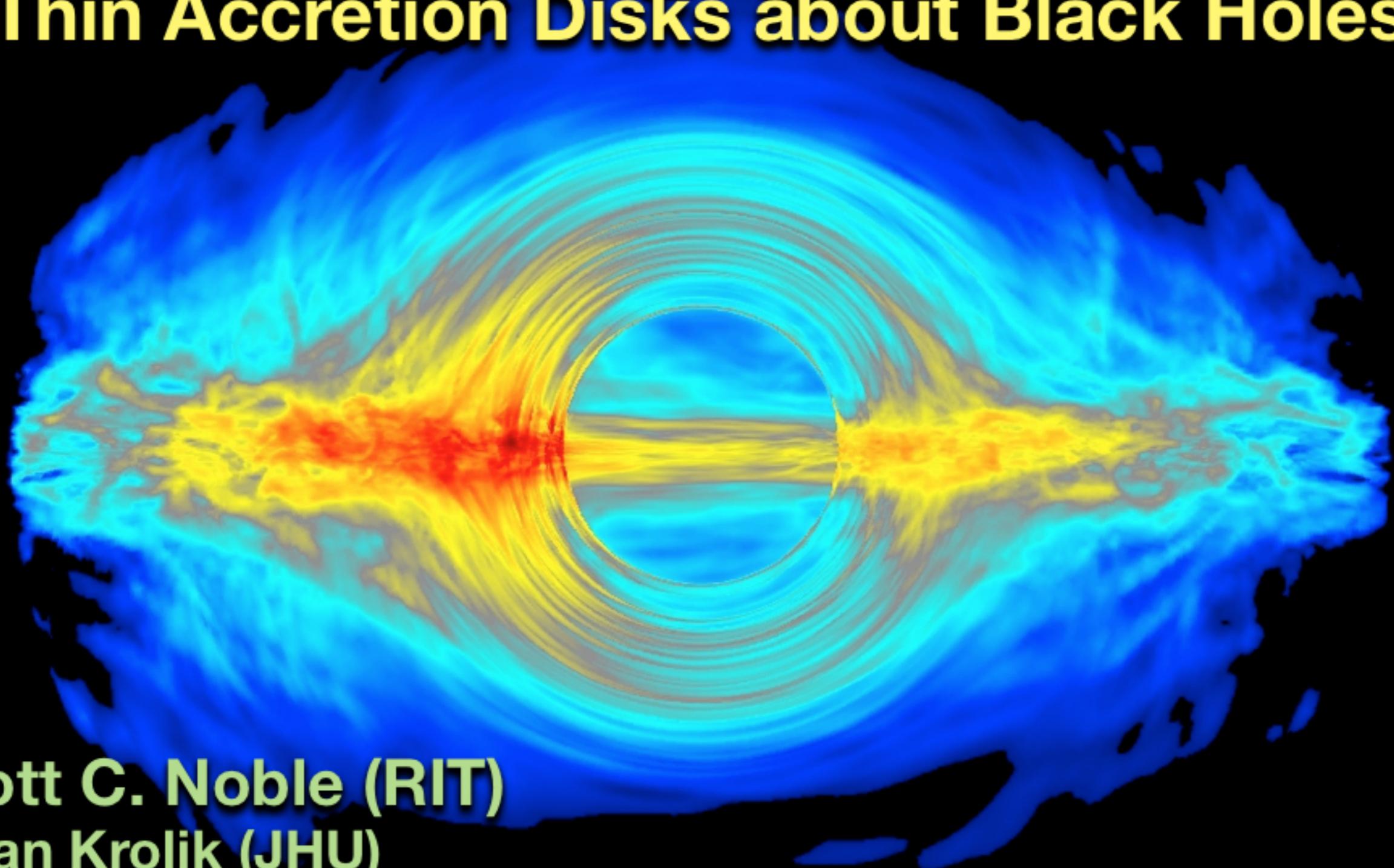


# Simulating the Light and Plasma of Thin Accretion Disks about Black Holes



**Scott C. Noble (RIT)**

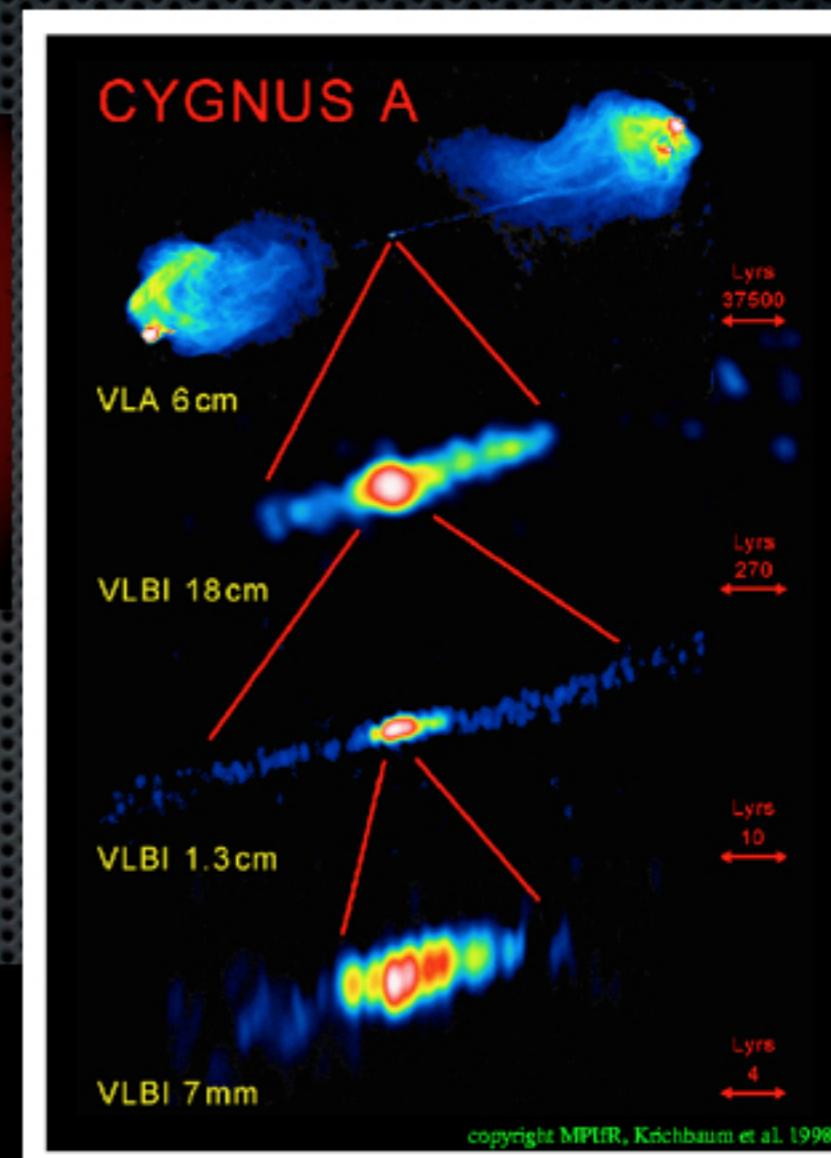
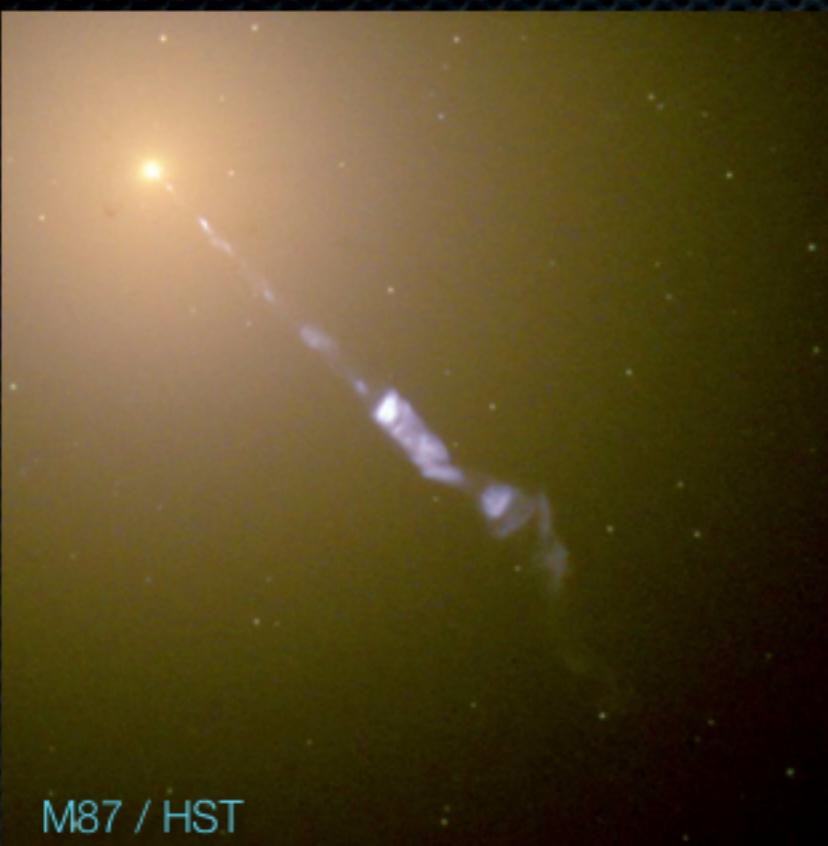
**Julian Krolik (JHU)**

**John Hawley (UVa)**

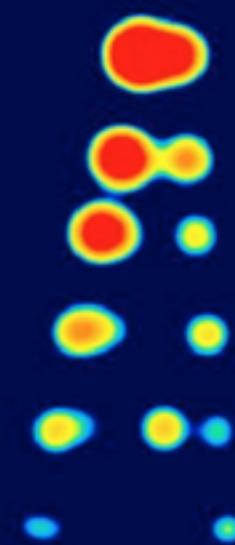
**Jeremy Schnittman (NASA/GSFC)**

RIT Astro Lunch Seminar  
June 15, 2011

# The Exciting World of Black Hole Accretion!

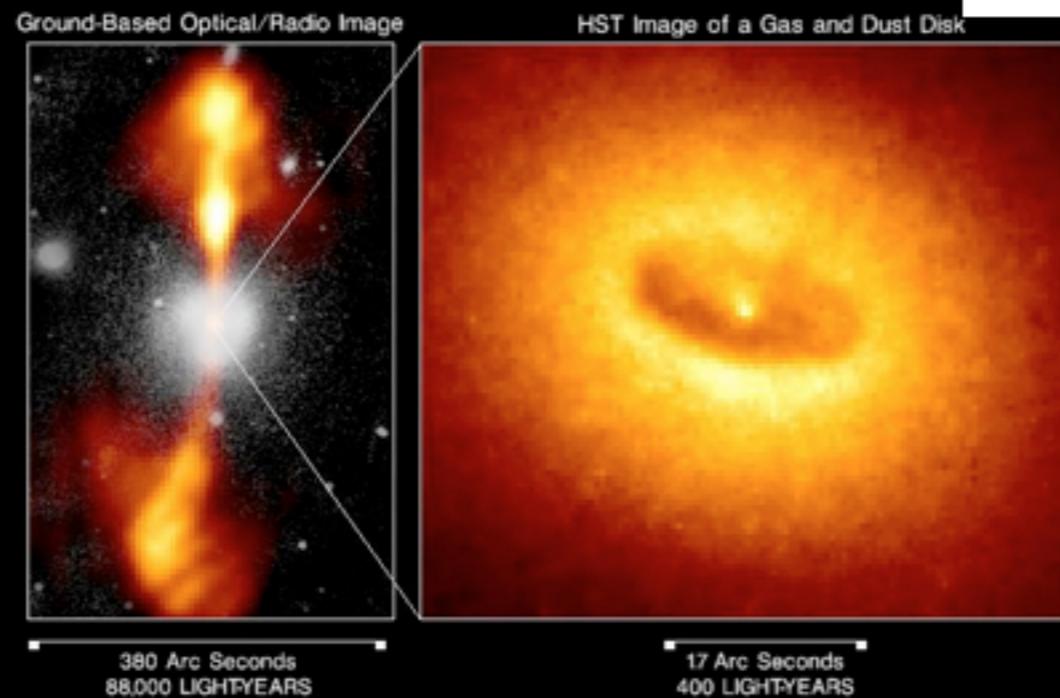


Microquasars!!



GRS 1915+105  
Mirabel & Rodriguez 1994 / VLA

Core of Galaxy NGC 4261  
Hubble Space Telescope  
Wide Field / Planetary Camera



Feedback!!

# Probing the Spacetime of BHs

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

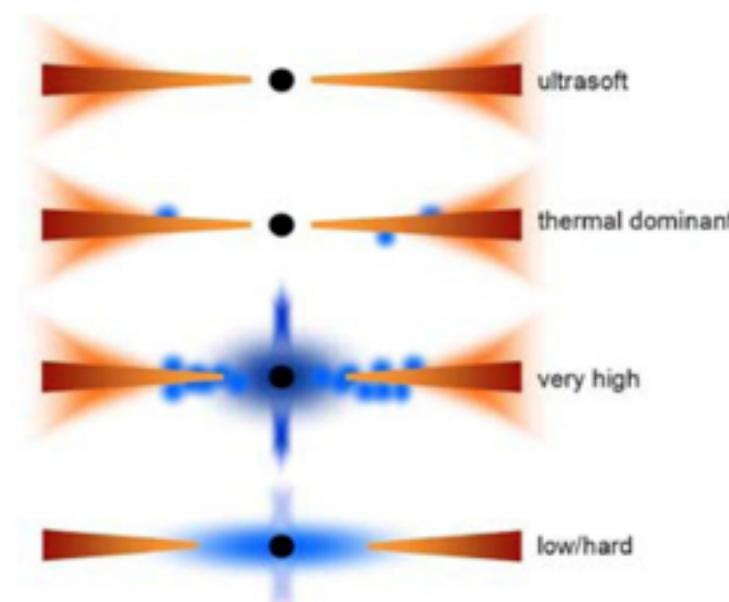
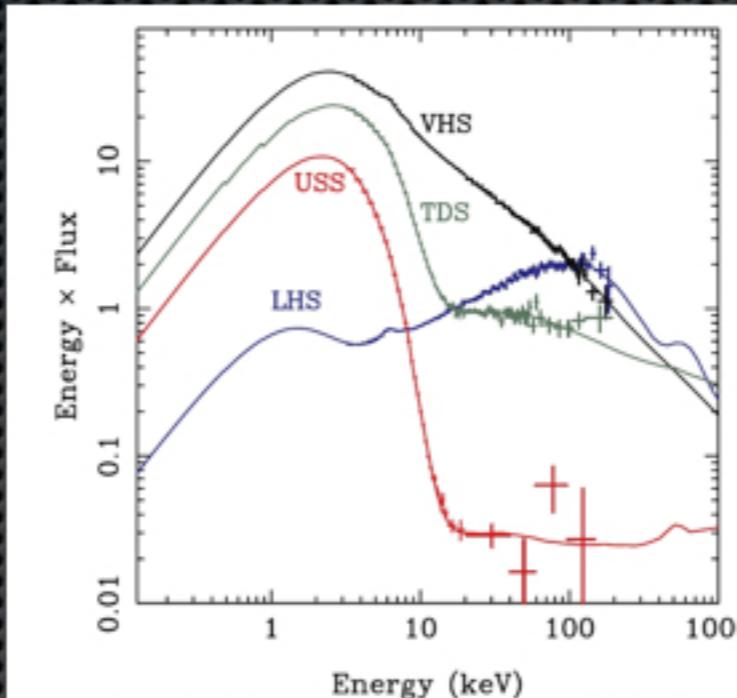
Done et al 2007

- Polarization

(e.g. Schnittman & Krolik 2009, 2011)

- Spectral Fitting of Thermal Emission

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

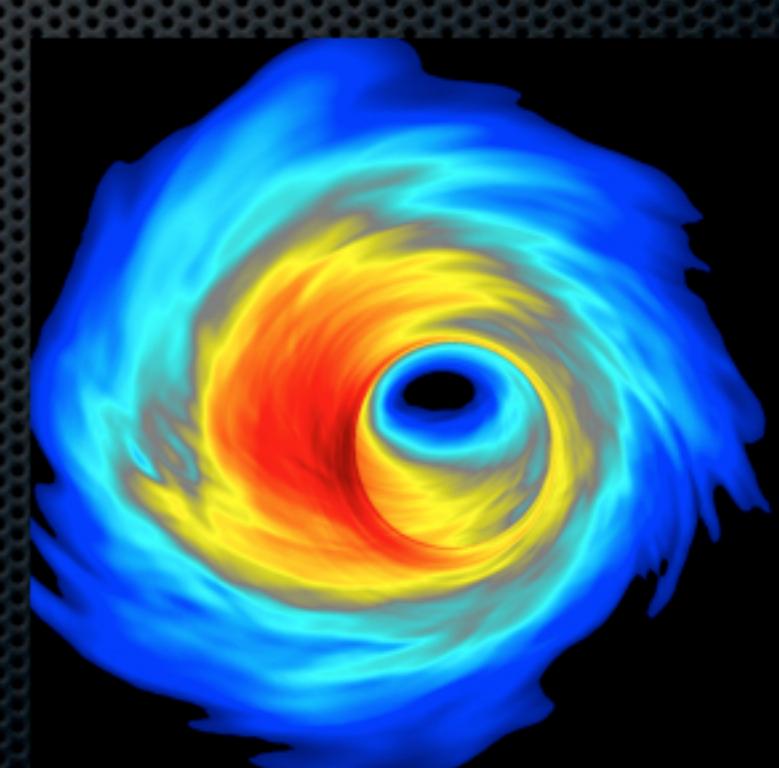


McClintock et al. 2006, Shafee et al. 2006

- Relativistic Iron Lines

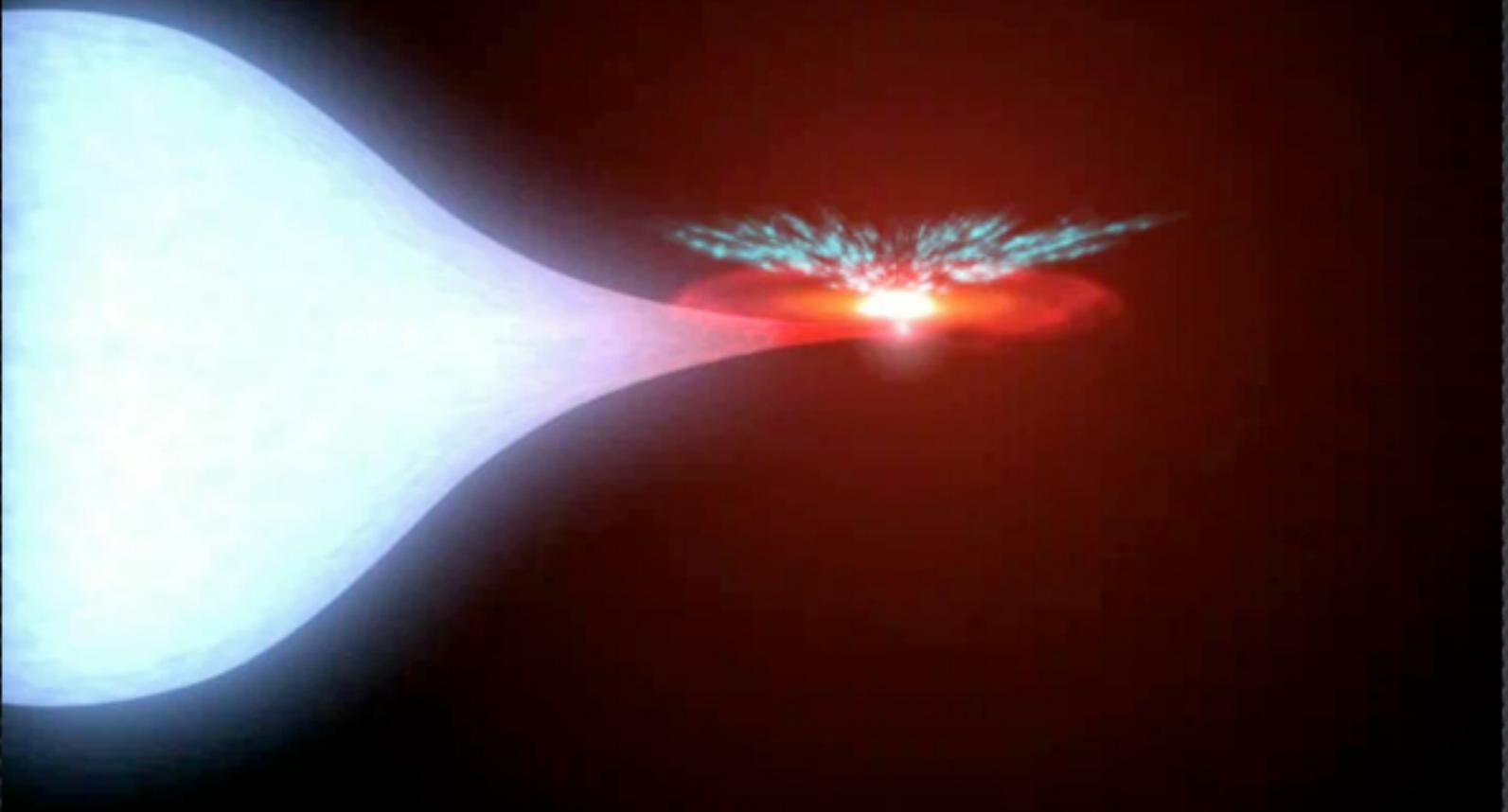
- Directly Resolving the BH Silhouette

- e.g. Sgr A\* with sub-mm/mm VLBI



Noble et al. 2007, Mościbrodzka et al 2009, Broderick et al 2006-2009, Doeleman et al. 2009

# Black Hole X-ray Binaries



$$M_{\text{BH}} \sim 10M_{\odot}$$

$$\dot{L} \sim 0.1 \dot{M} c^2$$

$$L \sim 10^{38} \text{ erg/s}$$

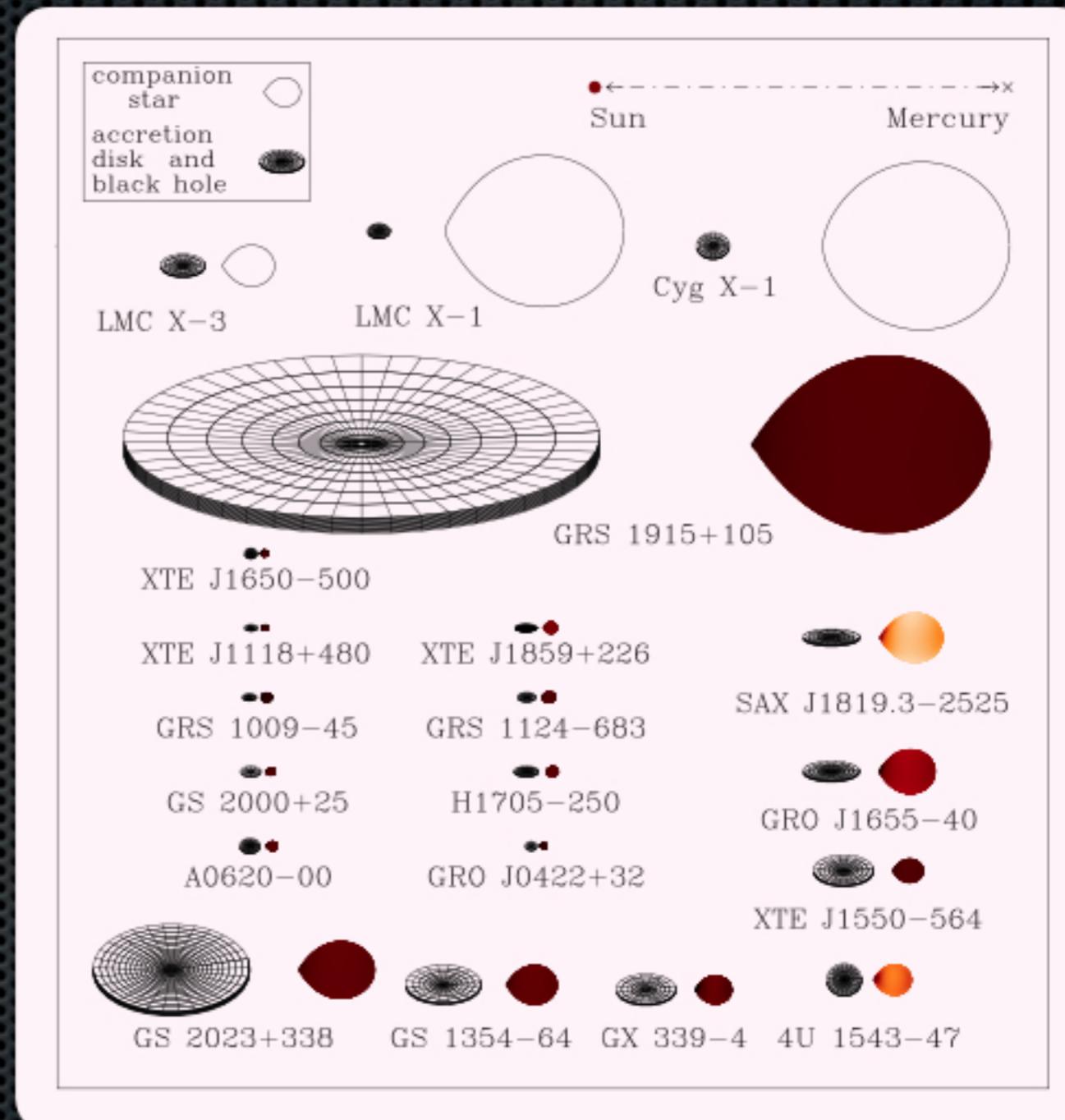
$$T_{\text{max}} \sim 1 \text{ keV}$$

- Black hole X-ray binaries exhibit rich phenomena
- X-ray hot matter serves as spacetime surveyor
  - Black holes uniquely parameterized by mass ( $M$ ) and spin ( $a$ ) in GR
  - Test GR, e.g.,  $|a/M| > 1$  ?
  - Constraints on SN models, re: nascent spin/masses of their product BHs
  - BH spin evolution, mass distribution --> important for establishing population models of GW events (e.g., LIGO, VIRGO,...)

- Useful for understanding high-energy physics in strong-field gravity
- How do really hot plasmas operate near extreme gravitational curvature? (these are but a few places in the universe at these extremes)
- Nearby jet laboratories (microquasars, e.g., GRS 1915+105)
- Many results carry over to AGN physics as well

# Black Hole X-ray Binaries

- 41 BHB suspects
  - 21 have dynamically confirmed masses
  - 3 are persistent, “High Mass” BHBs (Cyg X-1, LMC X-1, LMC X-3)
  - Remainder are intermittent
    - e.g. GRS 1915+105 “turned on” in 1992
  - $R_{\text{disk}} \sim R_{\odot} \sim 10^5 r_g$
  - Mass function
- $$f(M) = \frac{P_{\text{orb}} K_2^3}{2\pi G} = \frac{M_{\text{BH}} \sin^3 i}{(1 + M_{\star}/M_{\text{BH}})^2}$$
- $M_{\text{BH}} \gtrsim 3M_{\odot}$
  - Neutron stars “ruled out” for most BHBs via mass function limit and because BHBs lack surface emission



# Disk “Dichotomy”

- Shakura & Sunyaev (1973)
- Novikov & Thorne (1973)
- Page & Thorne (1974)

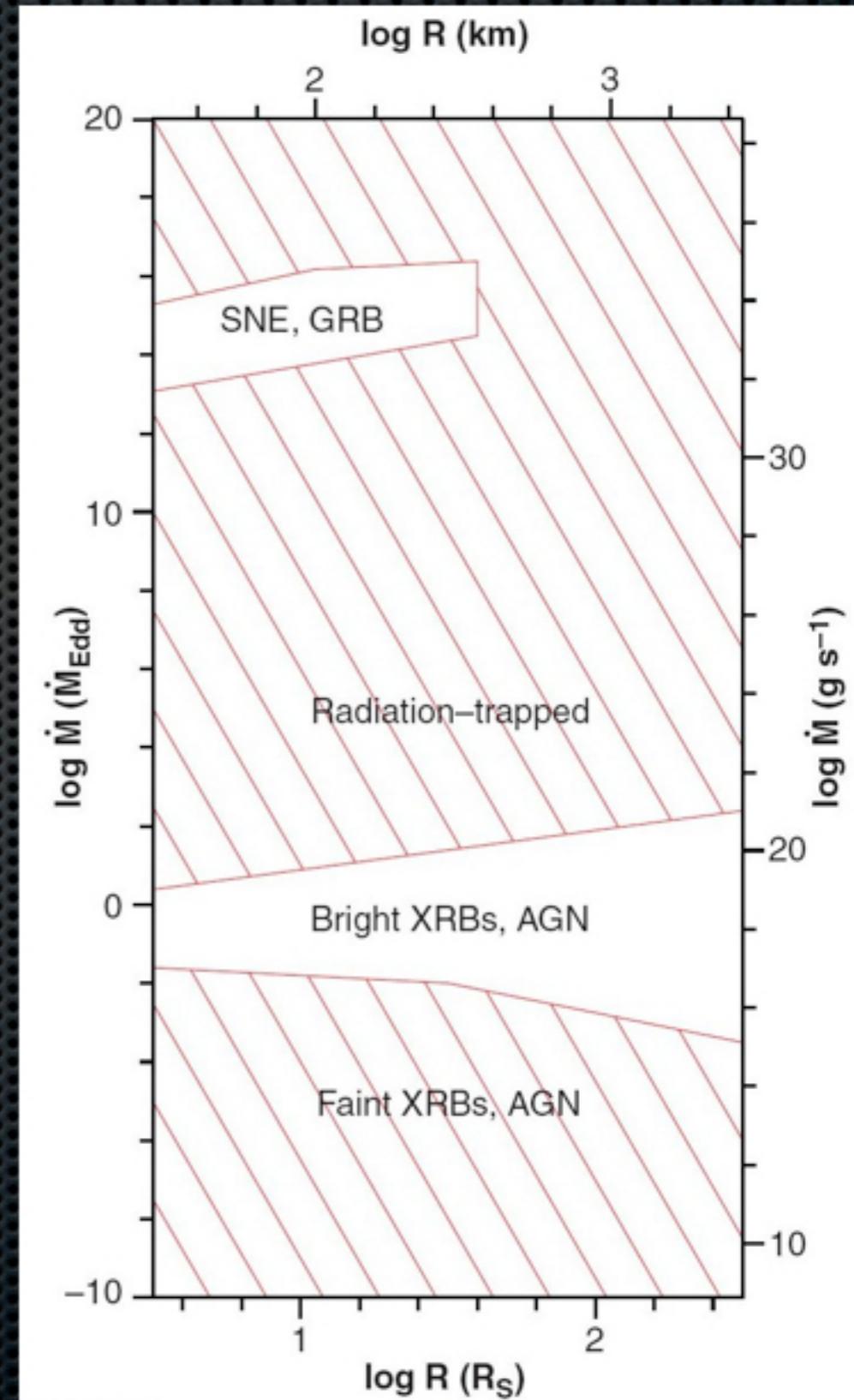
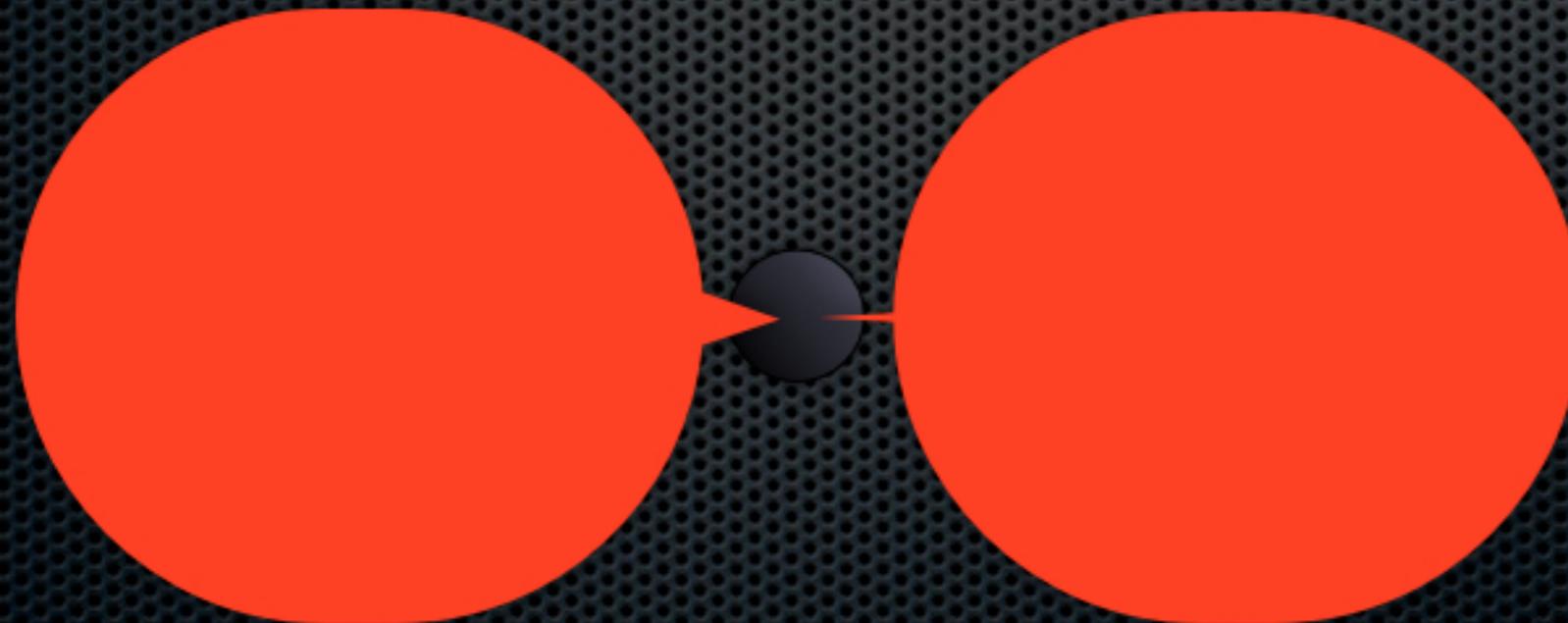
## Thin Disks:

- Dissipation Rate < Cooling Rate
- “Cold”, Optically Thick
- Thermal or Multi-temperature black body



## Thick Disks:

- Dissipation Rate > Cooling Rate
- “Hot”, optically thin, outflows
- 2 Temperature flow, advected heat



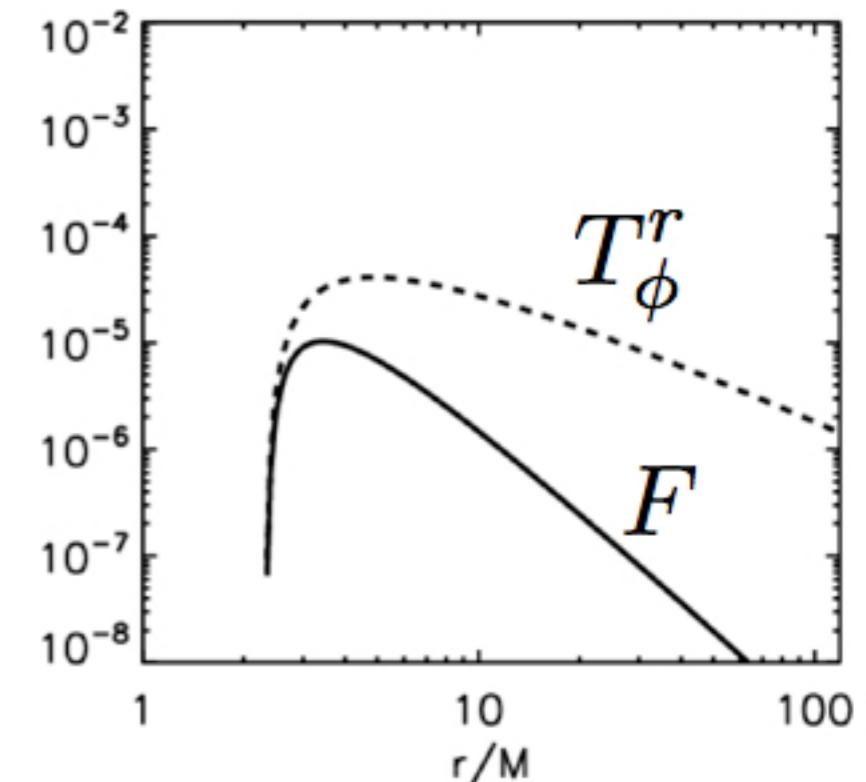
Narayan & Quataert (2005)

# Steady-state Thin Disk Models

Novikov & Thorne (1973)

$$L = \eta \dot{M} c^2$$
$$\eta = 1 - \epsilon_{\text{ISCO}}$$

- Stationary gravity
- Perfect radiator
- Work done by stress locally dissipated & radiated
- Zero stress at ISCO as boundary condition
- Luminosity as total liberation of binding energy up until plunge into ISCO



Shakura & Sunyaev (1973)

$$T_\phi^r = -\alpha P \quad P = \rho c_s^2$$

$$t_\phi^r = -\alpha c_s^2$$

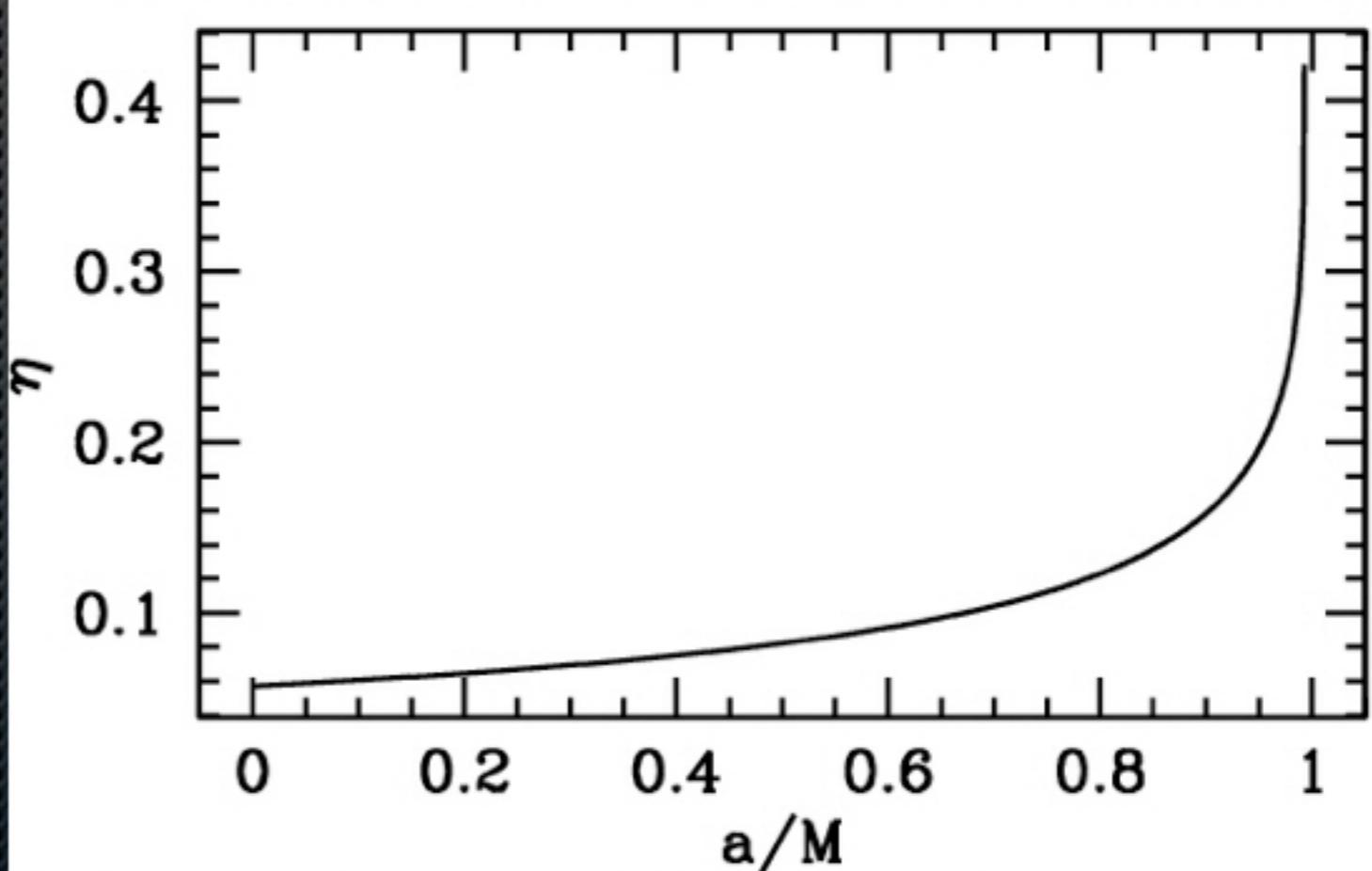
No stress at sonic point:

$$\rightarrow R_{\text{in}} = R_s \simeq R_{\text{ISCO}}$$

Muchotzeb & Paczynski (1982)

Abramowicz et al. (1988)

Afshordi & Paczynski (2003)



<sup>2</sup> It is conceivable that the disk material might contain extremely strong magnetic fields, and that these fields might transport a torque from the infalling material at  $r < r_{\text{ms}}$  to the disk at  $r \geq r_{\text{ms}}$ . In this case the boundary condition at  $r_{\text{ms}}$  would be modified, and the solution for  $f$  would be changed. It seems to us unlikely that the changes would be substantial, except very near  $r_{\text{ms}}$  (i.e., at  $r - r_{\text{ms}} \lesssim 0.1r_{\text{ms}}$ ). But when constructing explicit disk models, one should examine this possibility carefully.

## Page & Thorne (1974)

In these three cases it seems almost certain that the ultimate, limiting value of  $a_*$  will not exceed our value of 0.998—and, hence, that the efficiency for converting rest mass into escaping radiation will not exceed 30 percent.

Other ways in which our assumptions may fail are these:

- i) Magnetic fields attached to the disk may reach into the horizon, producing a torque on the hole (Ya. B. Zel'dovich and V. F. Schwartzman, private communication).
- ii) The disk will recapture some of the photons it emits, thereby preventing them from going down the hole.
- iii) The time-averaged, radial disk structure will be changed by photon recapture and resultant heating, and by magnetic torques that couple the innermost parts of the disk to the hole and couple them to matter that has fallen out of the disk and is plunging down the hole. The result will be deviations of the emitted photon flux  $F(r)$  from the law derived in Paper I, and deviations of the specific energy and angular momentum of the infalling matter from  $E^+_{\text{ms}}$  and  $L^+_{\text{ms}}$ .

## Thorne (1974)

### Gammie (1999)

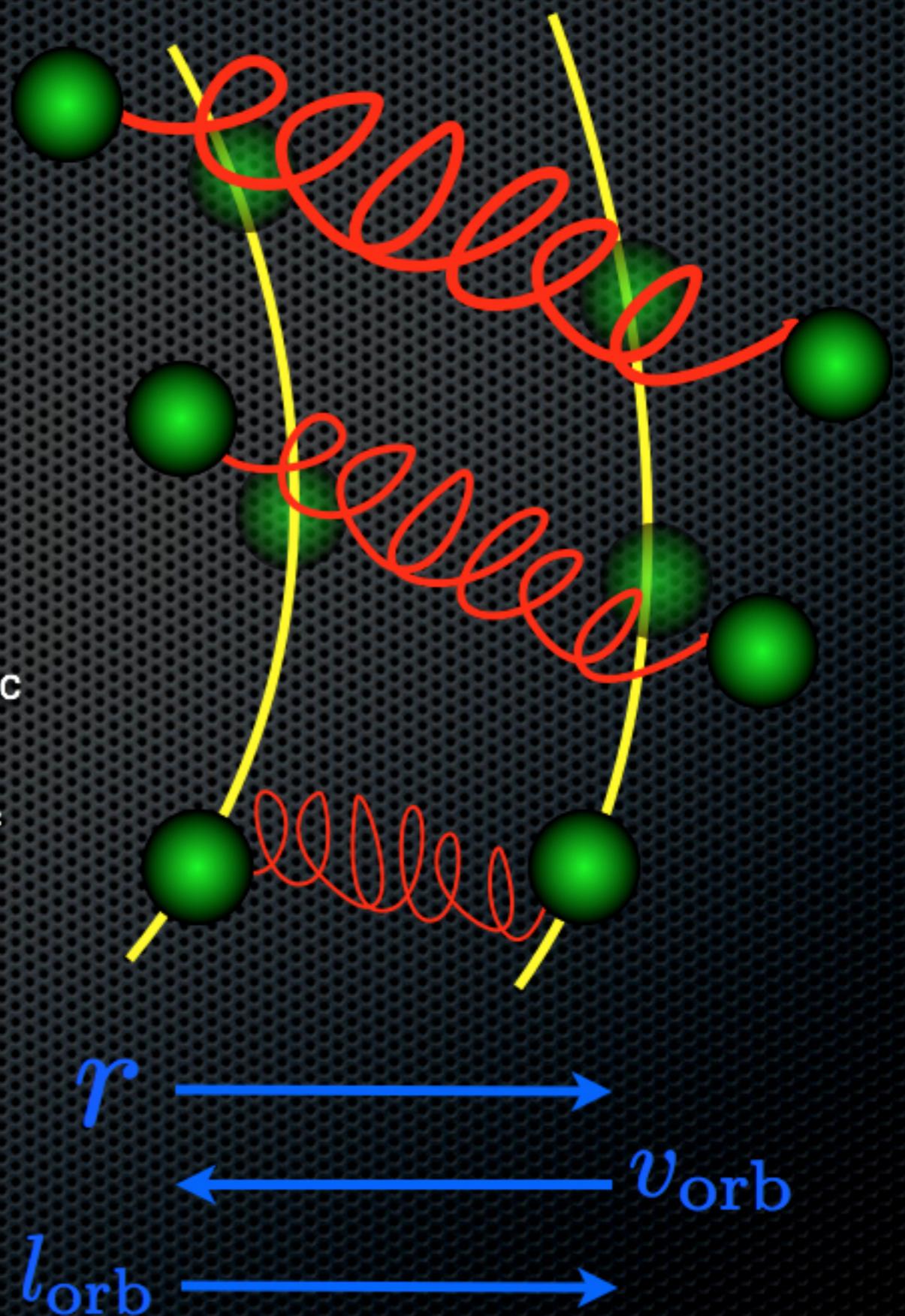
- Magnetized inflow model matched to thin disk
- Efficiency tied to mag. flux BC

### Agol & Krolik (2000)

- Magnetic torques at ISCO can affect radiative efficiency

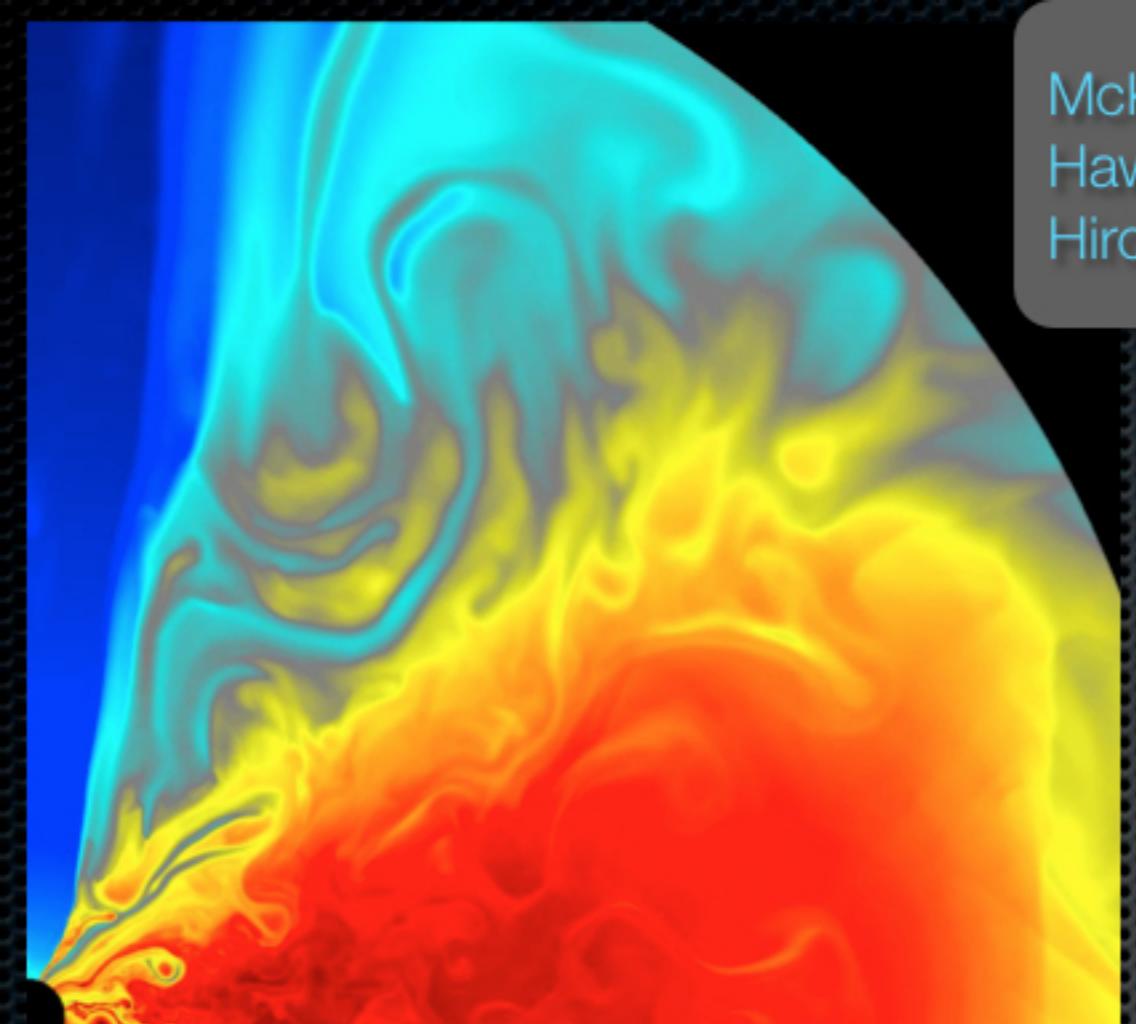
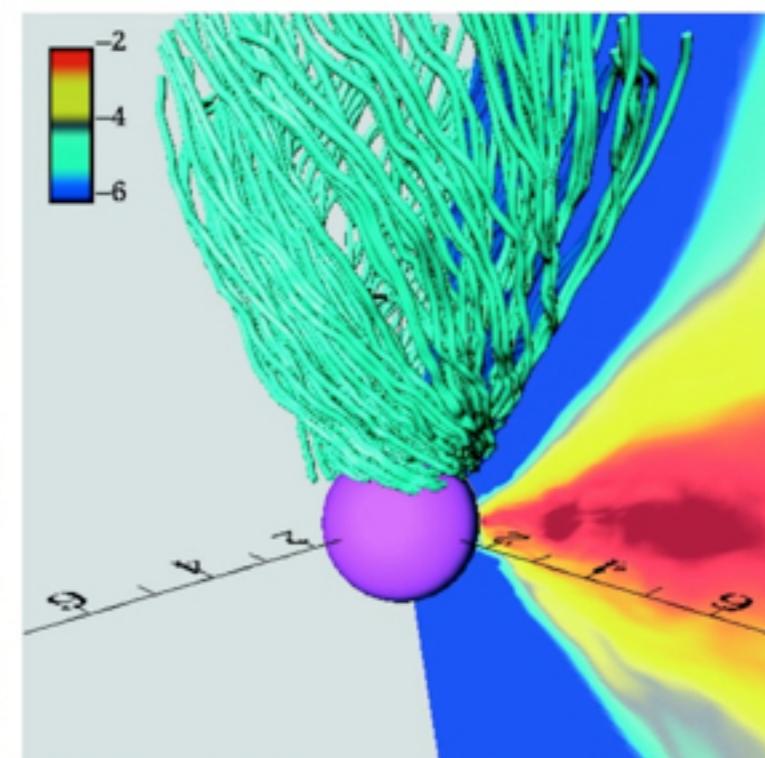
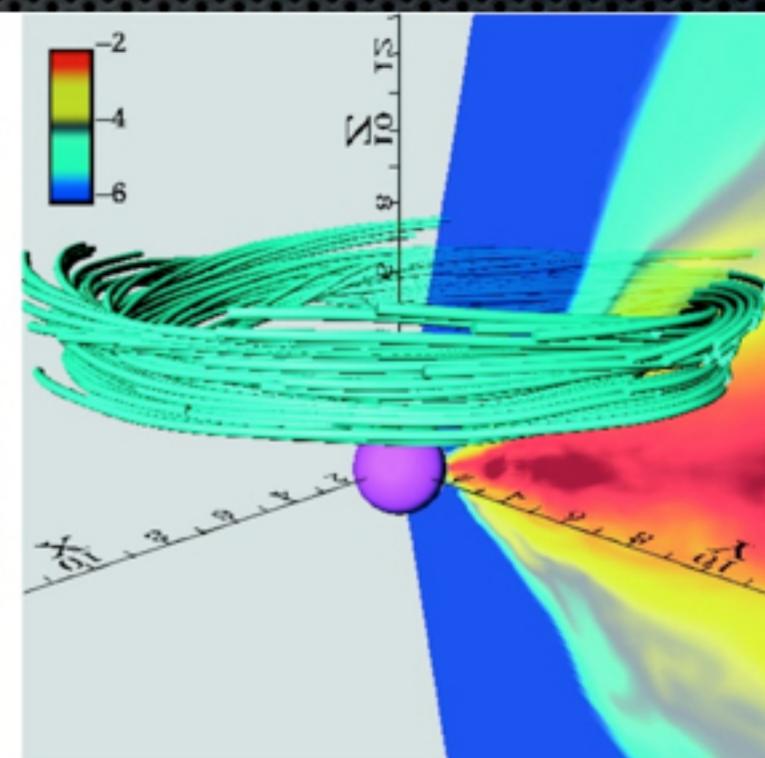
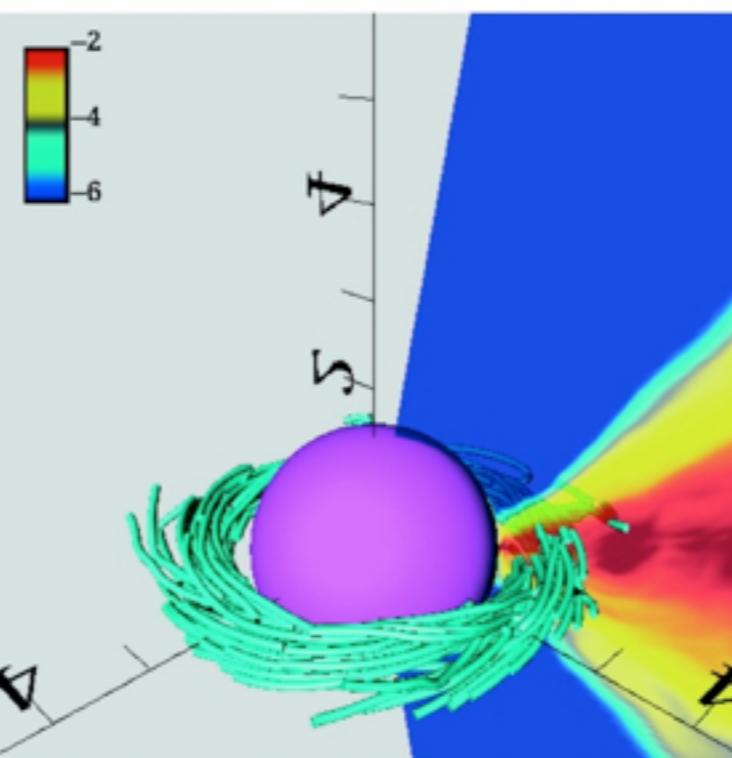
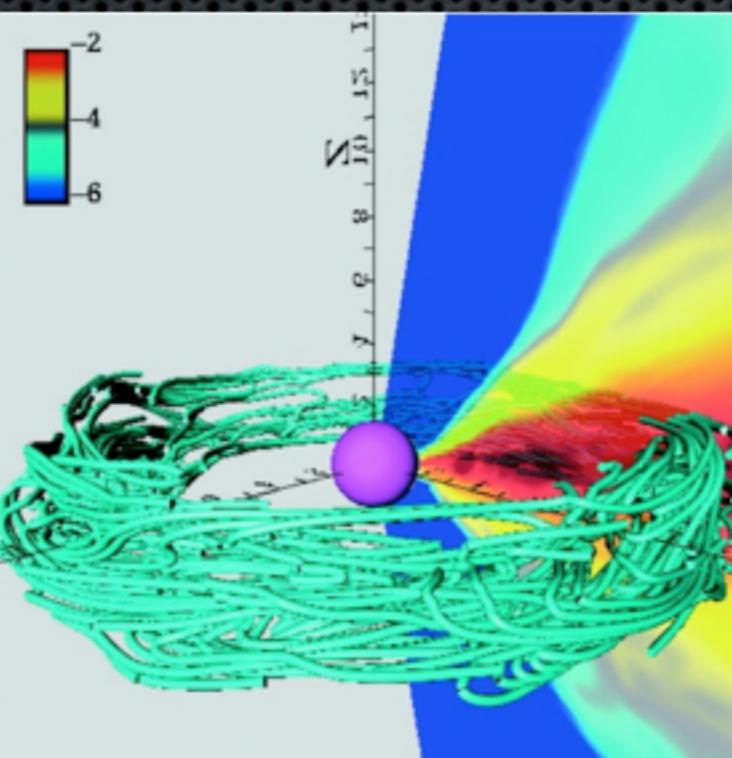
# Magneto-rotational Instability (MRI)

- Velikhov (1959)
- Chandrasekhar (1960)
- 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.
- Fastest instability known that feeds off free energy of differential rotation.
- Sustained turbulence only in 3D



# GRMHD Simulations

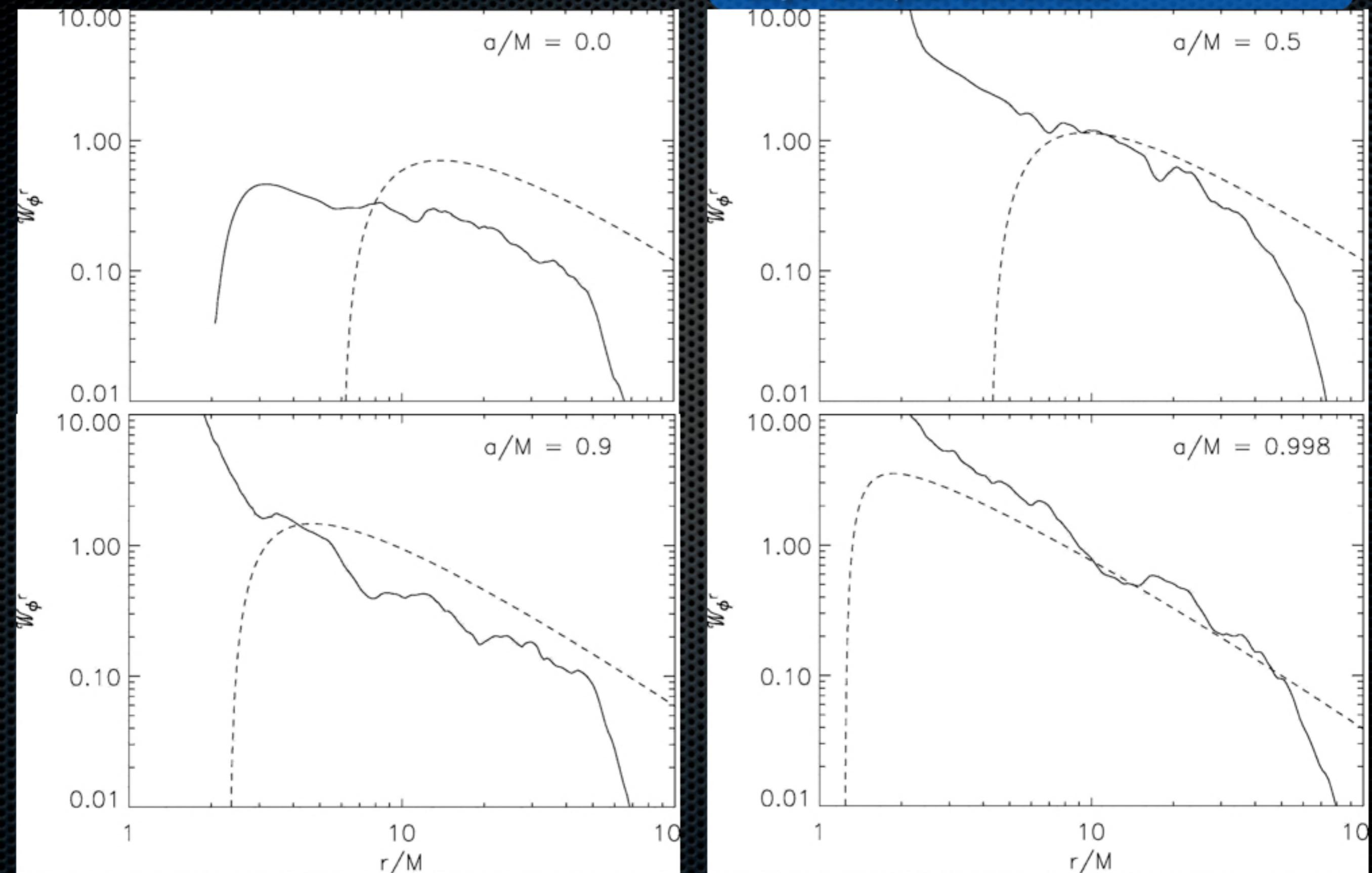
Hirose et al. (2004)



McKinney & Gammie (2004)  
Hawley, De Villiers, Krolik,  
Hirose 2003+

## Krolik, Hawley & Hirose (2005)

- Non-conservative --> uncontrolled cooling
- 3D GRMHD
- $H/R \sim 0.1 - 0.17$
- Boyer-Lindquist Coordinates



$$r \in [ < r_{\text{hor}}, 120M ] \quad \theta \in \pi [\delta, 1 - \delta] \quad \phi \in [0, \pi/2]$$

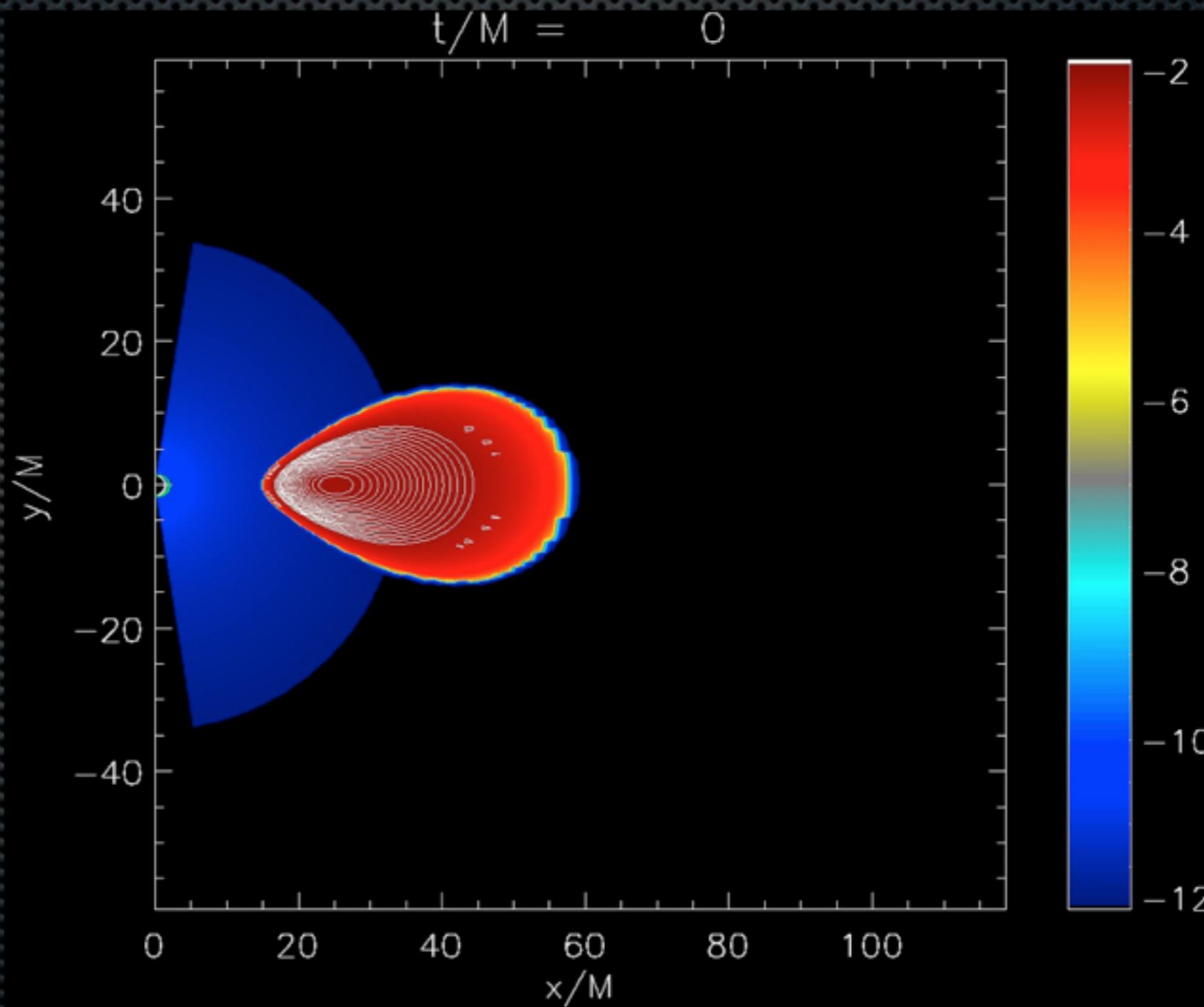
- **HARM3D:**

- Based on Gammie's Harm (2D) and HAM (non-rel) codes
- 3D Ideal GRMHD
- Kerr-Schild coordinates
- Modern high-res. shock-capturing methods
- Flux (energy) conserving
- Constrained Transport scheme
- Optically-thin cooling function
- Maintains constant H/R
- Cooling on orbital timescale

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

$$\mathcal{L} = \Omega_K \ u \ \Delta^q$$

$$T_o = \frac{\pi}{2} \left( \frac{H}{r} r \Omega_K \right)^2$$



$$r \in [ < r_{\text{hor}}, 120M ] \quad \theta \in \pi [\delta, 1 - \delta] \quad \phi \in [0, \pi/2]$$

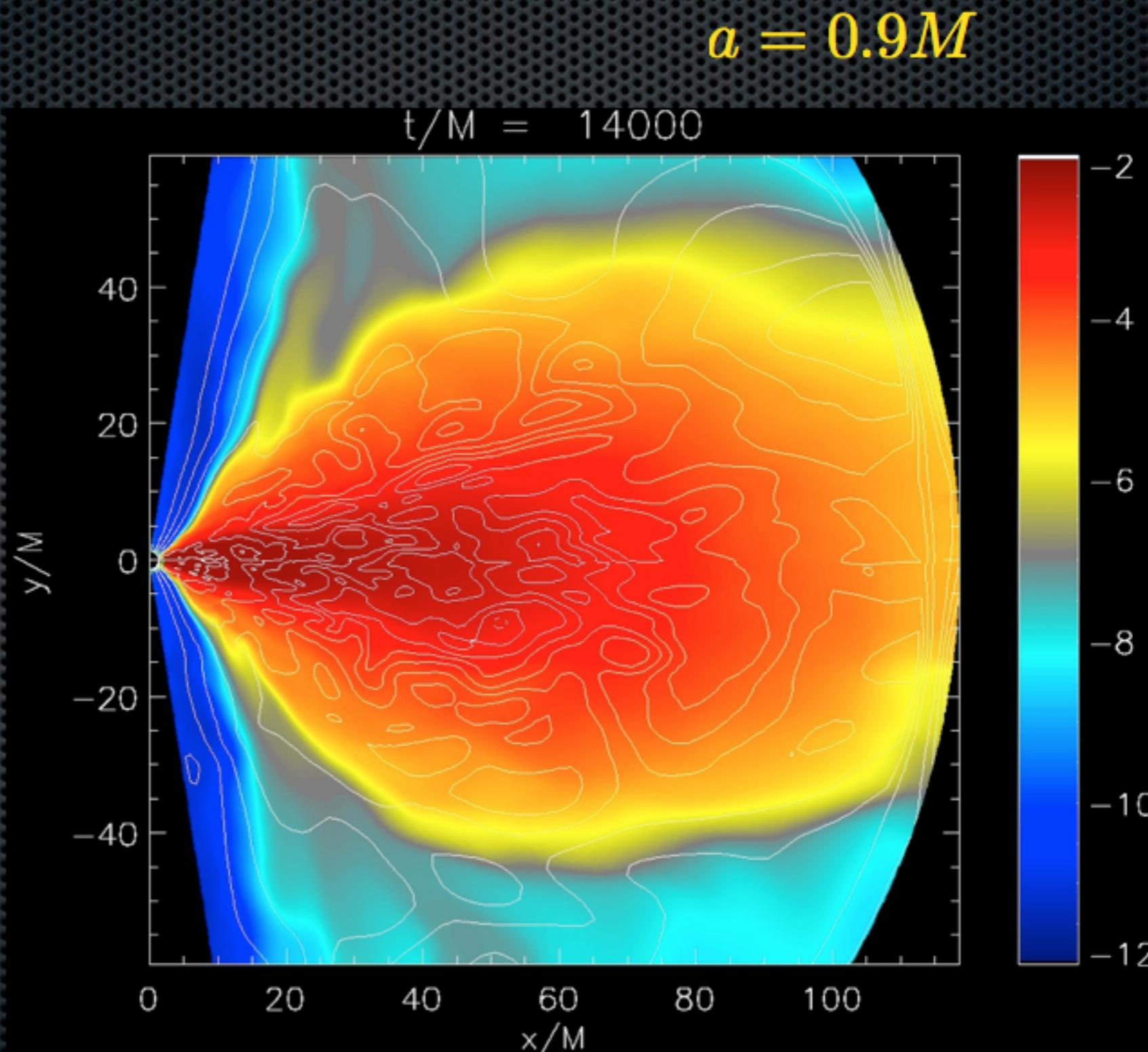
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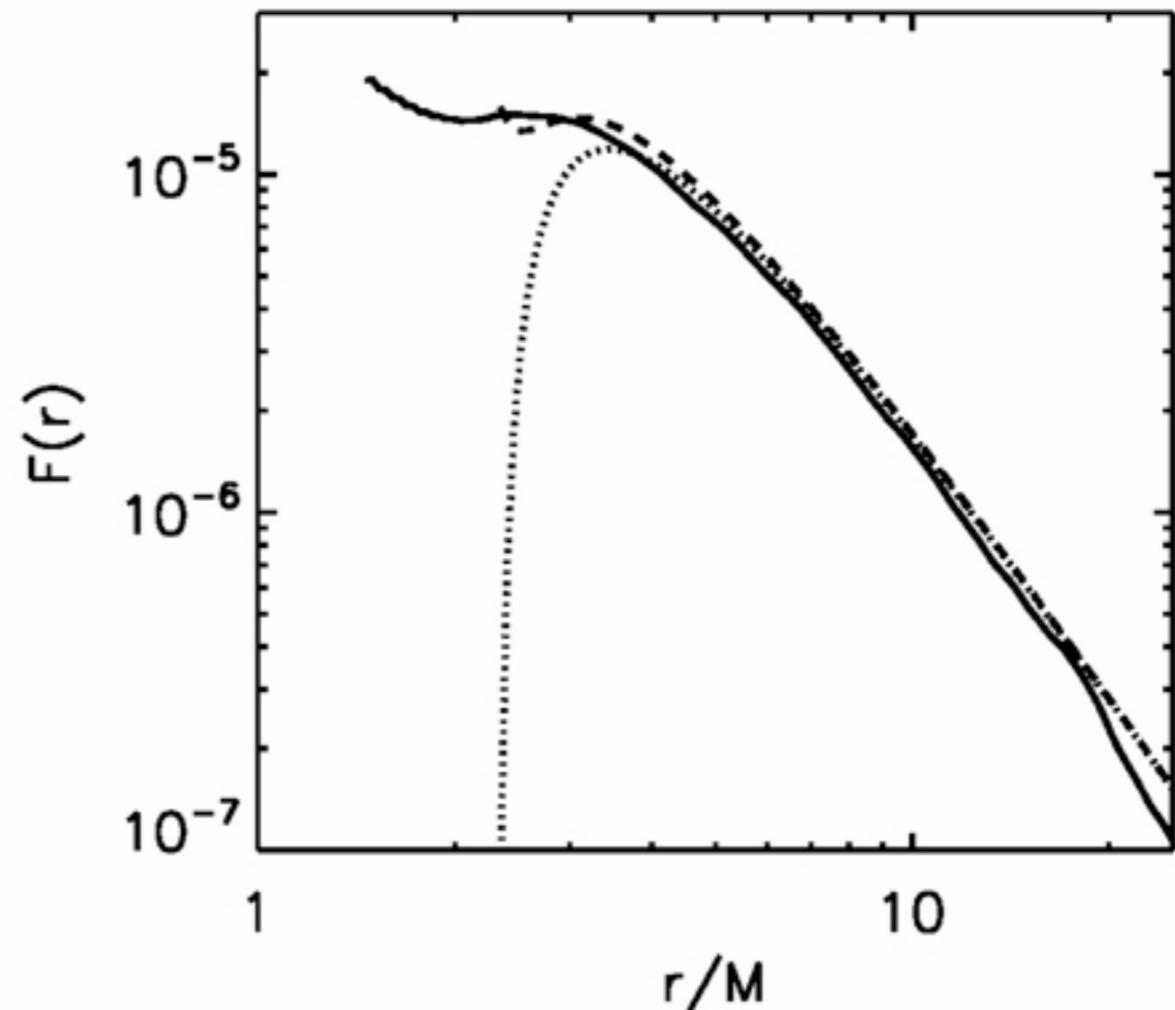
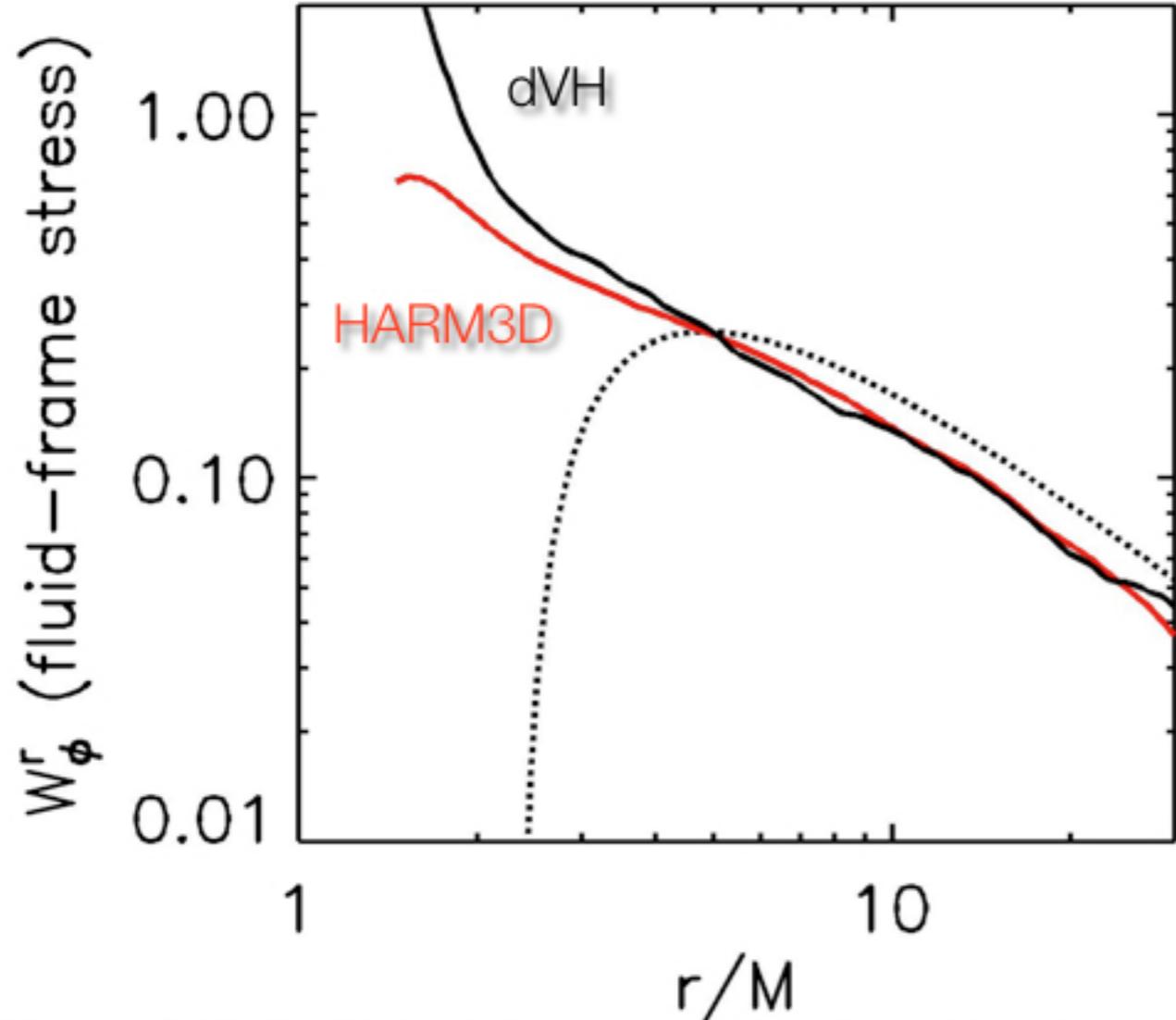
$$\nabla_\mu T^\mu{}_\nu = -\mathcal{L} u_\nu$$

$$\mathcal{L} = \Omega_K \ u \ \Delta^q$$

$$T_o = \frac{\pi}{2} \left( \frac{H}{r} r \Omega_K \right)^2$$



# Comparison to NT



- Retained Heat  $\rightarrow$  Stress Deficit
- Continuity through the ISCO

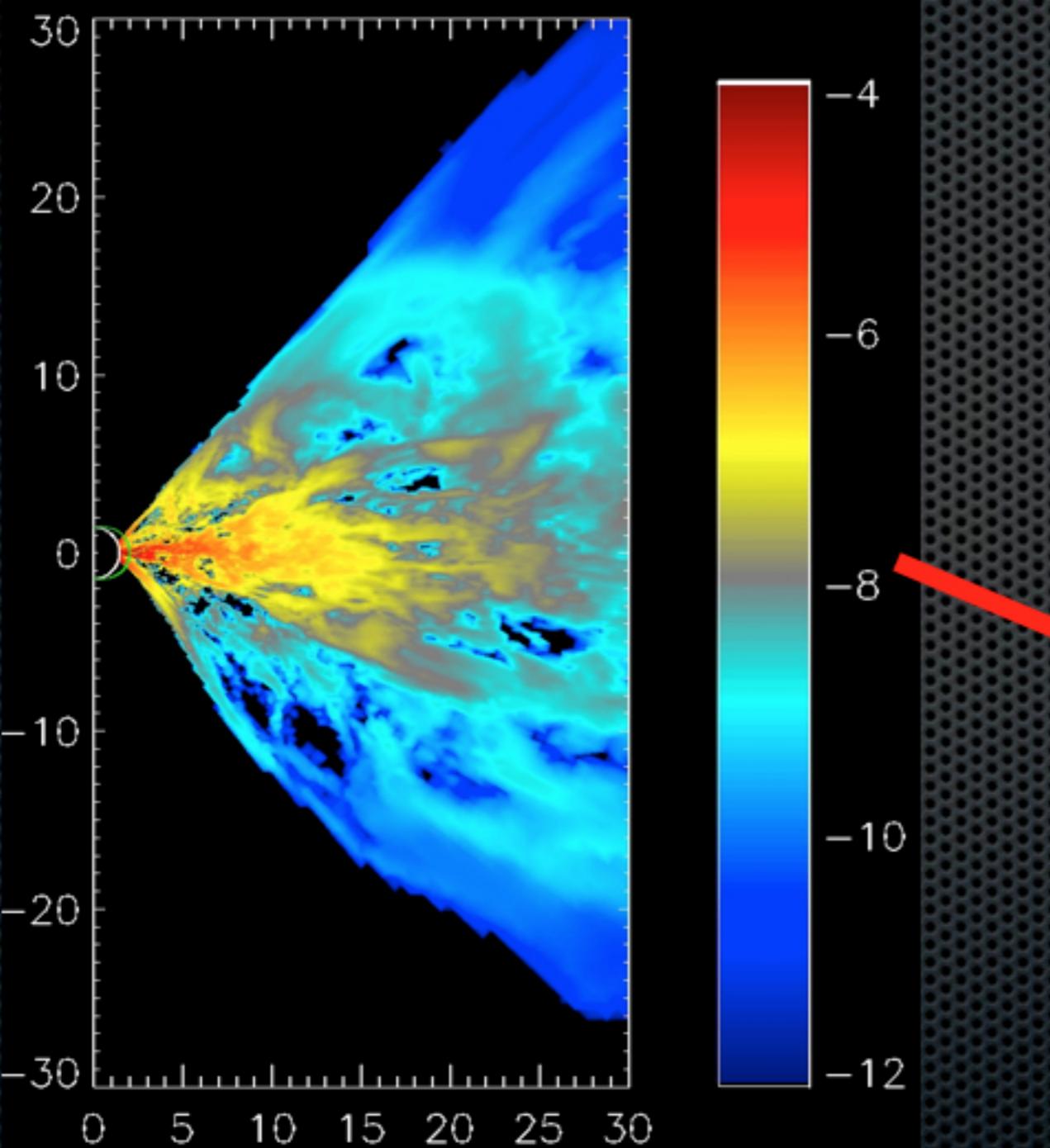
- Fits approx. to Agol & Krolik (2000)  
 $\Delta\eta = 0.01$     $\Delta\eta/\eta = 7\%$
- ~5% flux deficit at all radii
  - Due to retained thermal and magnetic energy densities.

# GR Radiative Transfer

$$\frac{d}{d\lambda} \left( I_\nu / \nu^3 \right) = j_\nu / \nu^2$$

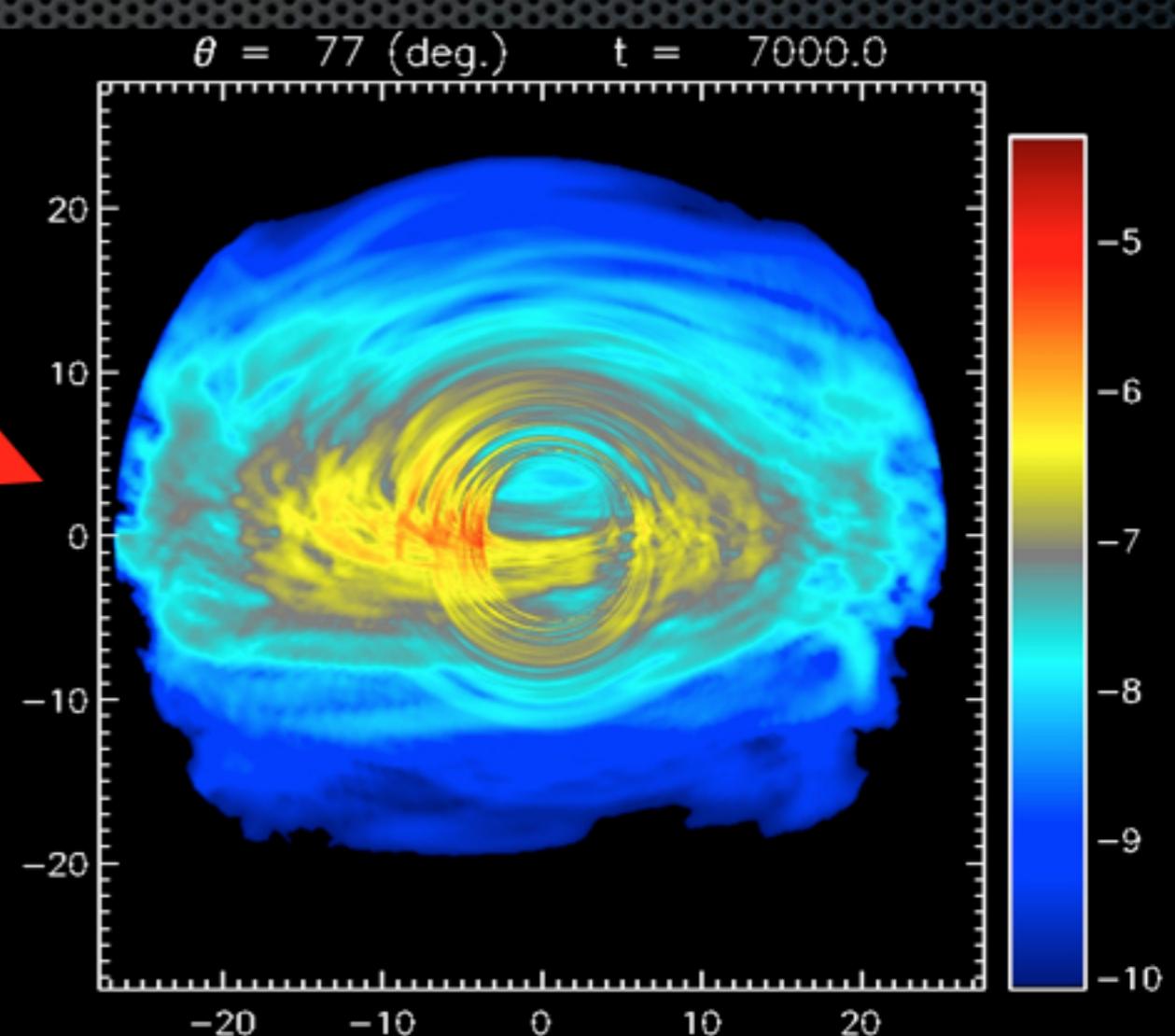
$$j_\nu = \mathcal{L} / 4\pi$$

$t = 7000.$

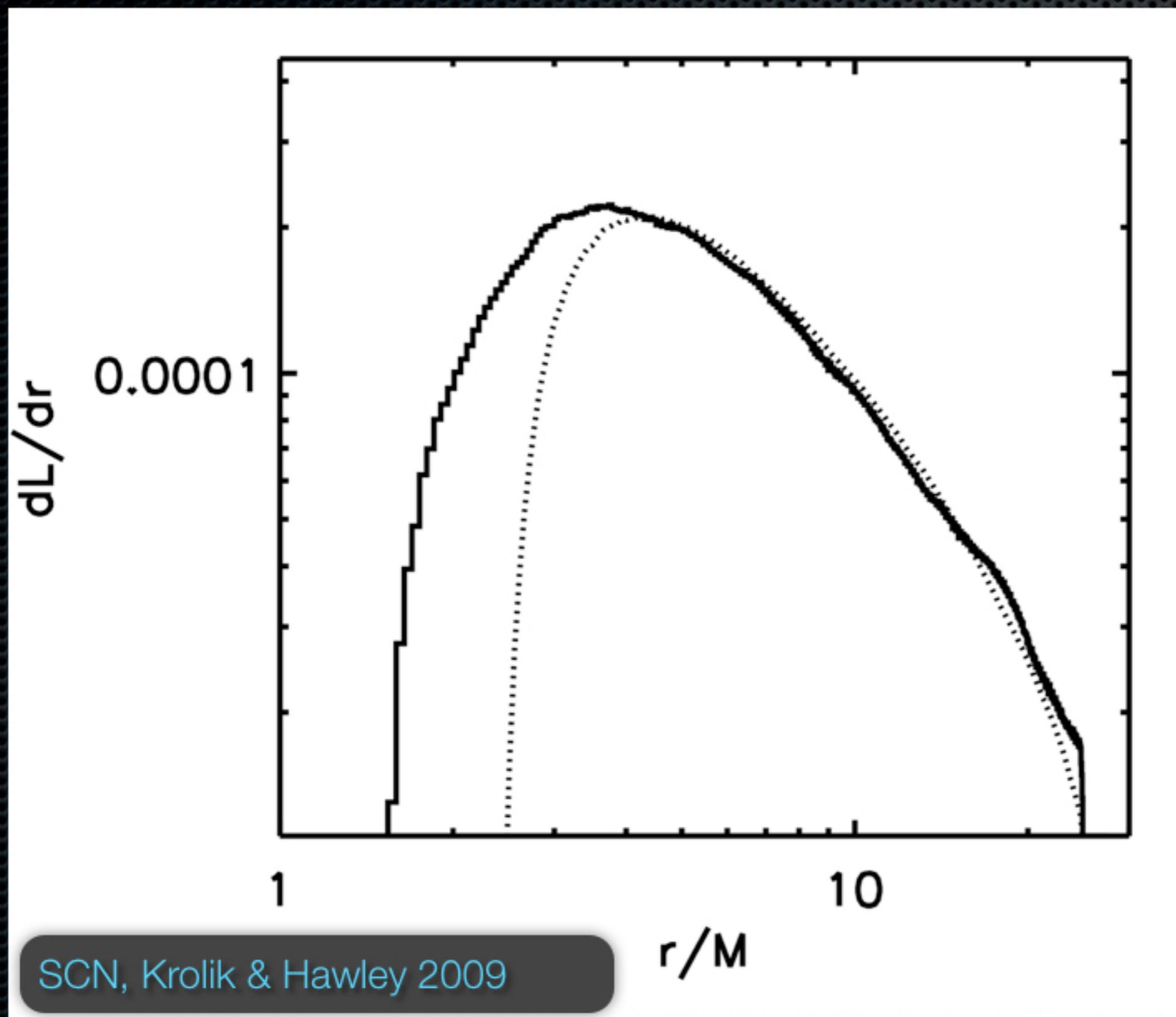


- GR geodesic integration
- Doppler shift
- Gravitational redshift
- Relativistic beaming
- Interpolates simulation data in space & time

Allows us to explore dependence on time and disk orientation on the sky.



# Angle & Time Average Bolometric Luminosity Profile



$$L = \eta \dot{M} c^2$$

$$\eta_{\text{NT}} = 0.143$$

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

$$\Delta T_{\max}/T_{\max} = 7\%$$

$$\Delta R_{\text{in}}/R_{\text{in}} = 80\%$$

$$T \rightarrow 0 : \Delta\eta/\eta = 20\%$$

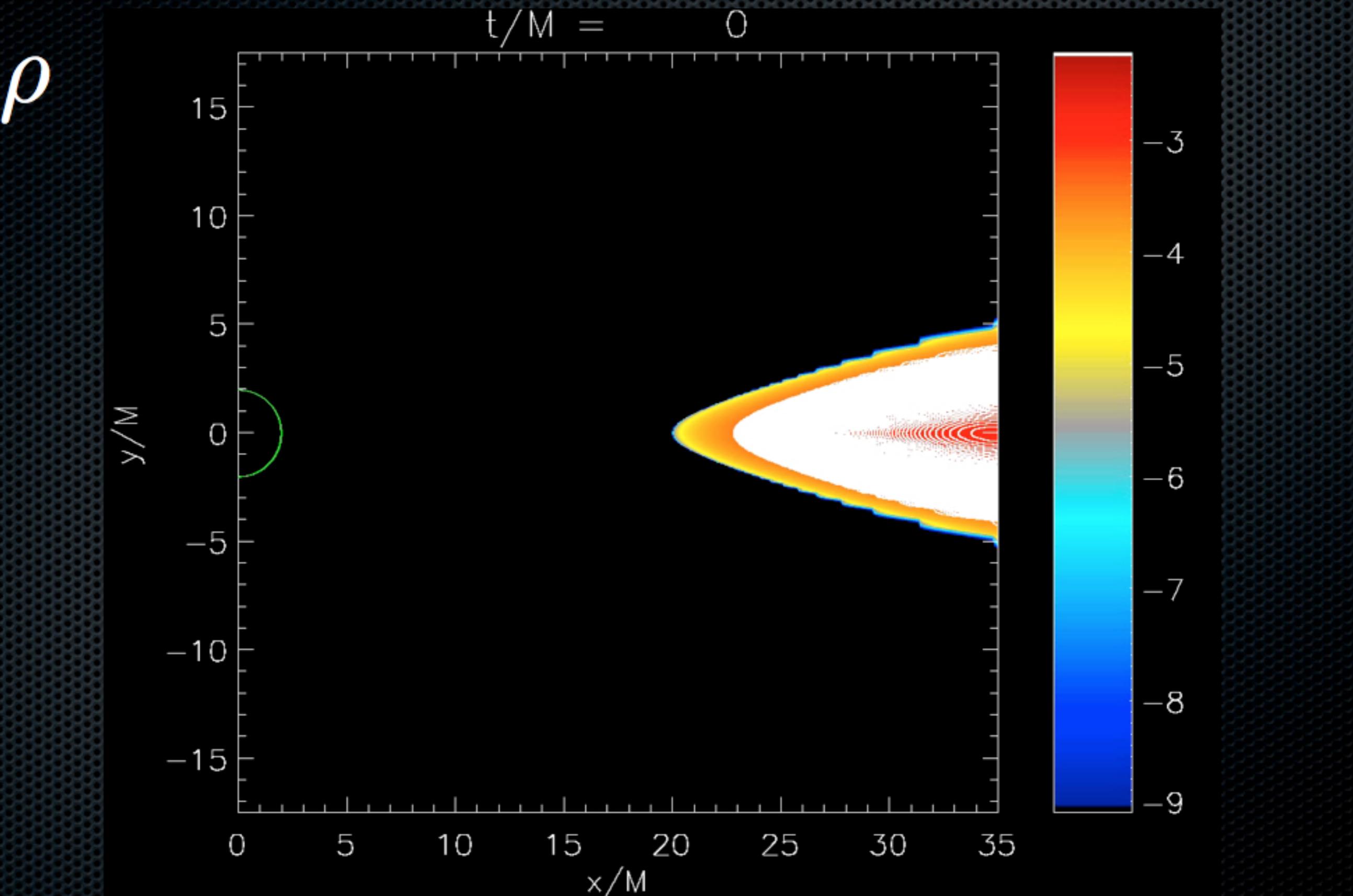
Suggests previous spectral fits may overestimate spin.

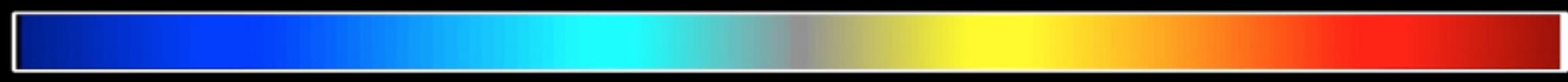
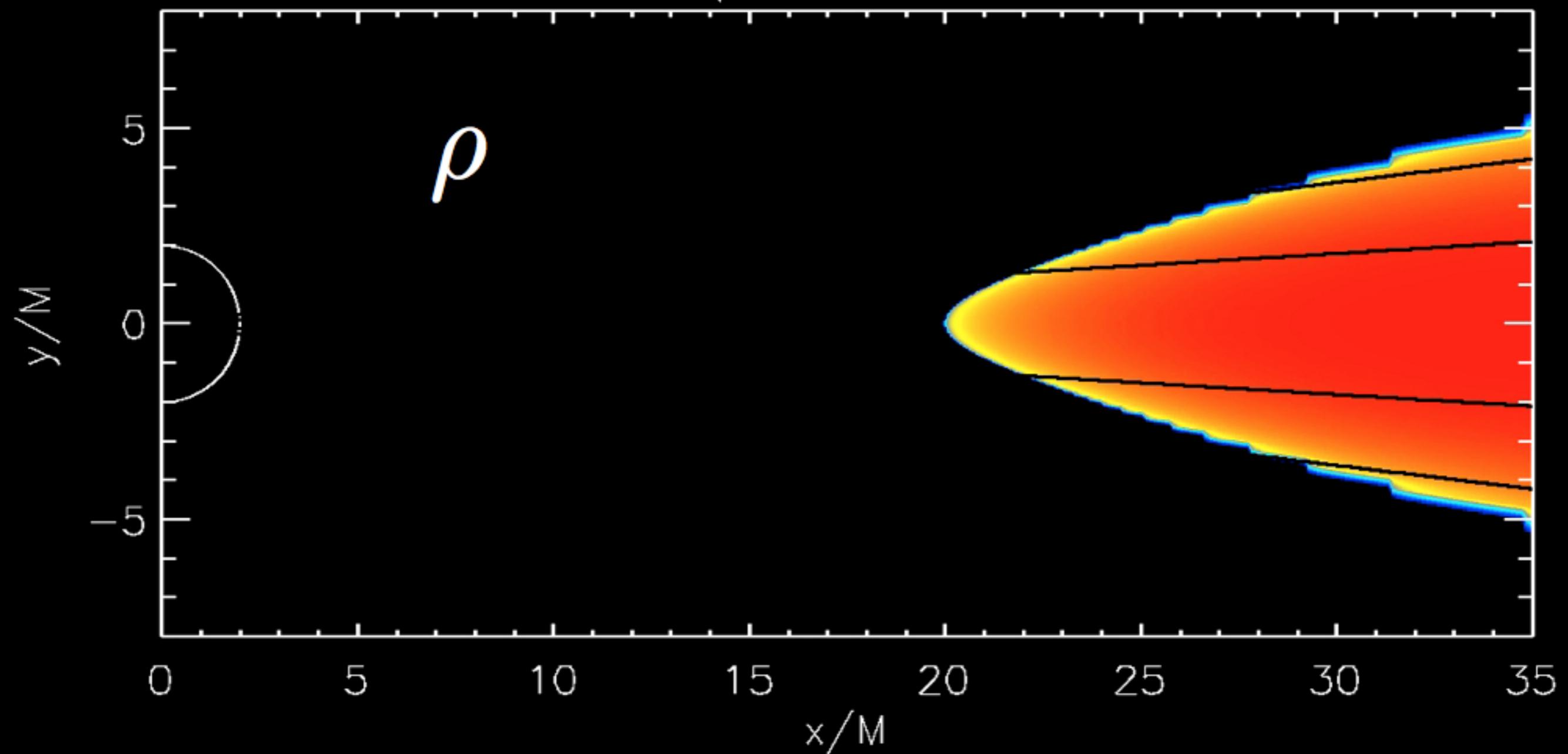
NT model may underestimate luminosity in some disks.

|  | Original   | ThinHR     | MediumHR   | ThickHR    |
|--|------------|------------|------------|------------|
| <b>BH Spin</b>   | 0.9M       | 0          | 0          | 0          |
| <b>Resolution</b><br>$N_r \times N_\theta \times N_\phi$ | 192x192x64 | 912x160x64 | 512x160x64 | 348x160x64 |
| <b>Target H/R</b>  | 0.1        | 0.06       | 0.08       | 0.16       |
| <b>Actual H/R</b>  | 0.07-0.12  | 0.061      | 0.10       | 0.17       |
| <b>Init. Inner Edge</b>                                  | 15M        | 20M        | 20M        | 20M        |
| <b>Init. Radius of <math>P_{\max}</math></b>             | 25M        | 35M        | 35M        | 35M        |
| <b>Start at Target H/R?</b>                              | No         | Yes        | Yes        | Yes        |
| <b>N<sub>cells</sub> per H/R</b>                         | 15-30      | 81         | 103        | 74         |

### Motivation:

- Explore H/R dependence;
- Resolve height with >60 cells (Davis++ 2009) ;
- Attempt at isotropic dissipation with nearly cubical cells;

ThinHR:  $H/R = 0.06$  $912 \times 160 \times 64$  $a = 0M$ 

ThinHR:  $H/R = 0.06$  $912 \times 160 \times 64$  $a = 0M$  $t/M = 0.$ 

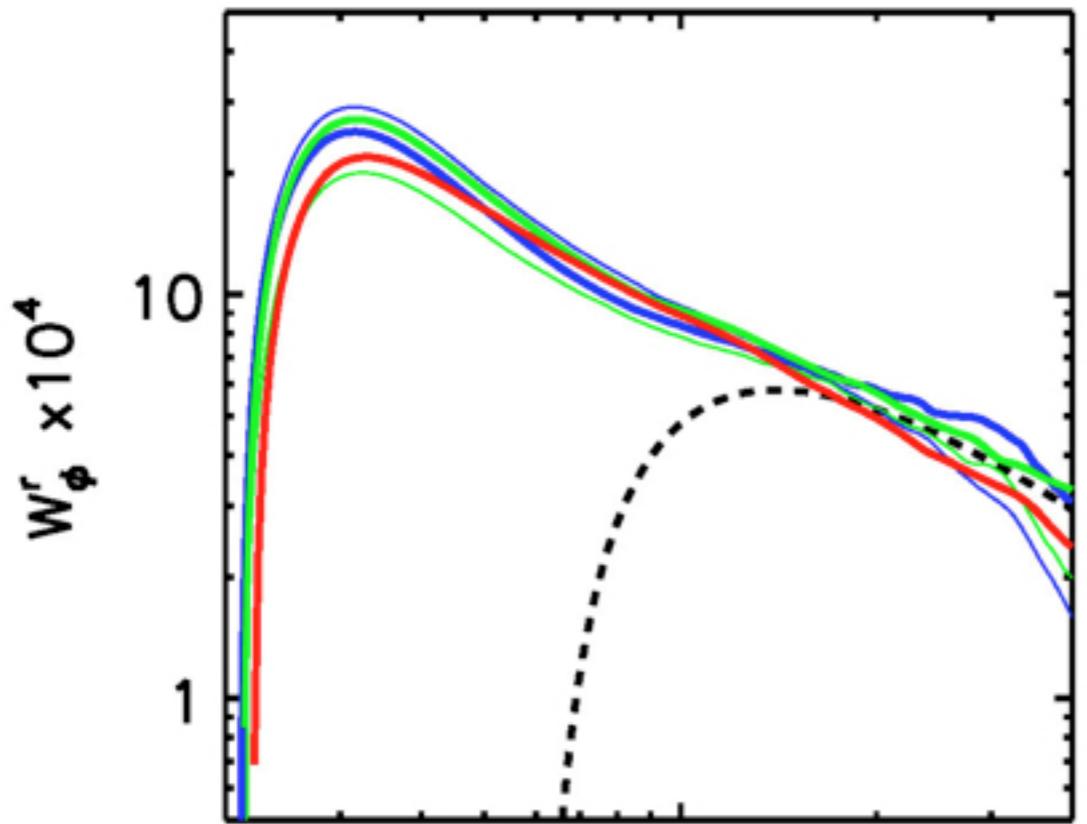
-10

-8

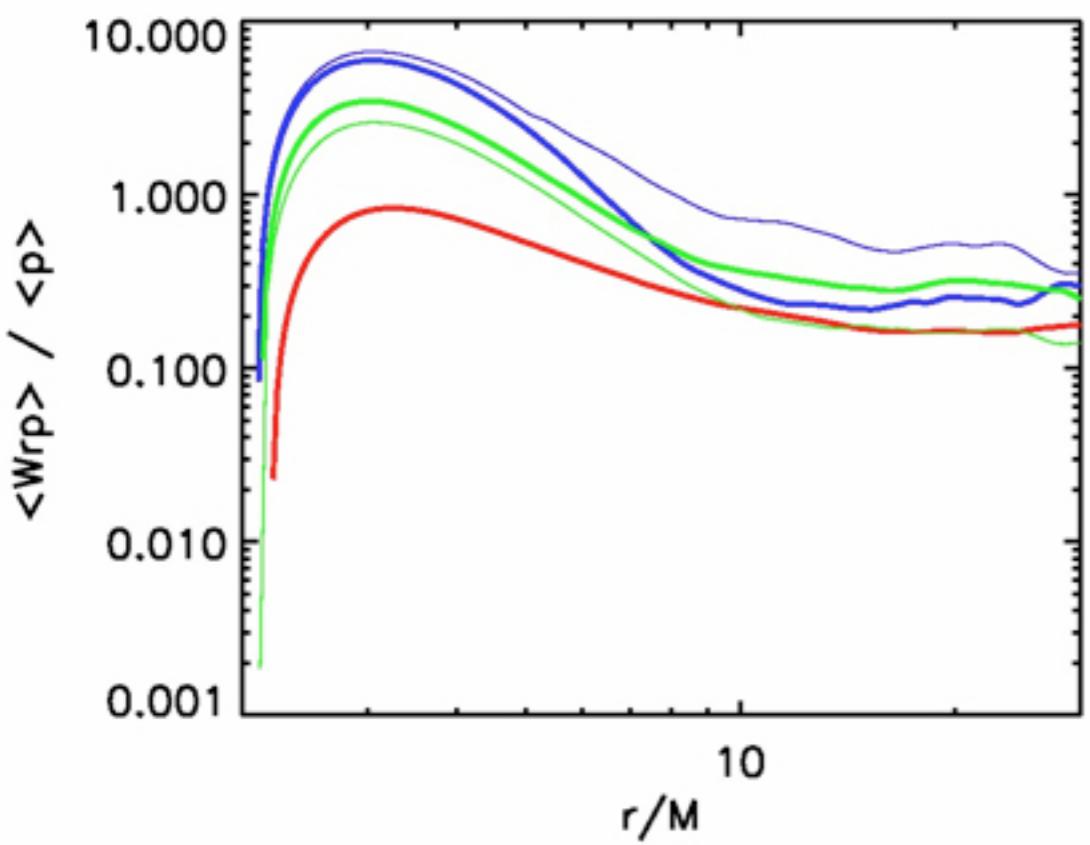
-6

-4

-2



$r/M$



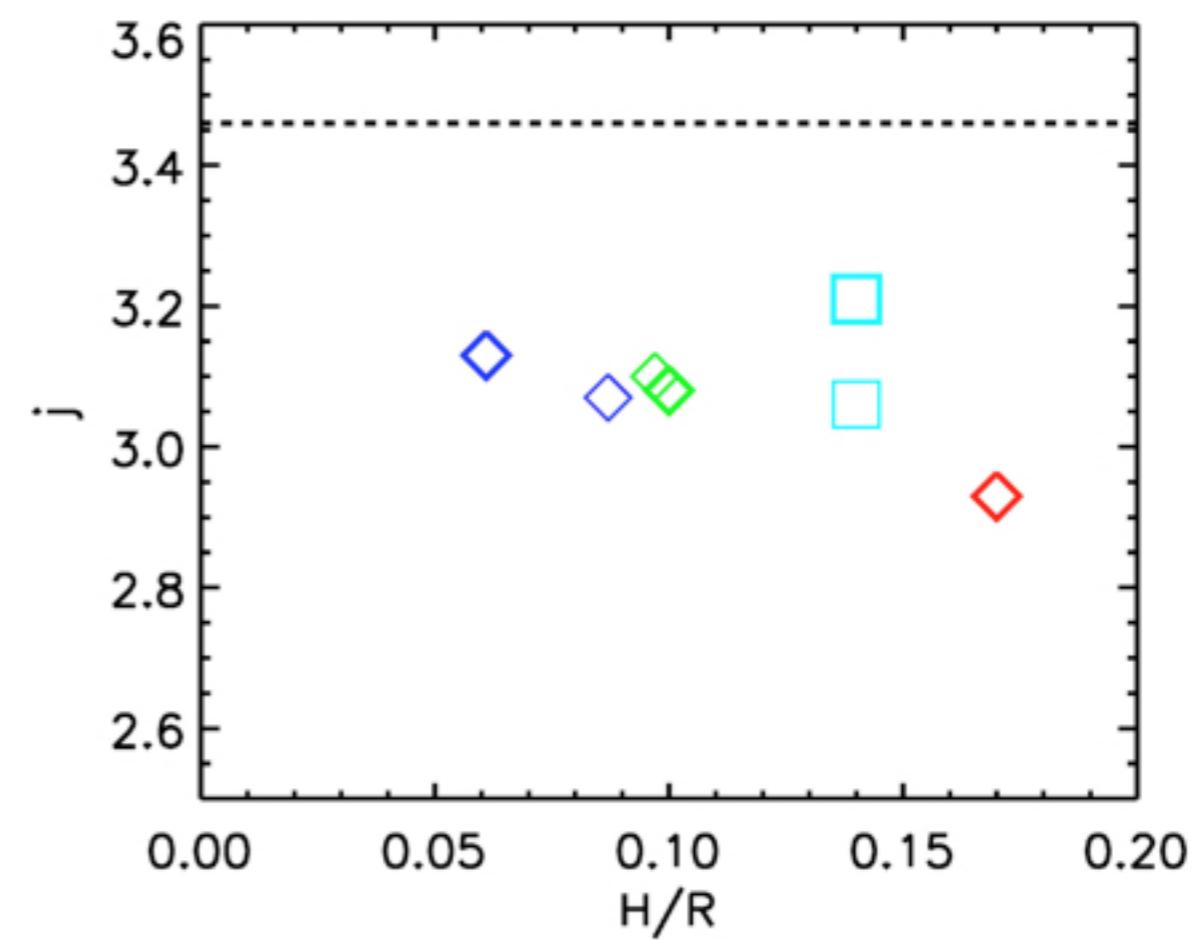
$r/M$

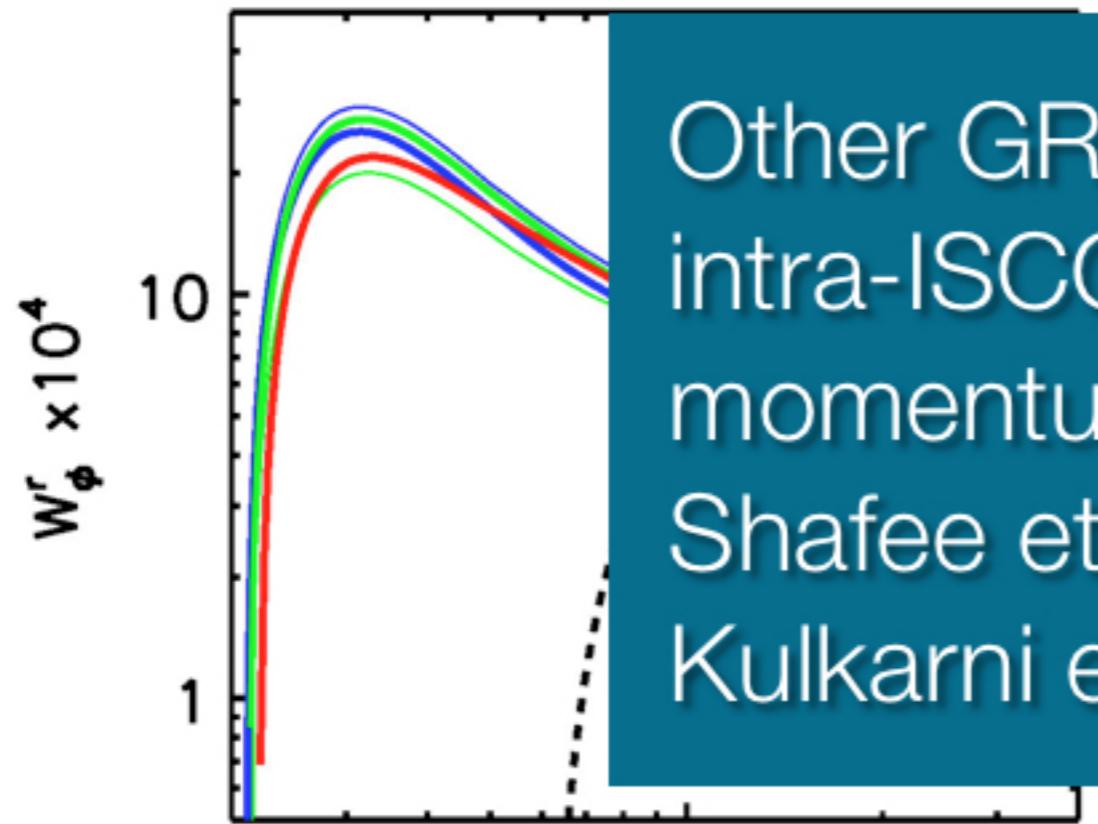
- No trend seen in Maxwell Stress
- Minor “sqrt” trend seen in spec. ang. mom.
- Due to additional Reynolds stress for thicker disks



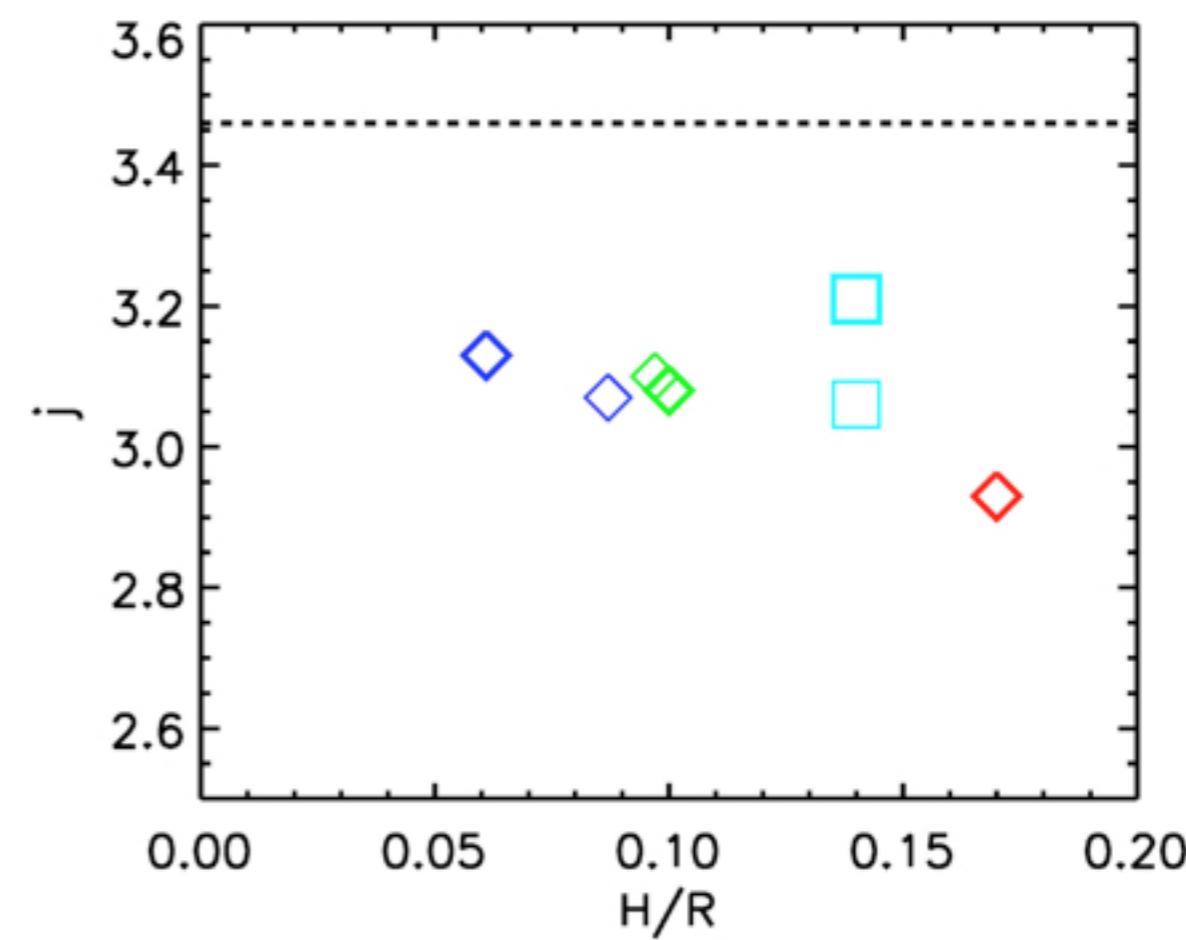
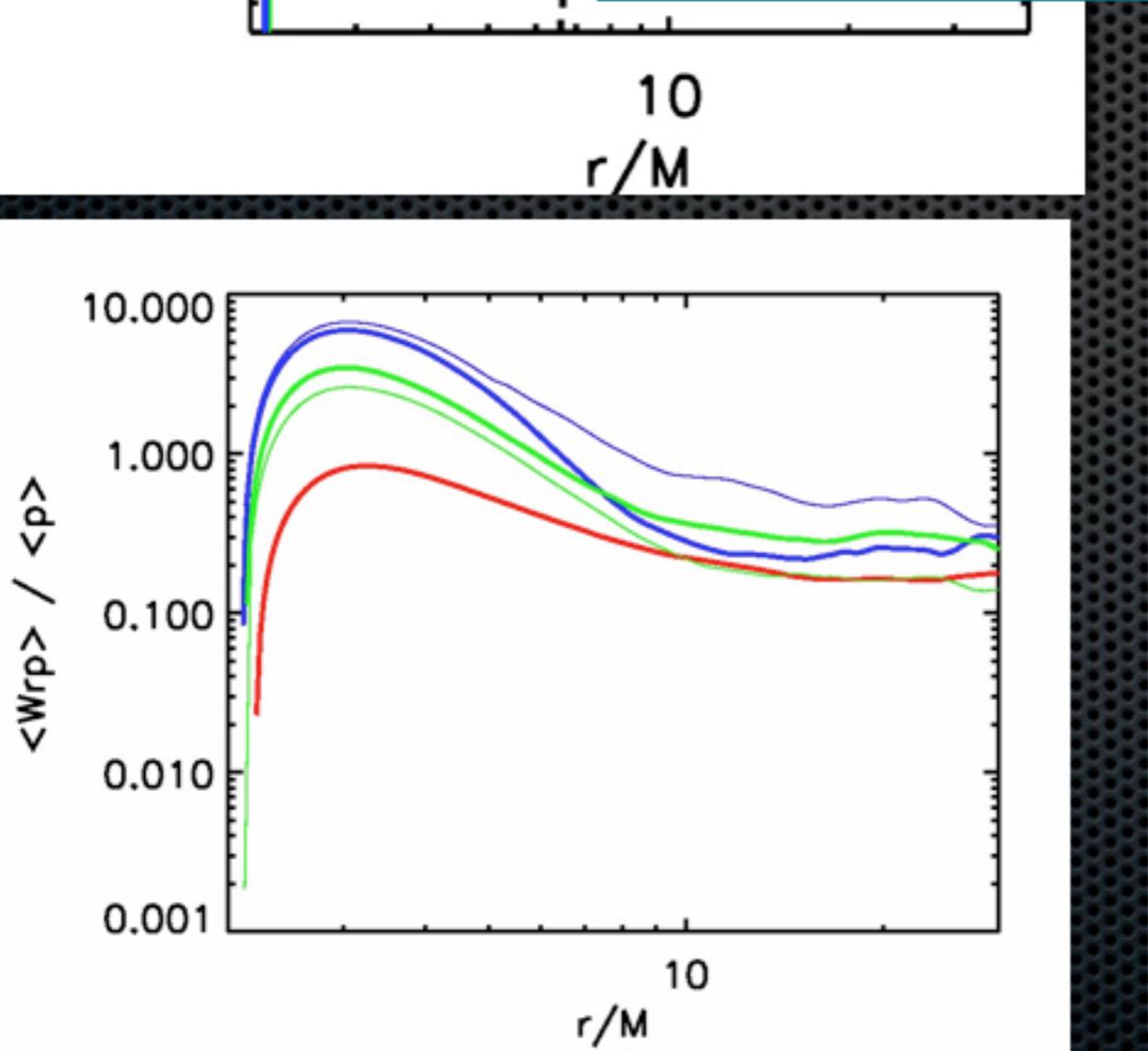
De Villiers & Hawley code

Vertical field with De Villiers & Hawley code

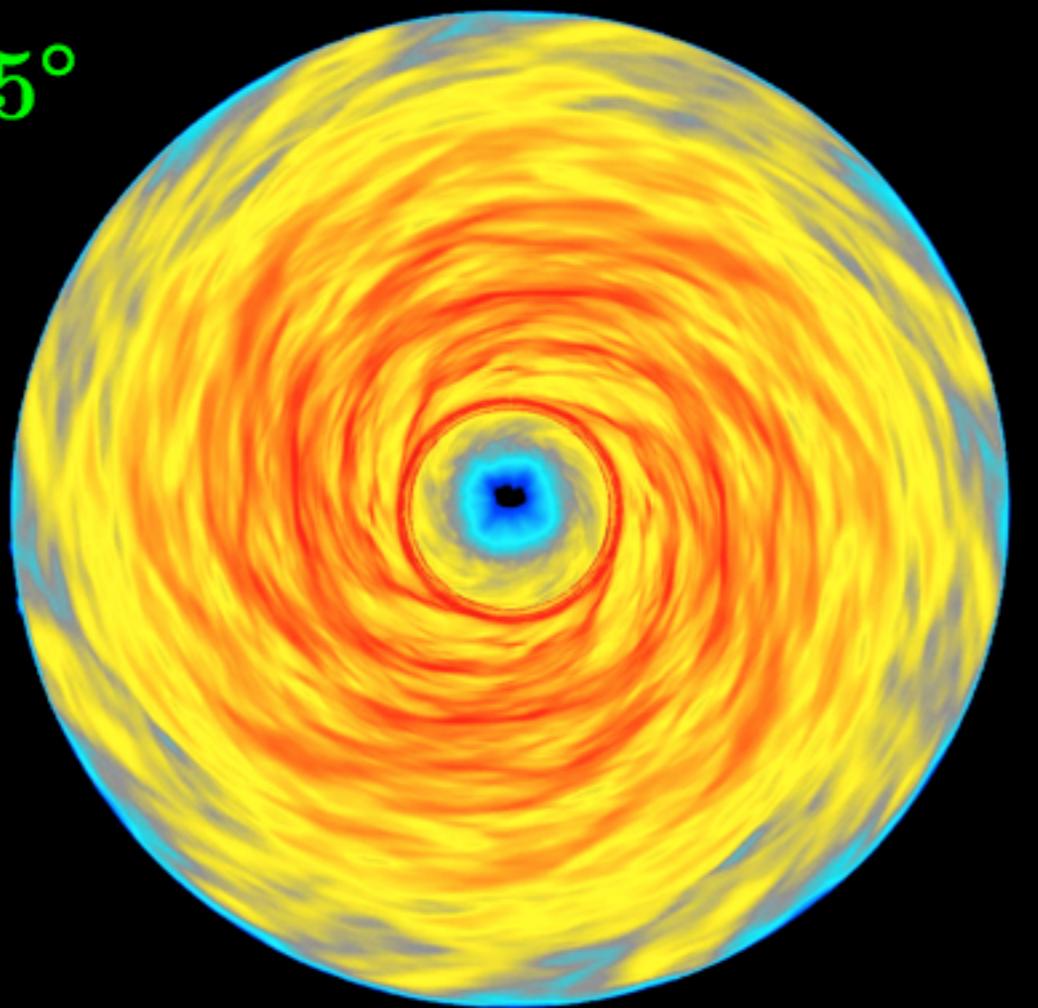




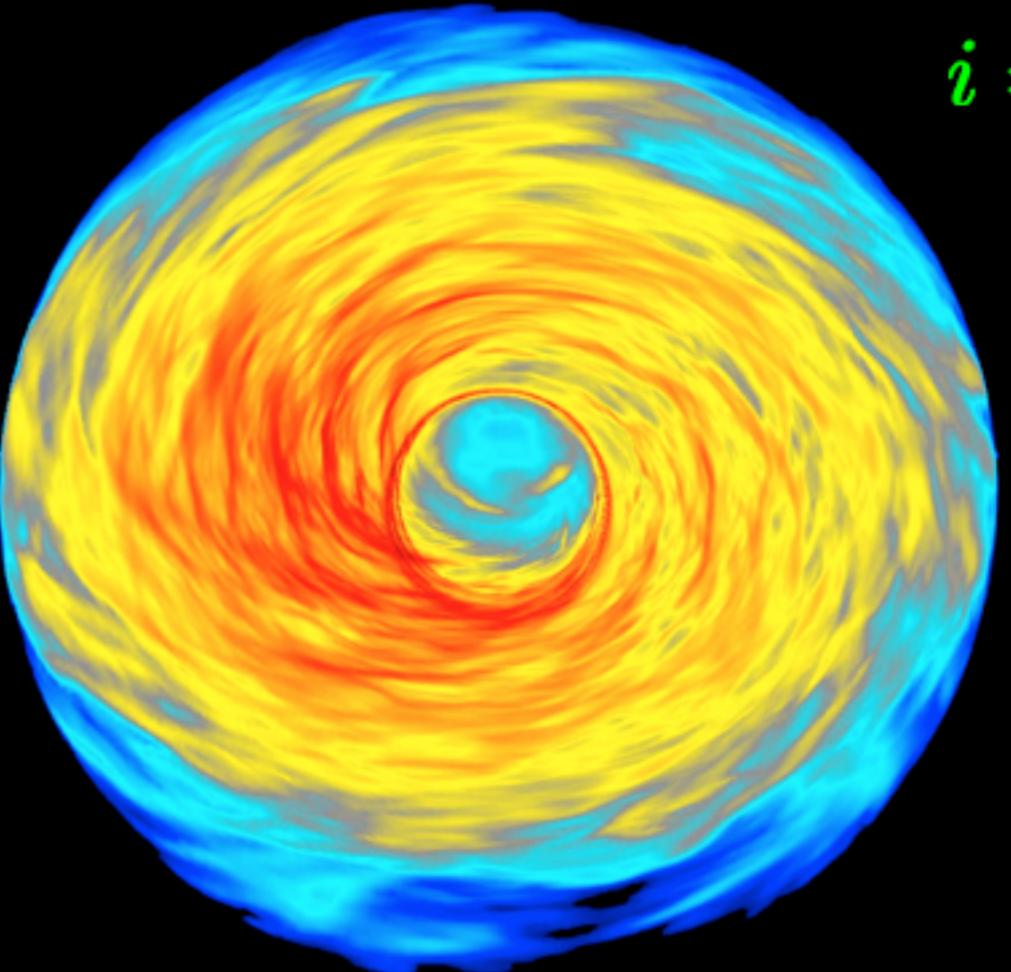
Other GRMHD simulations show weaker intra-ISCO stress levels, angular momentum transport and emission.  
Shafee et al. (2008), Penna et al. (2010),  
Kulkarni et al. (2011).



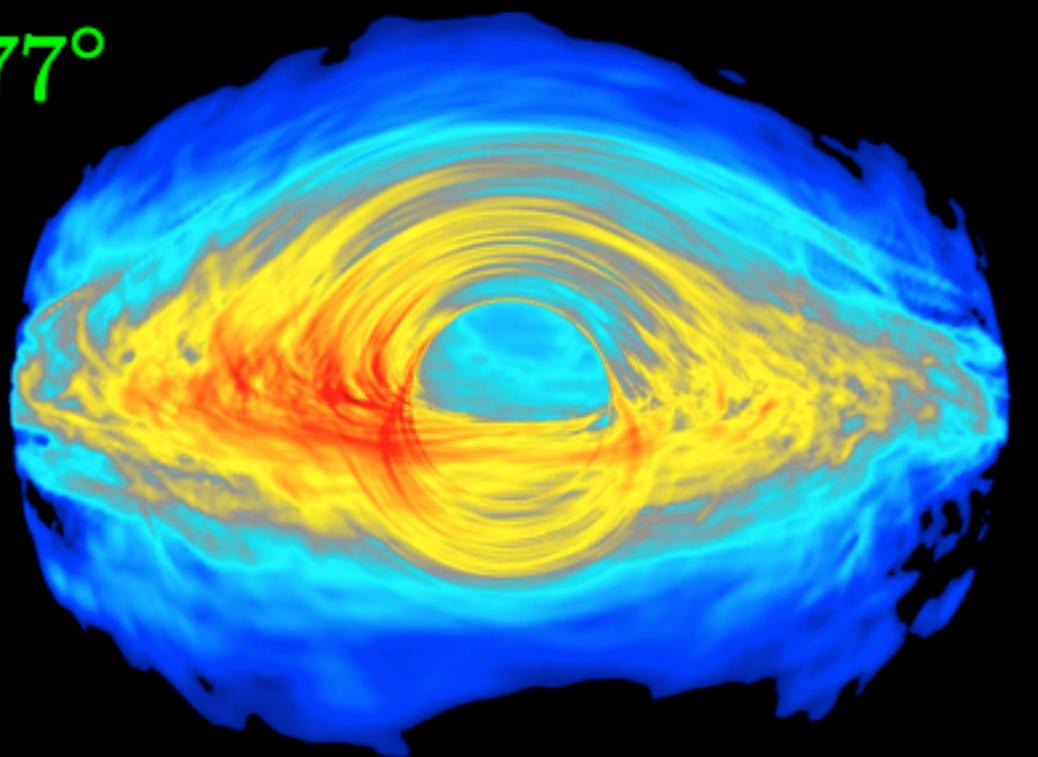
$i = 5^\circ$



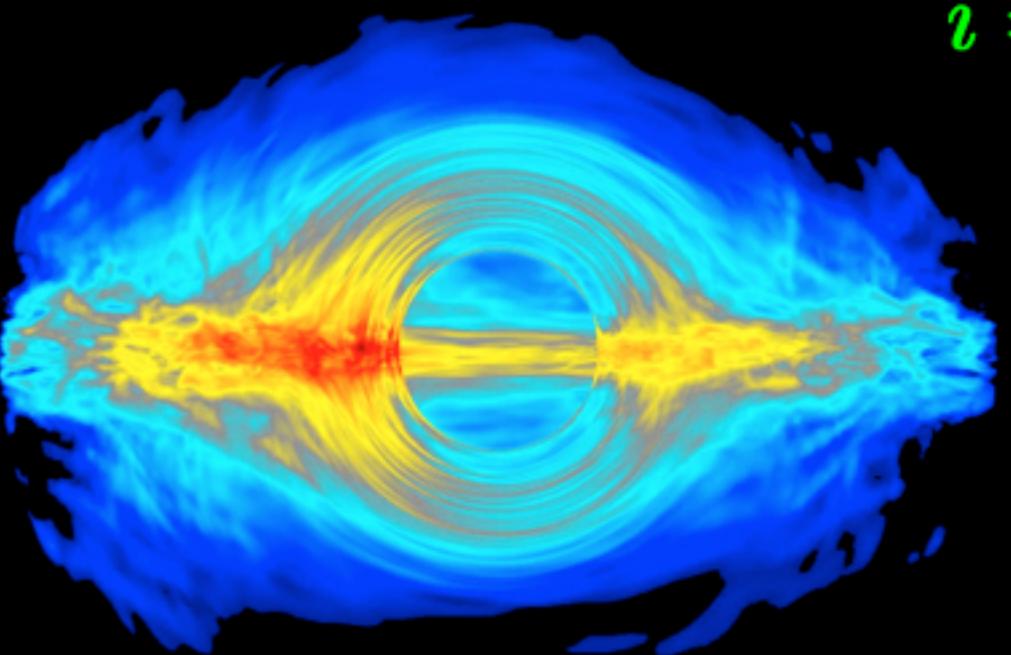
$i = 41^\circ$



$i = 77^\circ$

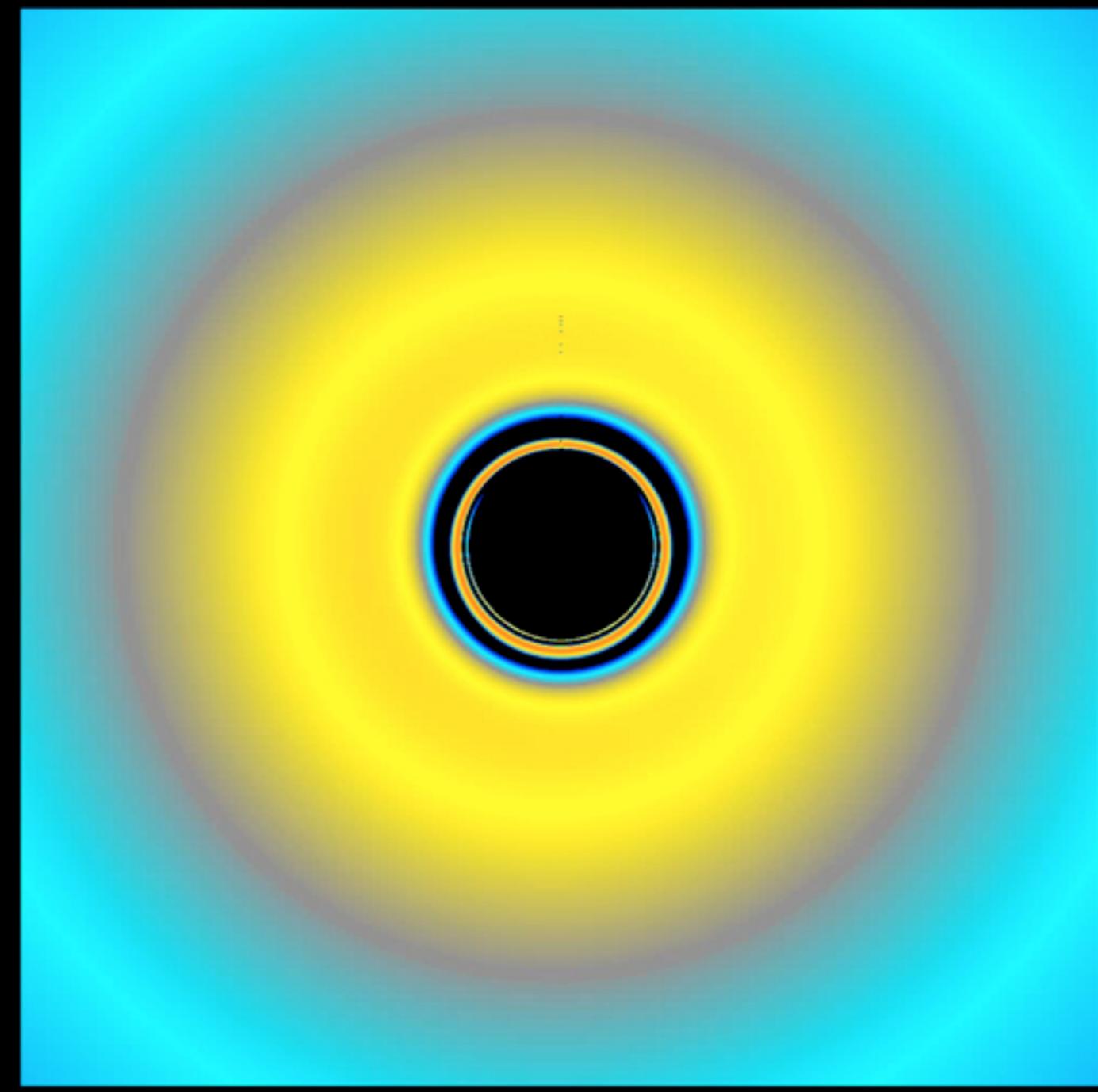
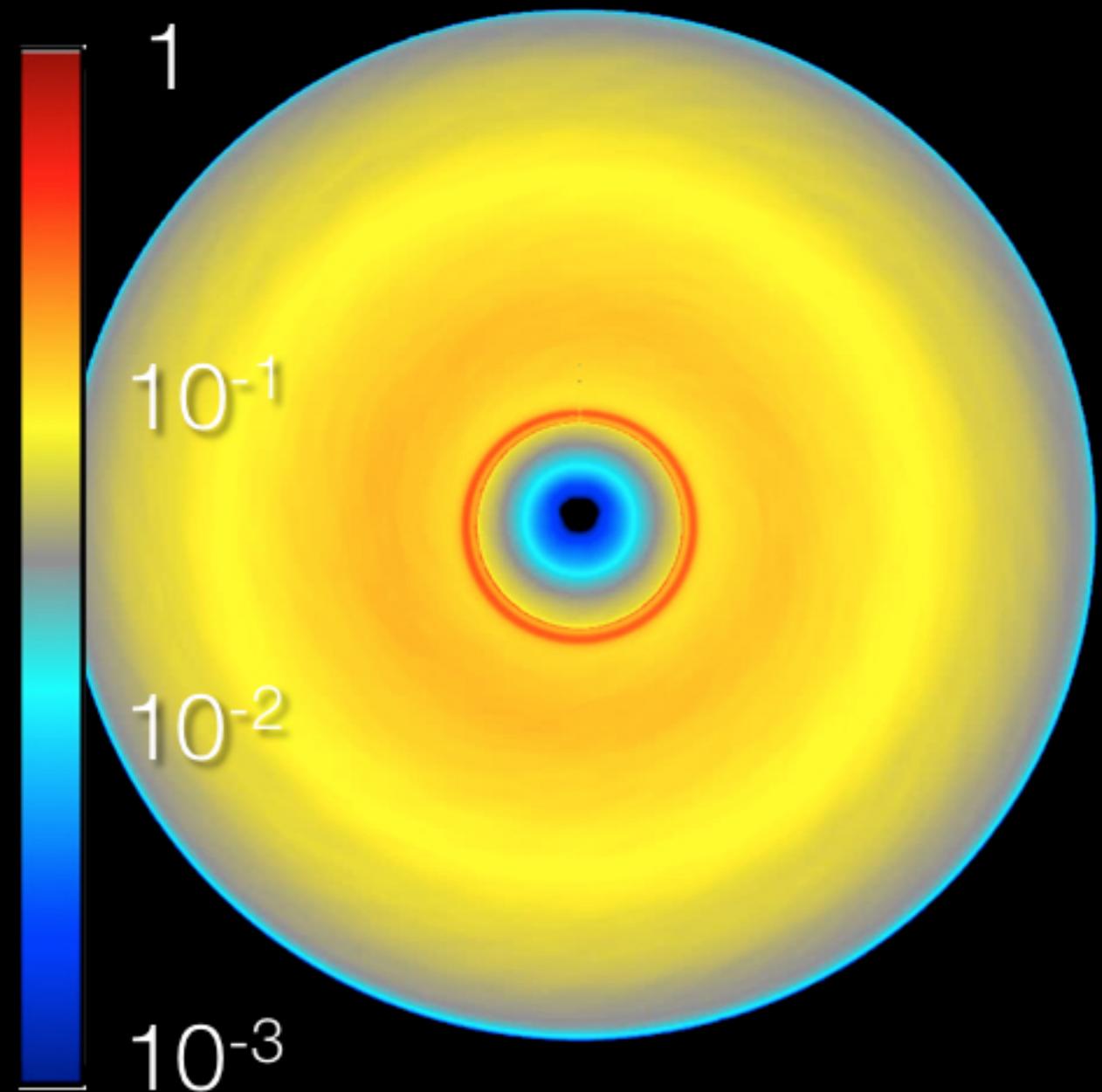


$i = 89^\circ$



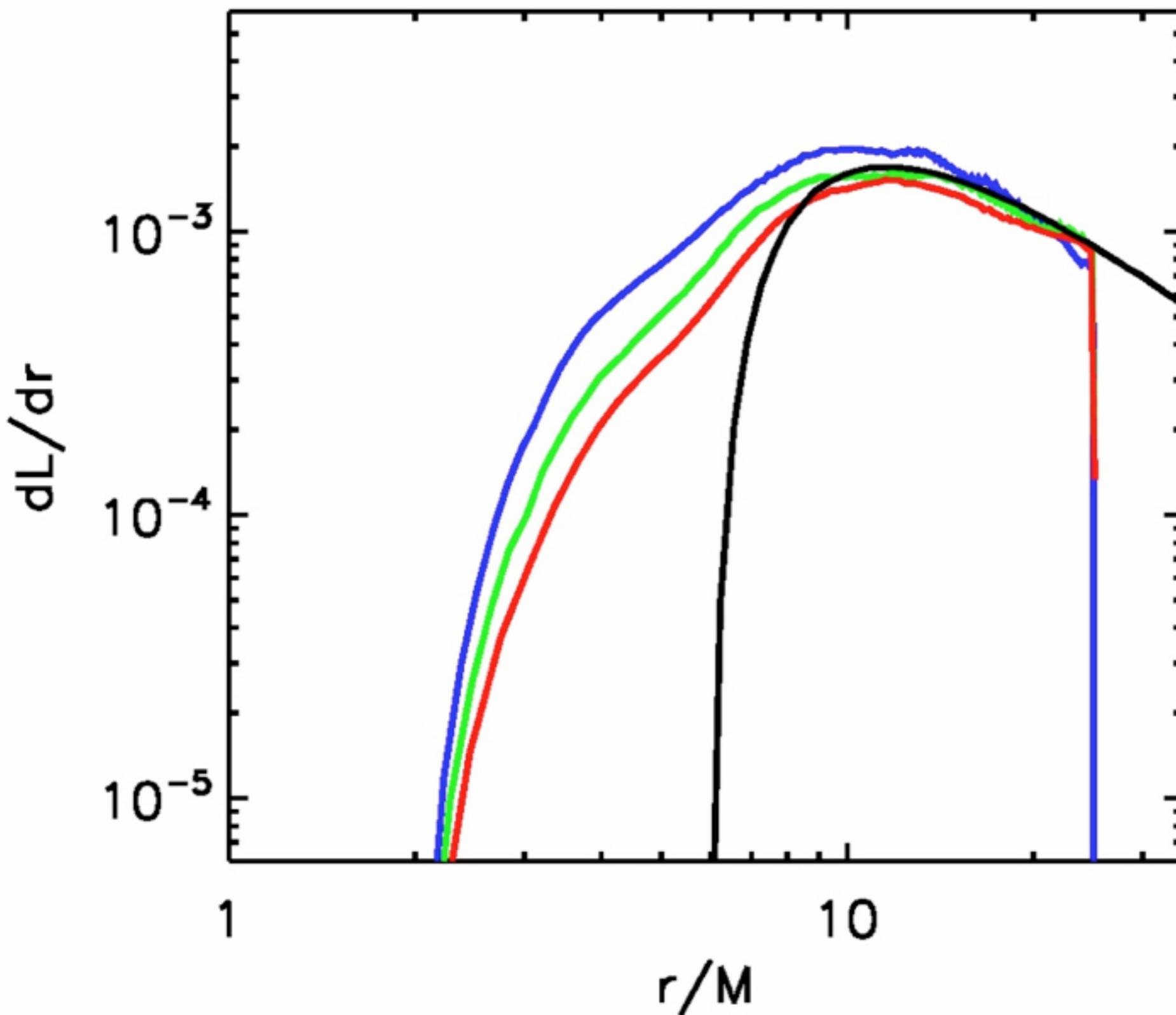
# Time-averaged ThinHR

NT



50 M

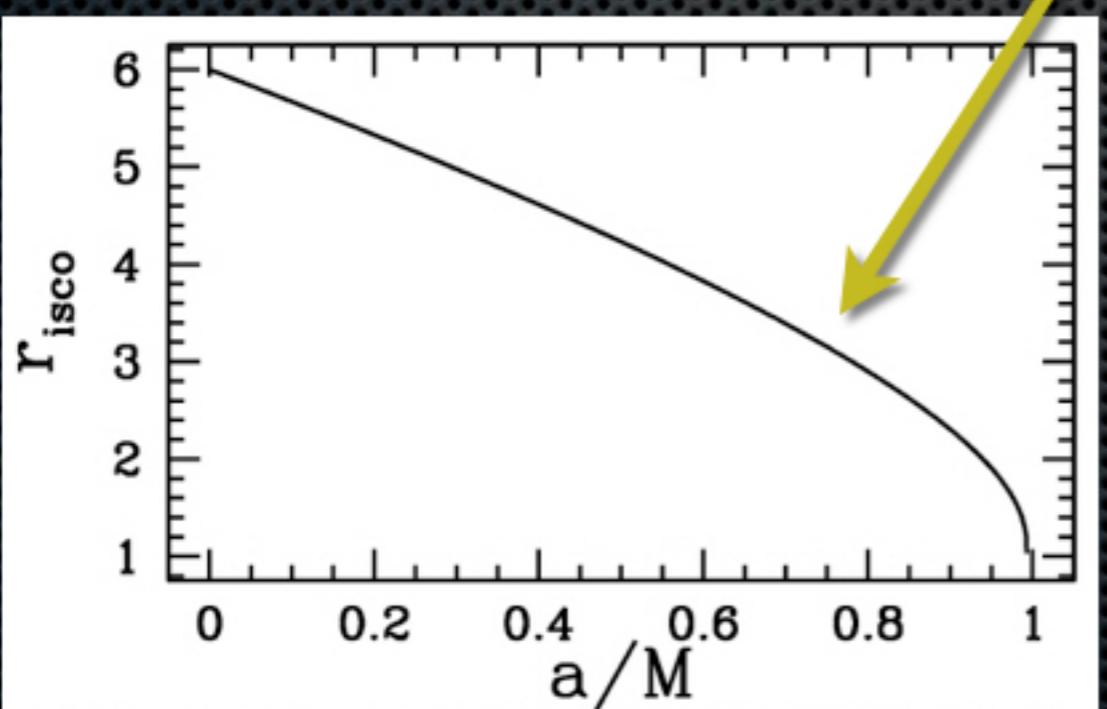
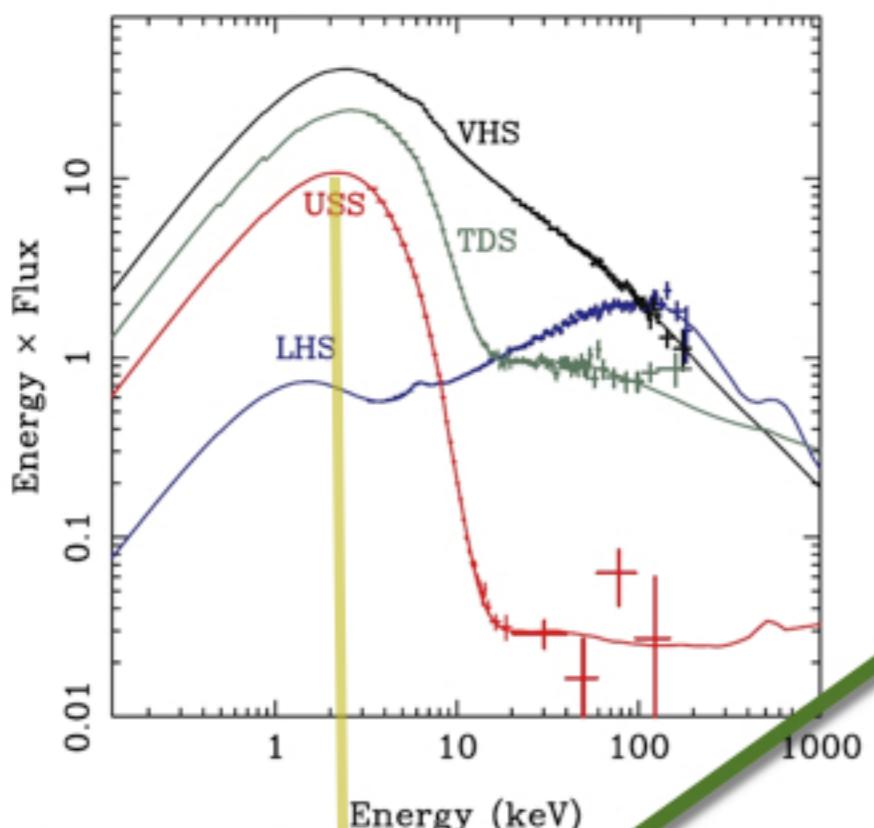
# Efficiency Trend with Scaleheight



$R_{\text{NT}} = 11.4$   
 $R_{\text{ThinHR}} = 10.3$   
 $\Delta T_{\max}/T_{\max} = 8\%$   
 $\Delta R_{\text{in}}/R_{\text{in}} = 11\%$   
 $\Delta \eta/\eta = 10\%$   
 $\Delta \eta/\eta = 4\%$   
 $\Delta \eta/\eta = -1\%$

Possibly, more light can be generated from retained heat and magnetic field.

# Thermal Spectral Fitting for BH Spin



Integrated Stefan-Boltzmann Law for Multi-T BB Disks

$$L = AR_{\text{in}}^2 T_{\max}^4$$

$$R_{\text{in}} = R_{\text{in}}(M, a) \simeq R_{\text{ISCO}}$$

Table 1. Spin Results to Date for Eight Black Holes<sup>a</sup>

|   | Source        | Spin $a_*$             | Reference              |
|---|---------------|------------------------|------------------------|
| 1 | GRS 1915+105  | $> 0.98$               | McClintock et al. 2006 |
| 2 | LMC X-1       | $0.92^{+0.05}_{-0.07}$ | Gou et al. 2009        |
| 4 | M33 X-7       | $0.84 \pm 0.05$        | Liu et al. 2008, 2010  |
| 3 | 4U 1543-47    | $0.80 \pm 0.05$        | Shafee et al. 2006     |
| 5 | GRO J1655-40  | $0.70 \pm 0.05$        | Shafee et al. 2006     |
| 6 | XTE J1550-564 | $0.34^{+0.20}_{-0.28}$ | Steiner et al. 2010b   |
| 7 | LMC X-3       | $< 0.3^b$              | Davis et al. 2006      |
| 8 | A0620-00      | $0.12 \pm 0.18$        | Gou et al. 2010        |

<sup>a</sup>Errors are quoted at the 68% level of confidence.

<sup>b</sup>Provisional result pending improved measurements of  $M$  and  $i$ .

# Spectral Fitting NT to Simulations

SCN, Krolik, Schnittman, Hawley  
(2011)

## Simulation:

- ThinHR:  $a=0$ ,  $H/R=0.06$
- Snapshots spaced  $dt= 500M$
- Effective Temperature from cooling function's bolometric emissivity

## GR Ray-tracing (Schnittman's code):

- Time-average snapshot spectra;
- Includes reflection radiation in optically thick case;
- Also consider optically thin emission to explore span of possibilities

$$M_{\text{BH}_{\text{sim}}} = 10M_{\odot}$$

$$\dot{M}_{\text{sim}} = 0.1\dot{M}_{\text{Edd}}$$

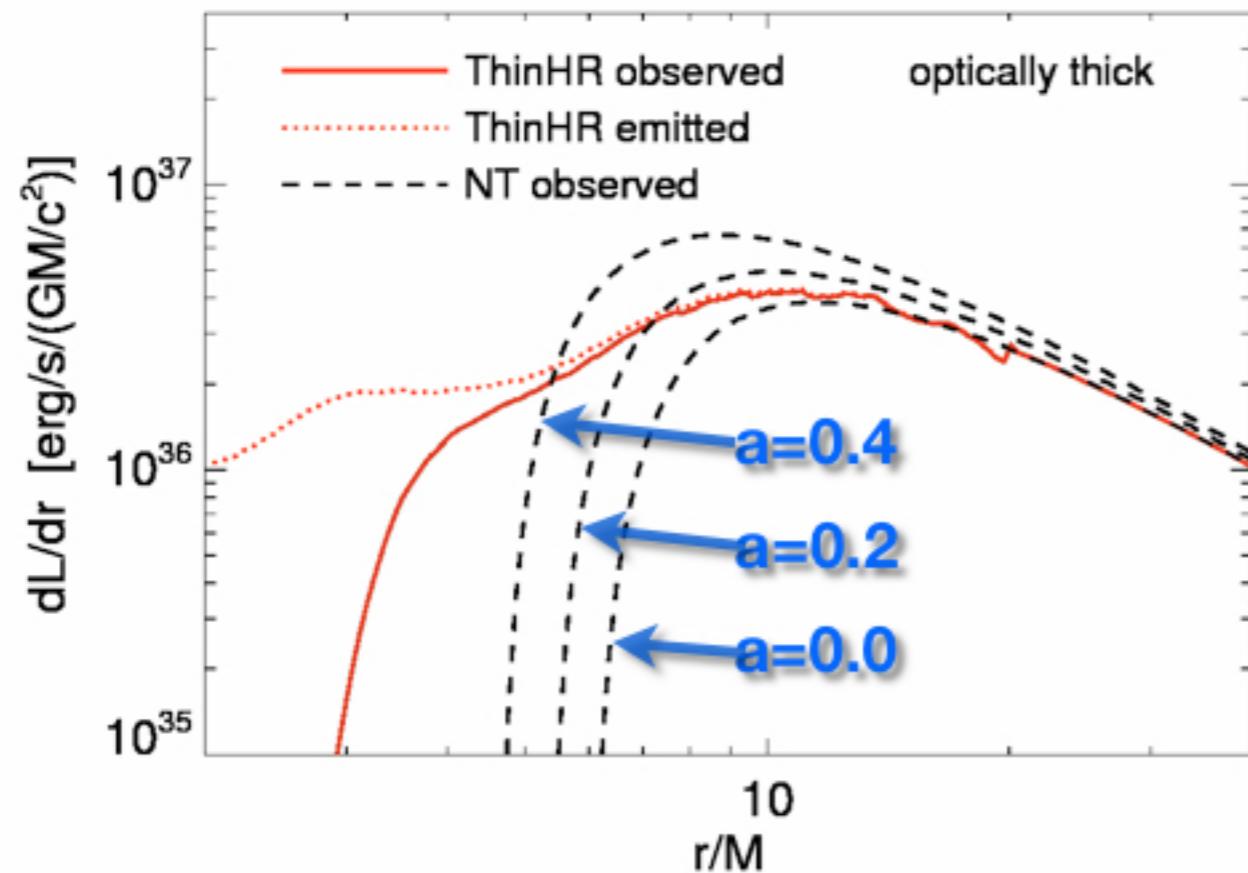
## • Free parameters:

$$D, M_{\text{BH}}, \dot{M}, i$$

- Can constrain some by other observations, though are sometimes quite uncertain;
- Problem is degenerate in  $D$ , so we eliminate it from the fitting procedure;

| Case # | Knowns<br>(constraints) | Unknowns<br>(fitting parameters) |
|--------|-------------------------|----------------------------------|
| 1      | D                       | $i, a, M, \dot{M}$               |
| 2      | $D, M$                  | $i, a, \dot{M}$                  |
| 3      | $D, M, i$               | $a, \dot{M}$                     |

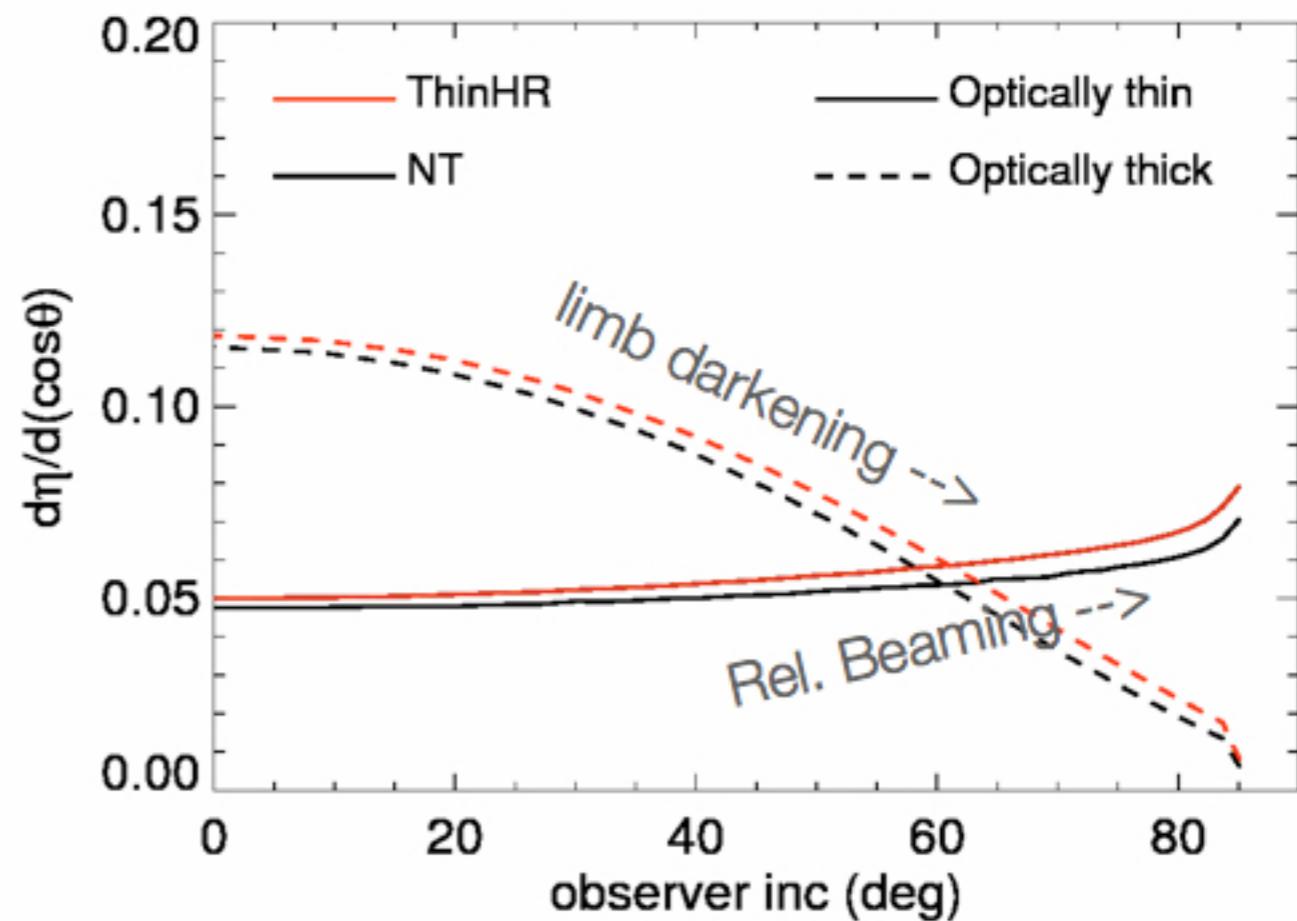
# Bolometric Luminosity



- ThinHR matches NT at large radius
- “Glue on” NT ( $a=0$ ) for radii beyond sim’s domain
- Excess radiation within ISCO
- >50% light emitted from  $r < 3M$  is captured by BH

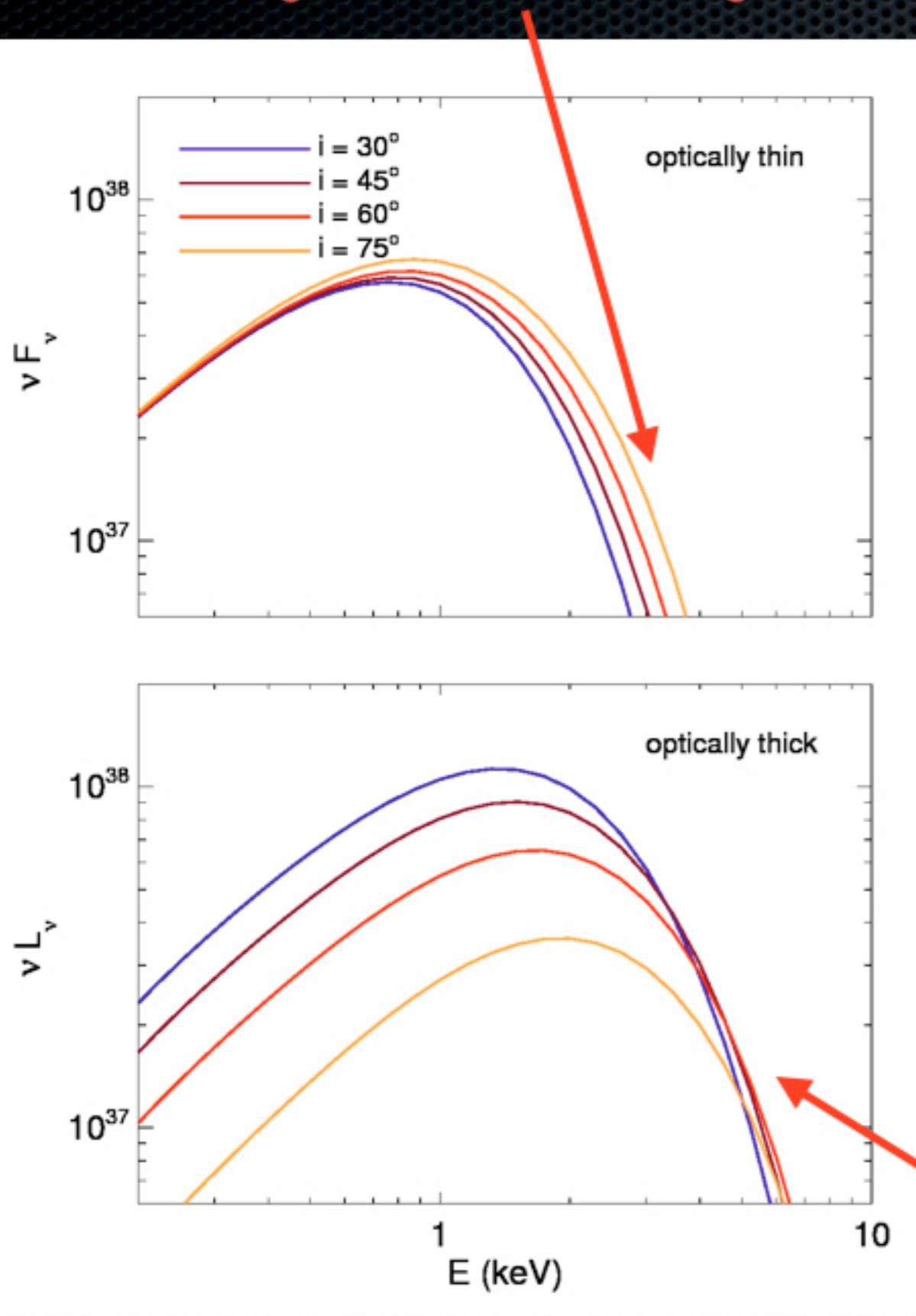
$$L = \eta \dot{M} c^2$$

- Opacity assumption affects trend in inclination angle;
- Optically thick emission’s trend dominated by limb darkening;
- Optically thin emission’s trend dominated by strong dependence on Doppler shift from approaching material;
- ThinHR is always brighter;

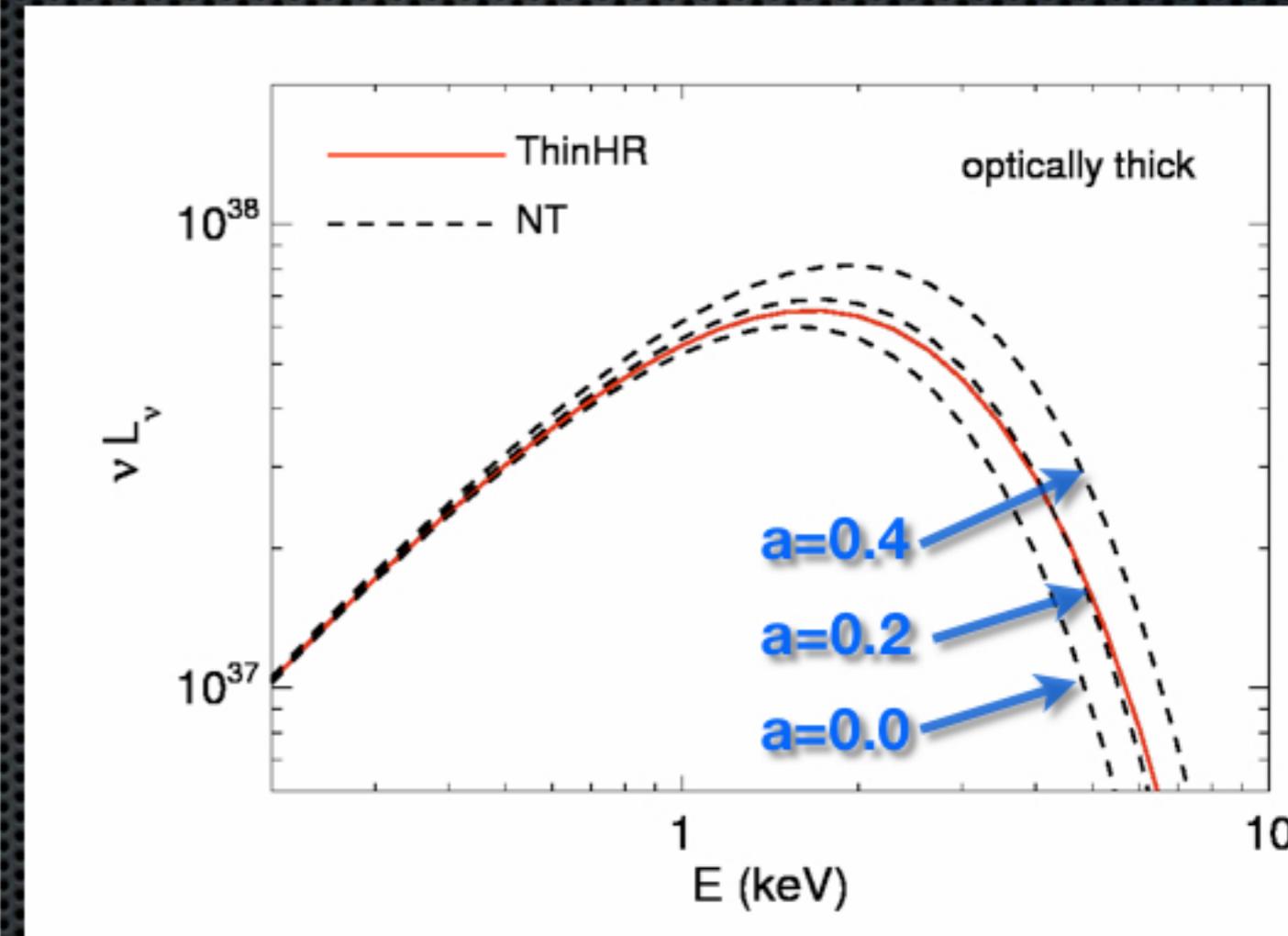


# Thermal Spectrum

- Hardening from Rel. Beaming



$$i_{\text{NT}} = i_{\text{ThinHR}} = 60^\circ$$
$$\dot{M}_{\text{NT}} = \dot{M}_{\text{ThinHR}}$$



- Hardening from coronal upscattering
- Flux diminution from limb darkening and obscuration

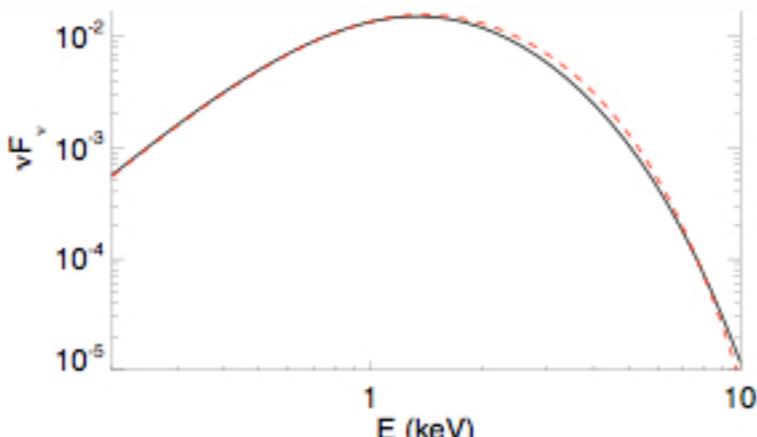
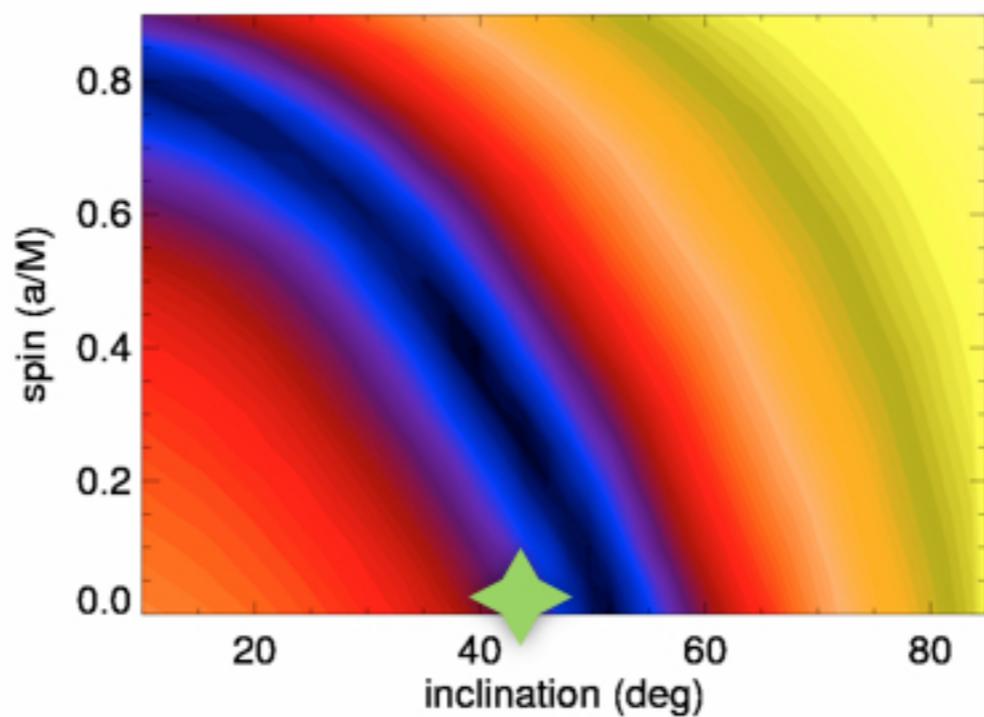
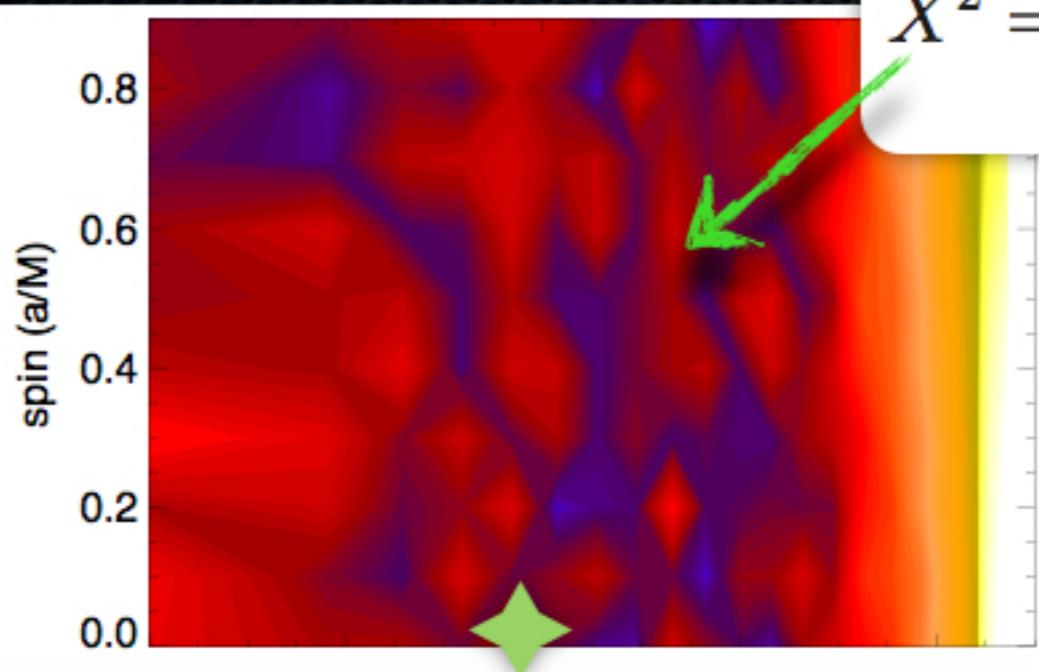
$$X^2 = \sum_i \frac{(F_i^{NT} - F_i^{sim})^2}{\sigma_i^2},$$

**Case 1:**  
**Fitting with**  
**a, i, M, Mdot**  
**(reduce M,Mdot)**

**Case 2:**  
**Fitting with**  
**a, i, Mdot**

**Case 3:**  
**Fitting with**  
**a, Mdot**

**a = 0.2-0.3**



**“Can fit anything!”**

Multiply degenerate

**“Fit to higher  
inclination or  
higher spin.”**

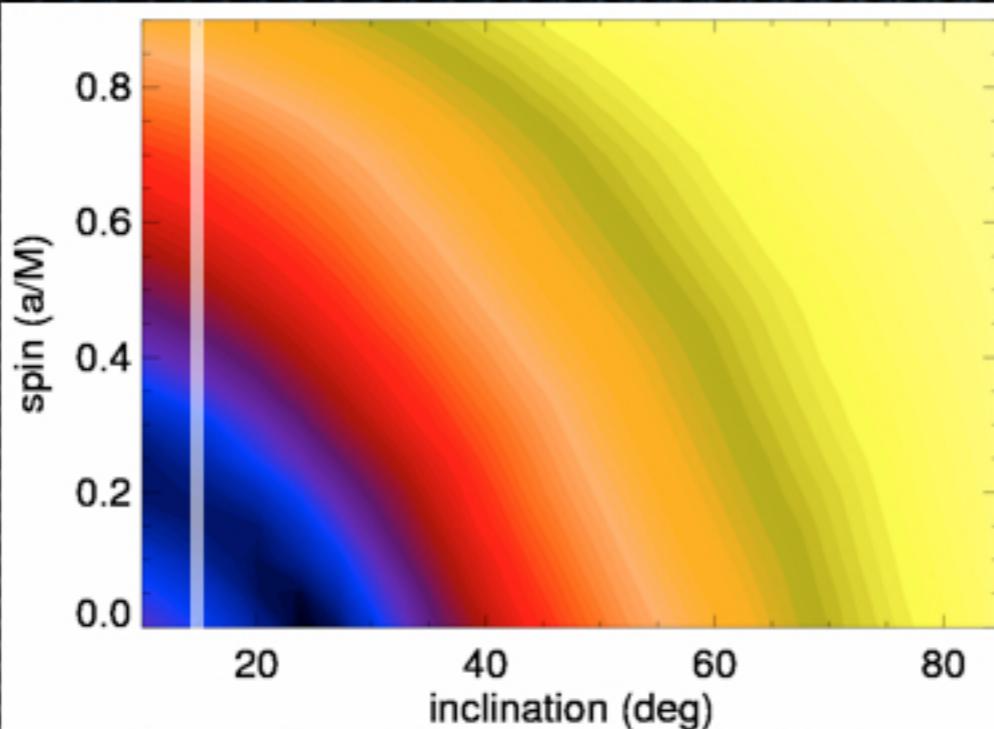
Single degeneracy

**“If all else is  
known, a higher  
spin is predicted.”**

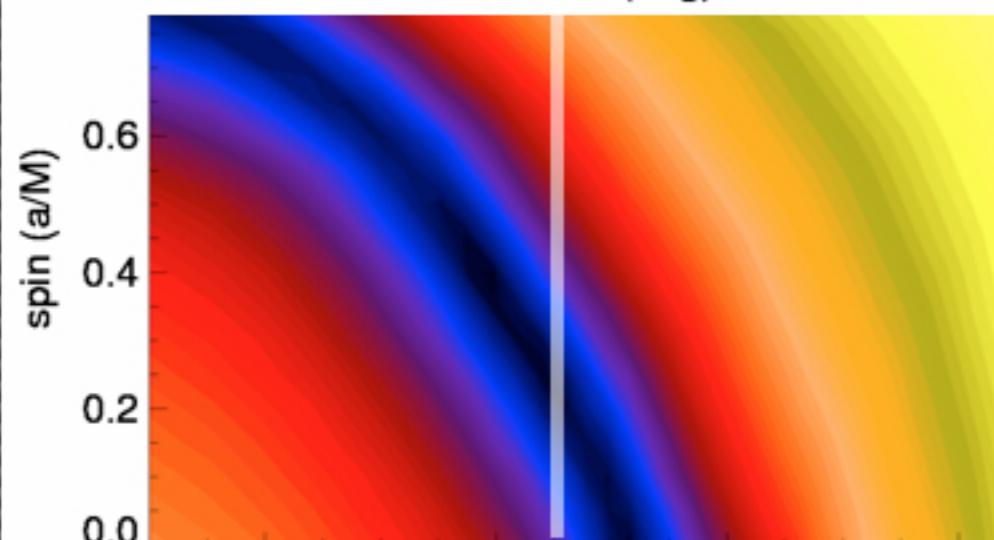
Systematic offset

$$X^2 = \sum_i \frac{(F_i^{NT} - F_i^{sim})^2}{\sigma_i^2},$$

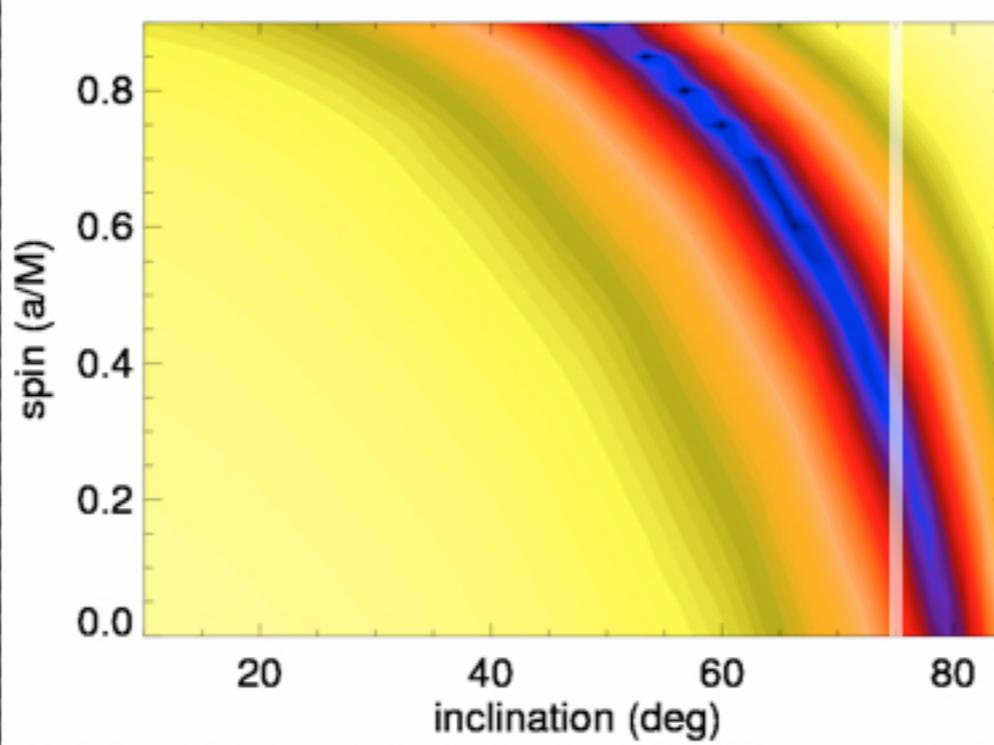
$i_{\text{sim}} = 15^\circ$



$i_{\text{sim}} = 45^\circ$



$i_{\text{sim}} = 75^\circ$

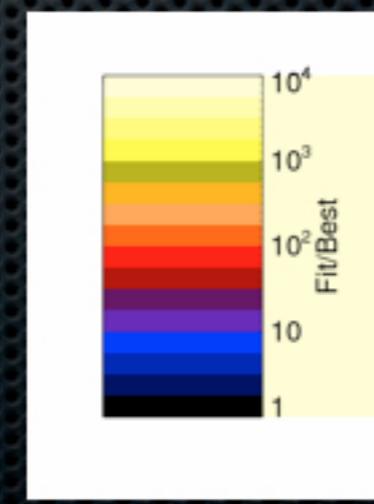


**Either**

**Over-estimate inclination  
by  $\sim 10\text{deg}$ .**

**or**

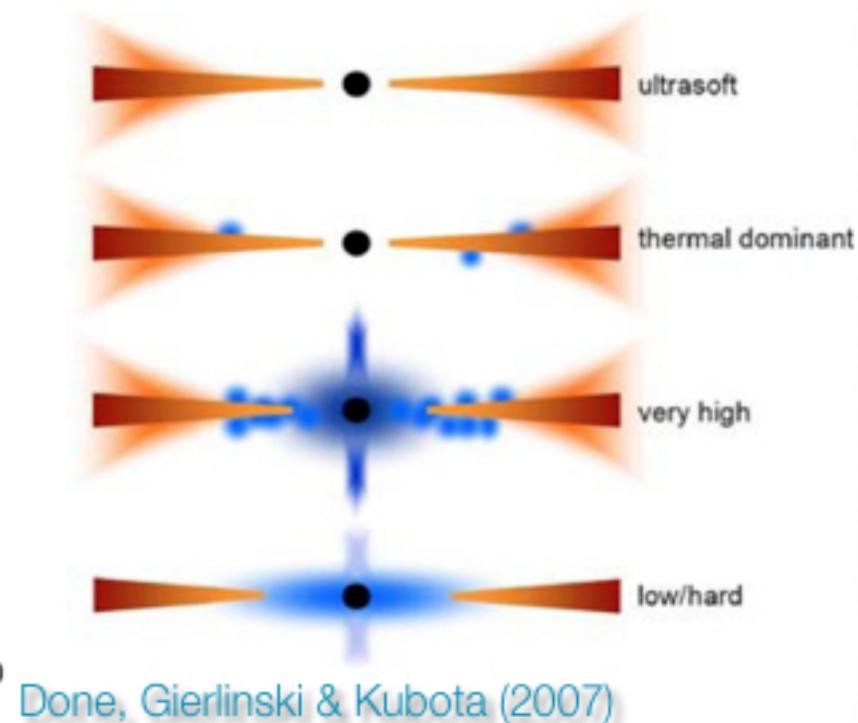
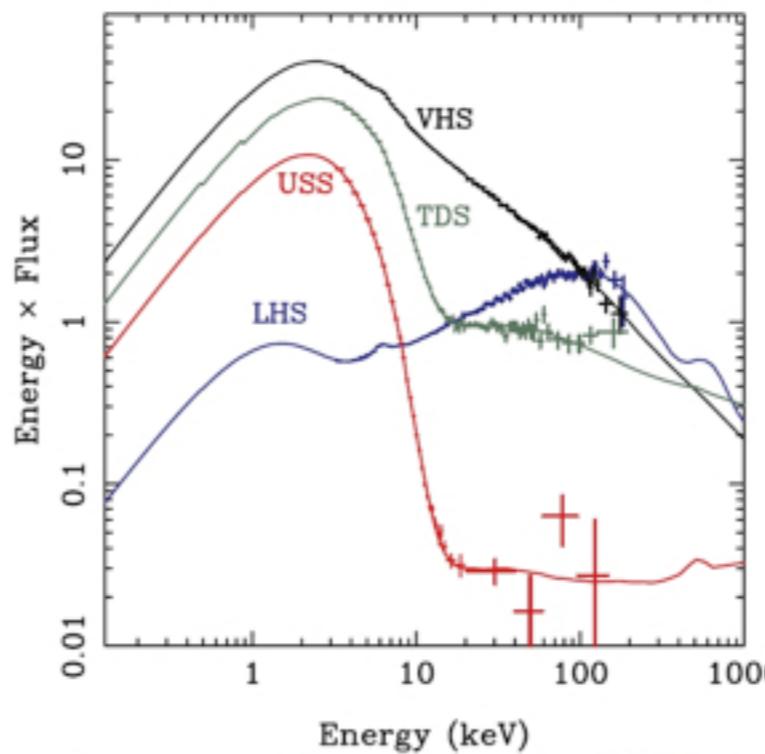
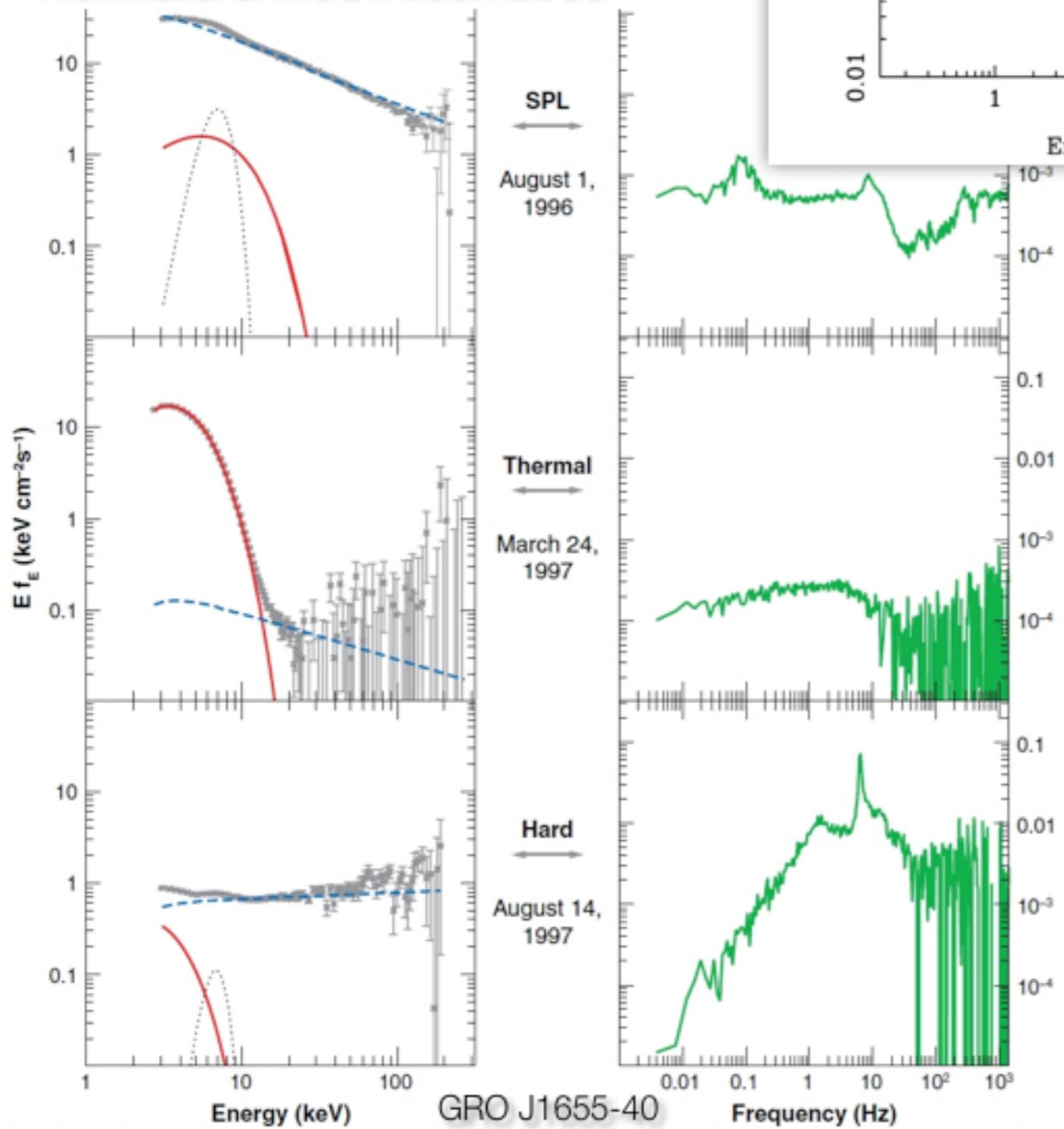
**Over-estimate spin  
by  $\sim 0.2\text{-}0.3$**



# Variability

# Accretion States

Remillard & McClintock 2006



Done, Gierlinski & Kubota (2007)

## Flux Components:

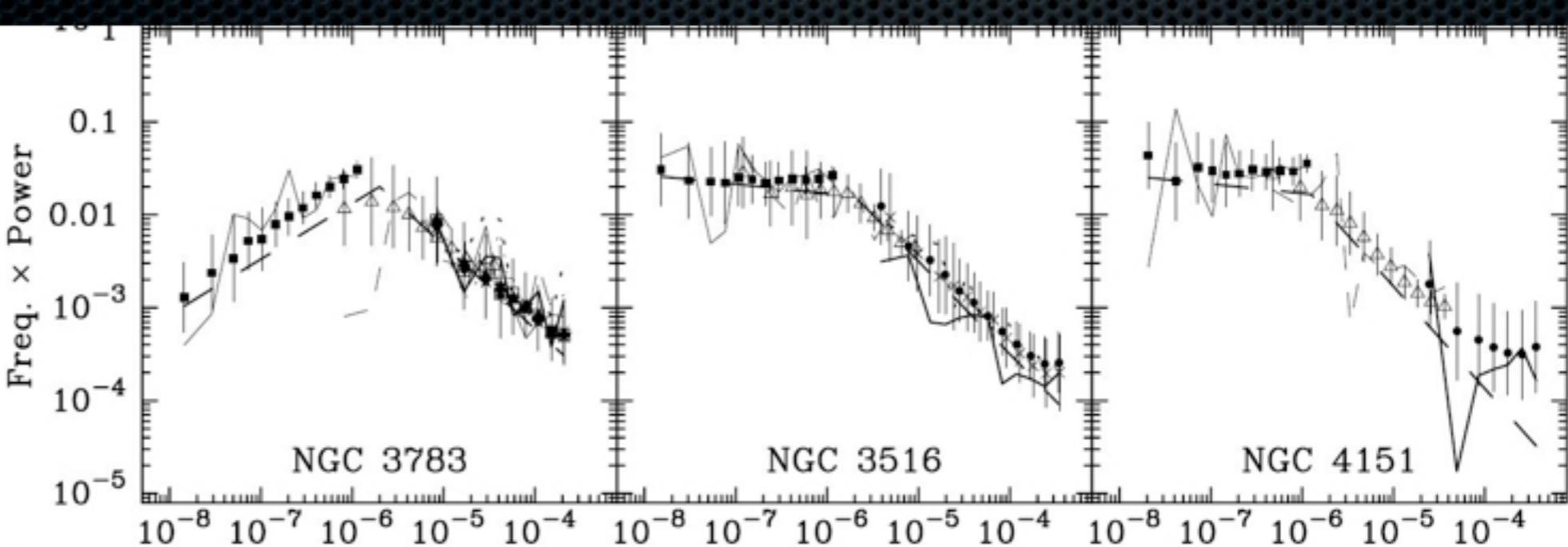
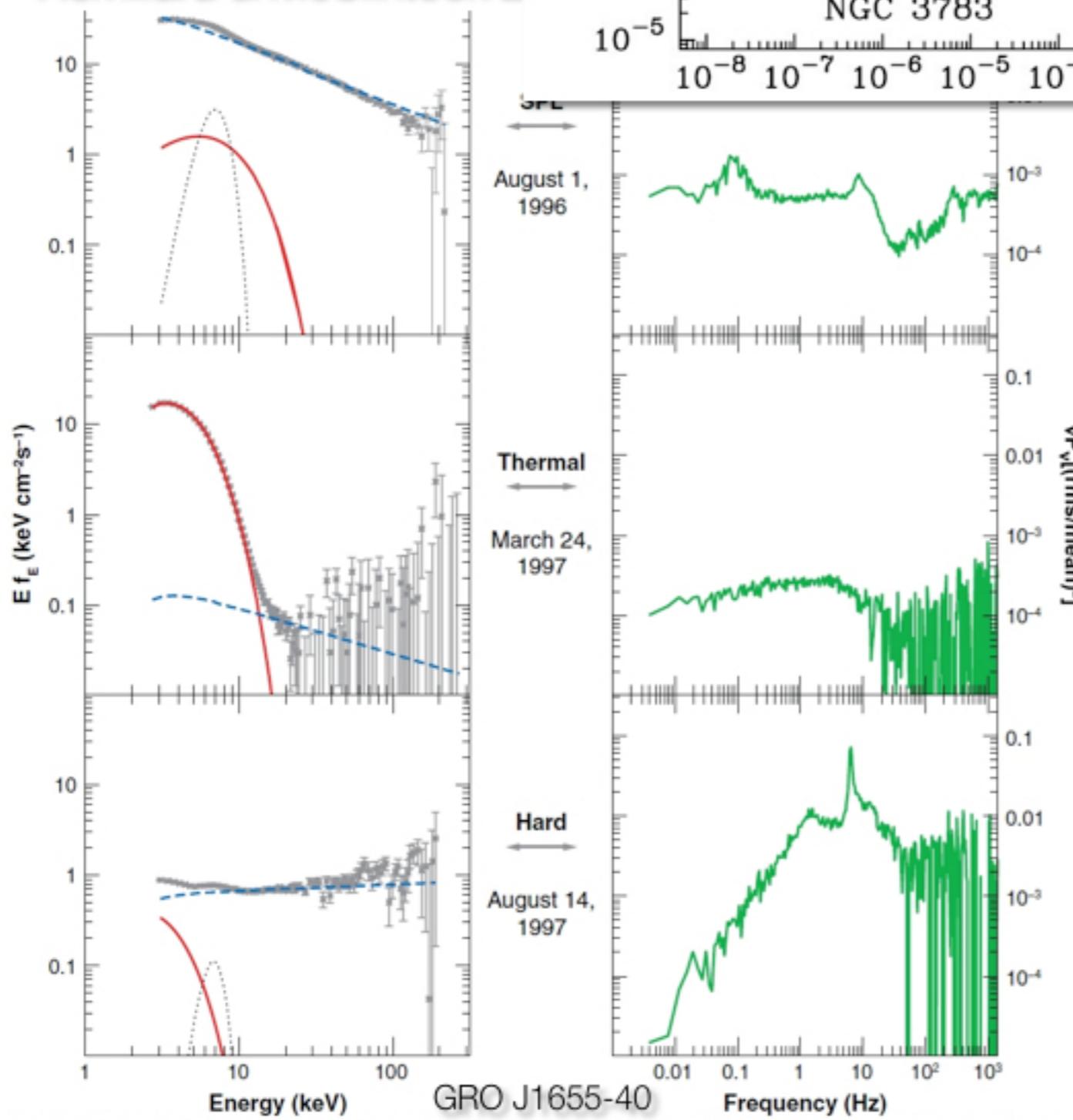
- Bulk --> Thermal
- Corona --> IC, Hard PL
- Reflection --> Fe K Line

## Temporal Variability:

- $P \sim \nu^\alpha$   $-3 < \alpha < -1$
- QPOs High & Low

# Accretion States

Remillard & McClintock 2003



AGN  
Markowitz et al 2003

## Flux Components:

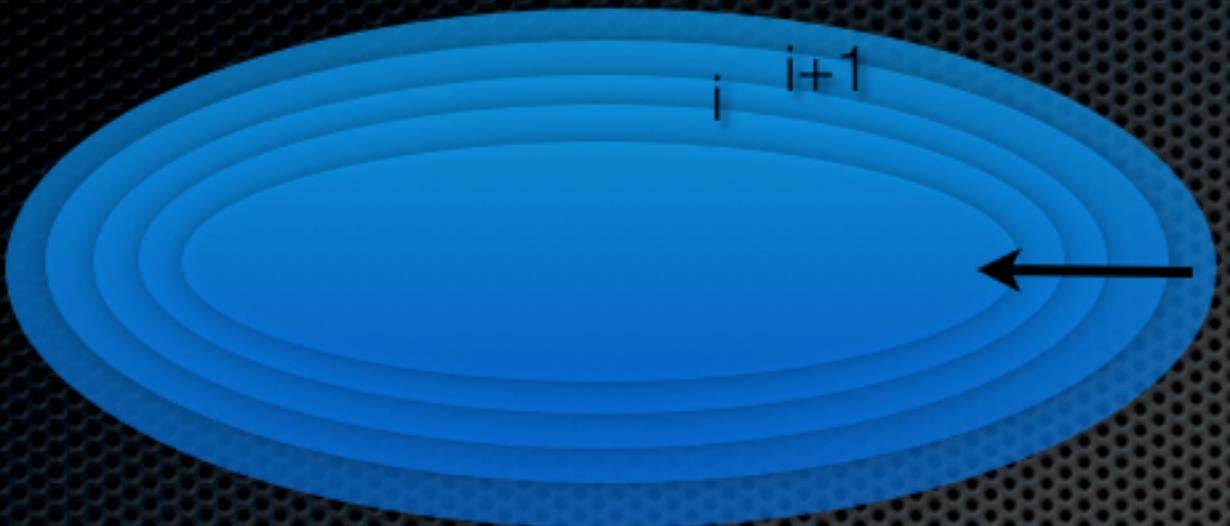
- Bulk --> Thermal
- Corona --> IC, Hard PL
- Reflection --> Fe K Line

## Temporal Variability:

- $P \sim \nu^\alpha$   $-3 < \alpha < -1$
- QPOs High & Low

# Variability Models

$$P \sim \nu^\alpha$$



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

- Accretion rate modulation modeled as variability of  $\alpha$  (disk parameter)
- Predicts phase coherence at frequencies longer than inverse of inflow timescale

Armitage & Reynolds 2003

Machida & Matsumoto 2004

Schnittman et al 2006

Reynolds & Miller 2009

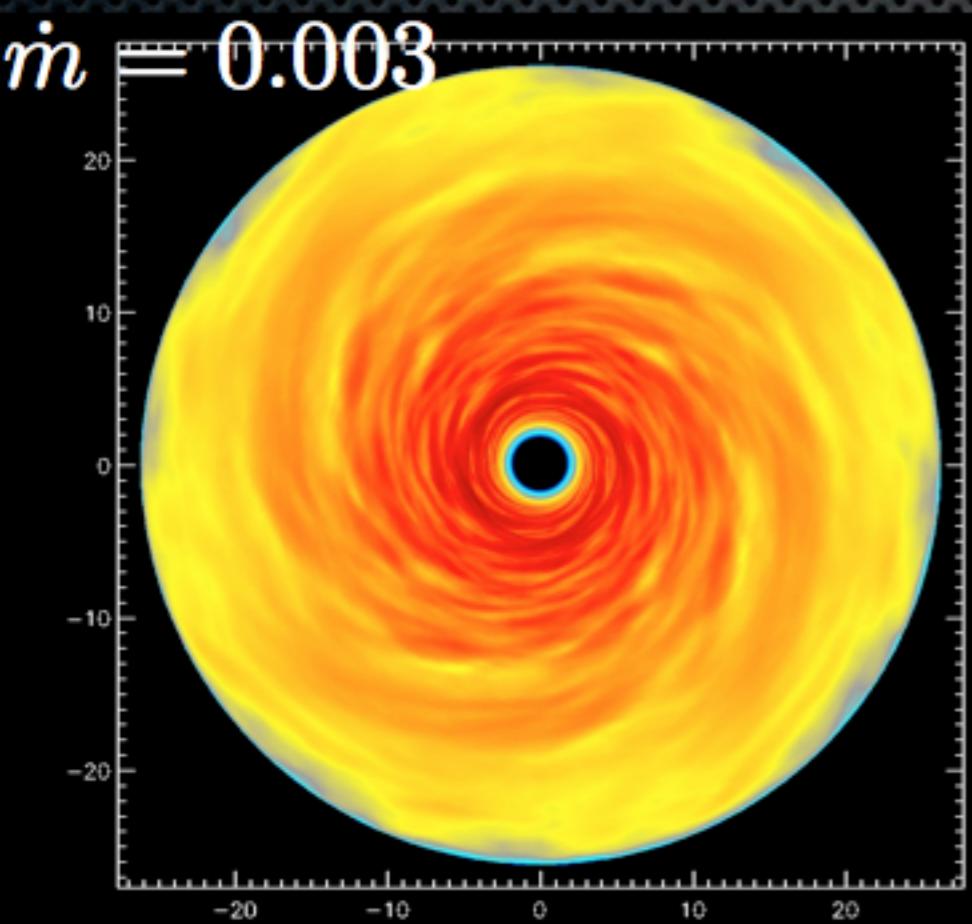
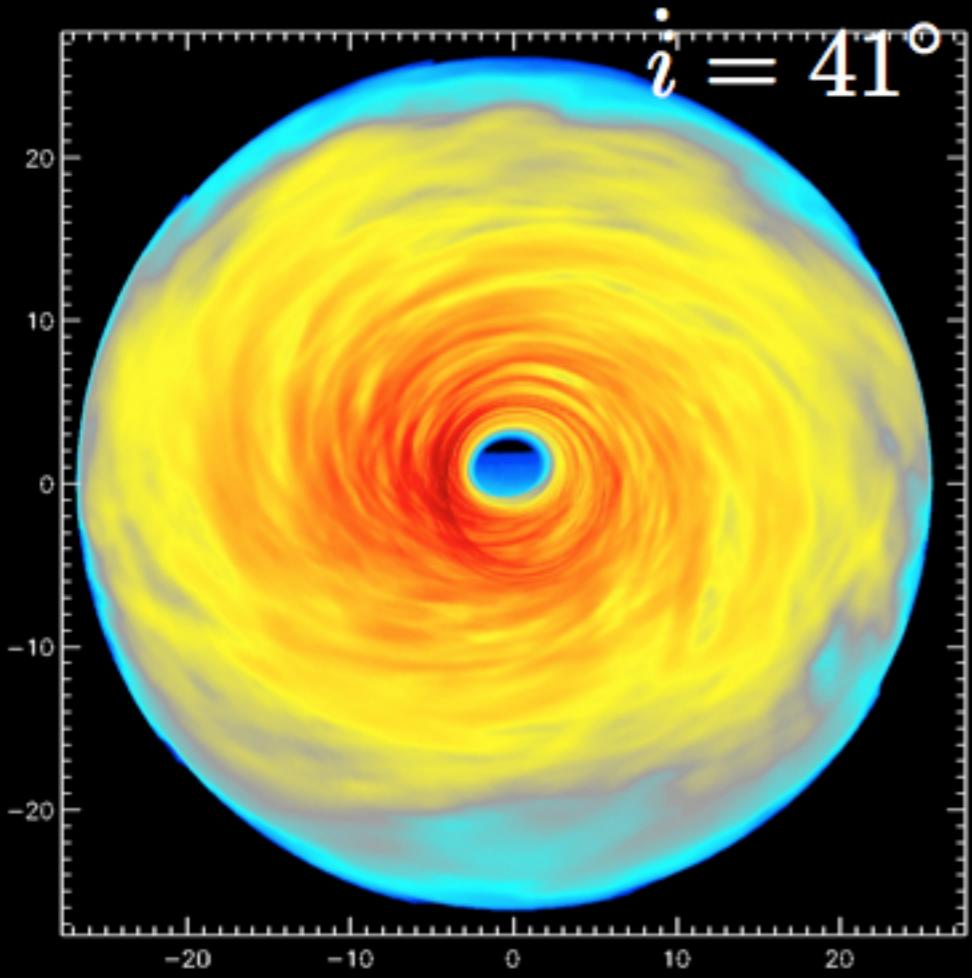
Lyubarskii et al 1997

- Total variability is a superposition of independent variability from larger radii modulating interior annuli on inflow (viscous) times scales

Churazov et al 2001

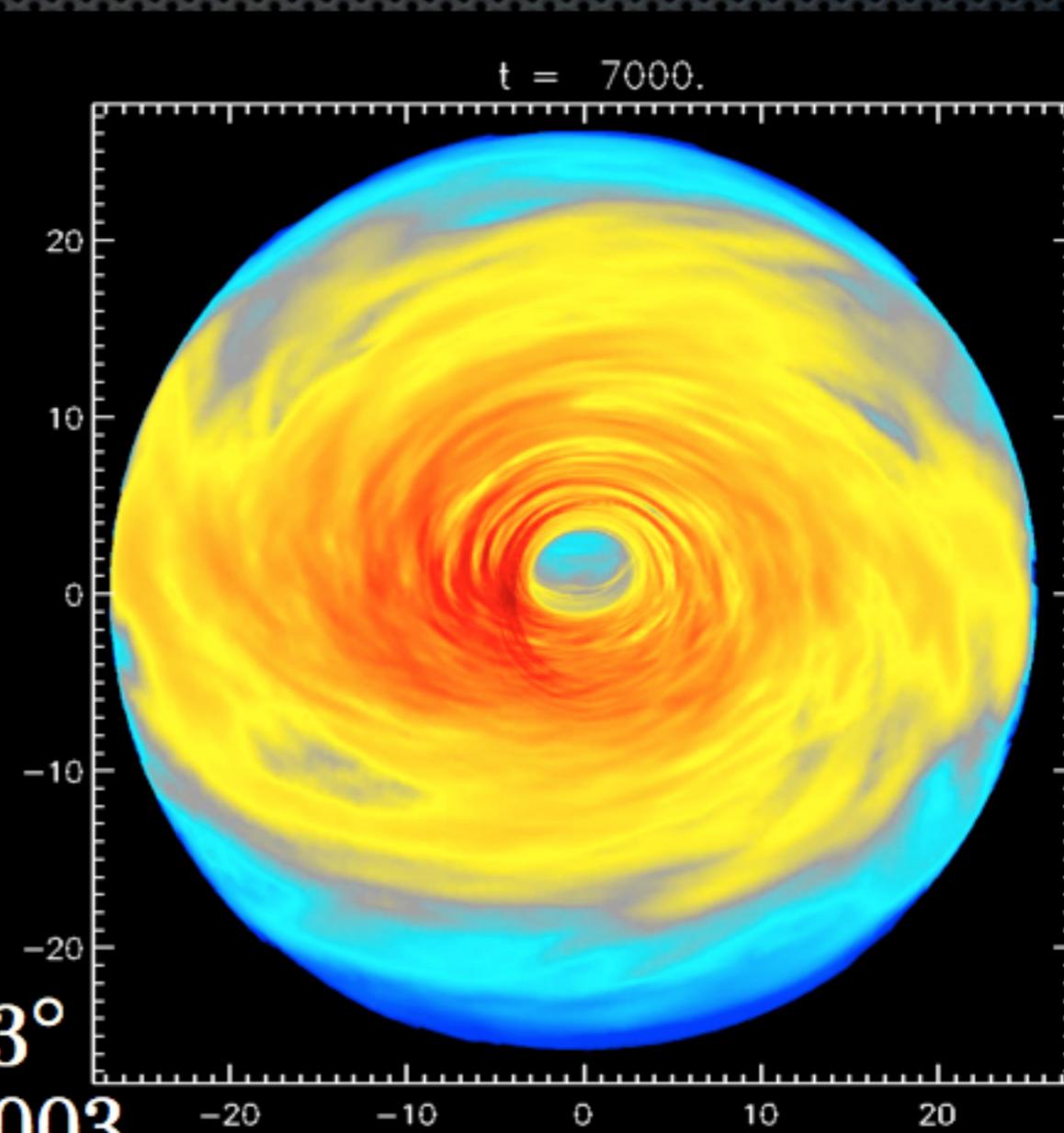
- Outer radius of corona may be cause of (temporal) spectral slope

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

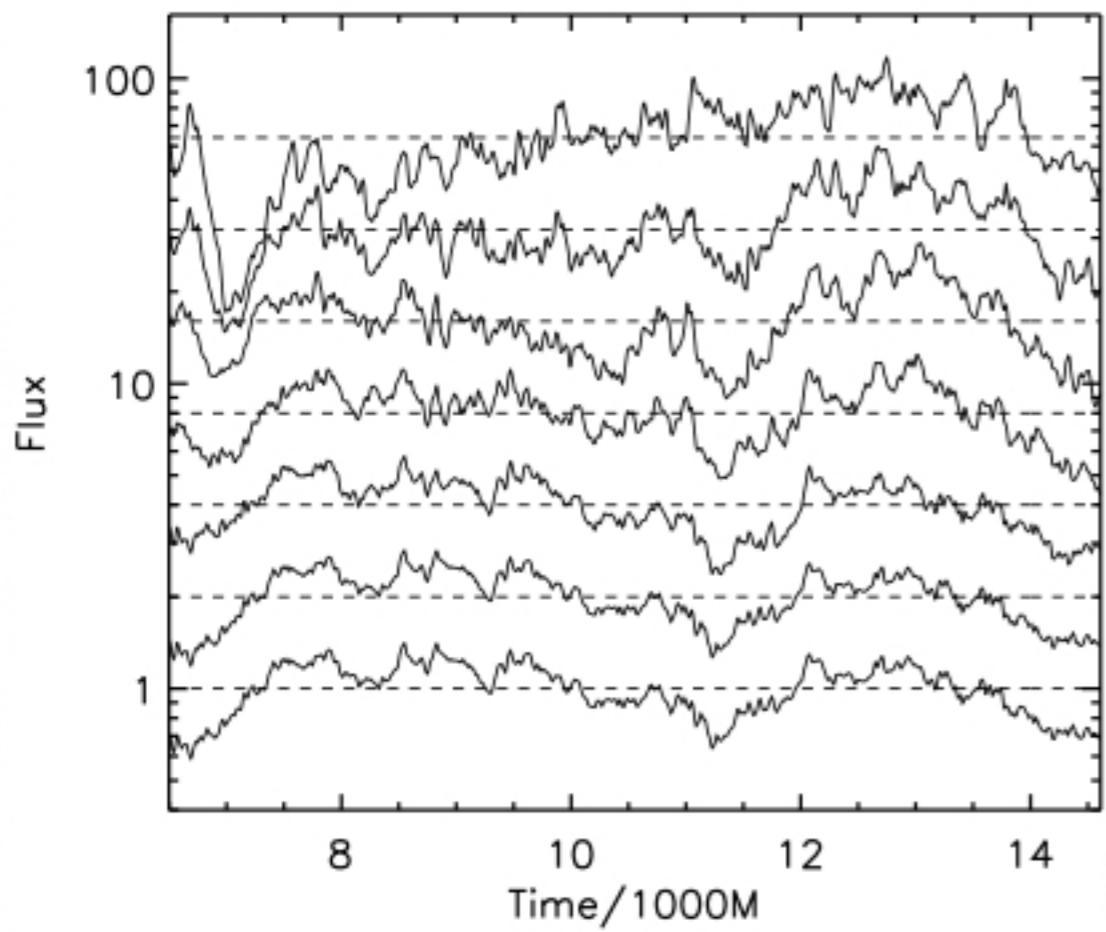


SCN & Krolik 2009

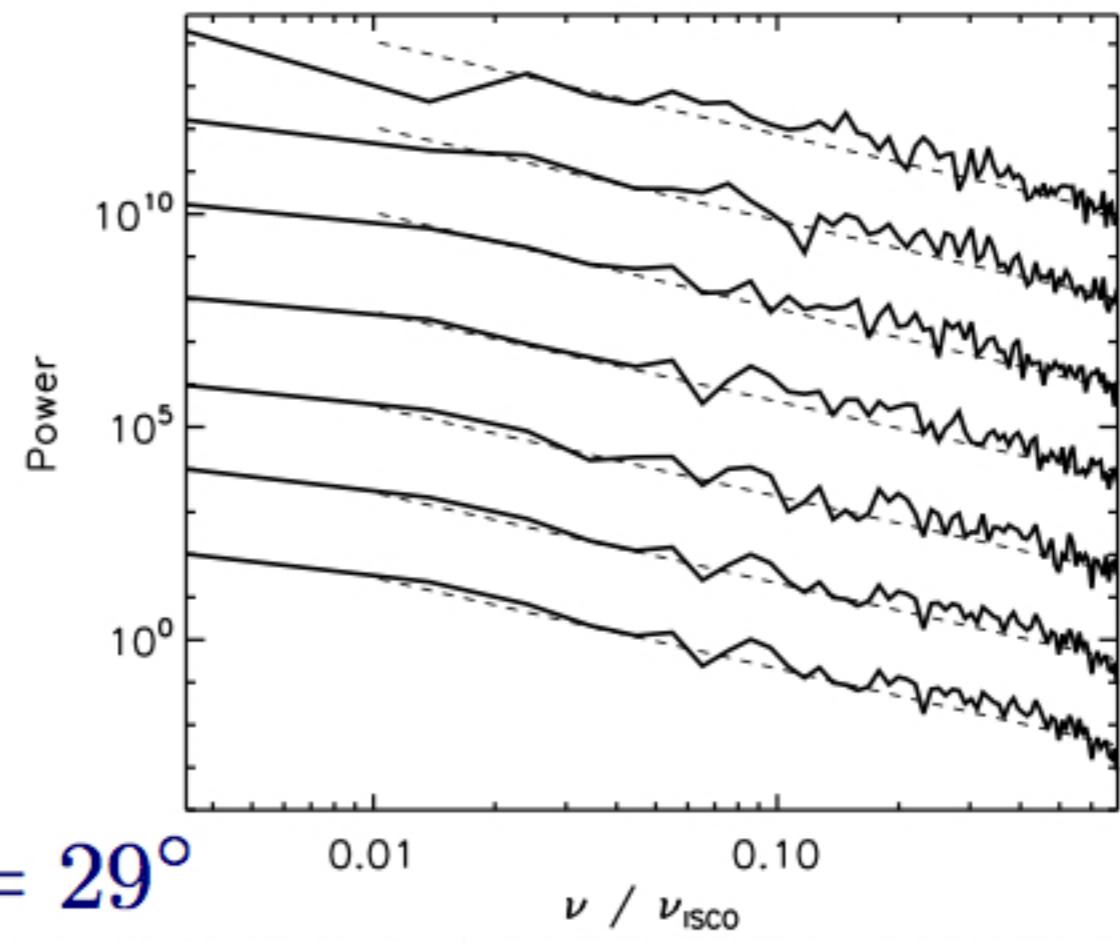
- Use “thin disk” cooling rate in corona as emissivity
- Thomson Opacity model (e- scattering)
- Integrate to photosphere ( $\tau = 1$ )
- Include finite light speed effect
- Parameterized by accretion rate and inclination



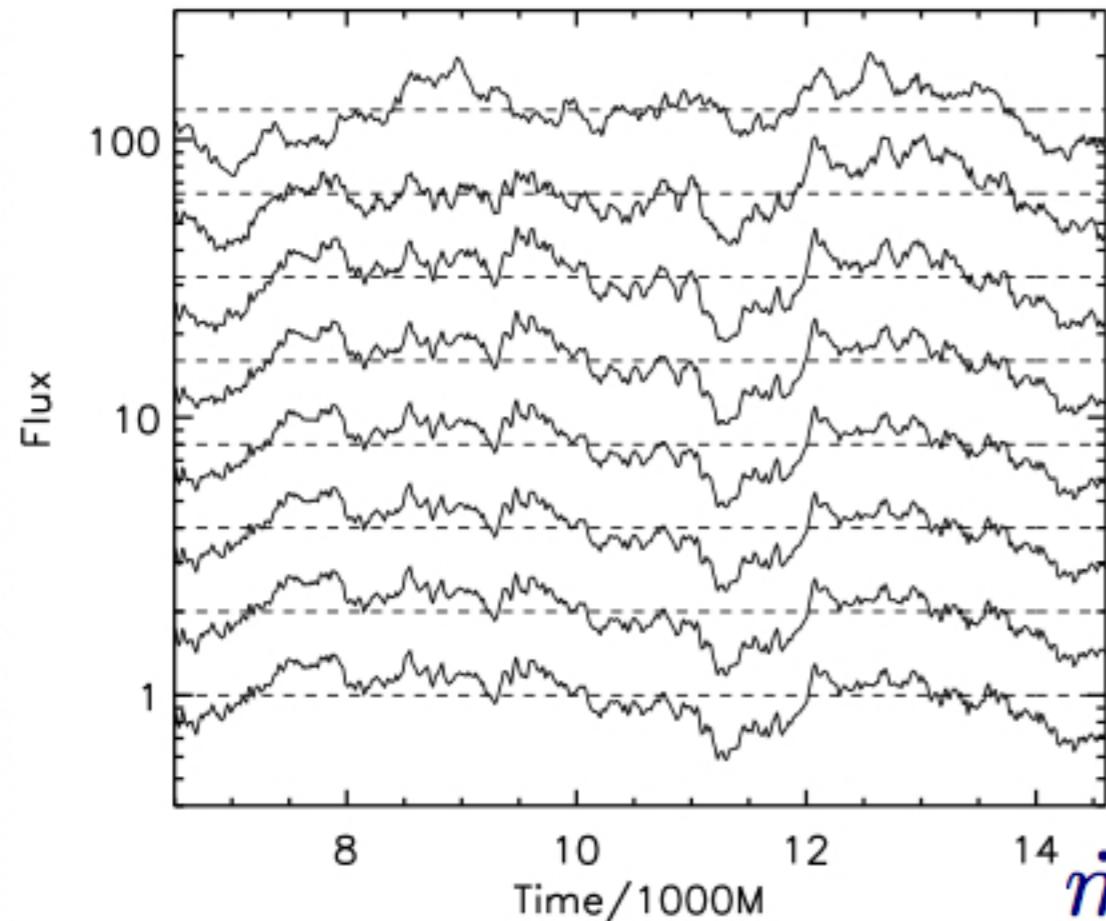
$i = 53^\circ$   
 $\dot{m} = 0.003$



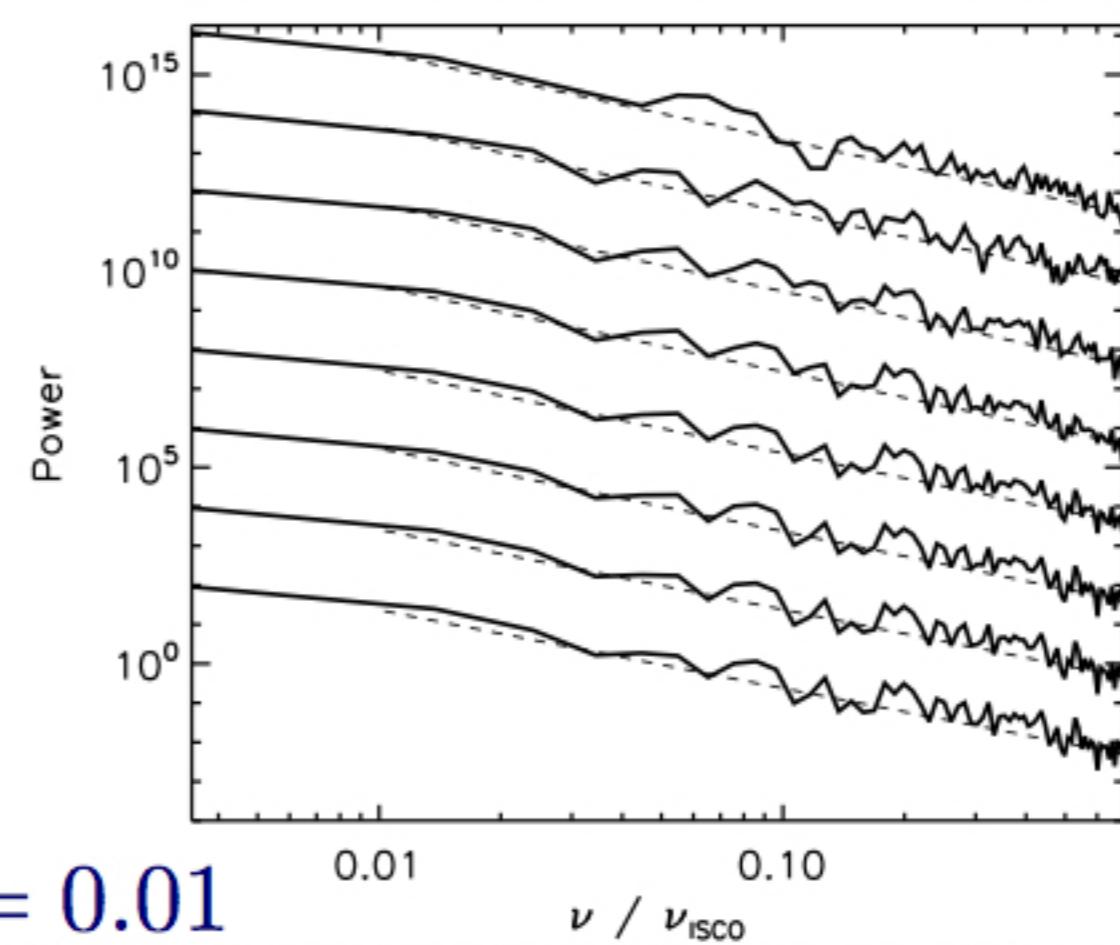
$i = 29^\circ$



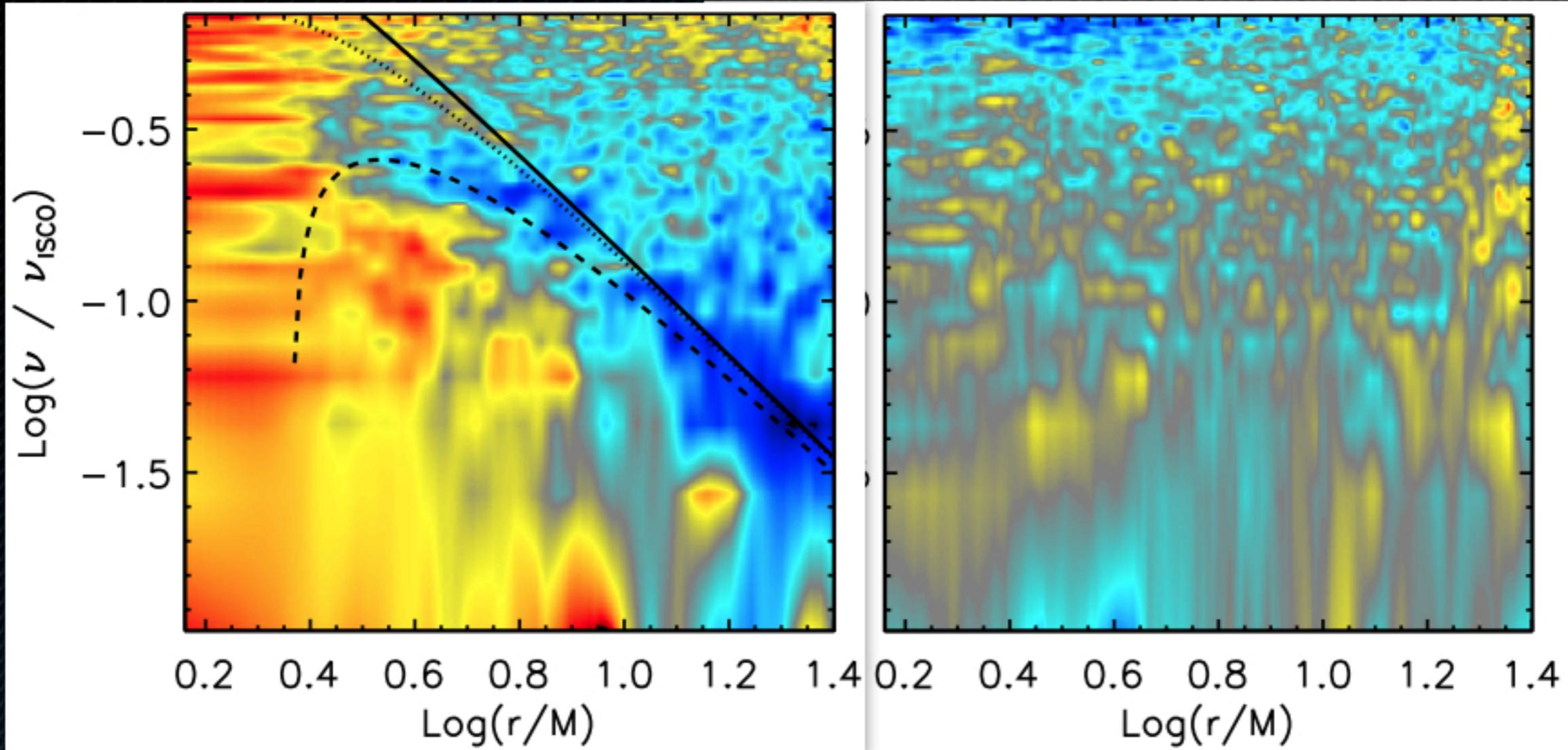
$\dot{m}$



$\dot{m} = 0.01$



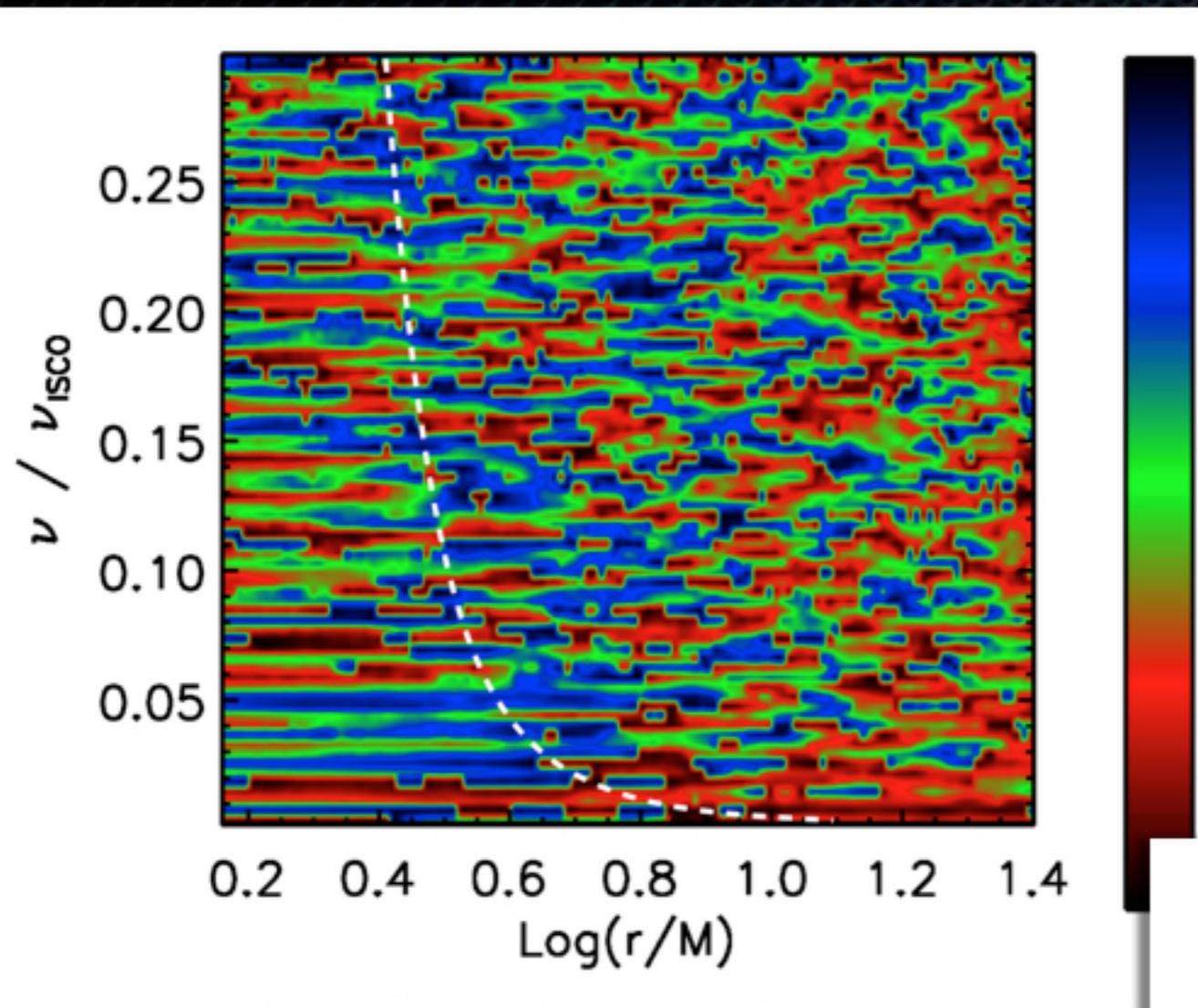
$i$



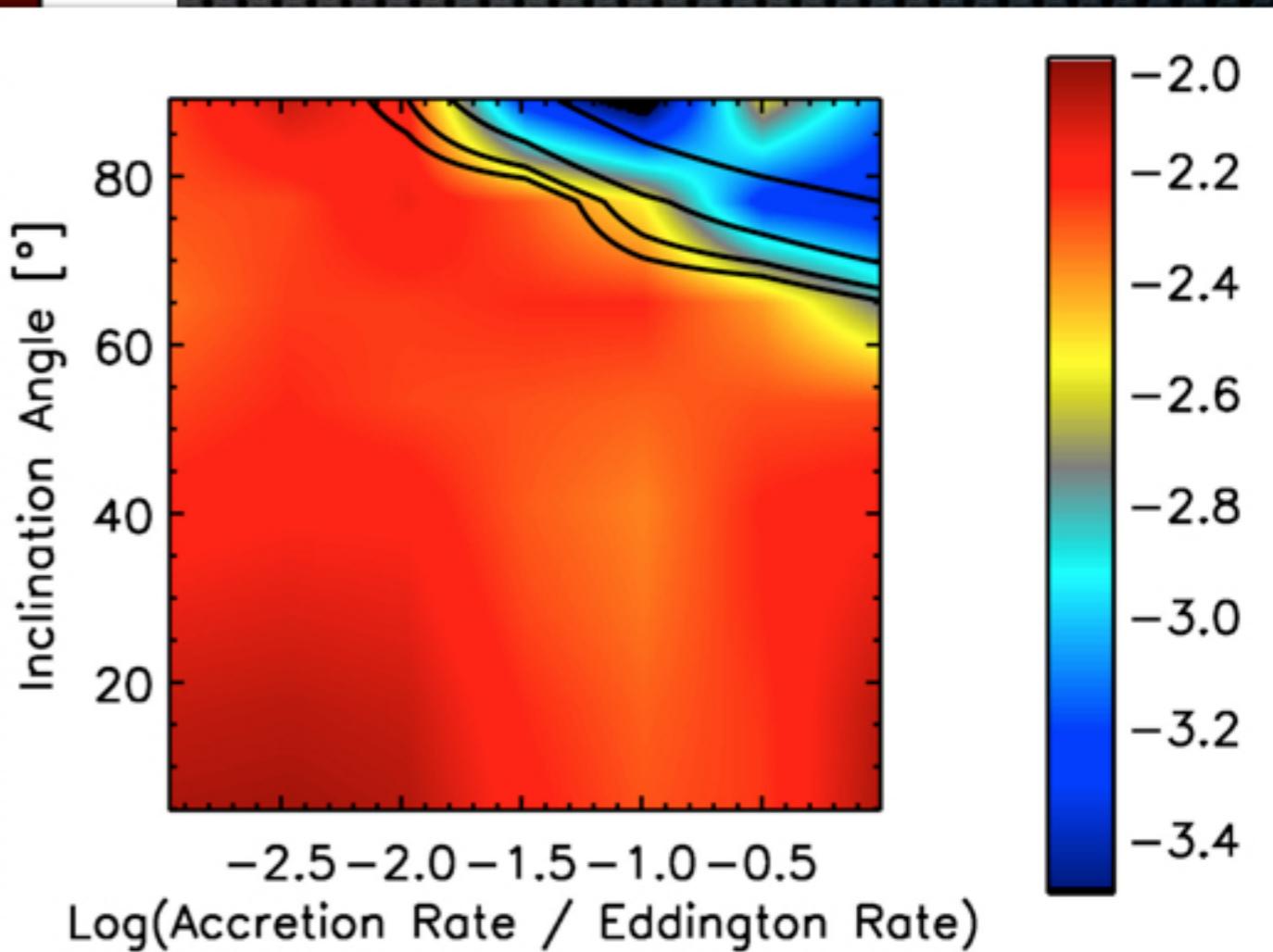
$$\log \frac{P_{\text{diss}}(\nu, r)}{P_{\dot{M}}(\nu, r)}$$

$$\log \frac{P_I(\nu, r)}{P_{\text{diss}}(\nu, r)}$$

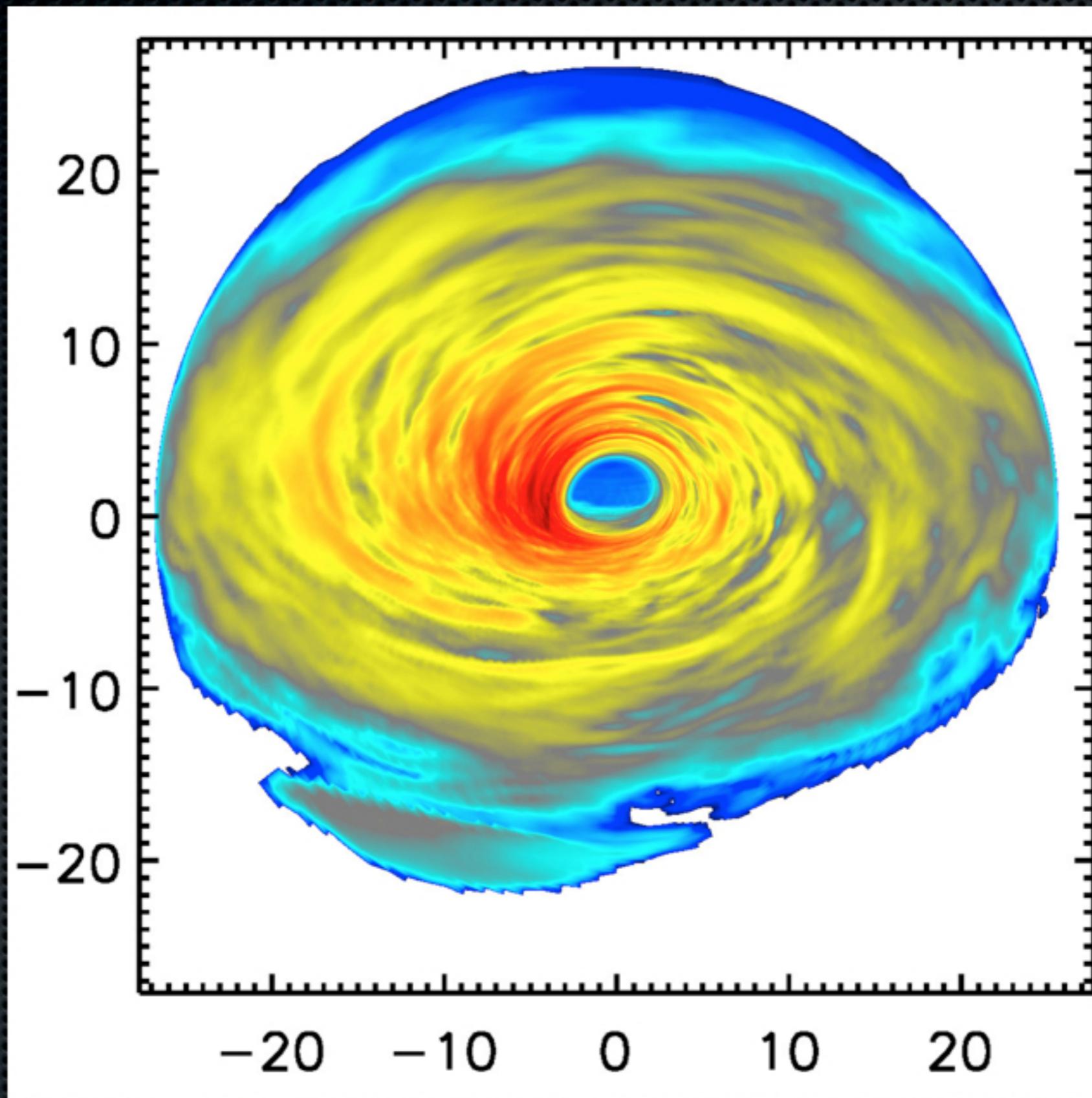
- Dissipation approximately follows accretion rate
- Not all accretion rate modes are dissipated
- Variability at infinity follows local dissipation var.



- Mostly incoherent between adjacent radii and frequencies;
- Possible coherence at  $\nu < 1/T_{\text{inflow}}(r)$
- Need longer runs to verify;

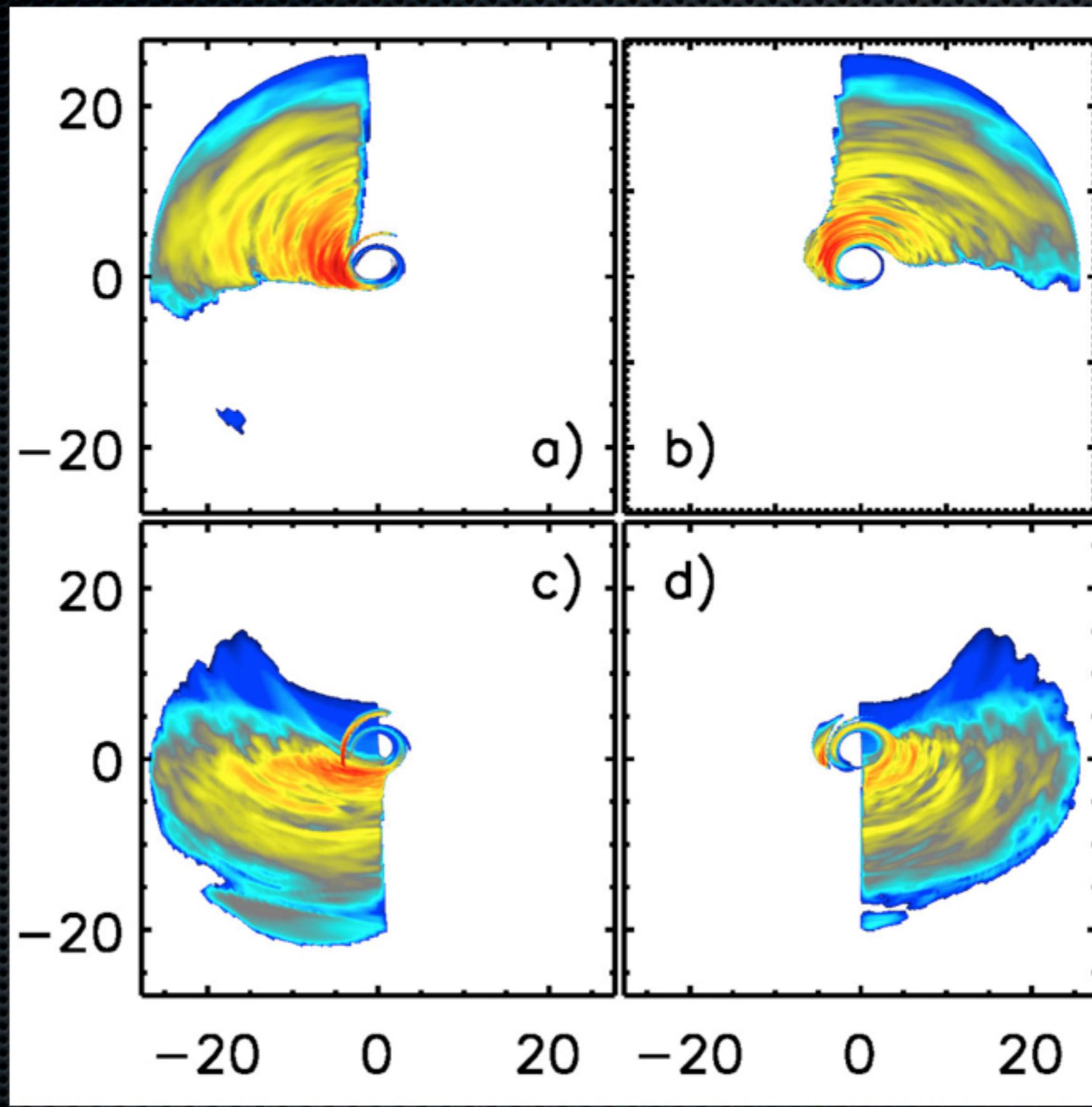


- Degenerate Result;
- No inclination angle effect;
- Consistent w/ observed power-law exponents
- See no QPOs, though we lie between LFQPO and HFQPO range



# Degeneracy Explanation

$\alpha_a > -2$



$\alpha_b > -2$

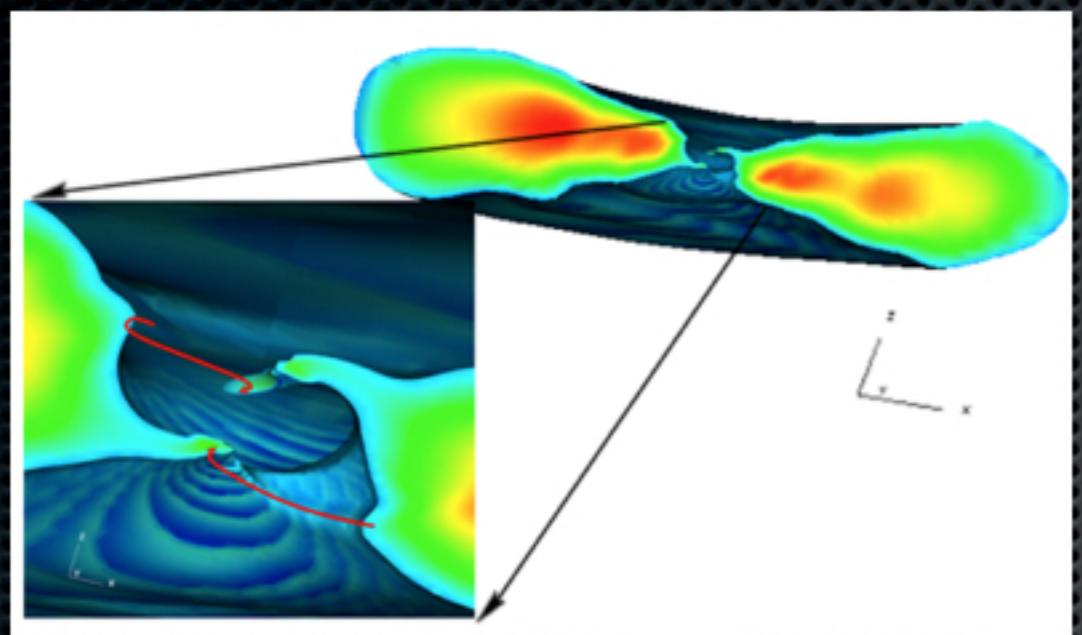
$\alpha_c < -2$

$\alpha_d < -2$

$i \sim 0^\circ$   
 $\alpha_i \simeq -2$

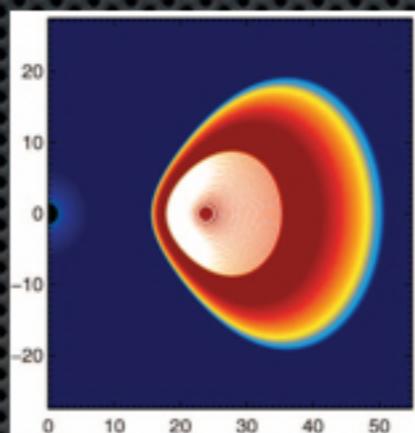
# Incomplete List of Out-standing Issues in BH Accretion

Warped Disks

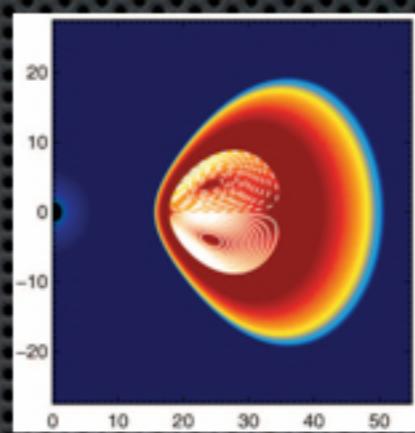


Fragile et al. 2007-2009

Initial Field Topology



Poloidal



Quadrupolar

Beckwith et al. 2008

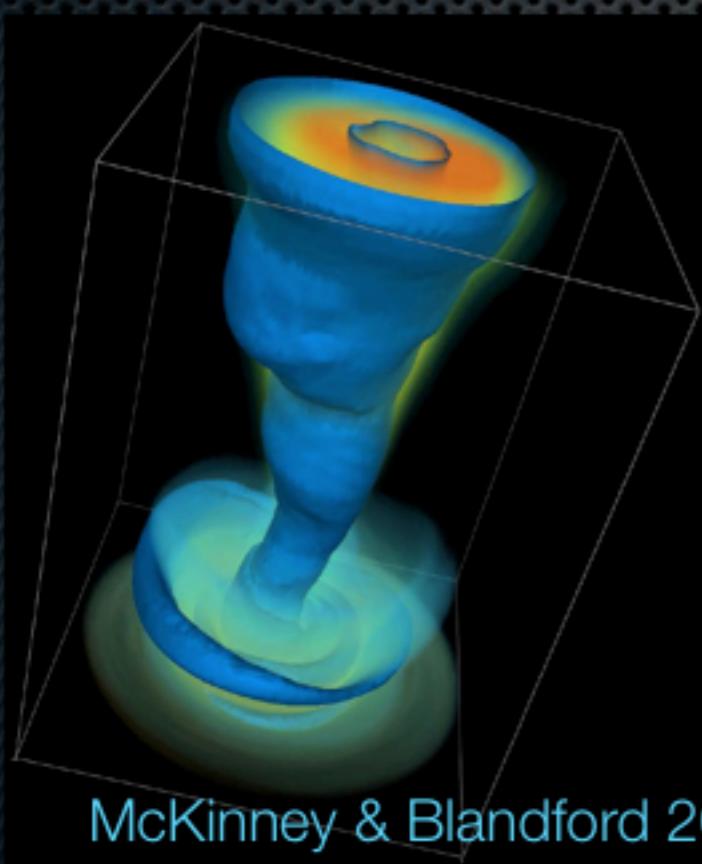
Image  
Unavailable

Toroidal

Jet

Jet

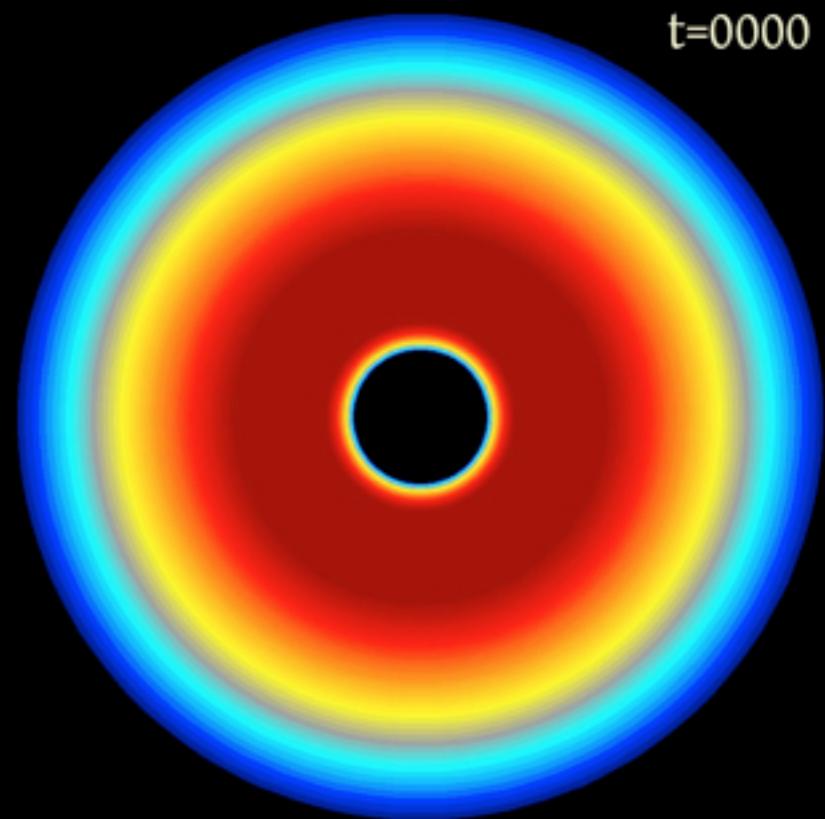
"No" Jet



McKinney & Blandford 2009

Full  $2\pi$  Evolutions  
 $m=1$  mode dominance

Gammie et al (unpub.)



# Summary & Conclusion:

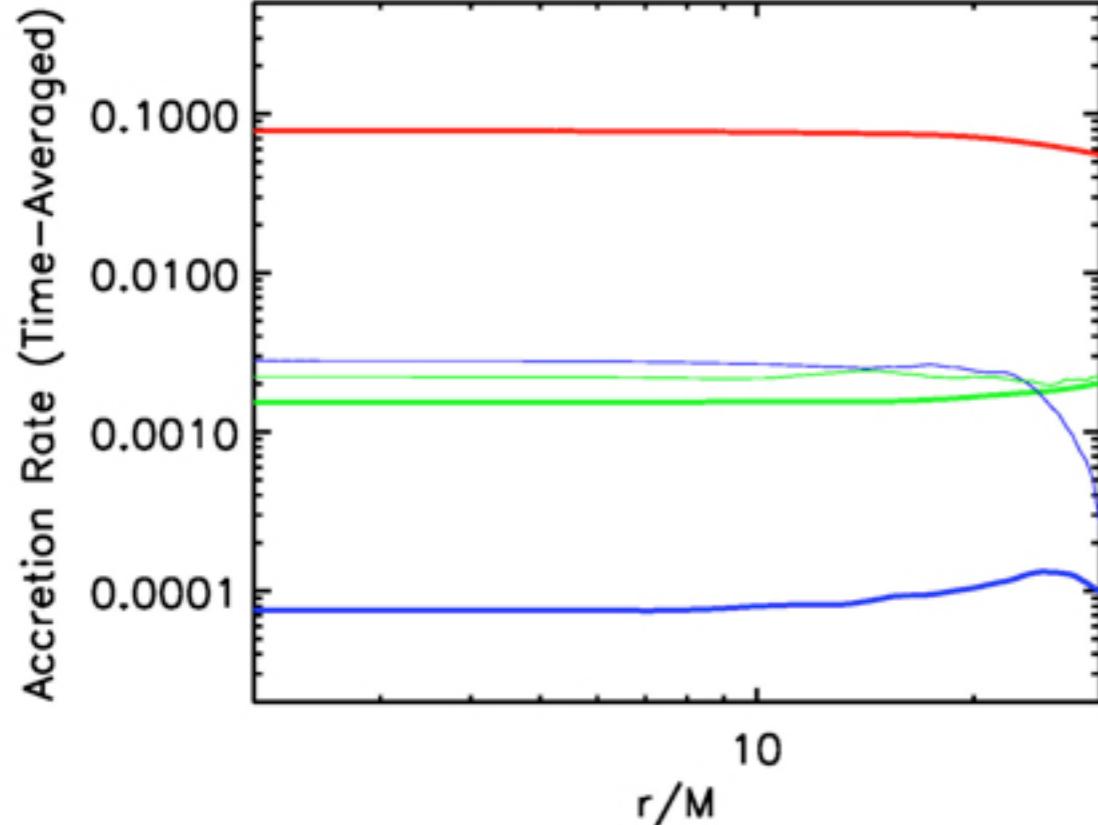
- Moving towards fully self-consistent accretion models;
- Magnetic fields can change the “thin disk” picture within the ISCO;
- Radiative efficiency increases with decreasing disk thickness
- Our two spin cases suggest that radiative efficiency accretion may be ~10% more efficient
- Our ray-traced simulation calculation suggests that present thermal spectrum fits may over-estimate black hole spin
  - Error (in the case presented) is at least as large as other uncertainties
- Simulation’s variability consistent with observations

# Future Work and Open Questions:

- More H(R)/R and spins: (use simulations to fit to observations);
- Does variability depend on disk thickness?
- Is the simulation’s variability within the observed near-constancy of Rmin?
- How are state transitions triggered?
- What are “realistic” (and realizable) initial disk conditions?

# Extra Slides

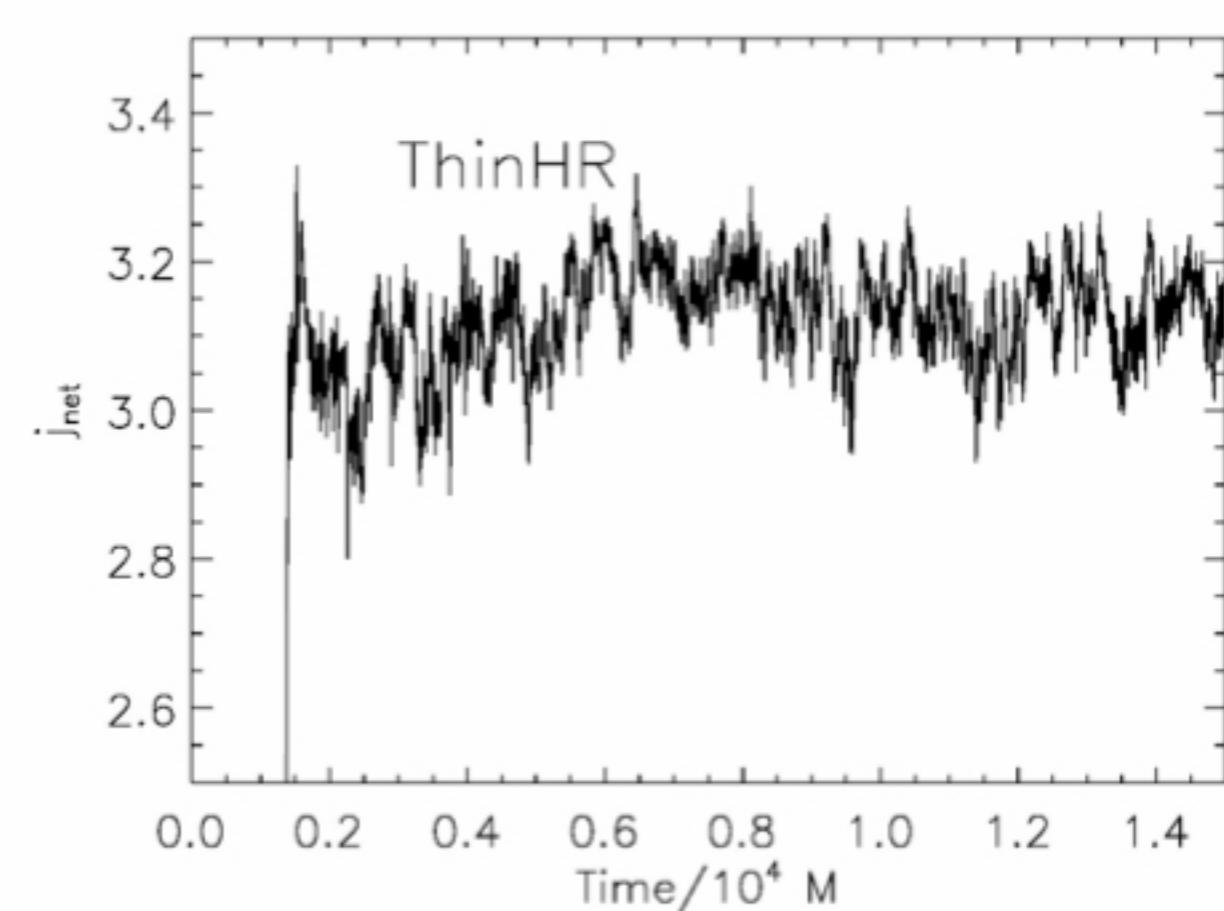
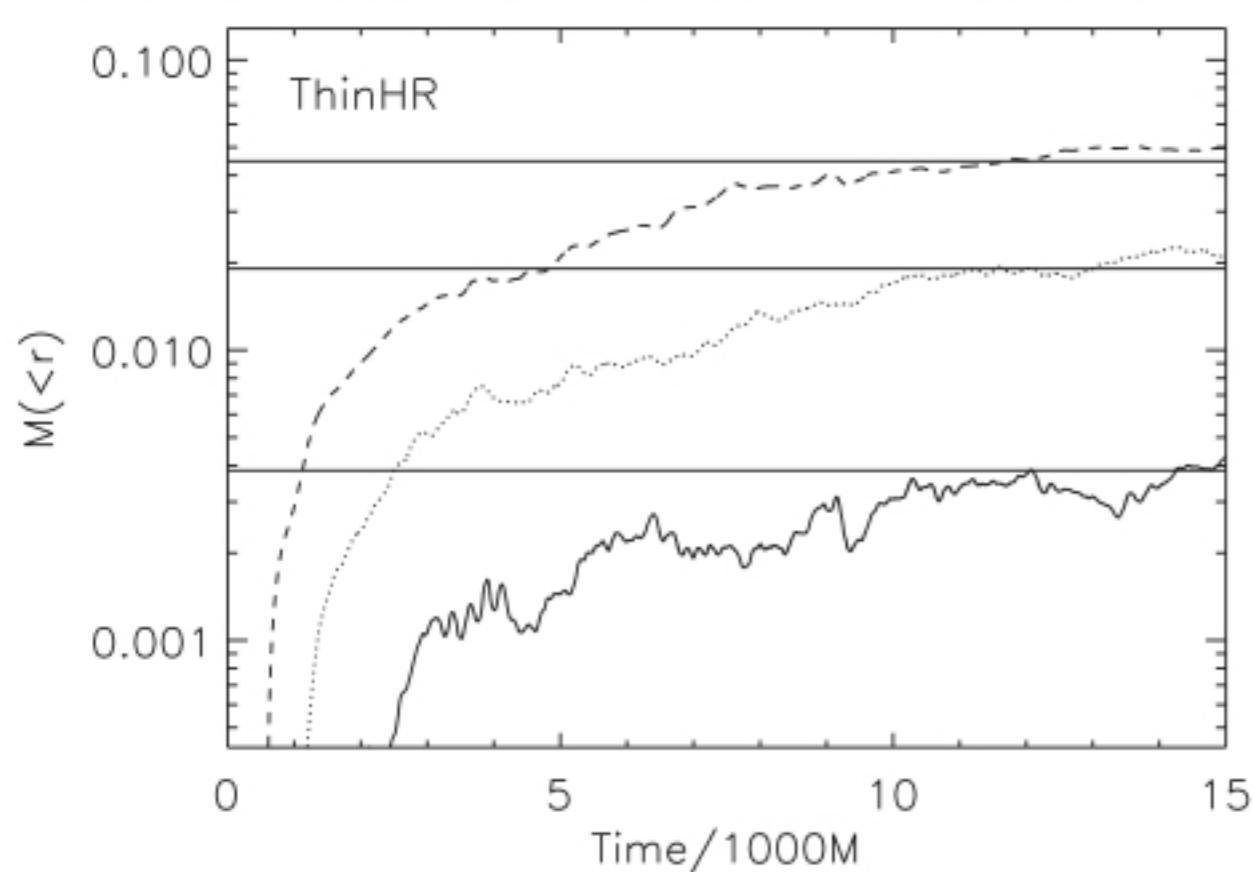
# Inflow Equilibrium



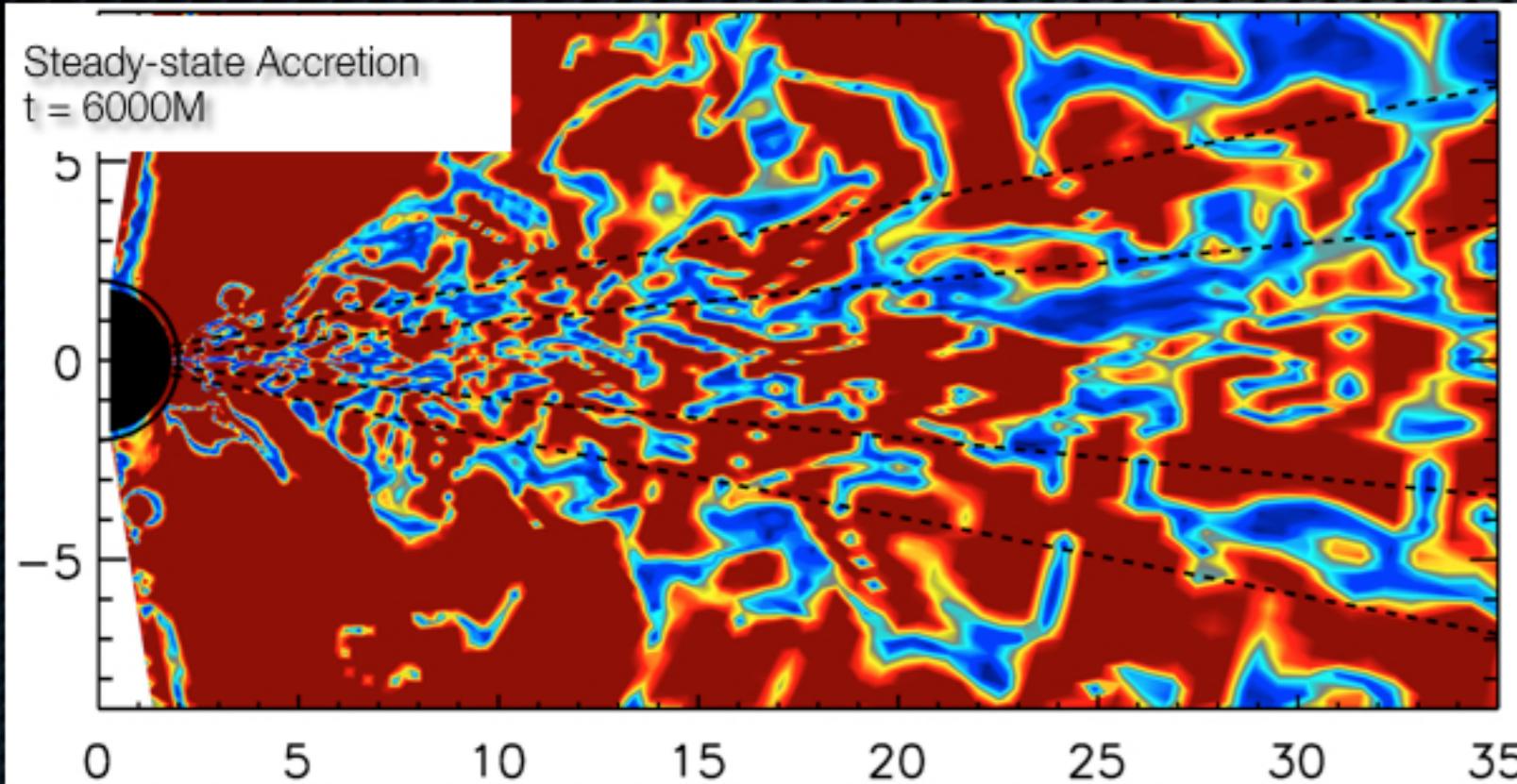
Defined to be when:

- 1) Accreted specific angular momentum ( $j_{\text{net}}$ ) is steady;
- 2) Mass flux shows no trends in time over radius;

Remember these are turbulent MHD flows---they need not reach any kind of steady-state!



# Track MRI Resolution for all time!

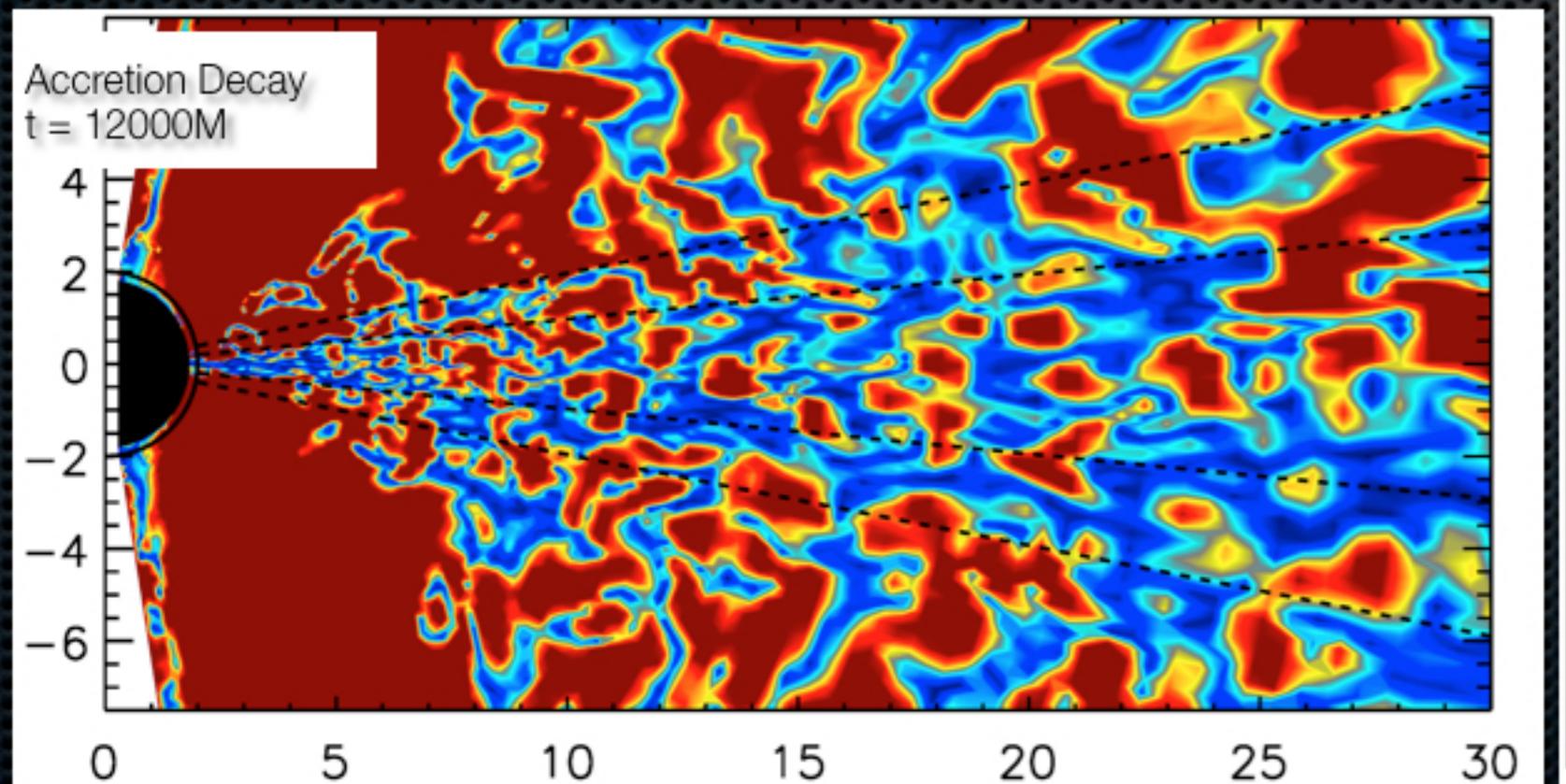


Suggestions from local  
shearing box simulations:

Sano et al. 2004

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

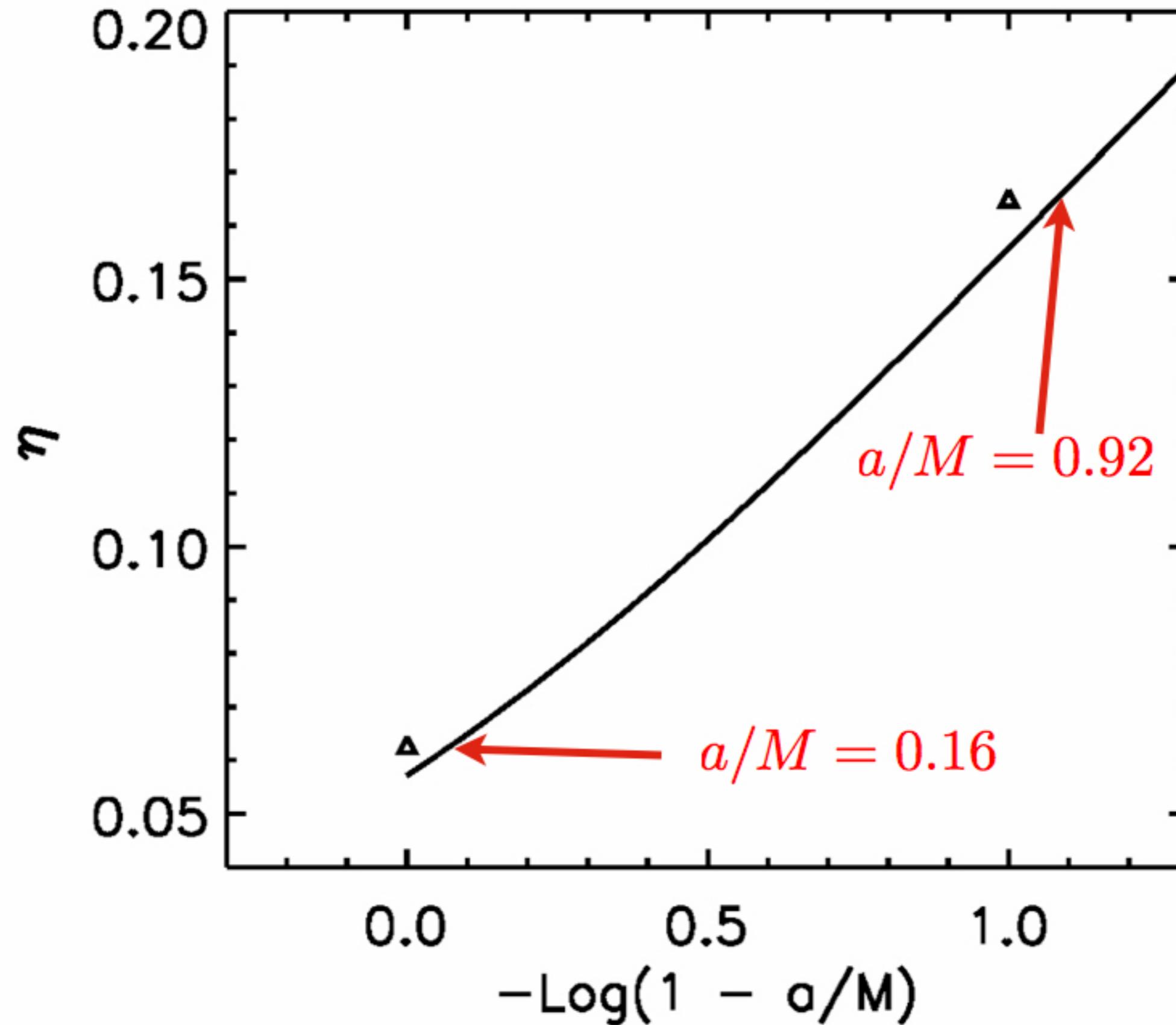
$$\frac{\lambda_{\text{MRI}}}{\Delta z} > 6$$



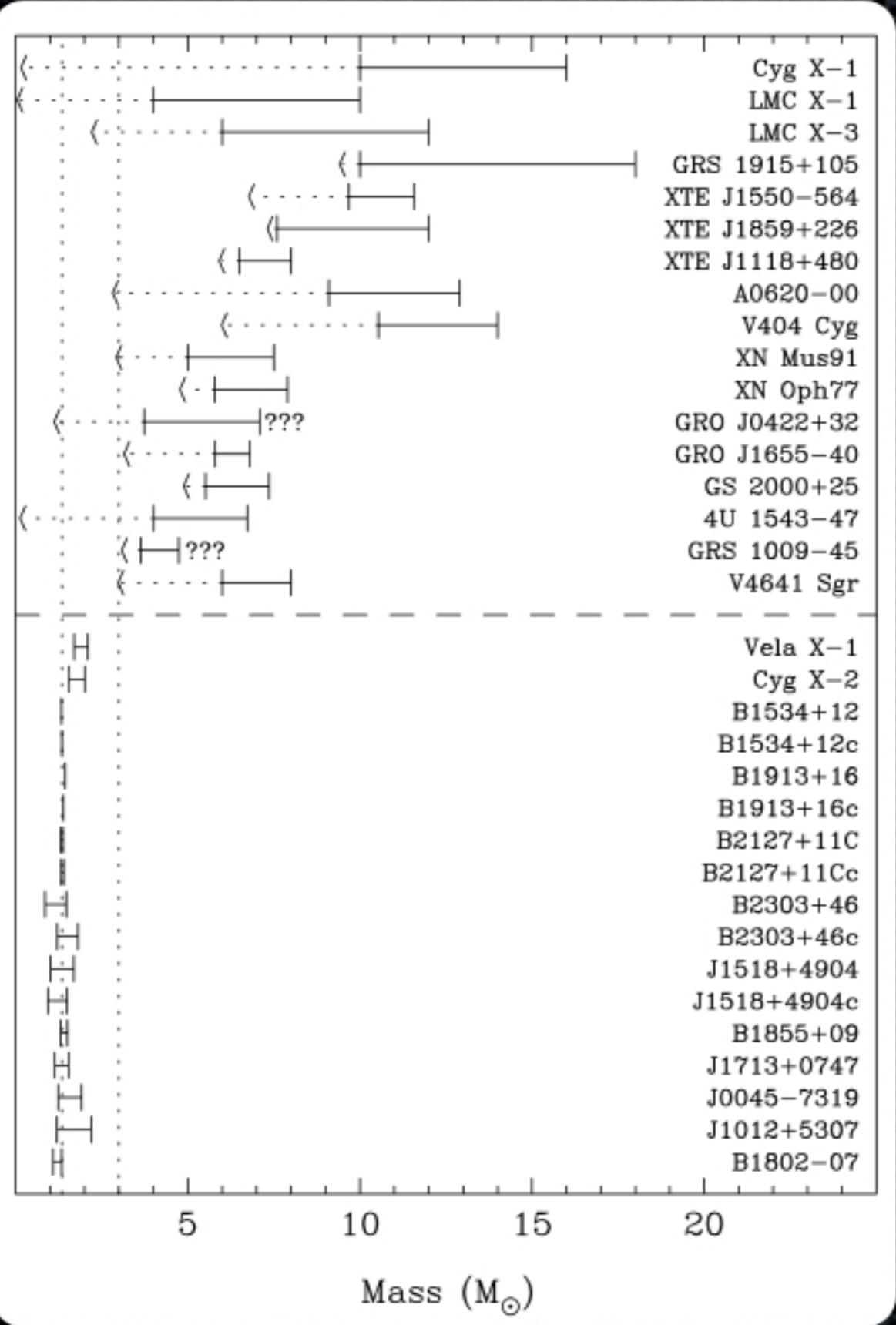
Davis, Stone, &  
Pessah 2009

$$\frac{H}{\Delta z} > 60$$

# Spin Over-estimation



# Black Hole X-ray Binaries



## Mass function

Provides firm lower bounds on mass of the black hole

Actual Mass M1 is found by modeling the light bending from the companion star to get the inclination angle

Neutron stars ruled out for most XRBs, as their predicted maximum mass is  $3M_{\odot}$

Lack of stellar surface emission lends credence to presence of an event horizon.