Title: Nonlinear dynamics of compact object mergers beyond General Relativity.

Speakers: Maxence Corman

Collection/Series: Strong Gravity

Subject: Strong Gravity

Date: February 13, 2025 - 1:00 PM

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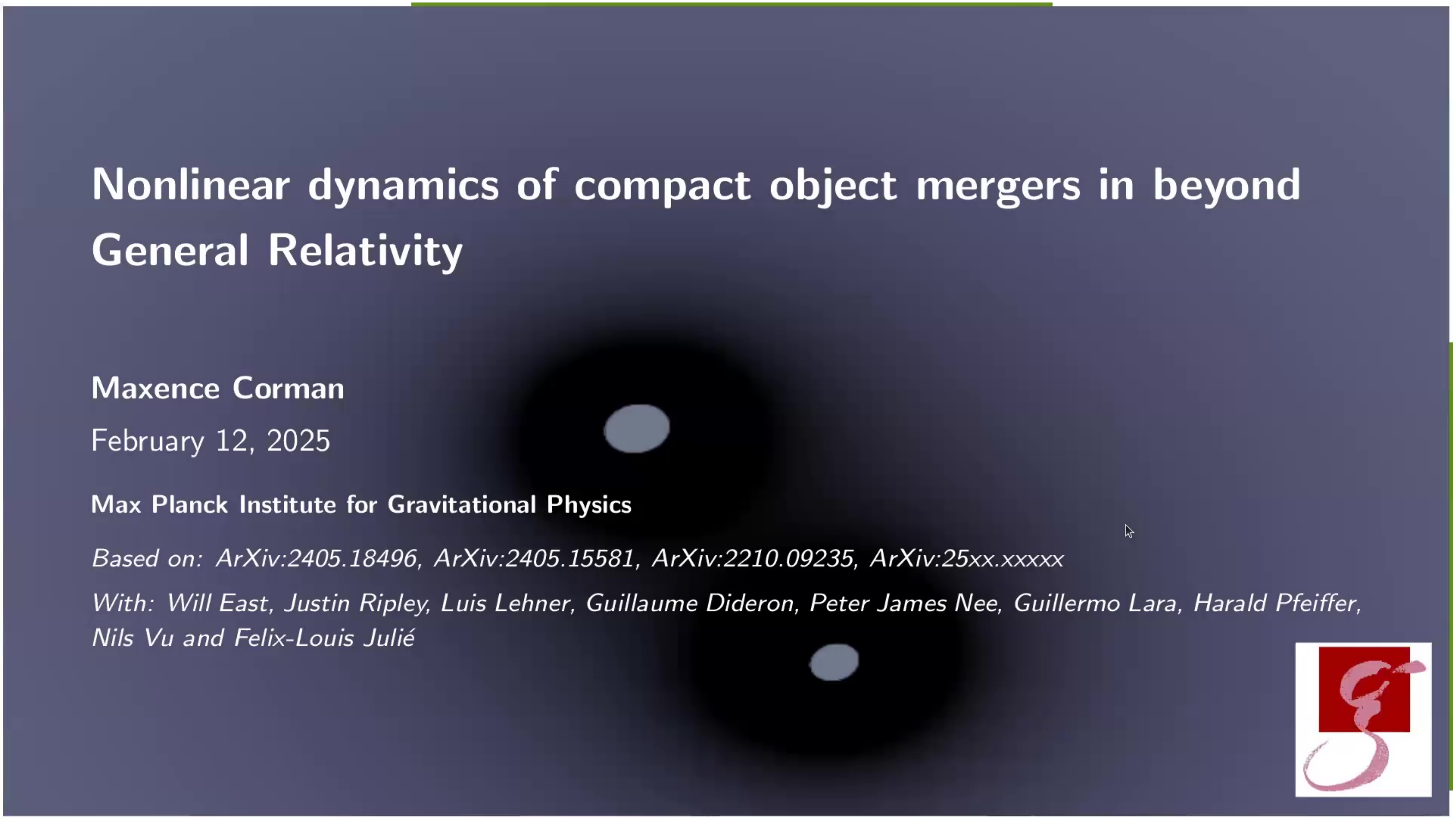
Abstract:

In recent years, gravitational wave observations of compact objects have provided new opportunities to test our understanding of gravity in the strong-field, highly dynamical regime.

To perform model-dependent tests of General Relativity with these observations, as well as to guide theory-agnostic tests, it is crucial to develop accurate inspiral-merger-ringdown waveforms in alternative theories of gravity.

In this talk, we discuss the challenges, recent progress, and future directions in incorporating modifications to full General Relativity. As a concrete example, we consider Einstein-scalar-Gauss-Bonnet gravity, which introduces deviations from General Relativity at small curvature length scales.



Nonlinear dynamics of compact object mergers in beyond General Relativity

Maxence Corman

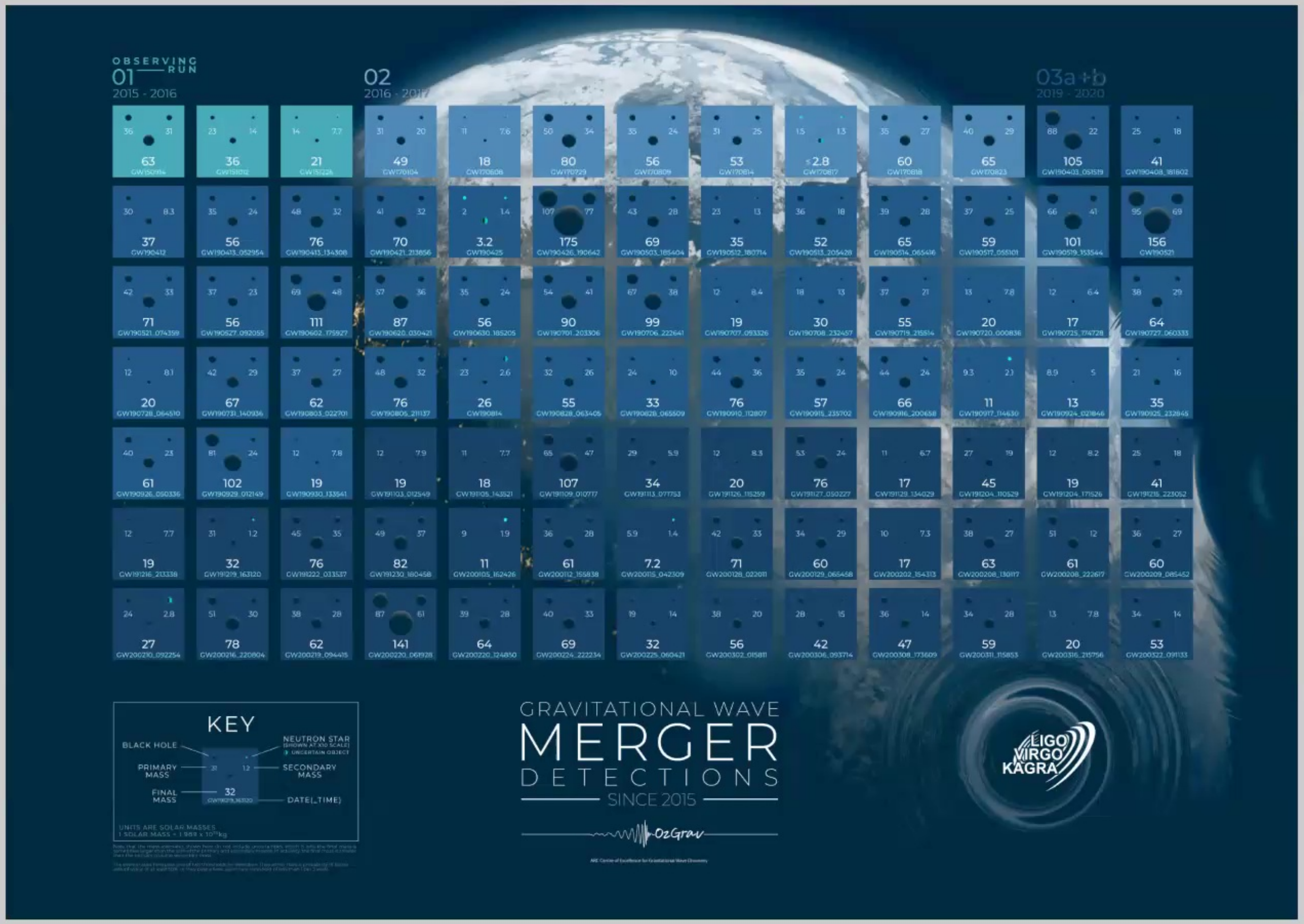
February 12, 2025

Max Planck Institute for Gravitational Physics

Based on: ArXiv:2405.18496, ArXiv:2405.15581, ArXiv:2210.09235, ArXiv:25xx.xxxxx

With: Will East, Justin Ripley, Luis Lehner, Guillaume Dideron, Peter James Nee, Guillermo Lara, Harald Pfeiffer, Nils Vu and Felix-Louis Julié

Motivation


OBSERVING RUN
01
2015 - 2016
02
2016 - 2017
O3a+b
2019 - 2020
KEY
BLACK HOLE
NEUTRON STAR
PRIMARY MASS
SECONDARY MASS
FINAL MASS
DATE(_TIME)
GRAVITATIONAL WAVE
MERGER
DETECTIONS
SINCE 2015
OzGrav
LIGO
VIRGO
KAGRA

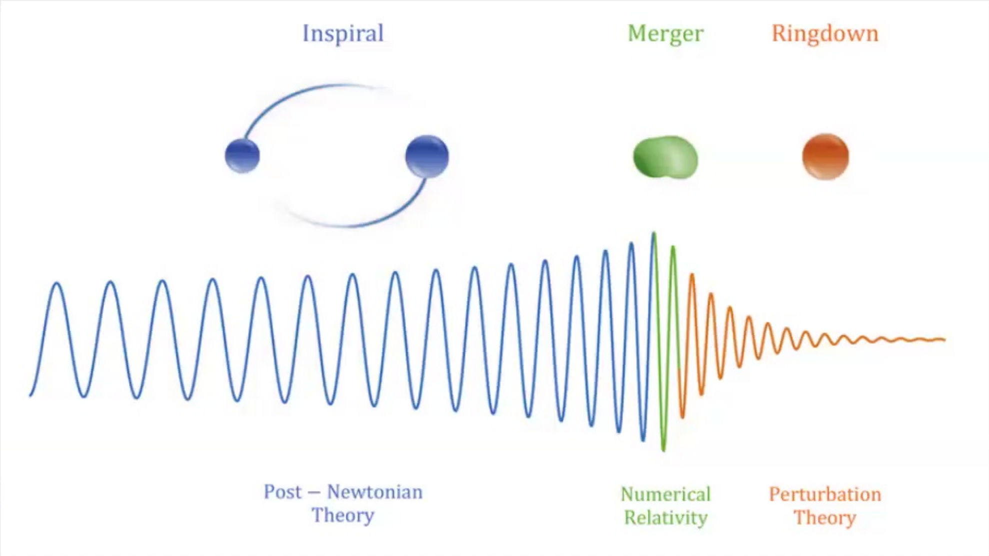
Testing General Relativity with Gravitational Waves

Modified theory of gravity

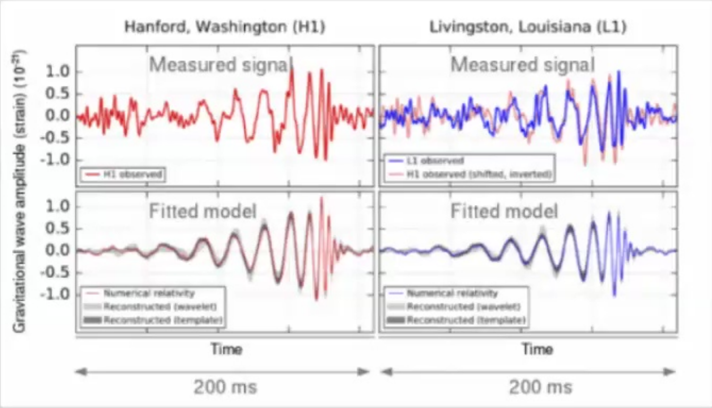
Top-down

Solve equations of motion and
Extract gravitational wave signal

Data

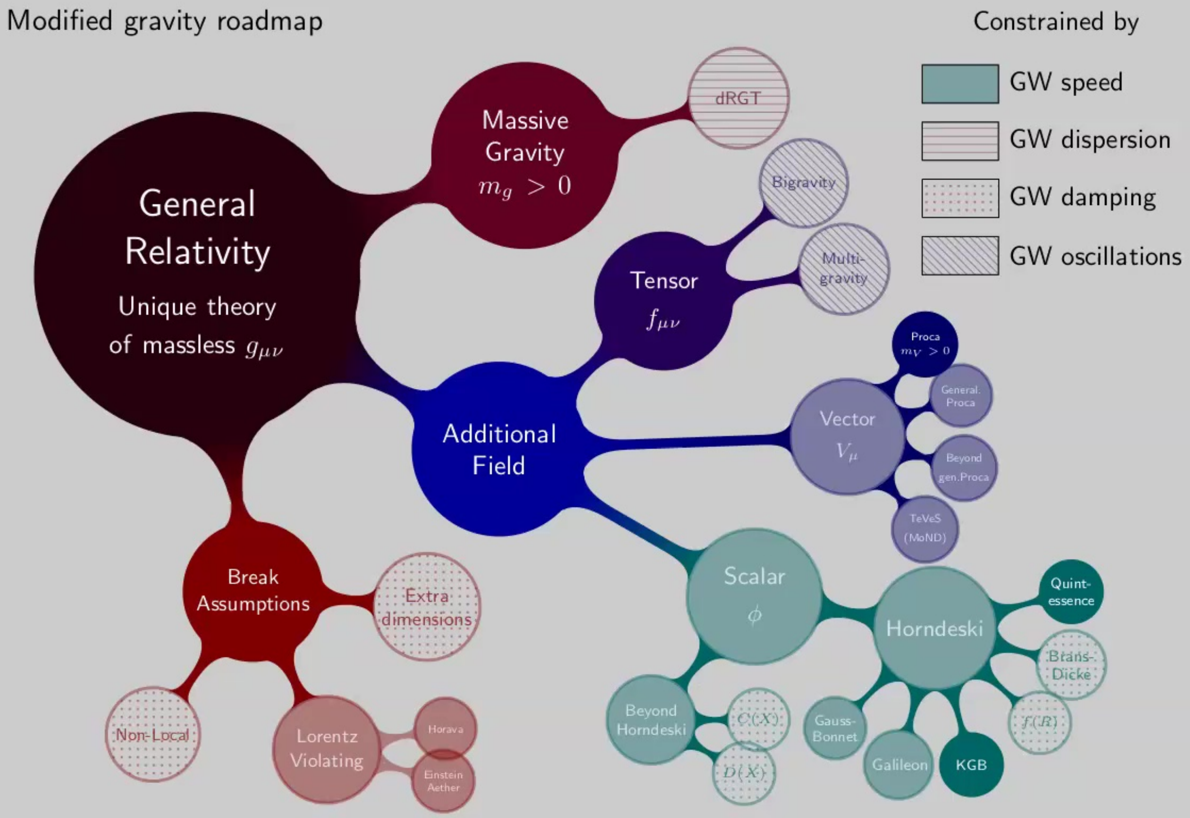


Introduction to Einstein's Theory of Relativity, Øyvind Grøn



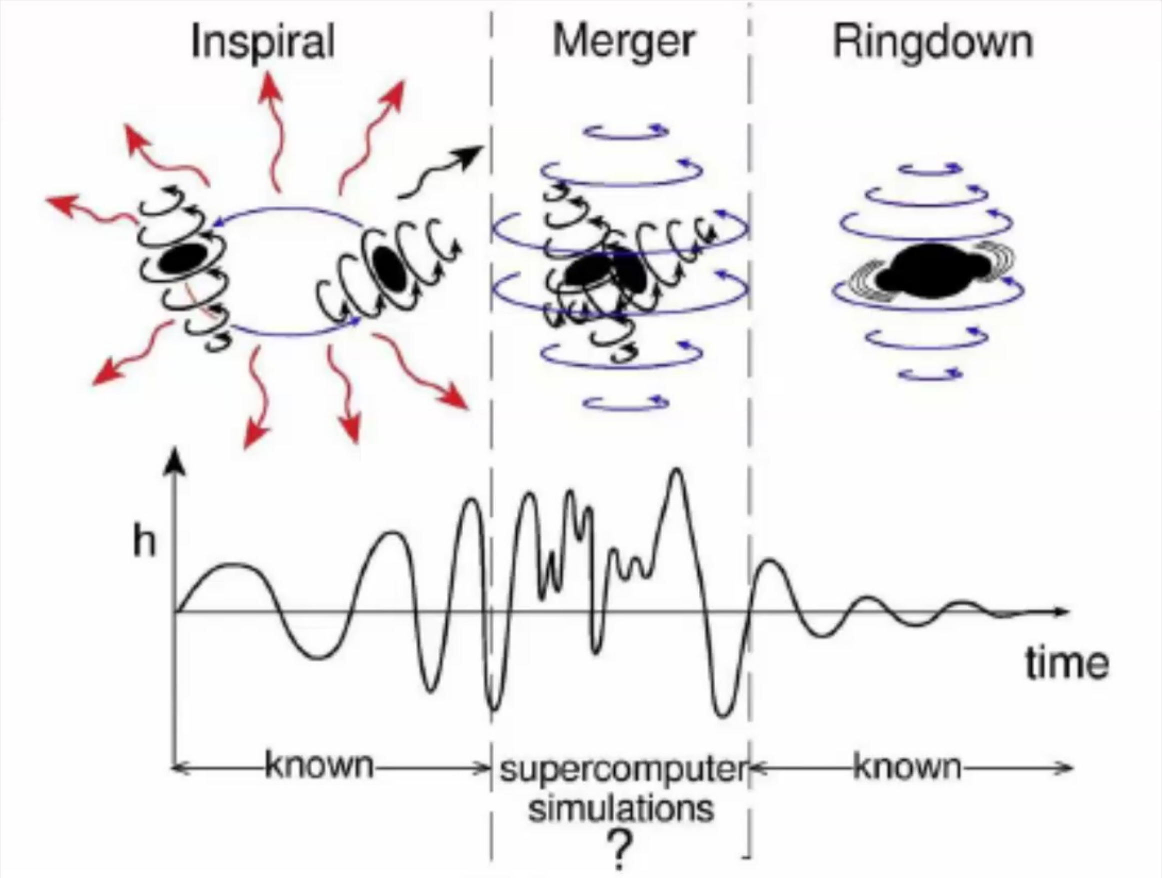
http://public.virgo-gw.eu/gw150914_en/

Testing General Relativity with Gravitational Waves



Modified gravity roadmap summarizing the possible extensions of GR from Ezquiaga and Zumalacarregui, arXiv:1807.09241

Testing General Relativity with Gravitational Waves



Credits:Kip Thorne

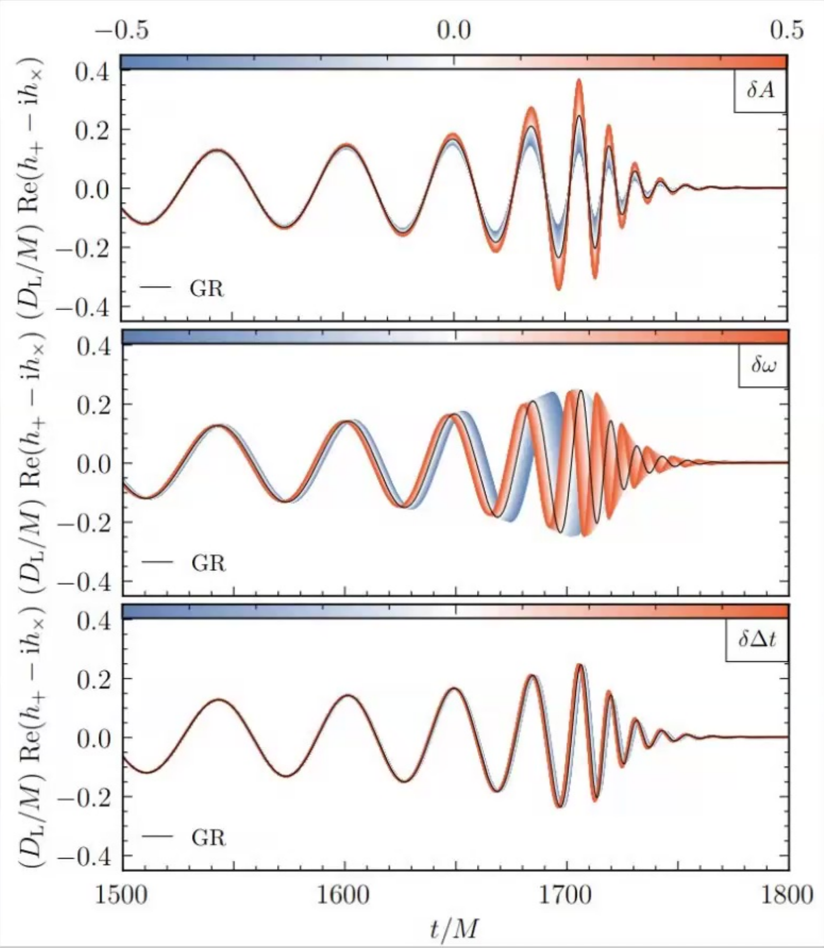
Testing General Relativity with Gravitational Waves

Modified theory of gravity

Phenomenological deviations from General Relativity

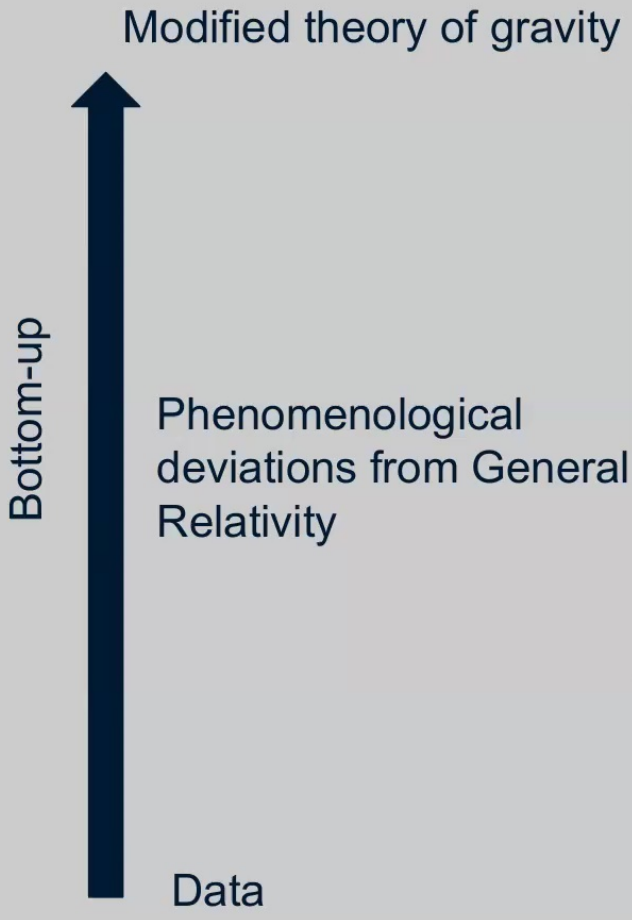
Data

Bottom-up



Maggio 2022, arXiv:2212.09655

Testing General Relativity with Gravitational Waves

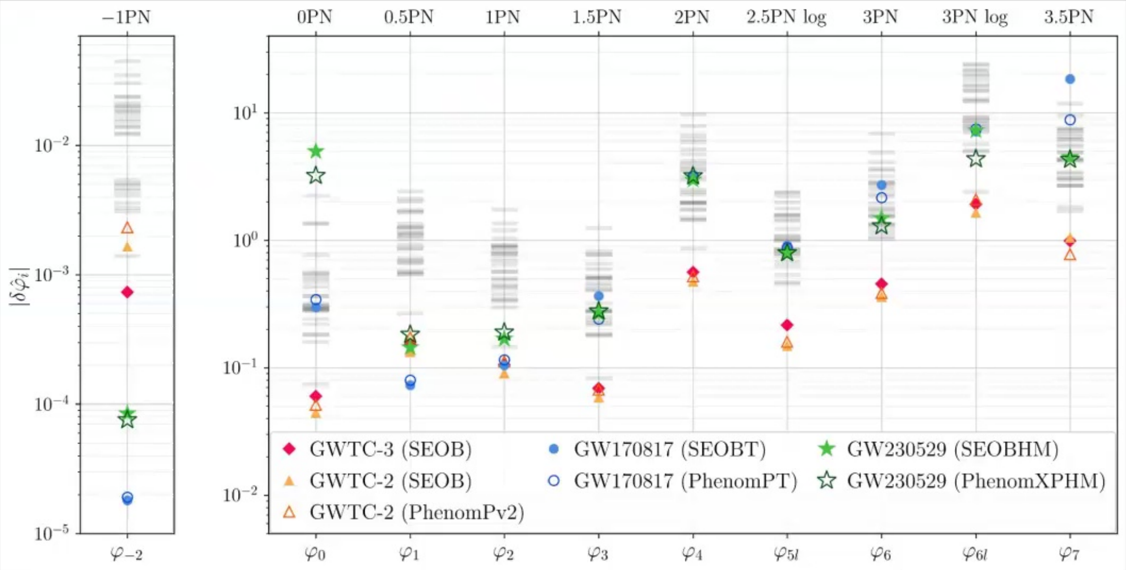


Modified theory of gravity

Bottom-up

Phenomenological deviations from General Relativity

Data



Parameterized test of GR during inspiral from Sanger+ 2024, arXiv:2406.03568

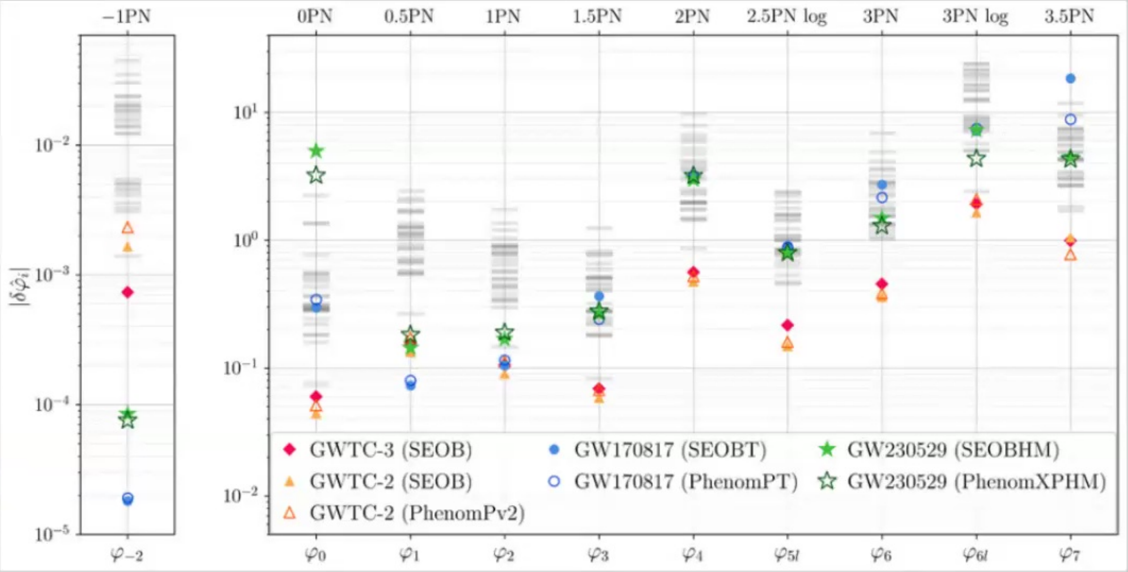
Testing General Relativity with Gravitational Waves

Modified theory of gravity

Bottom-up

Phenomenological deviations from General Relativity

Data



Top-down vs Bottom-up

✖ Theory agnostic tests suboptimal

✓ Theory agnostic tests represent larger group of theories

✓ Need for specific waveforms to test, improve and motivate generic tests

✓ Need for specific waveforms to interpret signal

Approaches to studying modifications to general relativity

Full solution: Requires well-posed initial value problem formulation

- Same principal part as GR: Scalar-Tensor theories Damour, Esposito-Farese → Barausse+,Shibata+, Quadratic Gravity Noakes ⇒ Held+,East+
- Only scalar part modified: Cubic Horndeski Figueras+, Screening theories Bezares+
- Horndeski theories: Modified Generalized Harmonic formulation Kovacs and Reall → East+,Corman+ or modified CCZ4 formulation Salo+

Approaches to studying modifications to general relativity

Order-by-order

- Solve the equations *perturbatively*
- Pros: same principal part as GR, easy to implement and flexible
- Cons: secular effects
- Applications: EdGB and dCS

Okounkova+,Stein+

Fixing

- Inspired by Israel-Stewart fixing of relativistic hydrodynamics
- Fix evolution equations below some short lengthscale
- Add new dynamical fields with driver equations
- Pros: Corrections fully backreact
- Cons: Computationally expensive
- Applications: EsGB, Higher derivative theories

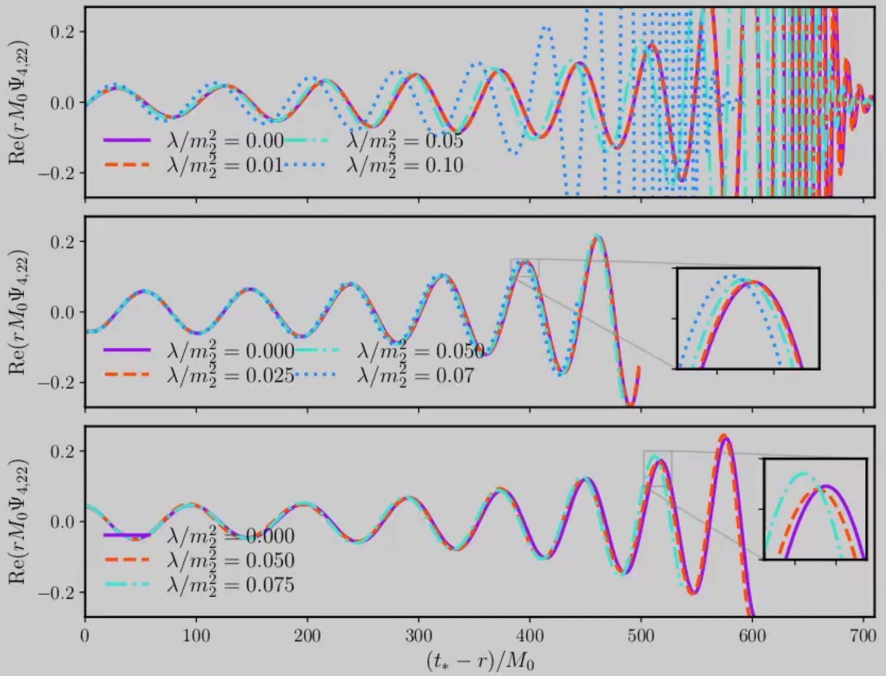
Cayuso+,Lehner+,Bezares+,Lara+,Franchini+

Einstein scalar Gauss Bonnet gravity

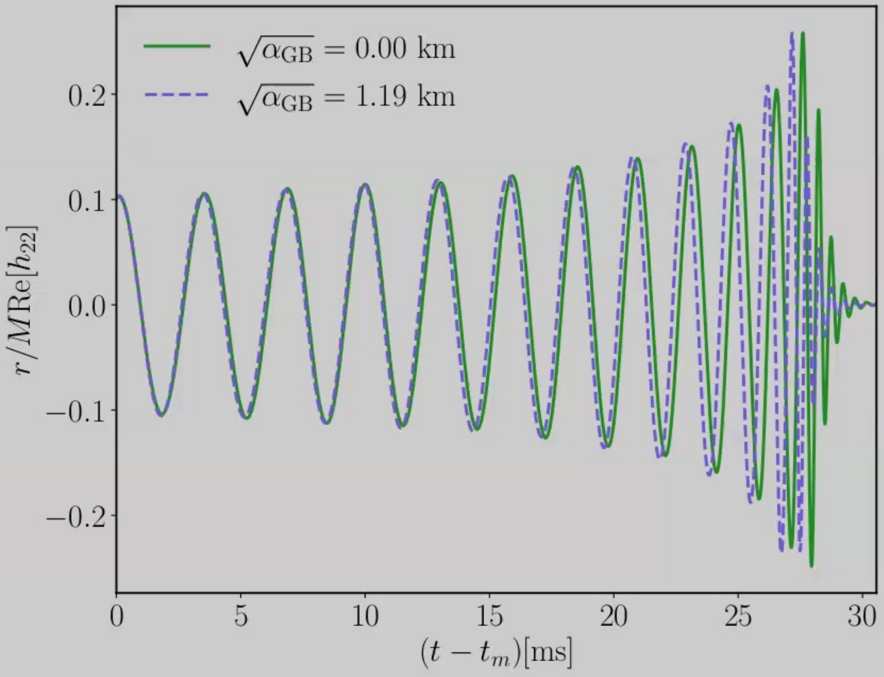
$$S = \frac{1}{16\pi} \int d^4x \sqrt{-g} \left[R - (\nabla\phi)^2 + \beta(\phi)\mathcal{G} \right]$$

with $\mathcal{G} \equiv R^2 - 4R_{ab}R^{ab} + R_{abcd}R^{abcd}$.

- Horndeski theory ⇒ second order equations of motion
- Shift-symmetric ⇒ $\beta(\phi) = 2\lambda\phi$
- Well-posed initial value formulation (Kovacs and Reall)
- Black hole solutions with scalar hair $\sim \lambda/m^2$ (Sotiriou & Zhou) ⇒ energy loss through scalar radiation, -1PN (at leading order) dephasing in GW signal (Yagi)



BBH (**MC**, Ripley and East 2022)

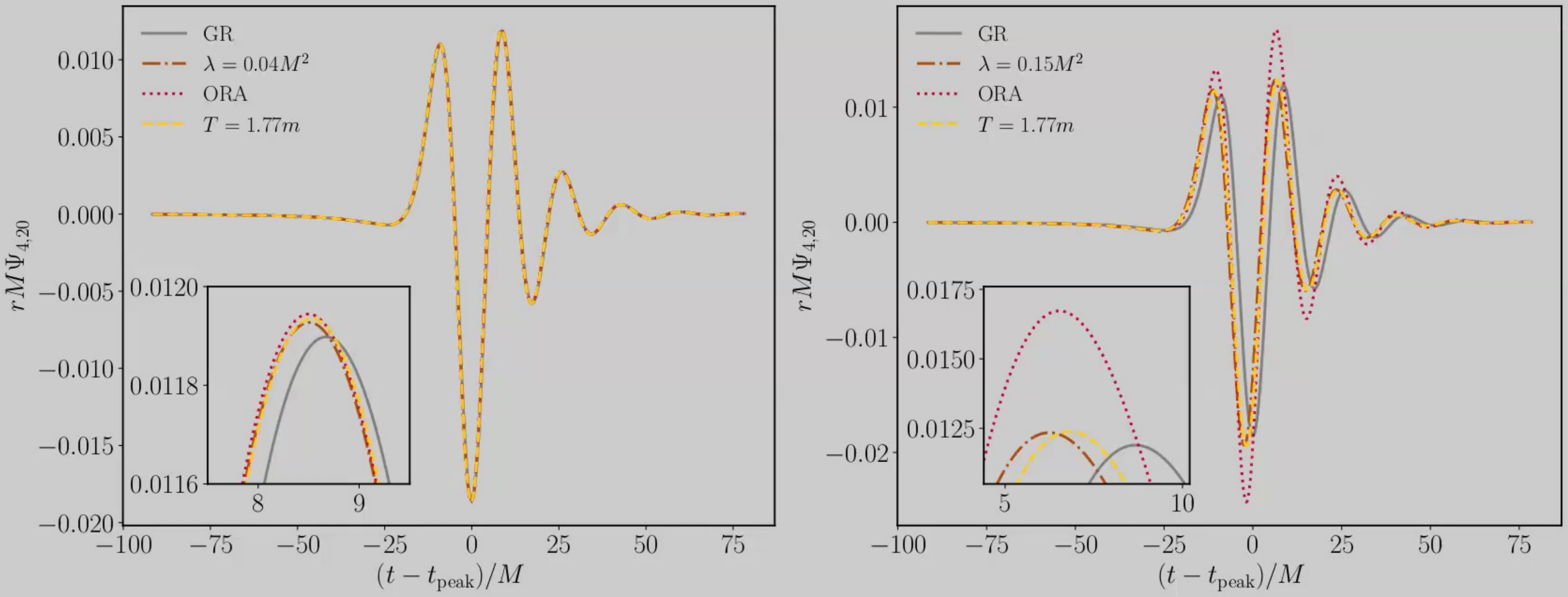


BHNS (**MC** and East, 2024)

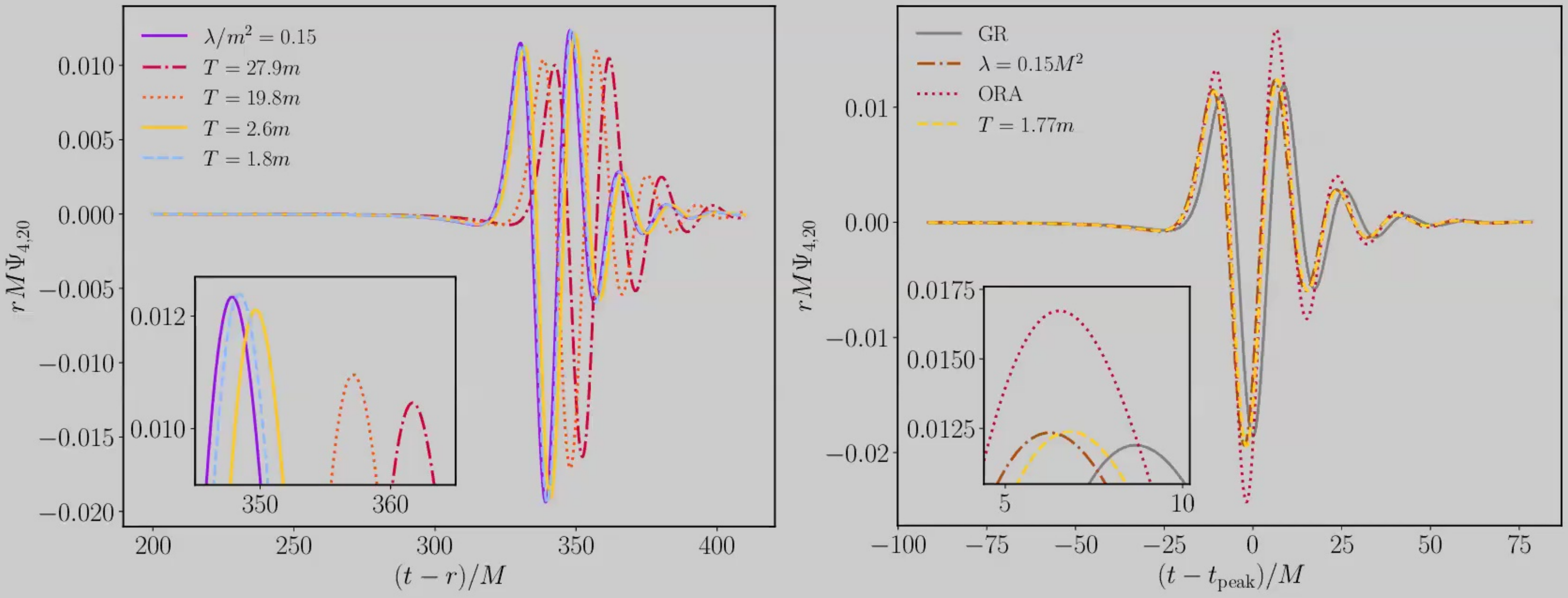
To what extent can predictions from approximate treatments such as the *order-by-order* and *fixing* approach be confronted with gravitational wave observations?

MC,Lehner,East and Dideron,2024

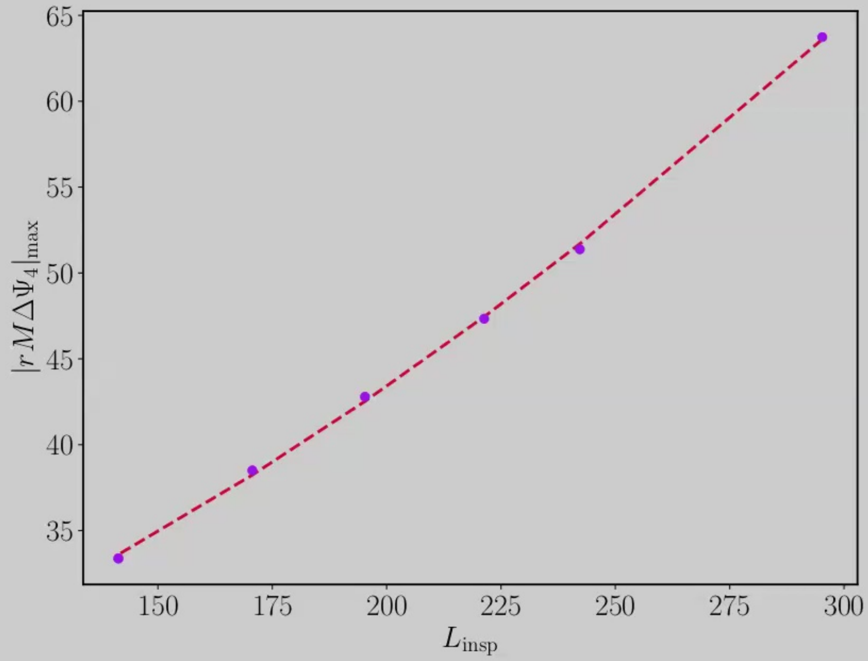
Head on collisions of equal-mass scalarized black holes



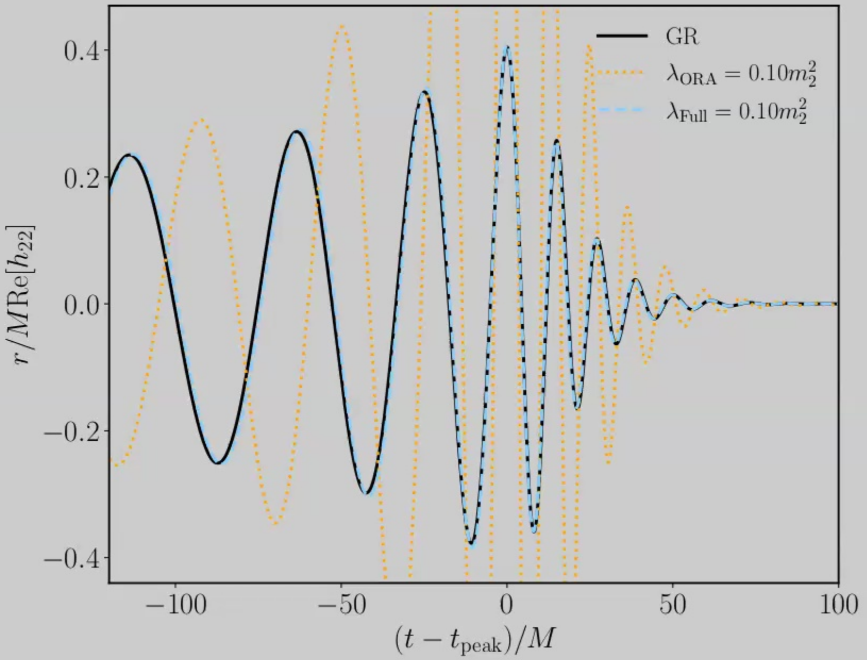
Head on collisions of scalarized black holes



Quasi-circular inspirals of scalarized black holes



Secular effects reflected in amplitude waveform at merger, $\Psi_4^{(2)} = \left(\frac{\lambda}{M^2}\right)^2 \Delta\Psi_4$.



Weak dependence of amplitude at merger for full solution. Order-by-order overshoots full solution.

Secular errors in the order-by-order approach: a toy model

- Anharmonic oscillator

$$\frac{d^2x}{dt^2} + \left(\frac{2\pi}{T_0}\right)^2 \left(x + \epsilon x^3\right) = 0$$

- Initial conditions

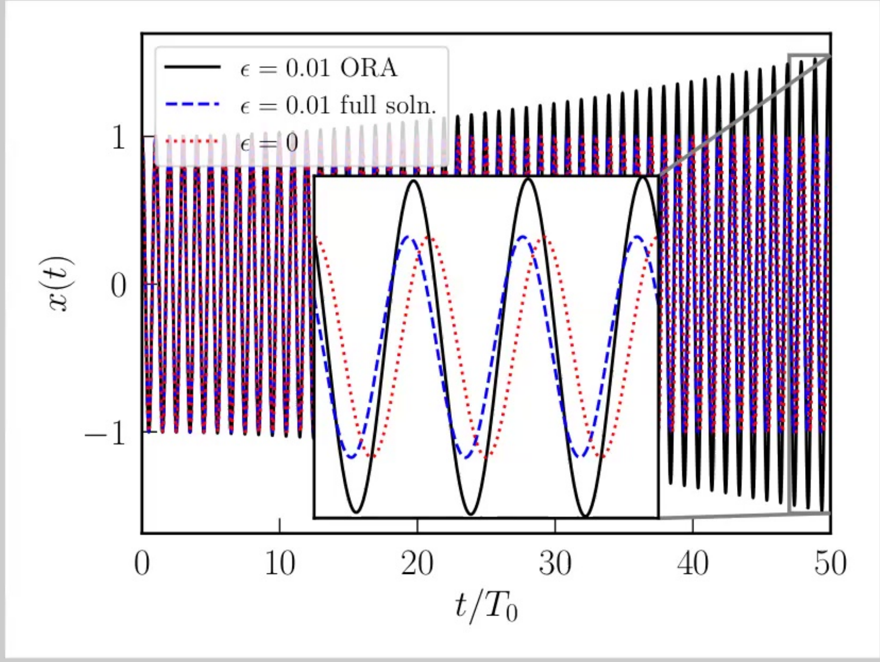
$$x(t = 0) = 1, \; \frac{dx}{dt}(t = 0) = 0$$

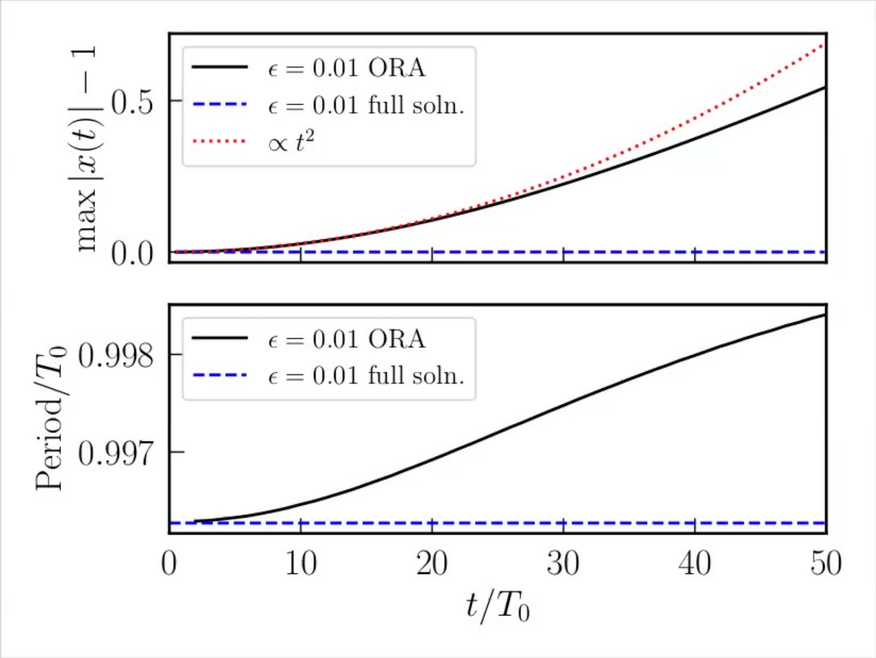
- Full solution: pure sine wave but shifted frequency
- Order by order solution:

$$x(t) = \cos(\omega_0 t) + \frac{\epsilon}{32}\left[\cos(3\omega_0 t) - \cos(\omega_0 t) - 12\omega_0 t \sin(\omega_0 t)\right]$$

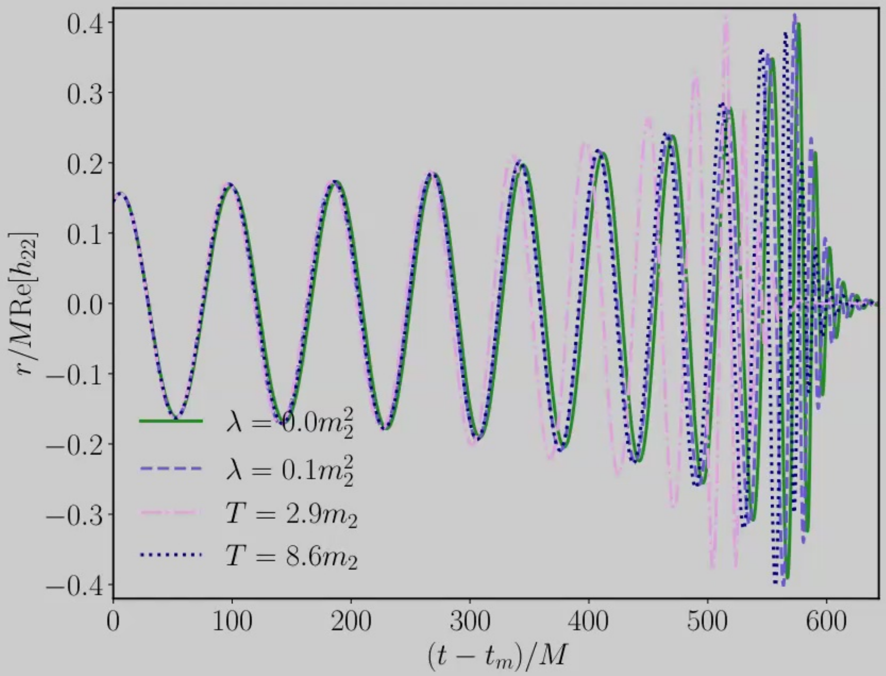
$\Rightarrow$ secular growth on timescales $\sim T_0/\epsilon$

Secular errors in the order-by-order approach: a toy model





Quasi-circular inspirals of scalarized black holes



Can we extrapolate to $T \to 0$?

Take aways comparison study

To what extent can predictions from approximate treatments such as the *order-by-order* and *fixing* approach be confronted with gravitational wave observations?

- Order-by-order approach cannot faithfully track the solutions when the corrections to general relativity are non-negligible.
- Fixing approach can provide consistent solutions, provided the ad-hoc timescale over which the dynamical fields are driven to their target values is made short compared to the physical timescales $\rightarrow$ computationally feasable?
- Obtaining full inspiral-merger-ringdown waveforms in various alternative theories is hard!

Dynamical de-scalarization

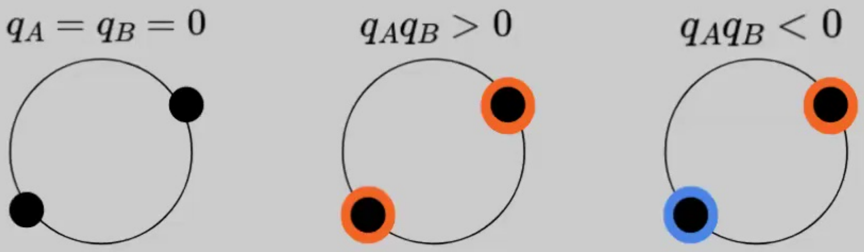
wit Guillermo Lara, Peter James Nee, Nils Vu and Harald Pfeiffer, *in prep*

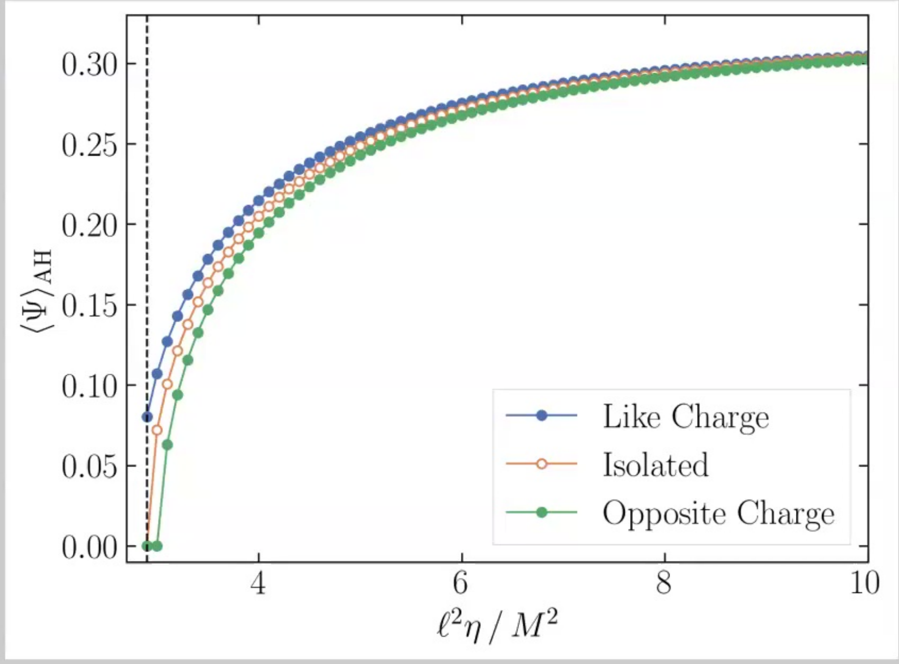
Different flavour of Einstein scalar Gauss Bonnet gravity

$$S = \frac{1}{16\pi} \int d^4x \sqrt{-g} \left[R - (\nabla\phi)^2 + \beta(\phi)\mathcal{G} \right]$$

now with $\beta(\phi) = \frac{\lambda}{2}\phi^2 + \frac{\sigma}{4}\phi^4$

- Spontaneous scalarization Silva+,2018, Dynamical scalarization Julie,2024

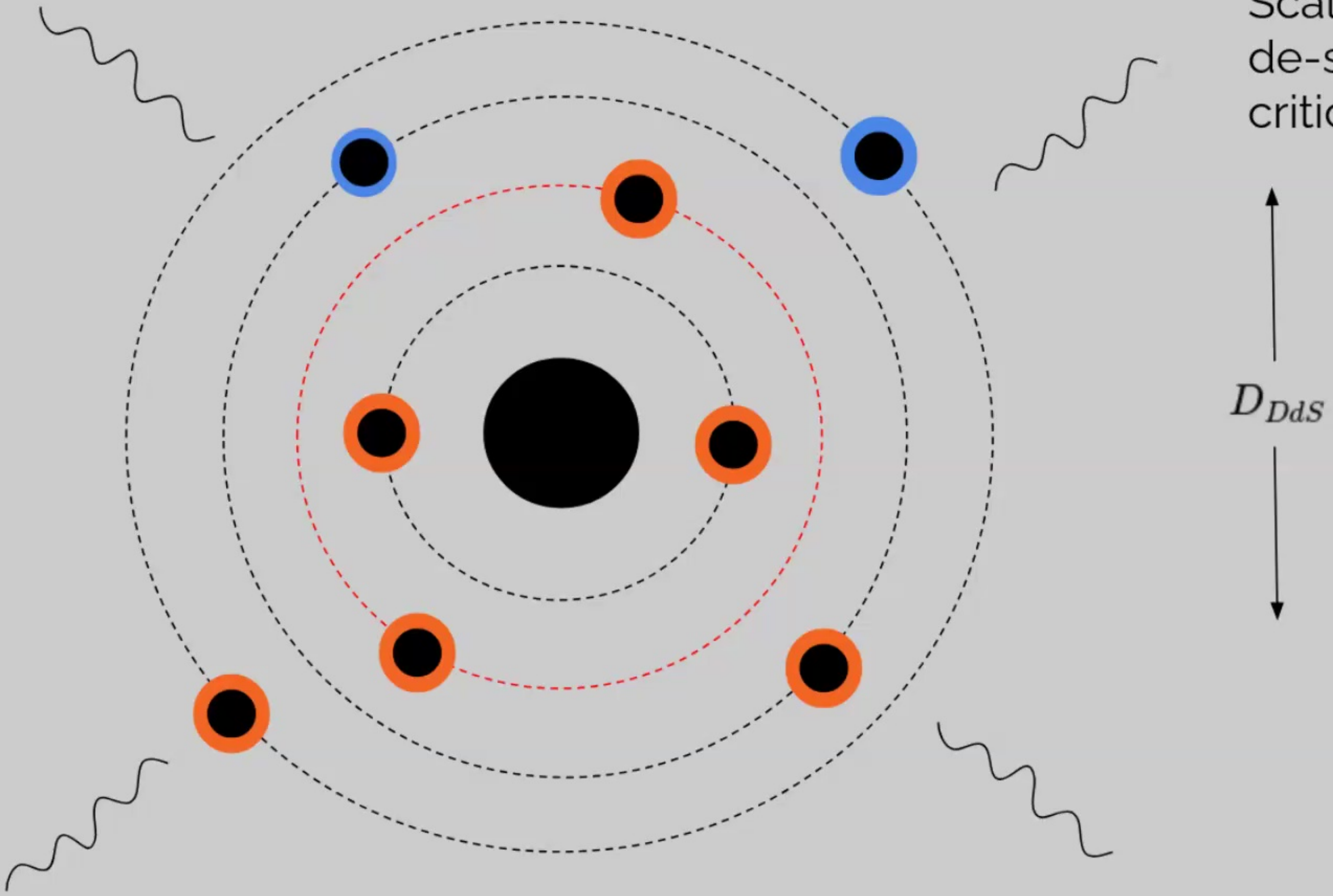


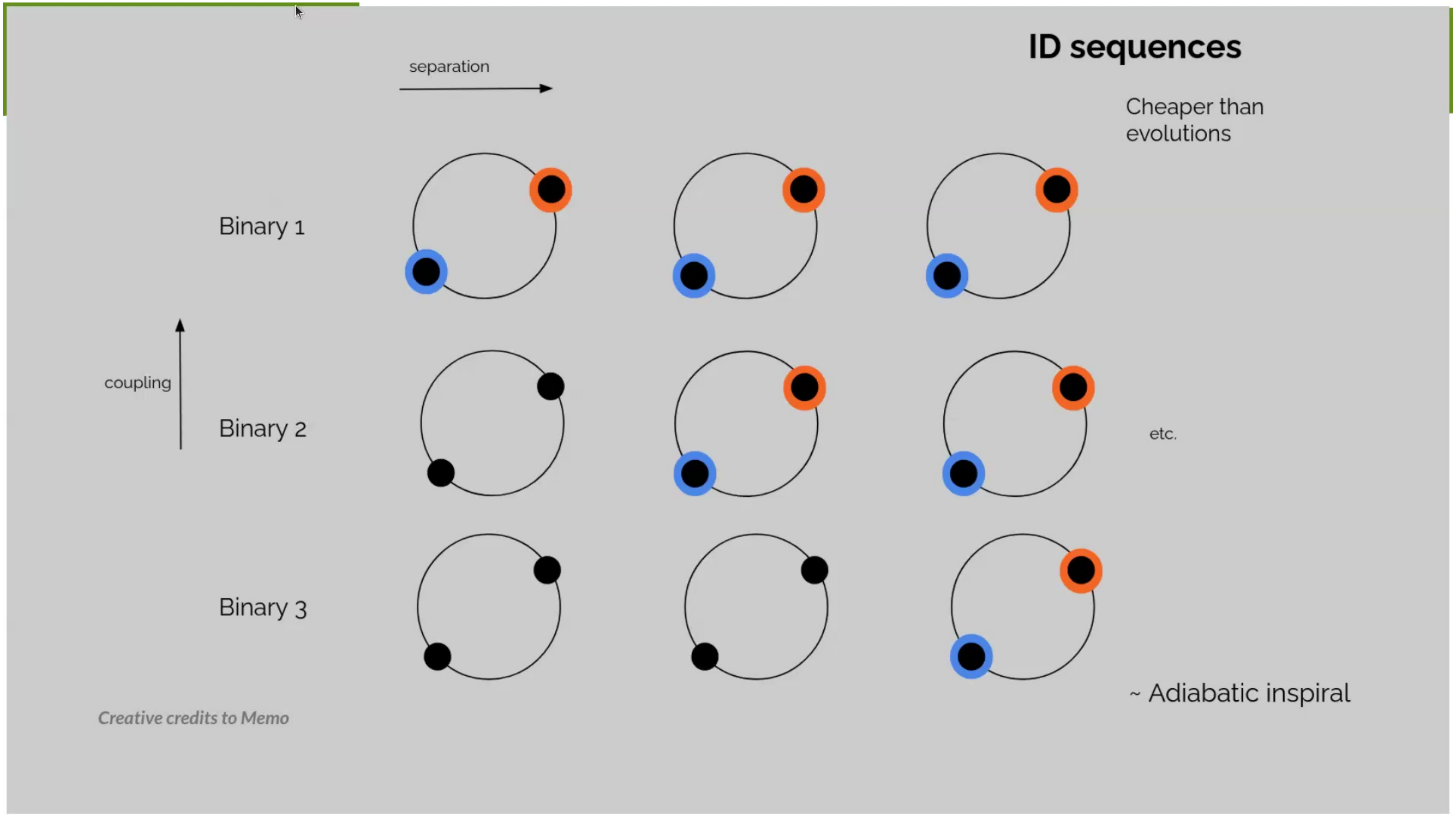


credit to Peter James Nee

Oppositely scalarized black hole binaries

Scalarized BHs
de-scalarize below a
critical separation D_{DdS}





ID sequences

separation

Cheaper than evolutions

Binary 1

coupling

Binary 2

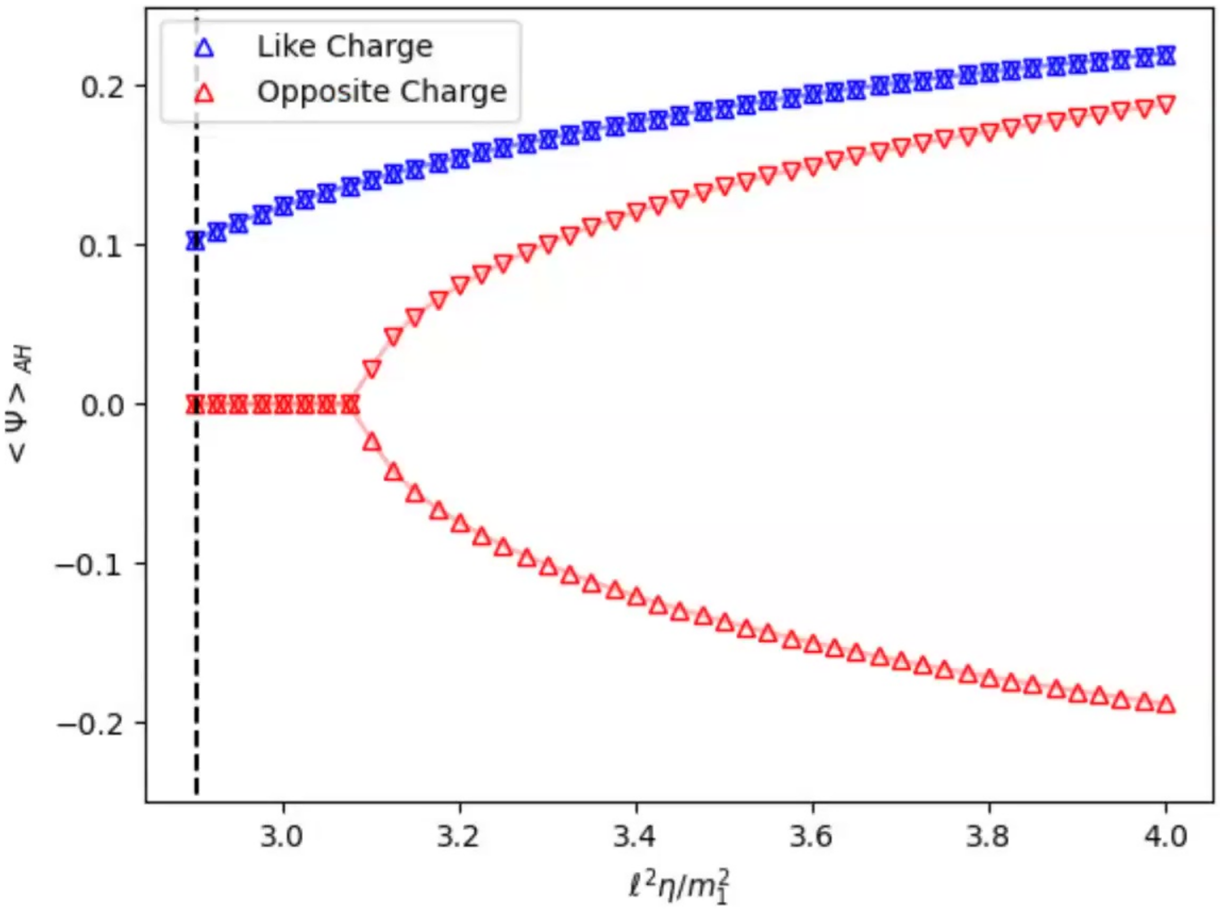
etc.

Binary 3

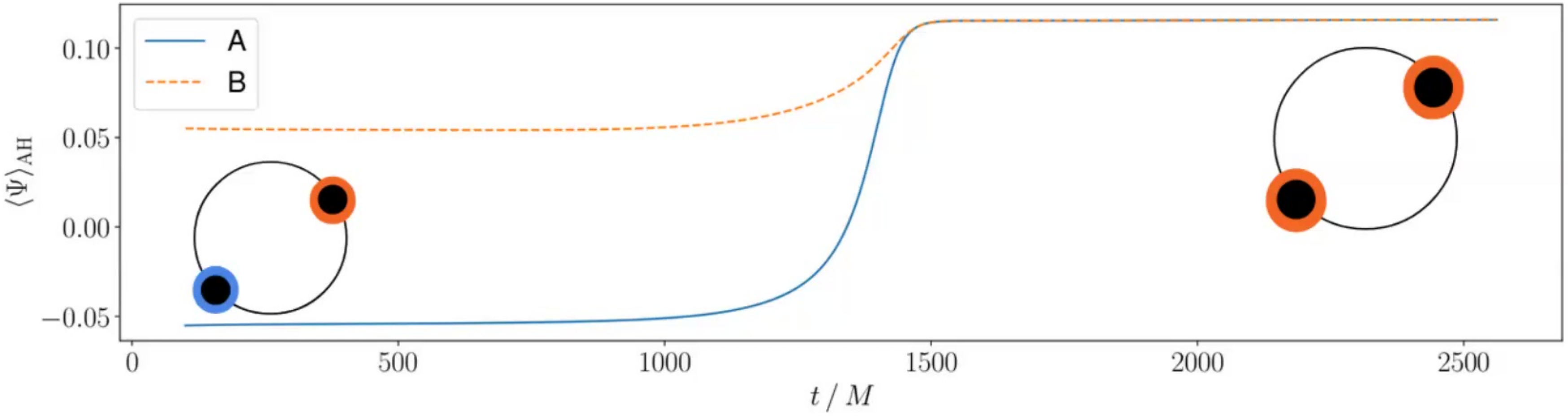
~ Adiabatic inspiral

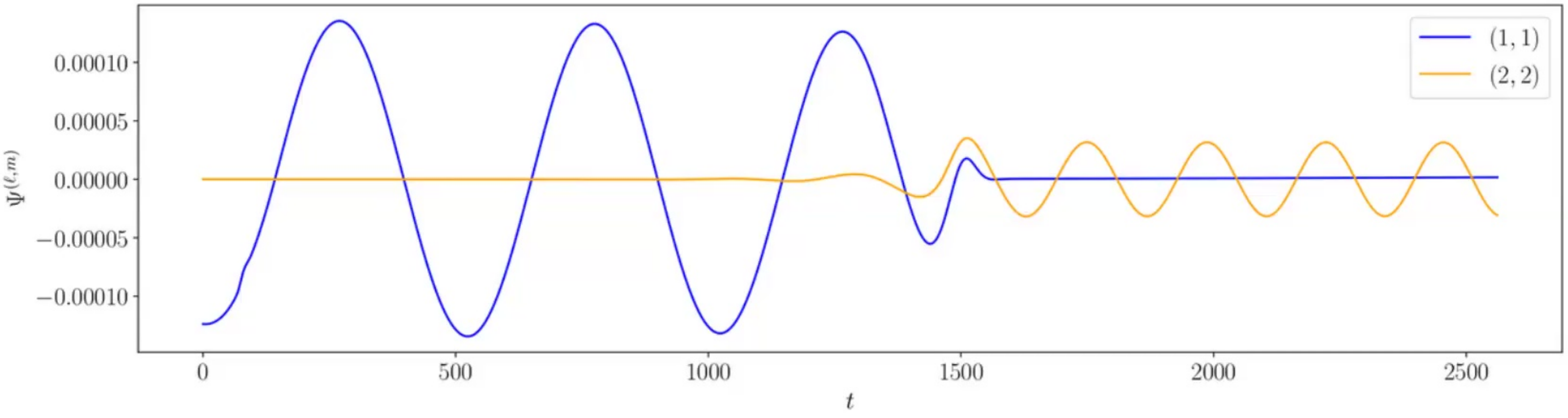
Creative credits to Memo

ID sequences credits to PJ

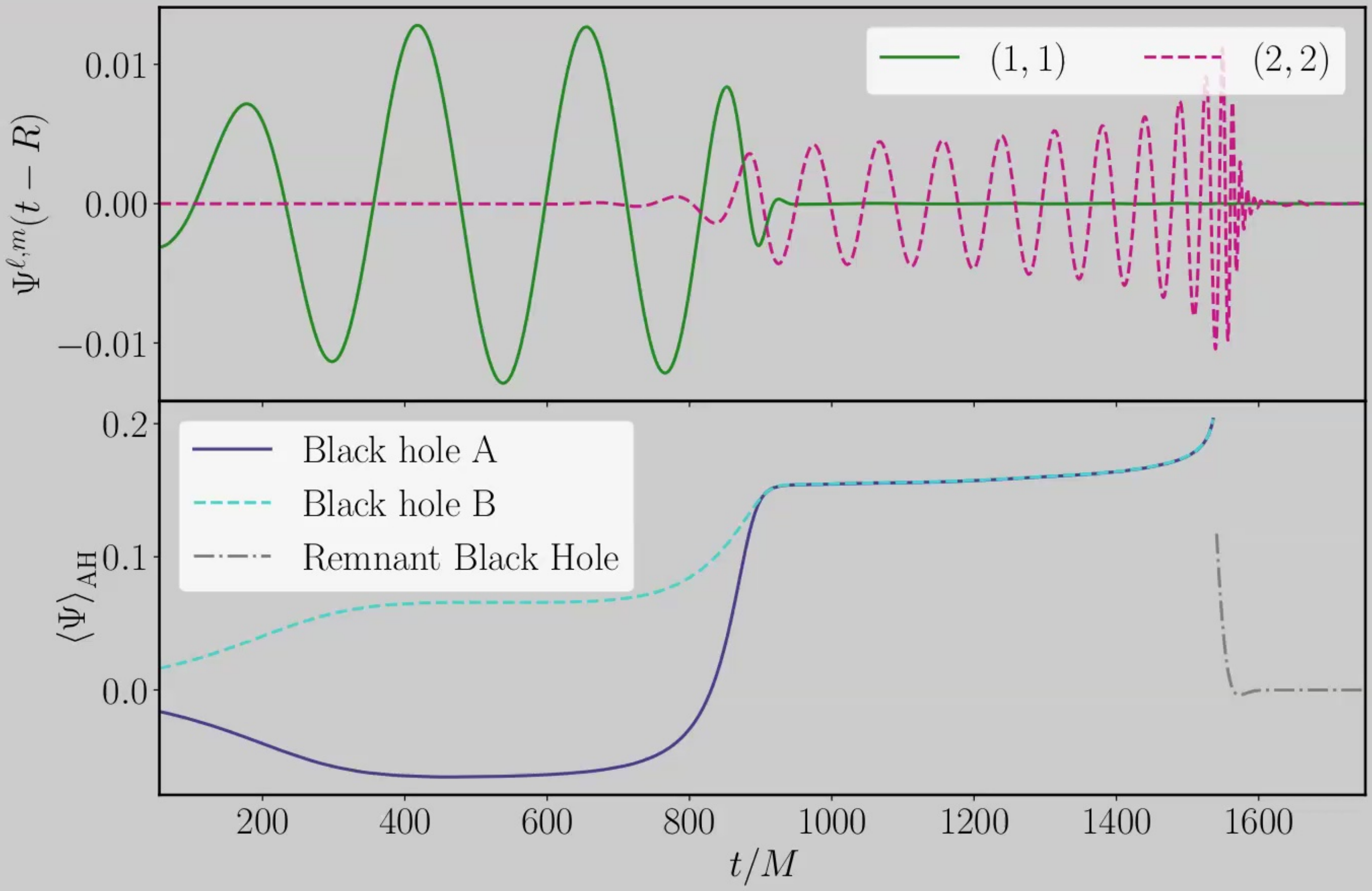


Decoupled evolutions *Credits to Memo*

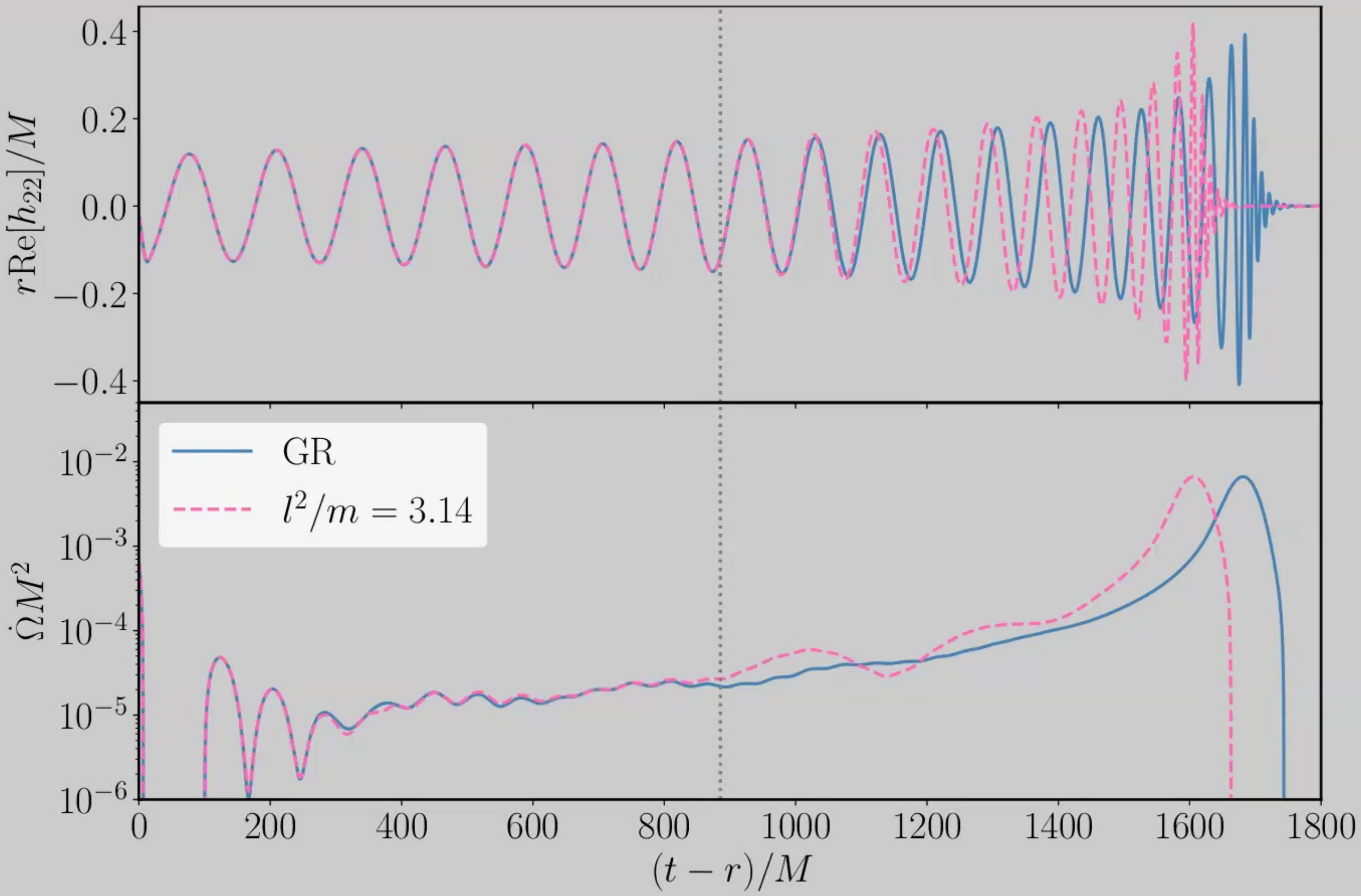




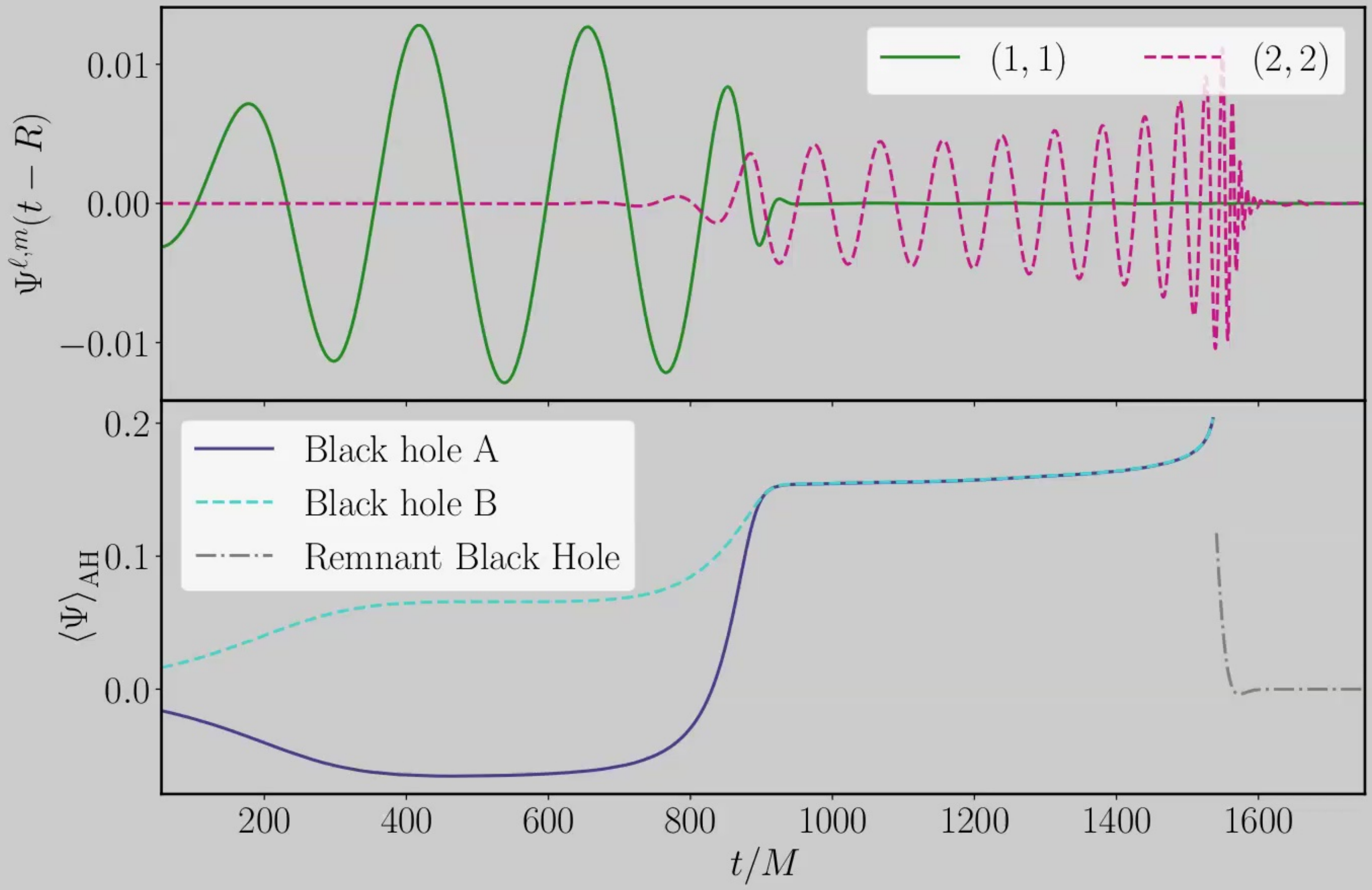
Fully coupled evolutions: scalar radiation



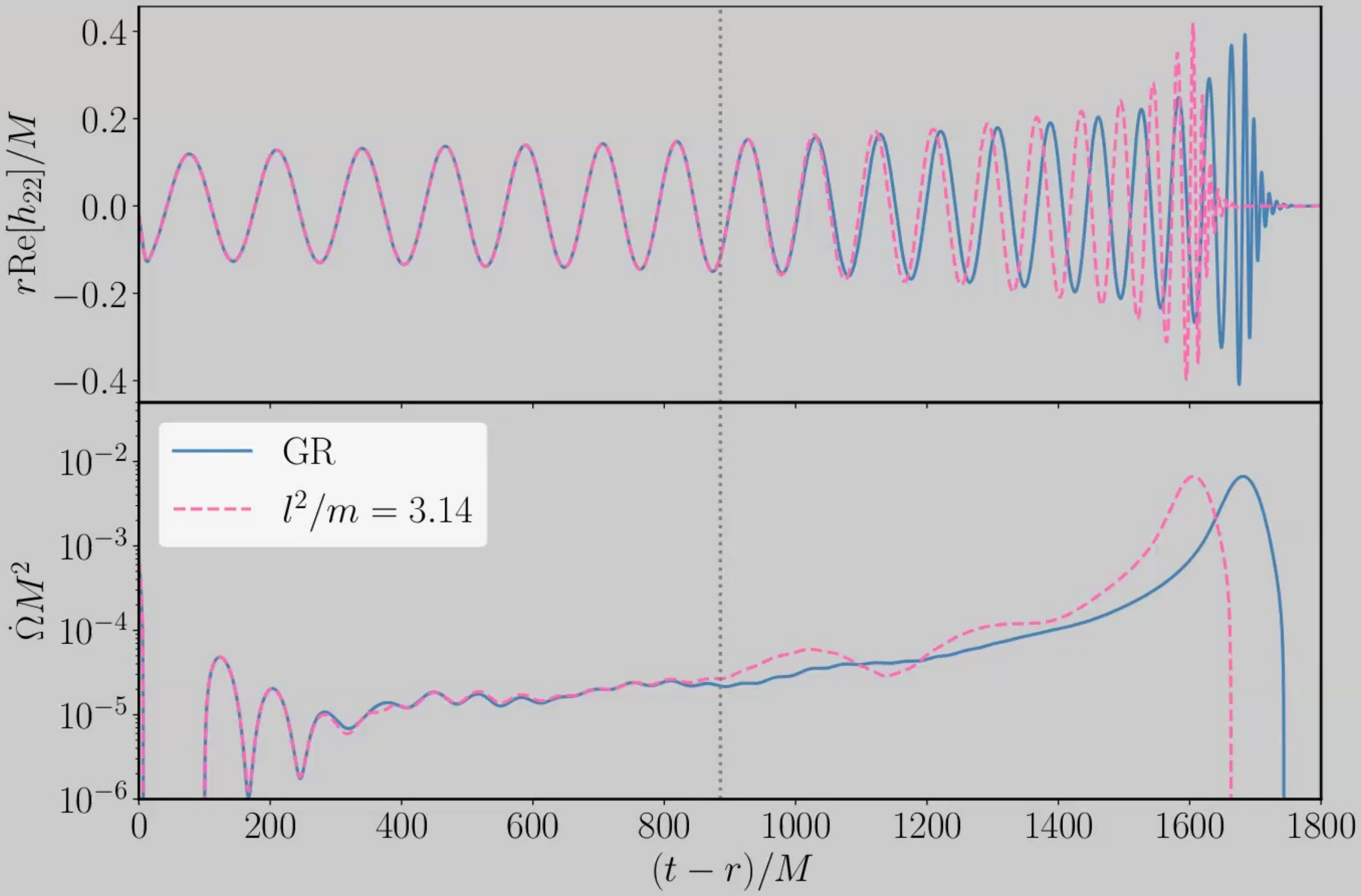
Fully coupled evolutions: gravitational radiation



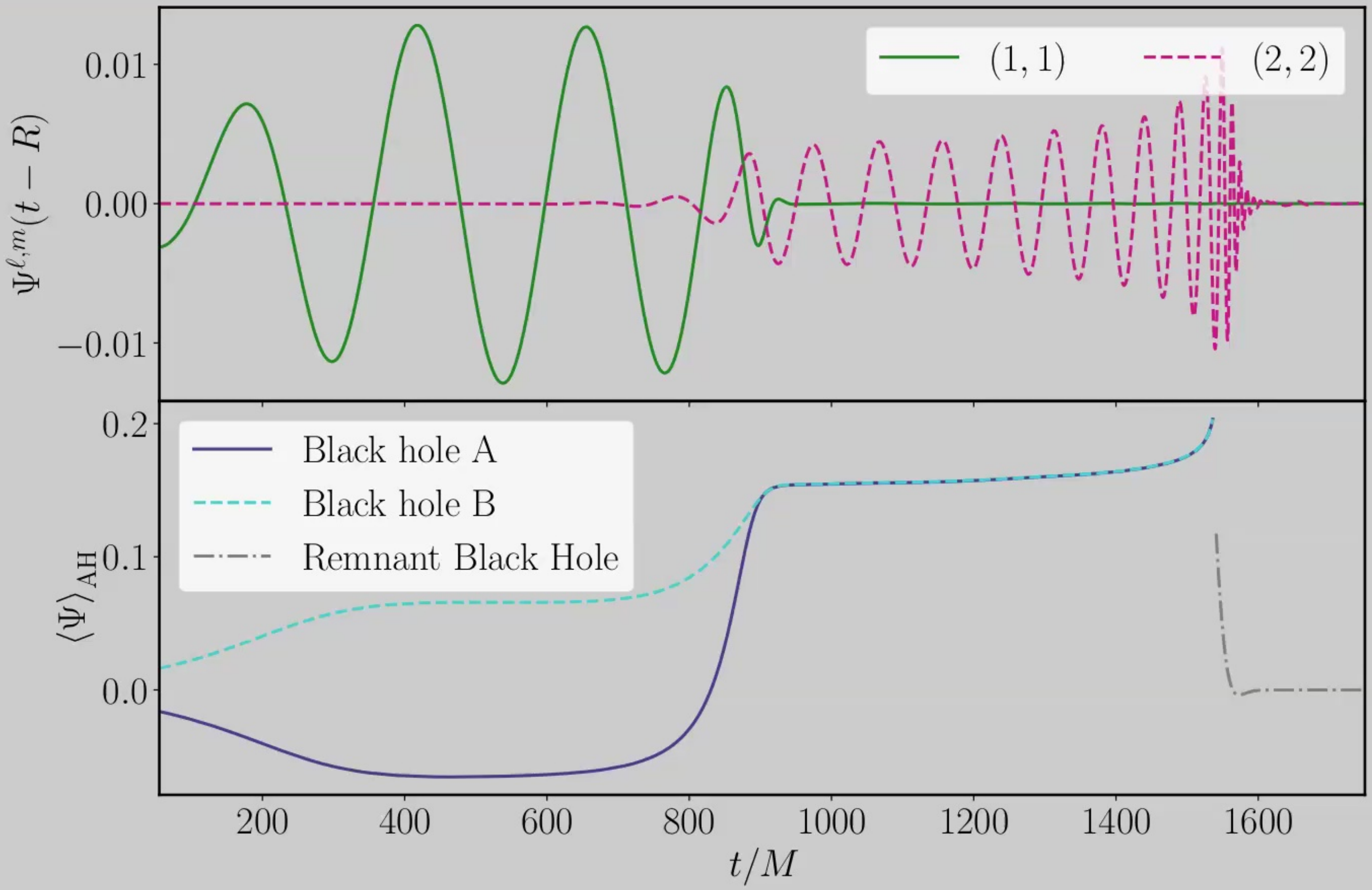
Fully coupled evolutions: scalar radiation



Fully coupled evolutions: gravitational radiation



Fully coupled evolutions: scalar radiation



Take aways

Beyond-GR waveform examples can provide valuable qualitative guidance to improve and motivate new theory-agnostic tests