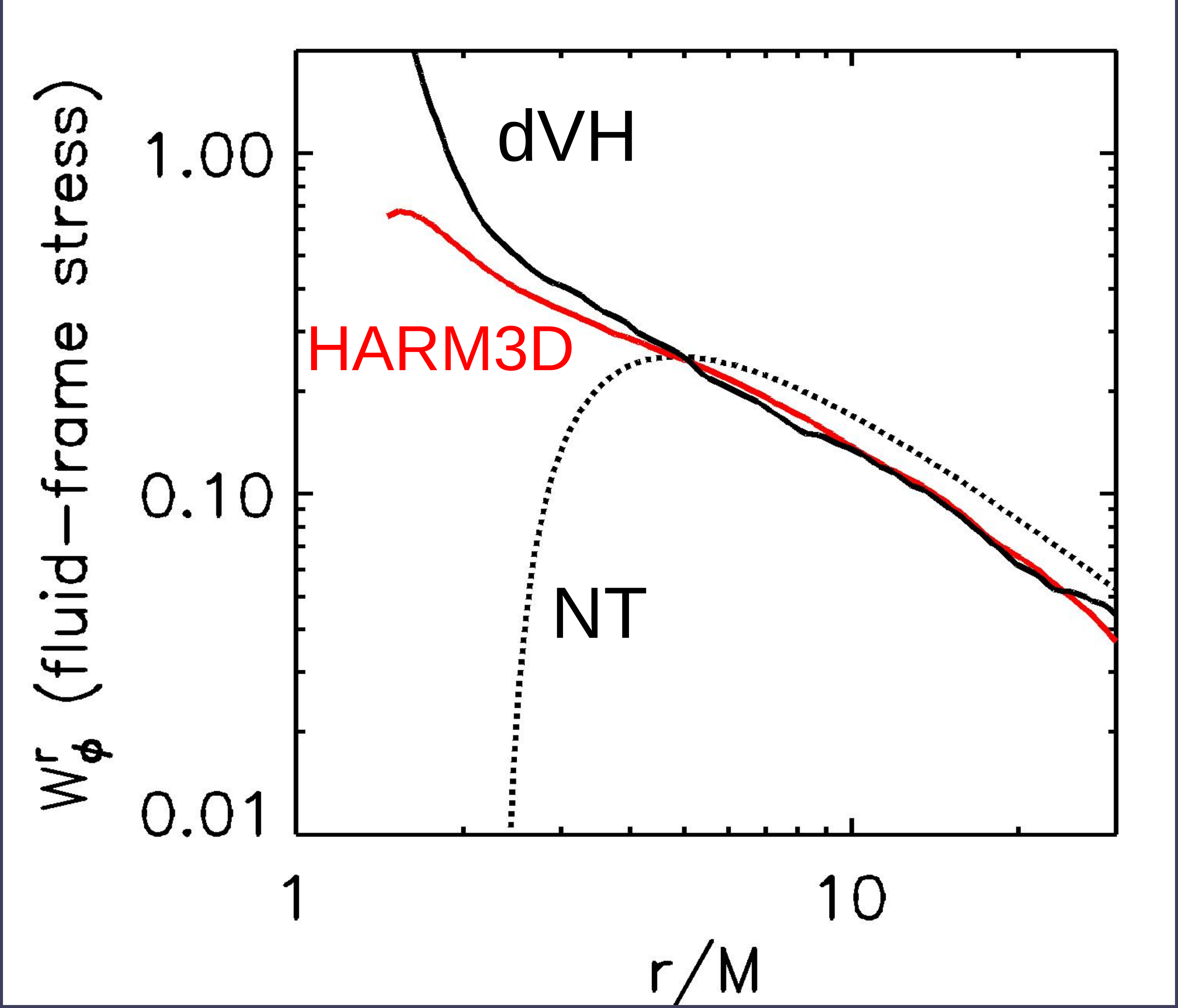


Departure from Keplerian Motion

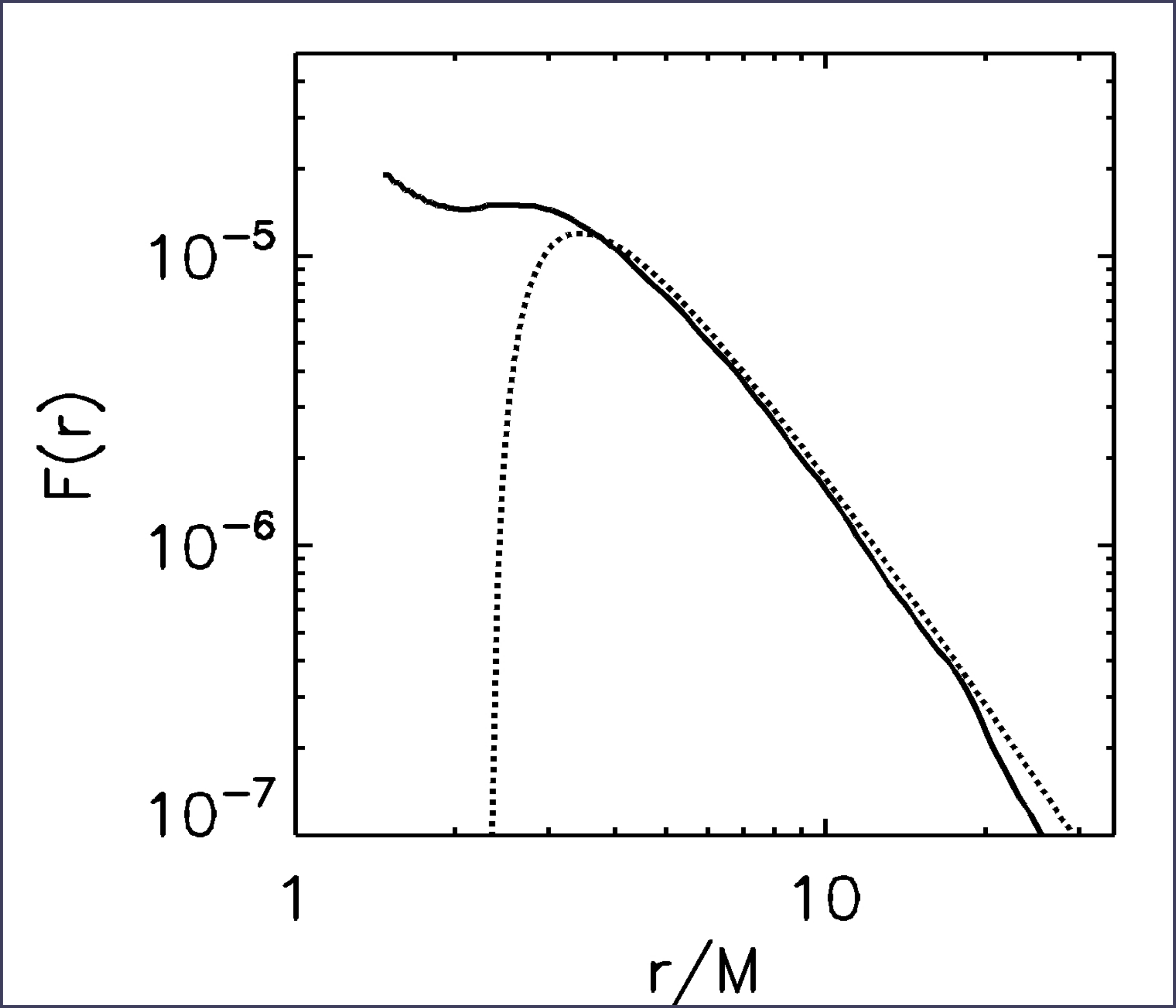




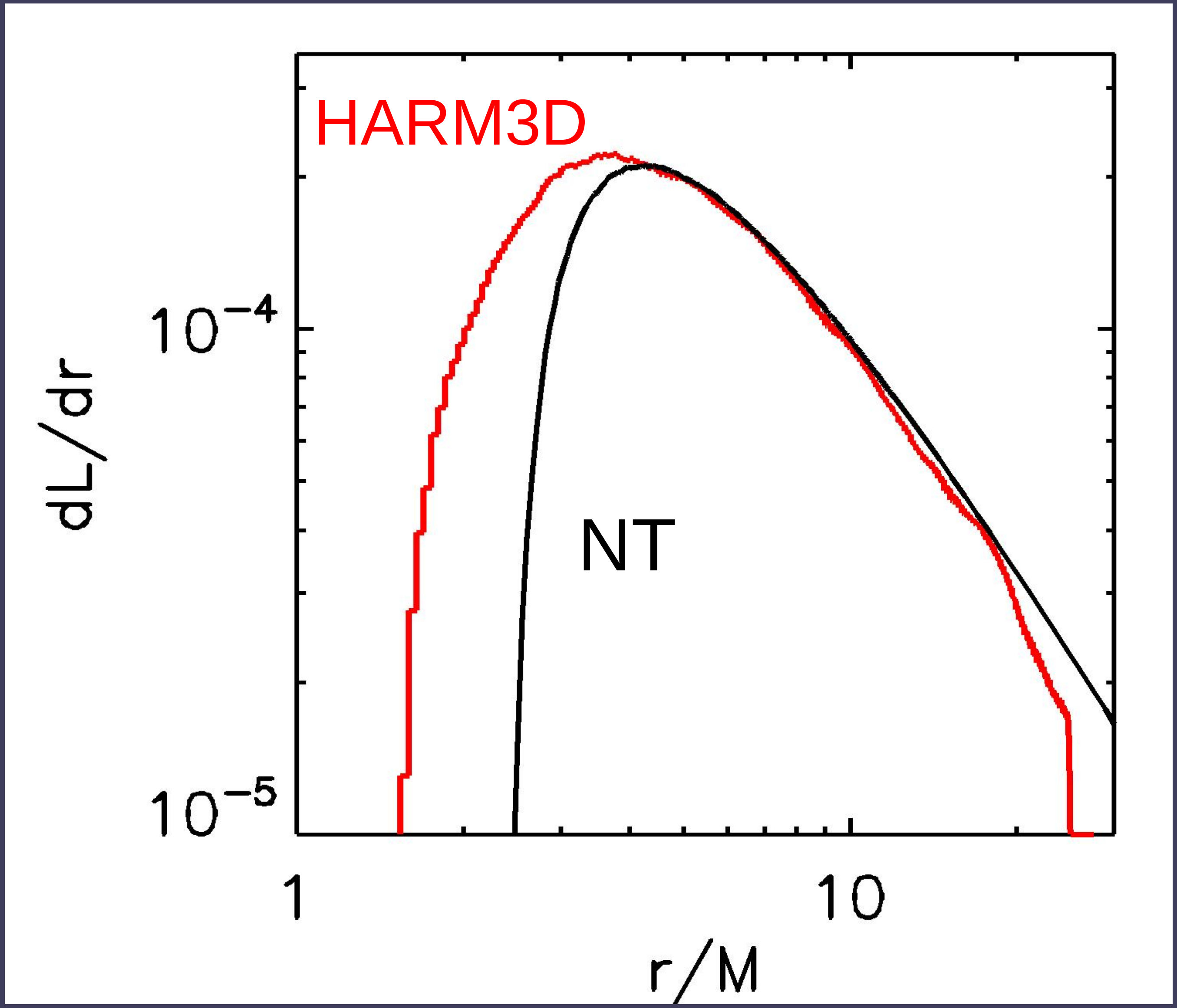
Magnetic Stress



Fluid Frame Flux



Observer Frame Luminosity: Angle/Time Average



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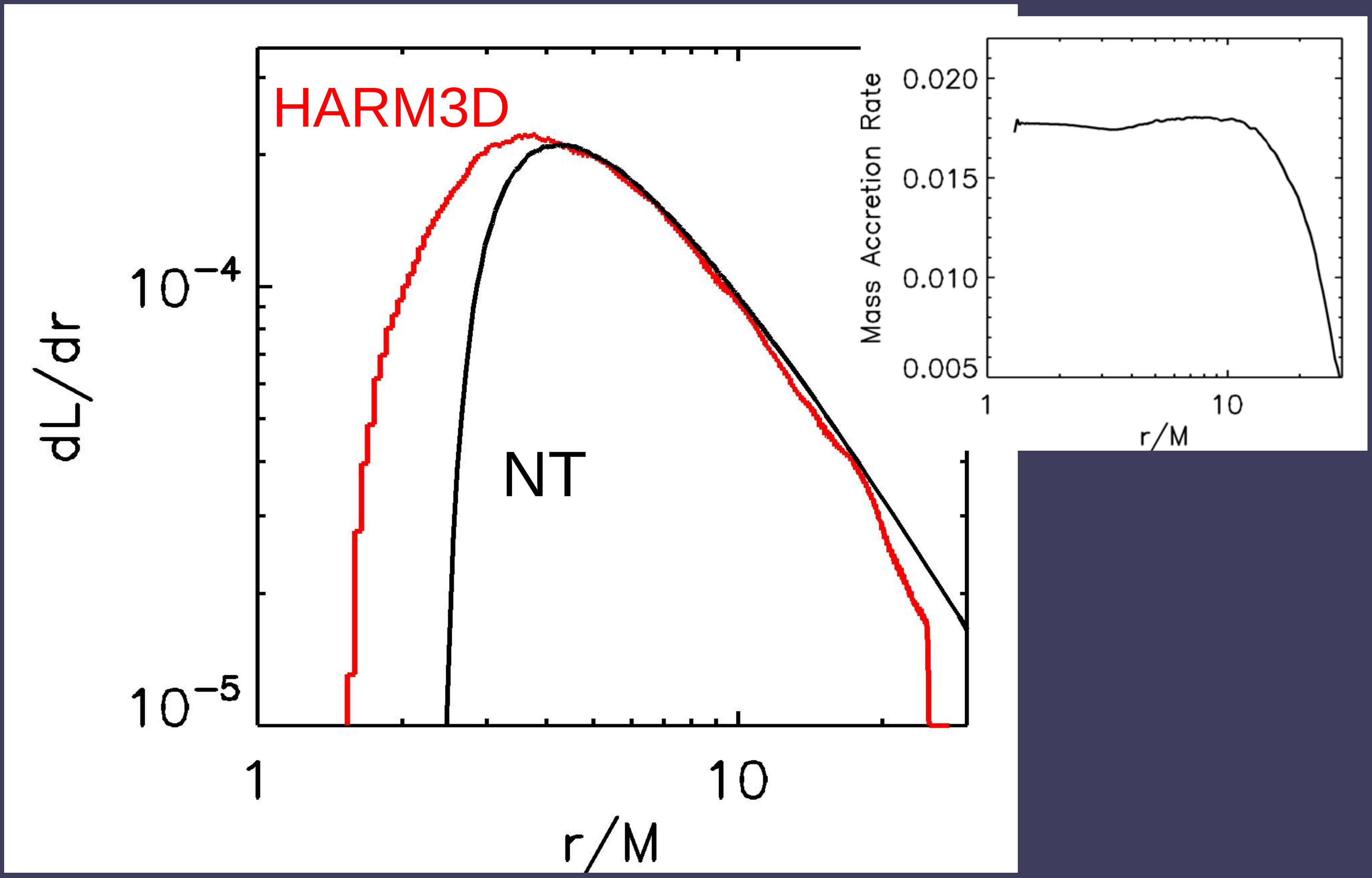

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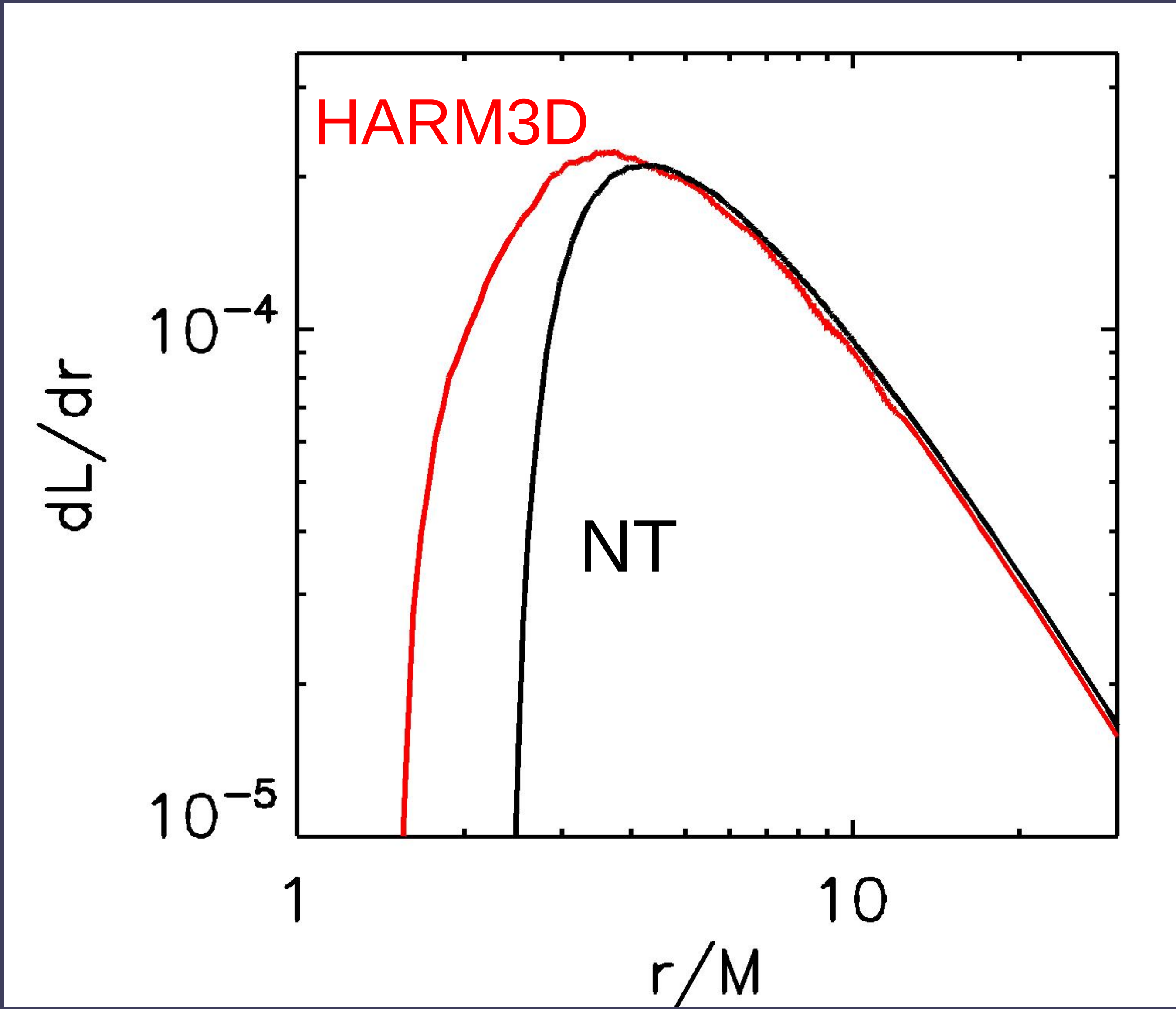
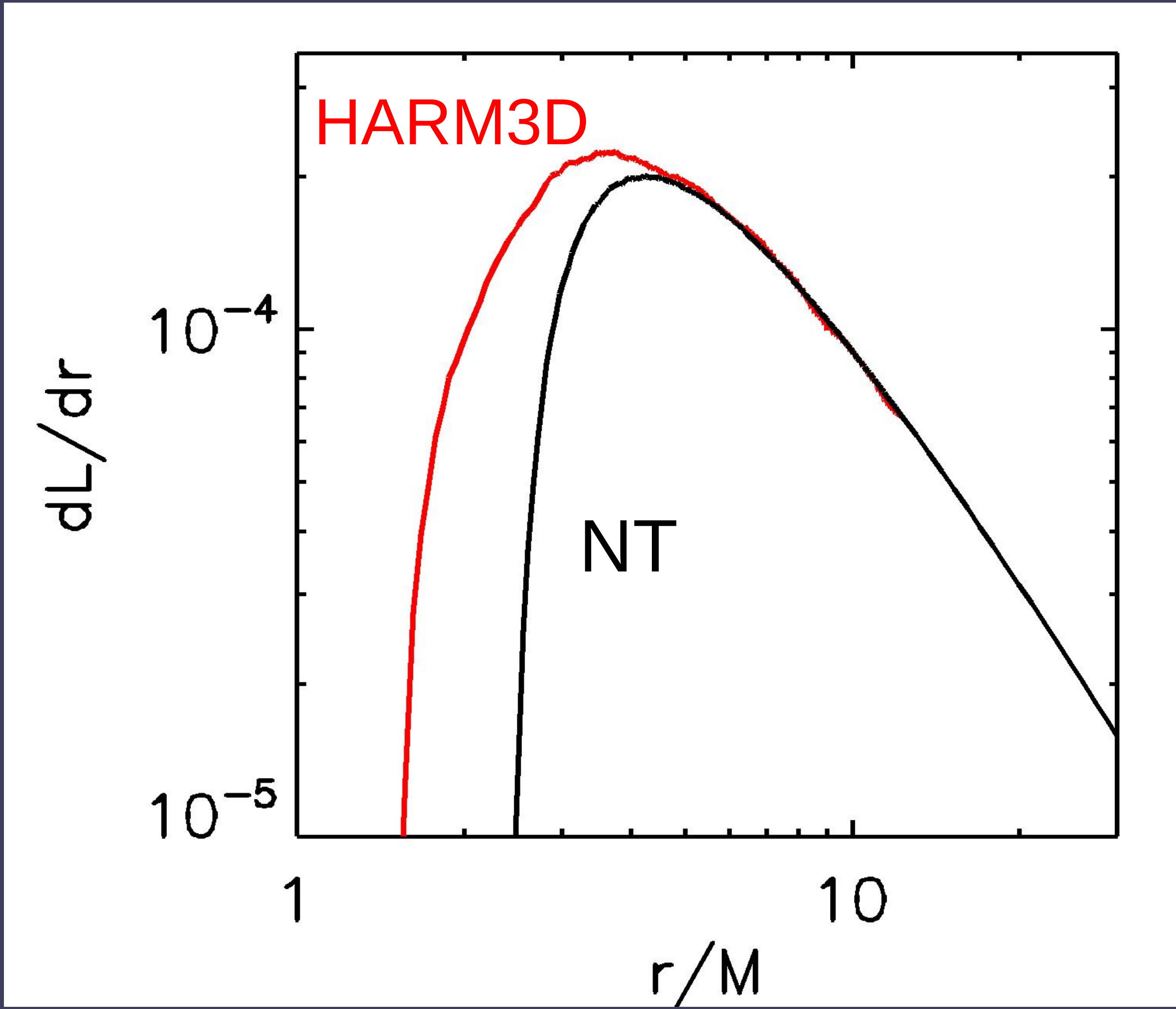


Assume NT profile for r > 12M .

$\Delta L = 4\% \; L$

Observer Frame Luminosity: Angle/Time Average



Assume NT profile for r > 12M .

Assume no difference at large radius.

$\Delta L = 9\% \ L$

Summary & Conclusions

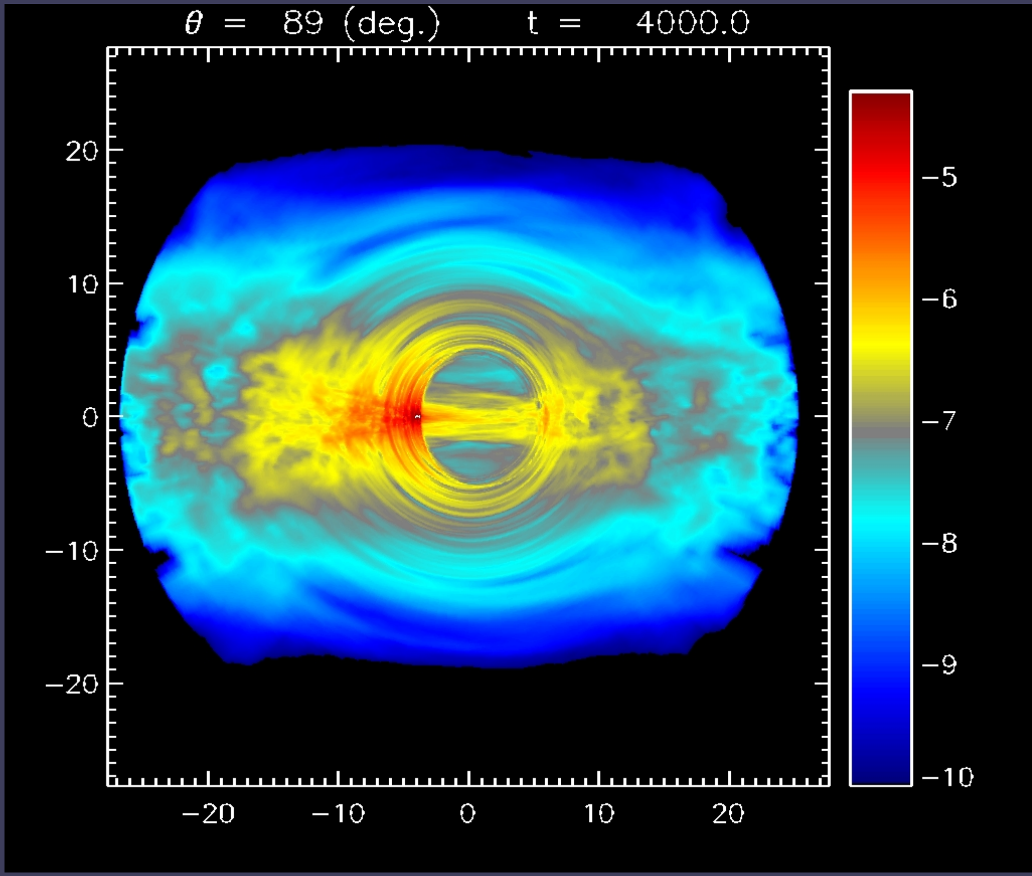
- We now have the tools to self-consistently measure dL/dr from GRMHD disks
  - 3D Conservative GRMHD simulations
  - GR Radiative Transfer

- Luminosity from within ISCO diminished by
  - Photon capture by the black hole
  - Gravitational redshift
  - $t_{cool} < t_{inflow}$

➢ Possibly greater difference for $a_{BH} < 0.9$ when ISCO is further out of the potential well.

Future Work

- Explore parameter space:
  - More spins
  - More H/R 's
  - More H(R) 's

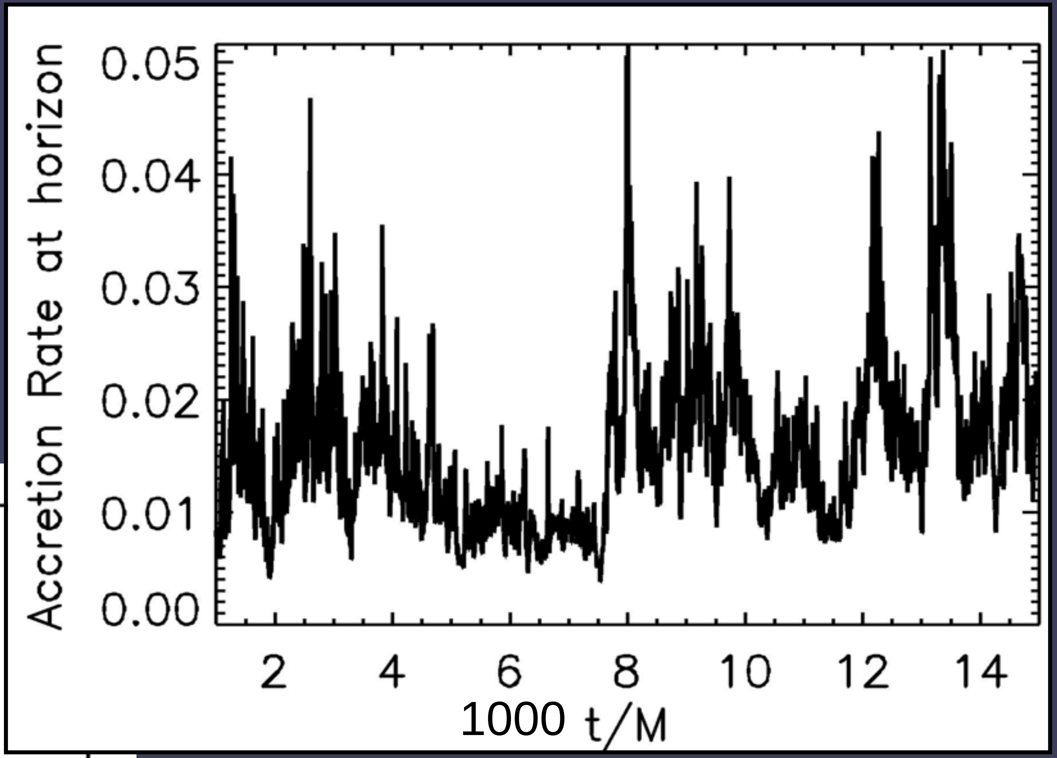


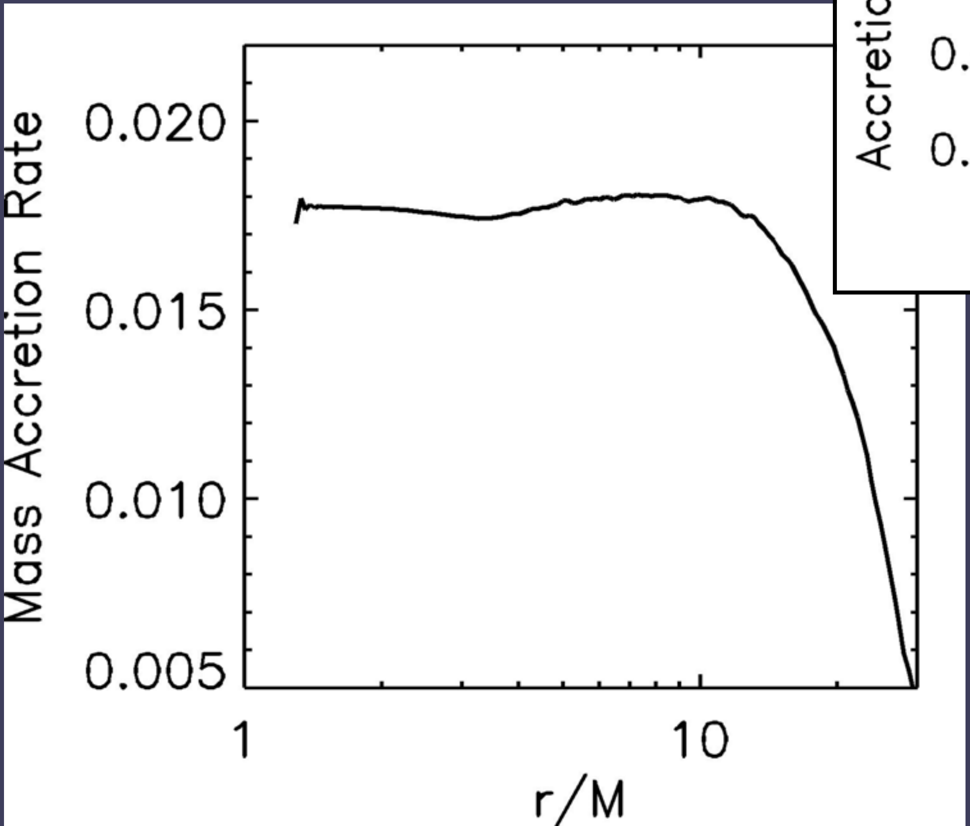
- Time variability analysis
  - Impossible with steady-state models

EXTRA SLIDES

Accretion Rate

Steady State Period = 7000 – 15000M



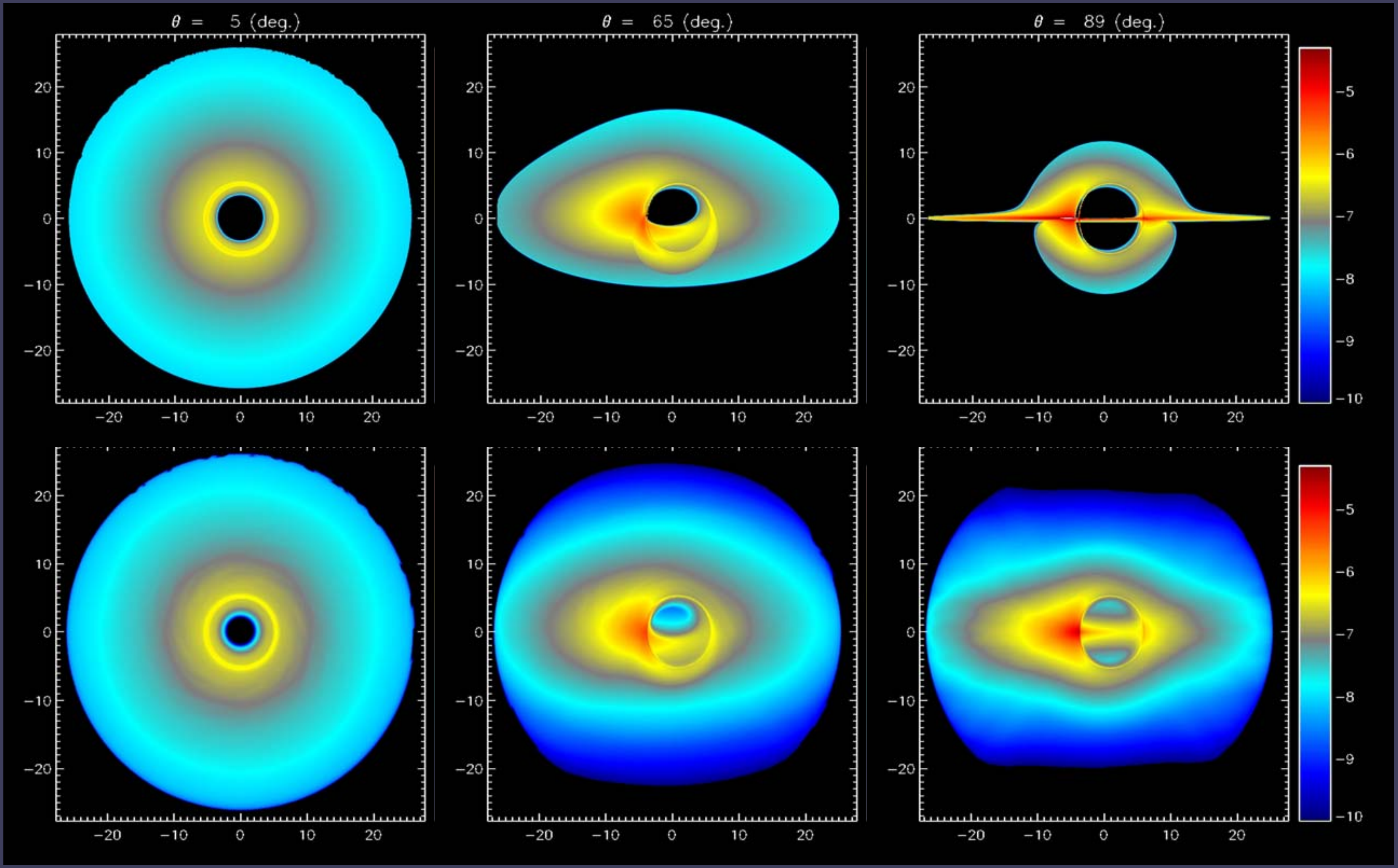


Steady State Region = Horizon – 12M

Observer Frame Luminosity: Time Average

NT

HARM



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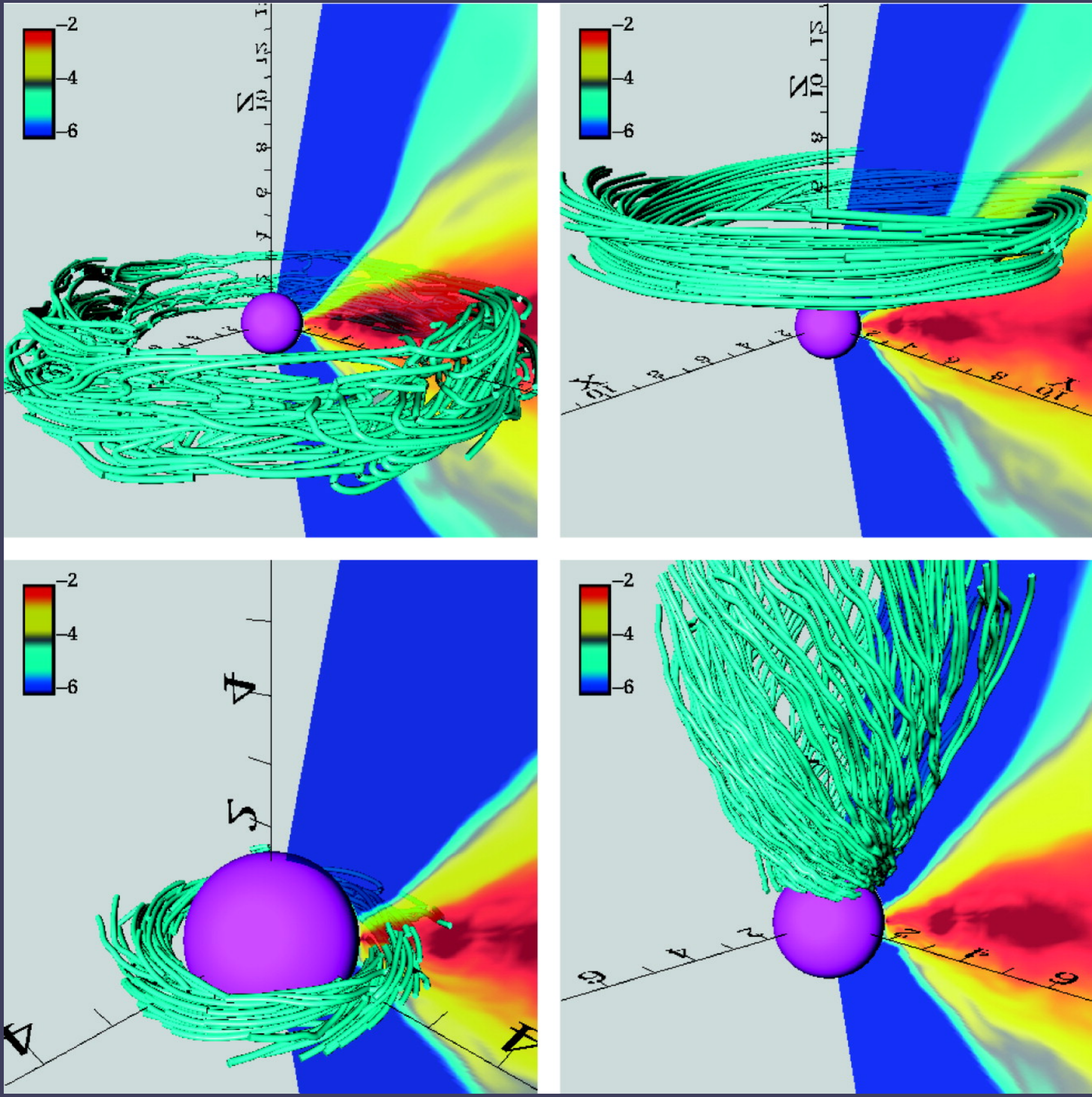

Hirose, Krolik, De Villiers, Hawley (2004)