The Radiative Efficiency of Thin Accretion Disks

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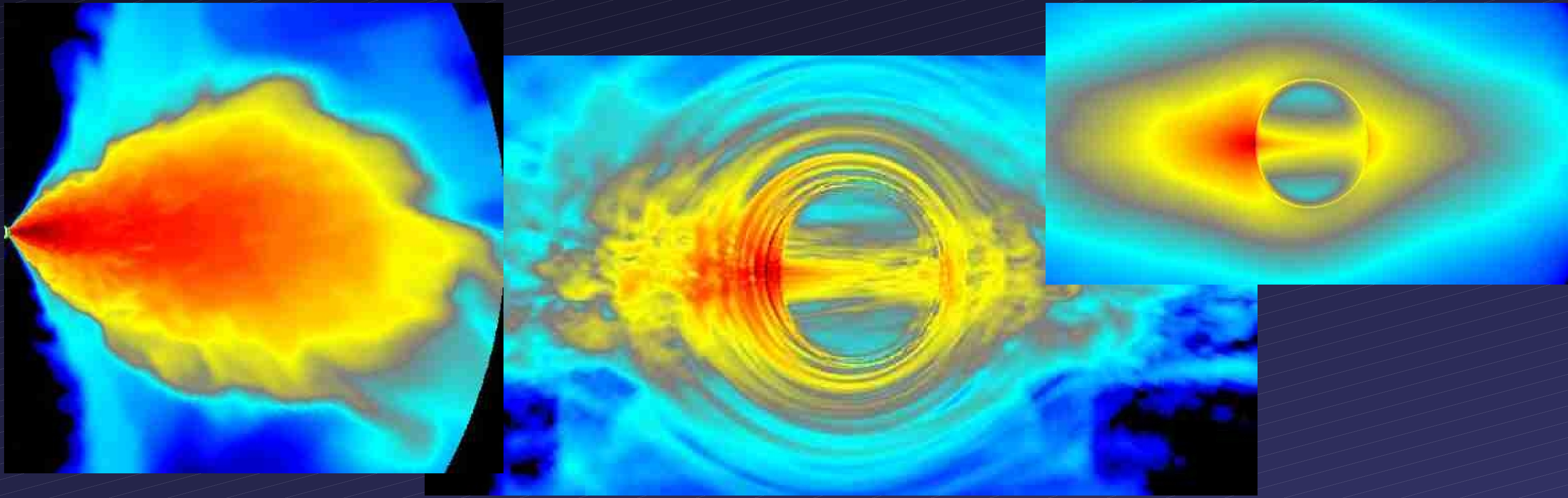
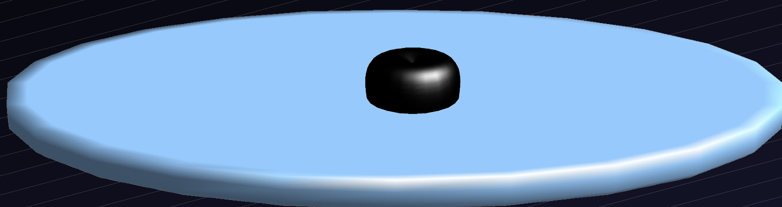


Outline

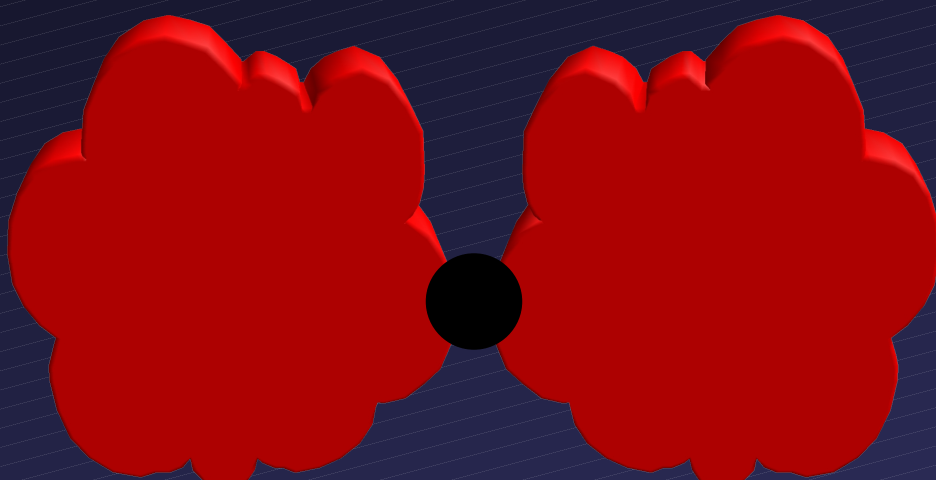
- How do we "see" black holes?
  - Disk Emission -> Spacetime Lighthouses
  - Measure properties of black hole (M,a)
- Standard (thin) disk model
- How can we improve upon these models?
  - Dynamical MHD Disks in GR.

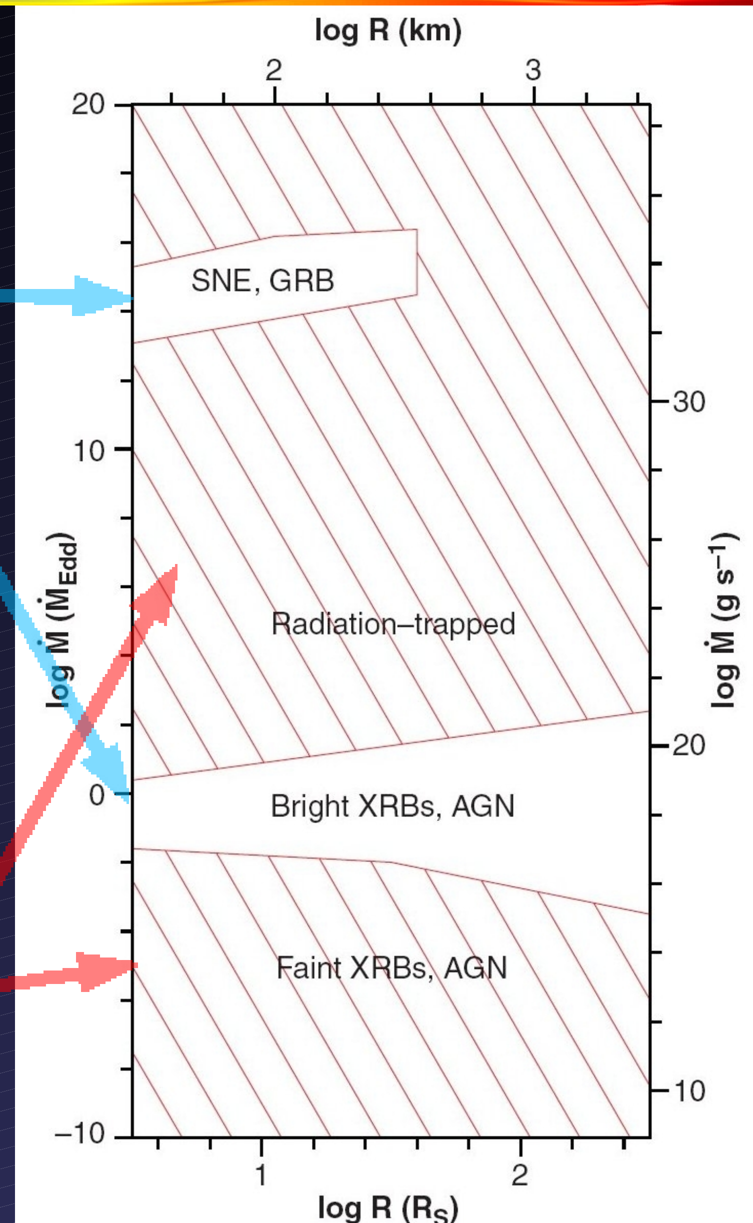
Radiative Efficiency of Disks

- Radiatively Efficient (thin disks)



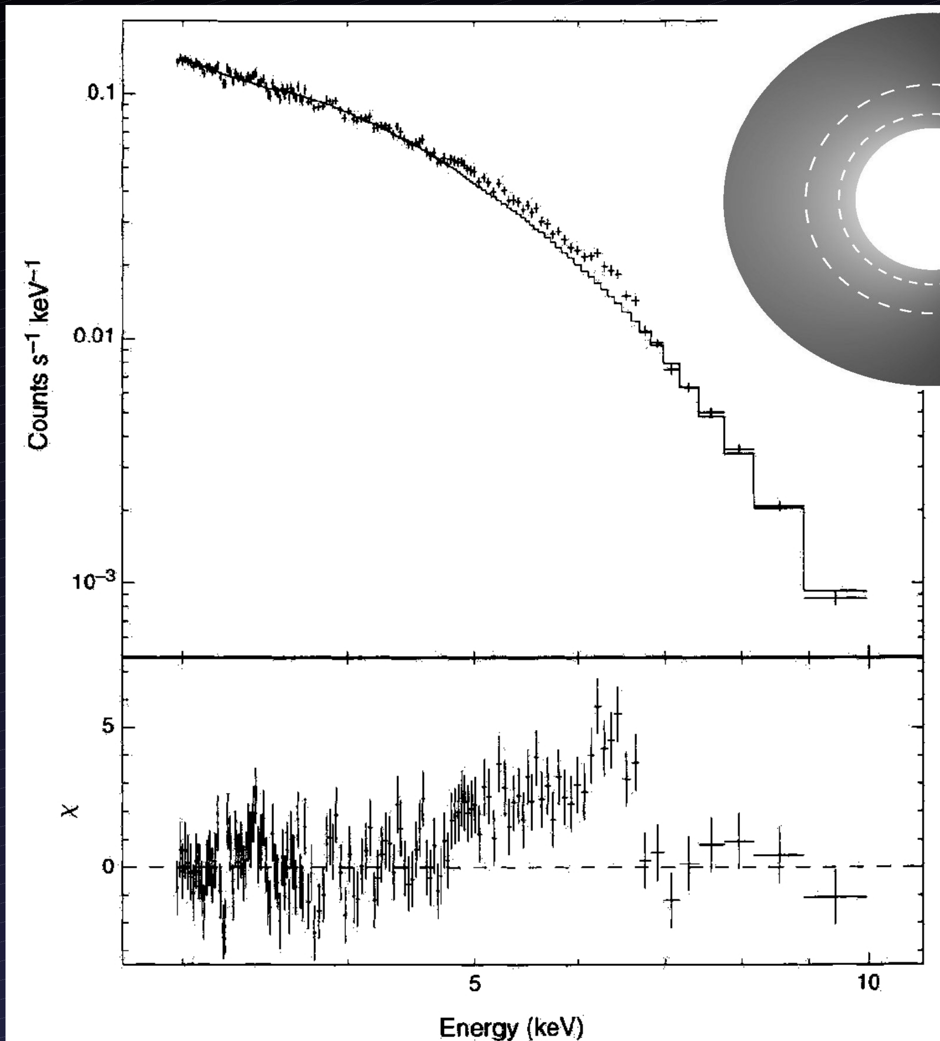
- Radiatively Inefficient (thick disks)



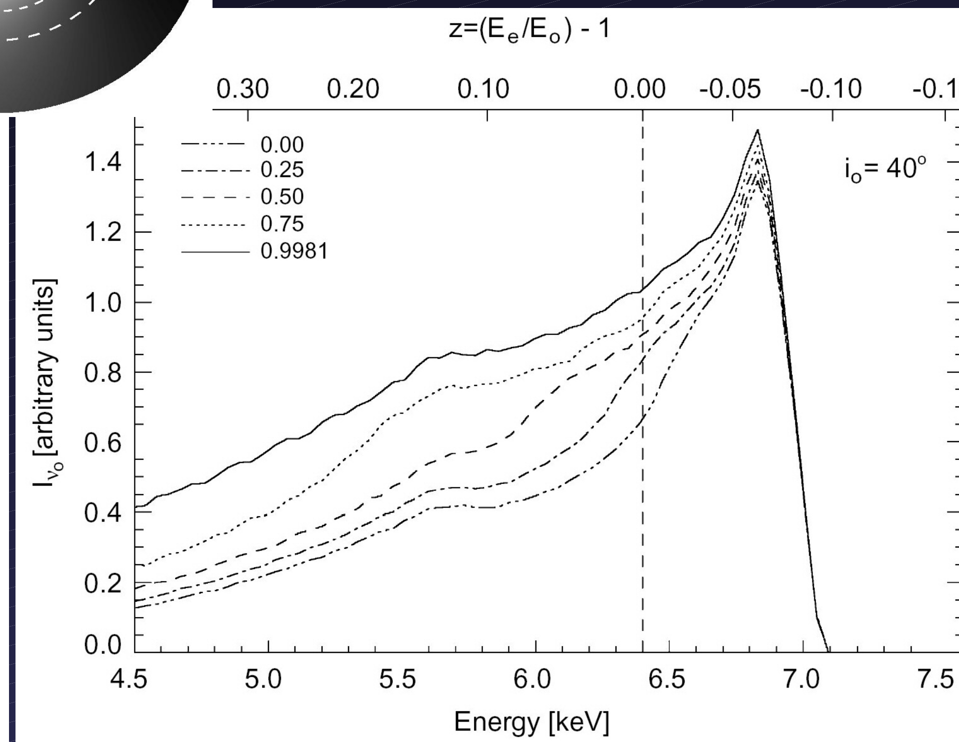


Narayan & Quataert (2005)

Relativistic Iron-Lines



$$R_{in} = R_{in}(M, a)$$



Tanaka et al. (1995)
MCG 6-30-15

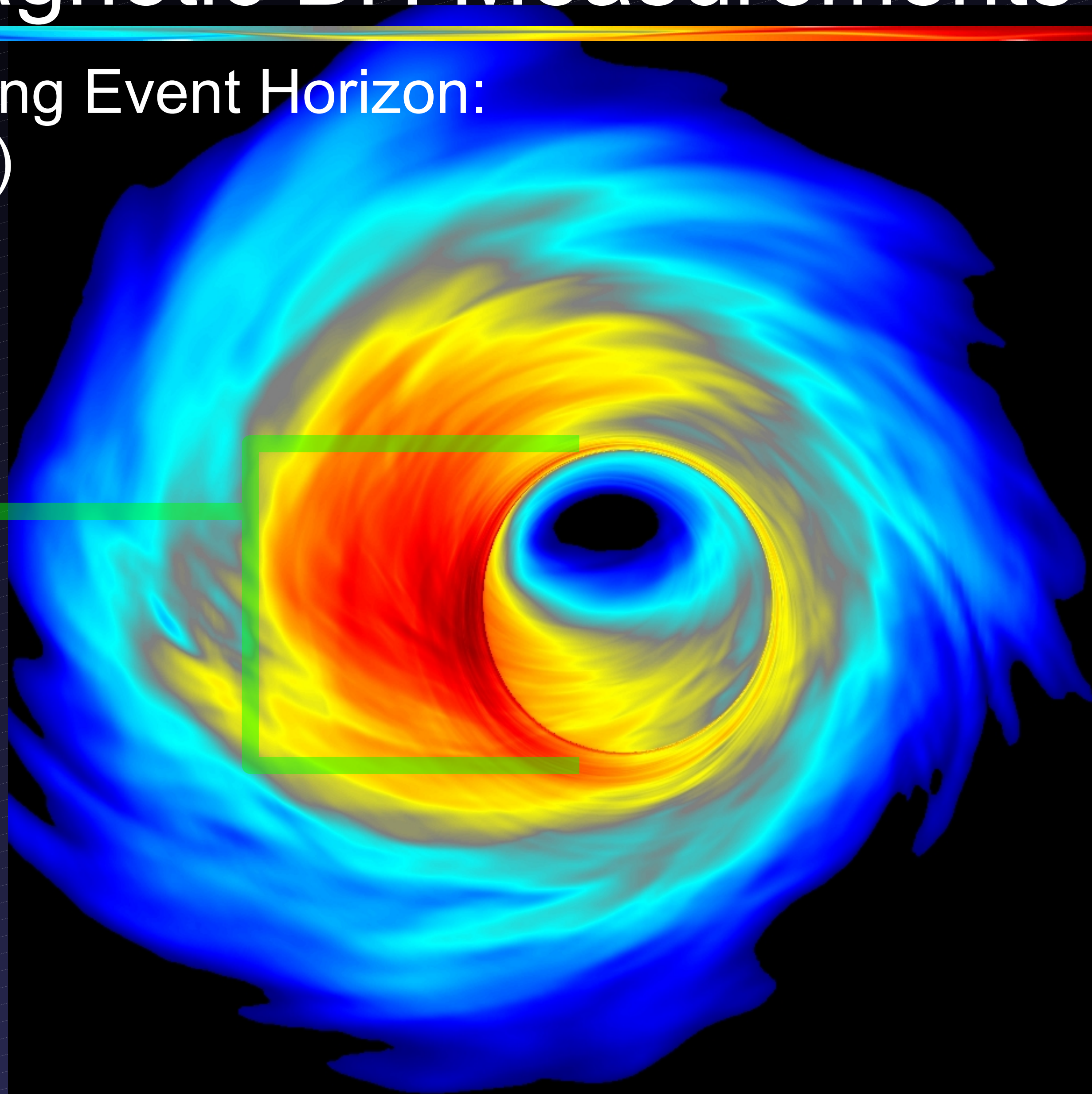
Reynolds & Nowak (2003)

Also, see talk by Brenneman this session

Electromagnetic BH Measurements

- Directly Resolving Event Horizon:
  - (e.g., Sgr A*)

$D(M, a)$



1mm synchrotron emission from 3D GRMHD simulation

a=0.9M , i = 45º

Electromagnetic BH Measurements

- Variability:

$$P = 2\pi\,\Omega^{-1}(M, a)$$

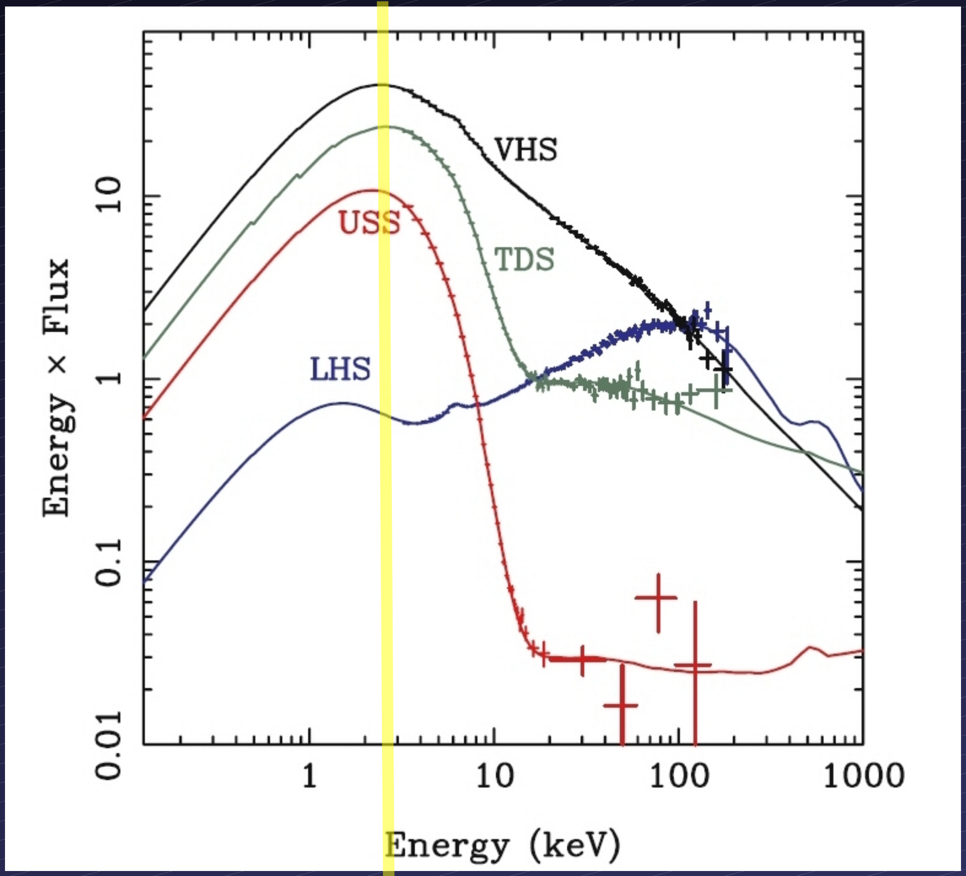
  - e.g. QPOs, short-time scale var.

- Spectral Fitting of Thermal Emission

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

$$T \sim (H/r)^2\,r^{-1}$$

$$R_{in} = R_{in}(M, a)$$



T_{max}

Done, Gierlinski & Kubota (2007)

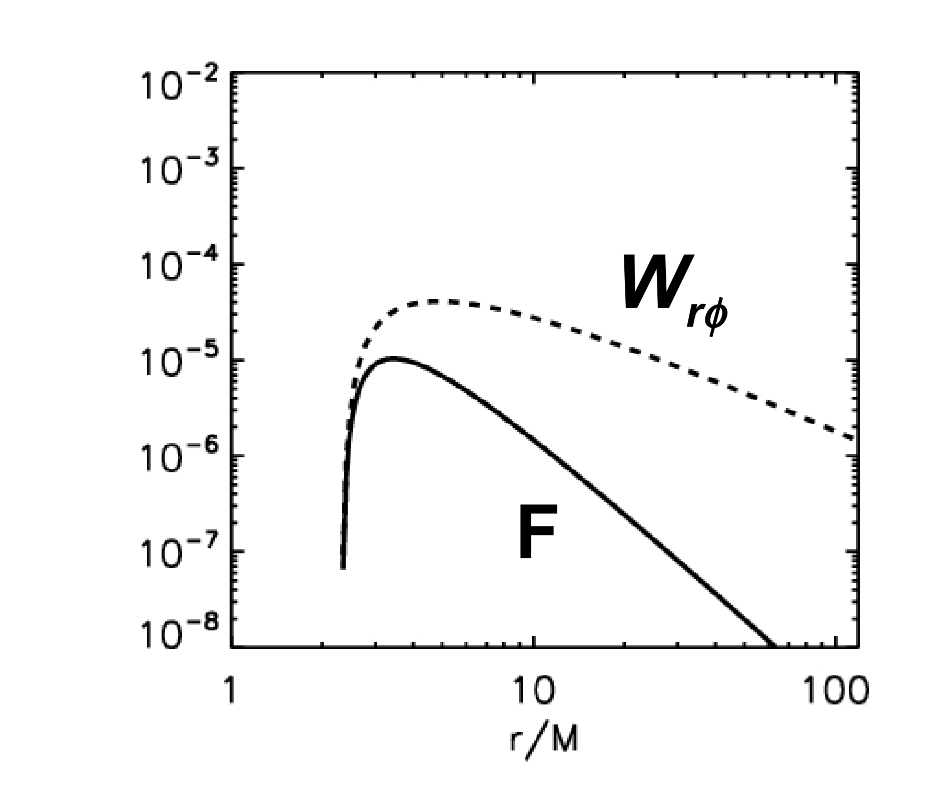
Shafee et al. (2006), McClintock et al. (2006)

Thin Disk Model: Novikov & Thorne (1973)

Assumptions:

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

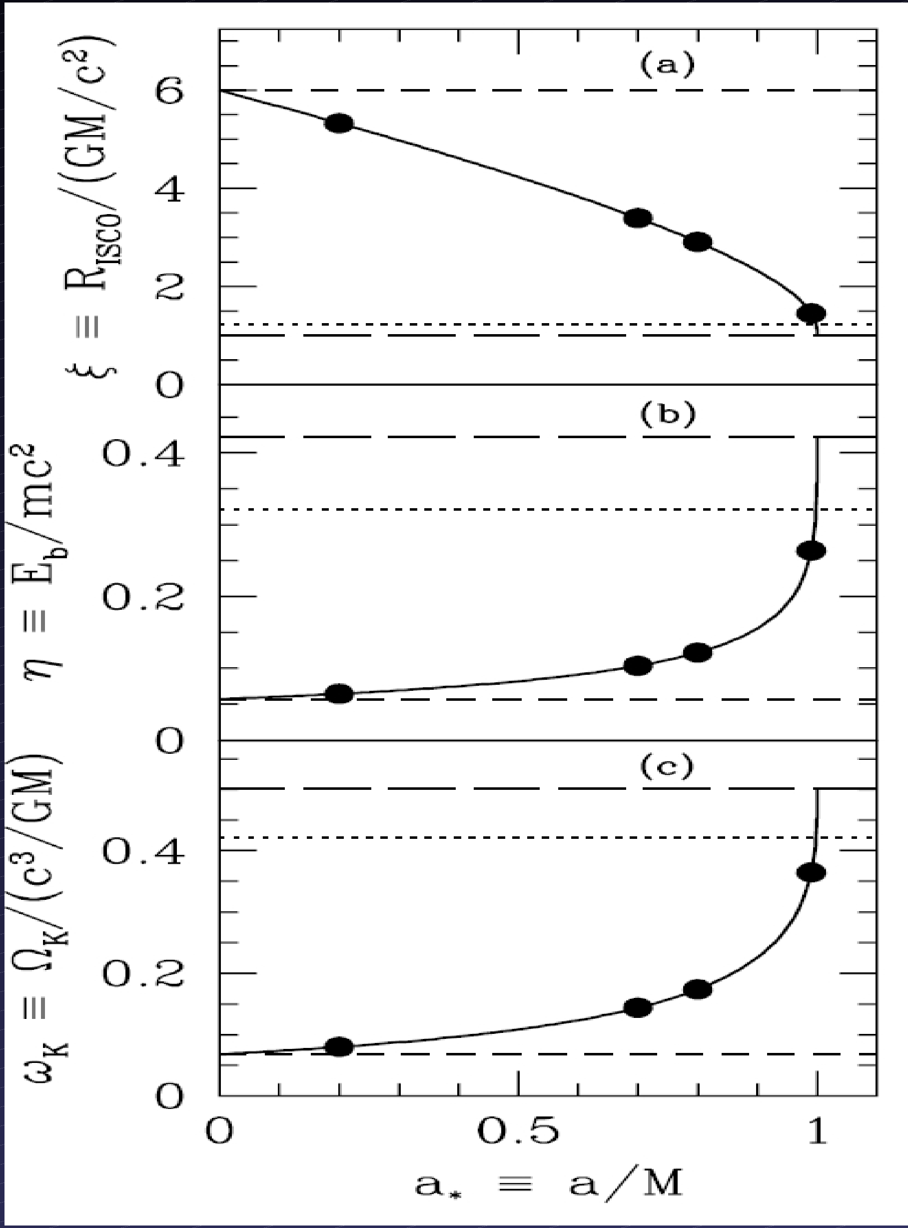
(Thorne 1974, Page & Thorne 1974)



Steady-State Models: Novikov & Thorne (1973)

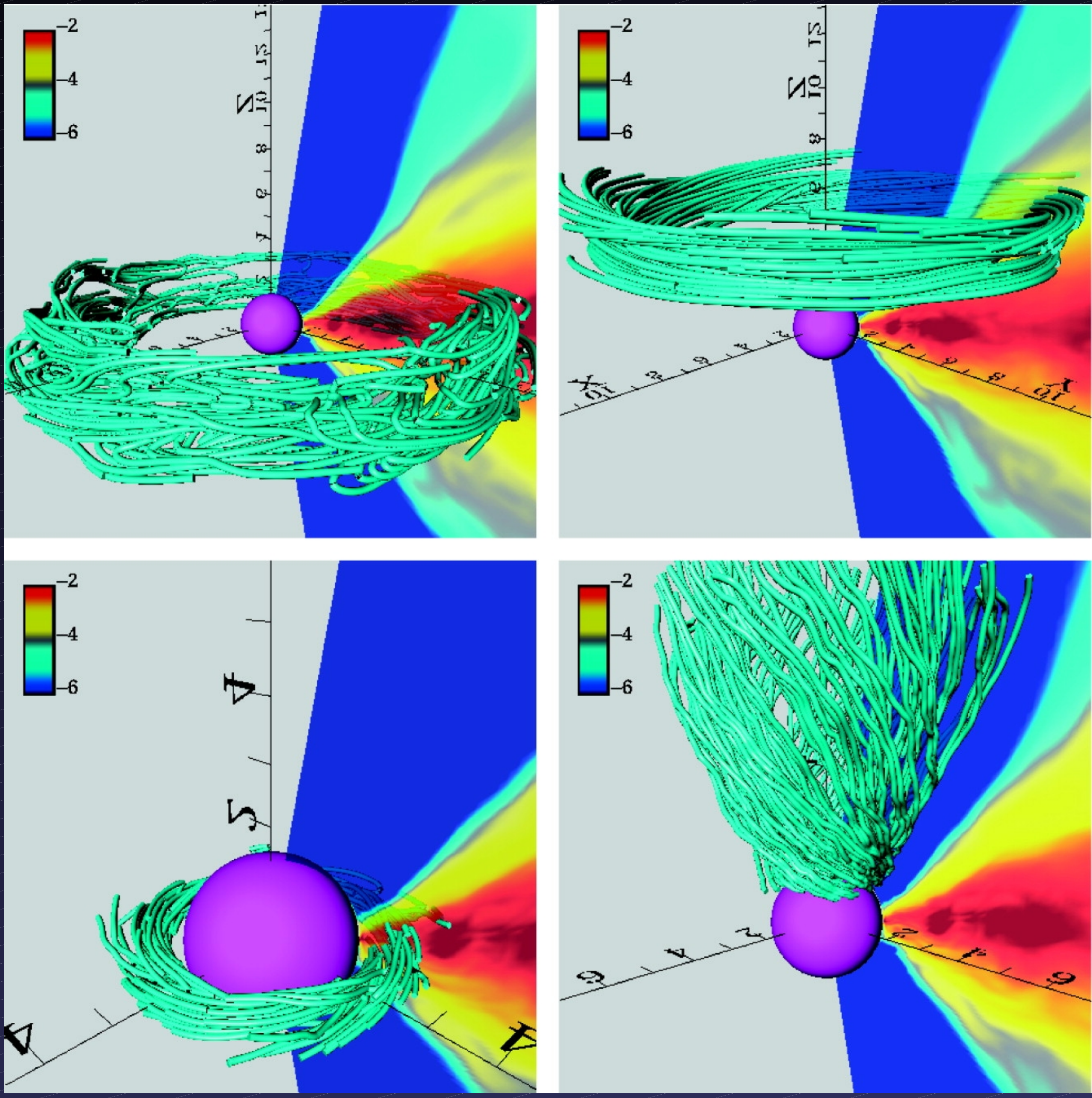
$$L = \eta \dot{M} c^2$$

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



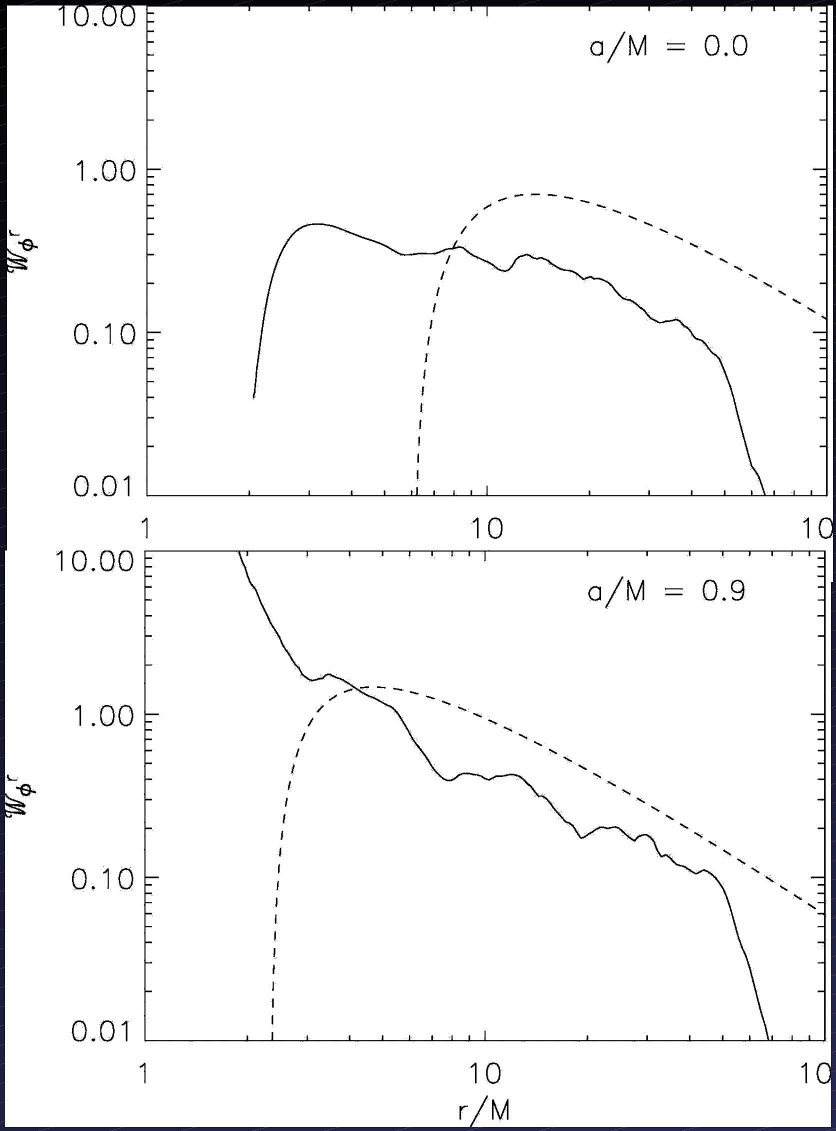
Dynamical Global GRMHD Disk Models

- Realistic Hydrodynamic shear viscosities cannot explain observed accretion rates
- De Villiers, Hawley, Hirose, Krolik (2003-2006)
- Magneto-Rotational Instability (MRI) develops from weak initial field, efficiently transports angular momentum outward.
- Significant field within ISCO up to the horizon.



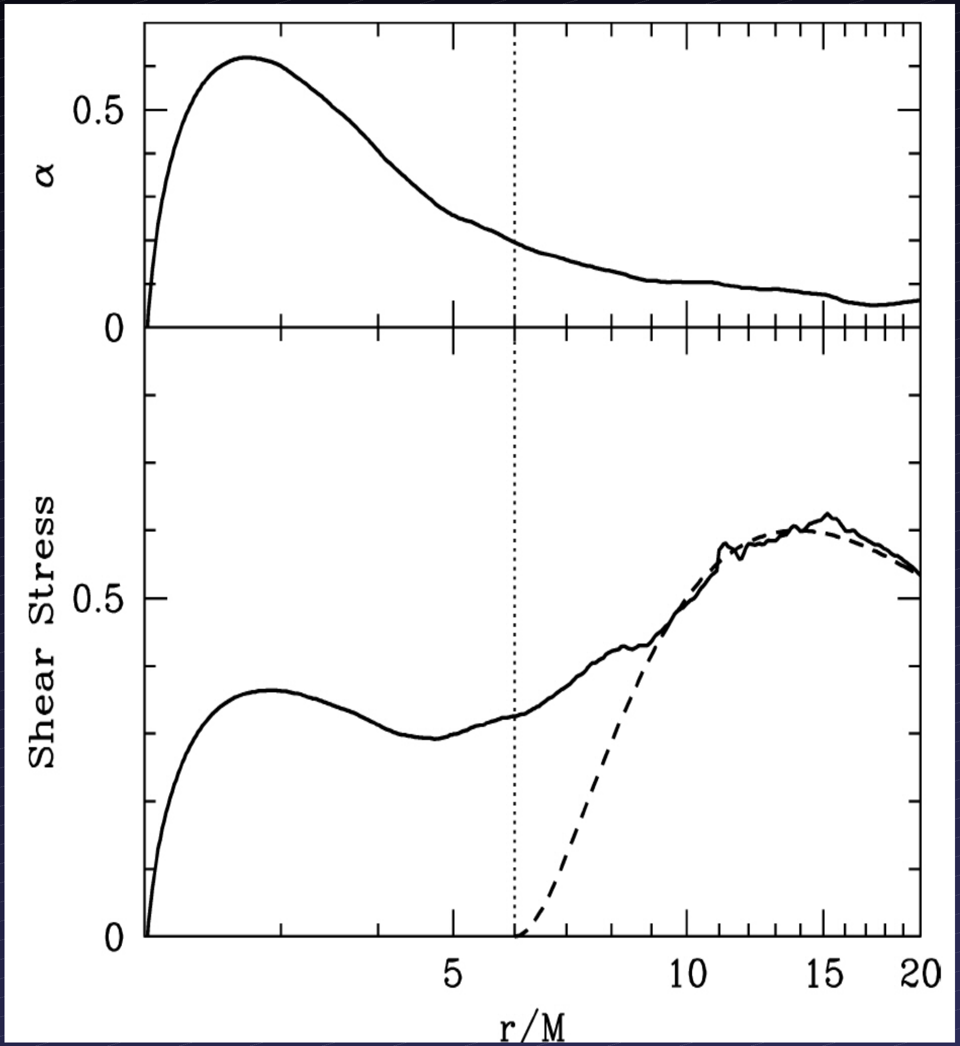
Hirose, Krolik, De Villiers, Hawley (2004)

Dynamical Global GRMHD Disk Models



Krolik, Hawley, Hirose (2005)

H/R ~ 0.1 - 0.15



Shafee et al. (2008)

H/R ~ 0.05

Our Method: Simulations

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

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

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

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

Our Method: Simulations

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

  - Cooling function:
    - Control 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

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

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

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

$H/R \sim 0.08$ $\qquad a_{BH} = 0.9M$

Cooling Function

- Optically-thin radiation: $T^{\mu}{}_{\nu;\mu} = -F_{\nu}$
- Isotropic emission: $F_{\nu} = f_c u_{\nu}$
- Cool only when fluid's temperature too high:

$$f_c = s\,\Omega\,u\,(\Delta - 1 + |\Delta - 1|)^q \qquad = 0 \;\; for\; \Delta < 0$$

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

GRMHD Disk Simulations

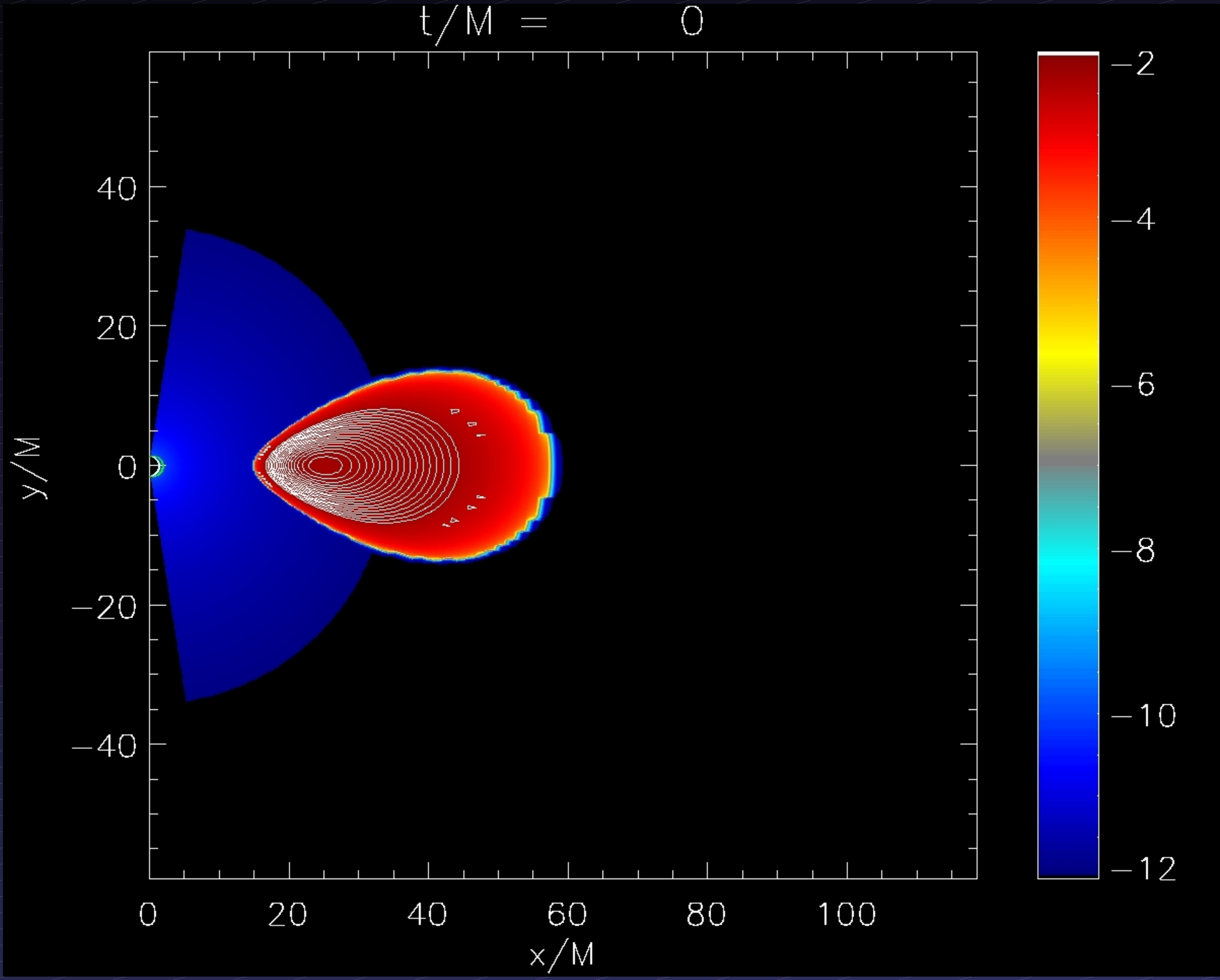
$$N_r \times N_\theta \times N_\phi$$
$$=$$
$$192 \times 192 \times 64$$

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

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

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

$$a = 0.9\mathrm{M}$$



GRMHD Disk Simulations

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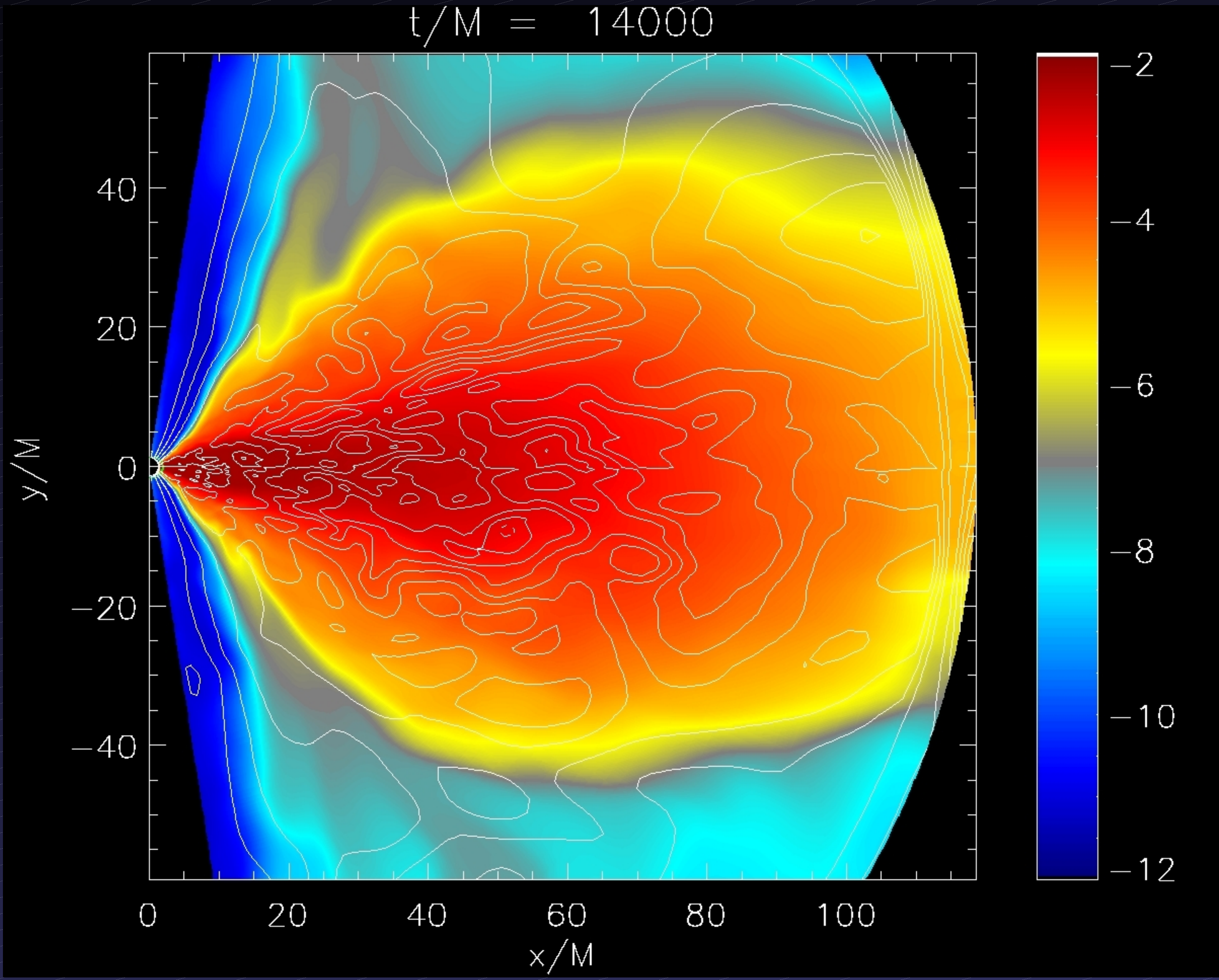
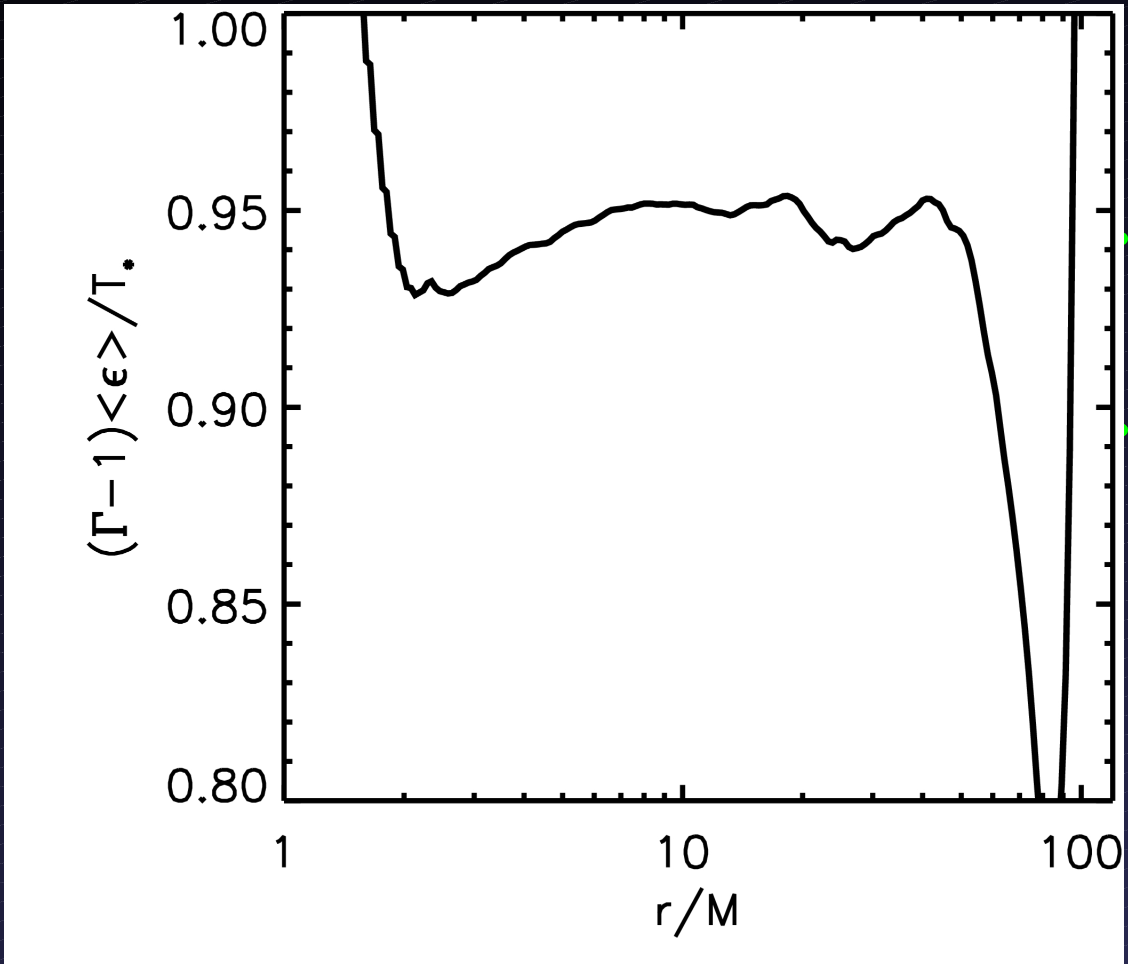
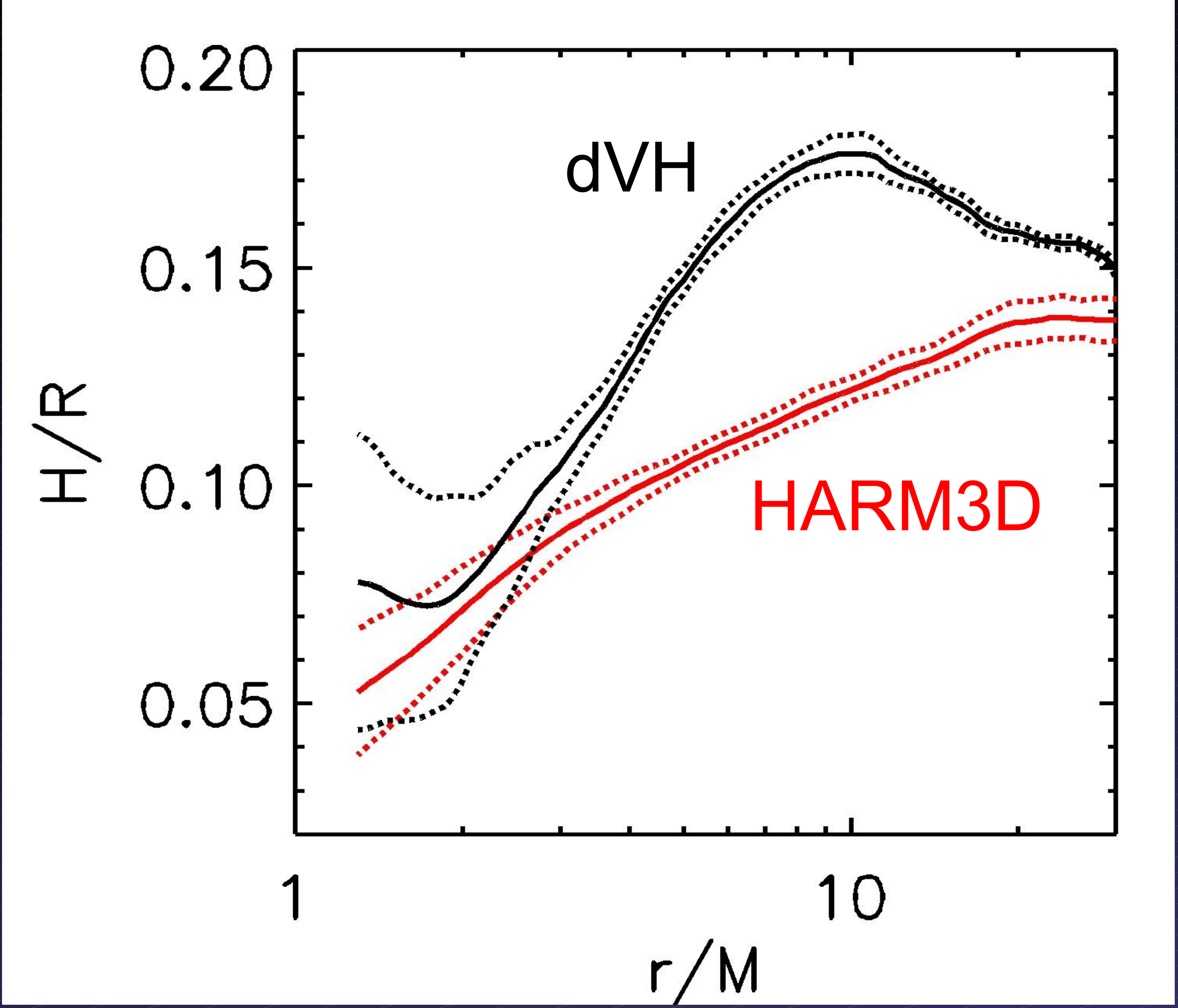


Target Temperature



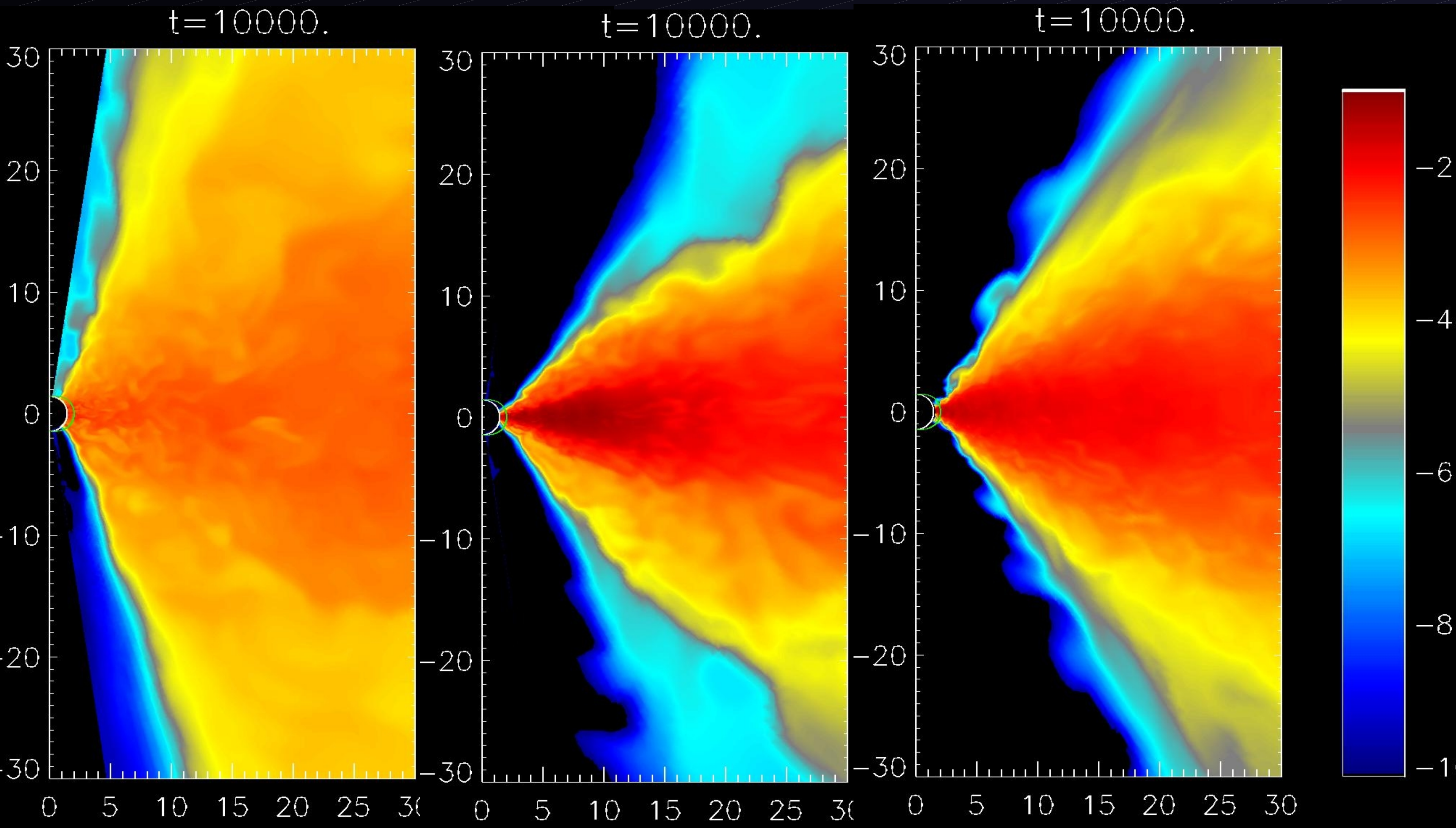
- Reaching to within 5% of Target Temperature
- Cooling Rate >~ Diss. Rate

Disk Thickness



HARM3D vs. dVH

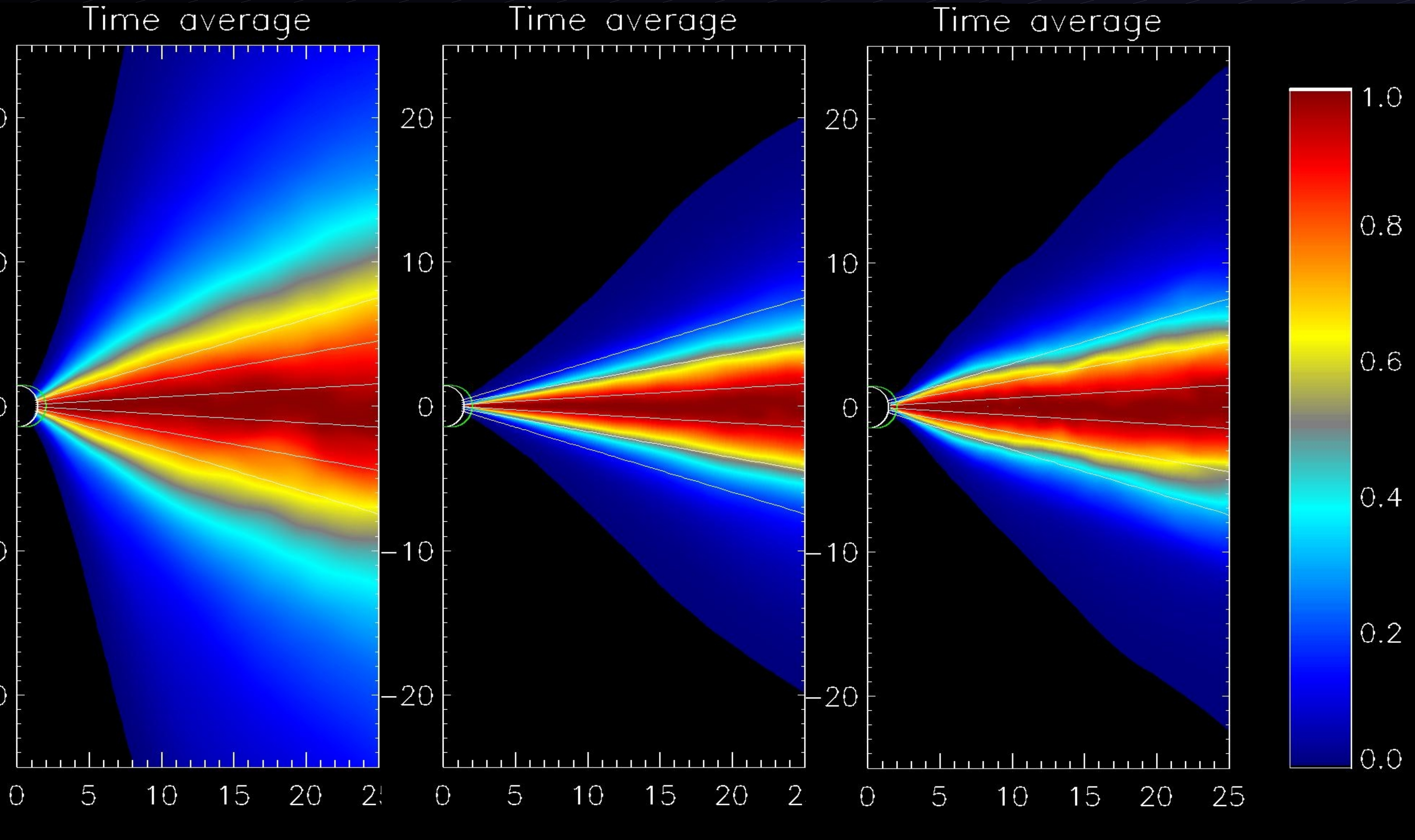
$\log(\rho)$



Uncooled **Cooled** **dVH**

HARM3D vs. dVH

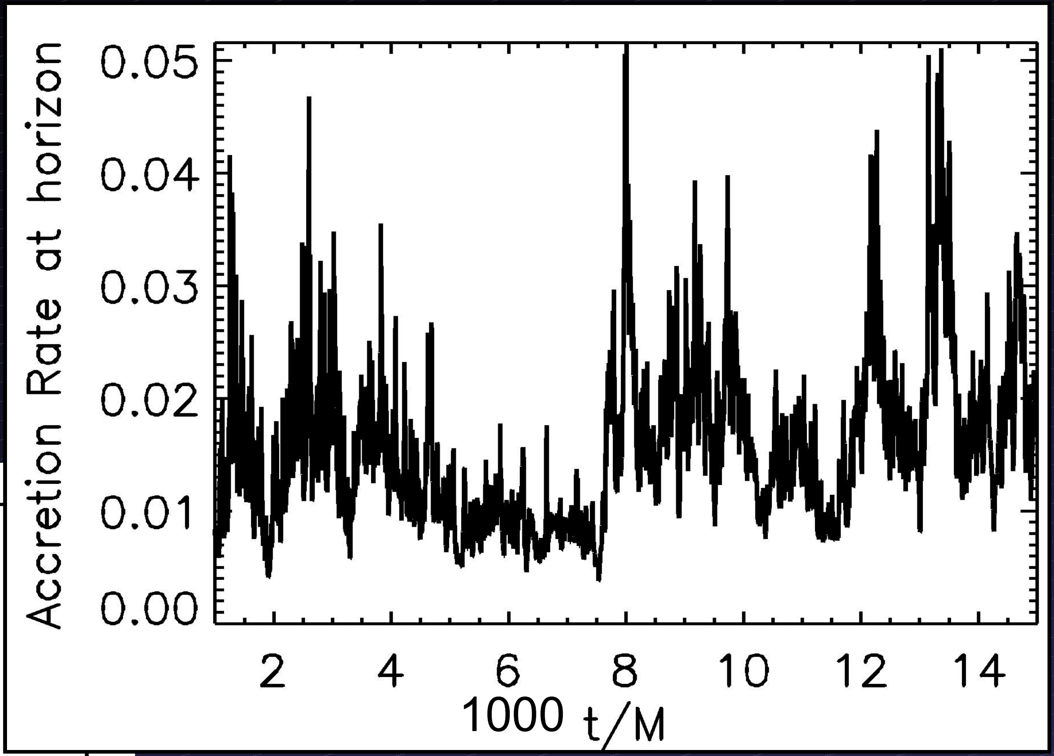
$\rho\, \rho_{max}^{-1}(r)$

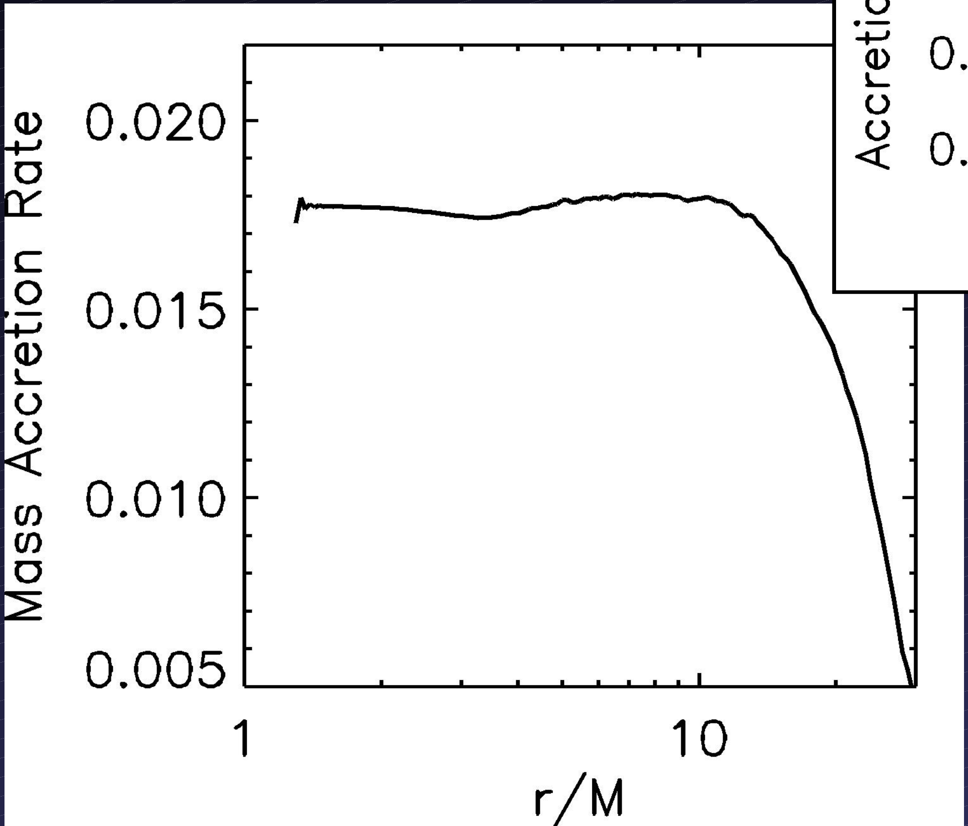


Uncooled **Cooled** **dVH**

Accretion Rate

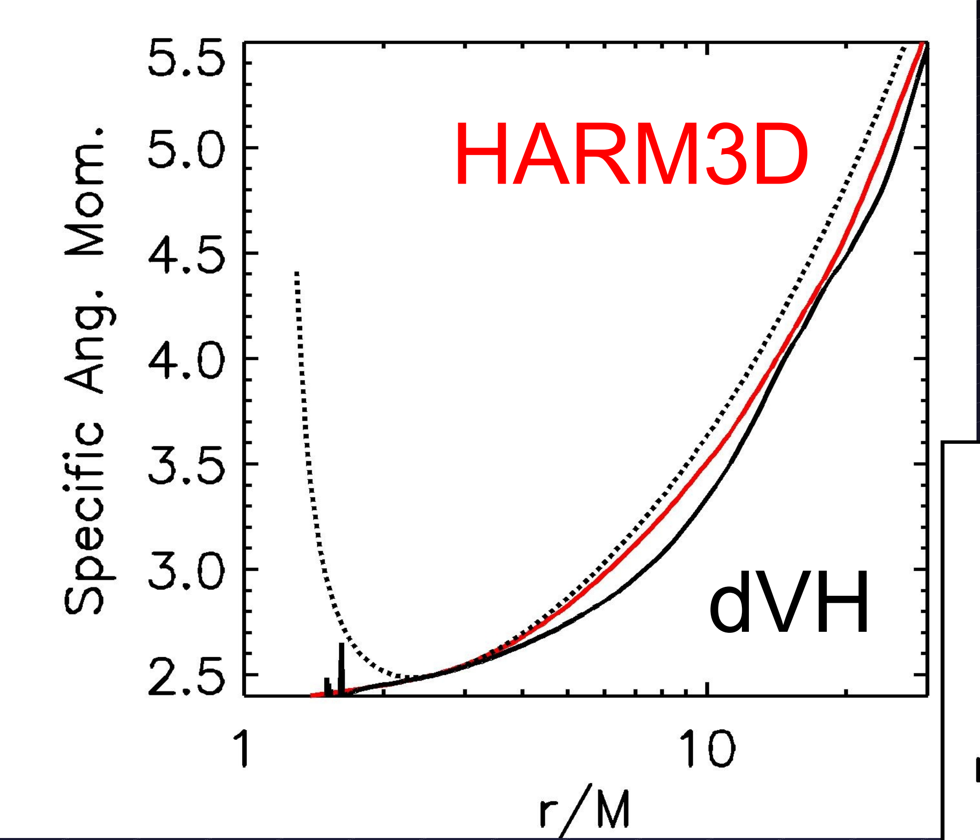
Steady State Period = 7000 – 15000M

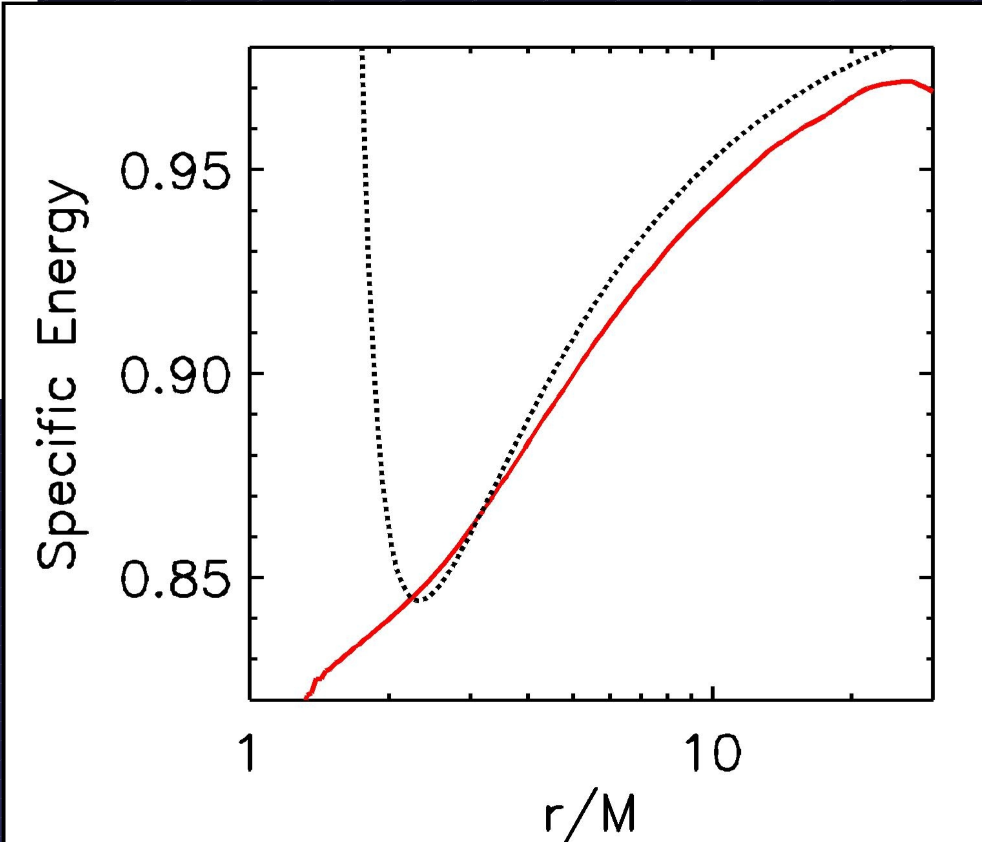




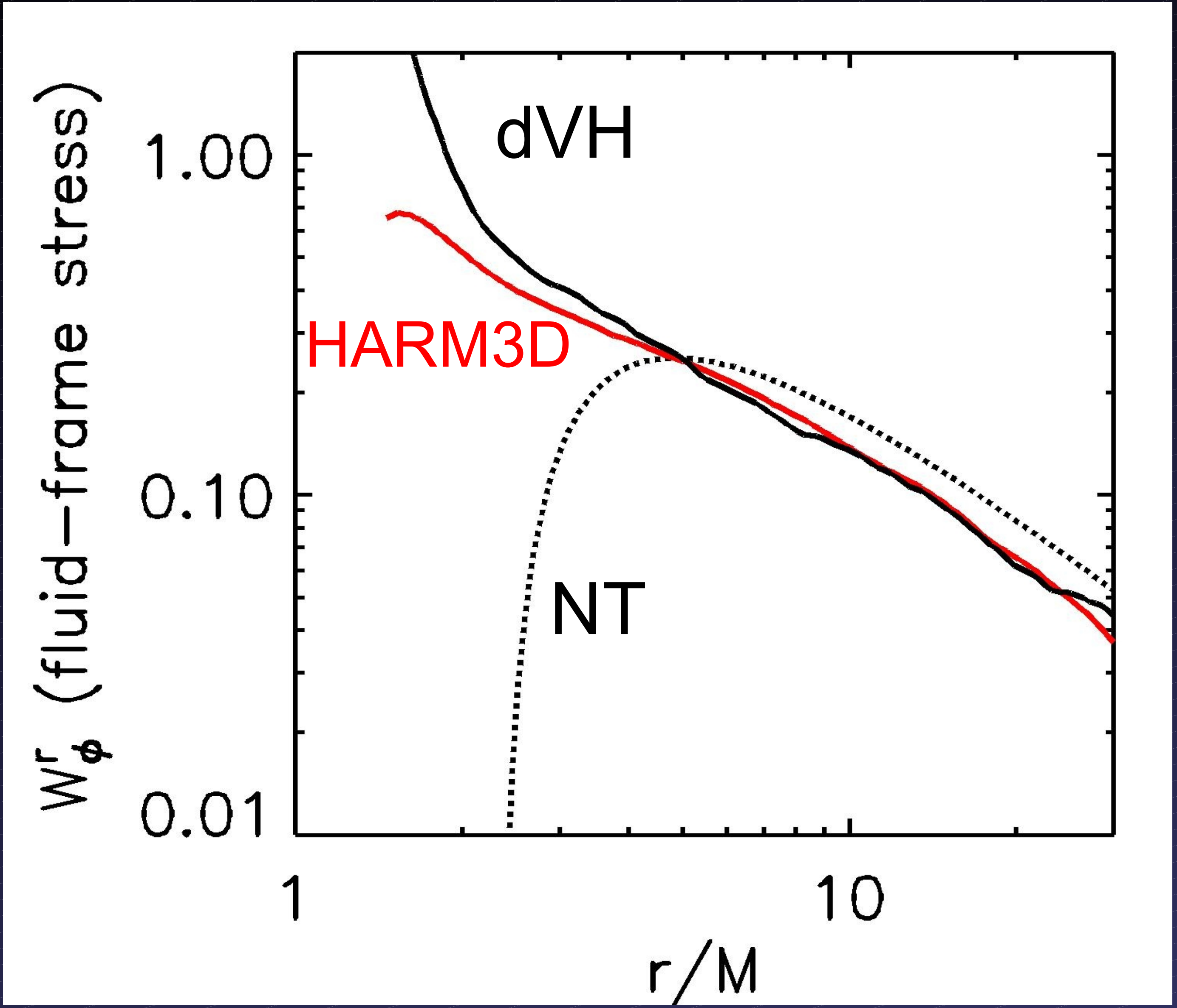
Steady State Region = Horizon – 12M

Departure from Keplerian Motion





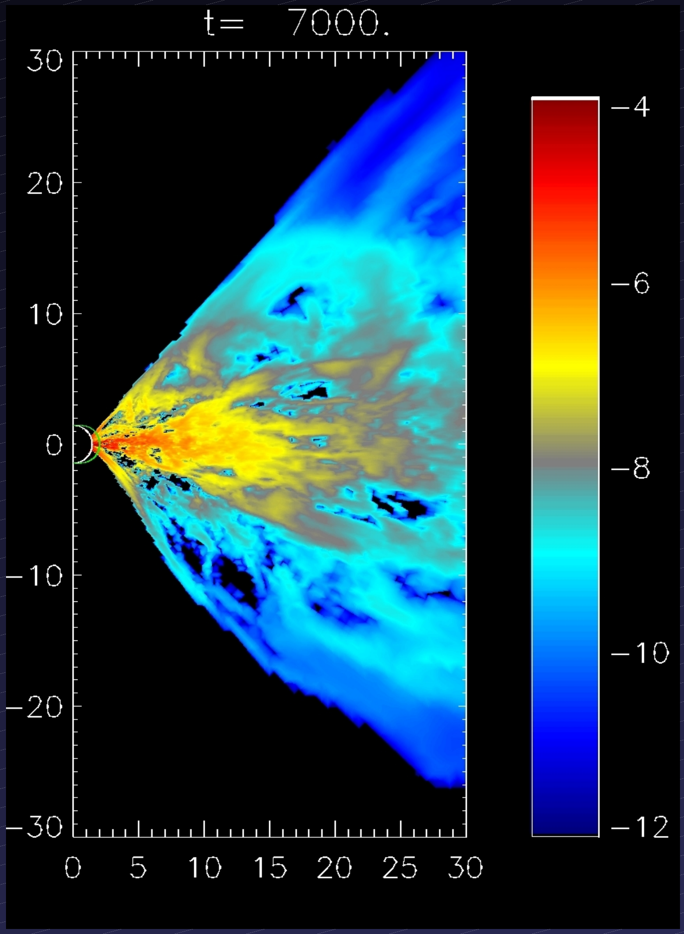
Magnetic Stress

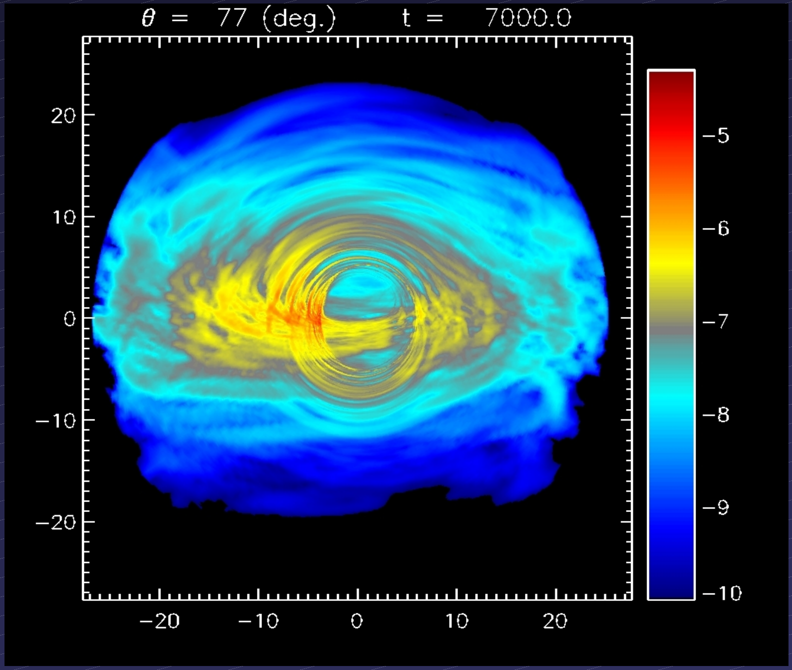


Radiative Transfer: From Disk to Observer

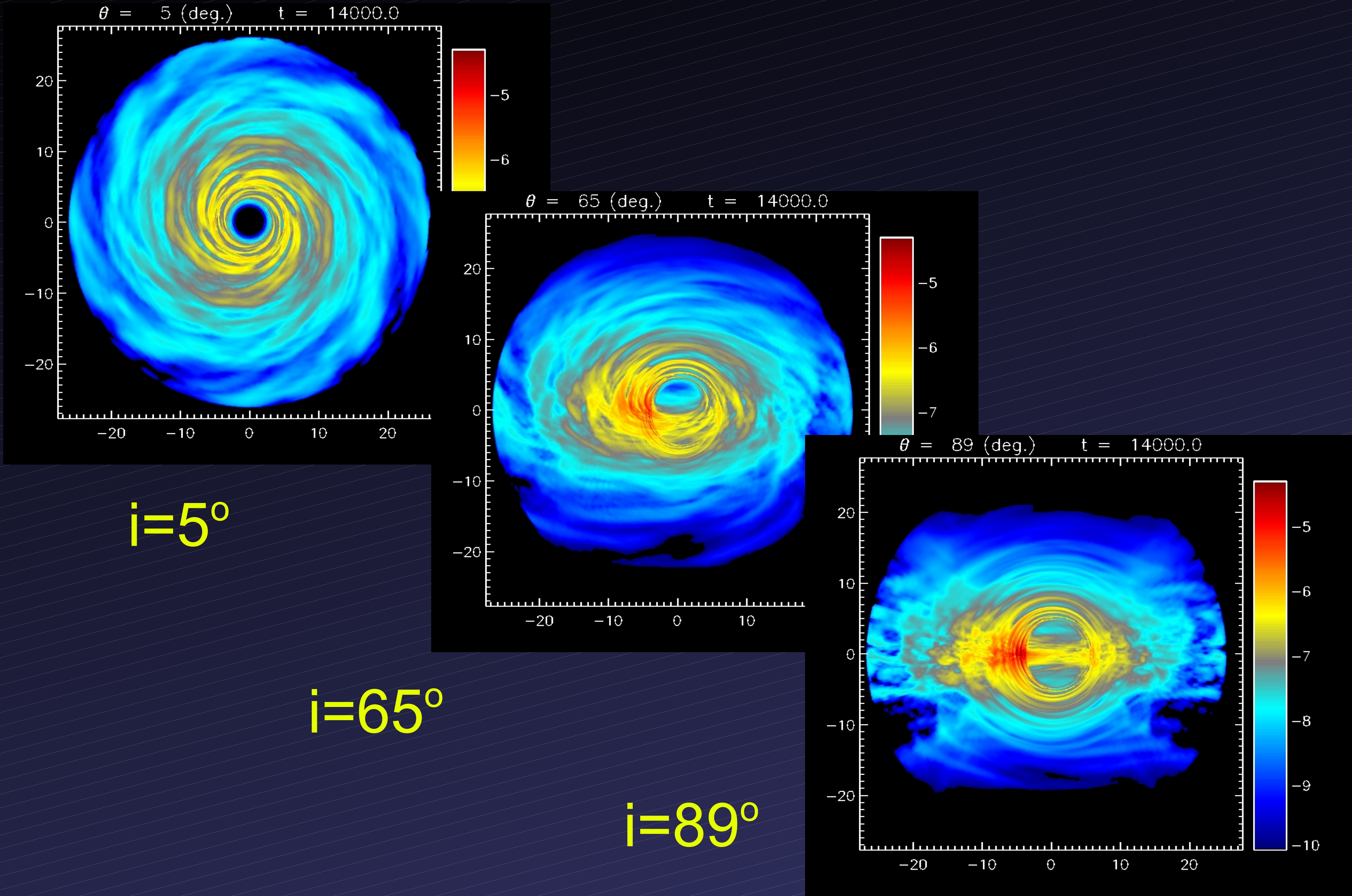
$$j_\nu = \frac{f_c}{4\pi\nu^2}$$

- 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 Intensity: Inclination

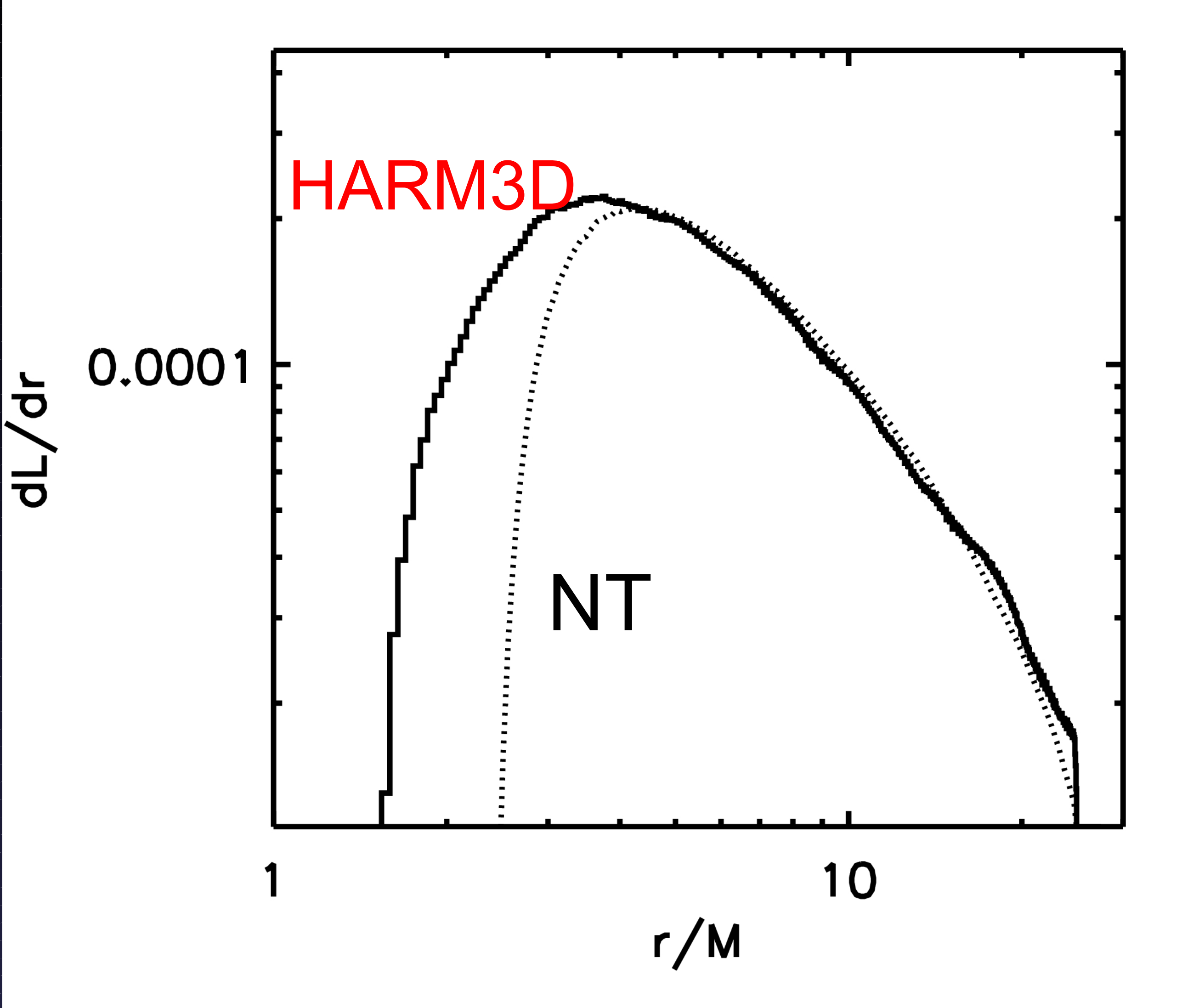


i=5°

i=65°

i=89°

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: $\Delta\eta/\eta \sim 20\ \%$

Summary & Conclusions

- We now have the tools to self-consistently measure dL/dr from GRMHD disks
    - 3D Conservative GRMHD simulations
    - GR Radiative Transfer

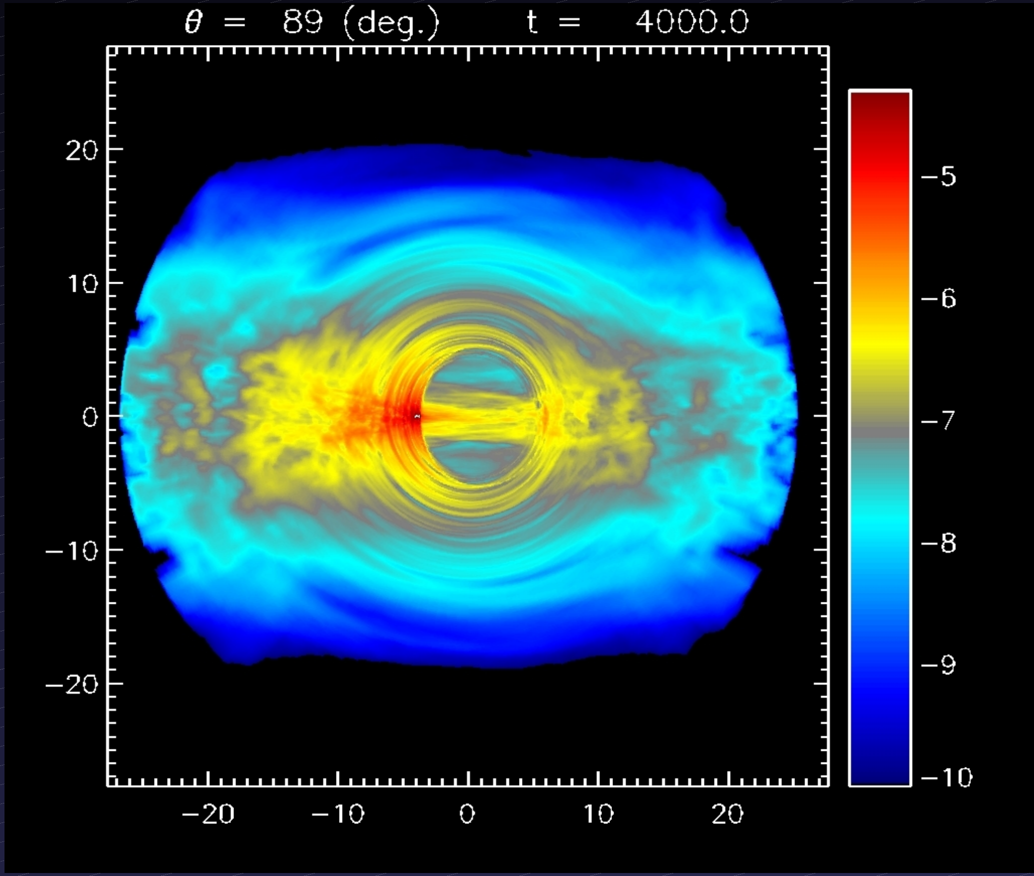
- Similarity to previous simulation with different algorithm implies robustness of our results.

- Luminosity from within ISCO diminished by
    - Photon capture by the black hole
    - Gravitational redshift
    - $t_{cool} > t_{inflow}$

➢ Possibly greater difference for $a_{BH} < 0.9$ when ISCO is further out of the potential well.

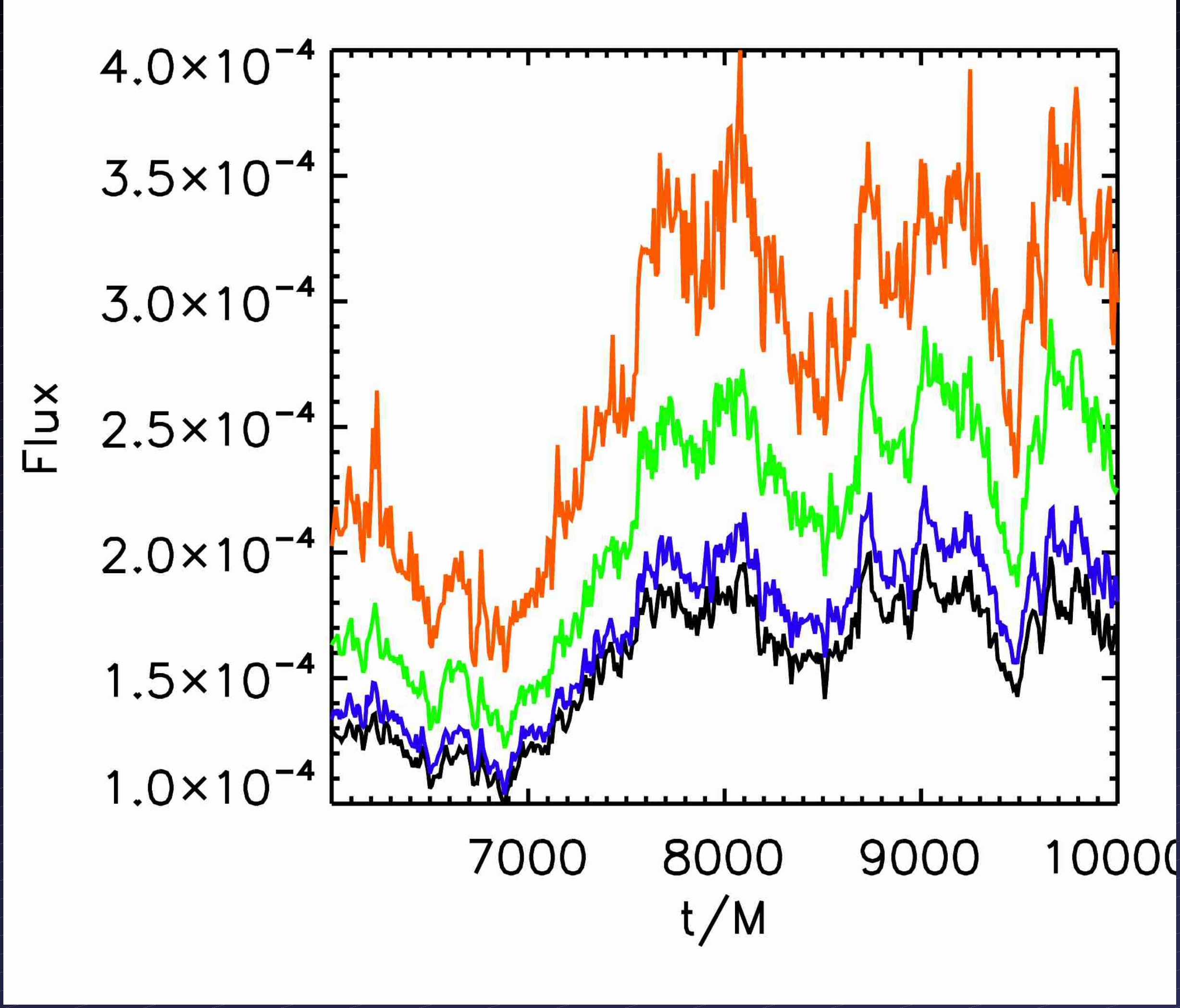
Future Work

- Explore parameter space:
  - More spins
  - More H/R 's
  - More H(R) 's



- Time variability analysis
  - Impossible with steady-state models

Variability of Dissipated Flux



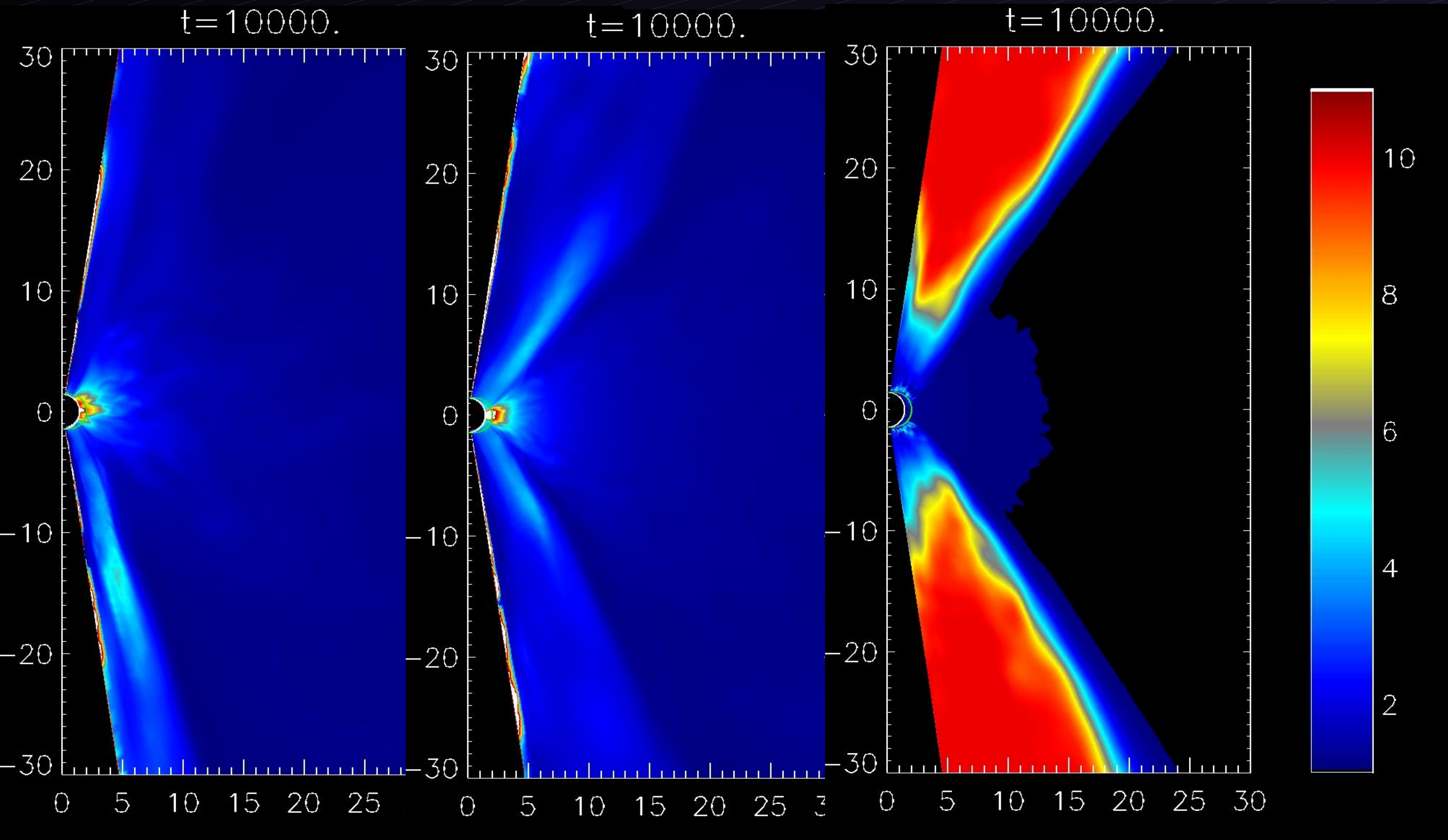
$\theta = 5\,deg.$

$\theta = 35\,deg.$

$\theta = 65\,deg.$

$\theta = 89\,deg.$

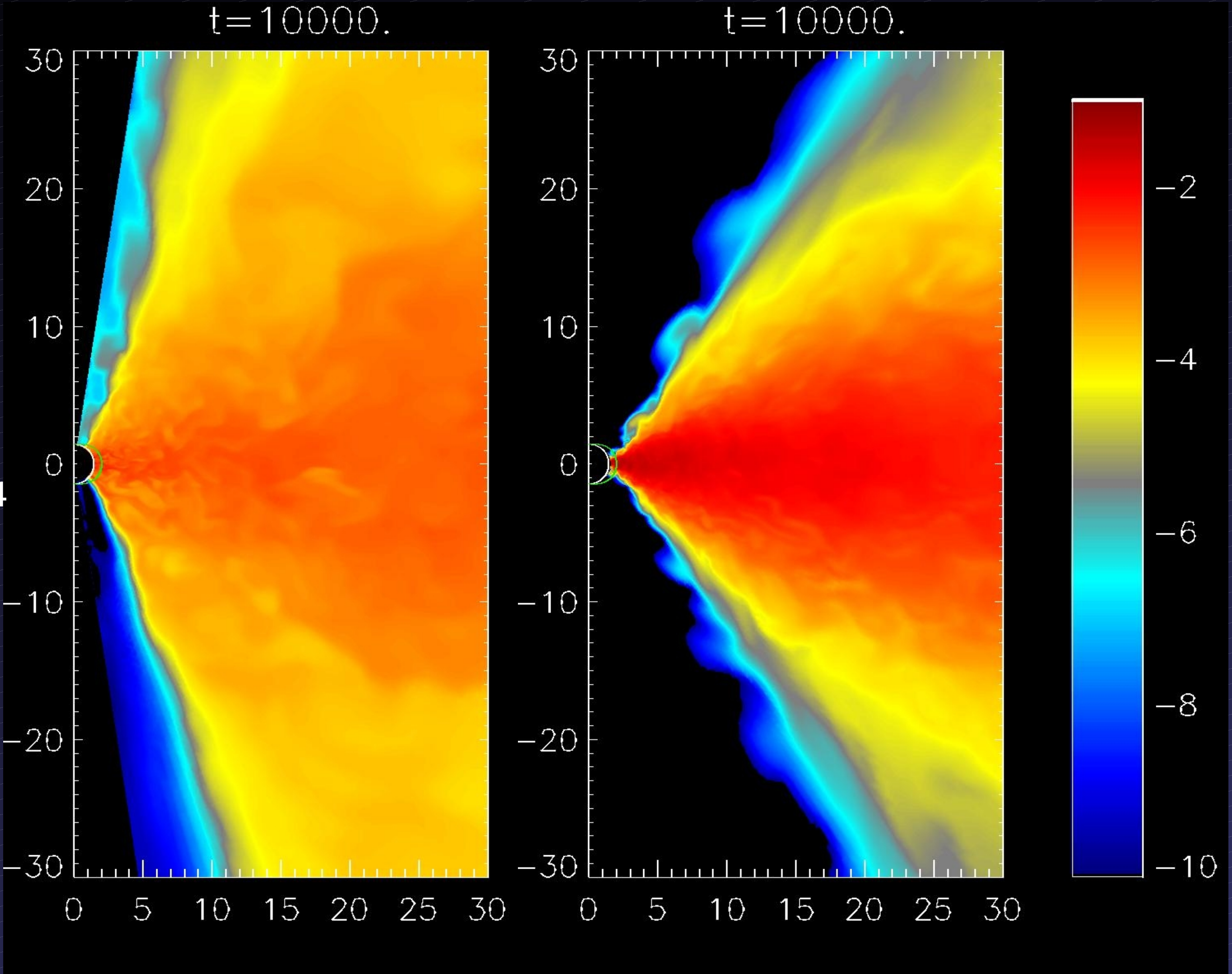
HARM3D vs. dVH $\gamma(\phi - avg)$



Uncooled **Cooled #2** **dVH**

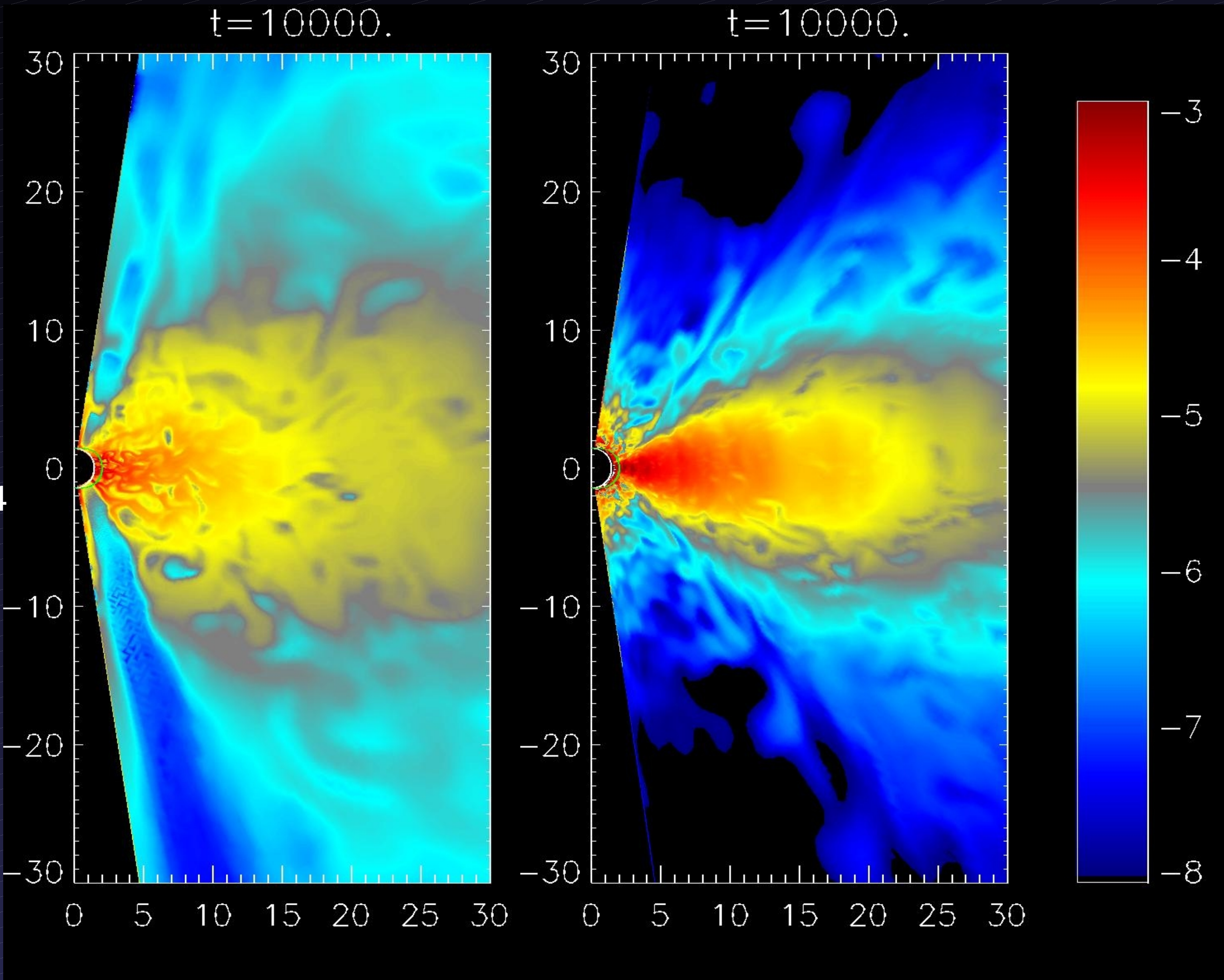
HARM3D vs. dVH $\log(\rho)$

192x192x64
a = 0.9 M

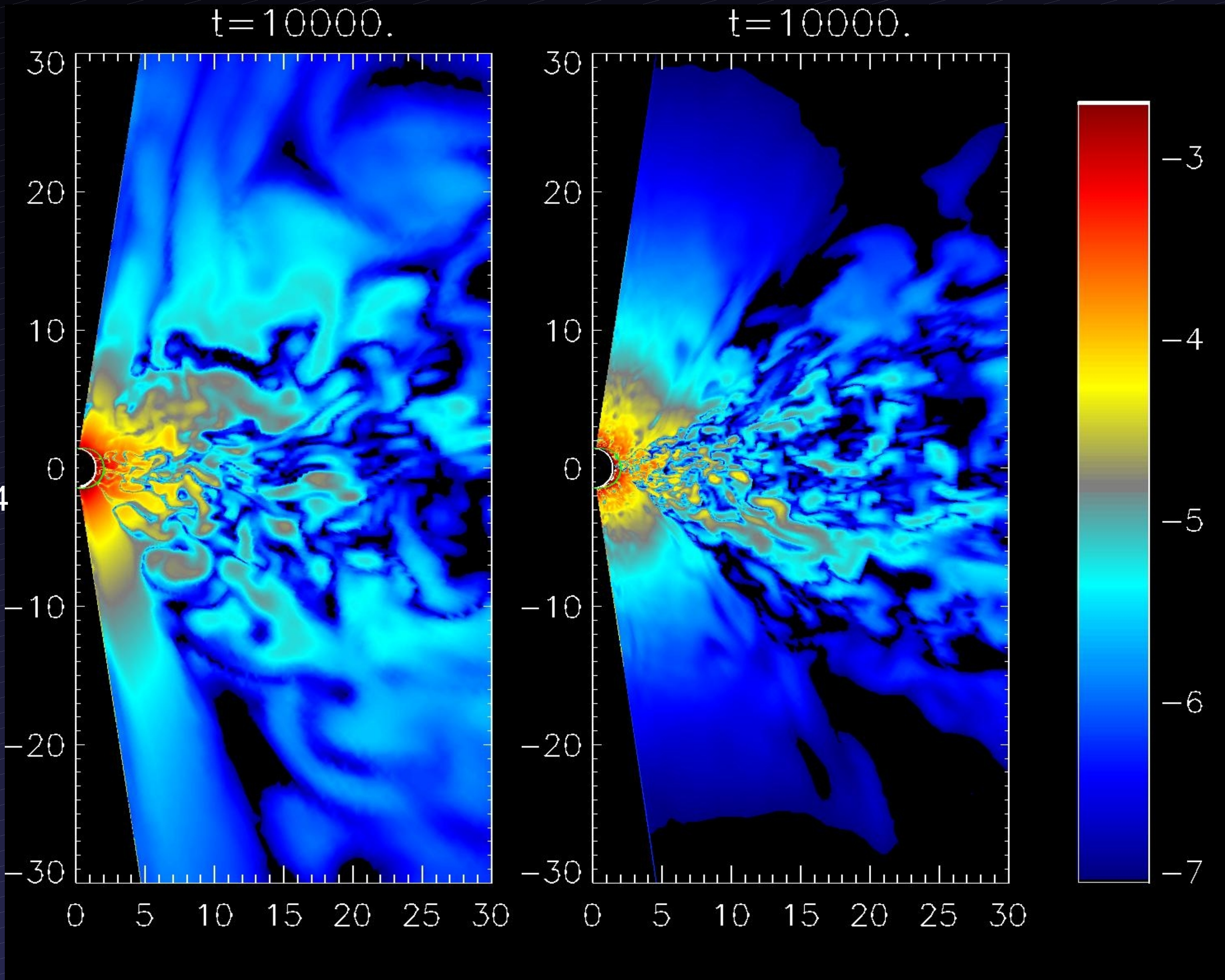


HARM3D vs. dVH $\log(P)$

192x192x64
a = 0.9 M

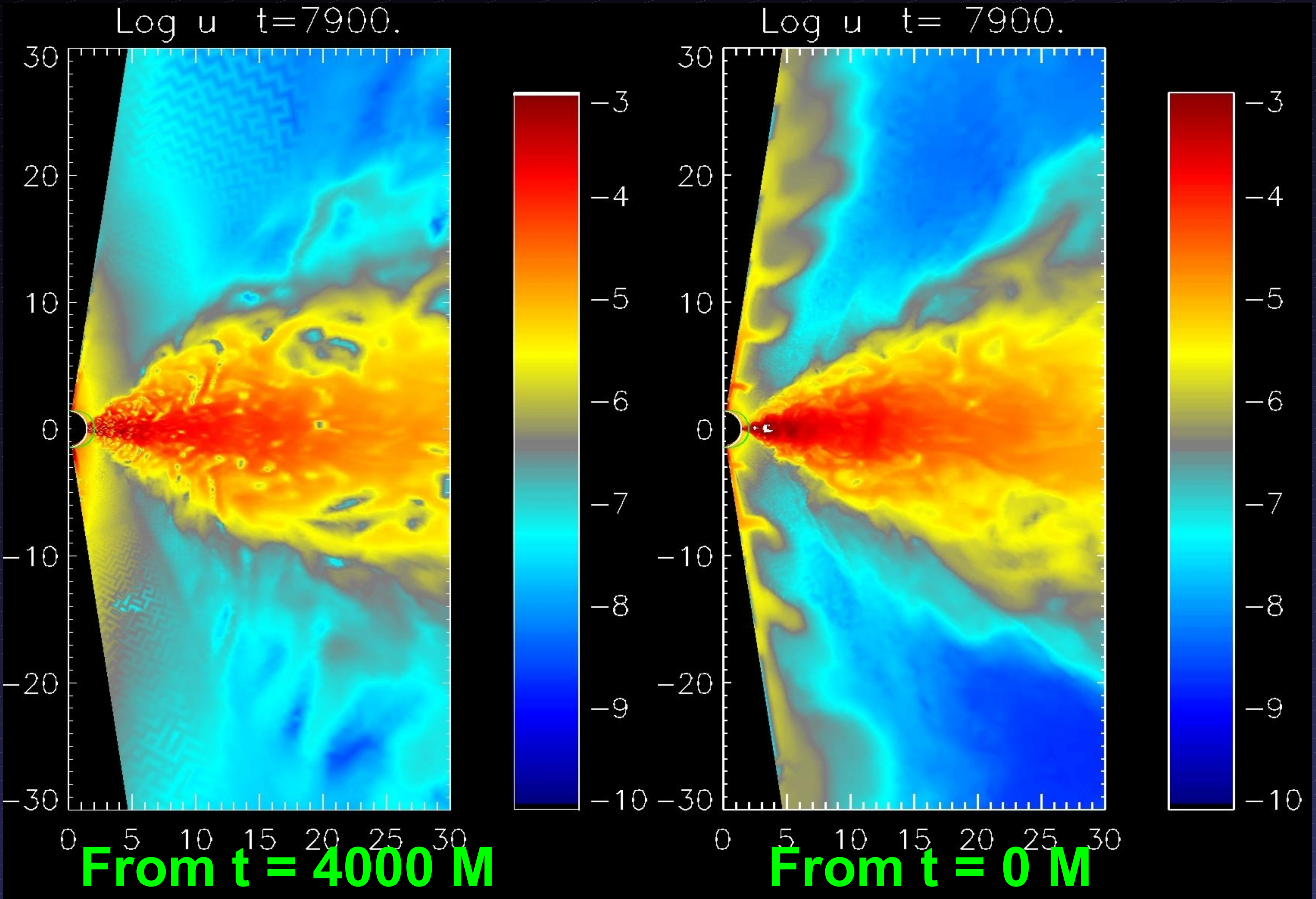


HARM3D vs. dVH $\log(P_{mag})$

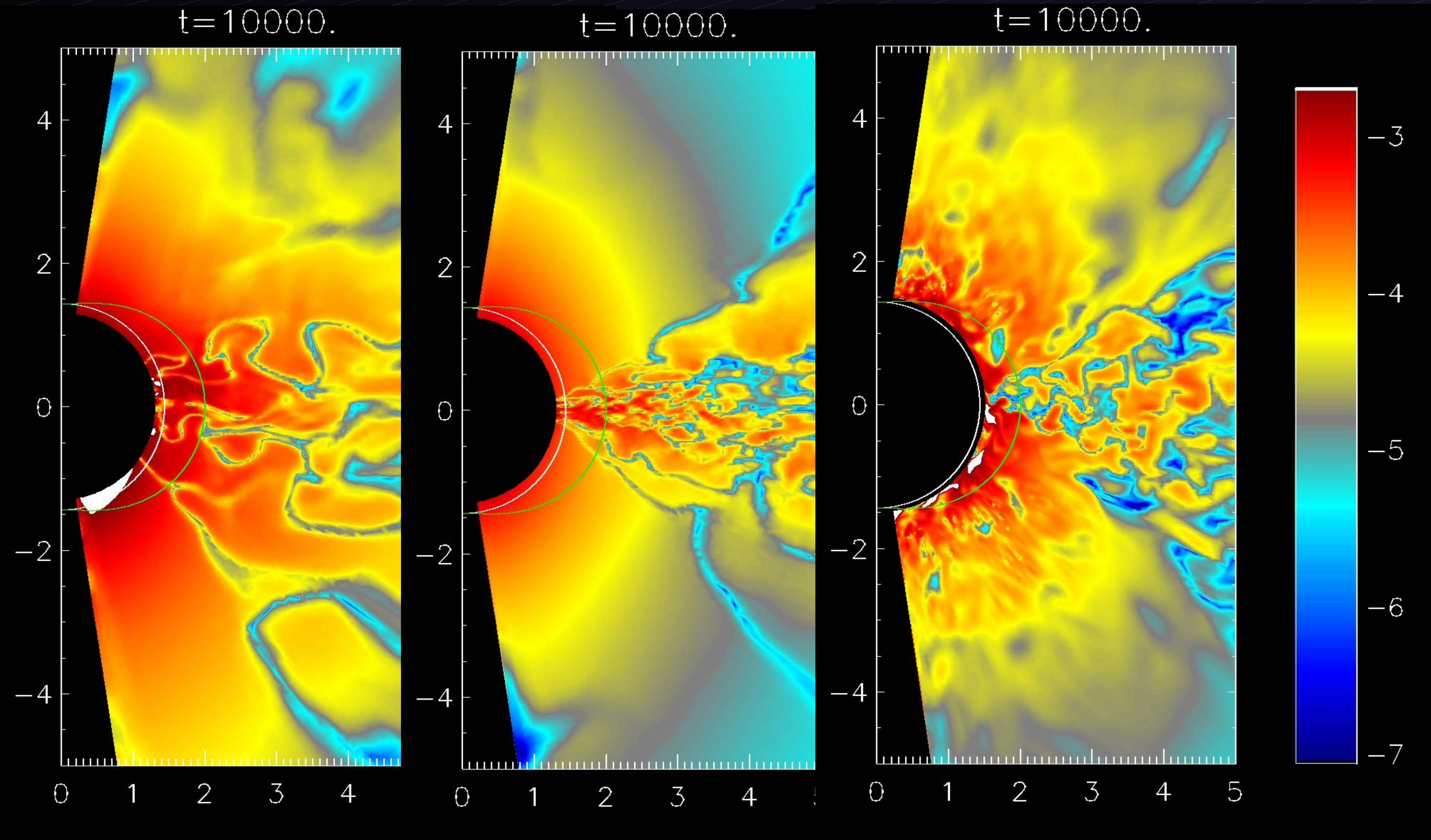


192x192x64
a = 0.9 M

Cooled #1 vs. Cooled #2 $\log(P)$

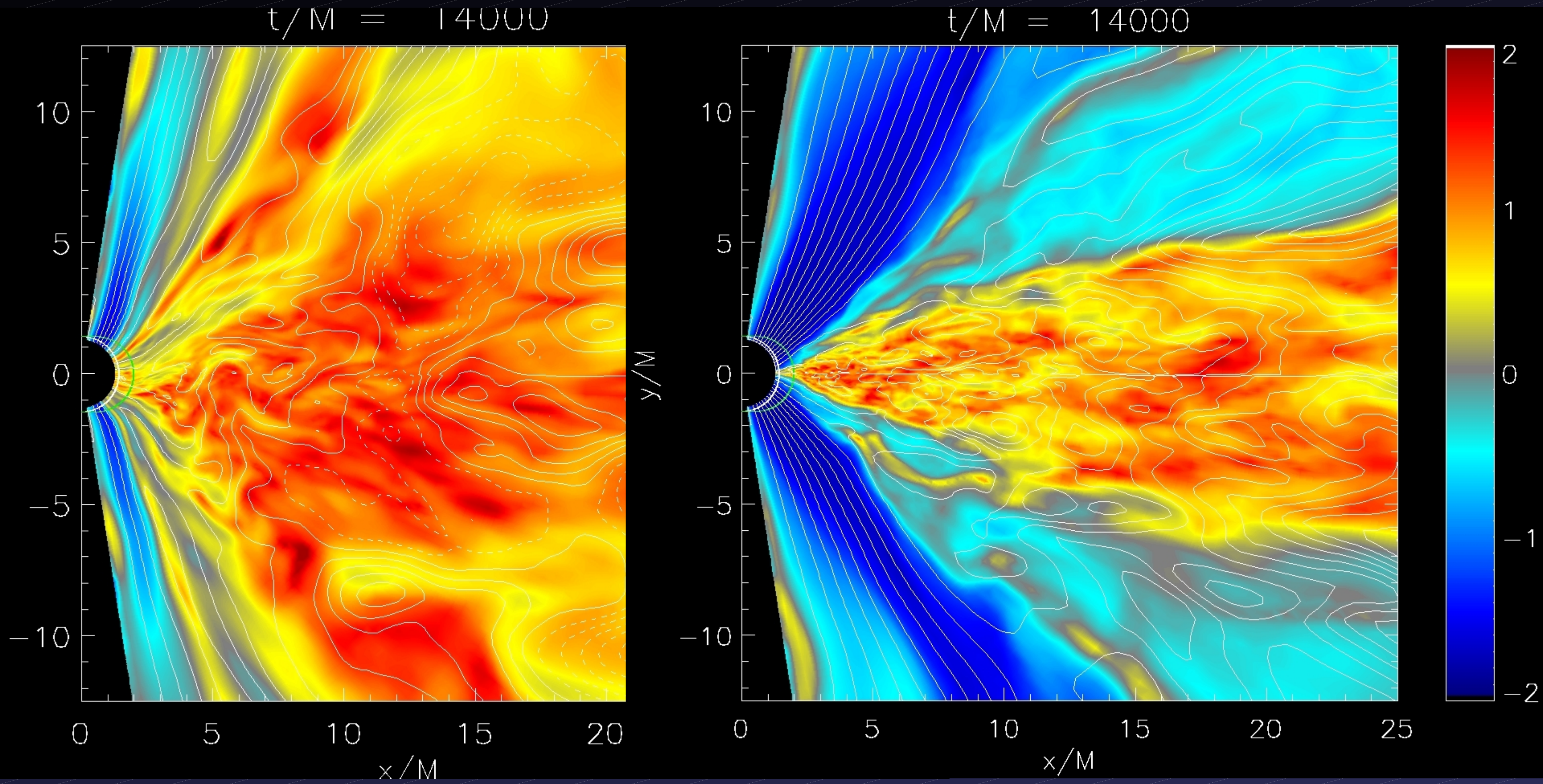


HARM3D vs. dVH $\log(P_{mag})$



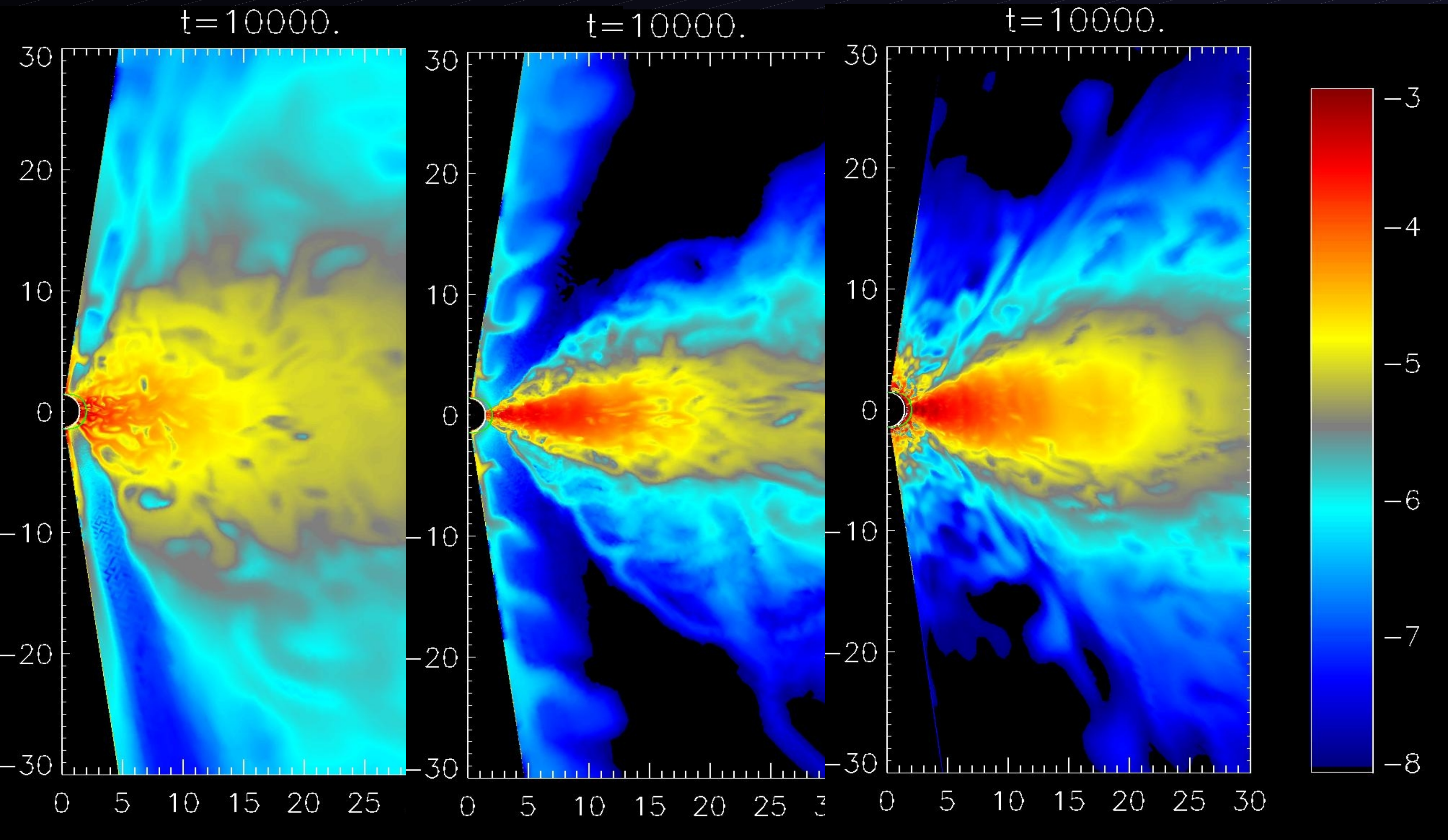
Uncooled **Cooled #2** **dVH**

HARM3D vs. dVH $\log(\beta)$



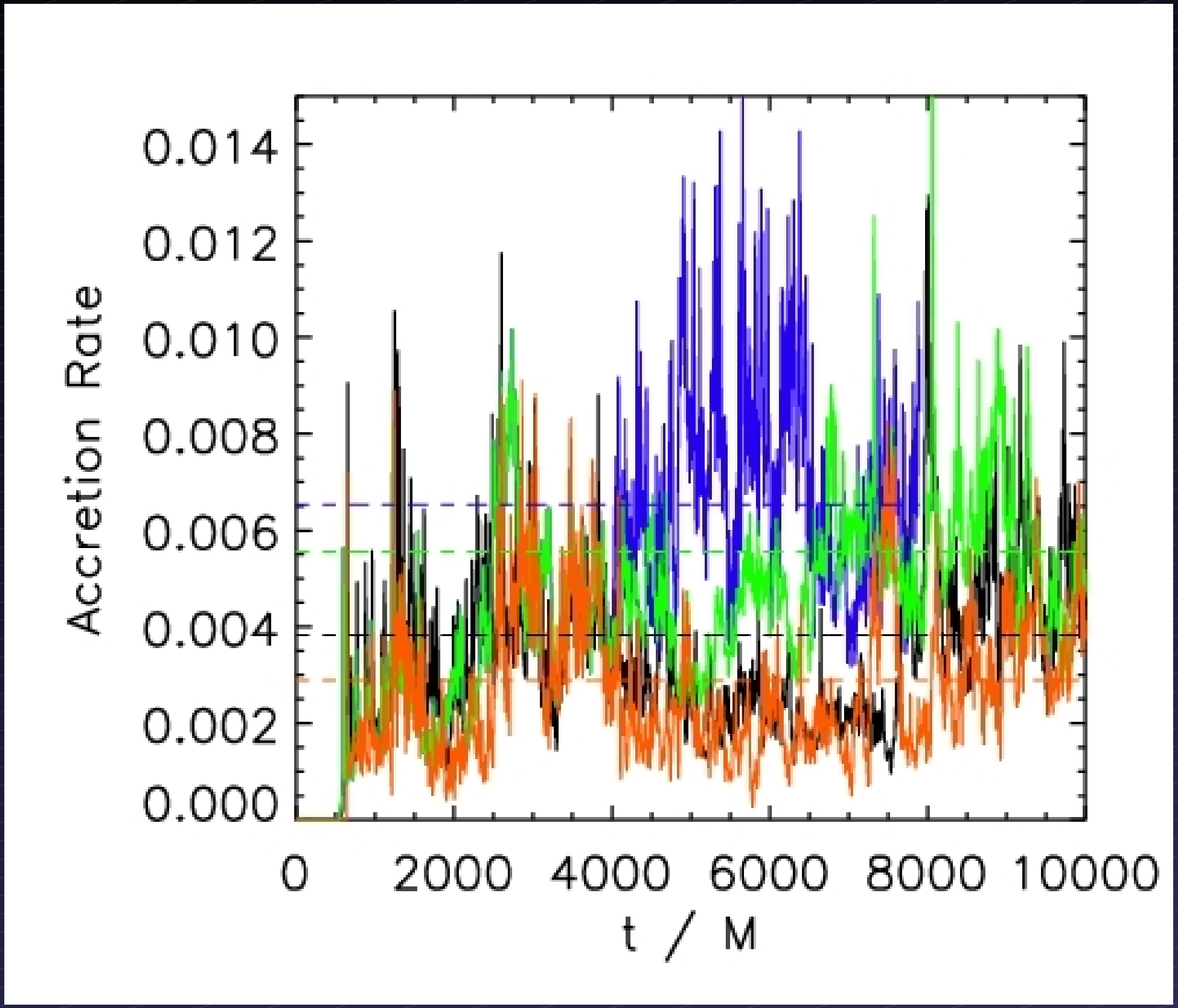
Uncooled **Cooled #2**

HARM3D vs. dVH $\log(P)$



Uncooled **Cooled #2** **dVH**

HARM3D vs. dVH $\dot{M}$



Cooled from t=0M

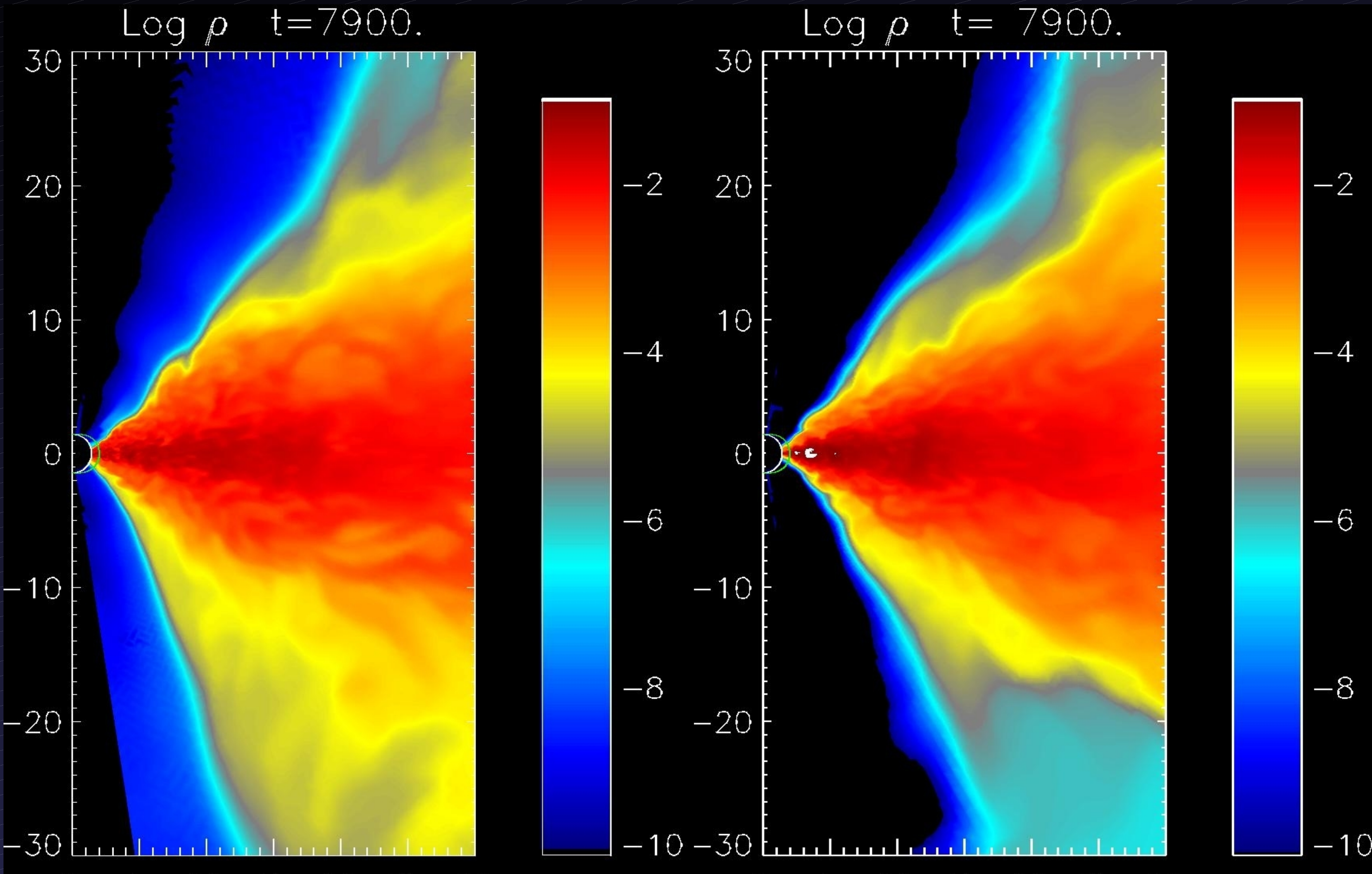
Cooled from t=4000M

Uncooled

Non-conservative

Cooling Methods

$\log(\rho)$

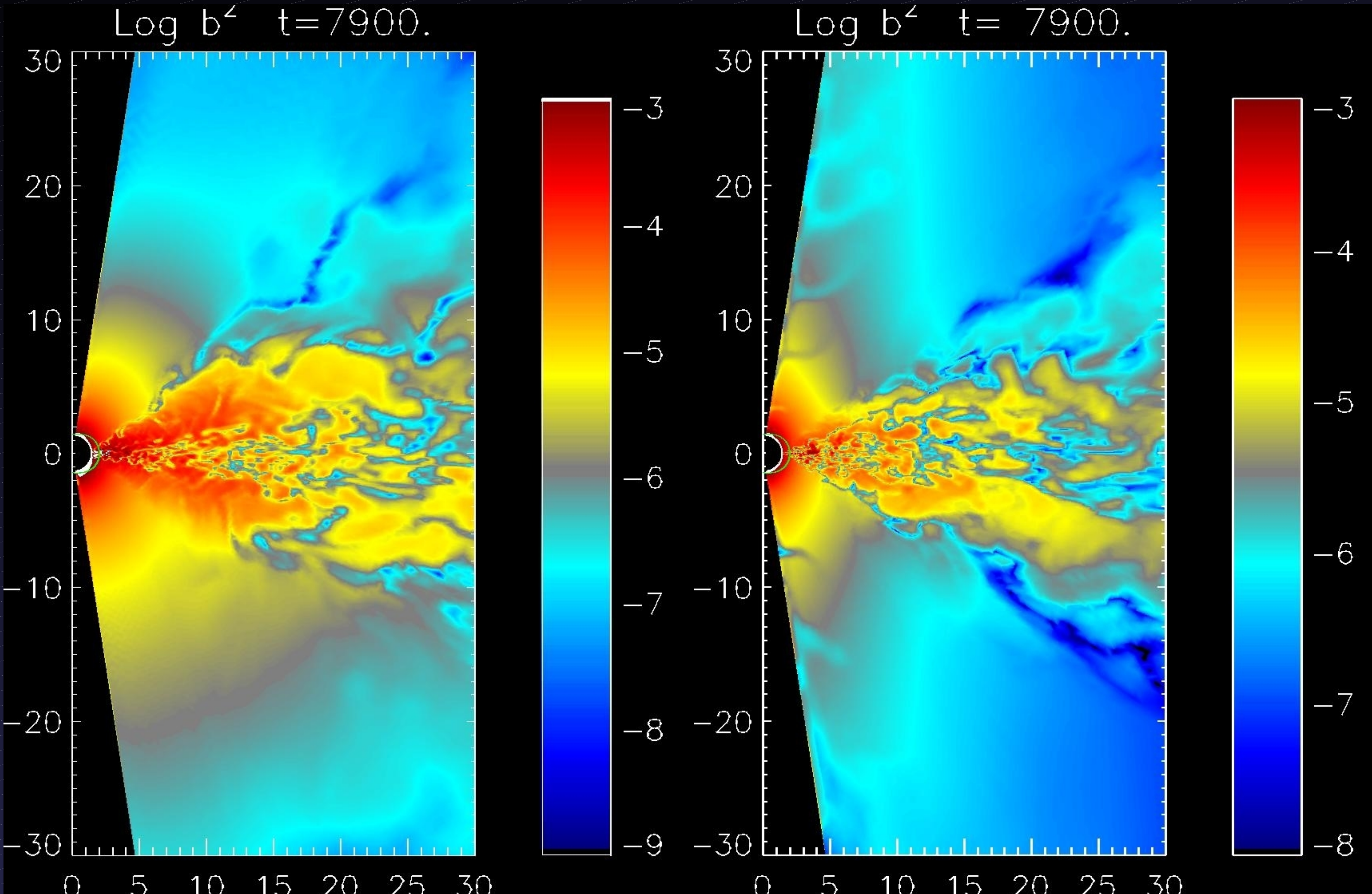


From t = 4000 M

From t = 0 M

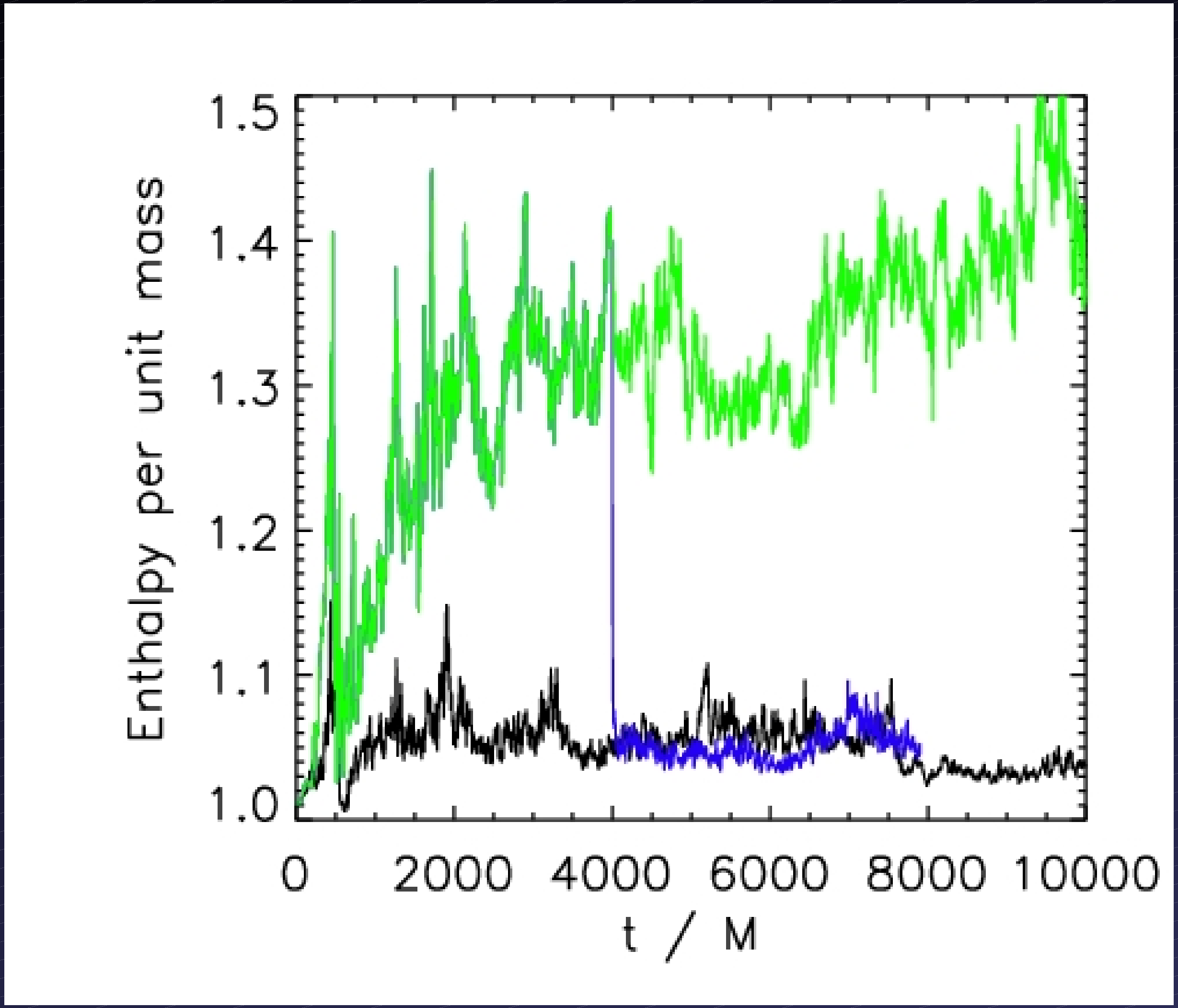
Cooling Methods

$\log(P_{mag})$



From t = 4000 M **From t = 0 M**

Cooling Efficacy



Cooled from t=0M

Cooled from t=4000M

Uncooled

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

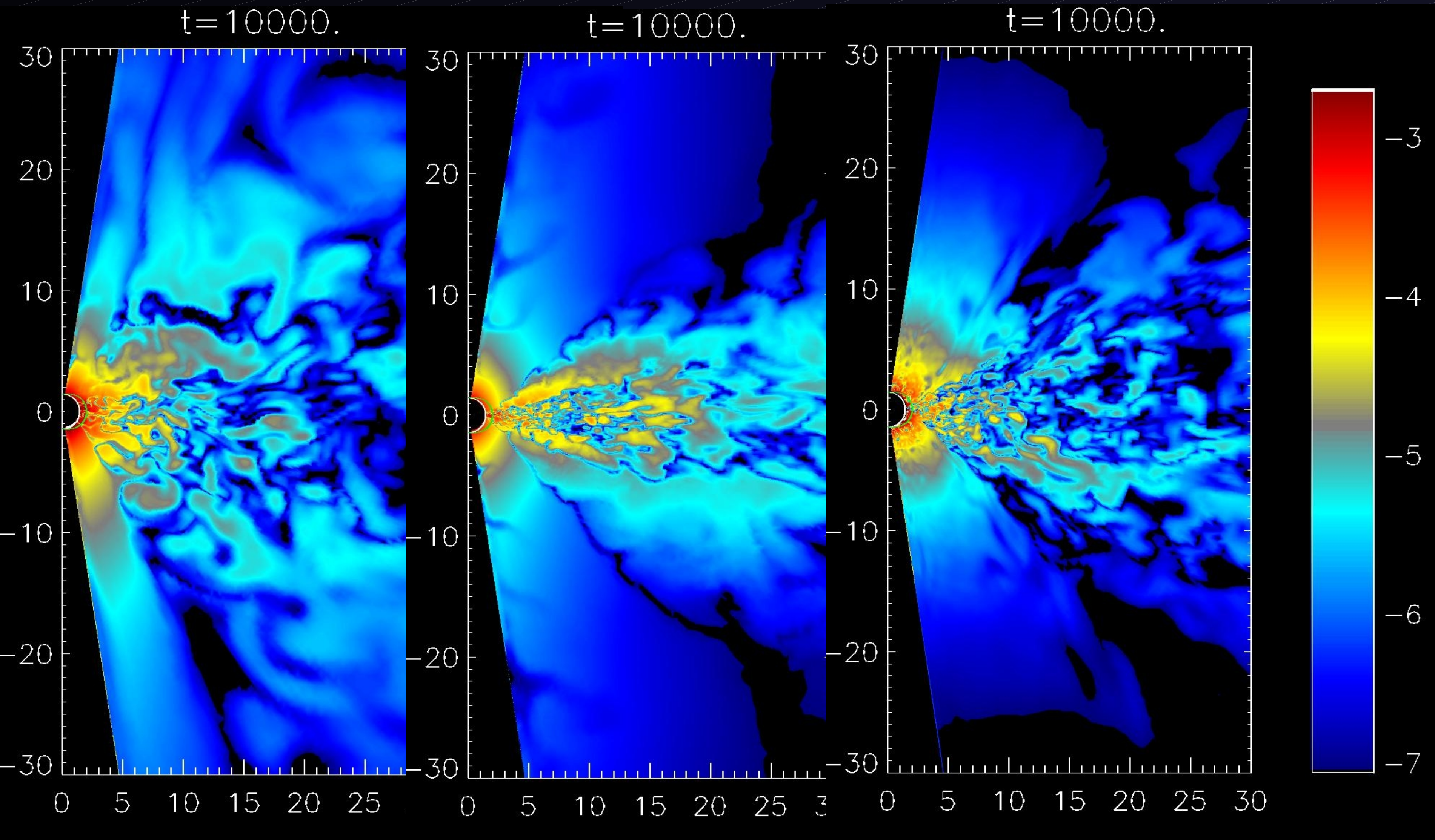
[a] Values adopted in this Letter.

Shafee et al. (2006)

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

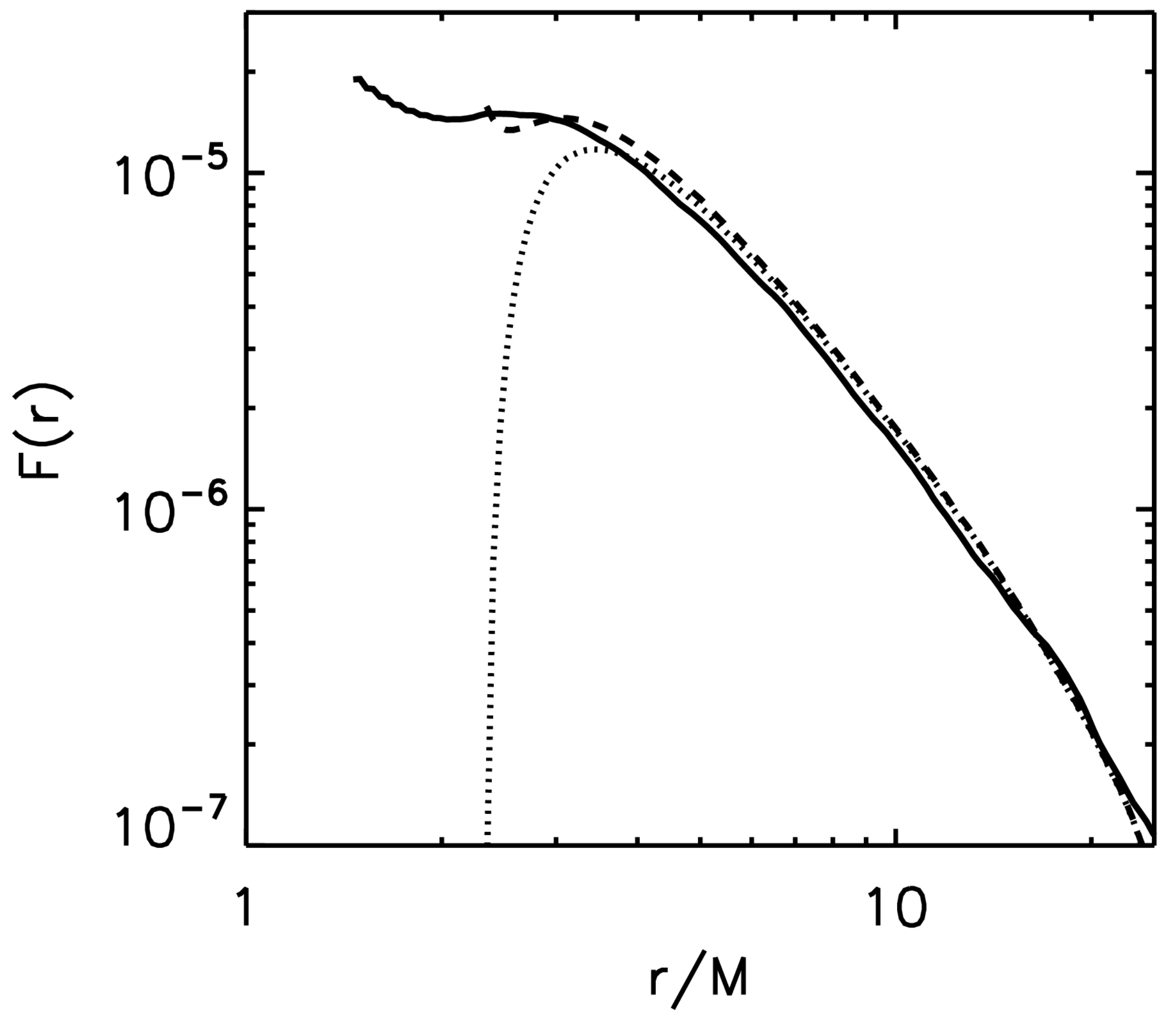
McClintock et al. (2006)

HARM3D vs. dVH $\log(P_{mag})$



Uncooled **Cooled** **dVH**

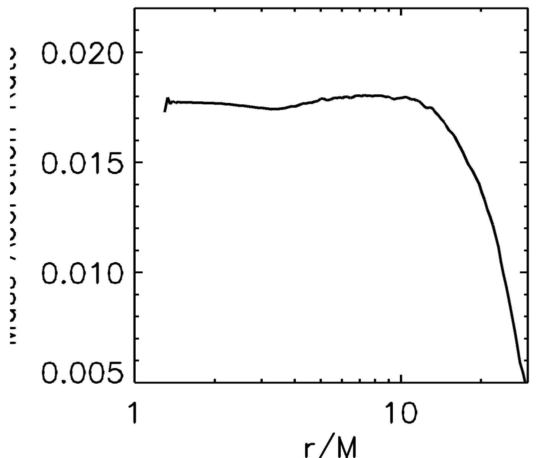
Fluid Frame Flux



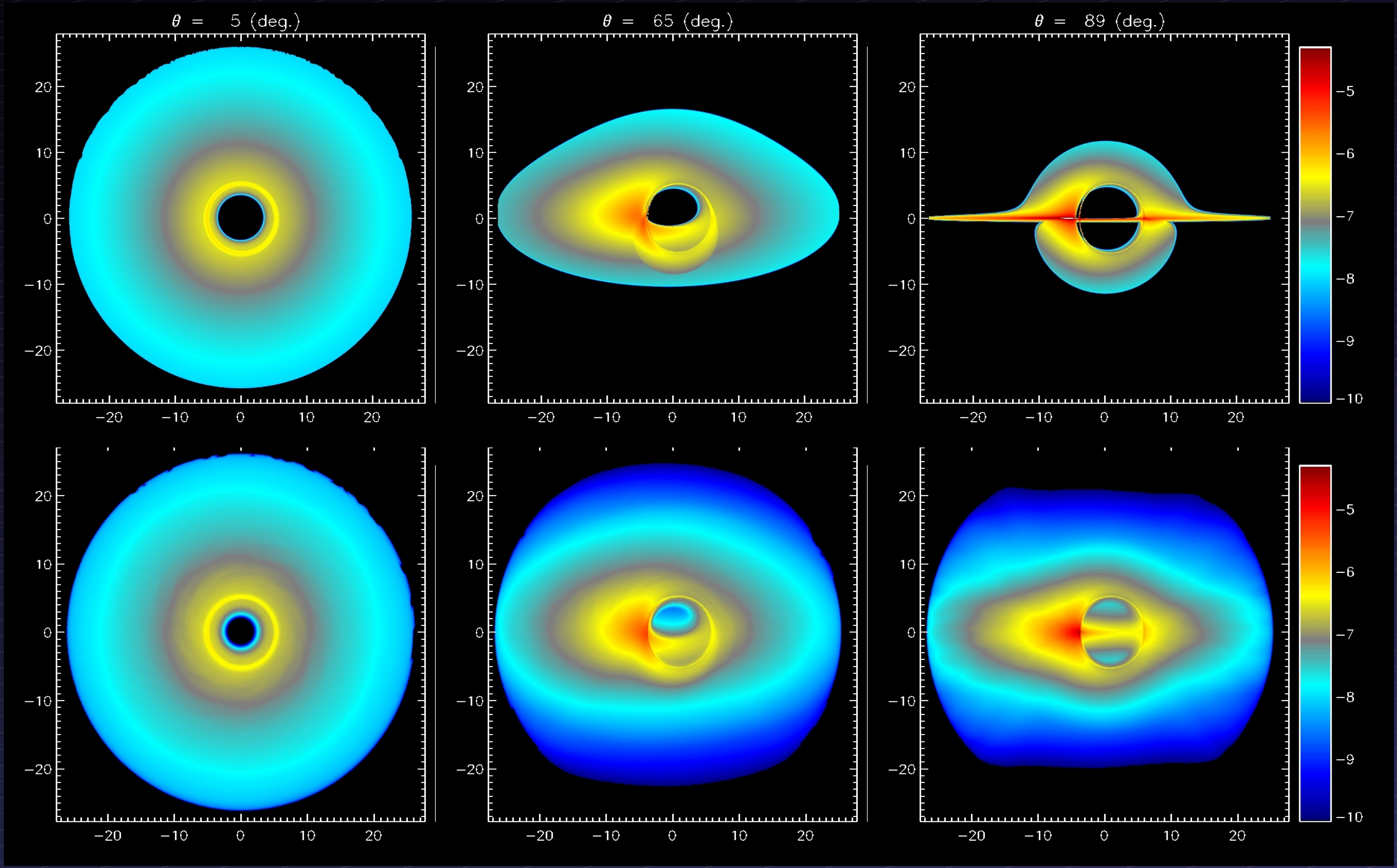
Agol & Krolik (2000) model

$$\Delta\eta = 0.01$$

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



Observer-Frame Intensity: Time Average



NT

HARM

i=5° i=65° i=89°