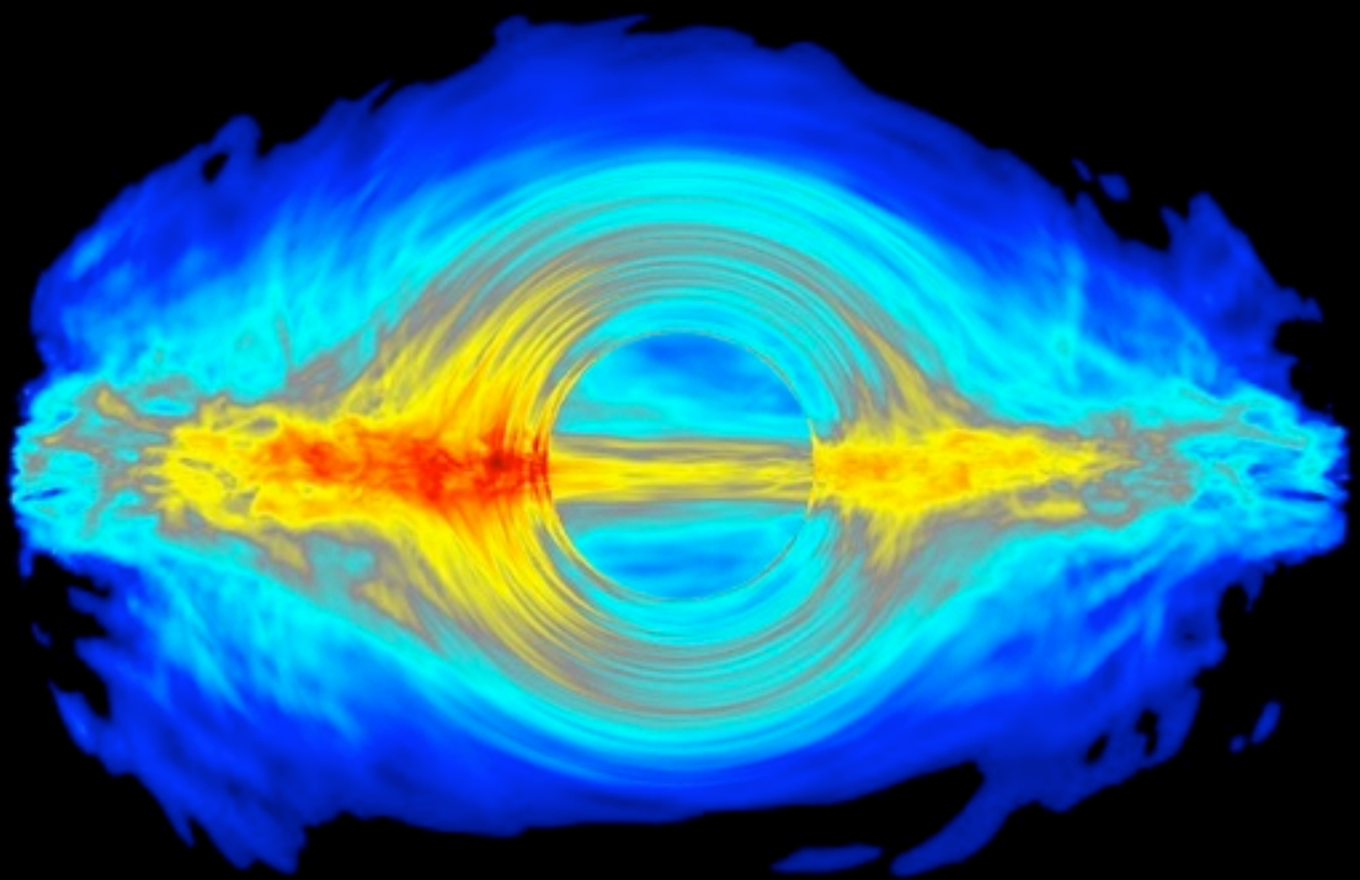
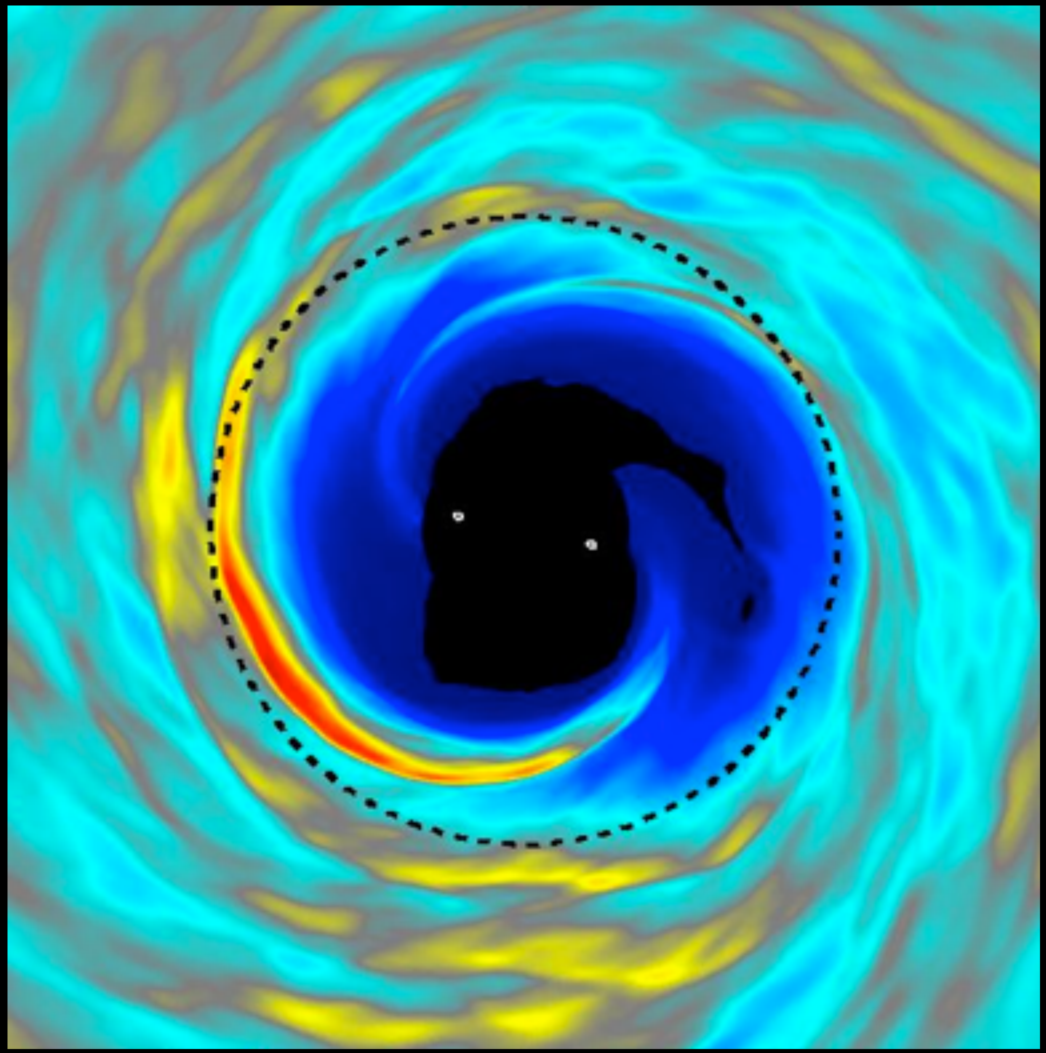
Predicting the Needle in the Haystack:

Simulating Accreting Supermassive Binary Black Holes





Scott Noble

M. Campanelli, J. Krolik, B. Mundim*, H. Nakano*,
J. Schnittman, N. Yunes, M. Zilhao, Y. Zlochower

RIT (* now at AEI & Yukawa Inst.)
Johns Hopkins
Montana State U.
NASA Goddard

BHOLES13 * KITP * August 7, 2013

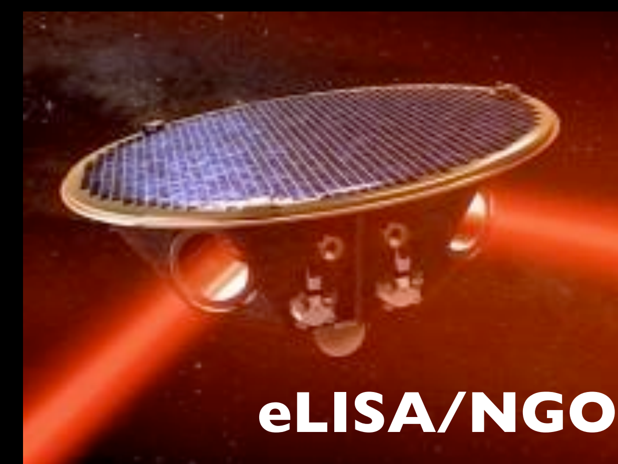
Multimessenger Synergy

Electromagnetic Surveys

Pan-STARRS:
- 2010-??
- 4 skies per month

Large Synoptic Survey Telescope (LSST):
- 2021-2032
- 1 sky every 3 days

Gravitational Wave Observatories



EPTA

NANOGrav

PPTA

- GW Detection/Localization <---> EM Detection/Localization;
- GW and light are connected theoretically but originate in wholly different mechanisms
  - --> independently constrain models;
- Either GW or EM observations of close supermassive BH binaries would be the first of its kind!
- Follow up (X-ray, sub-mm) observations can often be made via coordinated alert systems;
- Cosmological "Standard Sirens": New Distance vs. Redshift Measurement

  Schutz 1986, Chernoff+Finn 1993, Finn 1996, Holz & Hughes 2005

The Name of the Game:

- **Predict accurate EM signatures of BBHs over course of the binary's epochs** (focusing on the neighborhood of the merger):
  - **Inspiral --> Merger --> Ringdown --> one BH**

- **Gravity + Matter = Light**

  --> Detections --> People believing in what we're doing!

  --> Spectacular evidence of SMBBHs mergers and science!

- **GR(t) + MHD <--> GR Radiative Transfer**

- **We think we understand basic GRMHD+Rad. theory well, we just need good initial data and a decent thermodynamics...**

- **Ignore self-gravity of gas, the binary separation is too small;**

Brief Survey of Simulations w/ GR(t)

"Clouds"

Gaussian:
  Bode++2010

Binary Bondi-Hoyle-Lyttleton:
  Farris++2010

Disks

Hydro:
  Bode++2010, Farris++2010

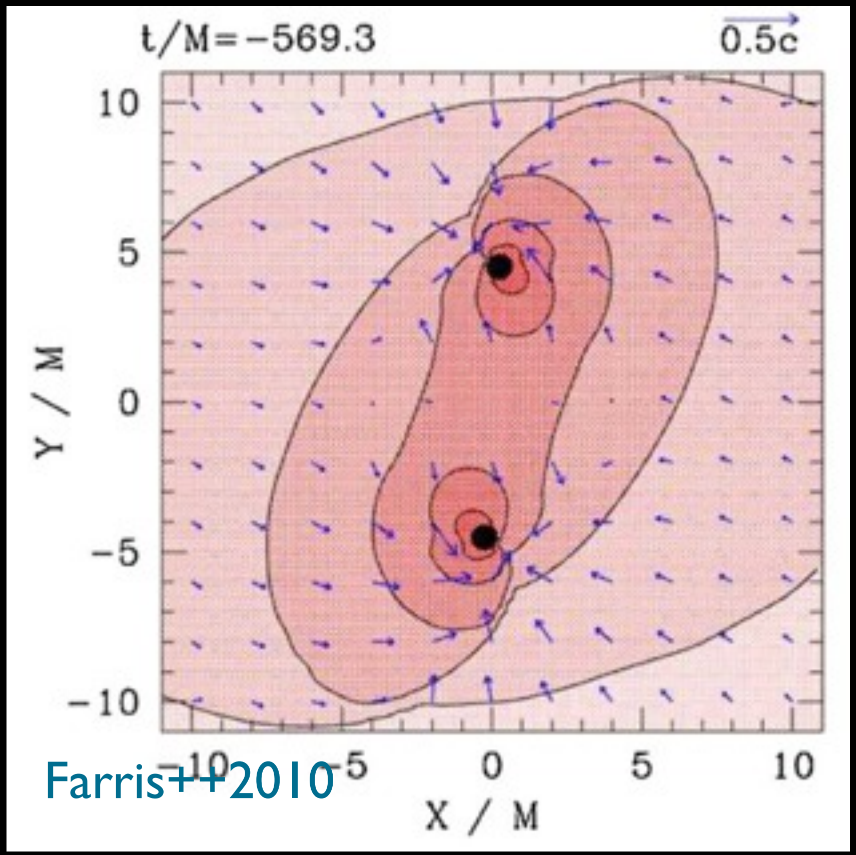
MHD:
  Farris++2012

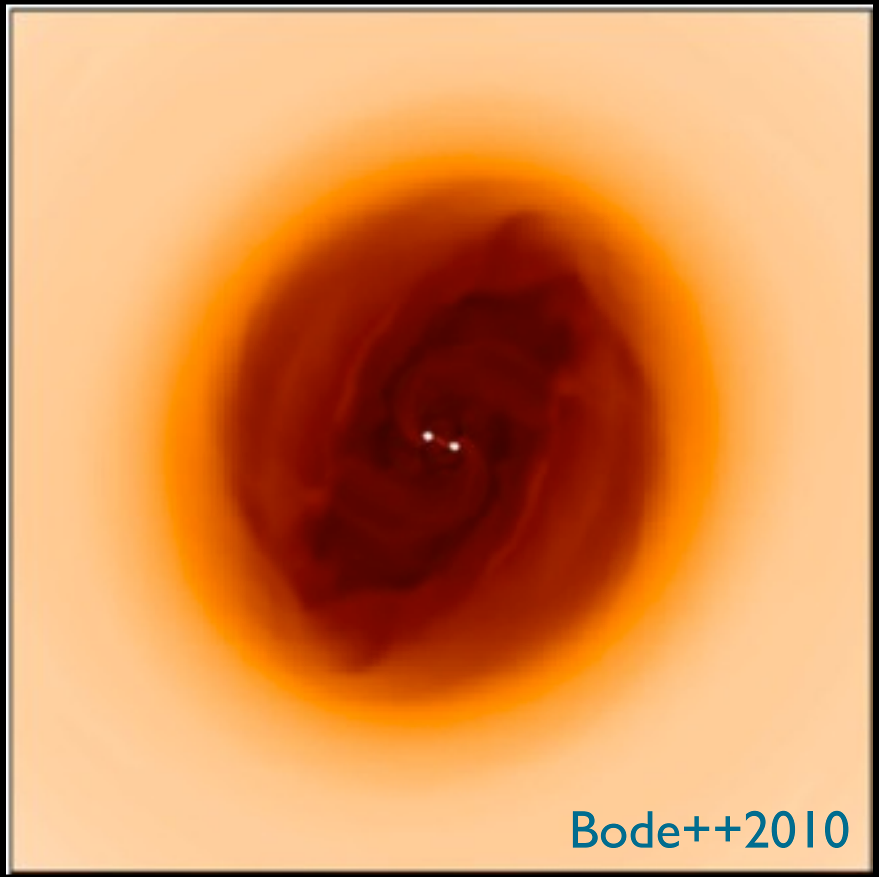
Jets

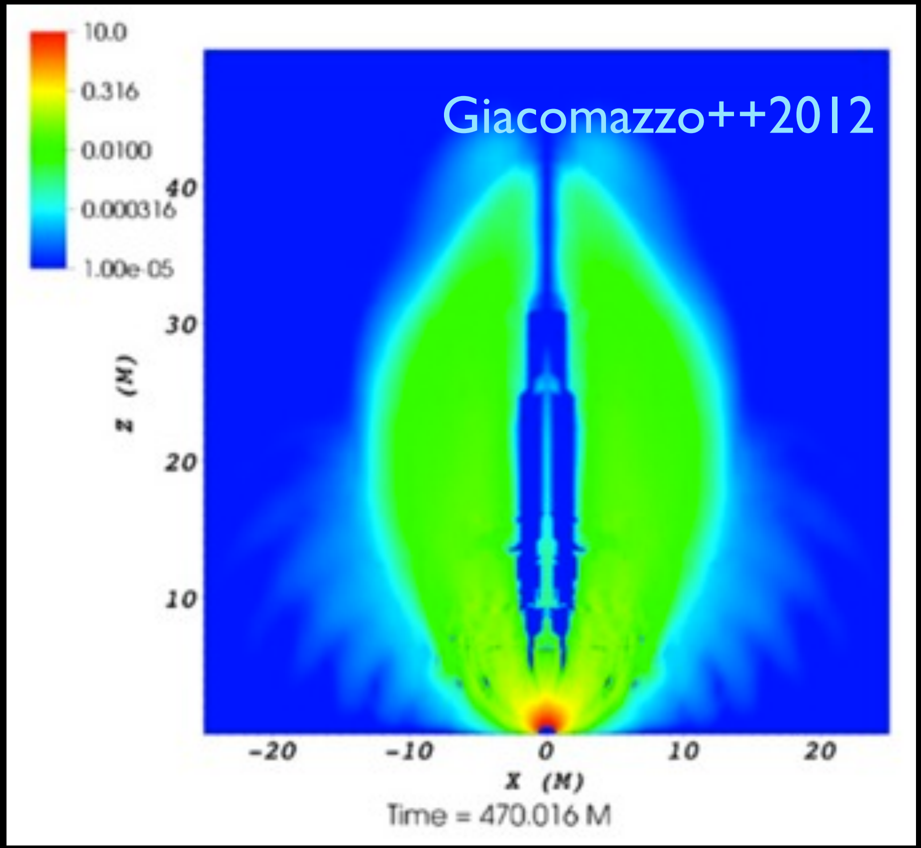
Electro-Vac:
  Palenzuela++2010, Moesta++2010

Force-free:
  Palenzuela++2012, Moesta++2012

MHD:
  Giacomazzo++2012







- Variability from:
  - Relativistic beaming from approaching/receding BH;
  - Binary's orbital motion w.r.t. background flow;
  - Accretion dynamics;
- EM signature coincident with merger;

$$8 \leq a_{\rm sep}/M \leq 10$$

$$L \sim 10^{47} \frac{\rm erg}{\rm s} \left(\frac{B}{10^4 G}\right) \left(\frac{M}{10^8 M_\odot}\right)^2$$

$$L/L_{\rm edd} \sim 0.002 \text{ to } > 1$$

Brief Survey of Simulations w/ GR(t)

“Clouds”

Gaussian:
Bode++2010

Binary Bondi-Hoyle-Lyttleton:
Farris++2010

Disks

Hydro:
Bode++2010, Farris++2010

MHD:
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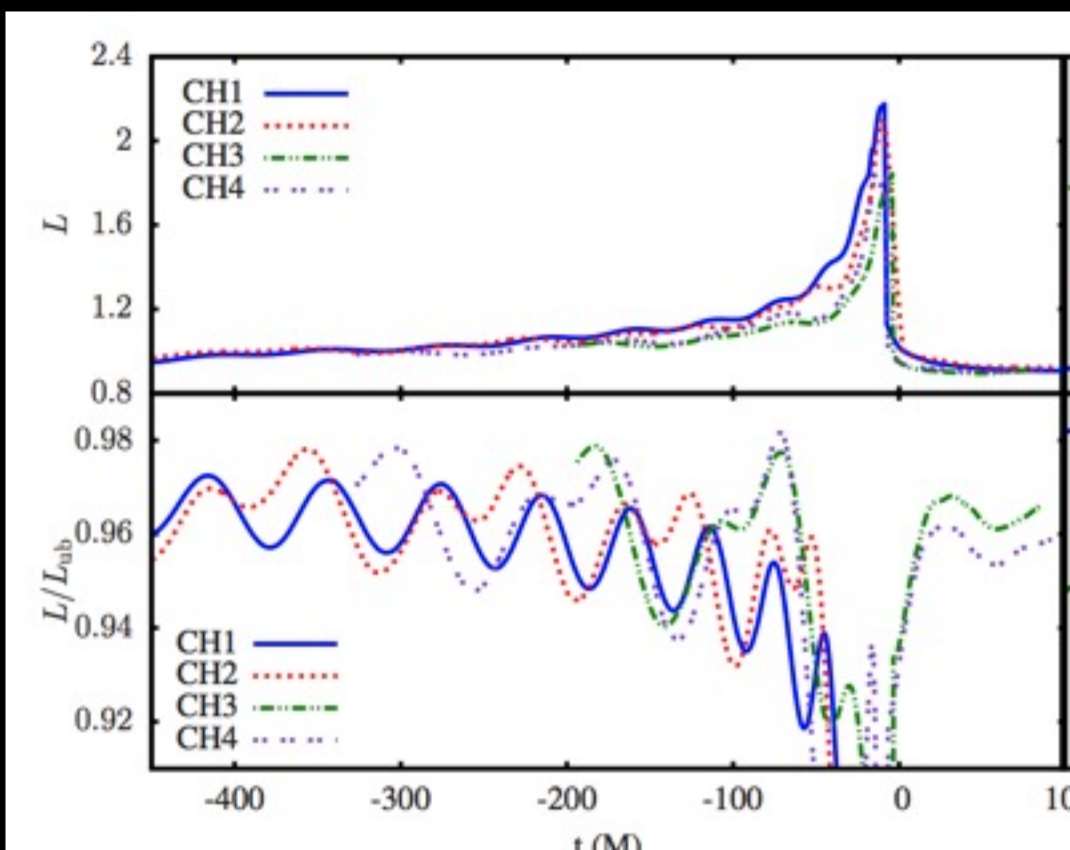
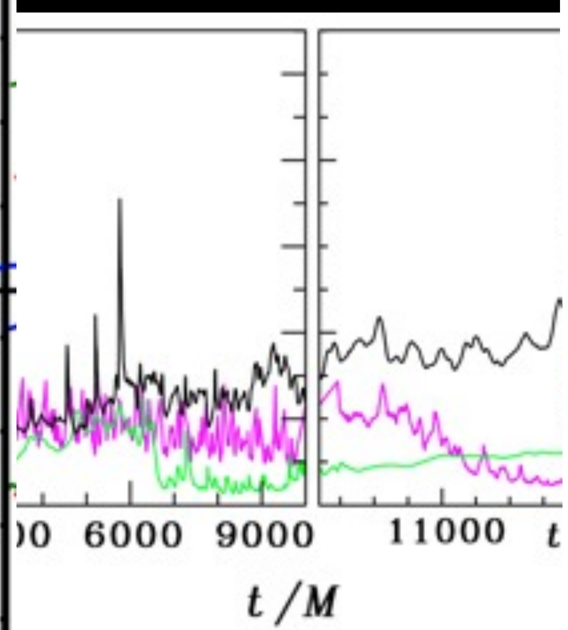
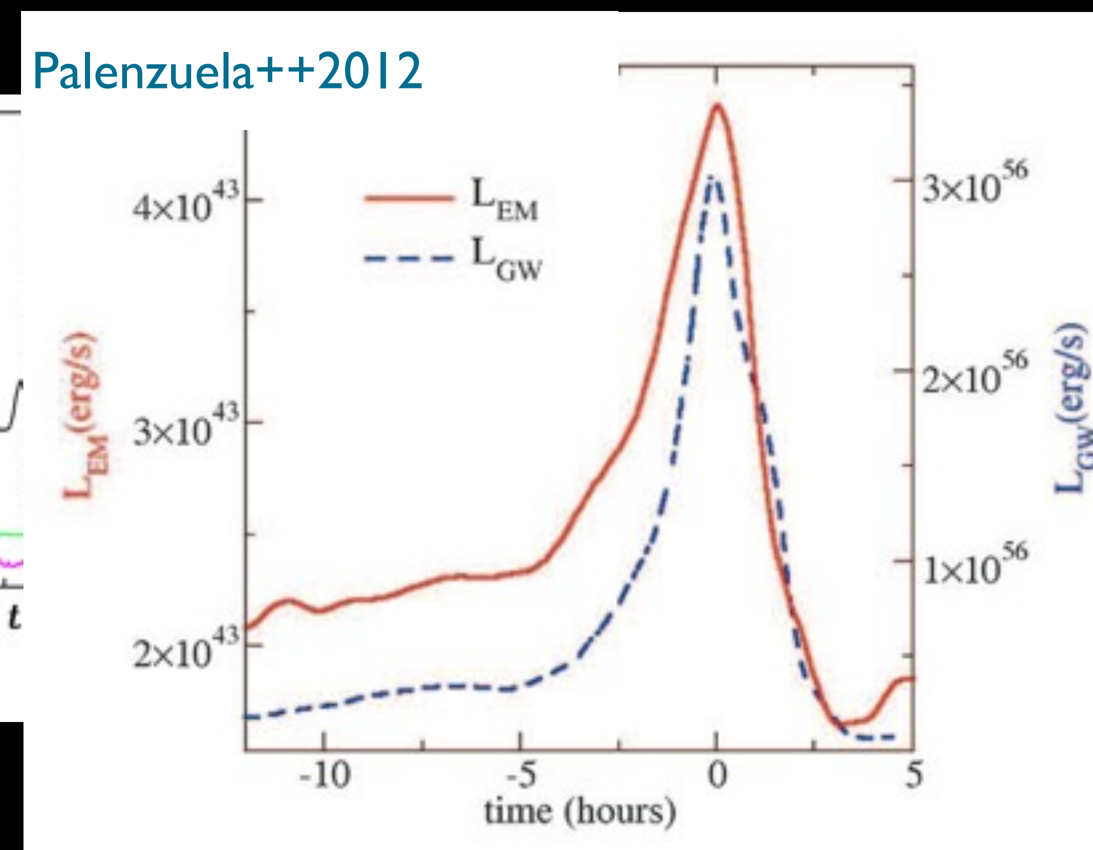
Force-free:
Palenzuela++2012, Moesta++2012

MHD:
Giacomazzo++2012







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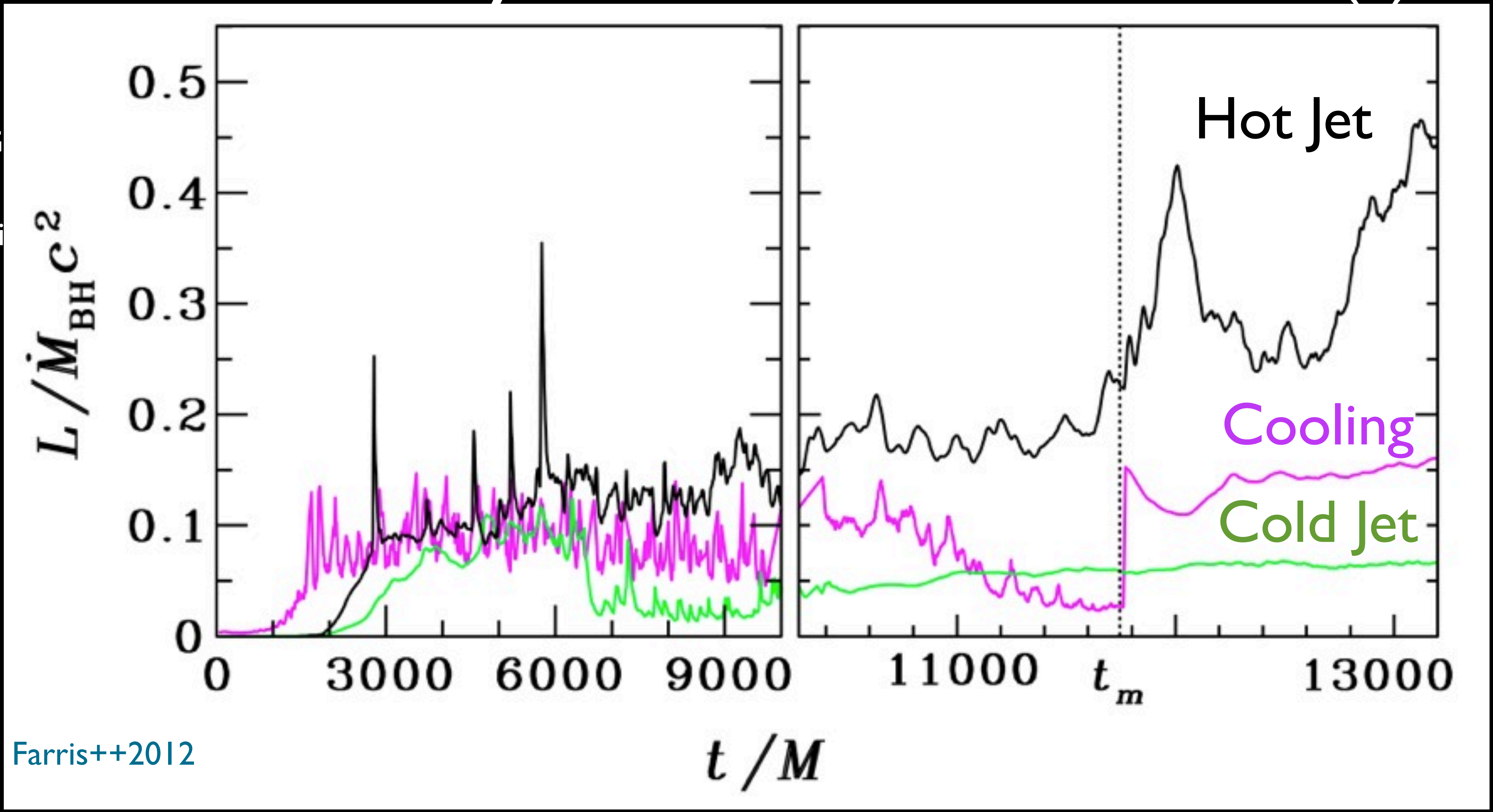
$$L/L_{\rm edd} \sim 0.002 \text{ to } > 1$$

Brief Survey of Simulations w/ GR(t)

G … +2010

Bi … +2012



$$L \sim 10^{45}\frac{\rm erg}{\rm s}\left(\frac{n}{10^{12}cm^{-3}}\right)\left(\frac{M}{10^8 M_\odot}\right)^2$$

- Variability from:
  - Relativistic beaming from approaching/receding BH;
  - Binary's orbital motion w.r.t. background flow;
  - Accretion dynamics;
- EM signature coincident with merger;

$$8 \leq a_{\rm sep}/M \leq 10$$

$$L \sim 10^{47}\frac{\rm erg}{\rm s}\left(\frac{B}{10^4 G}\right)\left(\frac{M}{10^8 M_\odot}\right)^2$$

$$L/L_{\rm edd} \sim 0.002 \text{ to } > 1$$

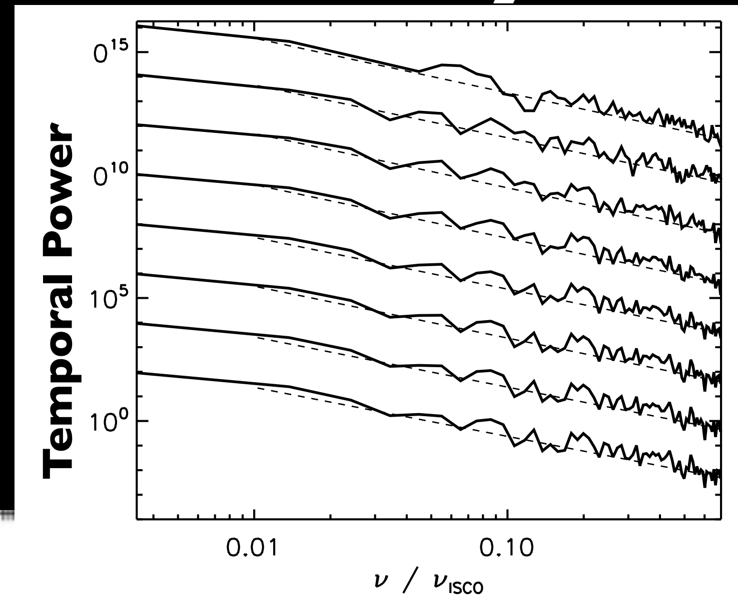
Accretion Disks with a Single Black Hole

Corona's X-ray Variability:

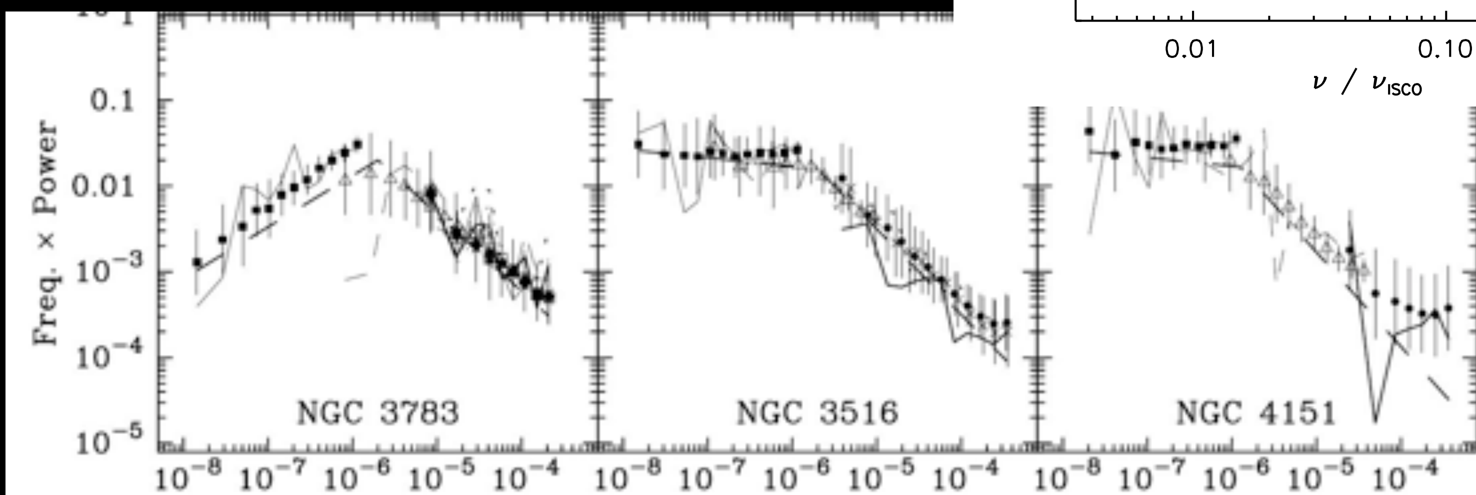
Noble & Krolik 2009

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

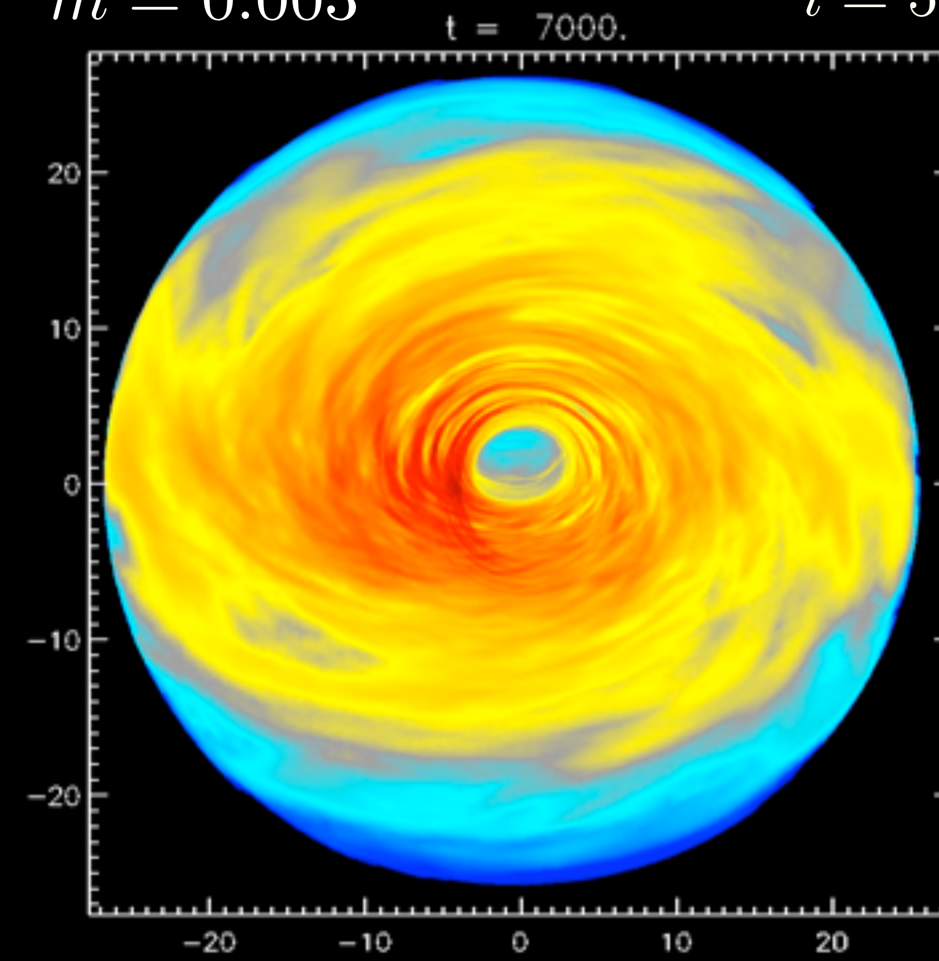
$$-3 < \alpha < -1$$



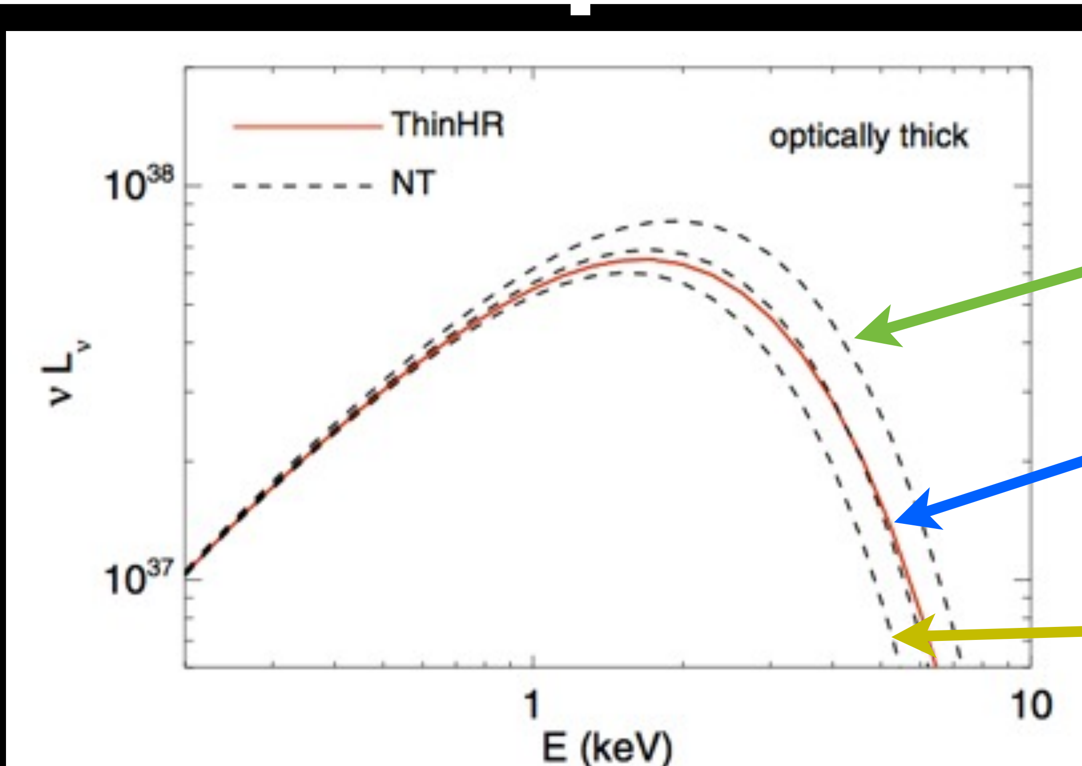
Markowitz et al 2003



$\dot{m} = 0.003$ $i = 53°$



Thermal Spectrum of Thin Disks:



spin = 0.4

spin = 0.2

spin = 0.0

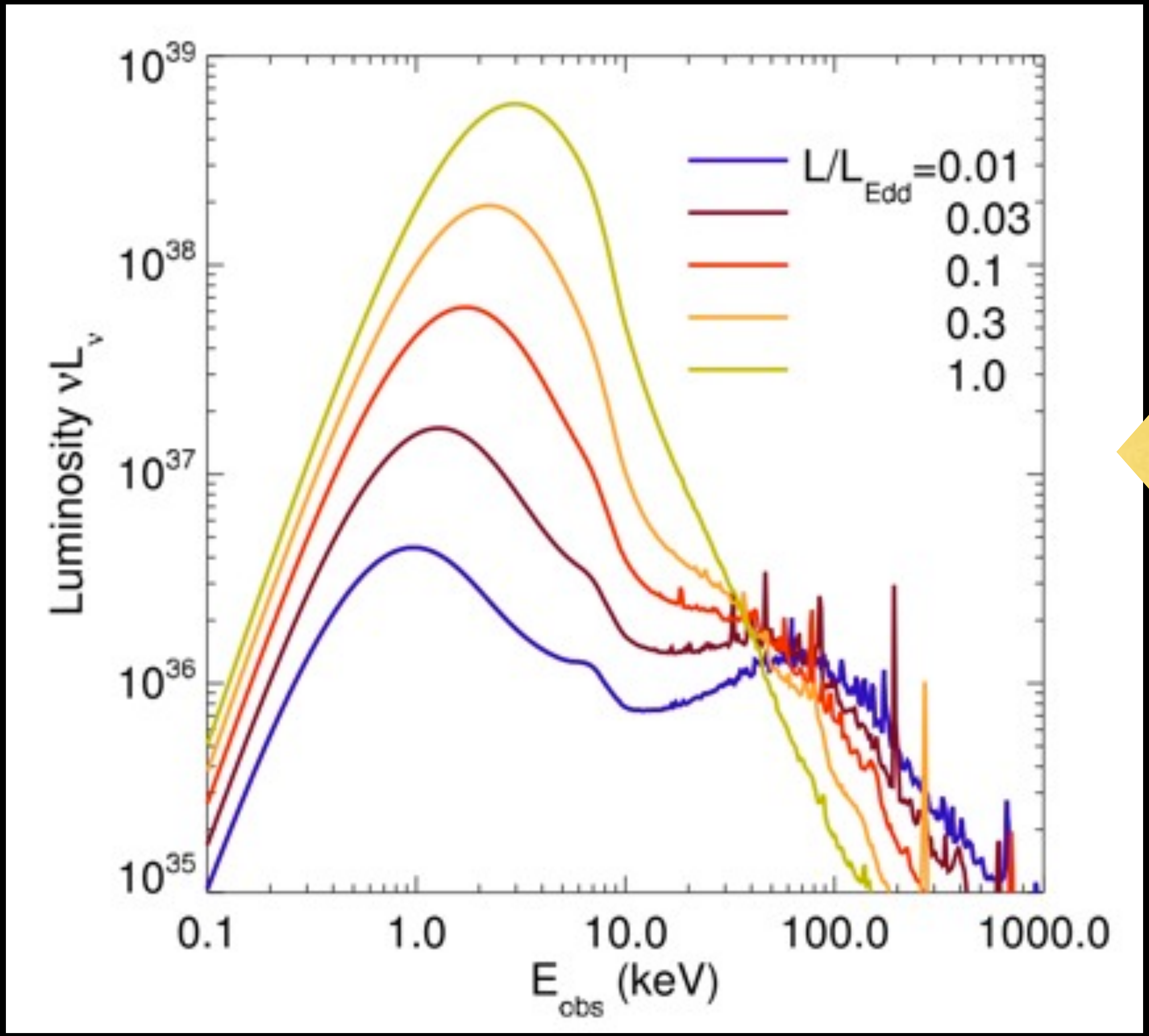
Noble, Schnittman, Krolik, Hawley 2011

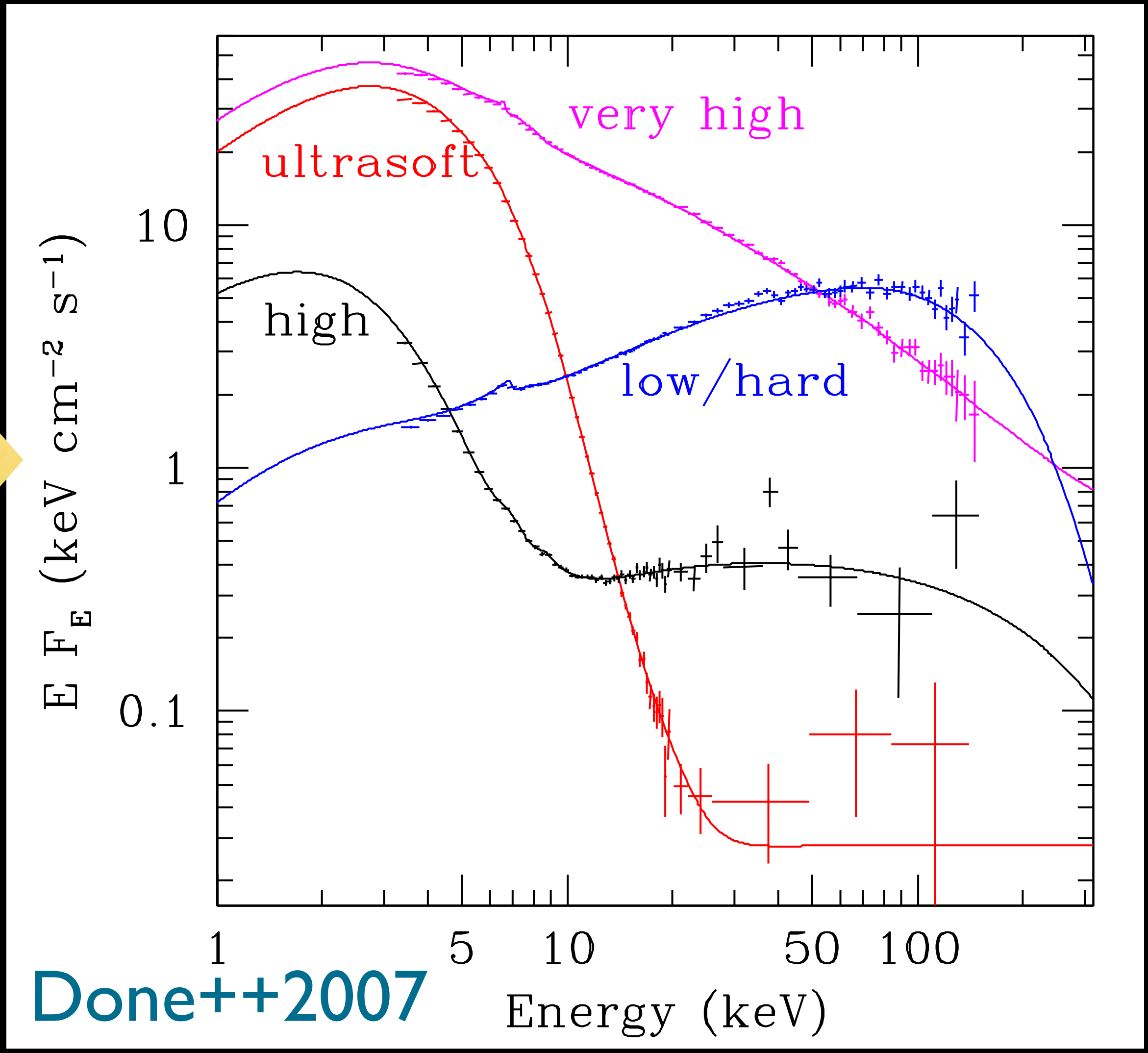
NT = Novikov-Thorne
= Standard time-axi-symmetric cold disk solution

Monte Carlo Inverse Compton Emission

Schnittman, Krolik, Noble 2013

Bremsstrahlung:
Red = Disk, Soft X-rays
Blue = Corona, Hard X-rays





Back to Binaries...

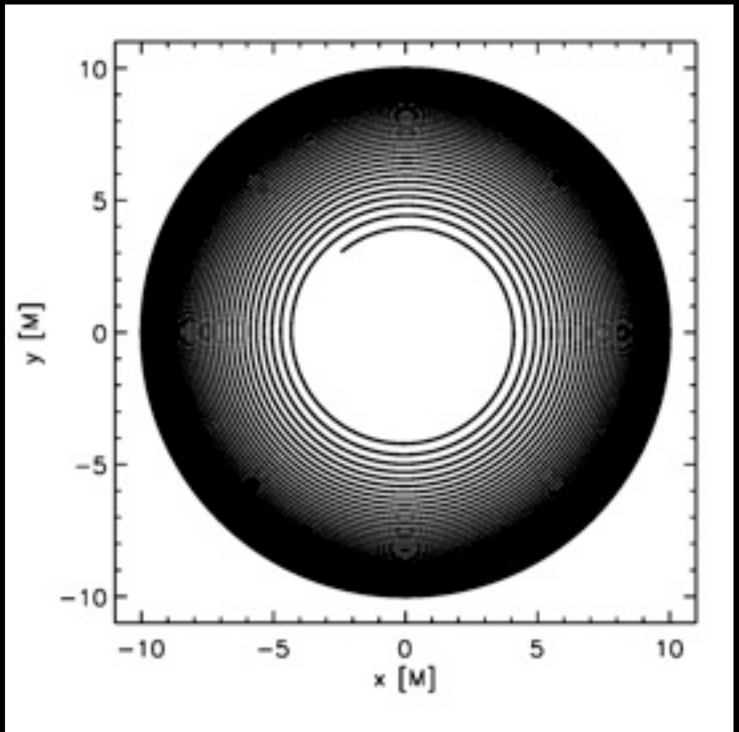
Approximate Two Black Hole Spacetimes

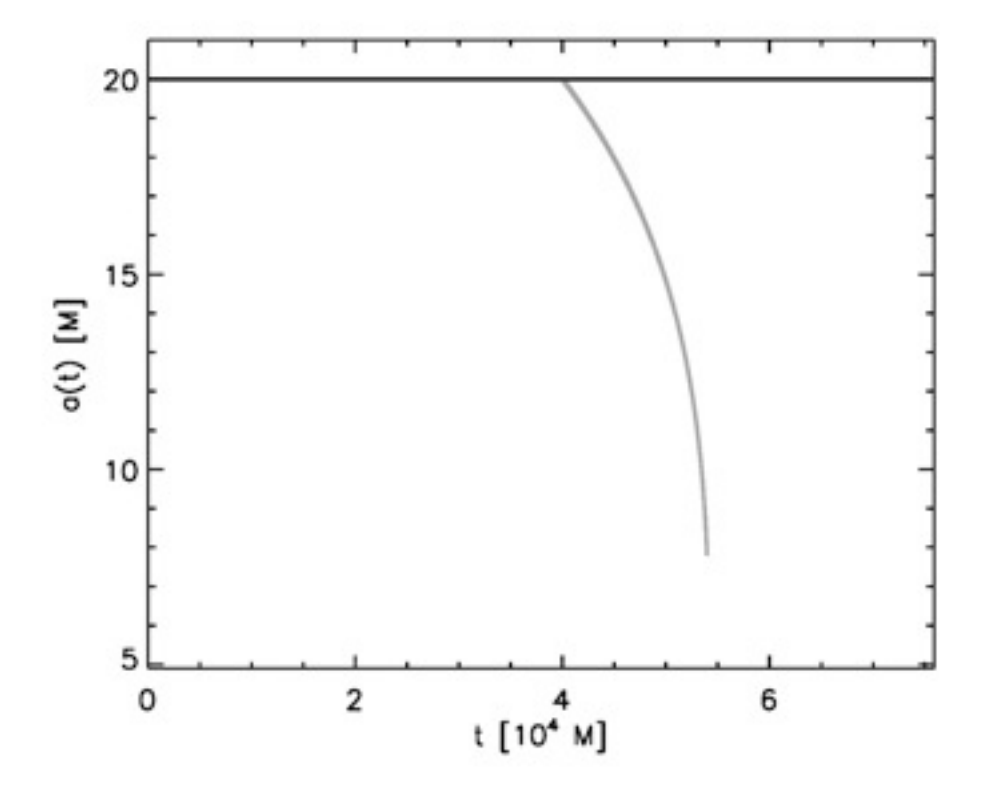
Yunes++2006
Mundim++2013

- Solve Einstein's Equations approximately, perturbatively;
- Expand equations to orders of 2.5 Post-Newtonian order

$$\epsilon_i = m_i / r_i \sim (v_i / c)^2$$

- Used as initial data of Numerical Relativity simulations;
- Black hole orbits include radiation-reaction terms --> merger;
- Closed-form expressions allow us to discretize the spacetime best for accurate matter solutions;

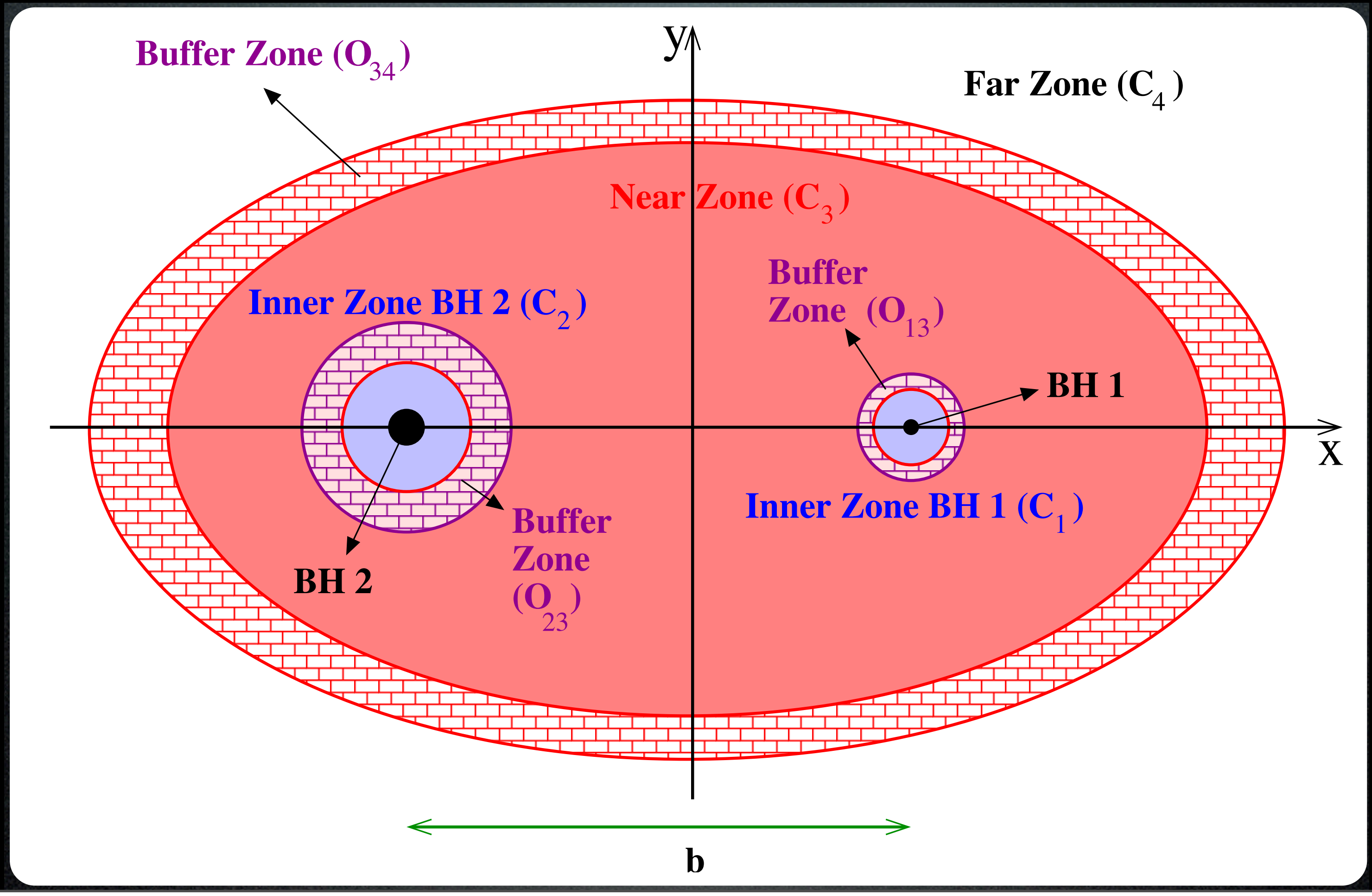




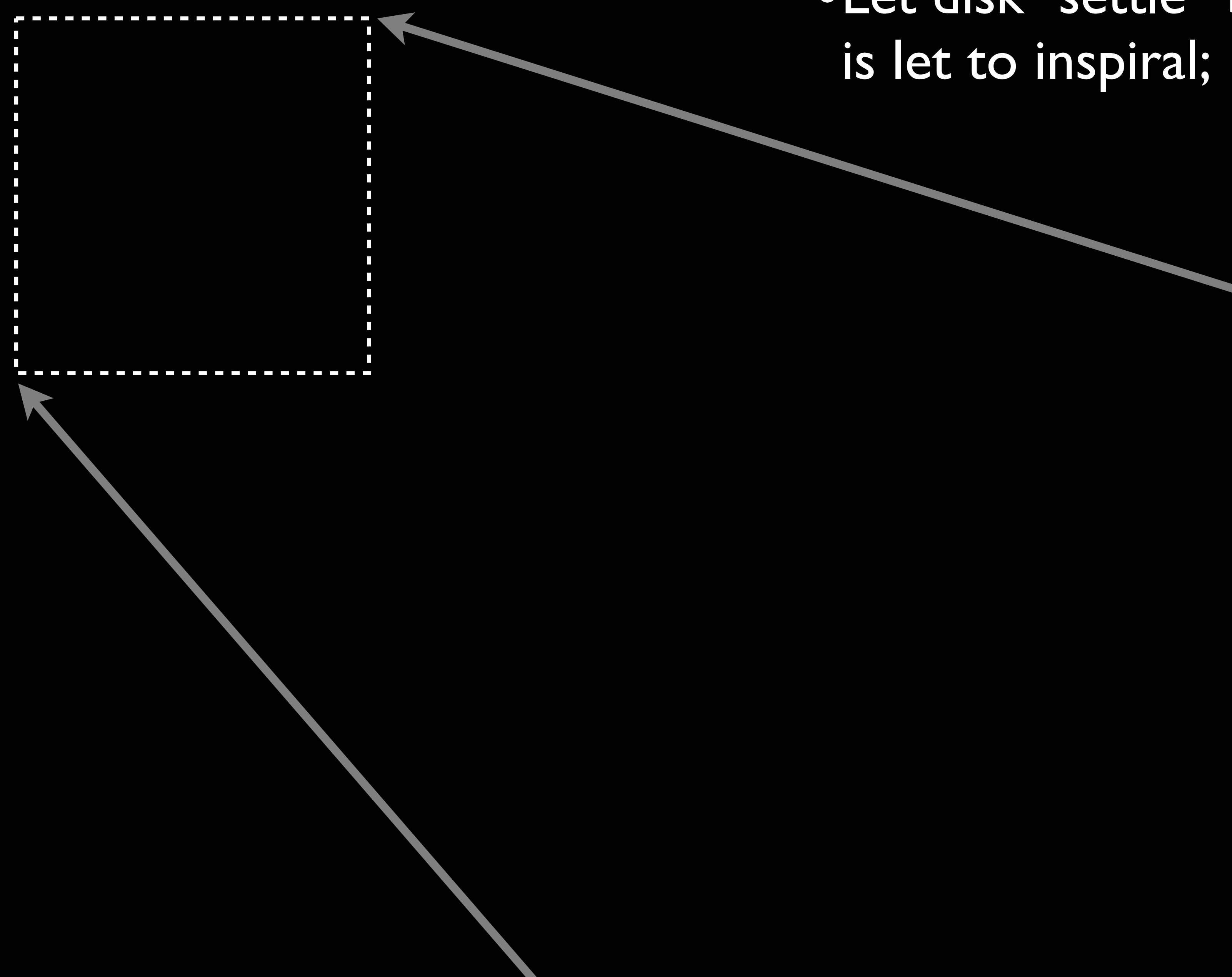
- q=1, non-spinning
- ~100, 120 orbits

$$P_{\rm bin} = 0.8\,{\rm hours} \left(\frac{M}{10^6 M_\odot}\right) \left(\frac{a}{20M}\right)^{3/2}$$

$$t_{\rm merge} = 17\,{\rm hours} \left(\frac{M}{10^6 M_\odot}\right) \left(\frac{a}{20M}\right)^{4}$$



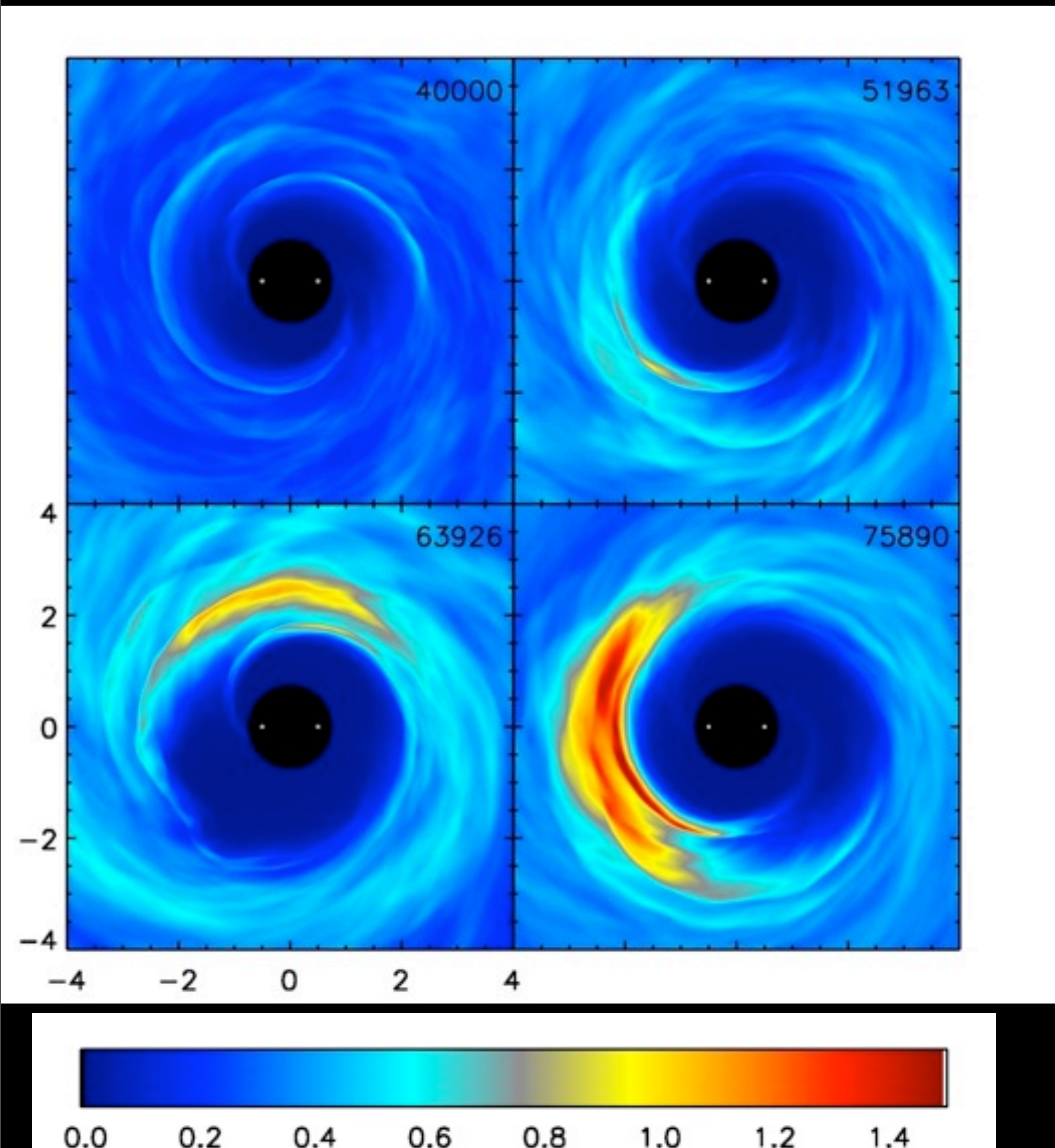
- HARM3d GRMHD sim.;
- Seed with weak B-field;
- Keep disk cool to H/R~0.1;
- Use recorded local cooling rate as emissivity proxy;
- Let disk “settle” before BBH is let to inspiral;



Log Surface Density

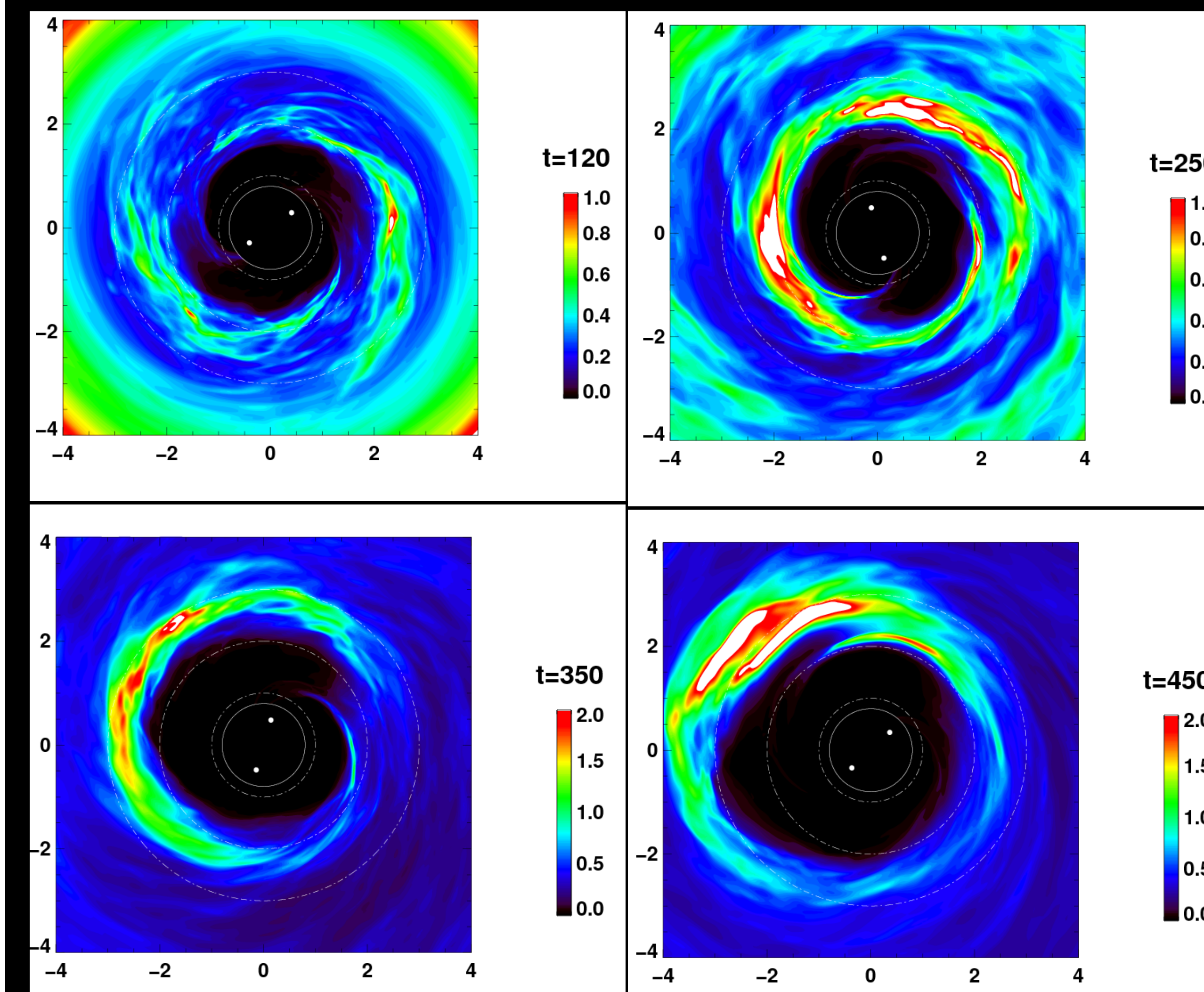
The “Lump”

$$\Sigma(r,\phi) \equiv \int d\theta \sqrt{-g}\,\rho / \sqrt{g_{\phi\phi}}$$



GRMHD: Noble++2012

Newtonian MHD:
Shi++2012



- Also, seen in:
  - Newtonian hydrodynamics:
    - D’Orazio++2012
    - Roedig++2012, at least in the torque var.

Disk-Binary Decoupling

Binary-disk separation when:

$$t_{\rm gr} = \frac{5}{64}\left(\frac{a}{M}\right)^4 \frac{(1+q)^2}{q} M \ll t_{\rm in} = \alpha^{-1}(H/r)^{-2}(d\ln\Sigma/d\ln r)^{-1}\Omega^{-1} = \alpha^{-1}(H/r)^{-2}(d\ln\Sigma/d\ln r)^{-1}(r/r_g)^{3/2}M.$$

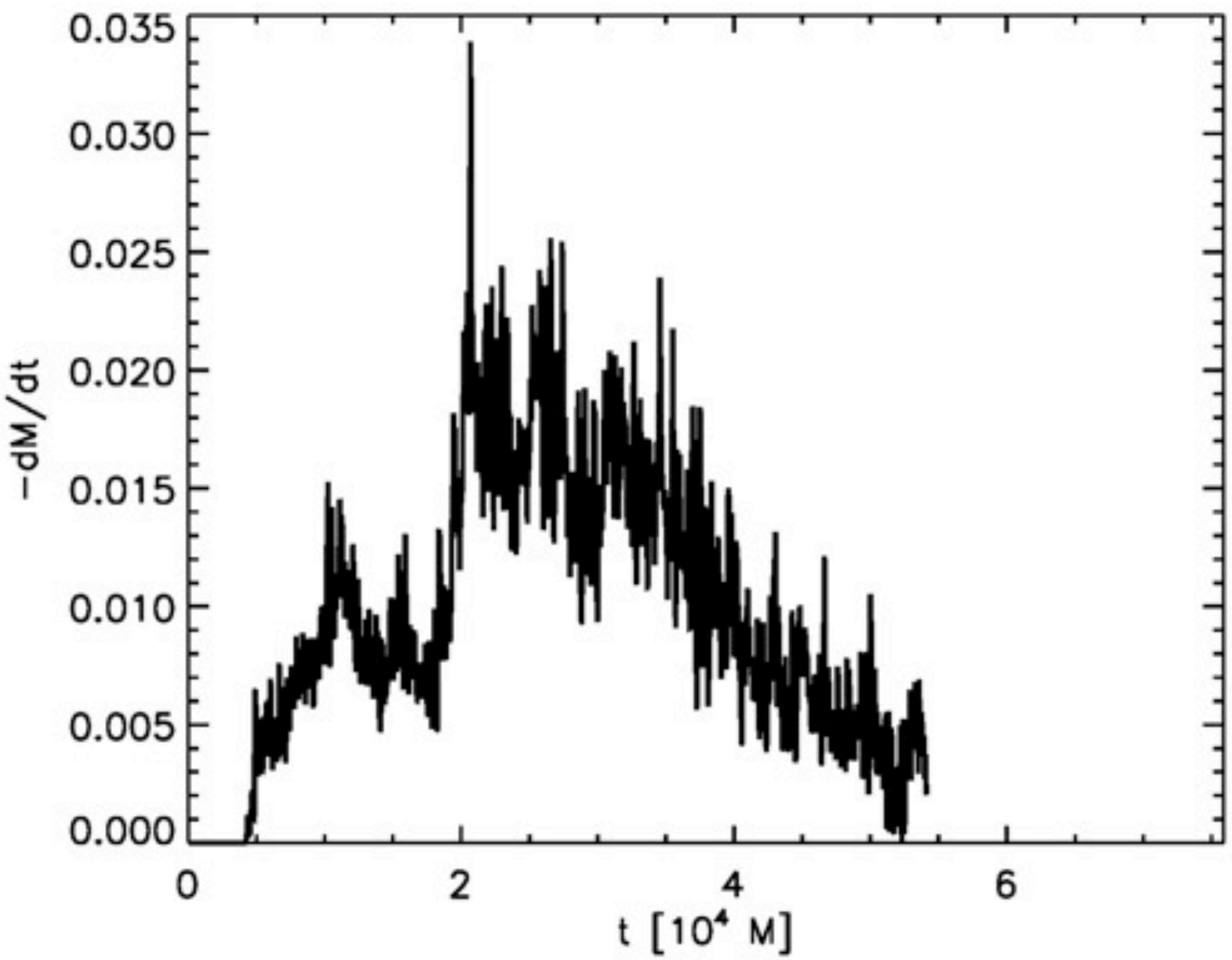
Commonly Imagined:

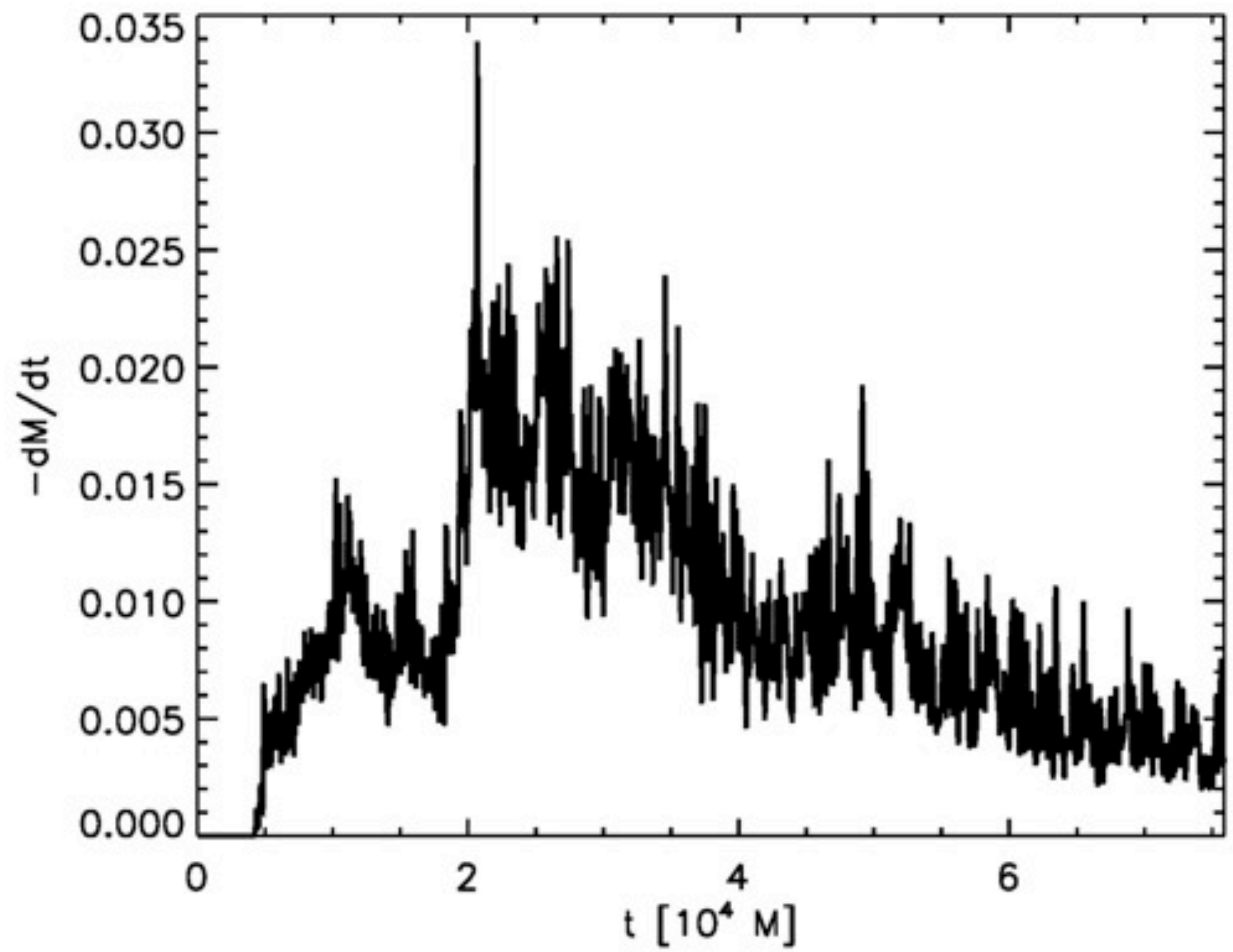
$$a_{\rm dec} = 70\,(d\ln\Sigma/d\ln r)^{-2/5}\left(\frac{H/r}{0.15}\right)^{-4/5}\left(\frac{\alpha}{0.01}\right)^{-1}$$

Ours:

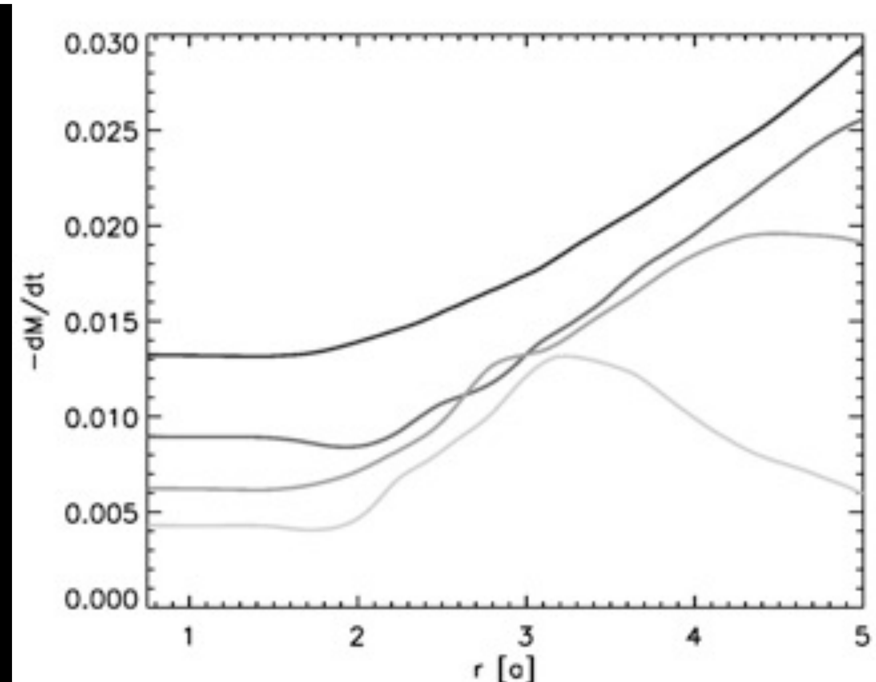
$$a_{\rm dec} \simeq 10[(d\ln\Sigma/d\ln r)/6]^{-2/5}\left(\frac{\alpha}{0.2}\right)^{-2/5}\left(\frac{H/r}{0.15}\right)^{-4/5} M$$

Accretion Rate:

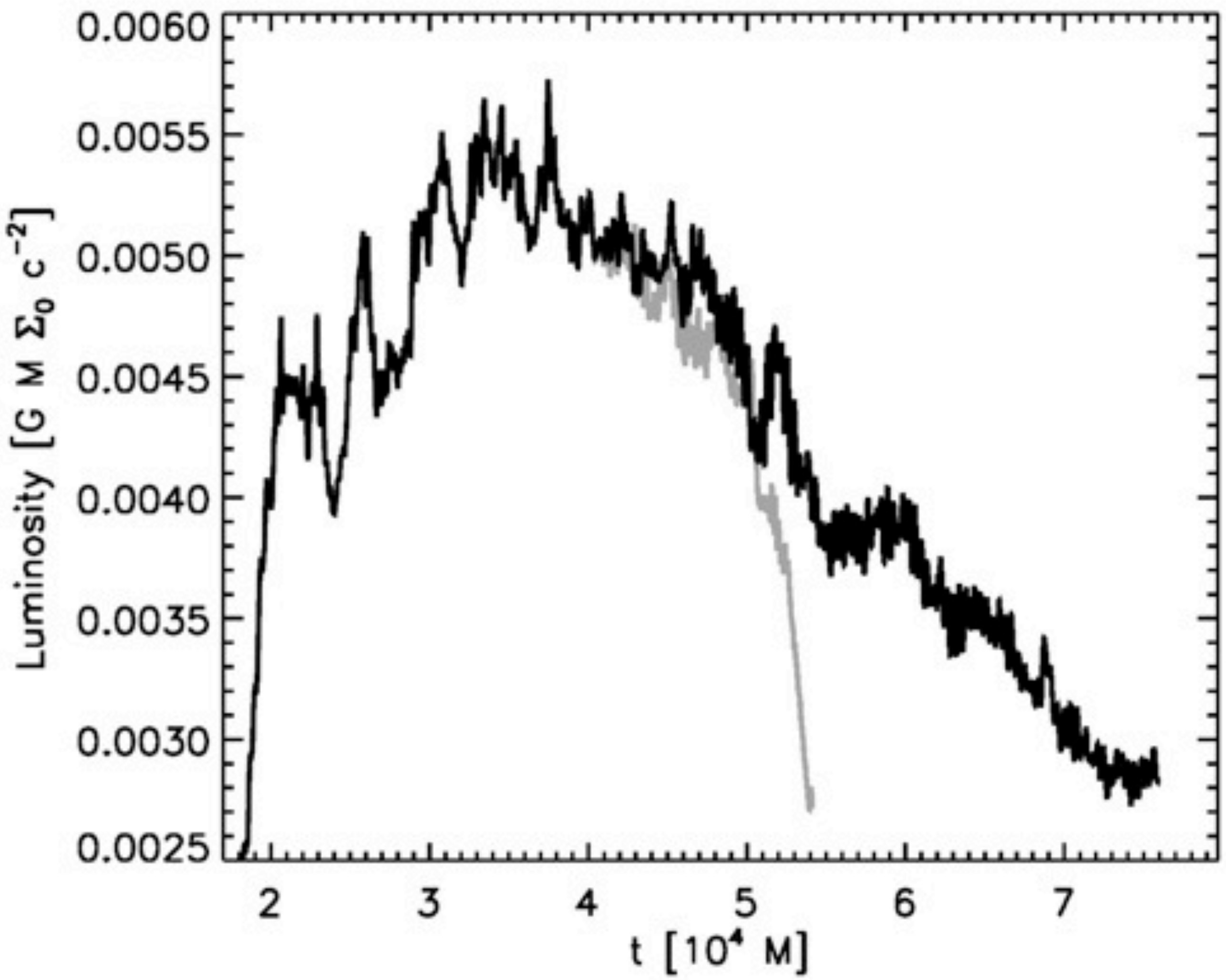


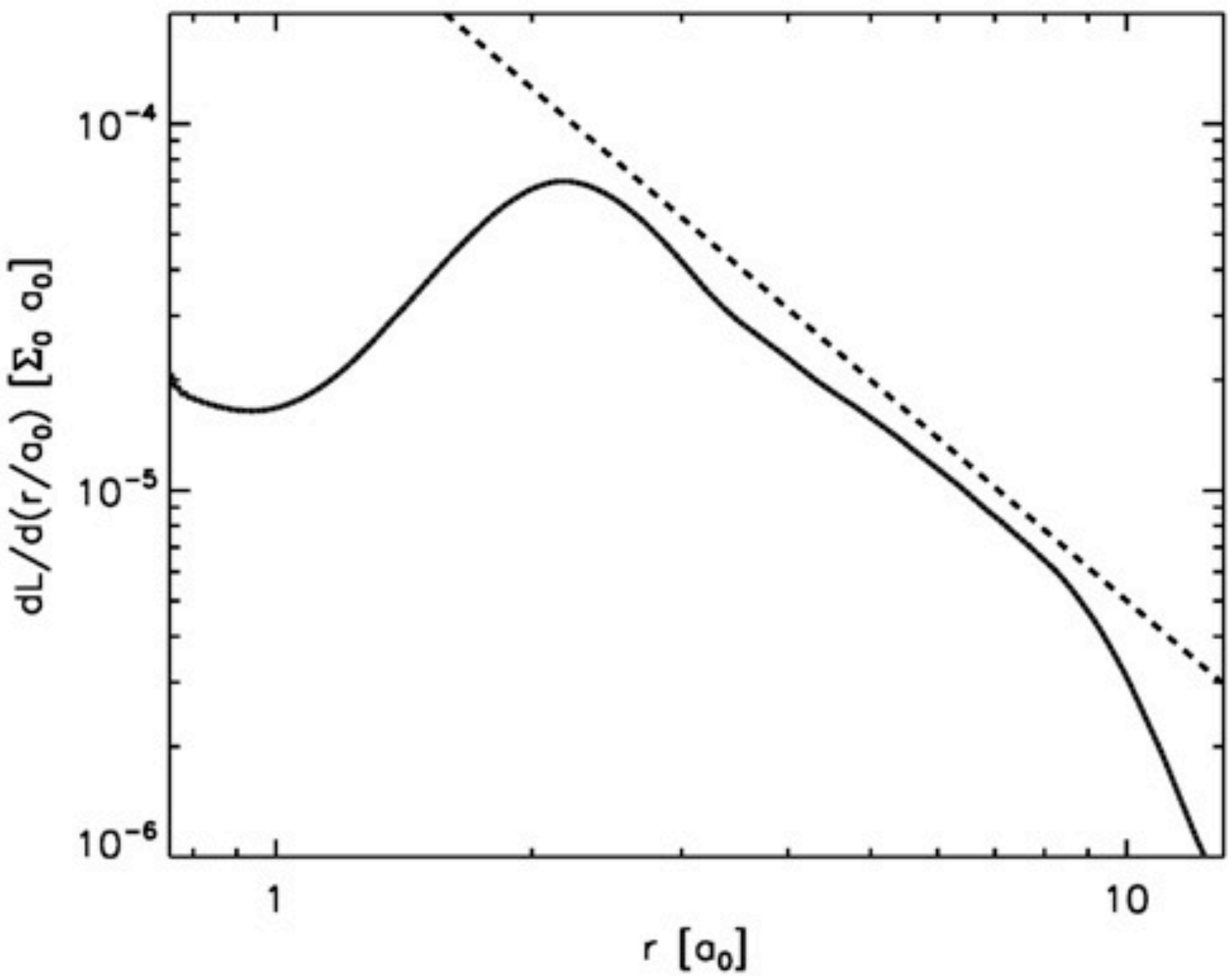


- More accretion than analytic estimates due to enhanced stress; about a factor of two greater than Newtonian MHD (Shi++2012);
- Gradual decrease due to cumulative effect of torques and weaker rates further out;
- Additional decrease of RunIn also due to decoupling at late times;



Luminosity





$$\frac{dL}{dr/a_0} = 4 \times 10^{-4} (\dot{M}/0.01)(r/a_0)^{-2} \Sigma_0 a_0.$$

$$L_{\rm disk} \simeq 2.4 \times 10^{40} (\hat{L}/10^{-3}) M_6 \tau_0 \ {\rm erg/s}.$$

$$T_{\rm eff} \simeq 4 \times 10^4 (\hat{L}/10^{-3})^{1/4} M_6^{-1/4} \tau_0^{1/4} \ {\rm K},$$

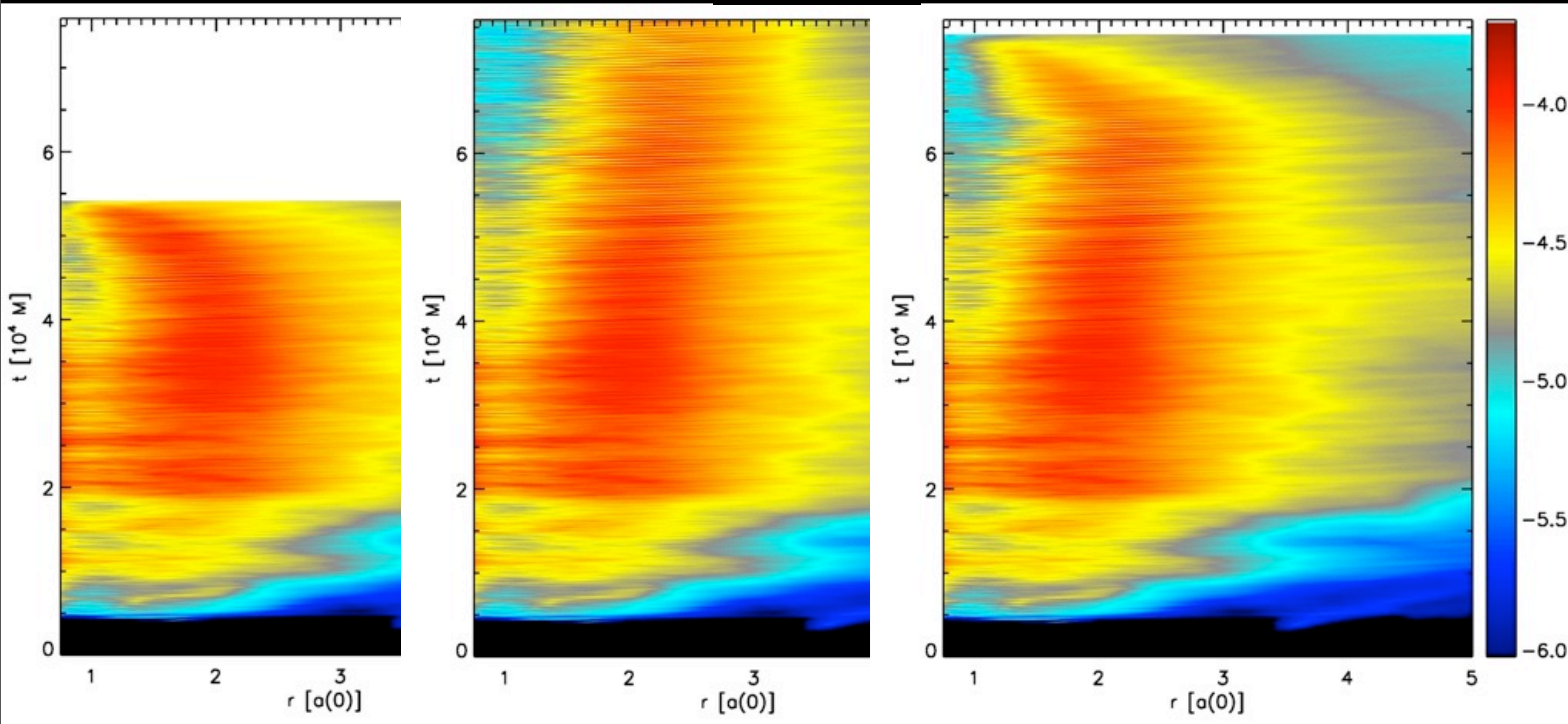
$$\tau_0(r = 20M) \sim 2 \times 10^3 (\alpha/0.1)^{-1} (\eta/\dot{m})$$

Typical for a Active Galactic Nucleus

--> peak in UV assuming thermal emission

Luminosity(r,t)

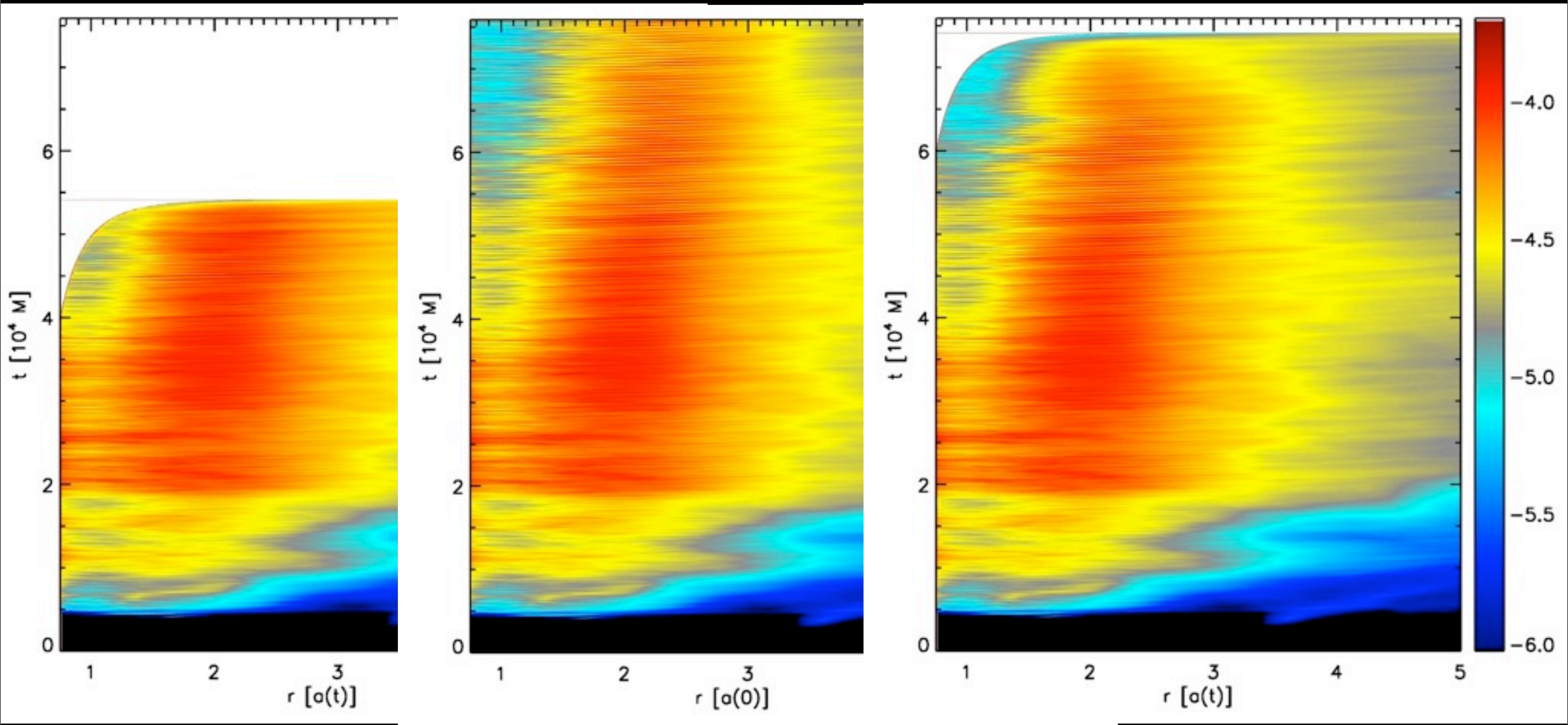
Noble++2013



$t_{\rm shrink} = 4 \times 10^4 M$ $\quad t_{\rm shrink} = \infty M$ $\quad t_{\rm shrink} = 6 \times 10^4 M$

Luminosity(r/a(t),t)

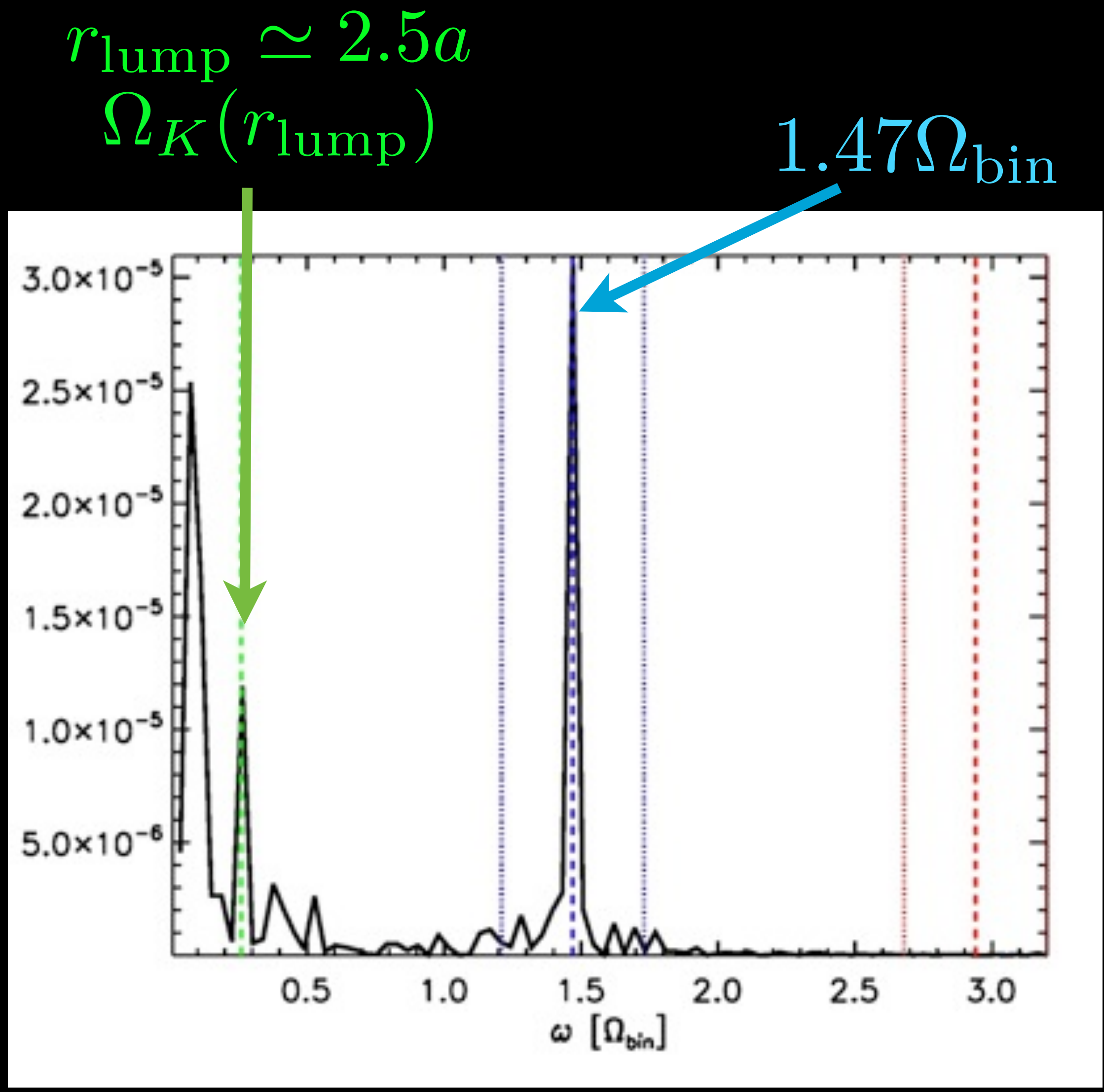
Noble++2013



$t_{\rm shrink} = 4 \times 10^4 M$ $t_{\rm shrink} = \infty M$ $t_{\rm shrink} = 6 \times 10^4 M$

- Emission tracks binary;
- Rate of signal decay dependent on when BBH starts to inspiral;

Periodic Signal



$$\omega_{\rm peak} = 2\left(\Omega_{\rm bin} - \Omega_{\rm lump}\right) \rightarrow 1 < \frac{\omega_{\rm peak}}{\left(\Omega_{\rm bin} - \Omega_{\rm lump}\right)} < 2 \qquad 0 < \frac{M_2}{M_1} < 1$$

May be obfuscated by "low-pass" filter of disk's opacity:

$$0.16\left(\frac{\alpha}{0.3}\right) \lesssim f_{\rm supp} \lesssim 0.32\left(\frac{\alpha}{0.3}\right)$$

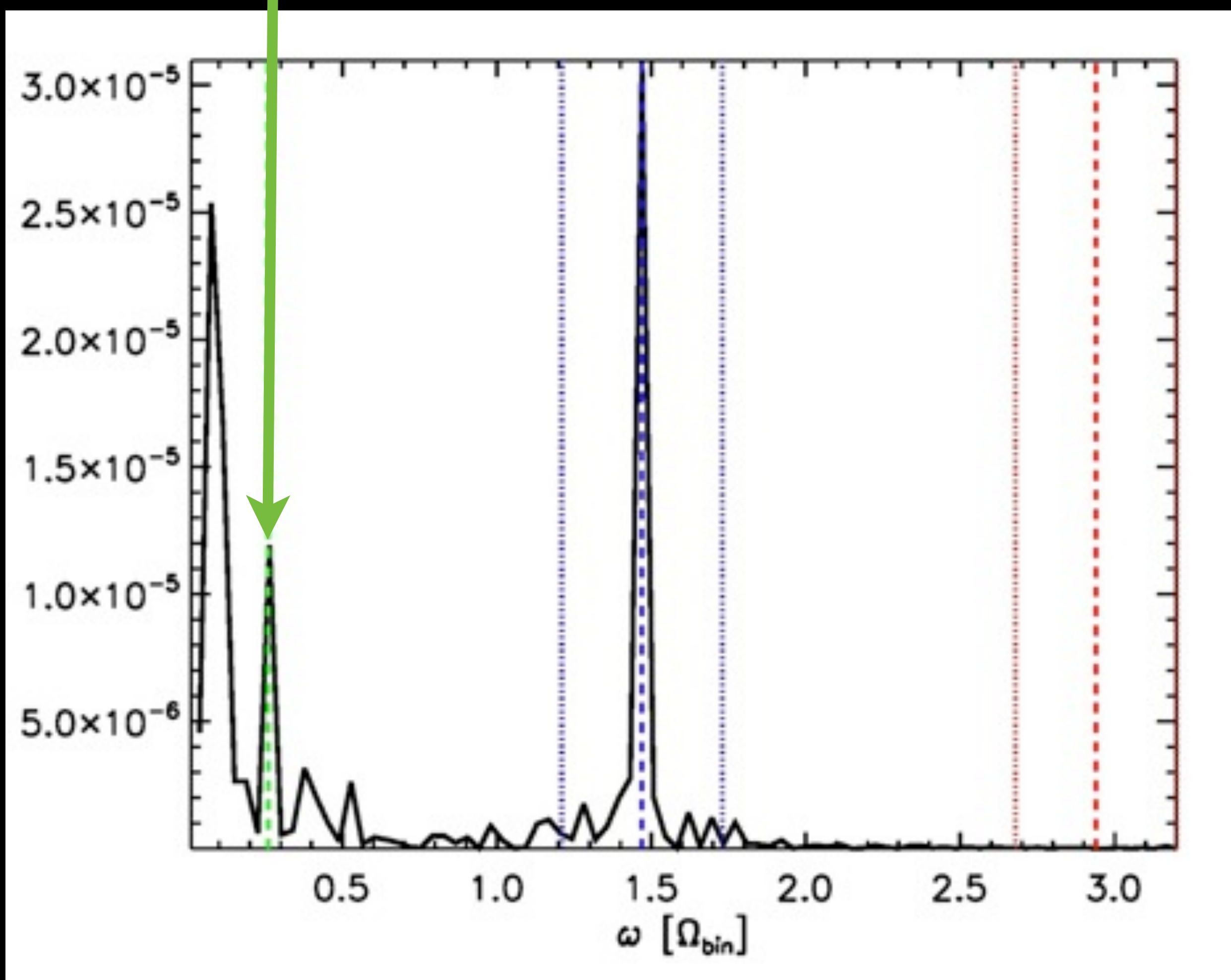
--> Ray-tracing may help determine quality of signal

Variabality vs. Mass Ratio:

q=1

$r_{\rm lump} \simeq 2.5a$

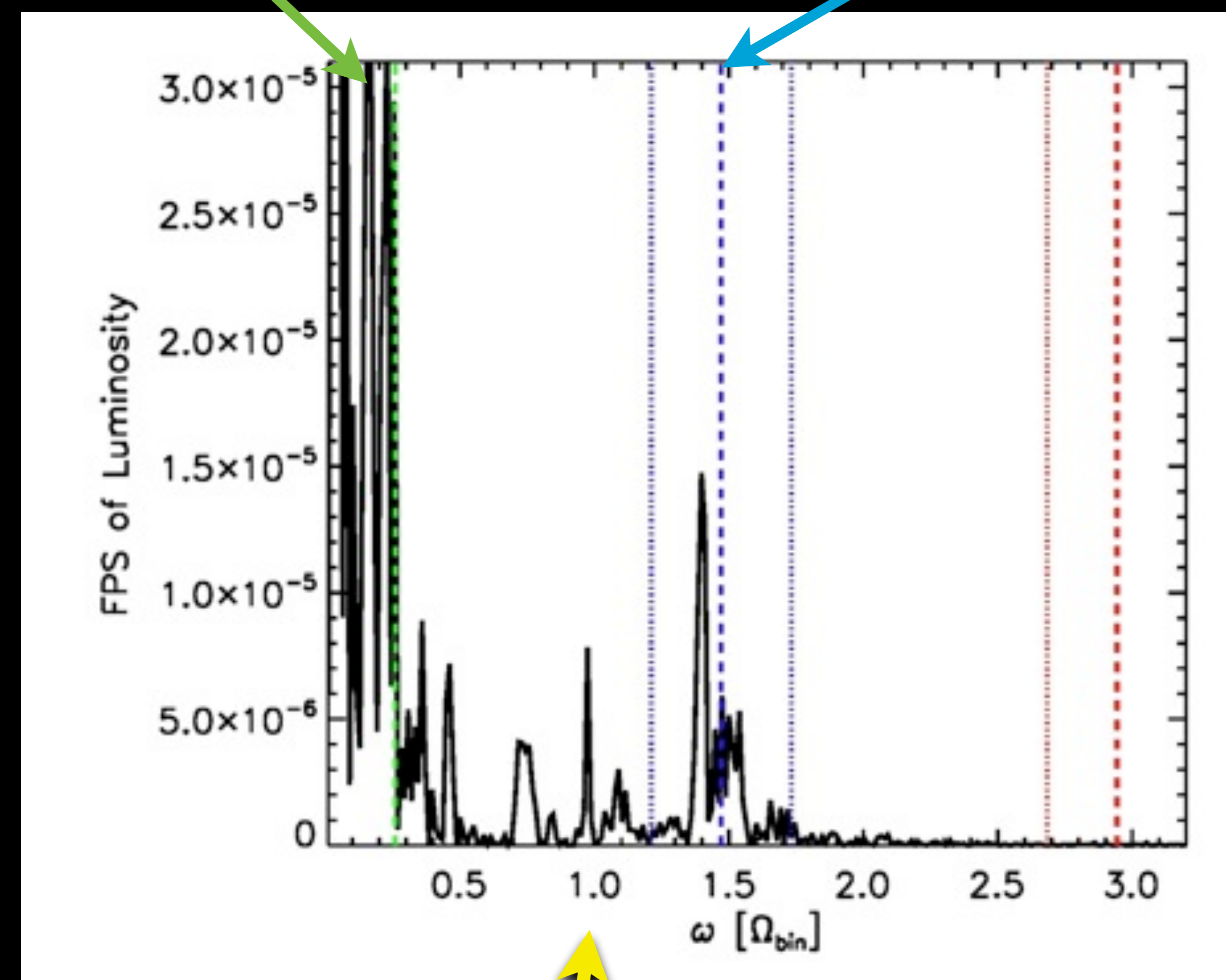
$\Omega_K(r_{\rm lump})$



q=1/2

$\Omega_K(r_{\rm lump})$

$1.47\Omega_{\rm bin}$



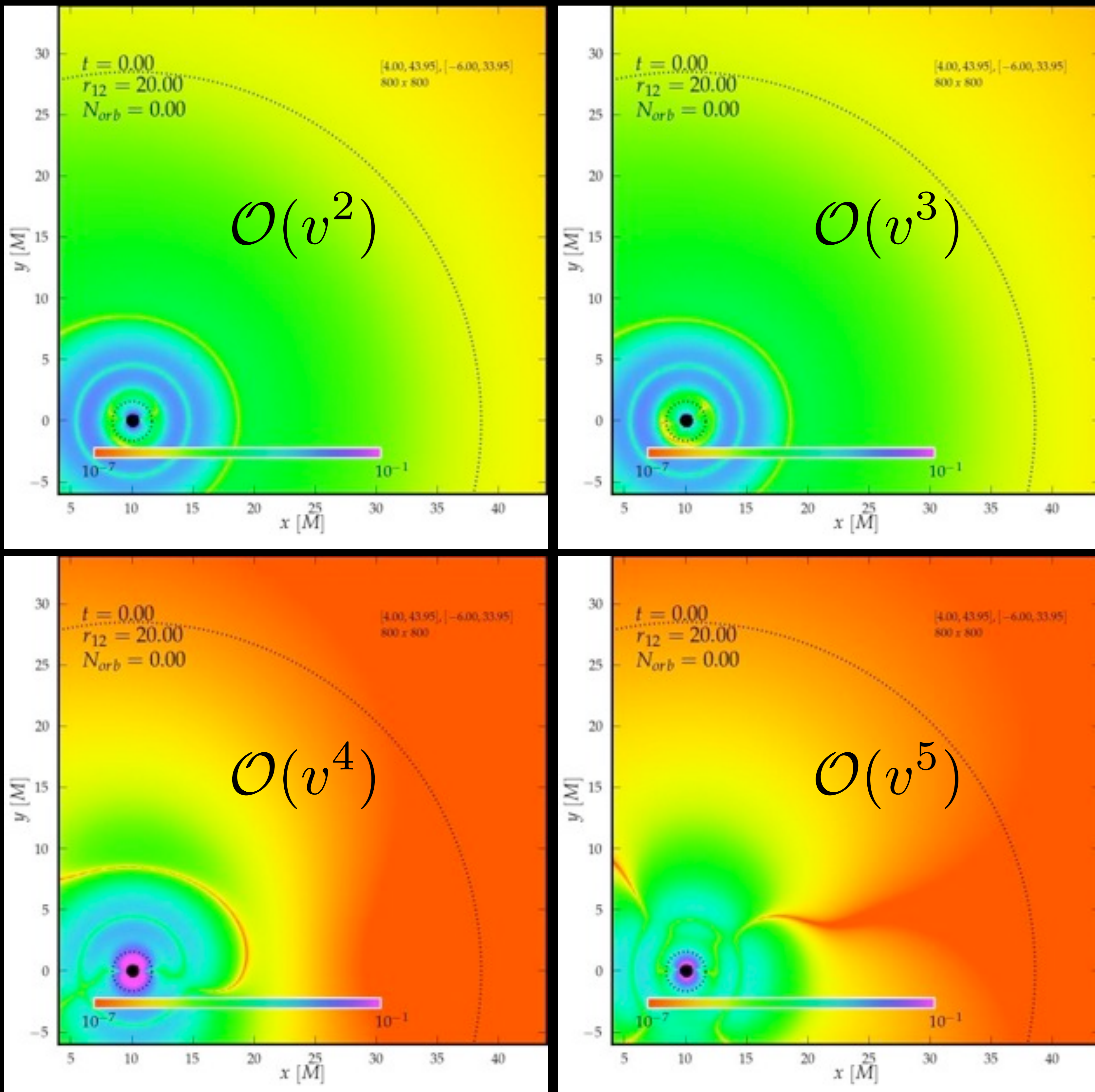
$\Omega_{\rm bin}$

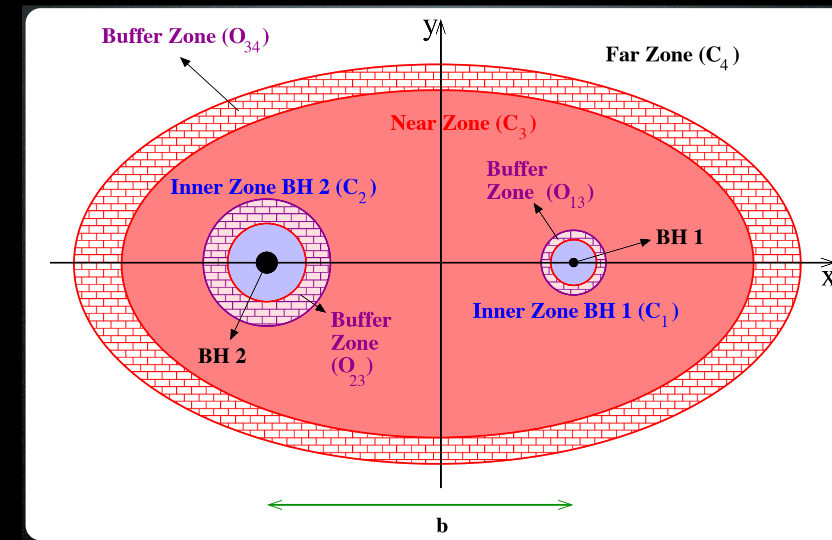
- Beat effect subdued, broader power distribution;
- New peak at binary's orbital frequency;
- More variability on lump's orbital timescale;

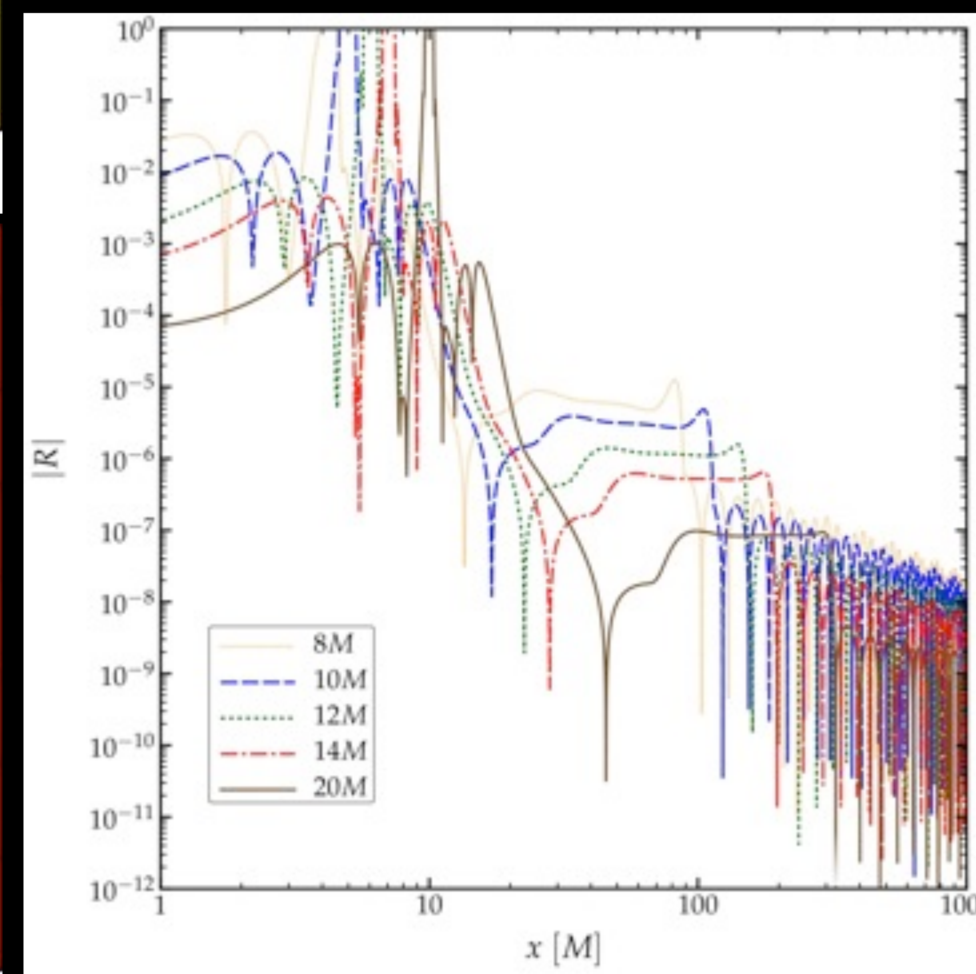
Noble++2013

Approximate Two Black Hole Spacetimes

Yunes++2006
Mundim++2013







Dependence on PN order
Ricci Scalar ~ "Fake Density"

Dependence on Separation

Dynamic Coordinates to Resolve Binary Black Holes on Shrinking Orbits

Zilhao & Noble 2013

- HARM3D is a fixed mesh refinement GRMHD code;
- Refinement through special gridding;
- Less overhead than AMR;

Advection of Magnetic Field Loop

384x384 cells

Zilhao & Noble 2013

Test Run:

- 2D Hydro, no B-field
- ~ 32 cells per horizon
- Full spacetime, all “zones”;

Zilhao & Noble 2013

Summary

- We have many of the tools in place to model single black hole accretion disks in 3D;
- We have the tools to make self-consistent temporal & spectral observational predictions from these simulations;
- We are in the process of applying these tools to the binary case;
  - Predicted a periodic EM signal that could be used for identifying close binaries by all-sky high-cadence campaigns (e.g., LSST, Pan-STARRS);
  - Working on techniques to resolve the black holes in an efficient manner;

Open Questions?

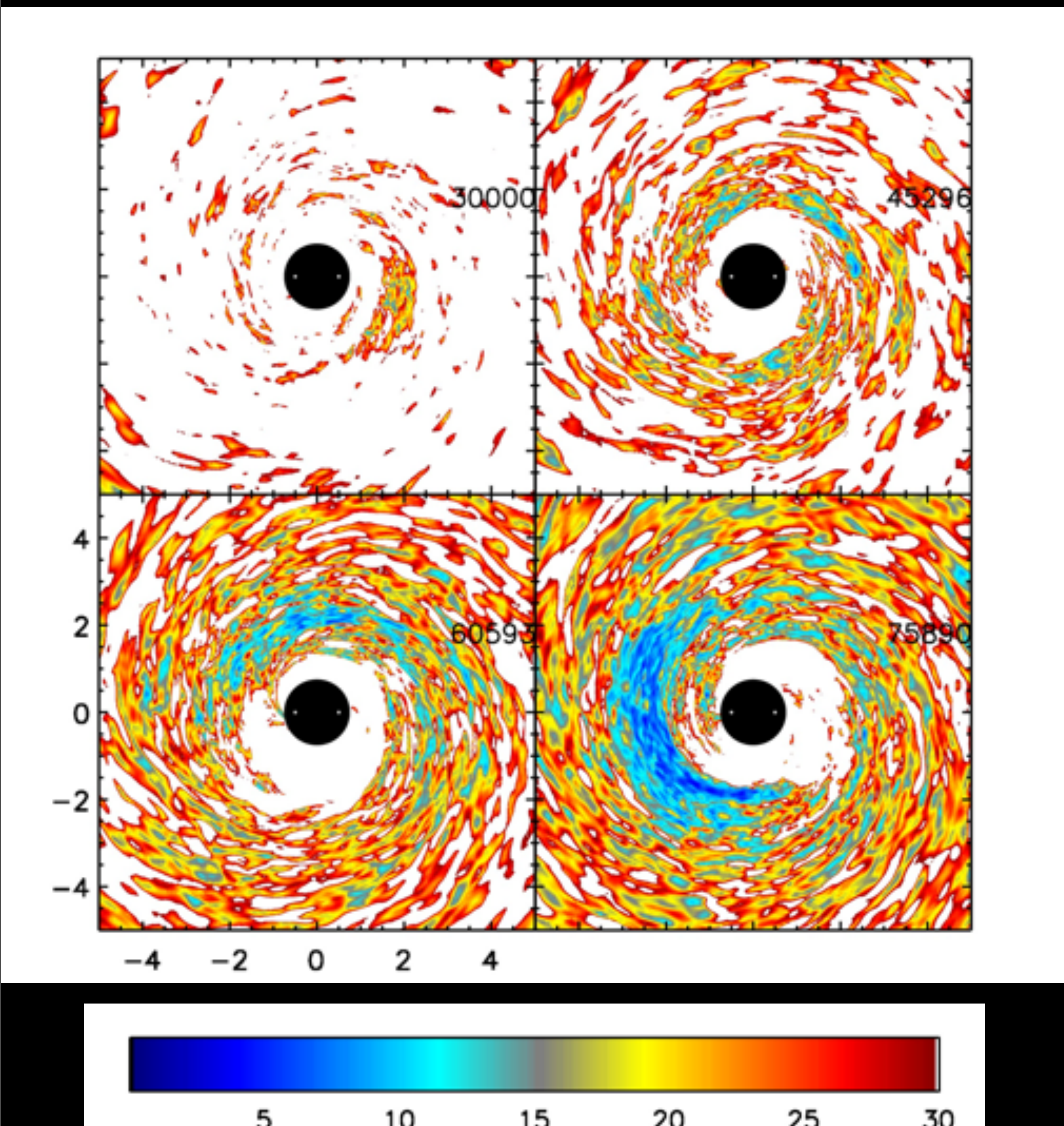
- What are good initial conditions for these simulations?
  - From simulations at larger scale? w/ MHD?
  - Effects from varying magnetic field strengths and configurations?
- Thermodynamic effects? Cooling effects? Radiation pressure and heating on gap's rim?
  - H(R) ~ const. ?   H(R) ~ f(R)?
- How do magnetic outflows affect the general picture?
- BBH effects: spin, orbital precession, misalignment
  - e.g., jet misaligned with disk's orbital plane...

Extra Slides

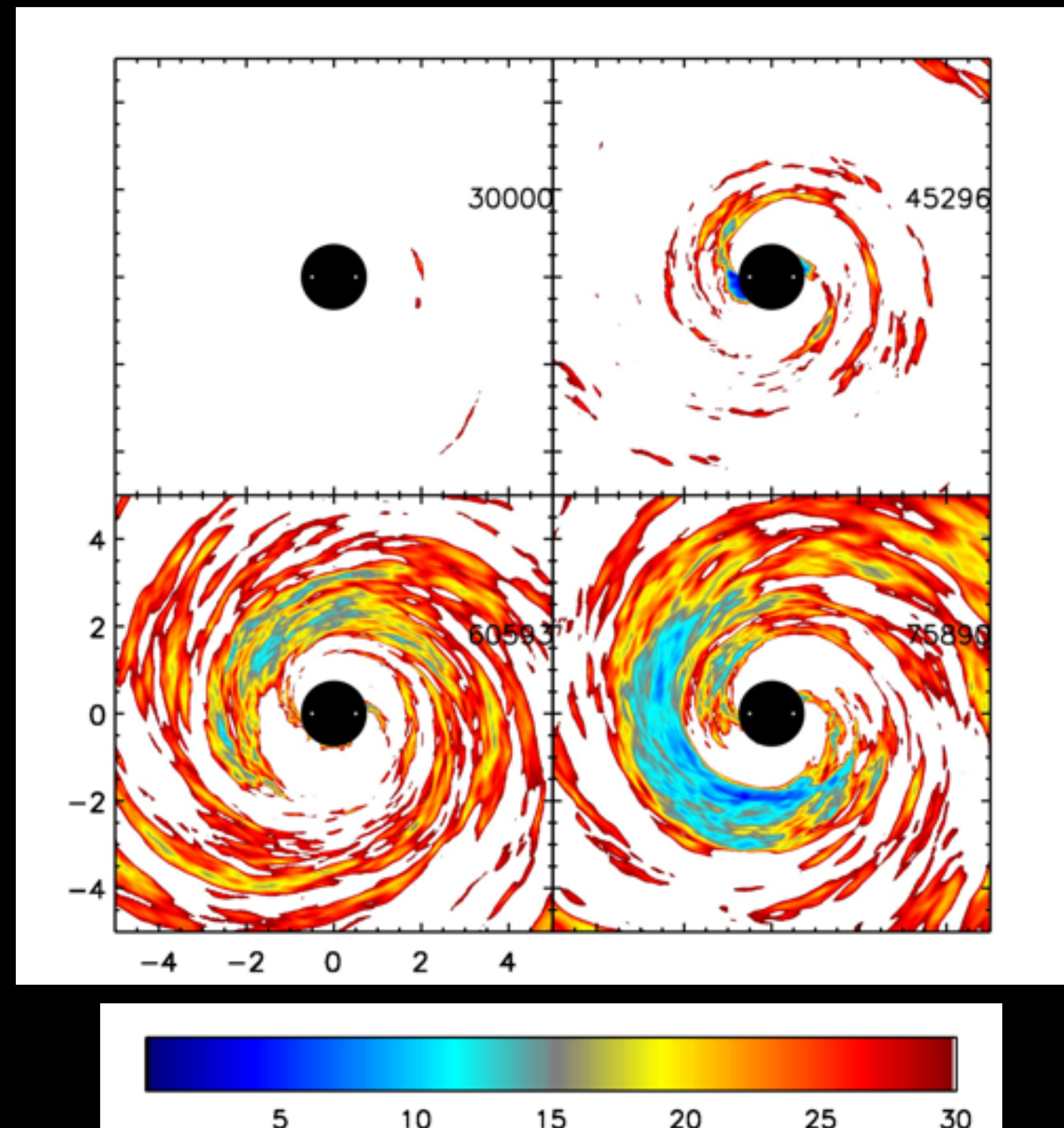
MRI Resolution

$$Q^i = \frac{2\pi \left|b^i\right|}{\Delta x^i \Omega(r)\sqrt{\rho h + 2p_m}}$$

Sano++ 2004 Noble++ 2010 Guan, Gammie 2010 Sorathia++ 2010, 2011
Hawley++ 2011

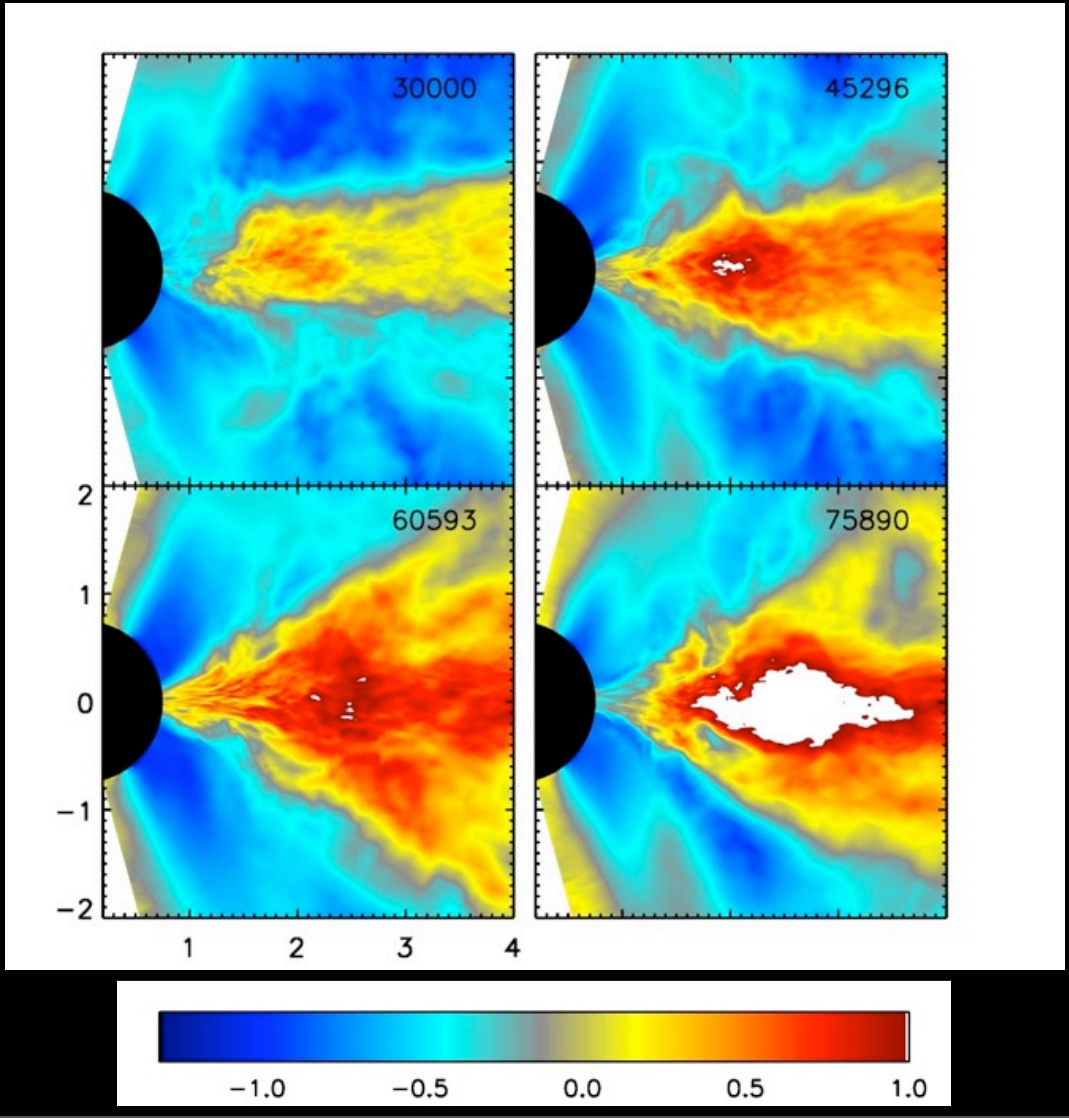


$Q^\theta > 10$



$Q^\phi > 25$

Plasma Beta parameter = pgas / pmag



Σ

p_{mag}

ρu^r

Flux

General Relativistic Magnetohydrodynamics

$$\frac{\partial}{\partial t}\mathbf{q}(\mathbf{P}) \quad + \quad \frac{\partial}{\partial x^i}\mathbf{F}^i(\mathbf{P}) \quad = \quad \mathbf{S}(\mathbf{P})$$

$$\frac{\partial}{\partial t}\sqrt{-g}\begin{bmatrix}\rho u^t \\ T^t{}_t + \rho u^t \\ T^t{}_j \\ B^k\end{bmatrix} + \frac{\partial}{\partial x^i}\sqrt{-g}\begin{bmatrix}\rho u^i \\ T^i{}_t + \rho u^i \\ T^i{}_j \\ \left(b^i u^k - b^k u^i\right)\end{bmatrix} = \sqrt{-g}\begin{bmatrix}0 \\ T^\kappa{}_\lambda \Gamma^\lambda{}_{t\kappa} - \mathcal{F}_t \\ T^\kappa{}_\lambda \Gamma^\lambda{}_{j\kappa} - \mathcal{F}_j \\ 0\end{bmatrix}$$

$$T_{\mu\nu} = (\rho + u + p + 2p_m)\, u_\mu u_\nu + (p + p_m)\, g_{\mu\nu} - b_\mu b_\nu$$

Radiative Energy & Momentum Loss

Mass Density

Internal Energy Density

Gas Pressure

Fluid's 4-velocity

Magnetic Pressure

Magneti c 4-vector

$$g_{ab} u^a u^b = -1$$

$$p_m = \frac{1}{2} g_{ab} b^a b^b$$

- Matter is highly ionized, and therefore highly conductive and magnetized;
- Matter evolves via conservation equations of mass, energy, and momentum, and Maxwell's equations;
- Set of 8 coupled nonlinear 1st-order (usually) hyperbolic PDEs with 1 constraint equation;
- After **q(P)** is updated, solve a set of nonlinear algebraic equations, **q = q(P)** to obtain **P(q)**; Noble++2006

General Relativistic Magnetohydrodynamics

$$\frac{\partial}{\partial t}\sqrt{-g}\begin{bmatrix}\rho u^t \\ T^t{}_t + \rho u^t \\ T^t{}_j \\ B^k\end{bmatrix} + \frac{\partial}{\partial x^i}\sqrt{-g}\begin{bmatrix}\rho u^i \\ T^i{}_t + \rho u^i \\ T^i{}_j \\ \left(b^i u^k - b^k u^i\right)\end{bmatrix} = \sqrt{-g}\begin{bmatrix}0 \\ T^\kappa{}_\lambda \Gamma^\lambda{}_{t\kappa} - \mathcal{F}_t \\ T^\kappa{}_\lambda \Gamma^\lambda{}_{j\kappa} - \mathcal{F}_j \\ 0\end{bmatrix}$$

Solenoidal Constraint:
"No magnetic monopoles"

$$\partial_i\left(\sqrt{-g}\,B^i\right) = 0$$

$$\begin{aligned}
x^{0'} &= t &&= x^0 \\
x^{1'} &= r &&= M e^{x^1} \\
x^{2'} &= \theta &&= \theta(x^2) = \frac{\pi}{2}\left[1 + (1-\xi)\left(2x^2 - 1\right) + \left(\xi - \frac{2\theta_c}{\pi}\right)\left(2x^2 - 1\right)^n\right] \\
x^{3'} &= \phi &&= x^3
\end{aligned}$$

$$g_{\mu\nu} = \frac{\partial x^{\mu'}}{\partial x^\mu}\frac{\partial x^{\nu'}}{\partial x^\nu} g_{\mu'\nu'}$$

- Equations solved via finite volume methods on a grid diffeomorphic to standard spherical coordinates;
- Initial hydrodynamic fields are solutions of the time-averaged PDEs:
    - Initial data is stable to perturbations assuming time-averaged geometry and no magnetic fields;
    - This procedure minimizes unphysical transients from its evolution and means to conform to expected configurations found in nature;
- MHD evolution leads to correlated turbulence which dictates how angular momentum moves through the disk and allows matter to accrete onto the black holes;

GRMHD Numerical Methods (Harm3D)

Geometry and Coordinates:

- Harm3d written largely independent of chosen coordinate system (covariant)
  - GRMHD code Noble++2009
  - Able to handle "arbitrary" spacetimes, though one must be specified;
  - Equations solved on a uniform discretized domain in system of coordinates tailored to the problem;
  - Efficiency through simple uniform domain decomposition:
    - Adaptivity pushed to the warped system of coordinates;
- Prefer to use coordinates similar to spherical coordinates to accurately evolve disks with significant azimuthal component;
  - Minimizes dissipation;
  - Allows us to better track transport of angular momentum --> essential for understanding disks;
- Typical run:
  - ~ 1 Million CPU-hours with ~2000 CPUs
  - 10,000 - 30,000 cell-updates/sec/CPU

Finite Volume Method:

- High-resolution Shock-capturing techniques;
- Reconstruction of Primitive var's (density, pressure, velocities) at cell interfaces:
  - Piecewise parabolic (PPM)
- Approximate Riemann problem solver:
  - Lax-Friedrichs
  - HLL = Harten, Lax, van Leer
- Conserved variables are advanced in time using Method of Lines with 2nd-order Runge-Kutta;
- Primitives are recovered from Conserved var's using "2D" and "1DW" root-finding algorithms for inverting set of nonlinear algebraic equations;

Solenoidal Constraint Enforcement:

- $\partial_i B^i \neq 0$ leads to :
  - Non-perpendicular Lorentz forces to B^i
  - Inconsistency with MHD;
  - Sometimes instabilities and artifacts;
- 3d, modified version of Flux-CT of Toth 2000

$$\mathcal{E}^z = v^x B^y - v^y B^x = f^x$$

General Relativistic Radiative Transfer

Geodesic Calculation:

- 8 coupled ODEs per ray;
- Burlisch-Stoer Method:
  - Adaptive stepsize
  - Richardson Extrapolation;
- Special stepsize control near black holes
- Integrations start at camera and go through source to guarantee desired image resolution:
  - Rays point forward in time;
  - Rays are integrated backward in time;

$$u^\mu = \frac{\partial x^\mu}{\partial \lambda} \qquad \frac{\partial u^\mu}{\partial \lambda} = -\Gamma^\mu{}_{\nu\kappa} u^\nu u^\kappa$$

$$\Gamma^\mu{}_{\nu\kappa} = \frac{1}{2} g^{\mu\sigma} \left(\frac{\partial}{\partial x^\nu} g_{\kappa\sigma} + \frac{\partial}{\partial x^\kappa} g_{\nu\sigma} - \frac{\partial}{\partial x^\sigma} g_{\nu\kappa} \right)$$

$$N_{\text{rays}} = N_t N_\theta N_\theta N_i N_j N_\nu N_M N_\rho$$

$$N_{\text{rays}} = 10^9 N_\nu N_M N_\rho$$

$$N_{\text{rays}} \sim N_{x^0} N_{x^1} N_{x^2} N_{x^3}$$

Radiative Transfer:

- 1 ODE per ray
- Same integrator as that used by geodesics;
- Neglects scattering;
- Difficulty is in accurate and fast emissivity and absorption function;
- Emissivity models:
  - Synchrotron;
  - Bremsstrahlung;
  - Black body;
  - Bolometric model; (see Noble++2009)

$$\frac{\partial I}{\partial \lambda} = j - \alpha I$$

$$\alpha = \alpha(\rho, p, u^\mu, B^i, \nu)$$

$$j = j(\rho, p, u^\mu, B^i, \nu)$$

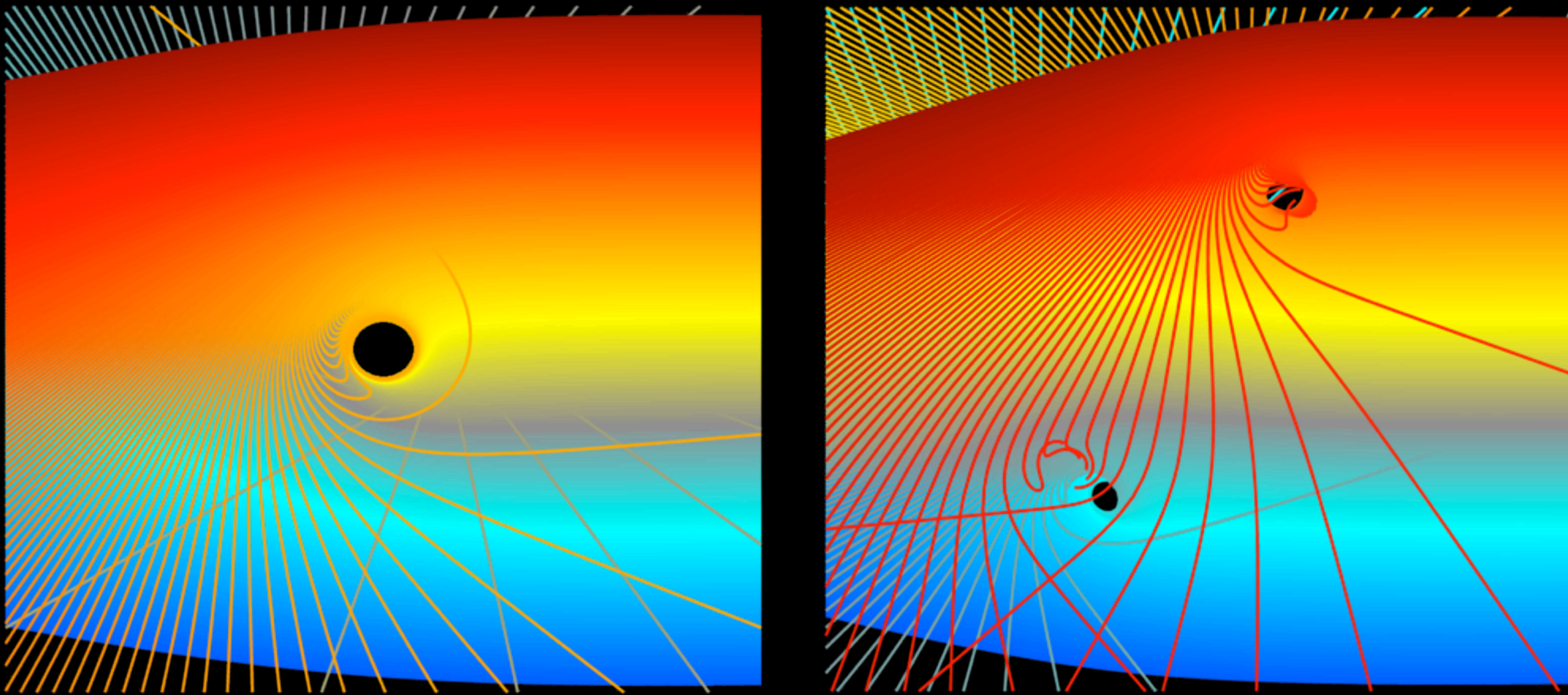
Monte Carlo Radiative Transfer:

- Schnittman & Krolik 2009
- Rays shot from source, collected at distance observer;
- All other emissivity models plus:
  - Inverse Compton Scattering;
  - Reflection emission (e.g., Fe lines);

Binary Black Hole Ray-tracing:

- With Billy Vazquez (grad student);
- Use Superimposed Boosted Dual Kerr-Schild black holes;
- Binary "orbits" via rigid rotation;

Bonning++2009



Binary Black Hole Ray-tracing:

- With Billy Vazquez (grad student);
- Use Superimposed Boosted Dual Kerr-Schild black holes; Bonning++2009
- Binary "orbits" via rigid rotation;

Constrained to BBH's Plane

Isotropic