GEMMA2 @ Rome, Italy.
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ICRR
Institute for Cosmic Ray Research
University of Tokyo

Direct searches for Ultra-light Dark Matter Using Gravitational-Wave Detectors

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Ultra-light bosonic dark matter

- Bosonic field with mass smaller than $1\ \mathrm{eV}$.

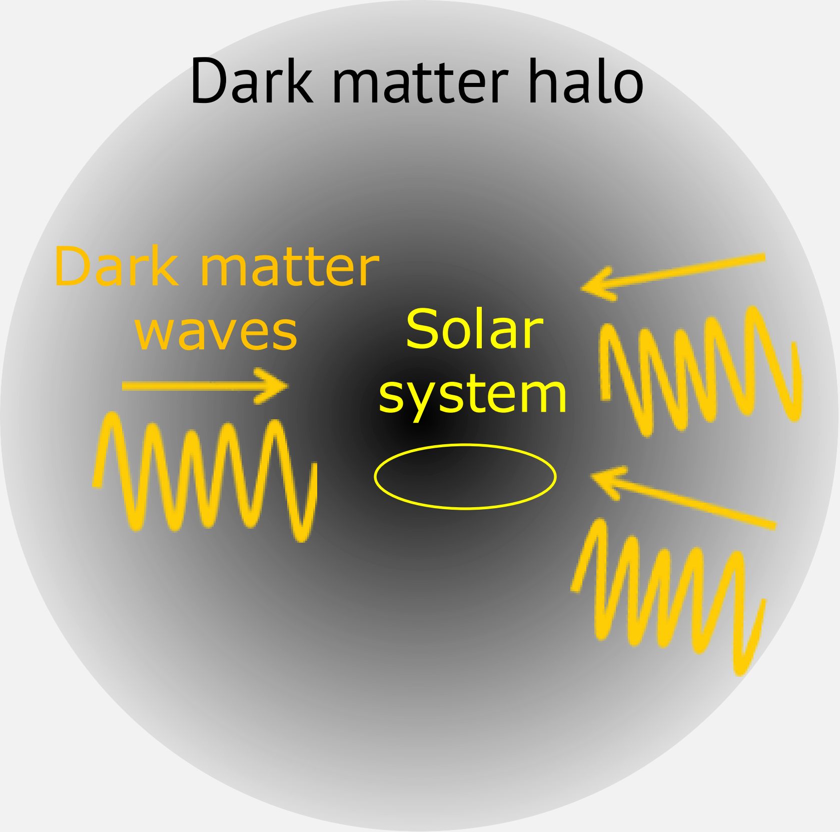
- It behaves as classical wave in the Galaxy due to its large occupation number:

$$\frac{\Delta N}{\Delta x^3 \Delta p^3} \sim \frac{\rho_{\mathrm{DM}}}{m_{DM}^4 v_{\mathrm{vir}}^3}$$

$$= 8 \times 10^3 \left(\frac{1\ \mathrm{eV}}{m_{DM}}\right)^4 \left(\frac{\rho_{\mathrm{DM}}}{0.4\ \mathrm{GeV/cm^3}}\right)\left(\frac{220\ \mathrm{km/sec}}{v_{\mathrm{vir}}}\right)^3.$$

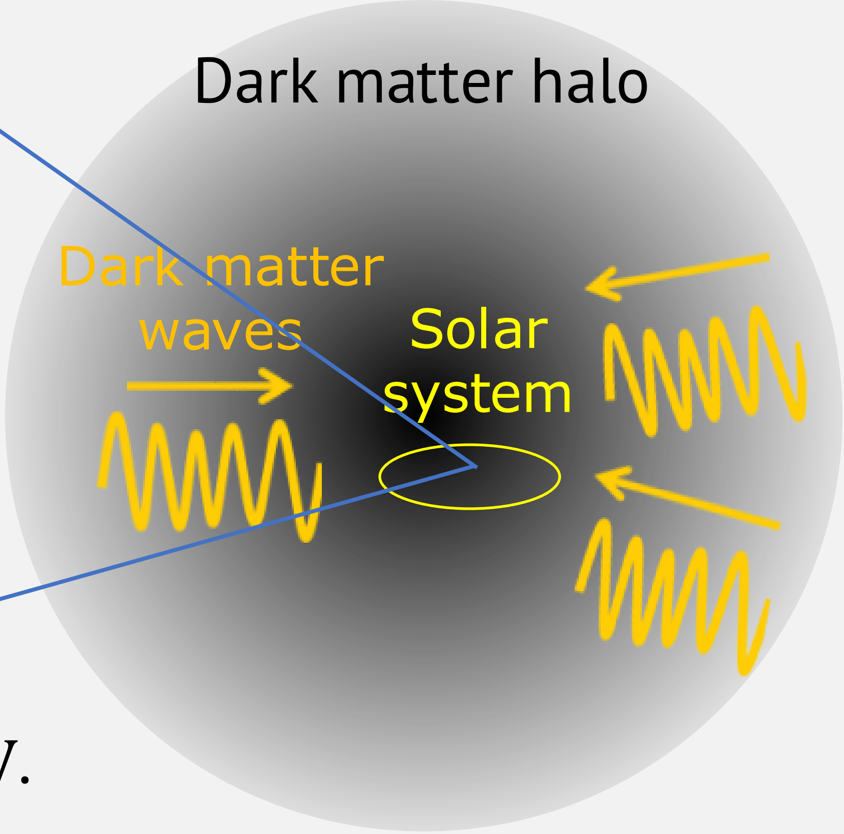
m_{DM}: boson's mass, ρ_{DM}: DM density,
v_{vir}: virial velocity.

- Sharp frequency spectra around $f_{DM} = m_{\mathrm{DM}}/2\pi$ due to small DM velocities, $v_{\mathrm{vir}}/c \sim 10^{-3}$.



Ultra-light bosonic dark matter

Figure credit:
The Virgo collaboration/CCO 1.0
ICRR, Univ. of Tokyo
Caltech/MIT/LIGO lab



- $1\ \mathrm{Hz} \lesssim f_{DM} \lesssim 10^4\ \mathrm{Hz}$ for $10^{-14}\ \mathrm{eV} \lesssim m_{DM} \lesssim 10^{-11}\ \mathrm{eV}$.
  → Ground-based GW detectors are sensitive to ultralight bosonic DM!
- Observed as a stochastic signal with sharp spectra .

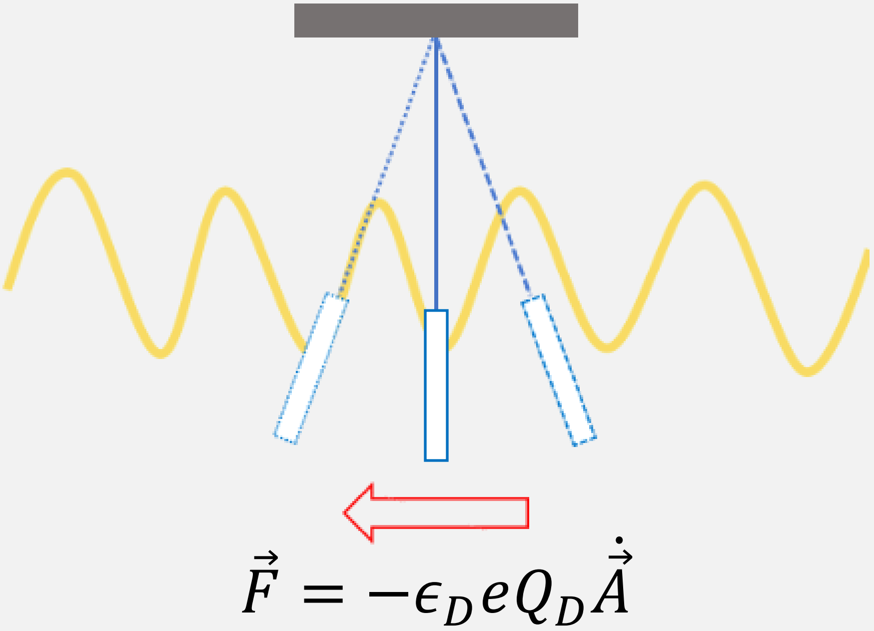
Dark photon: model

Ref: A. Pierce, K. Riles, Y. Zhao, PRL **121**, 061102 (2018).

Massive vector field A^μ coupling to B or $B-L$ current (B (L): baryon (lepton) number):

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

$D = B$ or $B-L$,
m_A: dark photon mass,
ϵ_D: coupling constant.



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

Dark photon exerts a force on the test masses.

Force is proportional to

- coupling constant ϵ_D, and
  (ϵ_D is constrained if no signal is found.)
- the D charge of a test mass, Q_D.
  (Force depends on composition of the mass.)

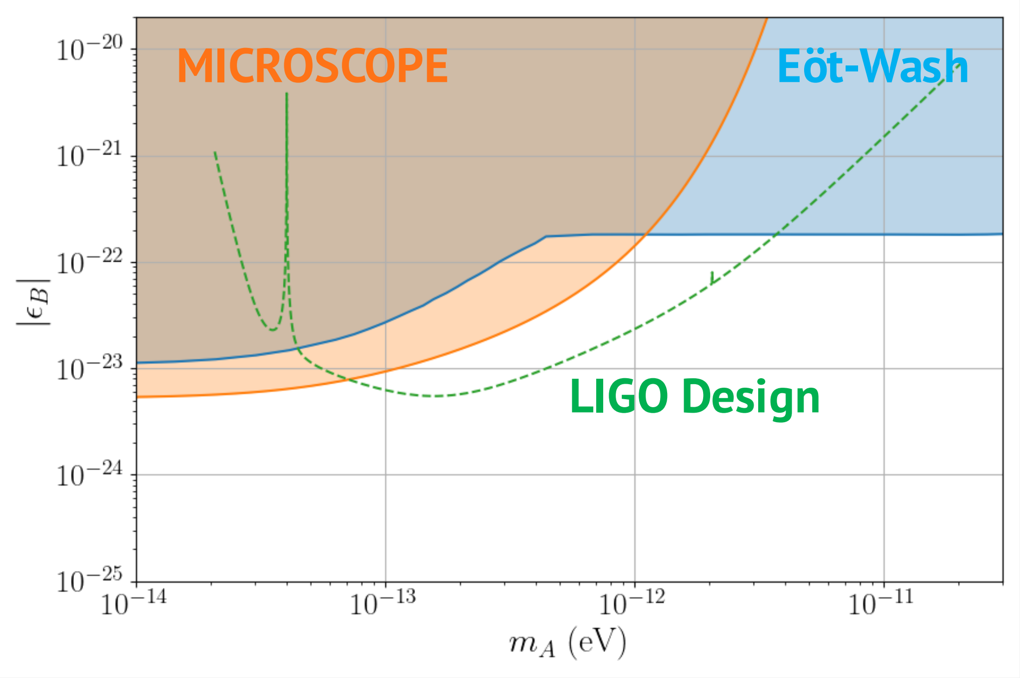
Dark photon: sensitivity

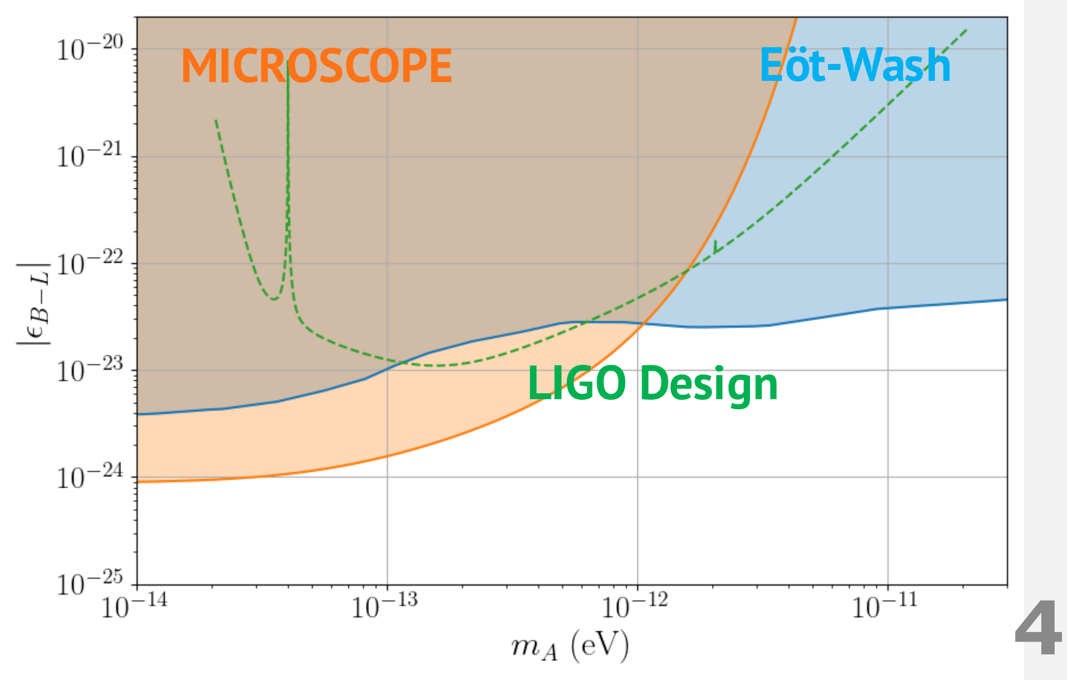
Signal is significantly suppressed because displacements of mirrors in LIGO and Virgo are almost common.

- Wavelength of dark photon is much larger than the detector sizes:

$$\lambda \sim 3 \times 10^{5} \left(\frac{10^{-3}}{v_{\mathrm{DM}}/c}\right)\left(\frac{1\ \mathrm{kHz}}{f_{\mathrm{DM}}}\right)\ \mathrm{km}.$$

- Their test mases are all made of fused silica and have the same composition.

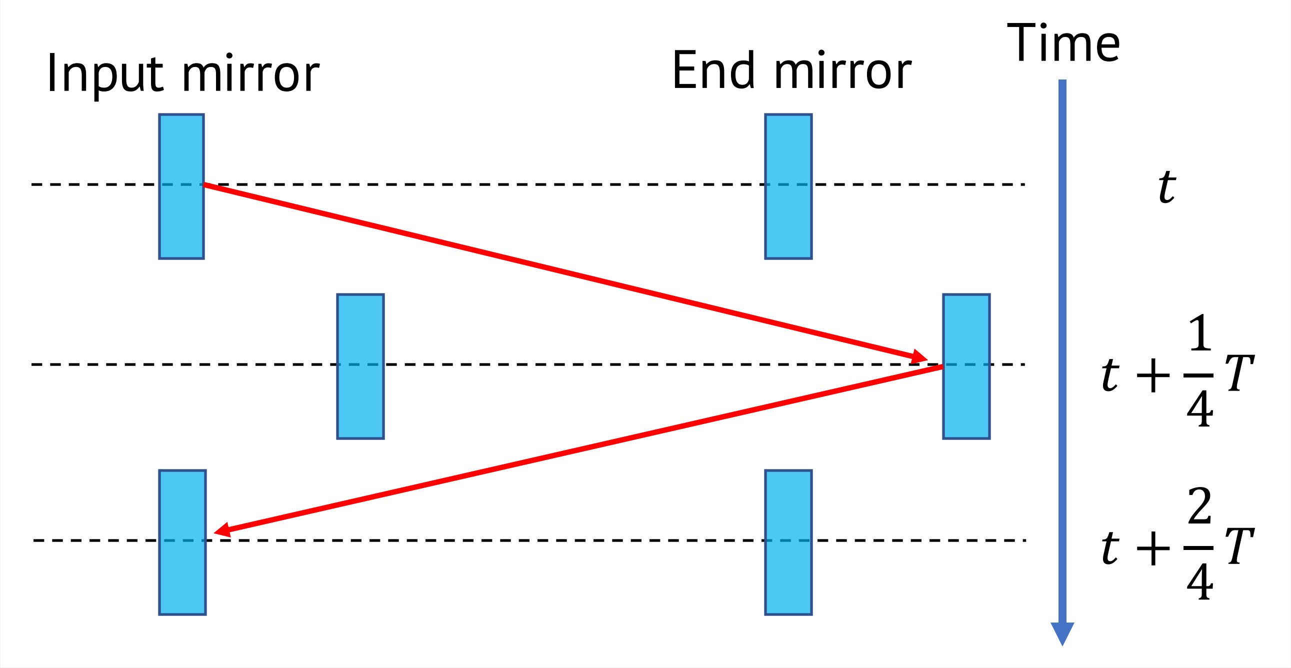


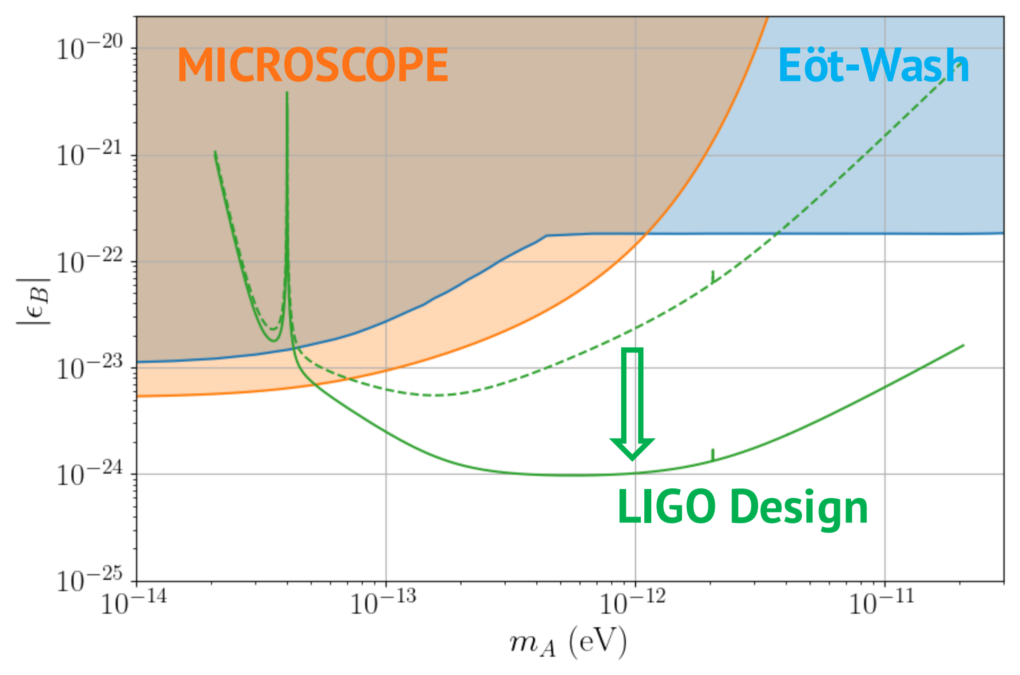


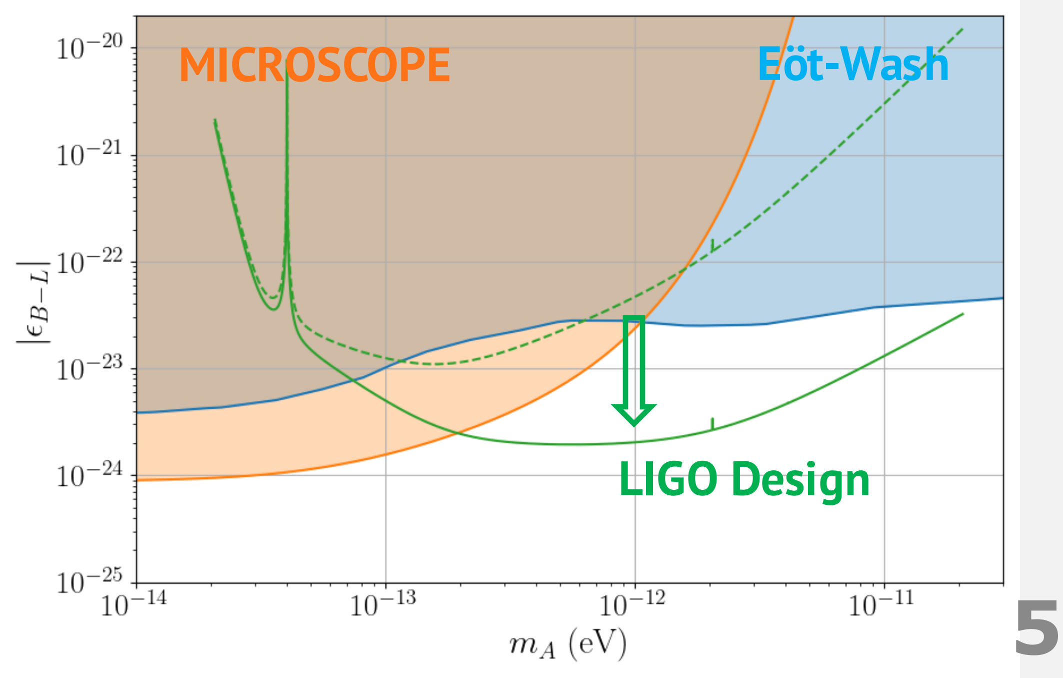
Dark photon: sensitivity

Even for common displacements ,
there is apparent length change due to
finite light-traveling time.

Ref: ***SM***, T. Fujita, Y. Michimura, H. Nakatsuka, I. Obata,
PRD **103** 5, L051702 (2021).







Dark photon: future prospects

Figure from ***SM***, T. Fujita, Y. Michimura, H. Nakatsuka, I. Obata, PRD **103** 5, L051702 (2021).

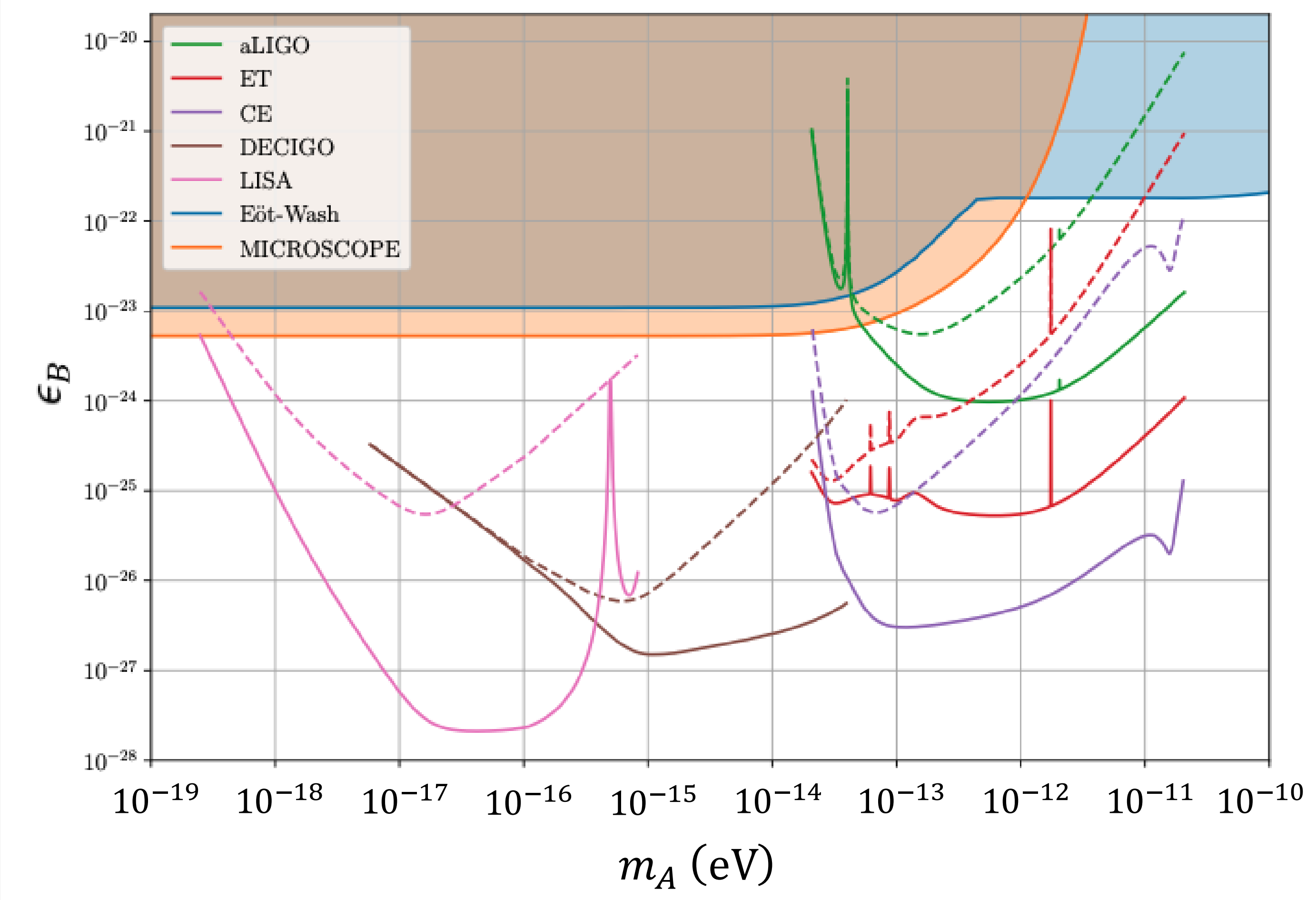


Figure: Estimated constraints with future gravitational-wave detectors

- Future ground- and space-based GW detectors can probe DM with much smaller couplings at $10^{-19}\ \mathrm{eV} \lesssim m_A \lesssim 10^{-10}\ \mathrm{eV}$.
- See Andrew's talk on Thursday for search results with LIGO/Virgo O3 data.

Dark photon: KAGRA auxiliary channels

KAGRA employs sapphire for cryogenic mirrors, which form cavities.

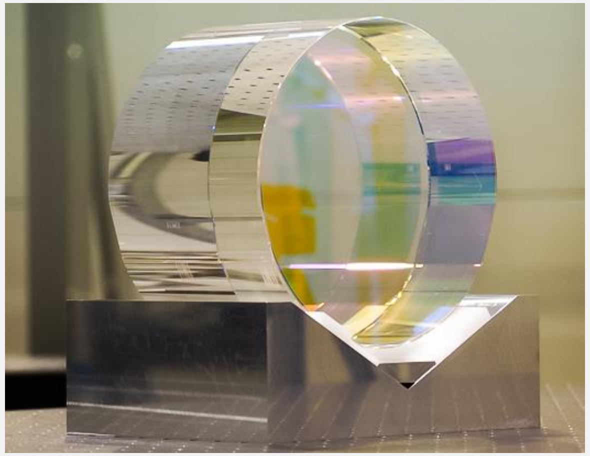
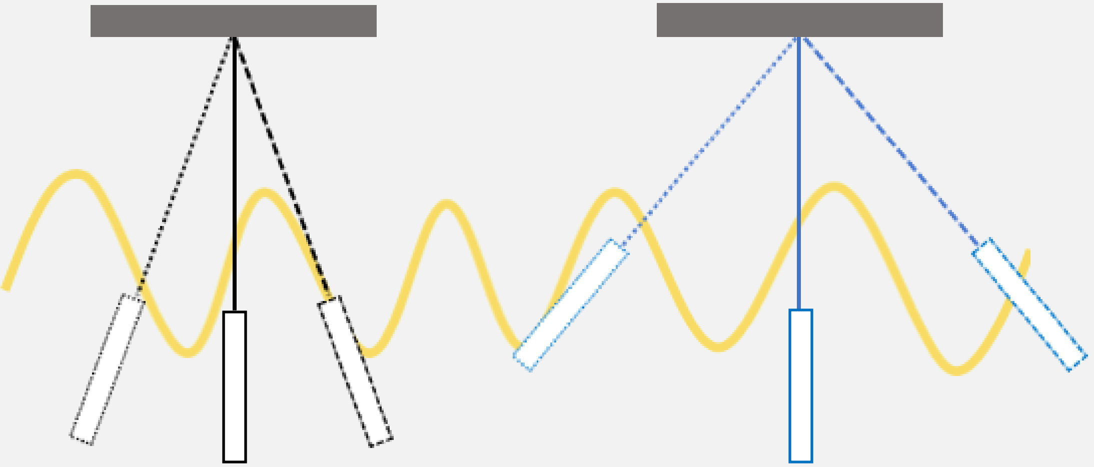


Figure: KAGRA's sapphire mirror



Beam splitter
(fused silica)

Input mirror of cavity
(sapphire, larger Q_{B-L} per unit mass)

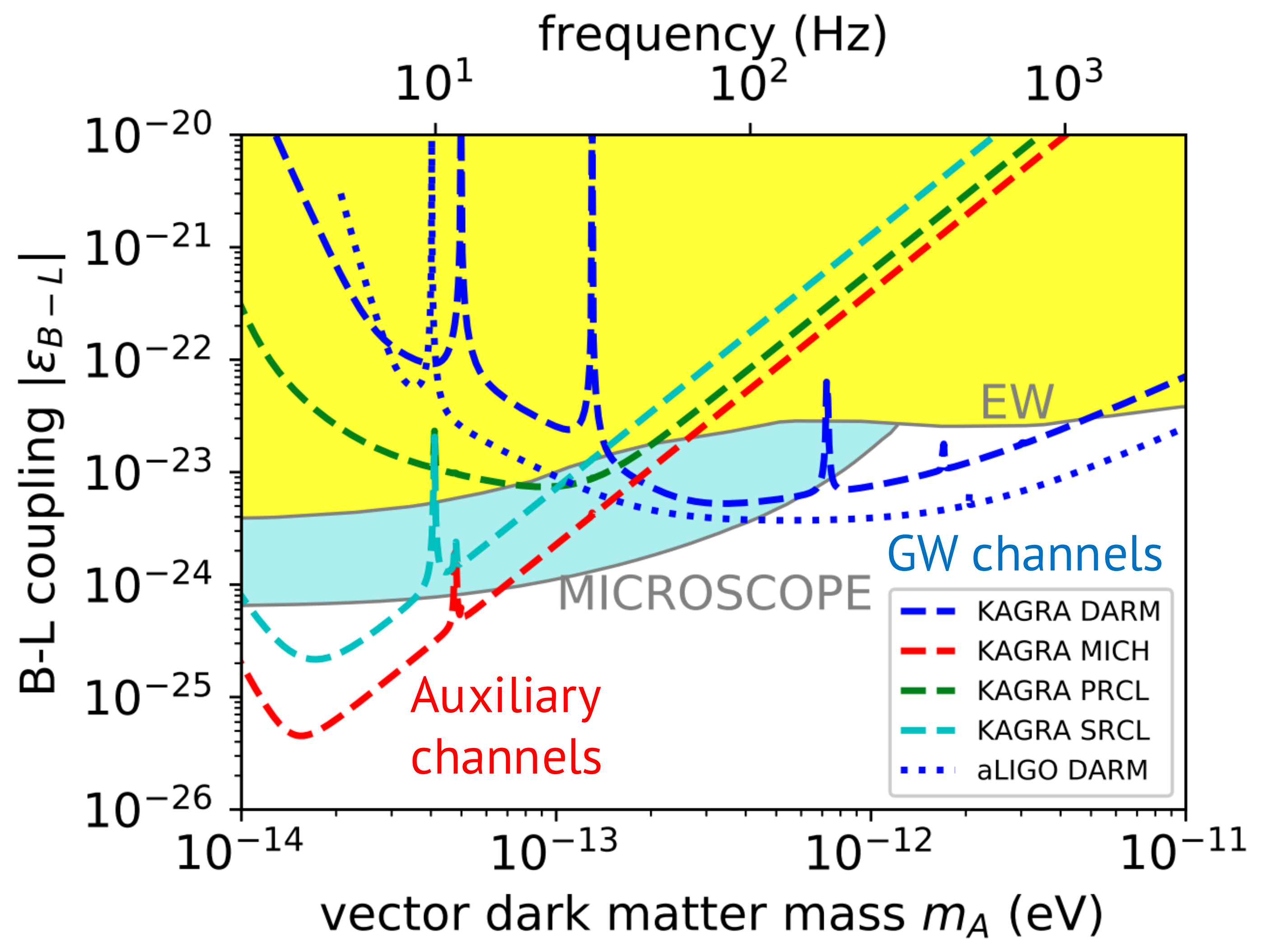
Different magnitudes of forces exerted on the beam splitter and cavity mirrors.
→ Varying length between them.

The signal can be observed in auxiliary channels (MICH, PRCL, and SRCL) of KAGRA.

Ref: Y. Michimura, T. Fujita, ***SM***, H. Nakatsuka, I. Obata, PRD **102**, 102001 (2020).

Dark photon: future prospects

From Y. Michimura T. Fujita, ***SM***, H. Nakatsuka, I. Obata (2020).



- KAGRA's auxiliary channels complement sensitivities at low masses.
- See Jun'ya's talk on Thursday for search results with KAGRA/GEO O3 data.

Dilaton

Refs:

- ***SM*** and T. Suyama, PRD **100**, 123512 (2019).
- K. Fukusumi, ***SM,*** and T. Suyama, PRD **108**, 095054 (2023).

A massive scalar field couples to Standard-Model particles,

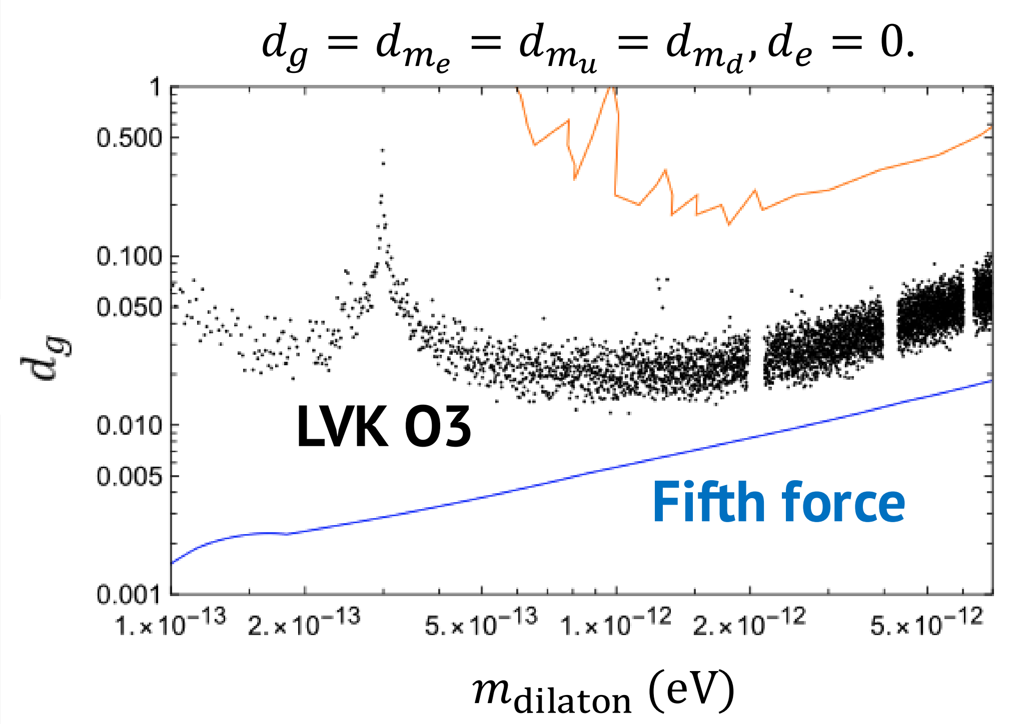
$$\mathcal{L}_{\mathrm{int}} = -\sqrt{4\pi G}\phi\left[\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G^{A\mu\nu} - \sum_{i=e,u,d}(d_{m_i}+\gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right].$$

$d_e, d_g, d_{m_e}, d_{m_u}, d_{m_d}$: coupling constants with photons, electrons, and up/down quarks.

- The force on test masses is proportional to d_i $(i = e, g, \dots)$ and spatial derivatives of ϕ:

$$\frac{d^2\vec{x}}{dt^2} = -\sqrt{4\pi G}\left(\sum_i k_i d_i\right)\vec{\nabla}\phi.$$

- Constraints from O3 data are comparable to the existing ones if $d_g = d_{m_e} = d_{m_u} = d_{m_d}, d_e = 0.$



Axion: model

Scalar field coupling to photon: $\mathcal{L} \supset \frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$

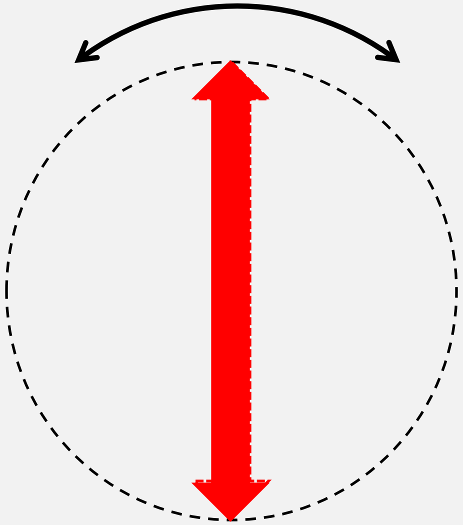
a: axion field $F_{\mu\nu}$: electromagnetic field strength $\tilde{F}^{\mu\nu} = \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$

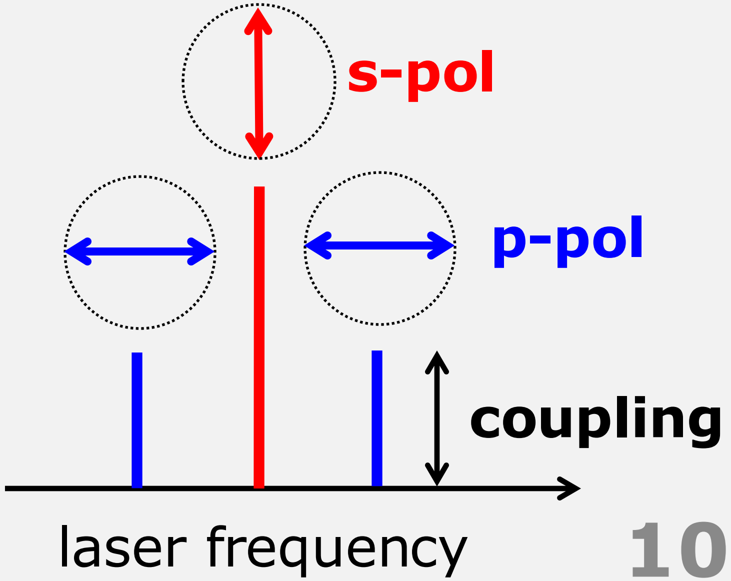
m_a: axion's mass $g_{a\gamma}$: axion-photon coupling constant

Different phase velocity between left- and right-handed circular polarized light:

$$c_{L/R} = \sqrt{1 \pm g_{a\gamma} \dot{a}/k}.$$

→ Modulated linear polarization (p-pol. sidebands from s-pol.)



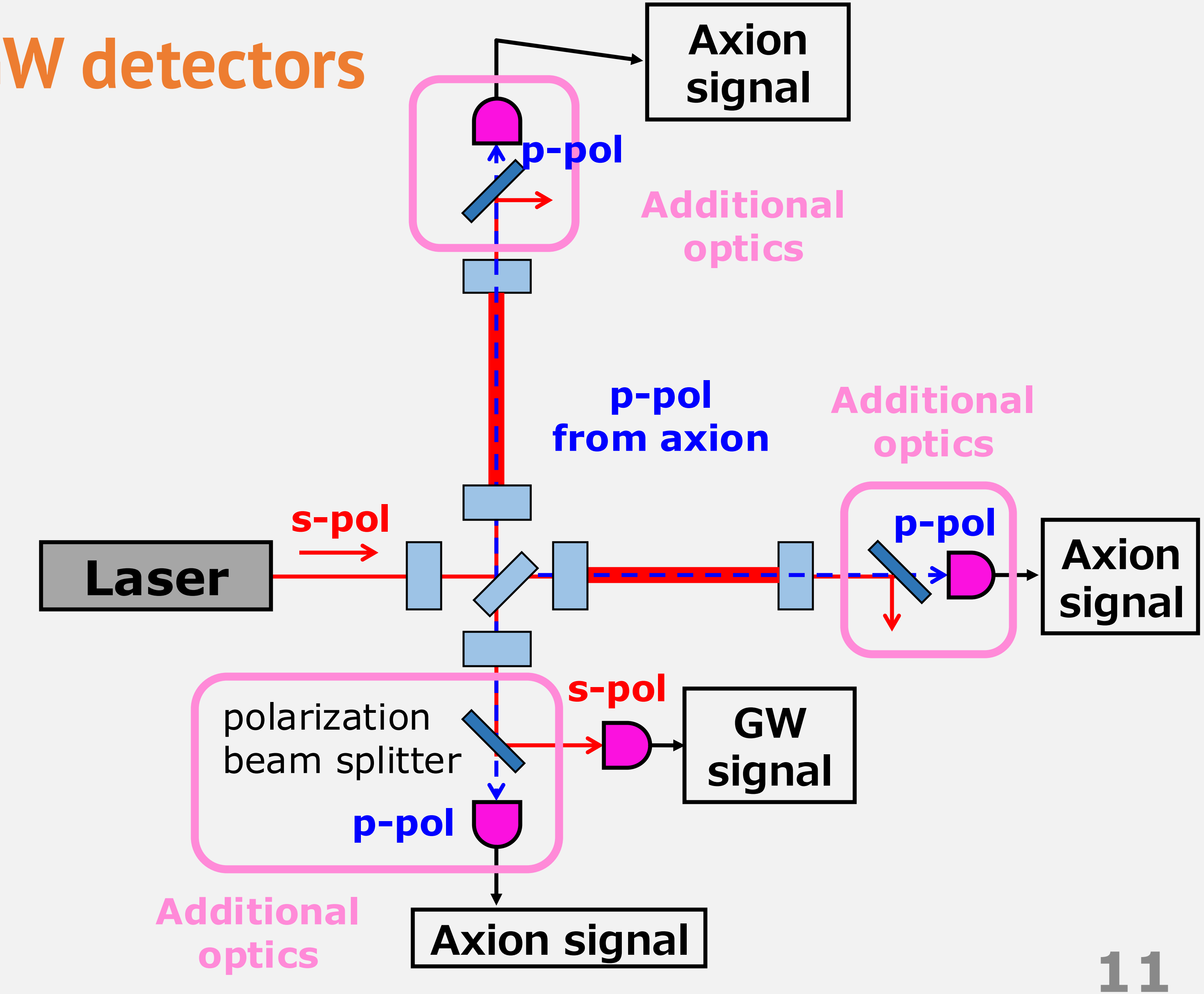


Axion: search with GW detectors

Axion searches and GW observations can be done simultaneously.

References:

- K. Nagano, T. Fujita, Y. Michimura, I. Obata, PRL **123**, 111301 (2019).
- K. Nagano, H. Nakatsuka, ***SM***, T. Fujita, Y. Michimura, I. Obata PRD **104**, 062008 (2021).



Data analysis: signal model

$$\vec{A}(t,\vec{x}) = \frac{A}{\sqrt{N}} \sum_{i=0}^{N-1} \vec{e}_i \cos\left(m_{DM} \left(1 + \frac{v_i^2}{2}\right) t - m_{DM}\, \vec{v}_i \cdot \vec{x} + \theta_i \right). \quad \text{(Here } \hbar = c = 1.\text{)}$$

From H. Nakatsuka, ***SM***, T. Fujita, J. Kume, Y. Michimura, K. Nagano, I. Obata, PRD **108**, 092010 (2023).

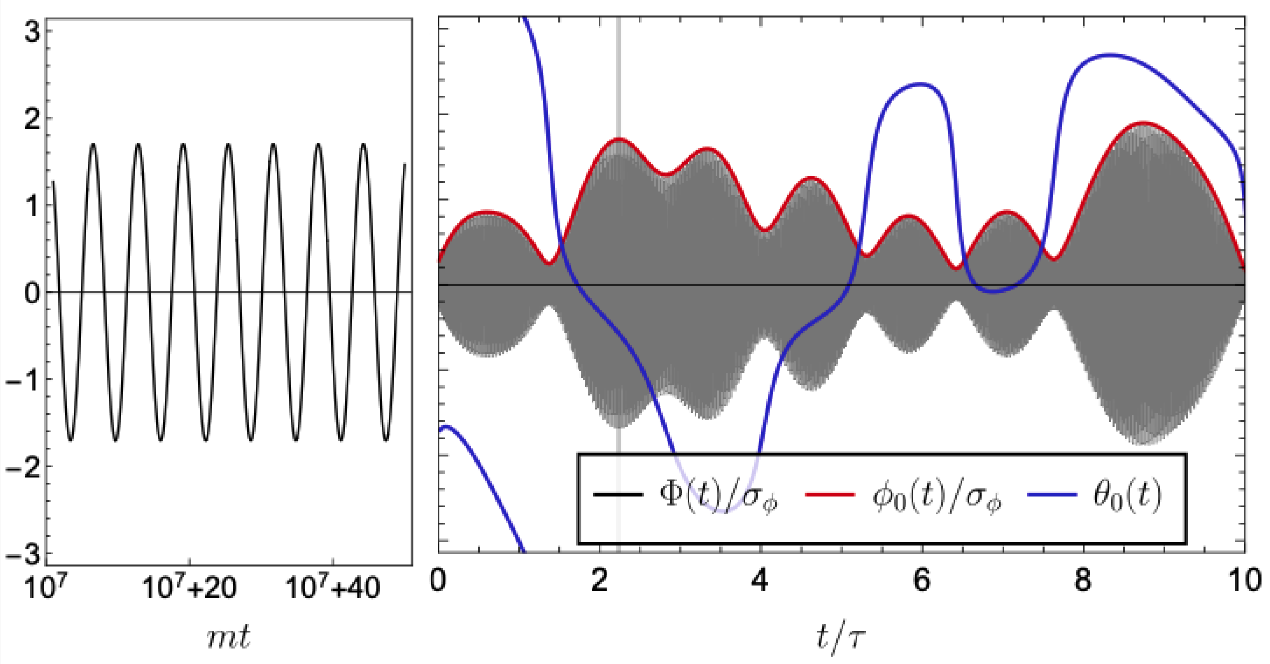


Figure: Time-domain signal generated by ultralight DM

$$v_{\mathrm{vir}} \sim 10^{-3} \ll 1.$$

→

Frequency: $f \simeq \dfrac{m_{DM}}{2\pi}$.

Frequency width: $\Delta f \sim \dfrac{m_{DM} v_{\mathrm{vir}}^2}{2\pi}$.

Coherence time: $\tau = \dfrac{2\pi}{m_{DM} v_{\mathrm{vir}}^2} \sim \dfrac{10^6}{f}$.

Data analysis: incoherent SNR

Ref: LIGO-Virgo-KAGRA, PRD **110**, 042001 (2024).

- In the KAGRA/GEO O3 search, data were divided into 30-minute segments and the **incoherent SNR**, defined below, was computed:

$$\rho(m_A) \equiv \sum_{\text{segments (indexed by } i)} \; \sum_{\frac{m_A}{2\pi} \leq f_k \leq \frac{m_A}{2\pi}(1+\kappa^2 v_{vir}^2)} \frac{4\left|\tilde{d}_i(f_k)\right|^2}{T S_i(f_k)}.$$

$\tilde{d}_i(f_k)$: The Fourier component of the i-th segment,

$S_i(f_k)$: Power spectral density of noise, $T = 30\text{min}$, $\kappa = 3.17$.

- Segments should be longer than the coherence time to optimally extract signal, but they can be very long: $\tau \sim \frac{10^6}{f} = 1.2\left(\frac{10\text{ Hz}}{f}\right)$ days. For comparison, the durations of contiguous KAGRA O3 data were at most about 7 hours.

Data analysis: signal correlation

Ref:
SM et al., in preparation.

We are optimizing the search method exploiting the correlation of signal values at different segments, $\langle \tilde{h}(f;t_0)\tilde{h}^*(f;t_1)\rangle$ (t_0, t_1: segments' starting time).

Assuming the phase of each DM wave is statistically independent,

$$\left\langle \widetilde{A_i}(f)\widetilde{A_j}^{\dagger}(f')\right\rangle = P_{ij}(f)\delta(f-f').$$

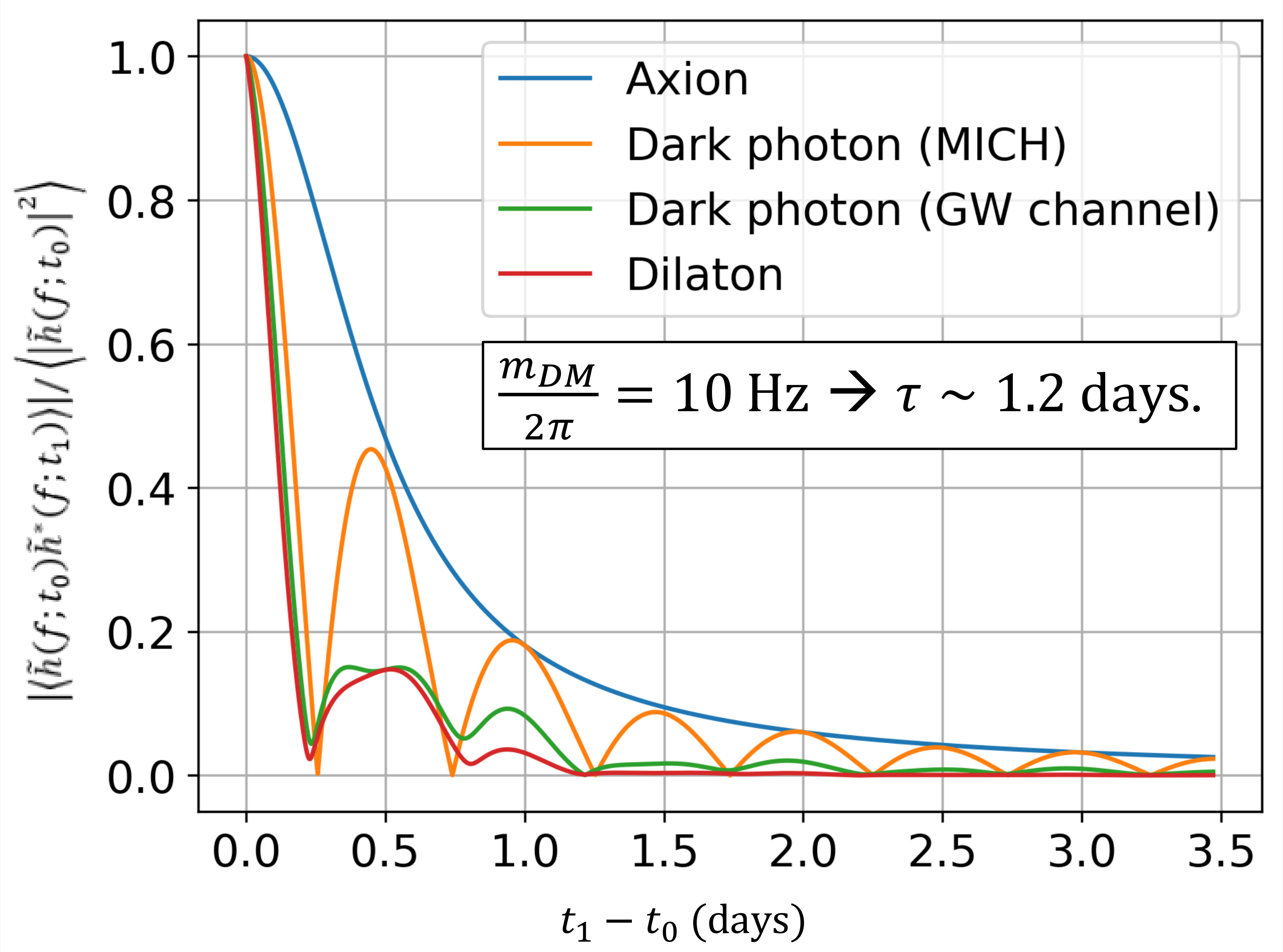
$P_{ij}(f)$ can be analytically calculated if velocities follow the standard-halo-model distribution and polarizations are isotropically distributed,

$$\vec{v} = \vec{v}_h - \vec{v}_{\odot}, \qquad \vec{v}_h \sim \frac{1}{\left(\pi v_{vir}^2\right)^{3/2}} \exp\left[-\frac{(\vec{v}_h)^2}{v_{\mathrm{vir}}^2}\right].$$

$$\longrightarrow \langle \tilde{h}(f;t_0)\tilde{h}^*(f;t_1)\rangle \simeq \underbrace{d^i(t_0)d^j(t_1)}_{\text{Detector response}} \int df' \underbrace{|\widetilde{w}(f-f'')|^2}_{\text{Window function}} P_{ij}(f) e^{2\pi i f''(t_0-t_1)}.$$

Data analysis: signal correlation

Ref:
SM et al., in preparation.



$$\frac{m_{DM}}{2\pi} = 10\ \mathrm{Hz} \rightarrow \tau \sim 1.2\ \text{days.}$$

- The correlation decays with the timescale of τ (coherence time).
- Daily oscillations due to the Earth rotation.

Data analysis: optimal detection statistic

Ref:
SM et al., in preparation.

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

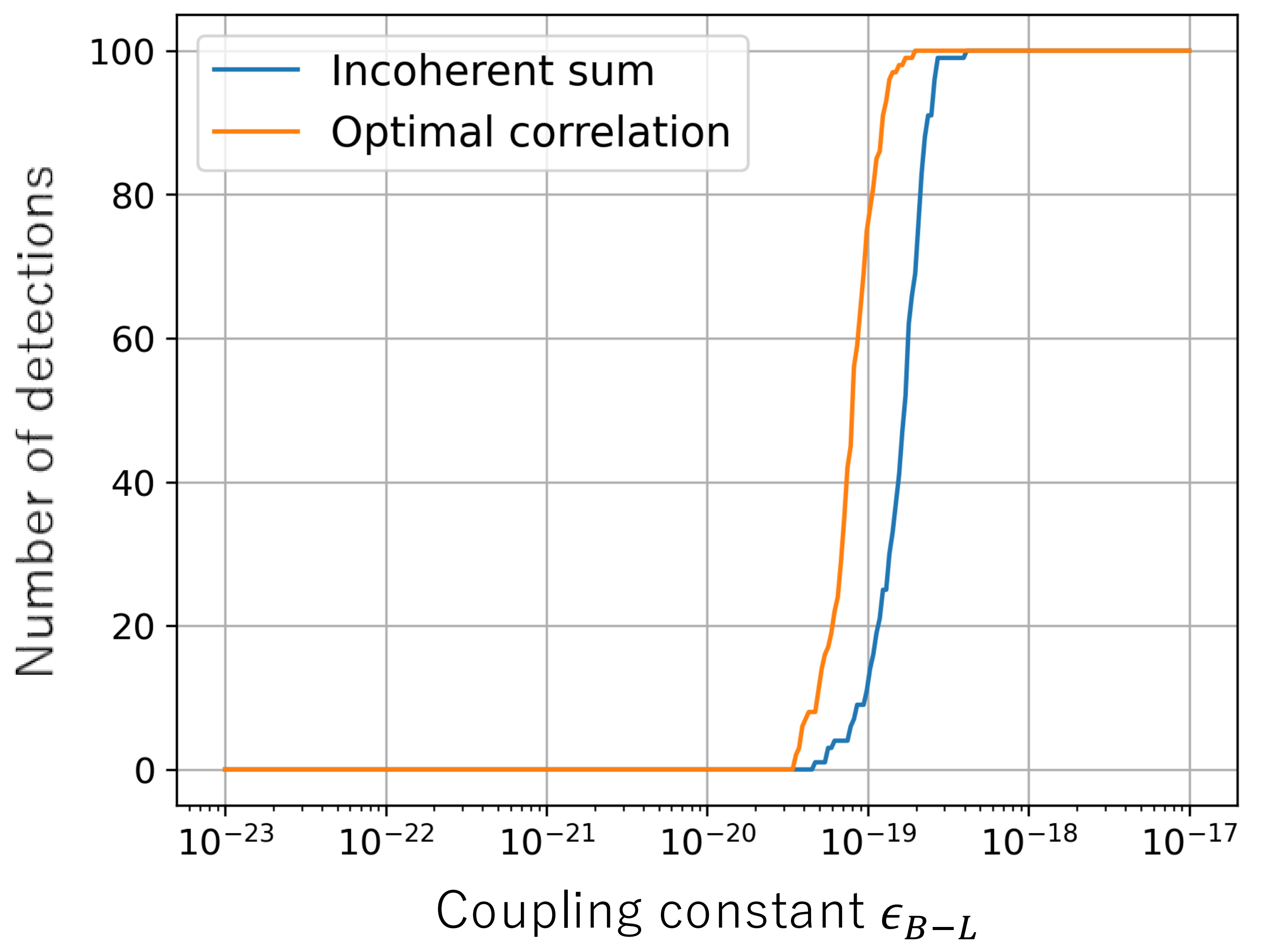
$\vec{d}$: Fourier components of data segments
$\mathcal{N}$: Noise covariance $\mathcal{S}$: Signal covariance

Two ways to derive this statistic:

- Consider a quadratic form, $\rho = \vec{d}^{\dagger} K \vec{d}$ $\left(K = K^{\dagger}\right)$, and determine K by maximizing $\mathrm{SNR} = \langle\rho\rangle / \sqrt{\mathrm{Var}[\rho]}$ (instrumental noise is assumed to be stationary and Gaussian).
- It is equivalent to locally optimal statistic, $\lim_{\epsilon^2 \to 0} \left(\ln p\left(\vec{d} \middle| \epsilon\right) / \epsilon^2\right)$ (See M. Anholm *et al.*, PRD **79**, 084030 (2009)).

Data analysis: injection tests

Ref:
SM et al., in preparation.



- 100 data realizations.
  - Dark-photon signal in MICH with $\frac{m_{\mathrm{DM}}}{2\pi} = 100$ Hz ($\tau \sim 10^4$ s).
  - Noise generated with KAGRA-O3 PSD.
- $T_{\mathrm{tot}} = 10^5$ s divided into chunks with $T = 10^2$ s.
- Thresholds determined with false alarm probability of 10^{-3}.

Summary

- Gravitational-wave detectors can be used to search for various types of ultralight bosonic dark matter.
  - Mirror displacements from **dark photon** and **dilaton** dark matter
  - Modulation of laser light polarization from **axion** dark matter

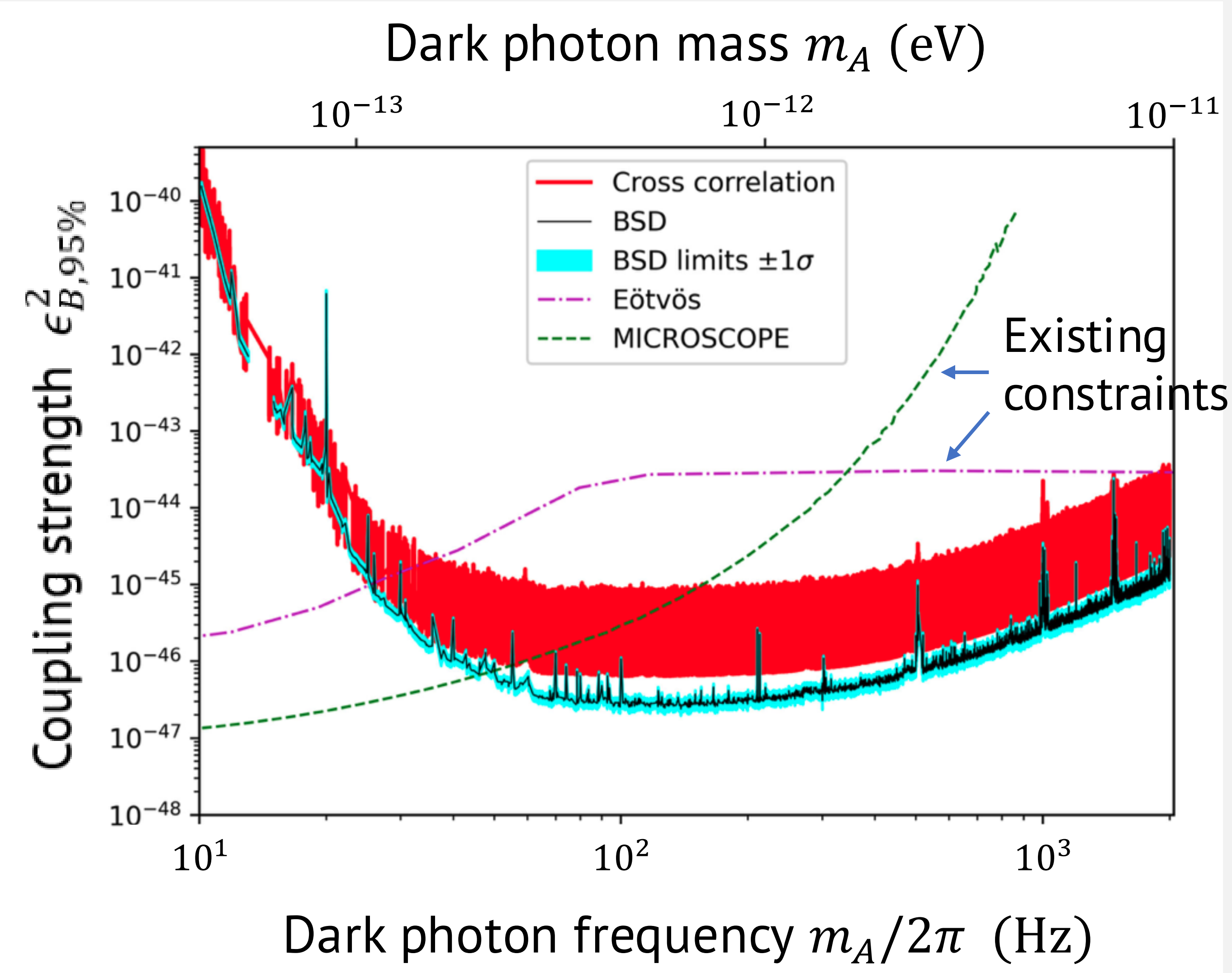
- KAGRA's auxiliary channels are useful to probe composition-dependent forces exerted by dark photon.

- Data analysis can be optimized using the correlation function of the signal.

This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation.

Dark photon: O3 results

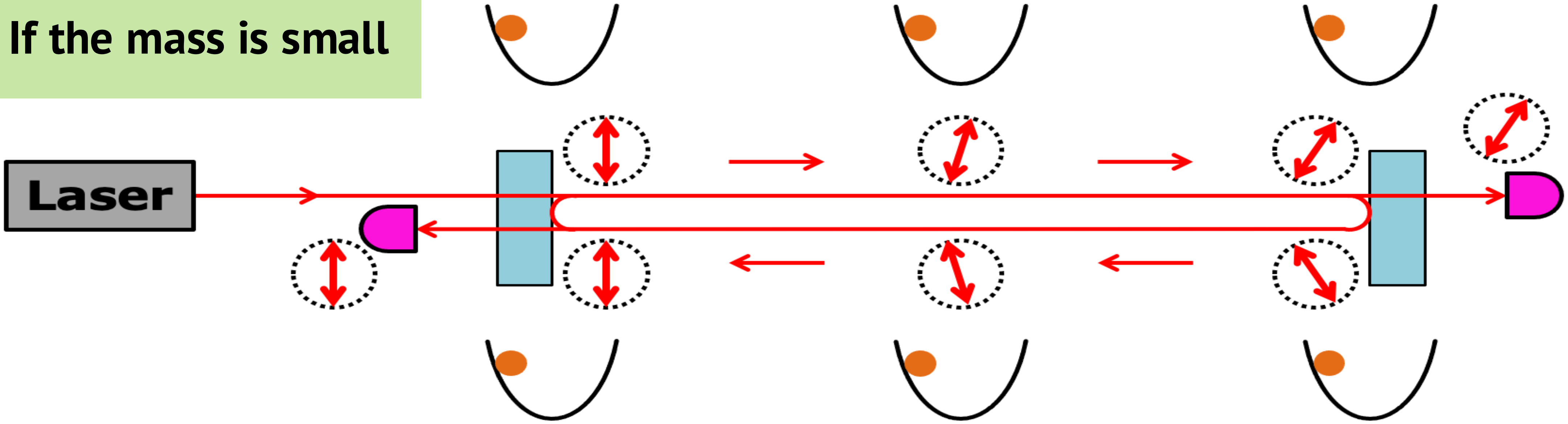
Ref: LIGO-Virgo-KAGRA, PRD **105**, 063030 (2022).



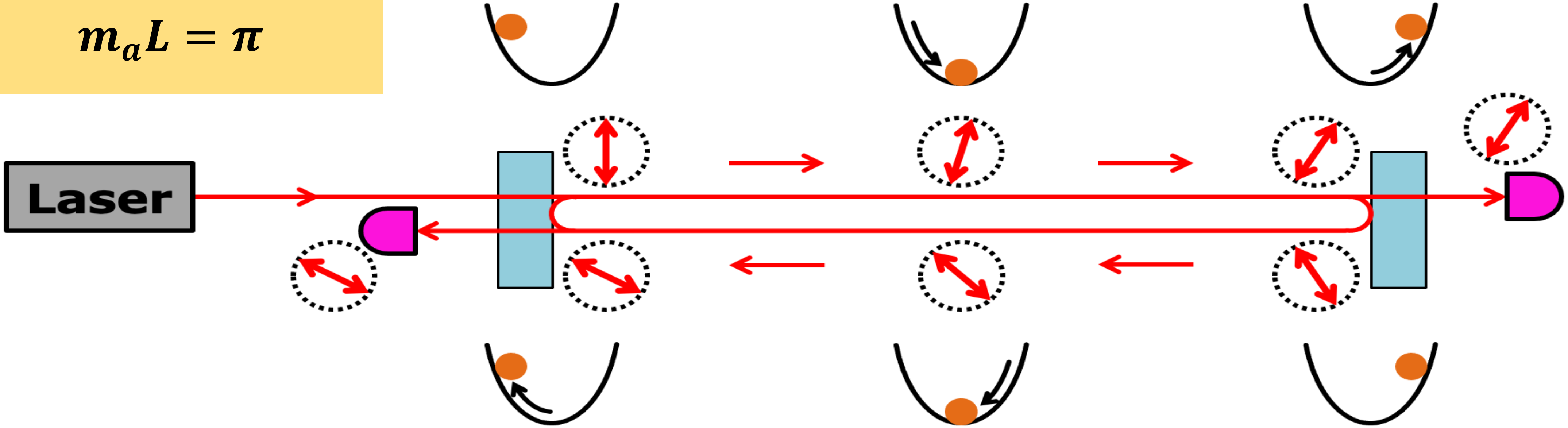
Existing constraints

- Searches were conducted with LIGO-O3 data.
- Most stringent constraints at 10^{-13} eV $\lesssim m_A \lesssim 10^{-11}$ eV.
- See the Andrew's talk on Thursday for their details.

If the mass is small

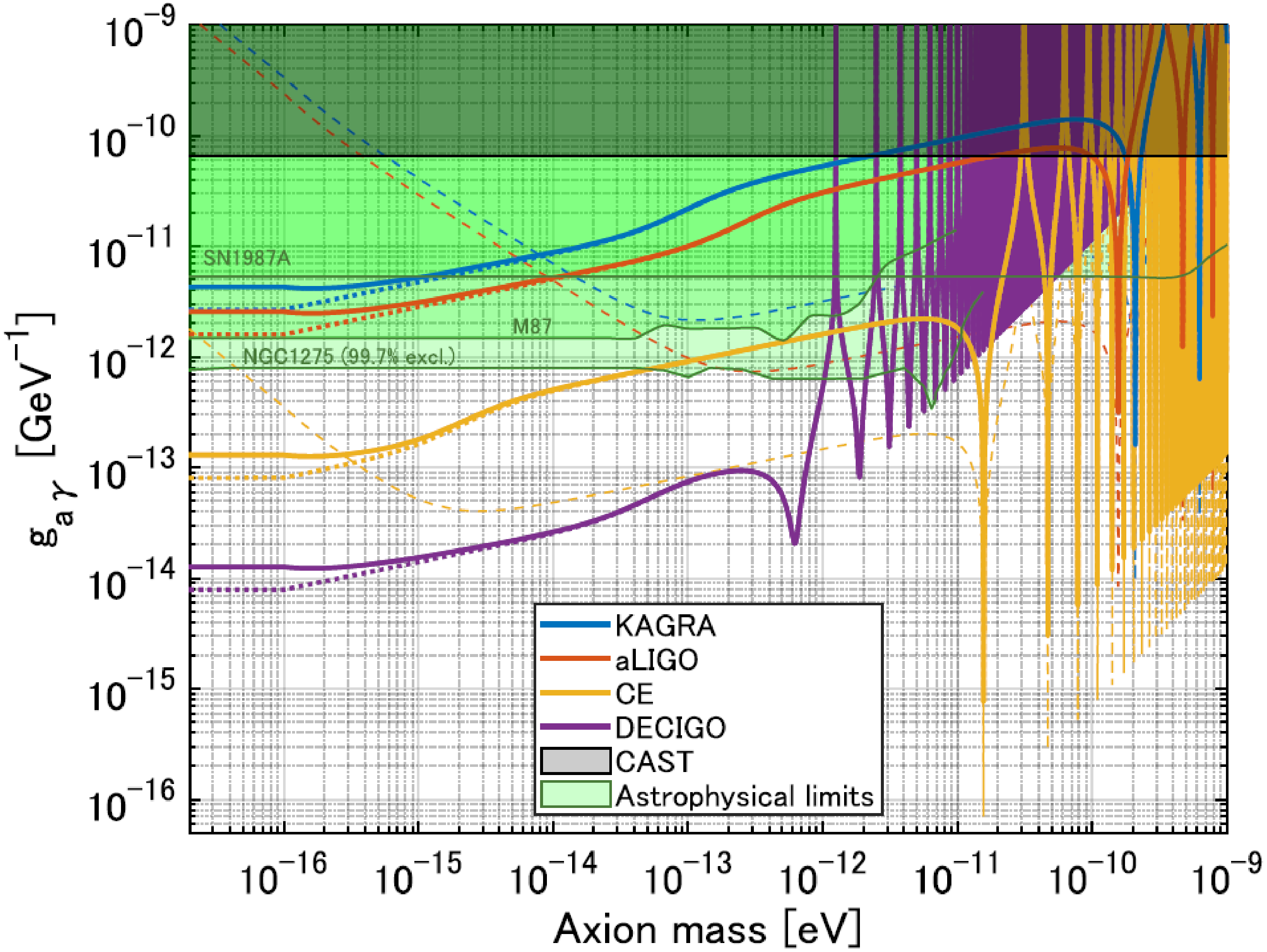


$m_a L = \pi$



Axion: future prospects

From K. Nagano, H. Nakatsuka, ***SM***, T. Fujita, Y. Michimura (2021).

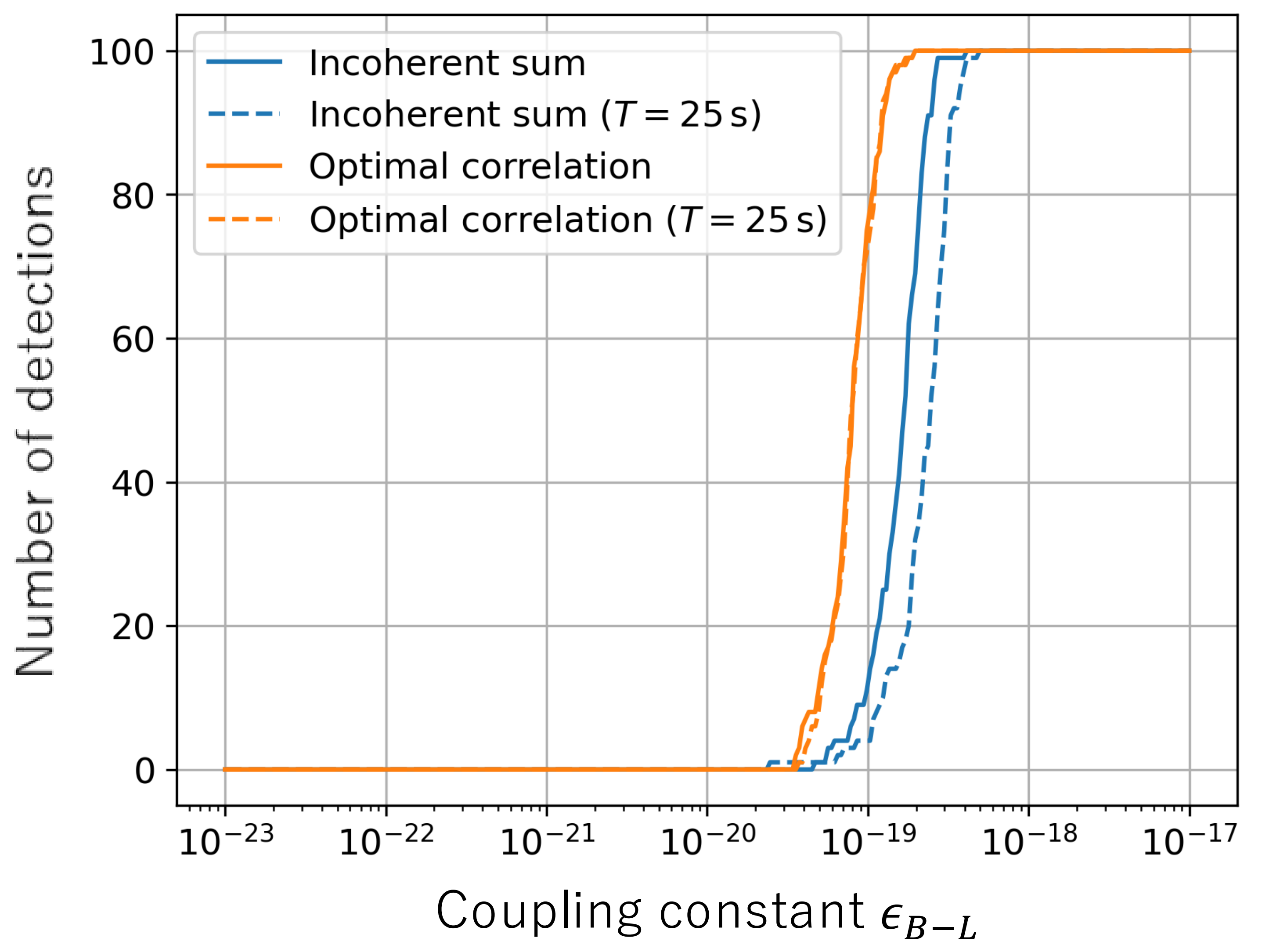


Black, green: existing constraints

Solid: transmission port
Dashed: detection port

GW detectors have much better sensitivities around $m_a = (2N-1)\pi/L$.

Sensitivity of optimal correlation



- The same data divided into shorter chunks ($T = 25$ s).

- The sensitivity of optimal correlation does not depend on the chunk length.