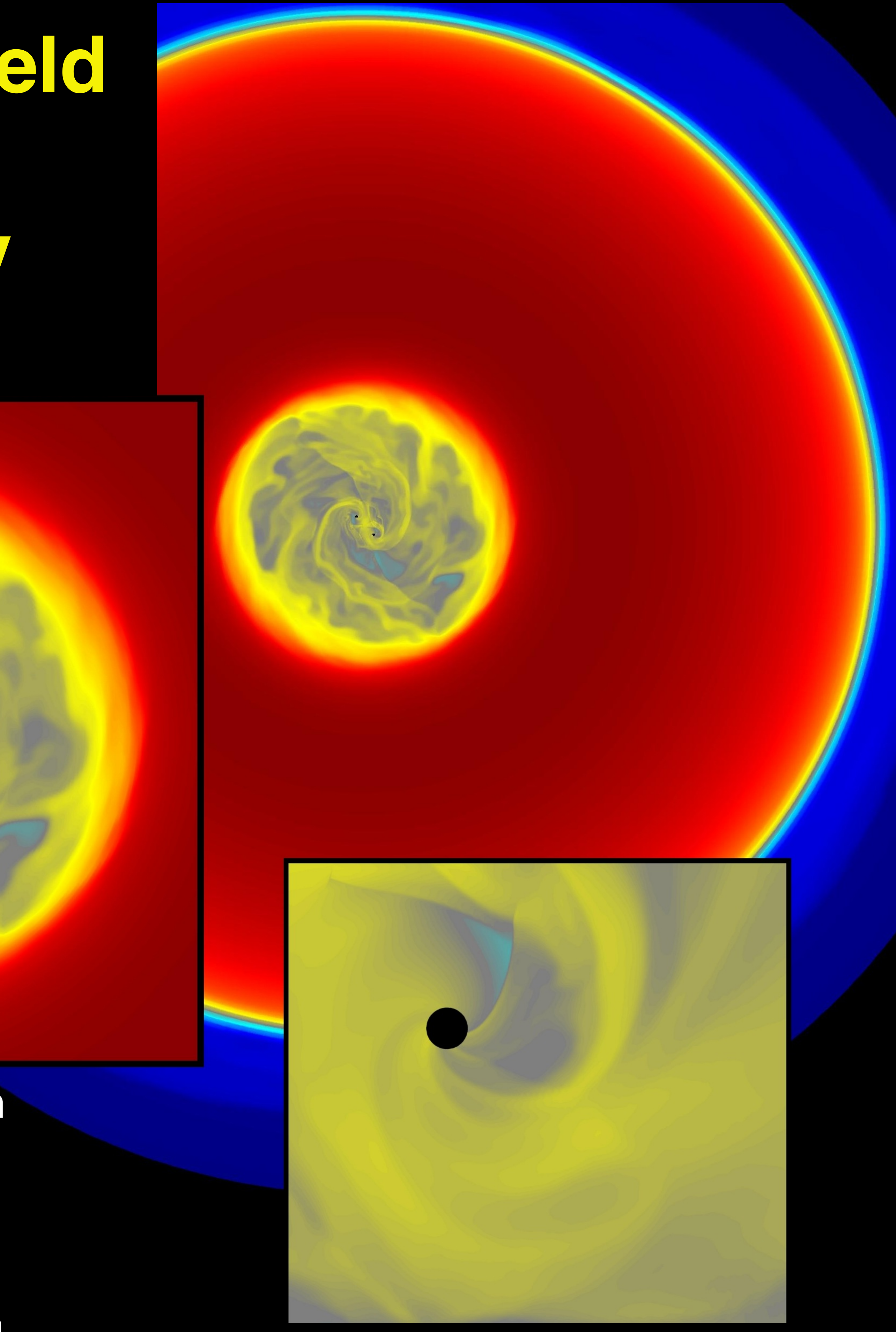
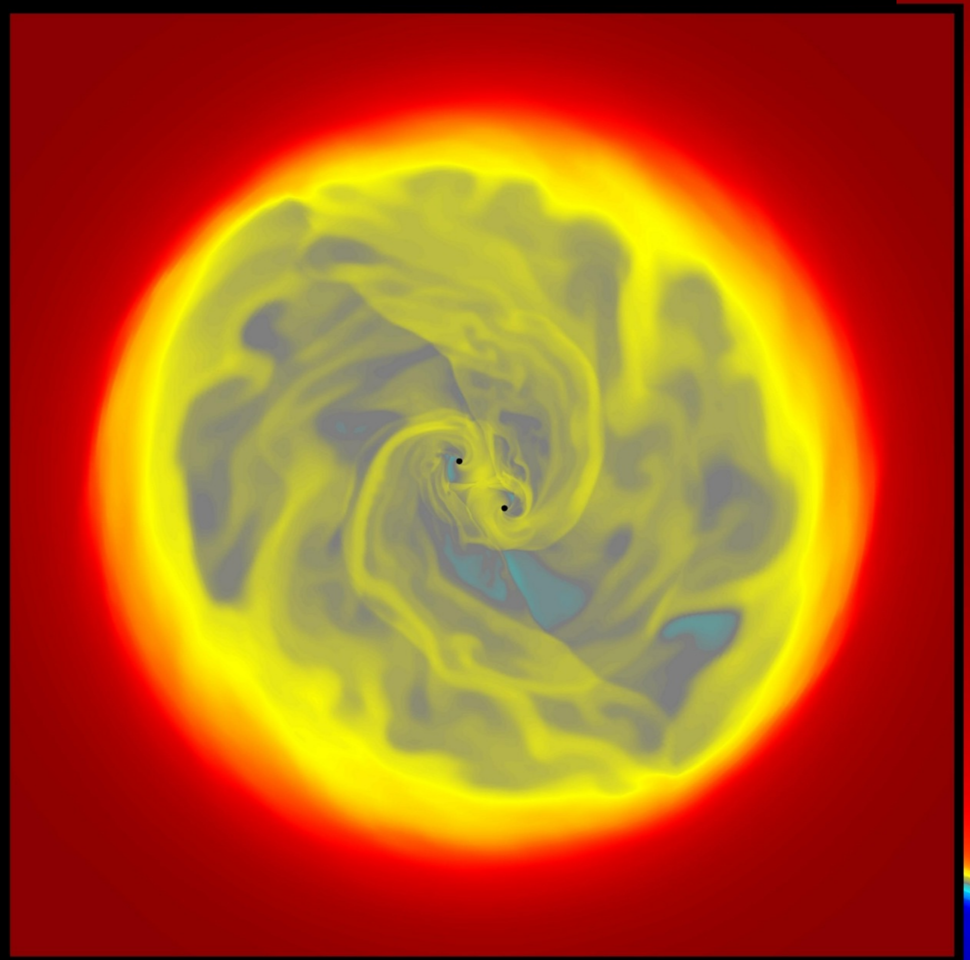
The Influence of Strong Field Spacetime Dynamics and MHD on Circumbinary Disk Physics





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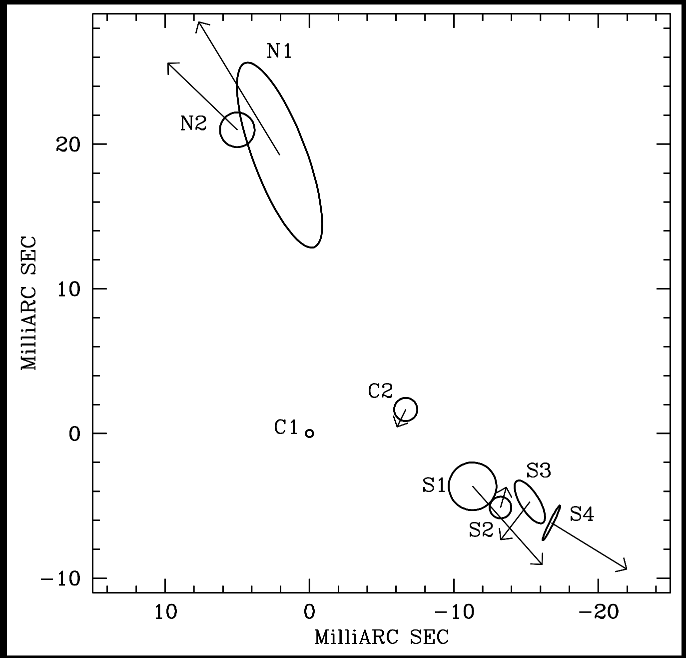
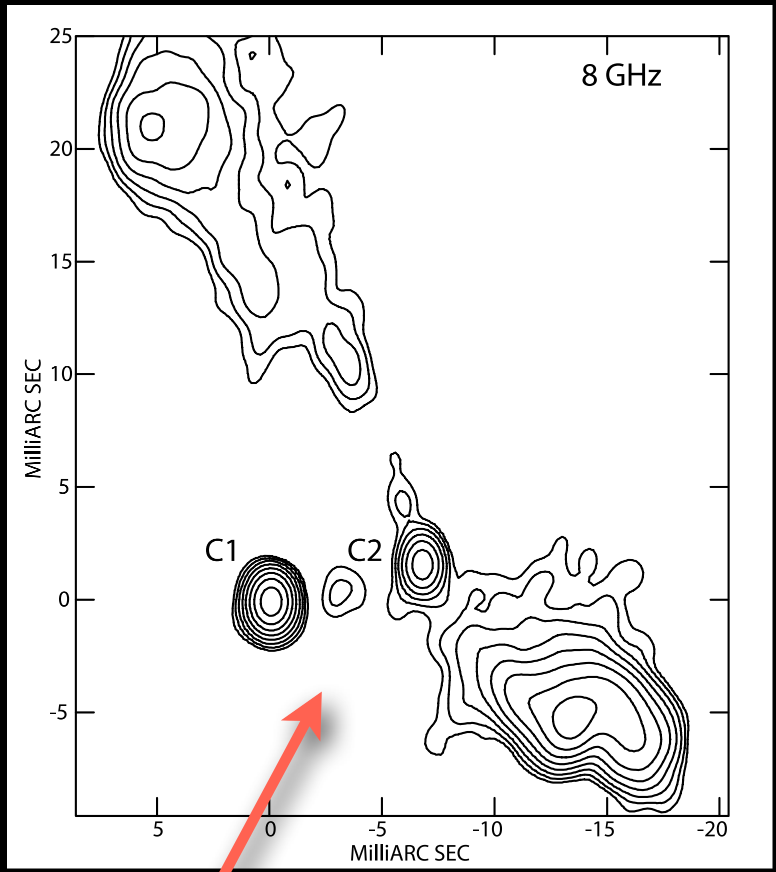
Systems with Two Black Holes

0402+379:

(Xu et al. 1994, Maness et al. 2004, Rodriguez et al. 2006):

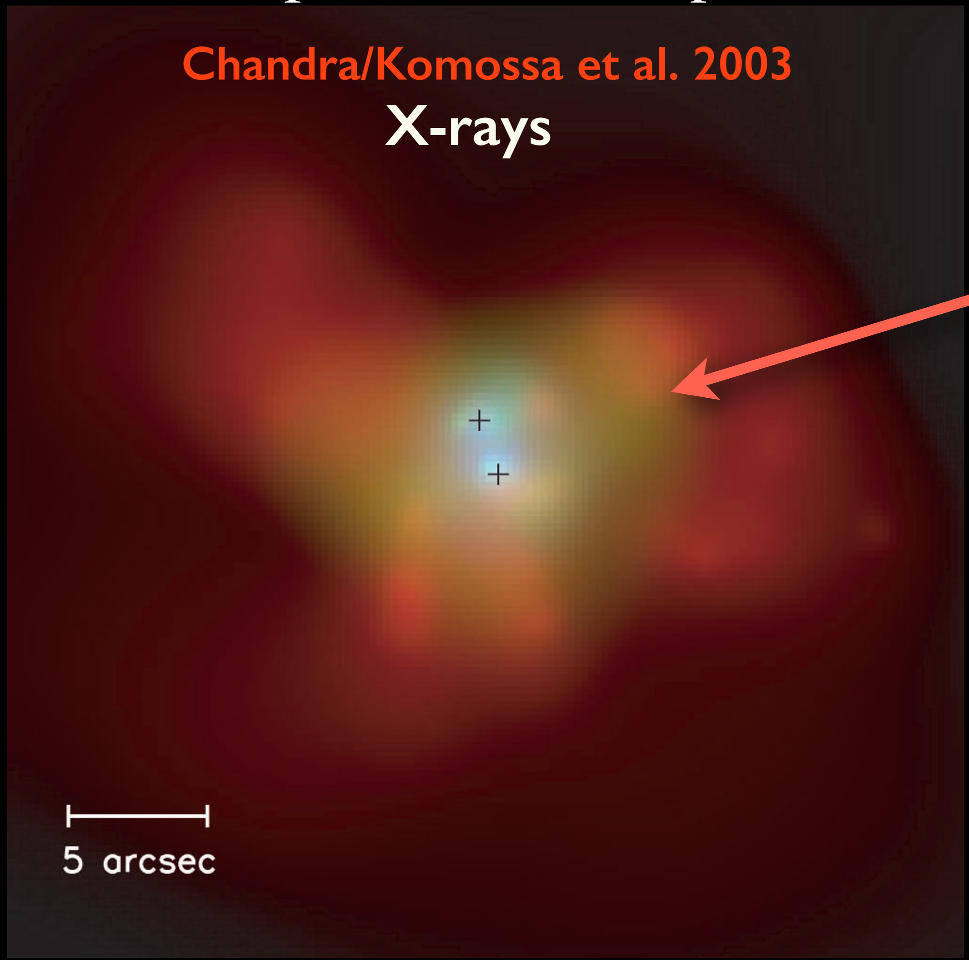
- Radio observation
- Separation = 5 pc
- $M \sim 10^8 M_\odot$





NGC 6240: (Komossa et al. 2003)

- Optical ID: (Fried & Schulz 1983)
- Separation = 0.5 kpc



Not close enough to make detectable gravitational waves!

SDSS J153636.22+044127.0

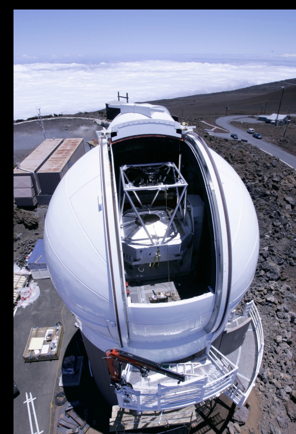
(Lauer & Boroson 2009)

Separation = 0.1pc

1pc = 1 parsec = 3.26 light-years = 1.9 x 10^{13} miles

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

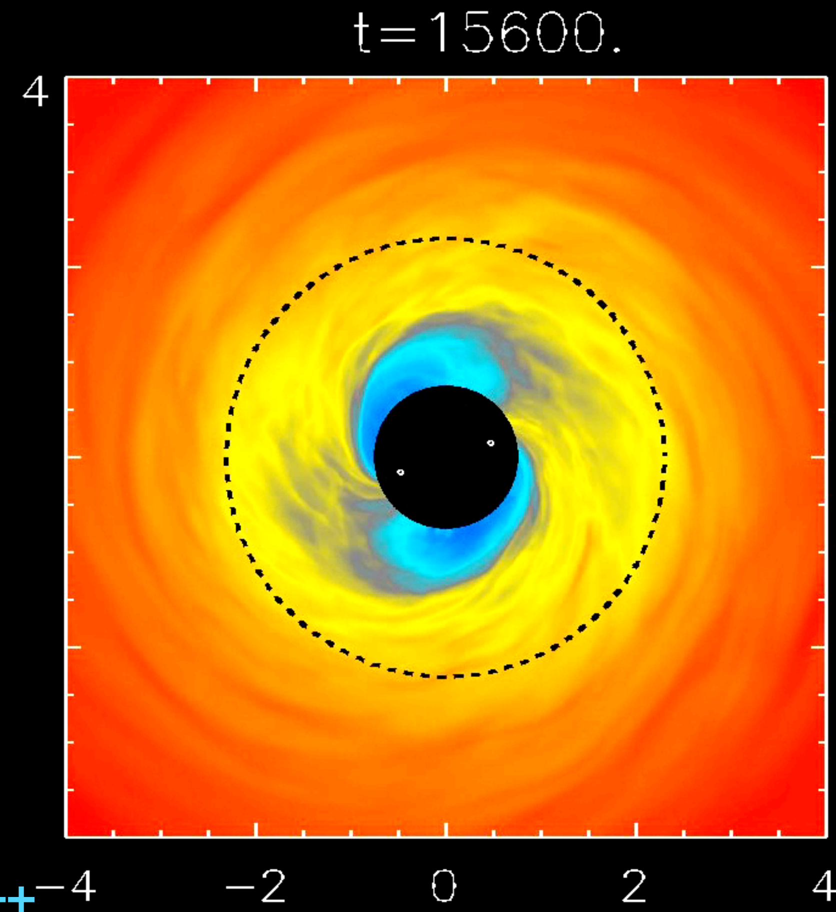
EPTA
NANOGrav
PPTA

- 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!
- Cosmological "Standard Sirens": New Distance vs. Redshift Measurement
  Schutz 1986, Chernoff+Finn 1993, Finn 1996, Holz & Hughes 2005

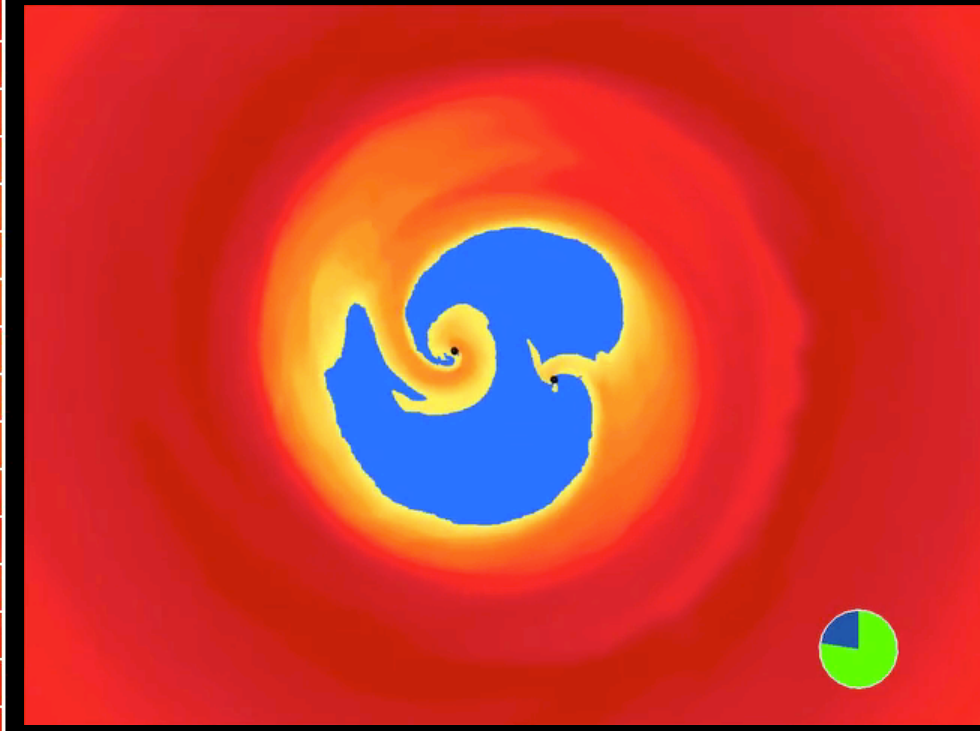
★ Need accurate predictions of the sources temporal variability and energy spectrum as many sources will be spatially unresolved;

Circumbinary Accretion Problem:

Hopkins, Hernquist, Di Matteo, Springel++



Noble++2012



Farris++2011

Physical Time (not to scale)

Galactic Merger | Binary Formation | Inspiral | Merger | Re-equilibration

Newtonian Gravity

Numerical Relativity

Post-Newtonian

Static GR

Harm3d

Harm3d

Eulerian, high-resolution/shock-capturing, 3-d, ideal MHD, dynamical GR, HLL fluxes, parabolic reconstruction, dynamical FMR

Key Challenges

1) Include the necessary physics to yield realistic EM predictions:
- Ideal MHD;
- Thermodynamics (radiative cooling);
- Post-processing radiative transfer tools;
- Accurate solution of the spacetime metric (gravity);

2) Establish natural initial conditions for inspiral and merger runs:
- At what binary separations are our results valid?
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3) Develop the necessary computational tools:
- Resolve BHs: dynamic warped coordinates;
- Evenly balance uneven spacetime computational effort;
- Magnetic monopole cleaner to remove magnetic divergences after interpolating to grids to start closer separation runs;

Why We Need Blue Waters

- Early runs with unresolved BHs (BHs excised from domain):
  - $O(10^7)$ cells
  - $O(10^7)$ time steps integrated;
  - $O(10^2)$ binary orbits;
  - ▷ $O(10^5)$ BW SUs;

1 BW SU = 1 node-hour on BW

- Extrapolating to the case with resolved BHs (WITHOUT new schemes):
  - $O(10^9)$ cells
  - $O(10^8)$ time steps integrated;
  - $O(10^2)$ binary orbits;
  - 4x slower from costlier spacetime calculation;
  - ▷ $O(10^9)$ BW SUs;

- Extrapolating to the case with resolved BHs (WITH new schemes):
  - New schemes:
    - ✓ Optimize spacetime code;
    - ✓ Load balance to even out nonuniform spacetime calculation;
    - ✓ Use warped coordinates to implement FMR-like solution;
  - $O(10^7)$ cells;
  - $O(10^8)$ time steps integrated;
  - 1.2x slower spacetime calculation with optimizations;
  - ▷ $O(10^6)$ BW SUs;

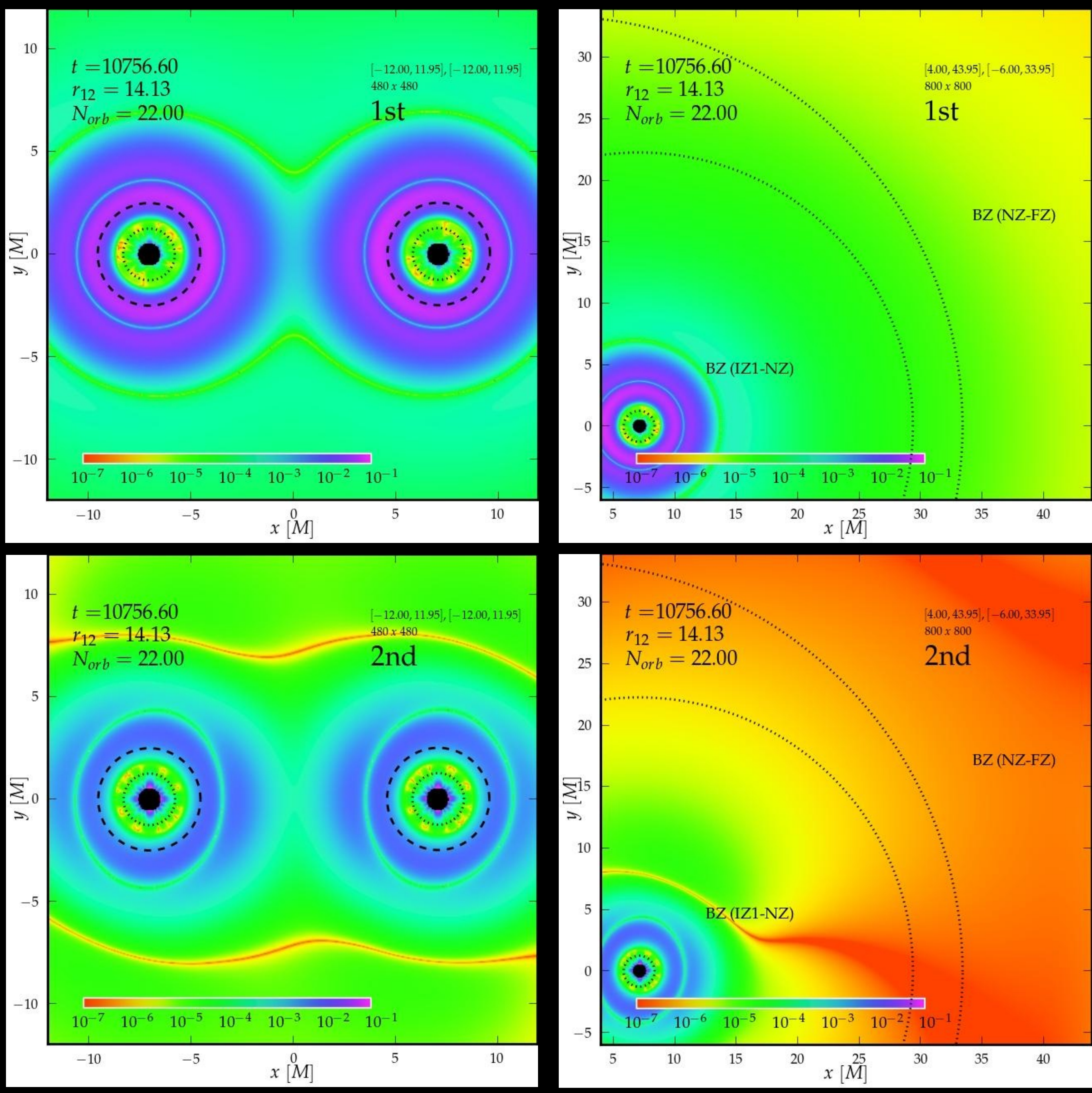
Approximate Two Black Hole Spacetimes

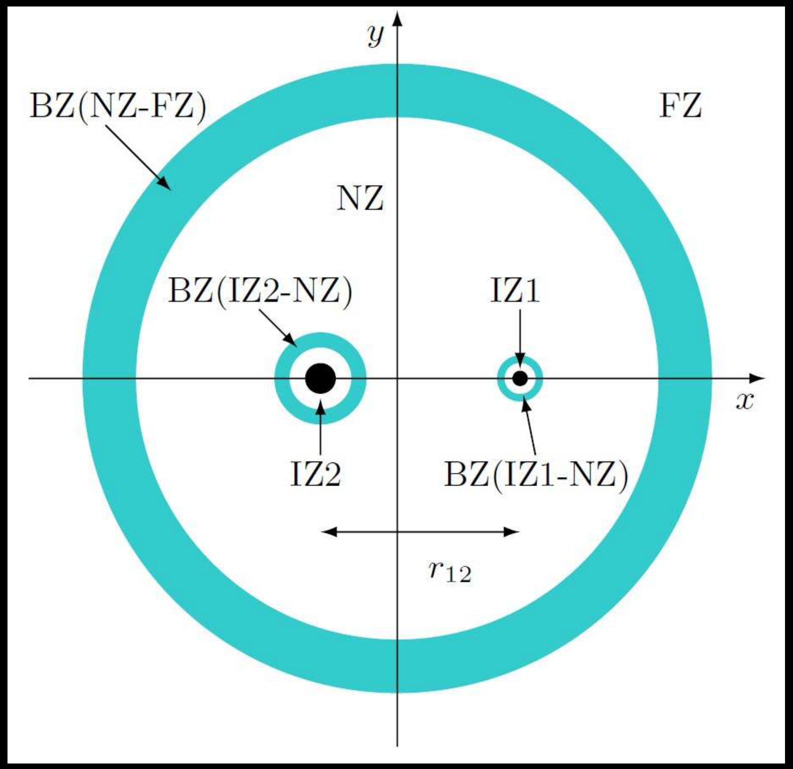
Yunes++2006, Noble++2012, Mundim++2014

- Solve Einstein's Equations approximately, perturbatively to orders of 2.5 Post-Newtonian order;
- Used as initial data of Numerical Relativity simulations;
- Black hole orbits include radiation-reaction terms;
- Closed-form expressions allow us to discretize the spatial domain best for accurate matter solutions and is much simpler to implement;
- Novel approach for simulating matter in dynamical spacetimes!

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

Ricci Scalar → 0





Matter's Response to PN-Order and Binary Separation

Relative deviations of density from initial conditions averaged in azimuth, plotted versus radius and time:

Tori of gas in orbit of the binary responds in different ways at closer separations between the two orders of Post-Newtonian accuracy;

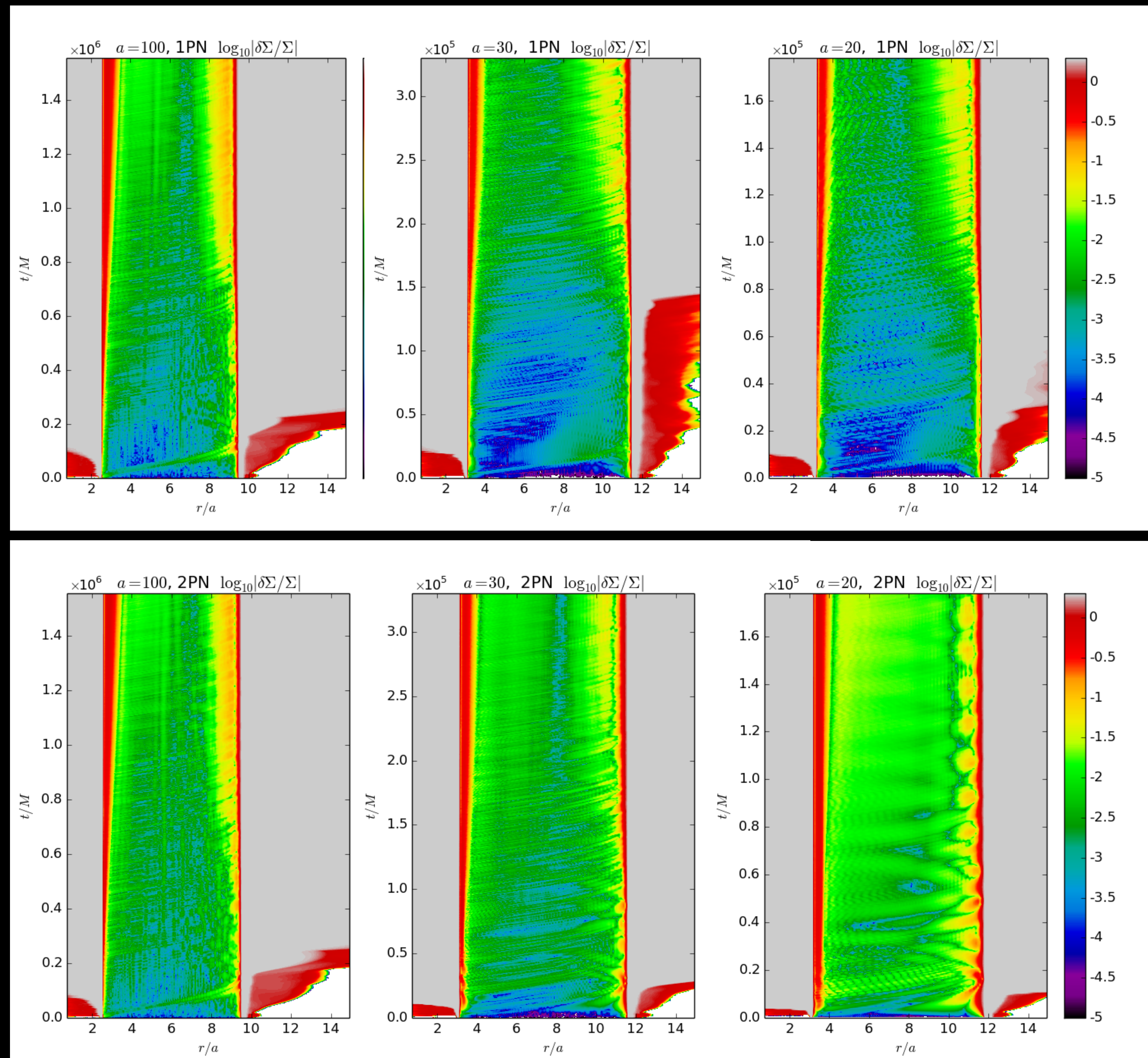
Implies that ~20M is a good starting point for our runs with the 2PN spacetime, but 1PN is valid for larger separations.

Differences seen between PN orders are because circular orbits are less stable in the 2PN spacetime and its higher-order terms result in a greater gravitational torque on the gas;

a = 100M **30M** **20M**

1 PN

2 PN



MHD Simulations with Unresolved BHs:

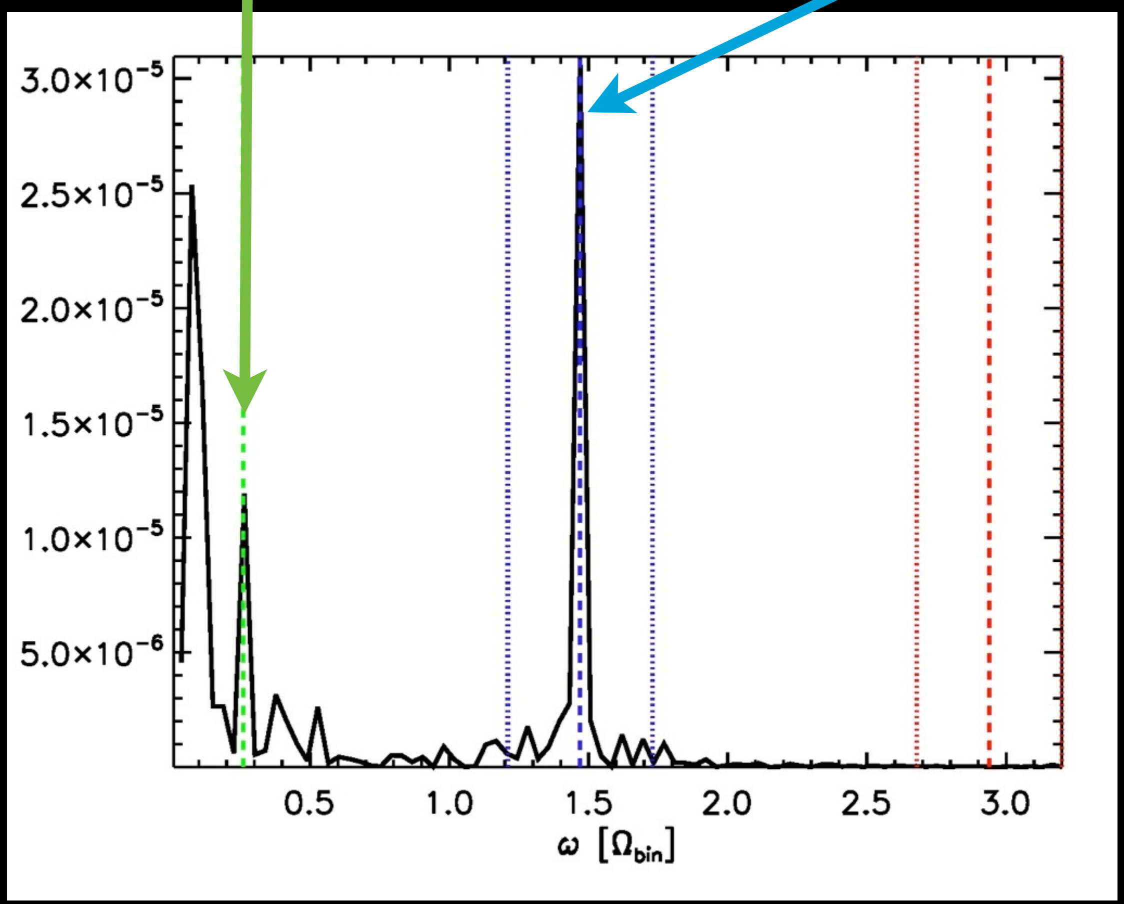
Noble++2012

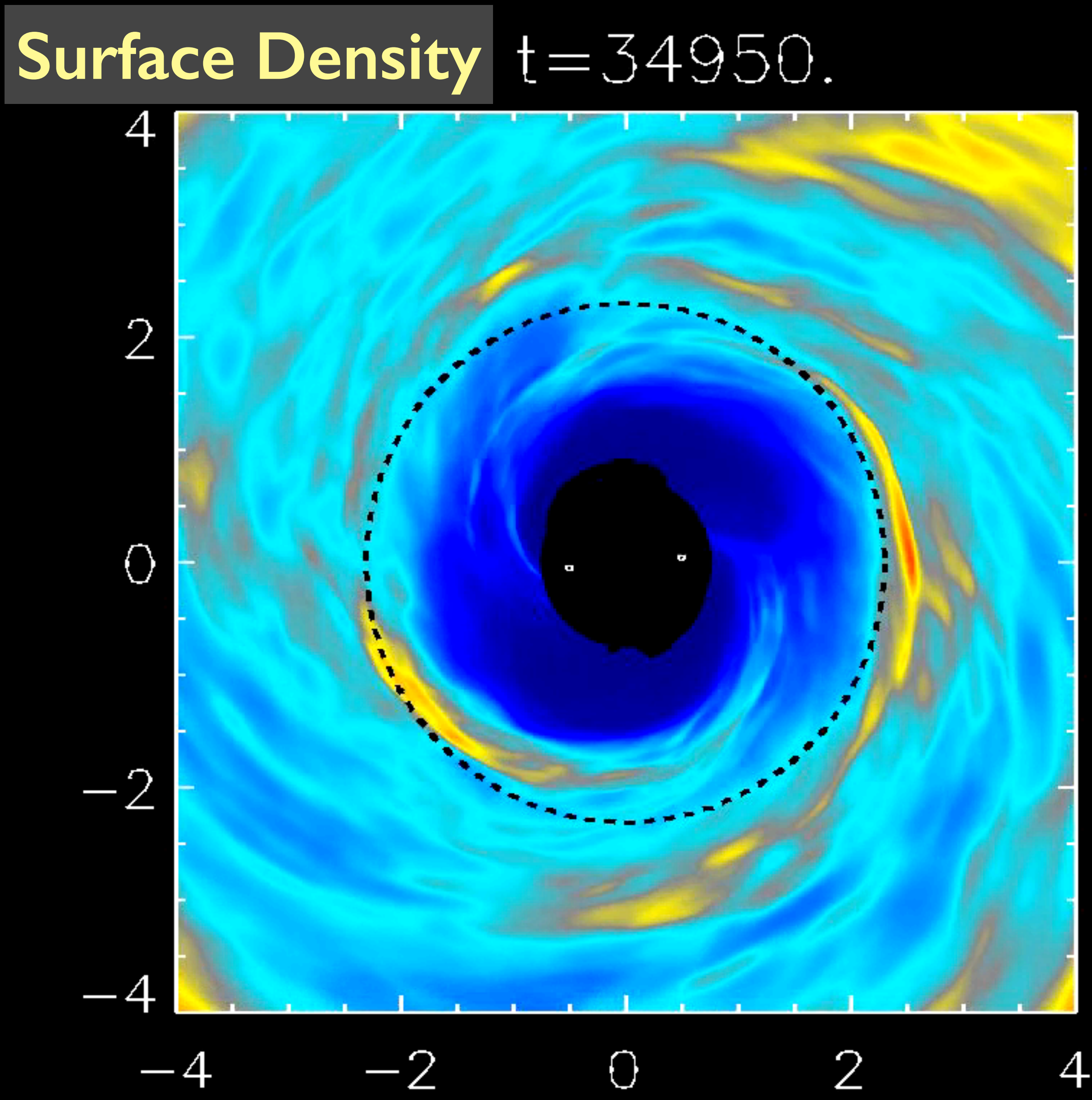
Periodic Signal

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

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

$1.47\Omega_{\rm bin}$



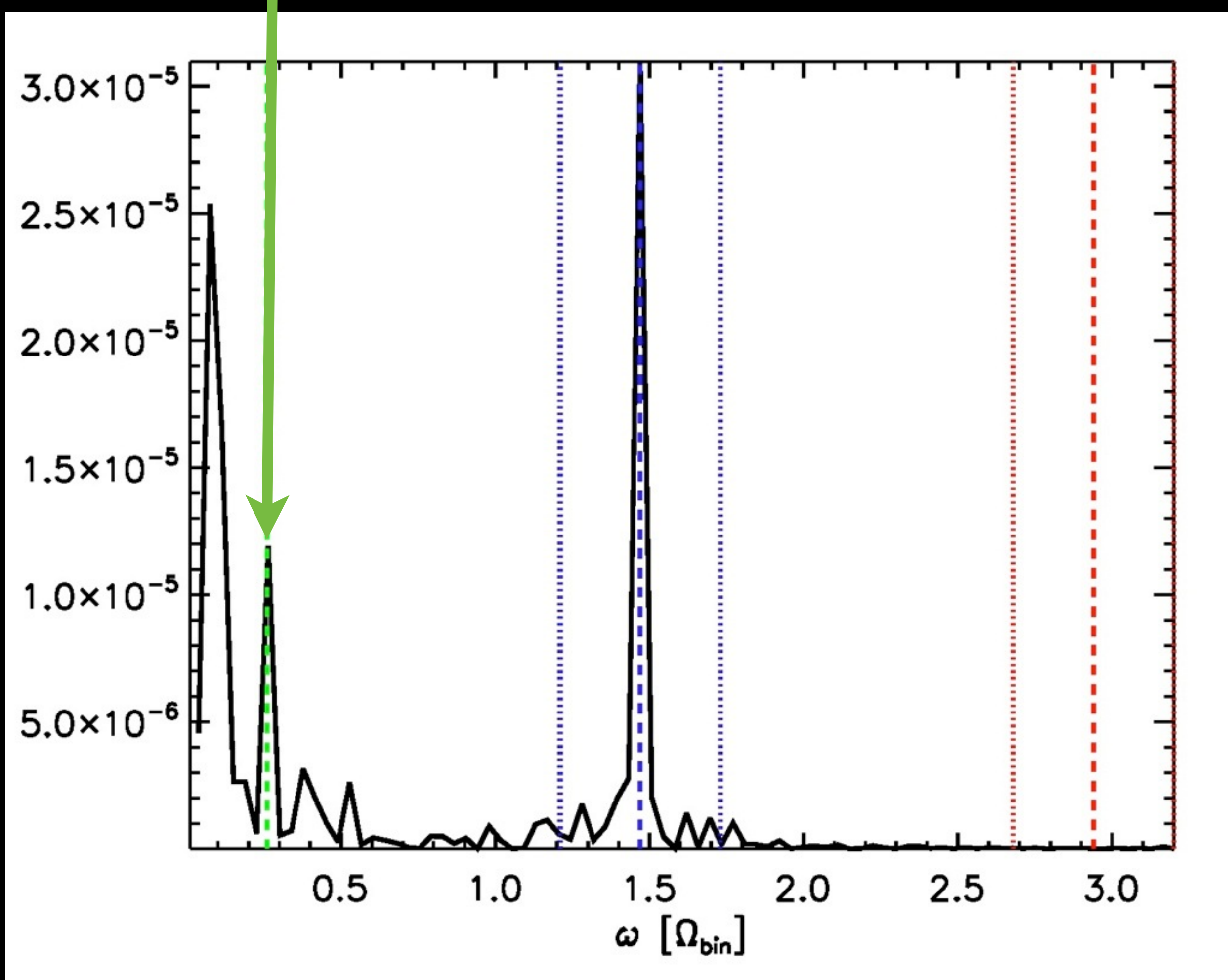


$$\omega_{\rm peak} = 2\left(\Omega_{\rm bin} - \Omega_{\rm lump}\right) \rightarrow 1 < \frac{\omega_{\rm peak}}{\left(\Omega_{\rm bin} - \Omega_{\rm lump}\right)} < 2 \qquad 0 < \frac{M_2}{M_1} < 1$$

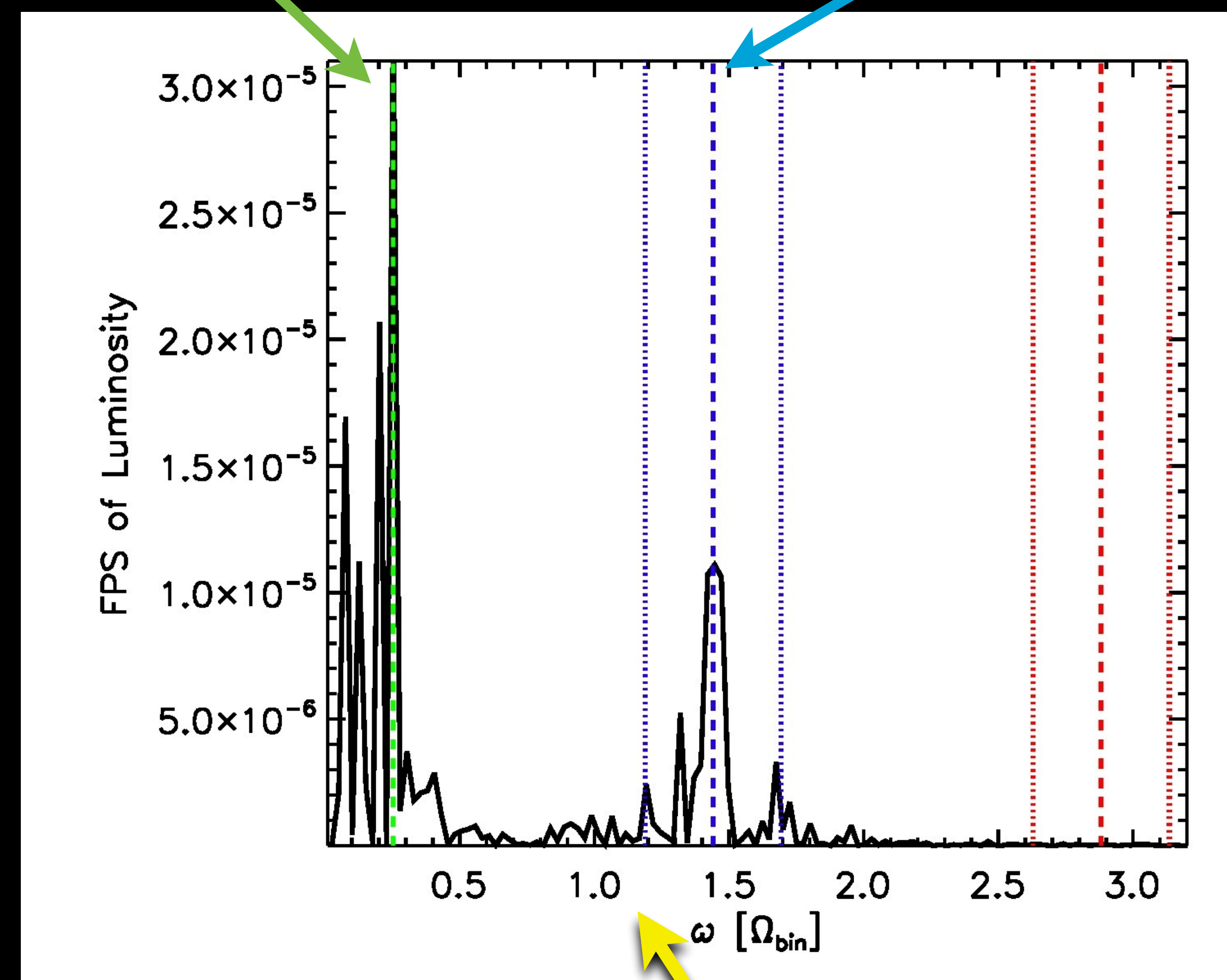
Variabality vs. Post-Newtonian Accuracy:

2.5PN (more accurate) $q = 1$ 1.5PN (less accurate)

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



$\Omega_K(r_{\rm lump})$ $1.47\Omega_{\rm bin}$



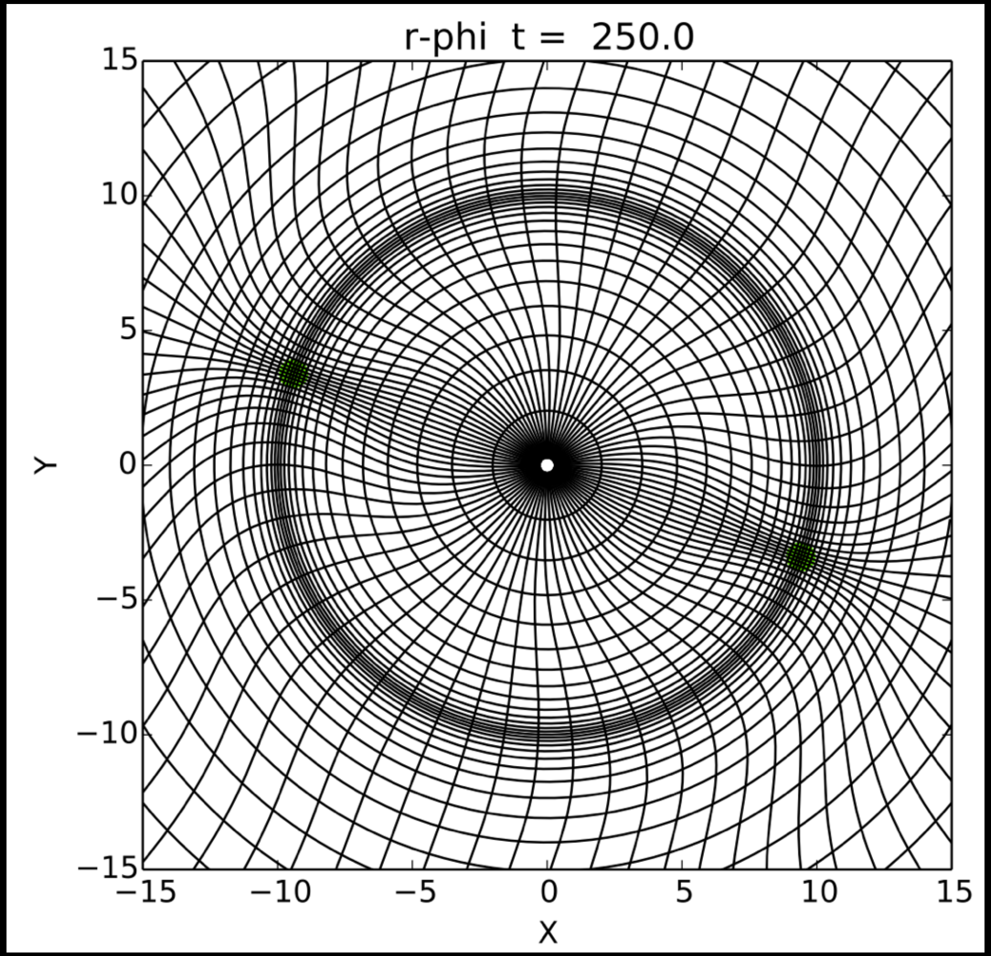
$\Omega_{\rm bin}$

- Stronger variability at lump's orbital frequency;
- Power at beat frequency spread to larger range of frequencies;
- More complex lump/binary modulation;

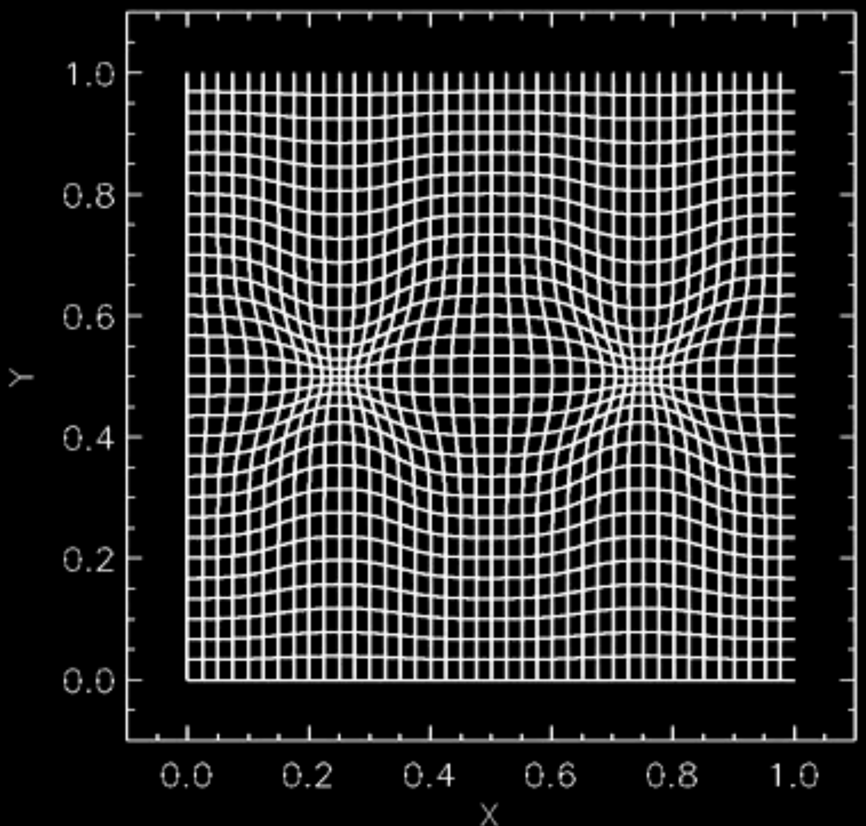
Noble++2014

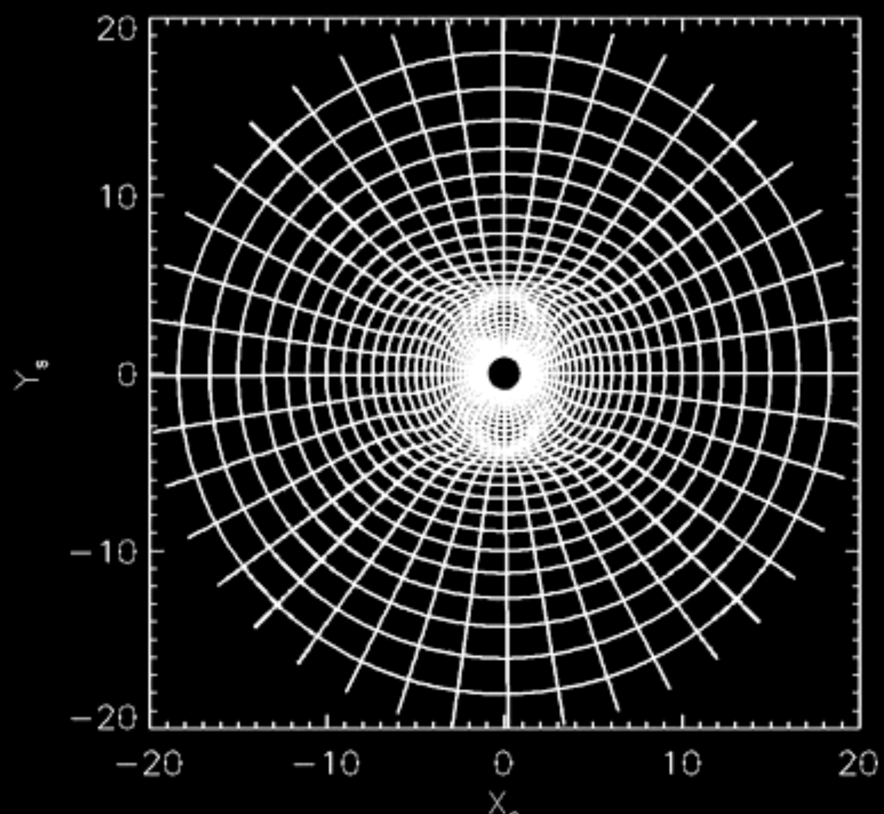
Dynamic Coordinates to Resolve Binary Black Holes

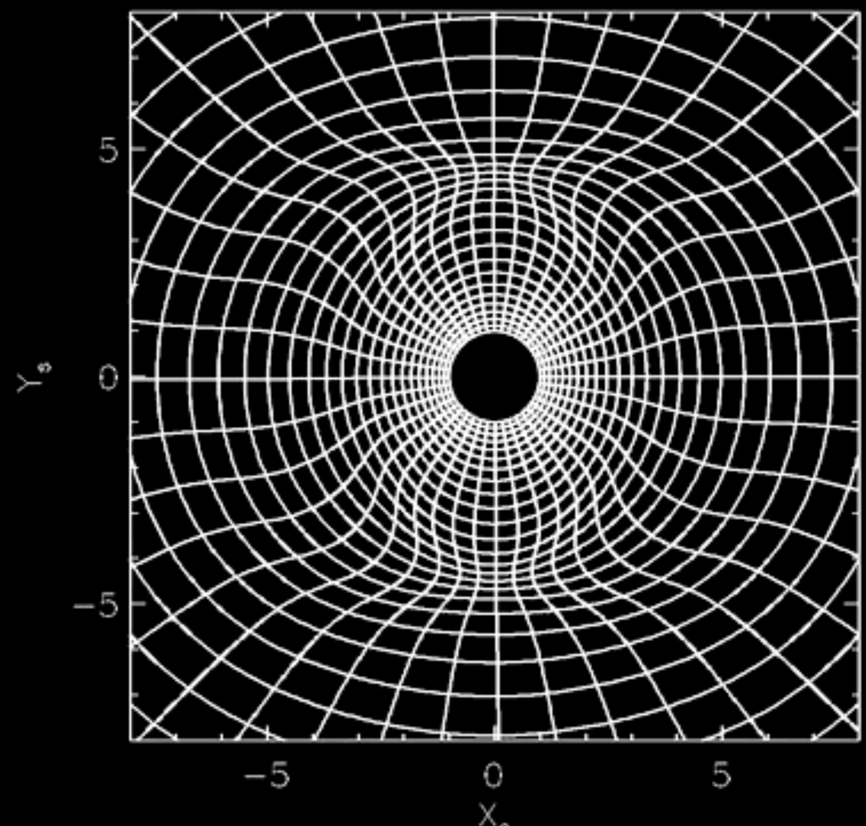
- Previous runs excised a sphere encompassing the orbit of the black holes since we lacked the ability to stably, accurately evolve the gas there;
- Grid distortions follow black holes to resolve accreting gas;
- Coordinates are isomorphic to spherical coordinates to conserve angular momentum well;
- Avoids the problems (e.g., infrastructure development, signal reflection/diffraction) associated with refinement level interfaces of AMR;



Zilhao & Noble 2014





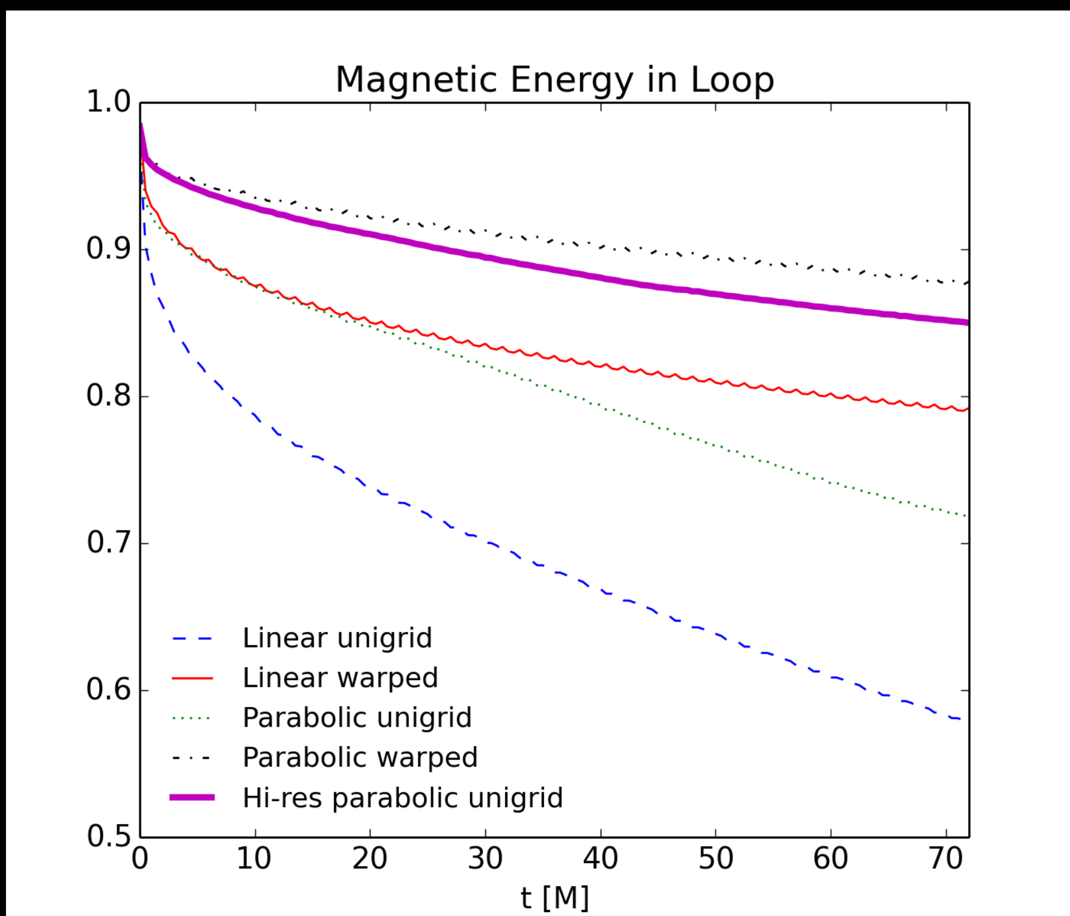


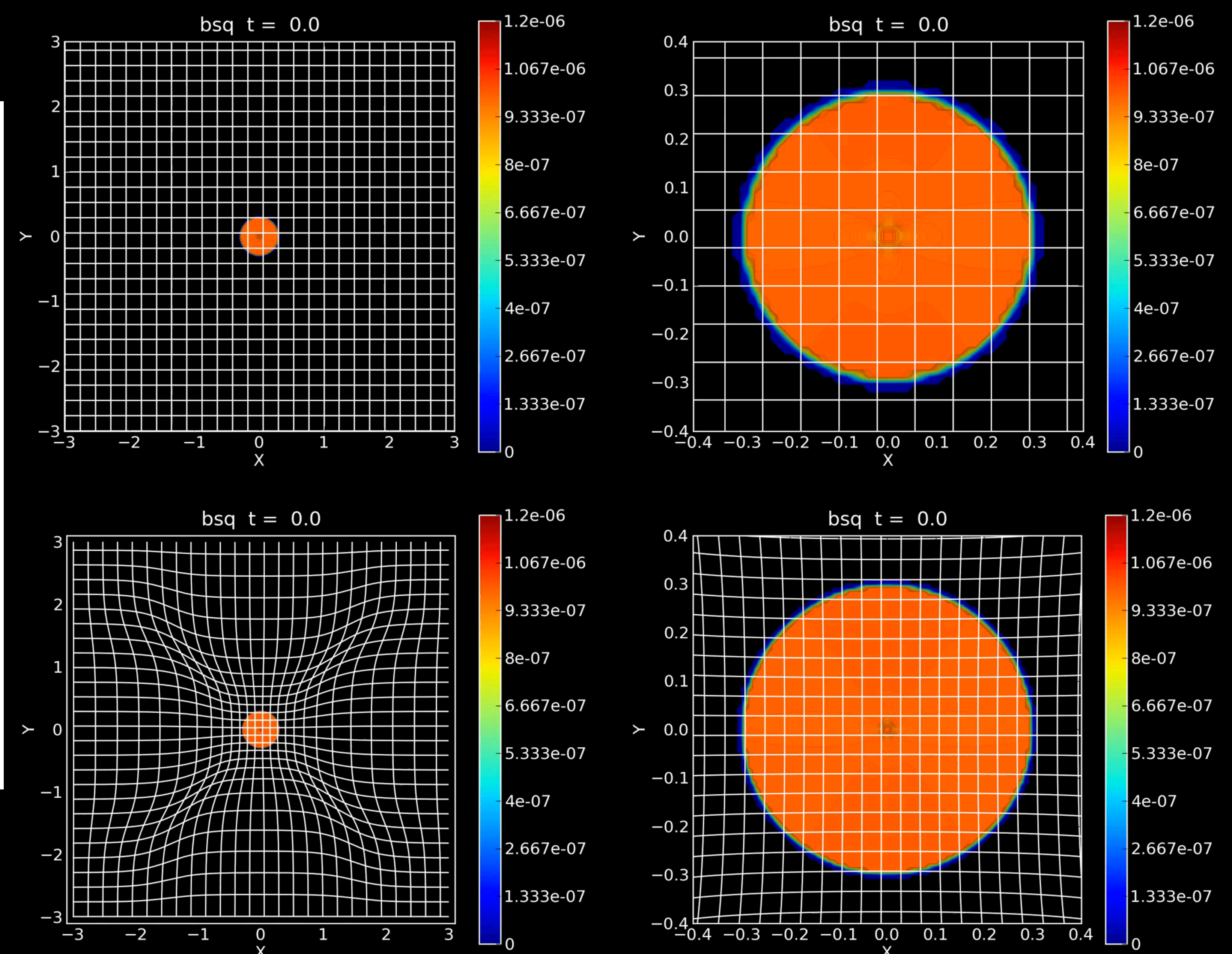
Dynamic Coordinates to Resolve Binary Black Holes

Zilhao & Noble 2014

Advection of Magnetic Field Loop

384x384 cells



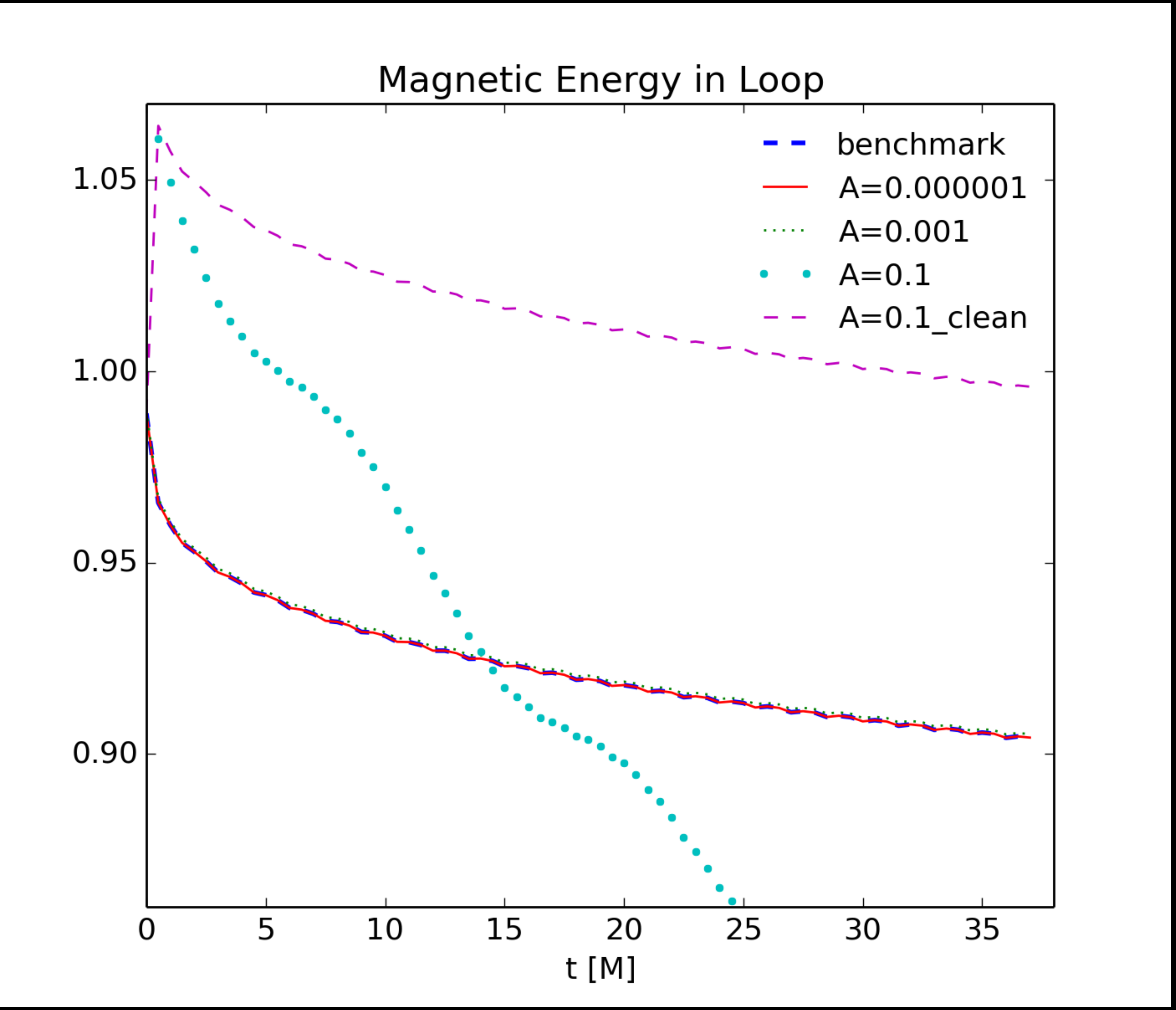


“Linear” = Linear reconstruction
“Parabolic” = Parabolic reconstruction

- Warped grid leads to an effective higher resolution calculation with little additional dissipation/diffusion!
- Additional overhead is insignificant!

Magnetic Monopole Cleaner

- Need to transfer “unresolved BH” sim. data to the warped coordinates of “resolved BH” sims.;
- Process is straightforward except interpolation introduces magnetic monopoles with our Contrained Transport scheme;
- We developed the first (?) monopole cleaner for arbitrary spacetime metrics:
  - Idea from Brackbill & Barnes (1980) who solved uniform, flat Cartesian case;
  - We use SOR to solve fully GR eq.;
- Will be very helpful when we start transferring data between groups simulating different phases of the binary’s evolution.

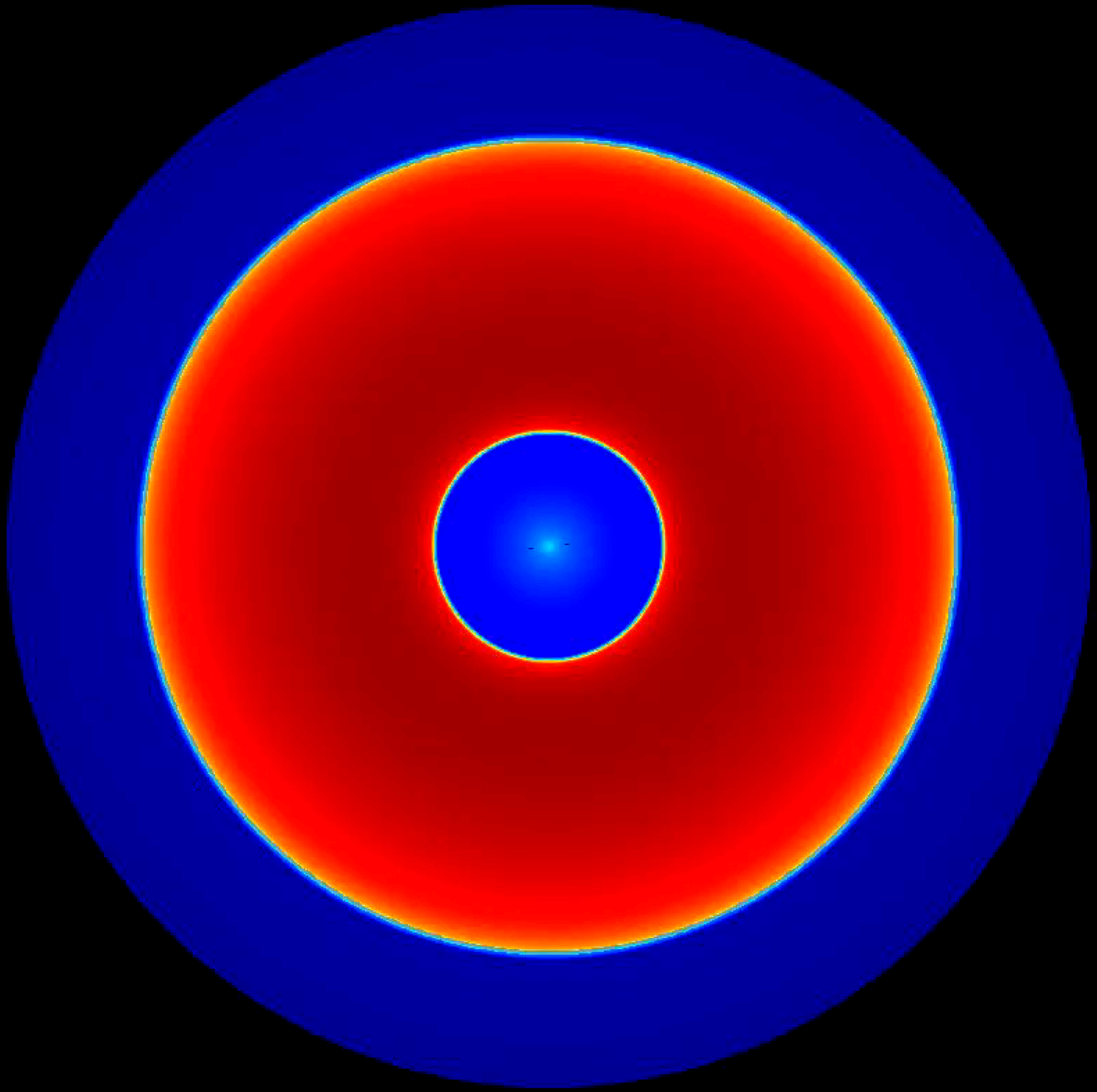


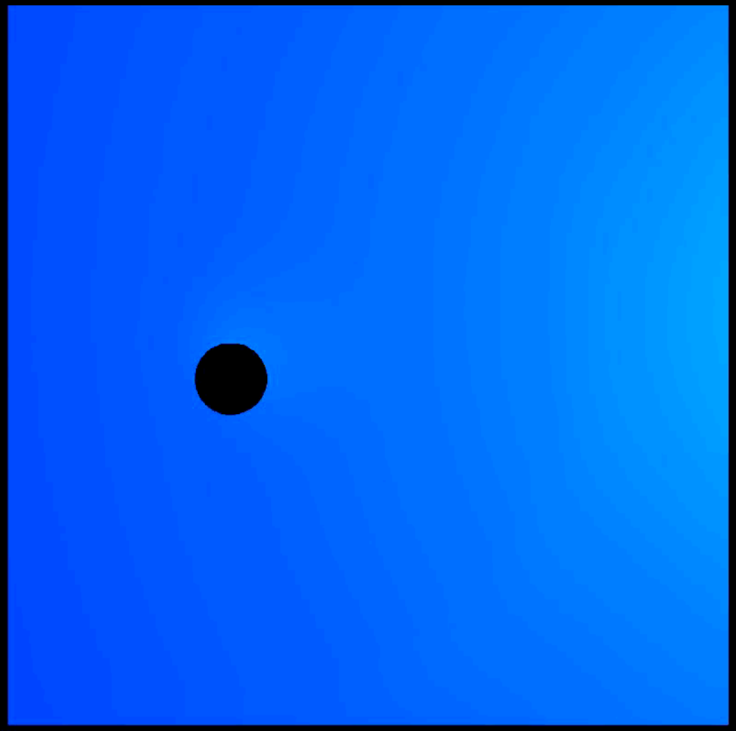
“A” = Amplitude of random perturbation used on magnetic field

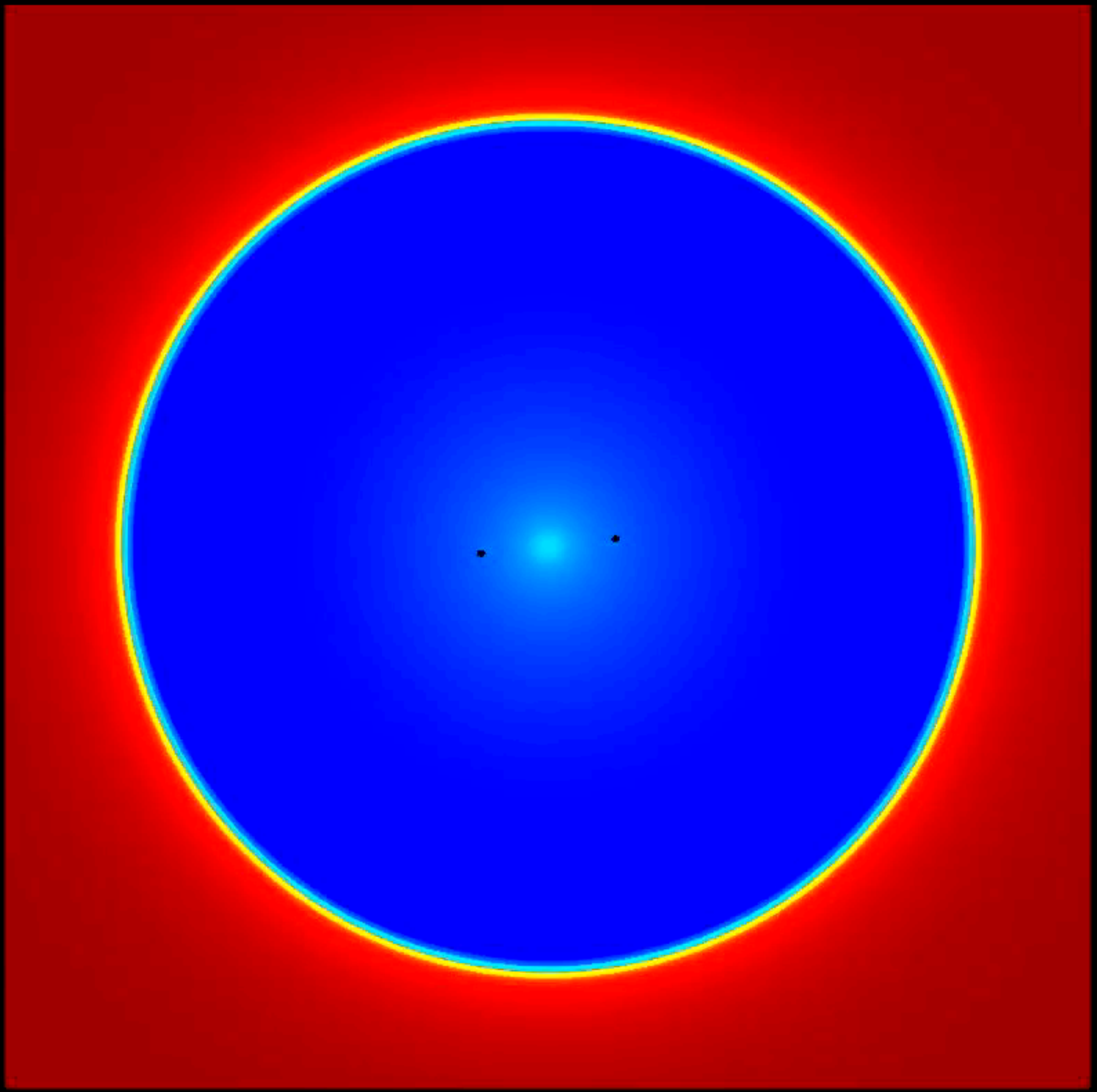
“Clean” = Whether the magnetic field was cleaned of monopoles after perturbation;

Putting It All Together

- Non-magnetized, non-viscous gas in orbit about the BHs, in the plane of the BHs;
- Binary's inspiral at the rate set by gravitational wave emission;
- 3-d MHD simulation currently underway…







Noble, Zilhao, Campanelli,++2014

Summary and Future Plans

Key Challenges

1) Include the necessary physics to yield realistic EM predictions:
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Key Challenges Accomplished & Future Challenges to Pursue

1) Include the necessary physics to yield realistic EM predictions:
   - ☑ Ideal MHD;
     - ☐ Non-ideal effects? (being explored now with single BHs)
   - ☑ Thermodynamics (radiative cooling);
     - ☐ Explore effects from different cooling models…
   - ☑ Post-processing radiative transfer tools;
     - ☐ Include in-situ, back-reacting radiation processes;
   - ☑ Accurate solution of the spacetime metric (gravity);
     - ☐ Explore vast parameter space of binary black hole configurations;

2) Establish natural initial conditions for inspiral and merger runs:
   - ☑ At what binary separations are our results valid?
   - ☐ How many orbits yield a reasonable "steady-state"?
     - ☑ Developed methodology for identifying steady-states;
     - ☐ Likely no general solution, requires case-by-case determination;

3) Develop the necessary computational tools:
   - ☑ Resolve BHs: dynamic warped coordinates;
   - ☑ Evenly balance uneven spacetime computational effort;
   - ☑ Magnetic monopole cleaner to remove magnetic divergences after interpolating to grids to start closer separation runs;