Estimating spinning binary parameters and testing alternative theories of gravity with LISA

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gr-qc/0411129, submitted to Phys. Rev. **D**

Content:

- **Binary-parameter–accuracy reduction when spin couplings are included**

- **How results depend on sensitivity of LISA at low frequencies**

Testing alternative theories of gravity with LISA

[Will 94; Krolak et al. 95; Damour et al. 97; Will 98; Scharre & Will 02; Will & Yunes 04]

- **Scalar-tensor theories: phasing modified by GW dipole radiation**
- **Massive graviton theories: GW–propagation-speed depends on wavelength ⇒ distortion in time of arrival with respect to GR**

$$\frac{df}{dt} = \frac{96}{5\pi\mathcal{M}^2}\,(\pi\mathcal{M}f)^{11/3}\left\{1 + \frac{5\,\hat{\alpha}^2\,\eta^{2/5}}{192\,\omega_{\rm BD}}\,(\pi\mathcal{M}\,f)^{-2/3} + \frac{96\,\pi^2\,\mathcal{M}\,D}{5\,(1+z)\,\lambda_g^2}\,(\pi\mathcal{M}f)^{2/3} + \text{PN corr.}\right\}$$

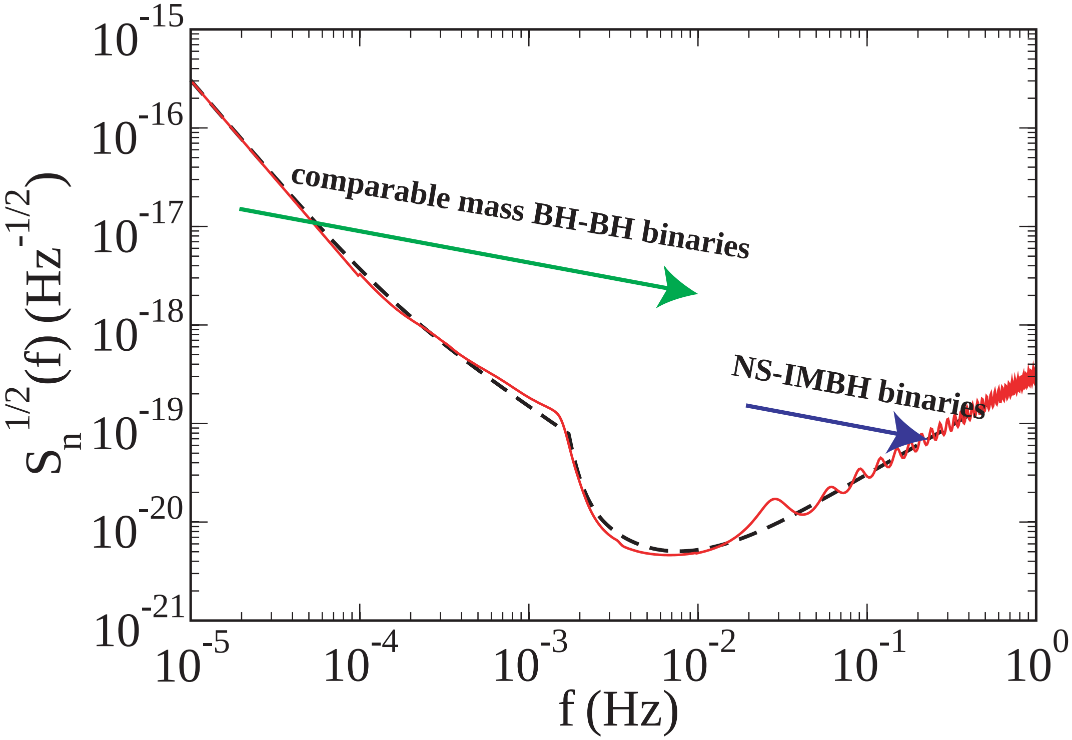
$\mathcal{M} = M\,\eta^{3/5} \rightarrow$ observed chirp mass; $M = m_1 + m_2$ and $\eta = m_1\,m_2/M^2$

- $\hat{\alpha} = \hat{\alpha}_1 - \hat{\alpha}_2$, $\hat{\alpha}_{\rm BH} = 0$, $\hat{\alpha}_{\rm NS} \sim 0.6 - 0.8$, $\hat{\alpha}_{\rm WD} > 0.998$
  $\omega_{\rm BD} > 4 \times 10^4$ (Cassini)
- $\lambda_g \rightarrow$ graviton Compton length; $\lambda_g > 10^{12}$ km (solar-system), $\lambda_g > 6 \times 10^{19}$ km (cluster dynamics)

Effective LISA noise curve and binary investigated

– **BH-BH binaries with**
$M = 10^4$–$10^7 M_\odot$

– **NS-IMBH binaries with**
$M_{\rm IMBH} = 10^2$–$10^4 M_\odot$



- **At low frequency the *effective* noise curve coincides with non–sky-averaged LISA curve**
- **Galactic and extragalactic WD confusion noise included** [Barack & Cutler 03]

GW templates for binaries moving along circular orbits

$$\tilde{h}_\alpha(f) = \mathcal{A}\, f^{-7/6}\, e^{i\psi(f)}\, \mathcal{A}_\alpha(t(f))\, e^{-i\phi(t(f))}$$

$$\begin{aligned}\psi(f) \quad &= \quad 2\pi f t_c - \phi_c + \frac{3}{128}\,(\pi\mathcal{M}f)^{-5/3}\left\{1 - \frac{5\hat{\alpha}^2}{336\omega_{\rm BD}}\,\eta^{2/5}\,(\pi\mathcal{M}f)^{-2/3} - \frac{128}{3}\,\frac{\pi^2 D\,\mathcal{M}}{\lambda_g^2\,(1+z)}\,(\pi\mathcal{M}f)^{2/3}\right.\\ &+ \quad \left(\frac{3715}{756} + \frac{55}{9}\eta\right)\eta^{-2/5}\,(\pi\mathcal{M}f)^{2/3} - 16\pi\,\eta^{-3/5}\,(\pi\mathcal{M}f) + 4\beta\,\eta^{-3/5}\,(\pi\mathcal{M}f)\\ &+ \quad \left.\left(\frac{15293365}{508032} + \frac{27145}{504}\eta + \frac{3085}{72}\eta^2\right)\eta^{-4/5}\,(\pi\mathcal{M}f)^{4/3} - 10\sigma\,\eta^{-4/5}\,(\pi\mathcal{M}f)^{4/3}\right\}\end{aligned}$$

$$\beta = \frac{1}{12}\sum_{i=1}^{2}\chi_i\left[113\frac{m_i^2}{M^2} + 75\eta\right]\widehat{\boldsymbol{L}}\cdot\widehat{\boldsymbol{S}}_i\,, \qquad \sigma = \frac{\eta}{48}\chi_1\chi_2\left(-27\widehat{\boldsymbol{S}}_1\cdot\widehat{\boldsymbol{S}}_2 + 721\widehat{\boldsymbol{L}}\cdot\widehat{\boldsymbol{S}}_1\widehat{\boldsymbol{L}}\cdot\widehat{\boldsymbol{S}}_2\right)$$

Effects of spins in GR for ground-based detectors [Poisson et al. 95; Krolak et al. 95]

LISA model and Monte Carlo simulation

- **We assume two independent Michelson outputs** [Cutler 97; Hughes 01; Vecchio 03]

- **Parameter estimation using Fisher matrix formalism with and without averaging over the relative orientation of the binary with respect to LISA**

- **Monte Carlo simulation using 10^4 sources distributed over sky positions and orientation**

$(\overline{\phi}_S, \cos\overline{\theta}_S) \Rightarrow$ **binary position with respect to solar-system baricenter**

$(\overline{\phi}_L, \cos\overline{\theta}_L) \Rightarrow$ **binary orientation with respect to solar system baricenter**

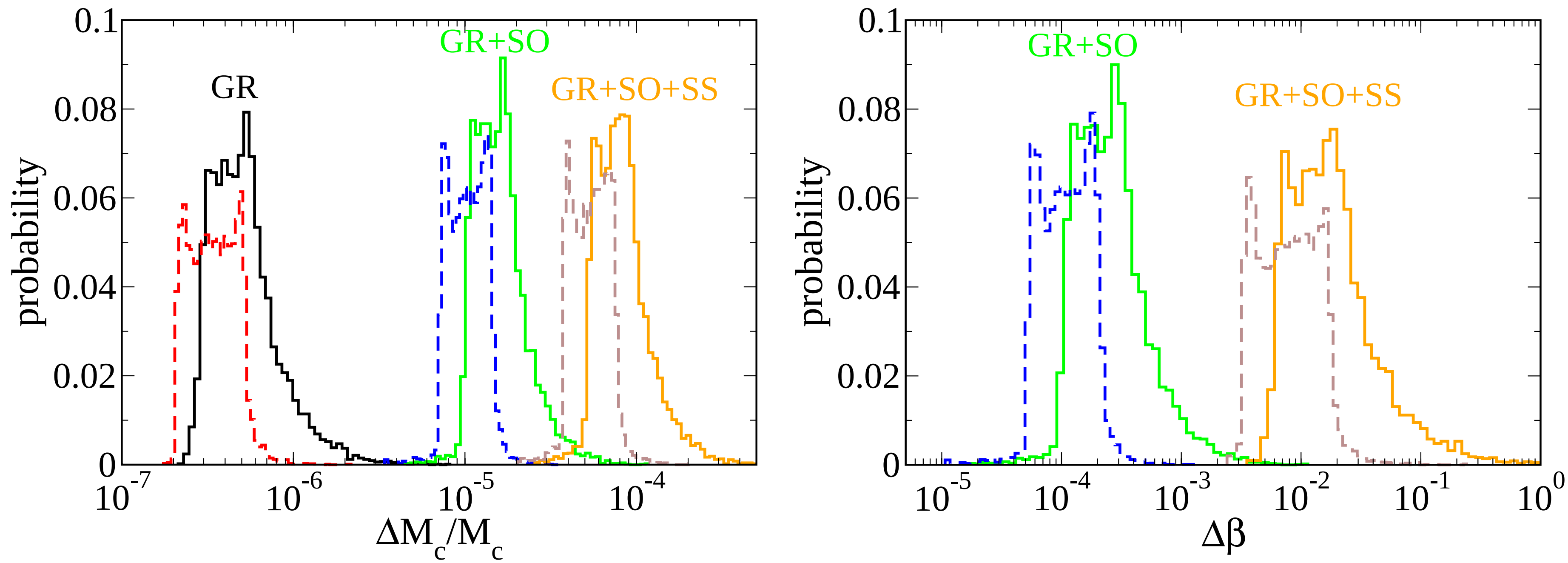
angular resolution:

$$\Delta\Omega_S = 2\pi \left\{ \langle \Delta\bar{\mu}_S^2 \rangle \langle \Delta\bar{\phi}_S^2 \rangle - \langle \Delta\bar{\mu}_S \Delta\bar{\phi}_S \rangle^2 \right\}^{1/2}$$

$$\overline{\mu}_S = \cos\overline{\theta}_S$$

Results in Einstein's theory when including spin couplings

Compact body inspiralling into IMBH: $M = (1.4 + 10^3) M_\odot$ with SNR = 10



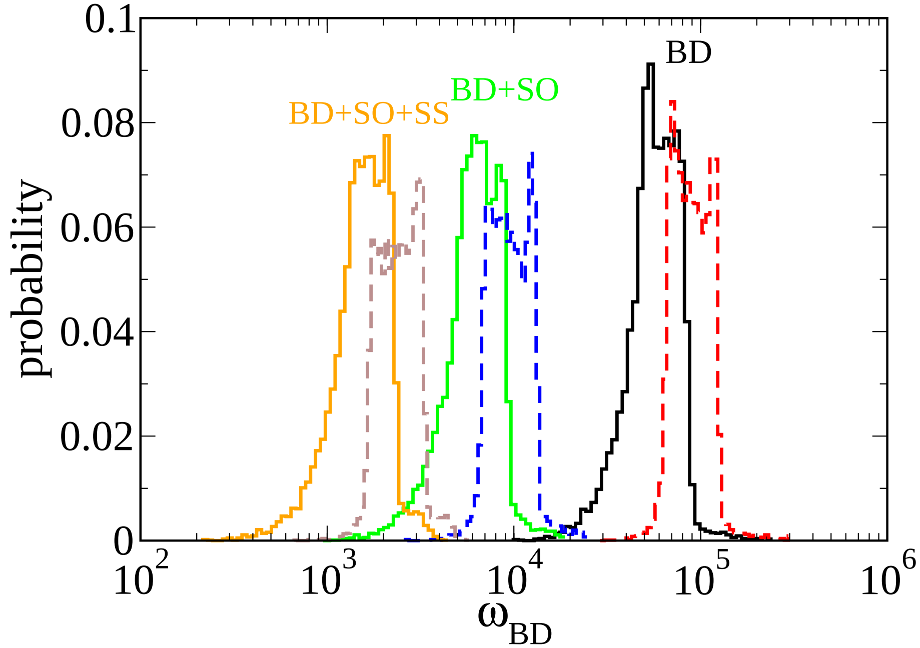
$\beta \propto$ **spin-orbit**

Results for Brans-Dicke parameter

Compact body inspiralling into IMBH: $M = (1.4 + 10^3) M_\odot$ with SNR $= 10$

$f_{\rm in} = 3.7 \times 10^{-2}$ Hz; $f_{\rm fin} = 1$ Hz

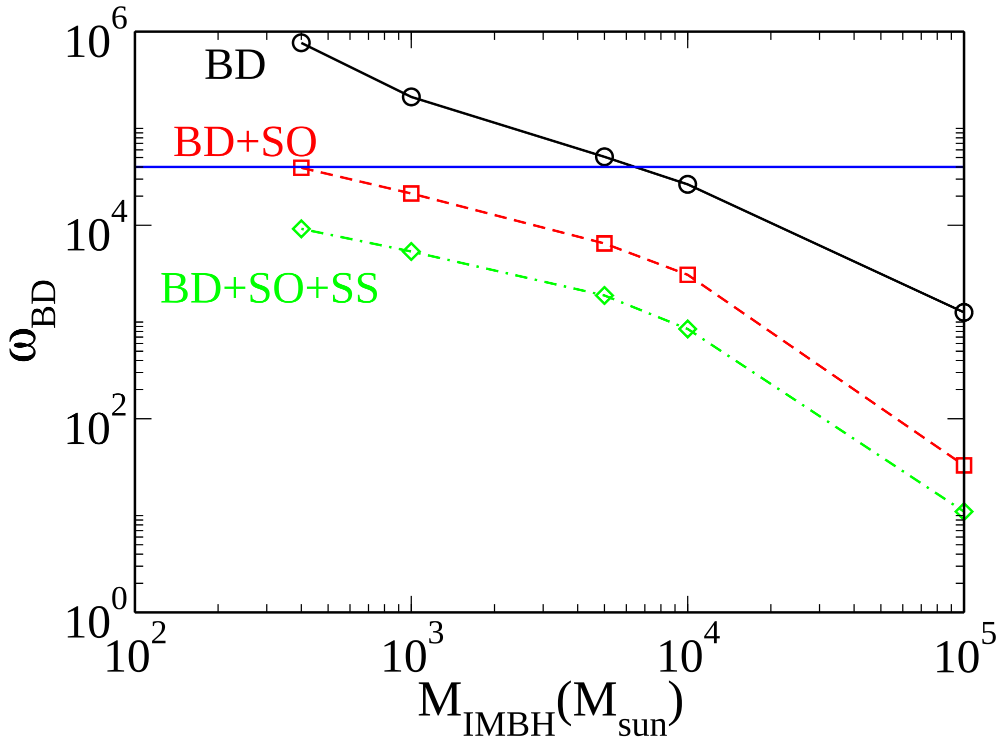
	Number of cycles
Newtonian:	1.83×10^6
1PN:	44712
1.5PN	-29081
Spin-orbit:	2314 β
2PN	868
Spin-spin:	-288 σ
Brans-Dicke:	-45 $\omega_{\rm Cassini}/\omega_{\rm BD}$



Bound from *Cassini* measurements of Shapiro time delay: $\omega_{\rm BD} = 40000$

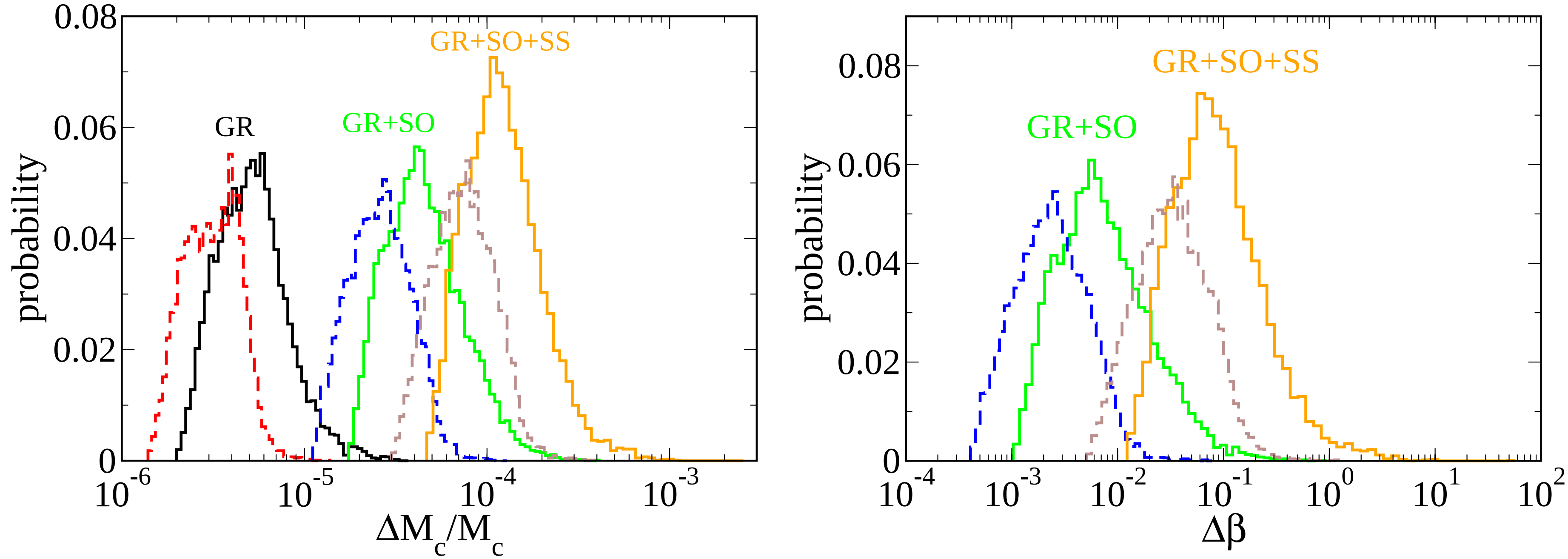
Summary of results for Brans-Dicke parameter

NS-IMBH binaries



Results in Einstein's theory when including spin couplings

$M = (10^6 + 10^6) M_\odot$ **at** 3 **Gpc**



$\beta \propto$ **spin-orbit**

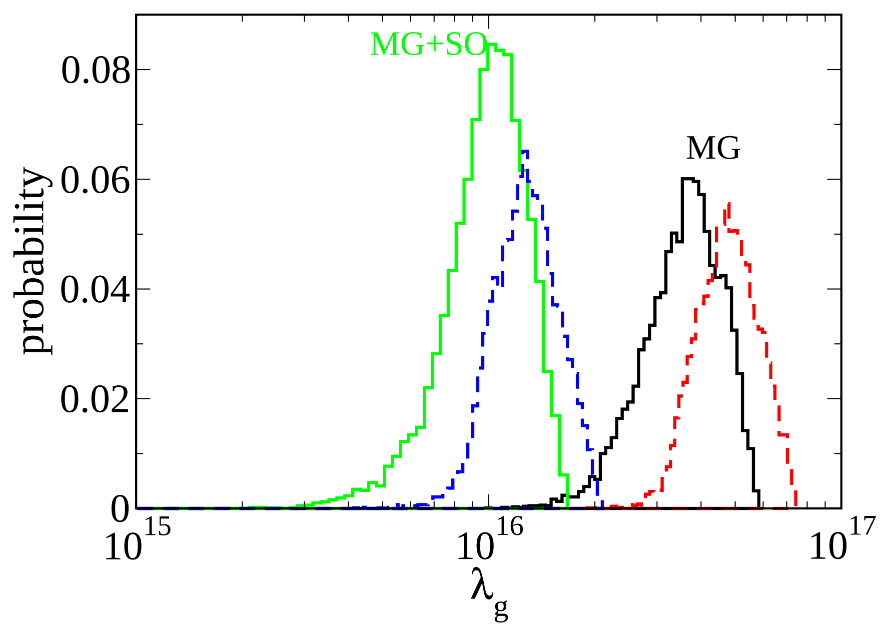
Results for graviton's Compton length

$M = (10^6 + 10^6) M_\odot$ **at** 3 **Gpc**

$\lambda_g = h/c/m_g$

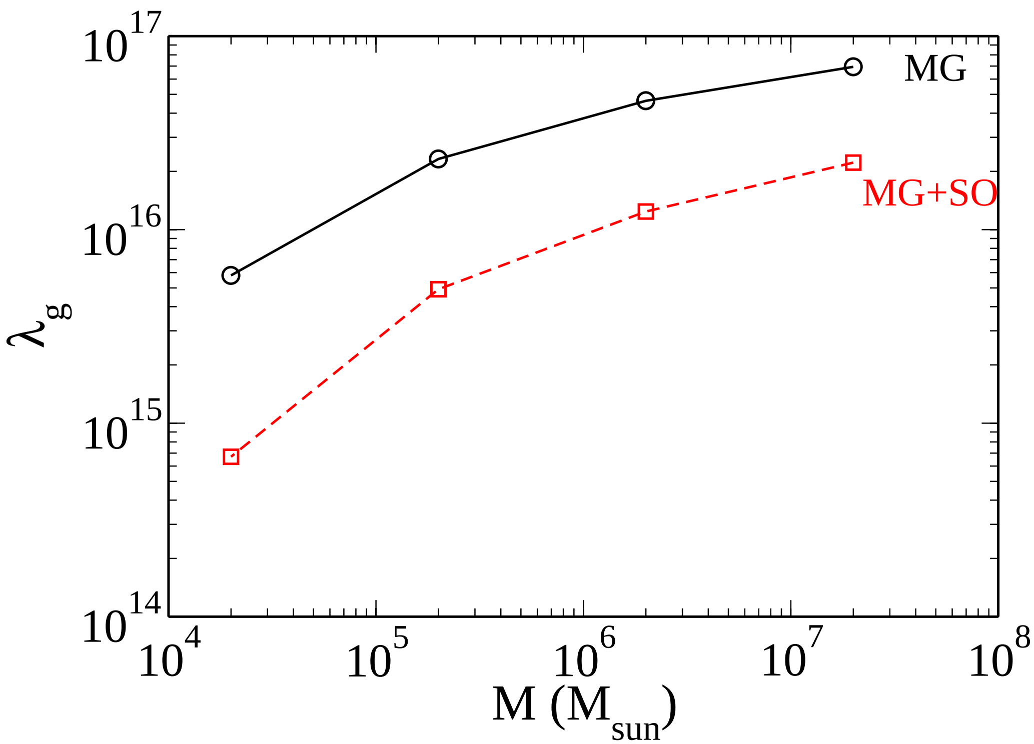
$f_{\rm in} = 4.5 \times 10^{-5}$ Hz; $f_{\rm fin} = 2.2 \times 10^{-3}$ Hz

	Number of cycles
Newtonian:	2266
1PN:	134
1.5PN	-92
Spin-orbit:	7 β
2PN	6
Spin-spin:	-1 σ
Massive graviton:	-217$(10^{14}\,{\rm km}/\lambda_g)^2$



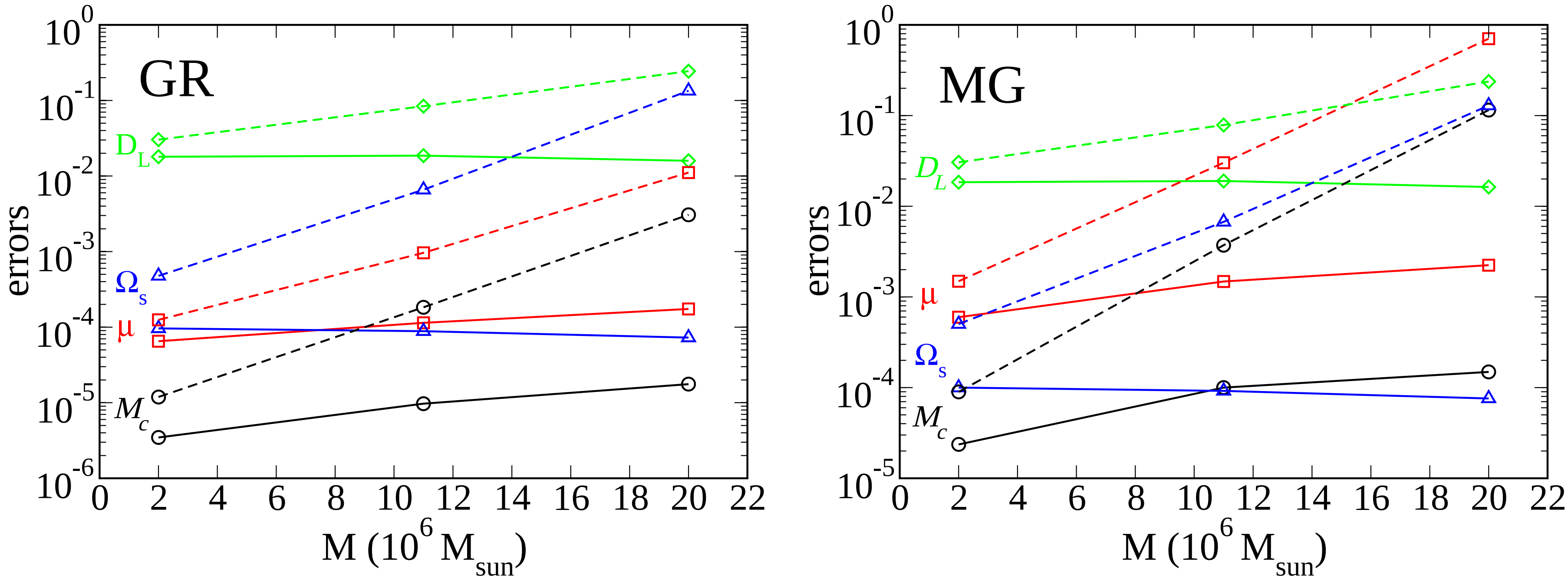
Summary of results for graviton's Compton length

Equal-mass binaries at 3 Gpc



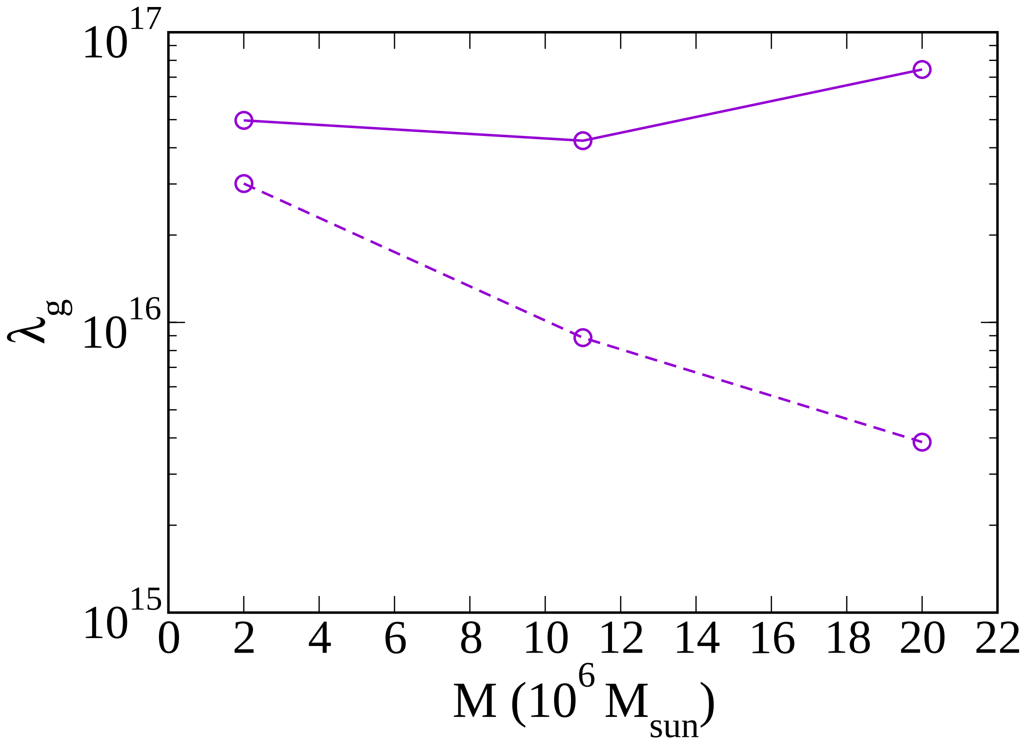
Effect of worsening LISA sensitivity at low frequencies

$D_L = 3$ **Gpc** $f_{\rm cut} = 10^{-5}$ **Hz (continuous lines)** $f_{\rm cut} = 10^{-4}$ **Hz (dashed lines)**



Effect of worsening LISA sensitivity at low frequencies and the bound on graviton Compton wavelength

$D_L = 3$ **Gpc** $f_{\rm cut} = 10^{-5}$ **Hz (dashed continuous)** $f_{\rm cut} = 10^{-4}$ **Hz (dashed lines)**



Conclusions/future work:

- Binary parameters in gravity-wave's phase are highly correlated ⇒ adding parameters effectively dilutes the available information

- Accuracy's degradation of binary parameters when black holes carry spins aligned or antialigned with angular momentum

  $\sim$ 10 - 20 with SO term; $\sim$ 30 - 80 with SO + SS terms for Brans-Dicke bound

  $\sim$ 4 - 5 with SO term for massive graviton bound

- Spin precession could help in decorrelating the parameters [Vecchio 03]

- Inclusion of eccentricity when studying binaries in scalar-tensor theories

- Systematic errors might not be negligible with respect to statistical errors for high SNR