Part II: Ultralight dark matter detection with gravitational-wave interferometers

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LIGO VIRGO KAGRA

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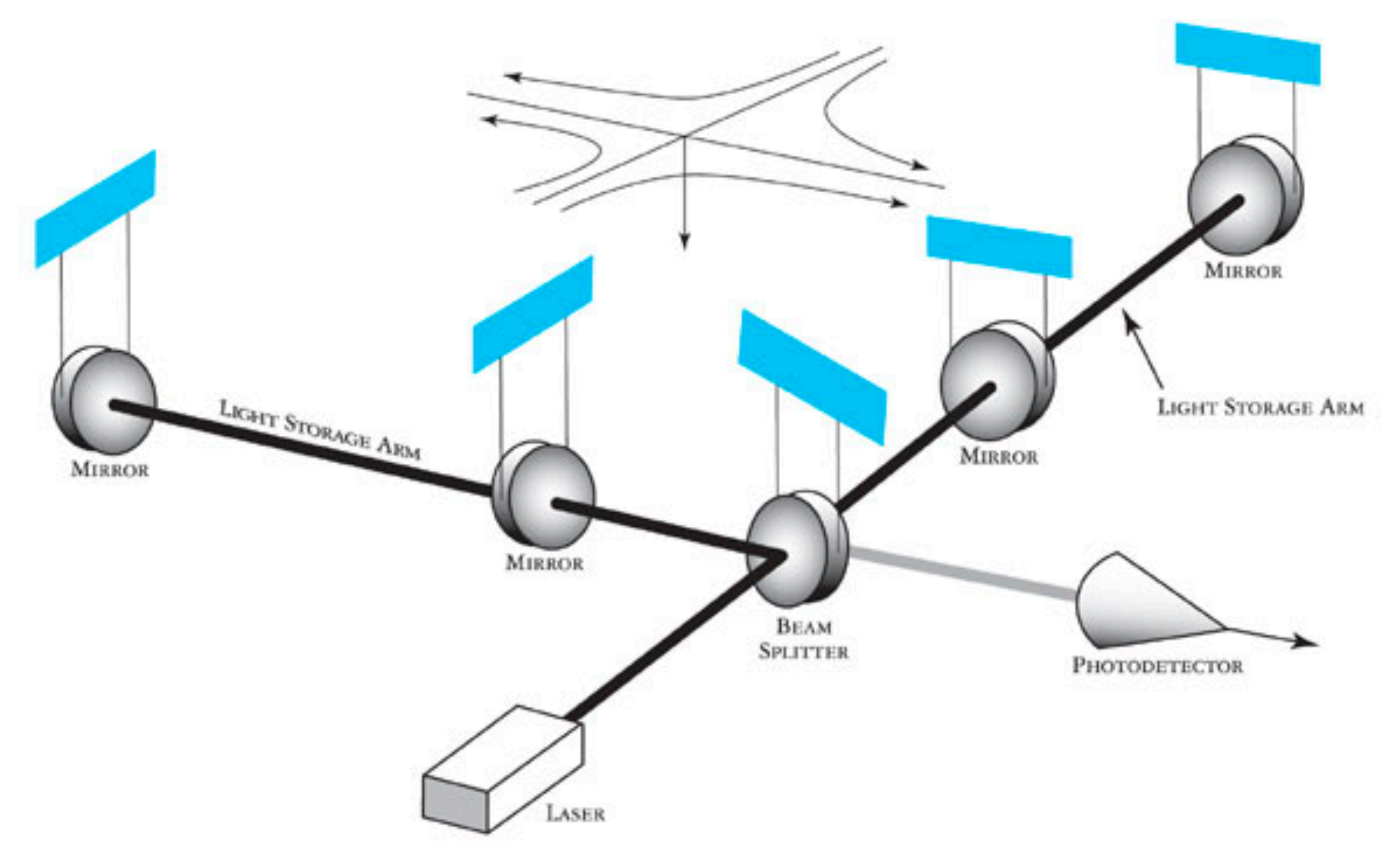
Background

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?



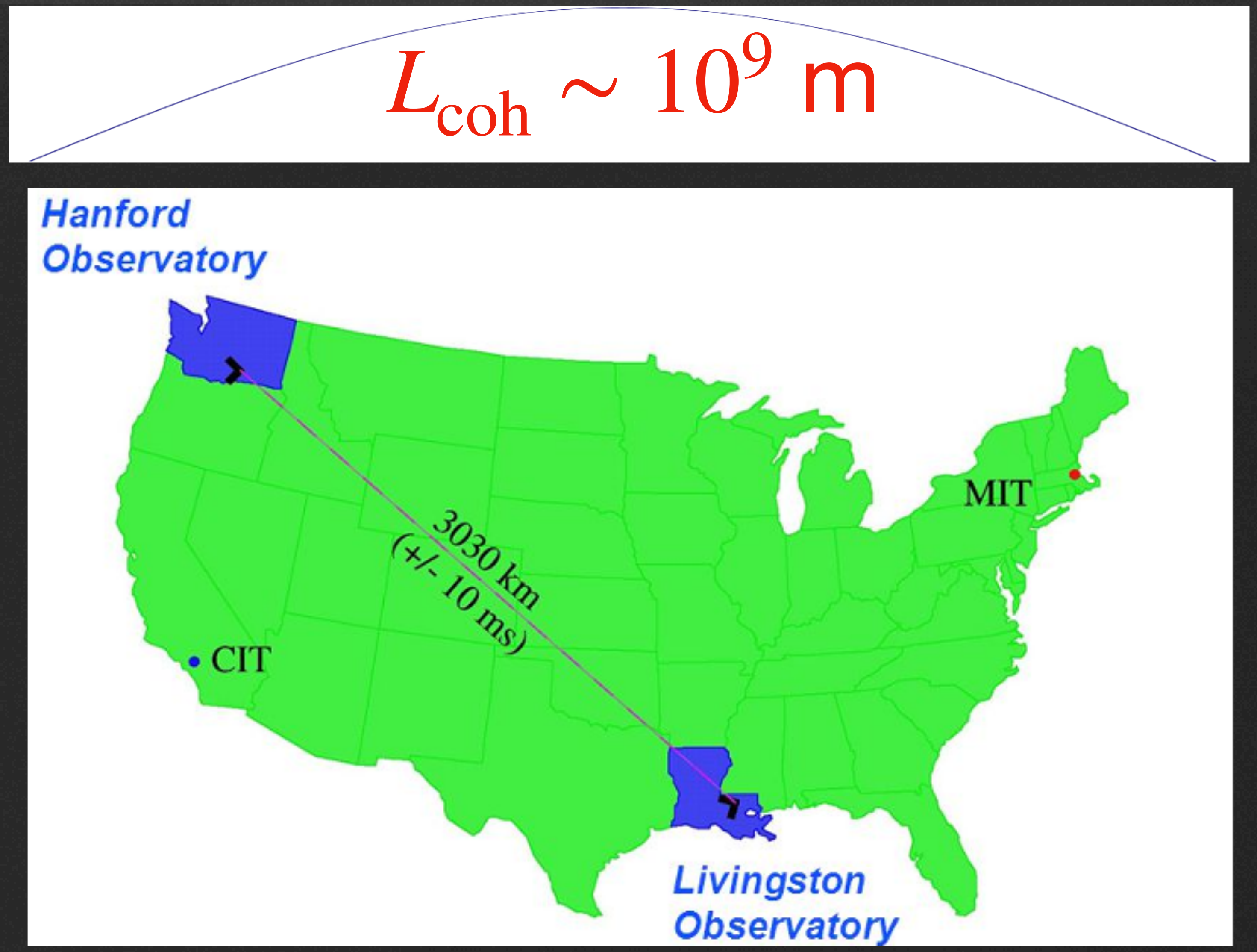
Pierce et al. 2018, Phys. Rev. Lett. 121, 061102
Morisaki et al. 2021, Phys. Rev. D. 103, L051702
Vermeulen et al. 2021, Nature 600, pages 424–428

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

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

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



Vector bosons: dark photons

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

$\underline{m_A}$: dark photon mass
$\underline{\varepsilon_D}$: coupling strength
$\underline{A_\mu}$: 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

True differential motion from dark photon field

- Differential strain results because each mirror is in a different place relative to the incoming dark photon field: this is a *spatial* effect
- Depends on the frequency, the coupling strength, the dark matter density and velocity

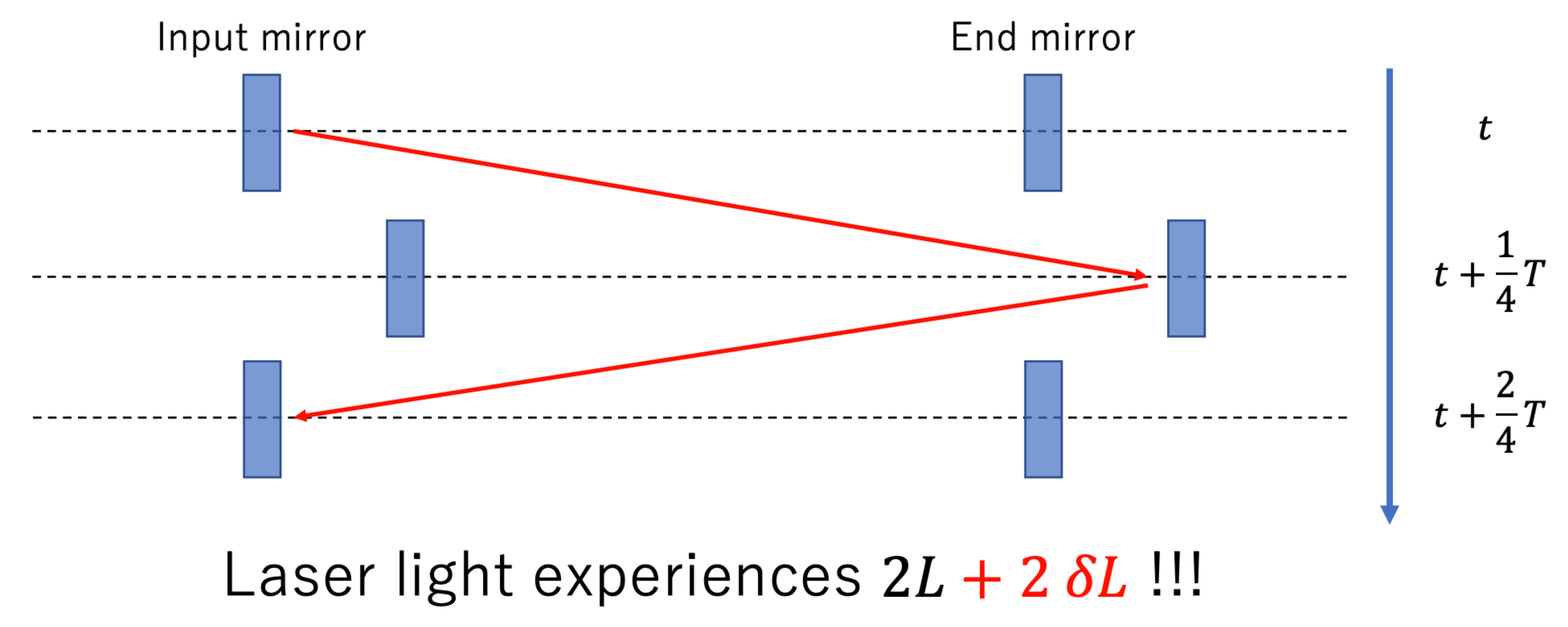
$$\sqrt{\langle h_D^2 \rangle} = C \frac{q}{M} \frac{\hbar e}{c^4 \sqrt{\epsilon_0}} \sqrt{2\rho_{\mathrm{DM}}} v_0 \frac{\epsilon}{f_0},$$

$$\simeq 6.56 \times 10^{-27} \left(\frac{\epsilon}{10^{-23}} \right) \left(\frac{100 \text{ Hz}}{f_0} \right)$$

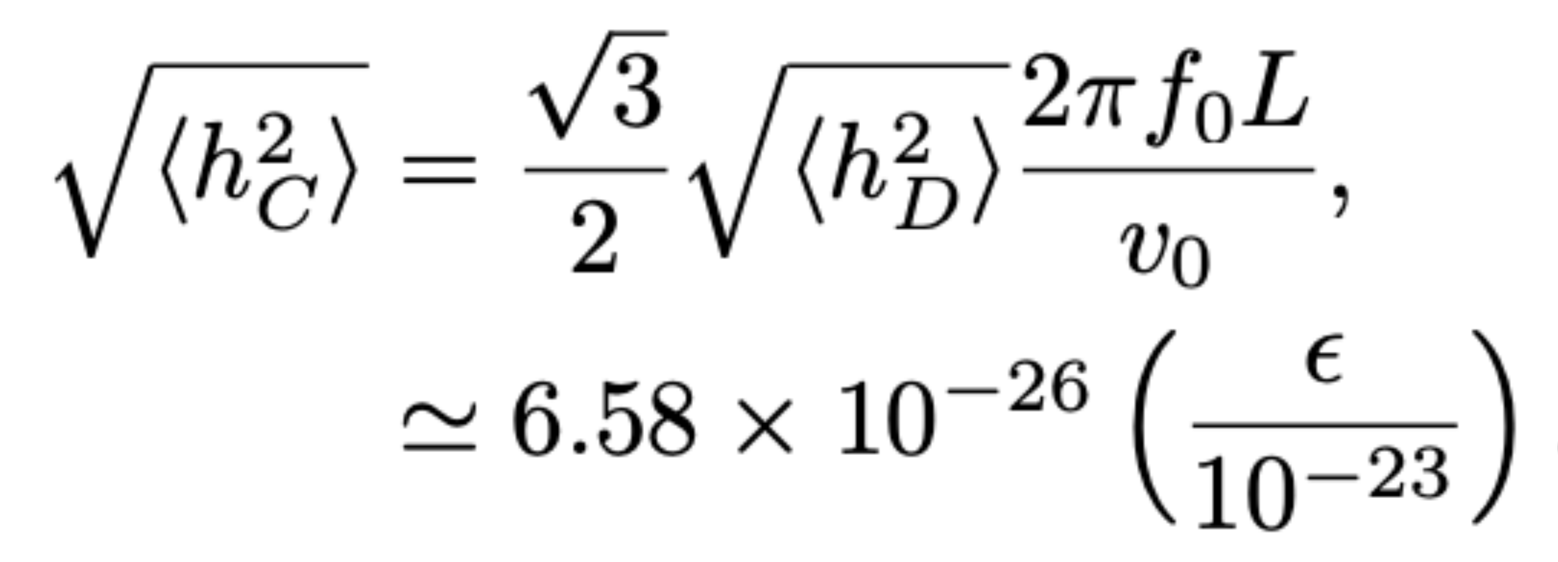
Pierce et al. 2018, Phys. Rev. Lett. 121, 061102

Common motion

- Arises because light takes a finite amount of time to travel from the beam splitter to the end mirror and back
- Imagine a dark photon field that moves the beam splitter and one end mirror exactly the same amount
- The light will “see” the mirror when it has been displaced by a small amount
- And then, in the extreme case (a particular choice of parameters), the light will “see” the beam splitter when it has returned to its original location
- But, the y-arm has not been moved at all by the field —> apparent differential strain



Laser light experiences $2L + 2\,\delta L$!!!



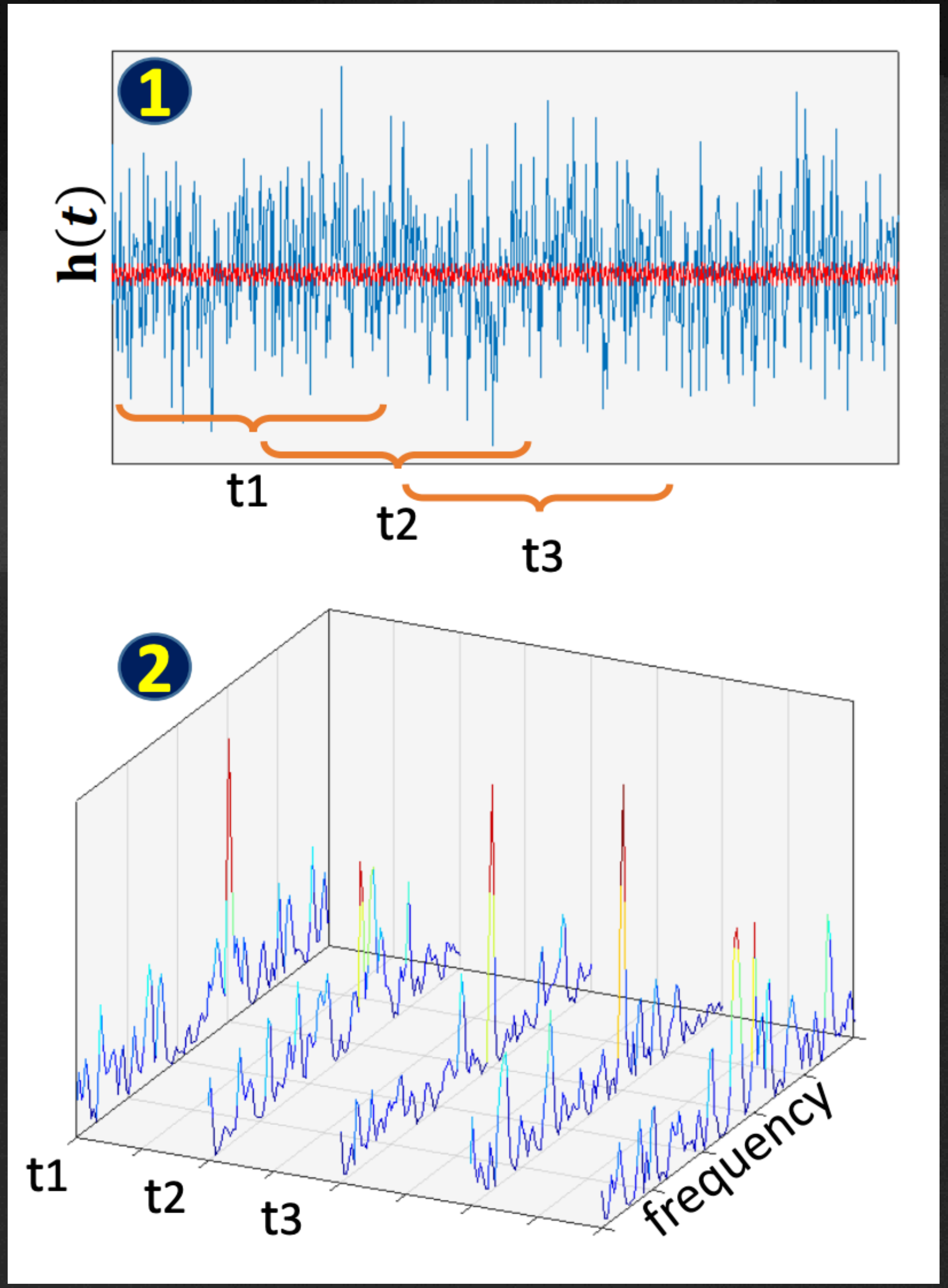
$$\sqrt{\langle h_C^2 \rangle} = \frac{\sqrt{3}}{2}\sqrt{\langle h_D^2 \rangle}\frac{2\pi f_0 L}{v_0}, \\ \simeq 6.58 \times 10^{-26}\left(\frac{\epsilon}{10^{-23}}\right)$$

Morisaki et al. 2021, Phys. Rev. D. 103, L051702

Methods to search for dark matter

How to search for DM?

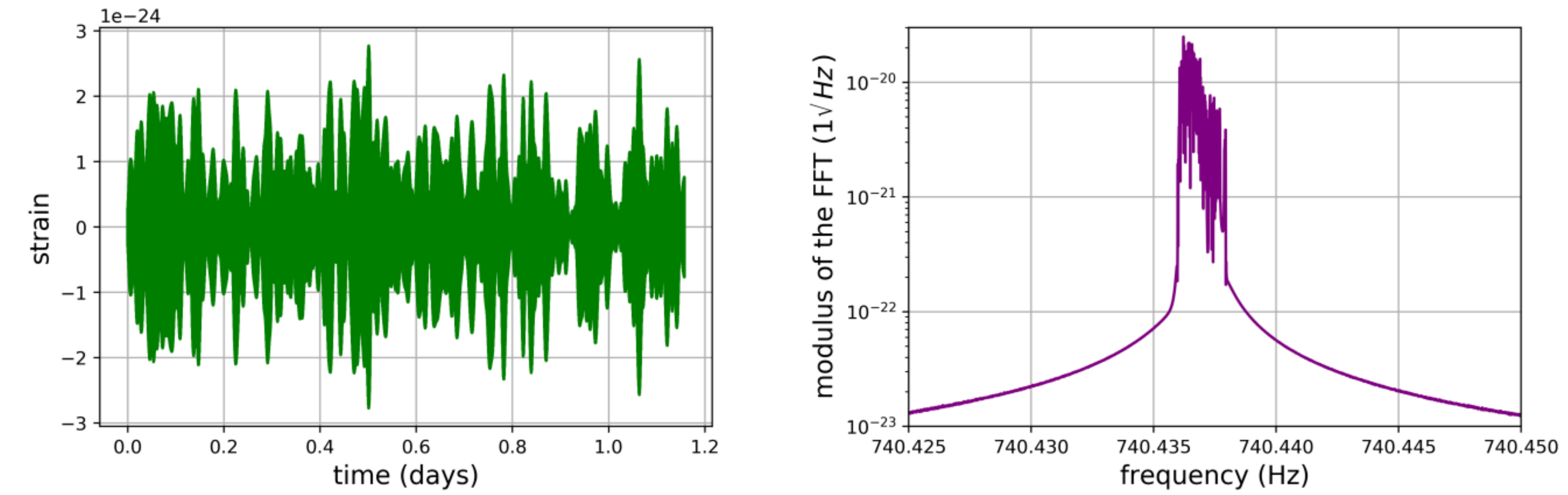
- Ideal technique to find weak signals in noisy data: matched filter
- But, signal has stochastic fluctuations —> matched filter cannot work
- The signal is almost monochromatic —> take Fourier transforms of length $T_{\mathrm{FFT}} \sim T_{\mathrm{coh}}$ and combine the power in each FFT without phase 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 $T_{\mathrm{FFT}} > T_{\mathrm{coh}}$
- Break dataset into smaller chunks of length $T_{\mathrm{FFT}} \sim T_{\mathrm{coh}}$ to confine this frequency modulation to one bin, then sum power in each chunk



(a) (b)

- 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

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

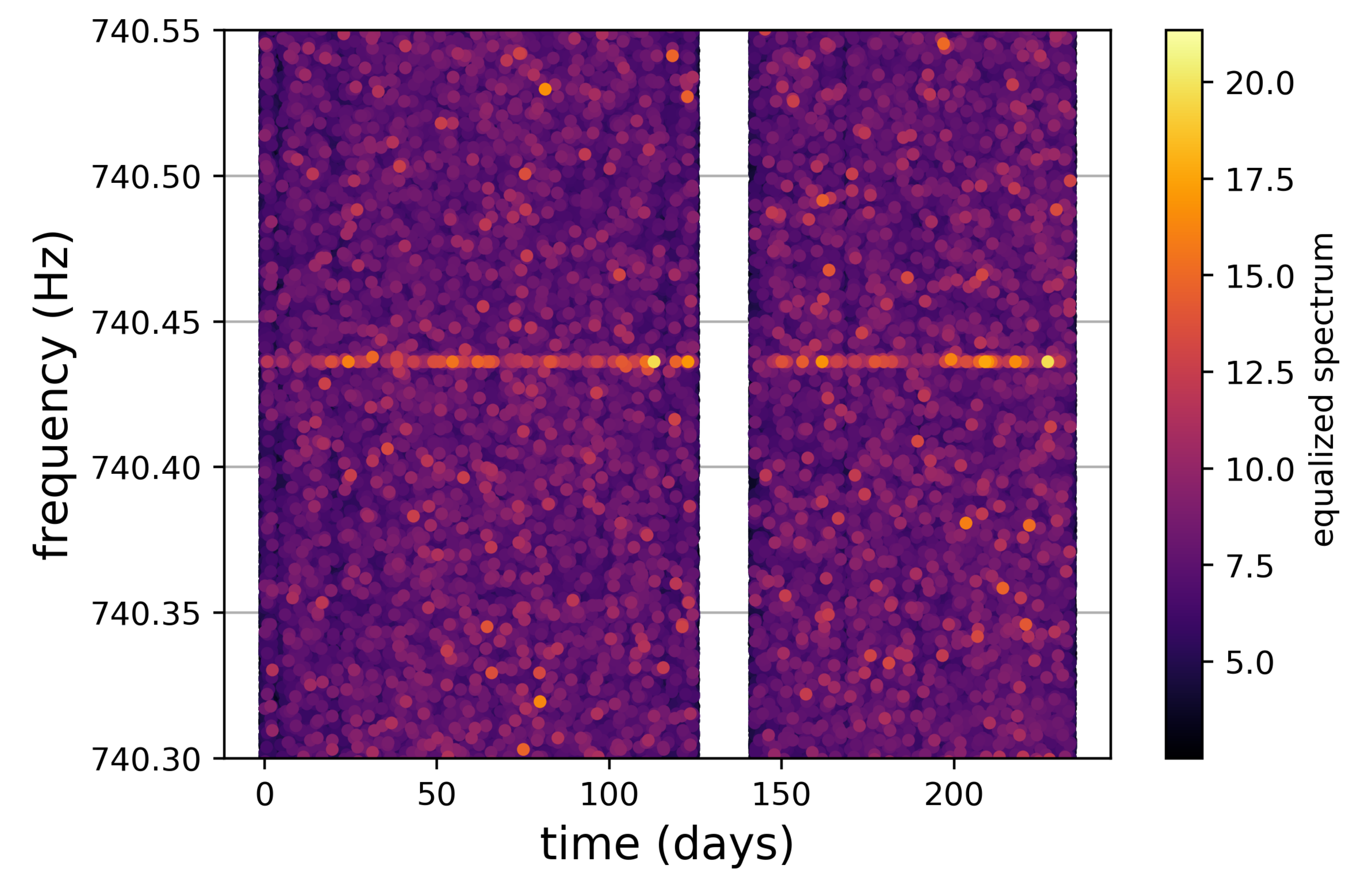
$$\sigma_j^2 = \frac{1}{N_{\text{FFT}}} \left\langle \frac{1}{2 P_{1,ij} P_{2,ij}} \right\rangle_{N_{\text{FFT}}}$$

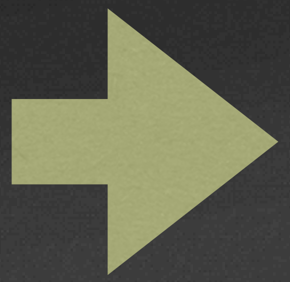
$$\text{SNR}_j = \frac{S_j}{\sigma_j}$$

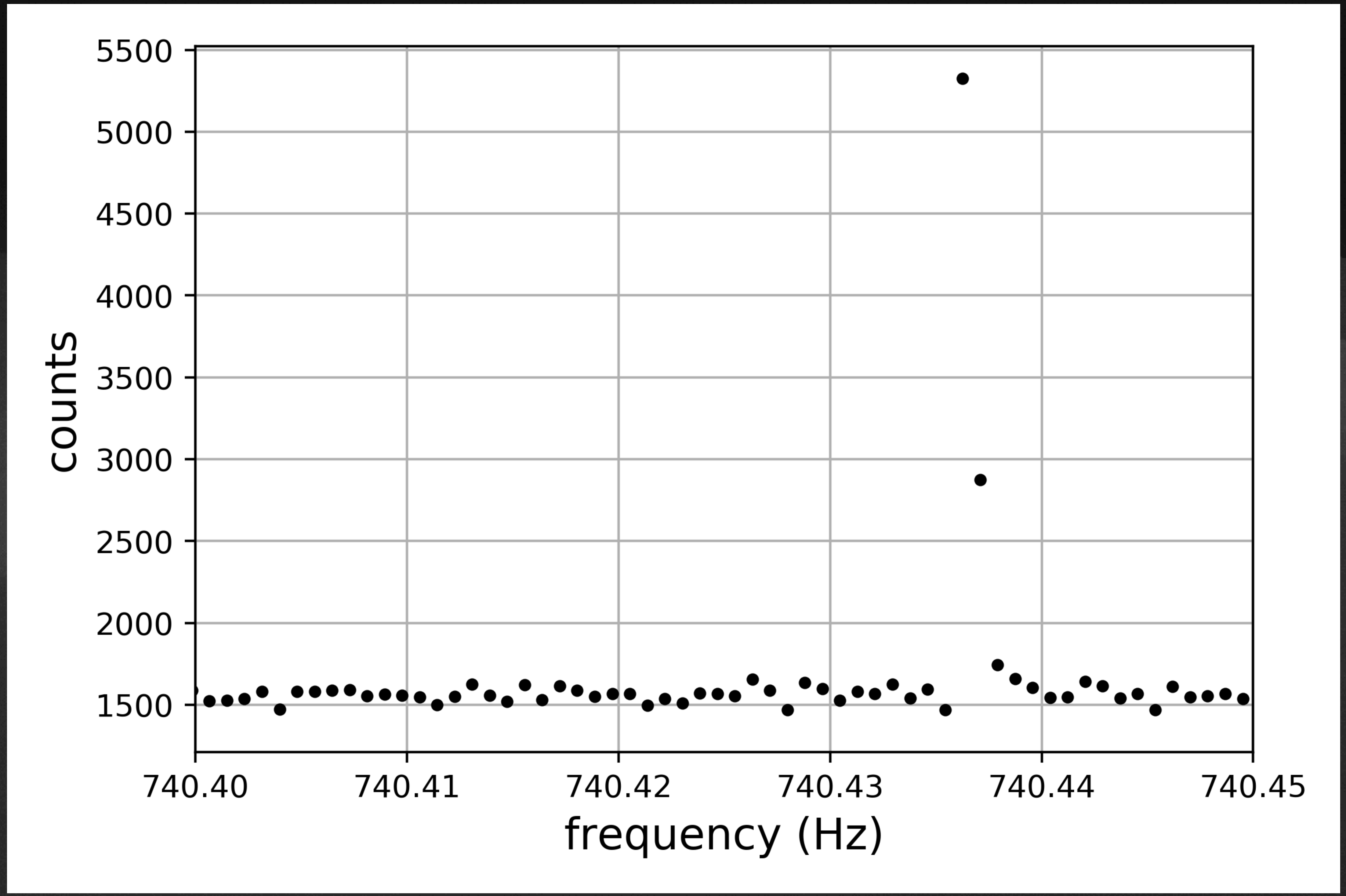
Pierce et al. 2018, Phys. Rev. Lett. 121, 061102

D'Antonio et al. 2018 Phys. Rev. D 98, 103017

Method: look for excess power







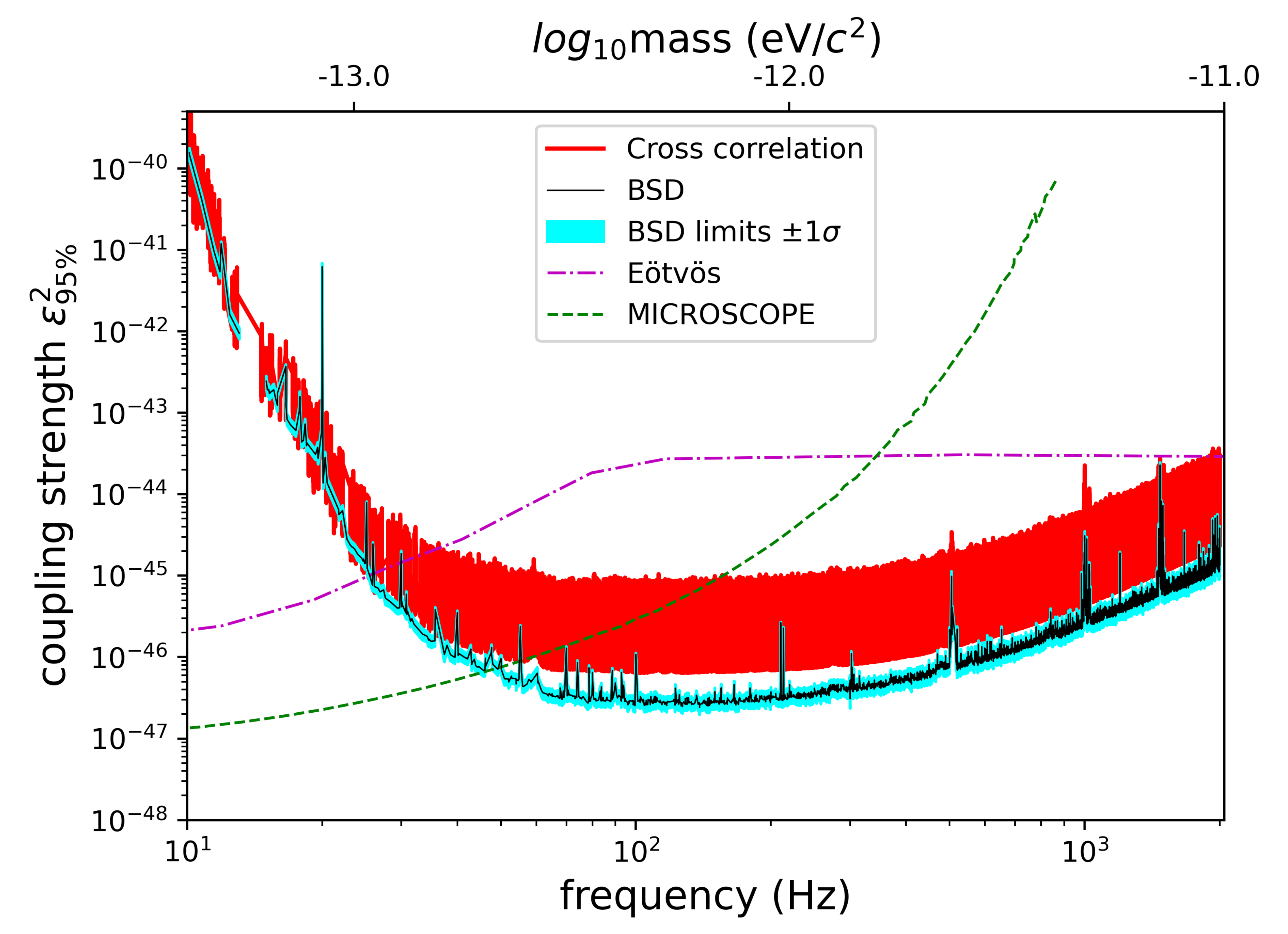
- Determine time/frequency points above a certain power threshold and histogram on frequency axis
- Benefits w.r.t. matched filtering: robust against noise disturbances, gaps, theoretical uncertainties
- Simulated signal shown here

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)

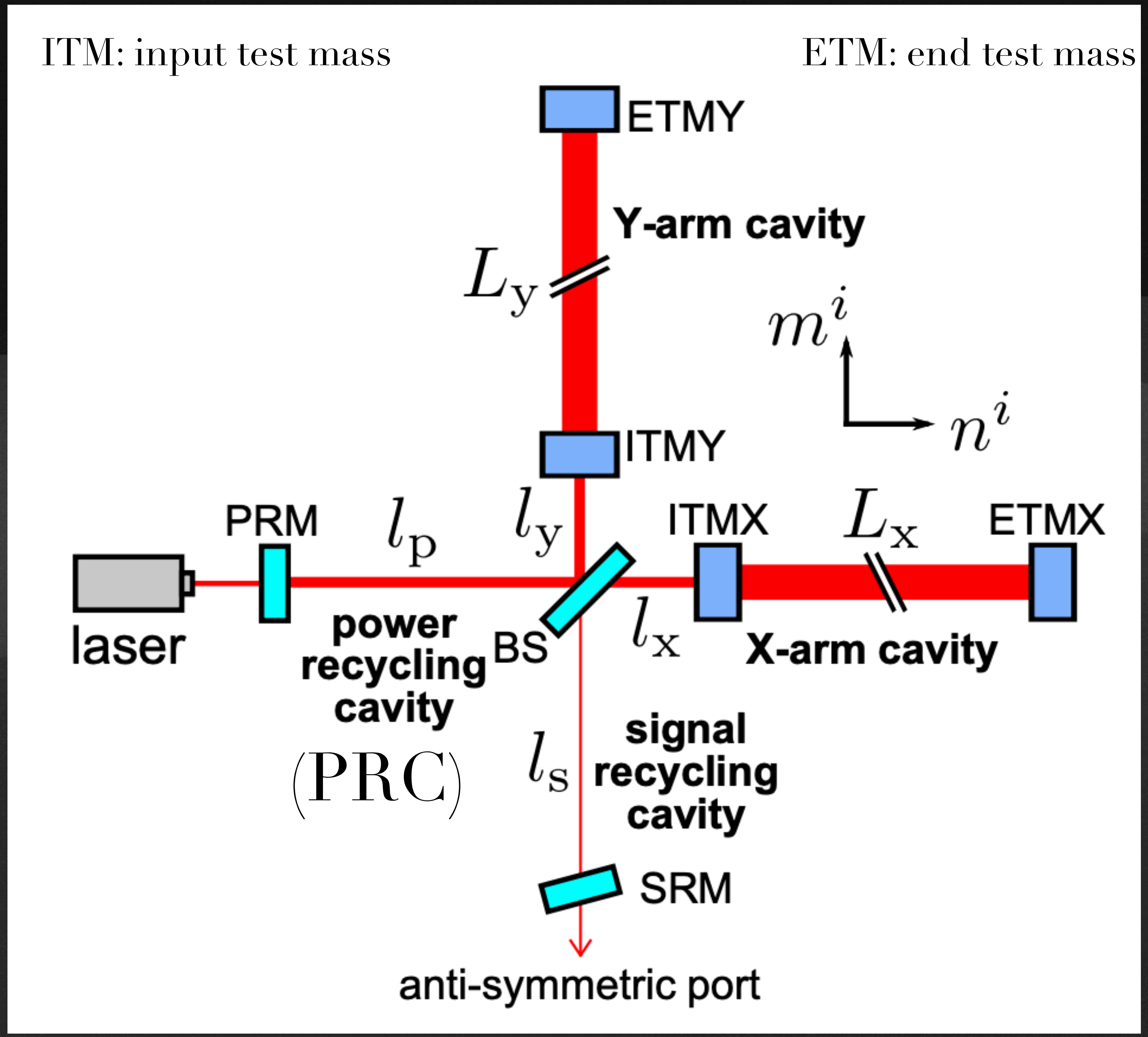


Guo et al. Nat. Commun.Phys. 2 (2019)

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 $\mathrm{U}(1)_{B-L}$ 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!

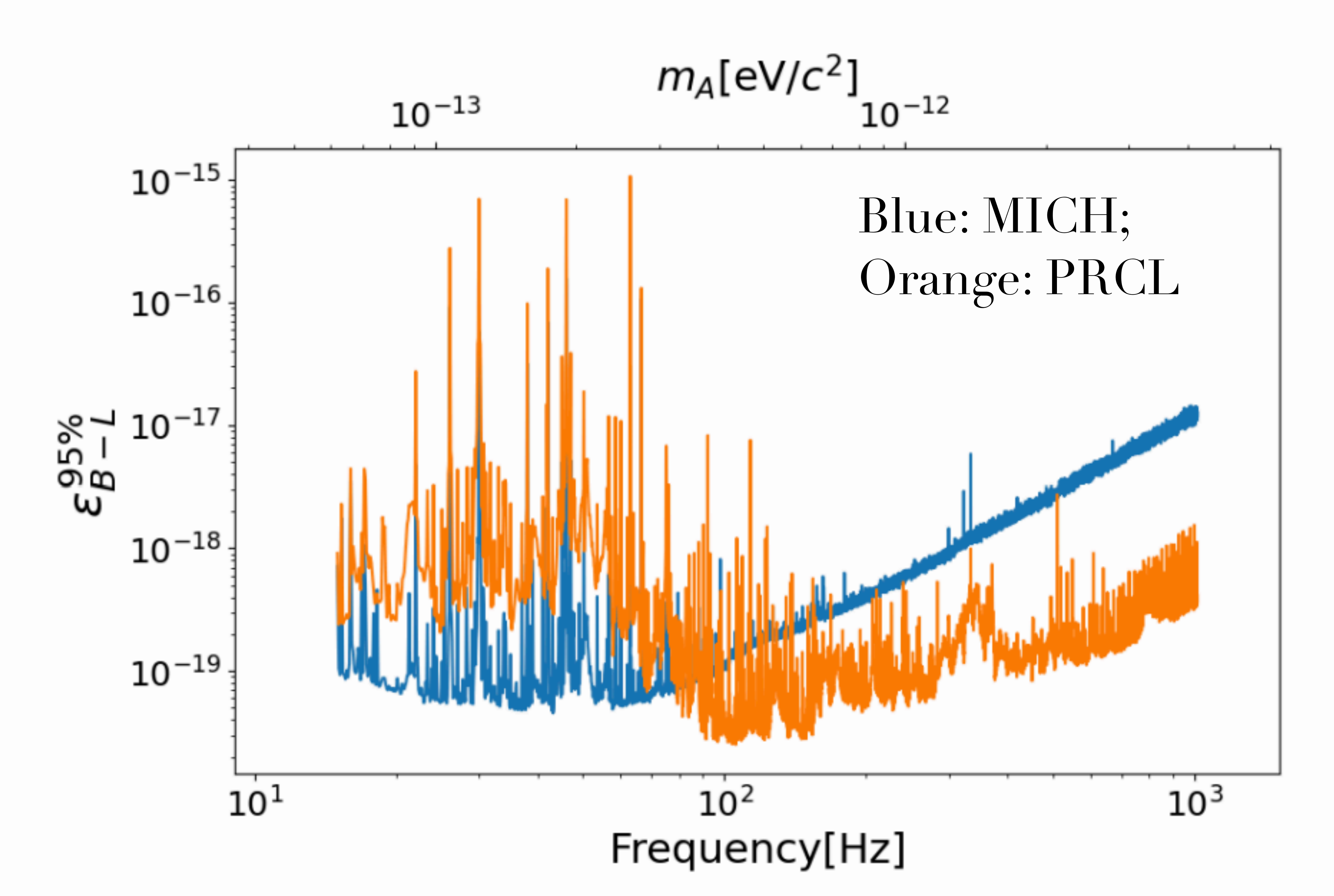


$$
\begin{aligned}
\delta L_{\mathrm{DARM}} &= \delta(L_{\mathrm{x}} - L_{\mathrm{y}}), \\
\delta L_{\mathrm{MICH}} &= \delta(l_{\mathrm{x}} - l_{\mathrm{y}}), \\
\delta L_{\mathrm{PRCL}} &= \delta[(l_{\mathrm{x}} + l_{\mathrm{y}})/2 + l_{\mathrm{p}}]
\end{aligned}
$$

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

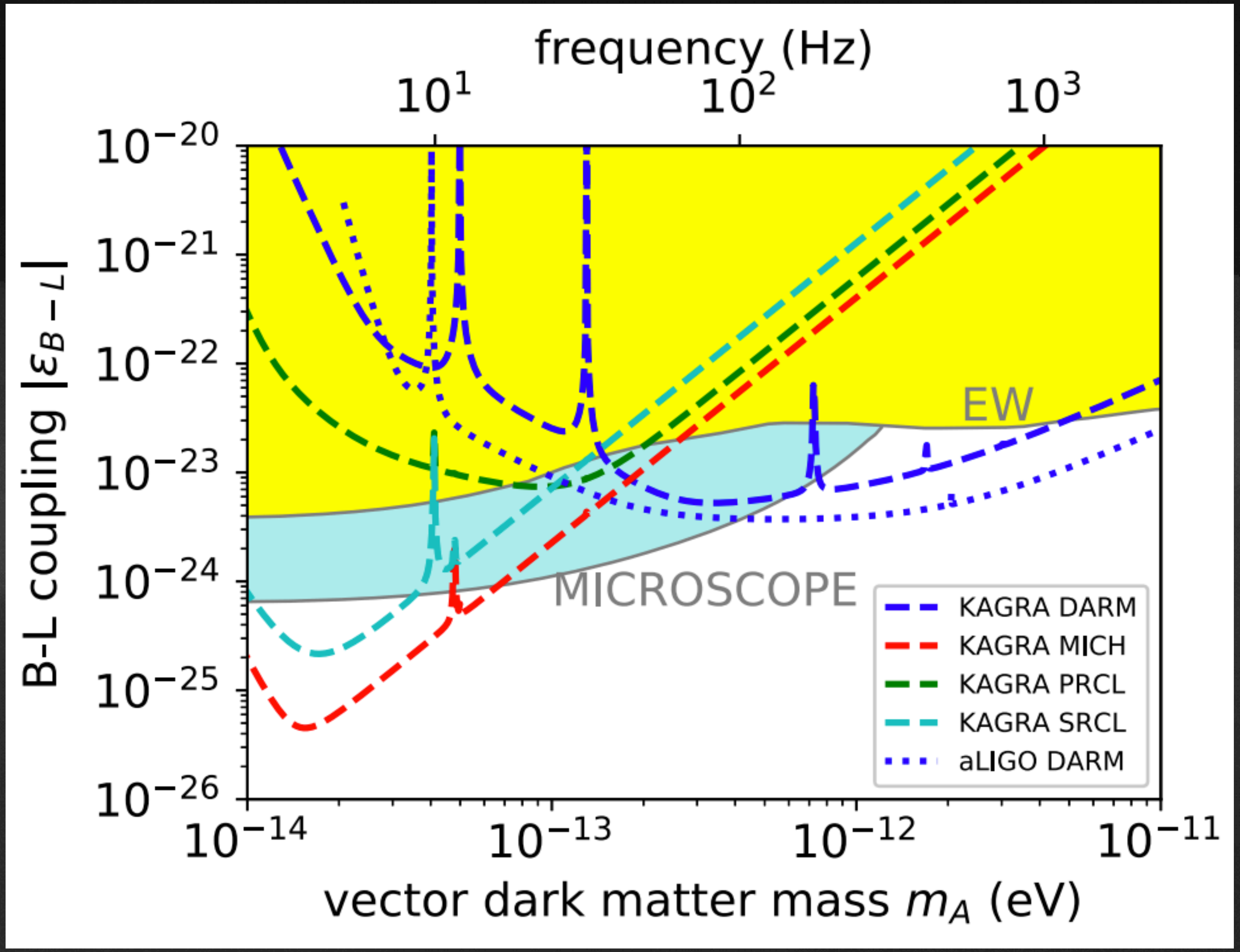
LVK 2024: Phys.Rev.D 110 (2024) 4, 042001

O3 KAGRA constraints and future



Blue: MICH;
Orange: PRCL

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



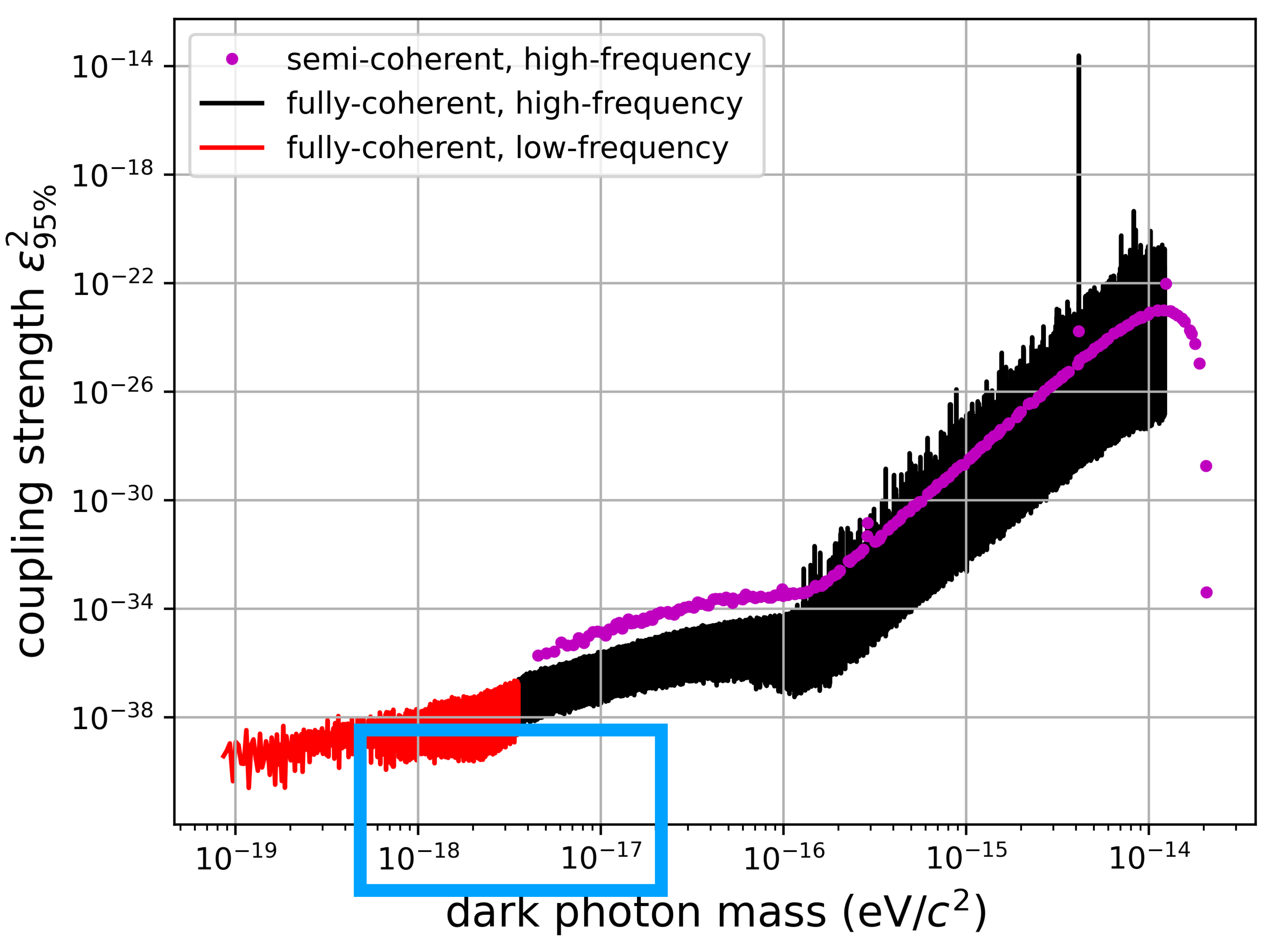
Michamura et al. (2020) PRD 102, 102001

- 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

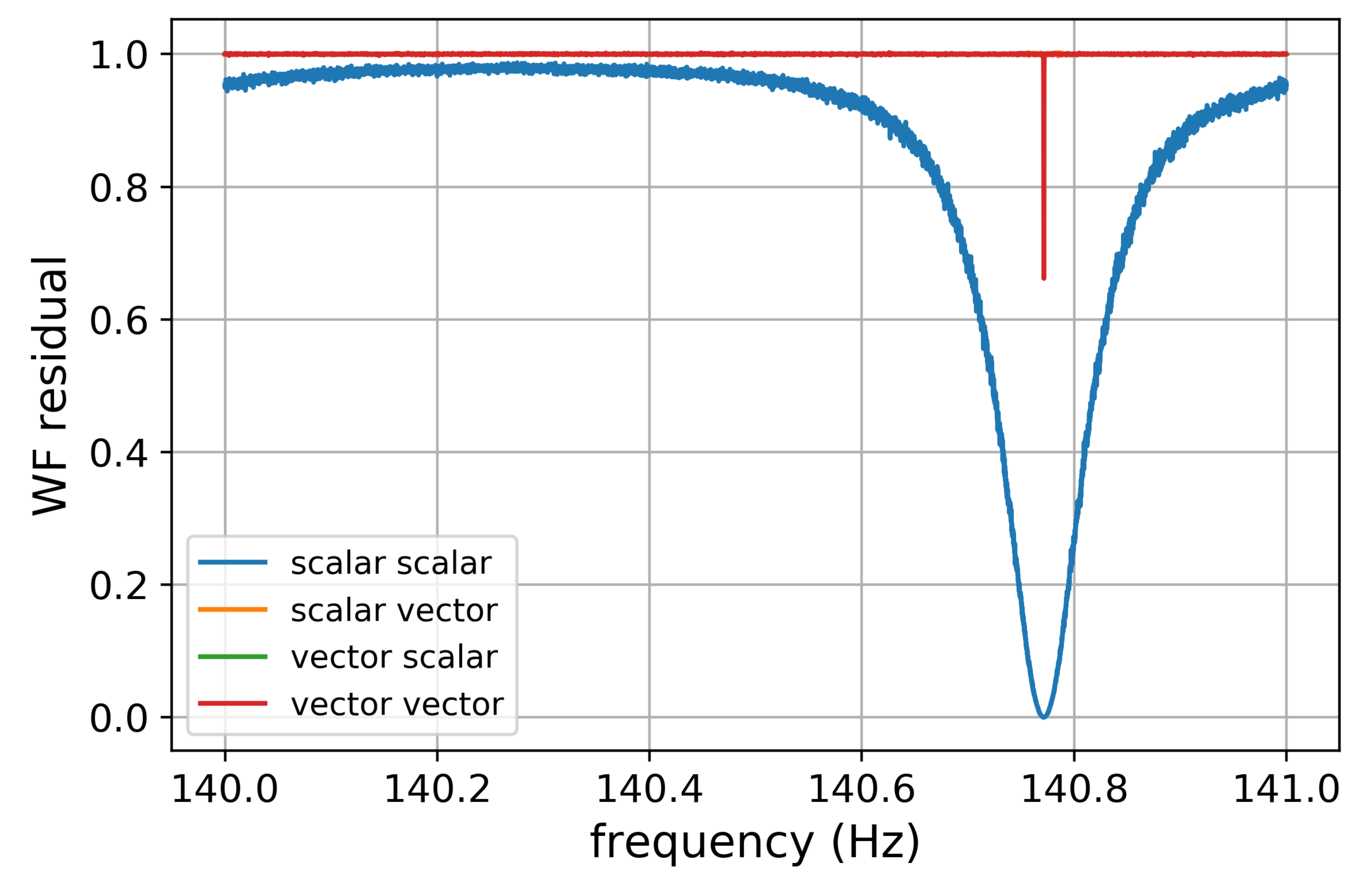
Frerick et al. Phys.Lett.B 848 (2024) 138328



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

Distinguish between DM types

- DM could take different forms and have different spins —> could couple to GW interferometers in unique ways
- However, current analyses are not sensitive to the kind of DM that could couple to the detectors
- Wiener filter proposed to distinguish between scalar, vector and tensor DM
    - Different correlations between detectors spread across the earth would exist for the different DM particles
- Method needs to be completely developed beyond "proof-of-concept" stage, compared with existing ones



Miller, A. L., Badaracco, F., & Palomba, C. (2022). PRD, 105(10), 103035.

Conclusions

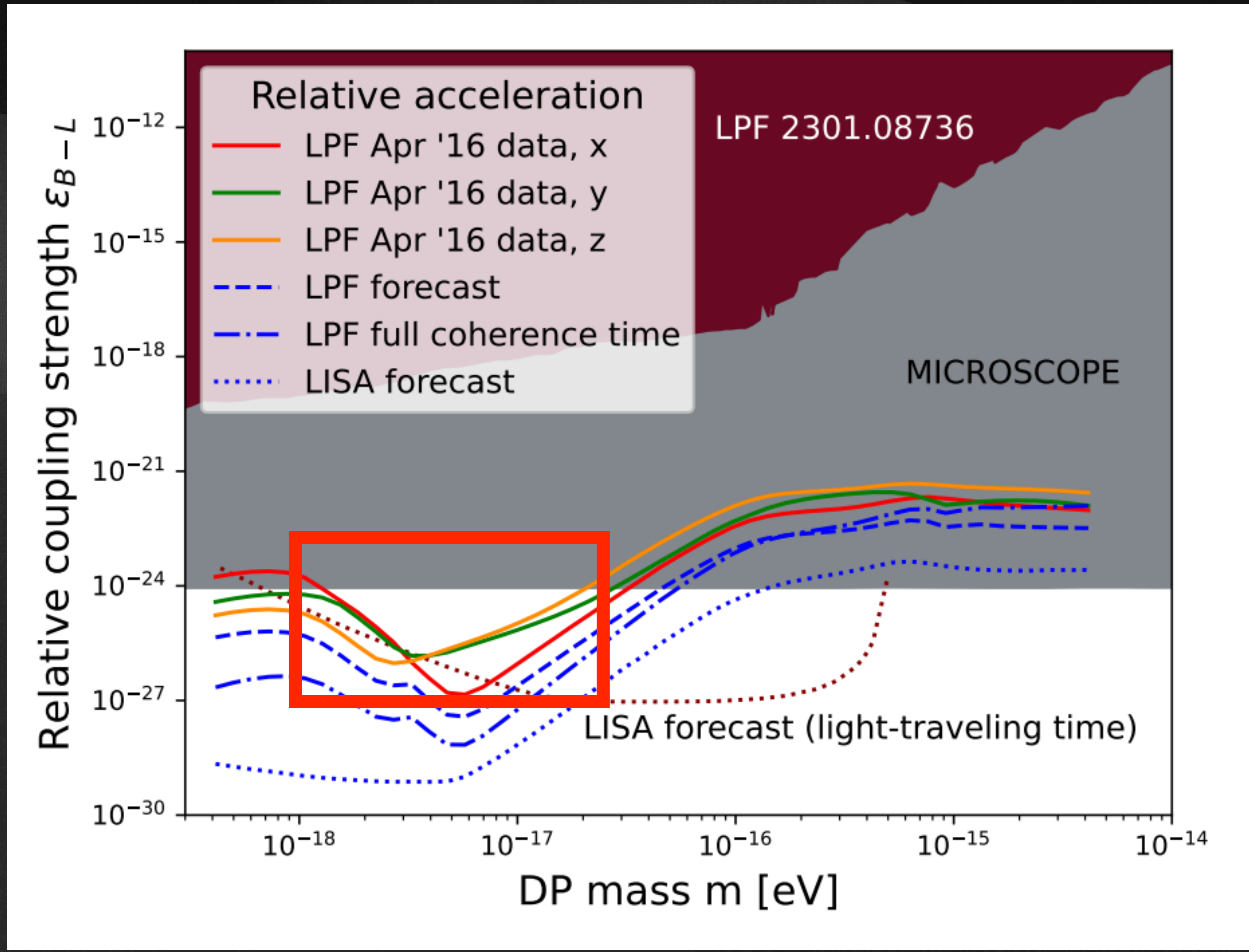
- Dark matter can be probed directly via its interactions with GW detectors without the need to design new instruments!
- A simple quasi-monochromatic signal model describes many types of dark matter
- Space-based gravitational-wave detectors can also be sensitive to these kinds of dark matter interactions, 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

Search for dark matter in LISA Pathfinder in different channel

Miller, A. L., et al. (2022). PRD, 105(10), 103035.

- Projected limits on the coupling of dark photons to baryon & baryon-lepton number using the relative acceleration of the test masses and spacecraft
- Promising in low-mass regime (10^{-18} – 10^{-17} eV) that real constraints could be produced
- We can search LPF data in this regime, which needs some method development because PSD estimation is not easy at low masses (low frequencies)
- Distinguishing method discussed can be applied here as well: how to distinguish this from other monochromatic sources in LISA?



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

Background

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