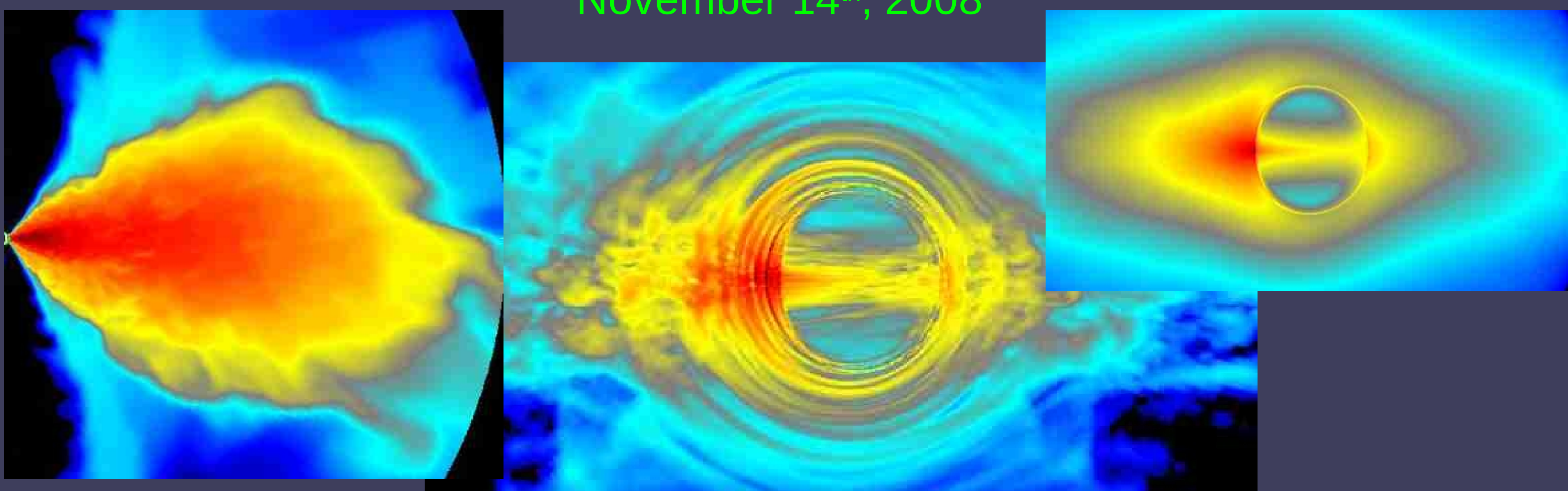
Calculating the Radiative Efficiency of Thin Disks with 3D GRMHD Simulations

Scott C. Noble, Julian H. Krolik (JHU)
John F. Hawley (UVa)

Gravity Group Astrophysics/Cosmology Lunch
Princeton U.
November 14th, 2008

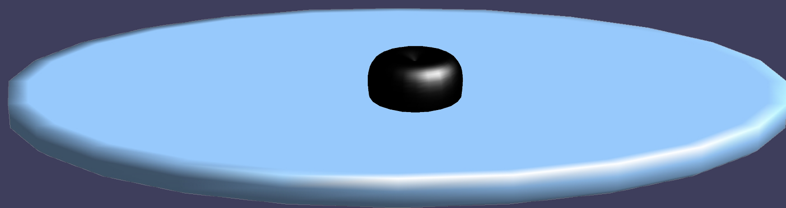


Astrophysical Disks

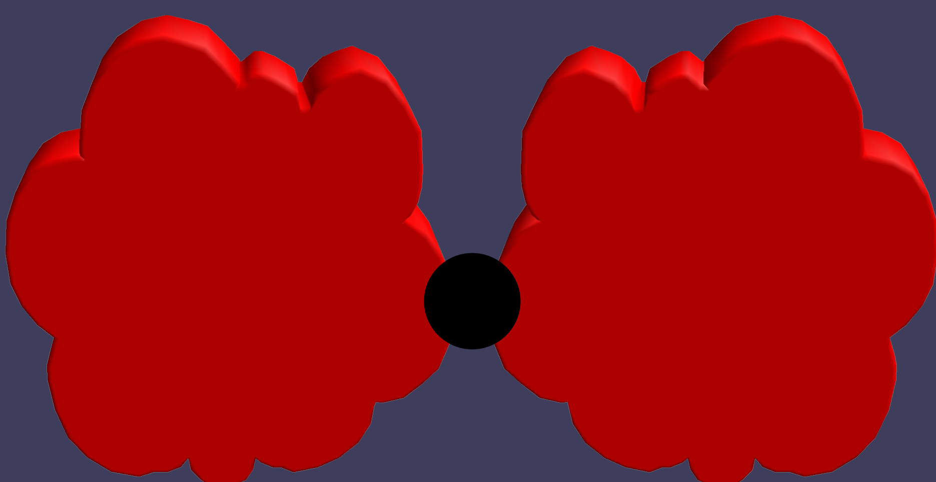
Disk Type	Gravity Model
Galaxies, Stellar Disks, Planetary Disks	Newtonian
X-ray binaries, AGN	Stationary metric
Collapsars, SN fall-back disks	Full GR

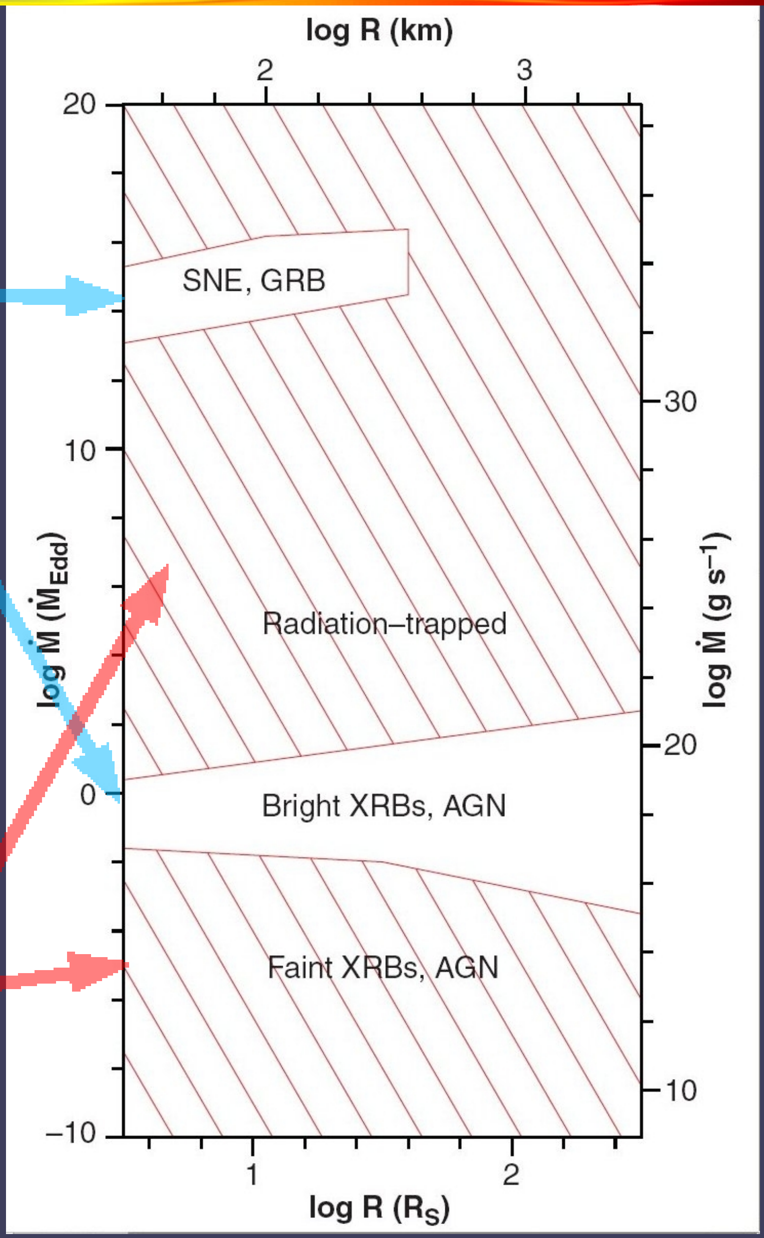
Radiative Efficiency of Disks

- Radiatively Efficient (thin disks)



- Radiatively Inefficient (thick disks)





Narayan & Quataert (2005)

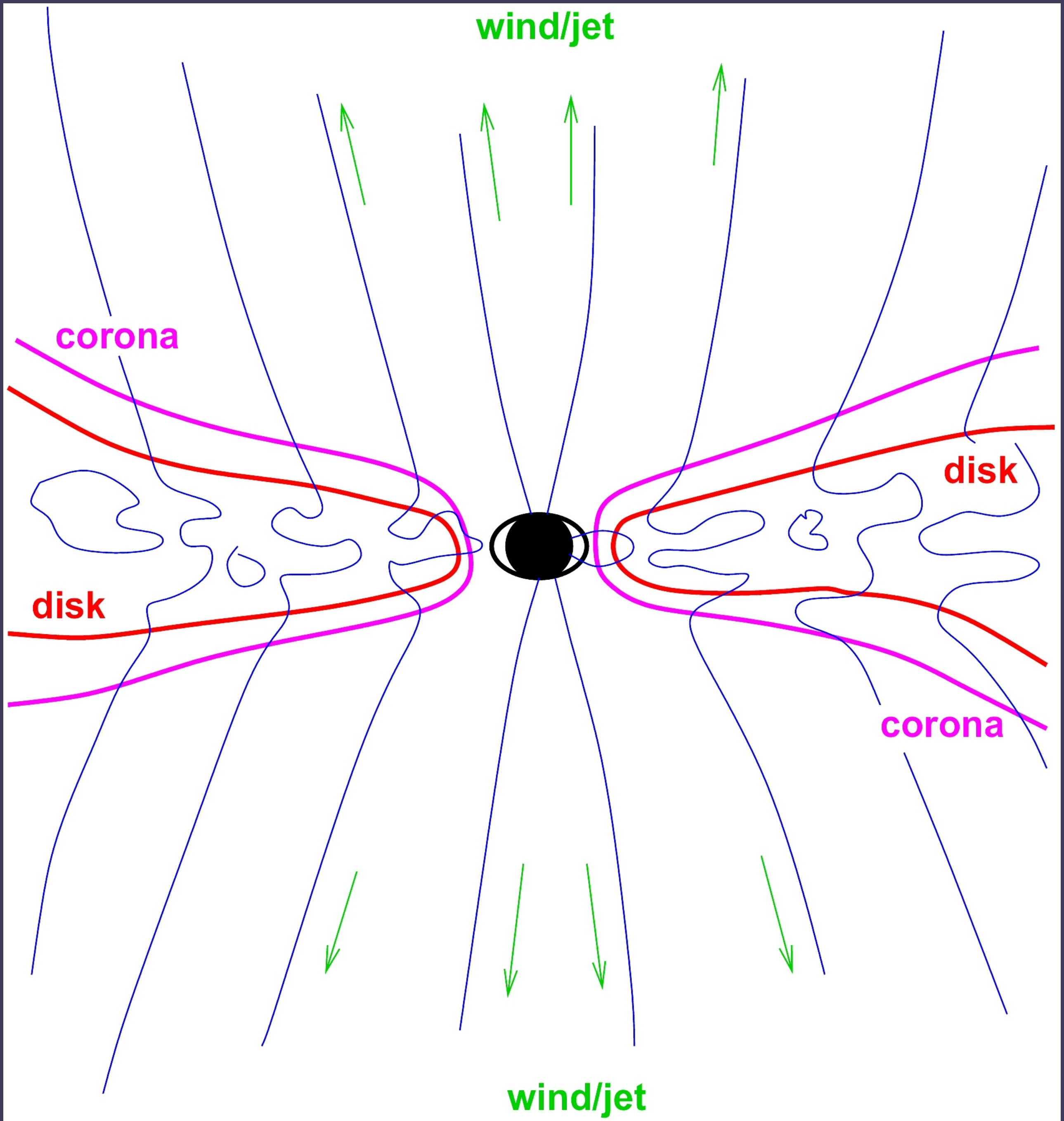


Illustration by
C. Gammie

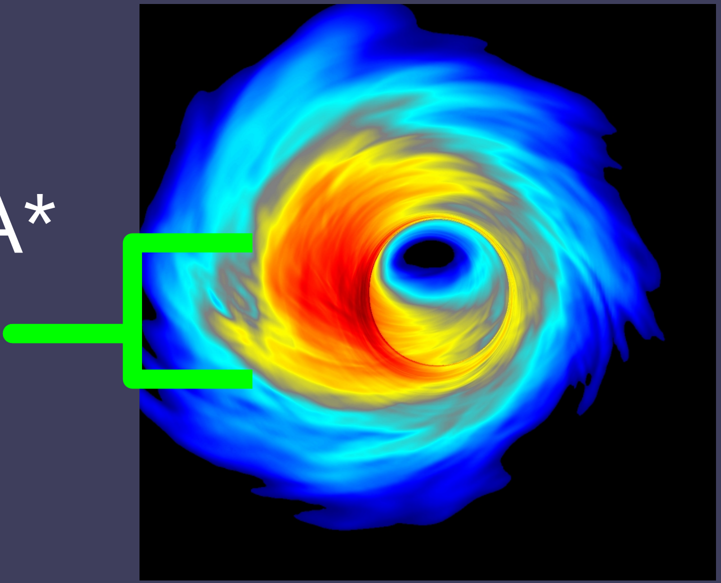
Electromagnetic BH Measurements

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

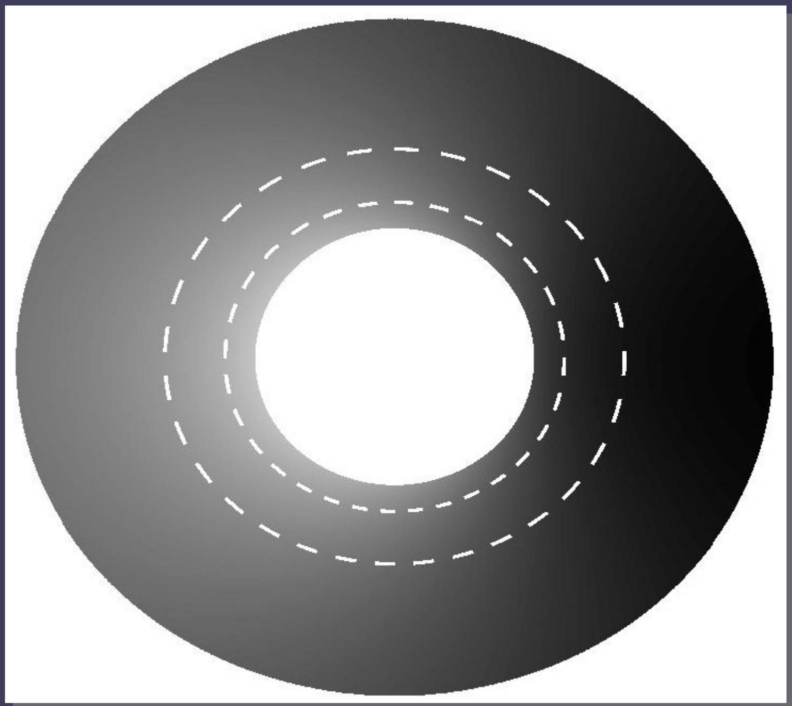
- Spectral Fitting: e.g. Thermal emission

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

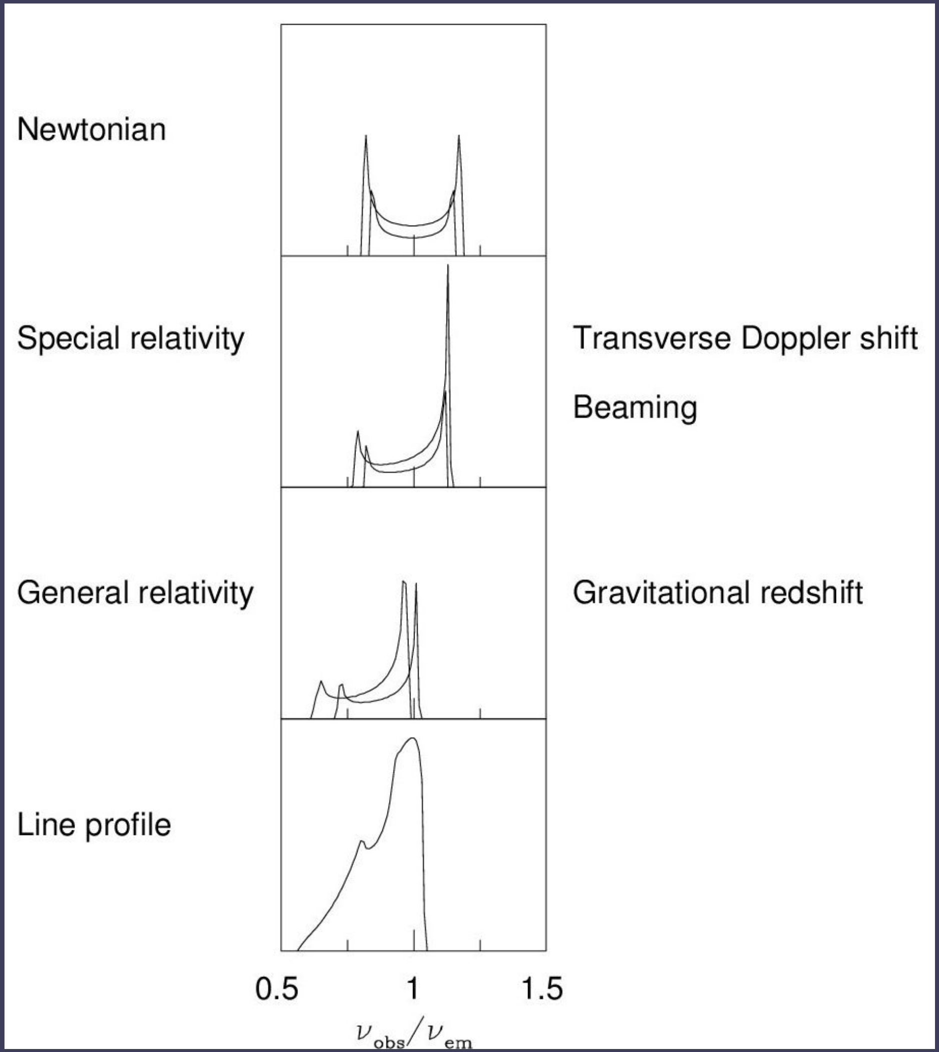
- Directly Resolving
  Event Horizon: e.g., Sgr A*
  - Silhouette size = D(M,a)



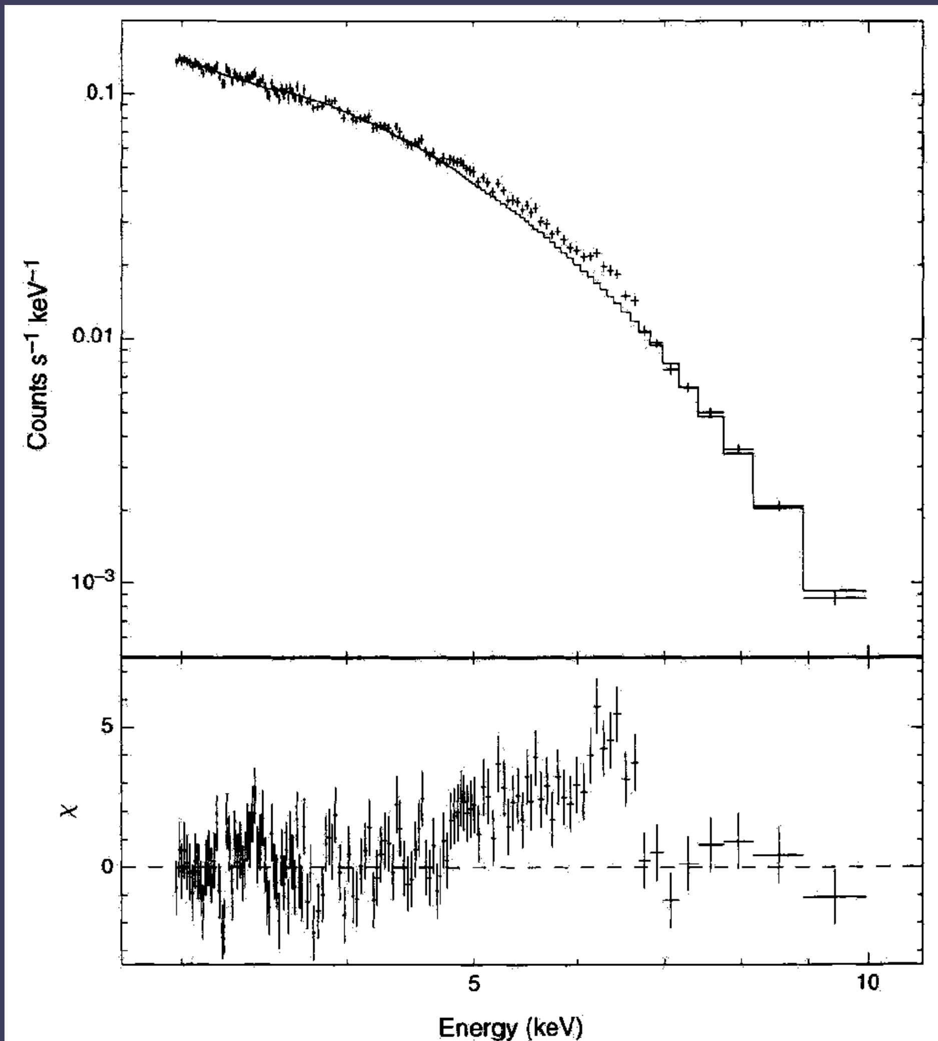
Relativistic Iron-Lines



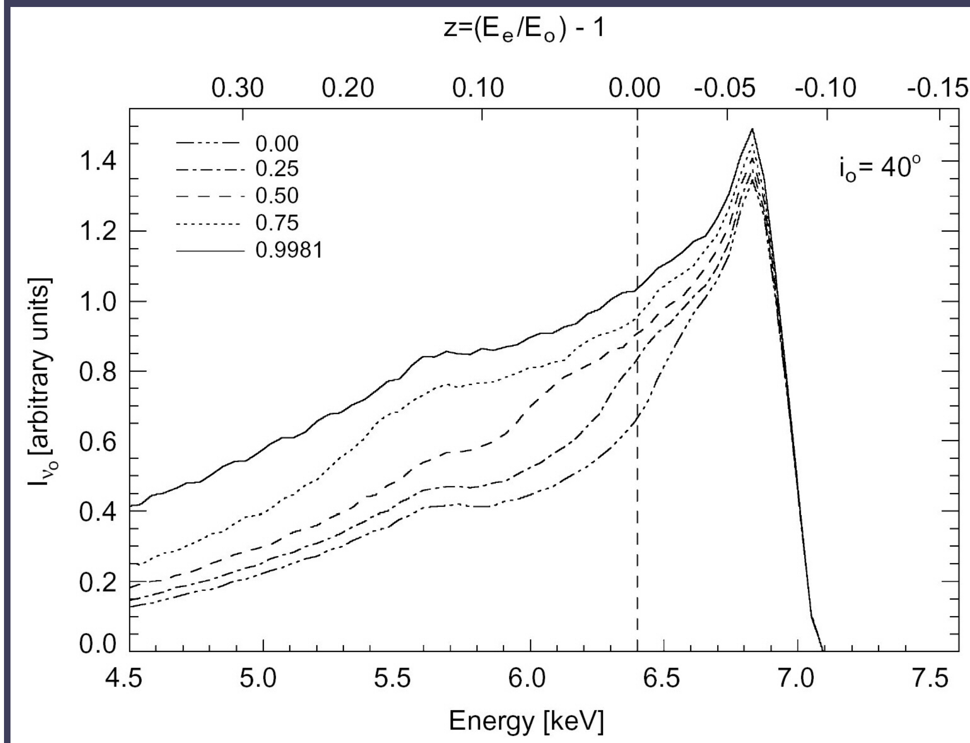
Fabian et al. (2000)



Relativistic Iron-Lines

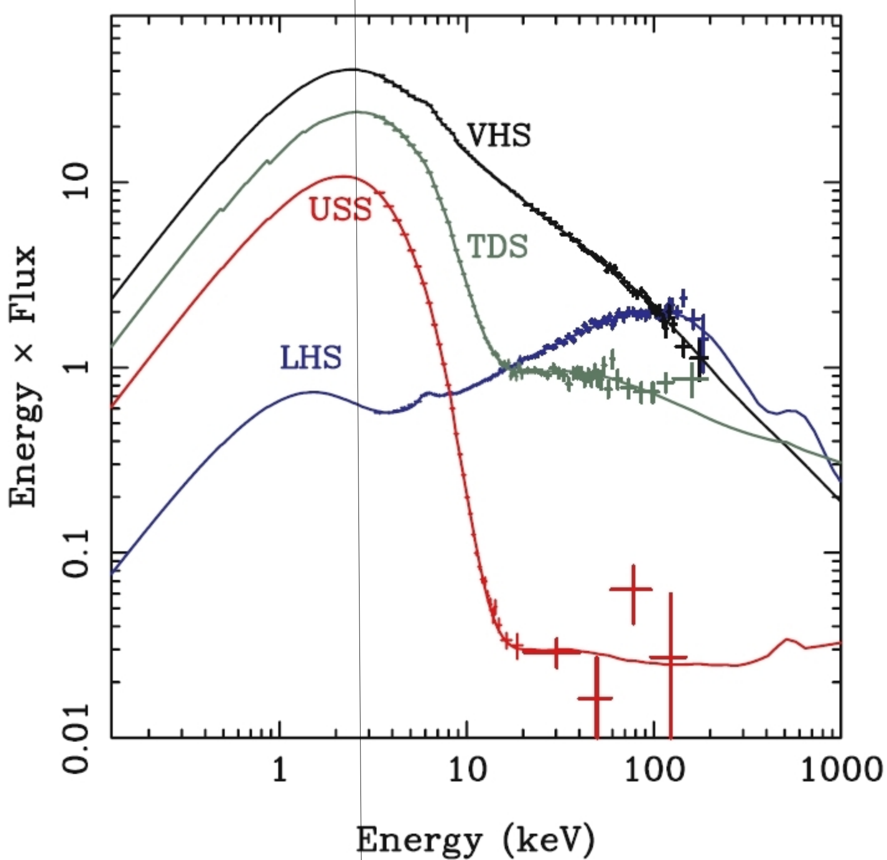


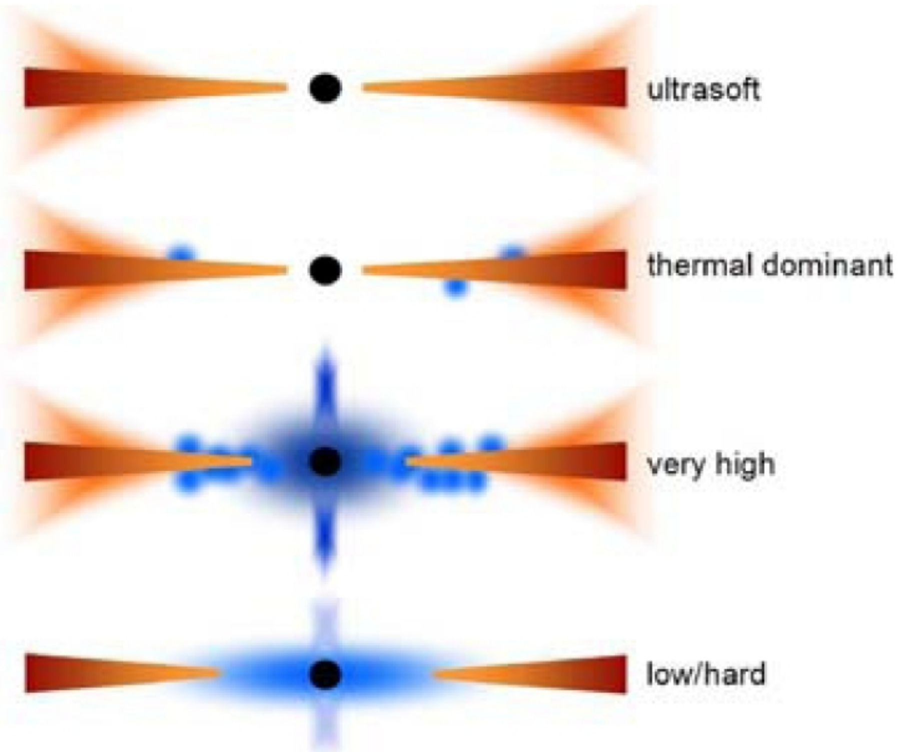
Tanaka et al. (1995)
MCG 6-30-15



Reynolds & Nowak (2003)

Accretion States





T_{max}

Done, Gierlinski & Kubota (2007)

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

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

Spectral Fits for BH Spin

TABLE 1

BLACK HOLE SPIN ESTIMATES USING THE MEAN OBSERVED VALUES OF M, D, AND i

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

[a] Values adopted in this Letter.

Shafee et al. (2006)

OBJECT	POWER LAW	
	Mean	Standard Deviation
GRS 1915+105[a]	0.998	0.001
GRS 1915+105[b]	0.998	0.001

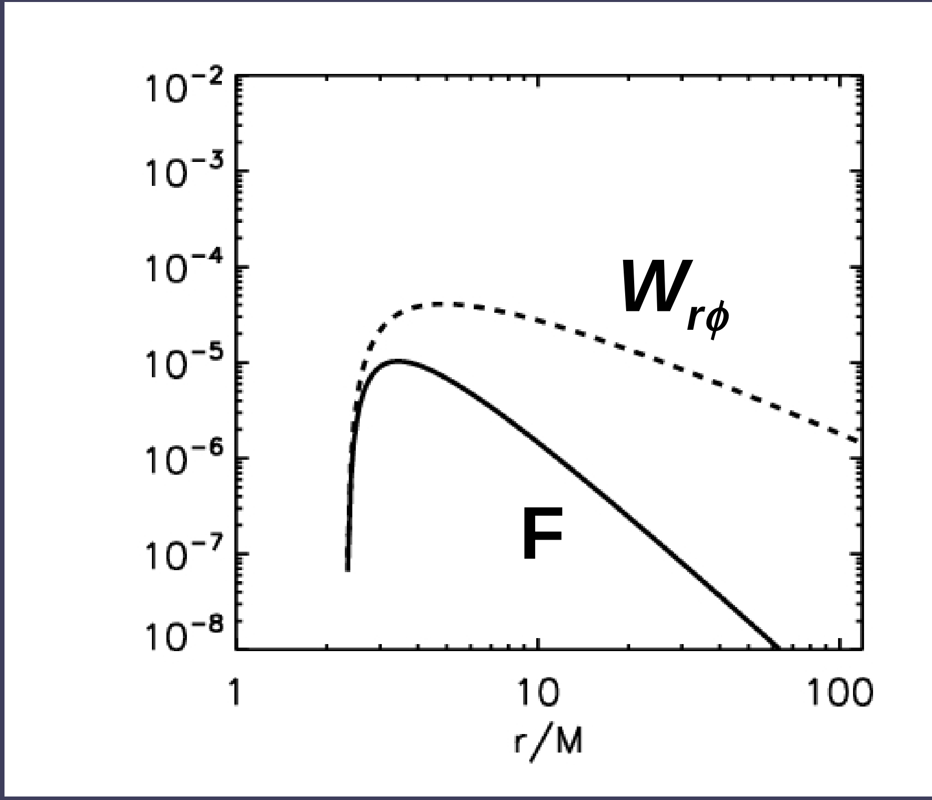
McClintock et al. (2006)

Steady-State Models: Novikov & Thorne (1973)

Assumptions:

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

(Thorne 1974, Page & Thorne 1974)



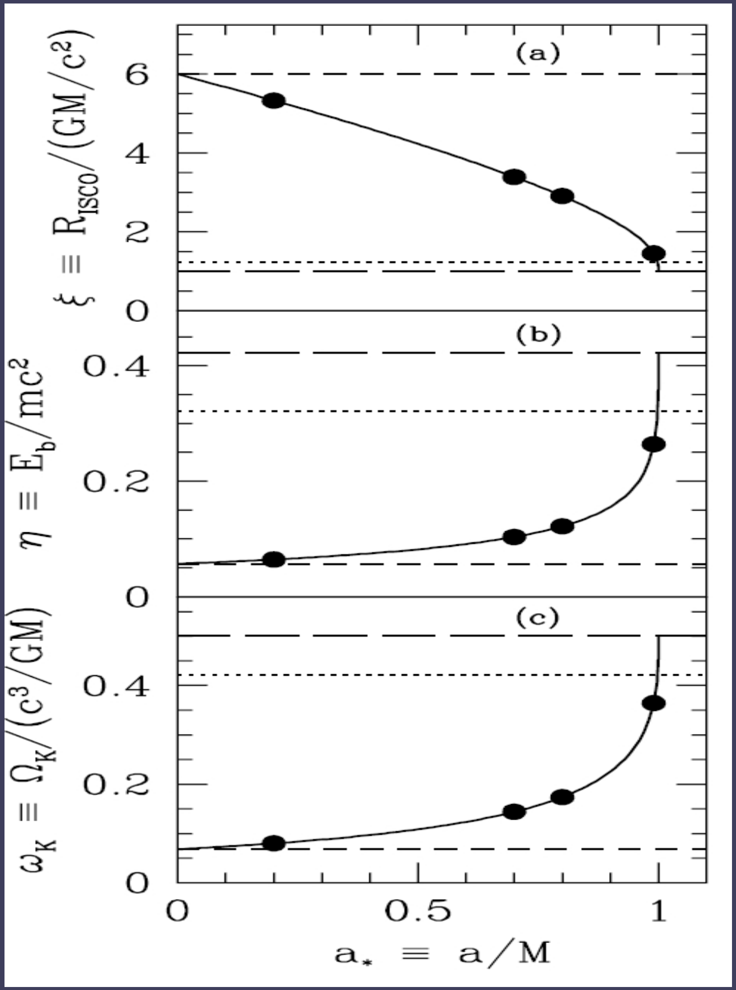
$$\eta = 1 - \dot{E}/\dot{M}$$
$$= 1 - \epsilon_{ISCO}$$

Steady-State Models: Novikov & Thorne (1973)

Assumptions:

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

   (Thorne 1974, Page & Thorne 1974)



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

Steady-State Models: α Disks

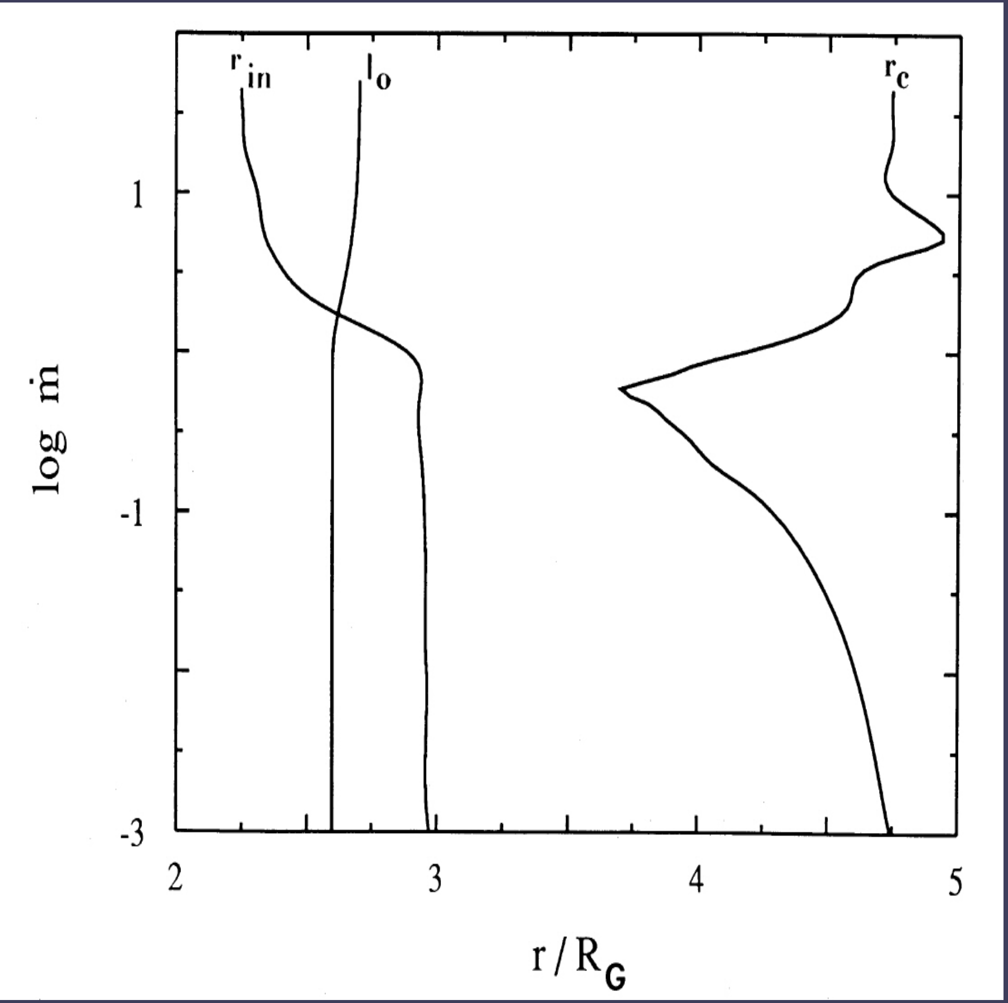
- Shakura & Sunyaev (1973):

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

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

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

  (Schwarzschild BHs)



Abramowicz, et al. (1988)

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

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

Steady-State Models: α Disks

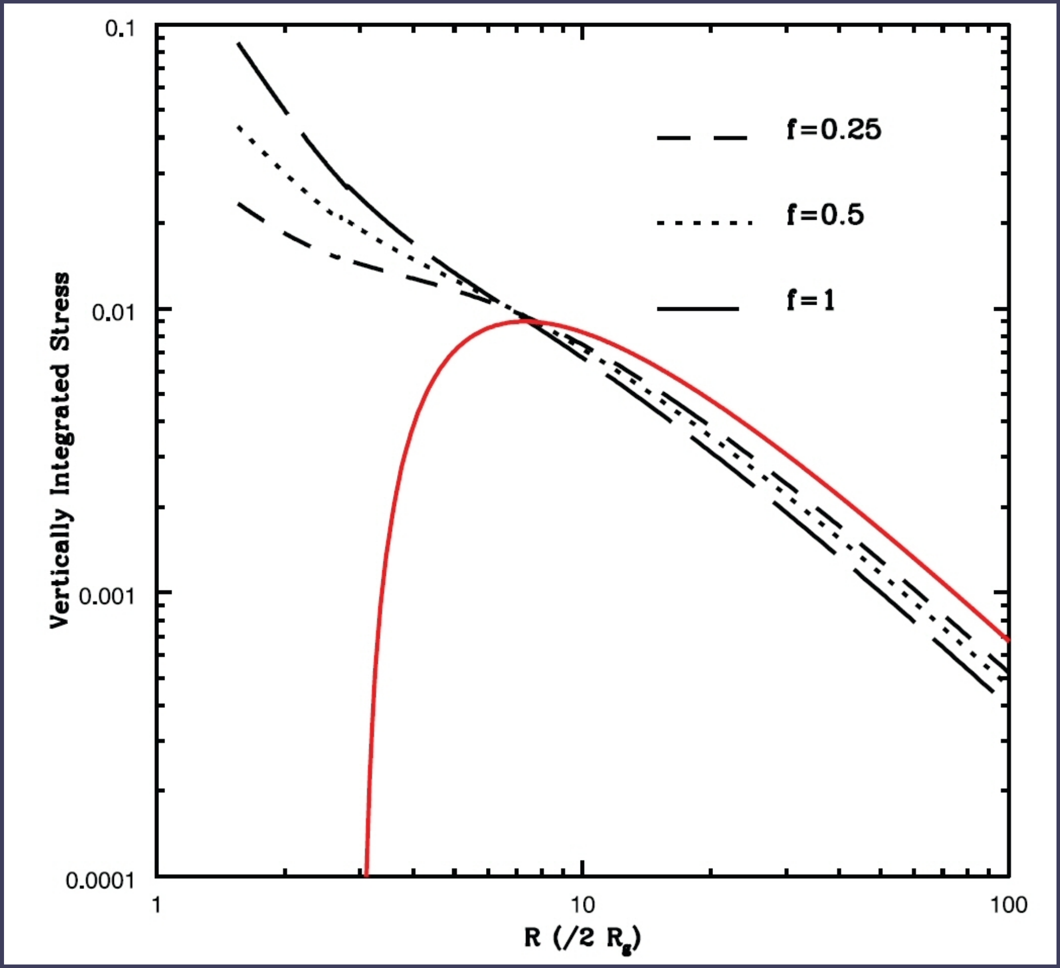
- Shakura & Sunyaev (1973):

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

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

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

  (Schwarzschild BHs)



Shafee, Narayan, McClintock (2008)

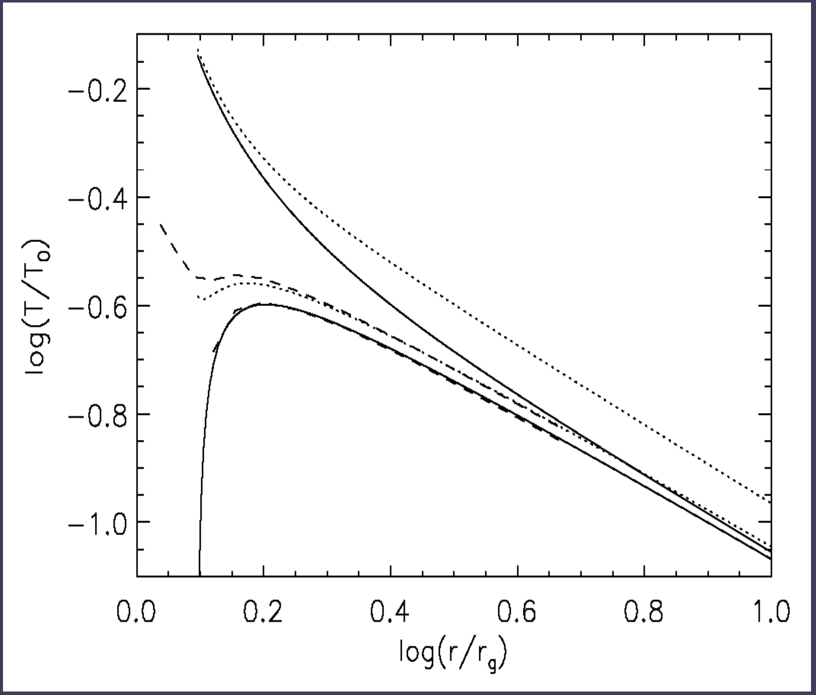
- Variable α
  e.g., Shafee, Narayan, McClintock (2008)

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

Steady-State Models: Finite Torque Disks

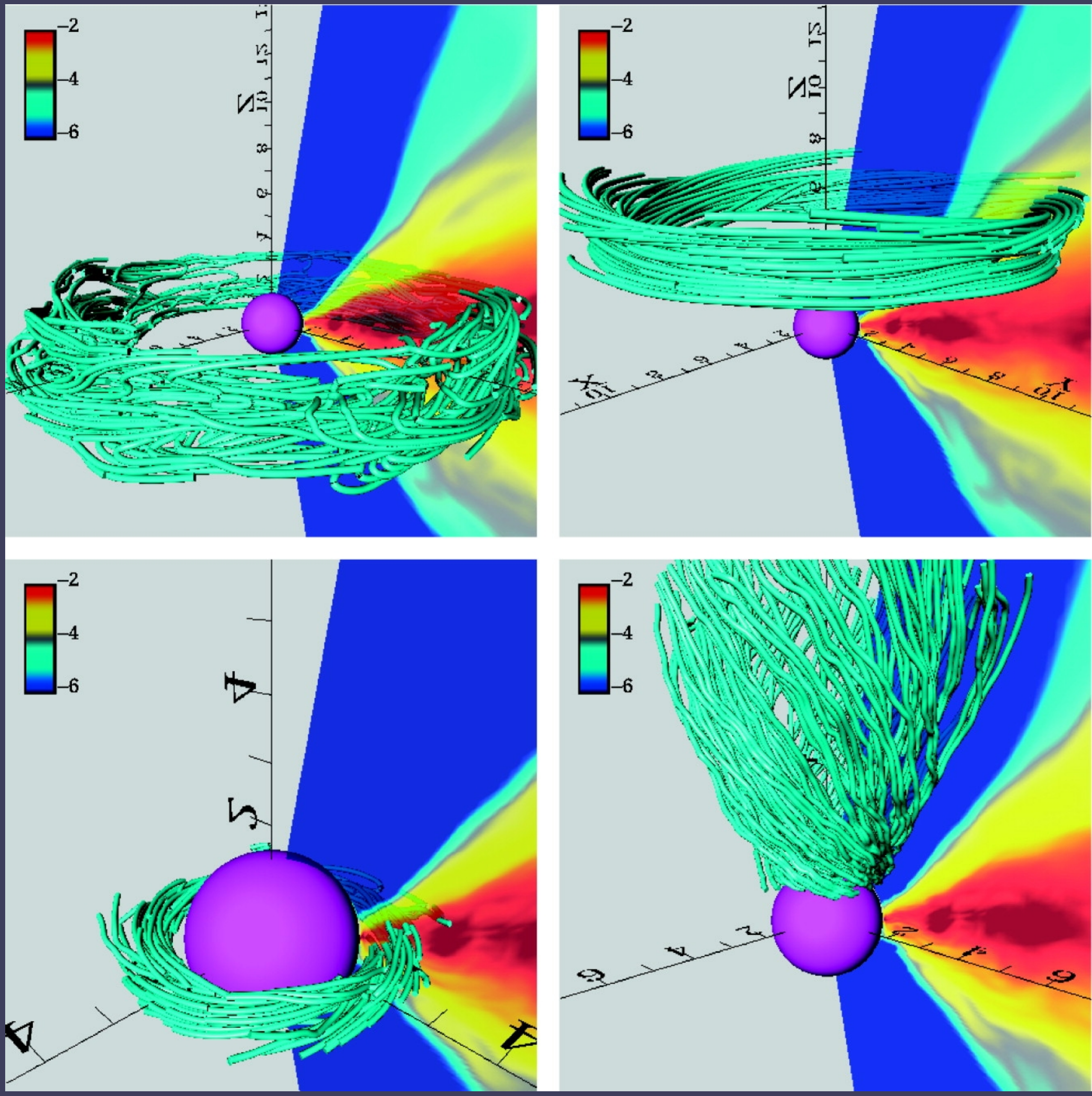
- Krolik (1999)
  - B-field dynamically significant for $r < r_{isco}$
- Gammie's Inflow model (1999)
  - Matched interior model to thin disk → $\eta > 1$ possible
- Agol & Krolik (2000)
  - Parameterize ISCO B.C. with η
  - η reduced by increased probability of photon capture

→ Need dynamical models!!!



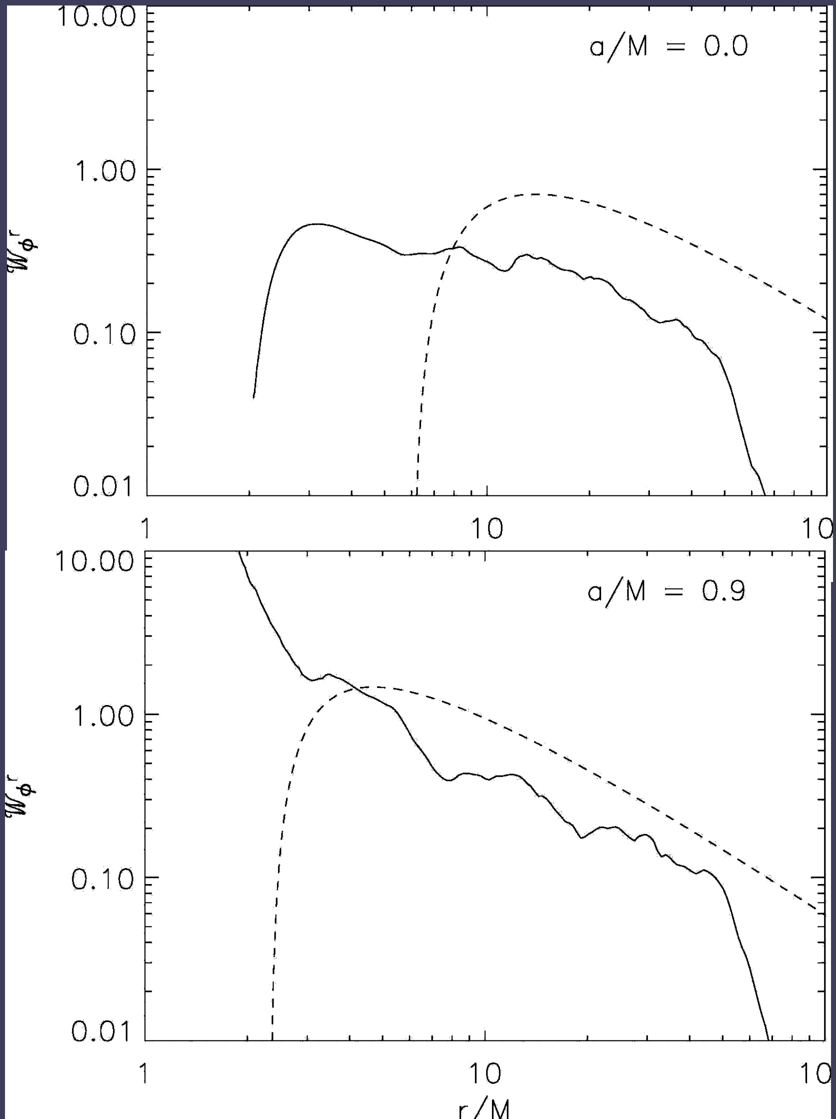
Dynamical Global Disk Models

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



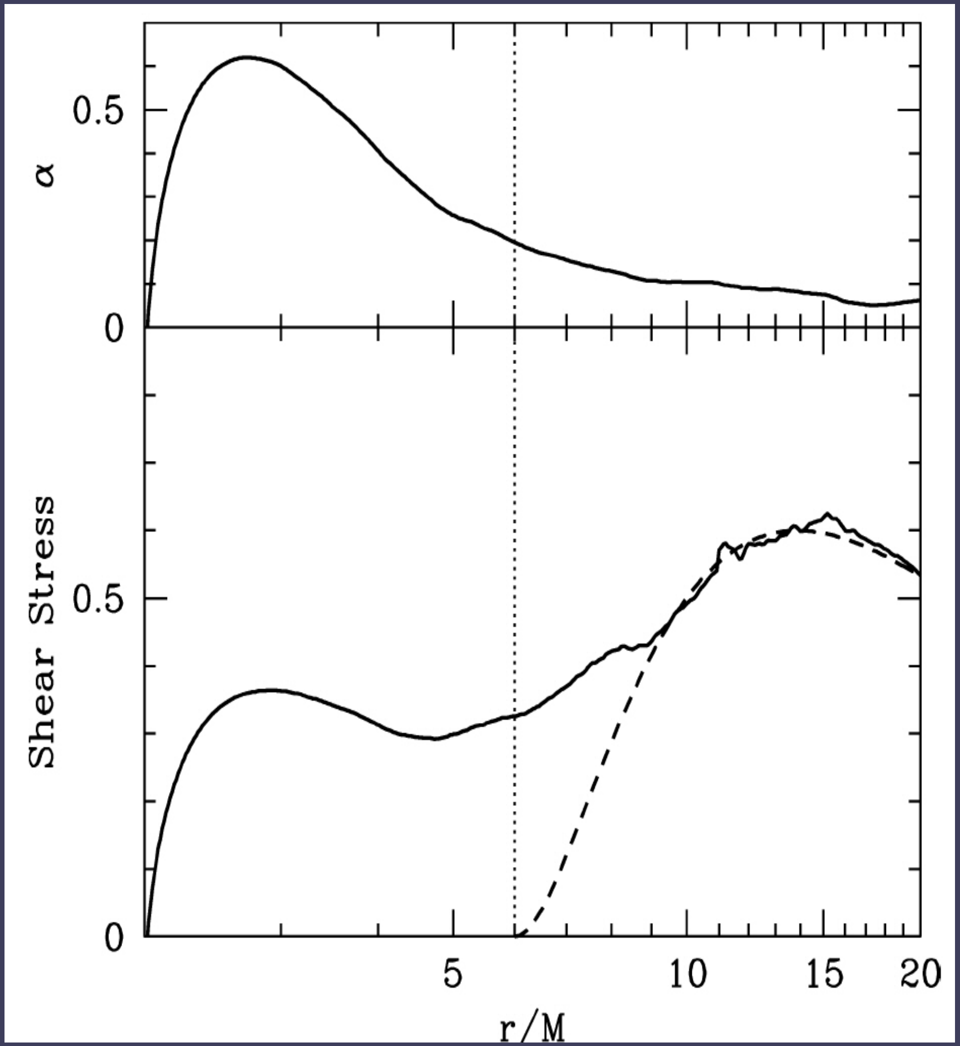
Hirose, Krolik, De Villiers, Hawley (2004)

Dynamical Global Disk Models



Krolik, Hawley, Hirose (2005)

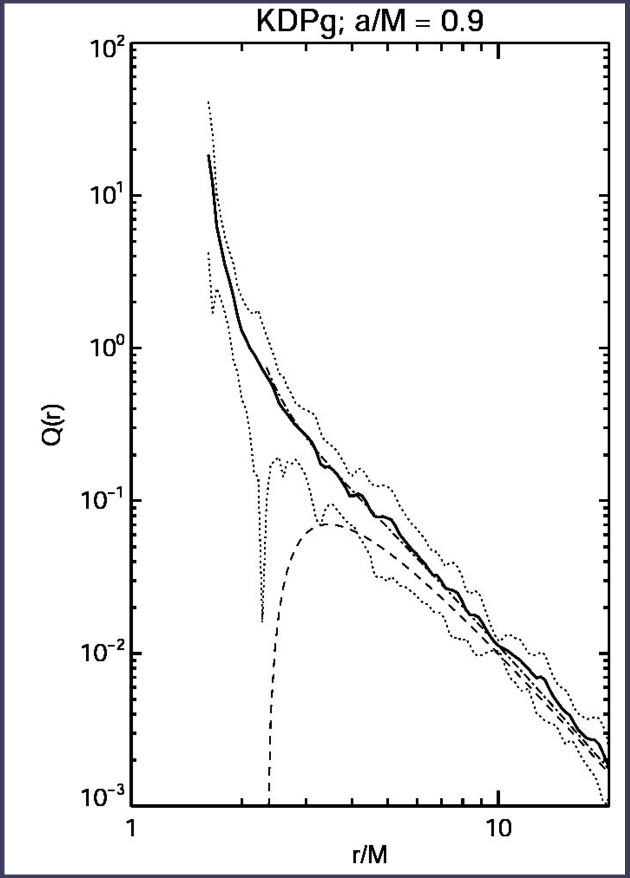
H/R ~ 0.1 - 0.15



Shafee et al. (2008)

H/R ~ 0.05

Inner Radiation Edge



- Beckwith, Hawley &Krolik (2008)

- Models dissipation stress as EM stress

- Large dissipation near horizon compensated partially by capture losses and gravitational redshift.

- Used (non-conserv.) int. energy code (dVH) assuming adiabatic flow
  - Fails to completely capture heat from shocks and reconnection events
  - Need a conservative code with explicit cooling to directly measure dissipation.

$$S^{\mu\nu} u_{\nu;\mu} = Q^{\theta}_{;\theta}$$

$$S^{\mu\nu} = T^{\mu\nu}_{EM}$$

Our Method: Simulations

- **HARM**:
  Gammie, McKinney, Toth (2003)

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

- Axisymmetric (2D)

- Total energy conserving
  (dissipation → heat)

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

- Modern Shock Capturing techniques
  (greater accuracy)

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

- Improvements:
  - 3D
  - More accurate (parabolic interp. In reconstruction and constraint transport schemes)
  - Assume flow is isentropic when $P_{gas} << P_{mag}$

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 ~ 0.08 $a_{BH} = 0.9$

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:

$$f_c = s\,\Omega\,u(\Delta - 1 + |\Delta - 1|)^q$$

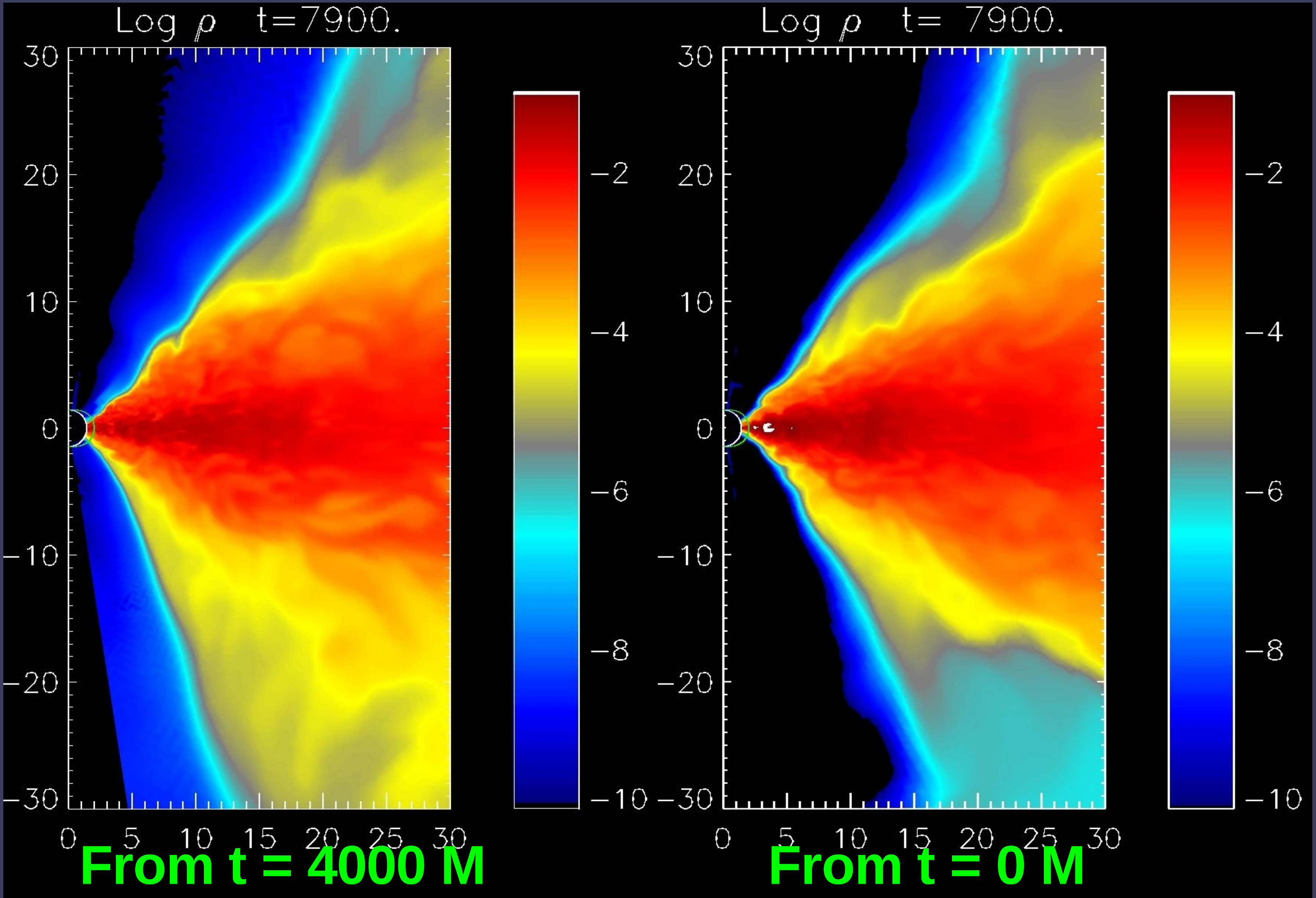
$$\Delta = \frac{u}{\rho T}$$

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

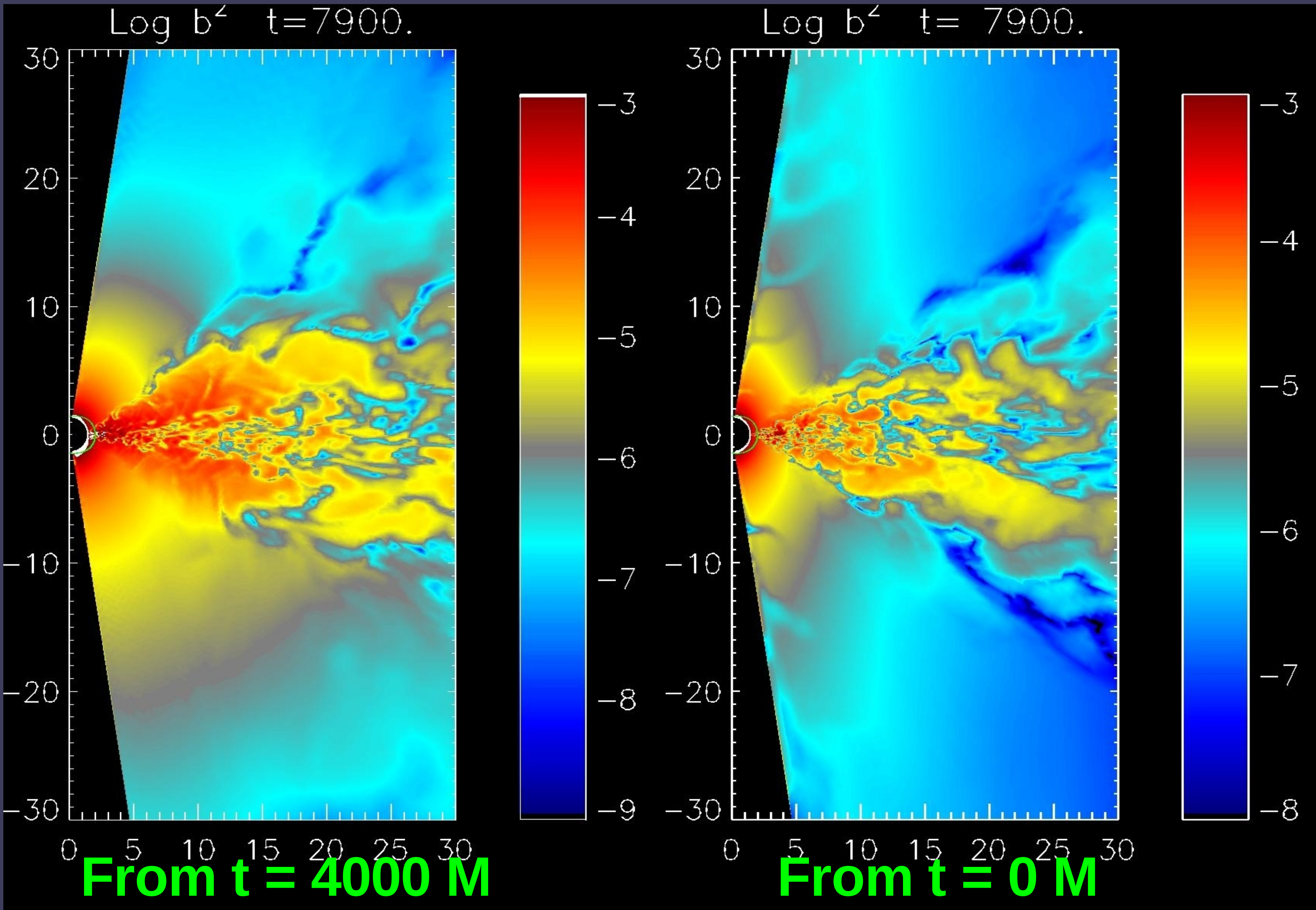
- $\Omega(r < r_{isco})$ is that of a geodesic with constant E & L from ISCO

Cooled #1 vs. Cooled #2

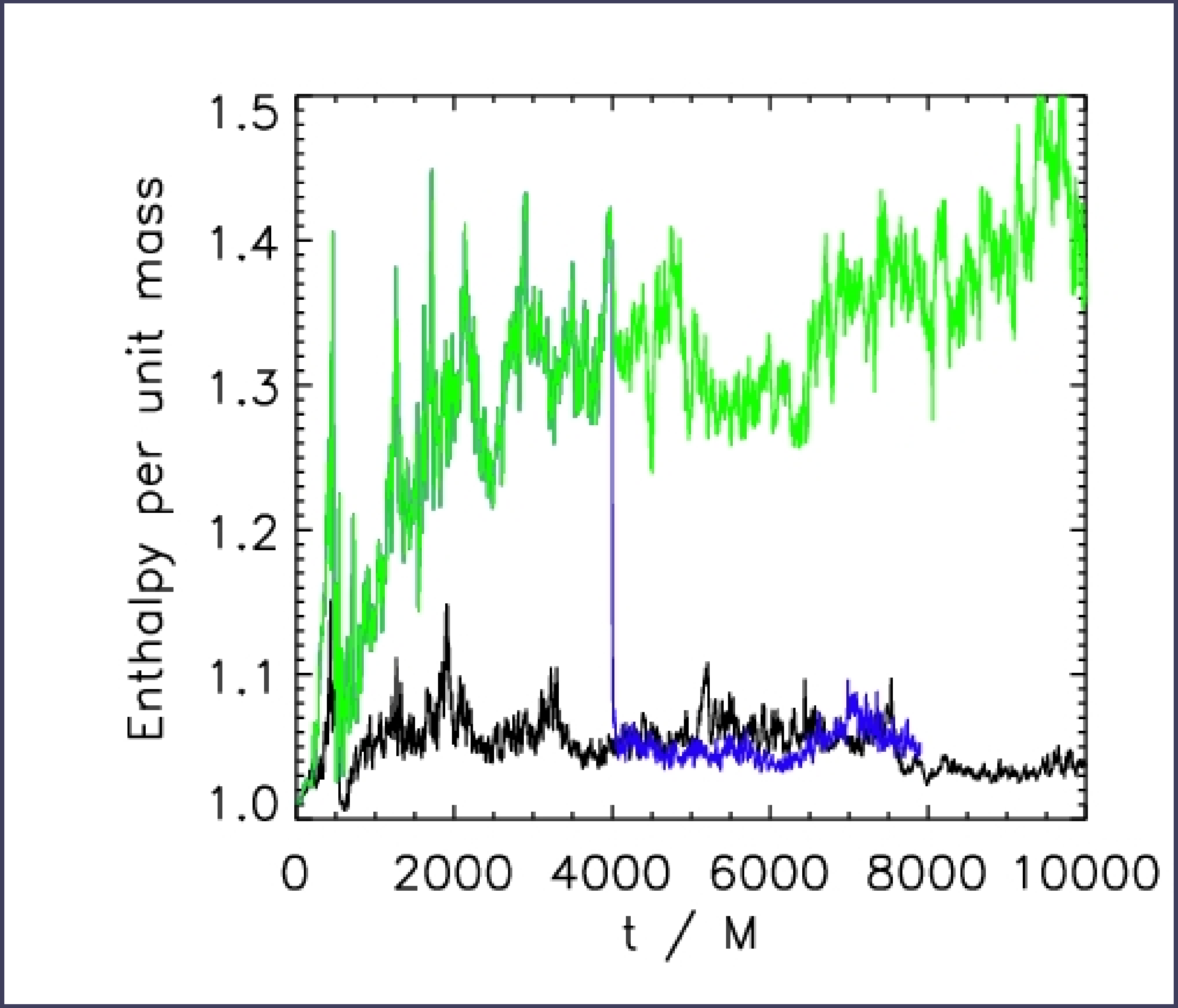
$\log(\rho)$



Cooled #1 vs. Cooled #2 $\log(P_{mag})$



Cooling Efficacy

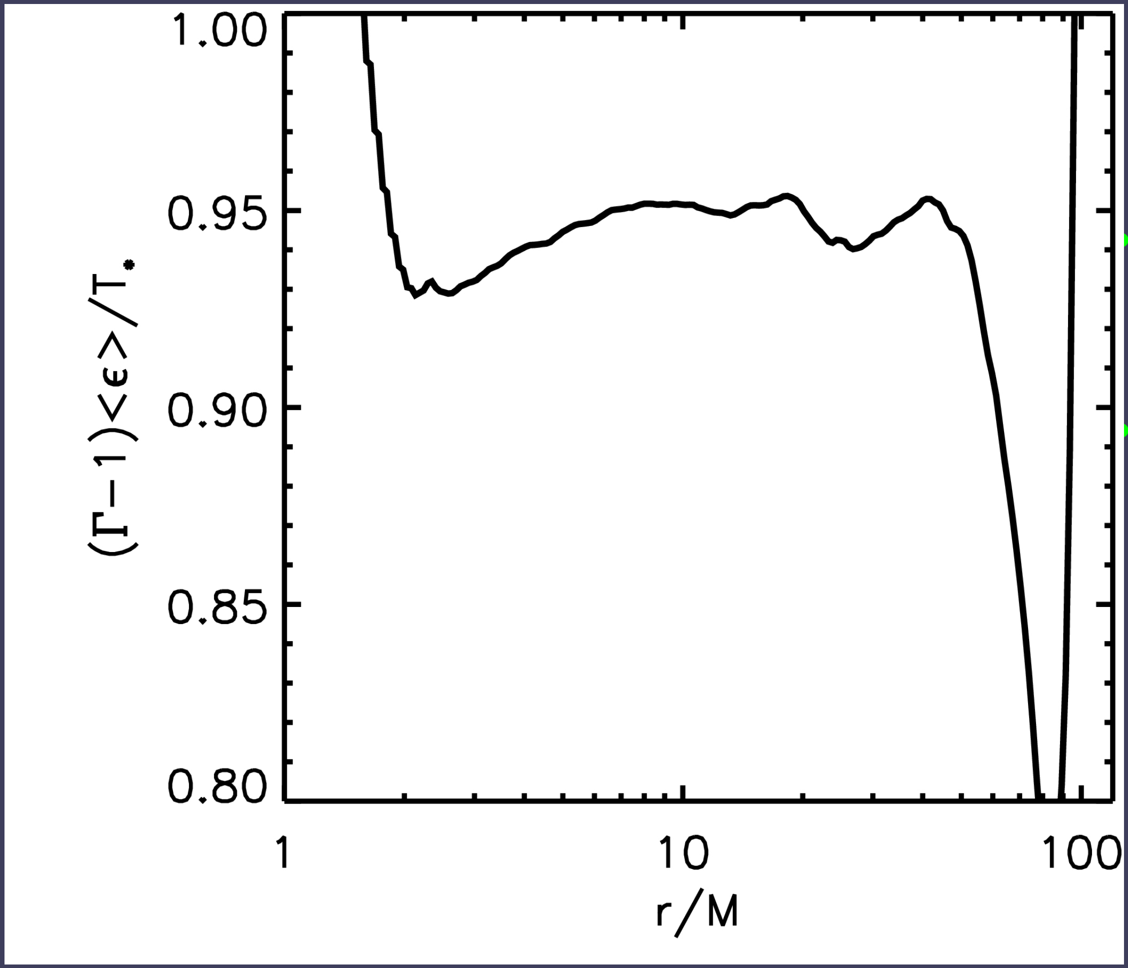


Cooled from t=0M

Cooled from t=4000M

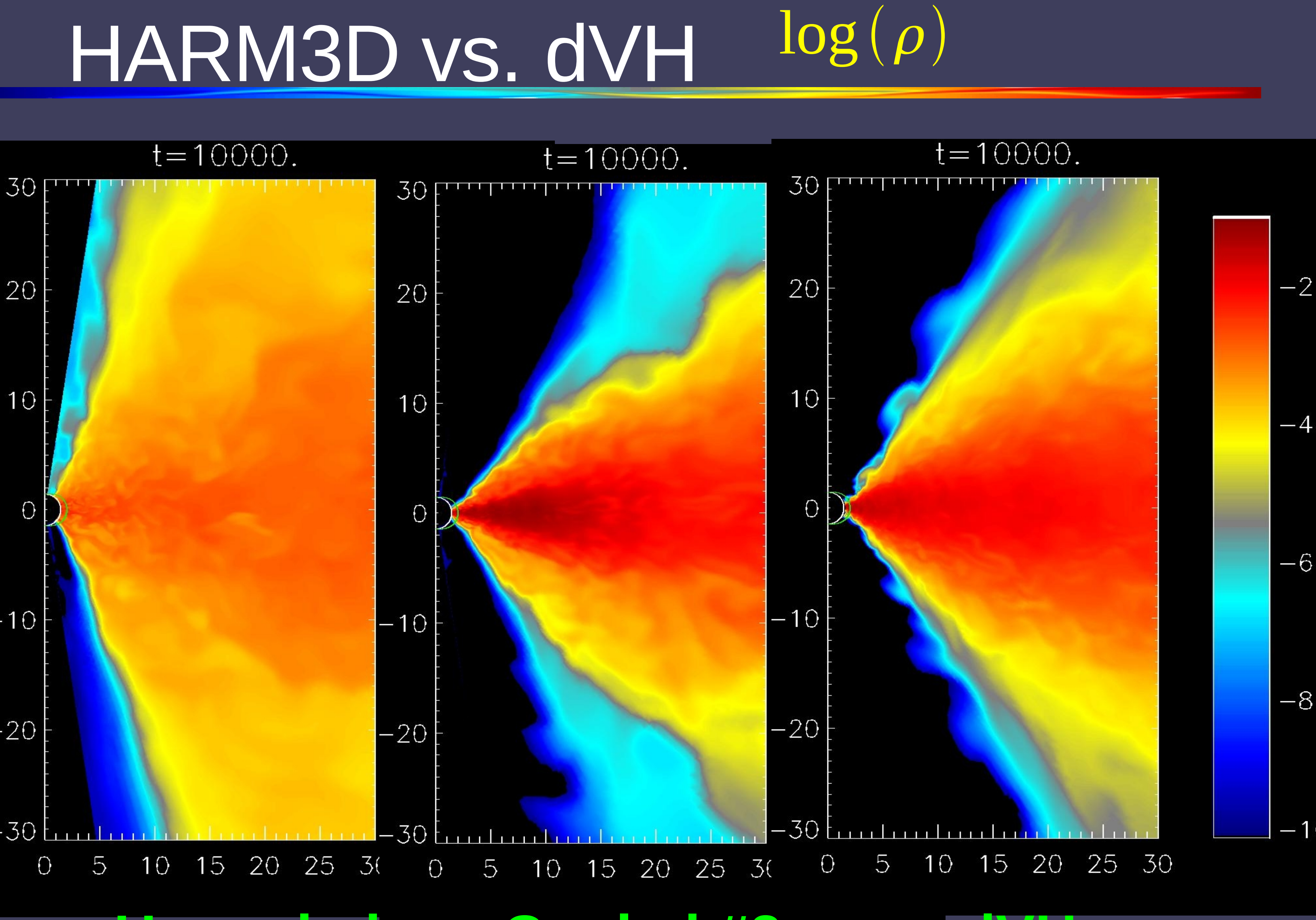
Uncooled

Target Temperature



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

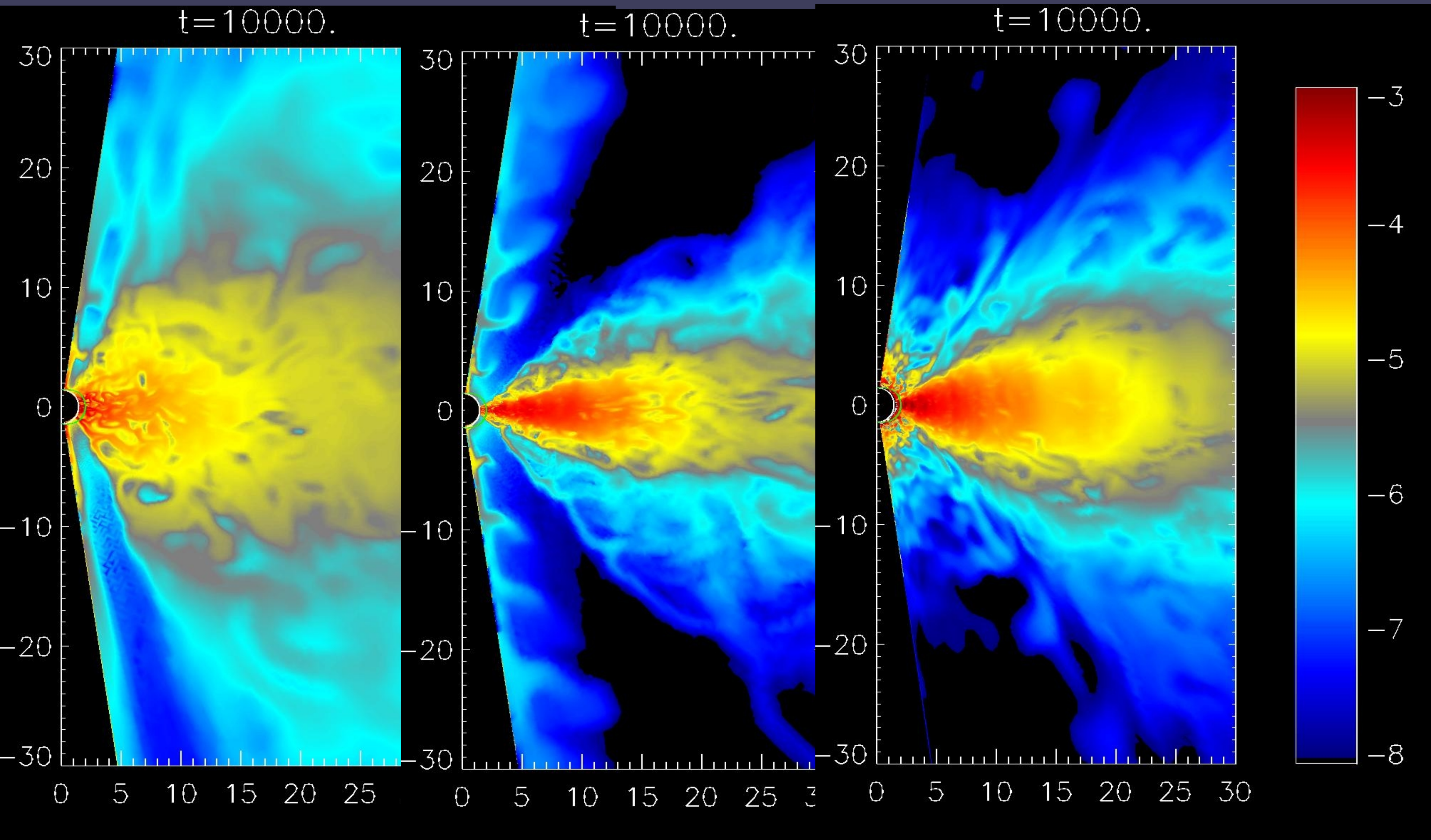
HARM3D vs. dVH



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

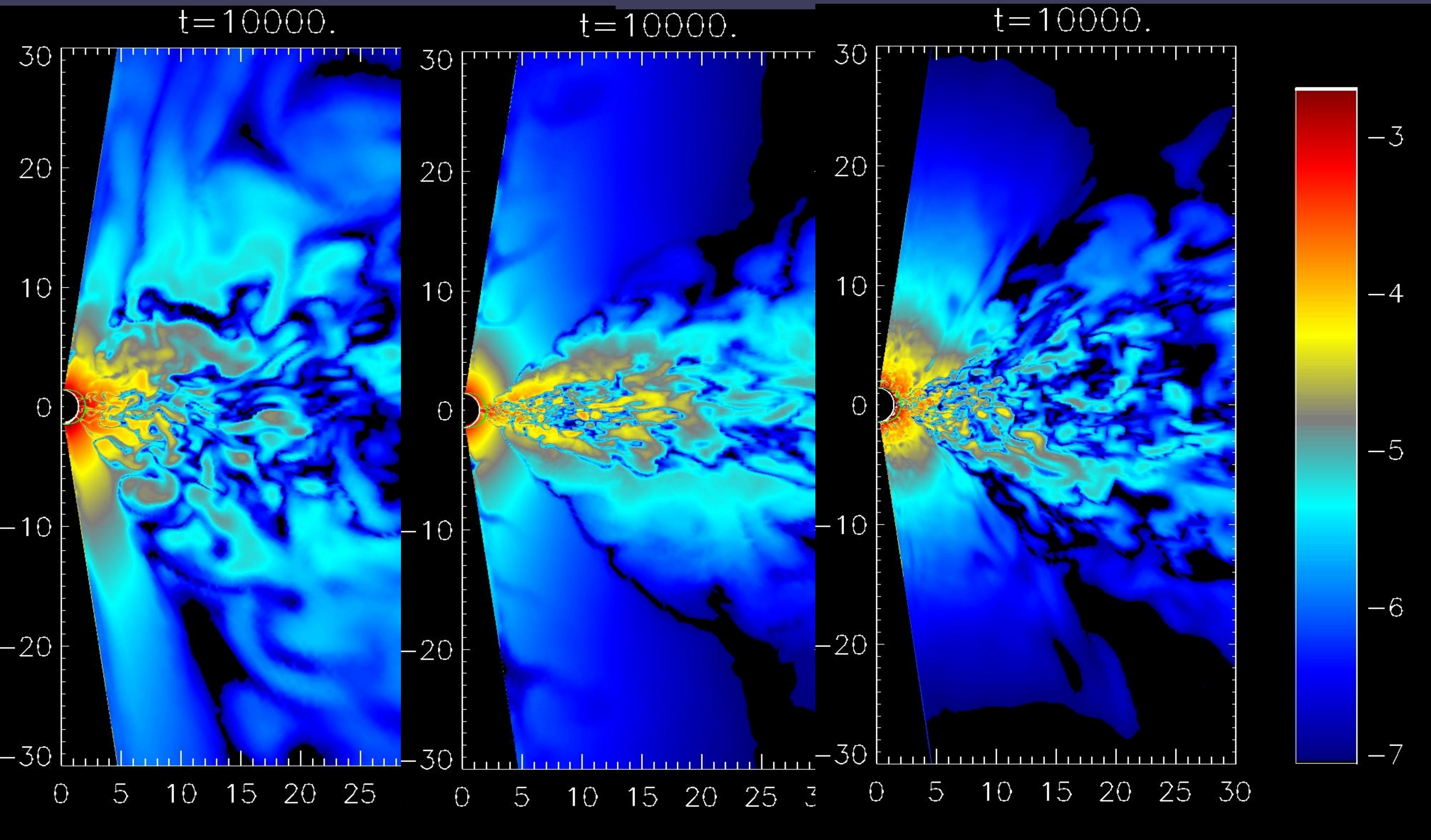
HARM3D vs. dVH

$\log(P)$



HARM3D vs. dVH

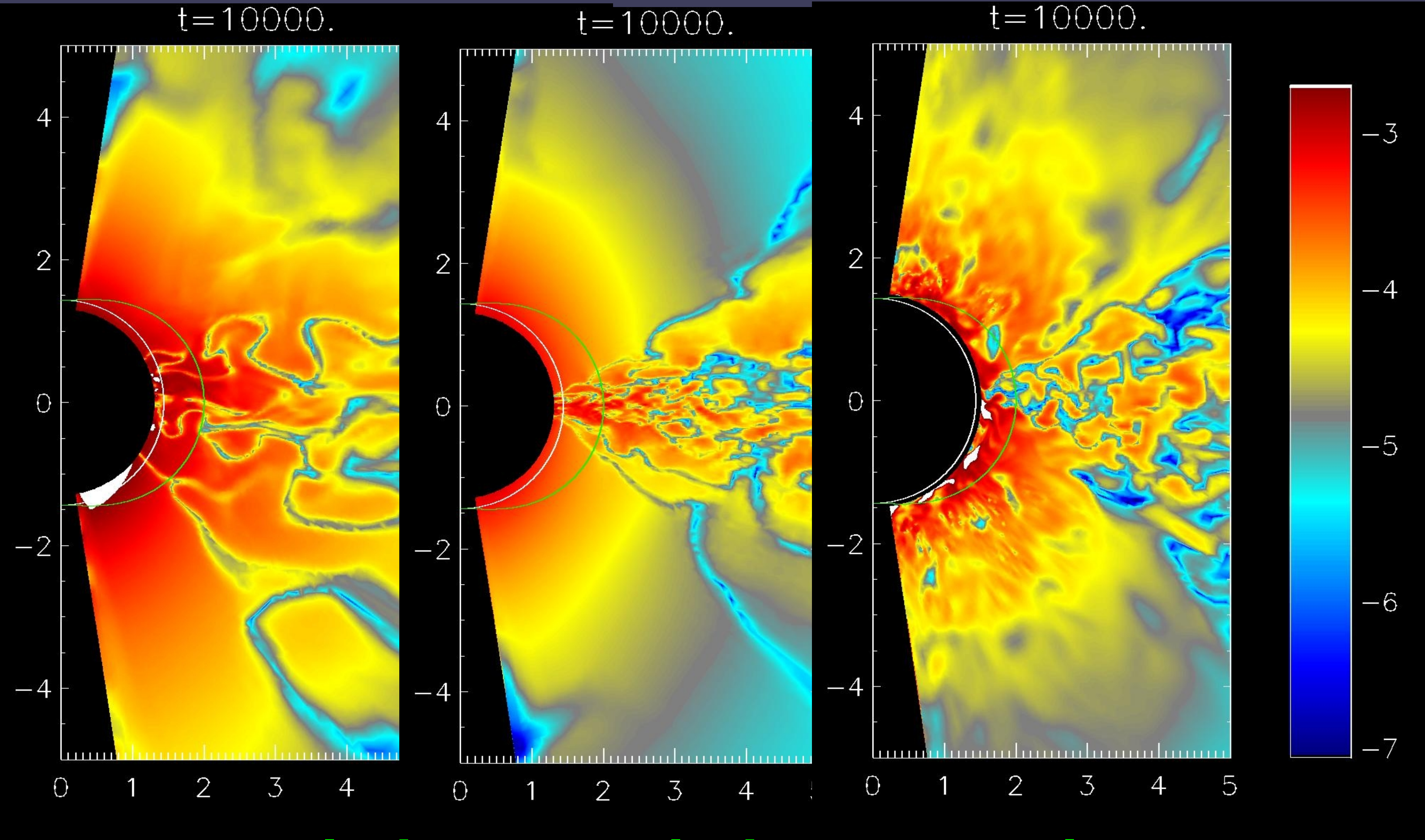
$\log(P_{mag})$



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

HARM3D vs. dVH

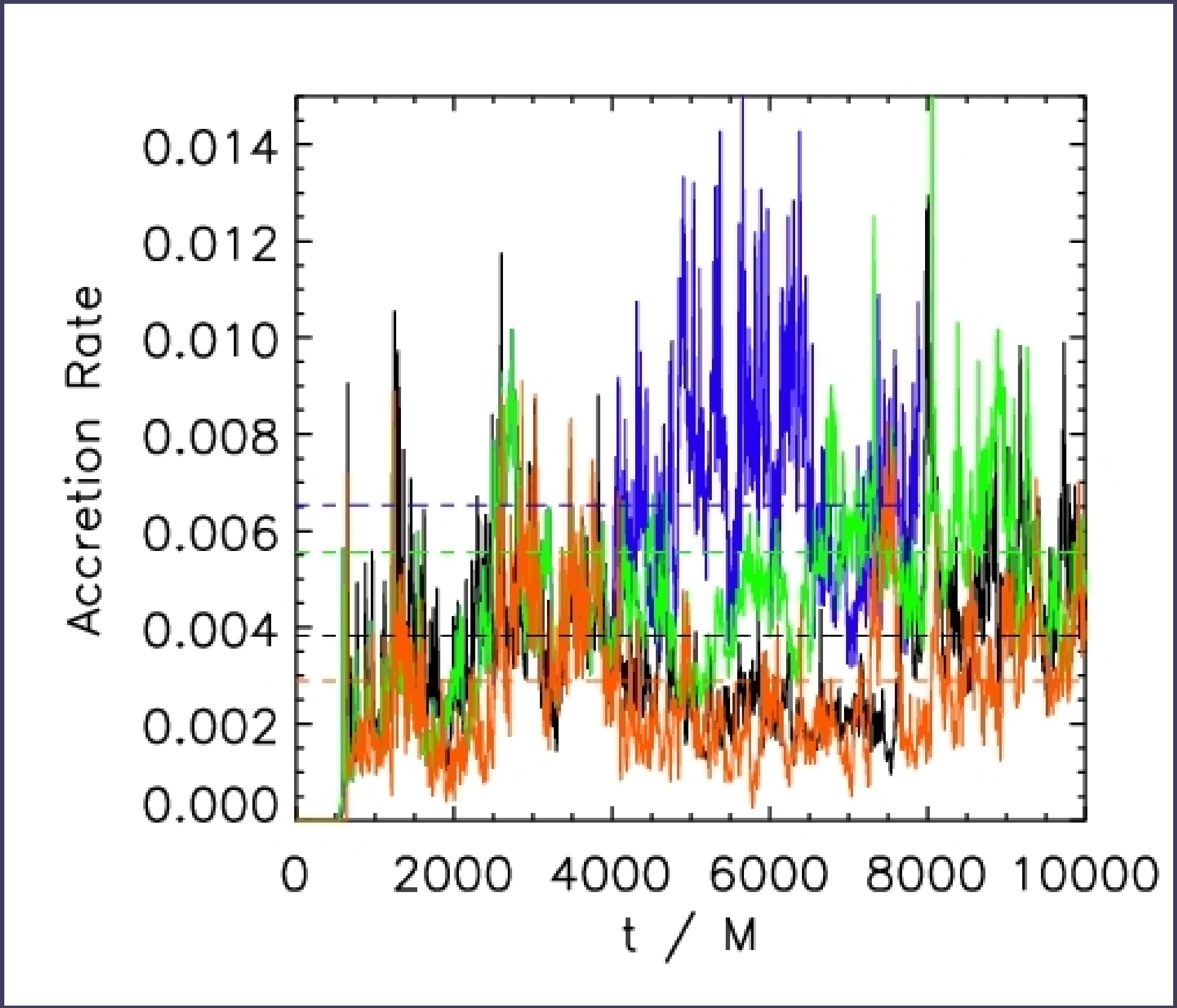
$\log\left(P_{mag}\right)$



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

HARM3D vs. dVH

$\dot{M}$



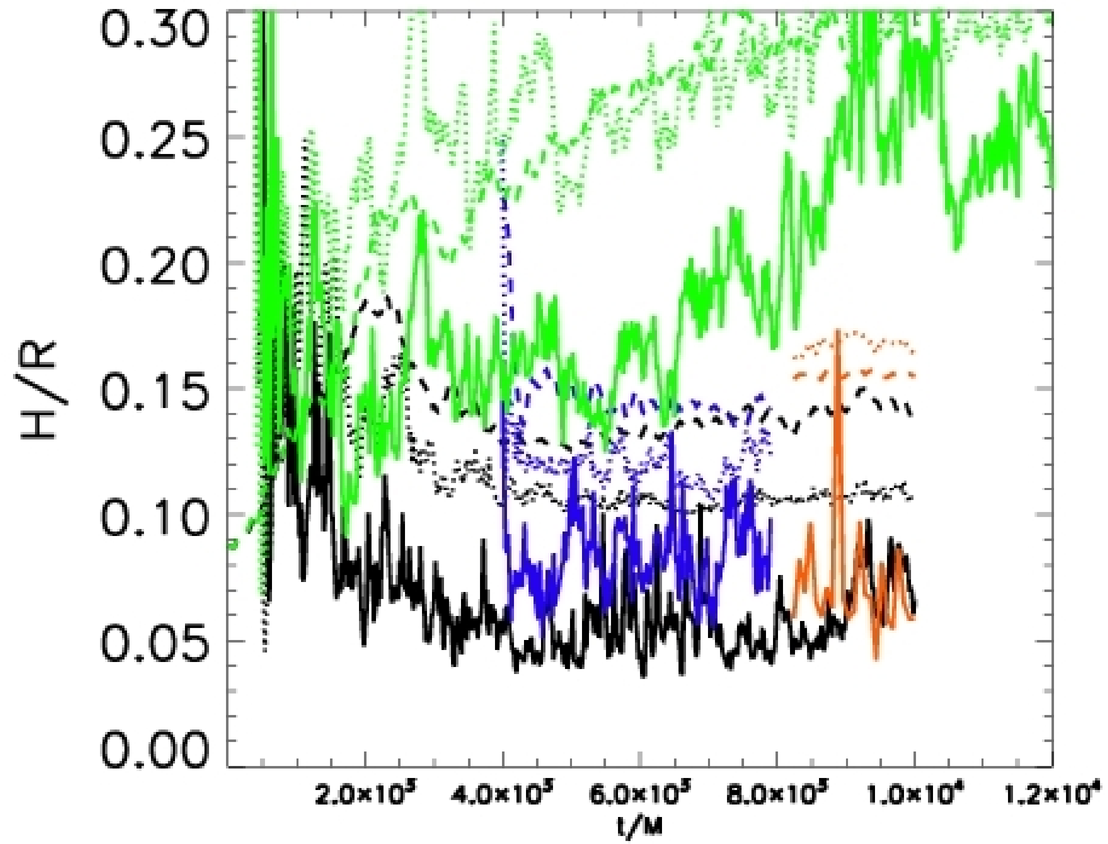
Cooled from t=0M

Cooled from t=4000M

Uncooled

dVH

HARM3D vs. dVH



Cooled from t=0M

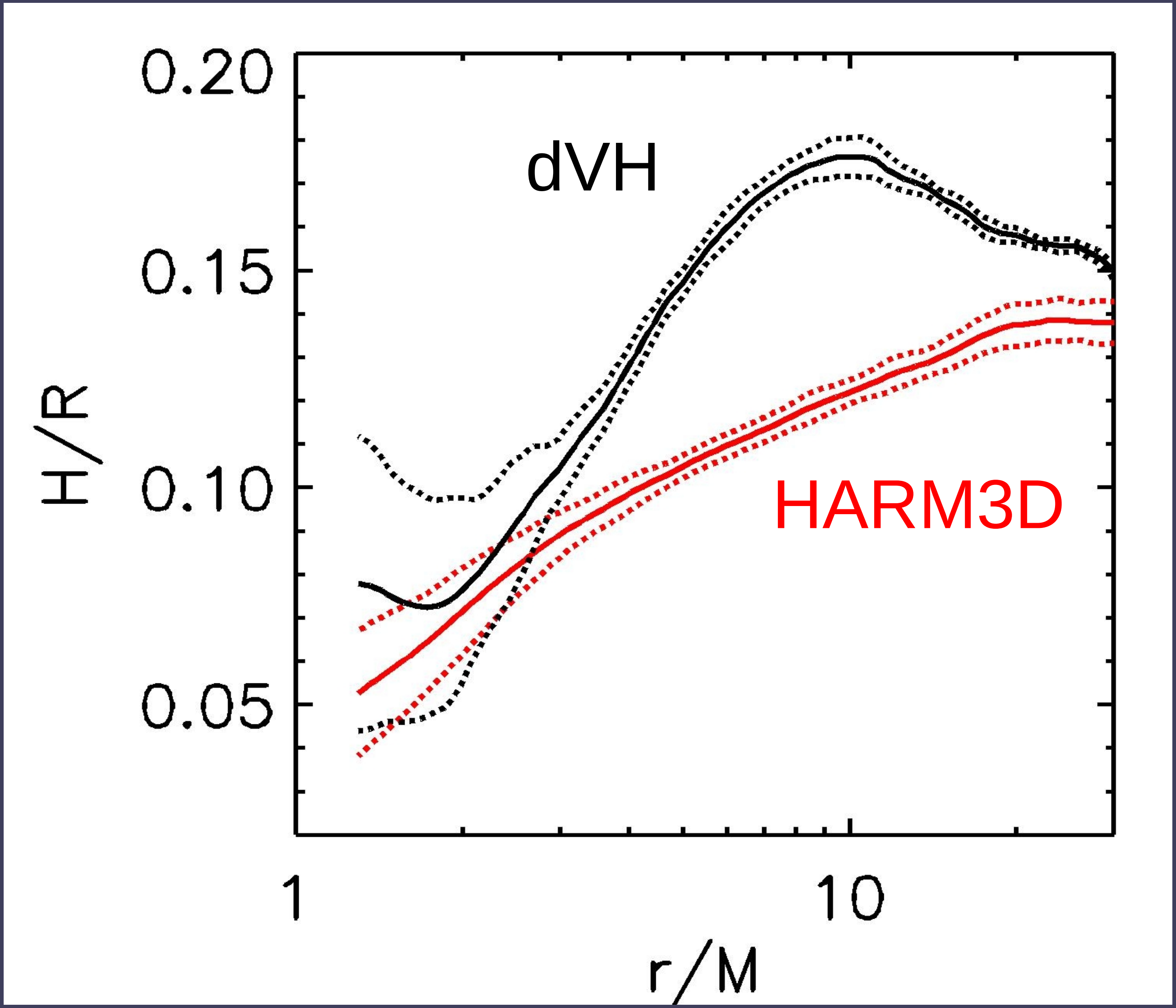
Cooled from t=4000M

Uncooled

dVH

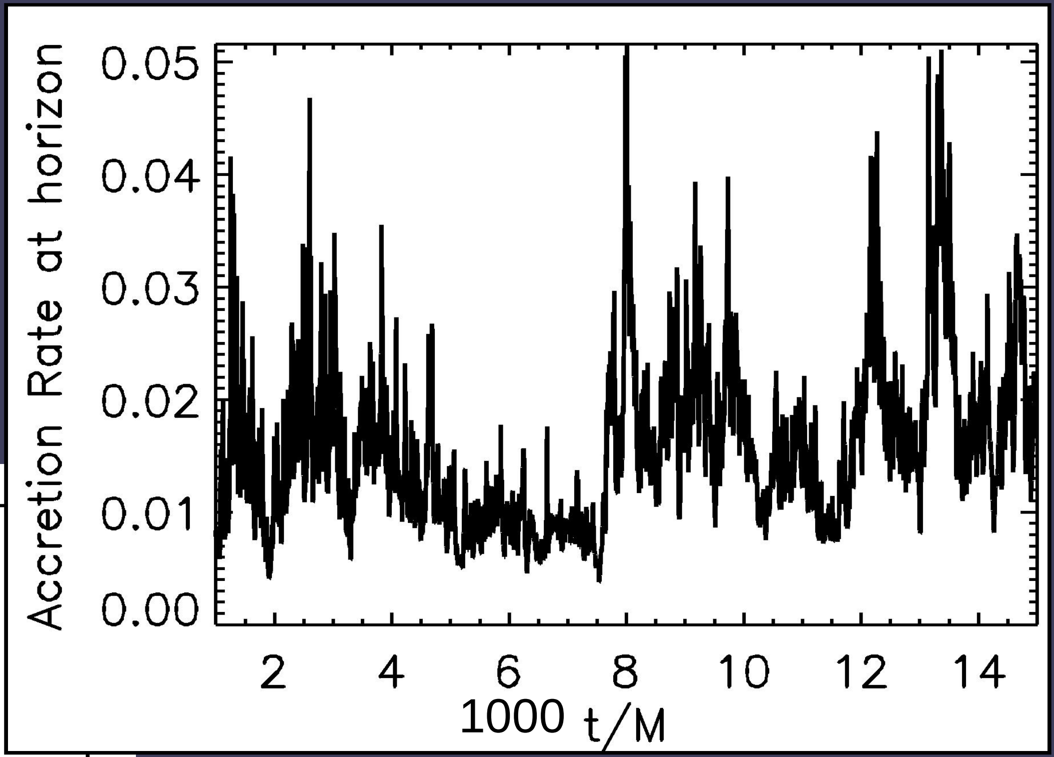
Solid : r = 1.6
Dotted : r = 5
Dashed : r = 20

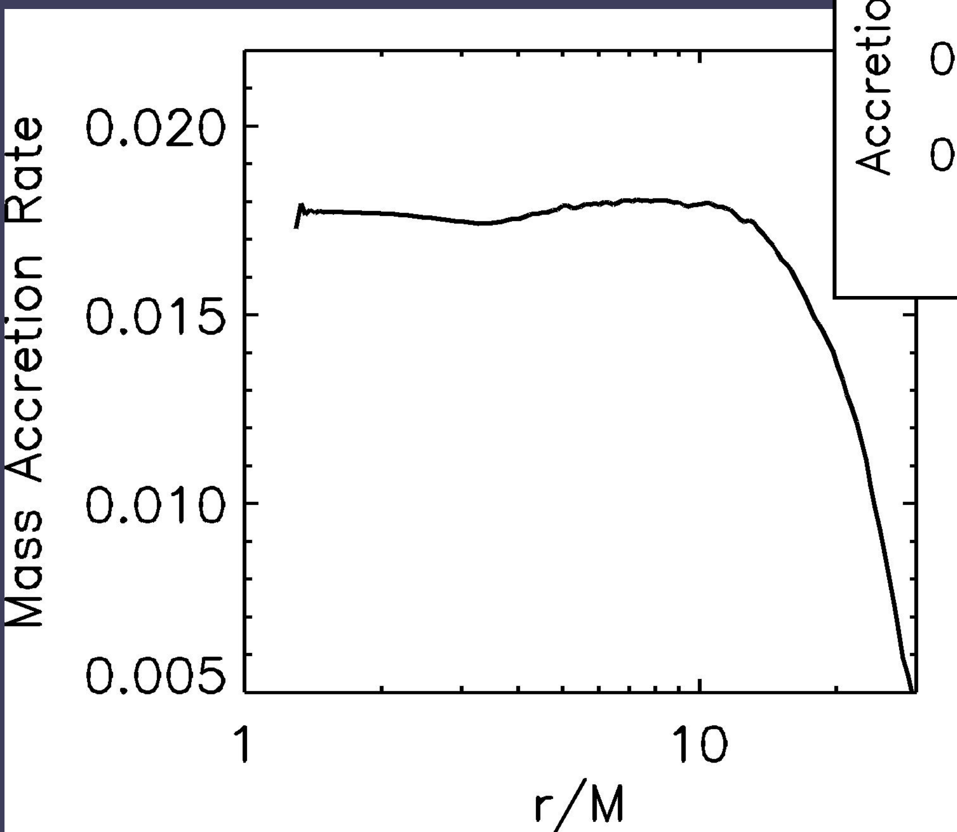
Disk Thickness



Accretion Rate

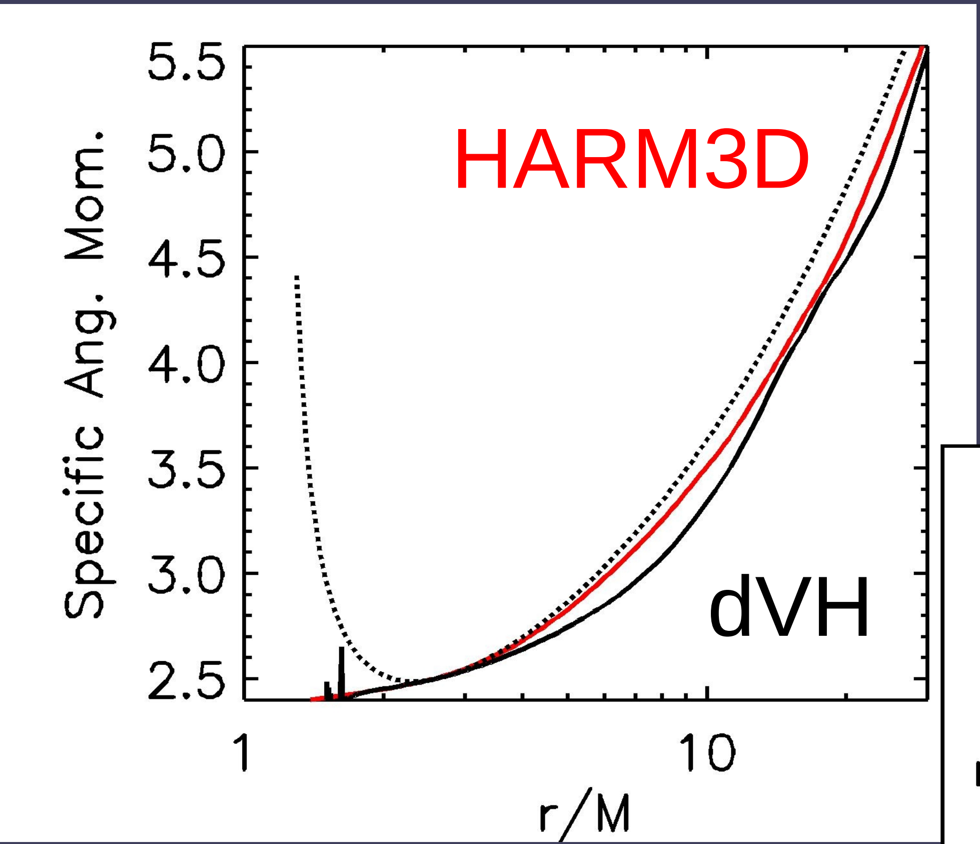
Steady State Period = 7000 – 15000M

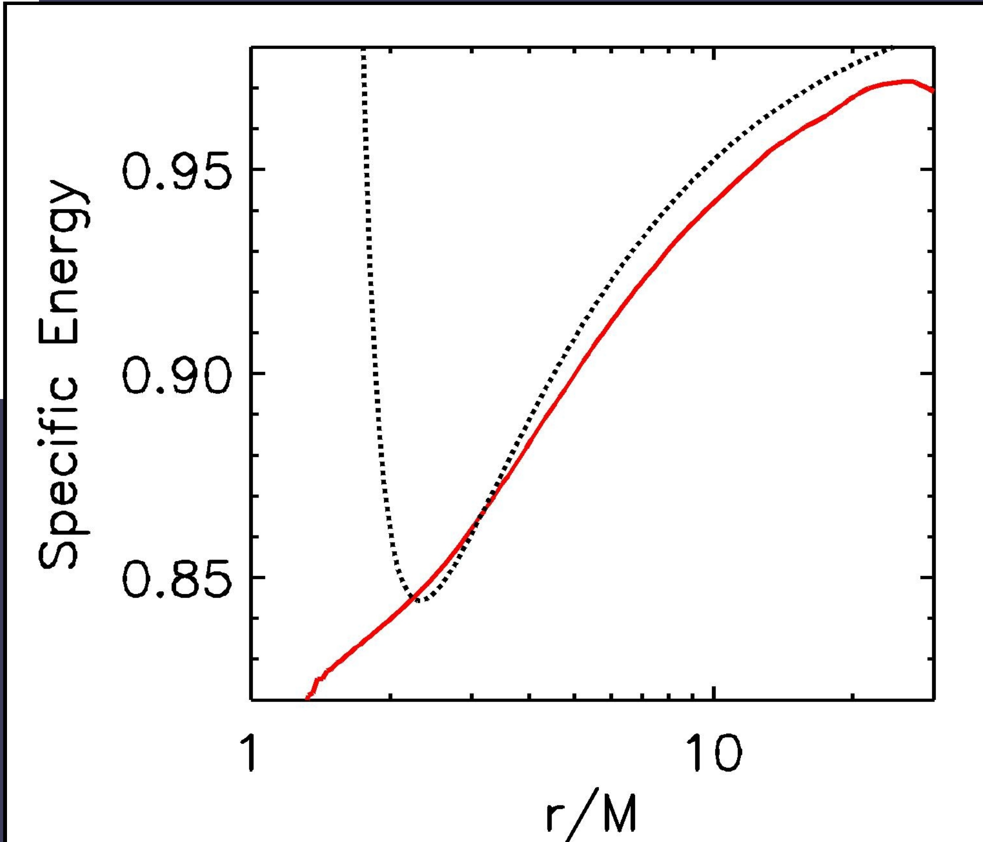




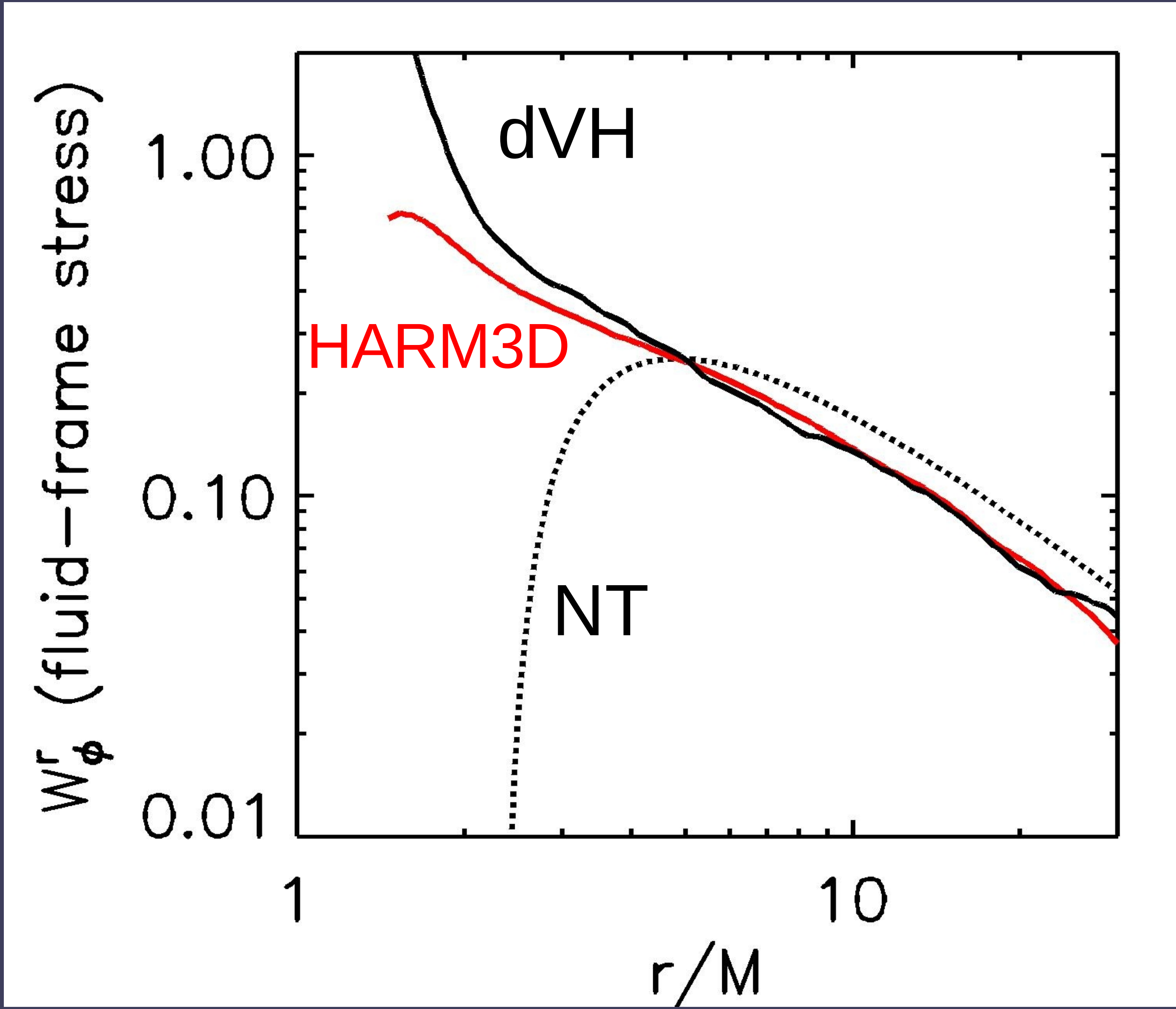
Steady State Region = Horizon – 12M

Departure from Keplerian Motion

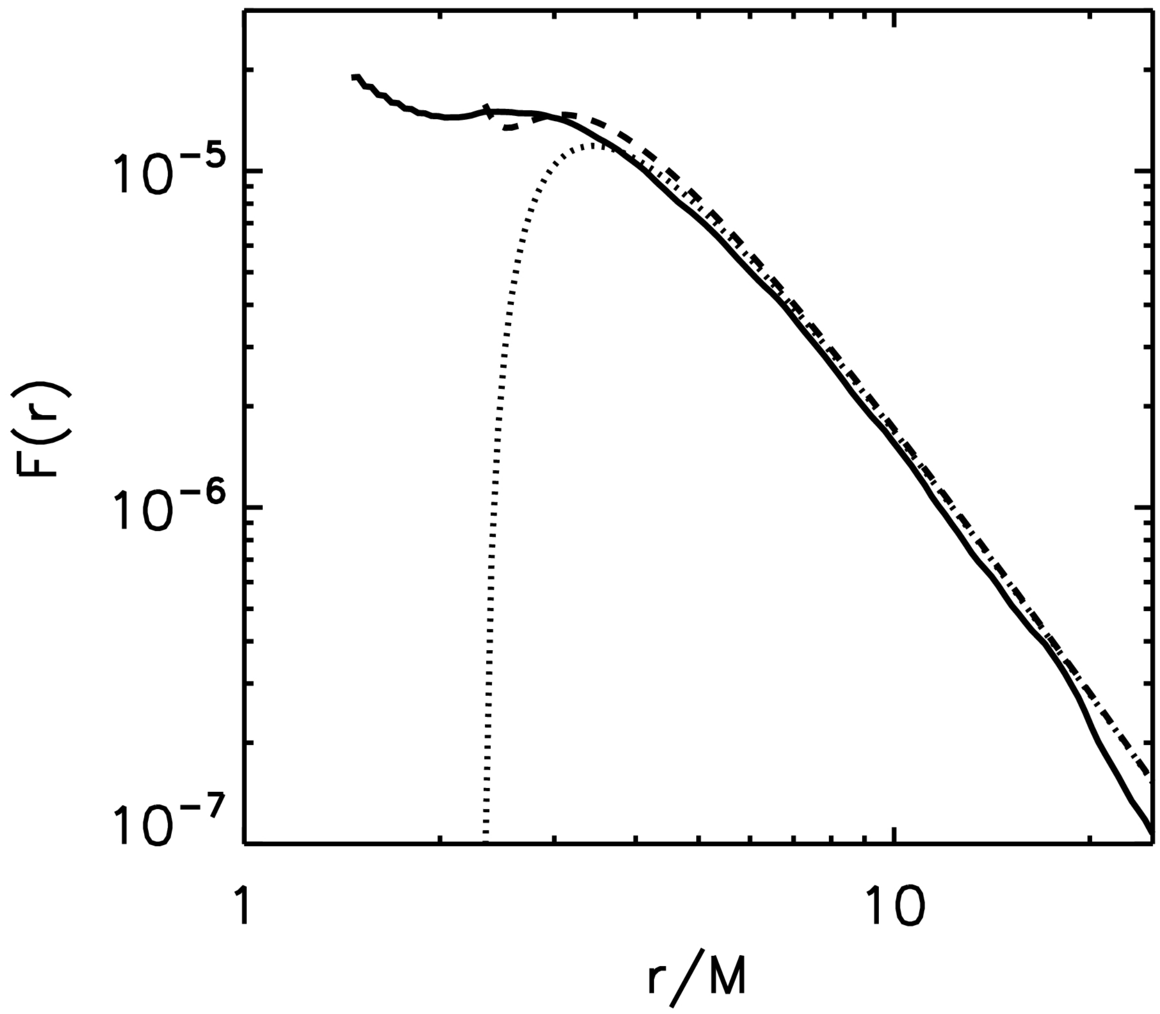




Magnetic Stress



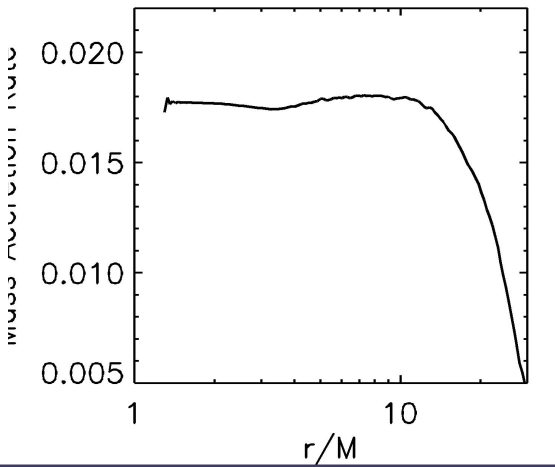
Fluid Frame Flux



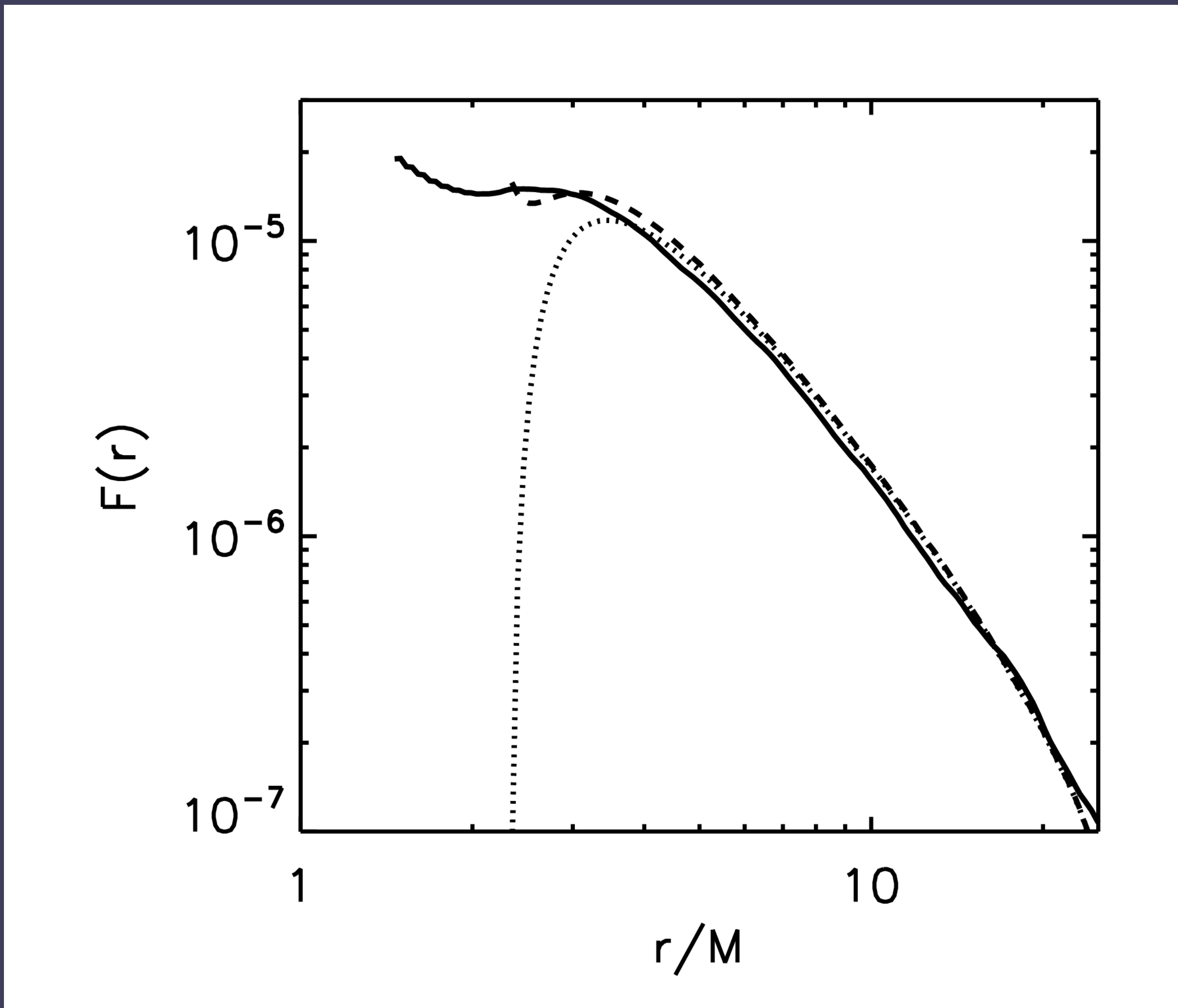
Agol & Krolik (2000) model

$$\Delta \eta = 0.01$$

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



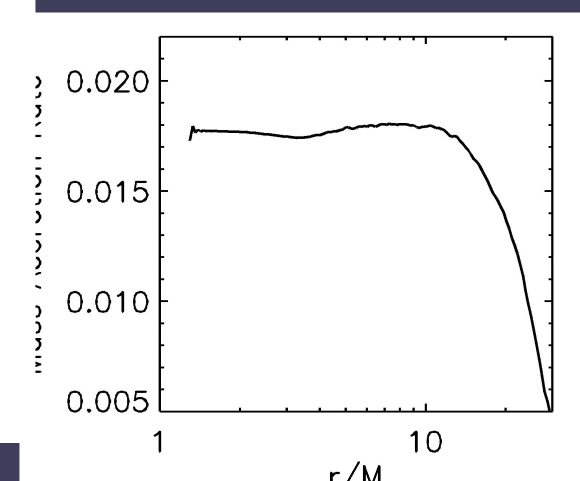
Fluid Frame Flux



Agol & Krolik (2000) model

$$\Delta\eta = 0.01$$

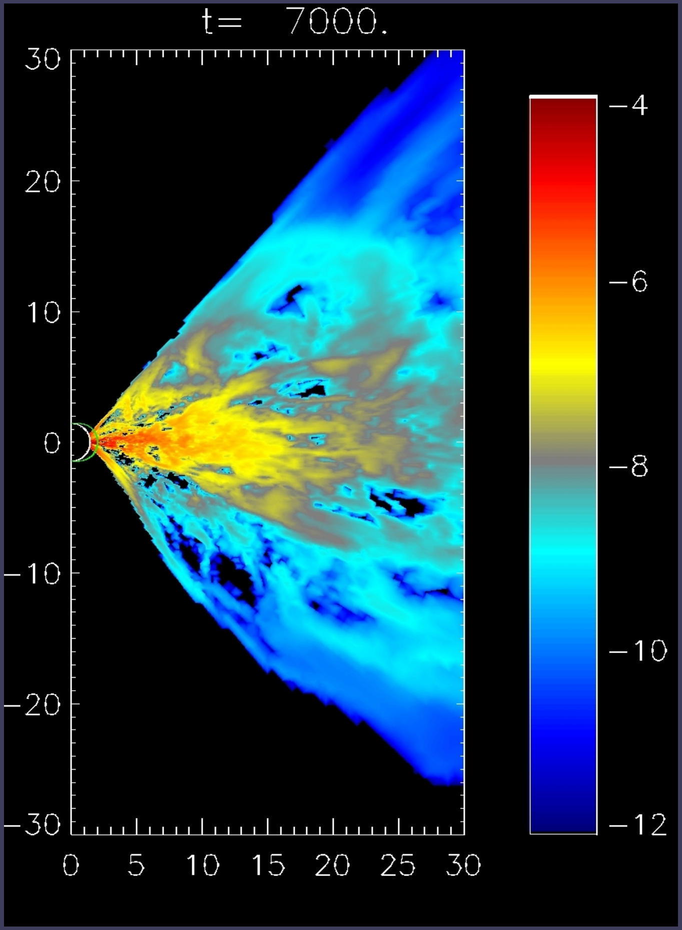
$$\Delta\eta/\eta = 7\%$$

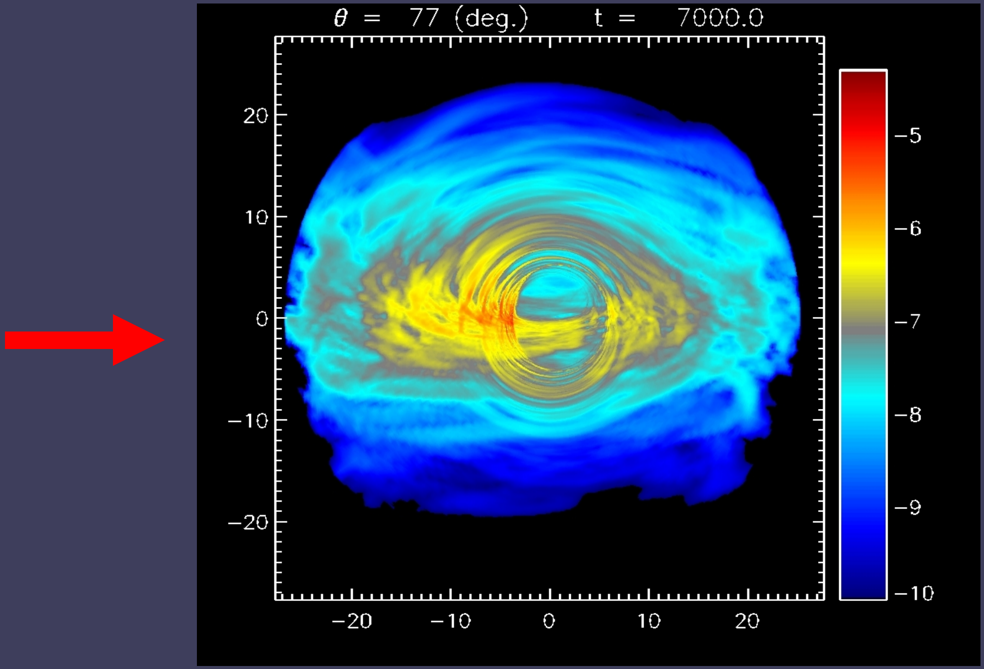


Our Method: Radiative Transfer

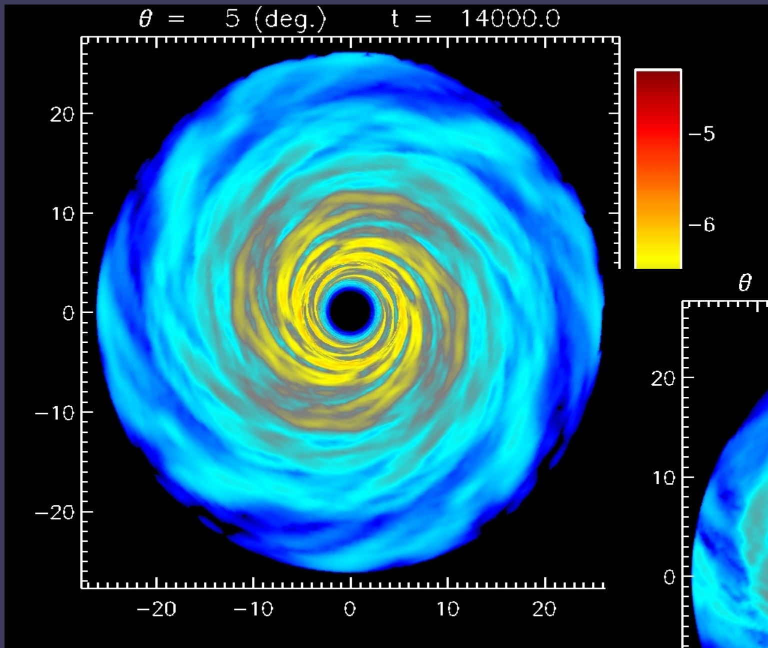
$$j_\nu = \frac{f_c}{4\pi\nu^2}$$

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

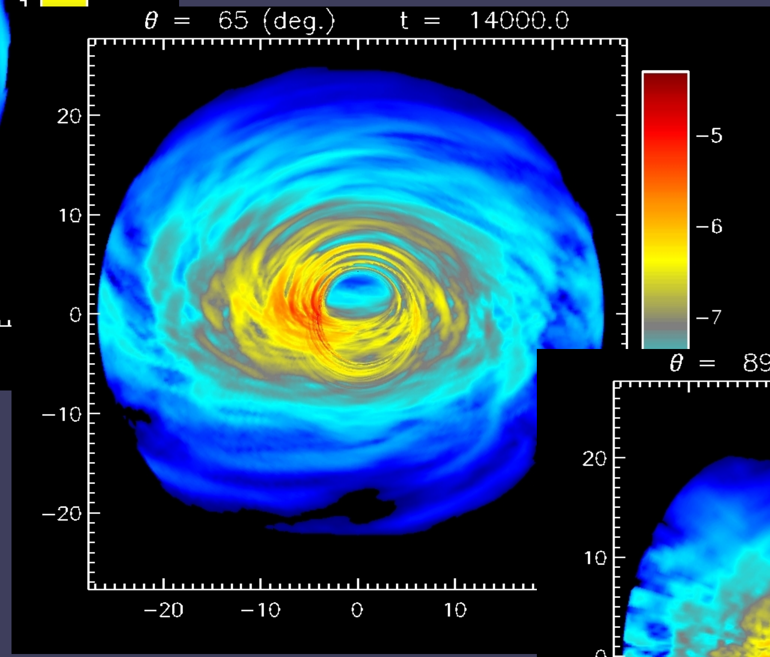




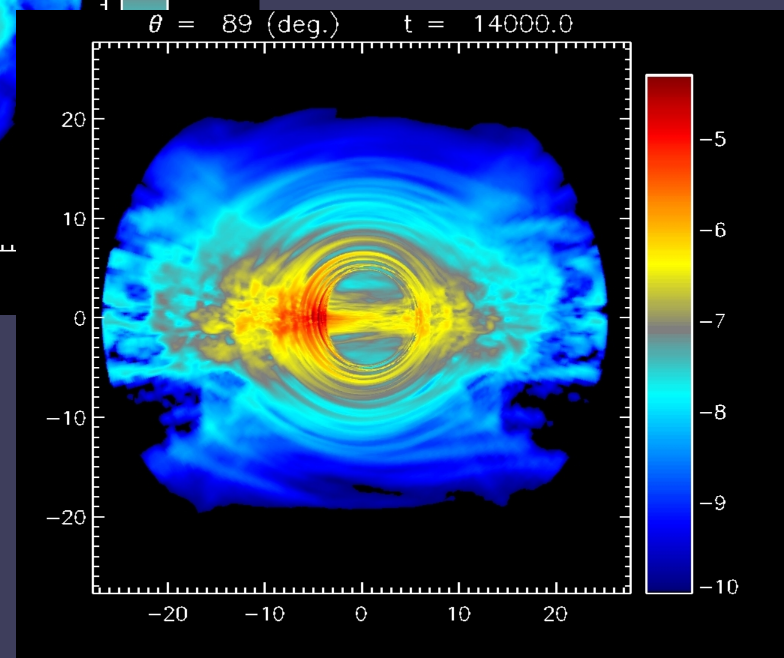
Observer-Frame Intensity: Inclination



i=5°

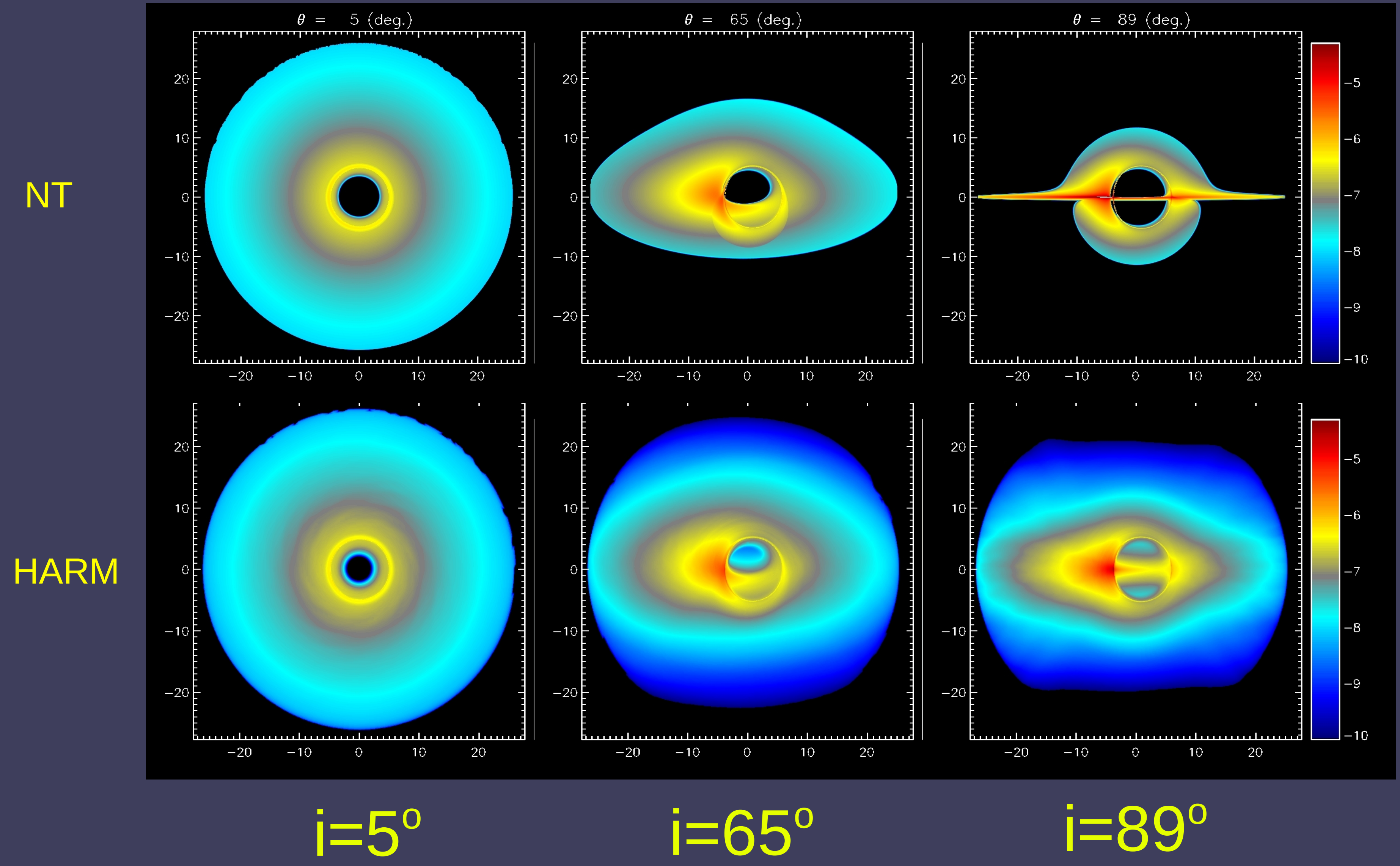


i=65°

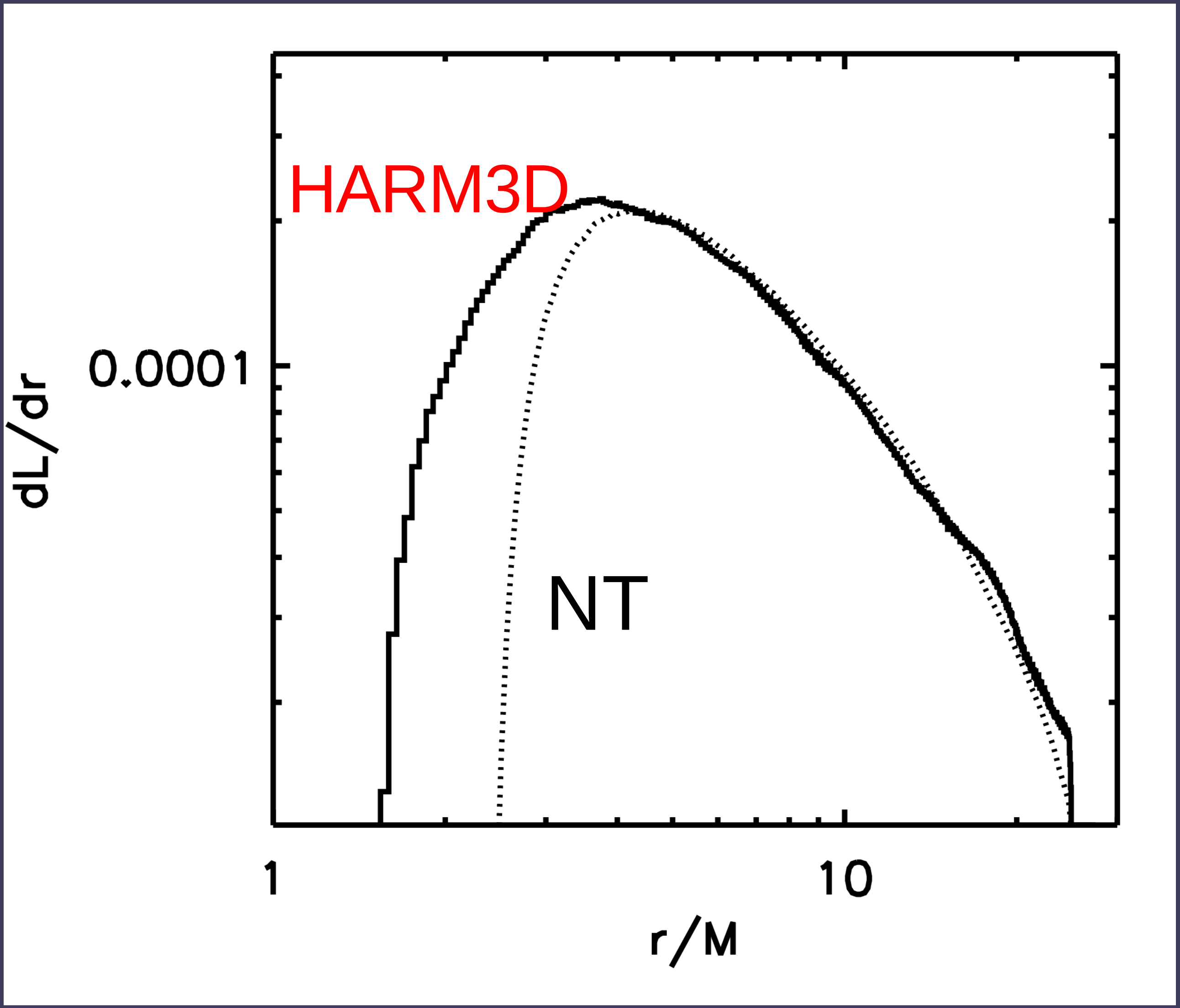


i=89°

Observer-Frame Intensity: Time Average



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 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

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

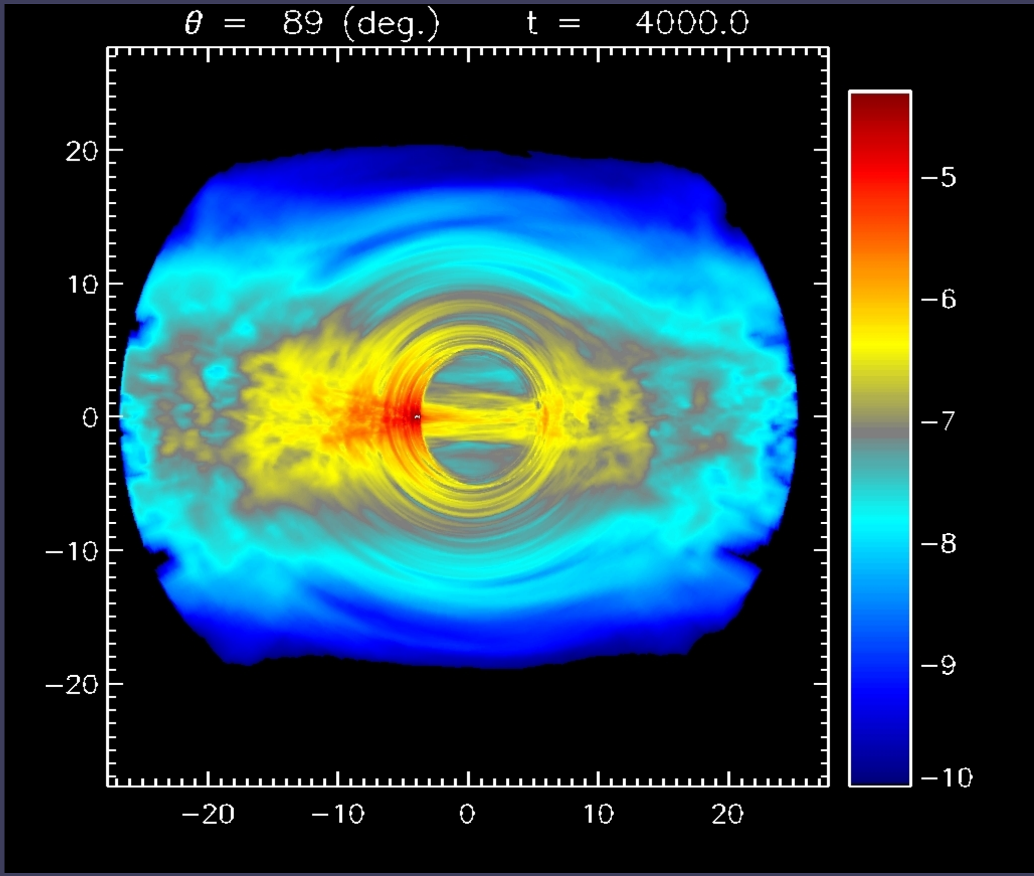
➢ Possibly greater difference for $a_{BH} < 0.9$ when ISCO is further out of the potential well.

Summary & Conclusions

- Comparison between cooled HARM3d and dVH runs:
  - HARM3d has less reconnection at horizon, more along the cutout boundary
  - HARM3d produces less power in the jet, reducing its relative efficiency to dVH
  - dVH has enhanced stress w/o enhanced magnetic field strength
  - Accretion rates surprisingly similar
  - Sudden cooling can trap magnetic field and enhance accretion

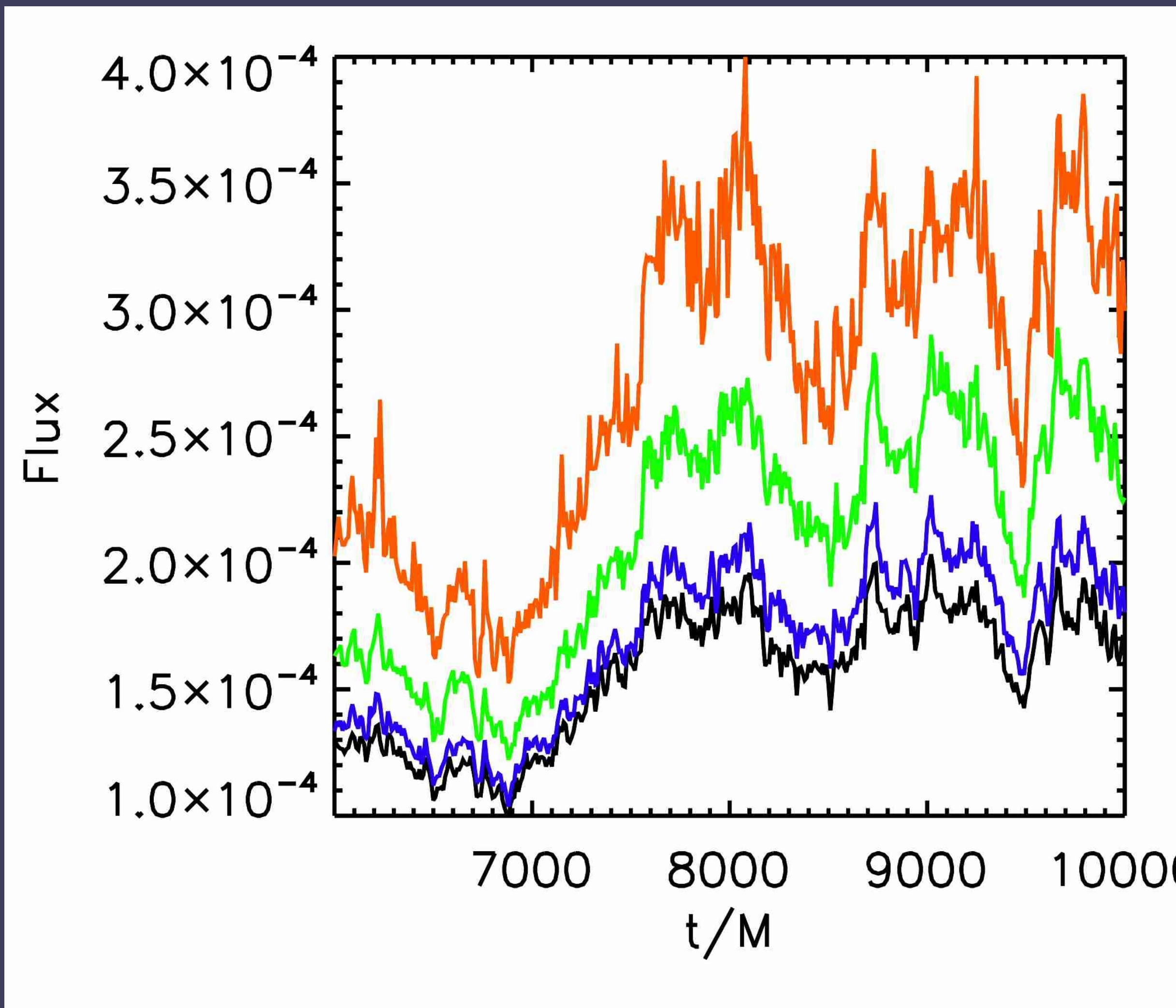
Future Work

- 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



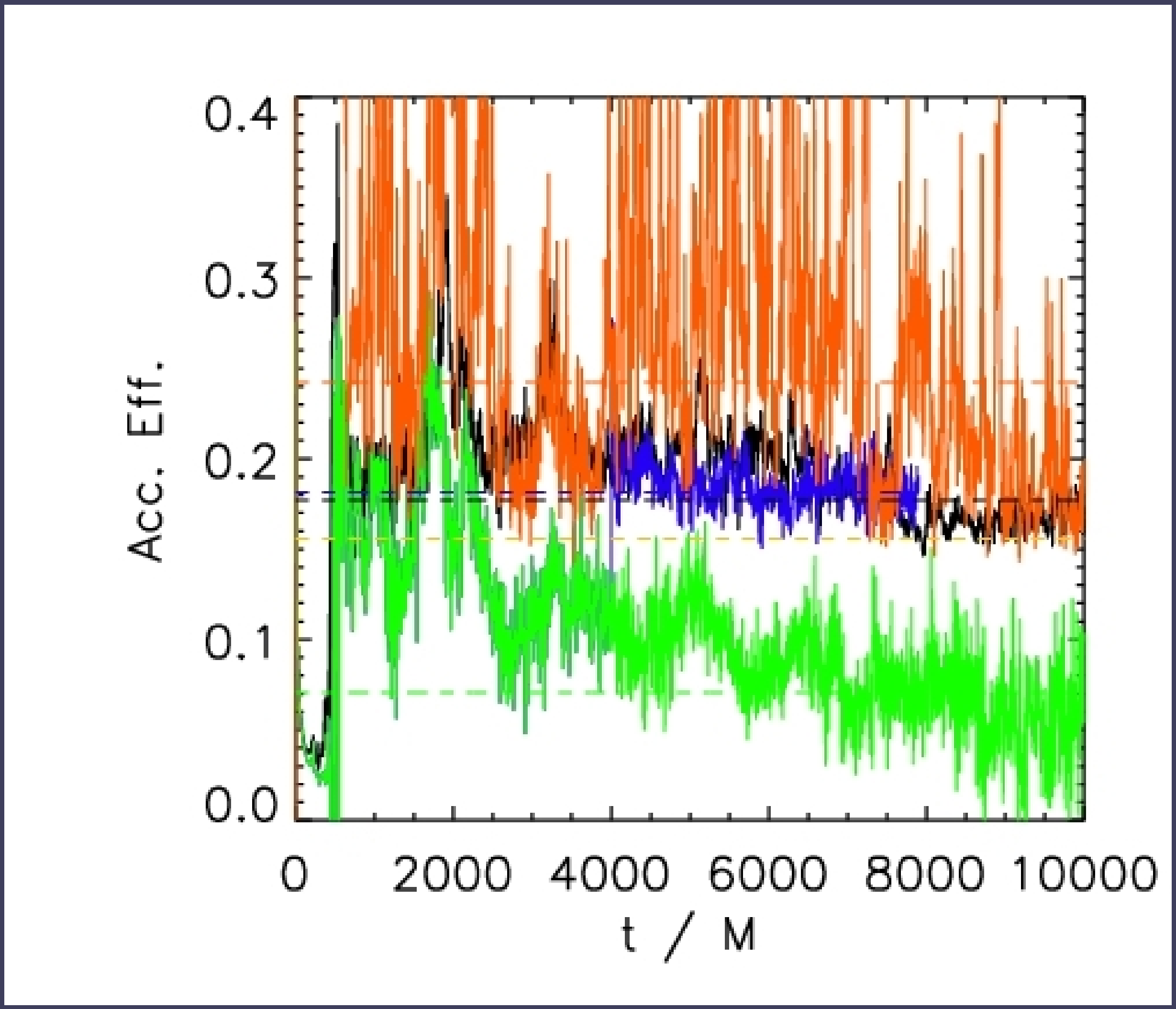
$\theta = 5\,deg.$

$\theta = 35\,deg.$

$\theta = 65\,deg.$

$\theta = 89\,deg.$

HARM3D vs. dVH



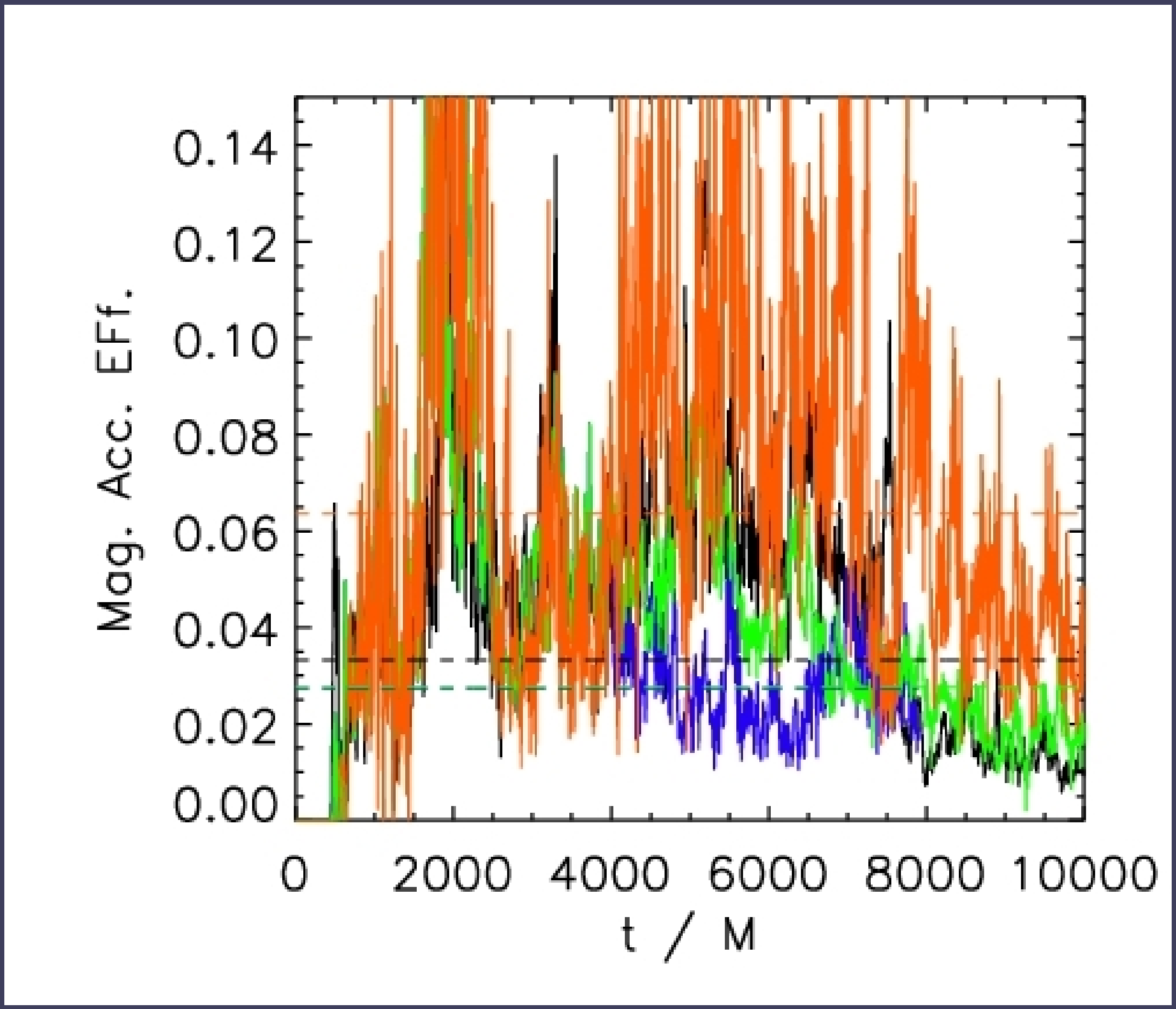
Cooled from t=0M

Cooled from t=4000M

Uncooled

dVH

HARM3D vs. dVH



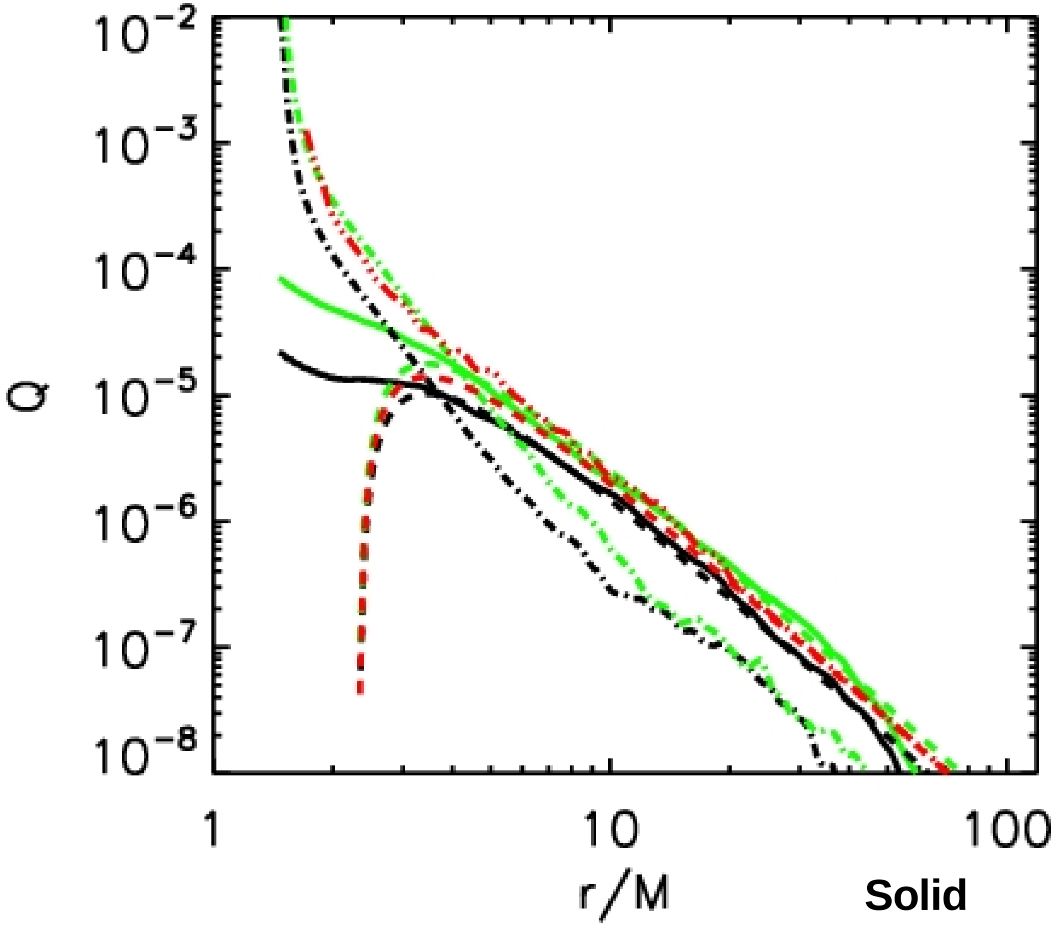
Cooled from t=0M

Cooled from t=4000M

Uncooled

dVH

HARM3D vs. dVH



Cooled from t=0M

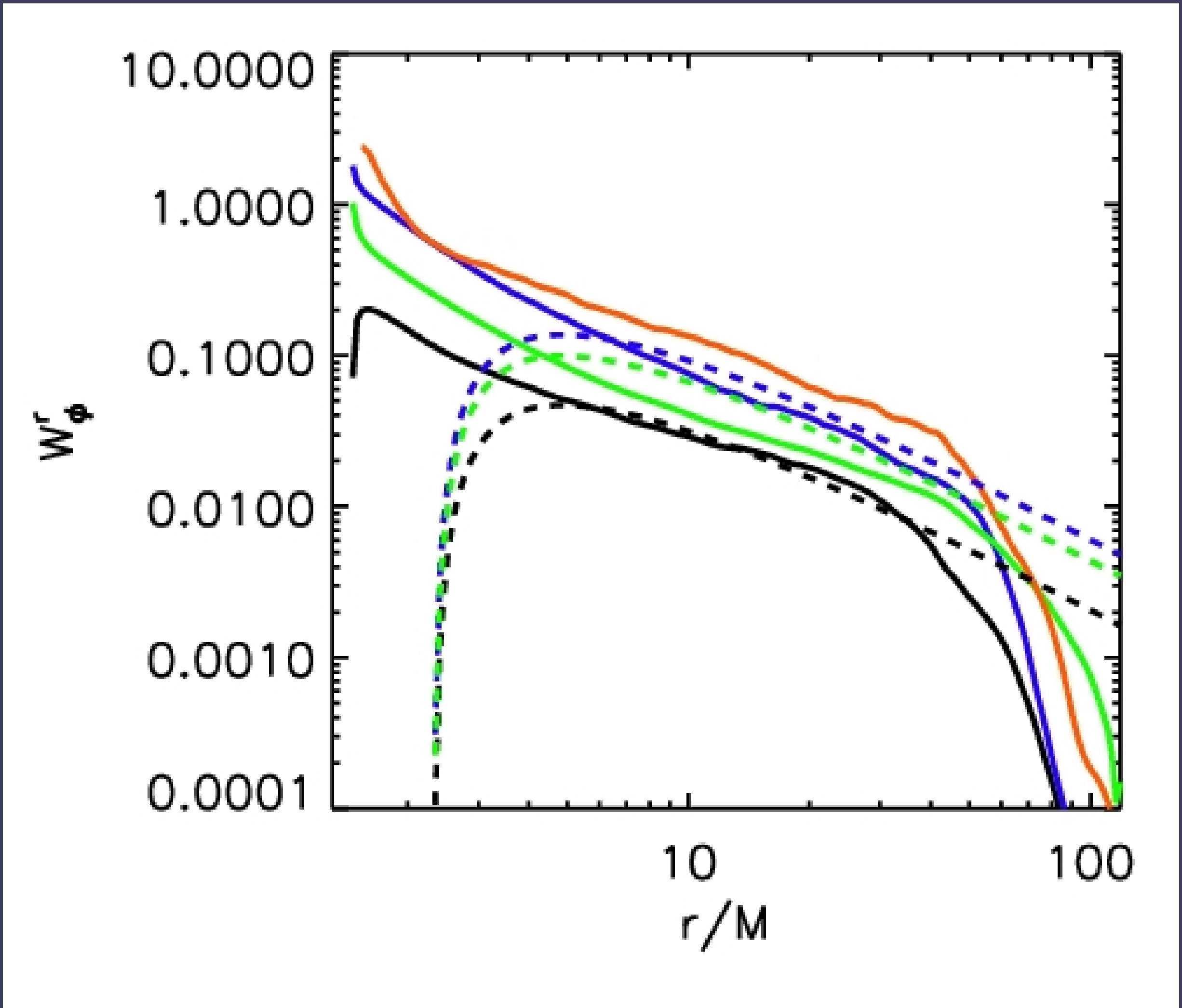
Cooled from t=4000M

dVH

Solid : Local Dissipation
Dashed : Novikov-Thorne
Dot-Dashed : Beckwith et al. (2008)

HARM3D vs. dVH

Stress



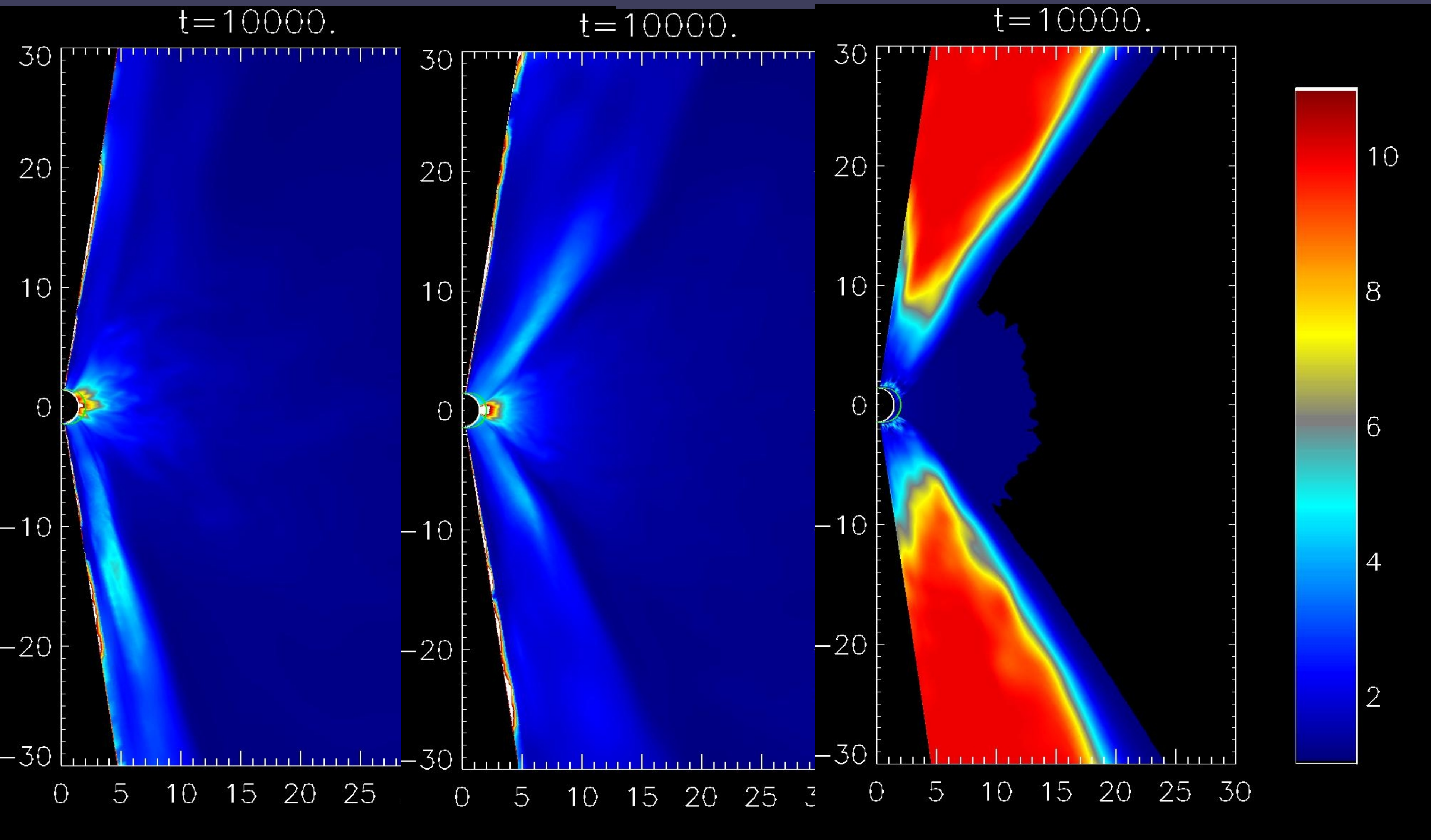
Cooled from t=0M

Cooled from t=4000M

Uncooled

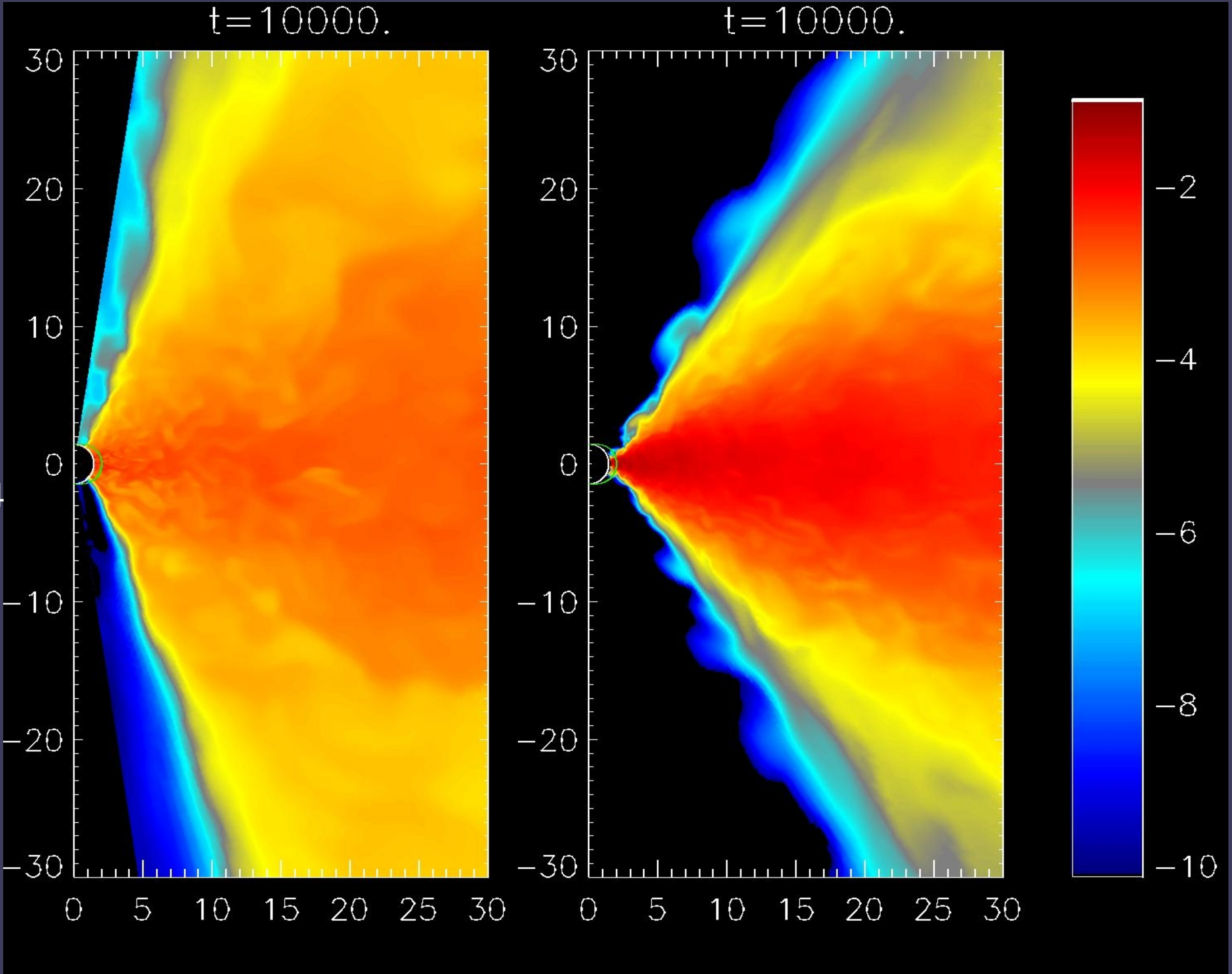
dVH

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



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

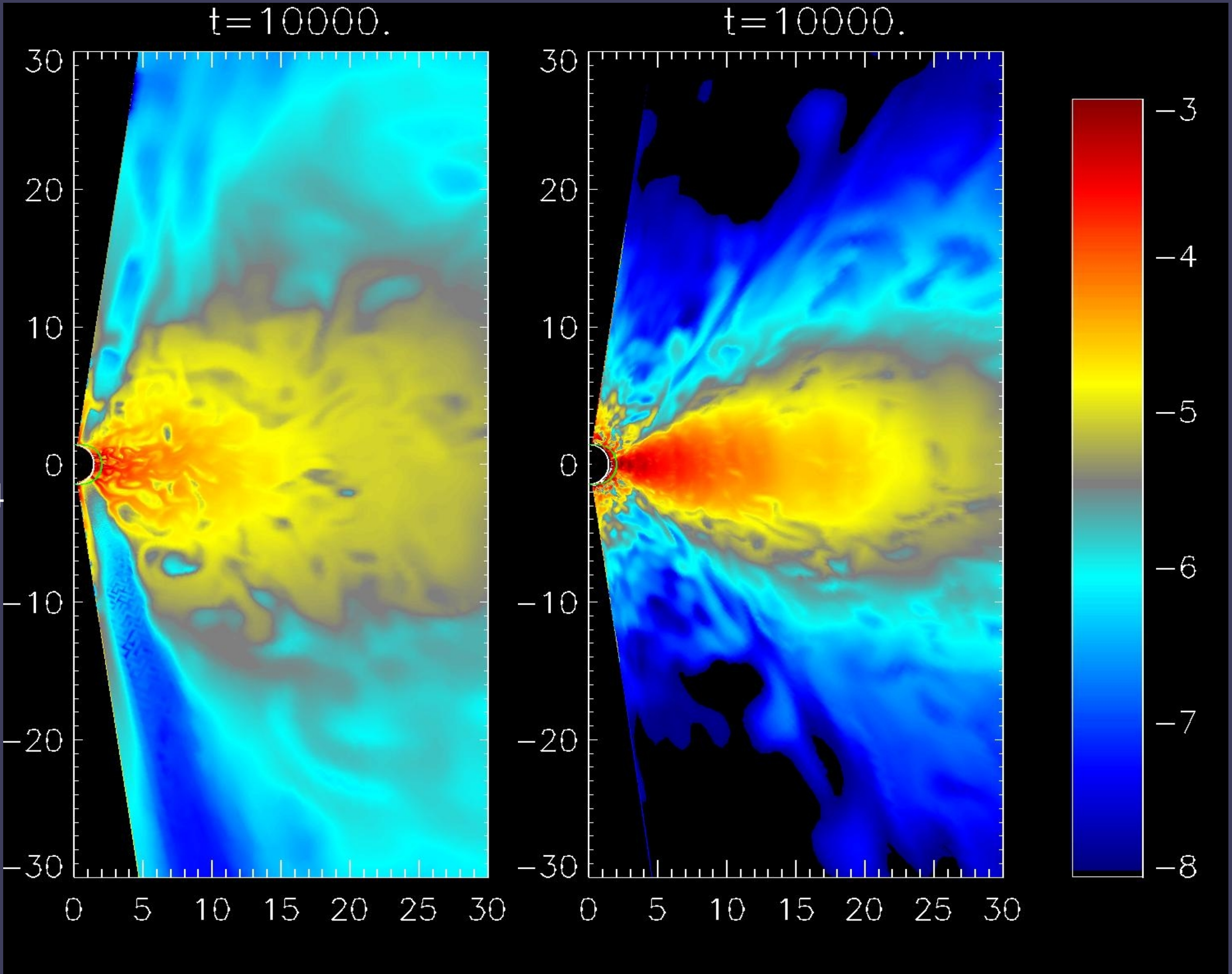
HARM3D vs. dVH $\log(\rho)$



192x192x64
a = 0.9 M

HARM3D vs. dVH $\log(P)$

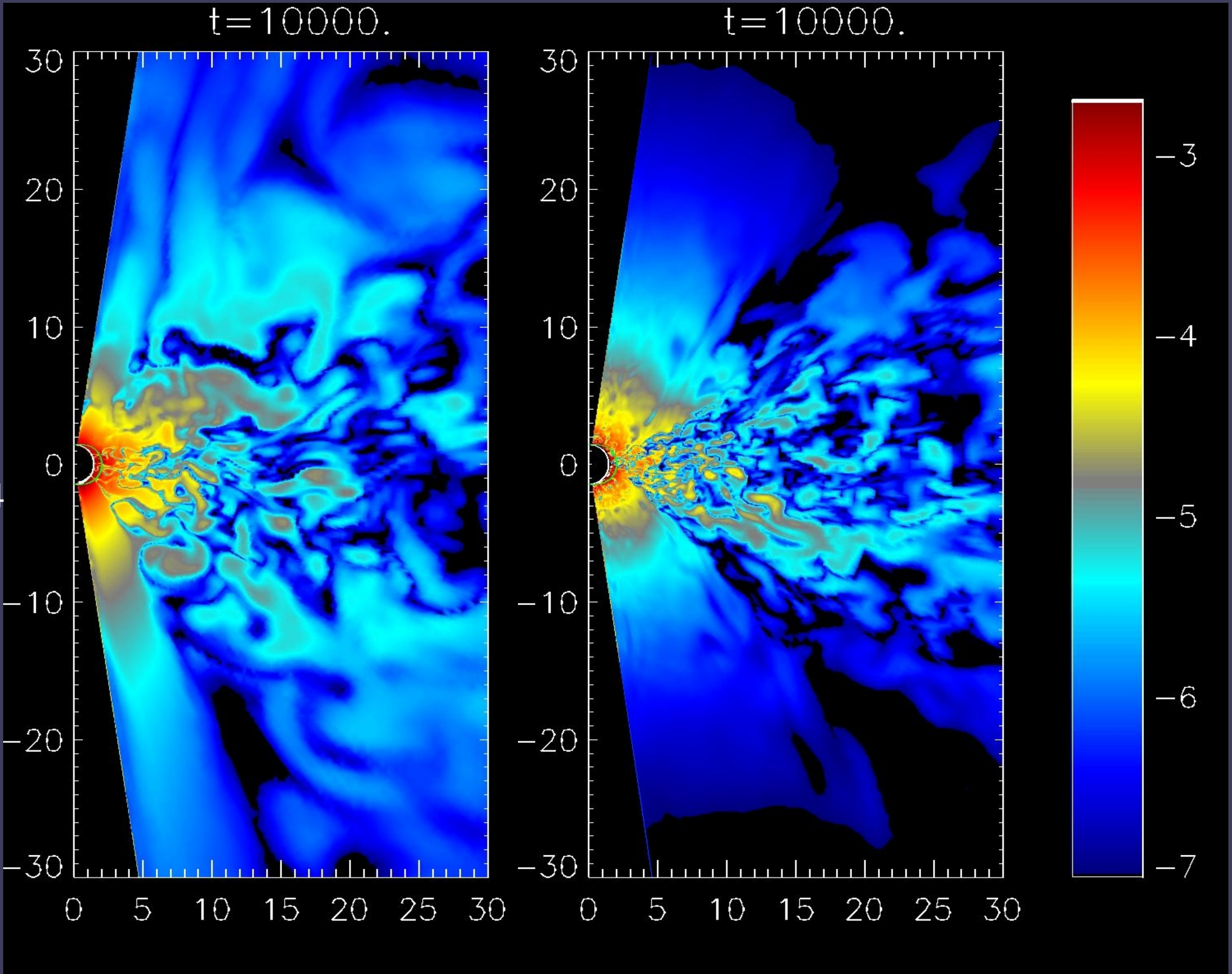
192x192x64
a = 0.9 M



HARM3D vs. dVH

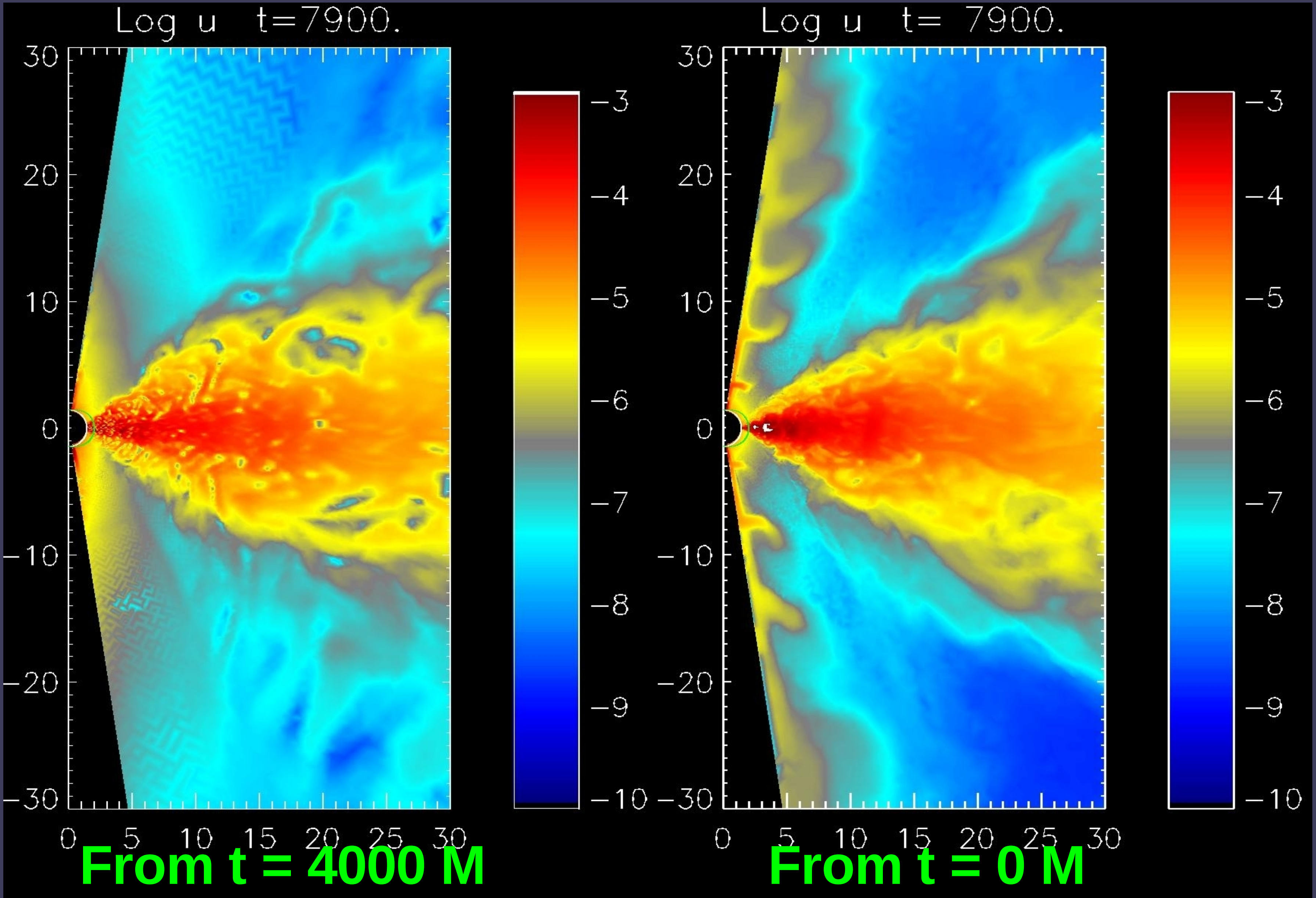
$\log(P_{mag})$

192x192x64
a = 0.9 M



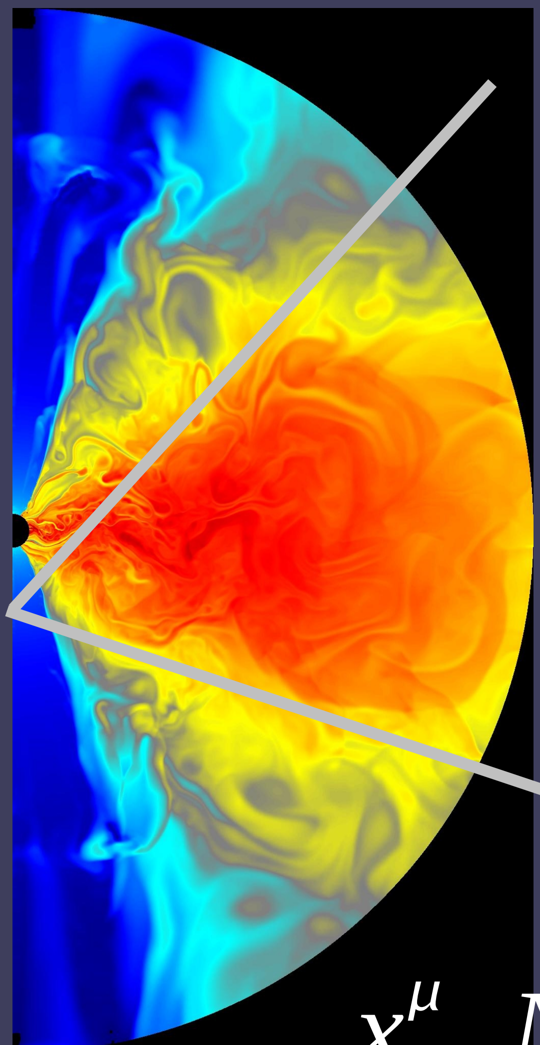
Cooled #1 vs. Cooled #2

$\log(P)$



Radiation Transfer in GR: Step #1

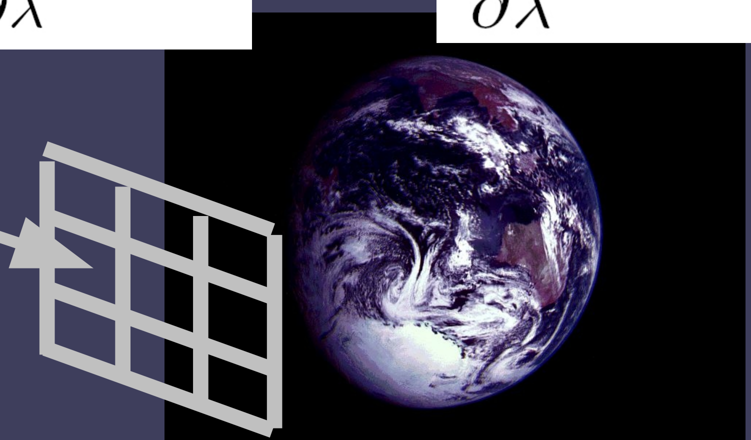
- Post-processing calculation
- Assume geodesic motion (no scattering):
- Rays start from Camera;
- Aimed at Camera, integrated to source
- Integrated back in time;
- A geodesic per image pixel ;
- Camera can be aimed anywhere at any angle;



$$\frac{\partial x^\mu}{\partial \lambda} = N^\mu$$

$$\frac{\partial N_\mu}{\partial \lambda} = \Gamma^\nu{}_{\mu\eta} N_\nu N^\eta$$

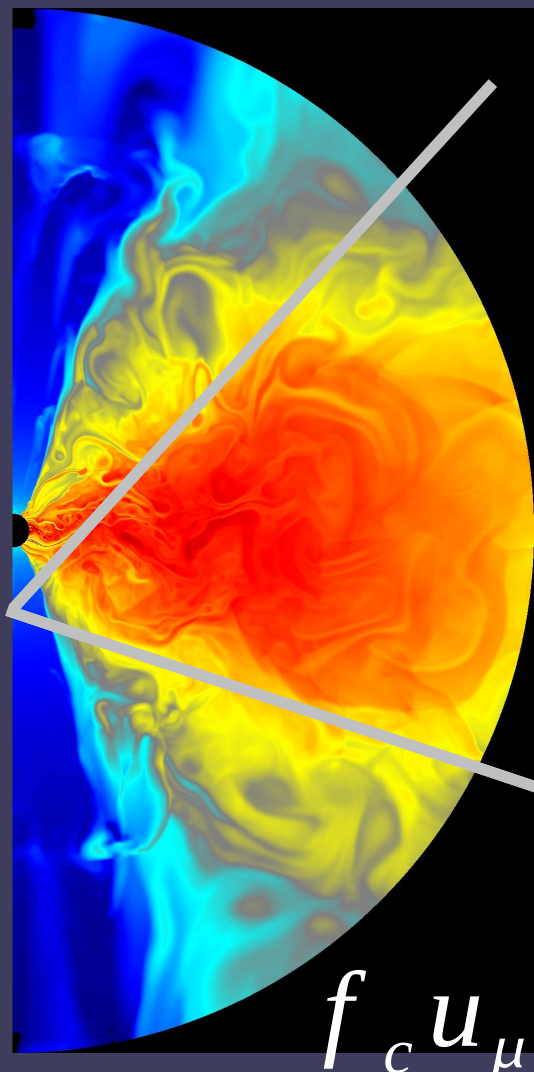
x^μ , N^μ

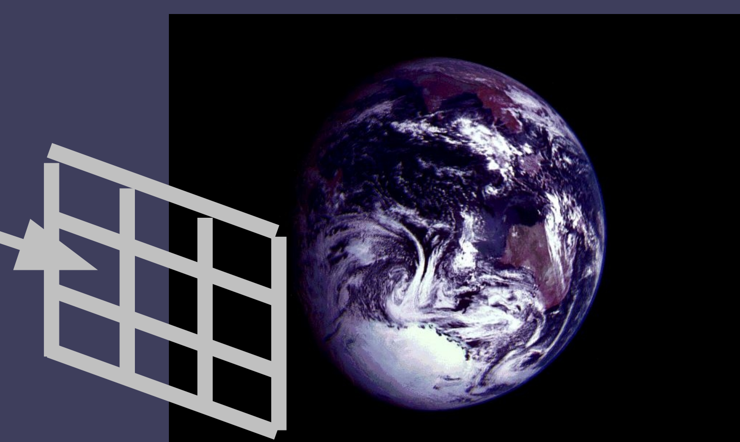


(objects not shown to scale)

Radiation Transfer in GR: Step #2

- Interpolate simulation data along rays
- Spatially interpolate single timeslice per image
  - Assume $t_{dyn} >> t_{crossing}$





(objects not shown to scale)

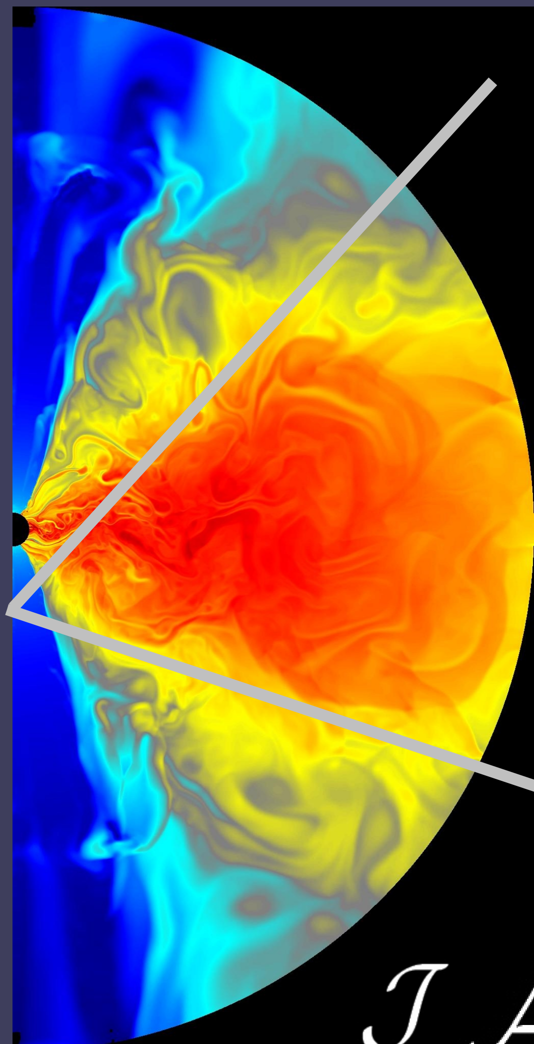
Radiation Transfer in GR: Step #3

- Calculate frame-independent quantities:

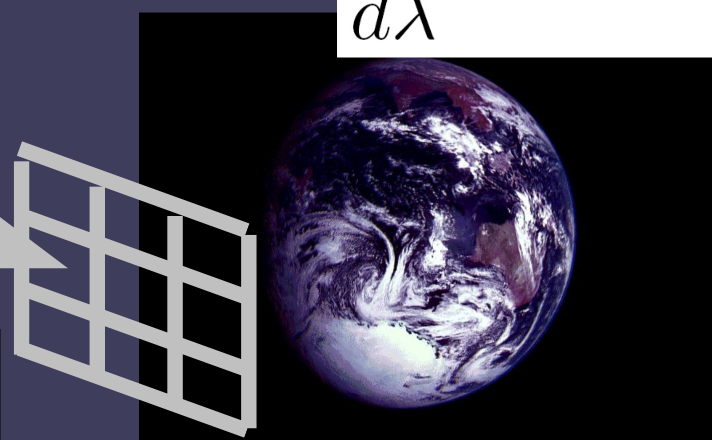
$$\mathcal{J} = \frac{j_\nu}{\nu^2} \qquad \mathcal{A} = \nu \alpha_\nu \qquad \mathcal{I} = I_\nu / \nu^3$$

- Integrate frame-independent RT equation along geodesics:

$$\frac{d\mathcal{I}}{d\lambda} = \mathcal{J} - \mathcal{A}\mathcal{I}$$

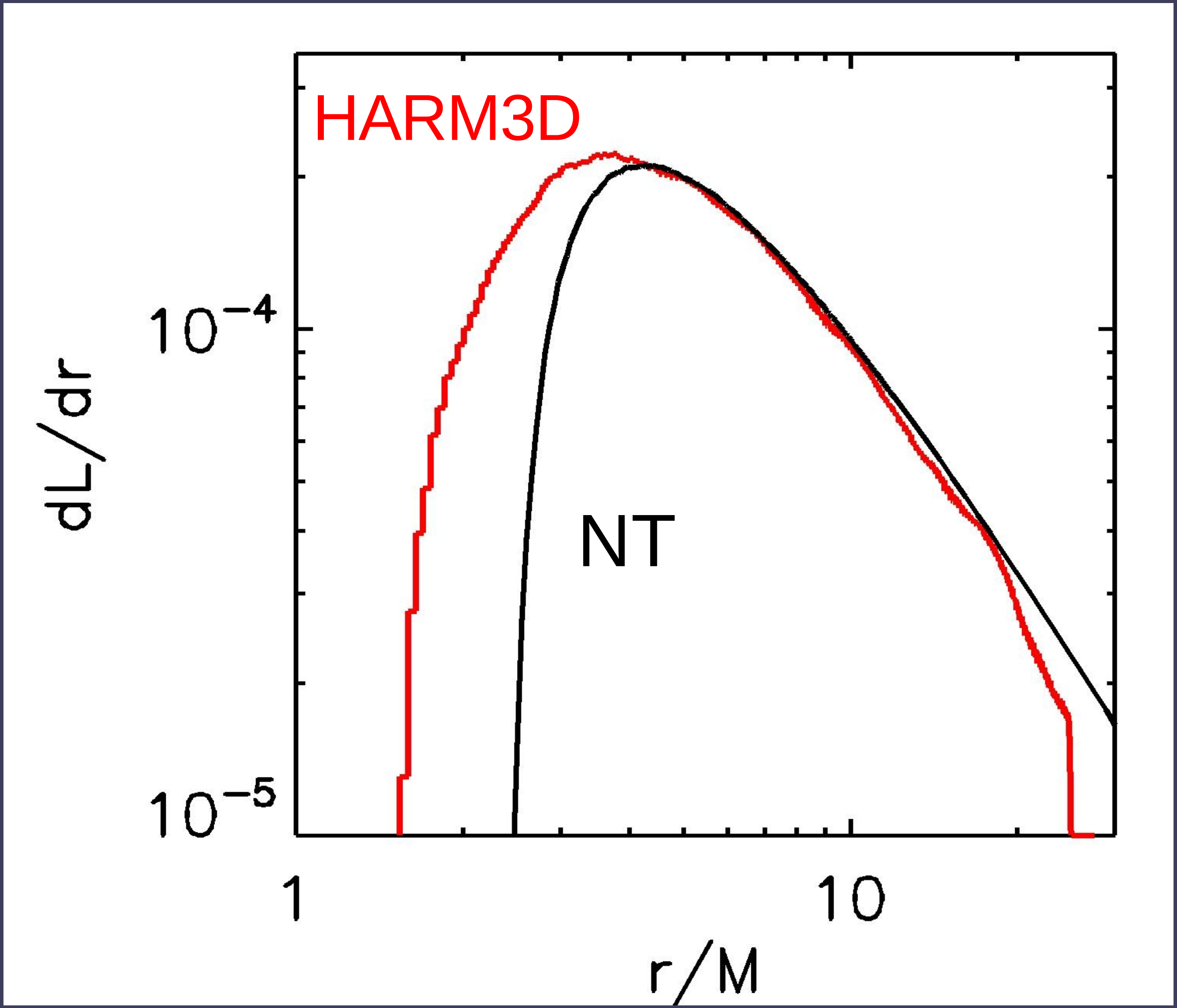


$\mathcal{J}$ $\mathcal{A}$ $\mathcal{I}$

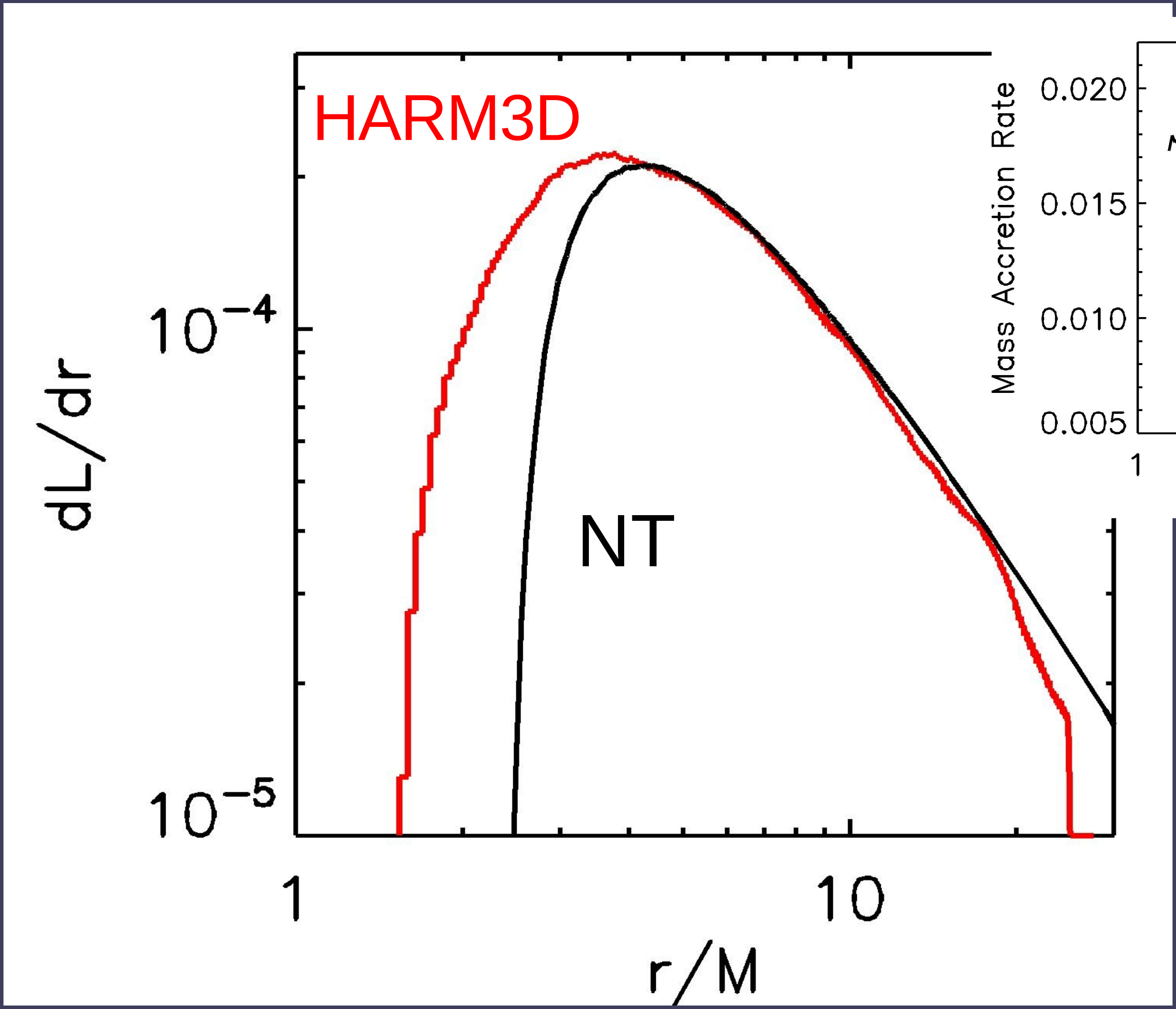


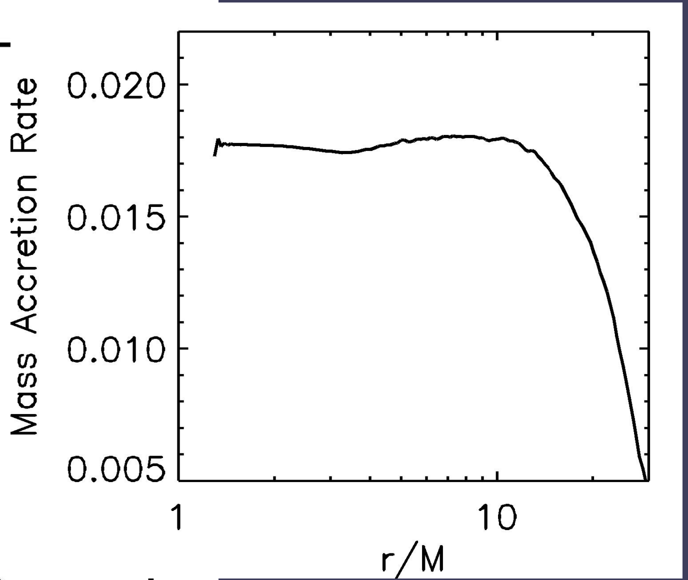
(objects not shown to scale)

Observer Frame Luminosity: Angle/Time Average

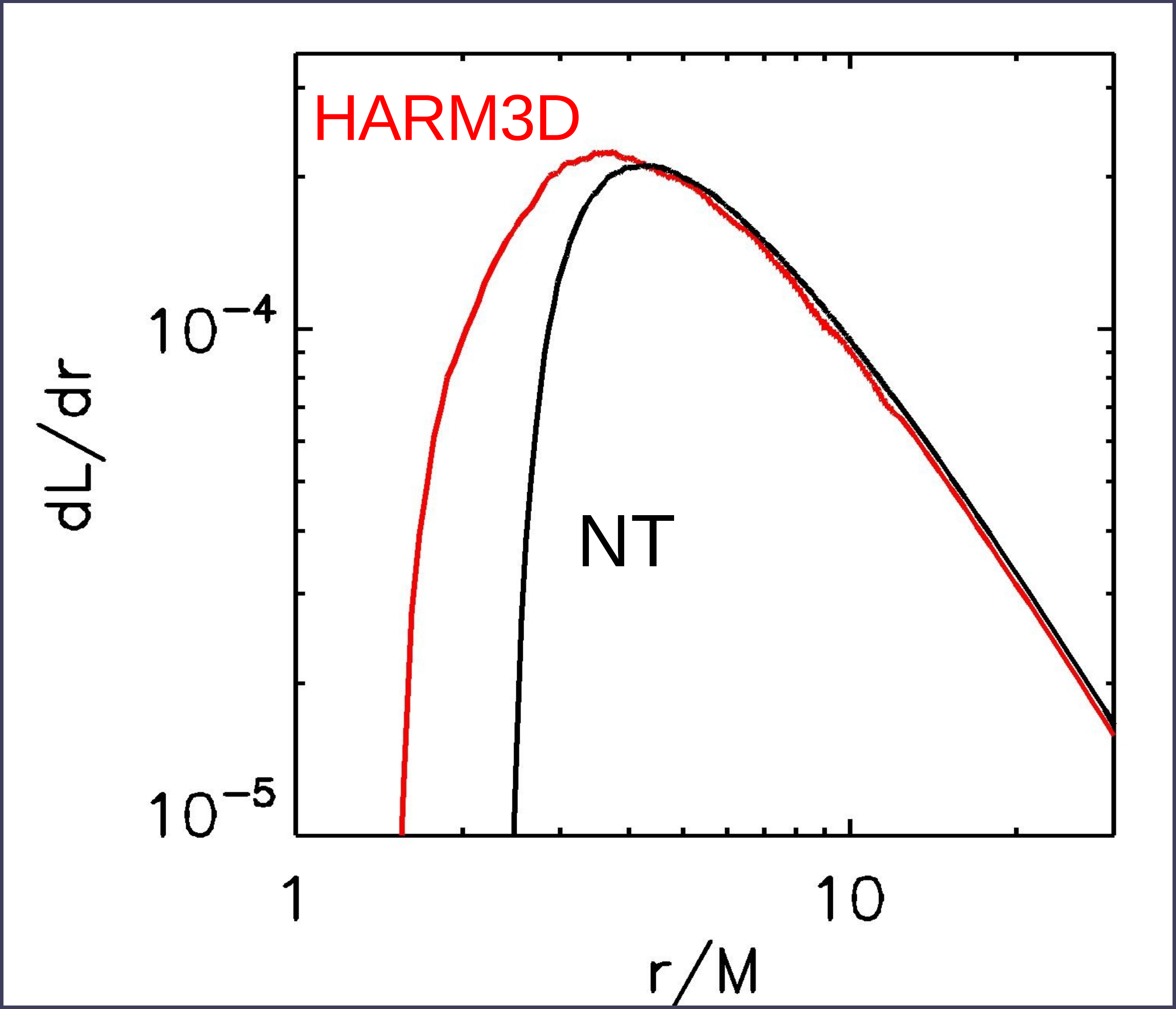


Observer Frame Luminosity: Angle/Time Average





Observer Frame Luminosity: Angle/Time Average



Assume NT profile for r > 12M .

$\Delta L = 4\% \ L$