KYOTO UNIVERSITY

Gravitational Wave Probes of Physics Beyond Standard Model

Exploring spin of ultralight DM with GW detectors

Based on 2310.10646 with H. Takeda, K. Aoki, T. Fujita, and S. Mukohyama

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Credit: The Virgo Collaboration/CCO 1.0

November 9, 2023

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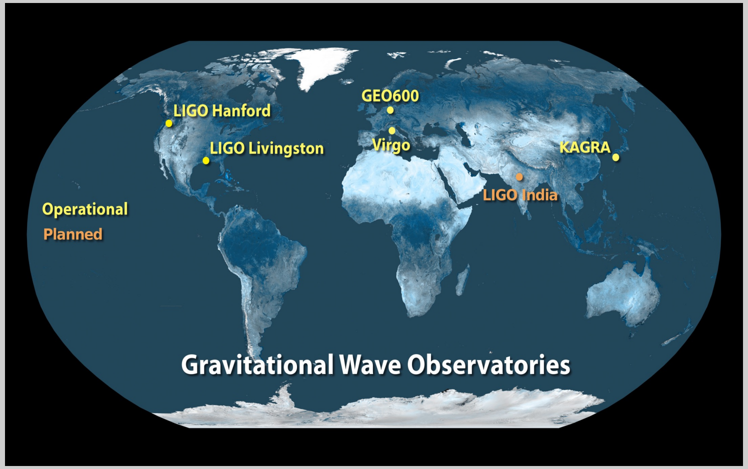

Credit Caltech/MIT/LIGO Lab

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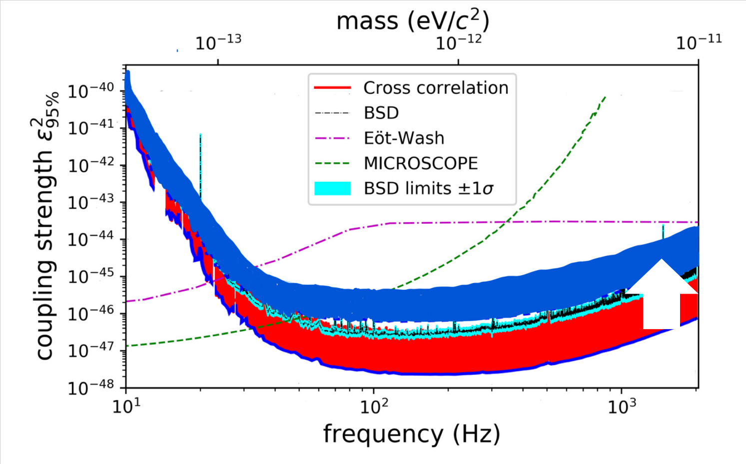
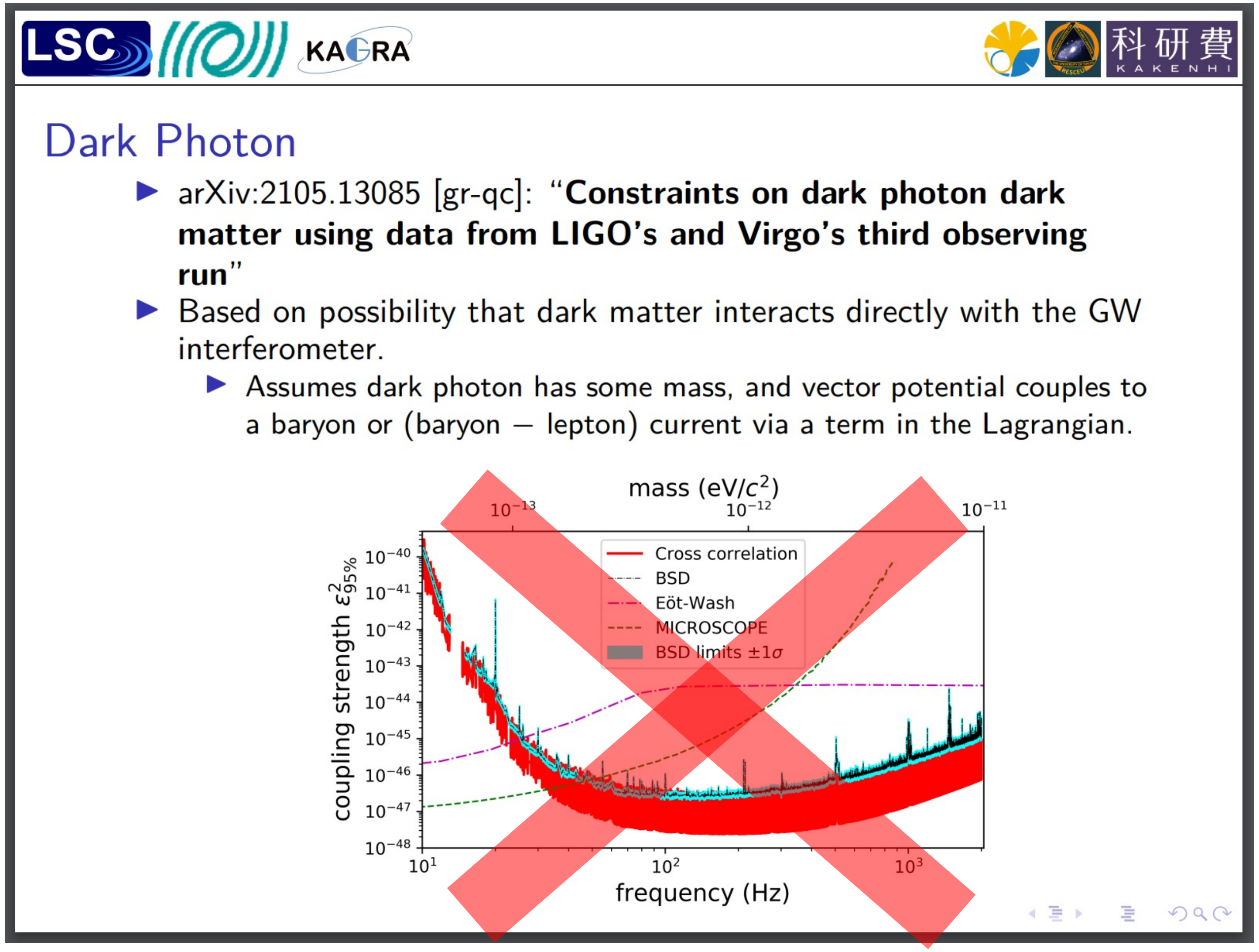


Credit LVK collaboration

Constraint on dark photon by LVK collabolation is not correct.

From Prof. Cannon's slide



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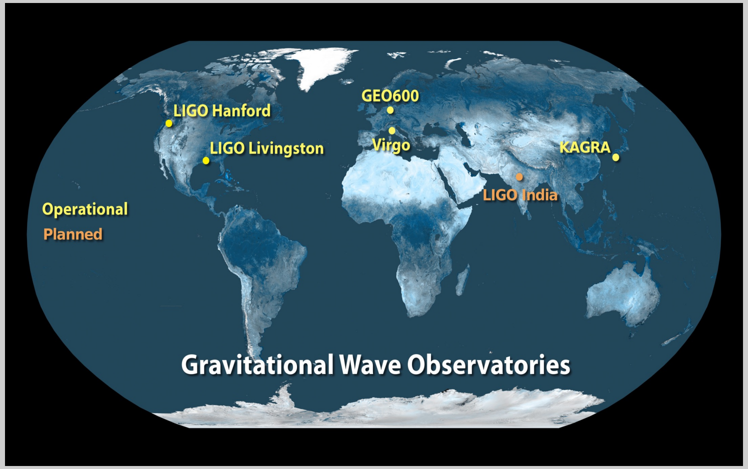

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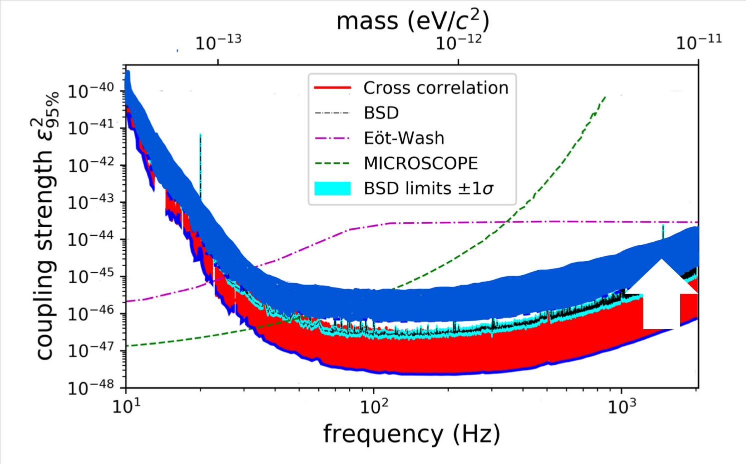

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Ultralight dark matter (ULDM) can be searched by GW detectors.

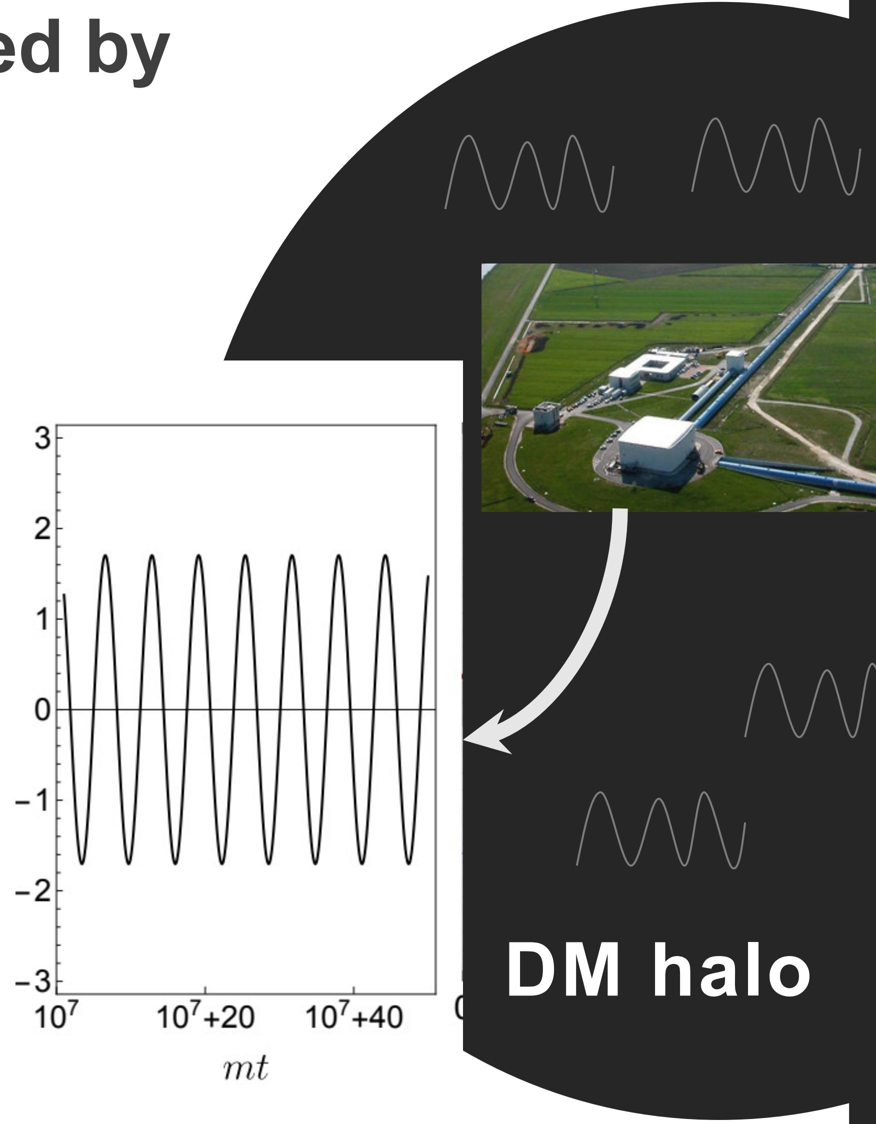
1. GW detectors are sensitive to small variations in their arms length.

2. ULDM is a wave-like dark matter model.

3. We are in DM halo.

If ULDM directly couples to SM,

ULDM would leave oscillating signals in the GW detectors !



Ultralight dark matter (ULDM) is a dark matter model with a tiny mass around 10^{-22} -1 eV.

Key features of ULDM

Boson	ULDM is composed of bosonic particles because fermionic particles are not possible to be dense enough due to the Pauli blocking. spin-0: Massive scalar field such as axion, dilaton, moduli, etc. spin-1: Massive vector field. Dark photon. spin-2: Massive tensor field, i.e., massive graviton. Based on bigravity or multigravity.
Non-relativistic	ULDM is a non-relativistic wave because the local DM speed is about $v \sim 10^{-3}$.
$f_{\rm Com} = \dfrac{m}{2\pi}$	ULDM is Oscillate with Compton wavelength corresponding to tis mass. $f_{\rm Com} = 242\ {\rm Hz}\left(\dfrac{m_{\rm DM}}{10^{-12}{\rm eV}}\right)$
$\tau_{\rm coh} = \dfrac{2\pi}{mv^2}$	ULDM has a long coherent time scale. $\tau_{\rm coh} = 7700{\rm s}\left(\dfrac{m}{10^{-12}{\rm eV}}\right)^{-1}$

The coupling with SM depends on the spin. Thus, the way to generate signals differs by its spin.

Spin-0	Through its dilatonic coupling to SM, ULDM fluctuate the fundamental constants such as fine structure constant and fermion mass.	$\mathcal{L}_{\rm int} = -\frac{\phi}{M_{\rm Pl}}\left[\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G^{A\mu\nu} - d_{m_e}m_e\bar{e}e - \sum_{i=u,d}(d_{m_i}+\gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right]$
Spin-1	It leaves a signal by pushing the mirrors through the Coulomb-like force.	$\mathcal{L}_{\rm int} = \epsilon_D e A_\mu j^\mu_D$
Spin-2	Since it originates from the gravity sector, it universally couples to matter fields. Thus, it leaves a signal in GW detectors like GW.	$\mathcal{L}_{\rm int} = \frac{\alpha}{M_{\rm pl}}\Phi_{ij}T^{ij}_{\rm m}$

[Spin-0] - Y. V. Stadnik & V. V. Flambaum, PRL 114, 161301 (2015) - Y. V. Stadnik & V. V. Flambaum, PRA 93, 063630 (2016) - A. A. Geraci+, PRL 123, 031304 (2019) - H. Grote & Y. V. Stadnik, PRR 1, 033187 (2019) - S. Morisaki & T. Suyama, PRD 100, 123512 (2019) - C. Kennedy+, PRL 125, 201302 (2020) - E. Savalle+, PRL 126, 051301 (2021) - S. M. Vermeulen+, Nature 600, 424 (2021) GEO600 data analysis
[Spin-1] - P. W. Graham+, PRD 93, 075029 (2016) - A. Pierce+, PRL 121, 061102 (2018) - H-K Guo+, Commun. Phys. 2, 155 (2019) LIGO O1 data analysis - Y. Michimura, T. Fujita, S. Morisaki, H. Nakatsuka, I. Obata, PRD 102, 102001 (2020) - D. Carmey+, New J. Phys. 23, 023041 (2021) - J. Manley+, PRL 126, 061301 (2021) - S. Morisaki, T. Fujita, Y. Michimura, H. Nakatsuka, I. Obata, PRD 103, L051702 (2021) - LIGO-Virgo-KAGRA Collaboration, arXiv:2105.13085 LIGO/Virgo O3 data analysis
[Spin-2] Y.Manita, K. Aoki, T. Fujita, S. Mukohyama, Phys.Rev.D 105 8, 084038 (2022) - J. M. Armaleo, D. Lopez Nacir, and F. R. Urban, JCAP 04, 053 (2021)

There are two types of origins for ULDM signals.

The change in the round-trip distance of the laser.

$$\delta L = \delta L_{\mathrm{time}} + \delta L_{\mathrm{space}}$$

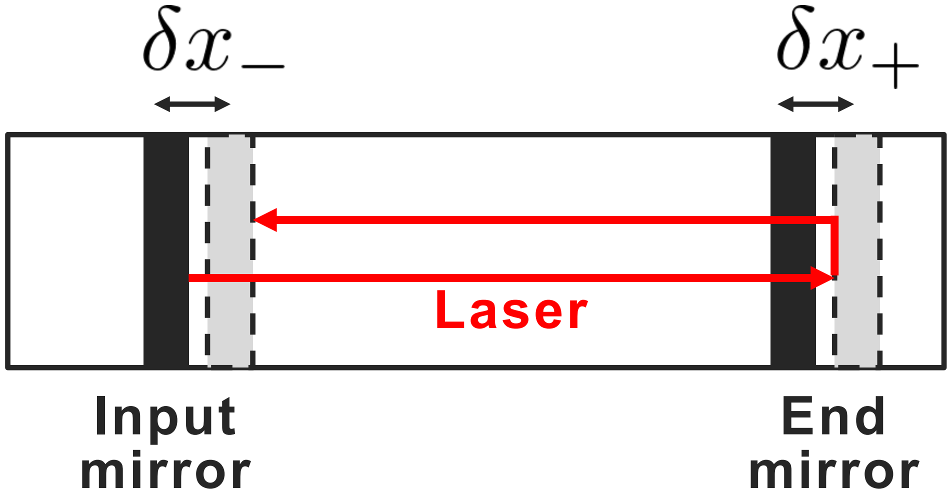
$$\delta L_{\mathrm{time}} = -\delta x_-(t) + 2\delta x_-(t-L) - \delta x_-(t-2L)$$

Finite time light traveling effect: This is caused by the displacement of mirrors during the round-trip of the laser. (Morisaki+,2021)

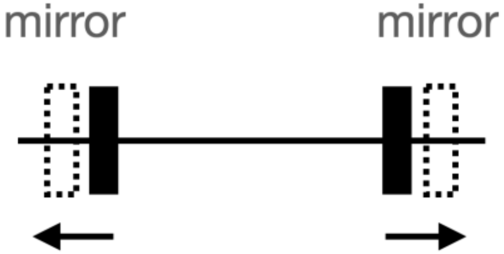
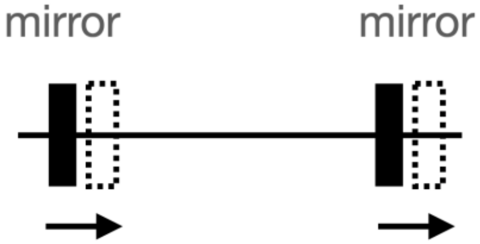
$$\delta L_{\mathrm{space}} = 2\left(\delta x_+(t-L) - \delta x_-(t-L)\right)$$

This is caused by the difference in displacement between the input and end mirrors.

Arm of detector



In the signals of spin-0 or spin-1 ULDM, $\delta L_{\rm time}$ cannot be ignored.

	Spin-2	Spin-0 and spin-1
	Differential motion	Common motion
		
$\delta L_{\rm time}$	$\sim \delta\ddot{x}L^2$ neglegible	$\sim \delta\ddot{x}L^2$
$\delta L_{\rm space}$	$\sim \delta x$	$\sim \partial(\delta x)L$
	$\frac{\delta L_{\rm time}}{\delta L_{\rm space}} = m^2L^2 \ll 1$	$\frac{\delta L_{\rm time}}{\delta L_{\rm space}} = \frac{mL}{v} \sim \mathcal{O}(1)$ for $m \simeq 50\mathrm{Hz}$

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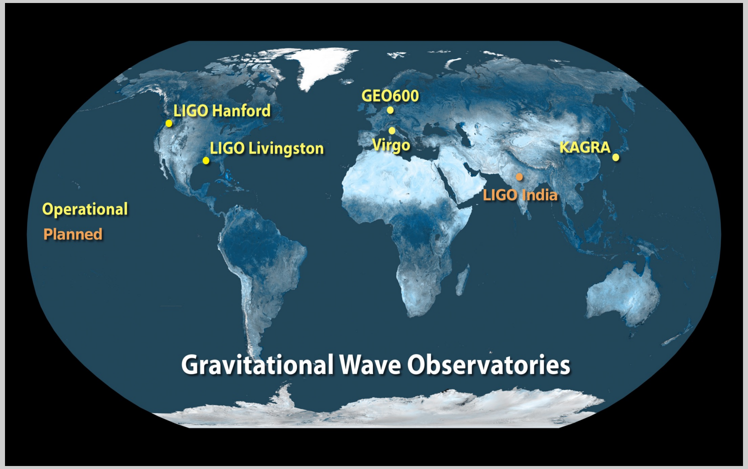

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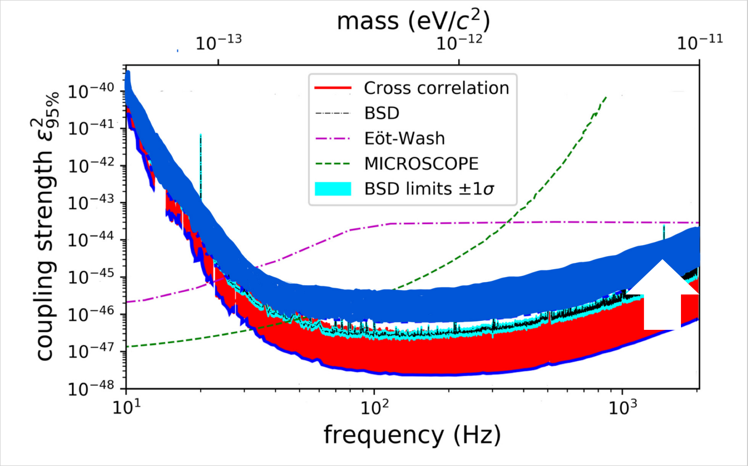


Credit LVK collaboration

Can we distinguish spin of ULDM by the signal from GW detectors?

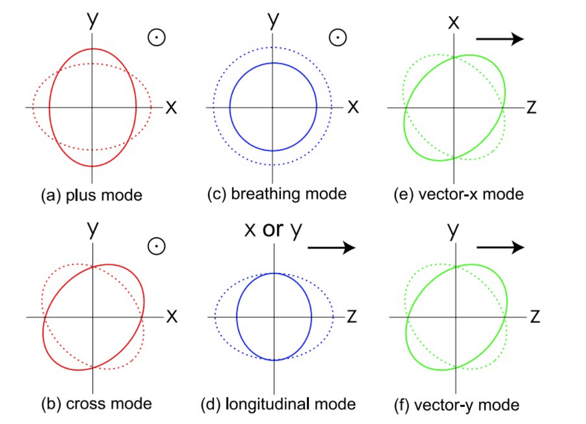
The methods for separating non-tensorial polarizations in SGWB are not applicable. This is because the frequency width of the signal is too narrow to distinguish the differences in the ORF.

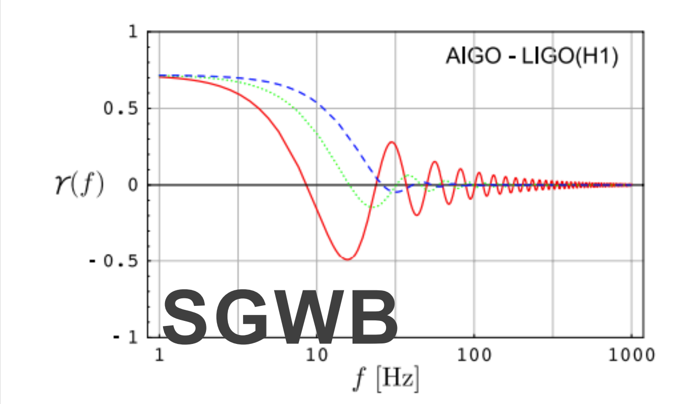
Cross correlational signal of two detectors

$$\left\langle \tilde{h}_a \tilde{h}_b \right\rangle = P(f)\gamma_{ab}(f)$$

Overlap reduction function (ORF)

Power spectrum



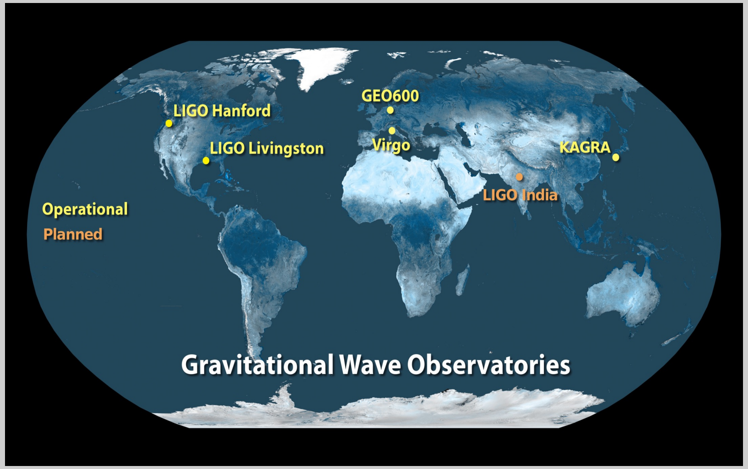


[A.Nishizawa, A. Taruya, K.Hayama, S. Kawamura, M. Sakagami, 2009]

Can we distinguish spin of ULDM by the signal from GW detectors?

Answer

We can distinguish the spin by using several cross correlation with multiple detectors. ORF is different for spin-1and spin-2.



Credit Caltech/MIT/LIGO Lab

$$\left\langle \tilde{h}_a \tilde{h}_b \right\rangle = P(f)\gamma_{ab}(f)$$

$\gamma_{ab}(f)$: **Overlap reduction function (ORF)**

$P(f)$: Power spectrum

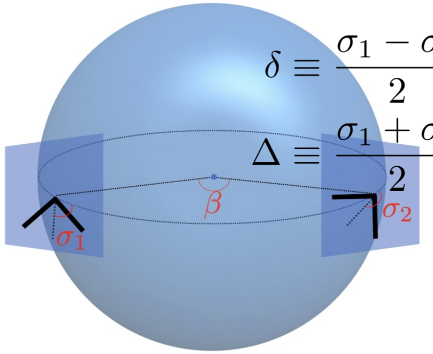
ORF for h_{time} and h_{space} has different dependence on orientation and position of detectors.

Spin-2	Spin-0 and spin-1
$\left\langle \tilde{h}_a^* \tilde{h}_b \right\rangle = \alpha^2 P(f) \gamma_{ab}$ ORF(space)	$\left\langle \tilde{h}_{\mathrm{time},a}^* \tilde{h}_{\mathrm{time},b} \right\rangle = \epsilon_D^2 P_{\mathrm{time}}(f) \Gamma_{ab}$ ORF(time) $\left\langle \tilde{h}_{\mathrm{space},a}^* \tilde{h}_{\mathrm{space},b} \right\rangle = \epsilon_D^2 P_{\mathrm{space}}(f) \gamma_{ab}$ ORF(space)

KEY POINT

$$\Gamma_{ab}(\beta, \delta, \Delta) = \cos^2\left(\frac{\beta}{2}\right)\cos(2\delta) - \sin^2\left(\frac{\beta}{2}\right)\cos(2\Delta) \quad \text{(time)}$$

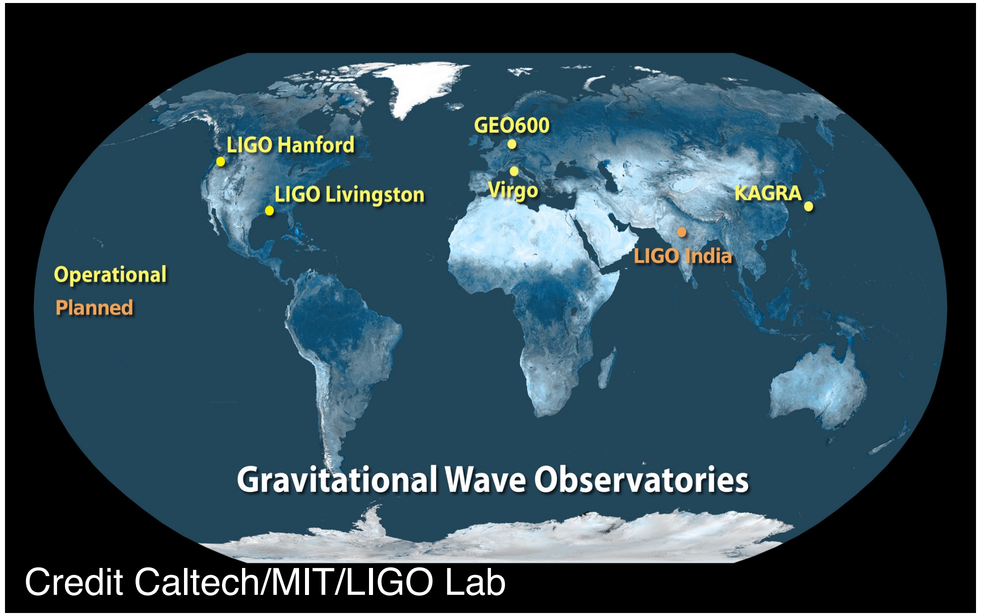
$$\gamma_{ab}(\beta, \delta, \Delta) = \cos^4\left(\frac{\beta}{2}\right)\cos(4\delta) - \sin^4\left(\frac{\beta}{2}\right)\cos(4\Delta) \quad \text{(space)}$$



$$\delta \equiv \frac{\sigma_1 - \sigma_2}{2}, \quad \Delta \equiv \frac{\sigma_1 + \sigma_2}{2}$$

Ideally, we can distinguish ULDM spin with three or more detectors.

Currently, there are 4 (or more) ground-based detectors (LVK), thus 6 (or more) combinations of cross-correlations can be considered.

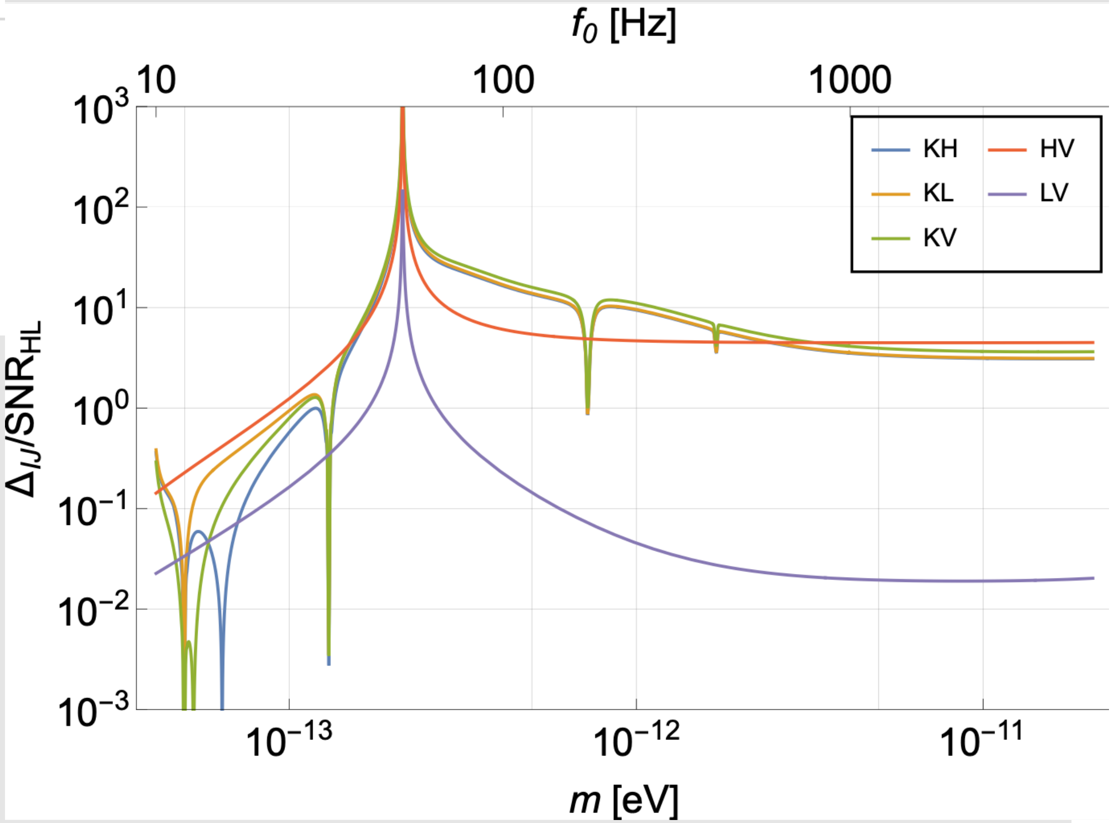


ORF(space)↓ ↓ORF(time)

Detectors	β	δ	Δ	γ_{IJ}	Γ_{IJ}
KL	54.8912	28.5968	102.703	-0.280	0.620
IH	112.279	-79.7392	164.518	-0.150	-0.880
IL	128.472	35.8711	203.311	0.009	-0.500
IV	59.7883	42.8974	159.522	-0.570	-0.130
KH	72.3721	-88.2092	117.523	0.460	-0.450
KL	99.2727	-135.139	160.223	-0.240	-0.450
KV	86.5230	31.6663	97.443	-0.360	0.690
HL	27.2233	-44.9735	241.550	-0.890	0.031
HV	79.6176	-28.856	144.217	-0.015	0.190
LV	76.7637	27.0677	172.467	-0.250	-0.012

Indicator of Distinguishability

$$\Delta_{ab} \equiv \left| \mathrm{SNR}_{ab}^{(\text{spin-1})} - \mathrm{SNR}_{ab}^{(\text{spin-2})} \right|$$



Case study

We suppose that a signal is detected through the cross-correlation analysis between LIGO-Livingston and LIGO-Hanford:

$$\mathrm{SNR}_{\mathrm{LH}} = \mathrm{SNR}_{\mathrm{LH}}^{(\text{spin-1})} = \mathrm{SNR}_{\mathrm{LH}}^{(\text{spin-2})}$$

Low mass

Since the effective ORF for spin-1 and spin-2 ULDM is the same, the distinguishability is low.

High mass

Since the finite time light traveling effect dominates, the distinguishability of spin is high.

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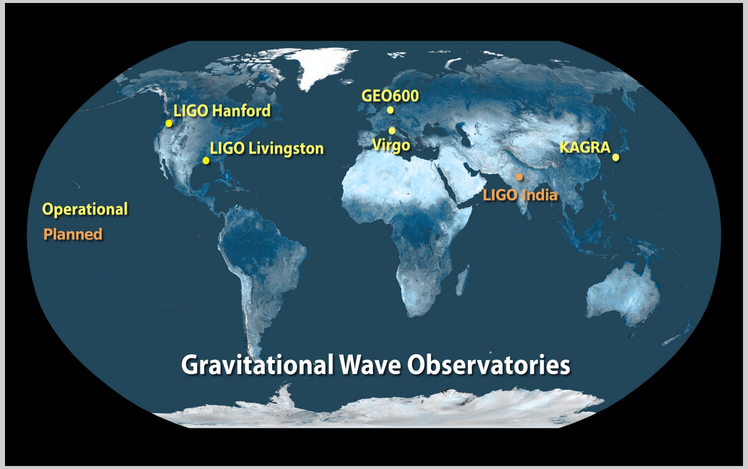

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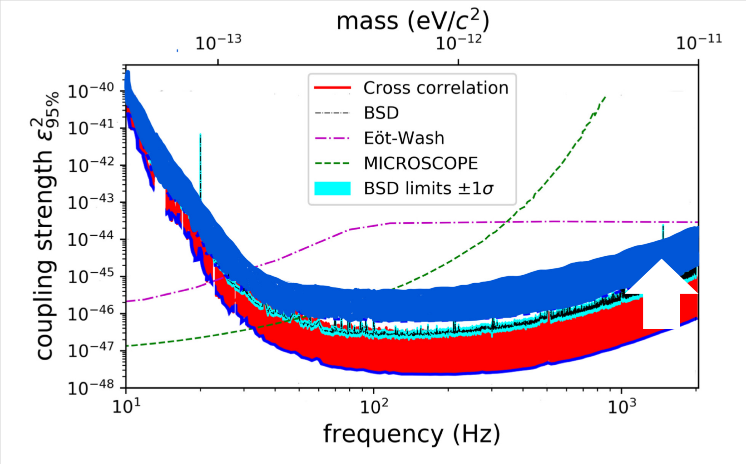


Credit LVK collaboration

The current constraint of the coupling constant for spin-1 ULDM become around 30 times weaker.

Usual ORF (space)

$$\gamma_{\rm HL} = -0.89$$

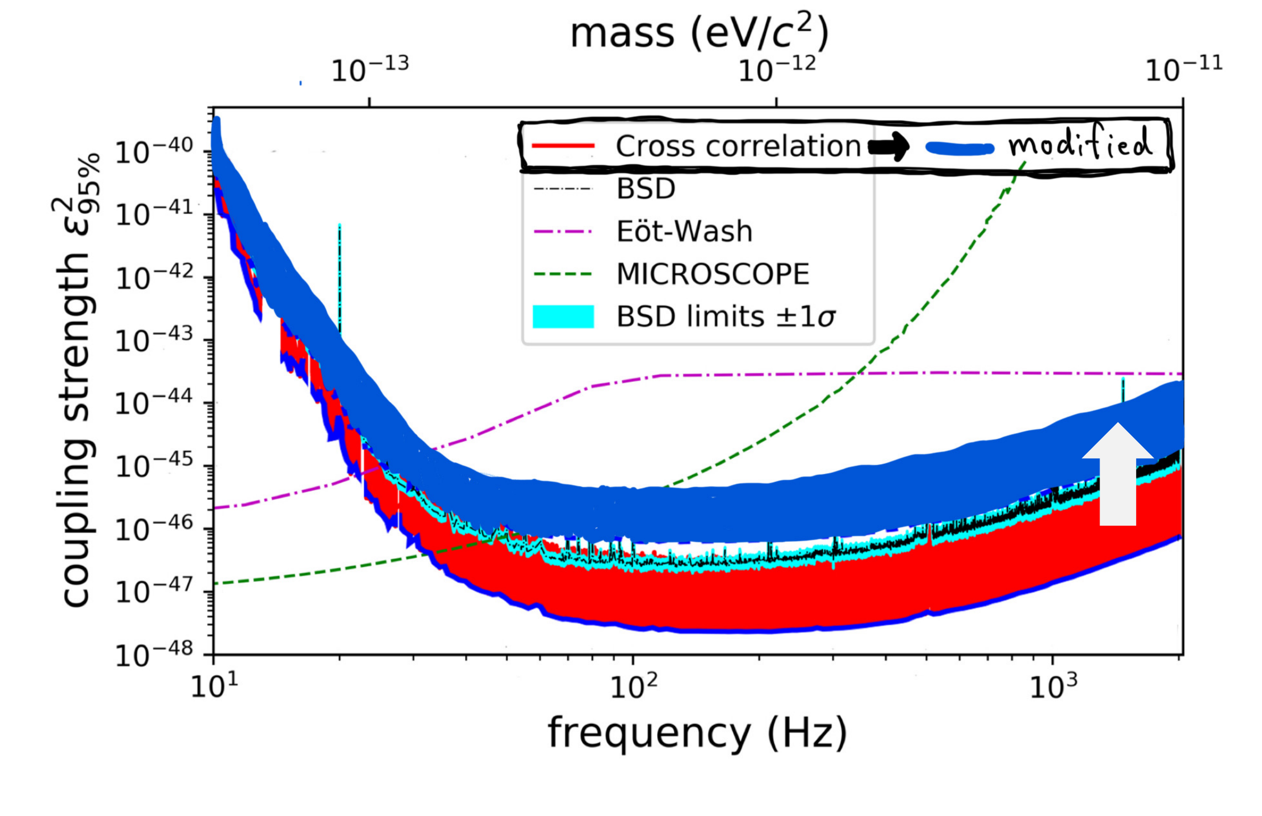
The LVK collaboration paper applies the usual gravity wave ORFs.

Modified ORF (time)

$$\Gamma_{\rm HL} = 0.031$$

We apply an ORF that accounts for finite-time light travel effects.

This figure is adopted from R. Abbott et al. (**LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration**) Phys. Rev. D 105, 063030



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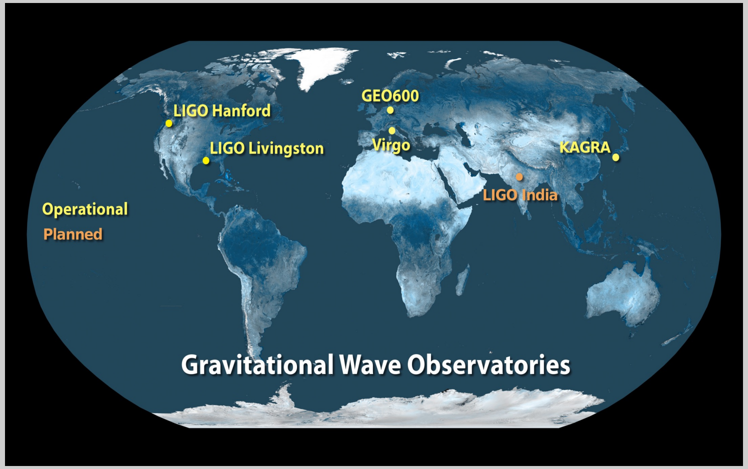

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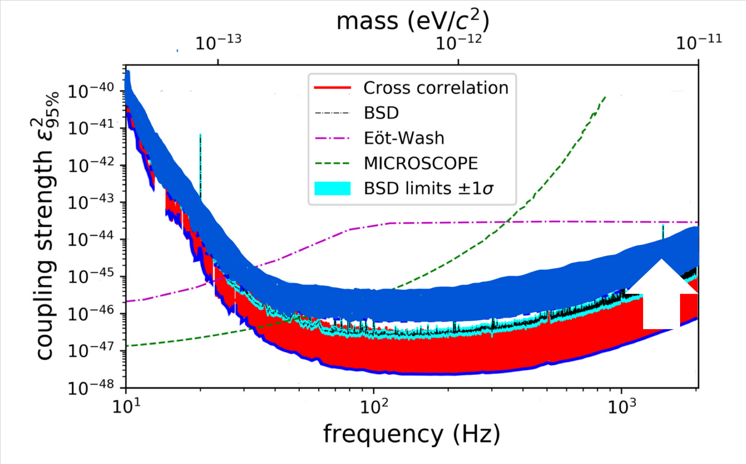

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SNR

Spin-2

$$\mathrm{SNR}_{IJ}^{\mathrm{DG}} \approx \left| \frac{2\sqrt{2}\alpha^2 f_{\mathrm{DG}} T_{\mathrm{eff}} \mathcal{A} \gamma_{IJ}}{\sqrt{S_{n,I}(\frac{m}{2\pi}) S_{n,J}(\frac{m}{2\pi})}} \right|, \tag{120}$$

Spin-1

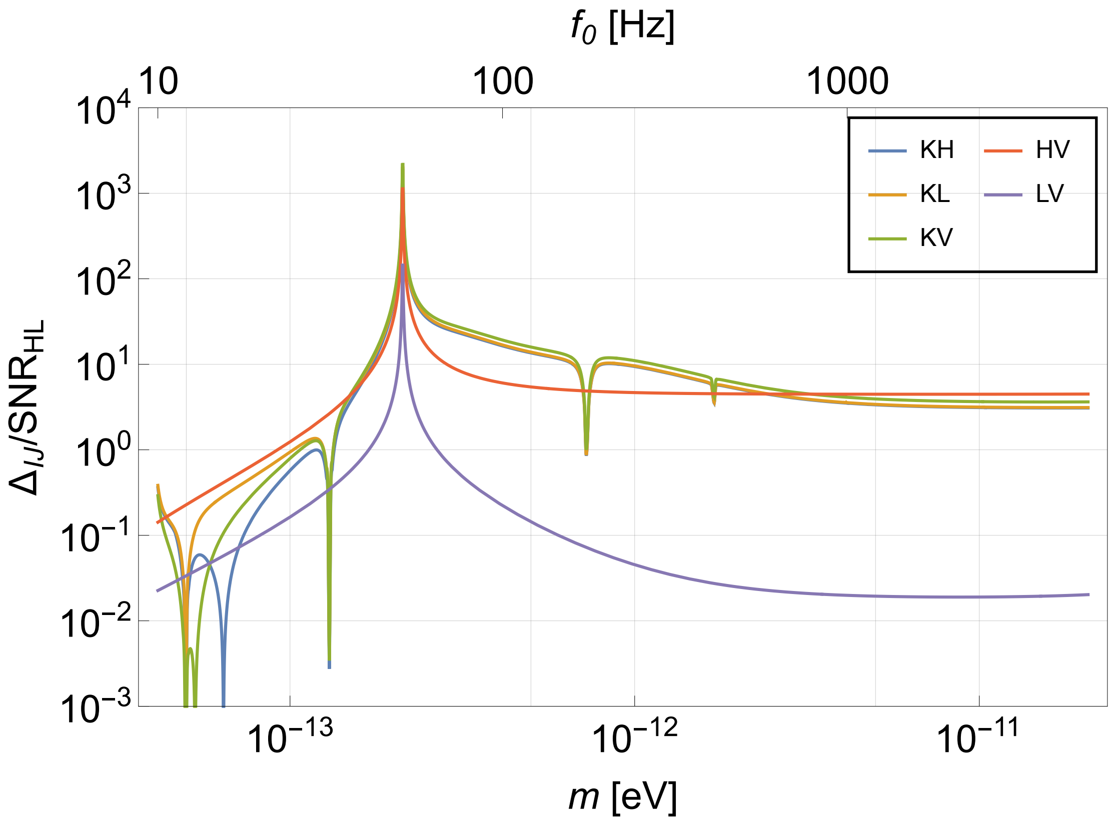
$$\mathrm{SNR}_{IJ}^{\mathrm{DP}} \approx \left| \frac{2\sqrt{2}\epsilon_D^2 f_{\mathrm{DP}} T_{\mathrm{eff}} (\mathcal{B}_{IJ}\Gamma_{IJ} + \mathcal{C}(1 + \frac{1}{3}\Omega_{\mathrm{DP}}^z)\gamma_{IJ})}{\sqrt{S_{n,I}(\frac{m}{2\pi}) S_{n,J}(\frac{m}{2\pi})}} \right|, \tag{121}$$

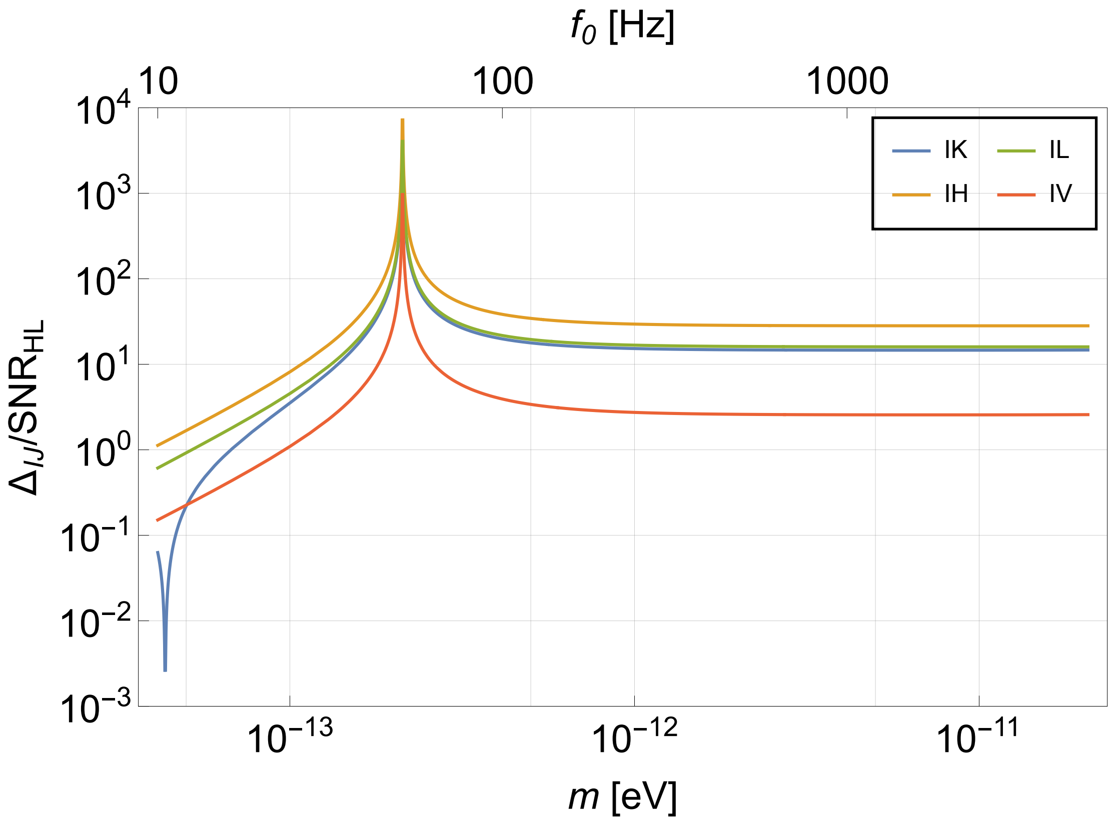
Spin-0

$$\mathrm{SNR}_{IJ}^{\mathrm{SD}} \approx \left| \frac{2\sqrt{2}\alpha_A^2 f_{\mathrm{SD}} T_{\mathrm{eff}} (\mathcal{B}'_{IJ}\Gamma_{IJ} + \mathcal{C}'\gamma_{IJ})}{\sqrt{S_{n,I}(\frac{m}{2\pi}) S_{n,J}(\frac{m}{2\pi})}} \right|. \tag{122}$$

Spin-2 and spin-1

$$\Delta_{IJ} \equiv \left|\mathrm{SNR}^{\mathrm{DG}}_{IJ} - \mathrm{SNR}^{\mathrm{DP}}_{IJ}\right| \,.$$





Spin-0 and spin-1

$$\tilde{\Delta}_{IJ} = \left|\mathrm{SNR}_{IJ}^{\mathrm{DP}} - \mathrm{SNR}_{IJ}^{\mathrm{SD}}\right| .$$