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

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T Evstafyeva, M Agathos, I Romero-Shaw

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

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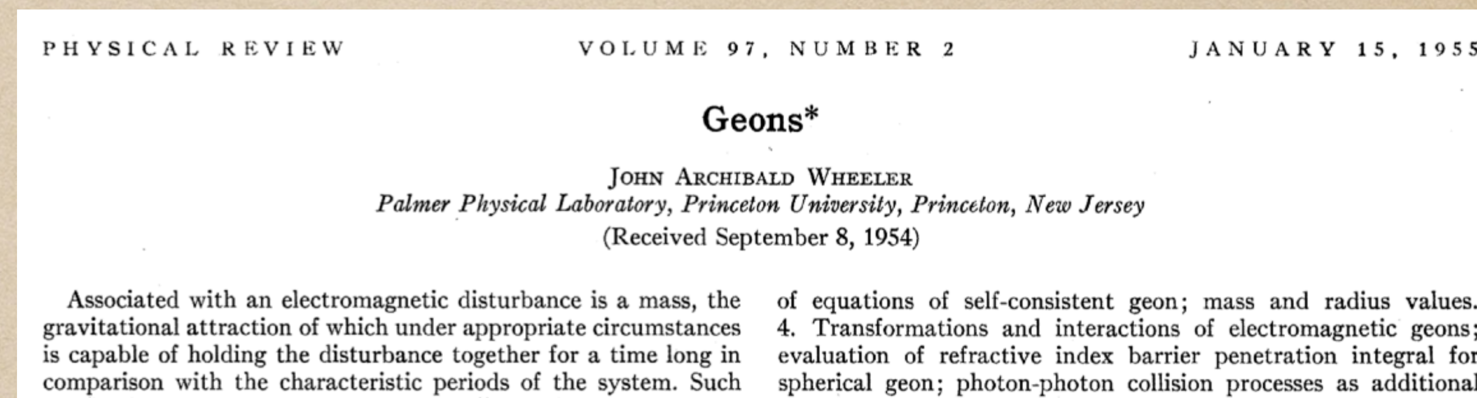
Federal University of Para, Belem *21 Nov 2024*

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 $\rightarrow$ Compact (equilibrium?) objects
- Geons are not equilibrium configurations
- Dark matter candidates: QCD axions, ALPs, dark photons,…
- Complex fields (scalar, vector,…)

  $\rightarrow$ Genuine equilibrium states; $T_{\alpha\beta}$ stationary!
- First shown for scalar fields $\rightarrow$ “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) $\rightarrow$ 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

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

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

- Potential; analogous to EOS:

$$V_{\min}(\varphi) = m^2 |\varphi|^2 , \qquad V_{\text{soli}}(\varphi) = m^2 |\varphi|^2 \left(1 - 2\frac{|\varphi|^2}{\sigma_0^2}\right)^2 , \qquad \text{or} \ldots$$

- Spherically symmetric equilibrium models

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

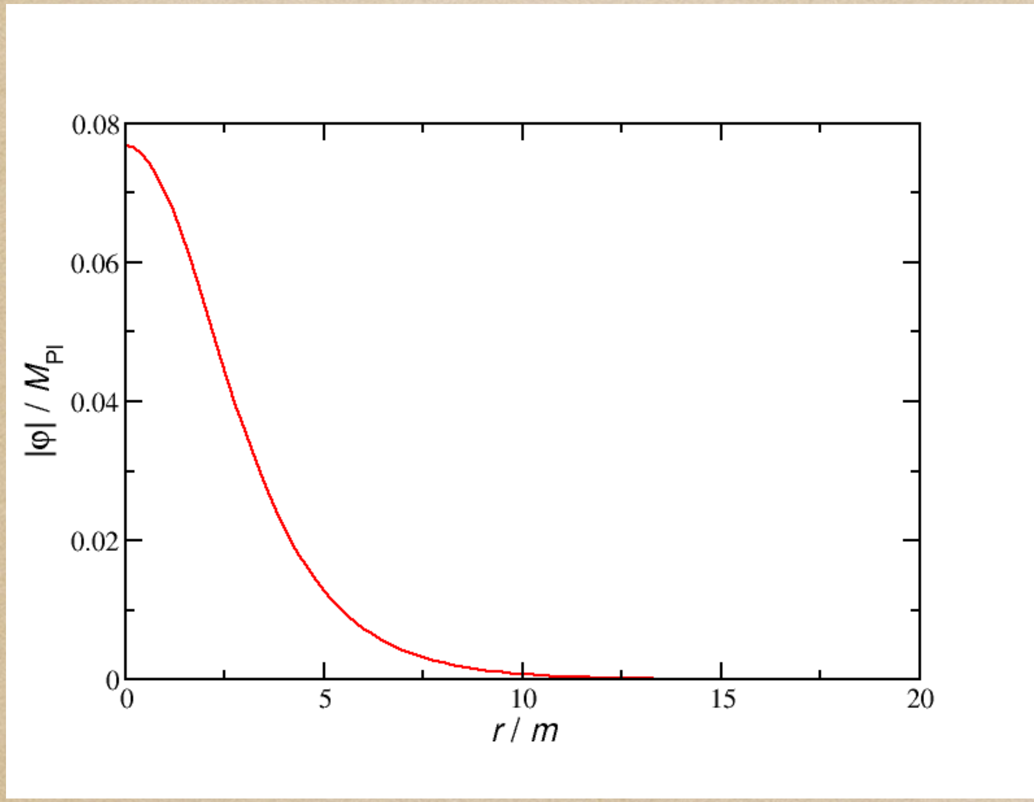
Regular solutions only for countably infinite values

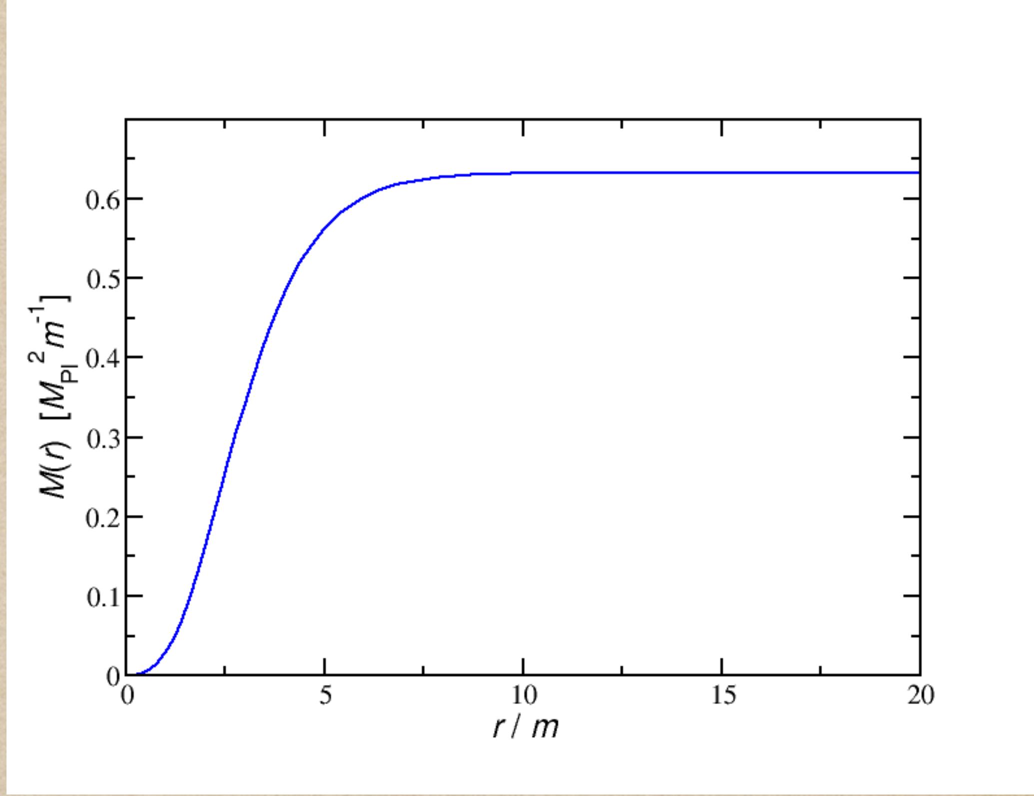
$\omega_0 < \omega_1 < \omega_2 < \ldots$ (ground state, excited states)

Formalism and basic features

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

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





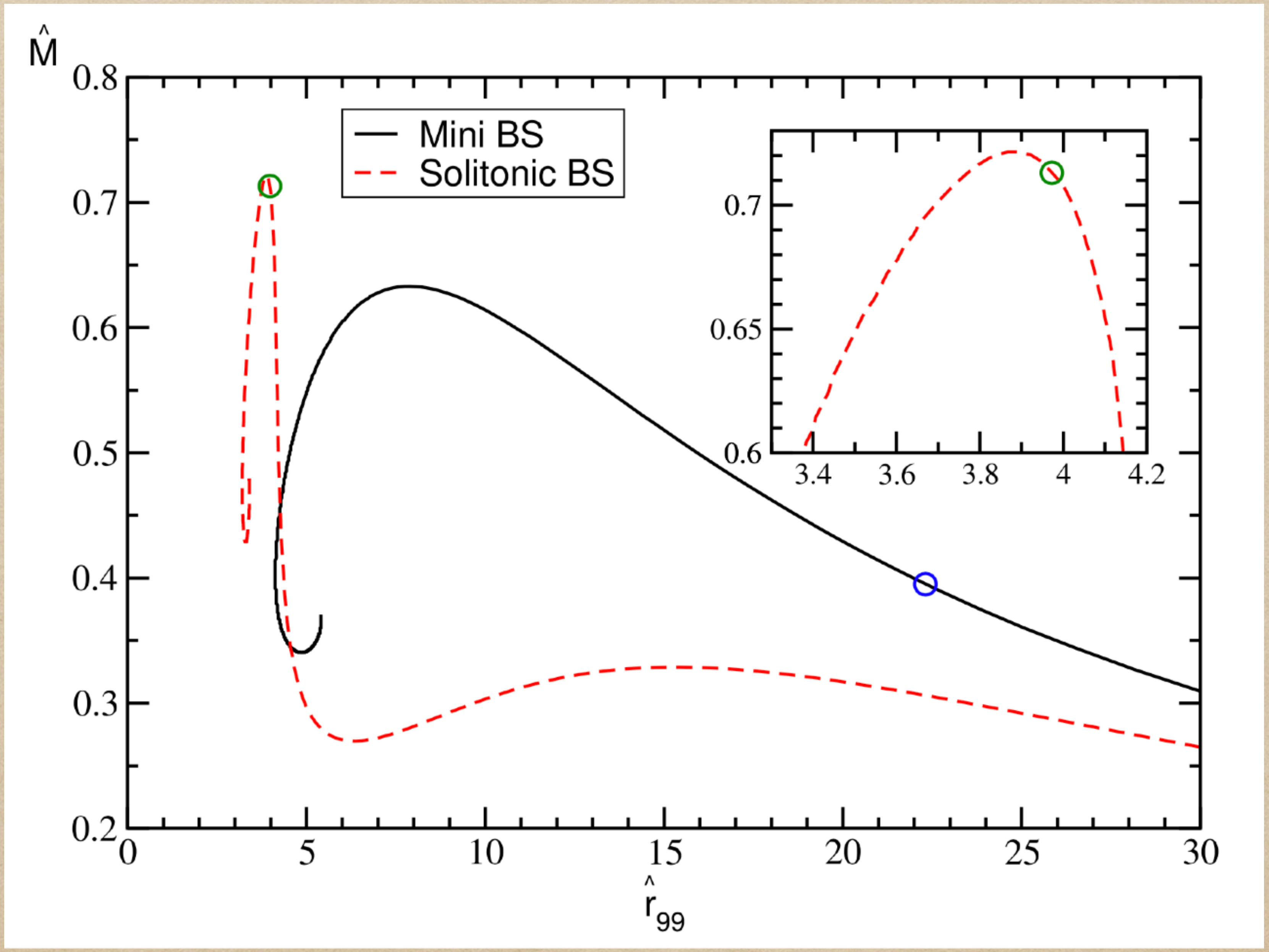
- Excited states unstable:

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

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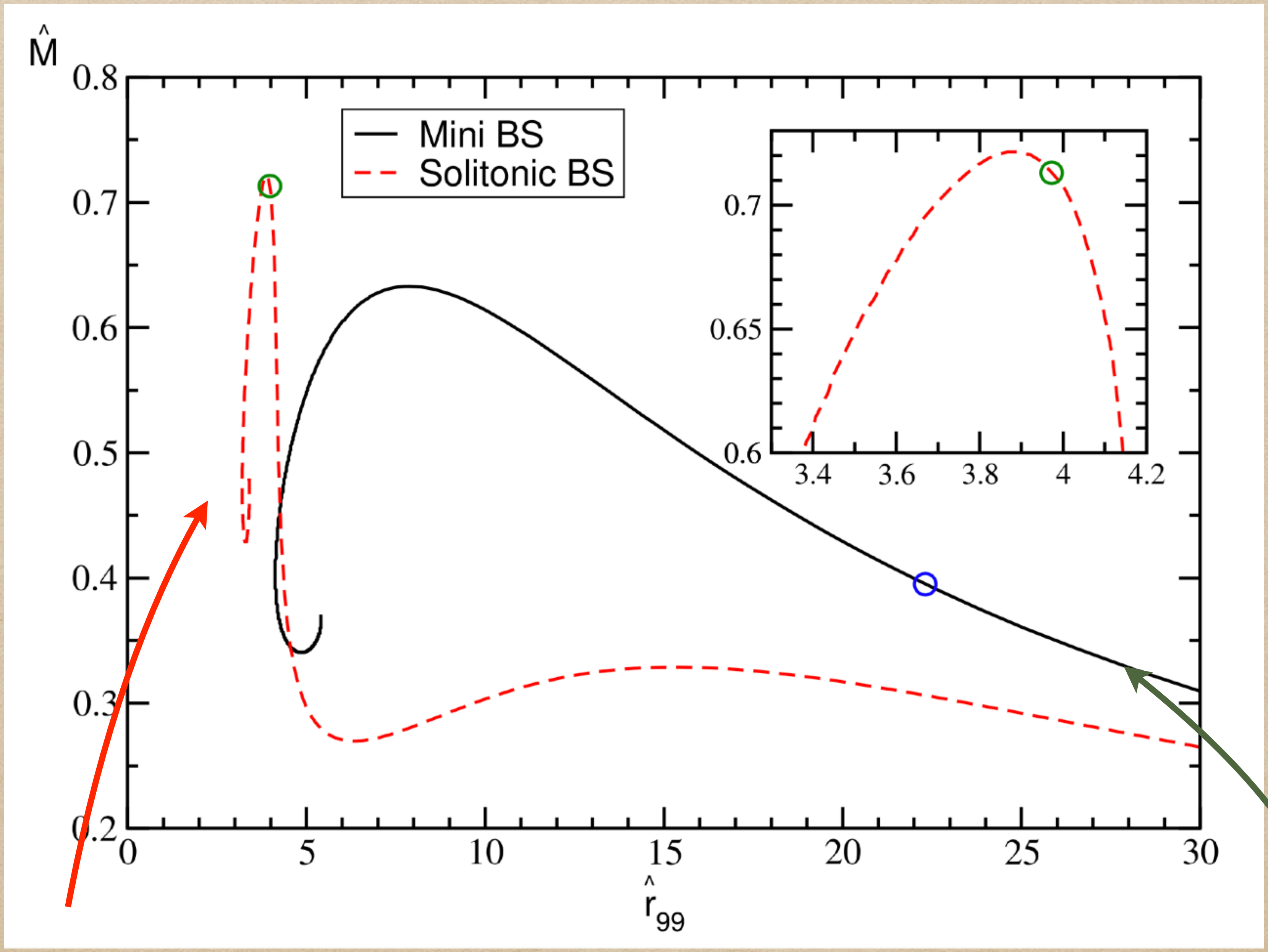


unstable

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?

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 $\longrightarrow$ Posterior

Boson-star binaries: parameters

- 8+1 Intrinsic parameters as for black holes

  Masses m_1 , m_2

  Spins $\boldsymbol{S}_1$, $\boldsymbol{S}_2$

  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

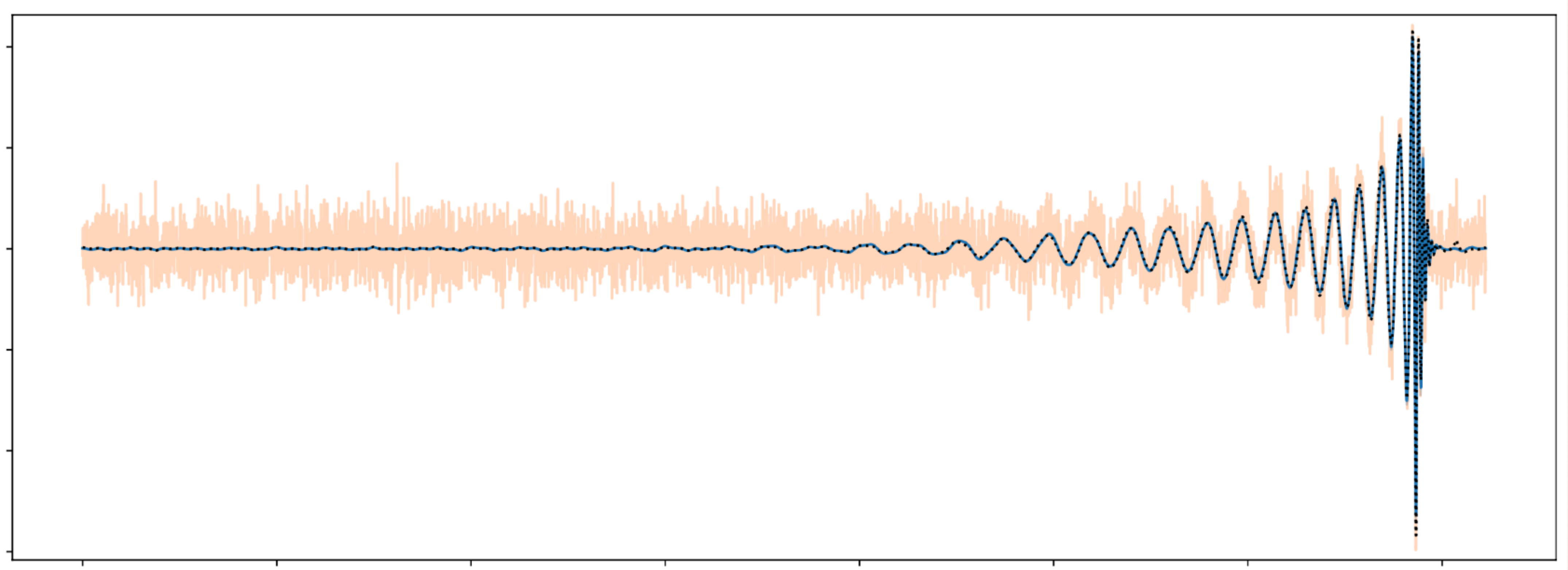
  Time t_c and Phase ϕ_c of coalescence

- 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 $10^{-11}\dots 10^{-20}\,\mathrm{eV}$
- 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

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

$\Rightarrow$ Einstein-Klein-Gordon equations

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

Alic et al 2012

- Use two numerical relativity codes

GRChombo Radia et al 2021

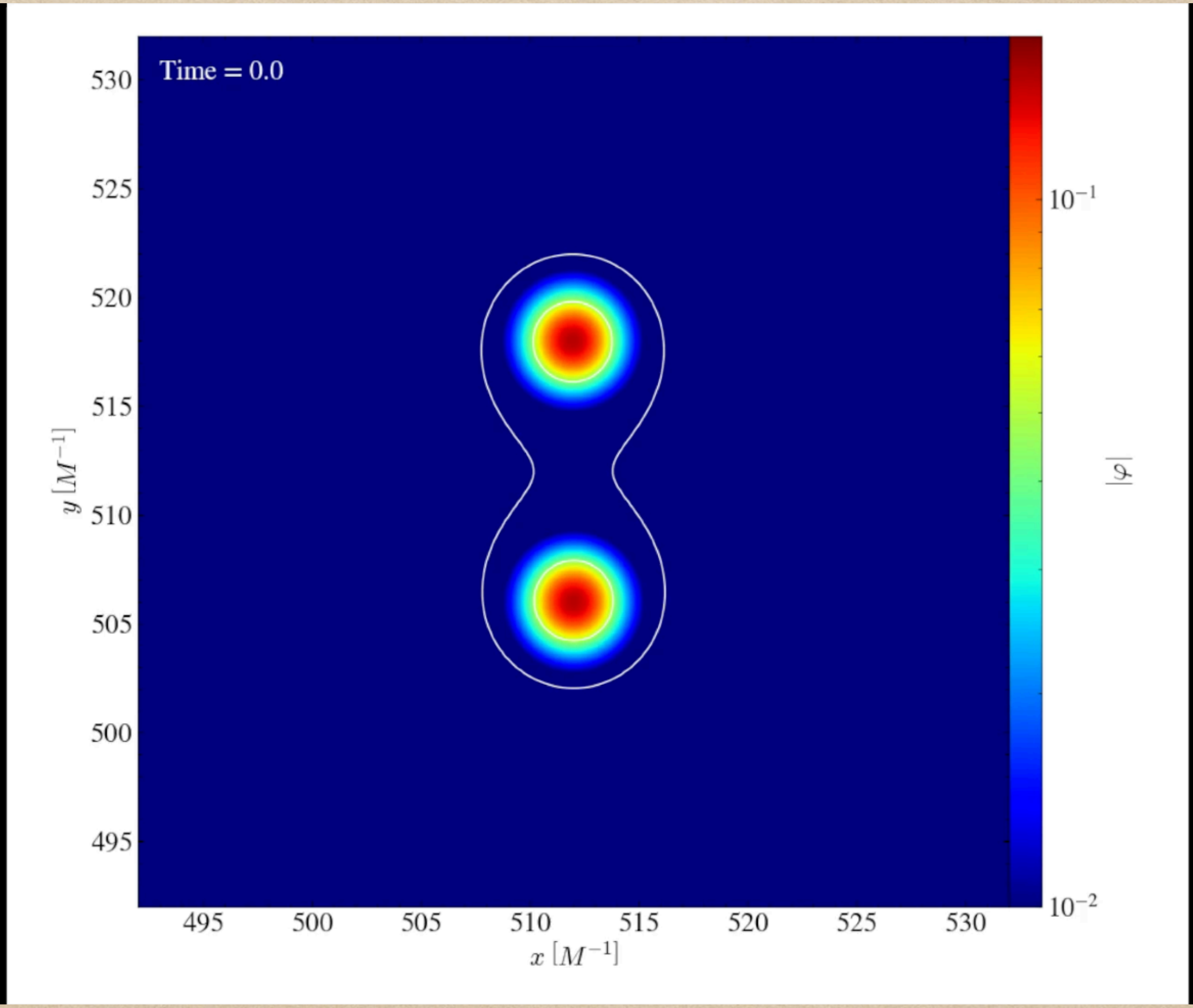
Lean US 2006

- Technical details:

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

3. Results

Example boson-star inspiral



Courtesy of T Evstafyeva

BS binaries

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

Characterized by

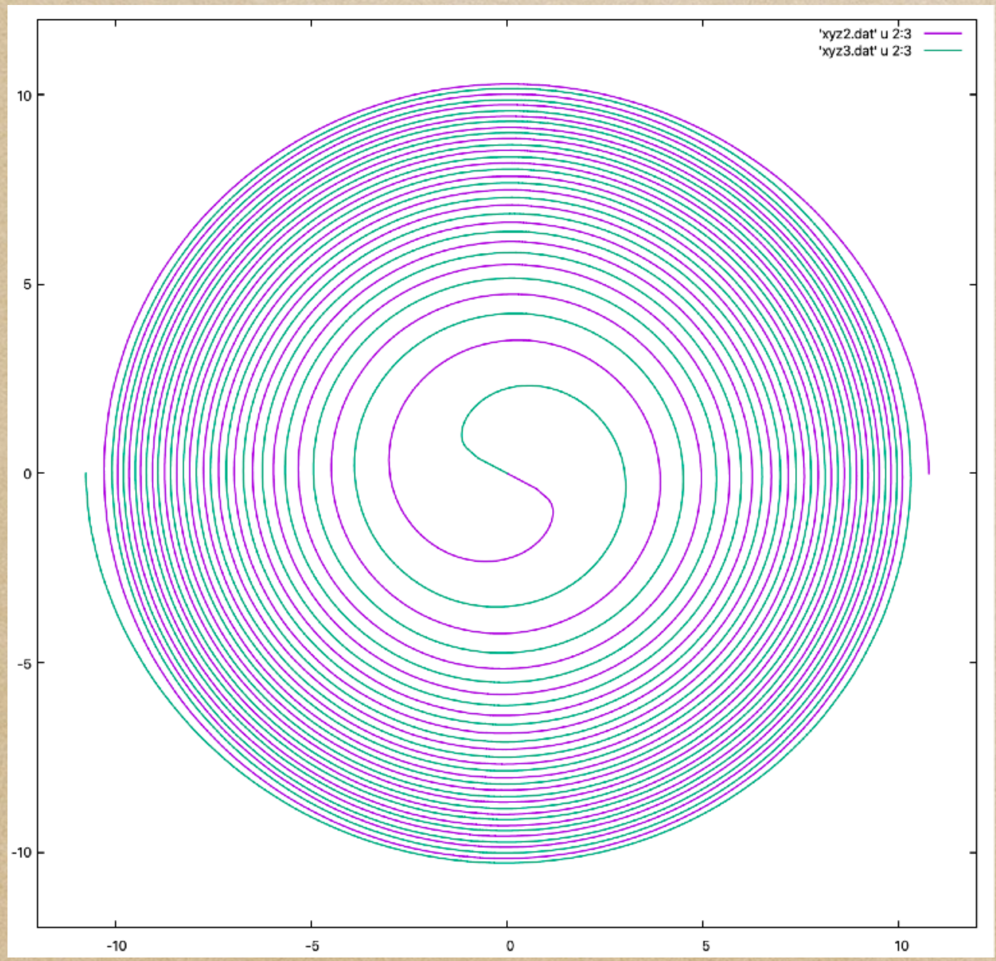
- Quasi-circular, non-spinning, equal-mass: $e \approx 0,\ \boldsymbol{S}_{1,2} = 0,\ q = 1$
- Number of orbits N
- Compactness 0.1 or 0.2
- Scalar dephasing $\delta\phi \in [0,\pi]$
- BS-BS or BS-anti BS binary?
- Total mass: Any by trivial rescaling of the scalar mass

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

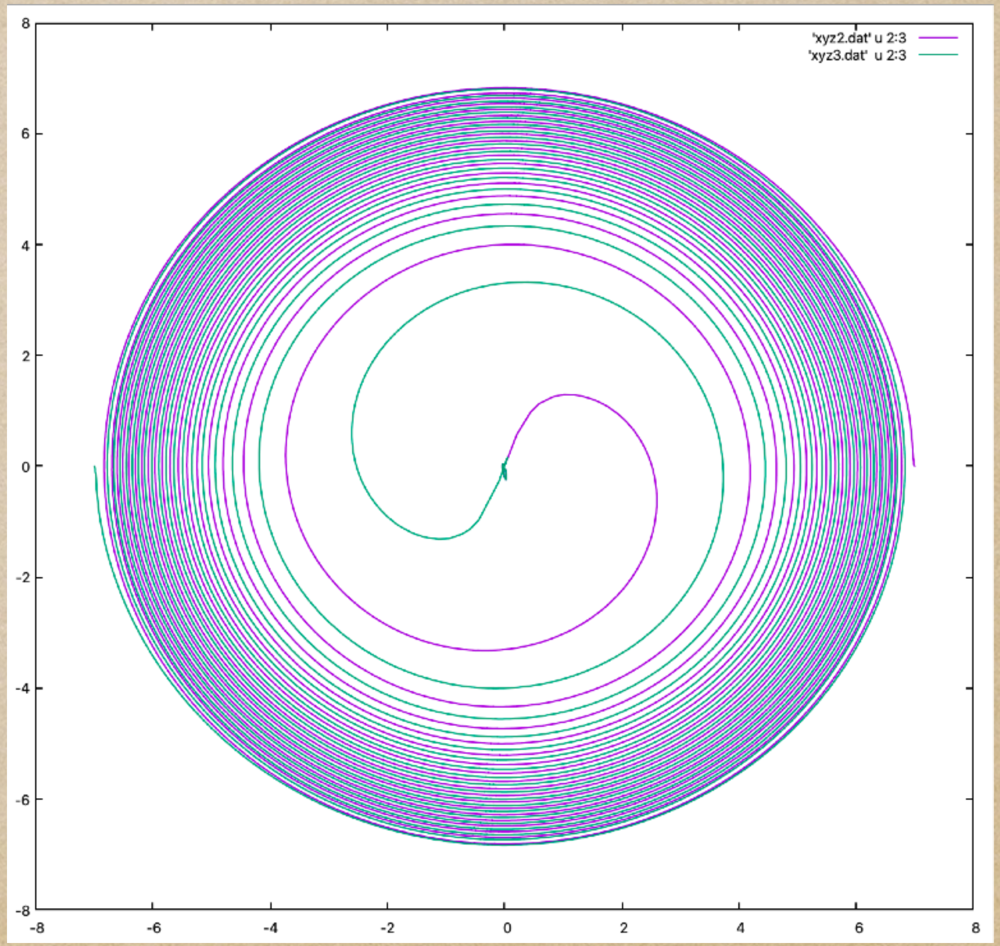
BS binaries

- Phase error $\approx 0.1 \;\ldots\; 0.2$
- Amplitude error $\lesssim 3\,\%$
- Eccentricity $\approx 0.002\ldots0.005$

A17-d14

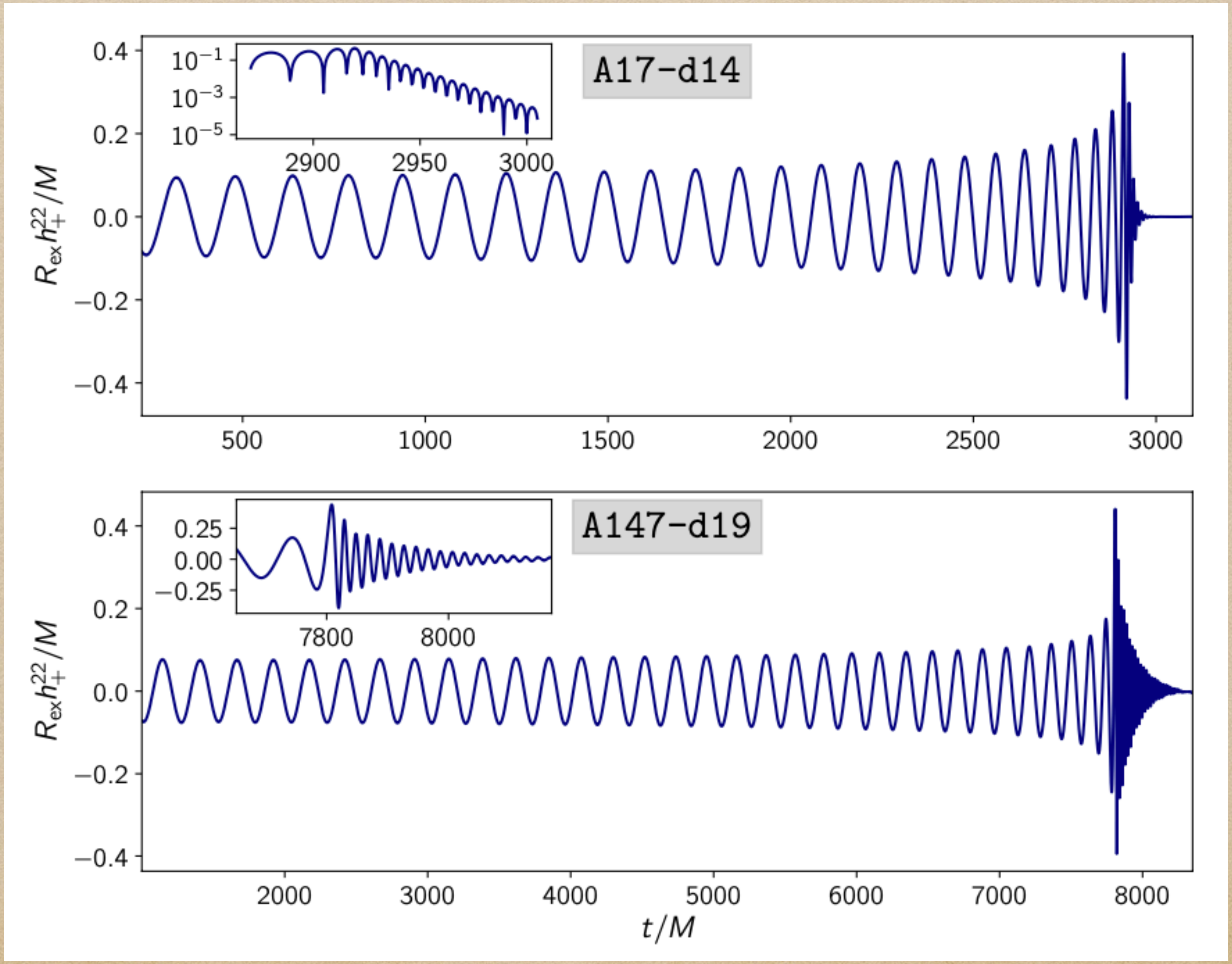


A147-d19



BS binaries

- GW strain from compact and fluffy BSs



Waveform approximants

- Parameter estimation performed with `Bilby` Ashton et al 2019
- `IMRPhenomXP`: Frequency domain Pratton 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

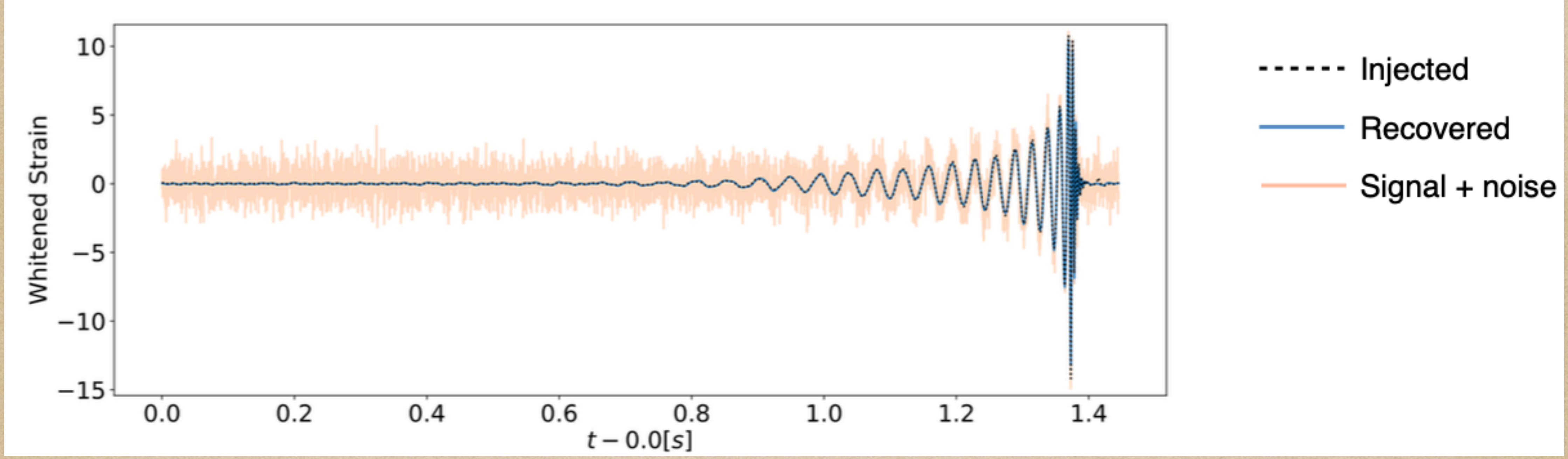
- 2 Approaches: (1) Allow spins to vary in the analysis

  (2) Spins fixed to zero throughout analysis

- Main diagnostics:
  - Recovered masses, spins
  - Recovered SNR, Log Bayes factor
  - Test residual for Gaussianity

Compact BSs using IMRPhenomXP

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



- Recovered: $M_1 = 37.8 \pm 1.1\,M_\odot,\, M_2 = 25.4 \pm 1.2\,M_\odot,\, d_L = 236 \pm 20\,{\rm Mpc},$

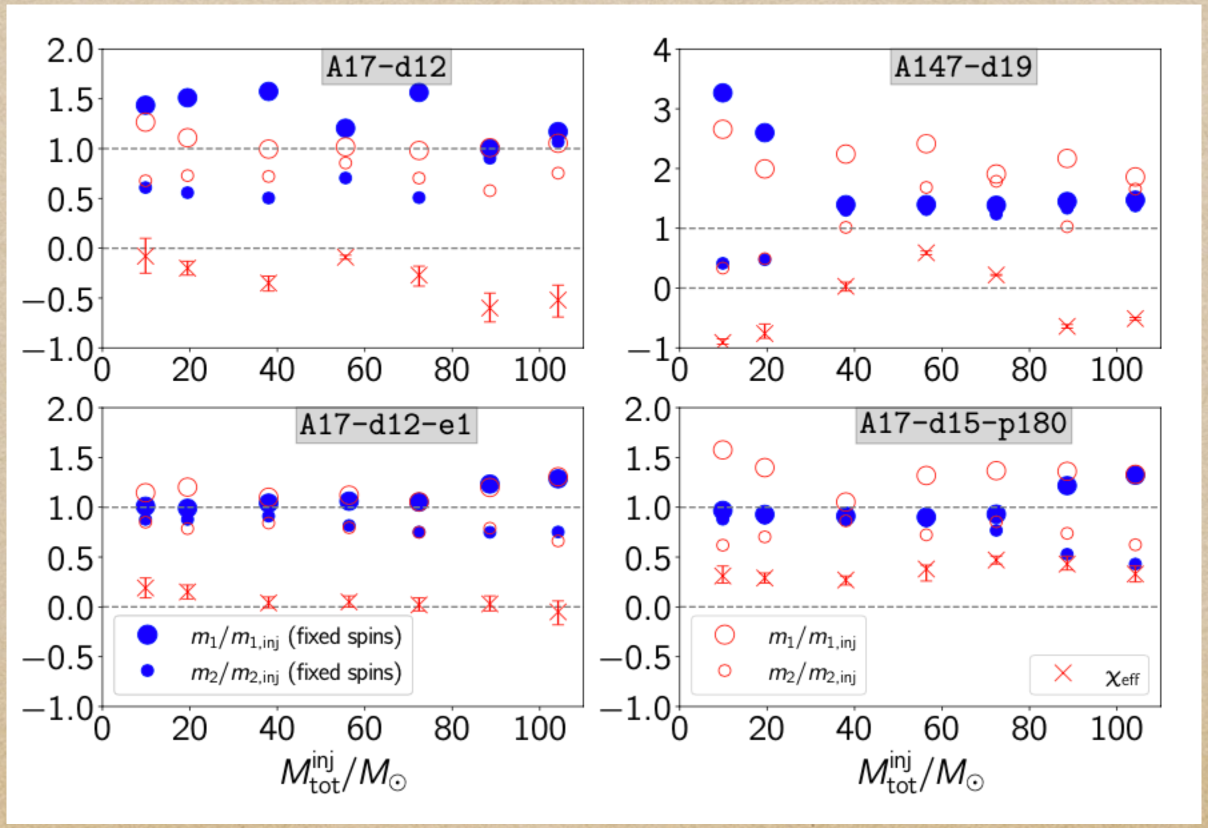
  $a_1 \approx 0.95,\, a_2 \approx 0.15$

  Recovered SNR $\approx$ injected SNR

  $\log \mathscr{B}^{\rm S}_{\rm N} = 5392$
- 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



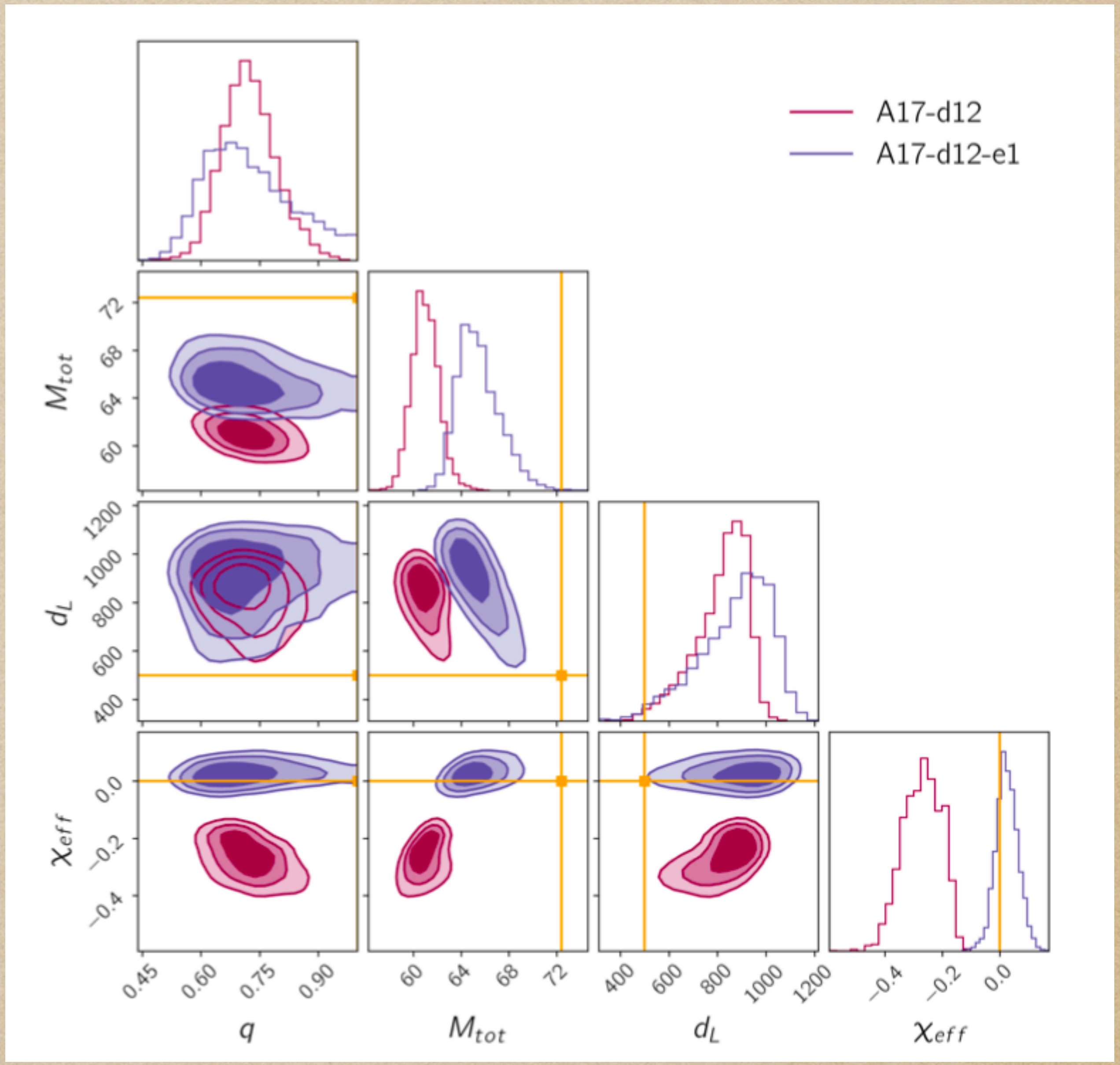
Results using IMRPhenomXP

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

  Corner plot:

  A17-d12-e1 vs. A17-d12

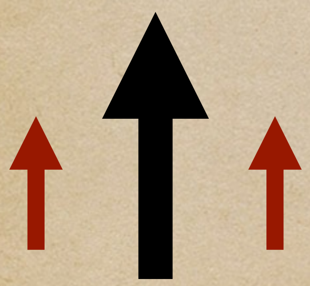
- These features can be explained with the chirp strength

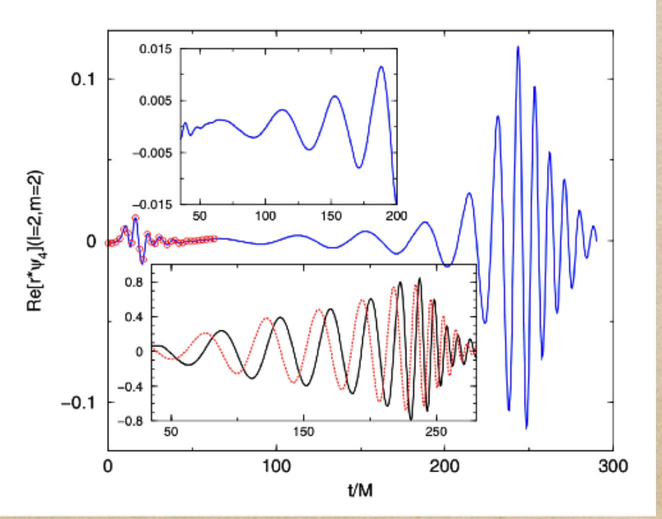


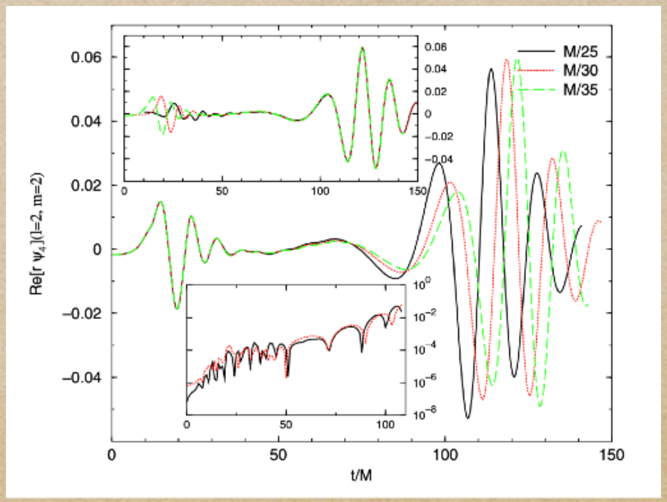
Understanding the PE bias

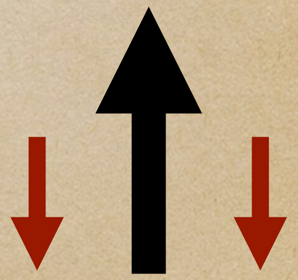
- Main feature: Steepness of chirp
- For non-spinning BH binaries:
  - equal mass ⇒ shallow chirp
  - unequal masses ⇒ steep chirp (think of EMRIs)
- For spinning BH binaries:
  - aligned spins ⇒ shallow chirp
  - anti-aligned spins ⇒ steep chirp

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







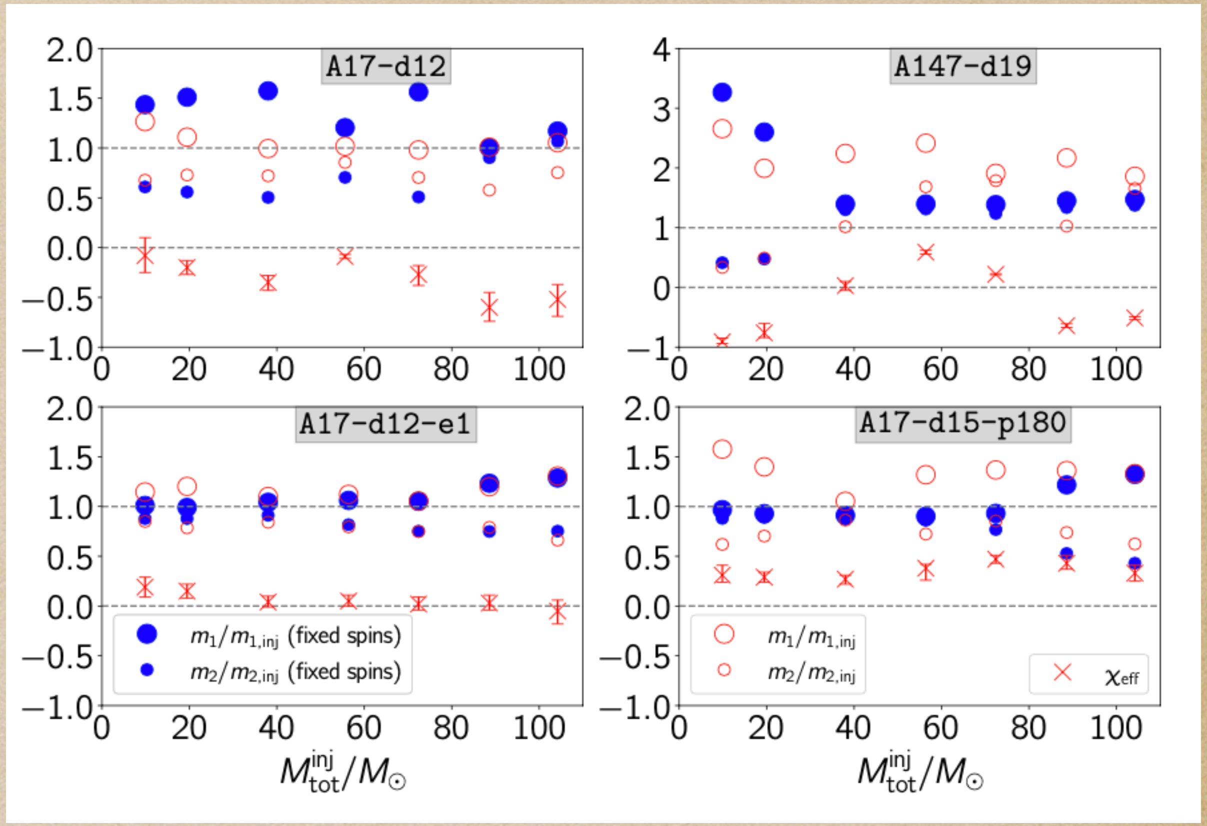


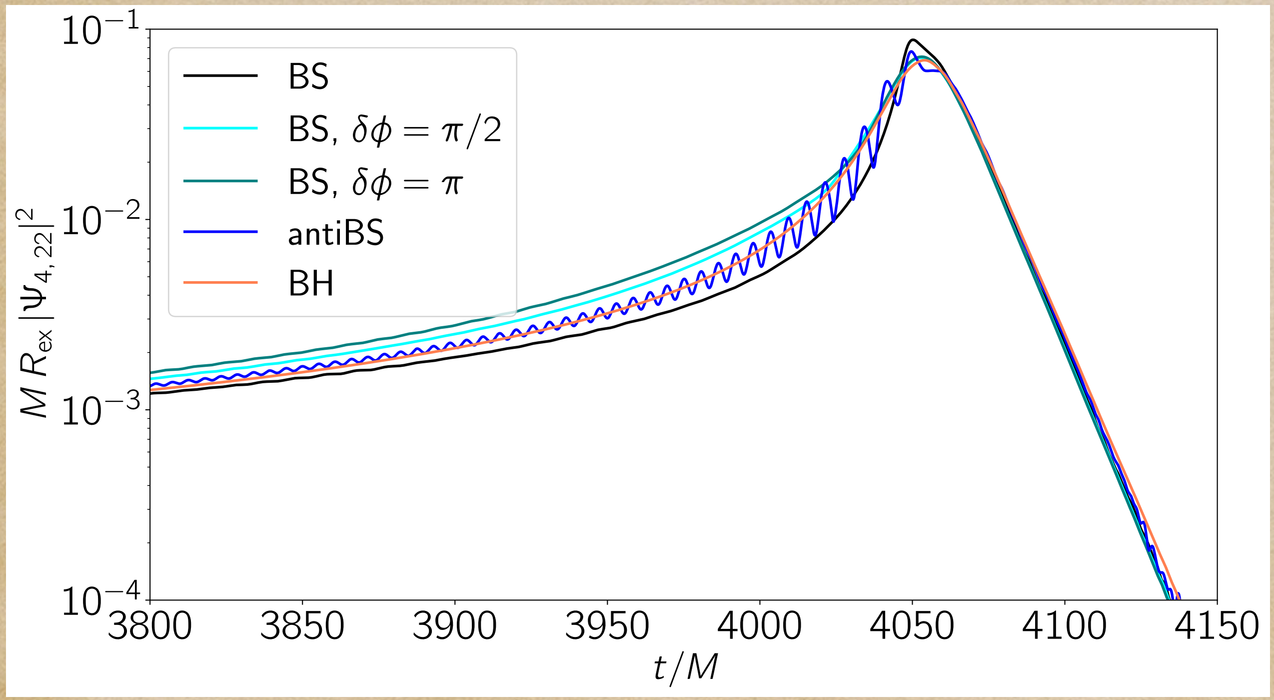
Understanding the PE bias

- PE bias

  vs

- Chirp steepness





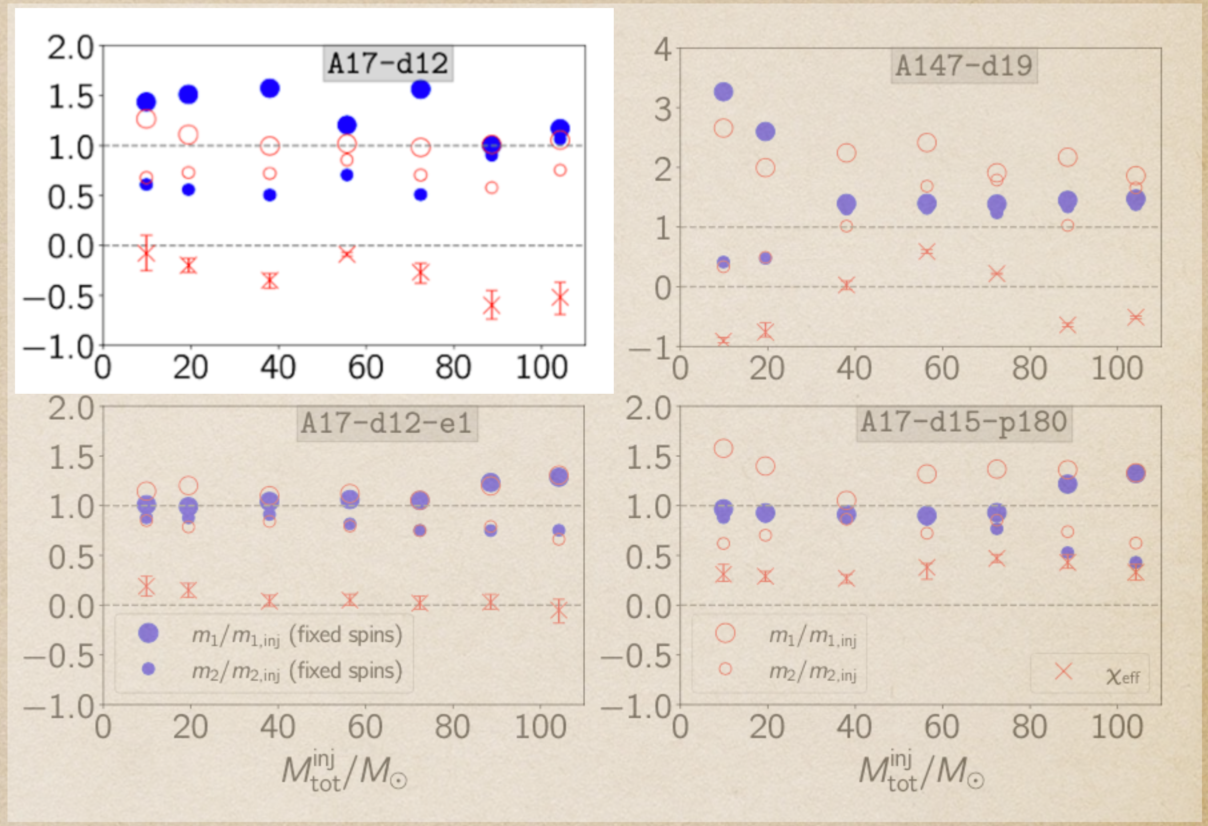
Understanding the PE bias: Standard BS

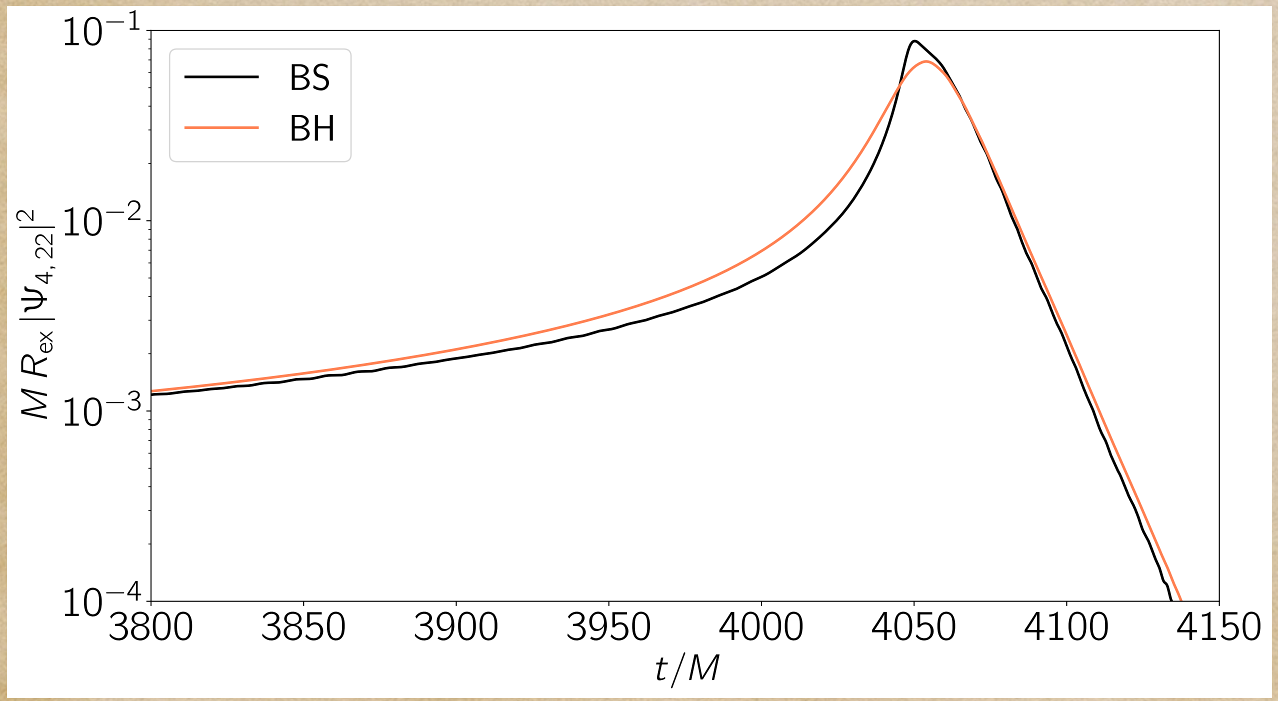
<u>Fixed spins</u>

BS chirp steeper

⇒ Like unequal-mass BHs

⇒ Bilby reports unequal masses





<u>Variable spins</u>

anti-aligned spins

⇒ Steeper chirp

⇒ Steep BS chirp also captured by anti-aligned spins

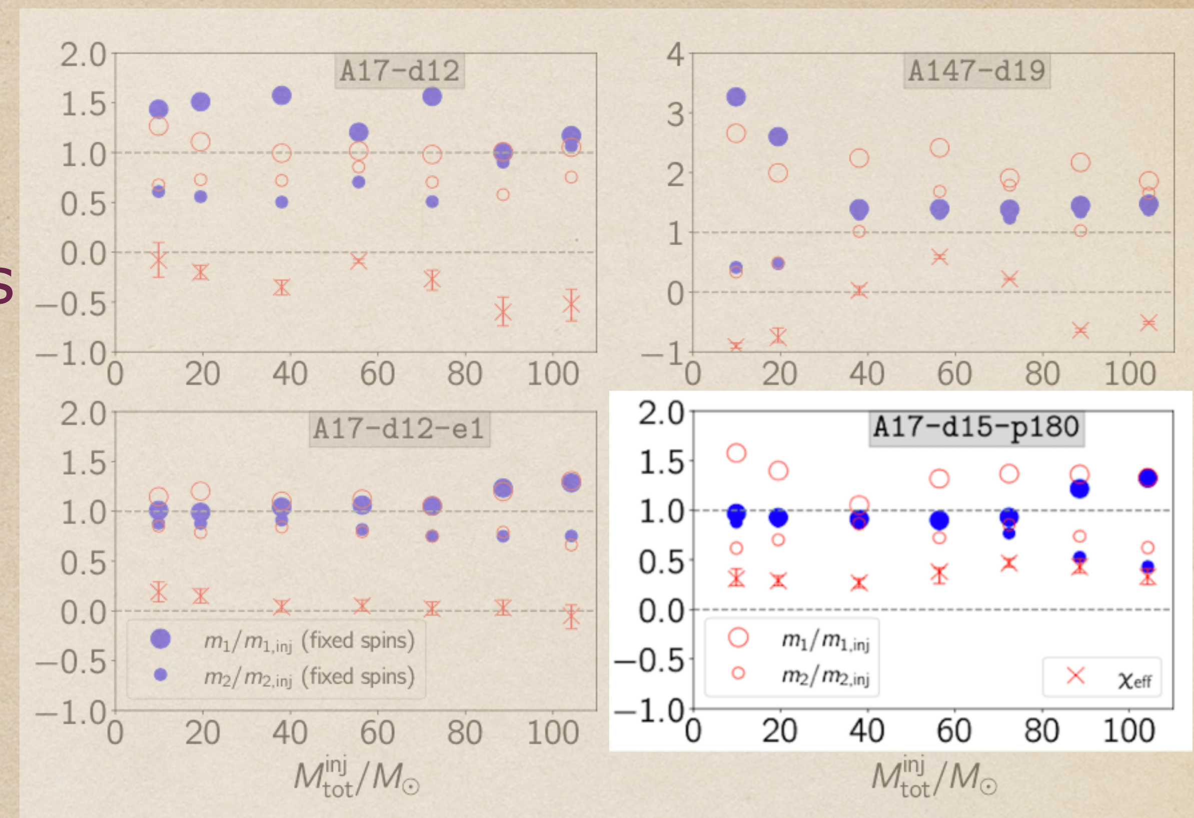
Understanding the PE bias: anti-phase

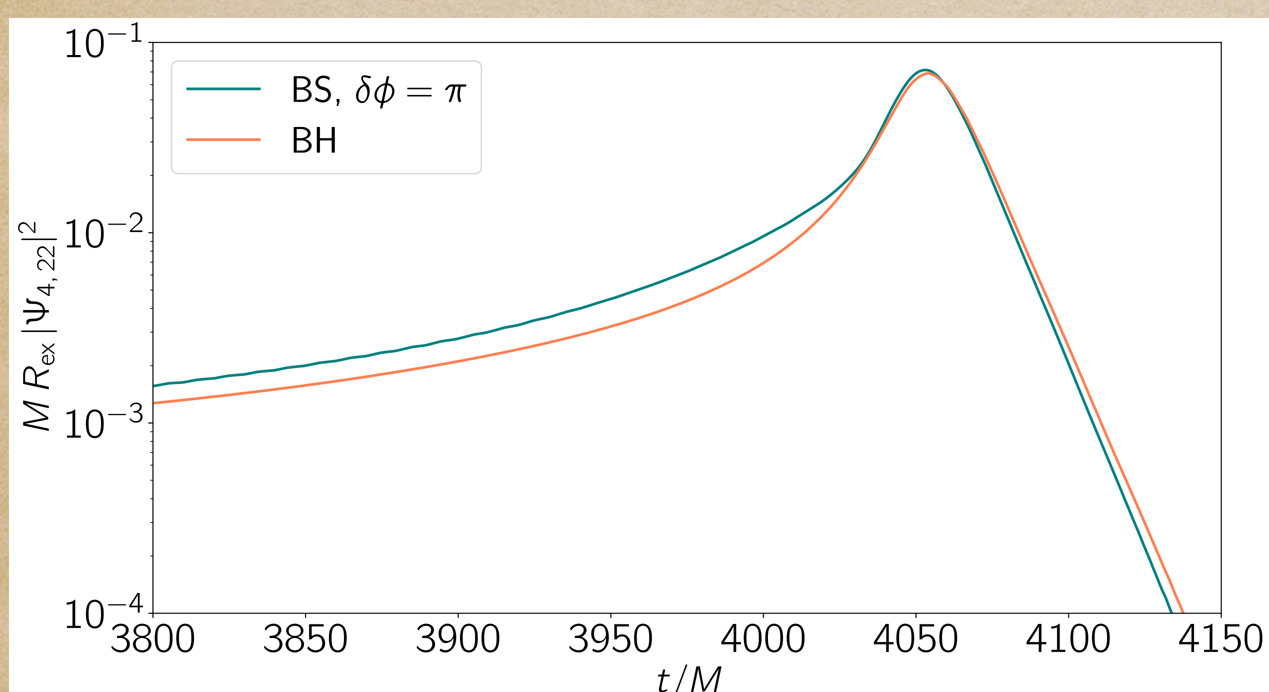
<u>Fixed spins</u>

BS chirp shallower

⇒ Best matched by ~equal mass BHs

⇒ Bilby reports ~equal masses





<u>Variable spins</u>

aligned spins

⇒ Shallow chirp

⇒ Bilby reports aligned spins and allows unequal masses

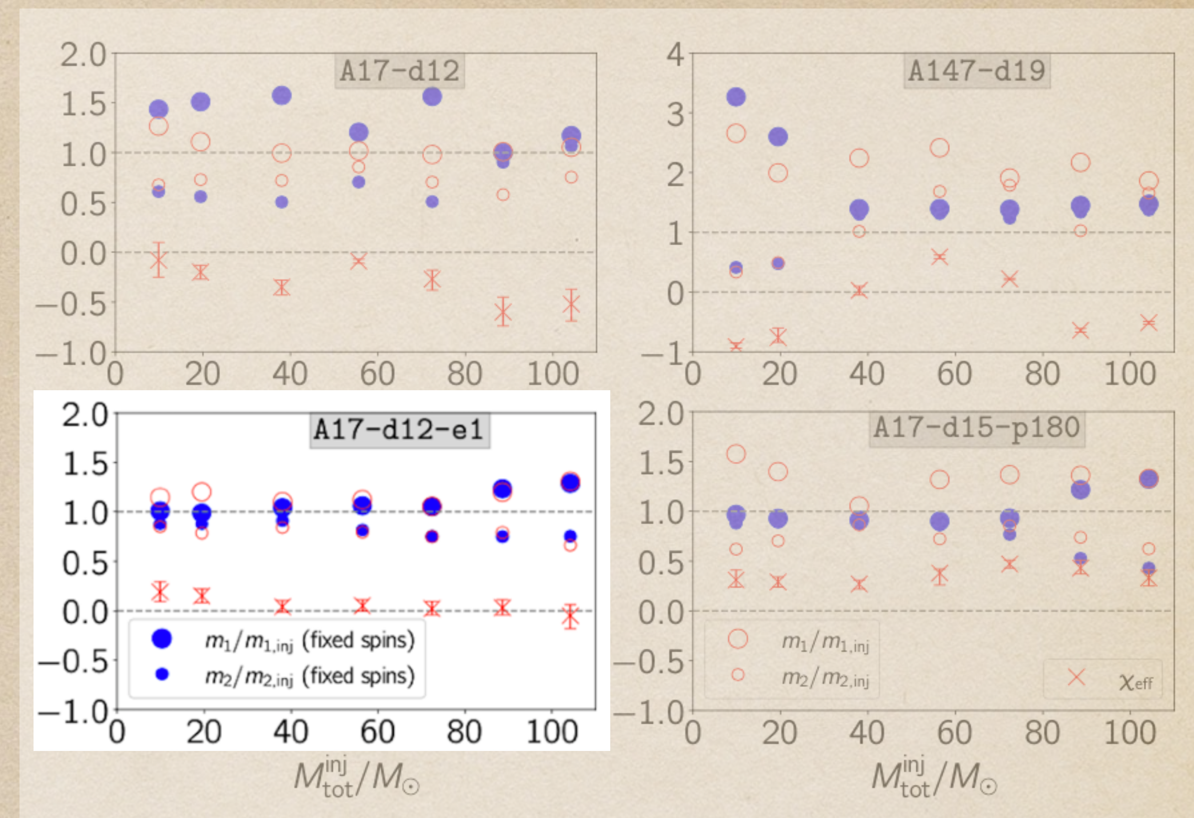
Understanding the PE bias: anti-BS

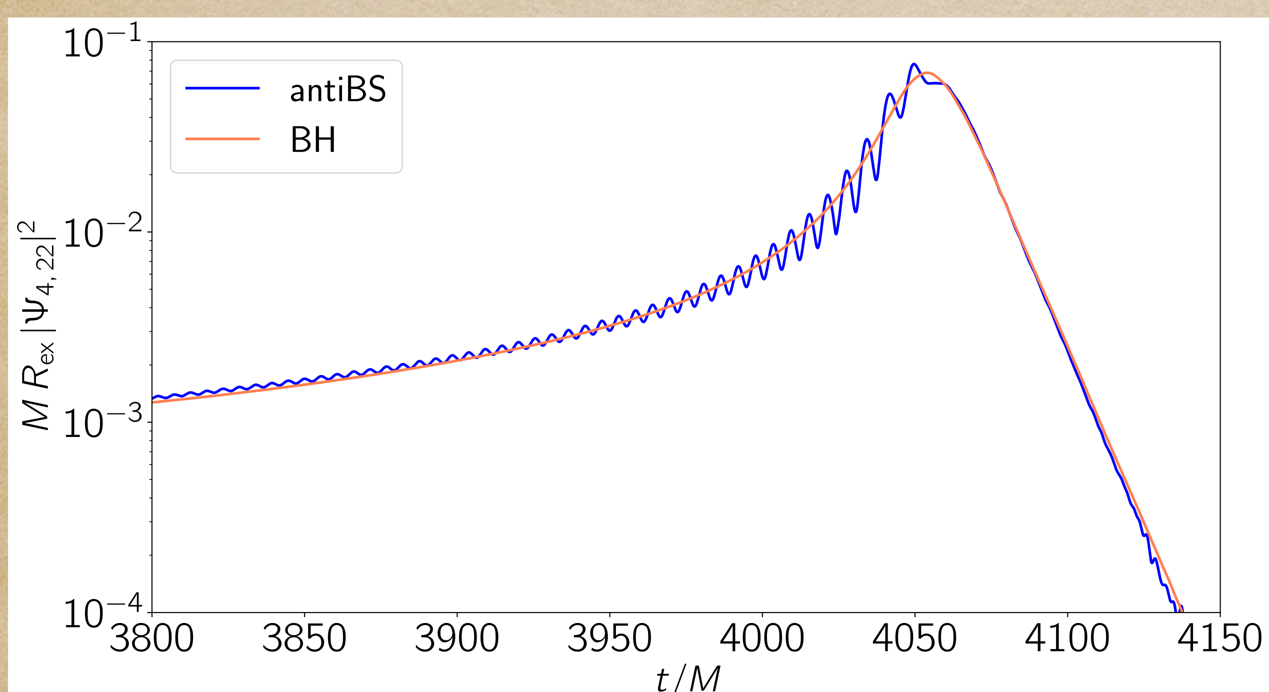
Fixed or variable spins

BS chirp similar to BHs

⇒ Comparable mass ratios

∧ Small spins





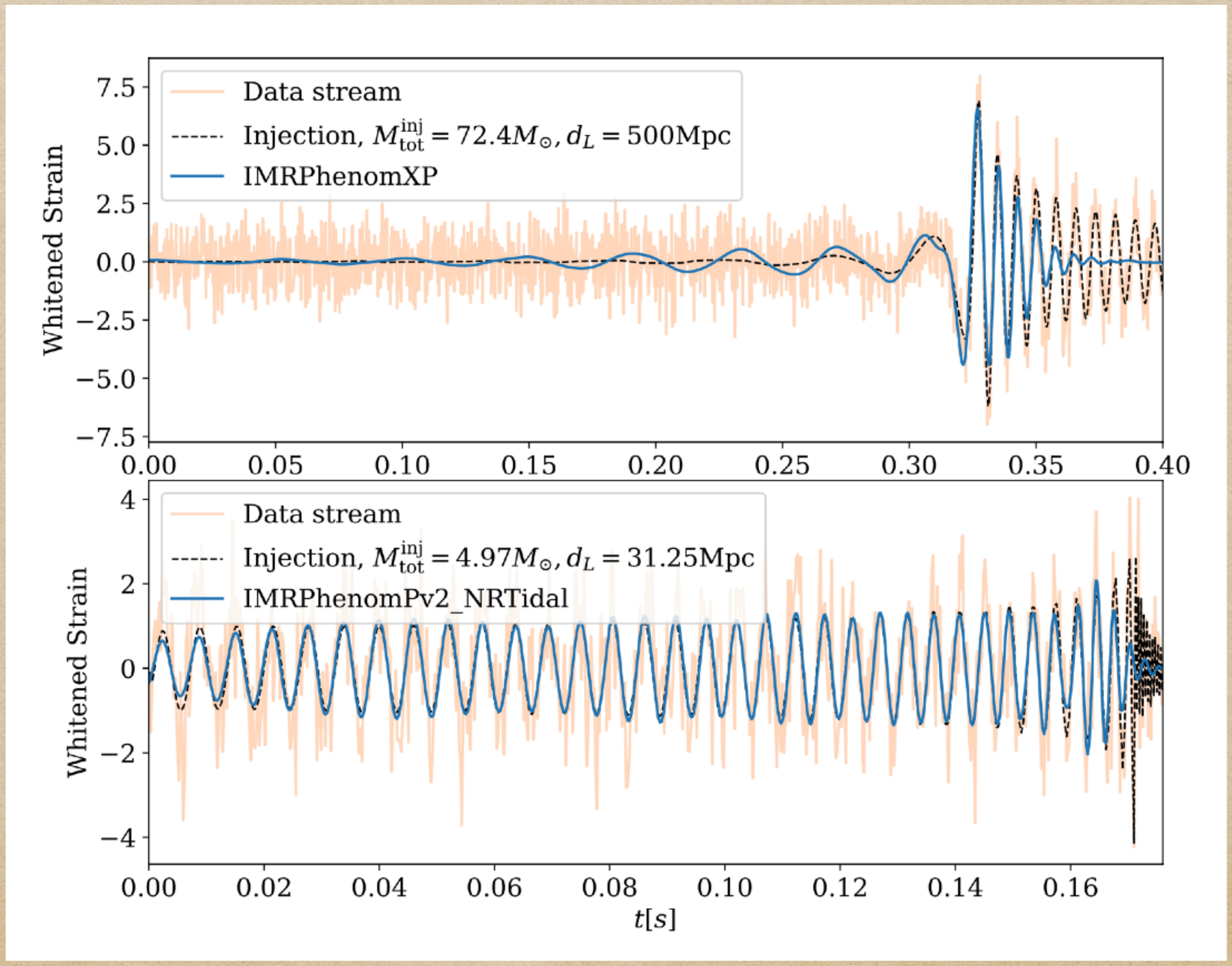
High-mass regime

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



Conclusions

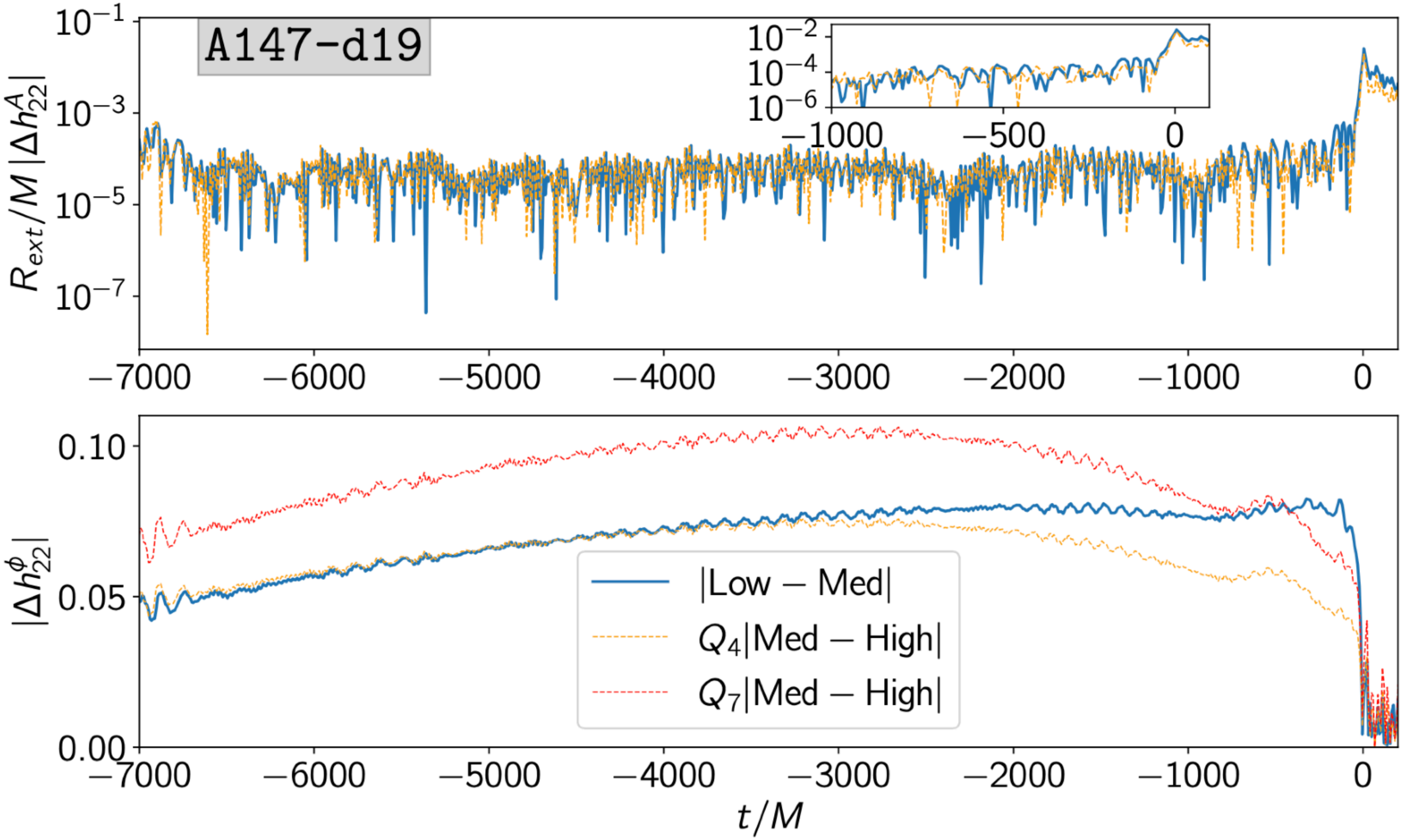
- NR simulations of BS binaries about as accurate as for BHs
- BS binaries recovered well with BH approximants → degeneracy
- But systematic bias in parameter estimation
- Compact BBSs “look” very similar to BBHs
- Fluffy BBSs have more characteristic signatures

Next Challenges

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

4. Extra slides

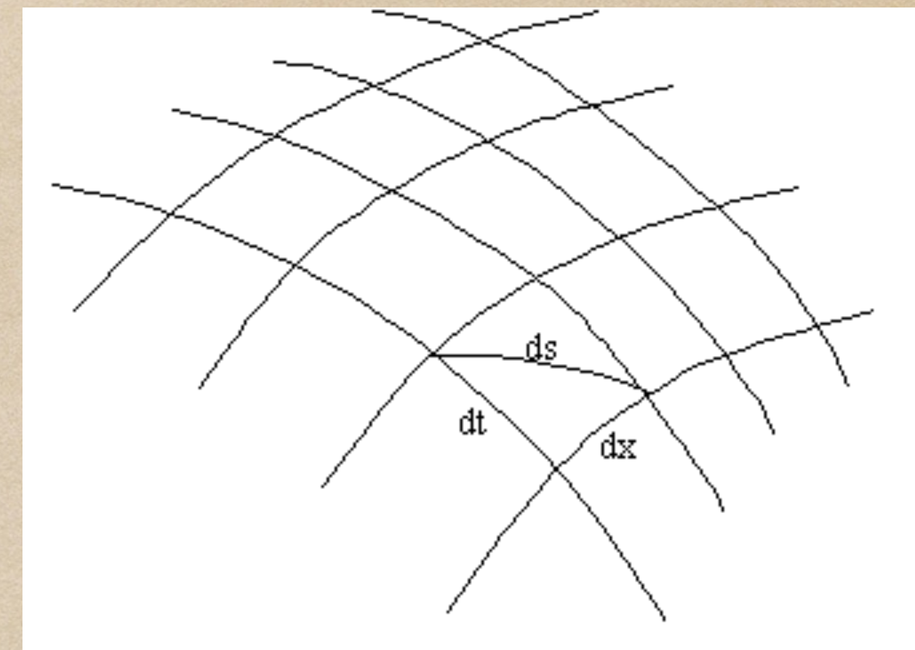
Convergence



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 $\mathcal{M} = \mathbb{R}^4, \quad \eta_{\mu\nu} = \mathrm{diag}(-1, 1, 1, 1)$
- "Perturbation": $h_{\mu\nu} = \mathcal{O}(\epsilon) \ll 1 \quad \Rightarrow \quad g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$
- Coordinate freedom: "Transverse-traceless (TT)" gauge

$$h^\mu{}_\mu = 0, \quad \partial^\nu h_{\mu\nu} = 0$$

- Vacuum, no cosmological constant: $T_{\mu\nu} = 0, \quad \Lambda = 0$
- Einstein's eqs.: $\Box h_{\mu\nu} = 0$
- Plane wave solution in z direction: $h_{\mu\nu} = H_{\mu\nu} e^{i k_\sigma x^\sigma}$

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

Effect on particles

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

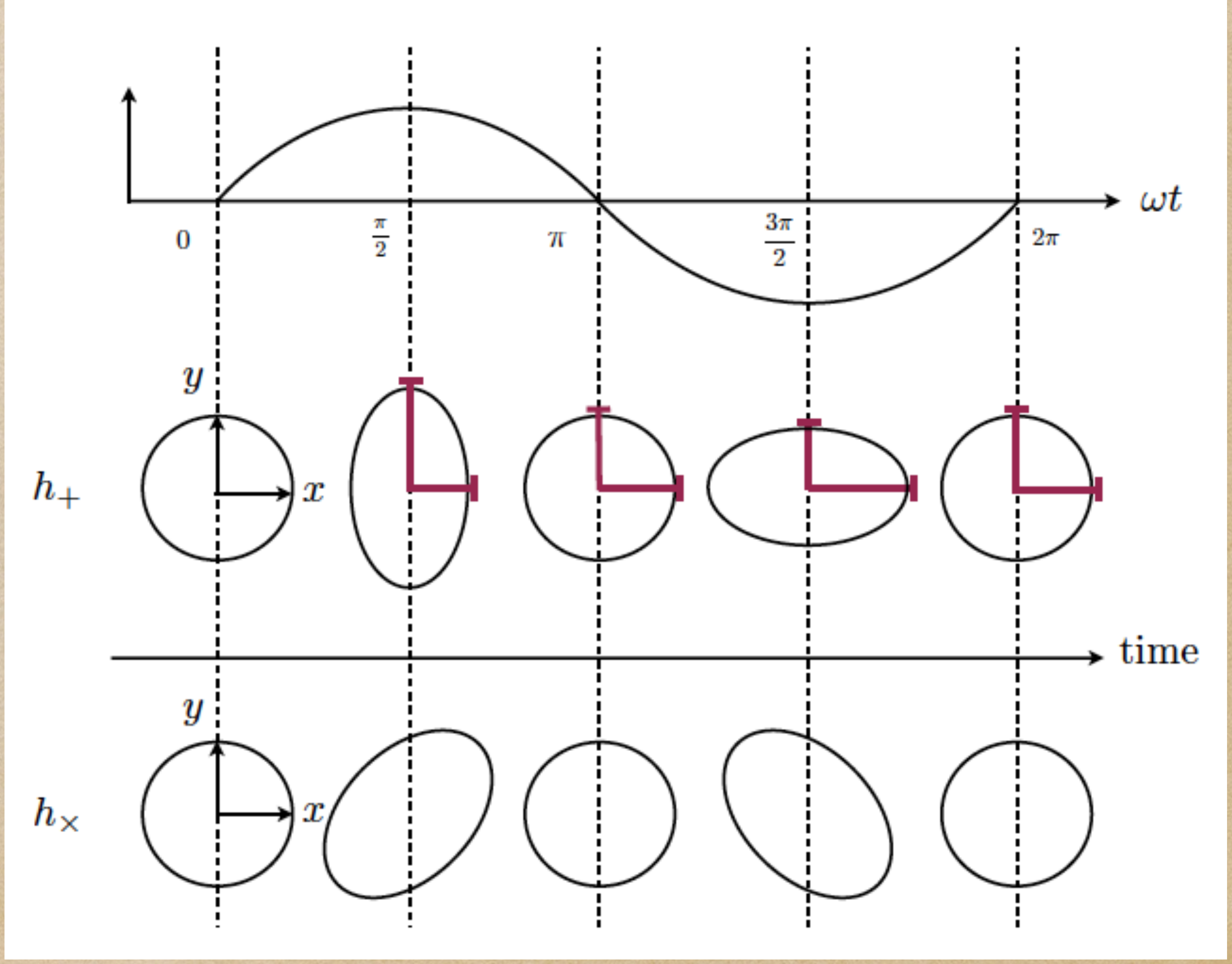
$$ds^2 = -dt^2 + (1+h_+)\,dx^2 + (1-h_+)\,dy^2 + 2h_\times\,dx\,dy + dz^2$$

- Effect on test particles:

  Mirshekari 1308.5240

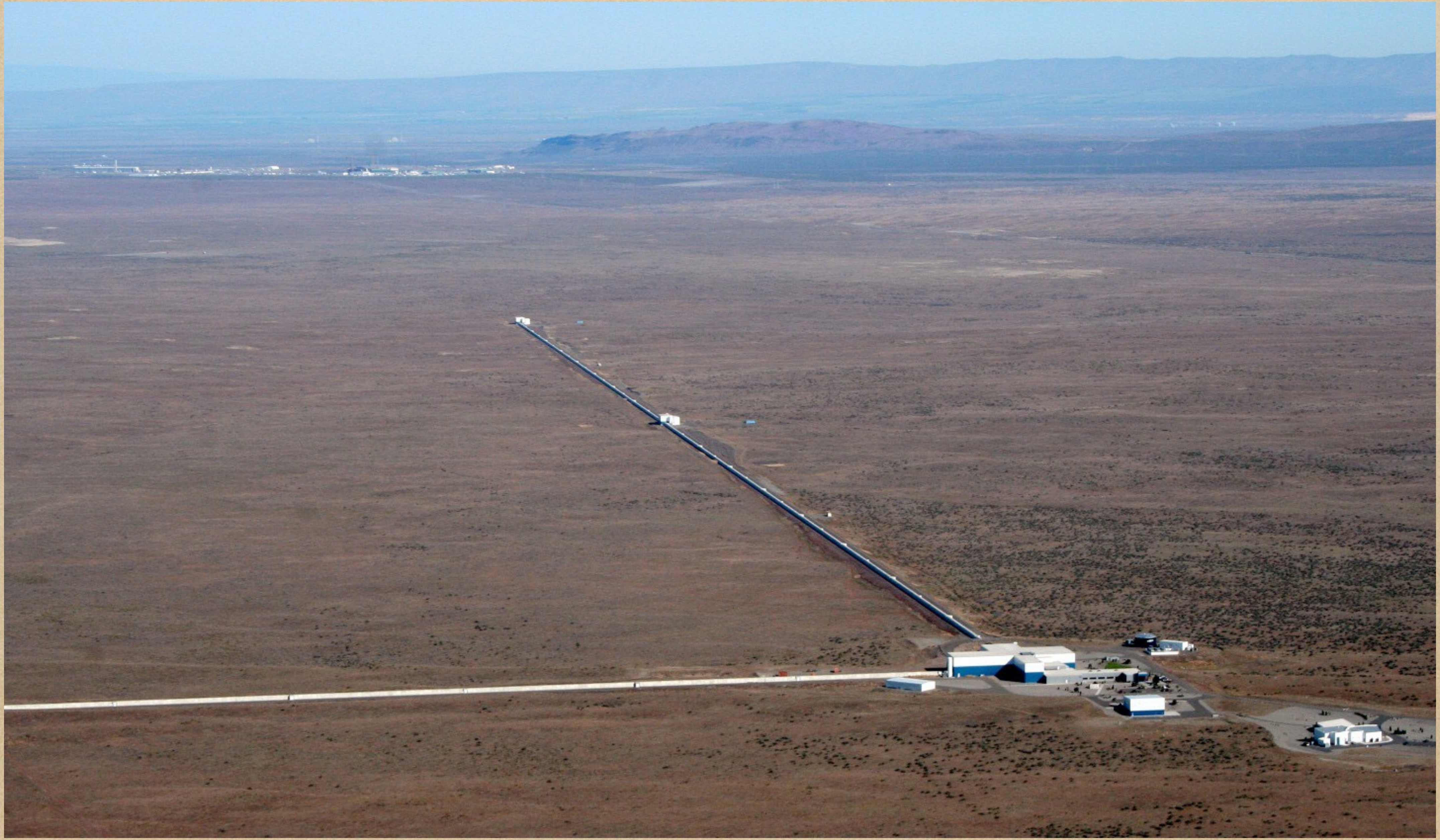
- Debate on physical reality until late 1950s

  e.g.Saulson GRG (2011)

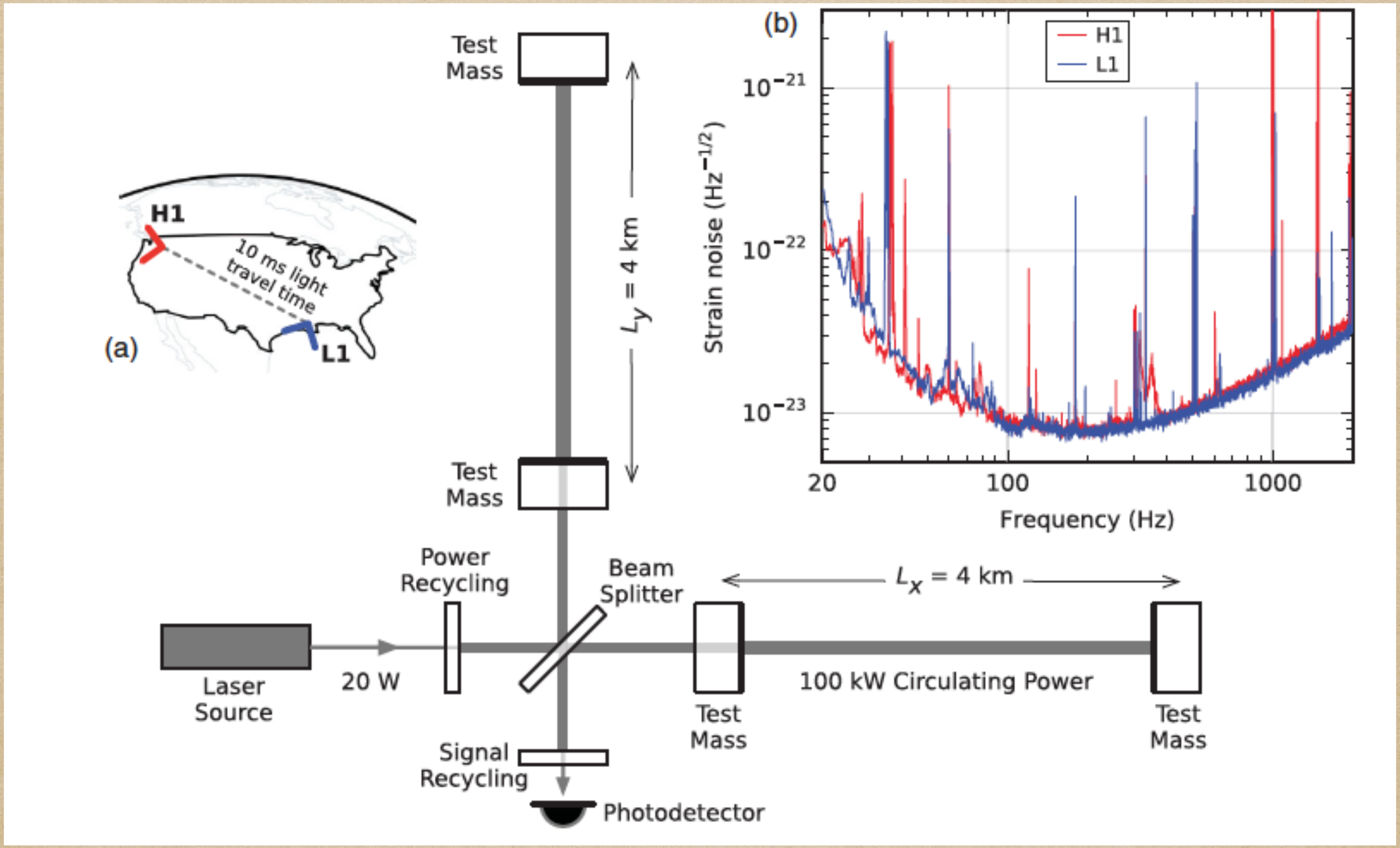


Effect on particles

- 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: $m_1 = 35^{+5}_{-3}\, m_\odot\,, \quad m_2 = 30^{+3}_{-4}\, M_\odot$