KYOTO UNIVERSITY

Cosmology from Home2023

Distinguishing Ultralight Dark Matter Spin with Gravitational Wave Detectors

Based on the ongoing work with H. Takeda, K. Aoki, T. Fujita, S. Mukohyama

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CONCEPT

Dark Matter Search with Gravitational Wave Detectors

GW detectors are devices that capture small variations in arm length with high precision. In principle, it can capture anything that changes their arm length.

Ultralight dark matter may also interact with the GW detectors and change their arm length.

So, it may leave a detectable signal in the GW detectors.

Ultralight dark matter nature

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

Boson	ULDM consists of bosonic particles because fermionic particles are not possible to be dense enough due to the Pauli blocking.
$\lambda_{\rm Com} = \frac{2\pi}{m}$	ULDM is regarded as a classical wave oscillating at Compton wavelengths.
Non-relativistic	ULDM is a non-relativistic wave because the local speed of DM is about $v \sim 10^{-3}$.
$\tau_{\rm coh} = \frac{2\pi}{mv^2}$	ULDM has a long coherent time scale. $\tau_{\rm coh} = 7700{\rm s}\left(\frac{m}{10^{-12}{\rm eV}}\right)$

ULDM signals in GW detectors

ULDM within the mass range of 10^{-13} to 10^{-11} eV can be detectable in grand-based GW detectors.

$$f_{\mathrm{Com}} = 242\ \mathrm{Hz}\left(\frac{m_{\mathrm{DM}}}{10^{-12}\mathrm{eV}}\right)$$

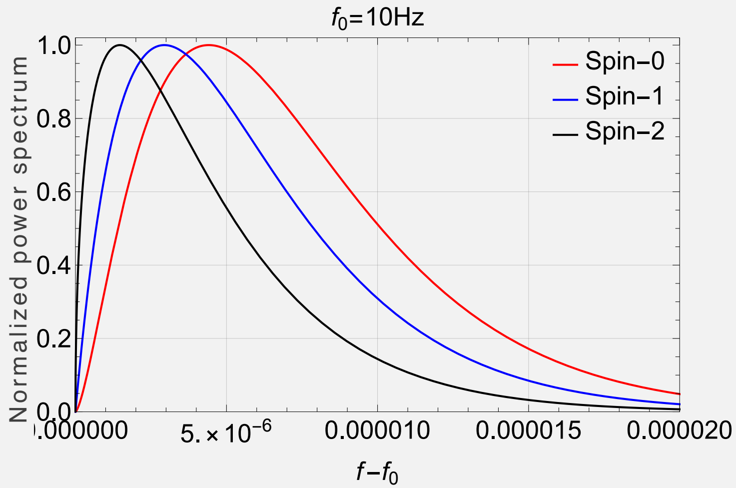
Spin-0	QCD axion, ALP, etc.	These particles leave a signal by fluctuating the fundamental constants such as fine structure constant.
Spin-1	Dark photon	They leave a signal by pushing the mirrors through the new Coulomb force.
Spin-2	Spin-2 dark matter	Since it originates from the gravity sector, it universally couples to matter fields. Thus, it leaves a signal in GW detectors like GW.

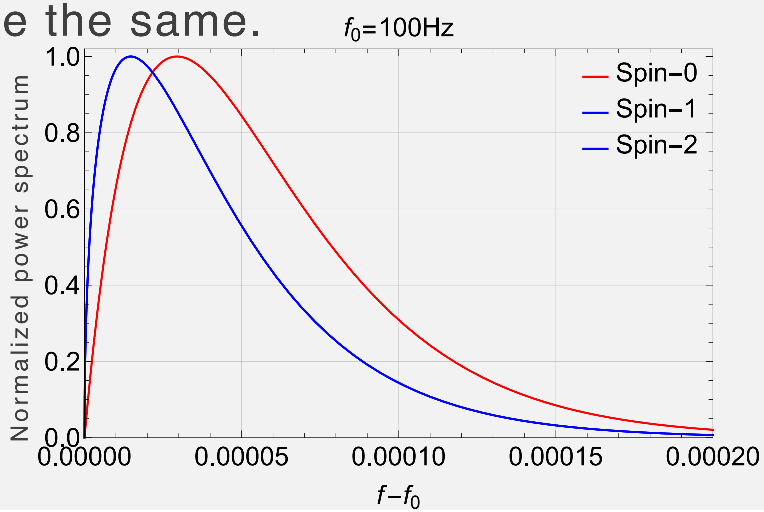
[Spin-0] - Y. V. Stadnik & V. V. Flambaum, PRL 114, 161301 (2015) - Y. V. Stadnik & V. V. Flambaum, PRA 93, 063630 (2016) - A. A. Geraci+, PRL 123, 031304 (2019) - H. Grote & Y. V. Stadnik, PRR 1, 033187 (2019) - S. Morisaki & T. Suyama, PRD 100, 123512 (2019) - C. Kennedy+, PRL 125, 201302 (2020) - 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)

Distinguishing Spin by Power Spectrum

It seems challenging to distinguish between spin-1 and spin-2 ULDM with using the power spectrum at $f \gtrsim 30\text{Hz}$.

$f \lesssim 30\text{Hz}$	$f \gtrsim 30\text{Hz}$
Spin-0, spin-1, and spin-2 ULDM give a different power spectrum.	While spin-0 and spin-1 ULDM give different power spectrums, the power spectrum of spin-1 and spin-2 ULDM are the same.





QUESTION

How can we distinguish spin-1 and spin-2 ULDM signals at $f > 30\mathrm{Hz}$?

ANSWER

They can be distinguished by using cross-correlational analysis with

multiple gravitational wave detectors.

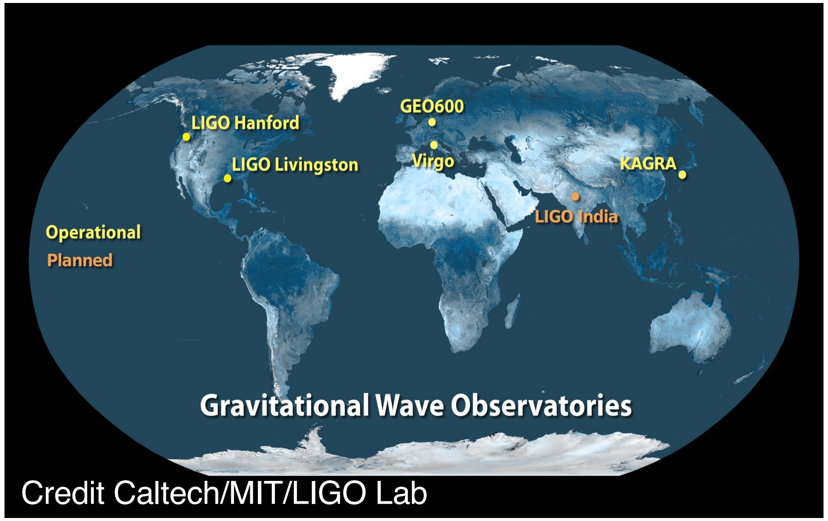
Cross-correlation

Currently, there are 5 (or more) ground-based detectors in existence, thus 10 (or more) combinations of cross-correlations can be considered.

Cross-correlational signal

$$S_{ab} \equiv \int_{-T_{\rm obs}/2}^{T_{\rm obs}/2} dt \int_{-T_{\rm obs}/2}^{T_{\rm obs}/2} dt' s_a(t) s_b(t') Q(t-t')$$

$s_a(t)$: output
$Q(t-t')$: filter function
$T_{\rm obs}$: observational time
a, b represent detectors.



Difference in Overlap Reduction Function by ULDM Spin

The Overlap Reduction Function (ORF) is a quantity that represents the dependency of the Signal-to-Noise Ratio (SNR) on the position and direction of two detectors.

$$\mathrm{SNR}_{ab} \equiv \frac{\mu[S_{ab}]}{\sigma[S_{ab}]} = \frac{2\alpha^2 \mathcal{A}\sqrt{\tau_{\mathrm{coh}} T_{\mathrm{obs}}}}{\sqrt{S_{n,a} S_{n,b}}} \times \gamma_{ab}(\beta, \delta, \Delta)$$

γ_{ab} : ORF

α : Coupling constant

$\mathcal{A}$: Dimensionless constant

T_{obs} : Observational time

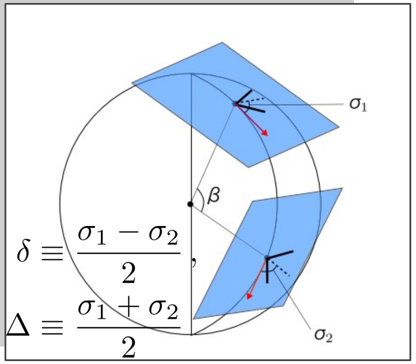
τ_{coh} : Coherent time

$S_{n,a}$: Noise power spectrum

The ORF for spin-1 and spin-2 ULDM have different dependencies on the detector's position and angle. These difference arises from the **finite time light traveling effect** in spin-1 ULDM signal.

$$\gamma_{ab}(\beta, \delta, \Delta) = \begin{cases} \cos^2\left(\frac{\beta}{2}\right)\cos(2\delta) - \sin^2\left(\frac{\beta}{2}\right)\cos(2\Delta) & \text{(spin-1)} \\ \cos^4\left(\frac{\beta}{2}\right)\cos(4\delta) - \sin^4\left(\frac{\beta}{2}\right)\cos(4\Delta) & \text{(spin-2)} \end{cases}$$

The figure is adopted from Nishizawa et al., Phys.Rev.D 79:082002 (2009)

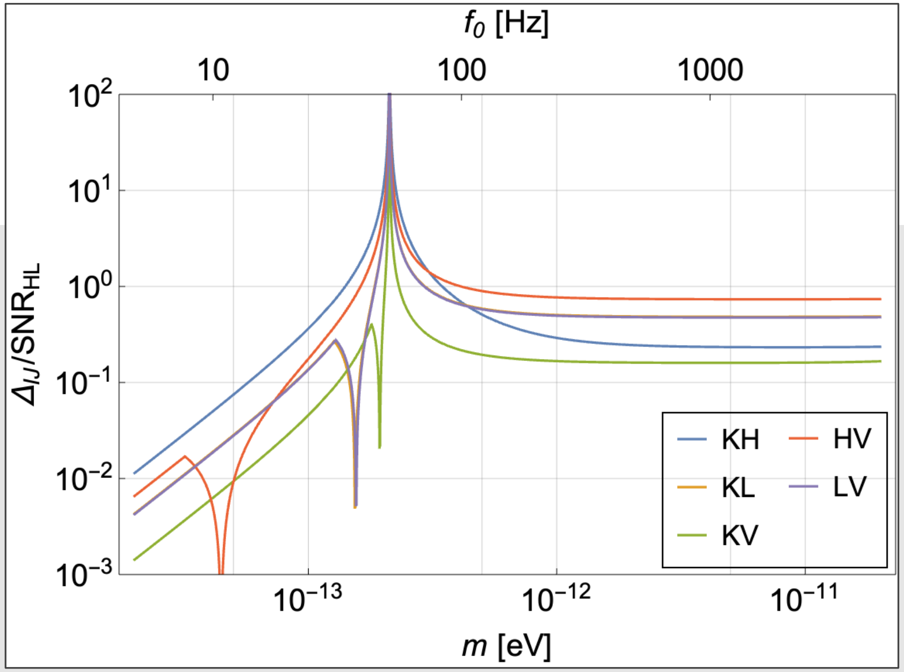


Thanks to the difference in ORF, the cross-correlational analysis can identify the signal as spin-1 or spin-2.

Spin Distinguishability with ORF

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 frequency

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

High frequency

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

Byproduct

The current constraint of the coupling constant for spin-1 ULDM ($U(1)_{B-L}$ gauge boson) is reduced by about 2 orders of magnitude.

Usual ORF

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

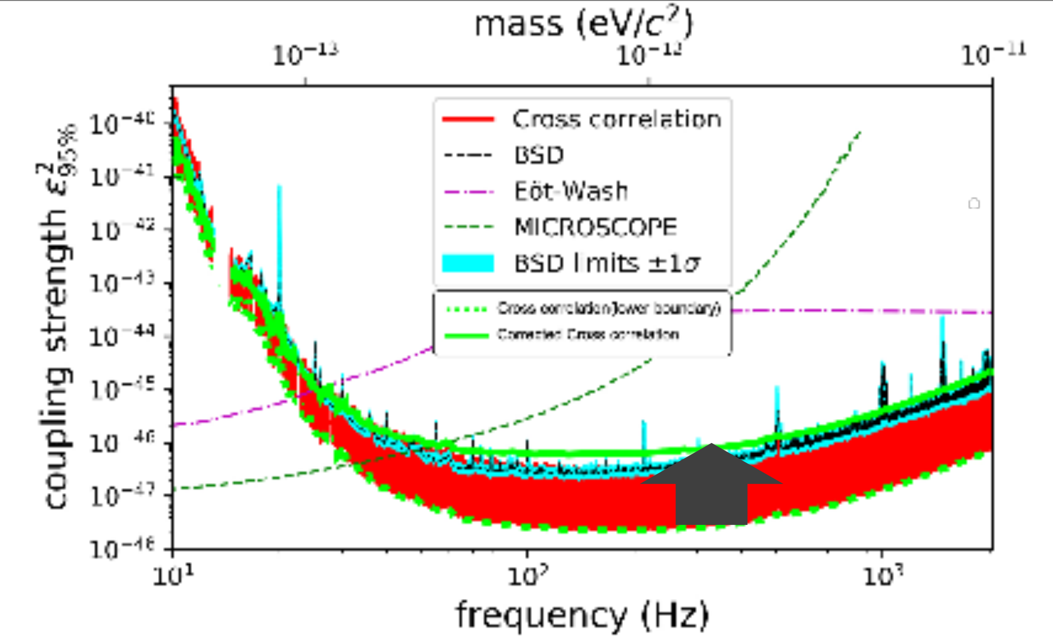
The LVK collaboration paper applies the usual gravity wave ORFs.

Modified ORF

$$\gamma_{\mathrm{HL}} = 0.031$$

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

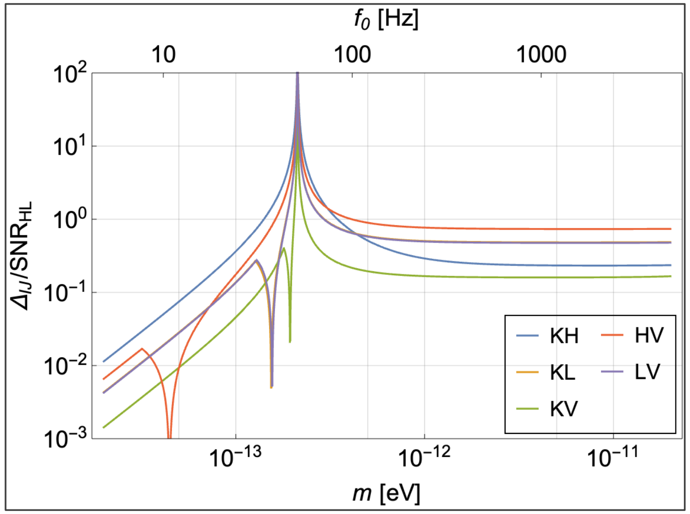
This figure is adopted from R. Abbott et al. (**LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration**) Phys. Rev. D 105, 063030

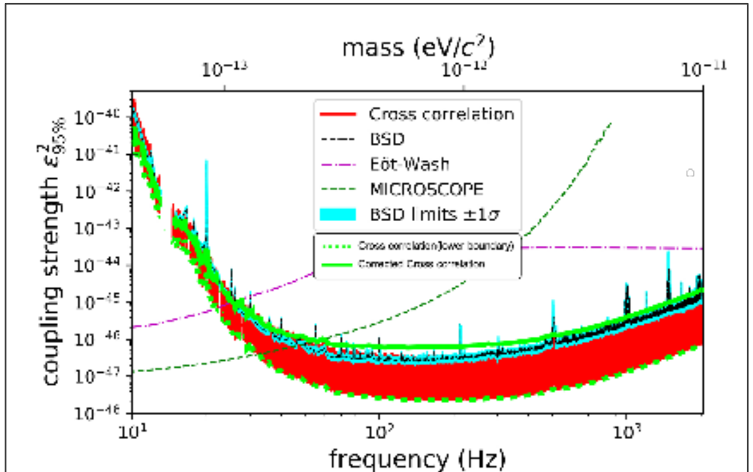


Summary and outlook

We have considered a method to distinguish the spin of ULDM signal in the GW detectors.

- Multiple detectors may be able to distinguish spin-1 from spin-2 by differences in ORF at f>30 Hz.
- We also found that the constraint of the spin-1 ULDM (dark photon) by the LVK collaboration should be relaxed.





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