

Tampere Cosmology Meeting, May 7th, 2026

# Gravitational Wave Interferometer as Ultralight Dark Matter Detector



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Collaborators:

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K. Nagano, A. Nishizawa, I. Obata, H. Takidera

Based on: Phys.Rev.D 108 (2023) 9, 092010

Phys.Rev.D 110 (2024) 4, 042001

Phys.Rev.D 113 (2026) 7, 075016

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

# Contents

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- A window for ultralight DM
- DM interaction with laser interferometers
- Optimizing ULDM signal search
- Summary

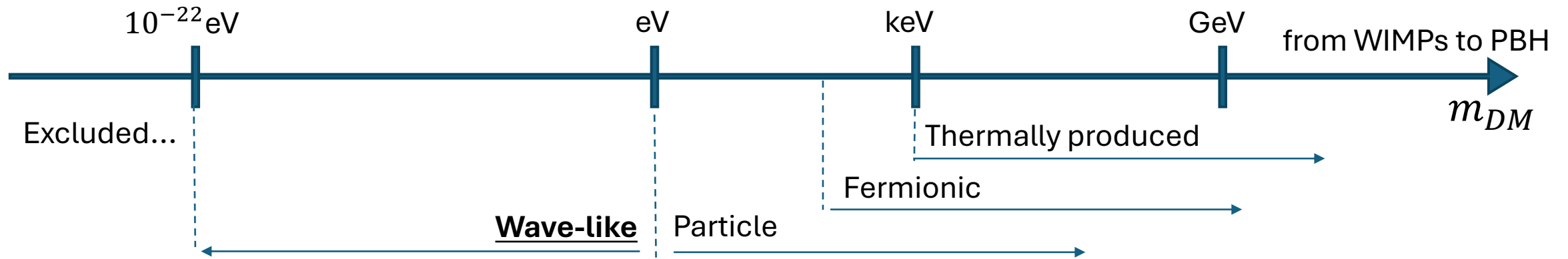
• A window for ultralight DM

Many indirect evidences!!

Structure formation      Galaxy rotation curve      Gravitational lensing      Bullet cluster

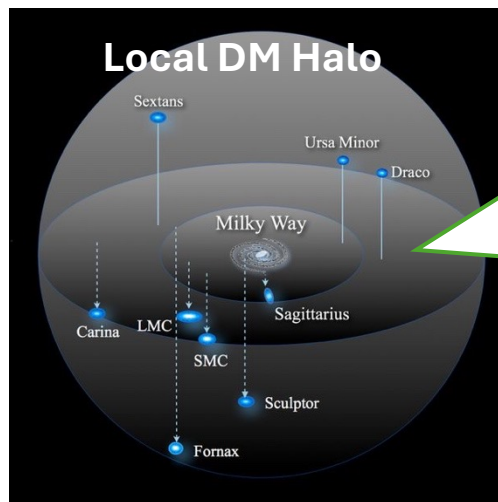
Vast discovery space ( $10^{-22} \text{ eV} \sim 10^{67} \text{ eV}$ ) for the DM:

90 orders of magnitude!!



If non-thermally produced,  $m_{DM} \lesssim \text{eV}$  is allowed for bosons.

- How do they behave?

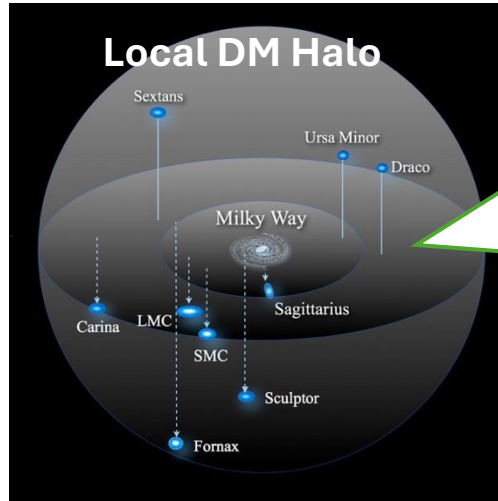


$$\rho_{\text{DM}} = 0.4 \text{ GeV/cm}^3$$
$$\gg \bar{\rho}_{\text{DM}} \approx 10^{-6} \text{ GeV/cm}^3$$

Higher density in DM halo!

w/ large de Broglie wavelength  
→ occupation number  $\gg 1$

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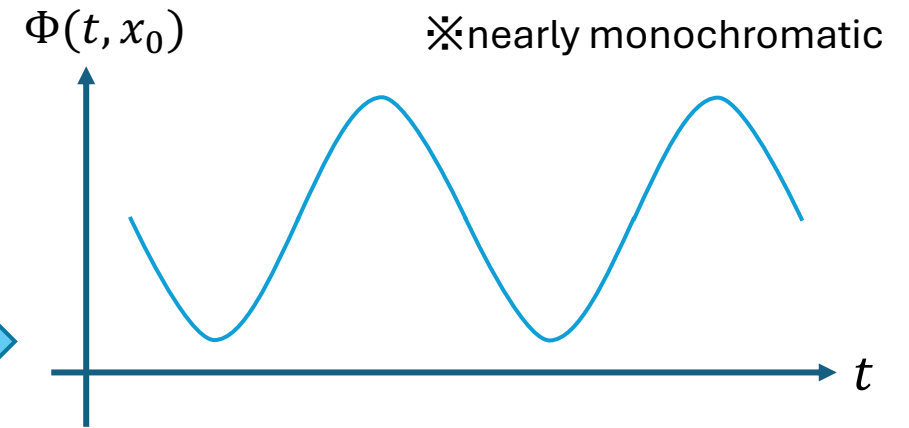


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**behave as classical waves!**

$\rightarrow$  solving small scale structure issue?

- Mass & frequency relation:

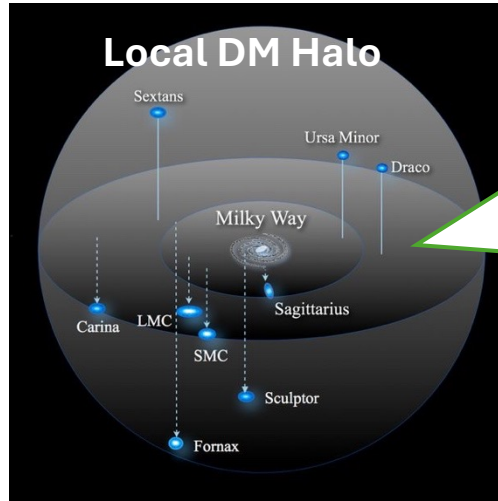
$$m = 4.1 \times 10^{-13} \text{ eV} \left( \frac{f_{\text{DM}}}{10^2 \text{ Hz}} \right)$$

- Coherence time:

$$\tau \equiv \frac{2\pi}{m\bar{v}^2} \simeq 0.3 \text{ day} \frac{10^{-13} \text{ eV}}{m} \quad \text{For } \Delta t \ll \tau$$

$\simeq$  const. amplitude & phase

- How do they behave?

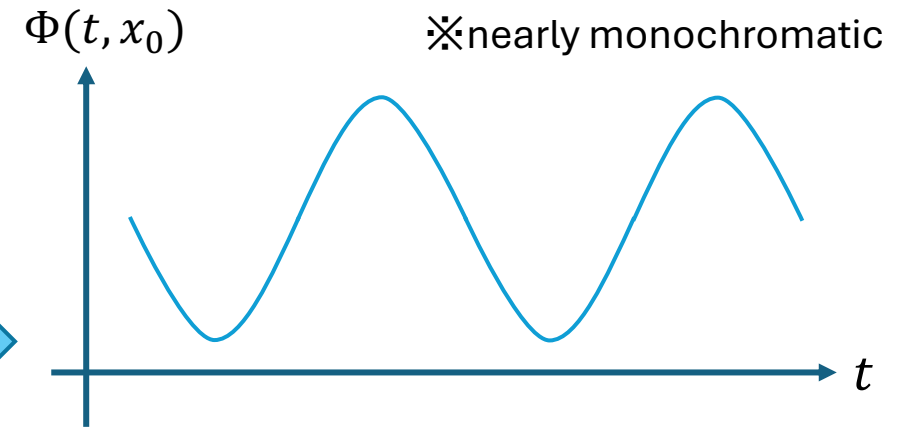


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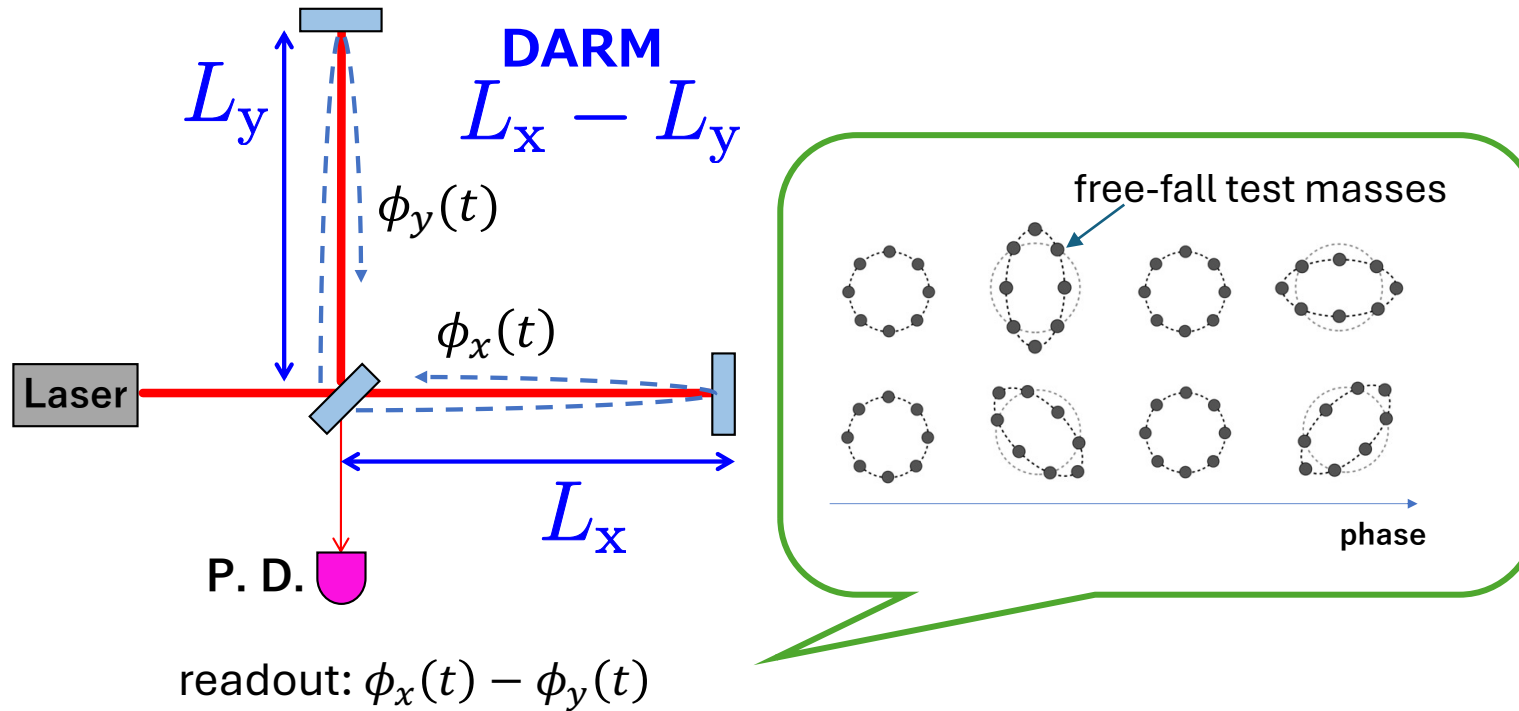
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**For  $m_{\text{DM}} \sim 10^{-14} - 10^{-11} \text{ eV}$ , ULDM oscillations fall into GW-interferometer band!**

- ULDM search with GW interferometers

We can search for DM interaction with GW detector as it is!

Schematics of Michelson interferometer

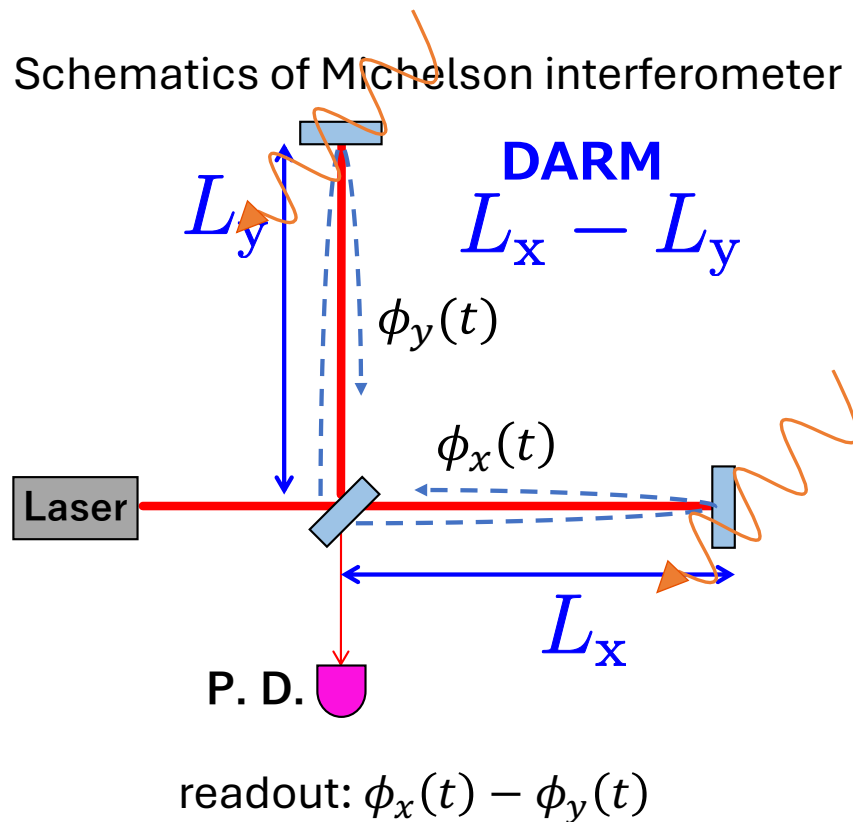


→ phase modulation due to ULDMs

- ULDM search with GW interferometers

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→ **phase modulation due to ULDMs**

spin-1 candidate:

- **dark photon**  $A_\mu$  (from gauged  $U_D(1)$ )

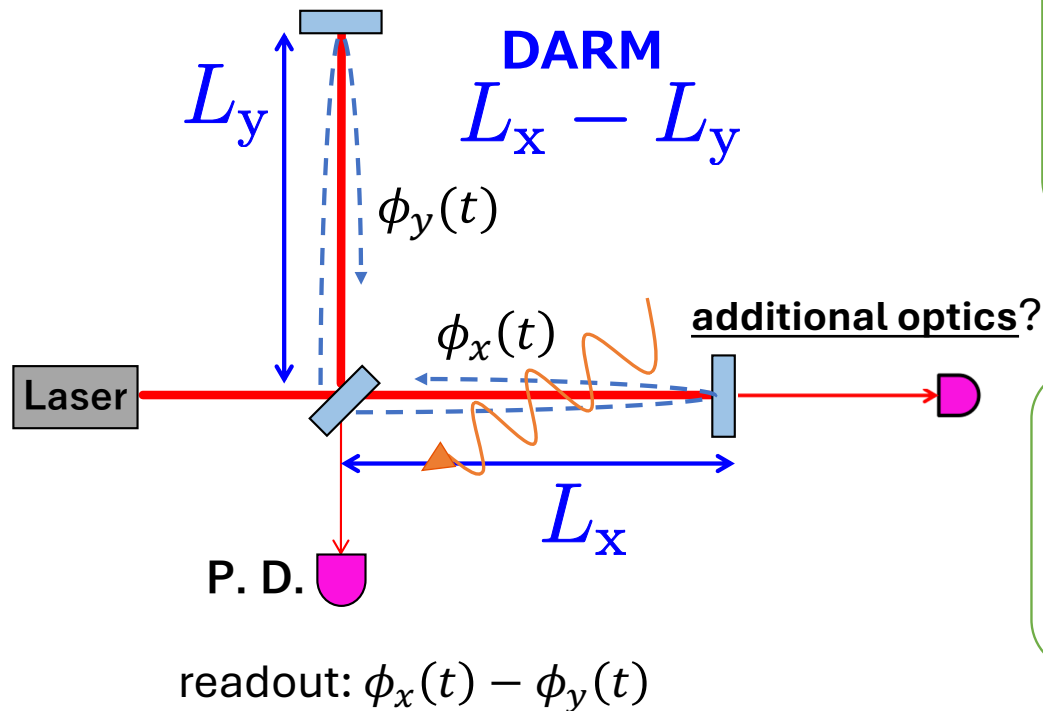
– **coupling to fermions**  $\epsilon_D e J_D^\mu A_\mu$

– **LIGO & Virgo puts tightest bound!**

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spin-0 candidate: (from string,  $U_{PQ}(1)$ , ...)

- **axion(-like) particle**  $a$

– **coupling to photon**  $g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$

– **polarization based axion search**

for dilatonic DM, see also... S. M. Vermeulen+ 2021

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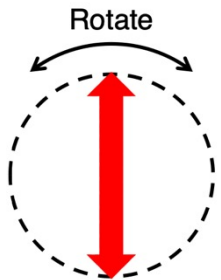
# DM interactions with laser interferometers

- Axion-like-DM & photon interaction

coherently oscillating axion

$$a(t) = a_0 \cos(m_a t + \phi) \quad \text{w/} \quad \mathcal{L} \supset \frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} \simeq \text{birefringent medium}$$

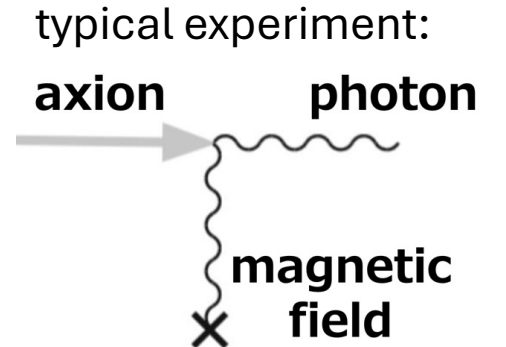
➡ phase velocity:  $c_{R/L} \simeq 1 \pm g_{a\gamma} \dot{a}(t) / 2k$



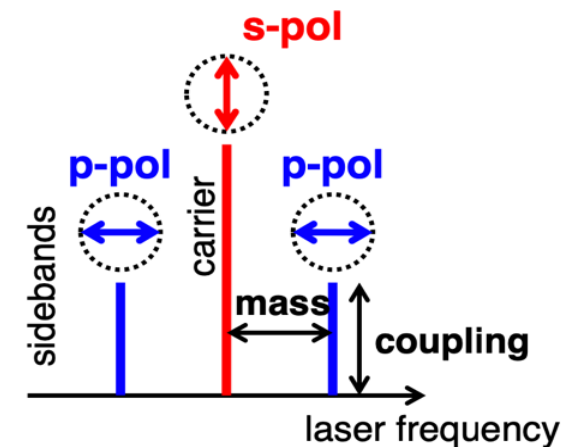
Oscillatory rotation of polarization angle:

$$\delta\theta = k \int_{t-L}^t dt (c_L - c_R) \propto g_{a\gamma} a_0 m_a L \sin(m_a(t - L/2))$$

$(m_a L \ll 1)$



In our case:



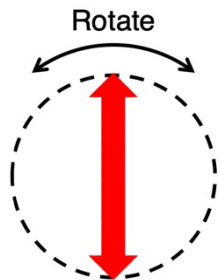
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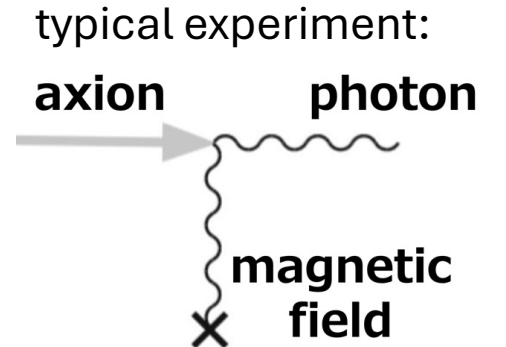
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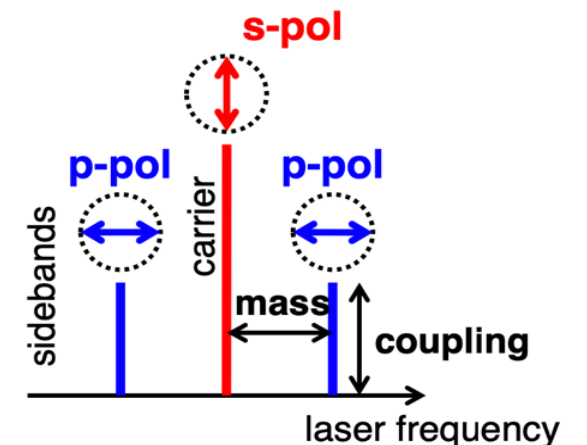
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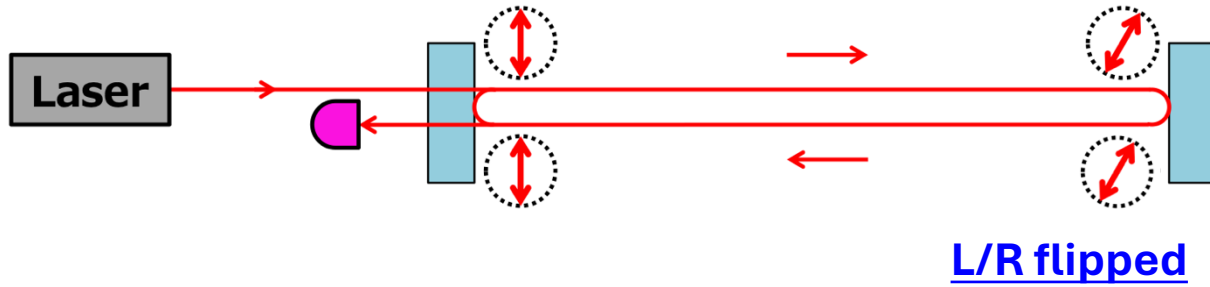


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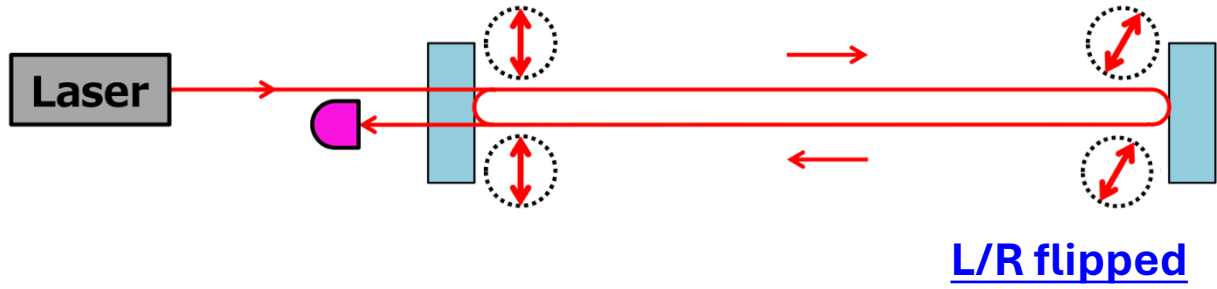
- Using an arm cavity of GW interferometer

Naively, it's not efficient with cavity...

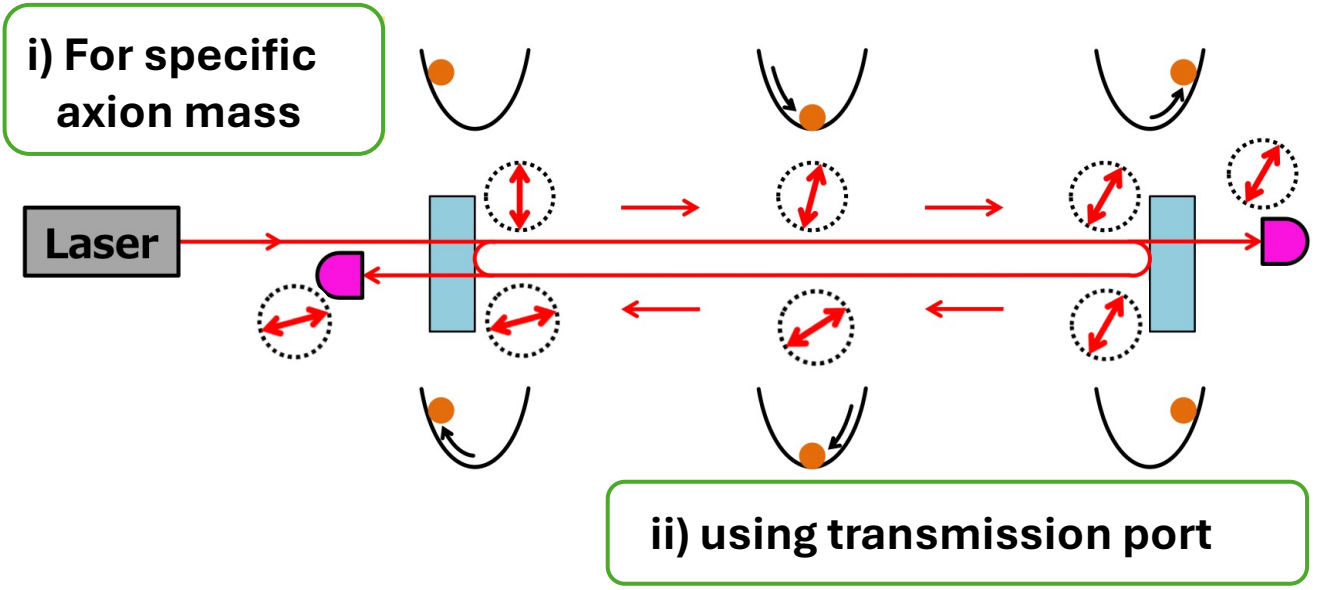


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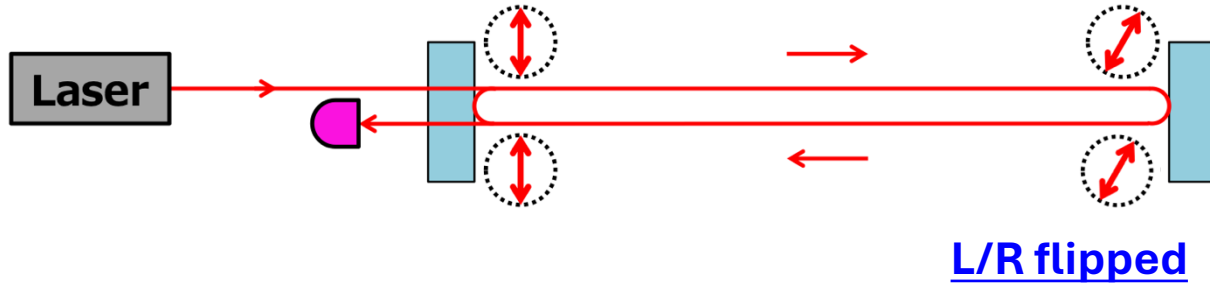


But we can have chances:



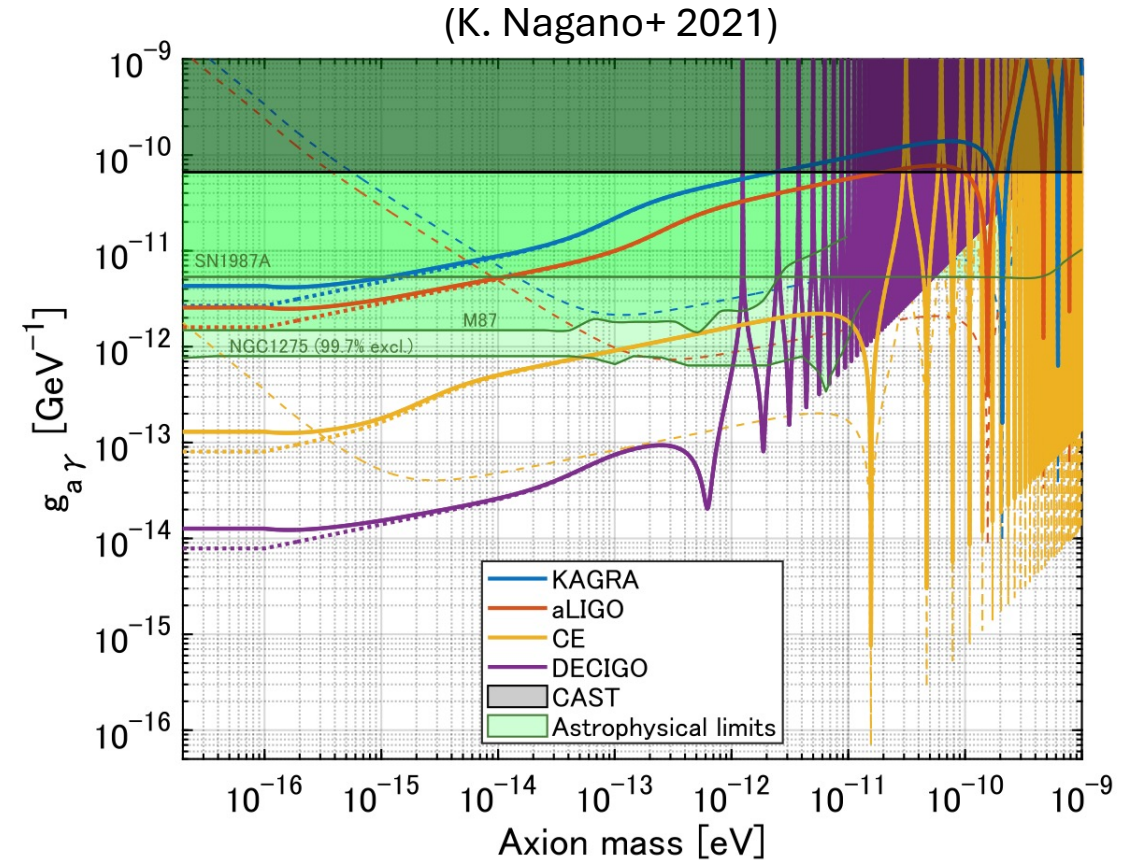
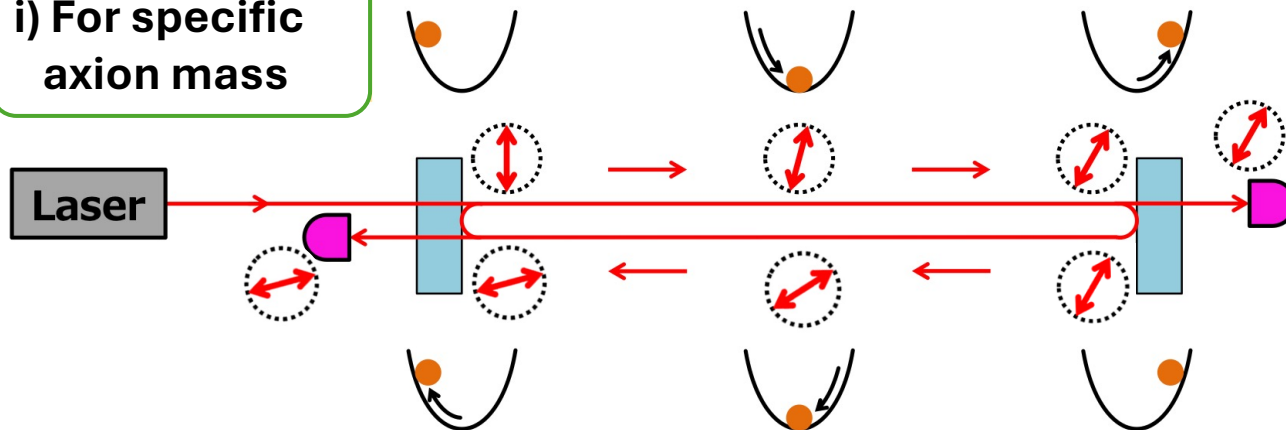
- Using an arm cavity of GW interferometer

Naively, it's not efficient with cavity...



But we can have chances:

**i) For specific axion mass**



i) GW detection port (dashed-line)

ii) **X/Y-arm end** (solid-line)

→ **O4c KAGRA data being analyzed!!**

- Vector DM & matter interaction

Coupling to the SM:  $U_D(1)$  current

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

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

- Lorentz gauge + SHM ( $v_{\text{DM}}^{\text{local}} \approx 10^{-3}$ )

$$\vec{A} = \vec{A}_0 \cos[\omega t - \vec{k} \cdot \vec{x}] \quad \text{with } k = m_A v \ll \omega$$

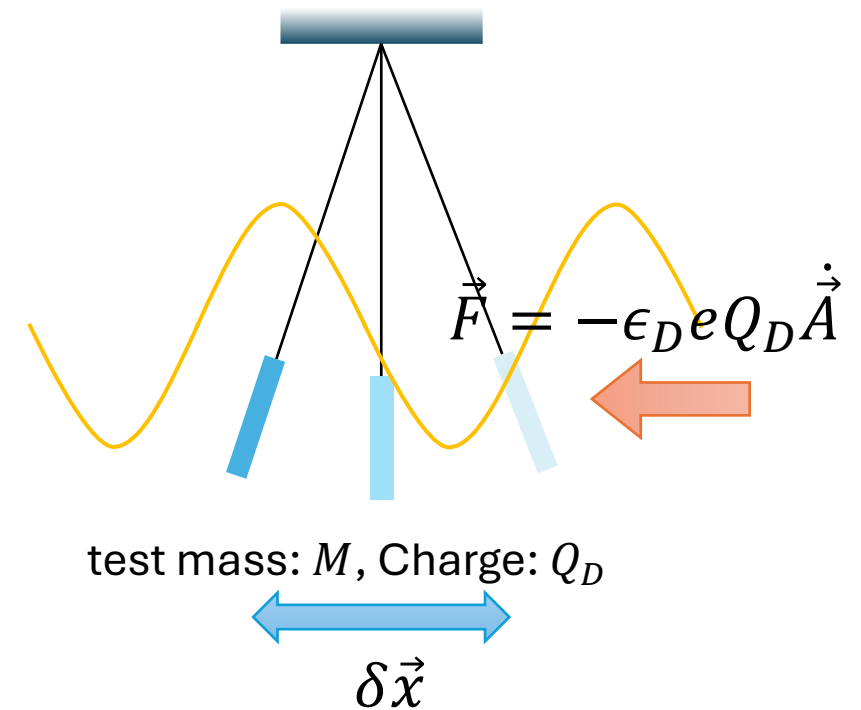
✧ temporal component suppressed by  $v_{\text{DM}}^{\text{local}}$

→ oscillating "dark" electric force on SM matter

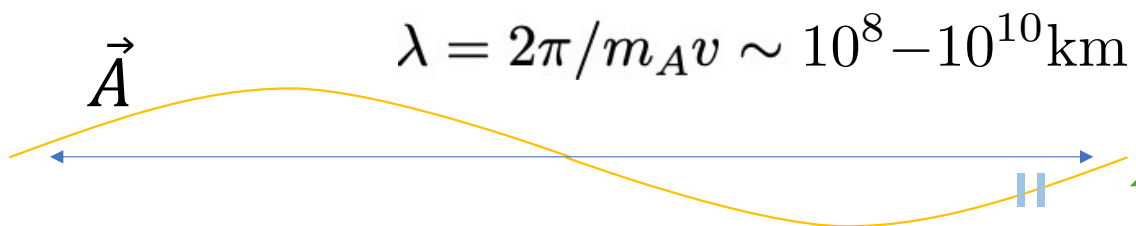
Can we probe it with GW interferometer? 🤔

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

(S. Schlaminger+ 2008, T. A. Wagner+ 2009)



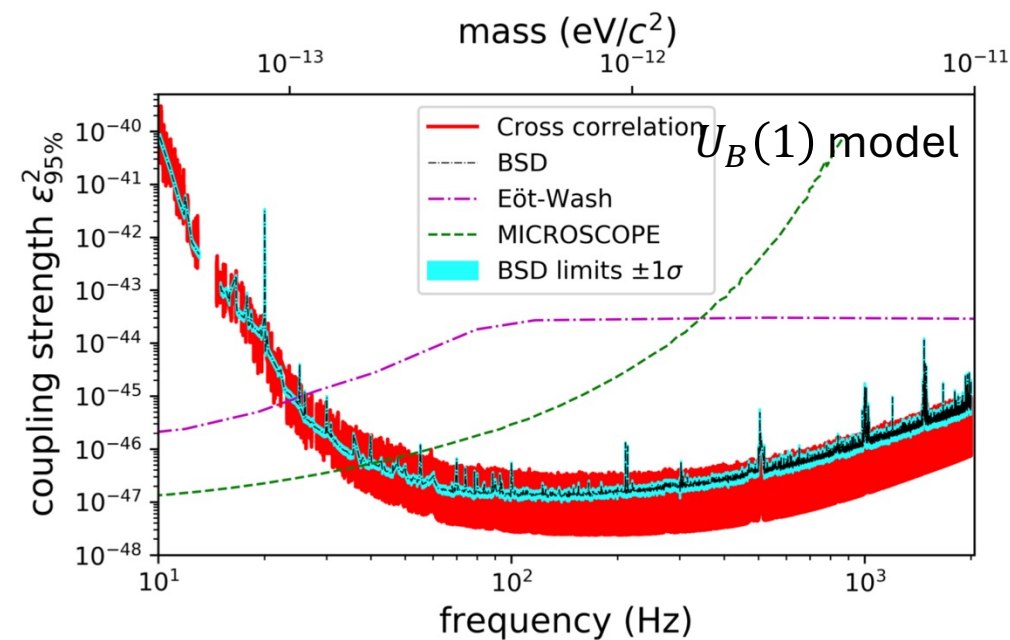
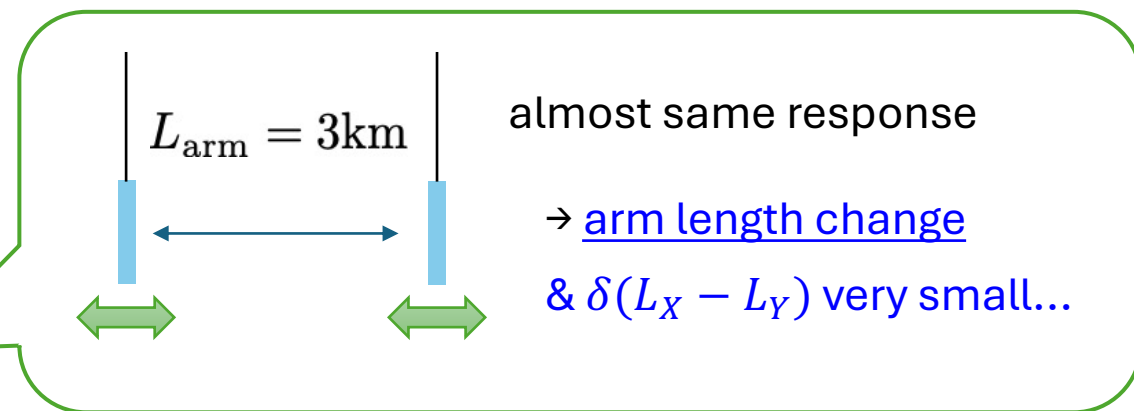
- Yes, but it's not so simple...



coherent wave-length  $\gg$  separation between mirrors

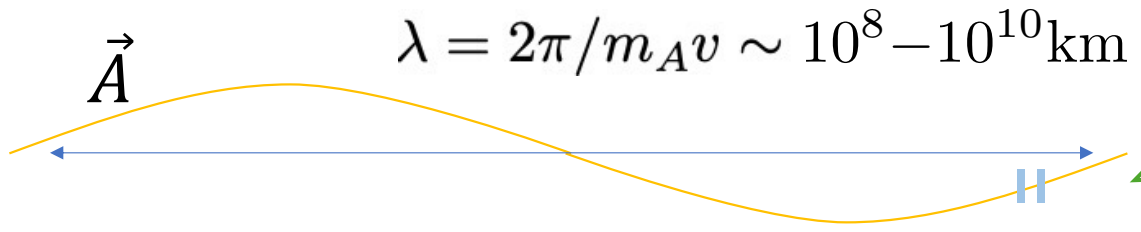
Still, LIGO-Virgo detectors are sensitive to very small difference of ULDM phases!!

➔ tightest bounds for  $m_A \sim 10^{-12} \sim 10^{-11} \text{ eV}$

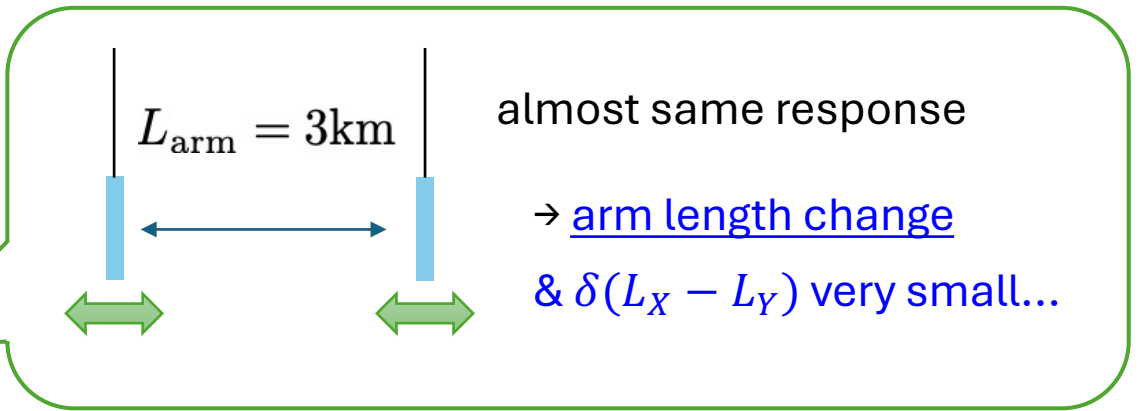


(LVK Collaboration 2022)

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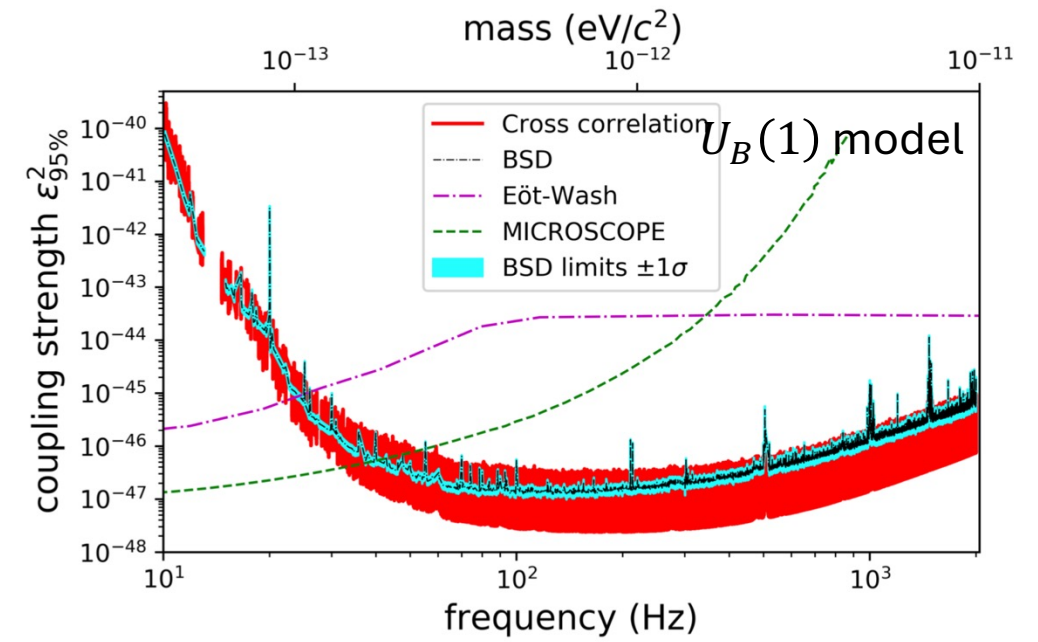
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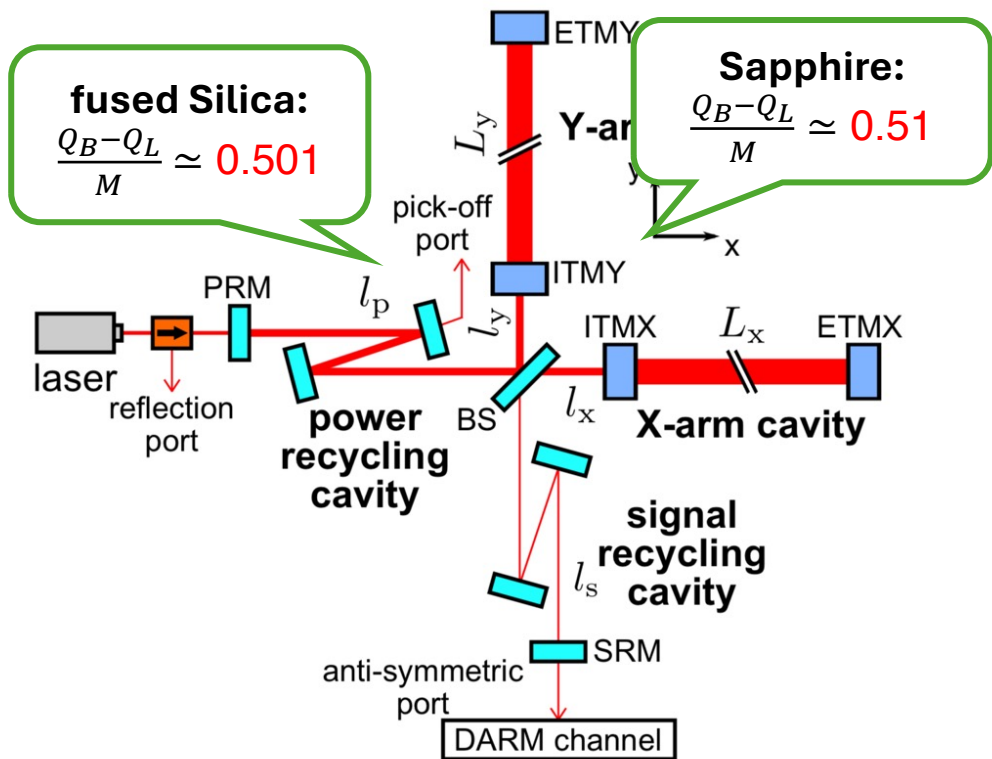
$\rightarrow$  tightest bounds for  $m_A \sim 10^{-12} \sim 10^{-11} \text{ eV}$

**KAGRA has a unique strength!!**



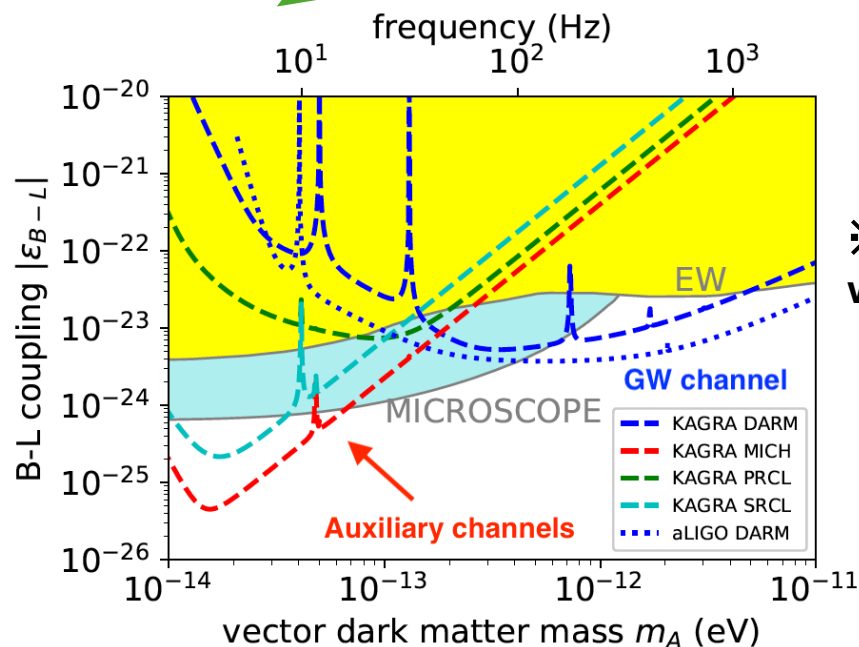
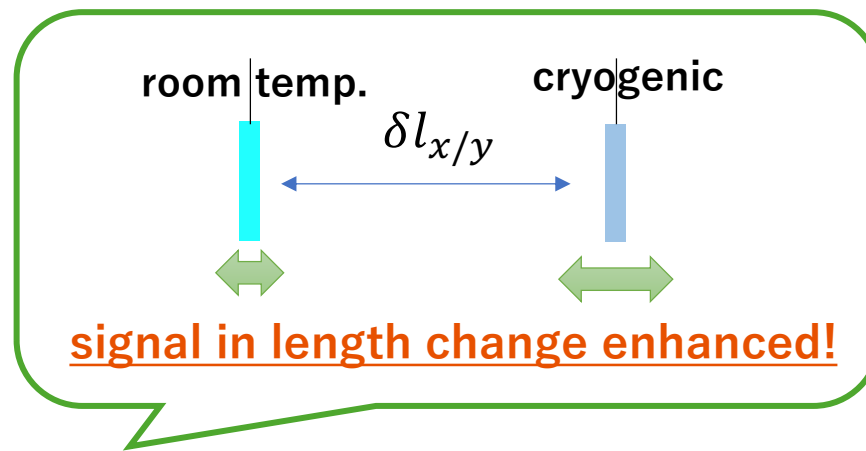
(LVK Collaboration 2022)

• VDM search in KAGRA: auxiliary DoFs



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

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



(Y. Michimura+ 2020)

✳1 year obs.  
w/ design sensitivity

For low mass  $U_{B-L}(1)$ ,  
KAGRA is the best!!

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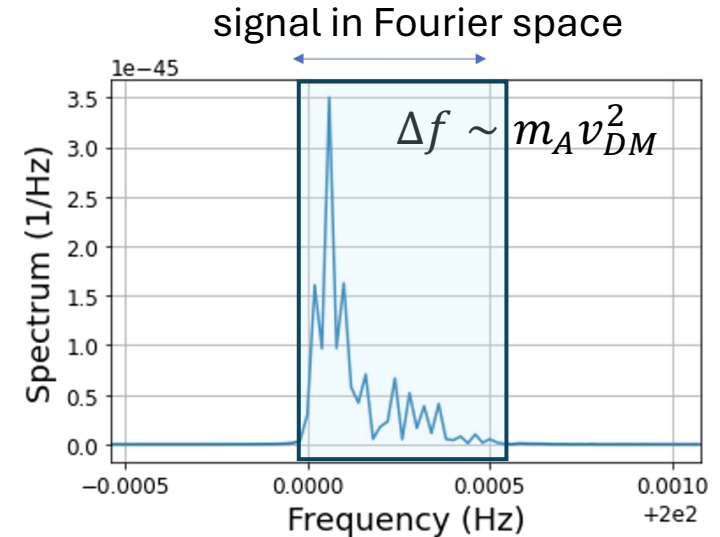
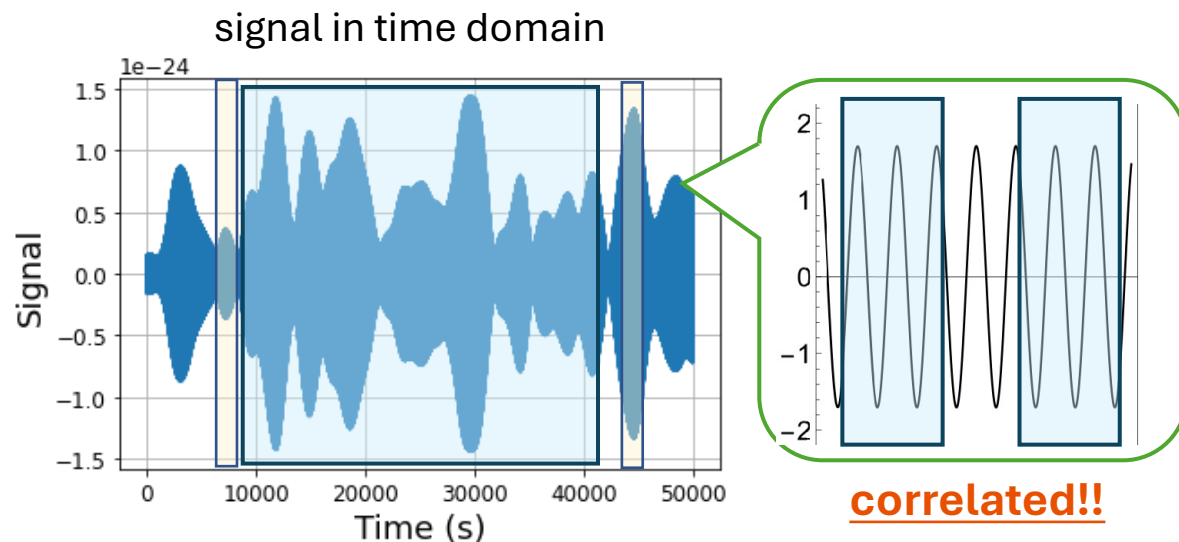
- A signal we're looking for...

$$\Phi(t, \vec{x}) = \sigma_\phi N_\phi^{-1/2} \sum_{i=1}^{N_\phi} \cos(m(1 + v_i^2/2)t + m\vec{v}_i \cdot \vec{x} + \theta_i)$$

narrow width:  $\Delta f \sim f_c v_{DM}^2 \sim 10^{-6} f_c$  with  $f_c = m_A/2\pi$

➔ similar to Continuous GW search 🤔

⚠ **ULDM statistics matters** in various aspects!!



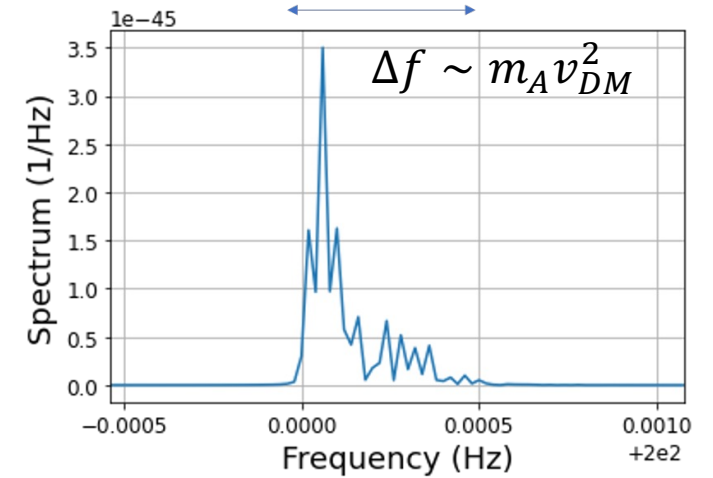
- Gaussian but  $\langle h^*(f, t)h(f, t') \rangle \neq 0$  for  $t \neq t'$
- $\text{SNR} \propto T_{\text{tot}}^{1/4}$  for  $T_{\text{tot}} > \tau \equiv 2\pi/m\bar{v}^2$
- Amplitude ambiguity for  $T_{\text{tot}} < \tau$ 
  - ➔ needs to be marginalized out in placing bounds (Nakatsuka, Morisaki, Fujita, **JK+** 2023)
- Chucked data  $T_{\text{ch}} < \tau$  loses signal coherence

- Incoherent sum: CW-inspired simple approach

accounting for the ULDM spectral feature:

$$\rho(f_c) \equiv \sum_i^{N_{\text{ch}}} \rho_i(f_c) \quad \rho_i(f_c) \equiv \sum_{f_c \leq f_n \leq f_c(1+\kappa^2\bar{v}^2)} \frac{4|\tilde{d}(f_n; t_i)|^2}{TS(f_n; t_i)}$$

- chunk the data, collect power excess within  $\Delta f$
- construct  $\mathcal{L}(\rho|\epsilon_D)$  by simulating  $\rho = \rho_{n^2} + \epsilon\rho_{n \cdot s} + \epsilon^2\rho_{s^2}$
- numerical likelihood naturally accounts for ULDM statistics
  - $\rho \propto T_{\text{tot}}^{1/4}$  for  $T_{\text{tot}} > \tau$
  - amplitude randomness for  $T_{\text{tot}} < \tau$

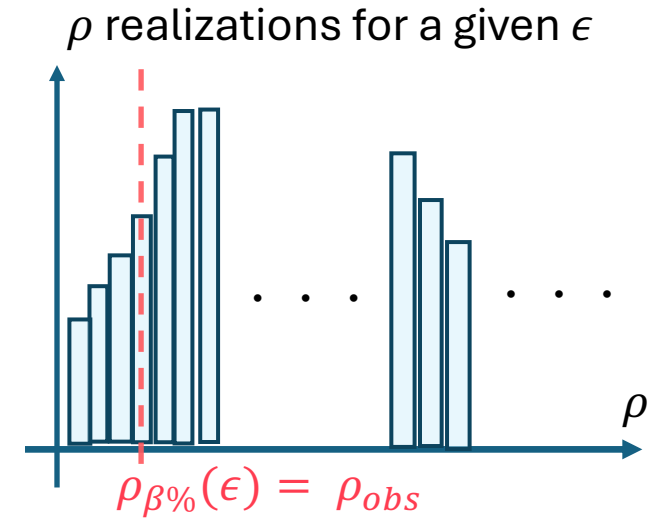


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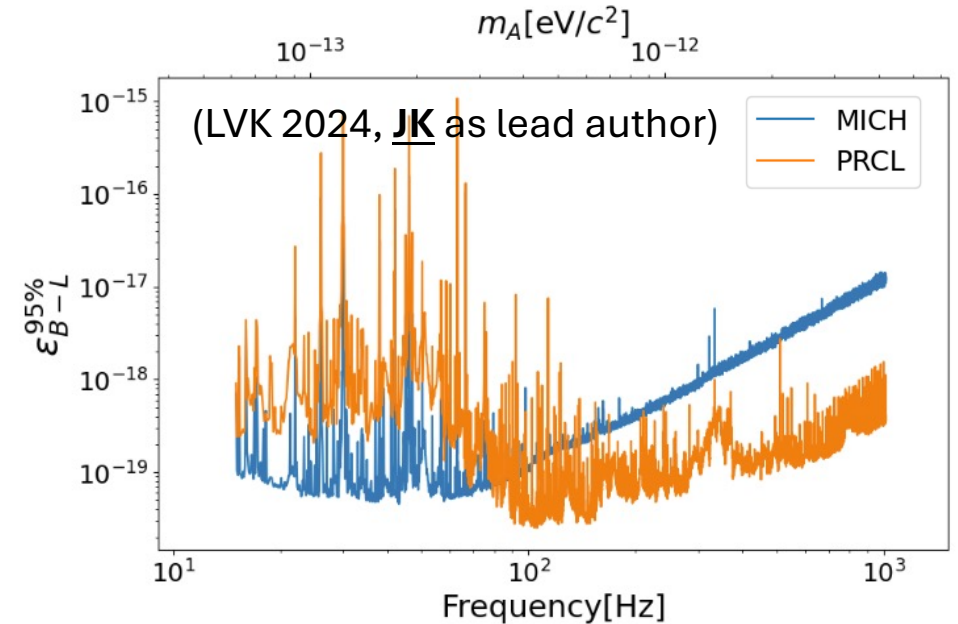
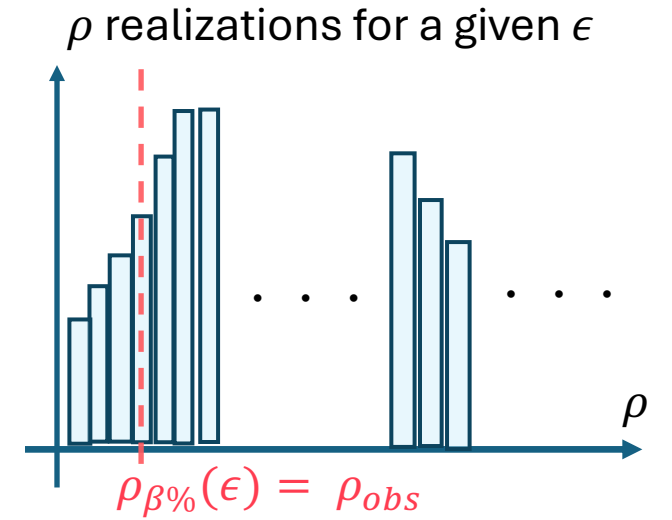


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- applied to KAGRA O3GK data  $\rightarrow$  **KAGRA's first deliverable!!**



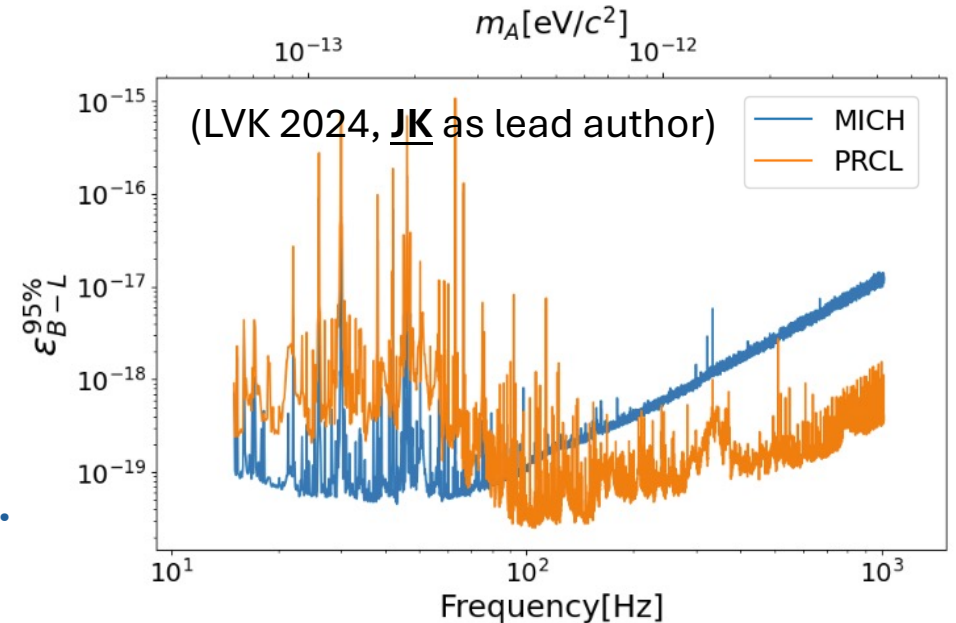
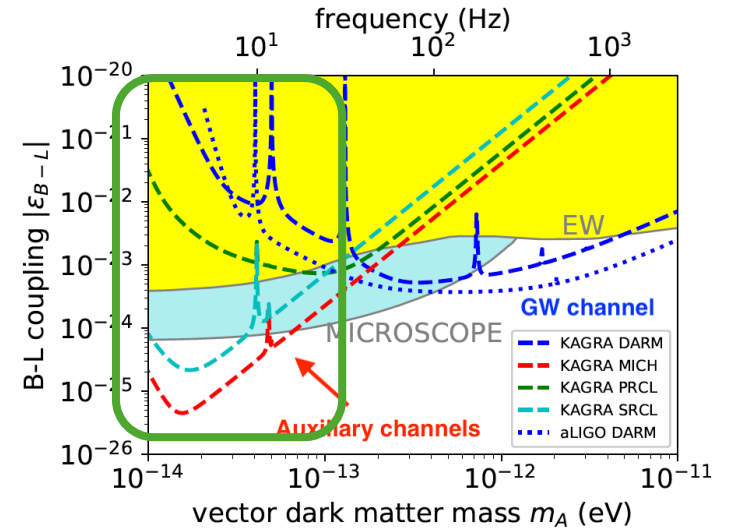
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- applied to KAGRA O3GK data  $\rightarrow$  **KAGRA's first deliverable!!**

For  $\tau(m_A) > T_{ch} = 1800s$ , summation of signal is degraded...



- Optimal filtering: maximizing SNR of quadratic form (Morisaki, JK+ 2025)

setting detection statistics:  $\rho = \vec{d}^\dagger \mathcal{K} \vec{d}$

and find  $\mathcal{K}$  that maximizes  $\text{SNR} \equiv (\langle \rho \rangle - \langle \rho \rangle|_{\epsilon=0}) / \sqrt{\text{Var}[\rho]|_{\epsilon=0}}$

※ Incoherent sum:  $\mathcal{K} = \mathcal{N}^{-1}$  (inv. of noise covariance)



**optimal filtering:**

$$\rho = \vec{d}^\dagger \mathcal{N}^{-1} \mathcal{H} \mathcal{N}^{-1} \vec{d}$$

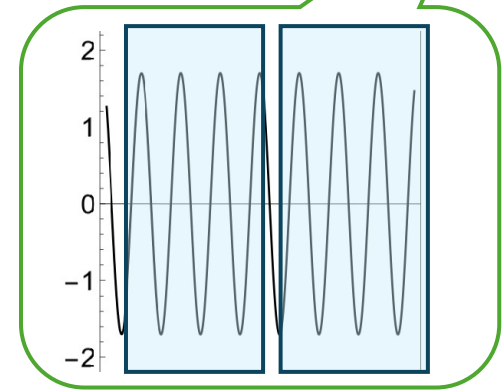
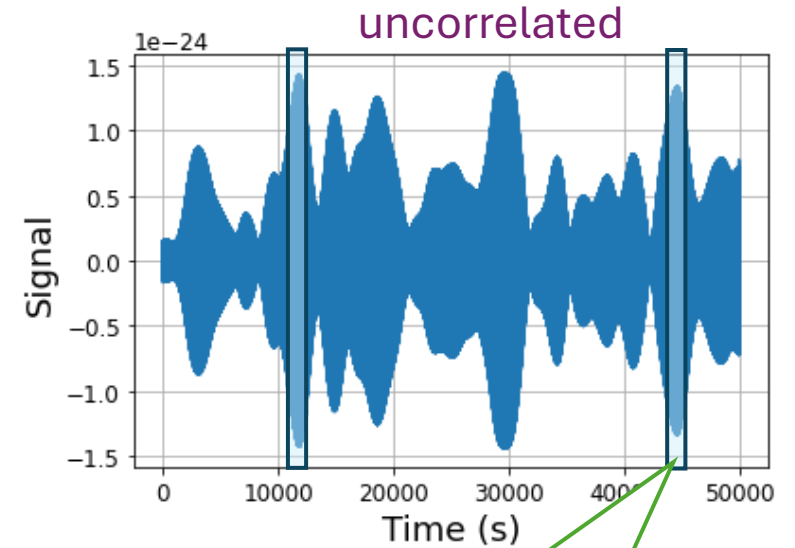
where  $\mathcal{H} \equiv \langle \tilde{h}(f, t_S) \tilde{h}^*(f', t_{S'}) \rangle / \epsilon^2$  is ULDM signal covariance

$\rho$  coherently sums the signal **over  $T_{\text{tot}}$ !!**

For  $T \ll \tau$ , covariance matrix is much simplified:

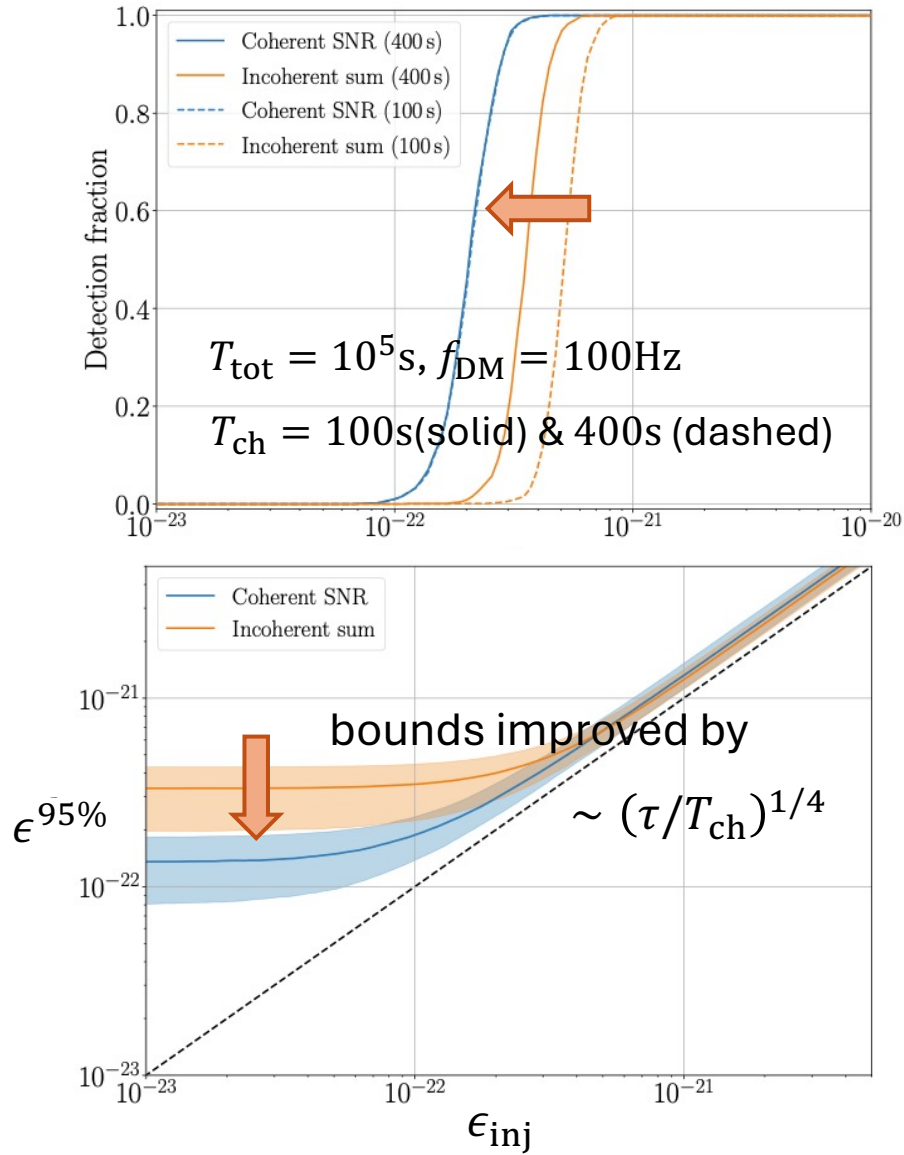
$$\mathcal{H}_{f_S, f'_{S'}} \propto \tilde{w}(f - f_c, S) \tilde{w}^*(f' - f_c, S') \mathbf{R}(t_S - t_{S'})$$

$\tilde{w}$ : window function      $\mathbf{R}(t_S - t_{S'})$ : **analytic function** (for SHM)

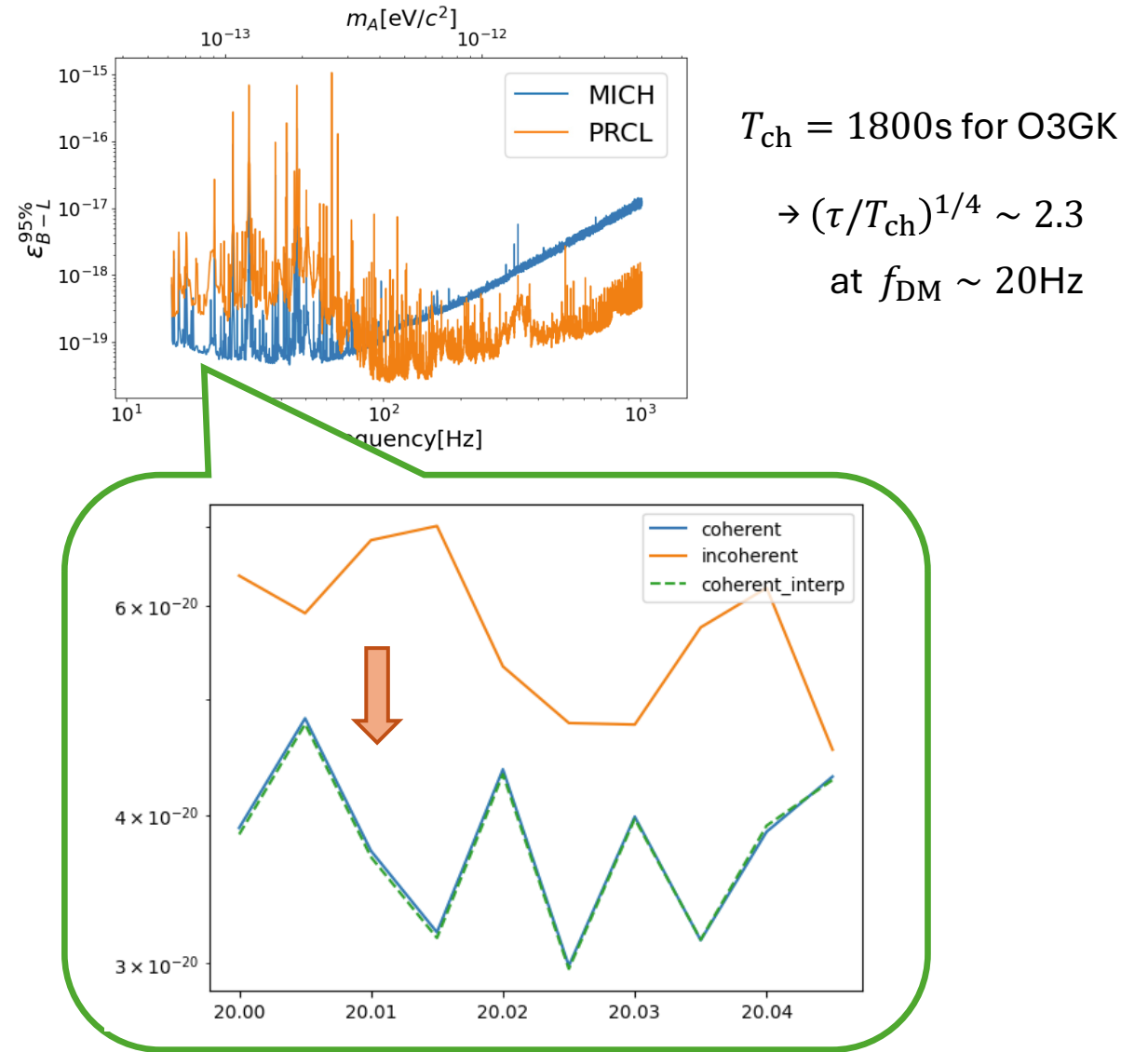


**correlated!!**

Incoherent vs coherent  
with simulated KAGRA MICH data



Re-analyze O3GK MICH data



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- A window for ultralight DM
- DM interaction with laser interferometers
- Optimizing ULDM signal search
- Summary

# Summary

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- **Ultralight bosonic fields** are widely investigated as DM candidate  
wave-like behavior and field covariance characterized by  $\tau_{\text{coh}}$  are universal nature!!
- Laser interferometers can probe those fields by measuring  
Polarization rotation → @transmission/reflection port of GW interferometer  
Test-mass displacement → KAGRA's auxiliary DoFs works for  $U_{B-L}(1)$  boson search
- **ULDM search in KAGRA has already initiated!!**  
O3GK: first & simple end-to-end analysis for vector DM  
O4c: analysis with an improved search method (coherent sum), both for vector & ALP!!!

Tampere Cosmology Meeting, May 7th, 2026

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# Gravitational Wave Interferometer as Ultralight Dark Matter Detector

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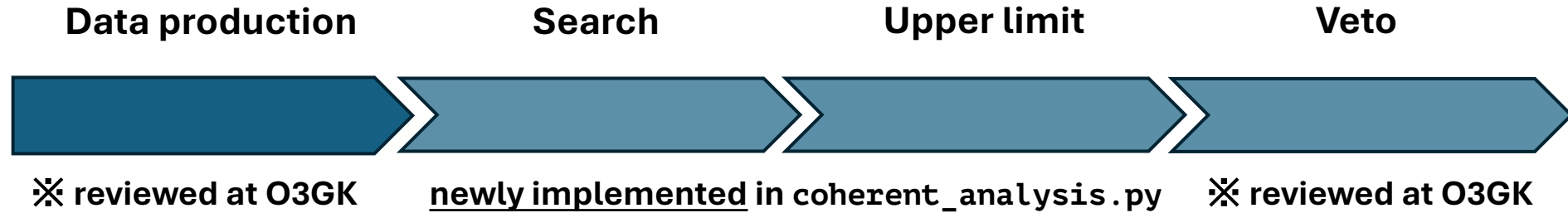
Based on: Phys.Rev.D 108 (2023) 9, 092010

Phys.Rev.D 110 (2024) 4, 042001

Phys.Rev.D 113 (2026) 7, 075016

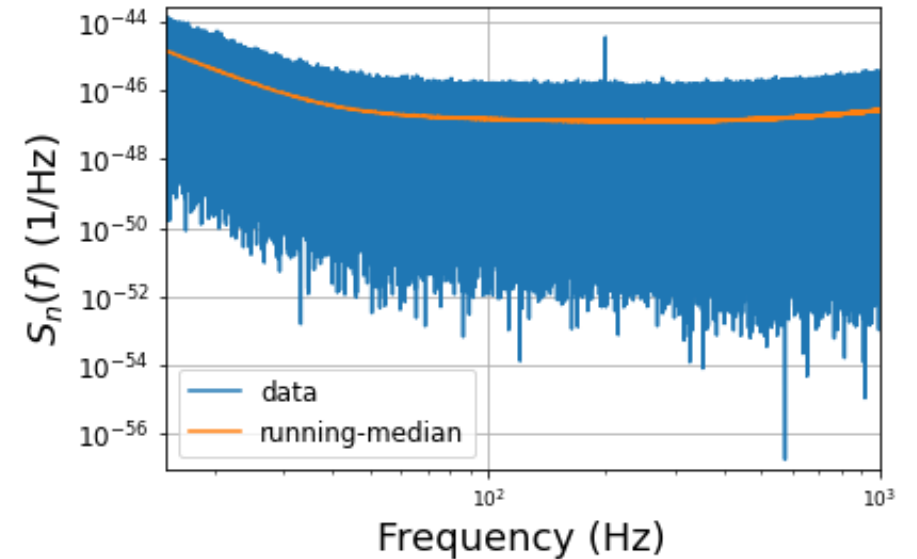
ダークマターの正体は何か？  
広大なディスカバリースペースの網羅的研究  
What is dark matter? - Comprehensive study of the huge discovery space in dark matter

- Analysis Flow (source code: `kagra_dm_search`)

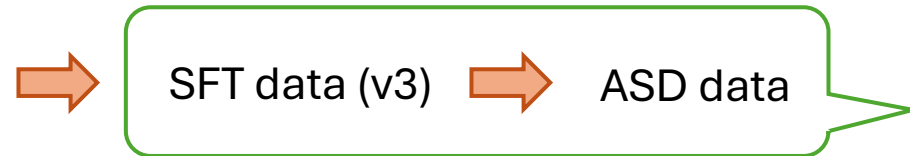


Producing inputs of our analysis code

- `lalpulsar_MakeSFTs` (cf. LIGO-T040164)  
 options: window, chunk duration, frequency range, ...  
 Tukey window with  $r = 10^{-3}$ , no overlap  $\rightarrow \tilde{w}(f) \sim T\delta(f)$
- `kagra_dm_estimate_asd` (`or_estimate_asd.py`)  
 running median method  $\rightarrow$  mitigate narrow band outlier

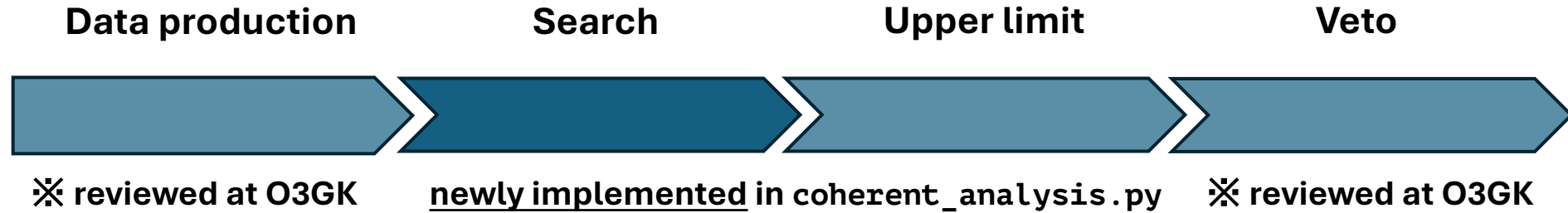


MICH/PRCL DISPLACEMENT  
polarization data



read as `SFT_ASD_Database` class

- Analysis Flow (source code: `kagra_dm_search`)



SFT\_ASD\_Database & FrequencyRangeIndex -> analysis class: OnBinAnalytic

# class for  $T_{\text{seg}} \ll \tau_{\text{coh}}$  -> analytic expression of signal covariance

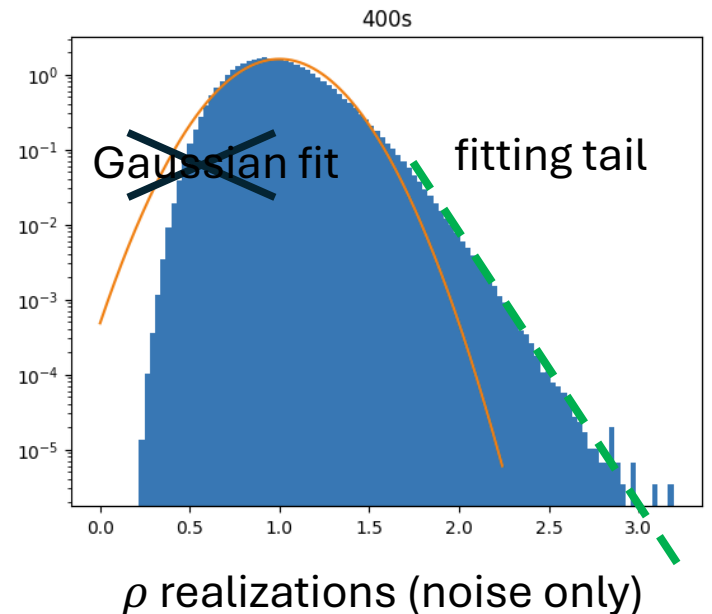
## FrequencyRangeIndex -> binning info & job splitting (also reviewed at O3GK)

- `compute_snrs` -> detection statistics  $\rho$
- `search` -> detection threshold at a given FAP

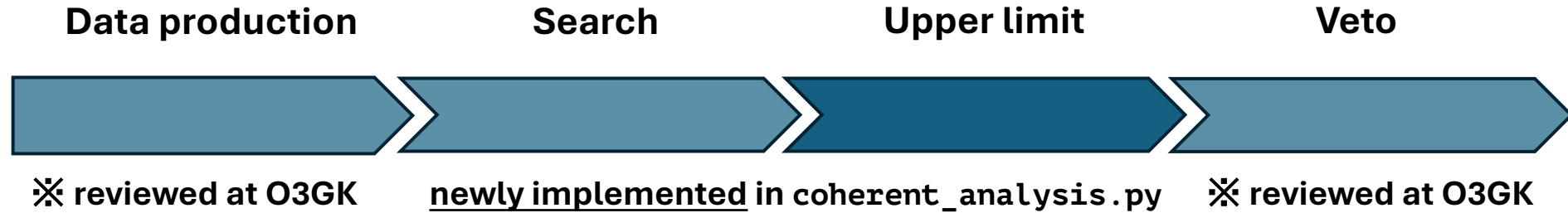
$\vec{d}$ : stationary & Gaussian noise only  $\rightarrow \rho$  obeys “generalized chi2” dist.



- saddle point approximation for CDF (Lugannai-Rice 1980)
- importance sampling of tailed distribution (e.g. Esscher 2007)



- Analysis Flow (source code: kagra\_dm\_search)



SFT\_ASD\_Database & FrequencyRangeIndex -> analysis class: OnBinAnalytic

- compute\_snrs -> detection statistics  $\rho$
- constrain -> frequentist upper limit on DM coupling at a given CL

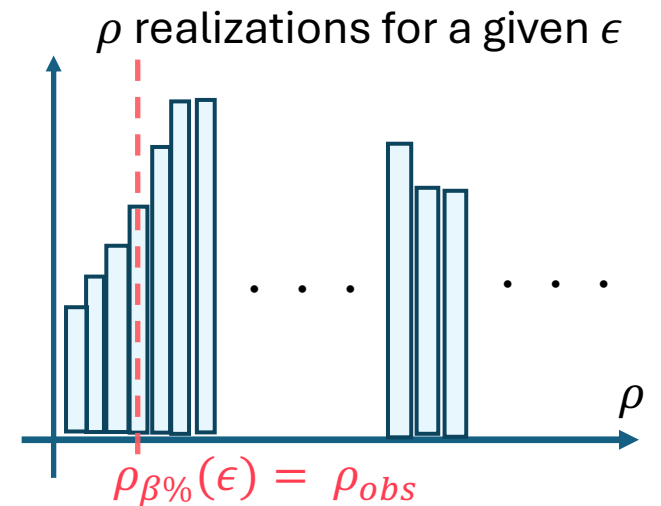
simulate many realizations of  $\rho(f_c, \epsilon) = \rho_{n^2} + \epsilon \rho_{n \cdot s} + \epsilon^2 \rho_{s^2}$

→ find the value of  $\epsilon$  where  $\beta\%$  percentile of  $\rho$

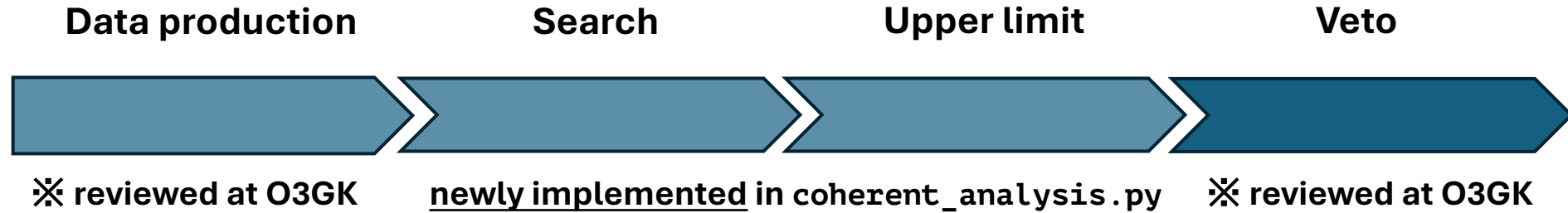
# same method as O3GK, but more expensive...

➡ • interpolator\_sample & interpolating\_bounds

construct  $\epsilon_{\beta\%}(\rho_{obs})$  from realizations at a given point, apply this interpolator for a given band



- Analysis Flow (source code: `kagra_dm_search`)



Two methods used at O3GK will be applied:

- Width of candidates

signal width must be  $\Delta f \sim 10^{-6} f_c$

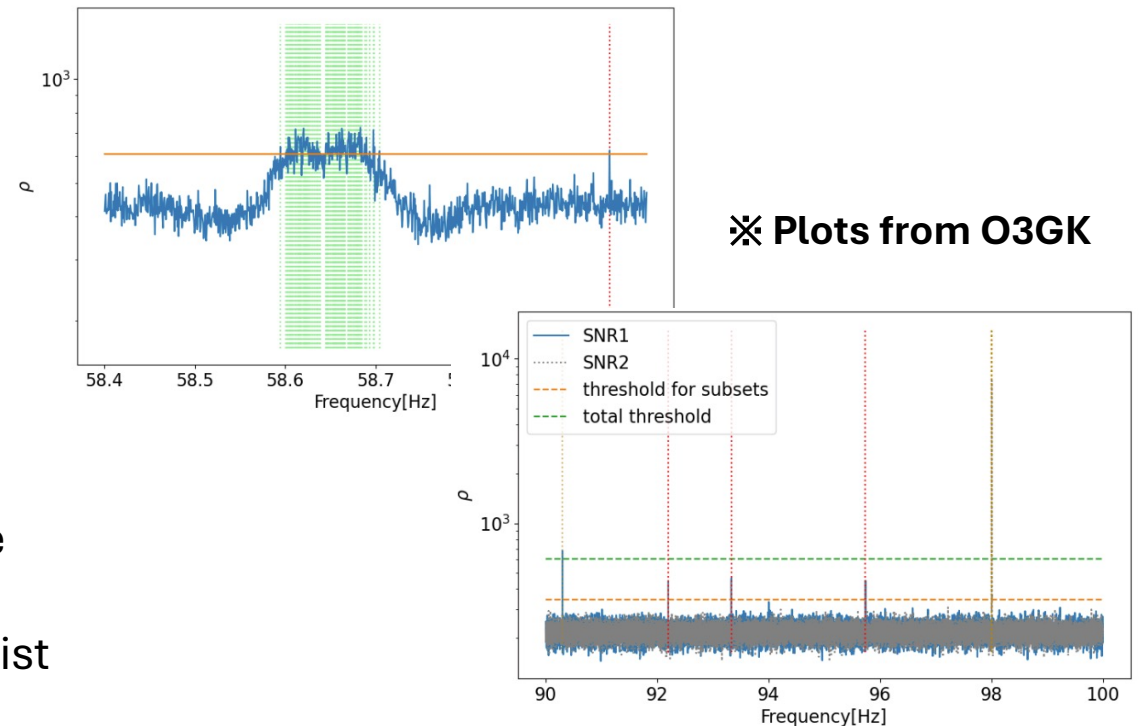
→ veto peaks wider than the twice of  $10^{-6} f_c$

- Persistency of signal

Signals can be distinguished from transient noise.

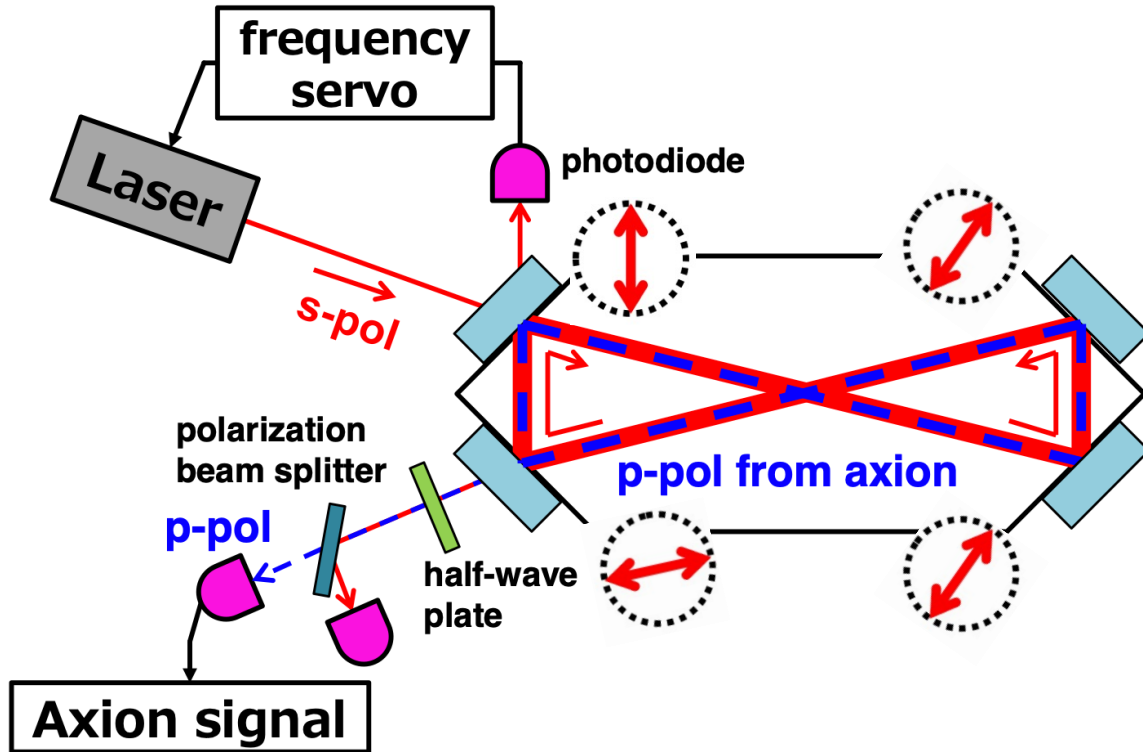
→ divide the data into two subsets & take coincidence

➔ Final candidates will be summarized into a list



# ⌘ Axion-like-DM “targeted” interferometer

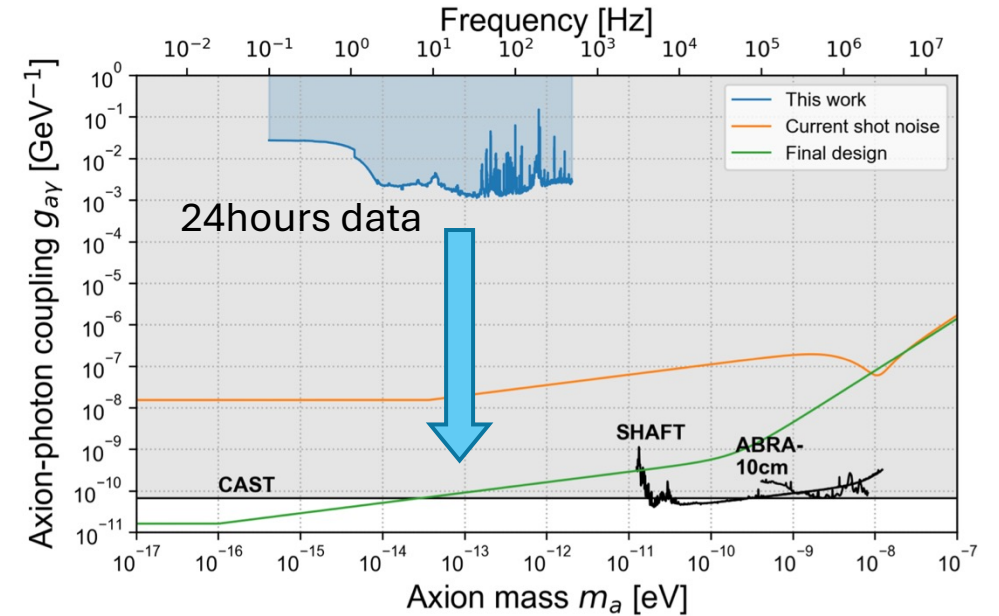
Bow-tie cavity can accumulate the rotation!!



Dark matter Axion search with riNg Cavity Experiment

(I. Obata+ 2018)

First end-to-end analysis from test run



(Oshima, Fujimoto, JK+ 2023)

To be upgraded further!

finesse, longer round-trip, laser power, ...

- Stochasticity of ULDM field and its effect

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

Fourier transformed field (over  $T$ ):

$$\tilde{\Phi}(f_n) \simeq \frac{T}{2} \sigma_\phi \sqrt{\Delta_s(f_n)} \left[ \frac{r_n}{\sqrt{2}} \exp(i\theta_n) \right]$$

narrow band spectra  
due to velocity dispersion

$\theta_n$ : uniform dist.  
 $r_n$ : Rayleigh dist.

( $\otimes$  summation of the random phase  $\rightarrow$  2d random walk)

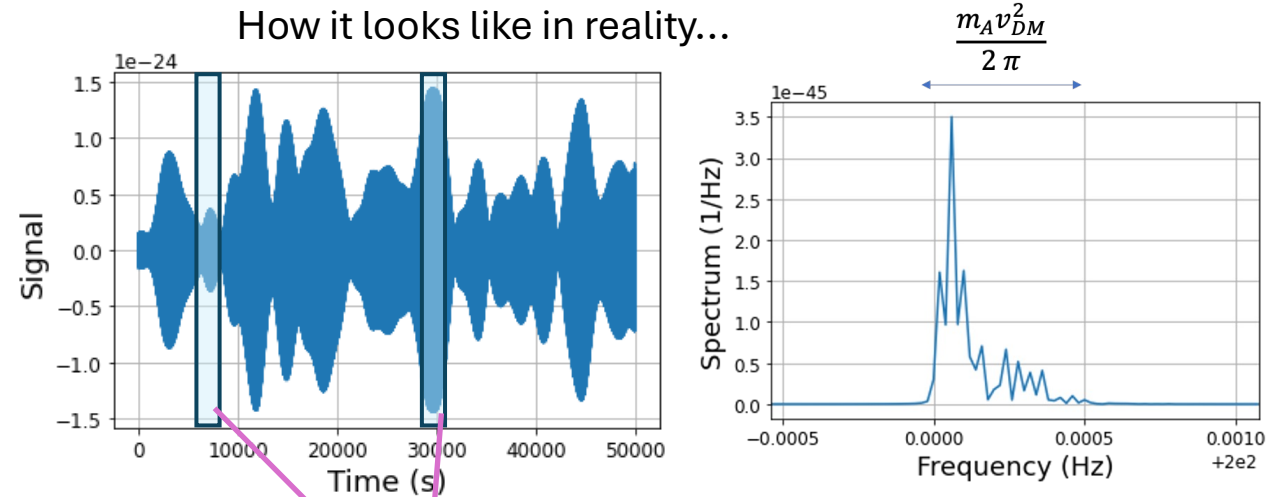
For  $T < \tau \equiv 2\pi/mv^2$  (lighter mass w/ fixed  $T$ ),  
randomness of amplitude loosens bound!

(e.g. G. P. Centers+ 2020)

For  $T > \tau$  (heavier mass w/ fixed  $T$ ),  
SNR slowly grows as  $T^{1/4}$  because of decoherence.

$\rightarrow$  analysis pipeline needs to take into account these.

How it looks like in reality...



Upper bound prediction for axion search

