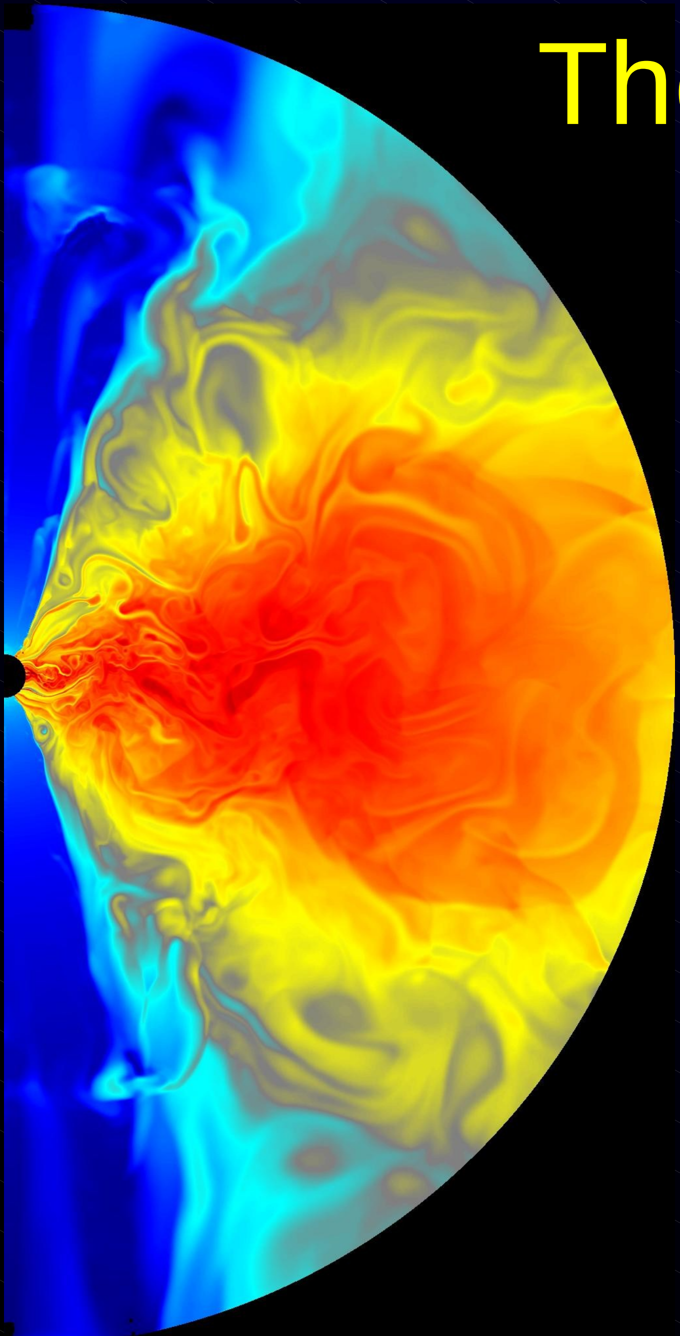


The GRMHD Paradigm of Black Hole Accretion

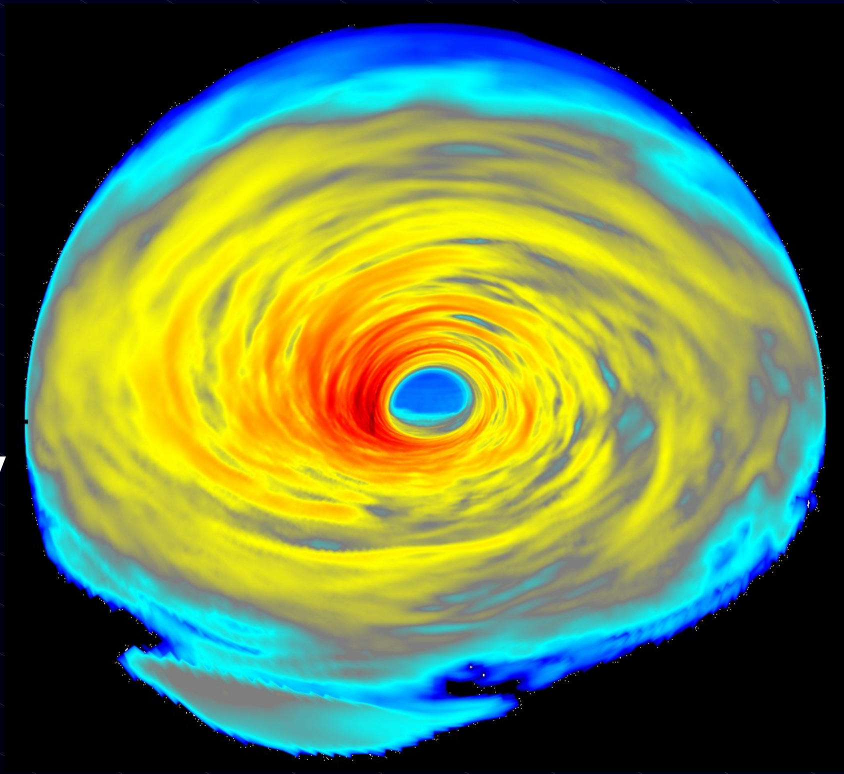
Scott C. Noble
RIT , JHU

with
Julian Krolik
JHU

John Hawley
UVa

&

Charles Gammie
UIUC

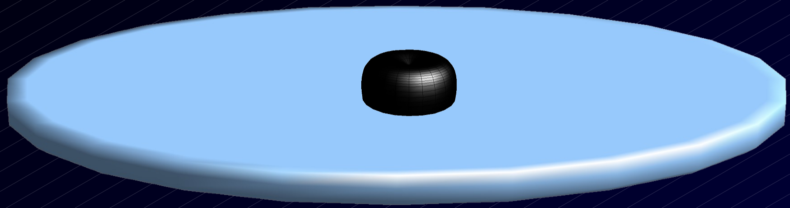


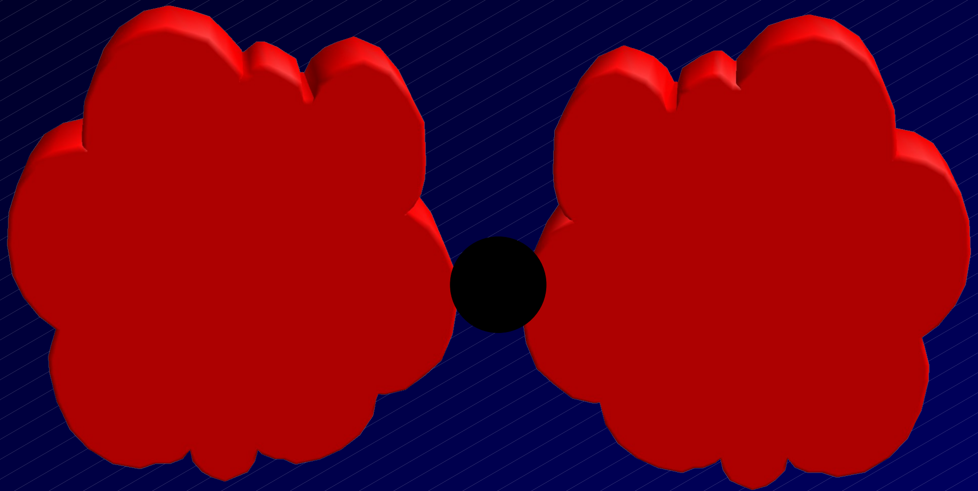
Astrophysical Disks

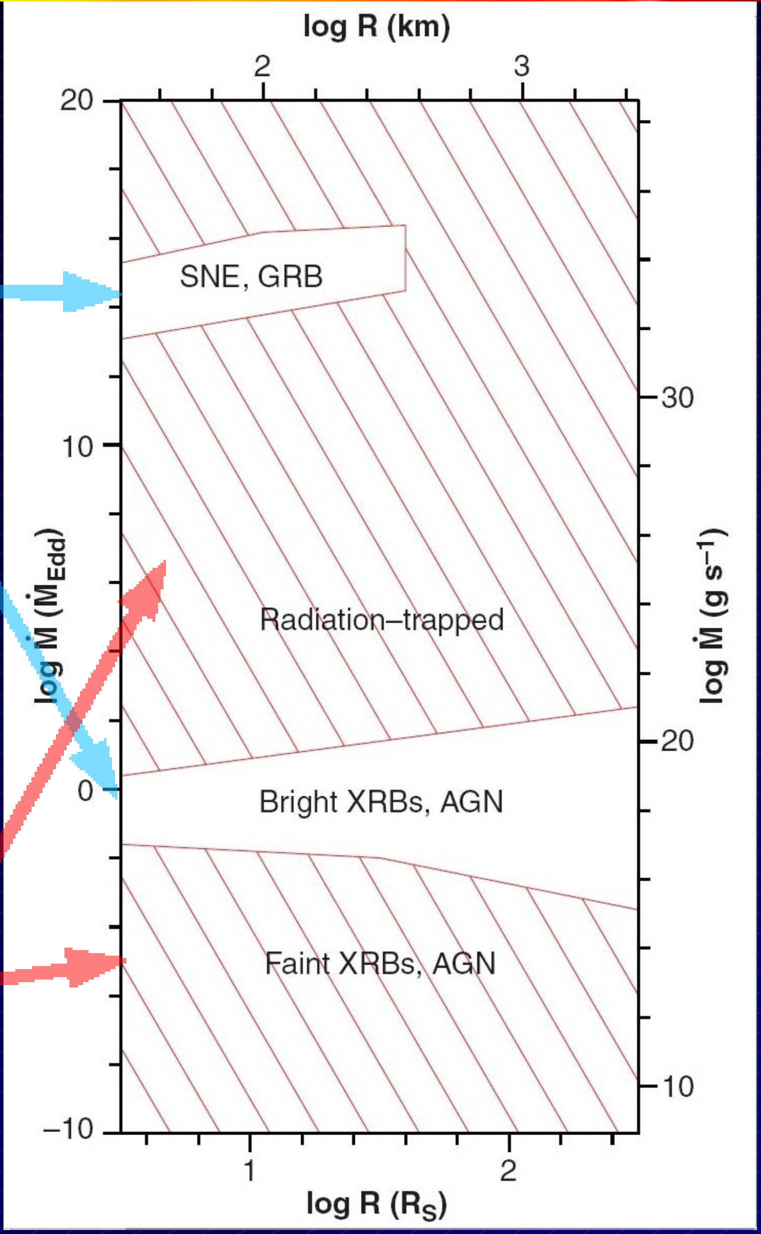
Disk Type	Gravity Model
Galaxies, Stellar Disks	Newtonian
X-ray binaries, AGN	Stationary metric
Collapsars, GRBs SN fall-back disks, Wet BBH Mergers	Full GR

Radiative Efficiency of Disks

- Radiatively Efficient (thin disks)
- Radiatively Inefficient (thick disks)







Narayan & Quataert (2005)

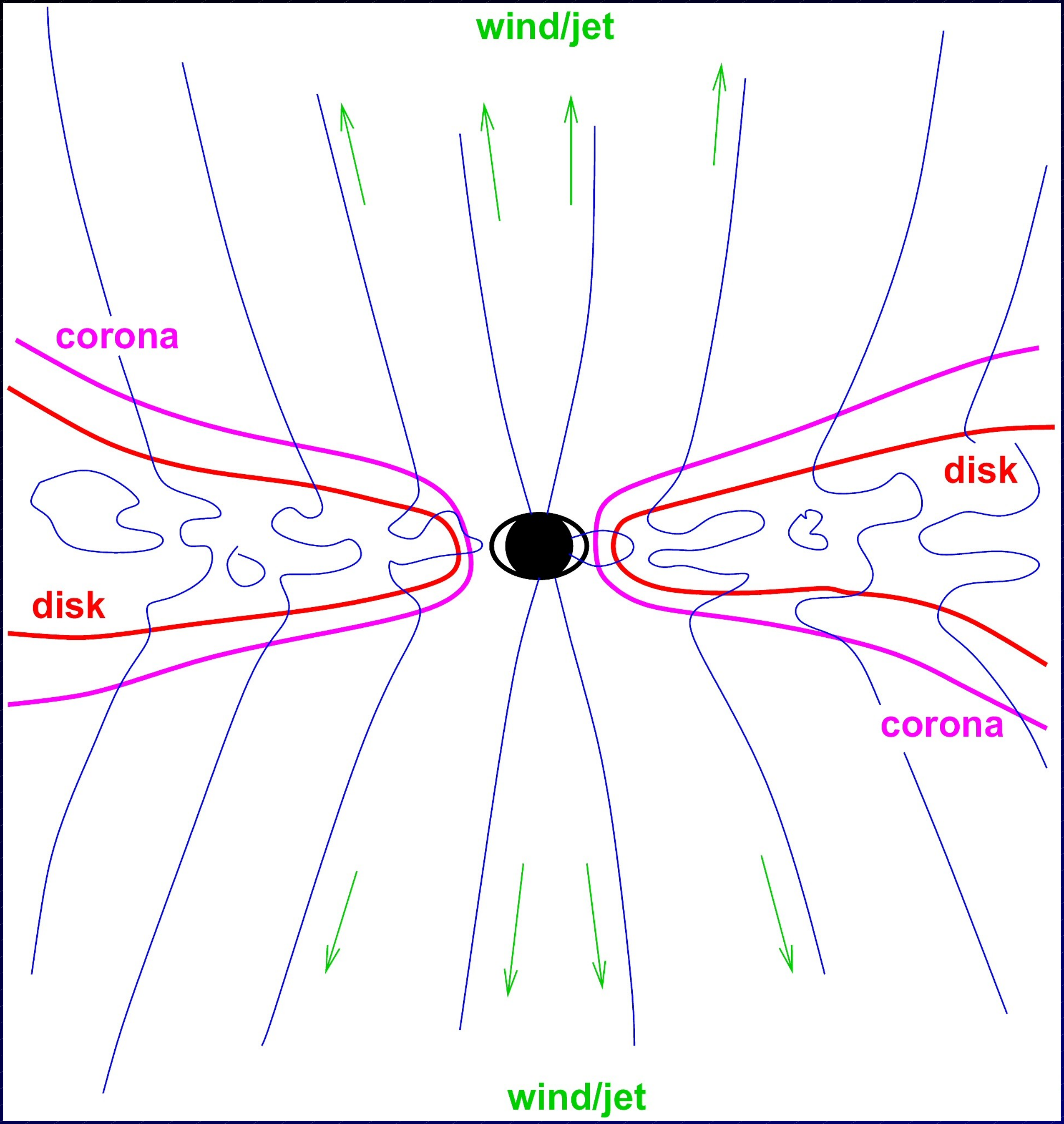


Illustration by
C. Gammie

Probing the Spacetime of BHs

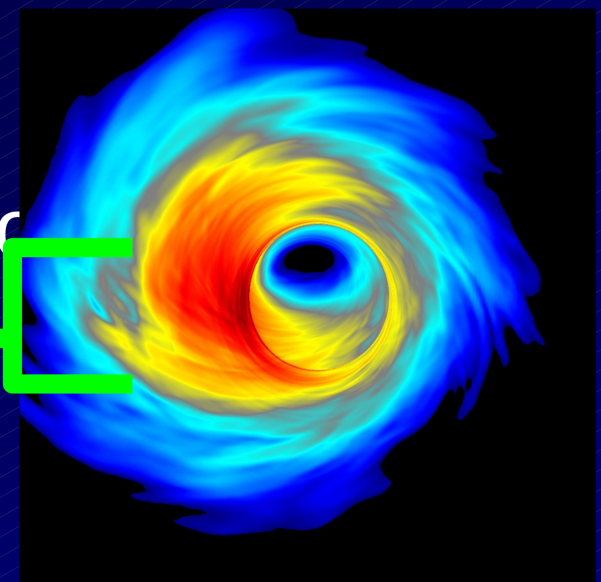
- Variability:
  - e.g. QPOs, short-time scale fluctuations

- Spectral Fitting Thermal Emission

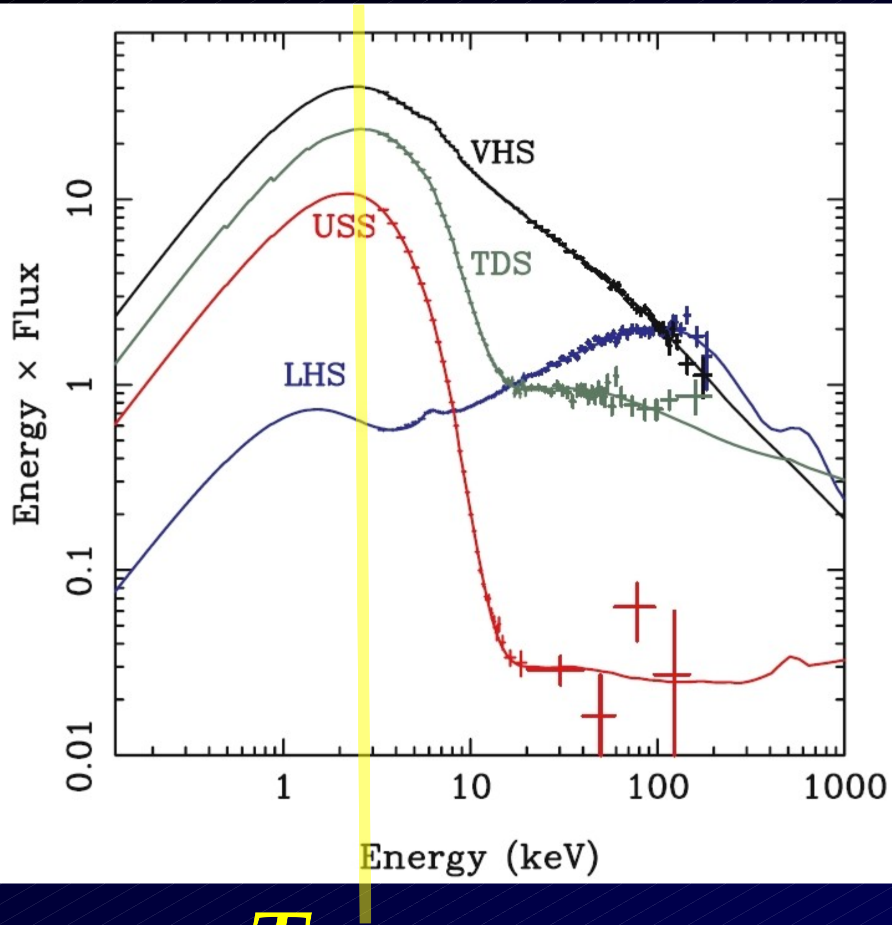
$$L = A\, R_{in}^2\, T_{max}^4 \qquad R_{in} = R_{in}(M, a)$$

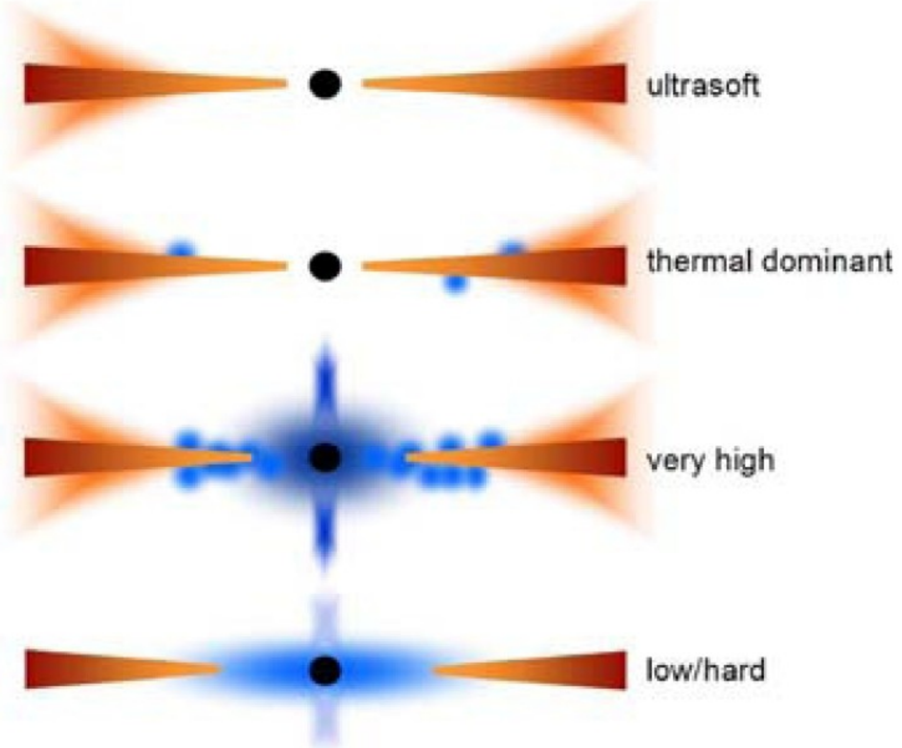
- Relativistic Iron Lines

- Directly Resolving Event Horizo
  (e.g., Sgr A*)
  - Silhouette size = D(M,a)



Accretion States





T_{max}

Done, Gierlinski & Kubota (2007)

$$L = A R_{in}^2 T_{max}^4$$

$$R_{in} = R_{in}(M, a) \sim R_{isco}$$

Spectral Fits for BH Spin

TABLE 1

Black Hole Spin Estimates Using the Mean Observed Values of *M*, *D*, and *i*

Candidate	Observation Date	Satellite	Detector	a_* (D05)	a_* (ST95)
GRO J1655−40	1995 Aug 15	*ASCA*	GIS2	~0.85	~0.8
			GIS3	~0.80	~0.75
	1997 Feb 25–28	*ASCA*	GIS2	~0.75[a]	~0.70
			GIS3	~0.75[a]	~0.7
	1997 Feb 26	*RXTE*	PCA	~0.75[a]	~0.65
	1997 (several)	*RXTE*	PCA	0.65–0.75[a]	0.55–0.65
4U 1543−47	2002 (several)	*RXTE*	PCA	0.75–0.85[a]	0.55–0.65

[a] Values adopted in this Letter.

Shafee et al. (2006)

	Power Law	
Object	Mean	Standard Deviation
GRS 1915+105[a]	0.998	0.001
GRS 1915+105[b]	0.998	0.001

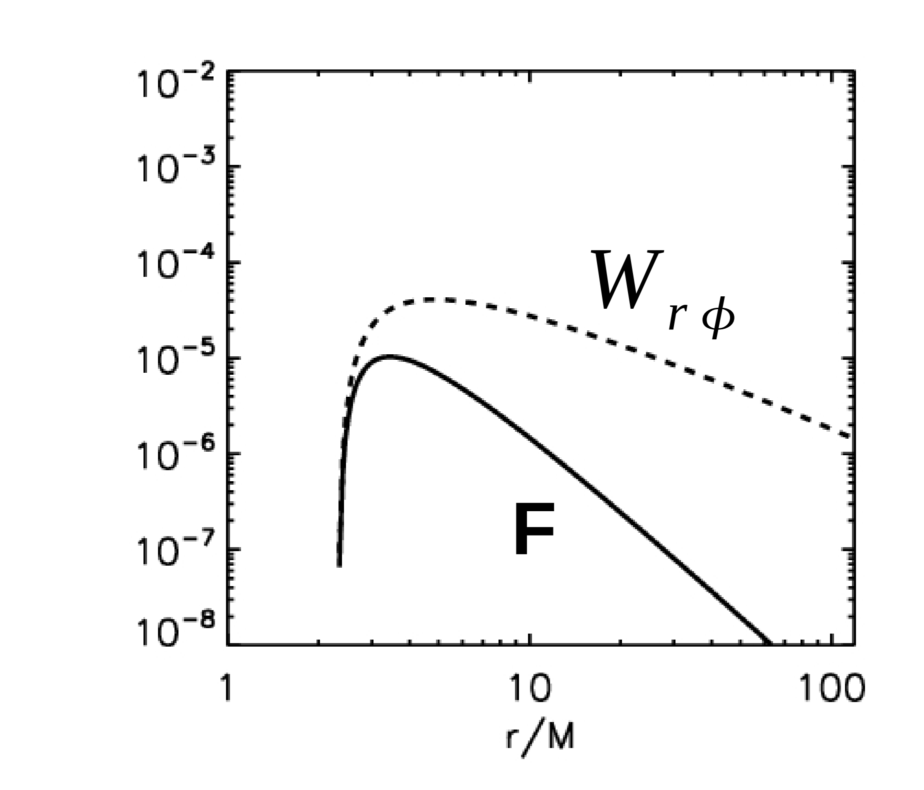
McClintock et al. (2006)

Steady-State Models: Novikov & Thorne (1973)

Assumptions:

1) Stationary gravity
2) Equatorial Keplerian Flow
   - Thin, cold disks
3) Time-independent
4) Work done by stress locally dissipated into heat
5) Conservation of M, E, L
6) Zero Stress at ISCO
   - Eliminated d.o.f.
   - Condition thought to be suspect from very start

(Thorne 1974, Page & Thorne 1974)



$$\eta = 1 - \dot{E}/\dot{M}$$

$$= 1 - \epsilon_{ISCO}$$

Steady-State Models: Novikov & Thorne (1973)

Assumptions:

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   - Thin, cold disks
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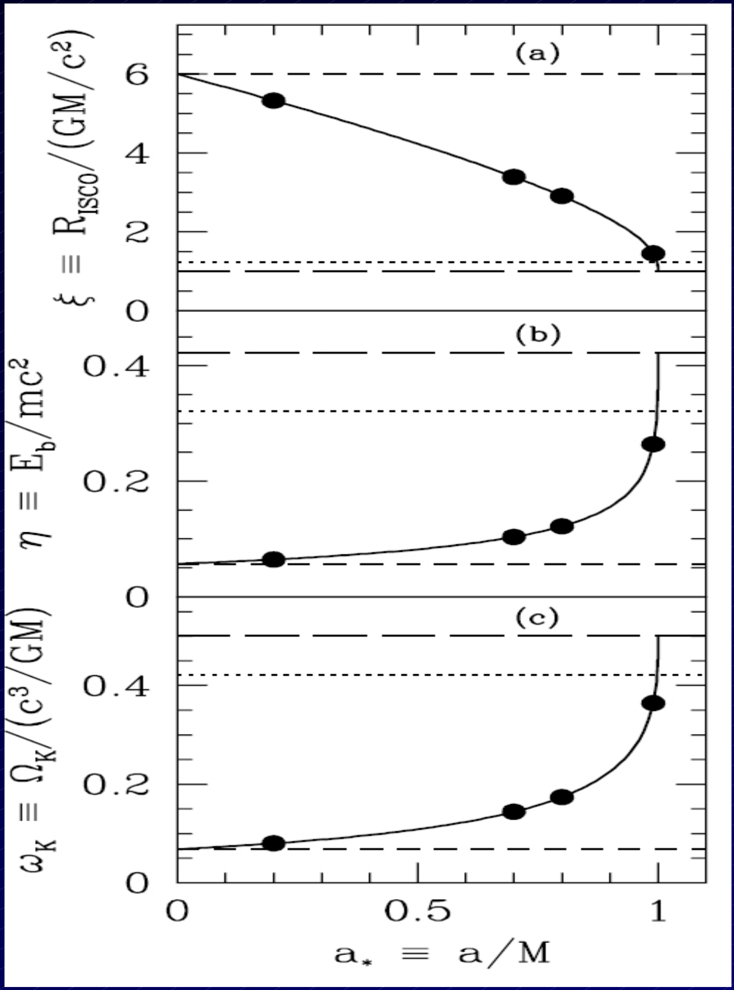


$$\eta = 1 - \dot{E}/\dot{M}$$
$$= 1 - \epsilon_{ISCO}$$

Steady-State Models: α Disks

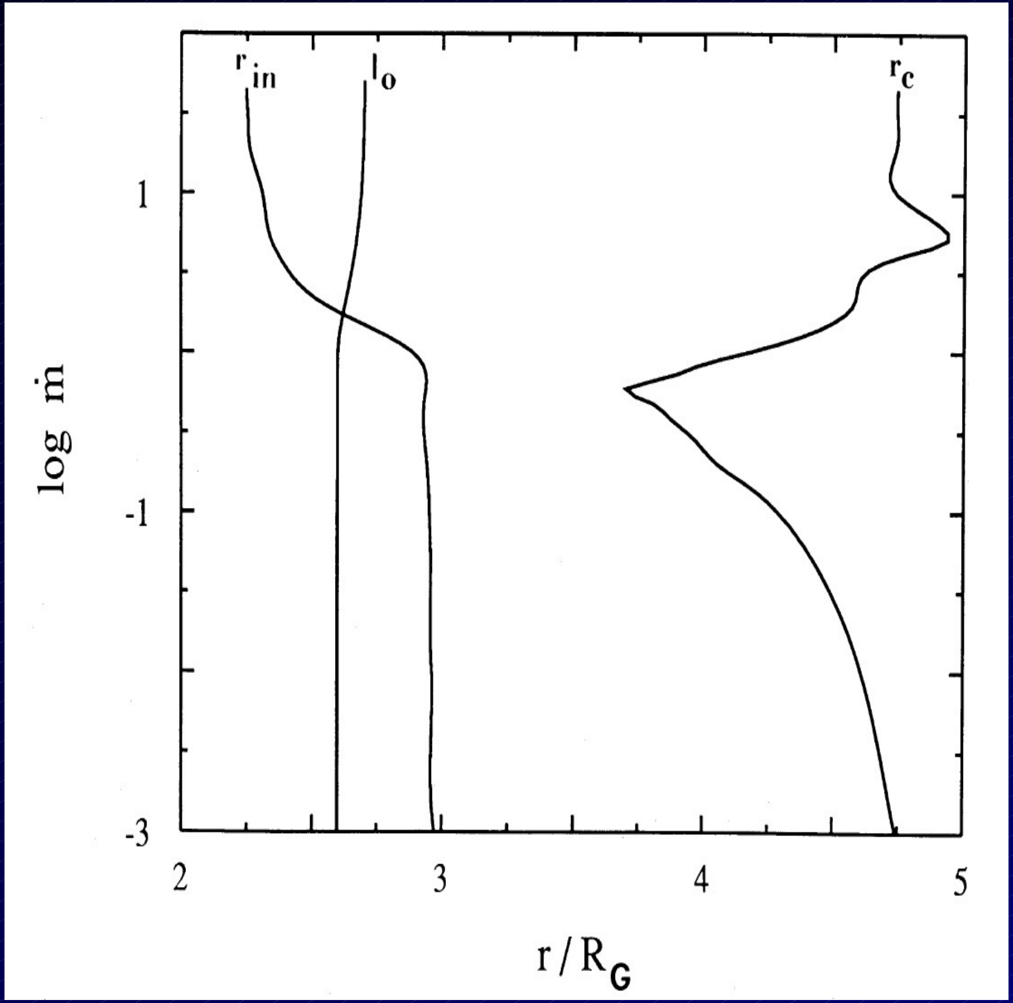
- Shakura & Sunyaev (1973):

$$T^r_\phi = -\alpha P$$

$$P = \rho c_s^2 \qquad t^r_\phi = -\alpha c_s^2$$

- No stress at sonic point:
  $\rightarrow R_{in} = R_s$
  e.g.:
  Muchotrzeb & Paczynski (1982)
  Abramowicz, et al. (1988)
  Afshordi & Paczyncski (2003)

  (Schwarzschild BHs)



Abramowicz, et al. (1988)

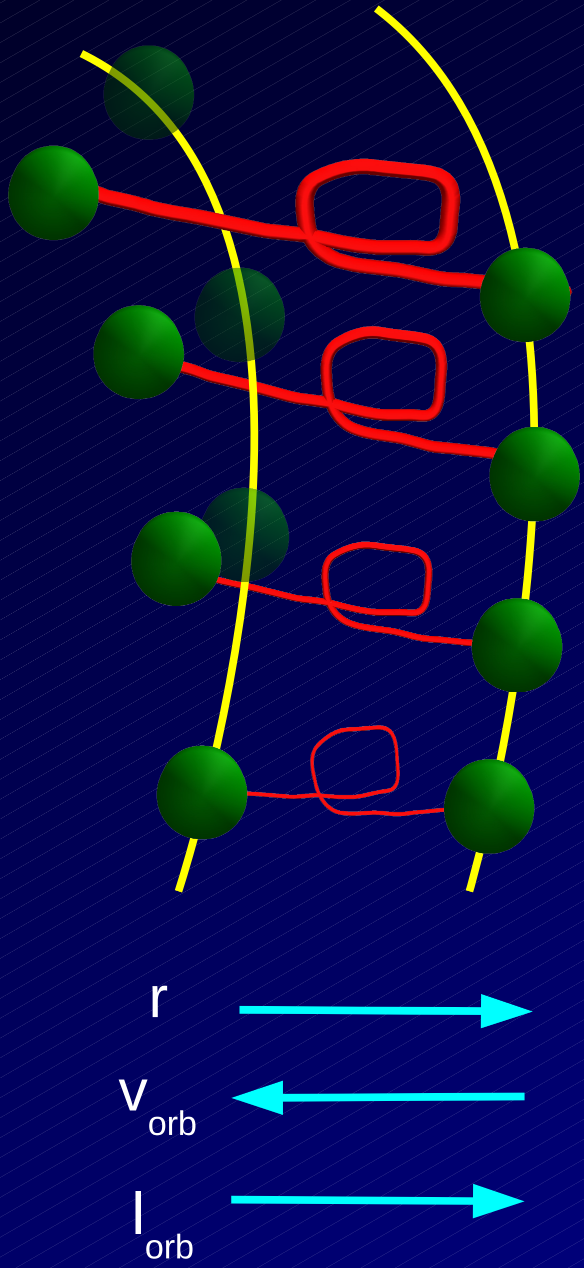
- Variable α
  e.g., Shafee, Narayan, McClintock (2008)

$$\eta \sim 1 - \epsilon_{isco}$$

Magneto-rotational Instability (MRI)

- Velikhov (1959)
- Chandrasekhar (1981)
- Balbus & Hawley (1991)

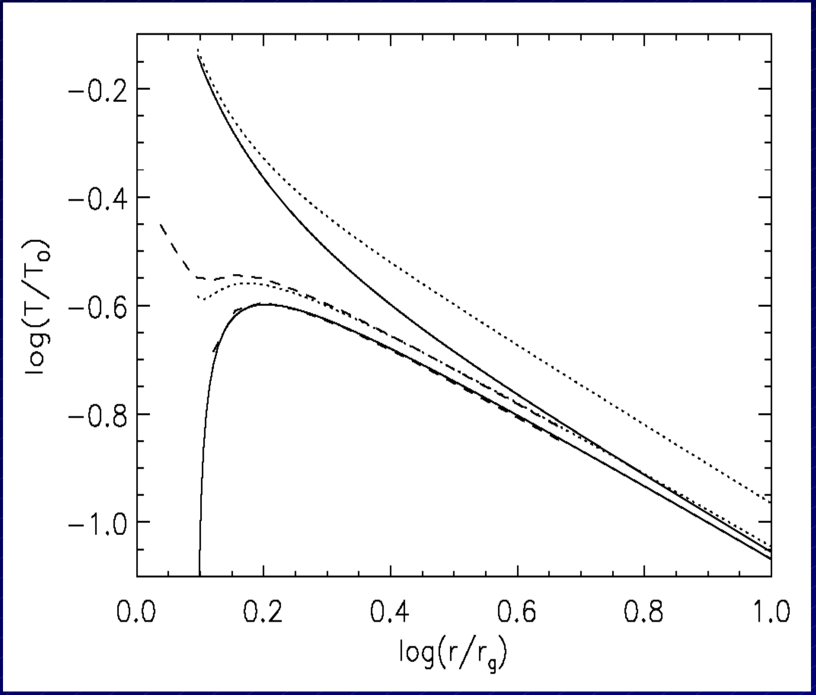
- Growth on orbital time scale.
- MRI develops from weak initial field --- relevant for any (partially) ionized gas.
- Magnetic coupling over different radii is not well described by local viscosity.
- Can explain high accretion rates where hydrodynamic viscosity cannot.



Steady-State Models: Finite Torque Disks

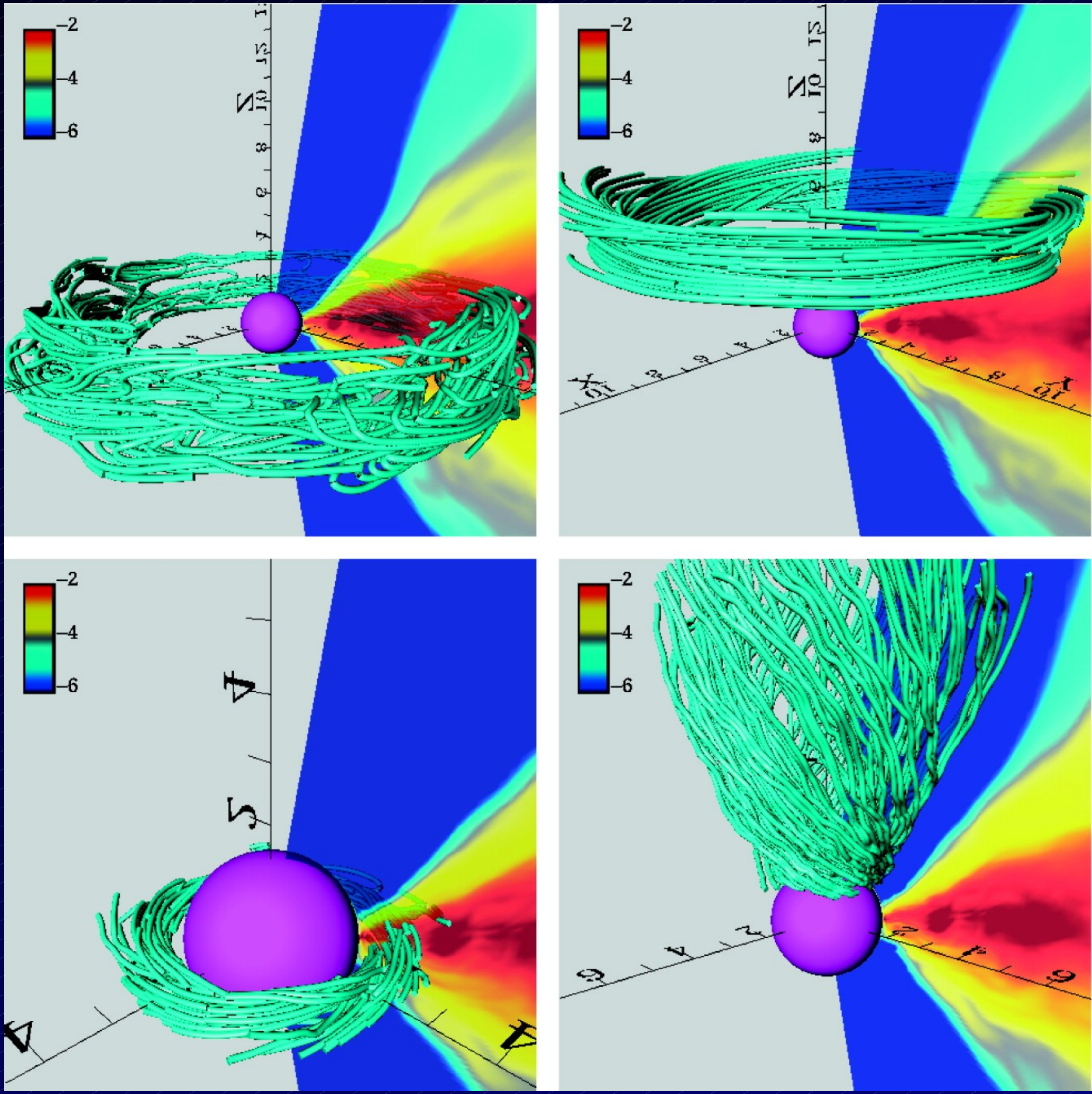
- Krolik (1999)
  - B-field dynamically significant for $r < r_{isco}$
- Gammie's Inflow model (1999)
  - Matched interior model to thin disk → $\eta > 1$ possible
- Agol & Krolik (2000)
  - Parameterize ISCO B.C. with η
  - η reduced by increased probability of photon capture

→ Need dynamical models!!!



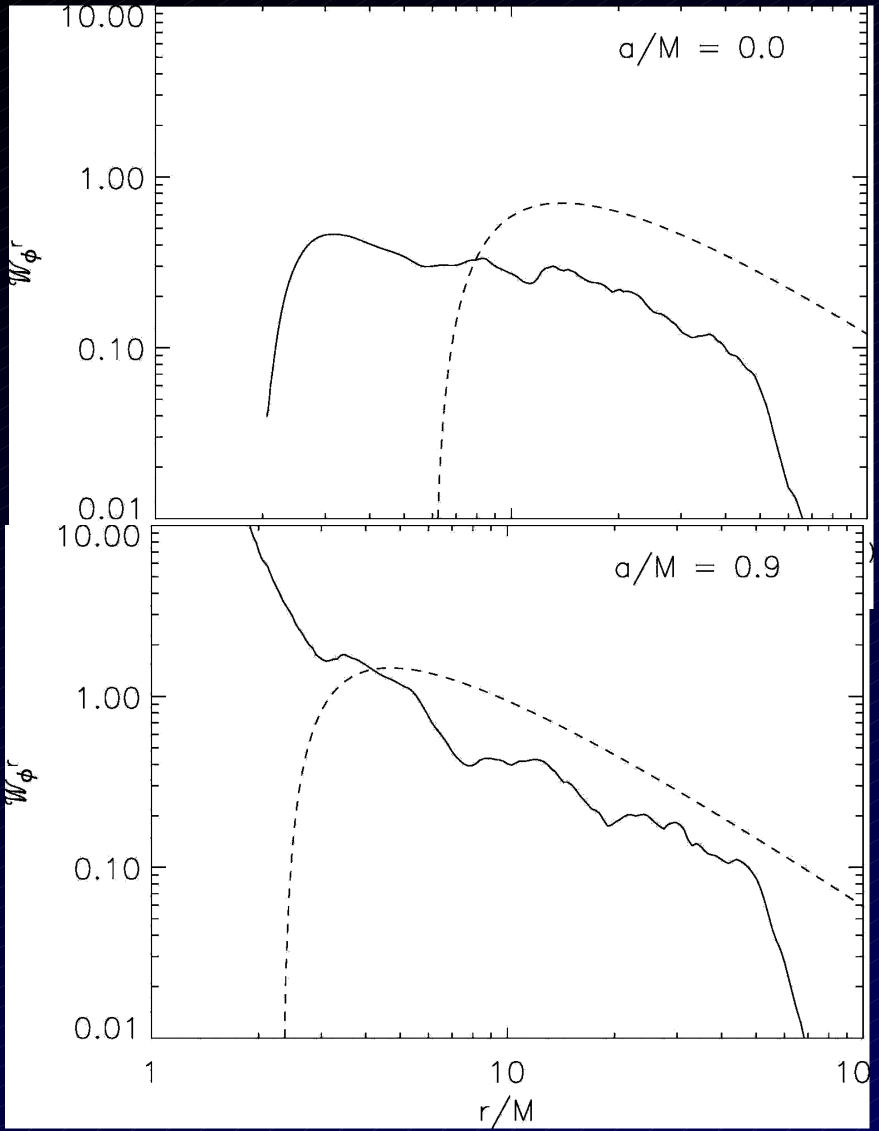
Dynamical Global Disk Models

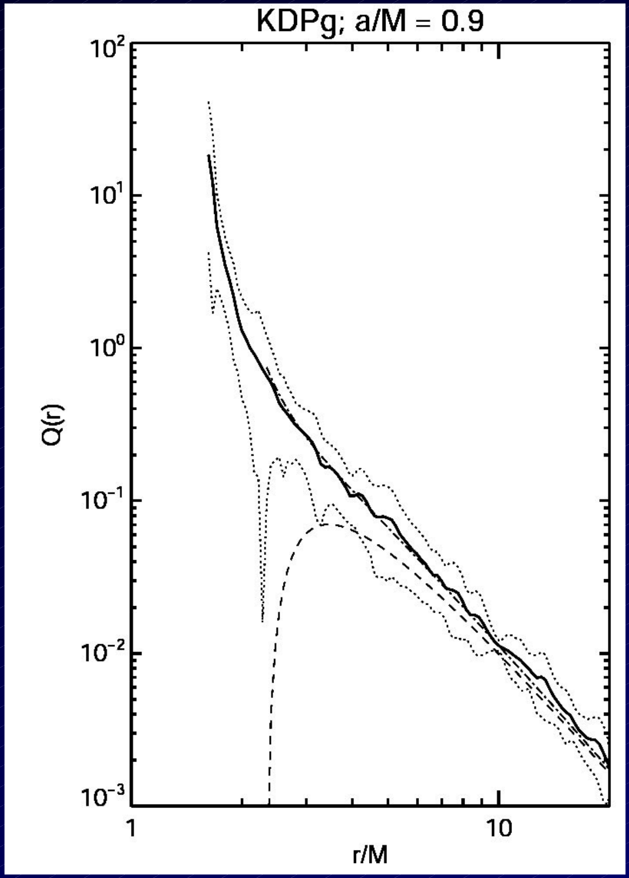
- De Villiers, Hawley, Hirose, Krolik (2003-2006)
  - MRI develops from weak initial field.
  - Significant field within ISCO up to the horizon.



Hirose, Krolik, De Villiers, Hawley (2004)

Dynamical Global Disk Models





Krolik, Hawley, Hirose (2005)
H/R ~ 0.1-0.15

Beckwith, Hawley &Krolik (2008)

- Models dissipation stress as EM stress
- Large dissipation near horizon compensated partially by capture losses and gravitational redshift.
- Used (non-conserv.) int. energy code (dVH) assuming adiabatic flow

Our Method: Simulations with HARM3D

- **HARM**:
  Gammie, McKinney, Toth (2003)
- Axisymmetric (2D)
- Total energy conserving
  (dissipation → heat)
- Modern Shock Capturing techniques
  (greater accuracy)
- Improvements in HARM3D:
  - 3D
  - More accurate
    (parabolic interpolation in reconstruction and constraint transport)
  - Assume flow is isentropic when $P_{gas} << P_{mag}$

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

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

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

$$T^\mu{}_\nu = \left(\rho + u + p + b^2\right) u^\mu u_\nu + \left(p + \frac{b^2}{2}\right) \delta^\mu{}_\nu - b^\mu b_\nu$$

Our Method: Simulations with HARM3D

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

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

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

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

$$T^\mu{}_\nu = \left(\rho + u + p + b^2\right) u^\mu u_\nu + \left(p + \frac{b^2}{2}\right) \delta^\mu{}_\nu - b^\mu b_\nu$$

$$T(r) = \left(\frac{H}{R} r\,\Omega\right)^2$$

GRMHD Disk Simulations

$N_r \times N_\theta \times N_\phi$

$=$

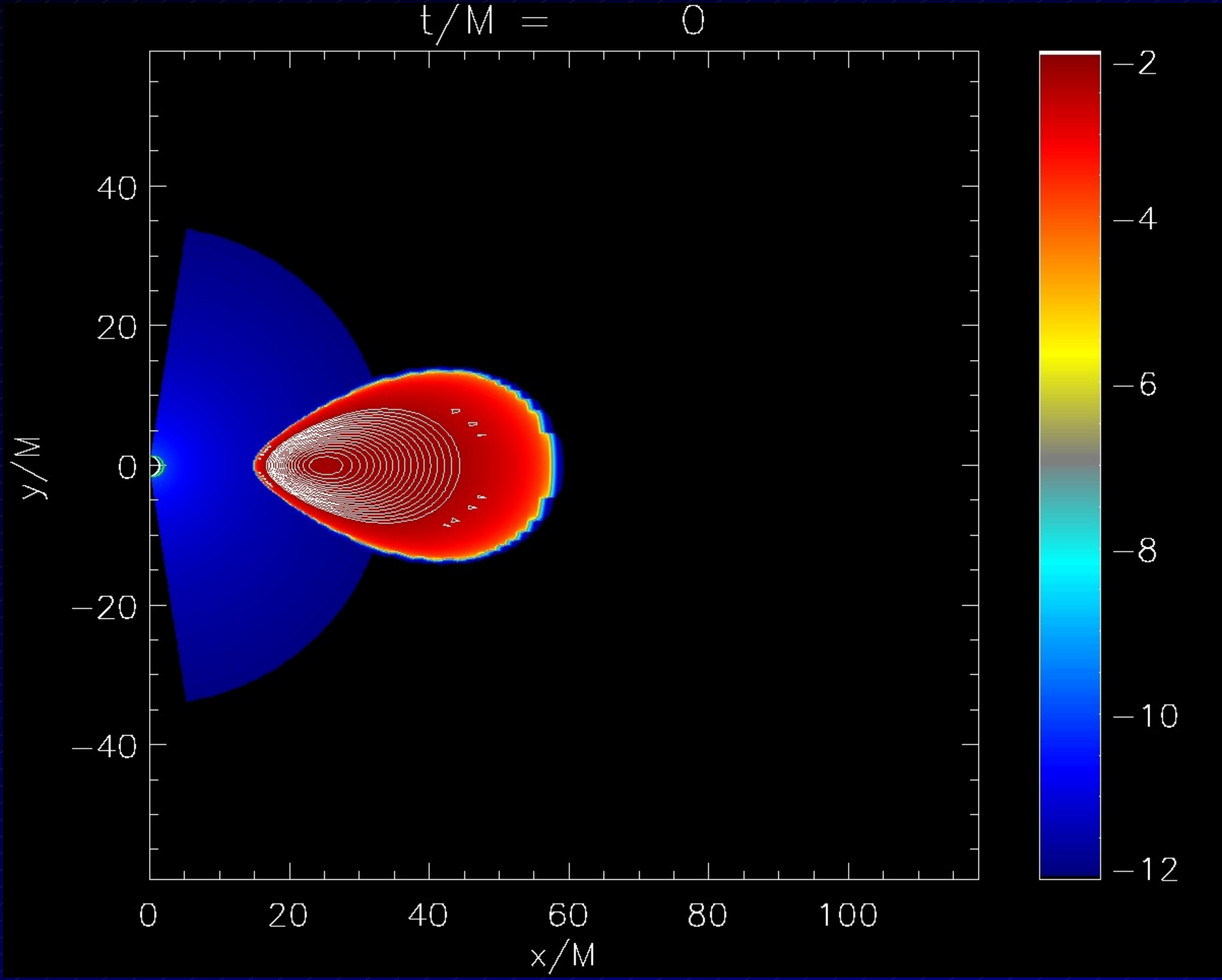
$192 \times 192 \times 64$

$r \in [r_{hor}, 120\mathrm{M}]$

$\theta \in \pi [0.05, 0.95]$

$\phi \in [0, \frac{\pi}{2}]$

$a = 0.9\mathrm{M}$



GRMHD Disk Simulations

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$$=$$
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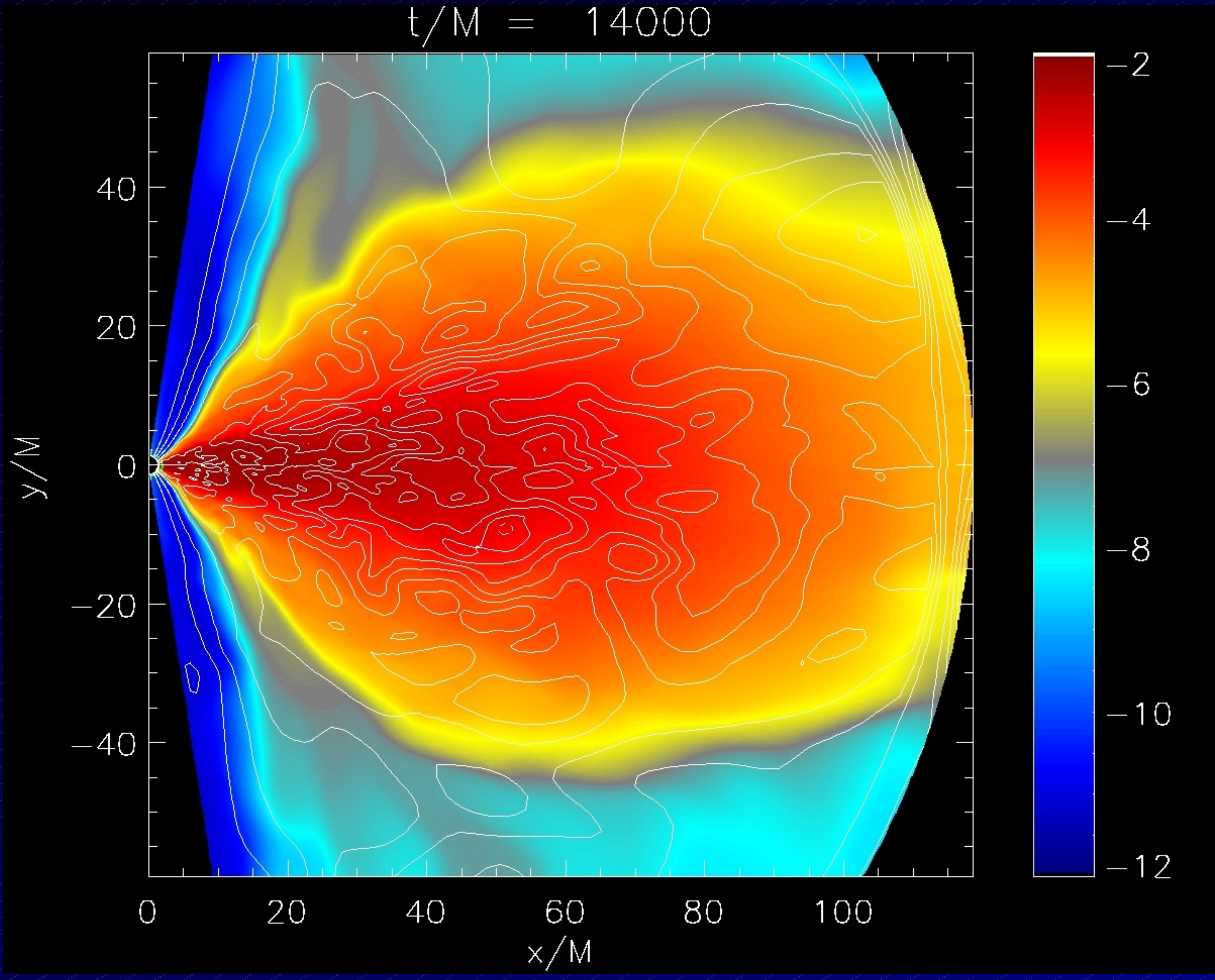
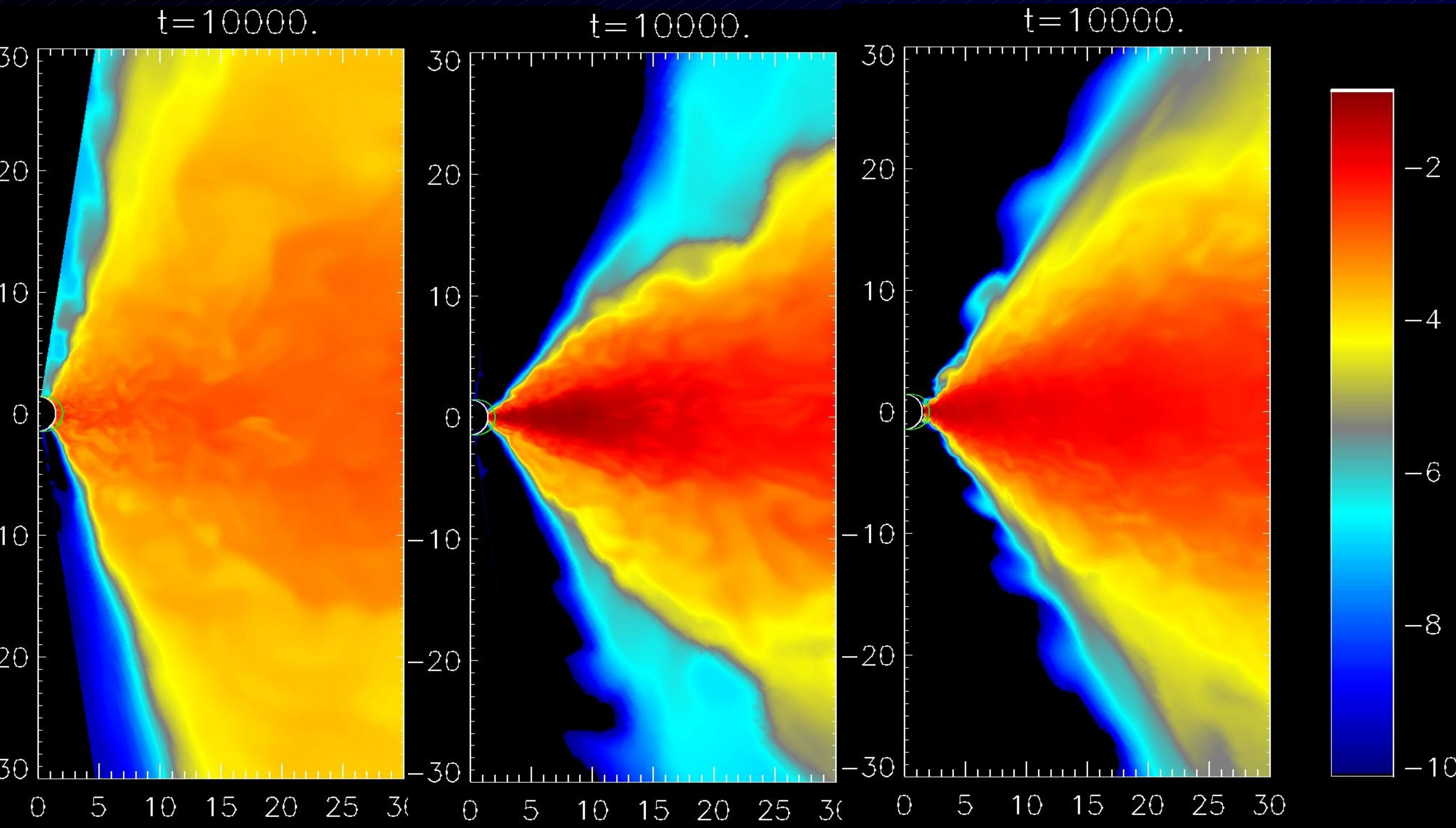


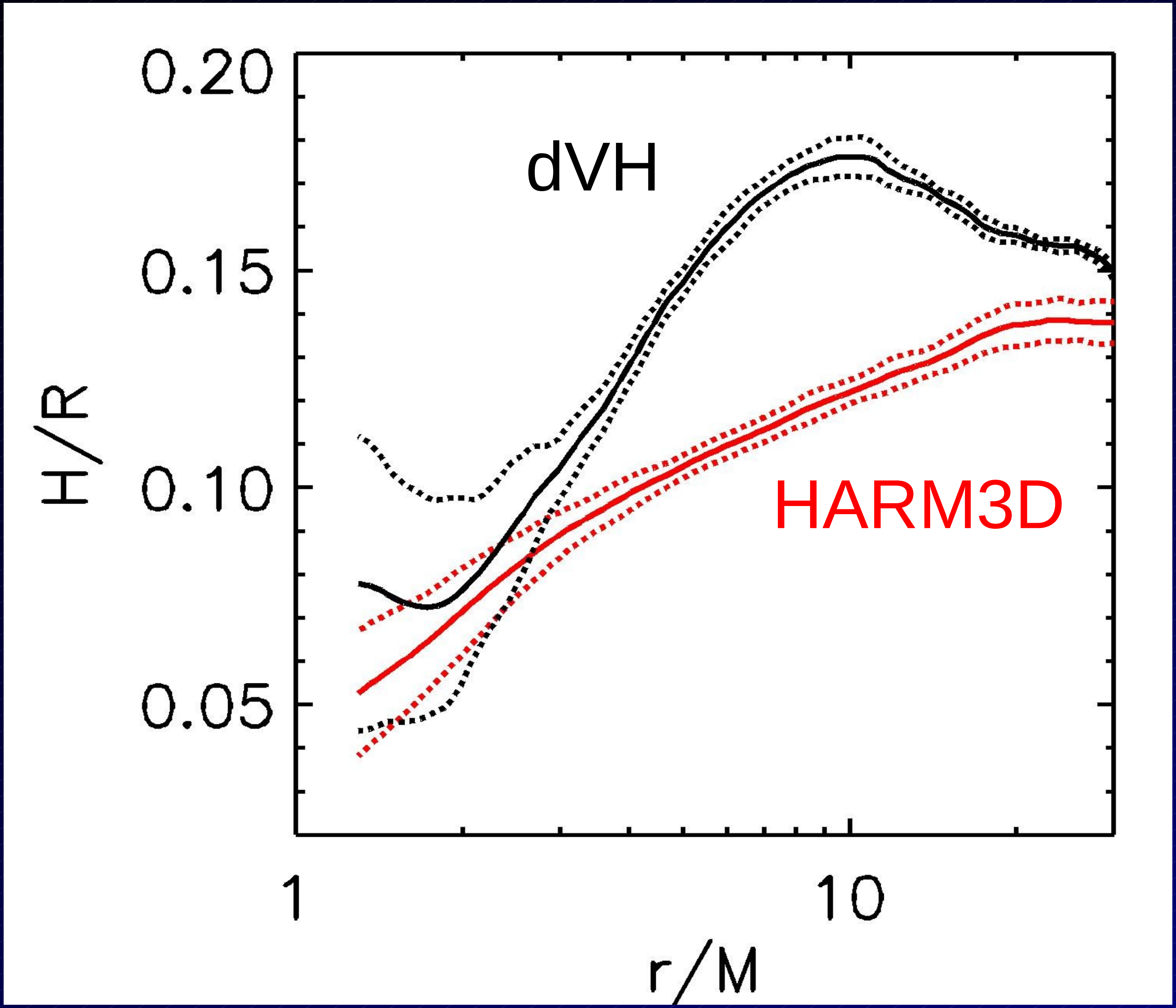
HARM3D vs. dVH

$\log(\rho)$



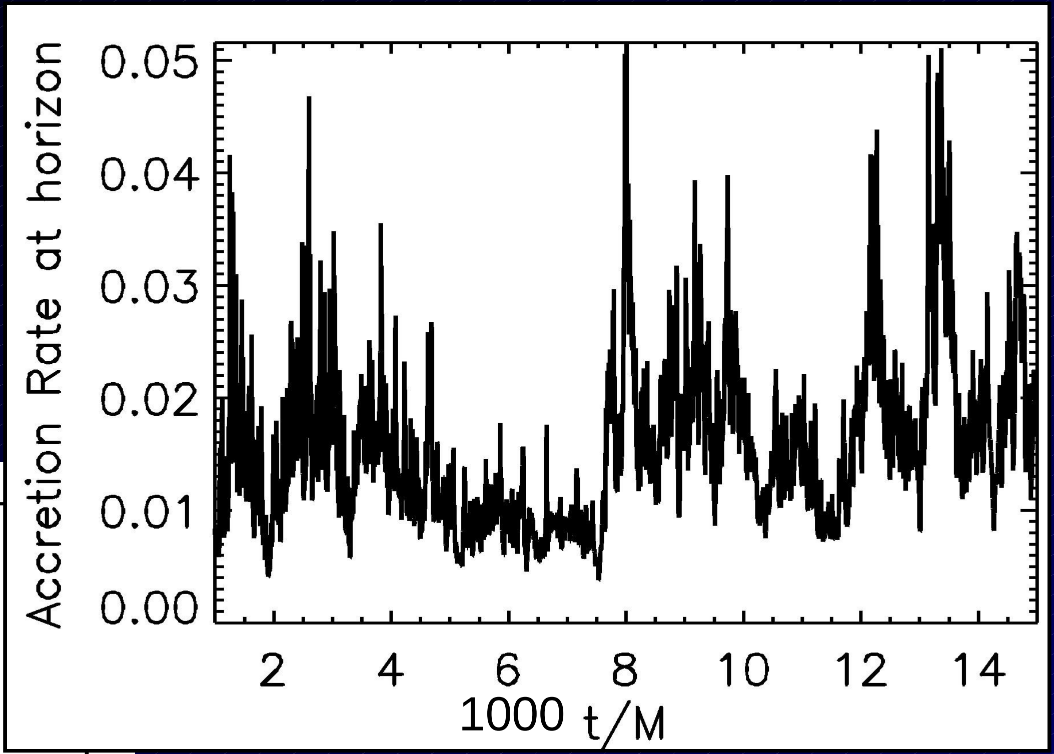
Uncooled **Cooled** **dVH**

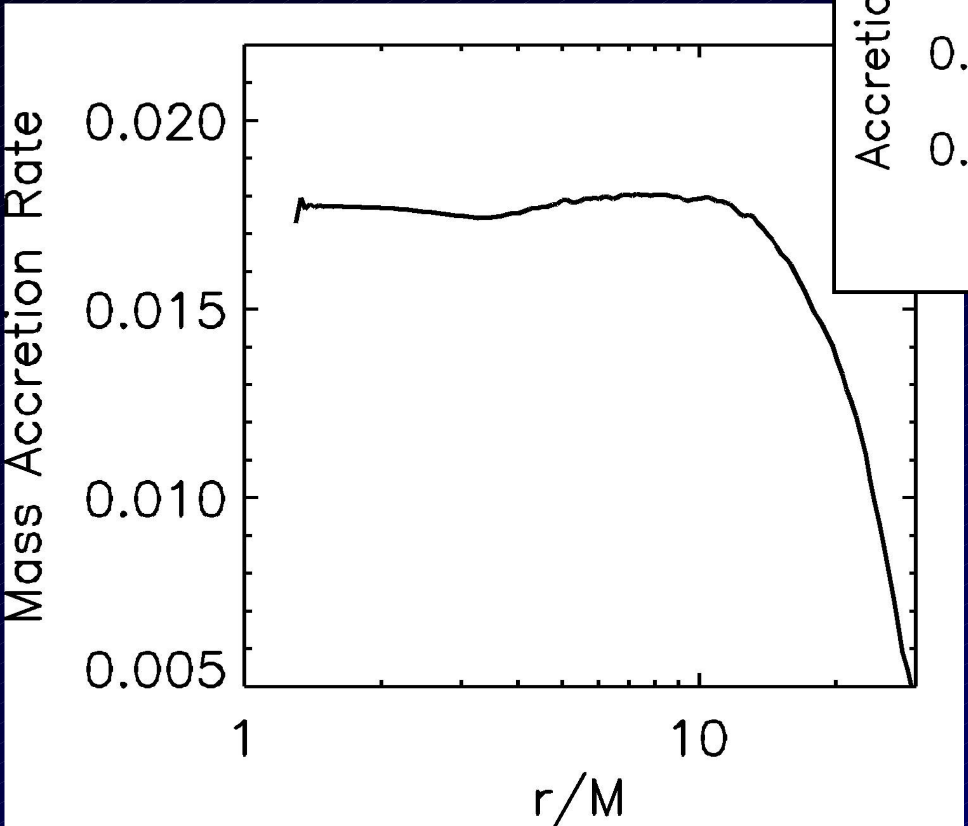
Disk Thickness



Accretion Rate

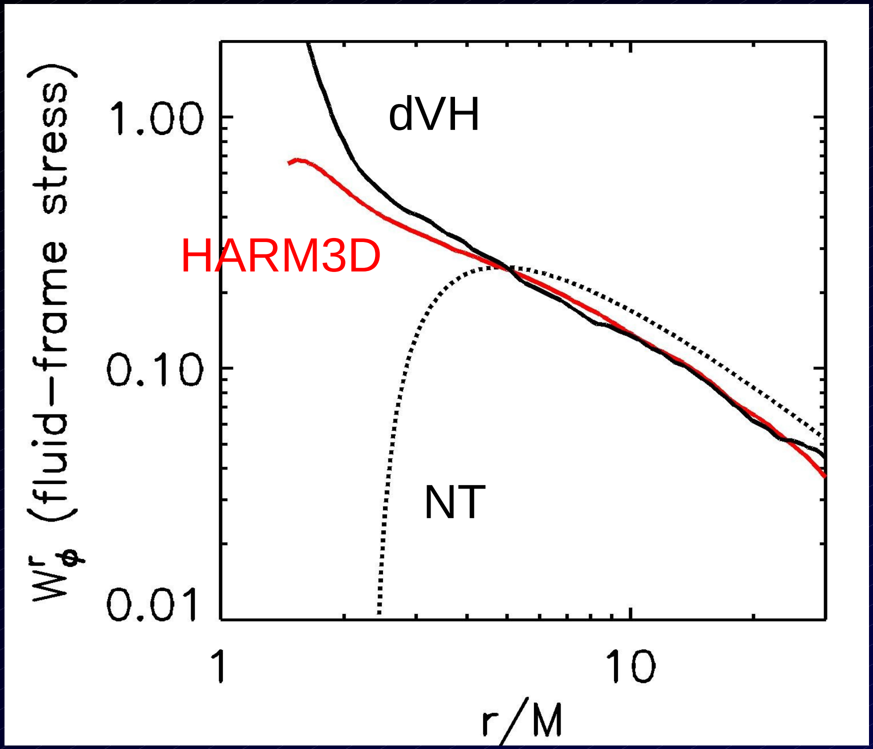
Steady State Period = 7000 – 15000M

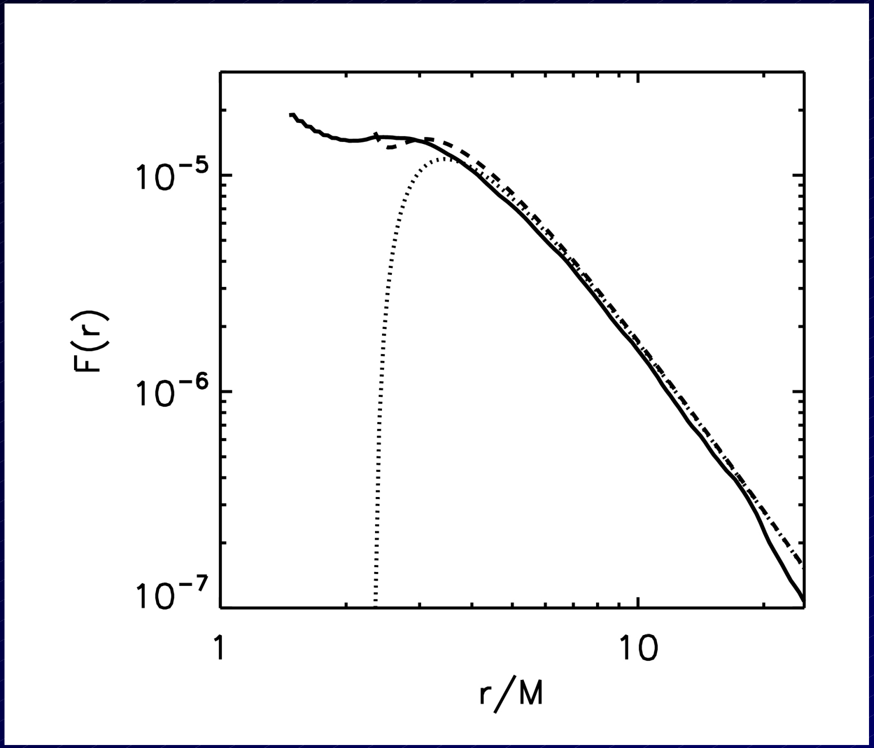




Steady State Region = Horizon – 12M

Magnetic Stress





Agol & Krolik (2000) model

- Retained Heat → Stress Deficit
- Stress Continuity through ISCO

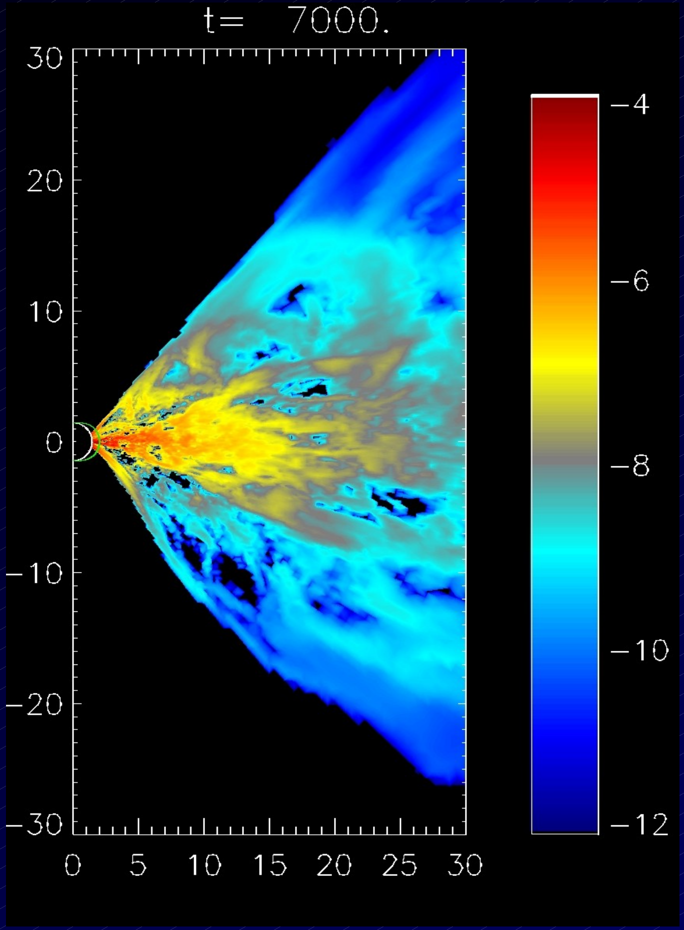
$$\Delta \eta = 0.01$$

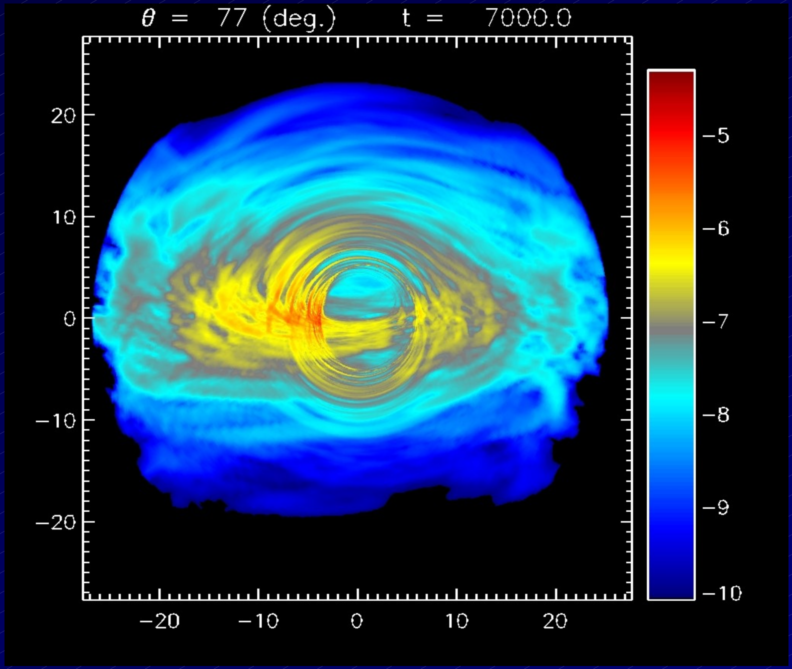
$$\Delta \eta / \eta = 7\ \%$$

Our Method: Radiative Transfer

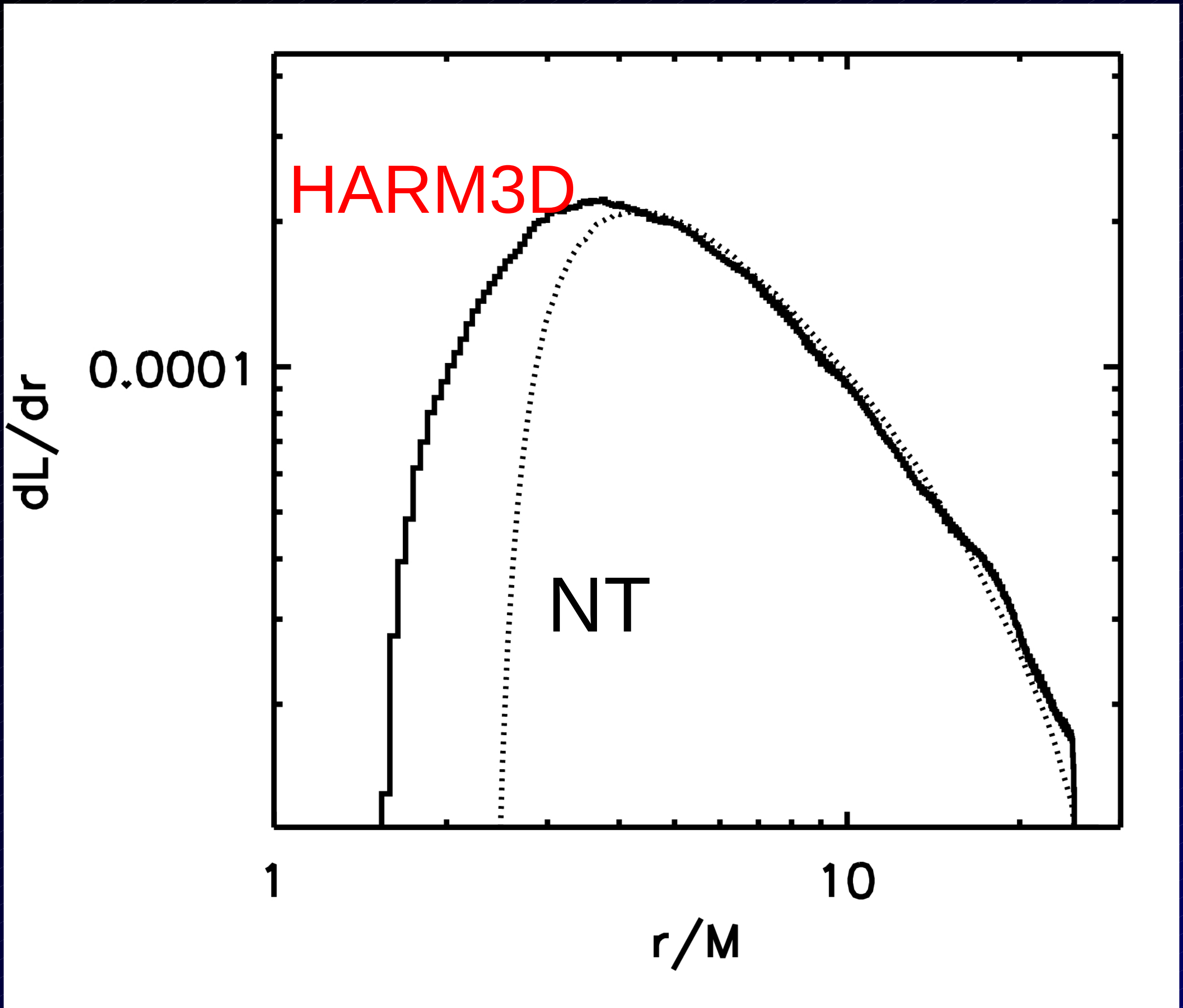
$$j_\nu = \frac{f_c}{4\pi\nu^2}$$

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





Observer Frame Luminosity: Angle/Time Average



Assume NT profile for r > 12M .

$$\eta_{H3D} = 0.151$$

$$\eta_{NT} = 0.143$$

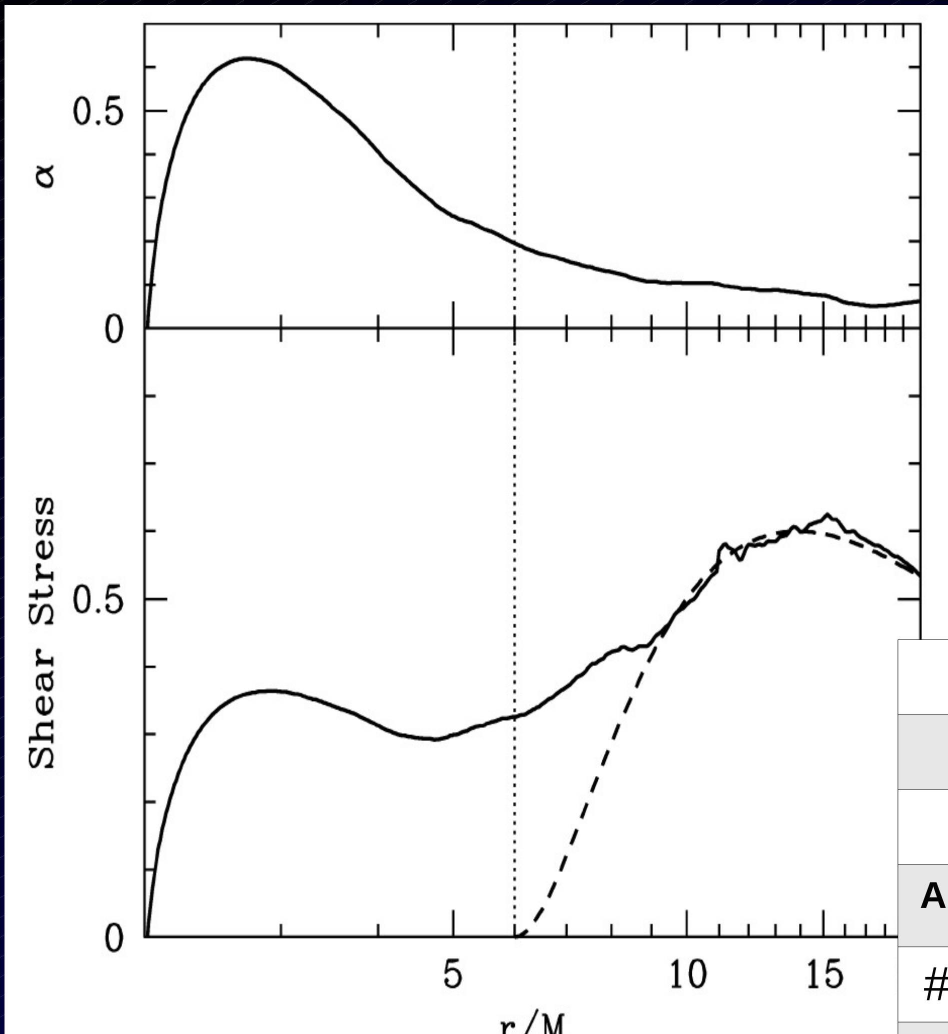
$$\Delta\eta/\eta = 6\ \%$$

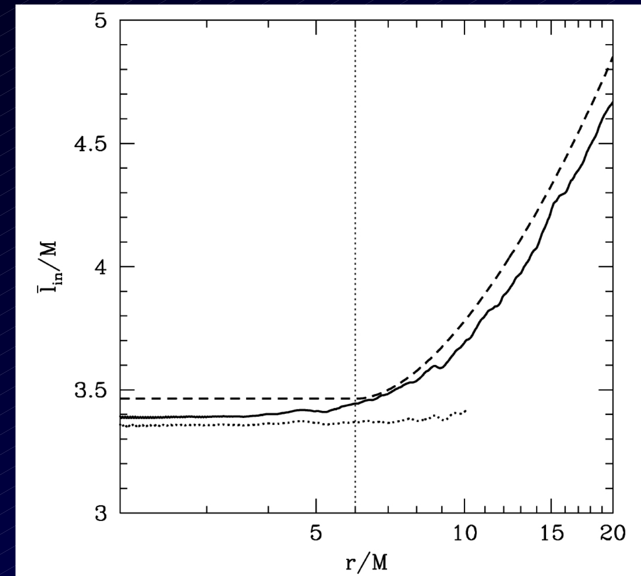
$$\Delta R_{in}/R_{in} \sim 80\%$$

$$\Delta T_{max}/T_{max} = 30\%$$

If disk emitted retained heat: $\Delta\eta/\eta \sim 20\ \%$

Counter Evidence



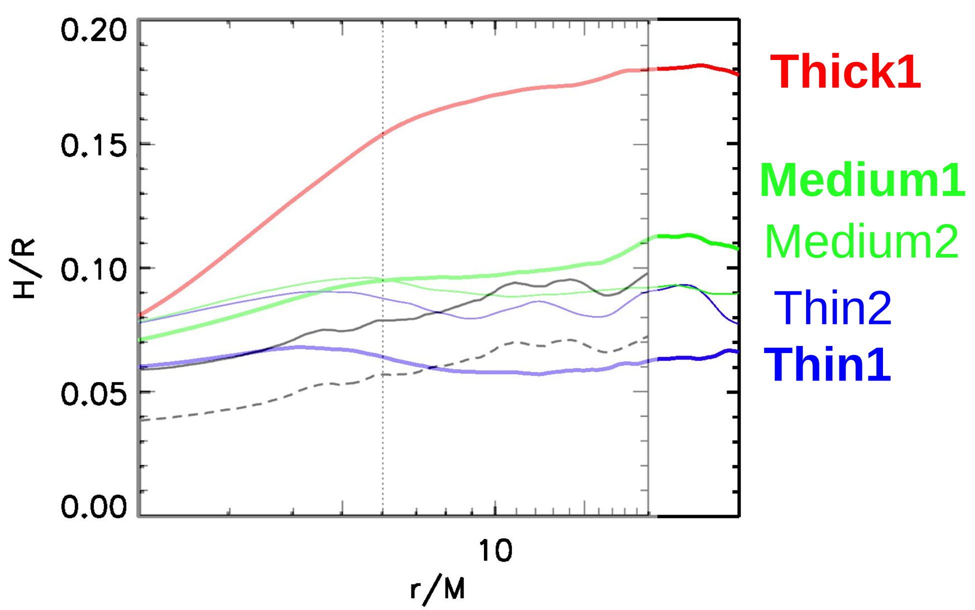


	Shafee et al.	Ours
BH Spin	a=0.0	a=0.9
Resolution	512x120x32	192x192x64
Azimuthal Extent	π/4	π/2
# of B Loops	2	1
H/R	0.05-0.07	0.07-0.13
Code	HARM + 3D	HARM3D

Shafee, McKinney, Narayan, Tchekhovskoy,
Gammie, McClintock (2008)

Counter Counter Evidence

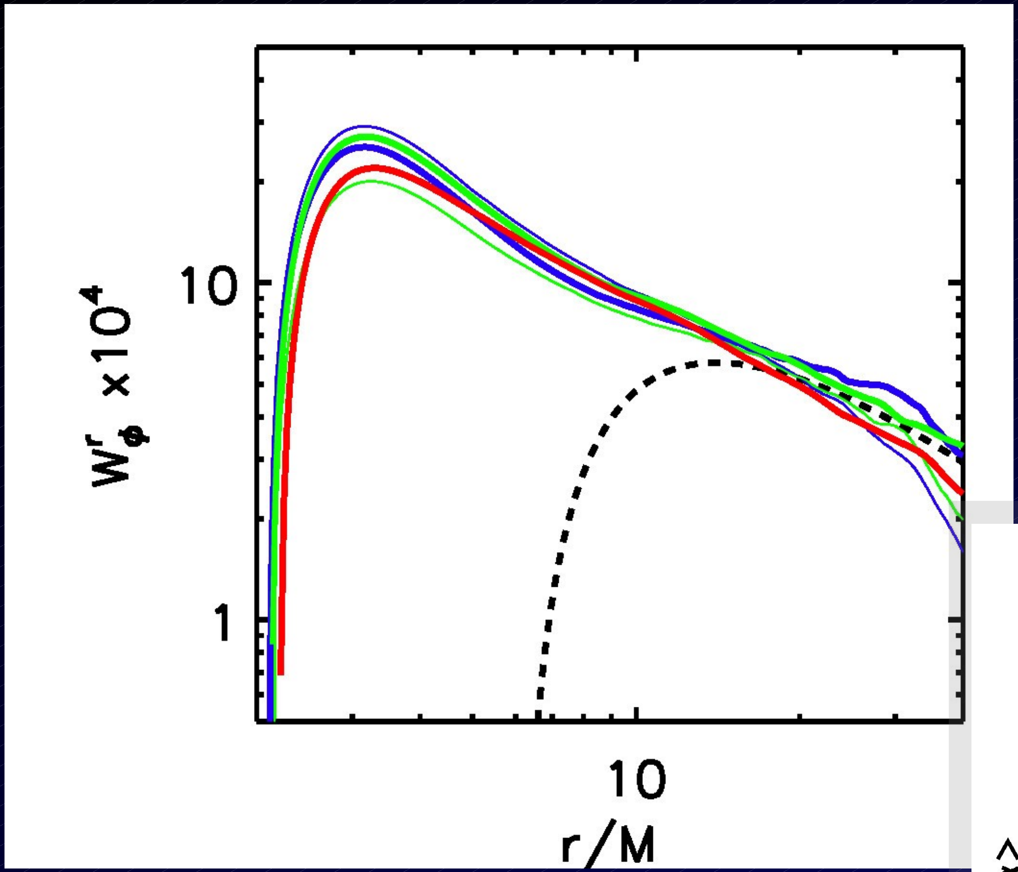
	Theirs	Our Original	Thin1	Medium1	Thick1	Thin2	Medium2
BH Spin	a=0.0	a=0.9	a=0.0	a=0.0	a=0.0	a=0.0	a=0.0
Resolution	512x120x32	192x192x64	912x160x64	512x160x64	384x160x64	192x192x64	192x192x64
ϕ Extent	$\pi/4$	$\pi/2$	$\pi/2$	$\pi/2$	$\pi/2$	$\pi/2$	$\pi/2$
# of Loops	2	1	1	1	1	1	1
Actual H/R	0.05 - 0.07	0.07 - 0.13	0.06	0.10	~0.17	0.087	0.097
N_{cells} per H/r	~60	6 - 30	80	100	40 - 70	60	35
Initial Data	"V. 1"	V. 2	V. 1	V. 1	V. 1	V. 2	V. 2

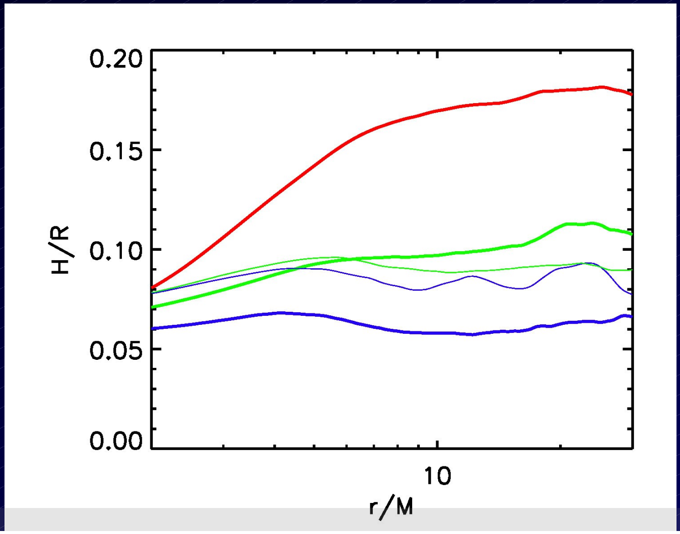


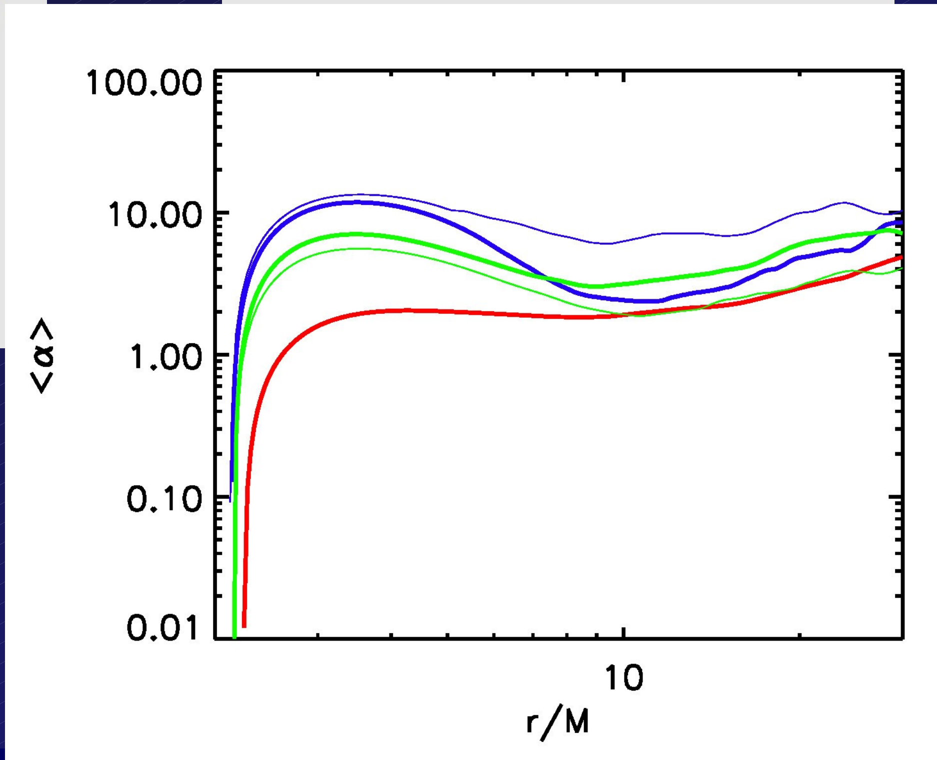
V.1 : Initial disk starts:
- At target thickness
- With inner radius = 20M
- With p_{max} at r = 35M

V.2 : Initial disk starts
- At H/R ~ 0.15
- With inner radius = 15M
- With p_{max} at r = 25M

Trends in Scaleheight

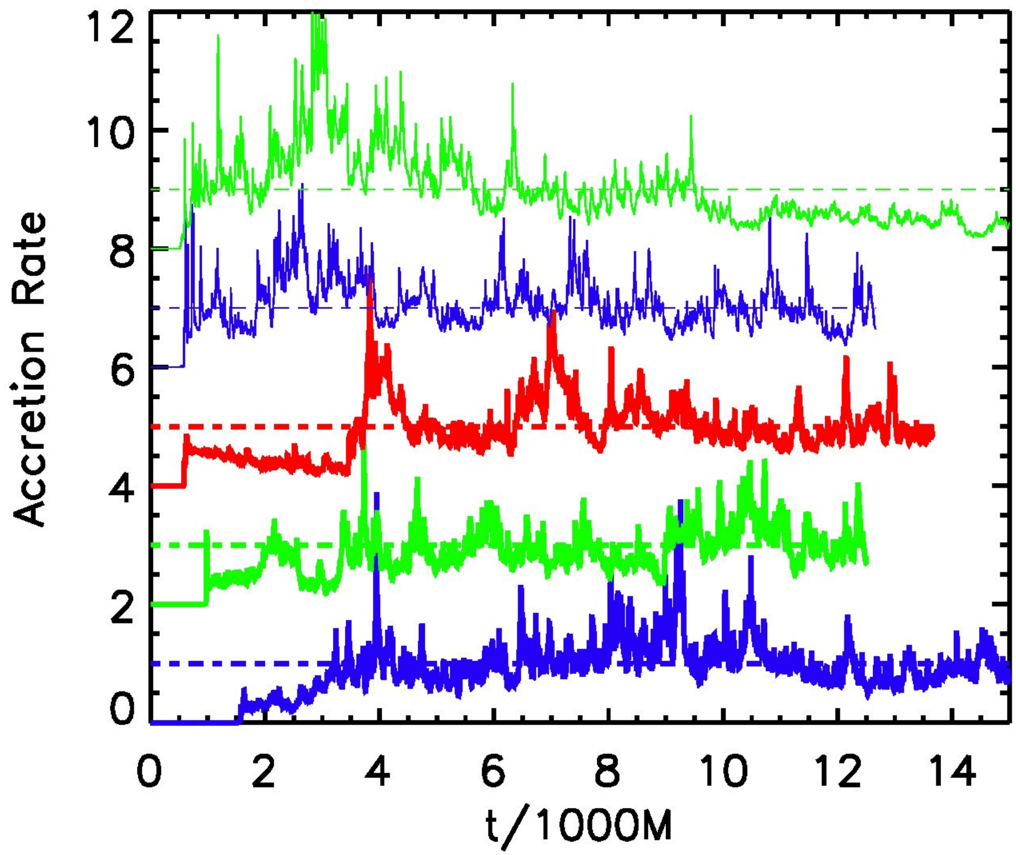


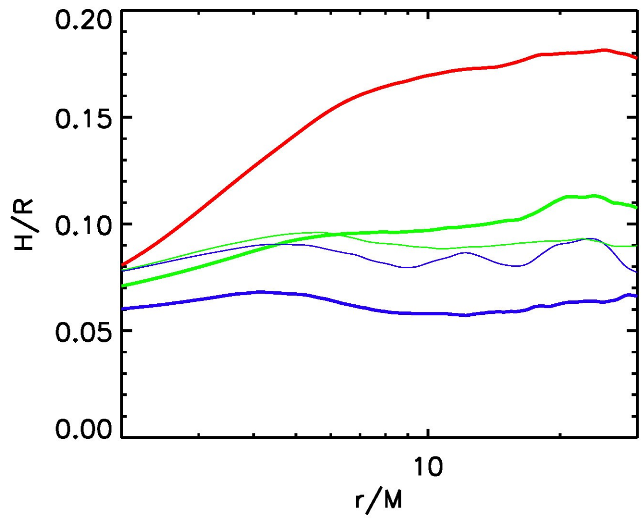


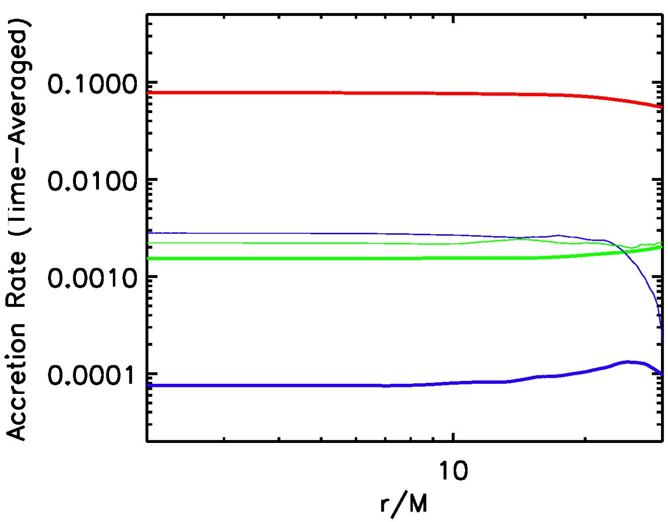


$$W^r_\phi = p\ \alpha$$

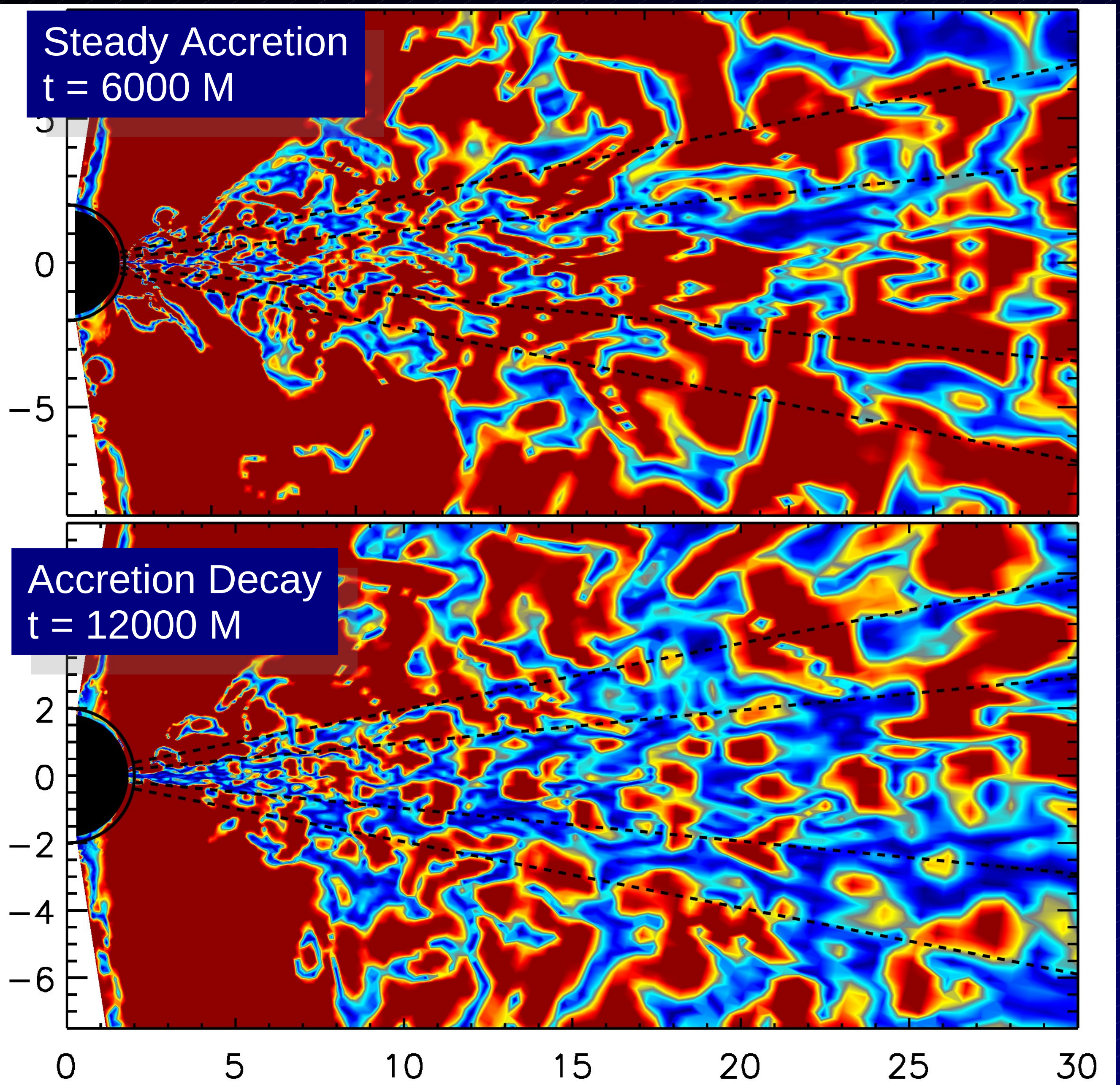
Steady State and Mass Flow Equilibrium







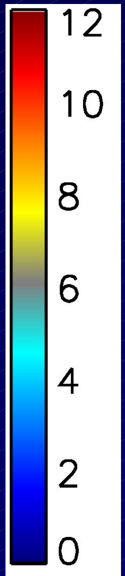
Resolution of the MRI



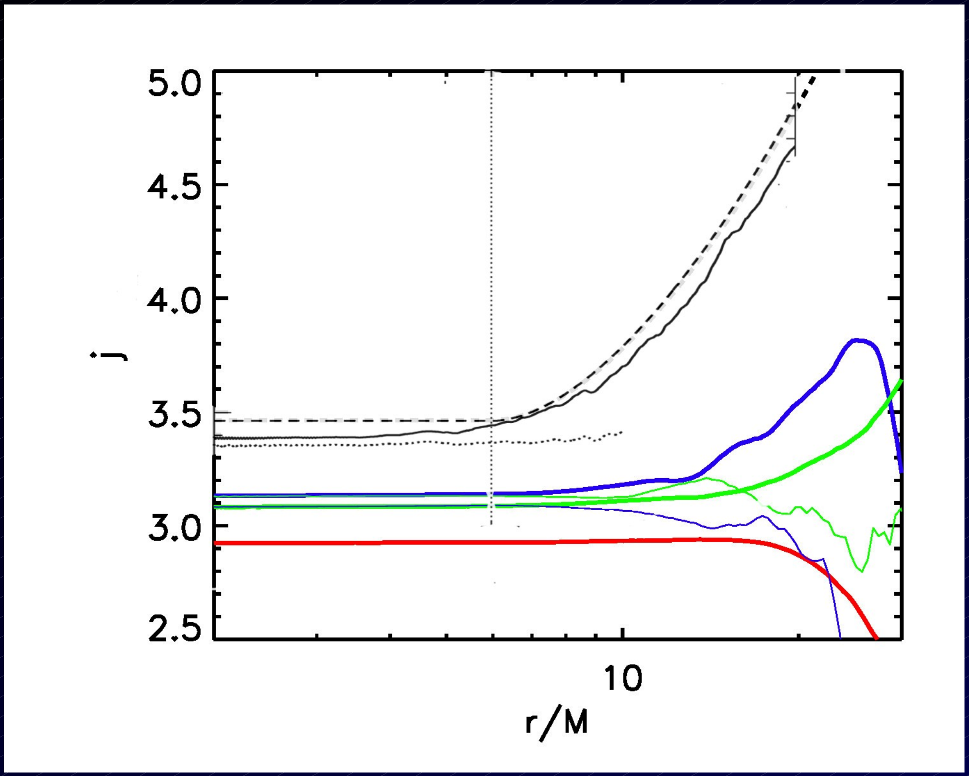
Sano et al. (2004)

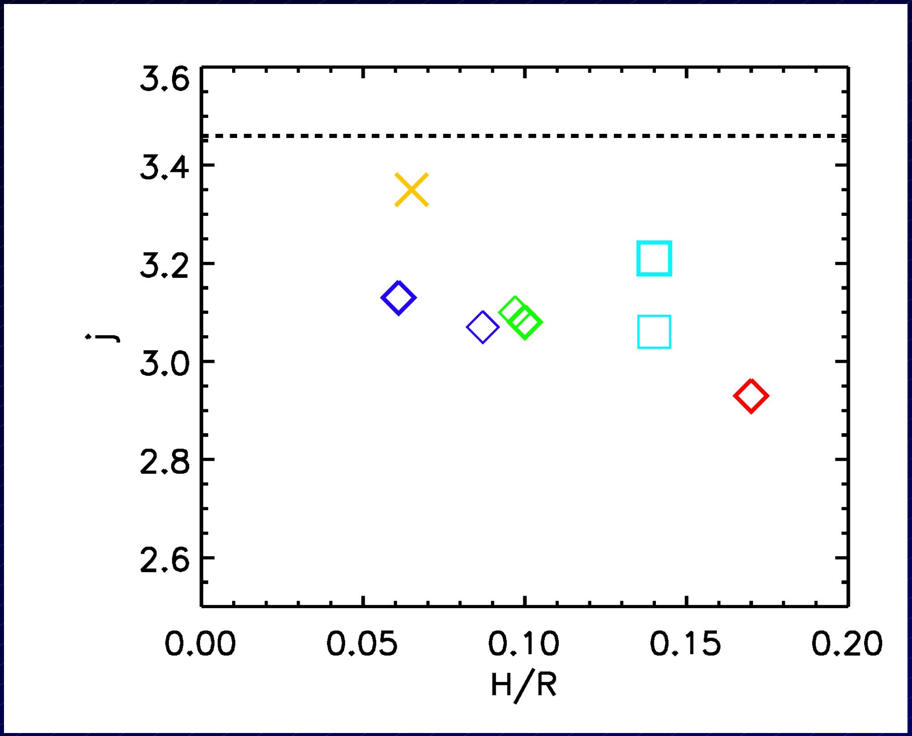
$$\lambda_{\mathrm{MRI}} \equiv \frac{1}{\sqrt{4\pi\rho\Omega(R)}} b_\mu \hat{e}^\mu_{(\theta)}$$

$$\frac{\lambda_{\mathrm{MRI}}}{\Delta z} > 6$$



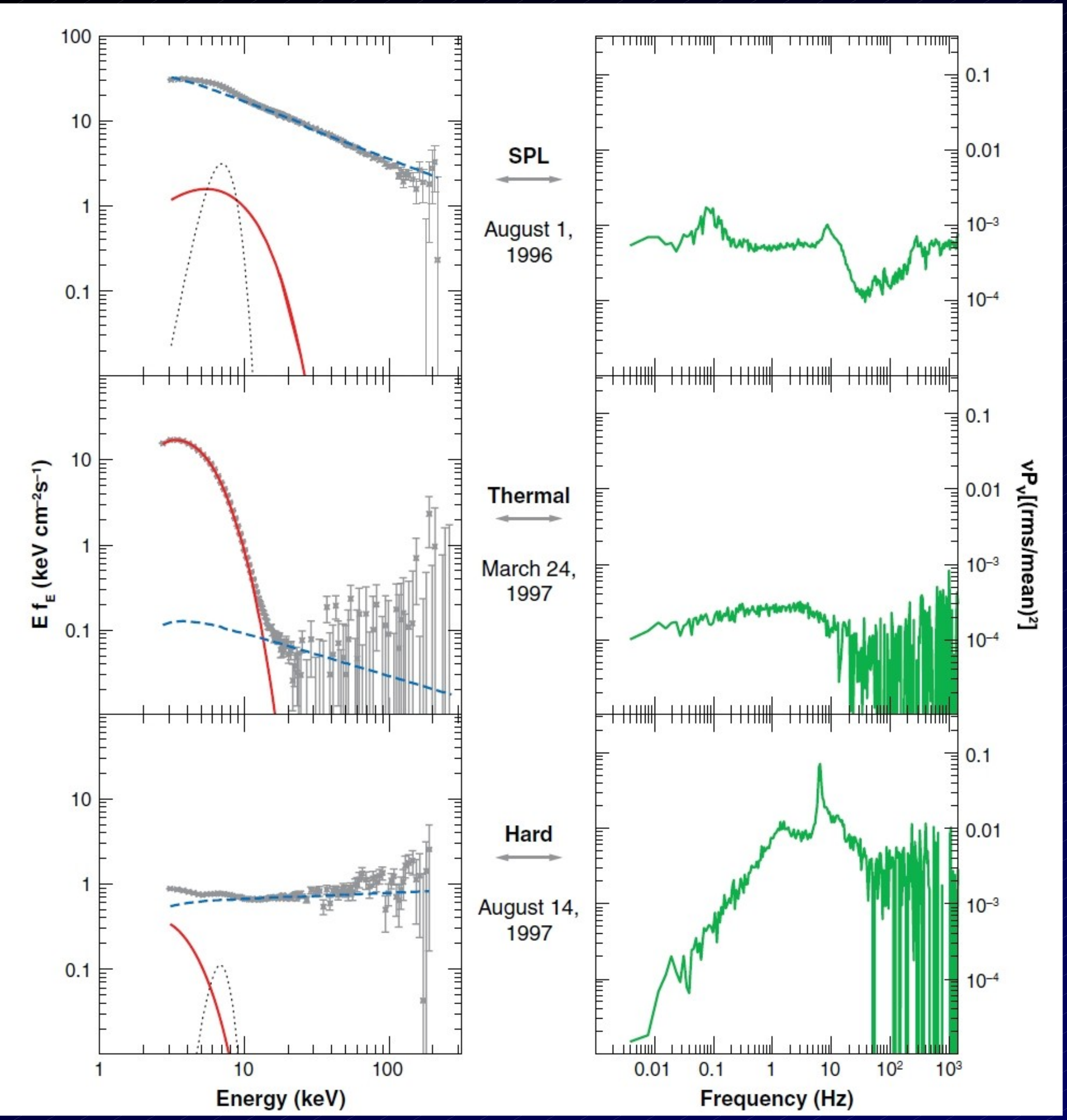
Accreted Specific Angular Momentum





- Dependence is weak ~ $(H/R)^{(1/2)}$ instead of "expected" $(H/R)^2$
- Possible Dependence on Initial Field Topology
- Independent of Algorithm (modulo Shafee et al. 2008)
- Still need to transport radiated energy to infinity to find efficiency

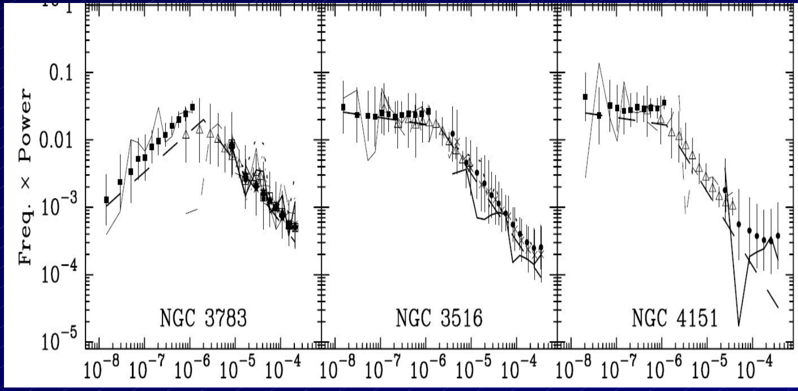
X-ray Variability of Accretion



- X-ray var. always dominated by corona
- XRB var. dependent on spectral state

$$P \sim \nu^{\alpha}$$

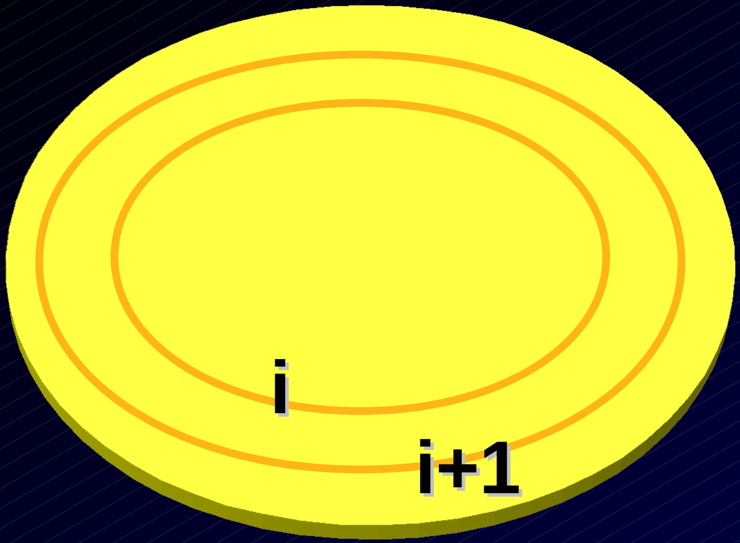
$$-3 < \alpha < -1$$



XRBs: Remillard & McClintock (2006)

AGN: Markowitz et al.(2003)

Variability Models



$$P \sim \nu^{\alpha}$$

Lyubarskii (1997)

Total variability is a superposition of independent variability from larger radii modulating interior annuli on inflow time scales

Churazov, Gilfanov, Revnivtsev (2001)

Outer radius of corona may be cause of (temporal) spectral slope.

$$\tau_a = \left[\alpha \left(\frac{H}{r} \right)^2 \Omega_K \right]^{-1}$$

- Accretion rate modulation modeled as variability of α
- Predict phase coherence at frequencies longer than inflow freq.

Armitage & Reynolds (2003)
Machida & Matsumoto (2004)
Schnittman et al. (2006)
Reynolds & Miller (2009)

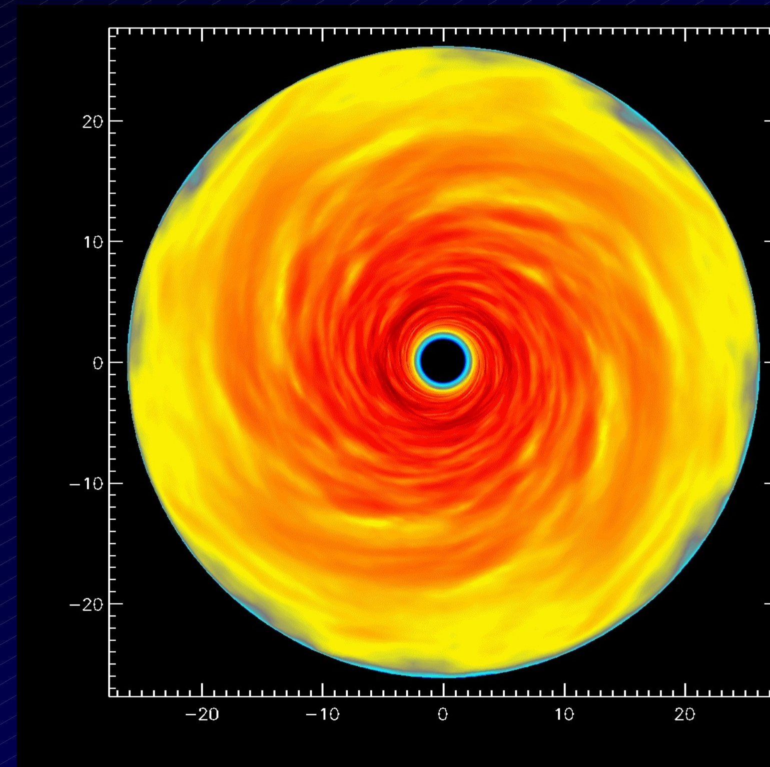
- Used accretion rate or stress as dissipation proxies
- PLD breaks at local orbital frequency per annulus
- Composite PLD $\alpha \sim -2$

Our Variability Model

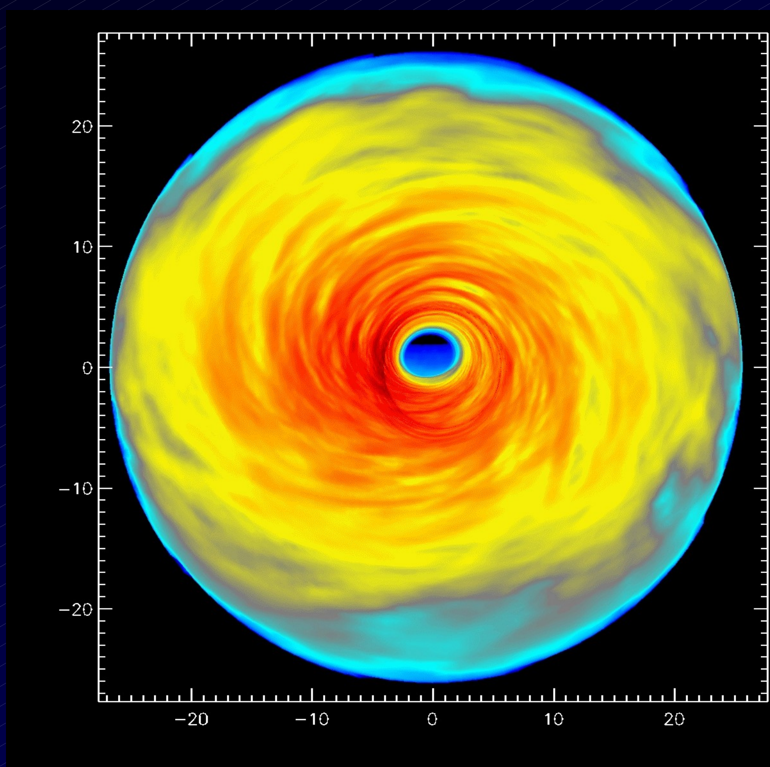
Noble & Krolik (2009)

Simulation: a = 0.9M H/R = 0.07 - 0.13

- Assume Thomson Scattering
- Optical depth set by $\dot{m} = L/\eta L_E$
- Integrate emission up to photosphere
- Include effect of finite light speed
- Parameterized by $\theta , \dot{m}$

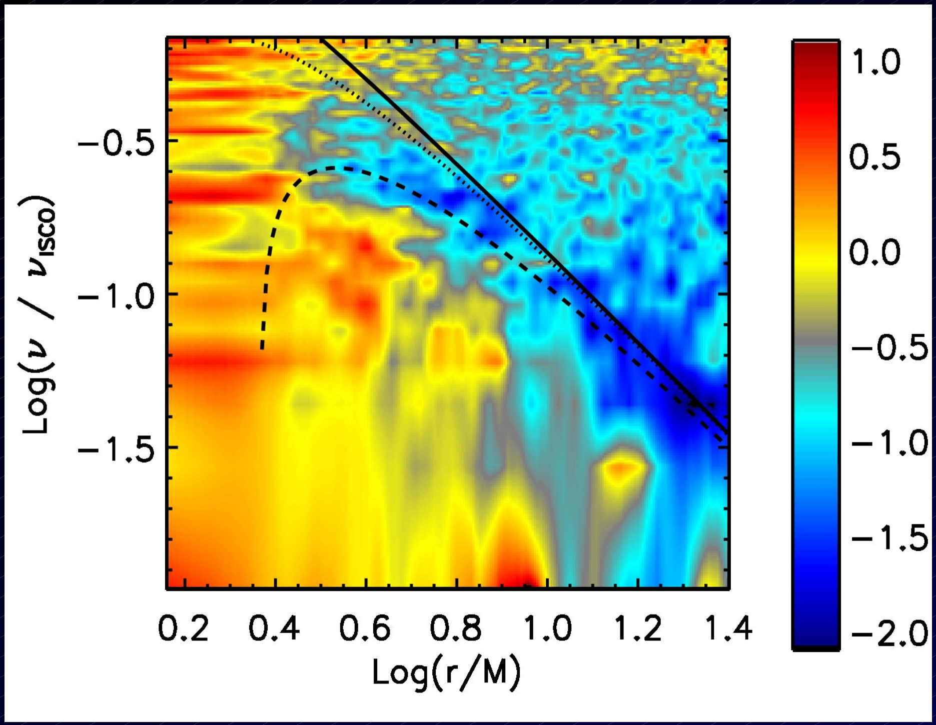


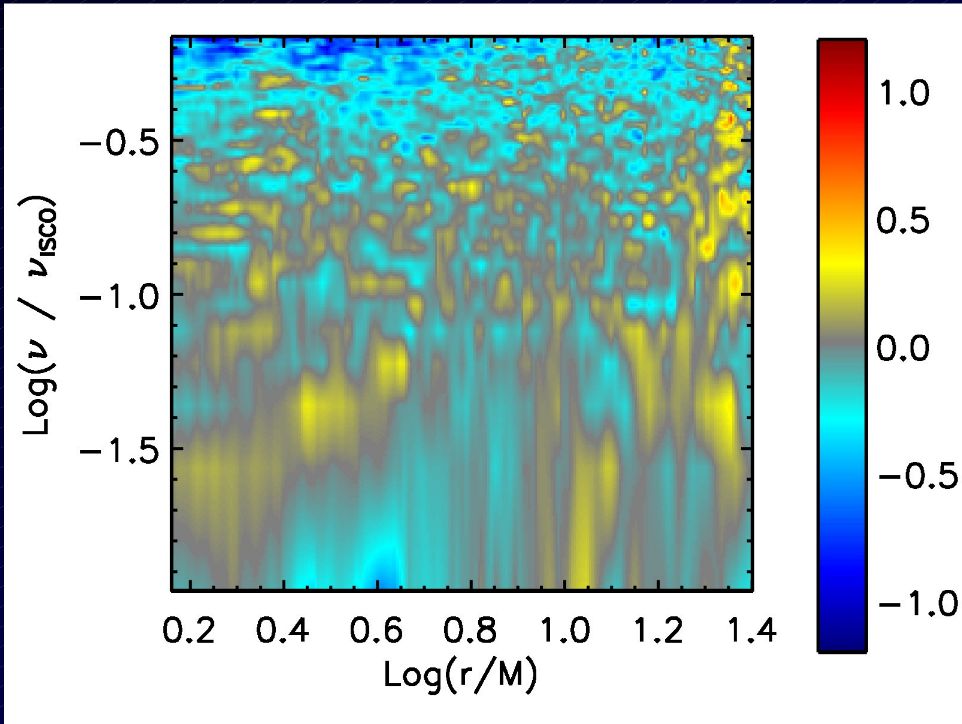
$\dot{m} = 0.003$



$\theta = 41^o$

Origin of Variability





$$P_{diss}(\nu, r)/P_{\dot{M}}(\nu, r)$$

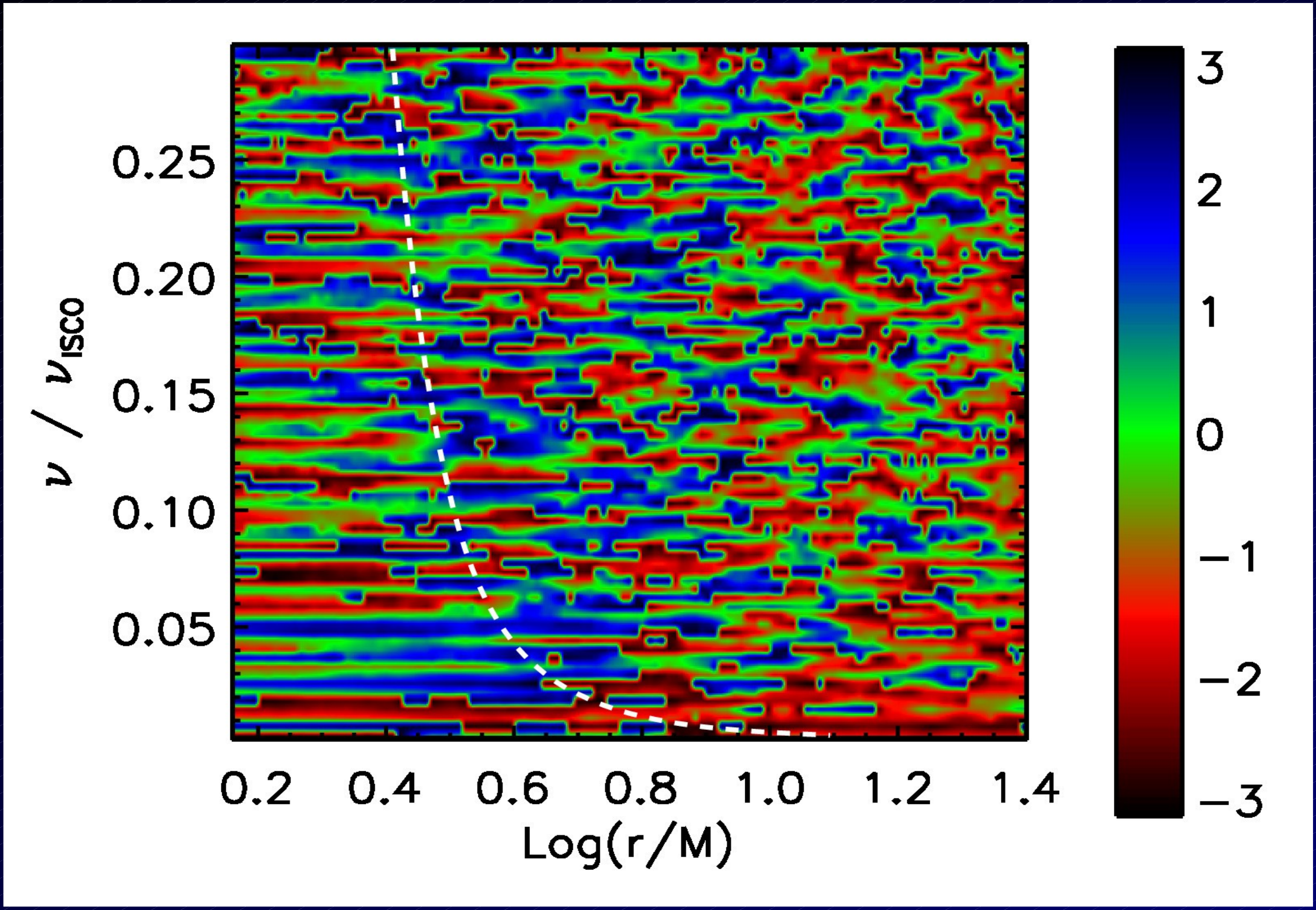
$$P_{inf}(\nu, r)/P_{diss}(\nu, r)$$

$$\theta = 5^o$$

- Epicyclic motion not dissipated
- Dissipation not well proxied by $\dot{M}$

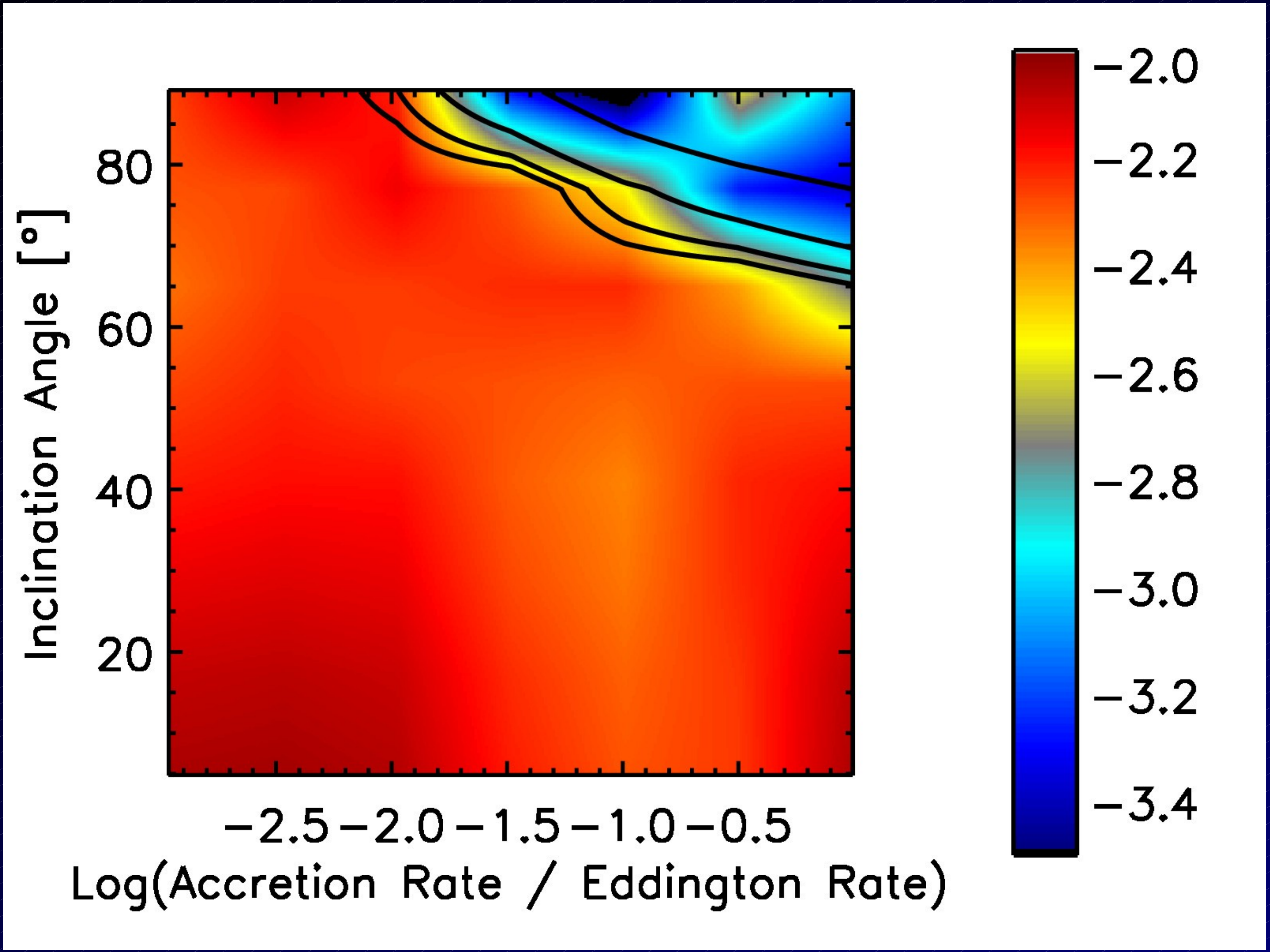
- Observed var. ~ local dissipation var.

Phase Coherence



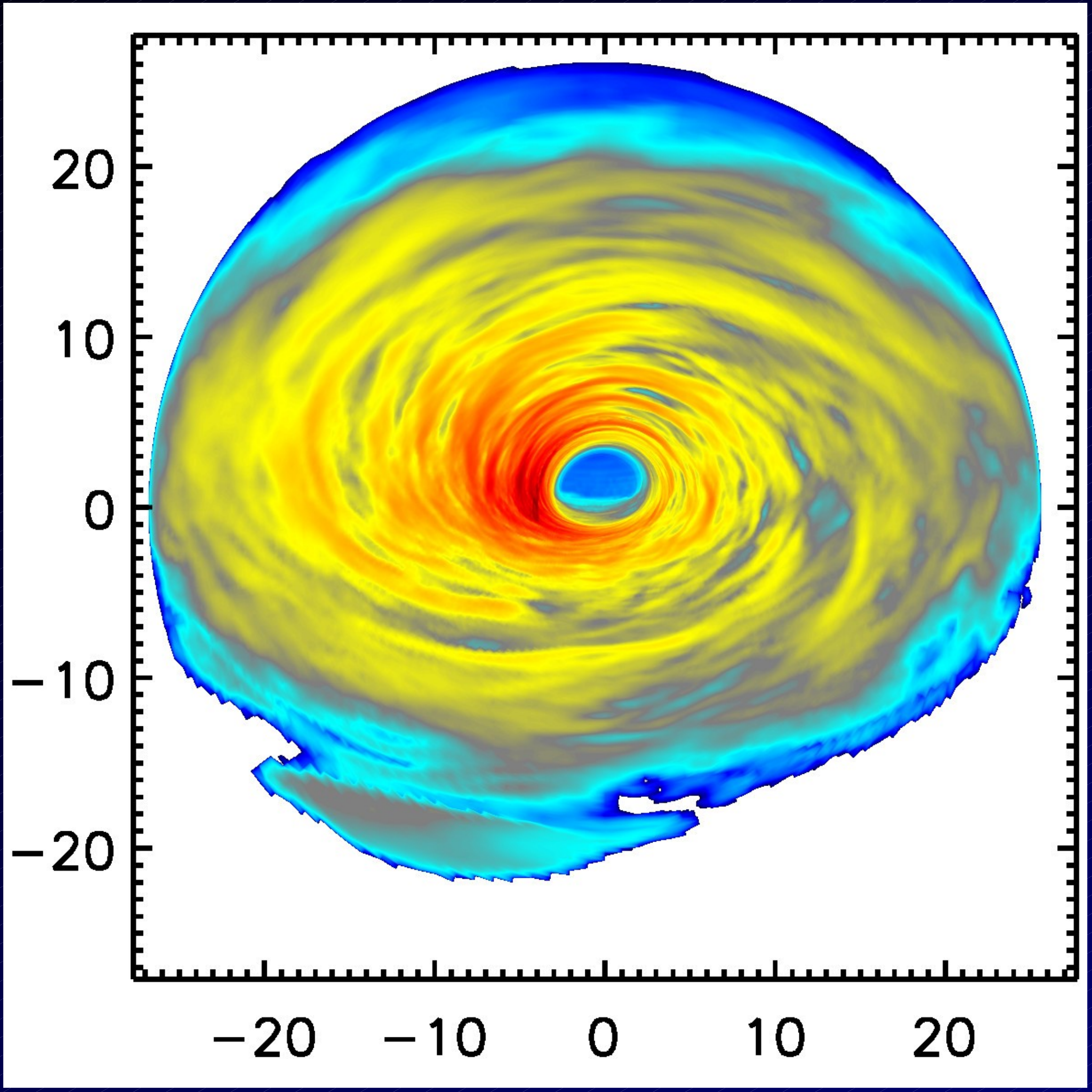
- Possible coherence below inflow frequency (ala Lyubarskii)
- Otherwise dissipation is incoherent over all scales

PLD Exponent vs. Parameter Space



- Complete degeneracy!!

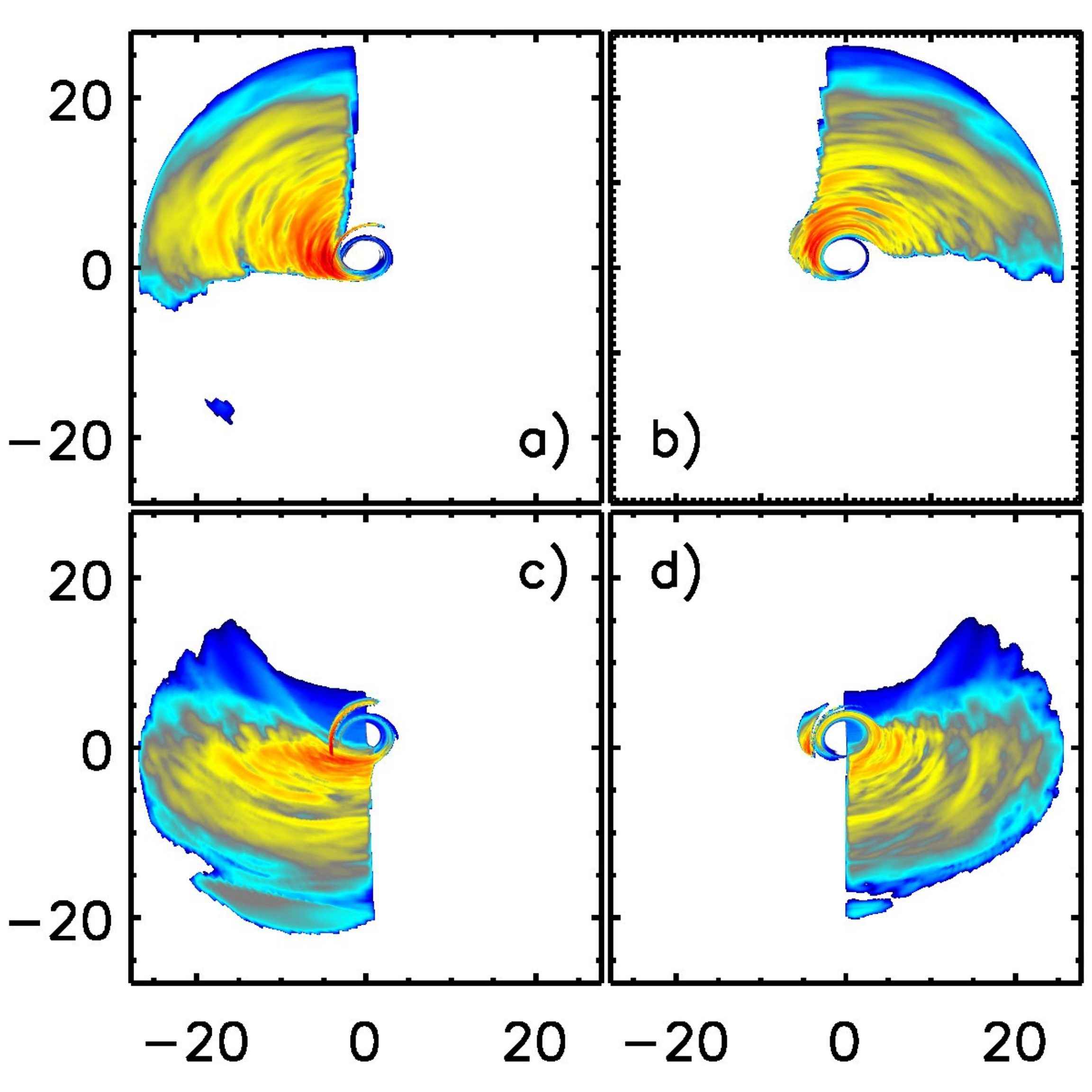
Degeneracy Explanation



Degeneracy Explanation

$\alpha_a > -2$

$\alpha_b > -2$



$\alpha_c < -2$

$\alpha_d < -2$

$\theta \sim 0^o$

$\alpha_i \simeq 2$

Summary & Conclusions

- Closer to ab initio calculations of accretion disk dynamics
- Magnetic stress is important within ISCO
- Stress does not vanish with disk height (at least for Schwarzschild)
- Dissipation variability approximates observed coronal variability

- What about
  … other spins?
  … other cooling models
    H = const. , H = H(t,r) Hysteresis? Spectral States?
  … other initial magnetic field topologies

Good thing I'm still far from retirement....