March 8th, 2024

Ultralight dark matter search with KAGRA
-the O3GK result and toward the O4 analysis-

Università degli Studi di Padova

INFN Padova
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

RESCEU

KAGRA

ダークマターの正体は何か？
広大なディスカバリースペースの網羅的研究
What is dark matter? - Comprehensive study of the huge discovery space in dark matter

Jun'ya Kume (Univ. of Padova, INFN, RESCEU)
on behalf of the KAGRA collaboration

Collaborators:
T. Fujimori, H. Fujimoto, T. Fujita, K. Komori,
Y. Manita, Y. Michimura, S. Morisaki,
A. Nishizawa, I. Obata Y. Oshima & H. Takidera

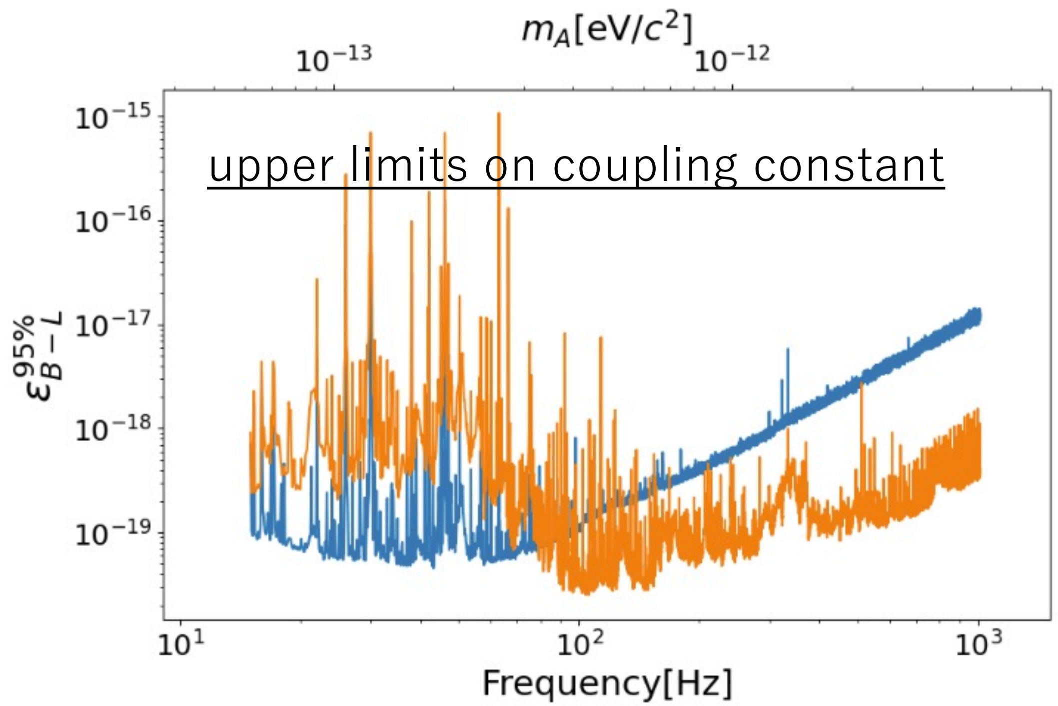
The paper finally came out! arXiv:2403.03004 [astro-ph.CO]

Ultralight vector dark matter search using data from the KAGRA O3GK run

(The LIGO Scientific Collaboration, the Virgo Collaboration, and the KAGRA Collaboration)
incl. J. Kume, S. Morisaki, Y. Michimura, K. Komori, A. Nishizawa, Y. Oshima

T. Fujimori,[190] H. Fujimoto,[267] T. Fujita,[306,36] Y. Manita,[295] I. Obata,[307] and H. Takidera[267]

(also available on https://dcc.ligo.org/P2300250/Public)



Our new pipeline has been approved

by the LVK research sub-group!

→ to be developed for O4 data analysis

Our study has been promoting

"Science with KAGRA GW telescope"

though it's not on GW physics 😜

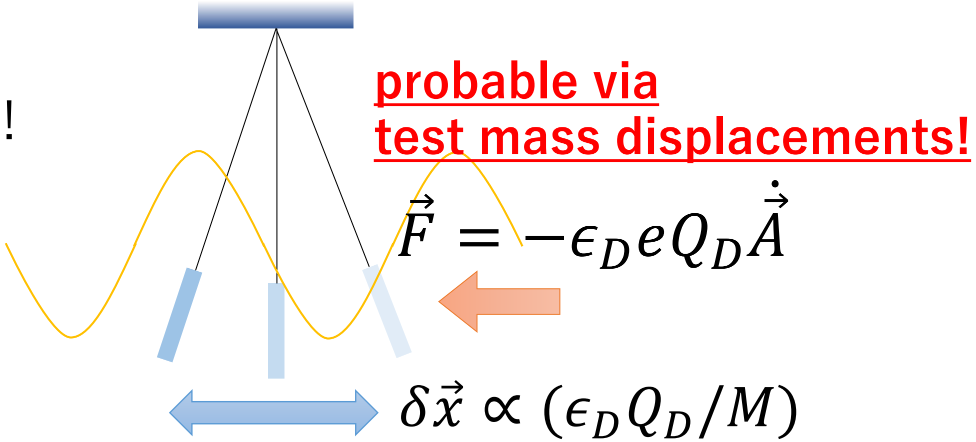
Contents

- Ultralight vector DM -target signal in O3GK analysis-
- Pipeline construction based on stochasticity study
- O3GK data analysis as a demonstration
- Summary & Discussion

- ULDM search with GW detector (e.g. LIGO O1/O3, GEO600, ...)

  Bosonic DM can have very light mass $m_{DM} \lesssim$ eV

  → $O(10^{-14} - 10^{-11})\mathrm{eV}/c^2$ testable with GW detector!



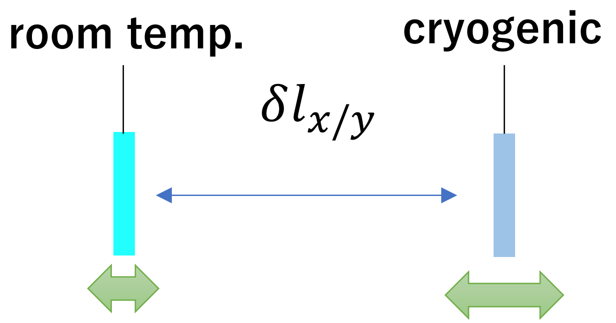
spin-1 candidate: (from gauged $U_D(1)$)

- **dark photon A_μ** $U_{B-L}(1)$: anomaly free!
- **coupling $\epsilon_D e J_D^\mu A_\mu$** "**Dark electric force**"

- Motivation to use KAGRA (Y. Michimura+ 2020)

  employs sapphire/fused silica mirrors

  → difference in Q_{B-L}/M enhances the sensitivity to VDM!



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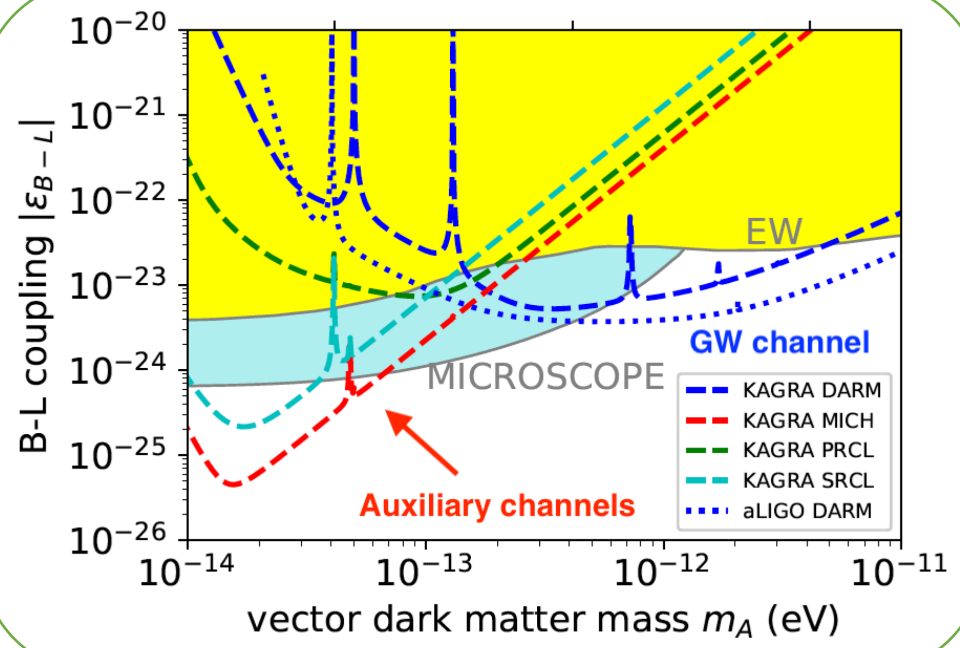

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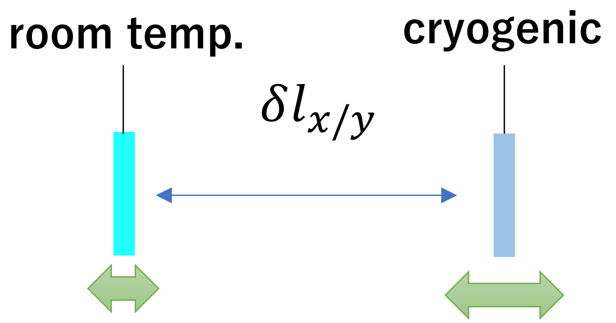
KAGRA can be the best detector for specific masses!

– How can we search the signal efficiently…?



<u>signal in length change enhanced!</u>

・DM signal in KAGRA's auxiliary length channels

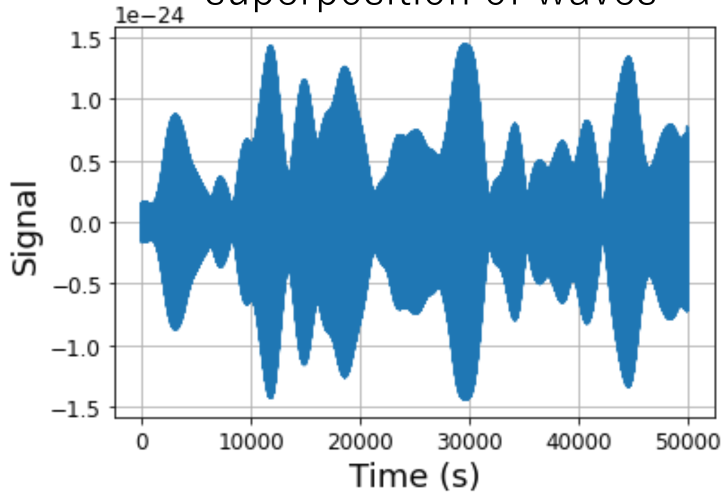
(Nakatsuka, Morisaki, Fujita, **JK**+ 2022)

$$\tilde{h}_X(f;t_0) = \mathrm{i}\frac{\epsilon e}{2\pi f}\Delta\left(\frac{Q}{M}\right) d^i_X(t_0)\tilde{A}_i(f;t_0)$$

field amplitude

※neither coherent nor monochromatic!!

superposition of waves



Statistical fluctuation:

superposition of waves → Gaussian dist.

$\langle\tilde{A}^*_i(f,t_0)\tilde{A}_i(f,t_1)\rangle$ characterized by $\tau \equiv 2\pi m_A/v^2_{vir}$

➡ Spacial care in deriving upper bound on ϵ_{B-L}

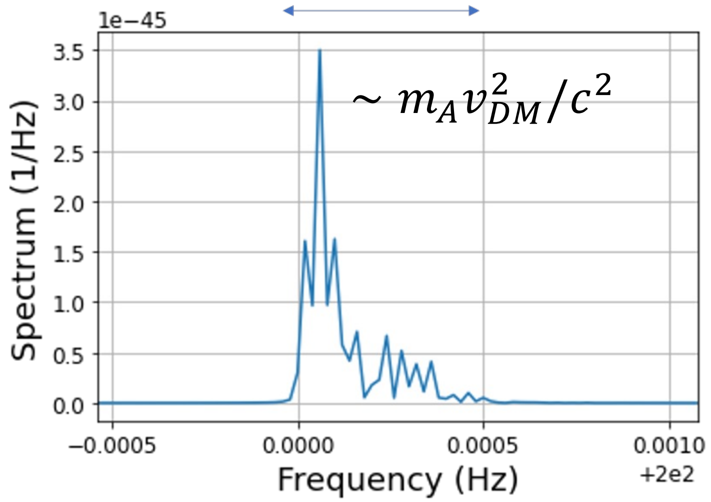
Non-relativistic dispersion:

peak of spectrum: $f_c = m_A/2\pi$

narrow width: $\Delta f \sim f_c v^2_{DM}/c^2 \sim 10^{-6} f_c \simeq$ **CW search**

➡ Incoherently collecting spectra in Fourier space

Spectrum of DM signal



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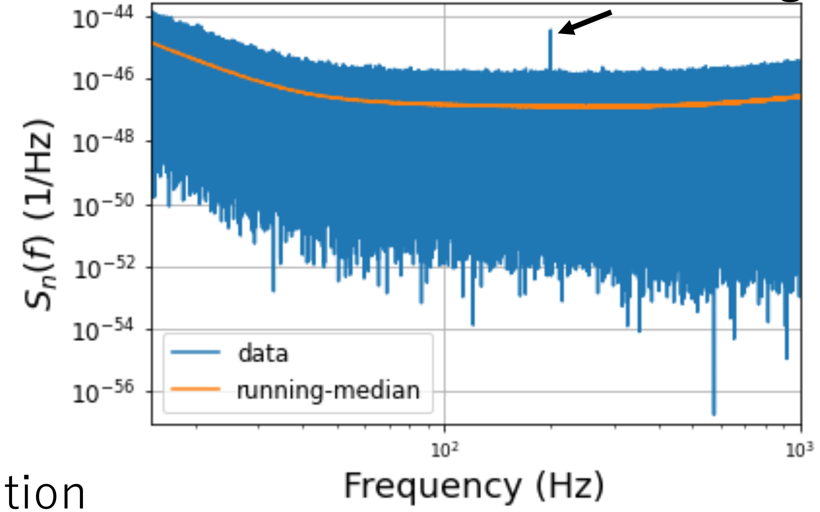
・Detection statistics inspired by CW search

inputs of pipeline:

Fourier Transform of data segment: $\tilde{d}(f_n; t_i)$

Noise PSD: $S(f_n; t_i)$ → estimated by running median

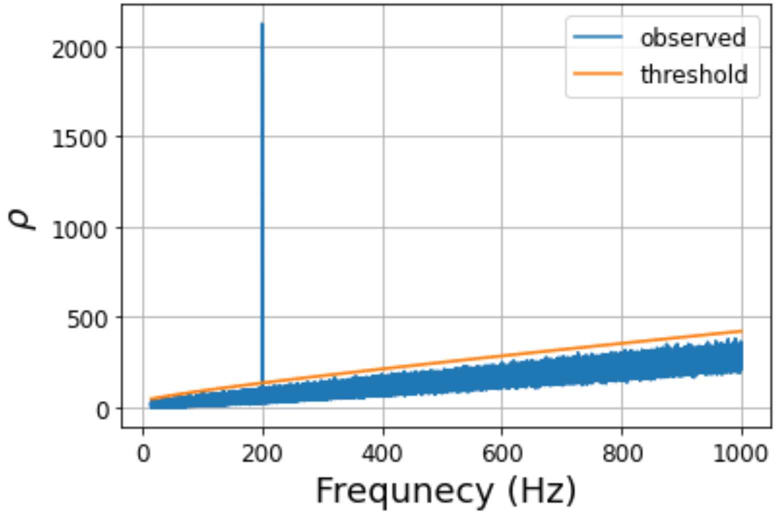


$$\rho(f_c) \equiv \sum_{t_i, f_n} \frac{4|\tilde{d}(f_n; t_i)|^2}{T S(f_n; t_i)}$$

Incoherent sum of spectrum

→ non-stationarity/detector rotation

summing up



Summation within the narrow band:

$f_c \leq f_n \leq f_c(1 + \kappa v_{vir}^2/c^2)$ $\kappa = 3.17$ → 1% loss in signal power

$T = 30$ min. ($\ll 1$ day, to avoid the effect of Earth rotation)

Gaussian noise only: χ^2 dist. with $2 N_{bin} N_{ch}$ DoFs

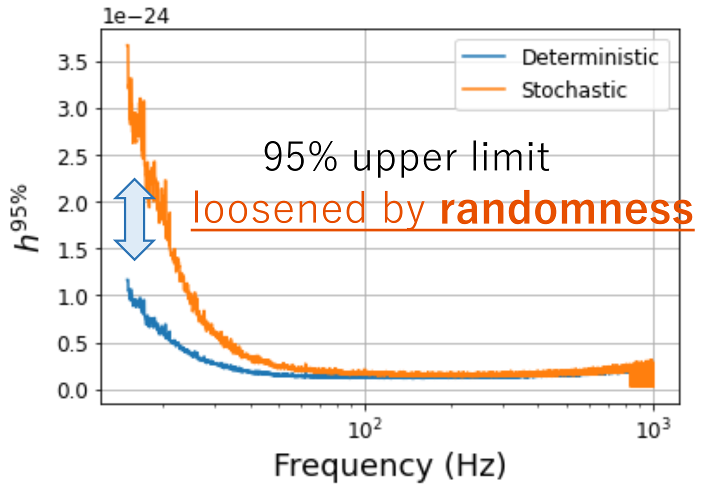
⇨ 95% percentile as a threshold for "detection"

・Upper limit estimation including stochasticity

Frequentist: $\int_0^{\rho_{obs}(f_c)} d\rho \ \mathcal{L}(\rho(f_c)|\epsilon_{B-L}^{95\%}) = 0.05$

※**random amp. of ULDM to be marginalized!** (cf. deterministic treatment →)

Analytical likelihood in Nakatsuka+ 2022 → **numerically unstable…**



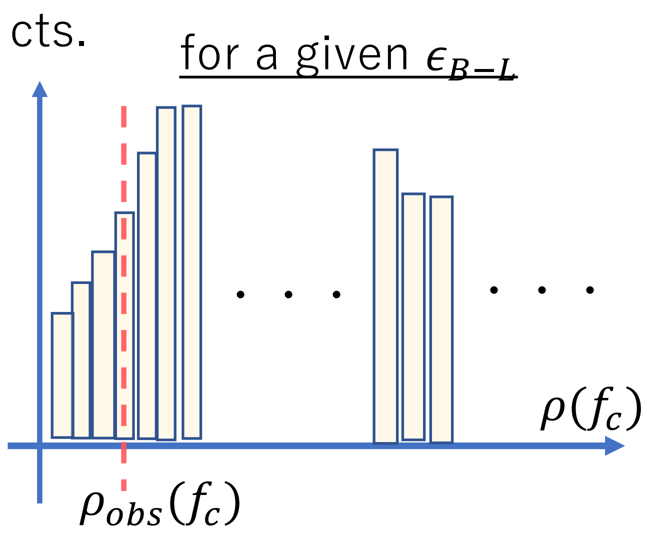
Simulation-based evaluation:

$$\rho(f_c;\epsilon_D) = \mathcal{N}^2 + \epsilon_D \mathcal{N}\cdot\mathcal{S} + \epsilon_D^2 \mathcal{S}^2$$ ← ※ϵ_D factorized

$\mathcal{N}$: $2N_{bin}N_{ch}$ unit Gaussian, $\mathcal{S}$: $\langle \tilde{h}_X^* \tilde{h}_X \rangle$ and noise PSD

・With analytically given $\langle \tilde{h}_X^*(f,t_0)\tilde{h}_X(f,t_1)\rangle$ ($\neq 0$ for $|t_1 - t_0| < \tau$), 10^5 realizations of $\mathcal{N}^2$, $\mathcal{N}\cdot\mathcal{S}$, $\mathcal{S}^2$ are simulated for each f_c.

・varying ϵ_{B-L} to find; $\rho_{obs}(f_c;\epsilon_{B-L}^{95\%}) = 5\%$ percentile.



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・Data from KAGRA O3GK run

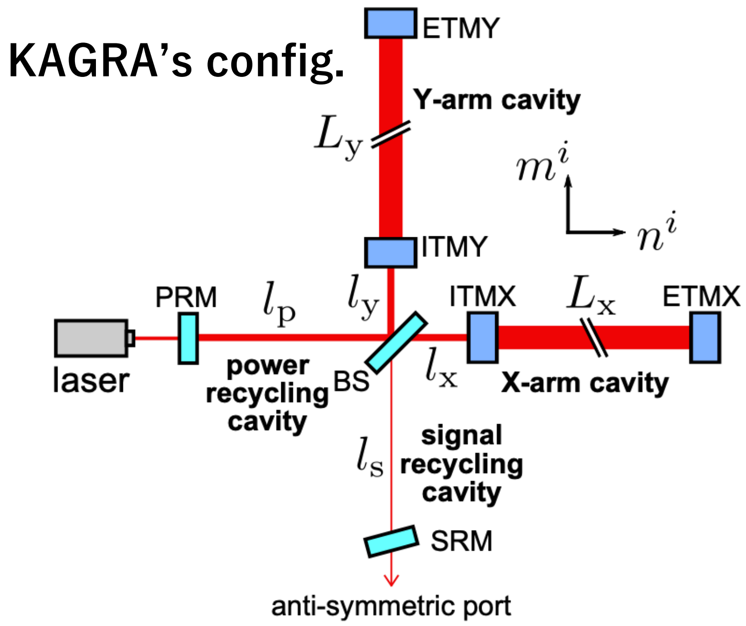
・MICH/PRCL length change

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

- calibration uncertainty $20\% - 30\%$

※less reliable for lower freq.

→ **Lower limit of frequency to be analyzed: 15Hz**

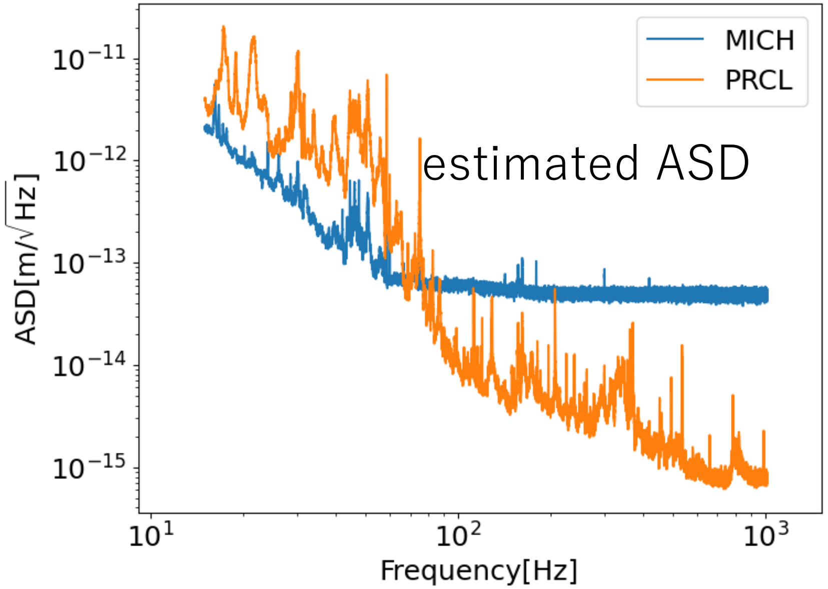


・O3GK: from 2020 April 7th to 21st

- detector in science mode ~ 53%

※unusable segments due to injection (last 2~3 days)

→ **number of 30 min. chunks: 217** ~ 4days ($\ll$ 1yr)



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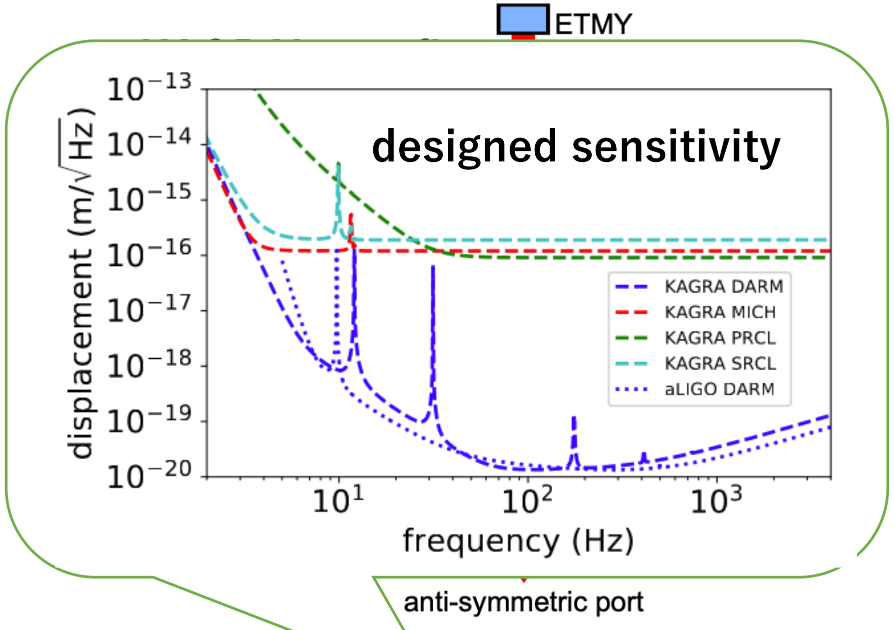

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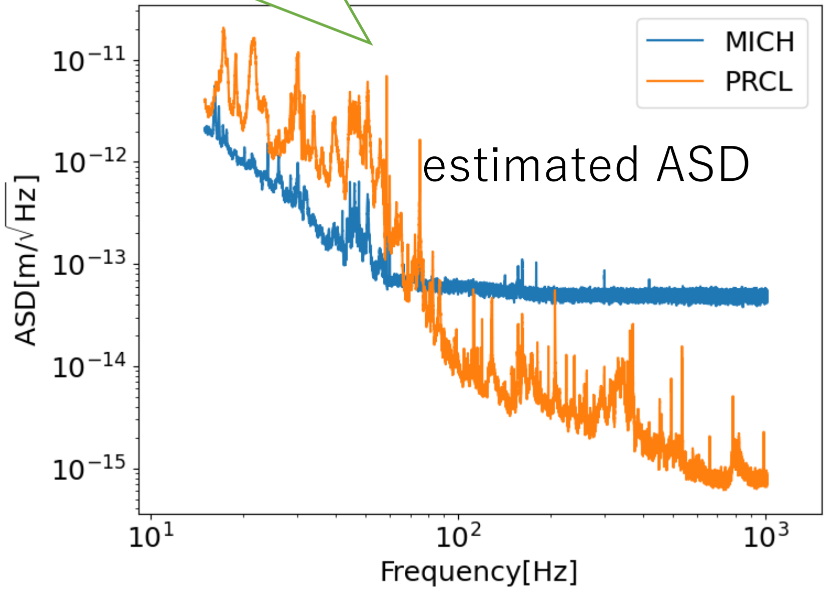
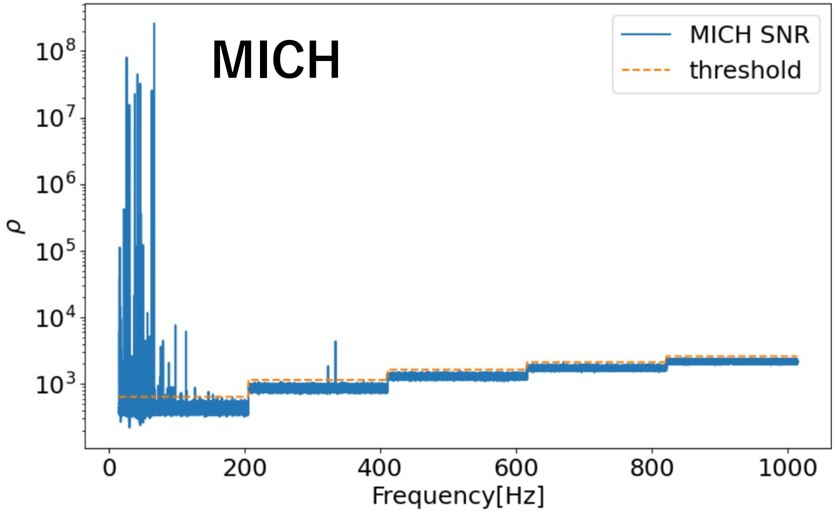
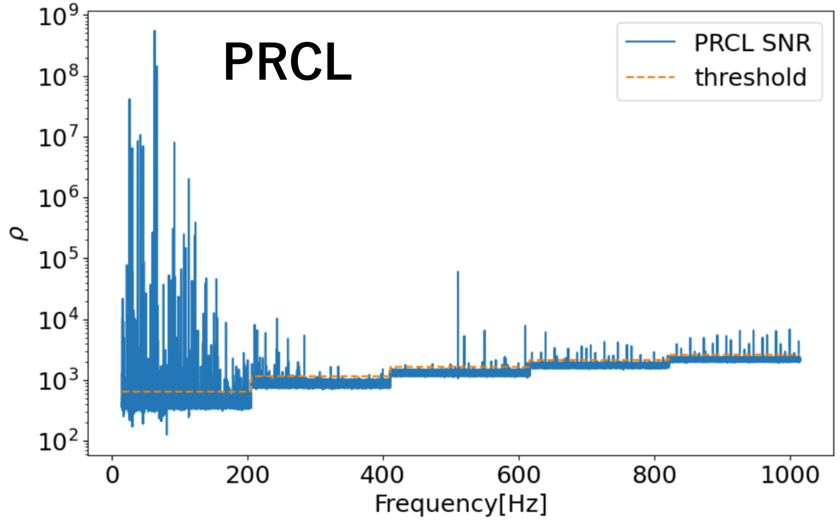


Demonstration of our pipeline with real data

・Candidates and Veto procedure





After passing the pipeline…

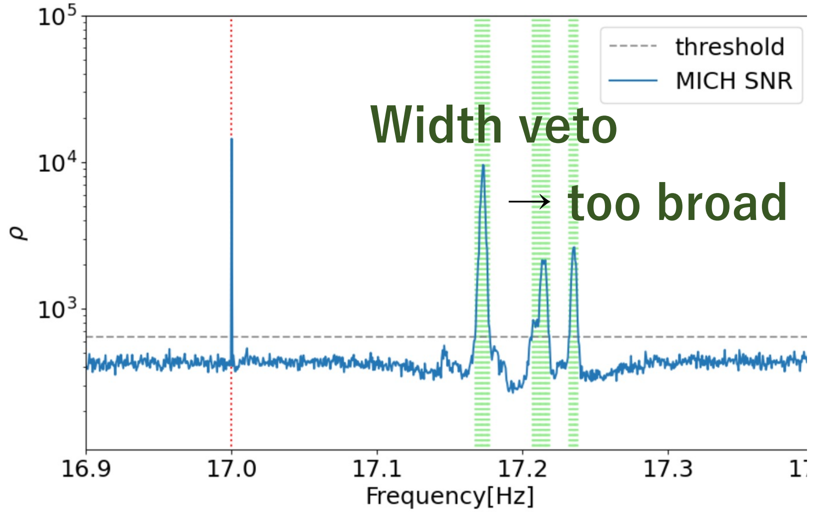
MICH: 1944

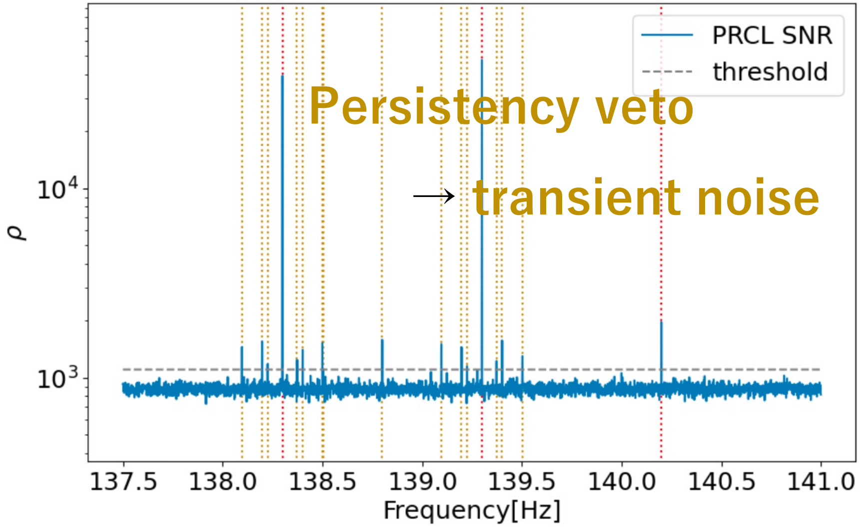
PRCL: 4133

candidates under 5% FAP.

after veto analysis

+ referring to line study





MICH: 20

PRCL: 148

still remains…

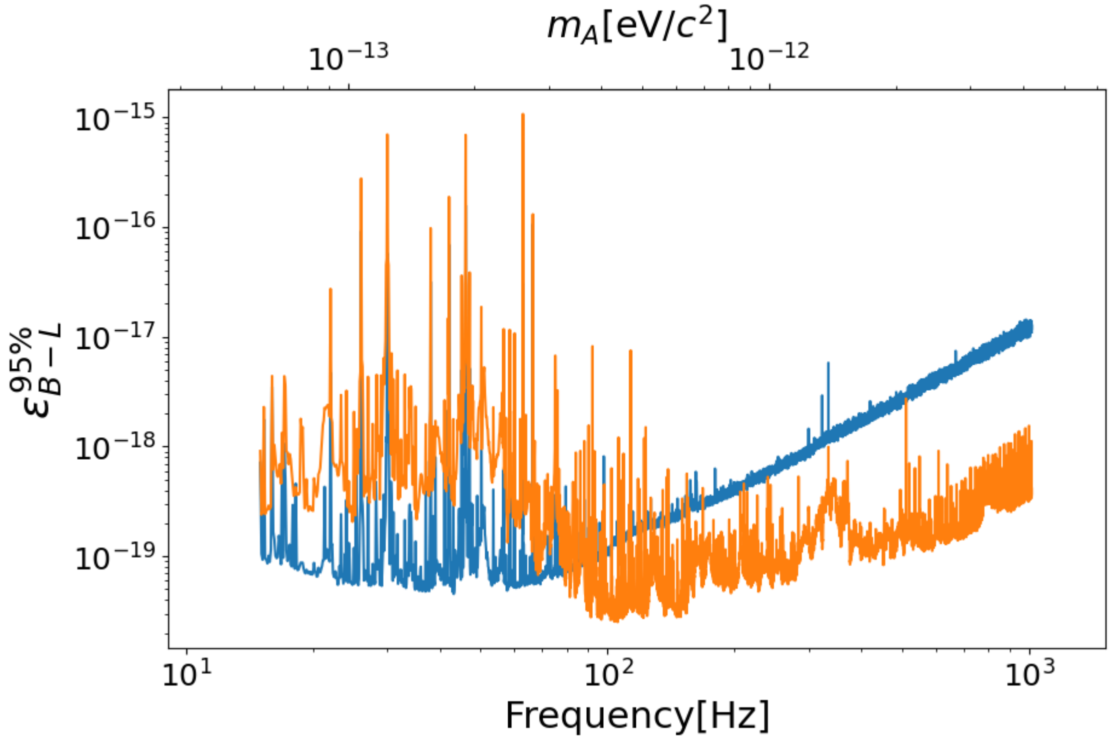
※less investigated so far

list of lines:

LIGO-L2300092 (JK, 2023)

・Upper limit on the coupling constant

- For simplicity, upper limits are derived for all bins (including the “detected” ones)
- Smoothed over $\Delta \mathrm{f} = 0.1$Hz by collecting the maximum value of $\rho(f_c)$



Remarks:

✓ $\langle \tilde{h}_X^*(f, t_0) \tilde{h}_X(f, t_1) \rangle$ matters for $m_A \lesssim 10^{-12}$eV

If improperly treated, bound gets too strong

(e.g. comparison to deterministic signal in Nakatsuka+)

✓ Consistent with $\propto T^{1/4}$ scaling at high mass

→ comparison to the prediction in Michimura+ 2020.

※another manifestation of ULDM “stochasticity”

Simulation-based pipeline: proper upper limits regardless of data length, masses of DM

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・Summary of O3GK analysis

- **The first-time vector ULDM search using KAGRA data** (from O3GK run)!

- **A new pipeline** is developed for DM signal search:
  - detection statistic inspired by CW search
  - veto making use of generic feature of ULDM
  - simulation based upper limit evaluation to deal with stochasticity

- Many lines (even after veto), less stringent bound on coupling constant…

  → With future upgrades, KAGRA could appreciate its uniqueness as VDM detector.

- Possible improvements on our pipeline → Inclusion of DARM, vector polarization, ...

・Toward O4 data analysis

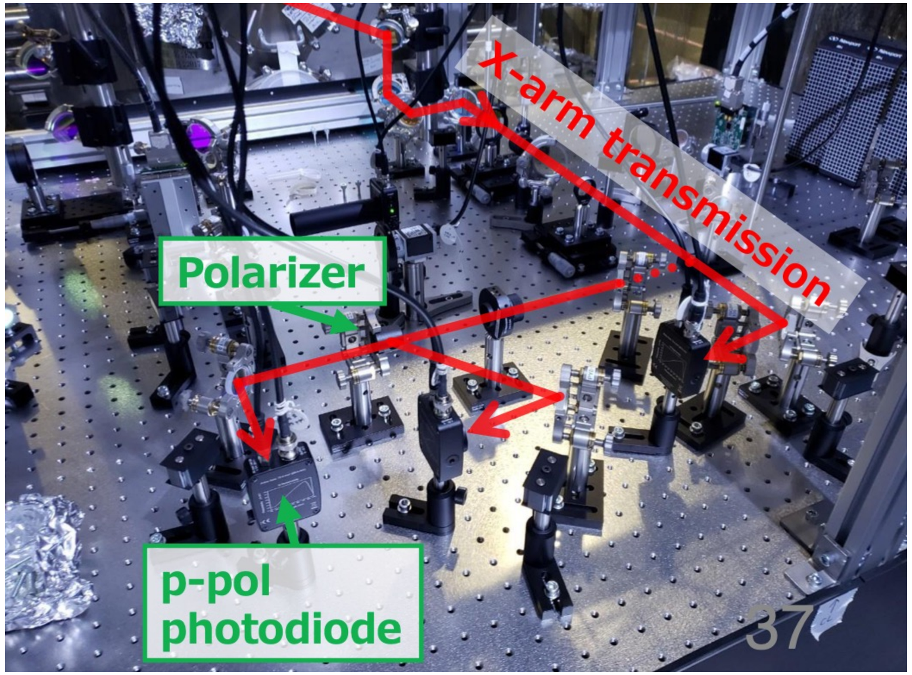
vector and axion DM simultaneous search:

・Polarization optics installed at X/Y arm transmission

- does not affect GW/VDM observation

⇨ axion DM search with KAGRA!!

※planned to start collecting data from O4b



Pipeline development:

・extension to ALP & spin-2 search (→ Y. Manita's talk), inclusion of DARM channel

- ALP search pipeline has been already applied to DANCE act1 (→ Y. Oshima, H. Fujimoto, **JK**+ 2023)

All the data products will be summarized in the O4 LVK DM paper.