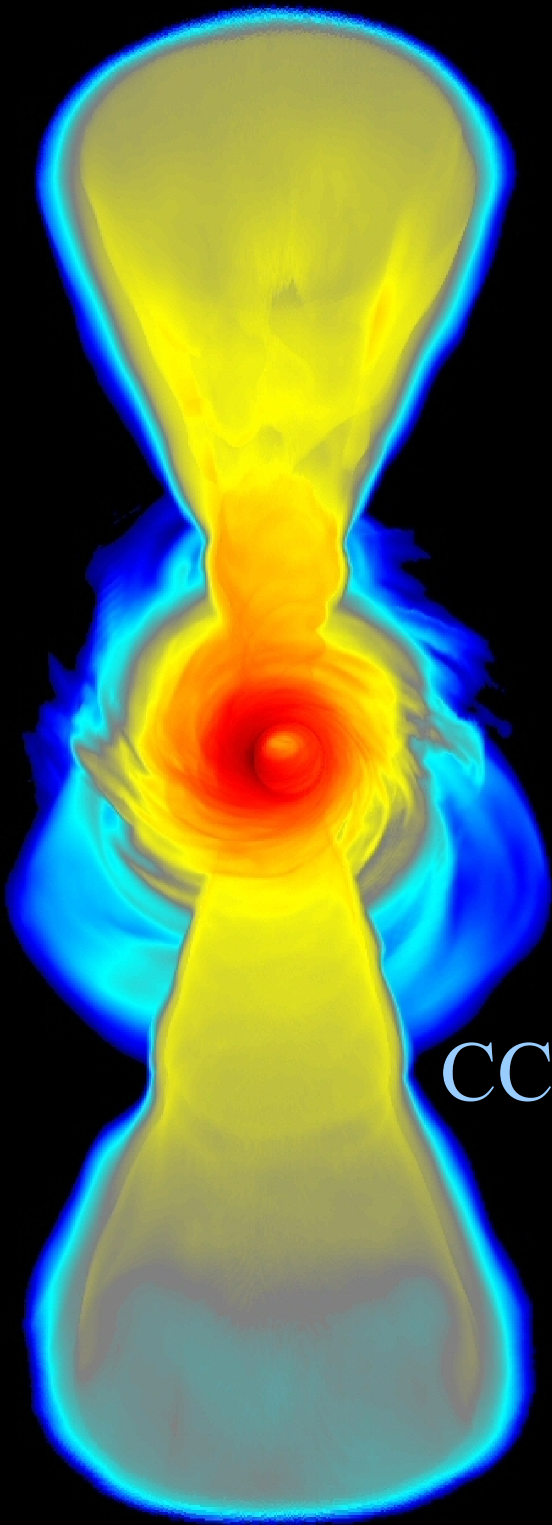
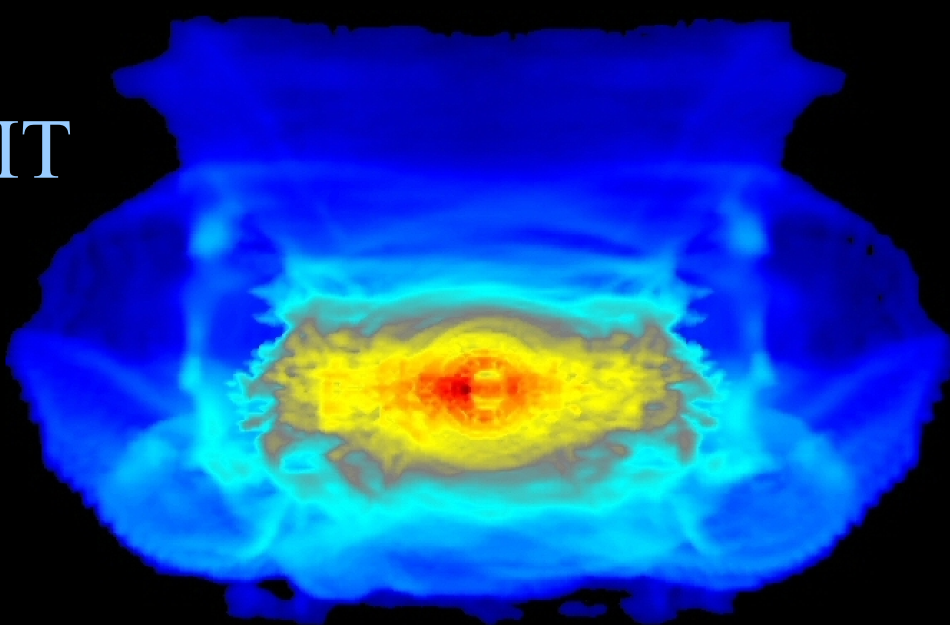


Simulating Black Hole Lighthouses

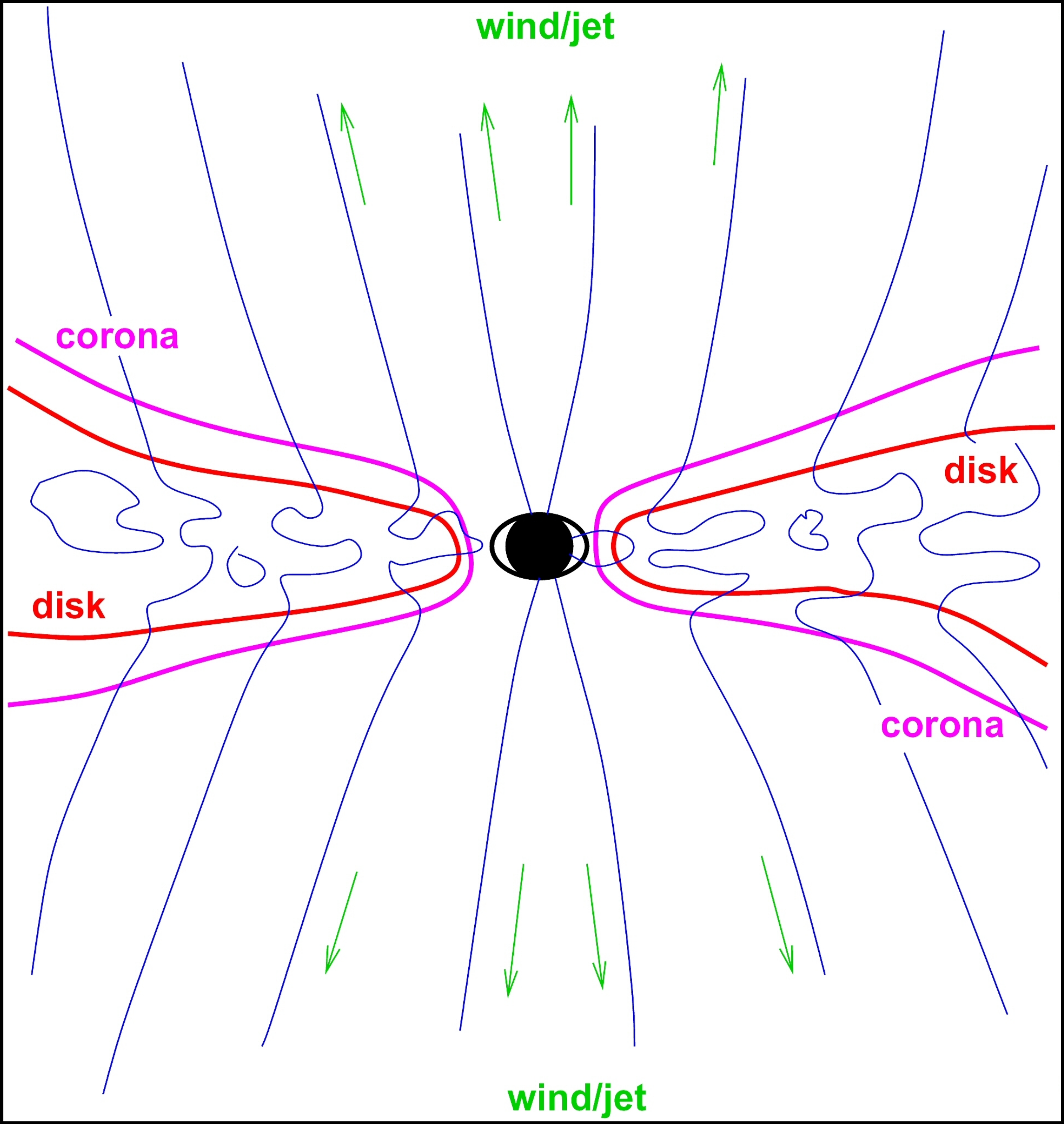
Scott C. Noble (JHU)
with
Julian Krolik (JHU)

CCRG Seminar, RIT
May 16, 2008



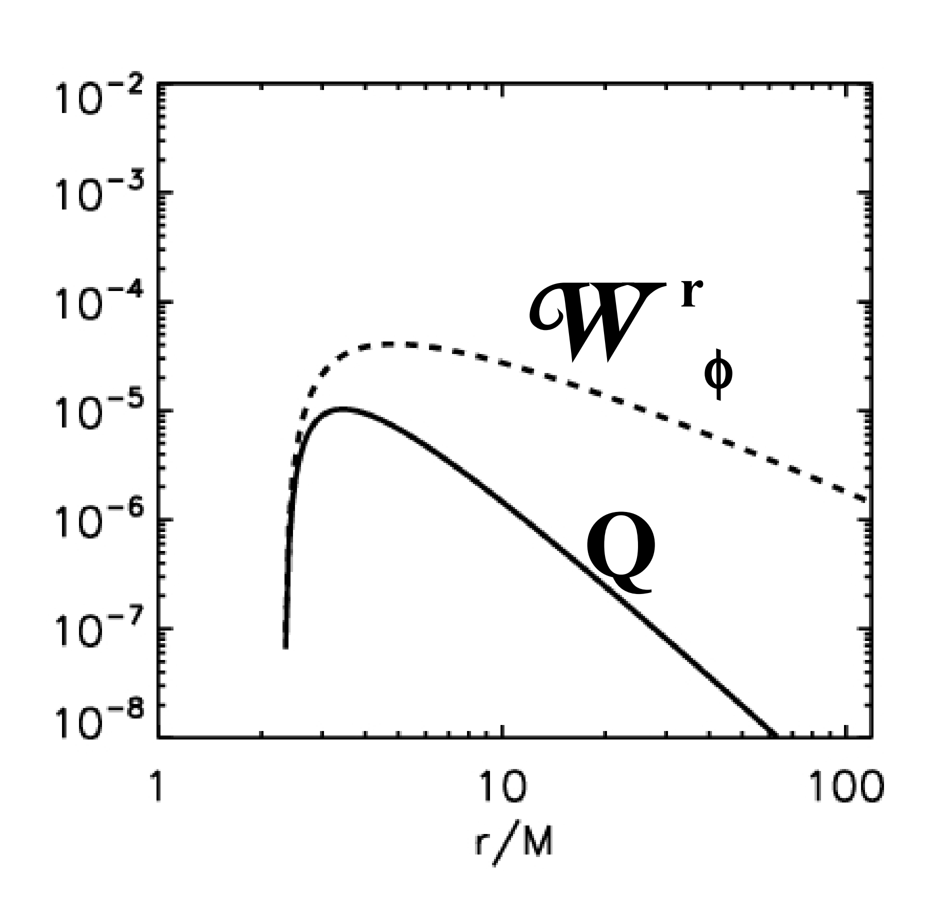
Astrophysical Disks

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



wind/jet
corona
disk
disk
corona
wind/jet

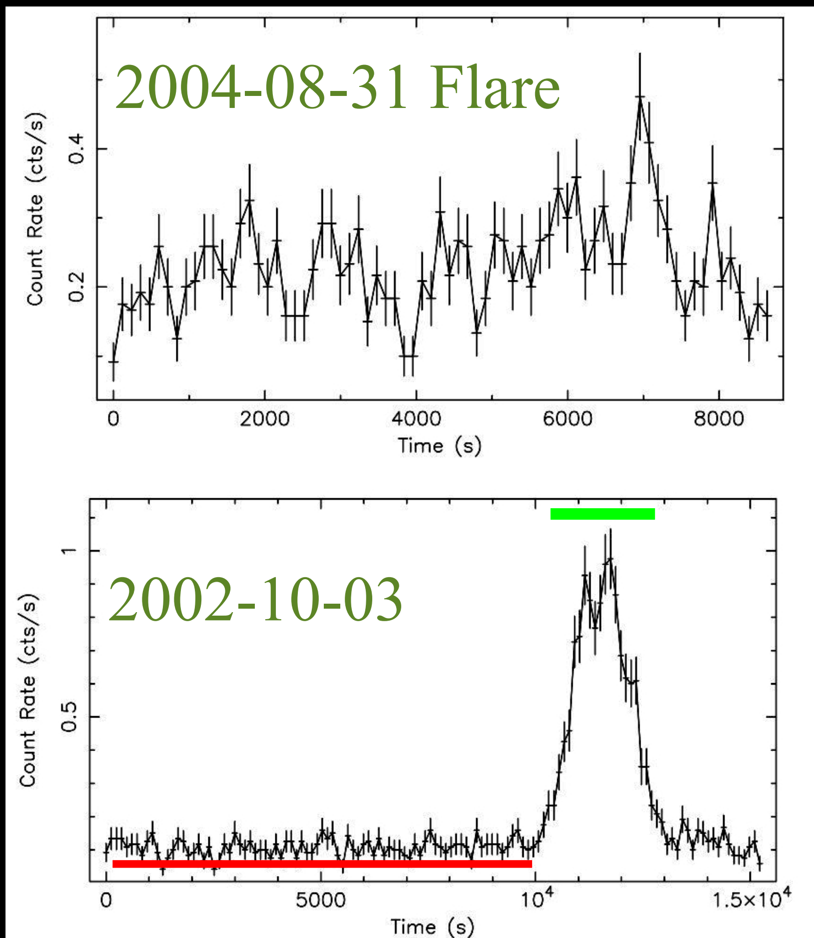
Novikov – Thorne (NT) (1973)

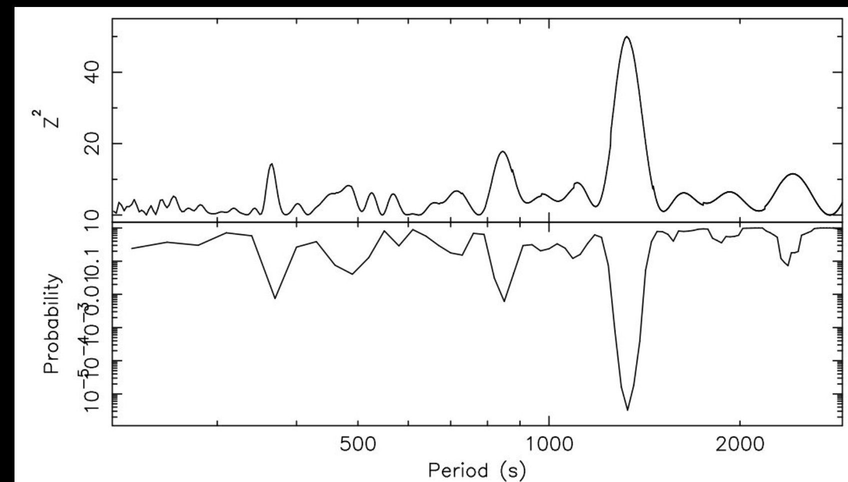


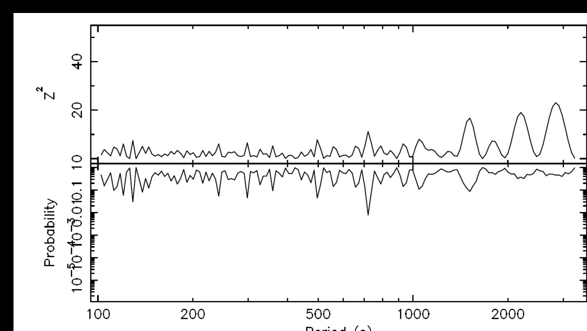
- Time-steady radiatively efficient (thin) disk model
- Annuli on equatorial circular orbits on Kerr
- Ang. mom. transport via visc. stress
- Dissipated energy promptly emitted vertically from disk (no reheating)
- Parameterized by accretion rate
- Page & Thorne (1974) :
  - M,E,L conservation laws closed by boundary condition at ISCO
  - Matter at ISCO quickly plunges into black hole
  - → Negligible luminosity beyond ISCO

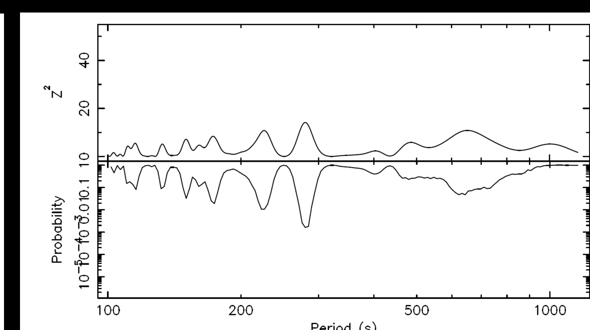
$$\eta = 1 - \dot{E} / \dot{M}$$
$$= 1 - \epsilon_{ISCO}$$

Sgr A*'s Spin





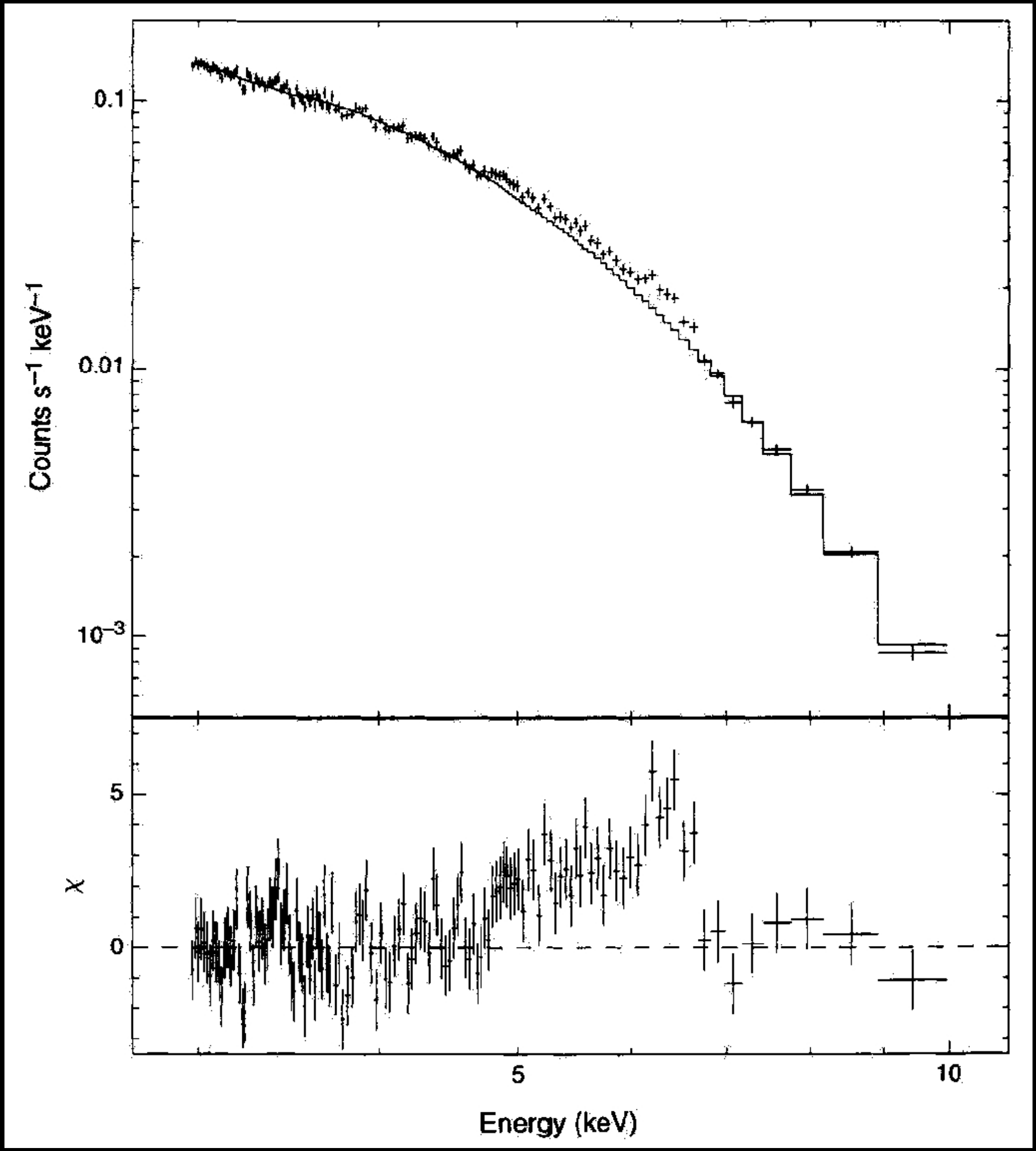




Belanger et al. 2006

-- Monte Carlo generated events sequences
-- 22min periodicity (X-ray) --> **a > 0.22**
-- 1 in 3 million chance of being random

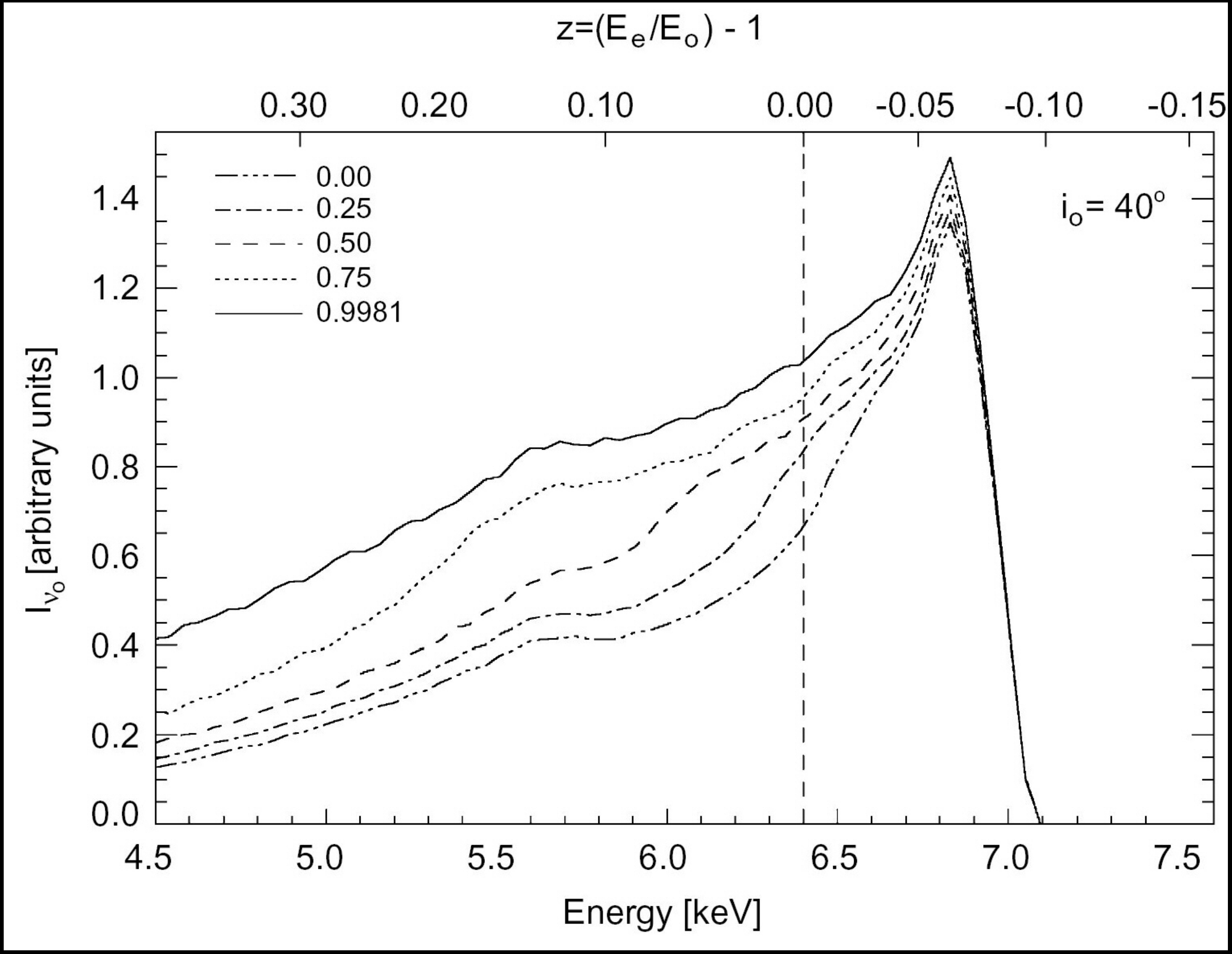
Relativistic Iron-Lines



Tanaka et al. (1995)

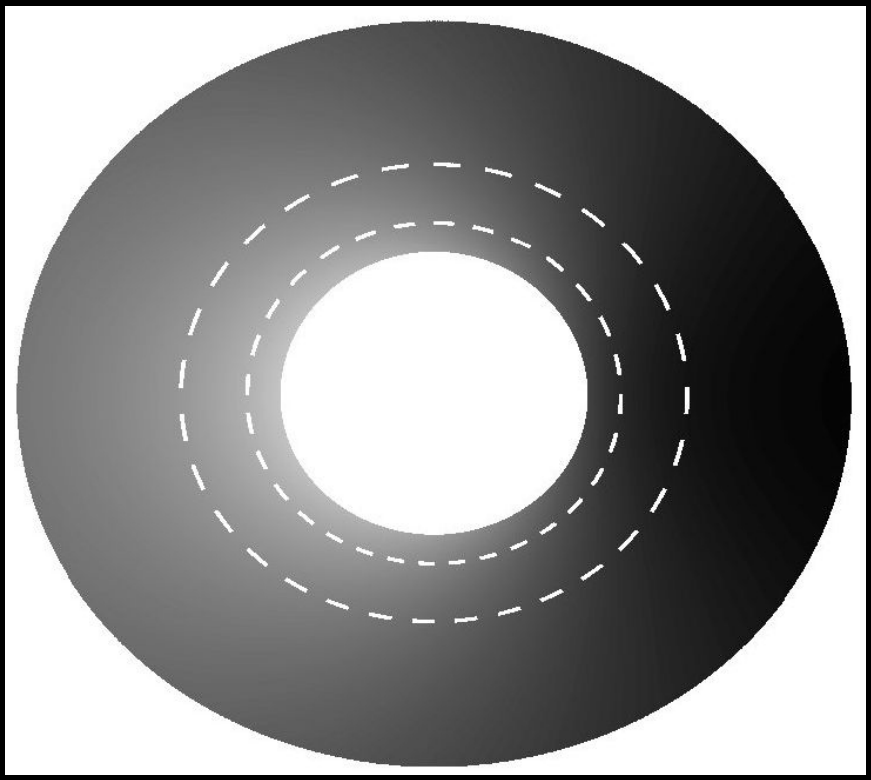
MCG 6-30-15

Relativistic Iron-Lines



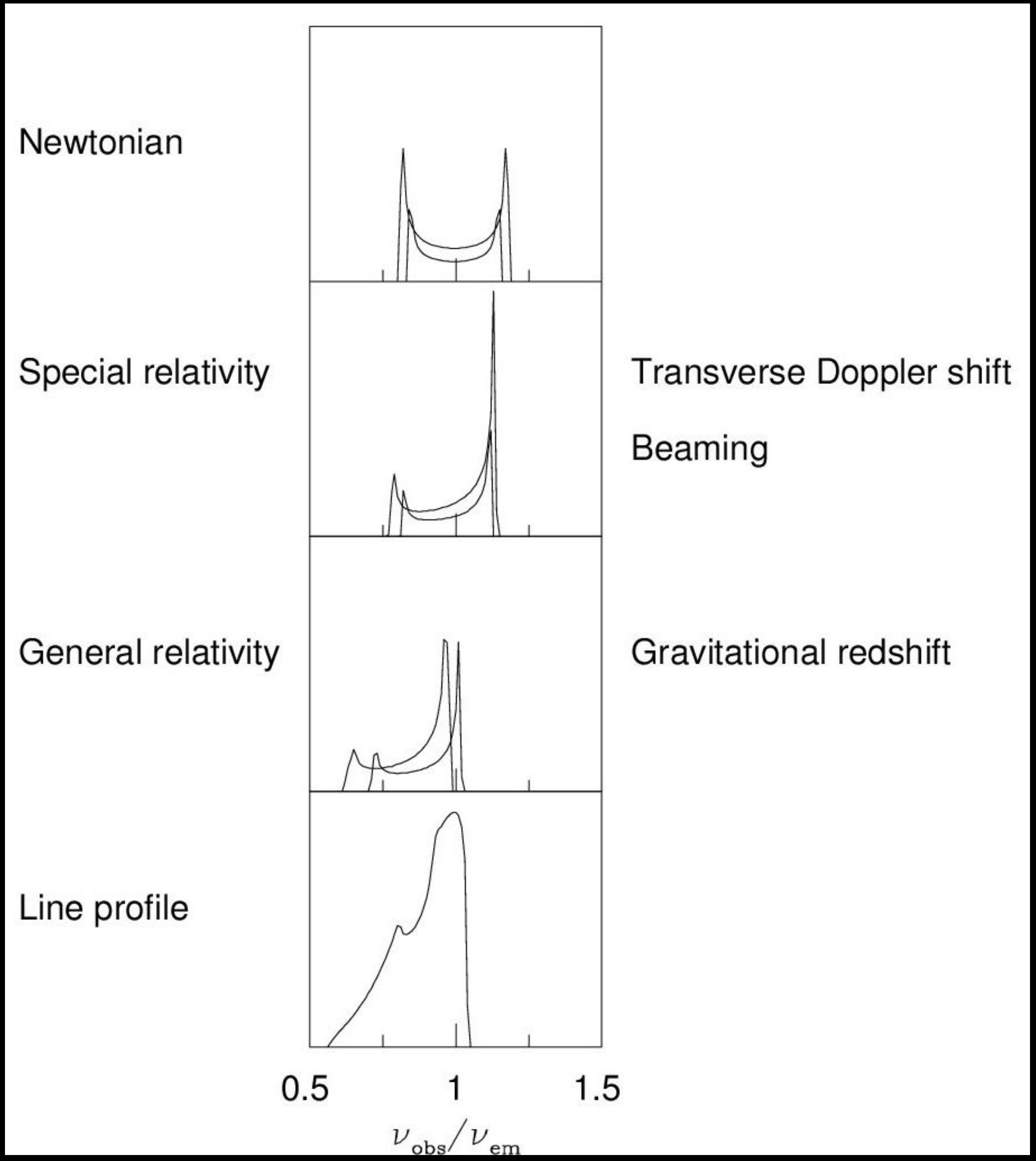
Reynolds & Nowak (2003)

Relativistic Iron-Lines



Fabian et al. (2000)

$$L = A(a, \theta) T^4$$

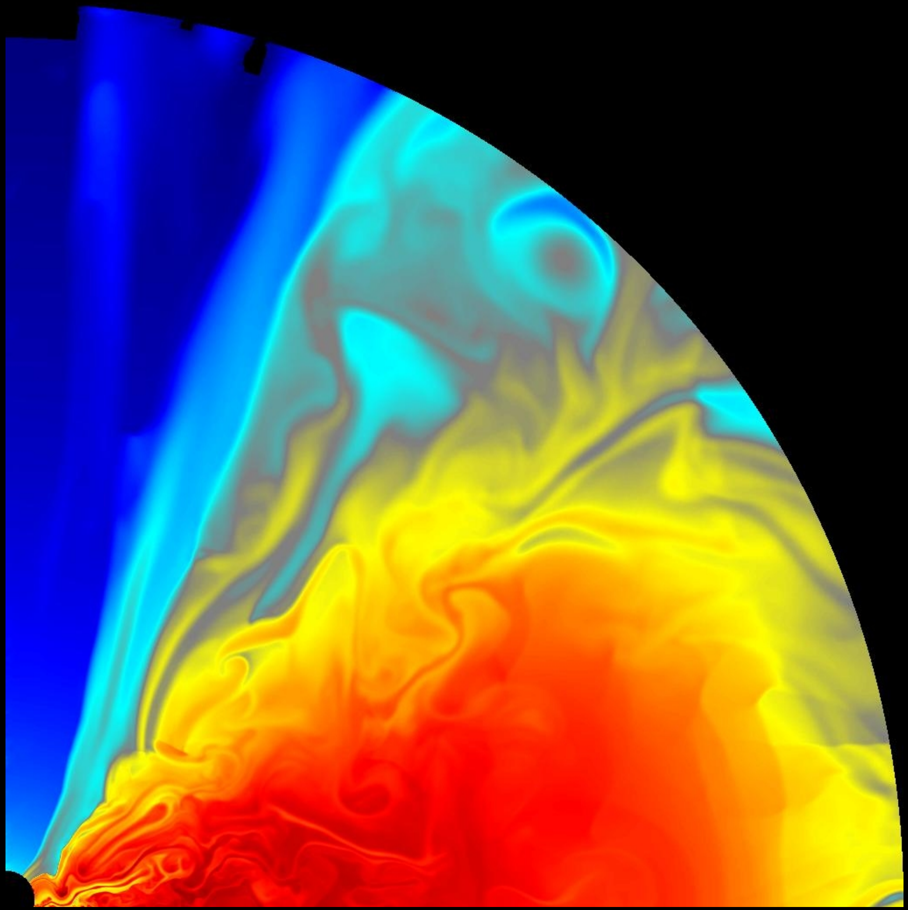


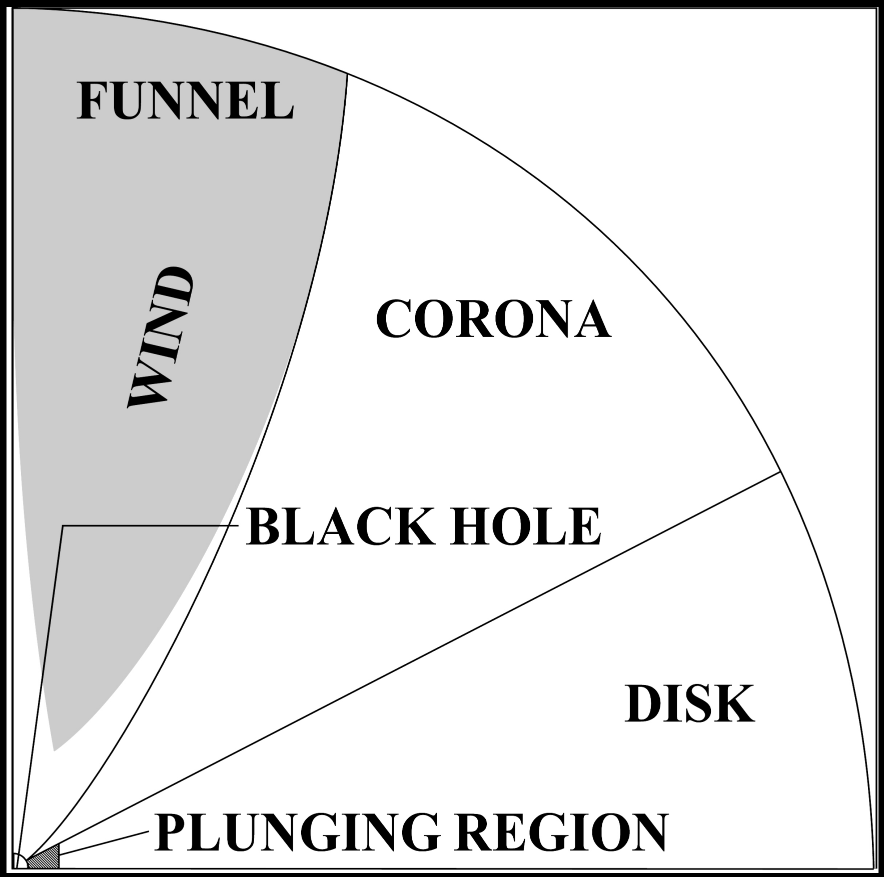
Continuity at ISCO

- Krolik (1999)
  - B-field dynamically significant r < rms
- 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!!!

Disk Morphology

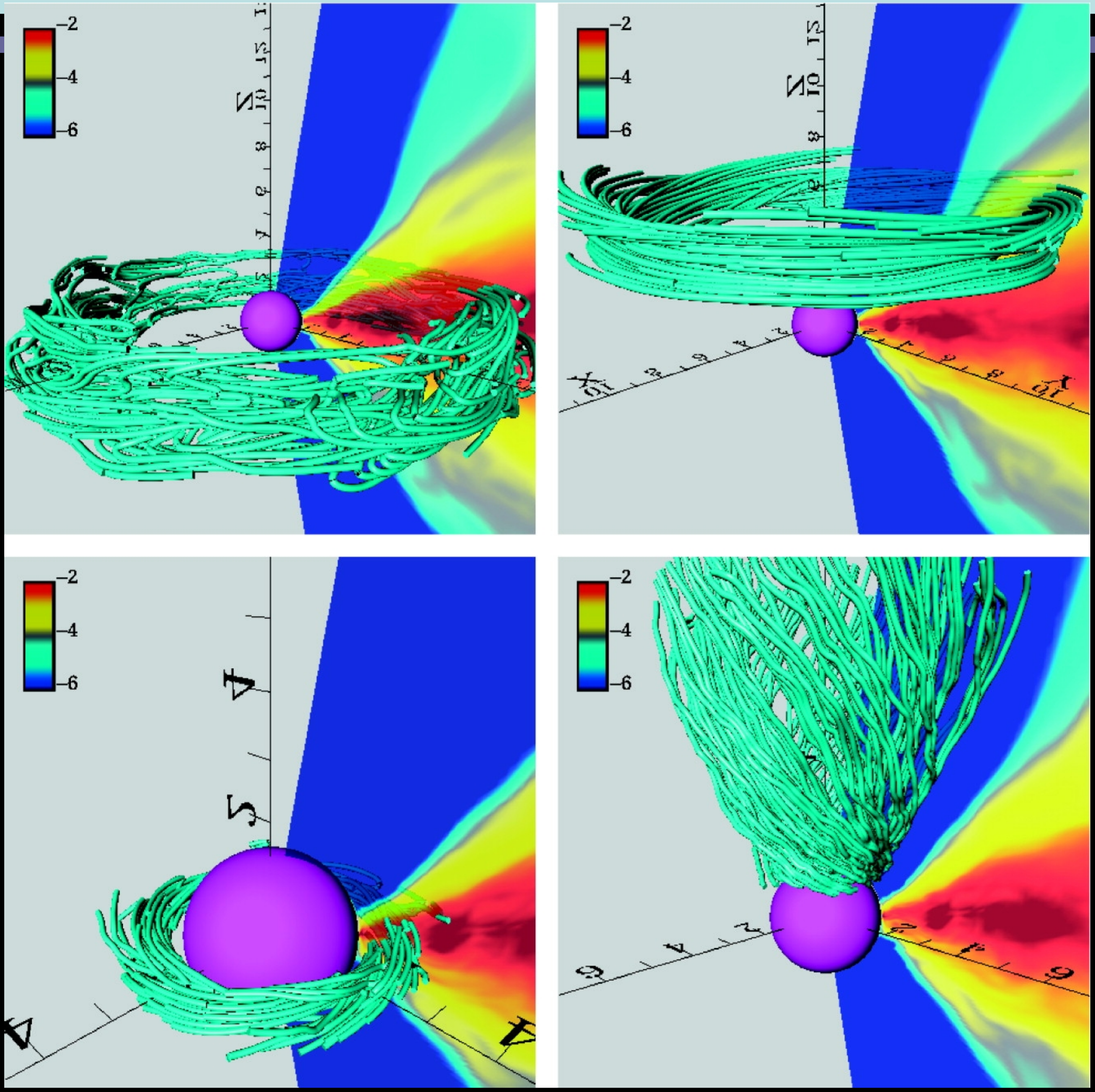




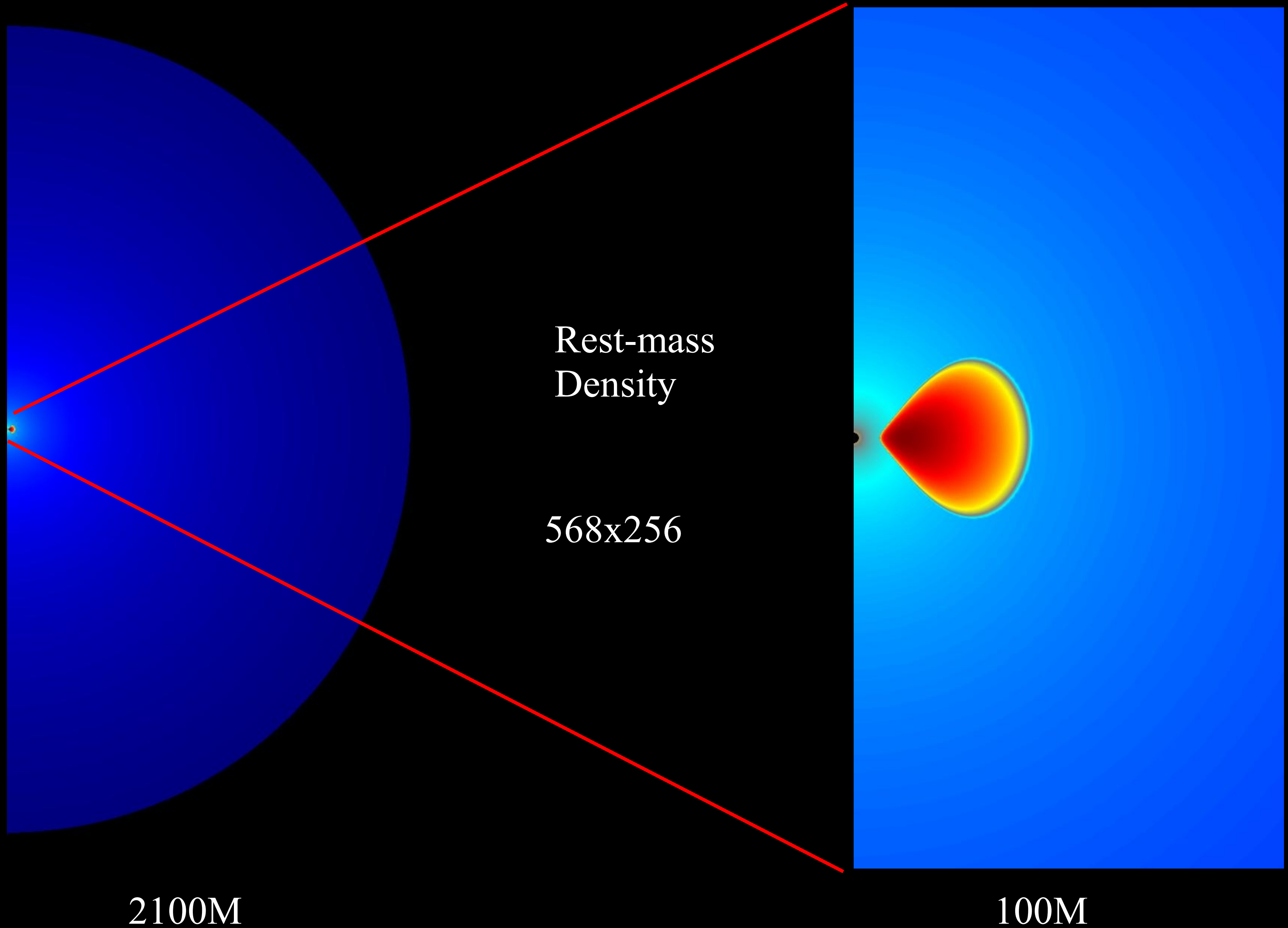
McKinney & Gammie (2004)
Hawley, De Villiers, Krolik, Hirose 2003+

Magnetic Field Structure

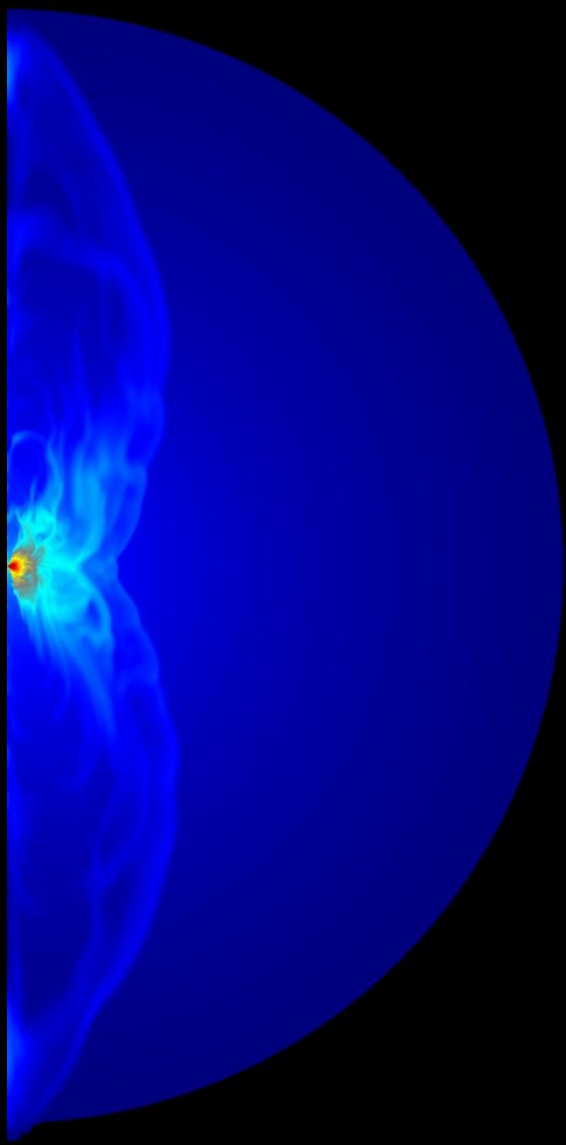
Hirose et al. (2004)



Outflows SCN, Leung, Gammie, Book (2007)



Outflows SCN, Leung, Gammie, Book (2007)

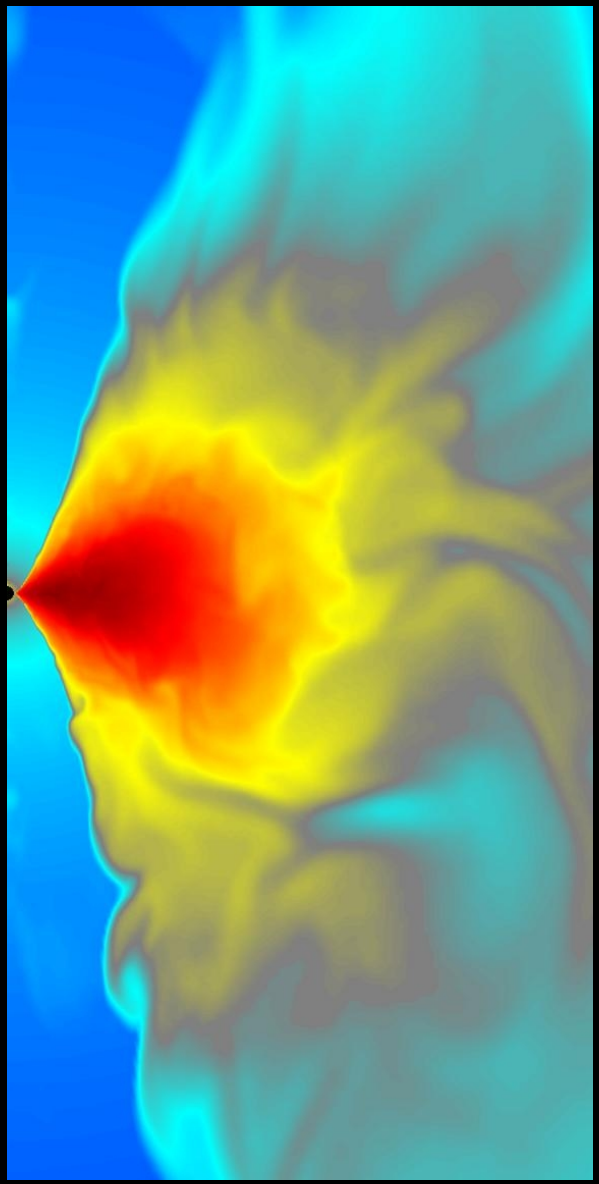


2100M

Rest-mass
Density

568x256

t=2900M



100M

Disk Outflows

$1-3.5$ | $10^{-8}-1\,(\log)$ | $10^{-10}-10^{-3}\,(\log)$ | $0-0.08$

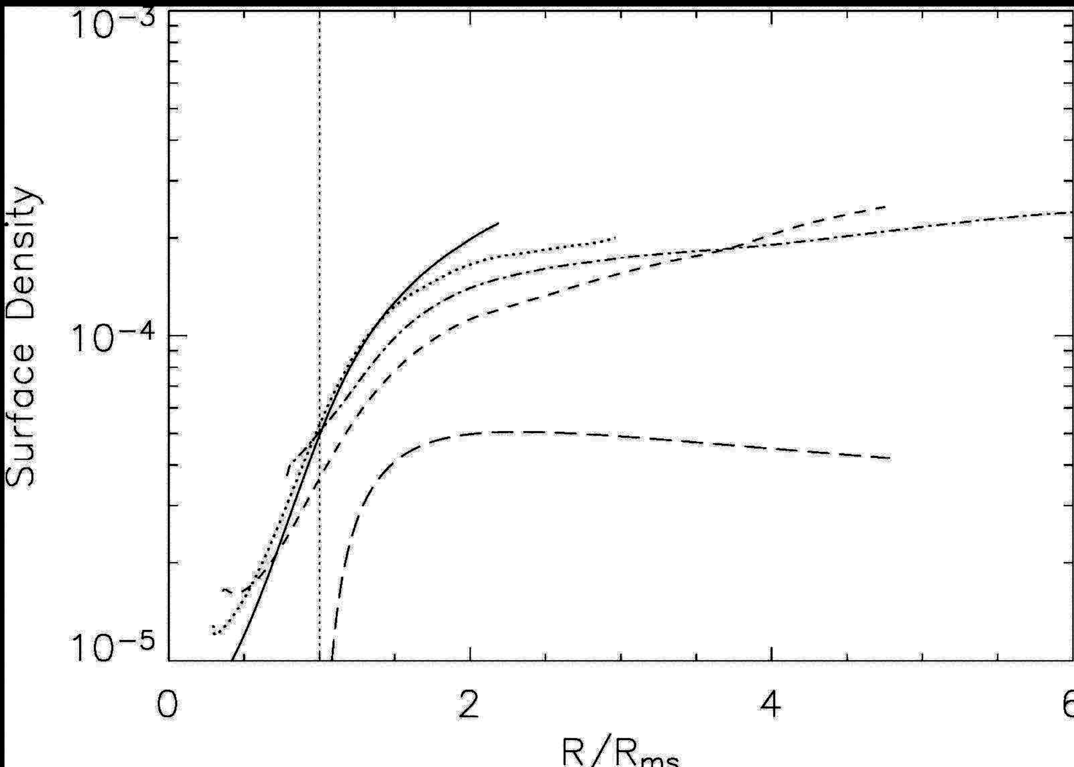
1500M

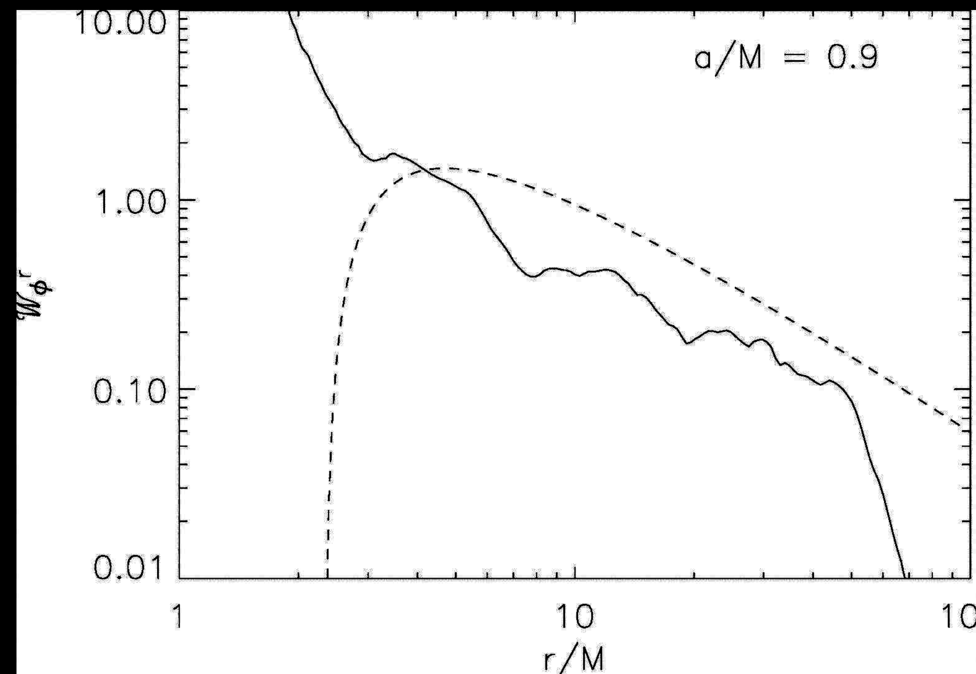
γ | ρ | P_{mag} | A_{ϕ}

$N=568\text{x}256$

SCN, Leung, Gammie, Book (2007)

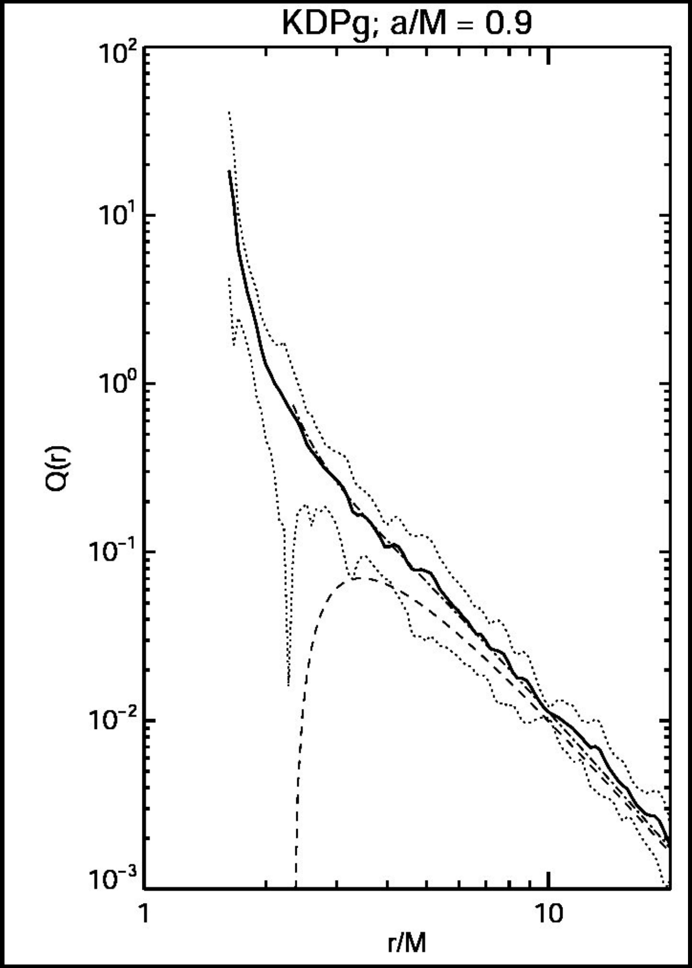
Inner Disk Structure





Krolik et al. (2005)

Inner Radiation Edge



- Beckwith, Hawley &Krolik (2008)

- Models dissipation stress as EM stress

- Measured effect from capture losses from matter near the horizon;

- 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

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

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

HARM3D

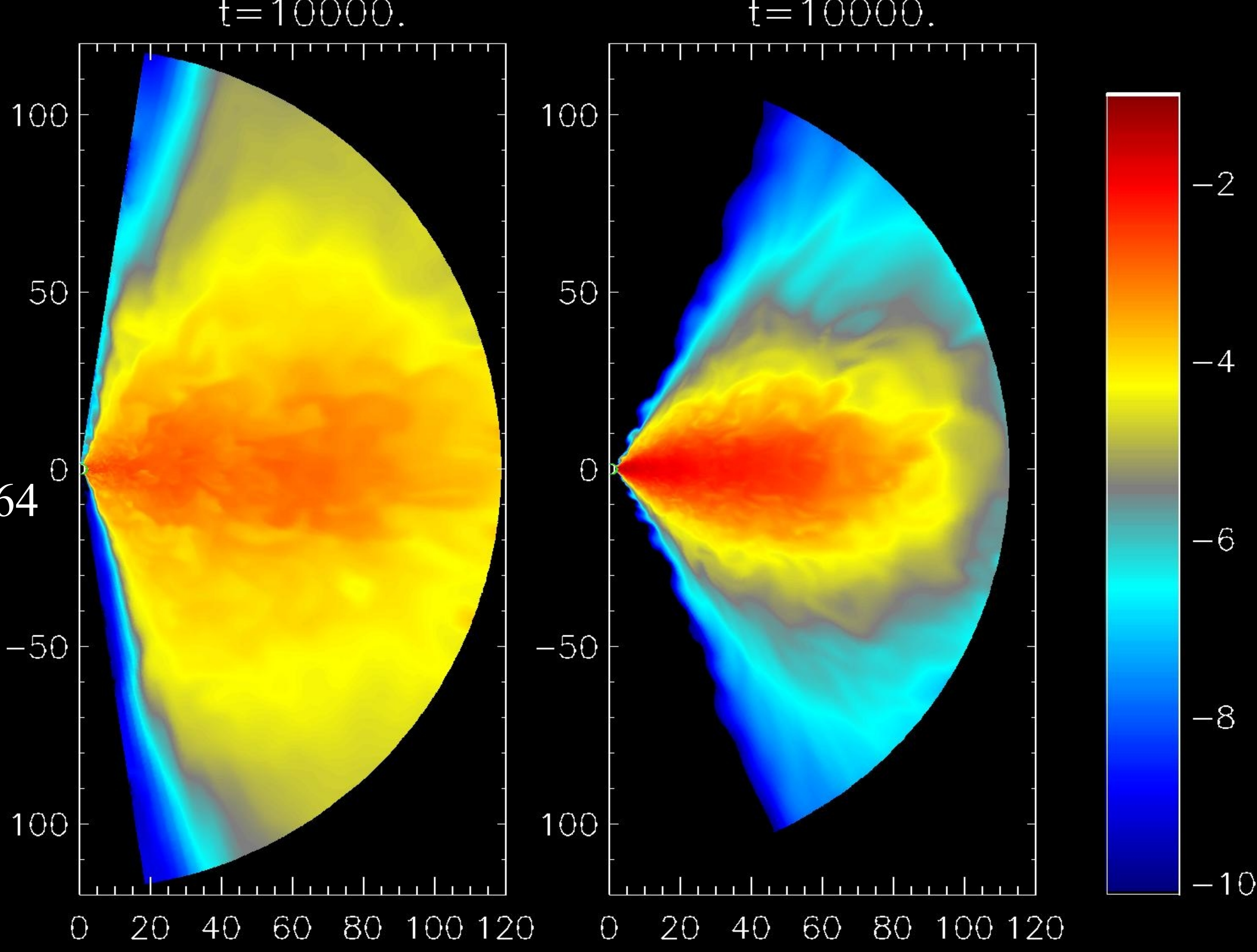
- HARM2D : Gammie et al. (2003), Noble et al. (2006)
- Flux-conservative (E,L,M conserved to round-off error)
- LF-like Kurganov-Tadmor flux, or HLL
- Piecewise Linear slope-limiters
- Covariant --- code written independent of geometry
  - (use non-uniform spherical Kerr-Schild coordinates)

New Features:

- Now in 3D!
- Piecewise Parabolic Limiters (accommodate smaller floors)
- Piecewise Parabolic reconstruction of EMFs (Constrained Transport)
- P > 0 maintained by solving $\left(\frac{P}{\rho^{\Gamma-1}} u^a\right)_{;a} = 0$ when $100\, P < b^2$

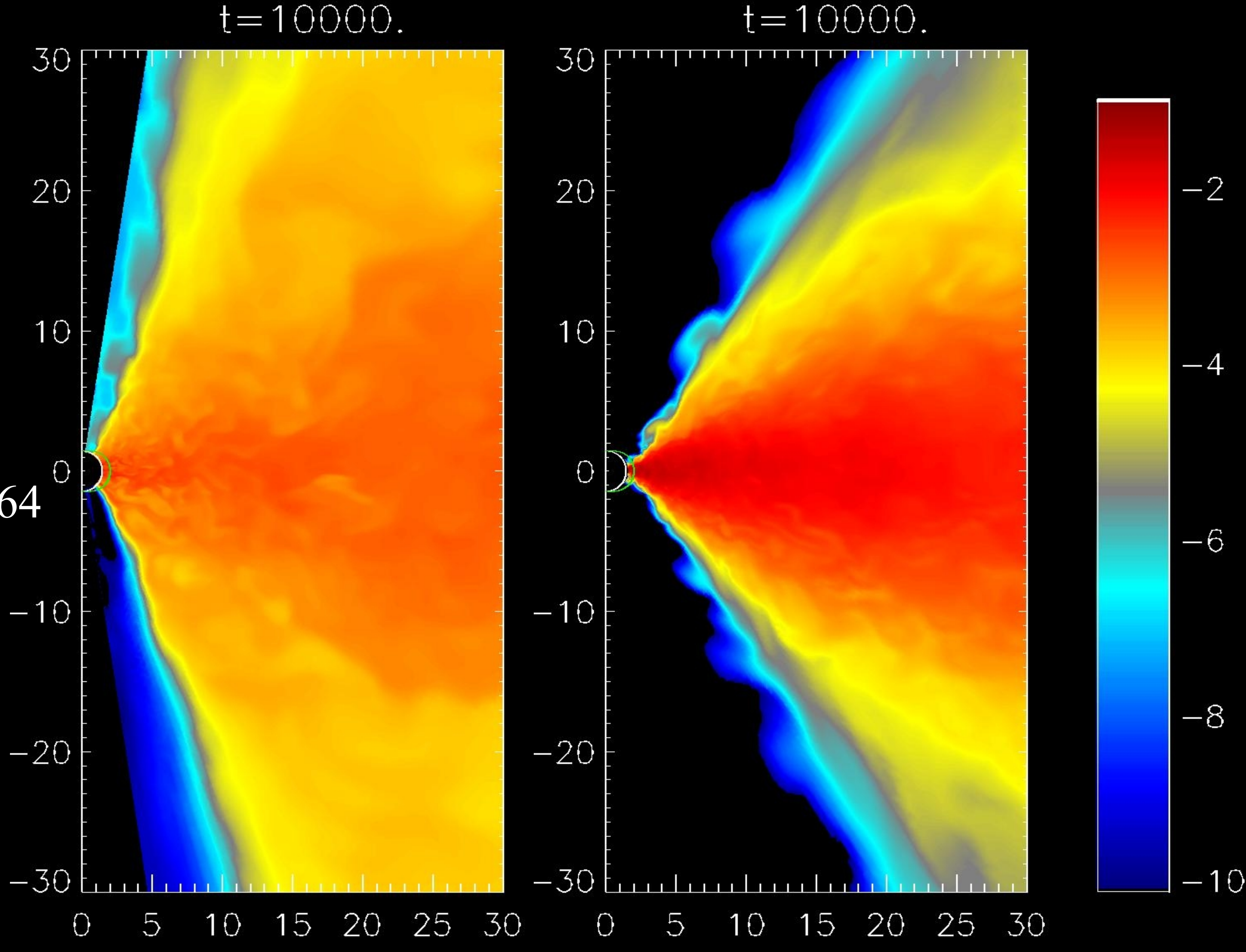
Balsara & Spicer (1999)

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



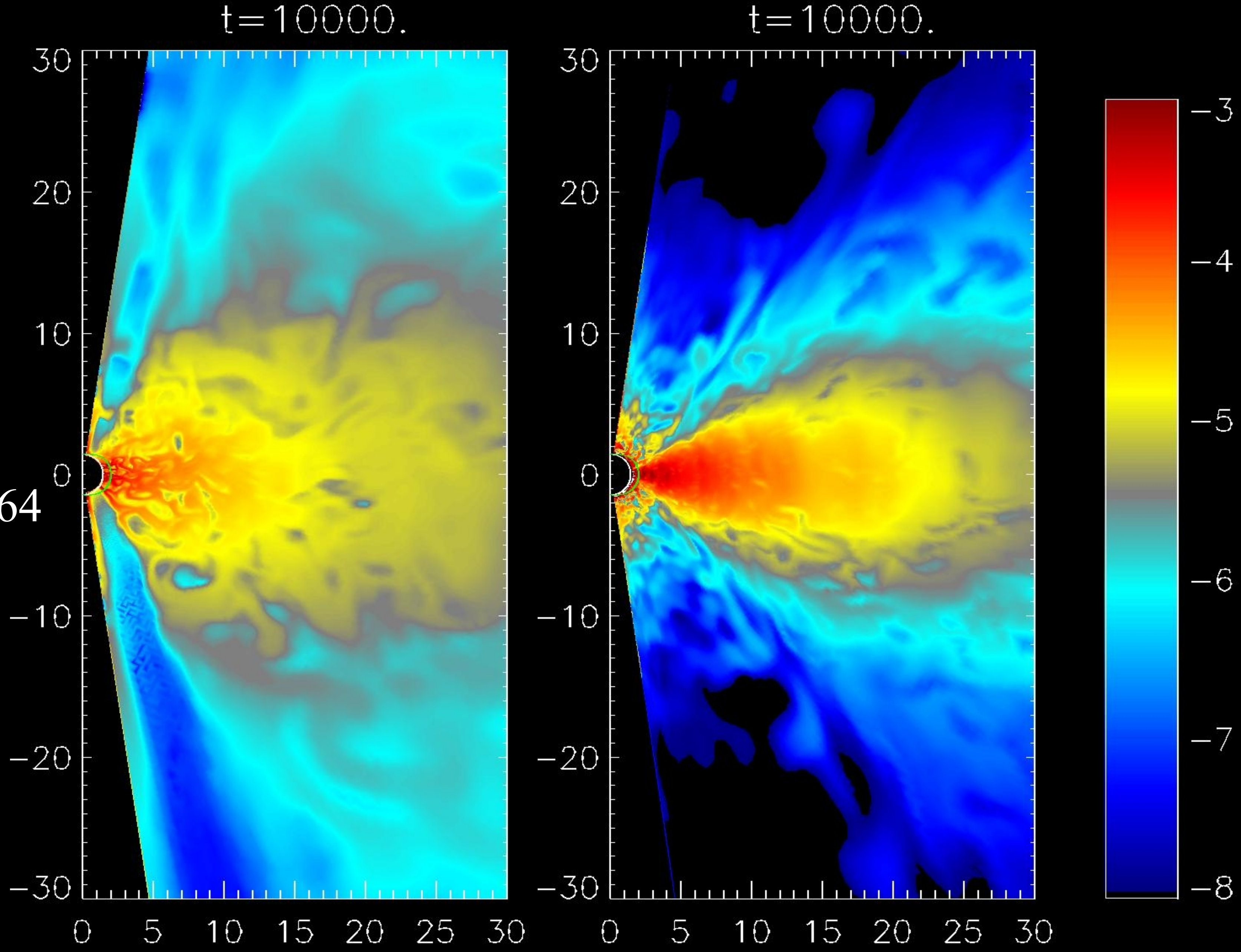
192x192x64
a = 0.9 M

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



192x192x64
a = 0.9 M

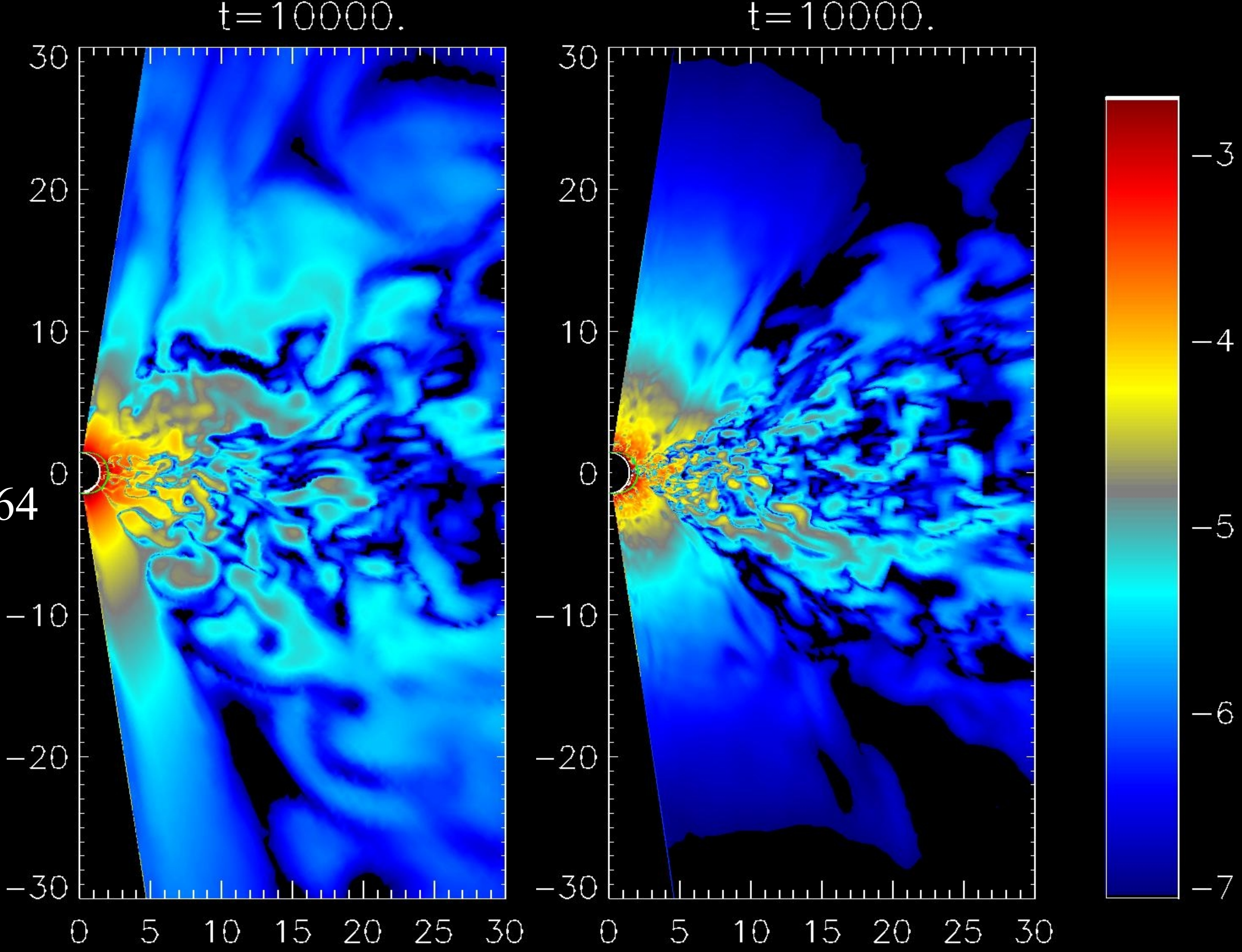
HARM3D vs. dVH $\log(P)$



192x192x64
a = 0.9 M

HARM3D vs. dVH

$\log(P_{mag})$



192x192x64

a = 0.9 M

Cooling Function

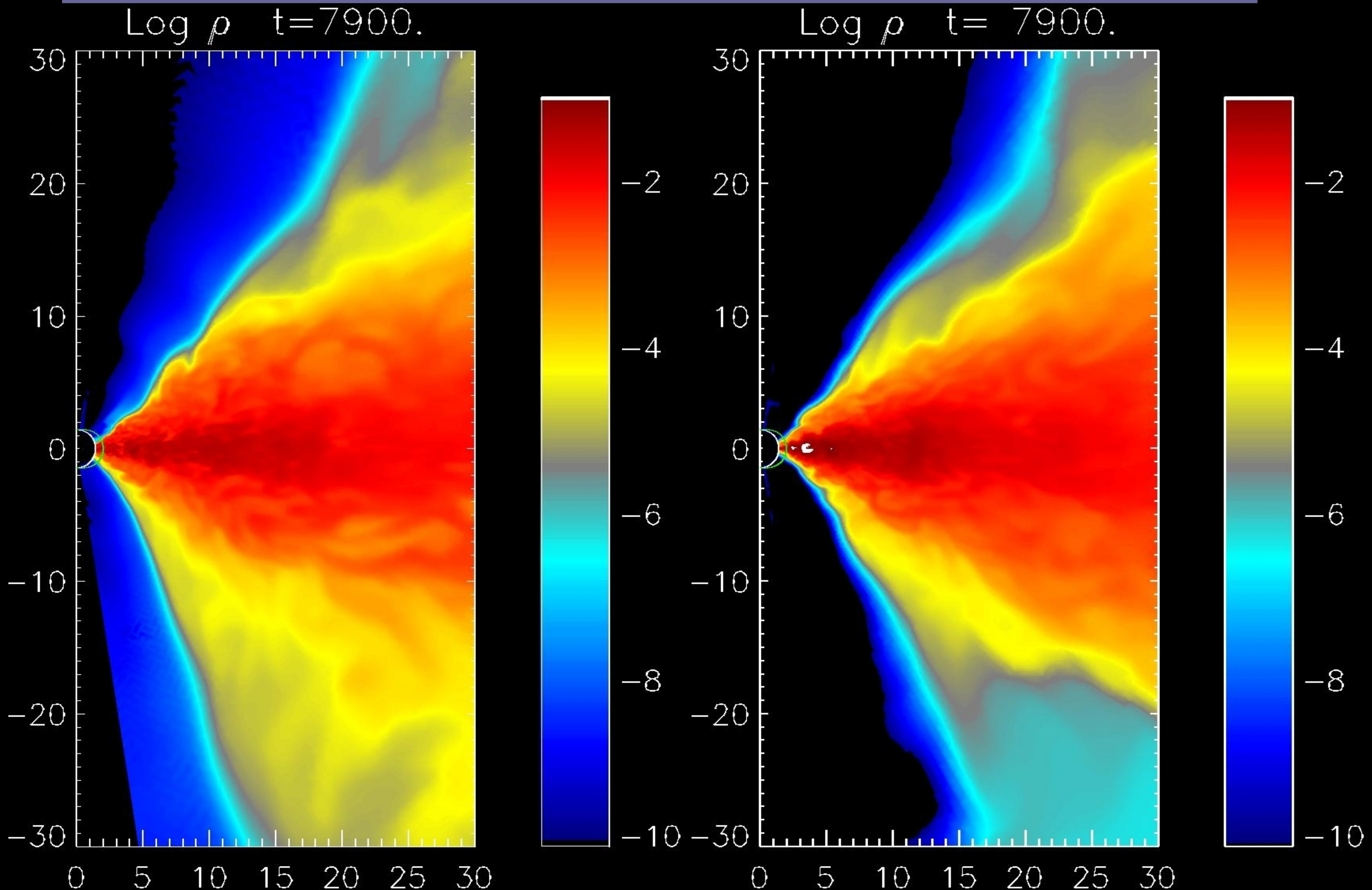
- Optically-thin radiation: $$T^{\mu}{}_{\nu;\mu} = -F_{\nu}$$
- Isotropic emission: $$F_{\nu} = f_c u_{\nu}$$
- Cool only when fluid's temperature too high: $$f_c = s\,\Omega\,u\,(\Delta - 1 + |\Delta - 1|)^q$$

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

- $\Omega(r < r_{isco})$ found assuming E & L are conserved on plunge from ISCO

Cooled #1 vs. Cooled #2

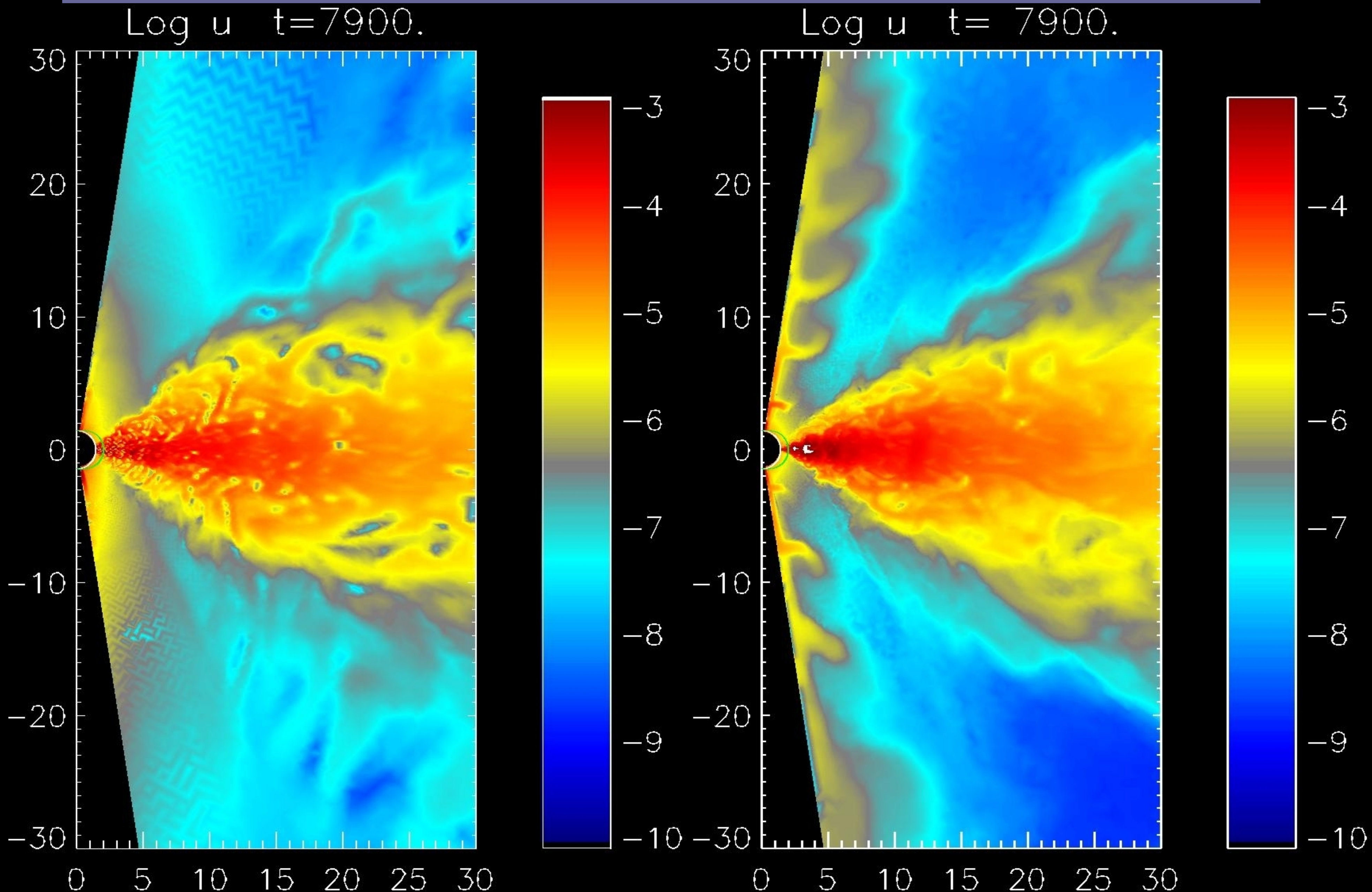
$\log(\rho)$



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

Cooled #1 vs. Cooled #2

$\log(P)$

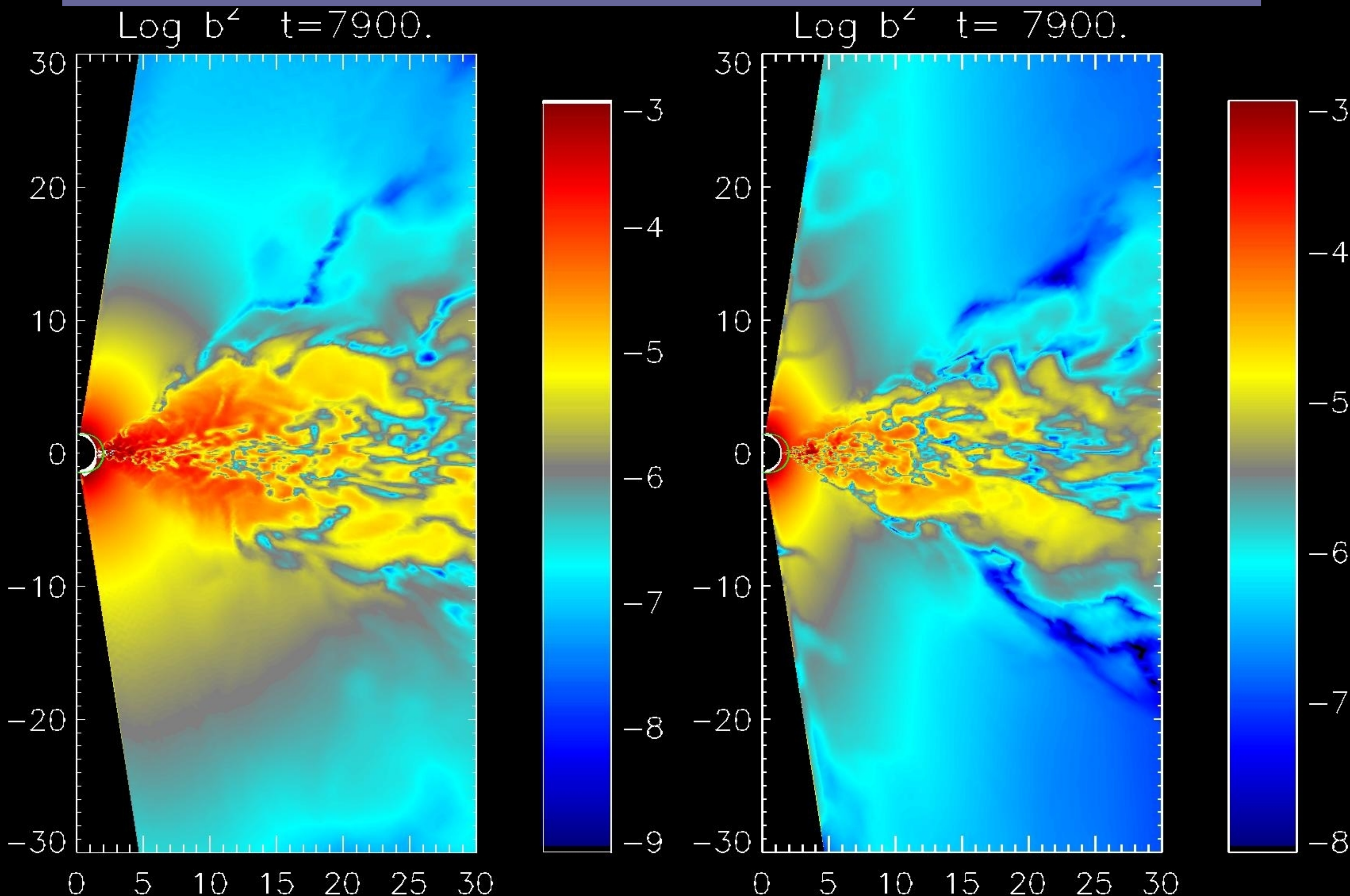


From t = 0 M

From t = 4000 M

Cooled #1 vs. Cooled #2

$\log(P_{mag})$

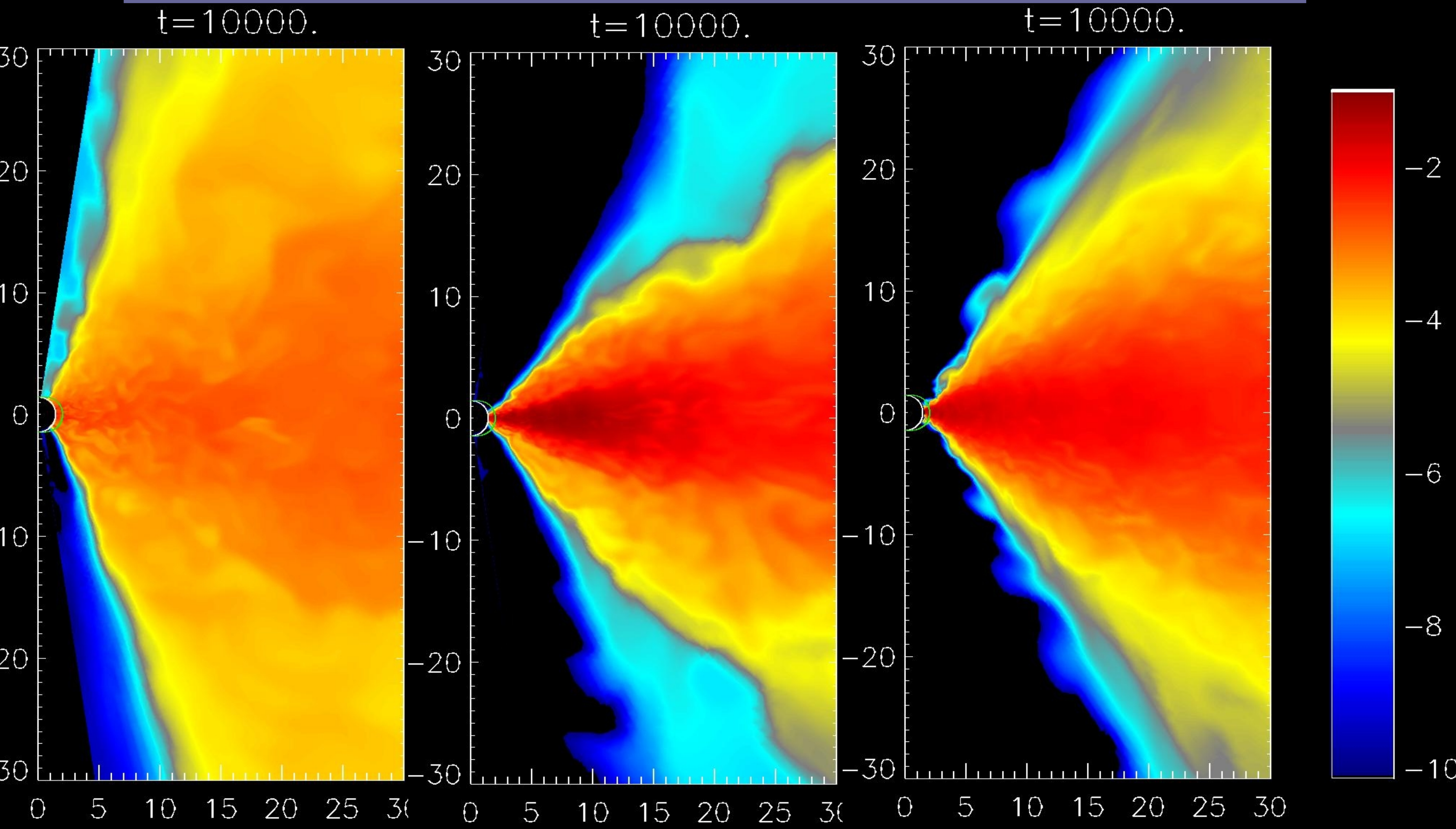


From t = 0 M

From t = 4000 M

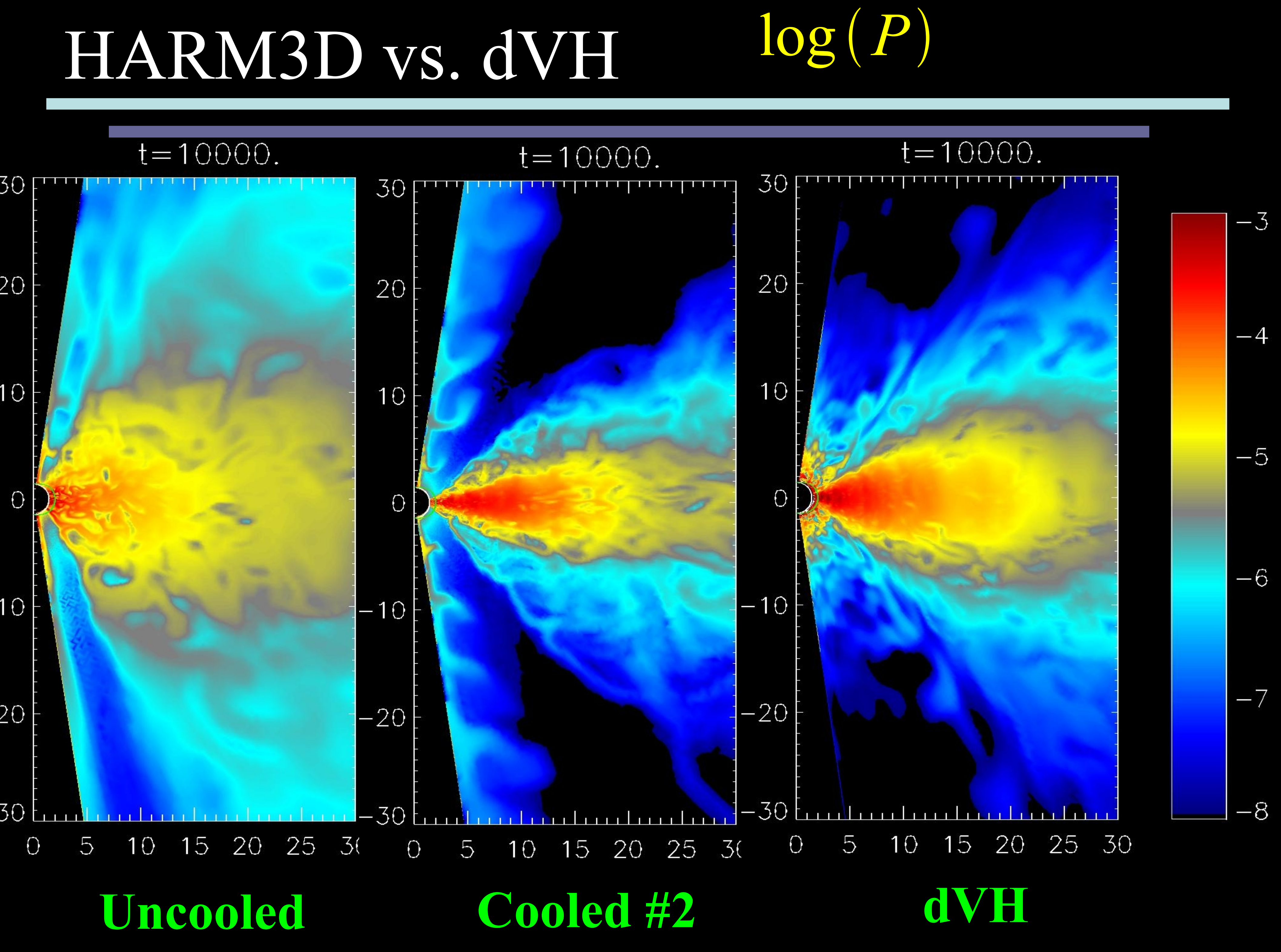
HARM3D vs. dVH

$\log(\rho)$



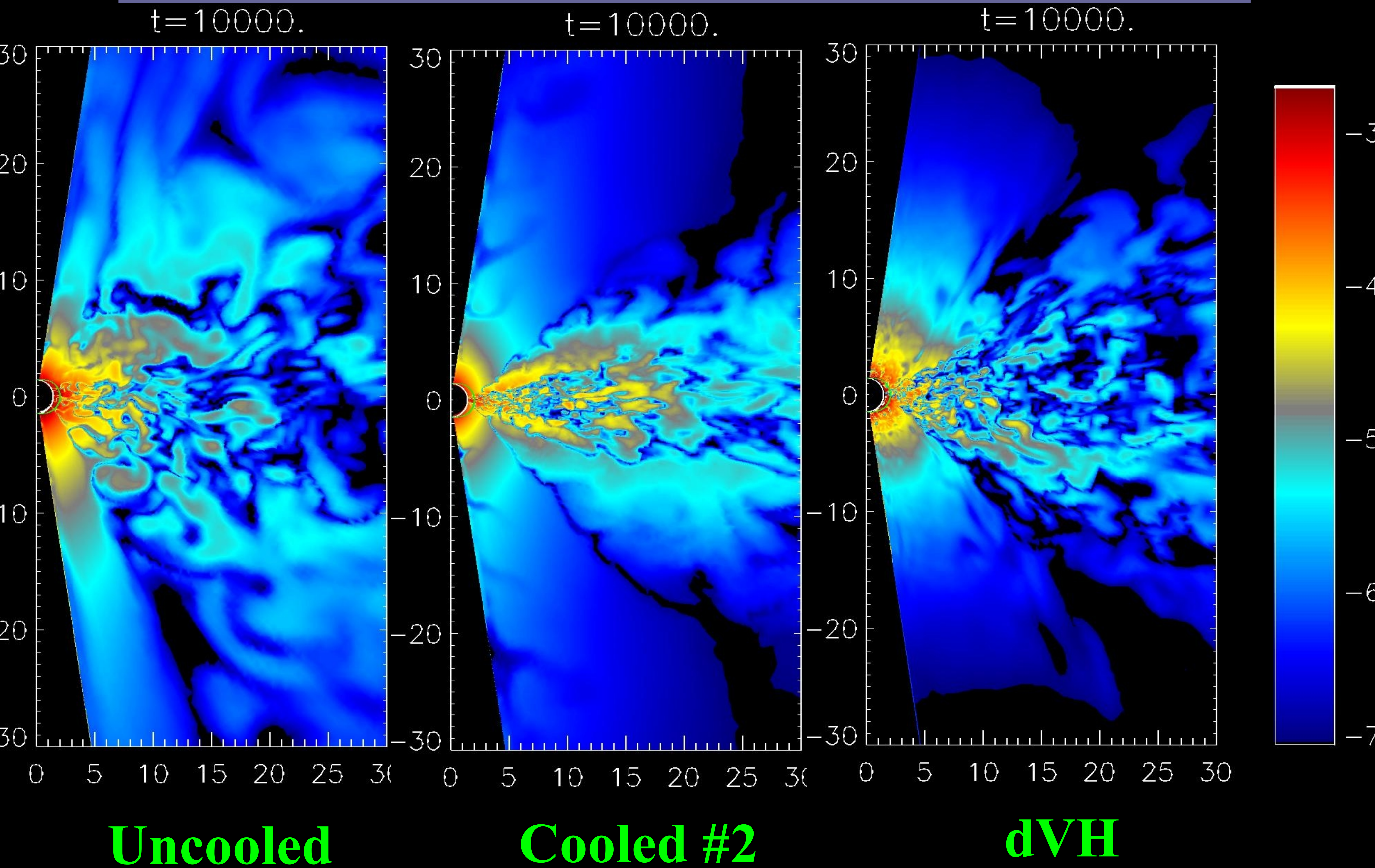
Uncooled **Cooled #2** **dVH**

HARM3D vs. dVH



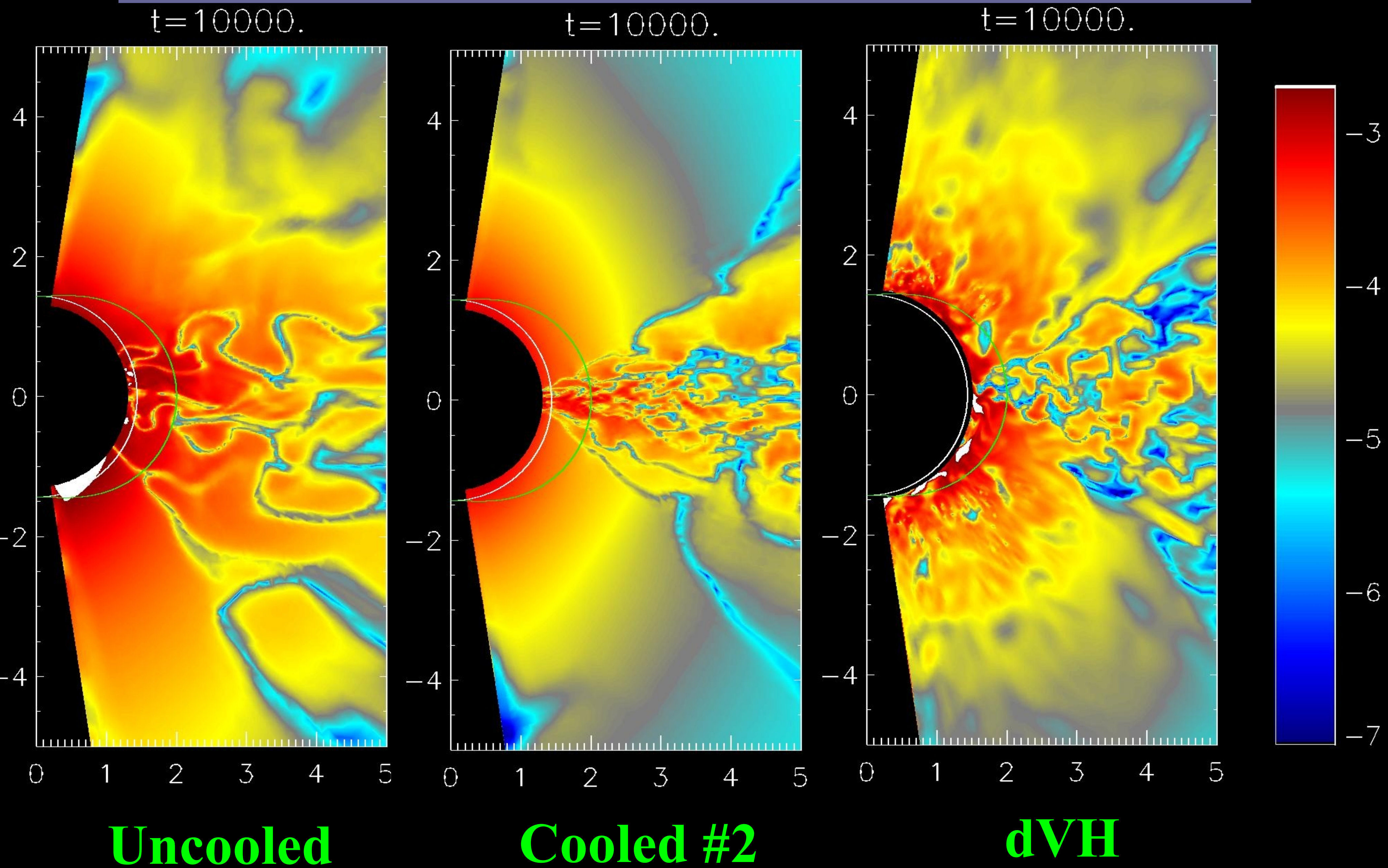
HARM3D vs. dVH

$\log(P_{mag})$



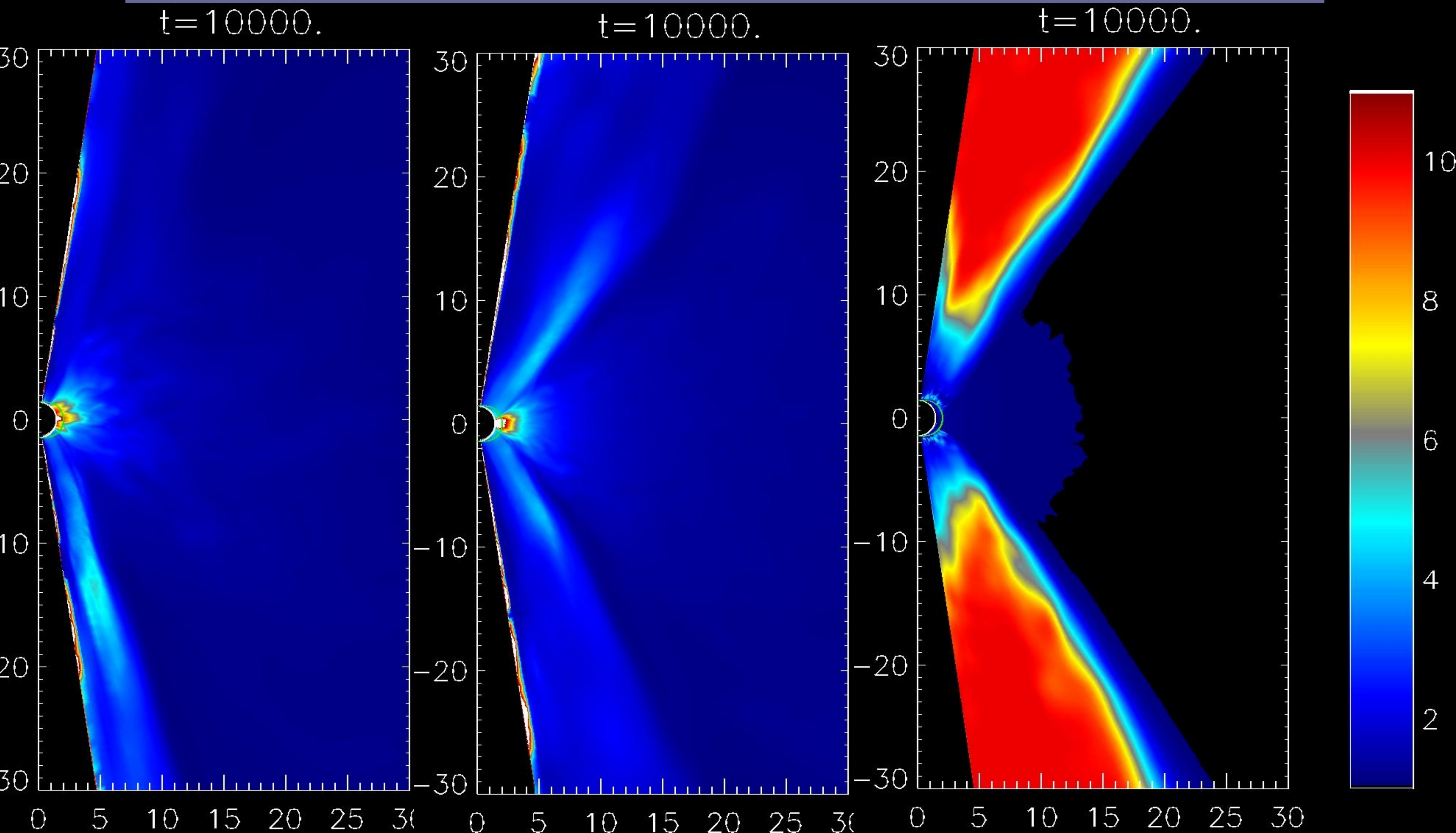
HARM3D vs. dVH

$\log(P_{mag})$



HARM3D vs. dVH

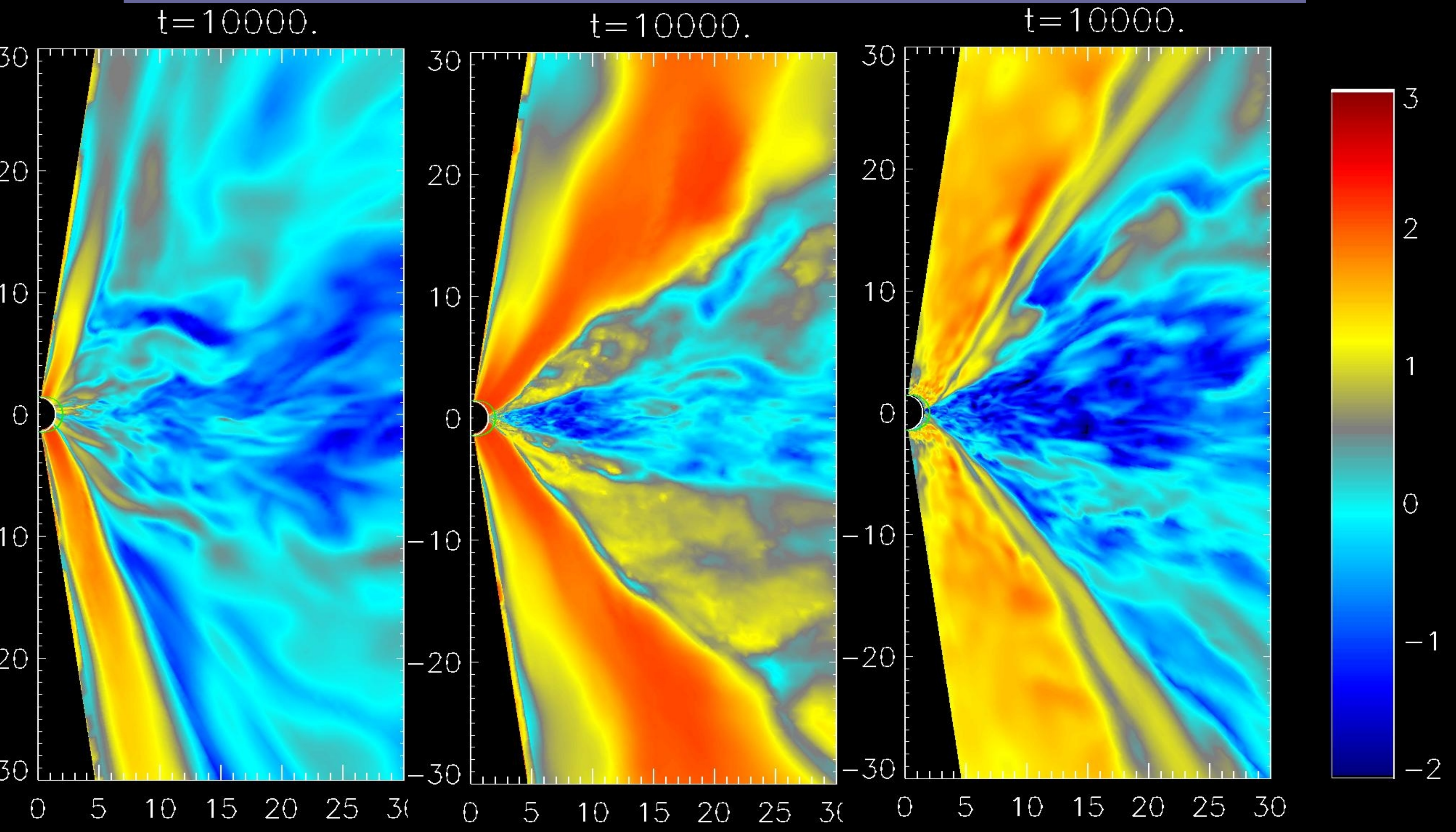
$\gamma(\phi - avg)$



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

HARM3D vs. dVH

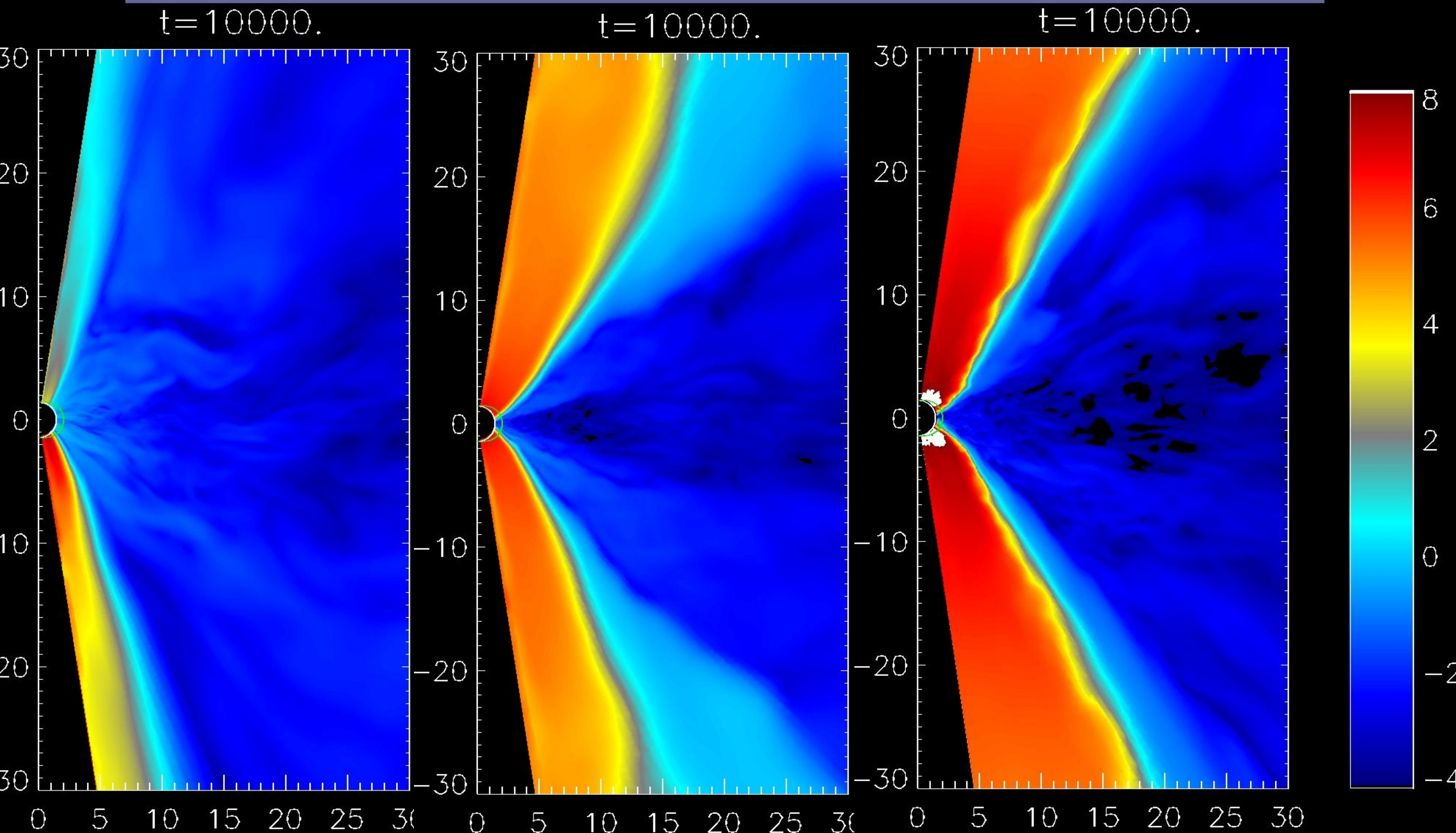
$\log(P_{mag}/P)$



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

HARM3D vs. dVH

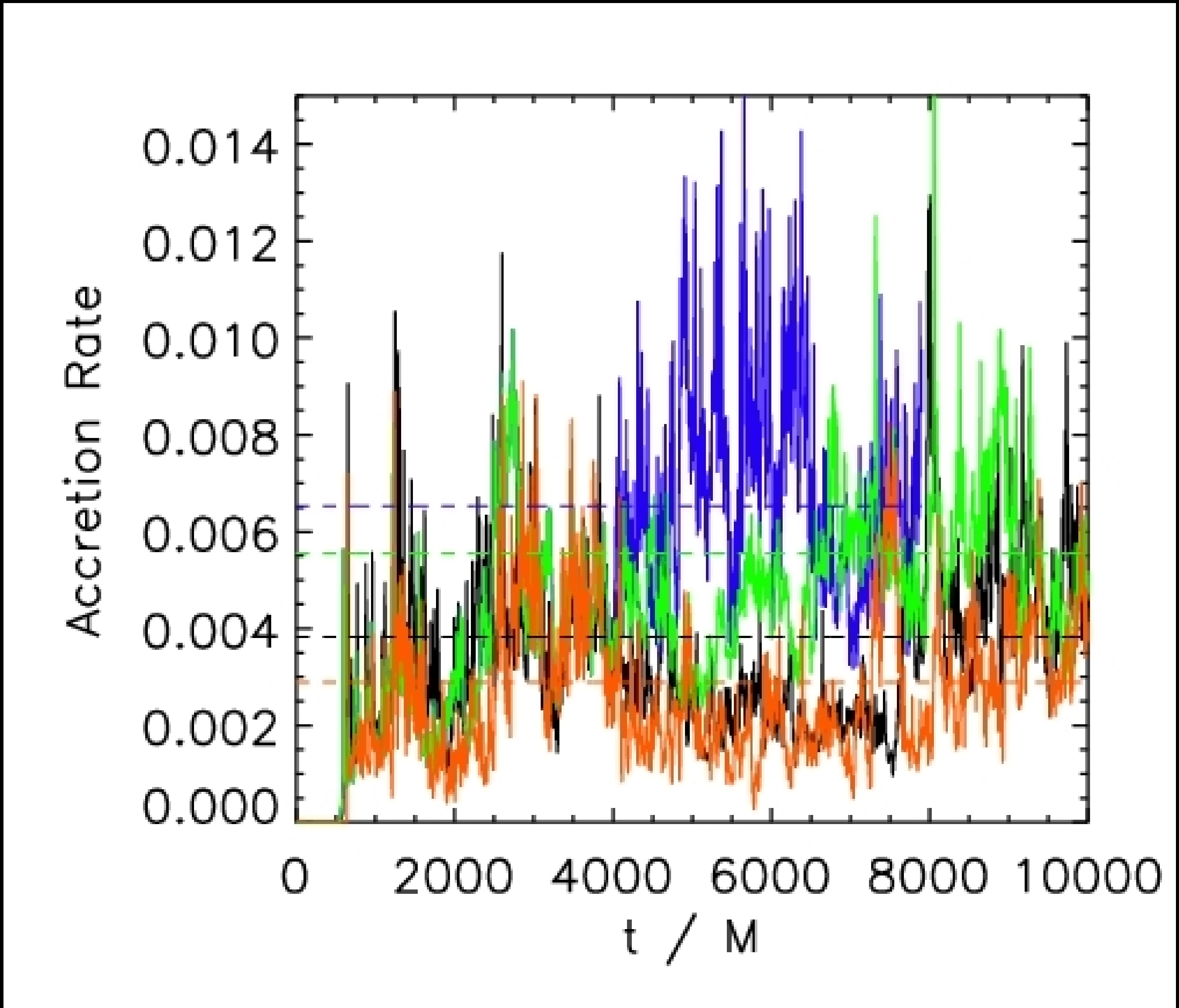
$\log(P_{mag}/\rho)$



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

HARM3D vs. dVH

$\dot{M}$



Cooled from t=0M

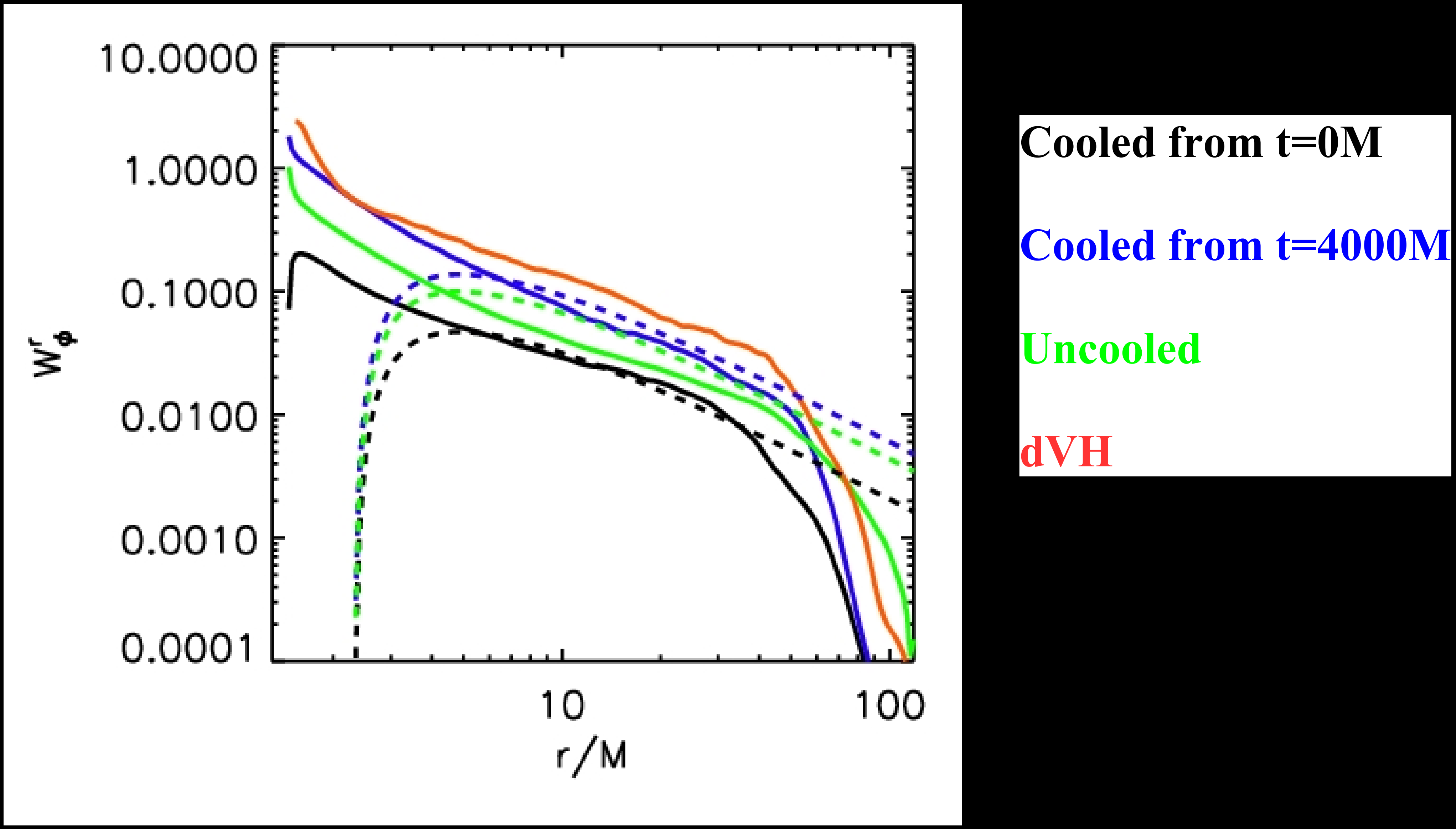
Cooled from t=4000M

Uncooled

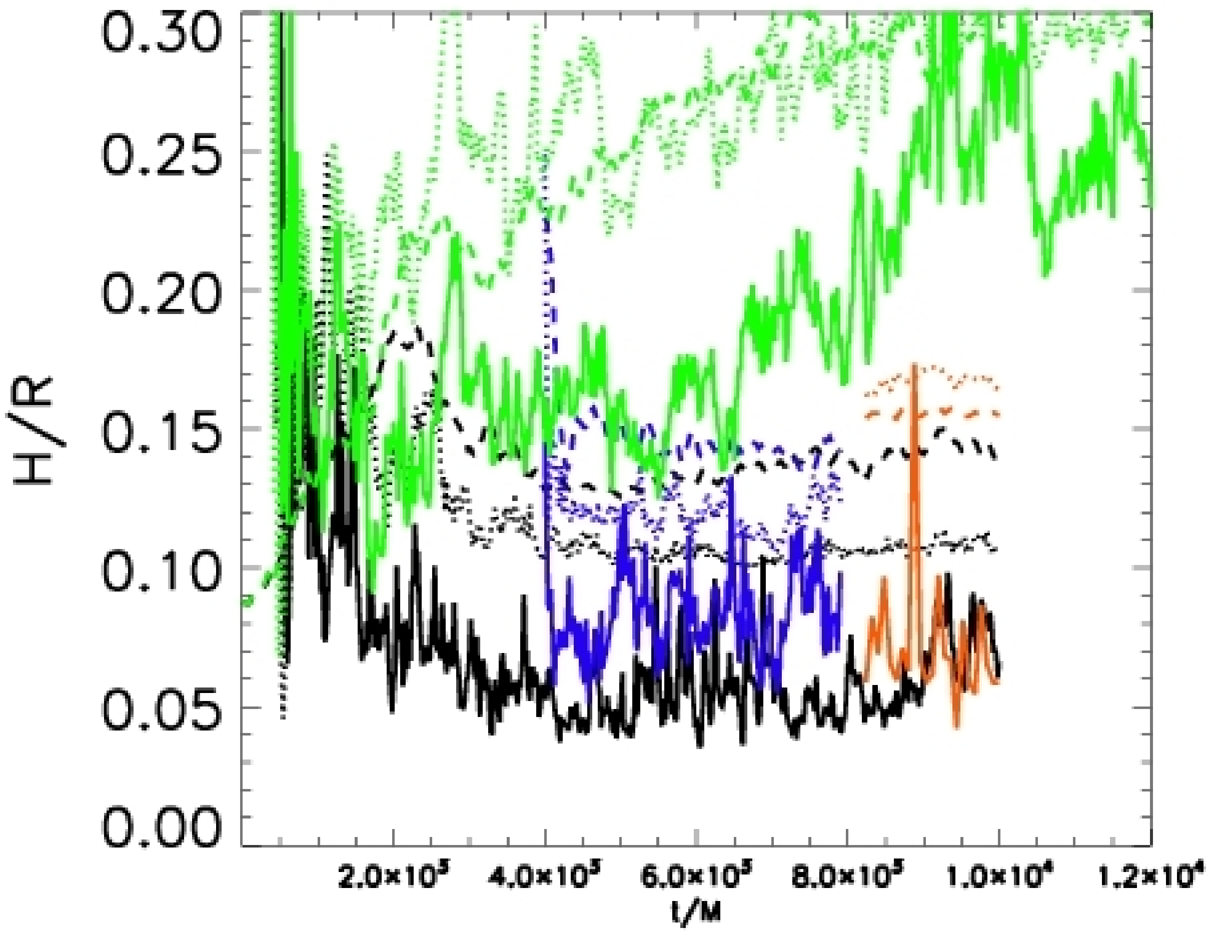
dVH

HARM3D vs. dVH

Stress



HARM3D vs. dVH



Cooled from t=0M

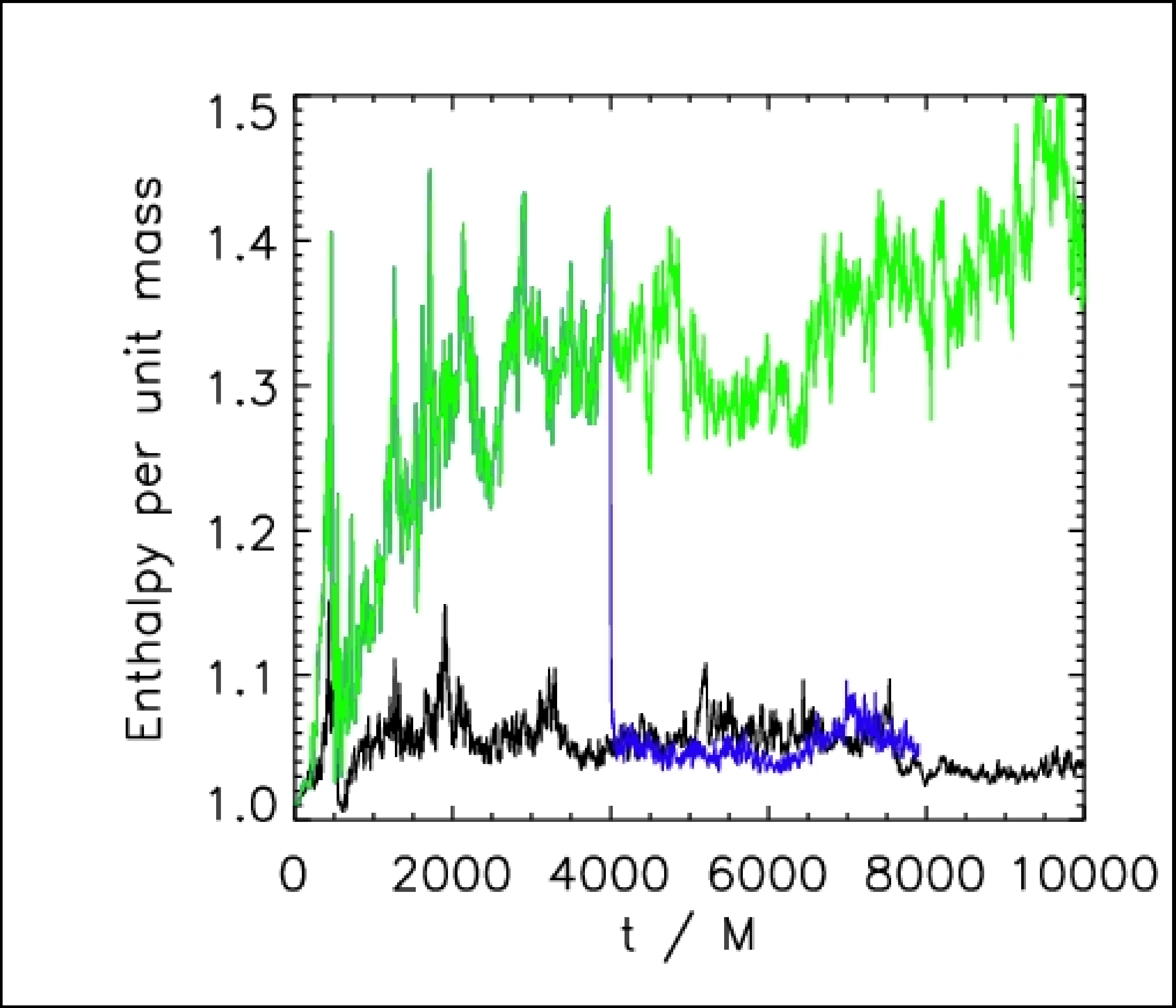
Cooled from t=4000M

Uncooled

dVH

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

HARM3D vs. dVH



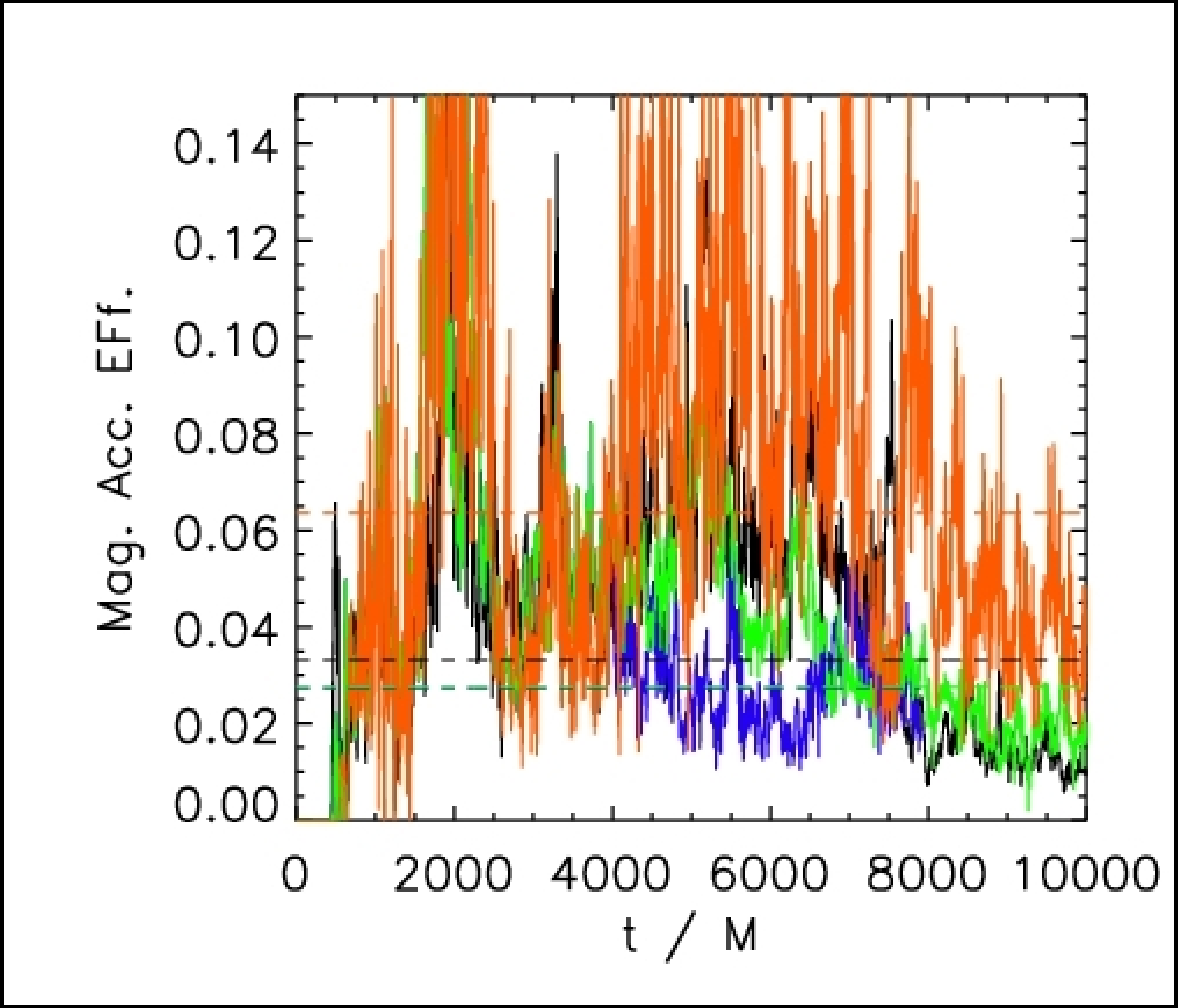
Cooled from t=0M

Cooled from t=4000M

Uncooled

dVH

HARM3D vs. dVH



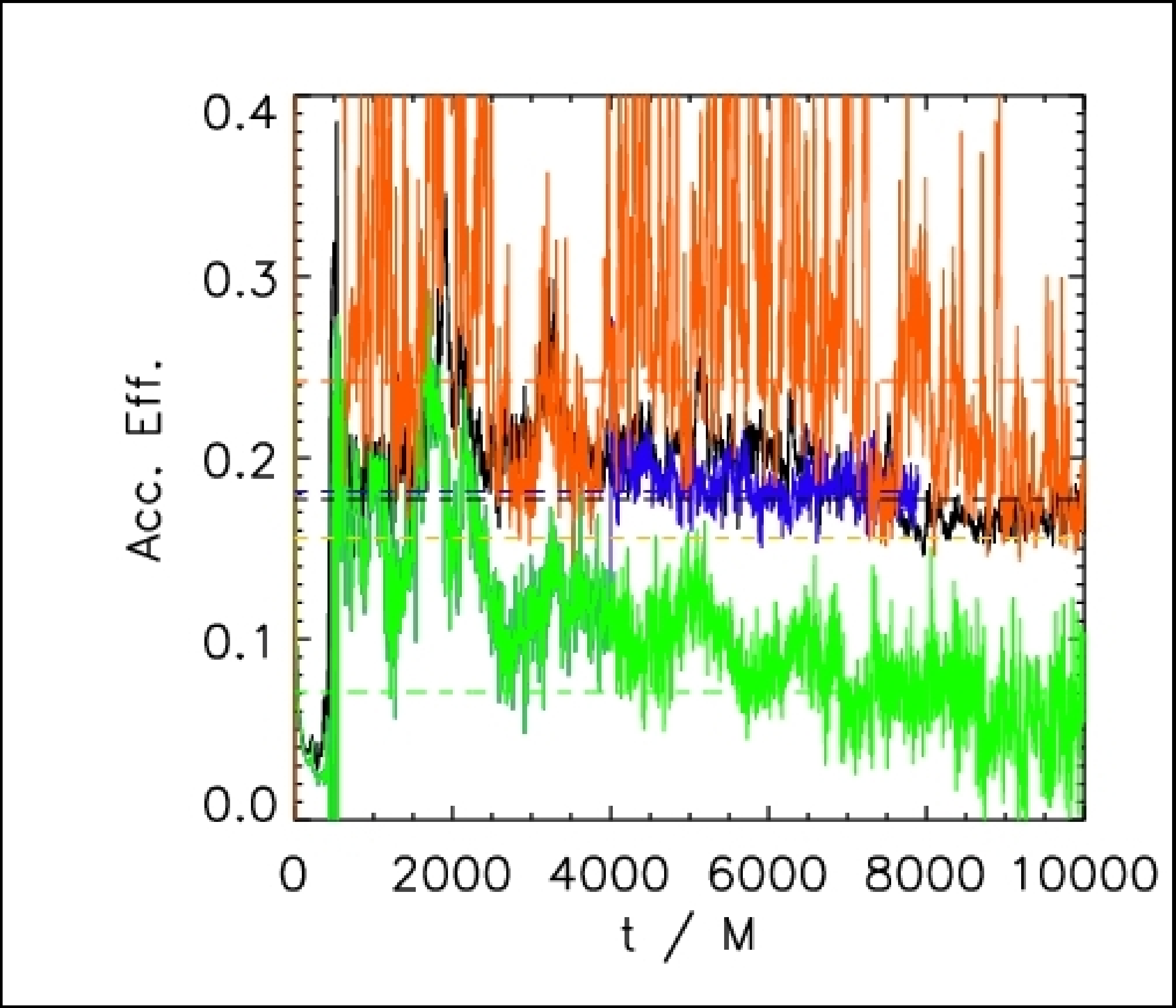
Cooled from t=0M

Cooled from t=4000M

Uncooled

dVH

HARM3D vs. dVH



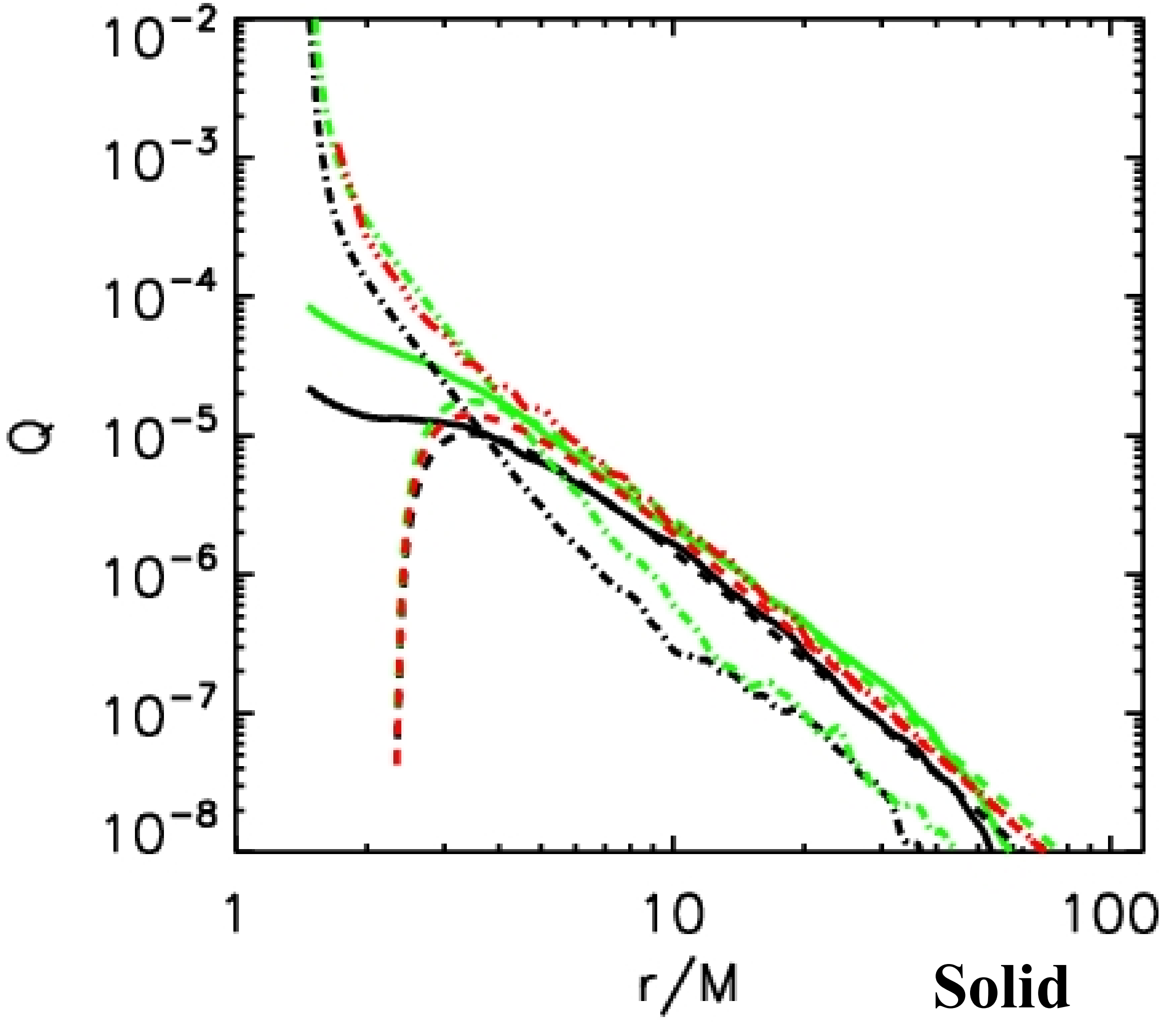
Cooled from t=0M

Cooled from t=4000M

Uncooled

dVH

HARM3D vs. dVH



Cooled from t=0M

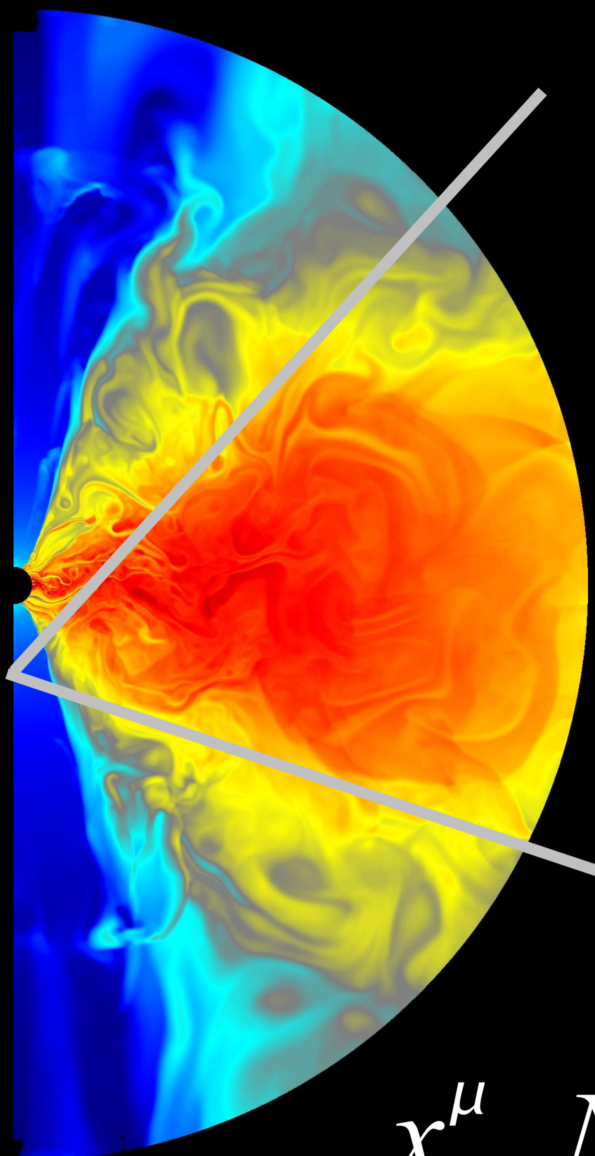
Cooled from t=4000M

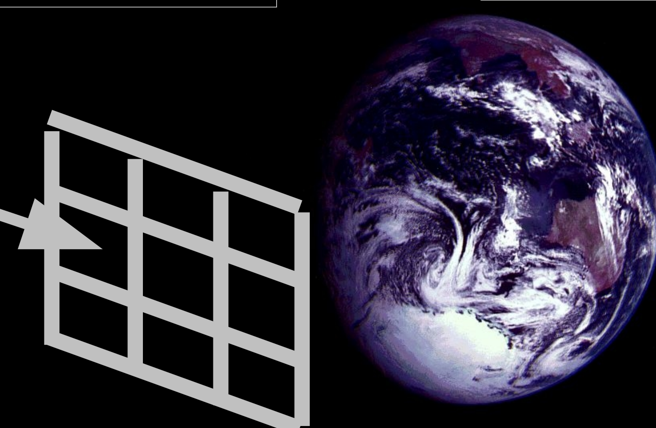
dVH

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

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;



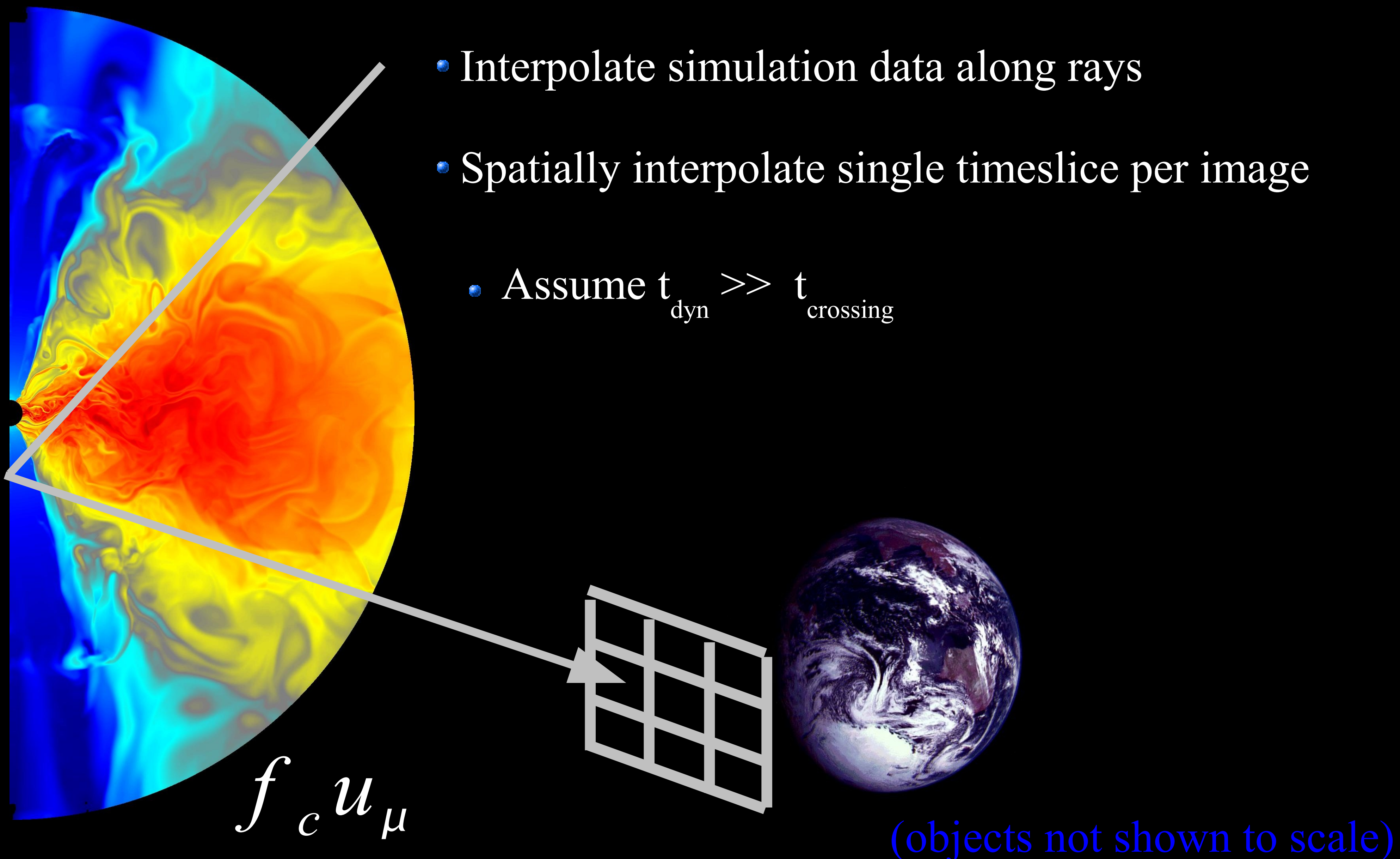


x^μ, N^μ

(objects not shown to scale)

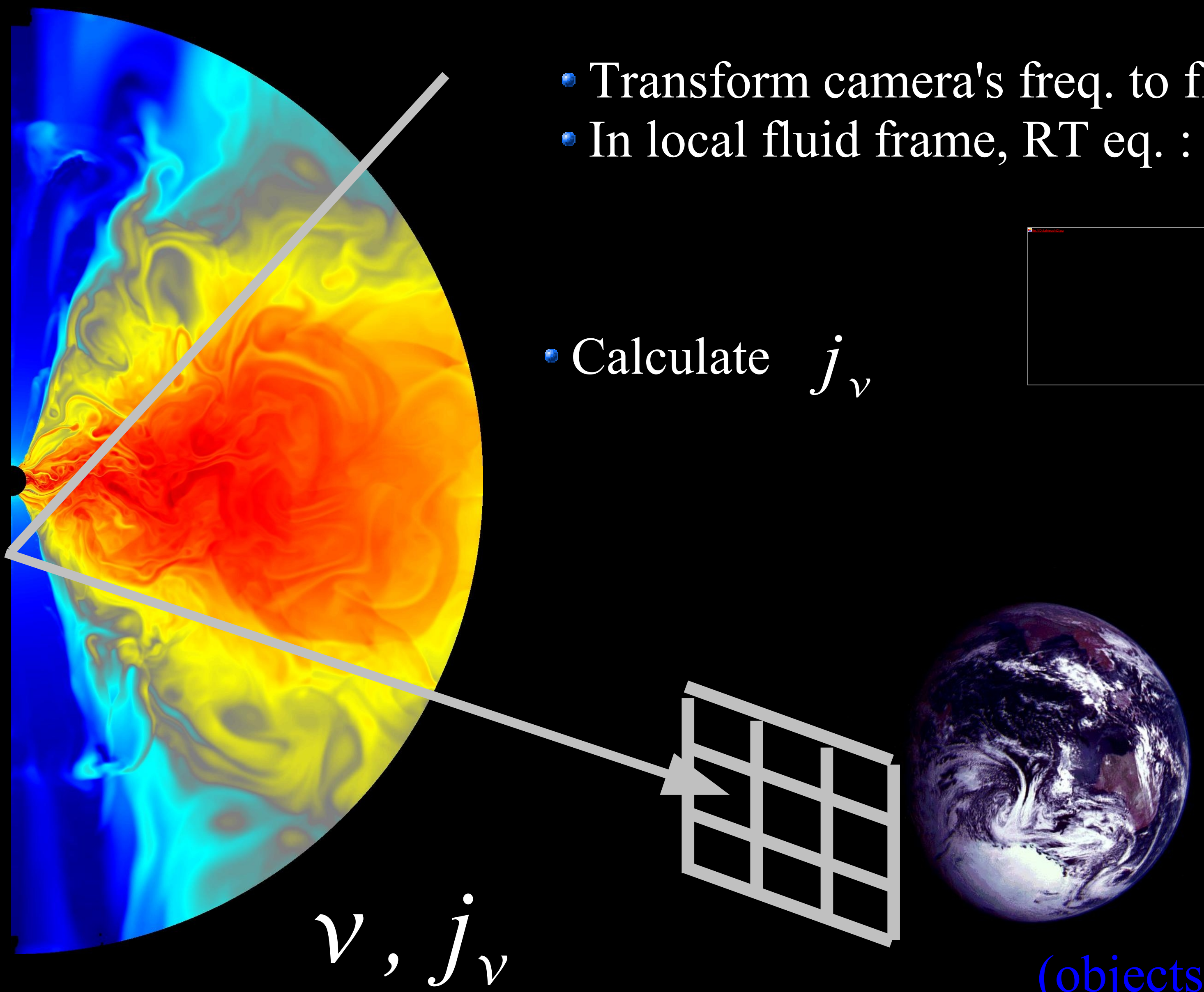
Radiation Transfer in GR: Step #2

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

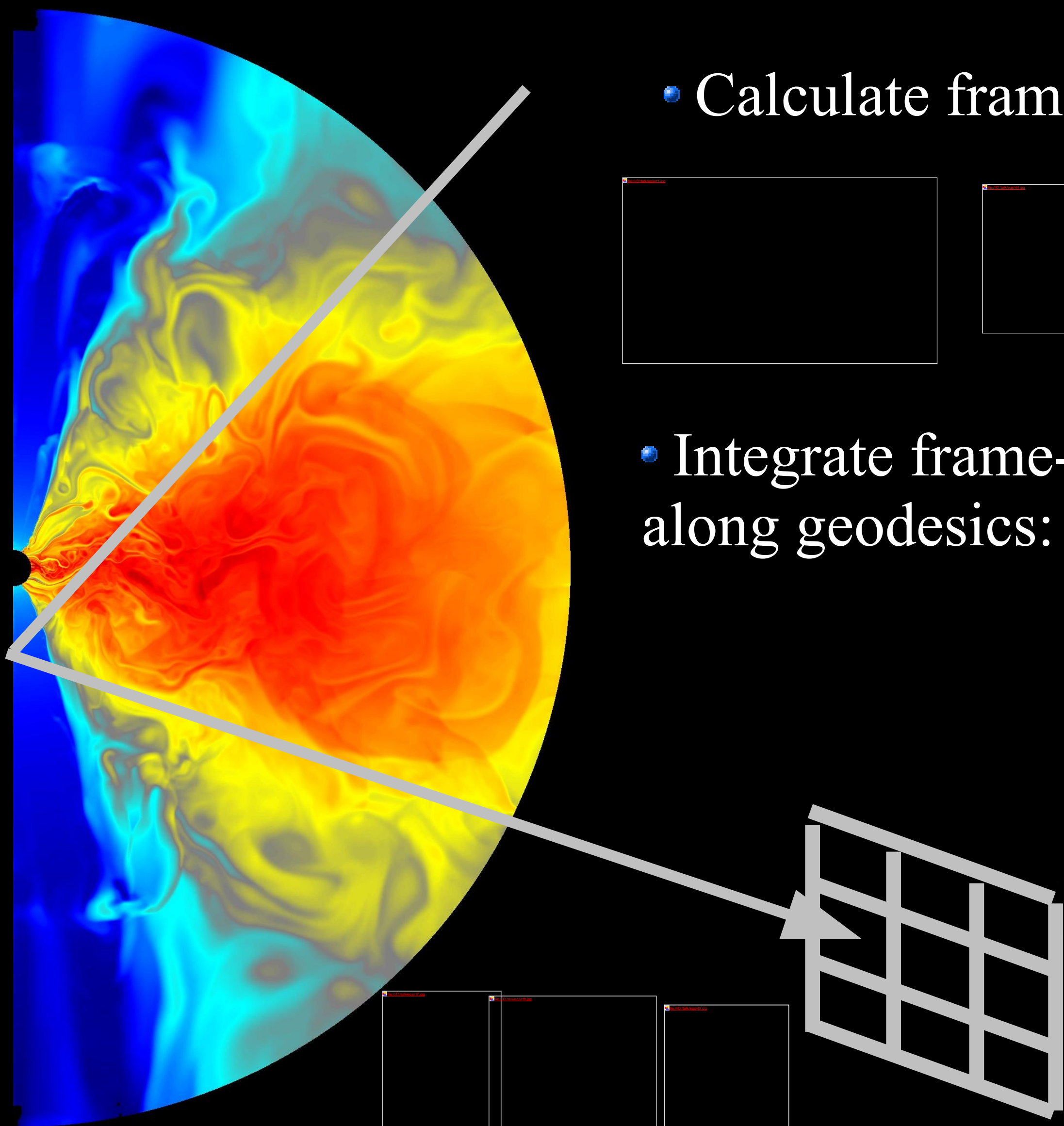


Radiation Transfer in GR: Step #3

- Transform camera's freq. to fluid frame: ν
- In local fluid frame, RT eq. :
- Calculate j_ν



Radiation Transfer in GR: Step #4

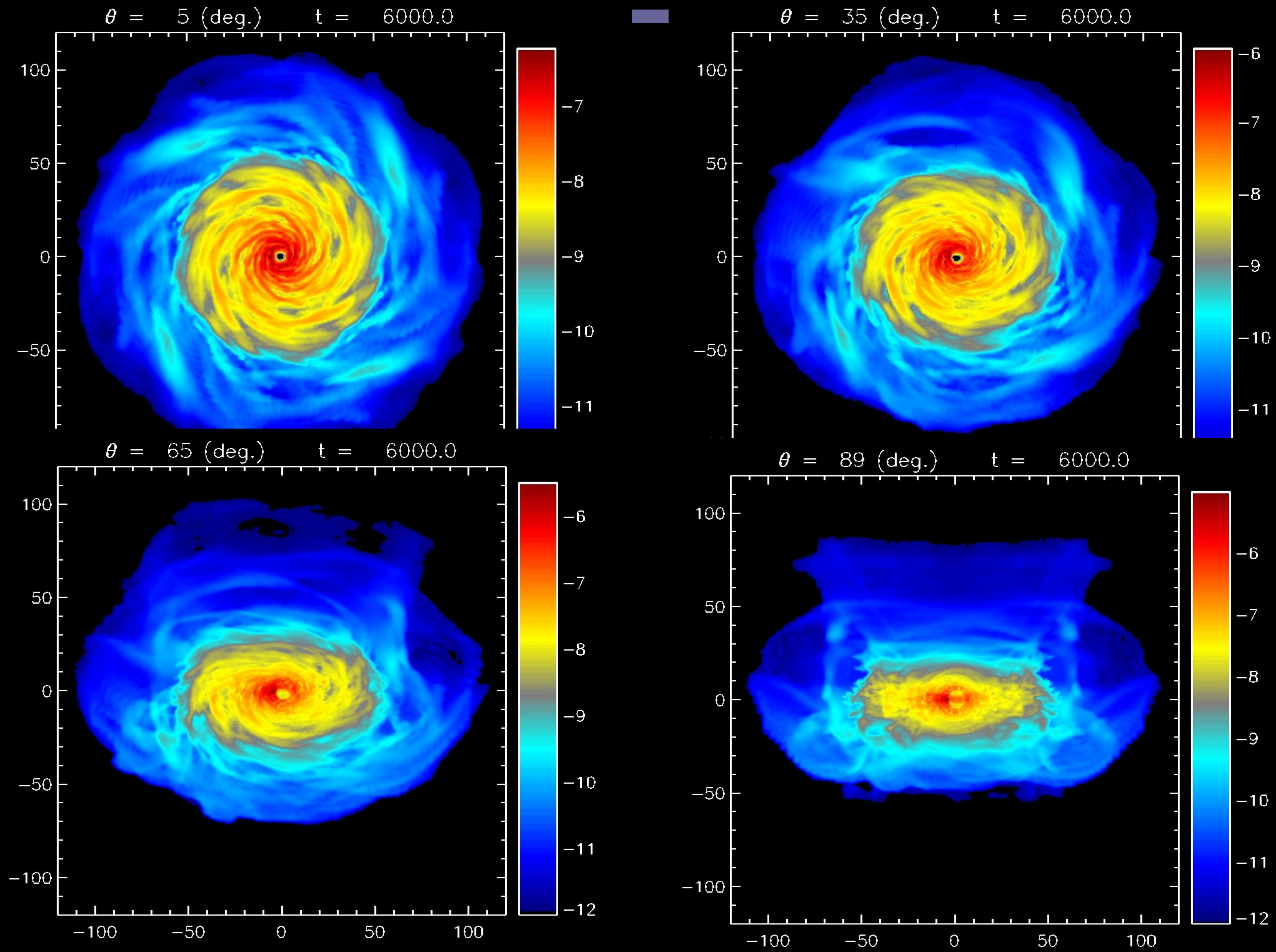


- Calculate frame-independent quantities:

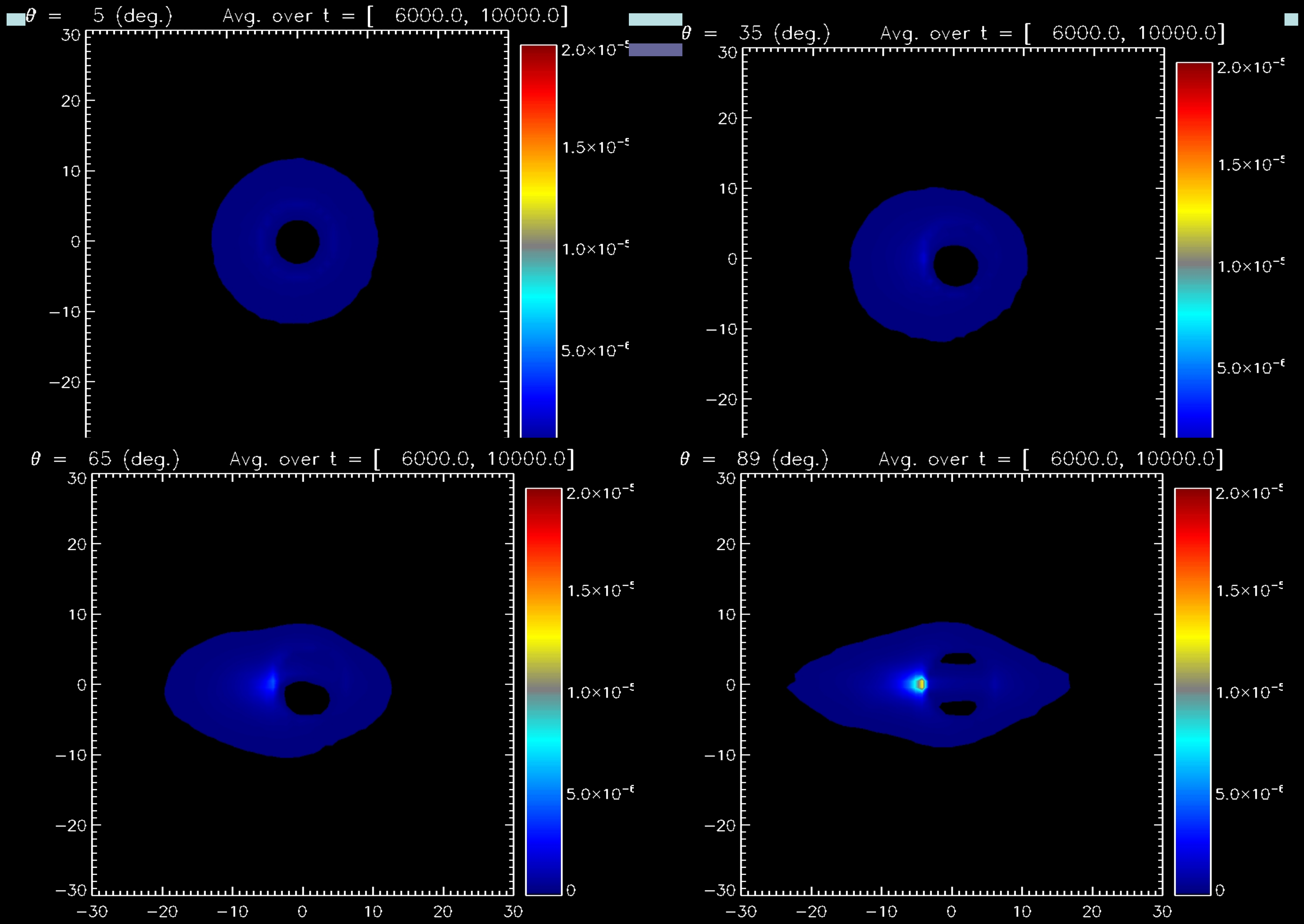
- Integrate frame-independent RT equation along geodesics:

(objects not shown to scale)

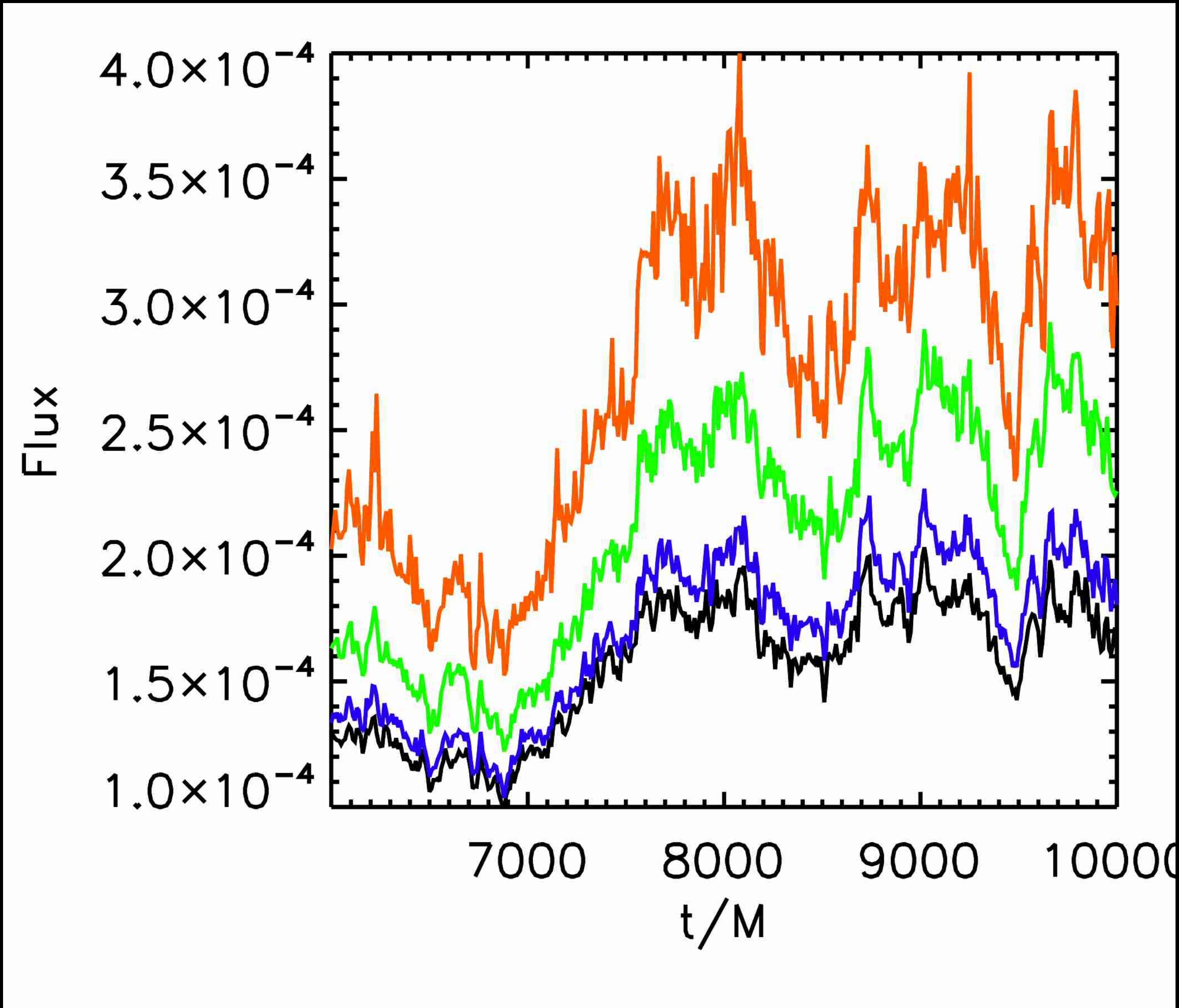
Transfer of Radiative Flux



Transfer of Radiative Flux



Variability of Dissipated Flux



$\theta = 5\,deg.$

$\theta = 35\,deg.$

$\theta = 65\,deg.$

$\theta = 89\,deg.$

Summary

- 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 efficiency relative efficiency to dVH
  - dVH has enhanced stress w/o enhanced magnetic field strength
  - Accretion rates surprisingly similar

- Cooling function controls scale height and temperature nearly as expected;
- Positive mag. energy flux and extra stress within ISCO → $\eta_{cooled} > \eta_{NT}$
- Stress model for dissipation over-estimates luminosity at small radii;
- Significant dependence of luminosity on inclination angle;
- Short timescale variability of observed flux suggests simple spin-variability arguments not appropriate for optically-thin emission

Future Work

- Finish comparison to Novikov-Thorne
- Measure radiative efficiency with photon losses
- Spin survey
- EOS survey

EXTRA SLIDES

Why Study Sagittarius A* (Sgr A*)?

- Biggest black hole on the sky! $(10 - 60\,\mu as)$
- #5 out of 25 of David Gross' "Future of Physics" questions (tests of GR)
- Test masses orbiting it! (post-Newtonian corrections)
- Luminous plasma orbiting it! (disk theory tests, spacetime tests)

Why Study Sagittarius A* (Sgr A*)?

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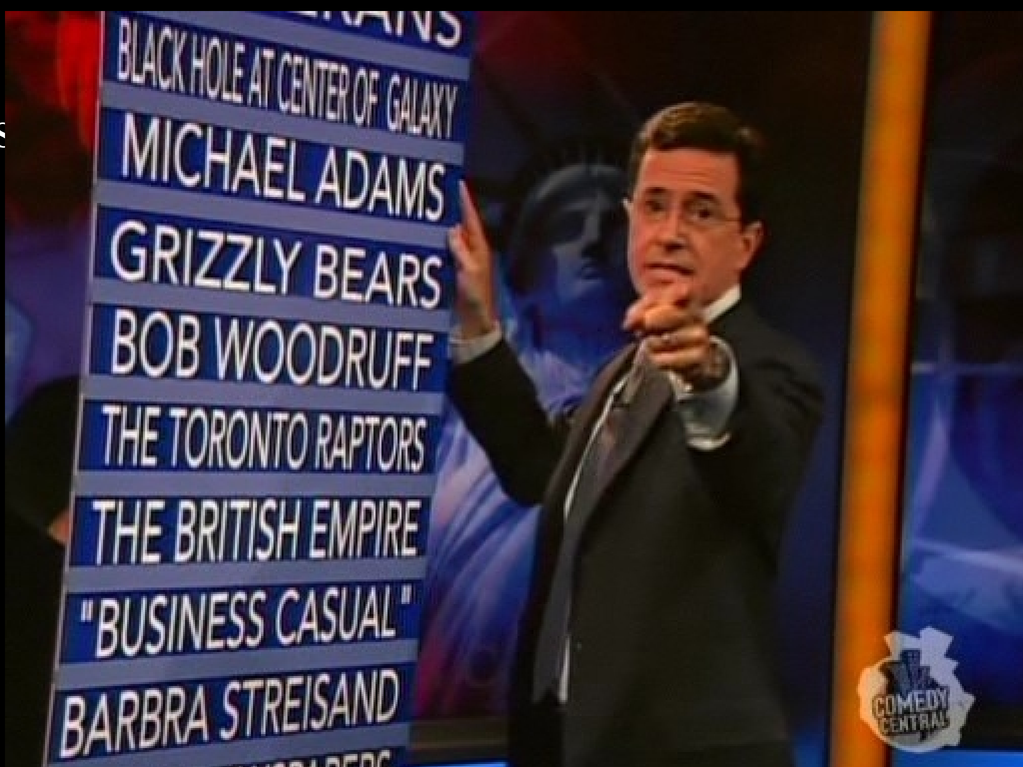
n't … off holding the Milky Way together, nor do I car
uns … On Notice."

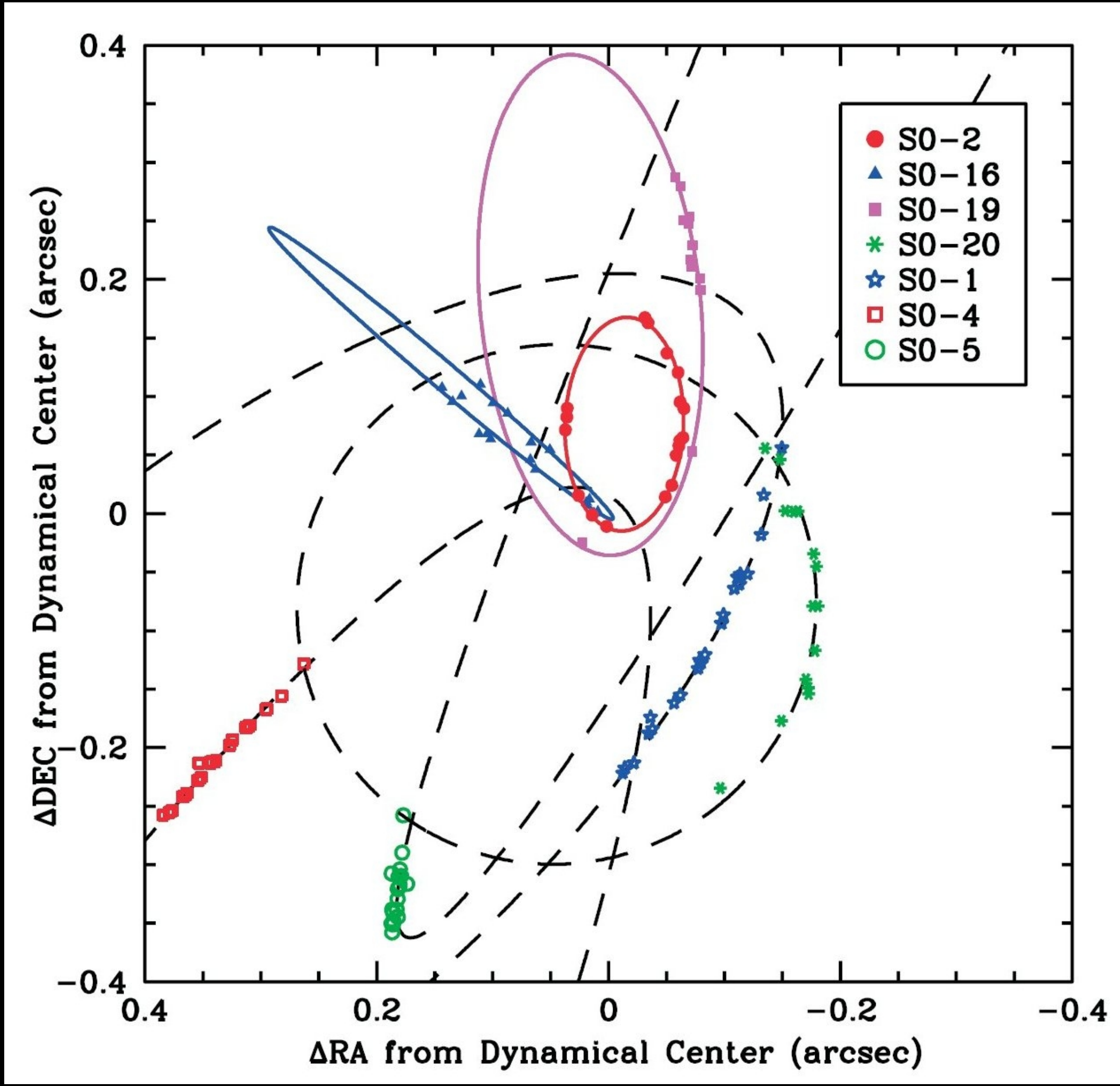


Sagittarius A* (Sgr A*)

NASA/UMass/D.Wang et al. (Chandra)
120x48 arcmin or 900x400 light-year

How Big is it?

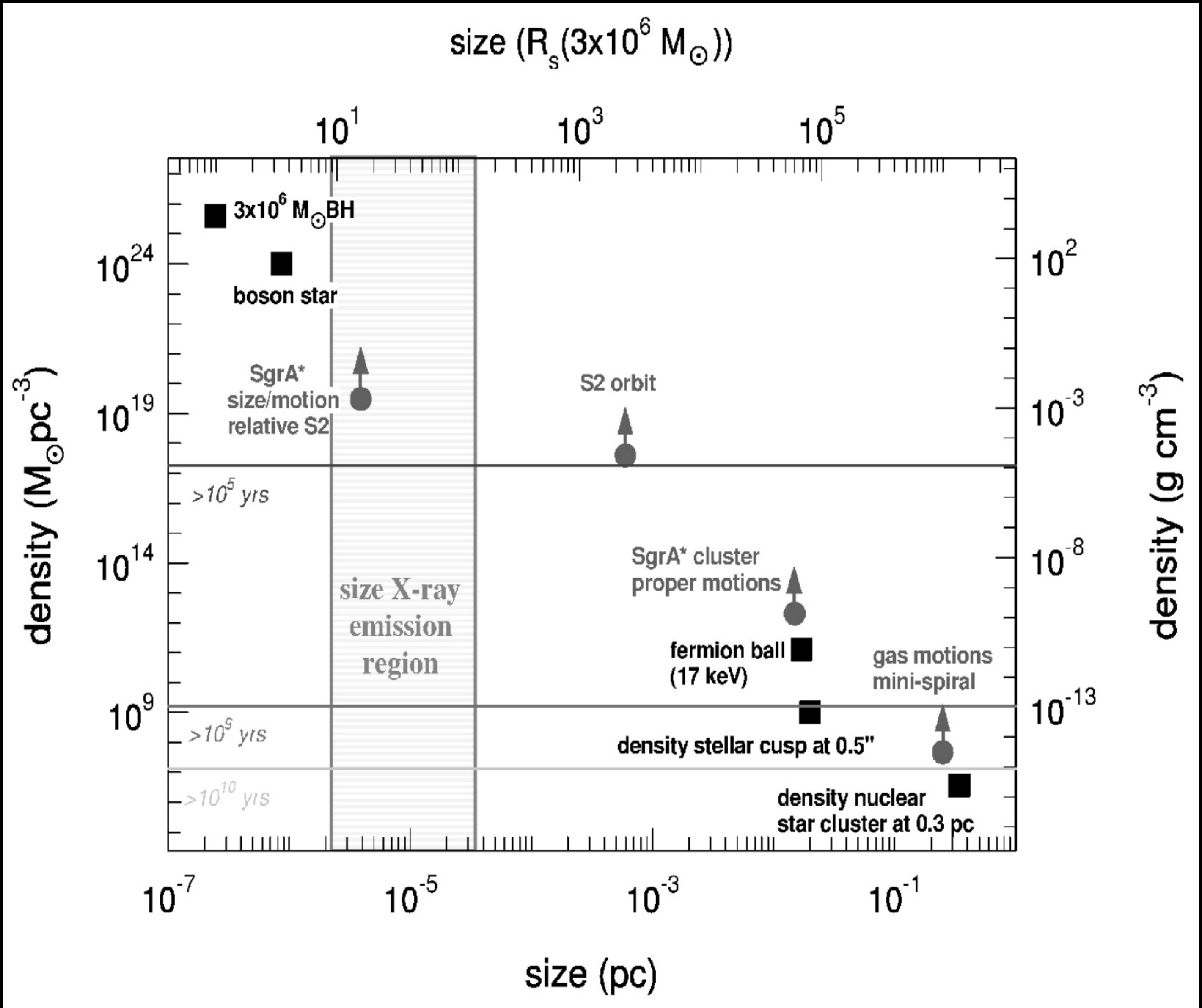
- Ghez et al. 2005 (UCLA)
  - New Keck diffraction limited observation, adaptive optics
  - Simultaneous 6-orbit fit
  - $M_{SgrA^*} = 3.7 \pm 0.2 \times 10^6\ M_{Sun}$
- Genzel et al., Nature, 2003
- Eisenhauer et al. 2005 (MPE/UCB)
  - ESO/VLT, adaptive optics
  - $M_{SgrA^*} = 3.6 \pm 0.3 \times 10^6\ M_{sun}$
  - $R_o = 7.6 \pm 0.3$ kpc



Ghez et al. 2005

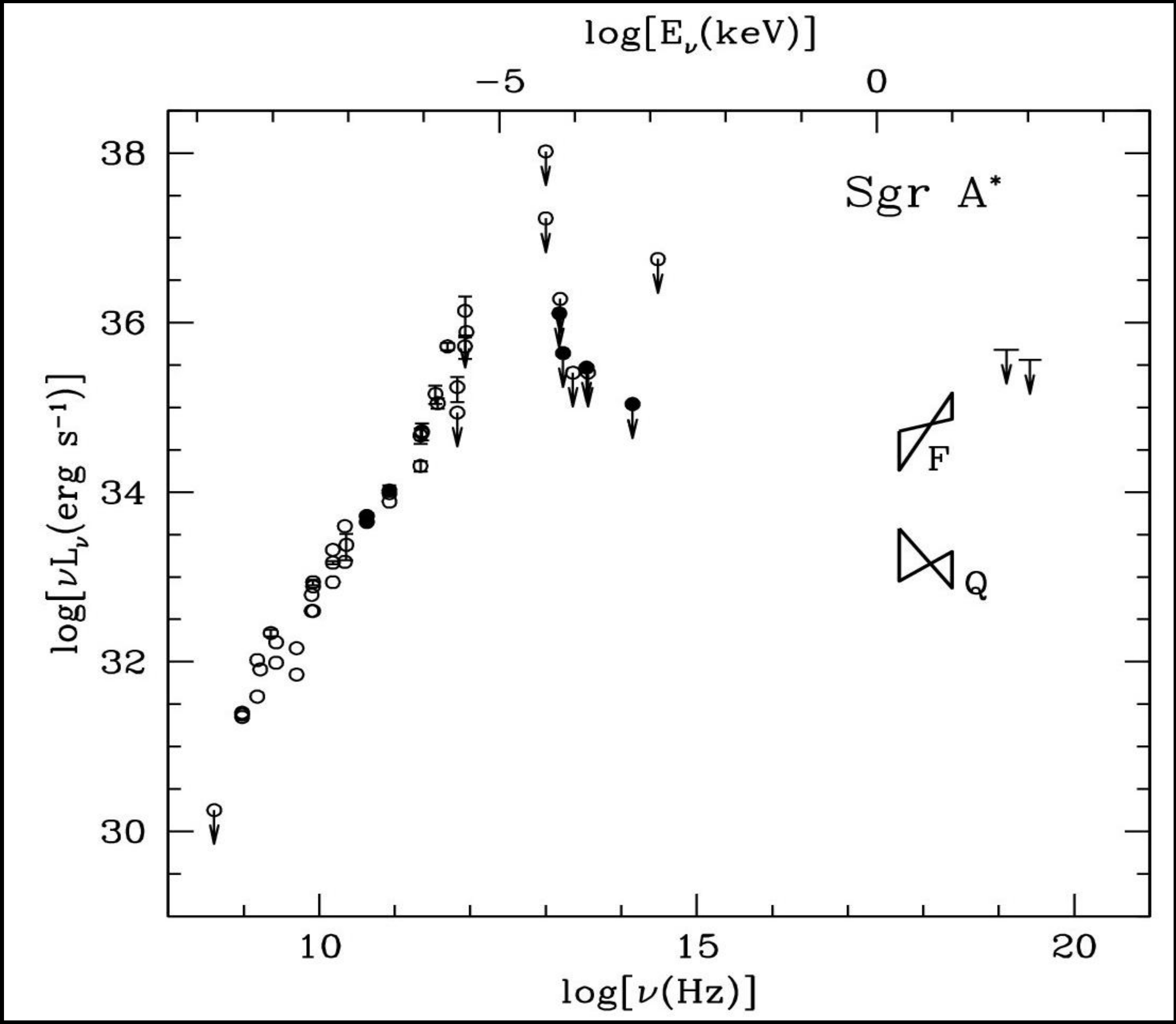
$$r_s = 1\times10^{12}\,cm = 3.6\times10^{-7}\,pc = 0.07\,AU = 10\,\mu as$$

It's (probably) a black hole



- Very few possible compact sources
- Who's seen a scalar boson anyway?
- Spectra fits well with jet & accretion models
- Some spectra features seem to indicate variability < 10 R_s
- Dark star clusters are short lived

Composite Spectrum

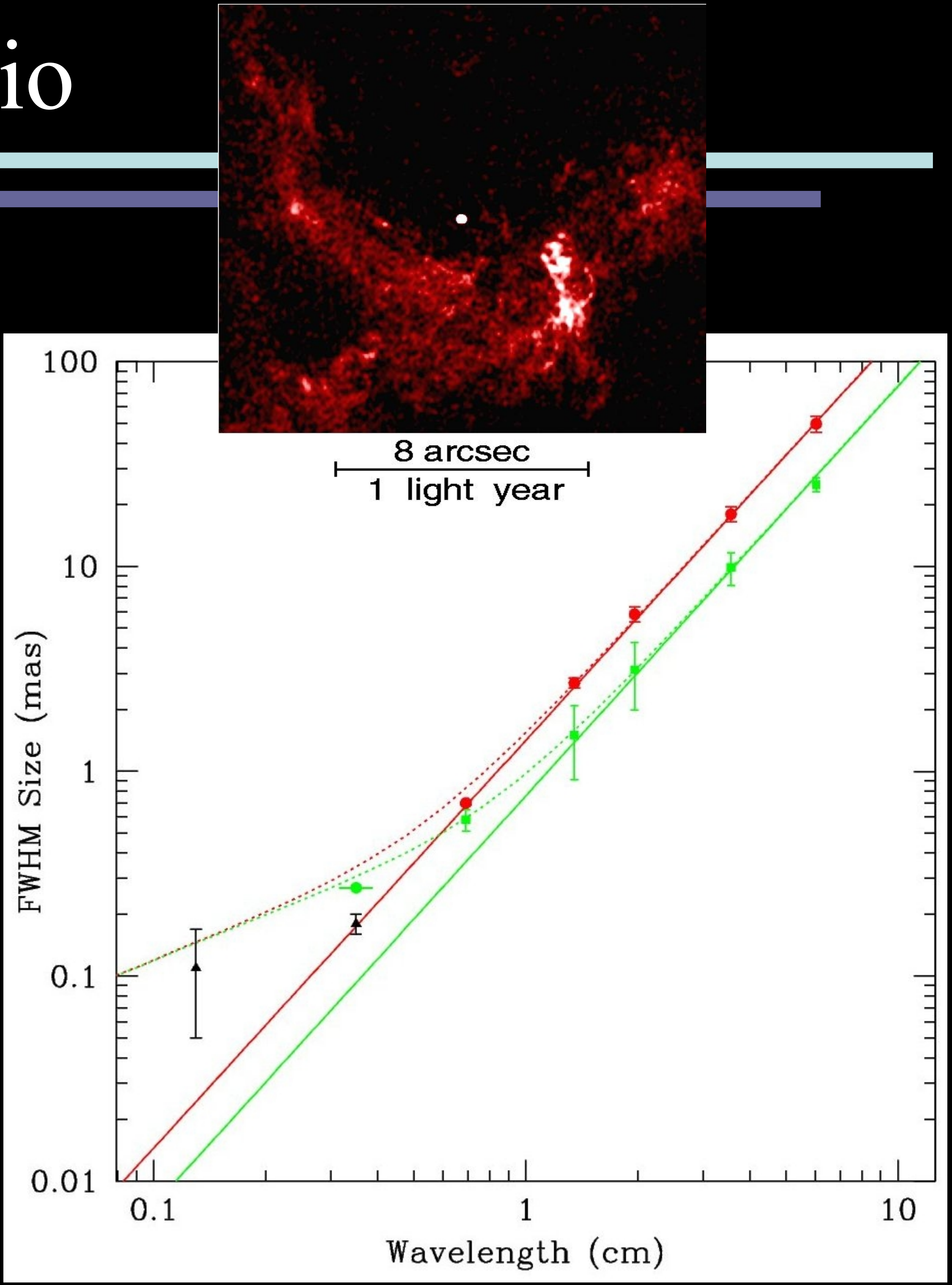


Sgr A* in the Radio

Shen et al. **Nature** (2005)
d < 25 M ~ 2 AU

- Shrinking with increasing frequency
- Power also increases with frequency to ~1mm
- Suggests disk may be becoming optically thin with freq.
- At limit of VLBI radio, working on mm VLBI (ALMA, SMA,...) and GRAVITY at VLT ;

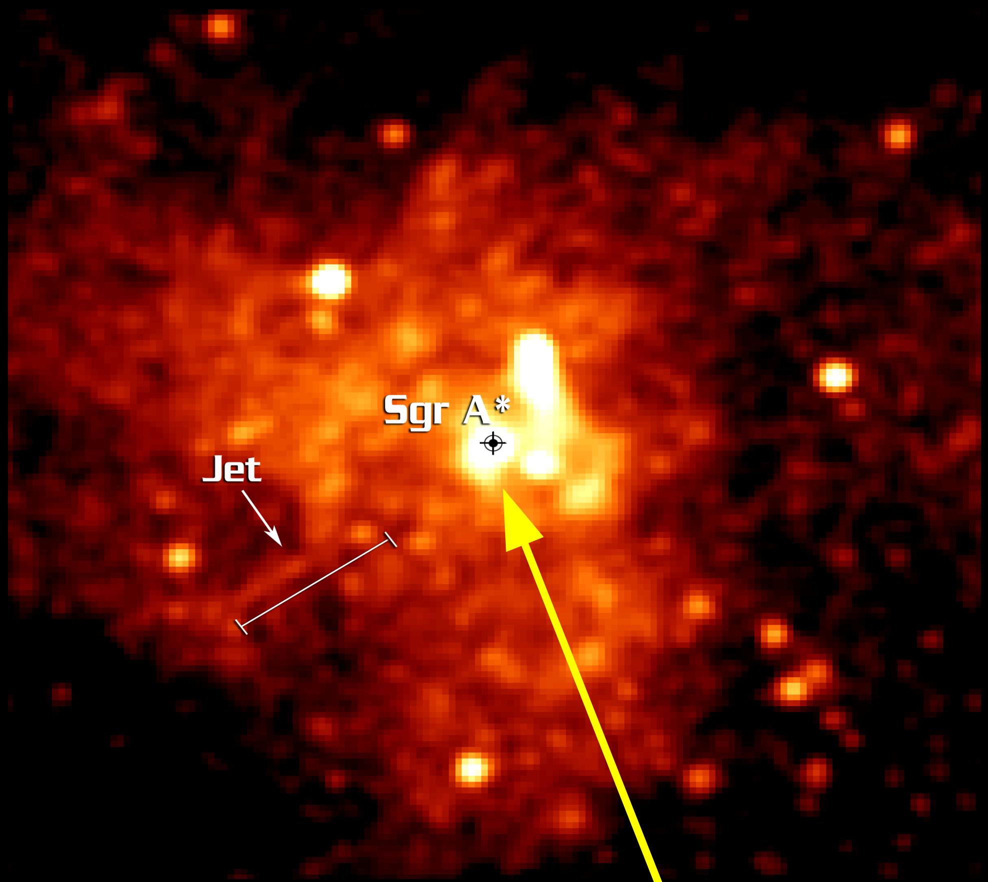
We w**ant to predict what they'll see!**



X-Ray Observations

8.4 arcmin

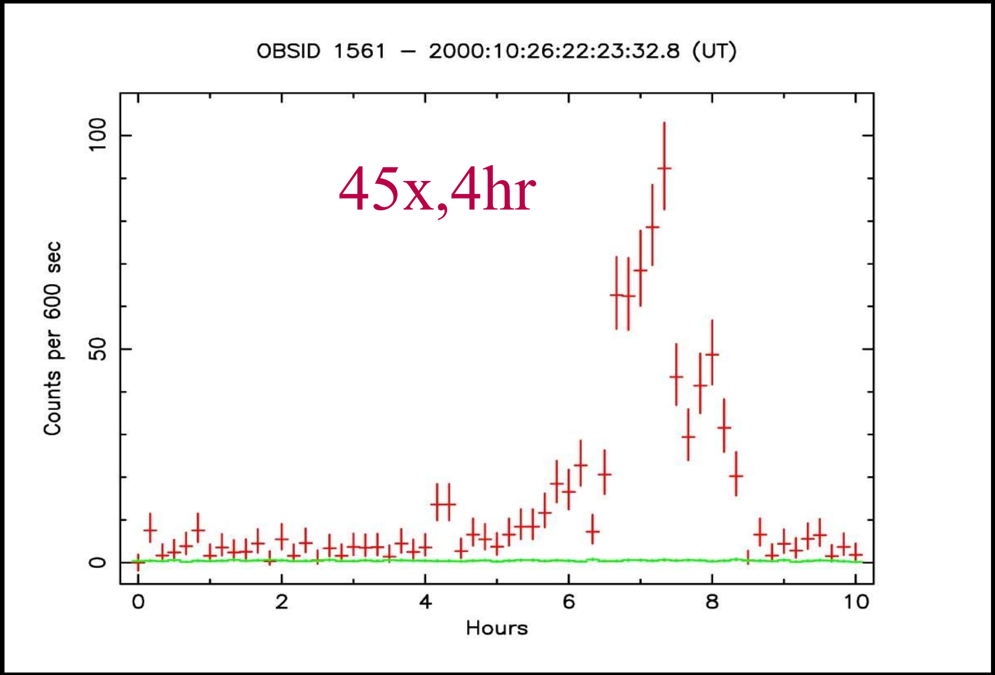
1.23 arcmin

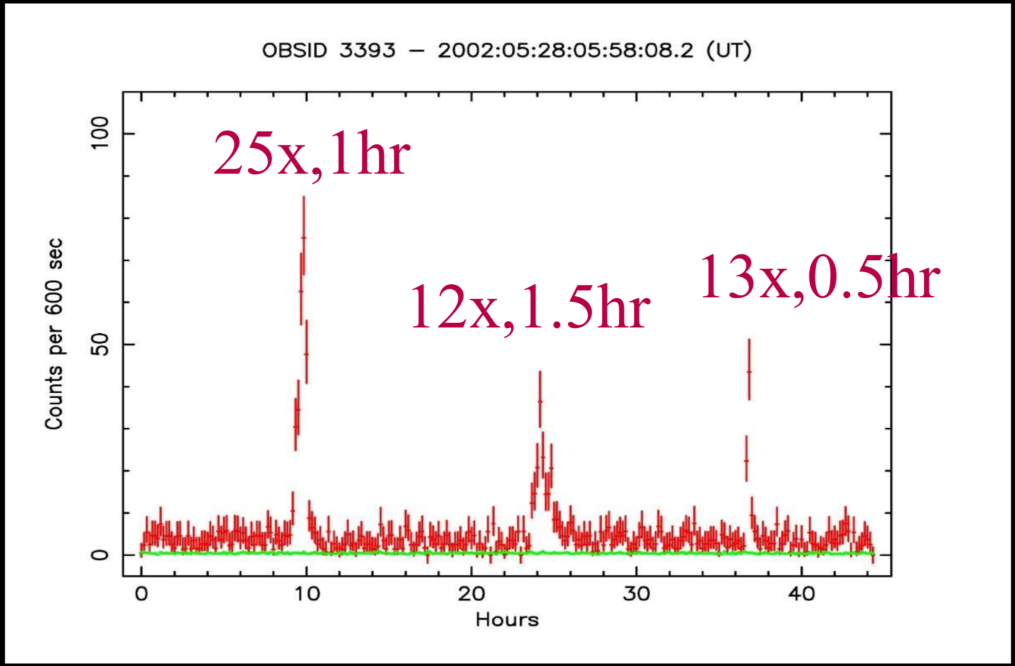


1.4 arcsec

NASA/CXC/MIT/ F.K. Baganoff et al.

X-Ray Variability

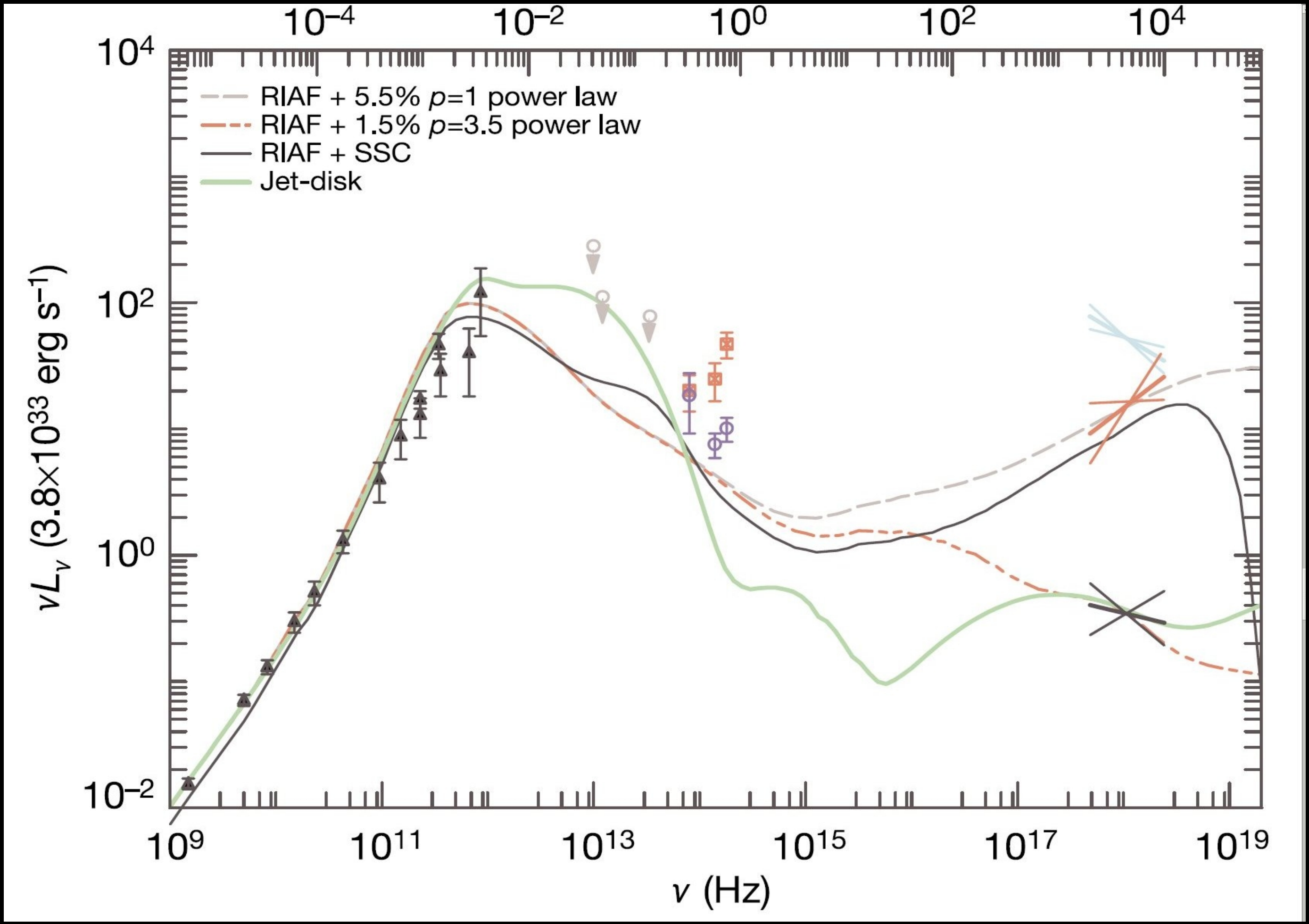




1hr variability --> ~20 R_s

Baganoff et al. (2000-2003) [Chandra]

Composite Spectrum (comparison)

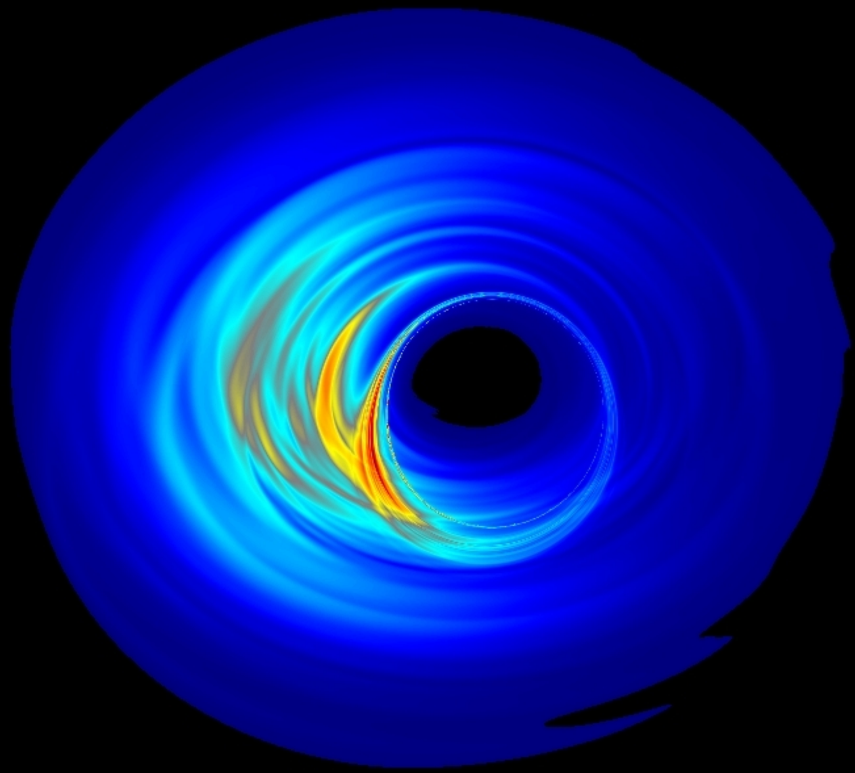


- RIAF's have problem with var. of brem. since $R_{brem} \sim 10^5 R_s$
- Instead, add PL n_e gives hard IC/SSC photons
- Solves Radio under-lum.
- Modern RIAF's have many parameters, need better constraints: simult. wide-freq. survey, submm VLBI

- Jets lack a mechanism, no launching mechanism
- Reliant on a disk model of some type
- Can it predict X-ray flare state?

Default Model

$$\nu_{obs}, \dot{M}, a, \theta_{inc}$$



20 M

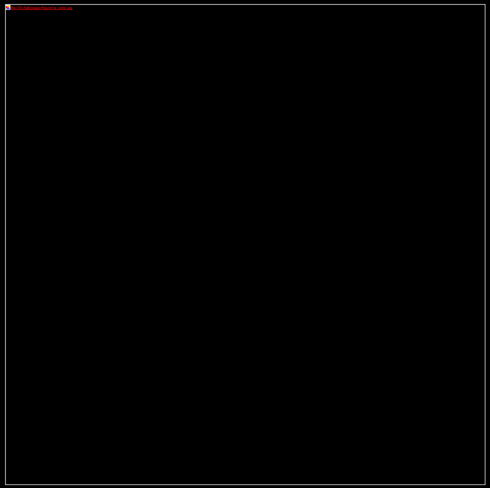
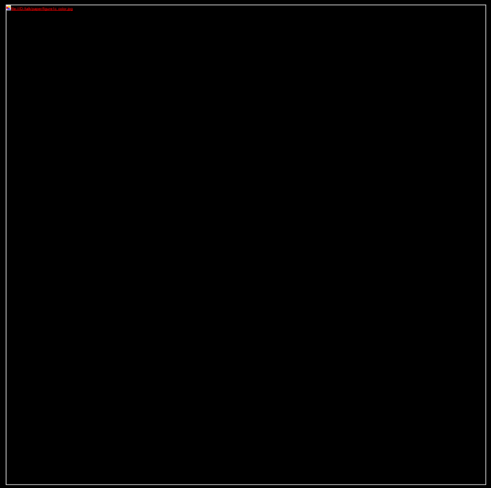
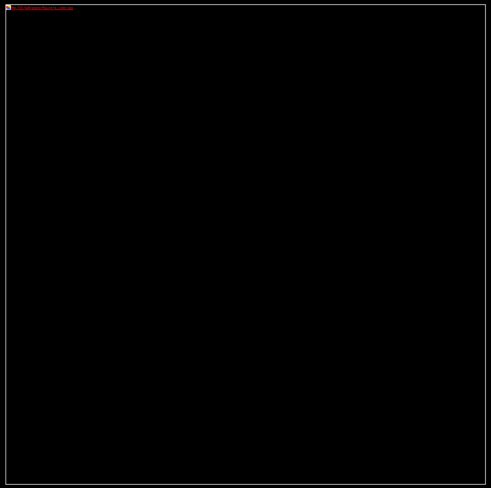
$$\nu_{obs} = 3x10^{11}\, Hz\, (1\mathrm{mm})$$

$$\dot{M} = 5x10^{-9}\, M_{sun}\, yr^{-1}$$

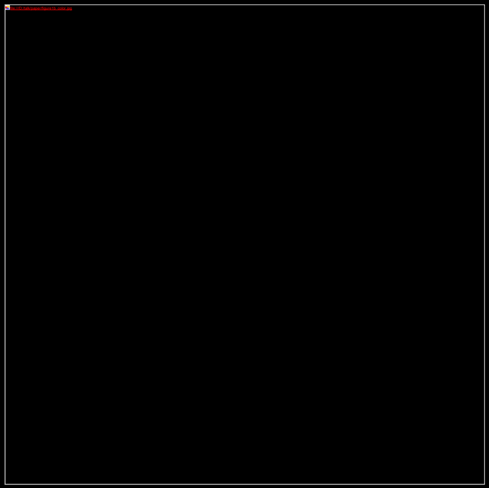
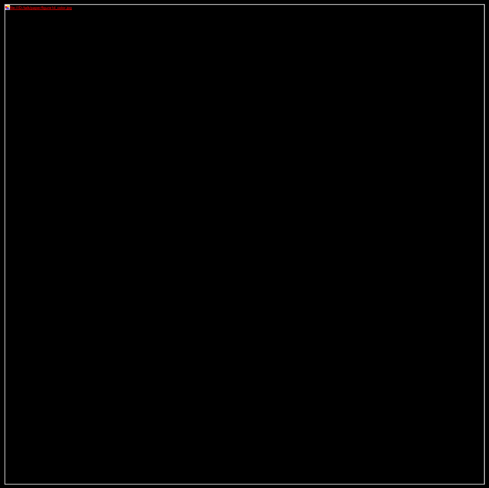
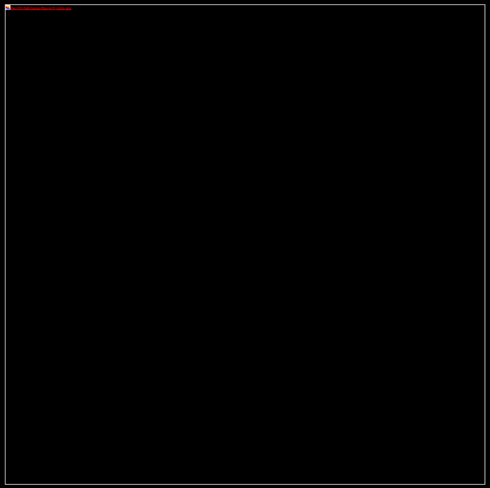
$$a = 0.94$$

$$i = 30^{o}$$

Inclination Survey

“Infinite” Resolution

Earth-based VLBI Resolution

$i = 5^o$ 30^o 90^o

Inclination Survey

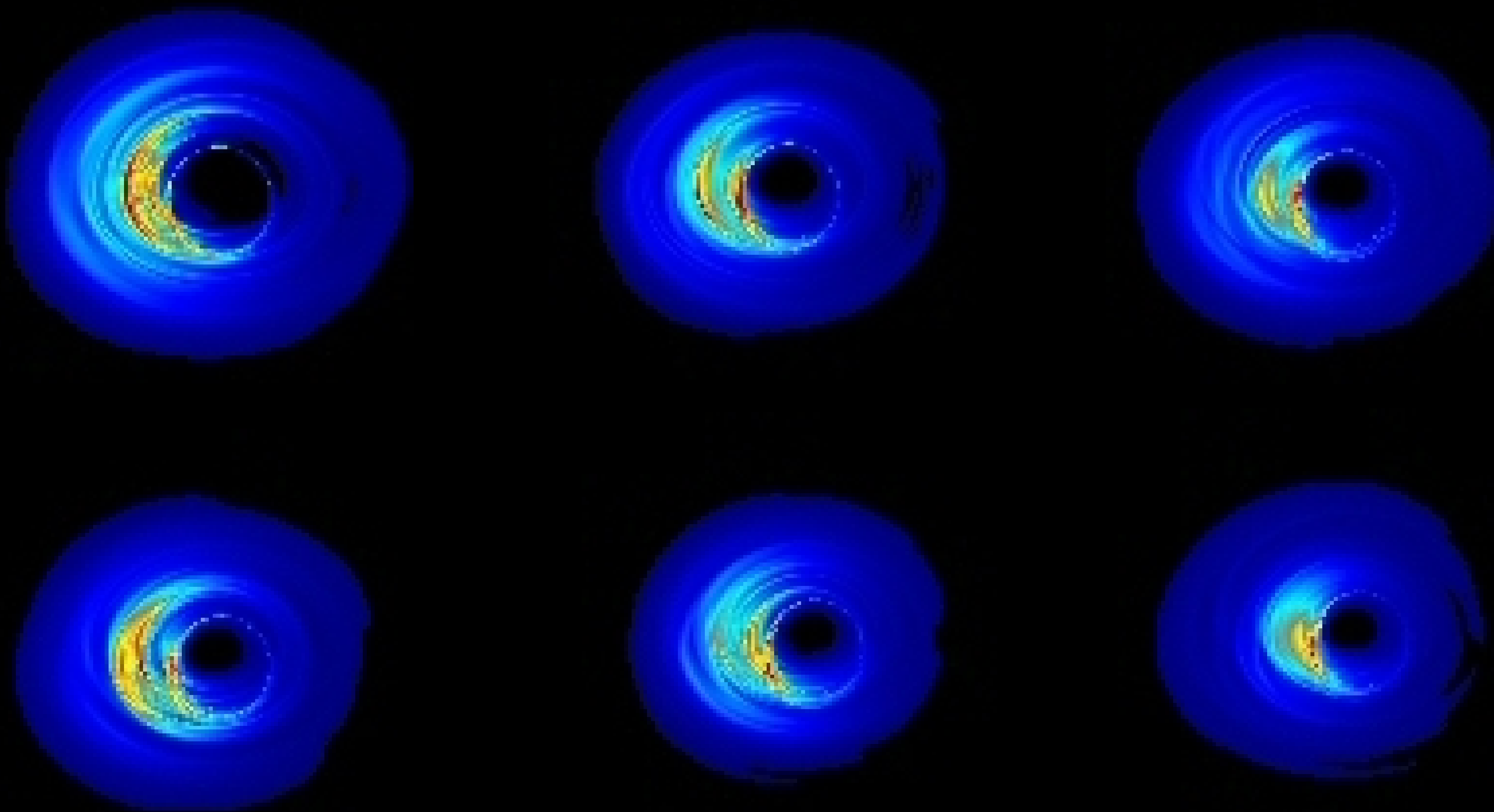
90 deg.

30 deg.

5 deg.

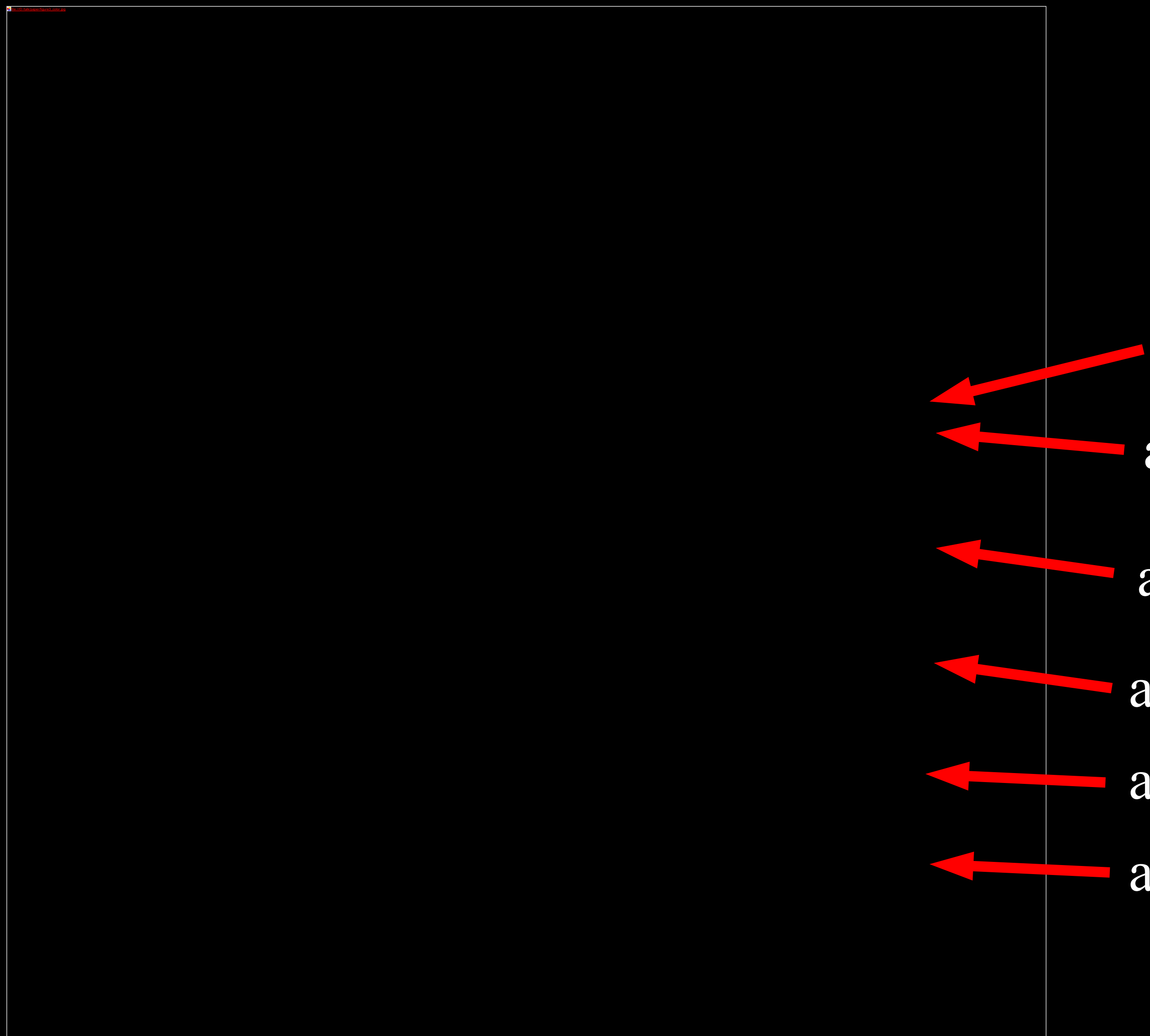
Spin Survey

0 0.5 0.75



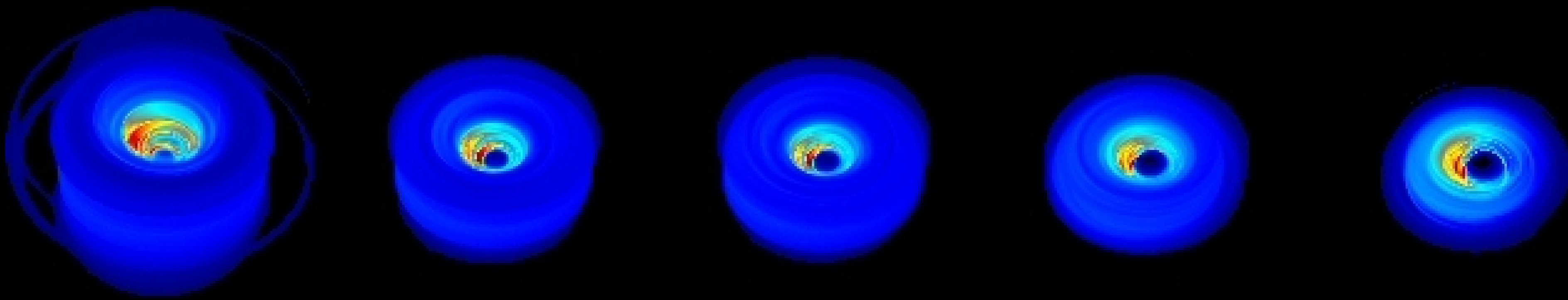
0.88 0.94 0.97

Spin Survey

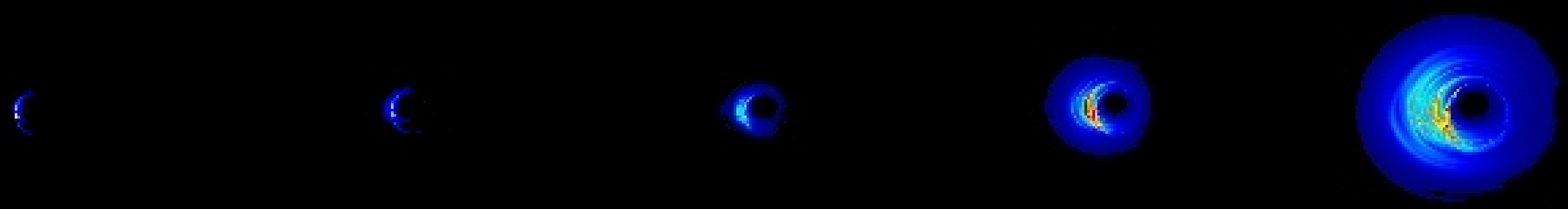


Angular Size with Frequency

$$i = 45^o \qquad a = 0.94\,M$$

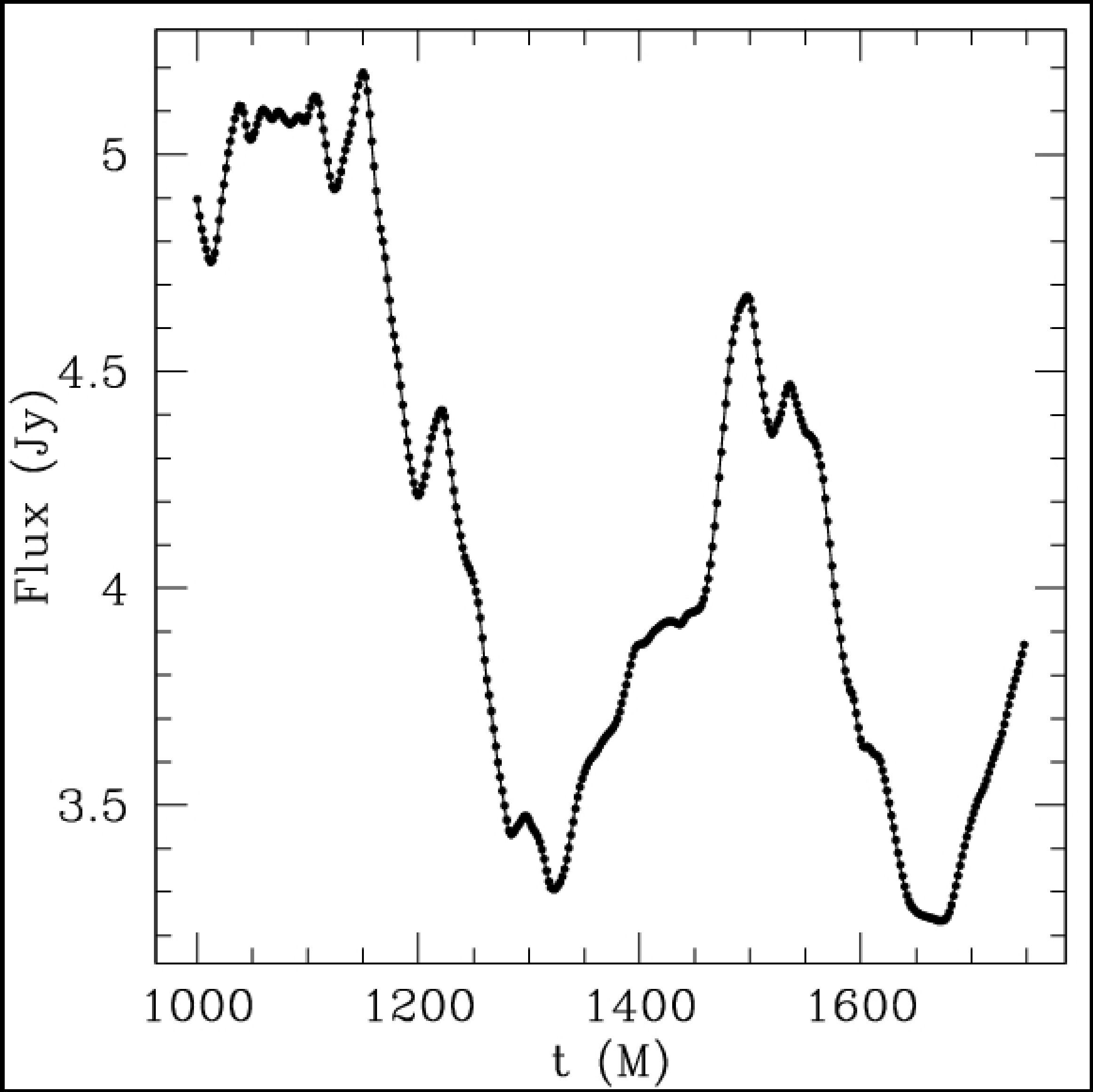


5 GHz | 15 GHz | 22 GHz | 43 GHz | 86 GHz



10^{15} Hz | 10^{14} Hz | 10^{13} Hz | 10^{12} Hz | 300 GHz

Time Variation



(t = 1150M, 1250M, 1326M, 1434M, 1500M, 1666M)

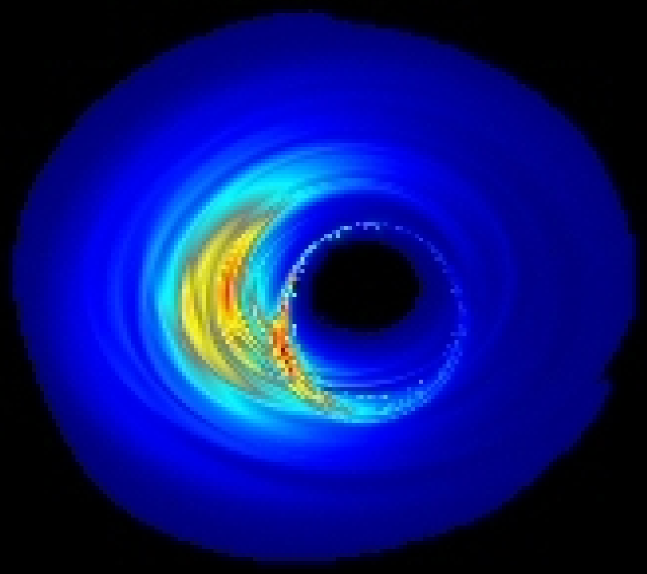
Time Variation

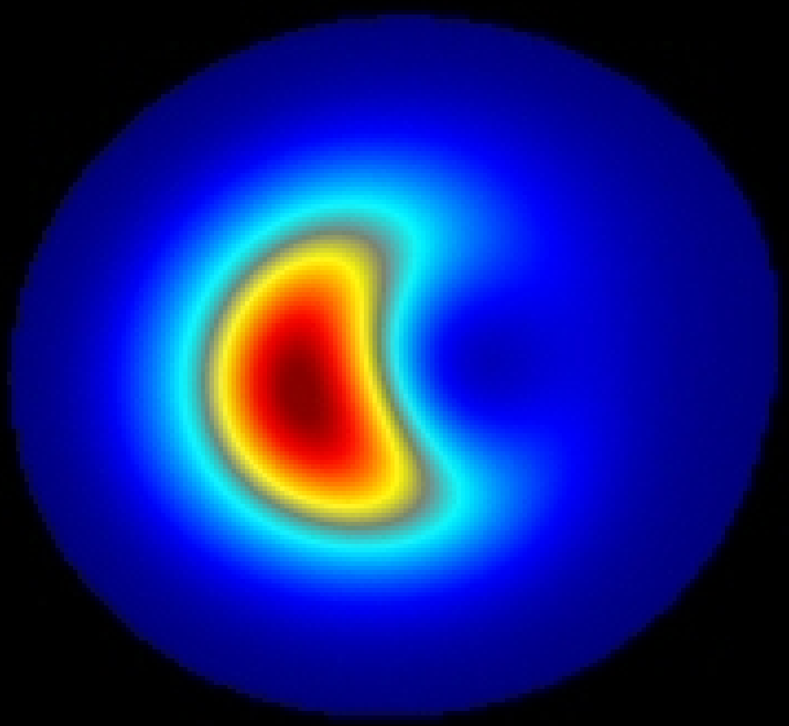
file:///D:/talk/paper/figure2_color.jpg

t = 1150M, 1250M, 1326M, 1434M, 1500M, 1666M

Time Variation

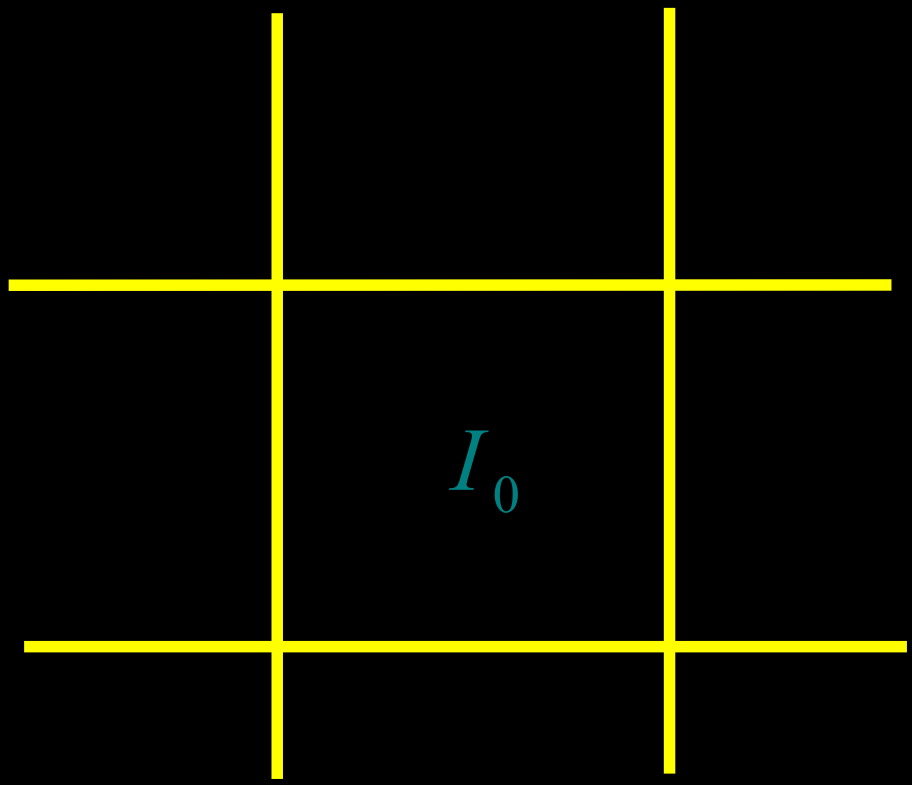
t = 1000M - 1700M





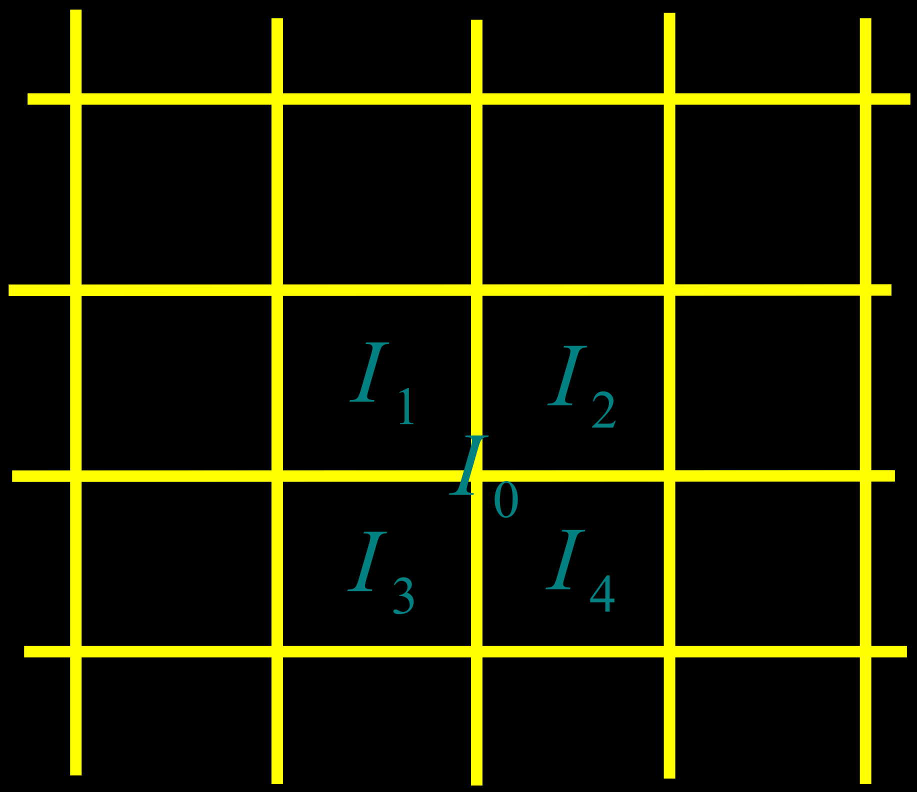
Adaptive Pixel Refinement

$$I_{ray} A_{pixel} \simeq \int_{pixel} I_{\nu} \, dA$$



Adaptive Pixel Refinement

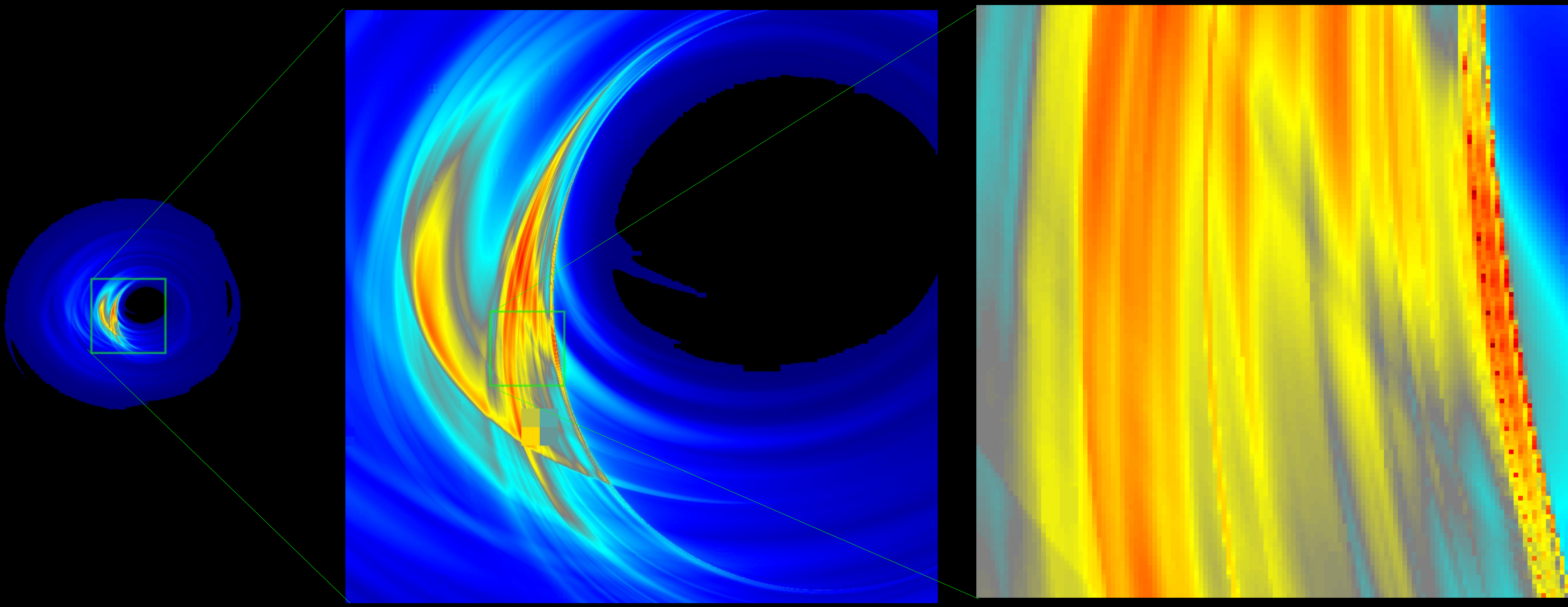
$$I_{ray} A_{pixel} \simeq \int_{pixel} I_{\nu} \, dA$$



$$I_0 = \frac{1}{4}\left(I_1 + I_2 + I_3 + I_4\right)$$

Adaptive Pixel Refinement

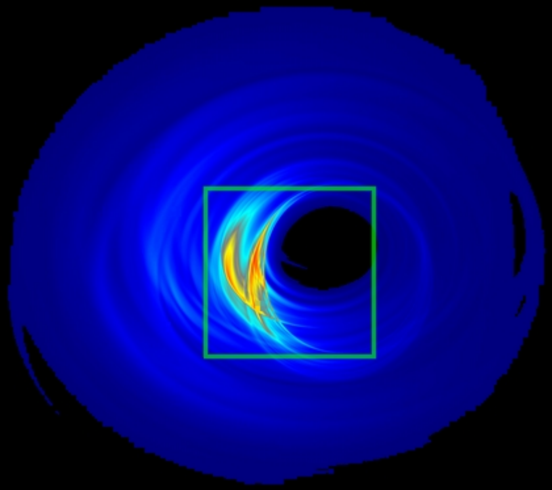
Base Resolution = 128x128 , 6 levels of refinement

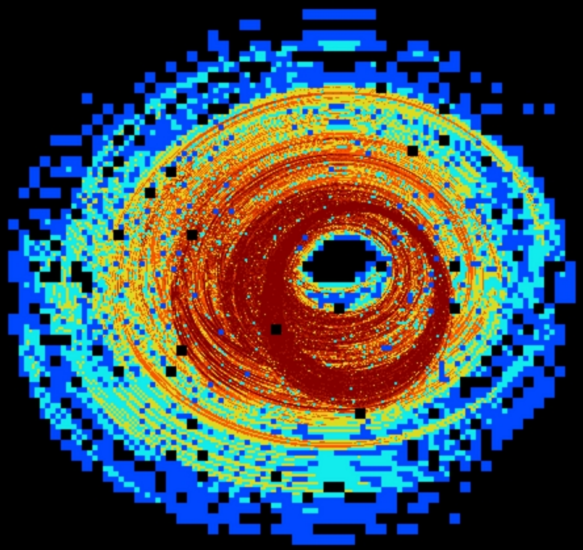


Effective Resolution = 8192x8192 = 2^13^2 = 67 Megapixel

Adaptive Pixel Refinement

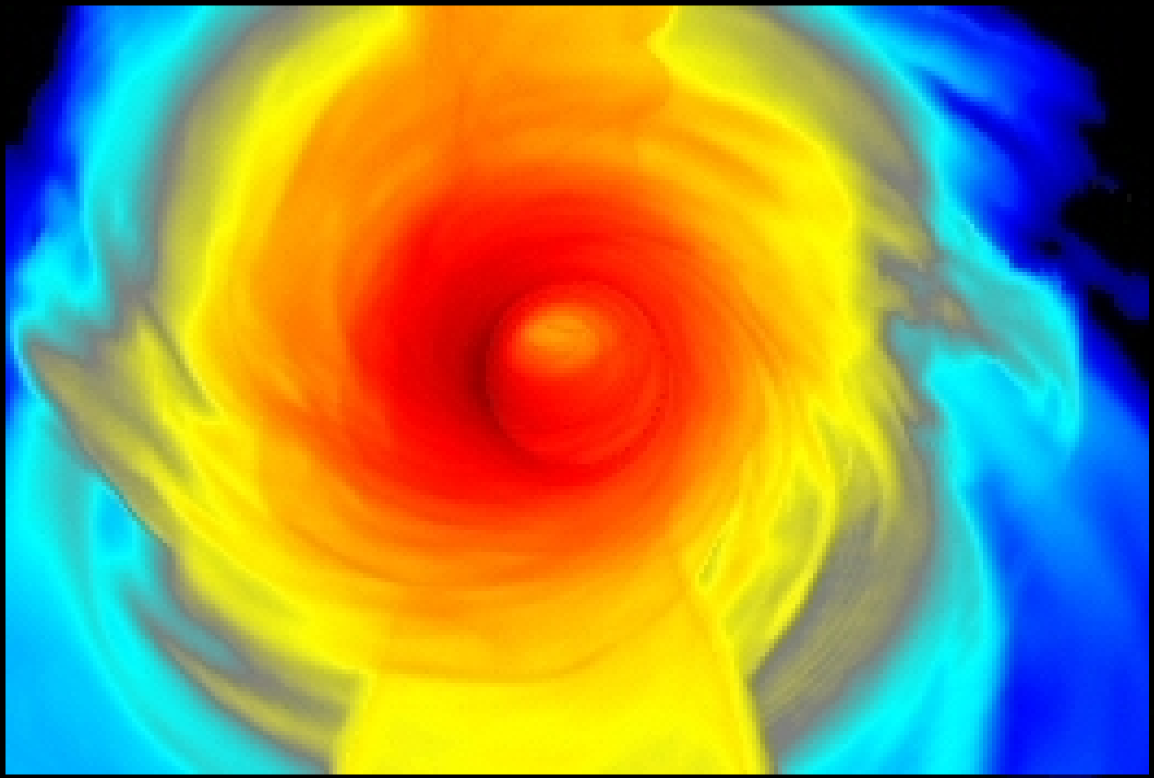
Base Resolution = 128x128 , 6 levels of refinement

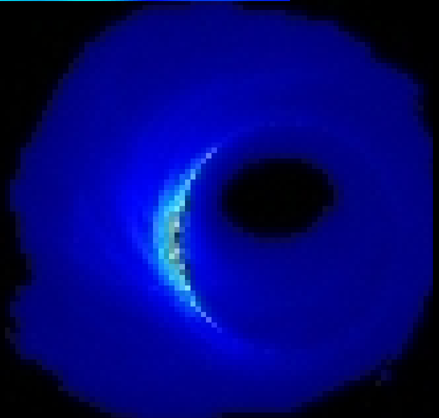




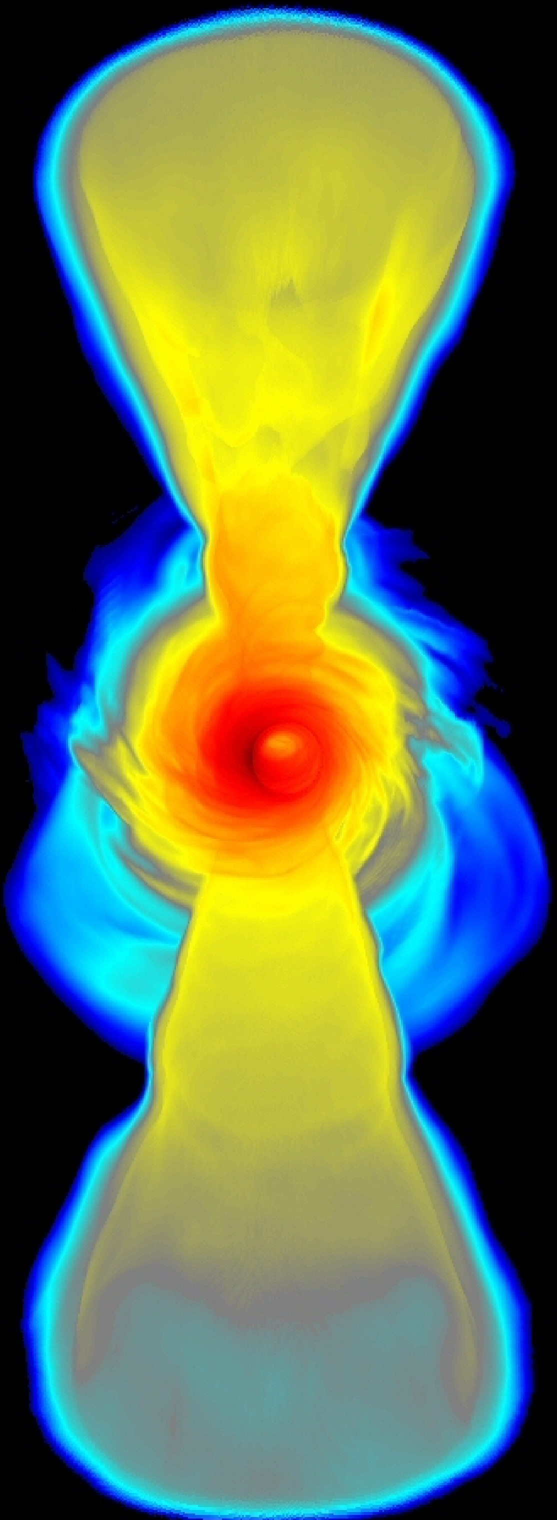
Effective Resolution = 8192x8192 = 2^13^2 = 67 Megapixel

3D Simulations





1024^2 Pixel Image
192x192x64 Uncooled Disk



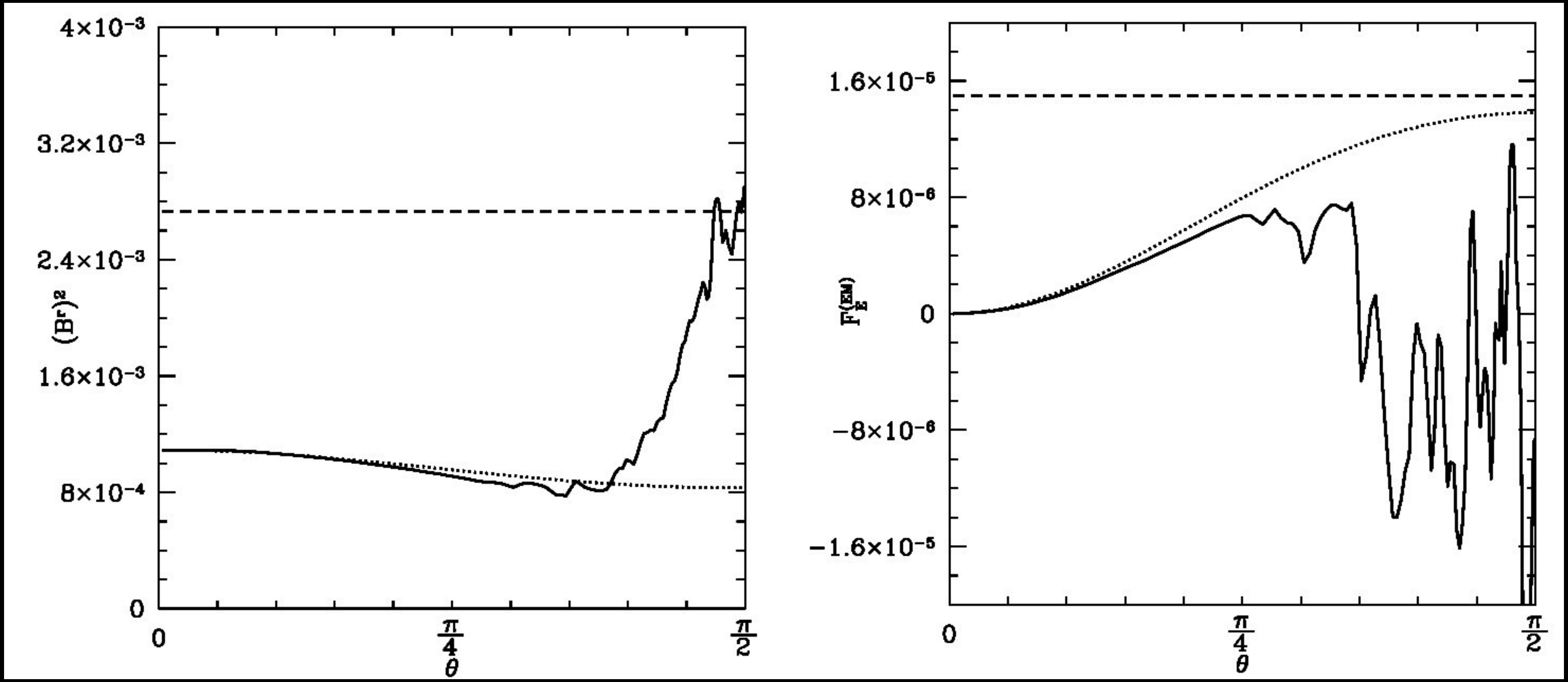
Summary

- Observable shadow for $\theta_{inc} < 30\, deg.$
- Spectral dependence on all degrees of freedom
- Greatest variability seen between disks of different spin
- Greatest variability seen at larger frequencies (ala relativistic beaming near horizon)
- Spatial/temporal variability important --- need dynamic models
- Amenable for identifying characteristics of SgrA*'s spacetime
- $\dot{M}_{num} \sim \dot{M}_{obs}$

Future Work

- Interpolate simulation data in TIME & space
- Temporal variability --> Need to time average images/spectra
- Calculate polarized emission.... (in the works: P. K. Leung)
- Add non-thermal distribution of electrons to model
    - Requires evolution of electron energy eq. in simulations
- Finish adaptive pixel refinement algorithm
- Compton scattering
    - Needs Monte Carlo (C. Gammie)
- Use 3D simulation data (HARM3D in the works...)

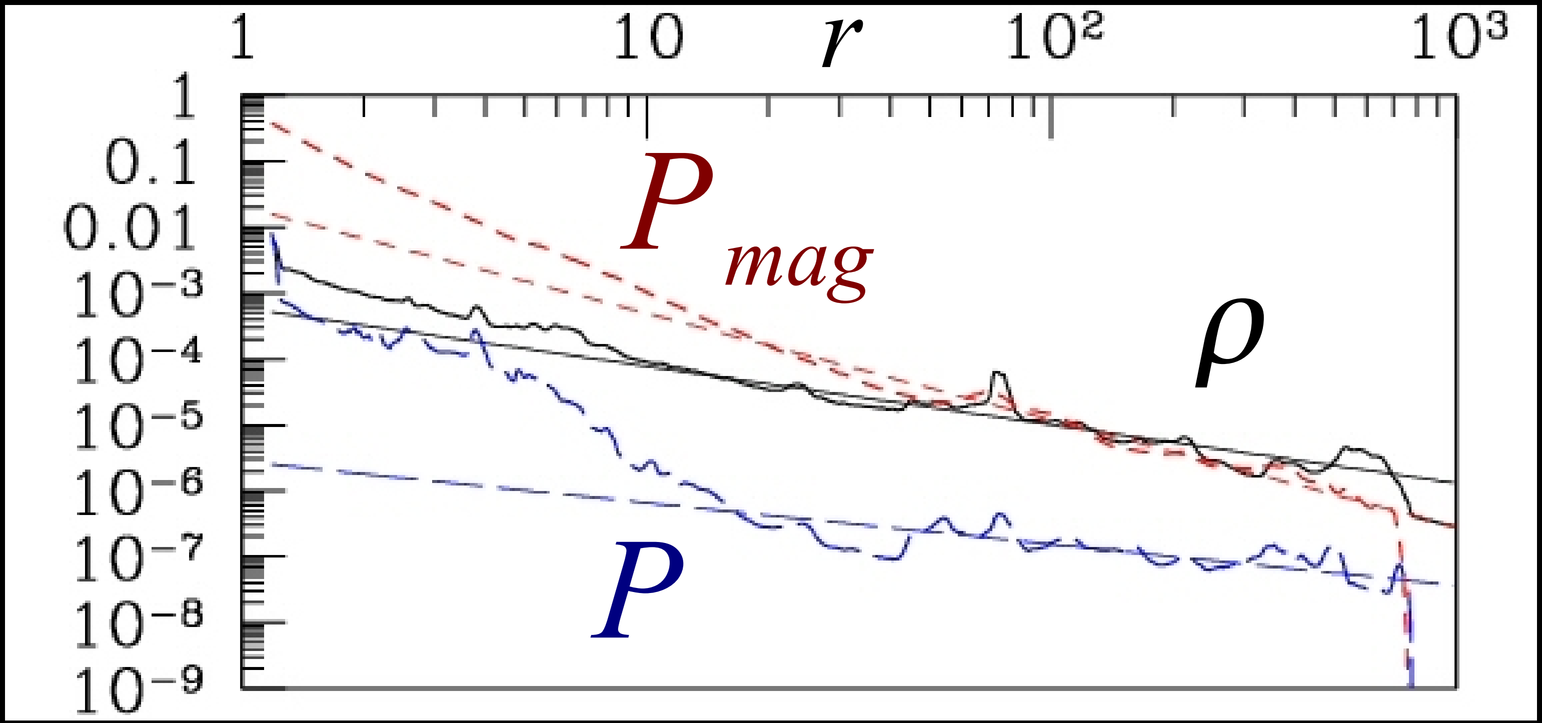
Magnetic Field Structure



McKinney & Gammie (2004)

Disk Outflows

SCN, Leung, Gammie, Book (2007)



$$\rho \sim r^{-0.9}$$

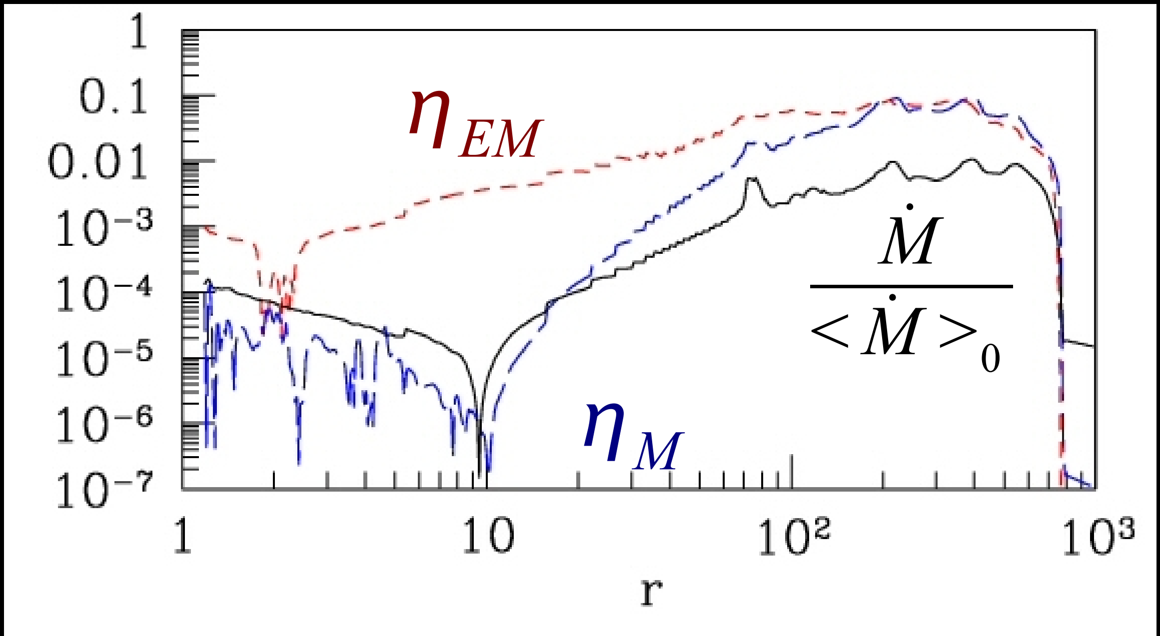
$$P \sim r^{-0.6}$$

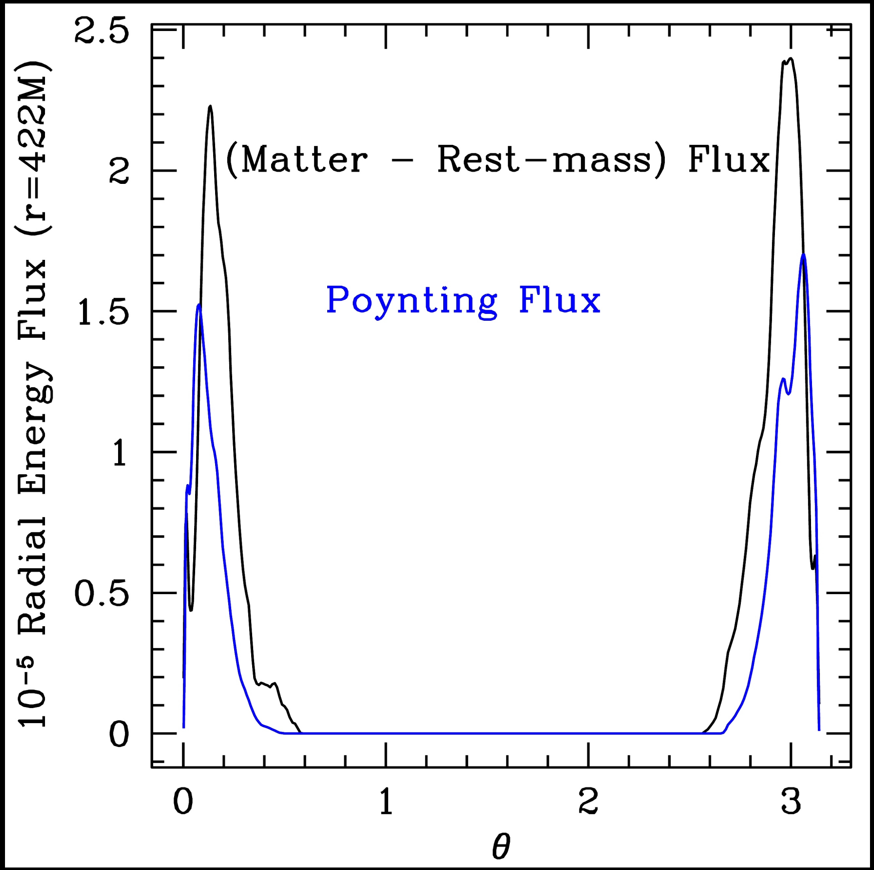
$$P_{mag} \sim r^{-1.6}$$

- Matter dominates energy at large r.
- Jet is not relativistically hot (maybe a floor issue).
- Shallower density profile than McKinney (2006) at r > 100M (floor issue).

Disk Outflows

SCN, Leung, Gammie, Book (2007)





- Fluxes averaged over constant opening angle from axes.
- Efficiencies are normalized by average free energy.
- Matter and EM fluxes asymptotically converge at large radii.

$$L_{jet} = 0.013\, \dot{M}\, c^2$$