Black-hole Mimickers and Dark-Matter Candidates: Modeling Boson Stars and their GW Signatures

Ulrich Sperhake

DAMTP, University of Cambridge

Belgian Dutch Gravitational-Wave Workshop
Radboud University, Nijmegen
27-28 Oct 2025

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 Collodel & Doneva 2203.08203
- Axion stars e.g. Helfer et al JCAP 2017
- 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 BSs, some Proca Stars

Motivation

- BS = Classical limit of a quantum field

  Ground state = Boson-Einstein condensate
- Only known scalar field: Higgs, $\mu = 125\,\mathrm{GeV}$
- Units $G = c = \hbar = 1$, scale determined by μ [inverse length]

  E.g. $\mu = 1.33 \times 10^{-10}\,\mathrm{eV} \;\Rightarrow\; \mu^{-1} = M_\odot = 1.48\,\mathrm{km}$
- Astrophysical stars need ultralight fields → Beyond SM

  axion like, dark matter candidates: $10^{-11} \ldots 10^{-20}\,\mathrm{eV}$
- Properties: Compactness 0 to > NSs, any Mass
- BSs can have light rings → Black-hole mimickers; stable???

Reviews: Liebling & Palenzuela LRR 2023, Visinelli 2109.05481,

Mielke Fund.Theor.Phys. 2016, Schunck & Mielke GRG 1999, ...

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:

$$V_{\mathrm{mas}}(\varphi) = \mu^2|\varphi|^2 + \lambda|\varphi|^4, \quad V_{\mathrm{soli}}(\varphi) = \mu^2|\varphi|^2\left(1 - 2\frac{|\varphi|^2}{\sigma_0^2}\right)^2$$

- Mini Boson Stars: $\lambda \to 0, \quad \sigma_0 \to \infty$
- Ansatz $\varphi(t,r) = A(r)e^{\mathrm{i}\epsilon\omega t + \delta\Phi}, \quad \varphi(t,r,\theta,\phi) = A(r,\theta)e^{\mathrm{i}(\epsilon\omega t + m\phi + \delta\Phi)}$

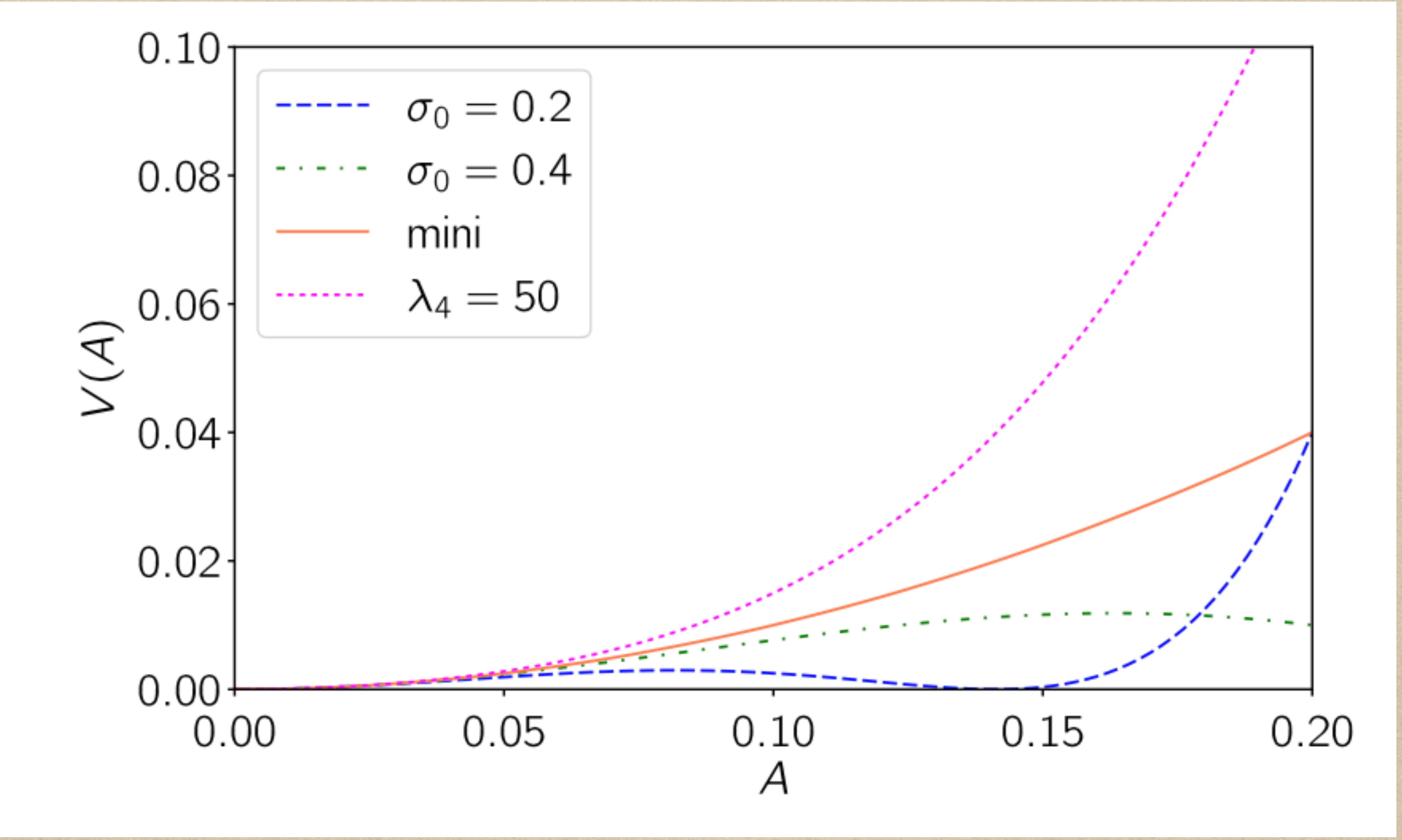
$\delta\Phi$ = phase offset, ϵ = BS vs anti-BS

- Regular solutions only for countably infinite values

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

Formalism and basic features

- Scalar potentials



Evstafyeva et al PRD 2023

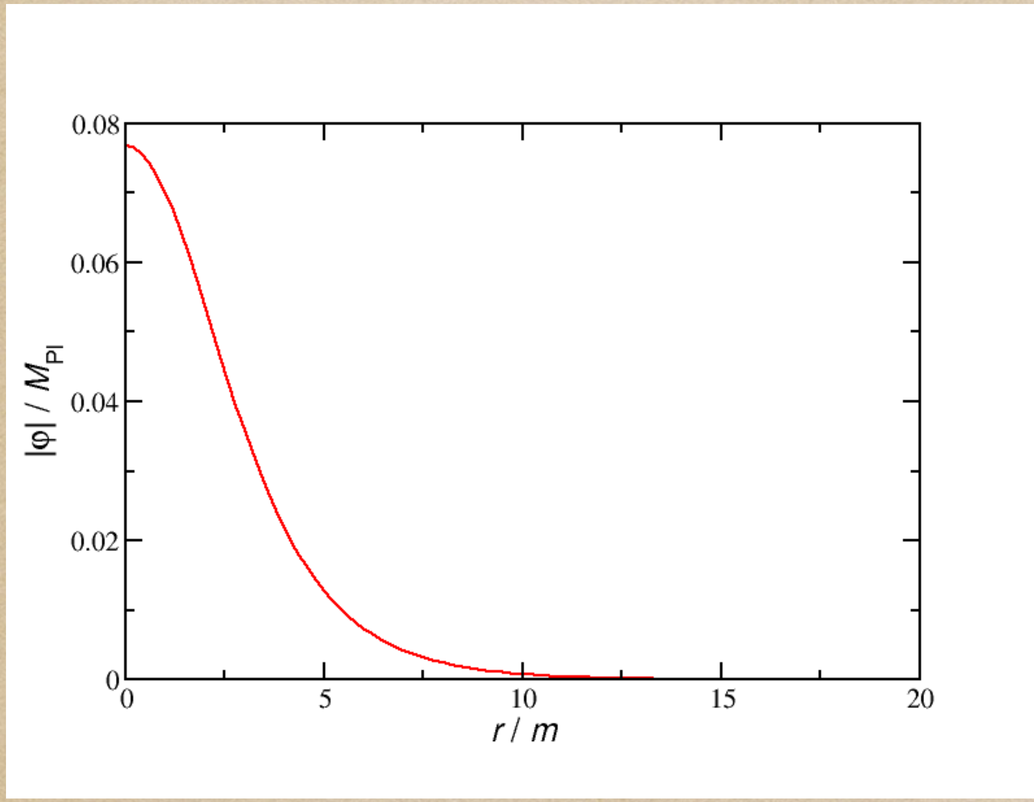
- Massive Potential: Stiff EOS

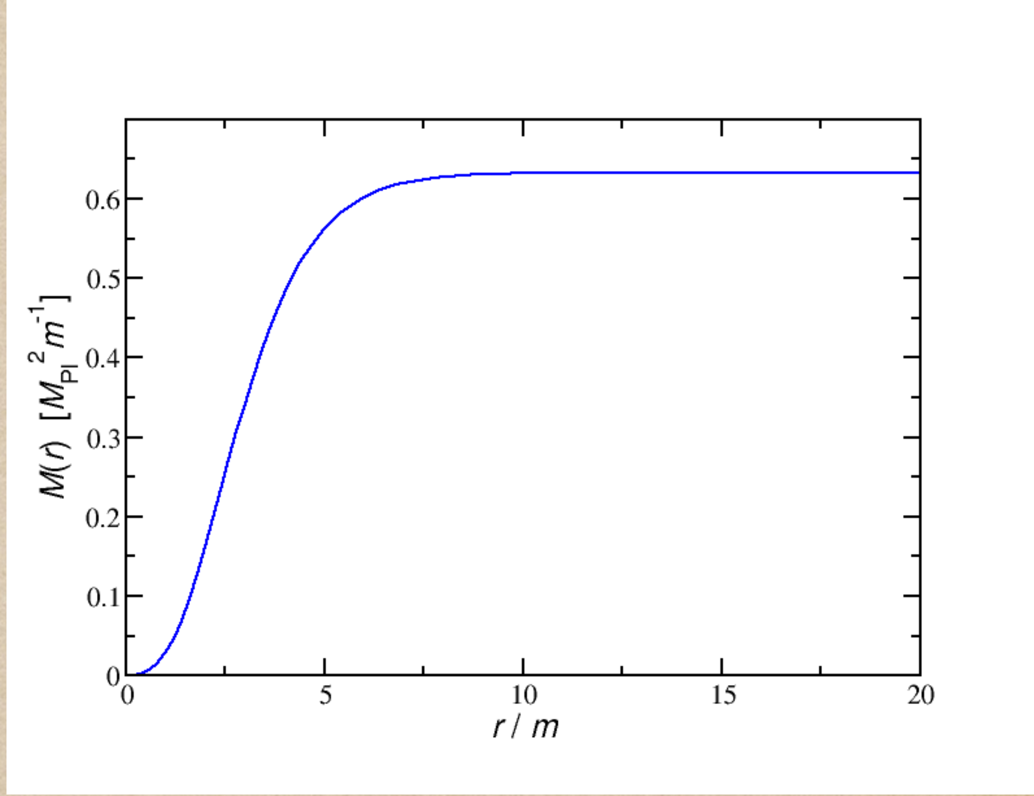
  Solitonic Potential: Soft EOS

Formalism and basic features

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

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





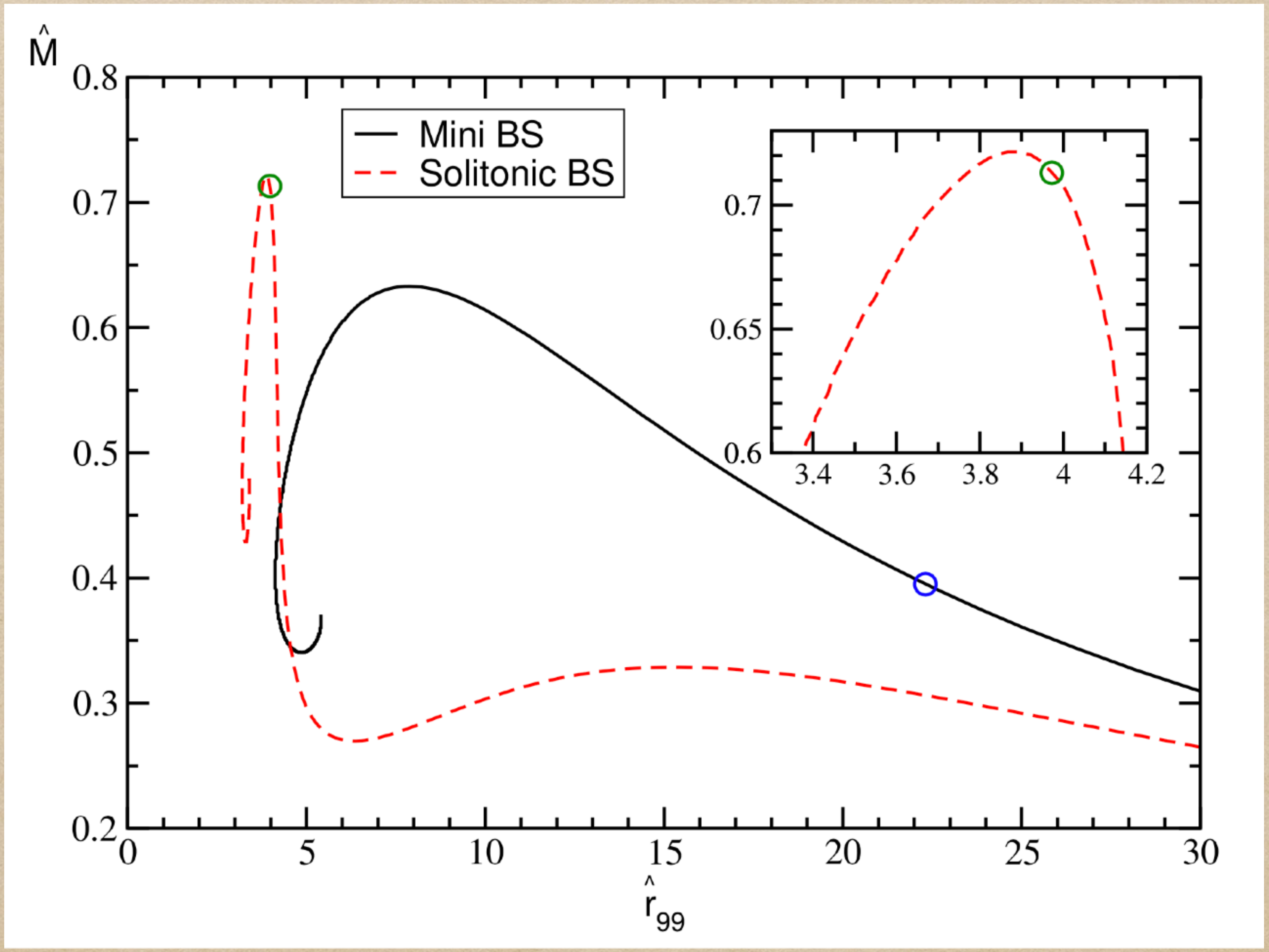
- Excited states unstable

collapse to BH, dispersion or migration to stable ground-state BS

Balakrishna, Seidel, Suen PRD (1998)

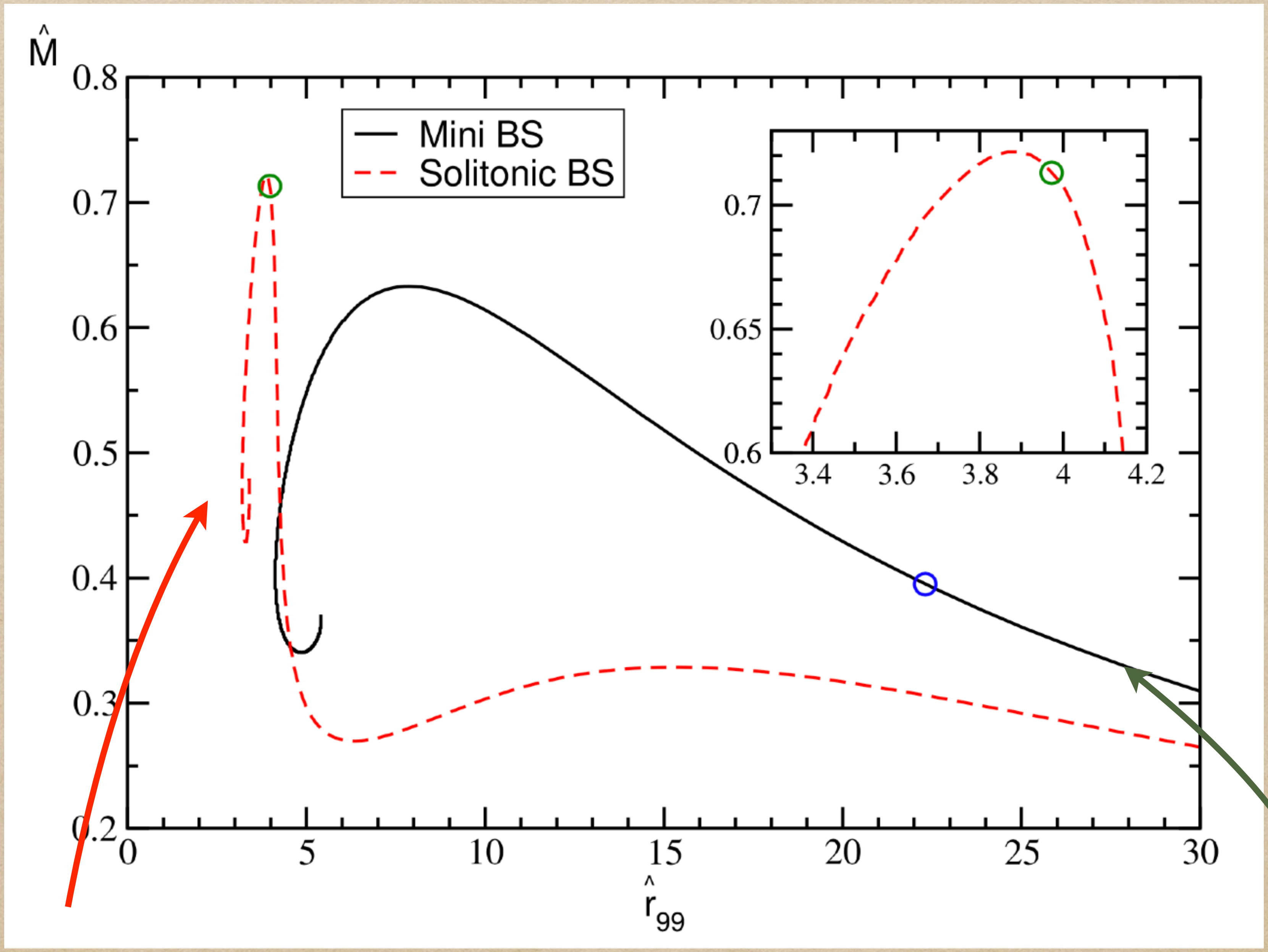
Formalism and basic features

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



Formalism and basic features

- 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 may be 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?

2. Boson-Star Binary Dynamics

Theory and Numerical Modelling

- Massive complex scalar field + GR

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

$\Rightarrow$ Einstein-Klein-Gordon equations

- Space-time formulations: GHG, CCZ4, BSSNOK
- Techniques like for BH binaries. We use:

GRChombo Radia et al CQG 2021

Lean US PRD 2006

- Typical grid setups:

$\mathrm{d}x = \frac{M}{48} \ldots \frac{M}{32}$, domain size $\sim 1024\,M$, 8 refinement levels

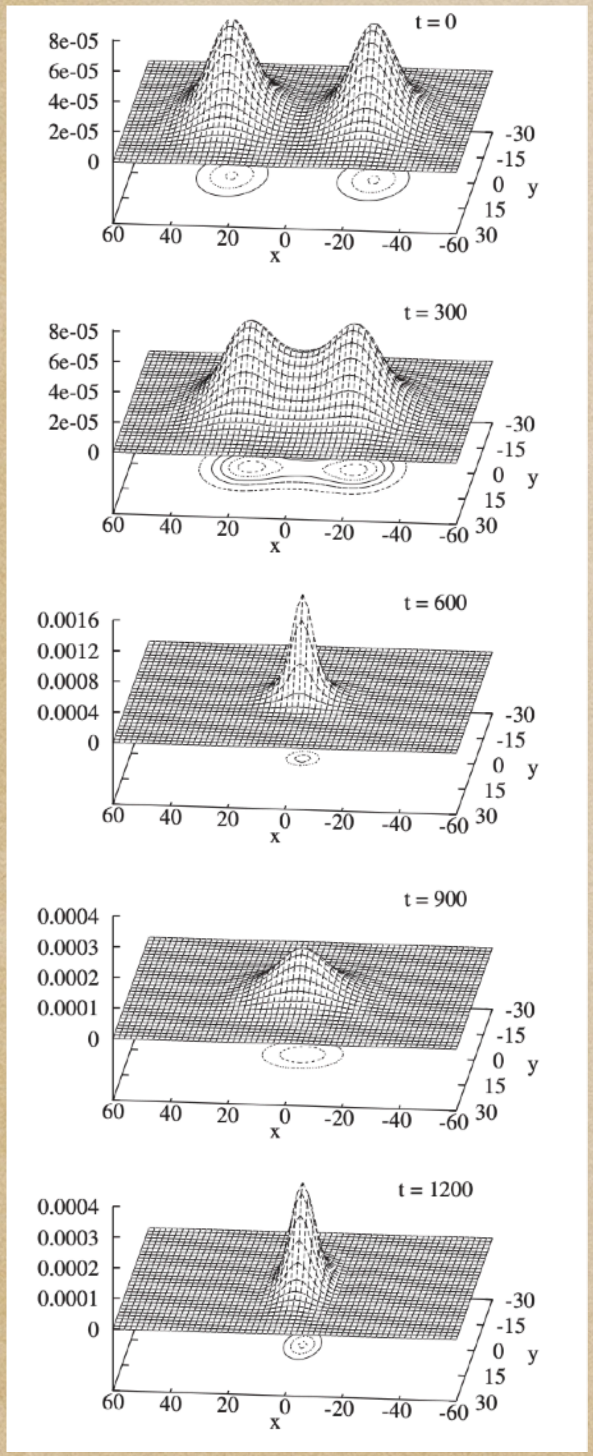
- Improve initial data: Constant Volume Element (CVE)

Helfer et al PRD 2019, CQG 2021, Evstafyeva et al CQG 2023,

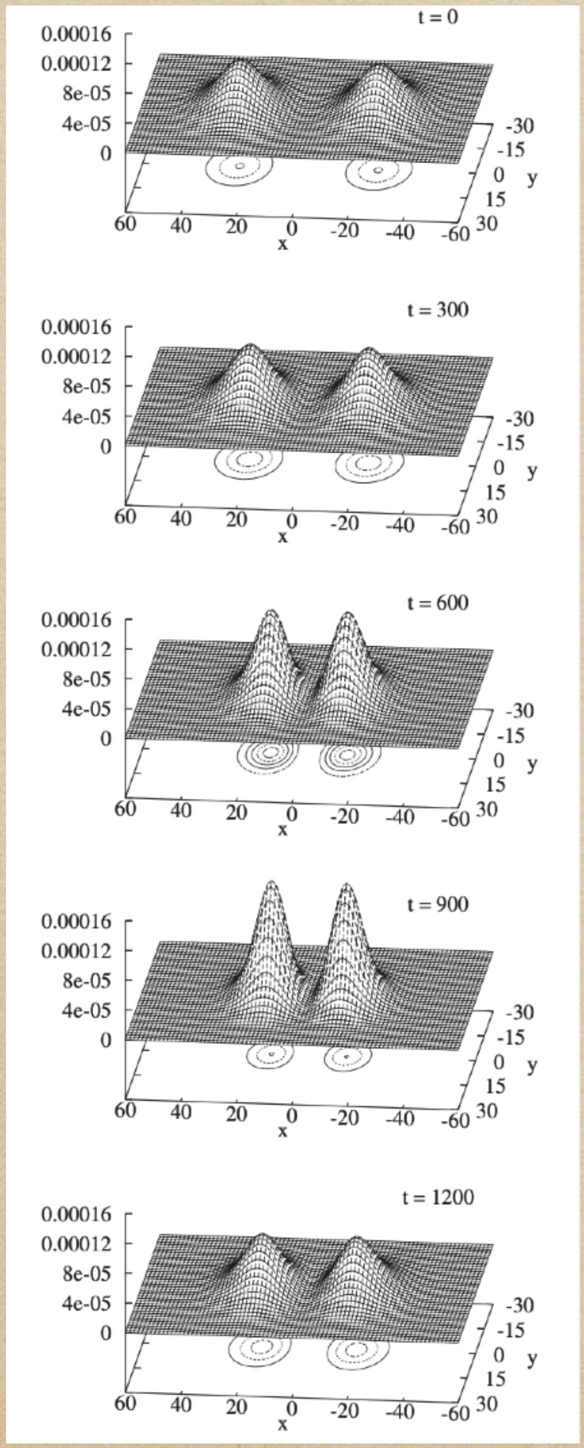
Atteneder et al PRD 2024

Equal-mass, nonspinning head-on collisions

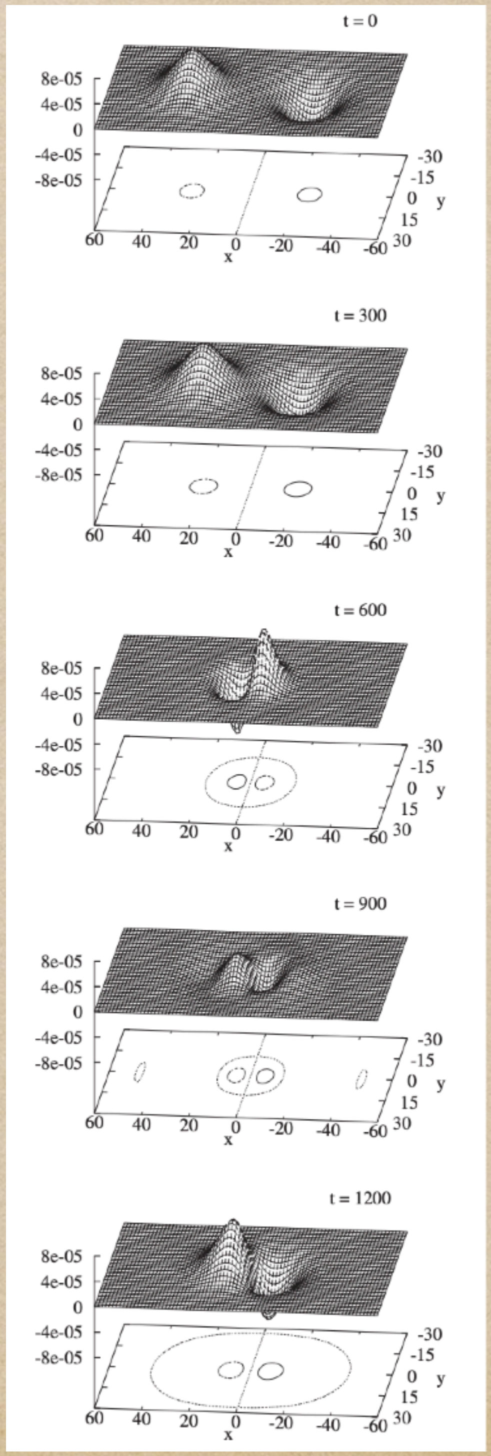
- $\mu M = 0.26$ mini BSs binaries with $\delta\Phi = 0, \;\; \delta\Phi = \pi, \;\; \epsilon = -1$



attractive



repellent



zero Noether charge

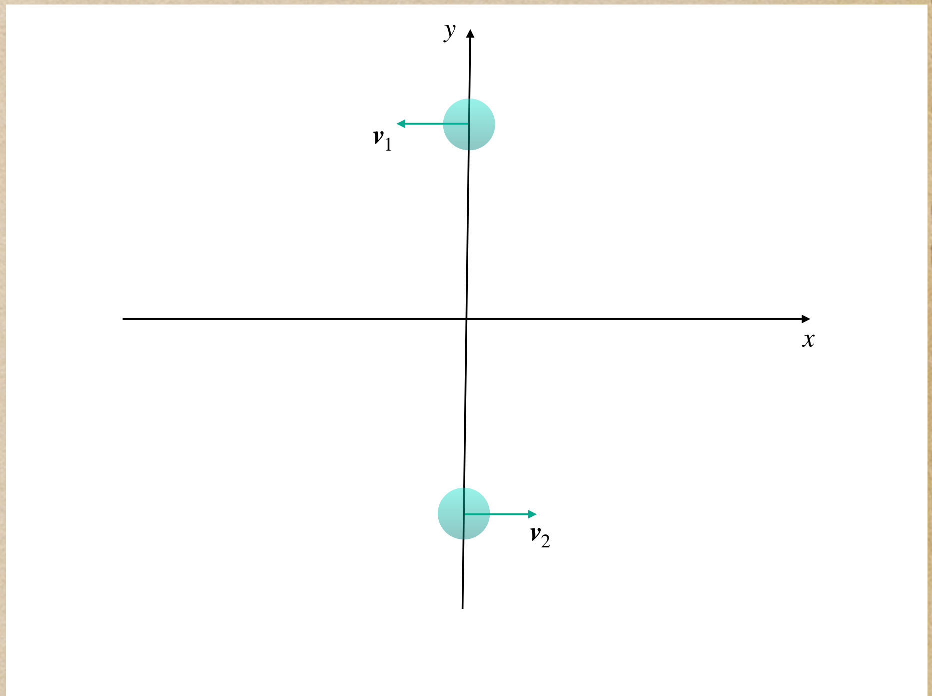
Palenzuela et al

PRD 2007

Merger remnants

- Eccentric and hyperbolic in-hase mini-BS binaries with $M/R \approx 0.04$

  Palenzuela et al PRD 2008

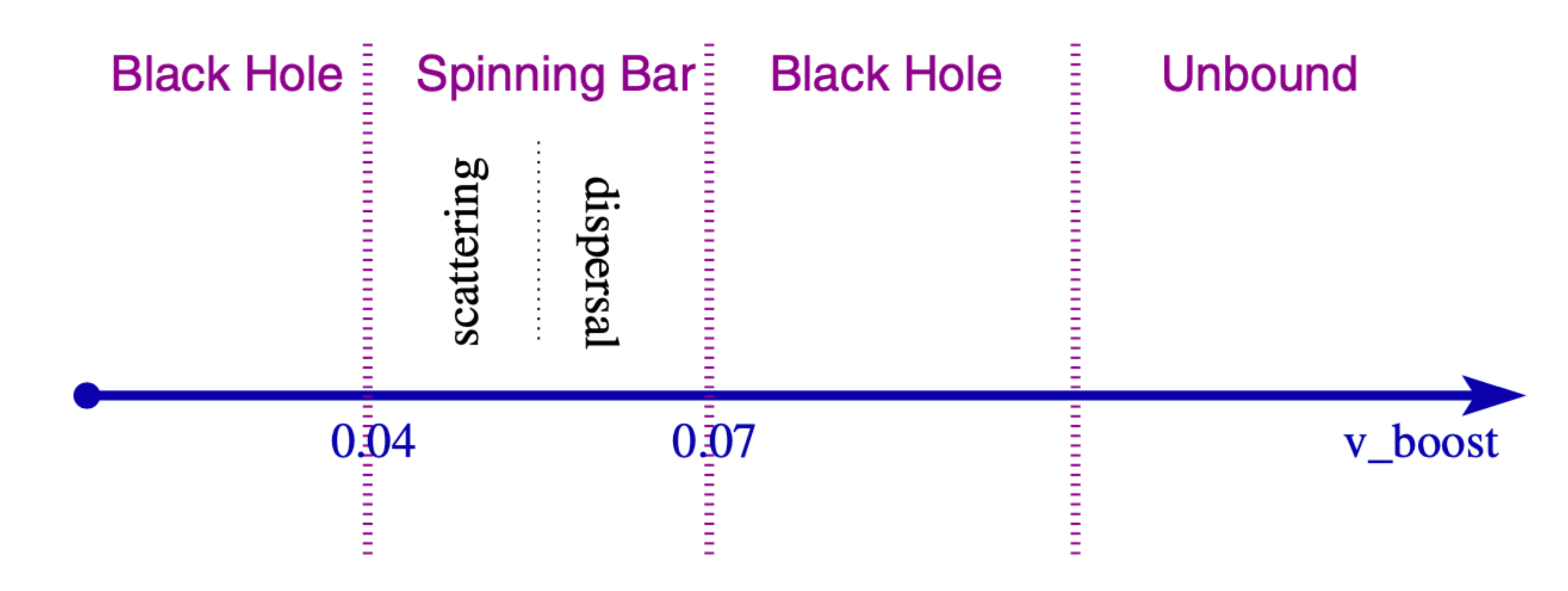


- Outcome:

  BH, spinning bar or unbound system

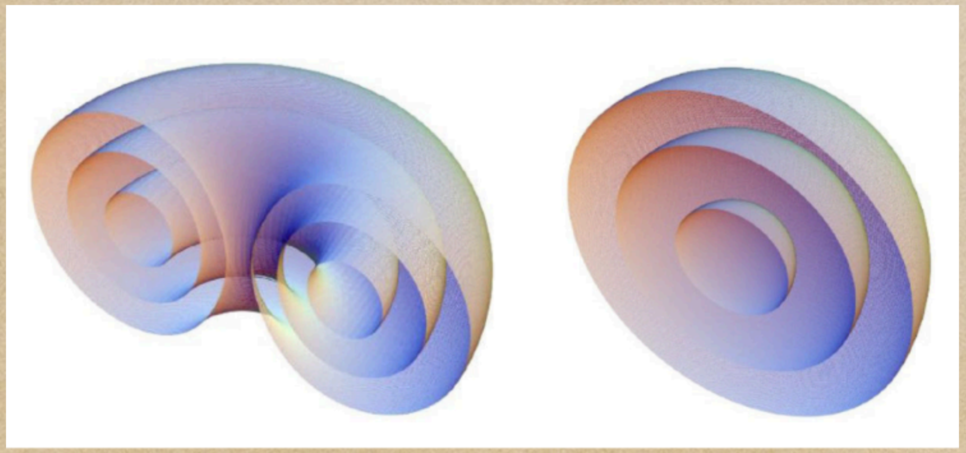
- BS spin is quantized

  → Hard to form a spinning BS

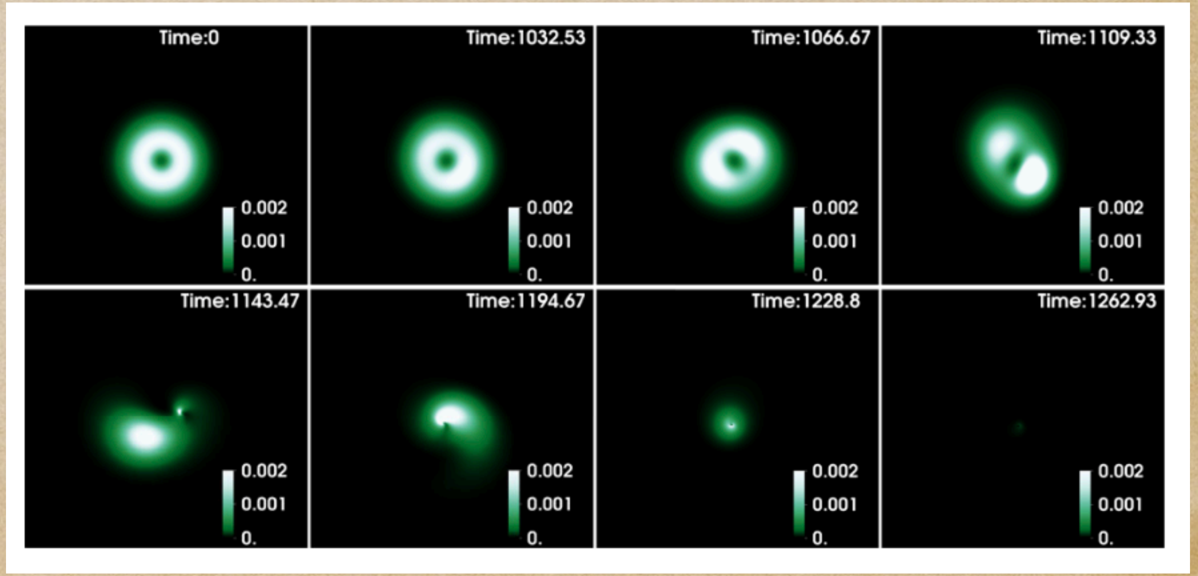


Formation and Stability of spinning BSs

- Evolve scalar or vector cloud; no self-interaction!
  - Cloud collapses due to gravitational cooling
  - Scalar case: Instability shedding all angular momentum
  - Vector case: No instability, spinning Proca star forming
- Evolve spinning equilibrium stars
  - Scalar case: Instability → Formation of spinning BH
  - Vector case: Stable evolutions even for explicit perturbations
- May be due toroidal/spherical energy profile

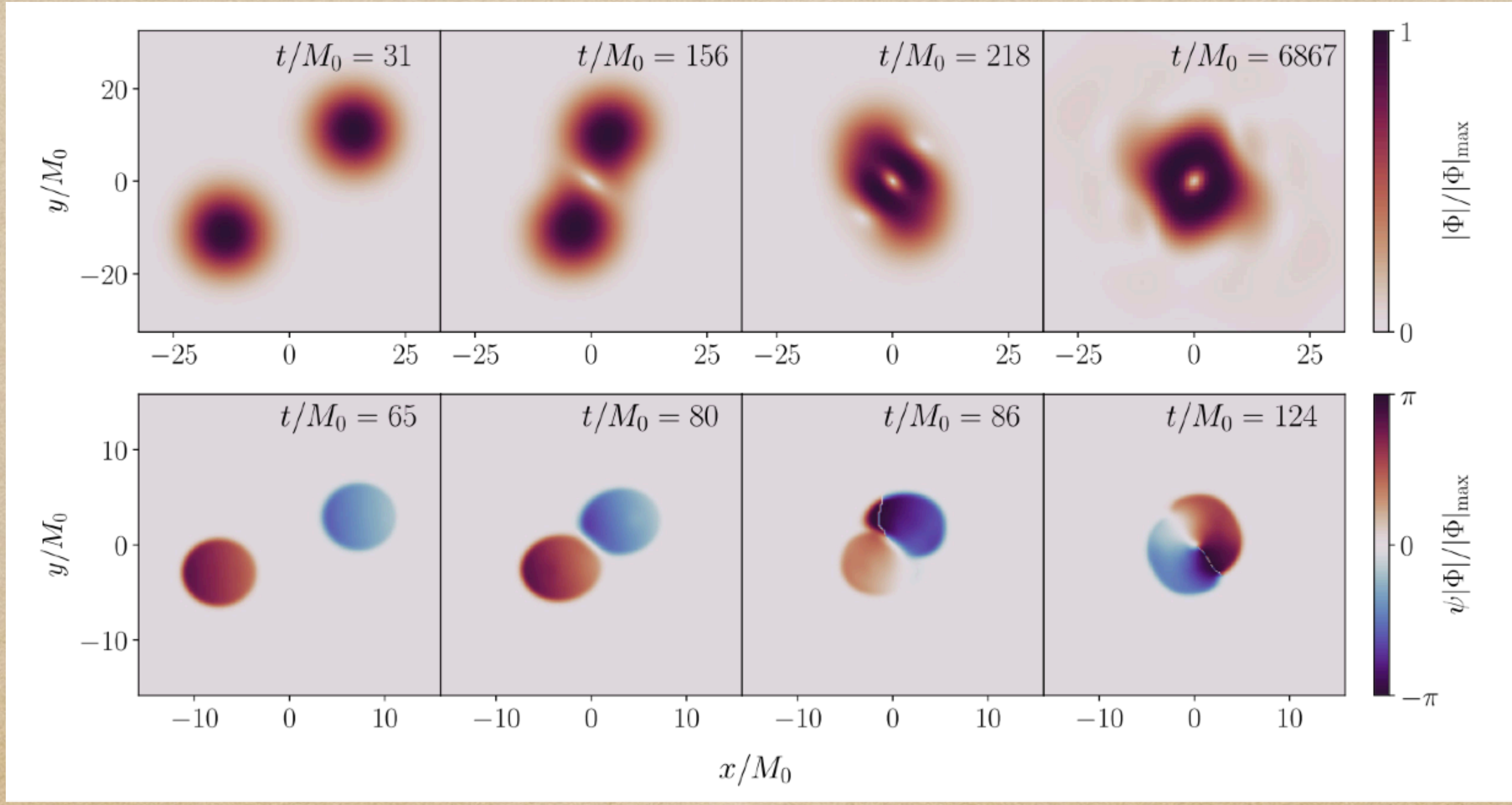


Sanchis-Gual et al PRL 2019



Spinning scalar BSs with self-interaction

- Nonrotating ($\delta\Phi = 0...\pi$, $M/r \approx 0.037$) scalar BS binary on eccentric orbits Siemonsen & East PRD 2023
- Massive and solitonic potentials
- Potential and angular momentum strongly affects GW signal
- Threshold dephasing $0 < \delta\Phi_{cr} < \pi$ required for forming spinning BS
- Dephasing, scalar interaction, vortex condition (J/M^2) important



3. GW Modelling

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 $\delta\Phi$, anti BS ϵ

GW detection and parameter estimation

Generic transient search

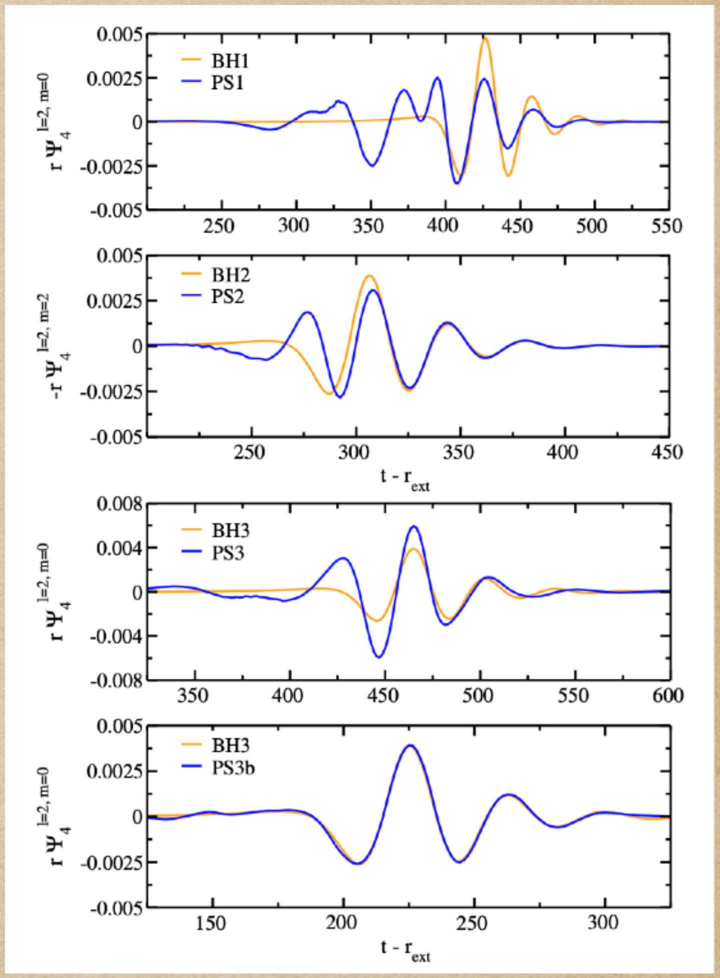
- No specific waveform model
- Identify excess power in detector strain data
- Use multi detector maximum likelihood   Klimenko et al. 1511.05999

Binary coalescence search

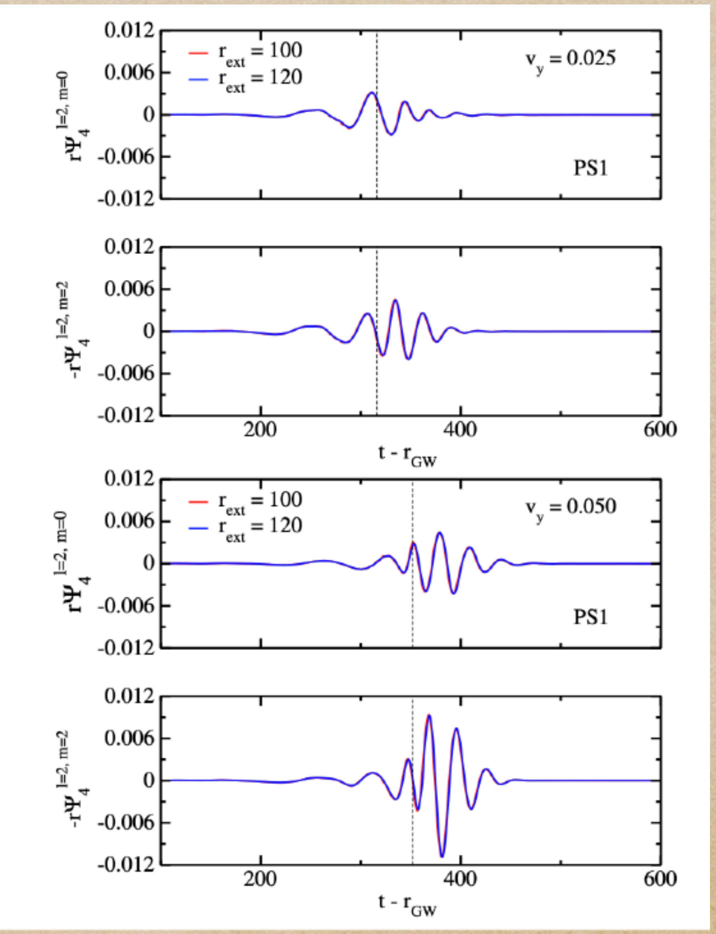
- "Matched Filtering"
- Compare data stream with GW templates ("Finger print search")
- Bayesian analysis: Prior $\longrightarrow$ Posterior

GW signals from Proca stars

- Proca stars with varying compactness Sanchis-Gual et al PRD 2019
- Compare head-on collisions with BH case:
  - 2 Effects on GW strength:
    Compactness, Asymmetry
  - High compactness ~ BH GWs



- GWs from orbiting binaries



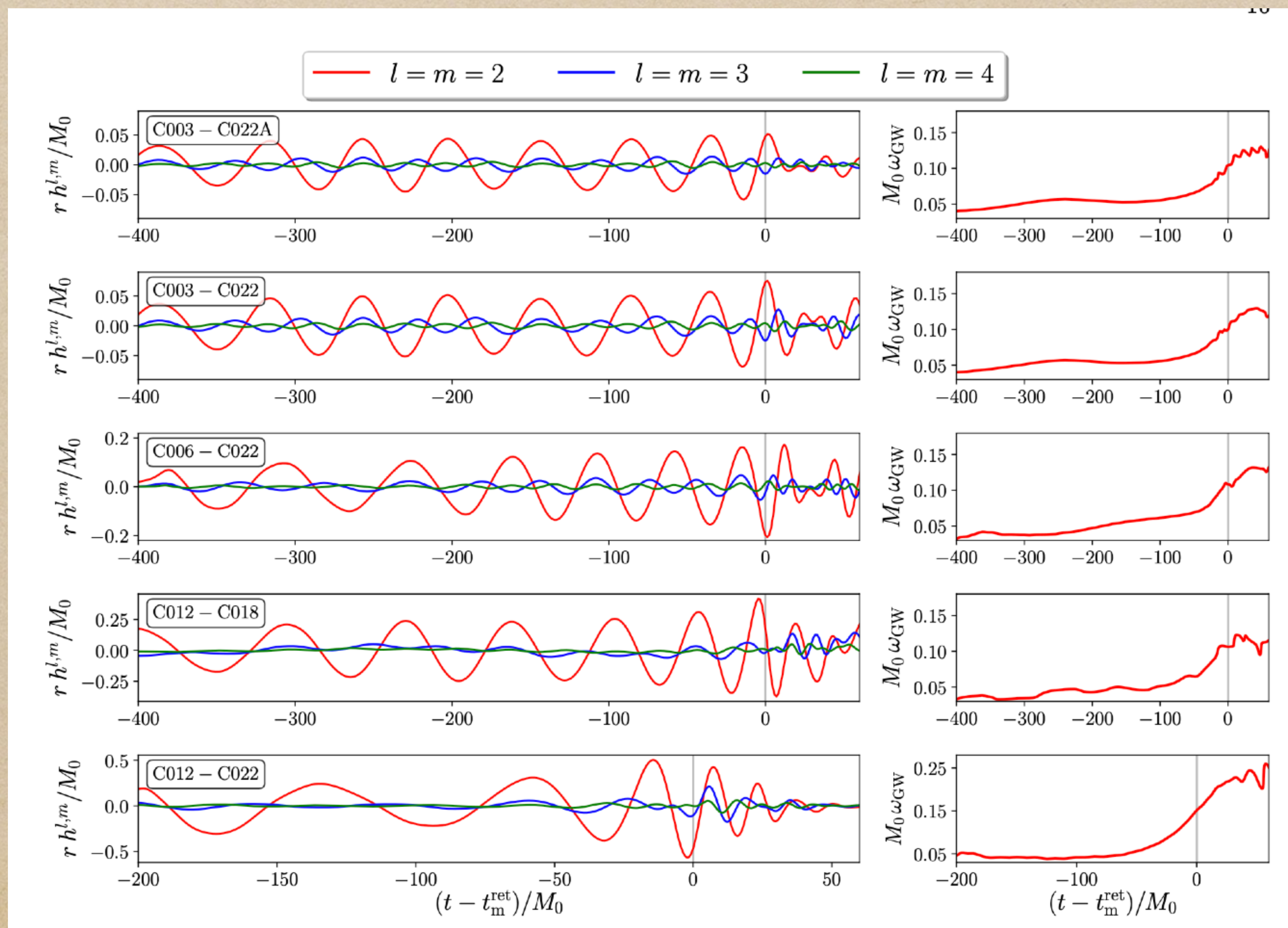
- Catalog of 759 head-on waveforms
- Compatible with GW190521

Bustillo et al PRD 2023

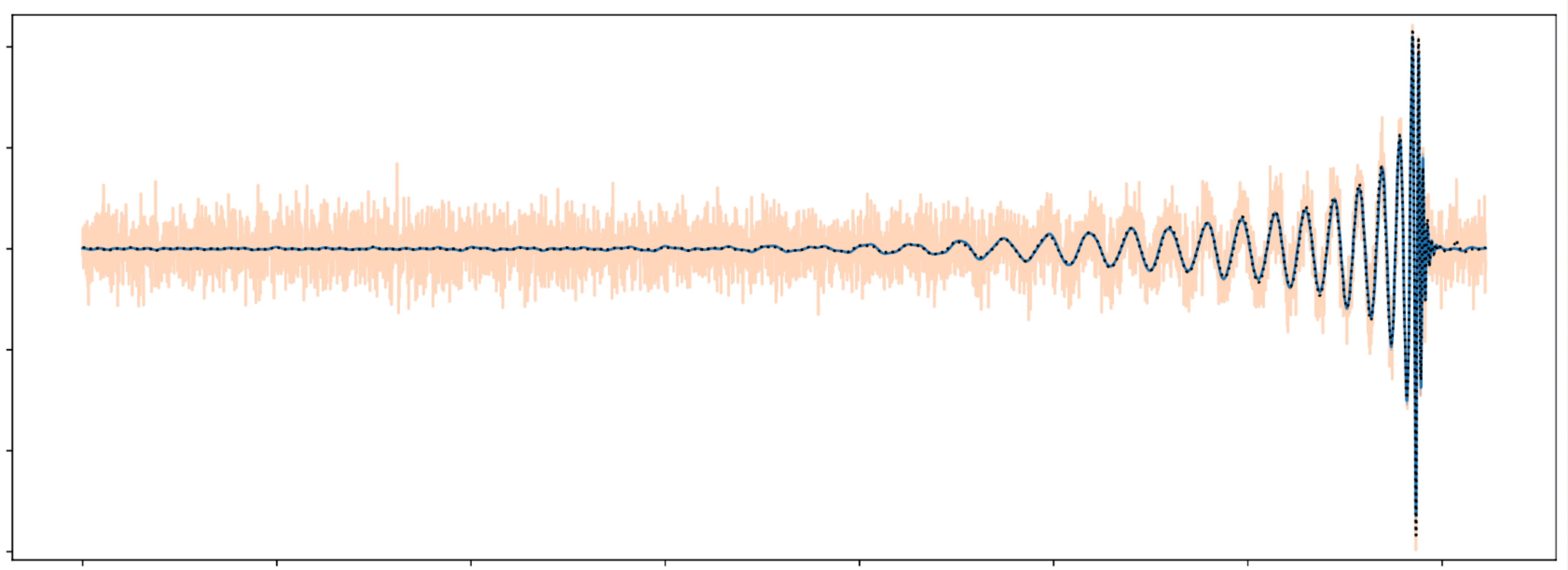
GW signals from BS binaries

- Nonspinning solitonic BSs with $M/R = 0.03...0.22, \quad q = 2.1...23.2$
- Large kicks $\sim 10^4\,\mathrm{km/s}$, but due to matter shedding, not GWs!

Bezares et al PRD 2022



Mimicking BH Binaries?



Evstafyeva et al. PRL 2406.02715

- How well do boson-star inspirals mimick BH inspirals?
- We need waveform models to distinguish them!
- Three effects: Point-particle (BH), Tidal, Scalar Interaction
- Properties: Compactness 0 to > NSs, any Mass

BS binaries

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

Characterized by

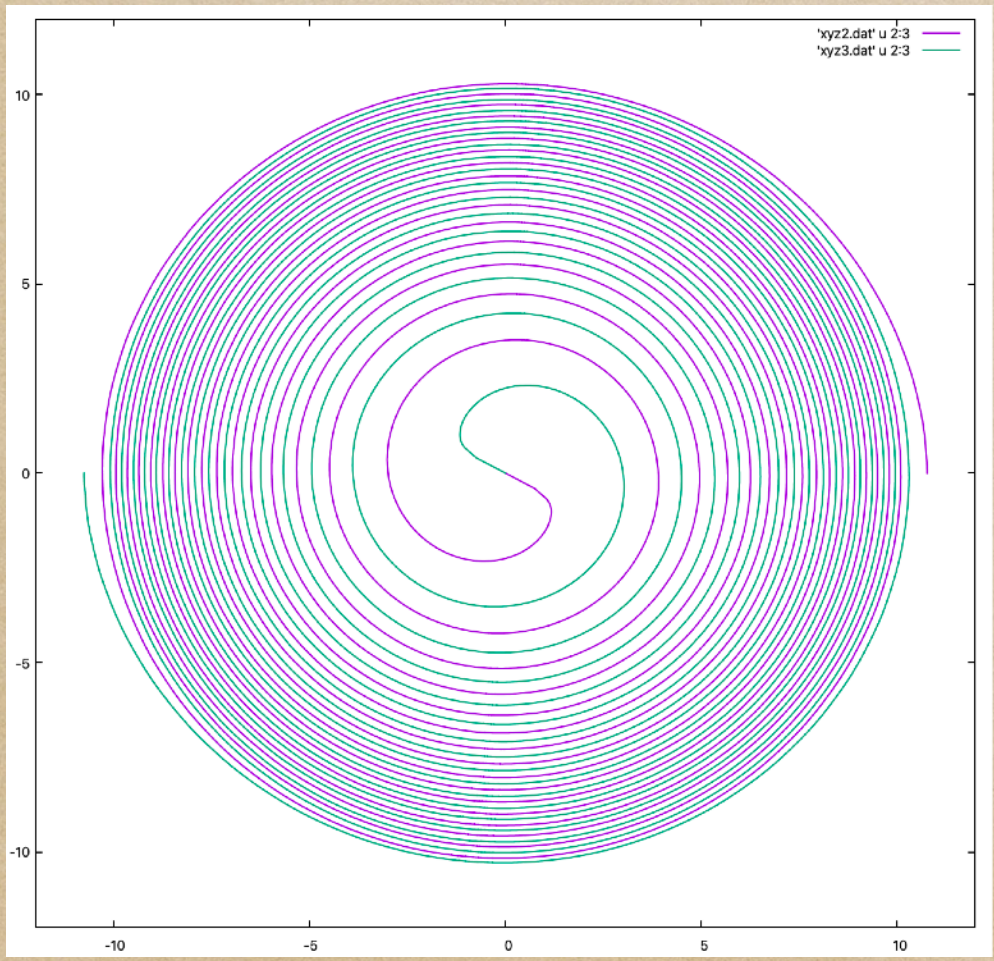
- Quasi-circular, non-spinning, equal-mass: $e \approx 0,\ \boldsymbol{S}_{1,2} = 0,\ q = 1$
- Number of orbits N
- Compactness 0.1 or 0.2
- Scalar dephasing $\delta\Phi \in [0,\pi]$
- BS-BS or BS-anti BS binary?
- Total mass: Any by trivial rescaling of the scalar mass

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

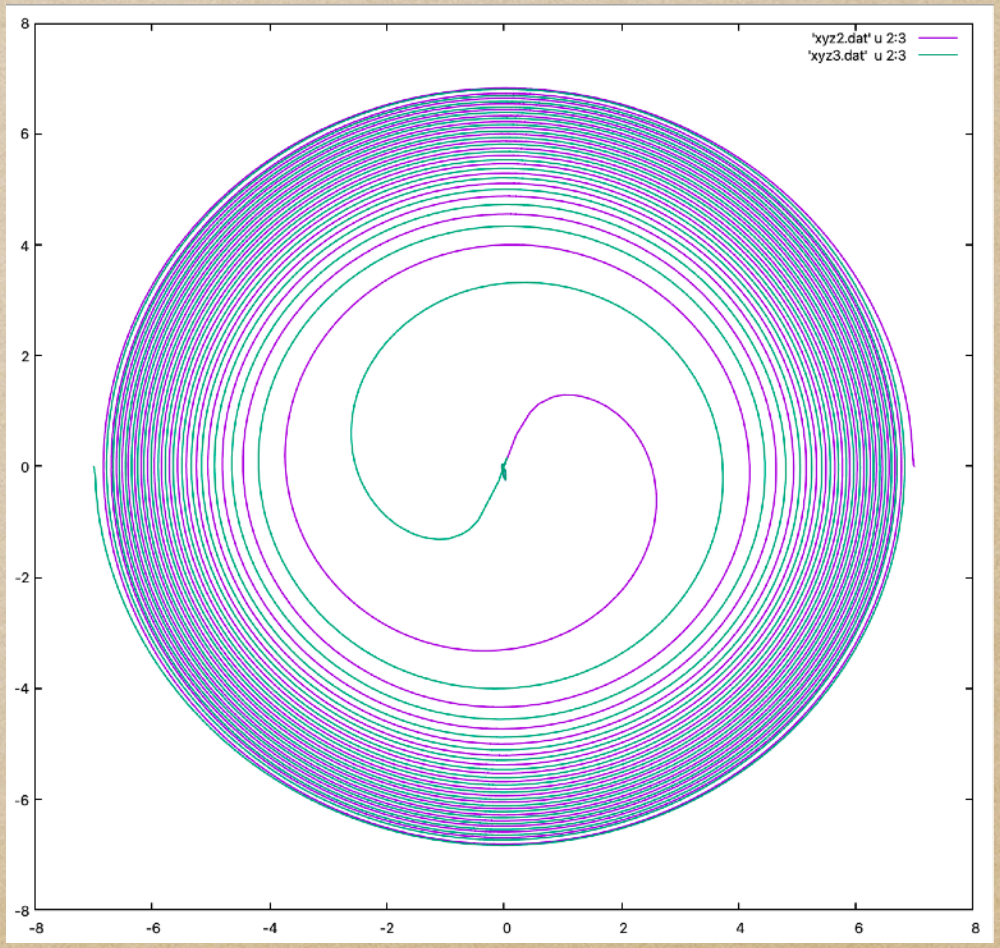
BS binaries

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

A17-d14

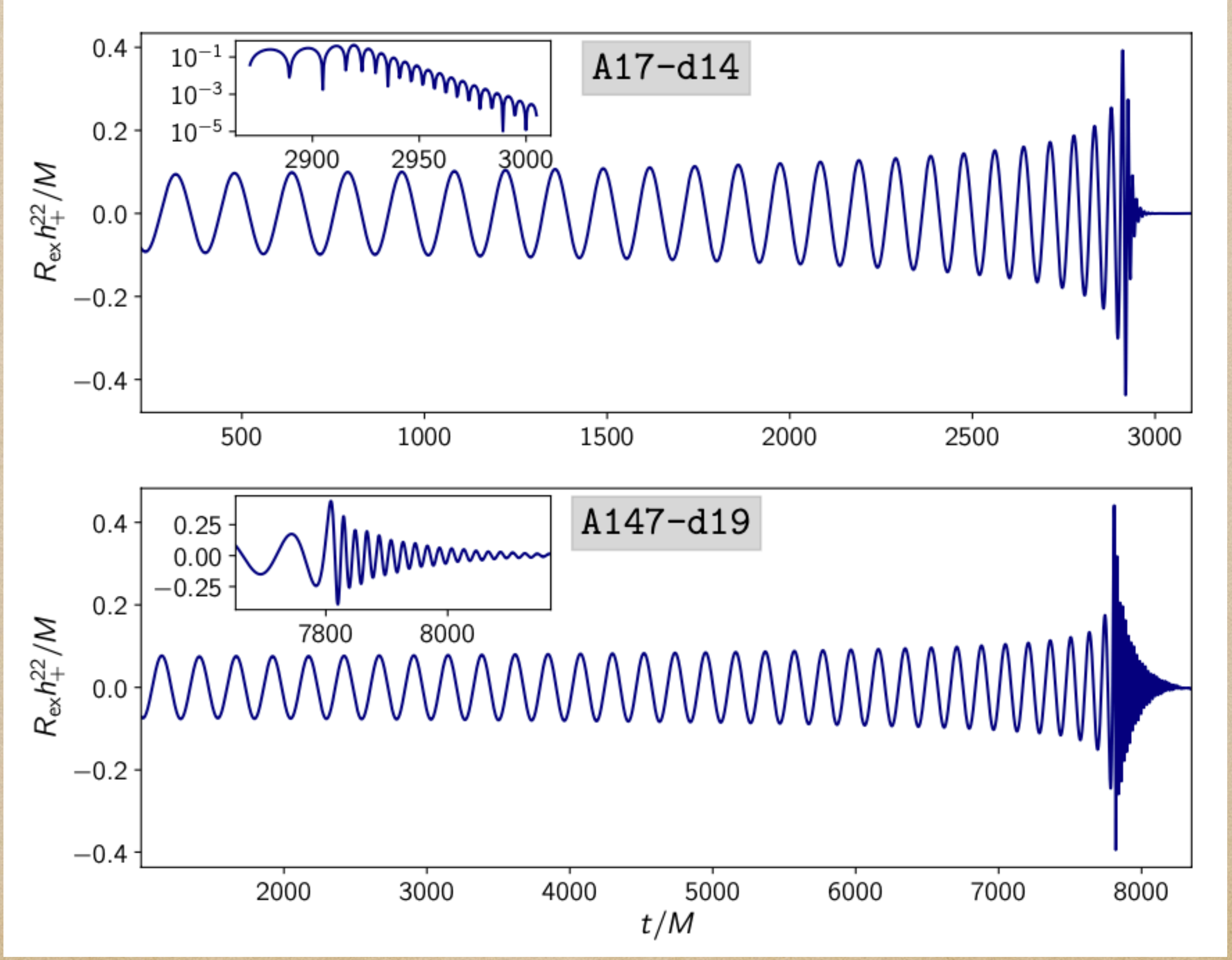


A147-d19



BS binaries

- GW strain from compact and fluffy BSs



Waveform approximants

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

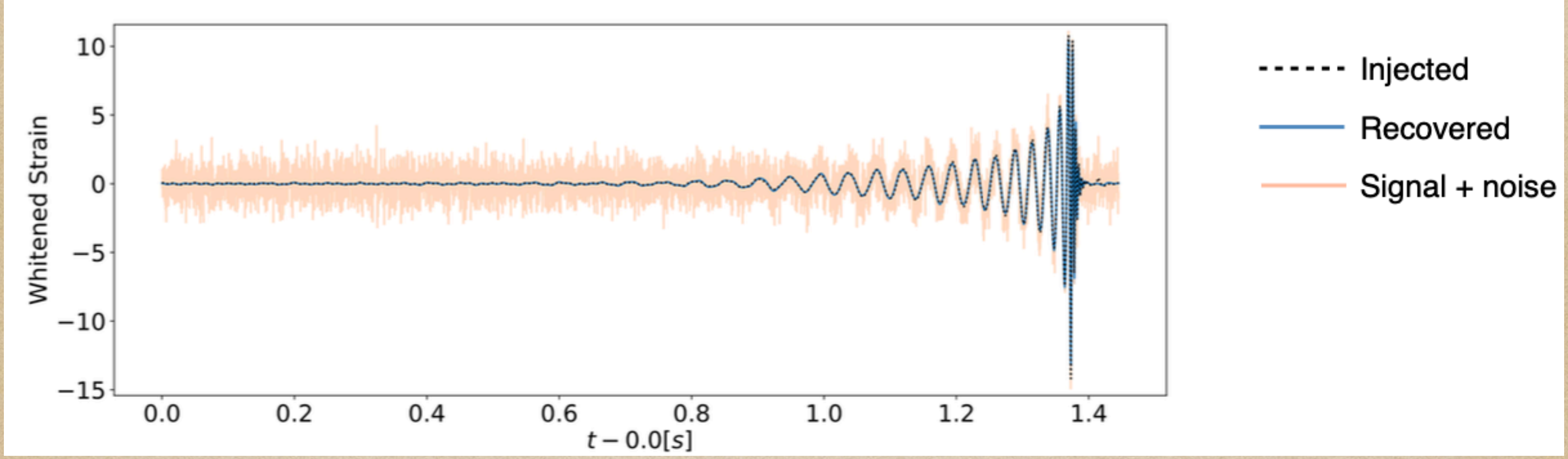
- 2 Approaches: (1) Allow spins to vary in the analysis

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

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

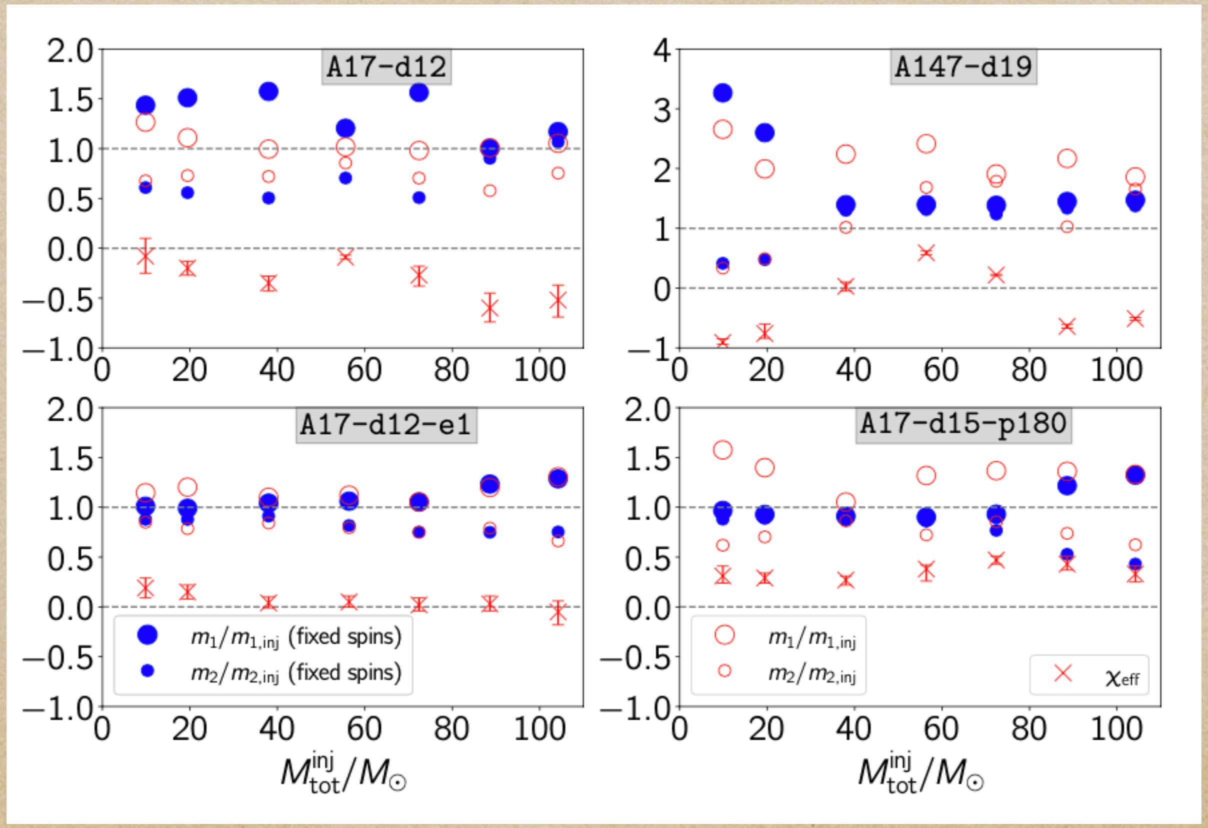
  Recovered SNR $\approx$ injected SNR

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

- 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

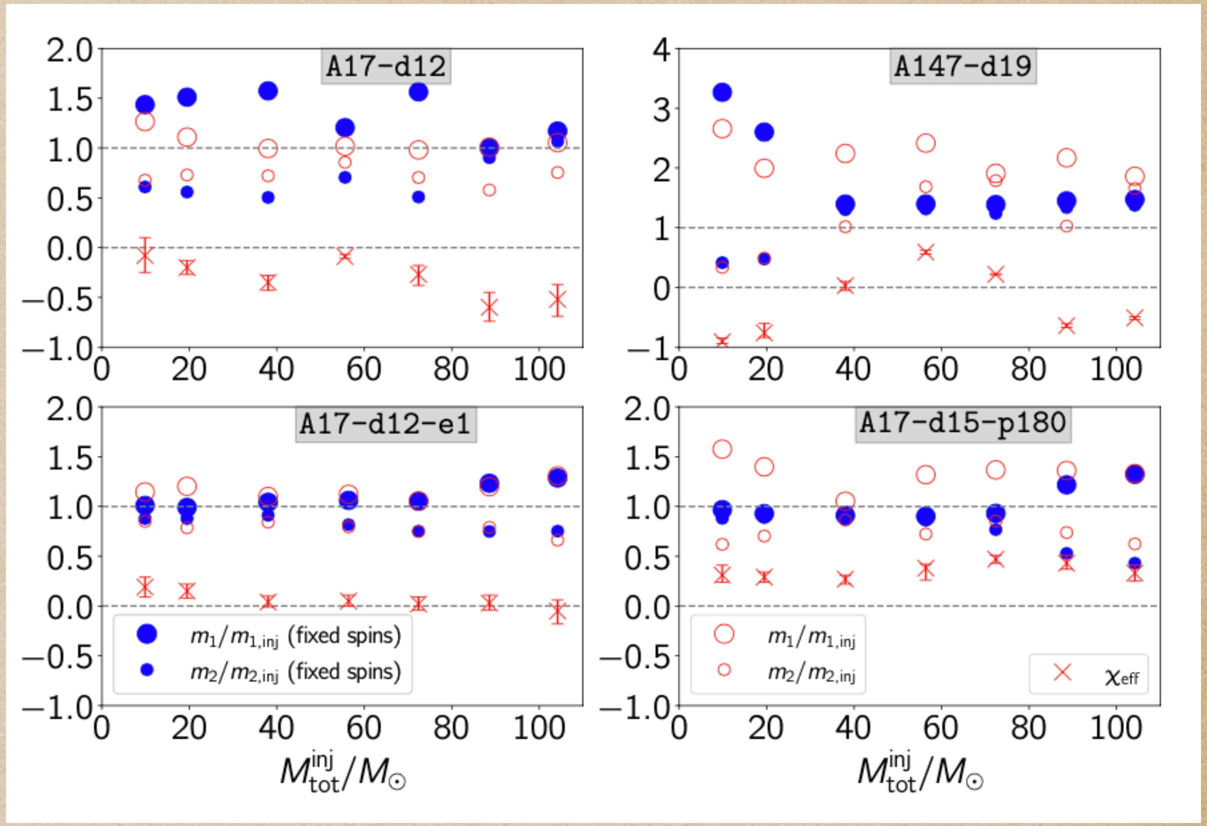


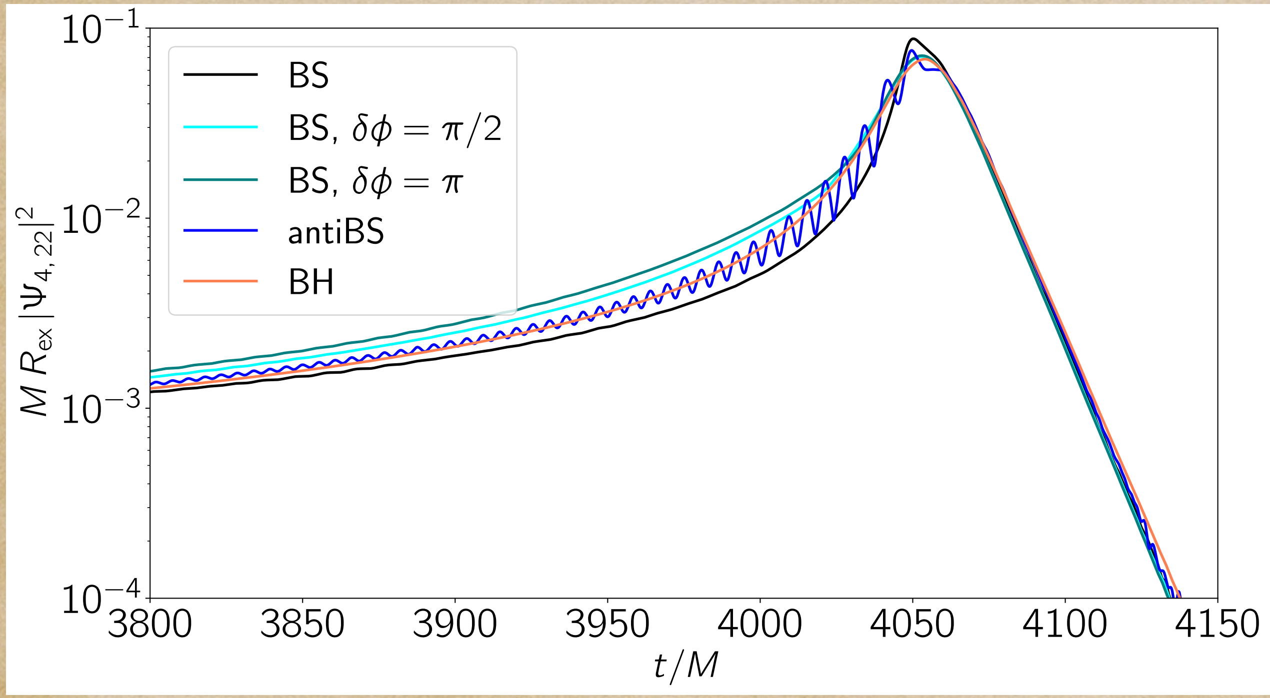
Understanding the PE bias

- PE bias

vs

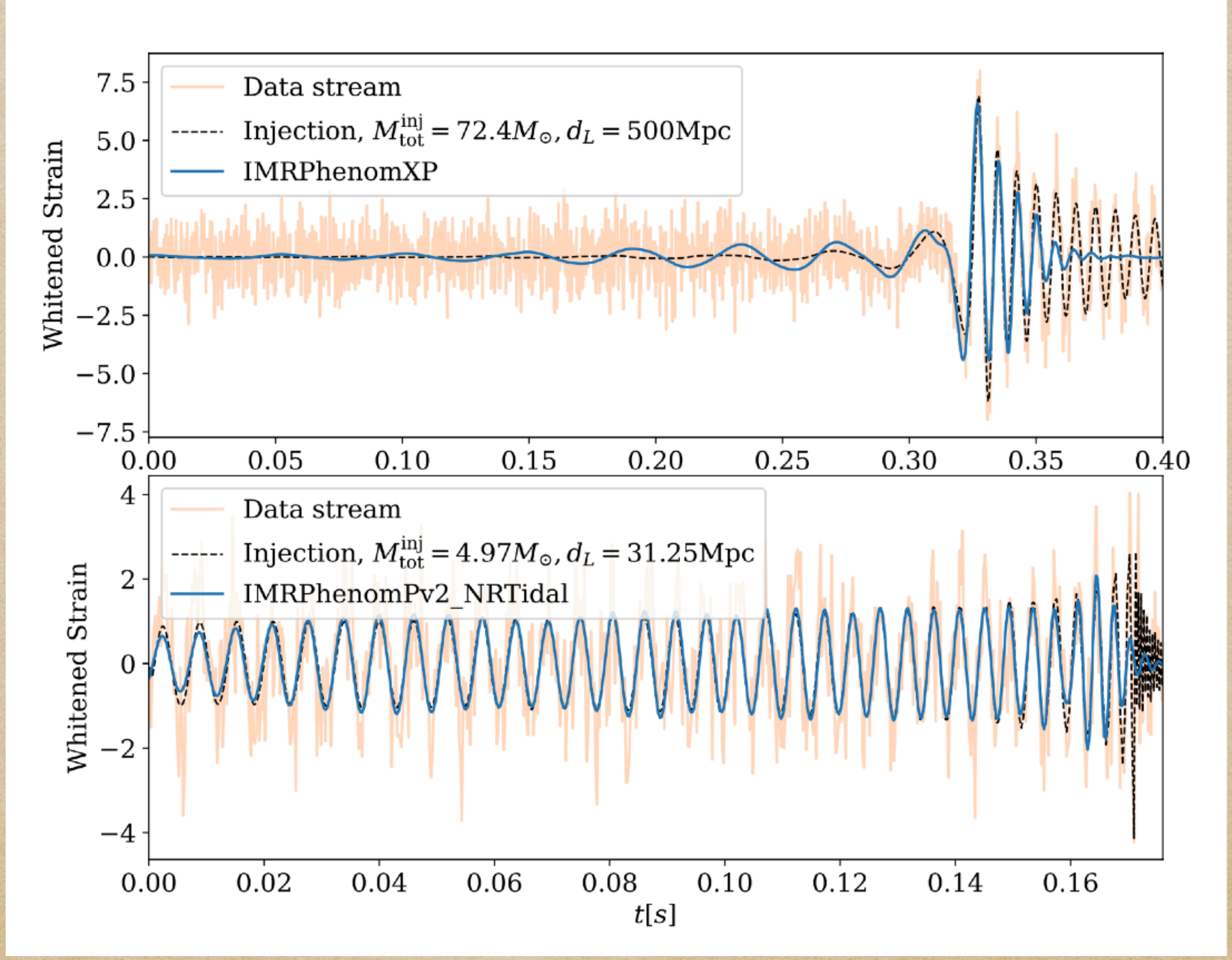
- Chirp steepness





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



Analytic Modeling of BS Binaries

- Calculation of tidal deformability parameters

  Cardoso et al PRD 2017, Sennett et al PRD 2017

- Model BS scattering with PM/EOB

  Damour, Jain & US in prep

  Three contributions

  - BH point particle:

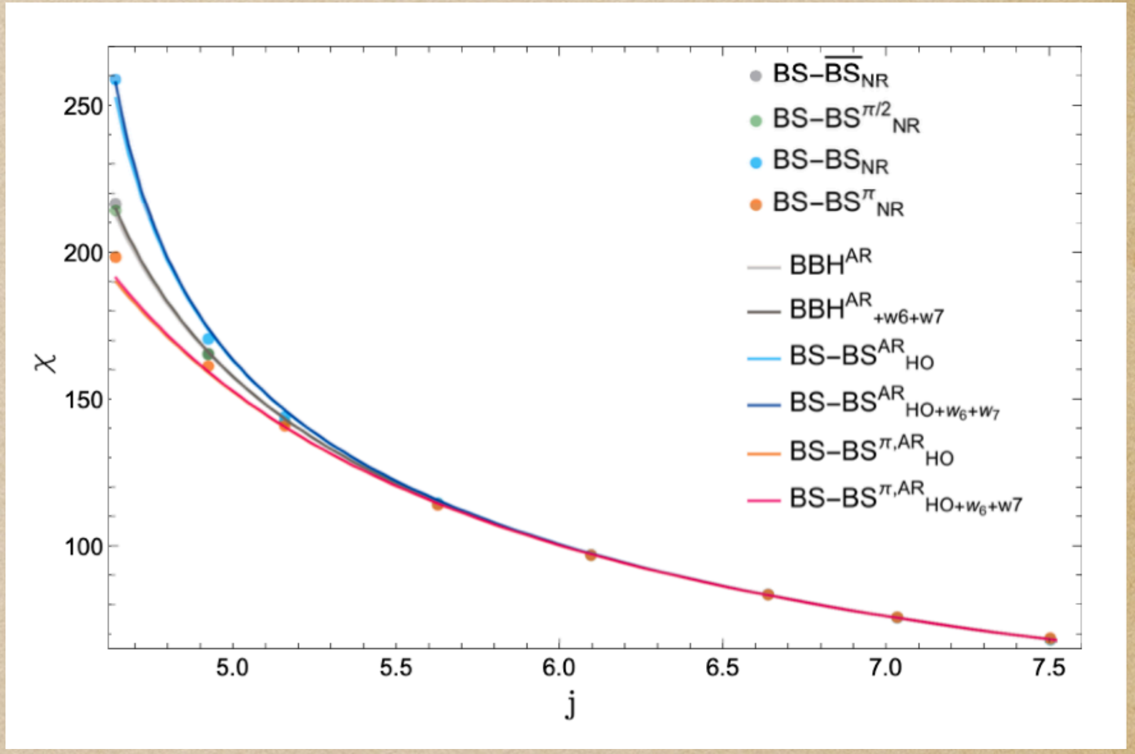
    $\chi_{\rm BH}$ to 4PM+5PM NR fitted term

  - Tidal effects:

    $\chi_{\rm tid}$ at 6PM, 7PM

  - New: Scalar-field interaction:

    $\chi_{\rm scl}$ at LO, phenom. HO terms



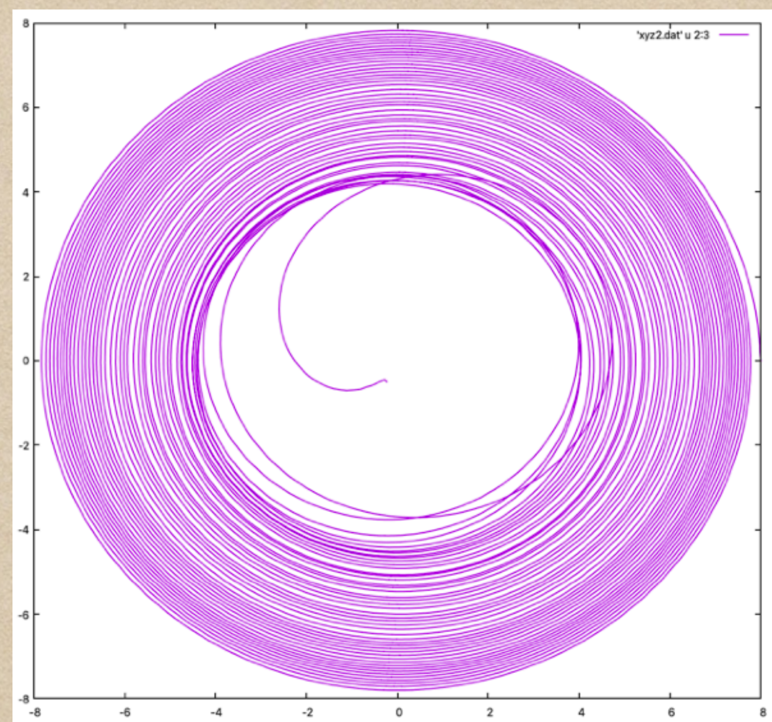
Some "weird" waveform samples

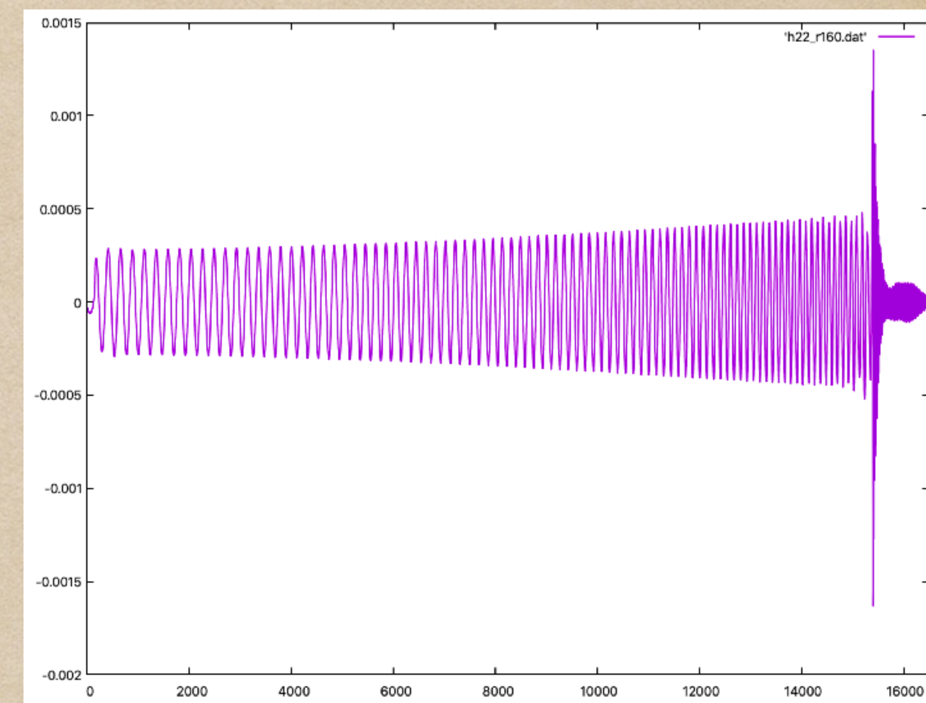
$(x(t), y(t))$

$h_{22}(t)$

$q = 1,$

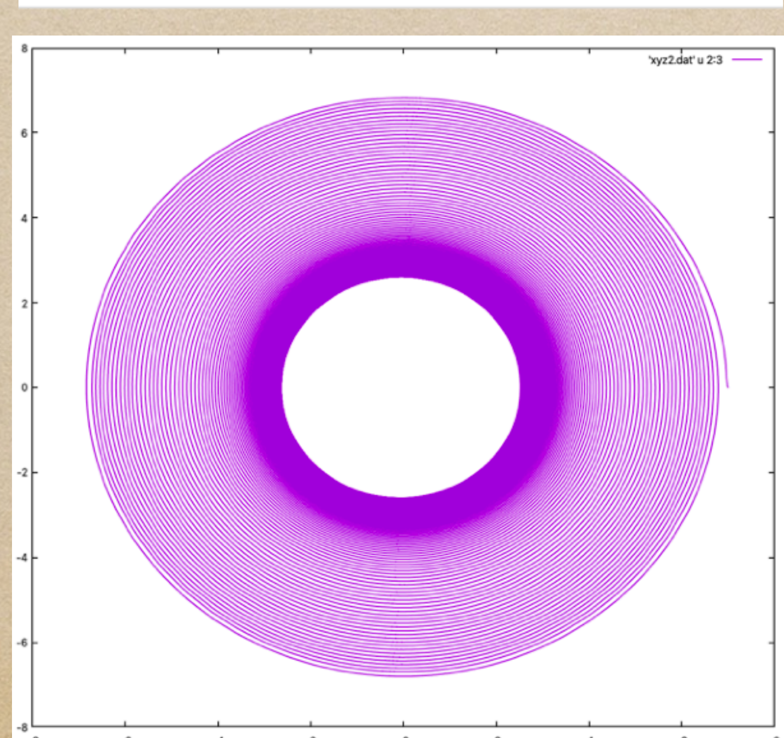
$\delta\Phi = 120^\circ$

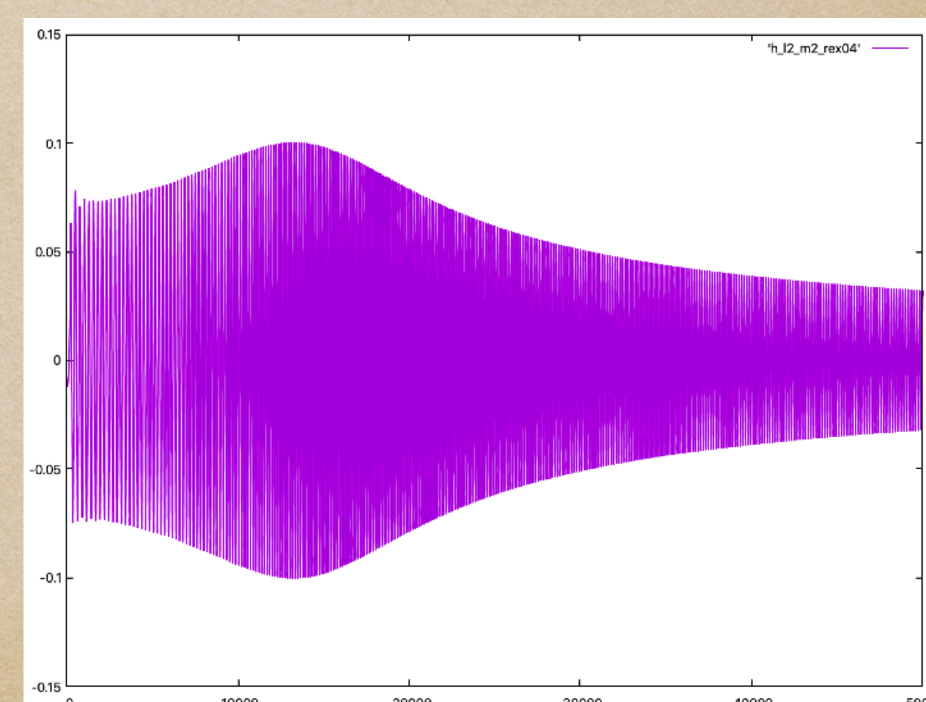




$q = 1,$

$\delta\Phi = 180^\circ$





4. BH Mimickers and (In)Stability

Black-hole mimickers

- Ultracompact objects with light ring but no horizon
- Observational evidence for BHs
  - Accretion
  - GWs + QNM ringdown

  Related closely to light rings rather than event horizon

Talk Seppe Staelens!

- Theorem: Smooth compact objects with light ring have at least two light rings, one them stable. Cunha, Berti & Herdeiro PRL 2017
- Stable LRs = attractor for (massless) particles → Instability?

  Keir CQG 2016, Cardoso et al PRD 2014, Cunha 2503.00117
- NR simulations of ultra compact boson stars inconclusive:
  - Migration or BH collapse: Cunha et al PRL 2023
  - Long-term stable BS evolutions: Marks et al PRL 2025, Evstafyeva et al 2508.11527, Siemonsen PRL 2024

Ergoregion Instability

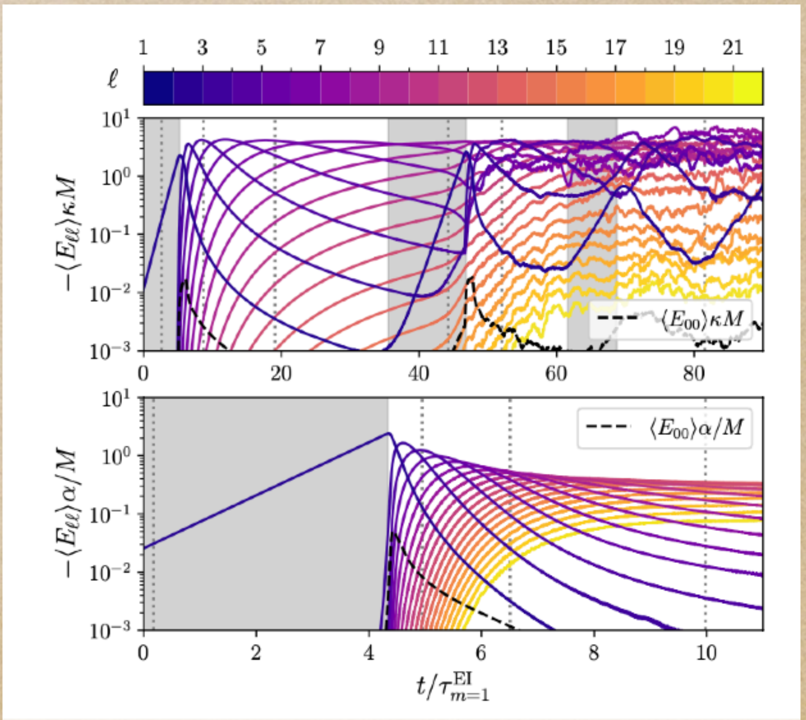
- Ergoregion = All dragged in rotation sense
- Horizonless compact objects with ergoregion

  → Ergoregion Instability: Exponential growth of negative energy modes through energy emission to ∞

Friedmann C.Ma.Ph. 1978, Vilenkin Ph.Lett.B 1978, Moschidis C.Ma.Ph. 2018

- Cf. R-Mode Instability of Neutron stars, but unlike Superradiance
- NR simulations of rapidly spinning BSs and toy problem:
  - $e-$folding time can be $10^4\,M$
  - $l = m = 1$ retrograde mode grows
  - Then turbulent cascade
  - (short) NR runs: No instability

Siemonsen 2510.07467, 2510.07468

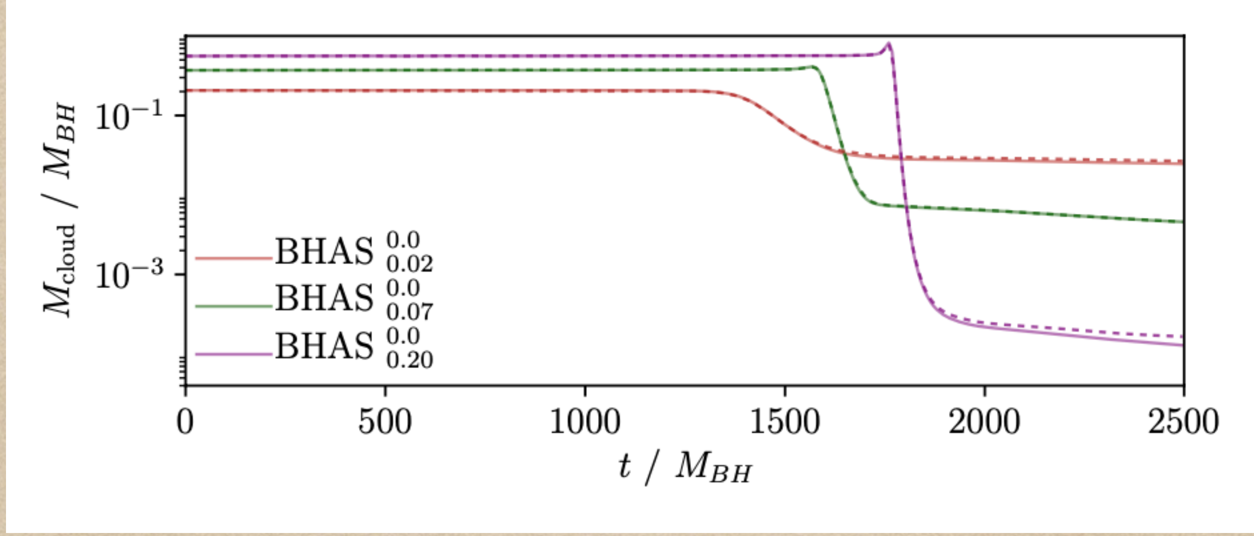


5. Mixed binaries

Mixed Axion-Star Binaries

- Axion Star - NS/BH collisions
  - BAM, GRChombo codes
  - AS-NS → Remnant BH (NS) with small (large) axion cloud
  - AS-BH → Remnant BH with $\leq 30\,\%$ axion cloud

Clough, Dietrich & Niemeyer PRD 2018



- Some GW, EM signatures from AS-NS mergers

Dietrich et al MNRAS 2018

BH-BS Binaries

- ”Piercing papers”

  Cardoso et al PRD 2022, Zhong et al PRD 2023

  BH passing through a fluffy mini or solitonic BS:

  $\gtrsim 90\,\%$ of BS mass accreted, even for light BHs (test particle limit)

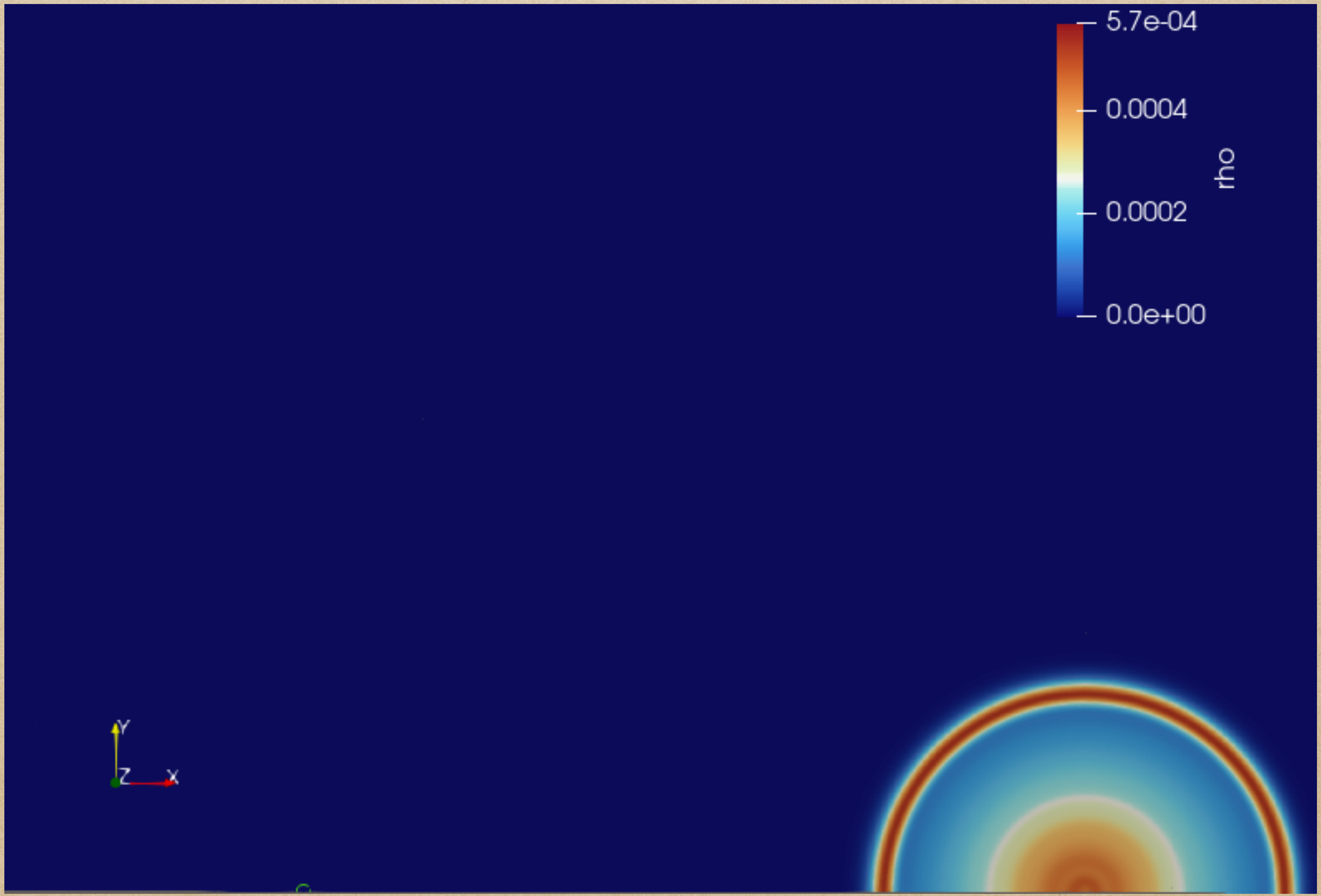
- Head-on collisions and orbital evolutions of BH-BS binaries

  Marks, Staelens & Sperhake in prep.

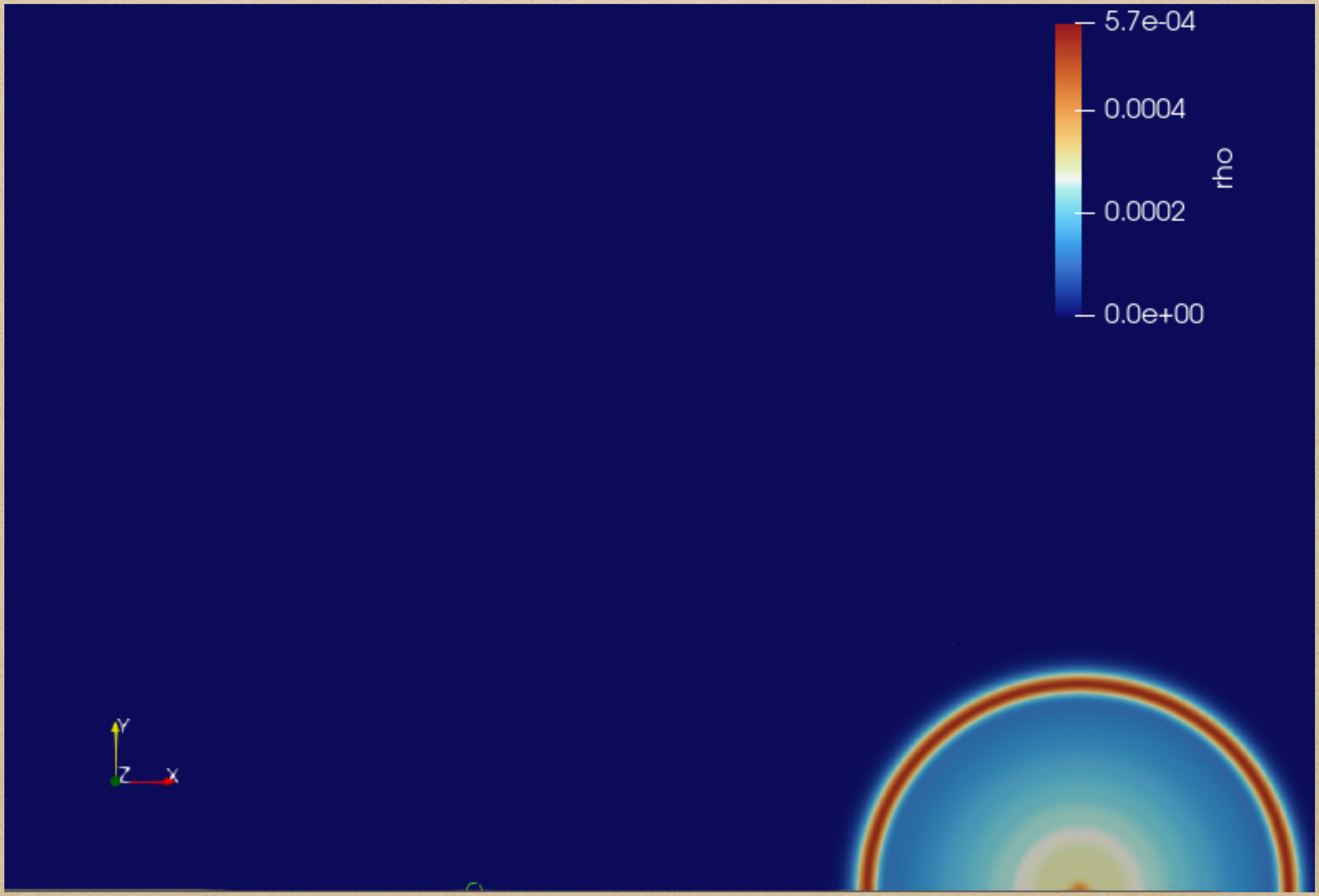
  - GRChombo code
  - CCZ4 formulation
  - Constant-Volume-Element initial data
  - Example: Thin-Shell BS Head-on collision with BH

  Credit to Gareth Marks!!!

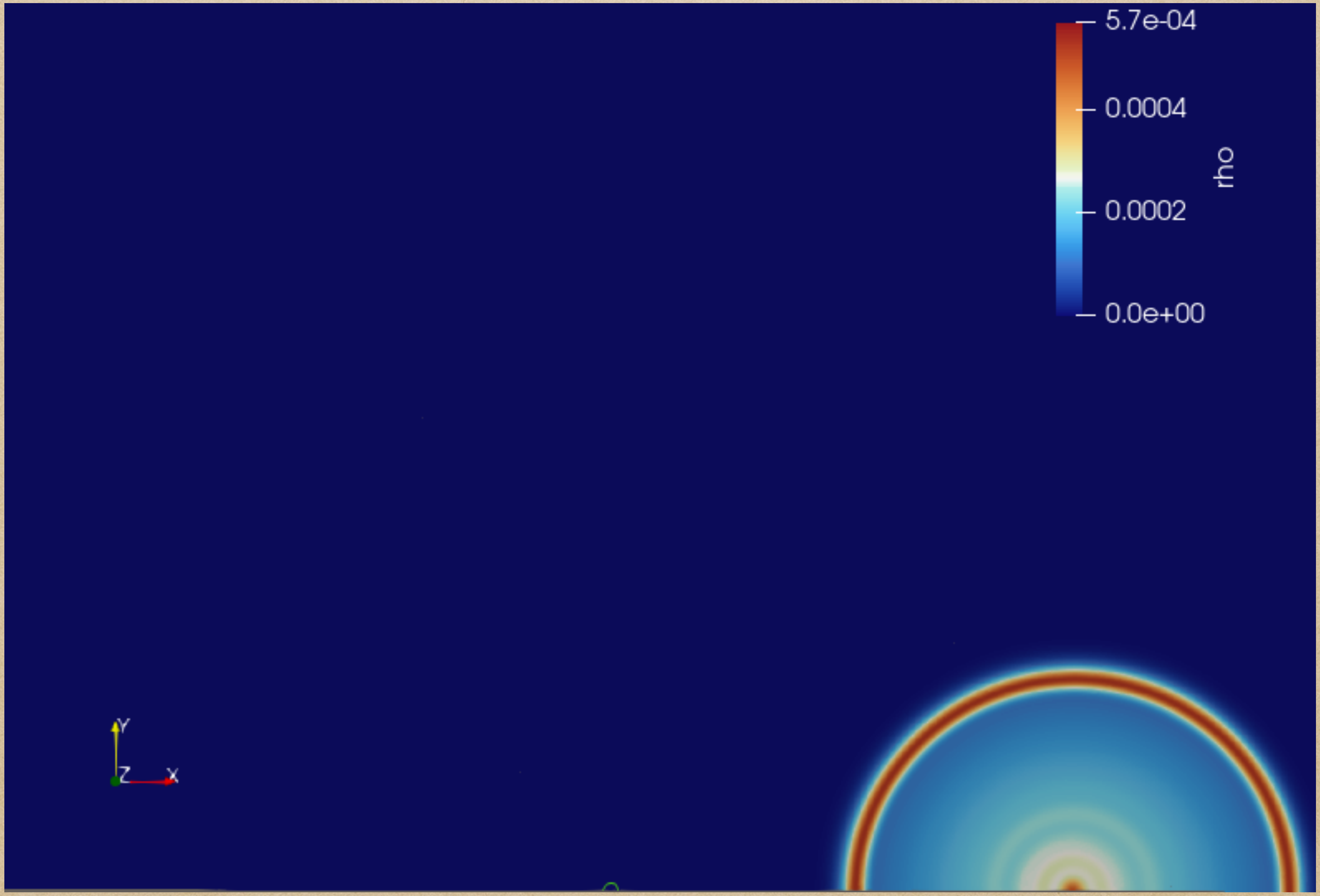
BH-BS Binaries



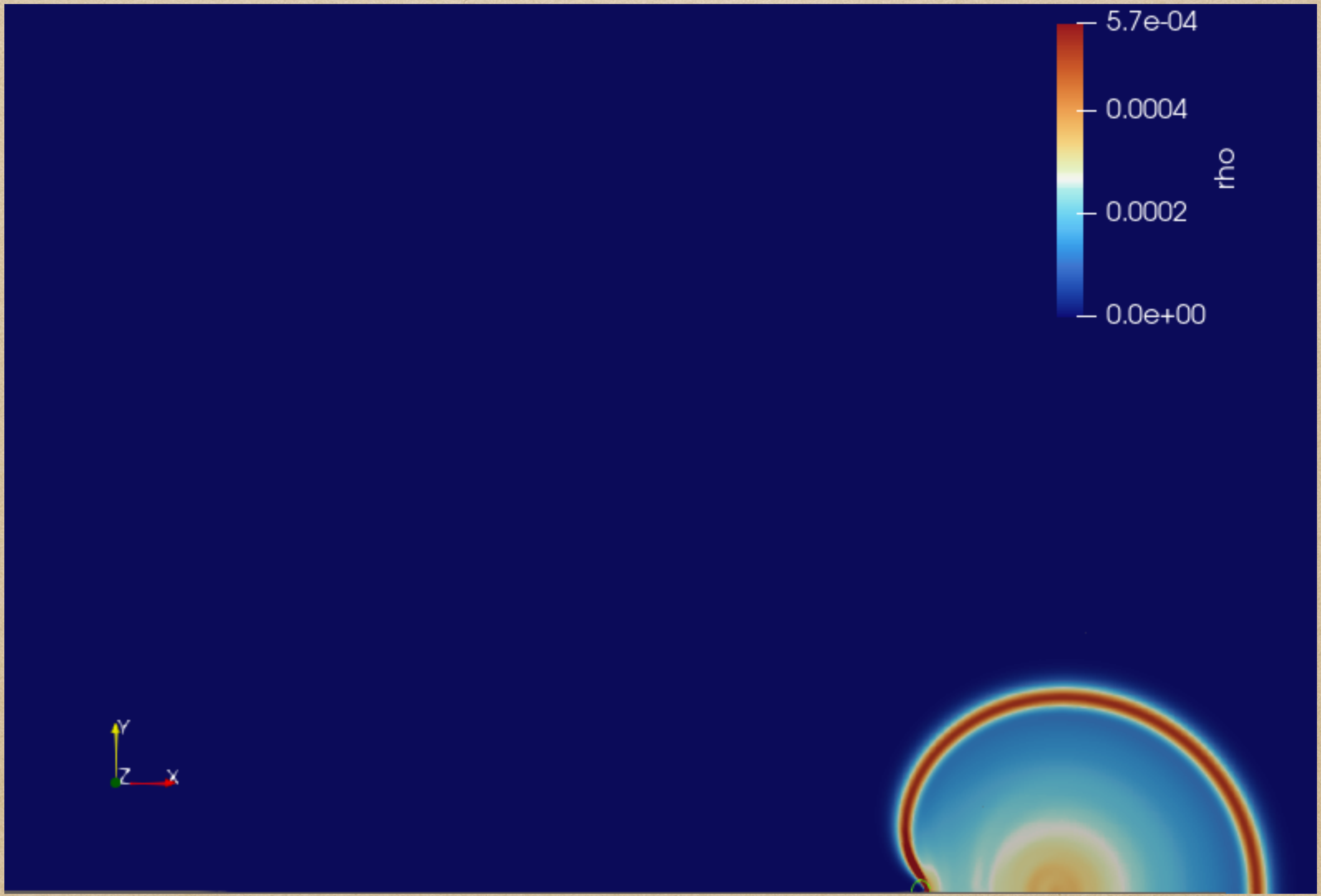
BH-BS Binaries



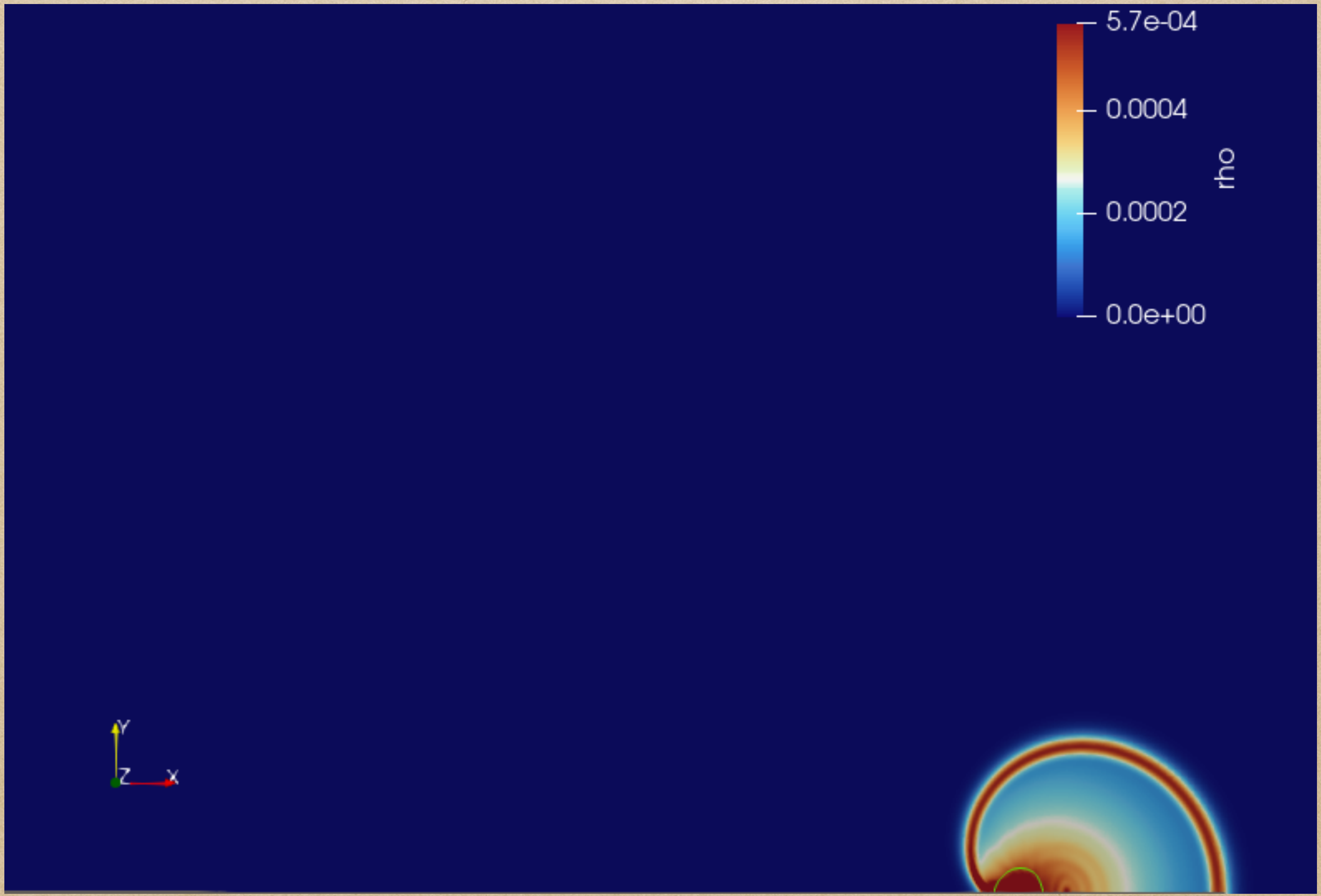
BH-BS Binaries



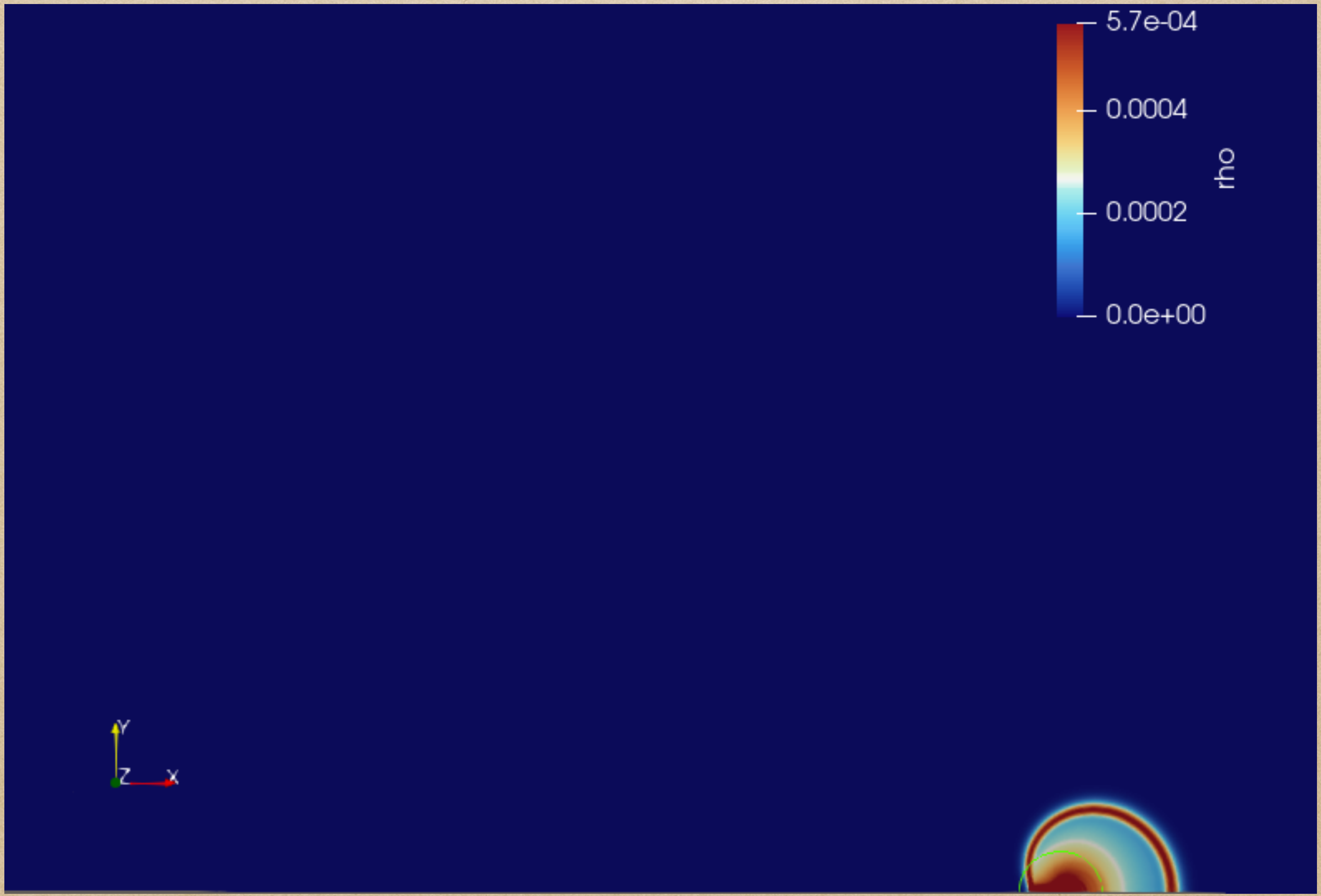
BH-BS Binaries



BH–BS Binaries



BH-BS Binaries



6. Summary

Conclusions

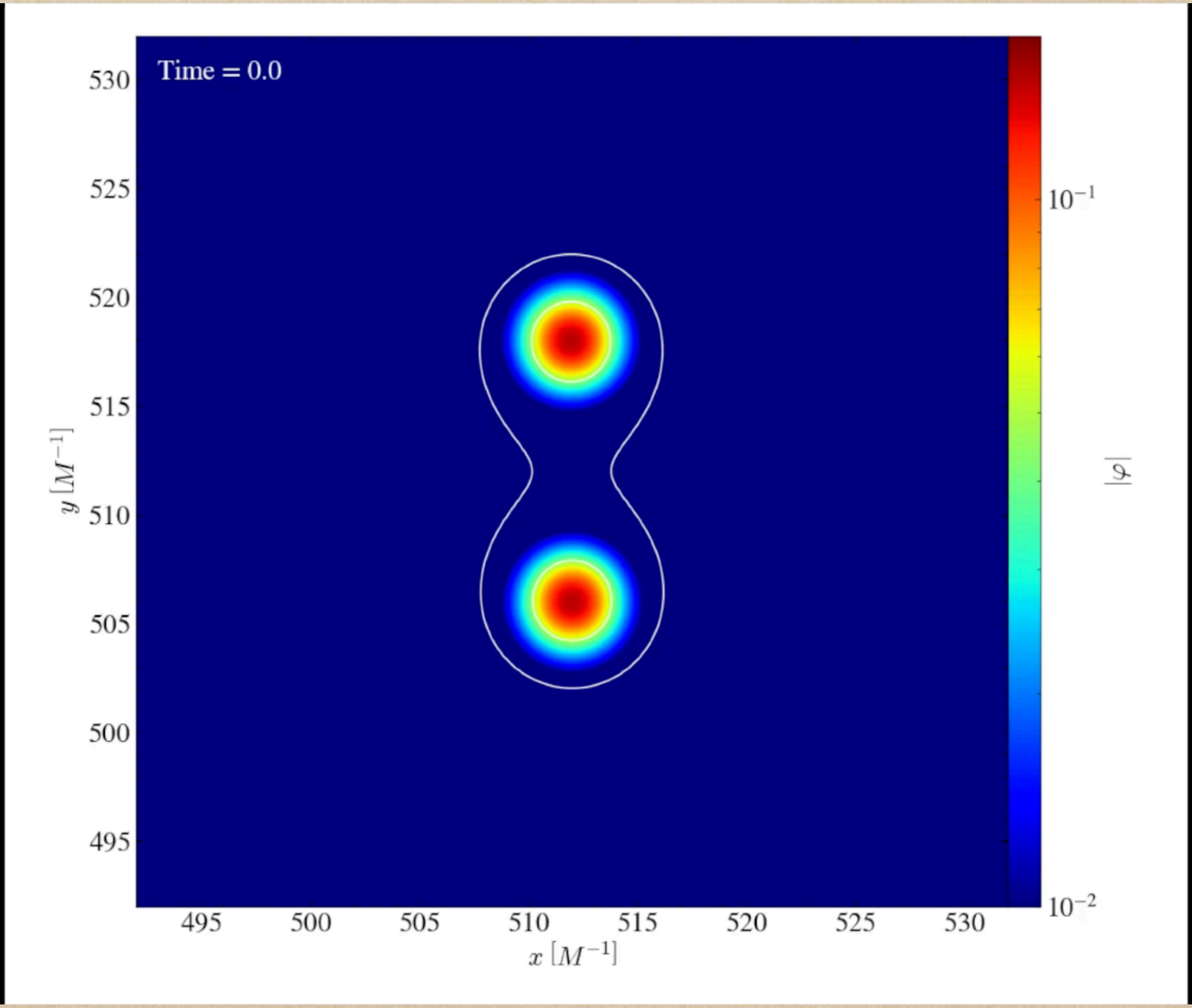
- BS highly amenable to NR! (Perhaps only ECO to be so…)
- Wide range of compactness and mass
- Stable and unstable branches similar to neutron stars
- Spin quantized; may form…
- Compact BBSs can look similar to BBHs → BS-BH degeneracy
- Three main contributions to GW forms: BH, Tidal, Field interaction
- Genuine BH Mimickers: Light ring + no horizon; seem to be stable
- Ergoregion instability

Next Challenges

- Need systematic NR waveforms
- Need for improved initial data!
- Need analytic waveform models
- Various stability questions: Spinning BSs, BH mimickers, ergoregion
- Mixed binary modeling in its infancy (foetus more like it…)

4. Extra slides

Example boson-star inspiral



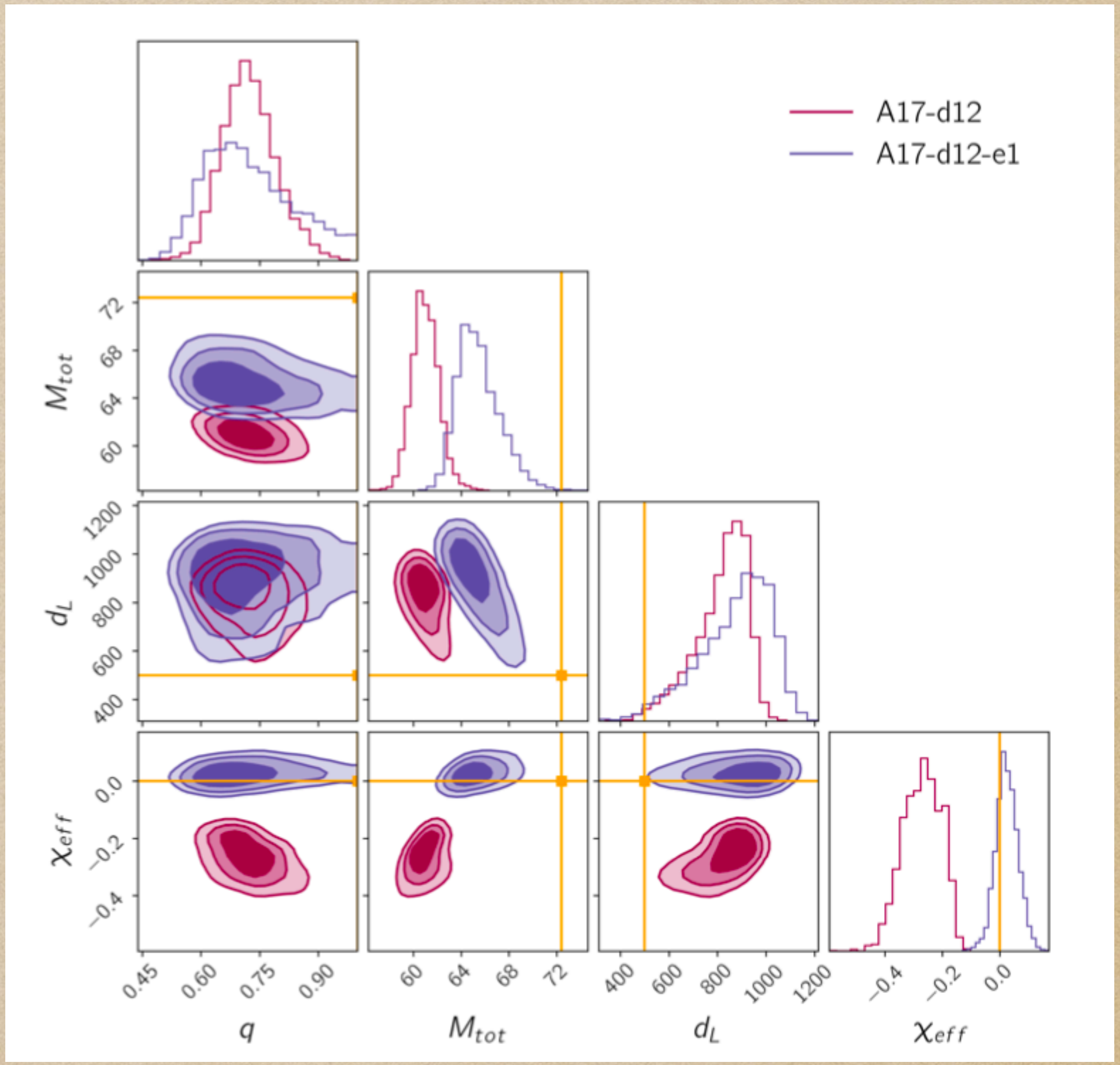
Courtesy of T Evstafyeva

Results using IMRPhenomXP

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

  Corner plot:

  A17-d12-e1 vs. A17-d12

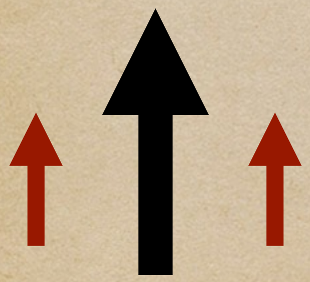


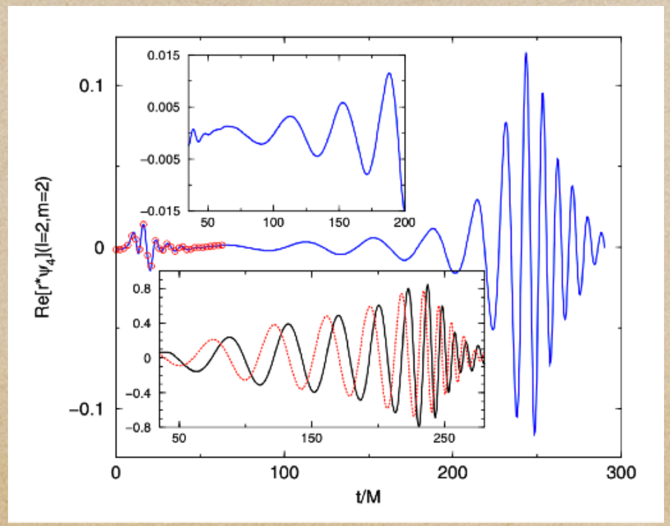
- These features can be explained with the chirp strength

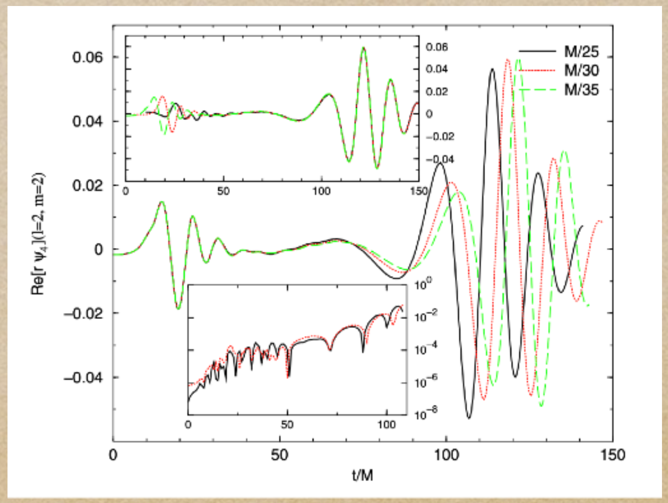
Understanding the PE bias

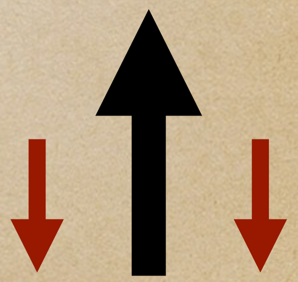
- Main feature: Steepness of chirp
- For non-spinning BH binaries:
  - equal mass ⇒ shallow chirp
  - unequal masses ⇒ steep chirp (think of EMRIs)
- For spinning BH binaries:
  - aligned spins ⇒ shallow chirp
  - anti-aligned spins ⇒ steep chirp

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









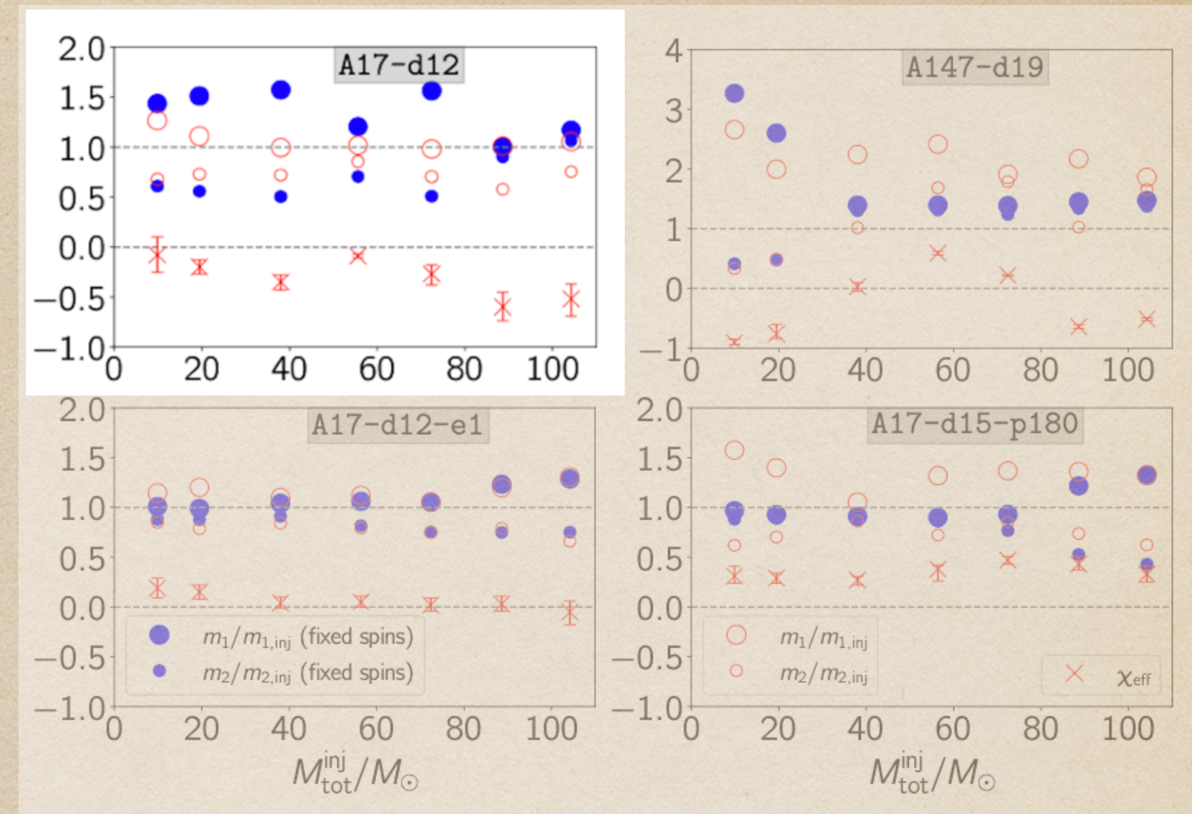
Understanding the PE bias: Standard BS

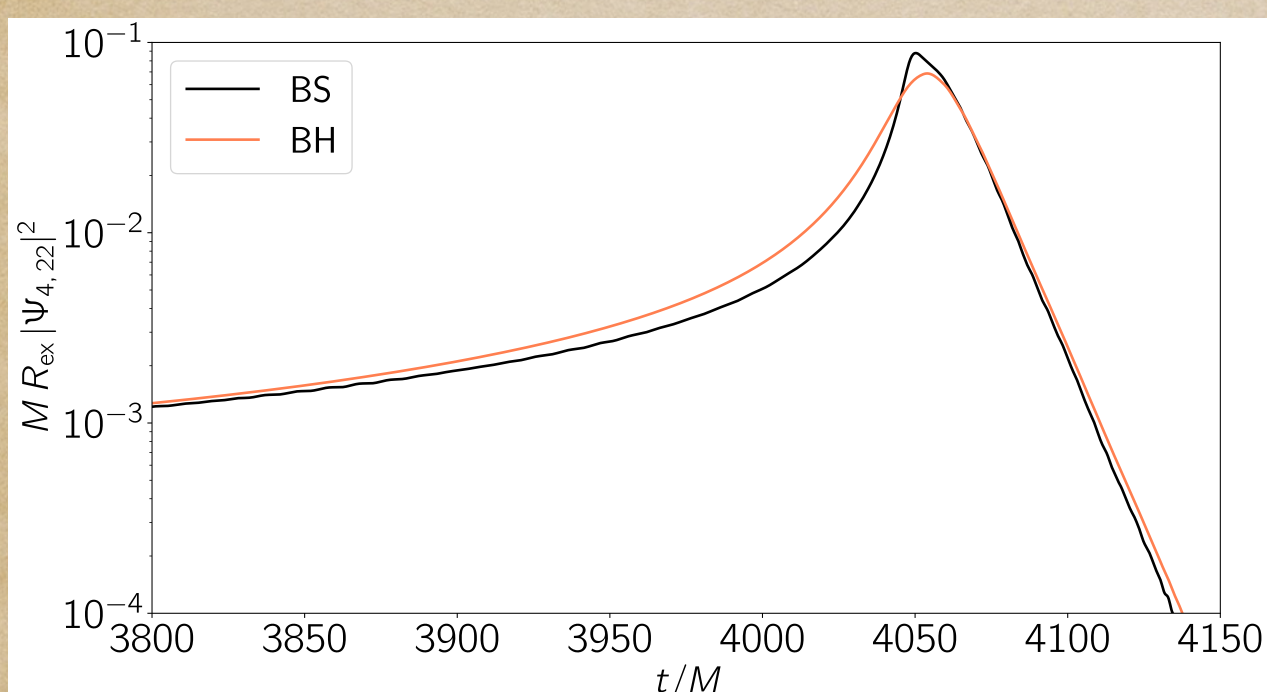
<u>Fixed spins</u>

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

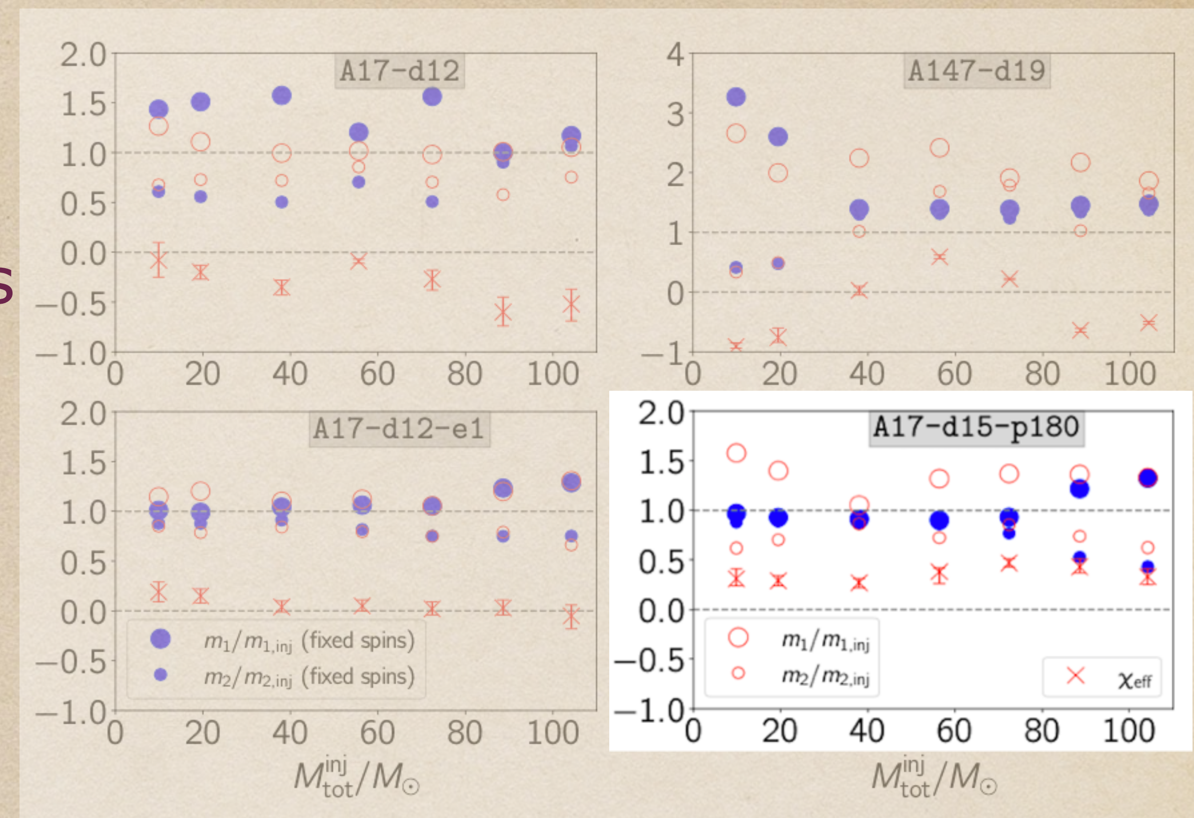
Understanding the PE bias: anti-phase

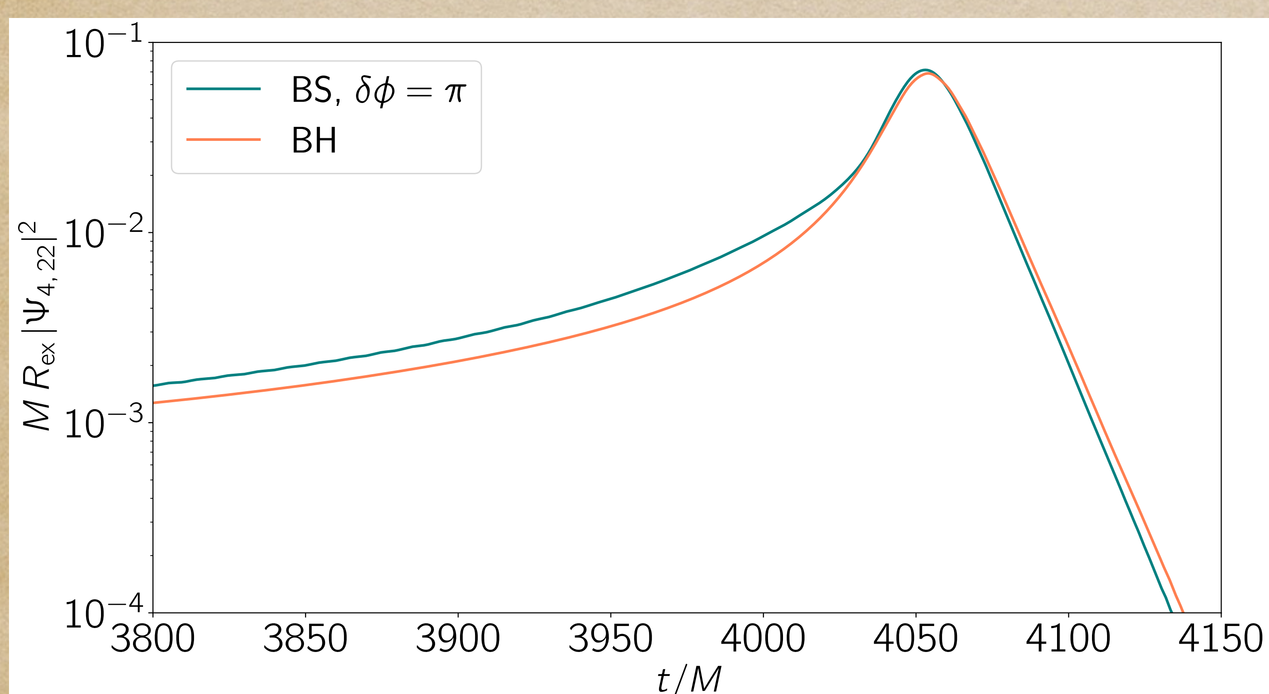
<u>Fixed spins</u>

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

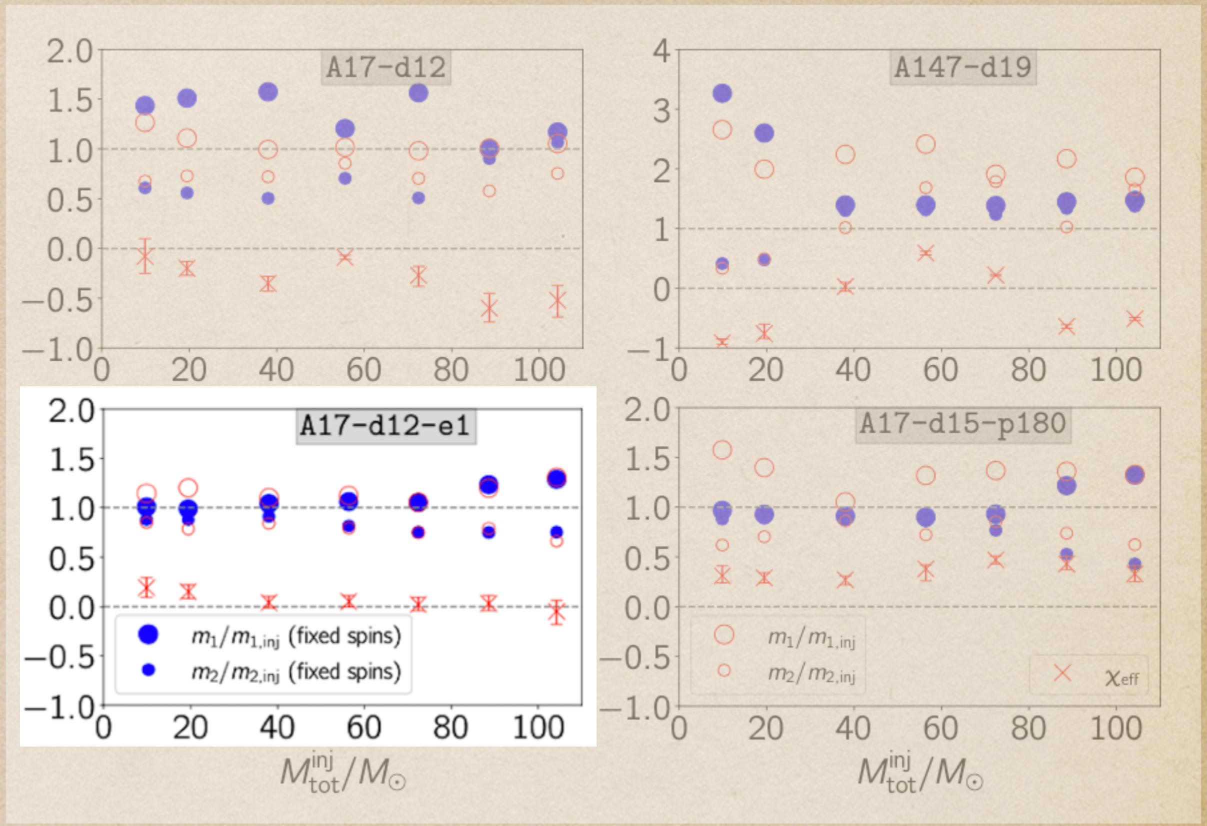
Understanding the PE bias: anti-BS

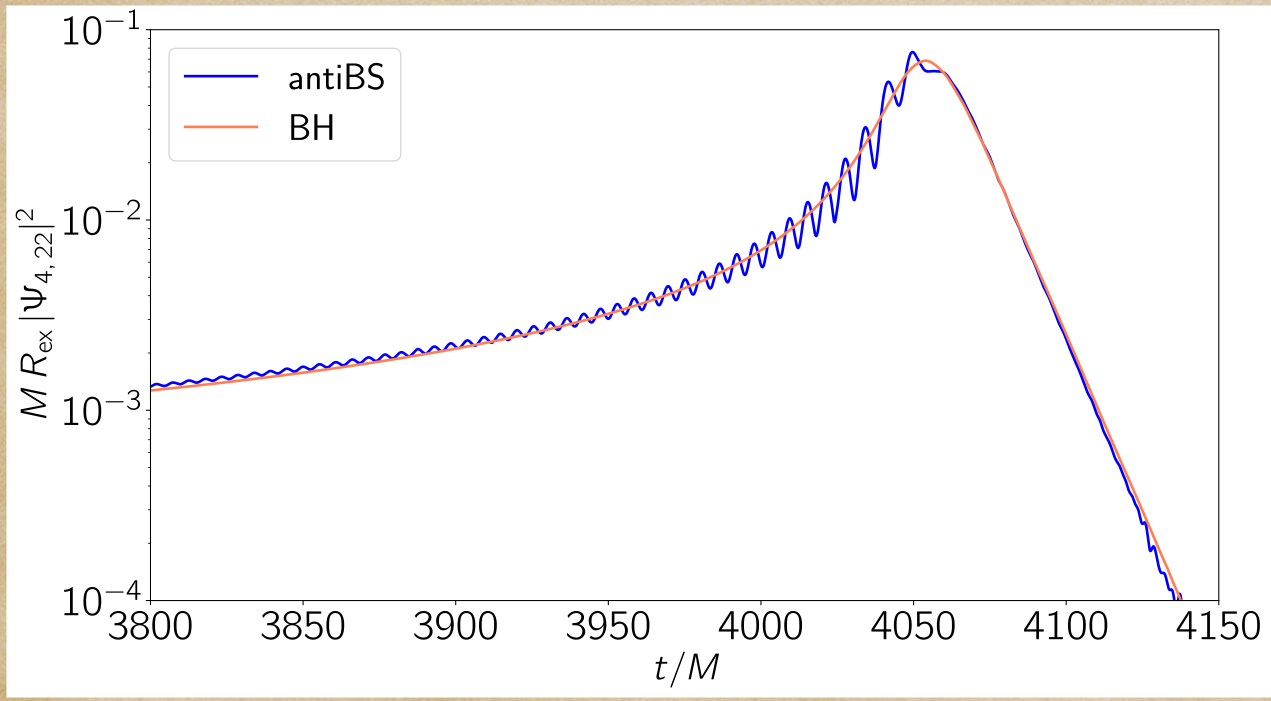
Fixed or variable spins

BS chirp similar to BHs

⇒ Comparable mass ratios

∧ Small spins



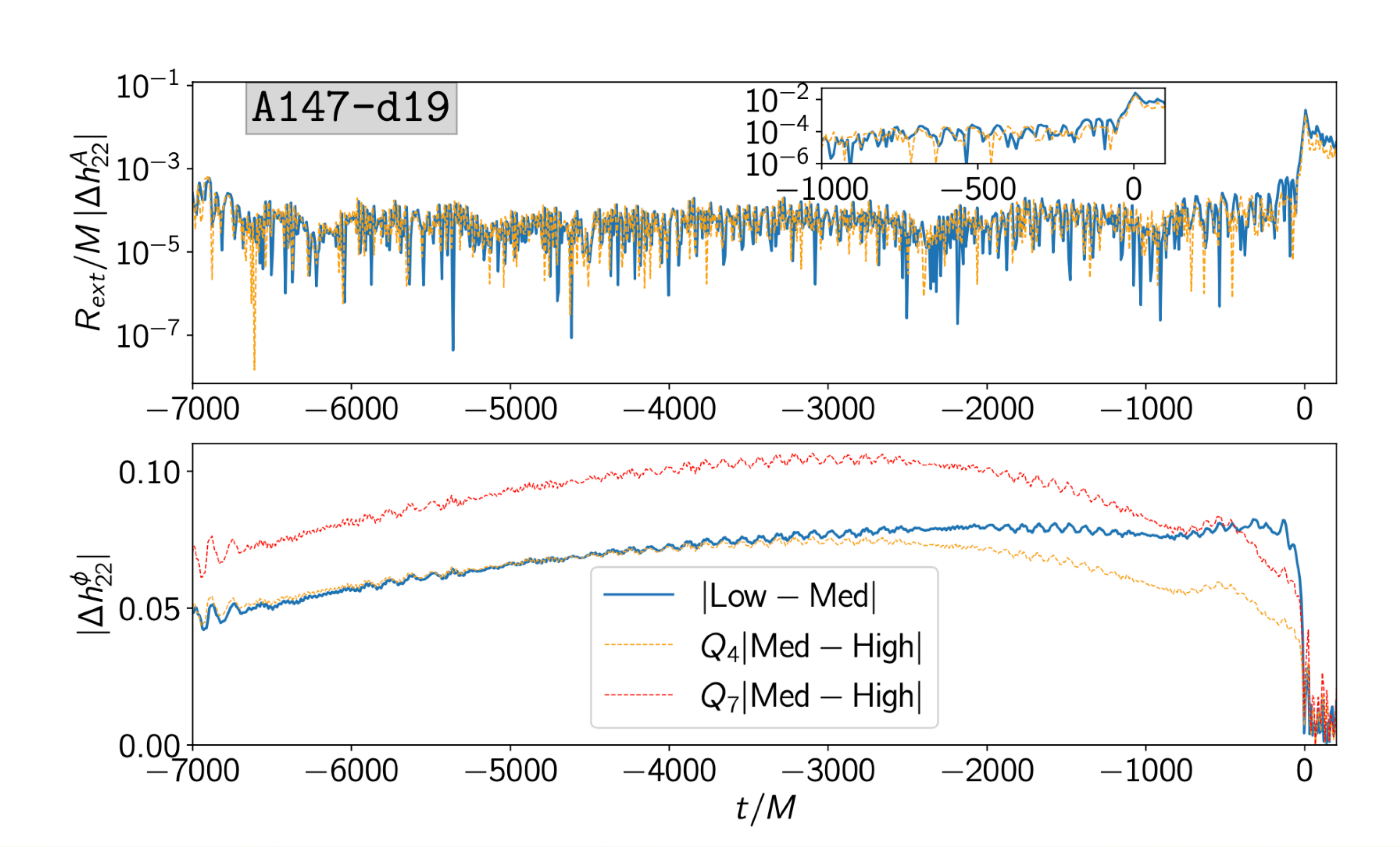


High-mass regime

LIGO mainly sees merger burst

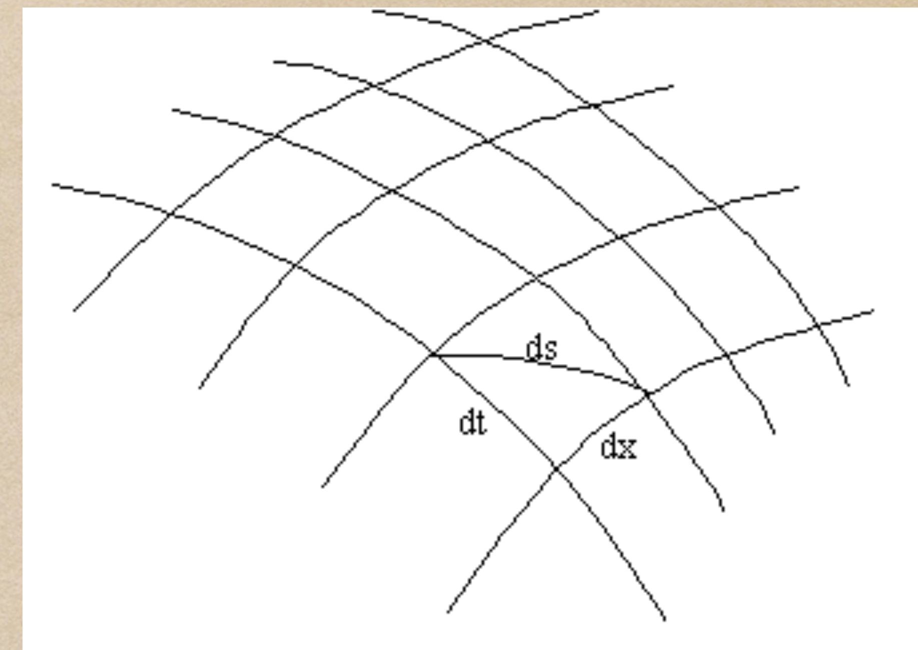
⇒ Less reliable PE

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

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

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

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

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

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

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:

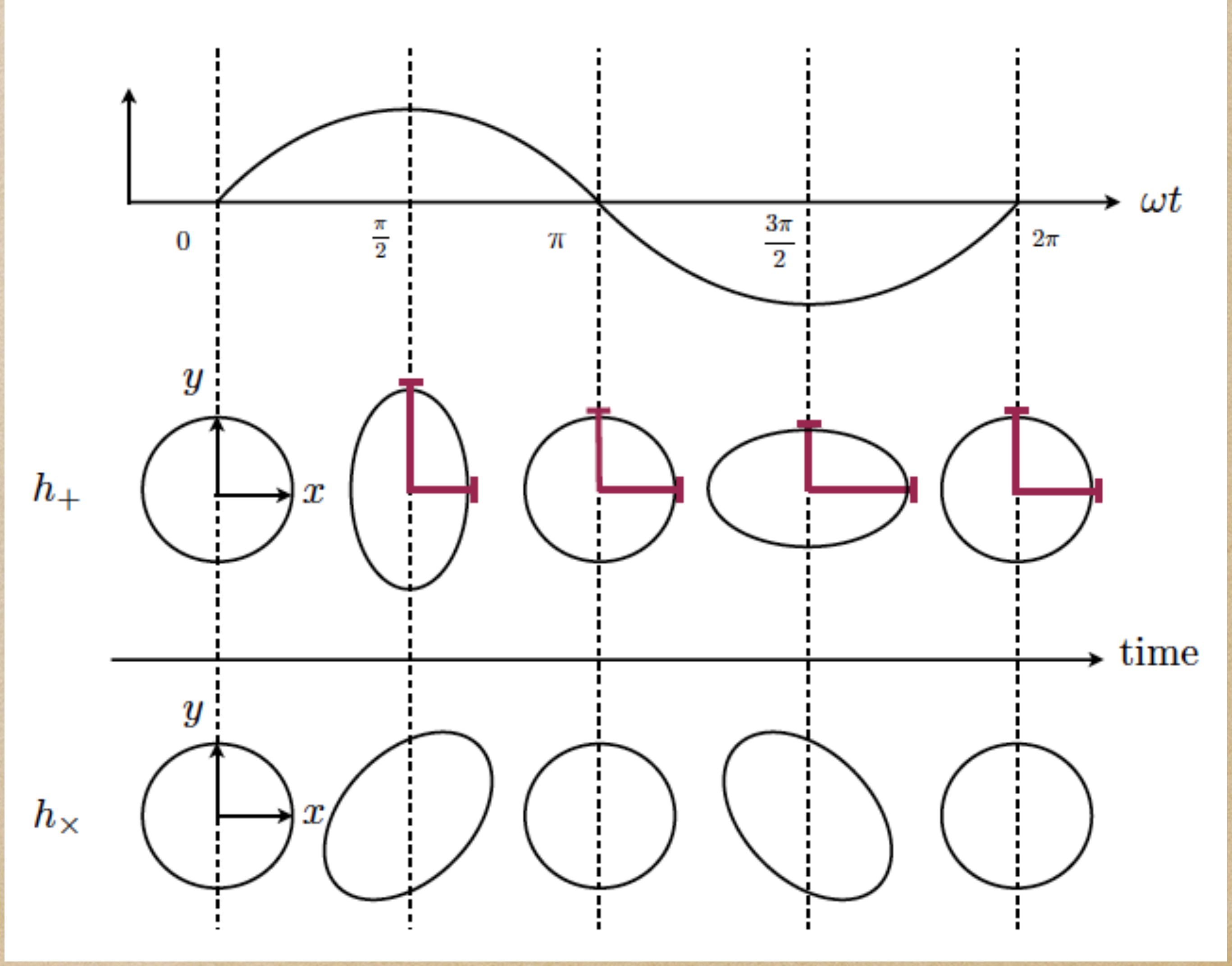
$$ds^2 = -dt^2 + (1+h_+)\,dx^2 + (1-h_+)\,dy^2 + 2h_\times\,dx\,dy + dz^2$$

- Effect on test particles:

Mirshekari 1308.5240

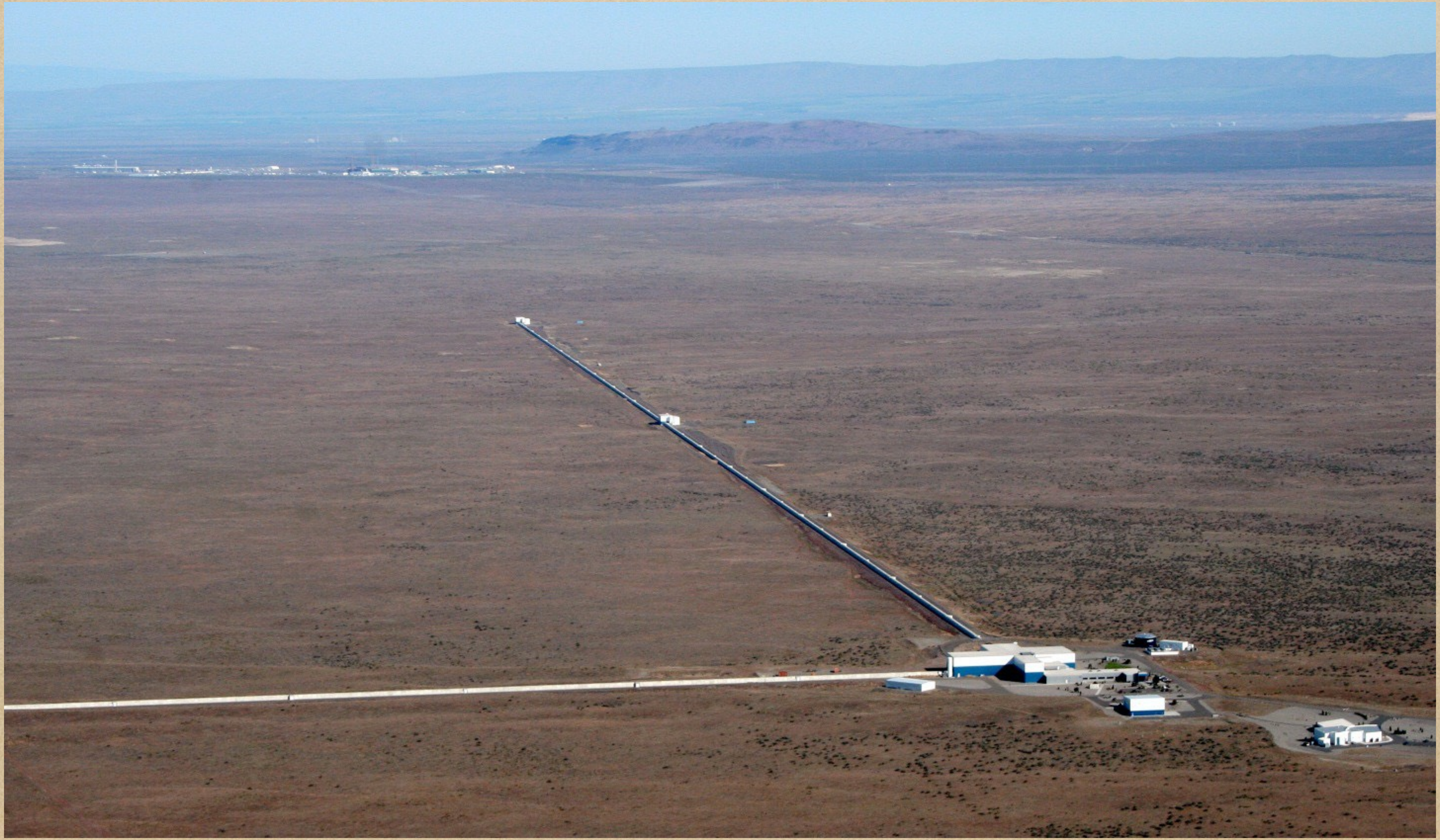
- Debate on physical reality until late 1950s

e.g.Saulson GRG (2011)

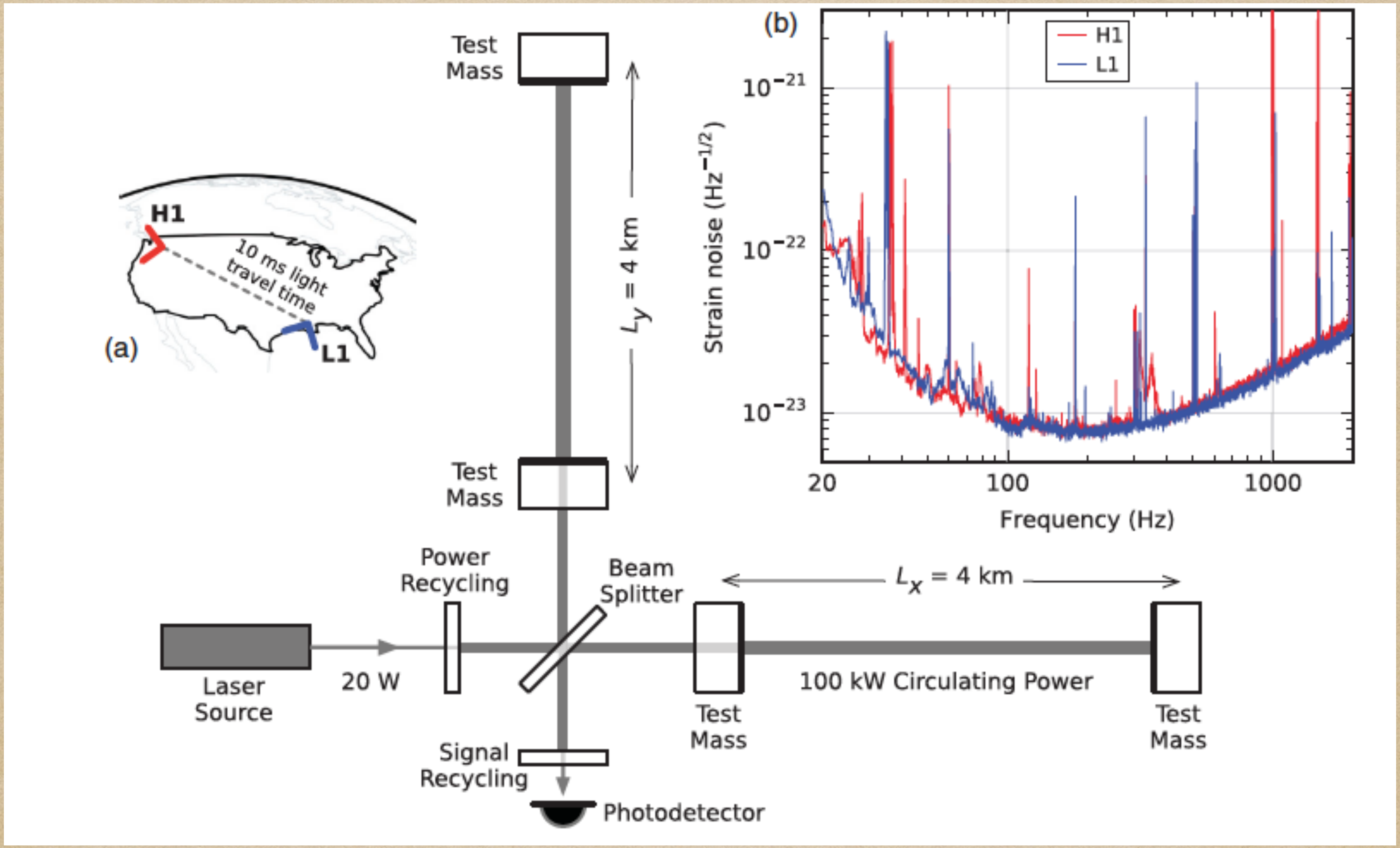


Effect on particles

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