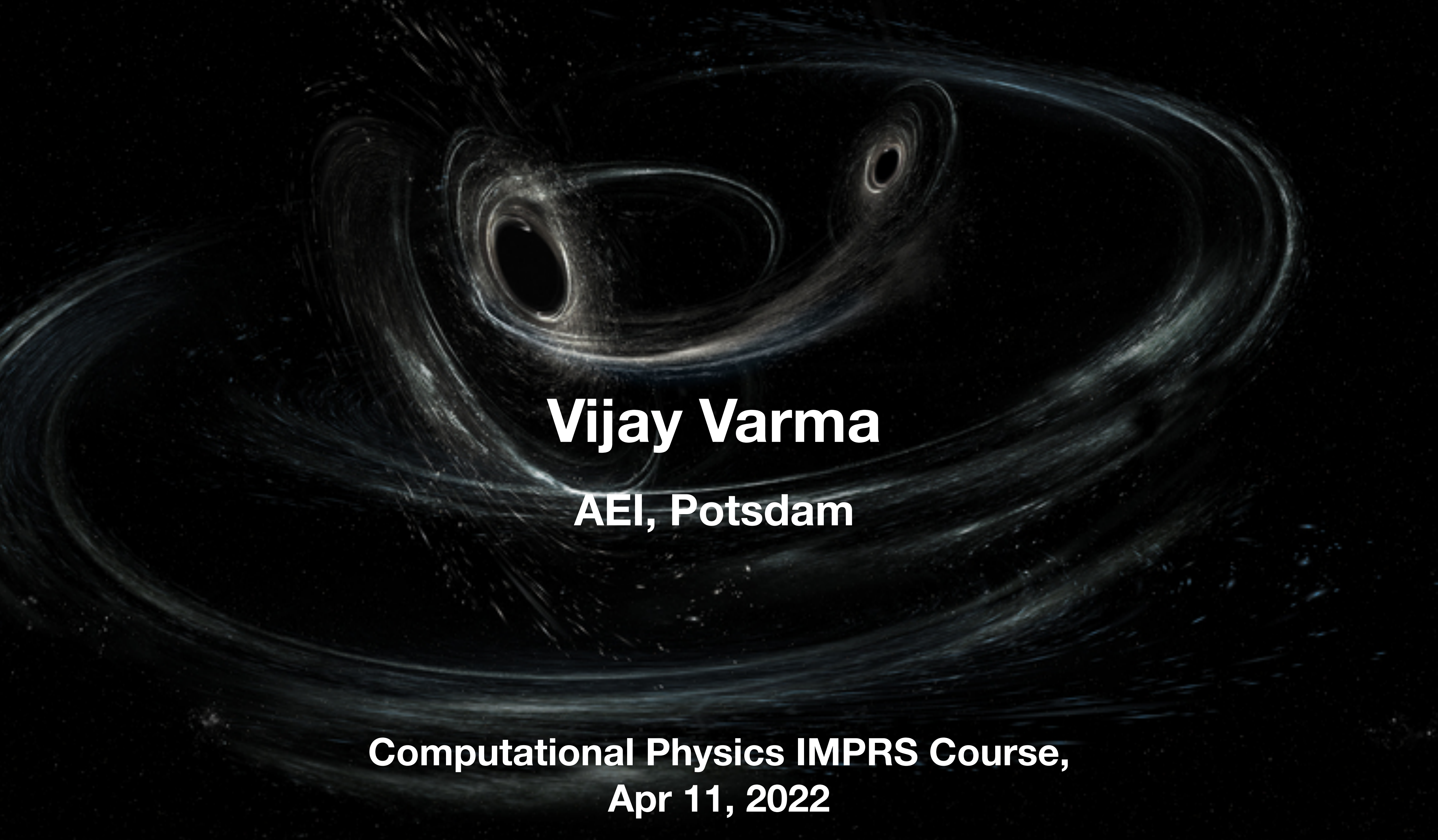
Overview of BBH results in NR



Vijay Varma

AEI, Potsdam

Computational Physics IMPRS Course,
Apr 11, 2022

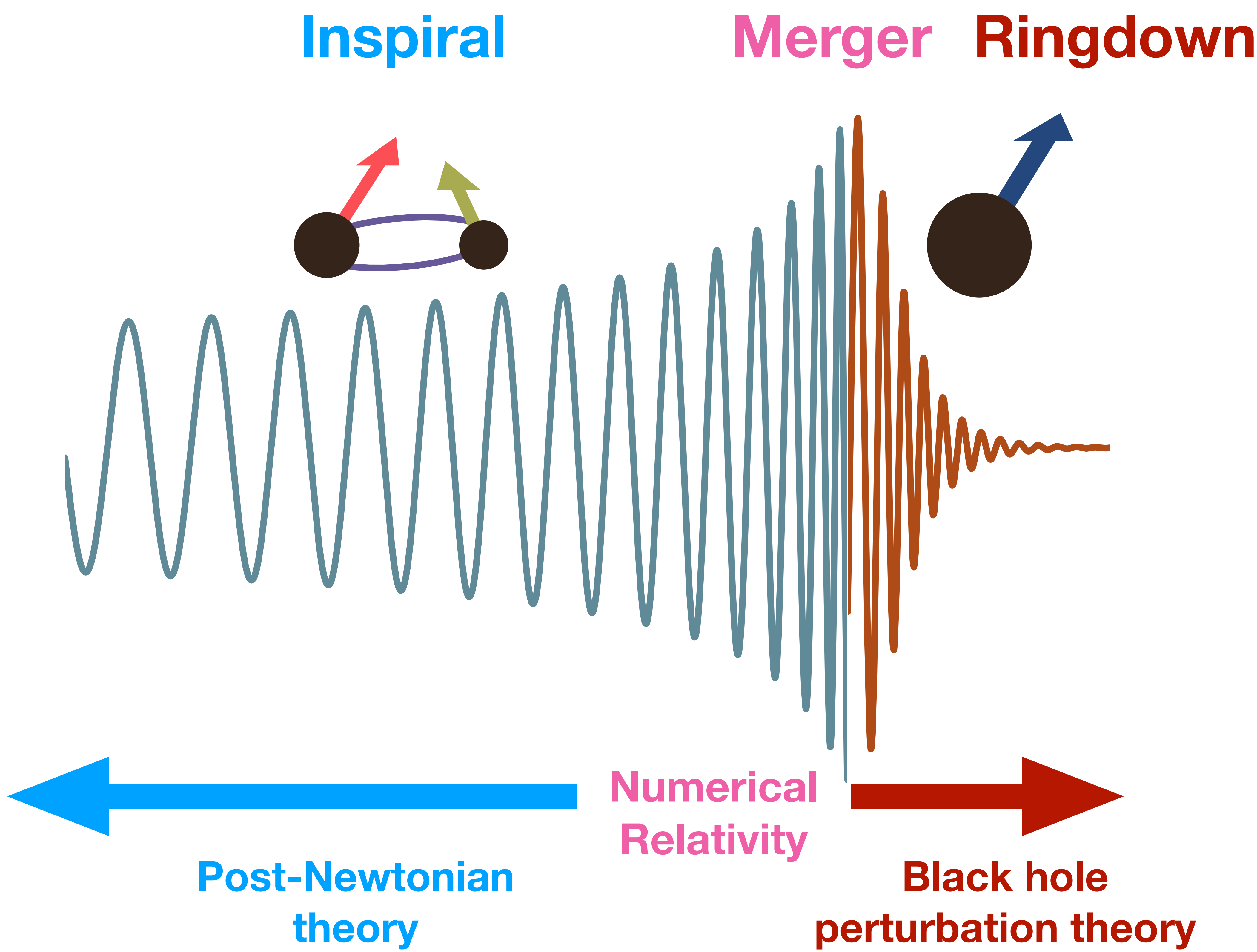
Credit: LIGO/Caltech/MIT/Sonoma State (Aurore Simonnet)

Outline

- Brief history of NR
- Important BBH phenomena everyone should know:
    - Higher order modes
    - Junk radiation.
    - Precession
    - “Hang-up” effect
    - Eccentricity
    - Kicks
- Status of the field and frontiers

Part I: Brief history of NR

Stages of a binary black hole



The very beginning

ANNALS OF PHYSICS: **29**, 304–331 (1964)

The Two-Body Problem in Geometrodynamics

SUSAN G. HAHN

International Business Machines Corporation, New York, New York

AND

RICHARD W. LINDQUIST

The numerical calculations were carried out on an IBM 7090 electronic computer. The parameters a and μ_0 were both set equal to unity; the mesh lengths were assigned the values $h_1 = 0.02$, $h_2 = \pi/150 \approx 0.021$, yielding a 51 × 151 mesh. The calculations of all unknown functions, including a great number of input-output operations and some built-in checking procedures, took approximately four minutes per time step. Different check routines indicated that results close to the point $\mu = 0$, $\eta = 0$ lost accuracy fairly quickly. Since these would, in the long run, influence meshpoints further away, the computations were stopped after the 50th time step, when the total time elapsed was approximately 1.8. Some of the results are shown in Table I.

Evolution time 1.8M

40 years later…

VOLUME 92, NUMBER 21 PHYSICAL REVIEW LETTERS week ending 28 MAY 2004

Numerical Simulation of Orbiting Black Holes

Bernd Brügmann, Wolfgang Tichy, and Nina Jansen
Center for Gravitational Physics and Geometry and Center for Gravitational Wave Physics, Penn State University, University Park, Pennsylvania 16802, USA
(Received 26 December 2003; published 24 May 2004)

We present numerical simulations of binary black hole systems which for the first time last for about one orbital period for close but still separate black holes as indicated by the absence of a common apparent horizon. An important part of the method is the construction of comoving coordinates, in which both the angular and the radial motion are minimized through a dynamically adjusted shift condition. We use fixed mesh refinement for computational efficiency.

DOI: 10.1103/PhysRevLett.92.211101 PACS numbers: 04.25.Dm, 04.30.Db, 95.30.Sf

First 50 years of numerical relativity for BBH

1962 *ADM*
3+1 formulation

1964
Hahn-Lindquist
2 wormholes

1984
Unruh
excision

1992,3
Choptuik;
Abrahams+Evans
critical phenomena

1997
Brandt-
Brügmann
puncture data

1994-98
BBH Grand Challenge

1999-00
AEI/PSU
grazing collisions

2000-04
AEI/UTB-NASA
revive crashing
codes (Lazarus)

~2000 *Choptuik;*
Schnetter;Brügmann
mesh refinement

2005
Gundlach ea
constraint damping

2005 *Pretorius*
inspiral-merger-
ringdown (IMR)
w/ harmonic

2005-06
Campanelli+; Baker+
IMR w/ BSSN &
moving punctures

2006-08
Scheel+ (*SXS*)
IMR w/ spectral

2007-
Ajith, AEI, Jena
phenom GW models

2009-
UMD, SXS
EOB GW models

2011
Schmidt ea;
Boyle ea
Radiation aligned
frame

2011
Lousto ea
q=100

2014-
precessing
GW models

2015
Szilagyi ea
175 orbits

1964 **~1999** **~2005** **2015**

1975-77
Smarr-Eppley
head-on
collision

1979 *York*
kinematics and
dynamics of GR

1989-95
Bona-Masso
modified ADM,
(hyperbolicity)

1994 *Cook*
Bowen-York
initial data

1994-95
NCSA-WashU
improved
head-on collision

1999
BSSN
evolution
system

1999 *York*
conformal thin
sandwich ID

1999-2005 *York,*
Cornell, Caltech, LSU
hyperbolic formulations

2000-02
Alcubierre
gauge conditions

2004
Brügmann ea
one orbit

2003-08
Cook, Pfeiffer ea
improved ID

2000 *Ashtekar*
isolated horizons

2006,07
Baker ea;
Gonzalez ea
non-spinning BBH
kicks

2007 *SXS*
PN-NR
comparison

2007-11
RIT; Jena; AEI;…
BBH superkicks

2008
all of NR
NINJA

2009-11
Bishop, …
Cauchy
characteristic
extraction

2010
Bernuzzi ea
C4z

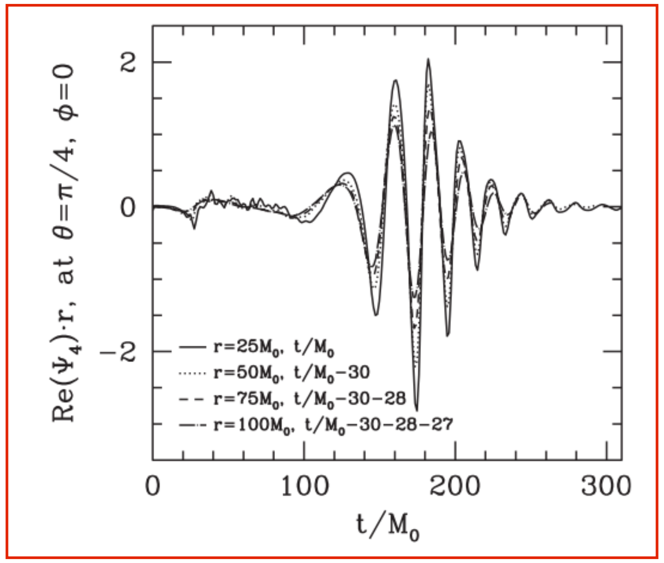
2011
Lovelace ea
$S/M^2=0.97$

2011-
Le Tiec ea
self-force studies

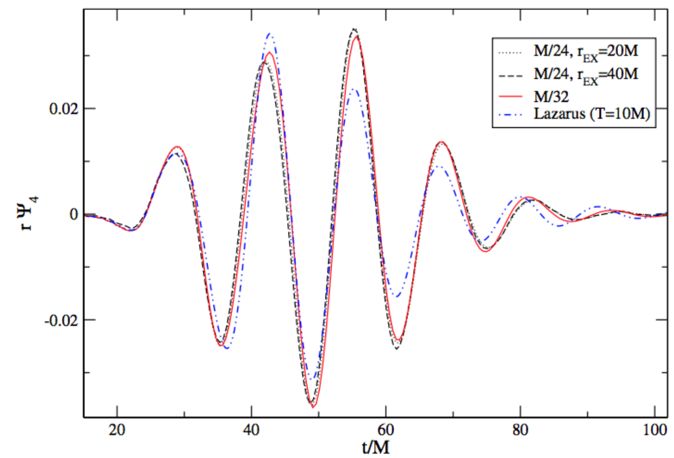
2013
GaTech; SXS
Precessing
parameter
studies

Credit: C. Lousto and H. Pfeiffer

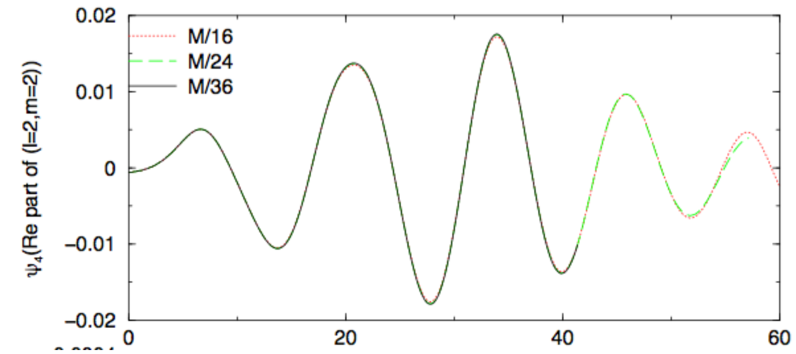
First BBH simulations



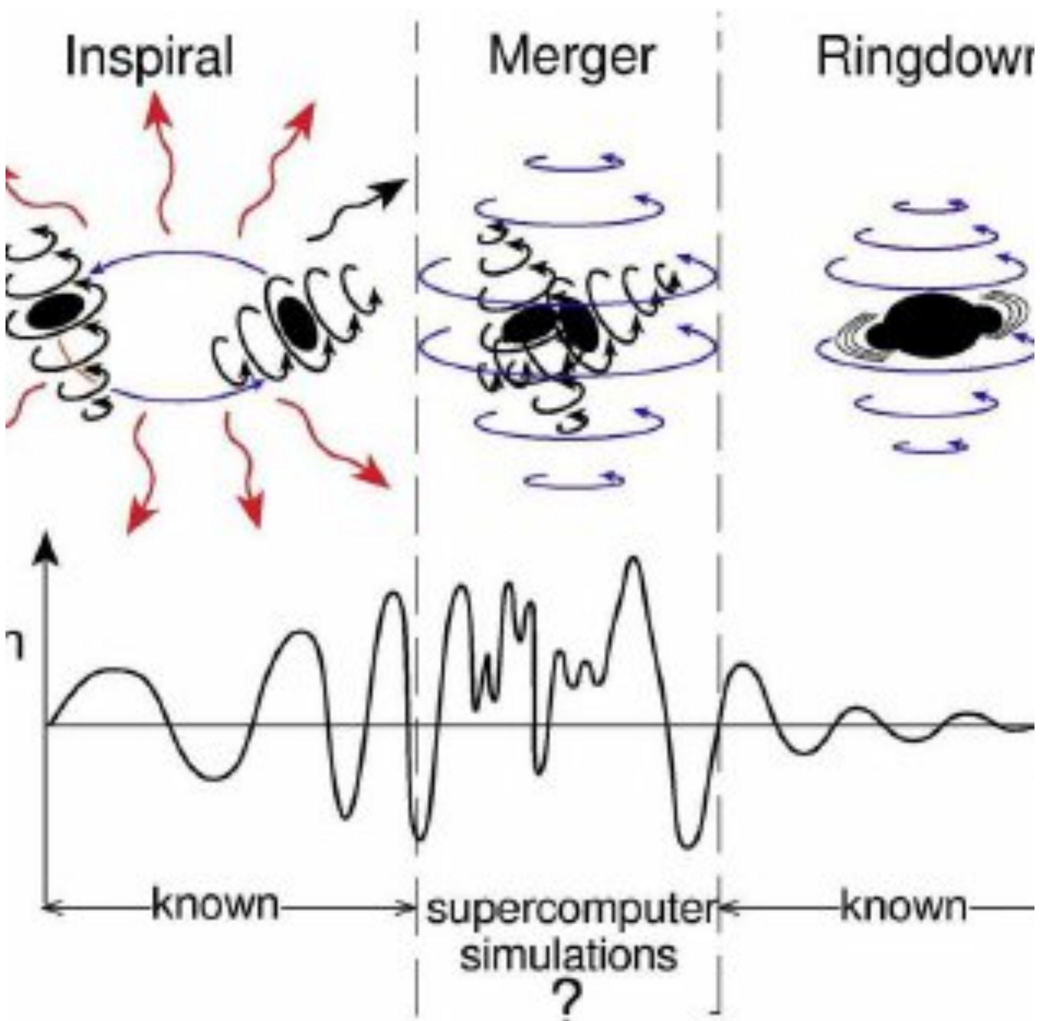
Pretorius 05



Baker+06



Campanelli+06



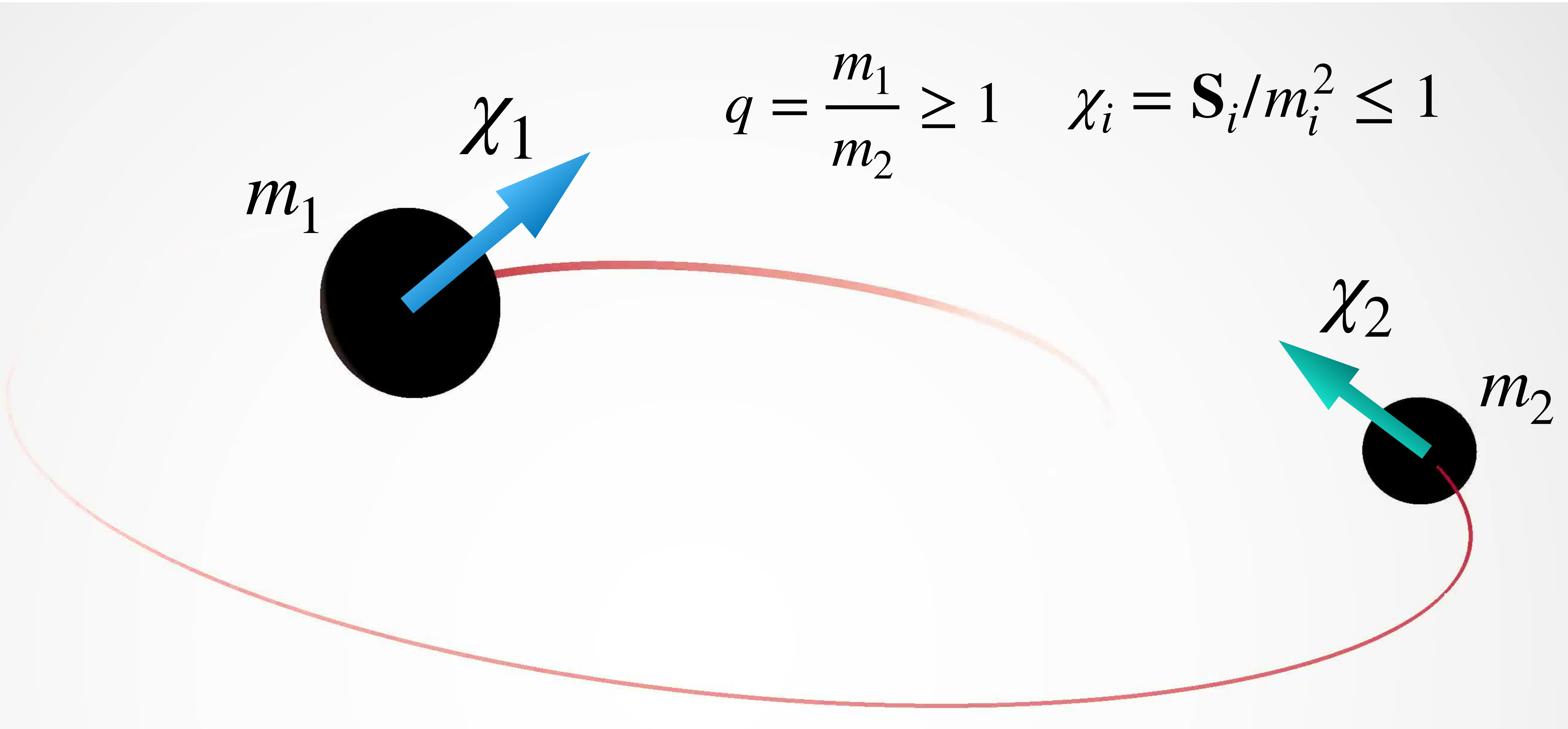
Kip Thorne

Important early result:
Simplicity of merger.

Continuous transition
inspiral → ringdown

Part II: Important BBH phenomena

Binary black hole parameters



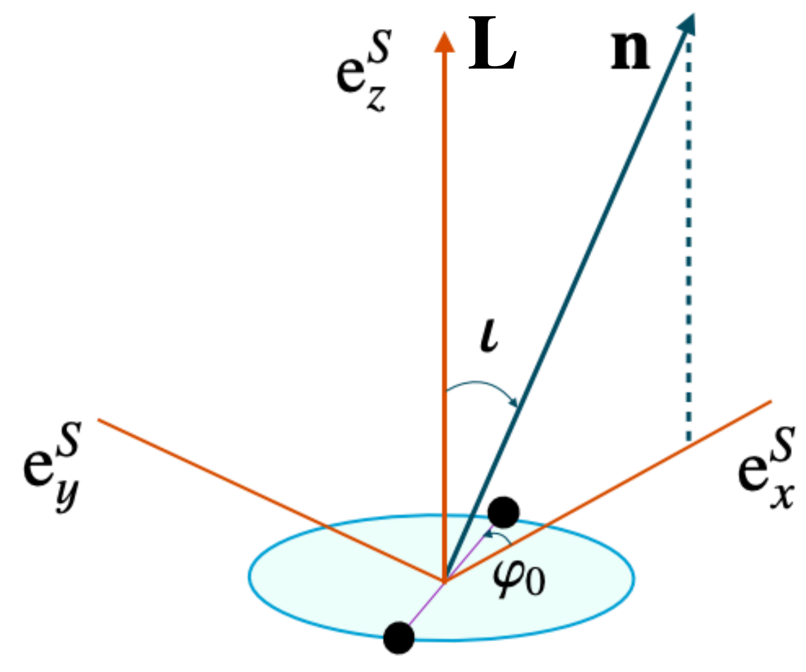
$$\Lambda = \{q, \chi_{1x}, \chi_{1y}, \chi_{1z}, \chi_{2x}, \chi_{2y}, \chi_{2z}\}$$

Higher order modes

$$h = h_+ - i\,h_\times$$

$$h(\iota, \varphi_0, t) = \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} {}_{-2}Y_{\ell m}(\iota, \varphi_0)\; h_{\ell m}(t)$$

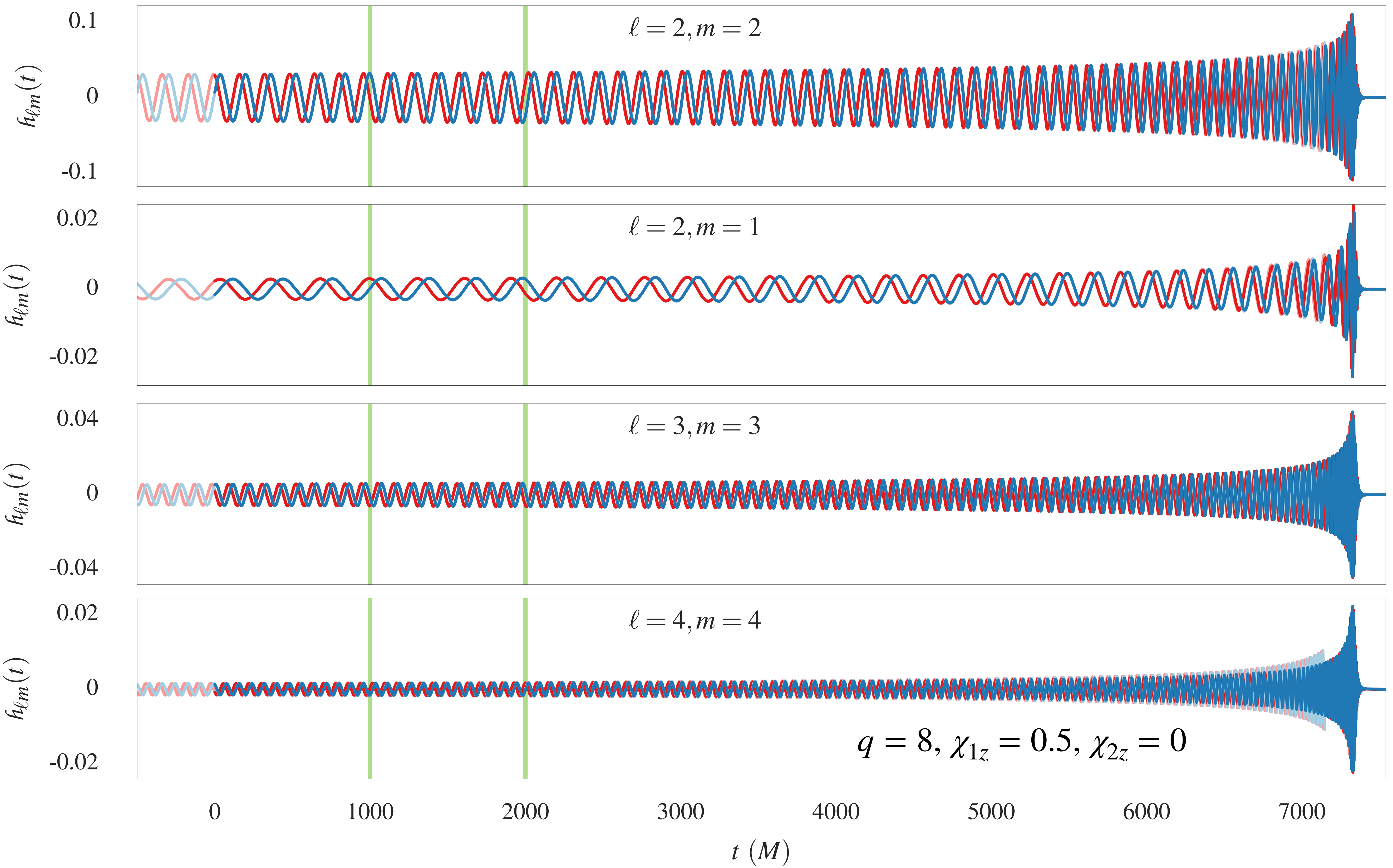
$$h_{\ell m} = A_{\ell m}\, e^{i\phi_{\ell m}}\; ; \quad \omega_{lm} = \frac{d\phi_{\ell m}}{dt} \sim m\,\omega_{\mathrm{orb}}$$



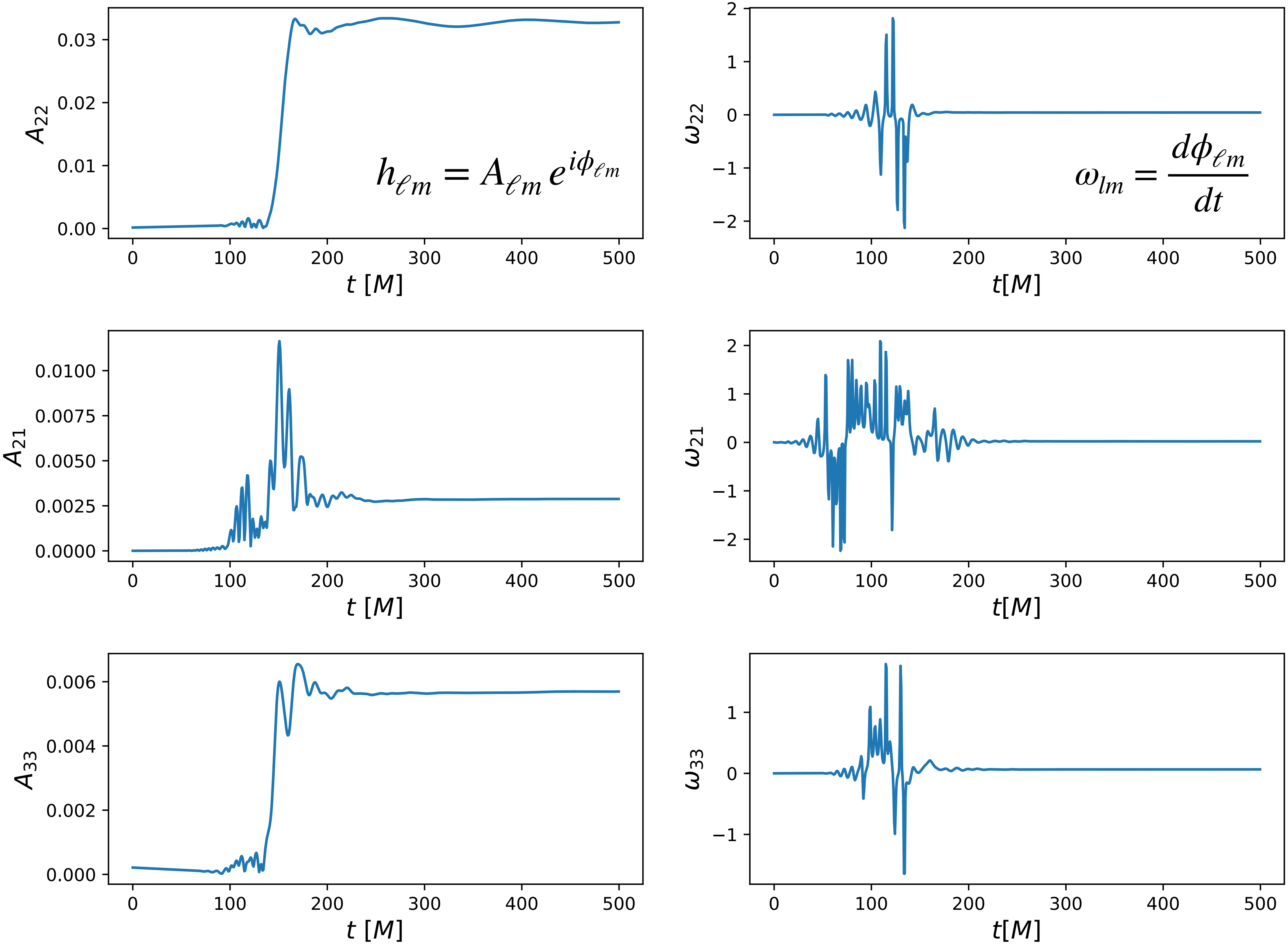
Source frame

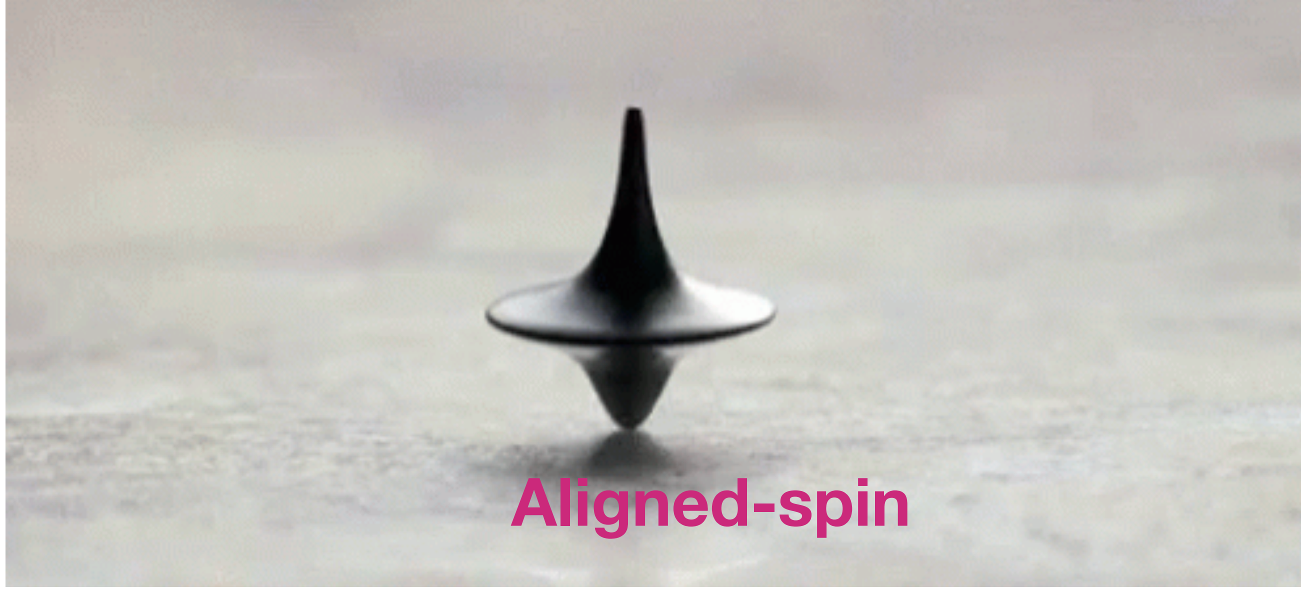
- **Quadrupole modes, $(2, \pm 2)$, are typically dominant.**
- **Other modes are referred to as higher (order) modes, higher harmonics, nonquadrupole modes, or subdominant modes.**
- **Become important at large q or large inclination angles θ.**

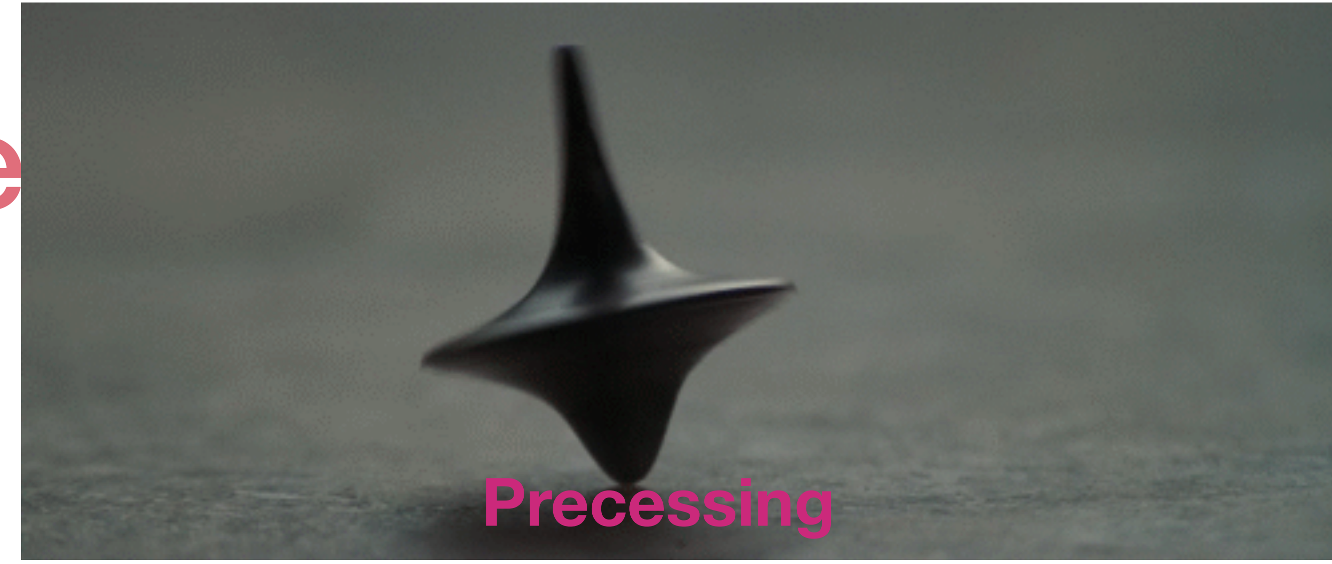
Higher order modes

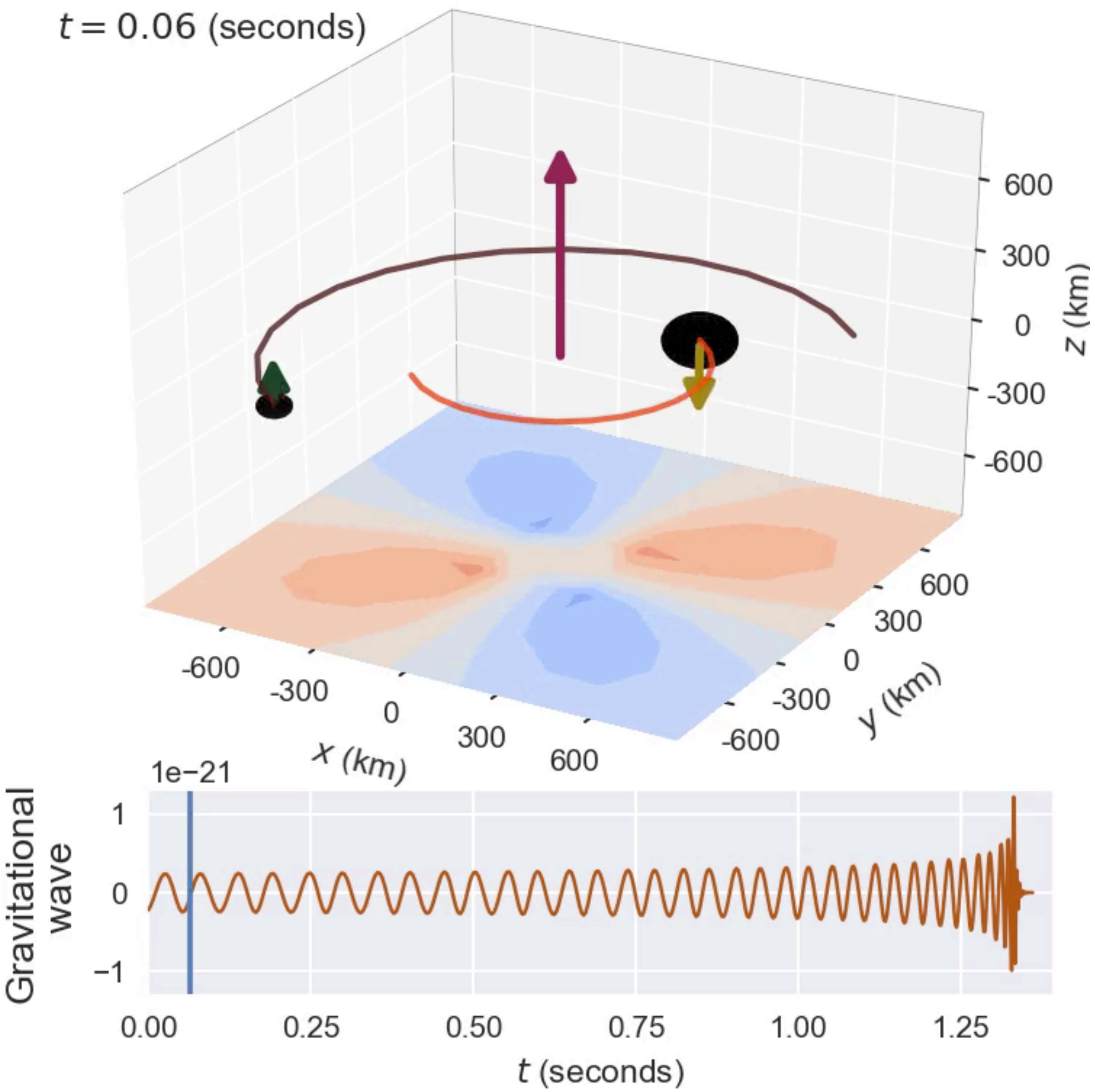


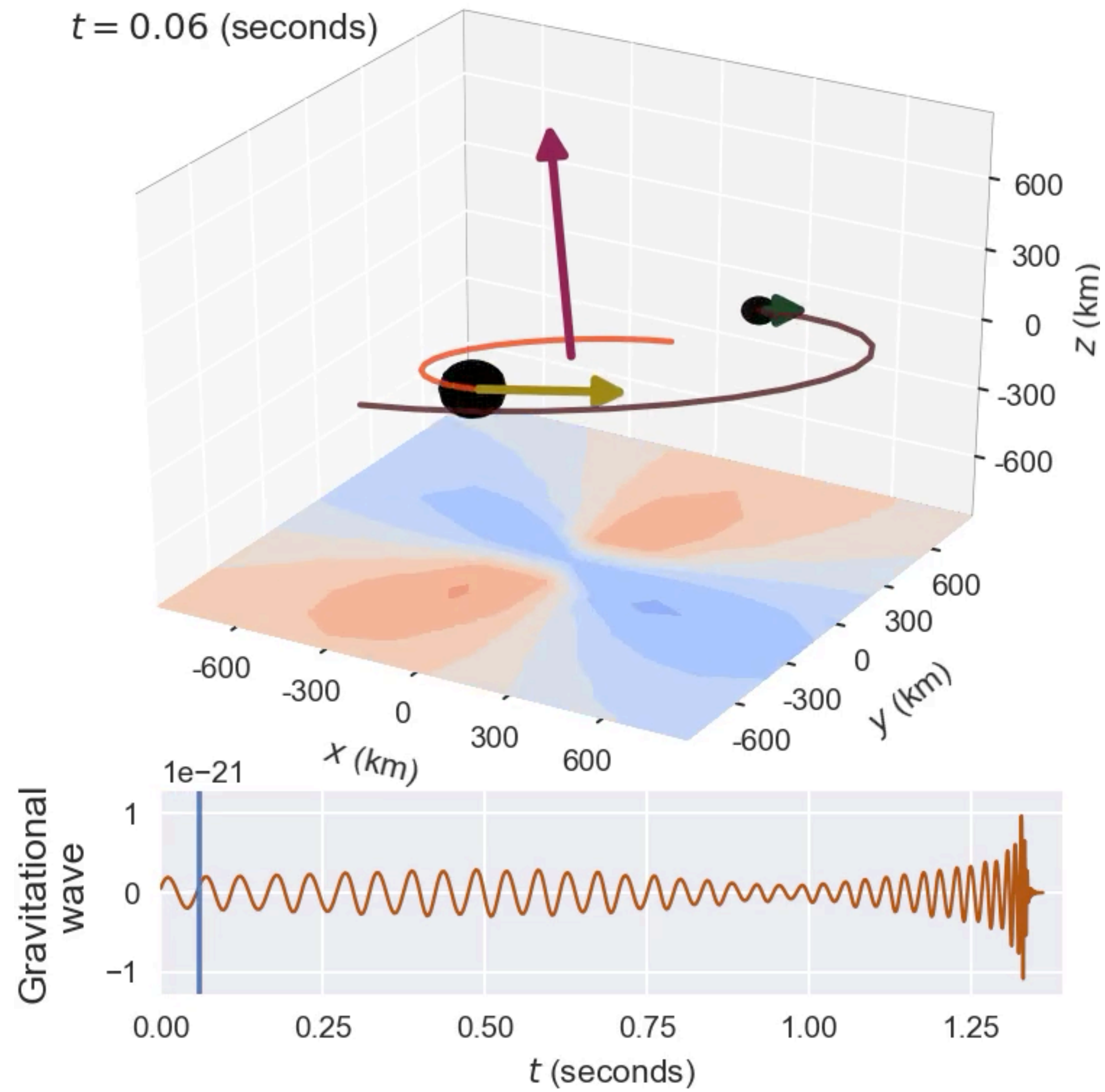
Junk radiation



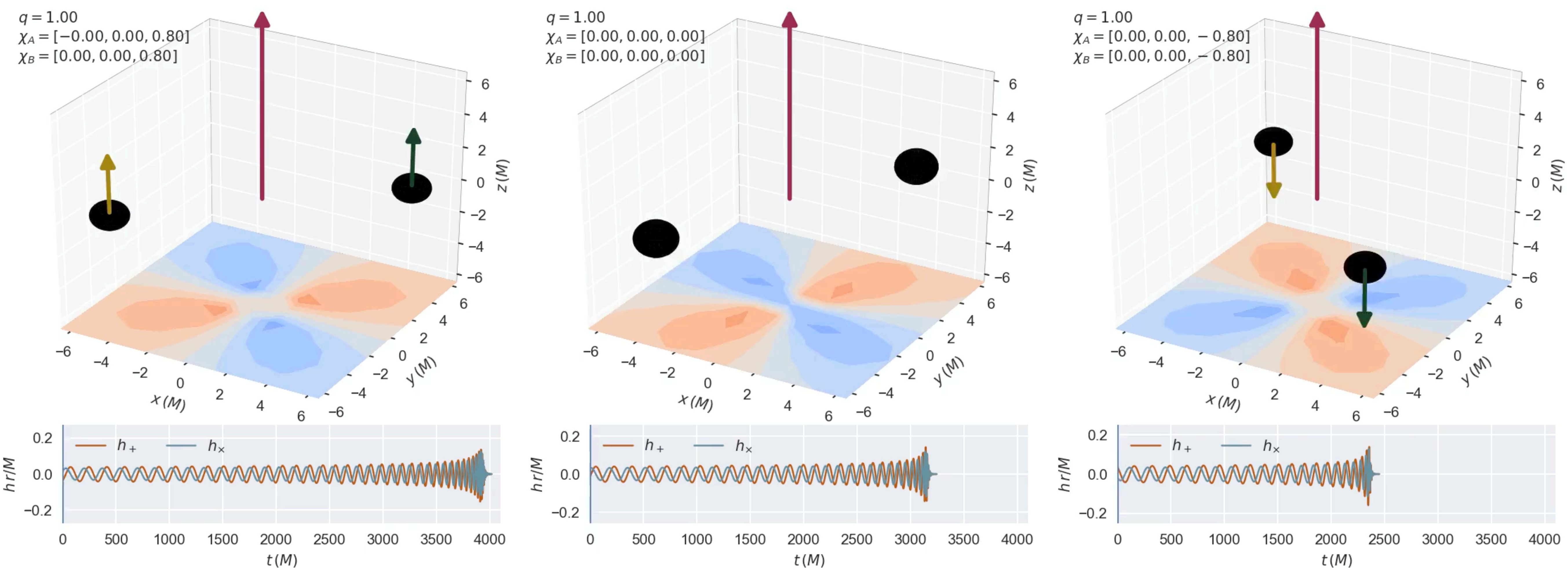

Aligned-spin


Precessing


$t = 0.06$ (seconds)
z (km)
x (km)
y (km)
1e−21
Gravitational wave
t (seconds)

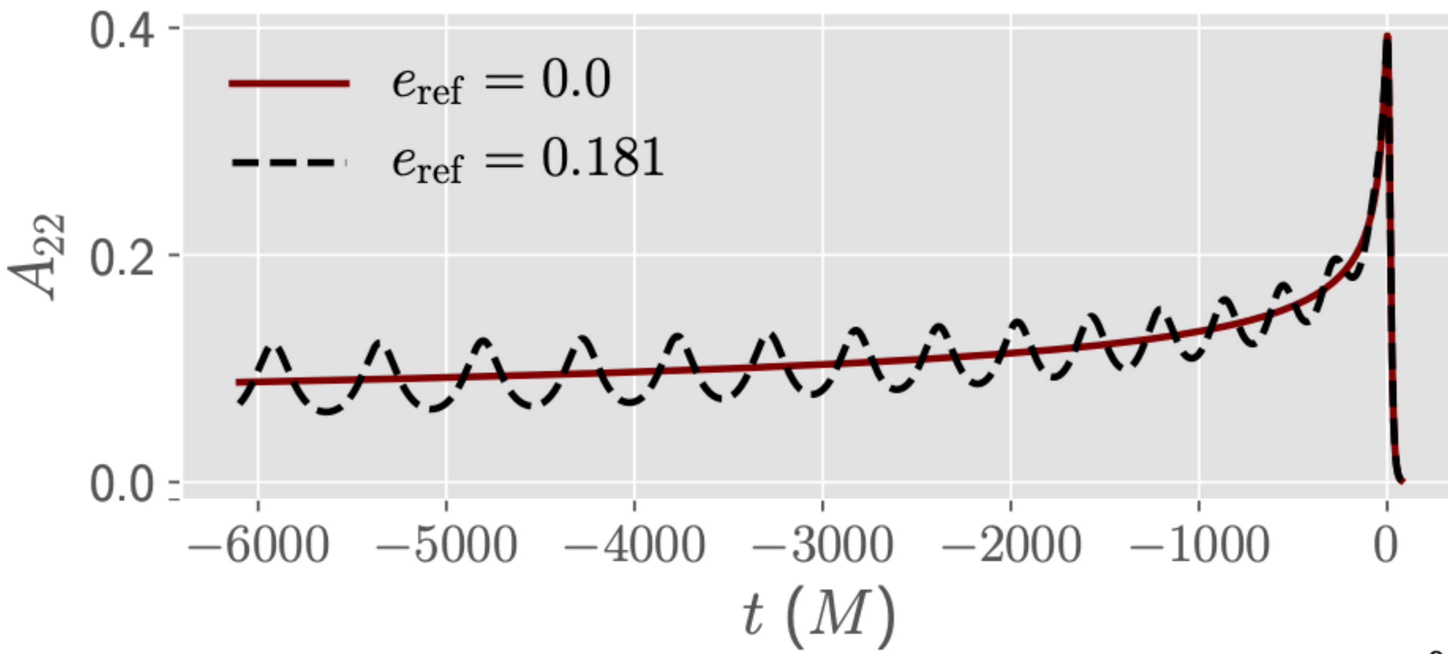

$t = 0.06$ (seconds)
z (km)
x (km)
y (km)
1e−21
Gravitational wave
t (seconds)

Effective spin and orbital "hang-up" effect



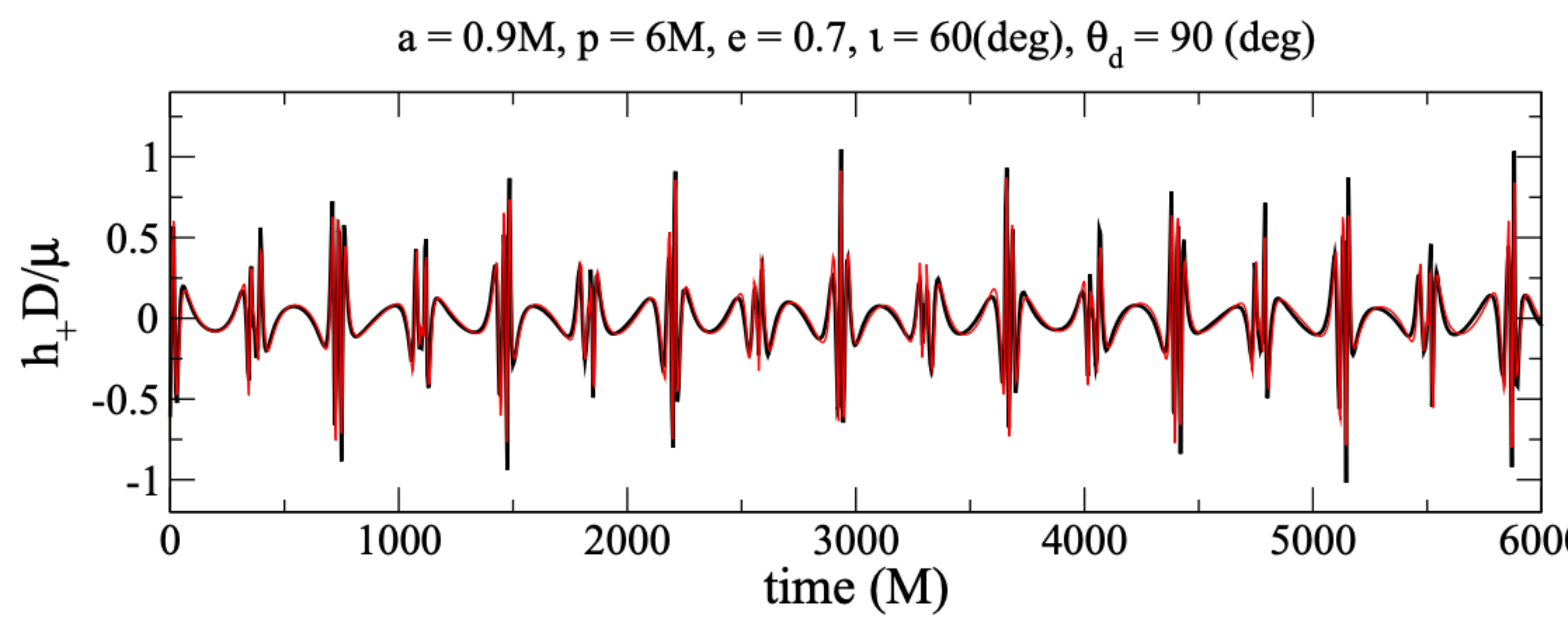
- **Effective spin:** $\chi_{\text{eff}} = (m_1\chi_1 + m_2\chi_2)/(m_1 + m_2)$.
- **Binaries with positive χ_{eff} merge at smaller separations, and at higher frequencies.**

Eccentricity



Islam+ (arxiv: 2101.11798)

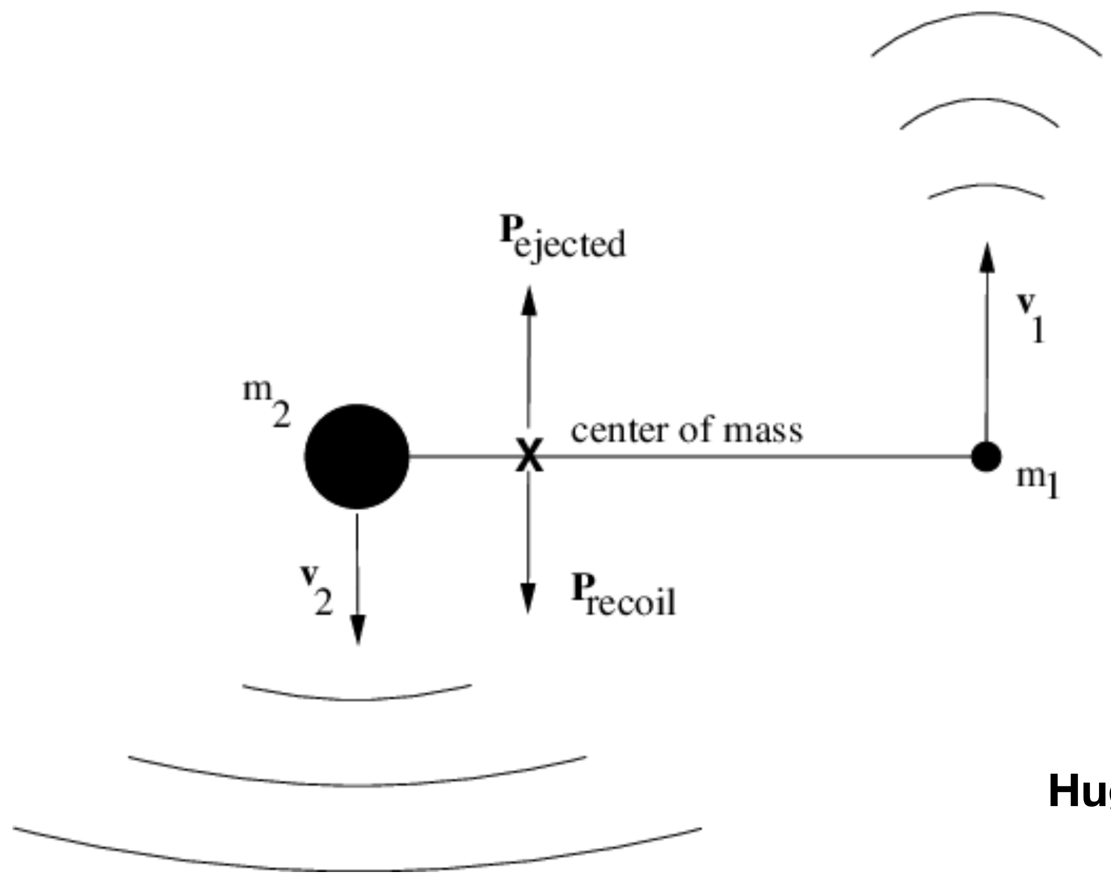
Babak+ (arxiv: 0607007)



- **Two additional parameters: eccentricity and mean anomaly.**
- **More important for LISA than LIGO.**

Merger kicks

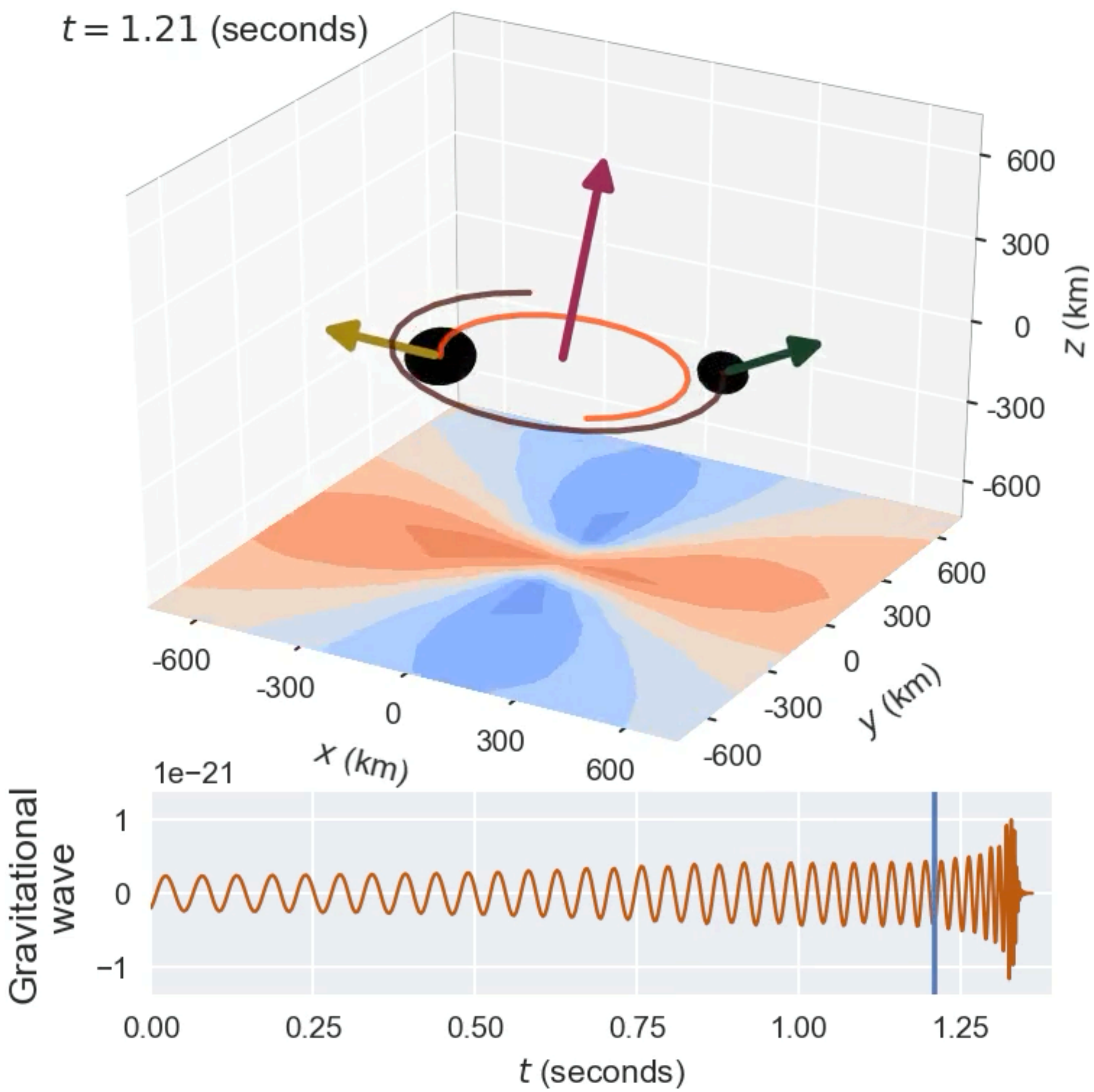
Asymmetry (in masses or spins) is necessary for kicks



Hughes+ (arxiv:0408492)

- GWs can carry linear momentum away from BBHs
- Center-of-mass recoils to compensate
- Recoil or “kick” velocity imparted to final BH
- Kicks up to 5000 km/s possible for precessing BBHs

Superkicks

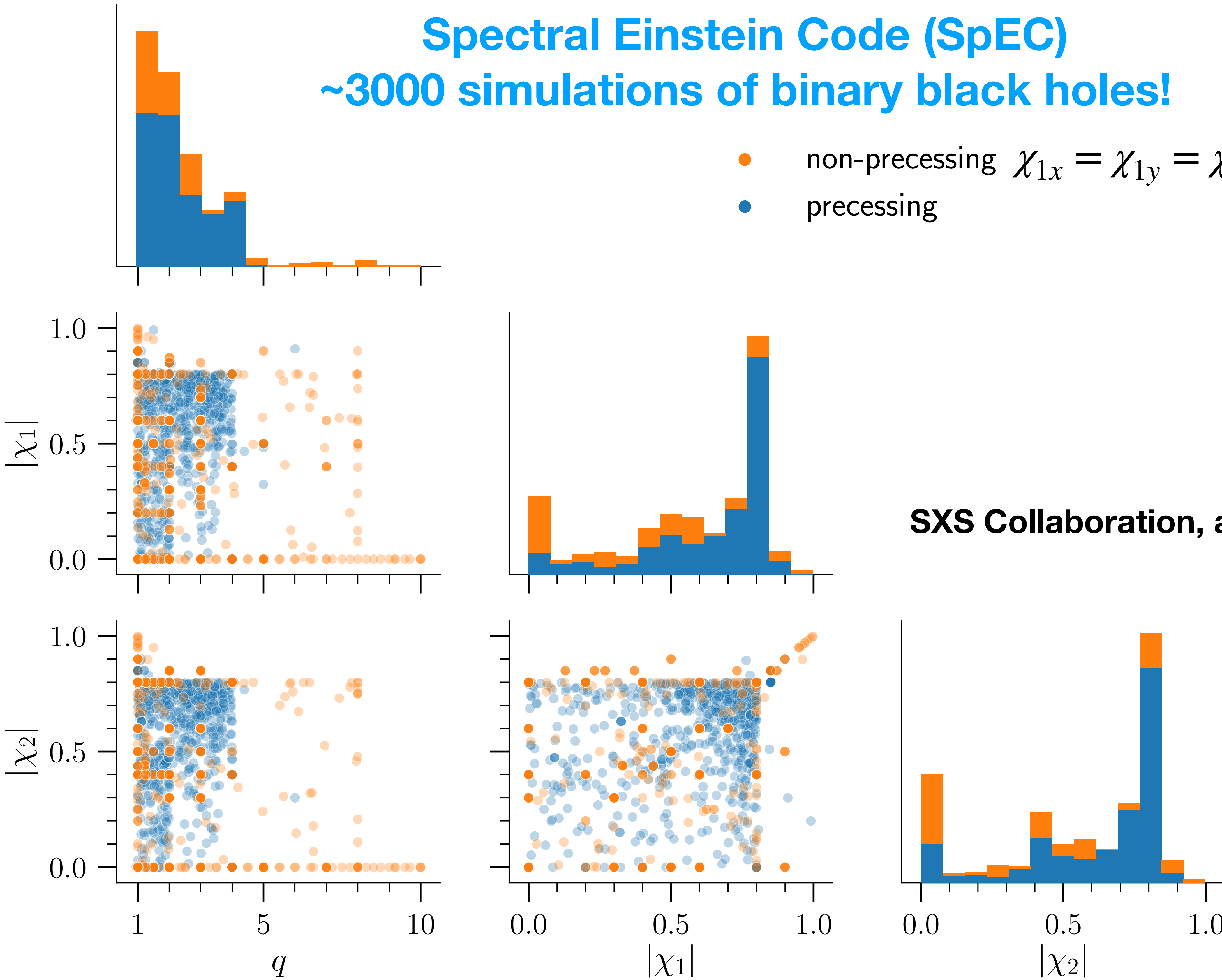


- **Spin asymmetry much more important than mass asymmetry.**

Part III: Status of the field

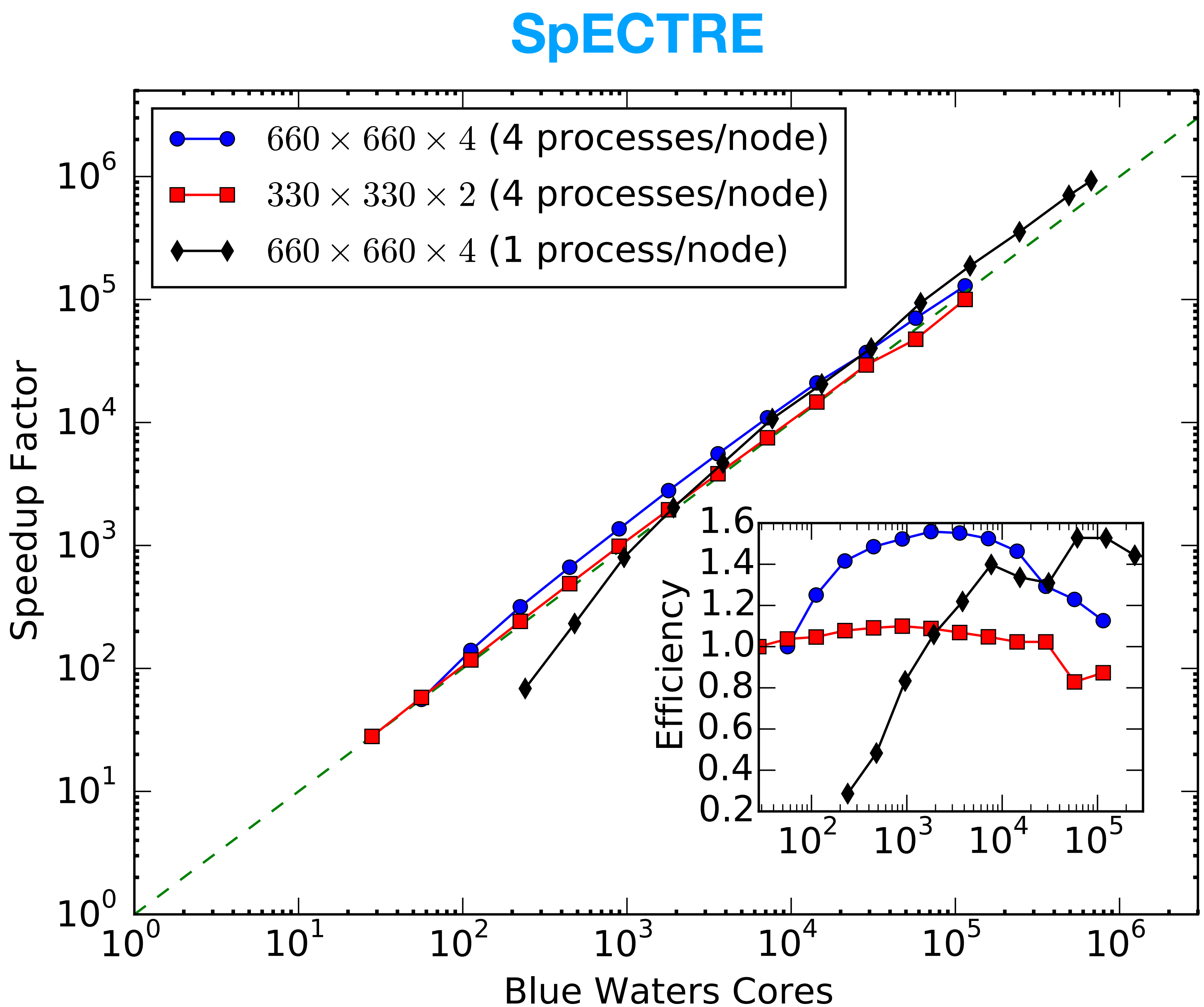
NR simulations today

Spectral Einstein Code (SpEC)
~3000 simulations of binary black holes!



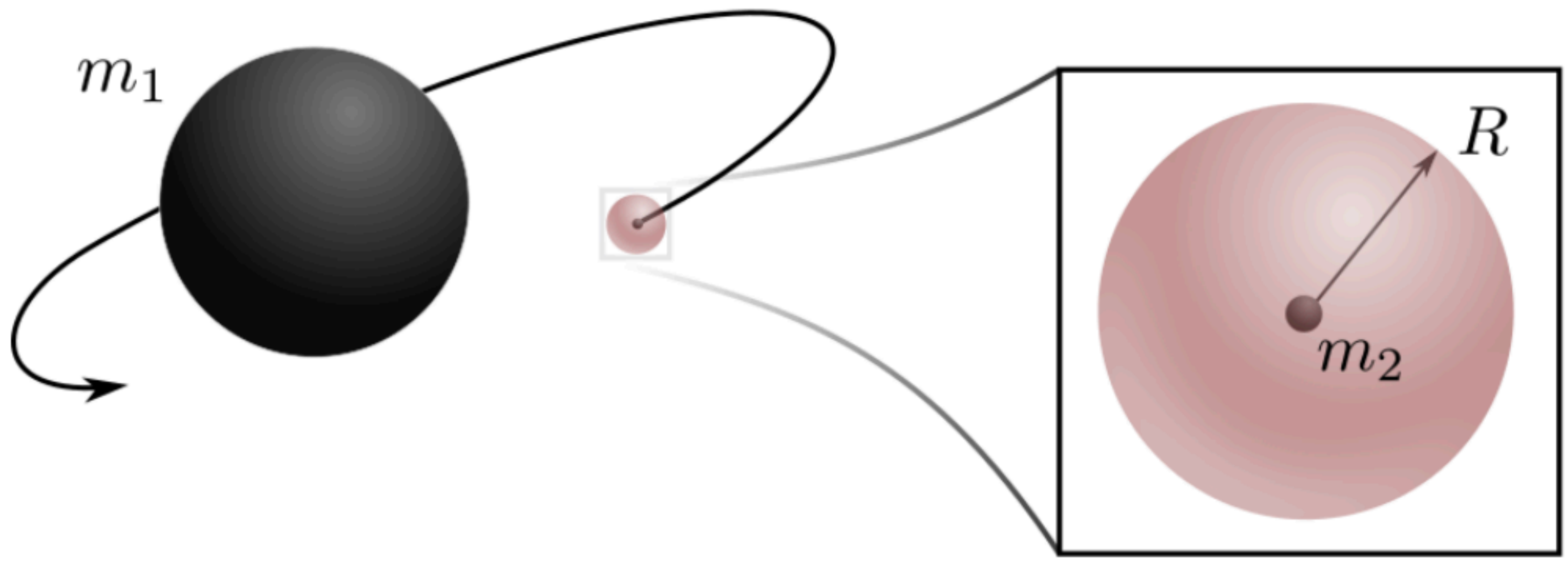
SXS Collaboration, arXiv:1904.04831

Frontiers: Next generation NR codes



Kidder+ (1609.00098)

Frontiers: Extreme mass ratios



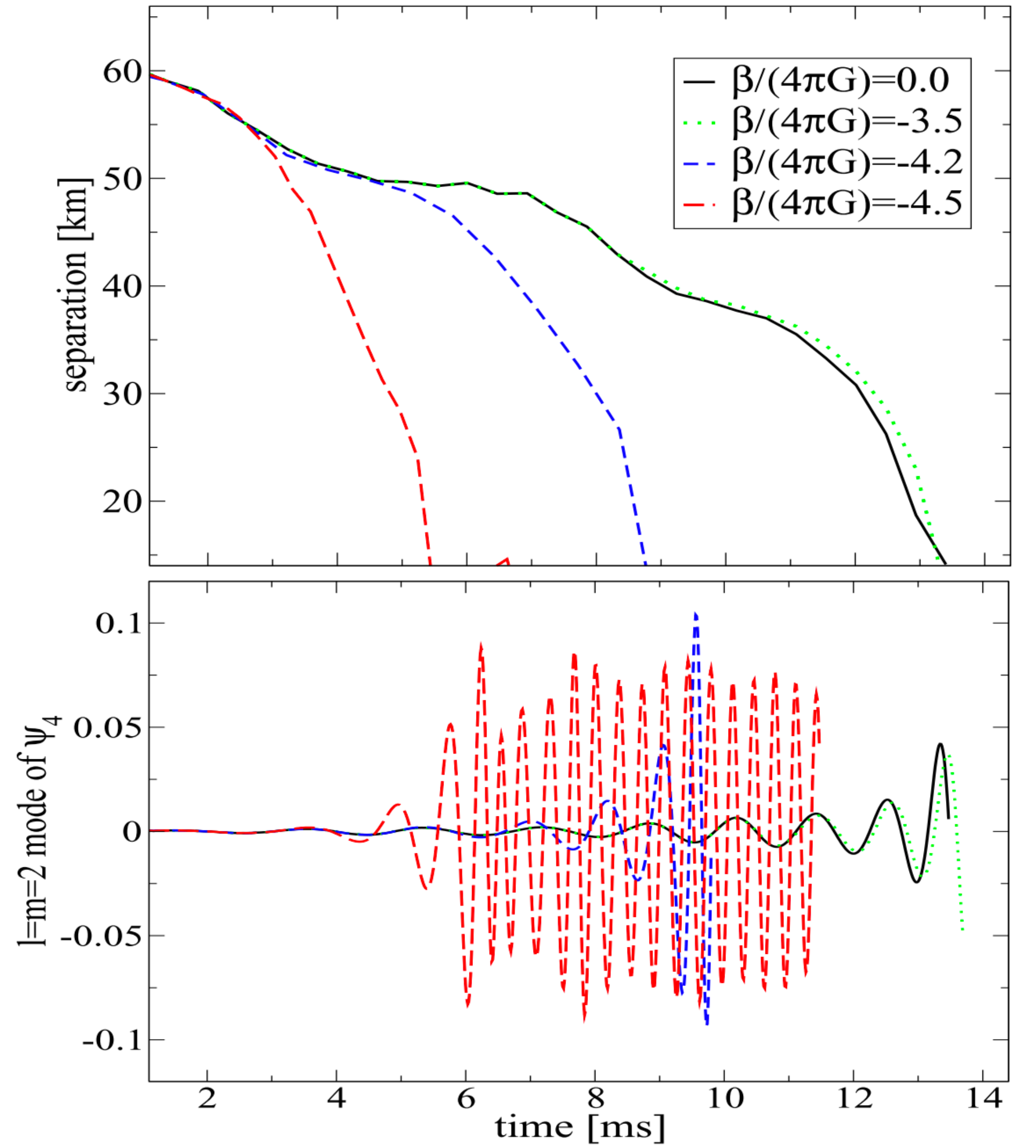
Dhesi+ (2109.03531)

- **Need to resolve the dynamics of the small BH.**
- **Maximum time steps $\sim m_2$, due to Courant condition.**
- **Talk to Niko.**
- **Near extremal spins: Scheel, Giesler+ (1412.1803)**

Frontiers: Simulations of alternate theories

- **BBHs in DCS, EdGB: Okounkova, Ripley, Witek, Silva, etc.**
- **BNS in scalar-tensor gravity: Barausse, Shibata, etc.**
- **BHNS in scalar-tensor gravity: Ma+Varma, etc.**

BNS merger in scalar-tensor



Barausse+ (1212.5053)

Challenges

- **Numerical stability (well-posed?).**
- **Dealing with 3rd/4th derivatives of metric.**
- **Large parameter space, extra fields.**
- **Degeneracies with GR parameters.**