Title: The Dynamical Strong-field Regime of General Relativity

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Abstract: In this talk I will discuss some of the consequences for our understanding of strong-field gravity that can be gleaned from the recent detection of gravitational waves by the LIGO/Virgo collaboration.
The event heard, GW150914, is consistent with the emission of gravitational waves from the late inspiral, merger and ringdown of two heavy stellar mass black holes. This has given us the first quantifiable pieces of evidence that the dynamics and properties of colliding black holes are governed by general relativity. At present certain exotic compact object alternatives to black holes within general relativity, such as boson stars or gravastars, cannot yet be ruled out due to lack of concrete predictions of the merger regime in such scenarios. However, I will argue that even if the progenitors of GW150914 where composed of such exotic matter, the gravitational wave data strongly suggests collision lead to the prompt formation of a Kerr black hole.

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The Dynamical Strong-Field Regime of General Relativity

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Perimeter Institute, June 15, 2016

Outline

- General Relativity in the wake of GW150194
  - entering the era of observational dynamical, strong-field gravity
  - aside from all the astrophysical consequences, we can finally start testing the most non-linear aspects of Einstein gravity
    - already giving us the first quantifiable piece of data supporting the existence and dynamics of Kerr black holes as described by general relativity
  - this will *eventually* be a game-changer for studies of alternative theories to GR, and exotic alternatives to black holes within GR
    - for now, bounds are somewhat weak and/or speculative; I will discuss implications for exotic compact object alternatives to black holes, Nico about more generic constraints on alterative theories
- Conclusions

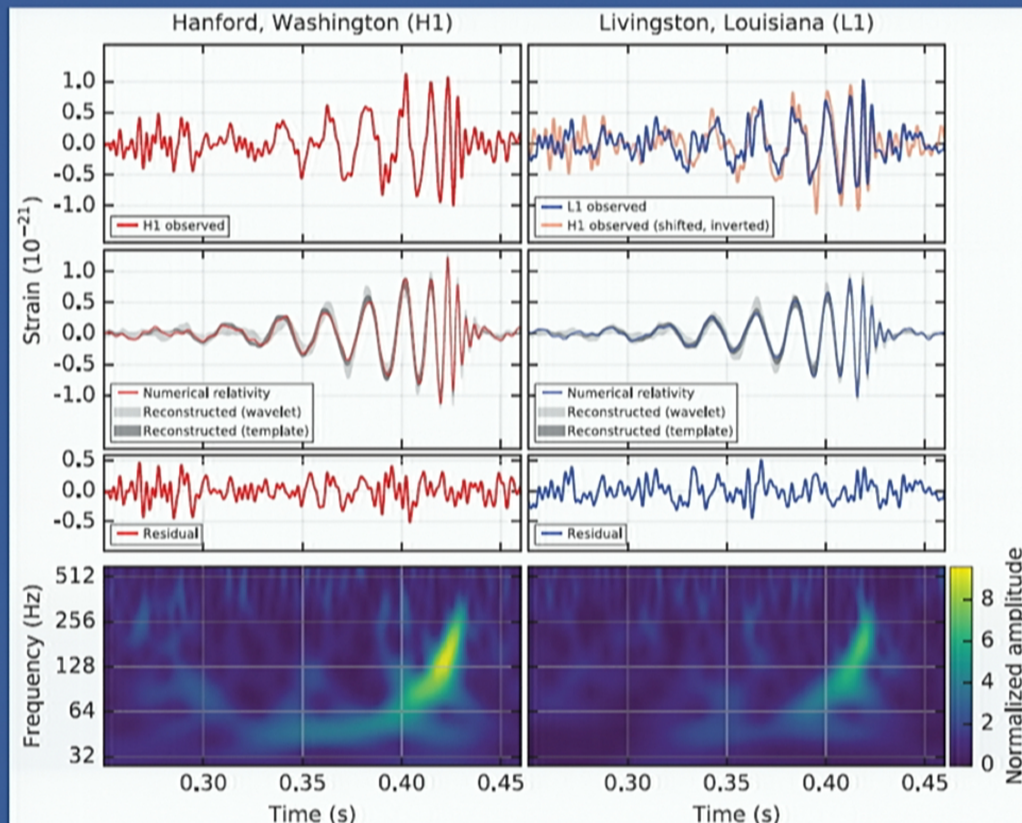
Reflections on the history of the strong field of GR

- Discovery :
  - Schwarzschild in 1915; cosmological solutions over the next several years
- Dark ages : ~ 1920's – 1950/60's
  - misinterpreted, misunderstood, dismissed and/or regarded as irrelevant to any physical process
- Renaissance : 1950-1970's
  - On the theory side, gained a solid understanding of the true nature of black holes, the genericity of singularities and gravitational collapse
  - On the observational side, discovery of quasars, X-ray binaries, pulsars and the CMB

Reflections on the history of the strong field of GR

- The (dark ages)$^{-1}$: post-renaissance prior to GW150914
  - The notions and predictions of the strong field were almost taken for granted, without verification from observation or experiment
    - the strong field is intimately connected with some of the deepest mysteries in theoretical physics today : dark energy, information loss/firewalls/quantum gravity.
    - It is astonishing that space and time can get so warped to form horizons and singularities ; must demand a similar "astonishing" level of evidence
      - Prior to GW150914, all evidence for this regime in nature was circumstantial (e.g., "what else could they be?" for BH candidates), or rely on models/assumptions that do not yet have independent confirmation (e.g evidence for lack of a surface in certain accreting BH systems, precision cosmological measurements if dark energy is taken to not be a problem with GR)

GW150914 : The era of observational, dynamical strong-field gravity has arrived



PRL 116, 061102 (2016), LIGO & Virgo Collaboration

The physics of GW150914

- The residual subtracting the best-fit numerical relativity template for a binary black hole merger is consistent with noise *[arXiv:1602.03841, LIGO/Virgo Collab.]*
  - fractional deviations in the waveform from the GR prediction of > 4% not supported by the data (other than those that can be absorbed in a re-definition of the parameters of the binary)
- This folds in all the rich physics of black hole collisions within general relativity
  - runaway inspiral due to GW emission
  - no naked singularities in the collision, and the horizons merge
  - astonishingly simple (as characterized by the waveform) transition from inspiral to merger-ringdown
  - very rapid ringdown to a unique, quiescent Kerr black hole remnant

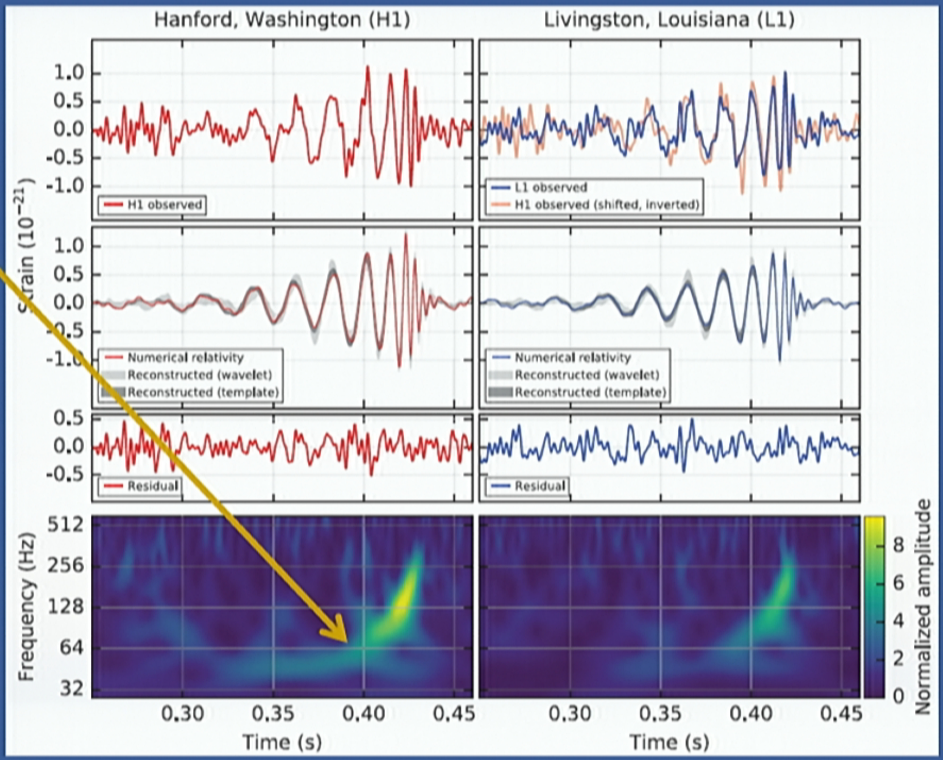
The physics of GW150914

- General relativity does not break apart the event into such distinct regimes and concepts, but this is essential for a deeper understanding of black holes and their dynamics
  - instructive to dissect the signal and measure consistency of the event with GR in terms of these ideas
    - also allows one to imagine how exotic alternatives could be consistent with/ruled out by the data
  - if this is a binary black hole merger in GR, then GR tells us all the properties of signal should be characterized by the small set of parameters defining the orbit and initial masses and spins of the black holes
  - though the SNR for individual segments are not high enough for very accurate tests of this sort, enough to see if the inspiral is consistent with the ringdown, constituting a "zero-order" test of the no-hair theorems

Phases of the event, and what we can learn from each

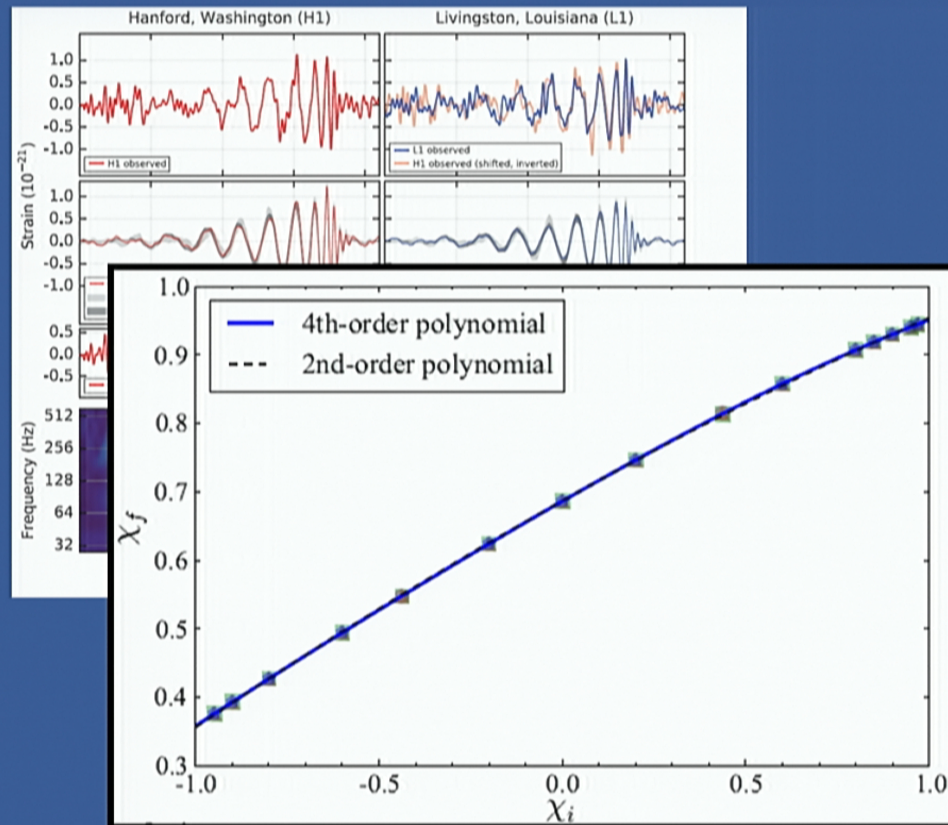
During the inspiral, how rapidly the signal sweeps up in frequency in time-frequency space can be used to compute the *chirp mass* of the binary :

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$



Phases of the event, and what we can learn from each

Not enough cycles above the noise floor prior to merger to get a good handle on the individual spins (through various spin-spin and spin-orbit interactions), though for comparable mass systems as these are, the orbital angular momentum prior to plunge offers the leading order contribution to the final spin of the remnant



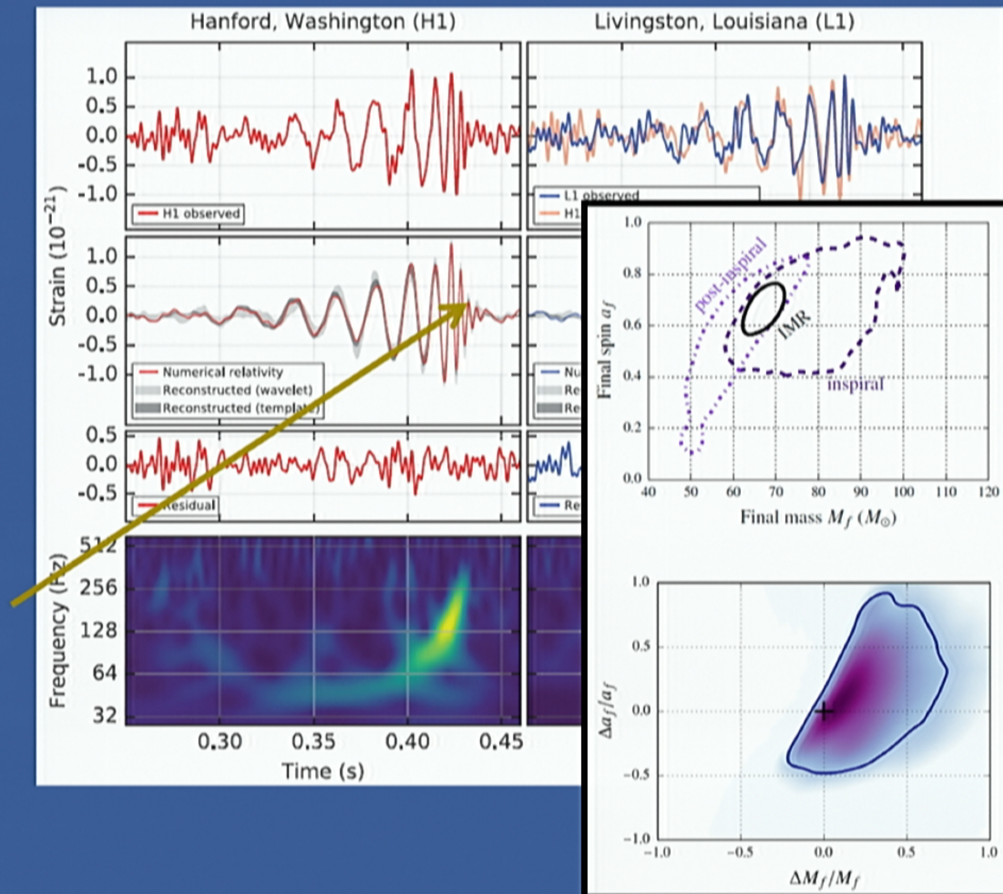
Equal mass, non-precessing mergers,
from D. Hemberger et al., PRD88 (2013)

Phases of the event, and what we can learn from each

Thus, from the inspiral part alone, one gets a constraint on the mass and spin of the remnant

The uniqueness theorems tell us all the properties of vacuum black holes in GR are governed by the Kerr solution, including all the quasi-normal ringdown modes

NR solutions show one is, to good approximation, within this regime after peak amplitude is reached, and the signal is dominated by the least damped mode; the observed frequency and decay time gives a good proxy to this, and can be inverted to yield an independent estimate of the mass and spin of the remnant



arxiv:1602.03841, *LIGO & Virgo Collaboration*

Beyond GR

- There is no anomaly in GW150914 that defies a conventional explanation, so the main significance of this event is to constrain/rule-out alternatives
  - a parameter bias could hide >4% inconsistencies, though would need a population of mergers to start searching for such a possibility
- The problem with doing so now, is pretty much all alternative theories, or "exotica" (boson stars, gravistars, traversable wormholes, etc.) are in the following, or worse situation:

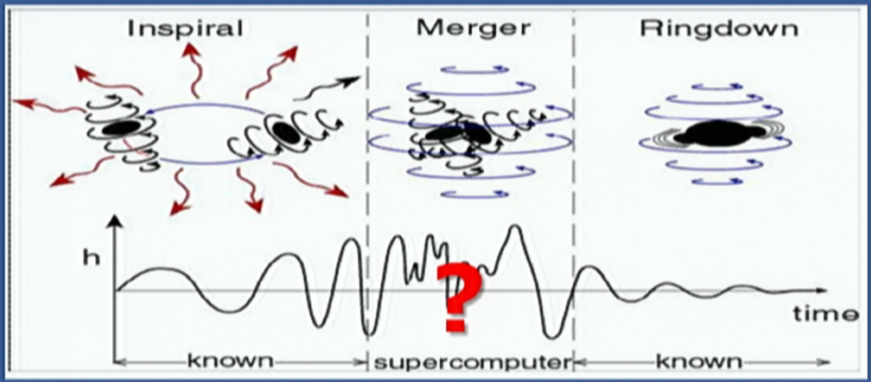
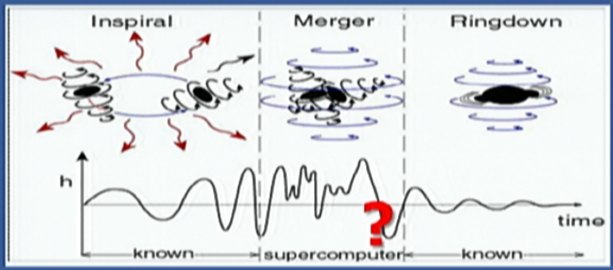
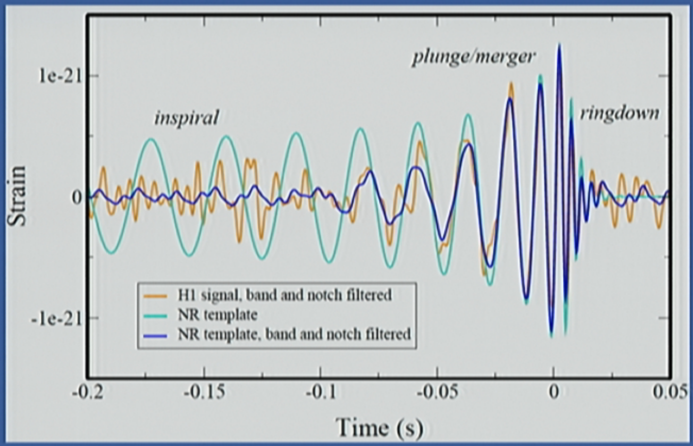


Illustration by Kip Thorne

Beyond GR



- Because of the "?" in non-conventonial GR, essentially all methods people have devised to constrain GR or to search for deviations are based on
  - ***the early inspiral***, where post Newtonian-like expansions are available, and reasonably well-motivated generic deformations of these, such as the parameterized post Einsteinian (ppE) approach have been developed
  - ***stationary isolated solutions***, where ringdown modes can be computed, or images of accretion disks about these solutions can be studied to be confronted with anticipated data from the event horizon telescope
- After GW150914 this no longer suffices; the bar has been raised for any alternative to claim viability in light of all experimental and observational data
  - ppE GW searches for generic deviations can only "nibble at the edges" of the data in GW150914, and unsurprisingly the constraints one can derive are weaker than one might have hoped for from an SNR 24 event *[N. Yunes et al., arxiv:1603.08955]*



Constraints on exotic compact object alternatives to black holes *within* general relativity

- *Heuristically*, GW1501914 gives a very strong constraint for the *remnant* to be an exotic alternative to a black hole within GR because of the rapid quenching of the signal after peak amplitude is reached

- Here we do have at least have some guidance from solutions of compact matter object mergers within GR, binary neutron star and binary boson star mergers, that show two generic outcomes :

  - ***Formation of a hypermassive, exotic remnant***. The violent merger excites equally violent dynamics in the matter, which in no way at early times post-merger can be described by linear perturbations of a stationary solution. I'm guessing this scenario could *not* be made consistent with GW150914, unless the matter has properties as "bizarre" as the effective material properties of a black hole

  - ***Prompt collapse to a black hole***. Here, with tuning and tweaking of parameters (need to support 30 solar mass objects, and need to be more compact than existing BS/BS or NS/NS simulations performed), I'm guessing could be made consistent with GW150914

    - *bottom line, GW150914 is <u>at least</u> giving evidence for the formation of a Kerr black hole via a binary merger, even if the progenitors are exotic compact objects*

Constraints on exotic compact object alternatives to black holes *within* general relativity

- One way to quantify how "bizarre" the material properties of the exotic compact object has to be to explain the signal is to use an effective hydrodynamic model

- Many conceivable ways to do this; for a simple, order of magnitude idea, consider the bulk and shear viscosities that would be needed to damp the dominant ($l=2$) mode in an incompressible Newtonian fluid star *[Cutler and Lindblom, 1987]*

$$\bar{\eta}_{\text{eff}} \sim 4 \times 10^{28} \frac{\text{g}}{\text{cm} \cdot \text{s}} \left(\frac{m}{65 M_\odot}\right) \left(\frac{370\text{km}}{R}\right) \left(\frac{4\text{ms}}{\tau_{\bar{\eta}}}\right)$$

$$\bar{\zeta}_{\text{eff}} \sim 3 \times 10^{30} \frac{\text{g}}{\text{cm} \cdot \text{s}} \left(\frac{m}{65 M_\odot}\right) \left(\frac{370\text{km}}{R}\right) \left(\frac{4\text{ms}}{\tau_{\bar{\zeta}}}\right)$$

i.e. this says, given the observed properties on the RHS, we can interpret the dynamics of the exotic object as an effective, viscous fluid with viscosity coefficients as given on the LHS.

Effective viscosities of some known compact objects

- Black holes (via the membrane paradigm, *Thorne, Price and McDonald 1986*) :

$$\bar{\eta}_{\rm BH} = -\bar{\zeta}_{\rm BH} \sim 1.3 \times 10^{30} \frac{\rm g}{\rm cm \cdot s} \left(\frac{m}{65 M_\odot} \right)^{-1}$$

- Neutron stars, where the damping comes from neutron scattering and strong magnetic fields

$$\bar{\eta}^{(n)}_{\rm NS} \sim 2 \times 10^{14} \rho_{15}^{9/4} T_{11}^{-2} \frac{\rm g}{\rm cm \cdot s}$$

$$\bar{\zeta}^{(n)}_{\rm NS} \sim 2.4 \times 10^{29} \rho_{15}^{2} T_{11}^{6} \omega_{10}^{-2} \frac{\rm g}{\rm cm \cdot s}$$

$$\bar{\eta}^{(B)}_{\rm NS} \sim 1.3 \times 10^{28} B_{16} R_{12} \sqrt{\rho_{15}} \frac{\rm g}{\rm cm \cdot s}$$

- Solitonic boson stars (*Macedo, Pani, Cardoso and Crispino and Cardoso, 2013*)

$$\bar{\eta}_{\rm BS} \sim 7 \times 10^{26} {\rm g/cm/s}$$

$$\bar{\zeta}_{\rm BS} \sim 5 \times 10^{28} {\rm g/cm/s}$$

(bosonic material has very low intrinsic viscosity; this is all coming from GW damping of the mode)

Beyond GR

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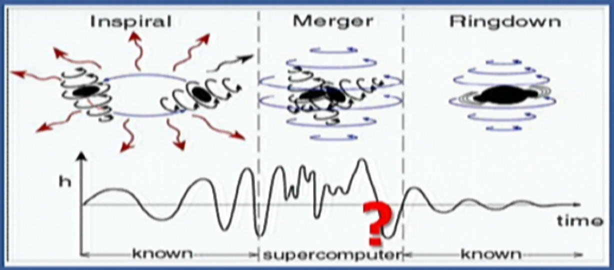

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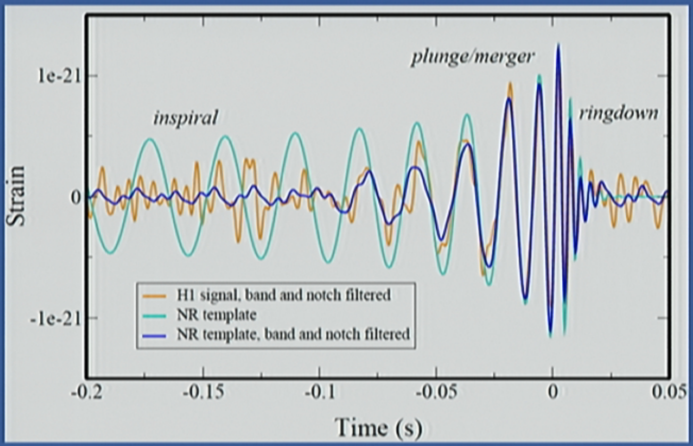
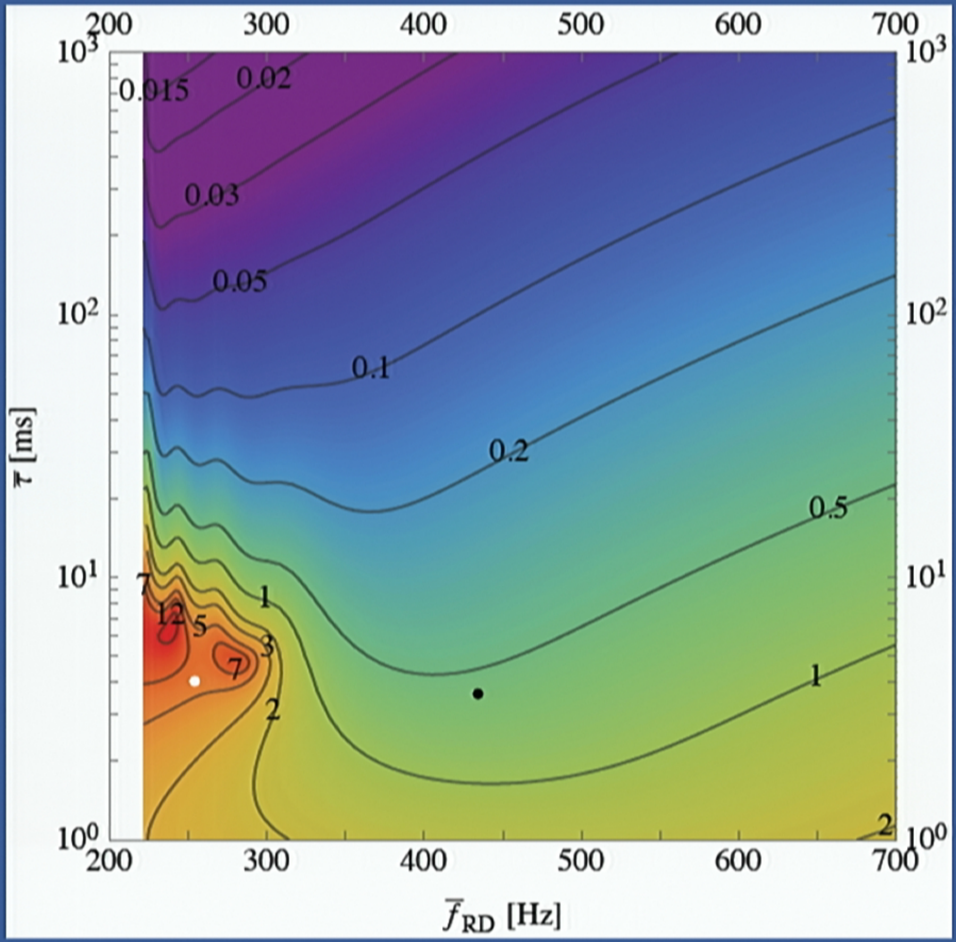


Exotic compact objects

- GW150914 essentially rules out an exotic remnant with bosonic or neutron star-like material, *if* the *l=2* matter mode was excited with an initial amplitude to give a signal as large as that observed
- ***Figure***: can invert the question, and place limits on the initial amplitude, for a given frequency and damping time, above which LIGO should have seen the mode

[N. Yunes et al., arxiv:1603.08955]



Conclusions I: looking ahead

- To make these heuristic arguments precise, and likewise constrain alternative theories to vacuum gravity, need to solve the 2-body problem in these scenarios
  - should be straightforward for boson stars
  - objects like gravastars are “dead in the water” until they can be formulated within a well-posed theory that can predict their collisional dynamics; likewise for alternative gravity theories like dynamical Chern-Simons gravity that (may) not have a well-posed initial value formulation
- Though the future looks bright given the wealth data we can hope to have within a few years of AdLIGO reaching design sensitivity
  - (and of course not covering the broad range of other data we can hope to have, from pulsar timing, the event horizon telescope, EM transients associated with mergers involving neutron stars, etc.)