Title: Extracting information from LIGO/Virgo observations of compact binaries, from determining the final state to constraining properties of black hole mimickers

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Abstract: <p>Detections of compact binary coalescences with Advanced LIGO and Advanced Virgo are now starting to become routine. However, thereis still considerably more information that can be gleaned from these observations, particularly as detector sensitivity and waveform modelsboth improve. We start by describing the methods currently used in LIGO/Virgo data analysis to determine the mass and spin of the remnant black hole of the binary black hole coalescences. These black holes have the most well-measured masses and spins of any stellar-mass black holes observed and comparable or better mass accuracies to Sgr A*. We also describe the method used to obtain a lower bound on the radiated energy of the binary neutron star coalescence GW170817, and discuss further information one can extract from these observations by postprocessing parameter estimation results. We also describe a method for placing constraints on properties of black hole mimickers, such as boson stars or gravastars, if binaries of these objects are to produce the signals identified as coming from binary black holes. We present initial results of the method applied to injections in simulated noise, and as a proof of principle show how it is possible to rule out or constrain the properties of a specific model of boson stars using a given detection.</p>

G1800807-v1

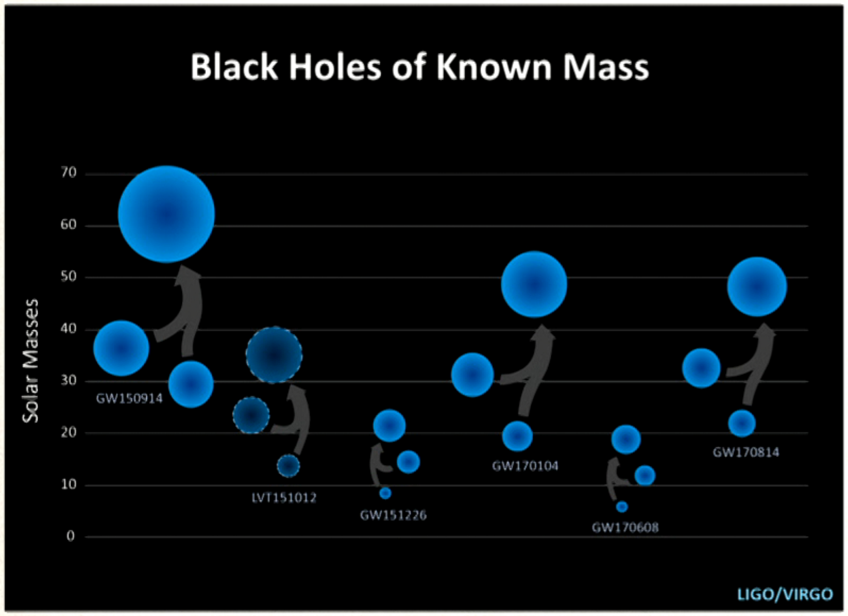
Extracting information from LIGO/Virgo observations of compact binaries:

From determining the final state to constraining properties of black hole mimickers

N. K. Johnson-McDaniel
Perimeter Institute strong gravity seminar

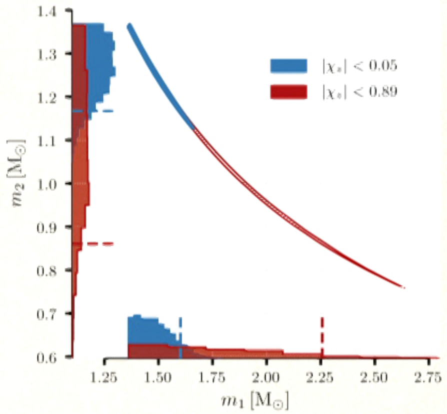
3.5.2018

Motivation



Credit: LSC / Sonoma State University / Aurore Simonnet

Binary neutron star
GW170817



LVC, PRL **119**, 161101 (2017)

Motivation (cont.)

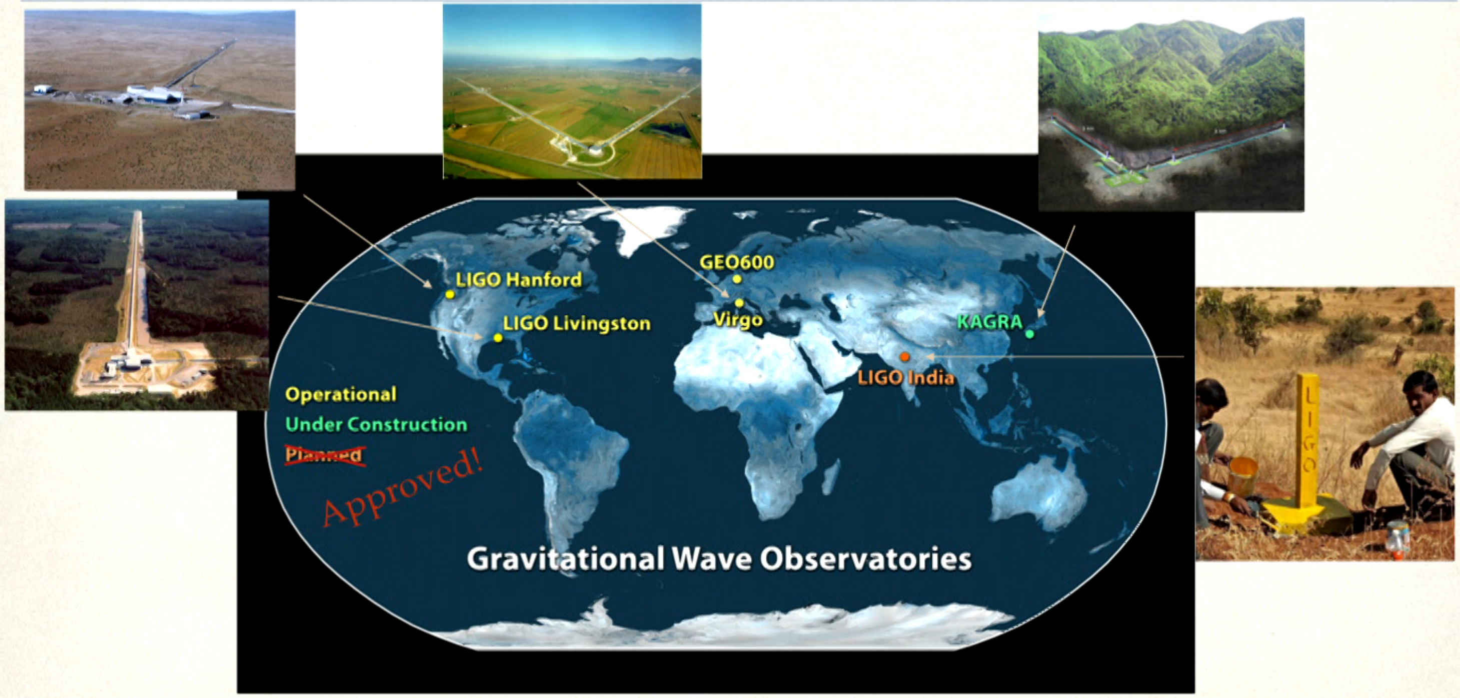
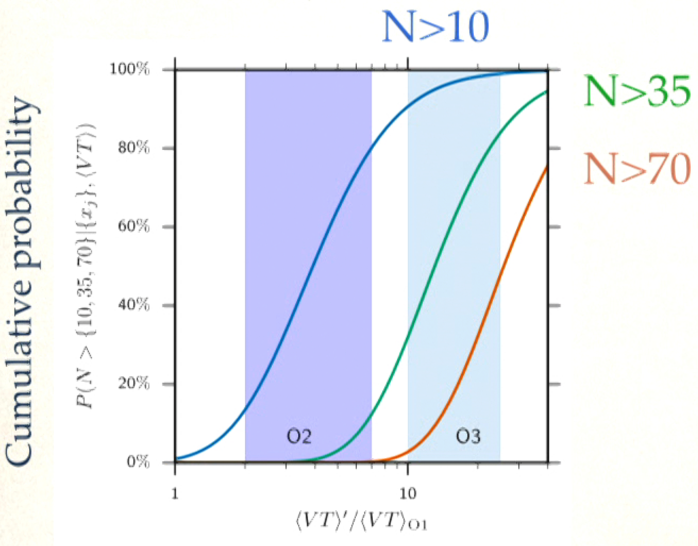


Image credits: Caltech/MIT/LIGO Lab, Virgo Collaboration, ICRR, LIGO India

Motivation (cont.)

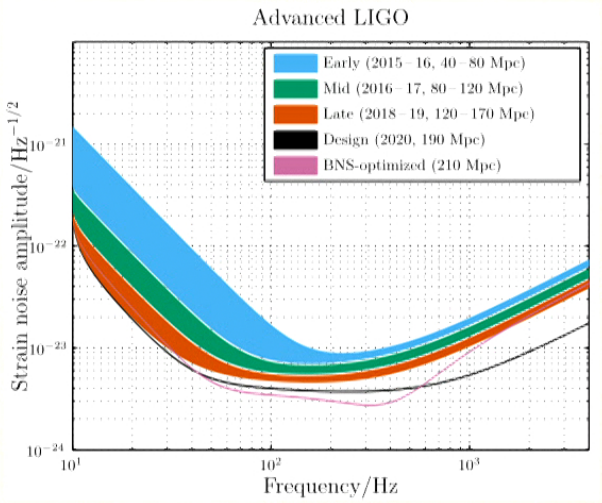
BBH rates projection after O1
(first observing run)



Volume surveyed
(relative to O1)

LVC, PRX **6**, 041015 (2016)

LVC, LRR **21**, 3 (2018)



Projected sensitivity increase of LIGO

Motivation (cont.)

We expect to detect many more compact binaries coalescences with gravitational waves in the coming years—in particular, many more binary black hole mergers.

What physics can we expect to extract from such observations?

[We'll just give a few examples here.]

Outline

- Brief overview of information obtainable from gravitational wave observations of compact binaries and a reminder about the current status of waveform modelling.
- **Application 1:** Determining the mass and spin of the remnant of a BBH merger
    - *Aside 1:* Determining the spin tilts at formation
    - *Aside 2:* What can one do for the BNS?
- **Application 2:** Constraints on black hole mimickers (method and results on injections)
- Conclusions

Information obtainable from compact binaries

- In GR, black hole binaries have 9 intrinsic parameters: 2 masses, 2 x 3 spin components, and 1 eccentricity [generally negligible; there is also a further angle giving the binary's position on its orbit at a given time required to completely specific initial conditions in the eccentric case].
- Binaries containing matter (for LIGO, just neutron stars, or exotic objects) have many more parameters than binary black holes (formally infinitely many).
- Even in the inspiral, where one can treat (in, e.g., the post-Newtonian picture) the binary's constituents as point particles endowed with multiple moments, one has to deal with several infinite sets of multipole moments describing spin-induced and tidally-induced deformations, as well as tidal heating. These all depend on the internal structure of the objects.

  Of course, only the leading several multipoles will likely be detectable in any realistic scenario. Additionally, for neutron stars, there are various quasi-universal relations that relate the different spin-induced and tidally-induced deformations [see, e.g., Yagi and Yunes, Phys. Rep. (2017)].
- In the merger of systems with matter, one has to deal with the full microphysics (including, e.g., magnetic fields, thermal effects, neutrinos), all of which is expected to imprint itself on the GW signal.

Waveform models for the inspiral, merger, and ringdown of BBHs

- While numerical simulations are the only way to generate accurate models for the late inspiral and merger of compact binaries, one cannot compute a numerical simulation for each point of parameter space needed for the template banks used in searches or the stochastic sampling used in parameter estimation, and has to make fast-to-evaluate models that interpolate over the parameter space (and include post-Newtonian predictions for when the binary is well-separated).

- Waveform models are quite well-developed for the dominant quadrupolar mode for binary black holes on quasicircular orbits with aligned spins.

- There are two standard models used in LIGO data analysis:
  - Effective-one-body (EOB)—natively time-domain
  - Phenomenological (Phenom)—natively frequency-domain.

- The state-of-the-art versions of these models are SEOBNRv4 [Bohé et al., PRD (2017)] and IMRPhenomD [Khan et al., PRD (2016)].

  There are also further tricks used to interpolate between EOB waveforms in the frequency domain to make them fast enough to be used for standard data analysis [see, e.g., Pürrer, CQG (2014), PRD (2016)].

Waveform models for the inspiral, merger, and ringdown of BBHs: Precession

- There are also EOB and Phenom models including precessing spins used in LIGO data analysis [SEOBNRv3 and IMRPhenomPv2], though only the Phenom model is used regularly, since the tricks used to interpolate the aligned-spin waveforms in the frequency domain have not yet been successfully applied to the precessing version, though the time-domain code has been optimized [Devine, Etienne, and McWilliams, CQG (2016)].

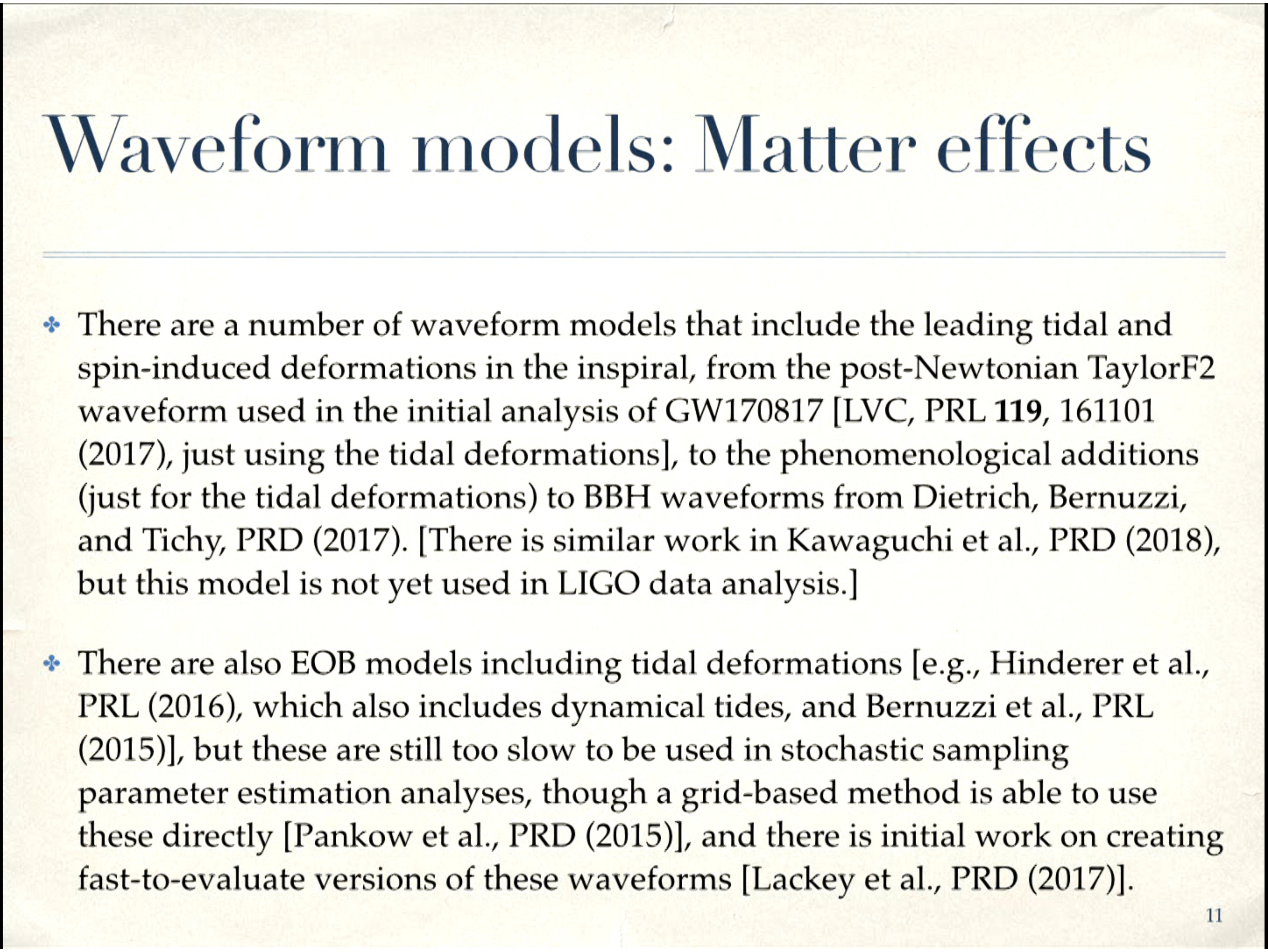
- However, the precessing EOB model contains more physics than the Phenom model (e.g., two-spin interactions, while the Phenom model only includes a single effective spin describing the precession), and was used to analyze GW150914 and GW170104 [LVC, PRX **6**, 041014 (2016) and PRL **118**, 221101 (2017)].

Waveform models: Higher modes and eccentricity

- Waveforms with higher modes and spin are now starting to be developed [e.g., London et al. PRL (2018); Cotesta et al. arXiv (2018)] as well as surrogate models that directly interpolate NR waveforms and include higher modes, though are currently only available in restricted portions of the parameter space [e.g., Blackman PRD (2018), which is applicable to precessing systems but only for spins up to 0.8 and mass ratios up to 2].

  These are starting to be applied in LIGO data analysis.

- Eccentric waveforms (for not-too-eccentric binaries) are also starting to be developed [Hinder, Kidder, and Pfeiffer, arXiv (2017); Hinderer and Babak, PRD (2018); Huerta et al., PRD (2018); Cao and Han, PRD (2017)], though these are not yet used in any LIGO data analyses.



Waveform models: Matter effects

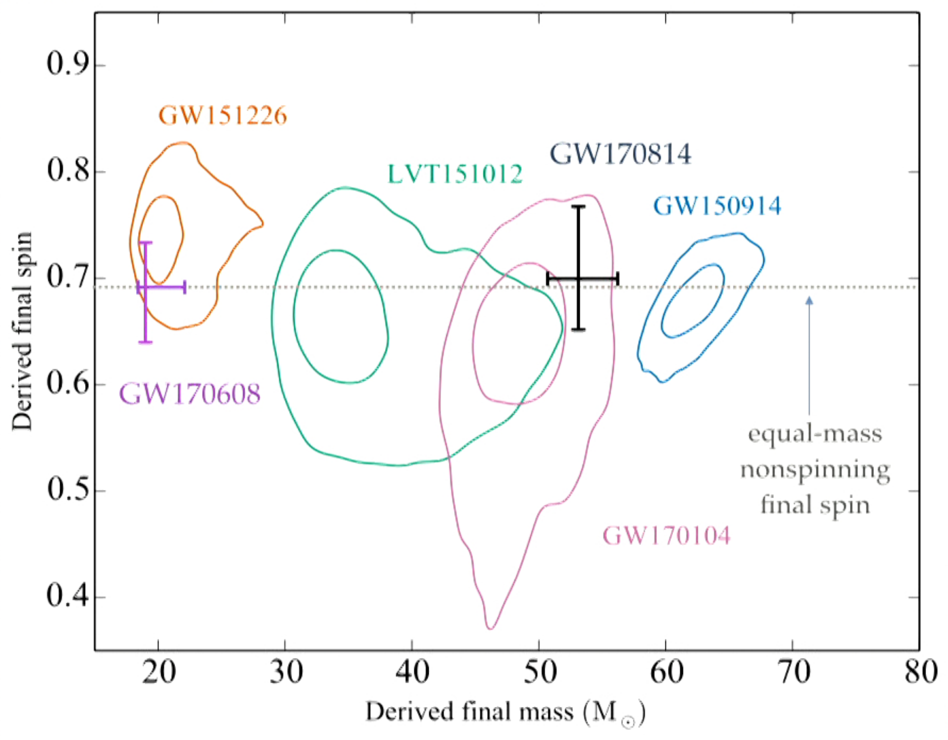
- There are a number of waveform models that include the leading tidal and spin-induced deformations in the inspiral, from the post-Newtonian TaylorF2 waveform used in the initial analysis of GW170817 [LVC, PRL **119**, 161101 (2017), just using the tidal deformations], to the phenomenological additions (just for the tidal deformations) to BBH waveforms from Dietrich, Bernuzzi, and Tichy, PRD (2017). [There is similar work in Kawaguchi et al., PRD (2018), but this model is not yet used in LIGO data analysis.]

- There are also EOB models including tidal deformations [e.g., Hinderer et al., PRL (2016), which also includes dynamical tides, and Bernuzzi et al., PRL (2015)], but these are still too slow to be used in stochastic sampling parameter estimation analyses, though a grid-based method is able to use these directly [Pankow et al., PRD (2015)], and there is initial work on creating fast-to-evaluate versions of these waveforms [Lackey et al., PRD (2017)].

Inferring BBH final mass and spin from GW observations

Work in collaboration with Anuradha Gupta (Penn State), David Keitel (Glasgow), P. Ajith (ICTS-TIFR), Ofek Birnholtz (AEI Hannover), Aaron Zimmerman (CITA), James Healy (RIT), Sascha Husa (UIB), and Frank Ohme (AEI)

Determining the final masses and spins of binary black holes: Overview

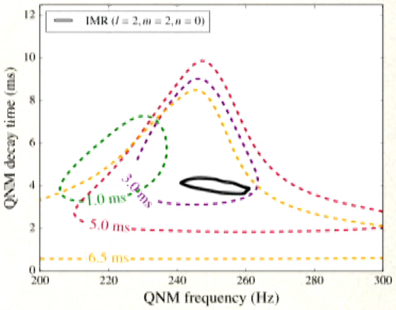


- The final black holes of the detected binary black hole coalescences have the best-determined masses and spins of any stellar mass black holes observed (and comparable or better accuracies to the mass accuracy of Sgr A*).
- How are these determined?

LVC, PRX **6**, 041015 (2016); PRL **118**, 221101 (2017); **119**, 141101 (2017); ApJL **851**, L35 (2017)

Determining the final masses and spins of binary black holes: Gravitational wave data analysis

- The mass and spin of the final black hole is encoded in the frequencies and damping times of quasinormal modes during the ringdown stage.
- This is accessible to gravitational wave data analysis, though mostly for future detectors, particularly LISA (and ringdown analyses are good for tests of GR, notably of the no-hair theorem).
- However, for current LIGO-Virgo observations, the SNRs in the ringdown are far too low to extract the final state parameters directly.
- Even for the loudest BBH signal so far—GW150914—all it was possible to do was show that the dominant QNM was consistent with GR.

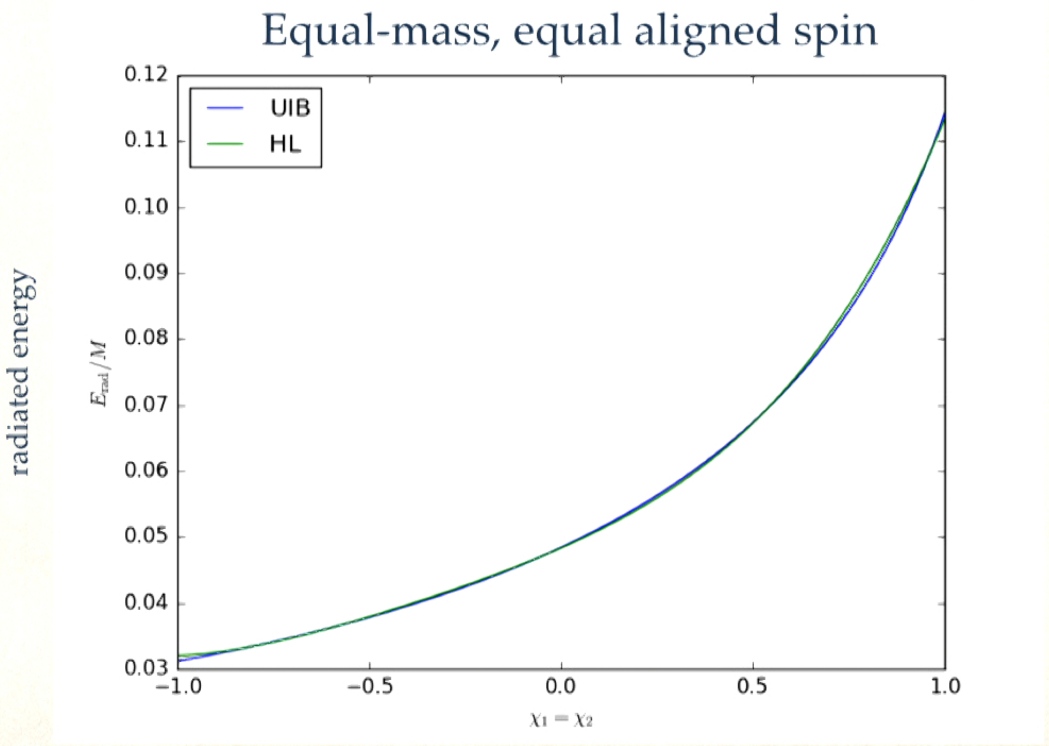


LVC
PRL **116**, 221101 (2016)

Determining the final masses and spins of binary black holes: Gravitational wave data analysis (cont.)

- The LIGO-Virgo gravitational wave analyses use fits to numerical relativity simulations to infer the final masses and spins from the masses and spins of the component black holes in the binary.
- These component masses and spins are the fundamental intrinsic quantities used to parameterize the waveform models. [The other relevant intrinsic quantity for BBHs is the eccentricity, but this is expected to be negligible close to merger, as gravitational waves efficiently circularize the orbit.]
- The analysis of GW150914 only used fits [from Healy, Lousto, and Zlochower (HLZ), PRD (2014)] that include the dominant effects of the spins—from the components along the binary's orbital angular momentum. Current analyses include the contribution of all the spin components to the final spin—it is not necessary to include more than the aligned components in the final mass fit at current accuracies.

Overview of the fits' predictions in some simple cases: Radiated energy



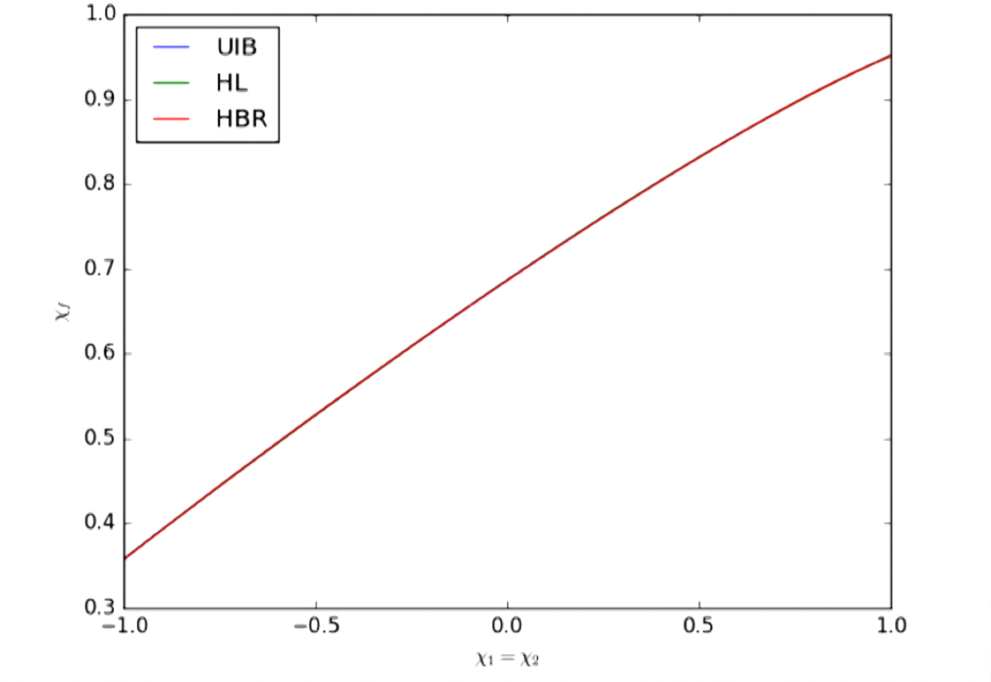
dimensionless spin

$E_{\rm rad} = M - M_f$

total mass at infinite separation (i.e., sum of individual black hole masses)

Overview of the fits' predictions in some simple cases: Final spin

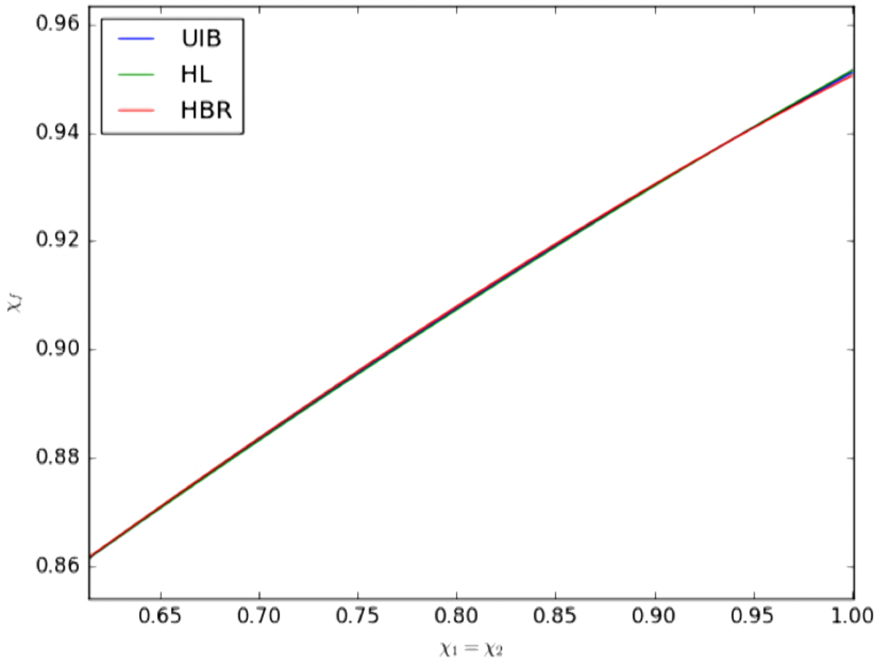
Equal-mass, equal aligned spin



final dimensionless spin

dimensionless spin

Overview of the fits' predictions in some simple cases: Final spin — zoomed

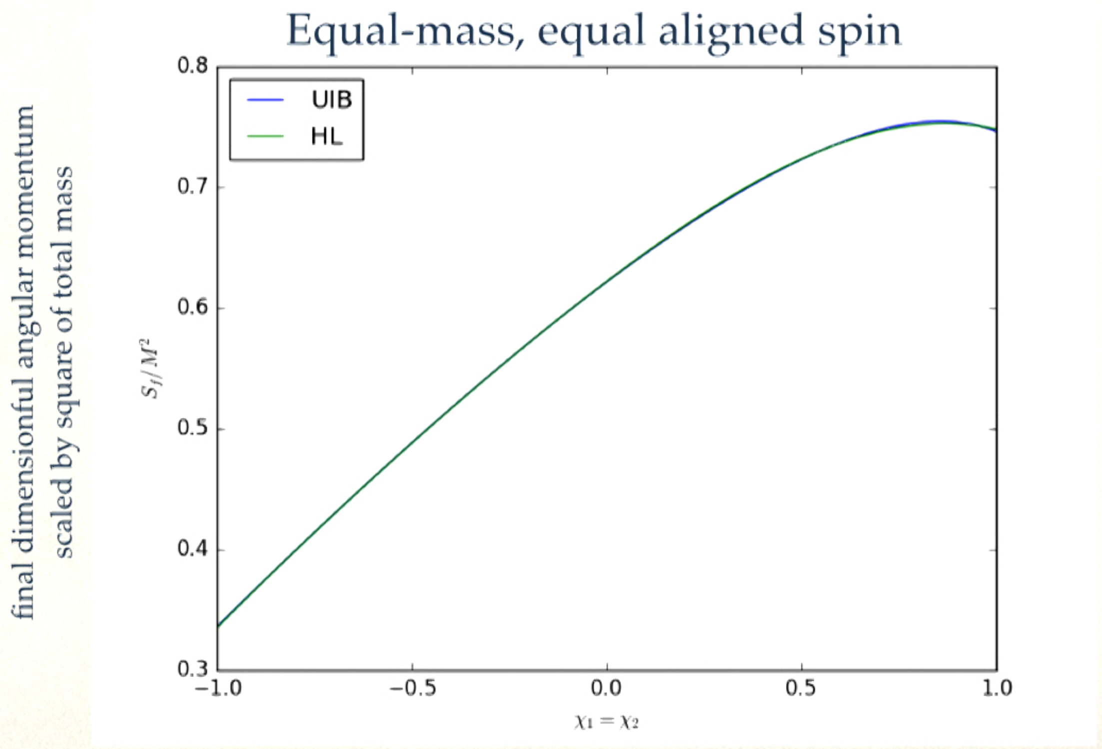


Equal-mass, equal aligned spin

final dimensionless spin

dimensionless spin

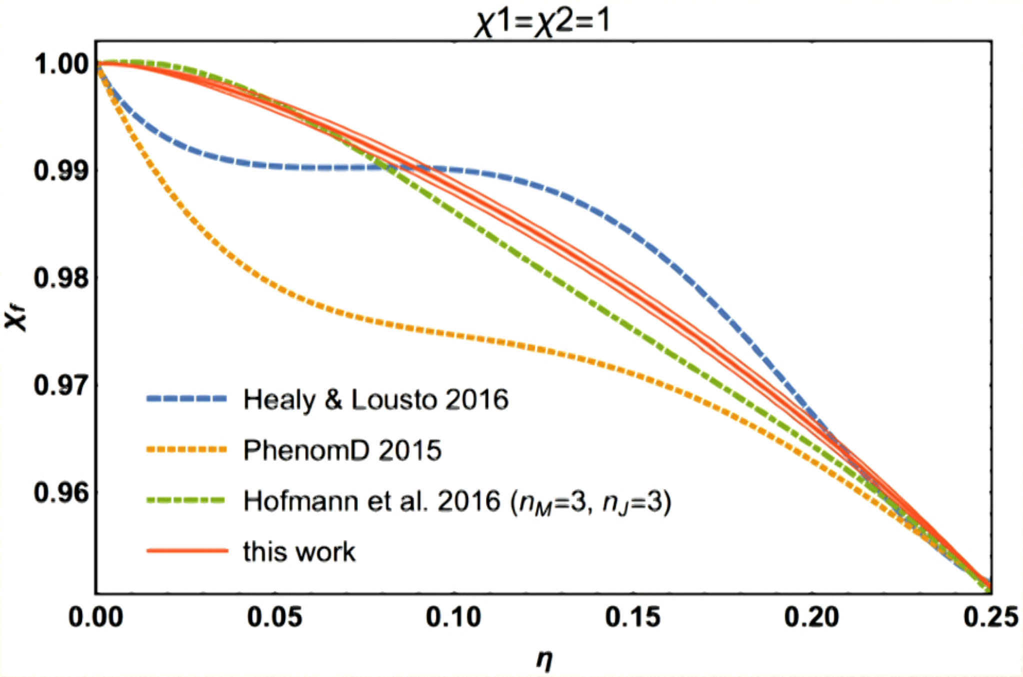
Overview of the fits' predictions in some simple cases: Final angular momentum



dimensionless spin

Overview of the fits' predictions in some simple cases: Final spin

Equal maximal aligned spin



final dimensionless spin

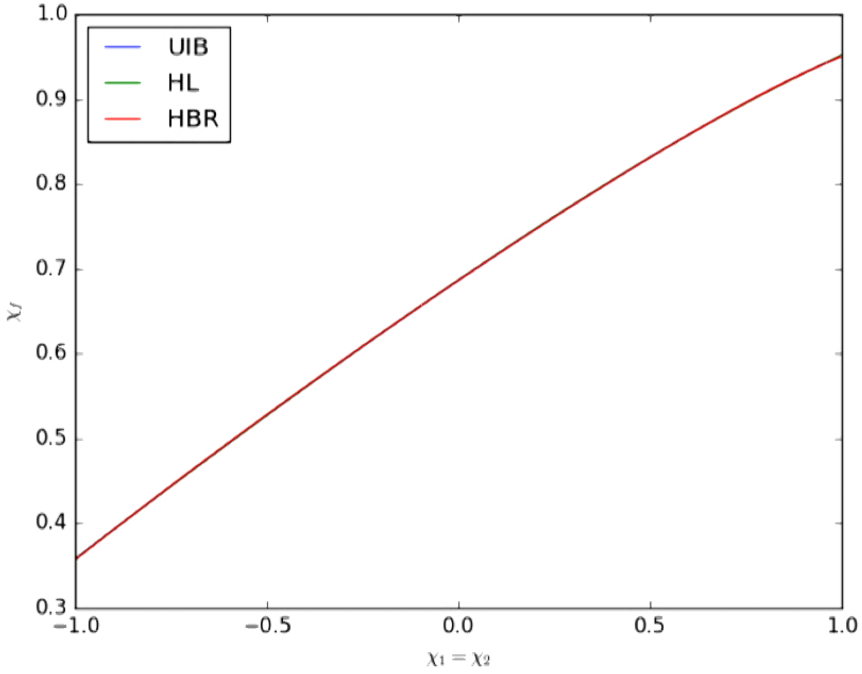
symmetric mass ratio, m_1m_2/M^2

From
Jiménez-
Forteza
et al.

Overview of the fits' predictions in some simple cases: Final spin

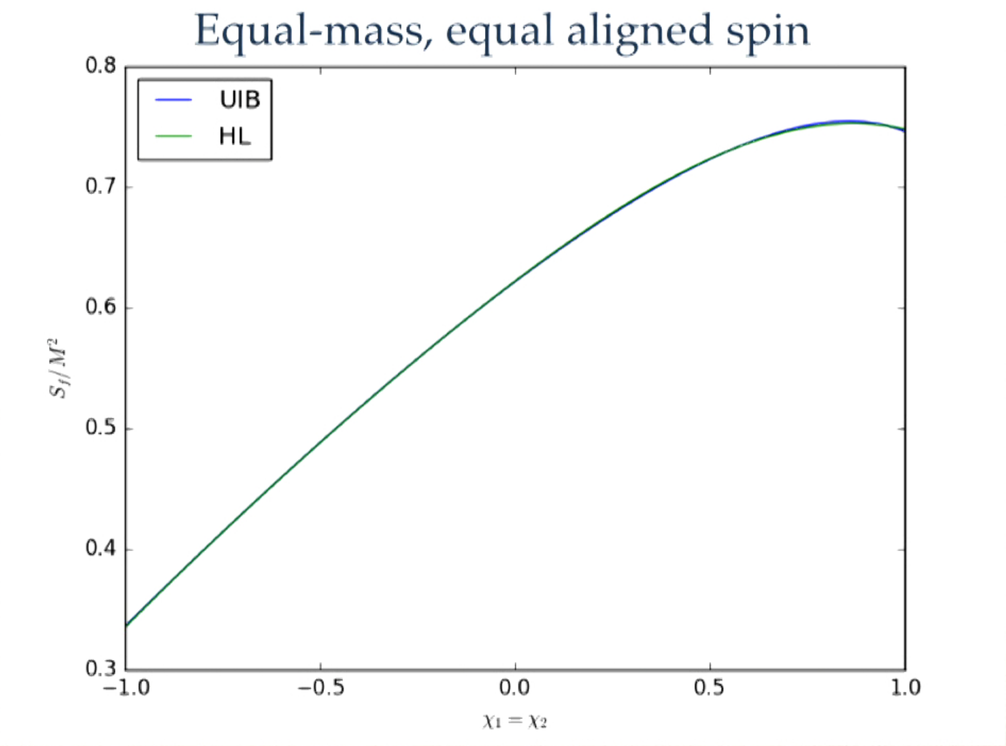
Equal-mass, equal aligned spin

final dimensionless spin



dimensionless spin

Overview of the fits' predictions in some simple cases: Final angular momentum



final dimensionful angular momentum scaled by square of total mass

dimensionless spin

Augmenting aligned-spin final spin fits with in-plane spins

- There is a simple phenomenological extension of aligned-spin final spin fits to include the dominant effects of the in-plane spins:

magnitude of the vector
sum of in-plane spins

$$\chi_f^{\text{full}} = \sqrt{\left(\chi_f^{\text{aligned}}\right)^2 + \left(S^{\text{in-plane}}/M^2\right)^2}.$$

[Using the system's total mass instead of its final mass gives better agreement.]

- One obtains further improvements when using post-Newtonian expressions [from Ajith, PRD (2011)] to evolve the spins to the ISCO frequency.

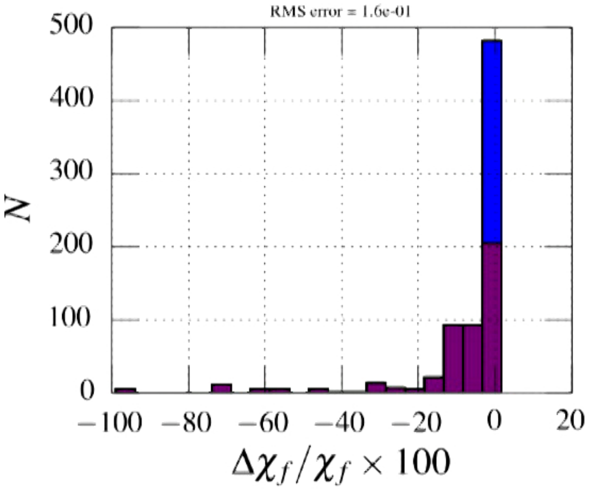
  This spin evolution should be even more important for low-mass black holes, where the waveform models are parameterized using the spins at some low frequency (e.g., 20 Hz, or a velocity of only ~0.07c for a 20 $M_\odot$ binary), than for relatively short NR simulations.

- As mentioned previously, for the final mass, one obtains good accuracy just applying aligned-spin fits—spin evolution only makes negligible changes. These expressions perform much better than the specific precessing fits given by Zlochower and Lousto, PRD (2015).

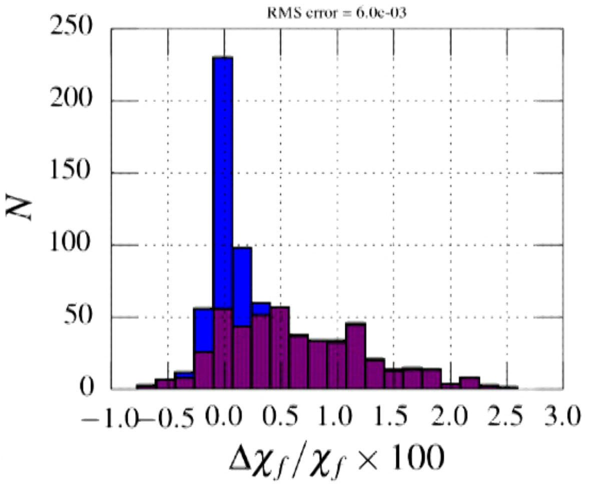
Illustrations of improvements in accuracy of final spin determination due to including in-plane spins

illustration using the HLZ fits (almost identical results with other fits)

only aligned spins used in fit



with augmentation

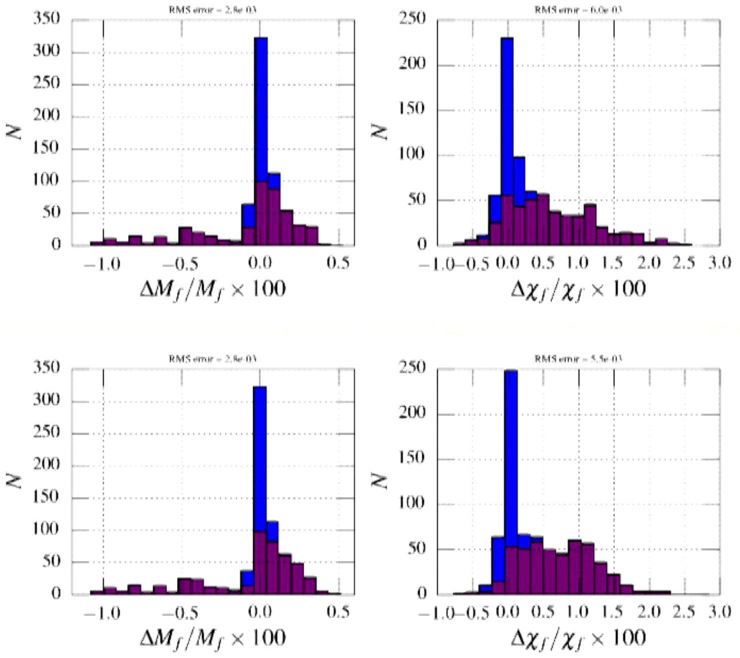


Use results of
763 NR simulations,
including 480 precessing ones,
from BAM, GATech, RIT, and SXS.
See LIGO-T1600168 for details.

Blue: aligned spin simulations
Purple: precessing simulations

Illustrations of improvements in accuracy of final spin determination from spin evolution

illustration using the HLZ fits (almost identical results with other fits)



Blue: aligned spin simulations

Purple: precessing simulations

without spin evolution (but with augmentation of the final spin fit)

spin RMS error: 6.0e-3

with spin evolution

spin RMS error: 5.5e-3

In both cases:

mass RMS error: 2.8e-3

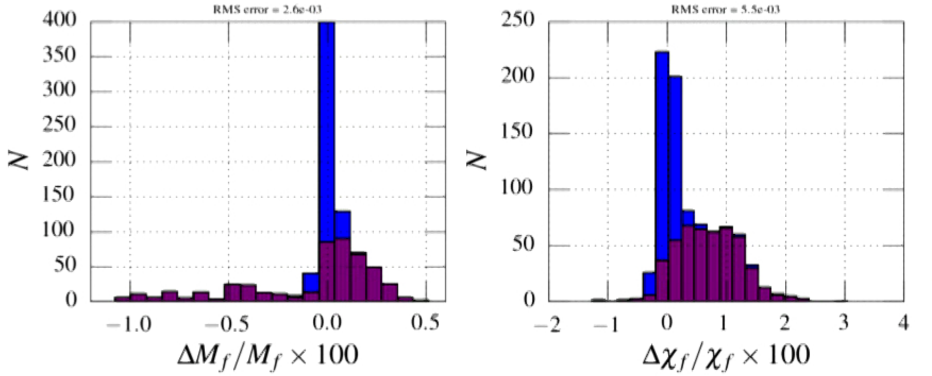
Accuracy of averaged fits (with augmentation and spin evolution)

RMS

errors:

M_f: 2.6e-3

χ_f : 5.5e-3



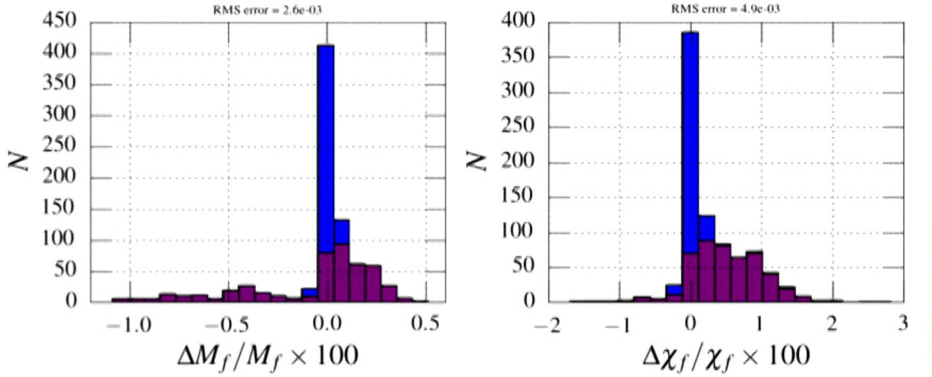
HLZ

RMS

errors:

M_f: 2.6e-3

χ_f : 4.9e-3



averaged

Accuracy of averaged fits (with augmentation and spin evolution)

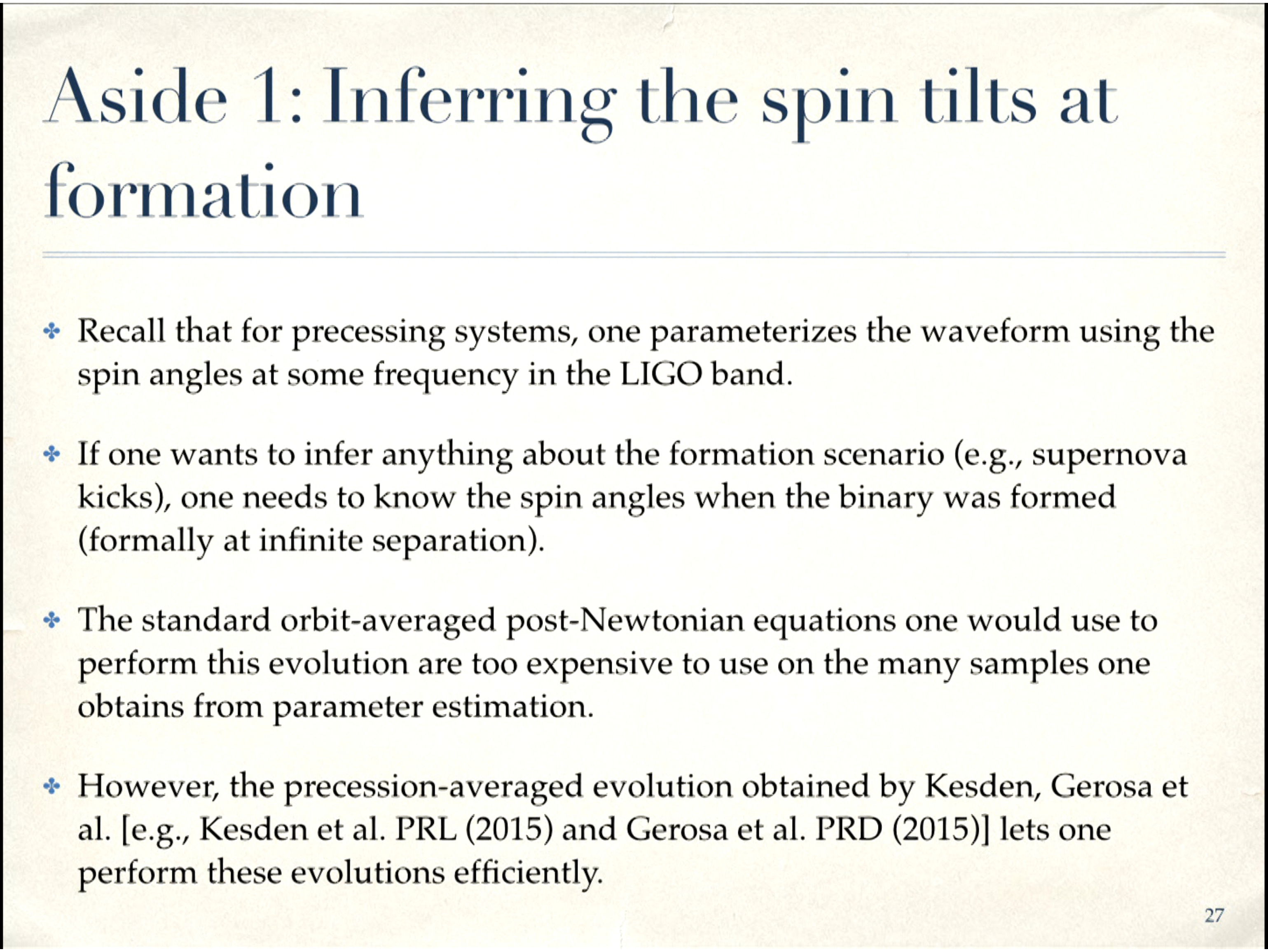
RMS
errors:
M_f: 2.6e-3
χ_f : 5.5e-3

- For all current LIGO-Virgo BBH detections, the statistical errors are significantly larger than the systematic errors from the fits.

- However, as the detectors are upgraded, the fits must also improve, in order for their systematic errors to remain negligible:

RMS
errors:
M_f: 2.6e-3
χ_f : 4.9e-3

GW150914 would be detected with an SNR of ~70 at design sensitivity, leading to statistical errors of only ~1%.

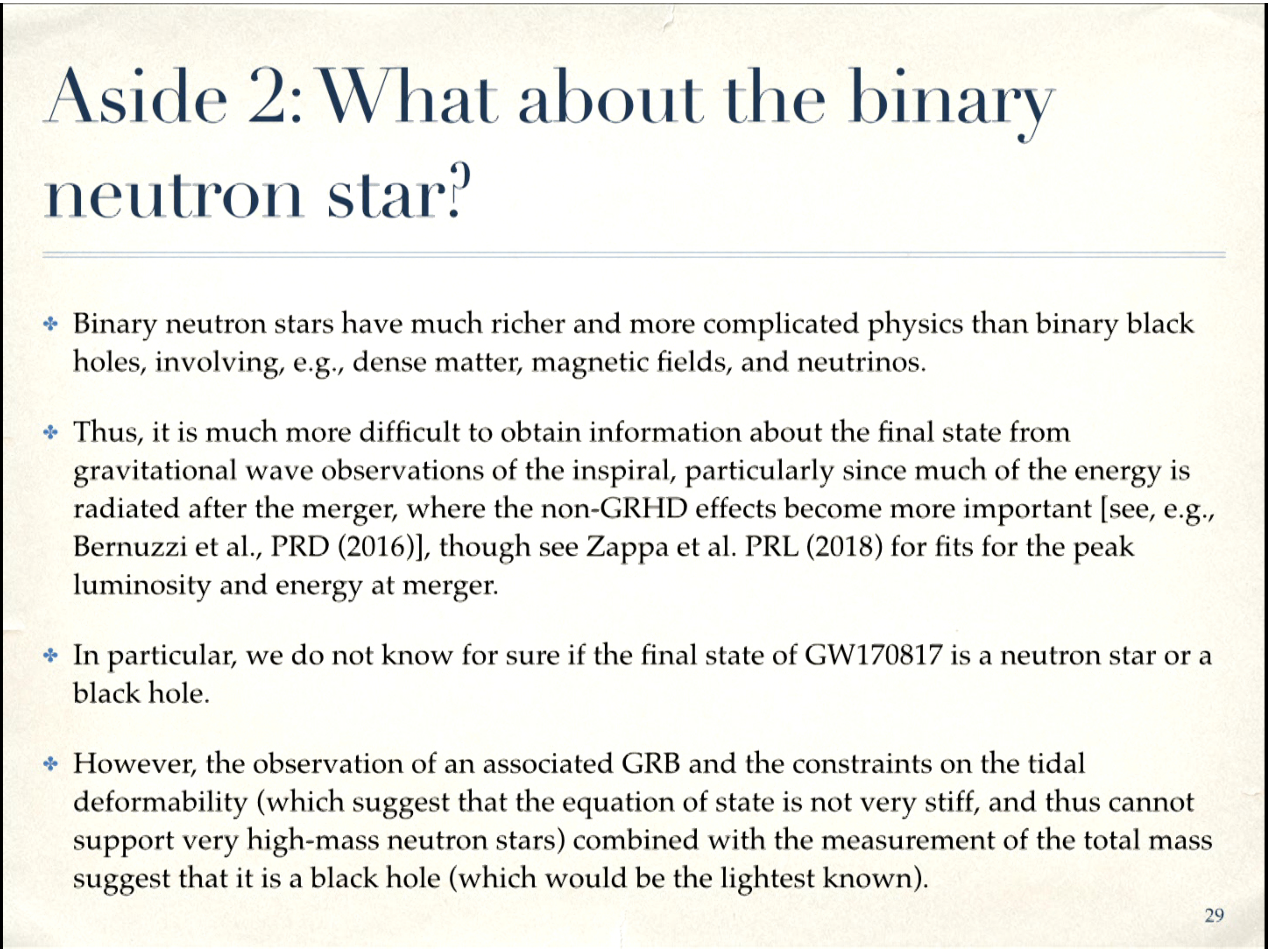


Aside 1: Inferring the spin tilts at formation

- Recall that for precessing systems, one parameterizes the waveform using the spin angles at some frequency in the LIGO band.
- If one wants to infer anything about the formation scenario (e.g., supernova kicks), one needs to know the spin angles when the binary was formed (formally at infinite separation).
- The standard orbit-averaged post-Newtonian equations one would use to perform this evolution are too expensive to use on the many samples one obtains from parameter estimation.
- However, the precession-averaged evolution obtained by Kesden, Gerosa et al. [e.g., Kesden et al. PRL (2015) and Gerosa et al. PRD (2015)] lets one perform these evolutions efficiently.

Precession-averaged evolution

- Evolve J as a function of L. Read off the tilts at infinity using
- I have implemented a streamlined method for solving the equations using elliptic functions from Chatziioannou et al. PRD (2017).
- In the course of implementing this, I have developed a regularized version of the equations that allow one to evolve close-to-equal-mass binaries and derived strict error bounds for when one can linearize the equation, significantly simplifying it.
- Anuradha Gupta and I are now testing to find out the maximum velocity at which one can transition from orbit-averaged to spin-averaged evolution. I will also see if it is possible to obtain an a priori error bound.
- However, there are still a few corners of parameter space where the precession-averaged evolution code runs into difficulties with some self-consistency checks, which I am currently investigating.

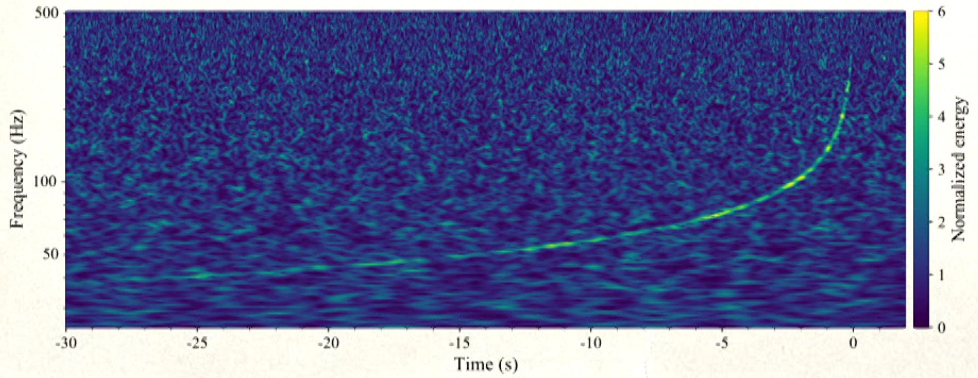


Aside 2: What about the binary neutron star?

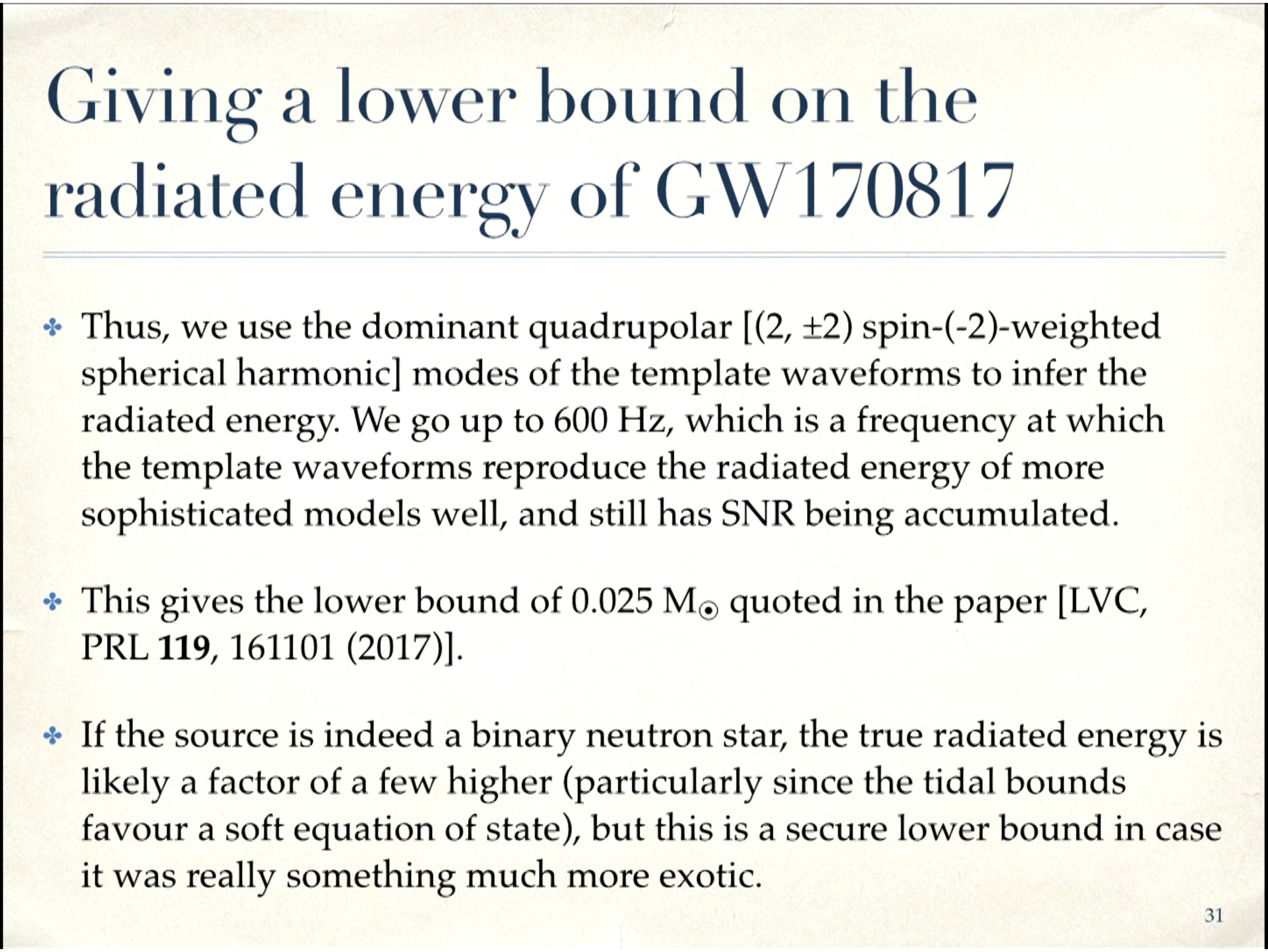
- Binary neutron stars have much richer and more complicated physics than binary black holes, involving, e.g., dense matter, magnetic fields, and neutrinos.
- Thus, it is much more difficult to obtain information about the final state from gravitational wave observations of the inspiral, particularly since much of the energy is radiated after the merger, where the non-GRHD effects become more important [see, e.g., Bernuzzi et al., PRD (2016)], though see Zappa et al. PRL (2018) for fits for the peak luminosity and energy at merger.
- In particular, we do not know for sure if the final state of GW170817 is a neutron star or a black hole.
- However, the observation of an associated GRB and the constraints on the tidal deformability (which suggest that the equation of state is not very stiff, and thus cannot support very high-mass neutron stars) combined with the measurement of the total mass suggest that it is a black hole (which would be the lightest known).

Giving a lower bound on the radiated energy of GW170817

- However, it is possible to give a lower bound on the radiated energy by only considering the observed waveform.
- The most direct way of doing this would be to use the unmodelled waveform reconstructions (using wavelets). However, these only reconstruct the signal up to ~300 Hz, and the templated analysis continues to accumulate SNR beyond this.



Credit: Alex Nitz/
Max Planck Institute for
Gravitational Physics/LIGO

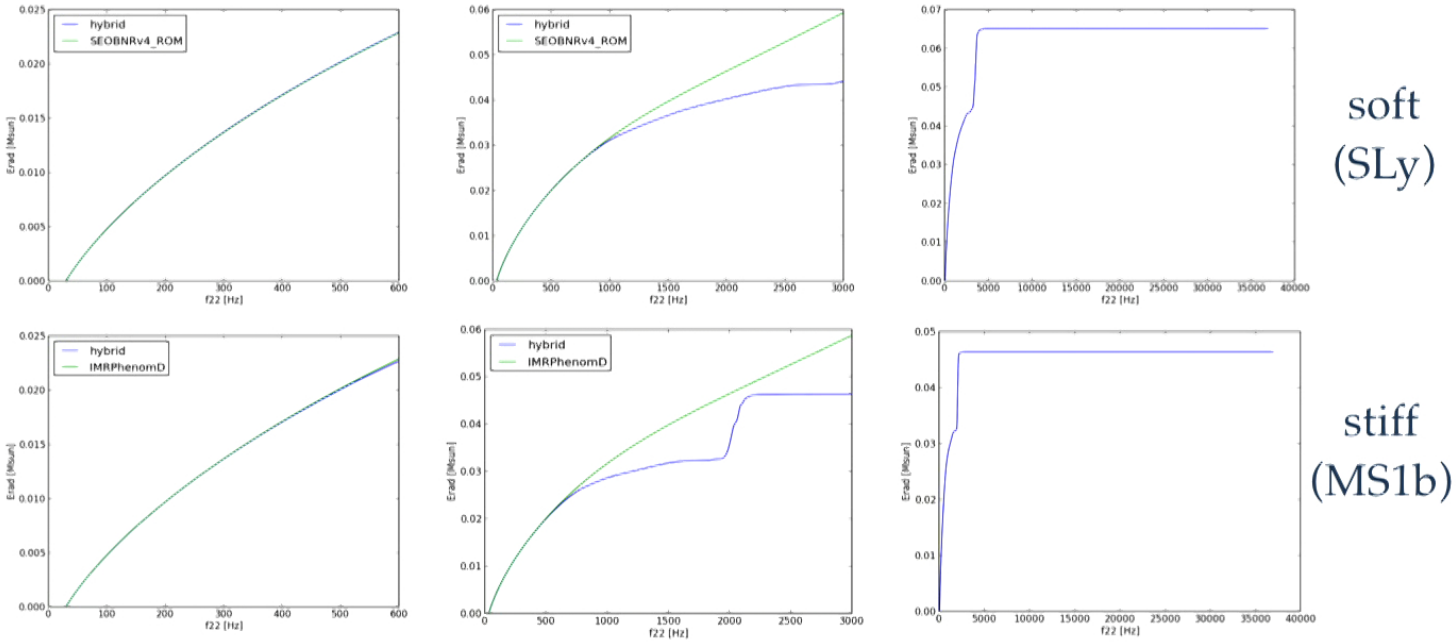


Giving a lower bound on the radiated energy of GW170817

- Thus, we use the dominant quadrupolar [(2, ±2) spin-(-2)-weighted spherical harmonic] modes of the template waveforms to infer the radiated energy. We go up to 600 Hz, which is a frequency at which the template waveforms reproduce the radiated energy of more sophisticated models well, and still has SNR being accumulated.
- This gives the lower bound of 0.025 $M_\odot$ quoted in the paper [LVC, PRL **119**, 161101 (2017)].
- If the source is indeed a binary neutron star, the true radiated energy is likely a factor of a few higher (particularly since the tidal bounds favour a soft equation of state), but this is a secure lower bound in case it was really something much more exotic.

Giving a lower bound on the radiated energy of GW170817

1.527 + 1.222 $M_\odot$ binaries



(EOB + NR hybrids created by Reetika Dudi based on NR simulations from Dietrich et al. PRD, 2017)

Constraining properties of black hole mimickers

Work in collaboration with Arunava Mukherjee (AEI), Rahul Kashyap, P. Ajith (ICTS-TIFR), Walter Del Pozzo (Pisa), and Salvatore Vitale (MIT)

arXiv:1804.08026

Black hole mimickers

- Dark, compact objects that can mimic many of the basic observational properties of black holes, but are material bodies instead of purely spacetime objects, and have no horizon.
- Black hole mimickers generally have nonzero tidal deformabilities, while the tidal deformabilities of black holes are zero. This imprints itself on the GW phasing, just like for binary neutron stars.
- Many families of black hole mimickers also have a maximum mass depending on the parameters in the model.
- Standard examples [see, e.g., Cardoso and Pani Nat. Ast. (2017) for an overview]:
    - **Boson stars** — stars constructed from a massive, possibly self-interacting scalar field [see Liebling and Palenzuela LRR (2017) for a review].
    - **Dark matter stars** (could be boson stars, or could be something more general), e.g., Giudice, McCullough, and Urbano JCAP (2016).
    - **Gravastars** — de Sitter interior surrounded by a thin shell of matter; generally have *negative* tidal deformabilities [e.g., Pani PRD (2015); Uchikata, Yoshida, and Pani PRD (2016)].

Binary black hole signals => constraints on black hole mimickers?

- Numerical simulations of even binaries of boson stars (the most straightforward black hole mimickers to simulate) are not advanced enough for use in GW data analysis.

- Additionally, one wants to have an analysis that isn't tied to a specific model, if possible [though model-dependent analyses are also useful, if the model is well-motivated].

- Thus, a first step is to use perfect fluid stars with a polytropic equation of state as a generic model for black hole mimickers with positive tidal deformabilities.

- One then uses standard tidal terms (1PN phasing in the stationary phase approximation from Wade et al. PRD [2014], using the PN calculation from Vines, Flanagan, and Hinderer PRD [2011]) added to a frequency-domain binary black hole waveform model (IMRPhenomD) in order to model the waveforms.

  One has to make sure that one only uses the waveform where it is valid—we describe a method for doing this later.

Constraints on properties of polytropic stars

- We consider nonrotating stars with a polytropic EOS

$$p = K\rho^{1+1/n}$$

tidal deformability

- Upper bound on Λ constrains n

- Lower bound on $M_{\max}$ constrains $K(n)$

- Properties of polytropic stars:

n	$C_{\max}$	$\Lambda_{\min}$
0.5	0.32	3.7
$\vdots$	$\vdots$	$\vdots$
2.0	0.074	8500

We allow for different values of K for the two stars, since we do not take the polytropic EOS as a fundamental model—we could also allow for different values of n, but have not tried this yet.

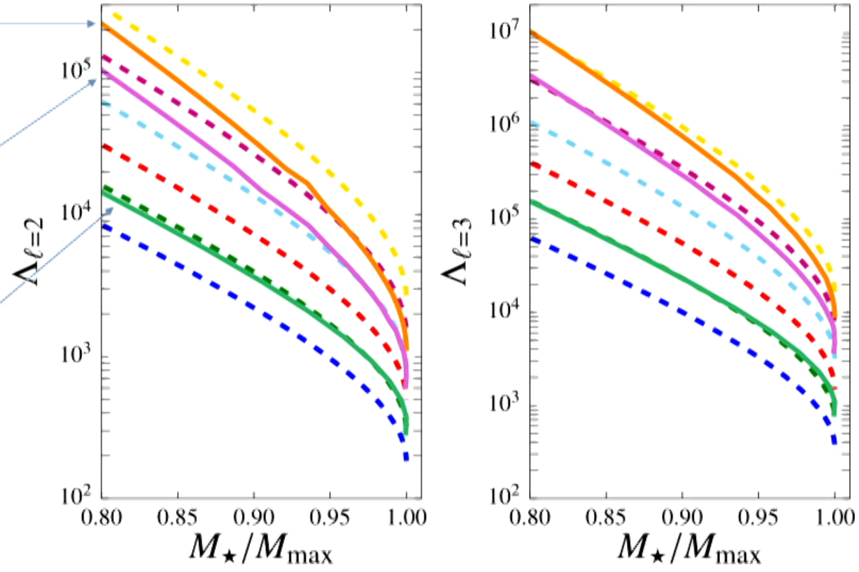
Polytropic stars as a generic model for black hole mimickers

- Compact boson stars have mass-tidal deformability relations that are well-approximated by that of a polytropic star.

free field
boson star

nonzero
quartic
coupling

10 times
larger
quartic
coupling



Quartic potential boson star and polytropic star tidal deformability vs. mass; boson star computations from Cardoso et al. PRD (2017).

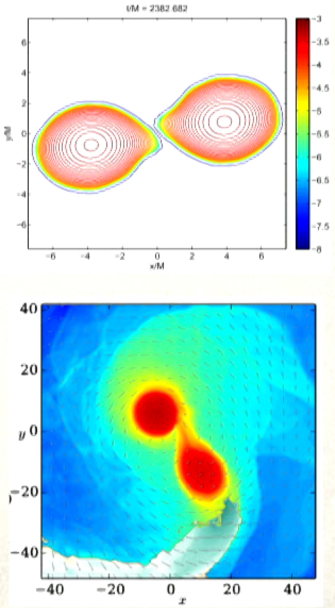
Upper frequency cutoff

- Since we are using linear tidal computations for the waveform, we want to cut off the likelihood integral at a low enough frequency that the objects will not yet have come into contact or have one of them become too tidally deformed to trust linear tidal computations.

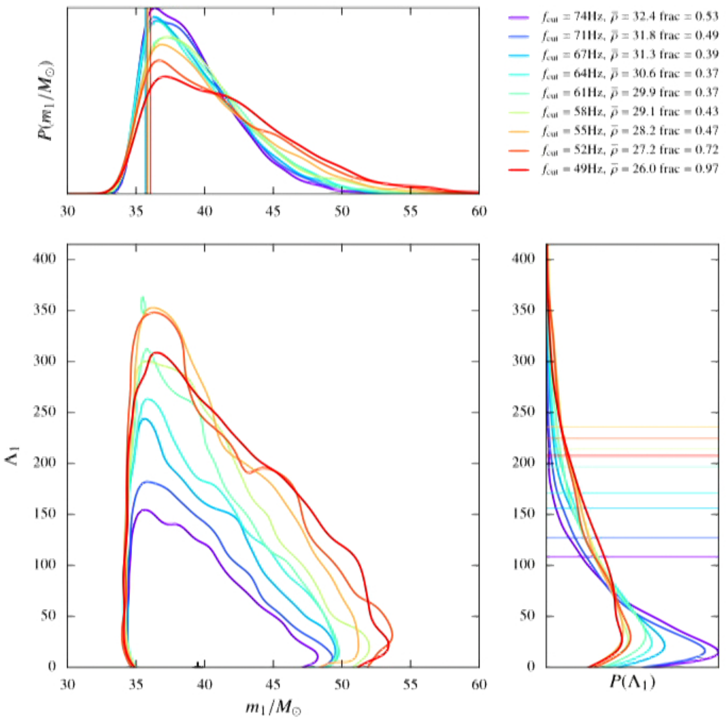
  For simplicity, we refer to both cases as "contact."

- We thus consider a range of upper cutoff frequencies (up to $1.2f_{\rm ISCO}$ of the injection; still well below the BBH merger frequency), and choose the largest frequency for which at least 90% of the samples that have a tidal deformability above the minimum allowed by the EOS have a contact frequency above the cutoff frequency.

Binary neutron star contact of equal mass system and disruption of q = 2 system from Bernuzzi et al. PRD (2012) and Dietrich et al. PRD (2017)



Upper frequency cutoff



← $1.2f_{\rm ISCO}$

← $0.8f_{\rm ISCO}$

Illustration for the GW150914-like case

Upper frequency cutoff

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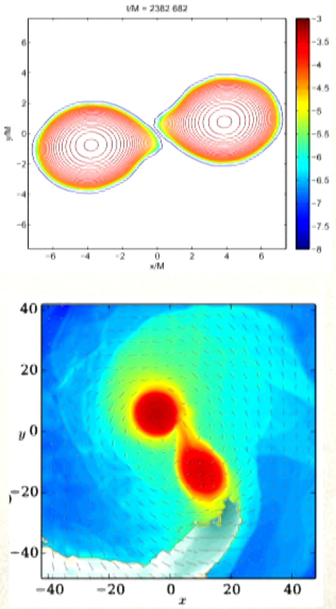

Estimating the contact frequency of a binary of tidally deformable objects

- The naïve contact frequency corresponds to an orbital separation equal to the sum of the bodies' unperturbed radii.
- However, this neglects tidal deformations, which can be quite large for the cases we are considering, particularly for large mass ratios.
- One can estimate the tidal deformation by using the surficial (or shape) Love numbers [calculated by Damour and Nagar, PRD (2009), and Landry and Poisson, PRD (2014)], which give the deformation of the star's surface.
- This gives an implicit expression for the contact separation that is used in Damour and Nagar's tidal EOB paper, PRD 2010 (using just the quadrupole surficial Love number).
- One can also include the higher multipoles and the known 1PN corrections to the quadrupole and octupole tidal fields (from NKJ-M et al., PRD 2009; need to try including the 1PN hexadecapole correction from Poisson and Corrigan's recent paper), as well as the tidal contributions to the radius-frequency relation. Truncating the multipole sum at $\ell = 5$ gives sufficiently accurate results.

Estimating the contact frequency of a binary of tidally deformable objects

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  curate results.

Newtonian tidal surface deformation from Landry and Poisson, PRD 2014

shape (a.k.a. surficial) Love number

radius of star

$$\delta R = -\sum_{\ell=2}^{\infty} \frac{h_\ell}{(\ell-1)\ell} \frac{R^{\ell+2}}{M} \mathcal{E}_L \Omega^L$$

mass of star

electric tidal field
(contracted with radial unit vectors)

Contact expression through octupole order and 1PN

quadrupole

octupole

$$R_c = \left[1 + h_2^{(1)} \frac{m_2}{m_1}\left(1 - \frac{m_2}{2R_c} - \frac{M}{R_c}\right)\left(\frac{R_1}{R_c}\right)^3 + h_3^{(1)} \frac{m_2}{m_1}\left(1 - \frac{3m_2}{R_c} - \frac{M}{2R_c}\right)\left(\frac{R_1}{R_c}\right)^4\right] R_1 + (1 \leftrightarrow 2)$$

contact
separation

here M is the total mass

radius of
star 1

Contact frequency checks

- We find that our expression gives contact frequencies that agree quite well with the contact frequencies for binary neutron stars with which we can compare in the literature [Bernuzzi et al. PRD (2012) and Radice et al. MNRASL (2014), both for equal-mass $n = 1$ polytrope binaries, with different compactnesses]:

Mf_c [NR]	Mf_c [Our expression]
0.078	0.0778
0.11	0.111

- However, note that determining the contact frequency in simulations is quite subtle, and it depends and generally increases monotonically with increasing resolution. If one attempts to include the expected coordinate transformation from Schwarzschild to PN coordinates in the contact radius computation, then one obtains higher frequencies, which might be correct, but we have used the lower frequencies here to be more conservative.

- In the future, we will compare the accuracy of our waveform model directly against NR waveforms (starting with those for neutron stars), and see if the contact frequency gives a good benchmark for when the waveform model is no longer a sufficiently accurate description of the NR waveform. Future work will also compare with NSBH tidal disruption frequencies.

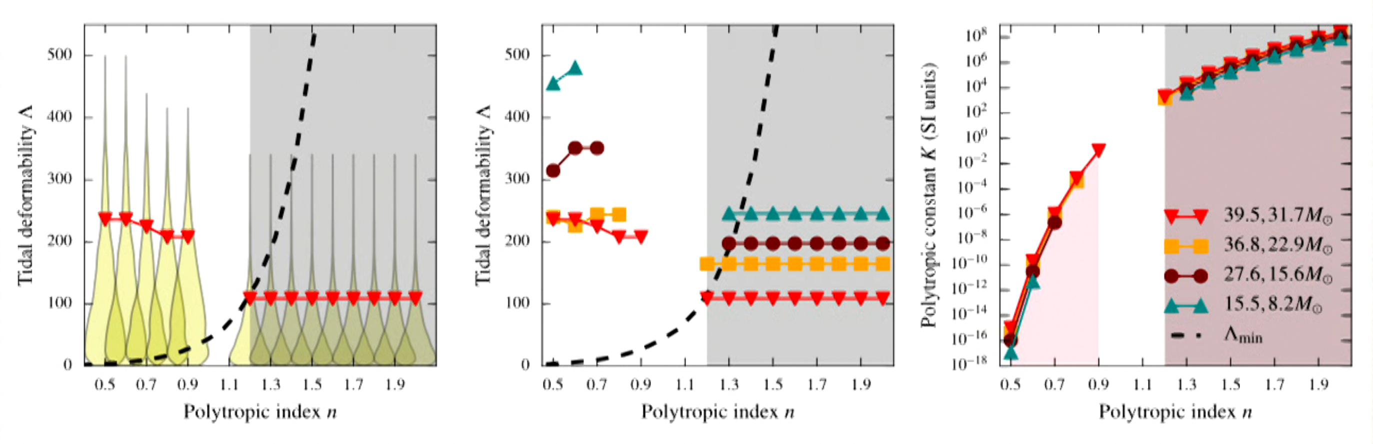
Results on injections: Constraints on polytropic EOS parameters at the 90% credible level

Test the method using injections into simulated noise of systems like GW150914, LVT151012, GW151226, and GW170104, but with O3-like sensitivity (only LIGO)

"late-high" noise curve from Abbott et al. LRR (2016)

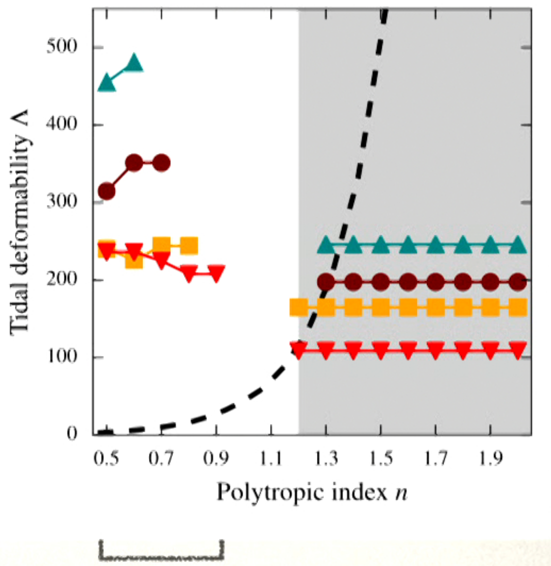
results for all 4 injections

GW150914-like results



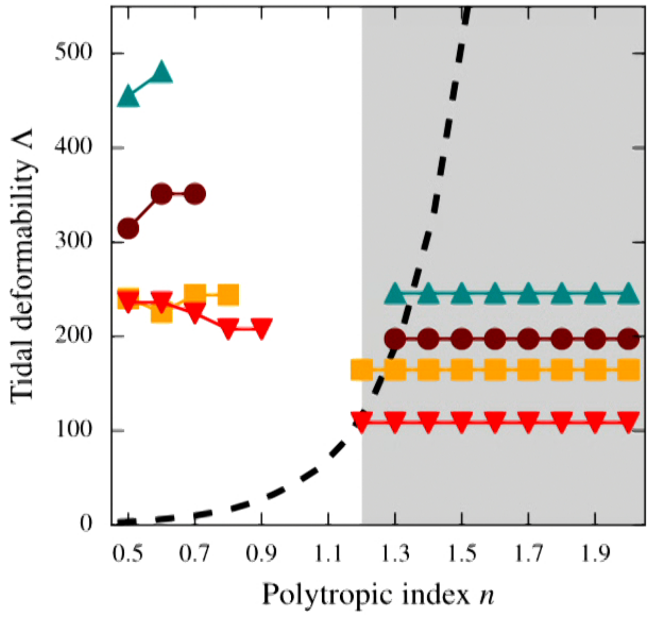
Results on injections: Constraints on radii and masses of polytropic stars

- The minimum radii of the polytropic stars considered range from 1.58 to 6.75 their Schwarzschild radii.
- For the small-*n* cases where the EOS is not ruled out completely, the radii are constrained to be at most 2.6–3.5 times the stars' Schwarzschild radii.
- The masses of the stars are also constrained to be 0.6–0.9 times the maximum mass allowed by the EOS.
- All of these fractions increase with increasing *n*.



Constraints on masses and radii from these *n*s

Cutoff frequencies used



0.8–0.9 f_{ISCO} 1.2 f_{ISCO} (still well below BBH merger frequency)

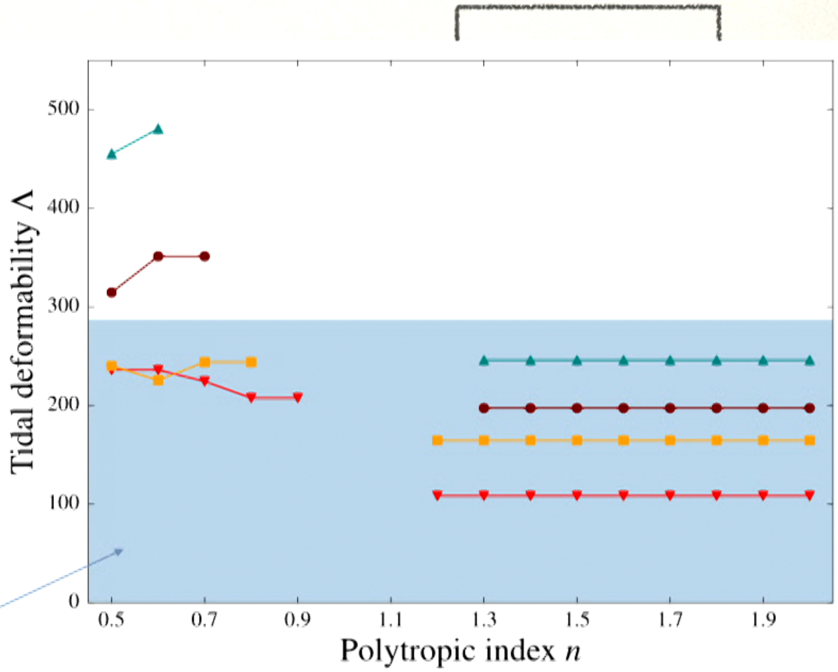
Results on injections: Ruling out binaries of boson stars with a quartic self-interaction as sources at the 90% credible level

Values of n that approximate quartic potential boson stars

Proof of principle
using the calculations
in Sennett et al. PRD (2017)

Stars described by a massive
complex scalar field ϕ with
potential

$$V(|\phi|^2) = m_B^2|\phi|^2 + \lambda_B|\phi|^4/2$$



ruled out by $\Lambda_{\min}$
for quartic potential
boson stars

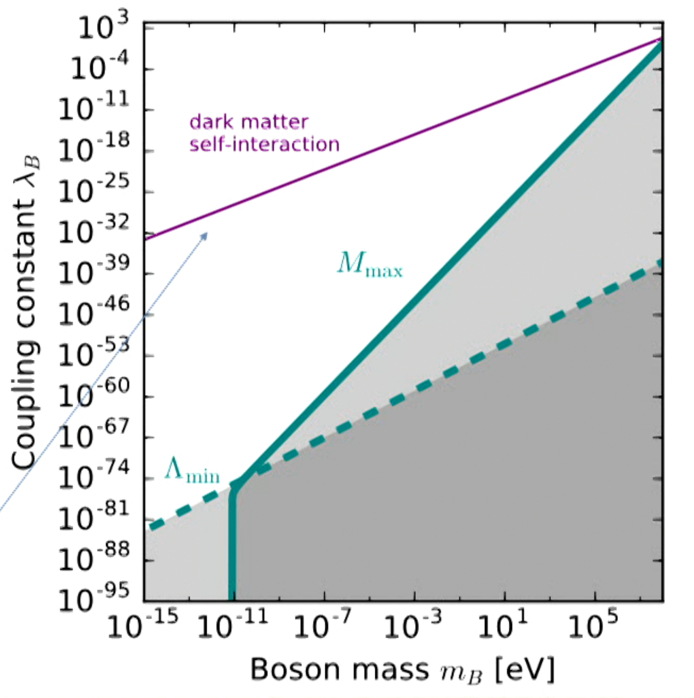
Results on injections: Constraints on boson star parameters at the 95% credible level

Constraints from the least massive system [GW151226-like]

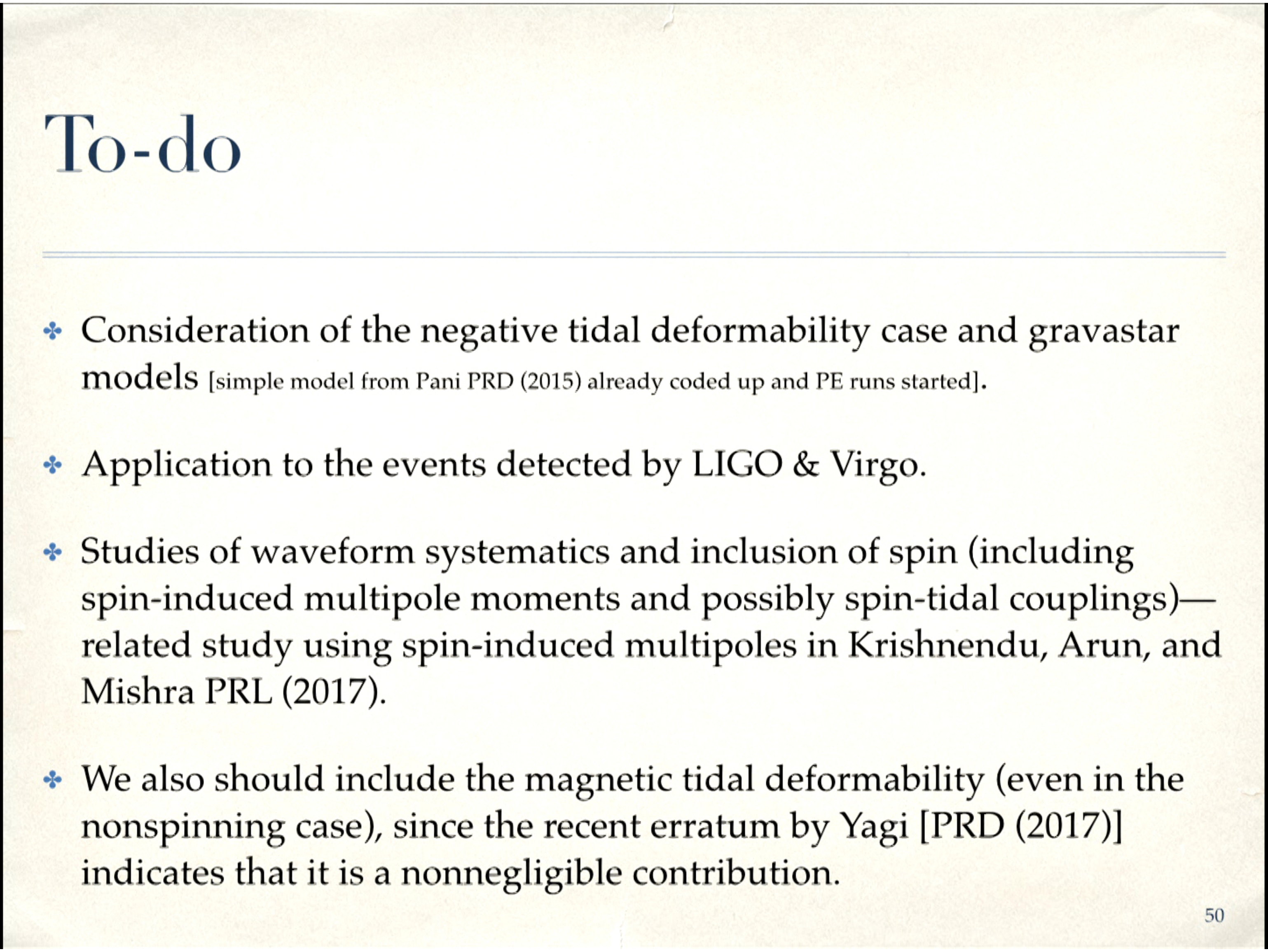
Proof of principle
using fits to the calculations
in Sennett et al. PRD (2017)
(provided by Noah Sennett)

Stars described by a massive complex scalar field ϕ with potential

$$V(|\phi|^2) = m_B^2|\phi|^2 + \lambda_B|\phi|^4/2$$



Dark matter self-interaction cross-section of 0.1–1 cm²/g, needed to account for various observations



To-do

- Consideration of the negative tidal deformability case and gravastar models [simple model from Pani PRD (2015) already coded up and PE runs started].
- Application to the events detected by LIGO & Virgo.
- Studies of waveform systematics and inclusion of spin (including spin-induced multipole moments and possibly spin-tidal couplings)—related study using spin-induced multipoles in Krishnendu, Arun, and Mishra PRL (2017).
- We also should include the magnetic tidal deformability (even in the nonspinning case), since the recent erratum by Yagi [PRD (2017)] indicates that it is a nonnegligible contribution.

Conclusions

- There is a considerable amount of information that can be extracted from the many gravitational wave observations of compact binaries—particularly binary black holes—that we expect to observe in the coming years.
- As an example, we have discussed the method used to obtain the final mass and spin of BBH coalescences in current LIGO data analyses, as well as the method used to obtain a lower bound on the radiated energy of GW170817 and plans to obtain the tilt angles at infinity.
- In the future, it should also be possible to obtain the kick velocity of the final black hole in a similar way, though here the impact of precession is much stronger than on even the final spin, and existing fits are not able to be applied to the problem directly, though there is recent work with surrogate models [Gerosa, Hébert, and Stein, arXiv (2018)] that may help solve the problem.

Conclusions

- We also showed how one can constrain properties of black hole mimickers, if binaries of such objects are to produce the signals identified as coming from binary black holes.
- We presented a method for obtaining these constraints self-consistently, and showed, using injections, that LIGO observations in O3 will likely rule out binaries of simple models of boson stars as sources of the observed BBH signals.