3D GRMHD SIMULATIONS OF BLACK HOLE ACCRETION DISKS

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BH Accretion

- Astrophysical black holes nearly always have observable accretion disks around them
- These accretion disks provide information on accretion physics, e.g., different spectral states, enabling us to check our models
- Conversely, observations of disk emission allow us to study the BH: M, a_*, event horizon
- Our group has estimated spin parameters of a number of stellar mass BHs in X-ray binaries by fitting the disk spectrum

Our Team

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BH Masses and Spins

Source Name	BH Mass (M_{ε})	BH Spin (a_*)
LMC X-3	5.9—9.2	~0.25
XTE J1550-564	8.4—10.8	(~0.5)
GRO J1655-40	6.0—6.6	0.65—0.75
M33 X-7	14.2—17.1	0.77 ± 0.05
4U1543-47	7.4—11.4	0.75—0.85
LMC X-1	9.0—11.6	0.85—0.97
GRS 1915+105	10—18	0.98—1

Shafee et al. (2006); McClintock et al. (2006); Davis et al. (2006); Liu et al. (2007); Gou et al. (2009) ; Steiner et al.

Theoretical Model

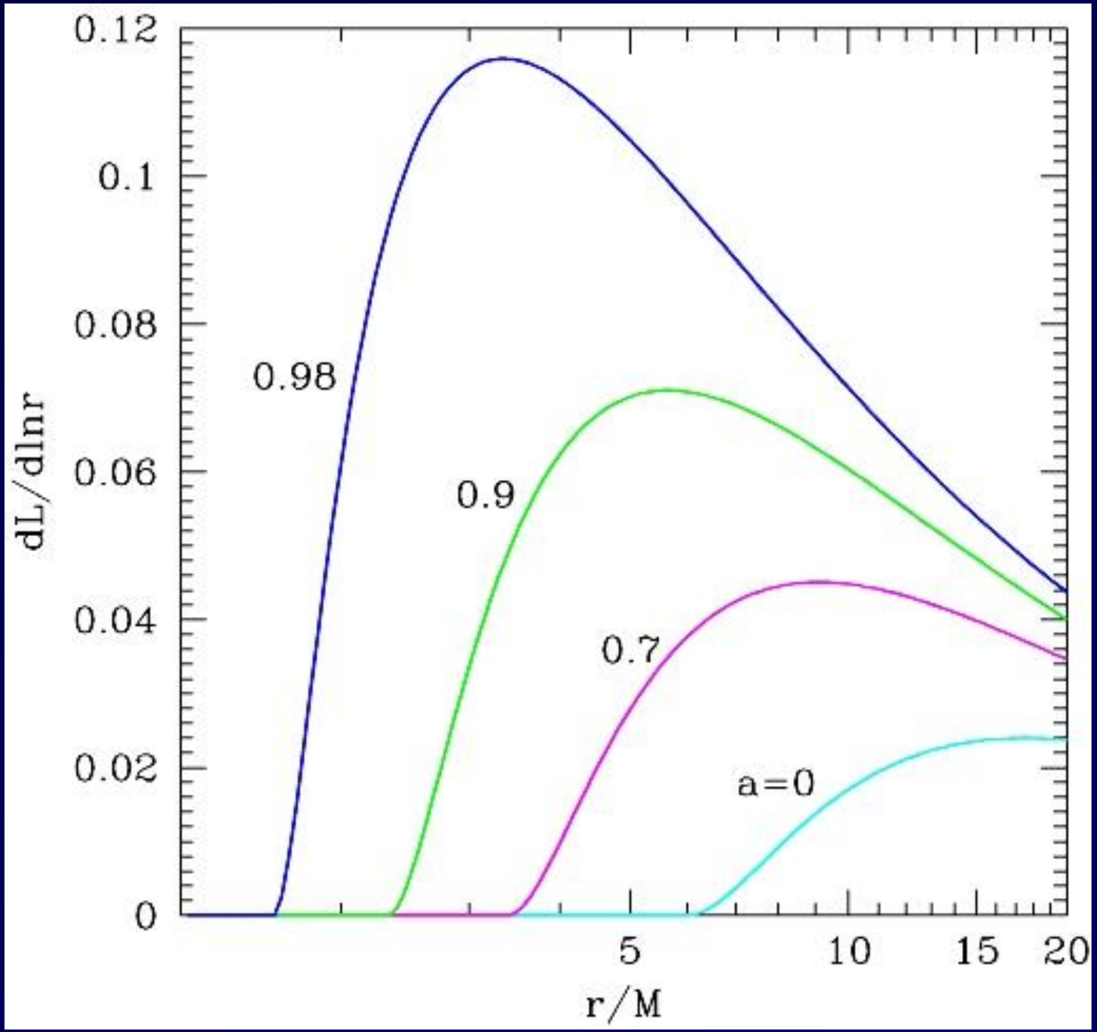
- Any method of measuring a_* is only as good as the theoretical model behind it
- Our method assumes that the accretion disk is well described by the GR disk model of Novikov & Thorne (1973)
- In particular, we assume that the disk luminosity profile L(r) takes the form predicted by the NT model

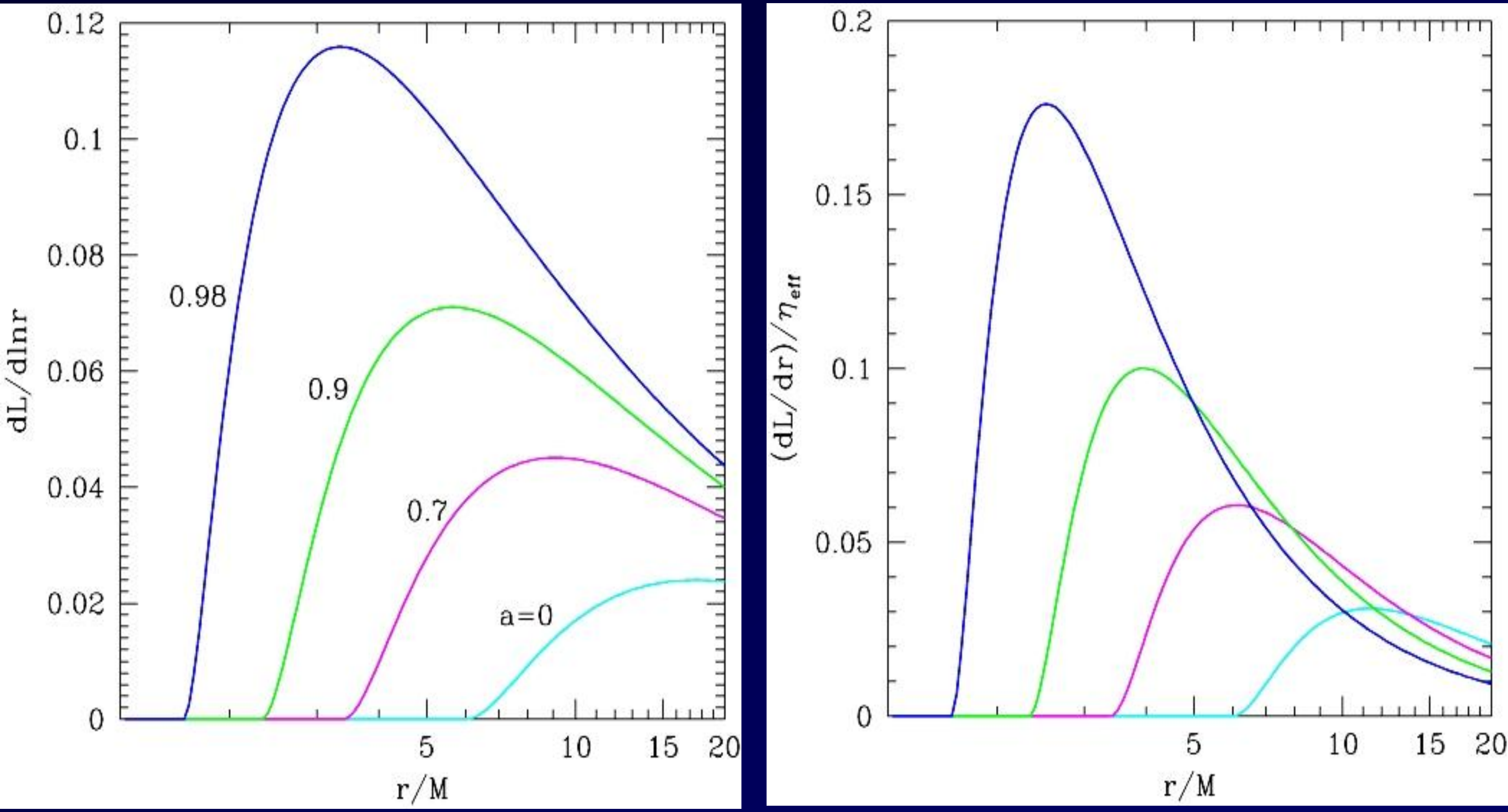
Novikov & Thorne L(r)

L(r) peaks at a different radius for each value of the dimensionless BH spin parameter a_*

Therefore, the observed spectrum depends on a_*

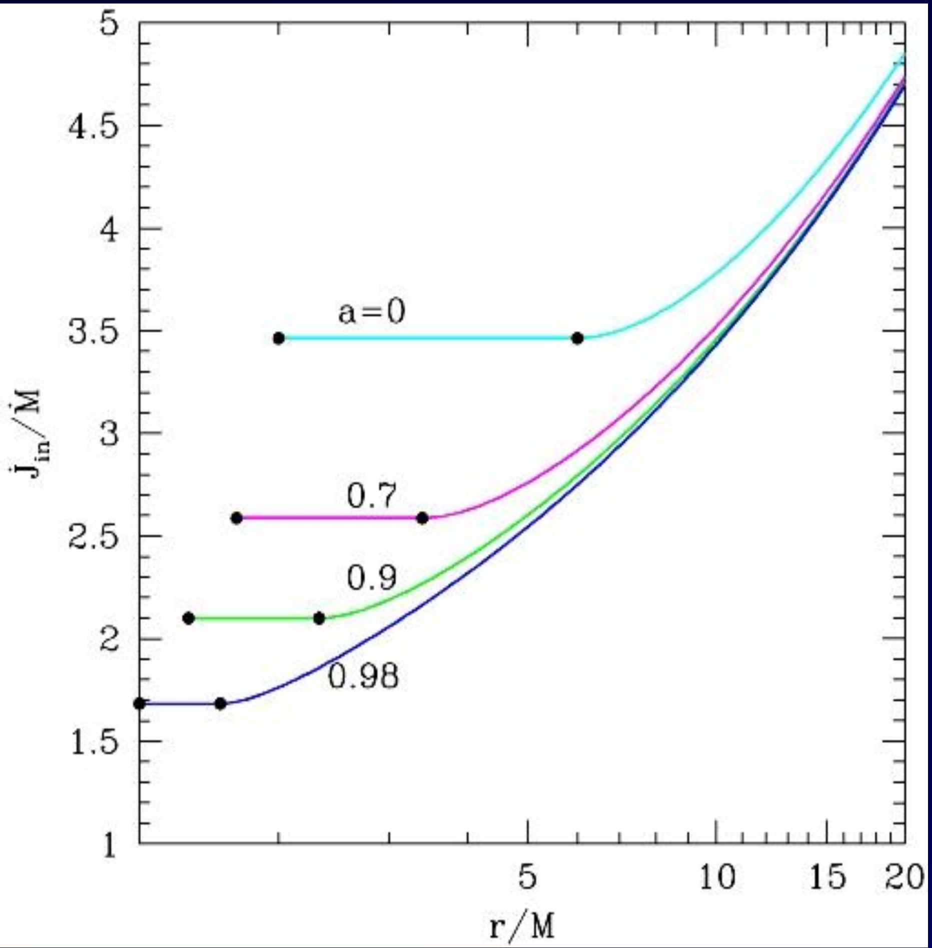
This is what enables us to estimate a_* from observations

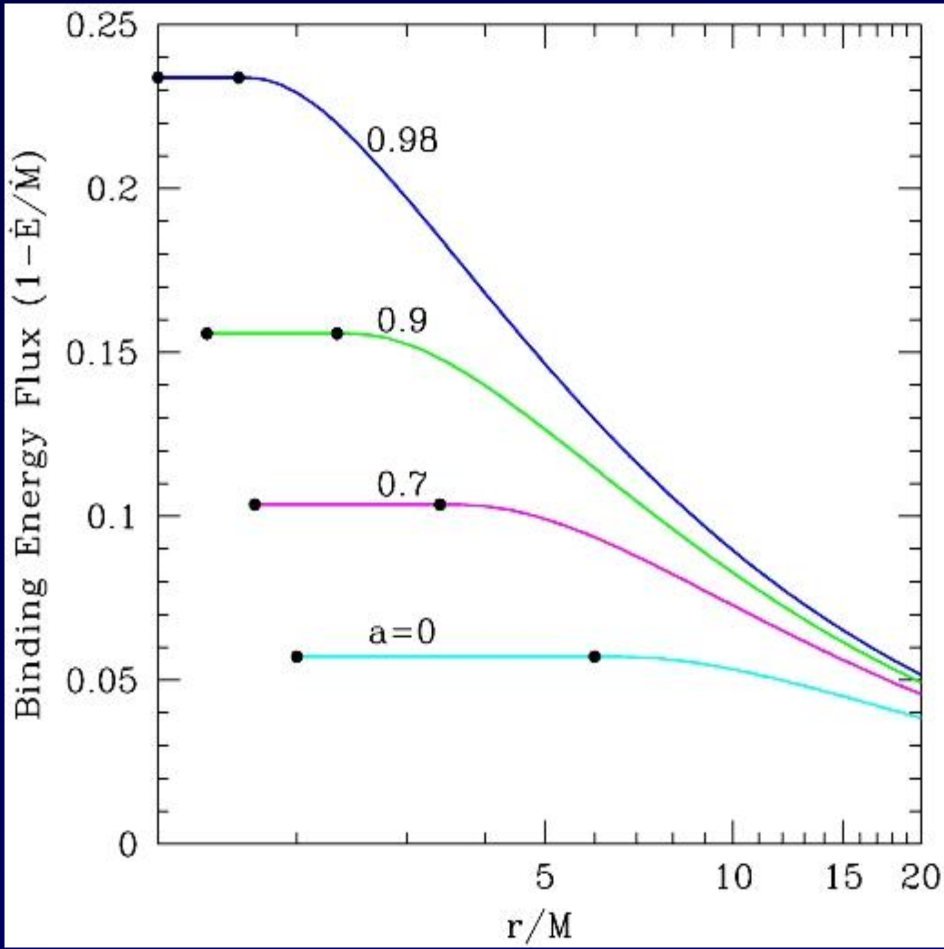




Different representations of the luminosity profile

Novikov-Thorne Model





But How Good is the Novikov-Thorne Model?

- The NT model assumes a geometrically thin disk
- It assumes that the "viscous" torque vanishes at the ISCO (Shakura & Sunyaev 1973; Novikov & Thorne 1973)
- But magnetic fields could produce significant torque at and inside the ISCO (Krolik 1999; Gammie 1999)
- Afshordi & Paczynski (2003) suggested that the effect is probably not important for a **THIN** disk (Shafee et al. 08)
- **Can we verify this?**

Testing the Novikov-Thorne Model using 3D GRMHD Simulations

- 3D MHD simulations in the Kerr metric
- Magnetic fields self-consistently generate "viscous" torques via the MRI (Balbus & Hawley 1991)
- We must simulate geometrically thin disks – numerically very challenging
- Reynolds & Fabian (2008); Shafee et al. (2008); Noble, Krolik & Hawley (2009)

Numerical Method

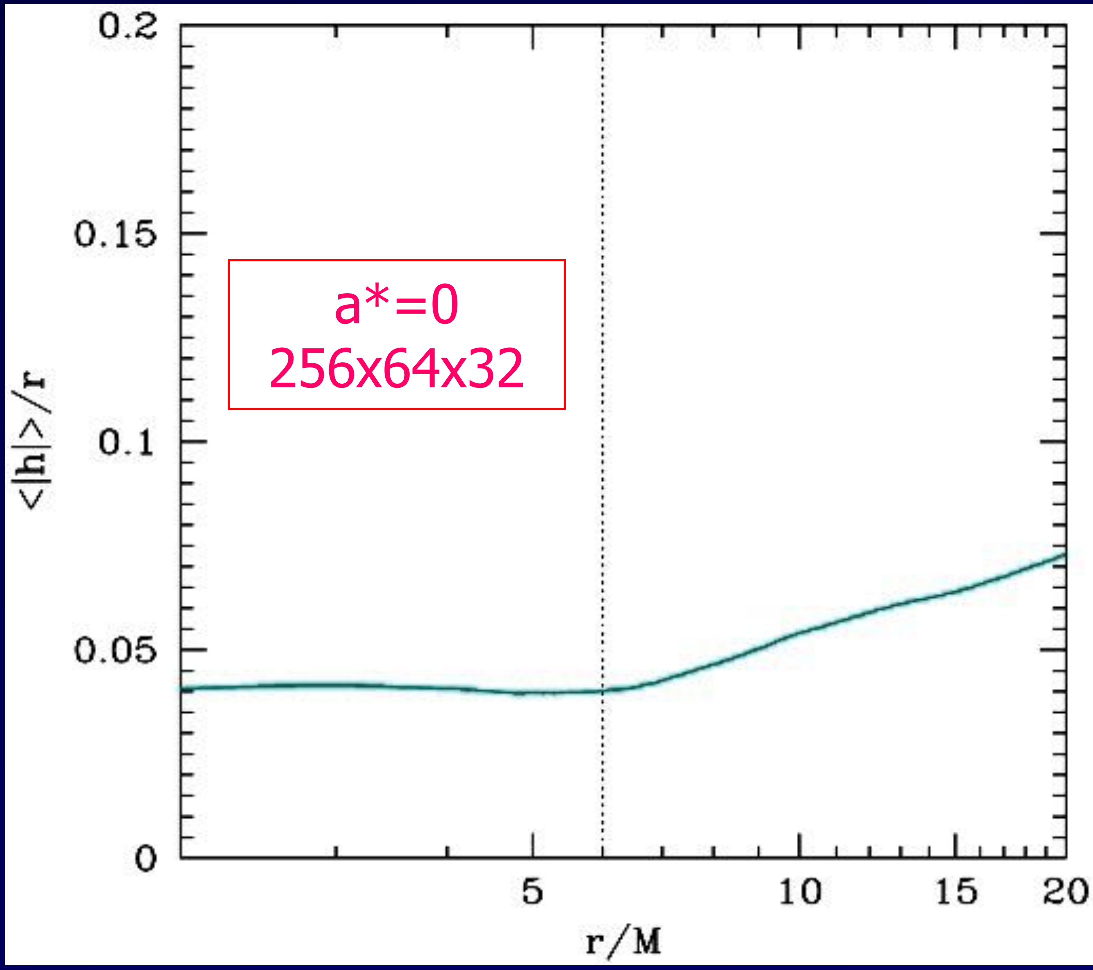
- We use the GRMHD code HARM (Gammie, McKinney & Toth 2003)
- Conservative code, runs in 3D in the stationary Kerr metric
- We add an ad hoc cooling where we specify the target entropy of the gas as a parameter:

$$\frac{du}{d\tau} = -\frac{\Omega_K \left(u - u_{\mathrm{target}}\right)}{2\pi}$$

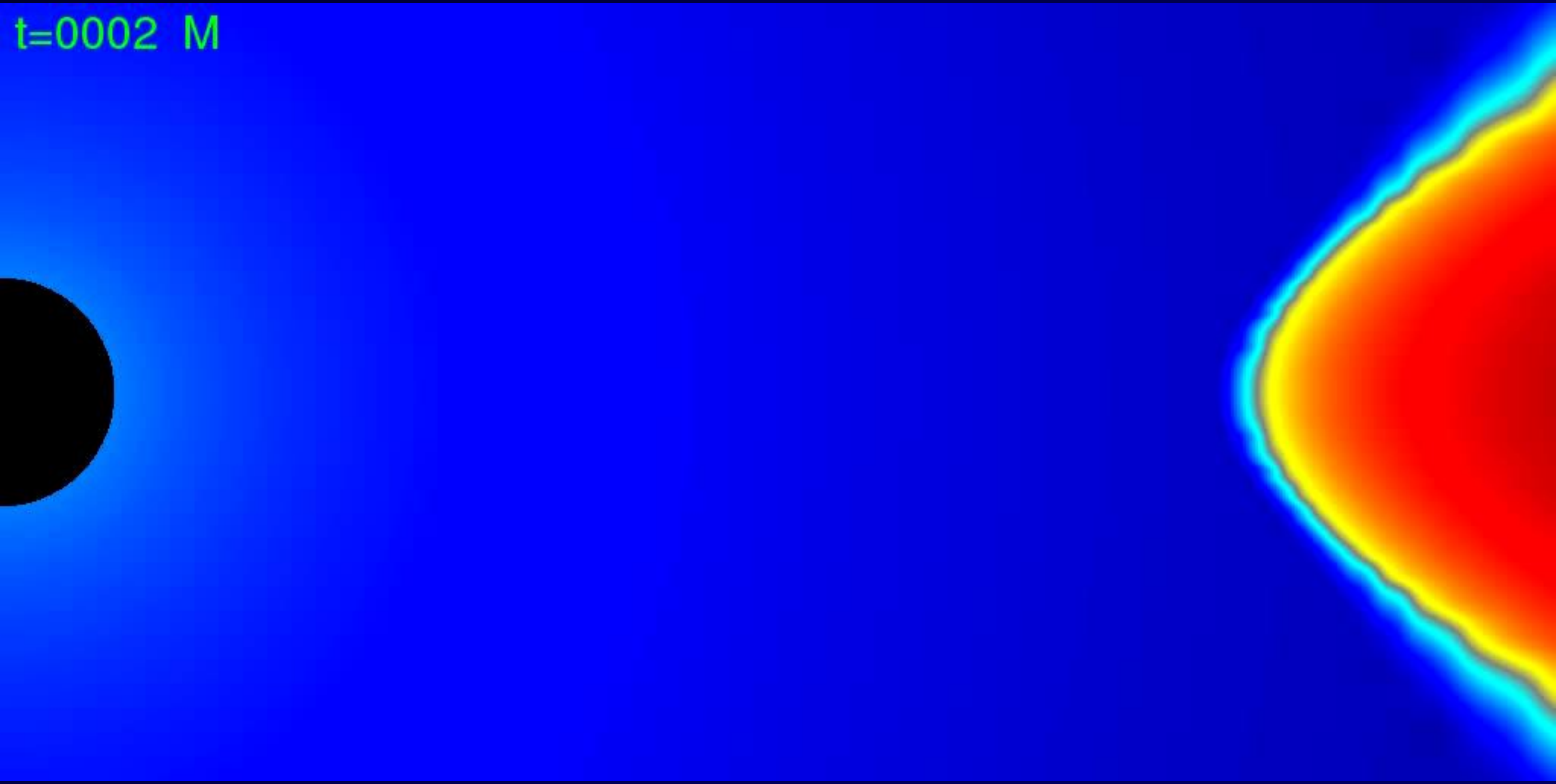
- This parameter lets us tune the disk thickness

Our Fiducial Run

- A very thin disk ($<|h|>/r \sim 0.05$) around a non-spinning BH ($a_* = 0$)
- 256 x 64 x 32 grid (φ-wedge angle: $\pi/2$)
- Gas is initially in a torus beyond r=20M
- Simulation is run for a time of 17000M
- Steady state after t ~ 12000M



Penna et al. (2009)



256 x 64 x 32

Penna et al. (2009)

Mass Conservation

$$\rho u^{\alpha}{}_{;\alpha} = 0$$

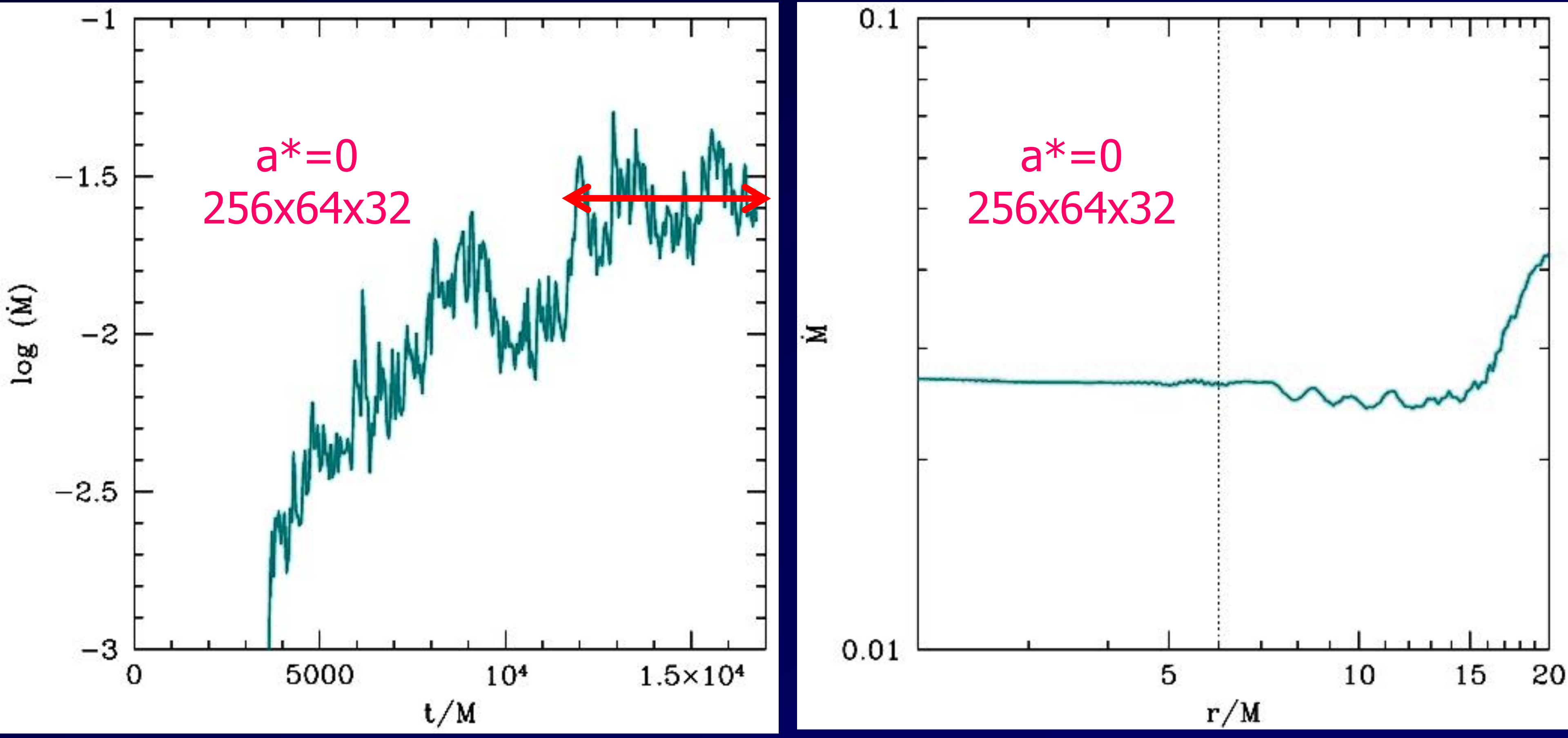
$$\text{Mass Flux} = \iint \rho u^{r} \sqrt{-g}\, d\theta\, d\phi$$

$$= \dot{M}(r) = \text{constant (steady state)}$$

$$\theta \text{ integral} = 0 - \pi : \text{all the fluid}$$

$$\theta \text{ integral} = \pi / 2 \pm 2h / r : \text{limited to disk}$$

Fiducial Run: Mass Accretion Rate



Penna et al. (2009)

Angular Momentum Conservation

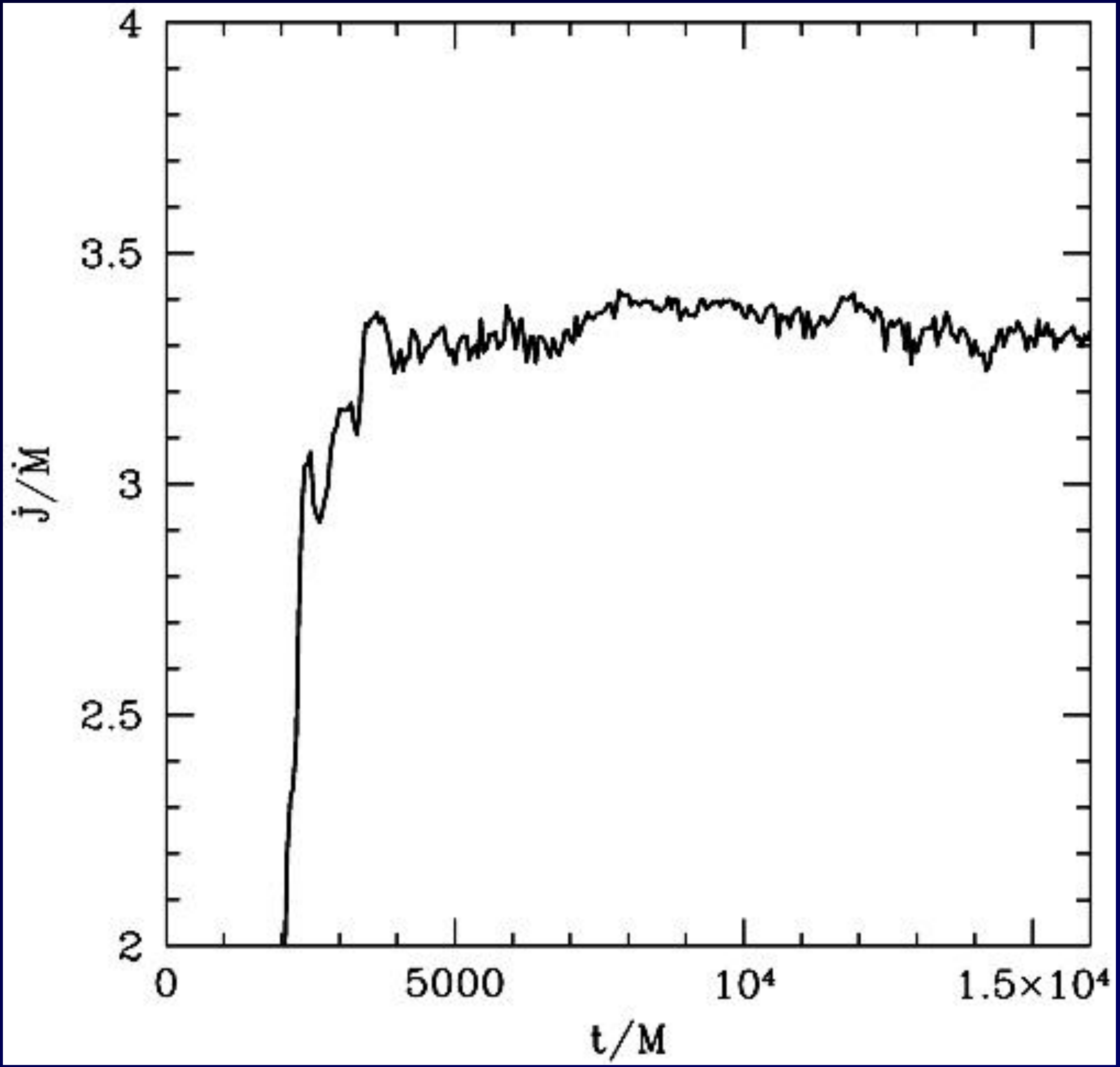
$$T^{\alpha}{}_{\phi;\alpha} = \text{ang mmtm loss via radiation}$$

$$\text{Flux} = \iint \left[\left(\rho + \Gamma u + b^2 \right) u^r u_\phi - b^r b_\phi \right] \sqrt{-g}\, d\theta\, d\phi$$

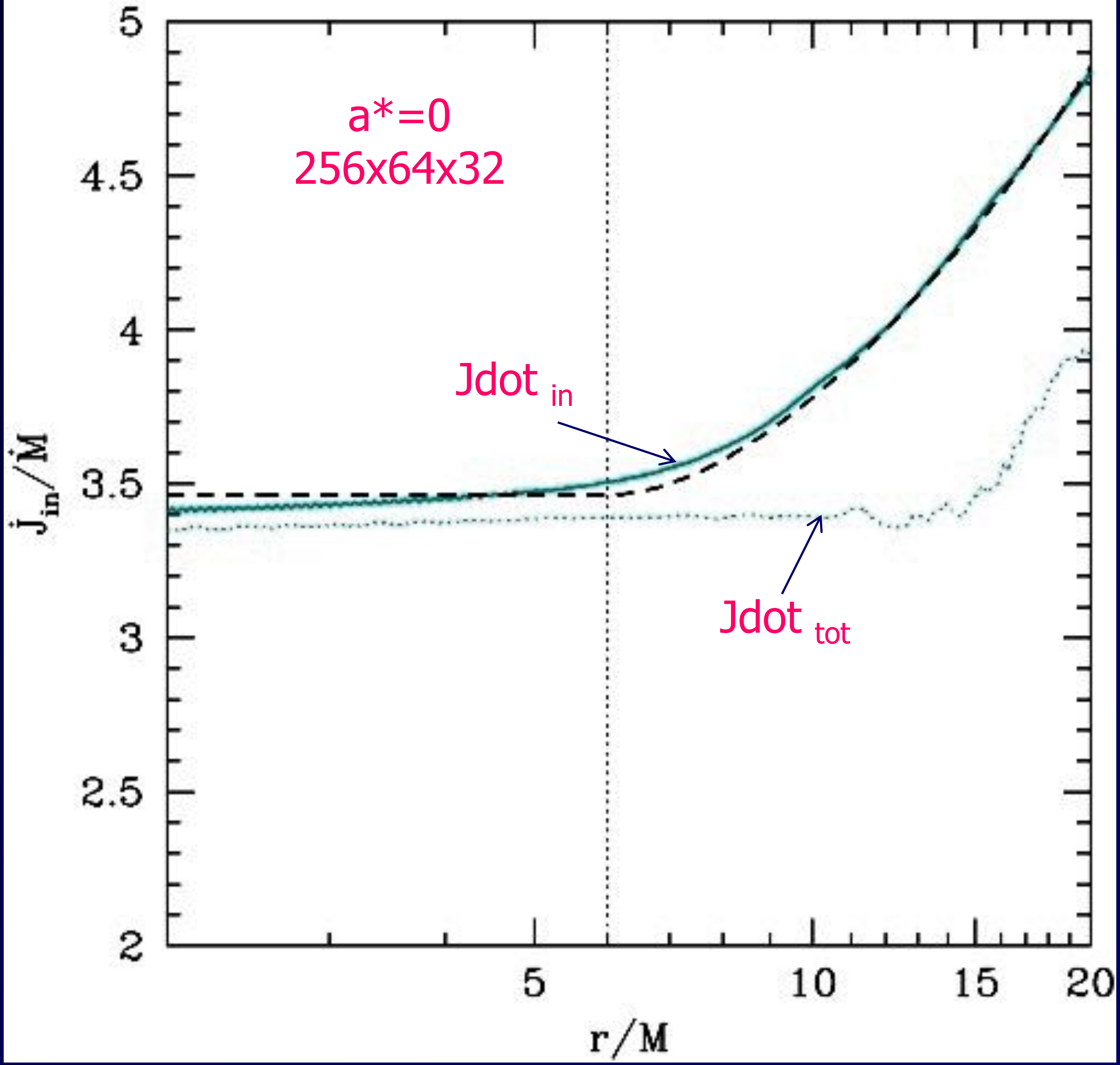
$$= \dot{J}(r) = \text{nearly constant}$$

$$\dot{J}(r) = \dot{J}_{\text{in}}(r) + \dot{J}_{\text{out}}(r) \quad \left(\text{for comparing with NT}\right)$$

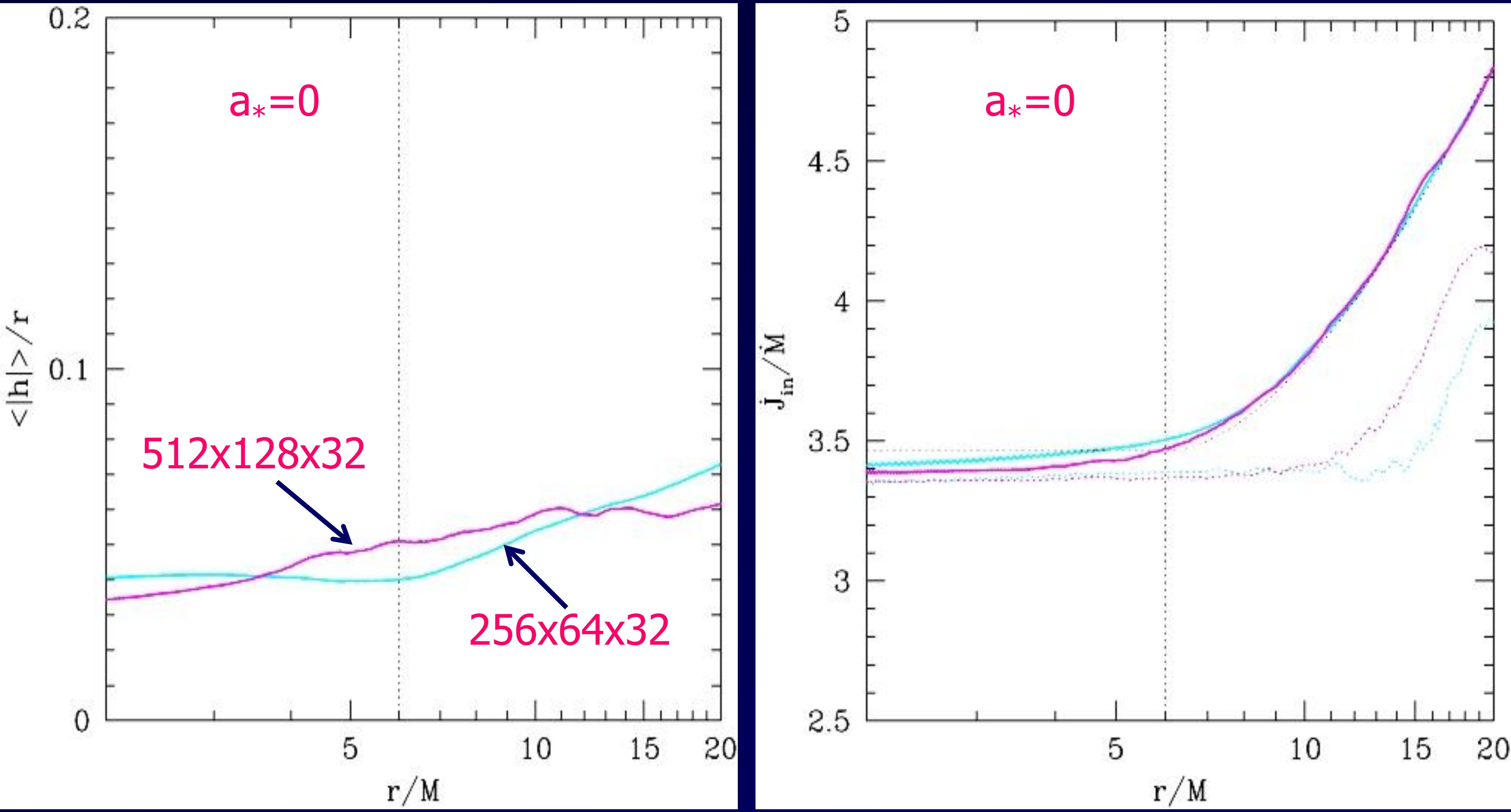
$$\dot{J}_{\text{in}}(r) = \iint \left\langle \left(\rho + \Gamma u + b^2 \right) u^r \right\rangle \left\langle u_\phi \right\rangle \sqrt{-g}\, d\theta\, d\phi$$



4
3.5
3
2.5
2
$\dot{j}/\dot{M}$
0
5000
10^4
1.5×10^4
t/M

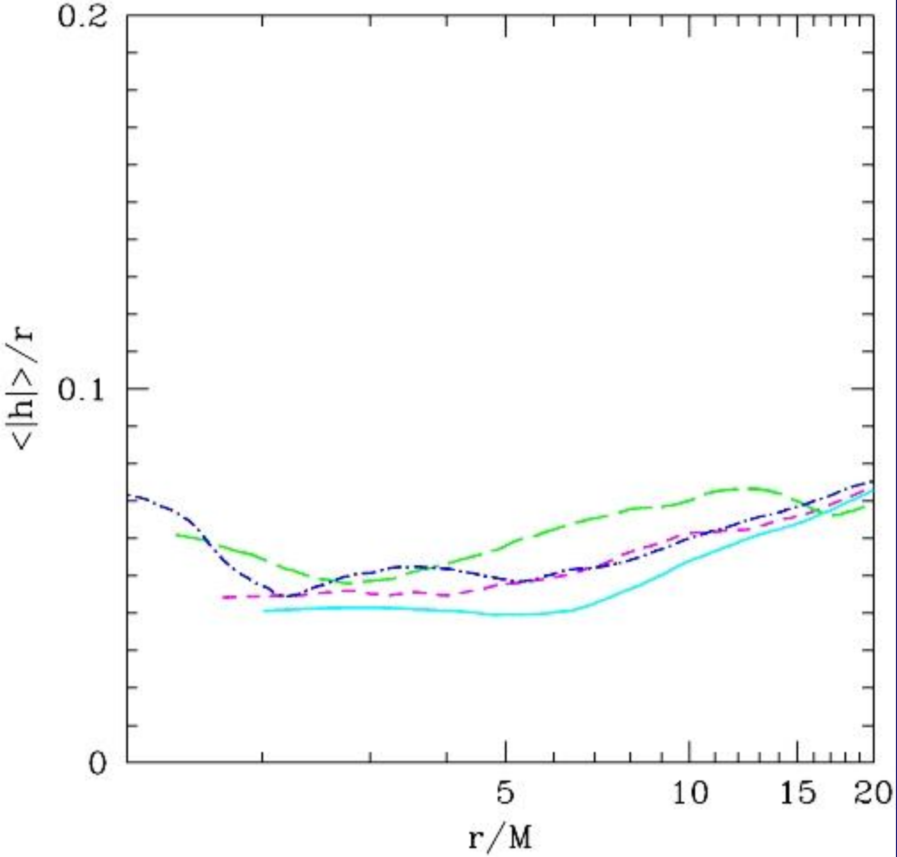


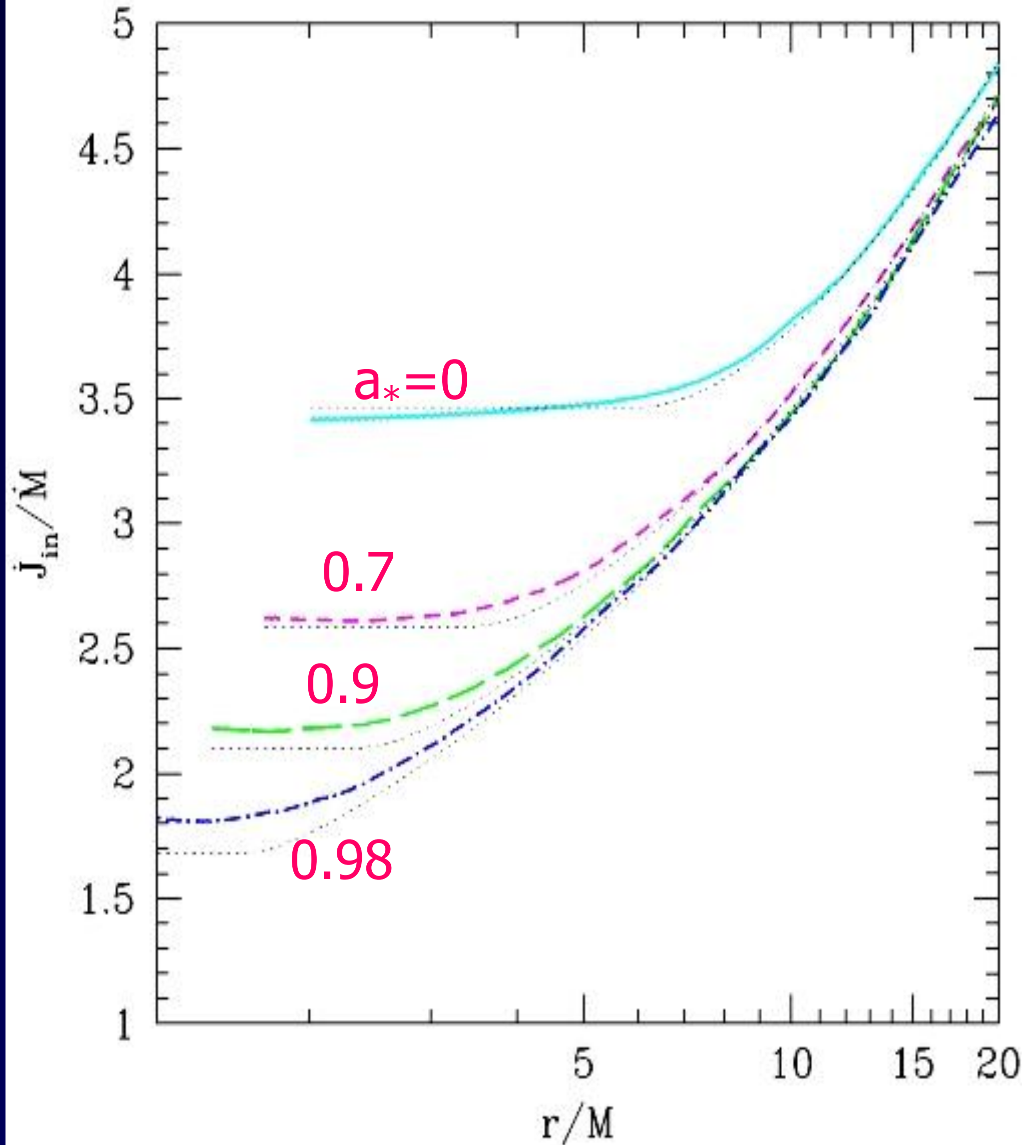
Our New Fiducial Run ($a_*=0$): Penna et al. (2009)



The results from the two runs appear to be similar.
We view the deviations as a measure of the errorbar

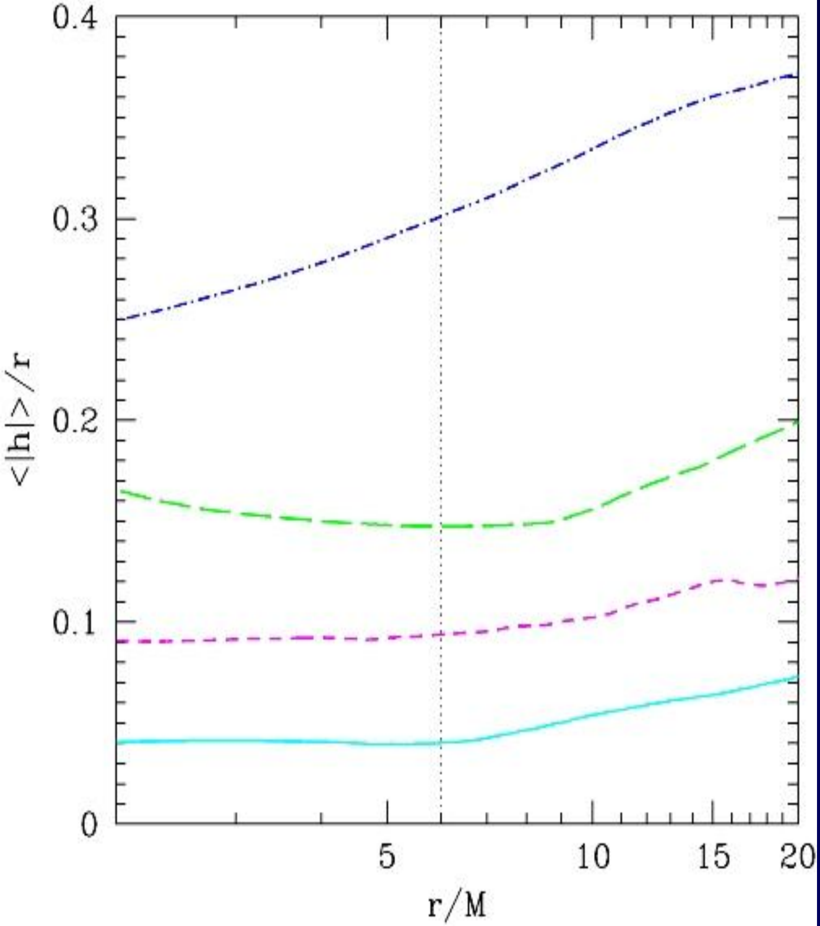
Thin Disks: Other Values of a_*

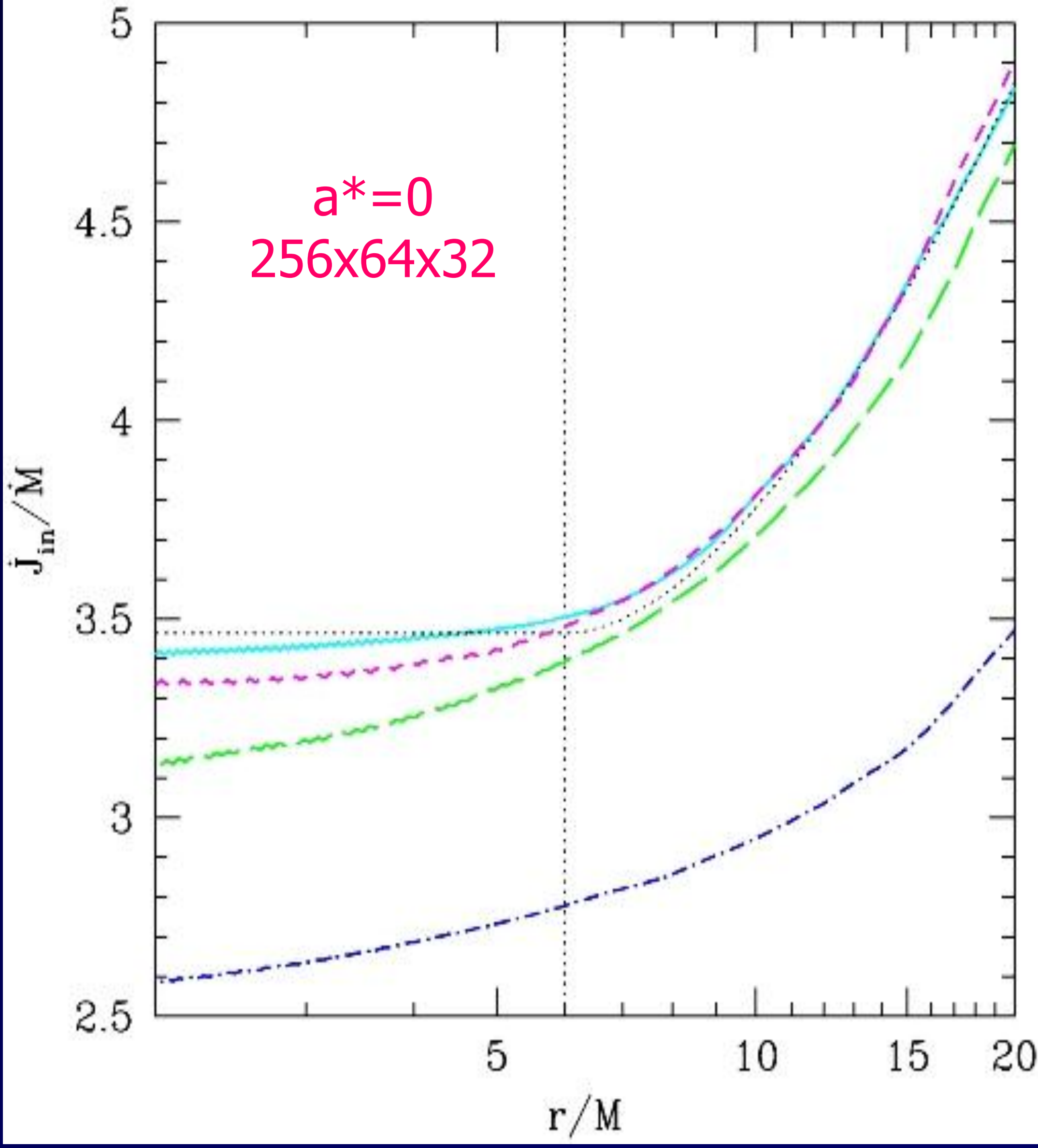




Pretty good agreement with Novikov-Thorne, except at the largest value of a_*

Thicker Disks with $a_*=0$





The accretion flow becomes quite sub-Keplerian as the disk thickness increases

Angular Momentum: Summary

- Thin disks with $h/r<0.1$ behave quite a lot like the Novikov-Thorne model
- Deviations are larger for larger values of a_*, but the dependence is modest
- However, deviations increase rapidly as the disk thickness increases
- Therefore, the NT model is not trustworthy for thick disks

Energy Conservation

$$T^{\alpha}{}_{t;\alpha} = \text{energy loss via radiation}$$

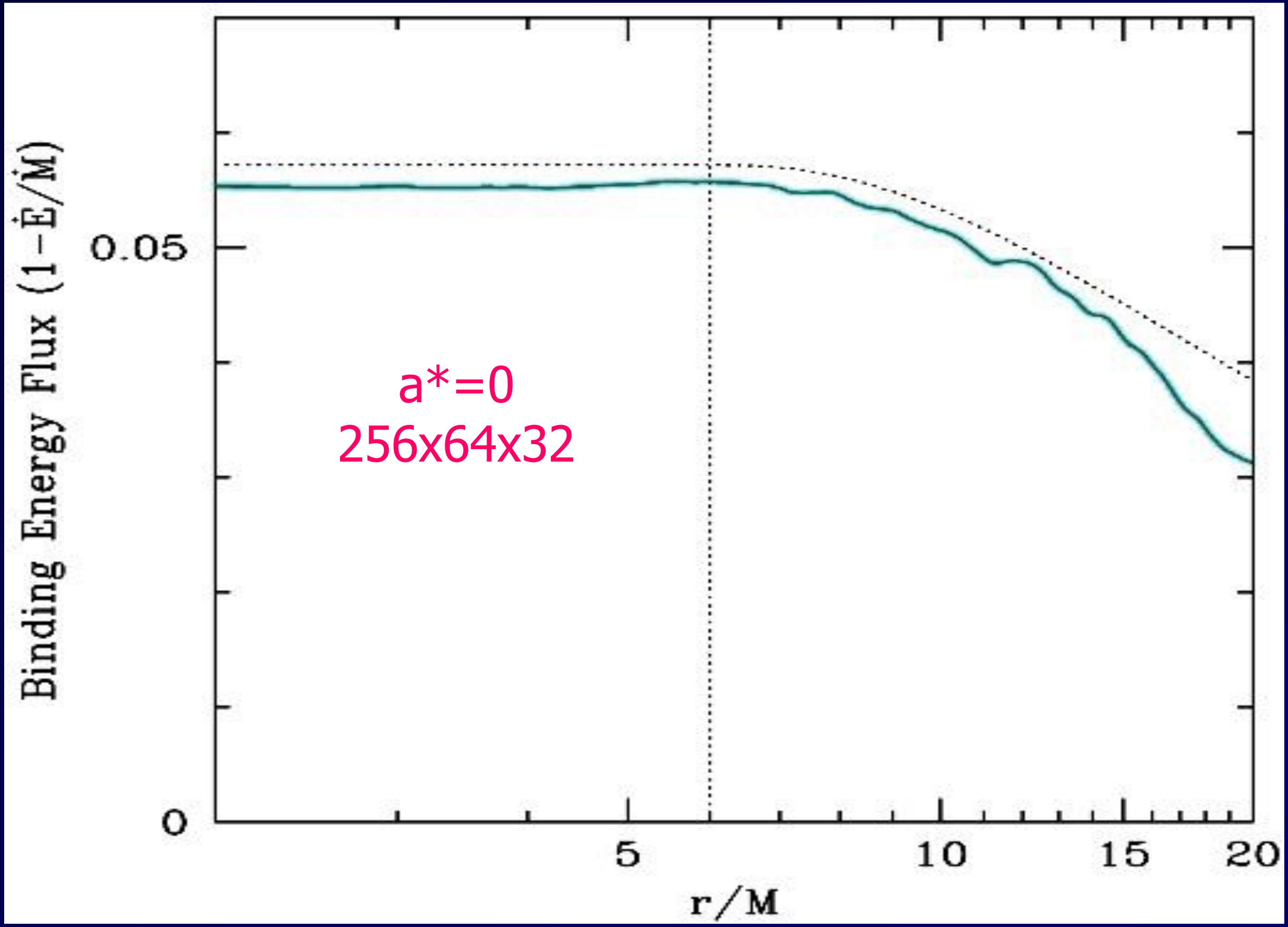
$$\text{Flux} = \iint \left[\left(\rho + \Gamma u + b^2 \right) u^r u_t - b^r b_t \right] \sqrt{-g}\, d\theta\, d\phi$$

$$= \dot{E}(r) : \text{increases with radius (radiation)}$$

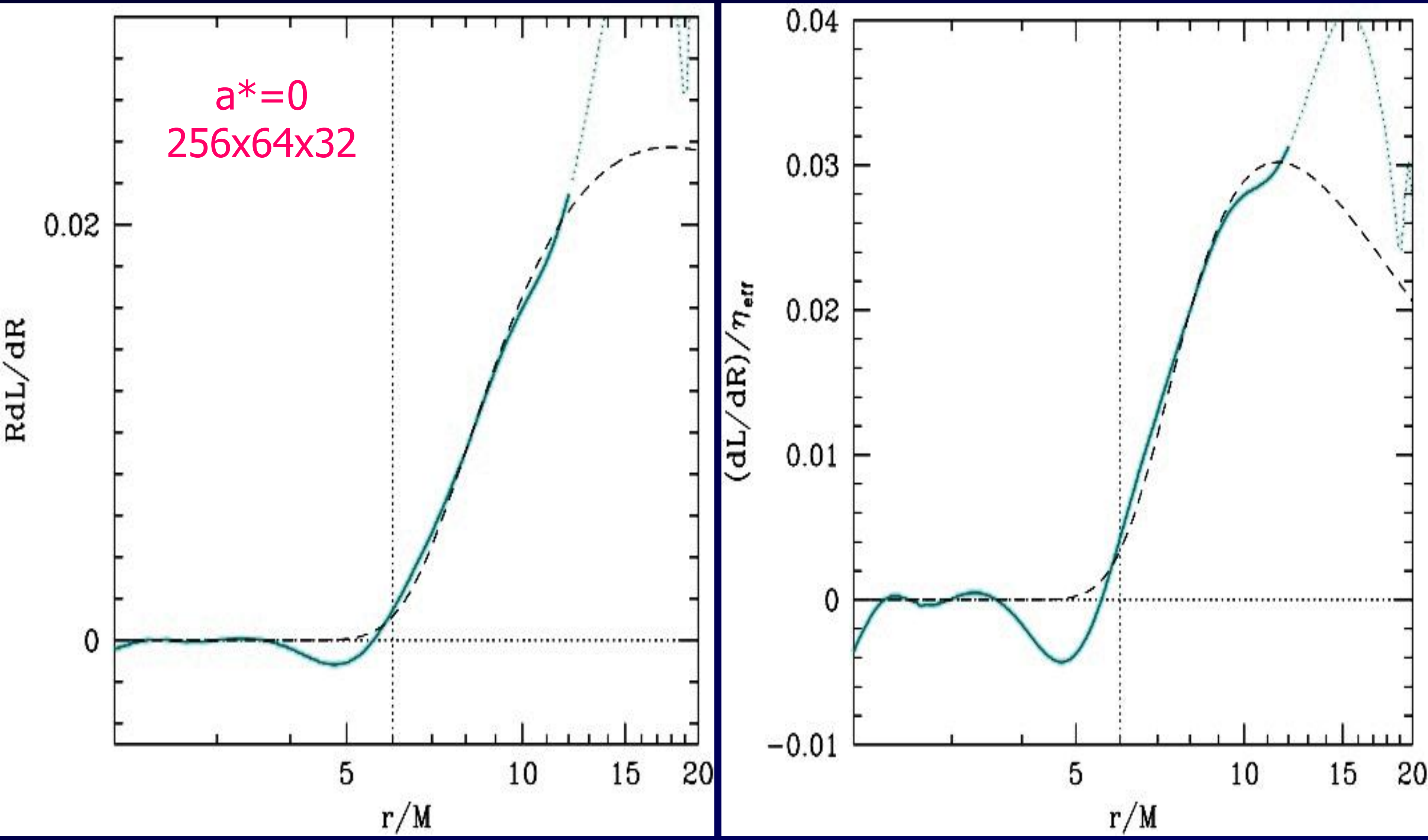
$$\left(1 - \frac{\dot{E}}{\dot{M}} \right) = \text{Binding energy released per unit mass}$$

$$\frac{dL}{d \ln r} = -\frac{d}{d \ln r} \left(1 - \frac{\dot{E}}{\dot{M}} \right)$$

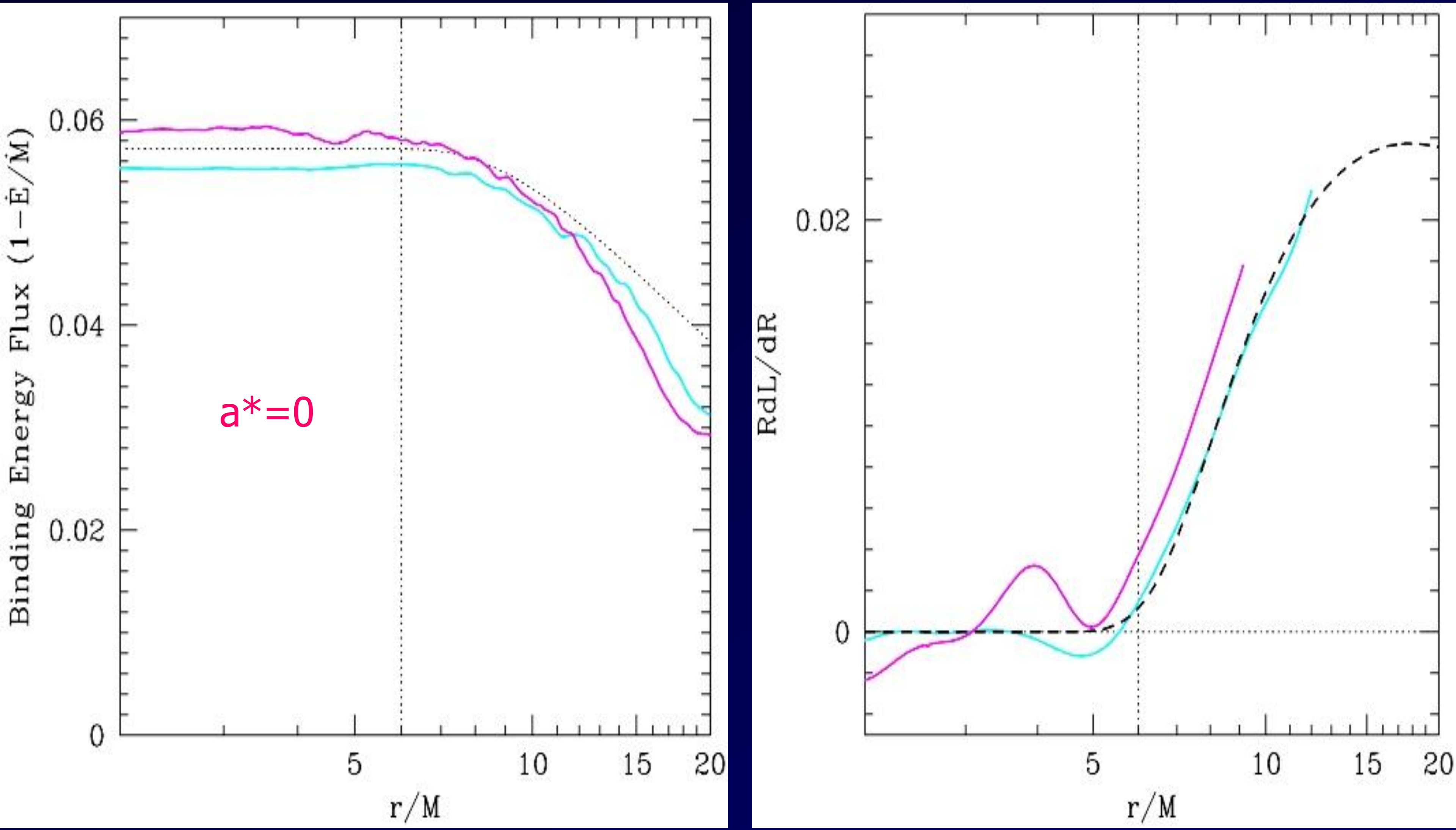
Fiducial Run: Energy Flux



!!Very Preliminary!!

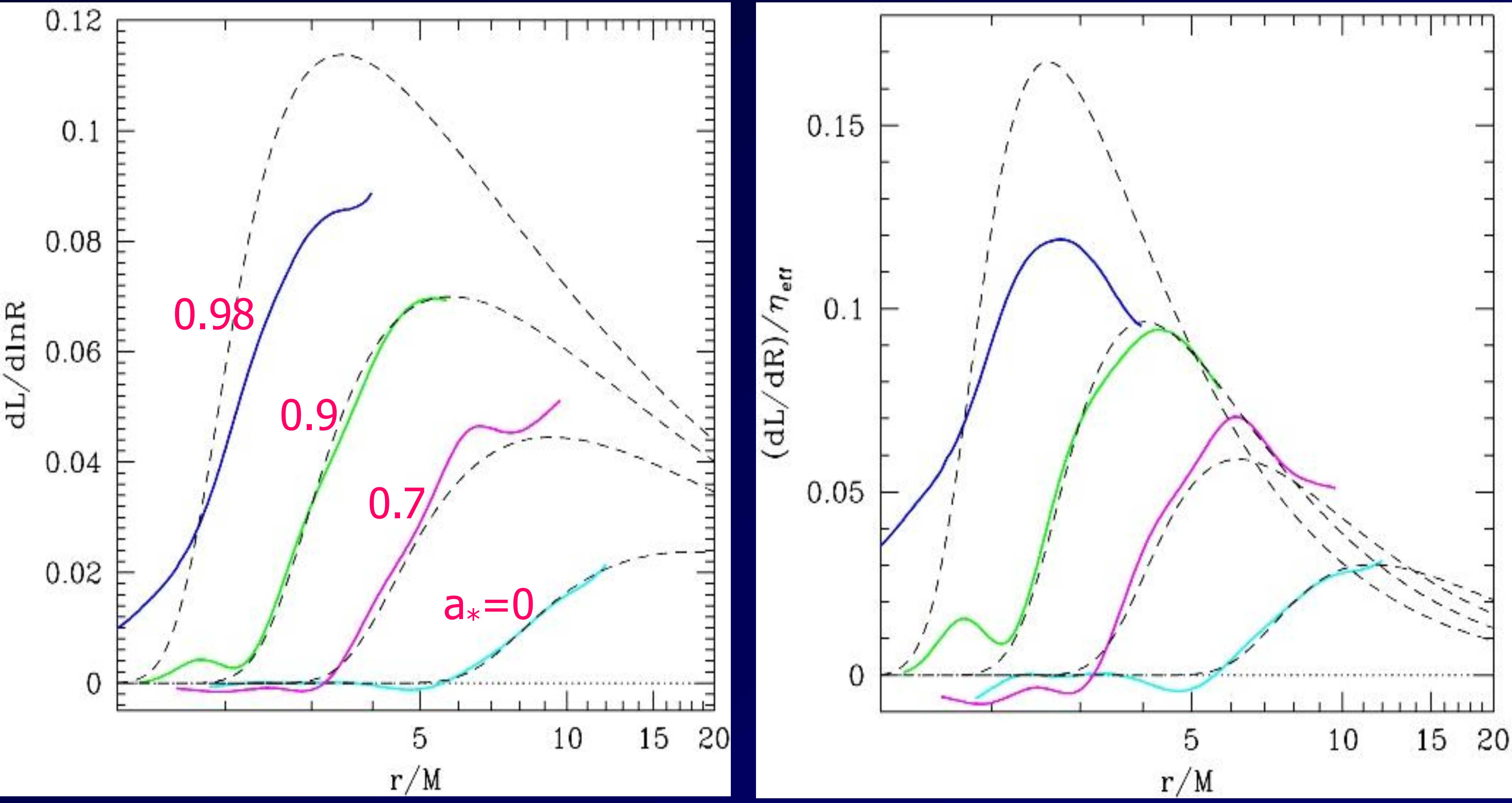


!!Preliminary Result!!

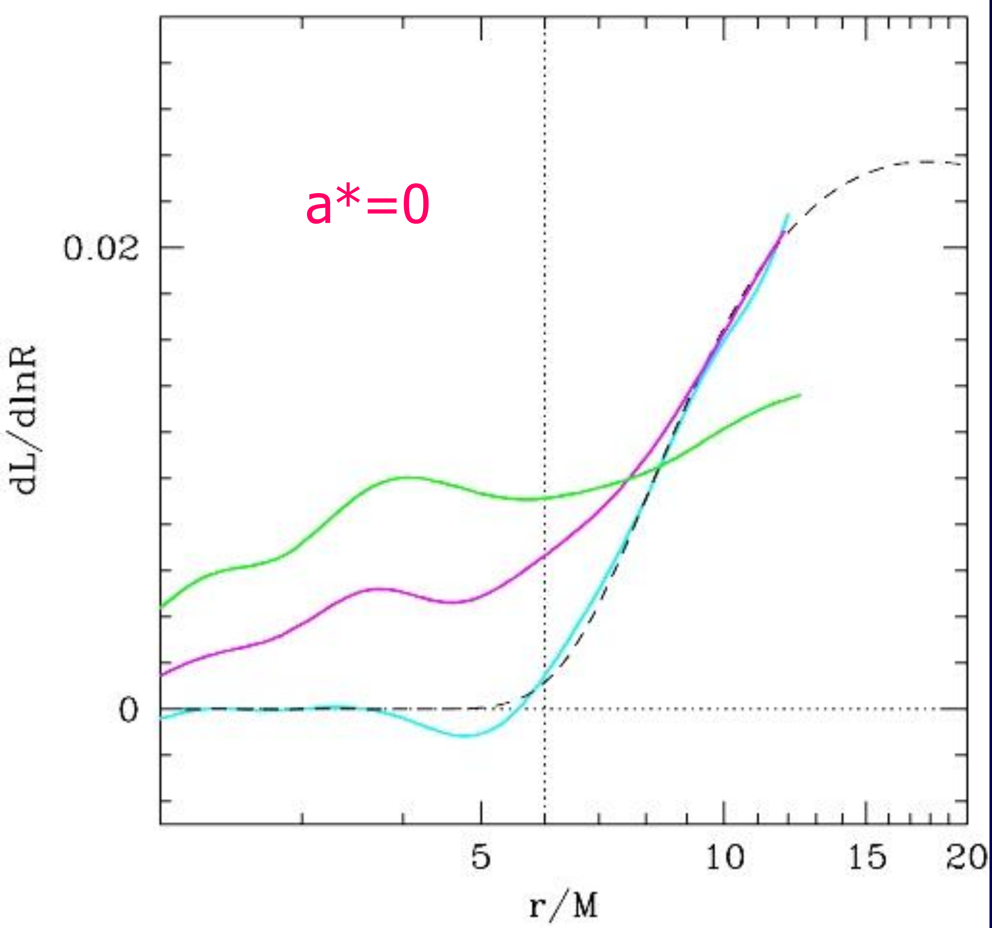


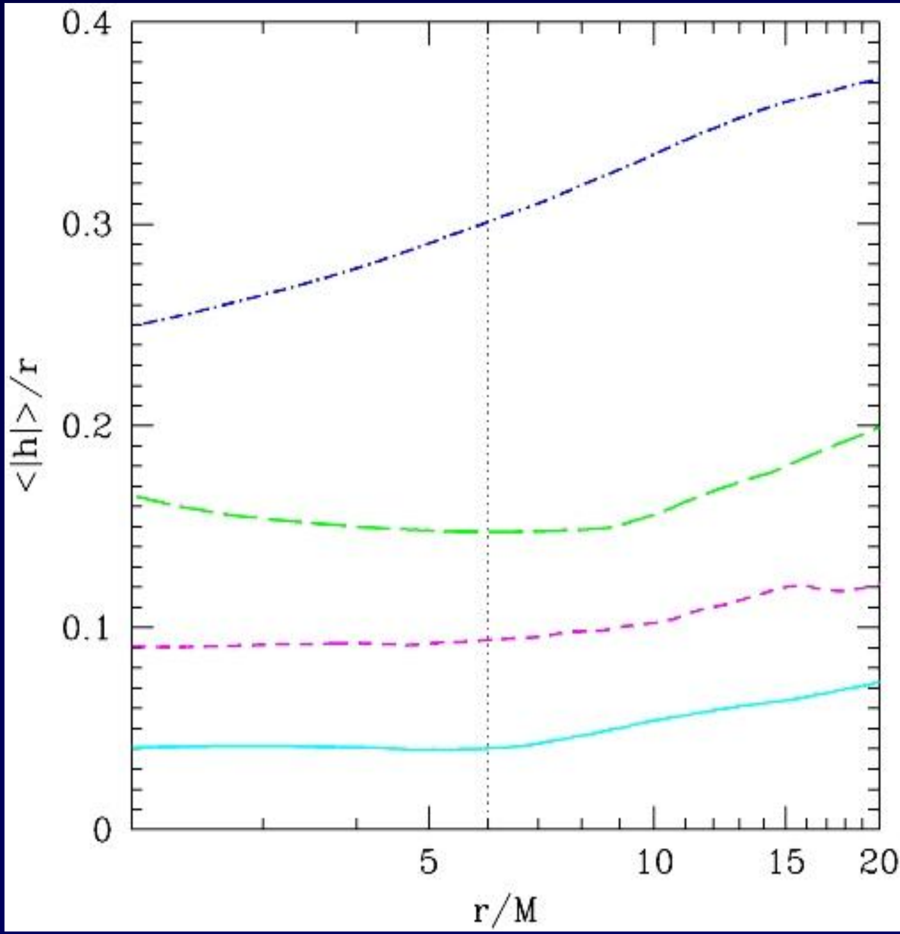
Cyan: 256 x 64 x 32 (Penna et al. 2009): ~5000M
Magenta: 512 x 128 x 32 (Shafee et al. 2008): ~2000M

Thin Disks: different a_*



Thicker Disks: $a_*=0$





Distinction between the disk and the plunging region becomes washed out as the disk becomes geometrically thicker

Energy and Luminosity: Summary

- Thin disks with $h/r<0.1$ seem to behave like the Novikov-Thorne model
- Deviations are larger for larger BH spins, and may be serious as $a_* \rightarrow 1$
- Deviations increase rapidly as the disk thickness increases
- Accretion luminosity/efficiency is not very different from NT value

Bottom Line

Current (very preliminary!) indication: geometrically thin accretion disks behave quite a lot like the Novikov-Thorne model

Suggests that our spin estimates are probably okay…

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