Constraints on dark photon dark matter using data from LIGO's and Virgo's third observing run

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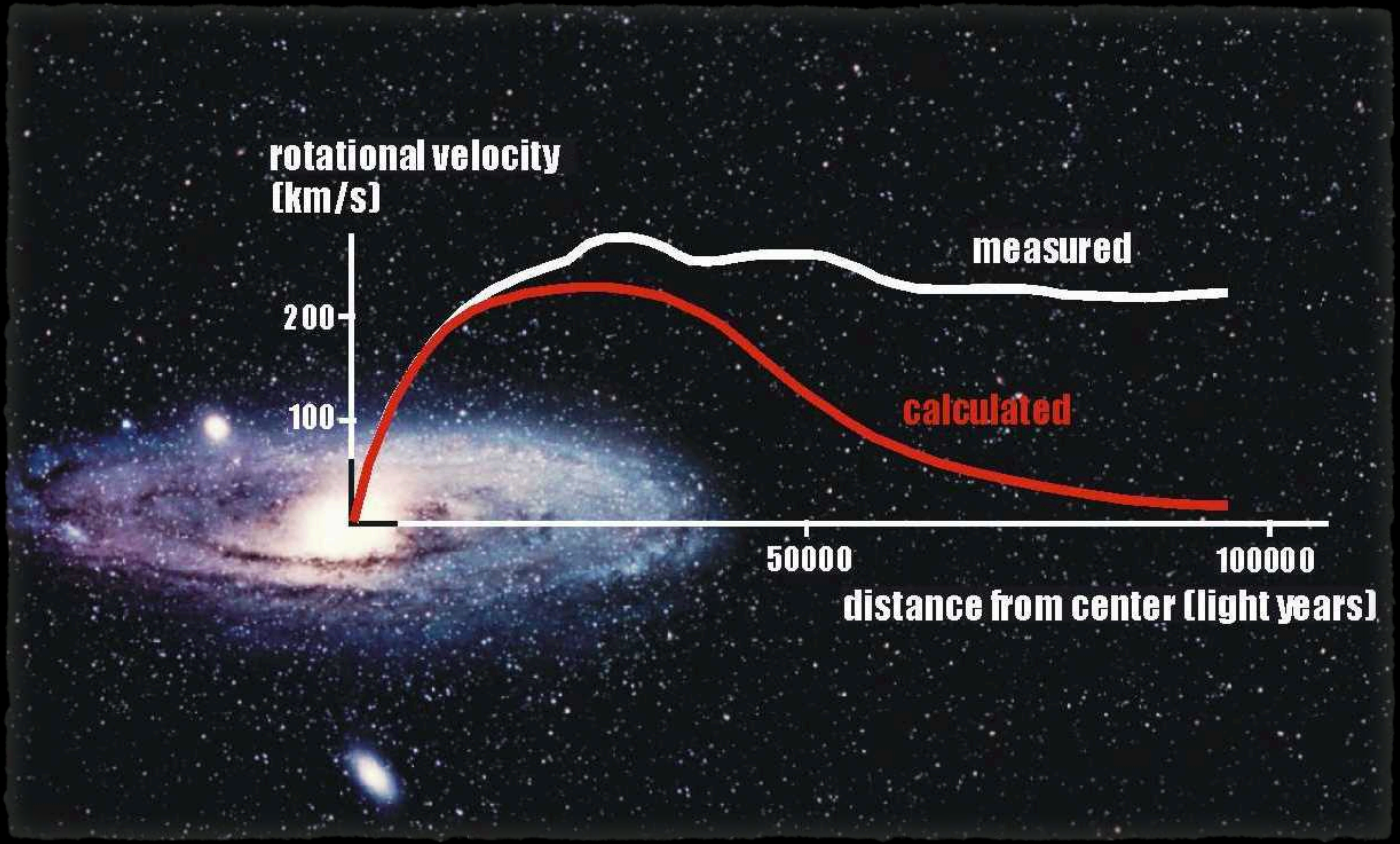
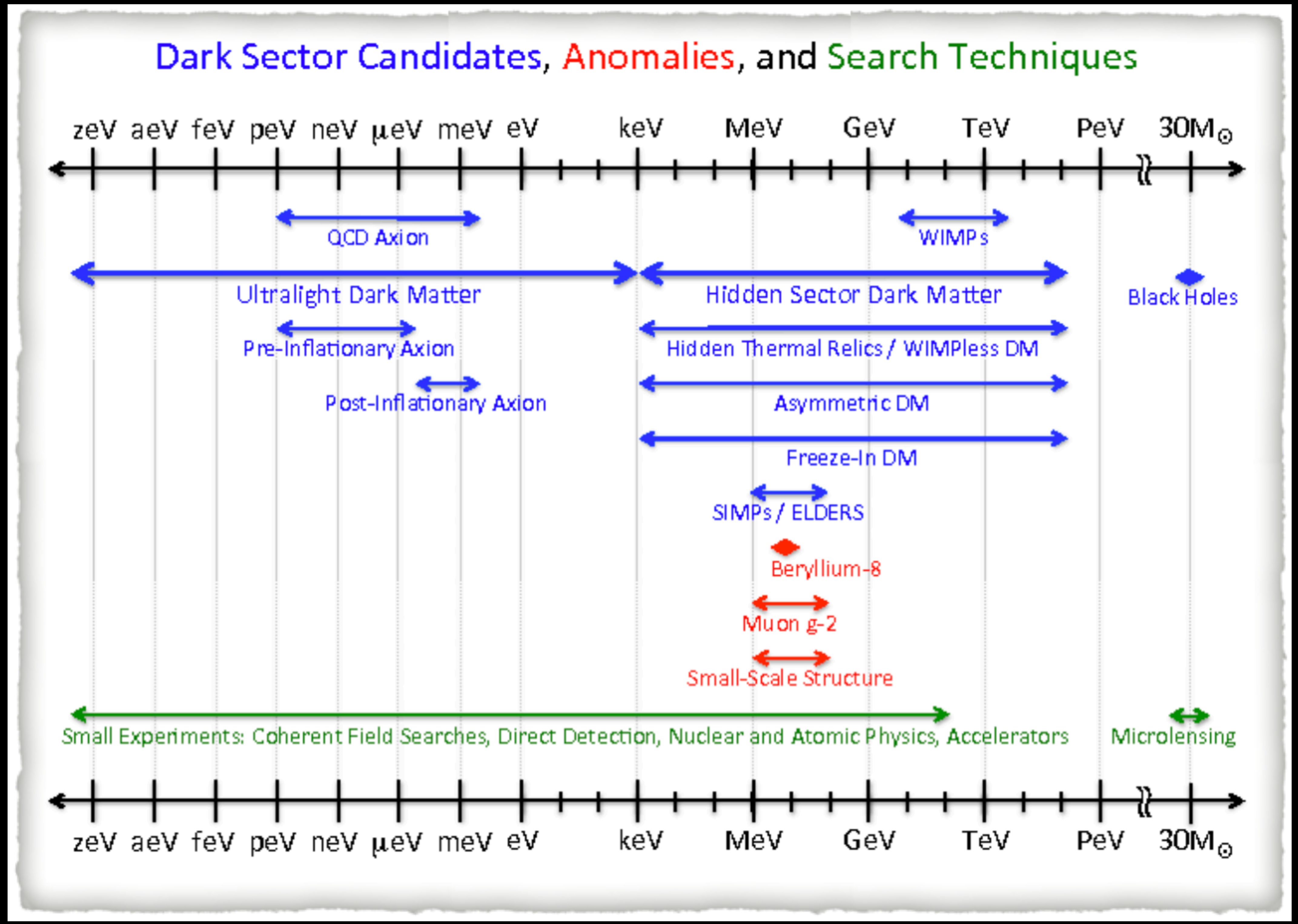
Abbott et al. 2021: arXiv 2105.13085

Dark matter





- Galaxy rotation curves and other observations could imply that dark matter exists
- We choose to study ultralight dark matter based on the frequency range to which ground-based gravitational-wave detectors are sensitive: 10-2000 Hz —> (10^{-14}–10^{-11} eV/c^2)

Context

D'Antonio et al. PRD, vol. 98, no. 10, p. 103017
Palomba et al. 2019, PRL, vol. 123, no. 17, p. 171101
Sun et al. 2019 PRD, vol. 101, no. 6, p. 063020

- LVK and others have focused on gravitational waves from dark matter candidates, e.g. boson clouds around black holes and primordial black holes
- However, this talk focuses on *direct detection* of ultralight dark matter signals via their interactions with GW interferometers
- These signals are NOT gravitational waves, but they still could cause a differential strain on the detector
- Other experiments exist to detect particles that could be dark matter as well, e.g. Eöt-Wash torsion balance, MICROSCOPE satellite, ALPS, ADMX,…

Schlamminger et al. 2008 PRL 577, vol. 100, p. 041101
Berge et al. 2018 Phys. Rev. Lett, vol. 120, no. 14, p. 141101

Recent searches

- Many recent efforts to search for dark matter directly interacting with GW interferometers
- O1 search for dark photon dark matter

  Guo et al. 2019 Nature Communications Physics 2
- GEO600 and table-top 3D interferometers search for scalar, dilaton dark matter

  Vermeulen et al. 2021, arXiv:2103.03783
  Vermeulen et al., 2021, CQG 38 (2021) 085008
- KAGRA axion search dark matter search

  Michimura et al. 2021, 102, 102001
  Nagano et al. 2019, PRL 123, 111301
  Nagano et al. 2021, arXiv:2106.06800

Dark photon dark matter

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

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

- Formulated as a contribution to the standard model action
- Gauge boson of U(1) group that interacts weakly with protons and/or neutrons in materials
- Well-motivated theoretically: can get mass through Higgs mechanism; relic abundance of dark matter could be generated via e.g. misalignment mechanism

Fabbrichesi et al. arXiv:2005.01515

- In the absence of a detection, we put limits on ε_D
- One of many dark matter interactions that could be seen with interferometers, e.g. scalar field upper limits with GEO600 data

Snowmass2021 - Letter of Interest

Pierce et al. 2018, Phys. Rev. Lett. 121, 061102
Morisaki et al. 2021, Phys. Rev. Lett. 103, L051702
Vermeulen et al. 2021, arXiv: 2103.03783

Dark photon signal

- Large, O(10^{50}), occupation number —> model field as a superposition of plane waves
- Signal results from coupling of dark photons to the mirrors; it is quasi-monochromatic and stochastic
- Modulations occur because dark photons are flowing through us at slightly different speeds
- Dark photon coupling to protons / neutrons contribute to two differential arm strains:
  1. True differential strain from a spatial gradient in the dark photon field
  2. Apparent differential strain from common-mode motion of the mirrors

$$A = \sum_i A_i \boldsymbol{e}_i \cos(\omega_i t - \boldsymbol{k}_i \cdot \boldsymbol{x} + \phi_i),$$

$$f_0 = \frac{m_A c^2}{2\pi\hbar}$$

<u>m_A</u>: mass of dark photon
<u>f_0</u>: frequency of dark photon

$$\Delta f = \frac{1}{2}\left(\frac{v_0}{c}\right)^2 f_0 \approx 2.94 \times 10^{-7} f_0,$$

<u>v_0</u> : virial velocity- the velocity that dark matter orbits the center of our galaxy
This is the <u>bulk</u> frequency modulation

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

Search method: excess power

- BSD excess power method: optimally choose Fourier Transform coherence time such that signal power is confined to one frequency bin
- Make time/frequency map in 10-Hz bands over all of O3 and project onto frequency axis
- Select a certain number of candidates to obtain, on average, one coincident candidate per 1-Hz band in Gaussian noise
- Analyze each detector’s data separately
- Candidates are considered in coincidence if they are within one frequency bin of each other, and if the critical ratio CR>5

$$CR = \frac{y - \mu}{\sigma}$$

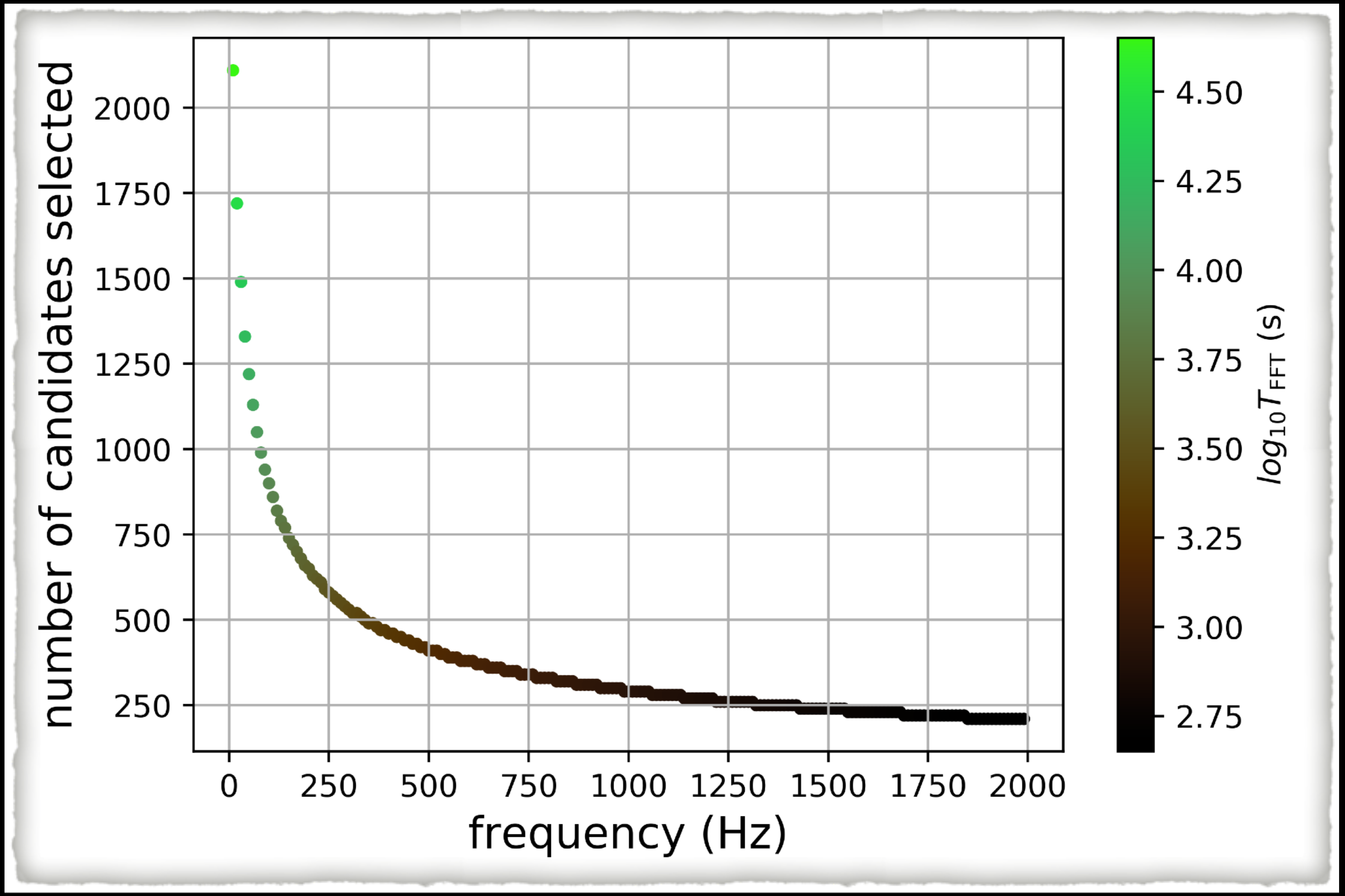


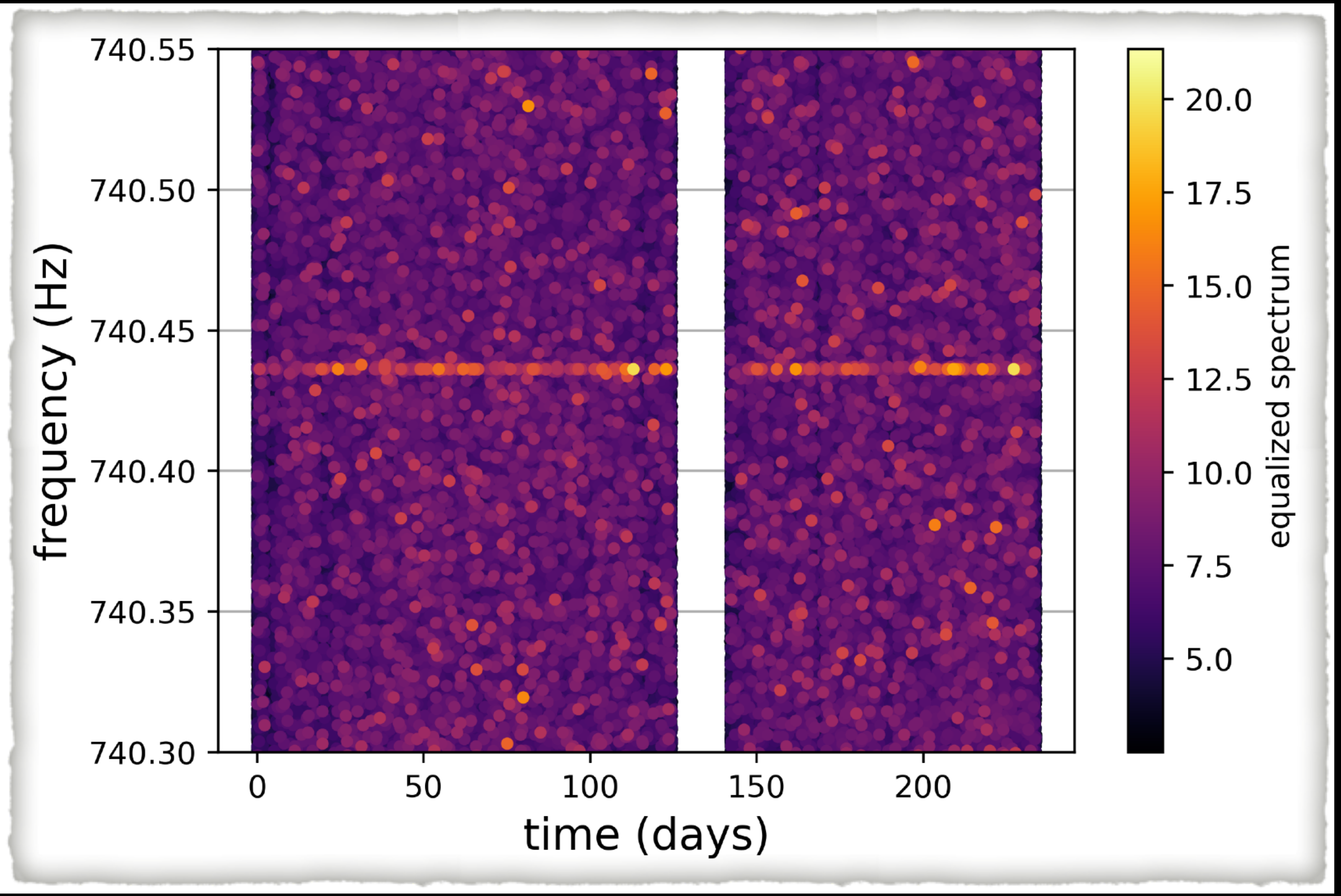
Figure 1: number of candidates to select as a function of frequency, with the Fourier Transform time coloured

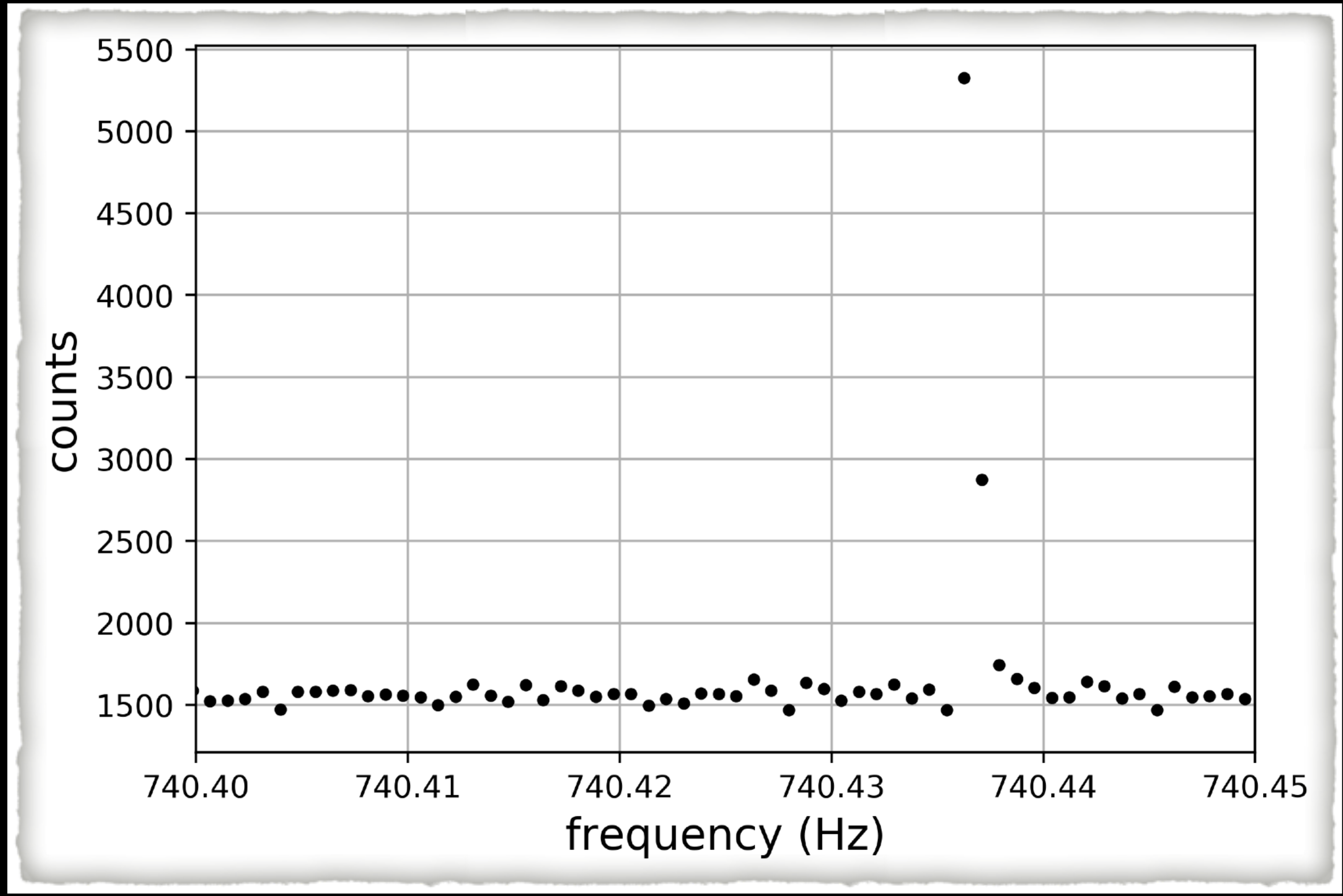
Miller et al. 2020, arxiv:2010.01925

Miller et al. 2021, Phys. Rev. D 103.103002

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

Excess power projection





- Carefully choose T_{SFT} —> peakmap and project
- O2 Livingston data shown here with a simulated dark photon signal

Results

- Cross correlation: no outliers with Re(SNR)<-5.8; number of sub-threshold outliers between |Re(SNR)| or |Im(SNR)|=[5,5.8] consistent with Gaussian noise expectation

- Excess power: 11 coincident outliers among the three baselines (HL, HV, LV), all determined to be due to noise disturbances

Results

- The 11 outliers were vetoed by averaging spectra and increasing the analysis coherence time to reveal new noise artifacts

- Example of a large comb that caused a strong outlier in H1 and L1

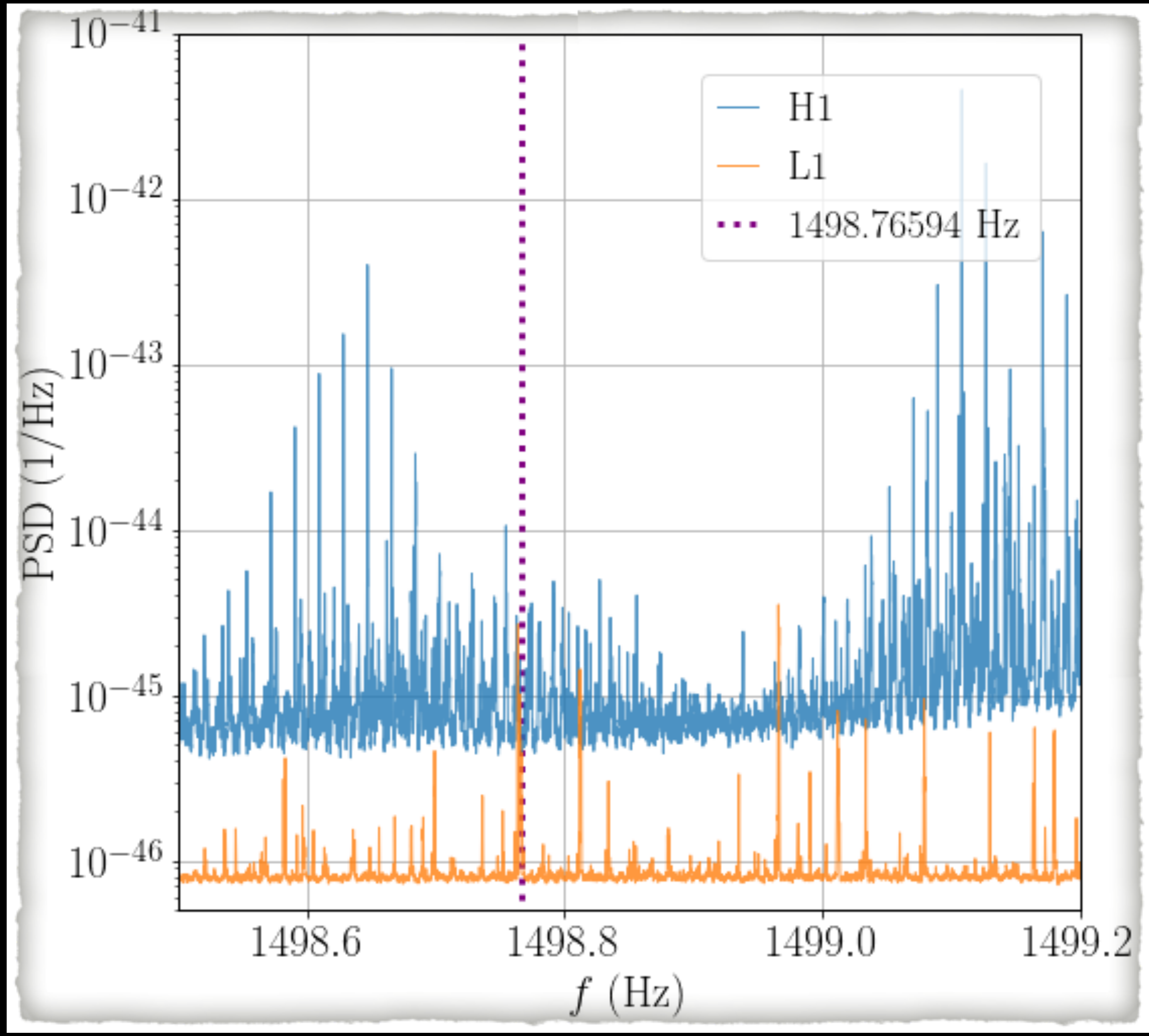


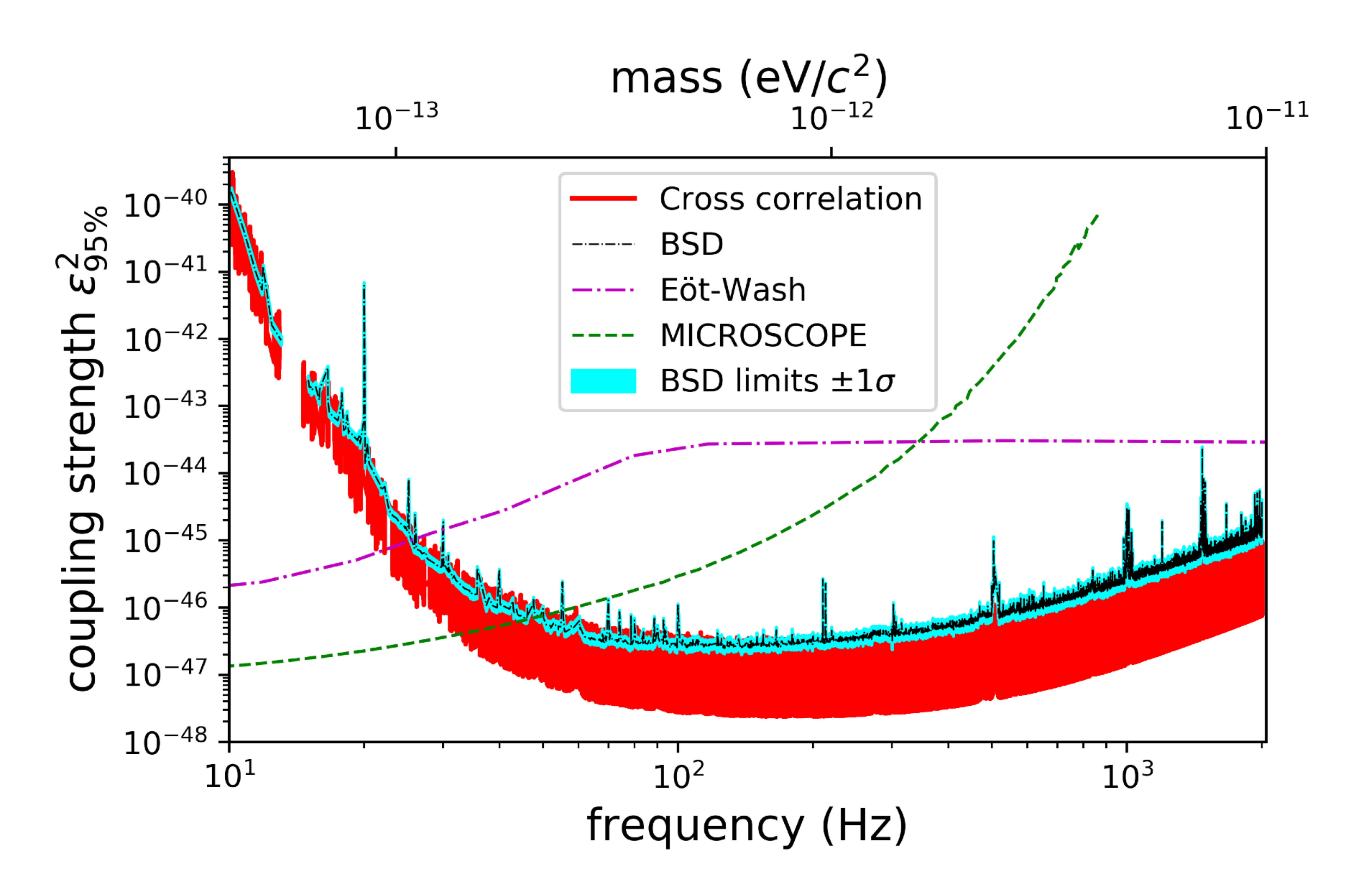
Figure 2: PSD around one outlier, given by the vertical purple line

Upper limits

- All outliers vetoed in excess power method; only 4 sub-threshold outliers consistent with Gaussian noise expectation for cross-correlation

- Feldman-Cousins approach used to set upper limits, which assume our detection statistics follow a Gaussian distribution

- Both common and differential motion strains considered when calculating these limits



Abbott et al. (LVK) 2021: arXiv 2105.13085

Conclusions

- Limits improve upon existing ones from direct dark matter detection experiments by about at least two orders of magnitude

- Accounting for the common motion of the arms is primarily responsible for improvements relative to the search run in O1 (though, longer analysis time and more sensitive instruments also contribute), which are also two orders of magnitude

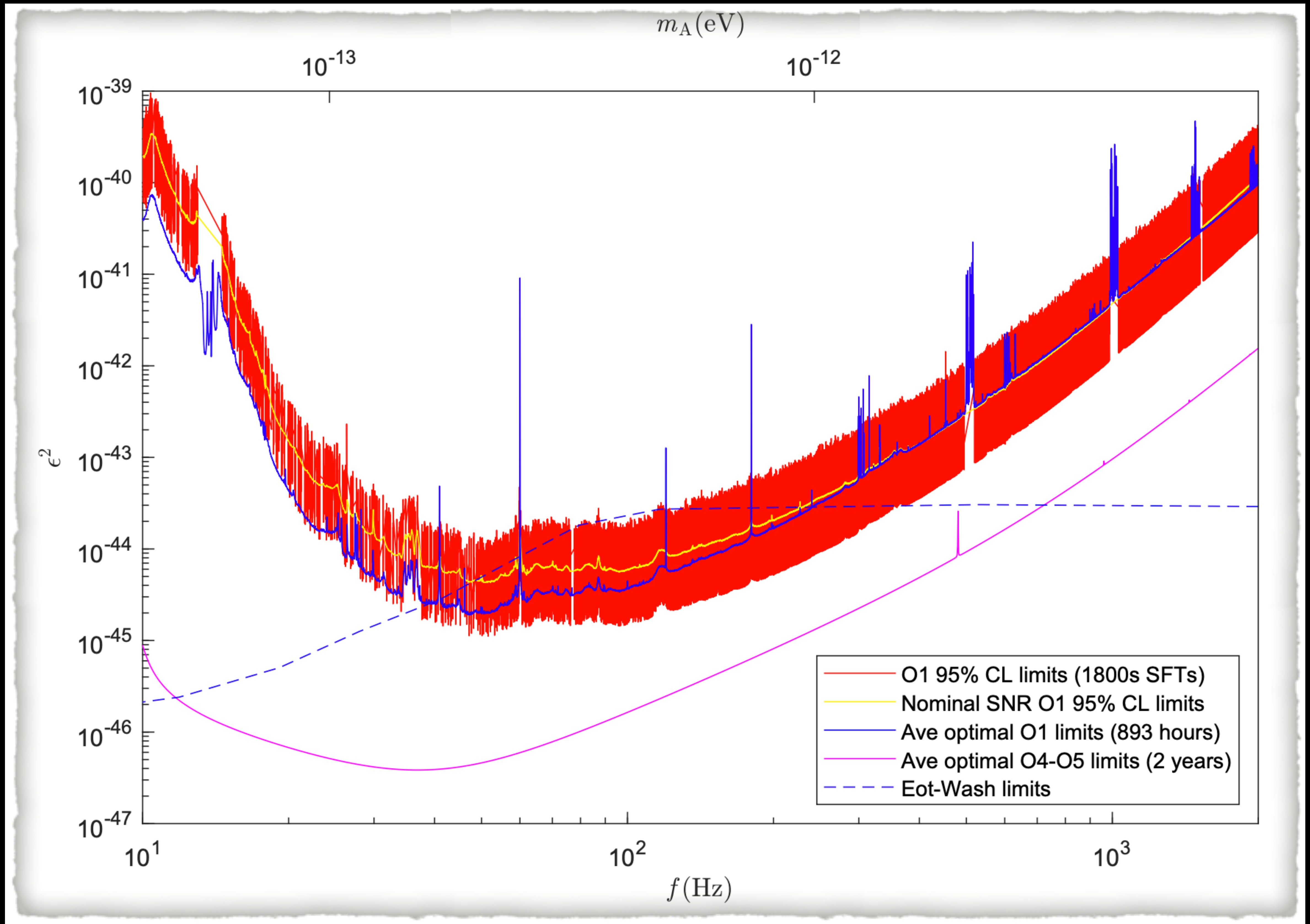
- Future upgrades and detectors (e.g. Einstein Telescope, LISA, DECIGO, TianQin) will result in improved sensitivity towards dark matter interactions, and will probe different mass ranges

- Using gravitational-wave detectors as particle physics experiments is a nice bridge between the two fields

Backup slides

Previous cross-correlation results

- T_{SFT}=1800 s
- Established method in stochastic gravitational-wave searches; used in O1 search
- Power is cross-correlated in each frequency bin, and bins with high enough signal-to-noise ratios are considered "outliers"



Guo et al. 2019, Commun. Phys, 2, 155

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 the dark matter 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

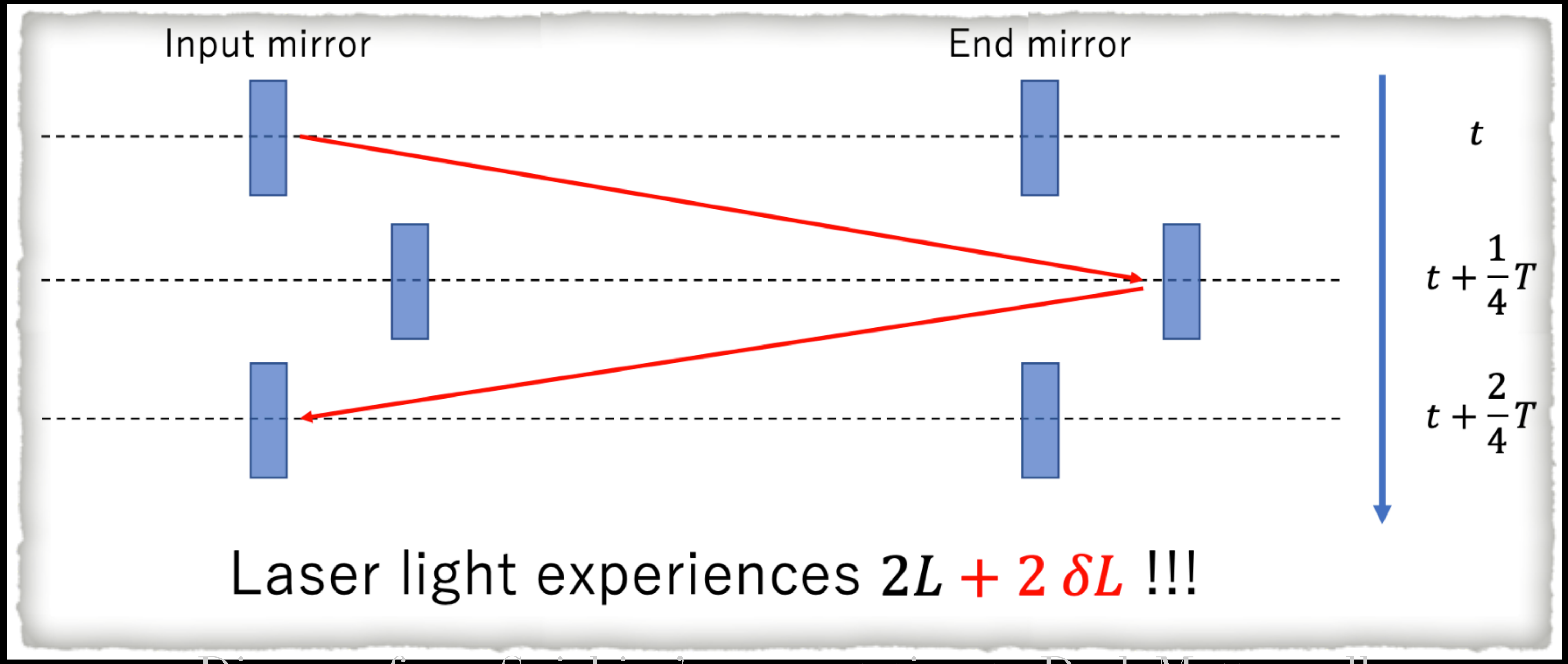


Diagram from Soichiro’s presentation to Dark Matter call

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

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