Magnetized Accretion onto Inspiraling Binary Black Holes: II. Disk Dynamics

Watch out for our paper next week on arXiv.org !!

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How do we find close ($a \lesssim 1000M$) SMBBHs with EM waves?

- Need superb theoretical predictions to weed through high-cadence all-sky survey data (e.g., PanSTARRS, LSST) and differentiate them from solo AGN;

- Improbability of spatially resolving a "close" pair of SMBHs forces us to look in other ways:
  - Spectral shape and evolution;
  - Temporal variability;
  - Polarization;
  - Extended structure: e.g., double jets, unique outflows;
  - ➡ Need sophisticated analysis tools (e.g., radiative transfer);

- We will first consider binaries of $q = M_2/M_1 \simeq 1$
  - Not as likely as q = 1/10 ;
  - May be best case for seeing *both* simultaneously (e.g. emission onto primary may dominate that due to smaller secondary);
  - Fundamental starting point from which to explore parameter space;
  - Easier to calculate;

Prior Work:

Refs.	Gravity Model	Matter Model	Code	Algorithm	Resolved Horizons	Timescales
Farris++	GR	Hydro Cloud (cold) Hydro Disk	UI's Cactus	Eulerian, HRSC	YES	$t_{disk} > t_{shrink}$
Bode++	GR	Hydro Cloud (hot) Hydro Disk	ET/Cactus	Eulerian, HRSC	YES	$t_{disk} > t_{shrink}$
Palenzuela++	GR	EM & Force-free plasma	HAD & Whisky (w/ Mosta)	Eulerian, FD	YES	(no disk)
Ours	2.5PN	(cool) MHD Disk	HARM3d	Eulerian, HRSC	NO (not yet)	$t_{disk} <=> t_{shrink}$
MacFadyen & Milosavljevic	Newtonian	(cold) Hydro Disk	FLASH	Eulerian, HRSC	NO	$t_{disk} < t_{shrink}$
Cuadra++	Newtonian, self-gravity	(cold) Hydro Disk	Gadget-2	SPH	NO	$t_{disk} < t_{shrink}$
Shi++	Newtonian	(cold) MHD Disk	Zeus	Eulerian, FD	NO	$t_{disk} < t_{shrink}$

Acronyms: **UI** = Univ. of Illinois, **ET** = Einstein Toolkit, **HAD** = Hydro. ADaptive mesh refinement, **HRSC** = High-Resolution Shock-Capturing, **FD** = finite difference

Newtonian Simulations:

- e.g., MacFadyen & Milosavljevic 2008, Hayasaki++2007, Cuadra++2009, Shi++2012
- ✓ Excellent for binary separations: $t_{inflow} << t_{merger}$
- ✓ Useful for understanding disk's history and prior condition before late phase of inspiral;
- ✓ Codes are relatively cheap --> can evolve for O(100) orbits
- − Invalid for small separations, non-relativistic MHD physics

NR Simulations:

- ✓ Have ability to simulate dynamics without approximation;
- ✓ Produced a recent surge of results:
  - Hot gas accretion: Farris++2009, Bode++2009
  - Inviscid hydrodynamic circumbinary disks: Bode++2011, Farris++2011
  - EM and FF plasma Jets: Palenzuela++2009-2010, Mosta++2009
  - Most of luminosity is from the immediate vicinity of the BHs
- − NR GRMHD is nascent;
- − Evolutions usually limited to only O(10) orbits: $t_{inflow} >> t_{merger}$
  - − Not long enough for disks to settle into quasi-steady state before merger happens;
  - − Results may be strongly dependent on initial conditions;

Harm3d

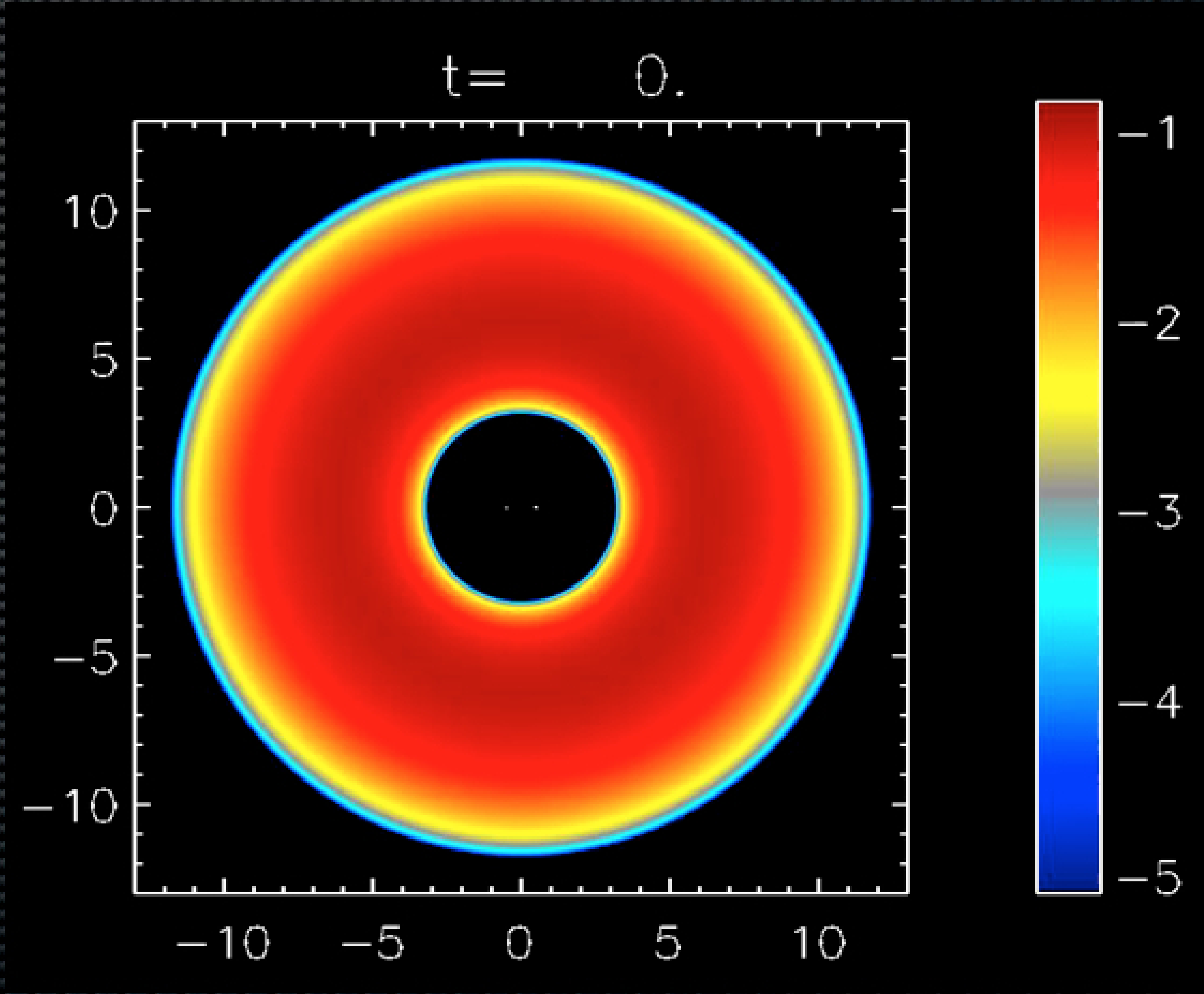
- Harm3d written largely independent of chosen coordinate system (covariance)
  - GRMHD code
  - ✓ **Already used for many single BH disk runs**
  - ✓ **Efficiency through static Fixed Mesh Refinement (FMR);**
  - Added support for time-dependent metrics;

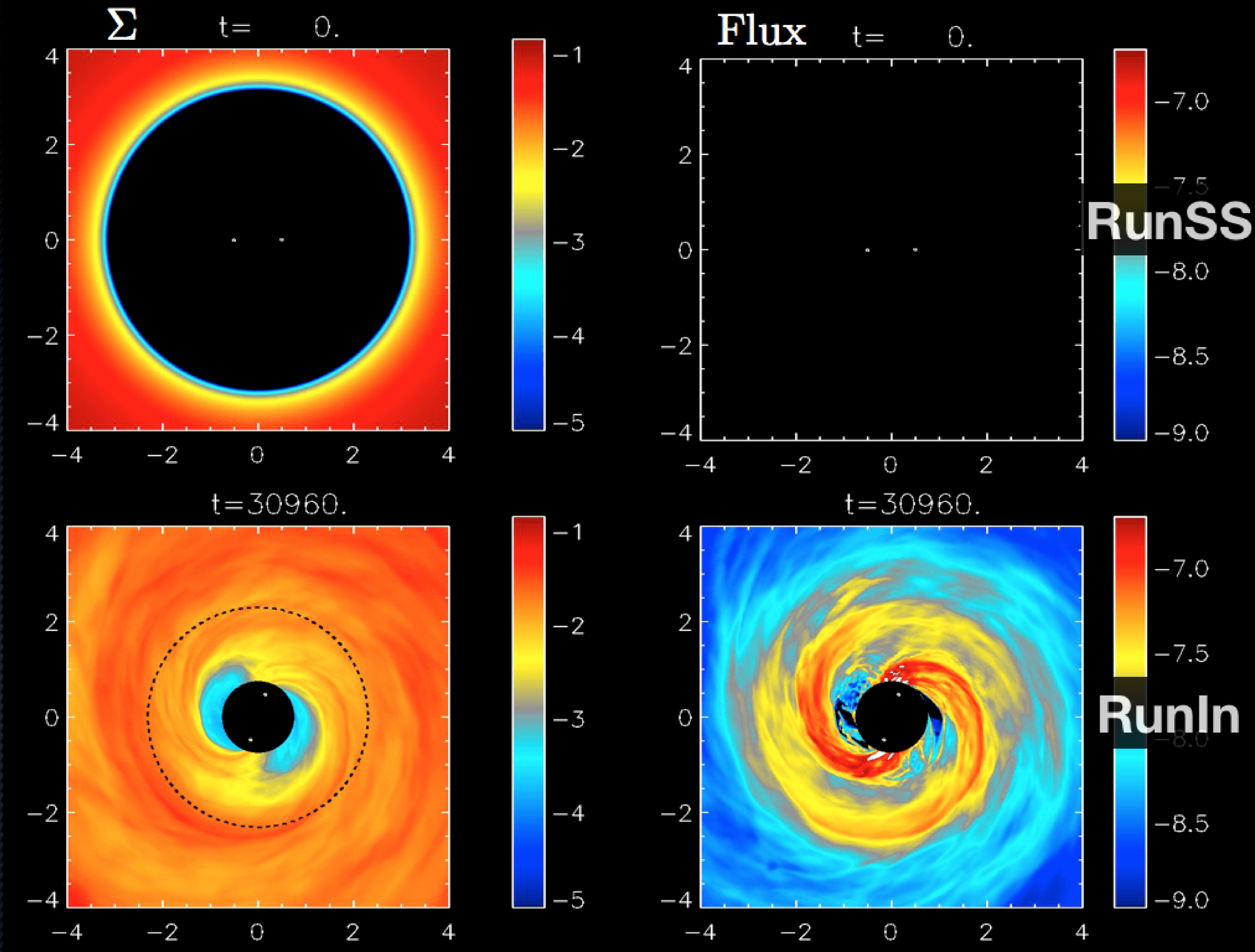
Grid:

- Resolves the MRI, spiral density waves
- Full azimuthal extent (resolve dominant m=1 mode)
- Nr x Nth x Nph = [300,160,400]
- ✓ **Spherical coordinates conserve ang. mom. well**
- ✓ **FMR eliminates excessive dissipation at AMR boundaries**
- **BHs not in domain, grid's extent: $r = [\,0.75, 13]a_0$**

Model Setup

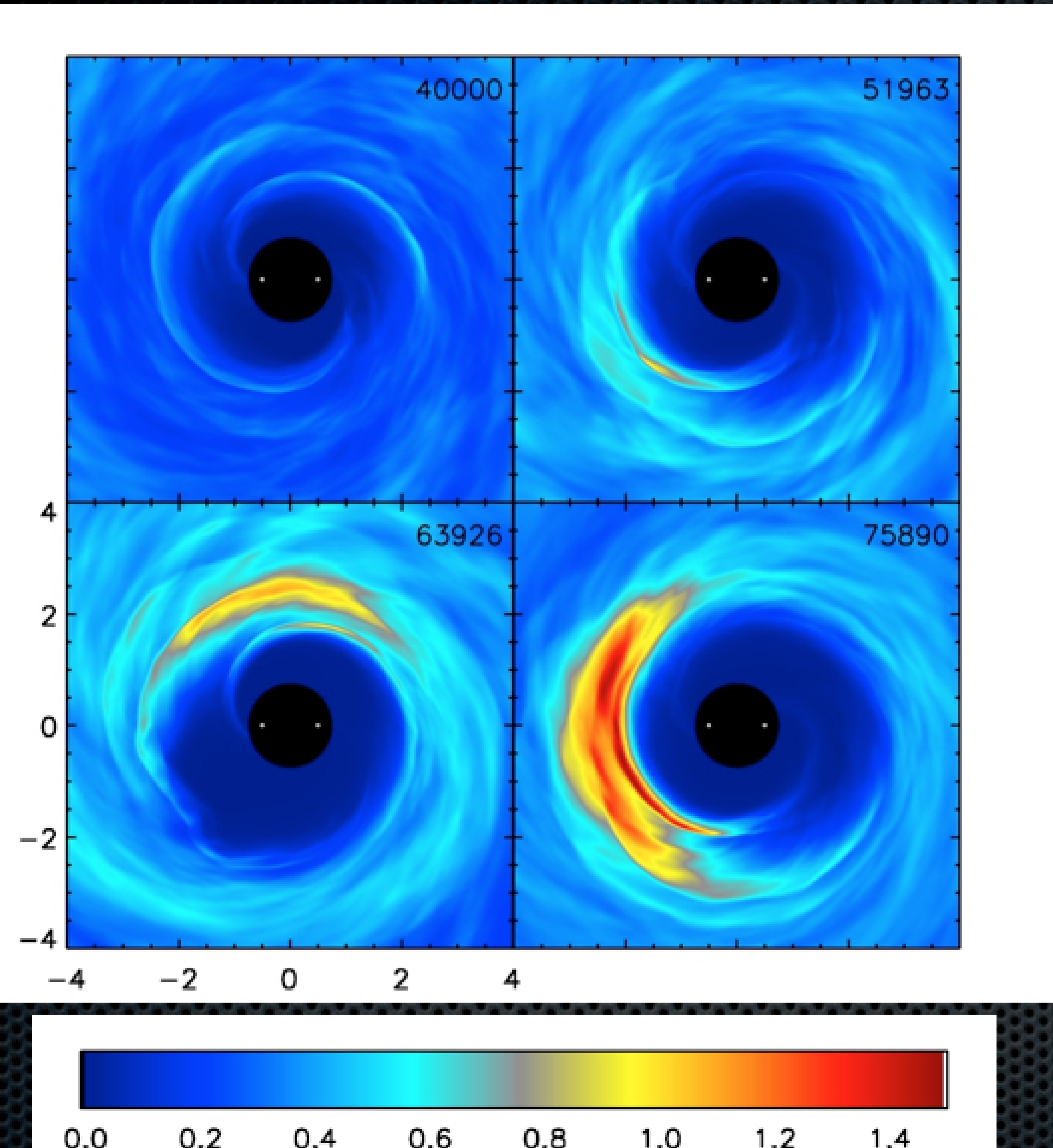
- Cool to constant entropy s.t. H/r=0.1
- ✓ **Radiation predictions consistent with disk's thermodynamics;**
- Pressure maximum $r_p = 5\,a_0$
- Poloidal Magnet field following density contours
- Disk extended over $r = [3\,a_0, 10\,a_0]$
- Near "Equilibrium" Disk solution using time-averaged spacetime



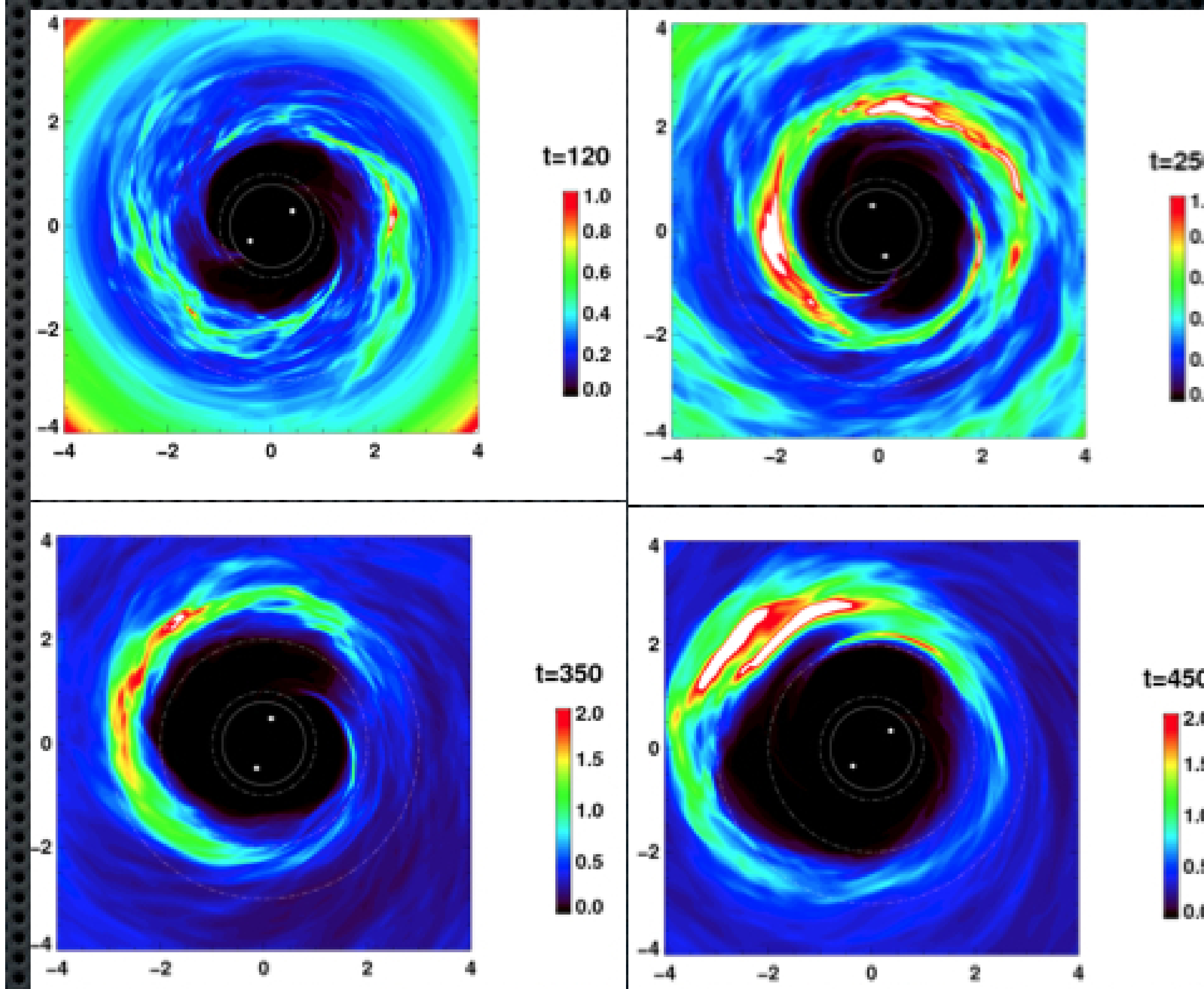

Σ t= 0.
Flux t= 0.
RunSS
t=30960.
t=30960.
RunIn

The "Lump"

$$\Sigma(r,\phi) \equiv \int d\theta \sqrt{-g}\rho / \sqrt{g_{\phi\phi}}$$

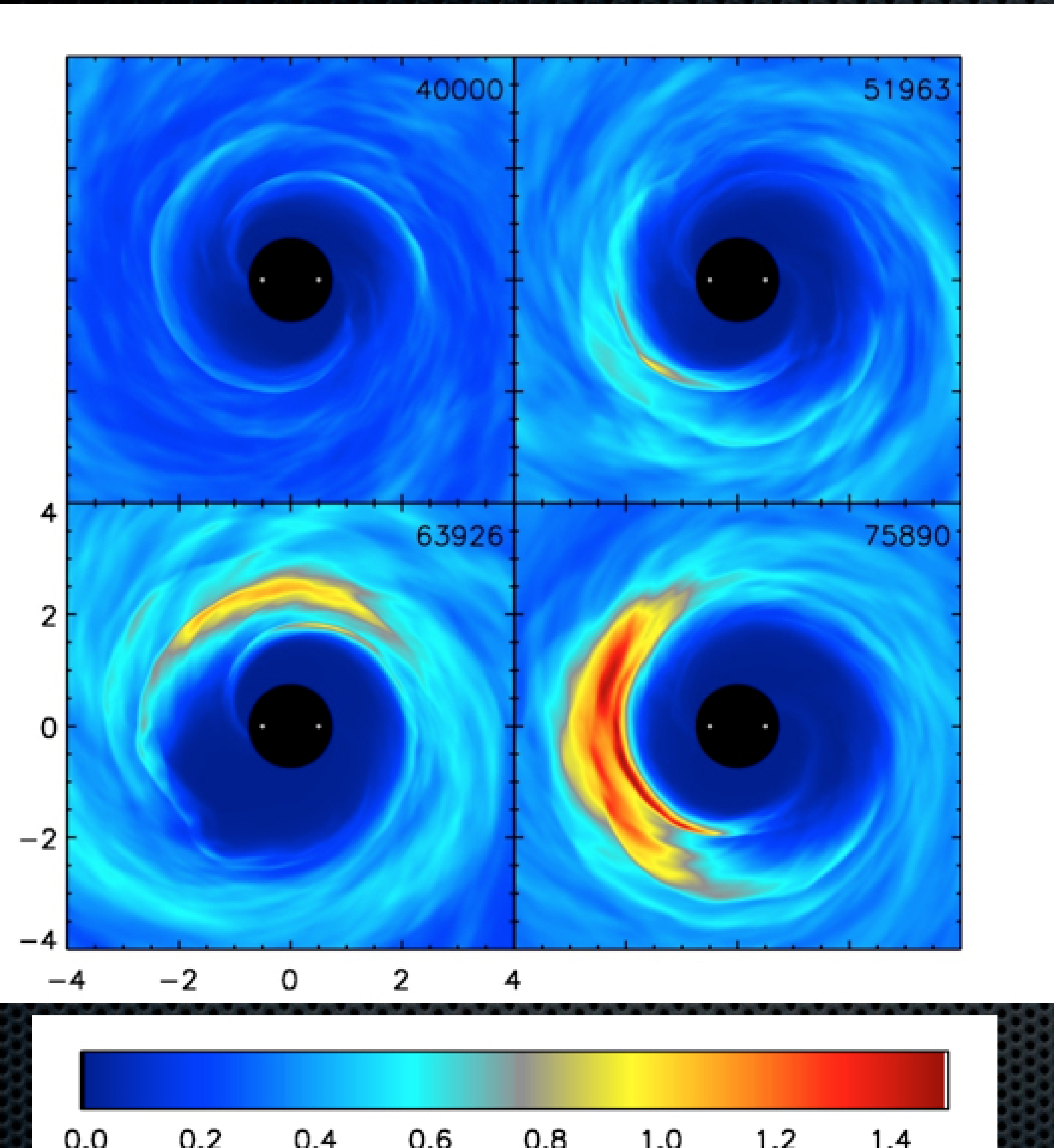


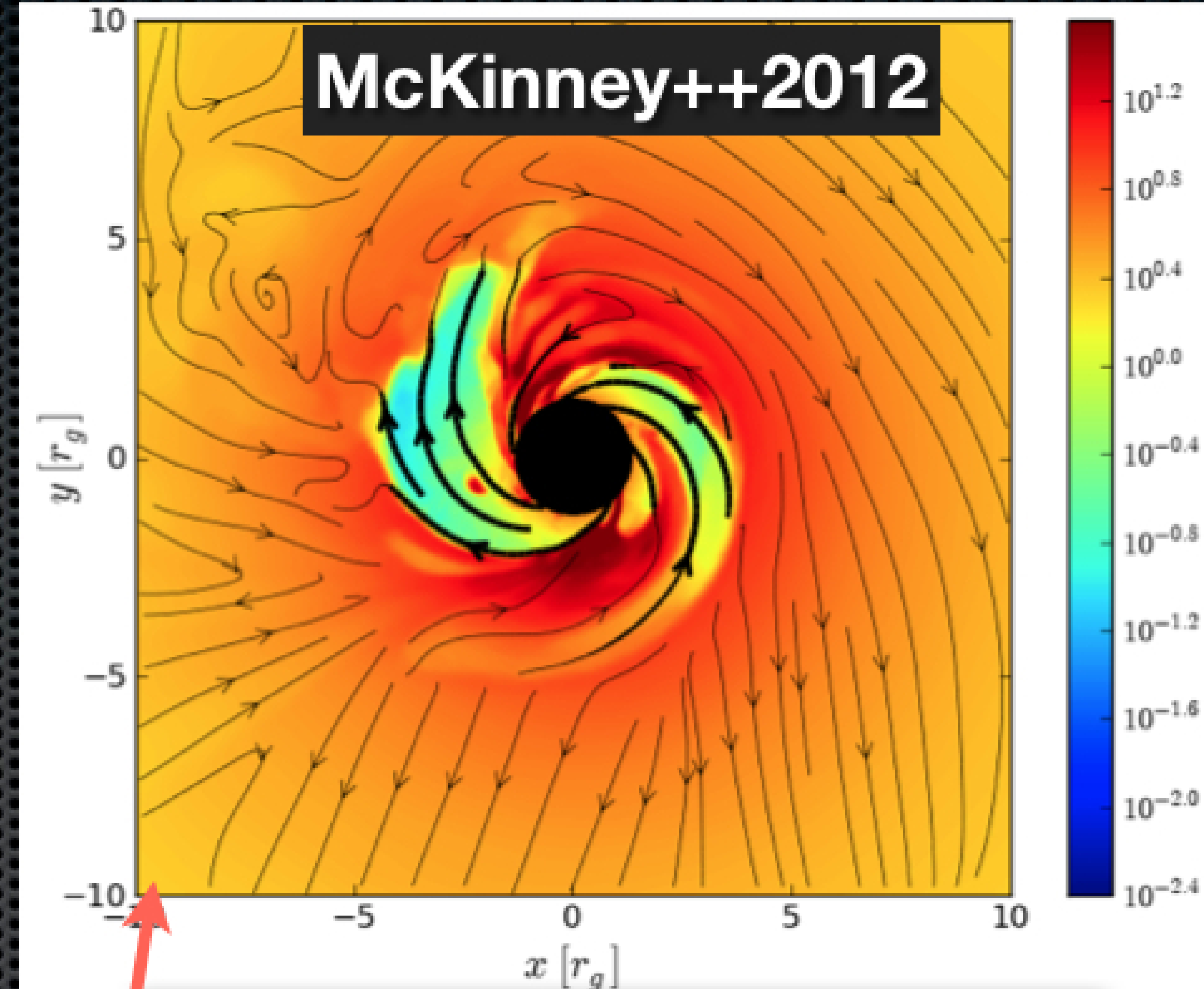
Ours

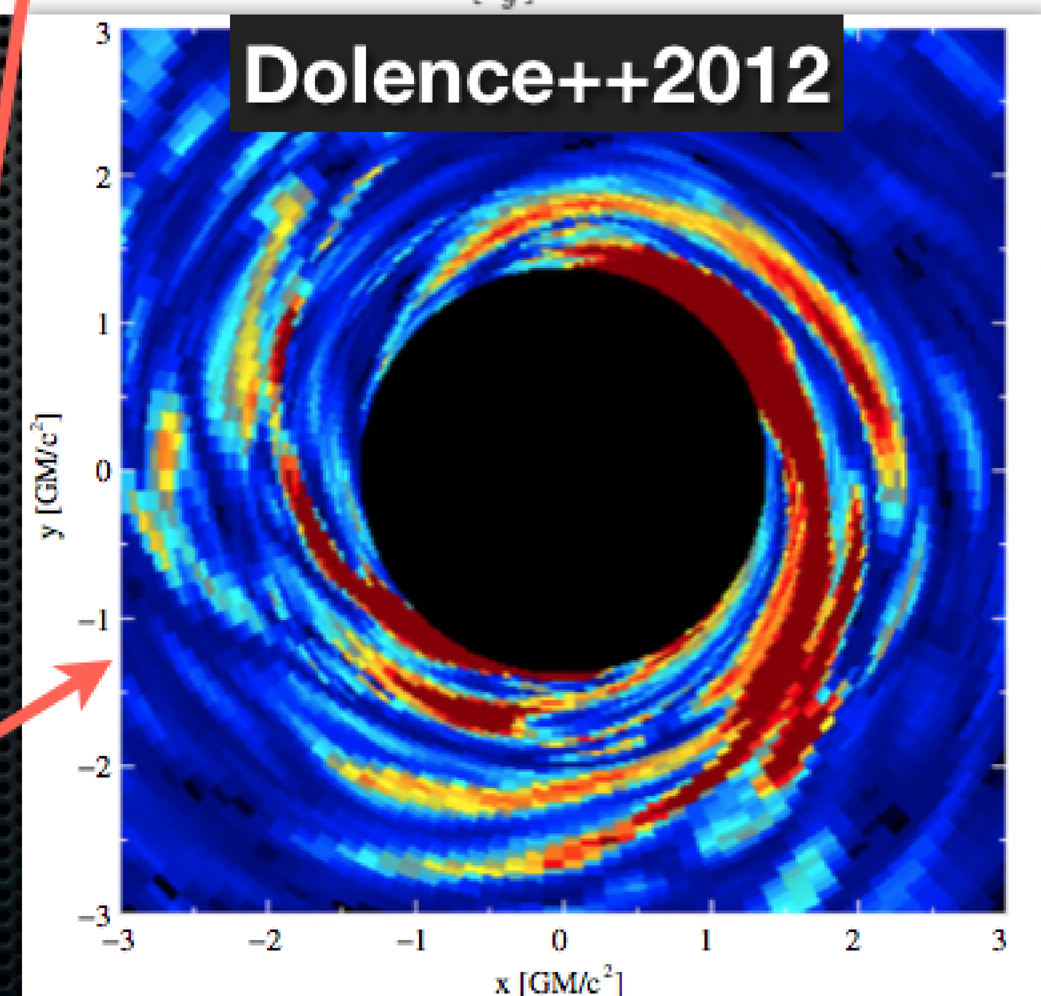


Newtonian MHD:
Shi++2012

The “Lump”







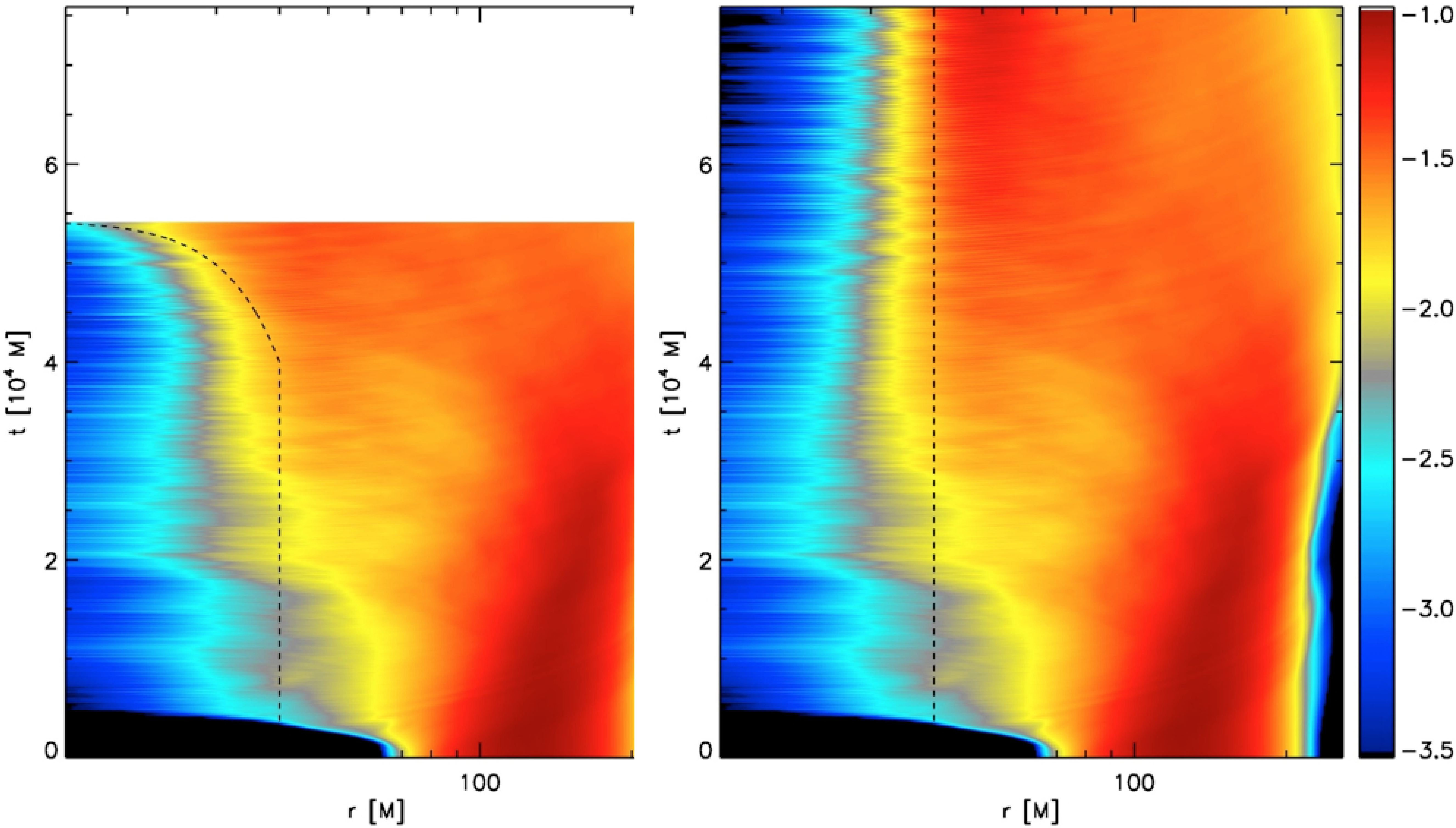
Ours

Single BH Disks

Surface Density

$$\Sigma(r,\phi) \equiv \int d\theta \sqrt{-g}\rho / \sqrt{g_{\phi\phi}}$$

RunIn **RunSS**



Surface Density

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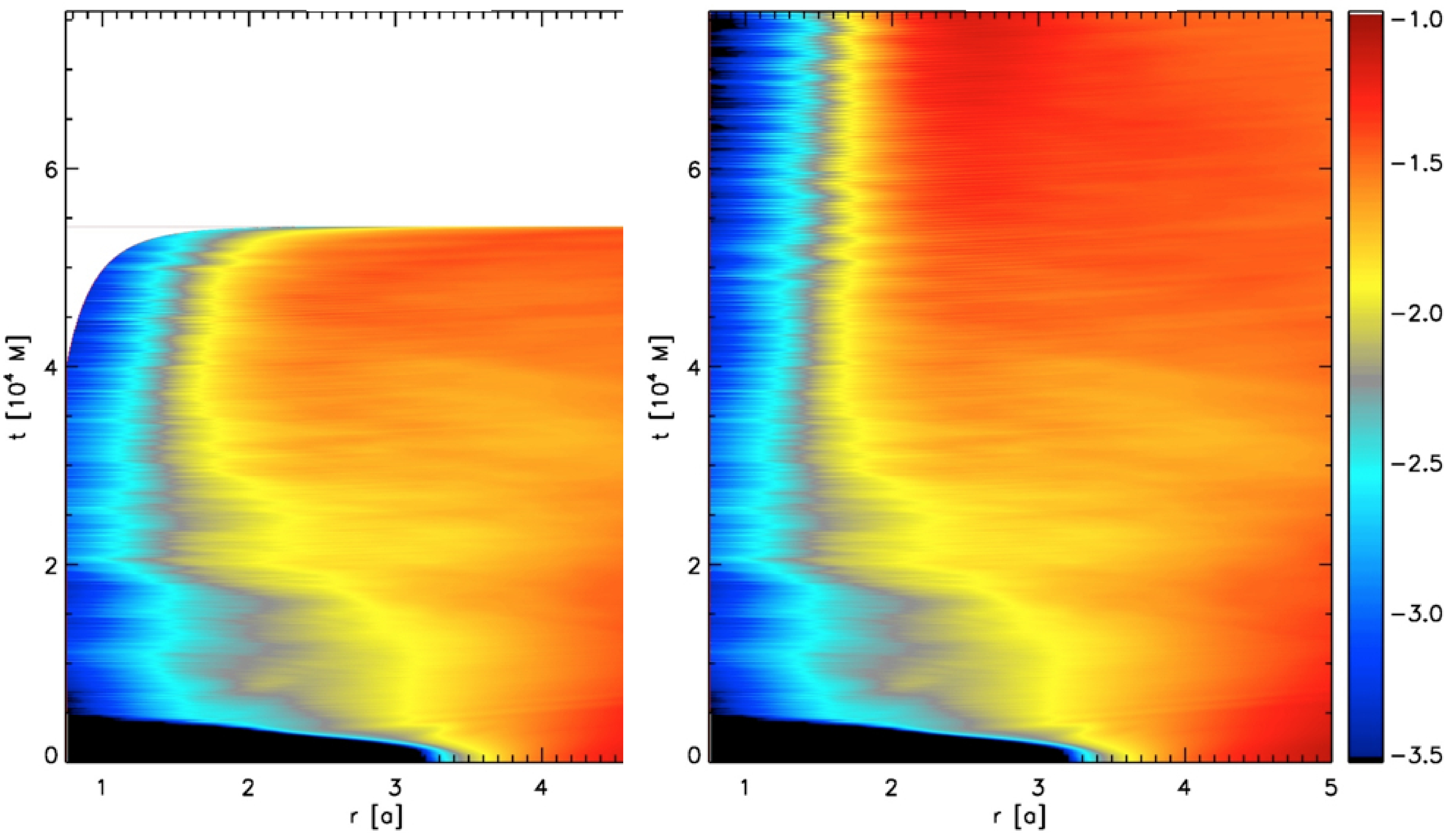
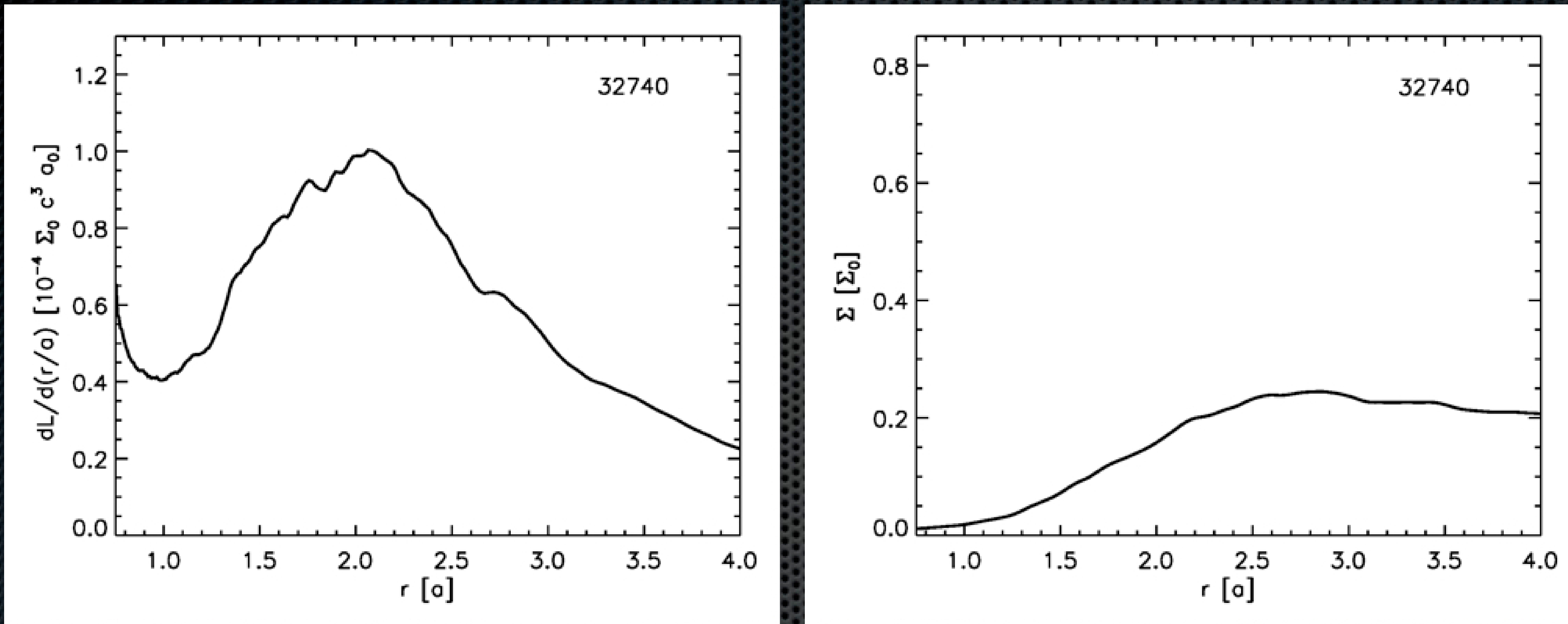
RunIn

RunSS



Disk-Binary Decoupling

RunSS **RunIn**



Binary-disk separation when:

$$t_{\rm gr} = \frac{5}{64}\left(\frac{a}{M}\right)^4 \frac{(1+q)^2}{q} M \ll t_{\rm in} = \alpha^{-1}(H/r)^{-2}(d\ln\Sigma/d\ln r)^{-1}\Omega^{-1} = \alpha^{-1}(H/r)^{-2}(d\ln\Sigma/d\ln r)^{-1}(r/r_g)^{3/2}M.$$

Commonly Imagined:

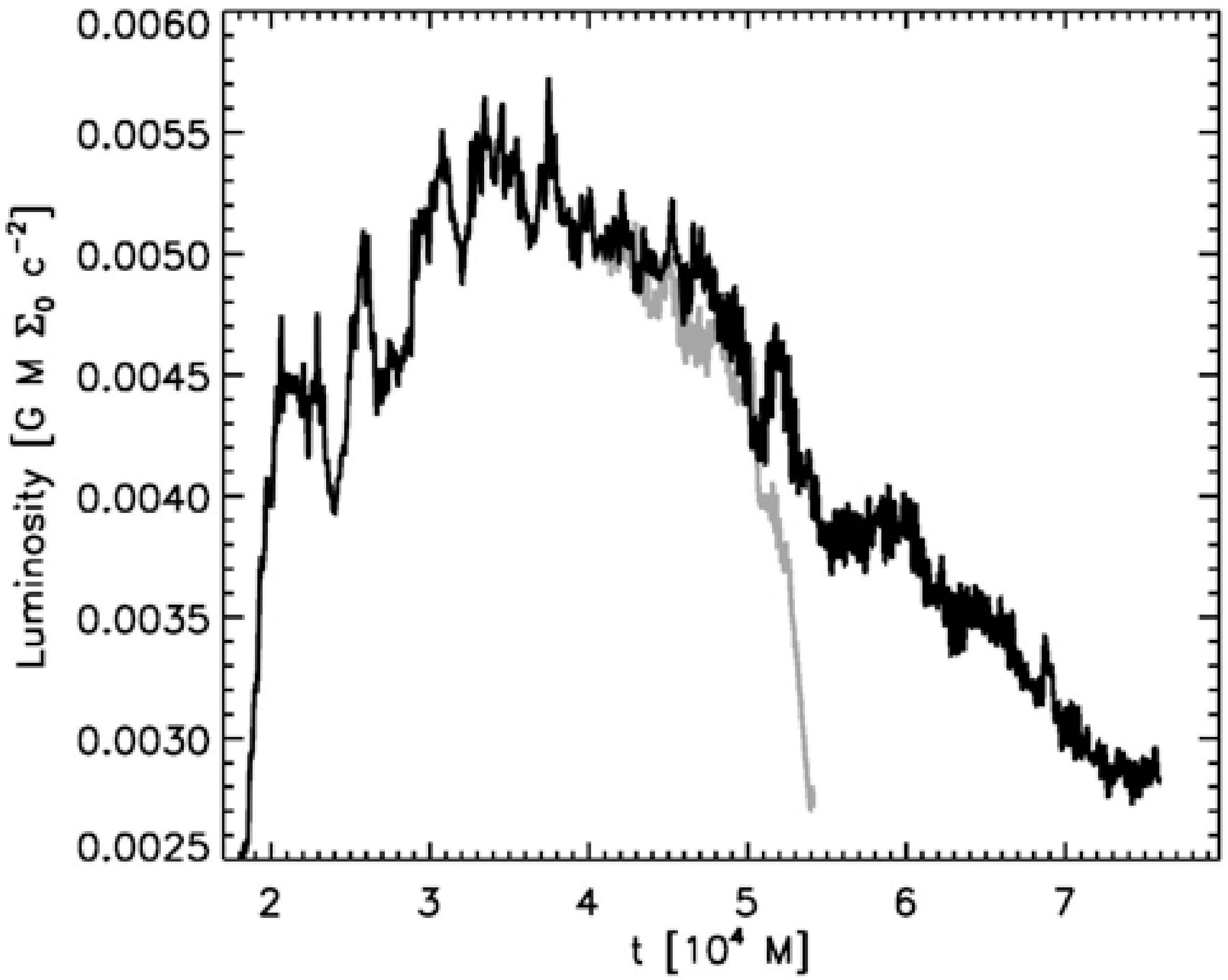
$$a_{\rm dec} \simeq 70M\,(d\ln\Sigma/d\ln r)^{-2/5}\left(\frac{\alpha}{0.01}\right)^{-2/5}\left(\frac{H/r}{0.15}\right)^{-4/5}$$

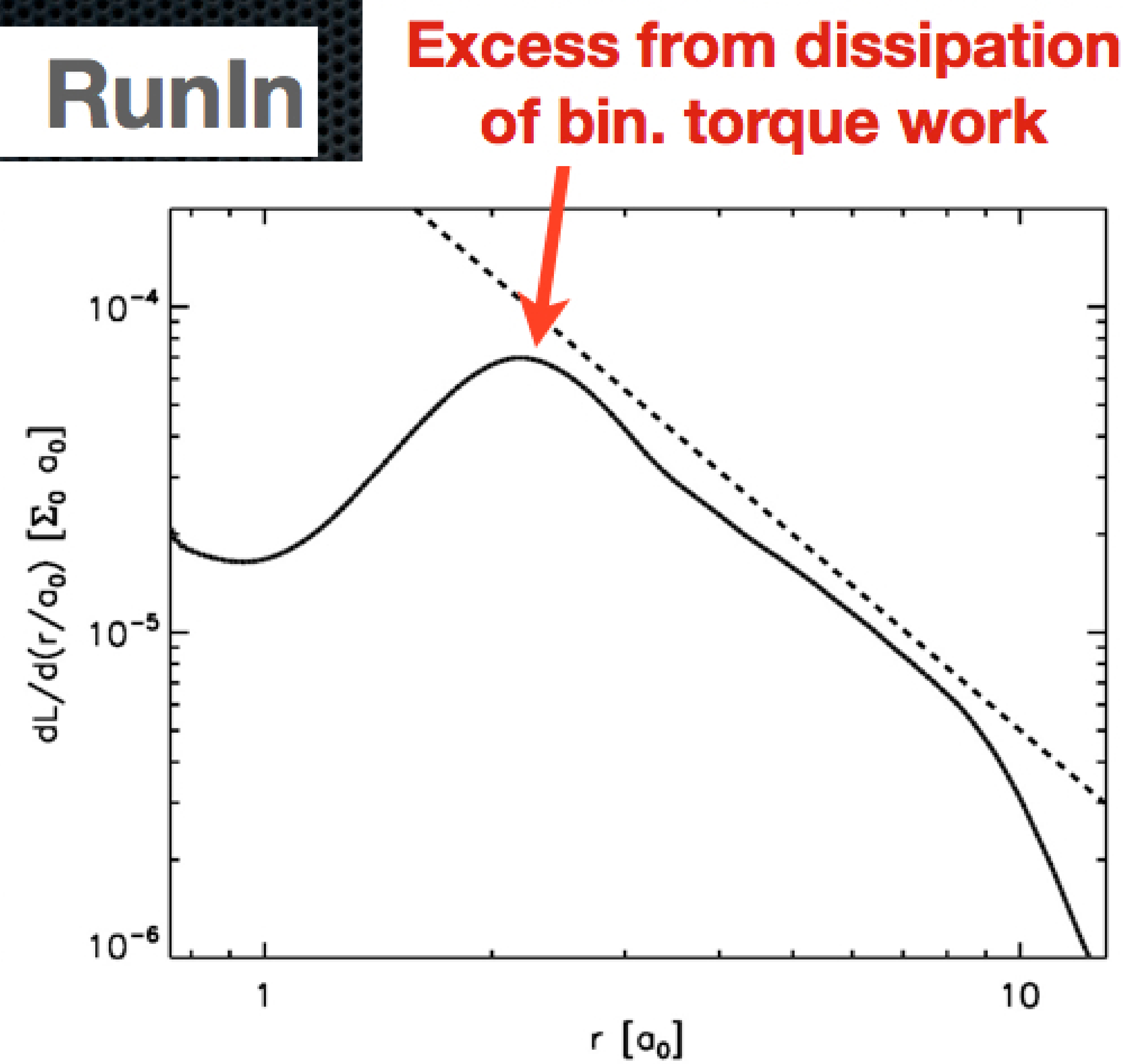
Ours:

$$a_{\rm dec} \simeq 10M\,(d\ln\Sigma/d\ln r/6)^{-2/5}\left(\frac{\alpha}{0.2}\right)^{-2/5}\left(\frac{H/r}{0.15}\right)^{-4/5}$$

Luminosity

RunSS **RunIn**





$$\frac{dL}{dr/a_0} = 4\times 10^{-4}(\dot{M}/0.01)(r/a_0)^{-2}\Sigma_0 a_0.$$

$$L_{\rm disk} \simeq 2.4\times 10^{40}(\hat{L}/10^{-3})M_6\tau_0 \ {\rm erg/s.}$$

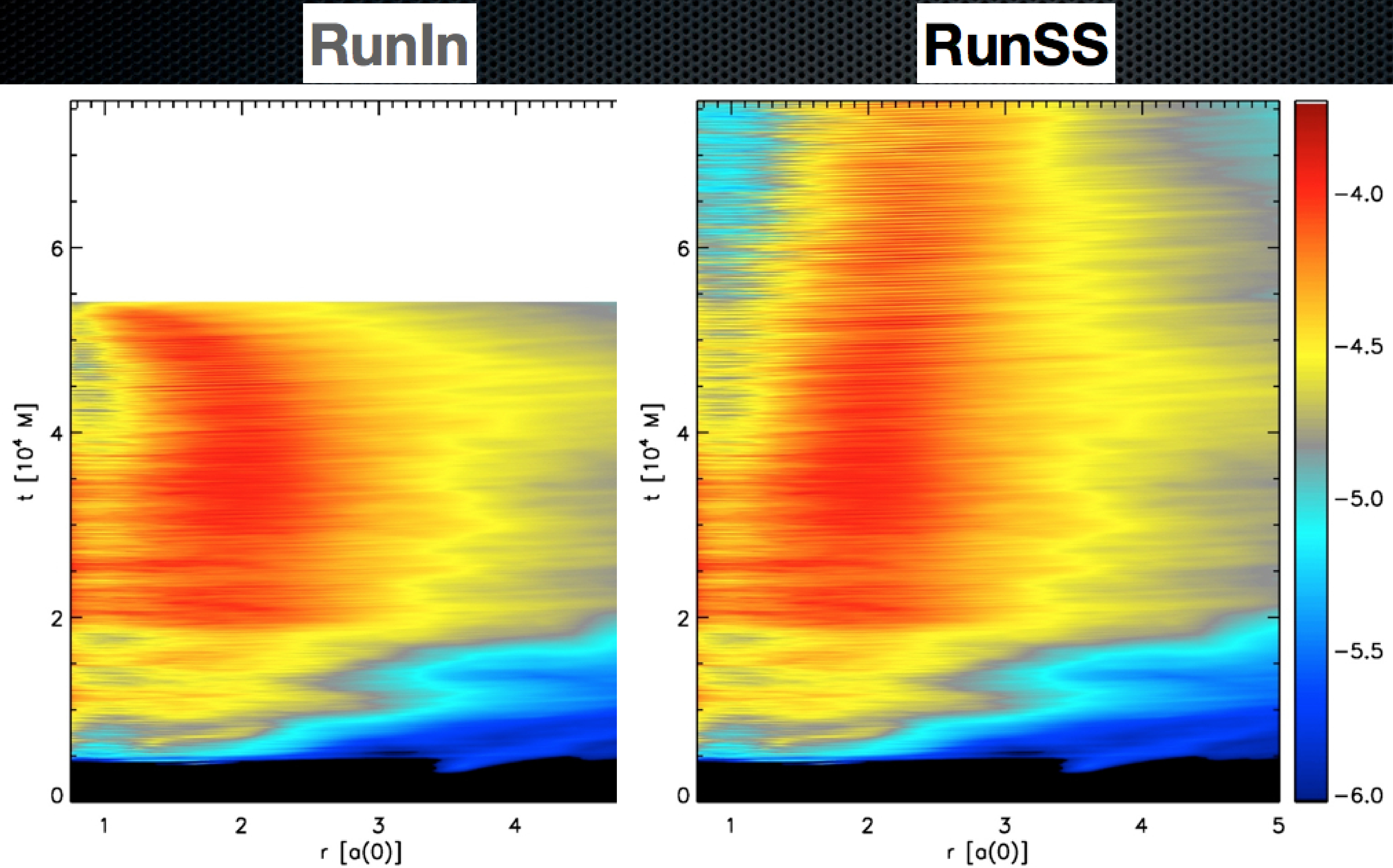
$$T_{\rm eff} \simeq 4\times 10^4(\hat{L}/10^{-3})^{1/4}M_6^{-1/4}\tau_0^{1/4}\ {\rm K},$$

$$\tau_0(r=20M) \sim \ 2\times 10^3(\alpha/0.1)^{-1}(\eta/\dot{m})$$

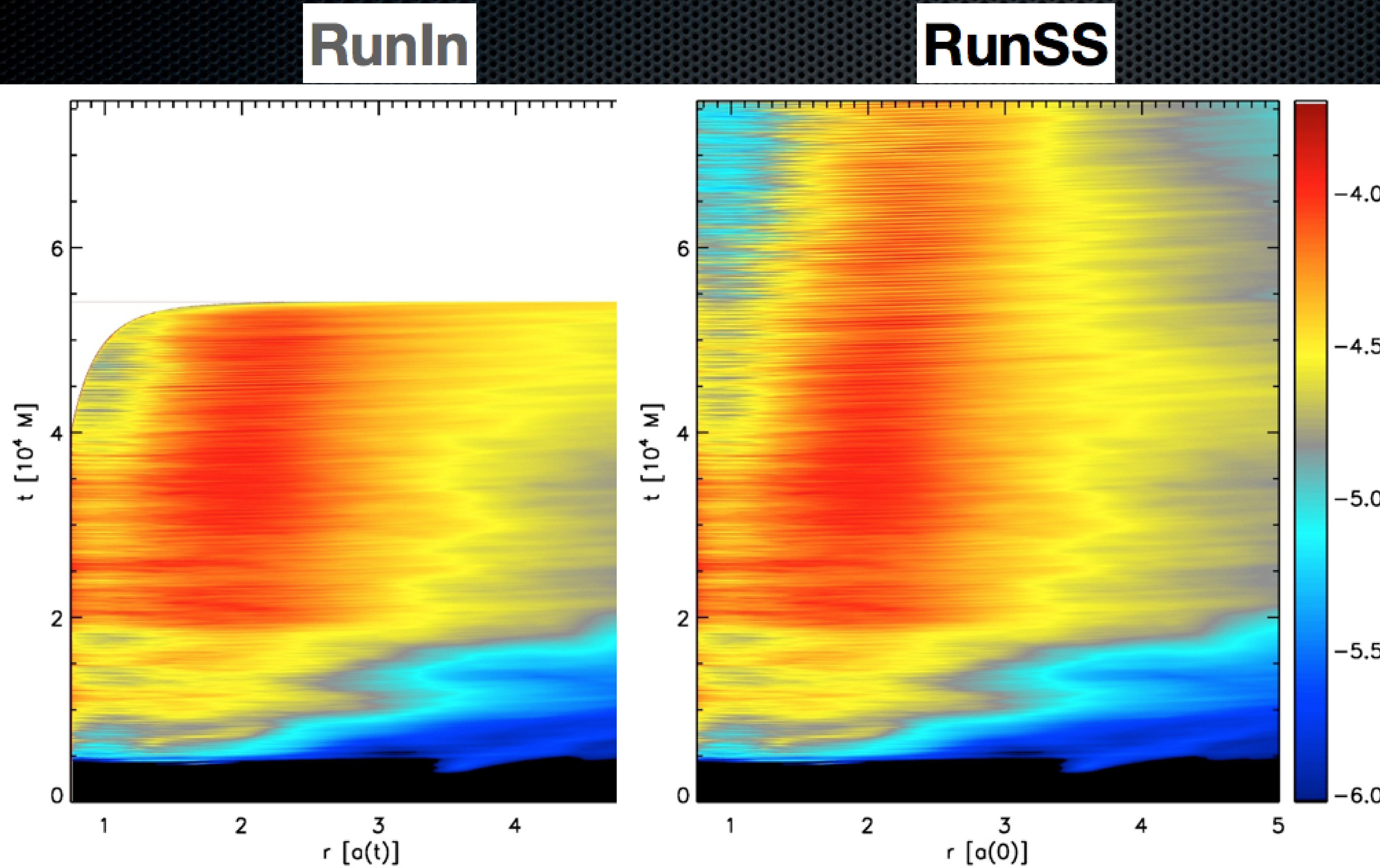
Typical for a AGN

--> peak in UV assuming thermal emission

Luminosity

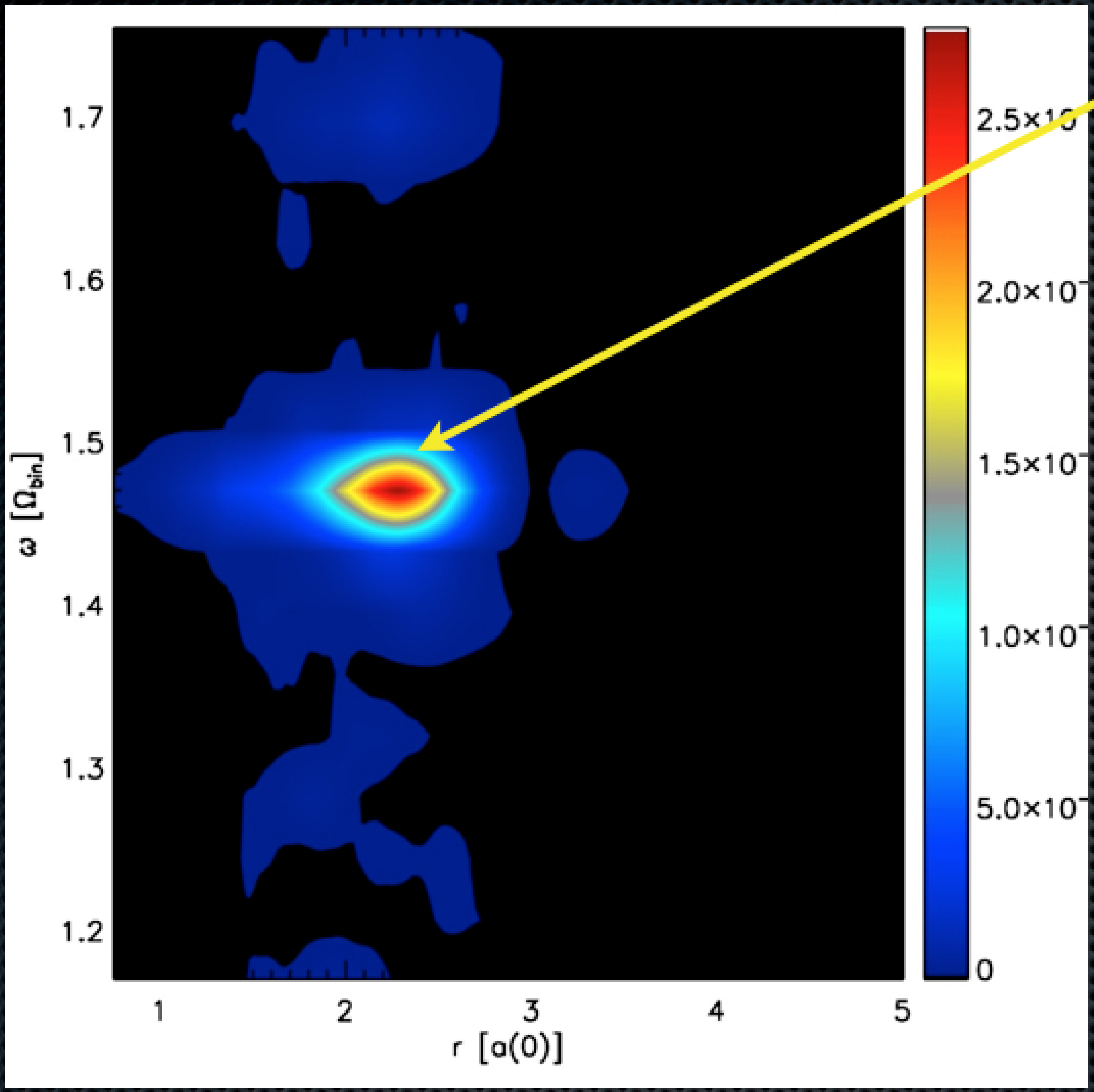


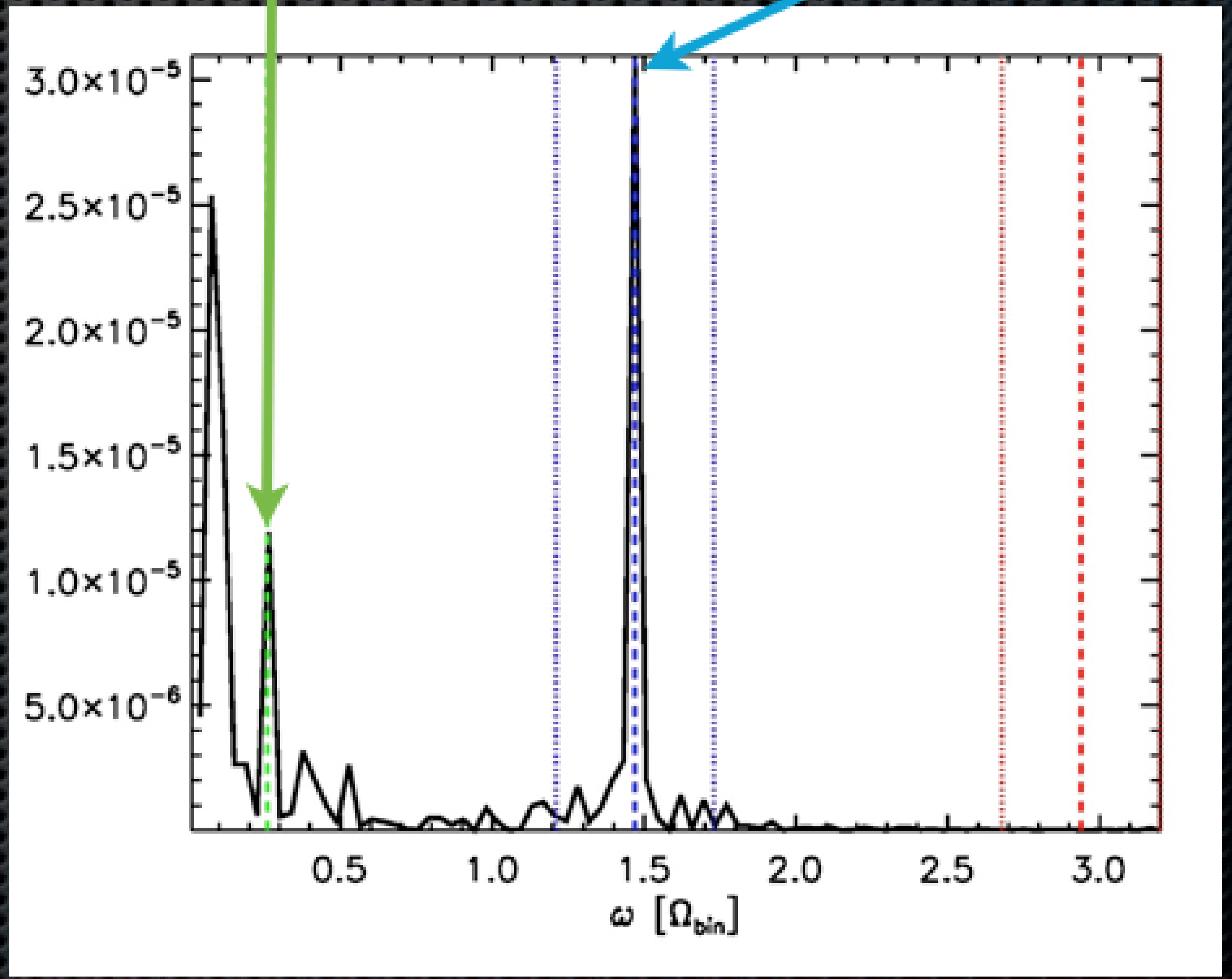
Luminosity



Variability

FFT close-up



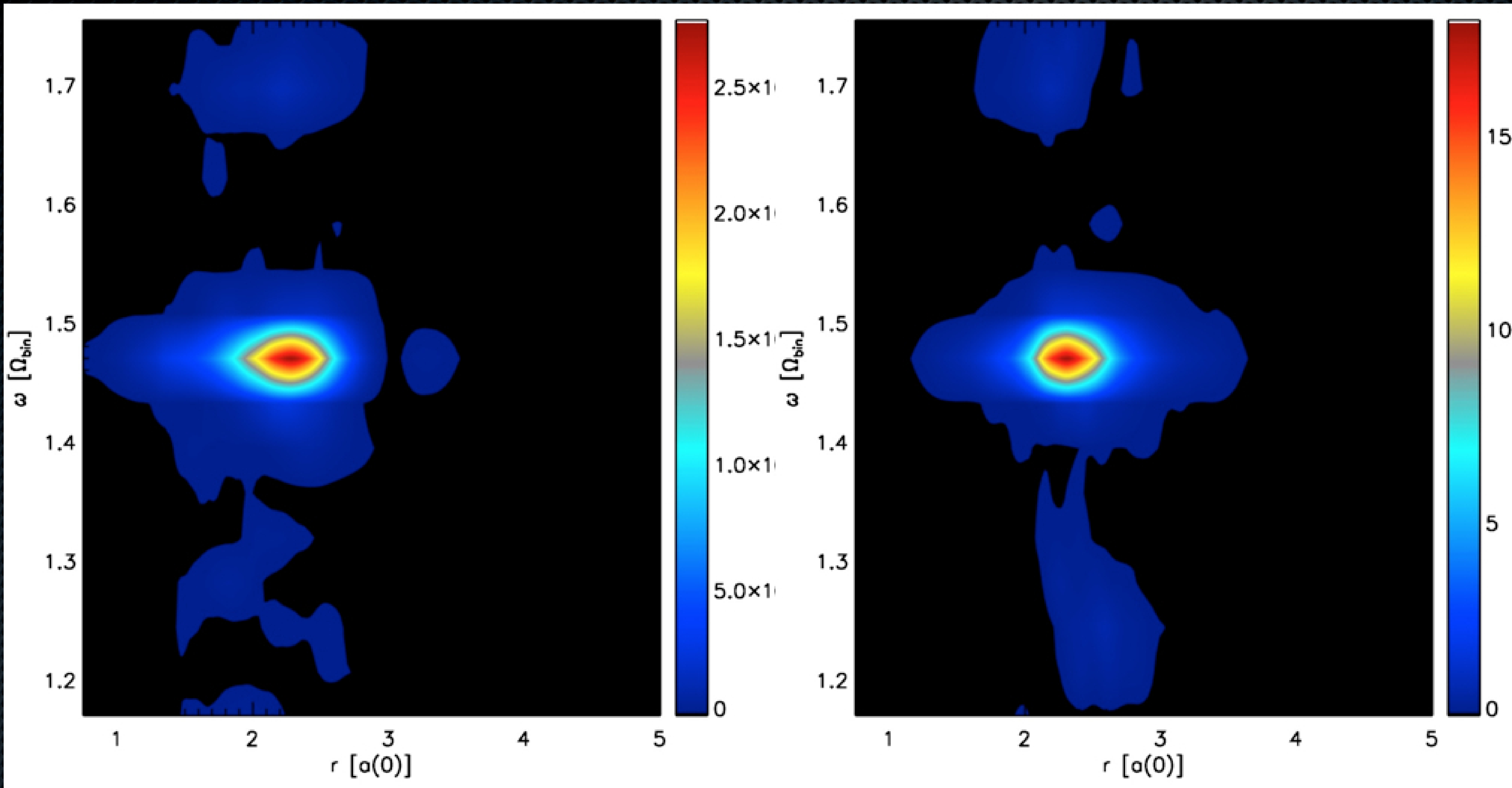


(r ,ω) space

integrated over radius

Variability

FFT close-up

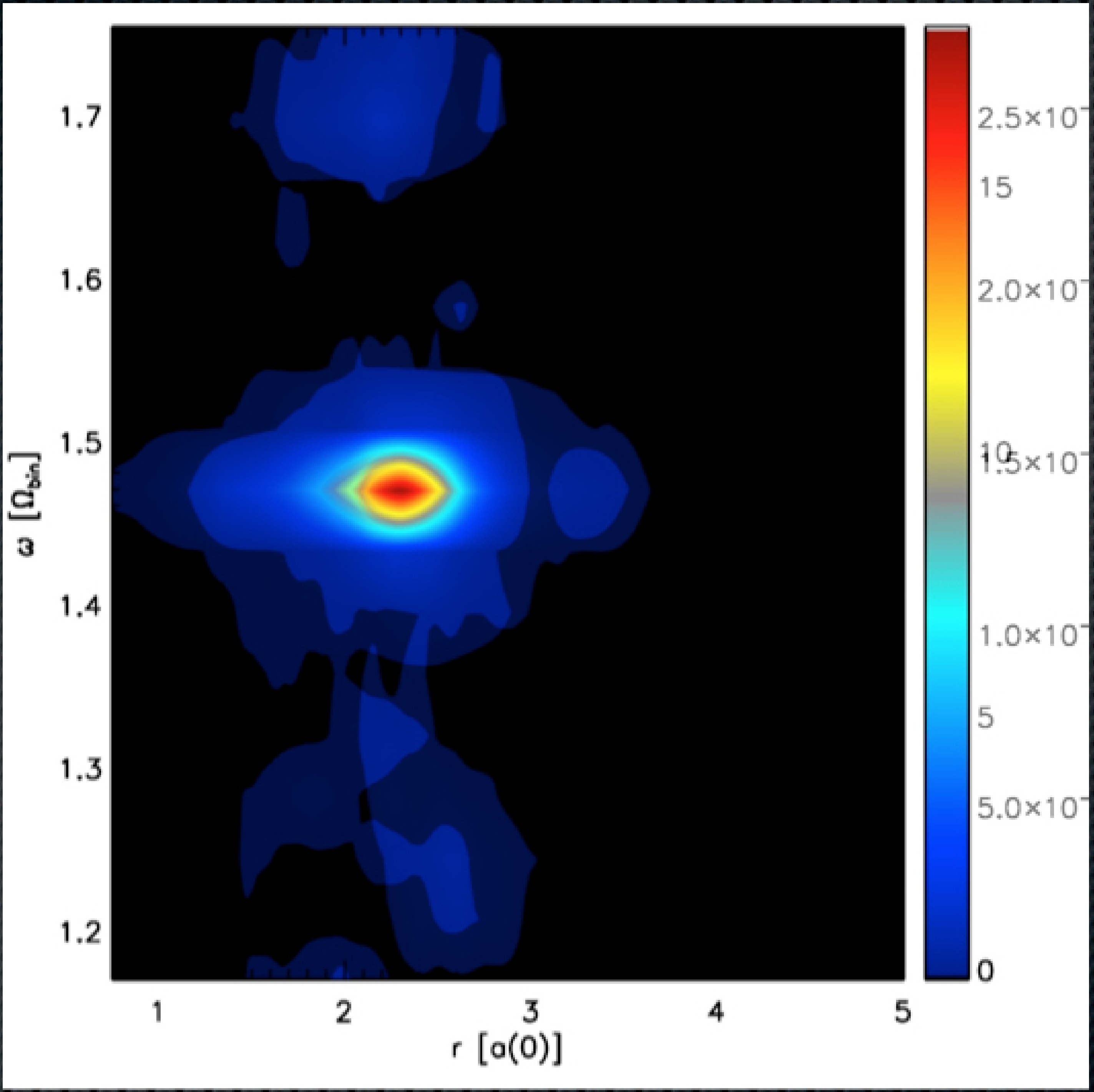


Luminosity

Surface Density

Variability

FFT close-up



Luminosity

Surface Density

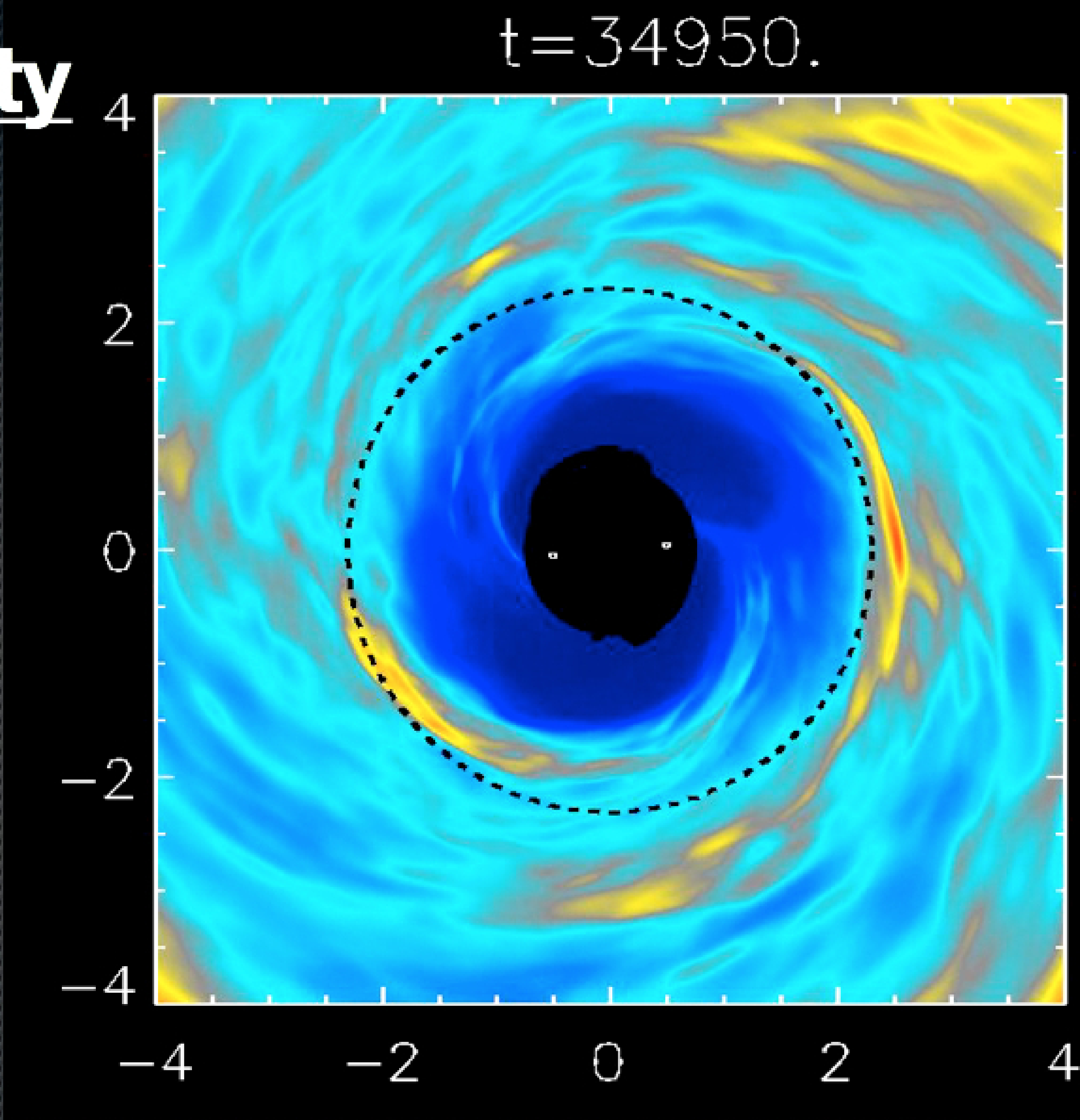
Origin of Variability

$$\omega_{\rm peak} = 2\left(\Omega_{\rm bin} - \Omega_{\rm lump}\right)$$

??

$$1 < \frac{\omega_{\rm peak}}{\left(\Omega_{\rm bin} - \Omega_{\rm lump}\right)} < 2$$

$$0 < \frac{M_2}{M_1} < 1$$



May be obfuscated by "low-pass filter" of disk's opacity and cooling rate:

$$0.24\left(\frac{200}{\tau_0}\right) \gtrsim f_{\rm supp} \gtrsim 0.12\left(\frac{200}{\tau_0}\right)$$

$$0.32\left(\frac{\alpha}{0.3}\right) \gtrsim f_{\rm supp} \gtrsim 0.16\left(\frac{\alpha}{0.3}\right)$$

→ **Ray-tracing will help determine quality of signal**

Summary:

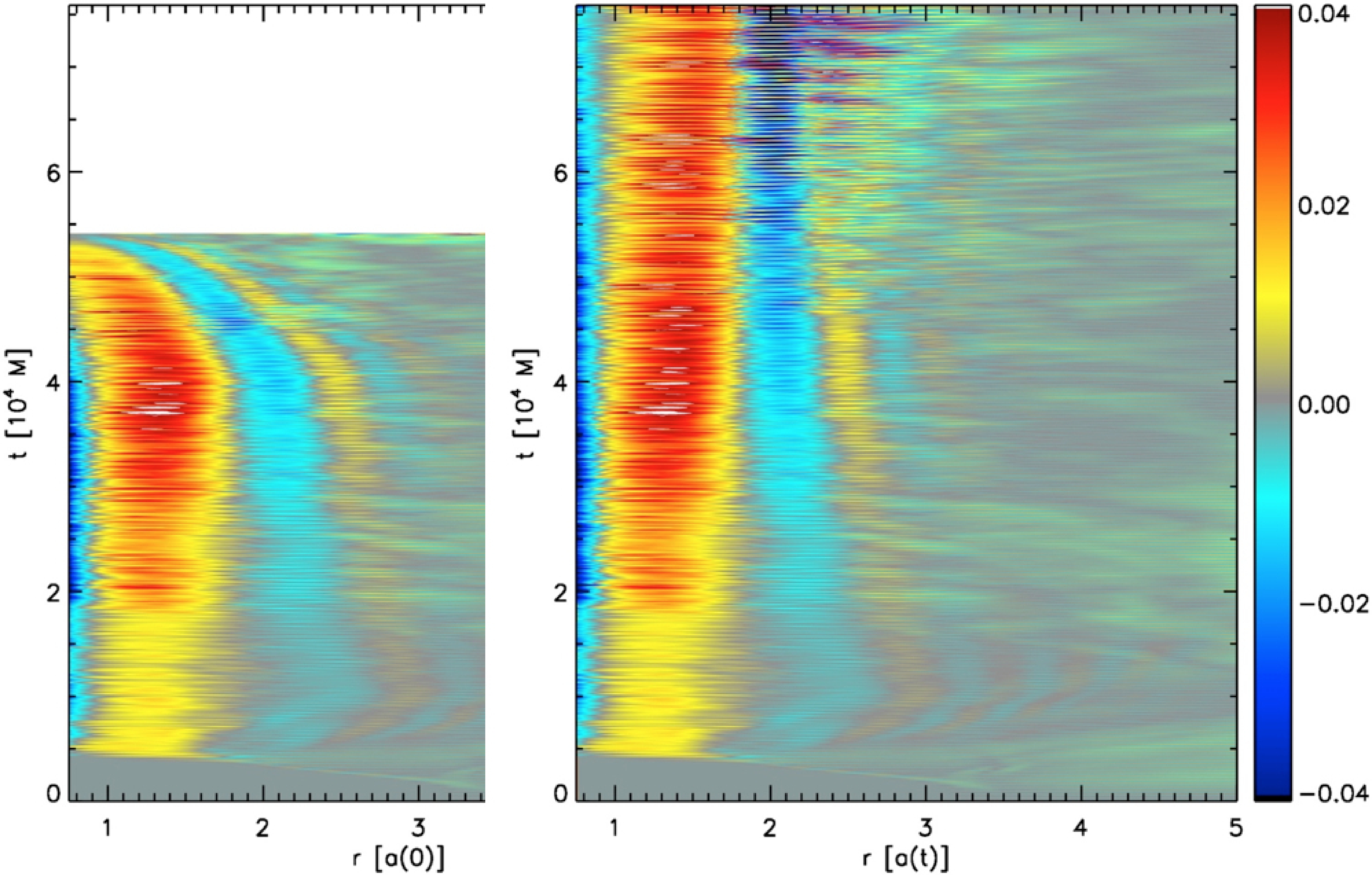
(Though I don't know what the next talks will include, I can safely say the following as this is fortuitously one of the first talks in this section)

- Evolve a circumbinary disk with grMHD for the first time;
- Observe binary/disk decoupling dynamically for the first time;
- Find first nontrivial periodic EM signal: binary/lump interaction;
  - It would not have been found without evolving for >70 orbits;
- Luminosity is characteristic of AGN with excess at edge of gap due to dissipated binary torque work, though small surface density within the gap leads to luminosity deficit there;
- Confident in our results as we agree well with prior Newtonian simulations;

Extra Slides

Binary Torque Density

$$\frac{dT}{dr} = \int \sqrt{-g}\, T^{\mu}{}_{\nu} \Gamma^{\nu}{}_{\mu\phi}\, d\theta d\phi$$



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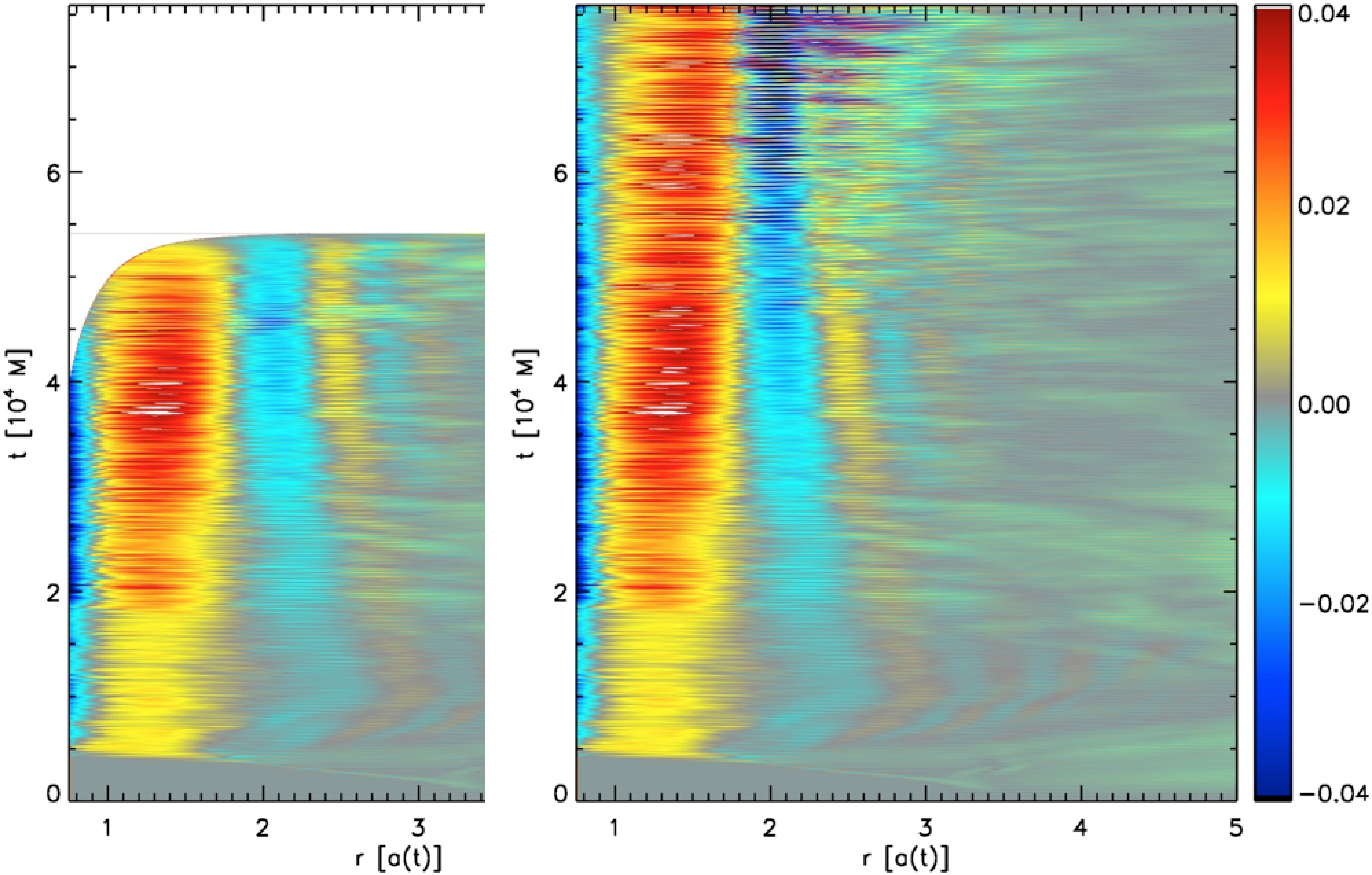
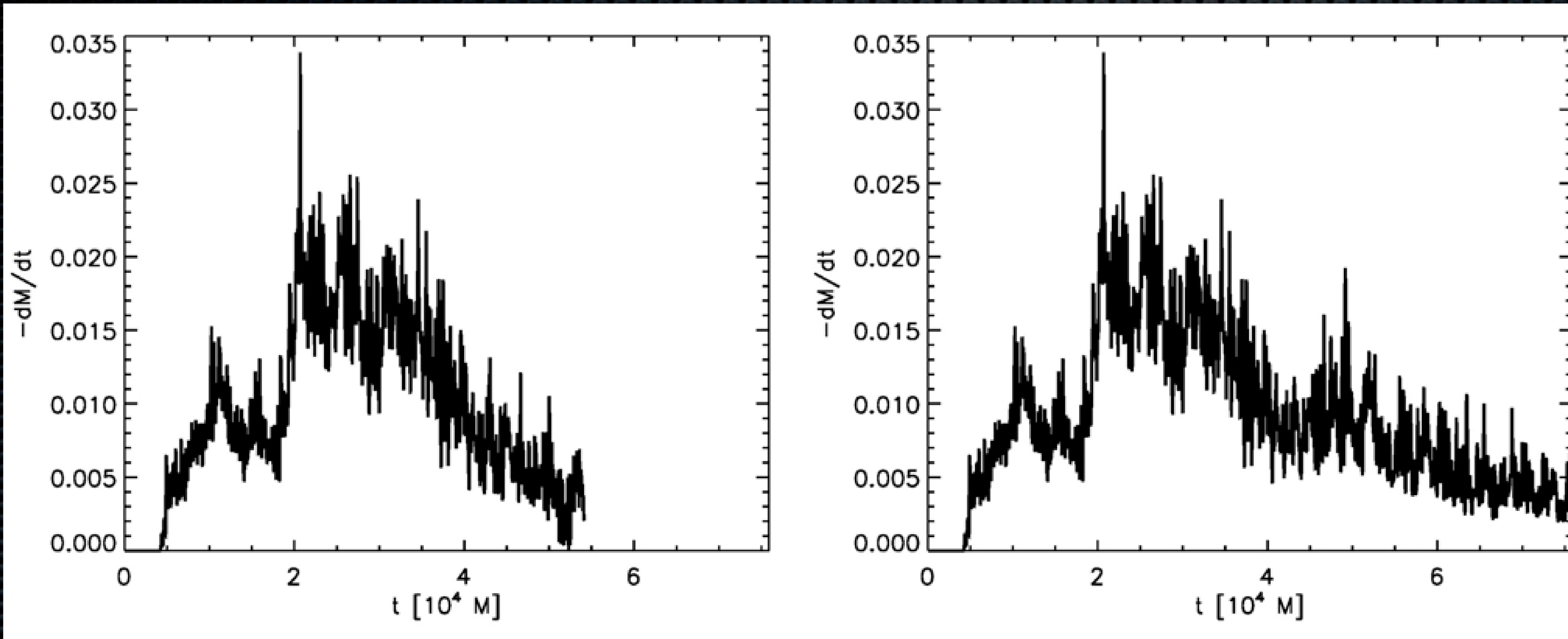
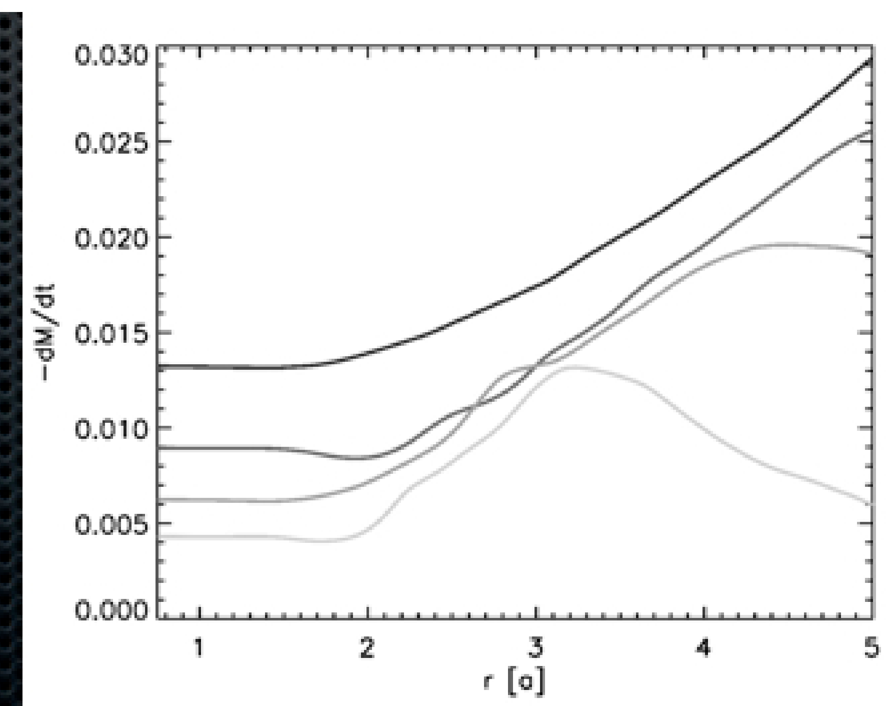


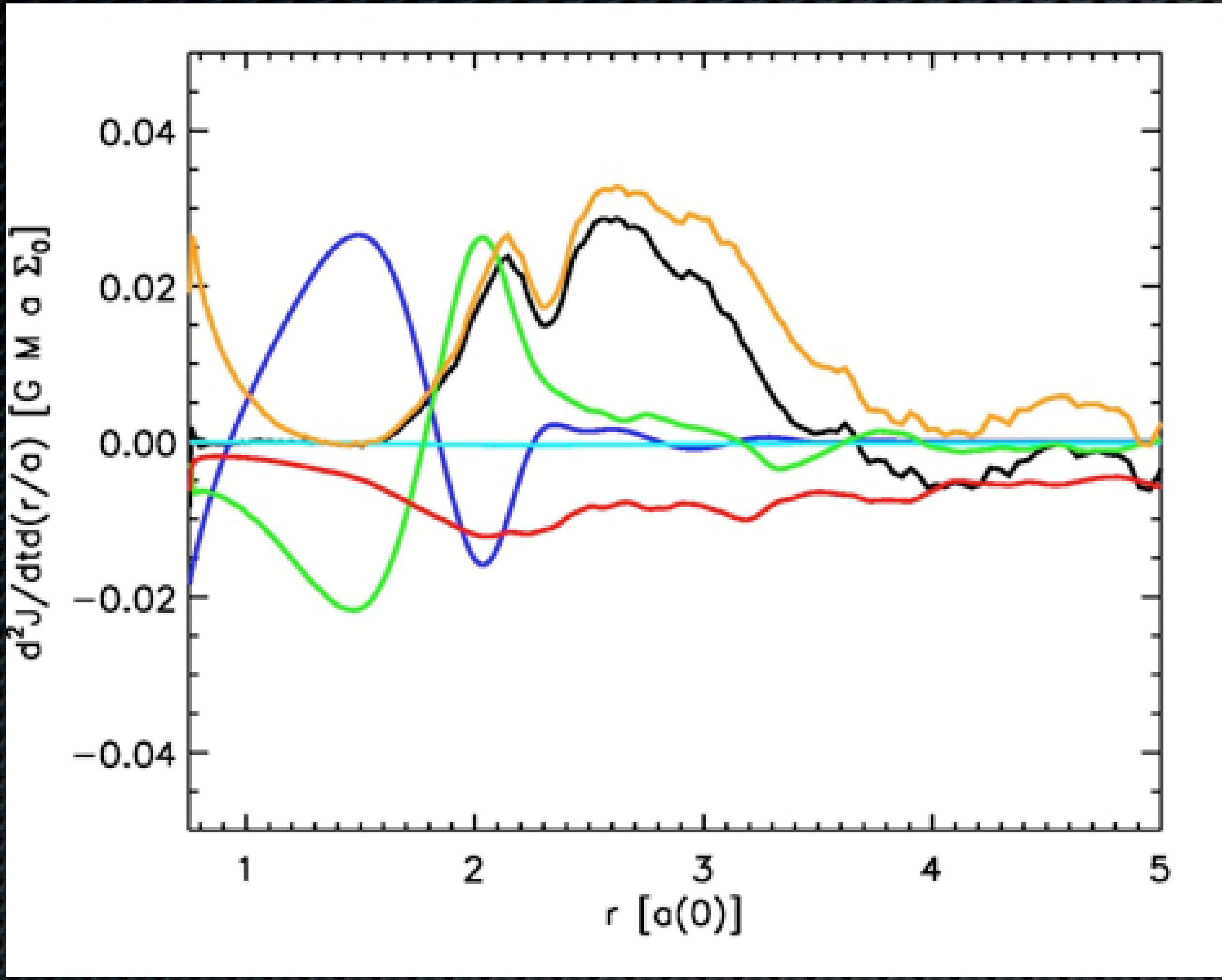
Accretion Rate:

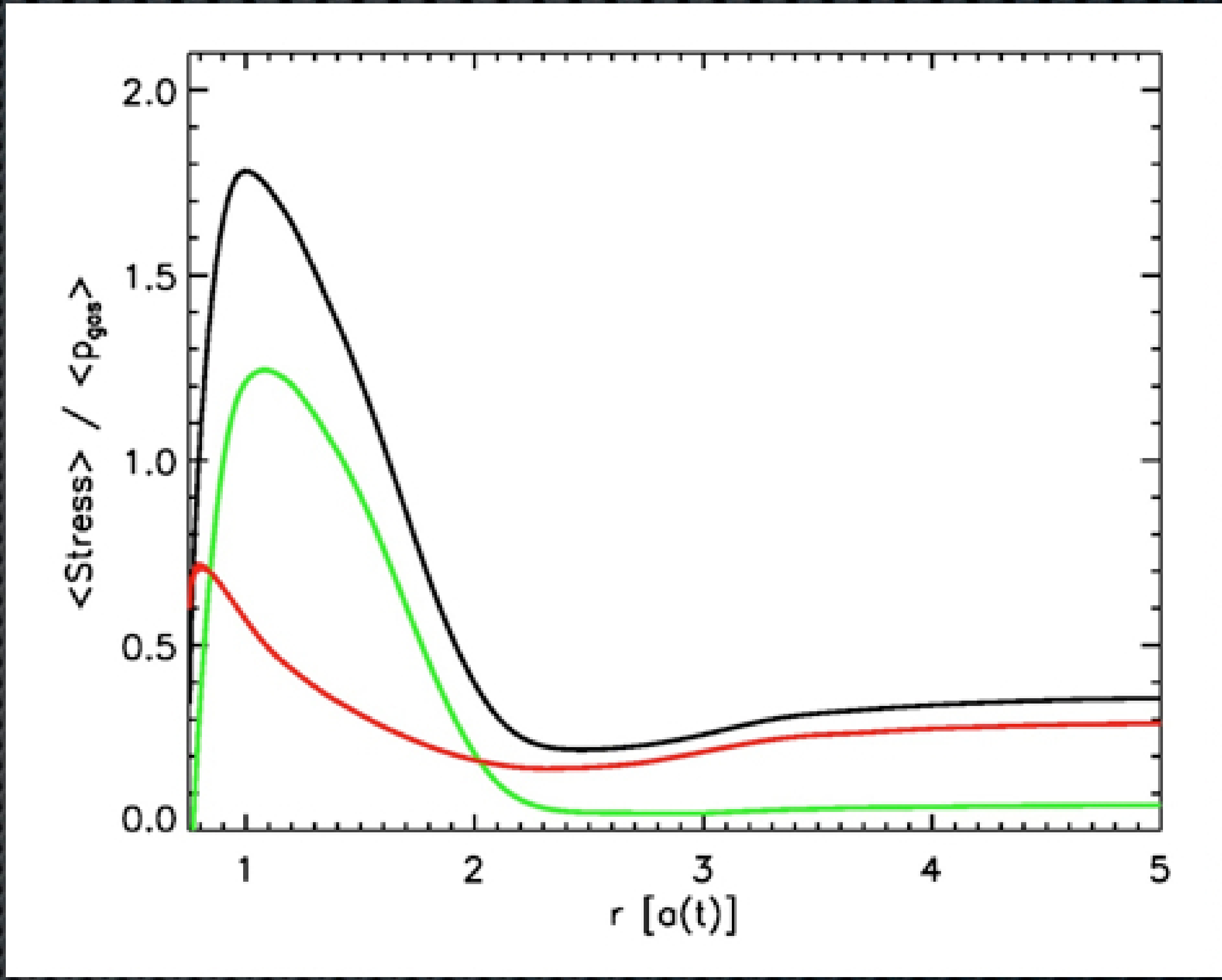


- Both decrease over time
- $Mdot_{Run1} > 0.3\ Mdot_{Run2}$
- Decrease due largely to torques
- Decrease of Run1 also due to decoupling



Angular Momentum Transport



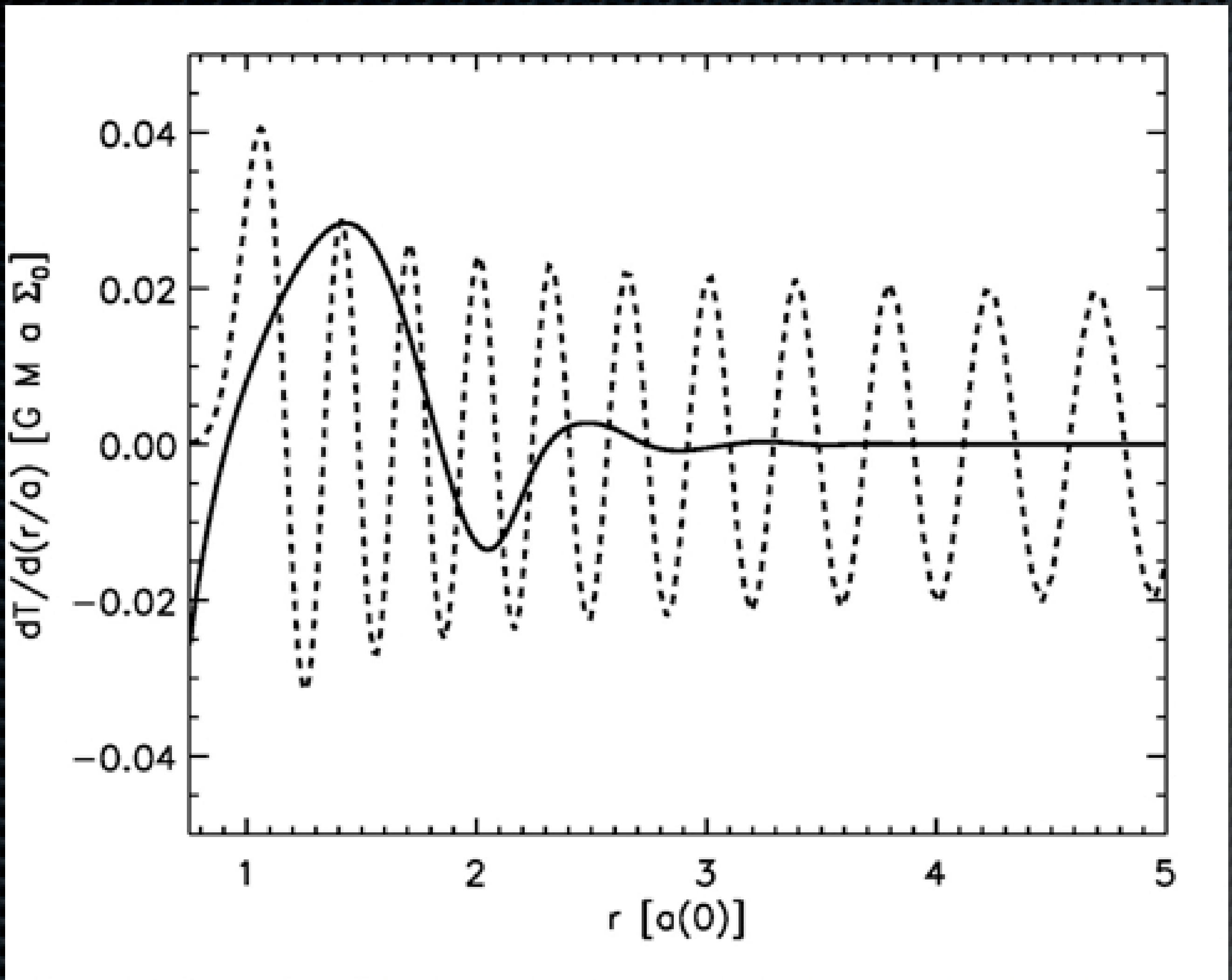


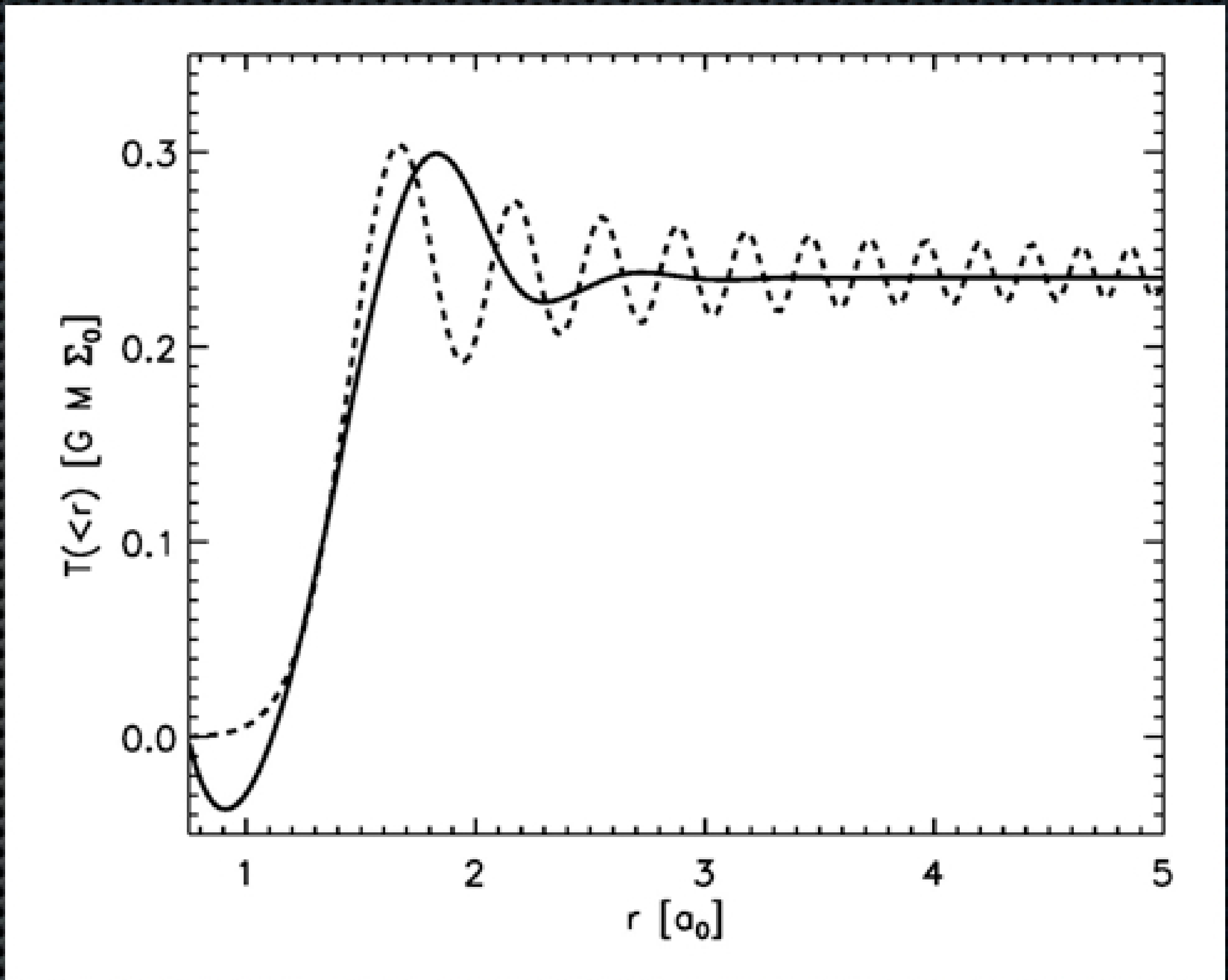
$$\partial_r \partial_t J = \frac{dT}{dr} - \{\mathcal{L} u_\phi\} - \partial_r \{M^r{}_\phi\} - \partial_r \{R^r{}_\phi\} - \partial_r \{A^r{}_\phi\}$$

$$\left(= [\text{Bin.}] - [\text{Rad.}] - [\nabla\text{Maxwell}] - [\nabla\text{Reynolds}] - [\nabla\text{Advected}]\right)$$

Binary Torque Density

$$\frac{dT}{dr} = \int \sqrt{-g}\, T^{\mu}{}_{\nu} \Gamma^{\nu}{}_{\mu\phi}\, d\theta d\phi$$





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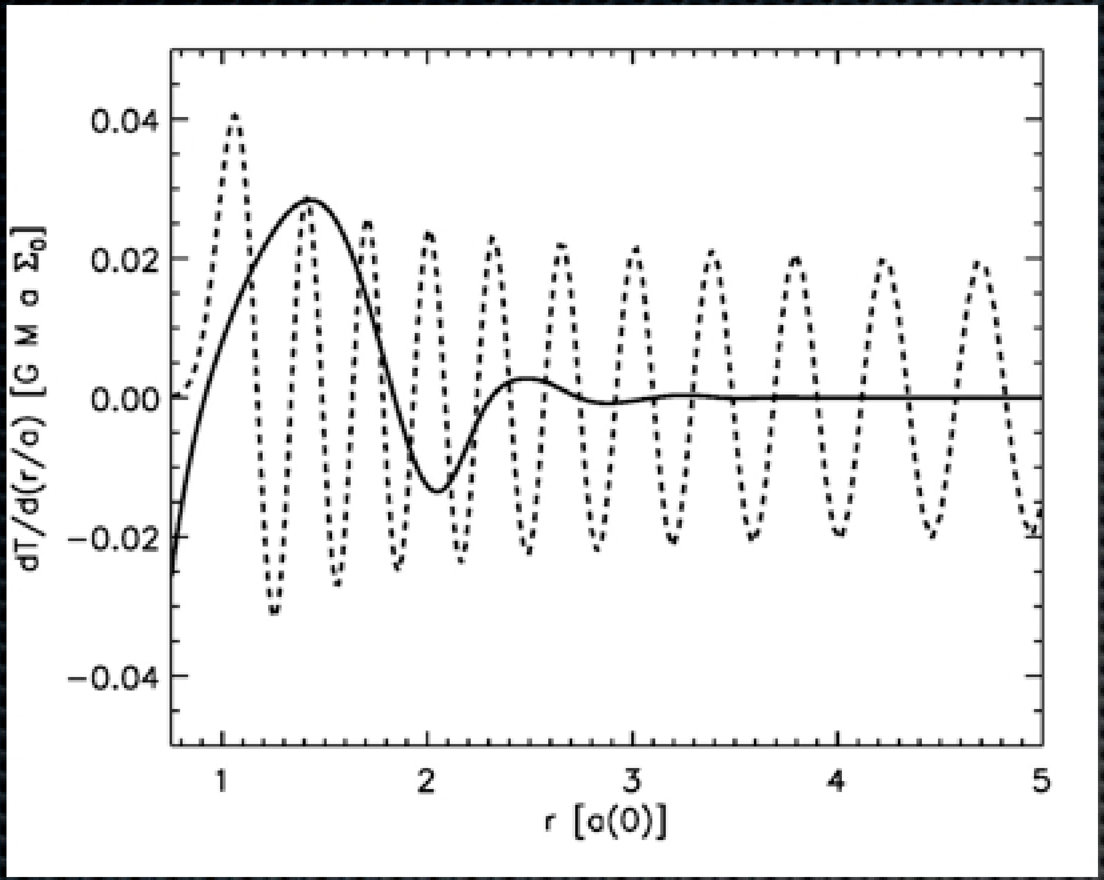
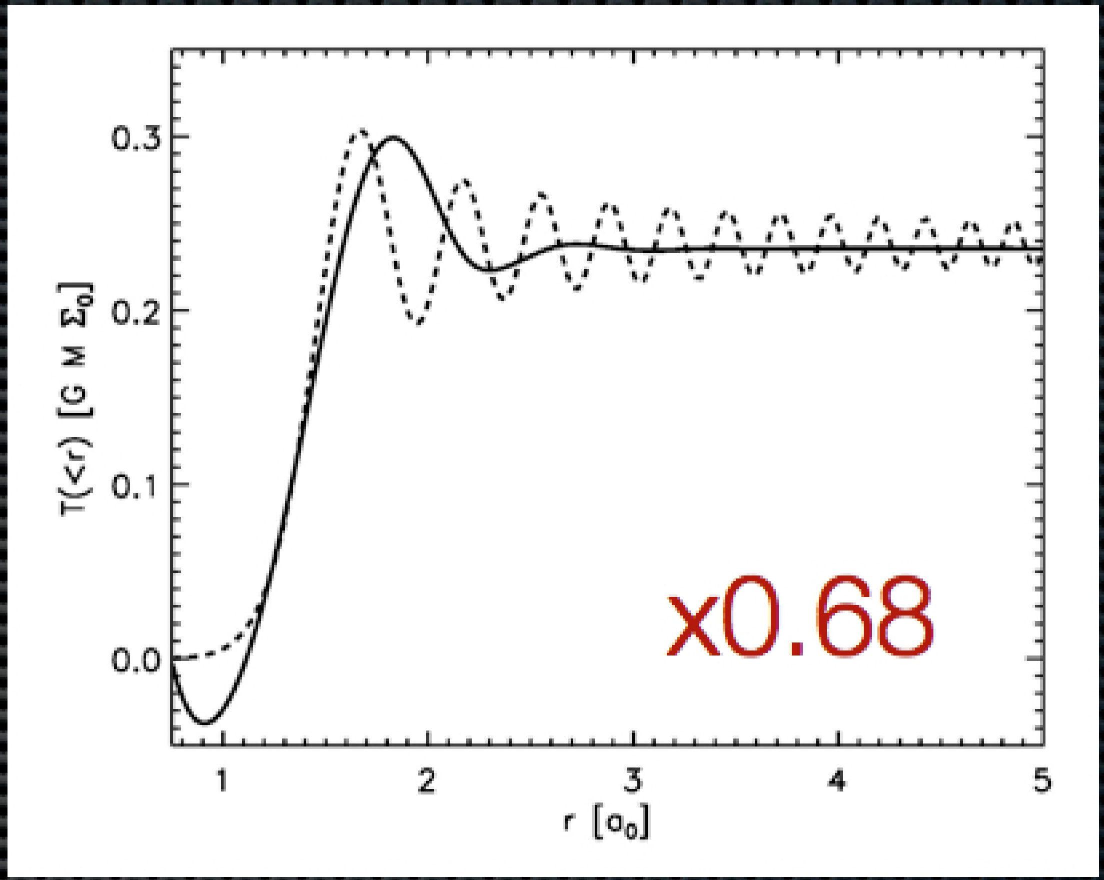
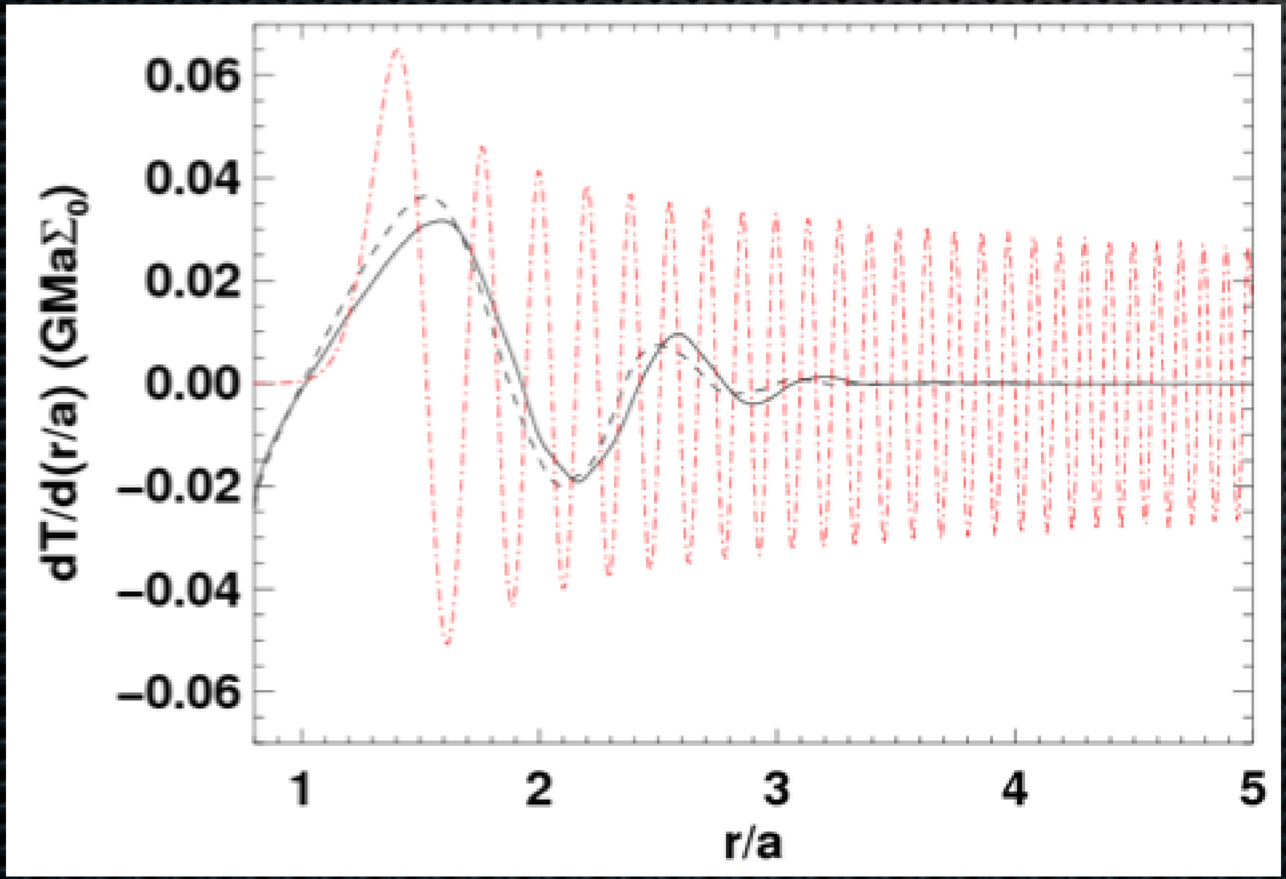
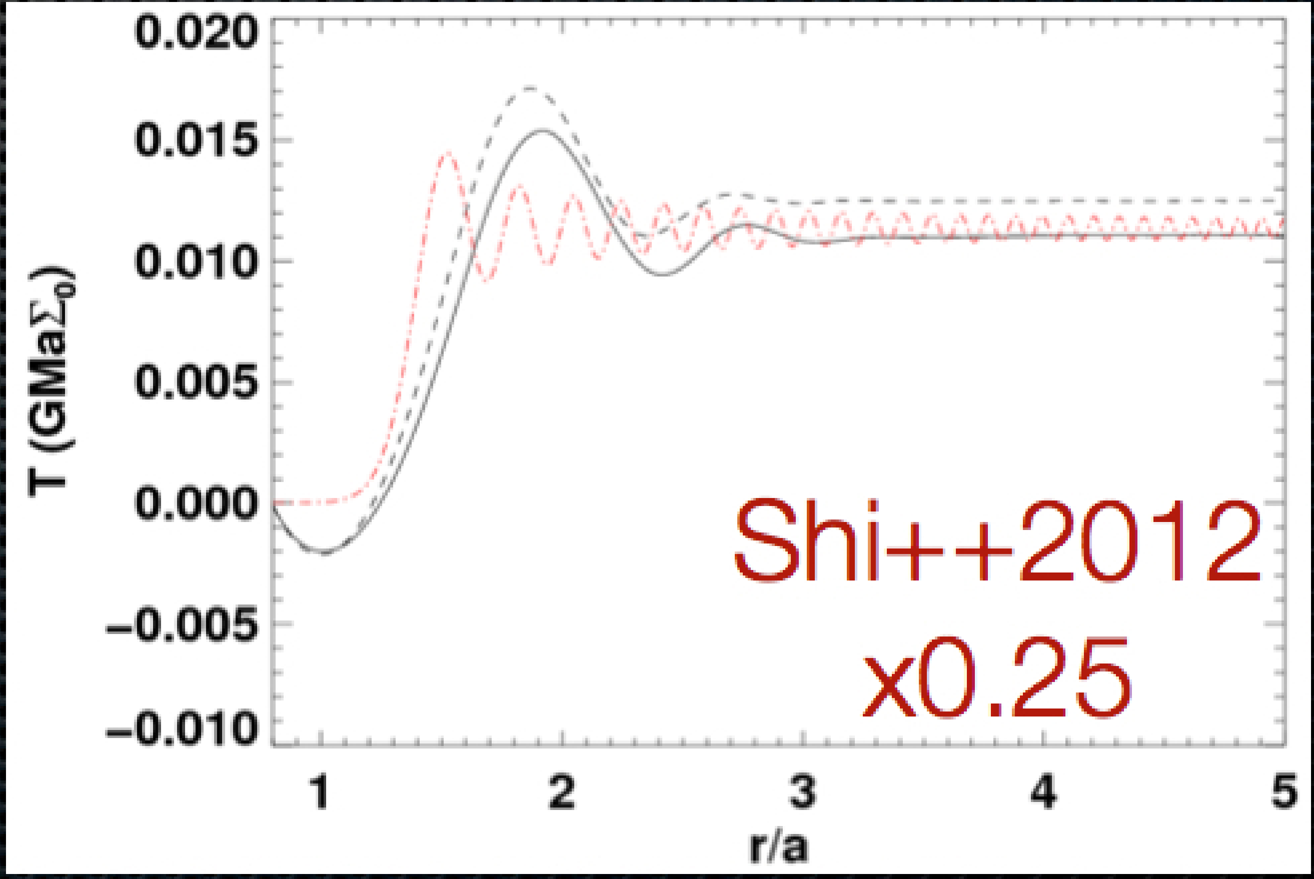
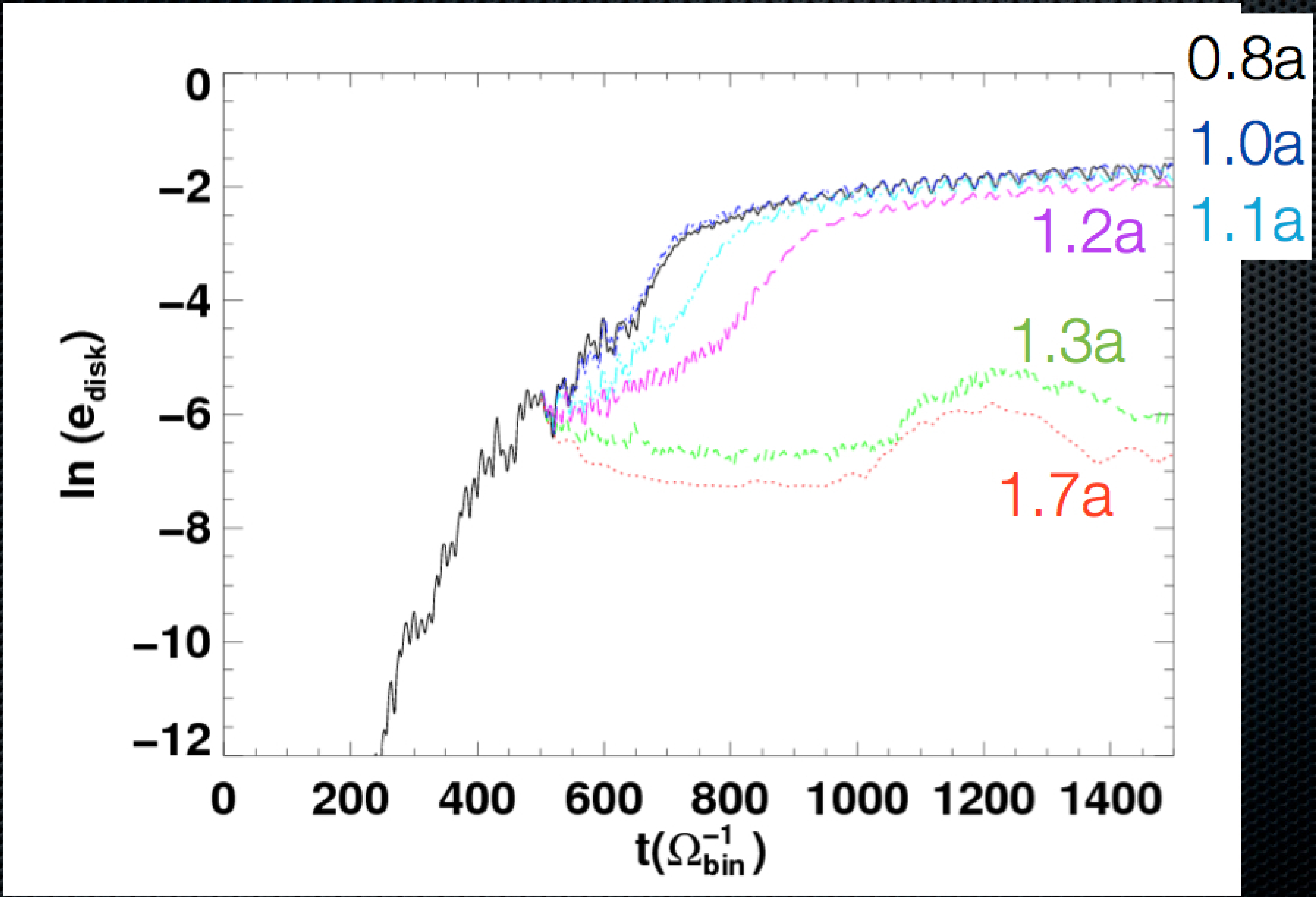








Surveying effects of r_{in}

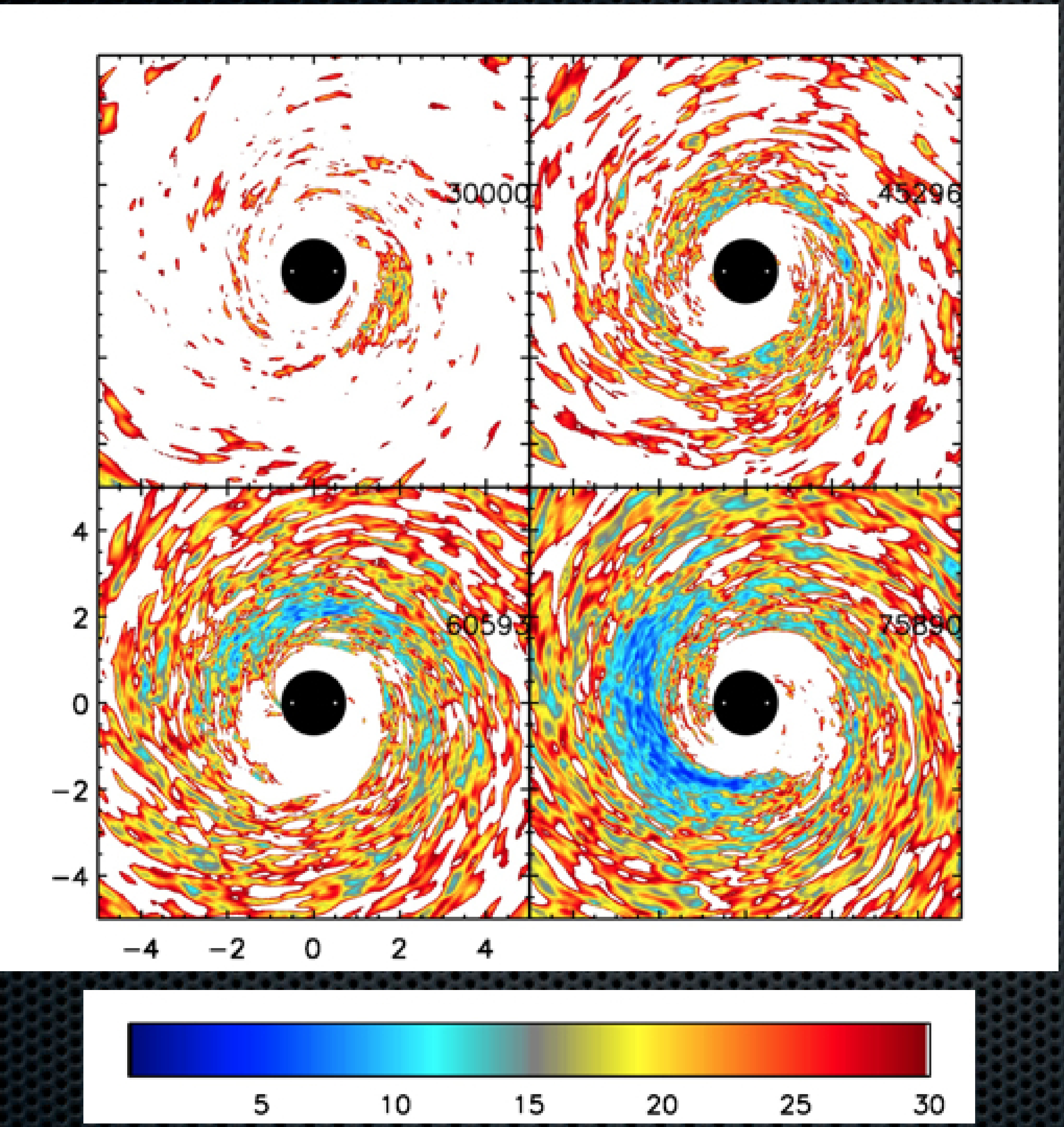


Shi++2012

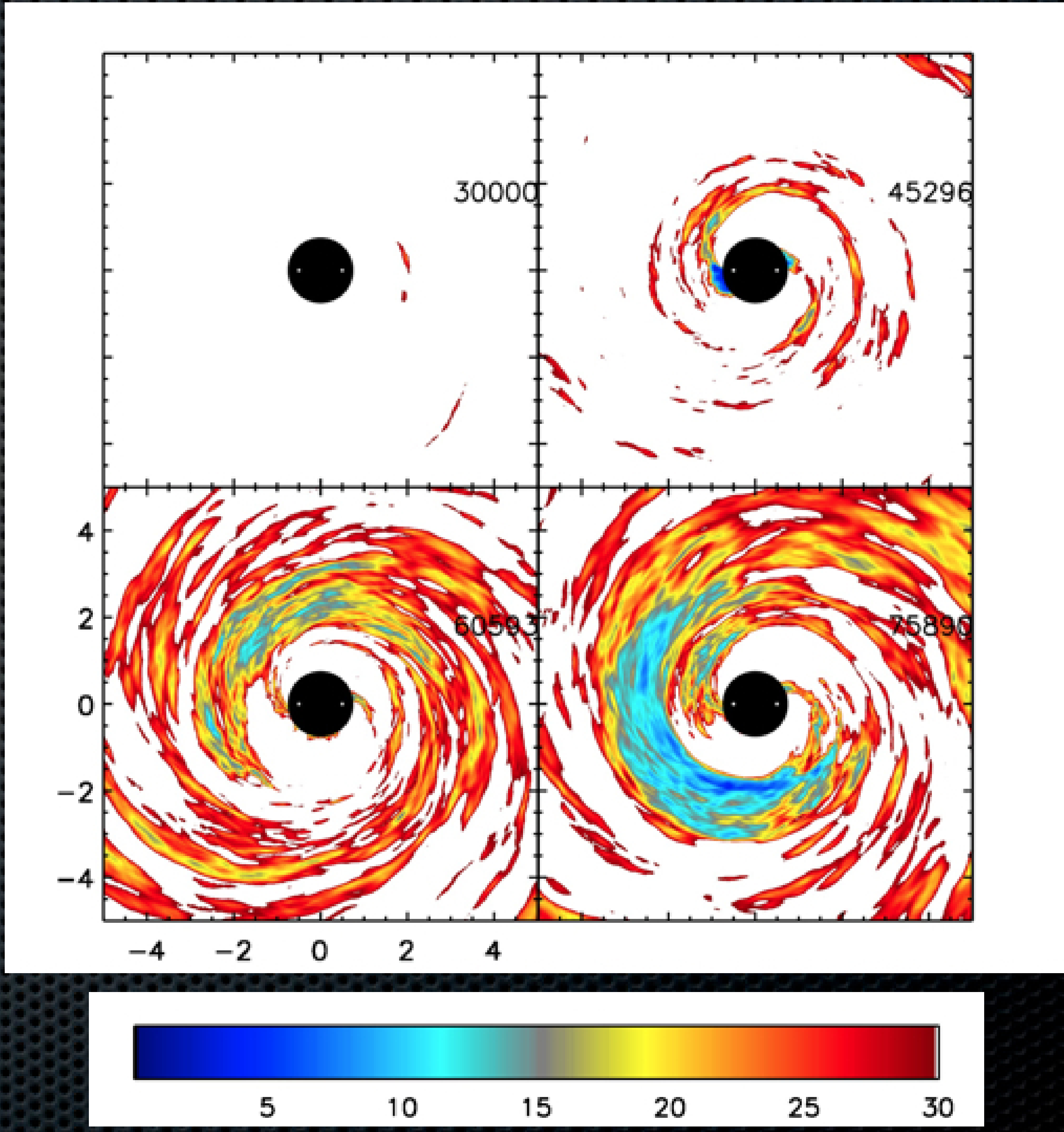
MRI Resolution

$$Q^i = \frac{2\pi \left|b^i\right|}{\Delta x^i \Omega(r) \sqrt{\rho h + 2p_m}}$$

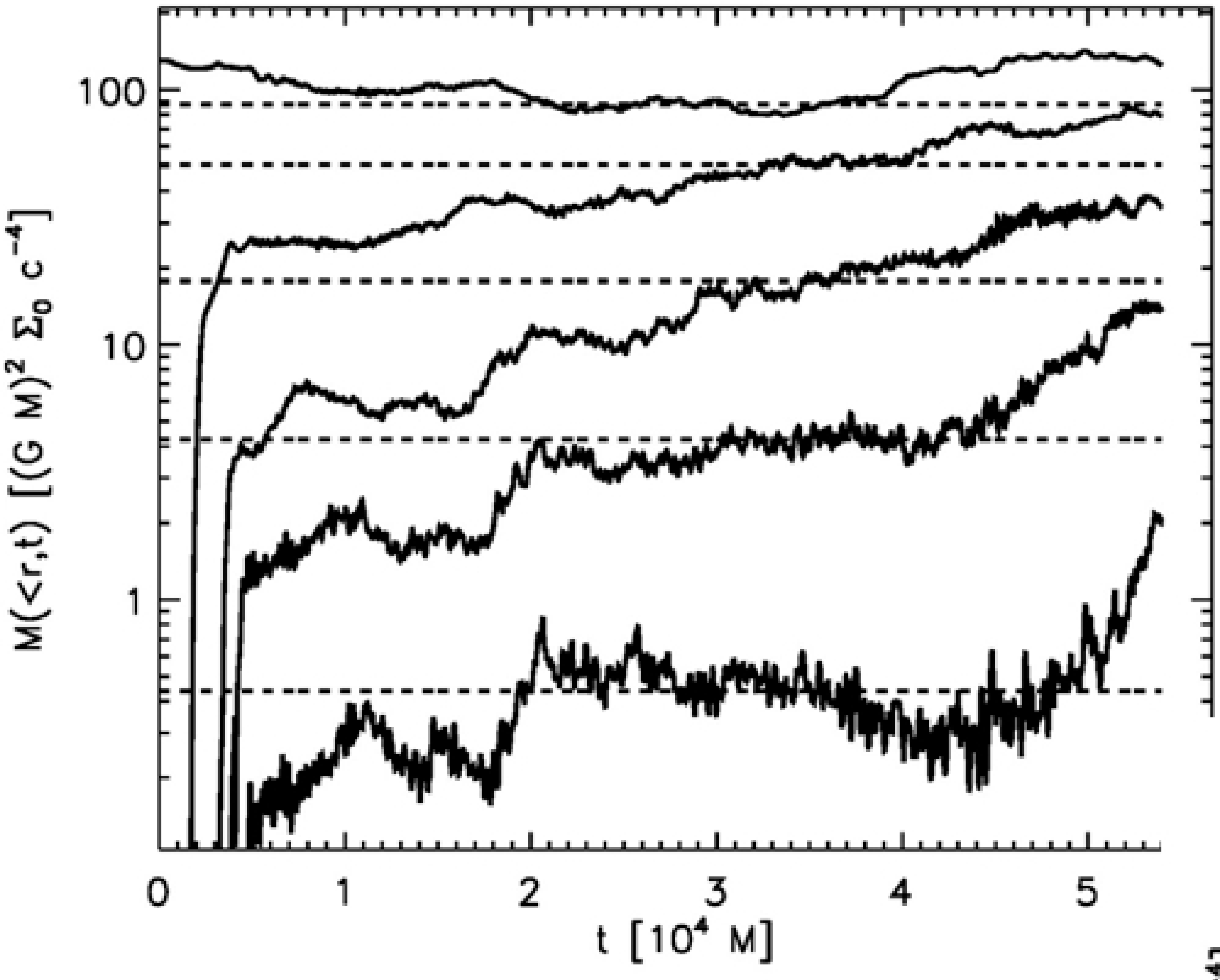
Sano++ 2004 Noble++ 2010 Guan, Gammie 2010 Sorathia++ 2010, 2011
Hawley++ 2011



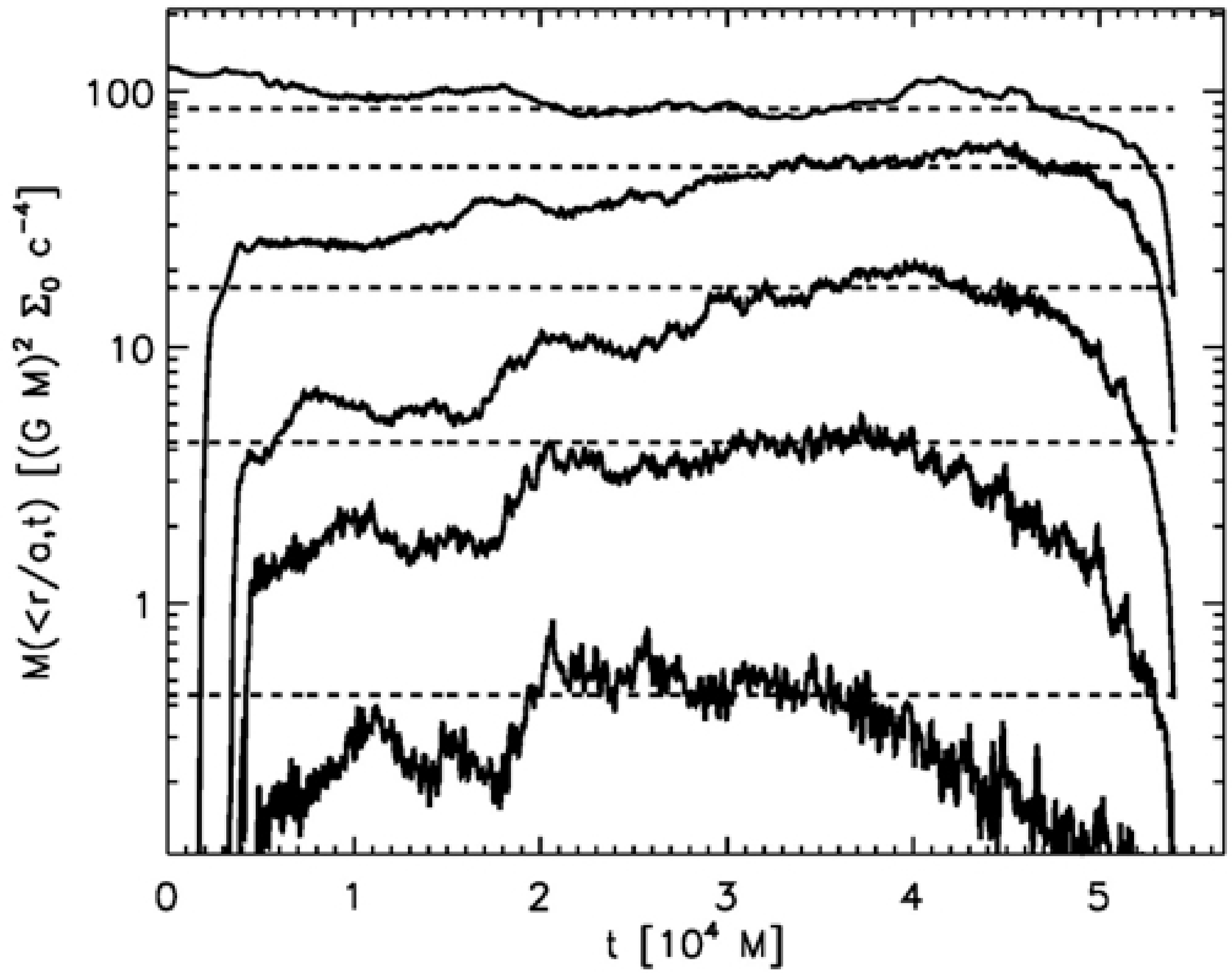
$Q^\theta > 10$



$Q^\phi > 25$



100
10
1
0
1
2
3
4
5
M(<r,t) [(G M)^2 Σ_0 c^{-4}]
t [10^4 M]



100
10
1
0
1
2
3
4
5
M(<r/a,t) [(G M)^2 Σ_0 c^{-4}]
t [10^4 M]

Plasma Beta parameter = pgas / pmag