Can post-Newtonian theory be tested using Advanced LIGO and Einstein Telescope?

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With Chandra Kant Mishra, K G Arun, & B S Sathyaprakash

Based on PRD 82, 064010 (2010) arXiv:1005.0304

Aside:What is IndIGO?

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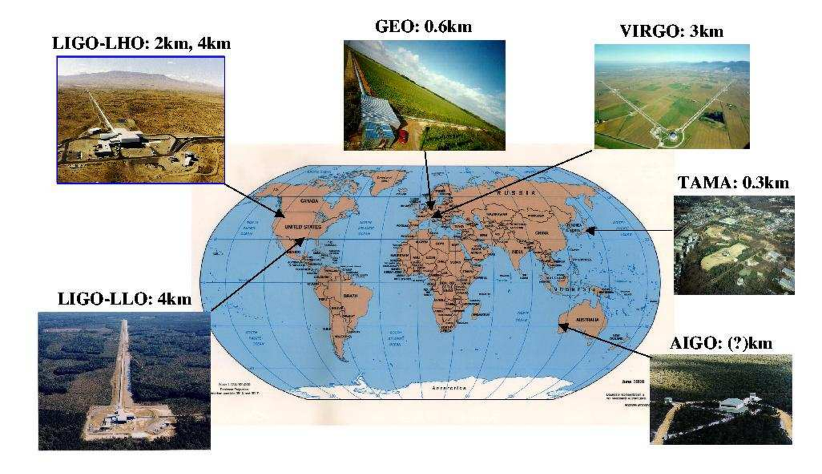
Current Global GW Network:

Initial LIGO and Virgo achieved Design sensitivity and Enhanced LIGO completed the final S6 run. Advanced LIGO and Virgo in 2015-2017



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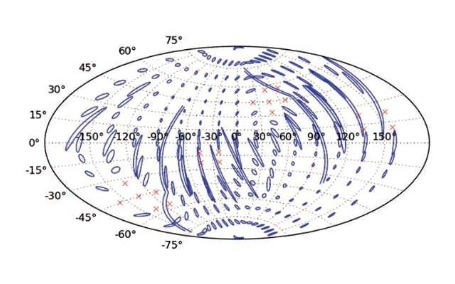

LIGO Hanford Livingston + Virgo

Wen and Chen

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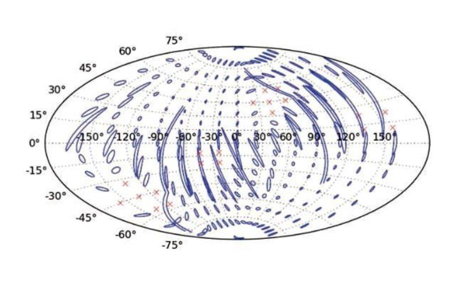

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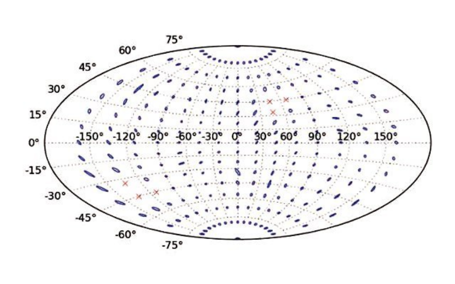

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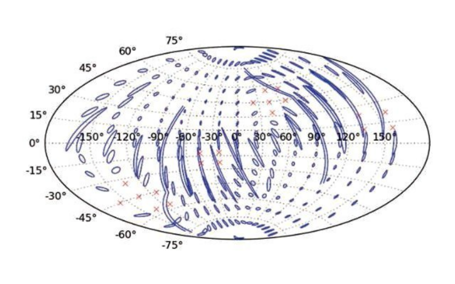

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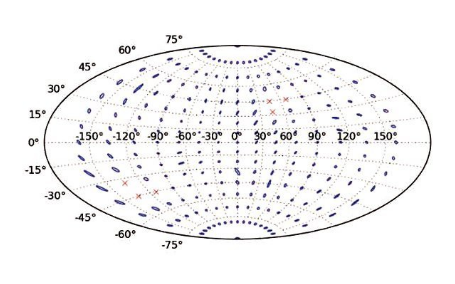

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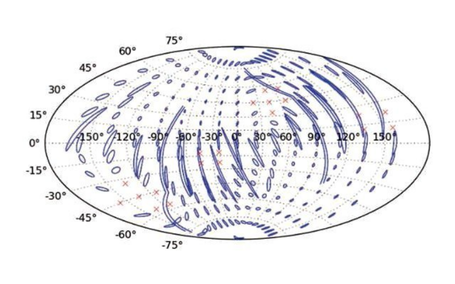

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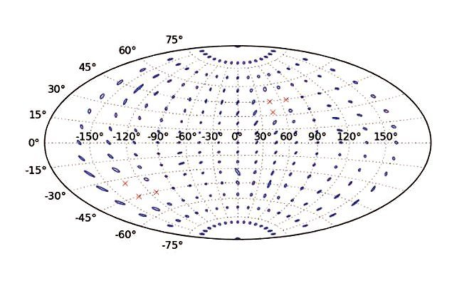

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IndIGO (Indian Initiative in GW Observations) Consortium will seek funds to collaborate with ACIGA to participate in LIGO-Australia.

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- General relativity passes these tests in flying colours!

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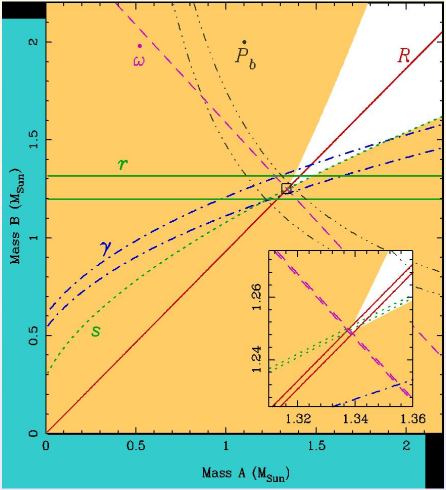

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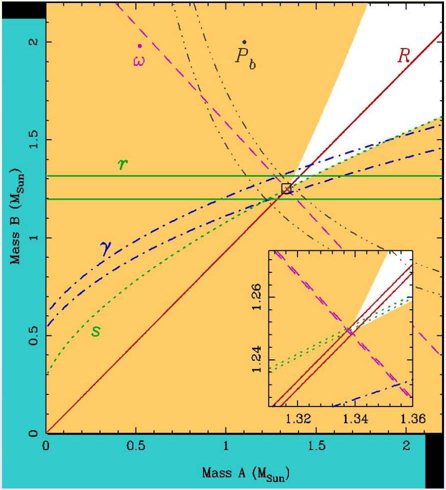

Tests possible due to physically motivated but structurally simple parametrisations (PPN, PPK) of observable quantities that could have different values in different theories of gravity.

Stretching general relativity further: Tests with GWs

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Gravitational Waves

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- How well can GW observations constrain deviations from GR?

Inspiralling compact binaries and testing general relativity

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  - Parametrizing the 1PN coefficient of the phasing formula in terms of the Compton wavelength of the massive graviton and bounding its value from GW observations [Will, 1998].

The question

Can these tests be generalized, without having to know a priori the parameters of the underlying theory of gravity at least in theories that do not deviate from GR to prevent *detection* with GR templates?

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

$$\psi(f) \;=\; 2\pi f t_c - \phi_c - \frac{\pi}{4} + \sum_{k=0}^{7} (\psi_k + \psi_{kl} \ln f)\, f^{\frac{k-5}{3}}, \qquad (1)$$

Log terms in the PN expansion

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- $\psi_k = \frac{3}{128\,\nu}(2\pi M)^{(k-5)/3}\alpha_k(\nu)$; $\psi_{kl} = \frac{3}{128\,\nu}(2\pi M)^{(k-5)/3}\alpha_{kl}(\nu)$

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- Independent determination of 3 or more of the phasing coefficients $\Rightarrow$ Tests of PN theory[KGA, Iyer, Qusailah & Sathyaprakash, 2006].

The α_l coefficients

$$\begin{aligned}
\alpha_0 &= 1,\;\; \alpha_1 = 0,\;\; \alpha_2 = \frac{3715}{756} + \frac{55}{9}\nu,\;\; \alpha_3 = -16\pi,\\
\alpha_4 &= \frac{15293365}{508032} + \frac{27145}{504}\nu + \frac{3085}{72}\nu^2;\\
\alpha_5 &= \pi\left(\frac{38645}{756} - \frac{65}{9}\nu\right)\left[1 + \ln\left(2\,6^{3/2}\pi M\right)\right],\\
\alpha_6 &= \frac{11583231236531}{4694215680} - \frac{640}{3}\pi^2 - \frac{6848}{21}C\\
&+ \left(-\frac{15737765635}{3048192} + \frac{2255}{12}\pi^2\right)\nu + \frac{76055}{1728}\nu^2 - \frac{127825}{1296}\nu^3\\
&-\frac{6848}{63}\ln\left(128\,\pi M\right);\;\; \alpha_7 = \pi\left(\frac{77096675}{254016} + \frac{378515}{1512}\nu - \frac{74045}{756}\nu^2\right).\\
&\alpha_{jl} = 0,\; j = 0, 1, 2, 3, 4, 7;\\
\alpha_{5l} &= \pi\left(\frac{38645}{756} - \frac{65}{9}\nu\right);\;\; \alpha_{6l} = -\frac{6848}{63}
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$C = 0.577\cdots$, - Euler's constant.

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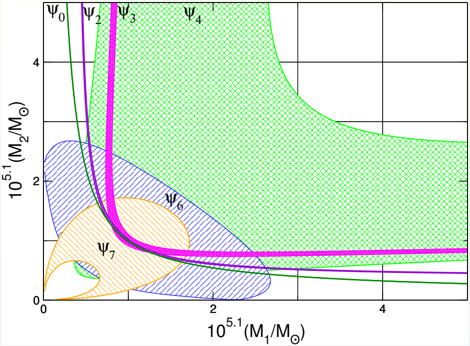

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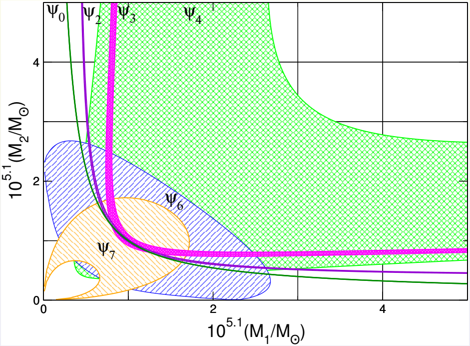

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Highly correlated parameters & Ill-conditioned Fisher matrix for a large parameter space.

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

- Treat two parameters as basic variables in terms of which one can parametrize *all* other parameters in the *restricted* phasing formula *except* one which is the *test* parameter. Dimensionality of the parameter space is thus considerably reduced.

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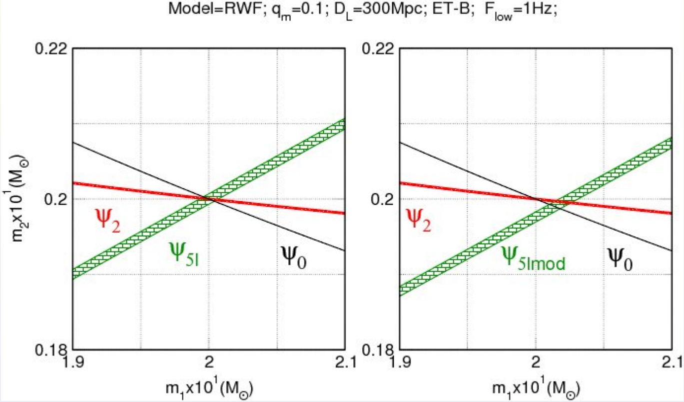
- If a theory agrees with GR at some PN order, reasonable to assume it agrees with GR at a lower PN order. Hence expressing PN coeffs of order lower than Test parameter in terms of basic variables seems natural.
- By expressing PN coeficients at order higher than the PN order of the test coefficient in terms of the basic variables one reduces the systematic effects in GR coming from higher order PN terms and focusses solely on the differences arising between GR and the *plausibly different correct* theory of gravity.

What Difference we expect to see??
GR vs Mock Alternative Gravity theory



Regions in the m_1-m_2 plane that corresponds to 1-σ uncertainties in ψ_0, ψ_2 and ψ_{5l}.
Left panel for GR.

Right panel assumes correct theory of gravity is a hypothetical non-GR theory in which the phasing coefficient ψ_{5l} and all higher PN coefficients, differ from the GR values by 1%

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- Effect of low frequency sensitivity of ET on our Test of GR.
- Use of 3PN accurate amplitude corrected waveforms ($f_k = f/k$)

$$
\begin{aligned}
\tilde{h}(f) &= \frac{2M\nu}{D_L} \sum_{k=1}^{8} \sum_{n=0}^{6} \frac{A_{(k,n/2)}\left(t\left(f_k\right)\right) \, x^{\frac{n}{2}+1}\left(t\left(f_k\right)\right)}{2\sqrt{k\dot{F}\left(t\left(f_k\right)\right)}} \\
&\times \; \exp\left[-i\phi_{(k,n/2)}\left(t\left(f_k\right)\right) + 2\pi i f t_c - i\pi/4 + ik\Psi\left(f_k\right)\right] \\
\Psi(f) &= -\phi_c + \sum_{j=0}^{7} \left[\psi_j + \psi_{jl} \ln f\right] f^{(j-5)/3} \\
\psi_j &= \frac{3}{256\,\nu}(2\pi M)^{(j-5)/3}\alpha_j, \; \psi_{jl} = \frac{3}{256\,\nu}(2\pi M)^{(j-5)/3}\alpha_{jl}.
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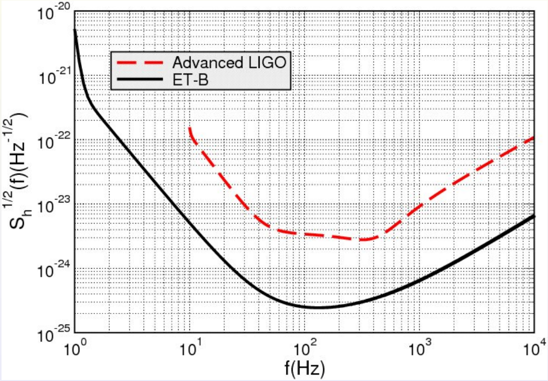
Amplitude spectrum of Advanced LIGO and ET



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- For a single terrestrial detector and ICB one can approximate detector's beam pattern functions as being constant over duration of signal and one can assume ($\cos\theta$, ϕ and ψ) and (D_L) are fixed and excluded from the analysis

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- Amplitude corrections depend on masses, luminosity distance, source location θ and ϕ, polarization angle ψ and inclination angle ι. Ten parameters $\mathbf{p} \equiv (\ln D_L, \cos\theta, \phi, t_c, \phi_c, \psi_0, \psi_2, \psi_T, \cos\iota, \psi)$
- For a single terrestrial detector and ICB one can approximate detector's beam pattern functions as being constant over duration of signal and one can assume ($\cos\theta$, ϕ and ψ) and (D_L) are fixed and excluded from the analysis
- Final parameter space is spanned by: $\{t_c, \phi_c, \psi_0, \psi_2, \psi_T, (\cos\iota, \psi)\}$

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- Compact binary in which one or both the components is a Stellar-mass ($\sim$ 2-30$M_\odot$) or Intermediate-mass ($\sim$ 50-1000$M_\odot$) Black Hole (the other being a neutron star).

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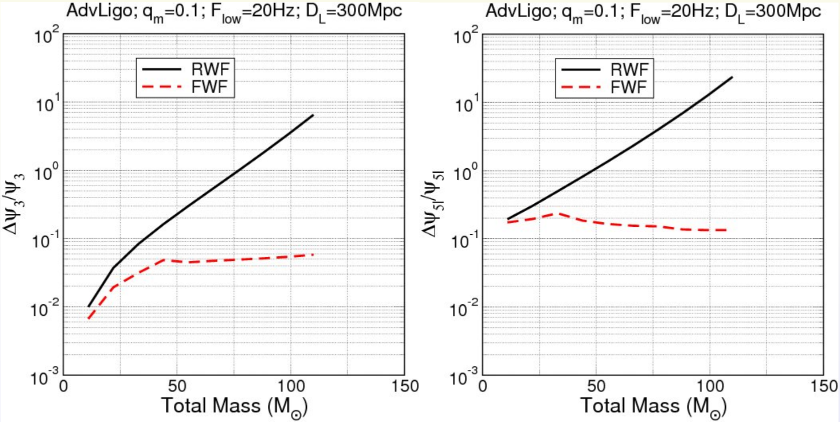
- Few coalescence events of IMBBHs within $z = 2$ or $z = 1$ depending on what triggered seed galaxies.

Advanced LIGO - Relative errors



Source orientations chosen arbitrarily to be $\theta = \phi = \pi/6$, $\psi = \pi/4$, $\iota = \pi/3$.

Advanced LIGO - Results

- GW observations of BBHs (in the range 11-110$M_\odot$ and at a luminosity distance of 300 Mpc) by Advanced LIGO can be used to estimate *only* the 1.5PN coefficient ψ_3 (leading tail) with fractional accuracy better than 6% when the FWF is used.

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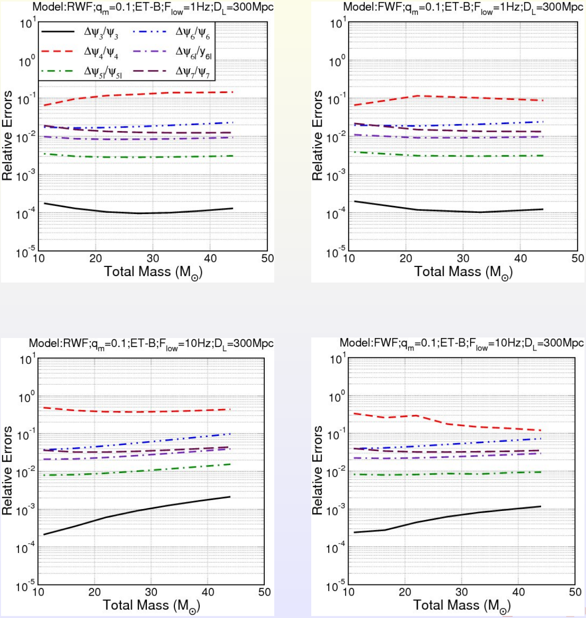
- Advanced LIGO could indeed begin the era of strong field tests of gravity.

Einstein Telescope (ET)- Stellar mass BH



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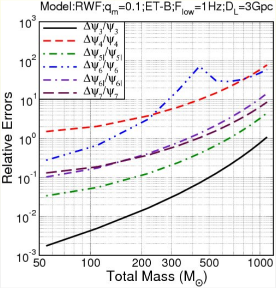

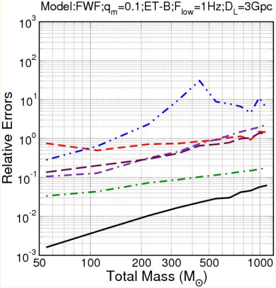

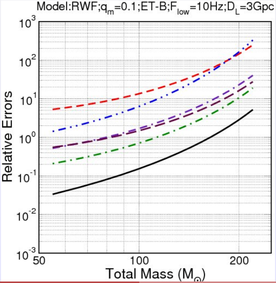

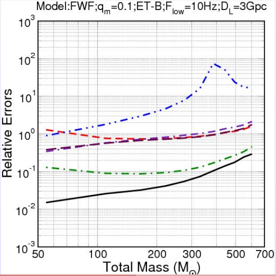

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- When total mass is less than about 100 $M_{\odot}$, all the ψ_k's are measured with relative errors less than unity, the most accurately determined parameters being ψ_3 and ψ_{5l} ; which are determined with accuracies better than 10%. Most interesting mass range for the proposed test in the ET band.

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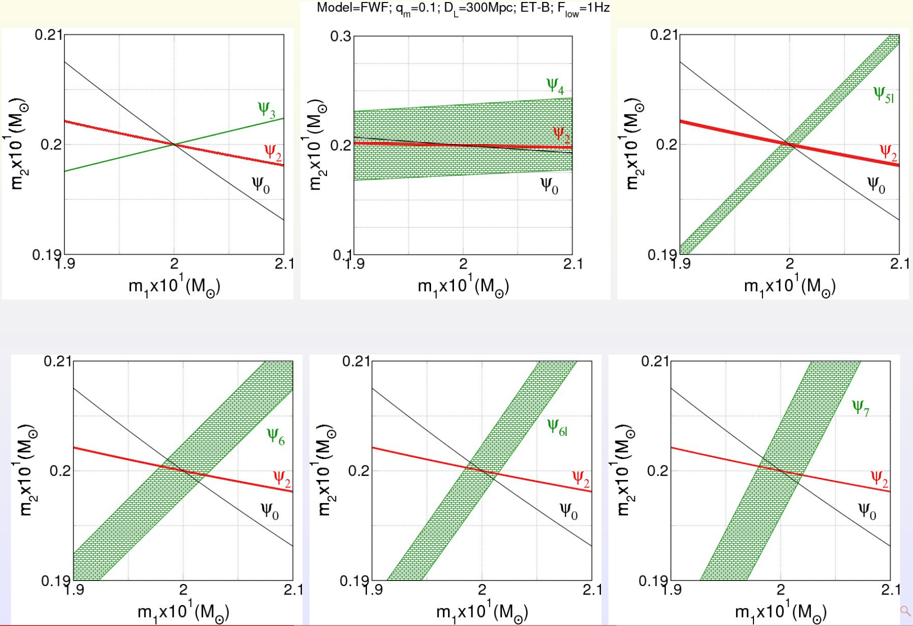
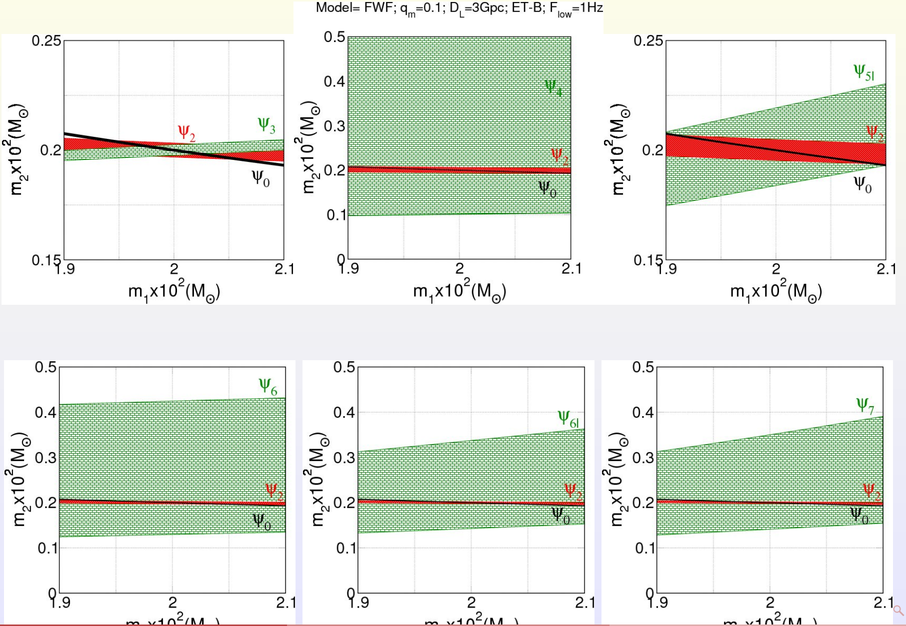
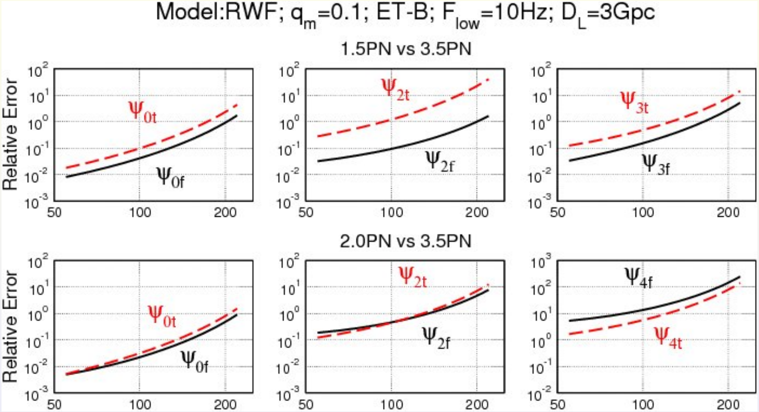
Testing GR by GW phasing - Stellar mass BH



Testing GR by GW phasing - IMBBH

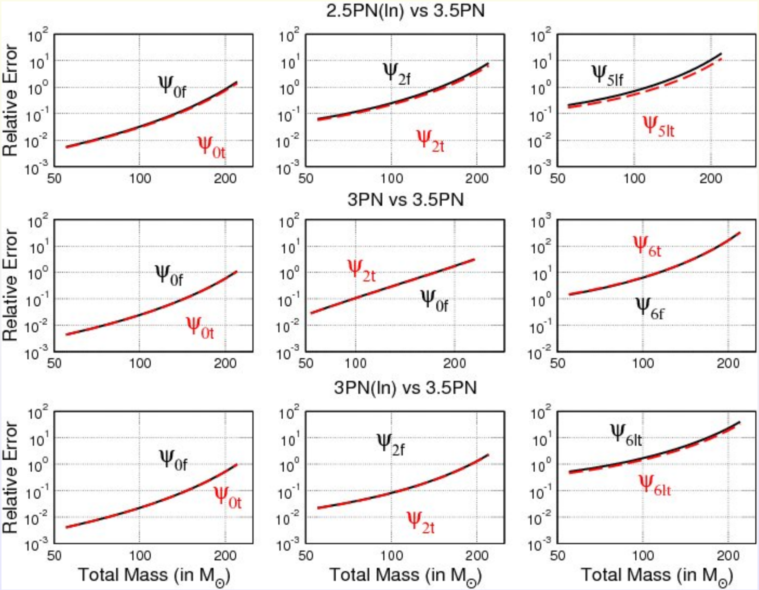


Truncated phasing vs Full 3.5PN phasing



ψ_0 and ψ_2 are basic parameters and all PN parameters up to 3.5PN (full phasing) except the test parameter are parametrized by ψ_0 and ψ_2. The other similarly constructed but the phasing truncated at the PN order corresponding to the test parameter. The test parameter with truncated phasing is denoted by ψ_{it} while with full 3.5PN phasing it is denoted by ψ_{if}.

Truncated phasing vs Full 3.5PN phasing



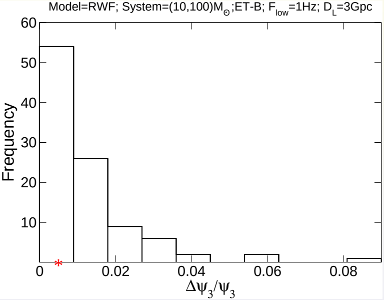
What to choose as basic parameters??

$(m_1, m_2) = (10,\ 100)M_\odot$; $f_s = 1$ Hz; $D_L = 3$ Gpc; Waveform Model: RWF							
	ψ_0-ψ_2	ψ_0-ψ_3	ψ_0-ψ_4	ψ_0-ψ_{5l}	ψ_0-ψ_6	ψ_0-ψ_{6l}	ψ_0-ψ_7
$\Delta\psi_0/\psi_0$	–	0.0015 (60)	0.0015 (60)	0.0015 (60)	0.0015 (60)	0.0015 (60)	0.0015 (60)
$\Delta\psi_f/\psi_f$	–	0.0092 (15)	0.010 (17)	0.017 (18)	0.043 (17)	0.020 (19)	0.022 (19)
$\Delta\psi_2/\psi_2$	–	0.027 (27)	0.027 (27)	0.027(27)	0.027(27)	0.027(27)	0.027(27)
$\Delta\psi_0/\psi_0$	0.0010 (55)	–	0.0010 (55)	0.0010(55)	0.0010(55)	0.0010(55)	0.0010(55)
$\Delta\psi_f/\psi_f$	0.0089 (13)	–	0.020 (16)	0.031(16)	0.082(16)	0.037(16)	0.042(16)
$\Delta\psi_3/\psi_3$	0.0050 (42)	–	0.0050 (42)	0.0050 (42)	0.0050(42)	0.0050(42)	0.0050 (42)
$\Delta\psi_0/\psi_0$	0.0011 (28)	0.0011(28)	–	0.0011 (28)	0.0011(28)	0.0011(28)	0.0011(28)
$\Delta\psi_f/\psi_f$	0.074(8)	0.15(8)	–	0.25(8)	0.65(8)	0.29(8)	0.33(8)
$\Delta\psi_4/\psi_4$	2.1 (8)	2.1(8)	–	2.1(8)	2.1(8)	2.1(8)	2.1(8)
$\Delta\psi_0/\psi_0$	0.00059 (77)	0.00059 (77)	0.00059(77)	–	0.00059(77)	0.00059(77)	0.00059(77
$\Delta\psi_f/\psi_f$	0.014(24)	0.026(23)	0.029(23)	–	0.12(23)	0.052(23)	0.058(23)
$\Delta\psi_{5l}/\psi_{5l}$	0.056 (17)	0.056(17)	0.056(17)	–	0.056(17)	0.056(17)	0.056(17)
$\Delta\psi_0/\psi_0$	0.00054 (64)	0.00054 (64)	0.00054 (64)	0.00054(64)	–	0.00054 (64)	0.00054(64
$\Delta\psi_f/\psi_f$	0.0067 (21)	0.013(20)	0.014(19)	0.021 (19)	–	0.025(19)	0.028(19)
$\Delta\psi_6/\psi_6$	0.67(13)	0.67 (13)	0.67(13)	0.67 (13)	–	0.67(13)	0.67(13)
$\Delta\psi_0/\psi_0$	0.00051(62)	0.00051 (62)	0.00051(62)	0.00051(62)	0.00051(62)	–	0.00051 (62
$\Delta\psi_f/\psi_f$	0.0051(21)	0.0096 (19)	0.010 (19)	0.016(19)	0.042(19)	–	0.021(18)
$\Delta\psi_{6l}/\psi_{6l}$	0.17(13)	0.17 (13)	0.17 (13)	0.17(13)	0.17(13)	–	0.17(13)
$\Delta\psi_0/\psi_0$	0.00049 (59)	0.00049(59)	0.00049(59)	0.00049(59)	0.00049(59)	0.00049(59)	–
$\Delta\psi_f/\psi_f$	0.0046 (20)	0.0087(18)	0.0094(18)	0.014 (17)	0.038(18)	0.017(17)	–
$\Delta\psi_7/\psi_7$	0.19(10)	0.19(10)	0.19(10)	0.19(10)	0.19(10)	0.19(10)	–

Number in parentheses is factor by which accuracy will be reduced for lower cutoff of 10 Hz. Fundamental pair is chosen to be

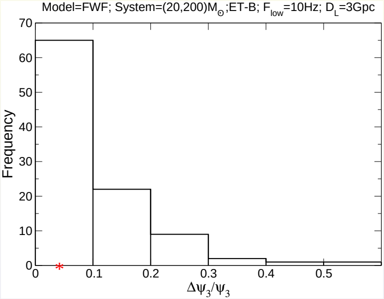
(ψ_0, ψ_f) where f can be any of 2, 3, 4, 5l, 6, 6l, 7. Relative error in the test parameter is listed in the third row.

Robustness of TOG wrt Angles - RWF



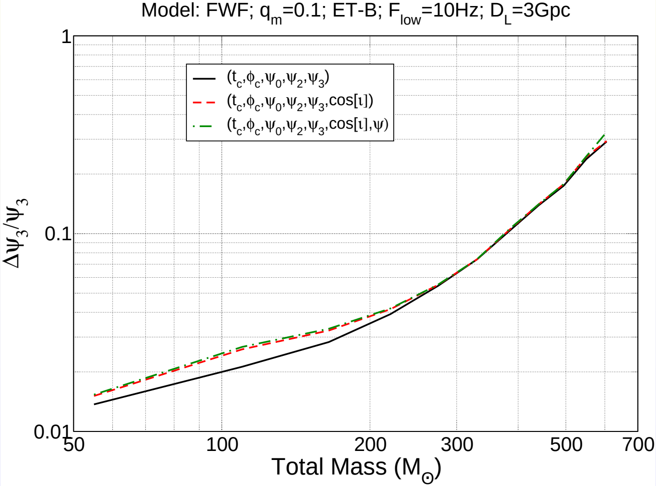
Histogram for the relative error in the estimation of the parameter ψ_3 using hundred different realizations of angular parameters for a $(10, 100) M_\odot$ binary located at the luminosity distance of 3 Gpc. The low frequency cutoff is 1 Hz and RWF has been used. $\Delta\psi_3/\psi_3$ was 0.005 for the arbitrary choice of angles we made.

Robustness of TOG wrt Angles - FWF



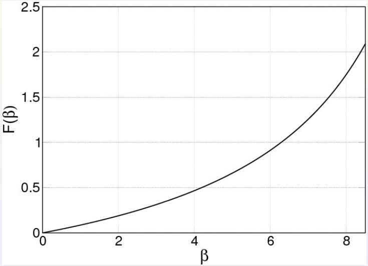
Histogram for the relative error in the estimation of the parameter ψ_3 using hundred different realizations of angular parameters for a (20, 200)$M_\odot$ binary located at the luminosity distance of 3 Gpc. The low frequency cutoff is 10 Hz and FWF has been used. $\Delta\psi_3/\psi_3$ was 0.042 for the arbitrary choice of angles we made.

Sensitivity of results to inclusion of ι and ψ in the Fisher analysis



Effect of spin on the test

- Effects of spin can offset estimation of the PN coefficients..e.g. $\beta \geq 6$ can affect 1.5PN coeff by 100%.



Plot shows the variation of systematic bias due to spin $F(\beta)$ with the spin parameter $0 \leq \beta \leq 8.5$, where $F(\beta)$ is given by $F(\beta) = 4\beta(16\pi - 4\beta)^{-1}$.

Summary and Conclusion

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  - Implies that implicit in our work is the assumption that we are dealing post detection with a known source and that ψ_0 and ψ_2 are as in GR. Much more work needed is needed to test the N and 1PN parameters..

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- If the PN expansion differs from GR slightly then the error in the estimation of parameters will not change to first order.

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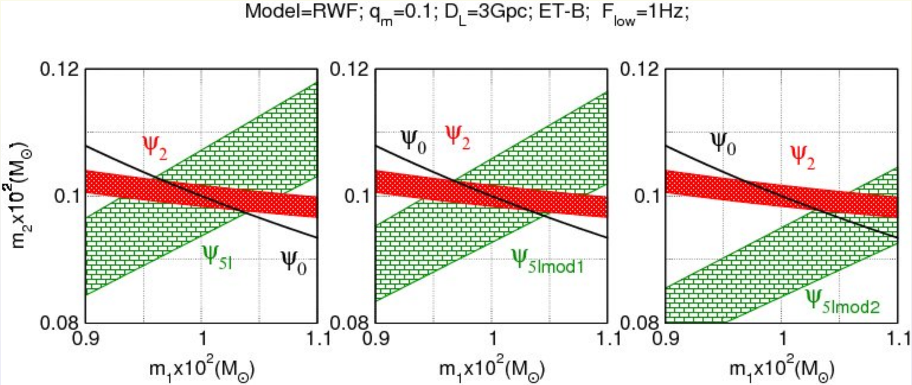
- Effect of merger, ringdown, orbital eccentricity not estimated
- To test fully the proposal one must mimic the whole exercise by mock data. One has to inject a non-GR signal into Gaussian bgd with a signal that differs from GR at 1.5PN and higher orders by certain degree. One would then need to extract the first three parameters by a MCMC technique using GR templates and check if what we expect from our study holds good.

What difference do we expect to see??
GR vs Mock Alternative Gravity theory



Regions in the m_1-m_2 plane that corresponds to 1-σ uncertainties in Newtonian, 1PN and 2.5PN coefficients in the PN series.
Left panel: GR as the correct theory of gravity

Middle and Right Panel correspond to hypothetical non-GR theories of gravity which have phasing coefficients ψ_{5l} (2.5PN) and higher differing from the GR values by 1% and 10% respectively.