



Numerical Simulations of the Gravitational Radiation Captures of Unequal Mass or Spinning Black Holes

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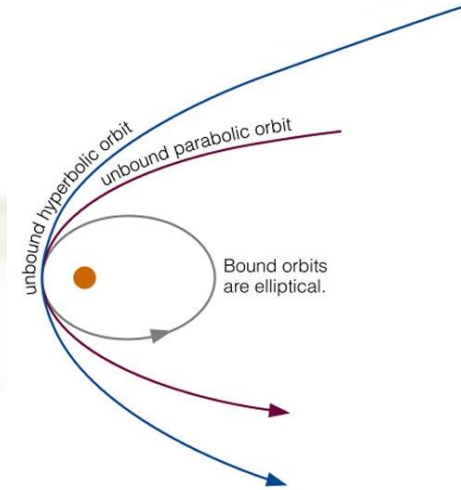
Introduction

- **BH-BH mergers are important sources of GWs for advanced detectors.**
- **Gravitational Radiation (GR) capture is one of the possible mechanisms for the binary formation**
 - Captured by emitting gravitational waves
 - Hyperbolic orbit → Elliptical orbit
- **GR capture of Unequal mass or spinning BHs**
 - Follow up research of equal mass & non-spinning BHs, presented by Dr. Kang

Introduction

- **Parabolic approximation (Quinlan & Shapiro 1987, 1989)**

- Hyperbolic orbit near periastron is almost indistinguishable from a parabolic orbit.
- Radiation emitted in a parabolic orbit is practically the same with that of hyperbolic orbit.
- Parabolic orbit simulations $\rightarrow E_{\text{rad}} \rightarrow$ Hyperbolic orbit with $E_{\text{Newtonian}} \approx E_{\text{rad}}$ would be captured.
- By parabolic approximation,
 $\Delta E = f(r_p) > E_0 \rightarrow r_{p,\text{max}} \rightarrow$ cross section



Method – Computational Tool

einstein
toolkit



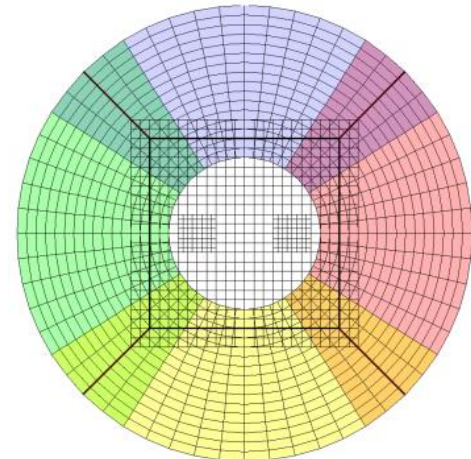
- **Software – Einstein Toolkit**
 - Collection of software components and tools for simulation & analysis for general relativistic phenomena
 - Free, open source (<http://einsteintoolkit.org>)
 - Based on Cactus code
 - Flesh(central core)+Thorns(application module)
 - Over 100 thorns for simulation management
 - Open and community-driven development
 - HDF5 parallel file I/O, adaptive mesh refinement, ...
- **Hardware - KISTI supercomputer: Tachyon2**

Method – Technical Issues

- **Asymmetric simulations**
 - Reflection & rotating symmetries are used for equal mass, non-spinning BH simulations (need only 1/4 domain).
 - Rotating symmetries cannot be used for unequal mass BHs.
 - No symmetries for non-aligned spinning BHs
- **High resolutions for smaller BHs**
- **More distant extraction radii for emitted energy and angular momentum**

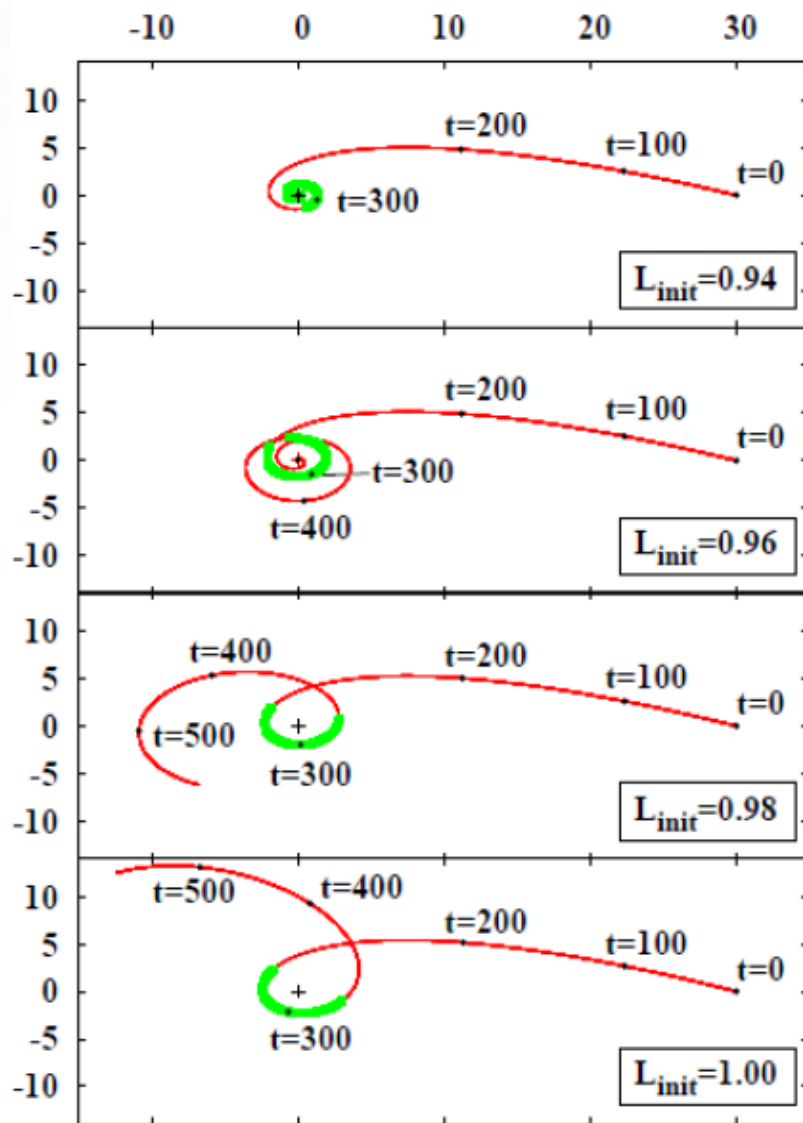
→ **Multi-patch setup – Llama code (Pollney et al. 2009)**

- Interior Cartesian + outer inflated cube
- Inter-patch interpolation
- $N \sim r$ (Cartesian: $N \sim r^3$)

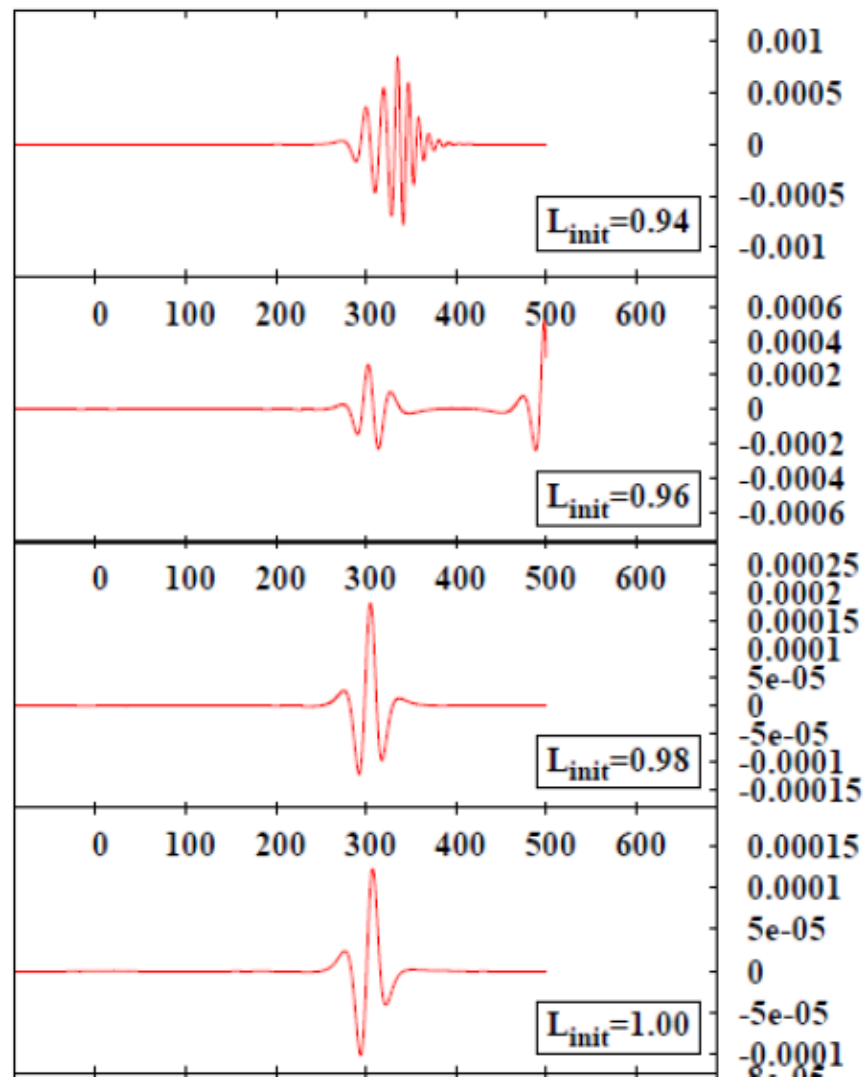


Equal mass, no spin – orbit & wave

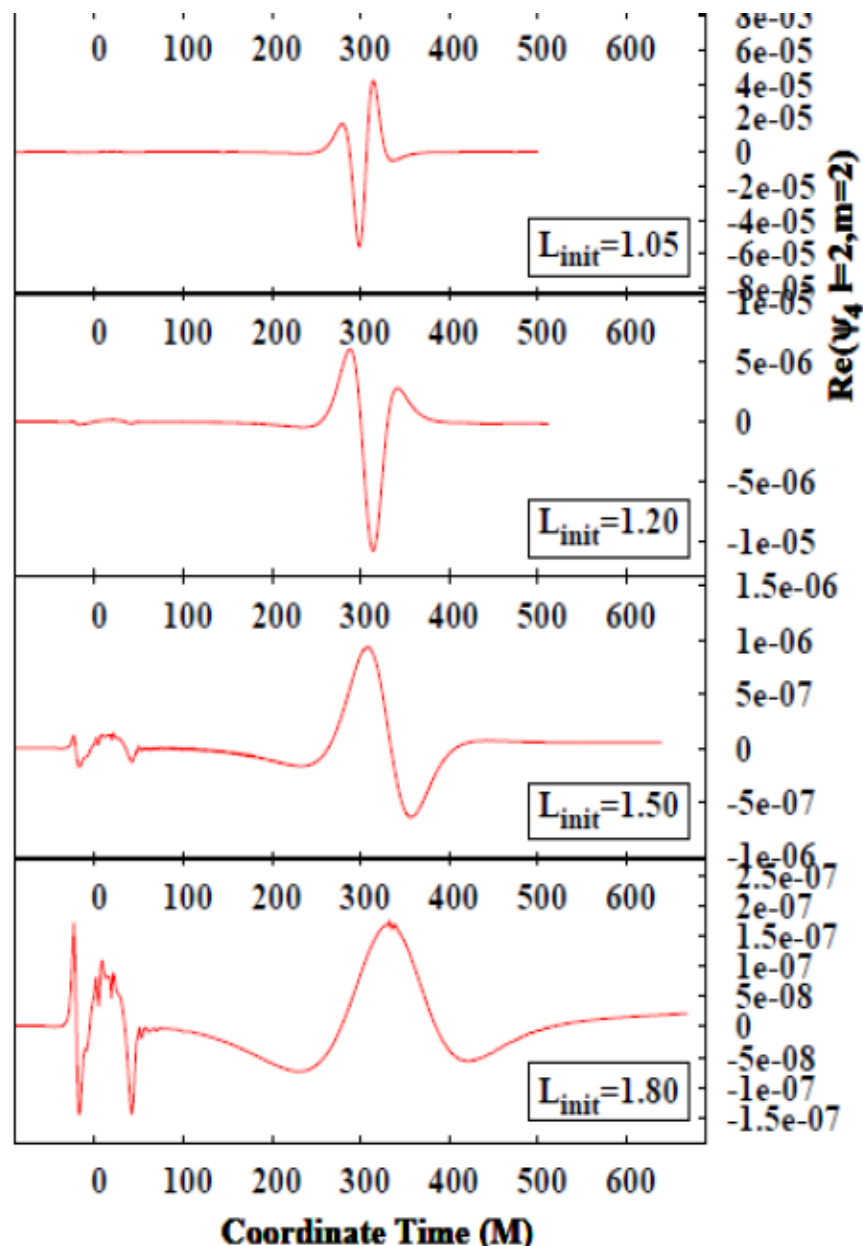
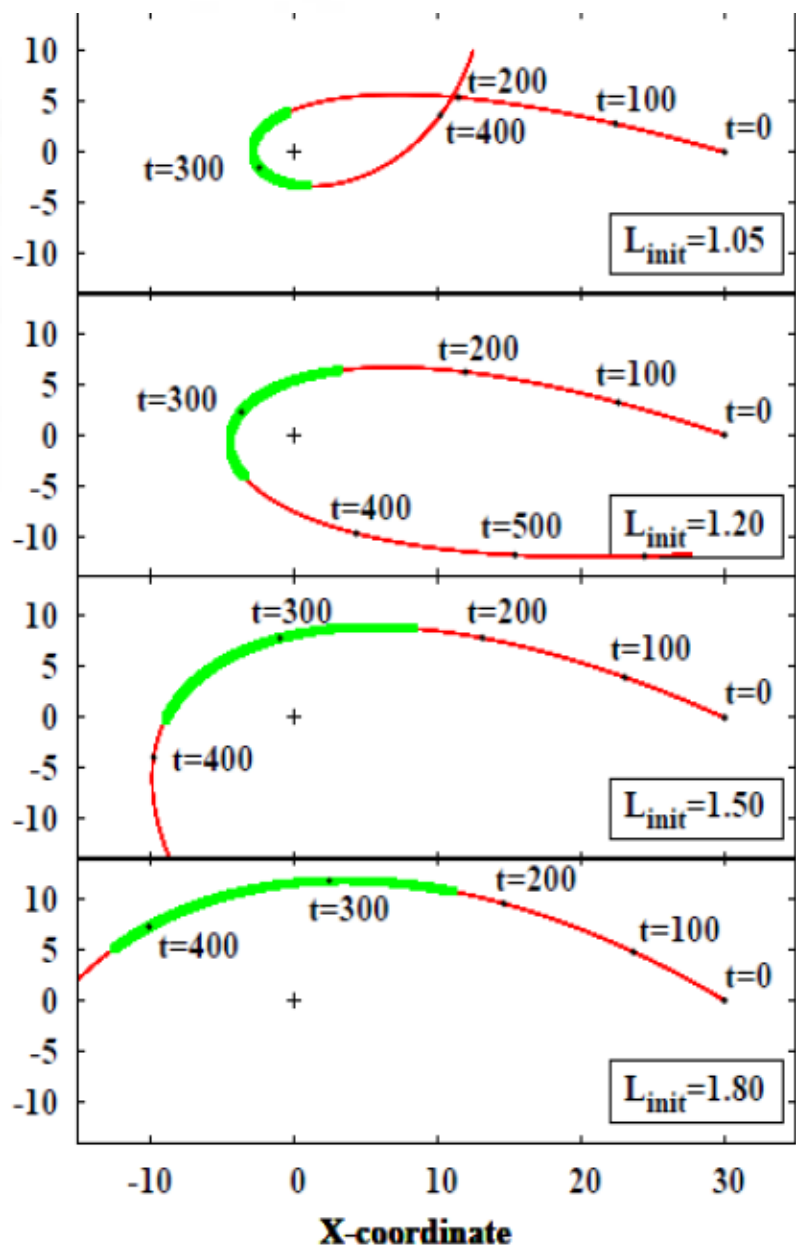
Orbits in X-Y plane for BH₊



Real part of ψ_4 $l=2, m=2$ mode



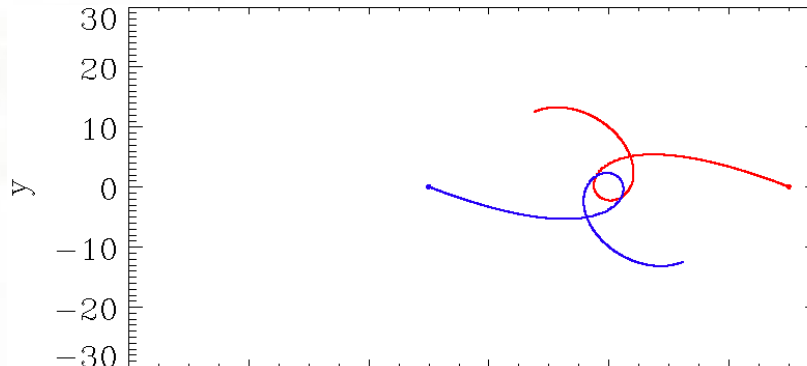
Equal mass, no spin – orbit & wave



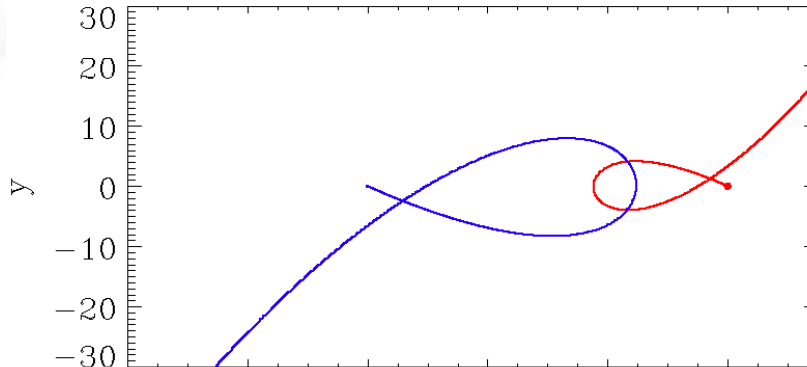
Unequal mass – orbit & wave

- Initial angular momentum $L = 1.0$

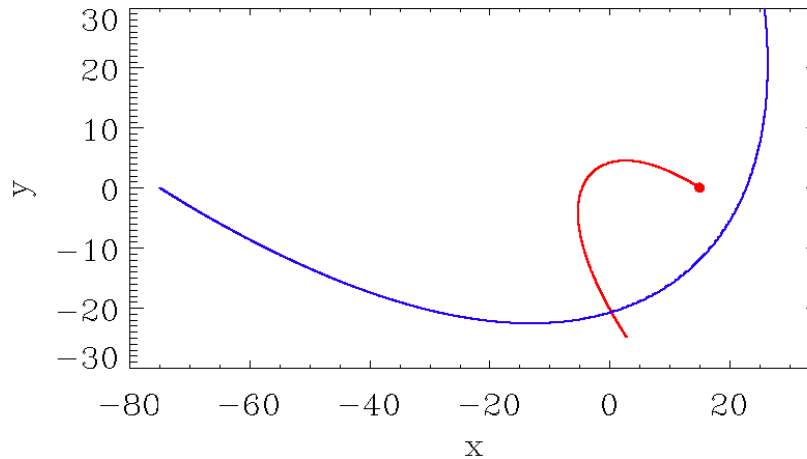
1 : 1
Initial distance
= 60



2 : 1
Initial distance
= 60



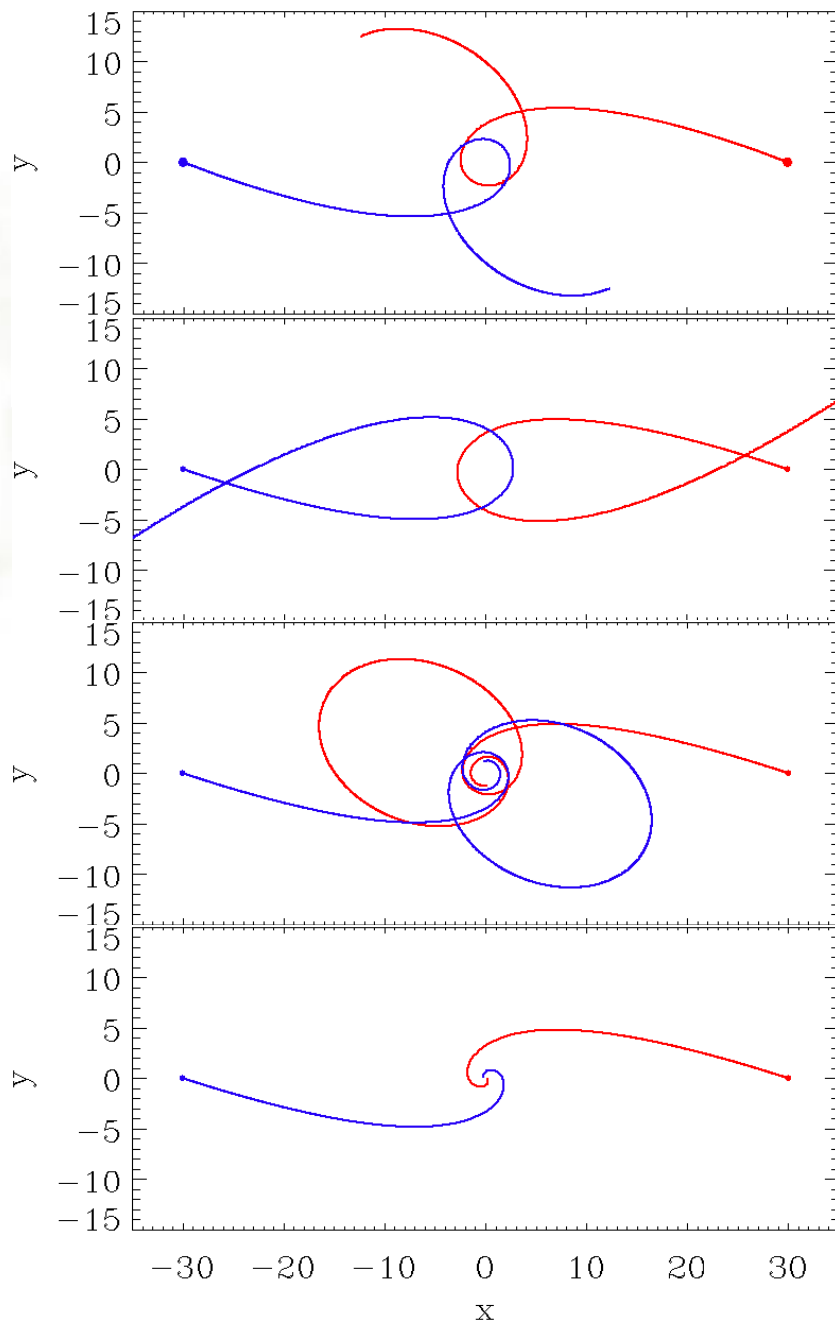
5 : 1
Initial distance
= 90



Spin

– orbit &
wave

- Initial
“orbital”
angular
momentum
 $L = 1.0$



Impact parameter

- **Impact parameter in classical mechanics**

$$b = L/\sqrt{2\mu E}$$

(μ : reduced mass)

- **Higher mass ratio BHs**
- **Spinning BHs**

Summary

- **Several cases of GR capture for unequal masses and spinning BHs were explored.**
- **Radiated energy & angular momentum are much smaller for higher mass ratio.**
- **Wider parameter spaces will be explored.**
 - **Search for the mass ratio where Full GR deviates from Post Newtonian**
 - **Various combination of spins**