Parametrized tests of post-Newtonian theory with GW detectors

Chandra Kant Mishra

ISGWA 2010, Delhi

21 Dec 2010

Tests of General Relativity

Most important tests of General Relativity (GR) are based on:

- Solar System observations.
- Radio observations of binary pulsars.

Tests of General Relativity

Most important tests of General Relativity (GR) are based on:

- Solar System observations.
- Radio observations of binary pulsars.
- General relativity passes these tests in flying colours.

Tests of General Relativity

Most important tests of General Relativity (GR) are based on:

- Solar System observations.
- Radio observations of binary pulsars.
- General relativity passes these tests in flying colours.
- But the gravitational fields involved in such tests are still very weak as compared to the strongest possible Gravitational fields in nature, *e.g.* those near the horizon of the black holes in a BH-BH binary system.

Stretching general relativity further: Tests with GWs

Stretching general relativity further: Tests with GWs

What if

Stretching general relativity further: Tests with GWs

What if

* General relativity breaks down when the gravitational fields are stronger than those of binary pulsars.

Stretching general relativity further: Tests with GWs

What if

* General relativity breaks down when the gravitational fields are stronger than those of binary pulsars.
* There is a scalar field coupled with the metric? [Scalar-tensor field theories]

Stretching general relativity further: Tests with GWs

What if

* General relativity breaks down when the gravitational fields are stronger than those of binary pulsars.
* There is a scalar field coupled with the metric? [Scalar-tensor field theories]
* Graviton has a mass which is so small that it starts to show up in the very strong field regime. [Massive Graviton Theories]

Stretching general relativity further: Tests with GWs

What if

* General relativity breaks down when the gravitational fields are stronger than those of binary pulsars.
* There is a scalar field coupled with the metric? [Scalar-tensor field theories]
* Graviton has a mass which is so small that it starts to show up in the very strong field regime. [Massive Graviton Theories]
* Gravity is described by some other theory.

Stretching general relativity further: Tests with GWs

What if

* General relativity breaks down when the gravitational fields are stronger than those of binary pulsars.
* There is a scalar field coupled with the metric? [Scalar-tensor field theories]
* Graviton has a mass which is so small that it starts to show up in the very strong field regime. [Massive Graviton Theories]
* Gravity is described by some other theory.

Gravitational Waves

- Gravitational Waves have direct imprints of all the strong field effects.

Stretching general relativity further: Tests with GWs

What if

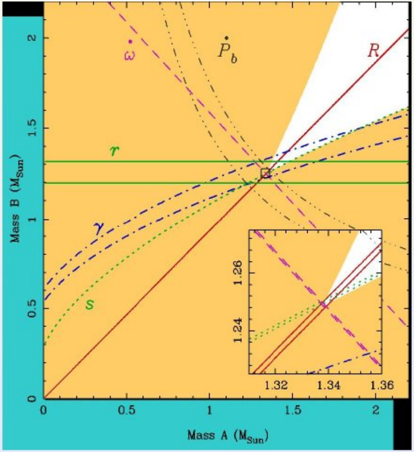
* General relativity breaks down when the gravitational fields are stronger than those of binary pulsars.
* There is a scalar field coupled with the metric? [Scalar-tensor field theories]
* Graviton has a mass which is so small that it starts to show up in the very strong field regime. [Massive Graviton Theories]
* Gravity is described by some other theory.

Gravitational Waves

- Gravitational Waves have direct imprints of all the strong field effects.
- How well can GW observations constrain deviations from GR?

Testing GR with Binary Pulsar J0737-3039

Measurement of various Keplerian and post-Keplerian parameters which are functions of component masses of the binary, led to a consistency check in the plane of masses.



Parametrized test of PN theory

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

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

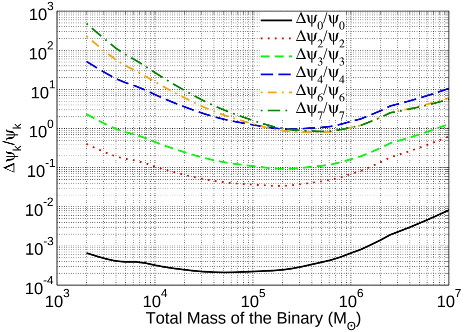
Log terms in the PN expansion

- In GR the phasing coefficients are functions of the component masses of the binary: $\psi_k(m_1, m_2)$ & $\psi_{kl}(m_1, m_2)$ [Spins neglected]
- Independent determination of 3 or more of the phasing coefficients $\Rightarrow$ Tests of PN theory[KGA, Iyer, Qusailah & Sathyaprakash, 2006].

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 measured.
- 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]



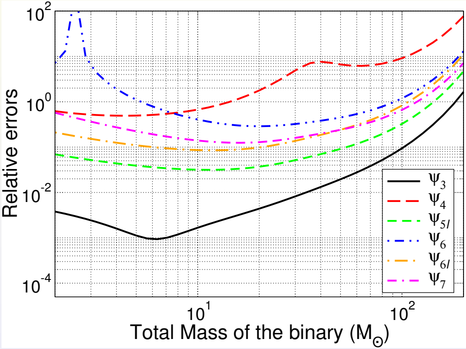
Issues

Large parameter space leads to a ill-conditioned Fisher matrix and makes the estimates less reliable.

Alternative Proposal

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

- 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.



- All parameters except ψ_4 determined quite well over a large range of masses.

A step ahead: Improving the quality of the test

[KGA, Iyer, Mishra & Sathyaprakash, 2010]

- Use of 3PN accurate amplitude corrected waveforms (as opposed to restricted waveforms).

A step ahead: Improving the quality of the test

[KGA, Iyer, Mishra & Sathyaprakash, 2010]

- Use of 3PN accurate amplitude corrected waveforms (as opposed to restricted waveforms).
- Possibility of testing the PN theory using GW observations of stellar mass BBHs in AdvLIGO and ET and Intermediate mass BBHs in ET has been explored.

A step ahead: Improving the quality of the test

[KGA, Iyer, Mishra & Sathyaprakash, 2010]

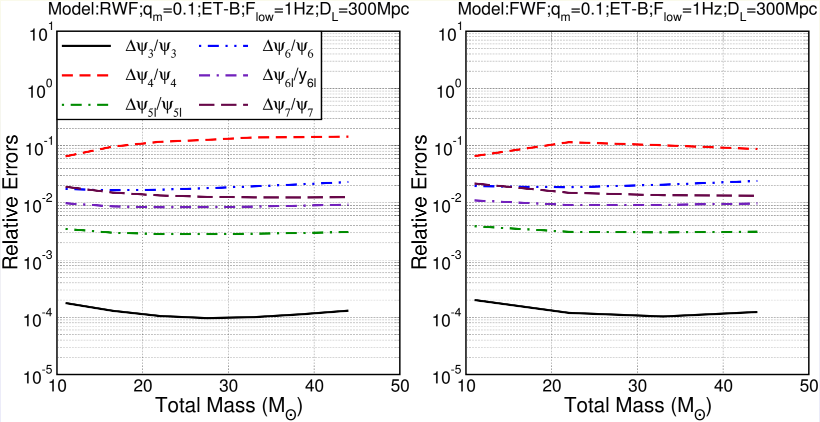
- Use of 3PN accurate amplitude corrected waveforms (as opposed to restricted waveforms).
- Possibility of testing the PN theory using GW observations of stellar mass BBHs in AdvLIGO and ET and Intermediate mass BBHs in ET has been explored.
- Effect of low frequency sensitivity as well as the effect of using the FWF on the Test have been studied in case of ET.

A step ahead: Improving the quality of the test

[KGA, Iyer, Mishra & Sathyaprakash, 2010]

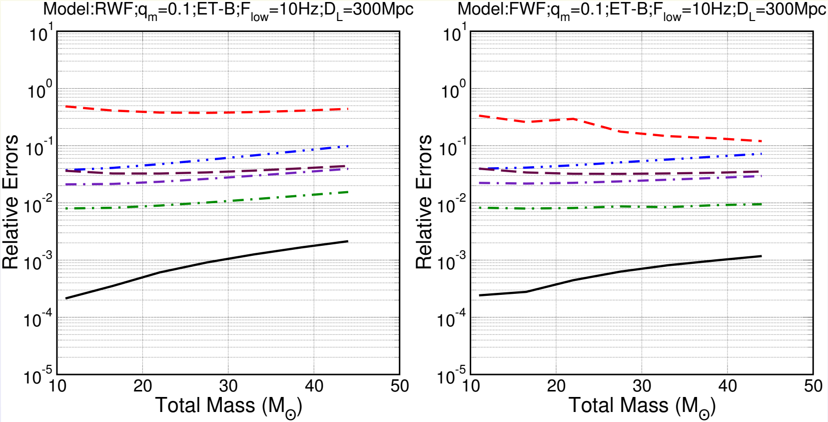
- Use of 3PN accurate amplitude corrected waveforms (as opposed to restricted waveforms).
- Possibility of testing the PN theory using GW observations of stellar mass BBHs in AdvLIGO and ET and Intermediate mass BBHs in ET has been explored.
- Effect of low frequency sensitivity as well as the effect of using the FWF on the Test have been studied in case of ET.
- Consideration of unequal mass systems.

Results

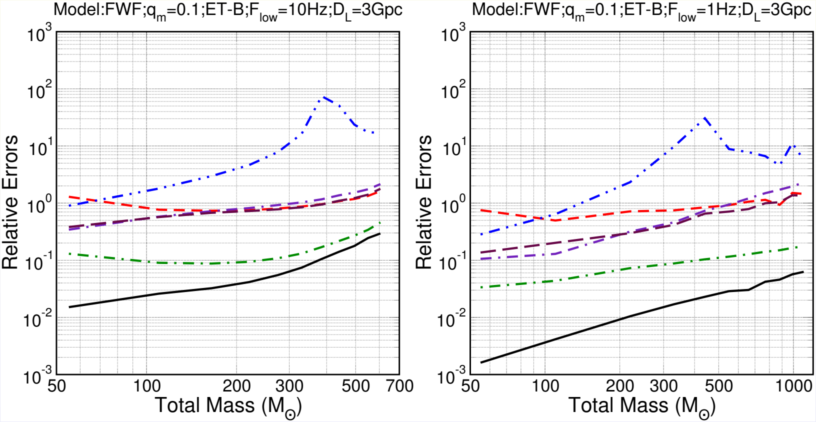


Model:RWF;q_m=0.1;ET-B;F_low=1Hz;D_L=300Mpc
Δψ3/ψ3
Δψ4/ψ4
Δψ5l/ψ5l
Δψ6/ψ6
Δψ6l/y6l
Δψ7/ψ7
Relative Errors
Total Mass (M⊙)
Model:FWF;q_m=0.1;ET-B;F_low=1Hz;D_L=300Mpc
Relative Errors
Total Mass (M⊙)

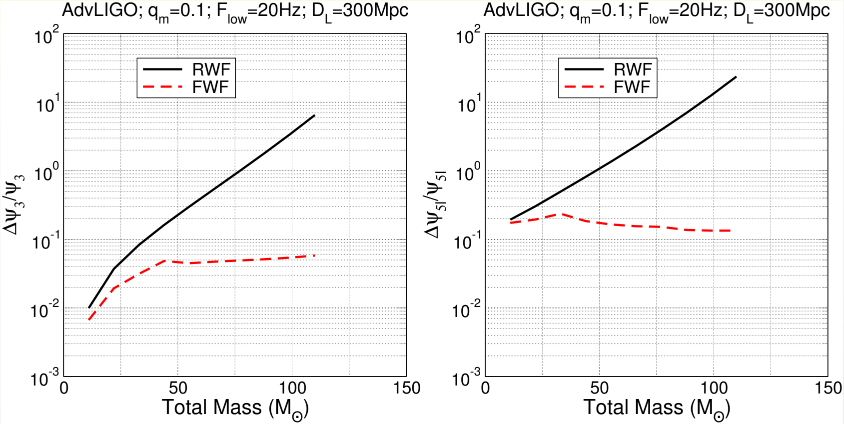
Results cont...



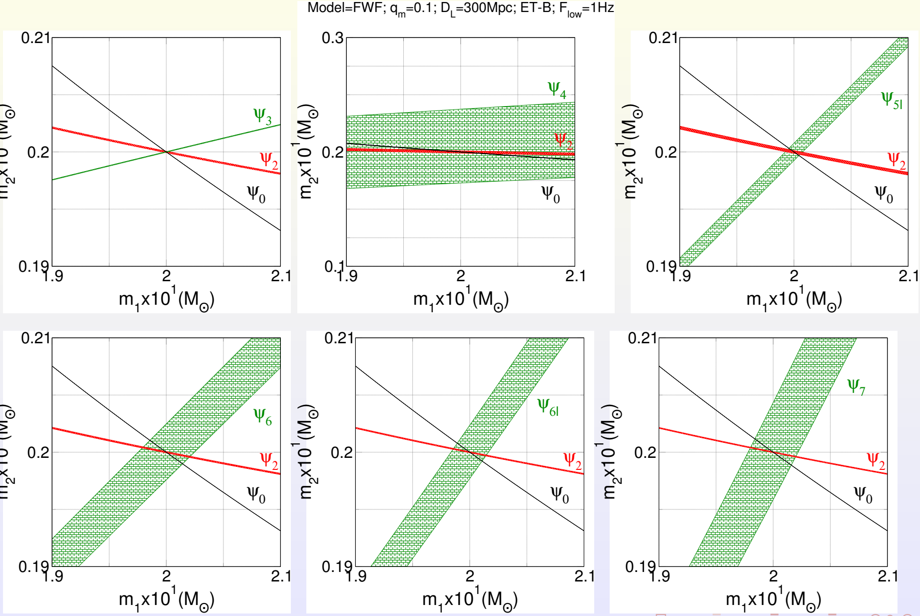
Results cont...



Results cont...



Results cont...



Results cont...