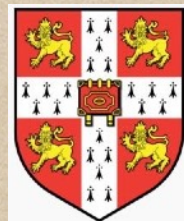


To be or not to be a Black-Hole Binary

Ulrich Sperhake

T Evstafyeva, M Agathos, I Romero-Shaw,
A Seifert, C J Moore, T Jain

arXiv:2406.02715 (PRL), arXiv:2604.25582
cf also 2108.11995, 2212.08023



DAMTP, University of Cambridge

X Amazonian Workshop on Gravity and Analogue Models,
Federal University of Pará, 2 Jul 2026



1. Background

The idea of boson stars

- “Gravitational-electromagnetic entities” or Geons

Wheeler 1955

PHYSICAL REVIEW

VOLUME 97, NUMBER 2

JANUARY 15, 1955

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

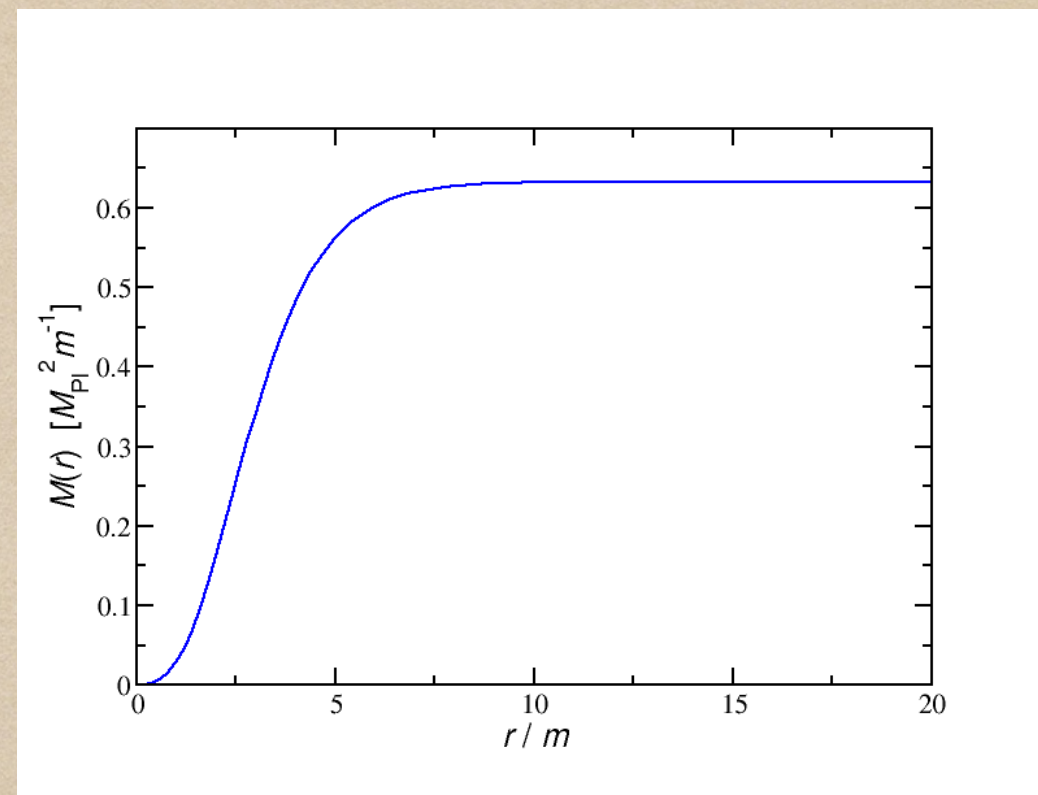
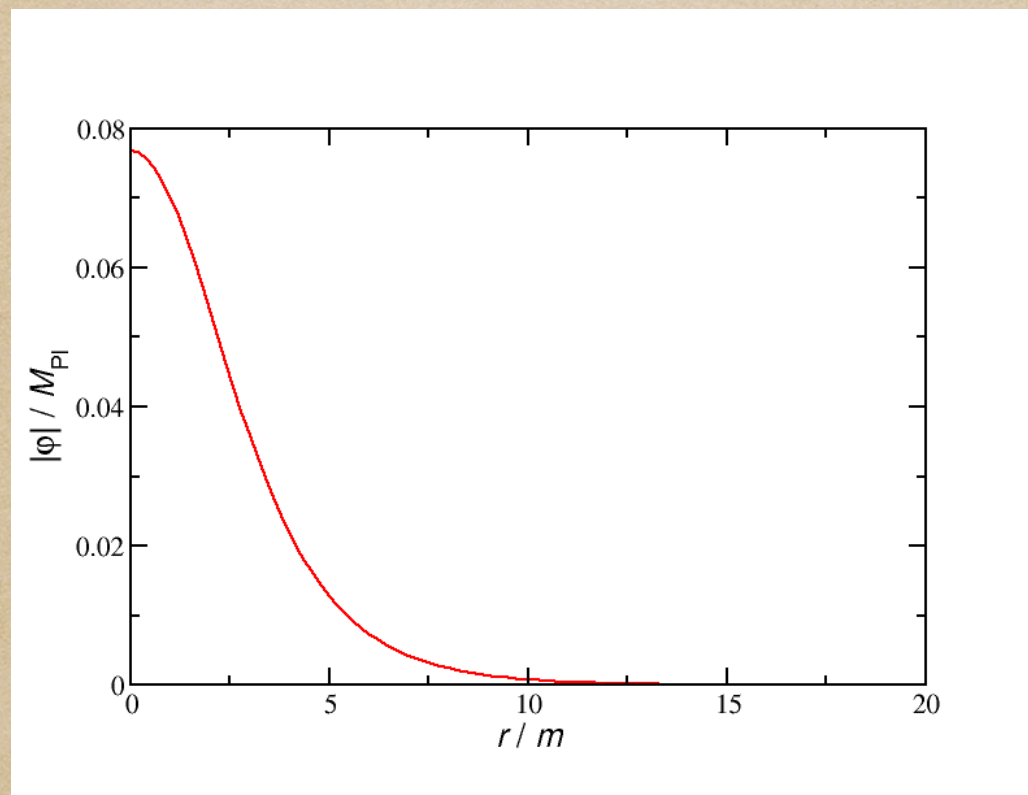
Regular solutions only for countably infinite values

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

Formalism and basic features

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

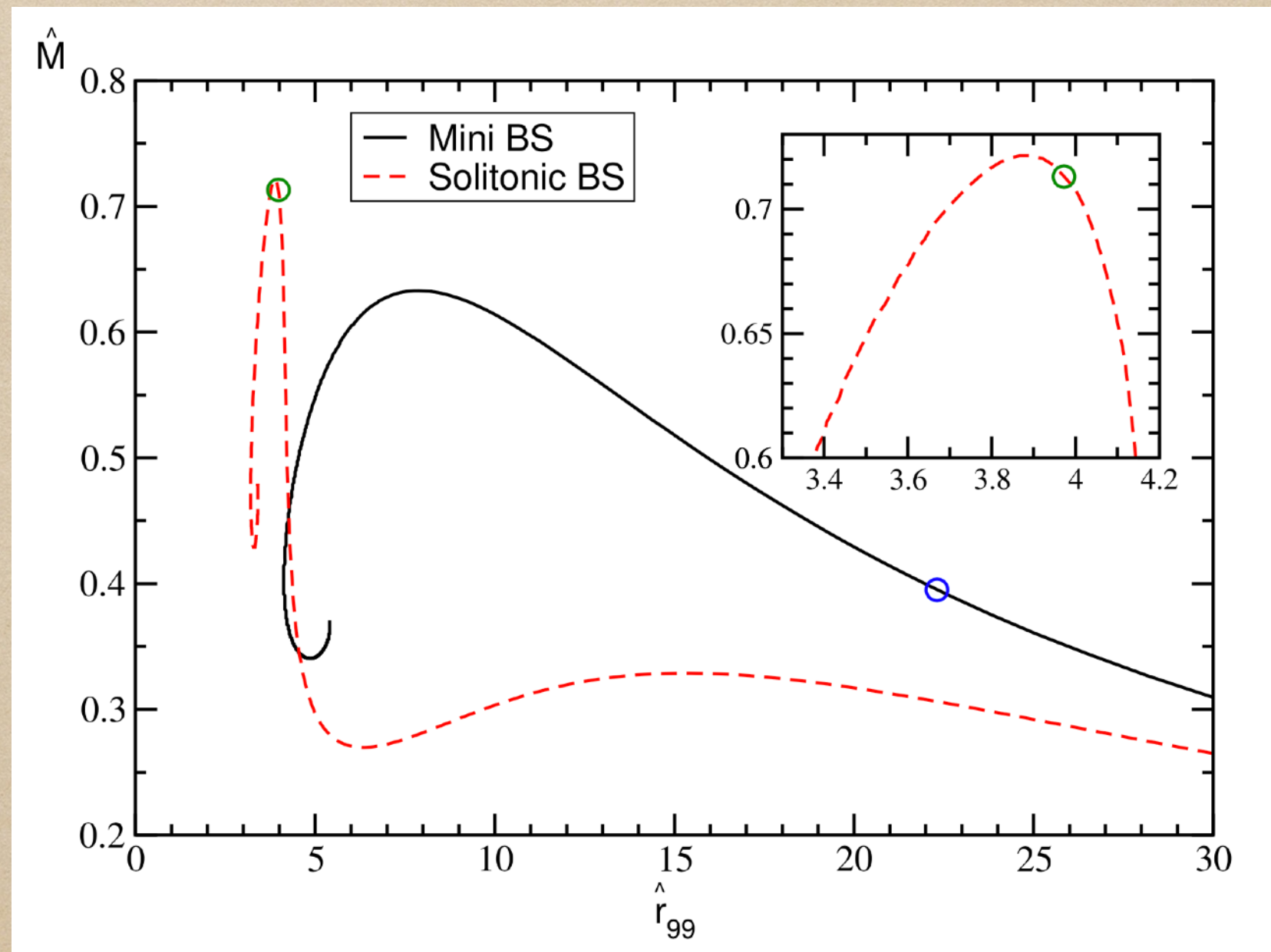
$$\omega_0 = 0.853 m, \quad M = 0.633 M_{\text{Pl}}^2 / m$$



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

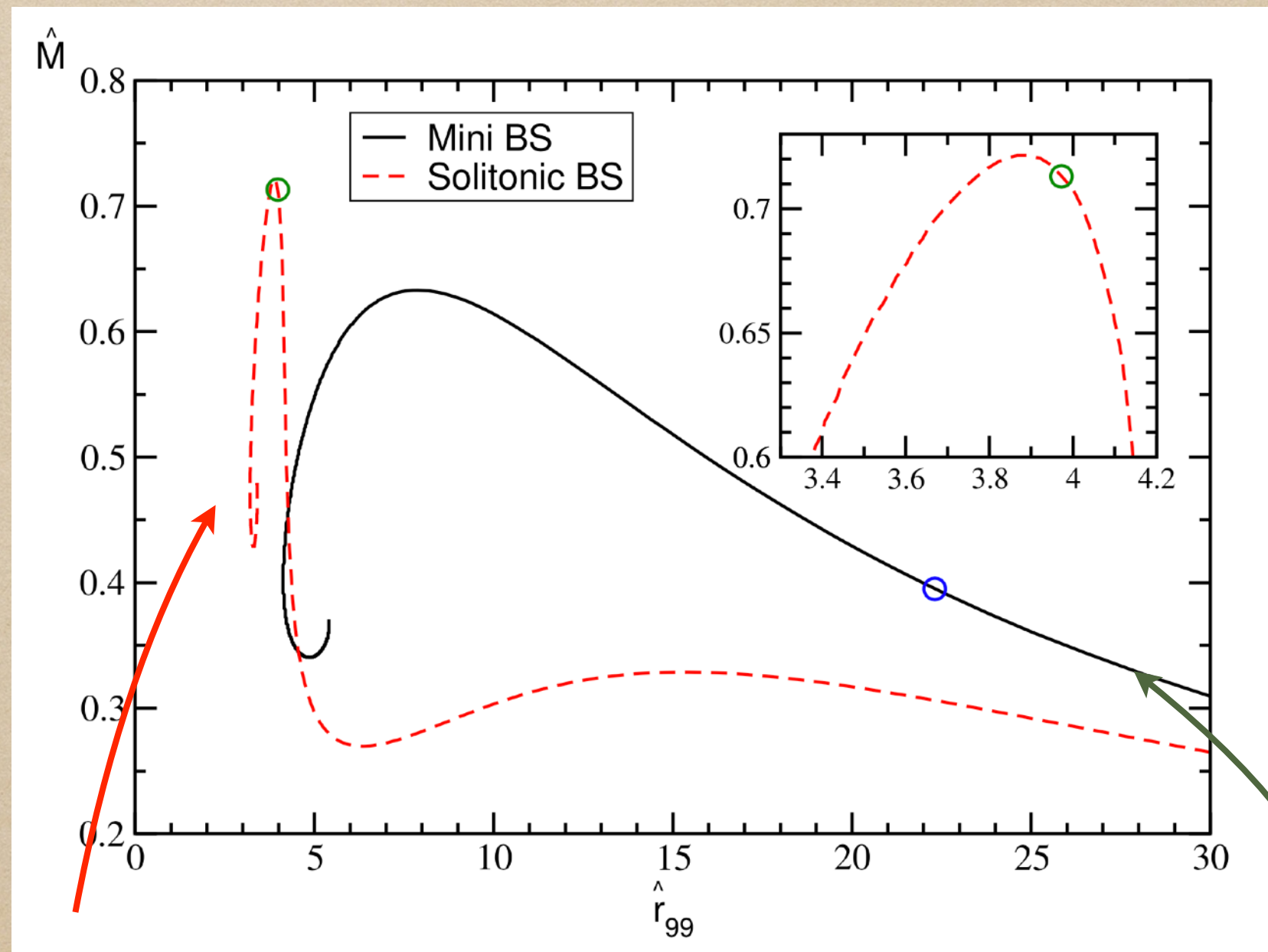
Formalism and basic features

- 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) mini BSs unstable in contrast to

spinning Proca stars! Sanchis-Gual+ 1907.12565

BSs with self-interaction can be stable Siemonsen & East 2302.06627

- What happens in scalar BS inspiral and merger?

- Kerr BH

- Non-spinning BS; angular momentum shed

- Total dispersal

- Spinning BS with shedding of excess angular momentum?

GW 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

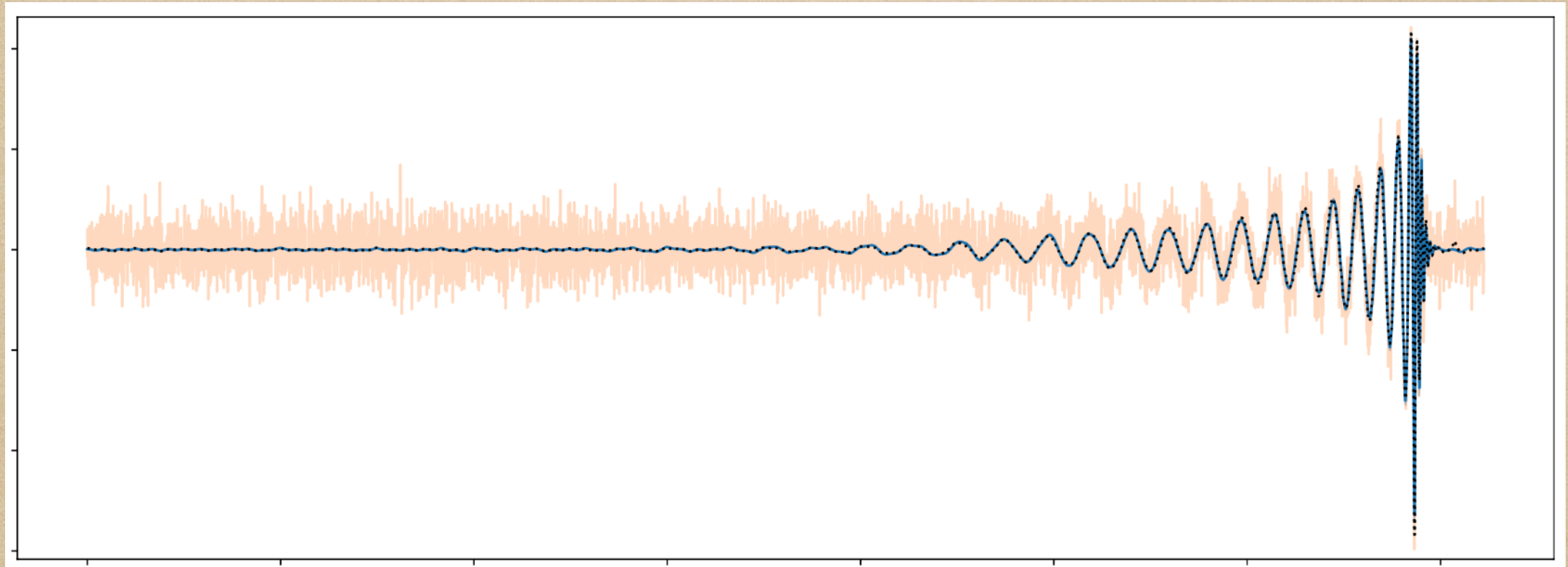
Time t_c and Phase ϕ_c of coalescence

- Other parameters

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

2. Motivation and tools

Motivation



- Test nature of compact objects: BHs, NSs, ECOs?
- Dark-matter candidates: Ultralight, axion-like fields $10^{-11} \dots 10^{-20} \text{ eV}$
- Bosonic fields can form equilibrium configurations:
Boson stars Kaup 1968
- Properties: Compactness 0 to $> \text{NSs}$, 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+ 1106.2254

- Use two numerical relativity codes

GRChombo Radia+ 2112.10567

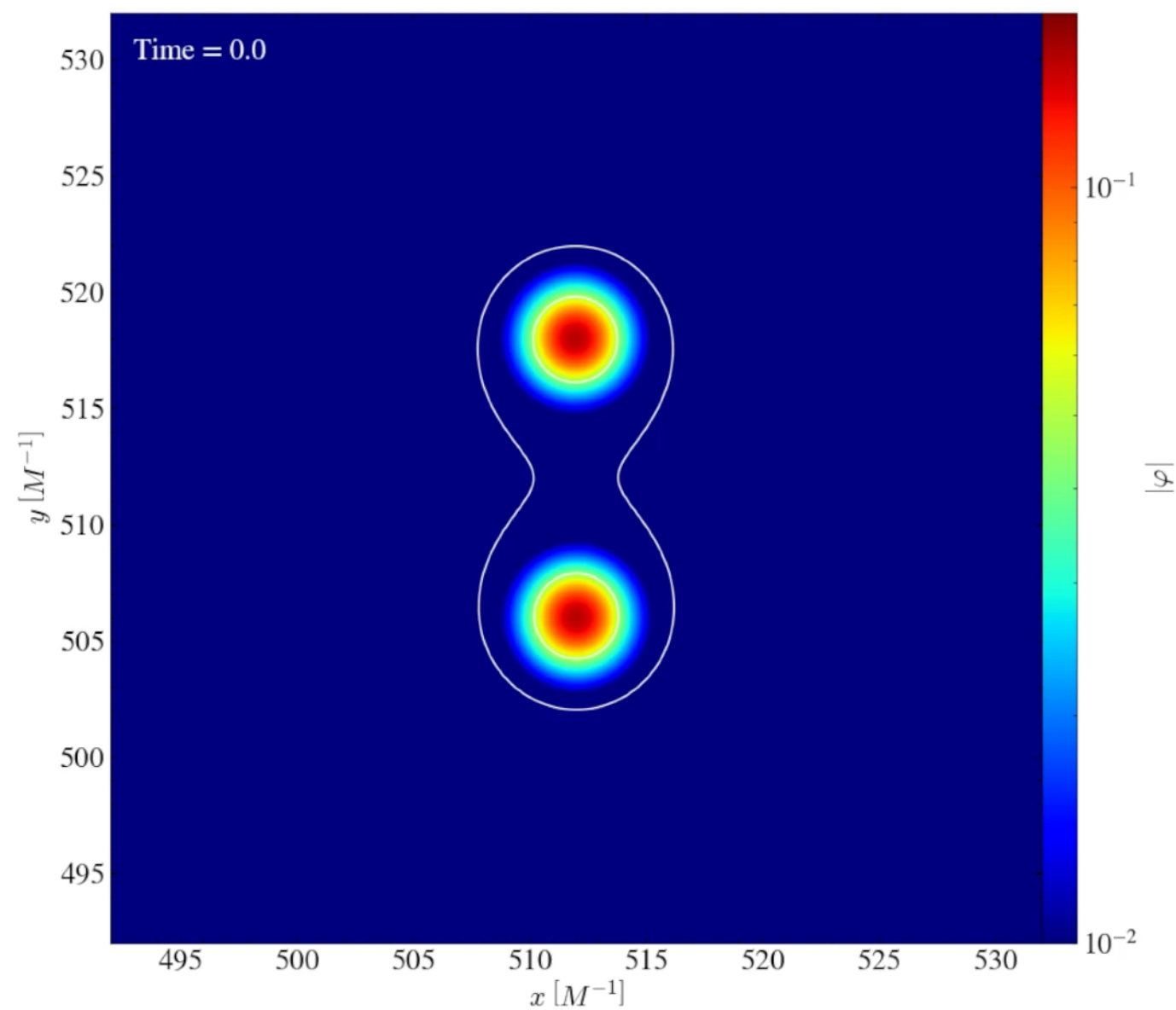
Lean US gr-qc/0606079

- Technical details:

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

3. Injecting BS waveforms into LIGO

Example boson-star inspiral



Courtesy of T Evstafyeva

BS binaries

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

Characterized by

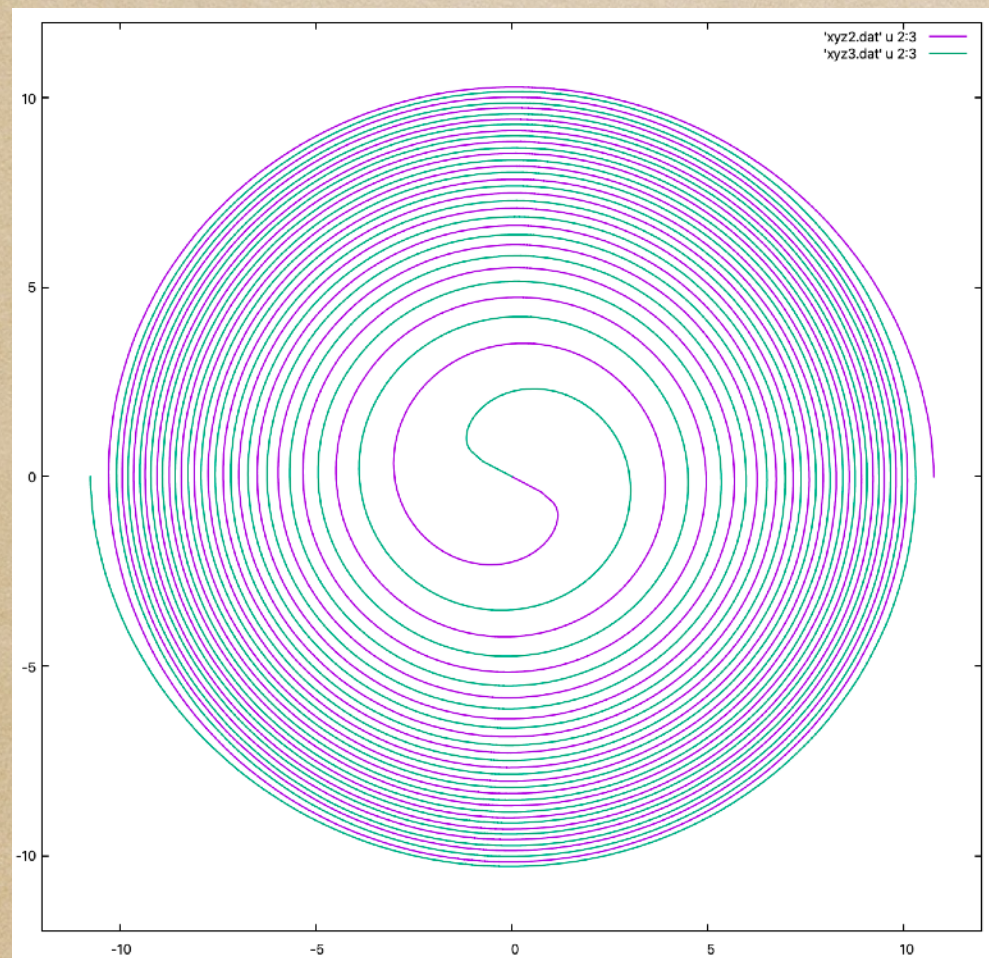
- Quasi-circular, non-spinning, equal-mass: $e \approx 0, S_{1,2} = 0, q = 1$
- Number of orbits N
- Compactness 0.1 or 0.2
- Scalar dephasing $\delta\phi \in [0, \pi]$
- BS-BS or BS-anti BS binary?
- Total mass: Any by trivial rescaling of the scalar mass

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

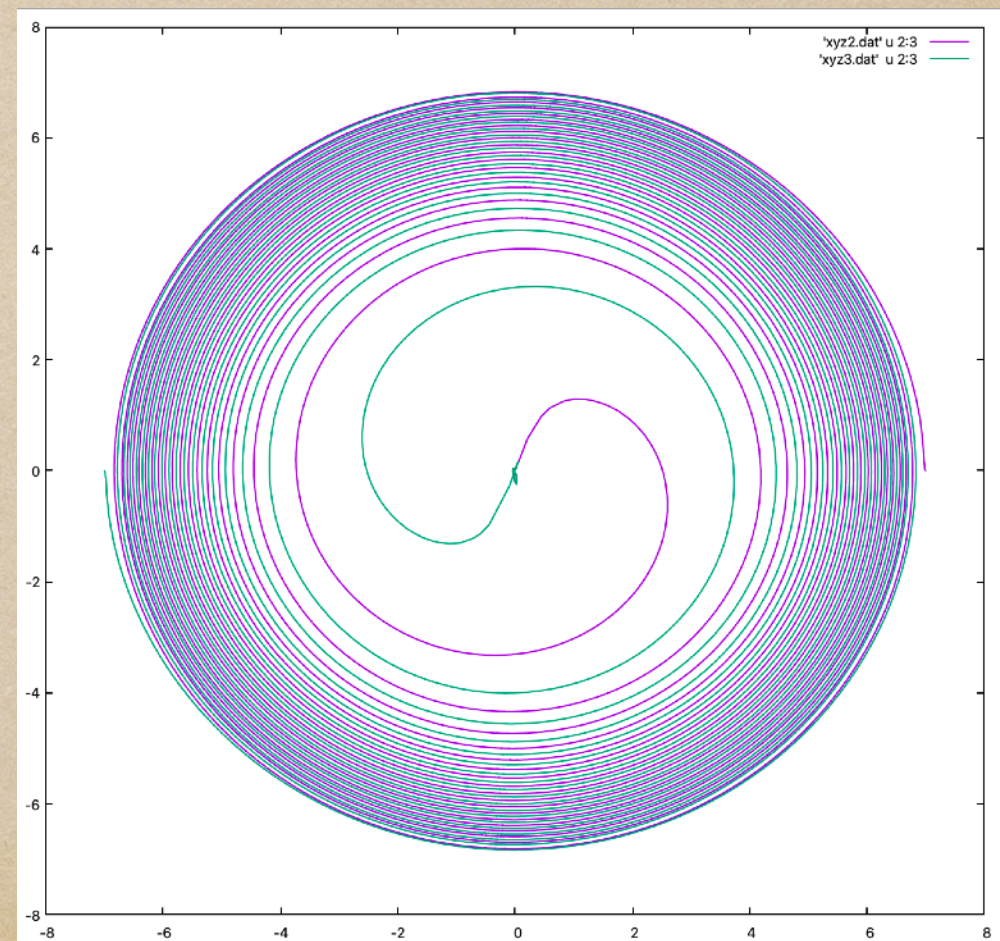
BS binaries

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

A17-d14

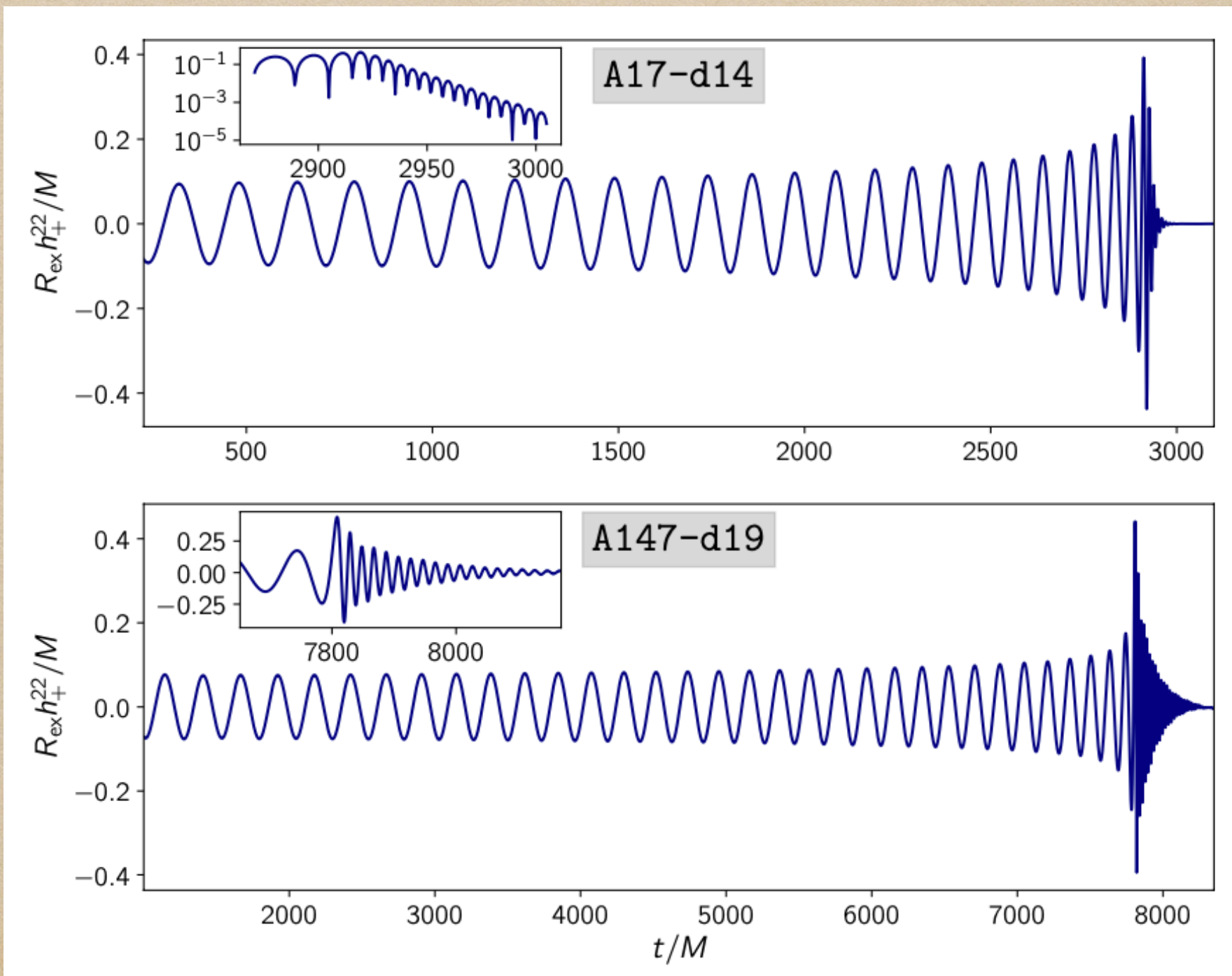


A147-d19



BS binaries

- GW strain from compact and fluffy BSs



Waveform approximants

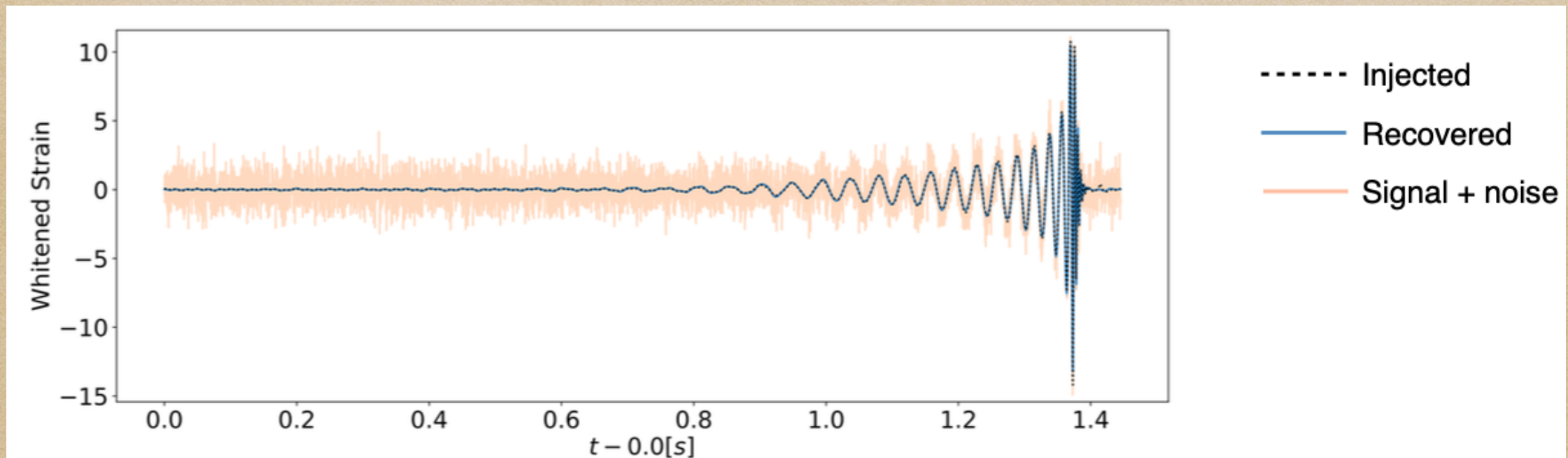
- Parameter estimation performed with Bilby Ashton+ 1811.02042
- IMRPhenomXP: Frequency domain Pratten+ 2004.06503
 - Quasi-circular, spin-precessing black-hole binaries
 - Quadrupole modes
- IMRPhenomPv2_NRTidal: f domain Dietrich+ 1706.02969, 1905.06011
 - Quasi-circular, spin-precessing neutron-star binaries
 - Tidal deformability parameters $\Lambda_{A,B}$
- We have tested more with similar results.

Injectons 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

Compact BSs using IMRPhenomXP

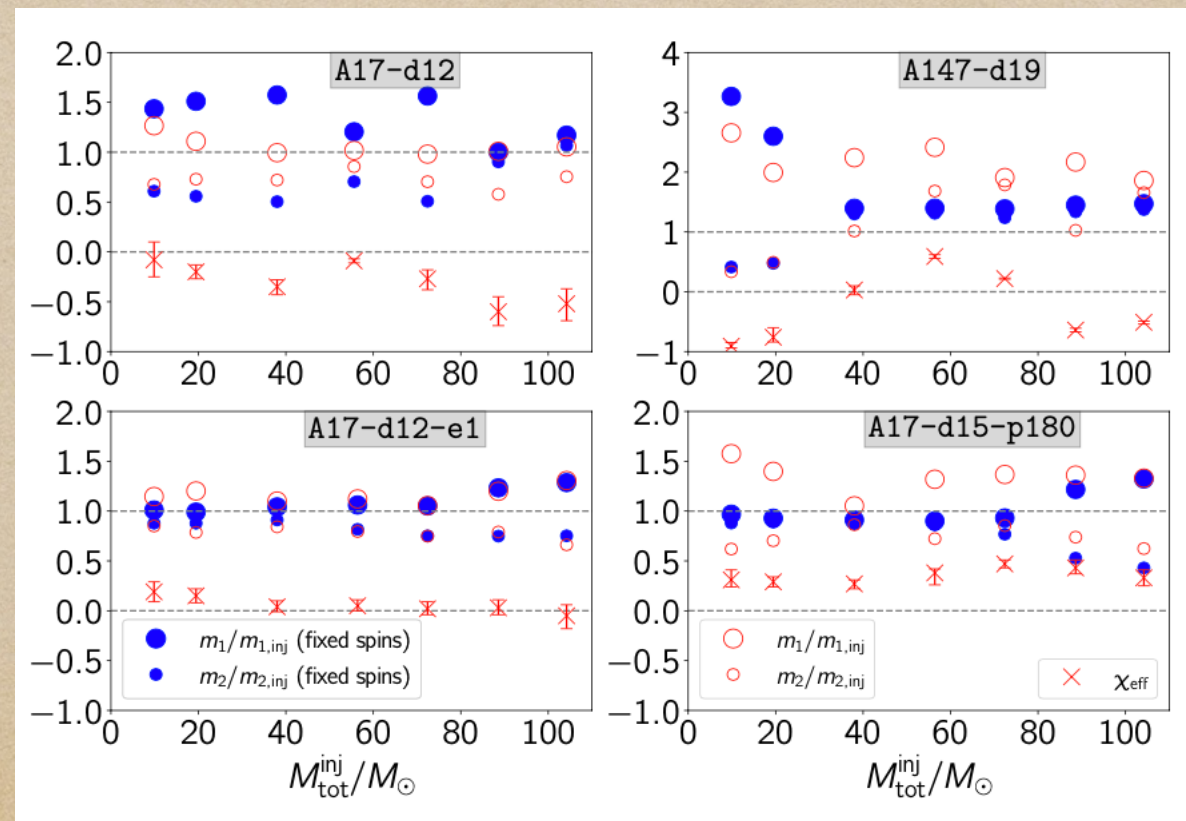
- Injections often recovered but with **biased** parameters!
- Example A17-d15 with $M_{\text{tot}} = 77 M_{\odot}$, $d_L = 200 \text{ Mpc}$ in the analysis



- **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



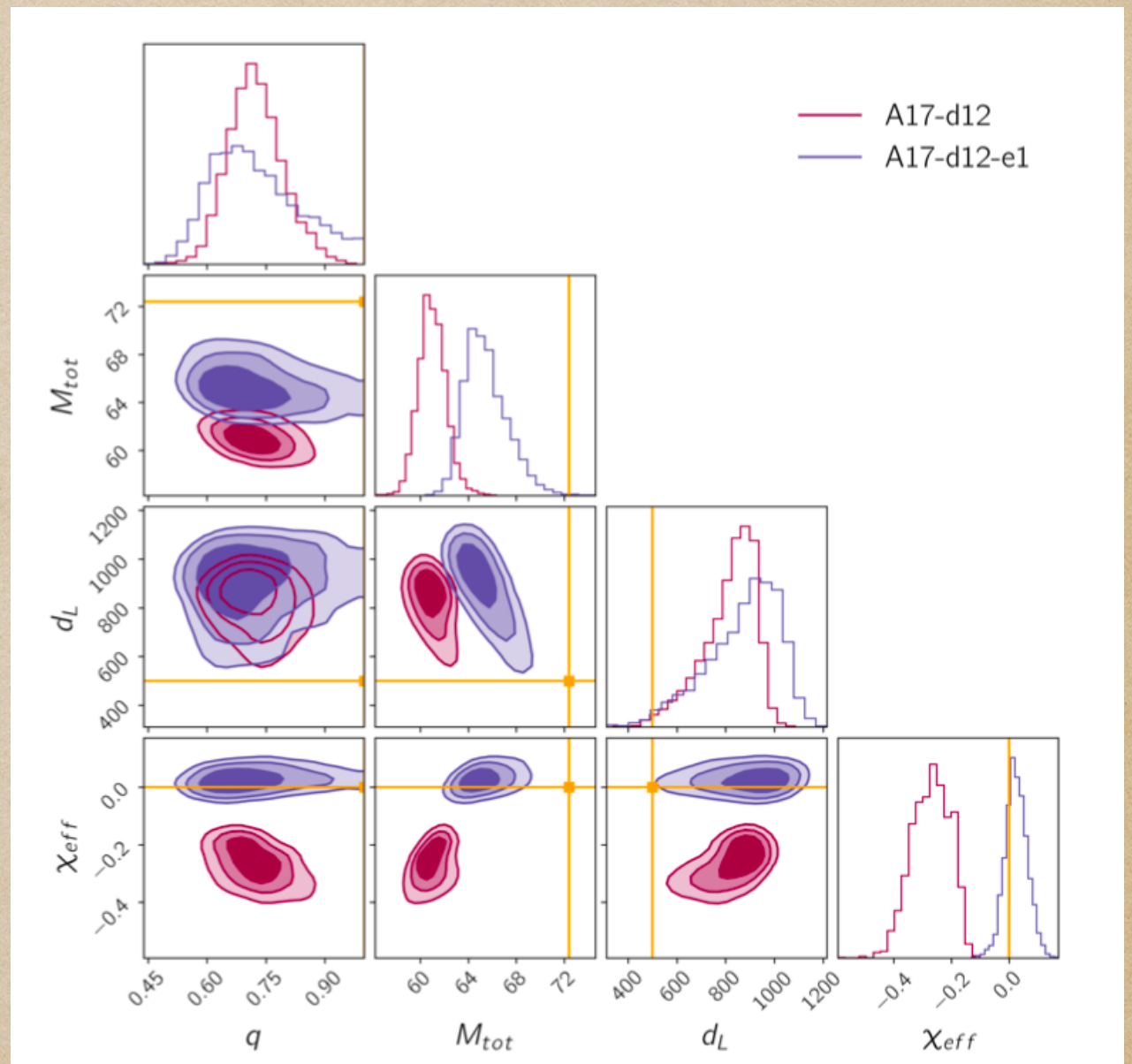
Results using IMRPhenomXP

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

Corner plot:

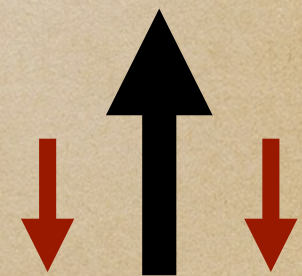
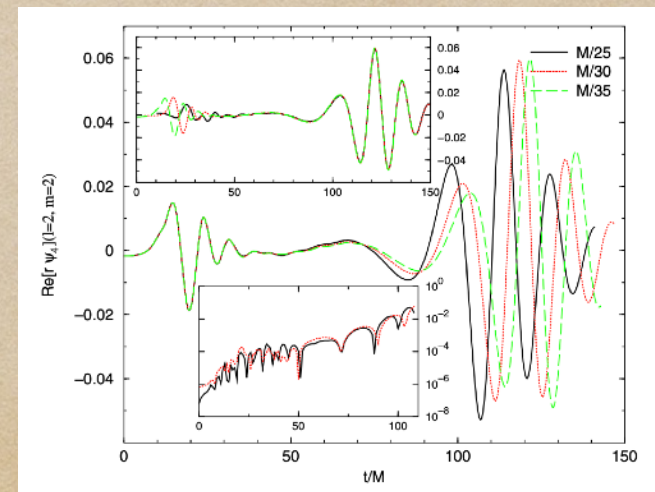
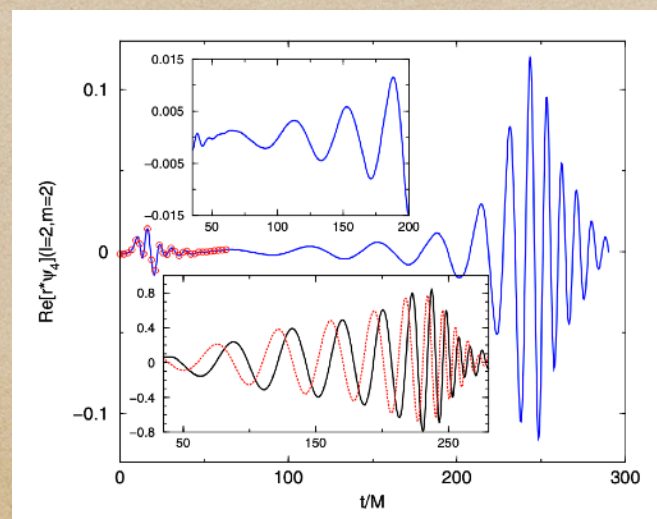
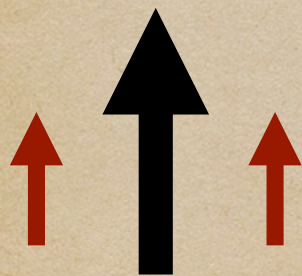
A17-d12-e1 vs. A17-d12

- These features can be explained with the chirp strength



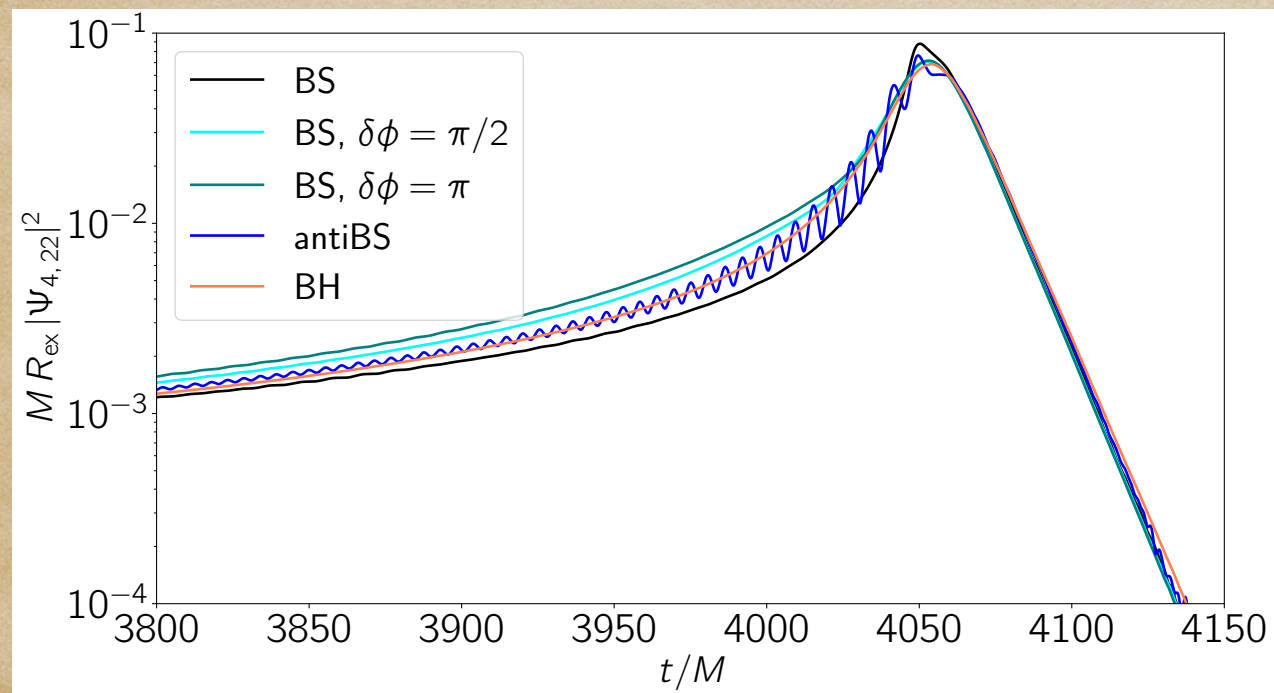
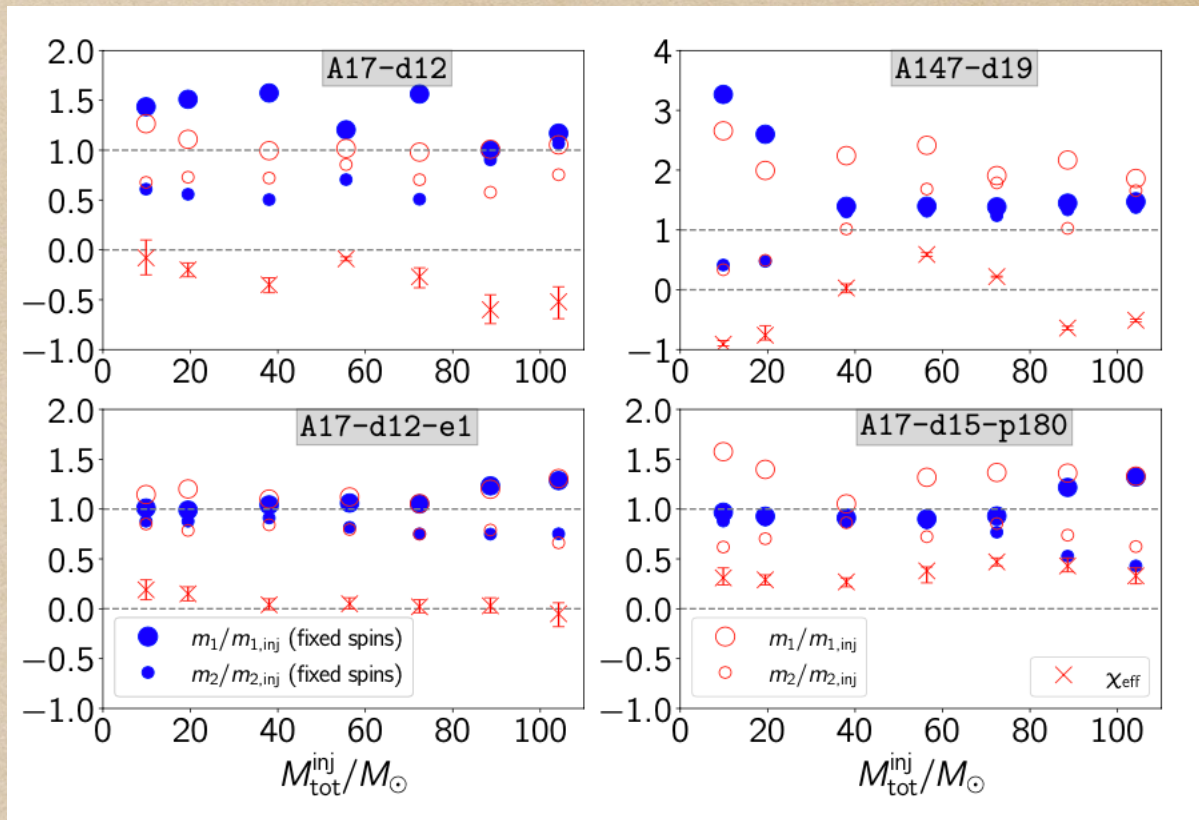
Understanding the PE bias

- 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 Campanelli+ gr-qc/0601091



Understanding the PE bias

- PE bias
- VS
- Chirp steepness



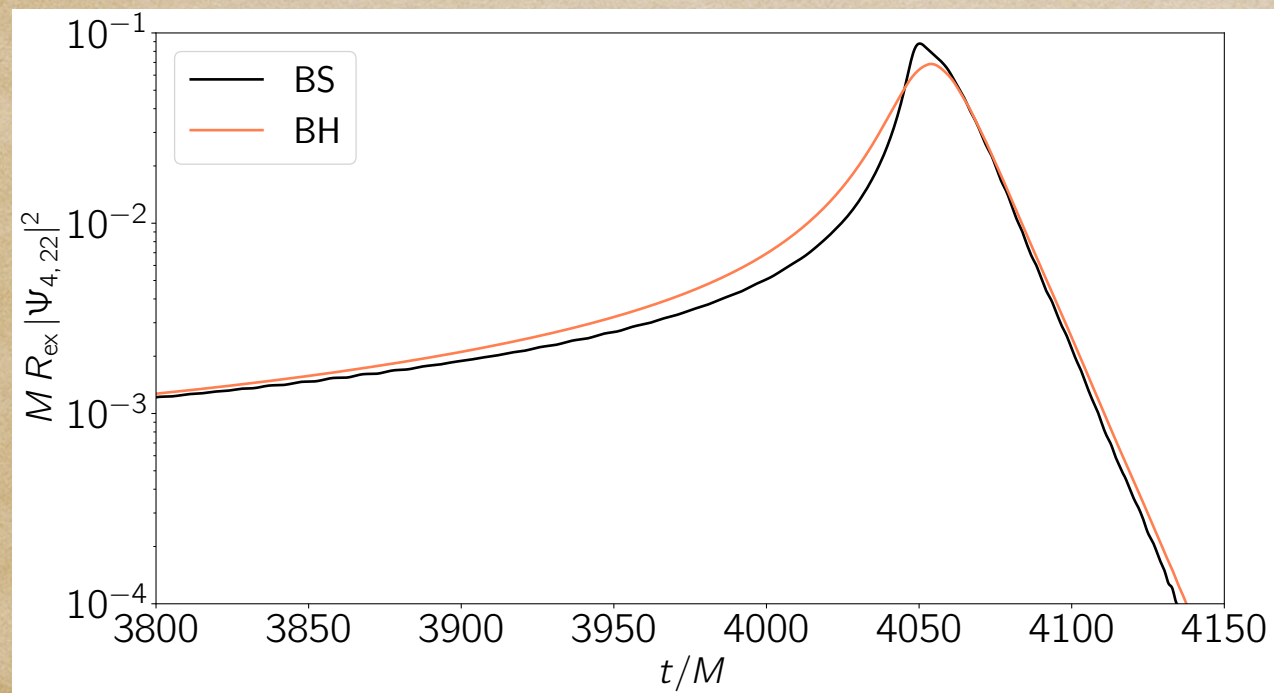
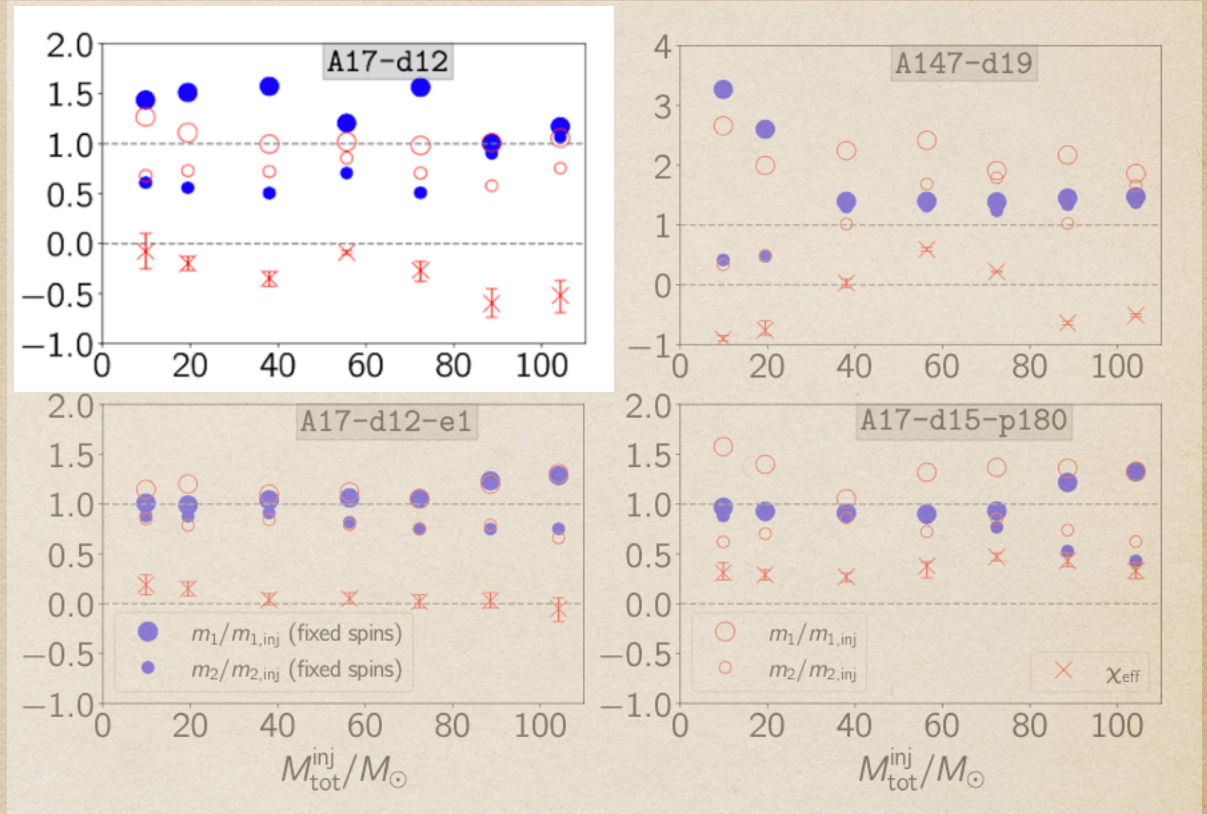
Understanding the PE bias: Standard BS

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

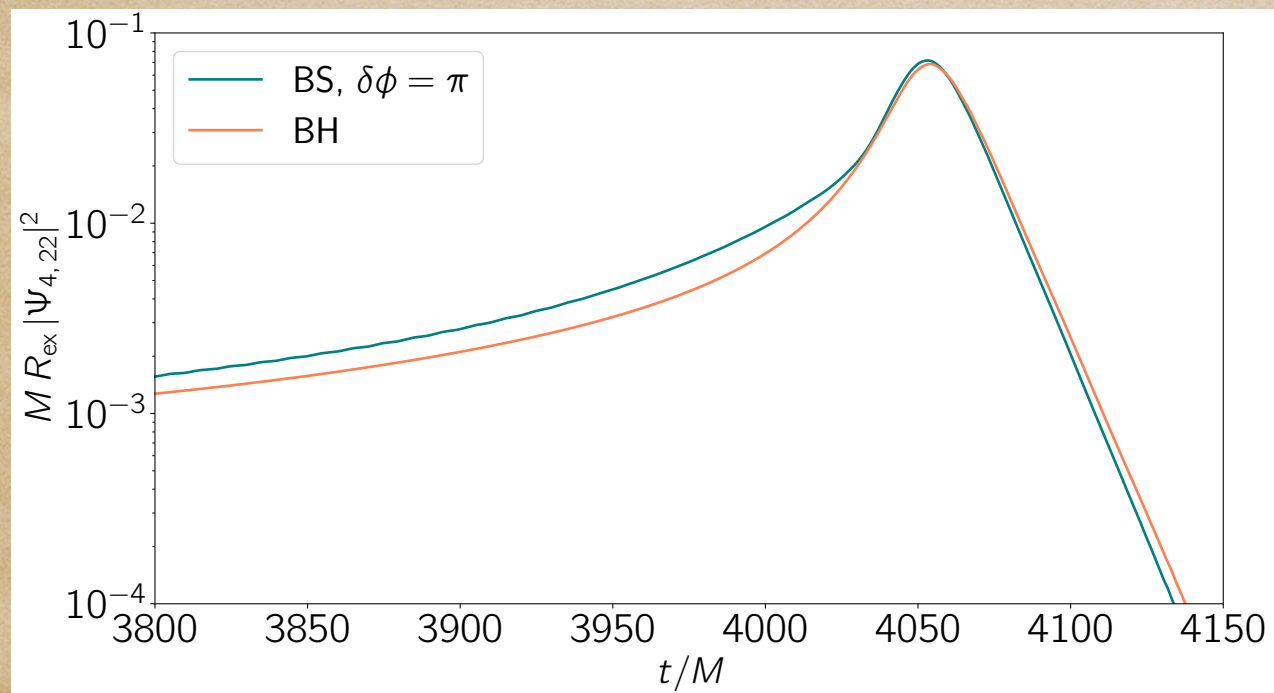
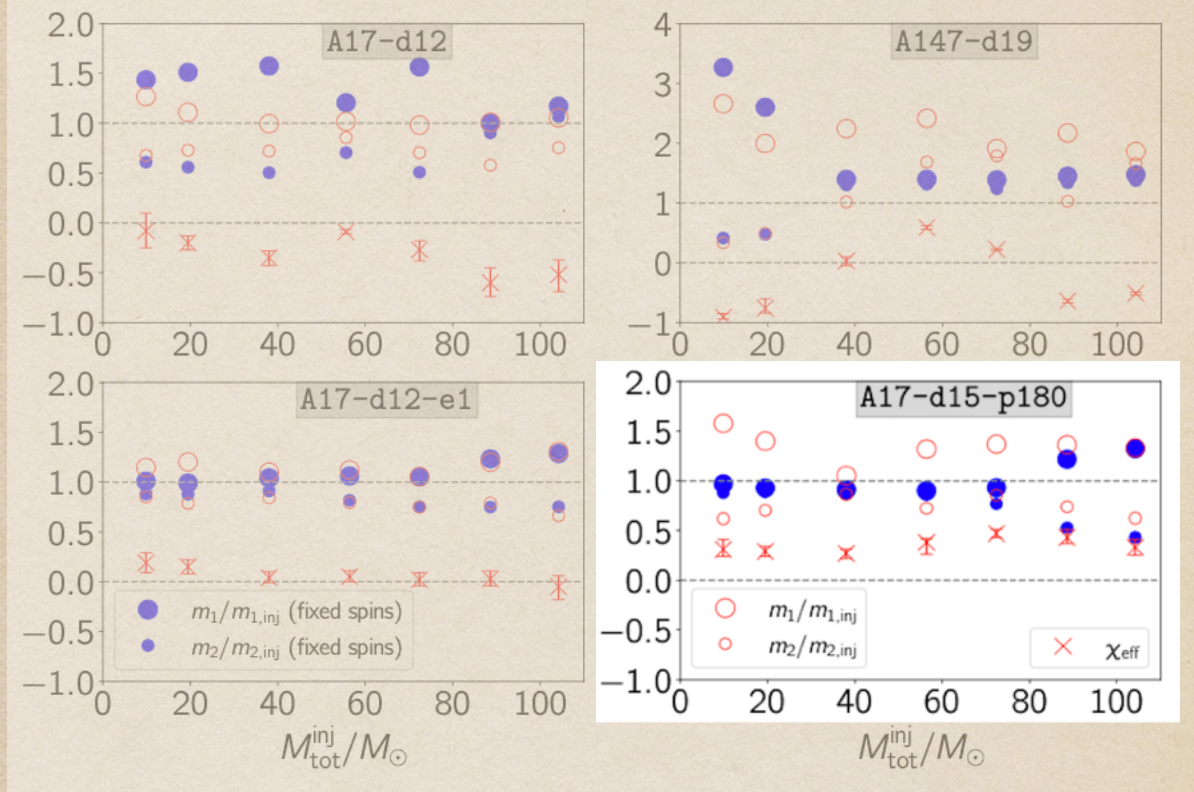
Understanding the PE bias: anti-phase

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

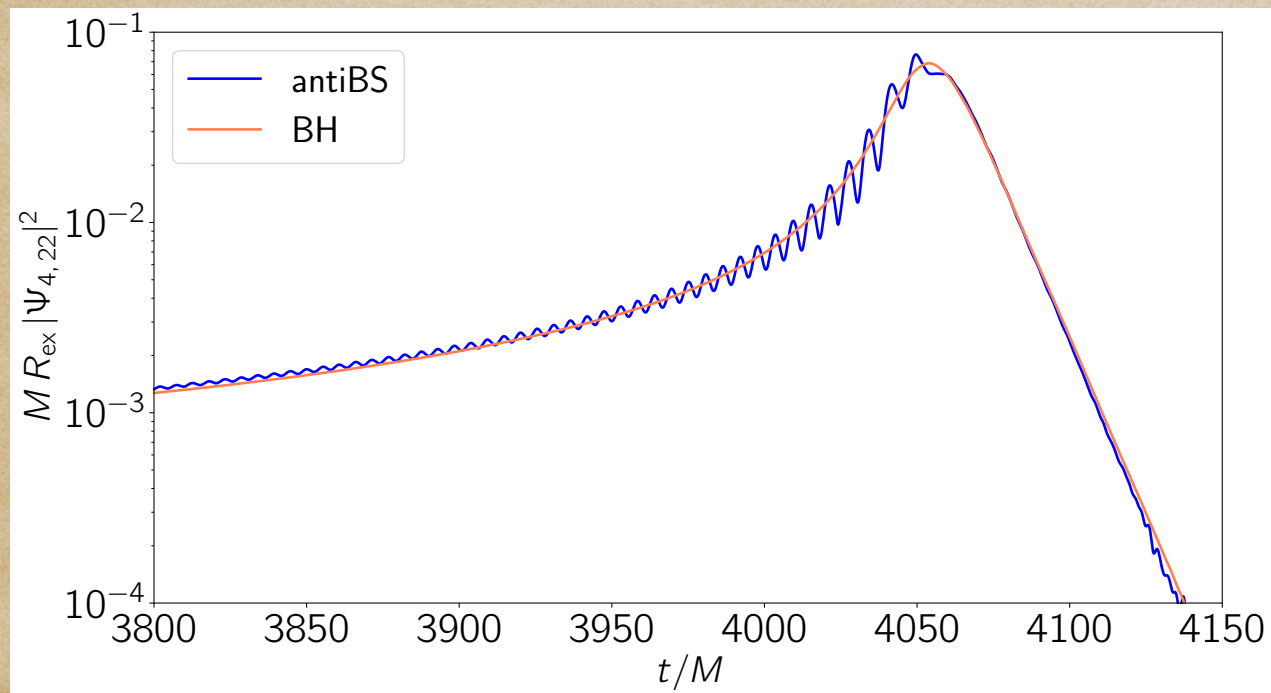
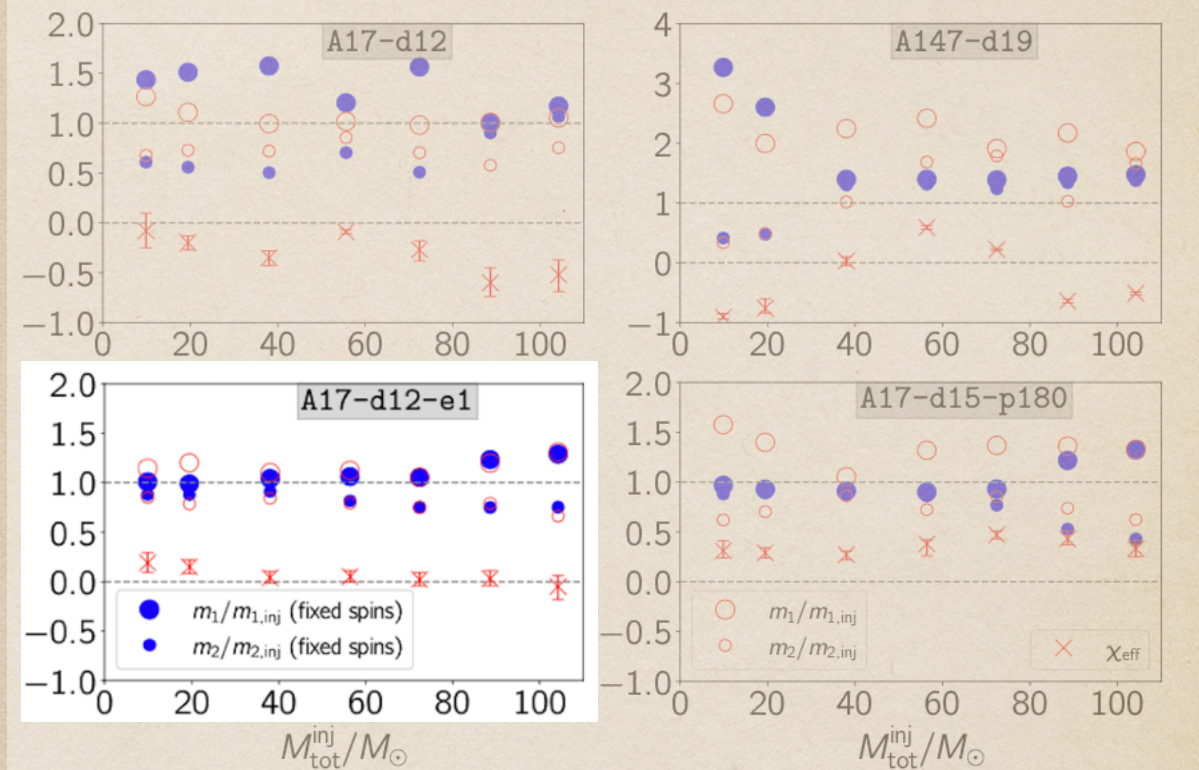
Understanding the PE bias: anti-BS

Fixed or variable spins

BS chirp similar to BHs

⇒ Comparable mass ratios

∧ Small spins



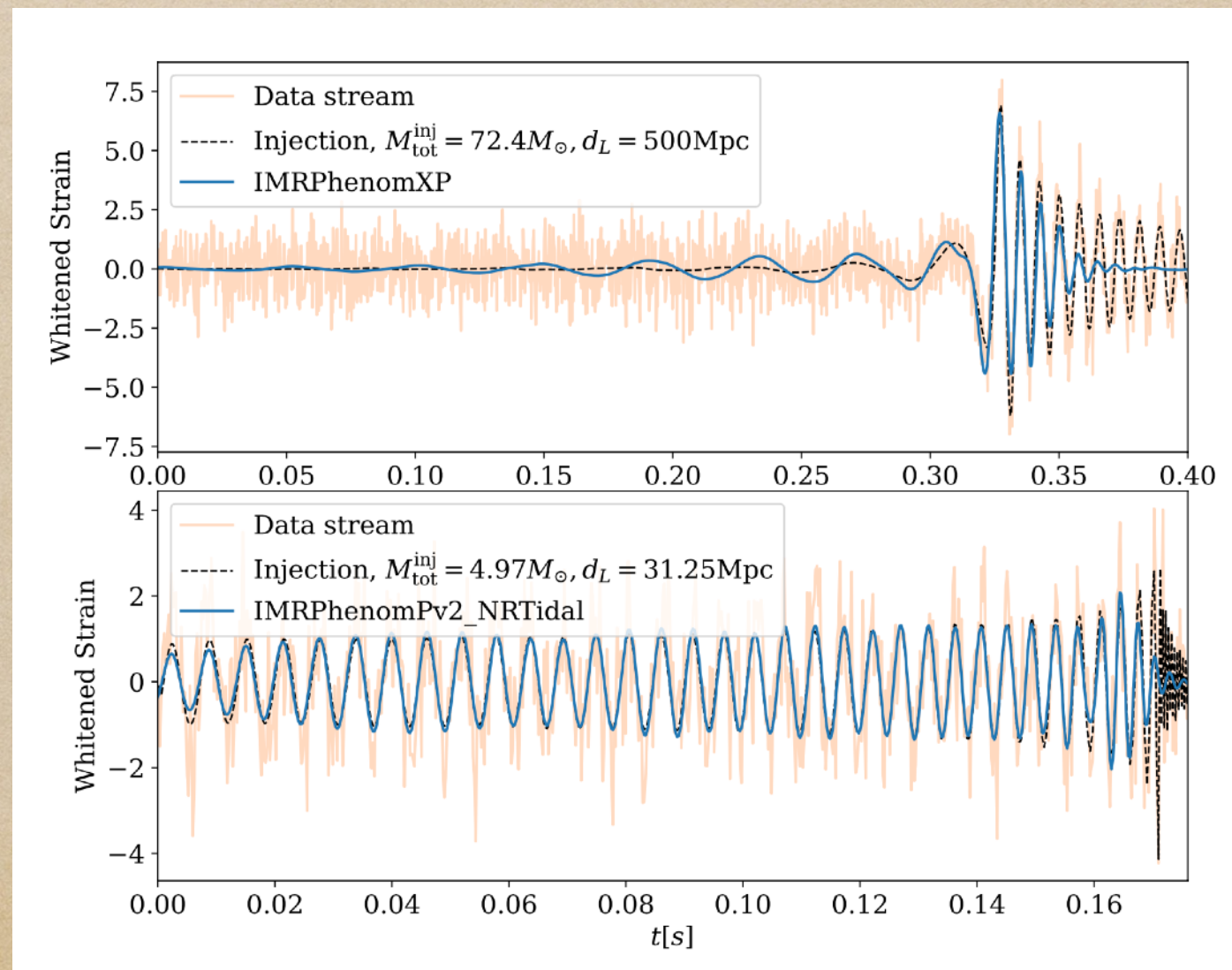
High-mass regime

LIGO mainly sees merger burst

⇒ Less reliable PE

Recovery of “Fluffy” BS binaries

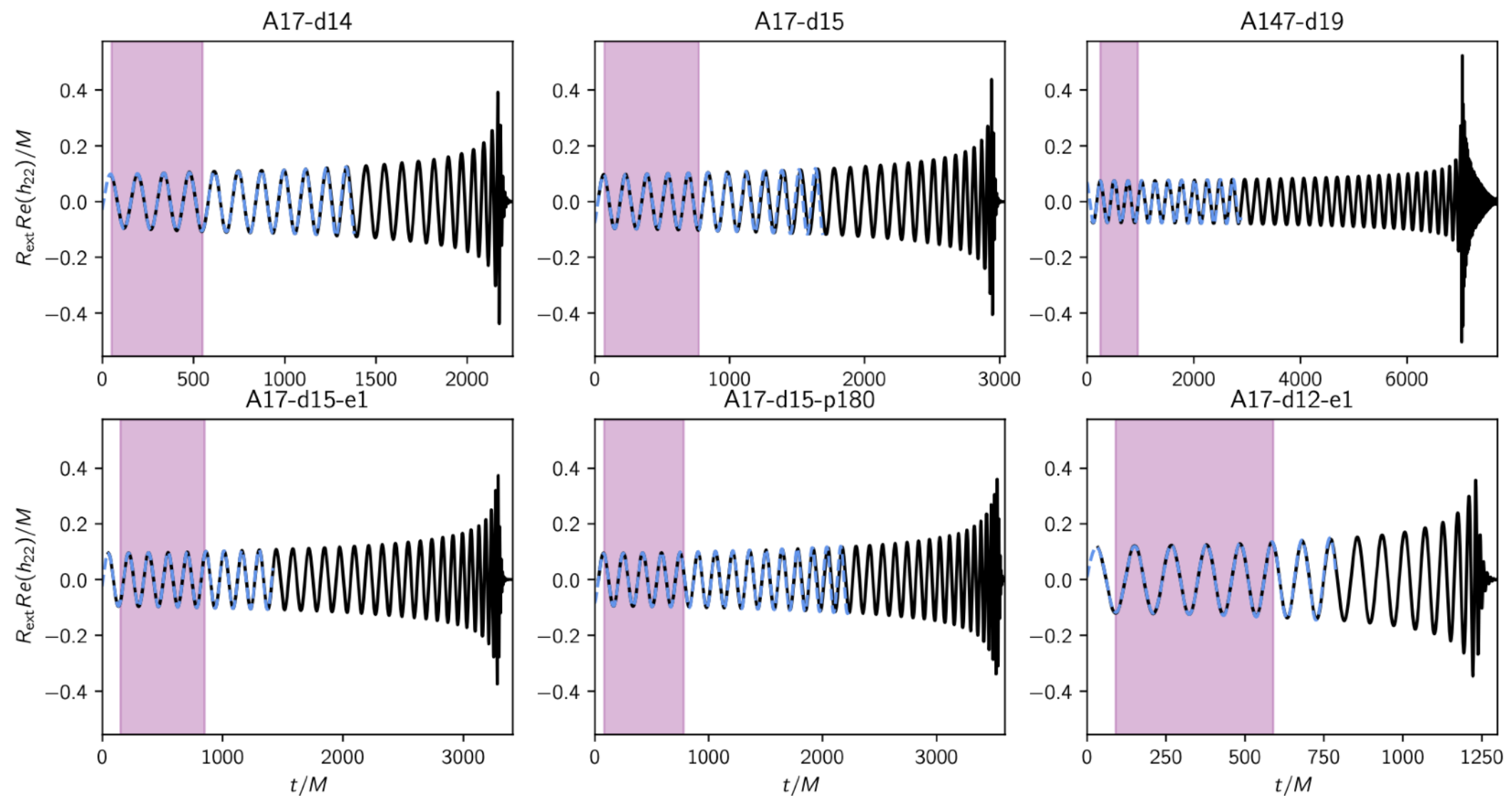
- Parameter estimation always erratic for *fluffy* BBS
- BH approximants may capture inspiral or merger but never both!
- Residual often not compatible with Gaussian noise



4. Inspiral, Merger, Ringdown, Test

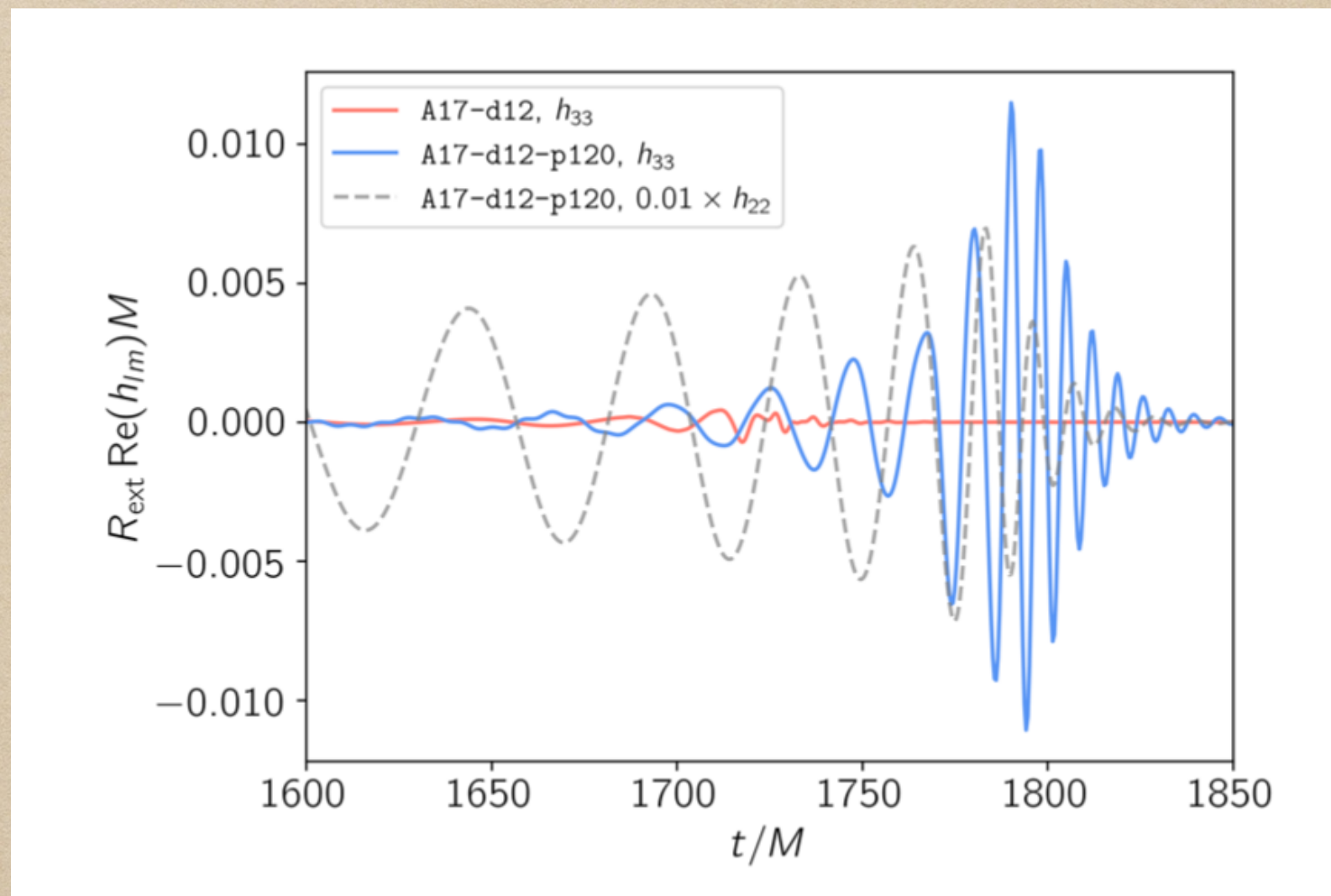
PN Hybridization

- Hybridize with 3.5 PN for BHs Blanchet LRR arXiv:1310.1528



New multipoles

- Dephasing $\delta\phi \neq n\pi$ breaks π rotation symmetry $\Rightarrow$ odd m multipoles



- Mode hierarchy: $(22) \gg (44) \gtrsim (32), (33), (21)$

Ringdown

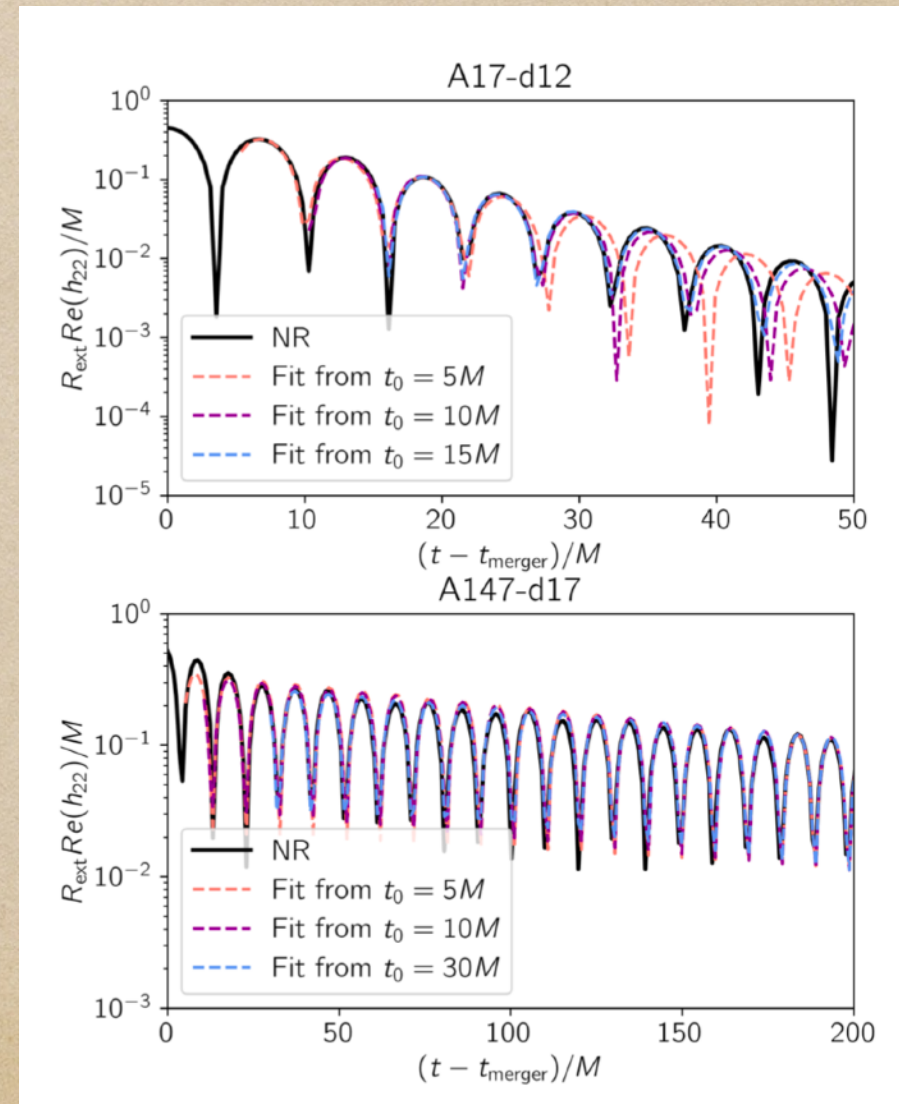
- Remnant: BS or BH, depending on progenitor compactness
- BS QNM frequencies from Yoshida+ (1994), Macedo+ 1307.4812
- Fit $h(t) = \sum_{k \in K} \mathcal{A}_k e^{-t/\tau_k} e^{-i\omega_k t}$ over $t - t_{\text{mer}} \geq t_0$ where $k = \{(l, m, n)\}$

Using jaxqualin (Python)

- Keep only modes consistently present for $5M \leq t_0 \leq 40M$
 $\Rightarrow (2, \pm 2, 0)$ mode

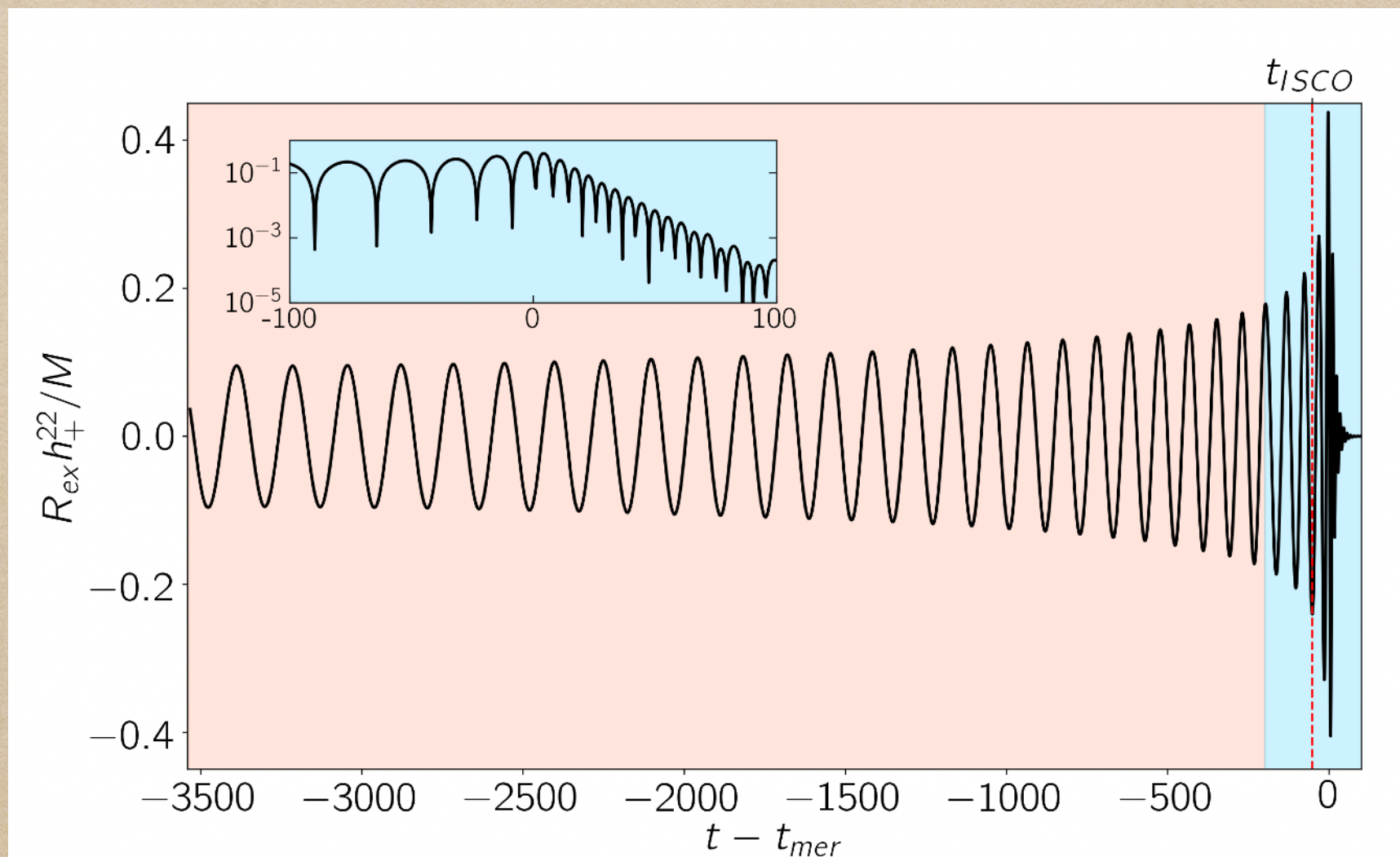
- Accuracy:

$$M\delta\omega = 0.2 \dots 5 \%, \quad \delta\tau/M = 5 \dots 15 \%$$



The IMR Consistency Test

- Do Parameter Estimation on low- and high-frequency parts of signal
Ghosh+ 1602.02453, 1704.06784
- Translates into Inspiral (low f) vs Merger+Ringdown (high f)



- Split at $f_{\text{cut}} \lesssim f_{\text{ISCO}}$

The IMR Consistency Test

- Inject $l = 2$ modes into LIGO+Virgo, $\alpha = 1.375$, $\delta = 1.2108$, $\iota = 60^\circ$
- Measure a_{fin} and M_{fin} separately from Inspiral vs Merger+Ringdown
- For inspiral: a_{fin} and M_{fin} from progenitor masses and spins via

NR fits Healy & Lousto 1610.09713

- Deviation: $\epsilon = 2 \frac{M_{\text{fin}}^{\text{I}} - M_{\text{fin}}^{\text{MR}}}{M_{\text{fin}}^{\text{I}} + M_{\text{fin}}^{\text{MR}}}$, $\sigma = 2 \frac{a_{\text{fin}}^{\text{I}} - a_{\text{fin}}^{\text{MR}}}{a_{\text{fin}}^{\text{I}} + a_{\text{fin}}^{\text{MR}}}$

$$Q_{\text{BH}} = \int_{P(\epsilon, \sigma) > P(0,0)} P(\epsilon, \sigma) d\epsilon d\sigma$$

- Significant deviation $:\Leftrightarrow Q_{\text{BH}} \geq 90 \%$

A17-d15, $M_{\text{tot}} = 40M_{\odot}$, $d_L = 250 \text{ Mpc}$, $\rho_{\text{net}} \approx 56$

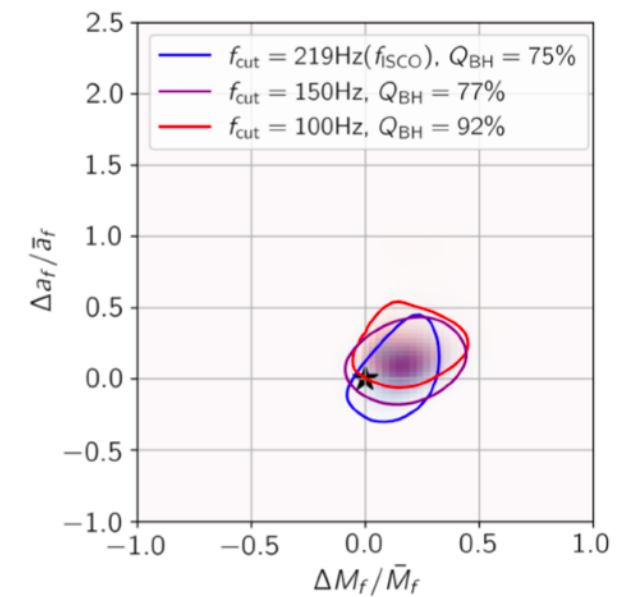
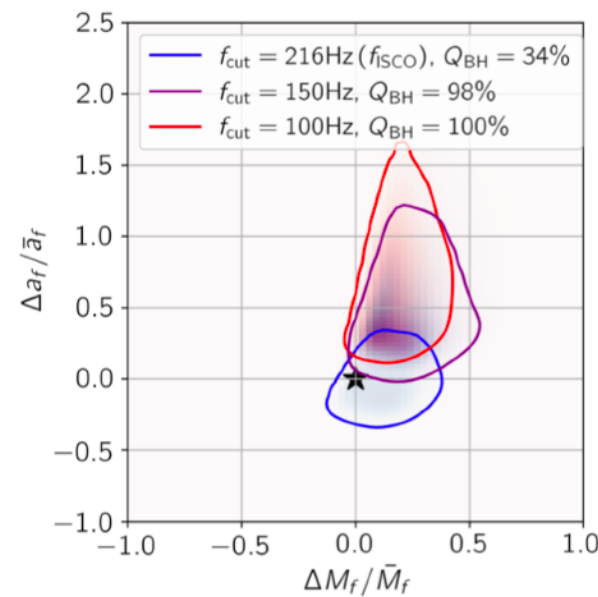
IMRPhenomXAS

Pratten+ 2001.11412

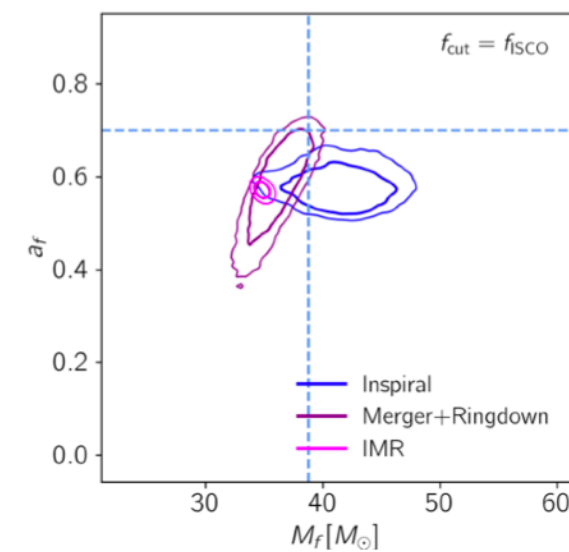
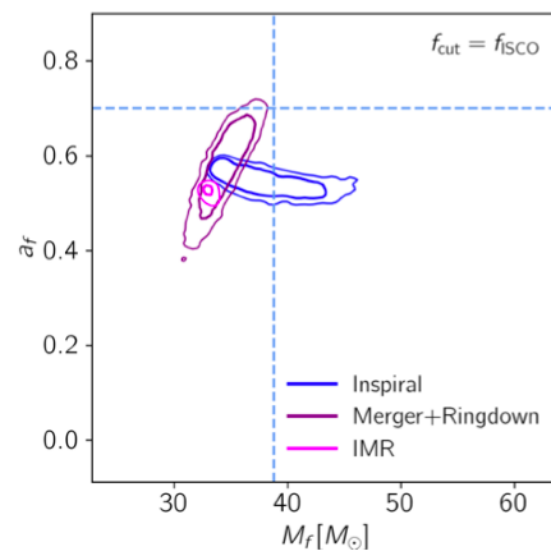
IMRPhenomXP

Pratten+ 2004.06503

90 % credible of $P(\epsilon, \sigma)$



68 % and 90 % credible
of $(a_{\text{fin}}, M_{\text{fin}})$



A17-d15, $M_{\text{tot}} = 40M_{\odot}$, $d_L = 250 \text{ Mpc}$, $\rho_{\text{net}} \approx 56$

IMRPhenomXAS

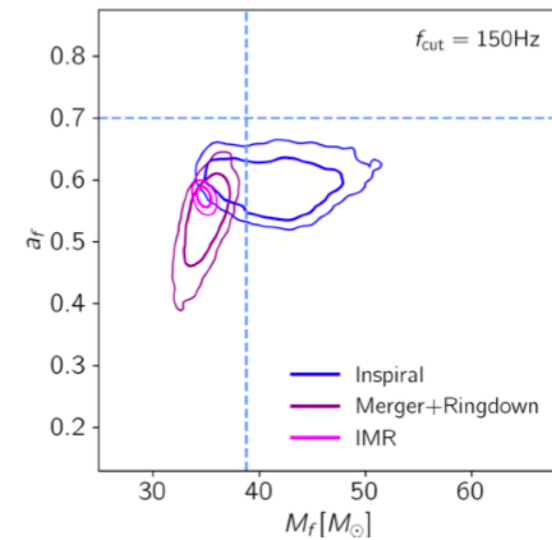
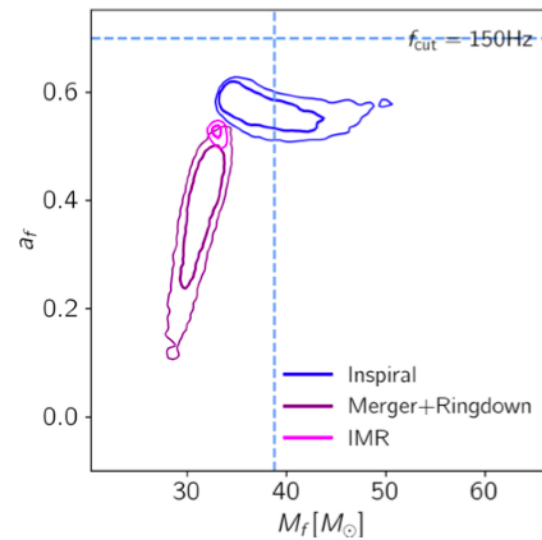
Pratten+ 2001.11412

IMRPhenomXP

Pratten+ 2004.06503

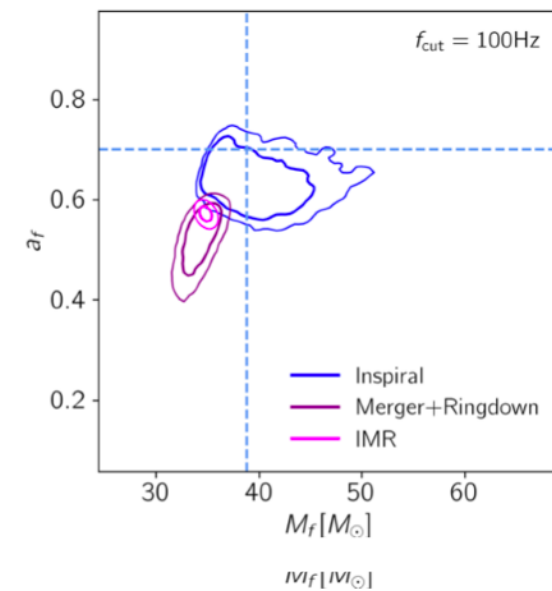
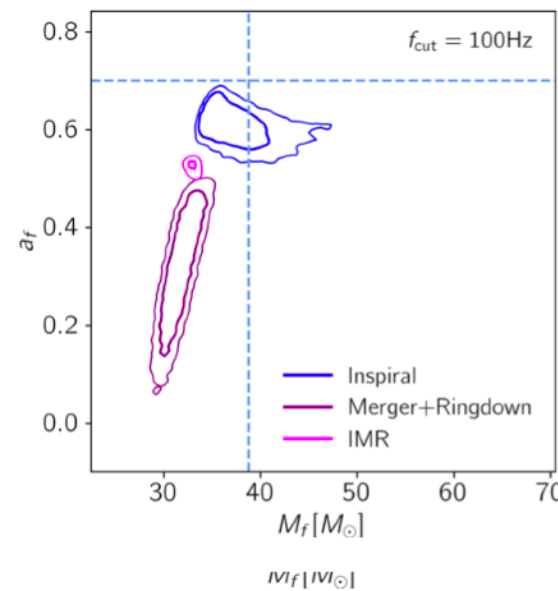
68 % and 90 % credible

of $(a_{\text{fin}}, M_{\text{fin}})$



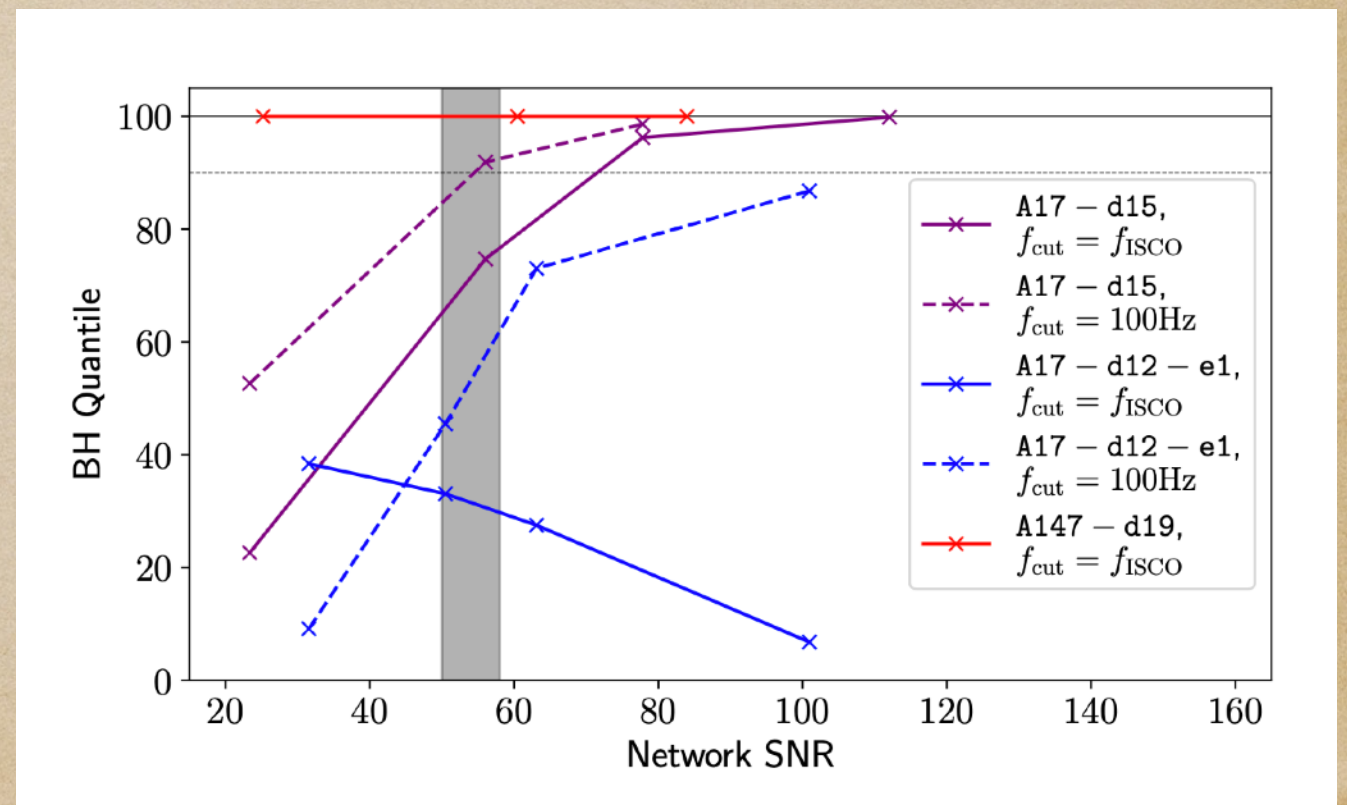
68 % and 90 % credible

of $(a_{\text{fin}}, M_{\text{fin}})$



Conclusions from A17-d15

- IMRCT's sleuthing depends on f_{cut}
 - $f_{\text{cut}} = f_{\text{ISCO}}$ $\Rightarrow$ Deviations from BH waveform either side of f_{cut}
 - Smaller "earlier" f_{cut} $\Rightarrow$ Inspiral BH like, Merger-Ringdown not
- Including spin-precession better accommodates BS features
 - $\Rightarrow$ degeneracy between BH and BS binaries increased
- Higher SNR
 - $\Rightarrow$ IMRCT more effective, except for anti-BS!
- IMRCT on fluffy BSs: slam dunk!

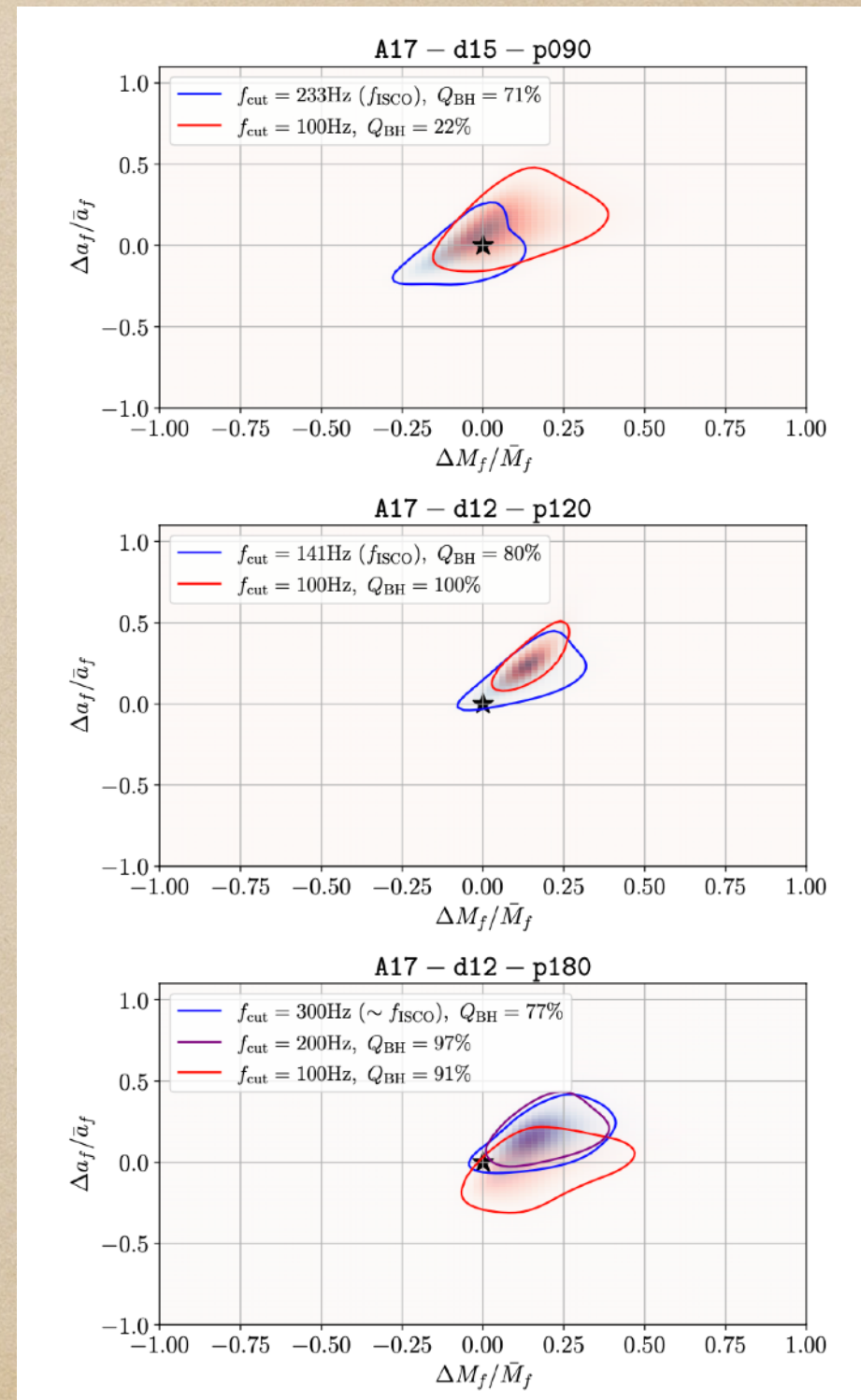


IMRCT on dephased BS Binaries

- $\delta\phi = \frac{\pi}{2}$ or anti BS: hard to spot!

- $\delta\phi = \frac{2\pi}{3}$ similar to $\delta\phi = 0$

- $\delta\phi = \pi$ similar to $\delta\phi = 0$



Conclusions

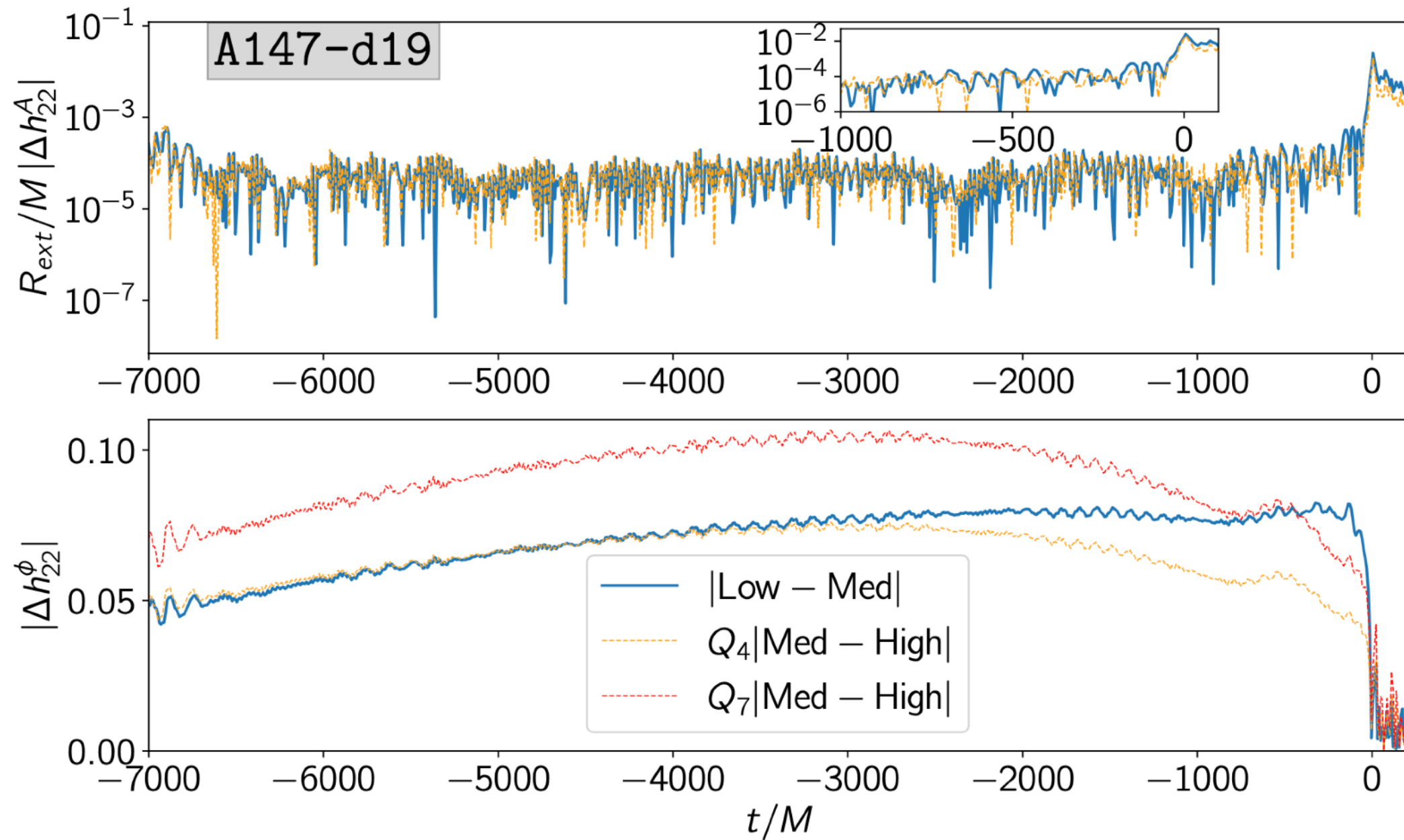
- NR simulations of BS binaries about as accurate as for BHs
- BS binaries recovered well with BH approximants → degeneracy
- But systematic bias in parameter estimation
- Compact BBSs “look” very similar to BBHs
- Fluffy BBSs have more characteristic signatures

Inspiral-Merger-Ringdown Consistency Test (IMRCT)

- Improves identification of BS binaries
- Works better with smaller “earlier” $f_{\text{cut}} < f_{\text{ISCO}}$
- Efficient tools for analysing GW observations with BS templates

4. Extra slides

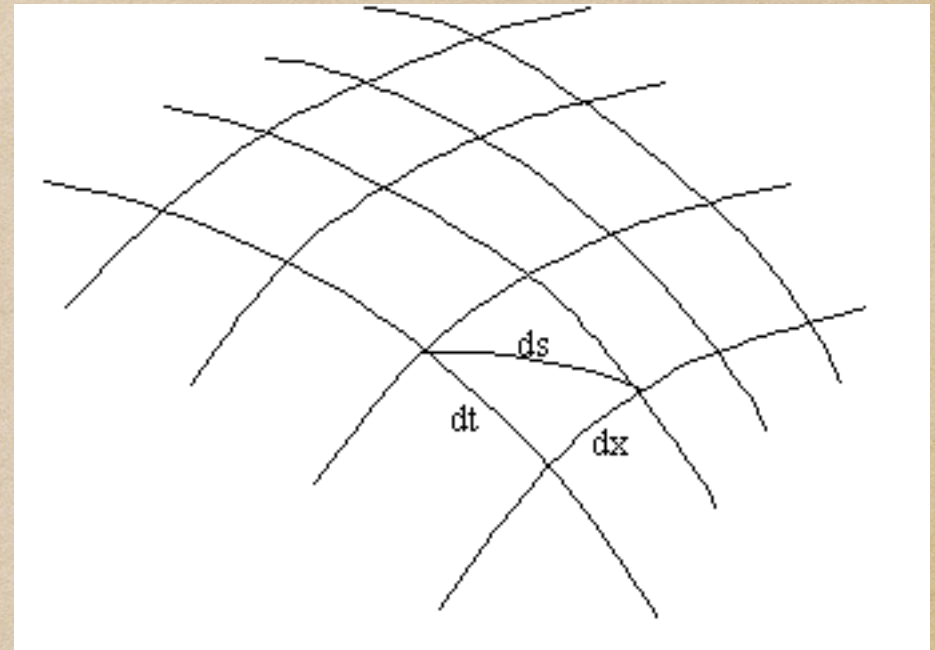
Convergence



General relativity in 30 seconds

- Spacetime as a curved manifold
- Key quantity: spacetime metric $g_{\alpha\beta}$
- Curvature, geodesics etc. all follow
- Einstein equations

$$R_{\alpha\beta} - \frac{1}{2}g_{\alpha\beta}R + \Lambda g_{\alpha\beta} = \frac{8\pi G}{c^4}T_{\alpha\beta}$$



- 10 non-linear PDEs for $g_{\alpha\beta}$
- $T_{\alpha\beta}$ = Matter fields
- Conceptually simple,
- hard in practice
- E.g. Schwarzschild

$$g_{\mu\nu} = \begin{pmatrix} \left(1 - \frac{2GM}{rc^2}\right) & 0 & 0 & 0 \\ 0 & -\left(1 - \frac{2GM}{rc^2}\right)^{-1} & 0 & 0 \\ 0 & 0 & -r^2 & 0 \\ 0 & 0 & 0 & -r^2 \sin^2 \theta \end{pmatrix}$$

$$ds^2 = c^2 dt^2 \left(1 - \frac{2GM}{rc^2}\right) - \frac{dr^2}{1 - 2GM/rc^2} - r^2 d\theta^2 - r^2 \sin^2 \theta d\phi^2$$

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Gravitational waves: weak-field solutions

- Consider small deviations from Minkowski in Cartesian coordinates
- "Background": Manifold $\mathcal{M} = \mathbb{R}^4$, $\eta_{\mu\nu} = \text{diag}(-1, 1, 1, 1)$
- "Perturbation": $h_{\mu\nu} = \mathcal{O}(\epsilon) \ll 1 \Rightarrow g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$
- Coordinate freedom: "Transverse-traceless (TT)" gauge
$$h^\mu{}_\mu = 0, \quad \partial^\nu h_{\mu\nu} = 0$$
- Vacuum, no cosmological constant: $T_{\mu\nu} = 0$, $\Lambda = 0$
- Einstein's eqs.: $\square h_{\mu\nu} = 0$
- Plane wave solution in z direction: $h_{\mu\nu} = H_{\mu\nu} e^{ik_\sigma x^\sigma}$

$$k^\mu = \omega(1, 0, 0, 1) \quad H_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & H_+ & H_\times & 0 \\ 0 & H_\times & -H_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Effect on particles

- Geodesic eq.
- Particle at rest at x^μ stays at $x^\mu = \text{const}$ in TT gauge

- Proper separation:

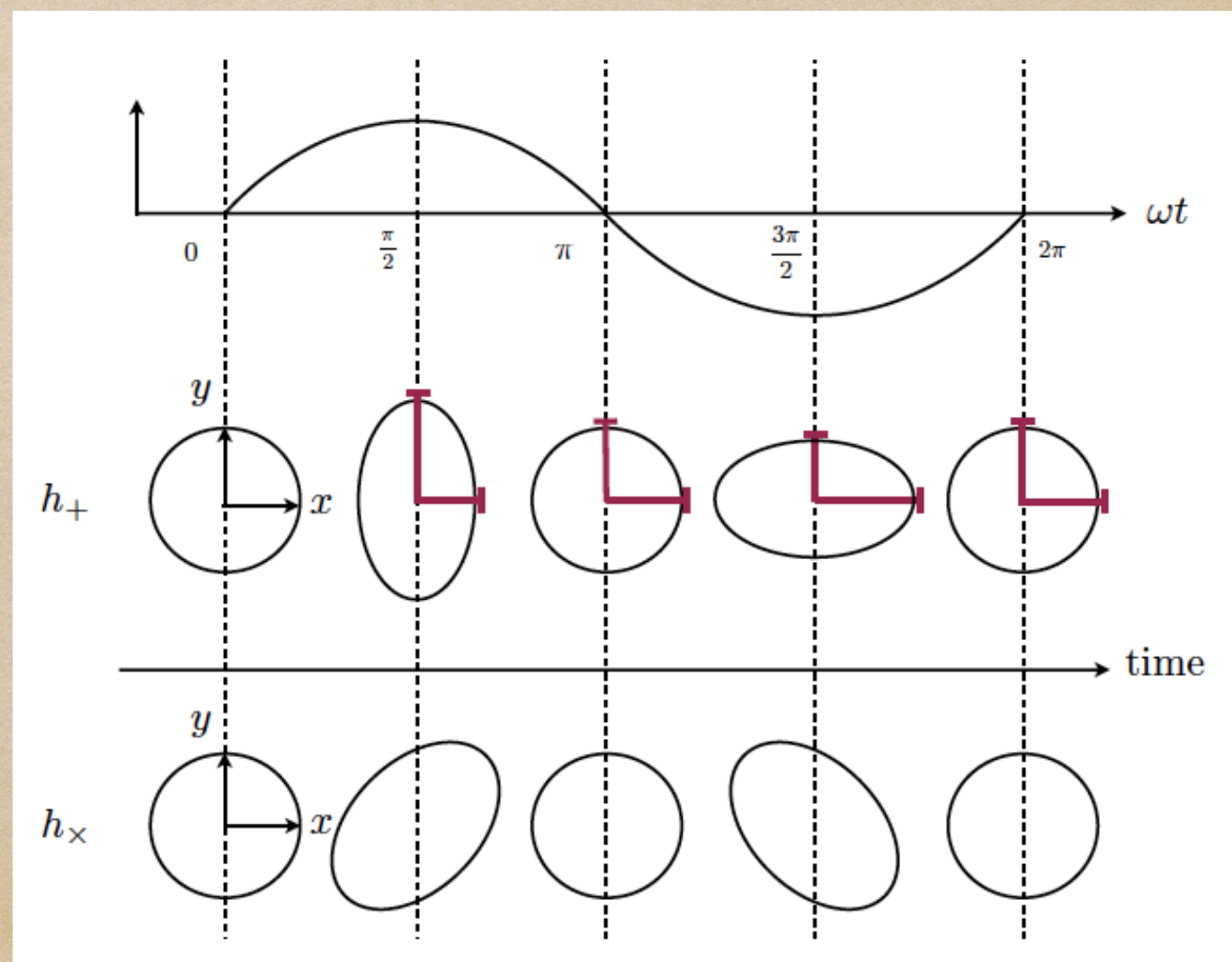
$$ds^2 = -dt^2 + (1 + h_+) dx^2 + (1 - h_+) dy^2 + 2h_\times dx dy + dz^2$$

- Effect on test particles:

Mirshekari 1308.5240

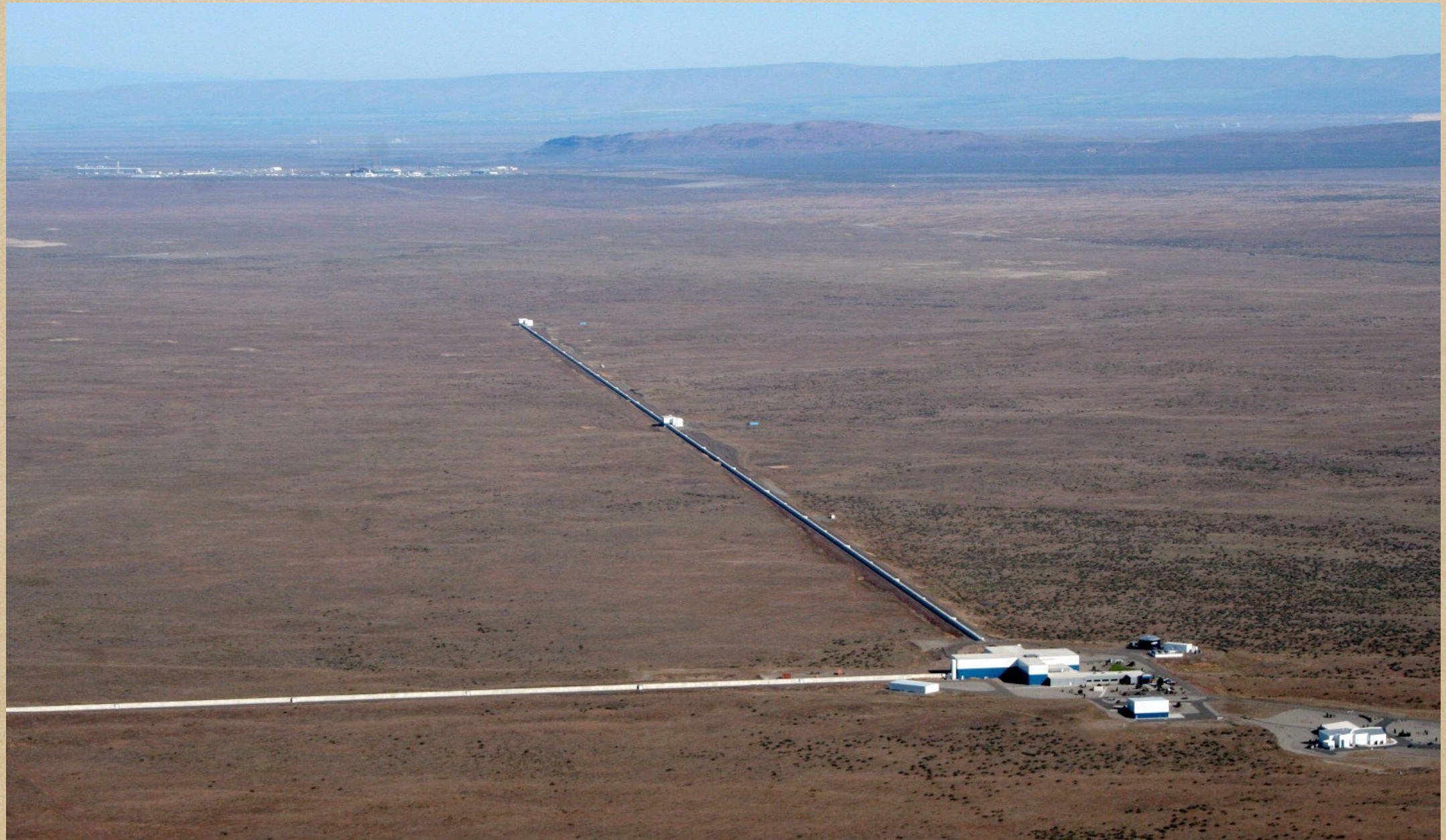
- Debate on physical reality until late 1950s

e.g. Saulson GRG (2011)

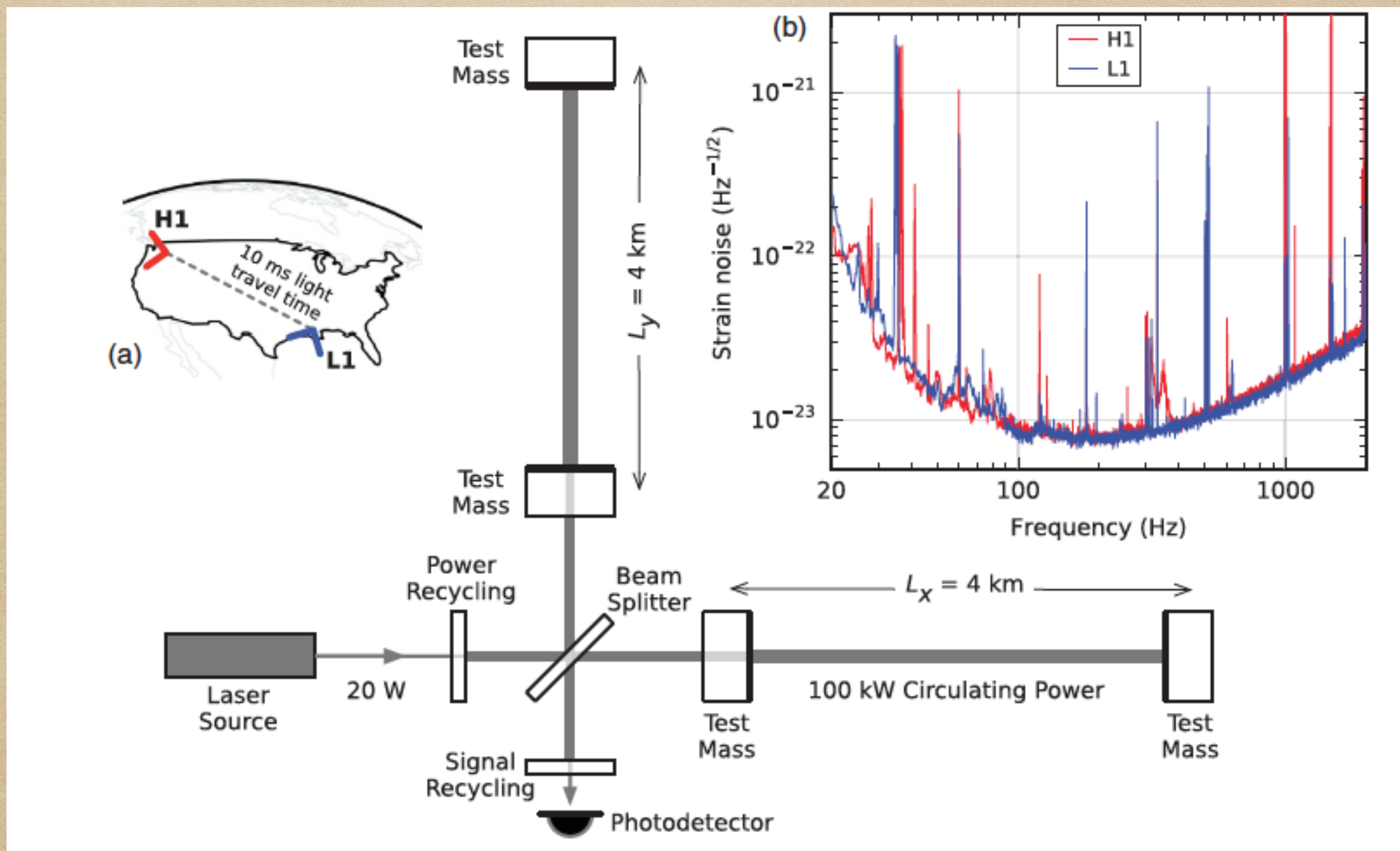


Effect on particles

- Measure this effect; Michelson-Morley type interferometer



The interferometer diagram: LIGO



Abbott et al, PRL 116 (2016) 061102

Seismic, thermal, shot noise

GW150914

- Sep 14, 2015 at 09:50:45 UTC: SNR ~ 24
Abbott et al. PRL 2016, Abbott et al. PRX 2016
- BBH inspiral, merger and ringdown: $m_1 = 35_{-3}^{+5} m_\odot$, $m_2 = 30_{-4}^{+3} M_\odot$

