Testing GR and constraining alternative theories with LIGO observations

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Outline

- General Relativity in the wake of GW150194, GW151226
  - Entering the era of observational dynamical, strong-field gravity
  - Can now start to test the most non-linear aspects of Einstein gravity, and begin to constrain alternatives to GR that predict deviations here
    - GW150914 could *eventually* be a game-changer constraining alternatives to GR, and exotic alternatives to black holes within GR, but not until alternatives can provide concrete predictions for merger events
      - Though can make some qualitative statements on properties exotica must have to be consistent with the data
    - Restricting to the better understood early inspiral, GW151226 provides somewhat stronger bounds despite its lower SNR

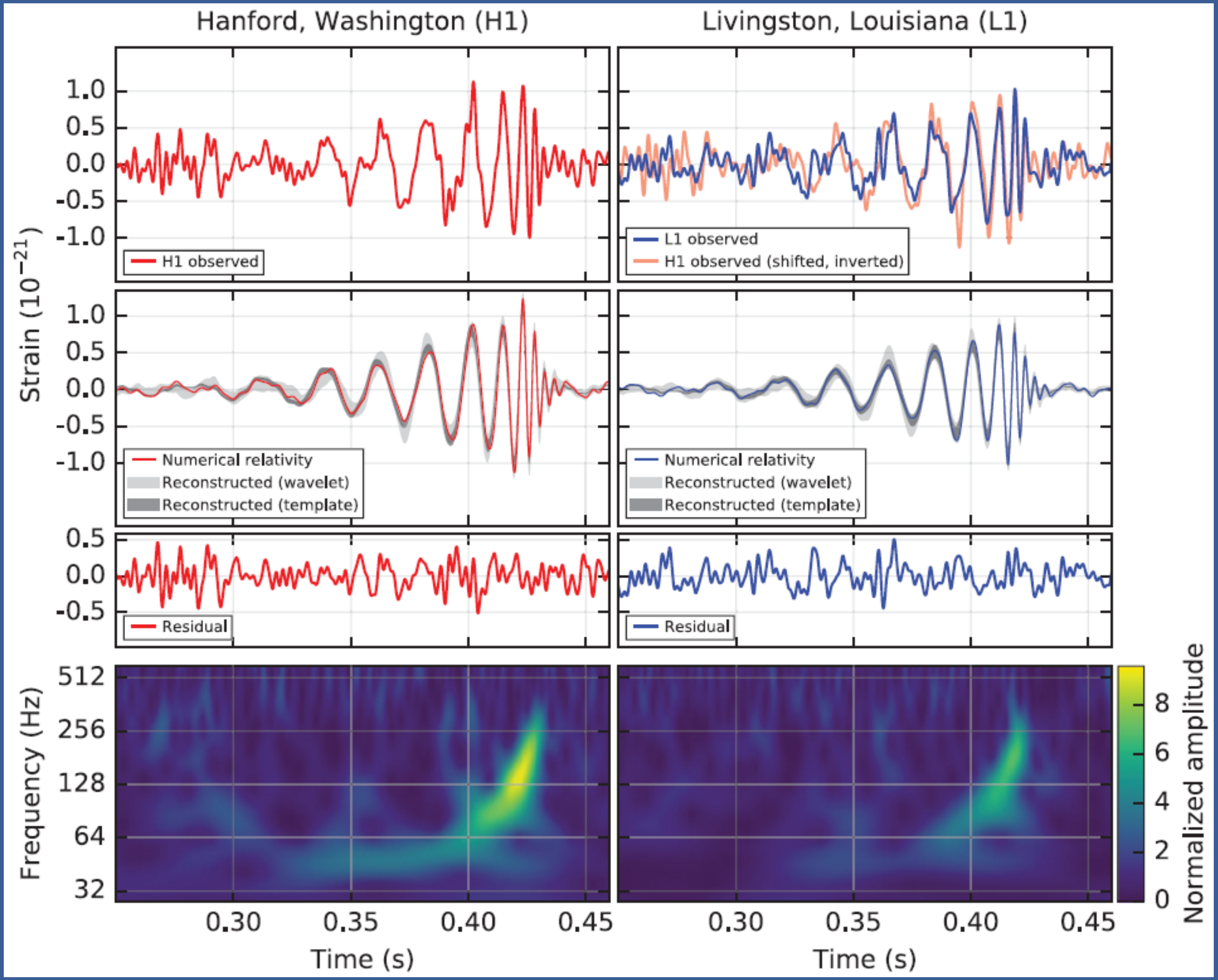
Reflections on the history of the strong field of GR

- 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 observable 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., for BHs, "what else can they be?"), 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 assumed not to 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

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

- The problem with doing so now, is pretty much all alternative theories, or "exotica" (boson stars, gravastars, traversable wormholes, etc.) are in the following, or worse situation:

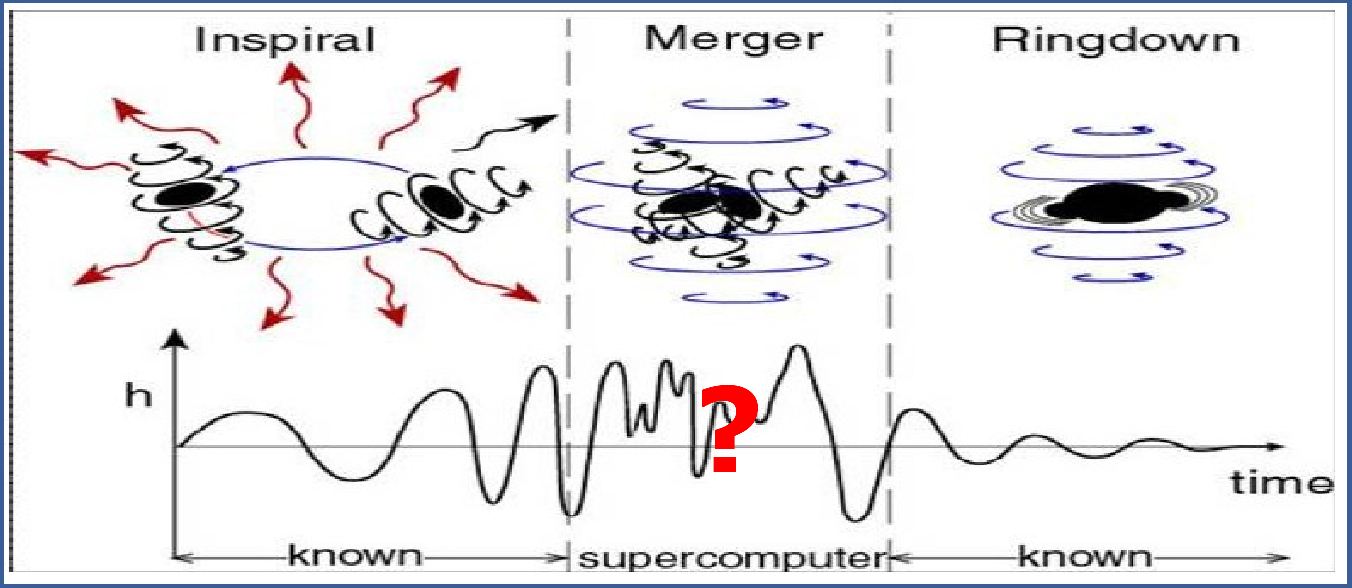
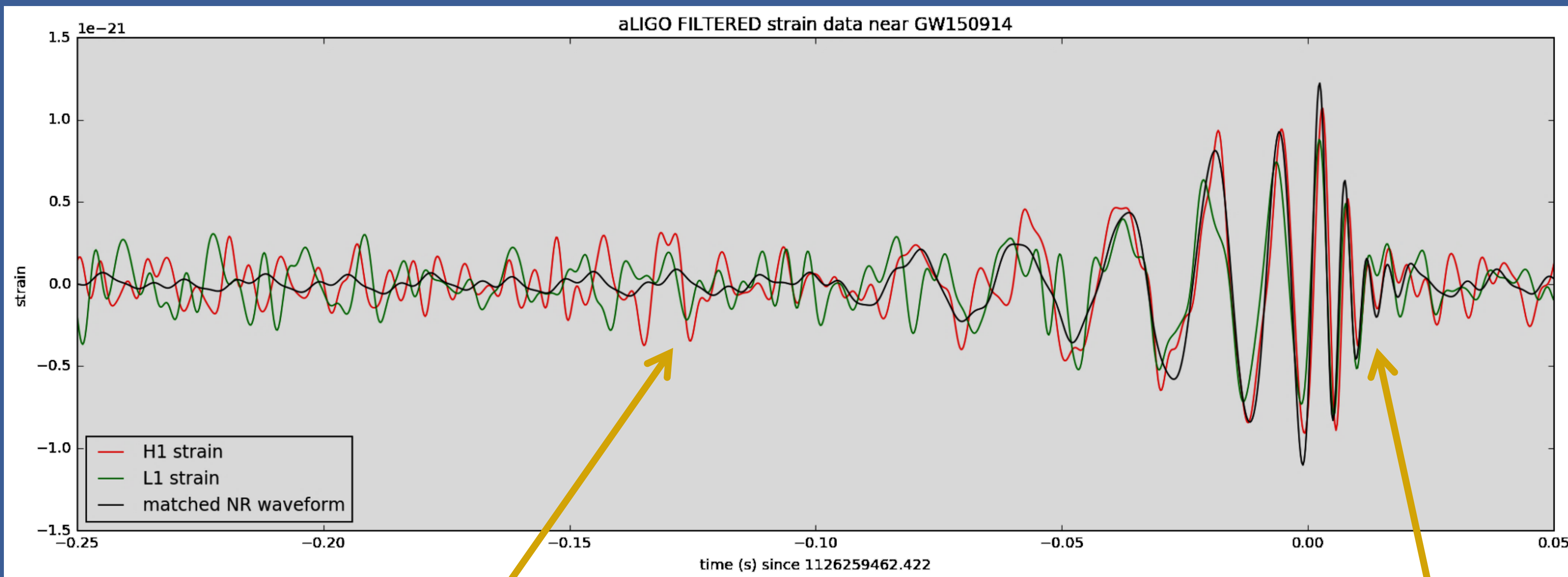


Illustration by Kip Thorne

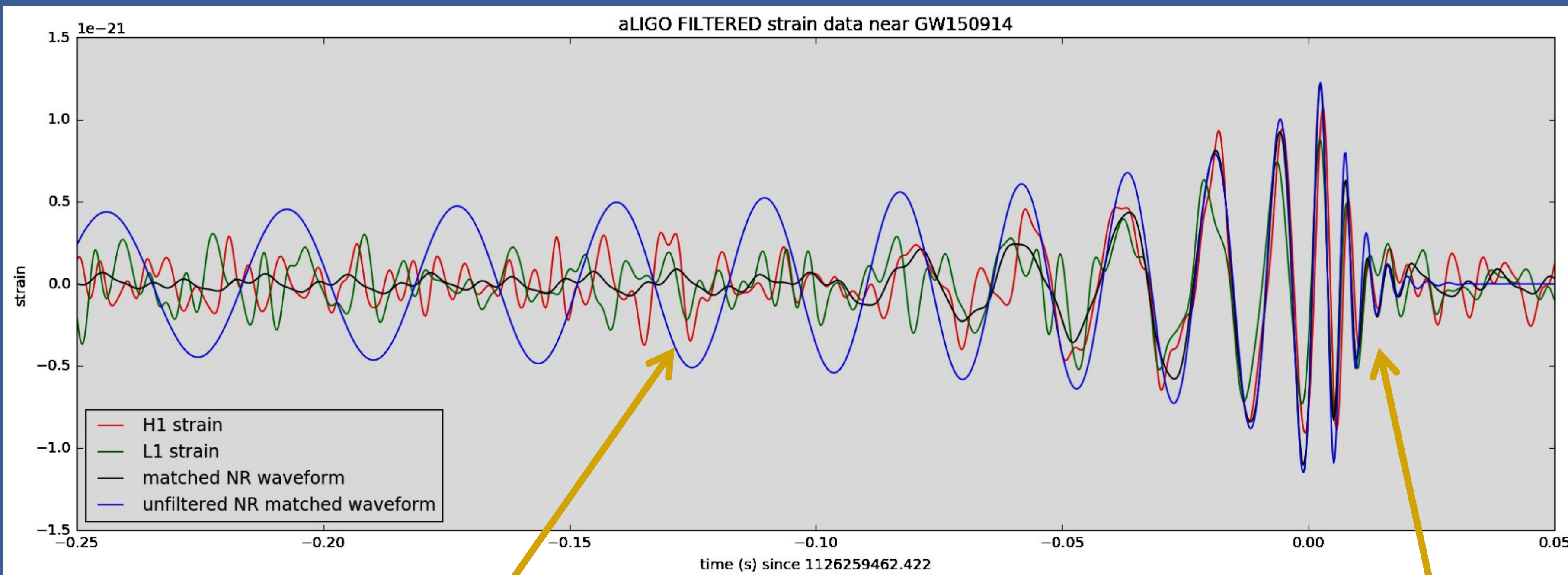
GW150914, Filtered Signal plus Best-Fit Template



Inspiral

Ringdown

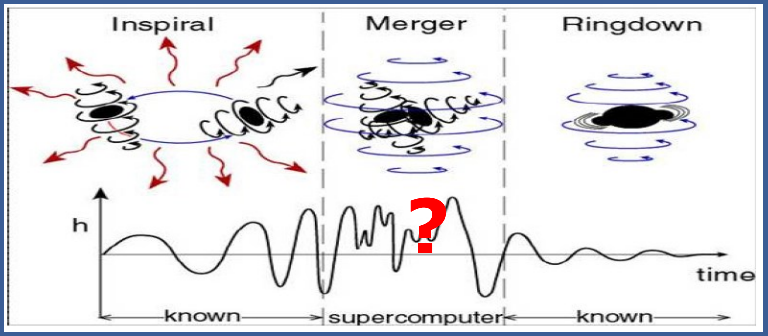
Filtered Signal plus Filtered & Unfiltered Best-Fit Template



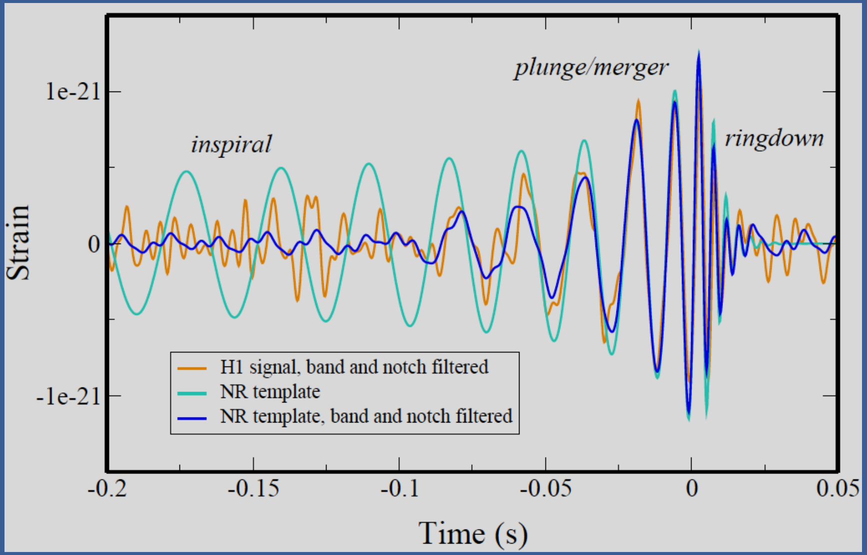
Inspiral

Ringdown

Beyond GR



- Because of the “?” in non-conventional 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
  - Can still ask what we can do with ppE-like methods, that to-date have most extensively developed for the inspiral phase of mergers



The parameterized post-Einsteinian (ppE) framework in brief

- Detecting the unknown or unexpected, especially with GW methods that rely on templates, is a nebulous problem

- The idea behind ppE *(Yunes and FP, 2009)* is more modest : take a class of event – binary compact object inspiral here – where there is good evidence GR is at least providing the correct leading order description

  - Compact objects exist (neutron stars, black hole candidates)

  - Binary pulsar observations give strong evidence for quadrupole GW emission

and then *deform* the GR inspiral templates in a well-motivated manner to capture deviations from the GR baseline. "Well motivated" could include

- – Consistent with all existing tests, yet can produce observable deviations in the dynamical, strong field regime

- – Predicted by a specific alternative theory

- – Characterizes a *plausible* strong-field correction, e.g. more rapid late time inspiral due to excitation of a new degree of freedom (scalar waves, different polarizations, etc).

The minimal ppE inspiral template

$$\boxed{\tilde{h}(f) = \tilde{h}_I^{GR}(f)\cdot\left(1+\alpha u^a\right)e^{i\beta u^b}}$$

- $h_I^{GR}(f)$ is *some* model of the GR inspiral component, e.g. to leading order

$$\boxed{\tilde{h}_I^{GR}(f) \propto f^{-7/6} e^{i2\pi f t_0}}$$

  - $u=\pi M f$, with M the chirp mass
  - a, b, α, β are ppE parameters
    - GW observations are most sensitive to the phase parameters *(b, β)*
  - Note : the GR baseline does not need to be the templates used for detection

GR: α=0, β=0

Brans-Dicke: α=0, b=-7/3

Massive graviton: α=0, b=-1

Chern-Simons like parity-violation: a=1, β=0

Dynamical Chern-Simons gravity: a=3, b=-1/3

varying G: a=-8/3, b=-13/3

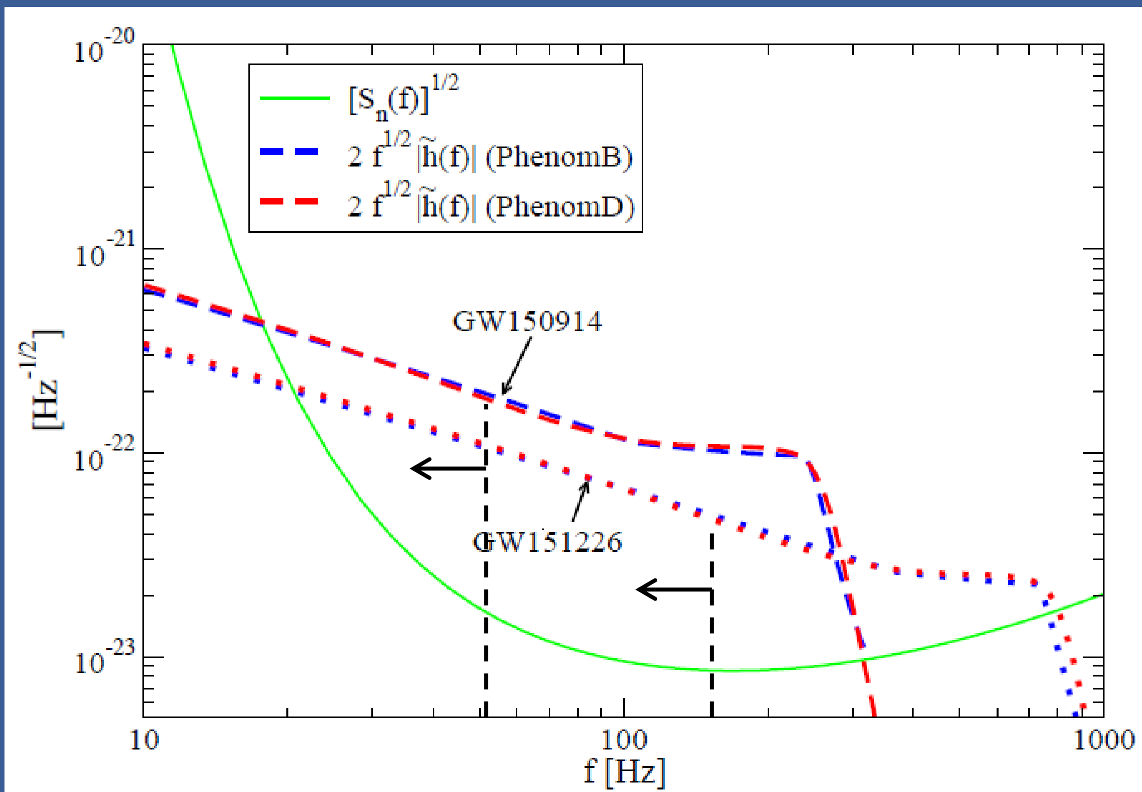
certain extra dimensions: α=0, b=-13/3

quadratic curvature: α=0, b=-7/3

modified PN: a=0, b≠0, b=(k-5)/3, k $\in$ I

Inspiral constraints from GW150914/GW151226

Work with Nico Yunes and Kent Yagi, arxiv:1603.08955

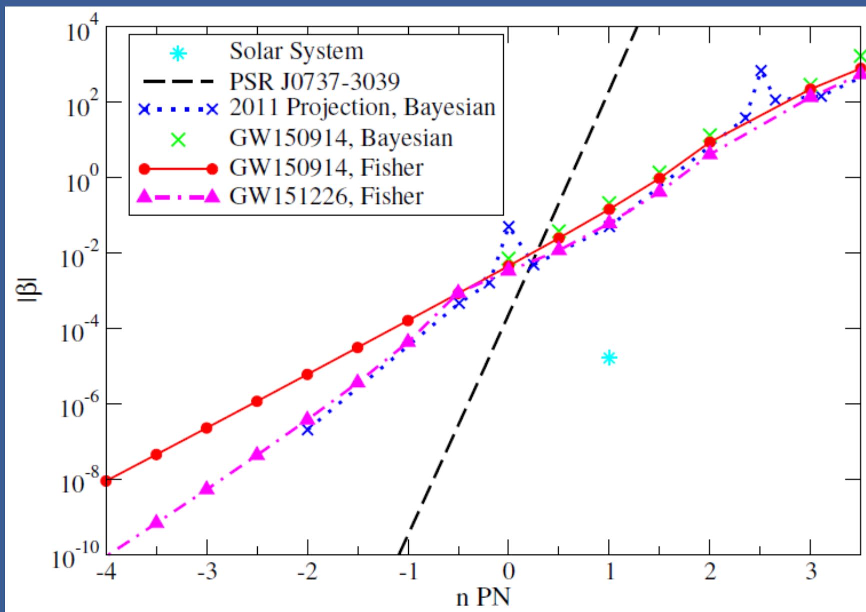


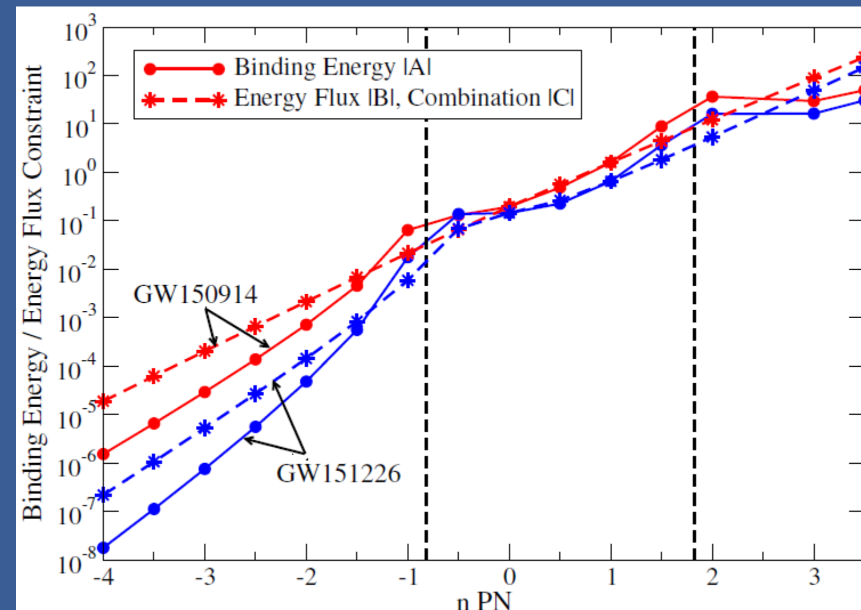
Event	GW150914	GW151226
Signal-to-noise ratio ρ	23.7	13.0
False alarm rate $\mathrm{FAR/yr^{-1}}$	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$
Chirp mass $\mathscr{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$
Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$
Final spin a_{f}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}

LIGO/Virgo, arXiv:1606.04856

Using the “IMRPhenom” model of LIGO (P. Ajith et al) excluding spin for the ppE baseline, truncated above 154 hz (52hz) for GW150914 (GW151226), and an analytic approximation to the aLIGO noise curve

Inspiral constraints from GW150914/GW151226





- Upper bound on β vs. PN order $n = (3b+5)/2$

  Note: Solar system, binary pulsar, and BBH GW tests should really ***NOT*** be displayed together on this kind of plot : apples vs. oranges comparison, constraining different “sectors”, and only within GR can they be mapped onto the same *(β,n)* plane. View this as a relative strength of GW vs. Binary Pulsar vs. solar system constraints in their respective “sectors”

- Sample of mapping of constraints on β to physical properties of the binary, here constraints to relative deviations in the binding energy and GW flux to those of the GR inspiral model, defined via

$$E_b = E_{b,\mathrm{GR}} \left(1 + A v^{2p}\right)$$

$$\dot{E} = \dot{E}_{\mathrm{GR}} \left(1 + B v^{2q}\right)$$

where the velocity $v = (m\pi f)^{1/3}$, and p & q are the pNs orders (n) where the effect enters

Conclusions

- We are all eagerly anticipating more events from ground based GW detectors, including those with EM counterparts; can anticipate data in 3 broad categories
  - ***Statistical : O(100) binary merger events***
    - start to search for small, systematic deviations from GR from the collection of inspirals with a ppE-like approach
    - gain evidence for/against speculative scenarios, such as the existence of ultra-light scalars that spin-down stellar mass black holes [the "axiverse"], observably bright EM counterparts to binary BH mergers, etc.
    - Use novel approaches like stacking to get more information from a population of events; results for targeting sub-leading QNM from BH mergers promising
  - ***Loud : an SNR O(100) event***
    - higher precision tests of GR/discovery of strong-field deviations, e.g. certain resolutions of the black hole information paradox/fire-wall problem propose macroscopic near-horizons deviations from classical physics *[see e.g. Giddings arXiv:1602.03622],* though because these proposals do not yet make concrete predictions will need a signal loud enough to give a measurable residual from the purely classical prediction
  - ***Rare :***
    - low probability events [eccentric mergers, large mass ratios, near extremal spins, etc.] that may be more sensitive to certain kinds of strong-field deviations