Distinguishing boson stars from black holes and neutron stars with tidal interactions

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Phys. Rev. **Dxx** xxx (2017)

Outline

1. Introduction
2. Tidal deformability of boson stars
3. Distinguishing boson stars from neutron stars and black holes
4. Conclusions

(To be fleshed out)

Probing new physics with gravitational waves

Gravitational waves provide an unprecedented view into the *highly dynamical, strong-field regime* of gravity

Detectors may be sensitive to new physics that emerge in this regime as:

1. modifications to general relativity
2. compact objects composed of exotic matter

Measuring (or constraining) new physics in an observed gravitational wave requires accurate waveform models.

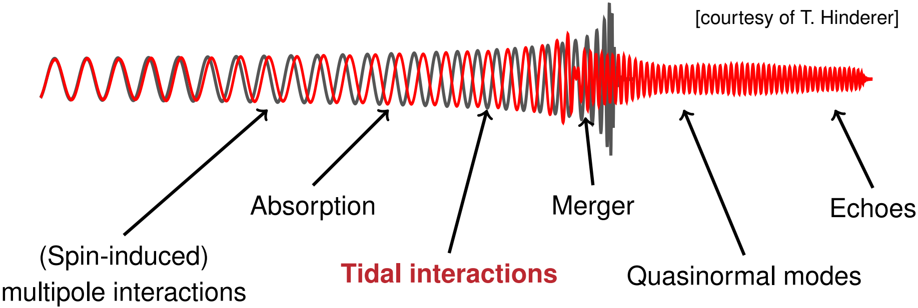
(See Chris van den Broeck's plenary talk on Thursday)

Probing new physics with gravitational waves

Can gravitational wave detectors distinguish *exotic compact objects* from black holes and/or neutron stars?

The bodies' composition impacts each part of the gravitational wave:

[courtesy of T. Hinderer]

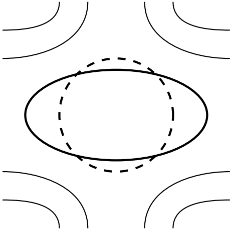


An abridged bibliography: [Chirenti+, 2007], [Pani, 2015], [Macedo+, 2013], [Cardoso+, 2016], [Cardoso+, 2017], [Krishnendu+, 2017] , [Bezares+, 2017], [Maselli+, 2017], . . .

Tidal interactions in compact binary systems

In a binary, the gravitational field from each body deforms its companion.

Decomposed into STF tensors, the response of each body is characterized by *dimensionless tidal deformabilities* Λ_ℓ



$$\mathcal{Q}_{i_1 \ldots i_\ell} = -\Lambda_\ell^{(E)} M^{2\ell+1} \mathcal{E}_{i_1 \ldots i_\ell}$$
$$\mathcal{S}_{i_1 \ldots i_\ell} = -\Lambda_\ell^{(B)} M^{2\ell+1} \mathcal{B}_{i_1 \ldots i_\ell}$$

The dominant effect in the waveform is *determined solely by* $\Lambda_2^{(E)}$

For black holes: $\Lambda_2^{(E)} = 0$ For neutron stars: $10^1 \lesssim \Lambda_2^{(E)} \lesssim 10^4$

We compute $\Lambda_2^{(E)}$ for a particular class of exotic compact objects and estimate whether such objects can be distinguished from black holes and neutron stars by measuring their tidal deformability

Boson stars

Boson stars are self-gravitating configurations of a complex scalar field

$$S = \int d^4x \sqrt{-g} \left[\frac{R}{16\pi} - \nabla^\alpha \Phi \nabla_\alpha \Phi^* - V(|\Phi|^2) \right]$$

Boson stars behave as *anisotropic perfect fluid stars* whose properties are determined by the potential $V(|\Phi|^2)$.

Boson stars

Boson stars are self-gravitating configurations of a complex scalar field

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi} - \nabla^\alpha\Phi\nabla_\alpha\Phi^* - V(|\Phi|^2)\right]$$

We consider boson star models *parameterized by two quantities*:

1. The boson mass (μ) *determines the overall size* of the star.
2. The scalar coupling (λ or σ_0) *determines the "EOS"* of the star.

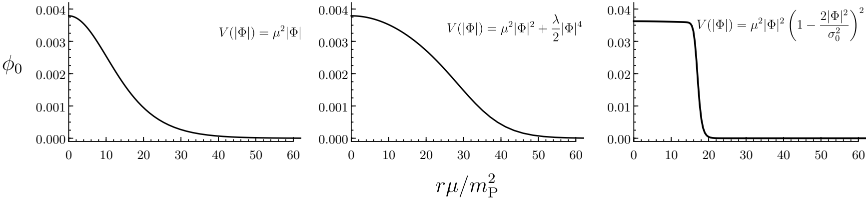
	$V(\lvert\Phi\rvert^2)$	$M_{\max}[M_\odot]$	Compactness
Mini BS	$\mu^2\Phi^2$	$\left(\frac{85\text{peV}}{\mu}\right)$	0.08
Massive BS	$\mu^2\Phi^2 + \frac{\lambda}{2}\lvert\Phi\rvert^4$	$\sqrt{\lambda}\left(\frac{270\text{MeV}}{\mu}\right)^2$	0.158
Neutron star		$2-4$	0.3
Solitonic BS	$\mu^2\Phi^2\left(1-\frac{2\lvert\Phi\rvert^2}{\sigma_0^2}\right)^2$	$\left(\frac{\mu}{\sigma_0}\right)^2\left(\frac{700\text{TeV}}{\mu}\right)^3$	0.349
Black hole		∞	0.5

Boson stars

We consider *spherically symmetric, non-spinning* boson stars in their ground state

$$ds_0^2 = -e^{v(r)}dt^2 + e^{u(r)}dr^2 + r^2 d\Omega^2$$

$$\Phi_0(t,r) = \phi_0(r)e^{-i\omega t}$$



Computing the tidal deformability of boson stars

We consider *static perturbations* to the metric and scalar field

$$g_{\alpha\beta} = g^{(0)}_{\alpha\beta} + h_{\alpha\beta}, \qquad \Phi = \Phi_0 + \delta\Phi$$

decomposed into spherical harmonics in the Regge-Wheeler gauge

$$h_{\alpha\beta} dx^\alpha dx^\beta = \sum_{\ell \geq |m|} Y_{\ell m}(\theta, \varphi) \left[e^v h_0^{\ell m}(r) dt^2 + e^u h_2^{\ell m}(r) dr^2 + r^2 k^{\ell m}(r) d\Omega^2 \right]$$

$$\delta\Phi = \sum_{\ell \geq |m|} \frac{\phi_1^{\ell m}(r)}{r} Y_{\ell m}(\theta, \varphi) e^{-i\omega t}$$

We restrict our attention to $\ell = 2$, *even-parity perturbations*

Computing the tidal deformability of boson stars

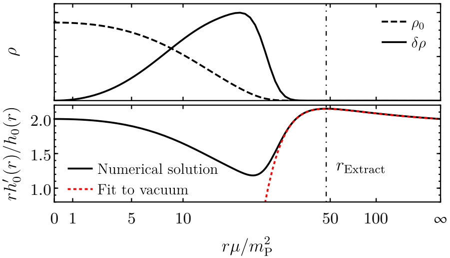
The BS "exterior" *exponentially approaches vacuum*, so h_0 satisfies

$$\lim_{r\to\infty} h_0(r) = c_1 \hat{Q}_{22}(r/M-1) + c_2 \hat{P}_{22}(r/M-1) \approx c_1 (r/M)^{-3} + c_2 (r/M)^2$$

The tidal deformability is extracted by *identifying the second and first terms with the tidal perturbation and the quadrupole moment it induces*, respectively

$$\Lambda = \frac{c_1}{3c_2}$$

By matching the numerical solution to vacuum solutions at different extraction radii r_{Extract}, *we estimate our precision on Λ at $\sim 0.1\%$*

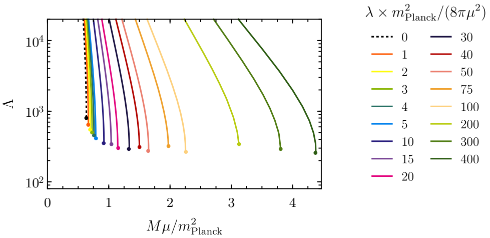


Tidal deformability of boson stars

Mini and massive boson stars

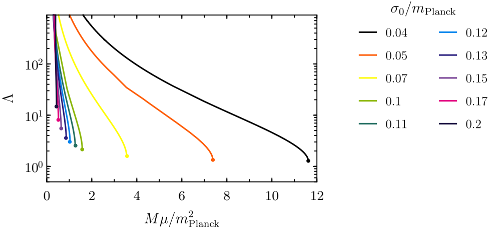
$$\sqrt{w}\tilde{M} = \left[-0.529 + \frac{22.39}{\log\Lambda} - \frac{143.5}{(\log\Lambda)^2} + \frac{305.6}{(\log\Lambda)^3}\right] w + \left[-0.828 + \frac{20.99}{\log\Lambda} - \frac{99.1}{(\log\Lambda)^2} + \frac{149.7}{(\log\Lambda)^3}\right](1-w)$$

where $w \equiv (1 + \lambda m_{\mathrm{Planck}}^2/(64\pi\mu^2))^{-1}$



Solitonic boson stars

$$\log(\sigma_0 \tilde{M}) = -30.834 + \frac{1079.8}{\log\Lambda + 19} - \frac{10240}{(\log\Lambda + 19)^2}$$



Tidal deformability of boson stars

	$V(\|\Phi\|^2)$	Compactness	Tidal Deformability
Mini BS	$\mu^2\Phi^2$	0.08	$\Lambda \gtrsim 900$
Massive BS	$\mu^2\Phi^2 + \frac{\lambda}{2}\|\Phi\|^4$	0.158	$\Lambda \gtrsim 280$
Neutron star		0.3	$\Lambda \gtrsim 5$
Solitonic BS	$\mu^2\Phi^2\left(1 - \frac{2\|\Phi\|^2}{\sigma_0^2}\right)^2$	0.349	$\Lambda \gtrsim 1.3$
Black hole		0.5	$\Lambda = 0$

(See also [Mendes+, 2016] for mini BSs and [Cardoso+, 2017] for massive and solitonic BSs)

Distinguishing black holes/neutron stars from boson stars

Distinguishing black holes/neutron stars from boson stars *hinges on our ability to measure the tidal deformability Λ with high precision*

We use a *Fisher information matrix approximation* to estimate the precision $\Delta\Lambda$ achievable by:

1. Advanced LIGO (aLIGO) at design sensitivity
2. Einstein Telescope (ET)
3. Cosmic Explorer (CE)

For each detector, we consider two fiducial systems:

A. Binary black holes (BBH) at 400 Mpc

B. Binary neutron stars (BNS) at 200 Mpc with soft (SLy) or stiff (MS1b) EOS

Fisher information matrix approximation

Let $h(f;\boldsymbol{\theta})$ be a waveform where $\boldsymbol{\theta}$ represents the parameters describing a binary system. For a signal s with *high signal to noise ratio (SNR)*, the probability distribution $p(\boldsymbol{\theta}|s)$ is given approximately by a Gaussian centered about the true values $\hat{\boldsymbol{\theta}}$ with covariance matrix

$$\Sigma^{ij} = (\boldsymbol{\Gamma}^{-1})^{ij}$$

where

$$\Gamma_{ij} = \left(\frac{\partial h}{\partial \theta^i}\middle|\frac{\partial h}{\partial \theta^j}\right), \qquad (a|b) = 2\int_0^\infty \frac{a^*(f)b(f) + a(f)b^*(f)}{S_n(f)}df$$

The root-mean-square measurement errors are given by

$$\Delta\theta^i_{\mathrm{RMS}} = \sqrt{(\boldsymbol{\Gamma}^{-1})^{ii}}$$

This approximation only yields a *lower bound on the errors.*

Fisher matrix estimate of tidal parameters

We model an *inspiral-only* waveform $h(f)$ with TaylorF2 (3.5PN non-spinning) with 1PN tidal corrections.

Leading-order tidal effects are parametrized by the symmetric average

$$\tilde{\Lambda}(m_1, m_2, \Lambda_1, \Lambda_2) = \frac{16}{13}\left[\left(1 + 12\frac{m_2}{m_1}\right)\frac{m_1^5}{M^5}\Lambda_1 + (1 \leftrightarrow 2)\right].$$

We consider only systems with total mass $M \leq 12 M_{\odot}$ so that merger occurs at frequencies $f_{\mathrm{merger}} \geq 900\,\mathrm{Hz}$.

The waveform begins at $f = 10\,\mathrm{Hz}$ and terminates at the merger frequency inferred from numerical relativity for BBH [Taracchini+, 2012] and BNS [Bernuzzi+, 2015].

Fisher matrix estimate of tidal parameters

We compute the Fisher matrix over the parameters $\boldsymbol{\theta} = \{\phi_c, t_c, \mathcal{M}, \nu, \tilde{\Lambda}\}$. The precision estimates for these observables can be translated into *bounds on the statistical uncertainty* in $\{\phi_c, t_c, m_1, m_2, \Lambda_1, \Lambda_2\}$.

$\boldsymbol{\theta}$

$\mathcal{M}$

ν

$\tilde{\Lambda}$

Measurable parameters

$$m_1 = \mathcal{M}\nu^{-3/5}(1 + \sqrt{1 - 4\nu})/2$$
$$m_2 = \mathcal{M}\nu^{-3/5}(1 - \sqrt{1 - 4\nu})/2$$

Assumptions

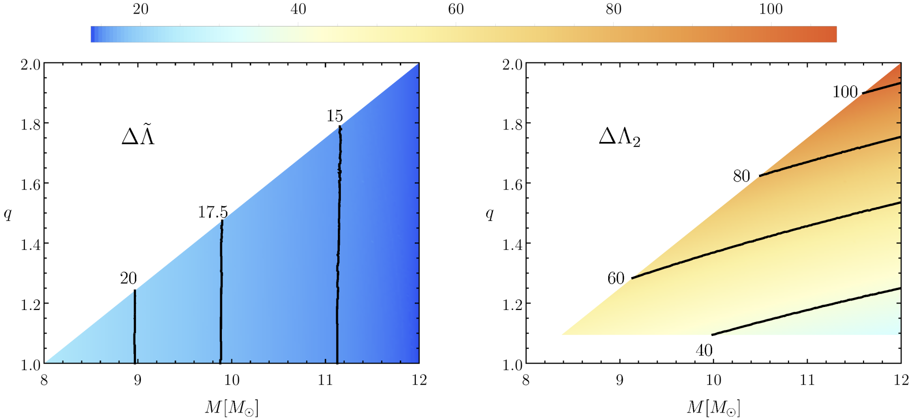
$$0 \leq \Lambda_1 \leq \Lambda_2$$

Boundable parameters

$$0 \leq \Lambda_1 \leq g_1(\nu)\tilde{\Lambda}$$
$$\Lambda_1 \leq \Lambda_2 \leq g_2(\nu)\tilde{\Lambda}$$

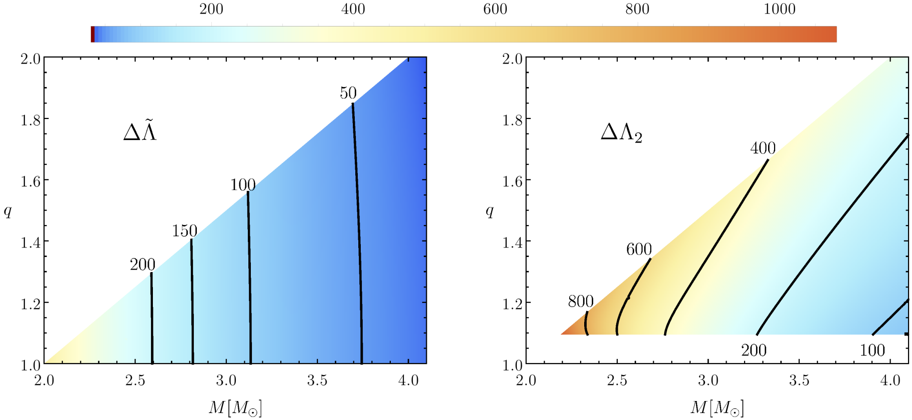
We constrain the precision of the latter observables by taking the first variation of these relations.

Fisher matrix estimate of tidal parameters: BBH



We restrict to $4M_\odot \leq m_i \leq 8M_\odot$. At 400 Mpc, $\mathrm{SNR} \sim 25$ with aLIGO. With ET and CE, the precision improves by factors of ~ 13.5 and ~ 23.5, respectively. (See also [Cardoso+, 2017]).

Fisher matrix estimate of tidal parameters: BNS



We restrict to $1M_\odot \leq m_i \leq m_{\rm max}$. At 200 Mpc, $\rm SNR \sim 15$ with aLIGO. With ET and CE, the precision improves by factors of ~ 13.5 and ~ 23.5, respectively.

Distinguishing black holes/neutron stars from boson stars

We propose two tests to determine the distinguishability of boson stars from conventional sources:

Test 1: Can we distinguish each body in the binary from a boson star?

For each boson star model, the deformability is bounded below by some $\Lambda^{\mathrm{BS}}_{\mathrm{min}}$. Can we achieve sufficient precision to constrain tidal deformability measurements in the gap $0 \leq \Lambda \leq \Lambda^{\mathrm{BS}}_{\mathrm{min}}$?

Test 2: Can we distinguish a binary system from a binary boson star system?

In a binary system whose components have deformabilities comparable to those of boson stars, can we rule out the possibility that both objects are boson stars?

Test 1: Can we distinguish each body in the binary from a boson star?

For each boson star model, the deformability is bounded below by some $\Lambda^{\rm BS}_{\rm min}$. Can we achieve sufficient precision to constrain tidal deformability measurements in the gap $0 \leq \Lambda \leq \Lambda^{\rm BS}_{\rm min}$?

For BBH at 400 Mpc, $\Delta\Lambda_i \leq 100$ with aLIGO, and thus *can be distinguished from mini and massive boson stars*. Black holes *cannot be distinguished from solitonic boson stars with aLIGO*, but could be marginally distinguished ($\Delta\Lambda \approx \Lambda^{\rm BS}_{\rm min}$) with ET and CE for nearly-equal mass systems.

For BNS at 200 Mpc, $\Delta\Lambda_i \leq 200$ with aLIGO for systems with near-maximal mass and nearly-equal mass ratio. These systems *can be distinguished from mini and massive boson stars*. However, less massive BNS cannot be distinguished because their deformability are comparable to that of boson stars, i.e. $\Lambda \geq \Lambda^{\rm BS}_{\rm min}$.

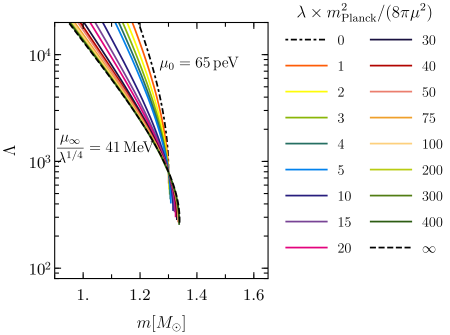
Test 2: Can we distinguish a binary system from a binary boson star system?

In a binary system whose components have deformabilities comparable to those of boson stars, can we rule out the possibility that both objects are boson stars?

If an object's deformability $\Lambda^* \gtrsim \Lambda^{\mathrm{BS}}_{\mathrm{min}}$, then the boson mass μ can be chosen to produce a boson star with the same mass and deformability (m^*, Λ^*).

In this case, single tidal deformability measurement cannot distinguish between boson stars and black holes/neutron stars.

To break this degeneracy, one must *combine measurements of both objects* in the binary.



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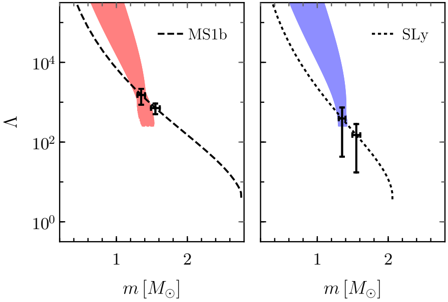


Consider a $(1.55+1.35)M_\odot$ BNS at 200 Mpc observed by aLIGO.

The shaded regions depict *all possible massive boson stars* consistent with the measurements of the smaller body.

Because the larger body is excluded from this region, *we can distinguish this BNS from a massive boson star binary system.*

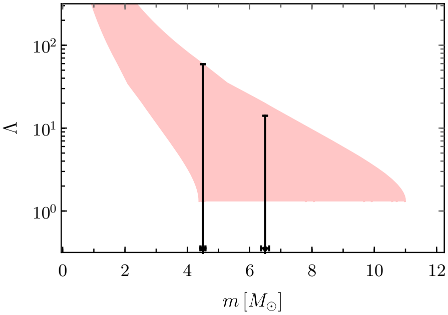
Test 2: Can we distinguish a binary system from a binary boson star system?

In a binary system whose components have deformabilities comparable to those of boson stars, can we rule out the possibility that both objects are boson stars?

Consider a $(6.5 + 4.5)M_\odot$ BBH at 400 Mpc observed by aLIGO.

The shaded regions depict *all solitonic boson stars* with $\sigma_0 = 0.05\, m_{\mathrm{Planck}}$ consistent with the measurement of the smaller body.

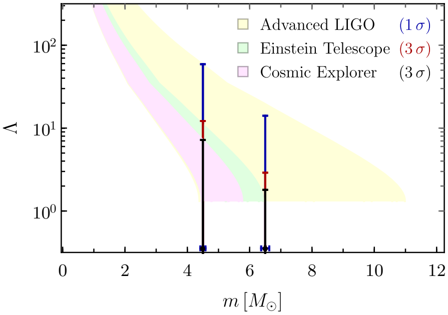
With aLIGO, *one cannot distinguish this BBH from a solitonic boson star binary.*



Test 2: Can we distinguish a binary system from a binary boson star system?

In a binary system whose components have deformabilities comparable to those of boson stars, can we rule out the possibility that both objects are boson stars?

With next-generation detectors, *this BBH can be distinguished from a solitonic boson star binary.*



Conclusions

- *Tidal interactions* occurring during the inspiral of a binary system can be used to distinguish black holes/neutron stars from *exotic compact objects*
- We computed the *tidal deformability* for three models of *boson stars* and produced fits
- We estimated the precision with which the tidal deformability can be measured using the *Fisher information matrix of TaylorF2 waveforms with tidal effects*
- We outlined *two tests* to determine whether conventional sources can be distinguished from boson stars in binary systems

		BNS	BBH
Test 1 Can we distinguish each body in the binary from a boson star?	Mini	Yes for sufficiently high-mass systems	Yes
	Massive	Yes for near-maximal mass systems	Yes
	Solitonic	No	No with aLIGO (Possibly with ET and CE for near-equal mass)
Test 2 Can we distinguish the binary system from a binary boson star?	Mini	Yes with sufficient mass ratio	Yes
	Massive	Yes with sufficient mass ratio	Yes
	Solitonic		No with aLIGO (Yes with ET and CE with sufficient mass ratio)