16th Patras Workshop on Axions, WIMPs and WISPs

Ultralight vector dark matter search using KAGRA

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on behalf of the KAGRA collaboration

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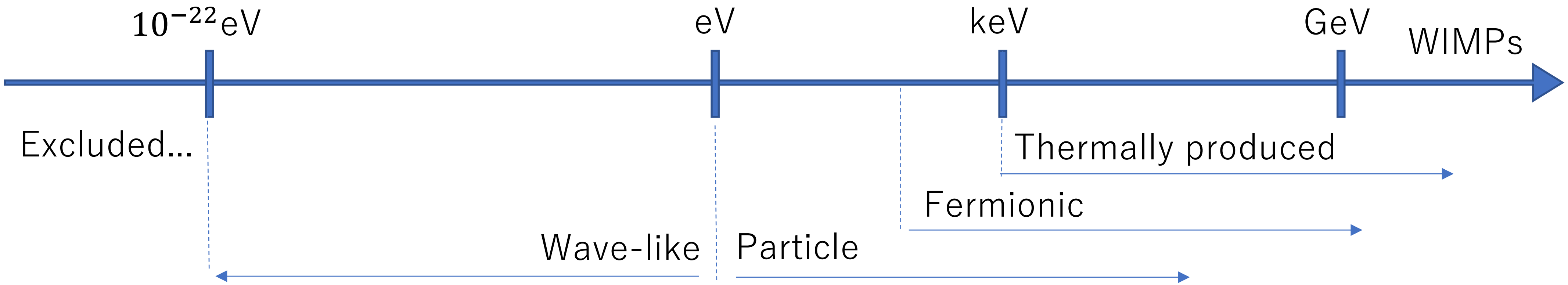
A. Nishizawa(U. Tokyo, RESCEU) and I. Obata(MPI)

Contents

Ultralight vector DM and GW interferometer

- Ultralight vector DM

Vast discovery space for the DM: 10^{-22}eV ~10^{67}eV 90 orders of magnitude!!



If non-thermally produced, $m_{DM} \lesssim$ eV is allowed for bosonic field!!

→**Ultralight vector DM** is well-motivated:

ex.) $U_B(1)$, $U_{B-L}(1)$ gauge boson

Ultralight vector DM and GW interferometer

- Ultralight vector DM

ex.) $D = B, B - L$

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_A^2 A^\mu A_\mu - \epsilon_D e J_D^\mu A_\mu$$

From equivalence principle tests
Coupling to SM: $\epsilon_D \lesssim 10^{-23}$

(S. Schlamminger et al. 2008, T. A. Wagner et al. 2009)

Ultralight → "classical wave" oscillating with $\omega \simeq m_A(1 + v^2/2)$.

$\vec{A} = \vec{A}_0 \cos[\omega t - \vec{k}\cdot\vec{x}]$ with $v_{\mathrm{DM}}^{\mathrm{local}} \approx 10^{-3}$, $k = m_A v \ll \omega$

→electric wave-like

Extremely sensitive measurement is required…

Ultralight vector DM and GW interferometer

- Ultralight vector DM

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Extremely sensitive measurement is required...

For $m_{DM} \sim 10^{-14}$~10^{-11} eV, **GW interferometer** is a good probe!!

Ultralight vector DM and GW interferometer

- DM search with GW interferometer

"Electric" DM wave acts on test masses:

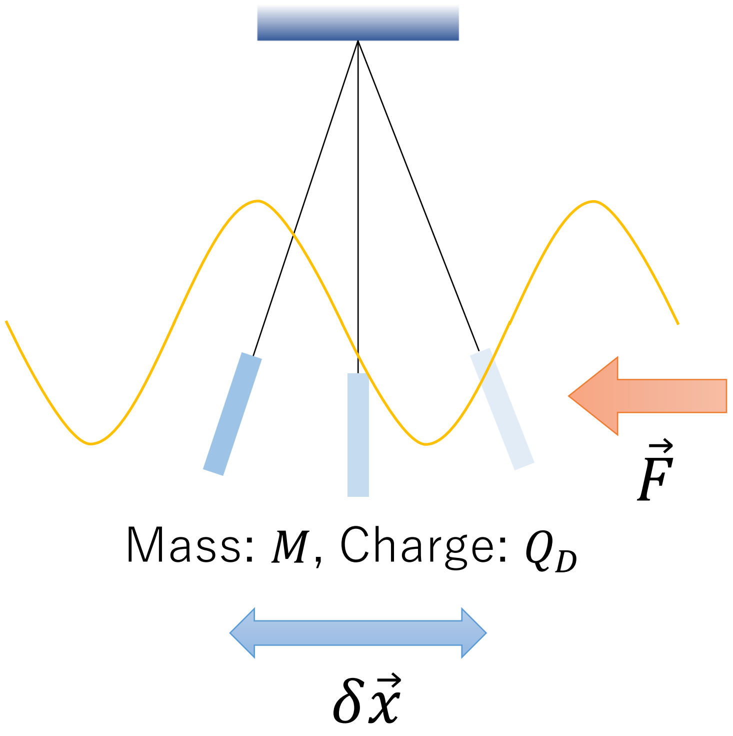
$$\vec{F} = -\epsilon_D e Q_D \dot{\vec{A}}$$

Displacement of the mirror:

$$\delta\vec{x} \sim -\frac{\epsilon_D e Q_D}{m_A M}\vec{A}_0 \sin[\omega t - \vec{k}\cdot\vec{x}]$$

The effect of the vector field can be read off!!

→ No detection = constraint on the coupling



Ultralight vector DM and GW interferometer

- DM search with GW interferometer

LIGO and Virgo O3 data has been analyzed.

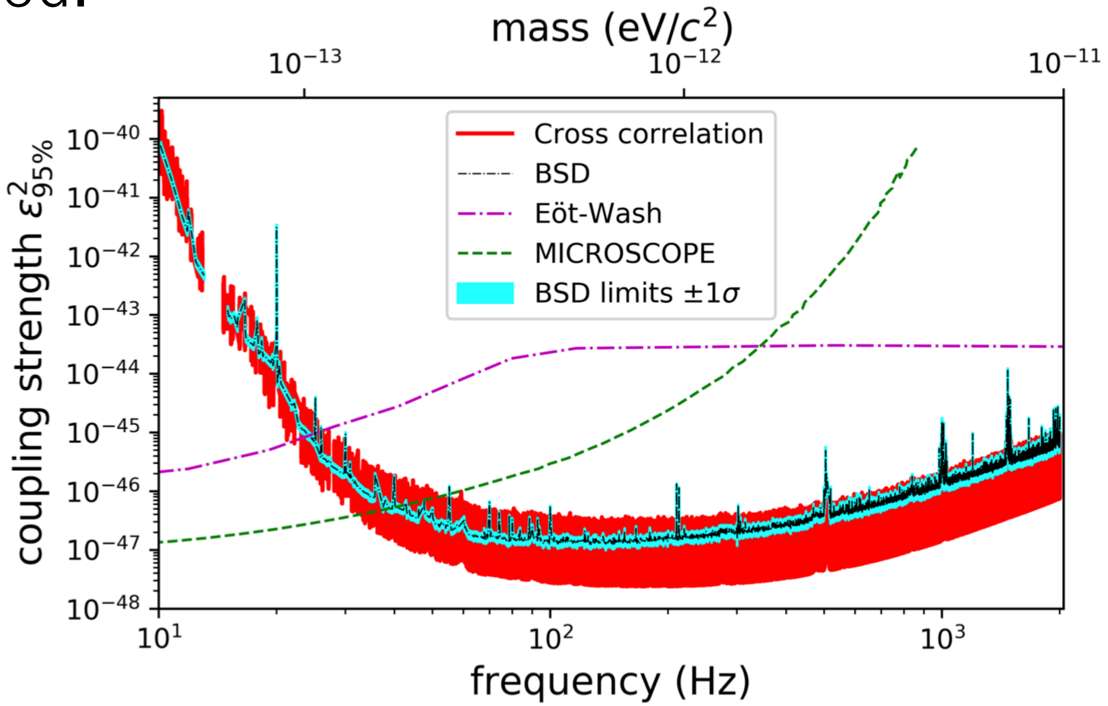
$U_B(1)$ model:

For $m_A \sim 10^{-12} \sim 10^{-11}$ eV,

largely surpass existing limit!!

GW interferometer can be

the best detector for Ultralight DM!!



LVK Collaboration, arXiv:2105.13085

Ultralight vector DM and GW interferometer

- DM search with GW interferometer

LIGO and Virgo O3 data has been analyzed!!

$U_B(1)$ …

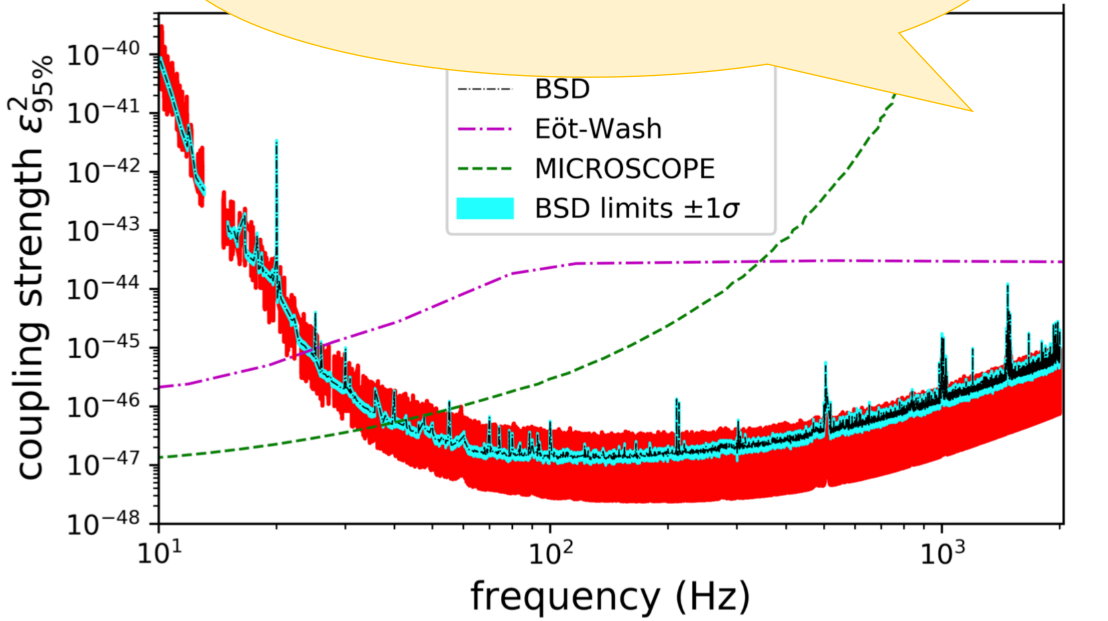
F…

largely surpass existing limit!!

Why KAGRA…??

GW interferometer can be
the best detector for Ultralight DM!!

LIGO's sensitivity is best.



LVK Collaboration, arXiv:2105.13085

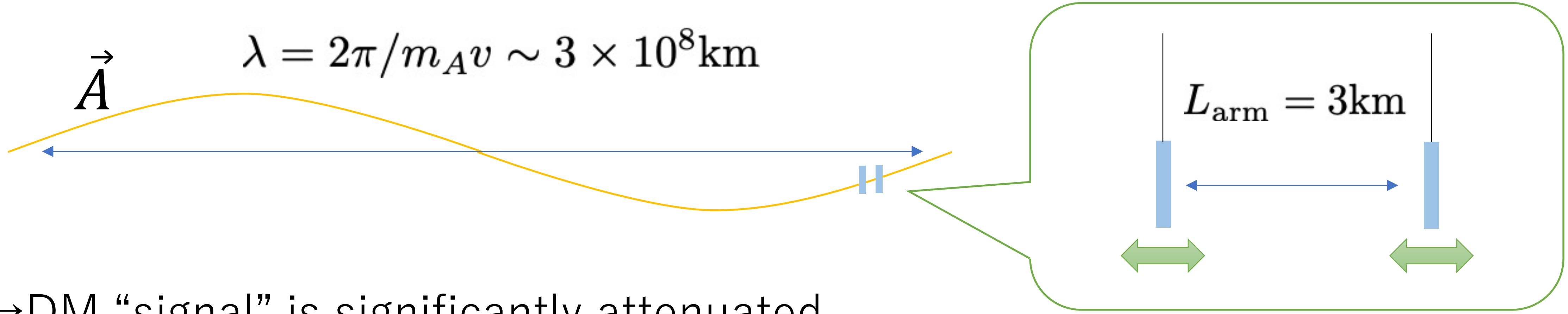
Contents

KAGRA and its auxiliary channels

- Difficulty in Ultralight DM search

GW interferometers → sensitive to the differential motion of the arms

But DM wave almost commonly affects the test mass...



→DM "signal" is significantly attenuated...

To enhance the signal, we need asymmetric response!!

KAGRA and its auxiliary channels

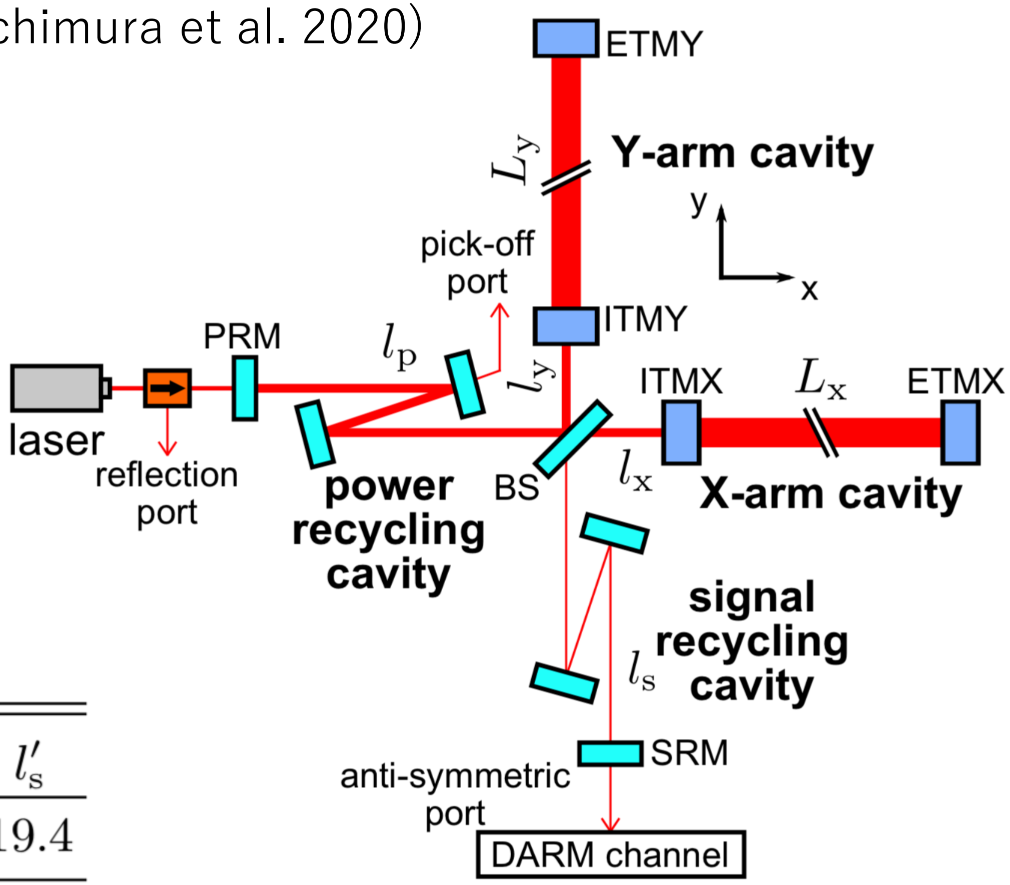
- Advantage of KAGRA in DM search (Y. Michimura et al. 2020)

Auxiliary channels:

$$\delta L_{\mathrm{MICH}} = \delta(l_x - l_y)$$

$$\delta L_{\mathrm{PRCL}} = \delta[(l_x + l_y)/2 + l_p]$$

$$\delta L_{\mathrm{SRCL}} = \delta[(l_x + l_y)/2 + l_s]$$



$$\delta L_{\mathrm{DARM}} = \delta(L_x - L_y)$$

	L_{arm}	l_{x}	l_{y}	l_{p}	l_{s}	l'_{p}	l'_{s}
KAGRA	3000	26.7	23.3	66.6	66.6	19.5	19.4

KAGRA and its auxiliary channels

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Auxiliary channels:

$\delta x \propto Q_D/M$

$$\delta L_{\mathrm{MICH}} = \delta(l_x - l_y)$$

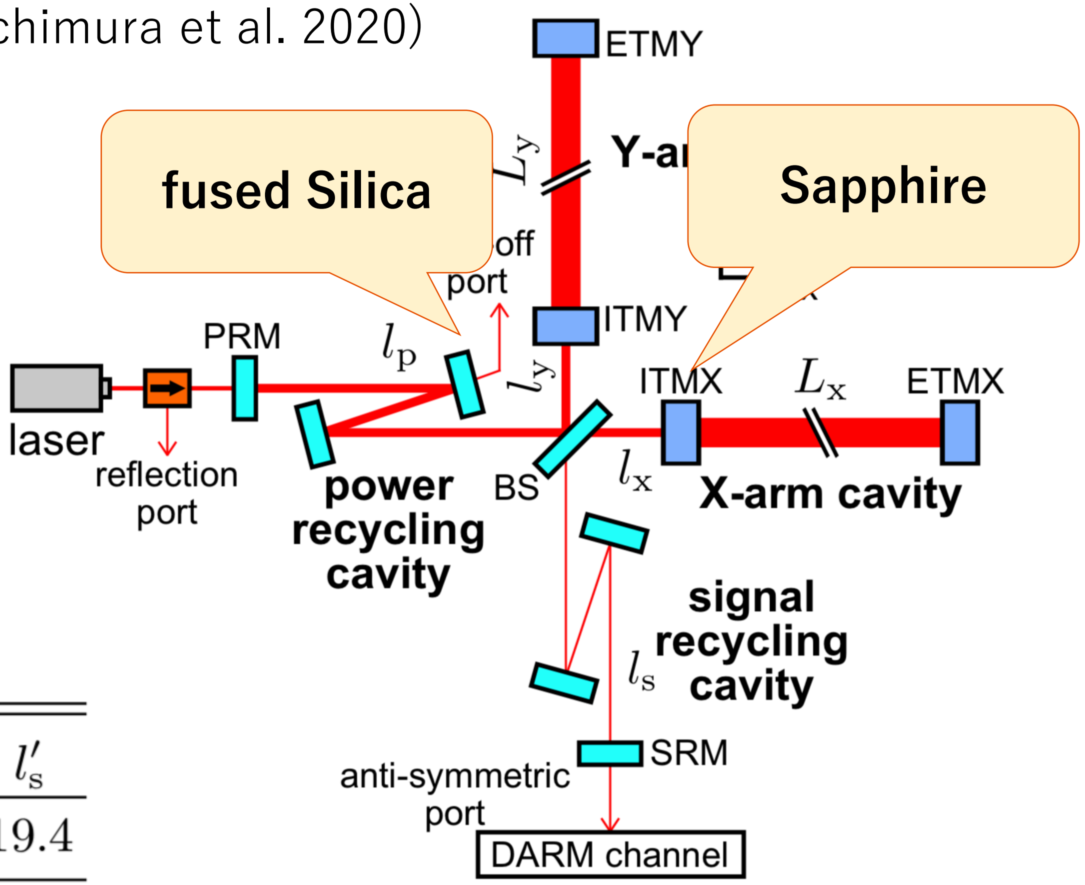
$$\delta L_{\mathrm{PRCL}} = \delta[(l_x + l_y)/2 + l_p]$$

$$\delta L_{\mathrm{SRCL}} = \delta[(l_x + l_y)/2 + l_s]$$

Due to the **charge difference**,

displacement becomes asymmetric!!

	L_{arm}	l_{x}	l_{y}	l_{p}	l_{s}	l'_{p}	l'_{s}
KAGRA	3000	26.7	23.3	66.6	66.6	19.5	19.4

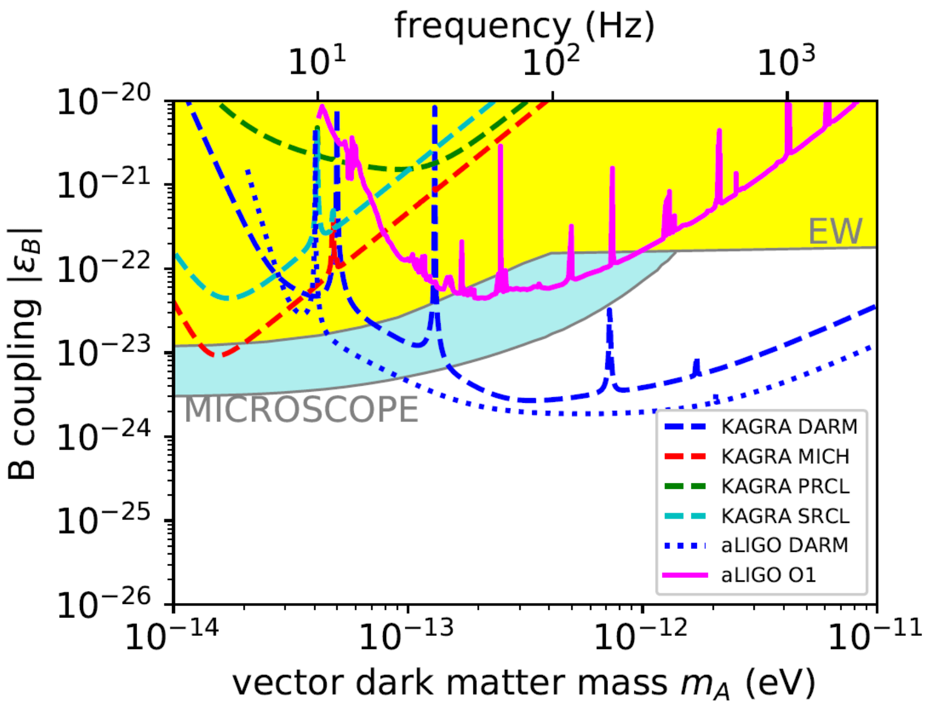


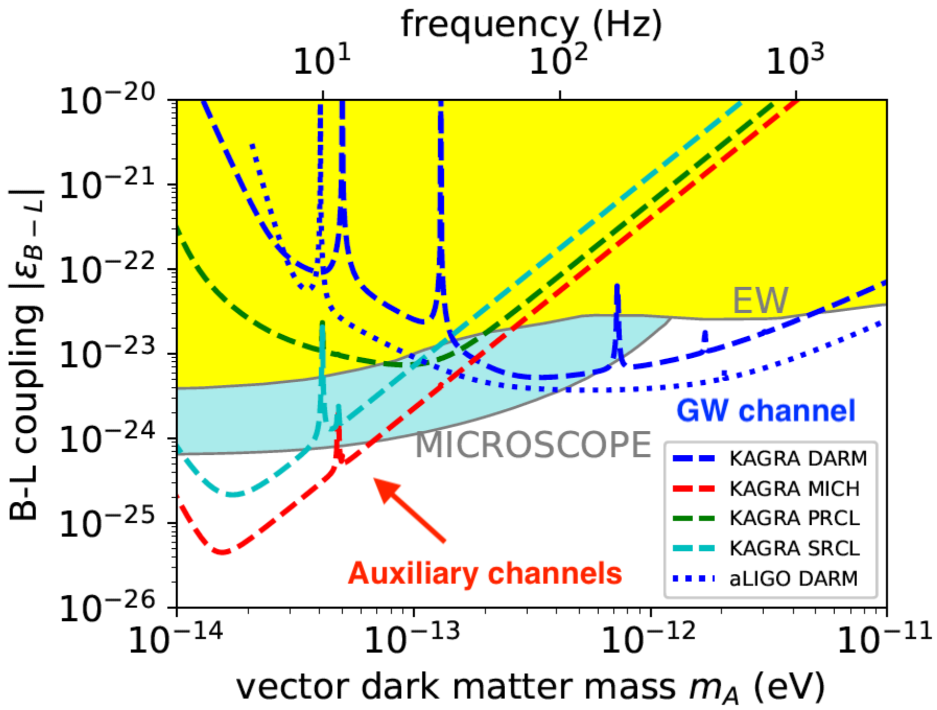
$$\delta L_{\mathrm{DARM}} = \delta(L_x - L_y)$$

KAGRA and its auxiliary channels

- Advantage of KAGRA in DM search (Y. Michimura et al. 2020)

For $U_{B-L}(1)$ model, **KAGRA reaches the unexplored region!!**





KAGRA and its

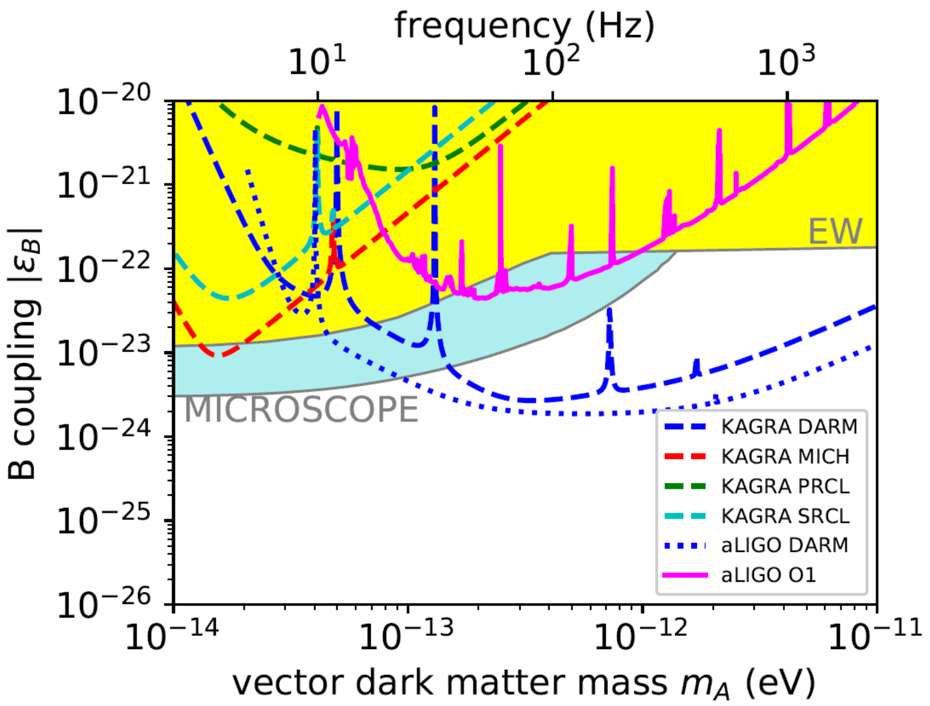
- Advantage of KAGRA

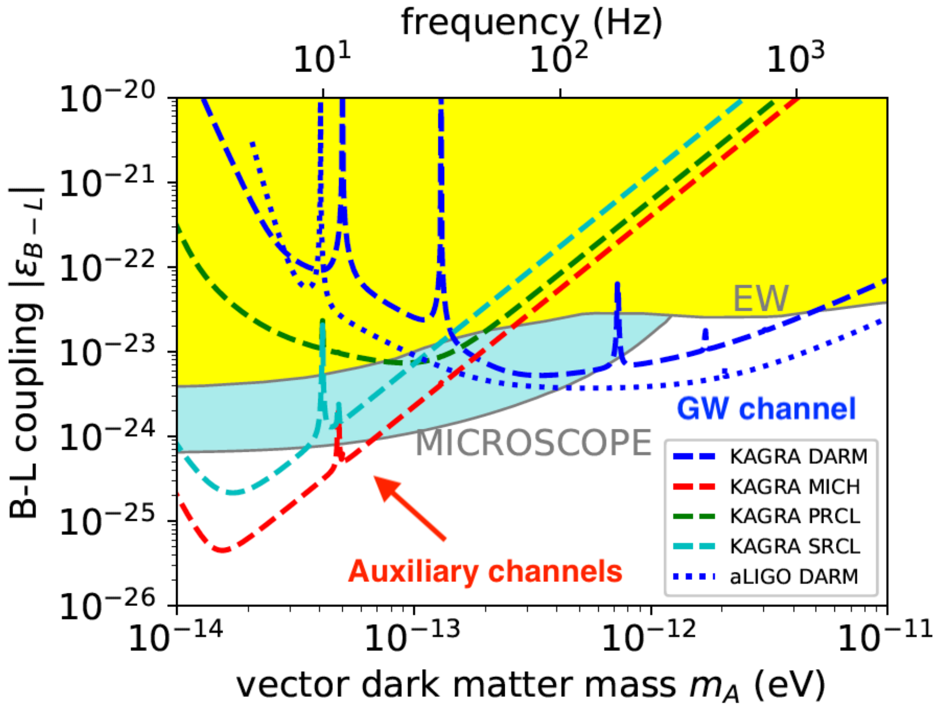
For $U_{B-L}(1)$ model, **KA**

$$\frac{Q_B}{M} \approx \frac{N_B}{N_B m_n} = \frac{1}{m_n} \quad \rightarrow 10^{-5} \text{ difference...}$$

$$\frac{Q_B - Q_L}{M} \approx \frac{N_B - N_L}{N_B} \frac{1}{m_n} \quad \rightarrow$$

Silica: 0.501
Sapphire: 0.51





Contents

Detection pipeline

- Signal properties

"DM wave" → superposition of waves with various momentum

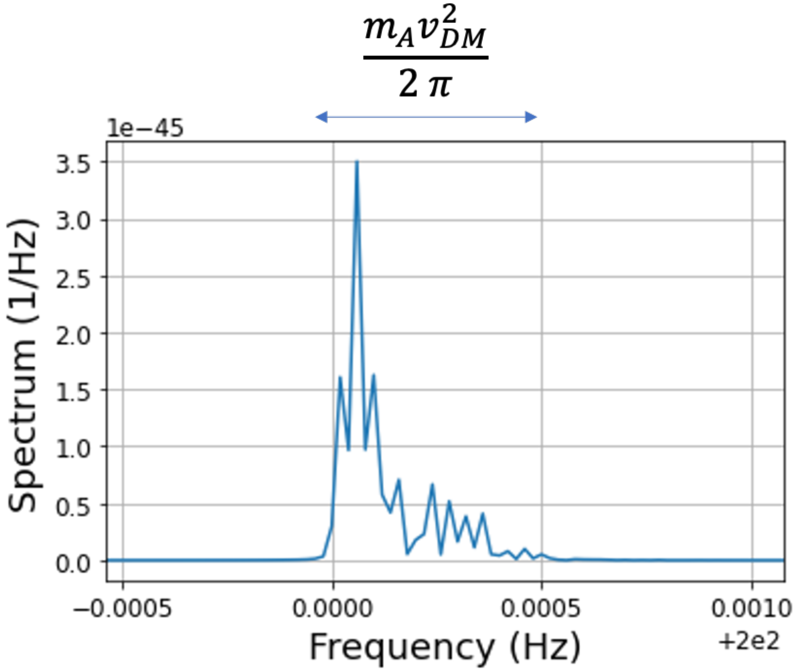
$$\vec{A} = \sum_i A_i \vec{e}_i \cos[m_A(1 + v_i^2/2)t - m_A \vec{v}_i \cdot \vec{x} + \phi_i]$$

$v_i \sim v_{\mathrm{DM}}^{\mathrm{local}} \sim 10^{-3}$ (※Standard Halo model is assumed)

Sharp spectrum with

$f \sim m_A/2\pi$ and $\Delta f \sim f {v^2}_{DM} \sim 10^{-6} f$

→DM signal is localized.



Spectrum of DM signal

Detection pipeline

- Signal properties

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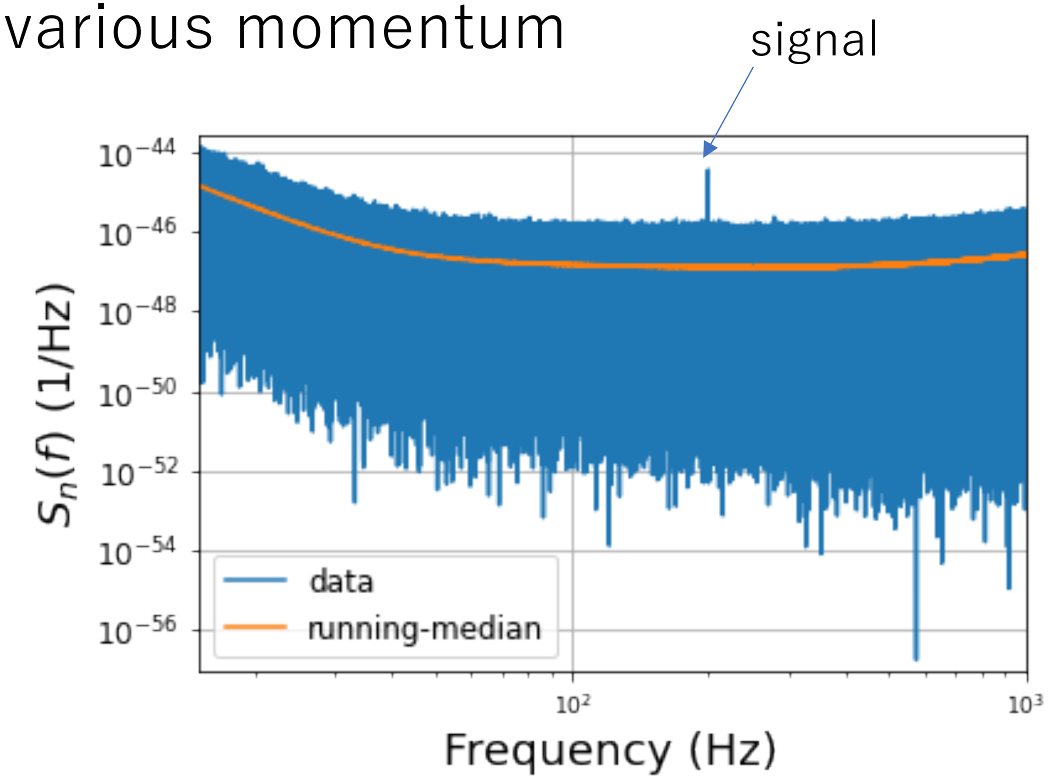


Spectrum of mock data

Detection pipeline

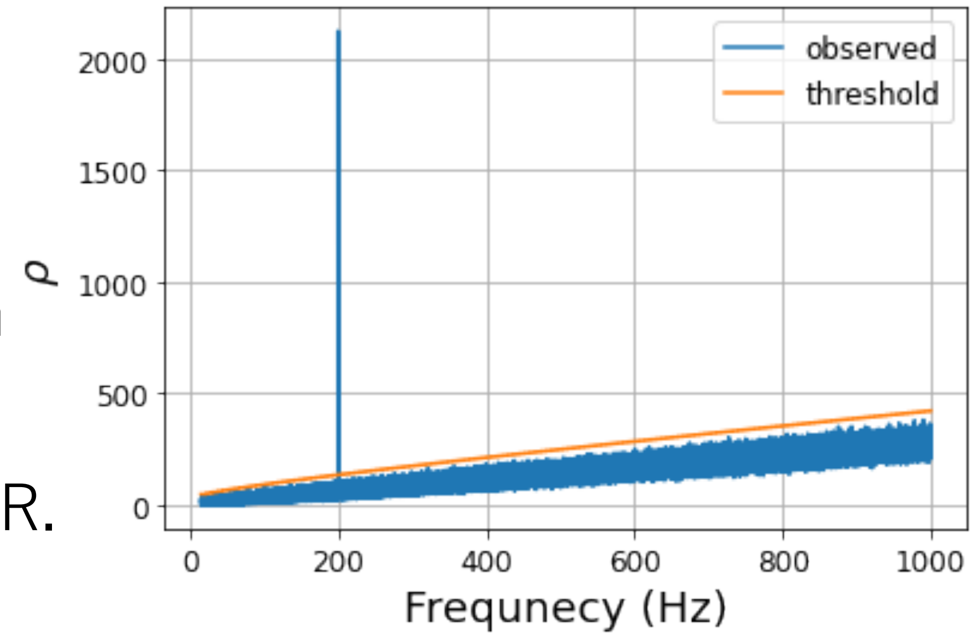
- Search Method

κ: $O(1)$ const.

Collect the spectra at the frequency bins: $m_A \leq 2\pi f_k \leq m_A(1+\kappa v_{DM}^2)$

$\rightarrow$ Detection statistic: $\rho = \sum \frac{4|\tilde{d}(f_k)|^2}{T_{\rm obs} S_n(f_k)}$

S_n: Power Spectrum Density
T_{obs}: Observational time



For Gaussian noise, ρ obeys χ_{2n}^2 distribution when there is no signal. (n: number of the bins)

$100(1-\alpha)\%$ upper limit of $\chi_{2n}^2 \rightarrow 100\alpha\%$ FAR.

Detection pipeline

- Search Method

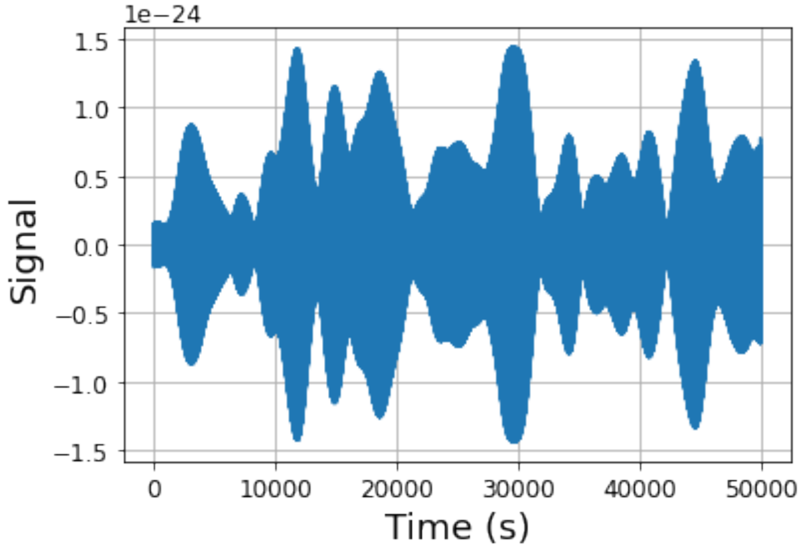
From the SNR ρ, 95% upper limit of the "coupling" is obtained as

$$\int_{\rho_{obs}}^{\infty} p(\rho|\epsilon_D^{95\%})d\rho = 0.95.$$

(When signal is present, ρ obeys non-central χ^2_{2n})

But we should care stochastic nature of DM.

(See G. P. Centers et al. 2020)



Detection pipeline

- Search Method

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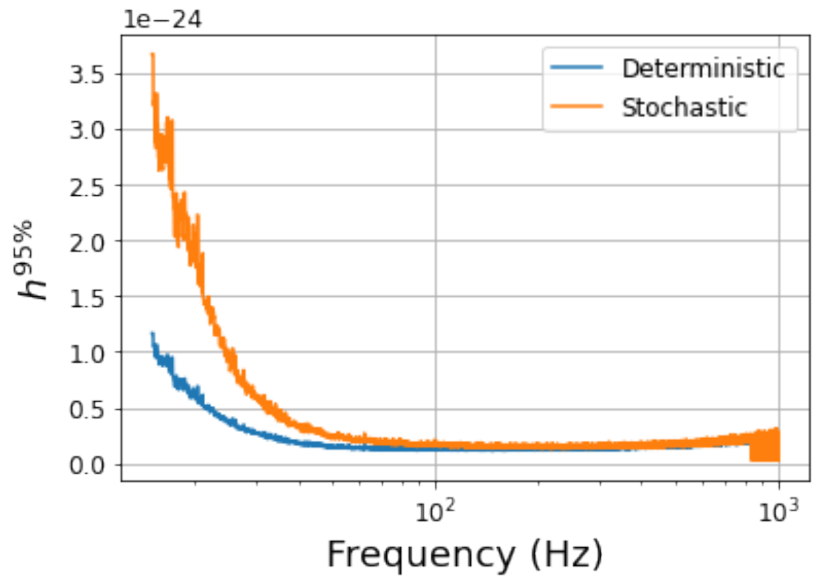
→In our pipeline, random amplitude of the wave is taken into account.

(H Nakatsuka et al. in prep)



95% upper limit of the amplitude

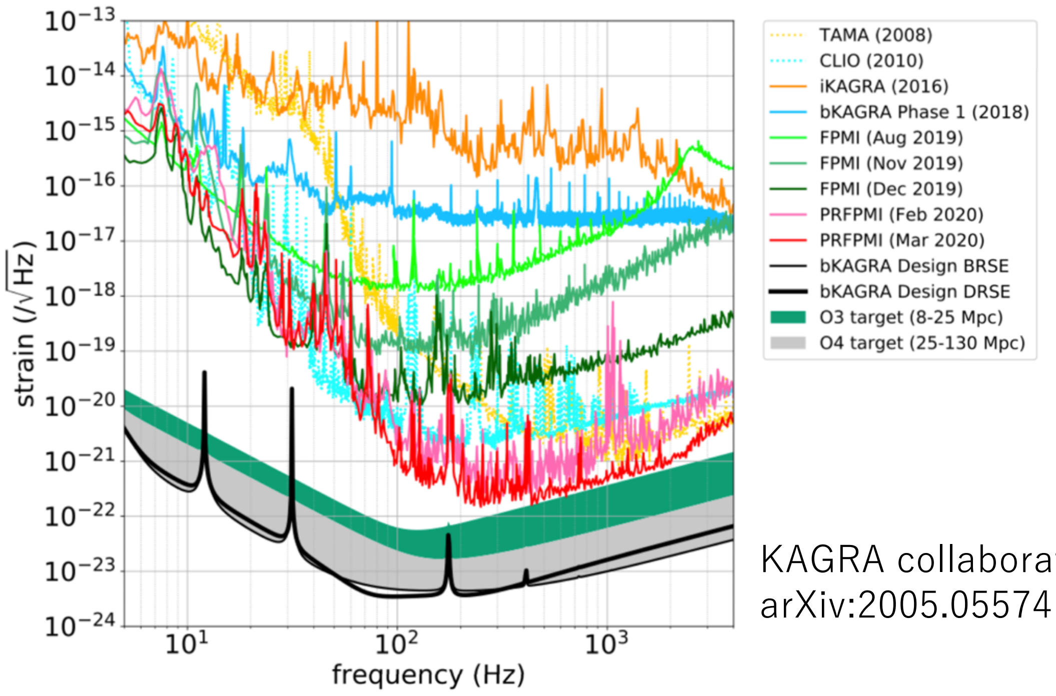
Detection pipeline

- Towards the analysis of KAGRA data

KAGRA performed a joint observing run with GEO600 in April 2020.
(referred as **O3GK**)

While the SNR $\propto T_{obs}^{1/4}$,
the observation was performed
for two weeks. not so long... 😢
(※ 1yr assumed in Y. Michimura et al. 2020)

Sufficient sensitivity of DM search
is not expected with the latest data...



KAGRA collaboration
arXiv:2005.05574

Detection pipeline

- Towards the analysis of KAGRA data

GW interferometer suffers from various noise sources.

→Line noise mimics the “signals”.

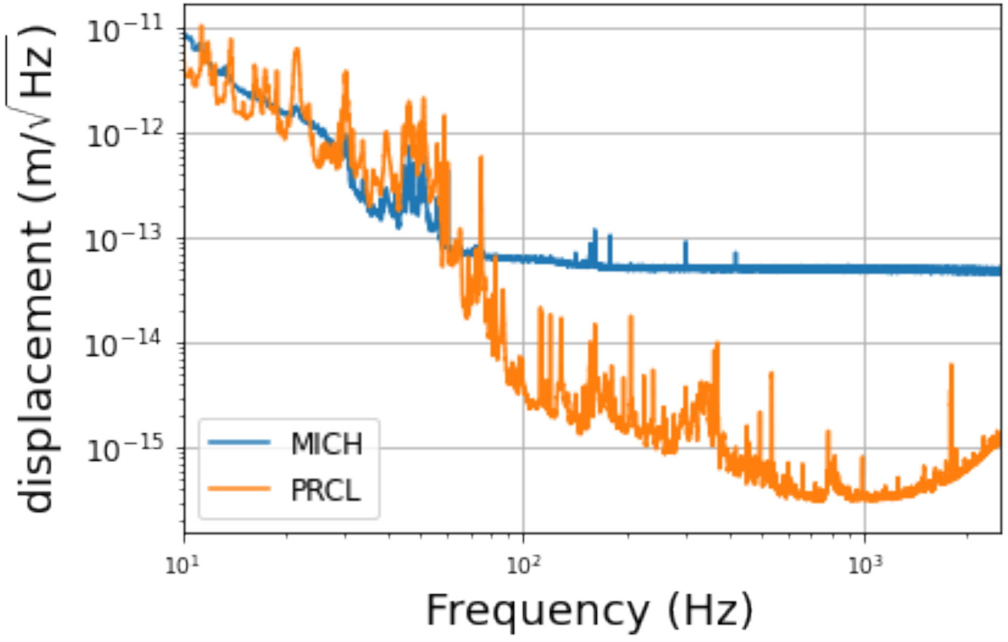
Such false signals needs to be systematically distinguished.

Veto procedure:

✓Sharpness of the spectrum

✓Coincidence btw several segments

estimated sensitivity



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- ➢Ultralight dark matter and GW interferometer
- ➢KAGRA and its auxiliary channels
- ➢Detection pipeline in KAGRA
- ➢Summary

Summary

- **GW interferometer** can probe the coupling between SM particles and the **Ultralight vector DM**.
- **KAGRA** probes unexplored discovery space of *e.g.* $U_{B-L}(1)$ gauge boson by making use of its **auxiliary monitor**.
- Pipeline construction is ongoing. Veto process and the formulation considering the **stochasticity** is now being developed.