Workshop on Very Light Dark Matter 2021

Ultralight Vector Dark Matter search with KAGRA

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on behalf of the KAGRA collaboration

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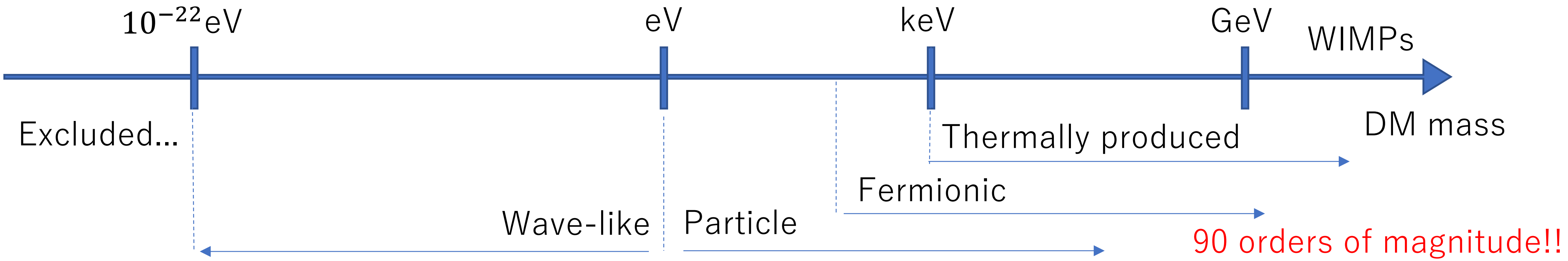
A. Nishizawa(U. Tokyo, RESCEU) and I. Obata(MPI)

Contents

Ultralight Vector DM and GW interferometer

- Ultralight Vector DM



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

axions, axion-like particles, dilatons,...

→**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 $v_{\rm DM}^{\rm local} \approx 10^{-3}$, $k = m_A v \ll \omega$

→electric wave-like

Extremely sensitive measurement is required...

Ultralight Vector DM and GW interferometer

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→electric wave-like

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:

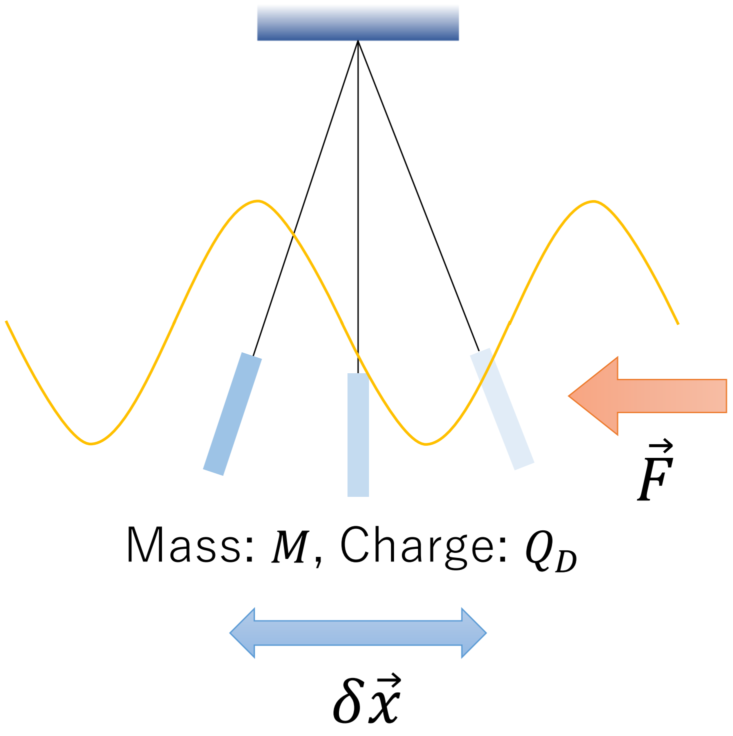
$$\vec{F} = -\epsilon_D e Q_D \dot{\vec{A}}$$

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 & Virgo O3 data has been analyzed. (→Andrew's talk)

$U_B(1)$ model:

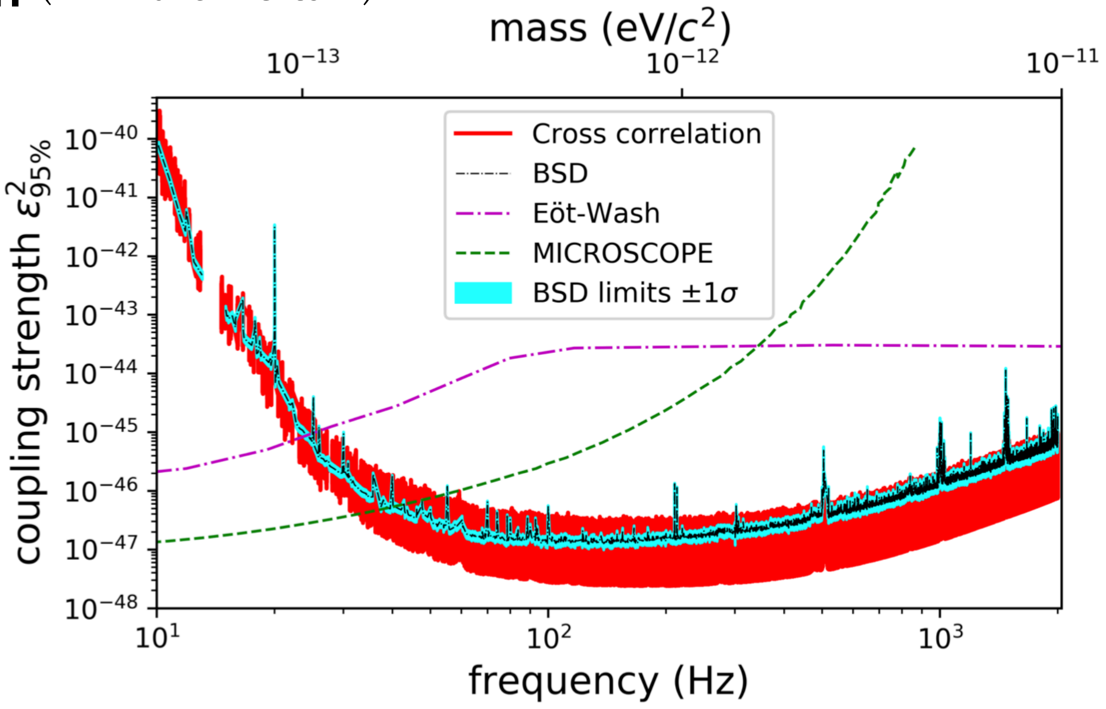
For $m_A \sim 10^{-12} \sim 10^{-11}$ eV,

largely surpass existing limit!!

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

(→Sander's talk for the dilatonic(scalar) ULDM)

Ref. arXiv:2103.03783



LVK Collaboration, arXiv:2105.13085

Ultralight Vector DM and GW interferometer

- DM search with GW interferometer

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$U_B(1)$

F

Why KAGRA...??

largely surpass existing limit!!

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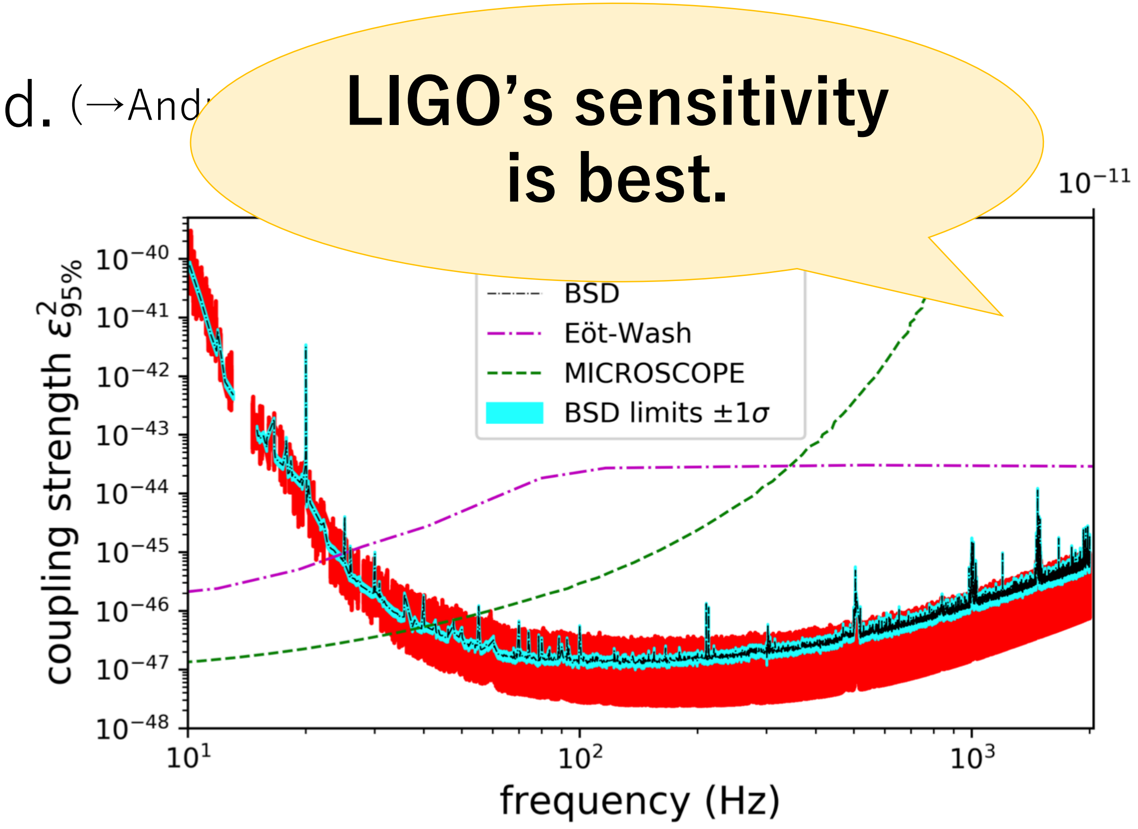

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Contents

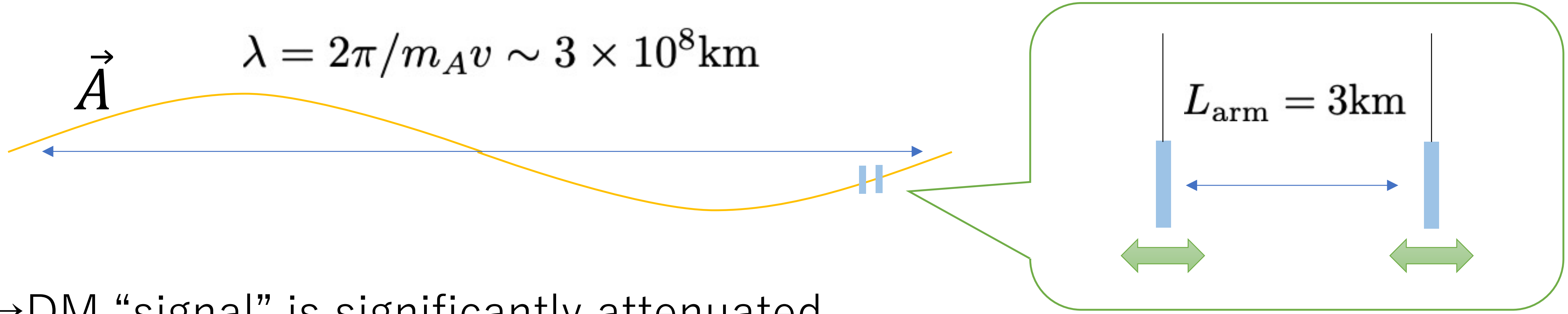
- ➢Ultralight Vector DM and GW interferometer
- ➢KAGRA and its auxiliary channels
- ➢Detection pipeline
- ➢Summary

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

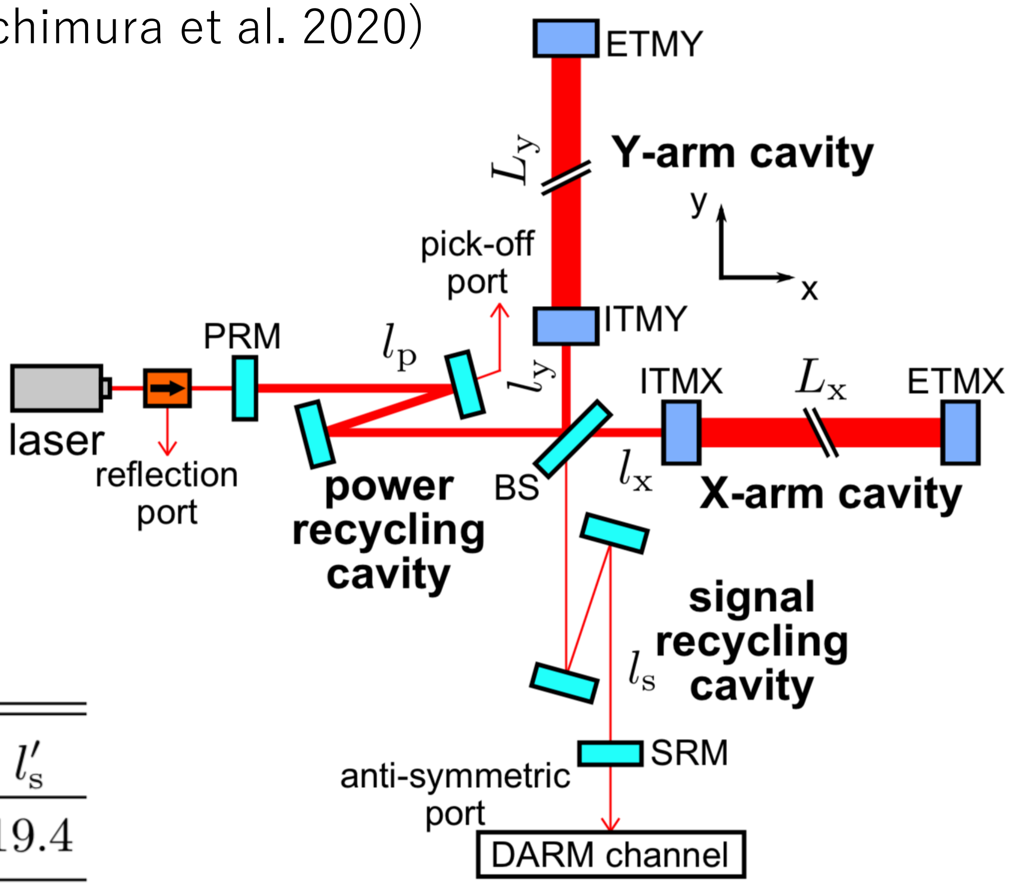
- Advantage of KAGRA in DM search (Y. Michimura et al. 2020)

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

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$\delta x \propto Q_D / M$

Due to the **charge difference**,

displacement becomes asymmetric!!

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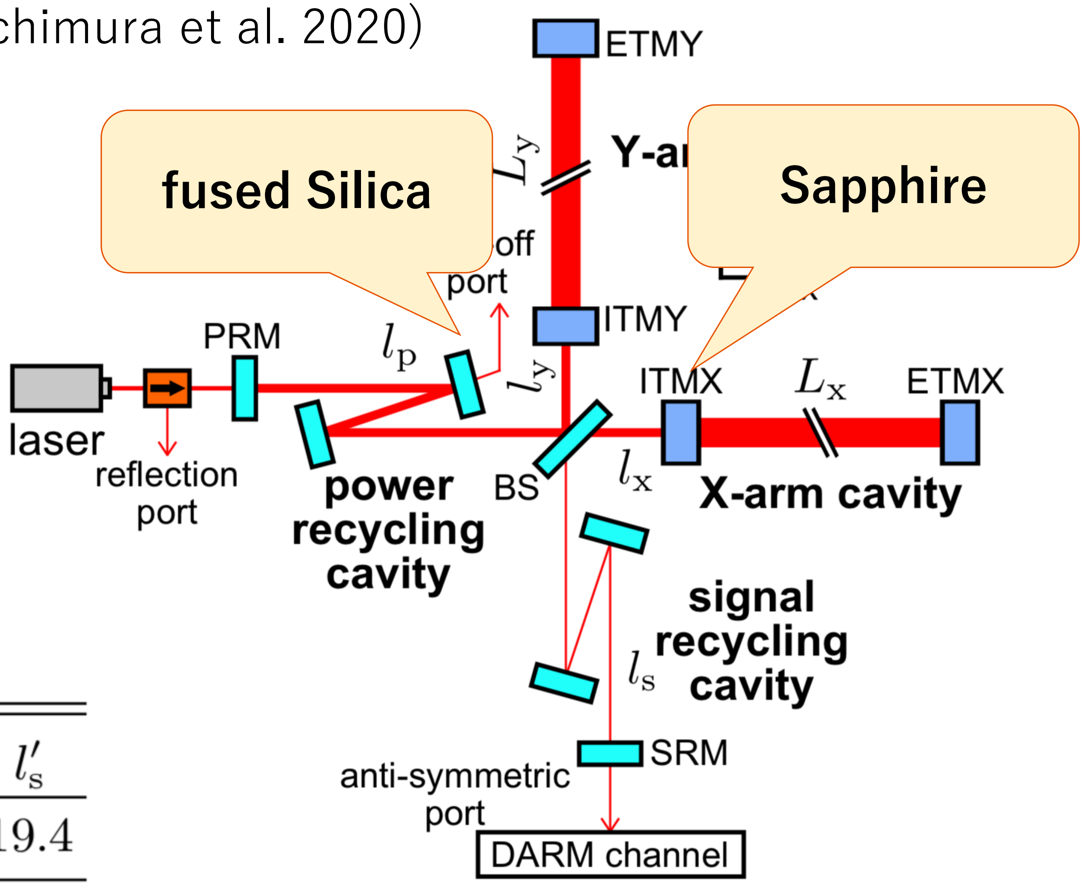

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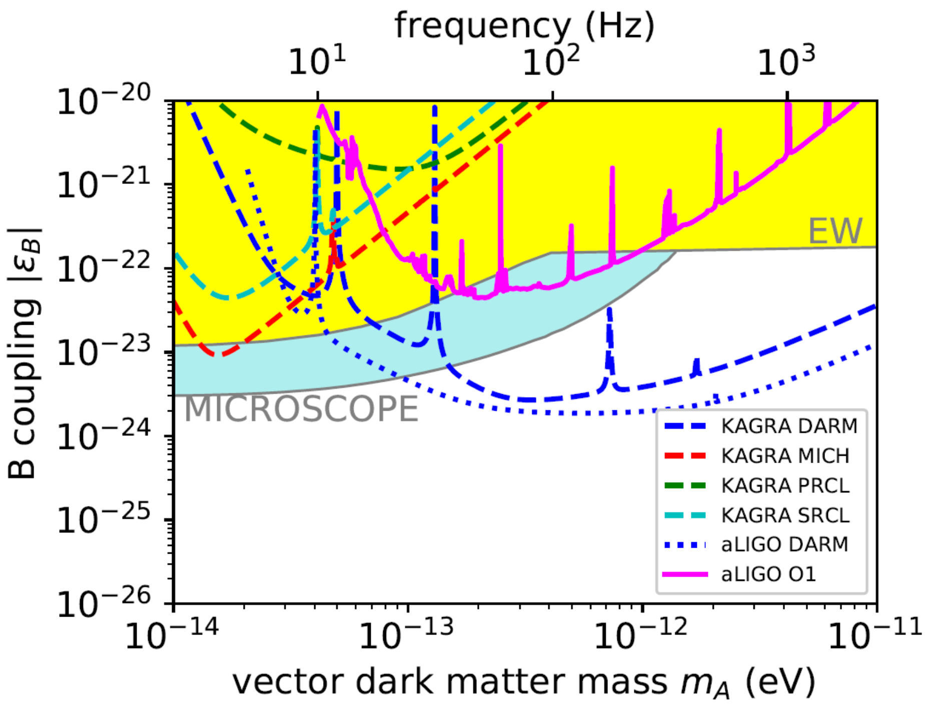
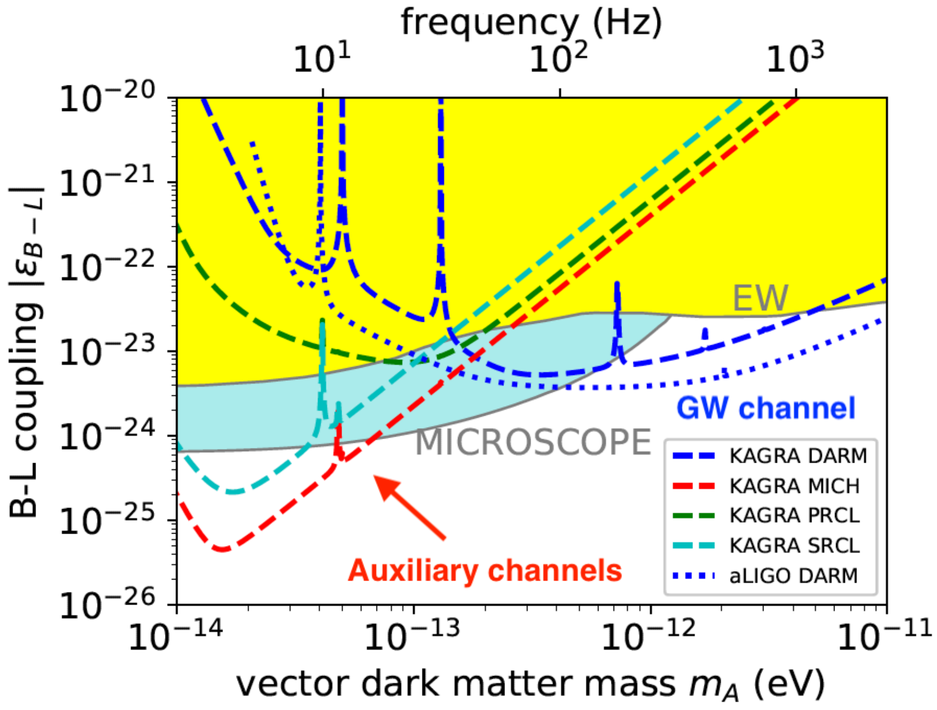
KAGRA and its auxiliary channels

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

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





(※ 1yr obs. with designed sensitivity)

KAGRA and its

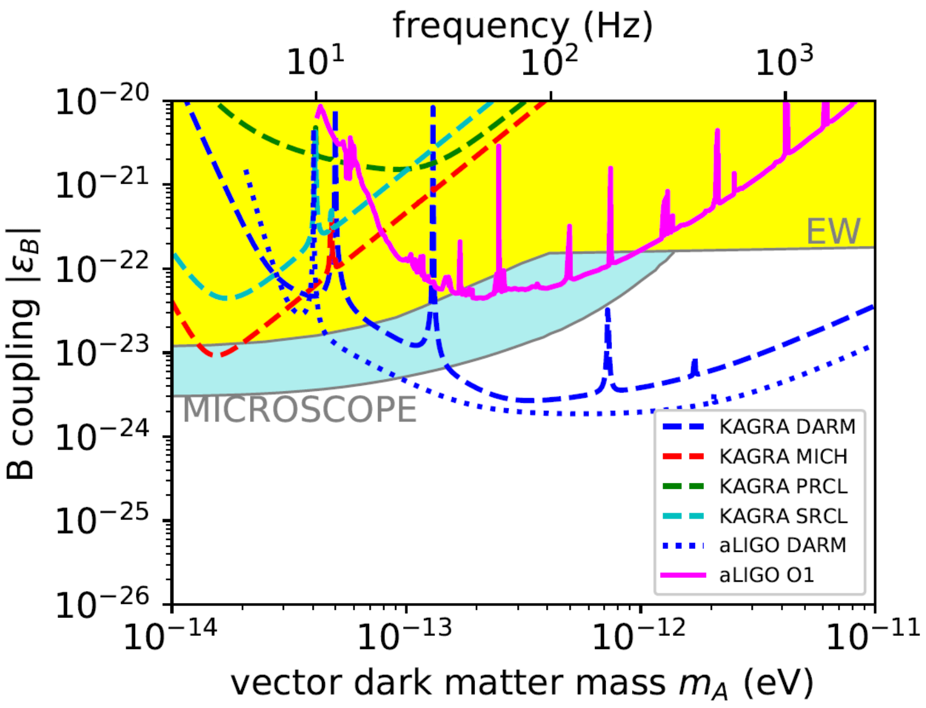
- Advantage of KAGRA

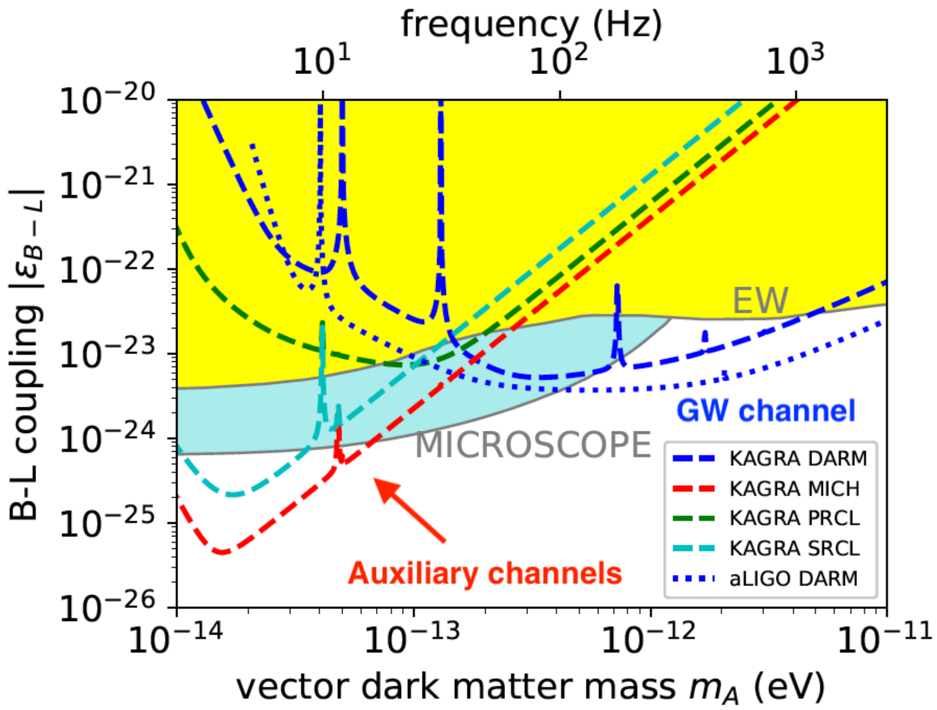
For $U_{B-L}(1)$ model, **KA** !

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

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

Silica: 0.501
Sapphire: 0.51





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- KAGRA and its auxiliary channels
- Detection pipeline
- Summary

Detection pipeline

- Search Method

Collect the spectra at the frequency bins:

$m_A \leq 2\pi f_k \leq m_A(1+\kappa v_{DM}^2)$ κ: $O(1)$ const.

→ Detection statistic:

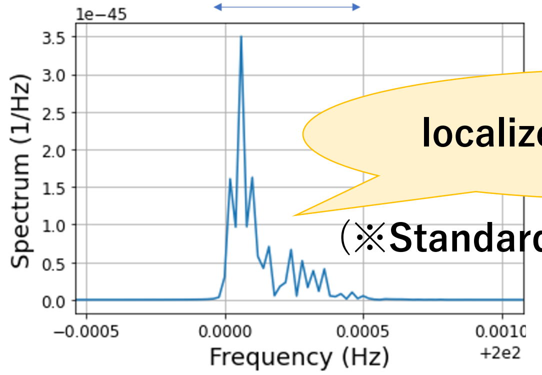
$$\rho = \sum \frac{4|\tilde{d}(f_k)|^2}{T_{\rm obs} S_n(f_k)}$$

S_n: Power Spectrum Density
T_{obs}: Obs. time

Assuming Gaussian noise, ρ obeys...

- χ^2_{2n} distribution for no signal (n: number of the bins)
- non-central χ^2_{2n} with signal present

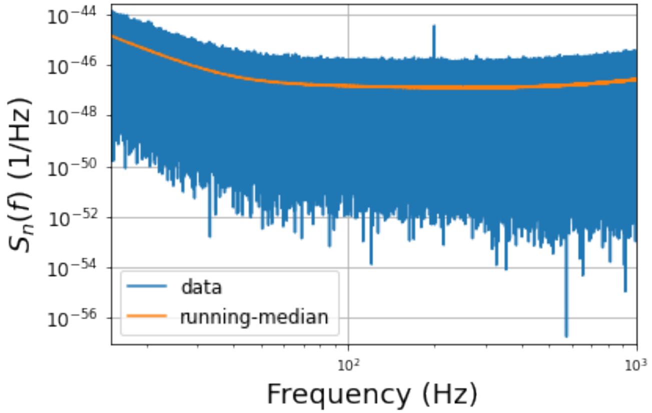
Spectrum of DM signal



localized in small width

(※**Standard Halo Model** is assumed)

Spectrum of mock data



Detection pipeline

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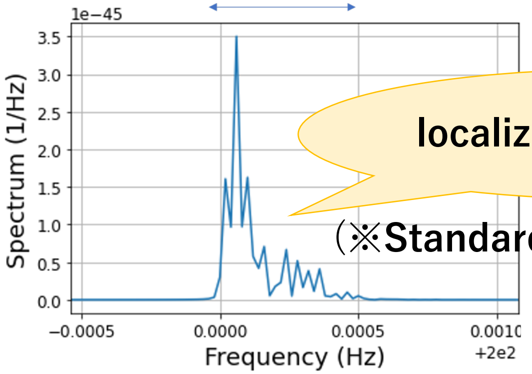

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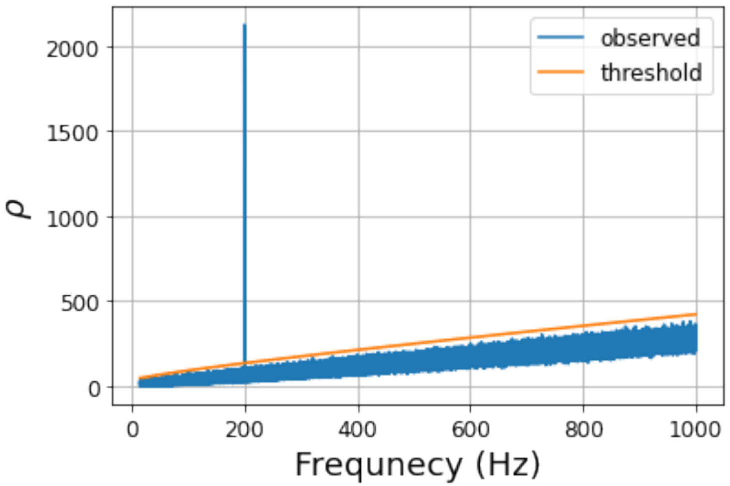
SNR of mock data



Detection pipeline

- Stochastic nature of ULDM (G. P. Centers et al. 2020)

Upper limit can be obtained from $\int_{\rho_{obs}}^{\infty} p(\rho|\epsilon_D^{95\%})d\rho = 0.95$

⚠ The signal would be superposition of waves with random amplitude!!

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

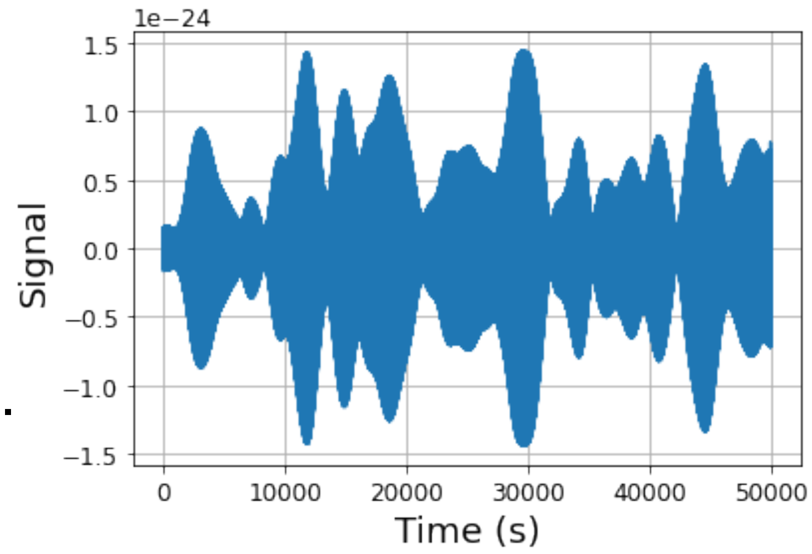
→we should marginalize it.

$$p(\rho|\epsilon_D) = \int dr\, P_R(r)\, \bar{p}(\rho|\epsilon_D r)$$

obeying Rayleigh dist.

Such a treatment will be implemented in our pipeline.

(H Nakatsuka et al. in prep)



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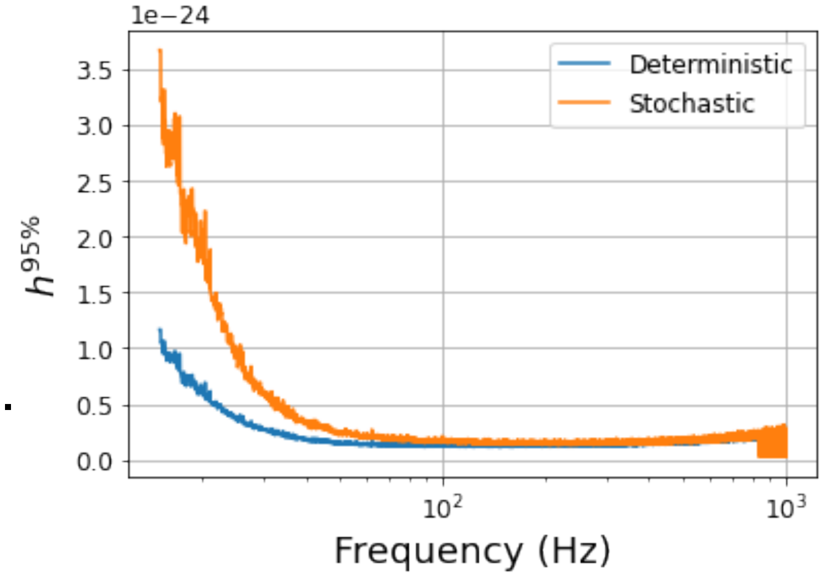
95% upper limit of the amplitude



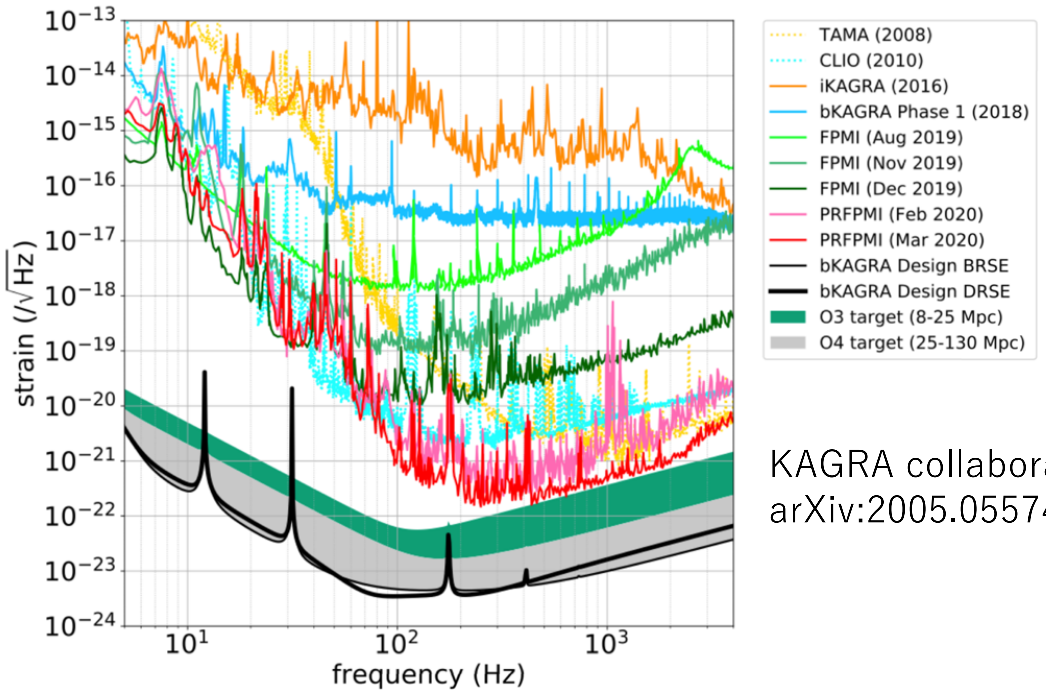
Detection pipeline

- Analysis of KAGRA's observational data

KAGRA performed a joint observation with GEO600 in April 2020. (**O3GK**)

Since it was only for two weeks,
sensitivity for DM is insufficient.
(※ SNR $\propto T_{obs}^{1/4}$ for $T_{obs} \gtrsim \tau$)

→Test for our pipeline with
KAGRA's first observational data.
First science result from KAGRA...!?



KAGRA collaboration
arXiv:2005.05574

Further upgrade is also required💪

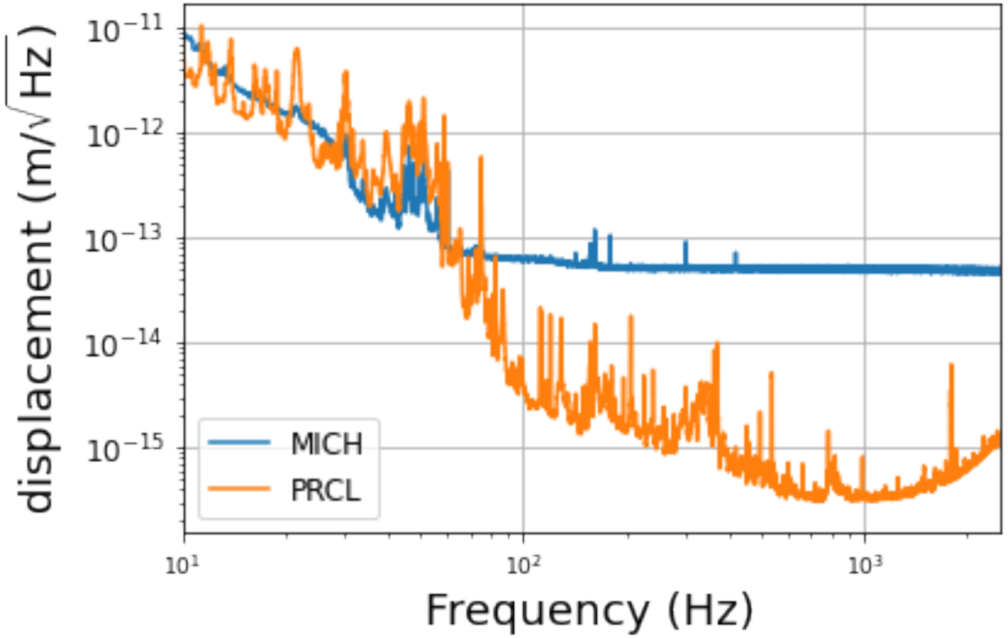
Detection pipeline

- Analysis of KAGRA's observational data

GW interferometer suffers from various noise sources.

→Line noise mimics the "signals".

estimated sensitivity



Veto procedure:

✓Sharpness of the spectrum

✓Coincidence btw several segments

After veto & noise identification,

we're going to release the result. 

Contents

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.