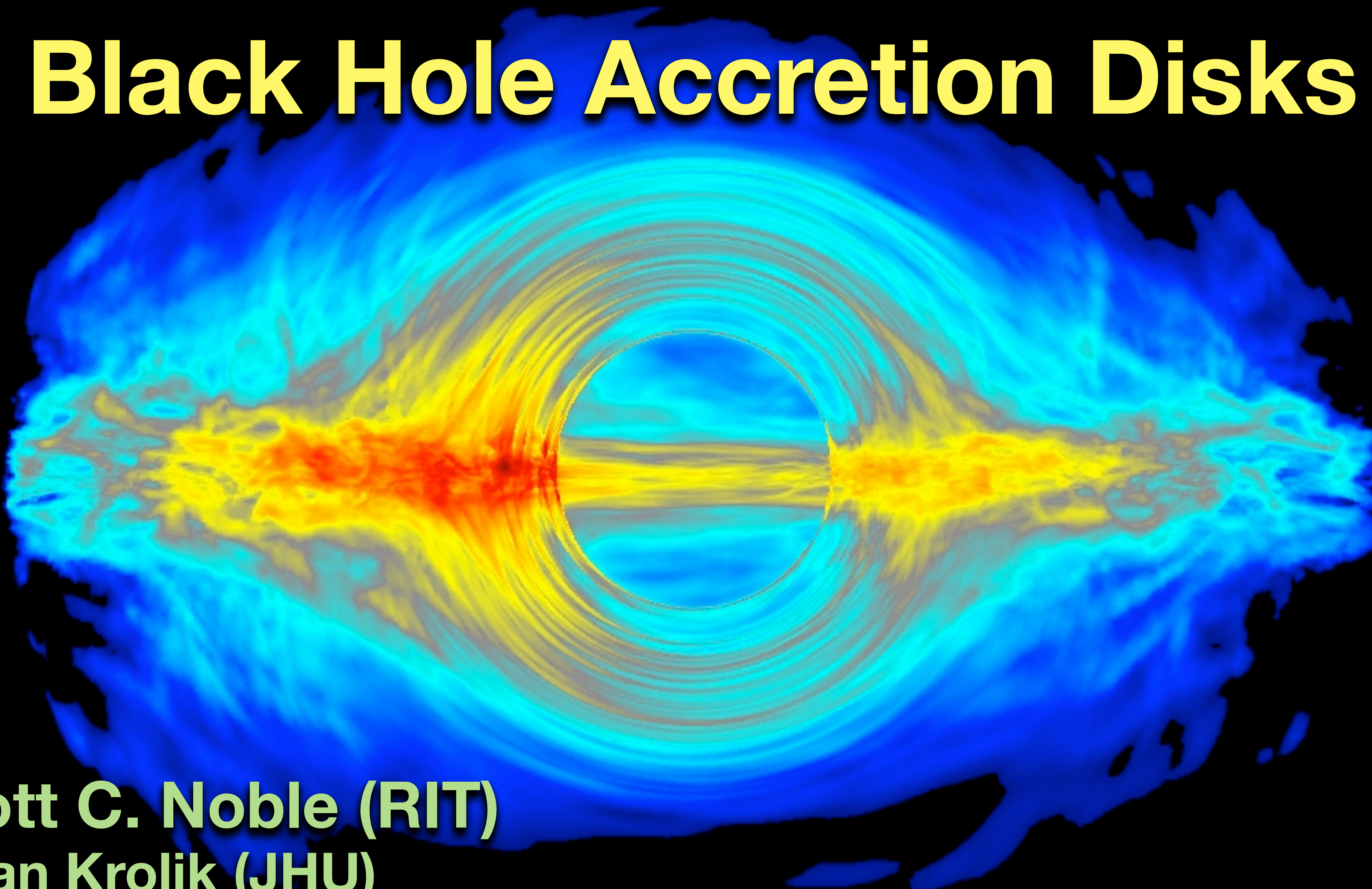
MHD Simulations of Black Hole Accretion Disks



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Julian Krolik (JHU)

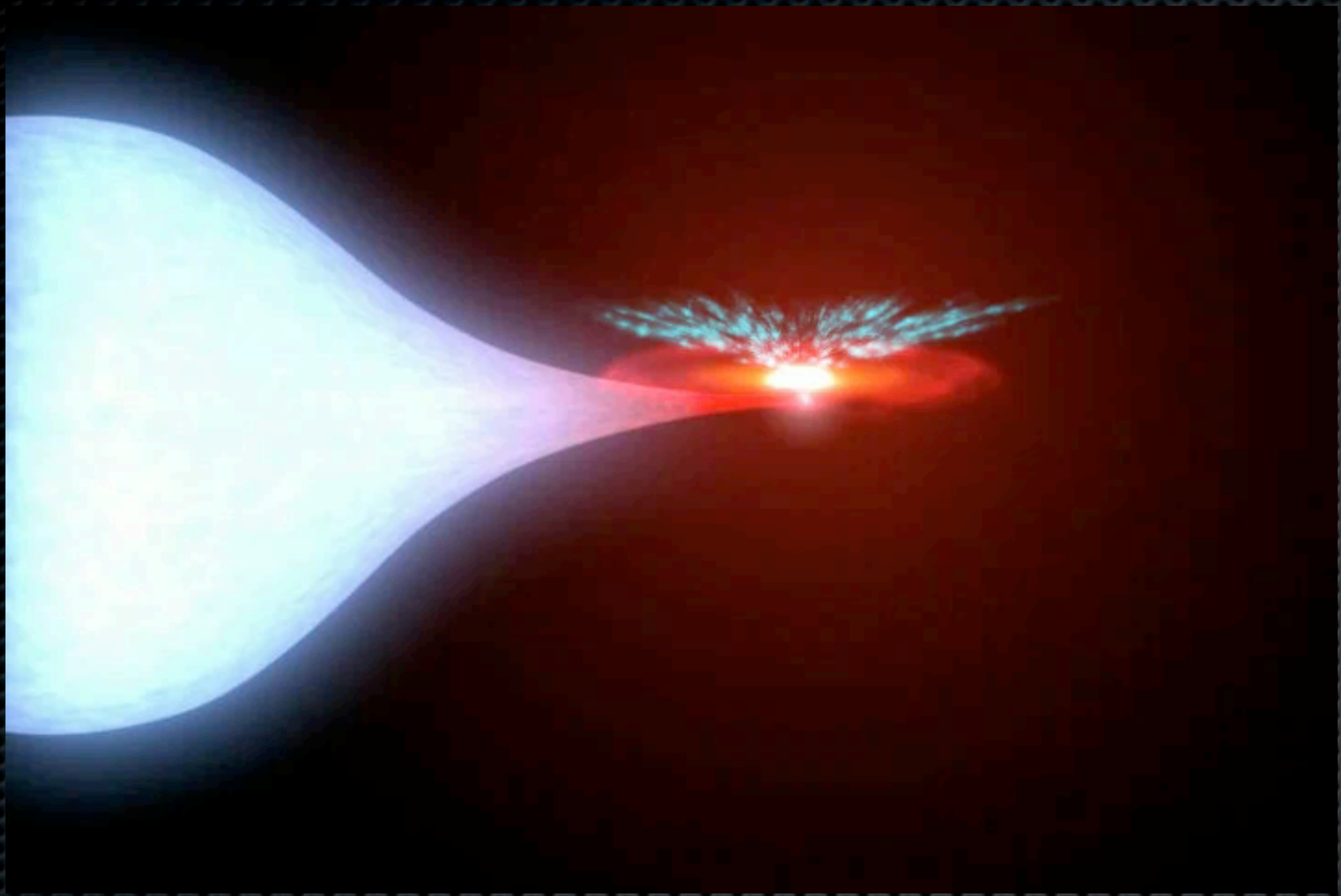
John Hawley (UVa)

Jeremy Schnittman (NASA/GSFC)

SNOWPAC

February 1, 2011

Black Hole X-ray Binaries



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

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

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

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

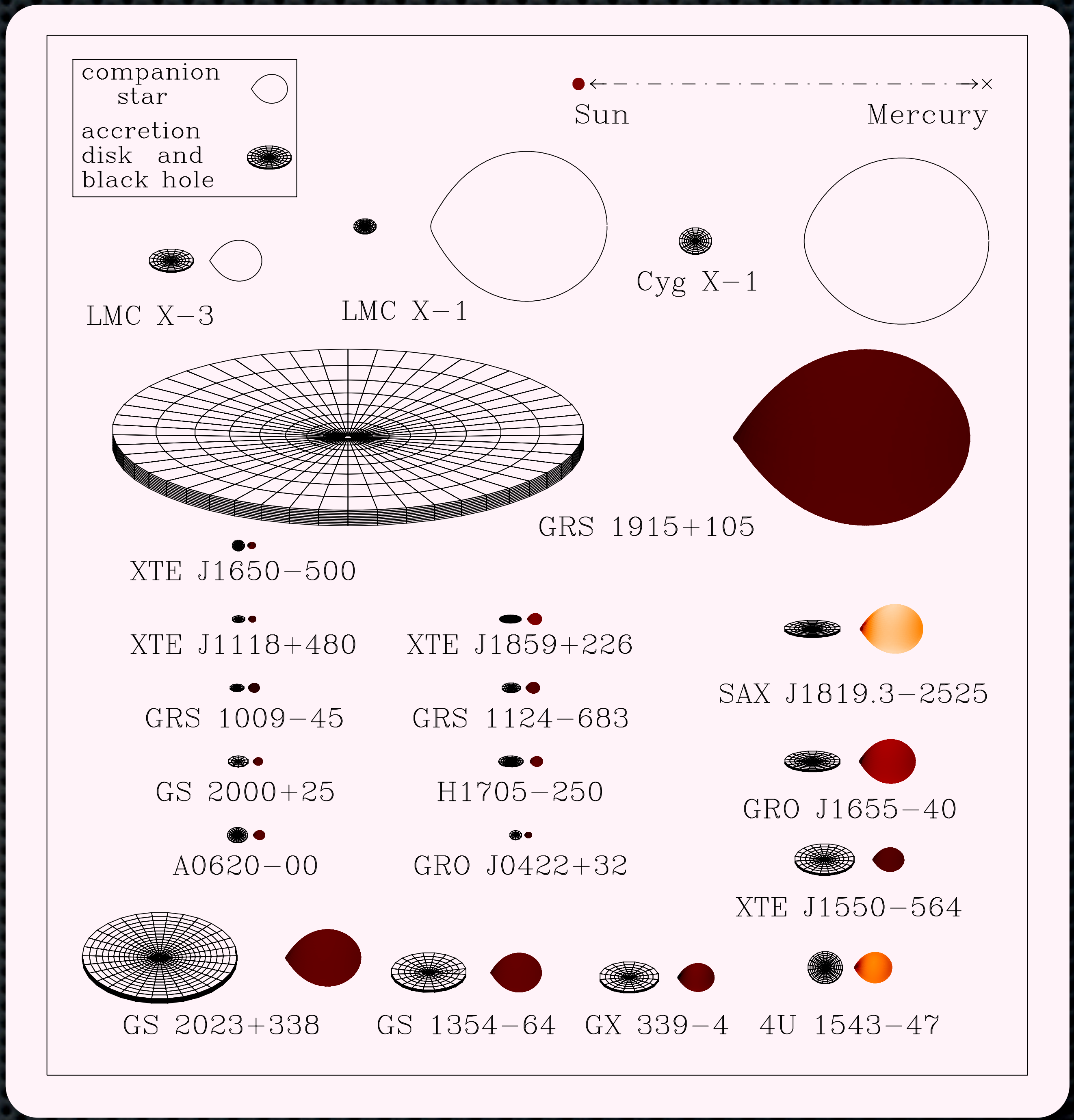
- Black hole X-ray binaries exhibit rich phenomena
- X-ray hot matter serves as spacetime surveyors
  - Black holes uniquely parameterized by mass (M) and spin (a) in GR
  - Test GR, e.g., |a/M| > 1 ?
  - Constraints on SN models, re: nascent spin/masses of their product BHs
  - BH spin evolution, mass 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 suspsects**
- **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**
- $R_{\rm disk} \sim R_\odot \sim 10^5 r_g$
- **Mass function**

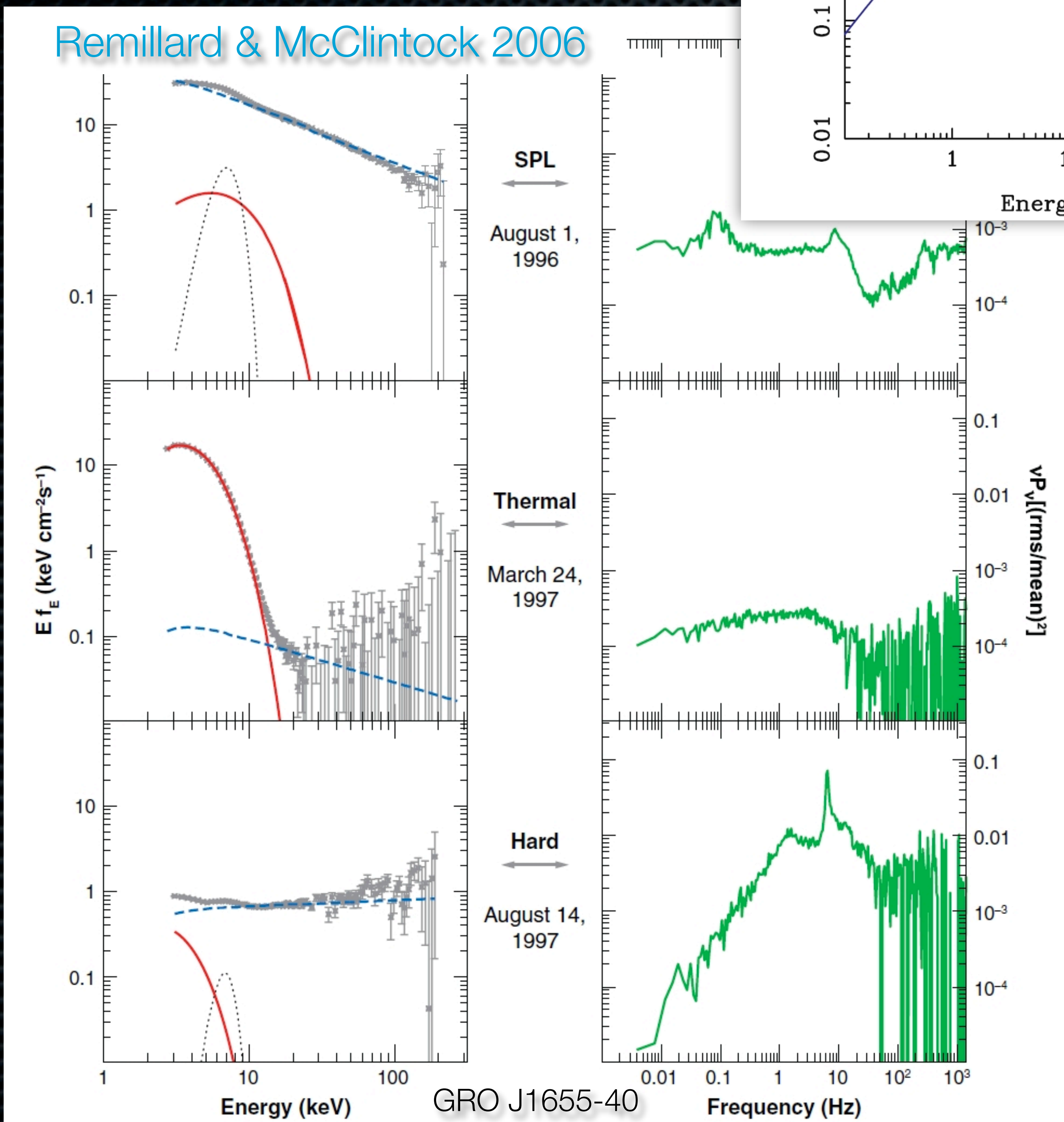
$$f(M) = \frac{P_{\rm orb} K_2^3}{2\pi G} = \frac{M_{\rm BH} sin^3 i}{(1 + M_\star / M_{\rm BH})^2}$$

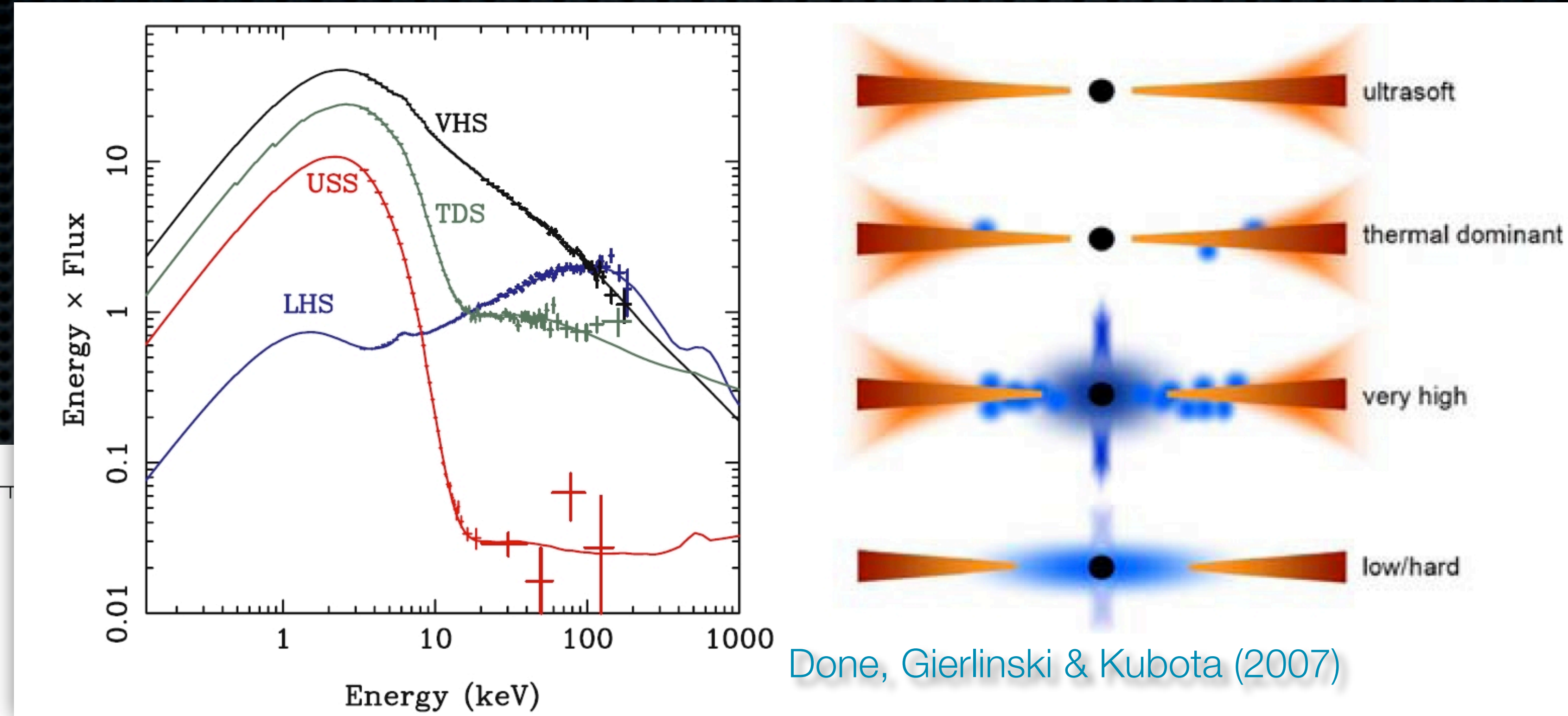
- $M_{\rm BH} \gtrsim 3 M_\odot$
- **Neutron stars "ruled out" for most BHBs via mass function limit and because BHBs lack surface emission**



J. Orosz (c. 2011)
http://mintaka.sdsu.edu/faculty/orosz/web/

Accretion States





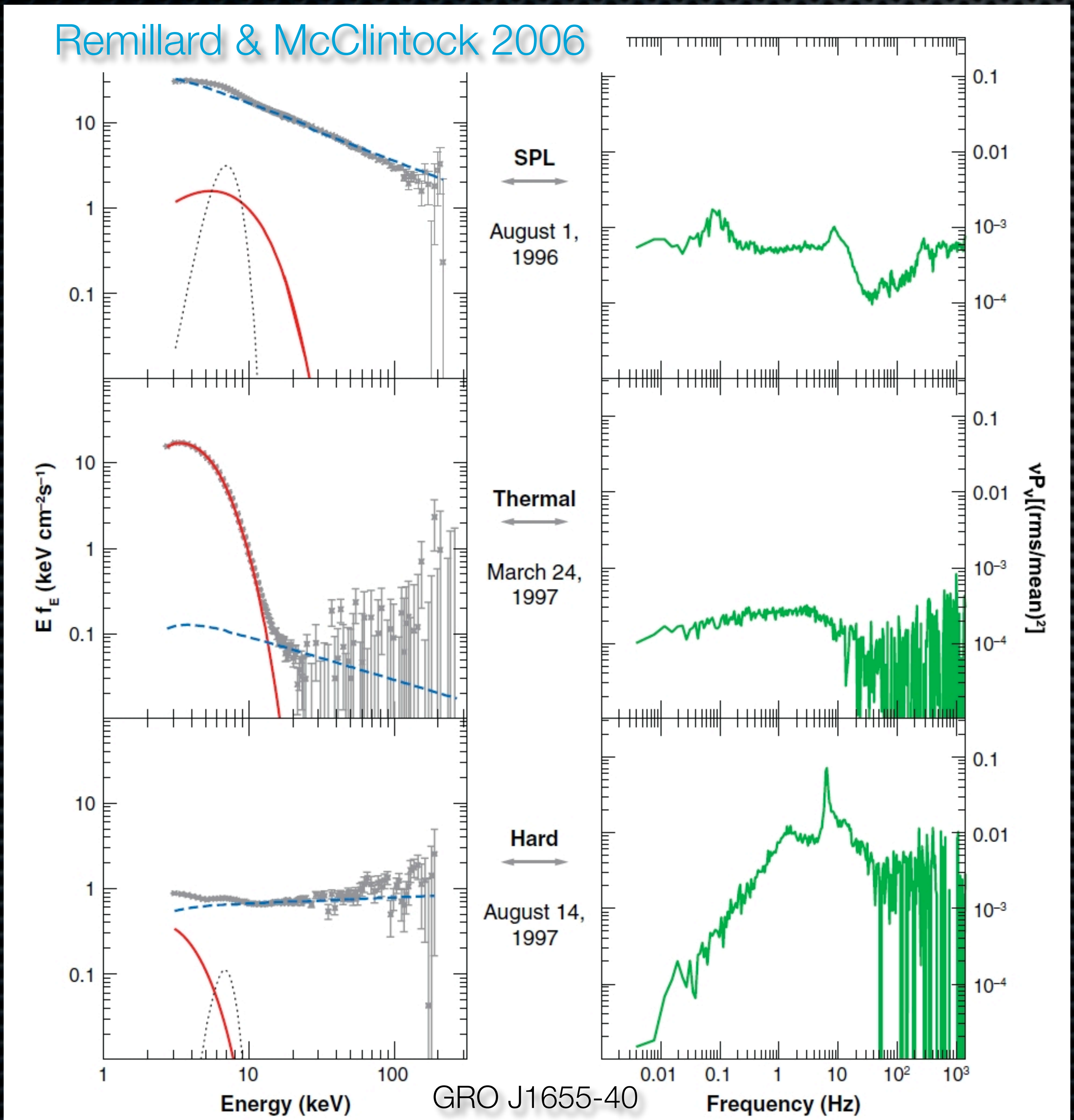
Flux Components:

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

Temporal Variability:

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

Accretion States



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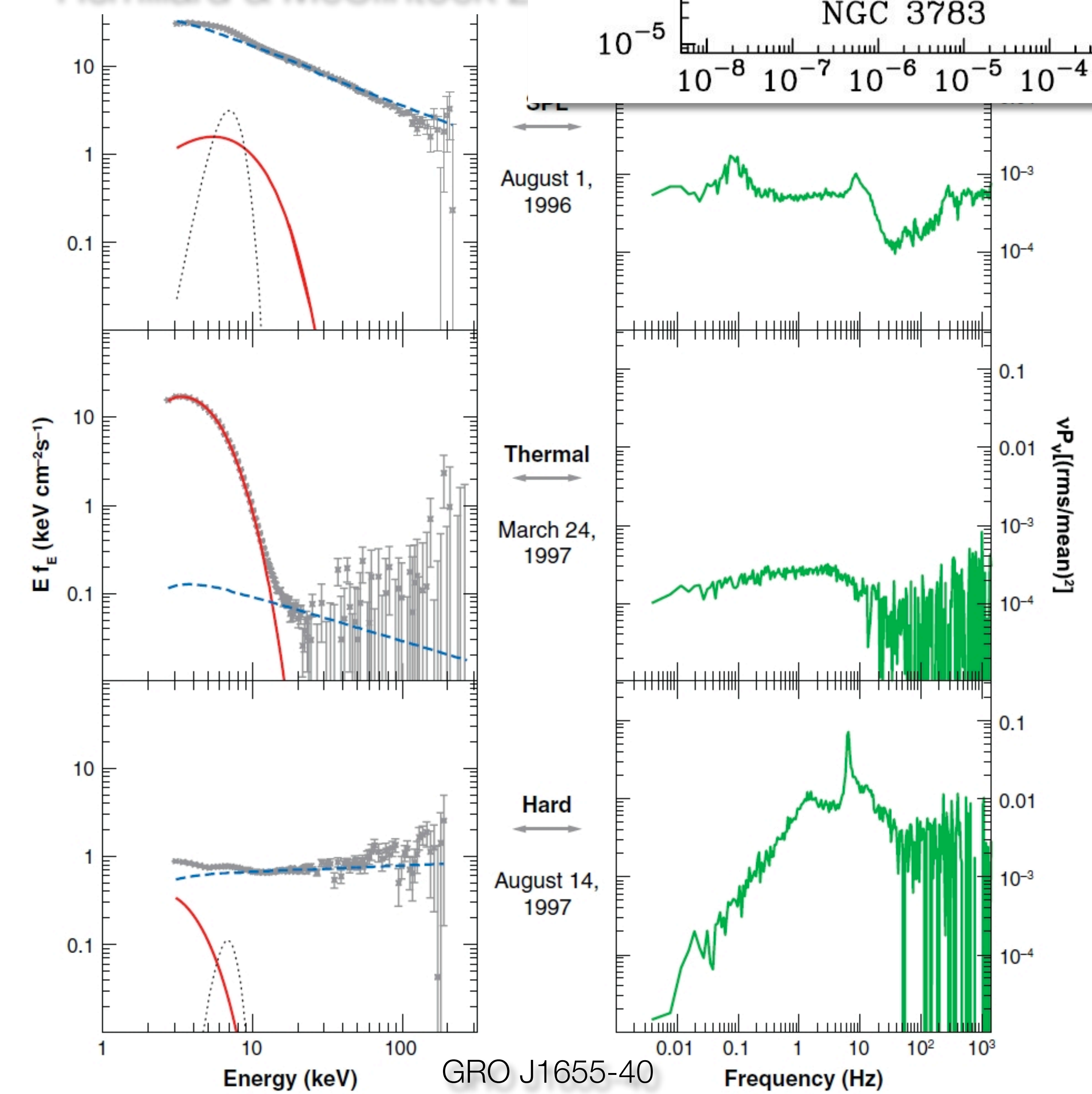
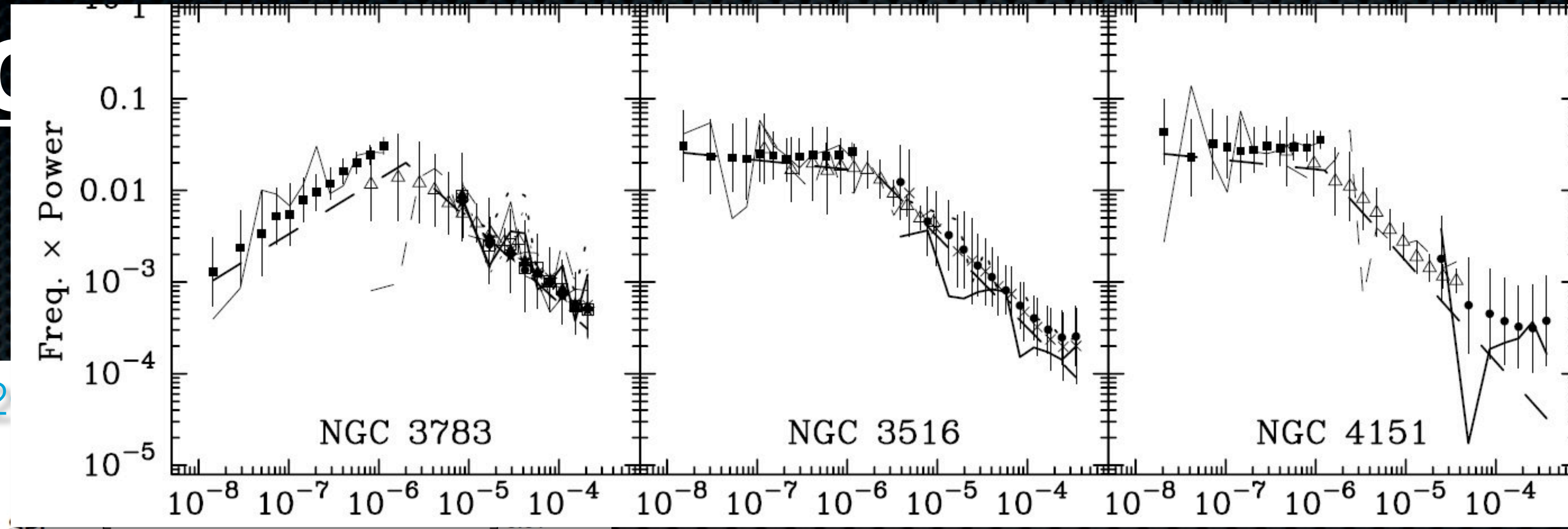
Accreti States

Remillard & McClintock 2





AGN

Markowitz et al 2003

Flux Components:

- Bulk --> Thermal
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- Reflection --> Fe K Line

Temporal Variability:

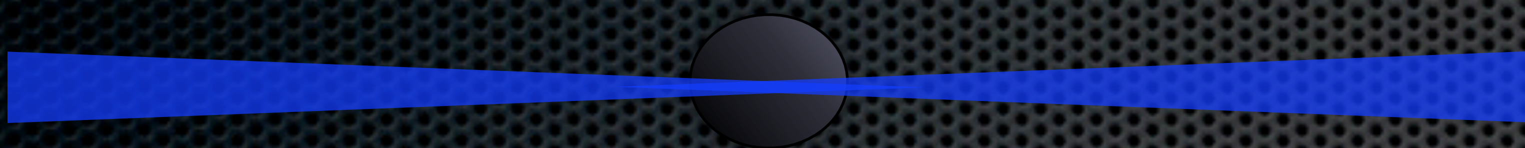
- $P \sim \nu^{\alpha} \quad -3 < \alpha < -1$
  - QPOs High & Low

Disk “Dichotomy”

Thin Disks:

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

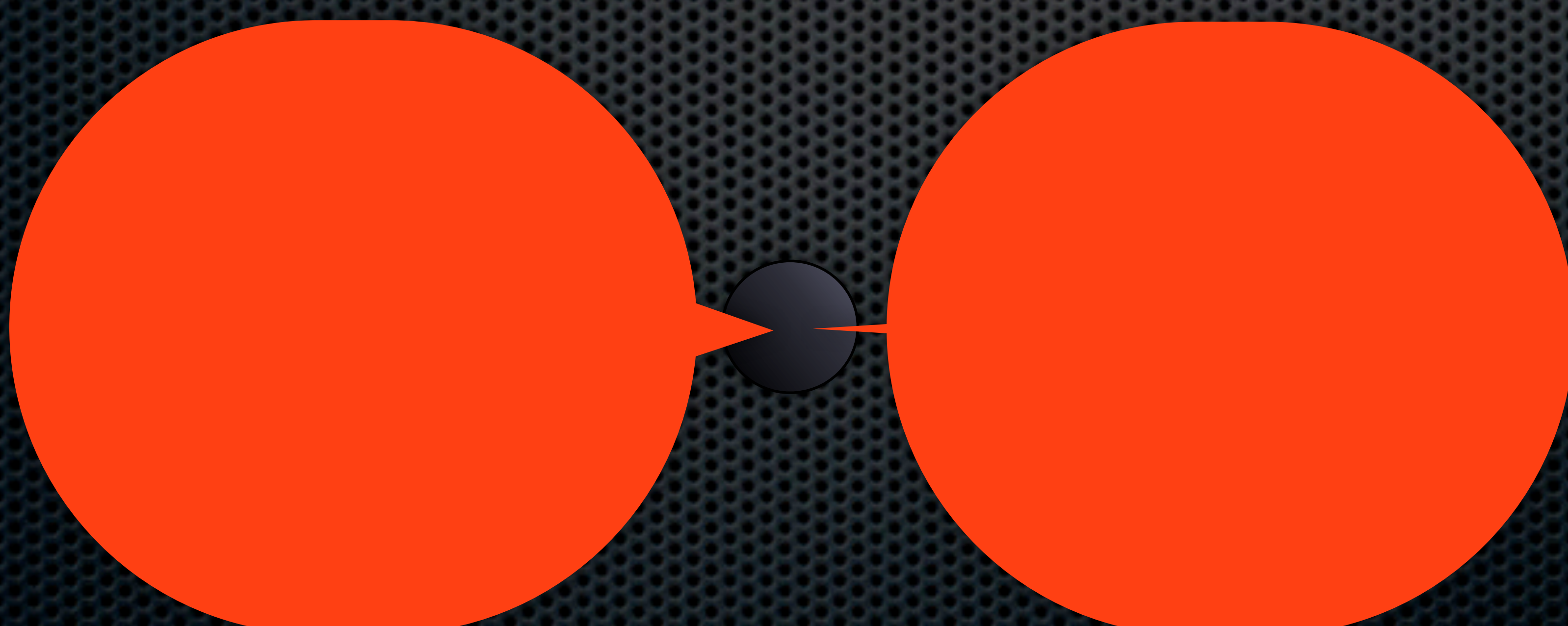
- Dissipation Rate < Cooling Rate
- “Cold” , Optically Thick
- Thermal or Multi-temperature black body

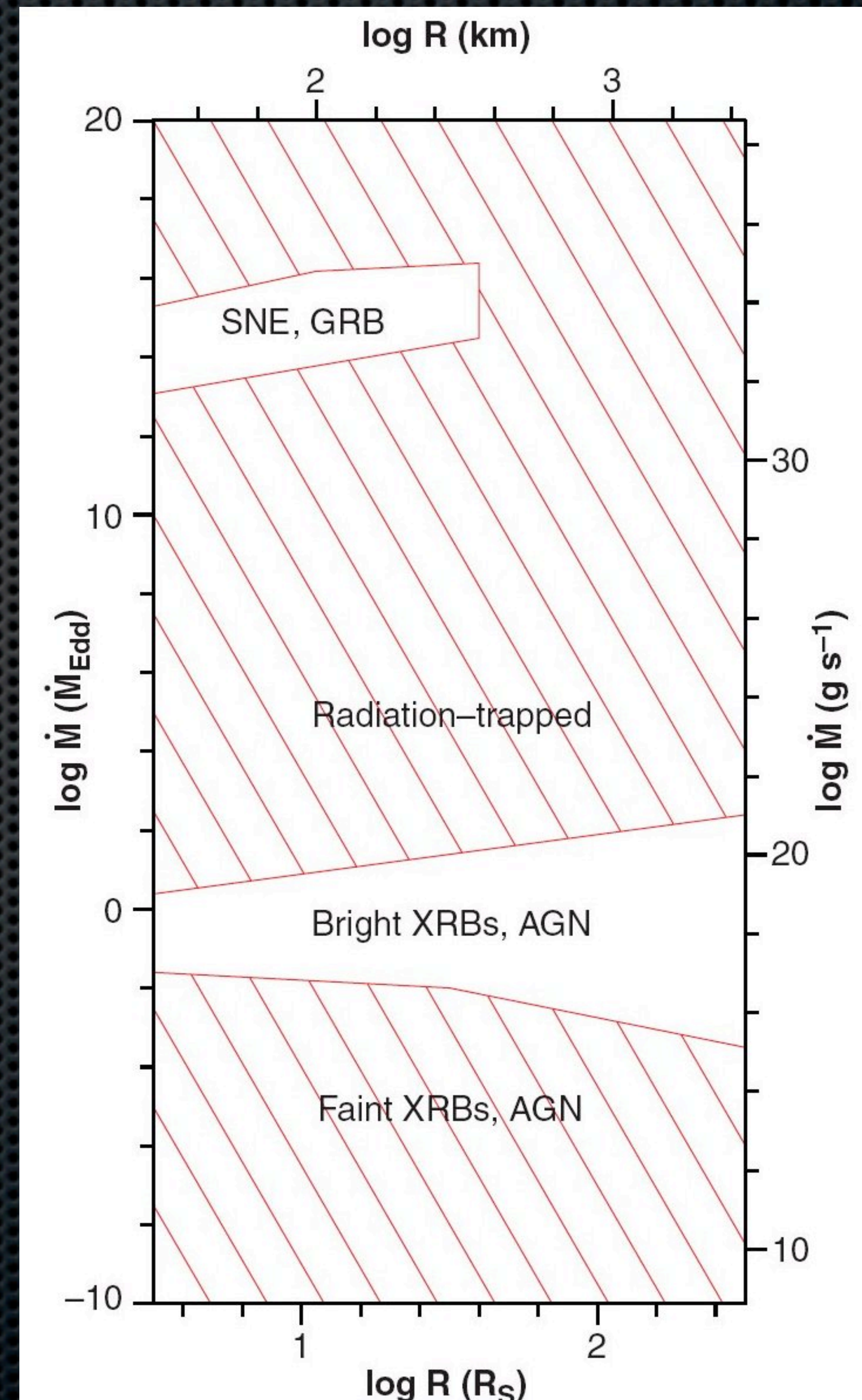


Thick Disks:

- Narayan & Yi (1994-5) (ADAF)
- Blandford & Begelman (1999) (ADIOS)
- Quataert & Gruzinov (2000) (CDAF)

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





Narayan & Quataert (2005)

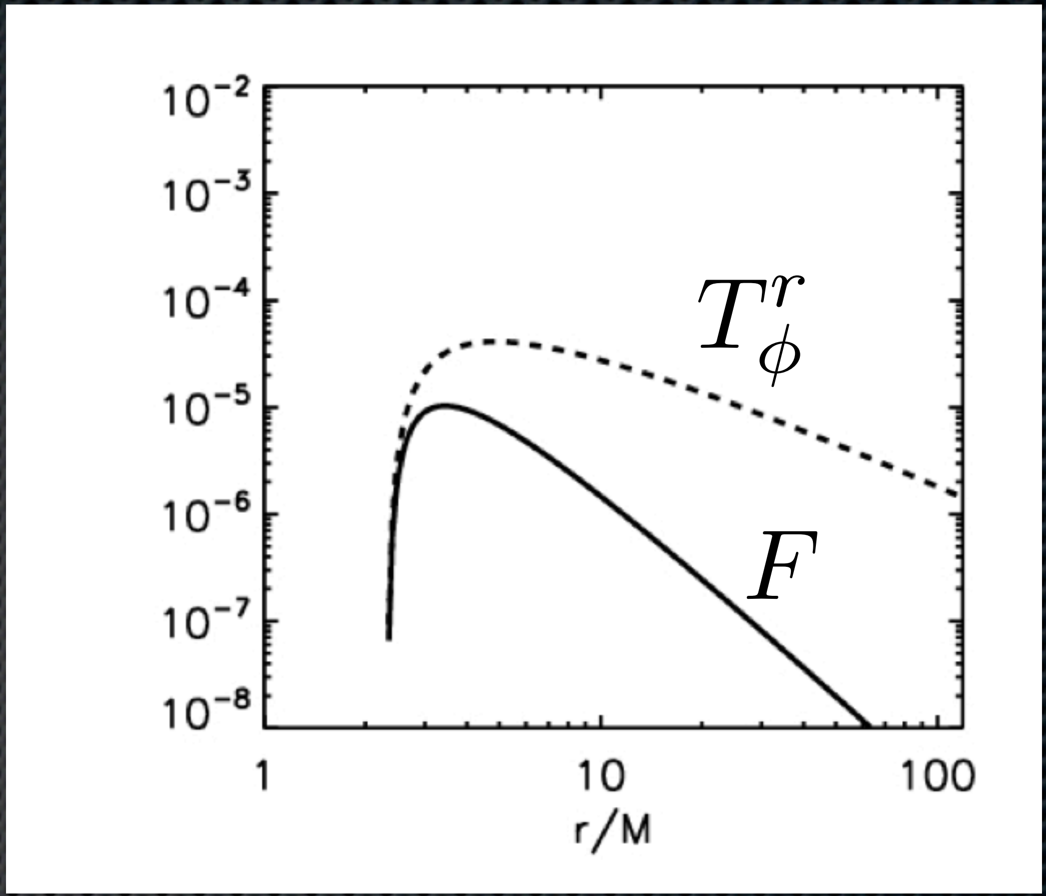
Steady-state Thin Disk Models

Novikov & Thorne (1973)

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

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

- 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)

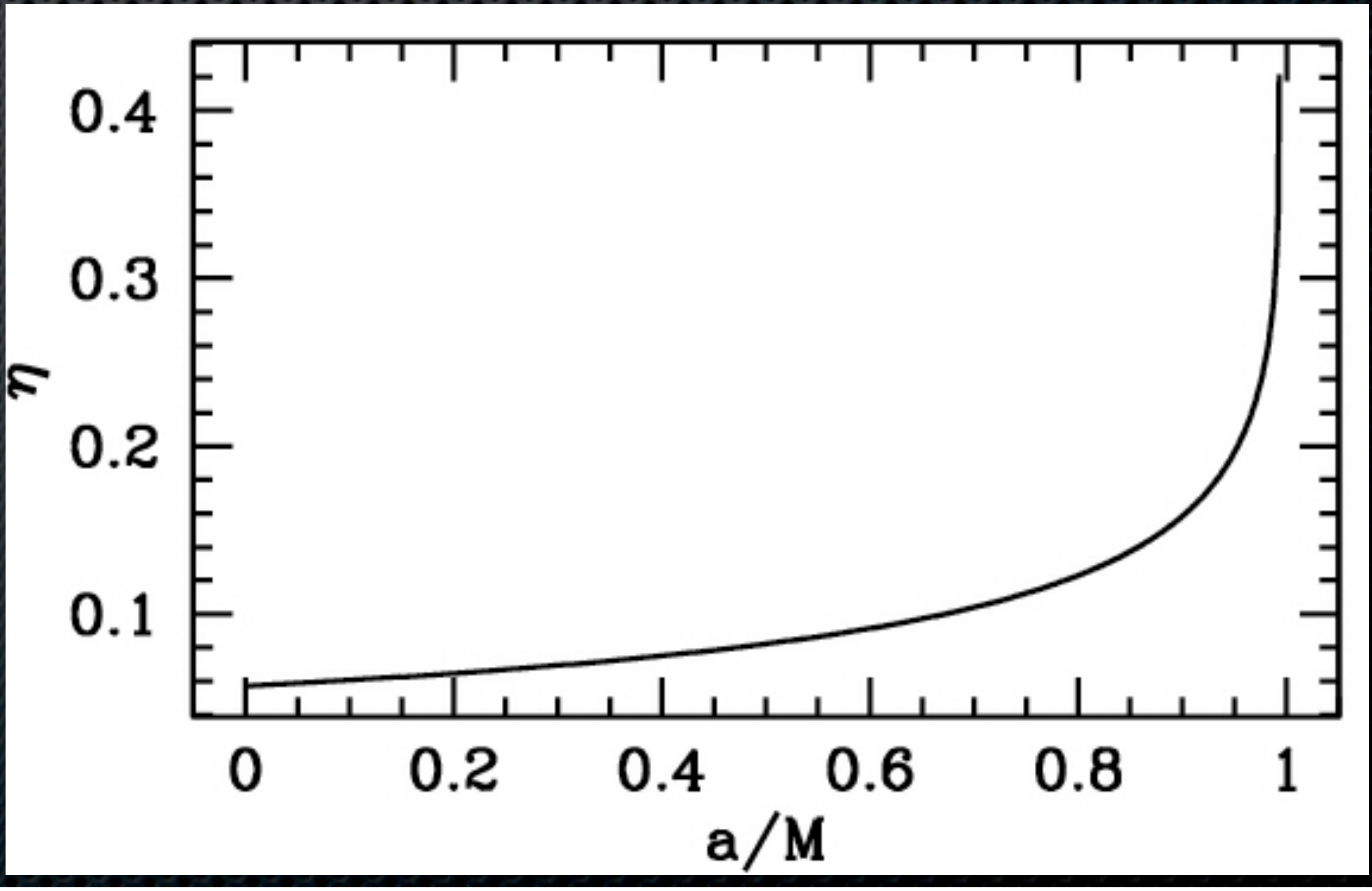
$$T^r_\phi = -\alpha P \quad P = \rho c_s^2$$

$$t^r_\phi = -\alpha c_s^2$$

No stress at sonic point:

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

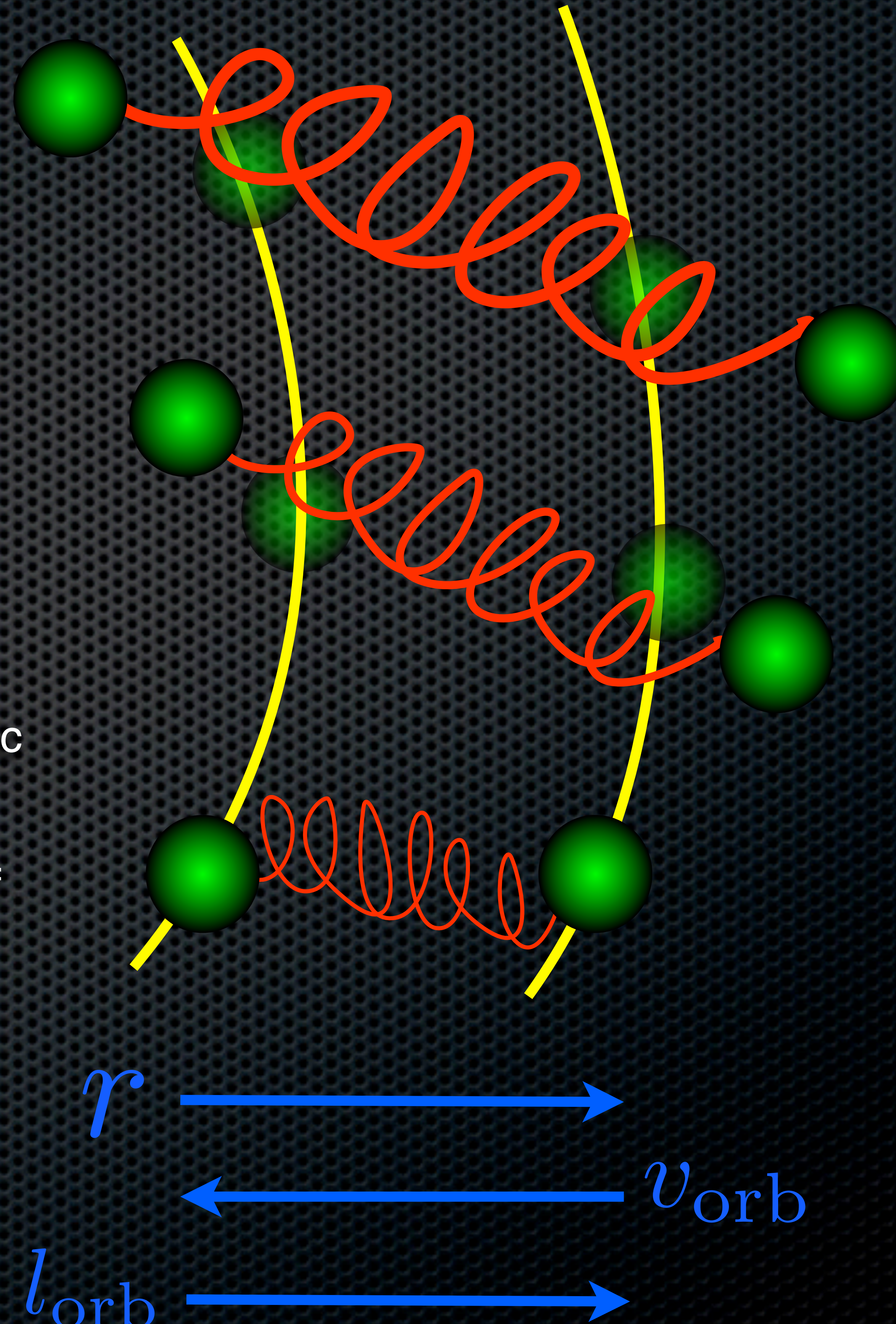
Muchotzeb & Paczynski (1982)
Abramowicz et al. (1988)
Afshordi & Paczyncski (2003)

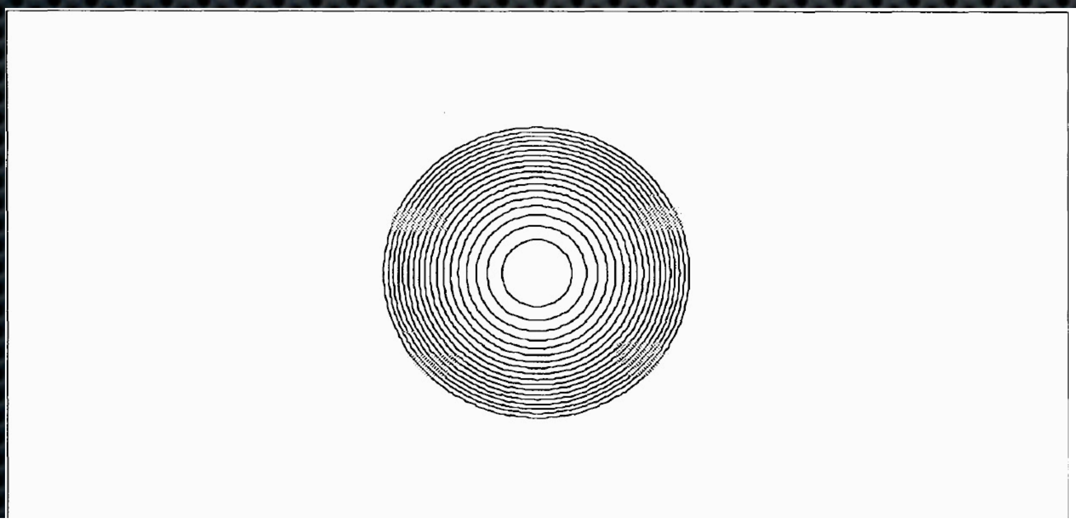


Magneto-rotational Instability (MRI)

- Velikhov (1959)
- Chandrasekhar (1960)
- Balbus & Hawley (1991)

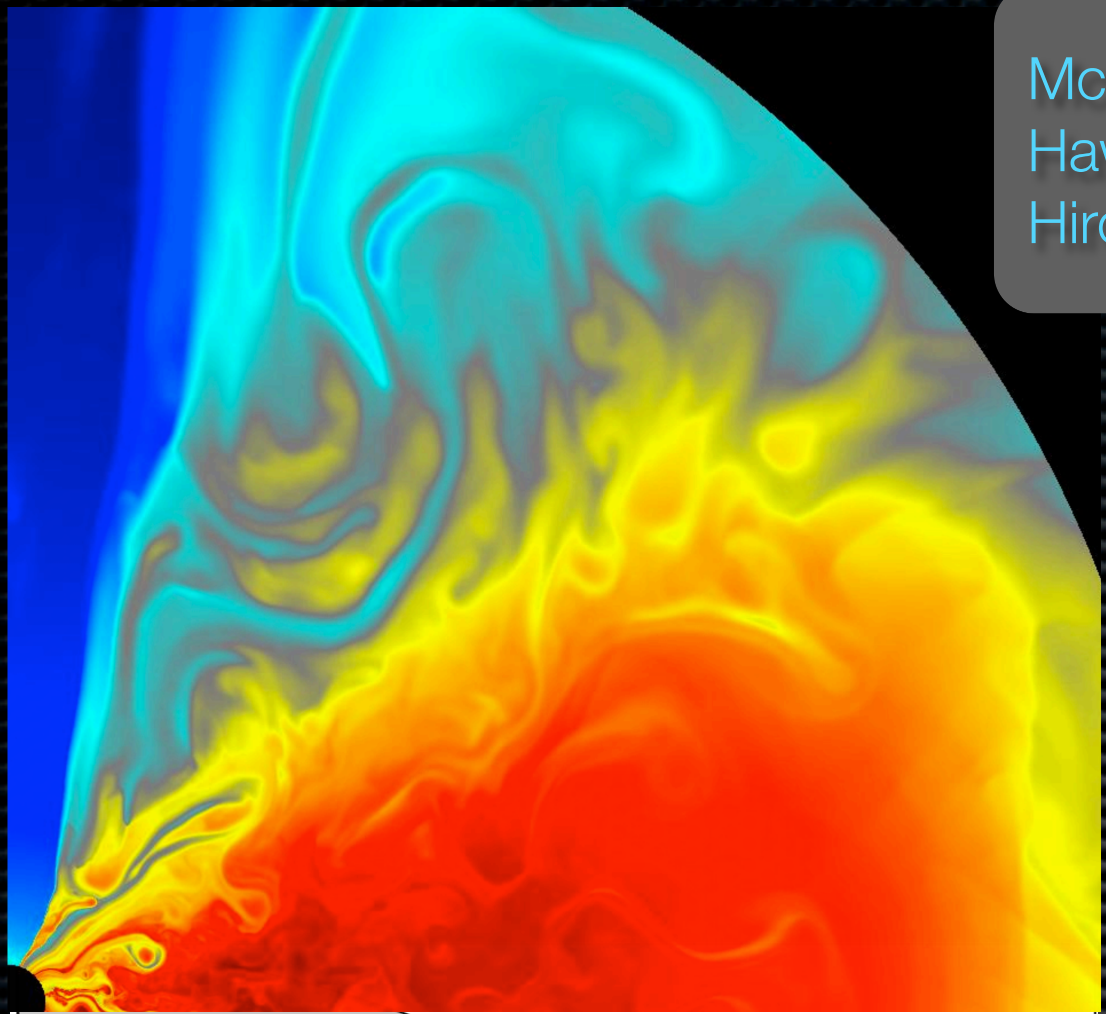
- Growth on orbital time scale.
- MRI develops from weak initial field --- relevant for any (partially) ionized gas.
- Magnetic coupling over different radii is not well described by local viscosity.
- Can explain high accretion rates where hydrodynamic viscosity cannot.
- Fastest instability known that feeds off free energy of differential rotation.

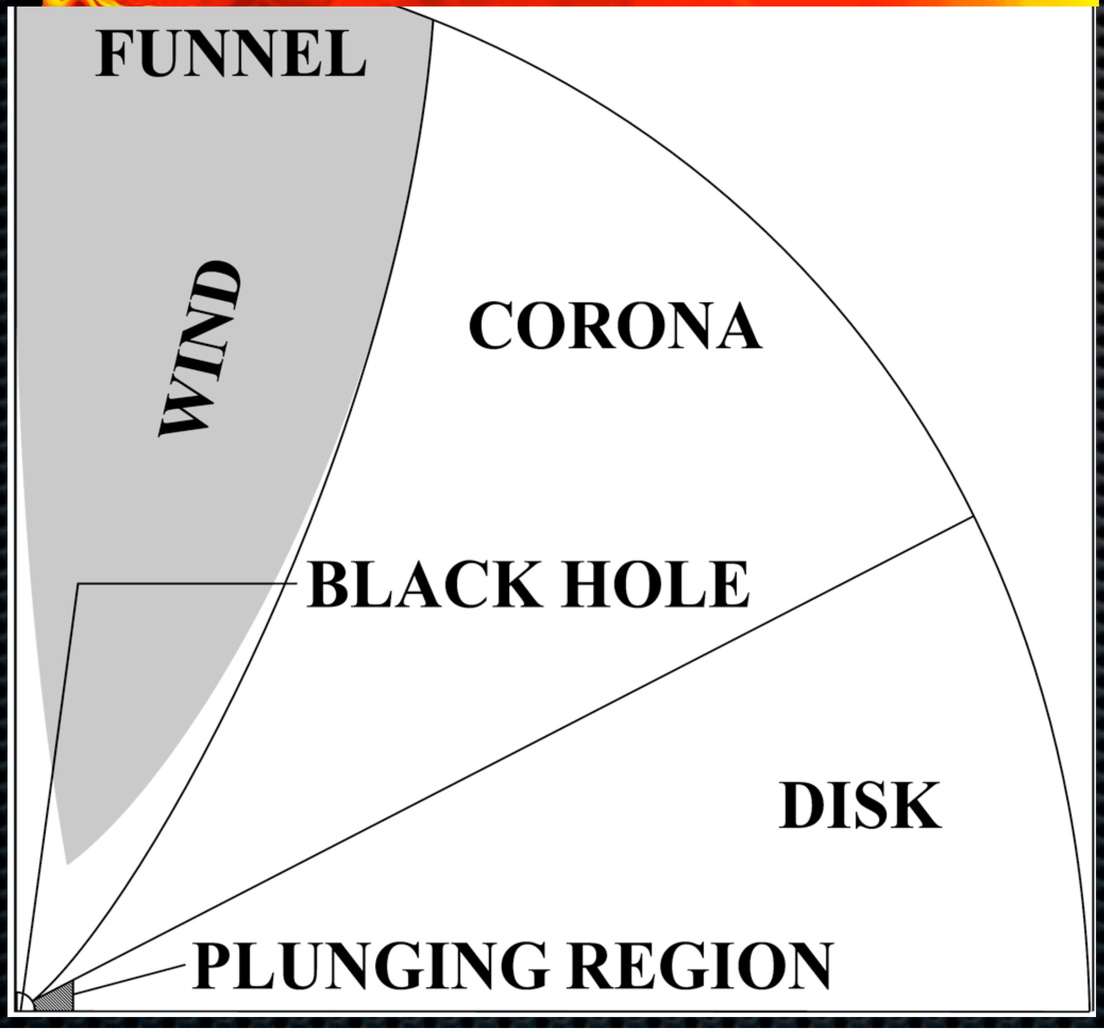




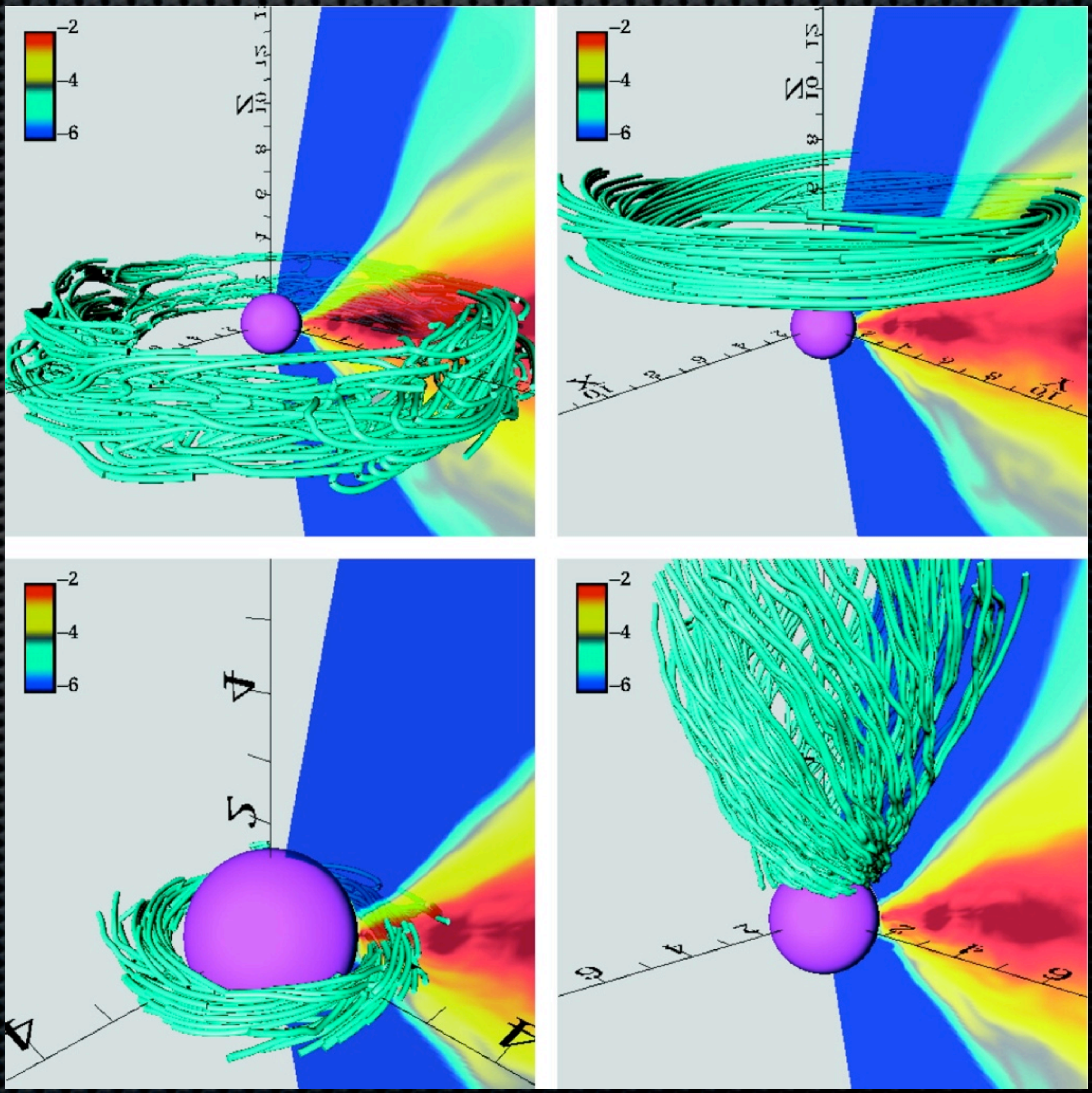
GRMHD Simulations

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



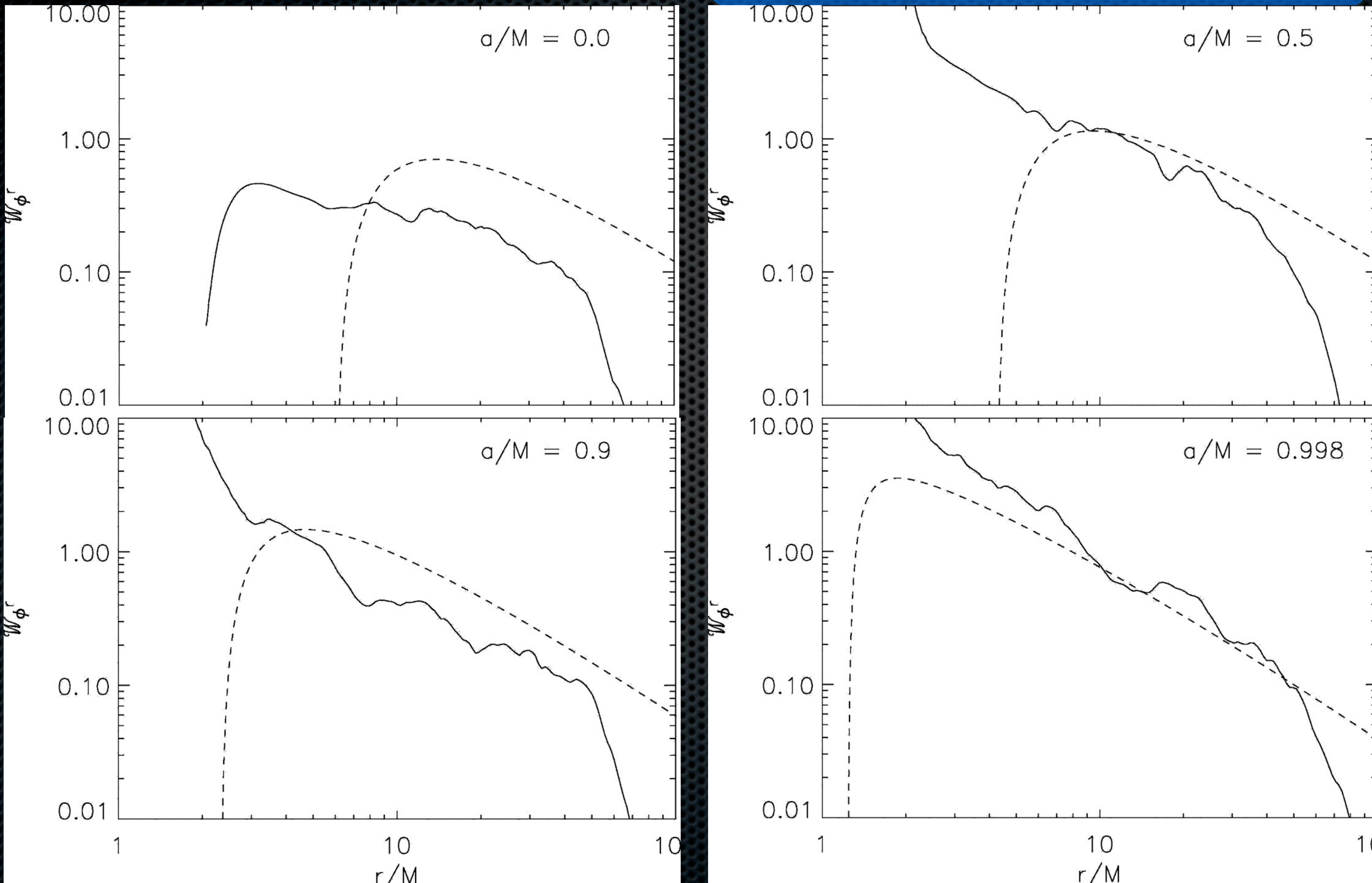


Hirose et al. (2004)



Krolik, Hawley & Hirose (2005)

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



SCN, Krolik & Hawley (2009)

$$N_r \times N_\theta \times N_\phi = 192 \times 192 \times 64$$

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

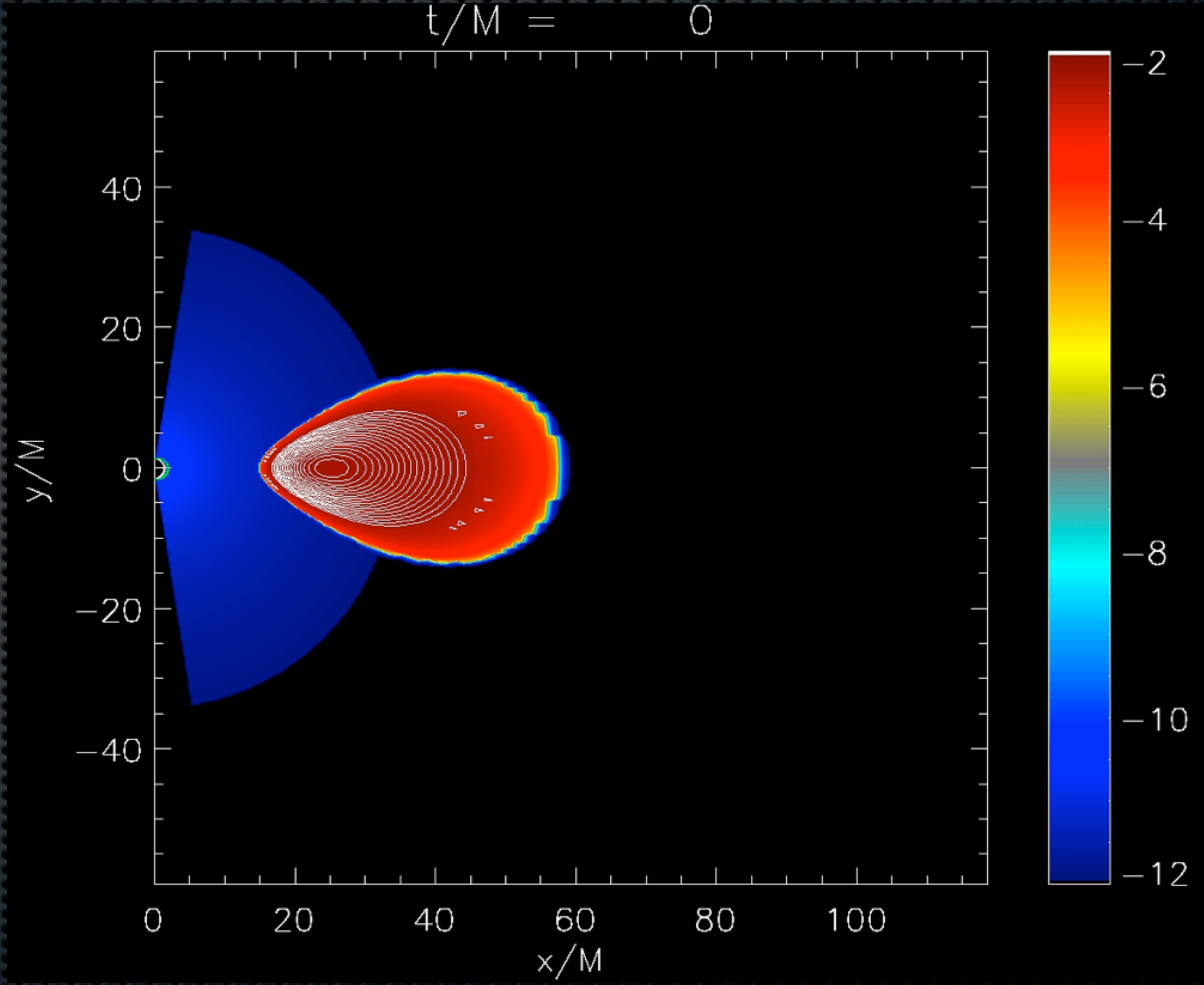
$$a = 0.9M$$

- 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
  - Contrained Transport scheme
- Optically-thin cooling function
- Maintains constant H/R
- Cooling on orbital timescale

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

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

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



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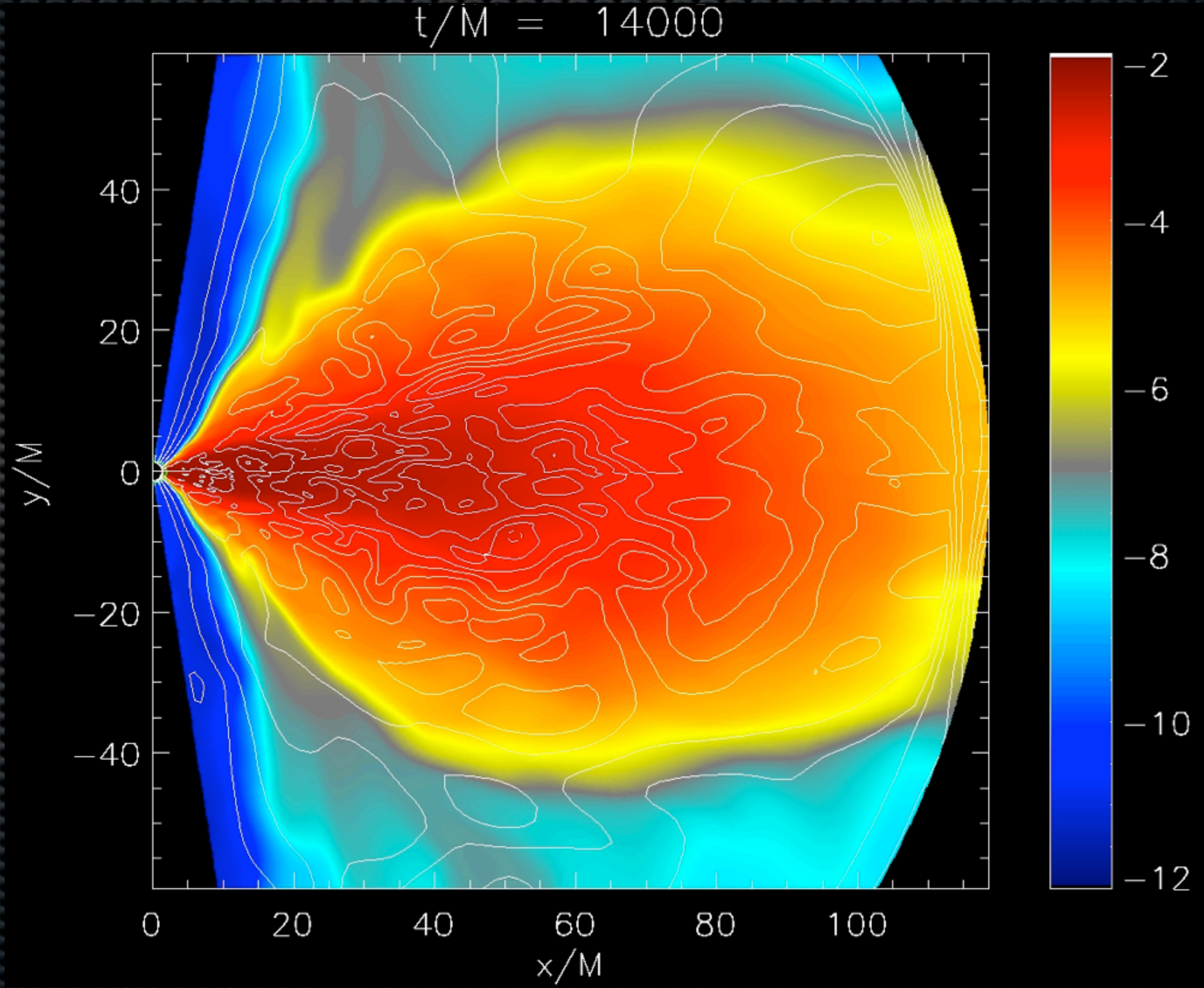
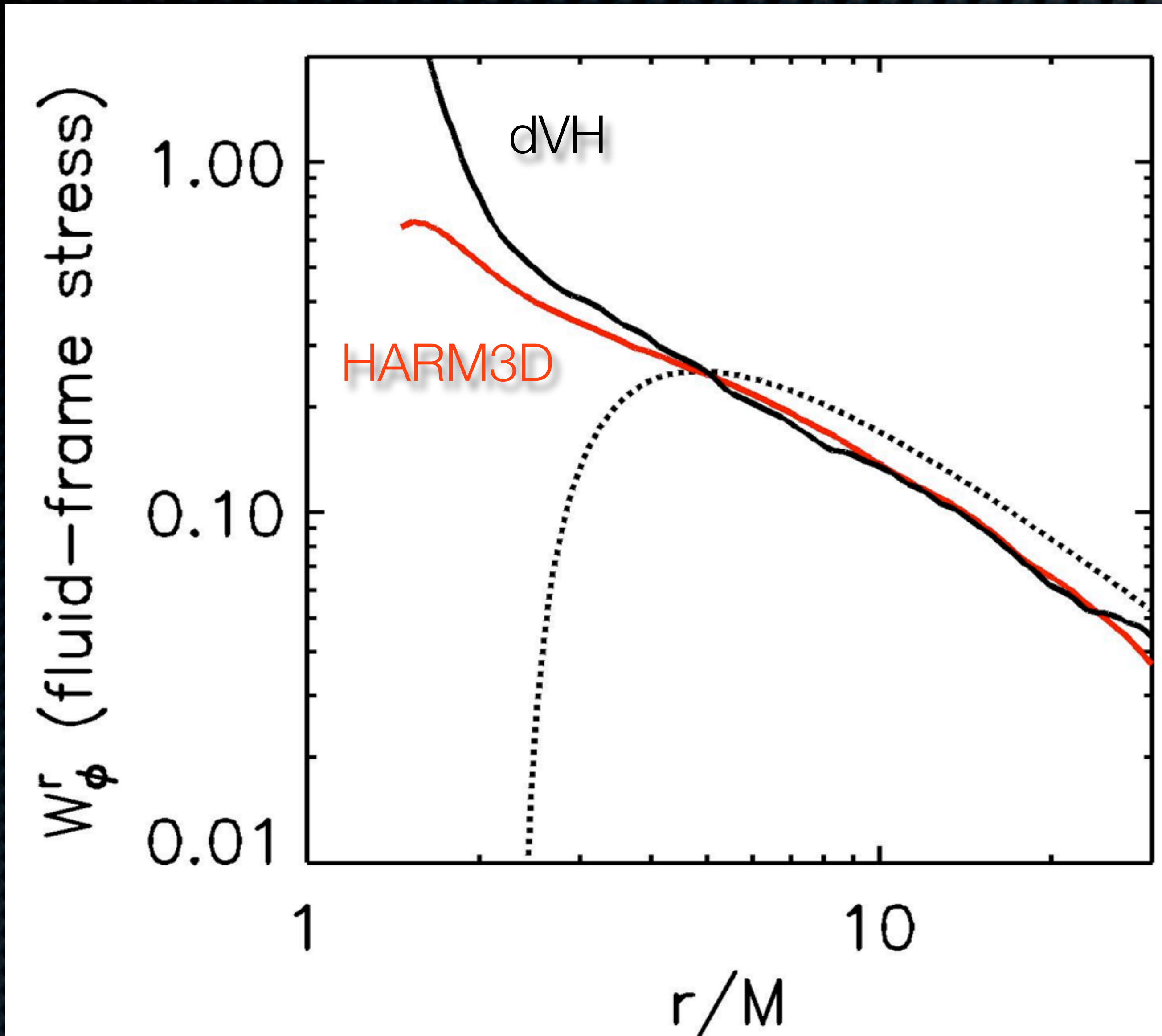
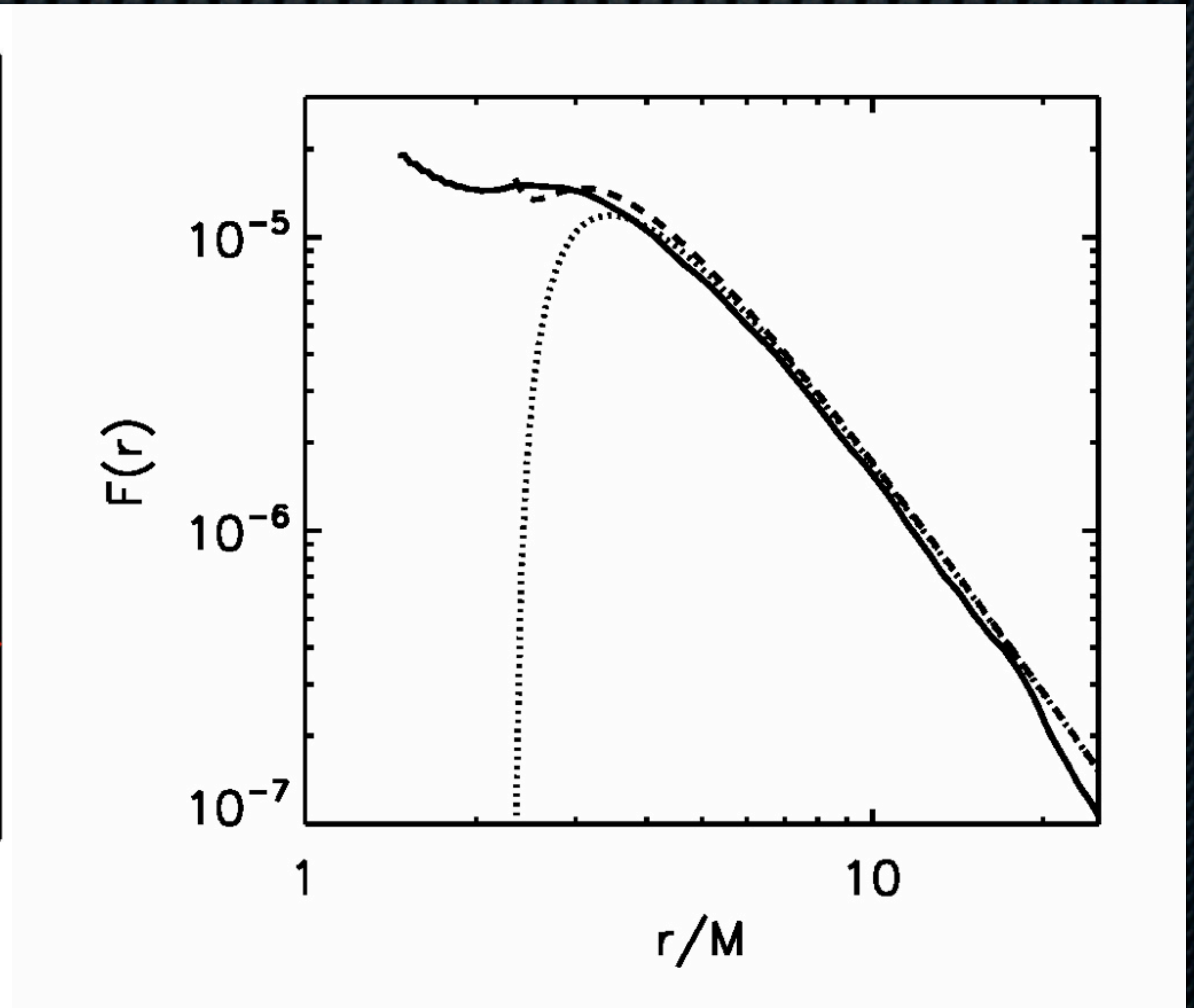


Comparison to NT





- Retained Heat --> Stress Deficit
- Continuity through the ISCO

- Fits approx. to Agol & Krolik (2000)

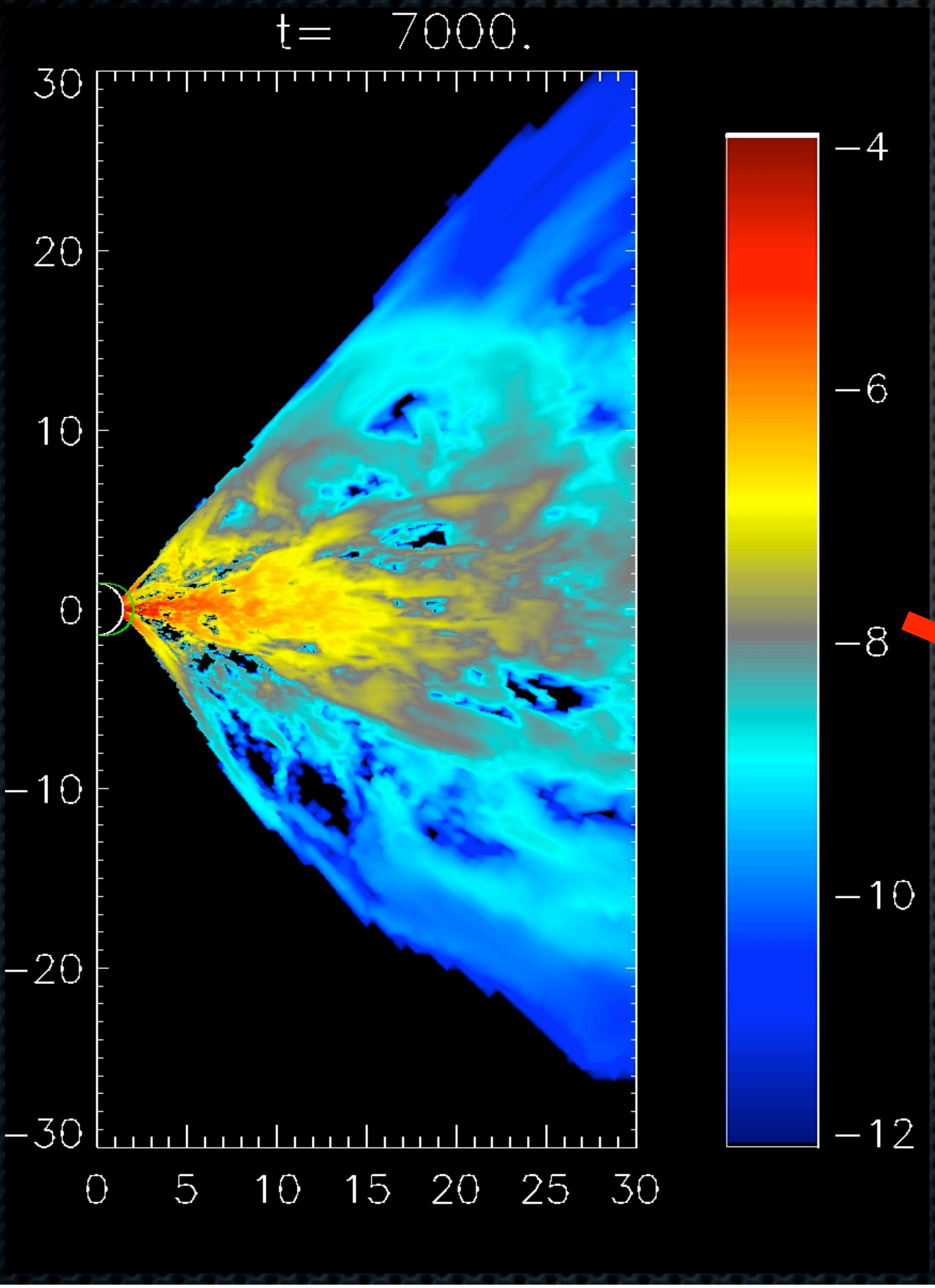
$$\Delta\eta = 0.01 \qquad \Delta\eta/\eta = 7\%$$

- ~5% flux deficit at all radii
  - Due to retained thermal and magnetic energy densities.

GR Radiative Transfer

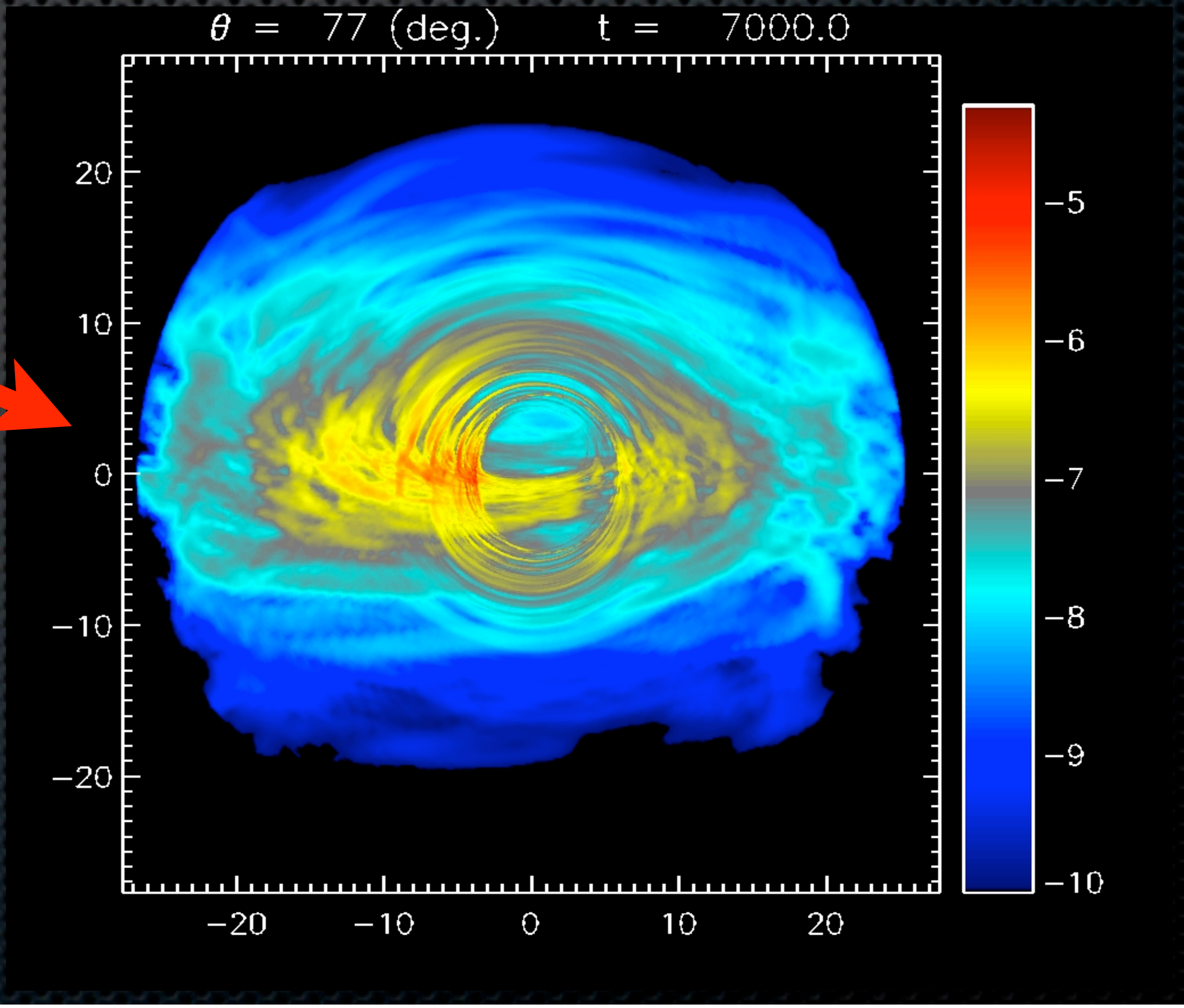
$$\frac{d}{d\lambda}\left(I_\nu/\nu^3\right) = j_\nu/\nu^2$$

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

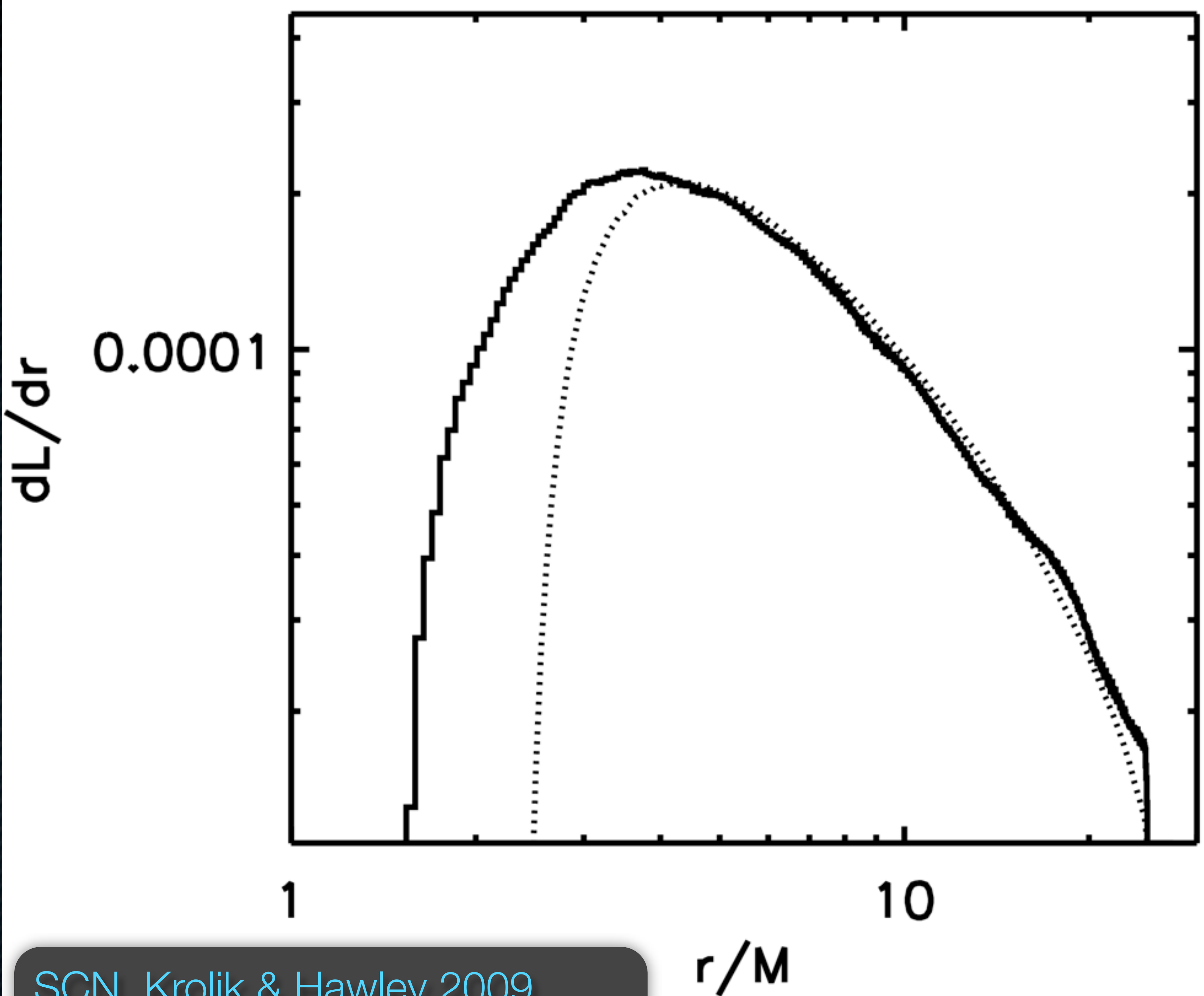


- GR geodesic integration
- Doppler shift
- Gravitational redshift
- Relativistic beaming
- Interpolates simulation data in space & time

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



Angle & Time Average Bolometric Luminosity Profile



SCN, Krolik & Hawley 2009

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

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

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

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

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

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

Suggests previous spectral fits may overestimate spin.

NT model may underestimate luminosity in some disks.

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

Motivation:

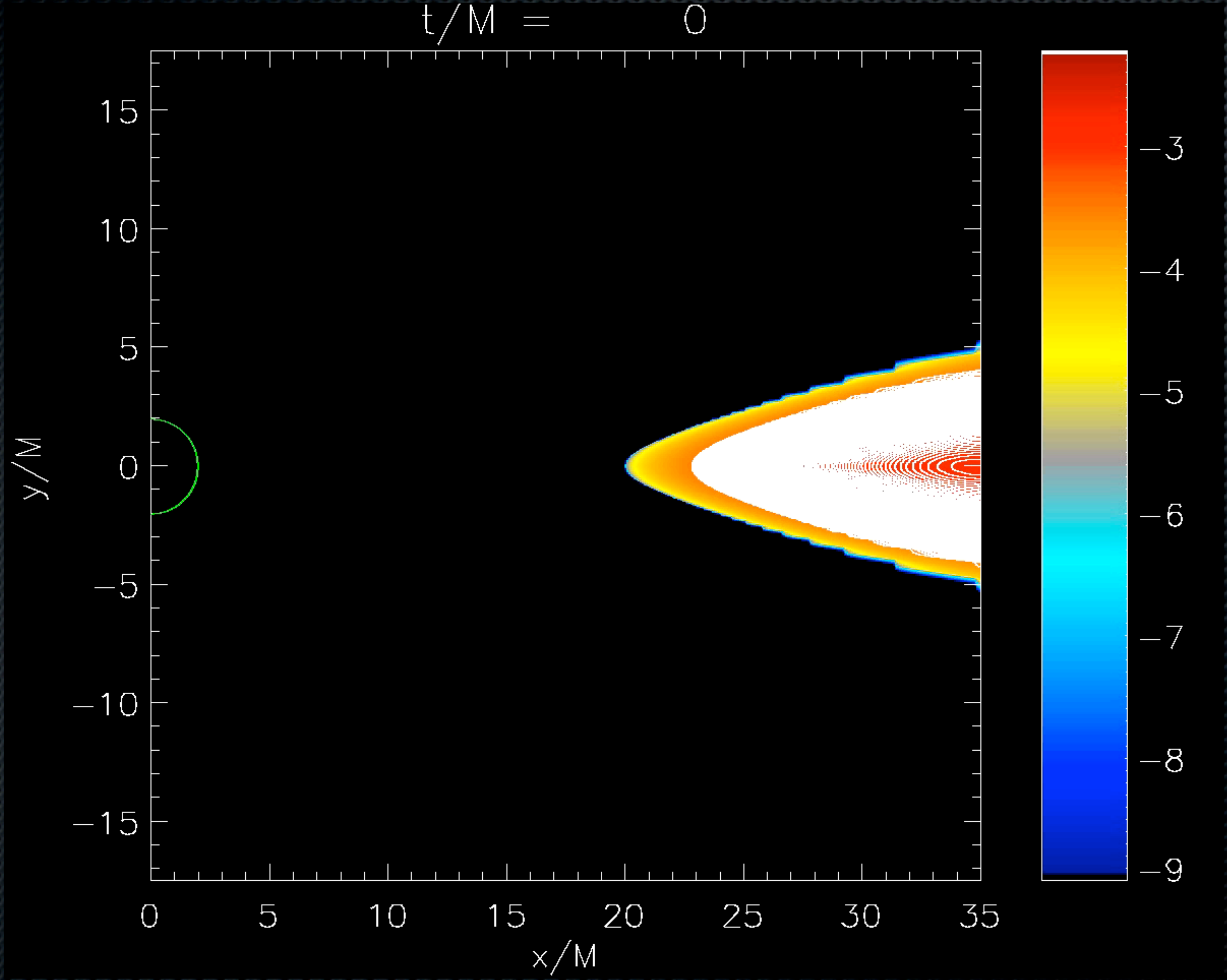
- Explore H/R dependence;
- Resolve height with >60 cells (Davis++ 2009) ;
- Attempt at isotropic dissipation with nearly cubical cells;

SCN, Krolik, Hawley 2010

SCN, Krolik, Hawley 2010

ThinHR: H/R = 0.06 912x160x64 $a = 0M$

ρ



SCN, Krolik, Hawley 2010

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ρ

SCN, Krolik, Hawley 2010

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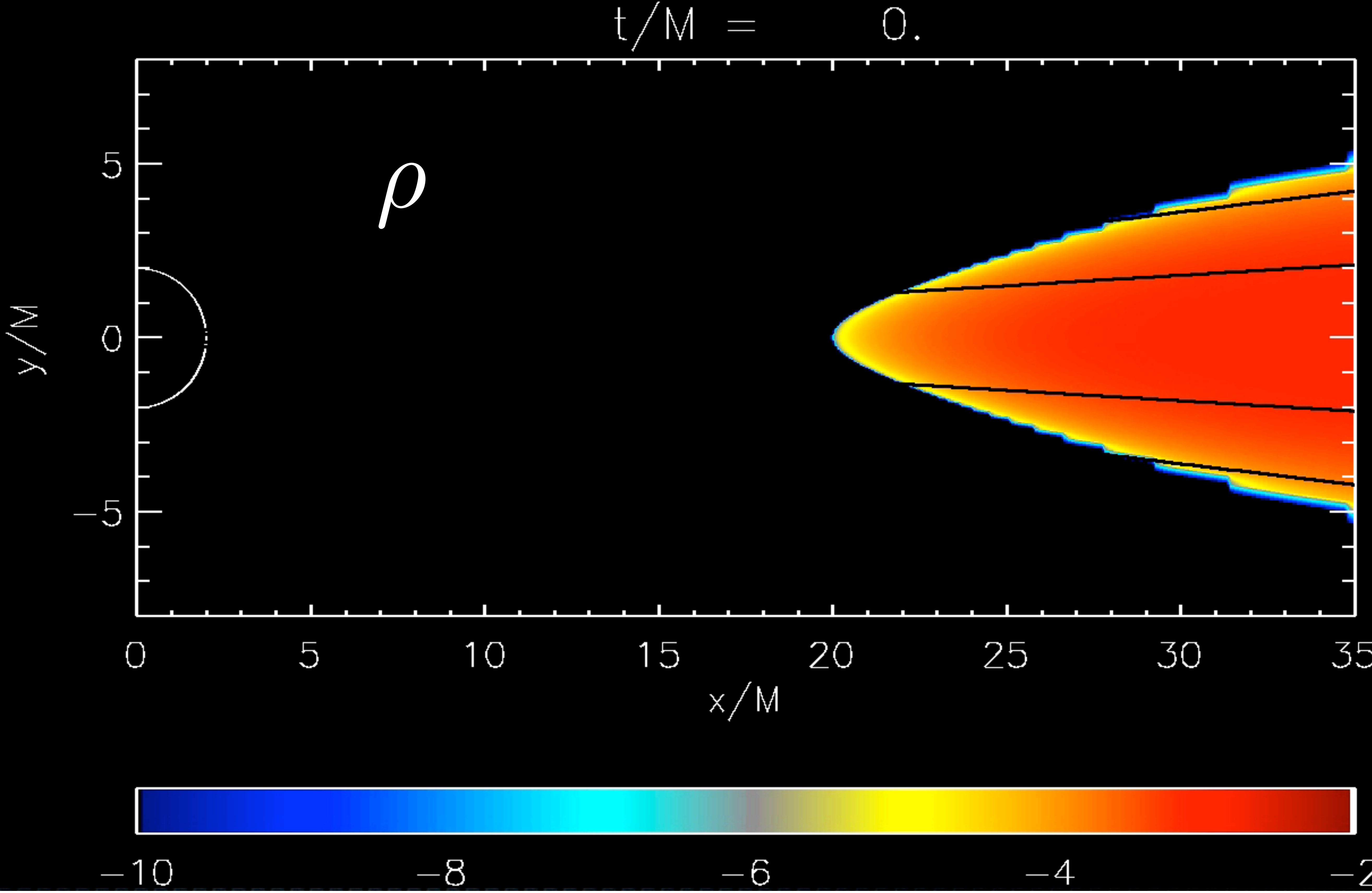
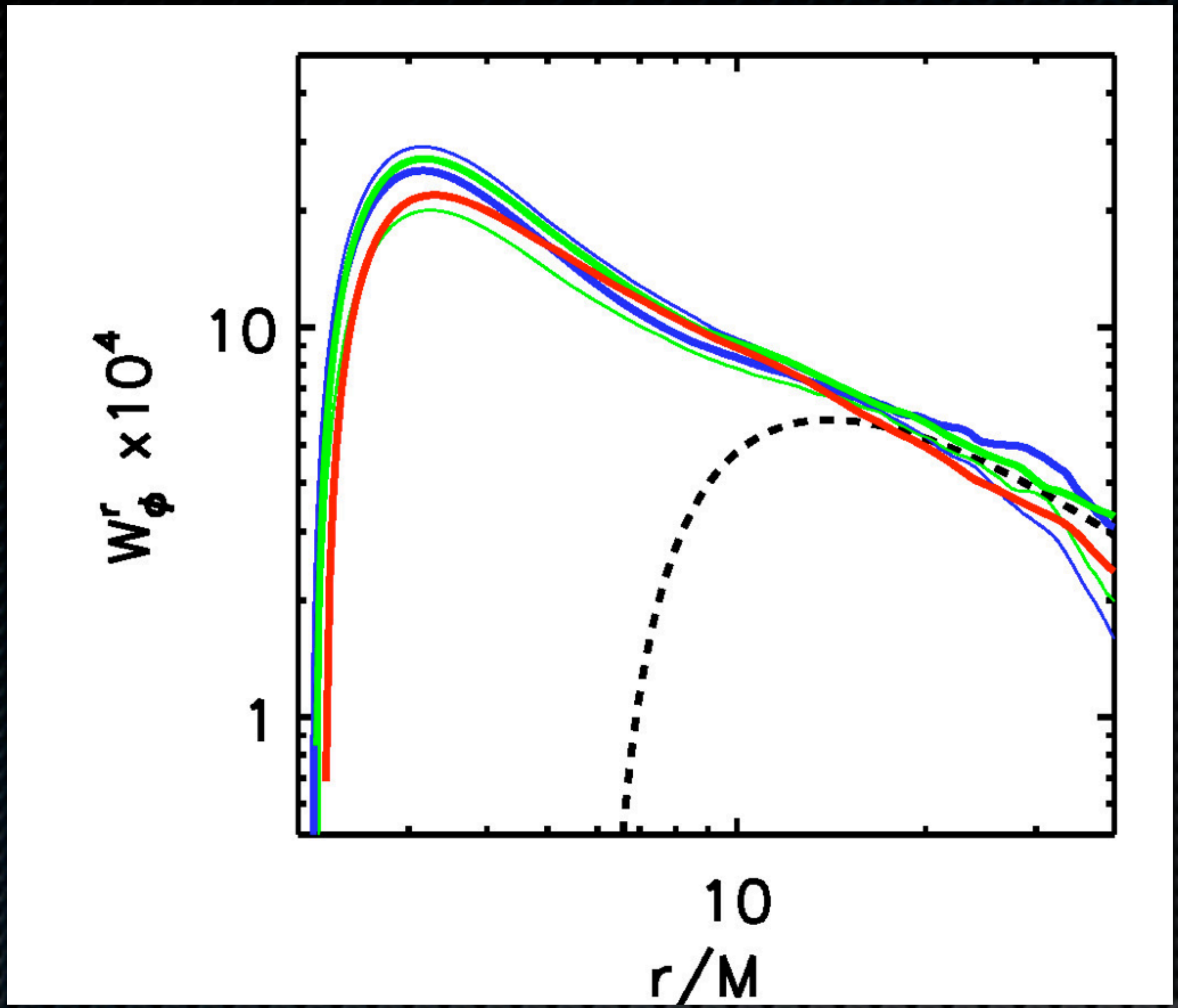
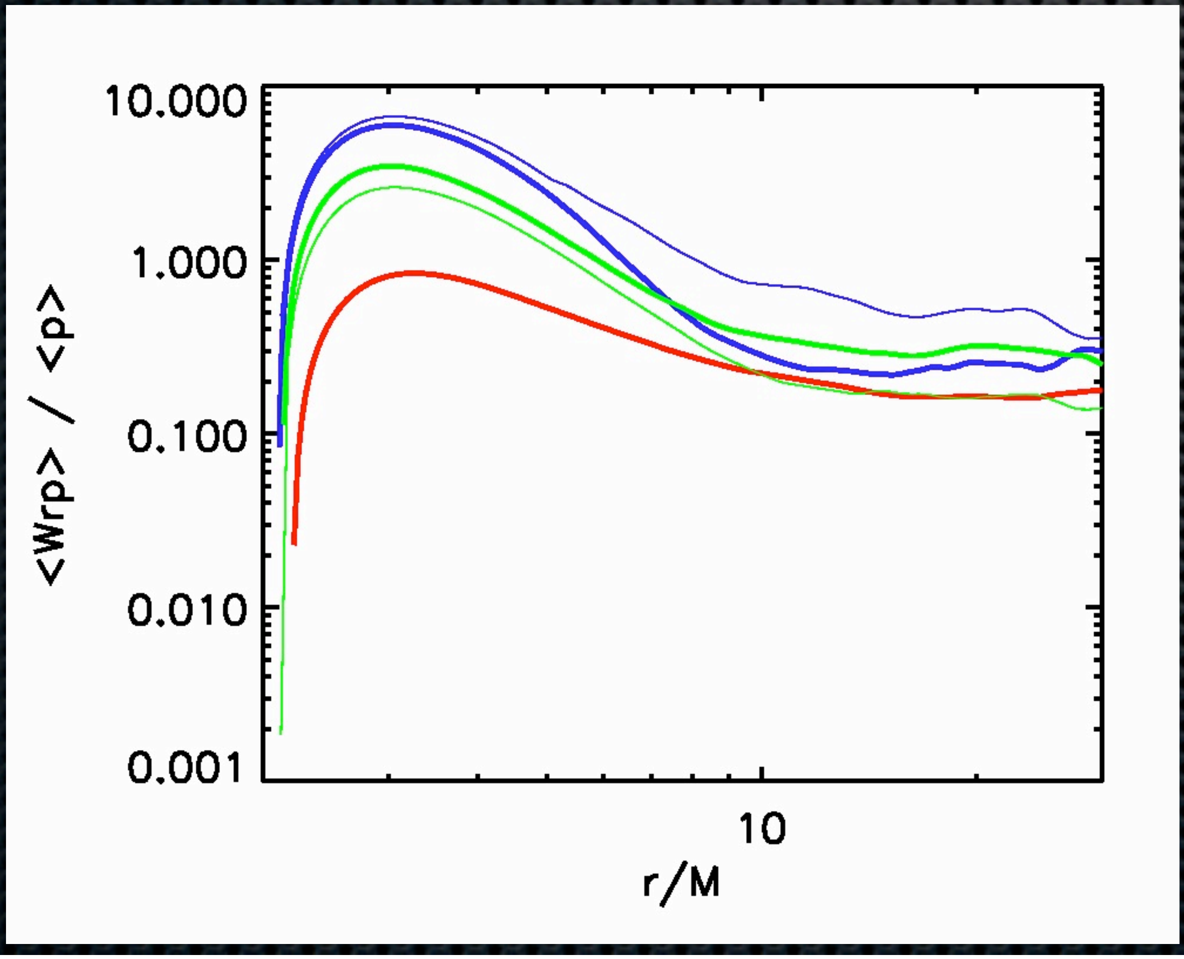
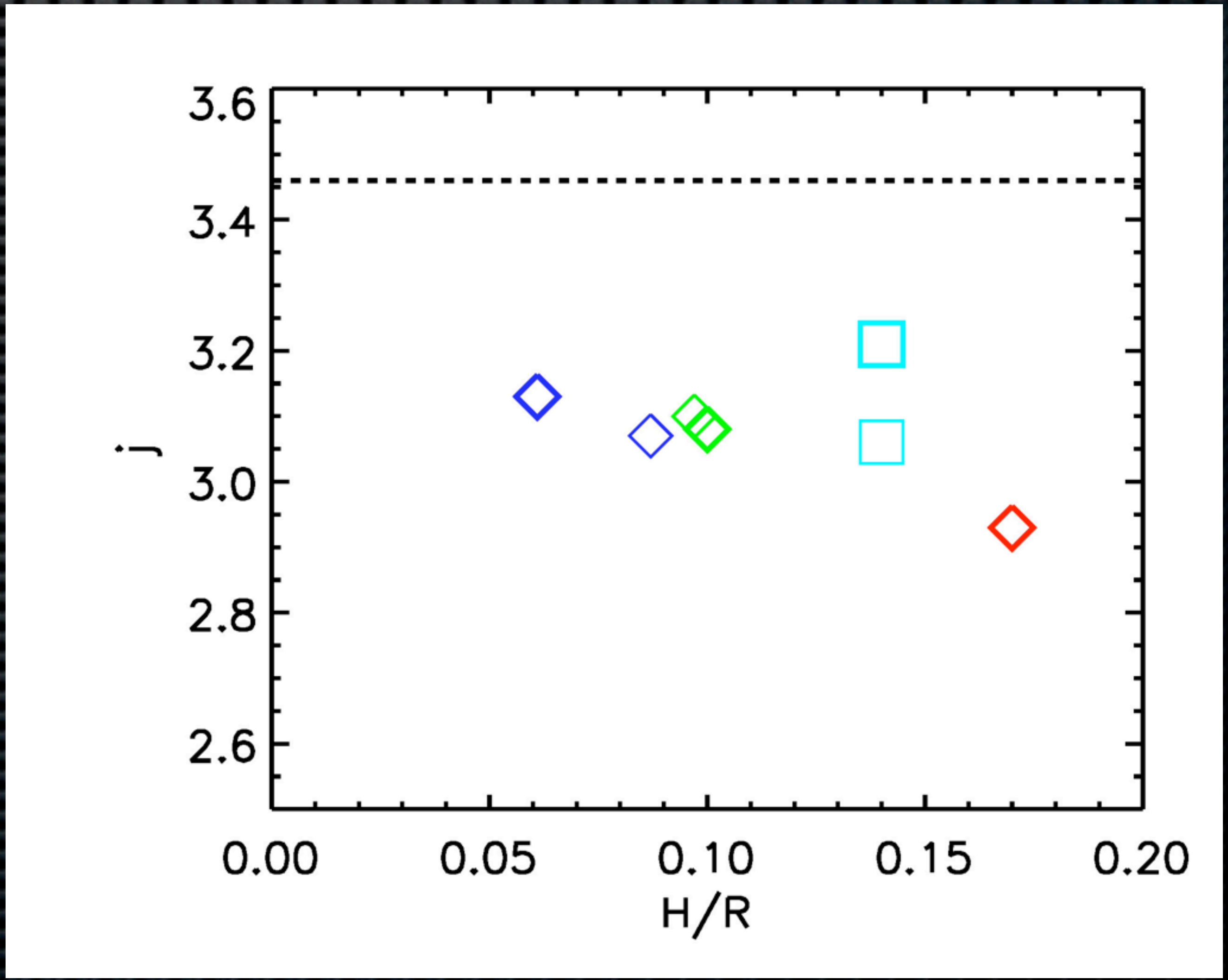
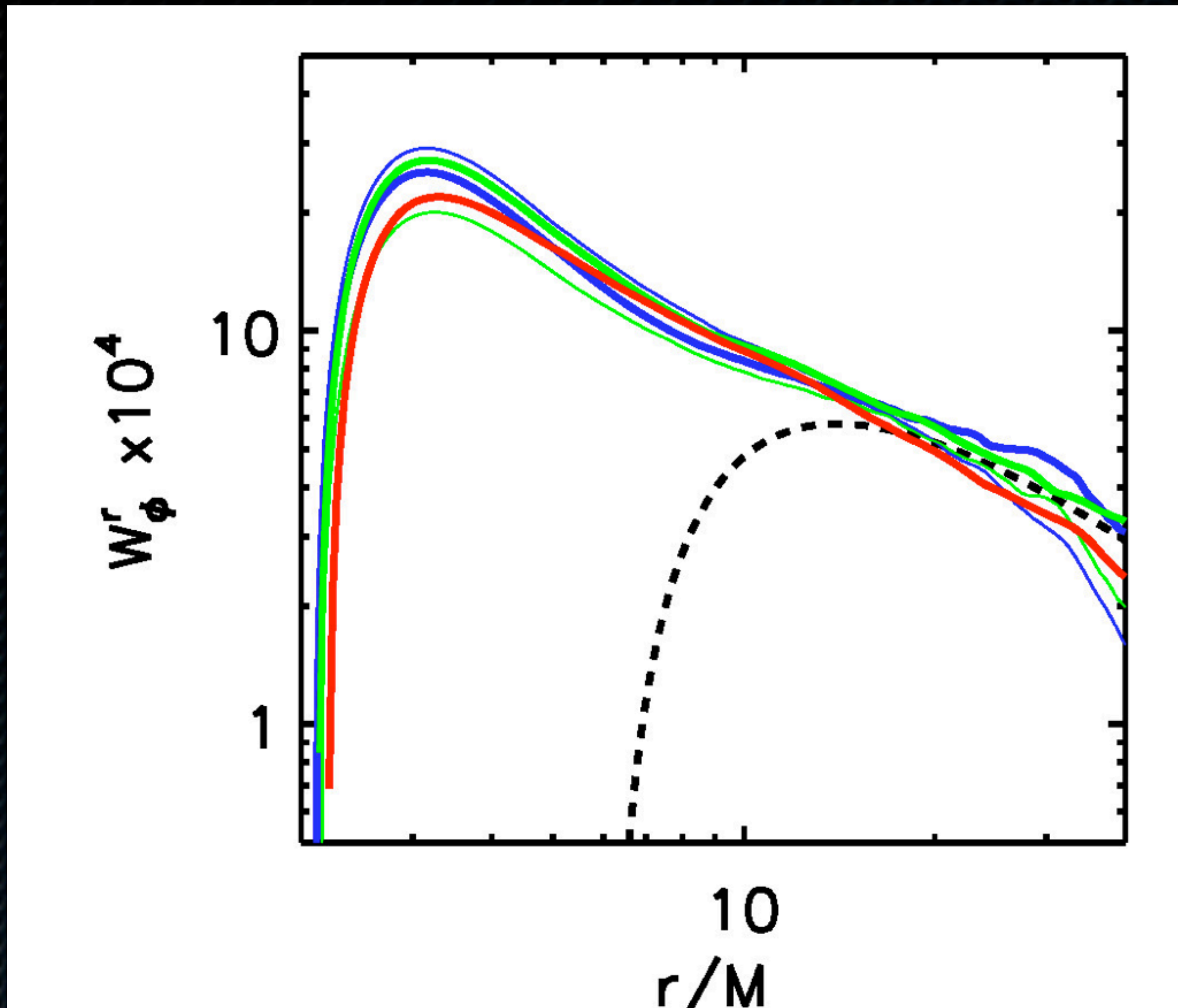




- No trend seen in Maxwell Stress
- Minor "sqrt" trend seen in spec. ang. mom.
    - Due to additional Reynolds stress for thicker disks







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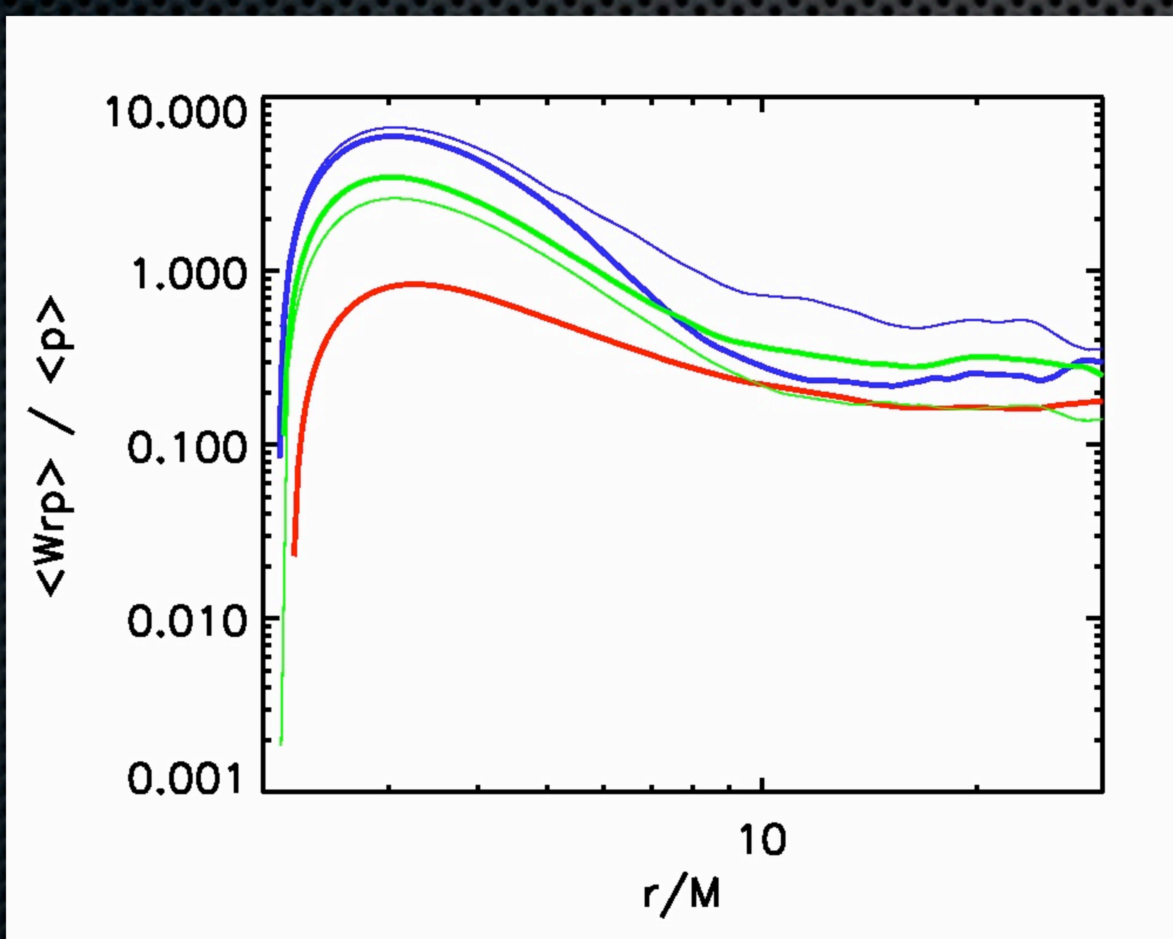
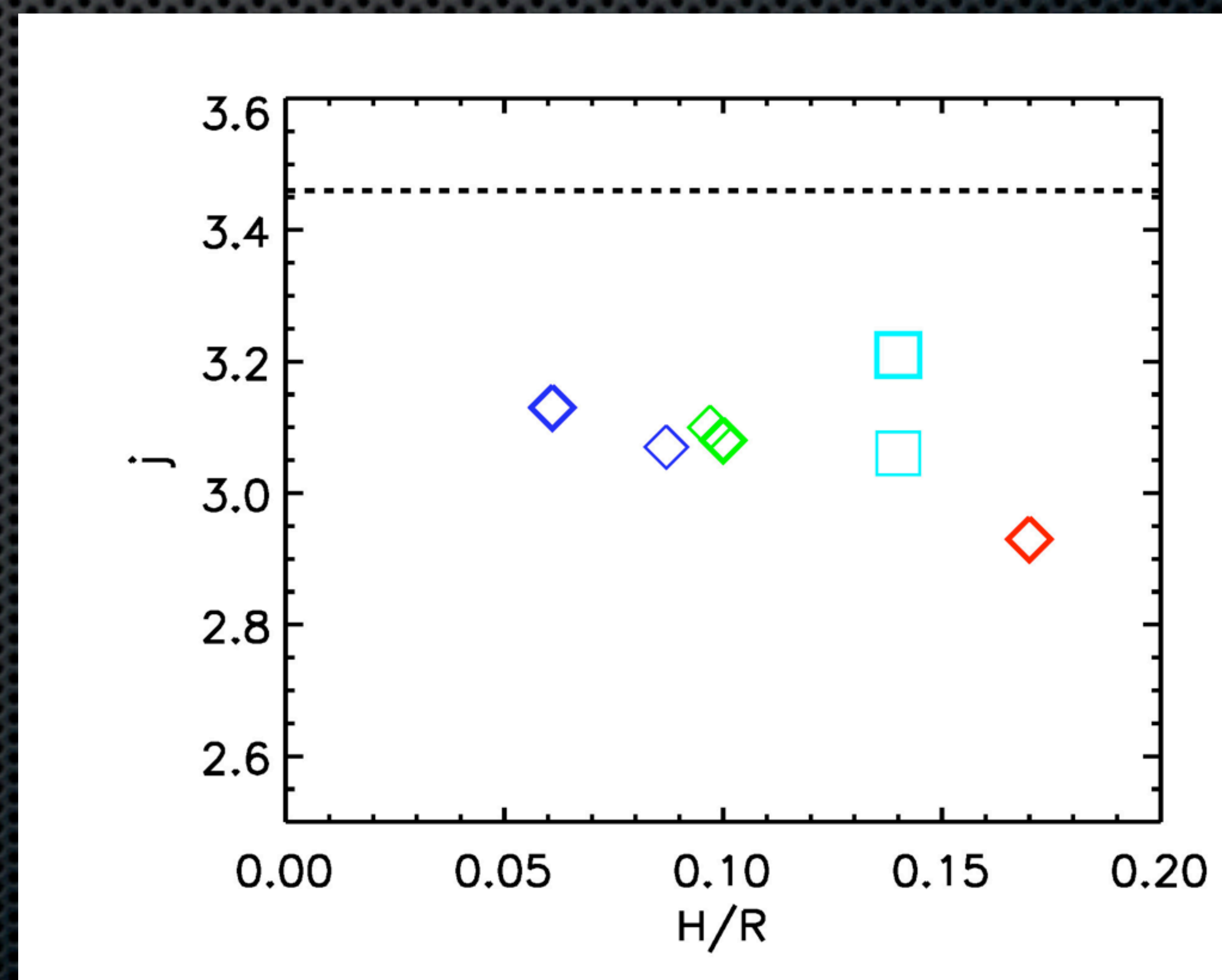
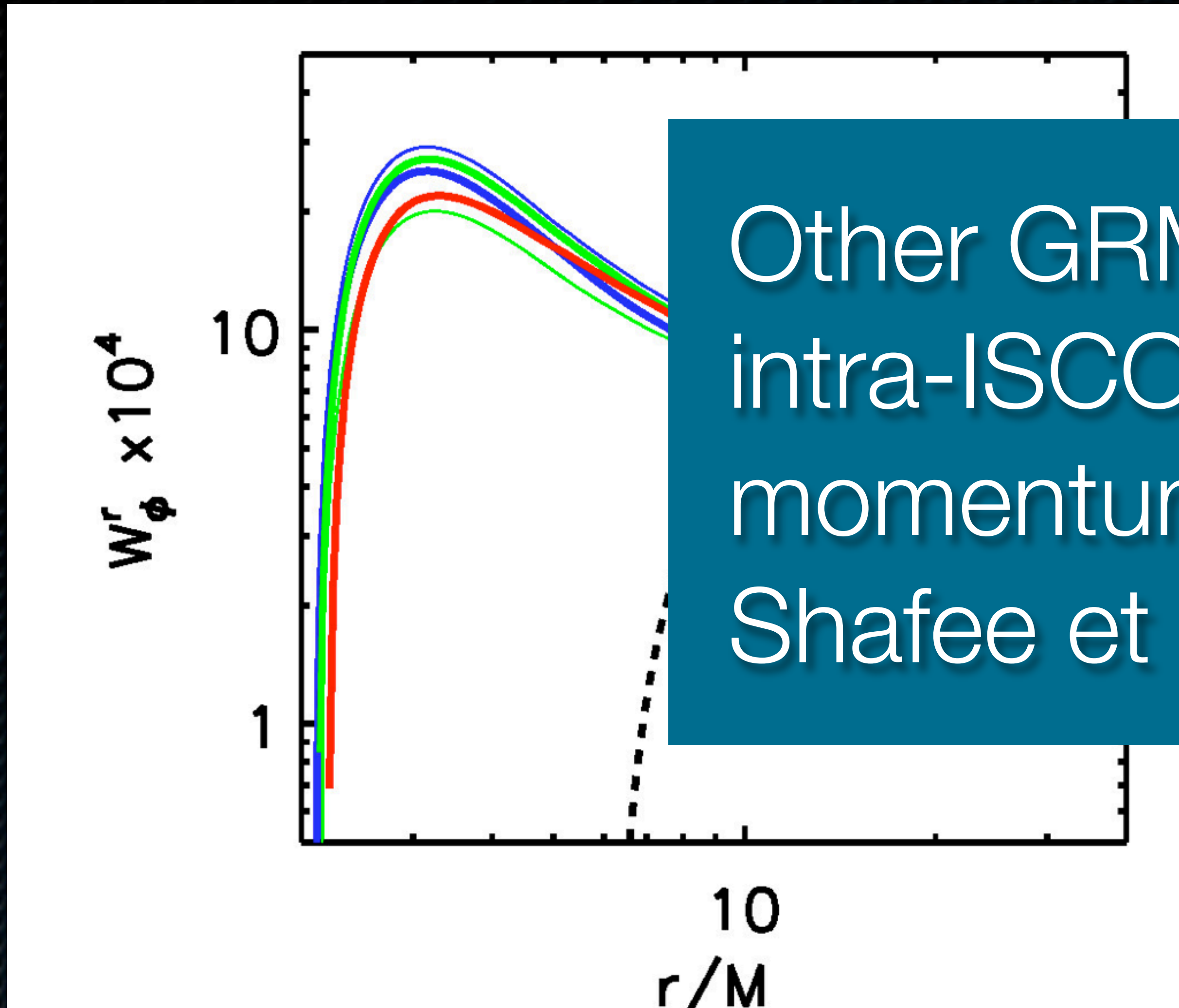
De Villiers & Hawley code

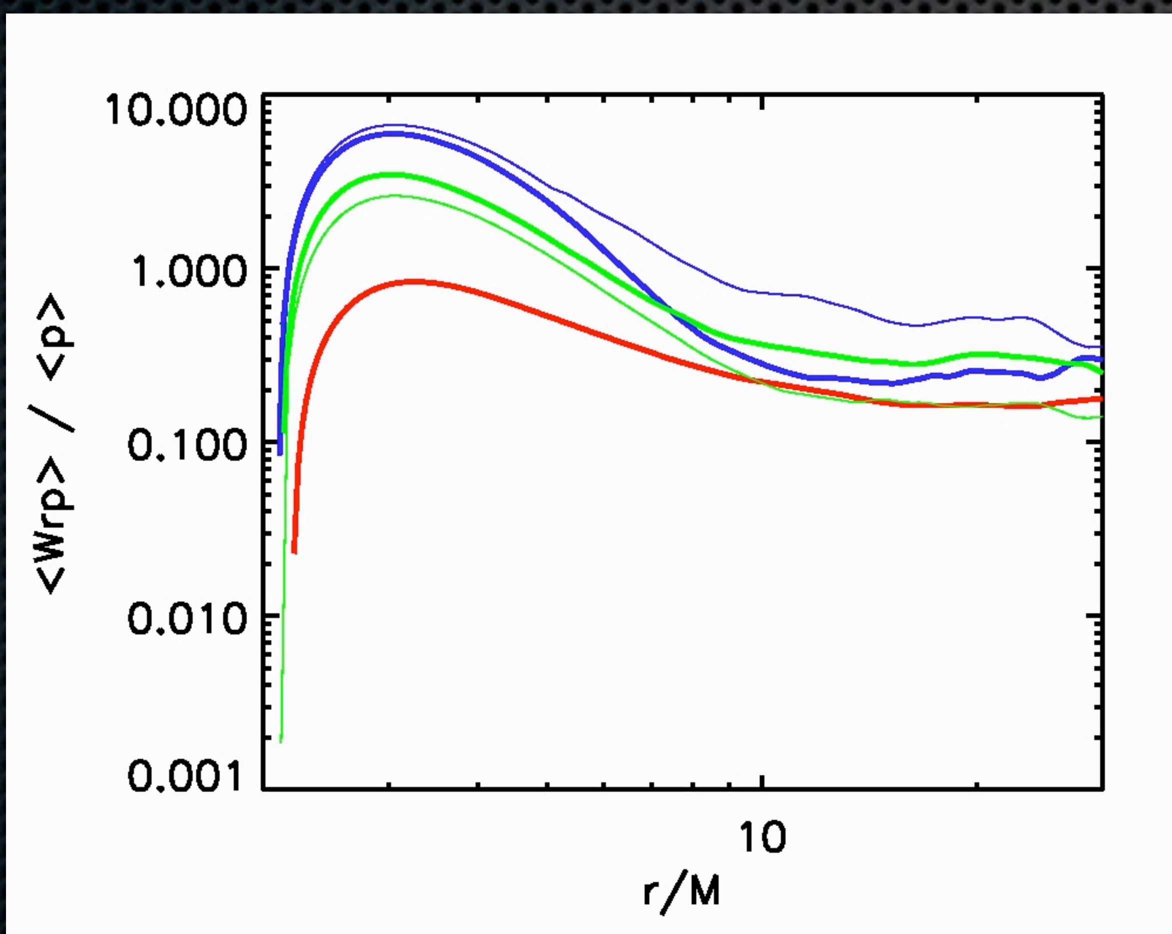
Vertical field with De Villiers & Hawley code

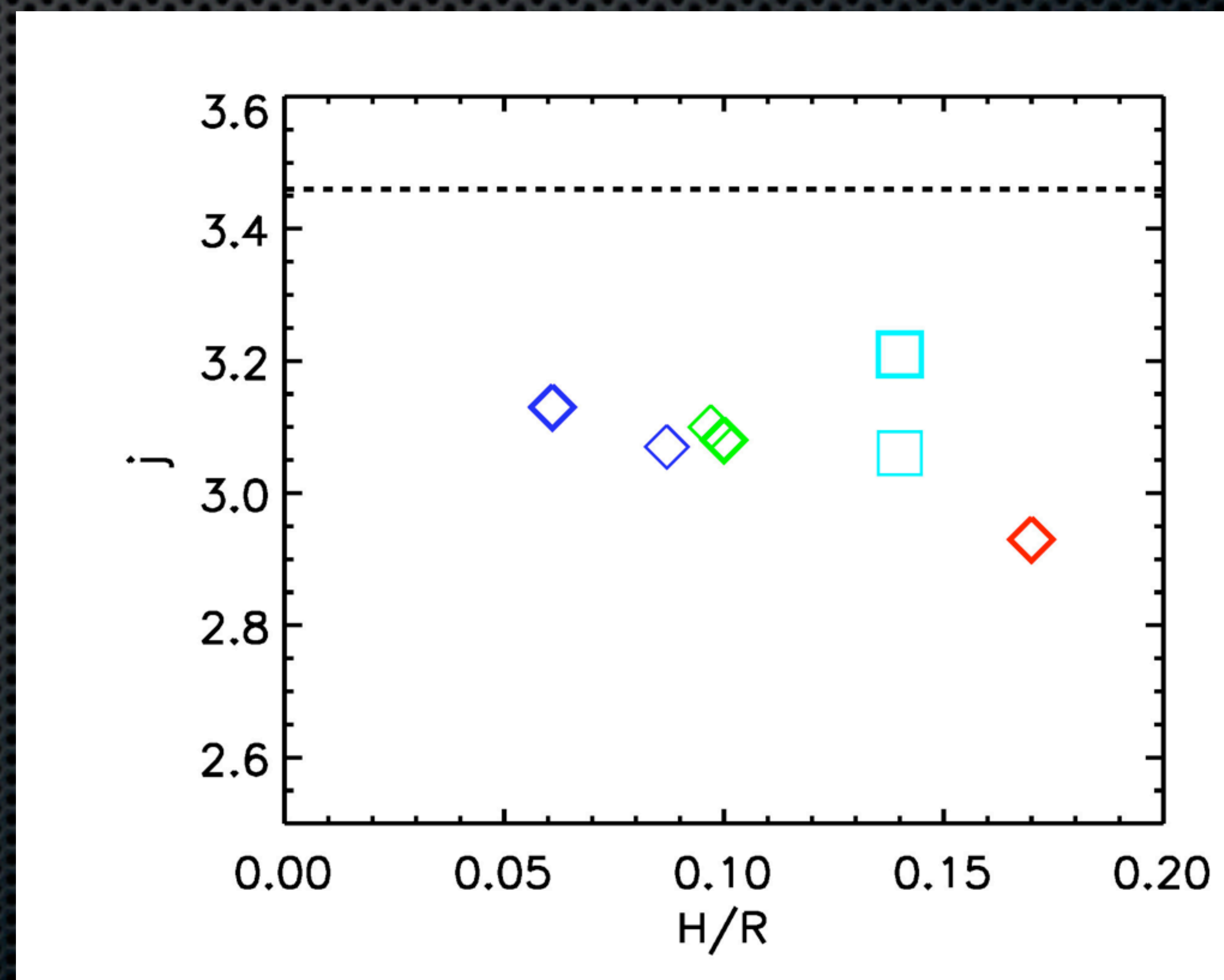




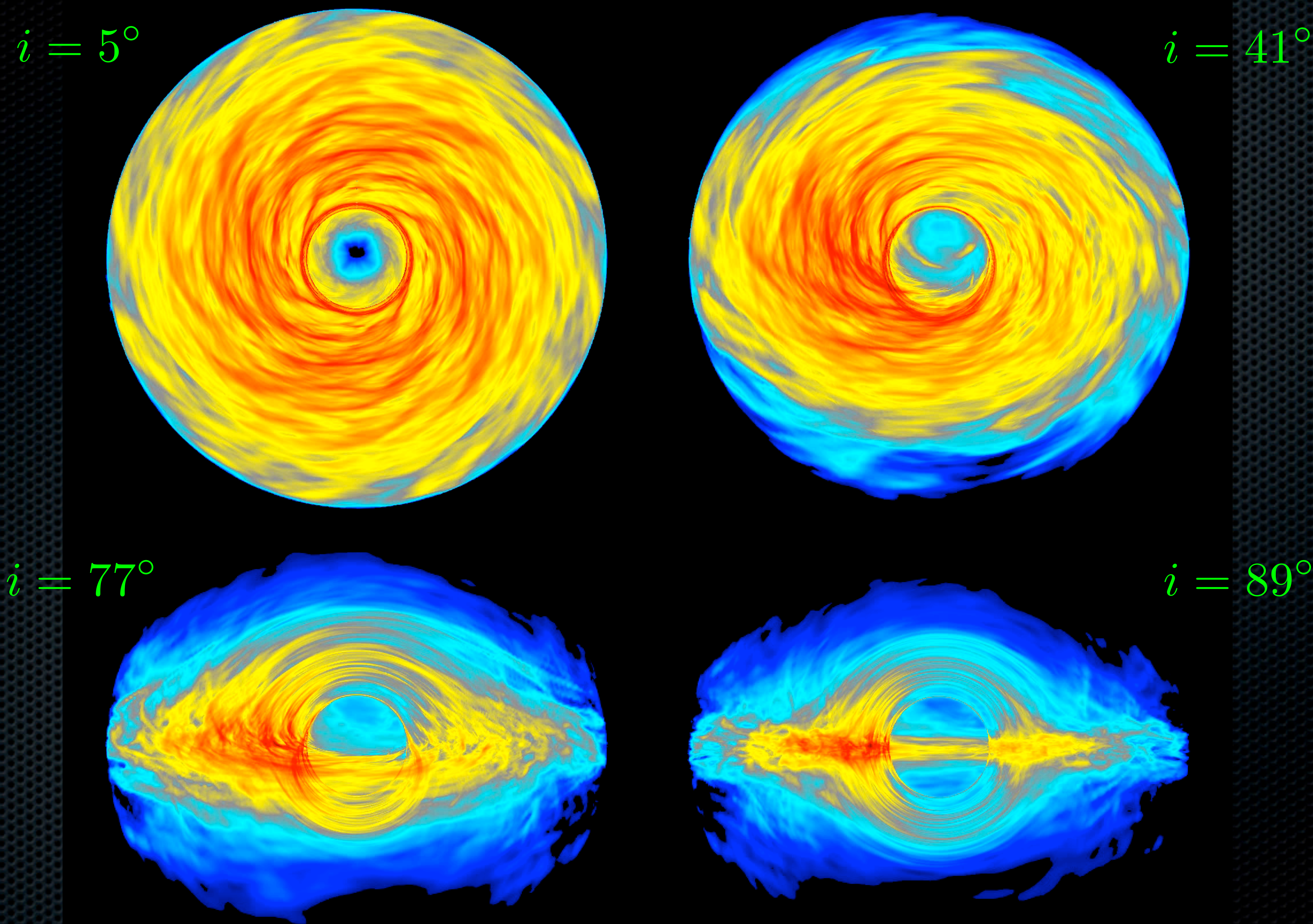


Other GRMHD simulations show weaker intra-ISCO stress levels and angular momentum transport.
Shafee et al. (2008), Penna et al. (2010)





Preliminary Results!!!


$i = 5^\circ$
$i = 41^\circ$
$i = 77^\circ$
$i = 89^\circ$

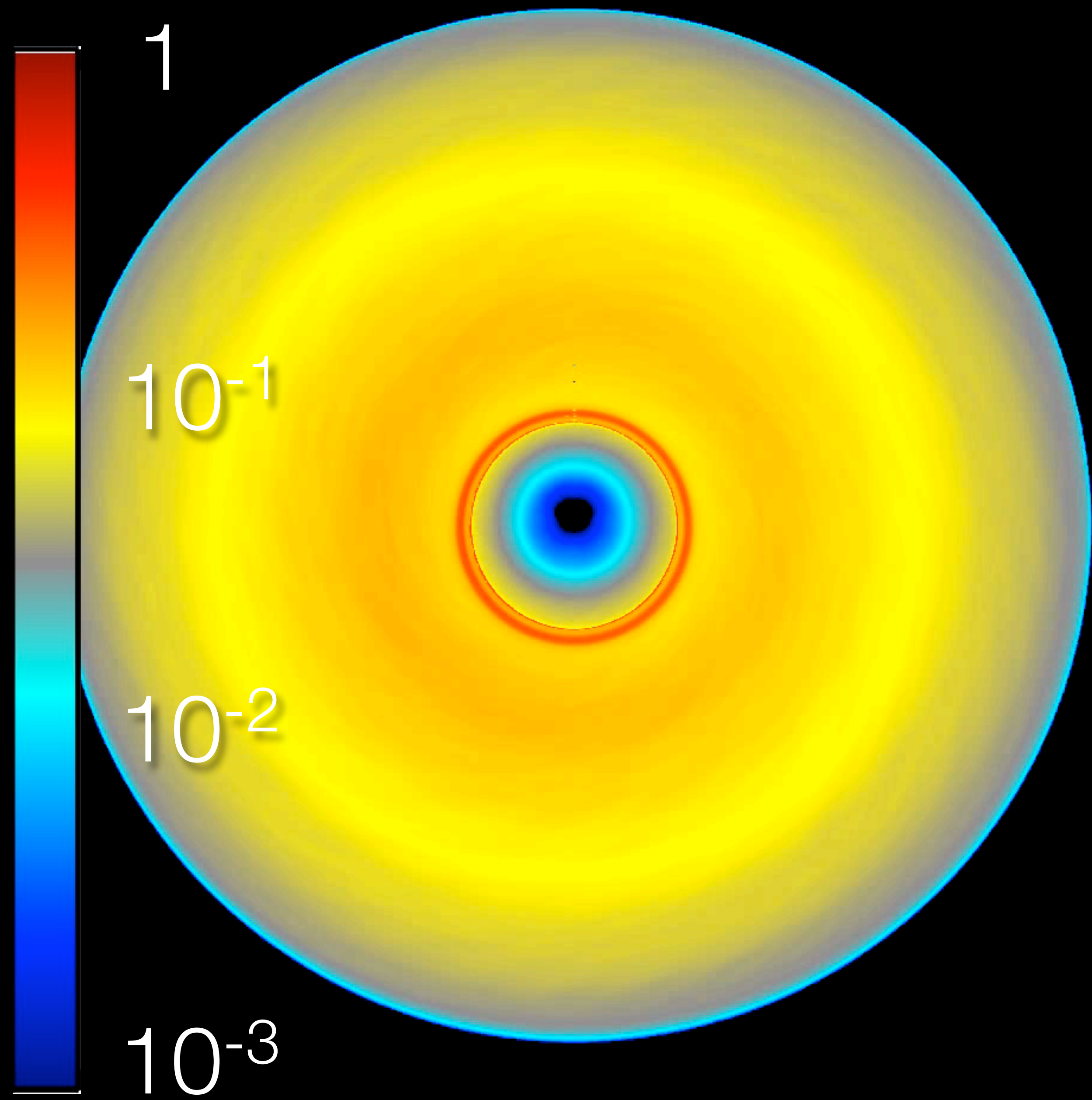
Time-averaged ThinHR

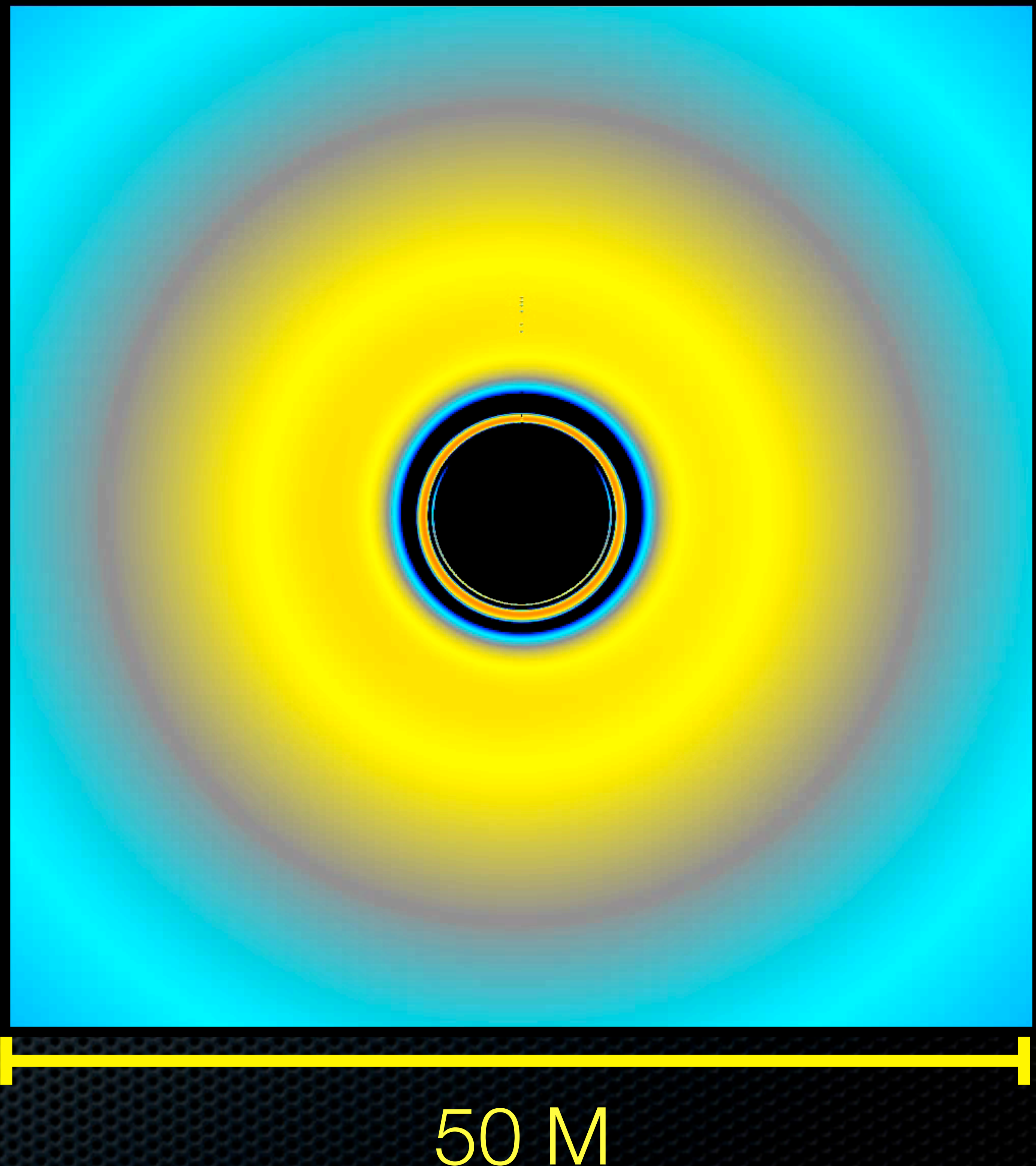
NT

50 M

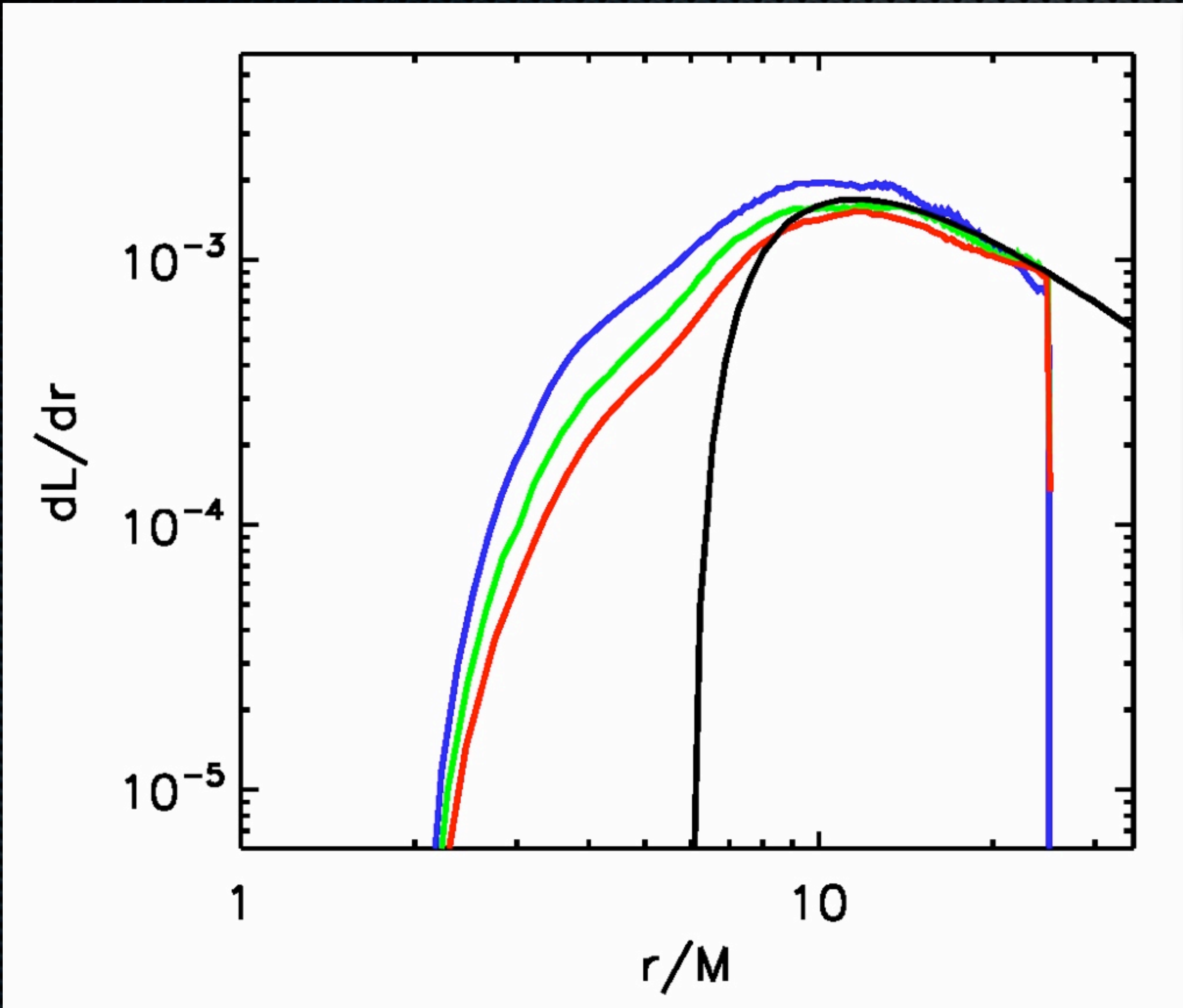
Time-averaged ThinHR

NT





Efficiency Trend with Scaleheight



$$R_{\rm NT} = 11.4$$

$$R_{\rm ThinHR} = 10.3$$

$$\Delta T_{\rm max}/T_{\rm max} = 8\%$$

$$\Delta R_{\rm in}/R_{\rm in} = 11\%$$

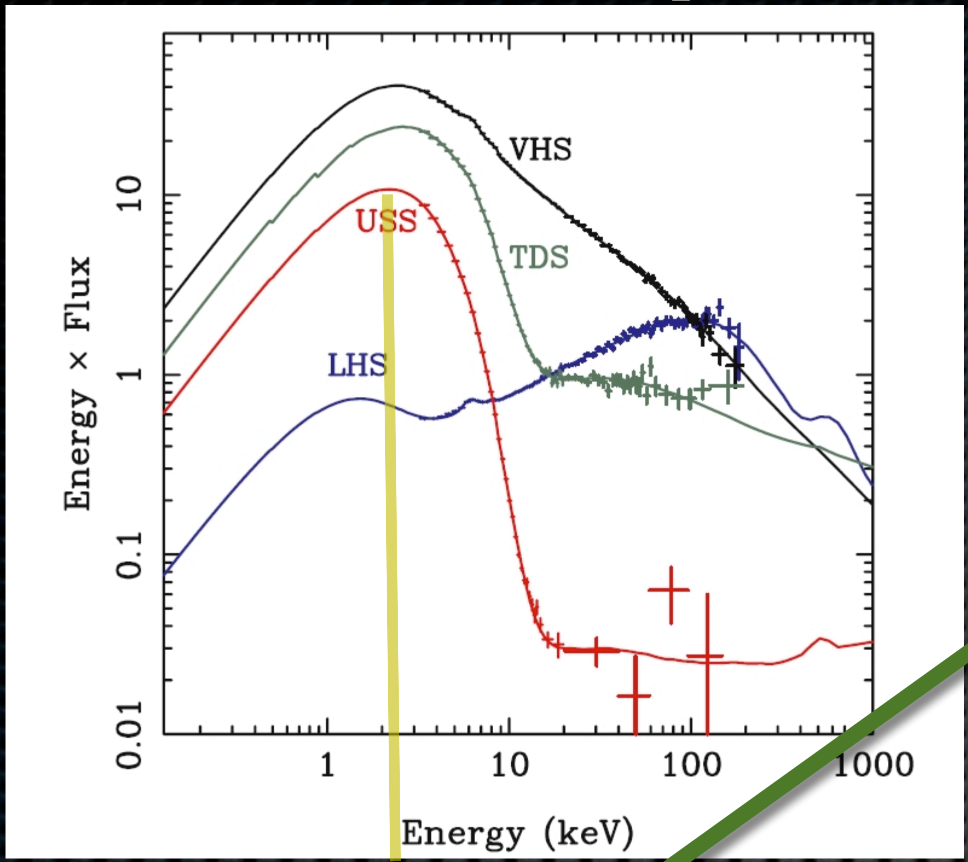
$$\Delta\eta/\eta = 10\%$$

$$\Delta\eta/\eta = 4\%$$

$$\Delta\eta/\eta = -1\%$$

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

Thermal Spectral Fitting for BH Spin



T_{max}

Integrated Stefan-Boltzmann Law for Multi-T BB Disks

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

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

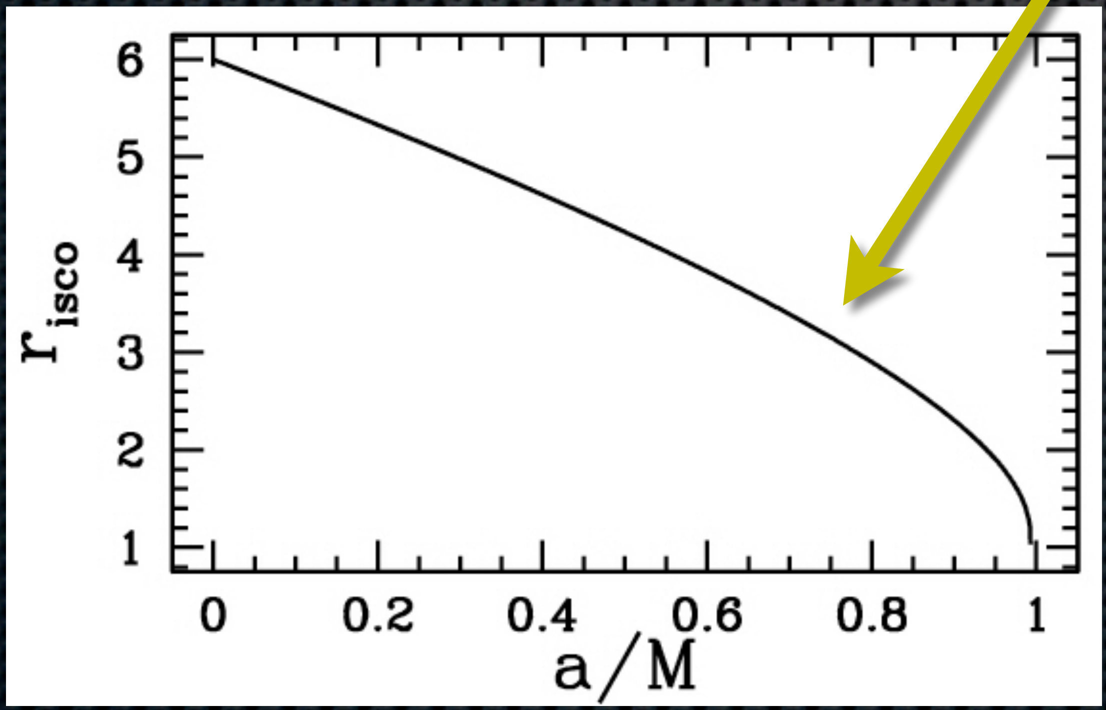


Table 1. Spin Results to Date for Eight Black Holes[a]

	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 ± 0.05	Liu et al. 2008, 2010
3	4U 1543–47	0.80 ± 0.05	Shafee et al. 2006
5	GRO J1655–40	0.70 ± 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 ± 0.18	Gou et al. 2010

[a]Errors are quoted at the 68% level of confidence.

[b]Provisional result pending improved measurements of M and i.

McClintock et al. (2011)

Spectral Fitting NT to Simulations

Schnittman, SCN, Krolik (2011)

Simulation:

- **ThinHR: a=0, H/R=0.06**
- **Snapshots spaced dt= 500M**

GR Ray-tracing (Schnittman's code):

- **Time-average snapshot spectra;**
- **Includes reflection radiation;**
- **Results shown use** $i_{\rm sim} = 60^\circ$

- **Free parameters:**

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

- **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 (constraints)	Unknowns (fitting parameters)
1	D	i , a , M , Mdot
2	D , M	i , a , Mdot
3	D , M , i	a , Mdot

Case A: "A Band" fit over [0.2,10] keV
Case B: "B Band" fit over [1.0,10] keV

--> 6 types of fits

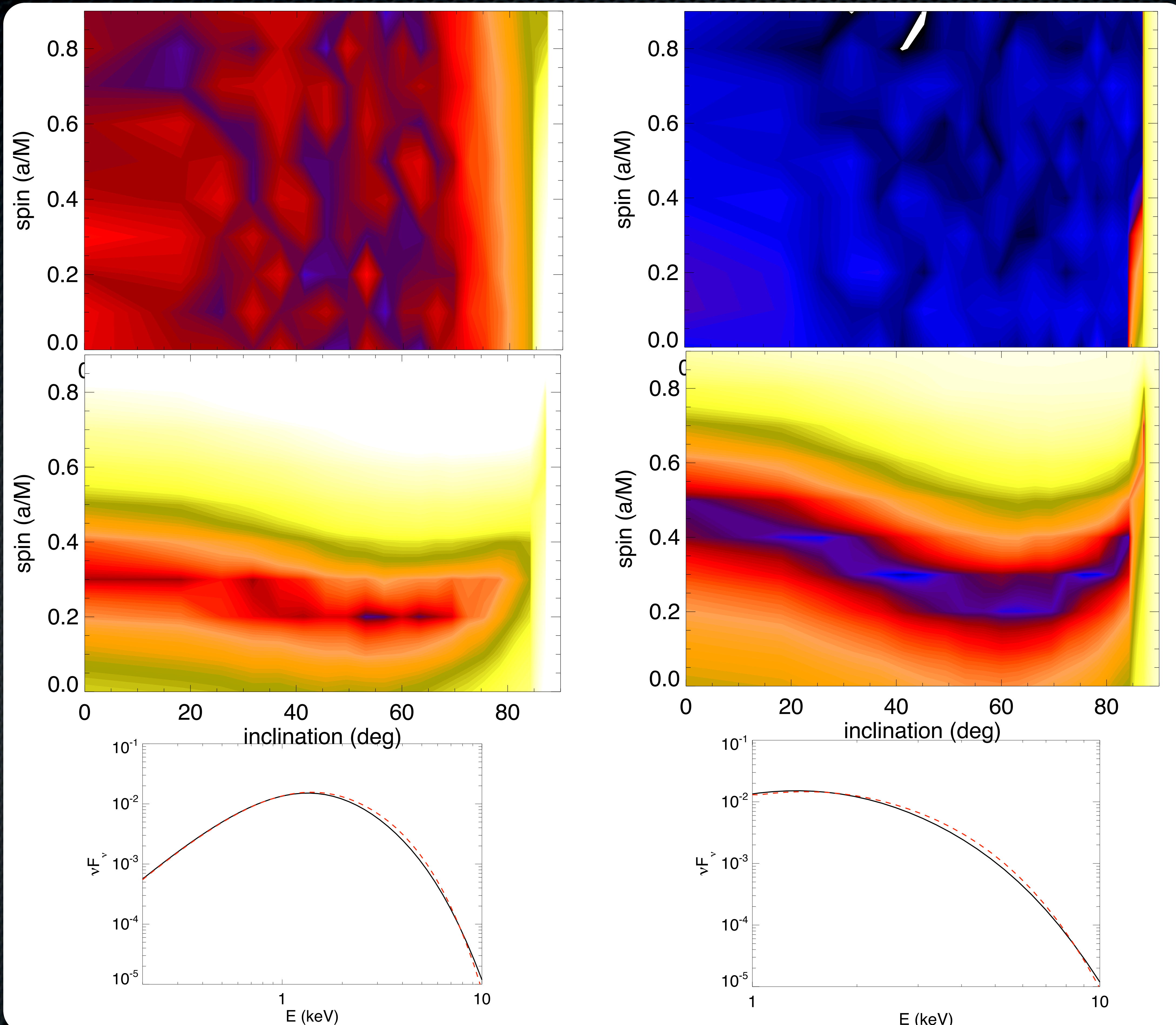
A (broader band) B (narrow, high-E band)

Case 1: Fitting with a, i, M, Mdot

Case 2: Fitting with a, i, Mdot

Case 3: Fitting with a, Mdot

a = 0.2-0.3



Summary & Conclusion:

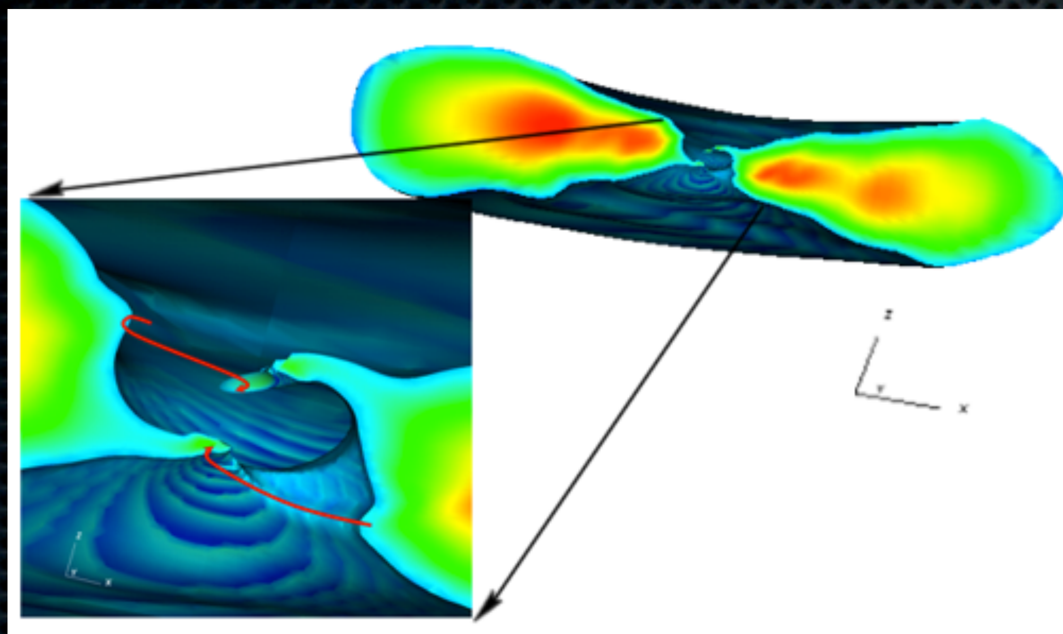
- Moving towards fully self-consistent accretion models;
- Magnetic fields can change the “thin disk” picture within the ISCO;
- Radiative efficiency increases with decreasing disk thickness (no surprise!)
- Our two spin cases suggest that radiative efficiency accretion may be ~10% more efficient
- Our 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

Future Work and Open Questions:

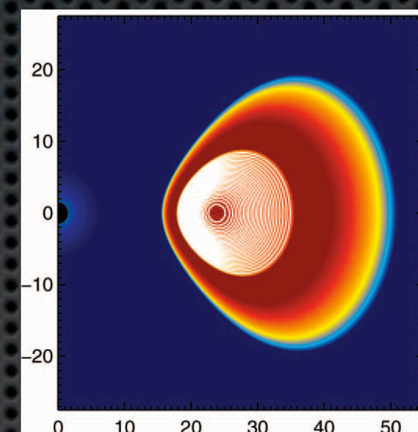
- More H(R)/R and spins: (use simulations to fit to observations);
- Does variability depend on disk thickness?
- Is the simulation’s variability within the observed near-constancy of Rmin?
- How are state transitions triggered?
- What are “realistic” (and realizable) initial disk conditions?

Incomplete List of Out-standing Issues in BH Accretion

Warped Disks Fragile et al. 2007-2009



Initial Field Topology Beckwith et al. 2008



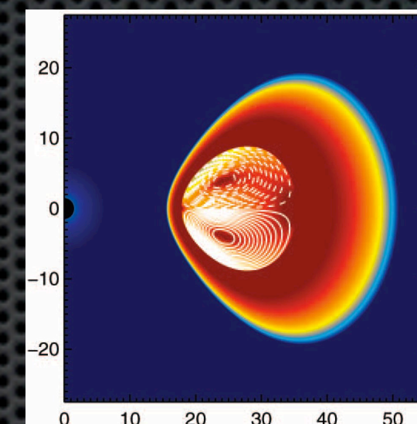
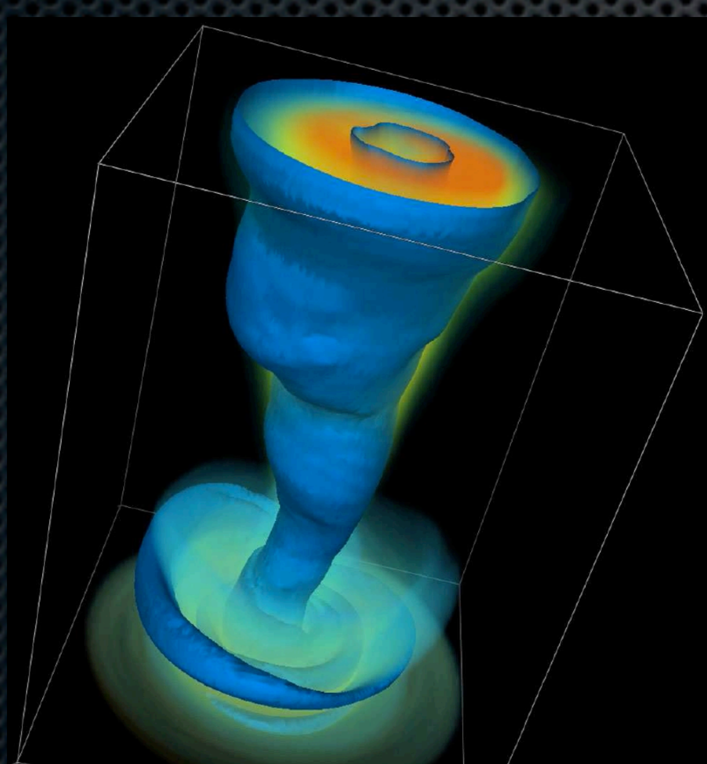


Image Unavailable

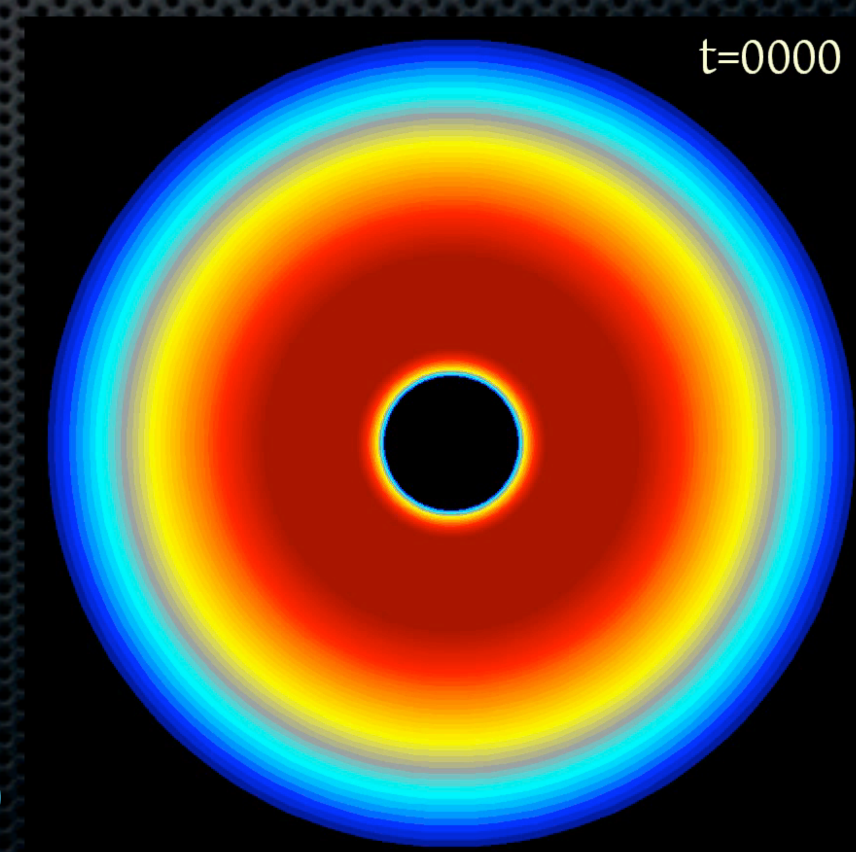
Poloidal	Quadrupolar	Toroidal
Jet	Jet	"No" Jet



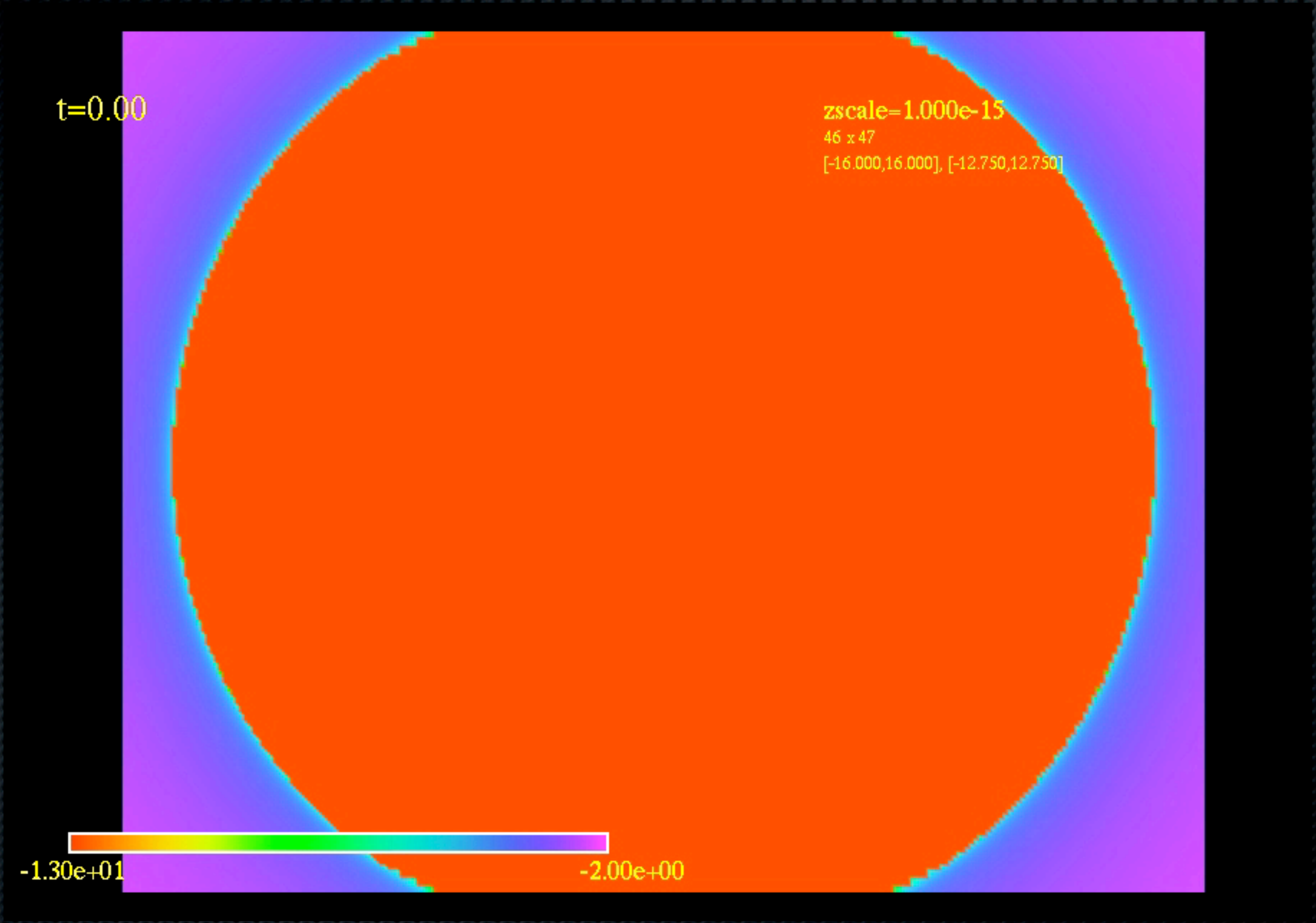
McKinney & Blandford 2009

Full 2pi Evolutions
m=1 mode dominance

Gammie et al (unpub.)



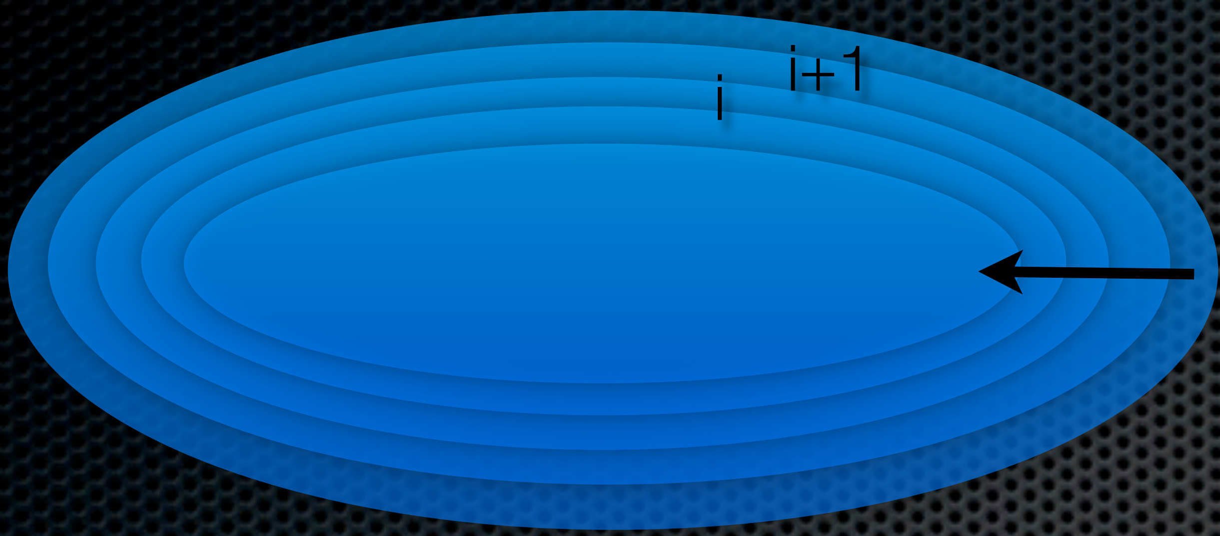
Binary Black Hole Accretion



Variability

Variability Models

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



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

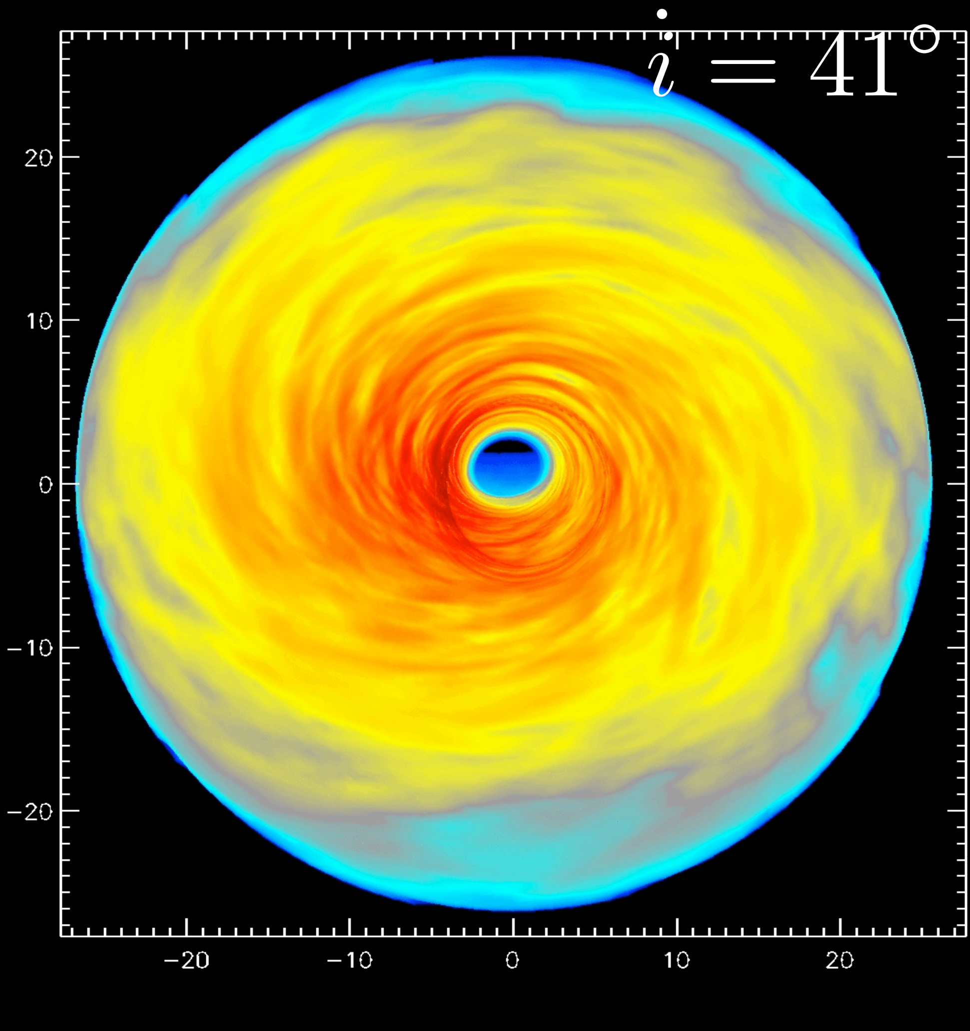
- Outer radius of corona may be cause of (temporal) spectral slope

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

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

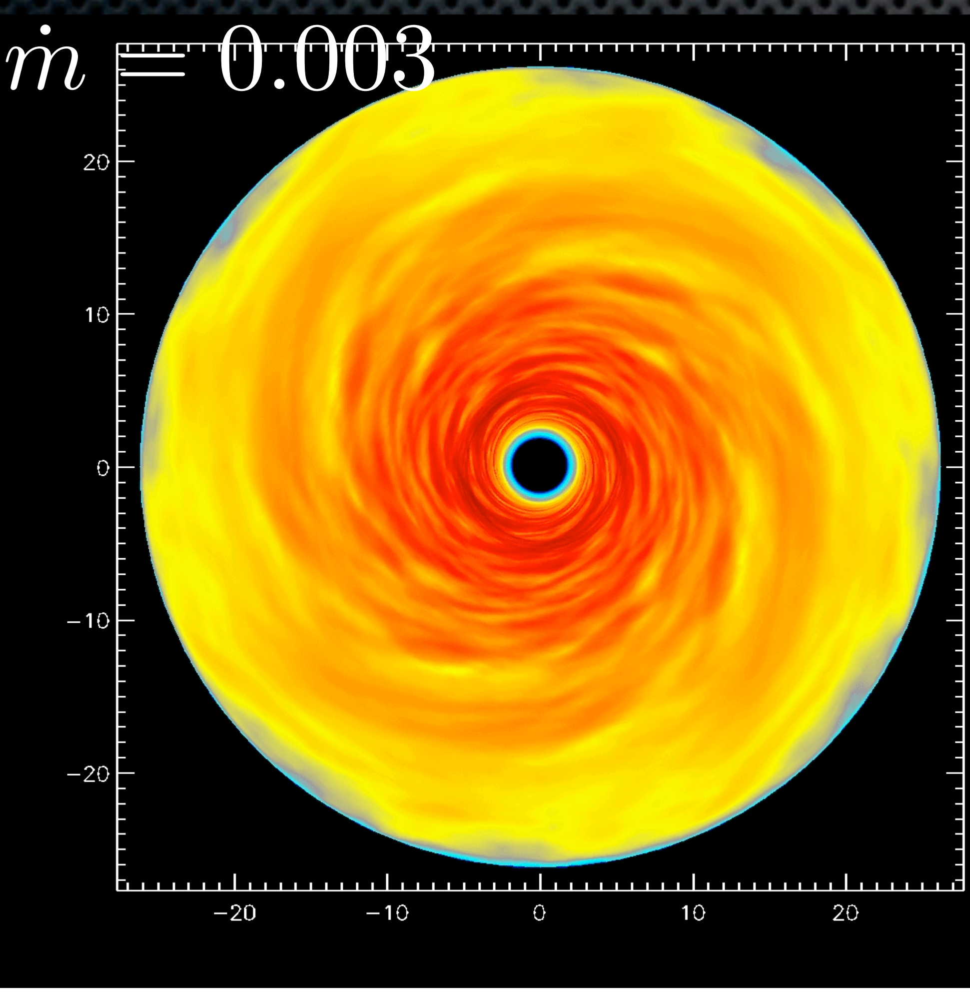
Armitage & Reynolds 2003
Machida & Matsumoto 2004
Schnittman et al 2006
Reynolds & Miller 2009

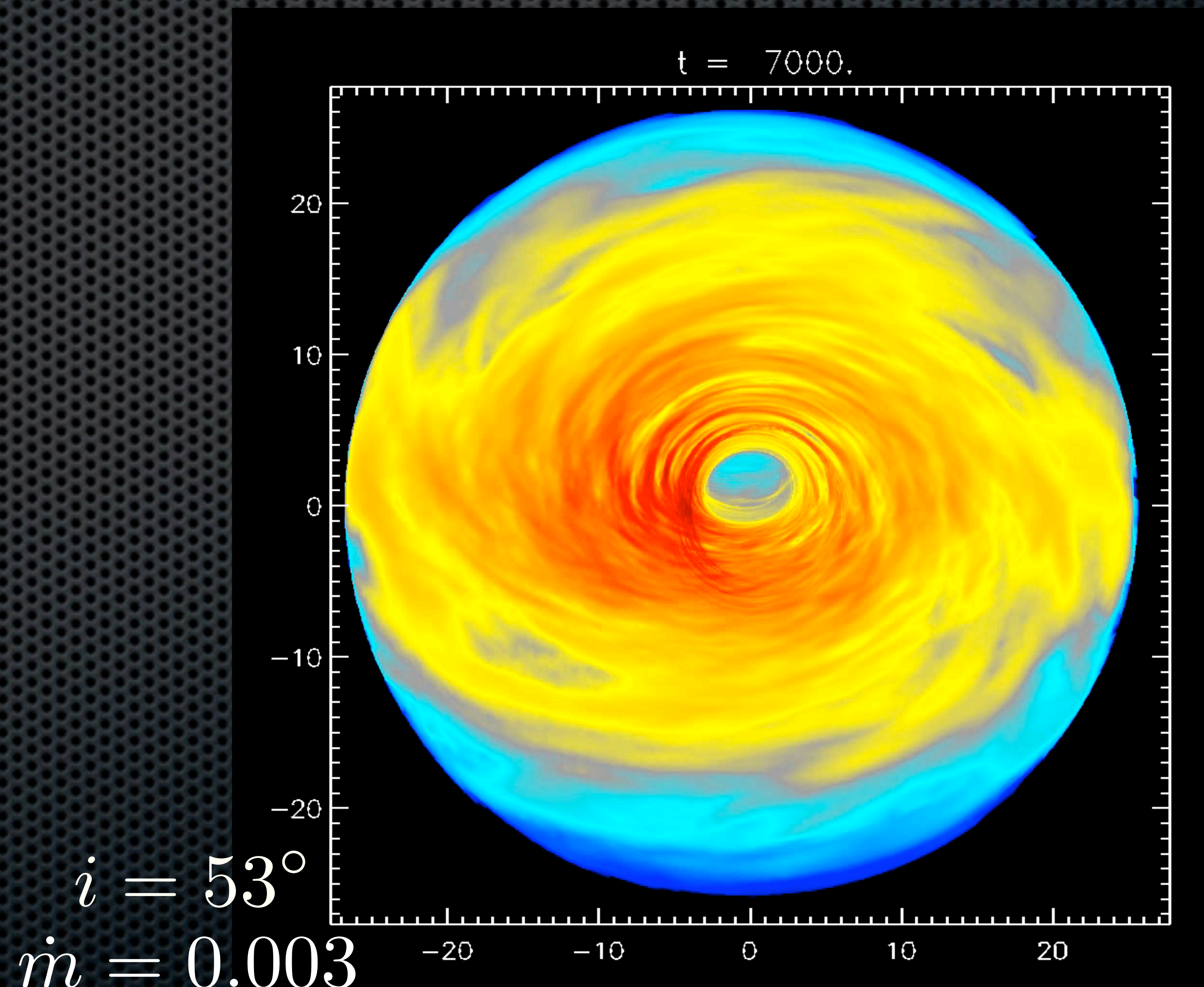
- Used accretion rate or stress as dissipation proxies
- PLD breaks at local orbital frequency per annulus
- Composite PLD $\rightarrow \alpha \simeq -2$

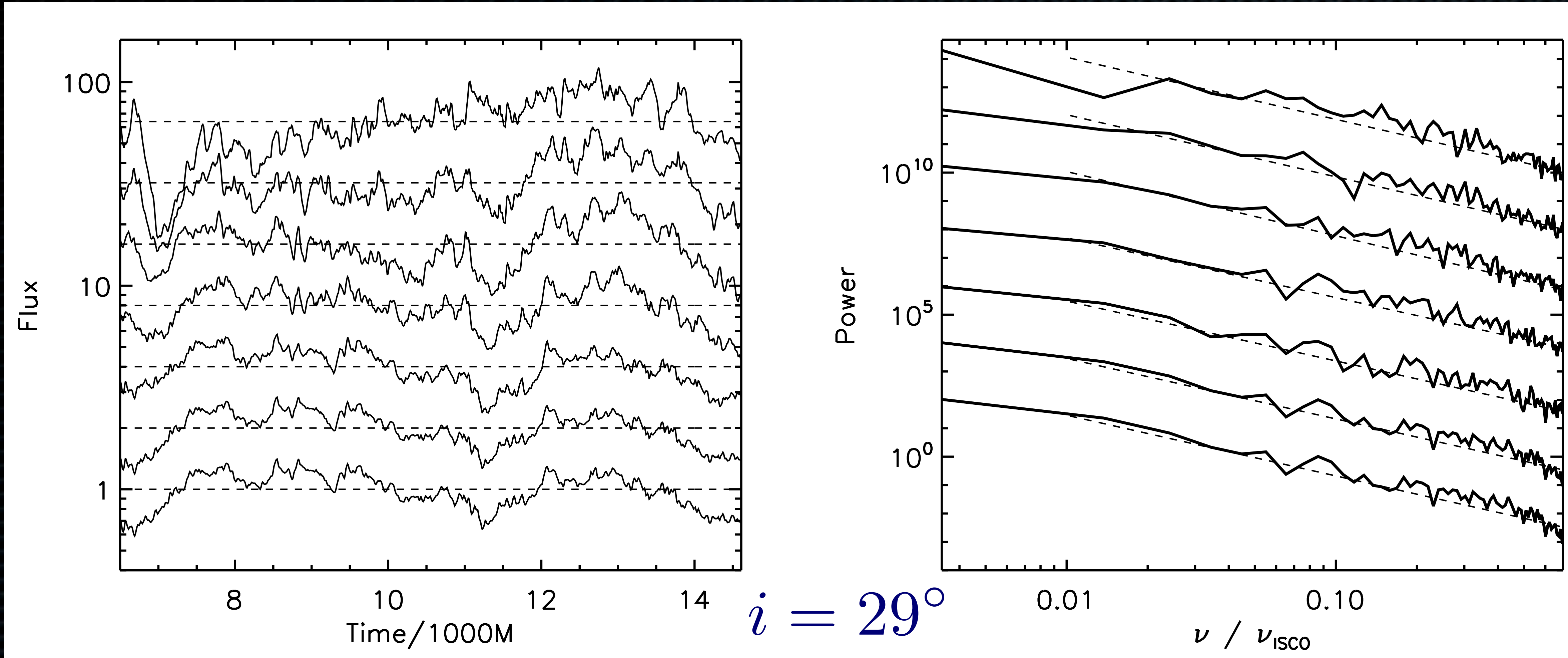


SCN & Krolik 2009

- 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

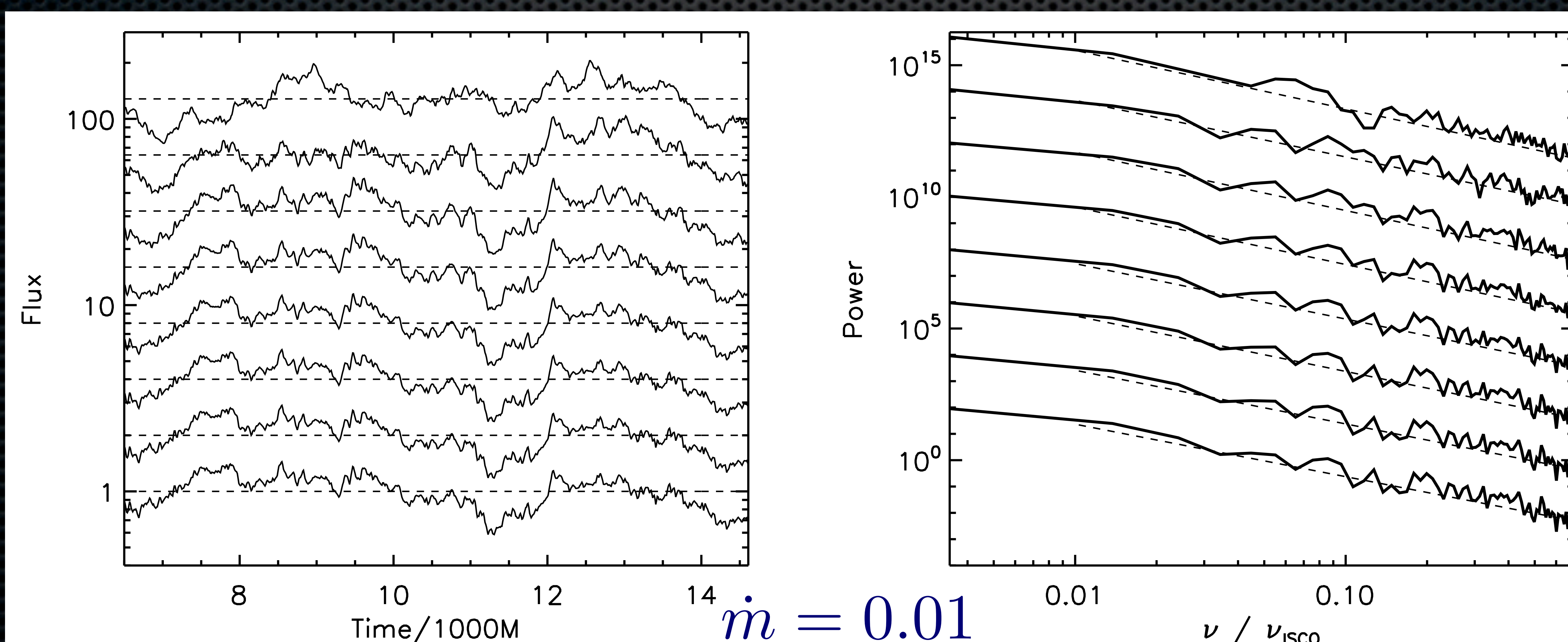






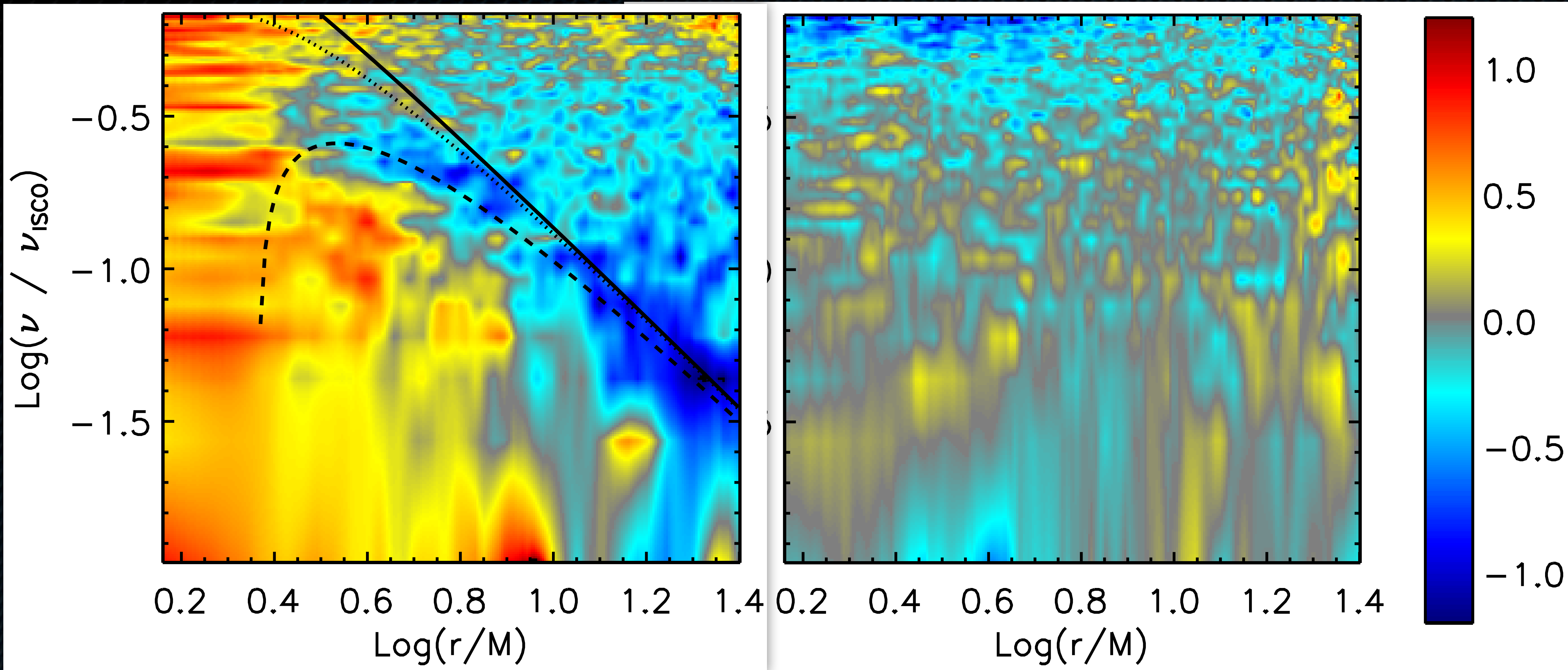
Flux
100
10
1
8
10
12
14
Time/1000M
$i = 29^\circ$
Power
10^{10}
10^{5}
10^{0}
0.01
0.10
ν / ν_{ISCO}

$\dot{m}$



Flux
100
10
1
8
10
12
14
Time/1000M
$\dot{m} = 0.01$
Power
10^{15}
10^{10}
10^{5}
10^{0}
0.01
0.10
ν / ν_{ISCO}

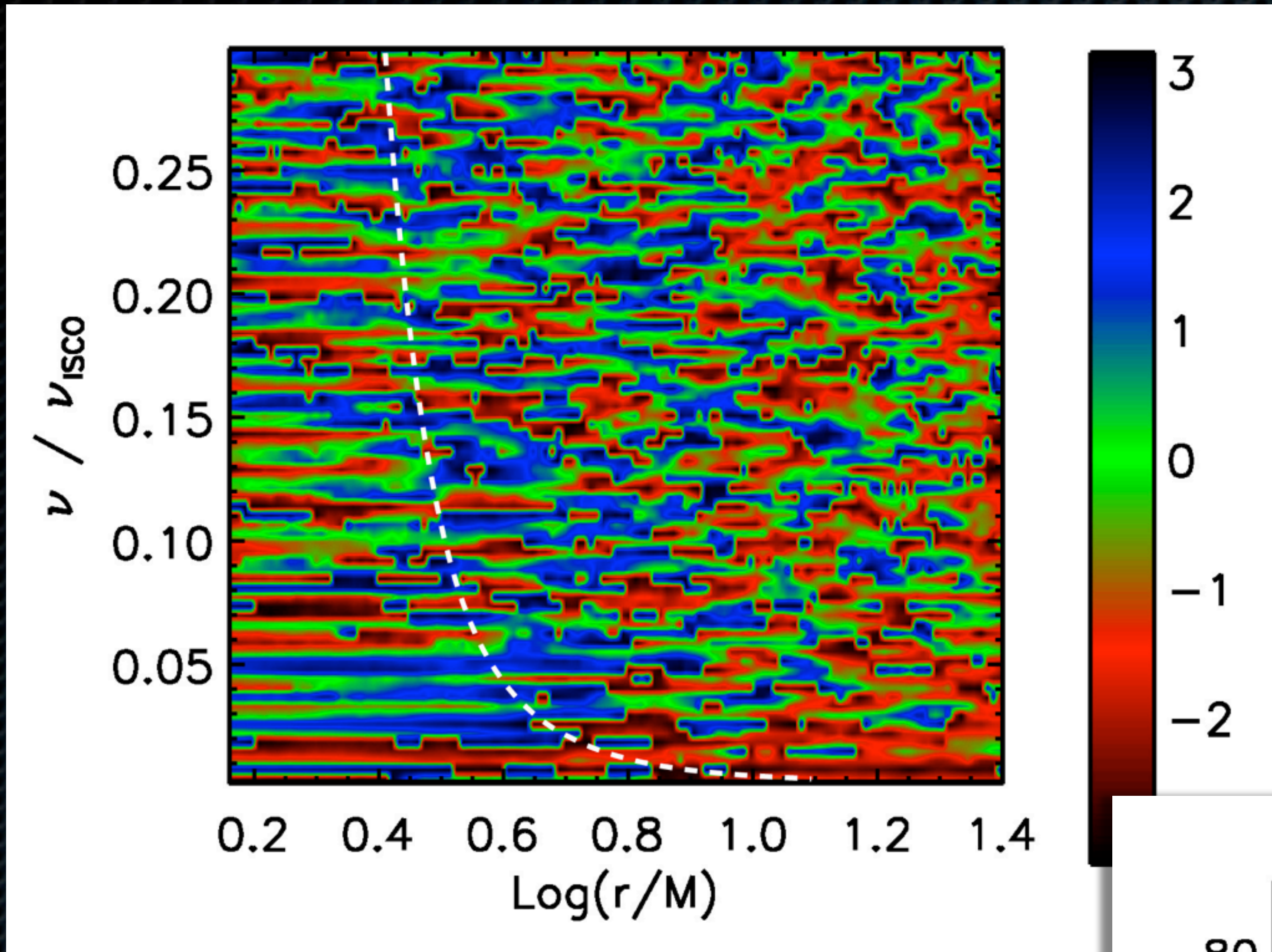
i



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

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

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

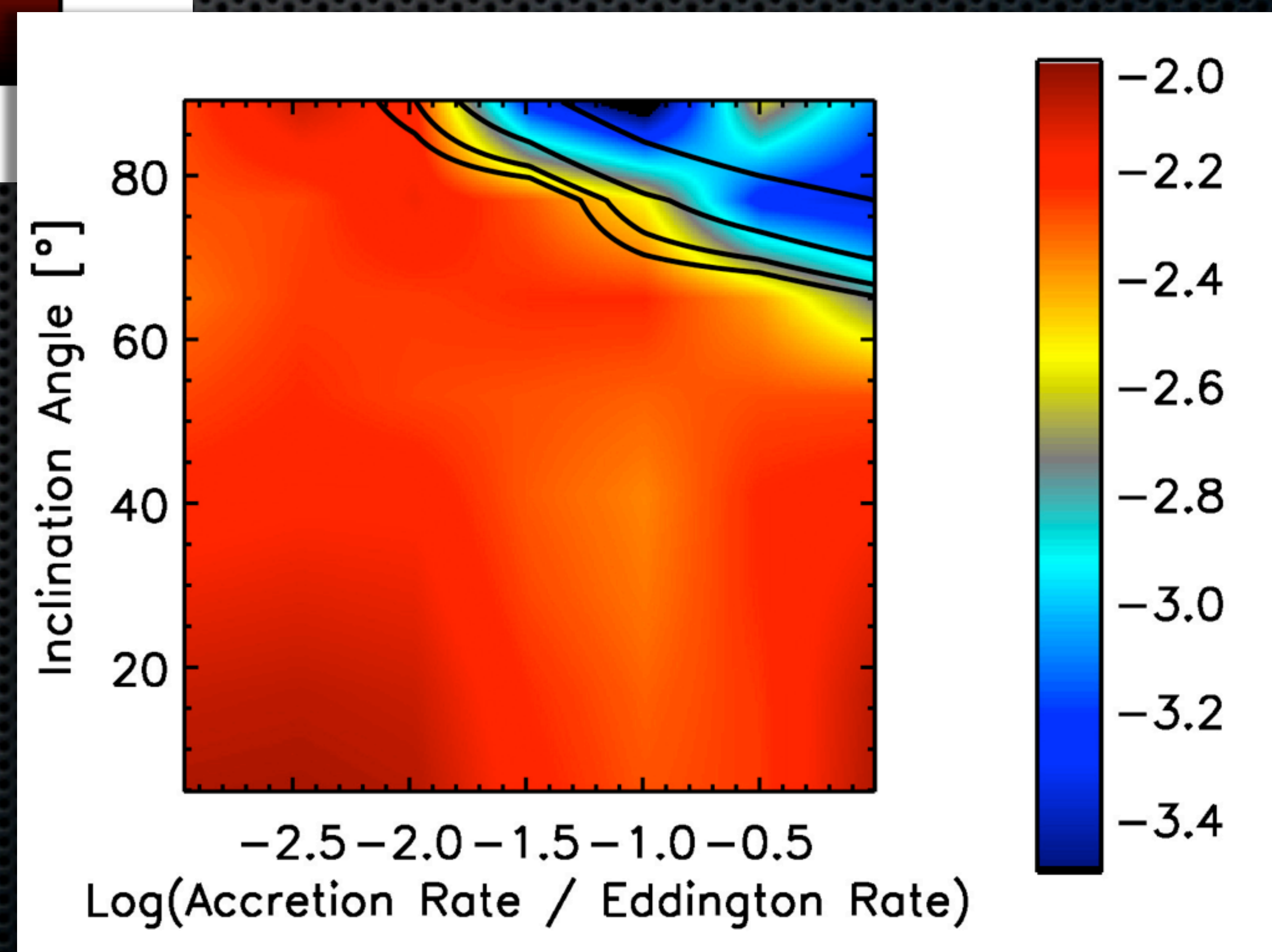


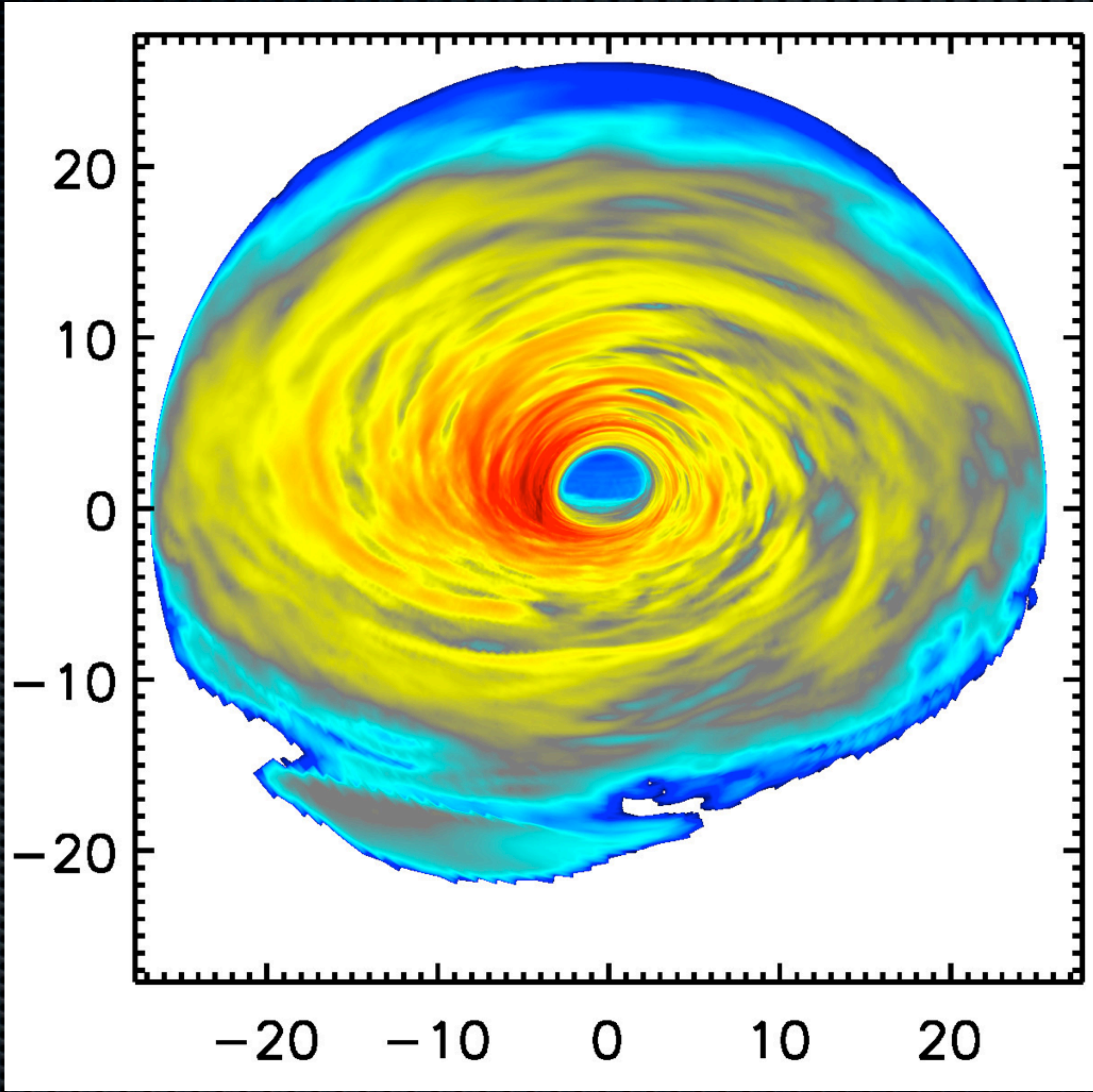
- Mostly incoherent between adjacent radii and frequencies;
- Possible coherence at

$$\nu < 1/T_{\rm inflow}(r)$$

  - 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

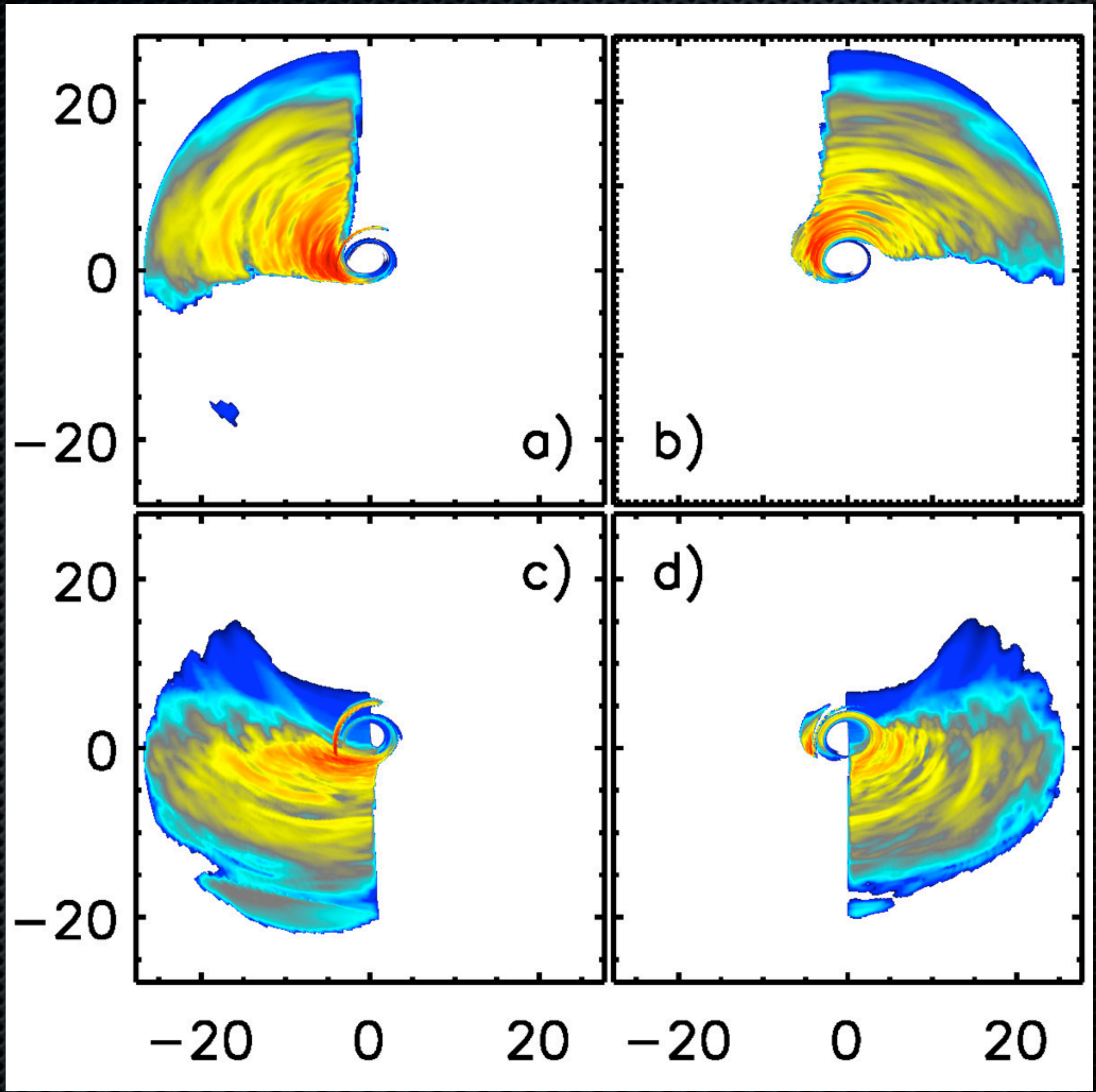



20
10
0
−10
−20
−20
−10
0
10
20

Degeneracy Explanation

$\alpha_a > -2$

$\alpha_b > -2$



$\alpha_c < -2$

$\alpha_d < -2$

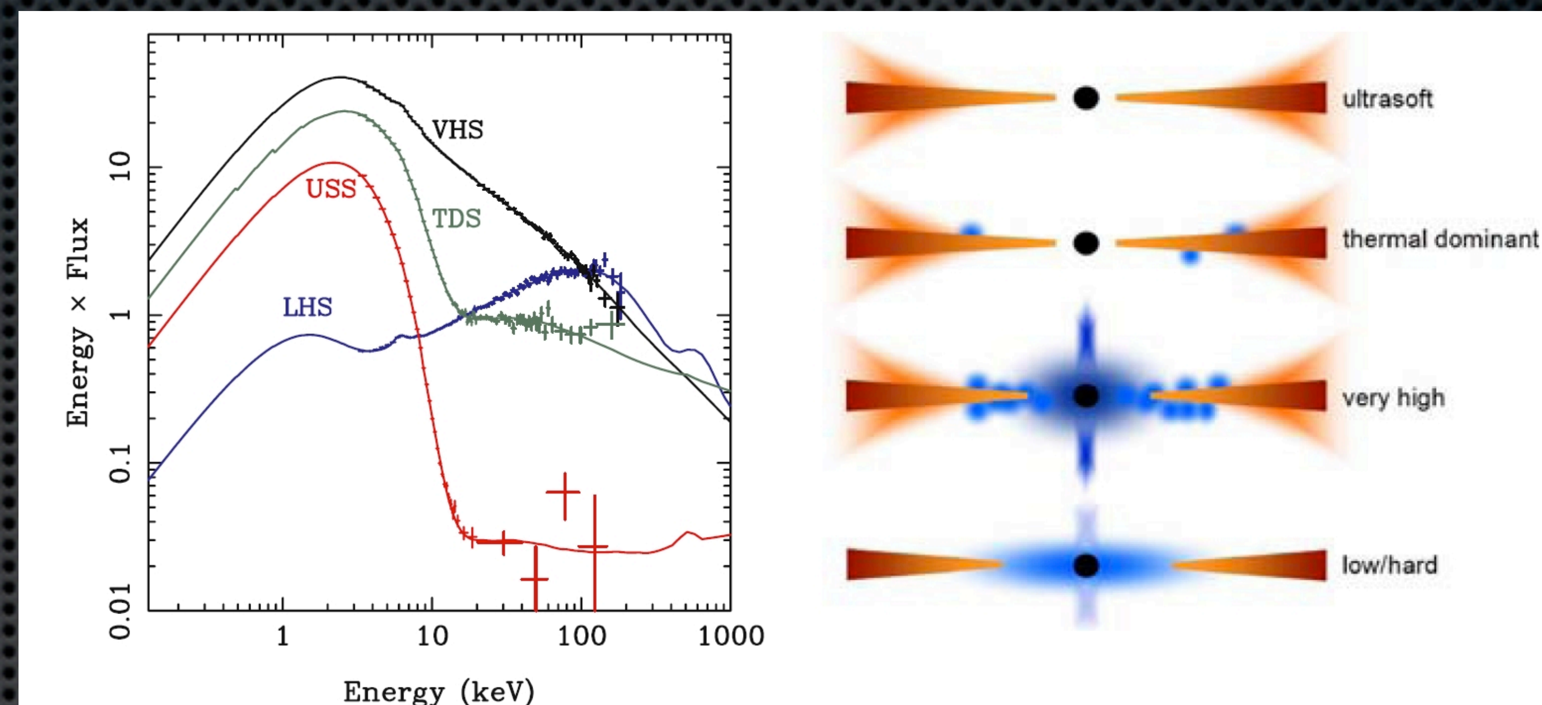
$i \sim 0^\circ$
$\alpha_i \simeq -2$

Extra Slides

Probing the Spacetime of BHs

- Variability: e.g. QPOs, short time scale fluctuations
- Polarization
  (e.g. Schnittman & Krolik 2009)

Done et al 2007

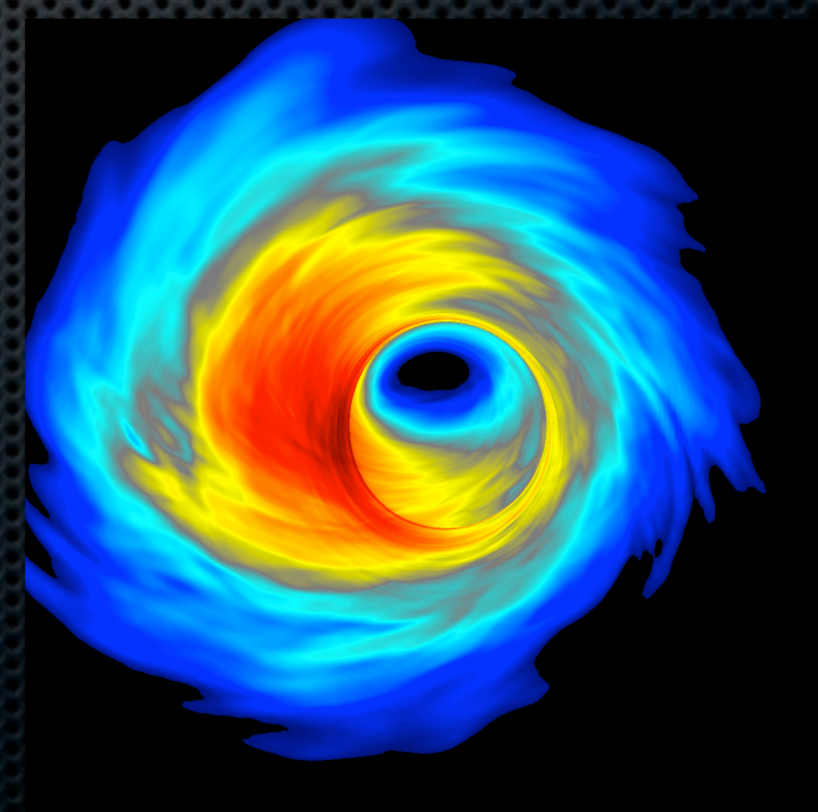


- Spectral Fitting of Thermal Emission

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

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

[2] 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 $r < r_{ms}$ to the disk at $r \geq r_{ms}$. In this case the boundary condition at r_{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_{ms} (i.e., at $r - r_{ms} \lessapprox 0.1 r_{ms}$). 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 $E^{\dagger}{}_{ms}$ and $L^{\dagger}{}_{ms}$.

Thorne (1974)

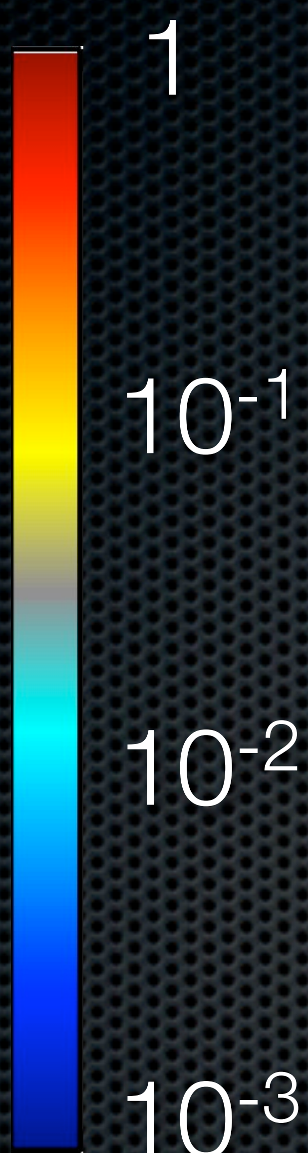
Gammie (1999)

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

Agol & Krolik (2000)

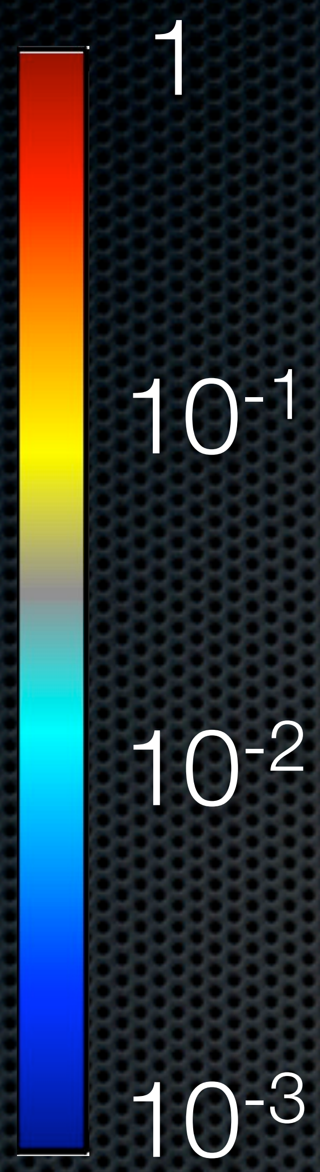
- Magnetic torques at ISCO can affect radiative efficiency

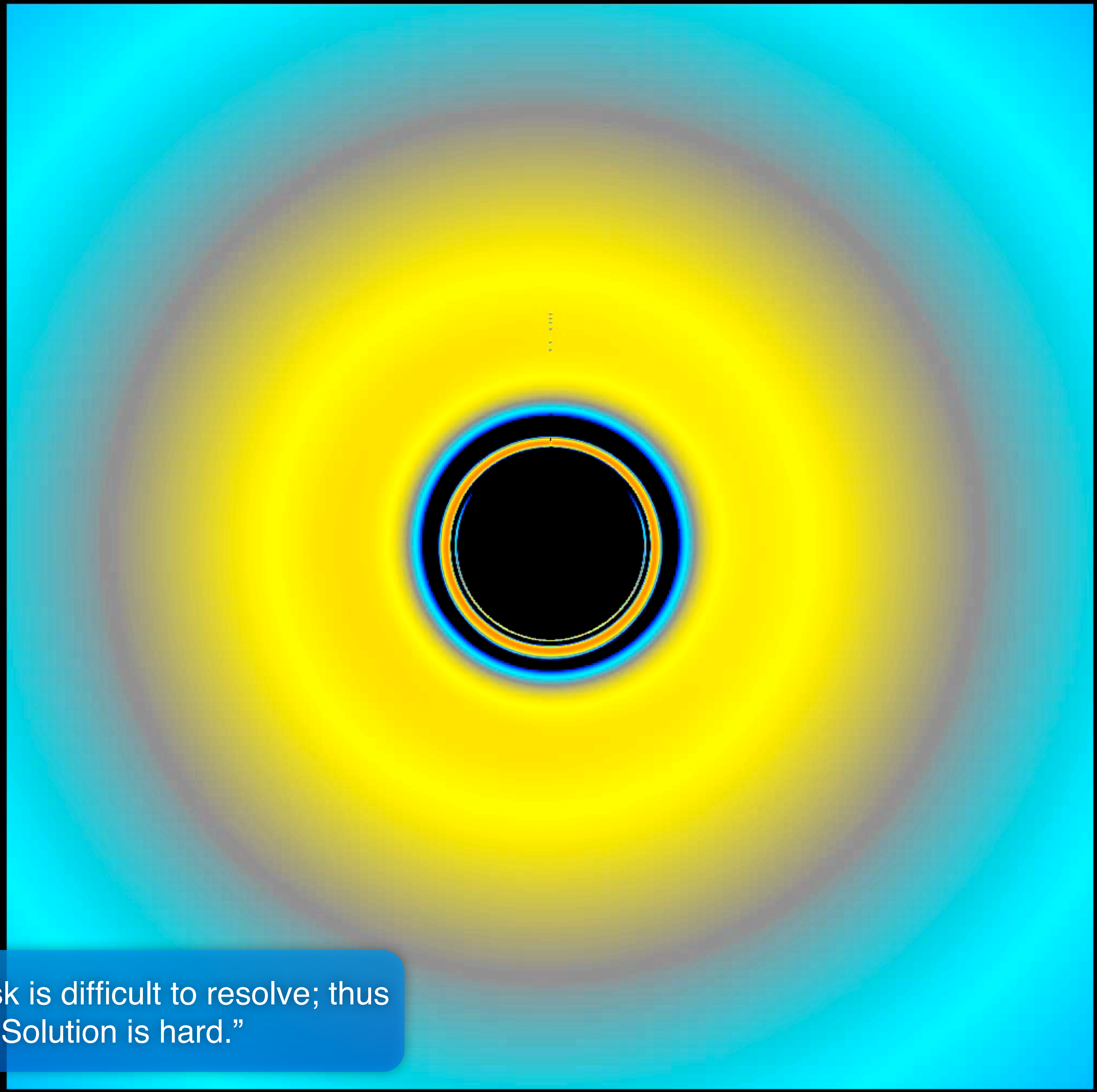
View of a razor-thin disk



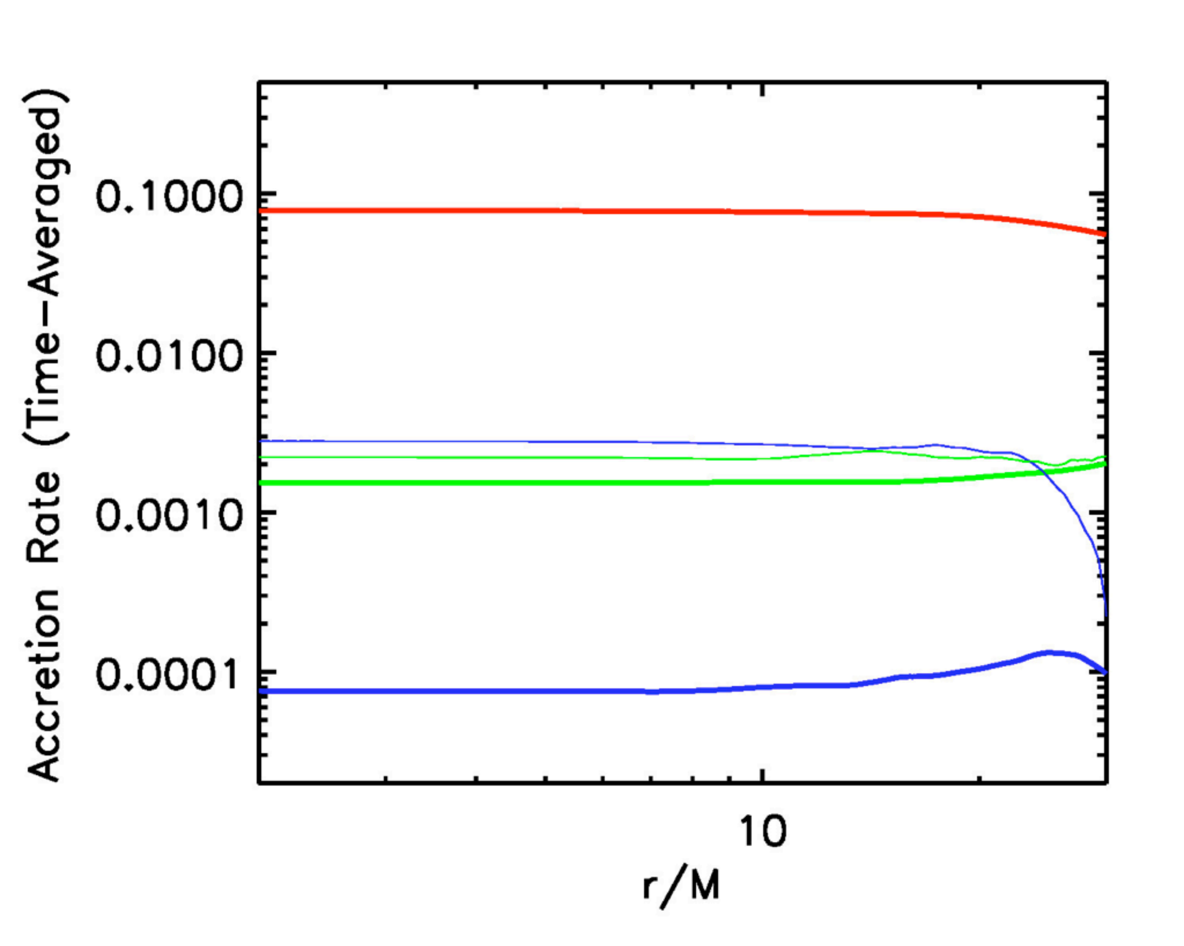
"The sharp edge of a disk is difficult to resolve; thus the wise say the path to Solution is hard."

View of a razor-thin disk





"The sharp edge of a disk is difficult to resolve; thus the wise say the path to Solution is hard.”

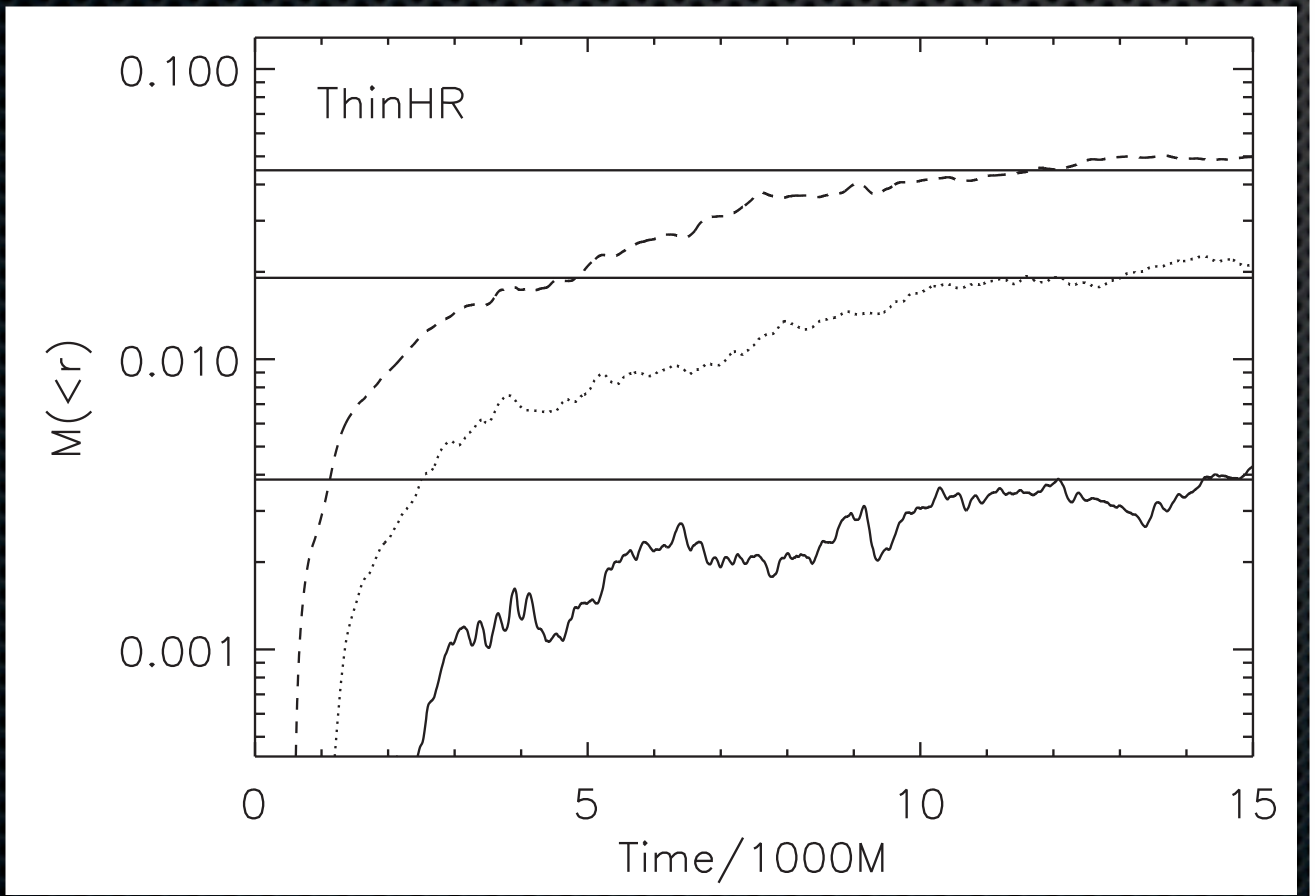


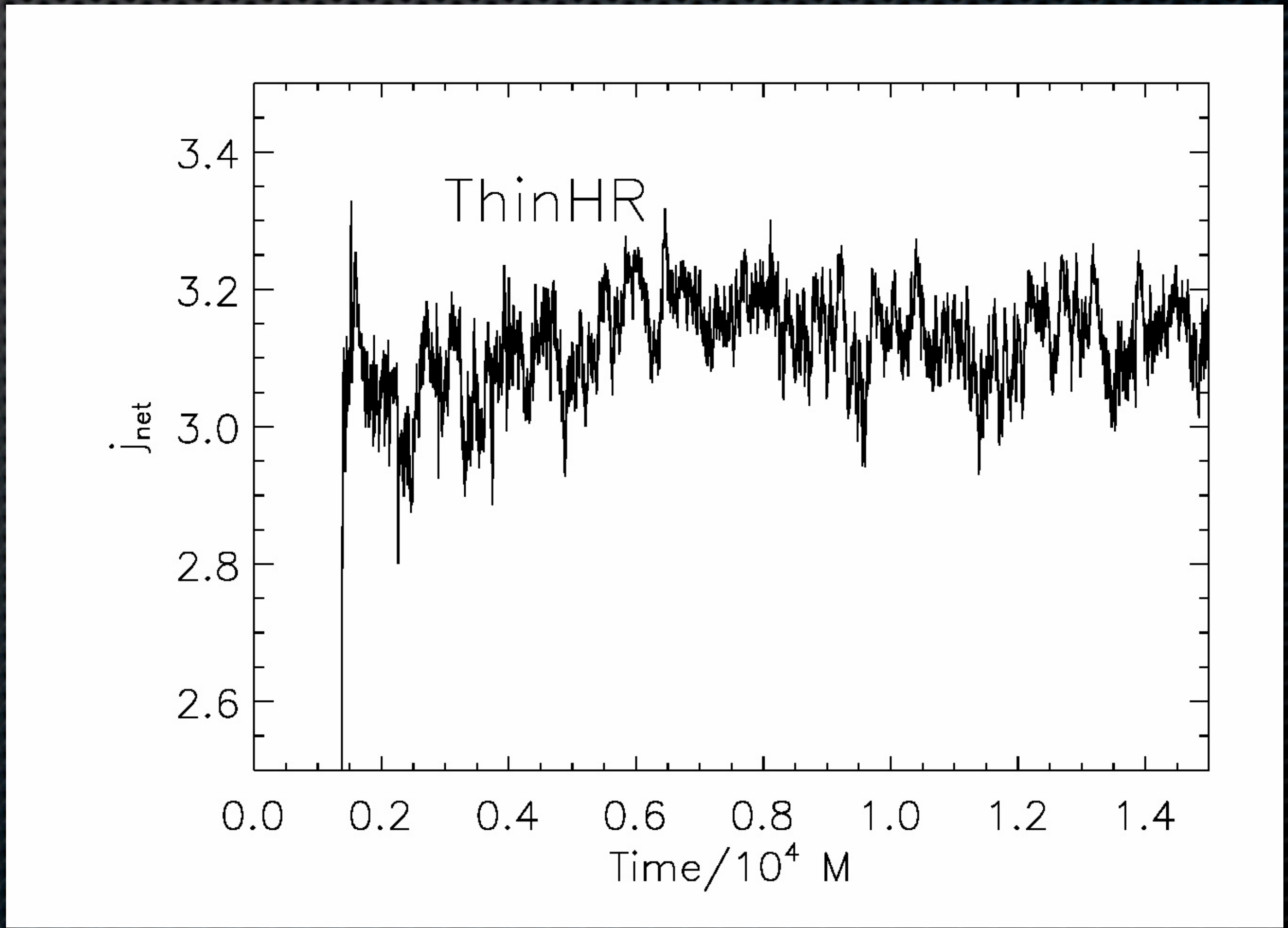
Inflow Equilibrium

Defined to be when:

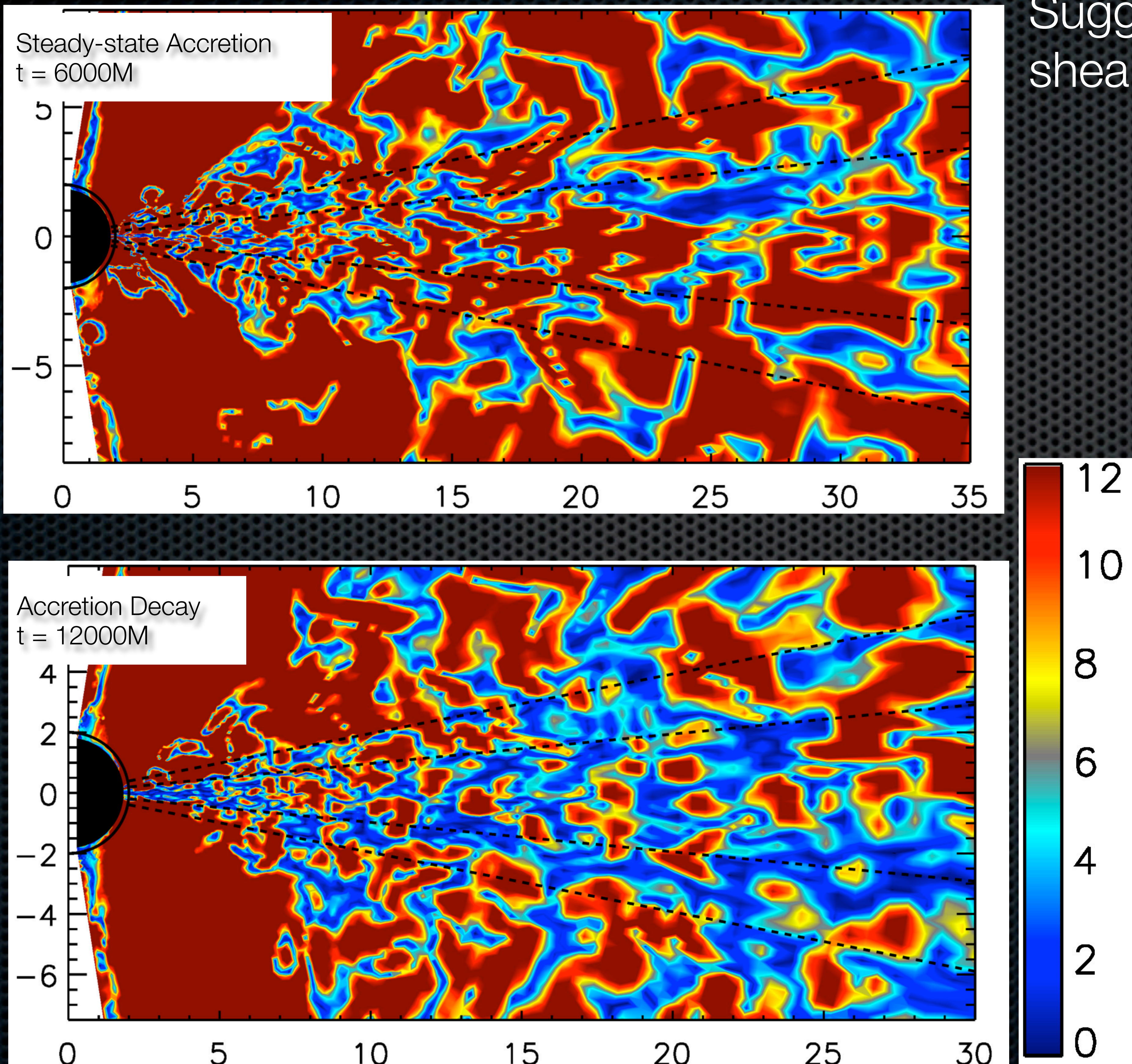
1) Accreted specific angular momentum (jnet) is steady;
2) Mass flux shows no trends in time over radius;

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:

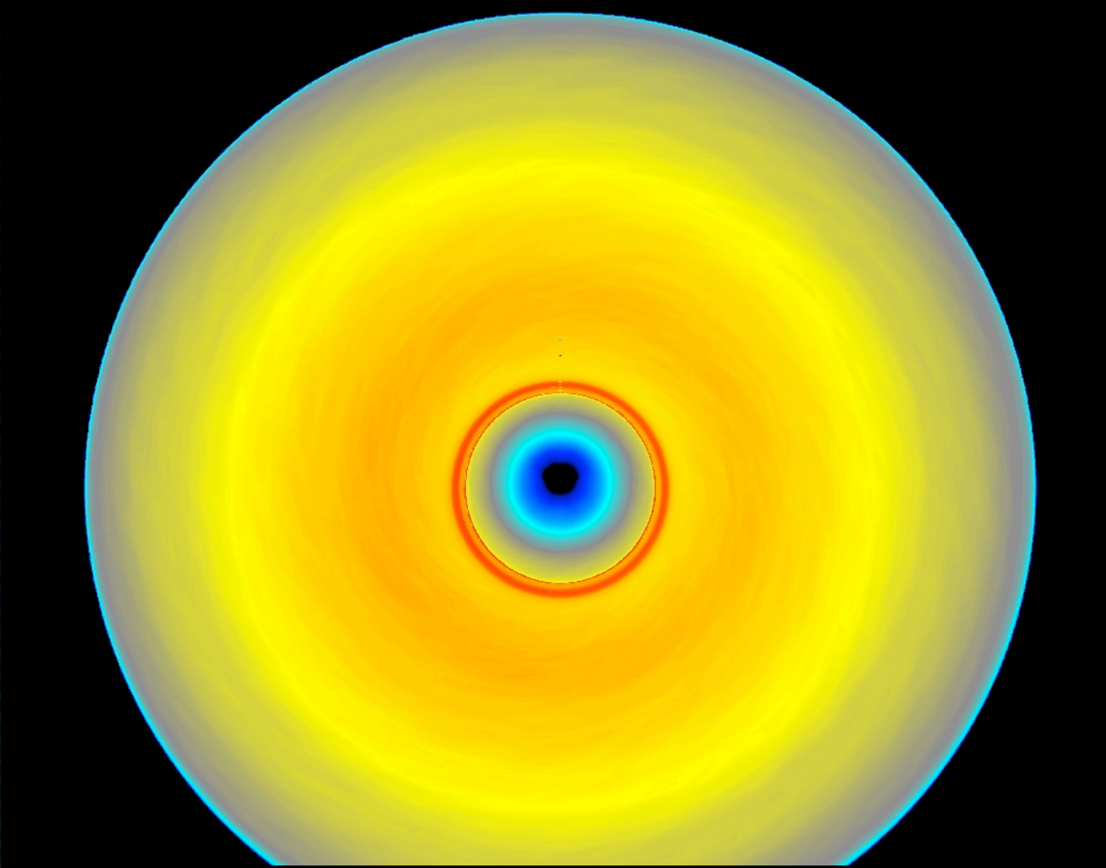
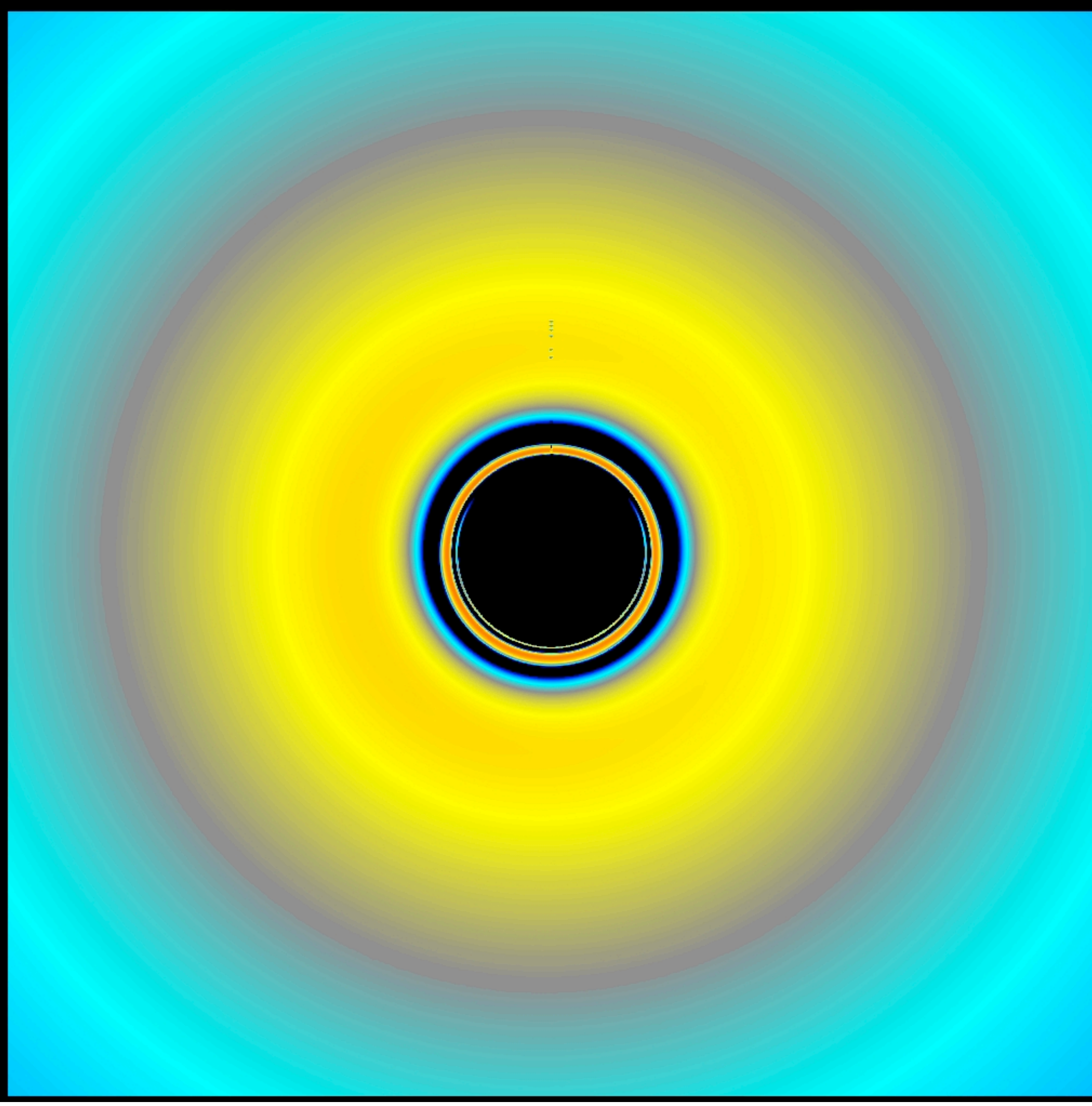
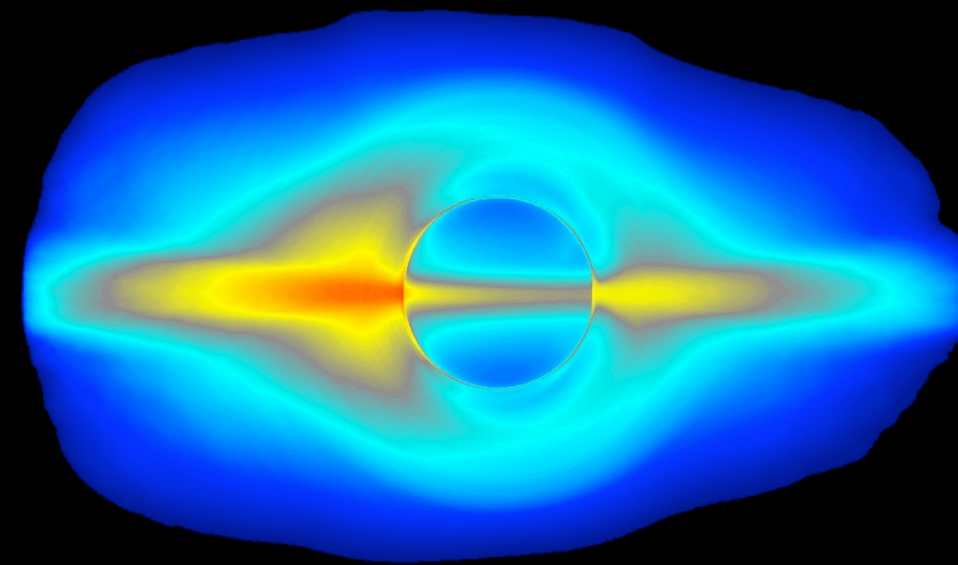
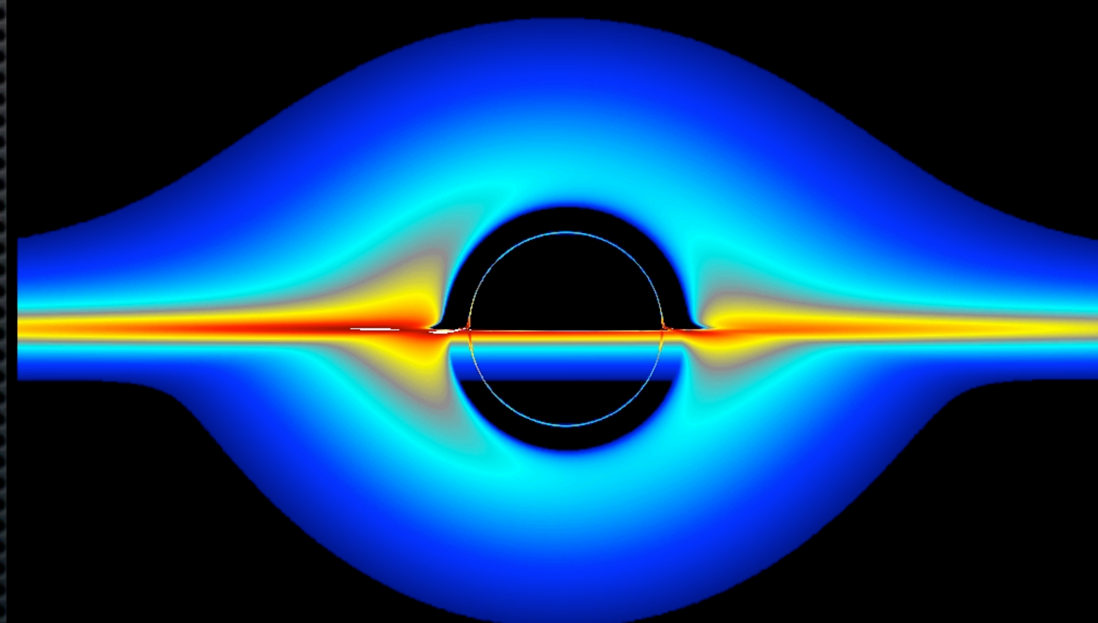
Sano et al. 2004

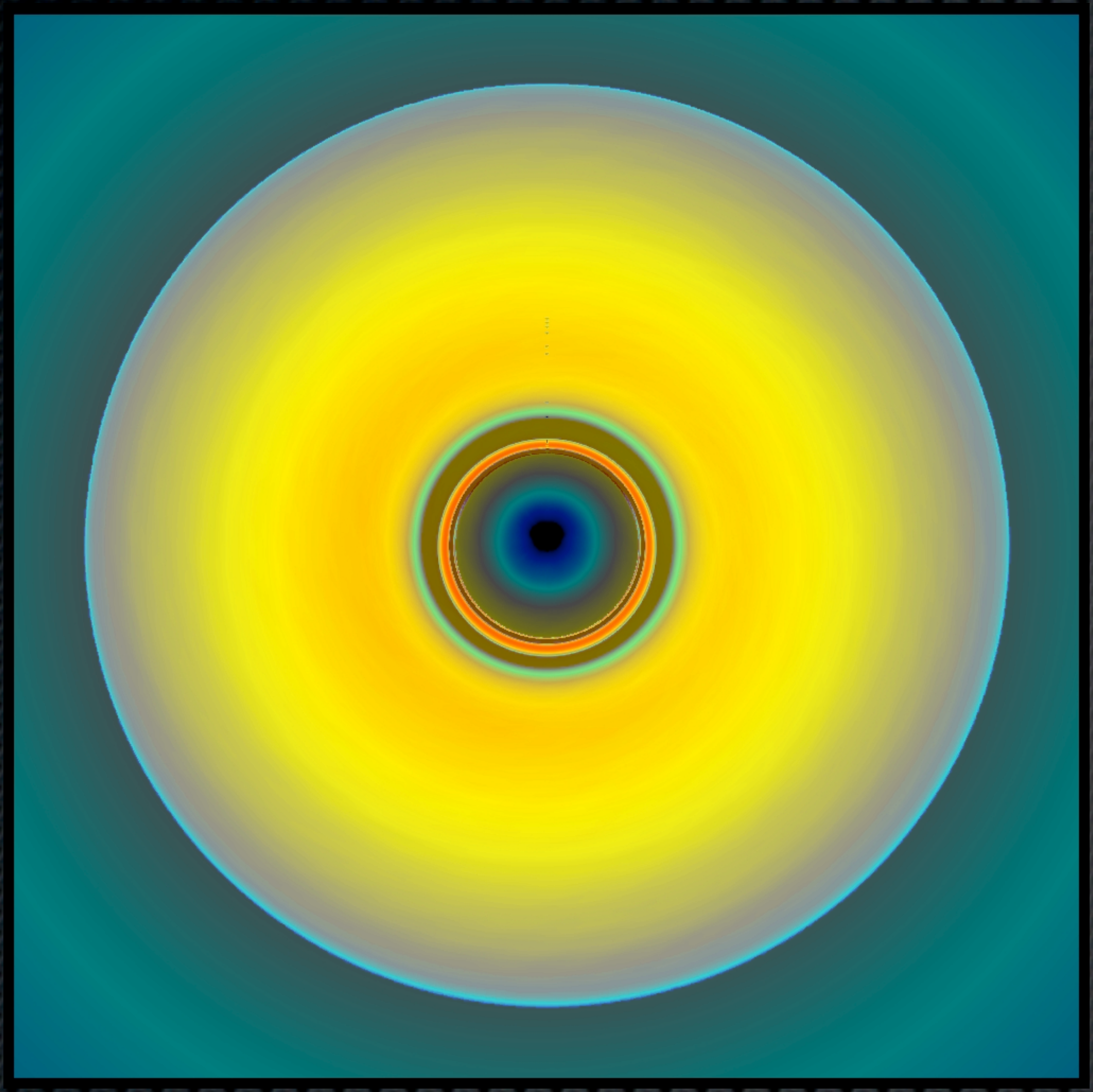
$$\lambda_{\rm MRI} \equiv \frac{1}{\sqrt{4\pi\rho\Omega(R)}} b_\mu \hat{e}^{\mu}_{(\theta)}$$

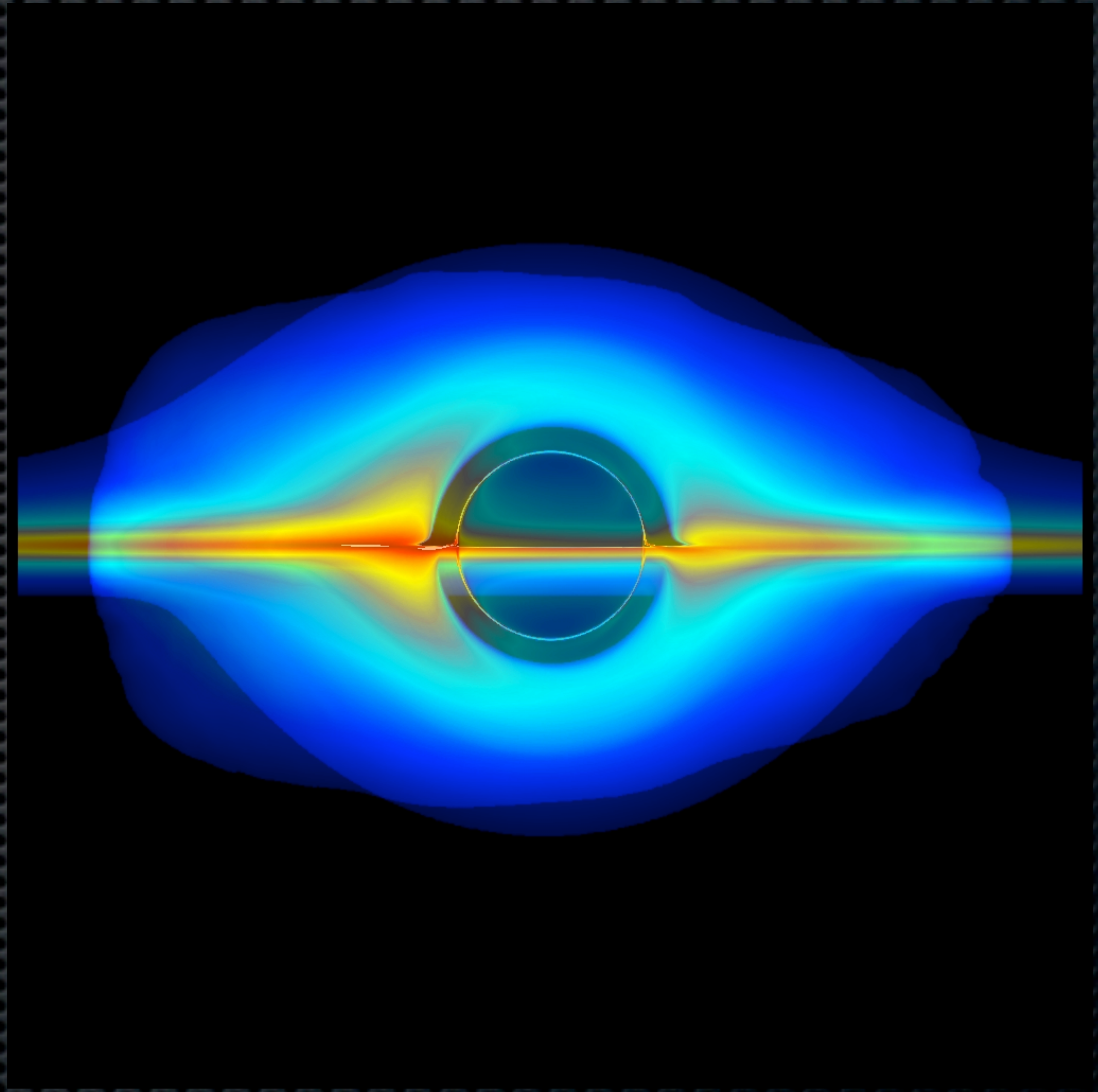
$$\frac{\lambda_{\rm MRI}}{\Delta z} > 6$$

Davis, Stone, & Pessah 2009

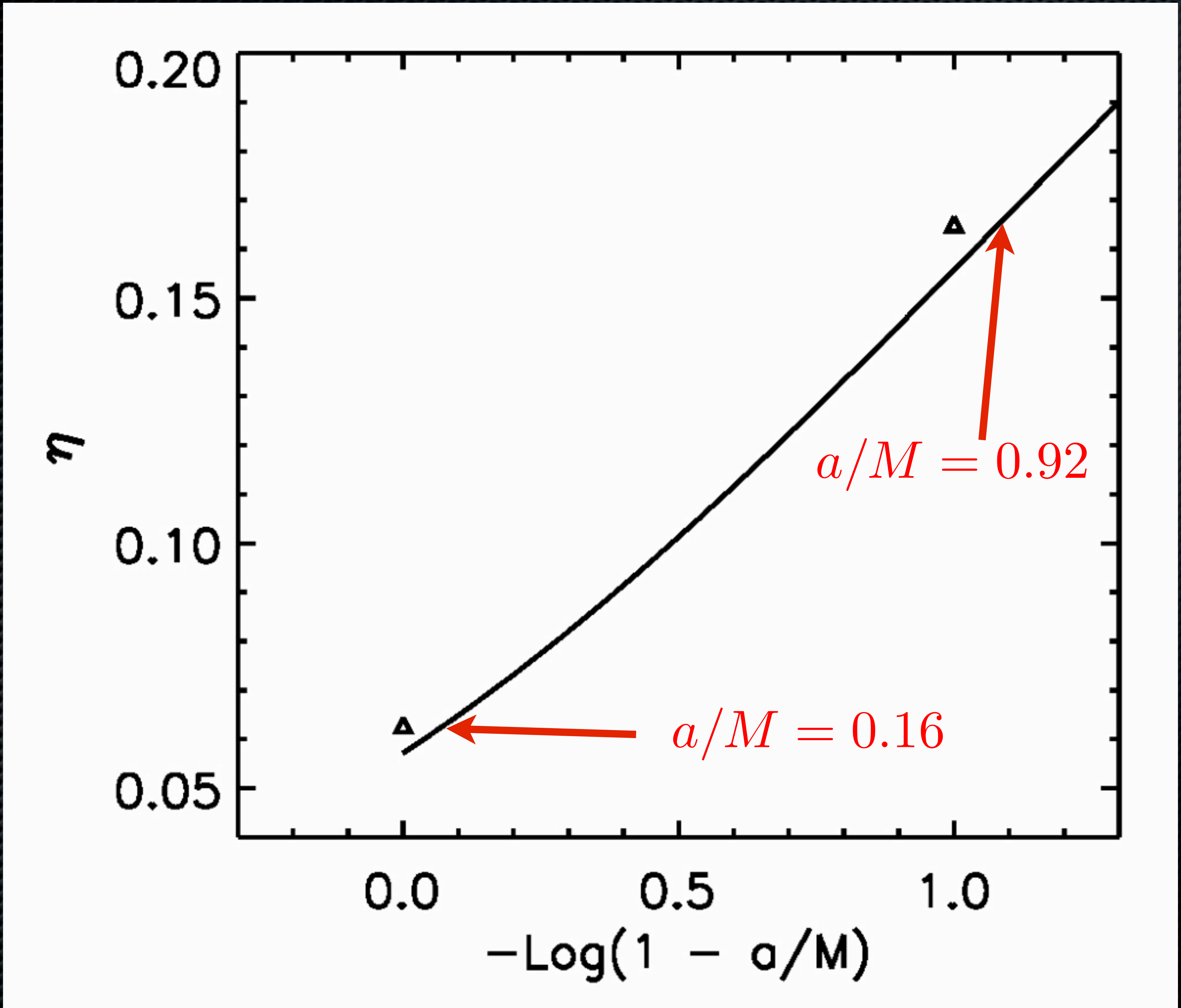
$$\frac{H}{\Delta z} > 60$$





Spin Over-estimation



	Original	ThinLR	MediumLR	ThinHR	MediumHR	ThickHR
BH Spin	0.9M	0	0	0	0	0
Resolution $N_r \times N_\theta \times N_\phi$	192x192x64	192x192x64	192x192x64	912x160x64	512x160x64	348x160x64
Target H/R	0.1	0.06	0.08	0.06	0.08	0.16
Actual H/R	0.07-0.12	0.085	0.091	0.061	0.10	0.17
Init. Inner Edge	15M	15M	15M	20M	20M	20M
Init. Radius of P_{max}	25M	25M	25M	35M	35M	35M
Start at Target H/R?	No	No	No	Yes	Yes	Yes
N_{cells} per H/R	15-30	60	35	81	103	74

Motivation:

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

SCN, Krolik, Hawley 2010

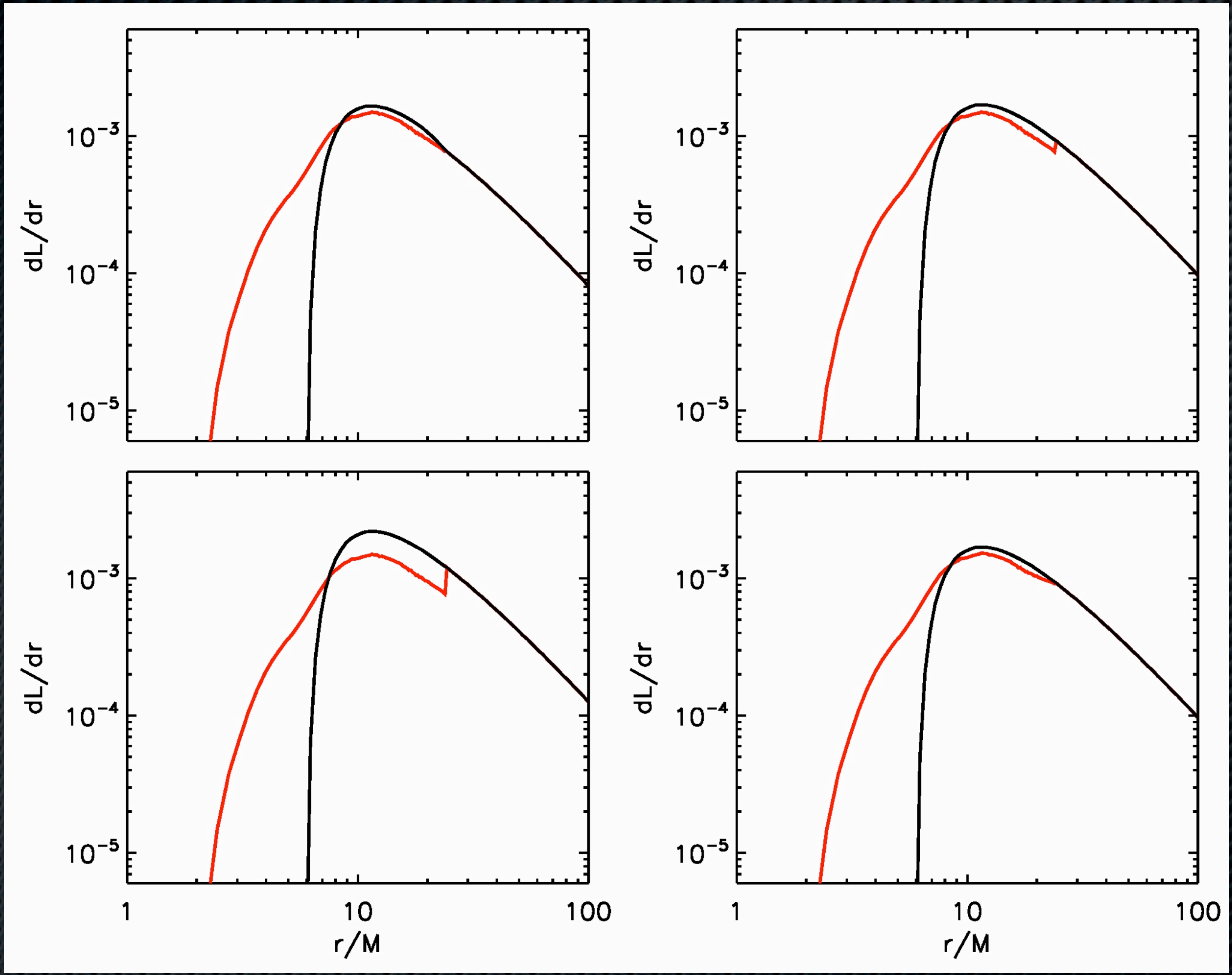
ThickHR

$\frac{\Delta\eta}{\eta}$

$\frac{\Delta\eta}{\eta}$

-1%

-3%



-12%

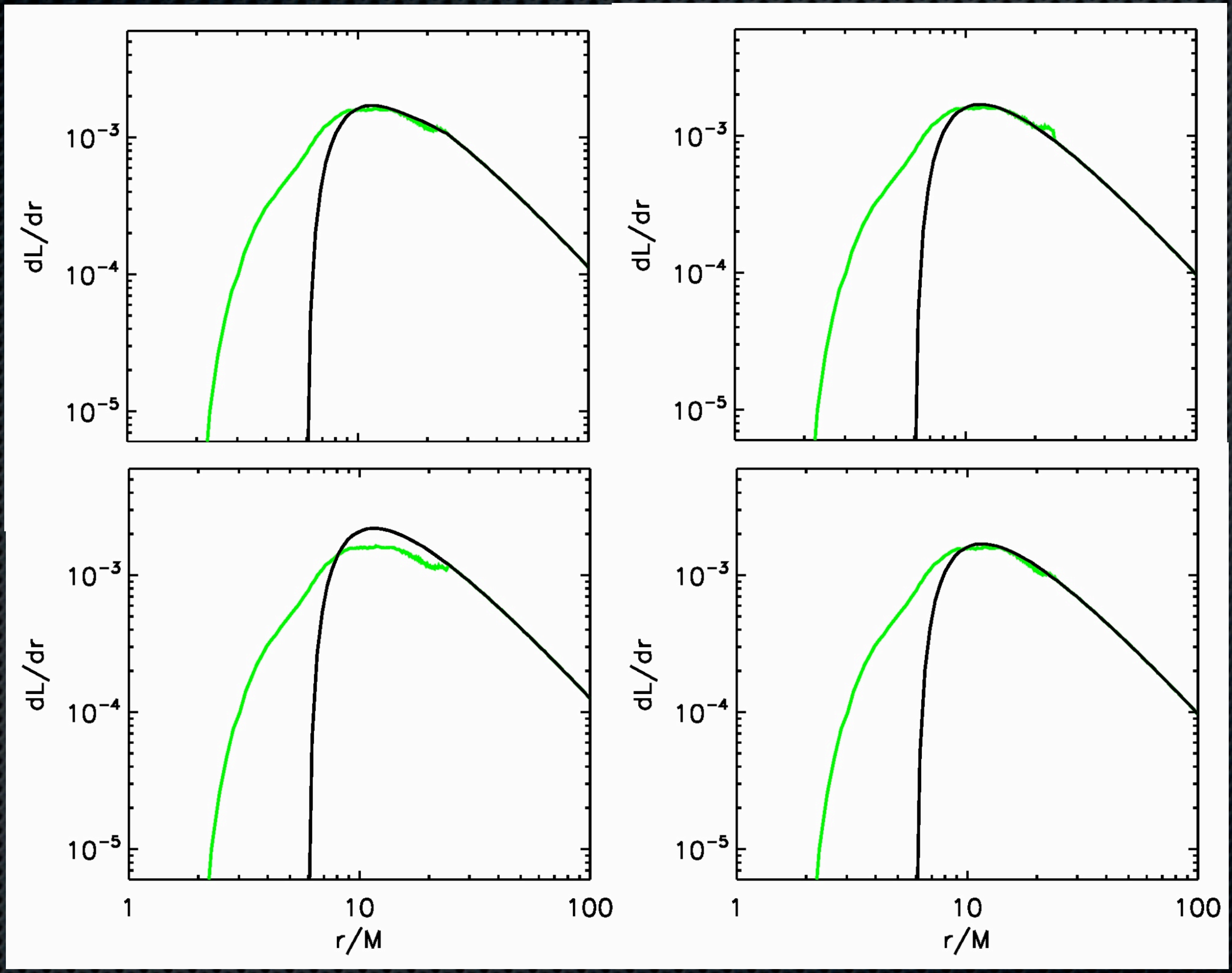
-1%

MediumHR

$\frac{\Delta\eta}{\eta}$

$+3\%$

$+6\%$



$\frac{\Delta\eta}{\eta}$

$+5\%$

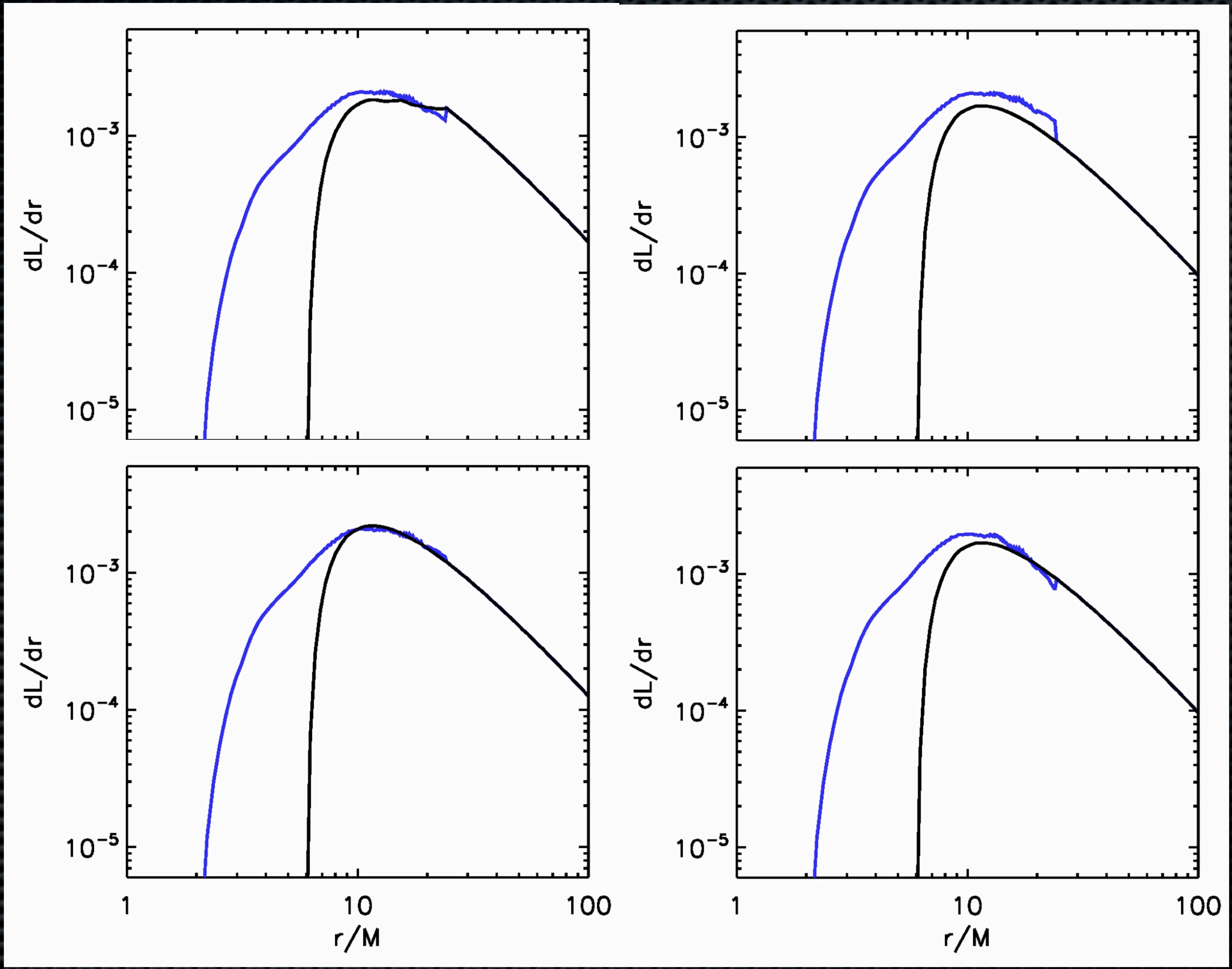
$+4\%$

ThinHR

$\frac{\Delta\eta}{\eta}$

$+7\%$

$+5\%$

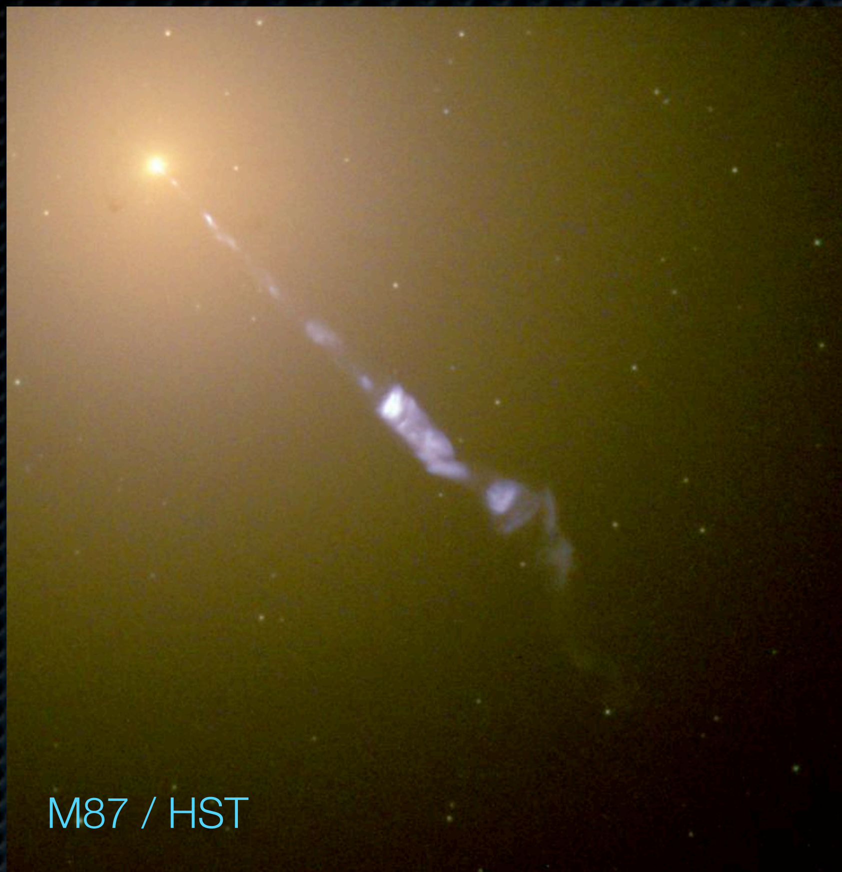


$\frac{\Delta\eta}{\eta}$

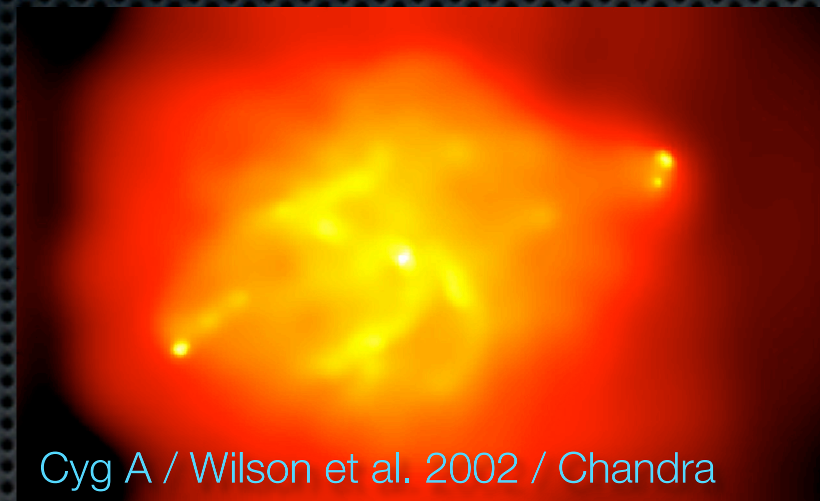
$+18\%$

$+10\%$

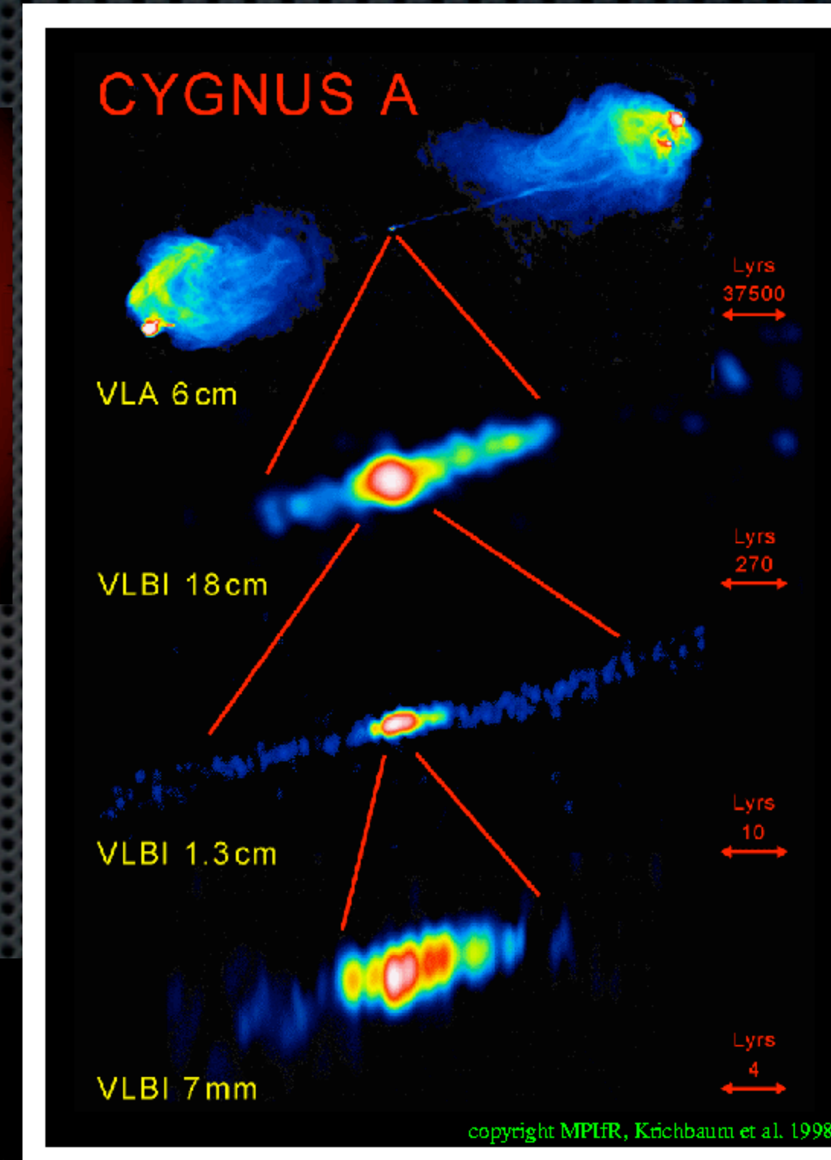
The Exciting World of Black Hole Accretion!



M87 / HST

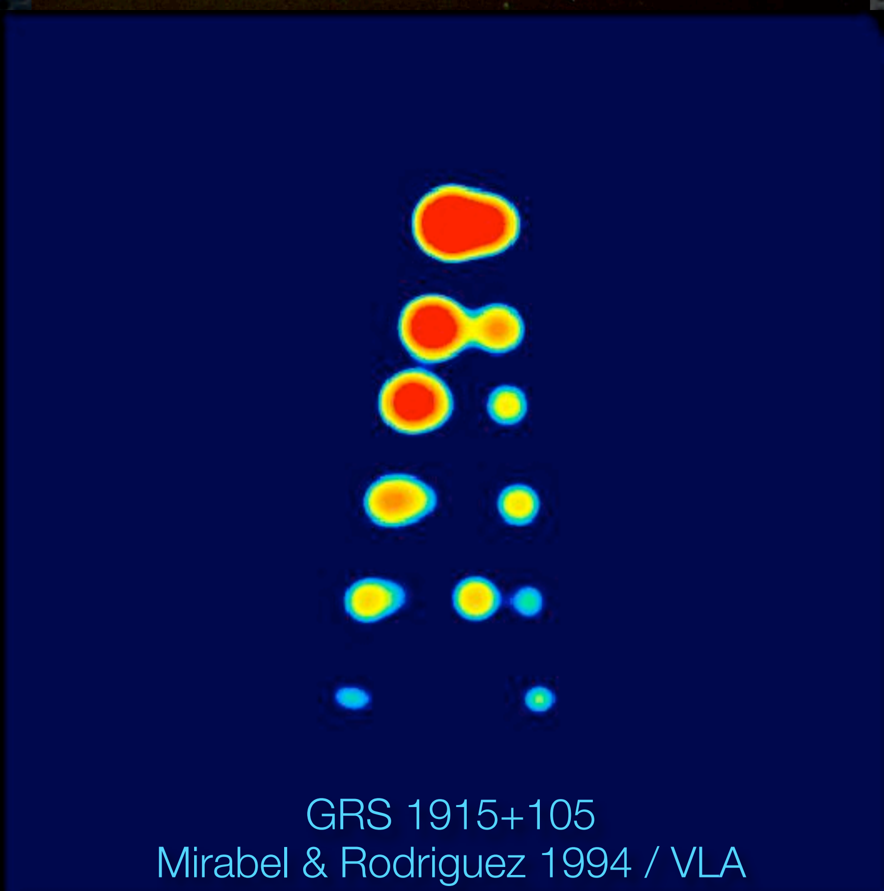


Cyg A / Wilson et al. 2002 / Chandra

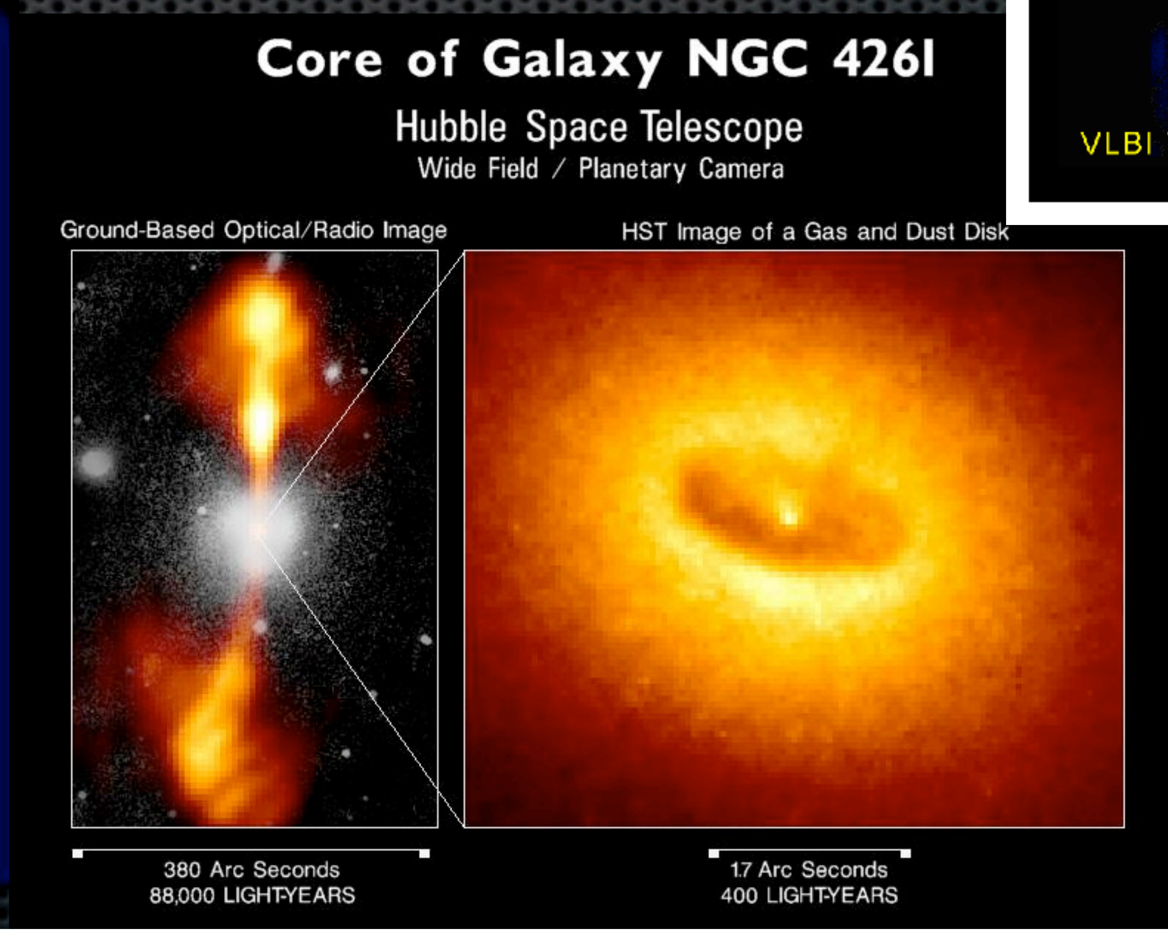


AGN!!

XRBs!!

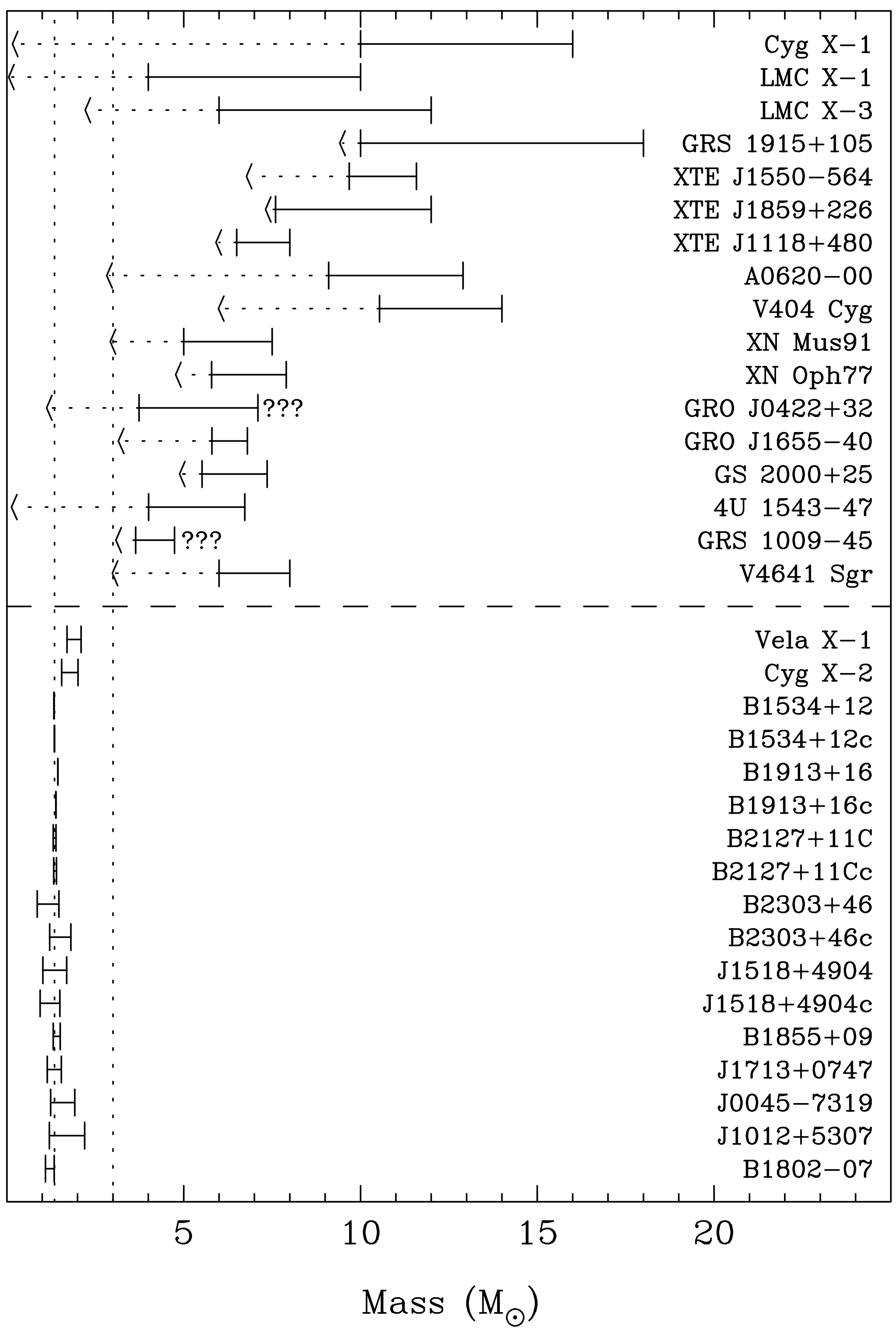


GRS 1915+105
Mirabel & Rodriguez 1994 / VLA



Feedback!!

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 3Msun

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