Fundamental Physics with Black Hole Binaries

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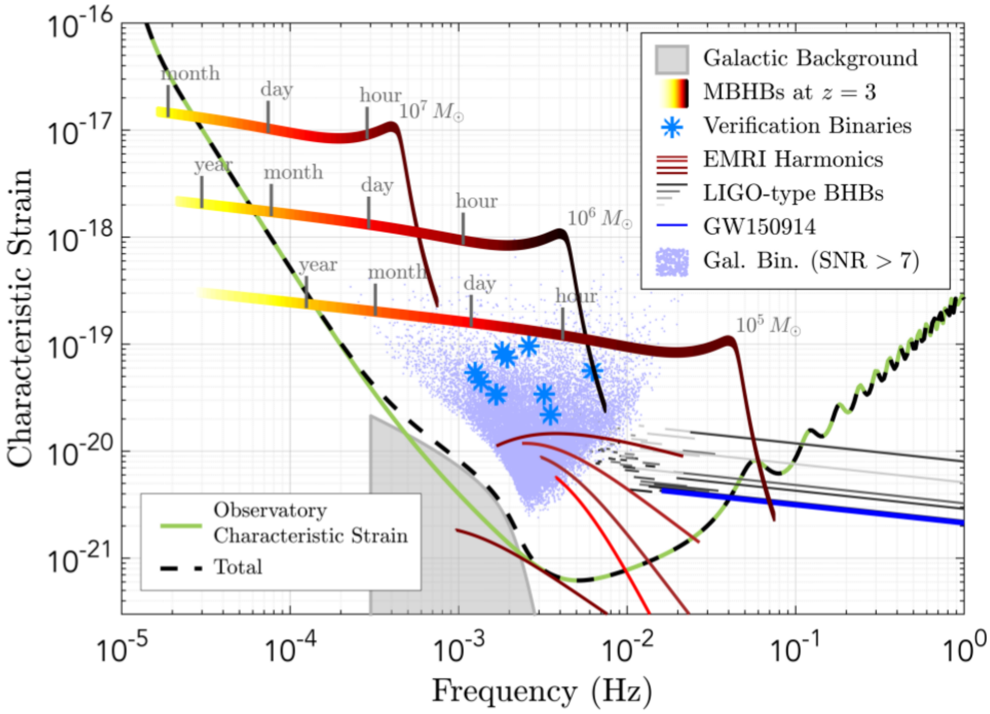
BHBs in the LISA band



(LISA proposal '17)

- 10s - 100s MBHBs/yr (Klein+ '16)
- 10s - 100s SOBHBs/yr (Sesana '16)

Massive BHs in GR

Massive BHBs in GR are (or will soon be) including a range of effects:

- Accurate inspiral phasing
- Multiple waveform harmonics
- Spin-induced precession
- Orbital eccentricity
- Merger signal
- Multiple ringdown harmonics
- Kicks

All can be affected by GR modifications

Massive black holes – beyond standard model

Gravity
• Is general relativity correct?
• Test in new regimes

• Black holes and light fields
• Black holes in modified gravity
• Exotic compact objects

Cosmology
• What is dark matter?
• What is dark energy?

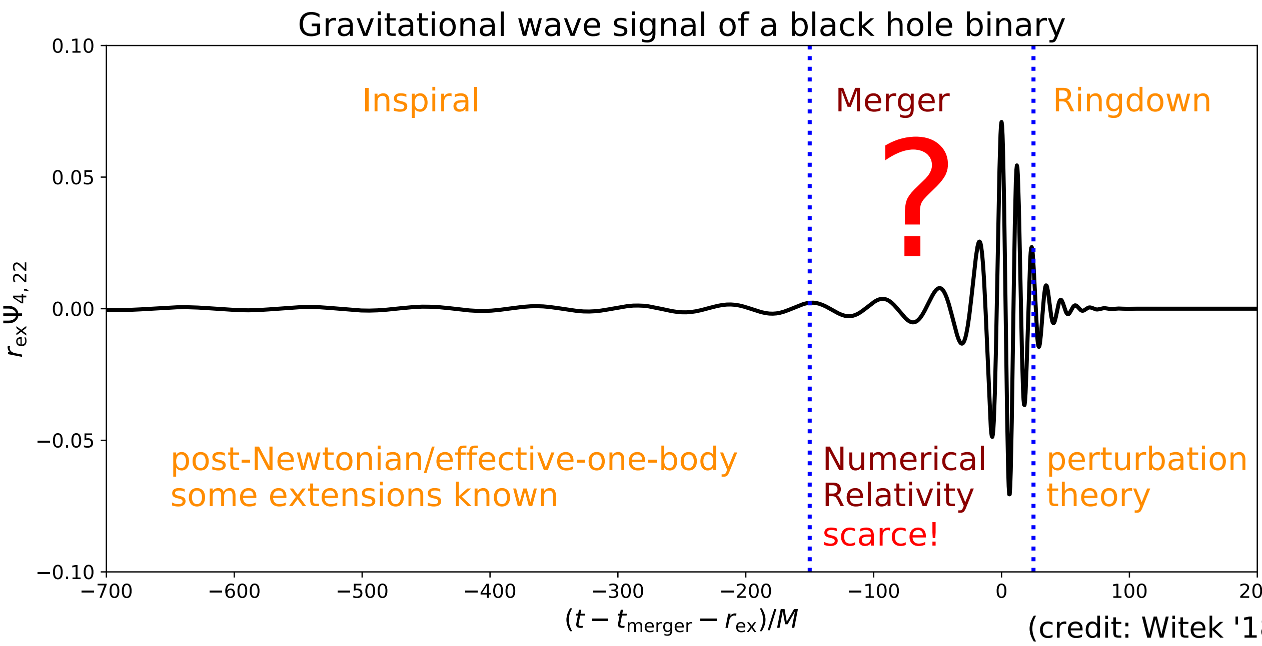
High-energy physics
• Quantum gravity?
• BSM particles?

smoking guns:

- additional radiation $\rightarrow$ dephasing of GW signal, new effects?
- additional polarizations, ringdown/echoes, ...
- inconsistency with GR prediction of full IMR – or is it?

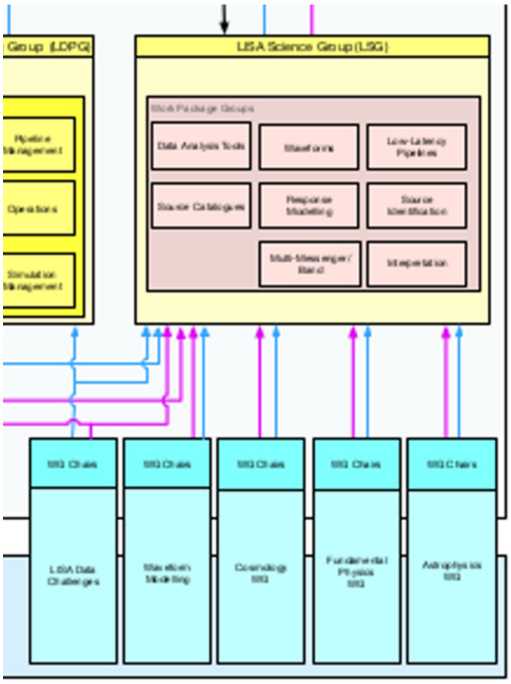
Methods – overview

- gravitational wave detections are theory-driven
- waveform templates needed for identification and interpretation of signal
- so far: (almost) only in GR, i.e., we are deaf to any "non-vanilla" models!
- waveform-free analyses are also being developed (data analysis session)



(credit: Witek '18)

FYI: LISA Waveform WG



(LISA Management Plan '18)

- consider joining LISA Waveform Working group
  (co-chairs: D. Shoemaker, M. van de Meent, N. Warburton, H. Witek)
- `wav-wg@lisamission.org`

Waveforms in GR: current status

PN/Phenom:

- IMR, full precession, subdominant harmonics, precession+harmonics, small eccentricity
- inspiral, eccentricity, full precession, subdominant harmonics

EOB:

- IMR, eccentricity, full precession, subdominant harmonics

Surrogate:

- Based on NR: moderate spins, circular, moderate mass ratio, full mode content (= what NR has)

Inspiral modifications: parametrized

Phasing and amplitude modifications: parametrized post-Einsteinian description
(Yunes & Pretorius '09)

Modification of the Fourier domain phase: $\Psi(f) = \sum_n a_{\rm GR} f^{n/3} + \beta f^{b/3}$.
Modification of the Fourier domain amplitude: $A(f) = A_{\rm GR}(f)(1 + \alpha f^{a/3})$

LIGO implementation: TIGER (Agathos+ '14)

- Modular
- Can be adapted to different WF models
- e.g. dynamical scalarization: $\Psi(f) = \sum_n a_{\rm GR} f^{n/3} + \theta(f - f_*)\beta f^{b/3}$
- Spin precession?
- Eccentricity?
- Number of parameters grow for each new effect included

Inspiral++ modifications: theory-specific

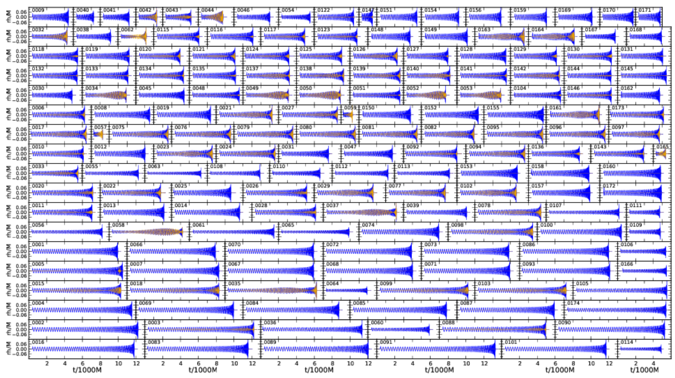
- Scalar-tensor, PN (Damour & Esposito-Farèse '96, Mirshekari & Will '13, Lang '14, ...)
- Scalar-tensor, EOB (Julié & Deruelle '17)
- Einstein-Maxwell-dilaton, EOB (Khalil+ '18)

- Avoid exponential growth in number of parameters
- Have to adapt each WF model for each alternative theory and search for modifications separately

Numerical Relativity in GR I

State-of-the-art (see, e.g., review by Duez & Zlochower '18)

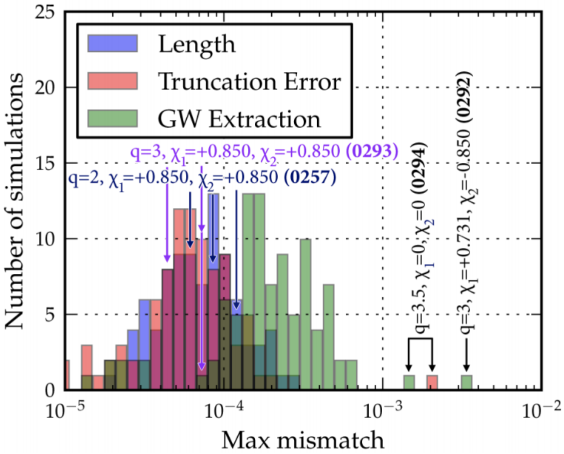
- performed regularly for
  - comparable-mass $q \lesssim 1/15$
  - moderate spins
  - quasi-circular binaries
- large spins
  (Lovelace et al '08, '11; Scheel et al '14;
  Ruchlin, Healy, Lousto, Zlochower '16, 17; Hinder et al '18)
- waveform catalogues
  (e.g. SXS/SpEC, RIT, GAT, ...)



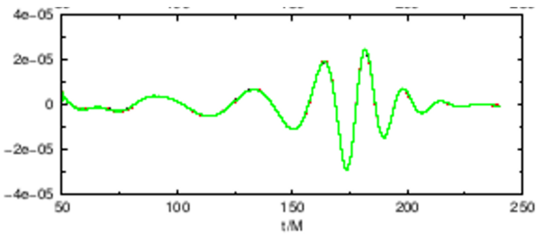
(SXS/SpEC '13)

Practical timescales: $\mathcal{O}$(1month) per simulation

Numerical Relativity in GR II



(Chu et al '16)



(Nakano et al '11)

New challenges

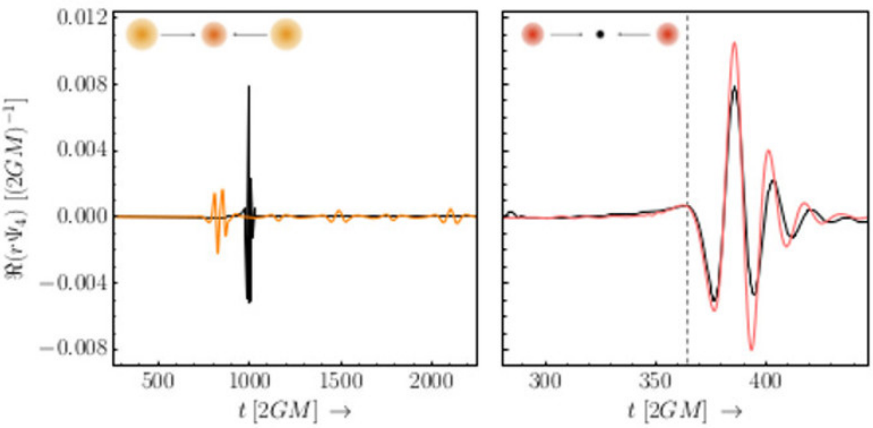
- better accuracy
- low-intermediate mass ratios $q \lesssim 1/100$

  (Lousto et al '10; Nakano et al '11; Sperhake et al '11)
- eccentric binaries
- Longer duration; more precession cycles
- (accurate) higher harmonics;
  inform ringdown studies (excitation factors)
- triple systems? Environmental effects?

Numerical relativity beyond GR I

- Black holes and light fields (Okawa, Witek, Cardoso '14; Zilhão, Witek, Cardoso '15; Pretorius & East '17, East '17, '18)
  - so far: only single BHs → monochromatic GWs
  - (M)BHB signatures? resonances & hang-ups? Dephasing?
  - so far: only weak-field approximation

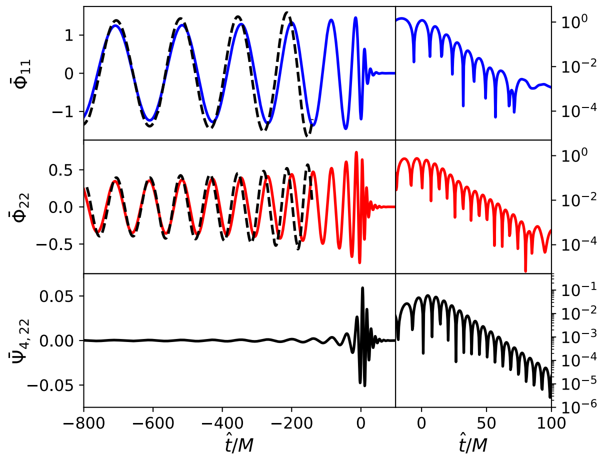
- exotic compact objects
  - (scalar) boson stars
    (Liebling & Palenzuela '12, Palenzuela et al '17, Helfer et al '18, Bezares et al '18, ...),
  - Proca stars (Sanchis-Gual et al '18)

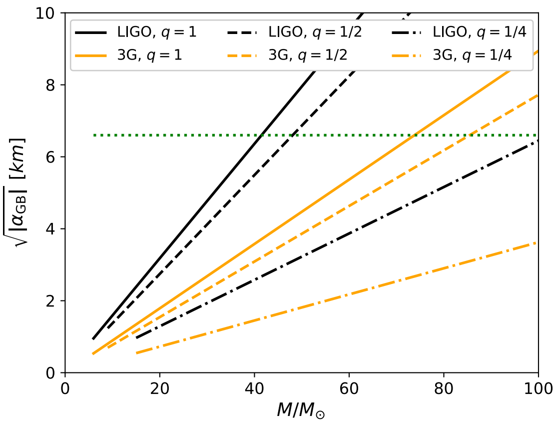


Example: boson stars (Helfer et al '18)

upcoming: CGQ Focus Issue "Numerical relativity beyond GR", eds. D. Gerosa, L. Stein, H. Witek

Numerical relativity beyond GR II





Example: sGB (Witek, Gualtieri, Pani, Sotiriou '18)

- BHs in modified gravity
  - compact binaries in scalar-tensor theory

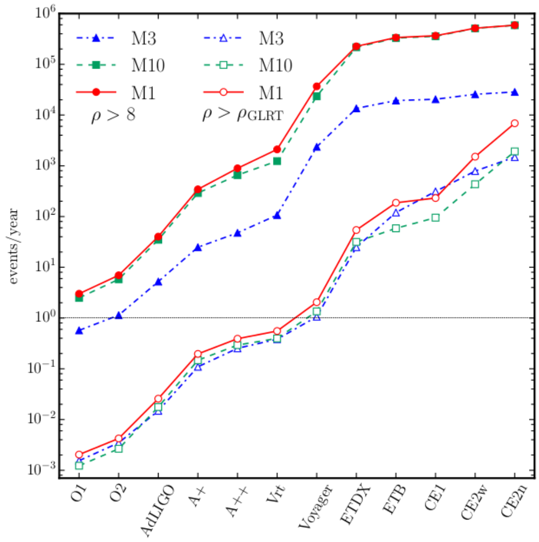
    (Barausse et al '12, Shibata et al '13, Healy et al '11, Berti et al '13)
  - Einstein-Maxwell-Dilaton models

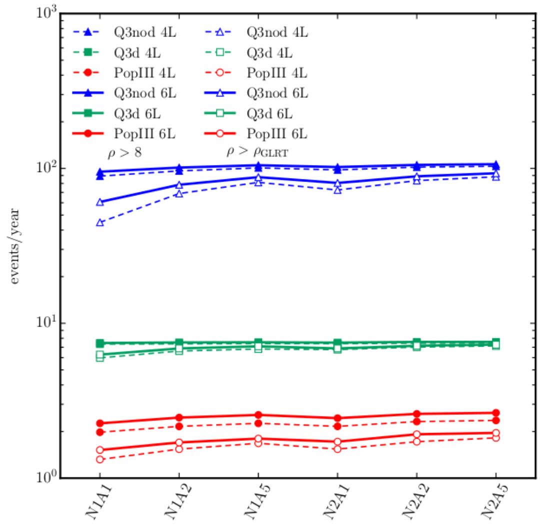
    (Hirschmann et al '17)
  - dynamical Chern-Simons gravity

    (Okounkova et al '17)
  - scalar Gauss–Bonnet gravity

    (Witek et al '18)
- relevance for LISA vs LIGO/3G; MBHBs vs SOBHBs?
- "full" models vs EFT-type approaches; well-posed IVPs

Ringdown modifications





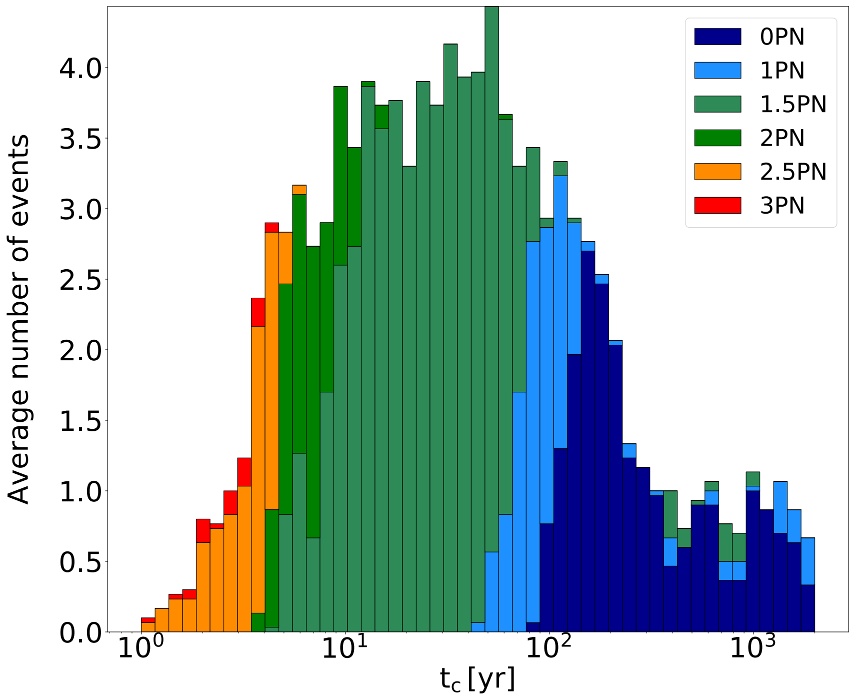
(Berti+ '16)

Parametrized approach: post-Kerr formalism (Glampedakis+ '17)

Link to specific theories?

Waveform accuracy requirements

Comprehensive accuracy requirement calculations are necessary

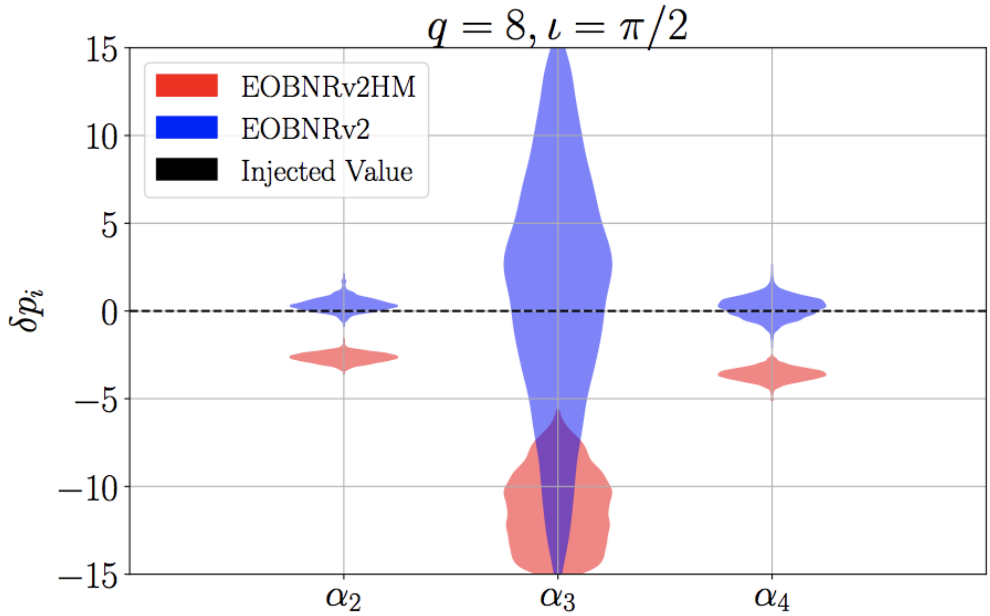


(Mangiagli et al '18)

- Fairly insensitive to the mass ratio
- Mostly depends on the total mass/time to coalescence

Waveform accuracy requirements

Unsurprisingly, a GR systematic (here lack of higher modes) can mimic beyond-GR effects (here ppE-type merger-inspiral terms)



(Pang et al. arxiv:1802.03306)

Testing GR – current status

A number of currently operational tests of GR

- Parametric deviations (very waveform dependent)
- Residual power (waveform dependent)
- Consistency test (less waveform dependent)
- Propagation effects (very waveform dependent)
- Polarization tests (less waveform dependent)

Parametric deviations – very waveform dependent

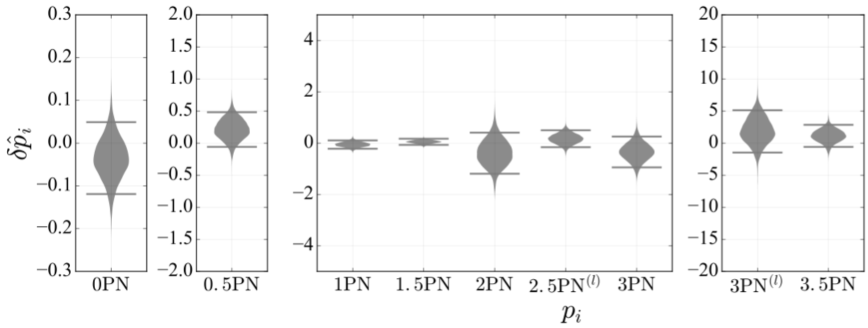
$$\tilde{h} \sim \tilde{A}(f;\vec{\theta}_{GR})e^{i\sum_i p_i(\vec{\theta}_{GR})f^i}$$

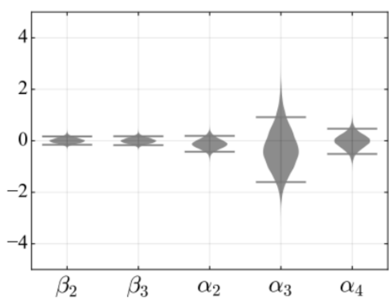
$$p_i \rightarrow p_i(1+\delta p_i)$$

Theory	a	α	b	β
Brans-Dicke	–	0	-7/3	β
Parity-Violation	1	α	0	–
Variable $G(t)$	-8/3	α	-13/3	β
Massive Graviton	–	0	-1	β
Quadratic Curvature	–	0	-1/3	β
Extra Dimensions	–	0	-13/3	β
Dynamical Chern-Simons	+3	α	+4/3	β

Yunes+ (arxiv:0909.3328)

Cornish+ (arxiv:1105.2088)





LVC (arxiv:1706.01812)

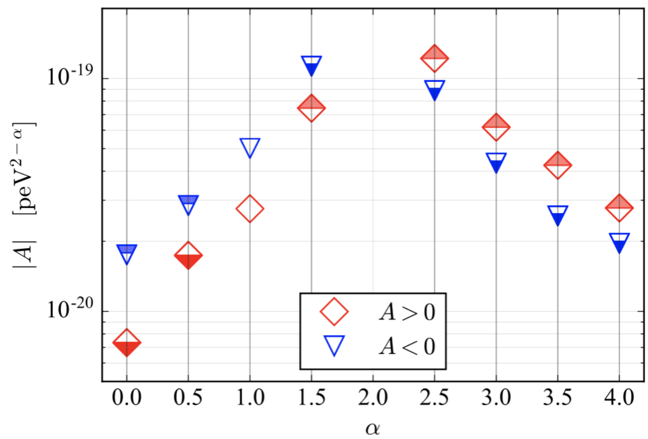
- Can be repeated for any BBH
- Relies heavily on an accurate background GR waveform

Propagation effects – very waveform dependent

$$E^2 = p^2c^2 + Ap^\alpha c^\alpha$$

$$\delta v_g \sim \frac{\text{GW period}}{\text{travel time}} \sim \frac{\text{GW wavelength}}{\text{distance}}$$

For 800Mpc and 250Hz, $\delta v_g \sim 5 \times 10^{-20}$



LVC (arxiv:1706.01812)

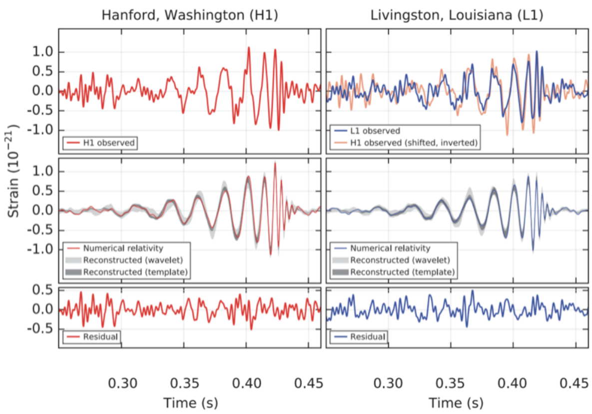
$$\delta v_g \sim AE^{\alpha-2} \Rightarrow A \sim \delta v_g E^{2-\alpha} \sim \delta v_g (h_{\text{Pl}} f)^{2-\alpha} \sim 10^{-20}\text{peV}^{2-\alpha}$$

For 2Gpc and 10^{-3}Hz, $\delta v_g \sim 5 \times 10^{-15}$ and A $\sim 10^{-15}\text{aeV}^{2-\alpha}$

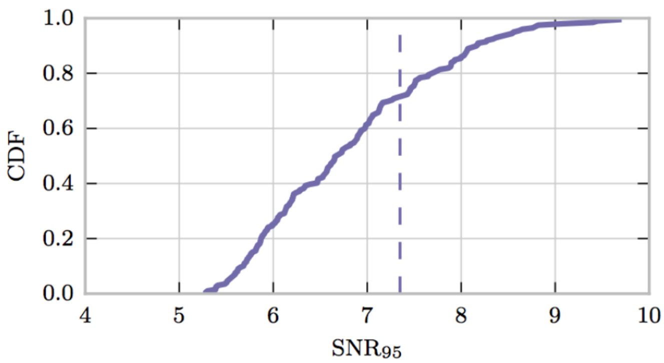
- Can be repeated for any BBH
- Relies heavily on an accurate background GR waveform

Residual power – waveform dependent

Subtract a (=maxL, maxP, fair draw) template waveform and check for residual power



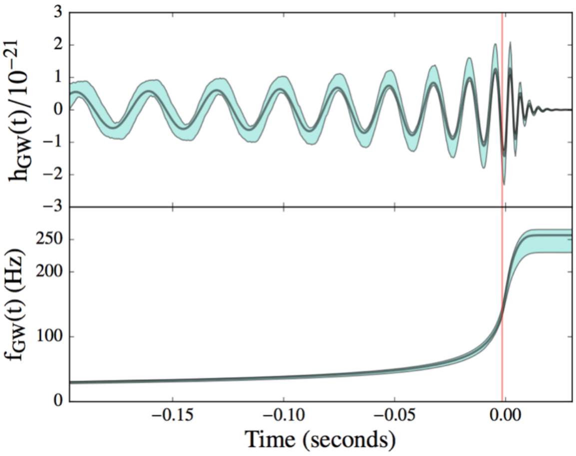
LVC (arxiv:1602.03837)



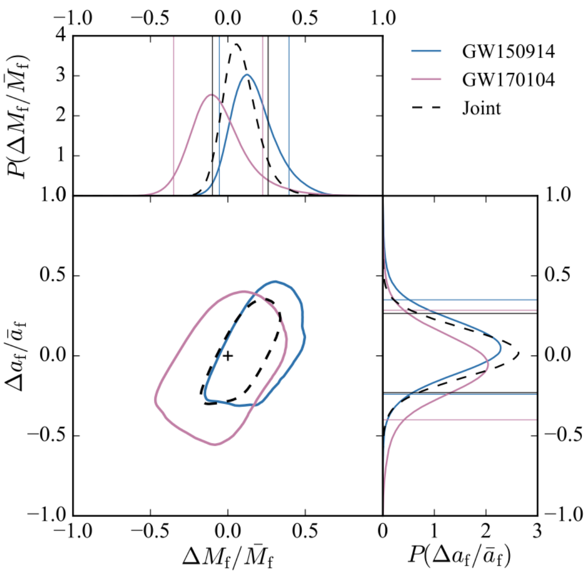
LVC (arxiv:1602.03841)
Cornish+ (arxiv:1410.3835)

- Can be repeated for any BBH
- Can capture generic unmodeled deviations
- Relies on an accurate template to subtract
- Perhaps limited applicability if many overlapping sources (data analysis session)

Consistency test – less waveform dependent



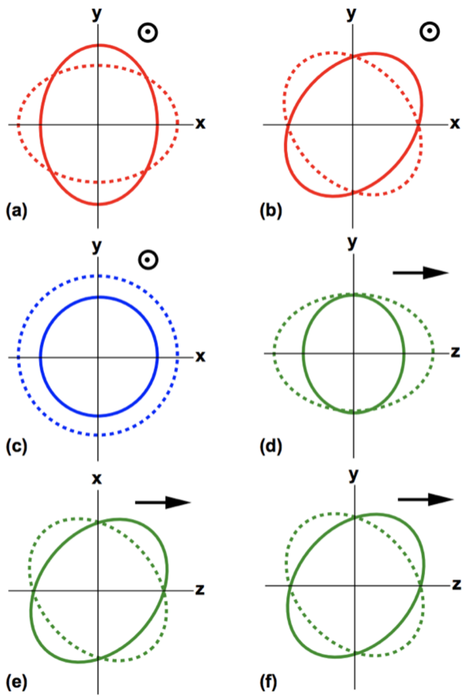
LVC (arxiv:1602.03841)



LVC (arxiv:1706.01812)

- Can be repeated for any BBH with a ringdown
- Relies on an accurate mapping between initial and final masses and spins
- In principle better ringdown tests with MBH (access to more ringdown harmonics)

Testing GR – more under construction



Will (arxiv:1403.7377)

- Continuous waves from bosonic clouds (Isi, Sun, Brito, Melatos '18)
- Null-stream test for beyond-GR polarization content (Guersel, Tinto '89)
- Parametrized test for beyond-GR polarization content (Chatziioannou, Yunes, Cornish '12)
- Modes consistency (Dhanpal, Ghosh, Mehta, Ajith, Sathyaprakash '12)
- Multipolar consistency (Kastha, Gupta, Arun, Sathyaprakash, van den Broeck+ '18)
- Theory-specific tests
- etc.

Discussion

- What (curvature/energy) regimes can we test with LISA vs LIGO / 3G?

Discussion

- Which beyond-GR models are more informative to study?
- Toy models vs fundamental models? How informative are they?

Discussion – “We need more NR simulations”

- Needed for synergy with PN/EOB and perturbation theory
- Next directions? What is feasible?
- Fill parameter space vs informed model building
- What are physically interesting / well-motivated theories to simulate?
- good news: “EFT-type” ($\sim$parametrized) approach adaptable to many models

Discussion – “We need better waveforms”

- Depends on effect in mind (parameter hierarchy)
- Accuracy for parametrized tests vs residuals vs global fits
- What do we need to prioritize (inspiral, merger, ringdown, eccentricity, precession, mass ratio...?)
- Astrophysical effects?
- Multibanding

Discussion – GW tests of GR

- Which tests are going to be the most useful?
- What are the current tests not probing?
- Null vs parametrized vs theory specific tests
- Consistency tests vs constraints
- How does the absence of beyond-GR effects help with theory development?