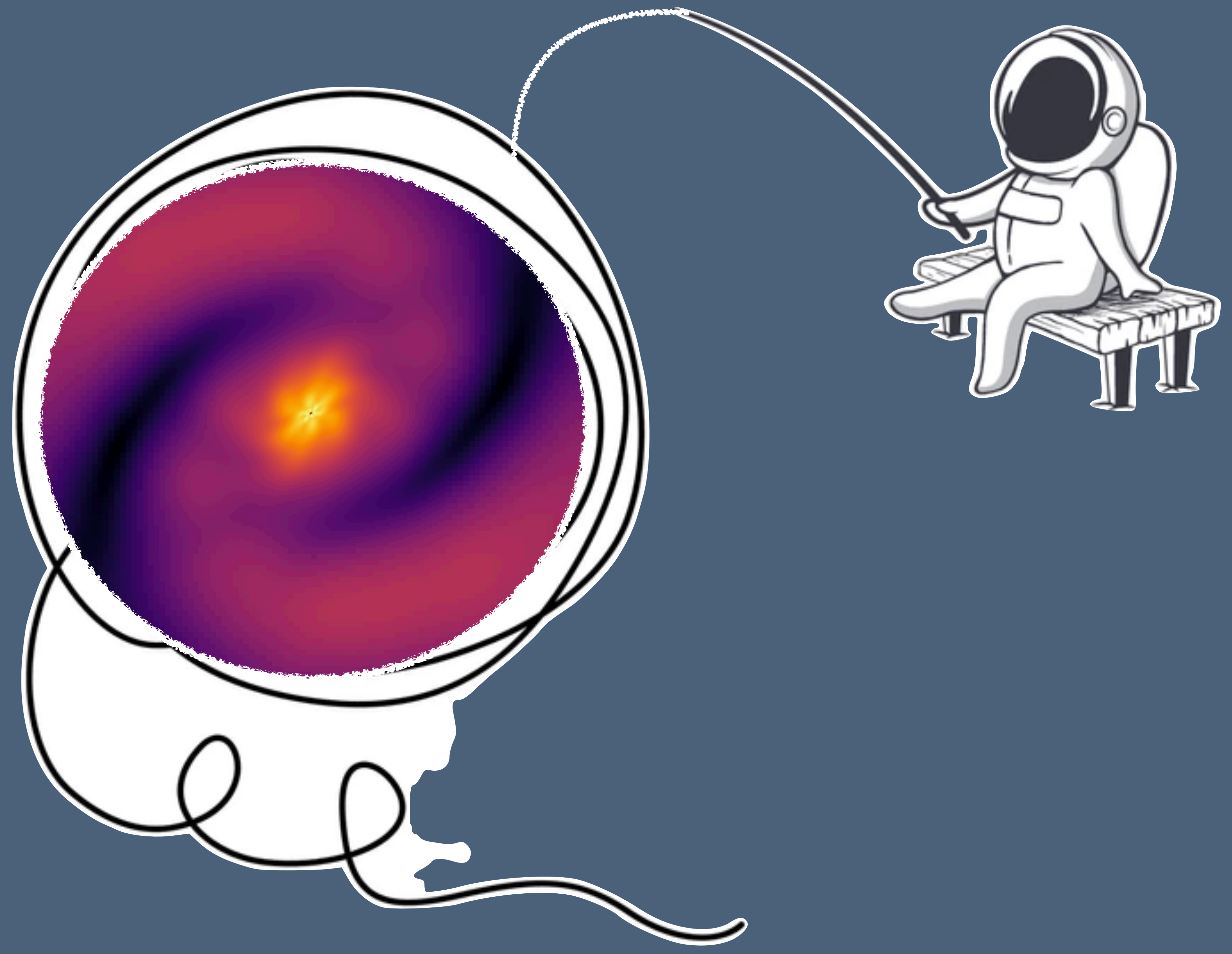
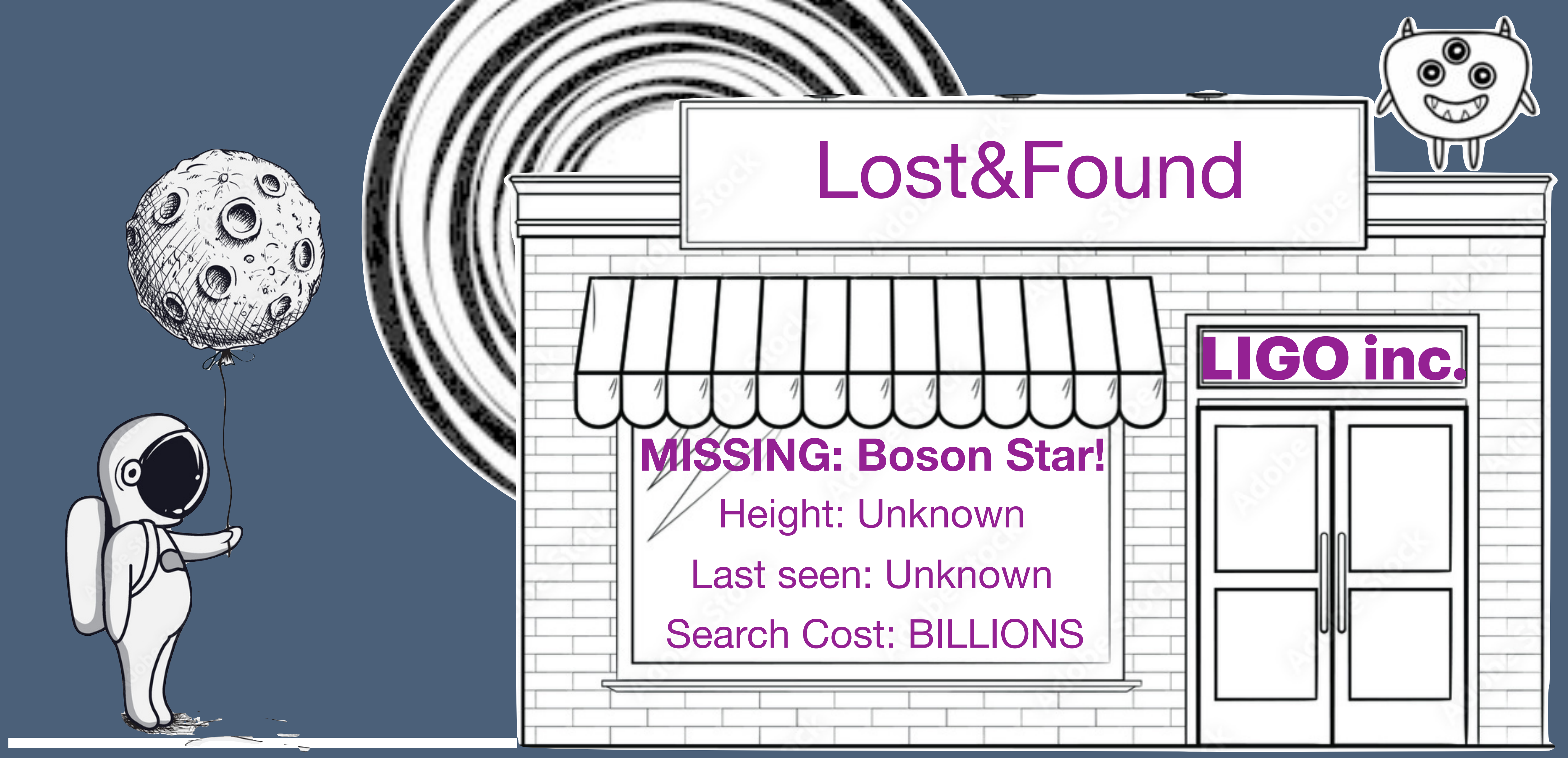




Boson stars in LIGO data

Towards testing the nature of compact objects

Based on arXiv:2406.02715 with Ulrich Sperhake, Isobel Romero-Shaw and Michalis Agathos

Tamara Evstafyeva (University of Cambridge)

The aim of this talk in a nutshell

- Many proposals of exotic compact objects (ECOs)... One of the most studied and sufficiently understood ECOs are **boson stars** (BSs). [See reviews by Liebling & Palenzuela (2012&2023) and Bezares & Sanchis-Gual (2024)]

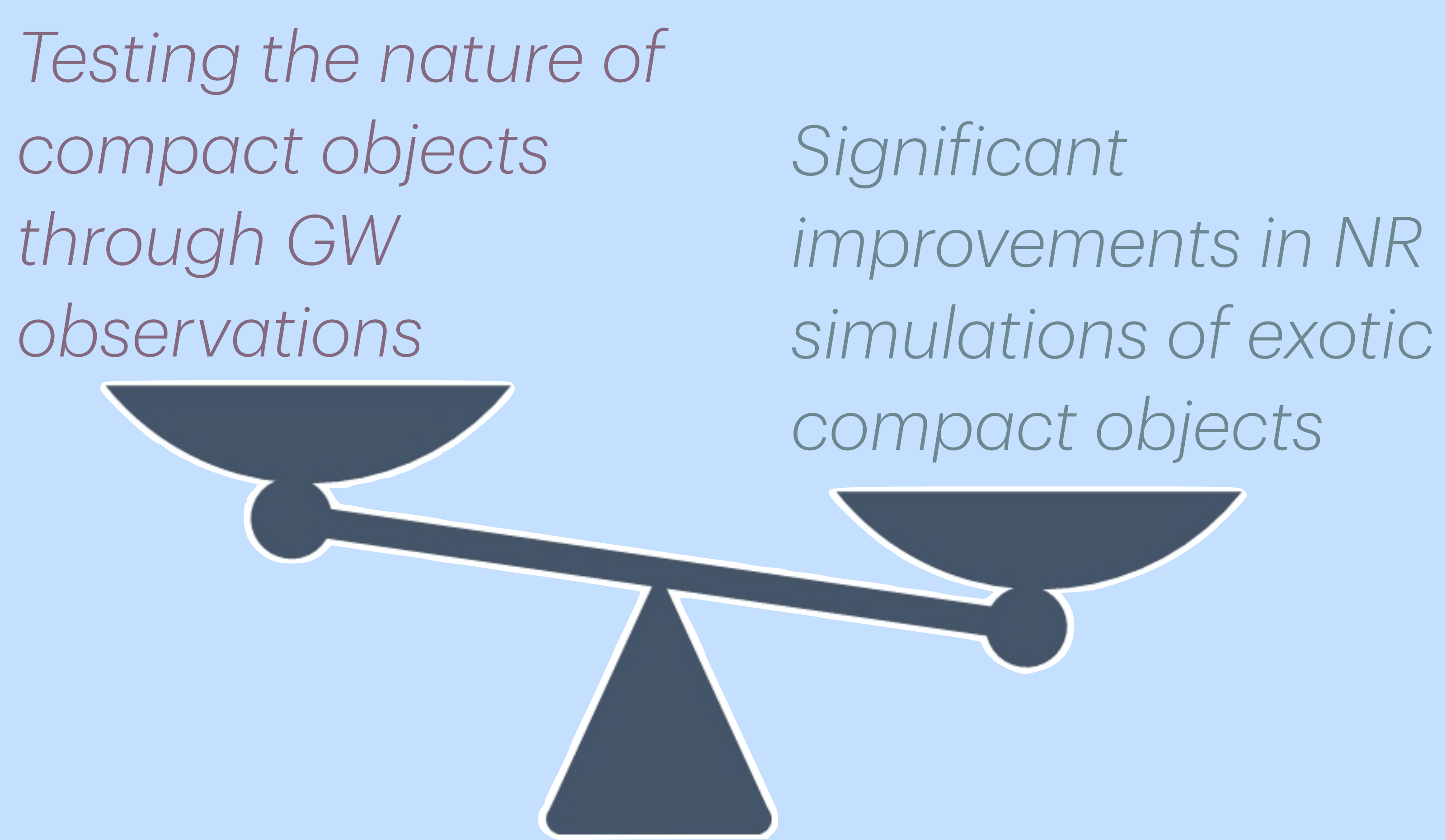
- BSs are gravitationally bound spherically symmetric configurations of **complex scalar field**, first found in the seminal work by Kaup (1968).

- BSs are often called **black-hole (BH) mimickers** but they are also great **proxies** for anything that is not a BH.

- The questions to be addressed in this talk:

   1. ***Supposing BS coalescences occur in the Universe, can we detect them?***

   2. ***Can we distinguish them from traditional BH and NS events?***



What are boson stars?

- Boson stars:

    1. are comprised of **bosons** $\mu \in [10^{-22}, 10^{-3}]eV$ (possibly ultralight)

    2. are **horizonless** (i.e. do not have a singularity)

    3. **do not have a surface** (the scalar field extends to infinity but falls off exponentially)

    4. have a **maximum mass**

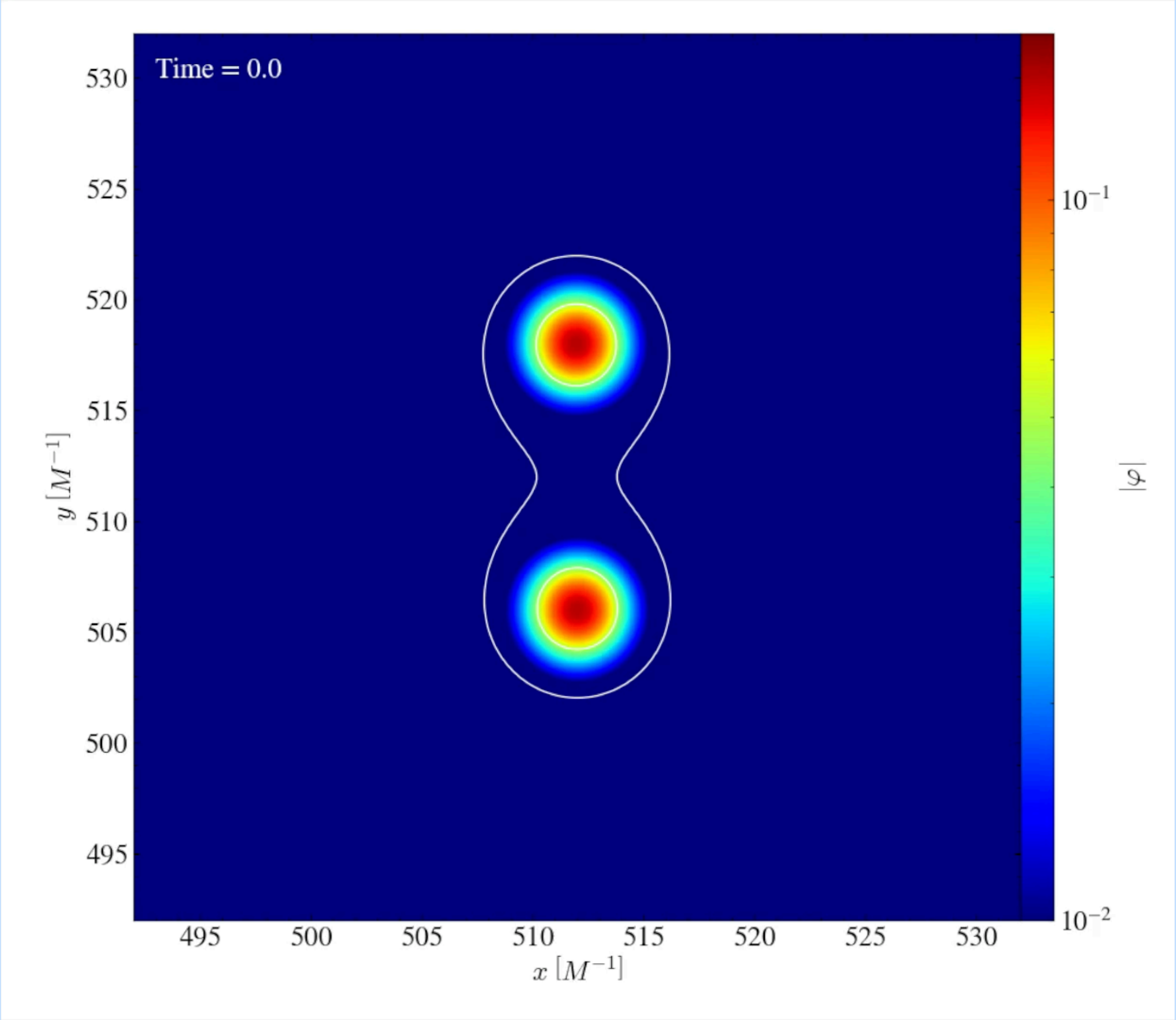
    5. may have large **tidal deformability**

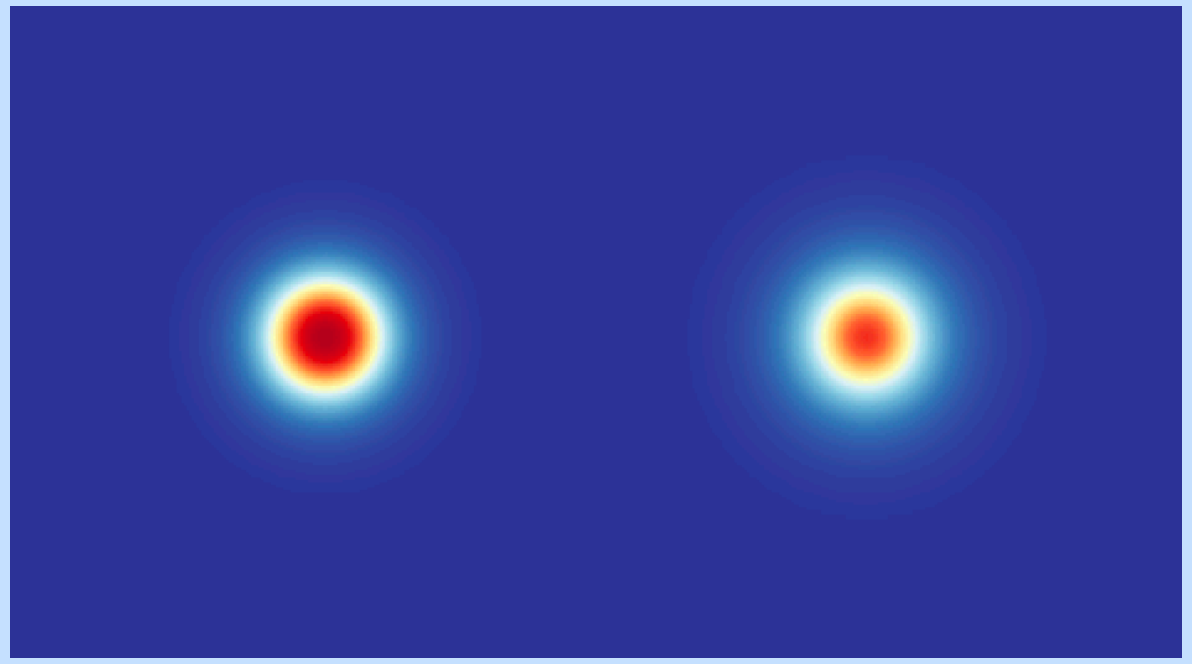
    6. may have **light rings**

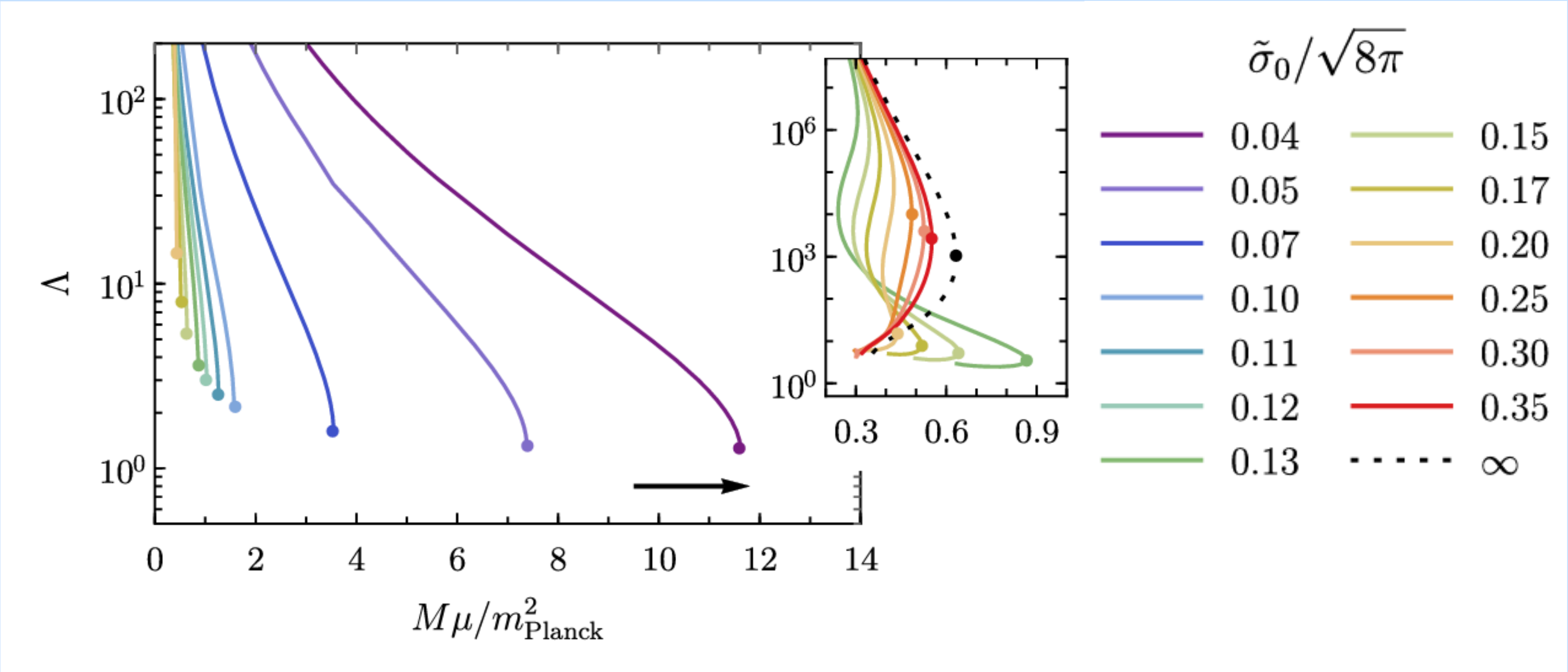
    7. have a conserved U(1) charge — **Noether charge**

- May account for some fraction of dark matter in our Universe; have a legitimate formation channel, e.g. via gravitational condensation from isotropic initial conditions.

Eby+ (2015), Levkov+ (2018), Cardoso+ (2022)







Sennett+ (2019)

Mathematical formulation

$$S = \int \sqrt{-g}\left[\frac{1}{16\pi G}R - \frac{1}{2}\left(g^{\mu\nu}\nabla_\mu\varphi^*\nabla_\nu\varphi + V(\varphi)\right)\right] d^4x$$

$$\Rightarrow$$

$$G_{\alpha\beta} = 8\pi G T_{\alpha\beta}$$

$$\nabla^\mu\nabla_\mu\varphi = \varphi\frac{\mathrm{d}V}{\mathrm{d}|\varphi|^2}$$

$$V_{\mathrm{sol}} = \mu^2|\varphi|^2\left(1 - 2\frac{|\varphi|^2}{\sigma_0^2}\right)^2$$

- V_{sol} is what we call a **solitonic potential**, σ_0 is the **self-interaction term** and μ the **BS scalar mass**.
- Let us consider **spherically symmetric solutions**

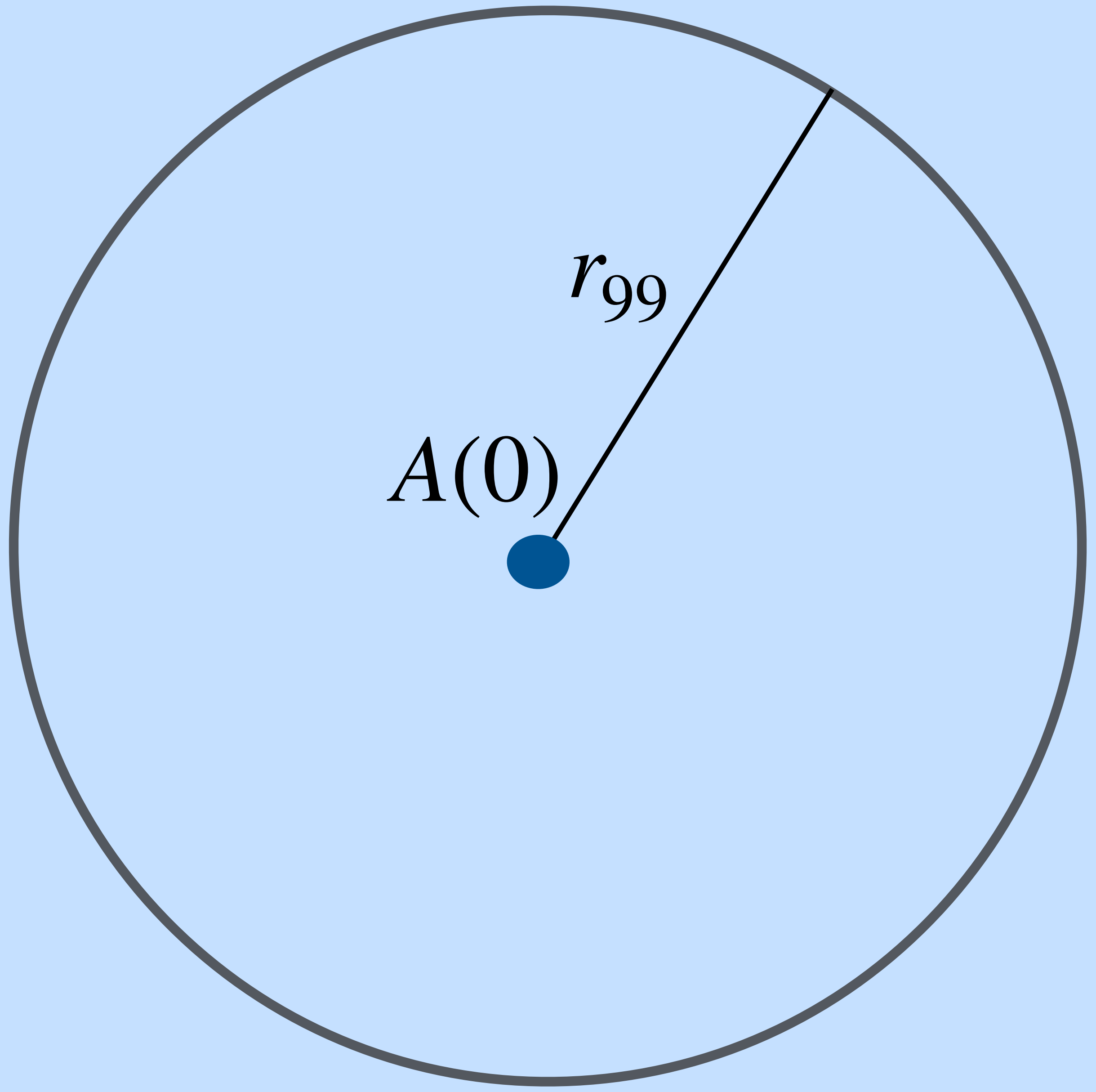
$$\varphi(t,r) = A(r)e^{i(\epsilon\omega t + \delta\phi)}$$

- Here $A(r)$ is the amplitude, ω is the frequency (const.), $\epsilon = \pm 1$ determines rotation in the complex plane and $\delta\phi$ is a constant phase offset.

Characteristics of BS solutions

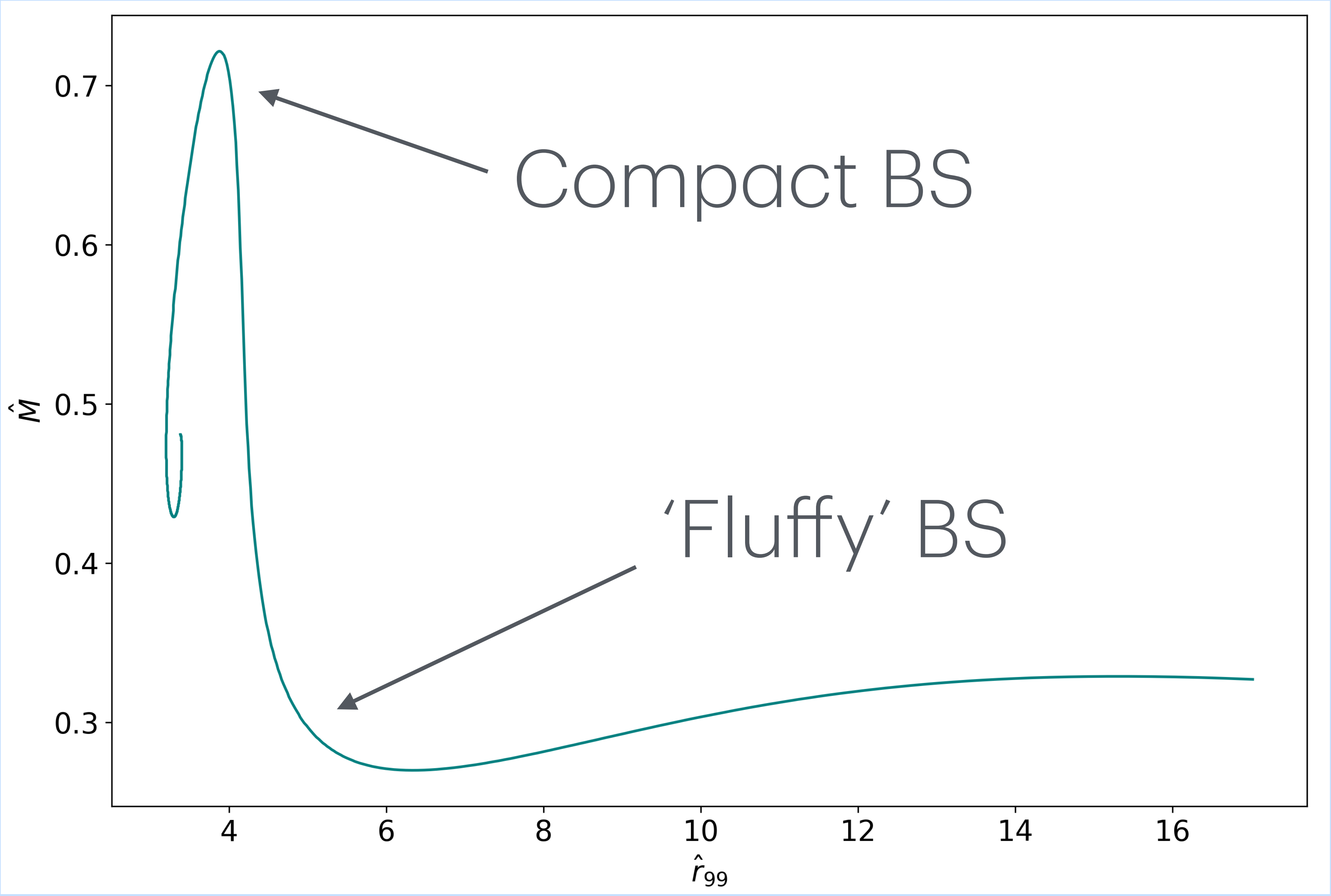
$$\varphi(t, r) = A(r)e^{i(\epsilon\omega t + \delta\phi)}$$

- By fixing the potential, and varying $A(0)$ we may construct a whole **family of BS solutions**, which will vary by the mass, radius, tidal deformability and so on.



r_{99} — the areal radius containing 99% of the BS mass

C — compactness, as $max(m(r)/r)$

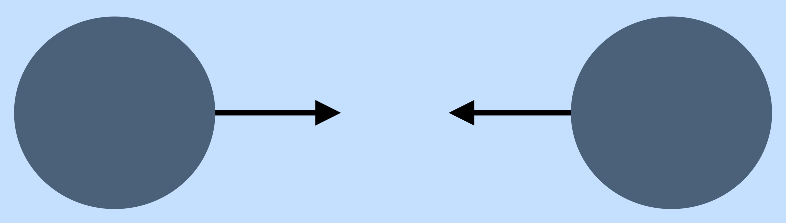


Numerical relativity and BSs

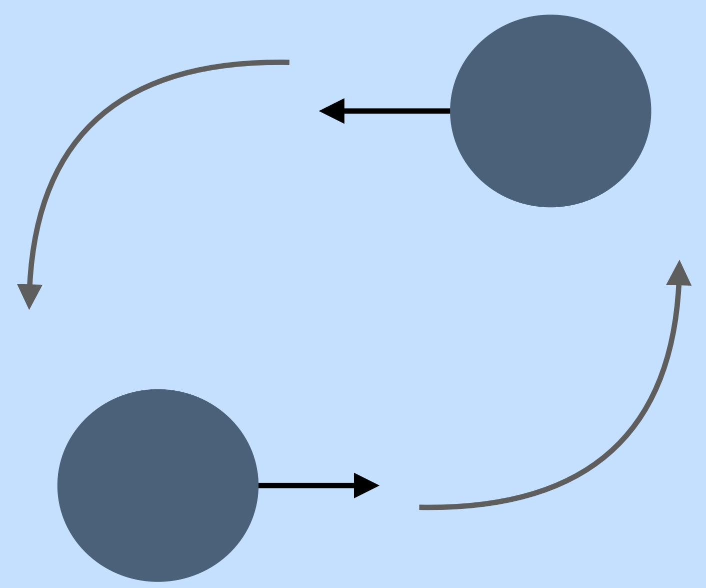
- Many groups studied binary BS systems, mainly in the context of **head-on collisions** [Palenzuela+ (2006), Bezares+ (2017), Jaramillo+ (2022), Evstafyeva+ (2023)]; a few also considered **inspiralling** binary systems [Bezares+ (2022), Siemonsen+ (2023), Evstafyeva+ (2024)].

- **Finite differencing** (GRChombo, Lean, MHDueT, Einstein Toolkit) and **pseudo-spectral** (bamps) codes are able to handle BSs.

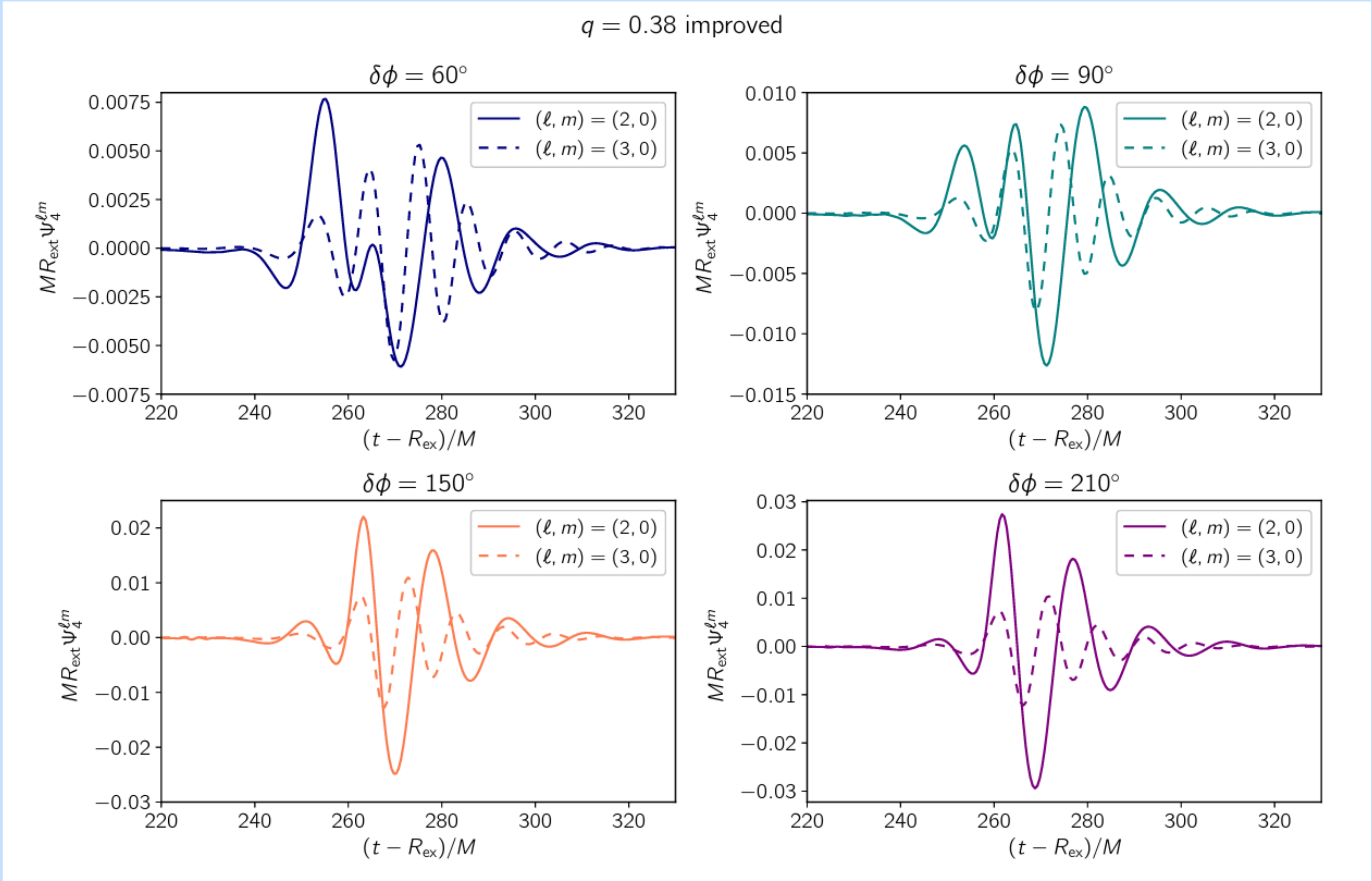
Head-on

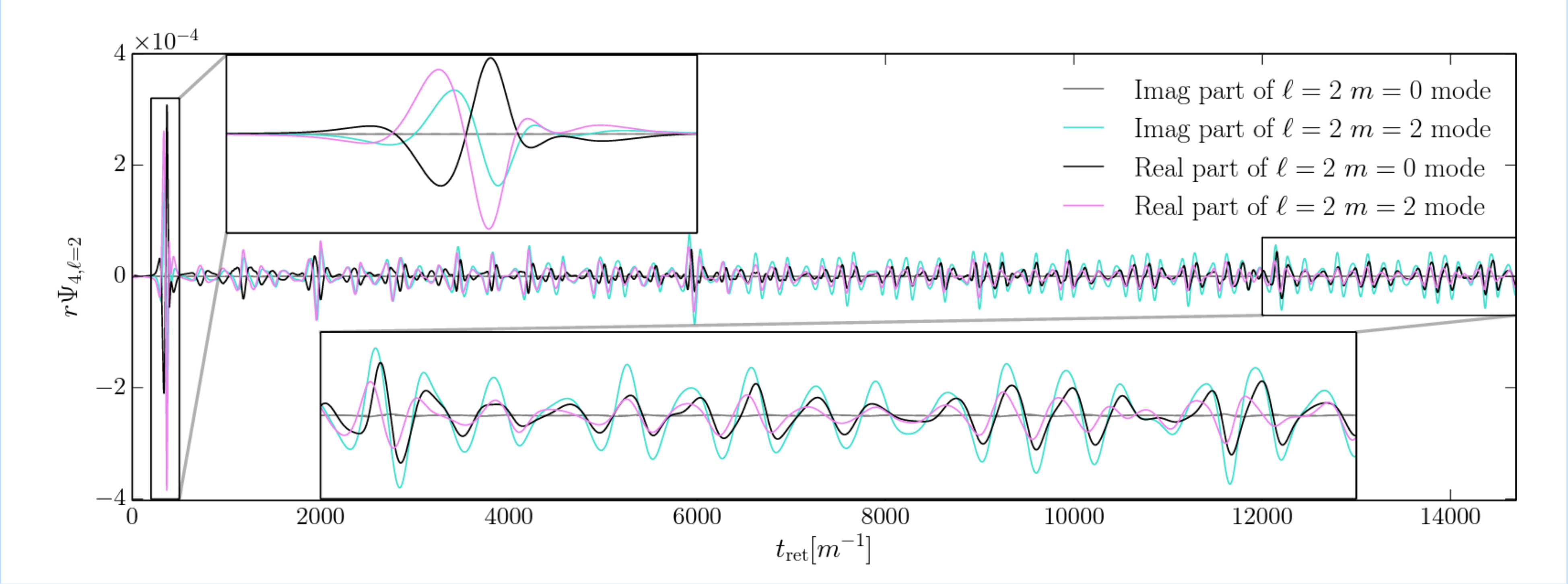


Inspiral



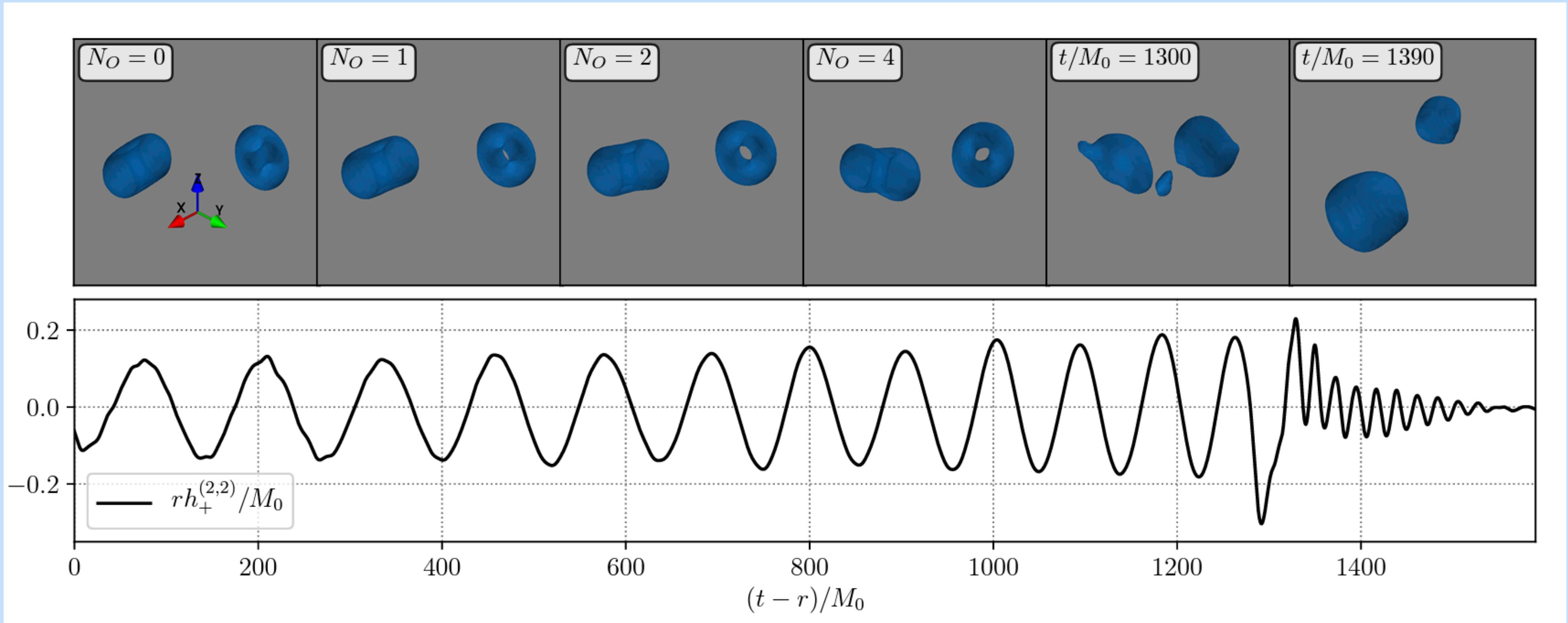
Evstafyeva+ (2023)





Croft+ (2023)

Siemonsen+ (2023)



Inspirals

Evstafyeva+ (2024)

- Focus on accuracy of equal mass $q = 1$, non-spinning inspiralling BS binaries.

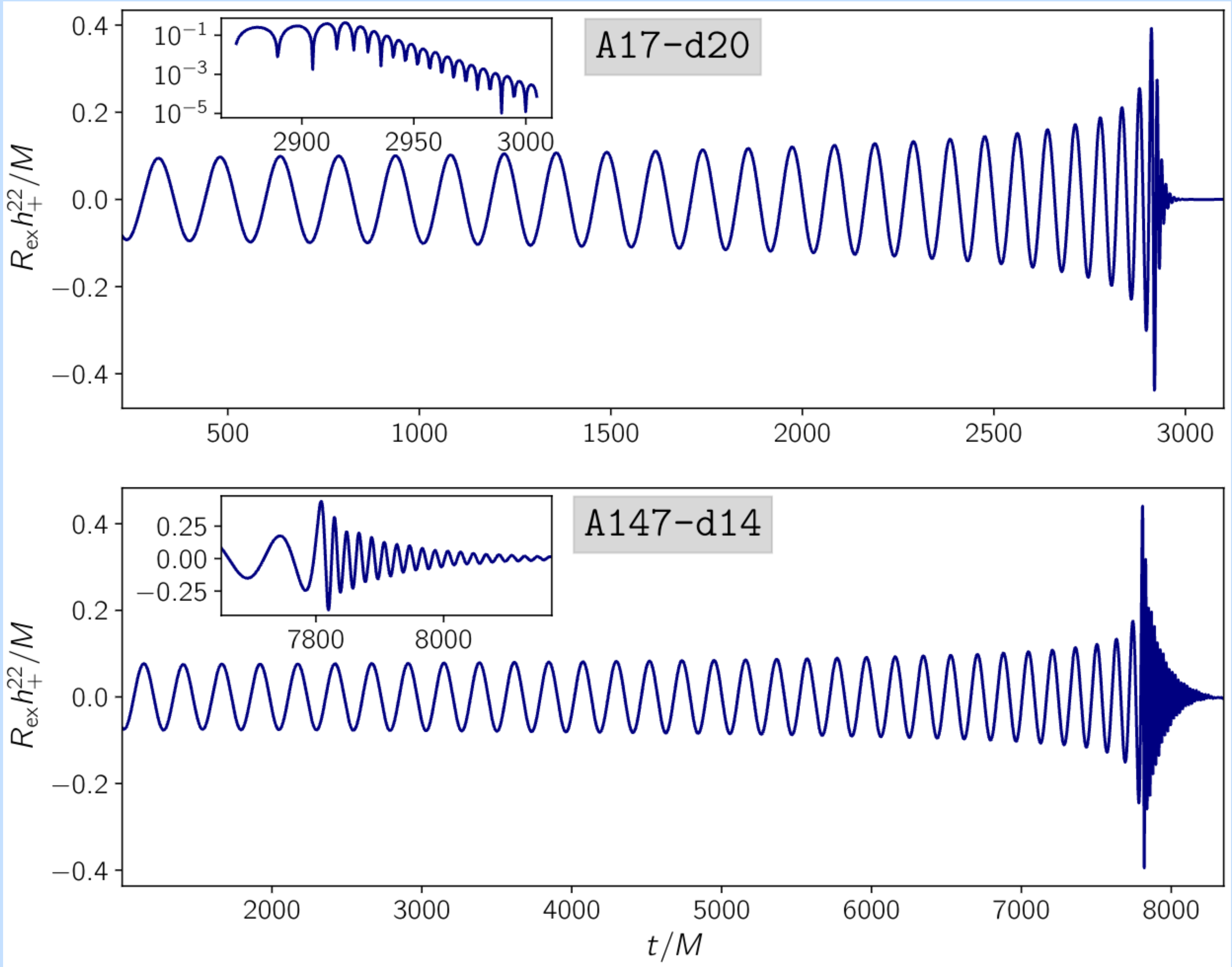
- For all runs we calibrate the eccentricity so that $e \sim 0.002 - 0.005$.

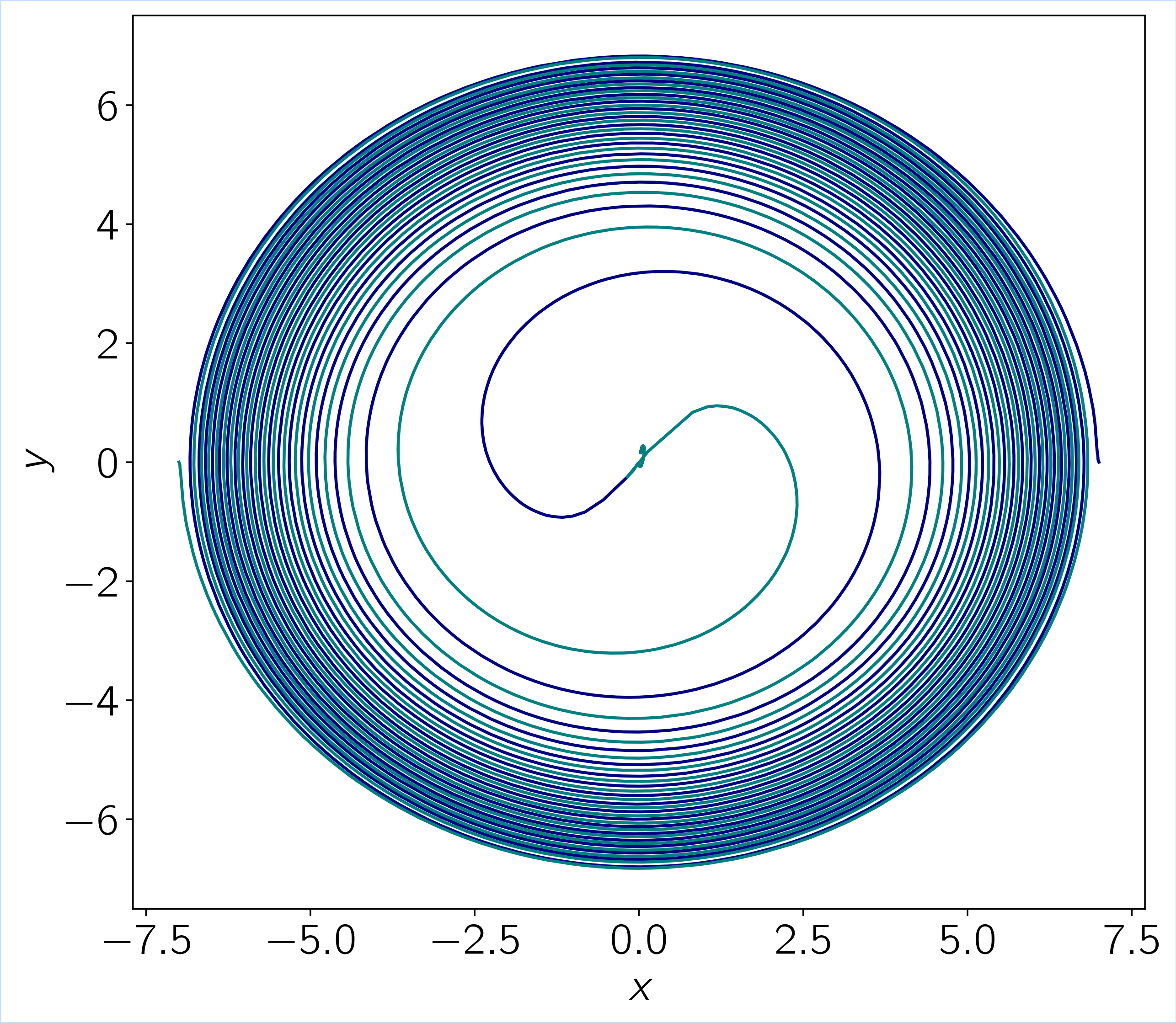
- We use **GRChombo** and **Lean** codes to evolve the binary systems. We find good agreement between the codes and both yield accuracy comparable to binary BH evolutions.

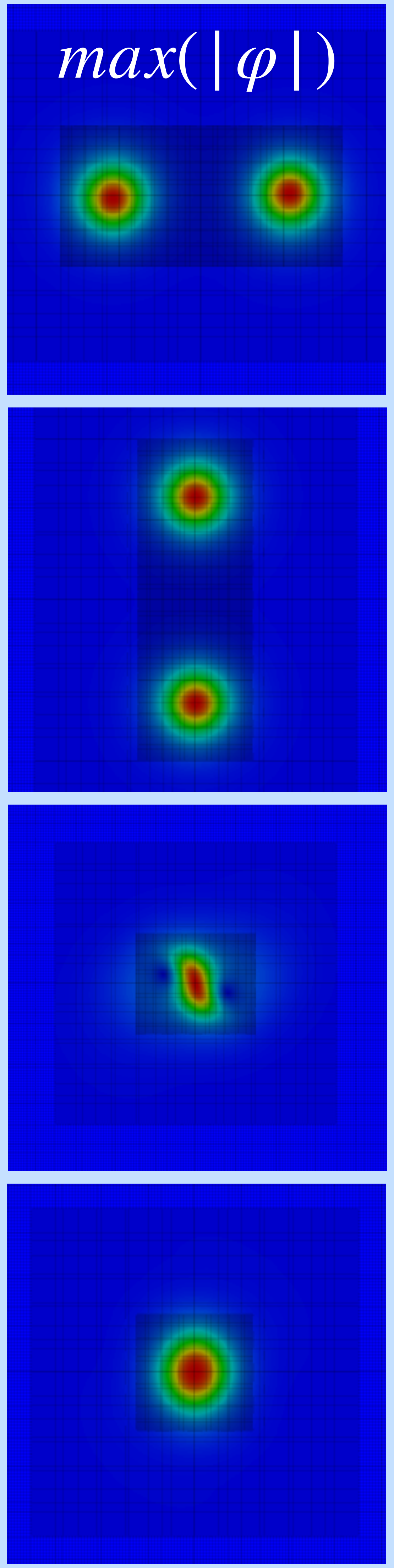
- Waveforms differ by the remnant:

Compact BS binary (A17) forms a BH post-merger.

'Fluffy' BS binary (A147) forms a BS post-merger.







Inspirals

- We also study the effect of the phase off-set $\delta\phi$ and the anti-BS companion $\epsilon = -1$

  (i) in-phase ($\epsilon = 1, \quad \delta\phi = 0$)

  (ii) de-phased ($\epsilon = 1, \quad \delta\phi = \pi/2$)

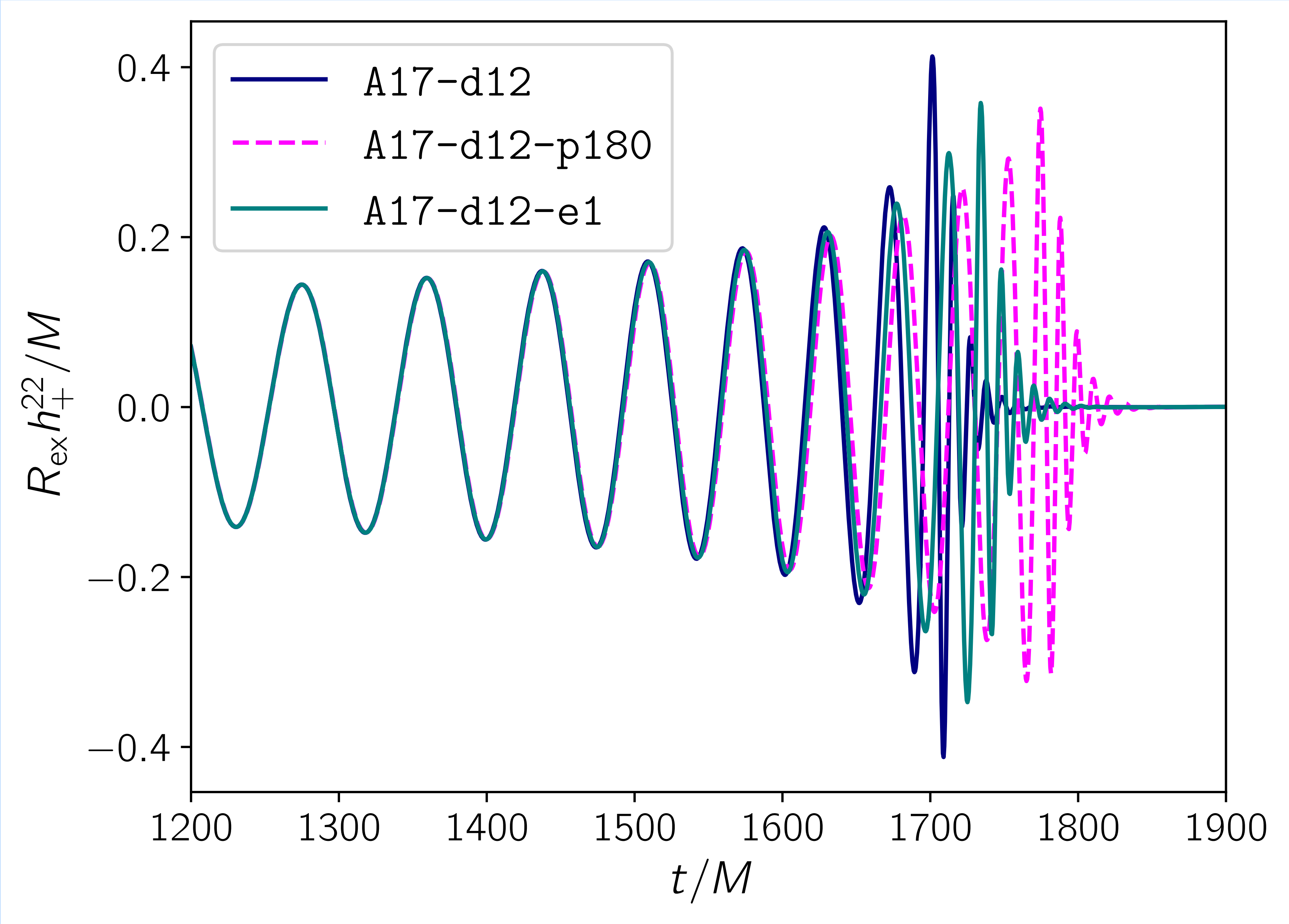
  (iii) anti-phase ($\epsilon = 1, \quad \delta\phi = \pi$)

  (iv) anti-boson ($\epsilon = -1, \quad \delta\phi = 0$)

  - Note the 'shape' of the chirp for different BS binaries.

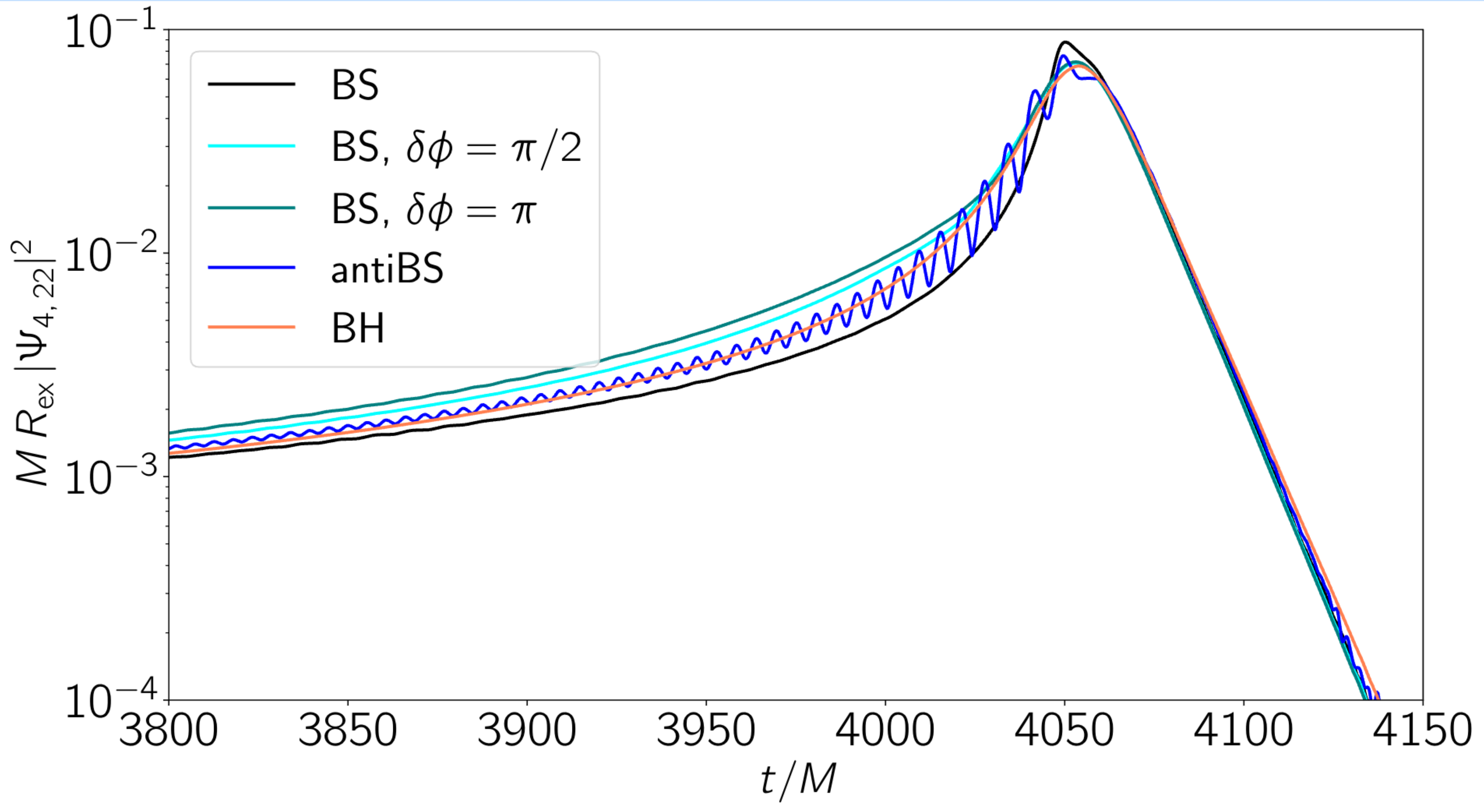
Chirp of the in-phase BS binary (black) is steeper more 'violent'; chirp of the anti-phase binary (teal) is shallower.

Compact binary (A17)



$$\varphi(t, r) = A(r) e^{i(\epsilon\omega t + \delta\phi)}$$

blue: in-phase
pink: anti-phase
teal: anti-boson

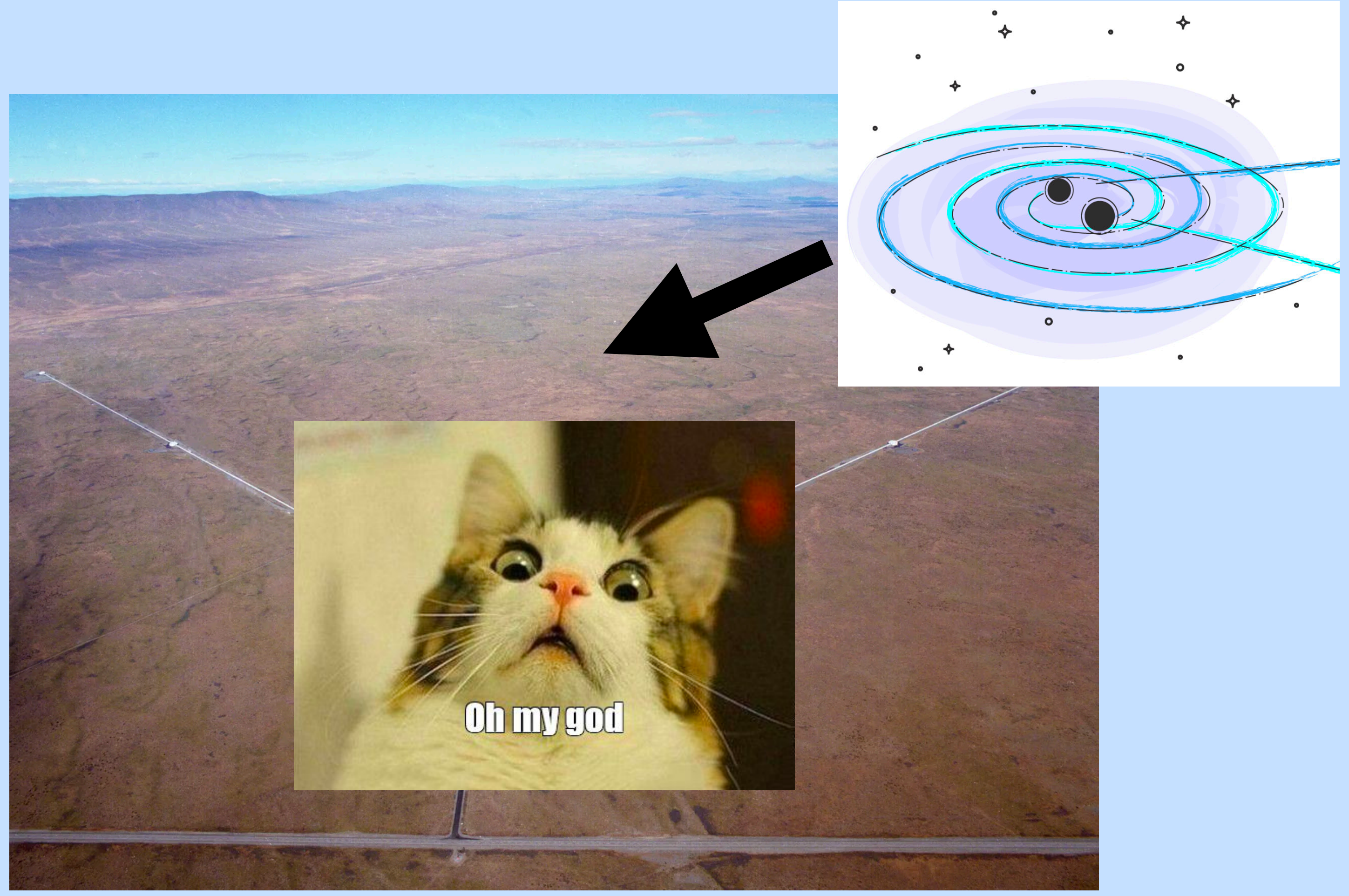


Waveform bank

Our NR waveforms are publicly available on:

https://github.com/tamaraevst/Boson-star-waveforms

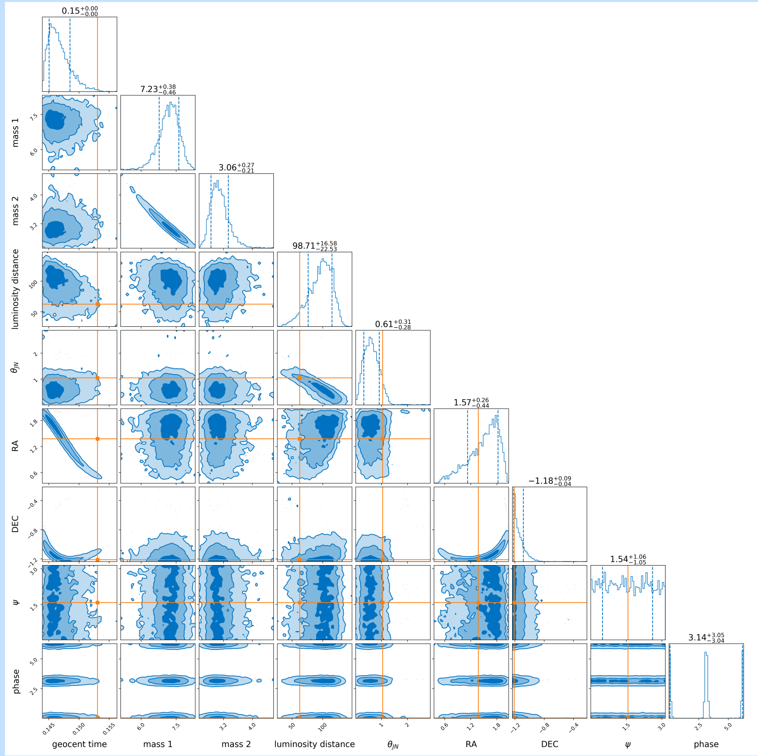
The scenario we would like to consider



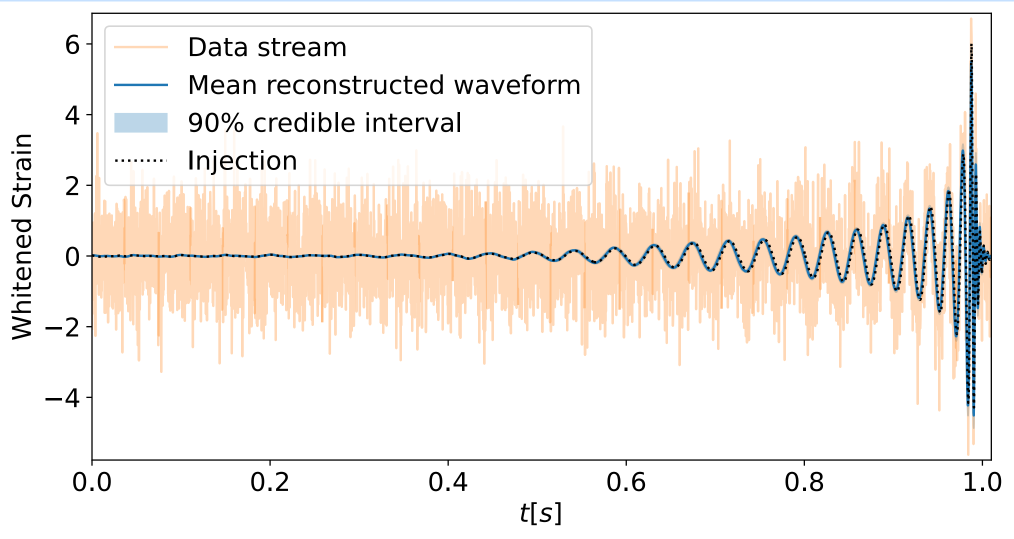
Inject NR signal into detector noise (requires fixing the total binary mass, luminosity distance, sky location)

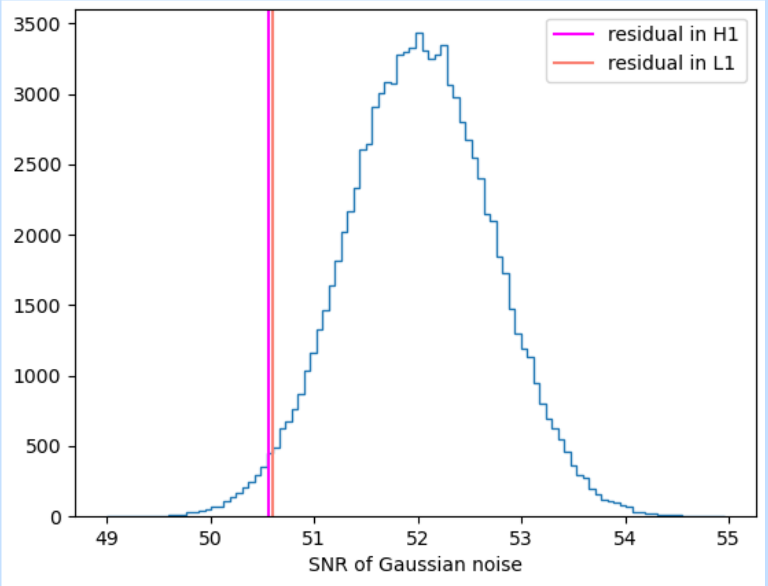
Ashton+ (2018)

Use Bilby to perform parameter estimation



Assess the recovery of the injected parameters





Assess the quality of the recovery using a residual test. Is the residual $r = d - h$ compatible with Gaussian noise?

Details of injections

Bottom line: *We inject our NR BS signals into noise of 2 LIGO detectors (H1, L1) and use Bilby for PE utilising common waveform approximants for recovery.*

- We focus on the dominant $l = 2$ modes only.
- All of the injections we perform have detectable SNR values, e.g. $\rho \in [15{,}60]$ in Hanford.
- We have tested an array of waveform approximants: IMRPhenomD, IMRPhenomPv3, **IMRPhenomXP**, IMRPhenomXPHM, TaylorF2, **IMRPhenomPv2_NRTidal**, TEOBResumS.
- We fix the right ascension, $\alpha = 1.375$, declination $\delta = -1.2108$, inclination angle, $\iota = \pi/3$ and polarisation angle $\psi = \pi/2$.
- In our exploration, we mainly vary the luminosity distance d_L and the total mass $M_{\rm tot} \in [5{,}120] M_\odot$ of the injected binaries, so $\mu \sim 10^{-13} - 10^{-12} eV$.

LISA Consortium Waveform Working Group (2023)

Waveform Family	Domain	Waveform Model	Spins	Mode Content		Eccentricity	Calibration Region
1st generation	FD	IMRPhenomA	✗		(2,±2)	no	$q \leq 4$
2nd generation		IMRPhenomB	✓				NR calibration: $q \leq 4$, $\lvert\chi_{1/2}\rvert \leq 0.75$ $\lvert\chi_{1/2}\rvert \leq 0.85$ (for $q = 1$)
		IMRPhenomC	✓				
		IMRPhenomP	✓✓	CP			
3rd generation		IMRPhenomD	✓				NR calibration: $q \leq 18$, $\lvert\chi_{1/2}\rvert \leq 0.85$ $-0.95 \leq \chi_{1/2} \leq 0.98$ (for $q = 1$)
		IMRPhenomPv2	✓✓	CP			
		IMRPhenomPv3	✓✓				
		IMRPhenomHM	✓		(2,±2),(2,±1),(3,±3),(4,±3),(4,±4)		
		IMRPhenomPv3HM	✓✓	CP			
4th generation		IMRPhenomXAS	✓		(2,±2)	in development	NR calibration: $q \leq 18$, $\lvert\chi_{1/2}\rvert \leq 0.99$ Teukolsky calibration: $q \leq 1000$
		IMRPhenomXP	✓✓	CP			
		IMRPhenomXHM	✓		(2,±2),(2,±1),(3,±2),(3,±3),(4,±4)		
		IMRPhenomXPHM	✓✓	CP			
	TD	IMRPhenomT	✓		(2,±2)	in development	NR calibration: $q \leq 18$, $\lvert\chi_{1/2}\rvert \leq 0.99$ Teukolsky calibration: $q \leq 1000$
		IMRPhenomTP	✓✓	CP			
		IMRPhenomTHM	✓		(2,±2),(2,±1),(3,±3),(4,±4),(5,±5)		
		IMRPhenomTPHM	✓✓	CP			

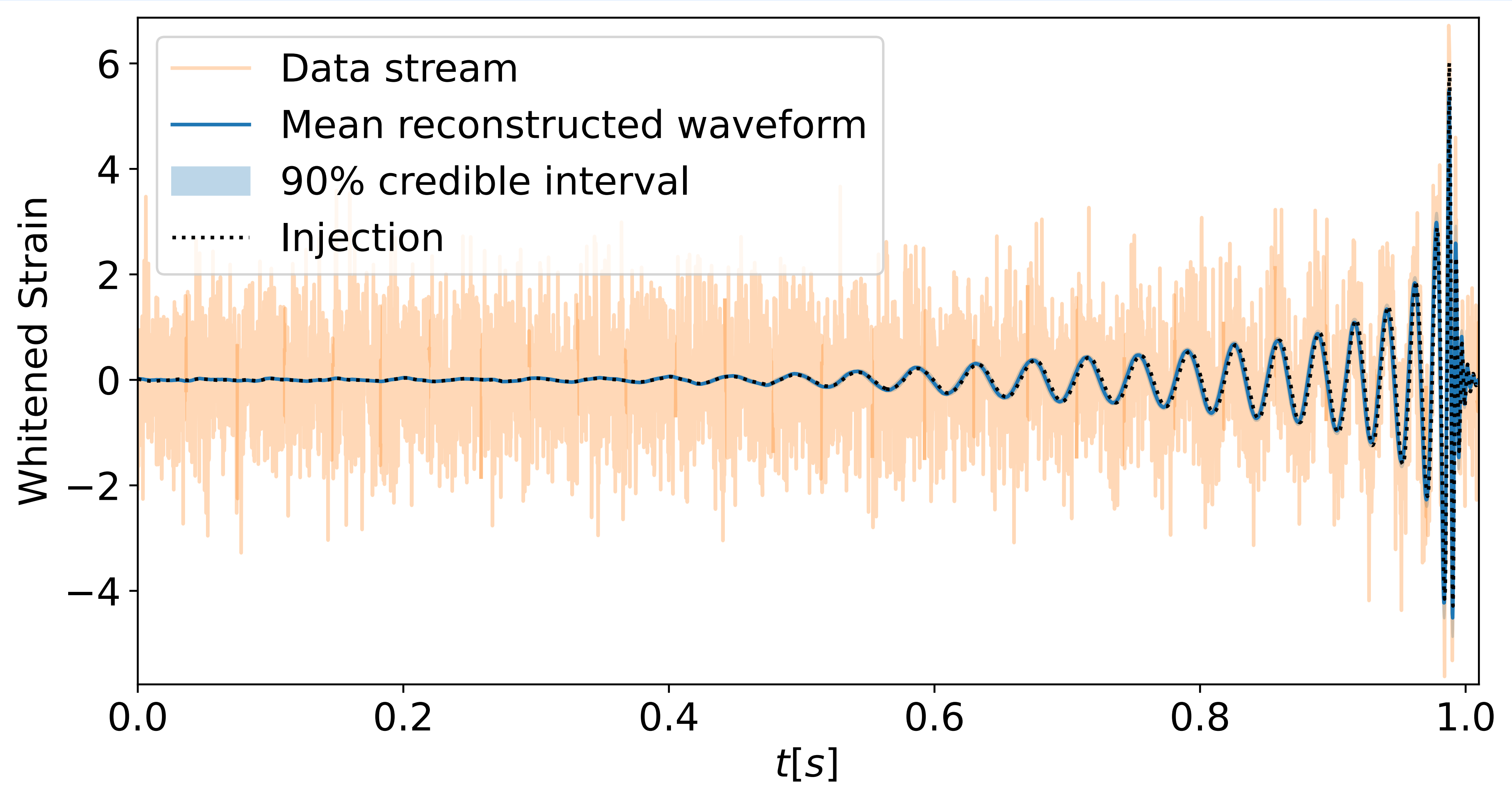
✗ no spins ✓ spins aligned with orbital angular momentum ✓✓ precessing spins CP mode content in co-precessing frame

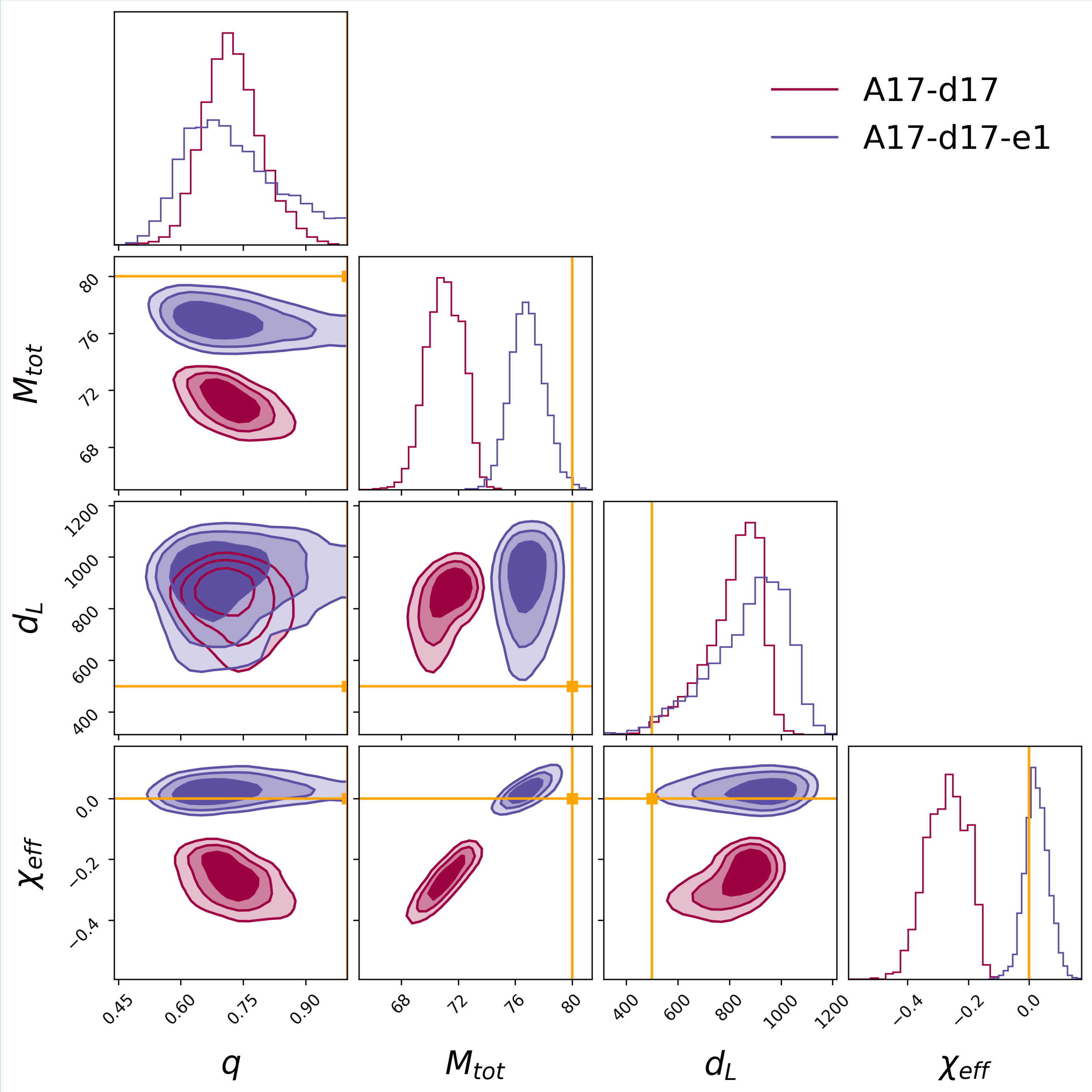
Compact binary example

- None of the approximants are able to recover the injected parameters within 90% confidence level: often biasing q and spins.

- For a wide range of d_L and $M_{\rm tot} \in [5{,}120]M_\odot$ we obtain a Gaussian residual, e.g. even for injections with $\rho \sim 170$

- Among compact A17 runs, anti-BS binary has the 'most accurate' PE.





Injection: in-phase compact BS binary with $M_{\rm tot} = 80M_\odot$ and $d_L = 500{\rm Mpc}$

purple: anti-BS
pink: in-phase

Fluffy binary example

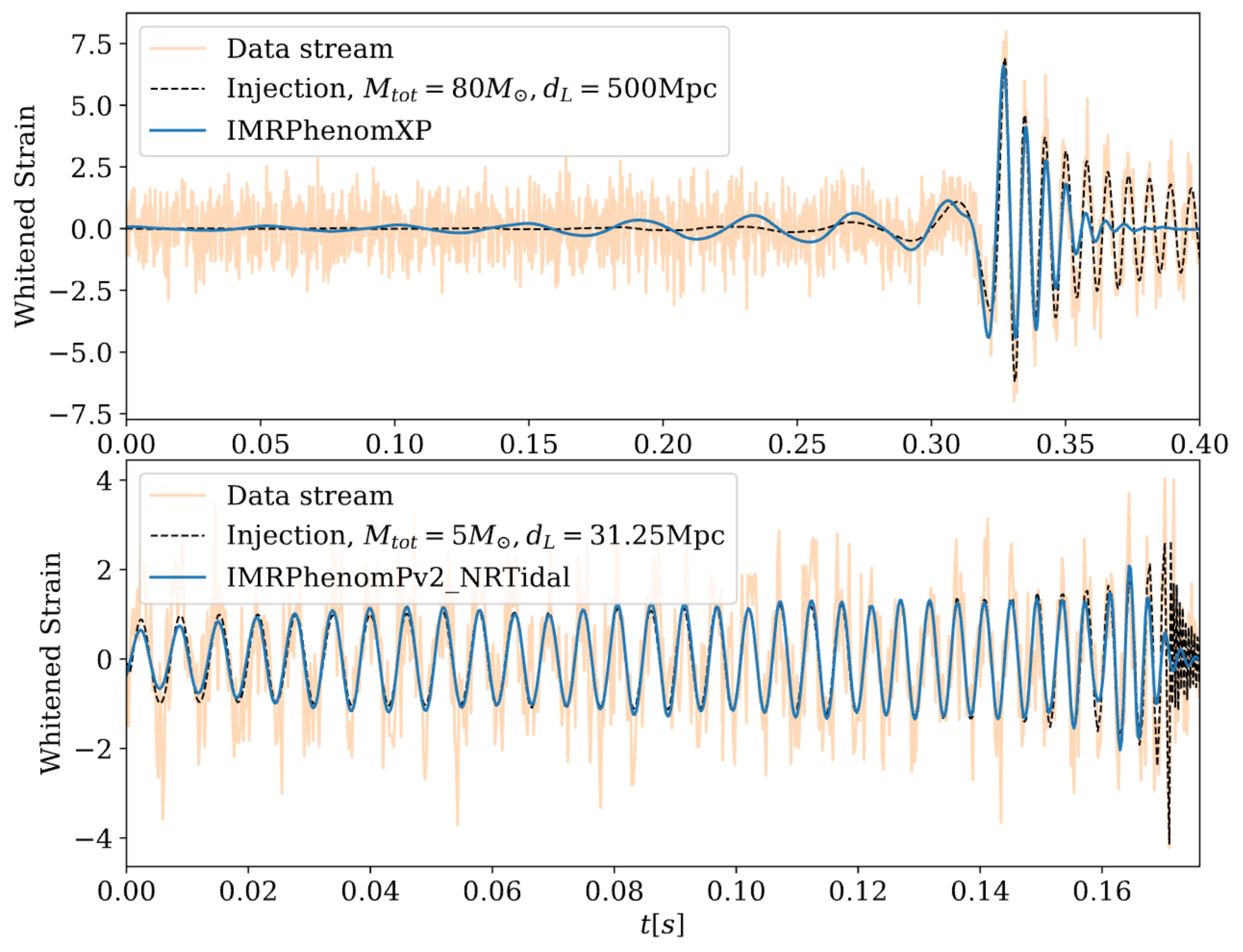
- None of the approximants are able to recover all of the injected parameters within 90% confidence level.

- For larger M_{tot} Bilby mainly fits the merger + ringdown, for smaller M_{tot} — the inspiral; but never both!

- For $\rho_{\text{inj}} \lesssim 30$ the residual is Gaussian, whilst for $\rho_{\text{inj}} \gtrsim 30$ — non-Gaussian.

Upper: IMRPhenomXP recovery results in $m_1 \sim 70M_\odot$, $m_2 \sim 65M_\odot$, $a_1 \sim 0.98$ and $a_2 \sim 0.60$.

Bottom: IMRPhenomPv2NRTidal recovery yields $m_1 \sim 3.7M_\odot$, $m_2 \sim 1.3M_\odot$, $a_1 \sim 0.96$, $a_2 \sim 0.63$, $\Lambda_1 \sim 3000$ and $\Lambda_2 \sim 11000$.



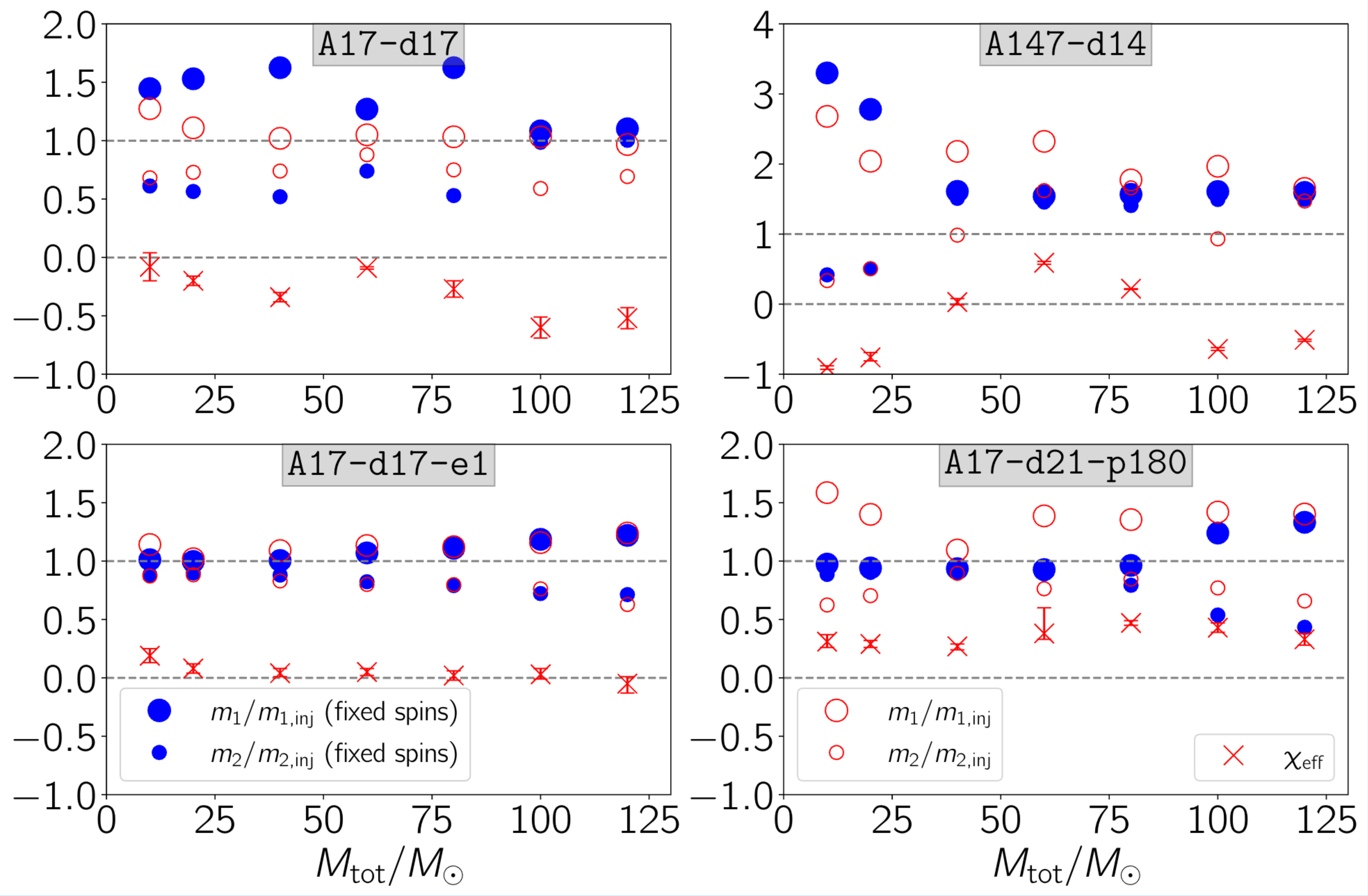
Interpreting PE results

- Essentially, most of the recovered parameters are 'inaccurate', but the PE results we are seeing are not random!

- Let us consider the recovery of the effective spin for binaries of various total masses.

- The recovered effective spins can be explained in terms of the shape of the chirp of injected BS binaries.

in-phase, compact **in-phase, fluffy**



antiBS, compact **anti-phase, compact**

Blue: PE using spins fixed to the injected values (zero spins).

Red: full PE (all parameters are varied).

x denotes the effective spin $\chi_{eff} = \dfrac{\chi_1 + q\chi_2}{1+q}, \quad \chi_i = S_i \cdot L$

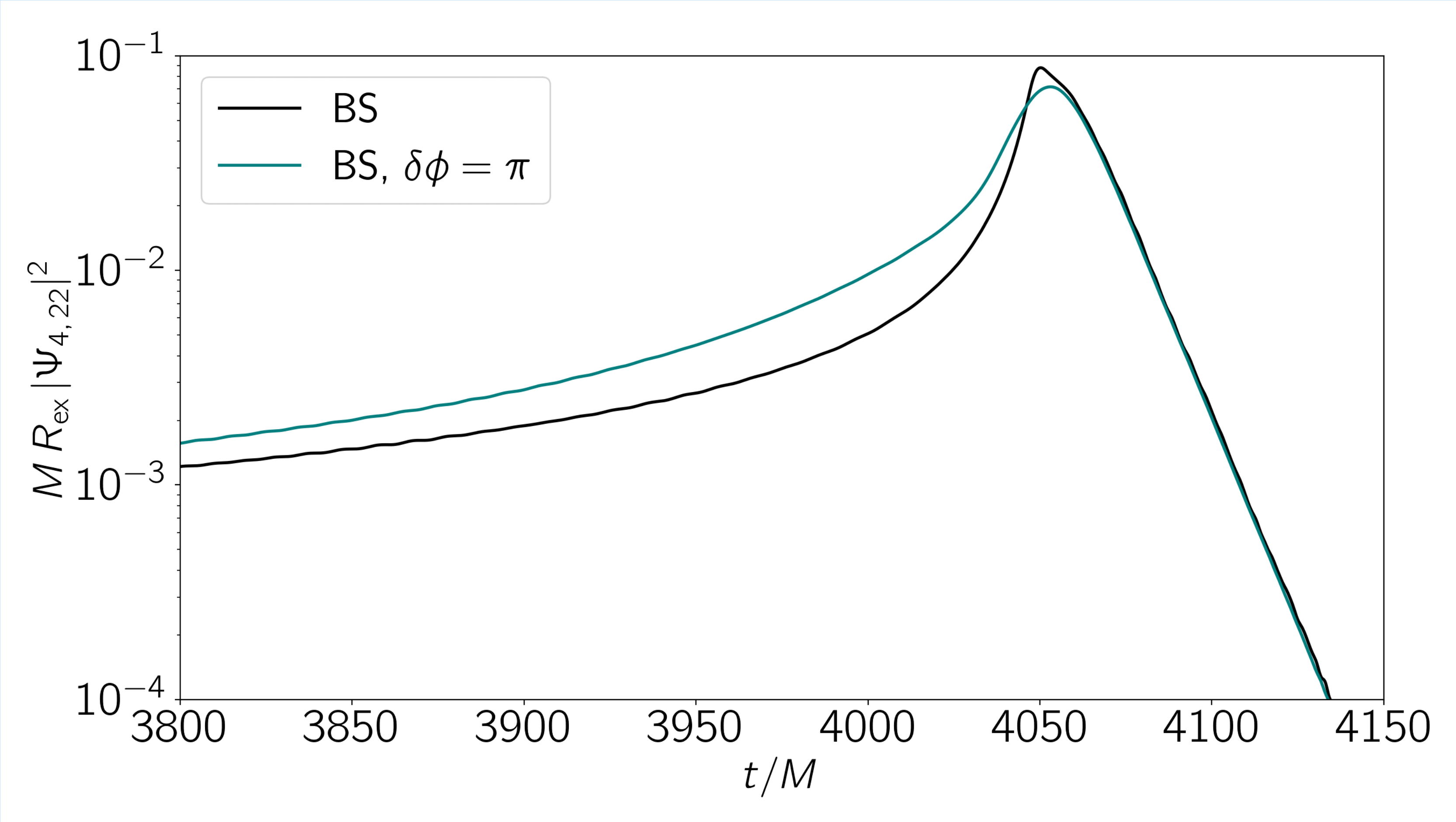
Interpreting PE results

Steep chirp

- In-phase BS binary
- BH binaries with anti-aligned spins.

Shallow chirp

- Anti-phase BS binary
- BH binaries with aligned spins (hang-up).



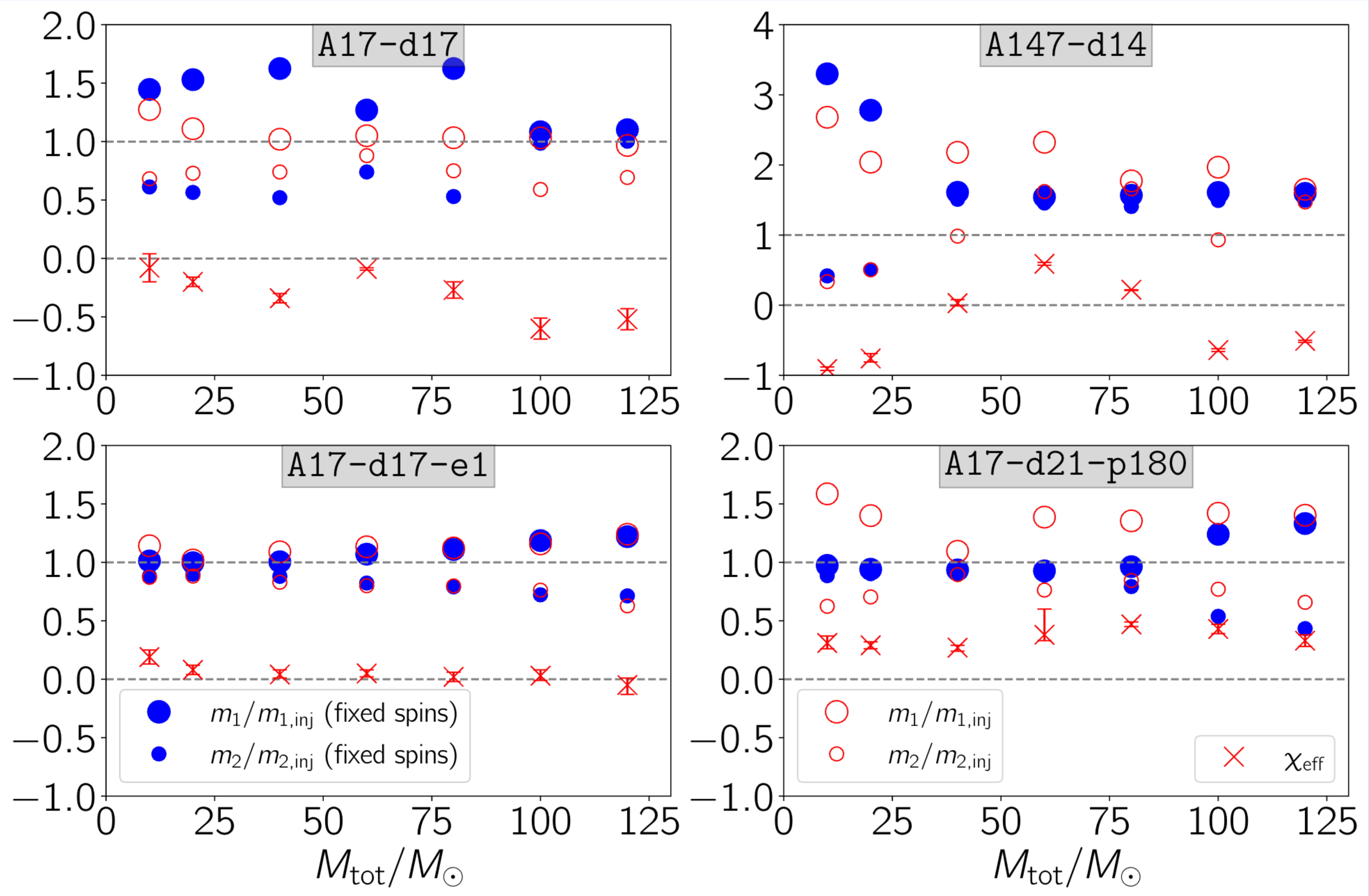
1. In-phase binary: negatively aligned spins

2. Anti-phase binary: positively aligned spins

3. Anti-BS binary: spins close to zero

in-phase, compact

in-phase, fluffy



antiBS, compact

anti-phase, compact

Summary

- **Supposing BS coalescences occur in the Universe, can we detect them?**

Yes; however, the BS scalar mass, μ, would determine the frequency of the signal.

- **Can we distinguish them from traditional BH events?**

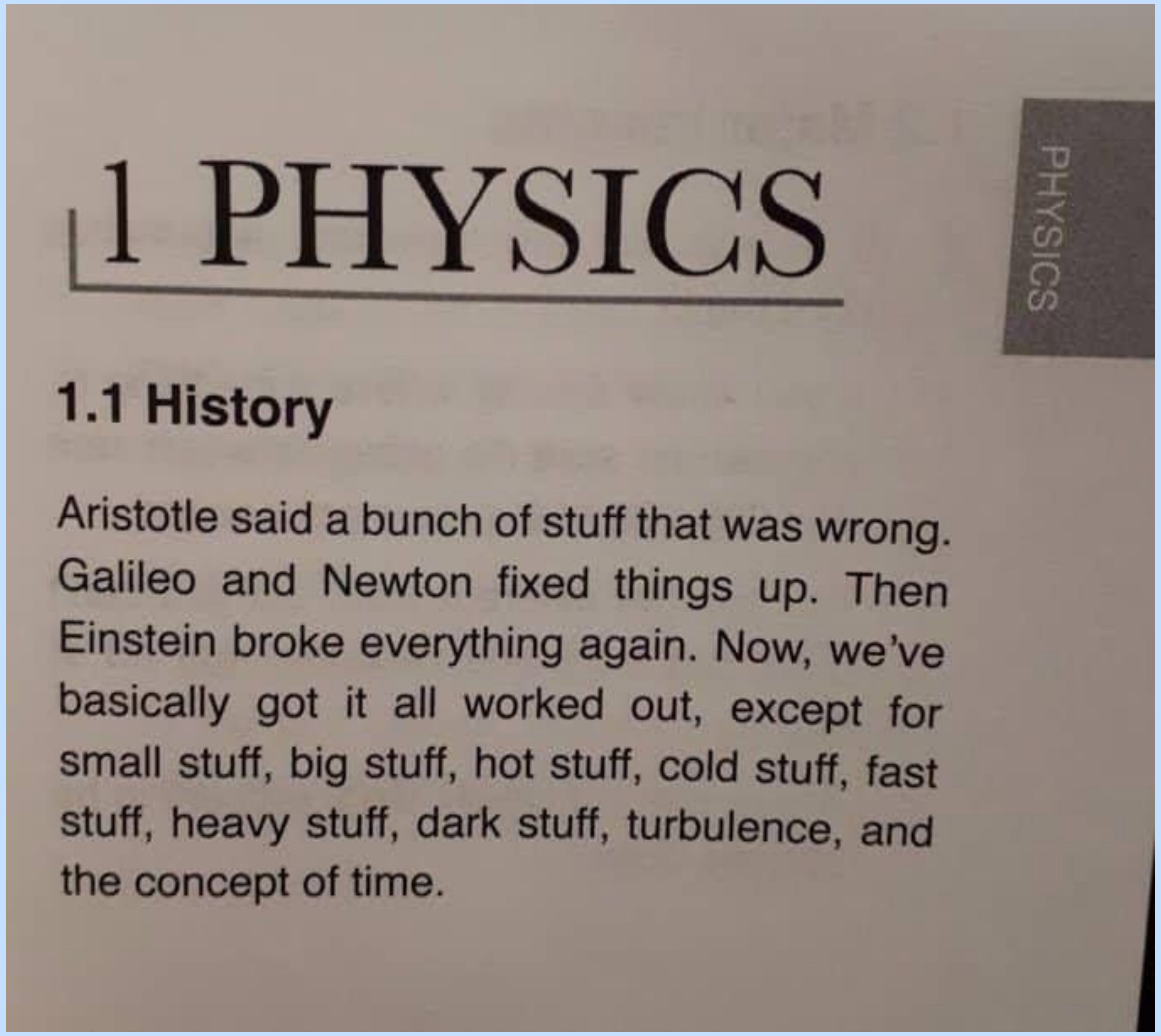
No, if we simply follow the results of PE for signals with a BH remnant. However, (1) consistency checks should be performed to assess whether we can break the degeneracies, and (2) high SNR > 200 injections should be considered in more detail.

Yes, especially in the regime of moderate SNR > 30 for signals forming a BS remnant.

- We are only at the beginning of modelling BS binaries and potentially having a simple phenomenological model. Need more exploration of the BS parameter space and potential smoking-gun effects. Plenty of room for interesting studies.

- It is important however to address the **'big elephant in the room': degeneracies**. Can we break the degeneracies between compact BS binaries and BHs? The same applies to modified theories of gravity.

Thank you!



1 PHYSICS
PHYSICS
1.1 History
Aristotle said a bunch of stuff that was wrong. Galileo and Newton fixed things up. Then Einstein broke everything again. Now, we've basically got it all worked out, except for small stuff, big stuff, hot stuff, cold stuff, fast stuff, heavy stuff, dark stuff, turbulence, and the concept of time.

Extra Slides

Numerical relativity and BSs

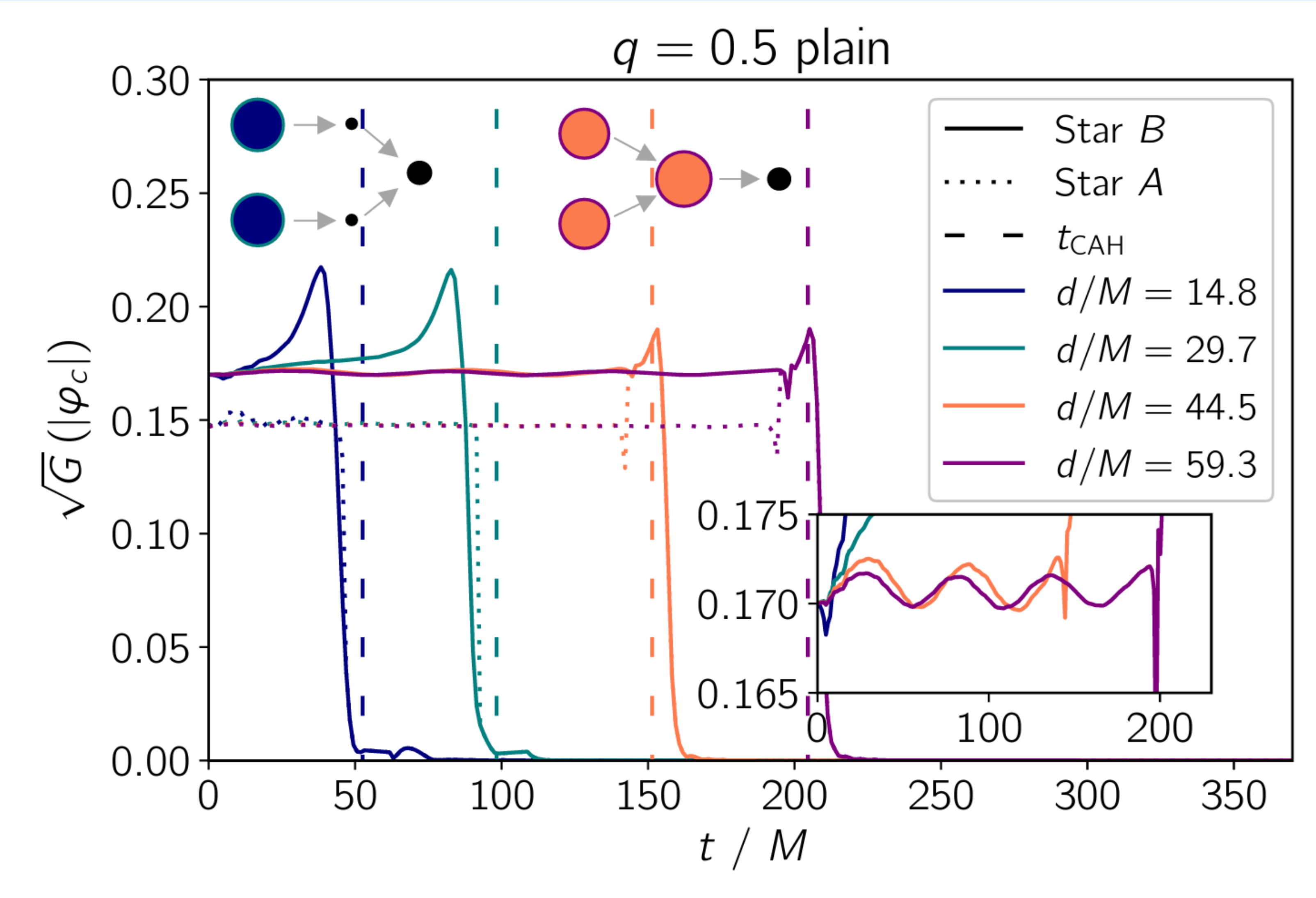
- If we want to perform NR simulations, a few considerations have to be taken into account:

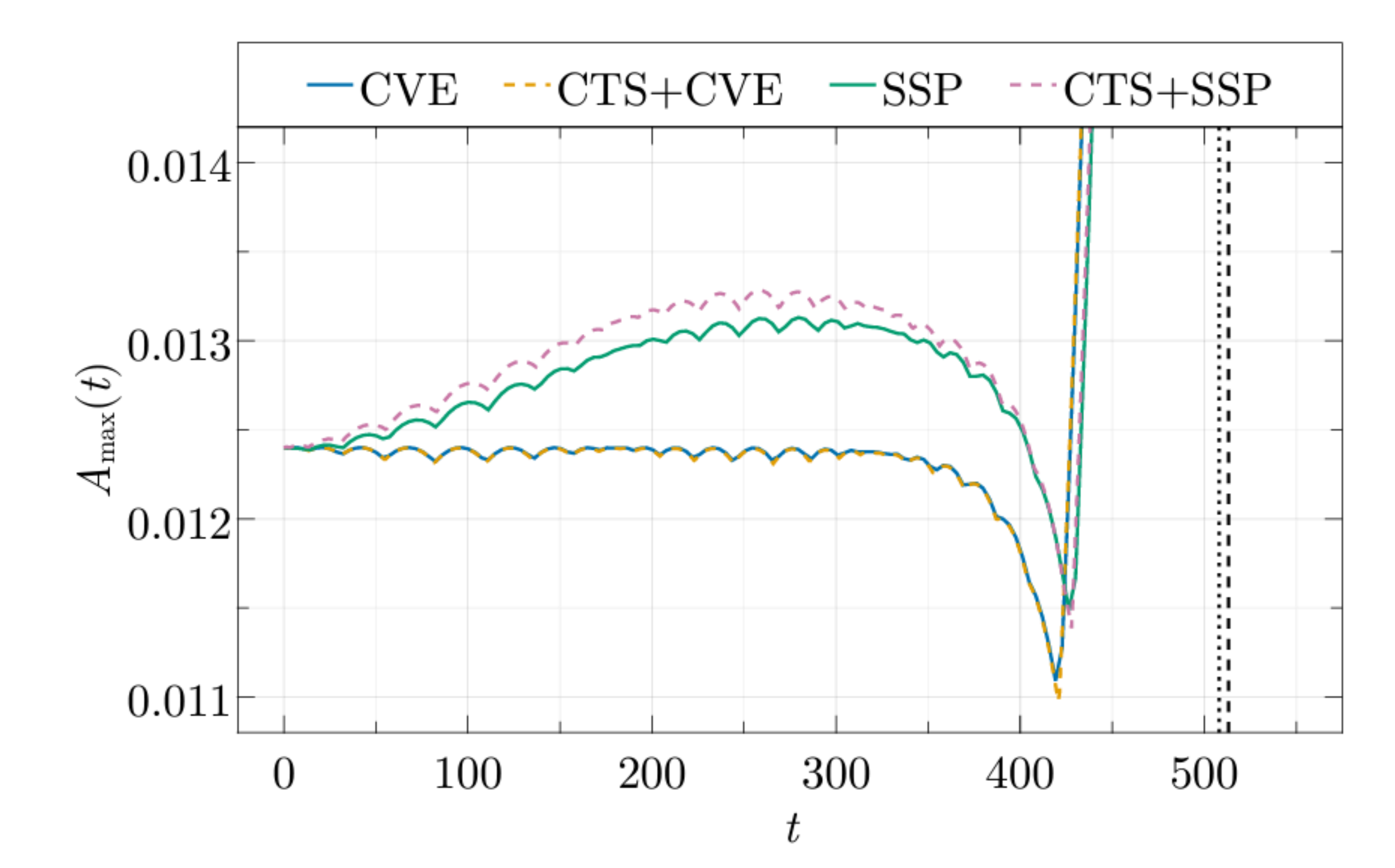
  1. **Initial data**: codes either utilise initial data superpositions that violate constraints to some degree OR solve the constraints using elliptic solvers [Siemonsen+ (2023), Atteneder+ (2024)].

  2. **Spurious oscillations** in the scalar field (the star becomes excited rather remains in equilibrium).

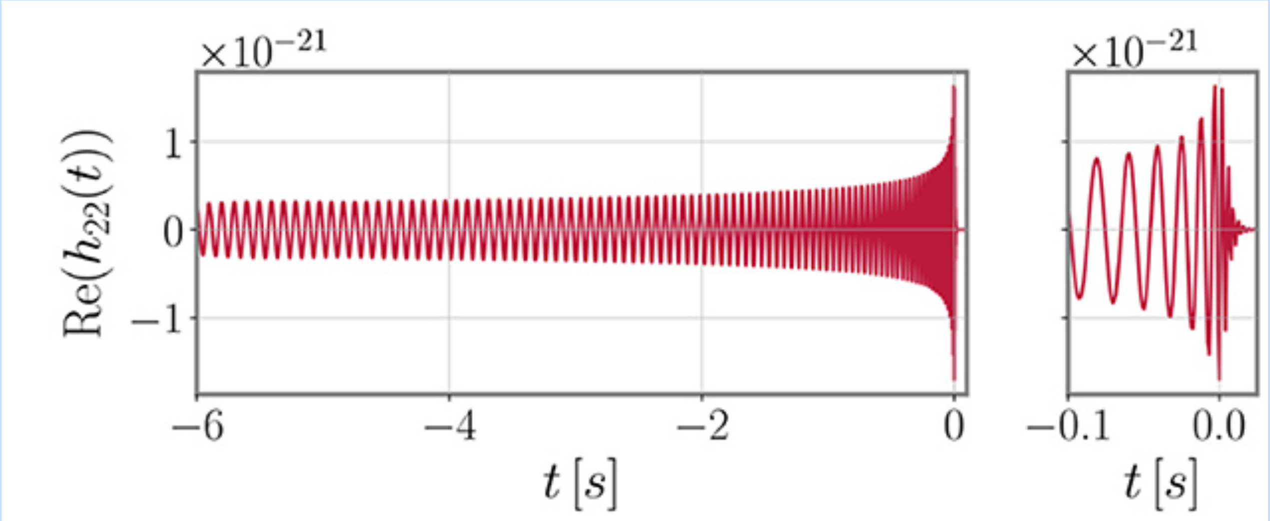
  3. **Adaptive mesh refinement** and/or **poor resolution** can be culprits of unphysical evolution.

  4. Understanding of the **accuracy and calibration** of most of the codes is lacking.



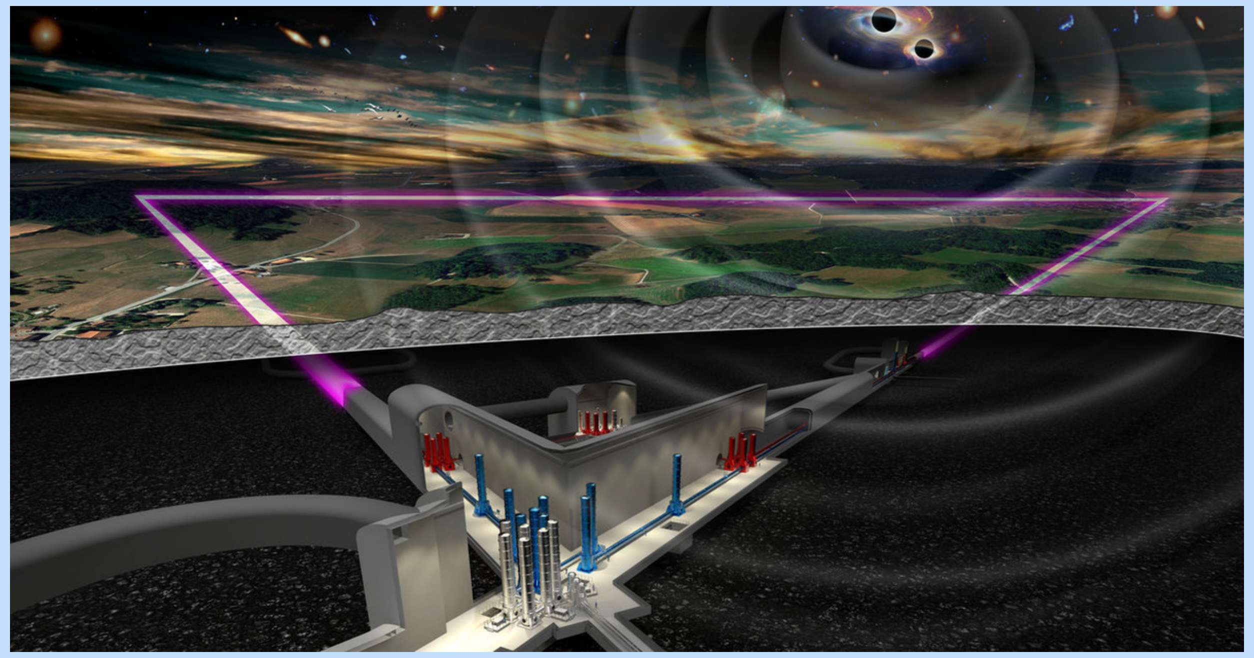


GW detection & Parameter estimation: 101



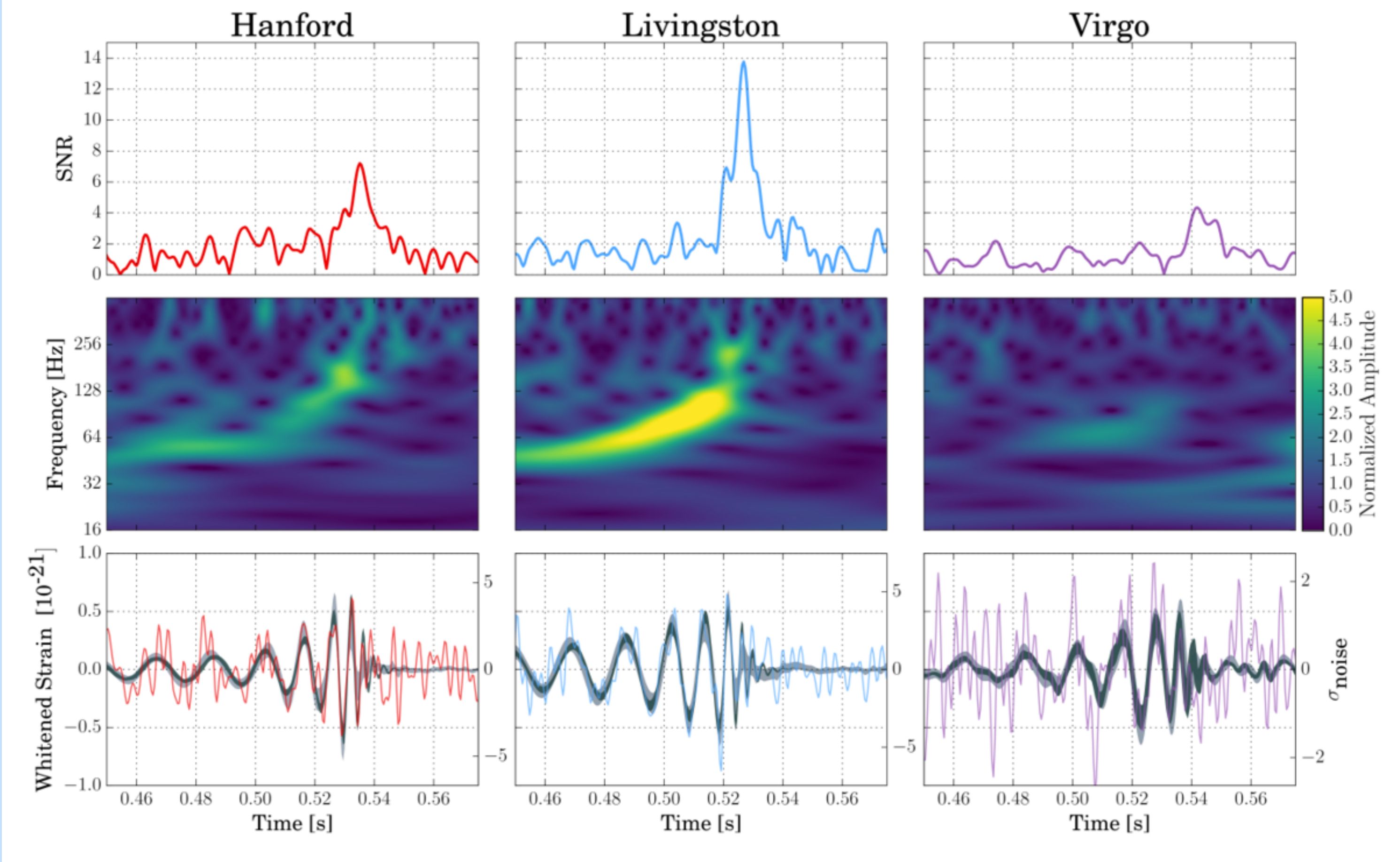
Incoming GW signal

Schmidt (2020)



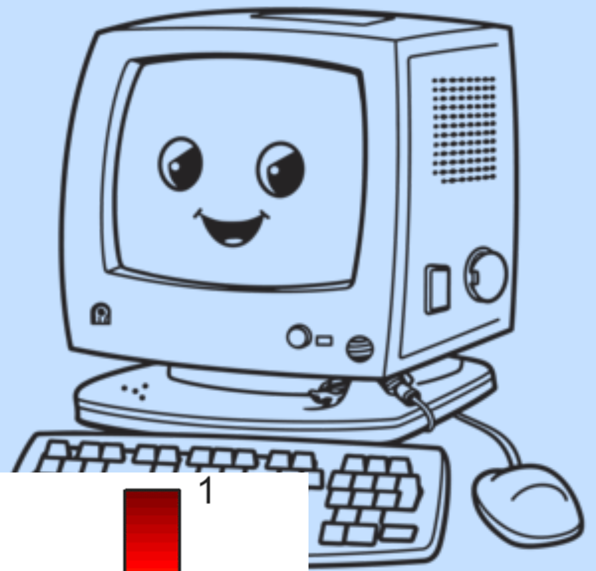
LIGO-Virgo-KAGRA detectors

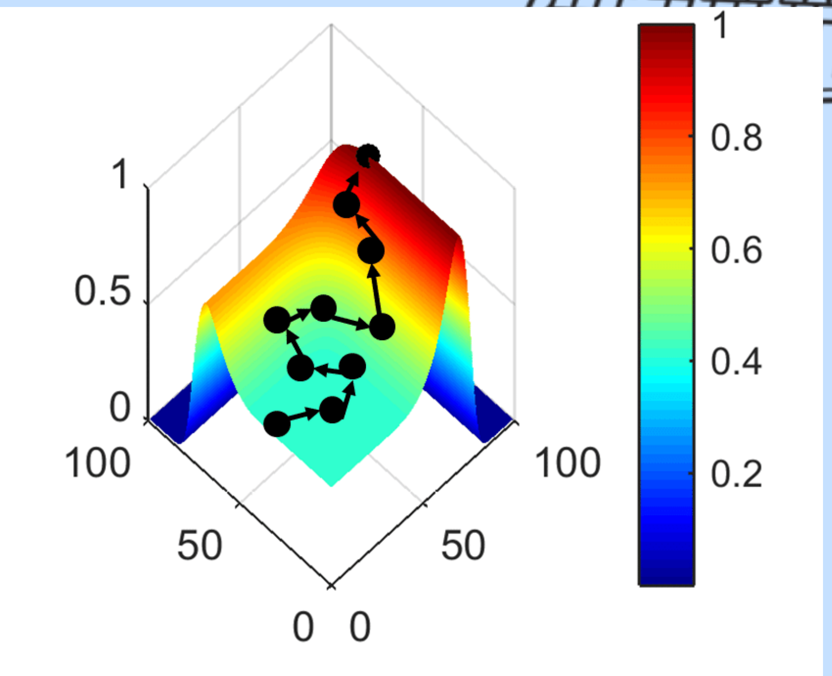
(Image credit: Nikheff)



Matched filtering

LIGO Scientific Collaboration: GW170814





Parameter estimation using statistical inference.

GW170814: BBH with

$m_1 \sim 30M_\odot, m_2 \sim 25M_\odot$

Both methods require the knowledge of the signal model as a function of source parameters — a **waveform approximant**. There are many phenomenological models calibrated to NR. *The number of NR waveforms used in the calibration process increased from 20 to ~ 400 for BBH systems*.

We present a new frequency-domain phenomenological model of the gravitational-wave signal from the inspiral, merger and ringdown of non-precessing (aligned-spin) black-hole binaries. The model is calibrated to 19 hybrid effective-one-body–numerical-relativity waveforms up to mass ratios of 1:18 and black-hole spins of $|a/m| \sim 0.85$ (0.98 for equal-mass systems). The inspiral part of the

Khan+ (2019)

BS & BH signals

For simplicity: consider the energy density for a complex scalar field φ in flat space-time

$$\rho = \frac{1}{2}\left(|\Pi|^2 + |\Phi|^2 + m^2\varphi^2\right), \quad \Phi = \partial_i\varphi$$

The energy density associated with the superposition of two stars $\varphi = \varphi_1 + \varphi_2$ can be expressed with $\rho = \rho_1 + \rho_2 + \Delta$, where Δ is the interaction potential, which vanishes when the two stars are well-separated. This interaction potential may be written as:

$$\Delta = \frac{1}{2}\left[\bar{\Pi}_1\Pi_2 + \Pi_1\bar{\Pi}_2 + \bar{\Phi}_1\Phi_2 + \Phi_1\bar{\Phi}_2 + m^2(\bar{\varphi}_1\varphi_2 + \varphi_1\bar{\varphi}_2)\right]$$

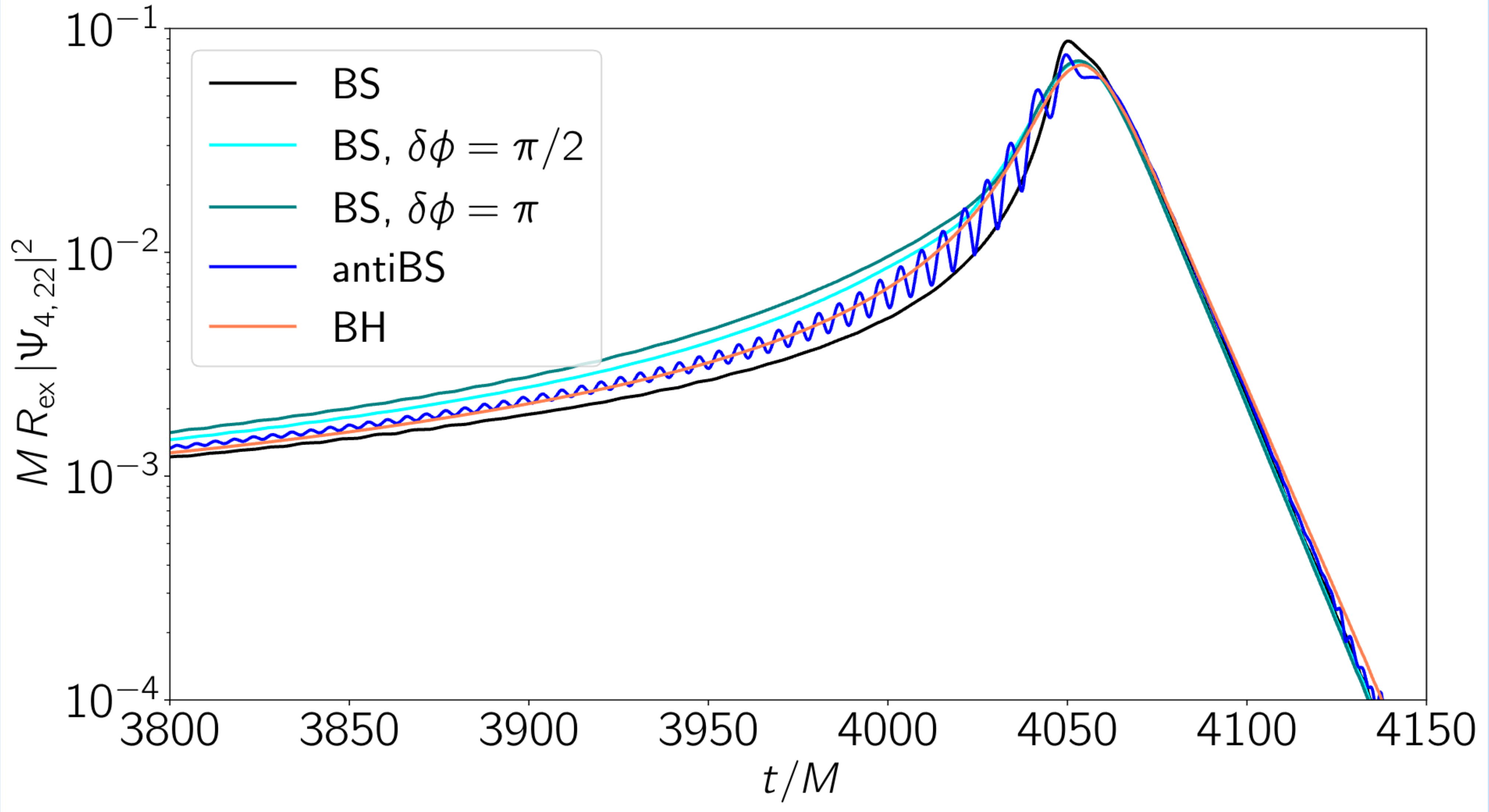
Assume $\varphi_1 = A(0)e^{i\omega t}$ and $\varphi_2 = A(0)e^{i(\epsilon\omega t + \delta\phi)}$ so that $\Delta = \Delta_0 cos[(1-\epsilon)\omega t - \delta\phi]$, where Δ_0 is strictly a non-negative function. Then by varying $\delta\phi$ and ϵ, we find:

$$\Delta_{Boson} = \Delta_0$$
$$\Delta_{Anti-phase} = -\Delta_0$$
$$\Delta_{Antiboson} = \Delta_0 cos(2\omega t)$$

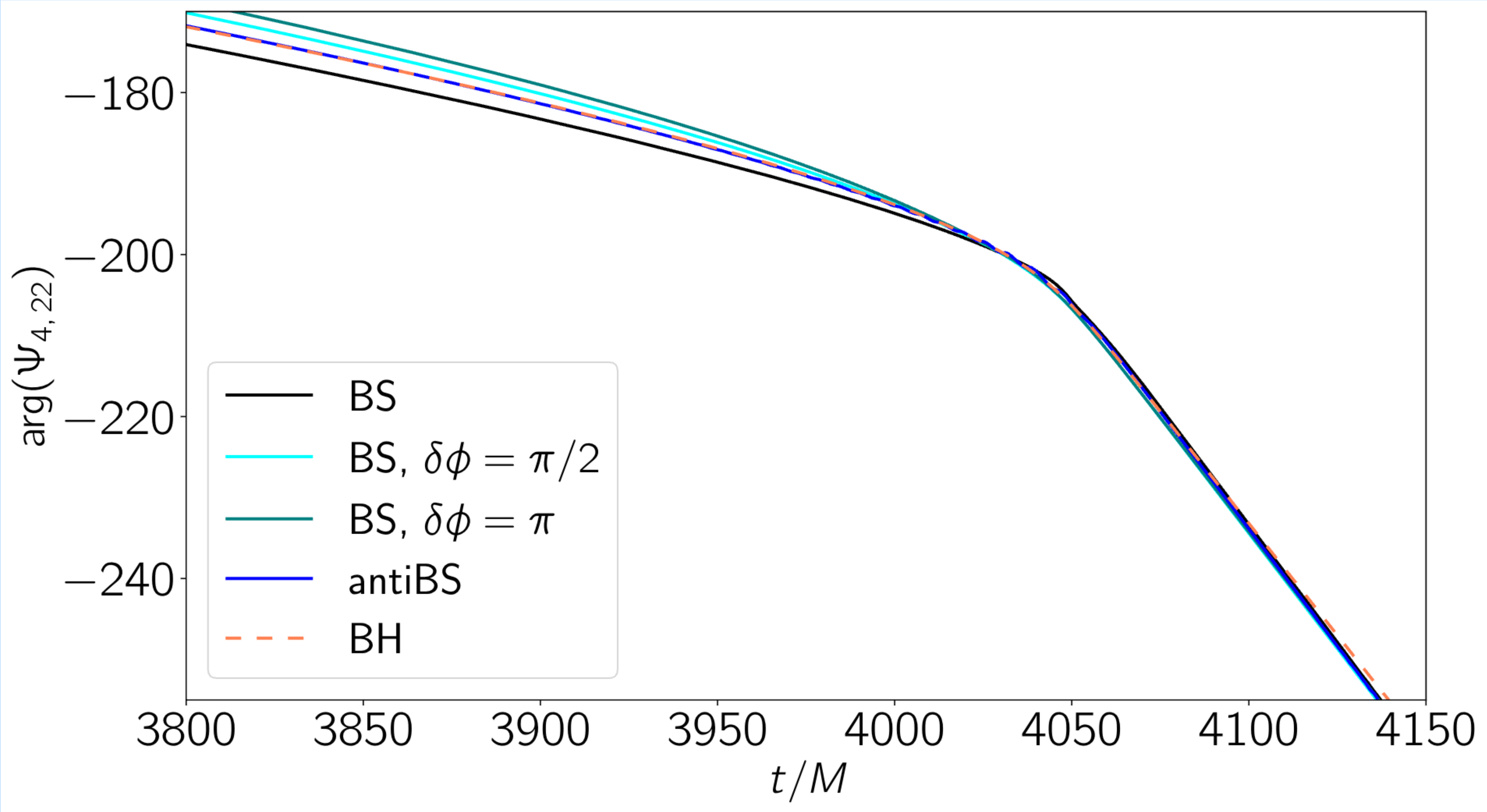
Palenzuela+ (2006)

Illustration (BH vs BS)

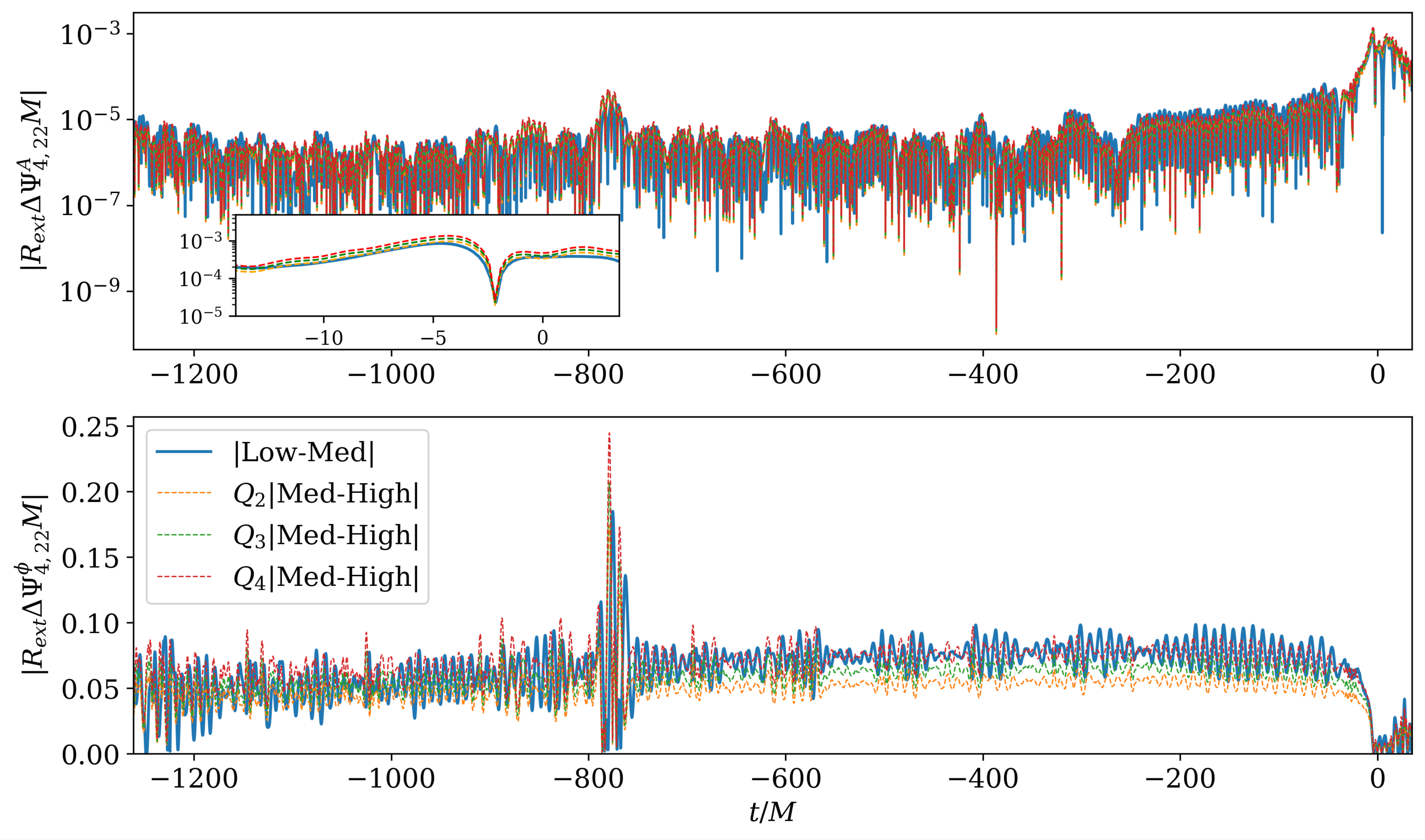
Amplitude



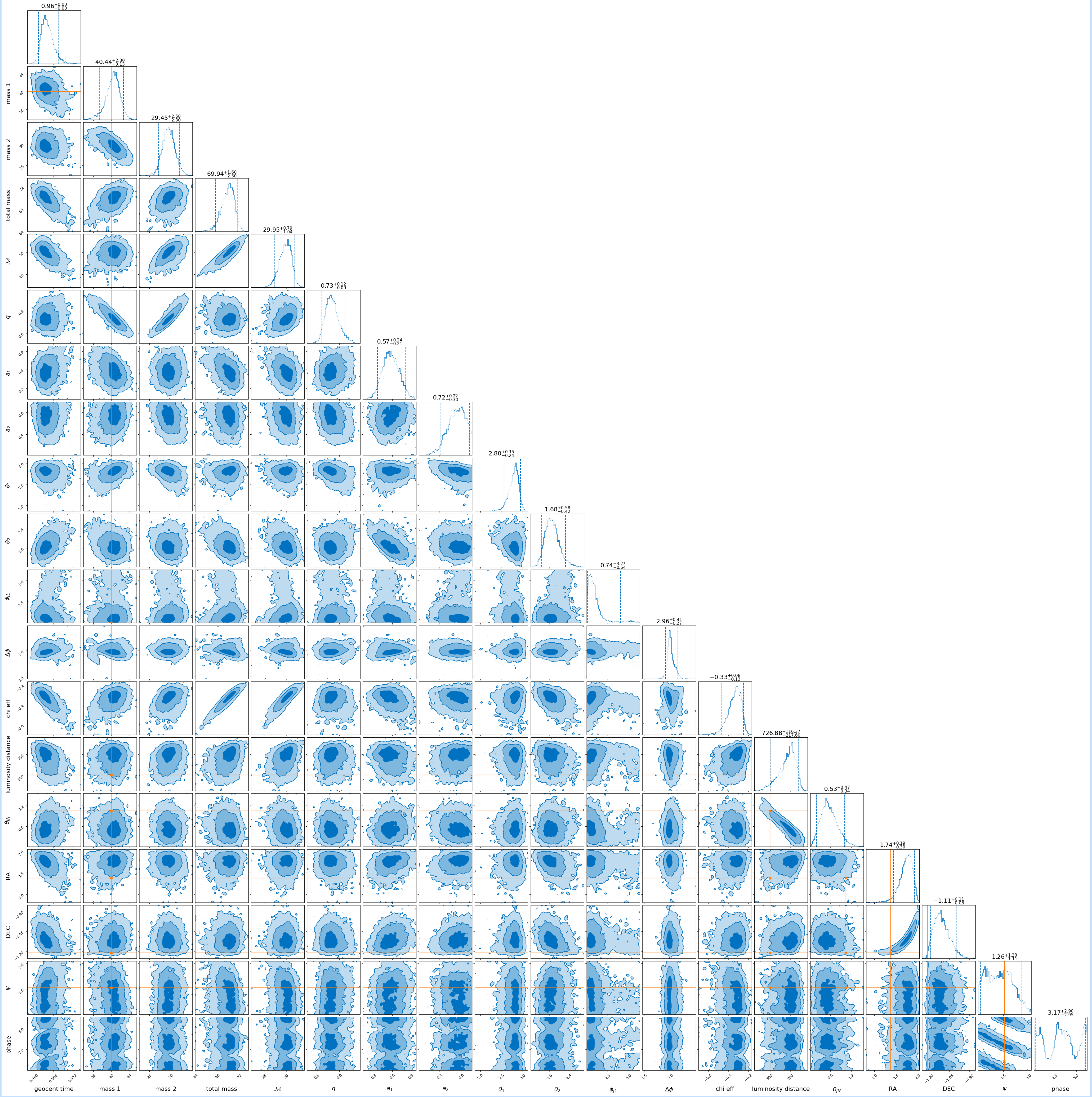
Phase



Convergence plot

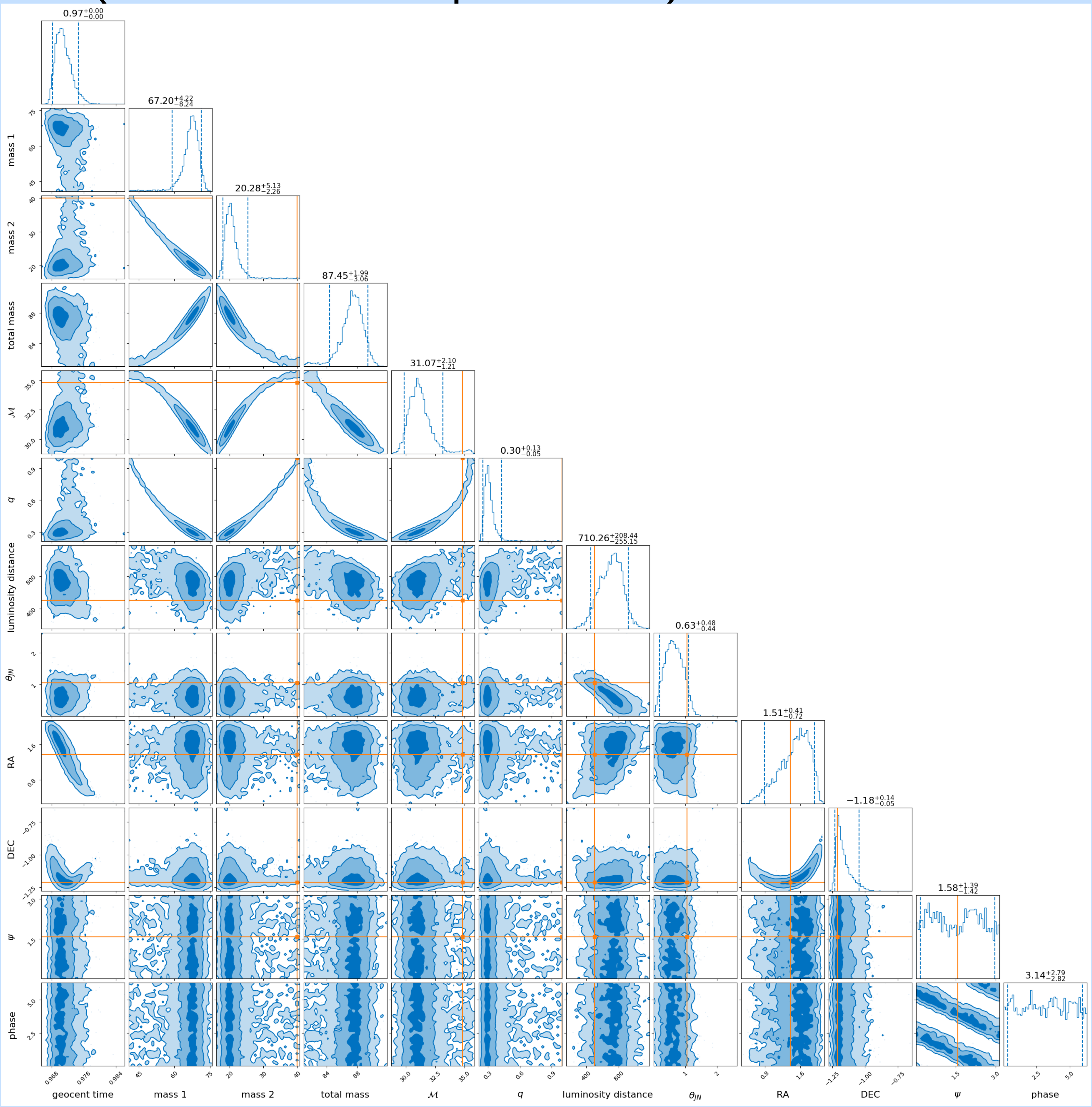


Corner plot (variable spins)



Injection of BS binary of $80M_\odot$.

Corner plot (fixed spins)



Injection of BS binary of $80M_{\odot}$.