Gravitational-wave interferometers as particle physics laboratories

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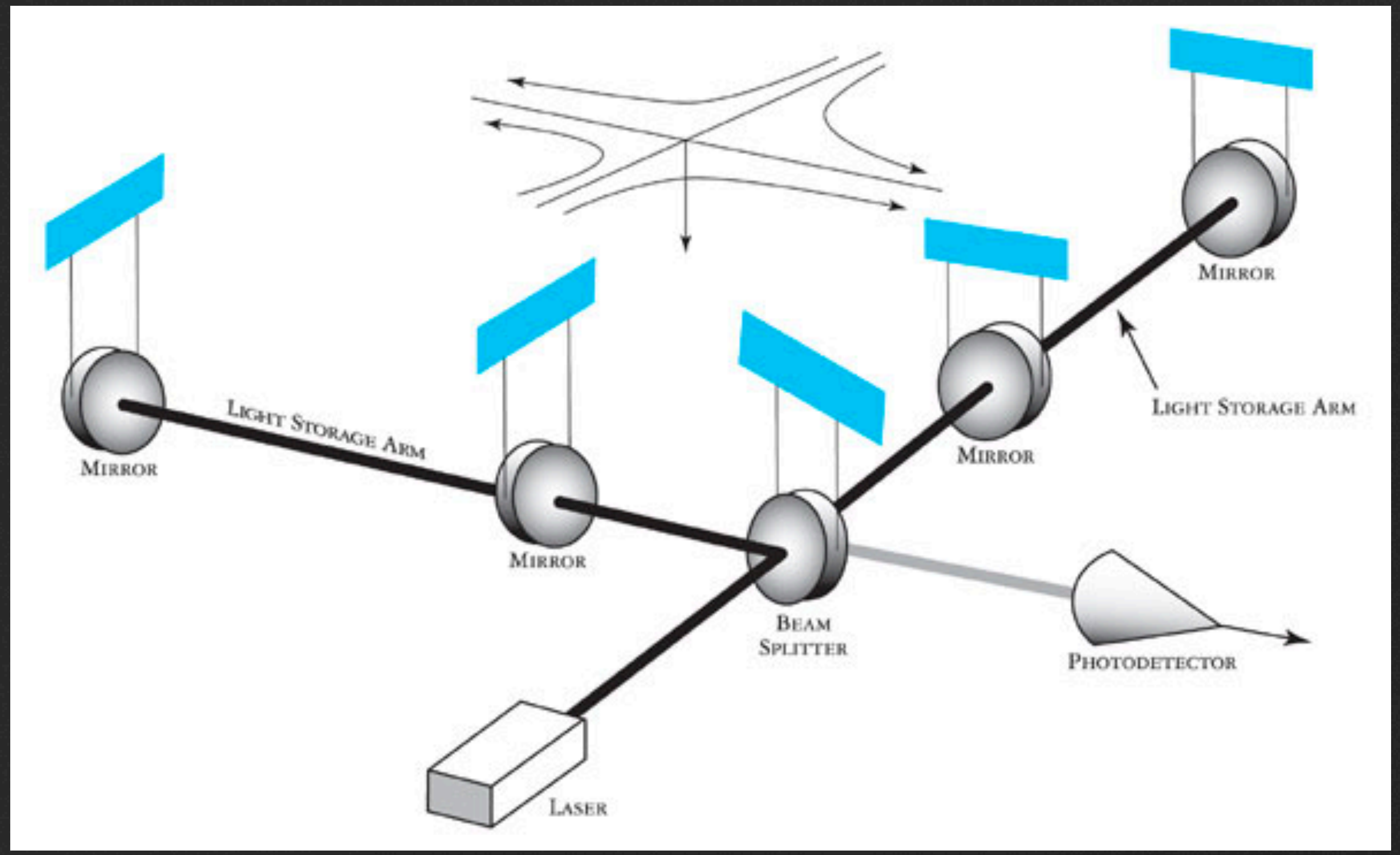
Outline

- Background
- Observational signatures of ultralight dark matter
- Methods to search for dark matter
- Constraints on dark matter using gravitational-wave detectors
- Conclusions

Background

Context

- LIGO, Virgo and KAGRA are km-long size interferometers designed to measure the displacement of test masses (mirrors) in the audio band (10-2000) Hz
- These are precision instruments that measure a *strain* $h \sim \Delta L/L$
  - Detection principle: anything that causes a change in length of the interferometer arms can be detected as a “signal”
- Can we use interferometers to detect dark matter?



Pierce et al. 2018, Phys. Rev. Lett. 121, 061102
Morisaki et al. 2021, Phys. Rev. D. 103, L051702
Vermeulen et al. 2021, Nature 600, pages 424–428

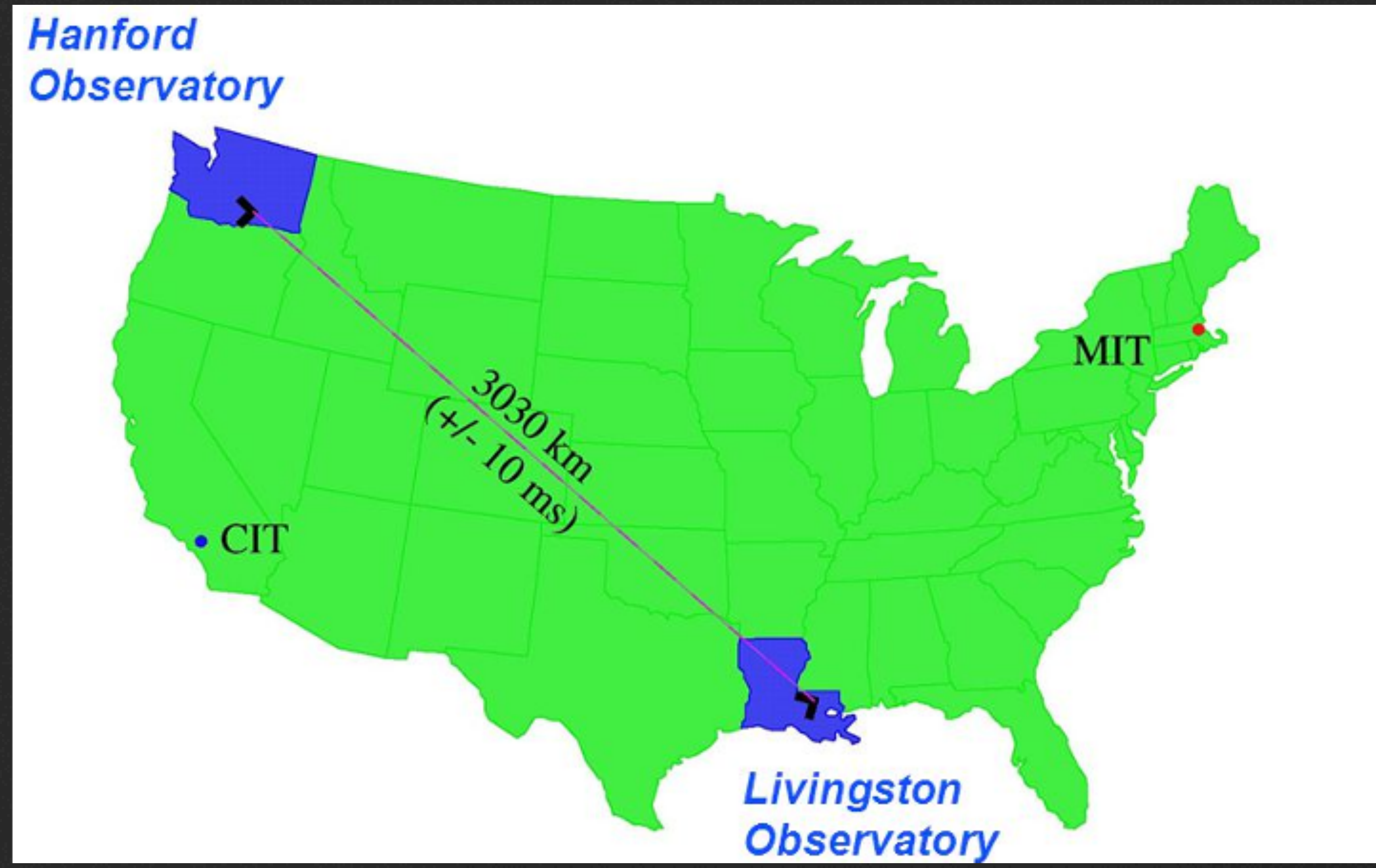
Ultralight dark matter

- Dark matter could directly interact with interferometer components, leading to an observable signal that is NOT a gravitational wave
- If we assume DM is ultralight, then we can calculate the number of DM particles in a region of space
- Huge number of particles modelled as superposition of plane waves, with velocities Maxwell-Boltzmann distributed around $v_0 \sim$ 220 km/s
- DM induces stochastic frequency modulation $\Delta f/f \sim v_0^2/c^2 \sim 10^{-6}$ —> finite wave coherence time

$$T_{\mathrm{coh}} = \frac{4\pi\hbar}{m_A v_0^2} = 1.4 \times 10^4 \ \mathrm{s} \left(\frac{10^{-12}\ \mathrm{eV}/c^2}{m_A}\right)$$

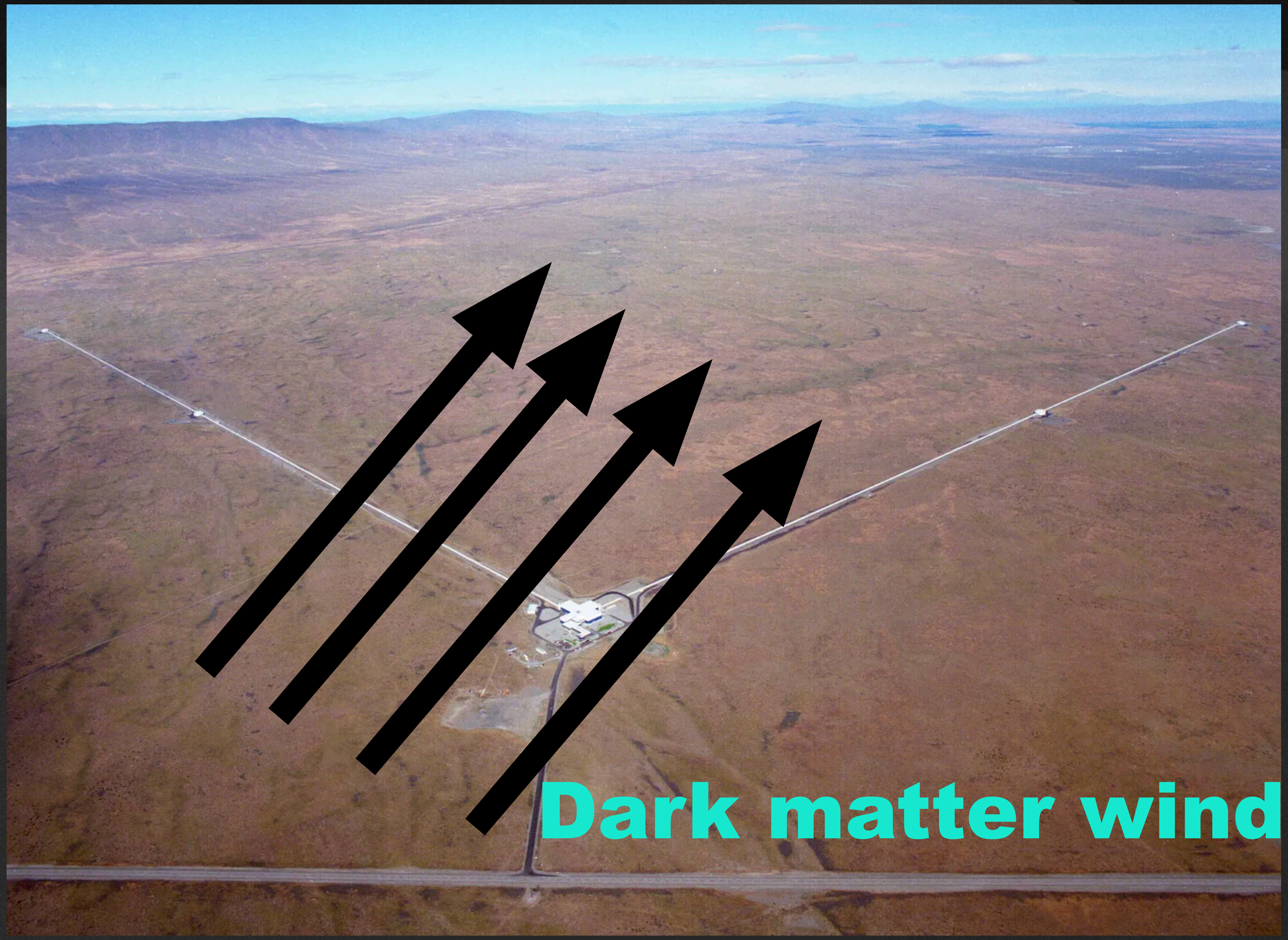
$$N_o = \lambda^3 \frac{\rho_{\mathrm{DM}}}{m_A c^2} = \left(\frac{2\pi\hbar}{m_A v_0}\right)^3 \frac{\rho_{\mathrm{DM}}}{m_A c^2}, \approx 1.69 \times 10^{54} \left(\frac{10^{-12}\ \mathrm{eV}/c^2}{m_A}\right)^4$$

$L_{\mathrm{coh}} \sim 10^9$ m



Ultralight dark matter

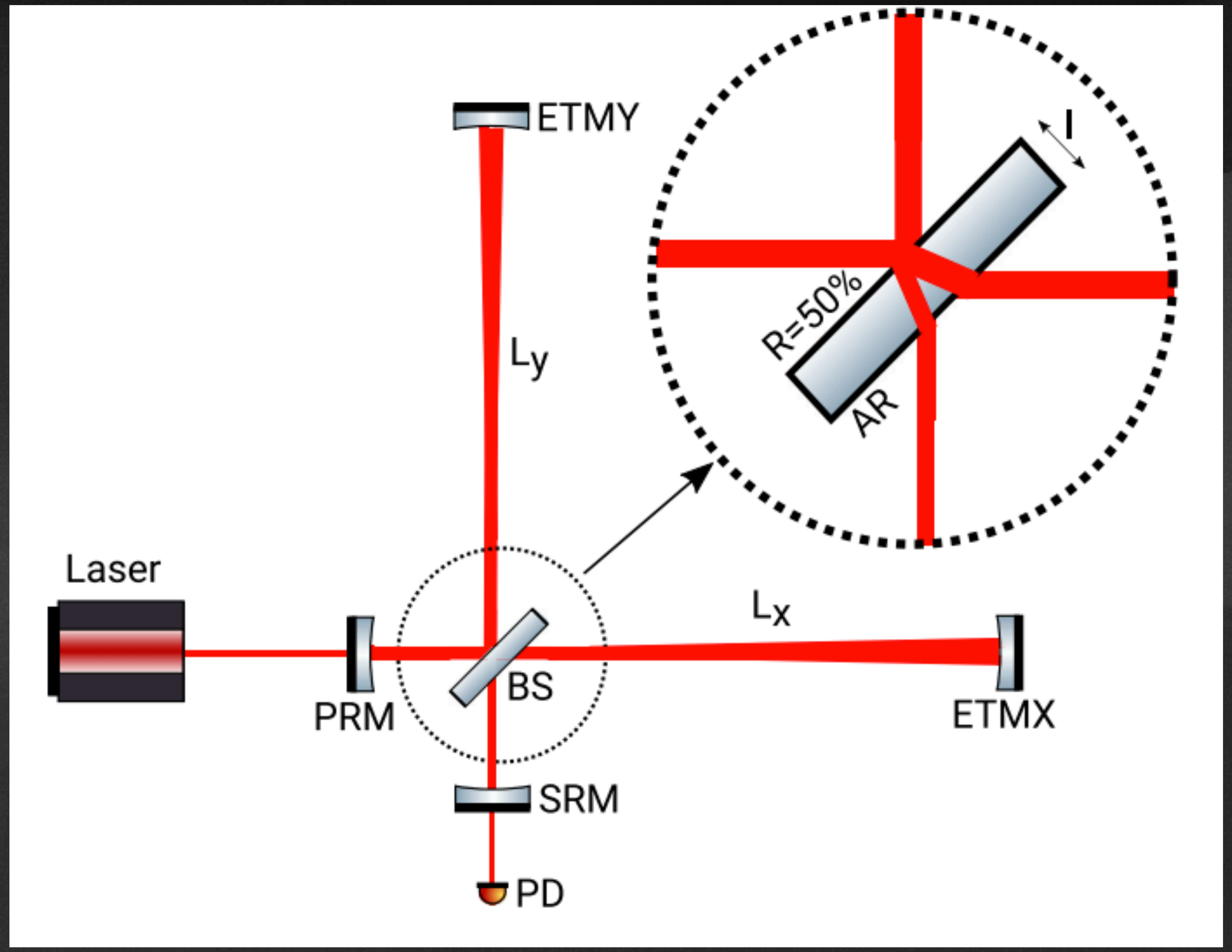
- The interferometers sit in a "wind" of DM
- We can search for *any* type of DM so long as it is cold, ultralight and causes some strain on the detector
- 10-2000 Hz —> DM mass range $[10^{-14}, 10^{-12}]$ eV/c^2
- Different DM particles with interact with different standard-model ones, leading to similar but distinguishable signals
- When we do not observe DM we place constraints on the coupling of DM to ordinary particles



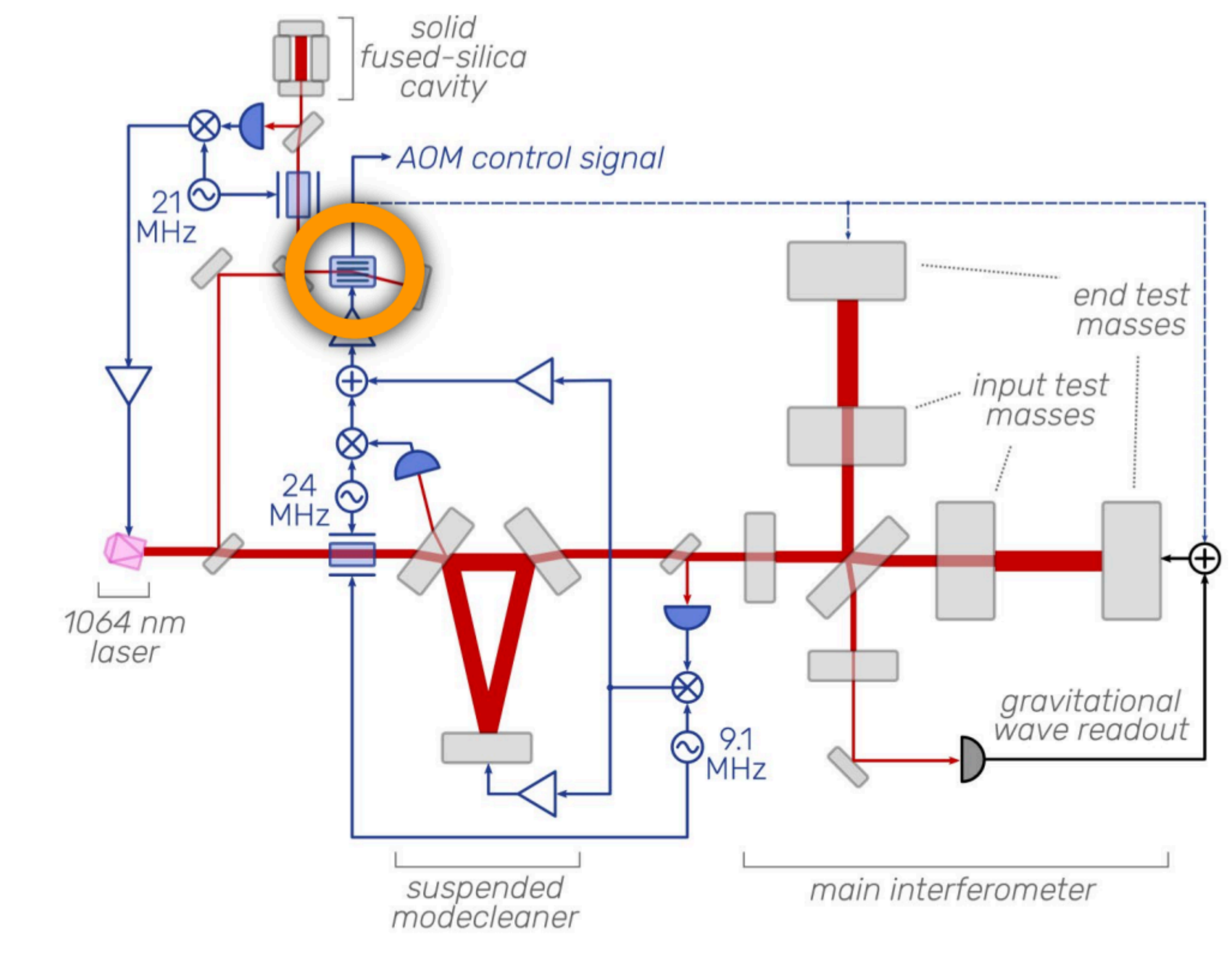
Observational signatures of ultralight dark matter

Scalar, dilaton dark matter

- Couples with strengths Λ_γ and Λ_e to standard model photon and electron fields, respectively
- Physically seen as oscillations in electron mass and atomic Bohr radius
- Leads to changes in size and index of refraction of solids



Size of beam splitter (and mirrors) will be altered —> differential strain

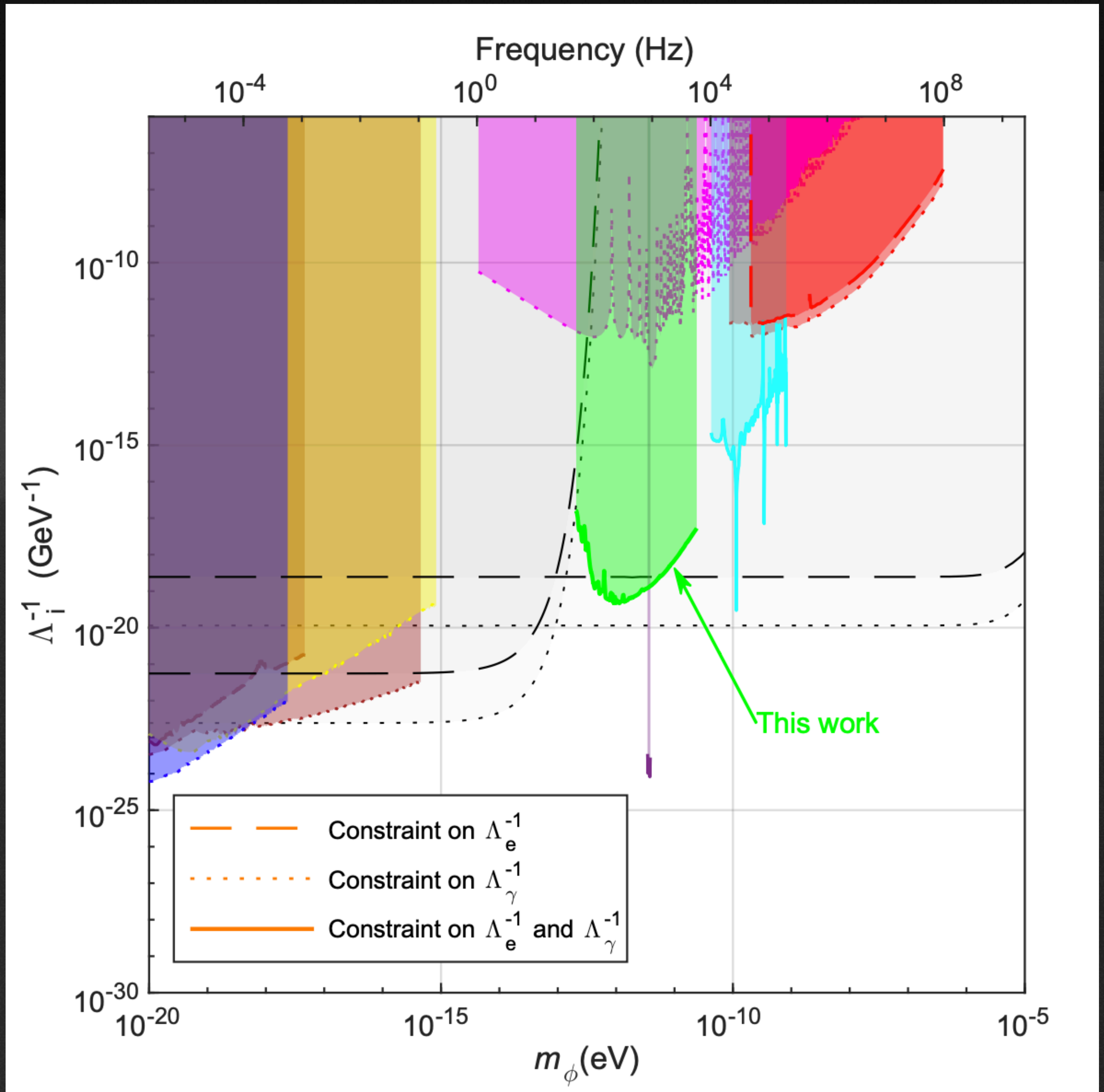


Changes in size of fused-silica cavity used to stabilize laser frequency w.r.t. suspended optics

Vermeulen et al. 2021, *Nature* 600, pages 424–428
Hall and Aggarwal, arXiv:2210.17487.

Searching for scalar dark matter

- Search performed on GEO600 data between 50-8192 Hz on seven segments each of 10^5 seconds
- Spectral estimation method (LPSD): varies the FFT length as a function of dilaton mass at every log(frequency)
- Average estimates of signal power spectrum (average the FFTs)
- Constrained scalar, dilaton/modulus (coupling to QCD with dominant coupling to gluon) and relaxation halo models (same as dilaton but mixing with Higgs boson)



Vermeulen et al. 2021, *Nature* 600, pages 424–428

Axions

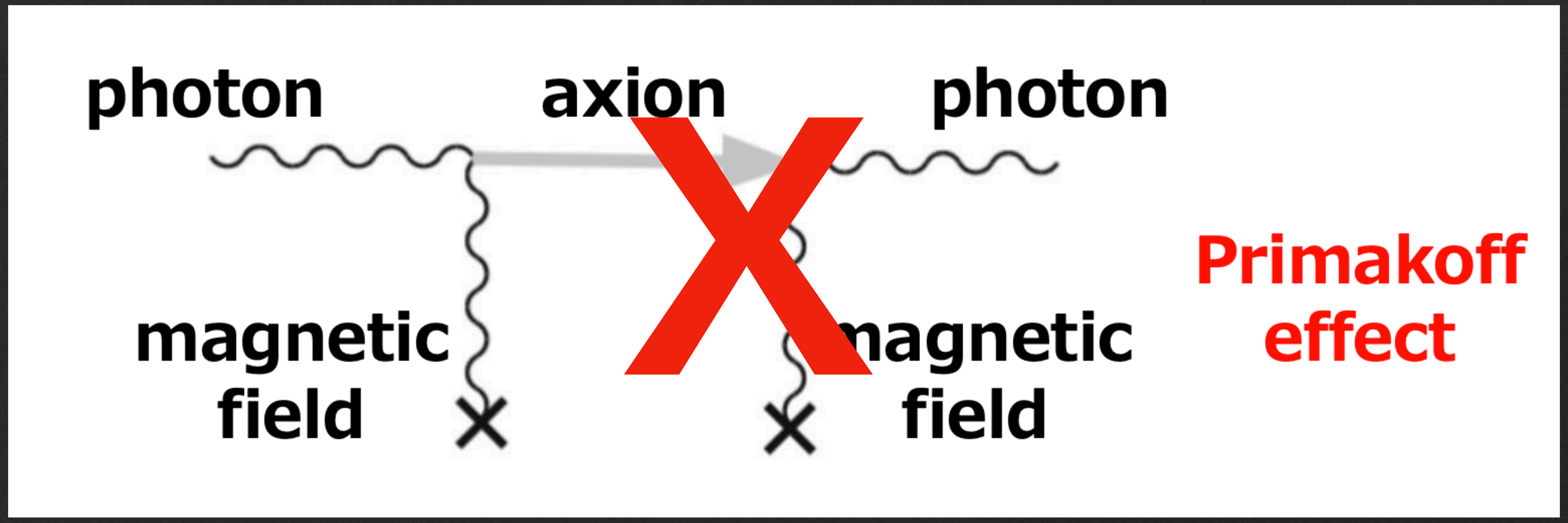
- Axions could couple to photons in the laser light shining down each arm
- Left- and right- circularly polarized light will travel at different speeds in the presence of an axion field
- No need for external magnetic field to induce axion/photon conversion
- Effect visible with additional polarization optics that would not compromise sensitivity to GW

$$c_{\mathrm{L/R}} = \sqrt{1 \pm \frac{g_{a\gamma} a_0 m_a}{k} \sin(m_a t + \delta_\tau)}$$

coupling constant

axion field

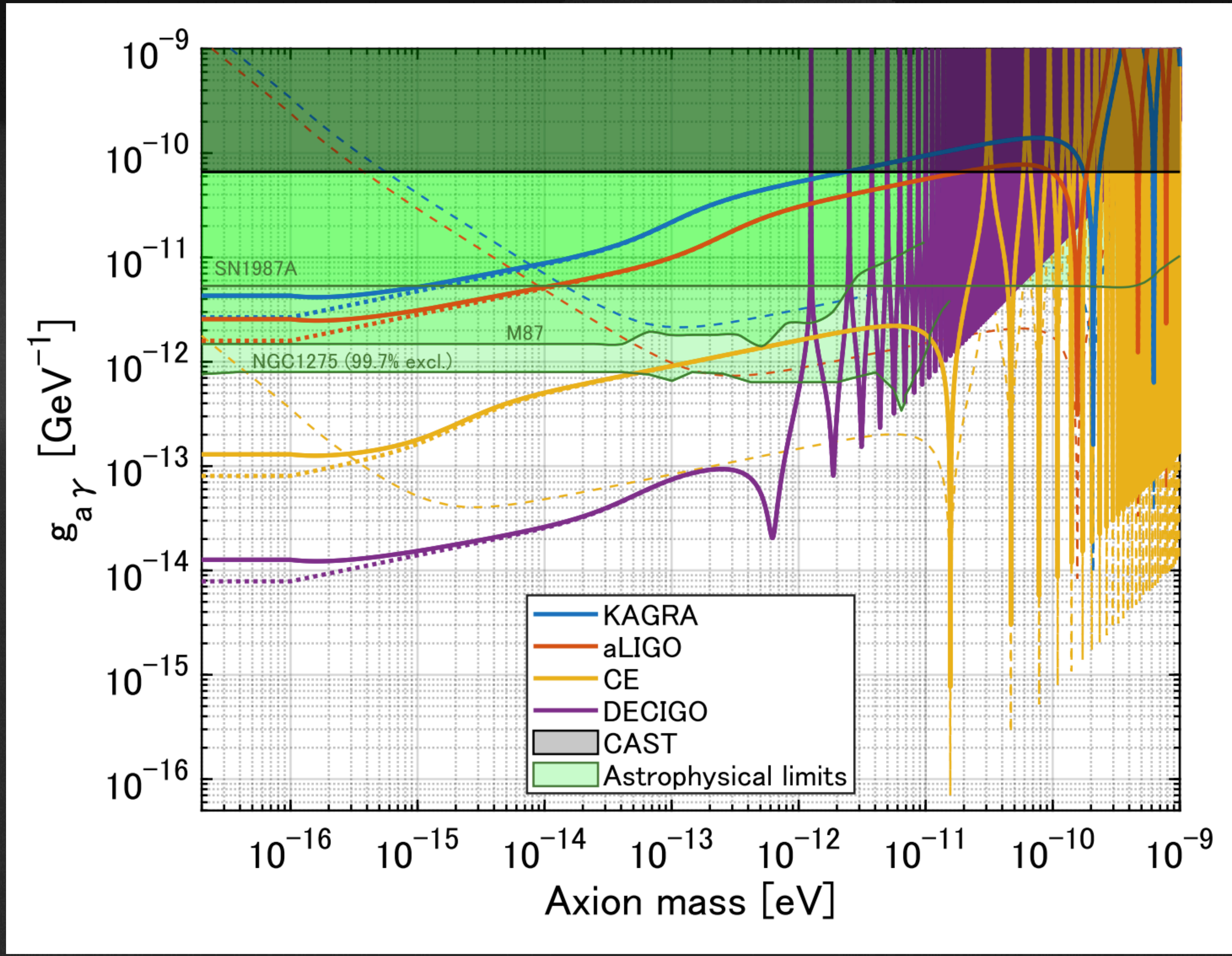
axion mass



Nagano et al. (2019) *Phys. Rev. Lett.* 123, 111301

Future searches for axions

- Can search for GWs and axions simultaneously, but additional optics needed near photodiode and mirrors
- Projected constraints for future detectors
- Different arm lengths give different resonances for all detectors
- Search in the reflection and the transmission ports of arm cavities.



Nagano et al. 2024: PRD 104, 062008

Vector bosons: dark photons

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

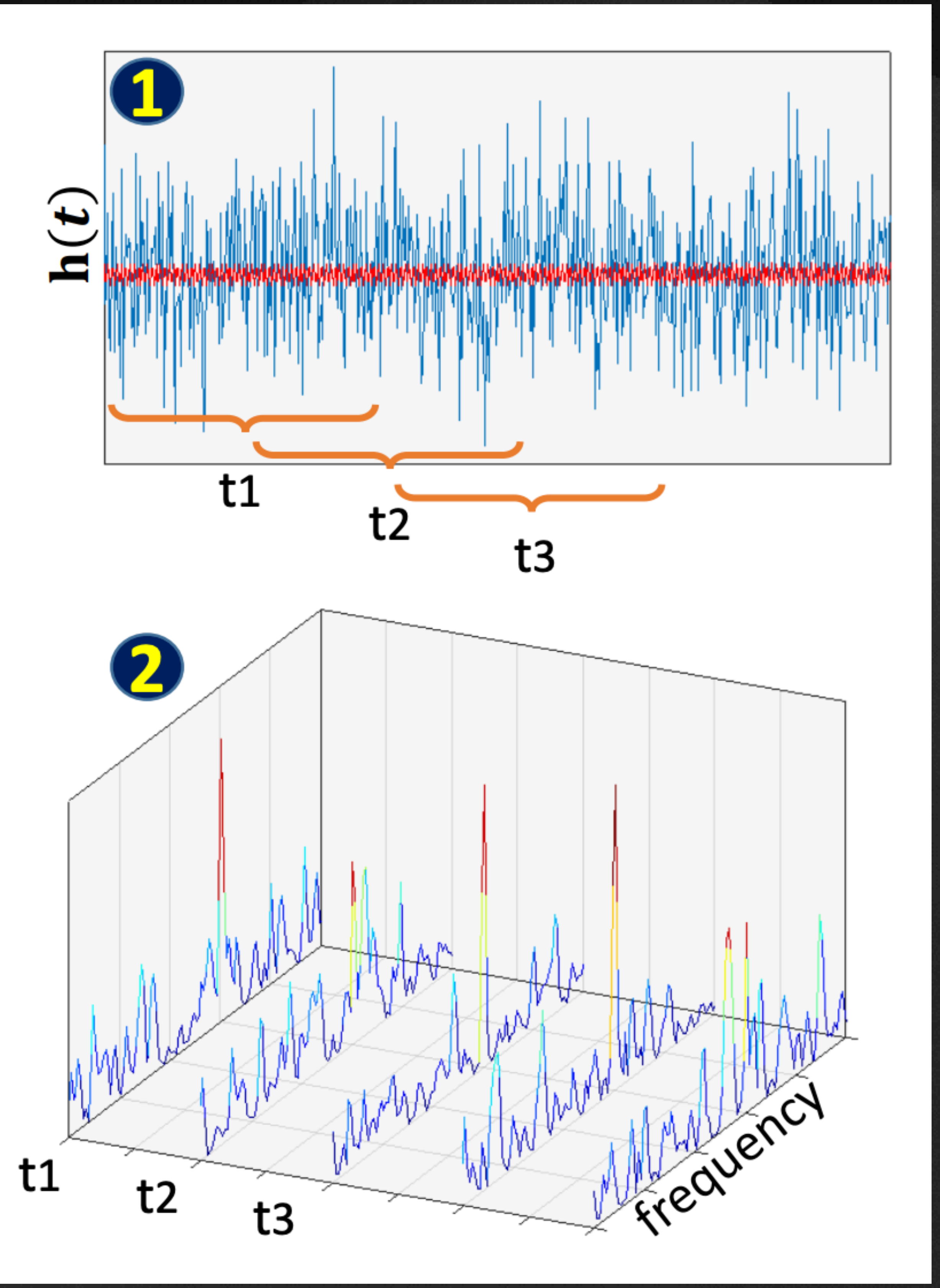
m_A : dark photon mass
ϵ_D : coupling strength
A_μ : dark vector potential

- Gauge boson that interacts weakly with protons and neutrons (baryons) or just neutrons (baryon-lepton number) in materials
- Mirrors sit in different places w.r.t. incoming dark photon field —> differential strain from a spatial gradient in the dark photon field
- Apparent strain results from a "finite light travel time" effect

Methods to search for dark matter

How to search for DM?

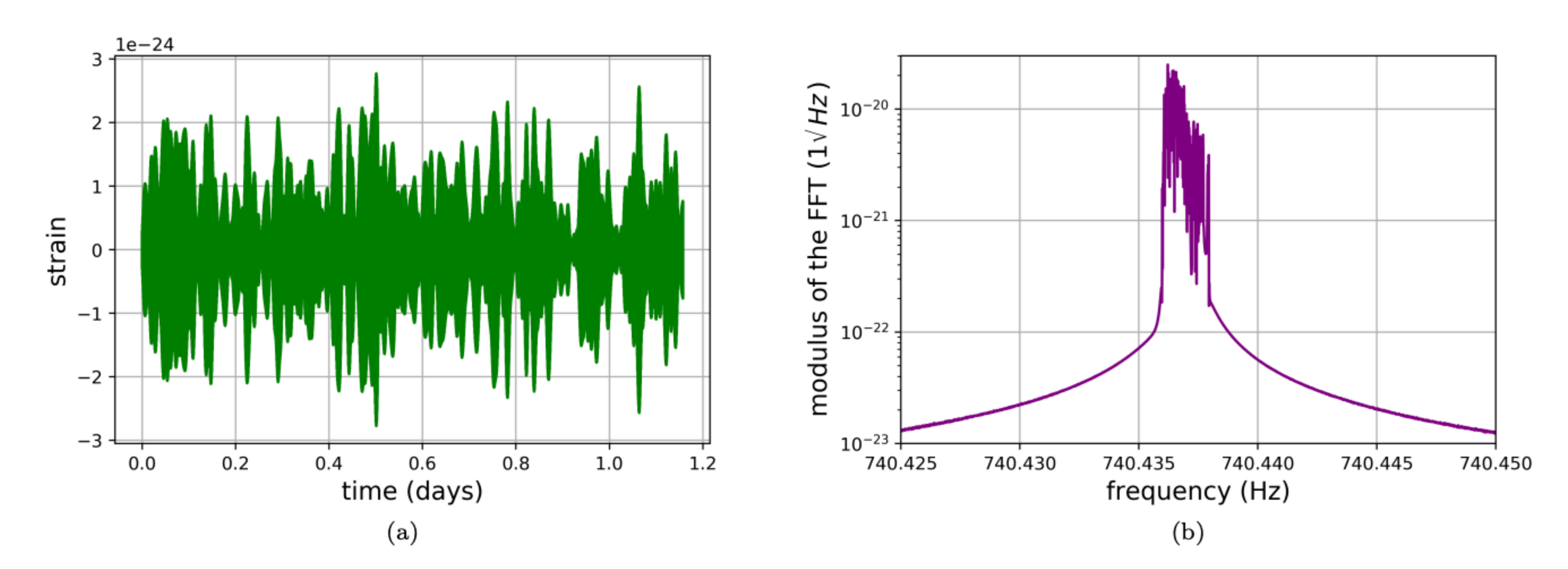
- Ideal technique to find weak signals in noisy data: matched filter
- But, signal has stochastic fluctuations —> matched filter cannot work
- The signal is almost monochromatic —> take Fourier transforms of length $T_{\text{FFT}} \sim T_{\text{coh}}$ and combine the power in each FFT without phase information



Credit: L. Pierini

The signal and analysis strategy

- Example of simulated dark photon dark matter interaction
- Power spectrum structure results from superposition of plane waves, visible when $T_{\text{FFT}} > T_{\text{coh}}$
- Break dataset into smaller chunks of length $T_{\text{FFT}} \sim T_{\text{coh}}$ to confine this frequency modulation to one bin, then sum power in each chunk



- One day shown, but signal lasts longer than observing run

Miller et al. Phys.Rev.D 103 (2021) 10, 103002

Search Method: Cross Correlation

- SNR = detection statistic, depends on cross power and the PSDs of each detector
- j: frequency index; i: FFT index
- SNR computed in each frequency bin, summed over the whole observation run
- Overlap reduction function = −0.9 because dark photon coherence length >> detector separation
- Frequency lags computed to estimate background

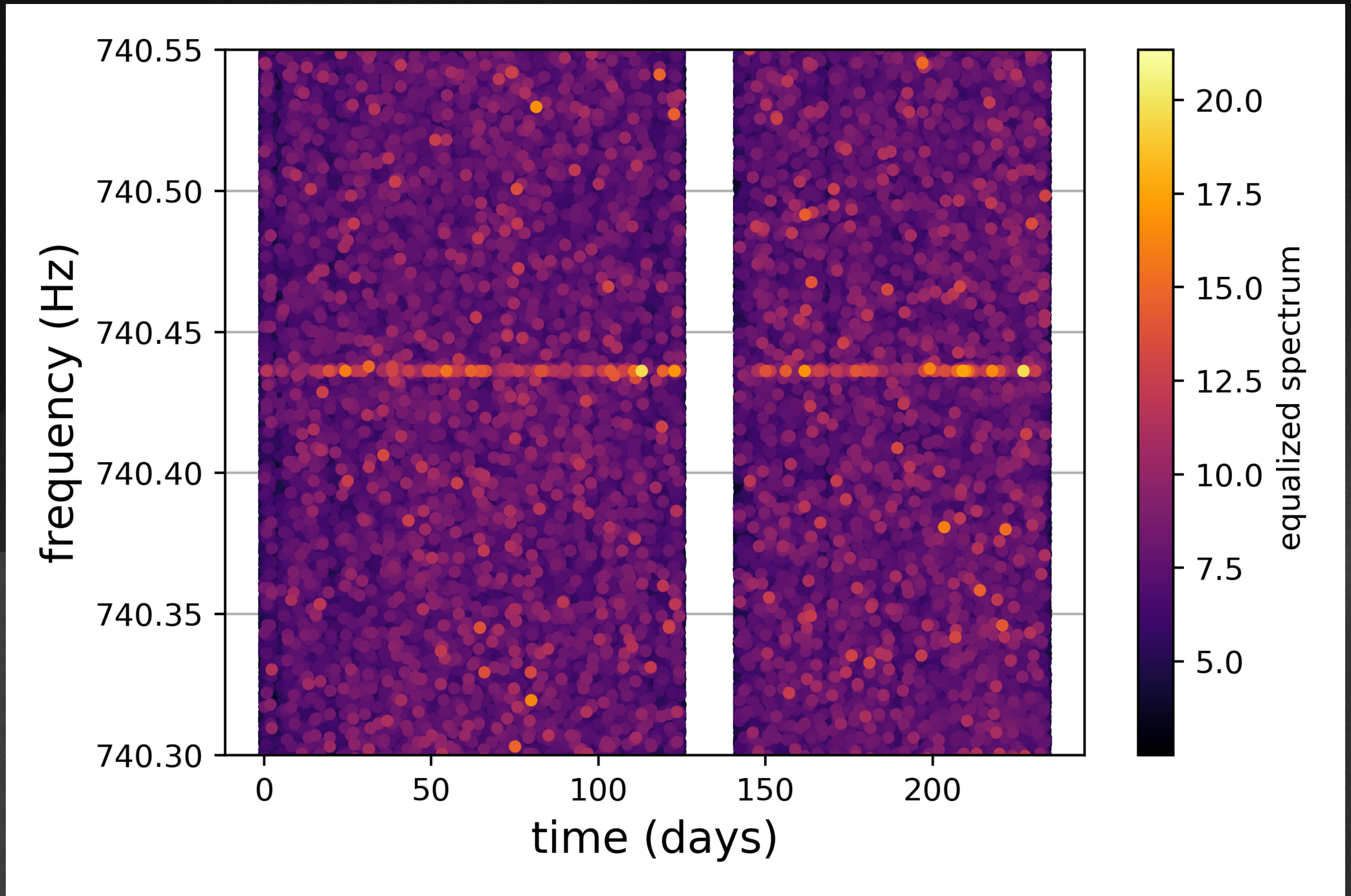
$$S_j = \frac{1}{N_{\mathrm{FFT}}} \sum_{i=1}^{N_{\mathrm{FFT}}} \frac{z_{1,ij} z_{2,ij}^*}{P_{1,ij} P_{2,ij}}$$

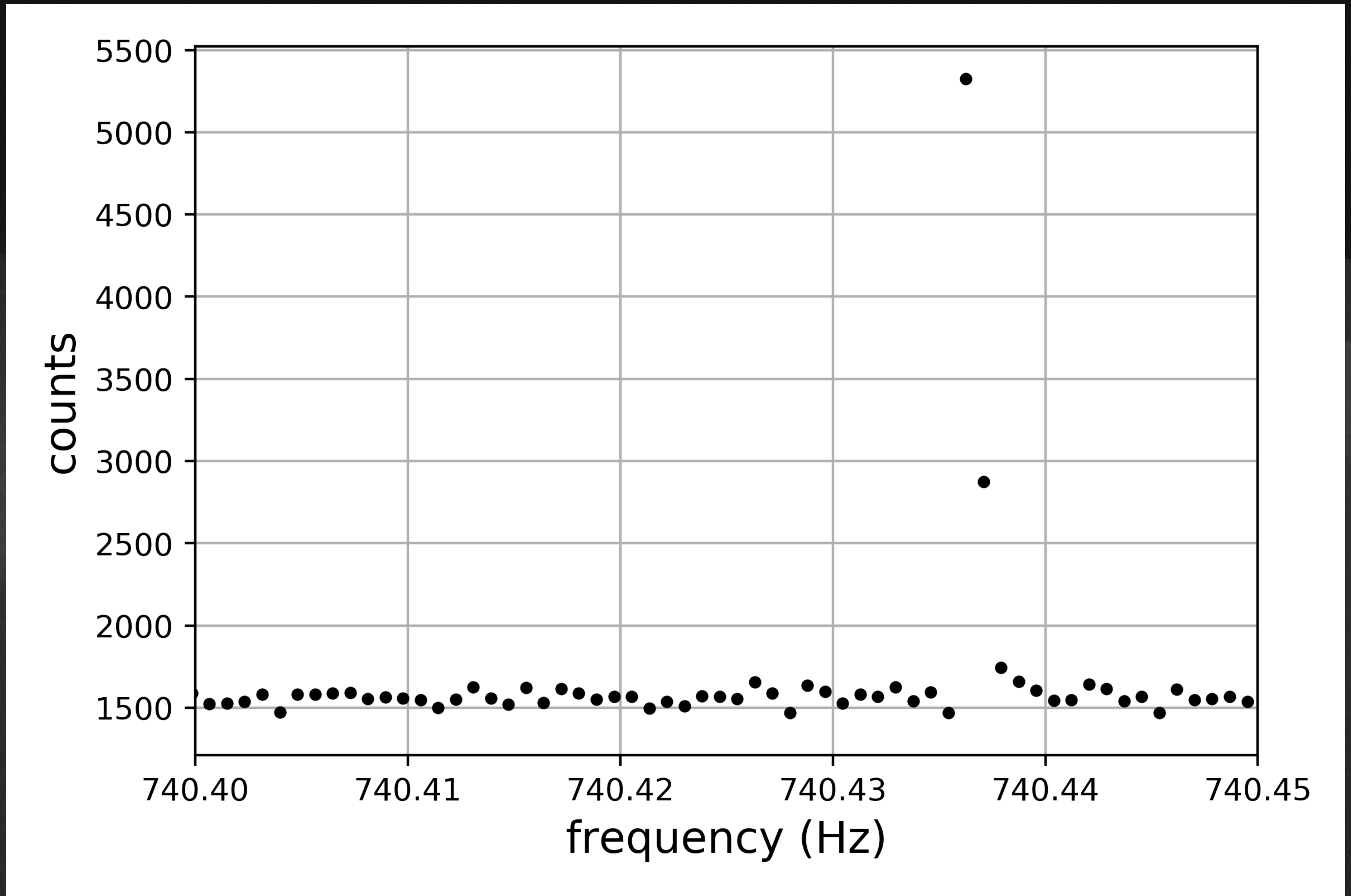
$$\sigma_j^2 = \frac{1}{N_{\mathrm{FFT}}} \left\langle \frac{1}{2 P_{1,ij} P_{2,ij}} \right\rangle_{N_{\mathrm{FFT}}}$$

$$\mathrm{SNR}_j = \frac{S_j}{\sigma_j}$$

Pierce et al. 2018, Phys. Rev. Lett. 121, 061102

Method: look for excess power





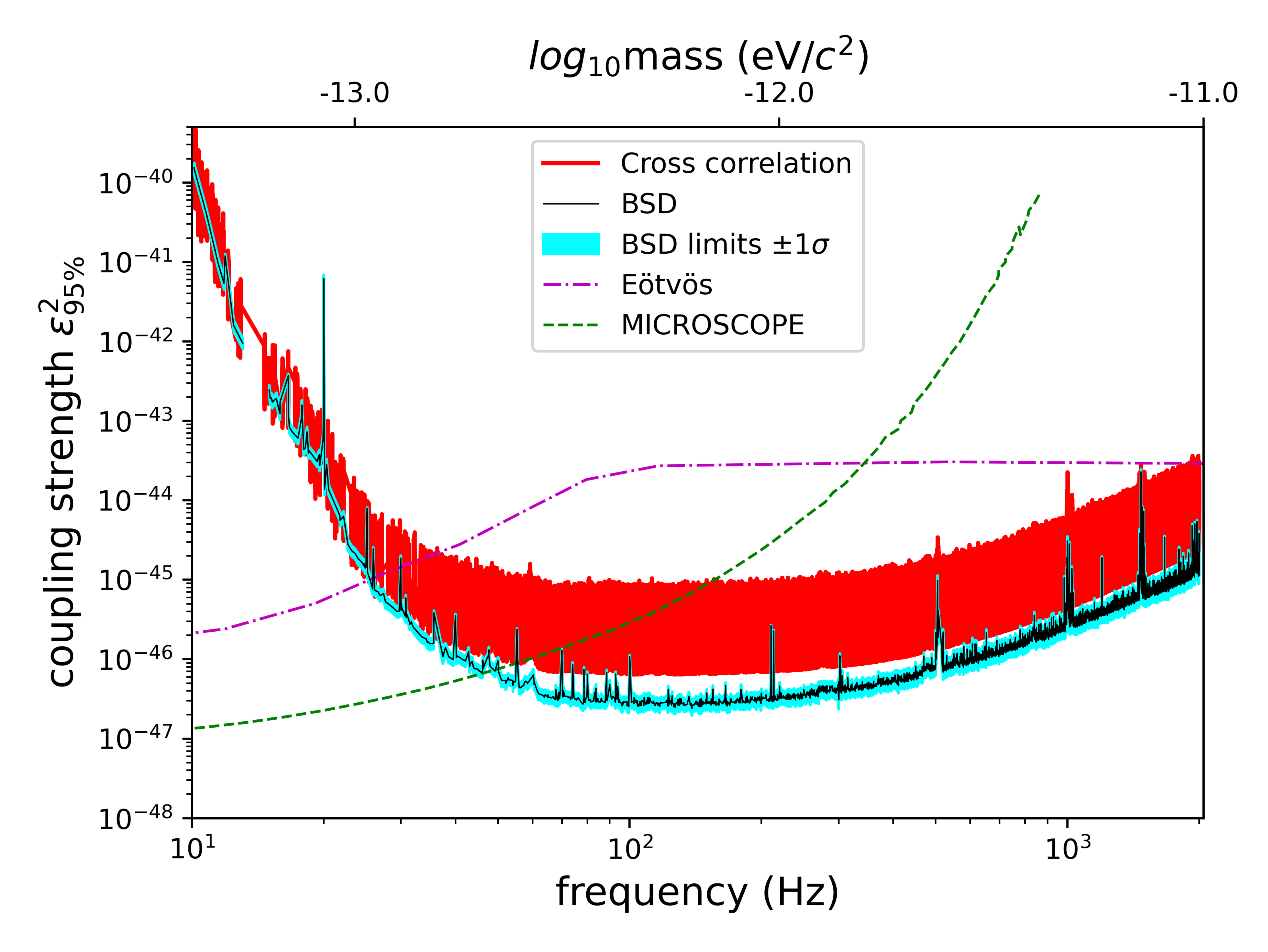
- Determine time/frequency points above a certain power threshold and histogram on frequency axis
- Benefits w.r.t. matched filtering: robust against noise disturbances, gaps, theoretical uncertainties
- Simulated signal shown here

Miller et al. Phys.Rev.D 103 (2021) 10, 103002

Constraints on dark matter using gravitational-wave detectors

O3 LVK dark photon search

- Upper limit from two methods (cross correlation and BSD)
- Cross-corr fixes $T_{\mathrm{FFT}} = 1800$ s; excess power matches T_{FFT} to T_{coh}
- Compared to limits from existing torsion balance experiments (Eötvös) and MICROSCOPE satellite
- Limits are generic — can also be applied to other types of DM can be searched for too (dilatons and tensor bosons in particular)

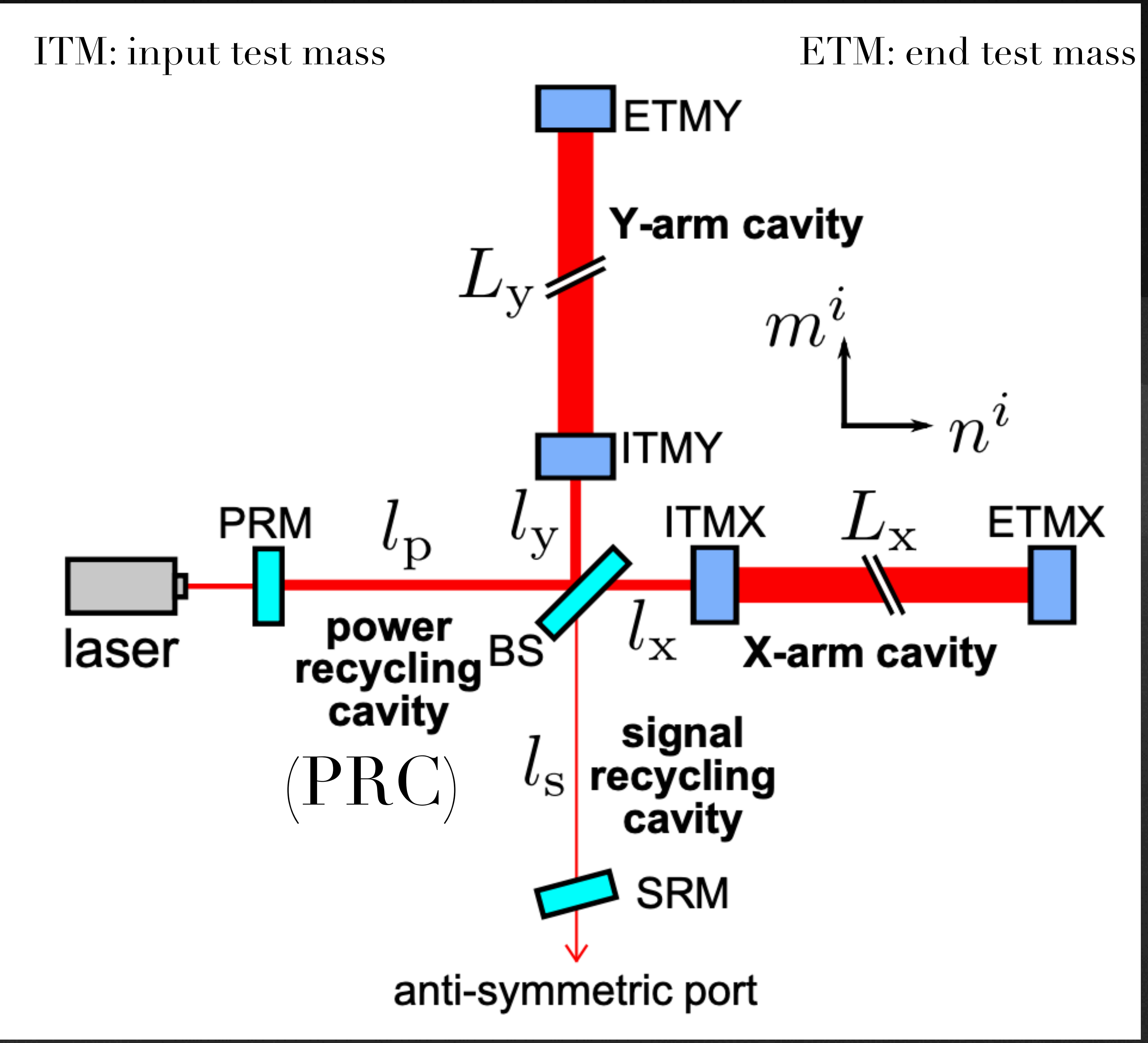


Guo et al. Nat. Commun.Phys. 2 (2019)

LVK 2021: Phys.Rev.D 105 (2022) 6, 063030

O3 KAGRA dark photon search

- Exploits the difference in materials of its mirrors:
  - Input and end test masses (ITMs/ETMs): sapphire
  - Power recycling mirror (PRM) and beam splitter (BS) : fused silica
- Signal strength of dark photons that couple to $U(1)_{B-L}$ is enhanced!
  - Dominant contribution: $h_0 \propto \Delta(Q/M)\epsilon f^{-1}$
- Data are from channel that monitors the length changes between the test masses and auxiliary mirrors. $l_x, l_y, l_p \sim \mathcal{O}(10)$ m!

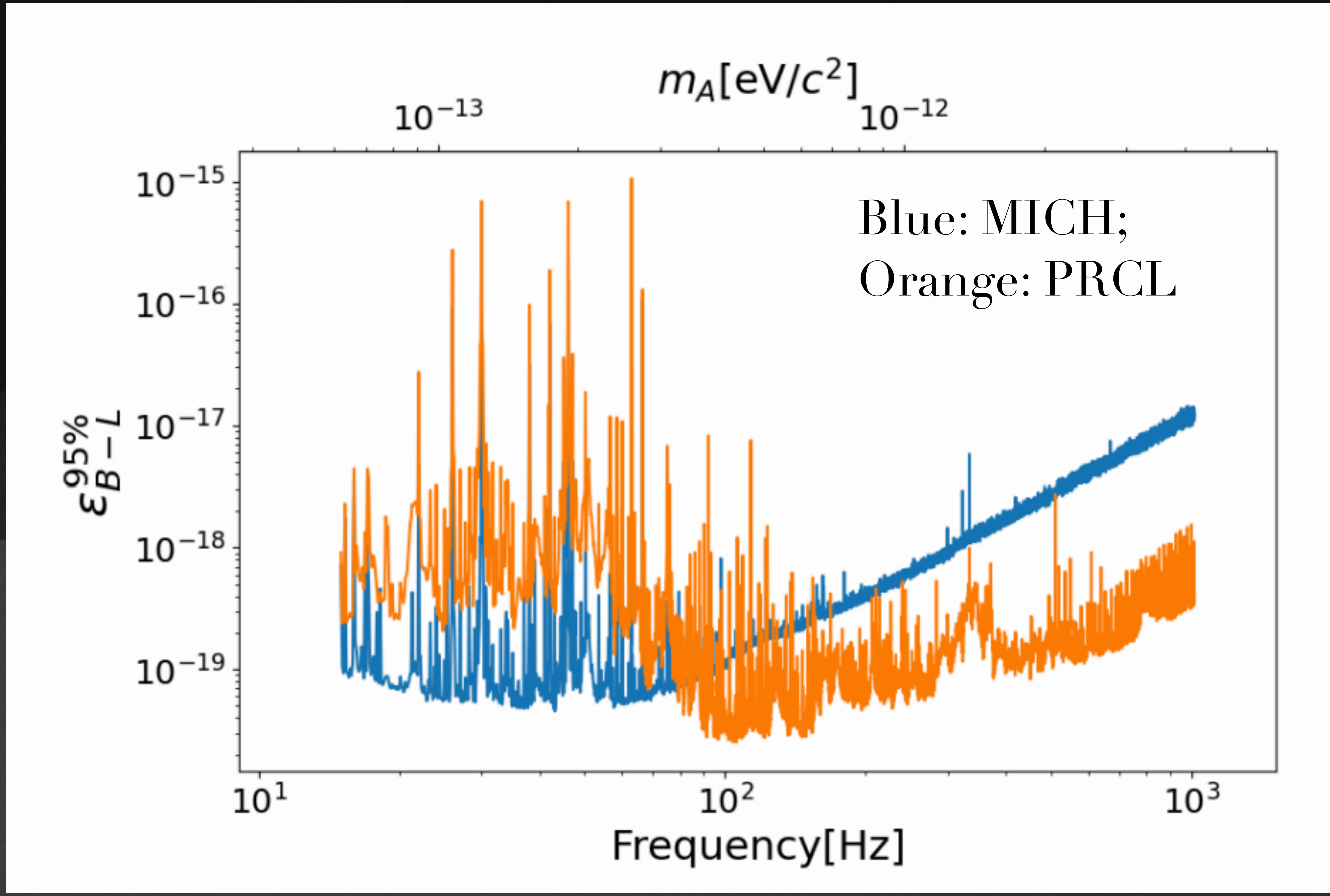


$$
\begin{aligned}
\delta L_{\mathrm{DARM}} &= \delta(L_{\mathrm{x}} - L_{\mathrm{y}}), \\
\delta L_{\mathrm{MICH}} &= \delta(l_{\mathrm{x}} - l_{\mathrm{y}}), \\
\delta L_{\mathrm{PRCL}} &= \delta[(l_{\mathrm{x}} + l_{\mathrm{y}})/2 + l_{\mathrm{p}}]
\end{aligned}
$$

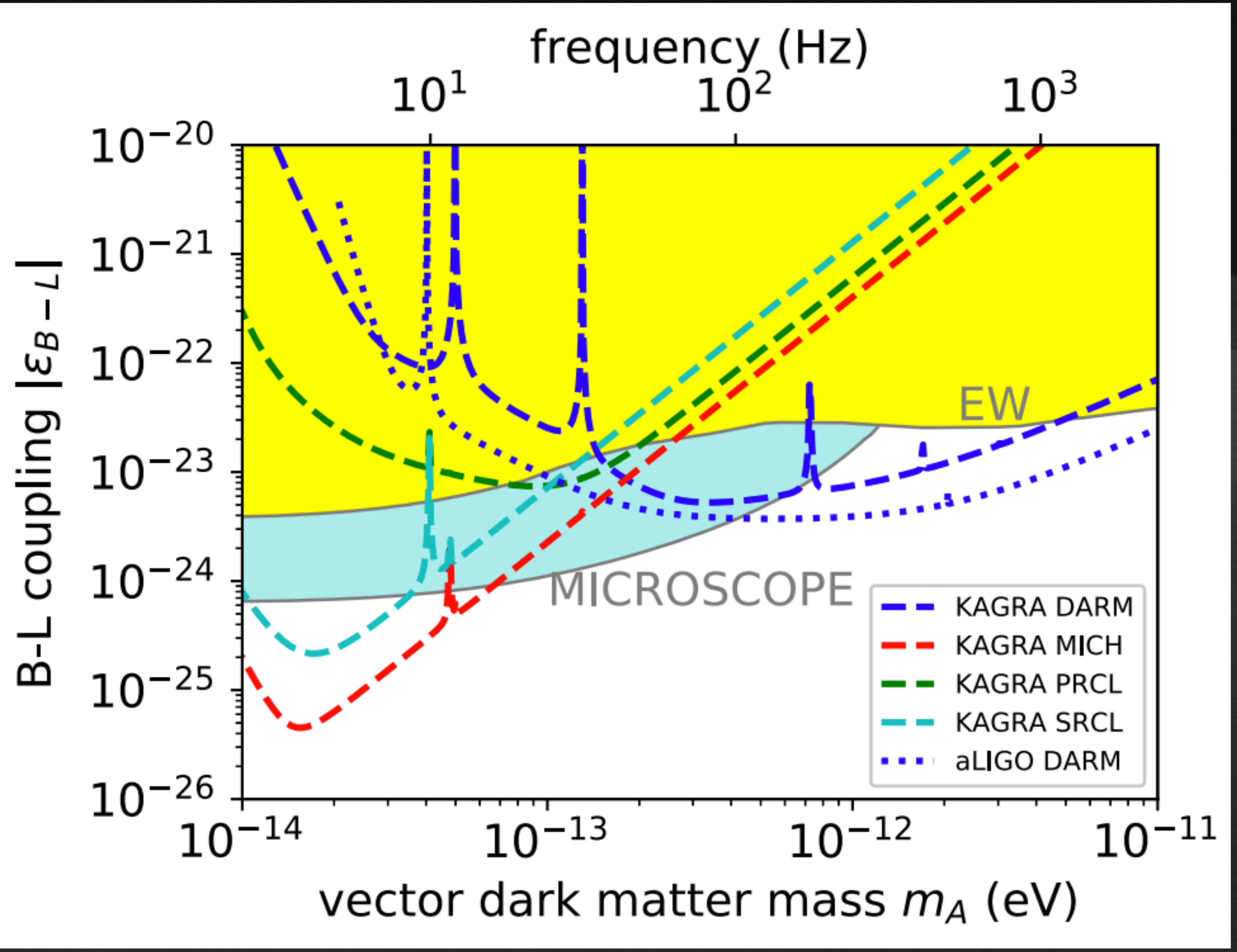
DARM: GW channel
MICH: Between BS and ITMs
PRCL: PRC and ITMs

LVK 2024: arXiv:2403.03004, accepted PRD

O3 KAGRA constraints and future



LVK 2024: arXiv:2403.03004, accepted PRD



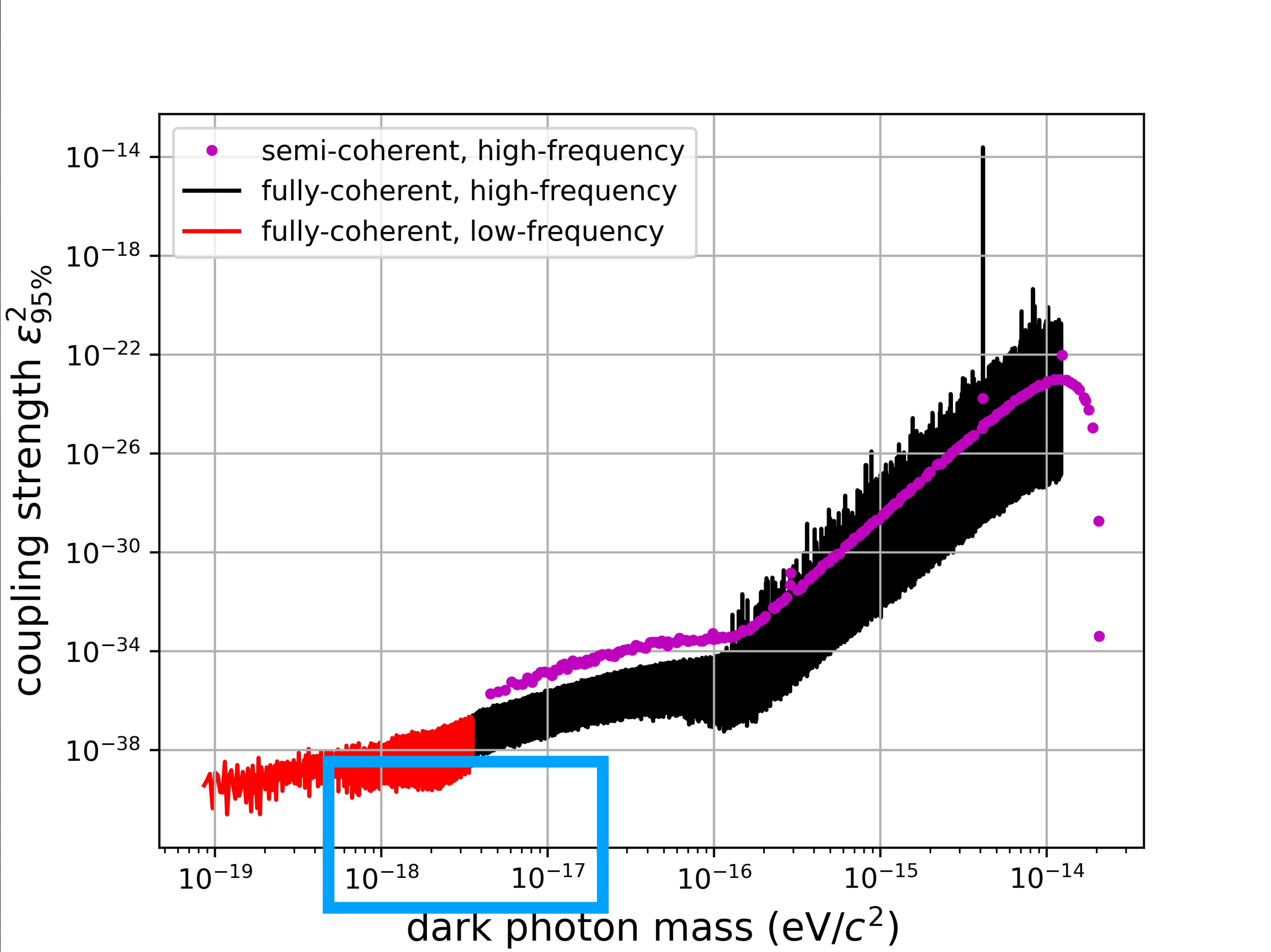
Michamura et al. (2020) PRD 102, 102001

- Constraints much weaker than existing ones because KAGRA is not yet at design sensitivity, but will get better !

LISA Pathfinder (LPF) probes of DM

- Space-based GW detectors will also be sensitive to dark photon dark matter, though at smaller masses
- Same techniques as mentioned before applied (and matched filtering)
- Not as constraining as existing experiments, but are proof-of-concept
- Other channel (relative acceleration of spacecraft and test mass) would give more stringent constraints on coupling of dark photons to neutrons at masses in blue box

Frerick et al. Phys.Lett.B 848 (2024) 138328



Miller and Mendes. Phys.Rev.D 107 (2023) 6, 063015

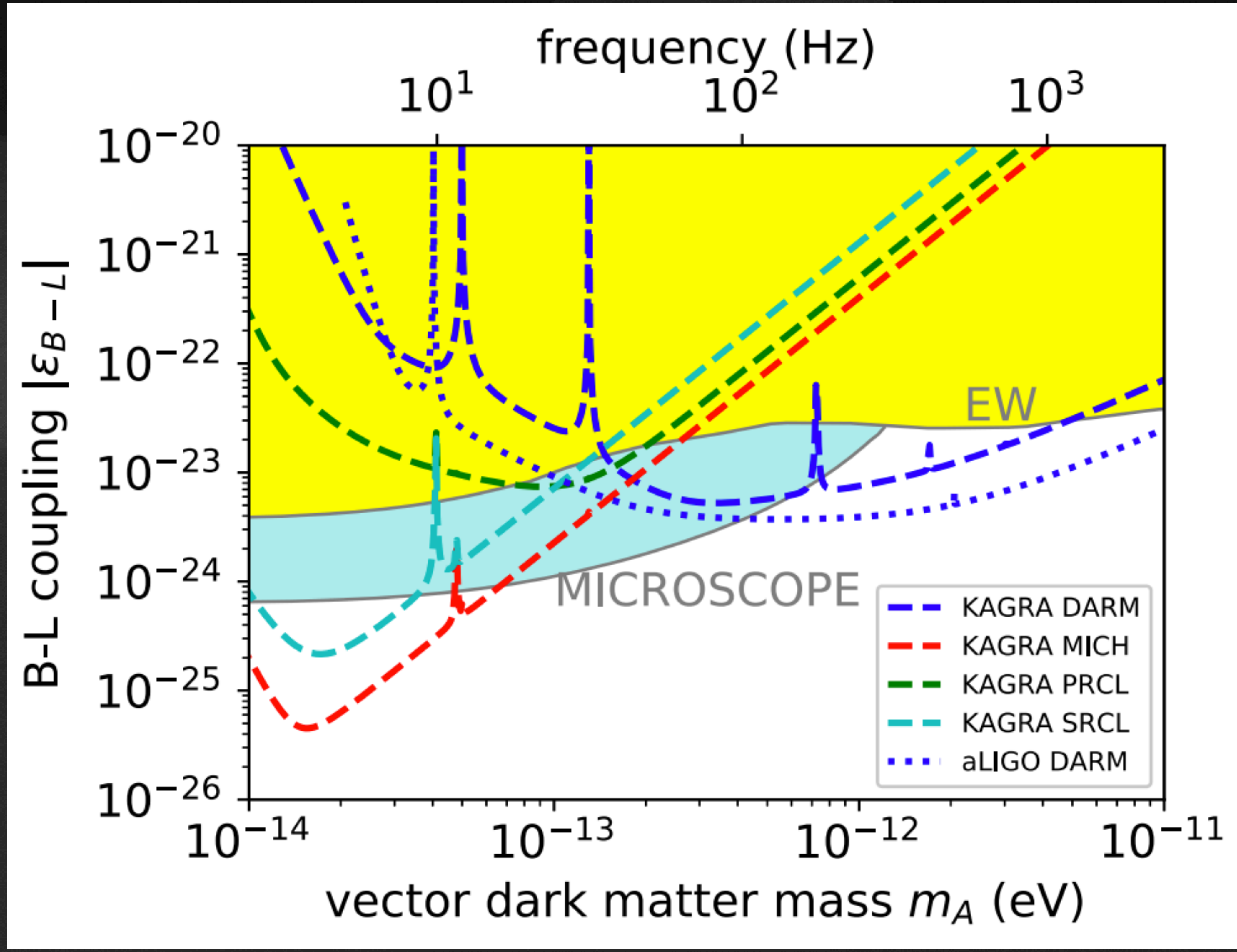
Conclusions

- Dark matter can be probed directly via its interactions with GW detectors without the need to design new instruments!
- A simple quasi-monochromatic signal model describes many types of dark matter
- Space-based gravitational-wave detectors can also be sensitive to these kinds of dark matter interactions, though at lower masses, $\mathcal{O}(10^{-19} - 10^{-14})$ eV
- If you are interested in working on any aspect of dark matter, please send me an email: amiller@nikhef.nl

Backup slides

Future KAGRA vector dark matter search

- Differential arm strain mostly cancelled out
- Sapphire mirrors for arm cavities, and fused silica mirrors for others
- B-L charge for
  - Fused silica: 0.501
  - Sapphire: 0.510
- KAGRA can do better than LIGO/Virgo in low mass range by using auxiliary length channels for the B-L coupling
- KAGRA can see DM at frequencies below 10 Hz!



Michamura et al. (2020) PRD 102, 102001