Generalized Harmonic Evolutions of Binary Black Hole Spacetimes

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Collaborators: Duncan Brown, Larry Kidder, Geoffrey Lovelace, Robert Owen, Oliver Rinne, Harald Pfeiffer, Mark Scheel, Saul Teukolsky

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- Moving Black Holes.
- Binary Black Hole Evolutions.

Methods of Specifying Spacetime Coordinates

- We often decompose the 4-metric into its 3+1 parts: $ds^2 = \psi_{ab}dx^a dx^b = -N^2 dt^2 + g_{ij}(dx^i + N^i dt)(dx^j + N^j dt)$. The lapse N and shift N^i specify how coordinates are laid out on a spacetime manifold. Consider the unit timelike normal $\vec{n}$: $\vec{n} = \partial_\tau = (\partial t/\partial\tau)\partial_t + (\partial x^k/\partial\tau)\partial_k = (\partial_t - N^k\partial_k)/N$.

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- An alternate way to specify the coordinates is through the generalized harmonic gauge source function H^a:
- Let H^a denote the function obtained by the action of the scalar wave operator on the coordinates x^a:

$$H^a \equiv \nabla^c\nabla_c x^a = -\Gamma^a,$$

where $\Gamma^a = \psi^{bc}\Gamma^a{}_{bc}$ and ψ_{ab} is the 4-metric.

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  where $\Gamma^a = \psi^{bc}\Gamma^a{}_{bc}$ and ψ_{ab} is the 4-metric.
- Specifying coordinates by the *generalized harmonic* (GH) method can be accomplished by choosing a gauge-source function $H_a(x,\psi) = \psi_{ab}H^b$, and requiring that
  $H_a(x,\psi) = -\Gamma_a = -\Gamma_{abc}\psi^{bc}$.

Important Properties of the GH Method

- The Einstein equations are manifestly hyperbolic when coordinates are specified using a GH gauge function:

$$R_{ab} = -\frac{1}{2}\psi^{cd}\partial_c\partial_d\psi_{ab} + \nabla_{(a}\Gamma_{b)} + F_{ab}(\psi, \partial\psi),$$

  where ψ_{ab} is the 4-metric, and $\Gamma_a = \psi^{bc}\Gamma_{abc}$. The vacuum Einstein equation, $R_{ab} = 0$, has the same principal part as the scalar wave equation when $H_a(x, \psi) = -\Gamma_a$ is imposed.

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- Imposing coordinates using a GH gauge function profoundly changes the constraints. The GH constraint, $\mathcal{C}_a = 0$, where

$$\mathcal{C}_a = H_a + \Gamma_a,$$

  depends only on first derivatives of the metric. The standard Hamiltonian and momentum constraints, $\mathcal{M}_a = 0$, are determined by the derivatives of the gauge constraint $\mathcal{C}_a$:

$$\mathcal{M}_a \equiv G_{ab}n^b = \left[\nabla_{(a}\mathcal{C}_{b)} - \frac{1}{2}\psi_{ab}\nabla^c\mathcal{C}_c\right]n^b.$$

Constraint Damping Generalized Harmonic System

- Pretorius (based on a suggestion from Gundlach, et al.) modified the GH system by adding terms proportional to the gauge constraints:

$$0 \;=\; R_{ab} - \nabla_{(a}\mathcal{C}_{b)} + \gamma_0\left[n_{(a}\mathcal{C}_{b)} - \frac{1}{2}\psi_{ab}\, n^c\, \mathcal{C}_c\right],$$

where n^a is a unit timelike vector field. Since $\mathcal{C}_a = H_a + \Gamma_a$ depends only on first derivatives of the metric, these additional terms do not change the hyperbolic structure of the system.

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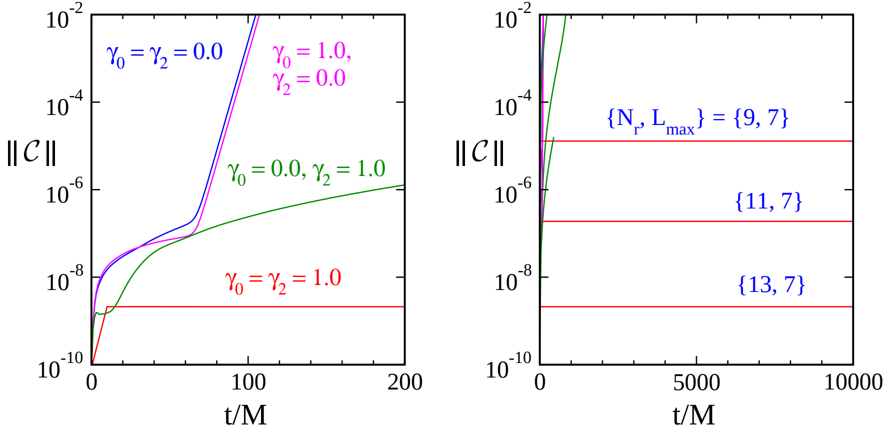
- Evolution of the constraints $\mathcal{C}_a$ follow from the Bianchi identities:

$$0 = \nabla^c\nabla_c\mathcal{C}_a - 2\gamma_0\nabla^c\left[n_{(c}\mathcal{C}_{a)}\right] + \mathcal{C}^c\nabla_{(c}\mathcal{C}_{a)} - \frac{1}{2}\gamma_0\, n_a\mathcal{C}^c\mathcal{C}_c.$$

  This is a damped wave equation for $\mathcal{C}_a$, that drives all small short-wavelength constraint violations toward zero as the system evolves (for $\gamma_0 > 0$).

Numerical Tests of the New GH System

- 3D numerical evolutions of static black-hole spacetimes illustrate the constraint damping properties of our GH evolution system.
- These evolutions are stable and convergent when $\gamma_0 = \gamma_2 = 1$.



Moving Black Holes in a Spectral Code

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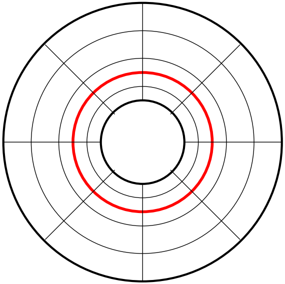

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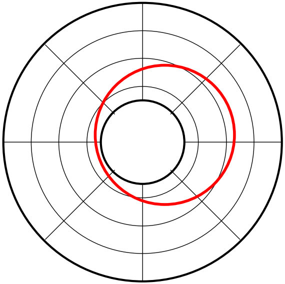

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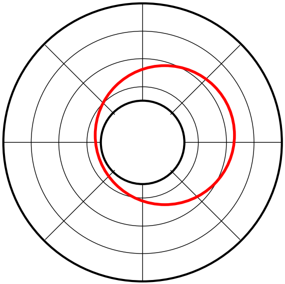

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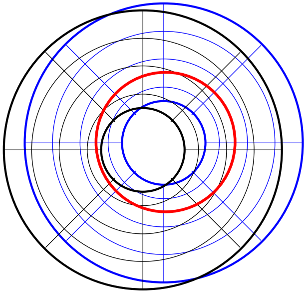

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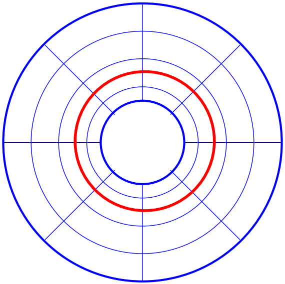

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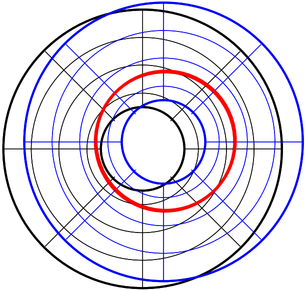

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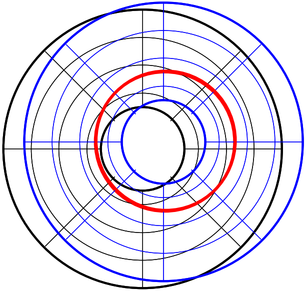

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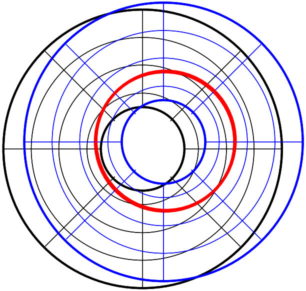

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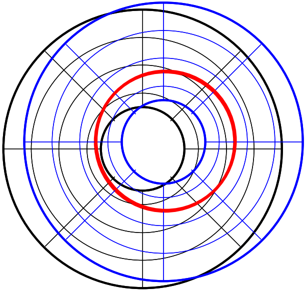

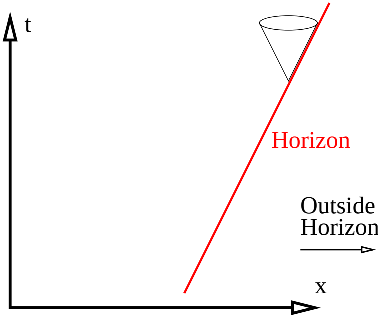

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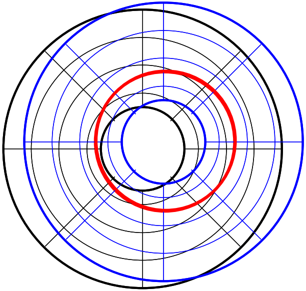

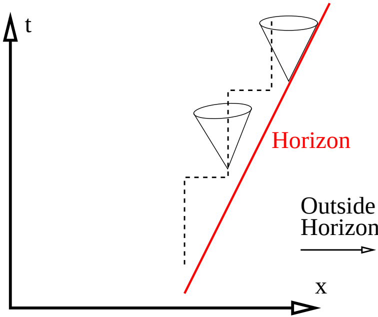

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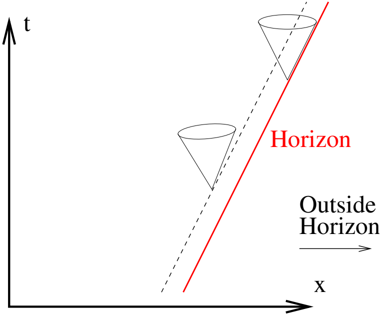
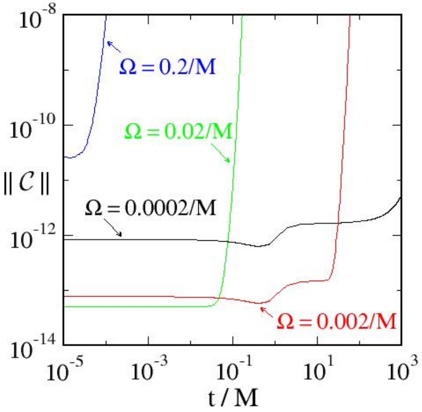
- Solution:
  Choose coordinates that smoothly track the location of the black hole.



Evolving Black Holes in Rotating Frames

- Coordinates that rotate with respect to the inertial frames at infinity are needed to track the horizons of orbiting black holes.
- Evolutions of Schwarzschild in rotating coordinates are unstable.



- Evolutions shown use a computational domain that extends to $r = 1000M$.
- Angular velocity needed to track the horizons of an equal mass binary at merger is about $\Omega \approx 0.2/M$.
- Problem caused by asymptotic behavior of metric in rotating coordinates: $\psi_{tt} \sim \rho^2\Omega^2$, $\psi_{ti} \sim \rho\Omega$, $\psi_{ij} \sim 1$.

Dual-Coordinate-Frame Evolution Method

- Single-coordinate frame method uses the one set of coordinates, $x^{\bar a} = \{\bar t, x^{\bar\imath}\}$, to define field components, $u^{\bar\alpha} = \{\psi_{\bar a\bar b}, \Pi_{\bar a\bar b}, \Phi_{\bar\imath\bar a\bar b}\}$, and the same coordinates to determine these components by solving Einstein's equation for $u^{\bar\alpha} = u^{\bar\alpha}(x^{\bar a})$:

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$$\partial_{\bar{t}} u^{\bar{\alpha}} + A^{\bar{k}\,\bar{\alpha}}{}_{\bar{\beta}} \partial_{\bar{k}} u^{\bar{\beta}} = F^{\bar{\alpha}}.$$

- Dual-coordinate frame method uses basis vectors of one coordinate system to define components of fields, and a second set of coordinates, $x^{a} = \{t, x^{i}\} = x^{a}(x^{\bar{a}})$, to represent these components as functions, $u^{\bar{\alpha}} = u^{\bar{\alpha}}(x^{a})$.

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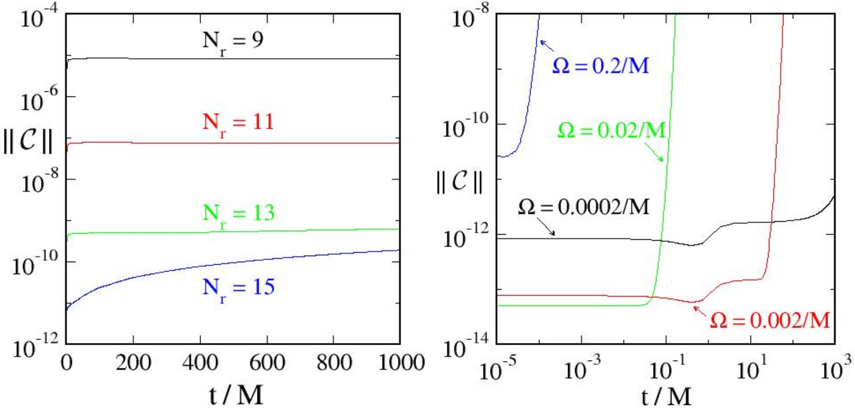
- These functions are determined by solving the transformed Einstein equation:

$$\partial_t u^{\bar\alpha} + \left[\frac{\partial x^i}{\partial \bar t}\delta^{\bar\alpha}{}_{\bar\beta} + \frac{\partial x^i}{\partial x^{\bar k}} A^{\bar k\,\bar\alpha}{}_{\bar\beta}\right]\partial_i u^{\bar\beta} = F^{\bar\alpha}.$$

Testing Dual-Coordinate-Frame Evolutions

- Single-frame evolutions of Schwarzschild in rotating coordinates are unstable, while dual-frame evolutions are stable:

Dual Frame Evolution   Single Frame Evolution



- Dual-frame evolution shown here uses a comoving frame with $\Omega = 0.2/M$ on a domain with outer radius $r = 1000M$.

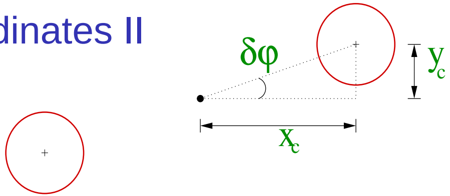
Horizon Tracking Coordinates

- Coordinates must be used that track the motions of the holes.
- For equal mass non-spinning binaries, the centers of the holes move only in the $z = 0$ orbital plane.
- The coordinate transformation from inertial coordinates, $(\bar{x}, \bar{y}, \bar{z})$, to co-moving coordinates (x, y, z),

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = e^{a(\bar{t})} \begin{pmatrix} \cos\varphi(\bar{t}) & -\sin\varphi(\bar{t}) & 0 \\ \sin\varphi(\bar{t}) & \cos\varphi(\bar{t}) & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \bar{x} \\ \bar{y} \\ \bar{z} \end{pmatrix},$$

  with $t = \bar{t}$, is general enough to keep the holes fixed in co-moving coordinates for suitably chosen functions $a(\bar{t})$ and $\varphi(\bar{t})$.
- Since the motions of the holes are not known *a priori*, the functions $a(\bar{t})$ and $\varphi(\bar{t})$ must be chosen dynamically and adaptively as the system evolves.

Horizon Tracking Coordinates II



- Measure the comoving centers of the holes: $x_c(t)$ and $y_c(t)$, or equivalently $Q^x(t) = [x_c(t) - x_c(0)]/x_c(0)$ and $Q^y(t) = y_c(t)/x_c(t)$.
- Choose the map parameters $a(t)$ and $\varphi(t)$ to keep $Q^x(t)$ and $Q^y(t)$ small.

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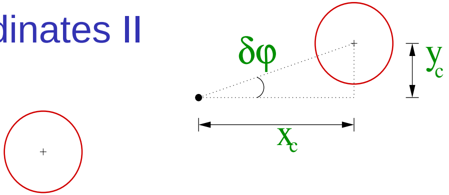

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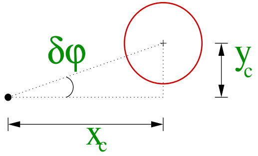
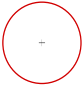
- Choose the map parameters $a(t)$ and $\varphi(t)$ to keep $Q^x(t)$ and $Q^y(t)$ small.
- Changing the map parameters by the small amounts, δa and $\delta\varphi$, results in associated small changes in δQ^x and δQ^y:

$$\delta Q^x = -\delta a, \qquad\qquad \delta Q^y = -\delta\varphi.$$

Horizon Tracking Coordinates II





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- Measure the quantities $Q^y(t)$, $dQ^y(t)/dt$, $d^2Q^y(t)/dt^2$, and set

$$\frac{d^3\varphi}{dt^3} = \lambda^3 Q^y + 3\lambda^2\frac{dQ^y}{dt} + 3\lambda\frac{d^2Q^y}{dt^2} = -\frac{d^3Q^y}{dt^3}.$$

  The solutions to this “closed-loop” equation for Q^y have the form $Q^y(t) = (At^2 + Bt + C)e^{-\lambda t}$, so Q^y always decreases as $t \to \infty$.

Horizon Tracking Coordinates III

- In practice the coordinate maps are adjusted only at a prescribed set of adjustment times $t = t_i$.
- In the time interval $t_i < t < t_{i+1}$ we set:

$$\begin{aligned}\varphi(t) &= \varphi_i + (t-t_i)\frac{d\varphi_i}{dt} + \frac{(t-t_i)^2}{2}\frac{d^2\varphi_i}{dt^2}\\ &\quad + \frac{(t-t_i)^3}{2}\left(\lambda\frac{d^2Q_i^y}{dt^2} + \lambda^2\frac{dQ_i^y}{dt} + \lambda^3\frac{Q_i^y}{3}\right),\end{aligned}$$

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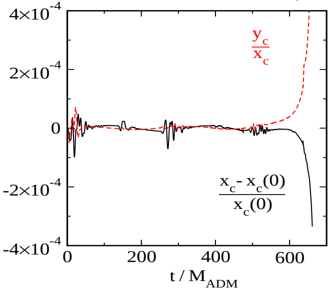
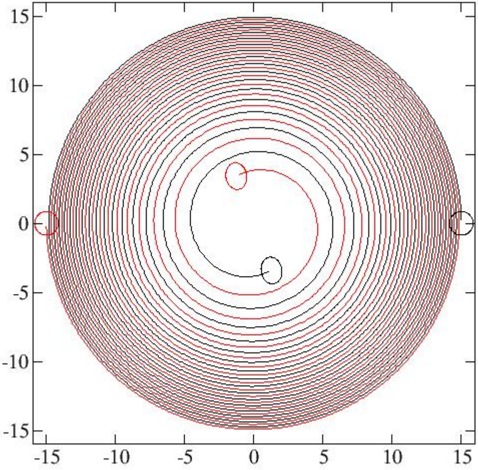
- **This works!** We are now able to evolve binary black holes using horizon tracking coordinates until just before merger.

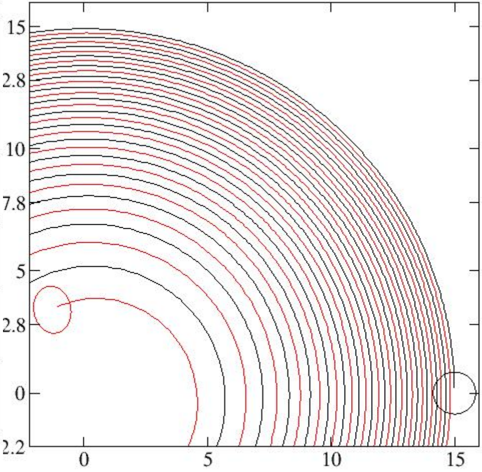


Evolving Binary Black Hole Spacetimes

- We can now evolve binary black hole spacetimes with excellent accuracy and computational efficiency through many orbits.



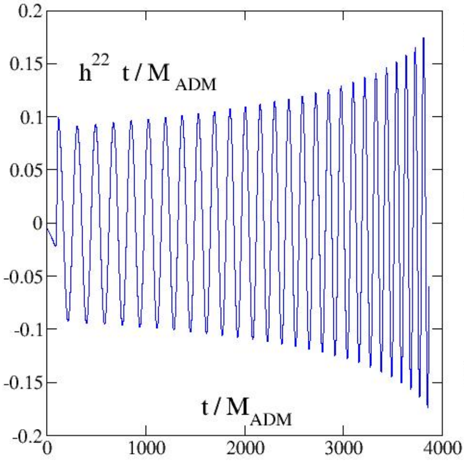
Head-on Merger Movie

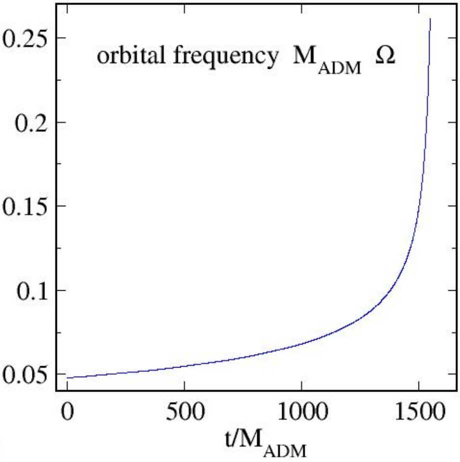


Lapse-Ψ_4 Movie

Evolving Binary Black Hole Spacetimes II

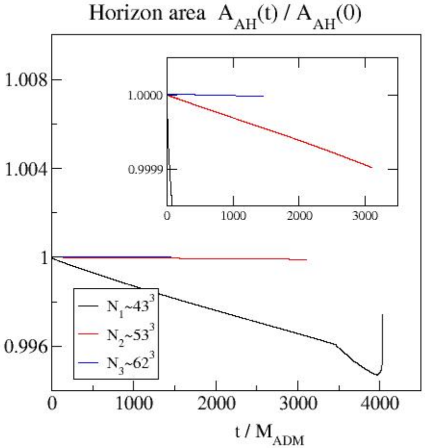
- Gravitational waveform and frequency evolution for the equal mass non-spinning BBH evolution.

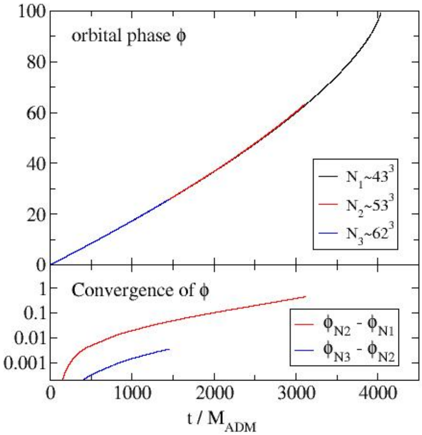




Evolving Binary Black Hole Spacetimes III

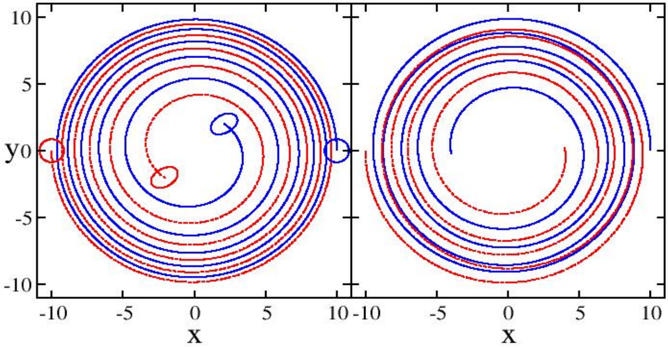
- Initial steps in convergence testing the 15 orbit evolution:





Reducing Orbital Eccentricity

- Astrophysical BBH systems are expected to have almost circular orbits by the time of merger.
- Commonly used “quasi-circular” initial data approximate the small radiation reaction driven radial velocities by setting them to zero.
- Our group (Pfeiffer and Lovelace) have constructed better BBH initial data with radial velocities chosen to reduce the orbital eccentricity.



Comparing Waveforms for Low Eccentricity Orbits

- Orbital eccentricity has little effect on gravitational waveforms.
- Overlap integrals between the low eccentricity orbit waveforms and the “quasi-circular” waveforms are greater than 0.99.
- Graphs compare low eccentricity waveforms (black) with “quasi-circular” waveforms (red).