Direct Calculation of the Radiative Efficiency of Thin Accretion Disks

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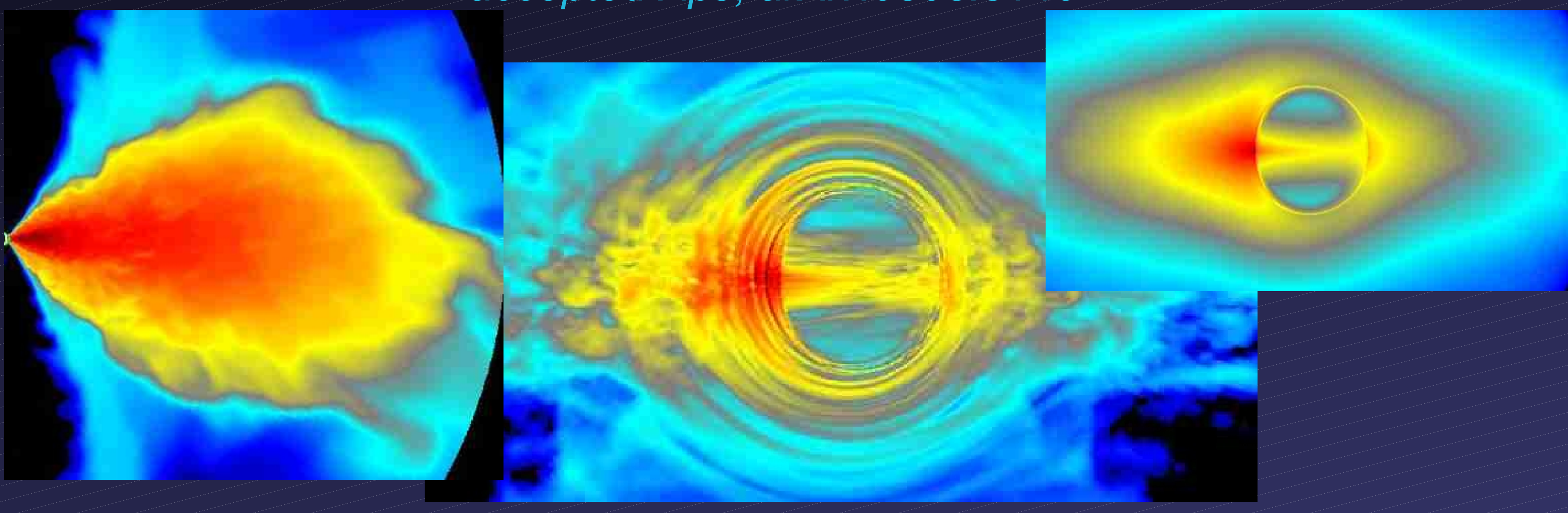
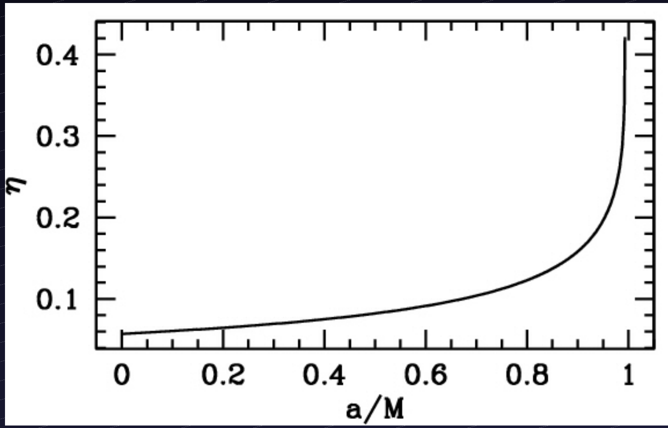


Understanding BH Accretion

(at least for the innermost regions of radiative efficient, geometrically thin disks)

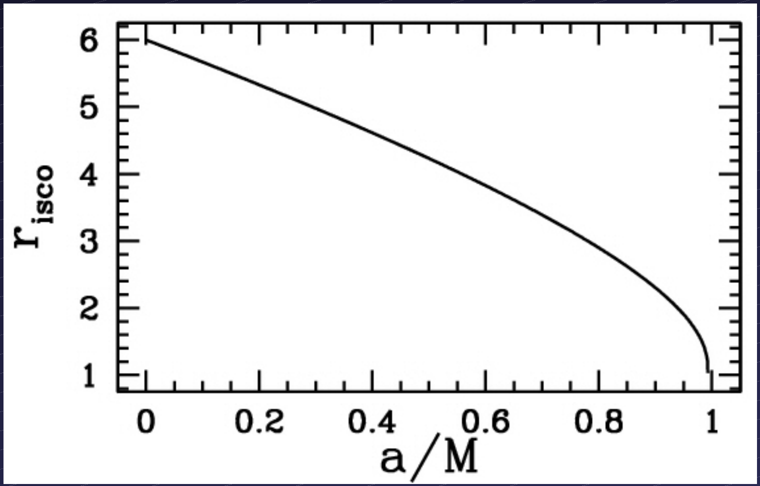
$$L = \eta \dot{M} c^2 \qquad \eta = 1 - \dot{E}/\dot{M} = 1 - \epsilon_{ISCO}$$

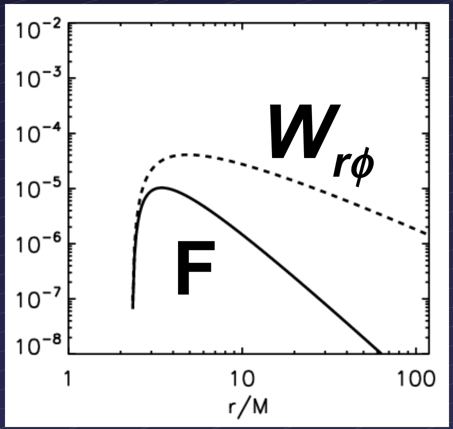
Novikov & Thorne (1973)

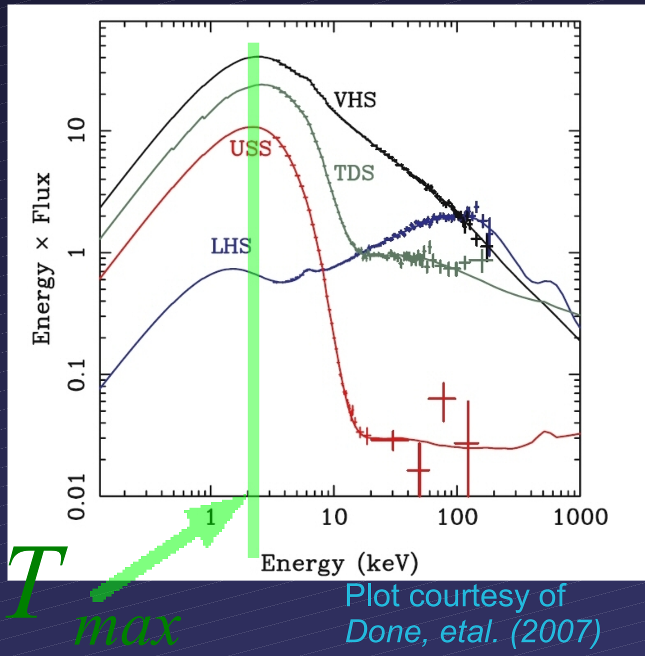


$$L = A R_{in}^2 T_{max}^4 \qquad T \sim (H/r)^2 r^{-1} \qquad R_{in} = r_{isco}(M, a)$$

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





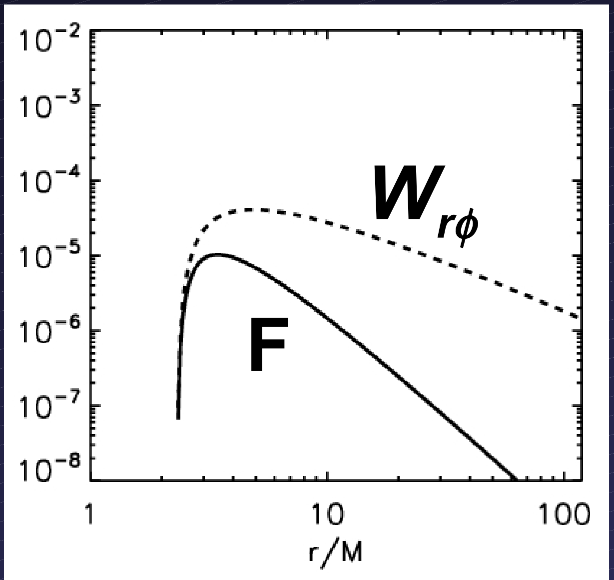


Plot courtesy of *Done, etal. (2007)*

Thin Disk Model: Novikov & Thorne (1973)

Assumptions:

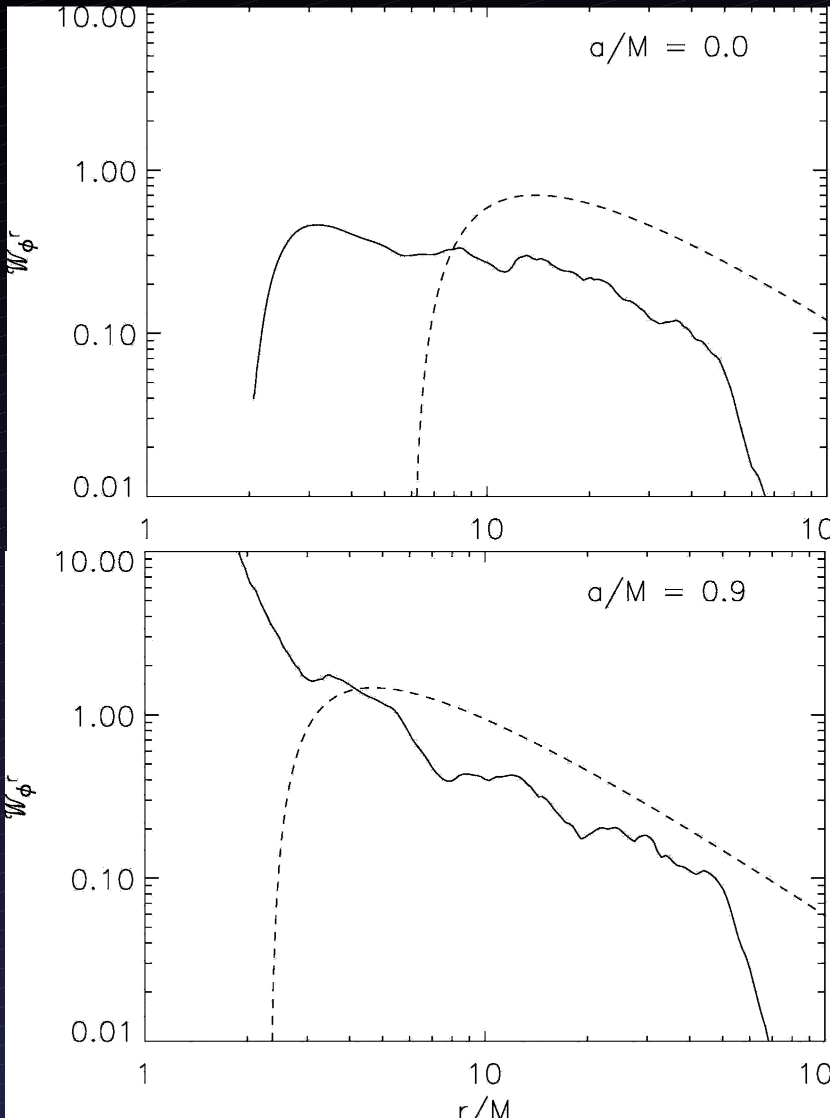
1) Equatorial Keplerian Flow
   - Thin, cold disks
2) Time-independent flow and BH
3) Work done by stress is locally dissipated into heat and radiated instantly
4) Conservation of M, E, L
5) Zero Stress at ISCO



Issues and Concerns:

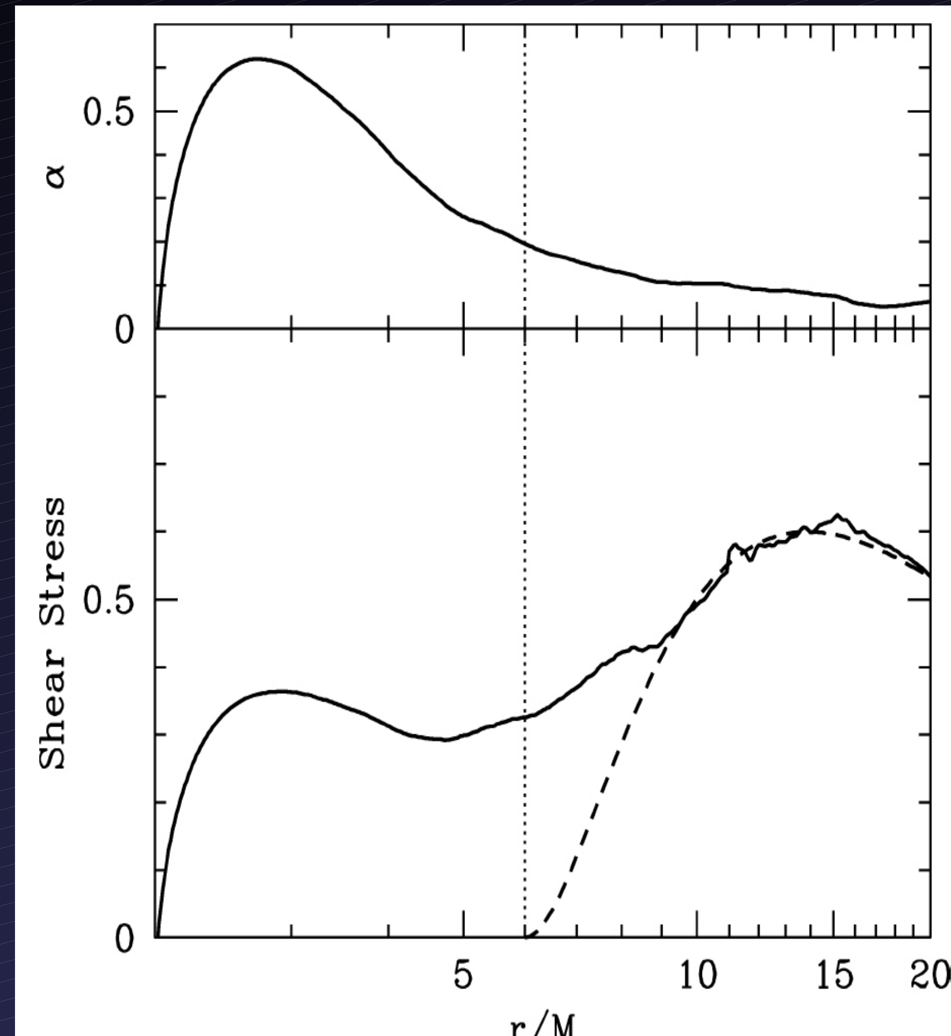
- Real disks...
  - ✗ Are dynamic
  - ✗ Have finite temperature/thickness
  - ✗ May be tilted
- Zero Stress Condition:
  - ✗ Thought to be suspect from very start *(Thorne 1974, Page & Thorne 1974)*
  - ✗ Magnetic field stress may connect plunging material to the disk: *(Gammie 1999, Agol & Krolik 2000)*
  - ✗ Previous 3D non-conservative GRMHD simulations show increasing stress through ISCO *(Krolik et al. 2005)*
  - ✔ (Contemporaneous) 3D conservative GRMHD a=0 simulation shows diminishing stress within ISCO *(Shafee et al. 2008)*

Dynamical Global GRMHD Disk Models



Krolik, Hawley, Hirose (2005)

H/R ~ 0.1 - 0.17



Shafee et al. (2008)

H/R ~ 0.05

Our Work

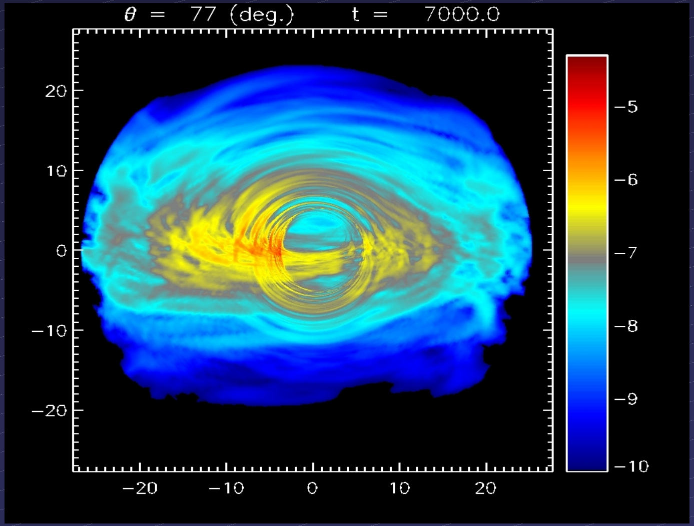
- 1st Self-consistent measurement of radiative efficiency from 3D GRMHD simulations
- 1st 3D GRMHD Thin Disk simulation around a ***spinning*** black hole

  (see contemporaneous work by *Shafee et al. 2008* for 3D GRMHD thin disk sim. w/ non-spinning BH)

  (see *Fragile & Meier 2008* for 2.5D GRMHD thin disk simulations with realistic cooling)

  (see *Reynolds & Fabian 2008* for 3D pseudo-Newt. MHD thin disk simulation)

- Uses new 3D Conservative GRMHD code (HARM3D)
  - 3D version of HARM *(Gammie et al. 2003)* with improvements
- GR Ray Tracer transfers local emission to distant observer's frame
  - Handles time-dependent 3D simulation data
  - Local Emissivity = Local Cooling Rate
  - Doppler shifts
  - Gravitational redshift
  - Relativistic beaming
  - Improved from earlier work *(Noble et al. 2007)*



Technical Details

GRMHD Simulation

- a = 0.9 M
- 192x192x64 cells
- $r \in [r_{hor}, 120\text{M}]$
- $\phi \in [0, \frac{\pi}{2}]$
- $\theta \in \pi [0.05, 0.95]$

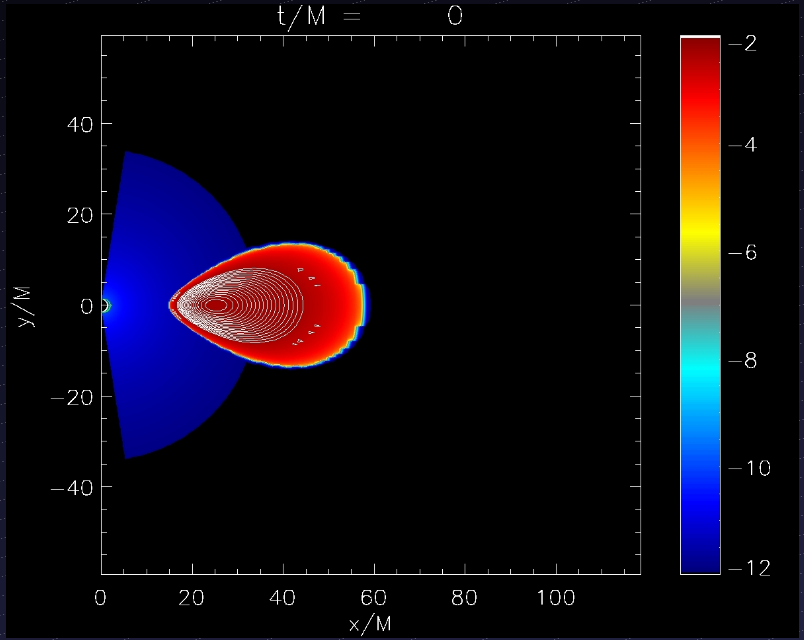
- Dissipation → Heat
- Optically thin cooling to

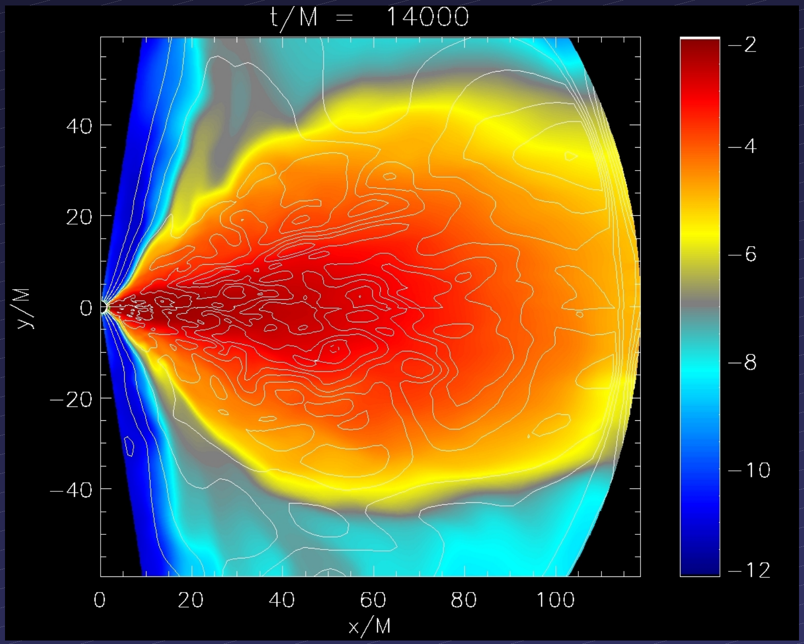
  H/R ~ 0.05 - 0.12
- Steady-state over

  $r \in [r_{hor}, 12\text{M}]$

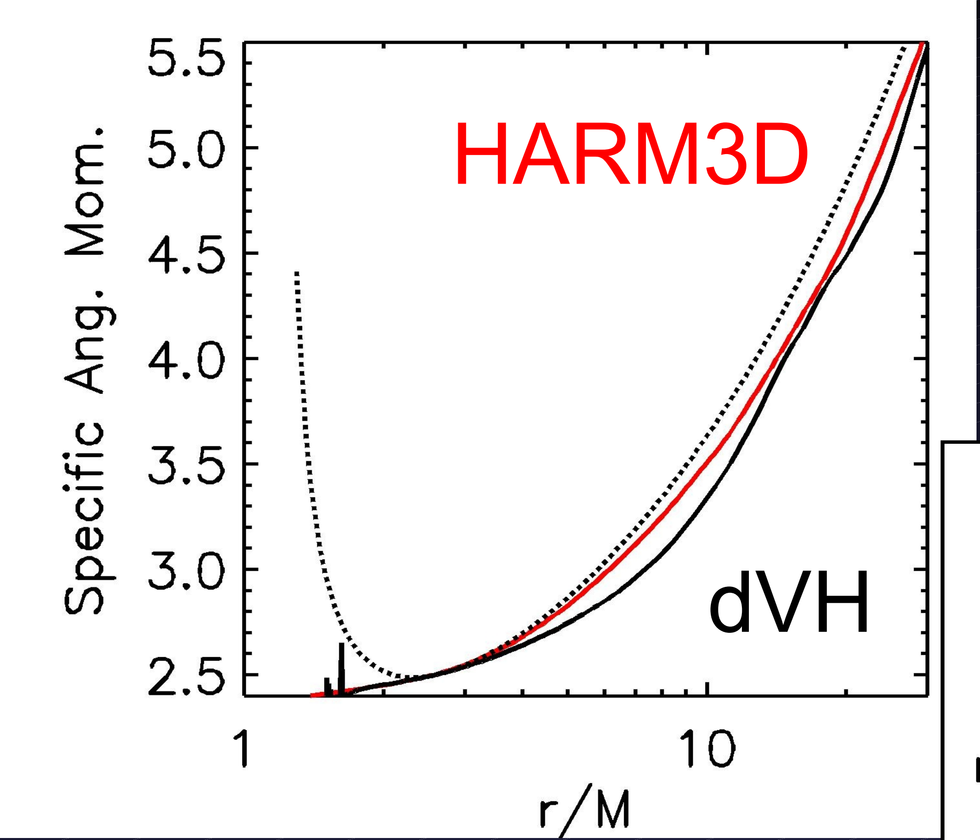
  $t_{avg} \in [7000\text{M}, 15000\text{M}]$
- Isotropic, thin emission of dissipation

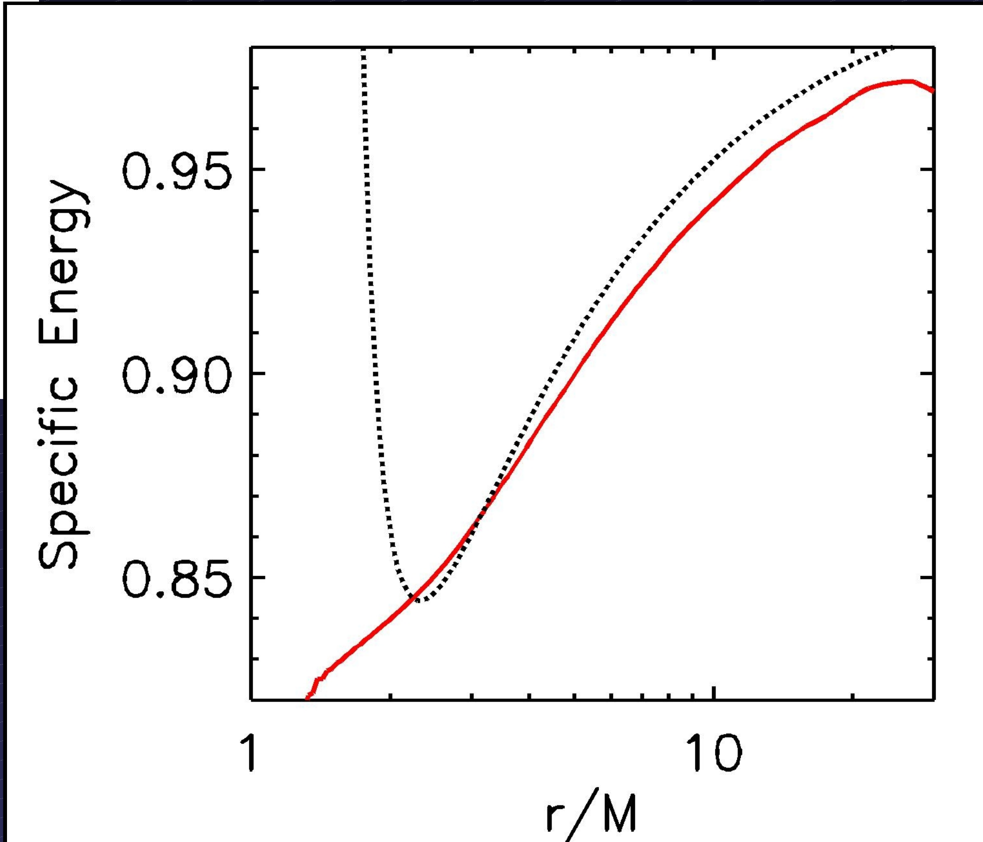
$t_{diff} \ll t_{dyn} \sim t_{orb}$ $j_{\nu} = \frac{f_c}{4\pi}$



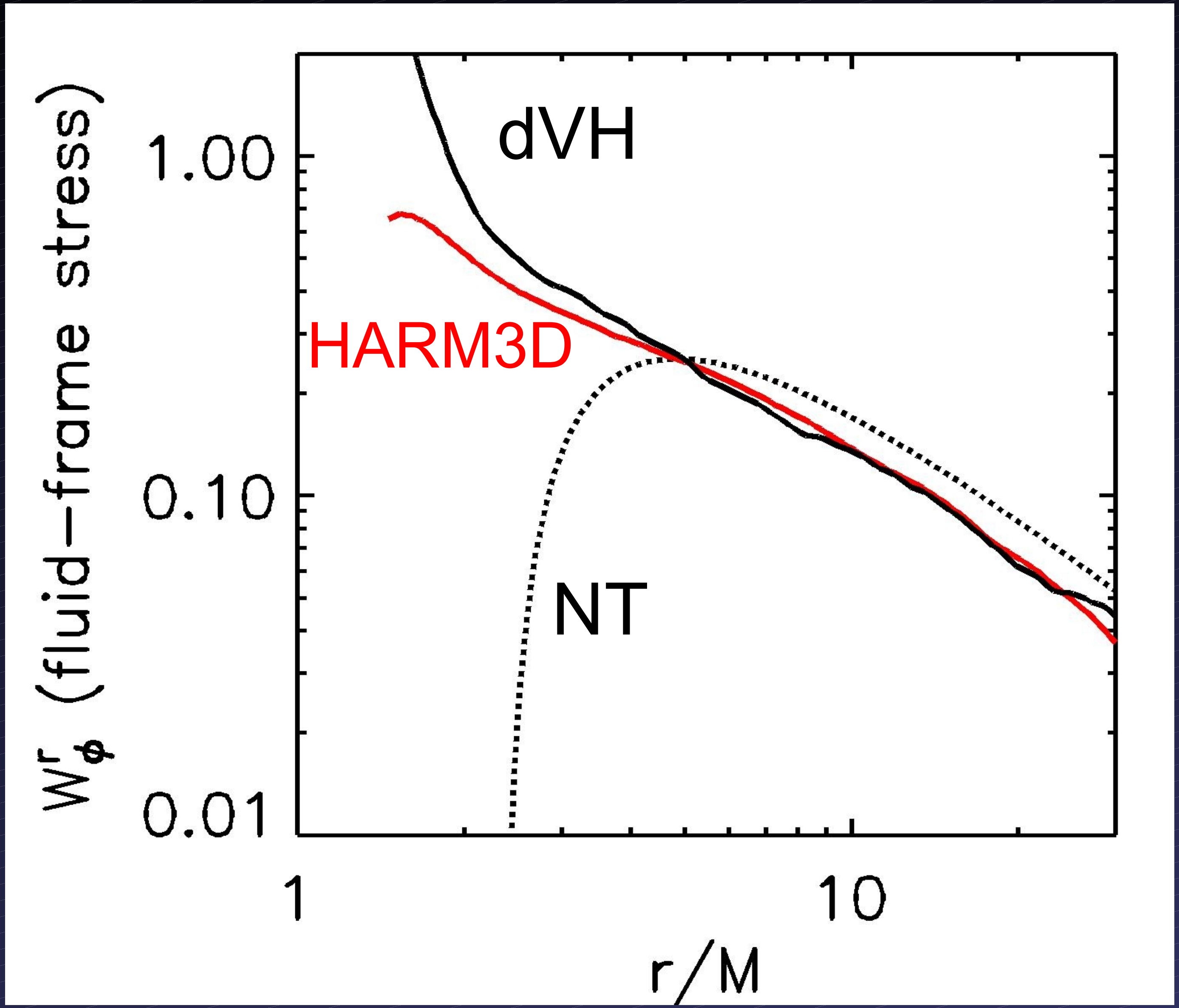


Departure from Keplerian Motion

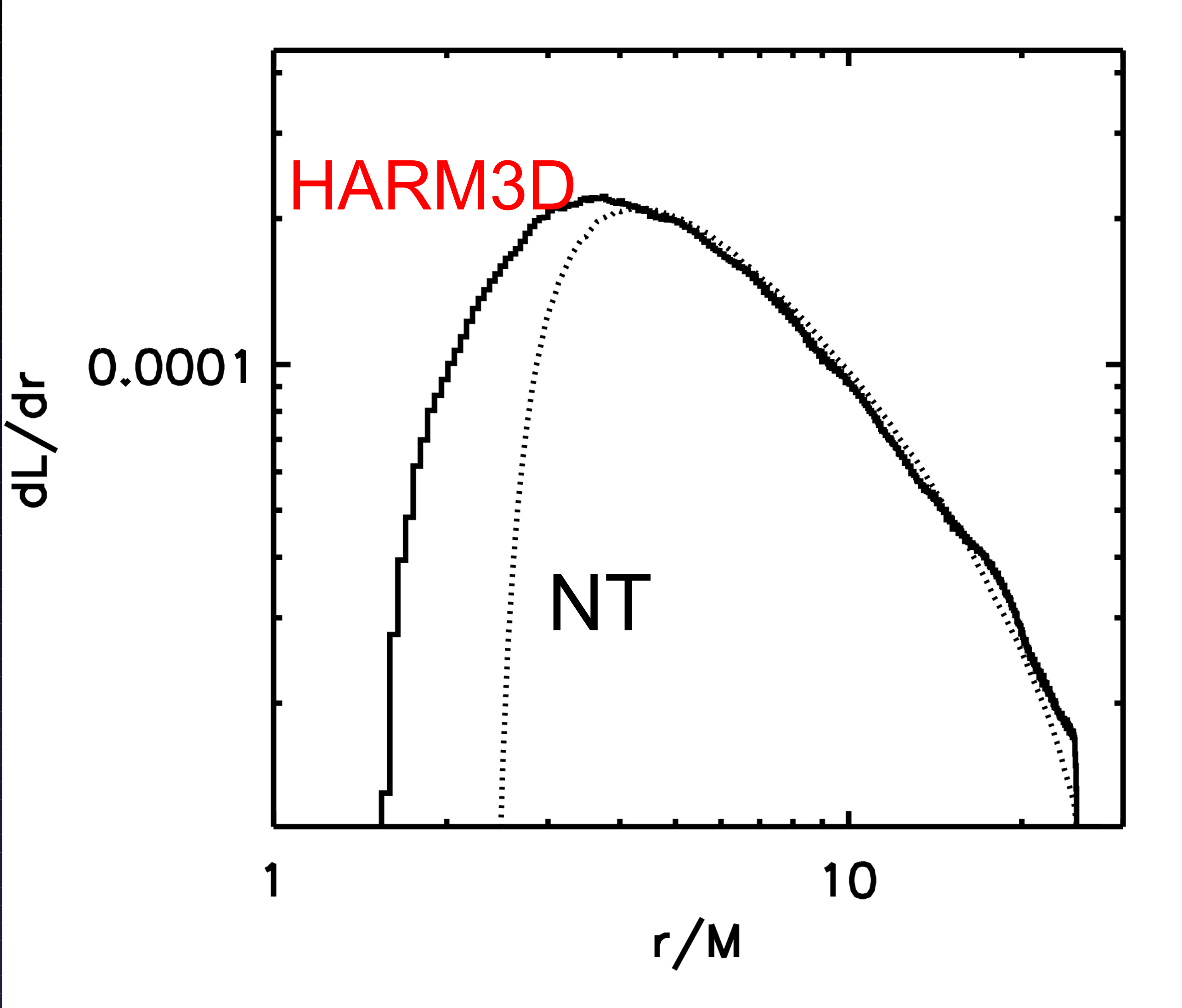




Magnetic Stress



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
  - $t_{cool} > t_{inflow}$

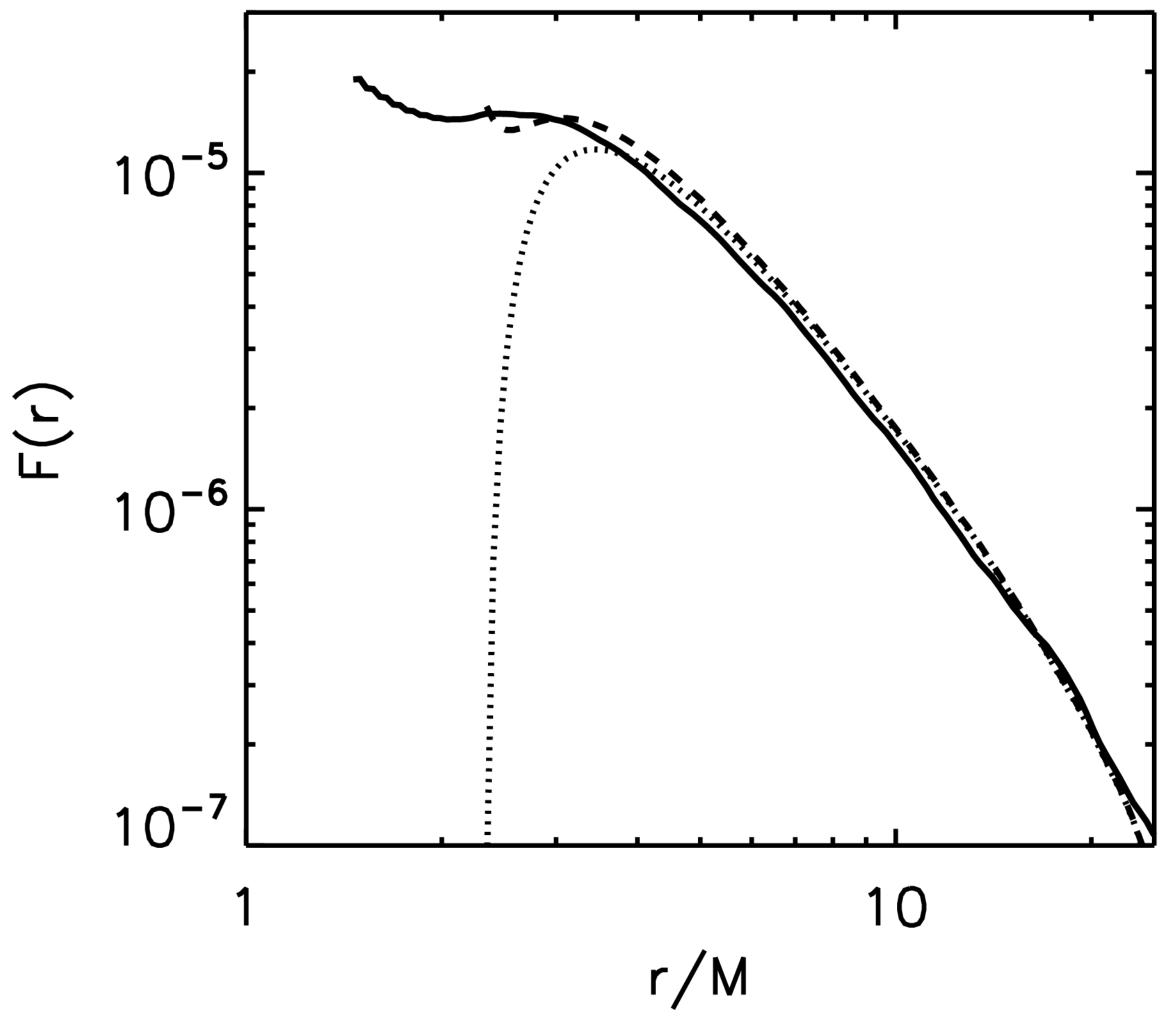
➢ Possibly greater difference for $a_{BH} < 0.9$ when ISCO is further out of the potential well.

Future Work:

- Explore parameter space: More spins, More H/R 's , More H(R) 's
  $\rightarrow$ dL/dr (a , H/R)
- Time variability analysis, Impossible with steady-state models

Extra Slides

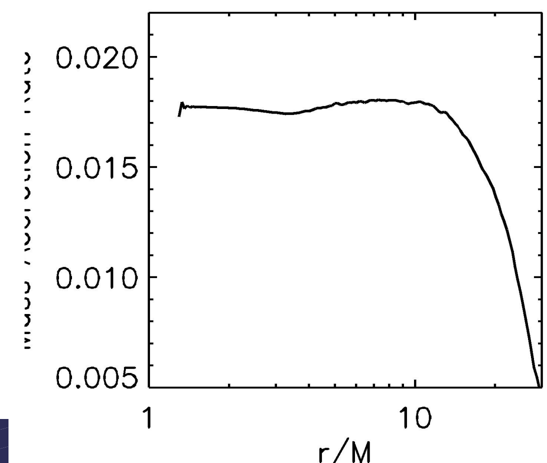
Fluid Frame Flux



Agol & Krolik (2000) model

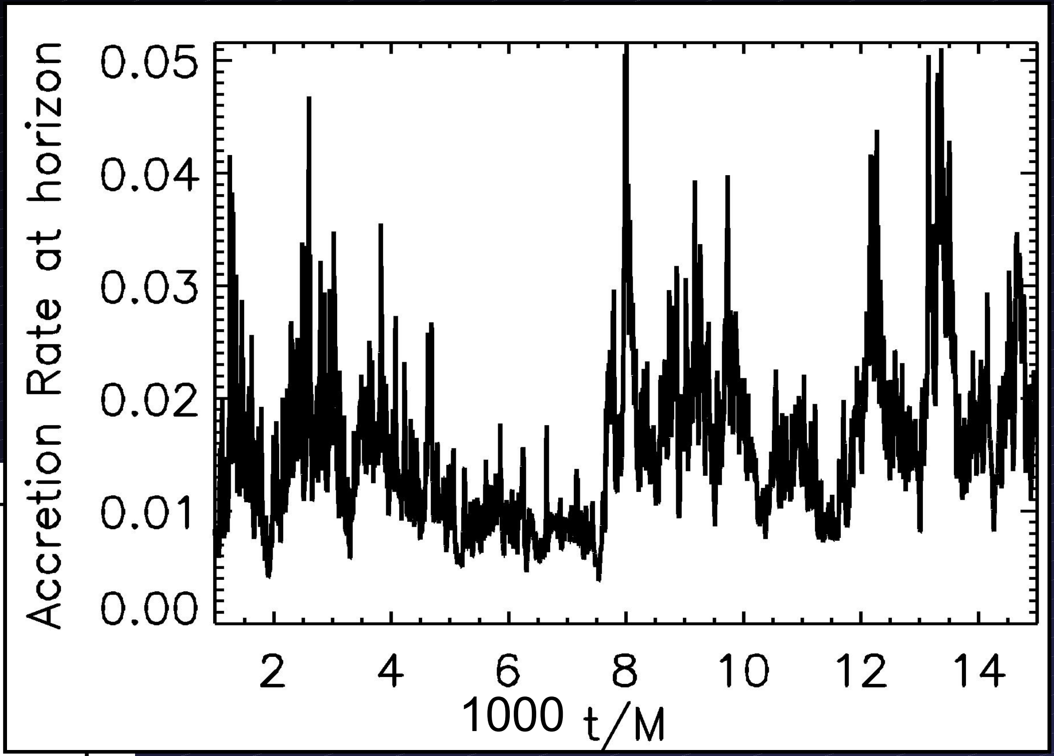
$$\Delta\eta = 0.01$$

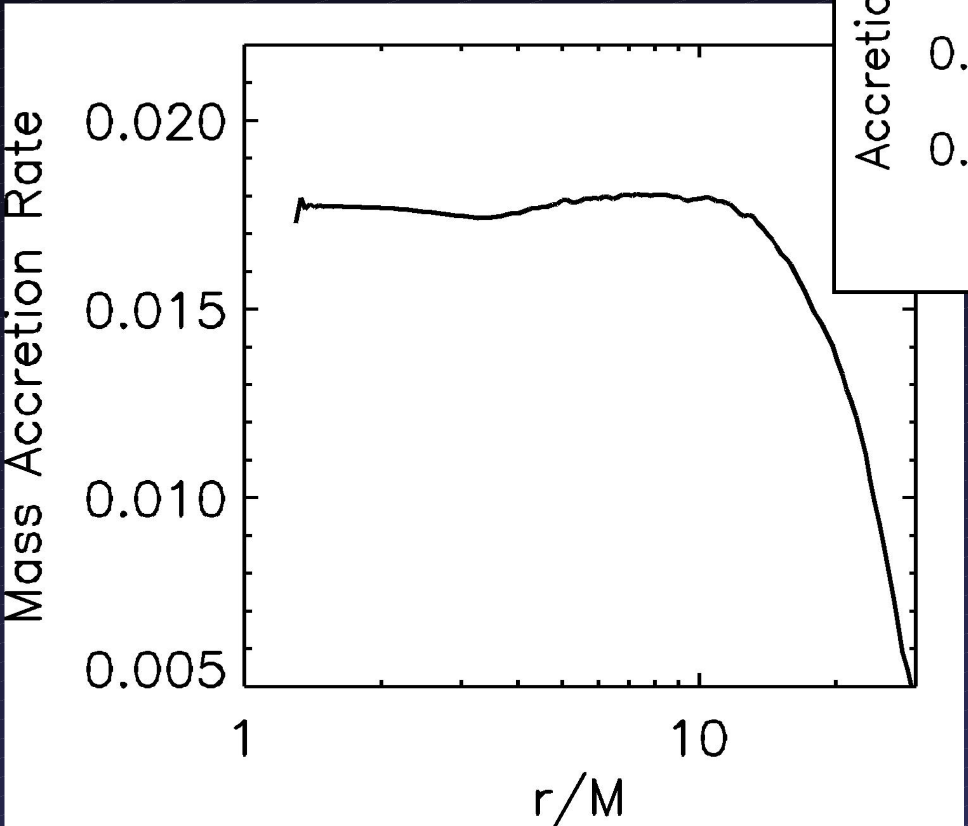
$$\Delta\eta/\eta = 7\%$$



Accretion Rate

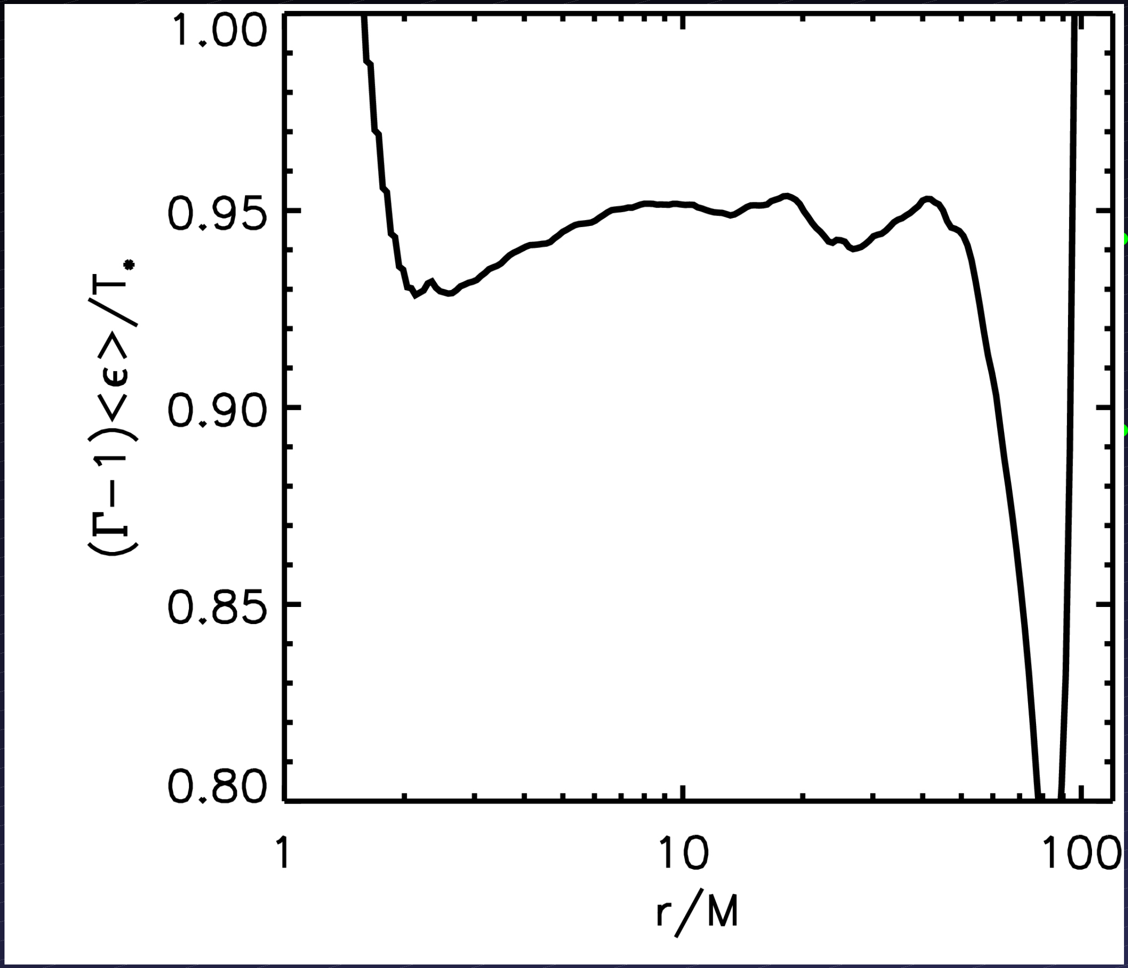
Steady State Period = 7000 – 15000M





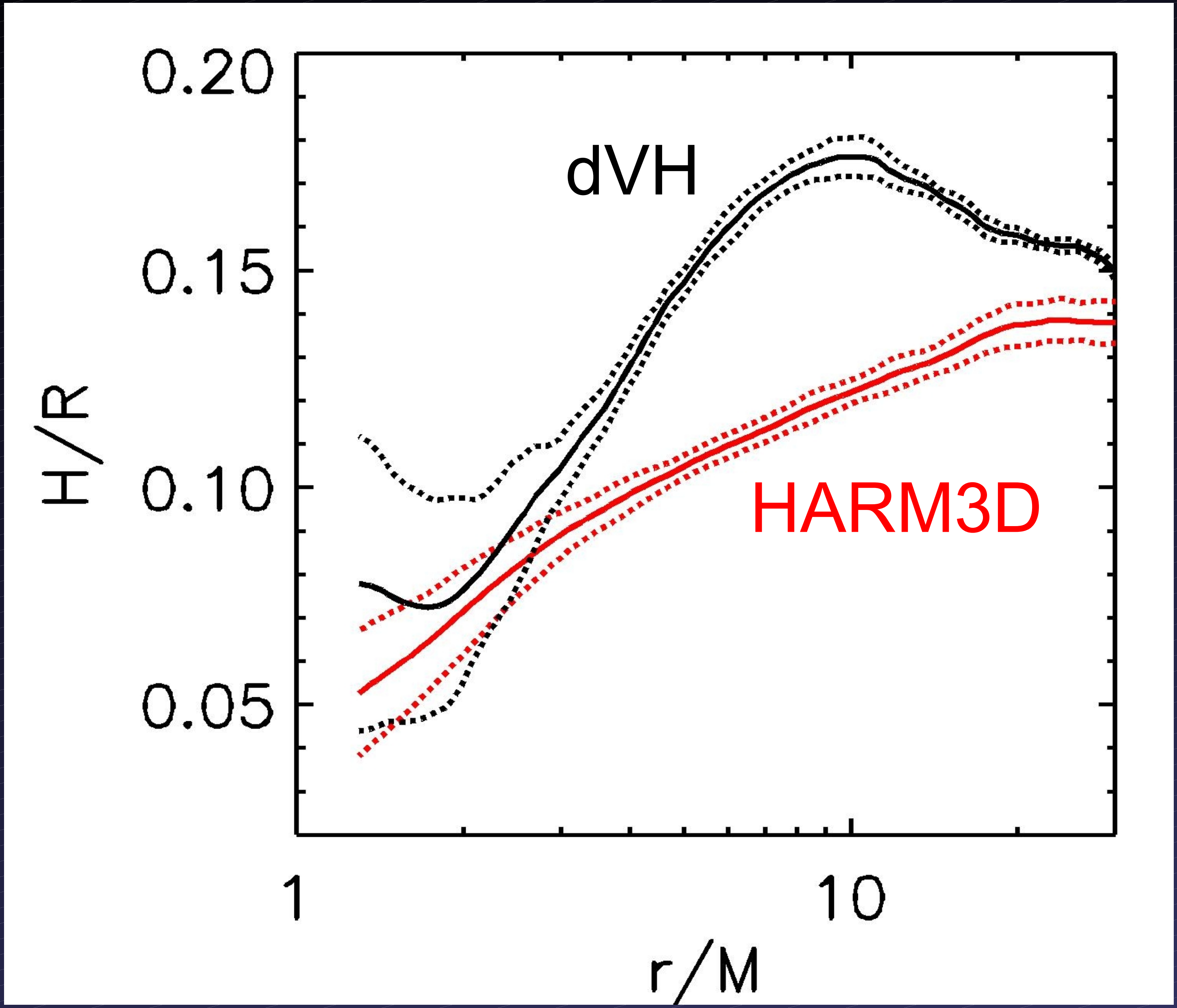
Steady State Region = Horizon – 12M

Target Temperature



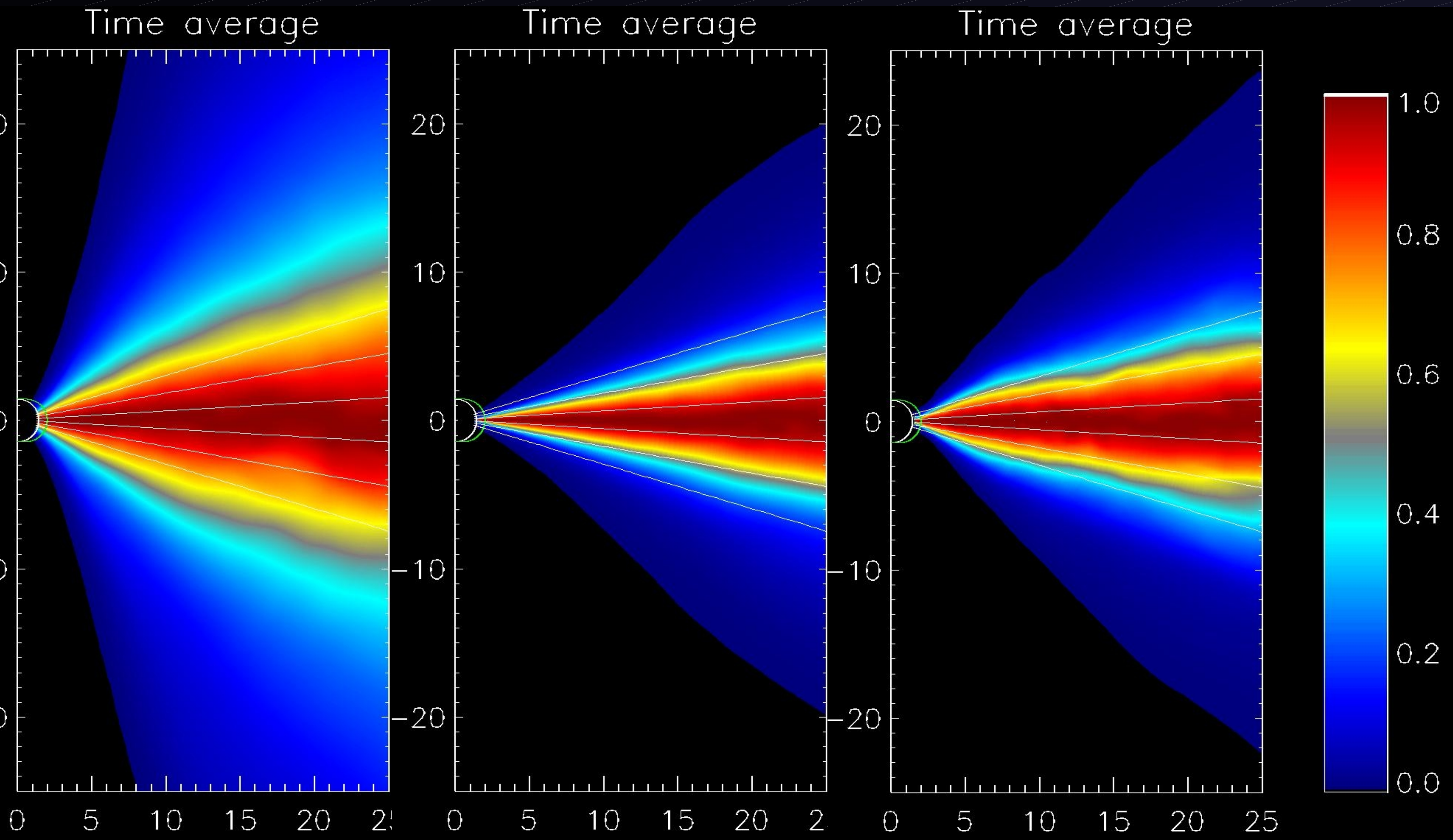
- Reaching to within 5% of Target Temperature
- Cooling Rate >~ Diss. Rate

Disk Thickness



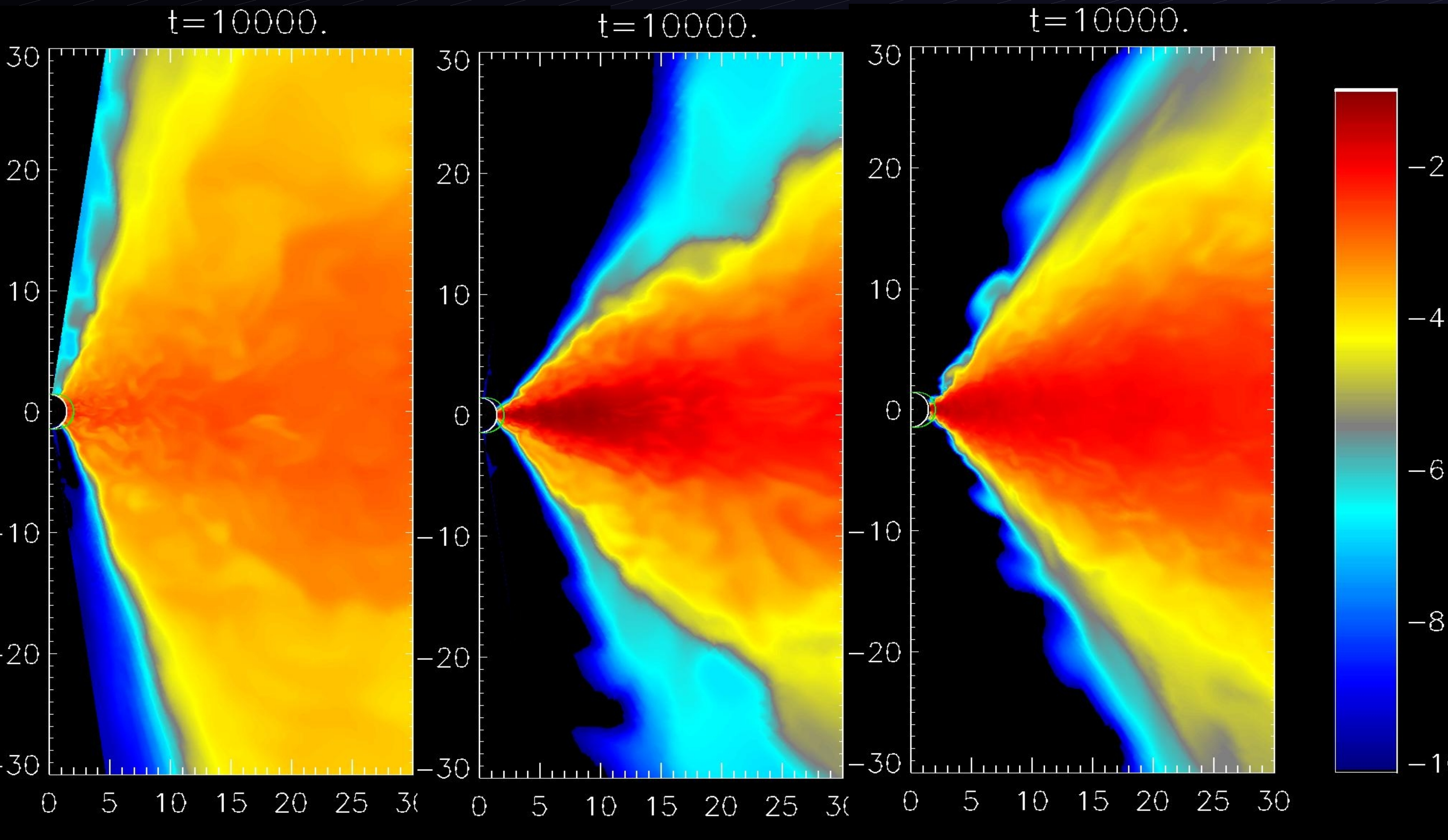
HARM3D vs. dVH

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



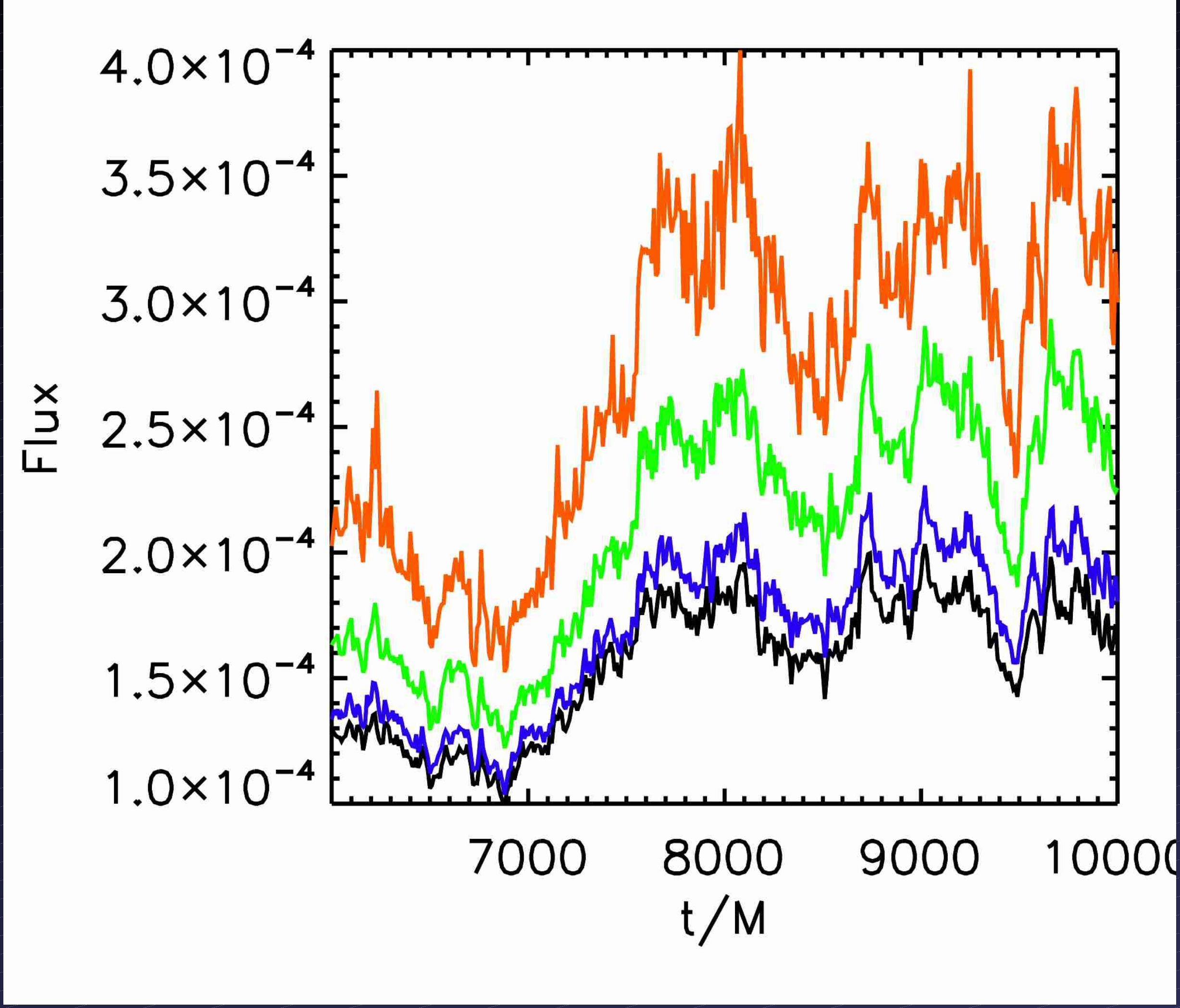
Uncooled **Cooled** **dVH**

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



Uncooled **Cooled** **dVH**

Variability of Dissipated Flux



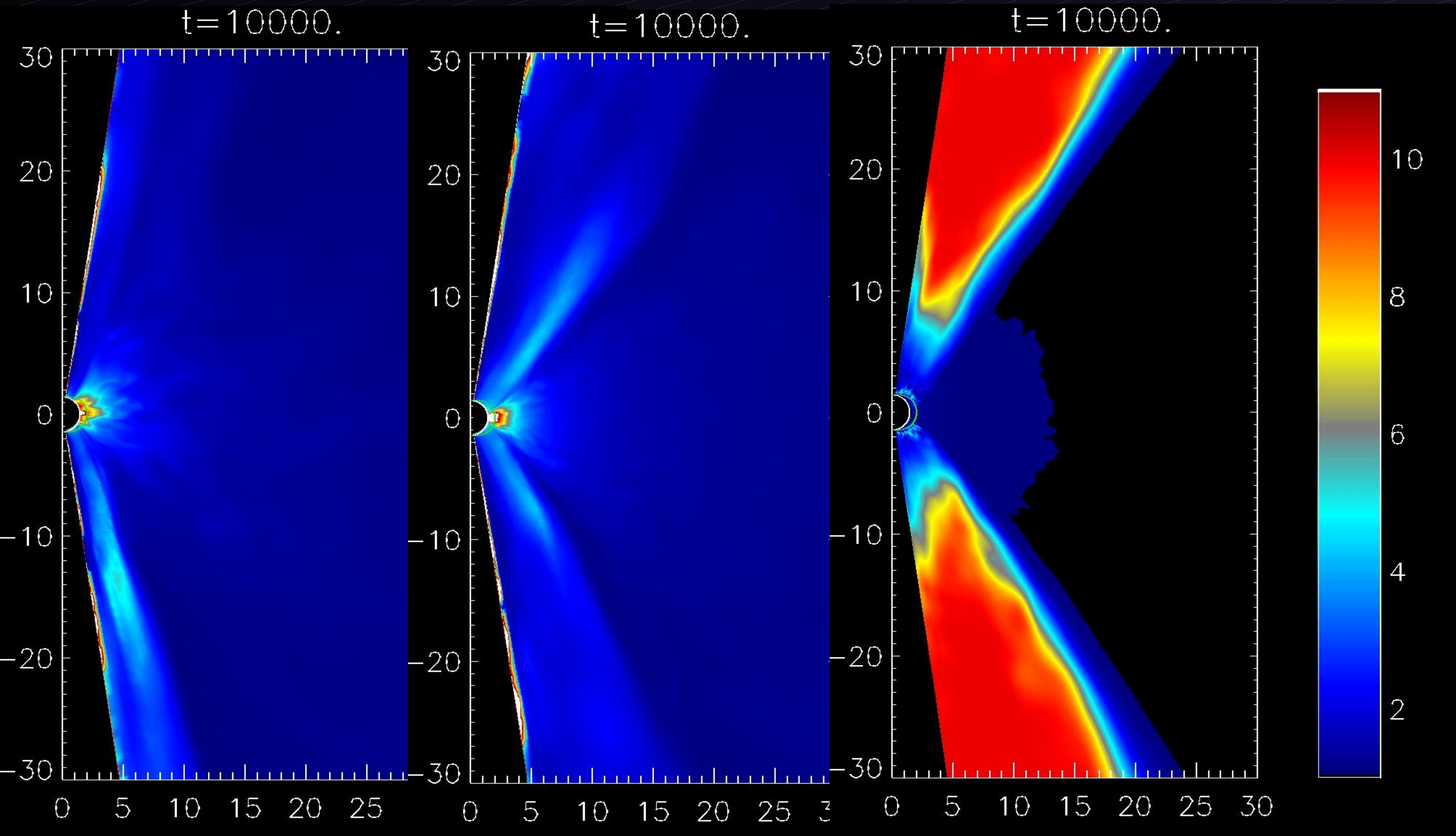
$\theta = 5\, deg.$

$\theta = 35\, deg.$

$\theta = 65\, deg.$

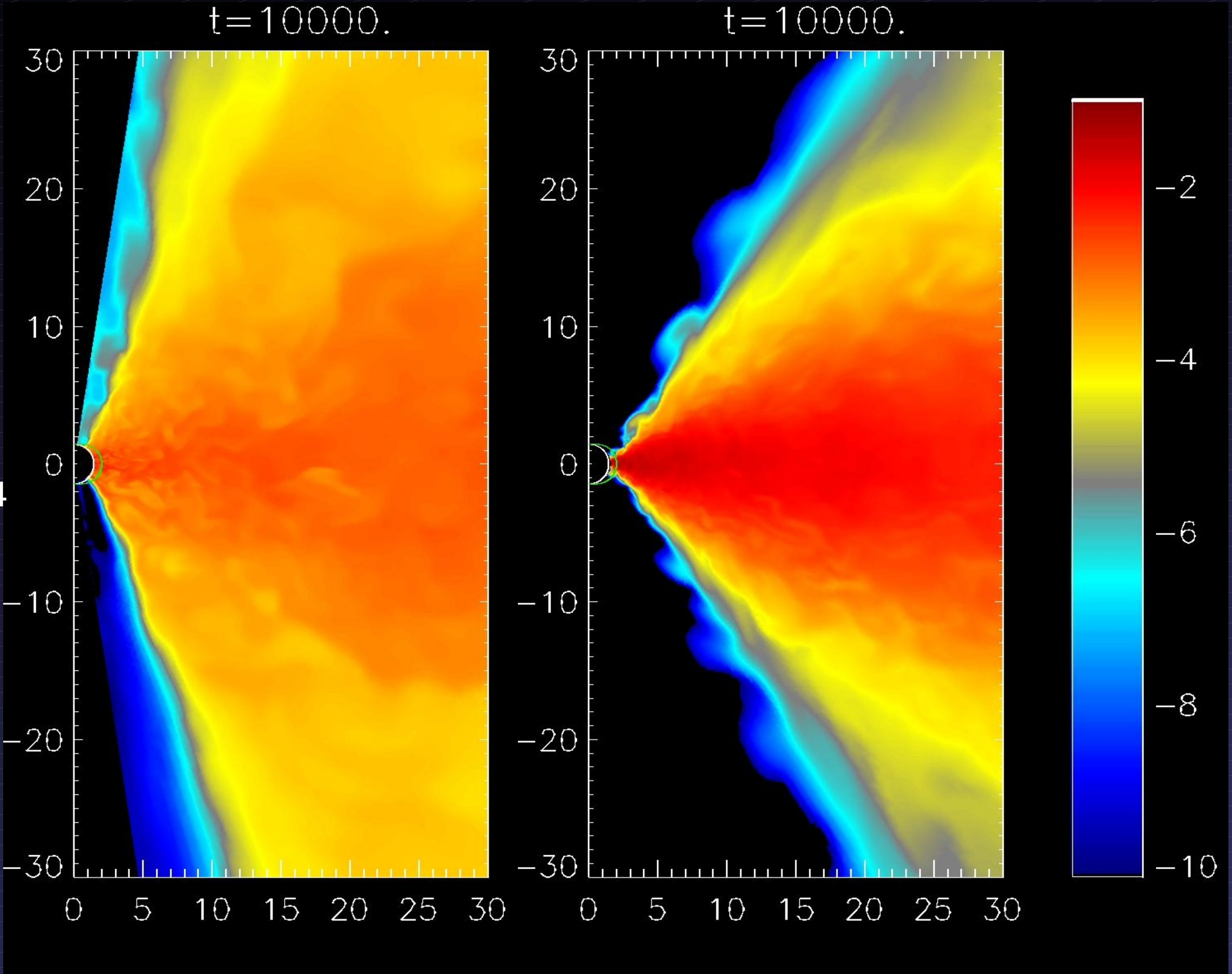
$\theta = 89\, deg.$

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



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

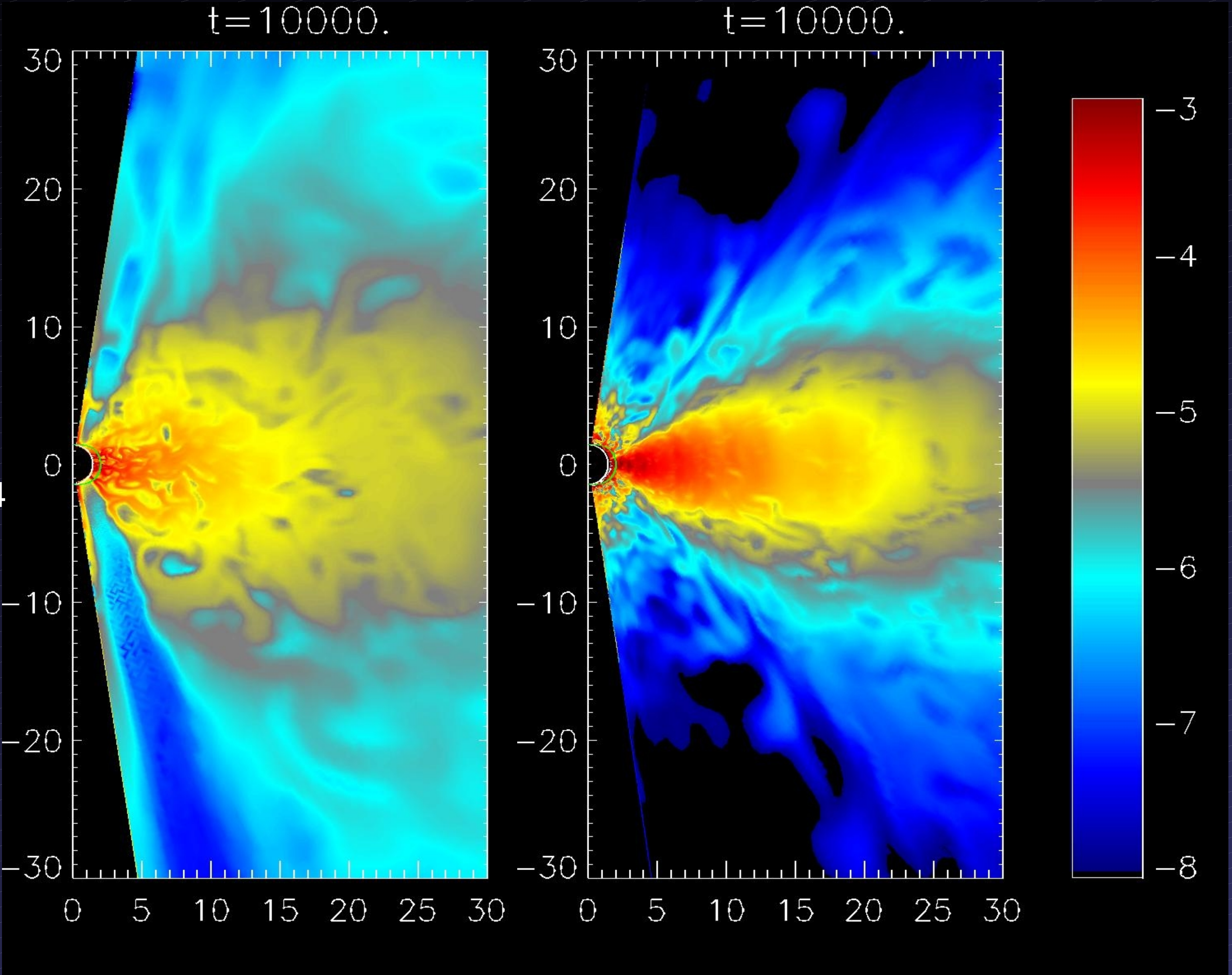
HARM3D vs. dVH $\log(\rho)$



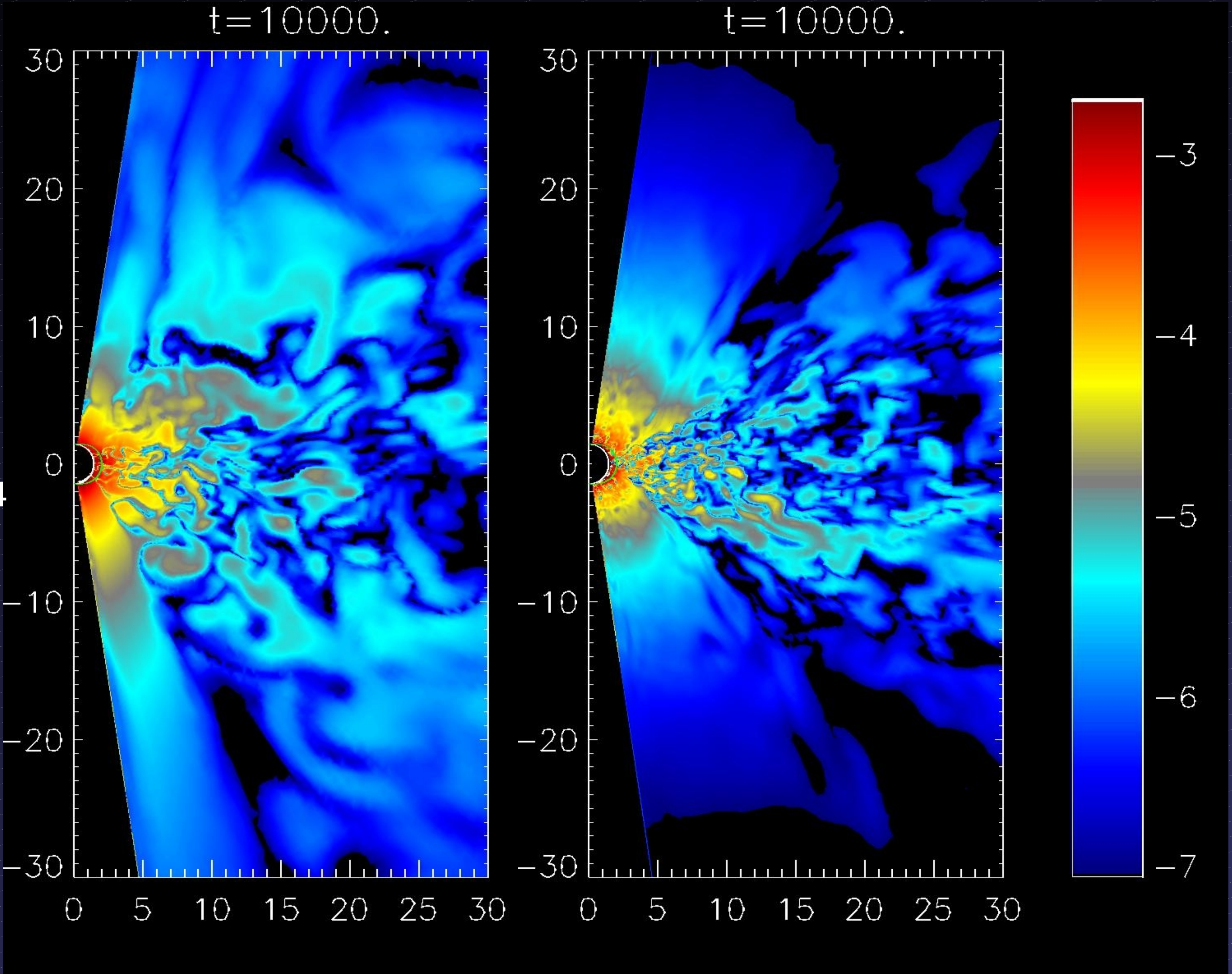
192x192x64
a = 0.9 M

HARM3D vs. dVH $\log(P)$

192x192x64
a = 0.9 M

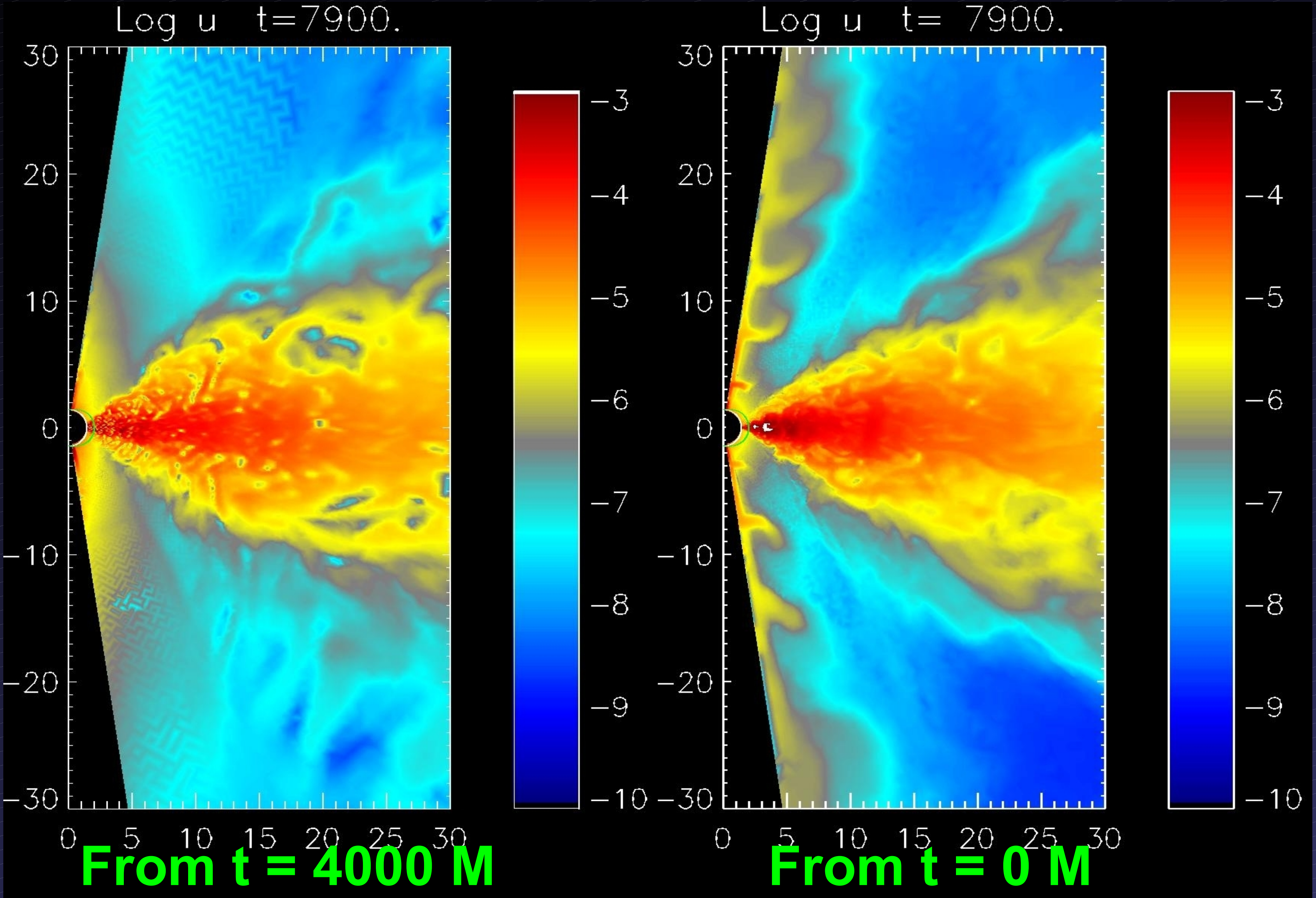


HARM3D vs. dVH $\log(P_{mag})$

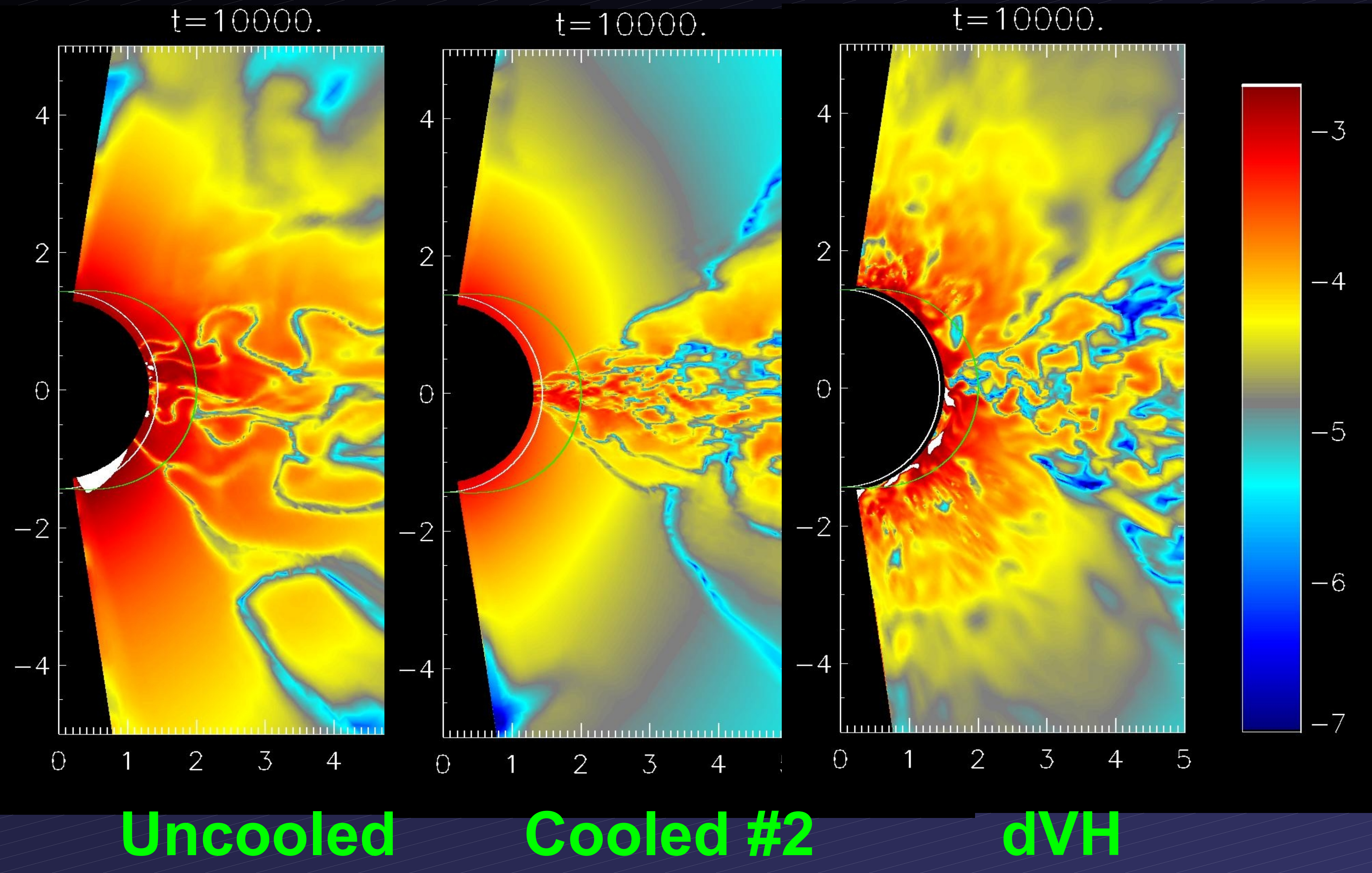


192x192x64
a = 0.9 M

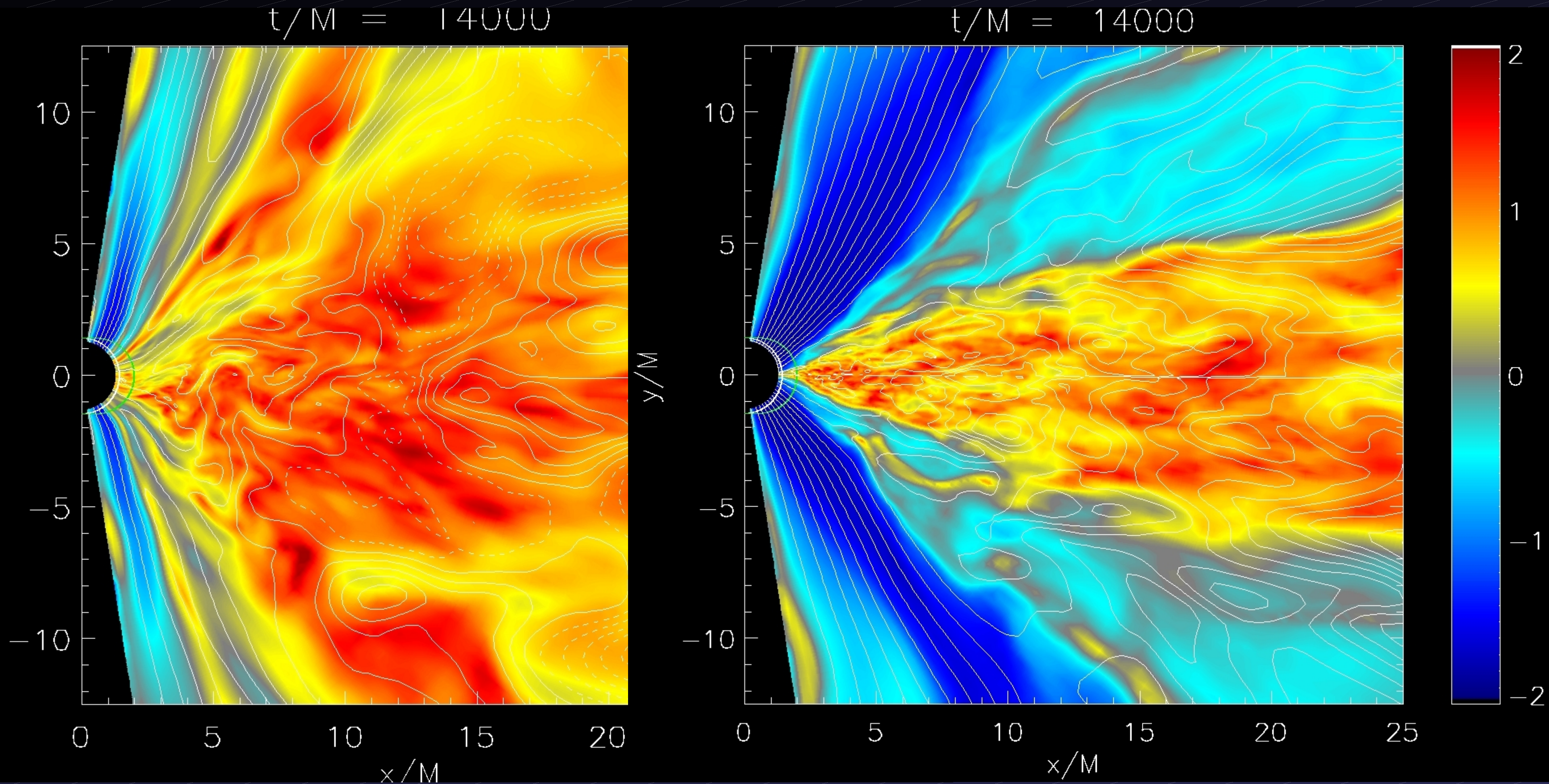
Cooled #1 vs. Cooled #2 $\log(P)$



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



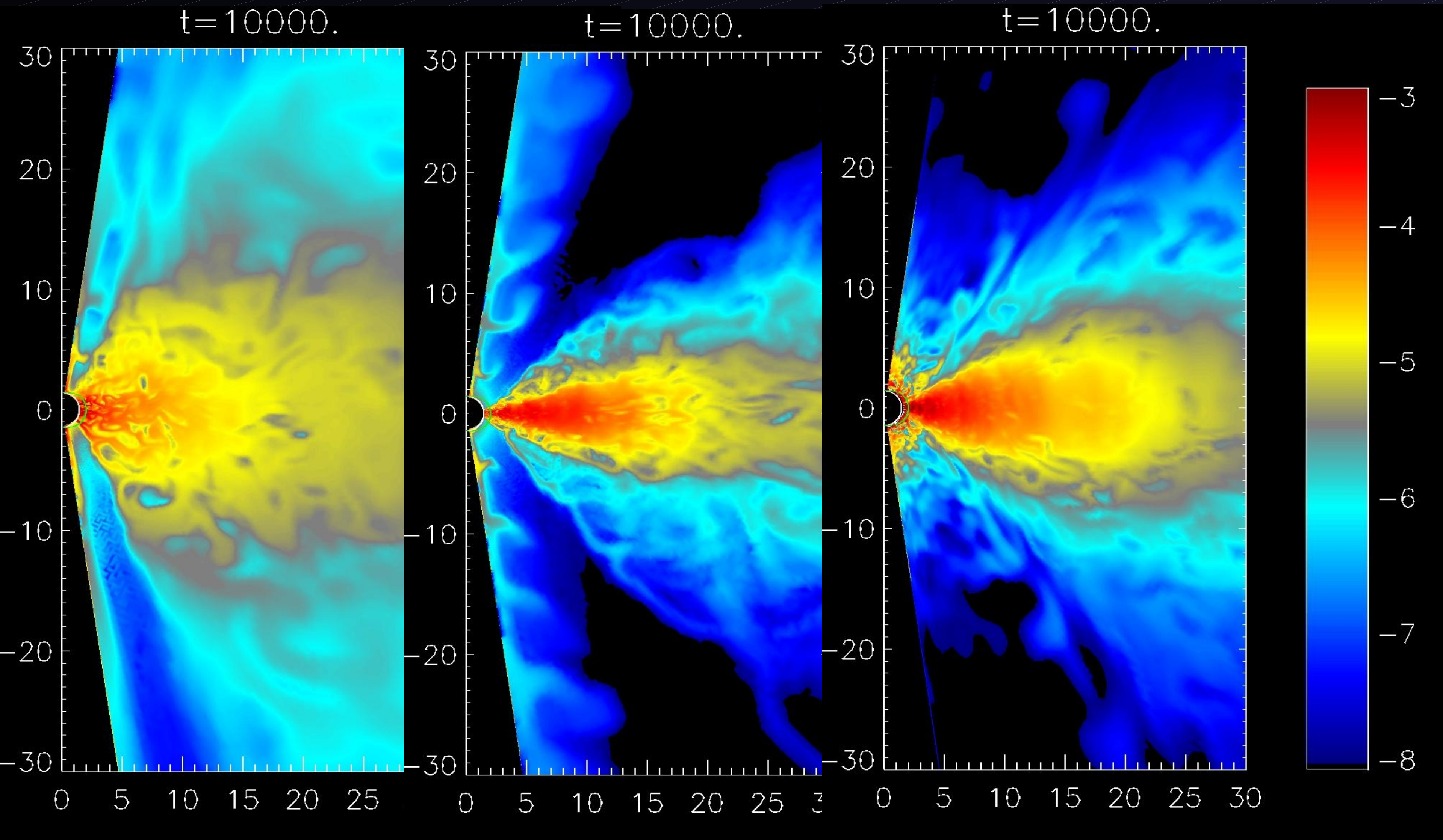
HARM3D vs. dVH $\log(\beta)$



Uncooled

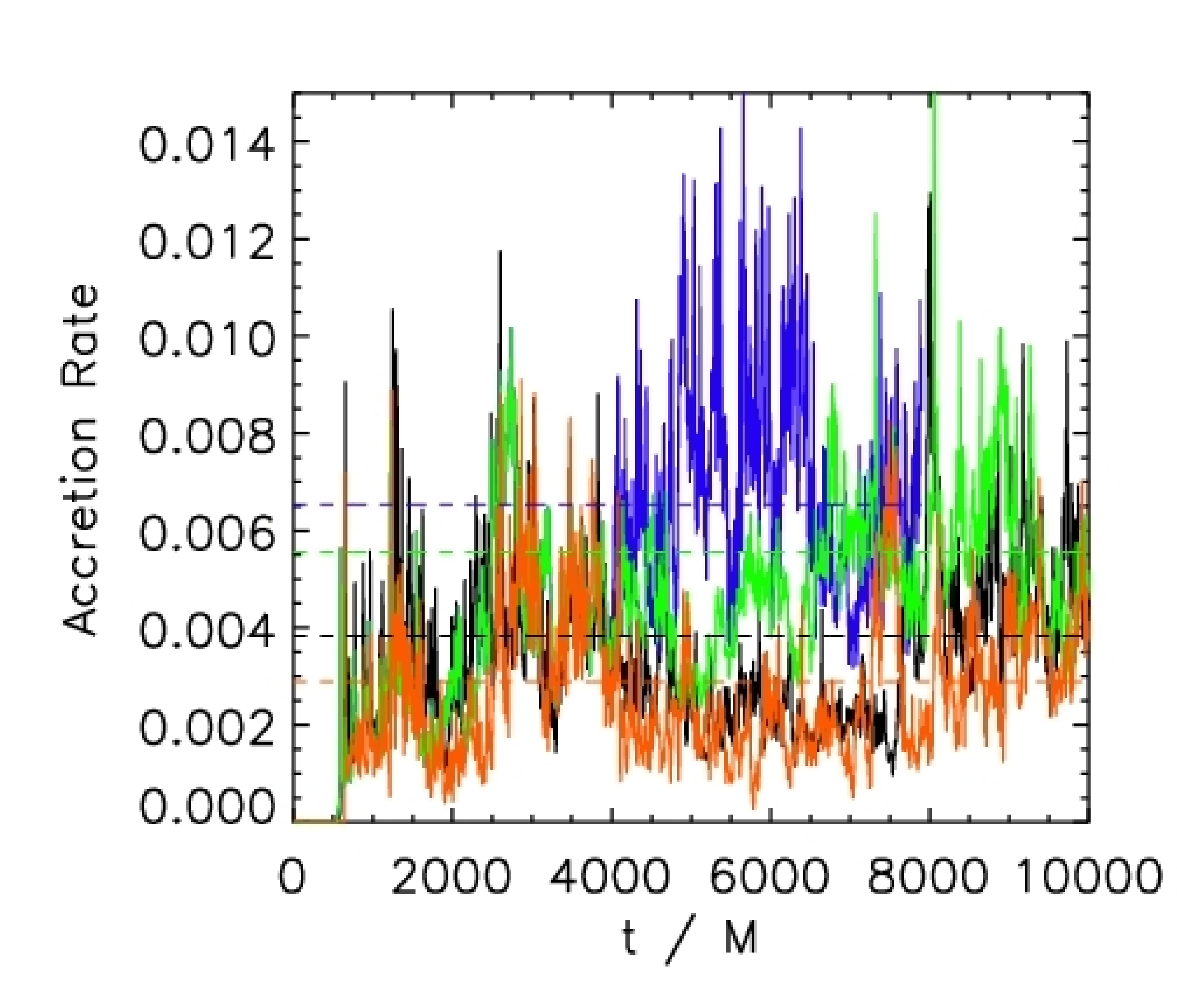
Cooled #2

HARM3D vs. dVH $\log(P)$



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

HARM3D vs. dVH $\dot{M}$



Cooled from t=0M

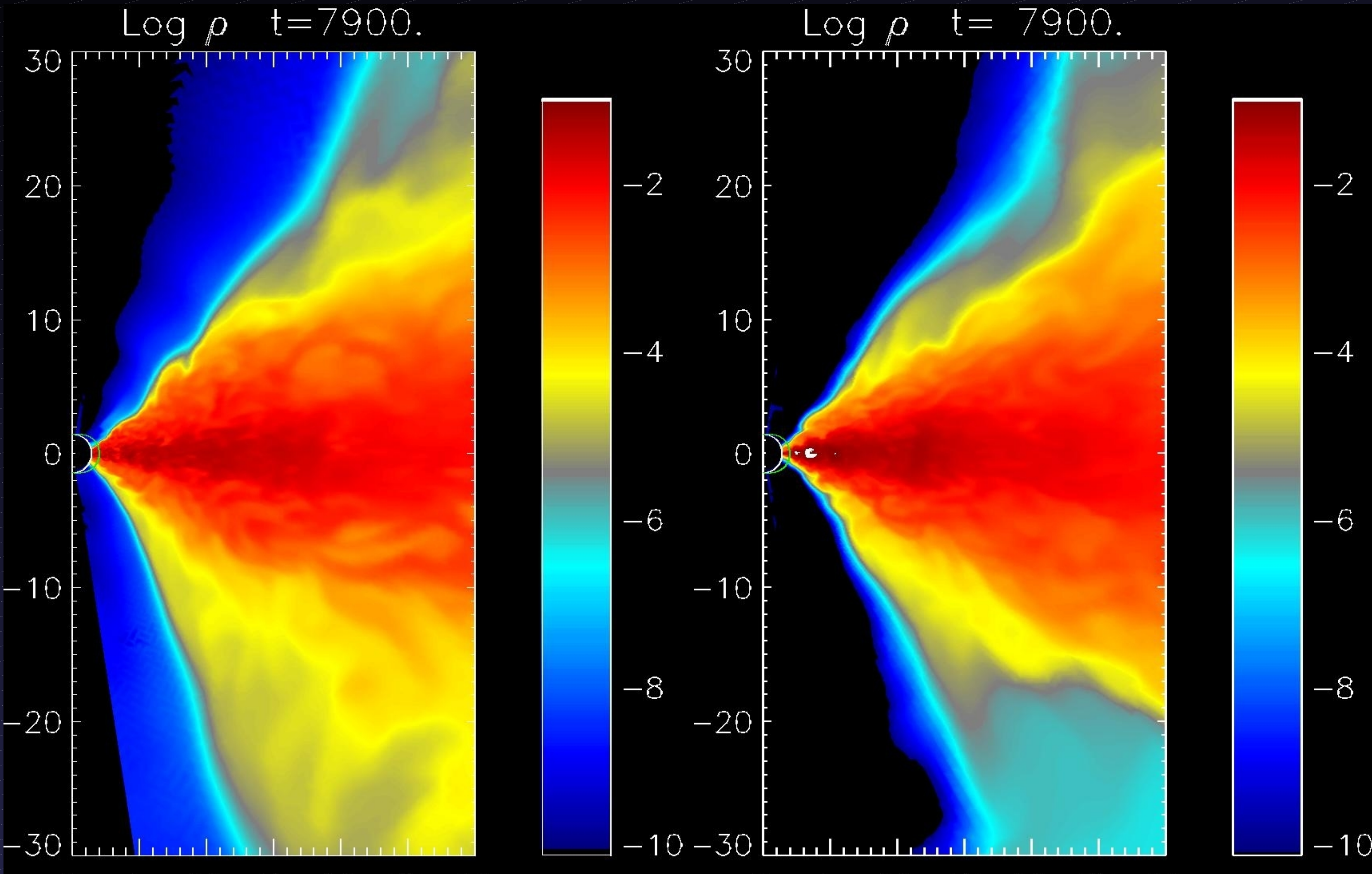
Cooled from t=4000M

Uncooled

Non-conservative

Cooling Methods

$\log(\rho)$

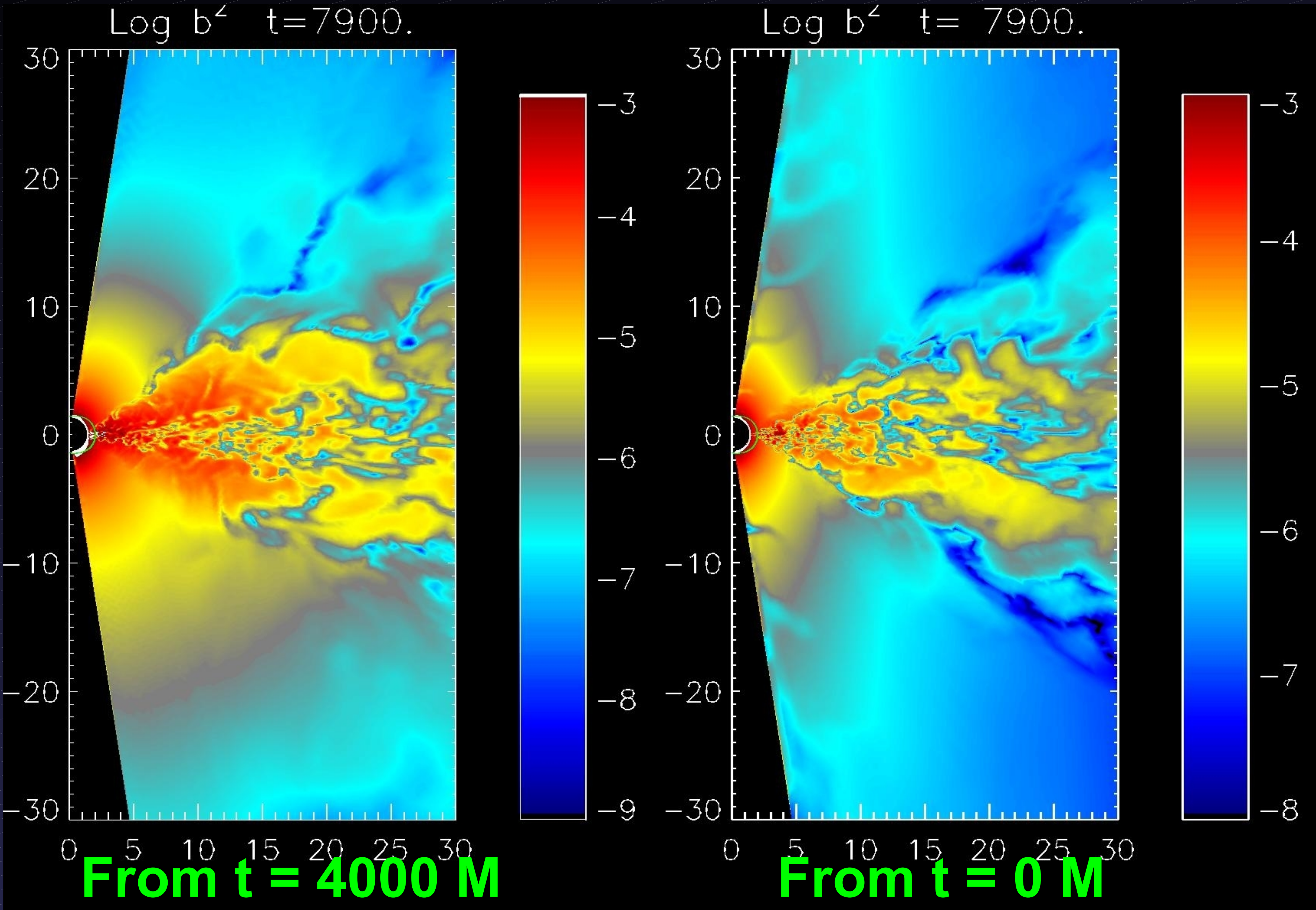


From t = 4000 M

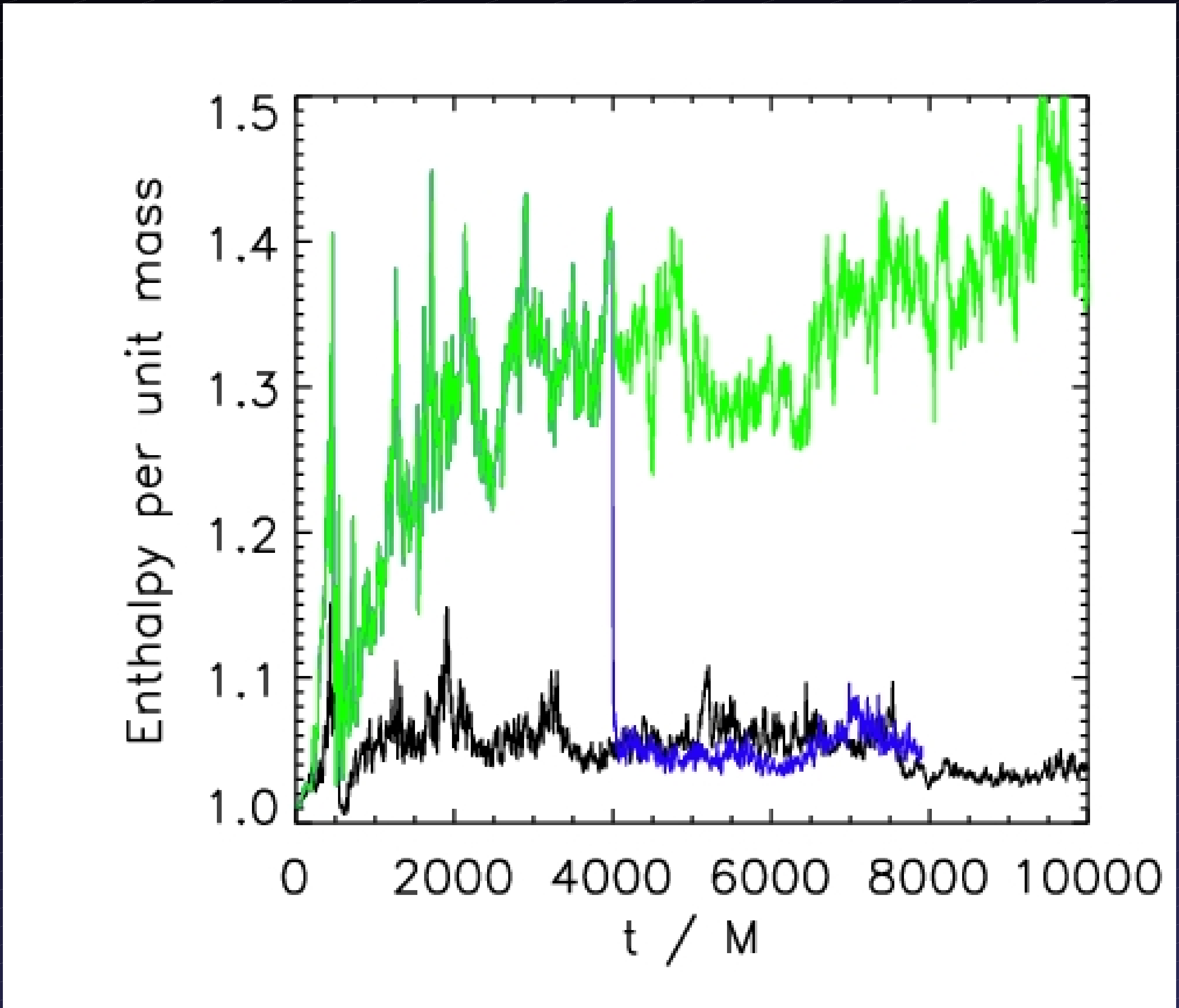
From t = 0 M

Cooling Methods

$\log\left(P_{mag}\right)$



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

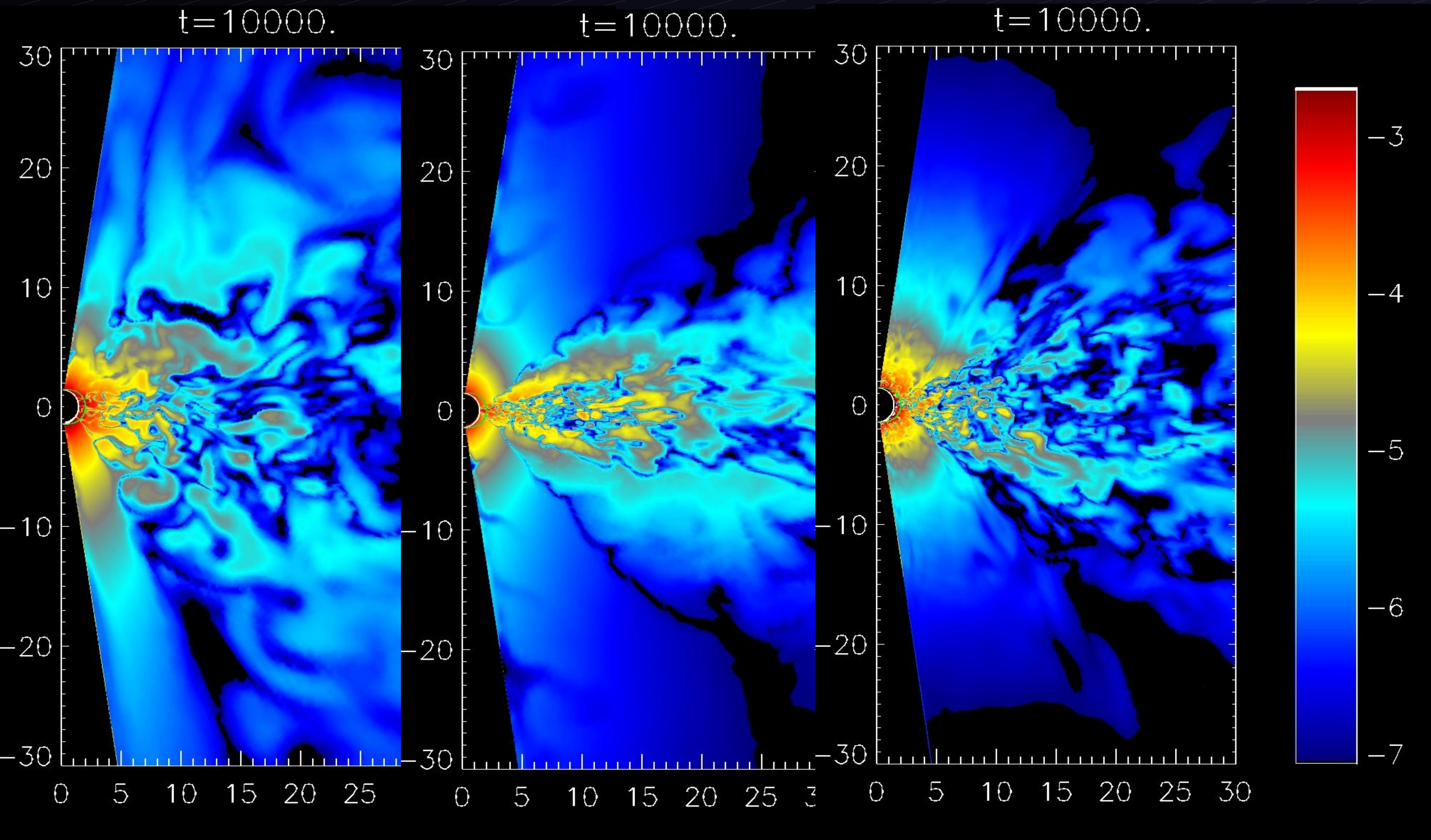
[a] Values adopted in this Letter.

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

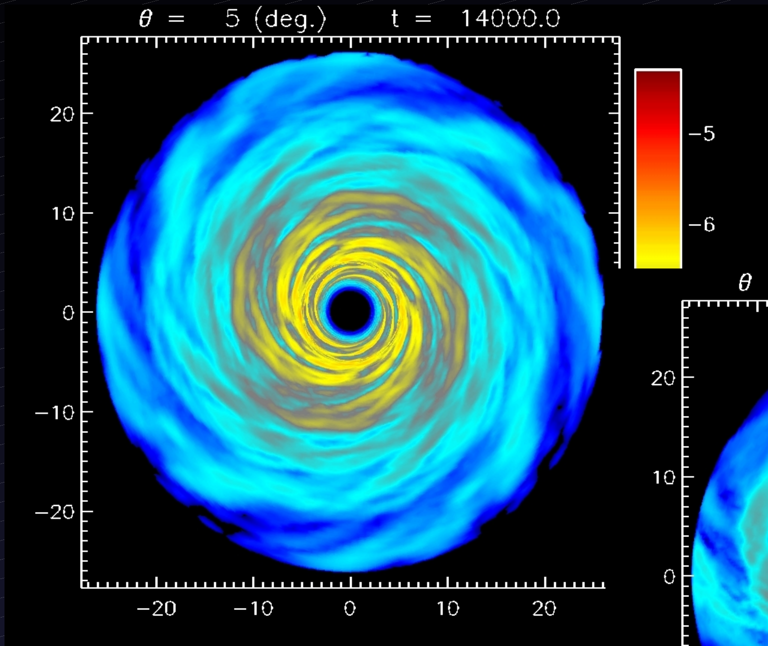
McClintock et al. (2006)

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

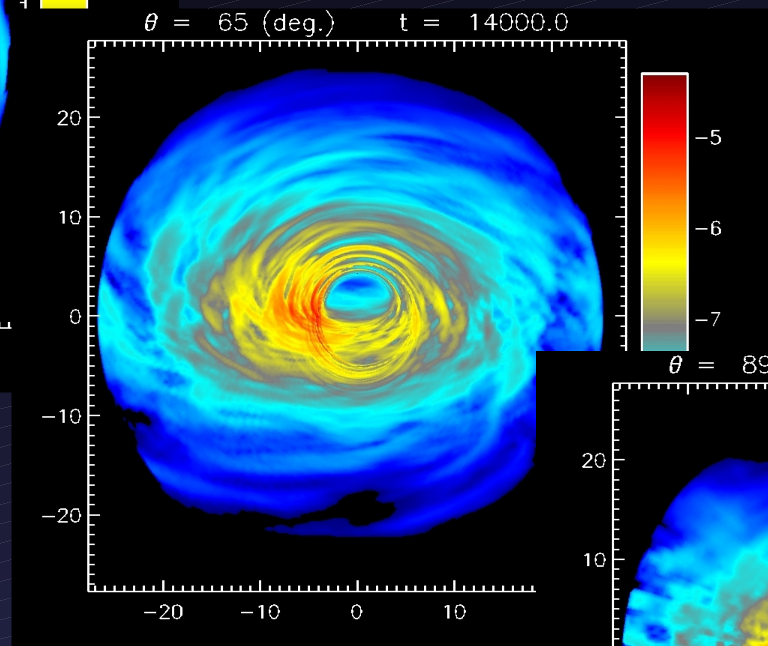


Uncooled **Cooled** **dVH**

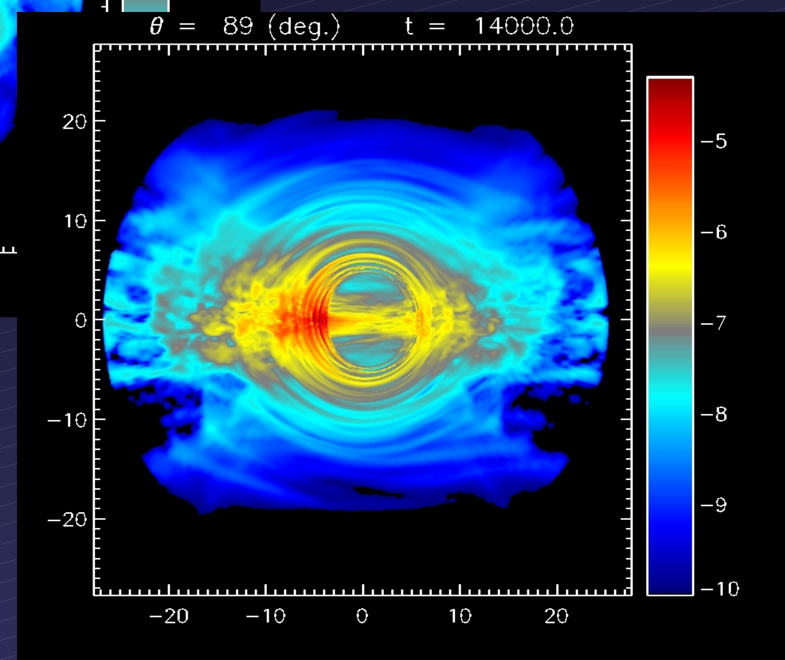
Observer-Frame Intensity: Inclination



i=5°

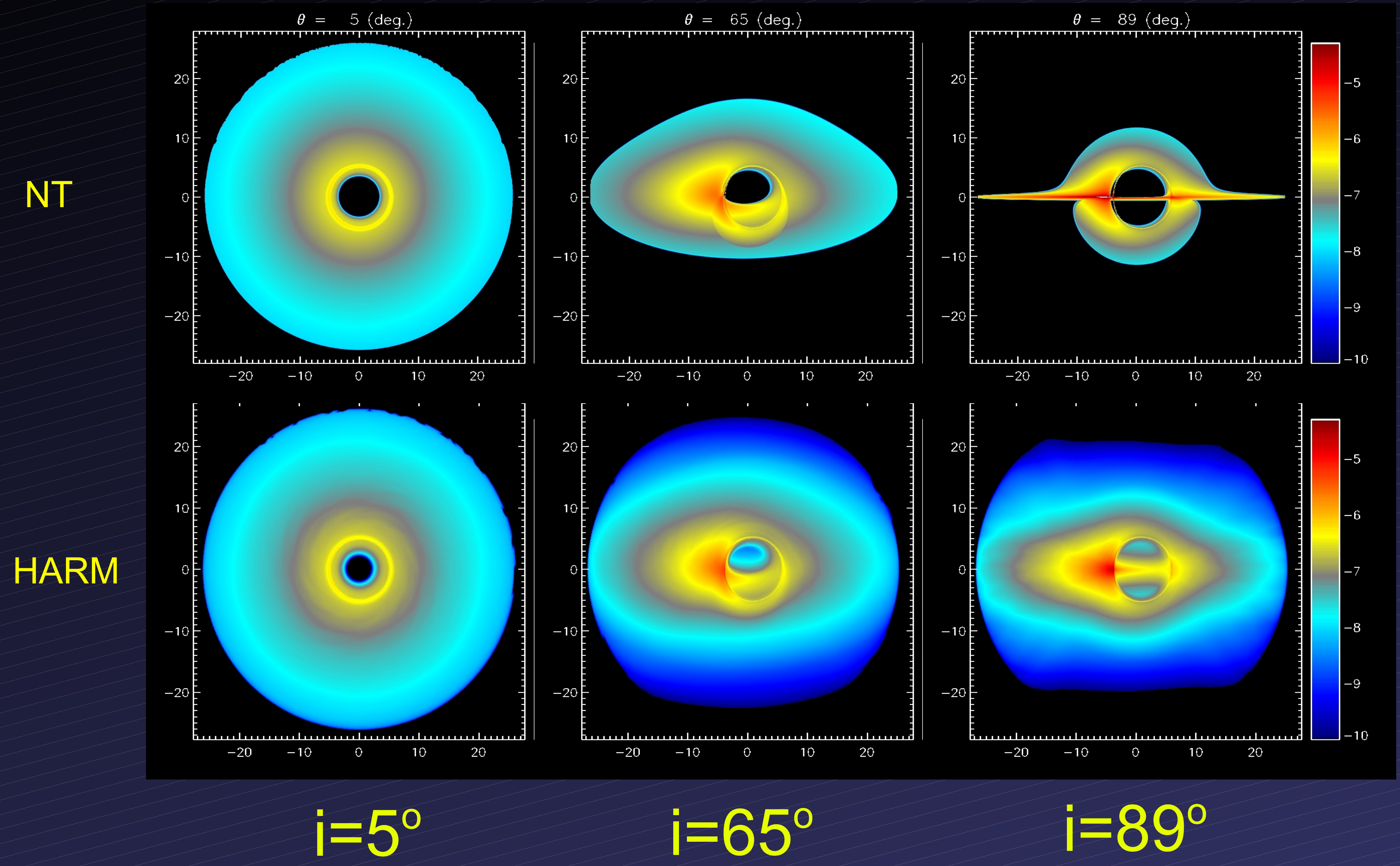


i=65°



i=89°

Observer-Frame Intensity: Time Average



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:

$$f_{c} = s\,\Omega\,u\left(\Delta - 1 + |\Delta - 1|\right)^{q} \qquad = 0 \;\; for\ \Delta < 0$$

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