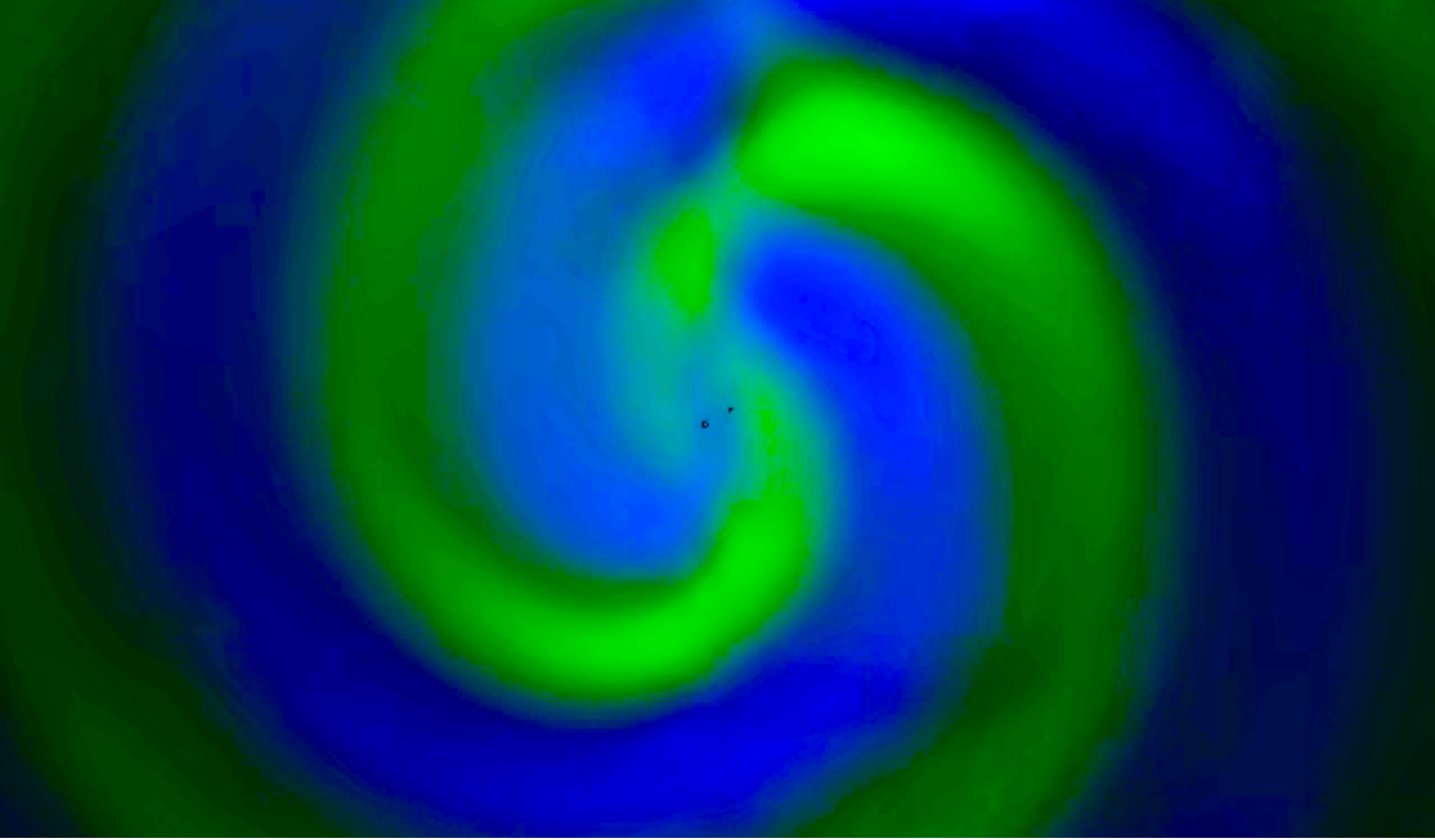


Numerical Relativity Examples

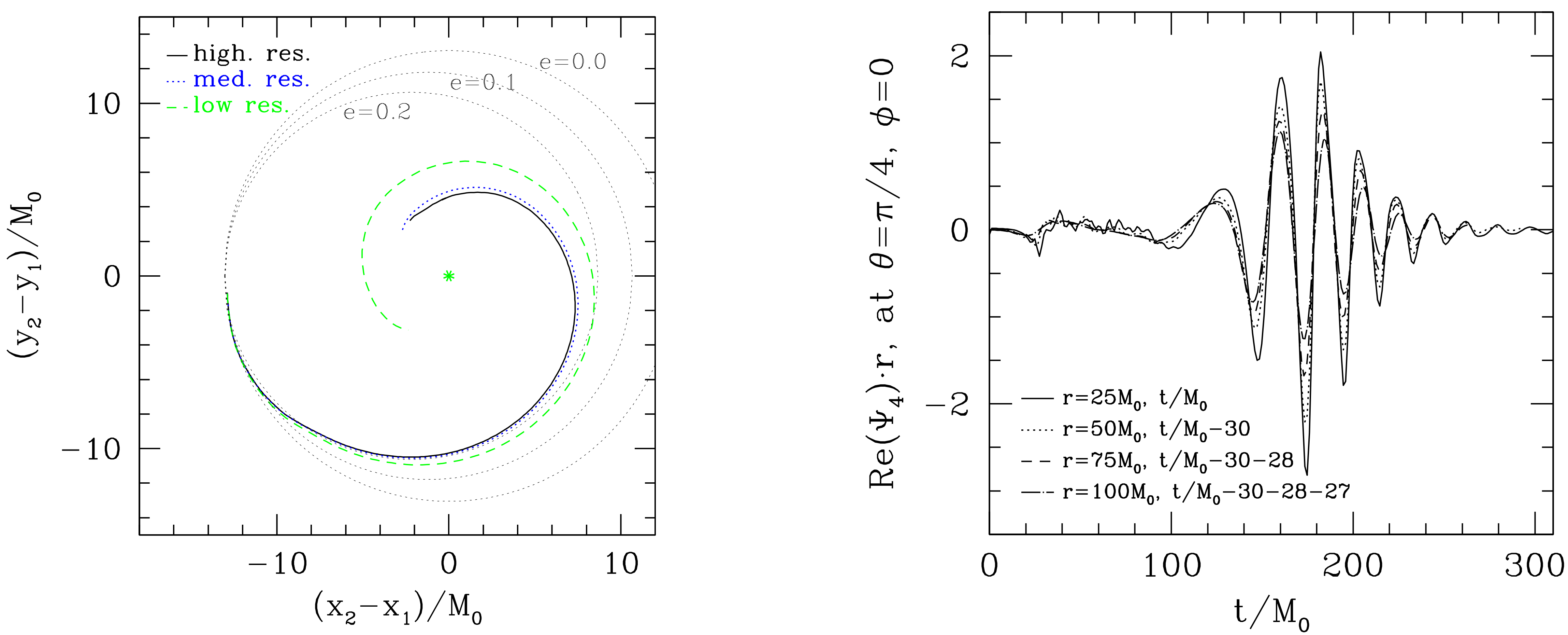
Ian Hinder, May 2017

Selected milestones in Numerical Relativity - Pre-revolutionary

1959	Arnowitt, Deser and Misner - ADM formalism: **initial value problem** for GR
1964	Hahn and Lindquist: **first numerical solution** to the Einstein equations: attraction between two wormholes in axisymmetry, 51x51 grid points
1980s	Piran, Stark - **gravitational waves** in axisymmetry from formation of axisymmetric BH
1980s	Choptuik - **Critical collapse** with adaptive mesh refinement
1990s	Binary Black Hole Grand Challenge - **Head-on BBH collision**
to 2005	Development of **formulations**, **coordinate conditions**, **excision** techniques, wave extraction formalisms.
	Finite simulation lifetime, solutions unstable, much frustration

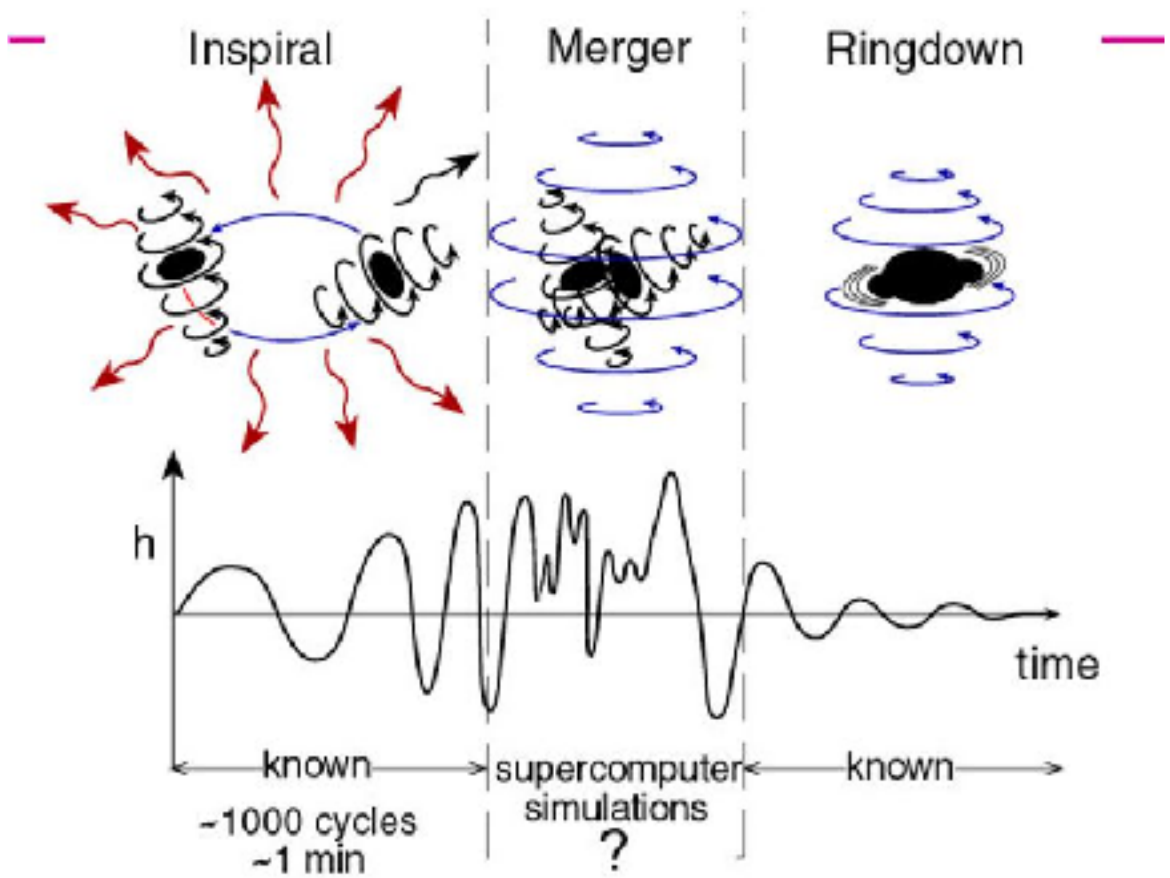
Milestones of Numerical Relativity - The revolution begins

2005 **Pretorius** is the first to successfully evolve **more than one orbit of a BBH** through **merger and ringdown** and compute the **gravitational waveform**

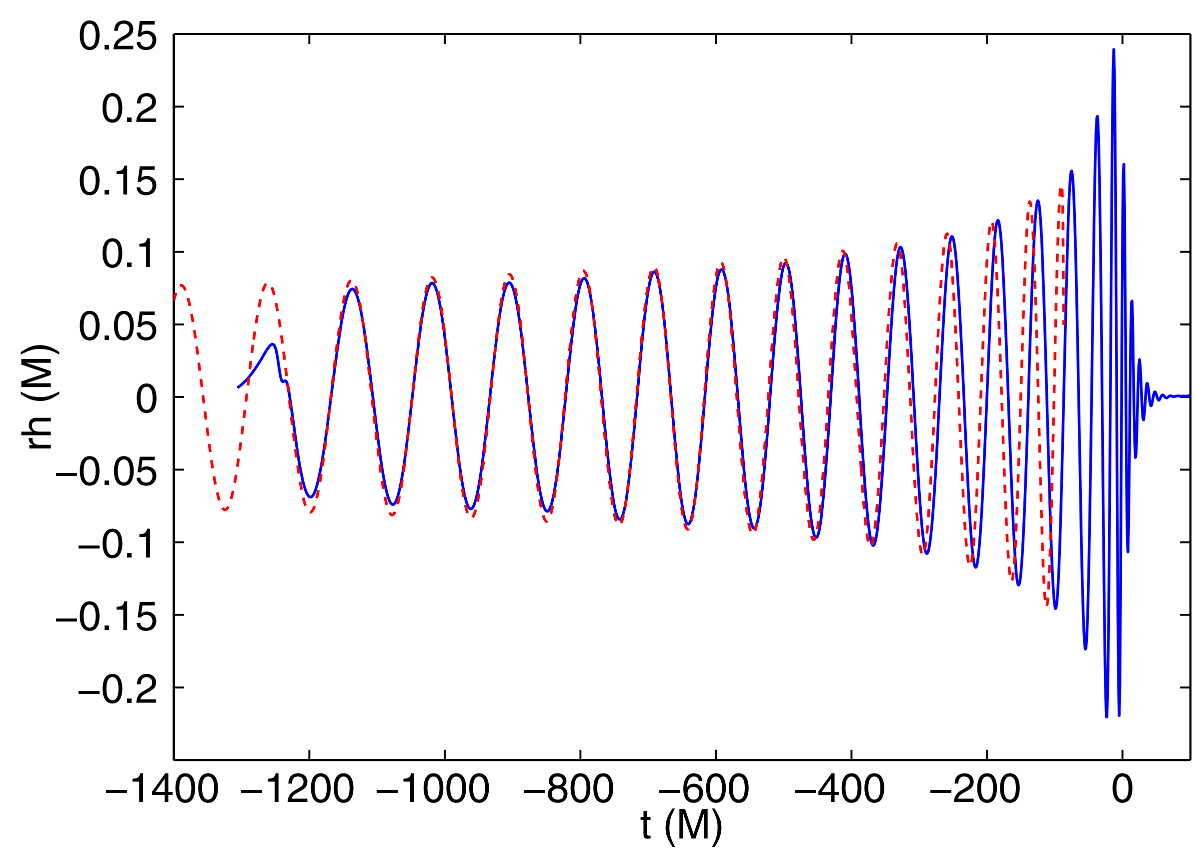


What does a BBH waveform look like?

- Before 2005: Kip Thorne's sketch



- After 2005: Numerical Relativity (e.g. Baker et al. 2007)



Selected milestones in Numerical Relativity - The Golden Age

2005 Pretorius, long-term stable method for orbit using **excision**, **finite difference** methods and **adaptive mesh refinement**, **generalised harmonic formulation**

2005 Goddard and Brownsville groups: **Moving puncture** method (no excision): **finite differences**, **BSSN formulation**

2007 Campanelli et al., Gonzalez et al. - Unexpectedly high "**super-kick**" of merging BHs for certain **spin** orientations

2011 Lovelace, Scheel, Szilagyi - Breaking the **high spin limit** (~0.93) of Bowen-York conformally flat initial data

2015 Waveform models built on NR results used in **LIGO** searches and parameter estimation for **first gravitational wave detection**

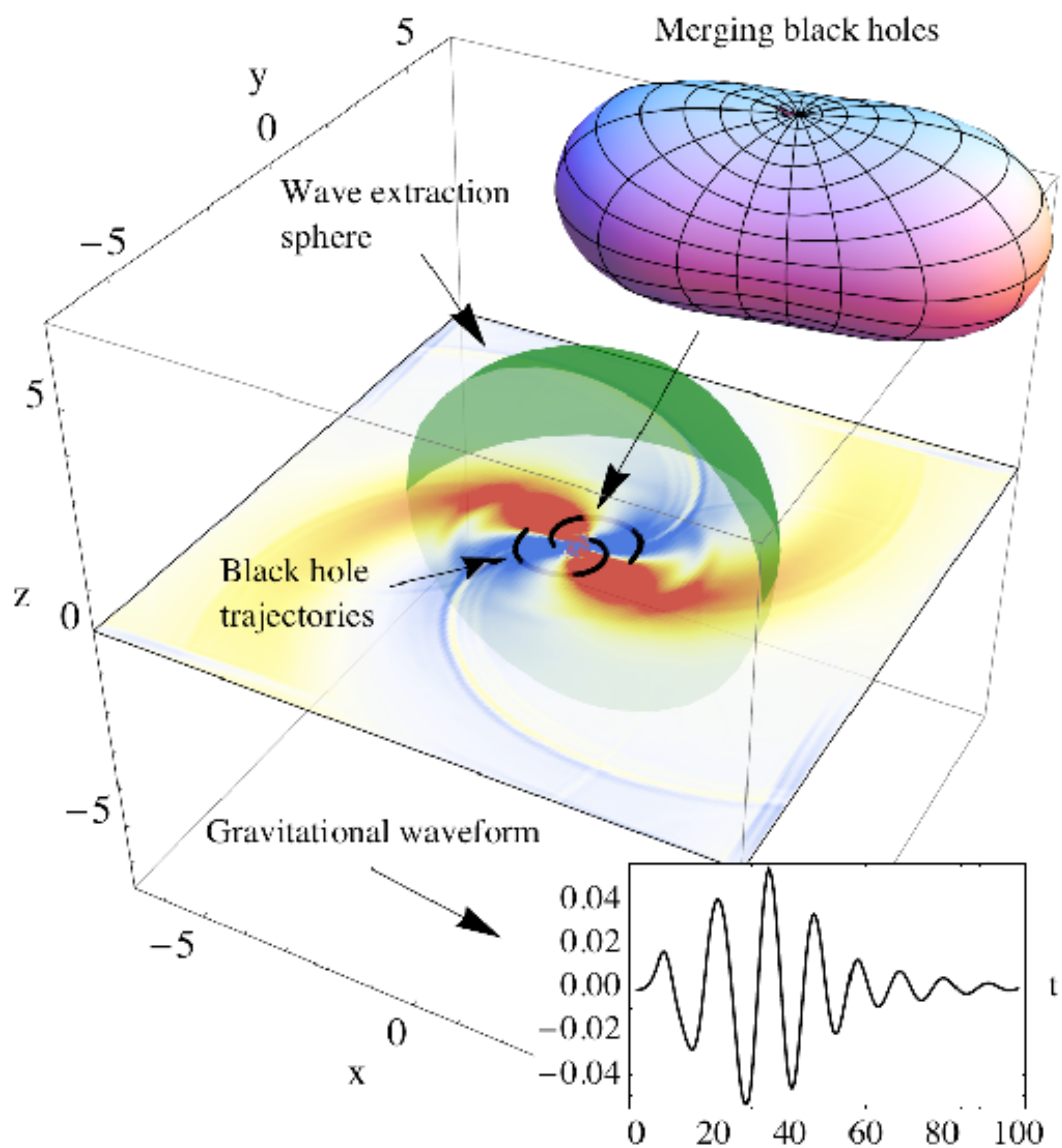
What can we do today?

- **Stable** long evolutions of **moderate** BBH configurations:
    - Mass ratio $q = m_1/m_2 \lesssim 8$
    - Spins chi $= S/m^2 \lesssim 0.6$
    - Number of orbits $N \lesssim 40$

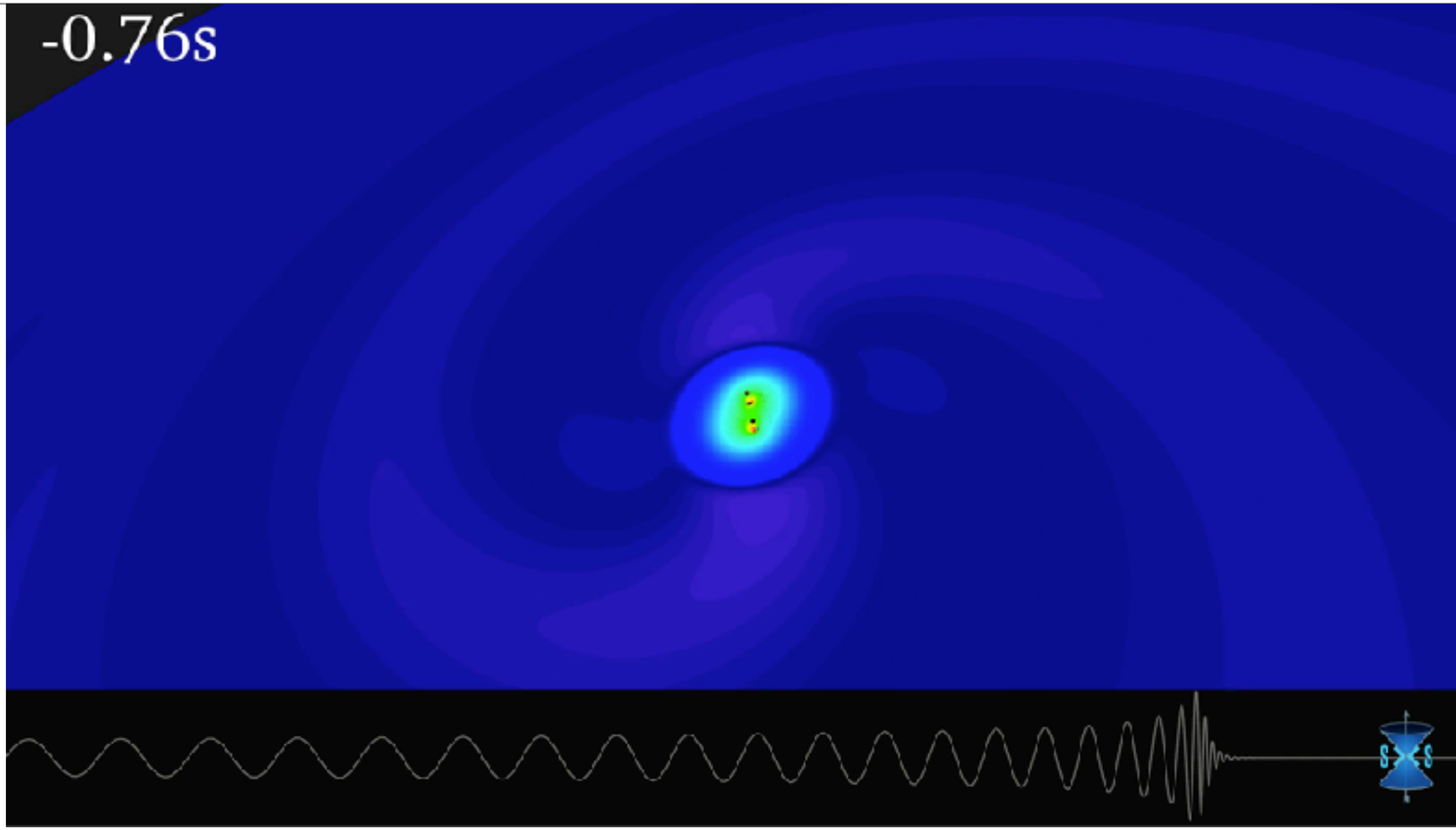
Examples

A binary black hole simulation

- Near zone: **horizons**
- Far zone: **waves**
- Postprocessing: **strain** timeseries in LIGO format



Warped spacetime and horizons

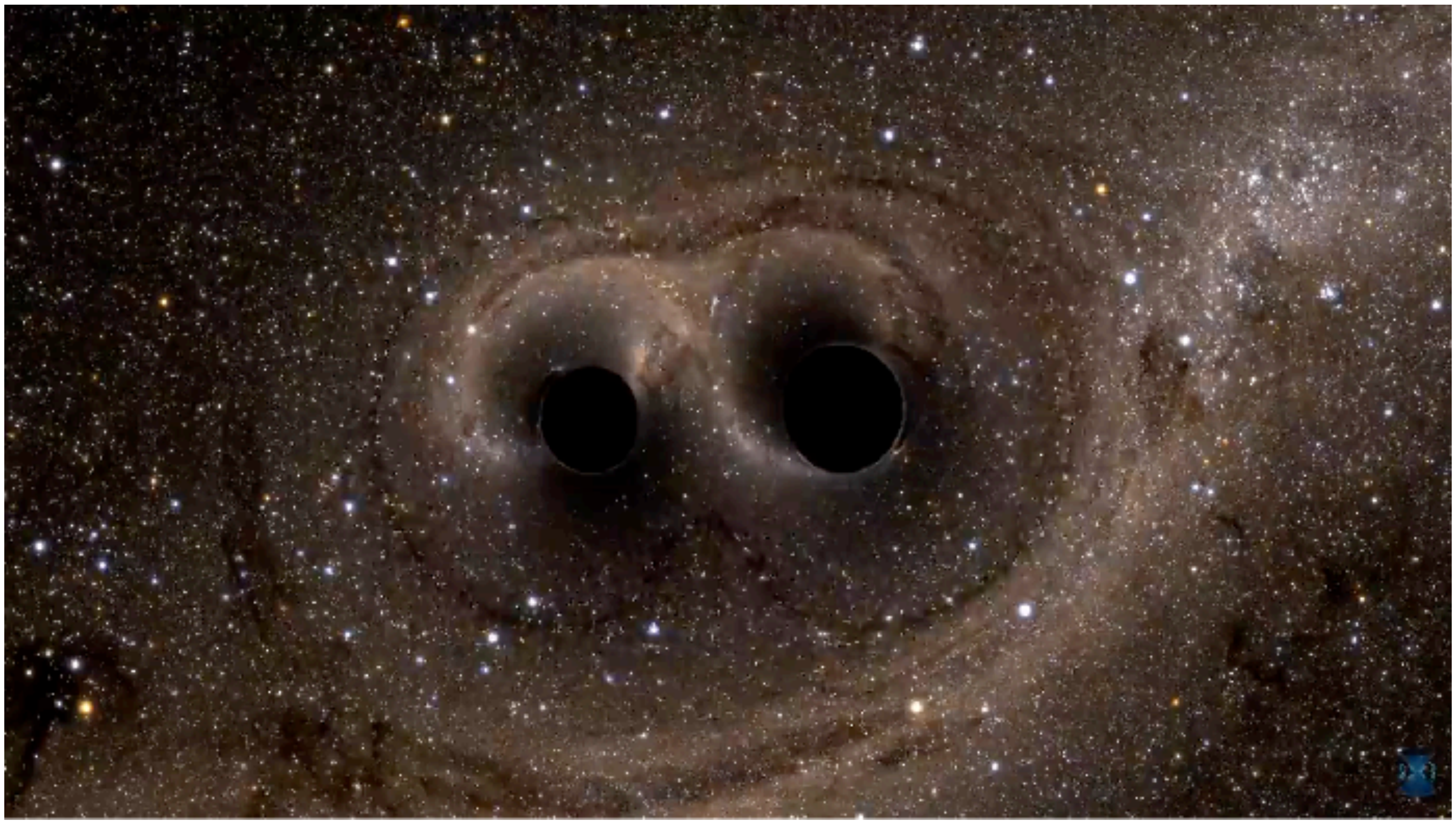


Simulating eXtreme Spacetimes (SXS)

3D gravitational waves

Simulation: Geoffrey Lovelace, Visualisation: Ian Hinder
Simulating eXtreme Spacetimes (SXS) - black-holes.org

What would GW150914 look like up close?



Simulating eXtreme Spacetimes (SXS) - black-holes.org

Open source Numerical Relativity

Open-source Numerical Relativity

- **Cactus** framework: open source, developed by **Ed Seidel**'s group at the **Albert Einstein Institute** in the late 90s
- Foundation of many NR codes today
- **Einstein Toolkit** is an entirely open source set of NR codes based around Cactus. See einsteintoolkit.org/gallery.html for examples
- **GW150914 example**, including fully open parameter file, instructions, and **tutorials** for analysis and visualisation [Wardell, Hinder, Bentivegna]
    - einsteintoolkit.org/gallery/bbh
    - Simulate GW150914 on ~100 cores in a few days **yourself**!

Simulation data

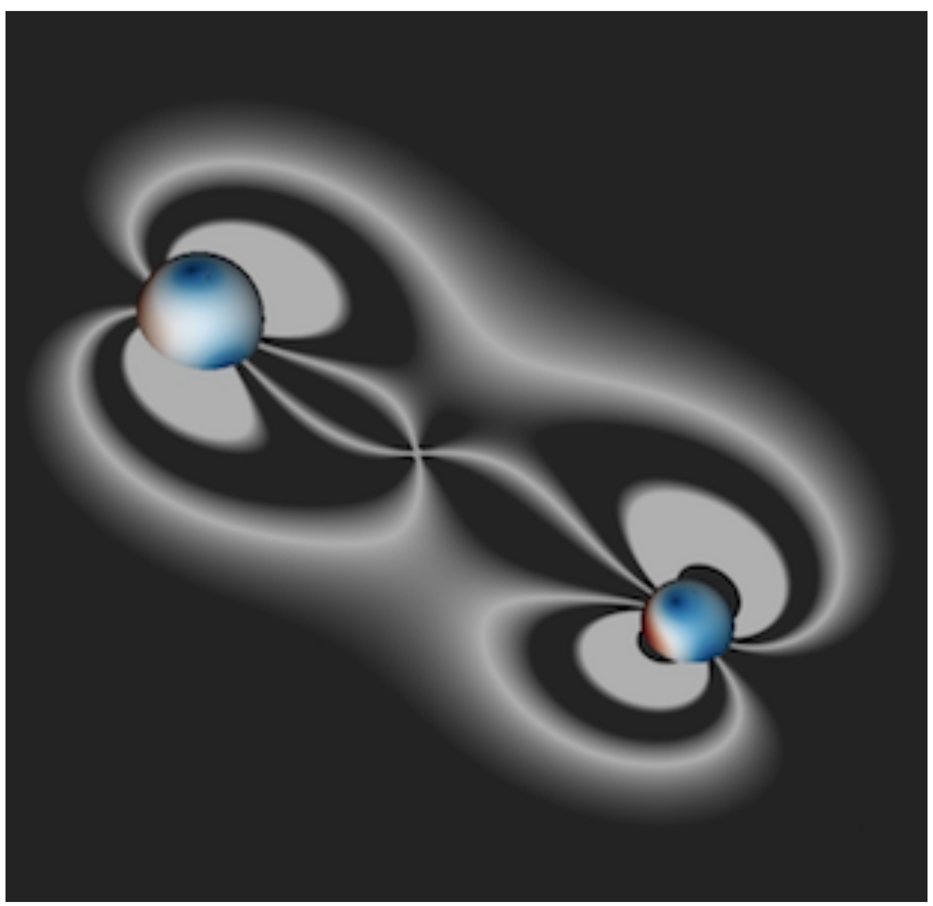
Lightweight simulation data with only a small number of iterations of 3D output is available for download from Zenodo:

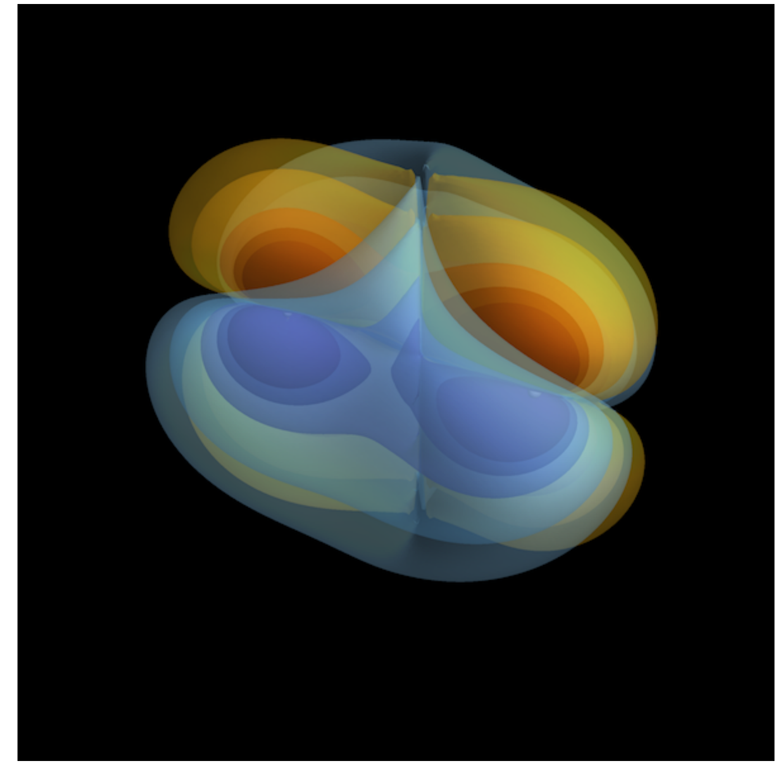
DOI 10.5281/zenodo.60213

The full simulation comprises several terabytes of data and can be made available upon request.

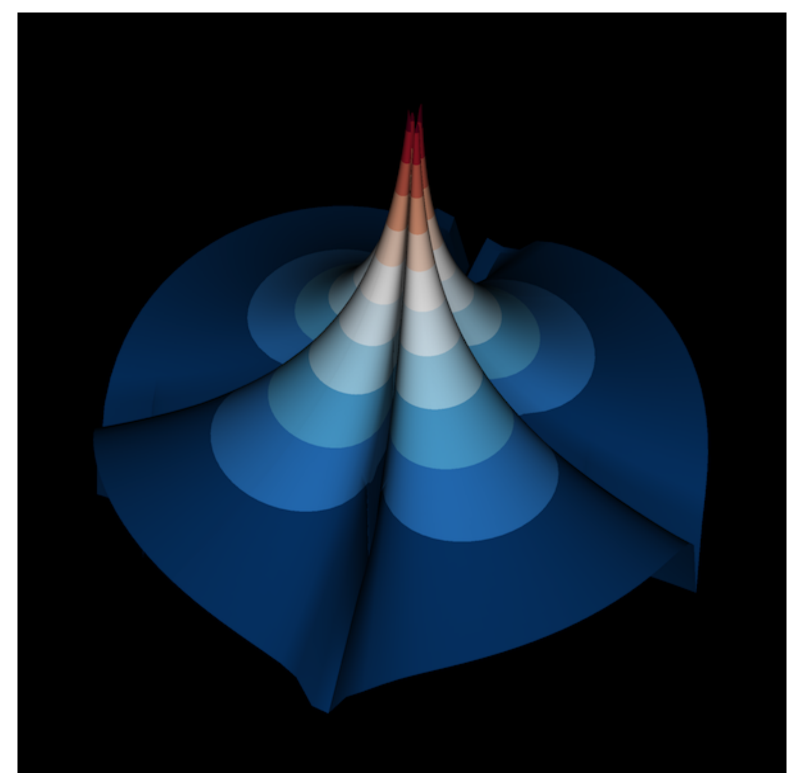
Images and movies

Horizons



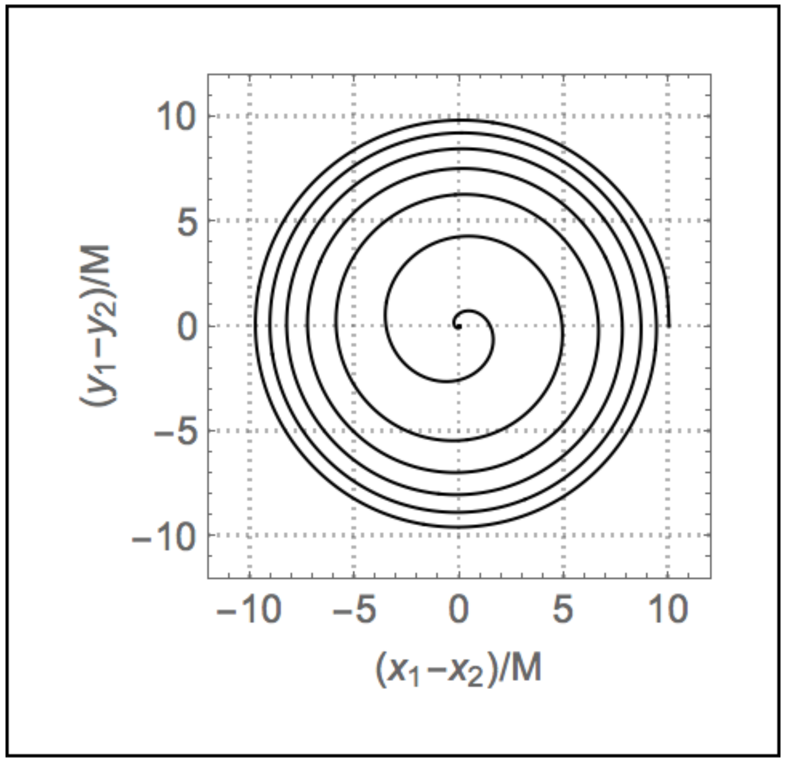


The real part of Ψ_4, the component of the Riemann tensor representing outgoing gravitational radiation.



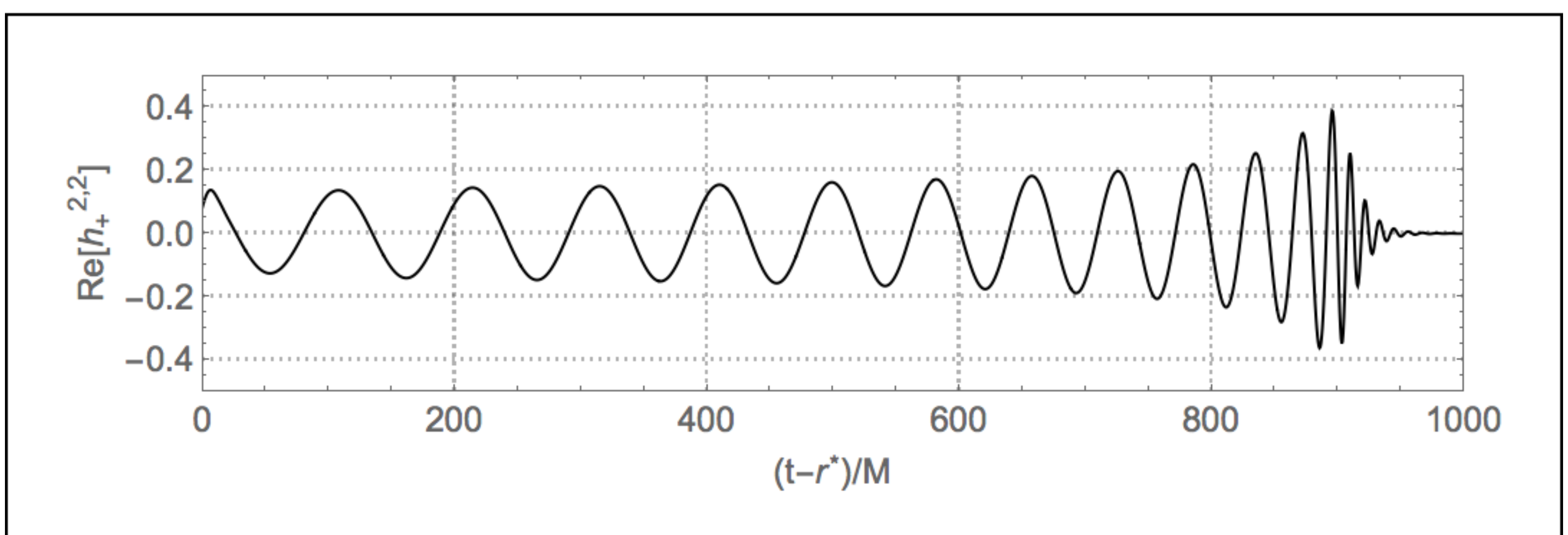
Elevation plot of the magnitude of Ψ_4 on the equatorial plane at $t = 0$.

Horizon coordinate trajectories

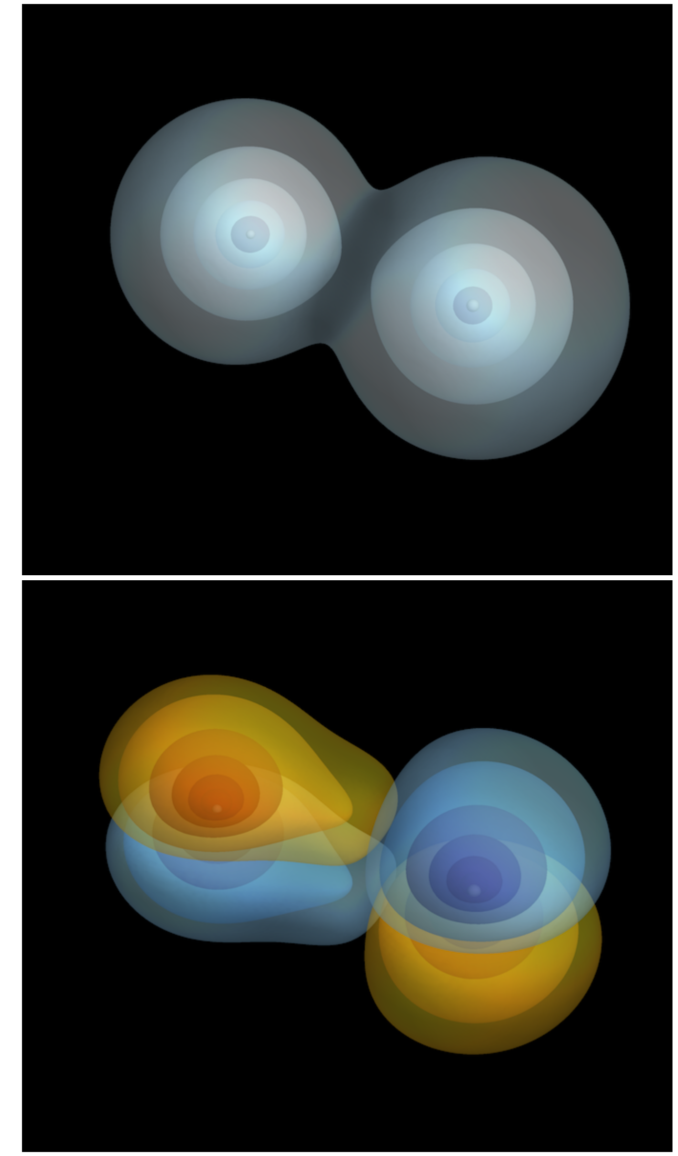


Coordinate tracks of the centroids of the apparent horizons showing inspiral of the binary due to emission of energy and angular momentum in gravitational waves

Gravitational waveform



Curvature scalars

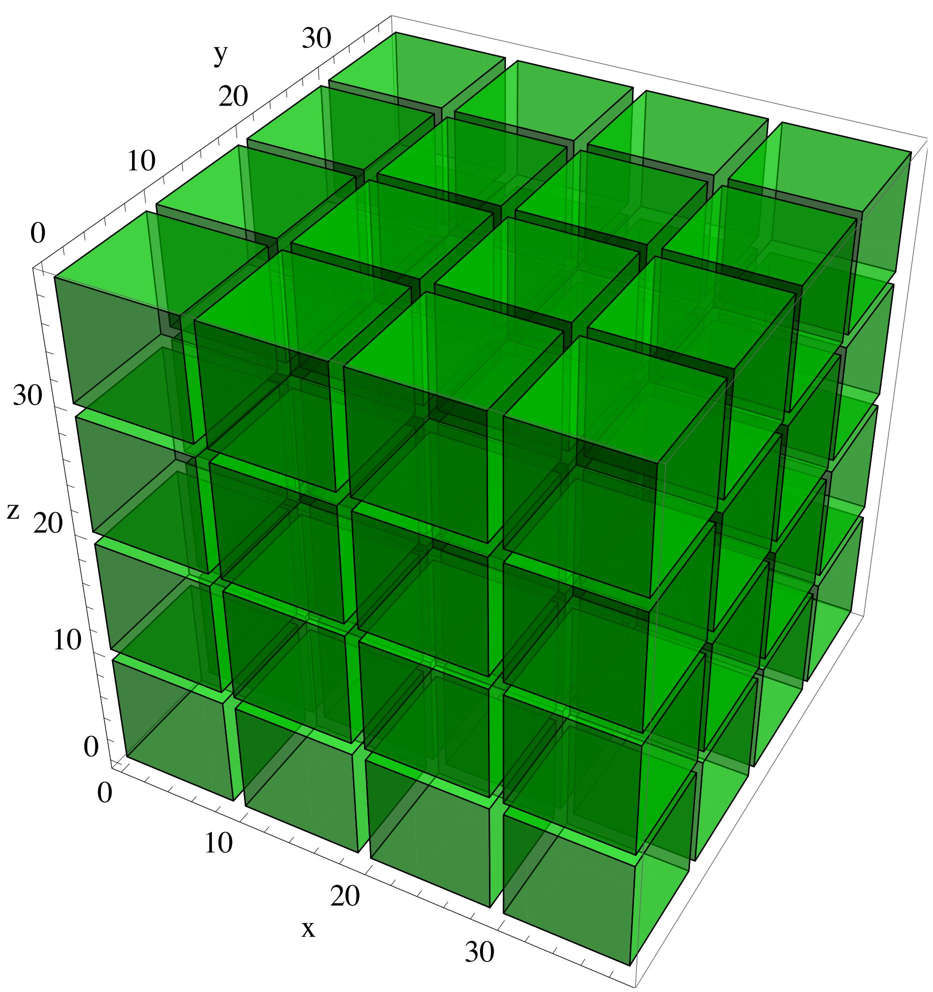


einsteintoolkit.org

Hardware

Why supercomputers?

- Need to **store** at least one 3D t = const grid of data **in memory**
- **Too many points** and too many variables to fit in a workstation



- Supercomputer consists of many individual **nodes** connected by a fast low-latency **network**
- **Split up** the grid into blocks and run each on a separate node
- **Parallel programming** required!

AEI Potsdam NR cluster: **Minerva**

- 38 TB of main memory
- 594 nodes (9504 cores)
- 302.4 TFLOPS (3×10^{14} calculations per second)
- 58 Gb/sec communication network
- 500 TB of disk space
- Used for Numerical Relativity: binary black hole and neutron star simulations