Testing General Relativity & Alternative Theories of gravity using Gravitational Wave Observations

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1. Testing GR and other theories of gravity

2. Gravitational Waves & testing GR
   - Testing Brans-Dicke theory
   - Testing Massive graviton theories
   - Parametrized tests of PN theory.

3. Plans to join LSC

Why test GR?

Successes of GR

GR has passed all the tests of gravity till date in flying colors.

Still..

- No fundamental reason why GR is the correct theory of gravity at all scales.
- Even if its 'correct', always good to quantify the correctness of GR.
- Weak-field tests put very stringent bounds, but these parameters may grow very rapidly as a function of field strength.
- Singularities in the theory.
- Early universe and quantum gravity.

Tests of GR at a glance

[Living Review Articles by Clifford Will, Psaltis, Stairs]

Existing Tests: EM observations

- Strong & Weak equivalence principle.
- Solar system bounds–Weak fields $v \sim 10^{-6}$ (PPN formalism)
- Binary Pulsar Tests–Stronger field $v \sim 10^{-3}$ (PPK formalism)
- Other tests:
  - Event Horizon.
  - Gravitational Lensing
  - No Hair Theorem.

GWs: natural way to probe strong-field gravity.

Tests of GR using GWs

GWs can probe

- Strong field aspects.
- Dynamical aspects.
- Radiative aspects.

Comparing various Tests of GR

- Solar System Experiments: $\frac{Gm}{rc^2} = 10^{-6}$.
- Binary Pulsar Tests: $\frac{Gm}{rc^2} = 10^{-3}$.
- Inspiralling compact binary sources: $\frac{Gm}{rc^2} = 0.1 - 0.2$.

When merger information is also included, GWs can probe highly nonlinear aspects of GR.

Tests of GR and Alternative theories of gravity using GWs

Types of Tests proposed

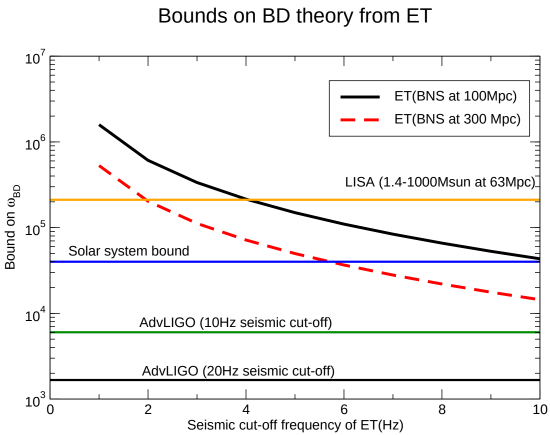
- Specific to a particular alternative theory of gravity:
  - * Tests of Scalar Tensor theories [Will 1994, Damour & Esposito Farése 1998, KGA, 2009.]
  - * Tests of Massive Graviton theories [Will, 1998, KGA & Will 2009, Keppel & Ajith 2010]
- Generic bounds:
  - * Parametrized tests of PN theory [KGA, Iyer, Qusailah & Sathyaprakash, 2006a, 2006b; Mishra, KGA, Iyer & Sathyaprakash, 2010] .
  - * Parametrized post-Einsteinian framework [Yunes & Pretorius, 2009] .

Testing Brans-Dicke Theory

[Will 1994]

- Brans-Dicke theory is scalar-tensor theory where in addition to the metric, there is a scalar field which determines the dynamics.
- This theory predicts the leading GW emission to be dipolar unlike theories like GR where its quadrupolar.
- The dipolar GW content can be parametrized in terms of a single parameter $\omega_{\rm BD}$ which can be bounded by GW observations.
- This term is proportional to the difference in 'sensitivities' of the binary components and is identically zero for binary BH systems.
- Sources which can provide best bounds are NS-BH systems.

Estimated bounds with GW observations



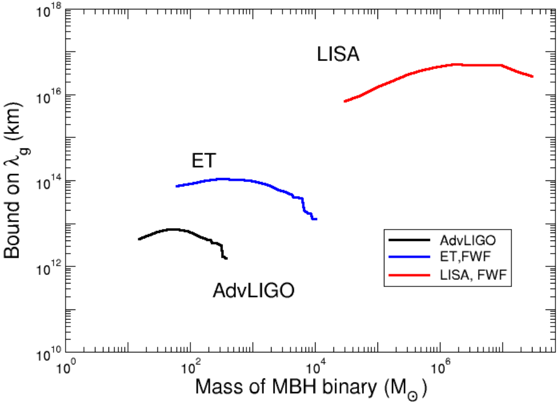
[KGA, Einstein Telescope design study document (Unpublished)]

Bounding Massive Graviton theories using GWs

[Will, 1998.]

- Massive Graviton theories are those theories which predict nonzero rest mass for graviton $\Rightarrow$ finite compton length.
- If the graviton compton wavelength is finite, it should have imprints on the GW spectrum in the form of "dispersion" $\Rightarrow$ different frequency components travel with different velocities which results in a distorsion of the inspiral GW signal.
- If there is a mass associated with the propagation of gravitational waves ("a massive graviton"), then the speed of propagation will depend on wavelength in the form $v_g \approx 1 - (\lambda/\lambda_g)^2$, where λ_g is the Compton wavelength of the graviton, in the limit where $\lambda \ll \lambda_g$.
- Hence GW observations of inspiralling compact binaries may put lower bound on λ_g

Projected bounds on λ_g using GW observations



[KGA & Will, 2009]

Parametrized tests of PN theory

[KGA, Iyer, Qusailah & Sathyaprakash, 2006a, 2006b]

Phasing formula in the restricted waveform approximation

$$\tilde{h}(f) = \frac{1}{\sqrt{30}\,\pi^{2/3}} \frac{\mathcal{M}^{5/6}}{D_L} f^{-7/6} e^{i\psi(f)},$$

and to 3.5PN order the phase of the Fourier domain waveform is given by

$$\psi(f) \quad = \quad 2\pi f t_c - \phi_c - \frac{\pi}{4} + \sum_{k=0}^{7} (\psi_k + \psi_{kl} \ln f)\, f^{\frac{k-5}{3}},$$

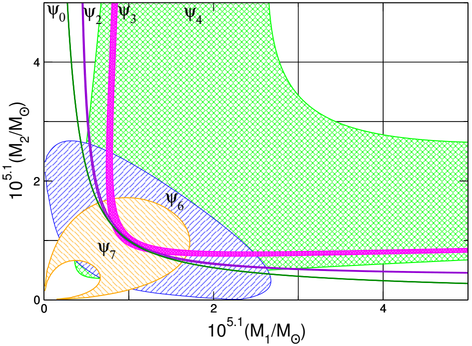
Log terms in the PN expansion

- Phasing coefficients are functions of component masses of the binary: $\psi_k(m_1, m_2)$ & $\psi_{kl}(m_1, m_2)$ [Spins negligible]
- Independent determination of 3 or more of the phasing coefficients ⇒ Tests of PN theory.

Basic Idea

- Parametrize the phasing formula in terms of various phasing coefficients where all of them are treated as independent.
- See how well can different parameters be extracted.
- Those which are well estimated, plot them (ψ_k & ψ_{kl}) in the $m_1 - m_2$ plane (similar to binary pulsar tests) with the widths of various curves proportional to $1 - \sigma$ error bars.

[KGA, Iyer, Qusailah, Sathyaprakash, 2006a]



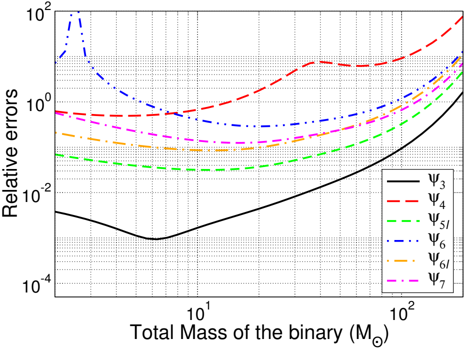
Issues

Highly correlated parameters & Ill-conditioned Fisher matrix for a large parameter space.

Alternative Proposal

- Treat two parameters as basic variables in terms of which one can parametrize all other parameters EXCEPT one which is the *test* parameter.
- This way, dimensionality of the parameter space is considerably reduced.
- Thus, one will have ${}^8C_3$ tests, not all of them independent.
- The best choice to be used as basic variables are the leading two coefficients at 0PN & 1PN, which are the best determined ones.
- Then one will have 6 tests.

[KGA, Iyer, Qusailah & Sathyaprakash, 2006b]



- Used an earlier EGO noise PSD (similar to one of the ET noise PSDs).
- All parameters except ψ_4 determined quite well over a large range of masses.

Plans to Join LSC

- Expected people: K G Arun, Bala Iyer, Chandra Kant Mishra, Rajesh Nayak.
- Project: Implementing the parameter estimation pipeline to test GR and alternatives for AdvLIGO.
- Method: Bayesian model selection method recently been discussed by Veitch et al.
- Collaborations: Cardiff University CBC group + P Ajith, Caltech.