

# The dawn of a golden age - report on recent results in numerical relativity

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# Binary neutron stars

- Neutron stars have been studied for years
- Binary systems add extra complication
- New progress exists with helical symmetry; hydro also included at Milwaukee
- Represents a quasi-equilibrium configuration
- Steady progress at Boca Raton/Brownsville
- Expect many results over next few years

# Initial Data for Binaries

- Quasi equilibrium parameters already exist
- Not necessarily astrophysically accurate
- Several works in progress to use post-Newtonian as seed for better astrophysics(?)
- Progress in Boca Raton/PSU, Brownsville/UF
- Other approaches in Caltech & Wake Forest
- This problem is a mission critical area
- Final validation will come through evolution

# Binary BH evolution

- Incredible progress in last few years
- Consistently evolve without blow-up
- Limitations now hardware, not software
- Successes in Penn State, Alberta/Caltech, Brownsville, Goddard, and Baton Rouge...
- Many others groups hot on their trail
- Convergence for up to 4 orbits without spin
- May soon know Post-Newtonian limits

## About orbiting binary black holes

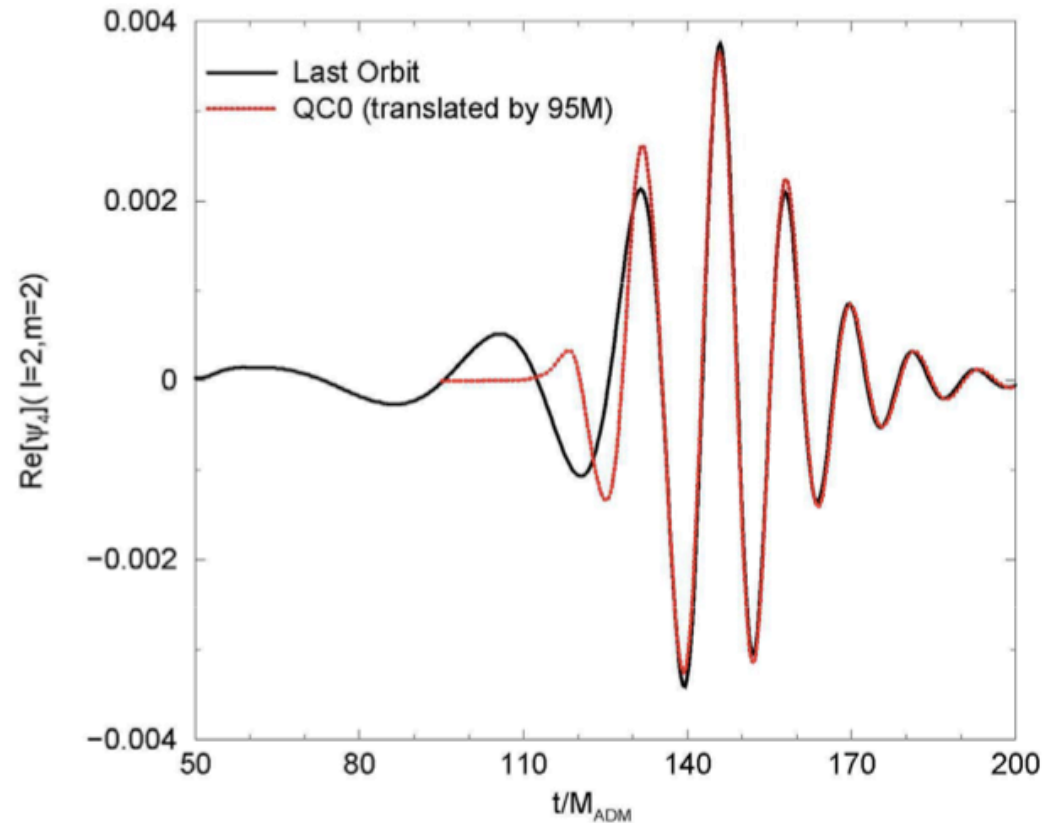
- B.Bruegmann et al PRL 92, 211101 (2004), [arXiv:gr-qc/0312112].
  - Puncture initial data (BTJ)
  - FMR
  - Corotating gauge
  - No common apparent horizon (CAH) observed before 1<sup>st</sup> orbit
  - No waveforms
- Diener et al (2006), [arXiv:gr-qc/0512108].
  - BTJ initial data
  - FMR, but requires high resolution  $\sim M/80$  to attain good accuracy
  - Several corotating gauges
  - CAH form after  $\sim 125M$
  - Last orbit period  $\sim 59M$
  - No waveforms
- Pretorius, PRL 95, 121101 (2005), [arXiv:gr-qc/0507014].
  - Harmonic approach
  - AMR
  - Physical outer boundaries
  - Waveform extraction
  - Elliptical orbit
  - Difficult for other groups to implement

## About orbiting binary black holes

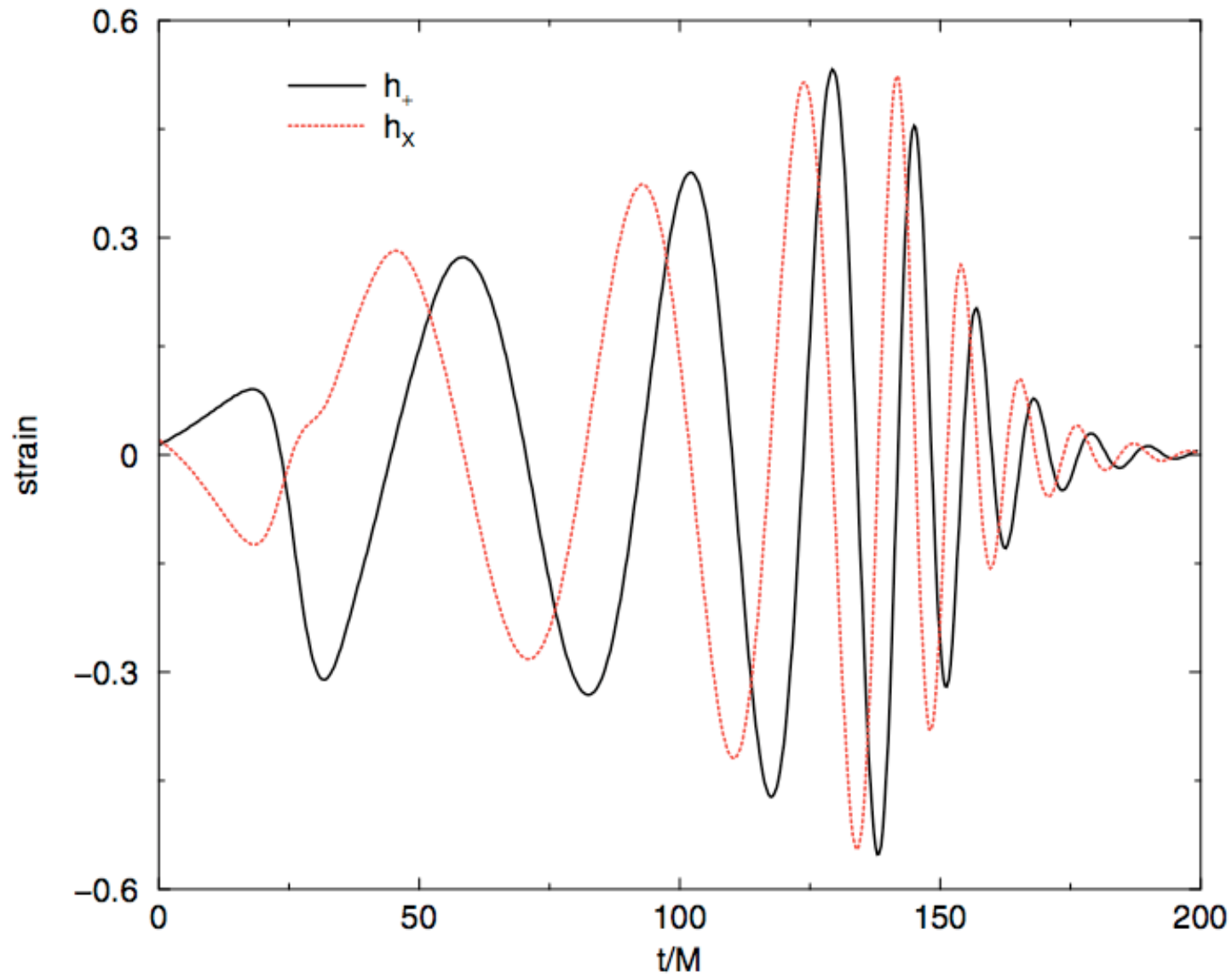
- M.Campanelli, C.O.Lousto, P.Marronetti & Y.Zlochower, PRL [arXiv:gr-qc/0511048]
- M.Campanelli, C.Lousto & Y.Zlochower, RP PRD (2006) [arXiv:gr-qc/0601091].
  - Puncture (BTJ) initial data
  - Moving punctures (new gauge, new way to handle the BSSN conformal factor)
  - 4<sup>th</sup> order FD
  - Fisheye
  - Waveforms and horizon dynamics
  - Plunge dynamics agrees with Lazarus results
- J. Baker, J.Centrella, D.Choi, M.Koppitz & J. van Meter, [arXiv:gr-qc/0511103].
- J.Baker, J.Centrella, D.Choi, M.Koppitz & J.van Meter, *Binary black hole merger dynamics and waveforms*, (2006) [arXiv:gr-qc/0602026].
  - Puncture initial data
  - Moving punctures (new gauge, discretize the BSSN conformal factor)
  - 2nd order FD
  - AMR
  - Waveforms and horizon dynamics
  - Plunge dynamics agrees with Lazarus results

# Remarkable consistency

- Ringdown waveform independent of start
- Inspiral merges to ringdown smoothly
- Similar results from different codes
- Consistent final state for energy and angular momentum



$\psi_4$  from the 'last orbit' and QC0 ( $\Delta t/M = 95$ )



Merge transition gradual



# What to look out for

- Spins, unaligned, unequal masses, hang-up
- Code flexibility: AMR, energy extraction, higher order - needs depend on group
- Demanding command of resources
- Exploration of Post-Newtonian limits
- Strong pressure for better initial data sets
- A veritable golden age is truly dawning