Numerical Simulations of Compact Binaries

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- Cornell-Caltech Spectral Einstein Code (SpEC)
- Binary Black Hole Simulations
- Neutron Star - Black Hole Simulations

Binary Black Holes

- Collaborators:
  - Cornell: Mike Boyle, Lawrence Kidder, Geoffrey Lovelace, Abdul Mroué, Rob Owen, Saul Teukolsky
  - Caltech: Luisa Buchman, Tony Chu, Mike Cohen, Lee Linblom, Keith Matthews, Mark Scheel, Bela Szilagyi, Kip Thorne
  - CITA: Harald Pfeiffer
- Motivation:
  - Gravitational waves
  - Properties of remnant BH
  - Study strong-field region
- Numerical approaches:
  - Generalized Harmonic with Excision

    [Pretorius; PRL 95, 121101 (2005)]
  - Moving puncture

    [Campanelli, Lousto, Marronetti, Zlochower; PRL 96, 111101 (2006)]

    [Baker, Centrella, Choi, Koppitz, van Meter; PRL 96, 111102 (2006)]

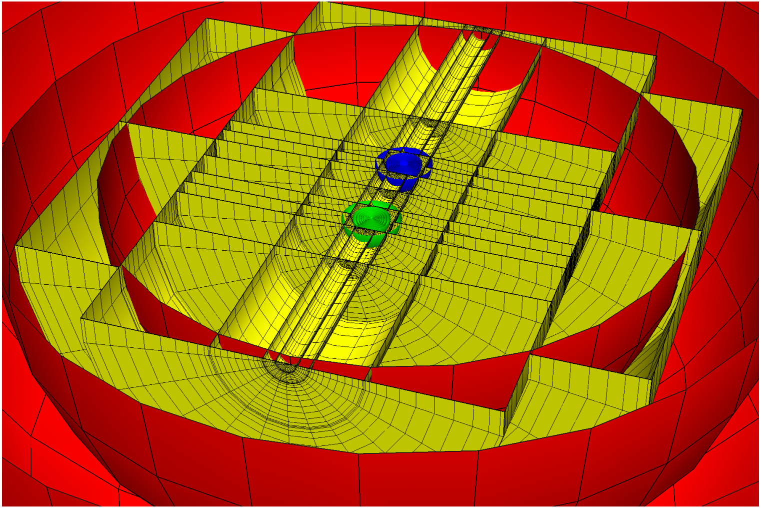
Spectral Einstein Code (SpEC)

[Kidder, Pfeiffer, Scheel]

- Generalized harmonic formulation of Einstein's equations
  [Friedrich; CMP 100, 525 (1985)]
  - 10 coupled first-order wave equations (50 variables)
    [Lindblom, Scheel, Kidder, Owen, Rinne; CQG 23, S447 (2006)]
  - Constraint damping
    [Gundlach, Calabrese, Hinder, Martin-Garcia; CQG 22, 3767 (2005)]
- Dual frame method with dynamic tracking of the black holes
  [Scheel, Pfeiffer, Lindblom, Kidder, Rinne, Teukolsky; PRD 74, 104006 (2006)]
  - Time-dependent rotation and scaling
  - Use control theory to adjust mapping to track holes
- Boundary conditions
  - Excision boundary is pure outflow (no BC needed)
  - Constraint preserving [Lindblom et al (2006)]
  - No incoming physical radiation
  - Minimize reflections of gauge modes
    [Rinne, Lindblom, Scheel; CQG 24, 4053 (2007)]

Multidomain pseudospectral method

- Exponential convergence for smooth solutions
- Highly efficient for high accuracy

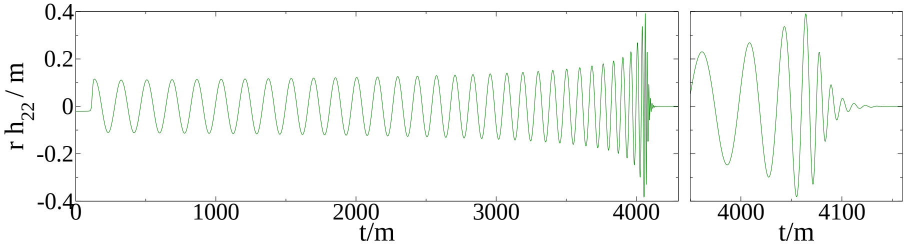


BH-BH equal mass, non-spinning simulation

- 16.5 orbit inspiral-meger-ringdown

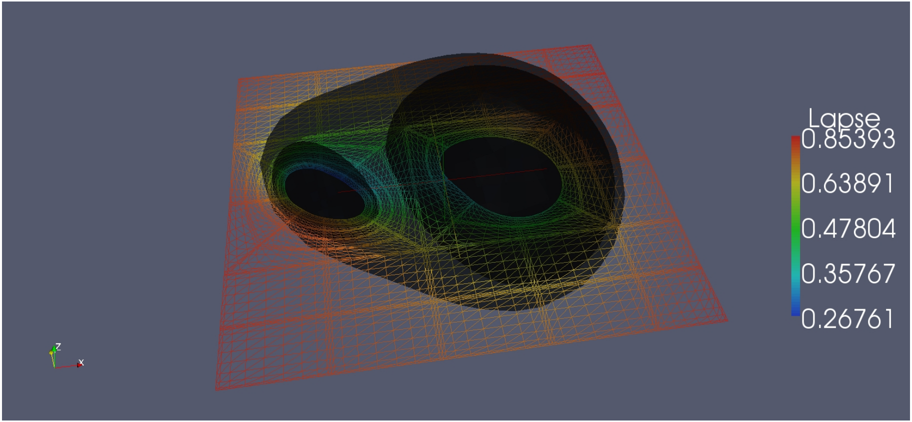
  [Boyle, Brown, Kidder, Mroué, Pfeiffer, Scheel, Cook, Teukolsky; PRD 76, 124038 (2007)]

  [Scheel, Boyle, Chu, Kidder, Matthews, Pfeiffer; PRD 79, 024003 (2009)]
- Non-spinning $S_i/m_i^2 < 10^{-5}$
- Low eccentricity $e \approx 6 \times 10^{-5}$
- Numerical error: $\delta\phi \approx 0.02$ radians; $\delta A/A \approx 0.003$
- $M_f/M_i = 0.95162(2)$
- $S_f/M_f^2 = 0.68646(4)$



BH-BH Getting from inspiral to ringdown

- Accurate, efficient inspirals up to an orbit before merger
- Choosing gauge source functions key to get common horizon
  [Lindblom, Szilagyi; arXiv:0904.4873 (2009)]
- Change grid decomposition, follow ringdown



BH-BH Current status

M_2/M_1	$\vec{S}_1/M_1^2$	$\vec{S}_2/M_2^2$	$N_{\rm orbits}$	Status	Reference
1	0	0	16	Ringdown	[Scheel et al (2009)]
2	0	0	15	Ringdown	[Buchman et al (in prep)]
3	0	0	15	Inspiral	[Buchman et al (in prep)]
4	0	0	15	Inspiral	[Buchman et al (in prep)]
6	0	0	8	Inspiral	[Buchman et al (in prep)]
1	0	$0.5\hat{z}$	4.5	Inspiral	[unpublished]
3	0	$0.5\hat{z}$	6	Inspiral	[unpublished]
1	$-0.4\hat{z}$	$-0.4\hat{z}$	11	Ringdown	[Chu et al (in prep)]
1	$0.4\hat{z}$	$0.4\hat{z}$	15	Merged	[Chu et al (in prep)]
1	$-0.5\hat{x}$	$-0.5\hat{z}$	6.5	Inspiral	[unpublished]
2	$\frac{0.2}{\sqrt{2}}(\hat{z}-\hat{x})$	$\frac{-0.4}{\sqrt{2}}(\hat{z}+\hat{y})$	1.5	Ringdown	[unpublished]
2	$\frac{0.2}{\sqrt{2}}(\hat{z}-\hat{x})$	$\frac{-0.4}{\sqrt{2}}(\hat{z}+\hat{y})$	8.25	Ringdown	[unpublished]

Inspiral -> Merger -> Ringdown

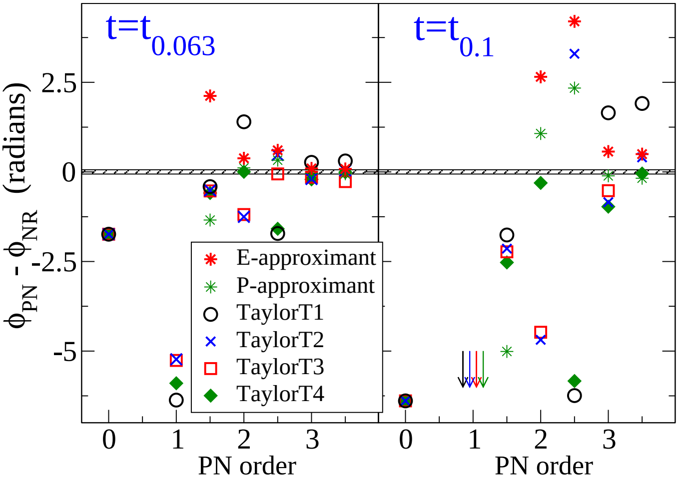
- First case: 1.5 years (not robust)
- Latest case: worked within days

NR vs PN: Waveforms

Matched at $m\omega \sim 0.04$ (about 24 cycles before merger)

$m\omega = 0.063(0.1)$ is about 10(5) cycles before merger

[Boyle, Buonanno, Kidder, Mroué, Pan, Pfeiffer, Scheel; PRD 78, 104020 (2008)]

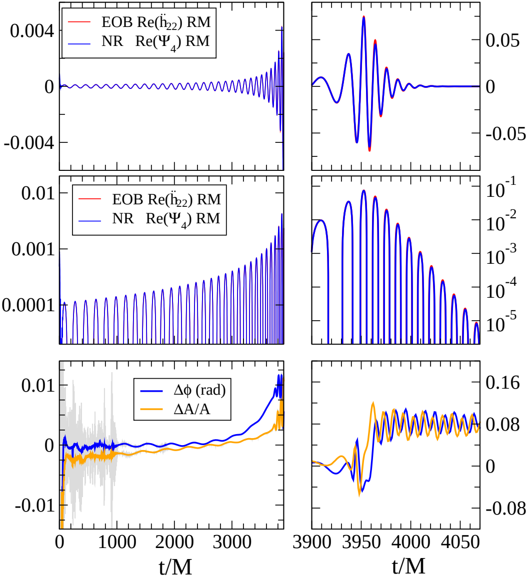


BH-BH calibrating EOB with NR

- [Buonanno, Pan, Pfeiffer, Scheel, Buchman, Kidder;

  PRD 79, 124028 (2009)]
- Numerical error:
  $\delta\phi \approx 0.02$ radians
  $\delta A/A \approx 0.003$
- Similar results using same NR data found by [Damour, Nagar;

  PRD 79, 081503 (2009)]



BH-BH Future work

- Comparison among codes
  [Hannam et al;PRD 79, 084025 (2009)]
  - Looked at (2,2) mode from equal mass, non-spinning BBH
  - Compared results from 5 codes
  - Results agreed within numerical accuracies of codes
- Improve robustness of gauge conditions, domain decomposition, constraint damping parameters
- Generate as many long simulations as reasonable to calibrate analytic waveforms and test data analysis pipelines
- Higher spins and more extreme mass ratios
- Improved extraction of gravitational waves

BH-NS binaries

- Collaborators:
  - Cornell: Matthew Duez, Francois Foucart, Lawrence Kidder, Saul Teukolsky
  - Caltech: Christian Ott
- Motivation:
  - Gravitational waves
  - Formation of post-merger disk (short GRB engine?)
- First crude efforts
  - [Shibata, Uryu; PRD 74, 121503(R) (2006)]
  - [Shibata, Uryu; CQG 24, S125 (2007)]
  - [Shibata, Taniguchi; PRD 77, 084015 (2008)]
  - [Etienne, Faber, Liu, Shapiro, Taniguchi, Baumgarte; PRD 77, 084002 (2008)]
  - [Duez, Foucart, Kidder, Pfeiffer, Scheel, Teukolsky; PRD 78, 104015 (2008)]

Recent results

[Shibata, Kyutoku, Yamamoto, Taniguchi; PRD 79, 044030 (2009)]

[Etienne, Liu, Shapiro, Baumgarte; PRD 79, 044024 (2009)]

- Effects of mass ratio $q = M_{BH}/M_{NS}$
  - For higher q, expect
    - disruption closer to plunge
    - smaller disk, more BBH-like GWs
  - Studied for $1 \le q \le 5$
- Effects of BH spin $s = S_{BH}/M_{BH}^2$
  - For higher aligned s, expect
    - smaller ISCO leads to larger disk
    - longer inspiral
  - Studied by [Etienne et al (2009)] for s = -0.5, 0, 0.75 (aligned)
  - High s led to big disk
- Effects of compactness $C = M_{NS}/R_{NS}$
  - Studied by [Shibata et al (2009)] for $0.145 \le C \le 0.178$
  - More compact star leads to smaller disk, stronger GW signal

BH-NS numerical methods

[Duez, Foucart, Kidder, Pfeiffer, Scheel, Teukolsky; PRD 78, 104015 (2008)]

[Duez, Foucart, Kidder, Ott, Teukolsky; unpublished]

- GR handled as with BBH
- Use shock-capturing finite volume for hydro
- 2 grids, interpolation, automated remapping
- fluid grid limited to where the fluid is

BH-NS initial data

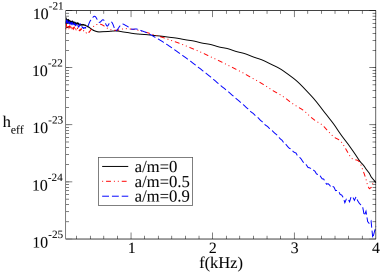
[Duez, Foucart, Kidder, Ott, Teukolsky; unpublished]

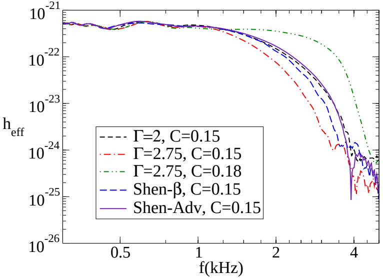
- $M_{BH} = 3M_{NS}$
- Initial separation $7.5M$ (at least two orbits of inspiral)
- Eccentricity reduced
- Vary spin
  - $\Gamma = 2$ polytrope, $C = M_{NS}/R_{NS} = 0.15$
  - Vary $s = S_{BH}/M_{BH}^2 = 0, 0.5, 0.9$
- Vary Equation of State
  - $s = 0.5$
    1. $\Gamma = 2$, $C = 0.15$
    2. $\Gamma = 2.75$, $C = 0.15, 0.18$
    3. Shen EoS, $C = 0.15$; advect Y_e or impose β-equilibrium

BH-NS gravitational waves

[Duez, Foucart, Kidder, Ott, Teukolsky; unpublished]

- Spin
  - orbital hangup
  - smear radius

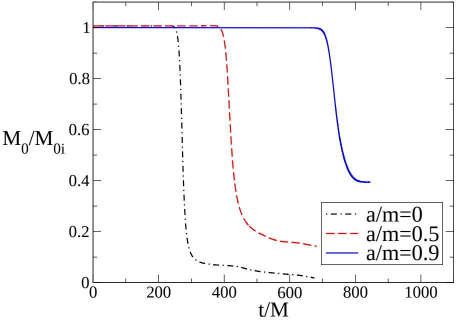


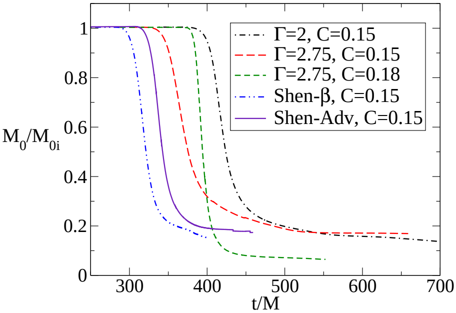


- EoS
  - large compaction effect
  - smaller Γ effect

BH-NS post-merger disks

[Duez, Foucart, Kidder, Ott, Teukolsky; unpublished]





BH-NS Future Work

- Improved resolution and fluid grid
- Try out multipatch FD for GR to reduce interpolation cost
  [Pazos, Tiglio, Duez, Kidder, Teukolsky; PRD 80, 024027 (2009)]
- Generic spins, masses, EoS
- MHD (MRI turbulence), ν-transport, nuclear reactions
- Longer inspirals, follow disk longer

Conclusions

- Binary black holes:
  - Can produce long accurate waveforms sufficient for building analytic templates and testing data analysis pipelines
- Black hole - neutron star binaries
  - Preliminary results suggest large disks can be formed (also seen by [Etienne, Liu, Shapiro, Baumgarte; PRD 79, 044024 (2009)])
  - Starting to explore effect of NS equation of state