Title: Extreme Black-Hole Binaries

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Abstract: In this talk I will show recent results obtained by the RIT group fromsimulations of highly-spinning binaries including new data that givesnear maximal spins and high-mass ratio binaries. Simulations in bothof these regimes are numerically challenging. However asastrophysical binaries are expected to be highly-spinning and havehigh mass ratios accurate simulations in these regimes are crucialfor understanding the dynamics of realistic binaries.

Extreme Black-Hole Binaries

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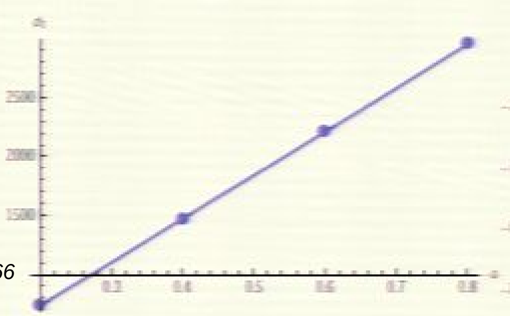
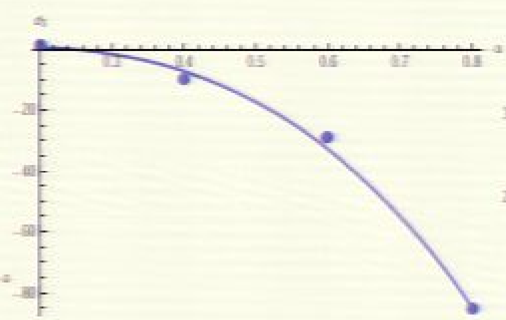
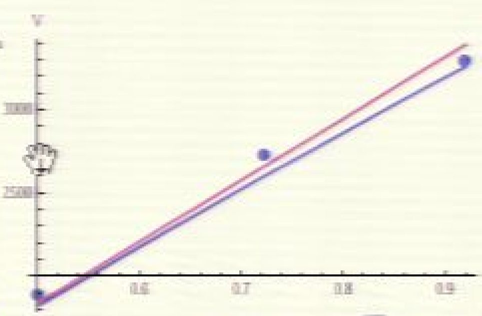
Outline

- Modeling kicks from sub-Extreme-Spin Binaries
- New data for Extreme-Spin Binaries
- Modeling waveforms from IMRBHBs
- Full NR simulations of small q BHBs
- Conclusion

Recoils from Moderate spins $\alpha \leq 0.92$

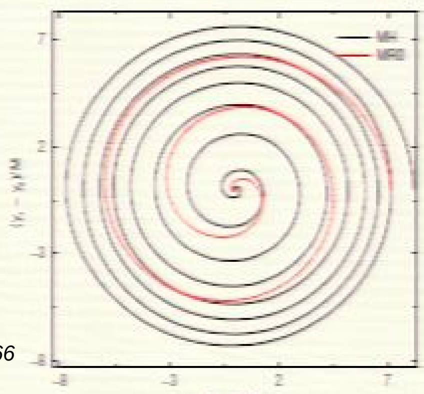
- Superkick configurations (5 angles) for $\alpha = 0.2, 0.4, 0.6, 0.8$
- Simulated last 3.75 orbits and measured recoil
- Fit recoil to $V_1 \cos(\theta - \Theta_1) + V_3 \cos(3\theta - \Theta_3)$ (removed junk) (Boyle & Kesden PRD 2008, Lousto, Campanelli, YZ CQG 27:114006 2010)
- Fit of V_1 gives $V_1 = (3670.8 \pm 4.8)\alpha + (15.8 \pm 9.5)\alpha^3$
- Fit of V_3 gives $V_3 = (10.9 \pm 7.9)\alpha - (182.3 \pm 15.5)\alpha^3$
- But V_1 and V_3 not 180° out of phase
- So max recoil $3500 < V_{\max} < 3700$
- Fit lower than previous results (lower eccentricity?)

Results from the highest spinning BHBs

Binaries with the largest spins evolved so far (from inspiral through ringdown) had $a/m = 0.92$ (Dain, Lousto, & YZ (2008))

- Evolved both Superkick and Hangup configurations
- Required very high resolution
- severe junk radiation (larger than binding energy) introduced eccentricity.
- Max spin well below goal of 0.97 - 0.99
- Still found interesting results:
  - Remnant $a/m_{\mathcal{H}} \approx 0.923$ and 9% of mass radiated for hangup configuration.
  - Max recoil configuration gives $v_{\rm recoil} = 3290$ km/s

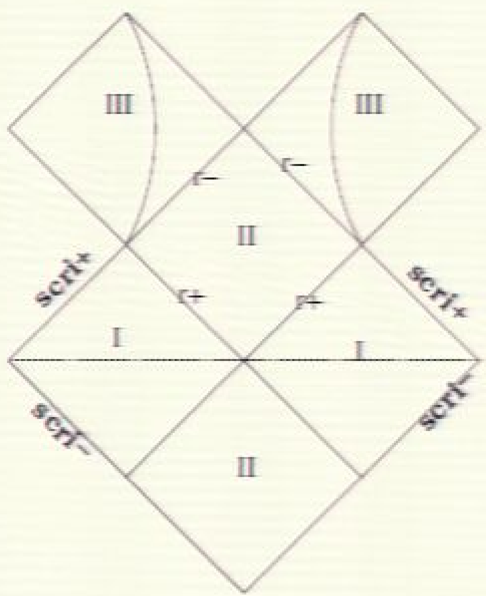


Why do we need new BHB data?

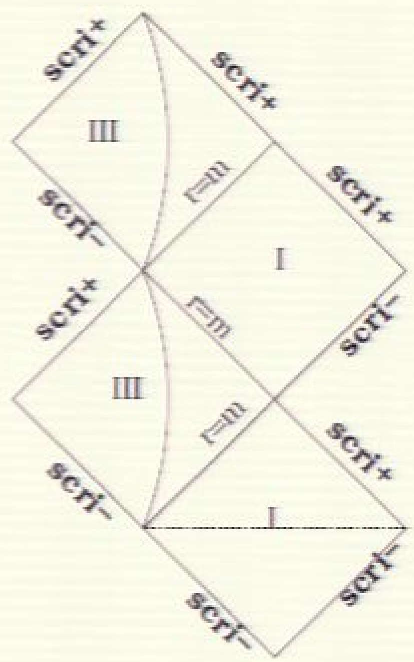
- Astrophysical binaries should have spins $a/m > 0.97$.
- Conformally flat data limited to $a/m \lesssim 0.92$.
- High spins affect recoils, AGN luminosity, radiated mass, etc.
- There are important higher-than-linear corrections to the recoil.
- This critical region of parameter space virtually unexplored.

Why are extreme black hole challenging? **There is no puncture**

- Puncture approach is based on an initial quasi-isotropic slice joining two asymptotically flat regions.
- This slice does not exist for Maximal BHs



a < m



Why are extreme black hole challenging?

- In the maximal case the slice ends at the horizons.
- So BH is completely unresolved !!!
- This is true for BY as well (Dain, Lousto, YZ (PRD78:024039,2008; Dain & Clement CQG.26:035020,2009.)
- $d^3v \to r^{-2}$ near the *'puncture'* ($\psi \to 1/\sqrt{r}$).

Why are extreme black hole challenging? **conformal flatness severely limits spin**

- The choice of $\gamma_{ij} \propto \delta_{ij}$ limits the spin to $a/m \lesssim 0.93$ (Cook & York (1990), Dain, Lousto, Takahashi (2002); Dain, Lousto, & YZ (2008))
- Changing K_{ij} from BY to Kerr doesn't help much (Dain, Lousto, Takahashi (2002)).
- Binaries with the largest spins evolved so far (from inspiral through ringdown) had $a/m = 0.92$ (Dain, Lousto, & YZ (2008))

Non-conformally Flat

- Conformally Kerr (Lovelace, Owen, Pfeiffer, Chu (2008)) data first proposed for excision data (generalized harmonic system).
  - Evolved head-on for $a/m = 0.97$
  - Evolved few orbits for $a/m = 0.93$
- A similar construction is possible in the puncture approach (see also Liu et al 2009).

Nearly Extreme Puncture Data

- Start with Kerr in isotropic coordinates
- $\gamma_{ij} = \psi^4(\delta_{ij} + \gamma_{ij}^K)$
- Superpose two attenuated conformally Kerr metrics
- $\gamma_{ij} = \psi^4(\delta_{ij} + A(r - r_a)\gamma_{ij}^K(\vec{r}_a) + A(r - r_b)\gamma_{ij}^K(\vec{r}_b))$
- $K_{ij} =????$
- For one BH with no momentum you could choose either K_{ij} from Kerr or BY.
- So try BY K_{ij} for two BHs.

The construction

- $\gamma_{ij}^{\mathrm{Kerr}} = \psi^4(\delta_{ij} + \gamma_{ij}^{\mathrm{K}})$
- $$\gamma_{ij}^{K} = \frac{1}{R^2}\begin{pmatrix} f(R,Y)x^2 & 0 & f(R,Y)xz \\ 0 & f(R,Y) & 0 \\ f(R,Y)xz & 0 & f(R,Y)z^2 \end{pmatrix}$$
- $g_{ij} = \delta_{ij} + A(R-R_1)\gamma_{ij}^{K_1}(\vec{R}-\vec{R}_1) + A(R-R_2)\gamma_{ij}^{K_2}(\vec{R}-\vec{R}_2)$
- $k^{ij} = (\sum K_0^{ij}) + \nabla^i\phi^j + \nabla^j\phi^i - 2/3\bar{\gamma}^{ij}\nabla_c\phi^c$
- $$K_0^{ij} = \frac{3}{2R^2}\left(P^i n^j + P^j n^i - (g^{ij} - n^i n^j)P^c n_c\right) + \frac{3}{R^3}\left(\epsilon^{icd} S_c n_d n^j + \epsilon^{jcd} S_c n_d n^i\right)$$

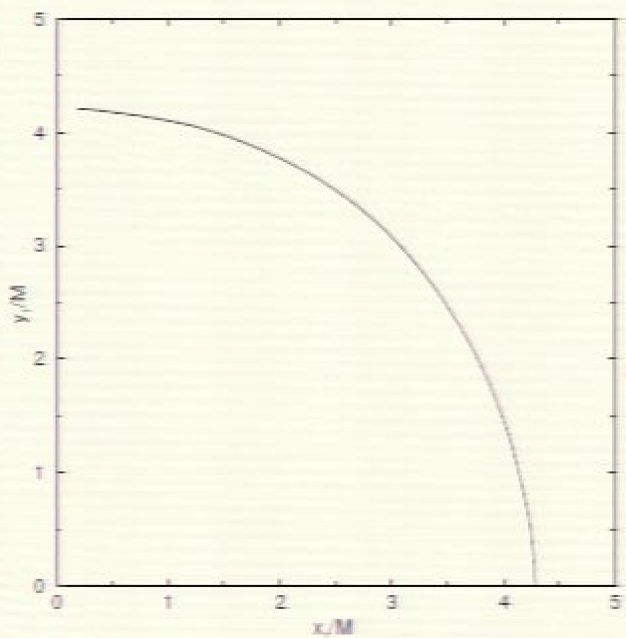
The construction: part 2

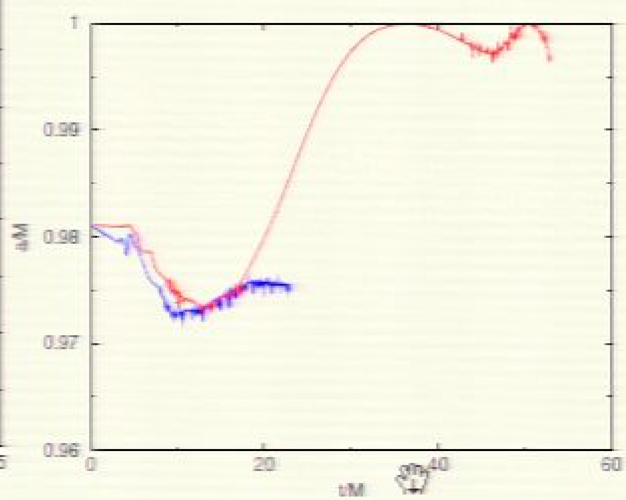
Solve the elliptical equations:

- $$\nabla_i \nabla^i \phi^j + \nabla_i \nabla^j \phi^i - \frac{2}{3} \nabla^j \nabla_c \phi^c = - \sum_{\text{puncts}} \nabla_i K_0^{ij}.$$
- $$g^{ij} \nabla_i \nabla_j \psi + K^{ij} K_{ij} \frac{1}{8\psi^7} - \frac{1}{8} R \psi = 0$$

Summary of Preliminary Results

- Evolved elliptical binaries with spins in-plane and out of plane.
- Obtained very high spins (0.97 and larger)
- Required high resolution due to small AH size.





Extreme-Mass-Ratio Binaries

- SMBH have masses in the range $10^5 \lesssim M \lesssim 10^{10}$
- SMBHBs should have mass ratios $10^{-5} \lesssim q \lesssim 1$ ($1/10 \leq q \leq 1$ most likely)
- SMBH/BH binaries will have mass ration $10^{-9} \lesssim q \lesssim 10^{-2}$
- In general SMBH seem to be highly spinning.
- So we need accurate models for the waveform and dynamics from EMR mergers.
- These simulations are very challenging numerically.
- Low q limit first explored in Baker et al. PRD 2008 ($q = 1/6$), Gonzalez et al PRD 2009 ($q = 1/10$), Lousto and YZ PRD 2009 ($q = 1/8$ spinning).
- Small q gauge condition: Mueller and Bruegmann CGQ 2010

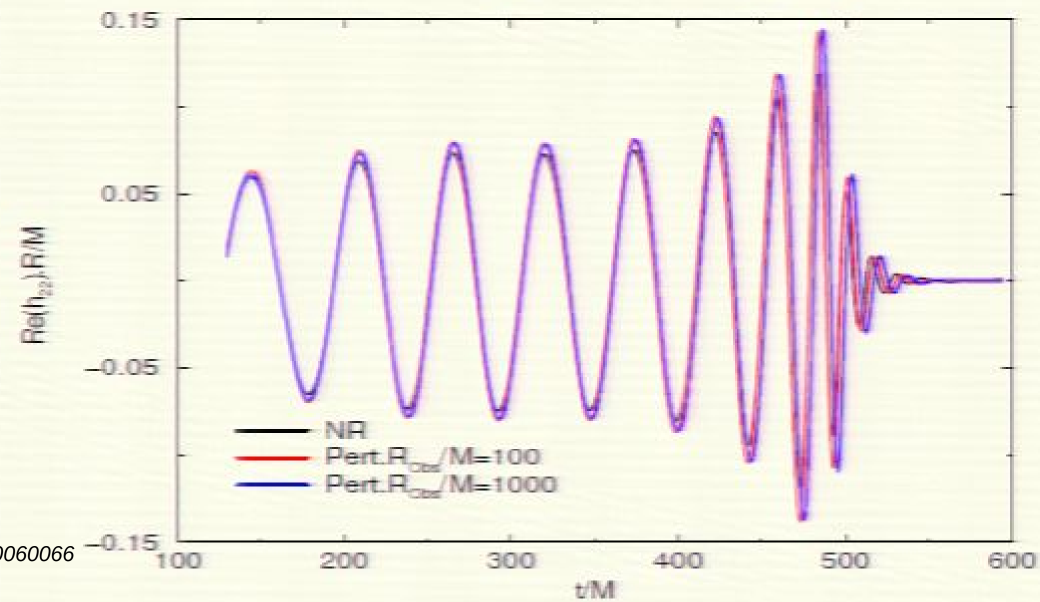
Modeling EMR Merger waveforms

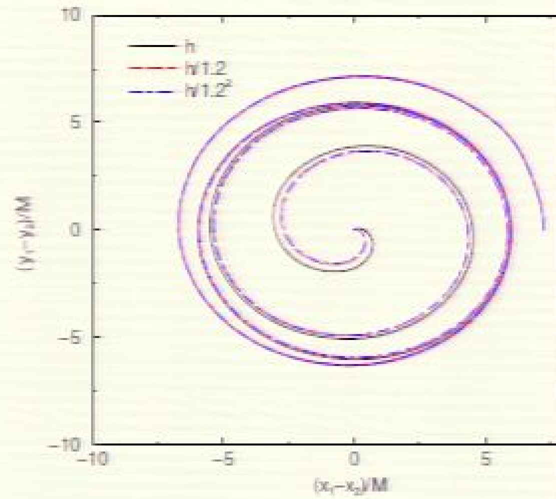
- Model trajectories for BHB inspirals with small, but numerically feasible mass ratios.
- Extrapolate trajectory to smaller q
- Model the waveform, perturbatively, as a function of trajectory (and q).

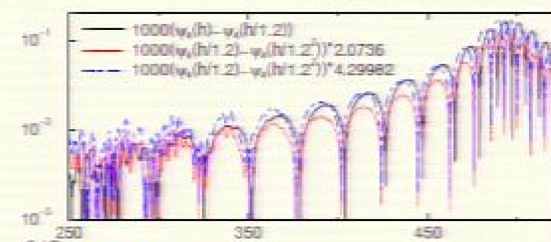
Testing the procedure [Lousto, Nakano, YZ, Campanelli PRL 2010]

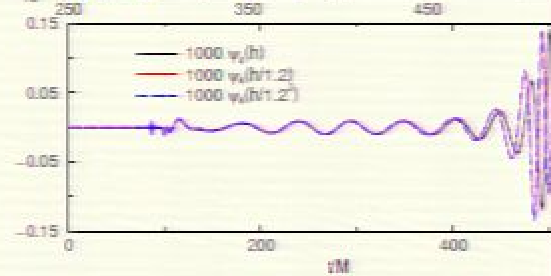
- Evolved a $q = 1/10$ eccentric binary for the last 3.5 orbits.
- Obtained convergent tracks and waveforms.
- Treat trajectory as particle path for a perturbative calculation.
- Only need the trajectory outside the horizon (don't need the full NR simulation).
- Obtain strain and compare to NR

- Tracks and Waveform Convergent
- 3.5 PN prediction gives high e orbit
- At $q = 1/10$ second-order important.
- First-order predicts too large amplitude.
- Spin of remnant non-trivial, but can be modeled perturbatively (H. Nakano).
- Expect the results to improve as $q \to 0$ but this is very challenging numerically.







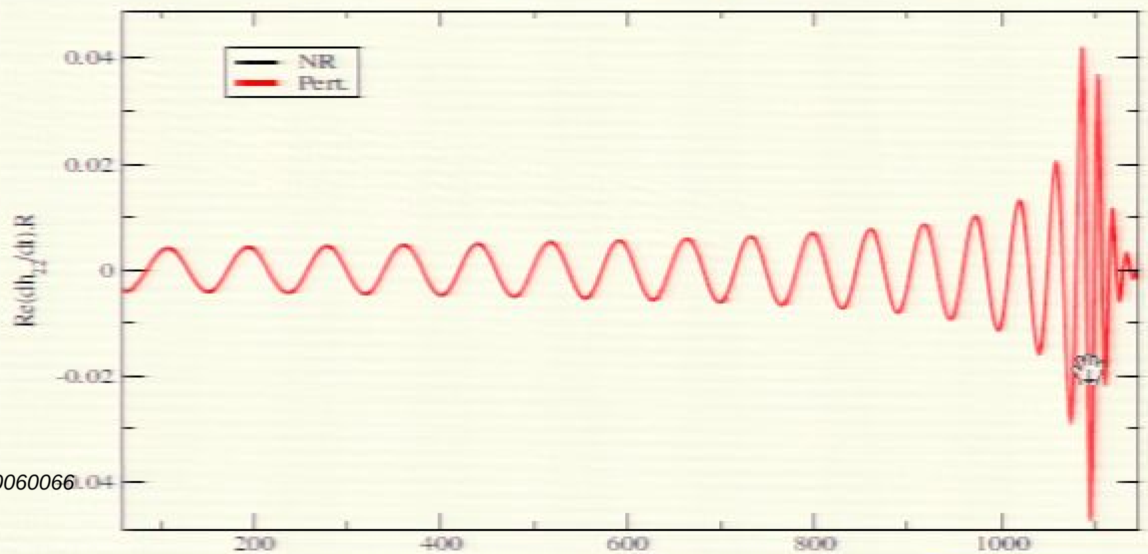


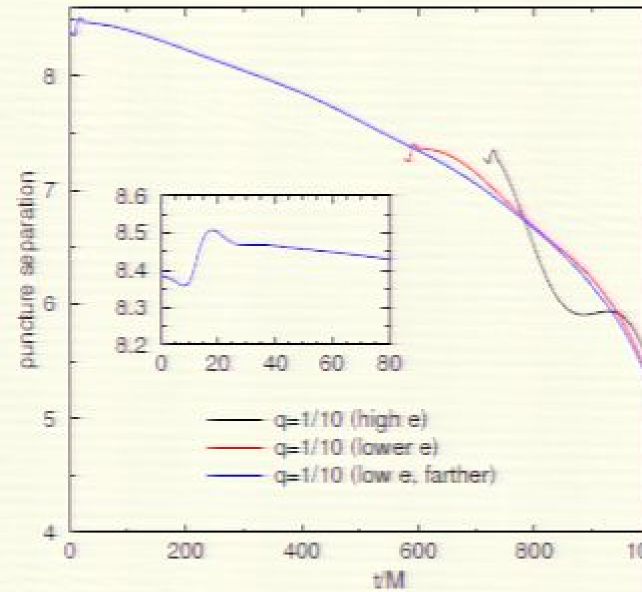
Additional tests and explorations

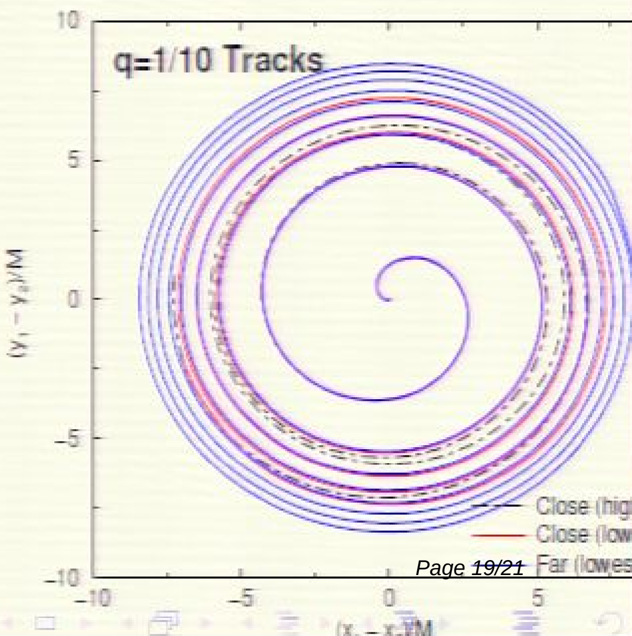
- Reduced eccentricity via iterative procedure (Pfeiffer et al. CQG 24 (2007))
- Increases separation (8 orbits)
- Decrease q
- Added remnant spin correction (perturbatively)

Lower eccentricity q=1/10 Runs

- BY ID leads to a "puffing out" of the orbit... the given ID parameters don't correspond to the actual binary momenta and positions.
- Can generate low eccentricity BHBs, but it's expensive.
- Get good agreement between NR and Pert waveforms (see H.N. talk)

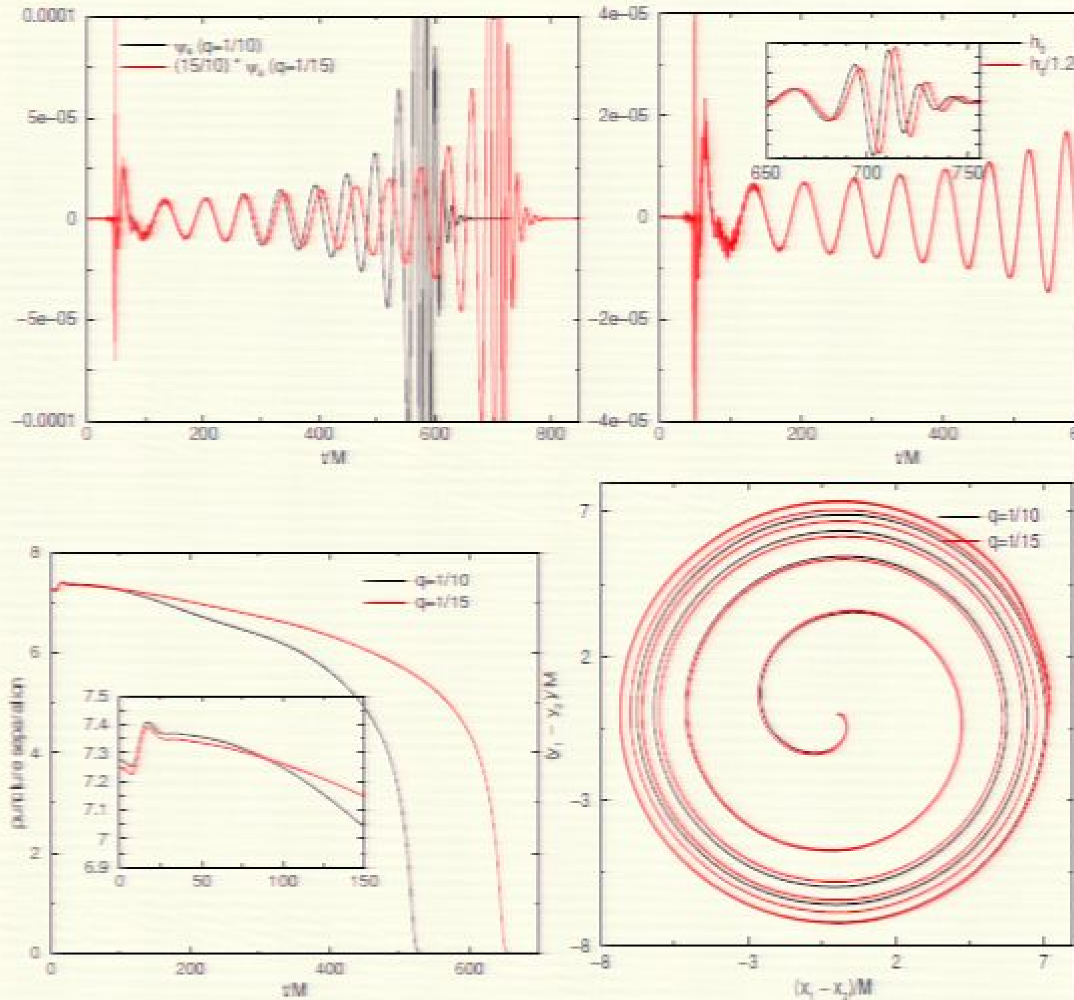






Compare with smaller q Runs

- Waveform amplitude scales with q and lower q gives more orbits.
- get a 'universal' plunge but last few orbits differ as $q \to 0$
- Require iterative procedure to get low eccentricity.
- Initial 'Jump' in the orbit roughly independent of q as $q \to 0$.



Consistent results for $q = 1/15$, $E_{rad} = .0022$, $\Delta M = 0.0023$, $J_{rad} = 0.023$, $\Delta J = 0.0229$, $V_{kick} = 33.5$, $Vp = 34.1$

Summary

- Need new data for small-mass-ratio and extreme-spin BHBs.
- Can generate low eccentricity BHBs, but it's expensive.
- The small *q* and high-spin regimes are challenging.
- They require significant work to get the correct parameters and to evolve accurately.
- Simulations are very expensive (easily 100's of thousands of SUs)
- Using NR / perturbative techniques increases efficiency
  - Can *extract* perturbatively, so don't need high res to large distances
  - Don't need to complete the full simulation to get the entire waveform
  - May be able to model very low *q* binaries impossible via NR.
- This is a rich area for further developments (more efficient AMR, new ID, better gauges, spinning background, etc.).