Numerical relativity waveforms: status, progress and open challenges towards 3G detectors

Antoni Ramos-Buades

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MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut
für Gravitationsphysik
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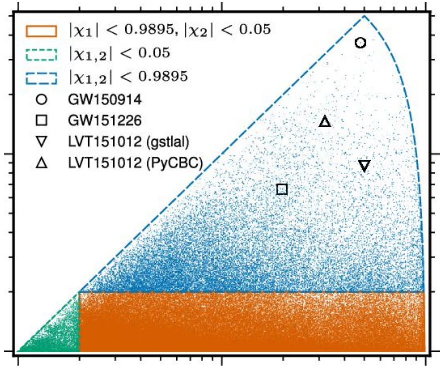
Waveform knowledge crucial for GW astronomy

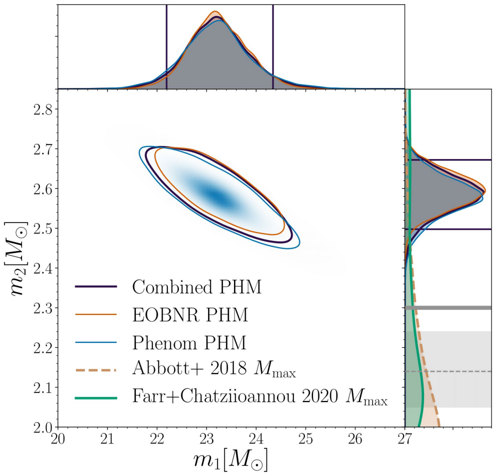
Matched filter searches

LIGO+Virgo, PRX2016 (1606.04856)



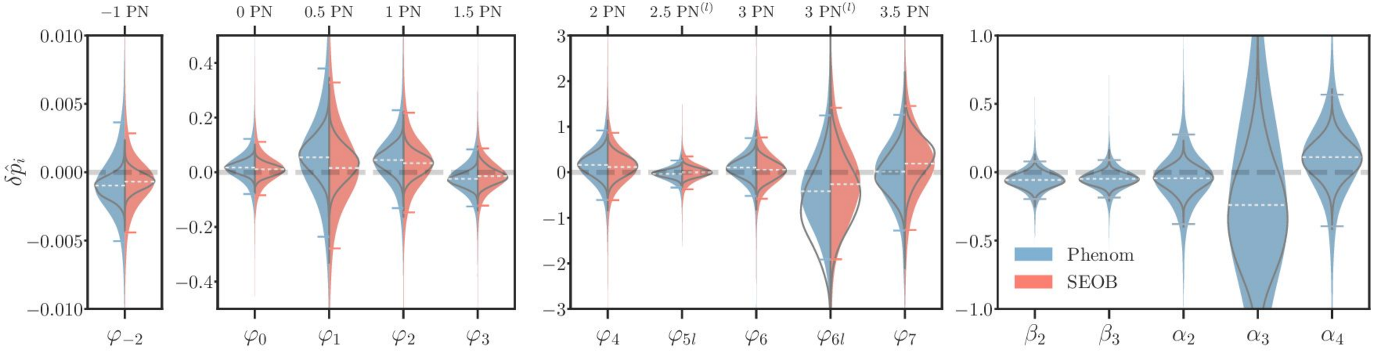
Parameter estimation

GW190814, LIGO+Virgo, AJL2020 (2006.12611)

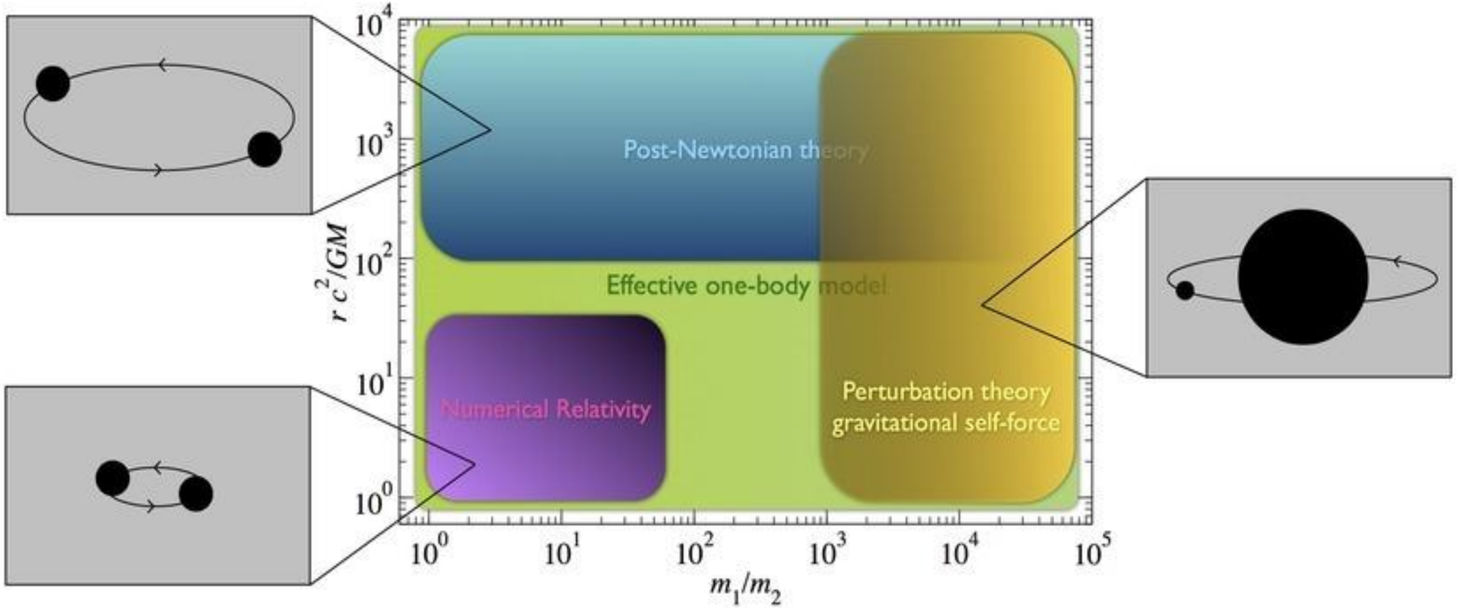


Testing GR

LIGO+Virgo+KAGRA PRD2021 (2010.14529)



Methods for modeling compact binaries



The first 60 years of numerical relativity for BBHs

1962 ADM
3+1 formulation

1964
Hahn-Lindquist
2 wormholes

1984
Unruh
excision

1992-93
Choptuik,
Abrahams+Evans
critical phenomena

1997
Brandt-Brugmann
puncture data

1994-98
BBH Grand Challenge

1999-00
AEI/PSU
grazing collisions

~2000 Choptuik;
Schnetter; Brugmann
mesh refinement

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

2005 Gundlach+
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, UIB, Cardiff
phenom GW models

2009-
UMD, SXS
EOB GW models

2011
Schmidt+; Boyle+
Radiation aligned frame

2018-22
BAM, Maya, RIT, SXS
large catalogs of BBHs

2018-
Huerta+;ARB+;Islam+
Catalogs of eccentric BBHs

1964 — ~1999 — ~2005 — ~2015 — 2023

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
NSCA-WashU
improved
head-on collision

1999 BSSN
evolution system

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

2000-02
Alcubierre
gauge conditions

1999 York
conformal thin
sandwich ID

2000 Ashtekar
isolated horizons

2006-07
Baker+; Gonzalez+;
non-spinning BH
kicks

2004
Brugmann+
one orbit

2003-08
Cook, Pfeiffer+
improved ID

2007-11
RIT; Jena, AEI;...
BBH superkicks

2007 SXS
PN-NR comparison

2009-11
Bishop, ...
Cauchy
characteristic
extraction

2010
Bernuzzi+
C4z

2008
all of NR
NINJA

2011
Lovelace+
a = 0.97

2011
Lousto+
q=100

2011
LeTiec+
self-force
studies

2013
GaTech; SXS
Precessing
parameter studies

2019-20
Pound+; Wardell+;
Second order self-force
NR comparisons

2019-
Kidder+; Fernando+;
Daszuta+; ...
Next generation of
numerical relativity codes
(SpECTRE, Athena++,
DendroGR,...)

Based on slide by Lousto and Pfeiffer

Two main approaches for BBH simulations

BSSN and moving punctures

BAM, ETK, LazEv, Goddard, GRChombo, Lean, …

Puncture initial data
spins<0.9 (except Zlochower+17)

BSSN or CC4z

Moving puncture
mergers "easy"

Sommerfeld outer boundary condition

Finite-difference methods

GW extrapolation
(Healy,Lousto20 for LazEv CoM correction)

Generalized harmonic and spectral

SpEC (SXS collaboration)

Quasi-equilibrium excision data
spins<0.999

Generalized harmonic evolution system

BH excision
mergers "difficult"

Constraint preserving, minimally reflective outer boundary condition

Spectral methods

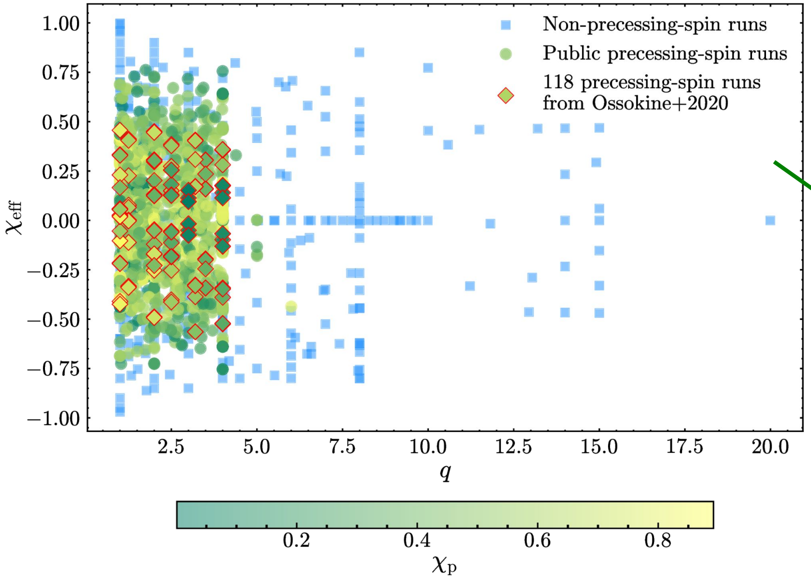
→ *long, accurate inspirals*

GW extrapolation & CoM correction

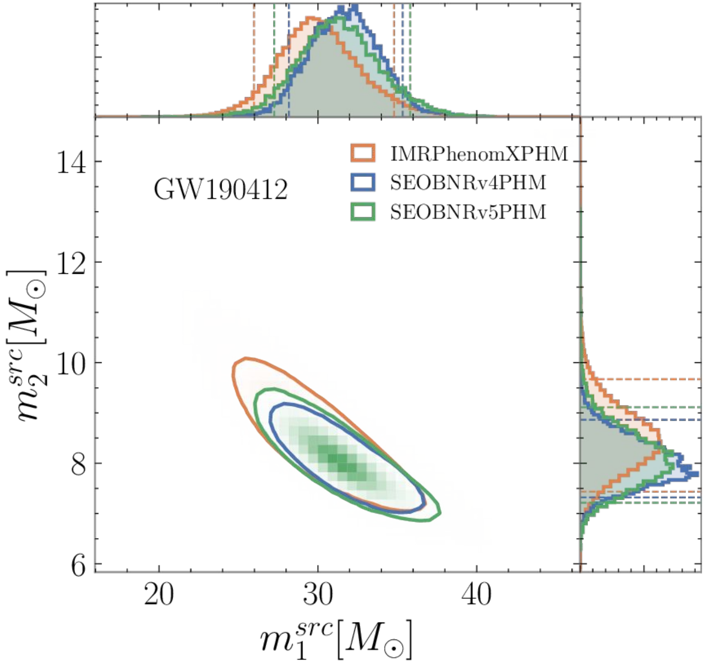
Cauchy-characteristic extraction
accurate m=0 modes, GW memory

Applications of BBH simulations

- Parameter space coverage (Maya, RIT, SXS catalogs)
- Improvement of semi-analytical waveform models.
- Benchmark perturbative methods.



SEOBNRv5PHM



ARB+2023 (2303.18046)

Challenge of NR: small mass ratios

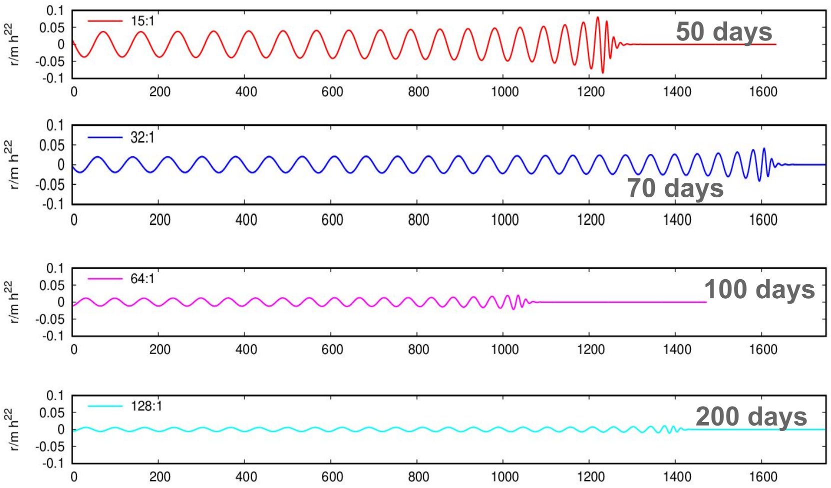
- Number of time-steps

$$N_{\rm steps} \propto \frac{1}{q^2}\frac{1}{(M\Omega_0)^{8/3}}$$

q : steps per orbit (Courant limit - numerics)
q : orbits per inspiral (physics)
$(M\,\Omega_0)^{8/3}$: starting frequency

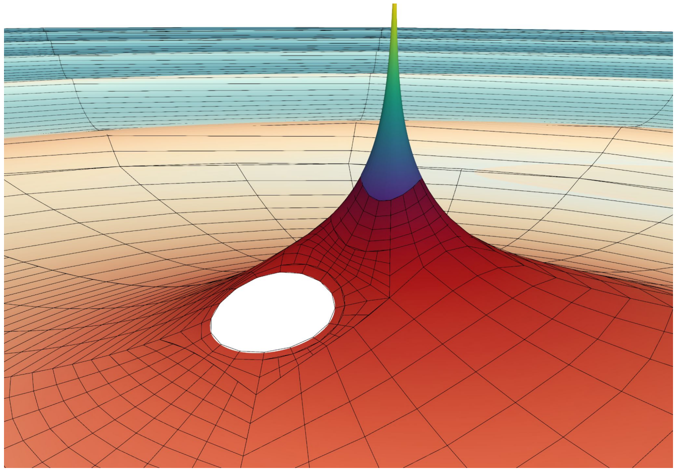
$\chi \gtrsim 0.6$: extra factor ~ $1/(1-\chi_1)(1-\chi_2)$

Lousto&Healy20 (2006.04818)



Very expensive and limited convergence tests for 1/q >32

- New methods to remove 1/q factor due to the Courant limit [Wittek+23]
    - Worldtube excision of the small BH.
    - Interior perturbative solution matched with outer full evolution.



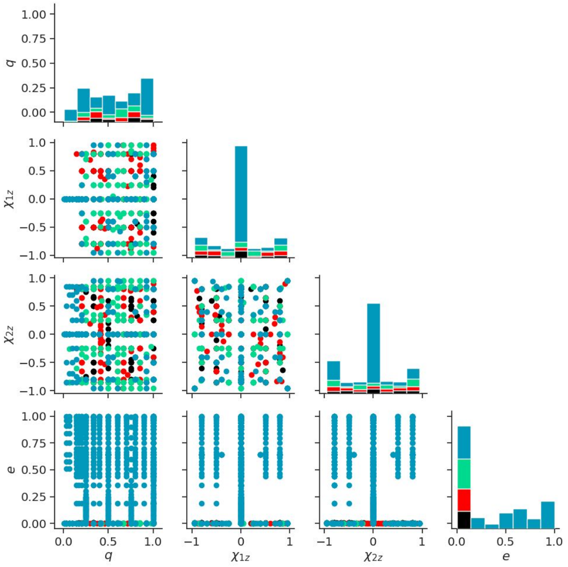
Wittek+23 (2304.05329)

Working example for scalar charge, implementation on BBHs on progress

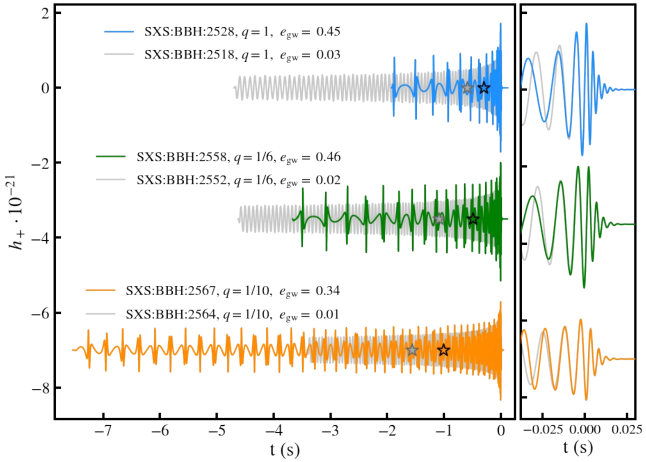
Beyond quasi-circular BBHs

- Full BBH parameter space : mass ratio, spins, eccentricity, radial phase.
- Large catalogs (Maya, RIT and SXS catalogs) → mostly quasi-circular.
- 3G detectors → higher sensitivity at low frequencies → non-circular binaries more likely (Sessana10,Samsing+2018)

Efforts to populate eccentric BBH parameter space
(Hinder+17,Huerta+19, ARB+20, Islam+20, Healy+22,ARB+22)

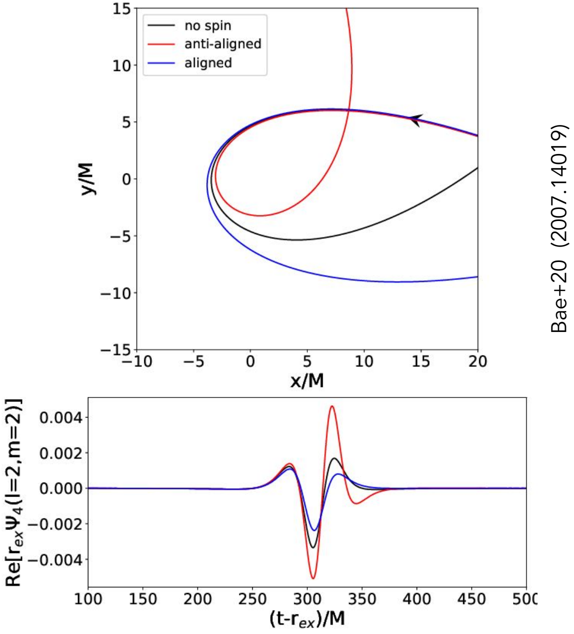


Healy+22 (2202.00018)



ARB+22 (2209.03390)

Unbound-orbit BBH parameter space exploration
(Damour+14, Bae+17, Bae+20, Hopper+22, Rueter+23)

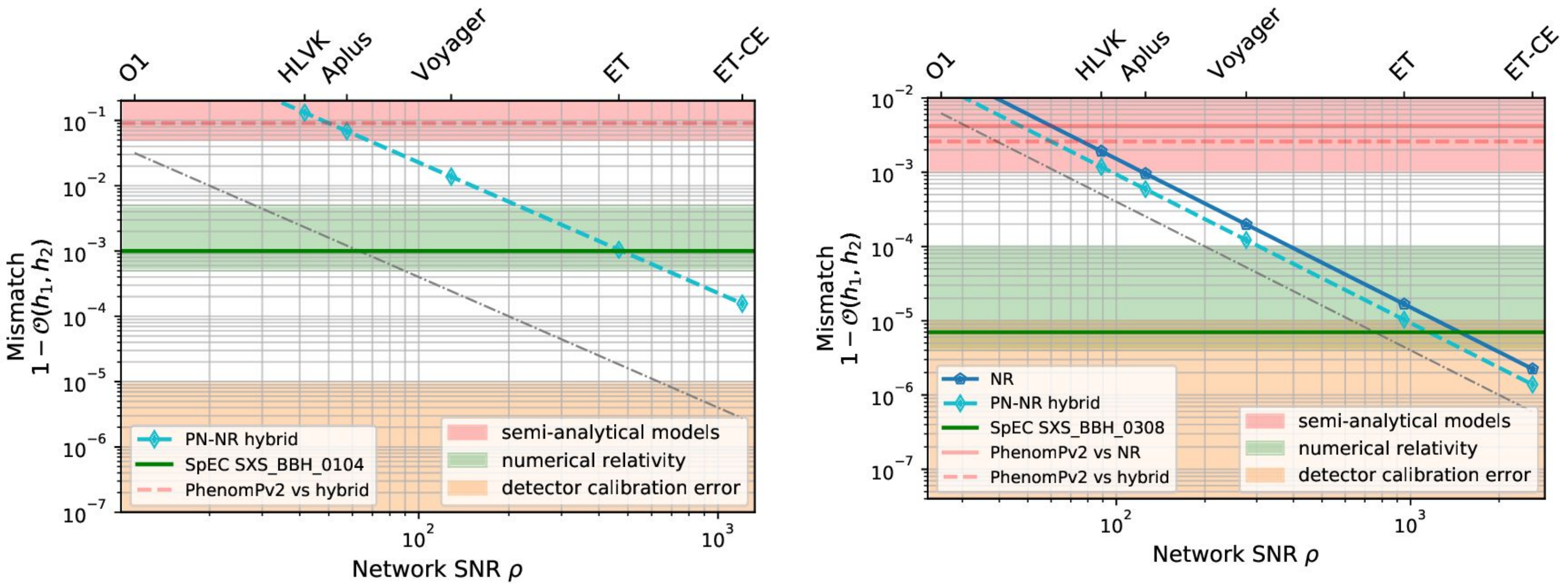


q=1, $|\chi_1|=|\chi_2|=0.5$

Eccentric and unbound-orbit waveform models
(Hinder+17, Huerta+19, Nagar+21, Islam+21, Liu+2021, ARB+21)

Accuracy requirements for future GW detectors

- Studies of accuracy requirements on waveform models and NR waveforms [Puerrer, Haster19; Ferguson+20].
- **For 3G waveform models to be at least 3 orders of magnitude more accurate, 1 order of magnitude for NR waveforms.**



q=1.22, χ_{eff} = -0.08, χ_p =0.3, θ_{JN}=2.7 (~GW150914-like)

q=3, χ_{eff} = 0.37, χ_p =0.14, θ_{JN}=1.08

Puerrer, Haster19 (1912.10055)

- Conservative estimate based on indistinguishability criterion → **More systematic studies needed!**

Conclusions

- Current NR codes → routinely simulations of compact binaries (BBHs, BNS, core-collapse supernovae,...)
- Main open challenges:
  - **BBHs:**
    - **Parameter space coverage.**
    - **Meet accuracy and length requirements.**
    - Initial data for extremal configurations and beyond GR theories.
    - Evolutions in beyond GR theories.
  - BNS:
    - Accuracy of codes to more complex EoS.
    - More accurate post-merger GW signals (MHD and neutrinos).
    - Resolution of the growth of large scale magnetic fields.
  - Core-collapse supernovae:
    - Parameter space coverage of microphysics accurate 3D simulations.
    - Realistic initial conditions from late-stage massive stars.
- Next generation of NR codes under development to address these challenges!