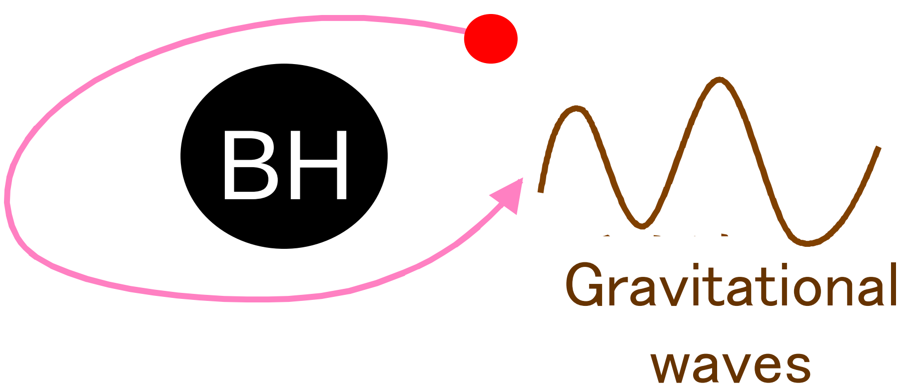
DECIGOと地上重力波干渉計のシナジー効果



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§ 1 Synergy effect on gravity test

Motivation for modified gravity

1) Incompleteness of General relativity

GR is non-renormalizabile

Singularity formation after gravitational collapse

2) Dark energy problem

3) To test General relativity

GR has been repeatedly tested since its first proposal.

The precision of the test is getting higher and higher.

⇒ Do we need to understand what kind of modification is theoretically possible before experimental test?

Yes, especially in the era of gravitational wave observation!

Constraint on the modification of gravity by GW150914

Theoretical Mechanism	GR Pillar	PN	$\lvert\beta\rvert$ GW150914	Example Theory Constraints: Repr. Parameters	GW150914	Current Bounds
Scalar Field Activation	SEP	-1	$\mathbf{1.6 \times 10^{-4}}$	$\sqrt{\lvert\alpha_{\rm EdGB}\rvert}$ [km]	—	10^7 [39], 2 [40–42]
	SEP, No BH Hair	-1	$\mathbf{1.6 \times 10^{-4}}$	$\lvert\dot{\phi}\rvert$ [1/sec]	—	10^{-6} [43]
	SEP, Parity Invariance	$+2$	$\mathbf{1.3 \times 10^{1}}$	$\sqrt{\lvert\alpha_{\rm CS}\rvert}$ [km]	—	10^8 [44, 45]
Vector Field Activation	SEP, Lorentz Invariance	0	$\mathbf{7.2 \times 10^{-3}}$	(c_+, c_-)	$\mathbf{(0.9, 2.1)}$	$(0.03, 0.003)$ [46, 47]
Extra Dimension Mass Leakage	4D spacetime	-4	$\mathbf{9.1 \times 10^{-9}}$	ℓ [μm]	$\mathbf{5.4 \times 10^{10}}$	10–10^3 [48–52]
Time-Varying G	SEP	-4	$\mathbf{9.1 \times 10^{-9}}$	$\lvert\dot{G}\rvert$ [10^{-12}/yr]	$\mathbf{5.4 \times 10^{18}}$	0.1–1 [53–57]
Massive graviton	massless graviton	$+1$	$\mathbf{1.3 \times 10^{-1}}$	m_g [eV]	$\mathbf{1.2 \times 10^{-22}}$ [12]	10^{-29}–10^{-18} [58–62]
Modified Dispersion Relation	$v_g = c$	$+5.5$	$\mathbf{2.3 \times 10^{2}}$	$\mathbb{A} > 0$ [1/eV]	$\mathbf{1.6 \times 10^{-7}}$	—
(*Modified Special Relativity*)		$+5.5$	$\mathbf{2.3 \times 10^{2}}$	$\mathbb{A} < 0$ [1/eV]	$\mathbf{1.6 \times 10^{-7}}$	2.7×10^{-36} [63]
Modified Dispersion Relation	$v_g = c$	$+7$	$\mathbf{8.7 \times 10^{2}}$	$\mathbb{A} > 0$ [1/eV^2]	$\mathbf{9.3 \times 10^{4}}$	—
(*Extra Dimensions*)		$+7$	$\mathbf{8.7 \times 10^{2}}$	$\mathbb{A} < 0$ [1/eV^2]	$\mathbf{9.3 \times 10^{4}}$	4.6×10^{-56} [63]
Modified Dispersion Relation (*Lorentz Violation*)	SEP, Lorentz Invariance	—	—	c_+	$\mathbf{0.7}$ [64]	$(0.03, 0.003)$ [46, 47]

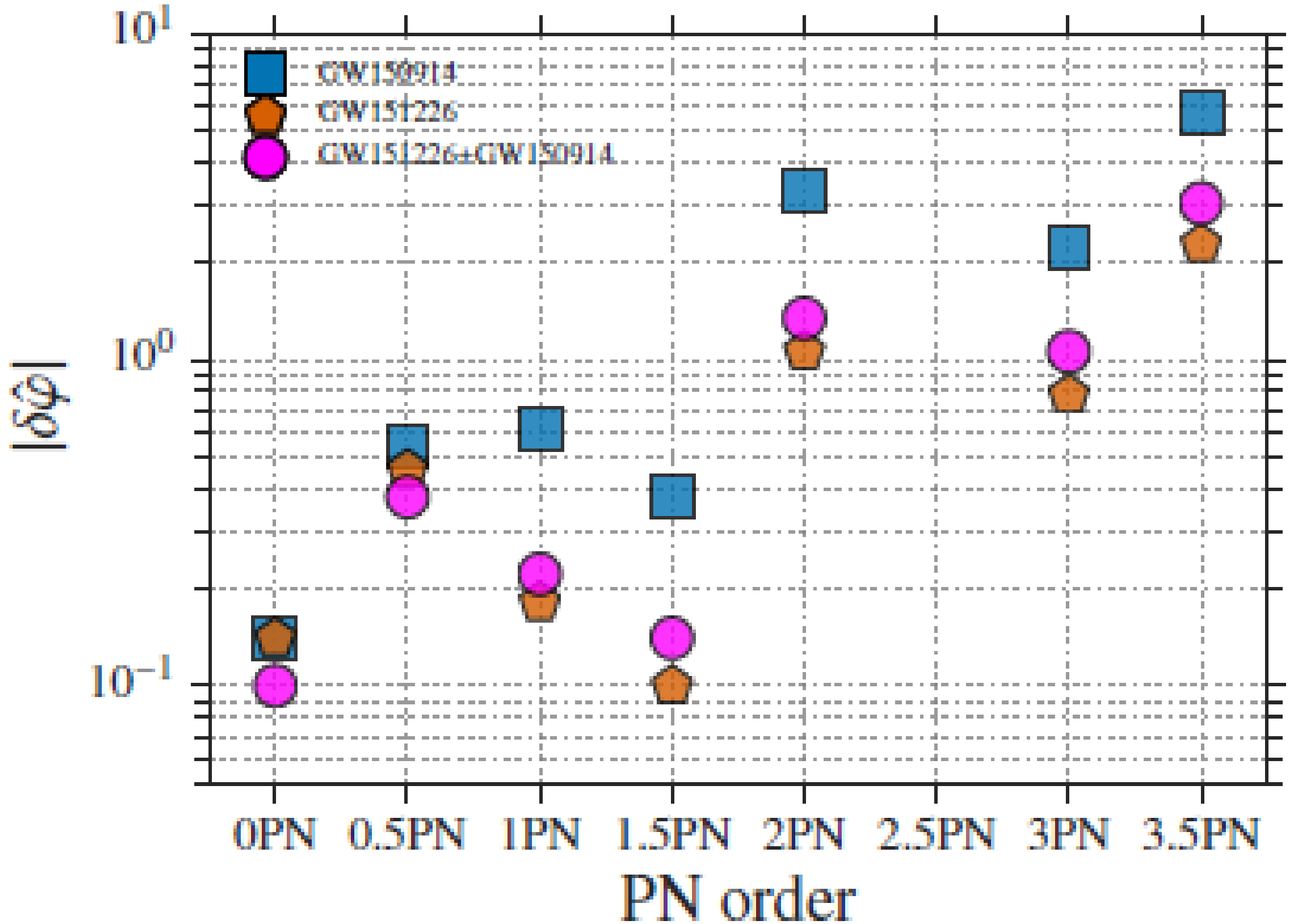
$$\tilde{h}_i(f) = A_i(f) e^{i\Phi_i(f)} . \qquad \delta\Phi_{\rm I,ppE}(f) = \beta\,(\pi \mathcal{M} f)^{b/3}$$

(arXiv:1603.08955)

Constraint on the graviton Compton wavelength is severer than the solar system bounds.

For the improvement of the precision, longer observation in the inspiral phase is necessary $\Rightarrow$ space interferometer

GW151226 improved the constraint a lot



→ Constraint on the 1PN coefficient became about 5 times more stringent

Parametorized post-Einstein

$$\boxed{h(f) \approx A f^{-7/6} e^{i\Psi(f)}}$$

GW waveform for Quasi-circular orbits

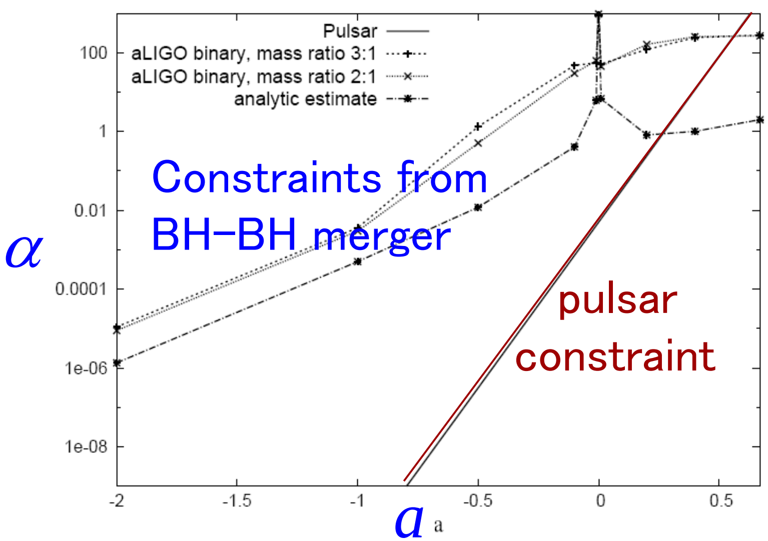
$$\Rightarrow \begin{cases} A(f) \to \left(1 + \sum_i \alpha_i u^{a_i}\right) A_{GR}(f) \\ \Psi(f) \to \left(\Psi_{GR}(f) + \sum_i \beta_i u^{b_i}\right) \end{cases}$$

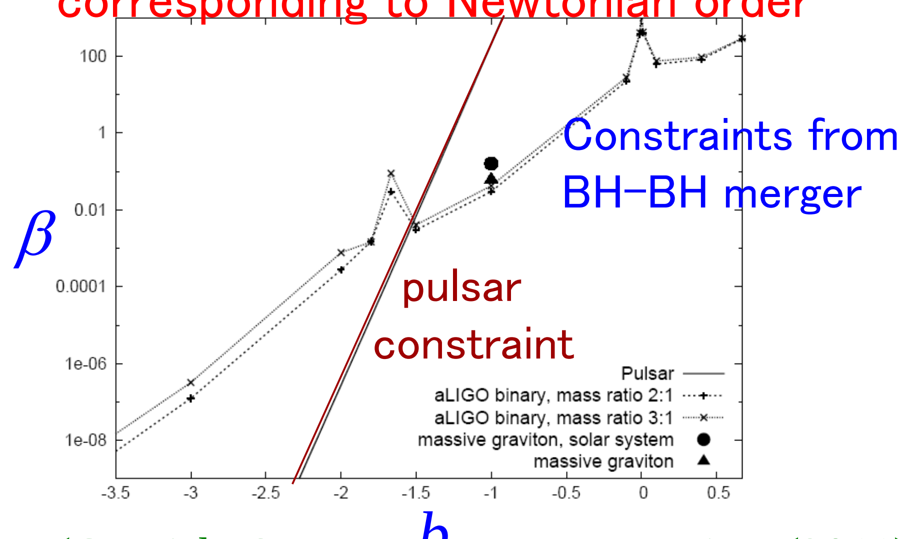
Theory	a	α	b	β
Brans-Dicke [9, 10, 14–16]	–	0	-7/3	β
Parity-Violation [22, 34–37]	1	α	0	–
Variable $G(t)$ [38]	-8/3	α	-13/3	β
Massive Graviton [8–14]	–	0	-1	β
Quadratic Curvature [23, 44]	–	0	-1/3	β
Extra Dimensions [45]	–	0	-13/3	β
Dynamical Chern-Simons [46]	+3	α	+4/3	β

(Yunes & Pretorius (2009))

Better constraint than pulsar timing for a_i>0 or b_i>−5/3.

corresponding to Newtonian order



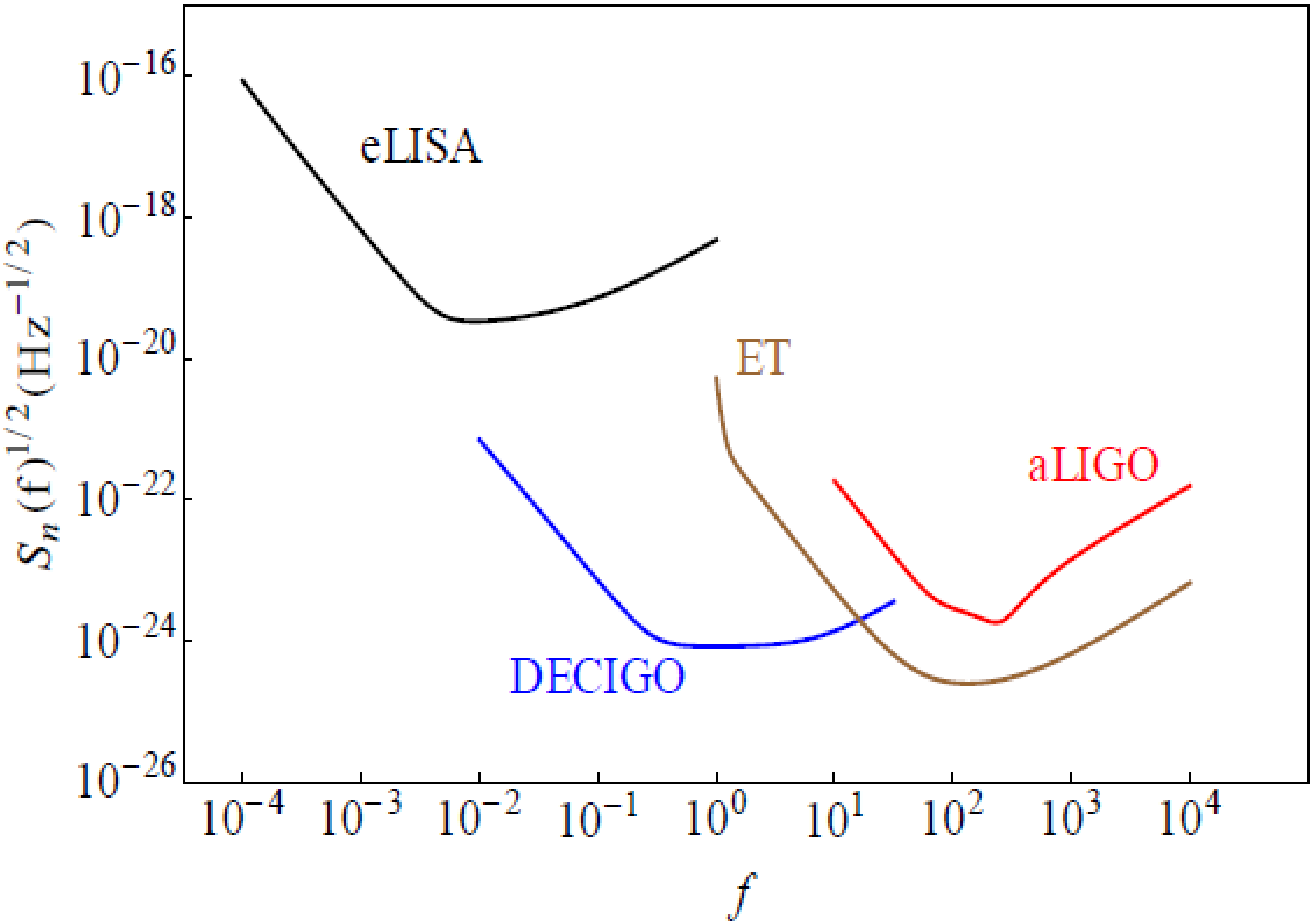


(Cornish, Sampson, Yunes, Pretorius. (2011))

12$M_\odot$BH–6$M_\odot$BH and 18$M_\odot$BH–6$M_\odot$BH mergers

If we use space and ground detectors together, …

- The constraint on the deviation from GR is limited by the degeneracy with the binary parameters.
- To determine effectively many parameters, we need wider frequency range.



$S_n(f)^{1/2}(\mathrm{Hz}^{-1/2})$
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
eLISA
ET
aLIGO
DECIGO
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4}
f

Fisher analysis

- We used 3.5PN wave form without spin for circular binary.

$$\left(h_1 \mid h_2\right) \approx 4\,\mathrm{Re}\int \frac{df}{S_n(f)} h_1(f)\, h_2^*(f)$$: inner product

$$\Gamma_{ab} = \left(\frac{\partial h(\boldsymbol{\theta})}{\partial \theta^a} \middle| \frac{\partial h(\boldsymbol{\theta})}{\partial \theta^b} \right)$$: Fisher matrix

θ : binary parameters

$$\left(\Delta\theta^a\right)^2 = \left(\Gamma^{-1}\right)^{aa}$$

If we have two completely independent observations (1) and (2) that estimate only one parameter,

$$\Delta\theta'^2 = \left(\Gamma^{(1)} + \Gamma^{(2)}\right)^{-1} = \boxed{\frac{\Delta\theta_{(1)}\Delta\theta_{(2)}}{\Delta\theta_{(1)}^2 + \Delta\theta_{(2)}^2}}$$

Reference value

However, when we estimate many parameters together, the joint probability distribution becomes

$$P \propto \exp\left(-\frac{1}{2}\left(\Gamma_{ab}^{(1)} + \Gamma_{ab}^{(2)}\right)\Delta\theta^a \Delta\theta^b \right)$$

The variance becomes

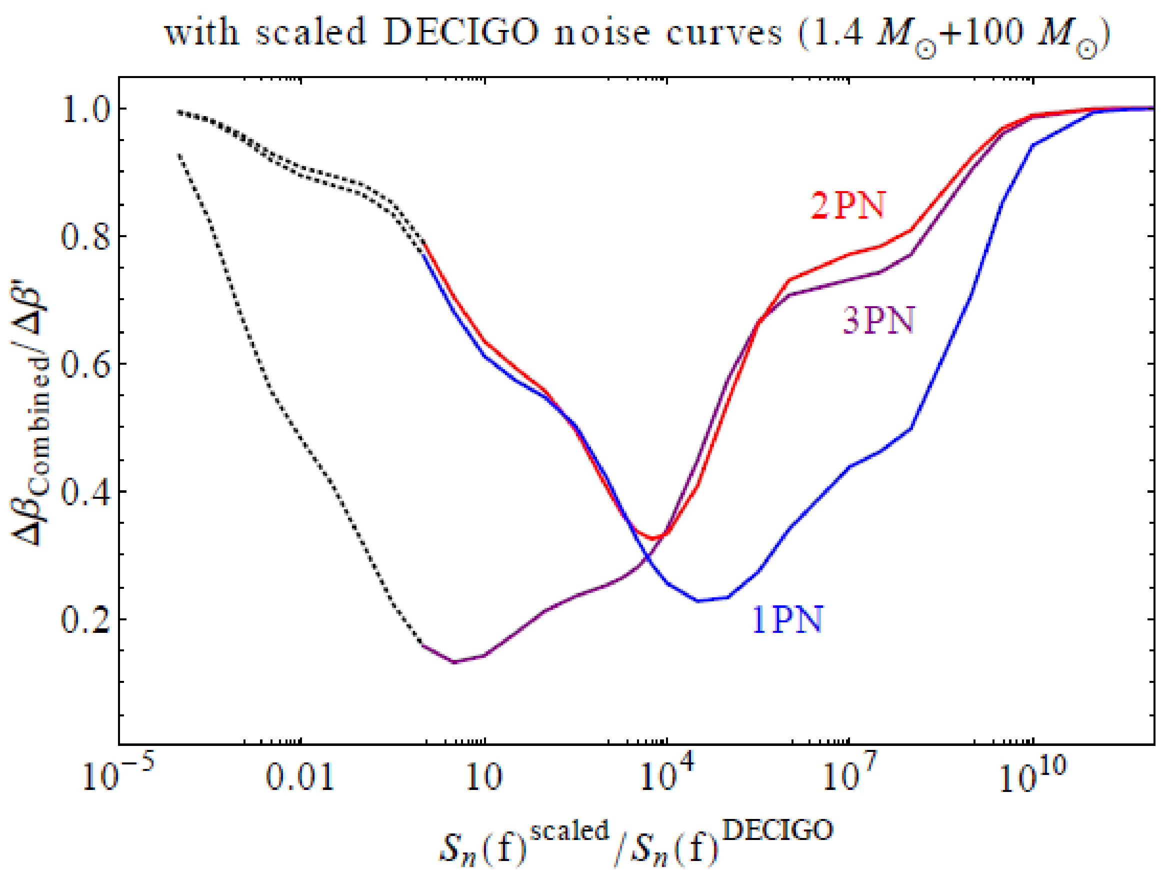
$$\left(\Delta\theta^a_{\mathrm{combined}}\right)^2 = \left(\left(\boldsymbol{\Gamma}^{(1)} + \boldsymbol{\Gamma}^{(2)}\right)^{-1}\right)^{aa}$$

We assume the pair of ET and rescaled DECIGO noise curves.

ppE waveform

$$\boxed{h(f) \approx A f^{-7/6} e^{i\Psi(f)}}$$

$$\Psi(f) \to \left(\Psi_{GR}(f) + \sum_i \beta_i u^{b_i} \right)$$



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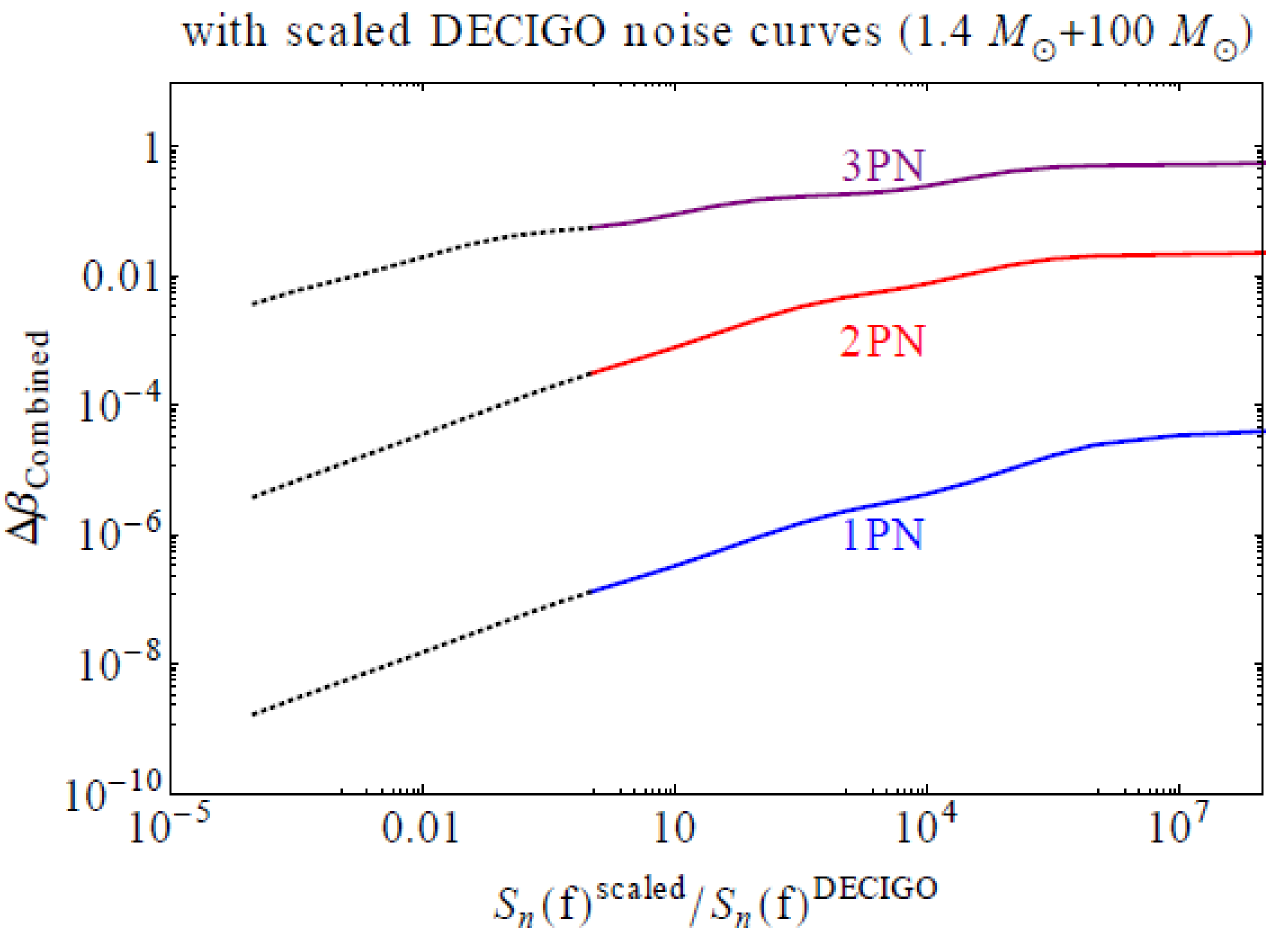


Summary

1) We have assessed the expected synergy effects between ground and space based detectors, on the estimated errors in parameters of coalescing binary systems.

2) Our aim was to demonstrate that the advantage of having a GW antenna which is sensitive at low frequencies, is larger than we naively expect.

3) Larger gain in the error estimate of the GW waveform parameters is obtained when the constraints from individual ground or space detectors are almost equal.

4) In case of the ppE parameters that characterize deviations from GR, some gain is always obtained irrespective of the level of sensitivity of the GW antenna.

§ 2 Synergy effect on sky localization

Motivation for identifying BH binary host galaxies

We extended our previous study taking into account

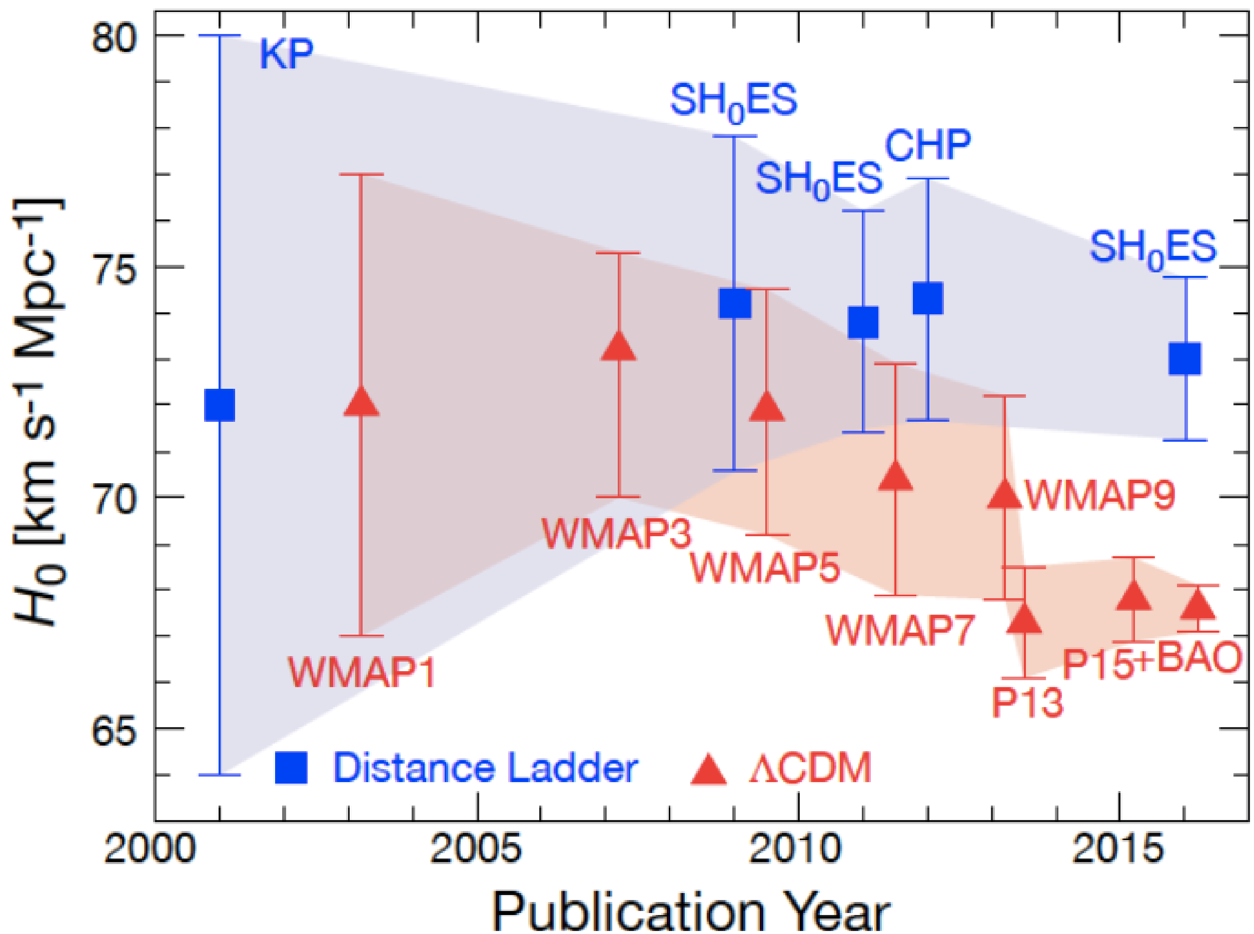
1) the sky position
2) the motion of the detectors
   comparison of helio-centric and geo-centric orbits
3) the source orientation
   We neglected spin precession.

Quick data analysis may help detecting optical counterpart.

Binary BHs may not have any detectable optical counterpart.

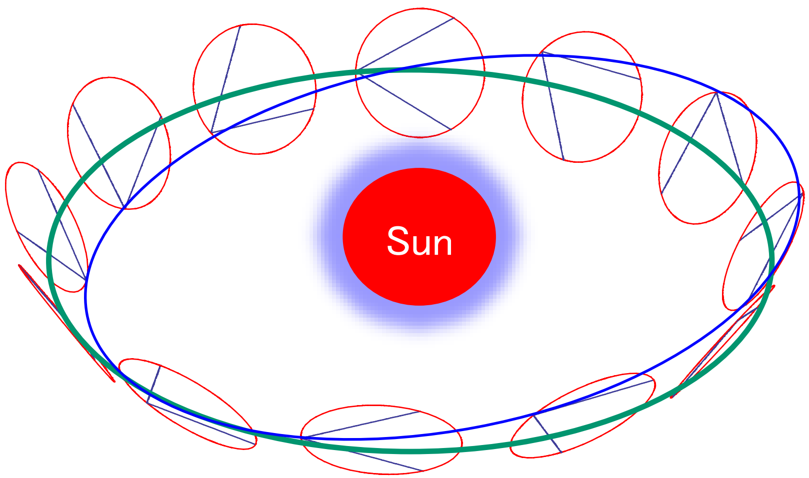
1) Identifying the type of host galaxies will tell us the formation history of binary black holes
2) We can use BH-BH binary to obtain redshift distance relation independent of IaSN

Existing descrepqancy in the estimates of Hubble parameter

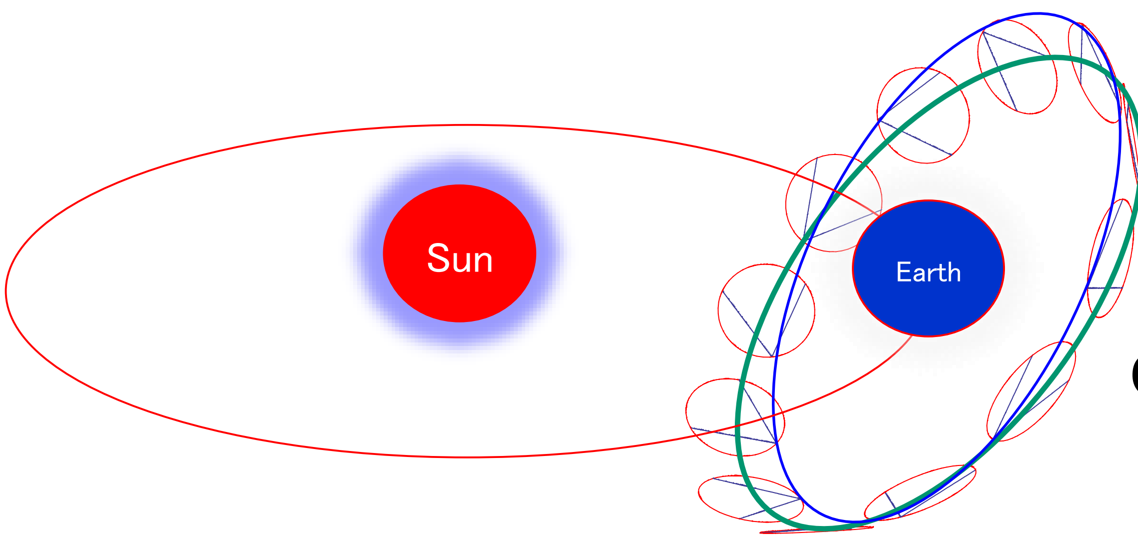


arXiv:1706.02739

Heliocentric and Geocentric orbits



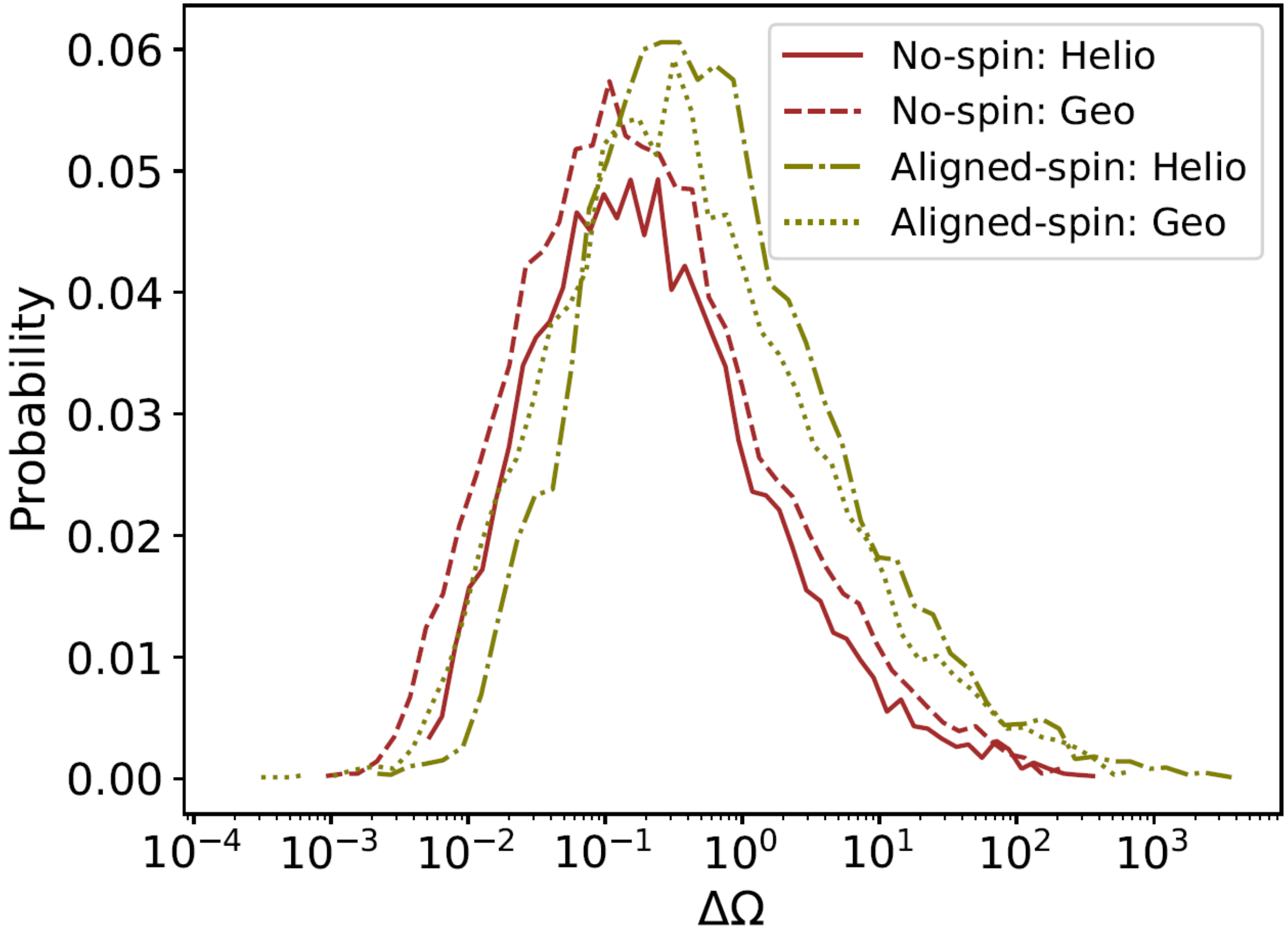
Heliocentric orbit



Geocentric orbit

Merit of adding Ground detector information

We consider $40M_{\odot}+30M_{\odot}$BHs@3Gpc



We focus on the sky localization (arcmin^2)

Merit of adding Ground detector information

$40M_{\odot} + 30M_{\odot}$BHs@3Gpc

Non-spinning case

Detector	Δt_c	$\Delta \phi_c$	$\Delta\mathcal{M}/\mathcal{M}(\%)$	$\Delta\nu/\nu(\%)$	$\Delta\Omega$ (arcmin^2)	SNR
DECIGO (H)	1.4×10^{-1}	1.7×10^{-2}	2.8×10^{-6}	4.4×10^{-3}	1.8×10^{-1}	~ 650
Joint (H)	2.4×10^{-3}	1.4×10^{-2}	8.1×10^{-7}	3.3×10^{-3}	1.8×10^{-3}	
DECIGO (G)	1.0×10^{-1}	1.5×10^{-2}	2.1×10^{-6}	4.3×10^{-3}	1.6×10^{-1}	~ 677
Joint (G)	1.0×10^{-1}	1.1×10^{-2}	2.0×10^{-6}	3.2×10^{-3}	1.4×10^{-1}	

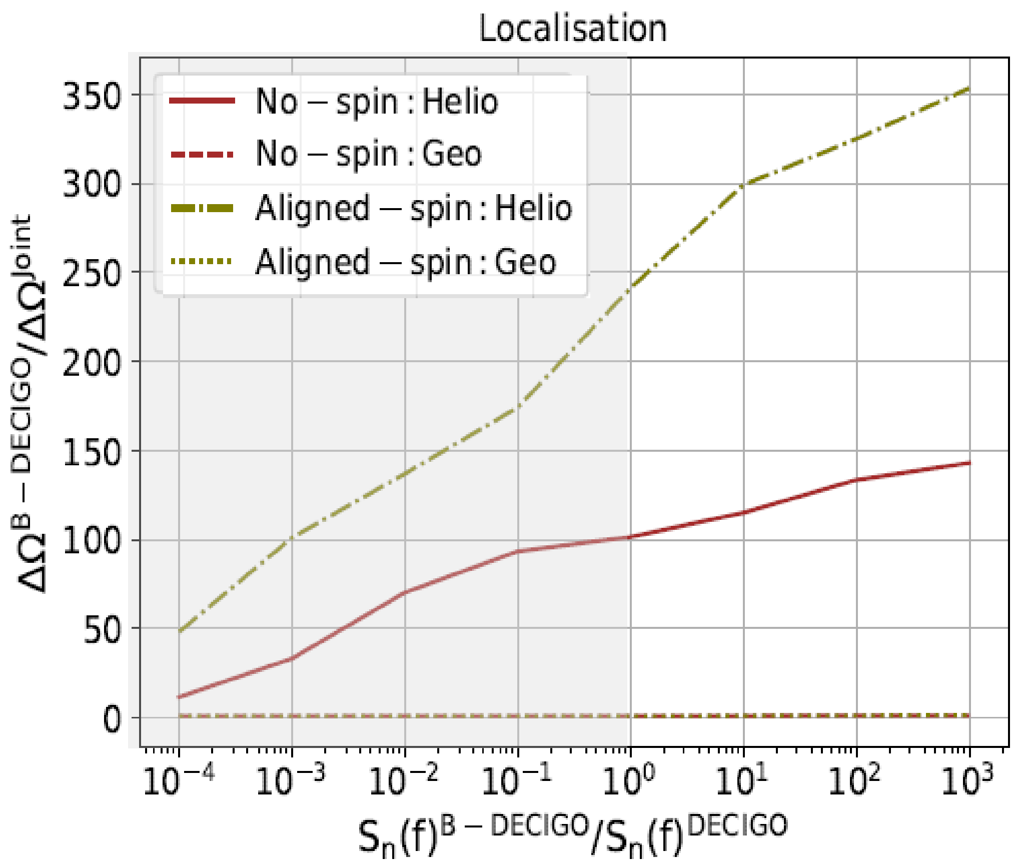
Aligned spin

Detector	Δt_c	$\Delta \phi_c$	$\Delta\mathcal{M}/\mathcal{M}(\%)$	$\Delta\nu/\nu(\%)$	$\Delta\Omega$ (arcmin^2)	$\Delta\sigma$	$\Delta\beta$	SNR
DECIGO (H)	4.2×10^{-1}	1.6×10^{-1}	6.2×10^{-5}	2.4×10^{-1}	4.8×10^{-1}	9.6×10^{-2}	2.2×10^{-3}	~ 650
Joint (H)	2.6×10^{-3}	5.2×10^{-2}	2.1×10^{-5}	8.6×10^{-2}	2×10^{-3}	3.4×10^{-2}	9.1×10^{-4}	
DECIGO (G)	2.2×10^{-1}	1.4×10^{-1}	4.4×10^{-5}	1.8×10^{-1}	3.1×10^{-1}	7.8×10^{-2}	2.2×10^{-3}	~ 678
Joint (G)	2.1×10^{-1}	4.9×10^{-2}	3.2×10^{-5}	1.1×10^{-1}	2.8×10^{-1}	4.2×10^{-2}	8.7×10^{-4}	

With and without spin, the joint analysis improves the sky localization by two orders of magnitude for helio-centric DECIGO, while the improvement is not significant for geo-centric configuration.

Merit of adding Ground detector information

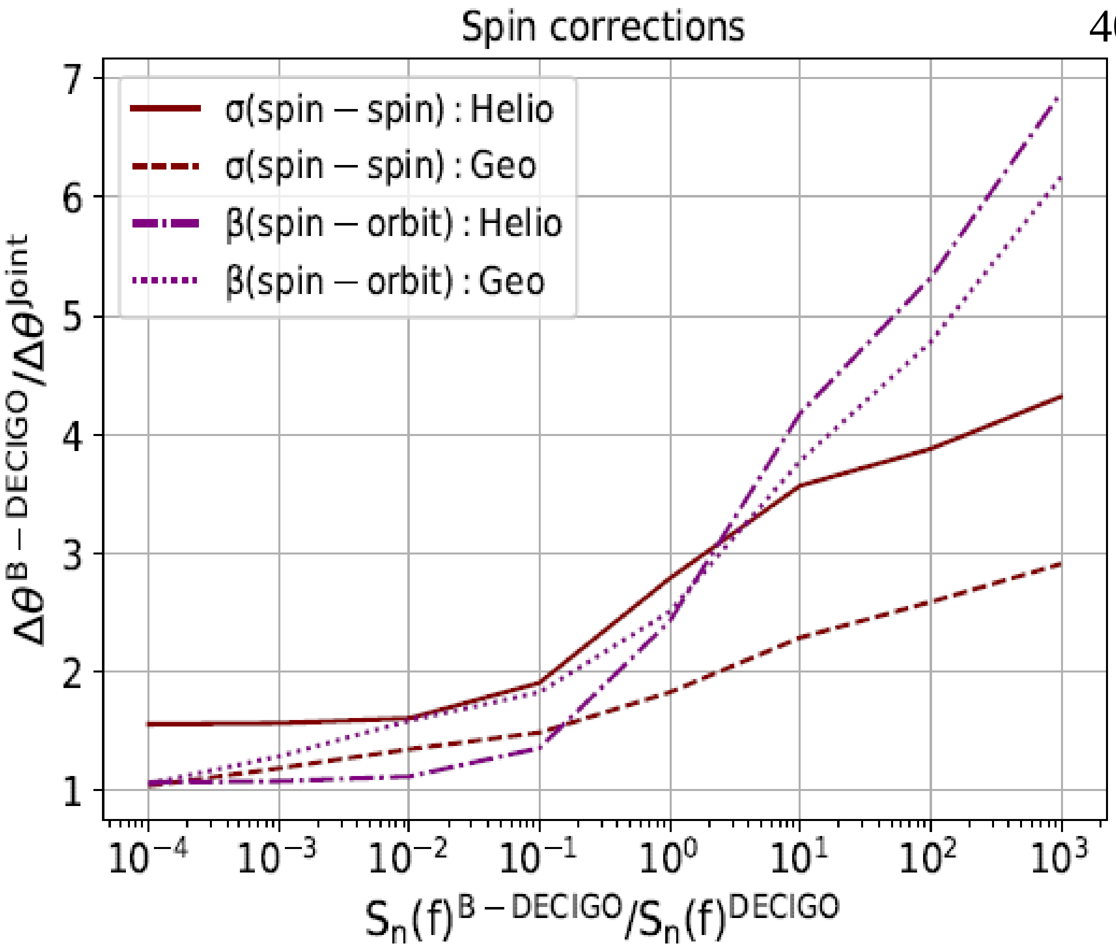
$40M_\odot + 30M_\odot$ BHs@3Gpc



The merit of combining the ground-based detector is bigger when the sensitivity of B-DECIGO is worse.

Effect on the spin parameter determination

$40M_{\odot} + 30M_{\odot}$BHs@3Gpc



The determination errors of spins do not depend much on the detector configuration.

Impact of the synergy effect on the sky localization

Localization improvement can be $O(300)$ in the helio-centric case

Detector	Δt_c	$\Delta\phi_c$	$\Delta\mathcal{M}/\mathcal{M}(\%)$	$\Delta\nu/\nu(\%)$	$\Delta\Omega$ (arcmin^2)	$\Delta\sigma$	$\Delta\beta$	SNR
B-DECIGO (H)	1.3×10^1	4.9	1.9×10^{-3}	7.5	4.8×10^2	3.0	7.0×10^{-2}	~ 20
Joint (H)	6.5×10^{-2}	4.3×10^{-1}	5.5×10^{-4}	2.0	1.4	7.0×10^{-1}	1.0×10^{-2}	
B-DECIGO (G)	7.1	4.5	1.4×10^{-3}	5.7	3.3×10^2	2.4	6.9×10^{-2}	~ 22
Joint (G)	4.6	4.5×10^{-1}	7.3×10^{-4}	2.5	1.9×10^2	8.5×10^{-1}	1.1×10^{-2}	

$S_n(f)^{\mathrm{B-DECIGO}} = 10^3 S_n(f)^{\mathrm{DECIGO}}$ $\quad 40M_\odot + 30M_\odot$BHs@3Gpc

Number of galaxies within the error box, adopting $2.35\times10^{-3}\,\mathrm{Mpc}^{-3}$

$$\Delta V = (4/3)\,\pi\, D_L^3 (\Delta\Omega/4\pi) \Rightarrow \sim 3000 \text{ galaxies}$$

Using synergy effect and also the distance information

$$\Delta V = \Delta\Omega\; D_L^3\; (2\times\Delta D_L/D_L) \Rightarrow \sim 9 \text{ galaxies}$$

$$\Delta D_L/D_L \approx 6.4\%$$

Notice that the number is roughly proportional to D_L^{-3}.

Summary

1) We have assessed the expected synergy effects between ground and space based detectors, on the estimated errors on the sky position of coalescing binary systems.

2) Our aim was to demonstrate that the advantage of having a GW antenna which is sensitive at low frequencies, is larger than we naively expect.

3) Improvement of the error estimate of the GW waveform source localization is significant, especially for heliocentric B-DECIGO.

4) For many gravitational wave events from coalescing BH binaries, we would be able to identify the host galaxy.