

Gravitational waves from boson stars and their potential signature in LIGO observations

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arXiv:2406.02715, cf also 2108.11995, 2212.08023



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1. Background

The idea of boson stars

- “Gravitational-electromagnetic entities” or Geons

Wheeler 1955

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Geons*

JOHN ARCHIBALD WHEELER

Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received September 8, 1954)

Associated with an electromagnetic disturbance is a mass, the gravitational attraction of which under appropriate circumstances is capable of holding the disturbance together for a time long in comparison with the characteristic periods of the system. Such

of equations of self-consistent geon; mass and radius values. 4. Transformations and interactions of electromagnetic geons; evaluation of refractive index barrier penetration integral for spherical geon; photon-photon collision processes as additional

- Energy = mass gravitates → Compact (equilibrium?) objects
- Geons are not equilibrium configurations
- Dark matter candidates: QCD axions, ALPs, dark photons,...
- Complex fields (scalar, vector,...)
→ Genuine equilibrium states; $T_{\alpha\beta}$ stationary!
- First shown for scalar fields → “Boson stars”
Feinblum & McKinley PR 168 (1968), Kaup PR 172 (1968),
Ruffini & Bonazzola PR 187 (1969)

A boson star zoo

- Mini BSs (no self-interaction) Kaup PR (1968) and others
- "Solitonic" BSs (self-interacting scalar field) → more compact
Colpi+ PRL (1986), Lee PRD (1987), ...
- Proca stars Brito+ Phys.Lett.B (2016)
- ℓ -boson stars (multiple scalar fields) Alcubierre+ CQG (2018)
- Multi-oscillating BSs Choptuik+ PRL (2019)
- Thin-shell BSs (one scalar with false vacuum state)
Collodel & Doneva 2203.08203
- Higher-spin fields Jain & Amin 2109.04892
- Multi-field BSs Sanchis-Gual+ PRL (2021)
- May condense from local over-densities Widdicombe+ JCAP (2018)

Focus here: Single-scalar, solitonic and mini BSs

Formalism and basic features

- GR + minimally coupled complex scalar field φ

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

$$T_{\alpha\beta} = \partial_{(\alpha} \bar{\varphi} \partial_{\beta)} \varphi - \frac{1}{2} g_{\alpha\beta} [g^{\mu\nu} \partial_\mu \bar{\varphi} \partial_\nu \varphi + V(\varphi)]$$

- Potential; analogous to EOS:

$$V_{\min}(\varphi) = m^2 |\varphi|^2, \quad V_{\text{solit}}(\varphi) = m^2 |\varphi|^2 \left(1 - 2 \frac{|\varphi|^2}{\sigma_0^2} \right)^2, \quad \text{or } \dots$$

- Spherically symmetric equilibrium models

Ansatz: $\varphi(t, r) = A(r) e^{i\omega t}$

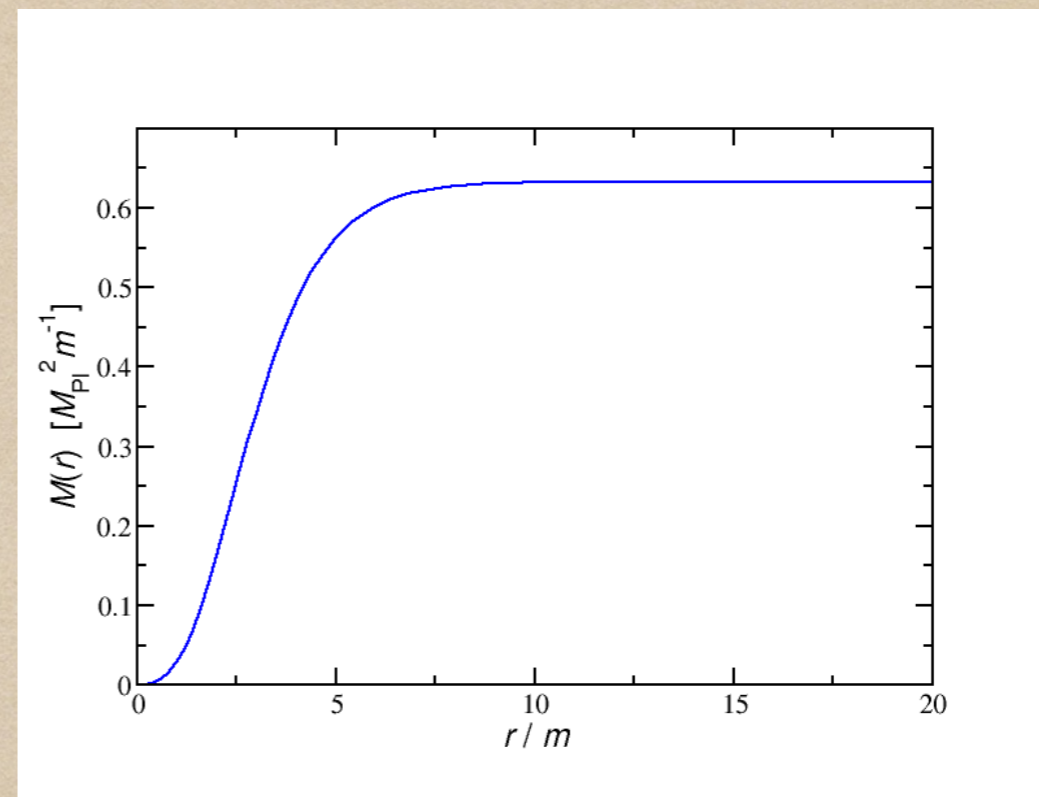
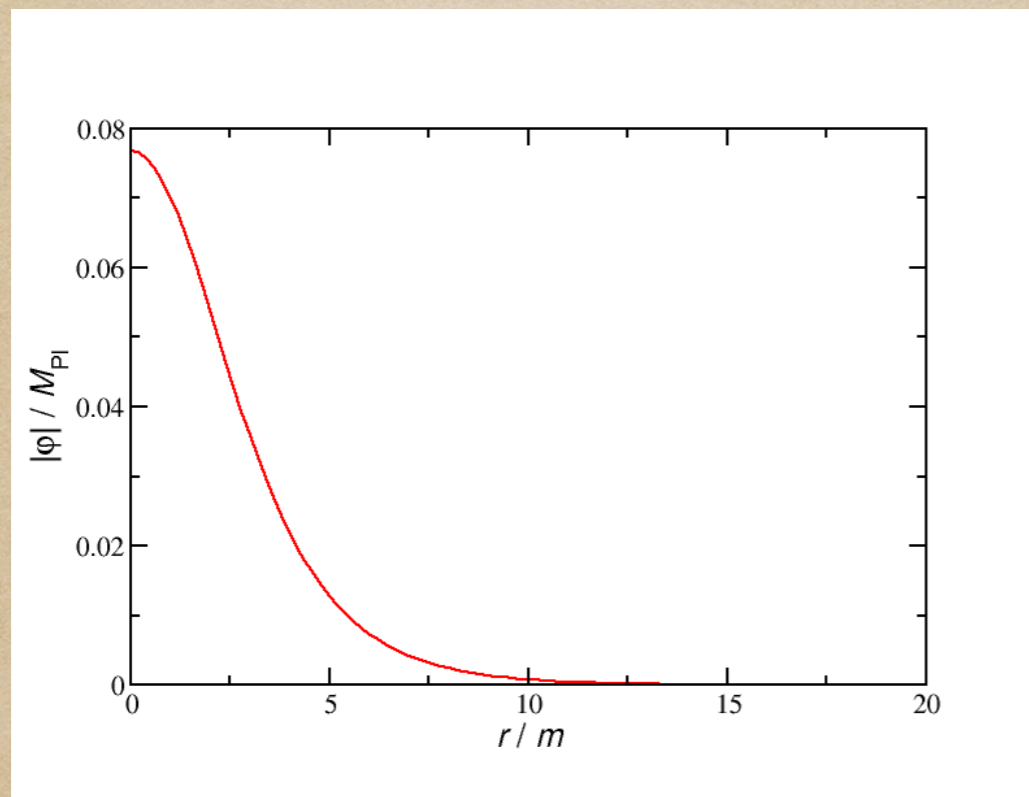
Regular solutions only for countably infinite values

$$\omega_0 < \omega_1 < \omega_2 < \dots \quad (\text{ground state, excited states})$$

Formalism and basic features

- E.g. Maximal-mass mini boson star (Kaup limit)

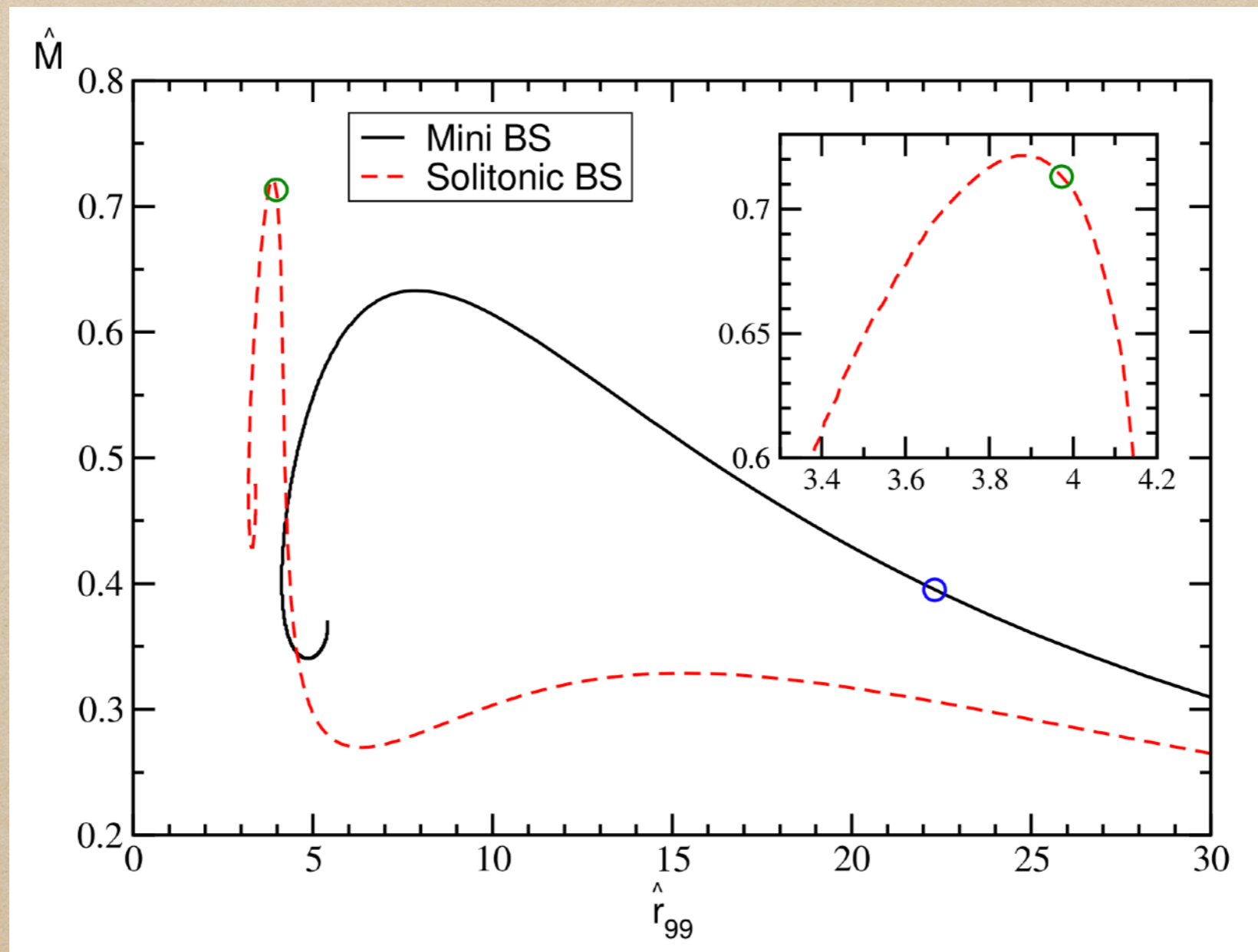
$$\omega_0 = 0.853 m, \quad M = 0.633 M_{\text{Pl}}^2 / m$$



- Excited states unstable:
collapse to BH, dispersion or migration to stable ground-state BS
Balakrishna, Seidel, Suen PRD (1998)

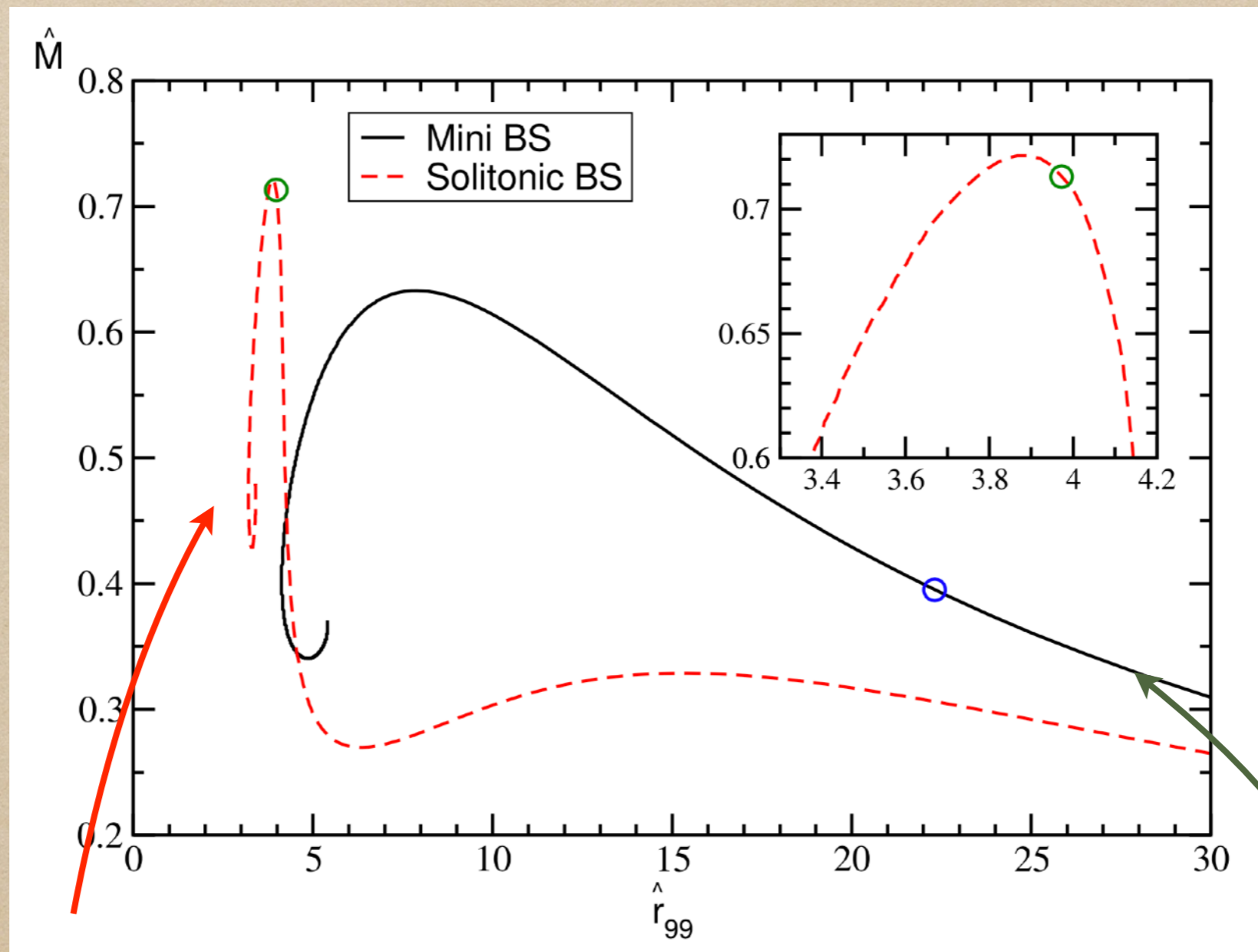
Formalism and basic features

- Mass-Radius curves similar to Tolman-Oppenheimer-Volkoff stars



Formalism and basic features

- Mass-Radius curves similar to Tolman-Oppenheimer-Volkoff stars



unstable

stable

Spinning Boson Stars

- Scalar BSs cannot spin perturbatively Kobayashi+ PRD (1994)
- Spinning scalar BSs exist with but have quantized spin
Schunck & Mielke Phys.Lett.A (1998)
- Spinning scalar BSs likely unstable in contrast to
spinning Proca stars! Sanchis-Gual+ PRL (2019)

Possibly due to toroidal structure: scalar field vanishes at origin

- What happens in scalar BS inspiral and merger?
 - Kerr BH
 - Non-spinning BS; angular momentum shed
 - Total dispersal
 - Spinning BS with exact angular momentum?

Detection and parameter estimation

Generic transient search

- No specific waveform model
- Identify excess power in detector strain data
- Use multi detector maximum likelihood Klimenko et al. 1511.05999

Binary coalescence search

- "Matched Filtering"
- Compare data stream with GW templates ("Finger print search")
- Bayesian analysis:
Prior \rightarrow Posterior



Boson-star binaries: parameters

- 8+1 Intrinsic parameters as for black holes

Masses m_1, m_2

Spins S_1, S_2

Eccentricity (often ignored; GW emission circularizes orbit)

- 7 Extrinsic parameters

Location: Luminosity distance D_L , Right ascension α , Declination δ

Orientation: Inclination ι , Polarization ψ

Time t_c and Phase ϕ_c of coalescence

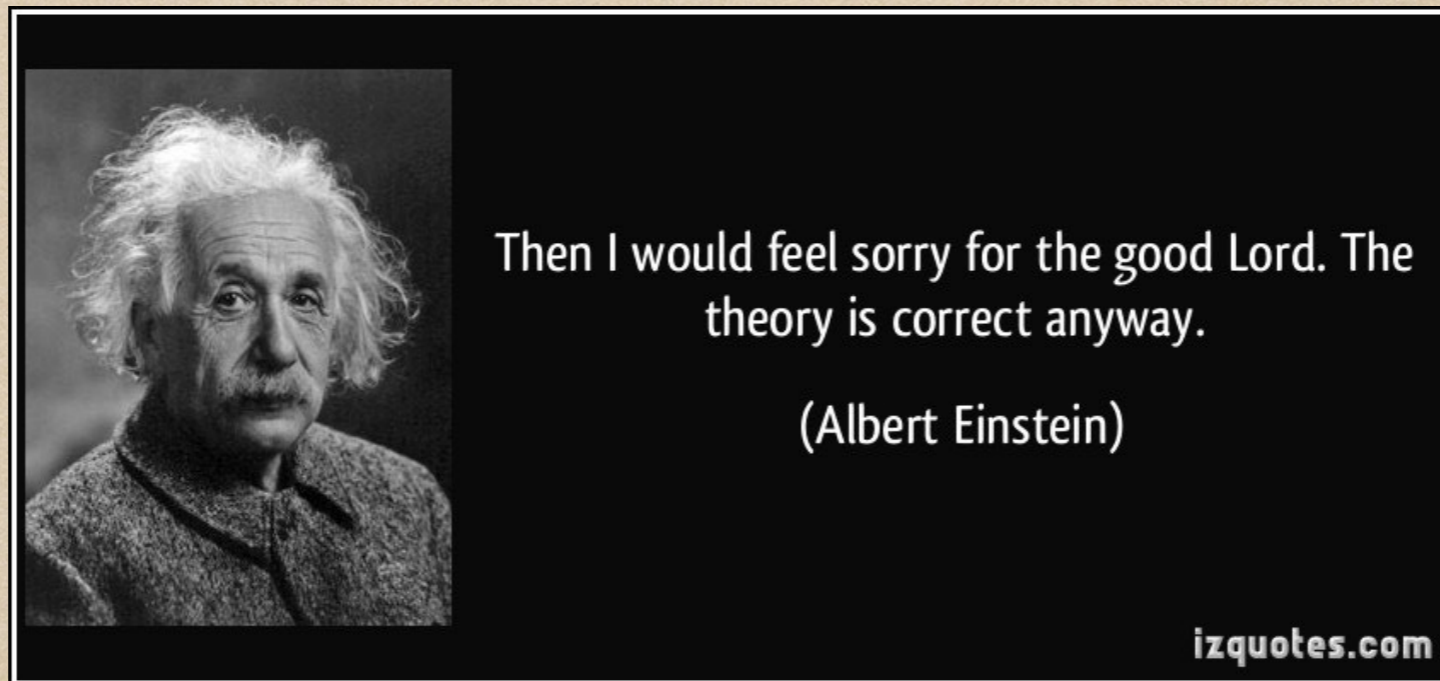
- Other parameters

Matter: Potential function σ_0 , scalar phase $\delta\phi$, antimatter ϵ

2. Motivation and tools

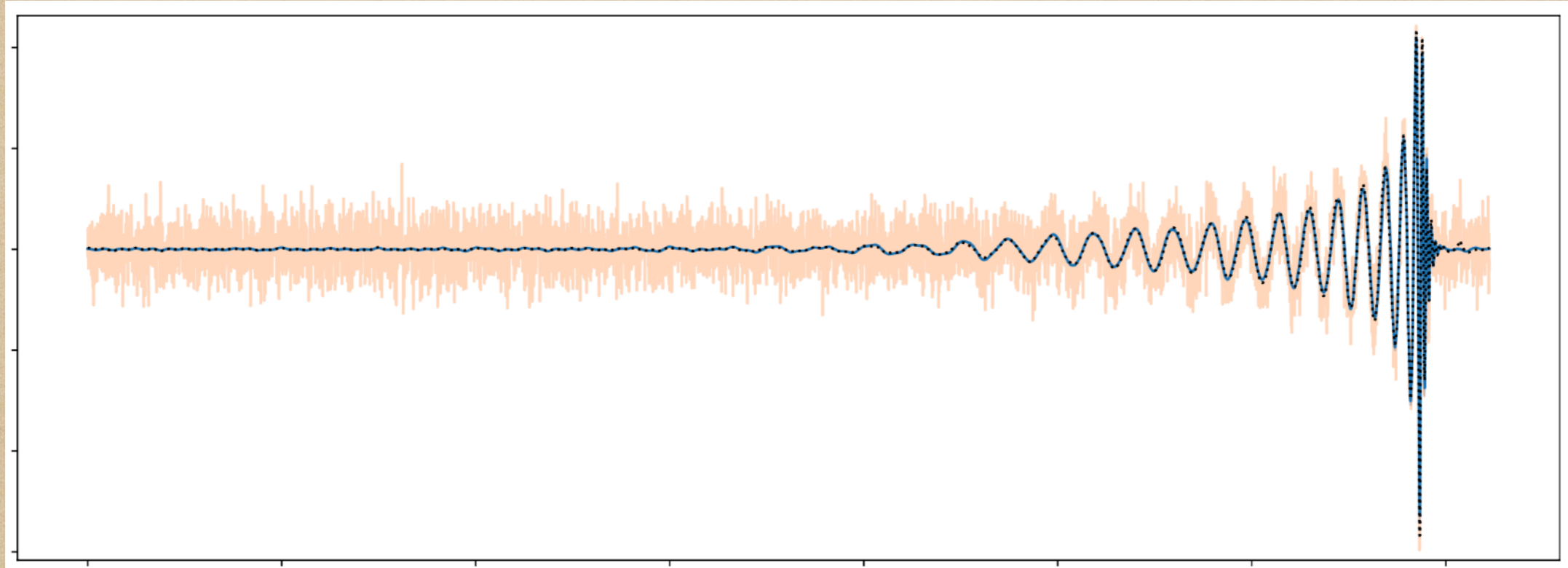
Do we need a theory beyond GR?

- When asked what he would do if Eddington's mission failed...



- But we have reasons to search for "beyond GR"
 - **Renormalization:** Requires, e.g., higher curvature terms.
→ GR is low-energy limit of more fundamental theory
 - **Dark energy:** Why is Λ so small and why $\rho_{\text{dark}} \sim \rho_{\text{mat}}$
 - **Dark matter:** "Neptun" or "Vulcan" ?

Motivation



- Test nature of compact objects: BHs, NSs, ECOs?
- Dark-matter candidates: Ultralight, axion-like fields
- Bosonic fields can form equilibrium configurations:
Boson stars Kaup 1968
- Properties: Compactness 0 to $>$ NSs, any Mass
- Use BSs as proxy for not BHs in GR

Questions and work plan

- Can we observe boson stars with LIGO-Virgo-KAGRA?
 - If yes, what does PE with current approximants yield?
 - Can we simulate BS binaries with sufficient accuracy?
-
- Perform high-precision NR simulations of BSs
 - Inject resulting waveforms into LIGO detector noise
 - Recover signals and parameters with Binary BH/NS approximants
 - Test residuals

Theory and Numerical Modelling

- Massive complex scalar field + GR

$$S = \int \frac{\sqrt{-2}}{2} \left\{ \frac{R}{8\pi G} - [g^{\mu\nu} \nabla_\mu \bar{\varphi} \nabla_\nu \varphi + V(\varphi)] \right\} d^4x$$

⇒ Einstein-Klein-Gordon equations

- Space-time (3+1) formulation: CCZ4

Alic et al 2012

- Use two numerical relativity codes

GRChombo Radia et al 2021

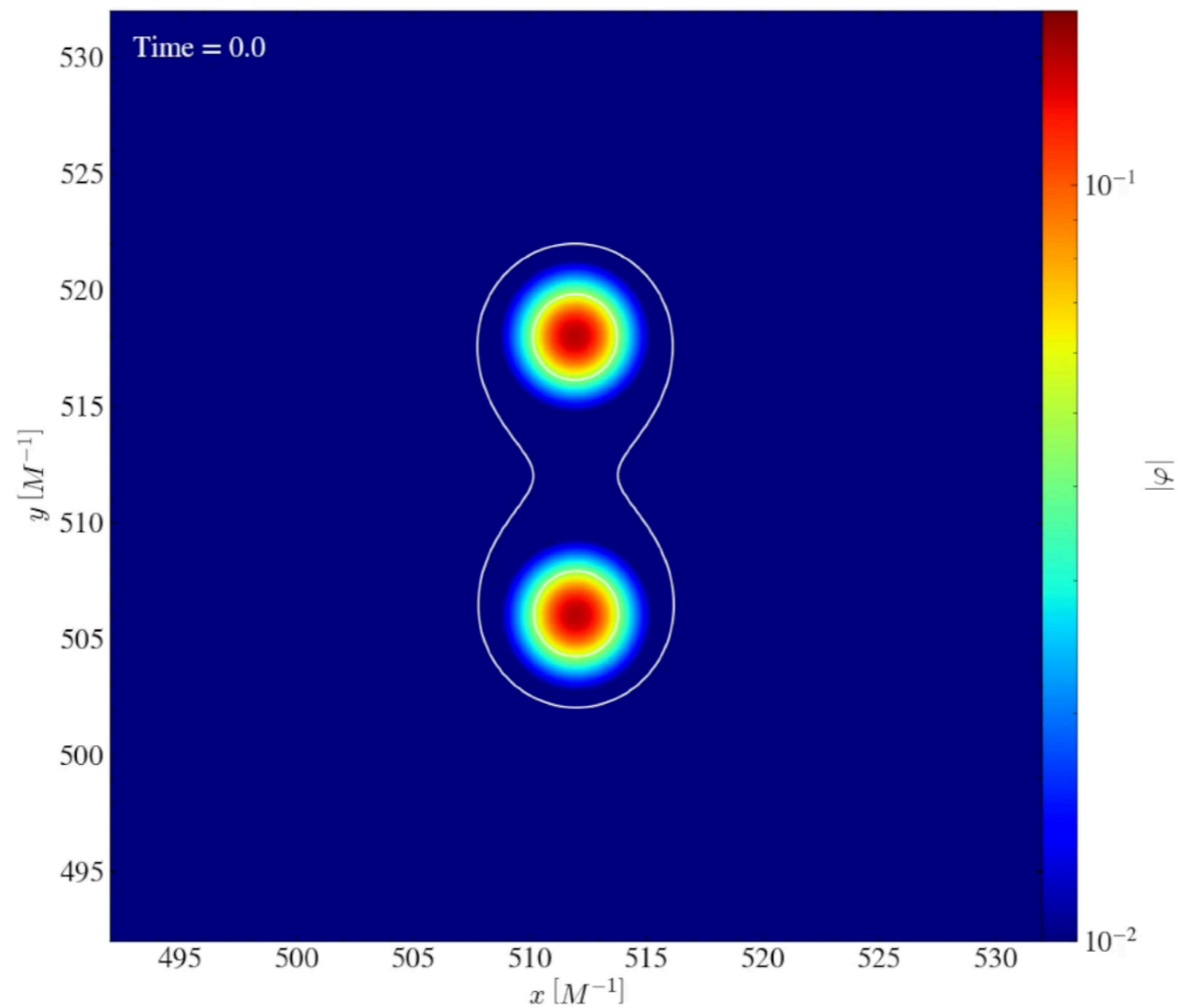
Lean US 2006

- Technical details:

$dx = \frac{1}{48} \dots \frac{1}{32}$, domain size ~ 1024 , 8 refinement levels

3. Results

Example boson-star inspiral



BS binaries

We simulate 5 BS binaries through inspiral, merger and ringdown.

Characterized by

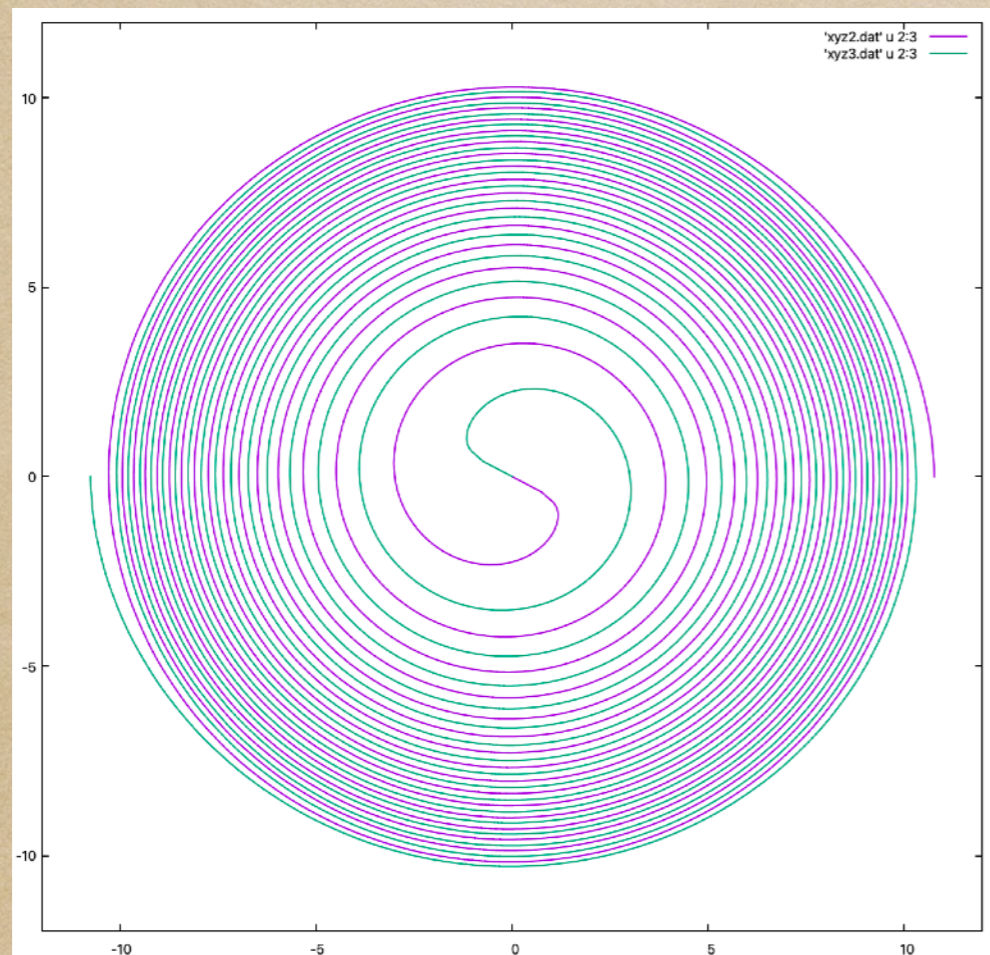
- Quasi-circular, non-spinning, equal-mass: $e \approx 0, S_{1,2} = 0, q = 1$
- Number of orbits N
- Compactness 0.1 or 0.2
- Scalar dephasing $\delta\phi \in [0, \pi]$
- BS-BS or BS-anti BS binary?
- Total mass: Any by trivial rescaling of the scalar mass

Name	Nickname	Compactness	N (orbits)	$\delta\phi$	BS or ABS
A17-d14, -d12	<i>standard</i>	0.2	14, 11	0	BS-BS
A17-d15-p090	<i>dephased</i>	0.2	16	$\pi/2$	BS-BS
A17-d15-p180	<i>anti-phase</i>	0.2	16	π	BS-BS
A17-d12-e1	<i>anti-BS</i>	0.2	11	0	BS-ABS
A147-d19	<i>fluffy</i>	0.1	18	0	BS-BS

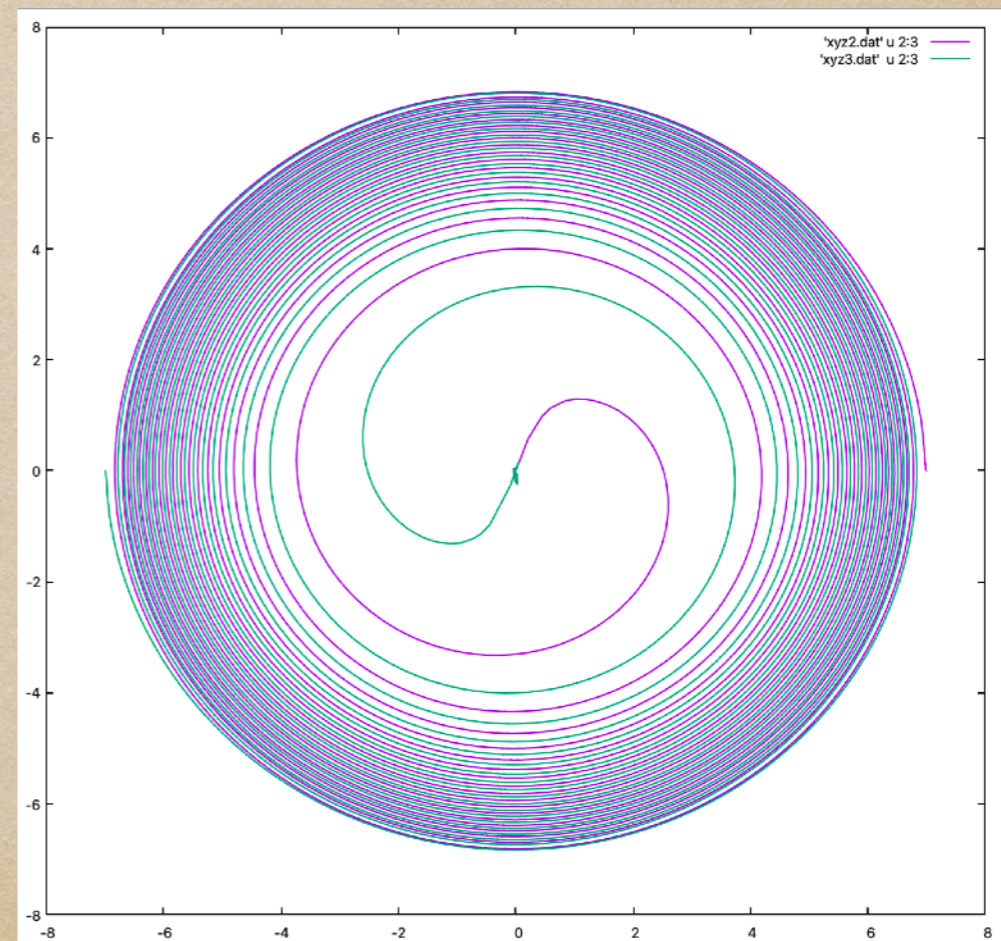
BS binaries

- Phase error $\approx 0.1 \dots 0.2$
- Amplitude error $\lesssim 3\%$
- Eccentricity $\approx 0.002 \dots 0.005$

A17-d14

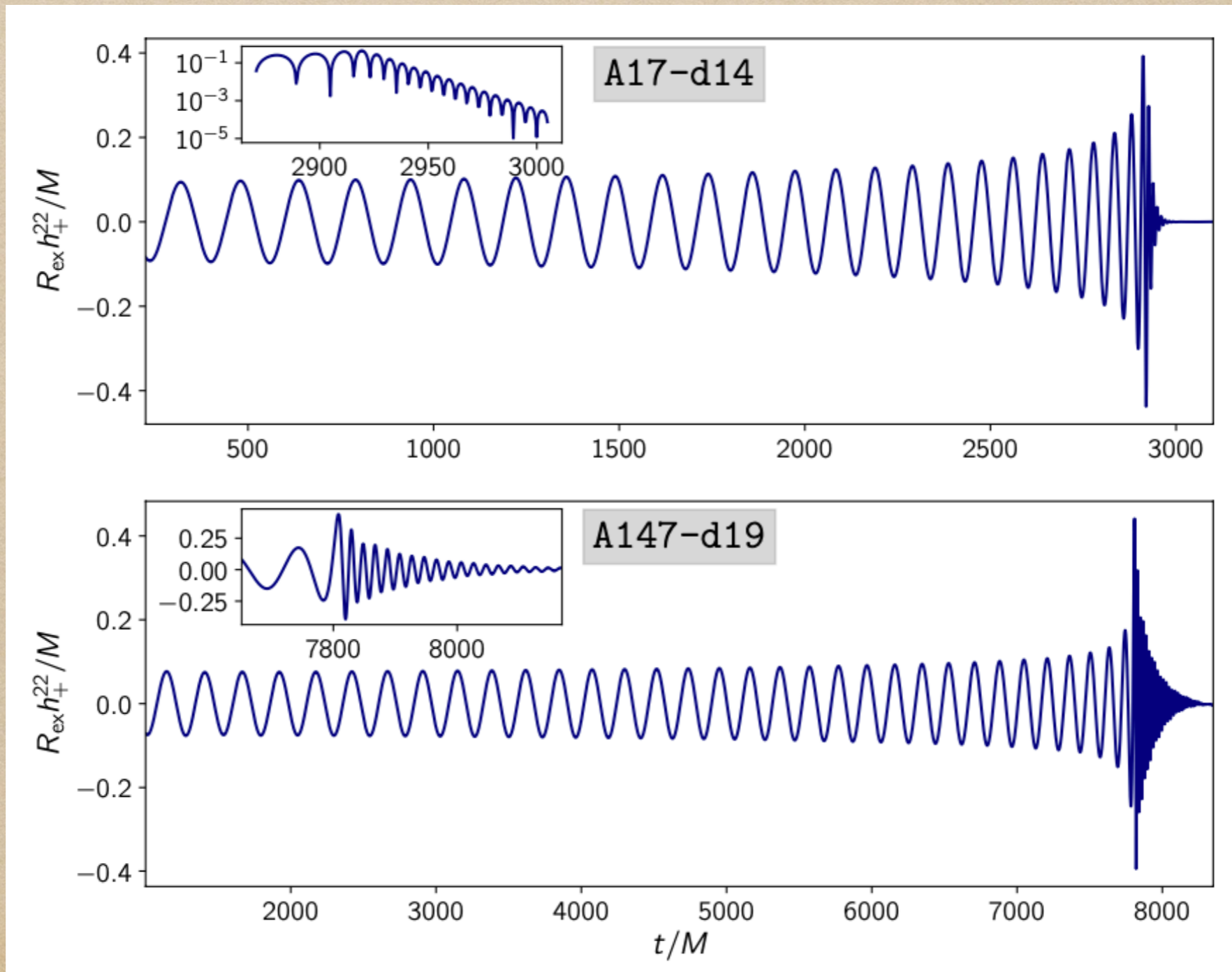


A147-d19



BS binaries

- GW strain from compact and fluffy BSs



Waveform approximants

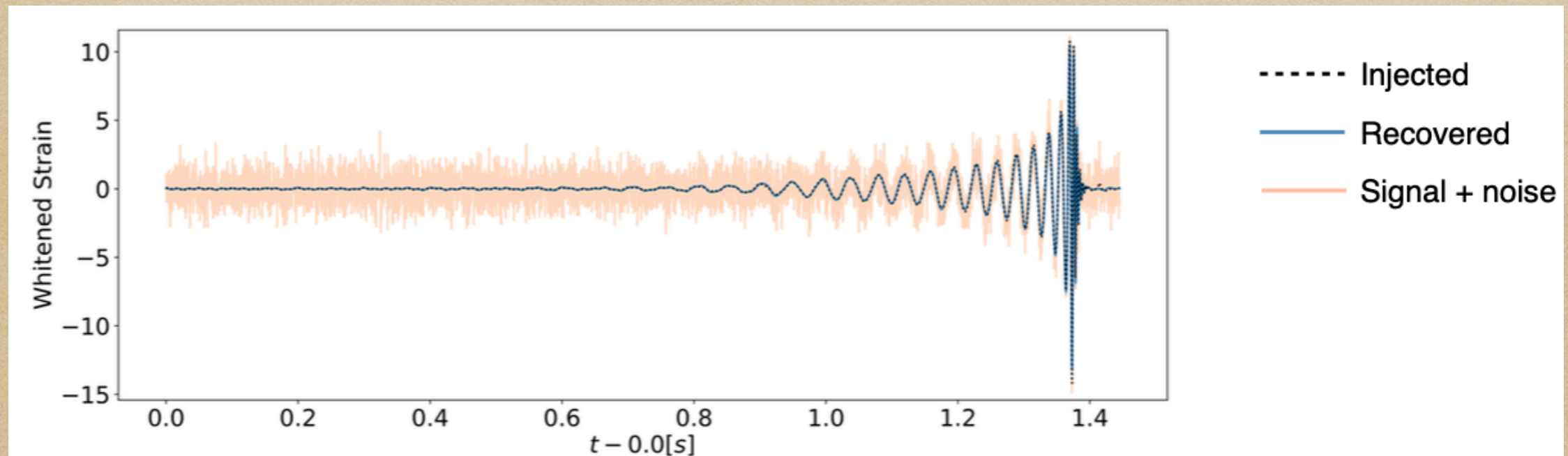
- Parameter estimation performed with `Bilby` Ashton et al 2019
- `IMRPhenomXP`: Frequency domain Pratten et al 2021
 - Quasi-circular, spin-precessing black-hole binaries
 - Quadrupole modes
- `IMRPhenomPv2_NRTidal`: Frequency domain Dietrich et al 2017, 2019
 - Quasi-circular, spin-precessing neutron-star binaries
 - Tidal deformability parameters $\Lambda_{A,B}$
- We have tested more with similar results.

Injections and parameter estimation

- Inject BS signals with specified parameters:
Fixed: sky location, inclination, initial phase, time etc
Variable: total mass, luminosity distance
- 2 Approaches: (1) Allow spins to vary in the analysis
(2) Spins fixed to zero throughout analysis
- Main diagnostics:
 - Recovered masses, spins
 - Recovered SNR, Log Bayes factor
 - Test residual for Gaussianity

Results using IMRPhenomXP

- Injections often recovered but with **biased** parameters!
- Example A17-d15 with $M_{\text{tot}} = 77 M_{\odot}$, $d_L = 200 \text{ Mpc}$ in the analysis



- **Recovered:** $M_1 = 37.8 \pm 1.1 M_{\odot}$, $M_2 = 25.4 \pm 1.2 M_{\odot}$, $d_L = 236 \pm 20 \text{ Mpc}$,
 $a_1 \approx 0.95$, $a_2 \approx 0.15$

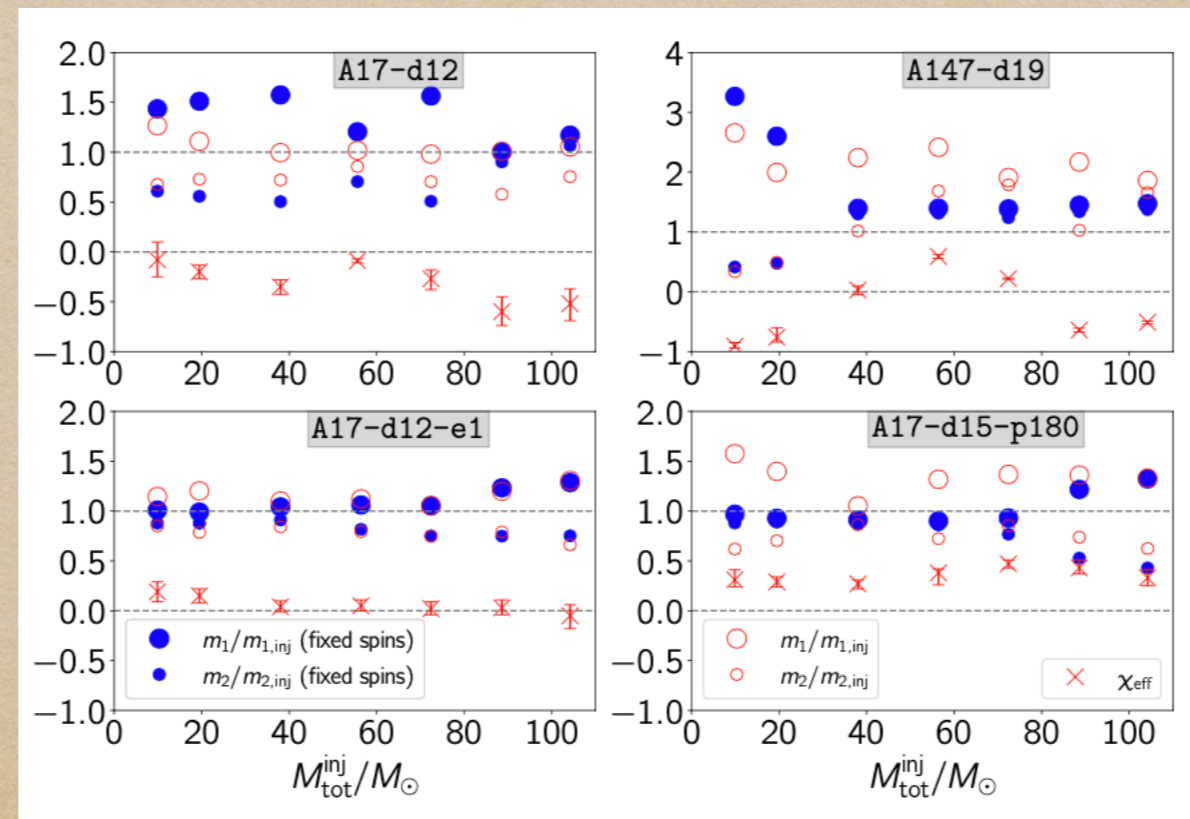
Recovered SNR \approx injected SNR

$$\log \mathcal{B}_N^S = 5392$$

- Parameter bias **not** random!

Results using IMRPhenomXP

- Fixing spins to zero:
 - poor m_1, m_2 for *standard* BBS
 - decent m_1, m_2 for *anti-phase* BBS
- Variable spins:
 - decent m_1, m_2 and anti-aligned spins for *standard* BBS
 - poor m_1, m_2 and aligned spins for *anti-phase* BBS



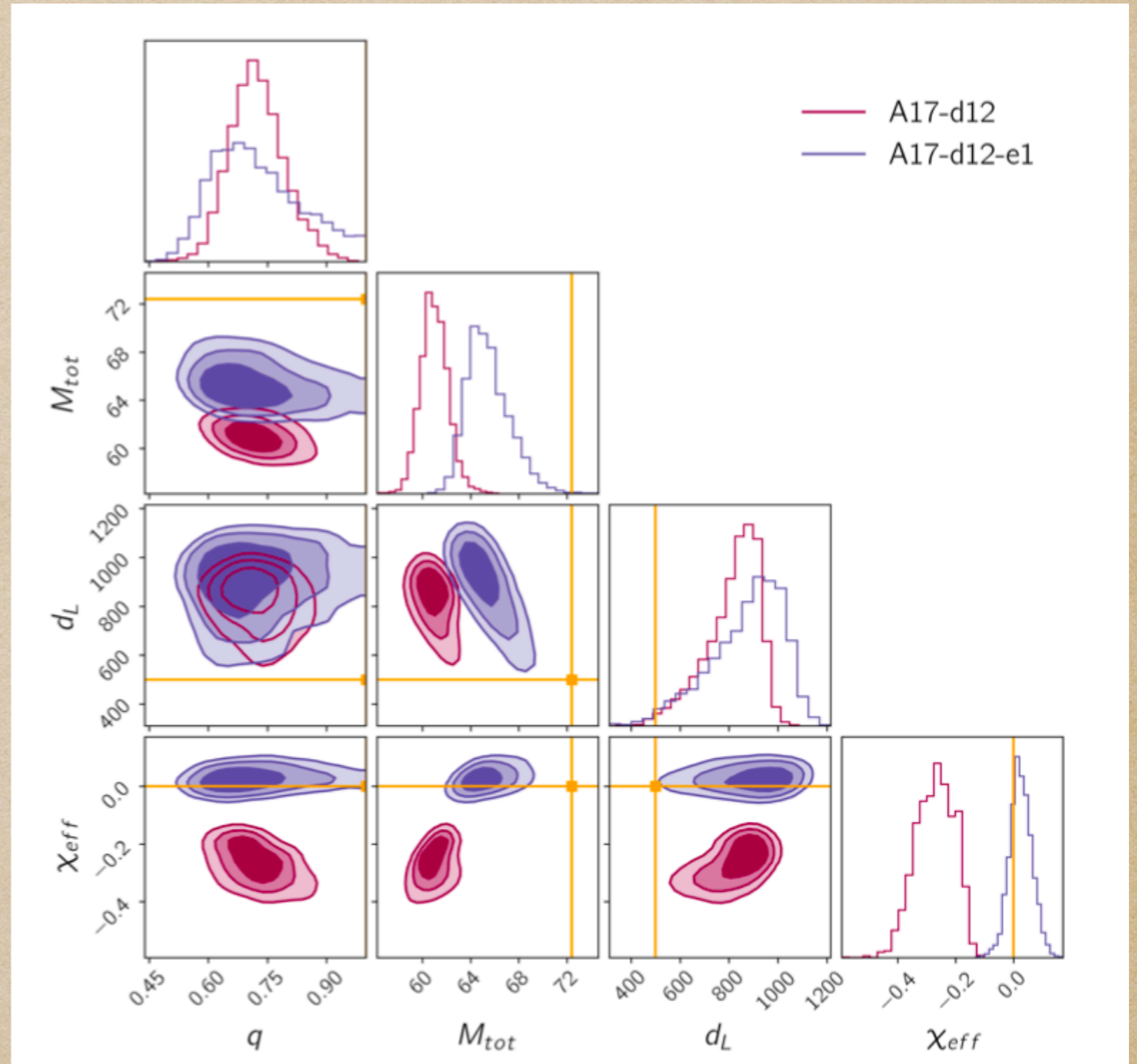
Results using IMRPhenomXP

- BBH approximants recover parameters best for *anti-BS* !!

Corner plot:

A17-d12-e1 vs. A17-d12

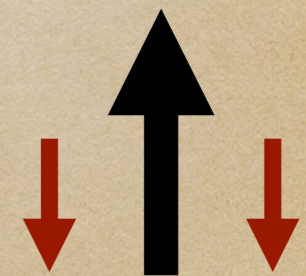
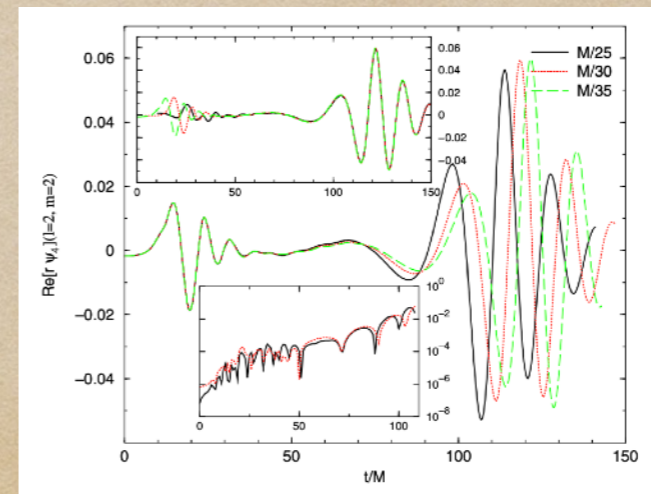
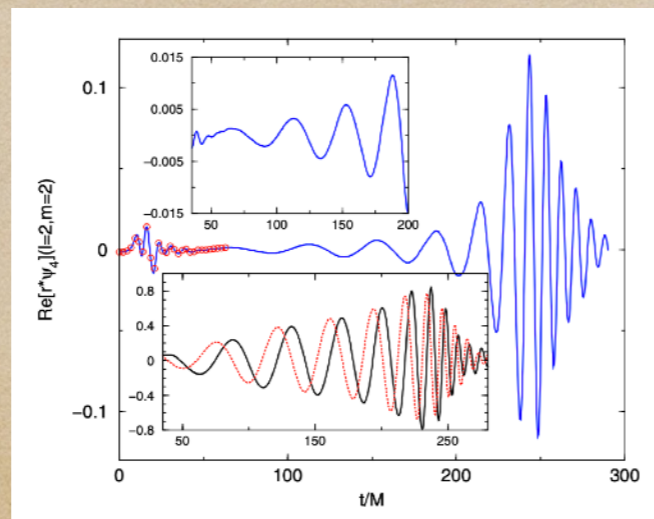
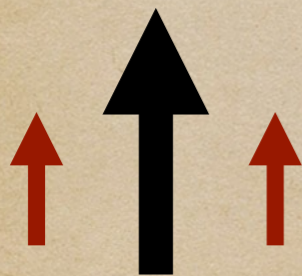
- These features can be explained with the chirp strength



Understanding the PE bias

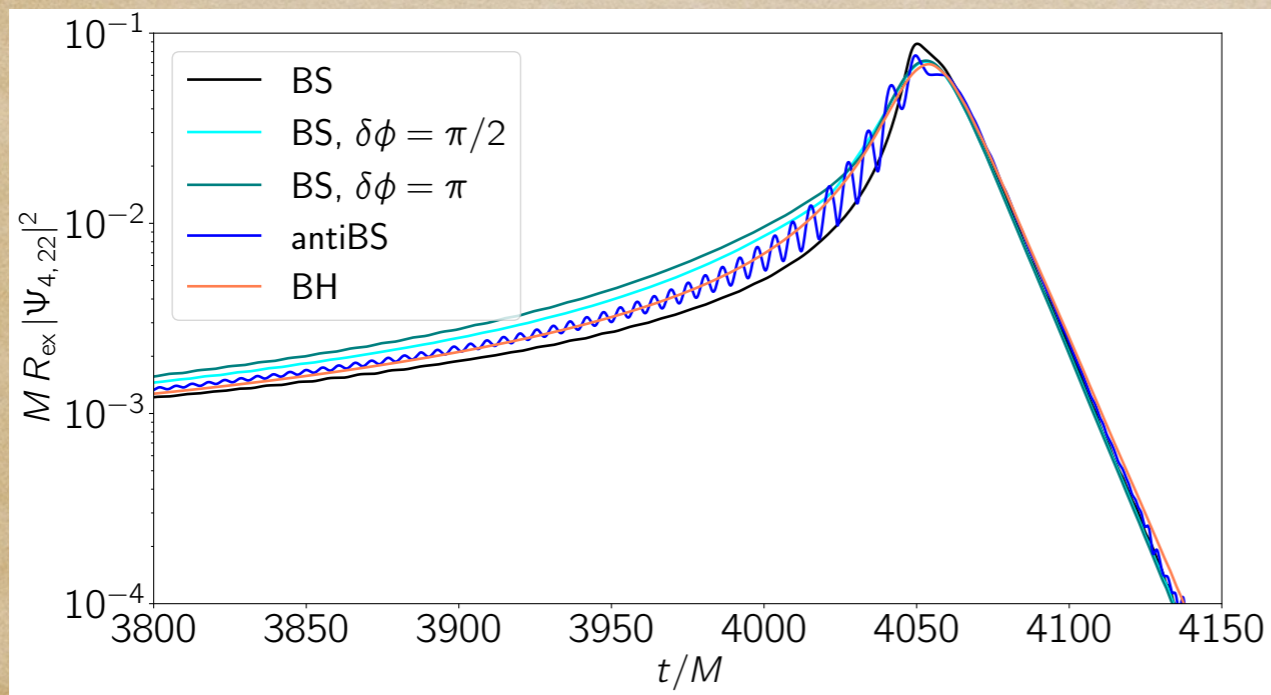
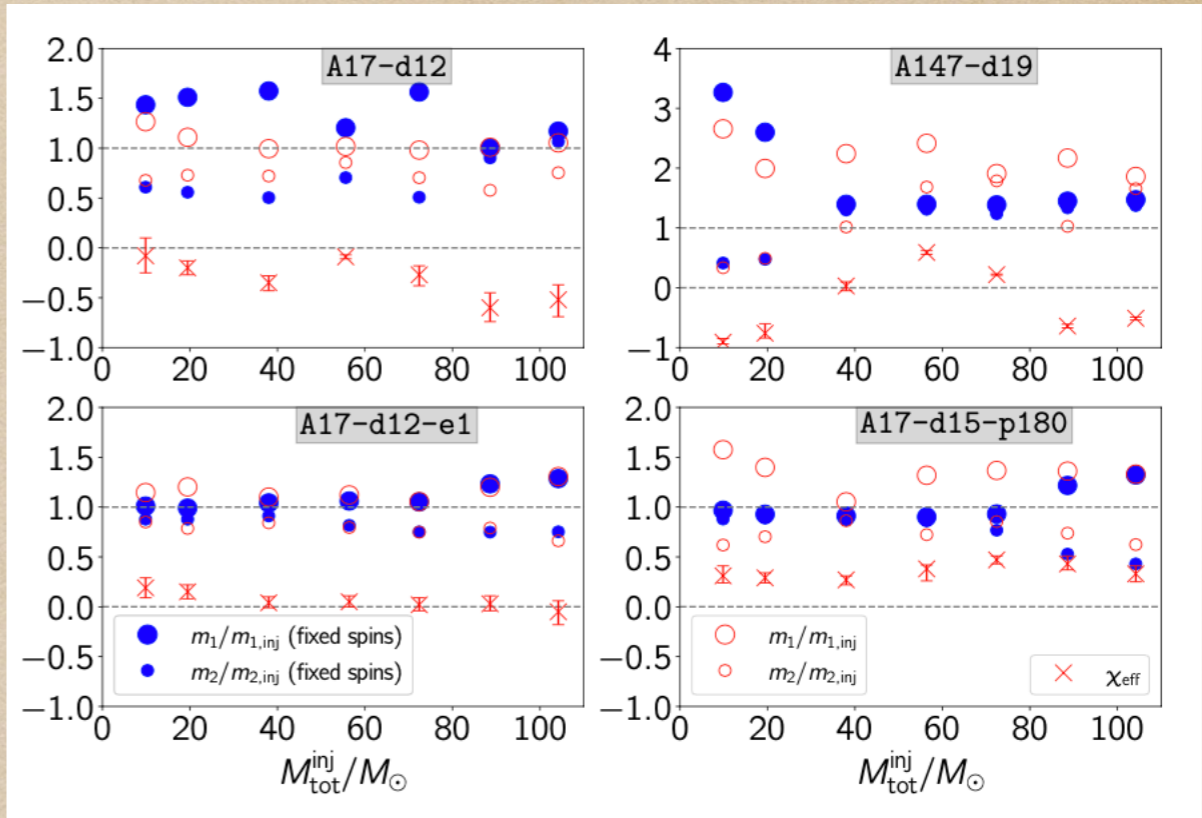
- Main feature: Steepness of chirp
- For non-spinning BH binaries:
 - equal mass \Rightarrow shallow chirp
 - unequal masses \Rightarrow steep chirp (think of EMRIs)
- For spinning BH binaries:
 - aligned spins \Rightarrow shallow chirp
 - anti-aligned spins \Rightarrow steep chirp

The orbital 'Hang-up' effect Capanelli et al gr-qc/0601091



Understanding the PE bias

- PE bias
- VS
- Chirp steepness



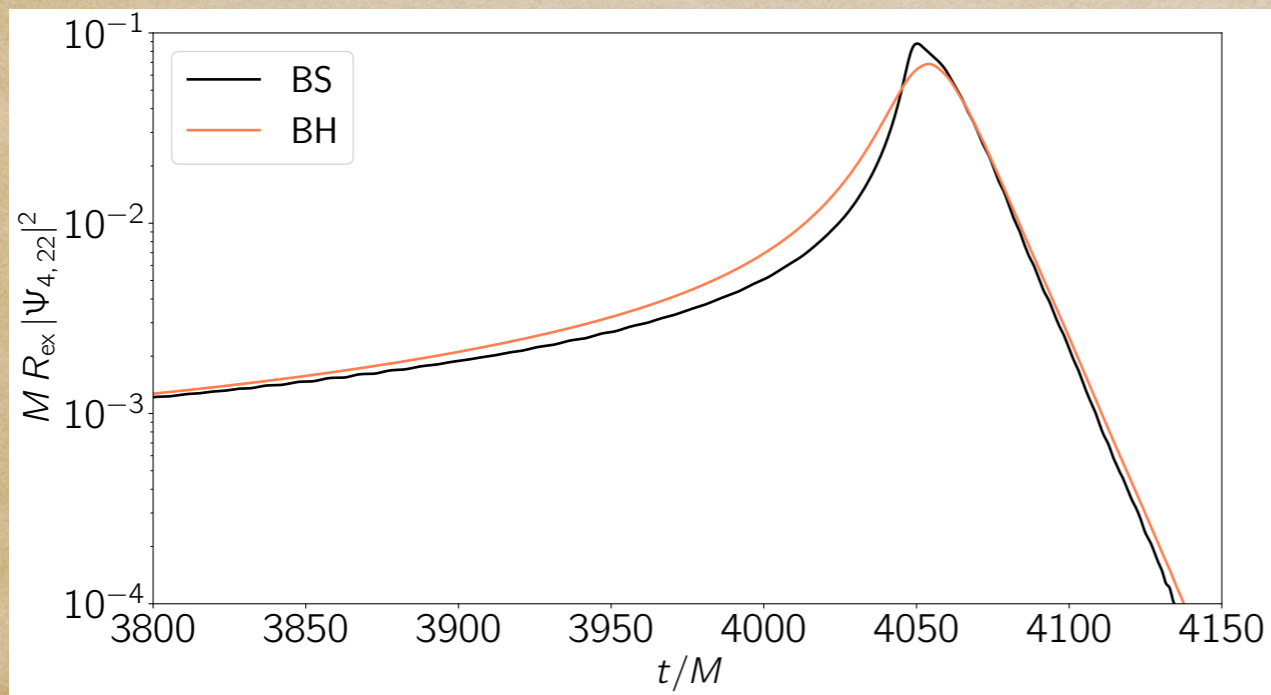
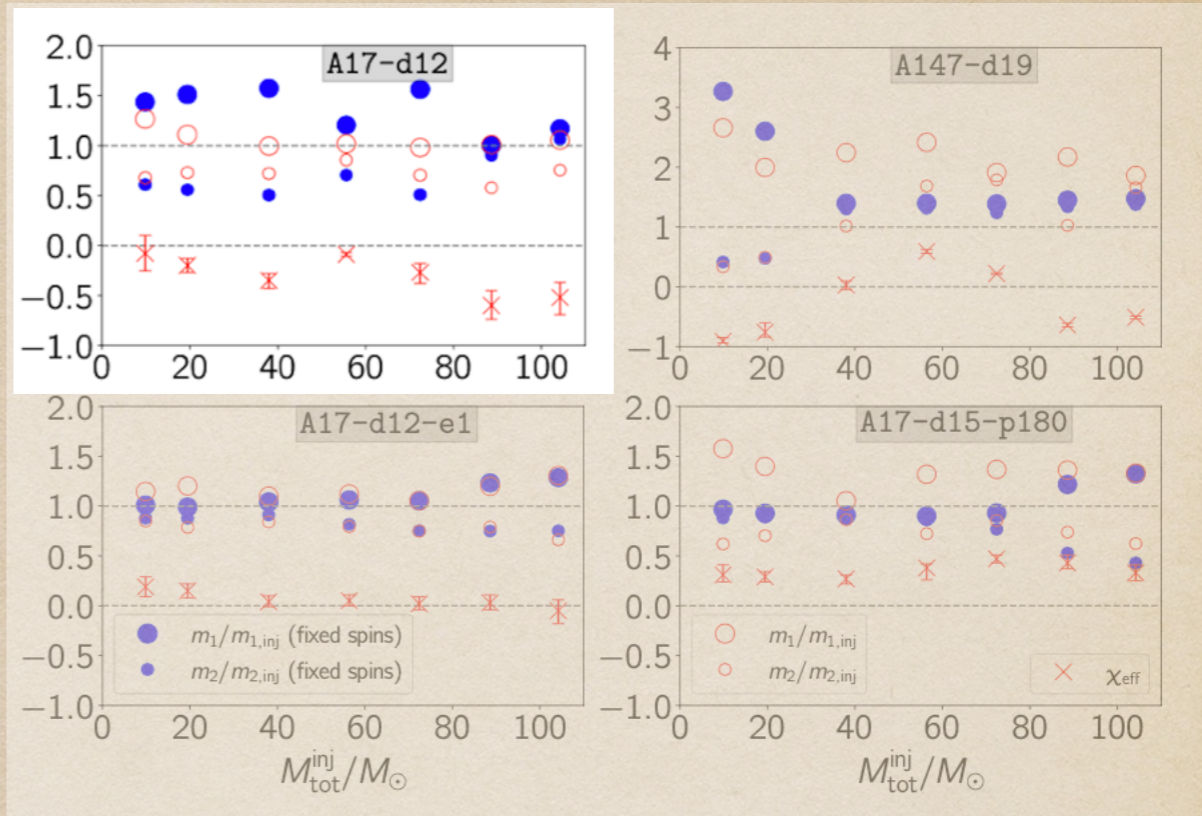
Understanding the PE bias: Standard BS

Fixed spins

BS chirp steeper

⇒ Like unequal-mass BHs

⇒ Bilby reports unequal masses



Variable spins

anti-aligned spins

⇒ Steeper chirp

⇒ Steep BS chirp also captured by anti-aligned spins

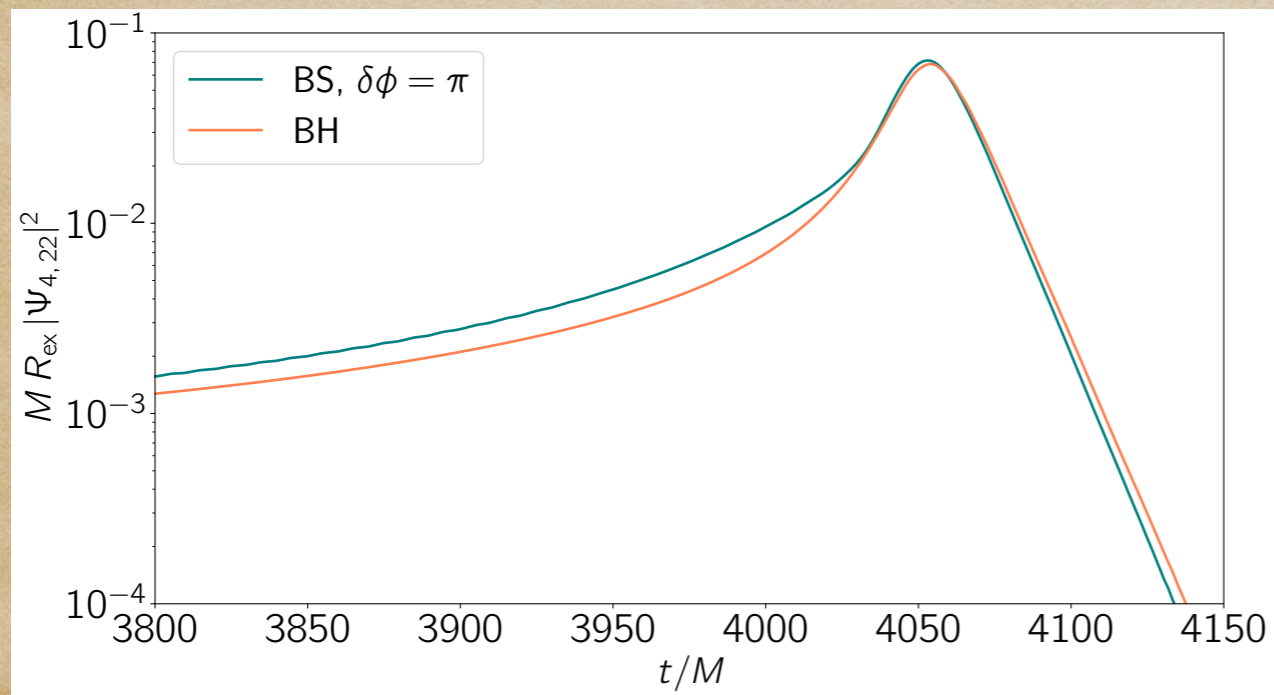
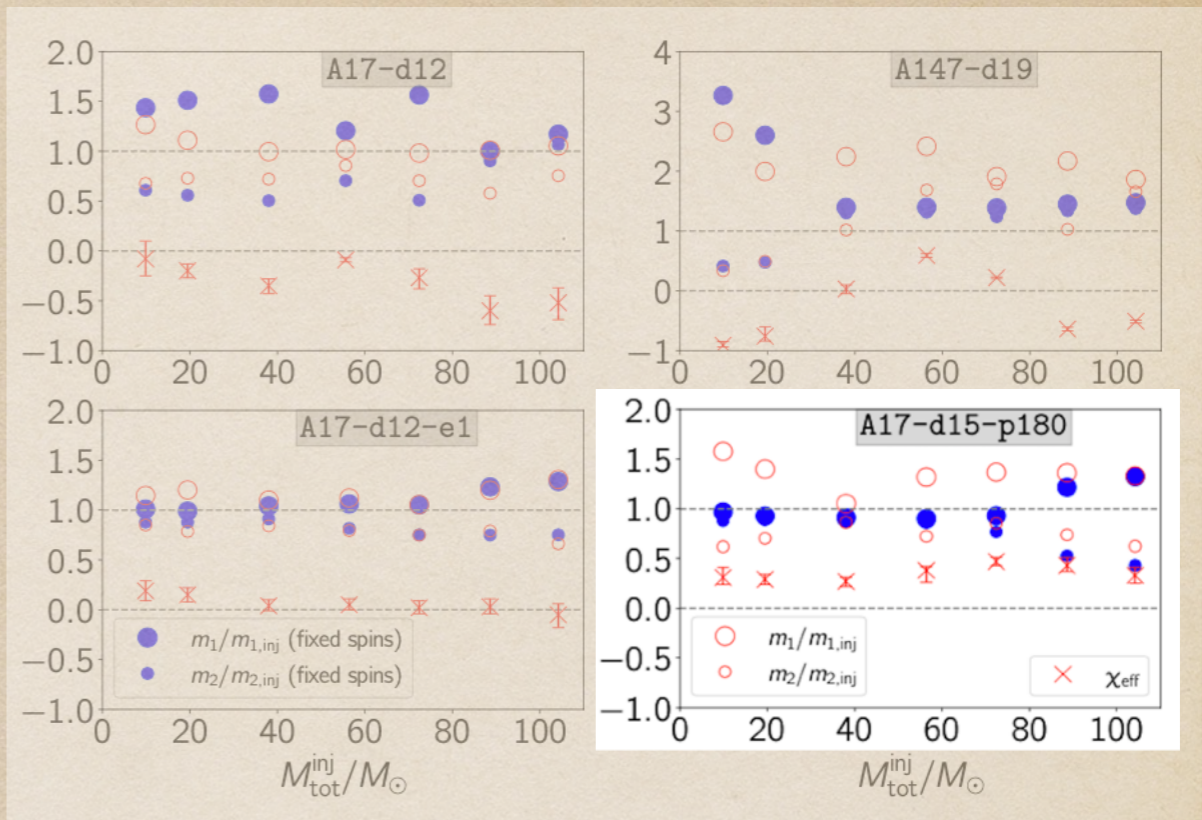
Understanding the PE bias: anti-phase

Fixed spins

BS chirp shallower

⇒ Best matched by \sim equal mass BHs

⇒ Bilby reports \sim equal masses



Variable spins

aligned spins

⇒ Shallow chirp

⇒ Bilby reports aligned spins and allows unequal masses

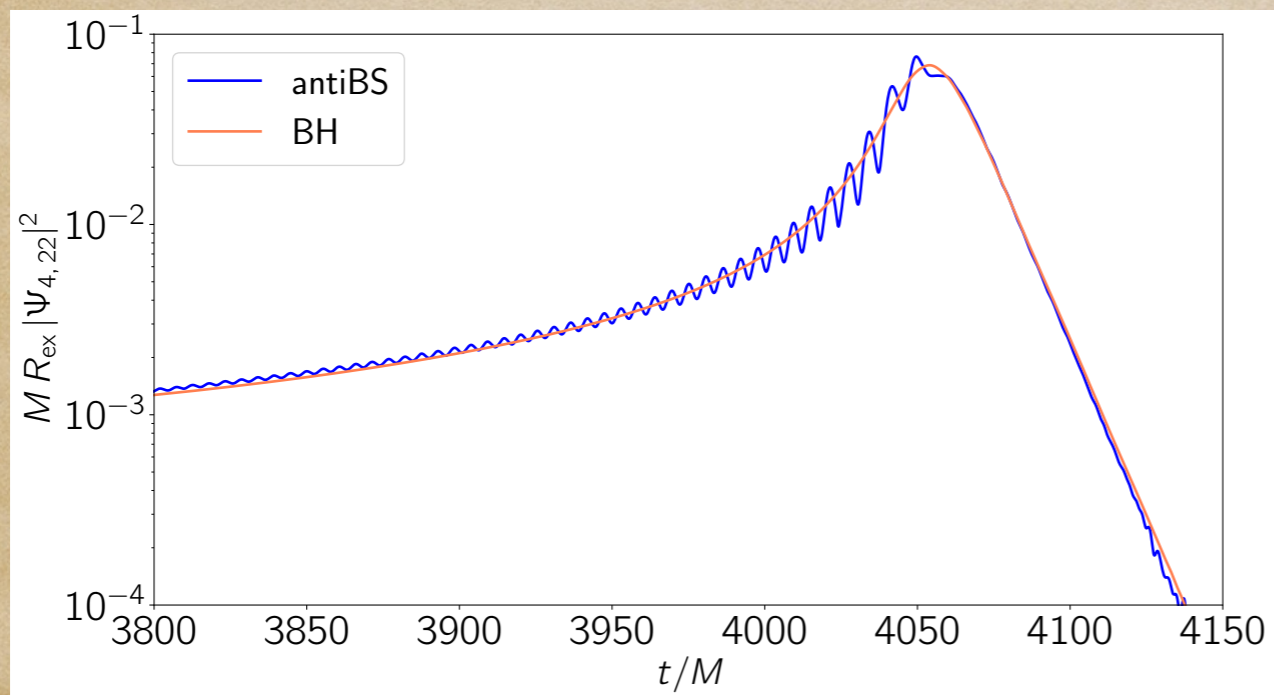
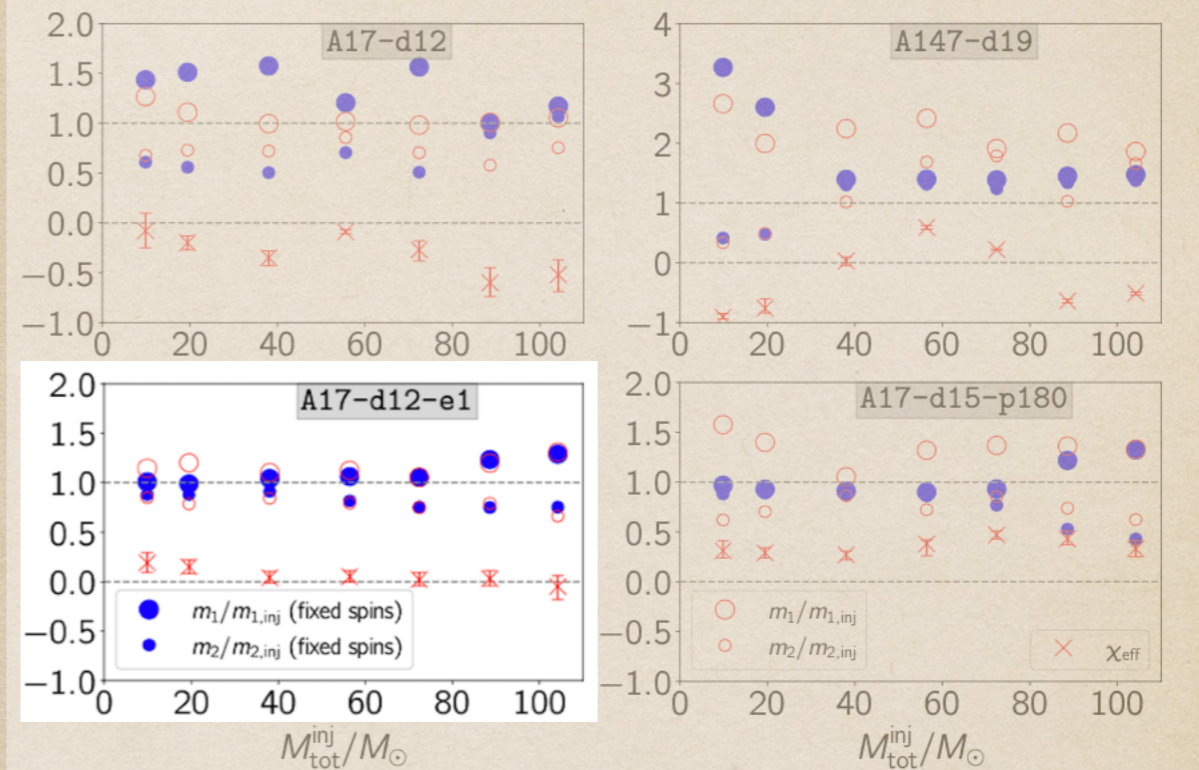
Understanding the PE bias: anti-BS

Fixed spins

BS chirp shallower

⇒ Best matched by \sim equal mass BHs

⇒ Bilby reports \sim equal masses



Variable spins

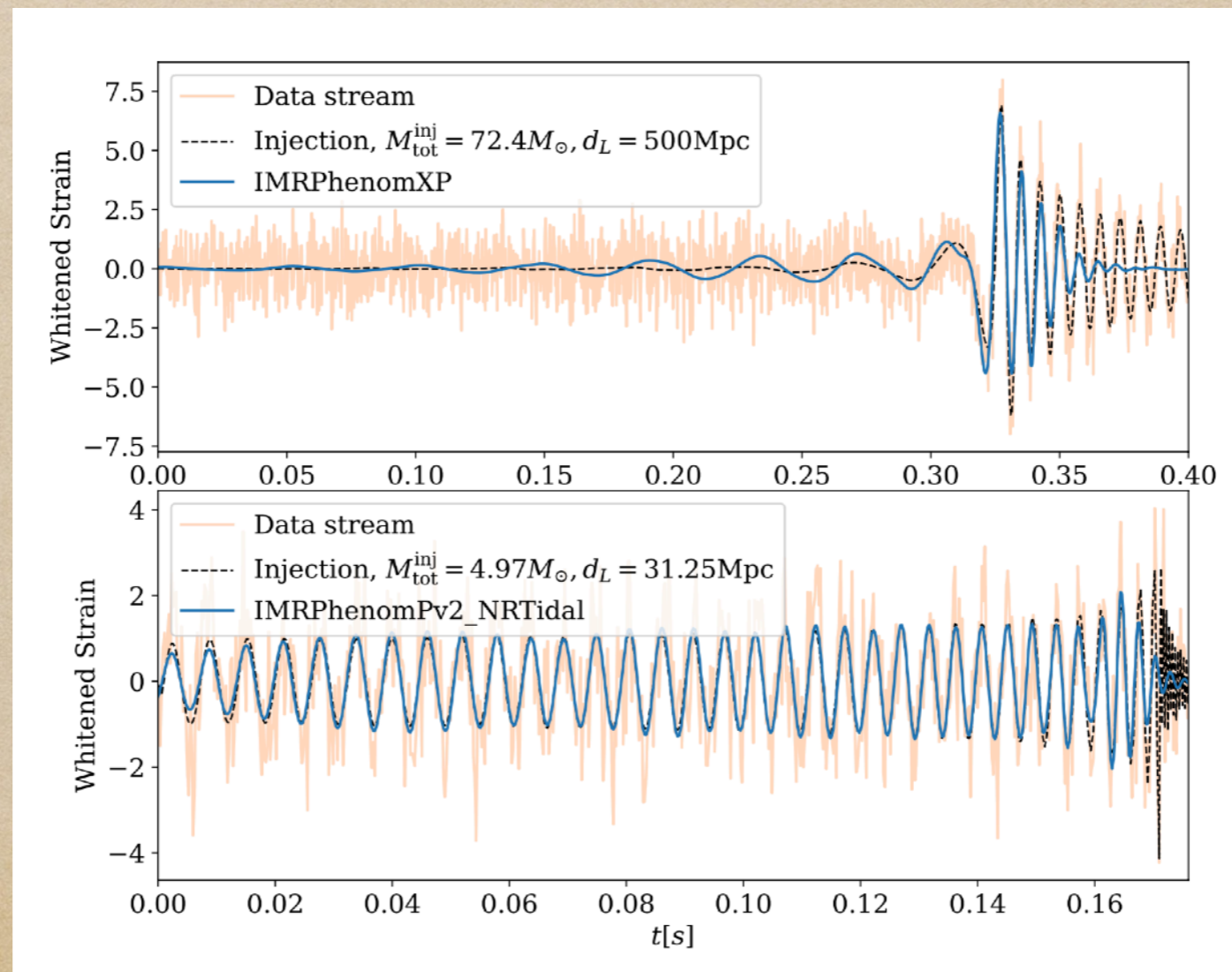
aligned spins

⇒ Shallow chirp

⇒ Bilby reports aligned spins and allows unequal masses

Recovery of "Fluffy" BS binaries

- Parameter estimation always erratic for *fluffy* BBS
- BH approximants may capture inspiral or merger but never both!
- Residual often not compatible with Gaussian noise



Conclusions

- NR simulations of BS binaries about as accurate as for BHs
- BS binaries recovered well with BH approximants → degeneracy
- But systematic bias in parameter estimation
- Compact BBSs “look” very similar to BBHs
- Fluffy BBSs have more characteristic signatures

Next Challenges

- Identify smoking-gun signatures from BS binaries
- Generate comprehensive GW template banks
- Efficient tools for analysing GW observations with BS templates