Searching for dark photon dark matter in the third observing run of LIGO/Virgo

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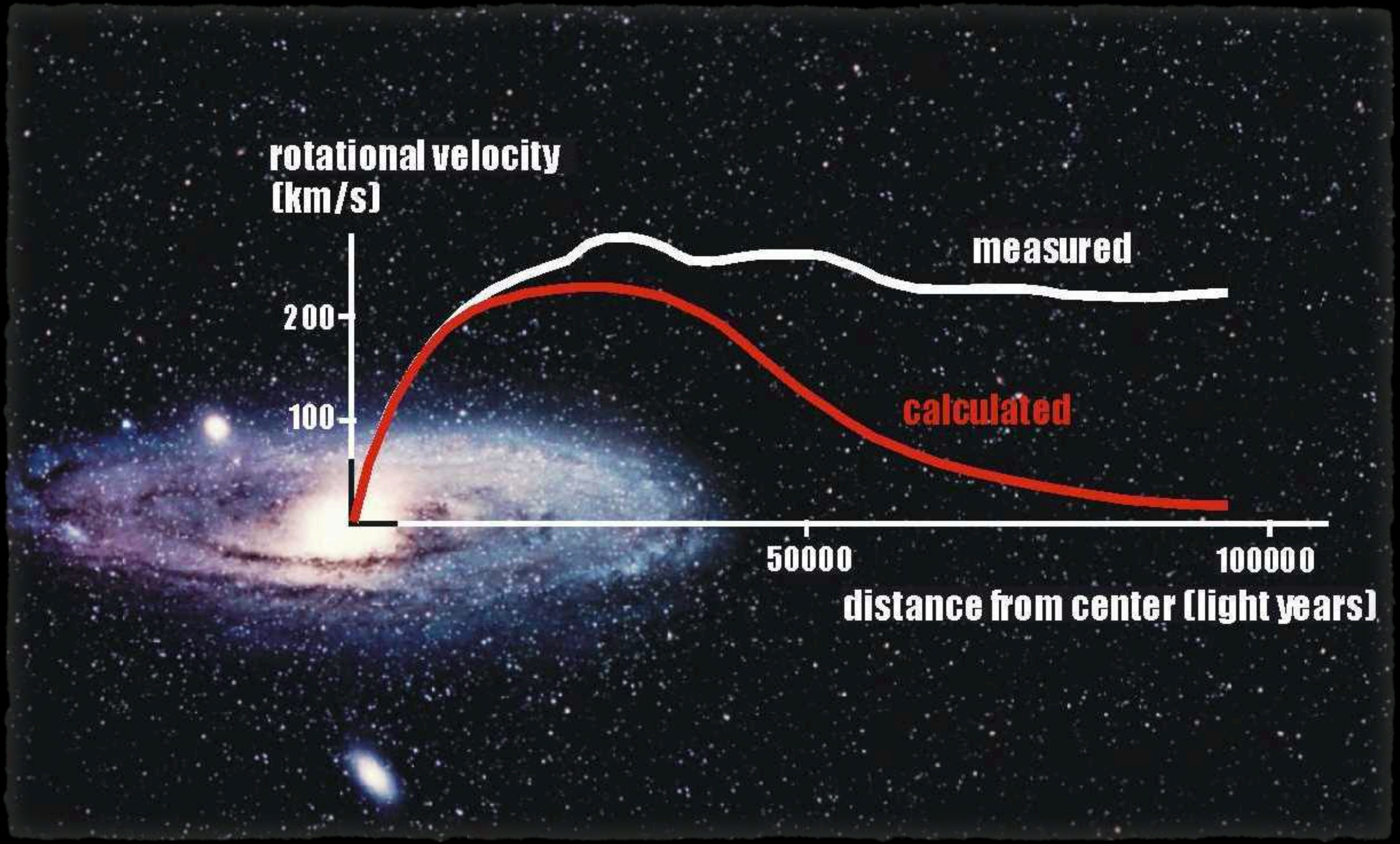
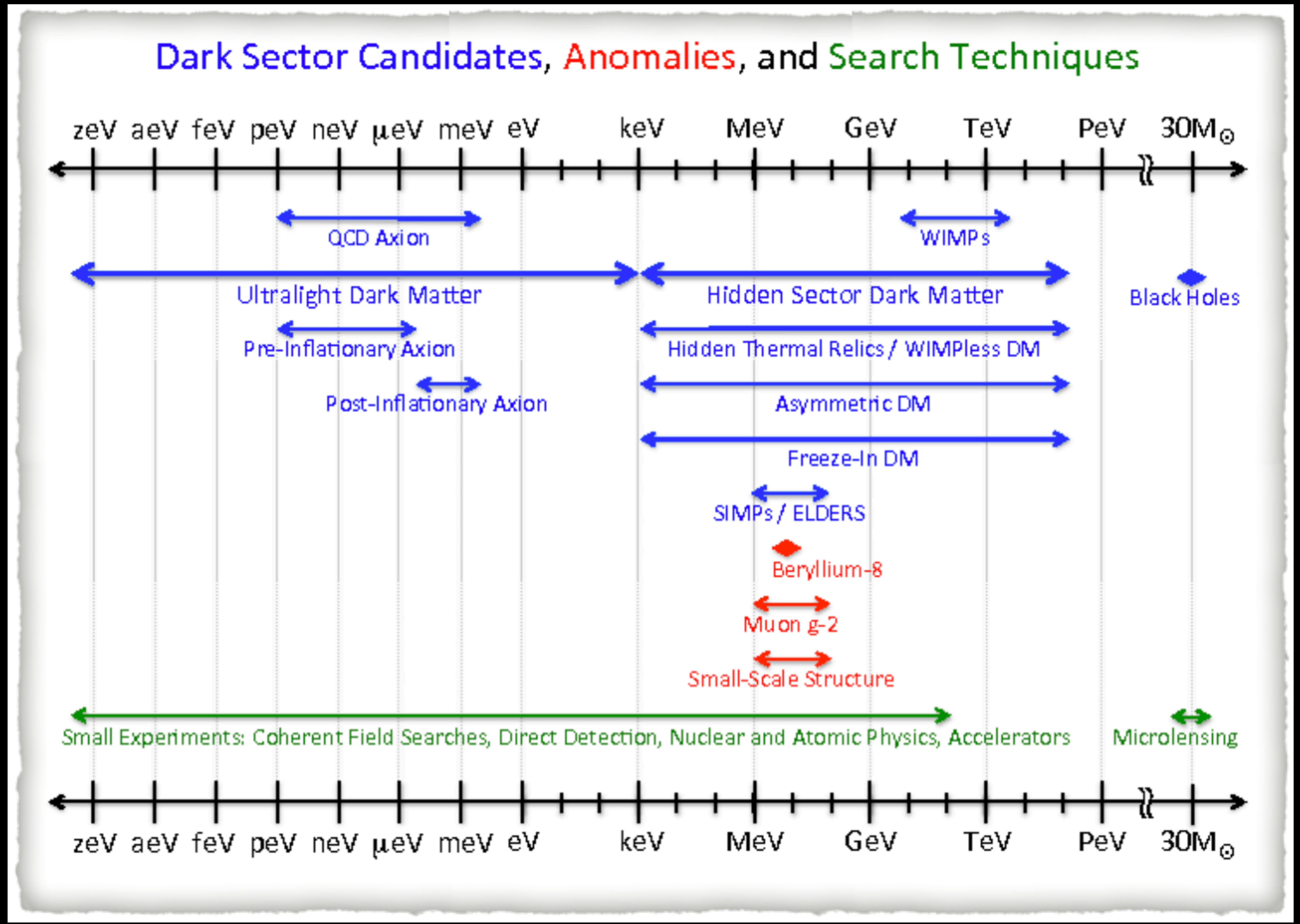
on behalf of the LIGO, Virgo and KAGRA Collaborations
Abbott et al. 2021: arXiv 2105.13085

Dark matter





- Galaxy rotation curves and other observations 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 —> masses of 10^{-14}–10^{-11} eV/c^2

Dark photon dark matter

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

<u>m_A</u> : dark photon mass
<u>ε_D</u> : coupling strength
<u>A_μ</u> : 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

<u>Snowmass2021 - Letter of Interest</u>

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

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

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

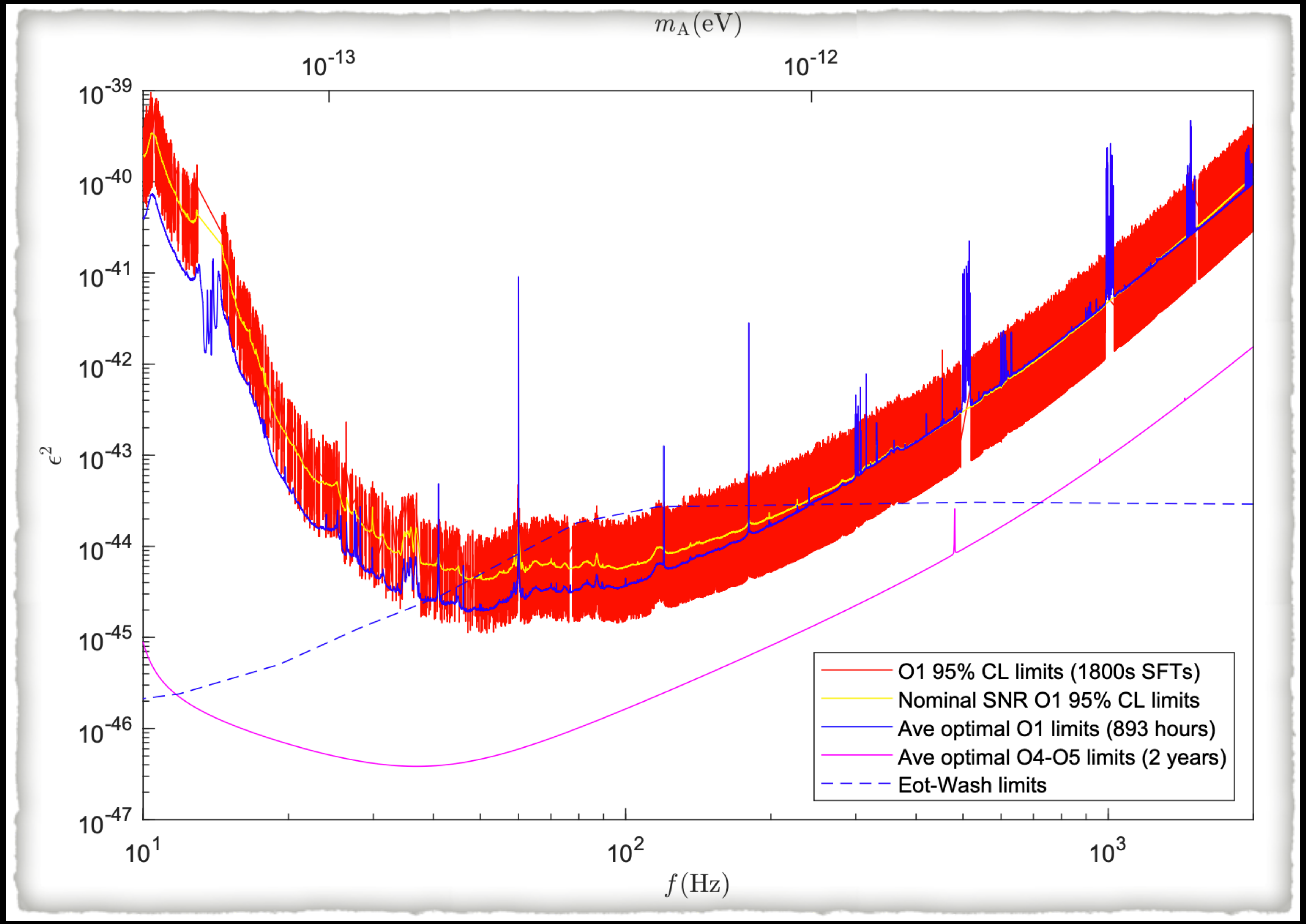
m_A: mass of dark photon
f_0: frequency of dark photon

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

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

Method 1: Cross-correlation

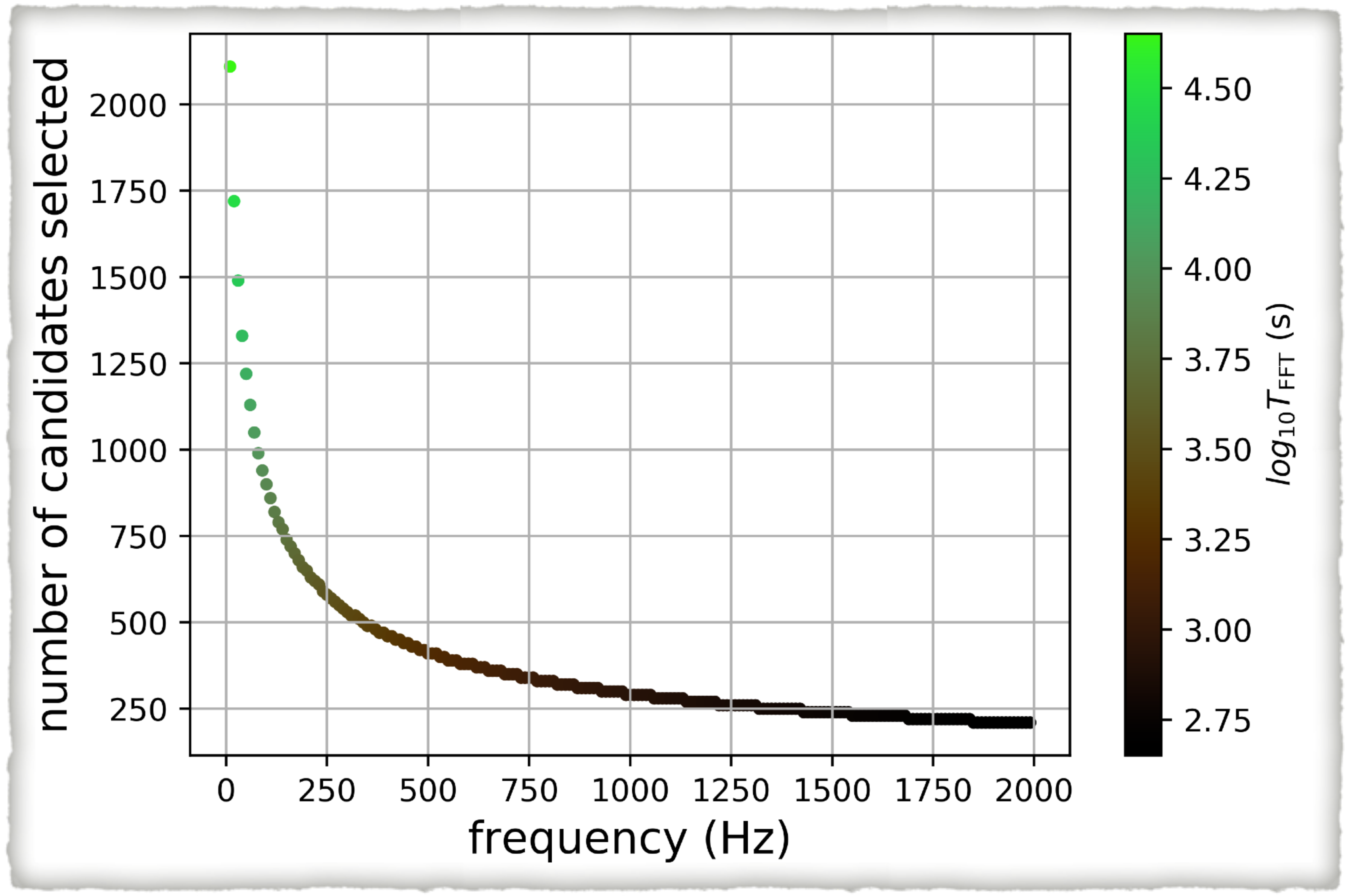
- T_{SFT}=1800 s
- Established method in stochastic gravitational-wave searches; used in O1 search
- Power is cross-correlated in each frequency bin, and bins with high enough signal-to-noise ratios are considered “outliers”



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

Method 2: Excess power

- Excess power method: optimally choose Fourier Transform coherence time such that signal power is confined to one frequency bin
- Produces time/frequency spectrograms that are integrated over time, i.e. projected onto the frequency axis, and strong candidates are selected
- Analyze each detector's data separately, and look for coincident candidates



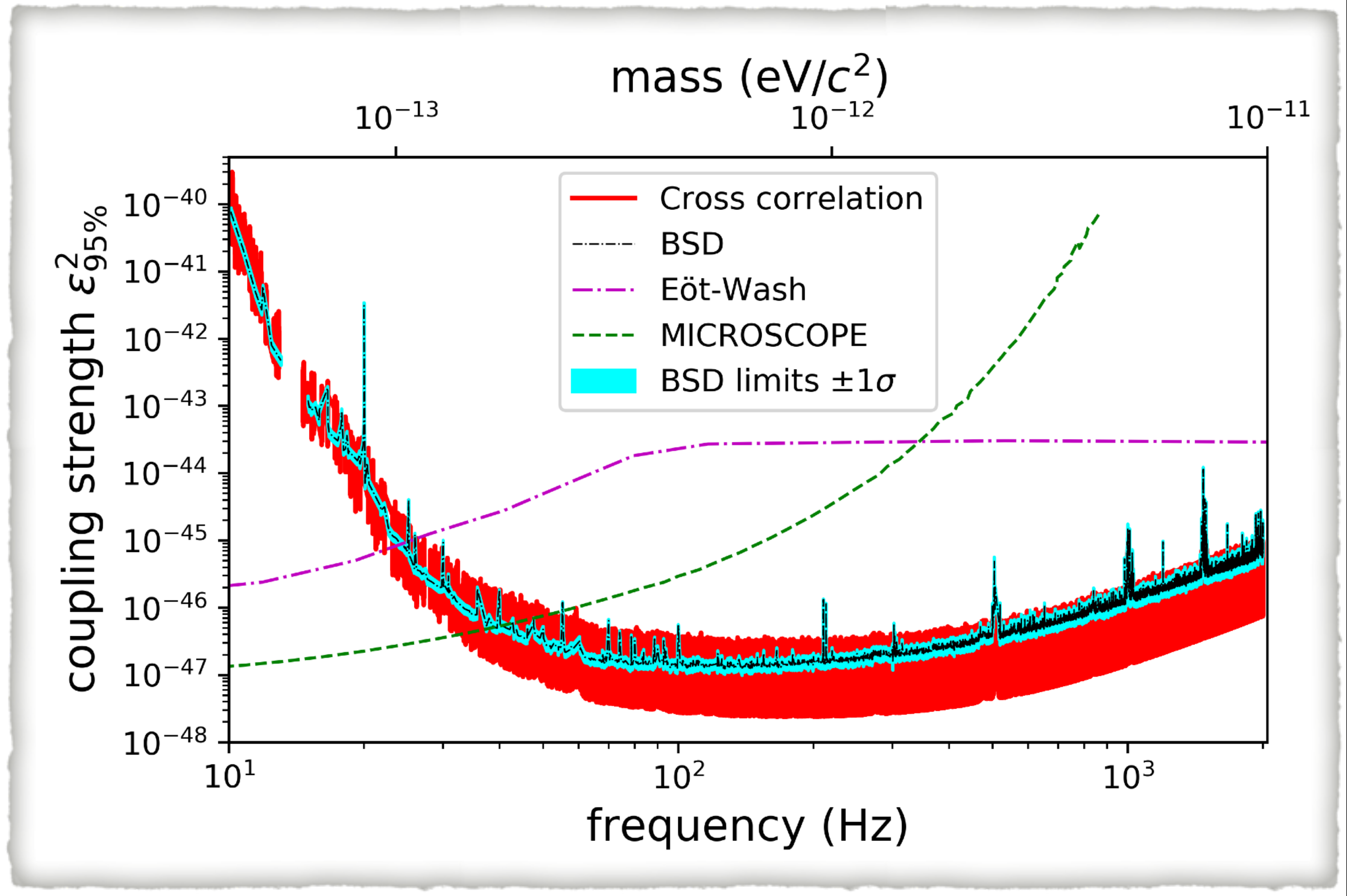
Number of candidates to select as a function of frequency, with the Fourier Transform time coloured

Miller et al. 2021 PhysRevD.103.103002

Abbott et al. (LVK) 2021: arXiv 2105.13085

Results: 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

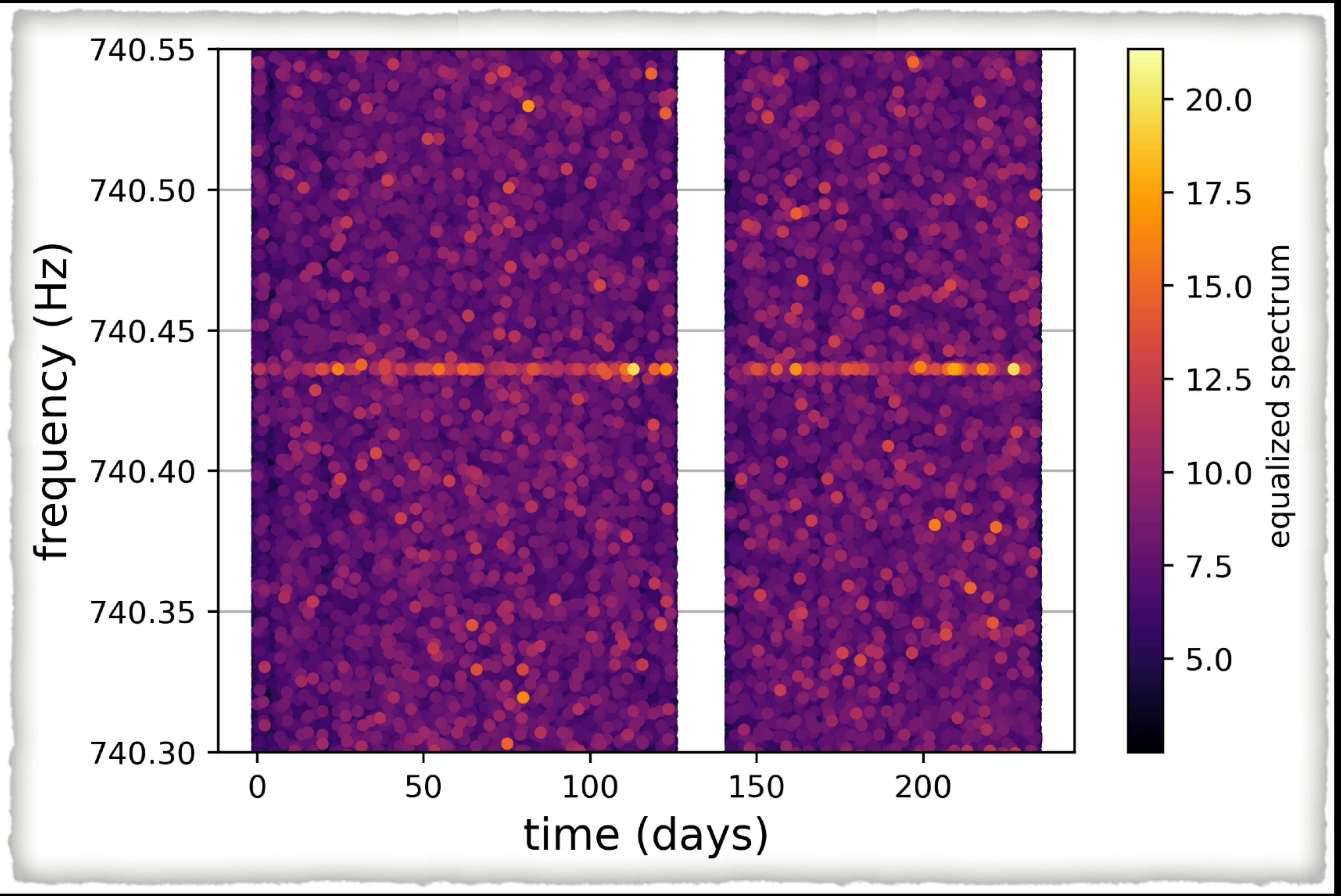
- Limits improve upon existing ones from direct dark matter detection experiments by about at least two orders of magnitude
- Accounting for the common motion of the arms is primarily responsible for improvements relative to the search run in O1 (though, longer analysis time and more sensitive instruments also contribute), which are also two orders of magnitude
- Future upgrades and detectors (e.g. DECIGO, Einstein Telescope, LISA) 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

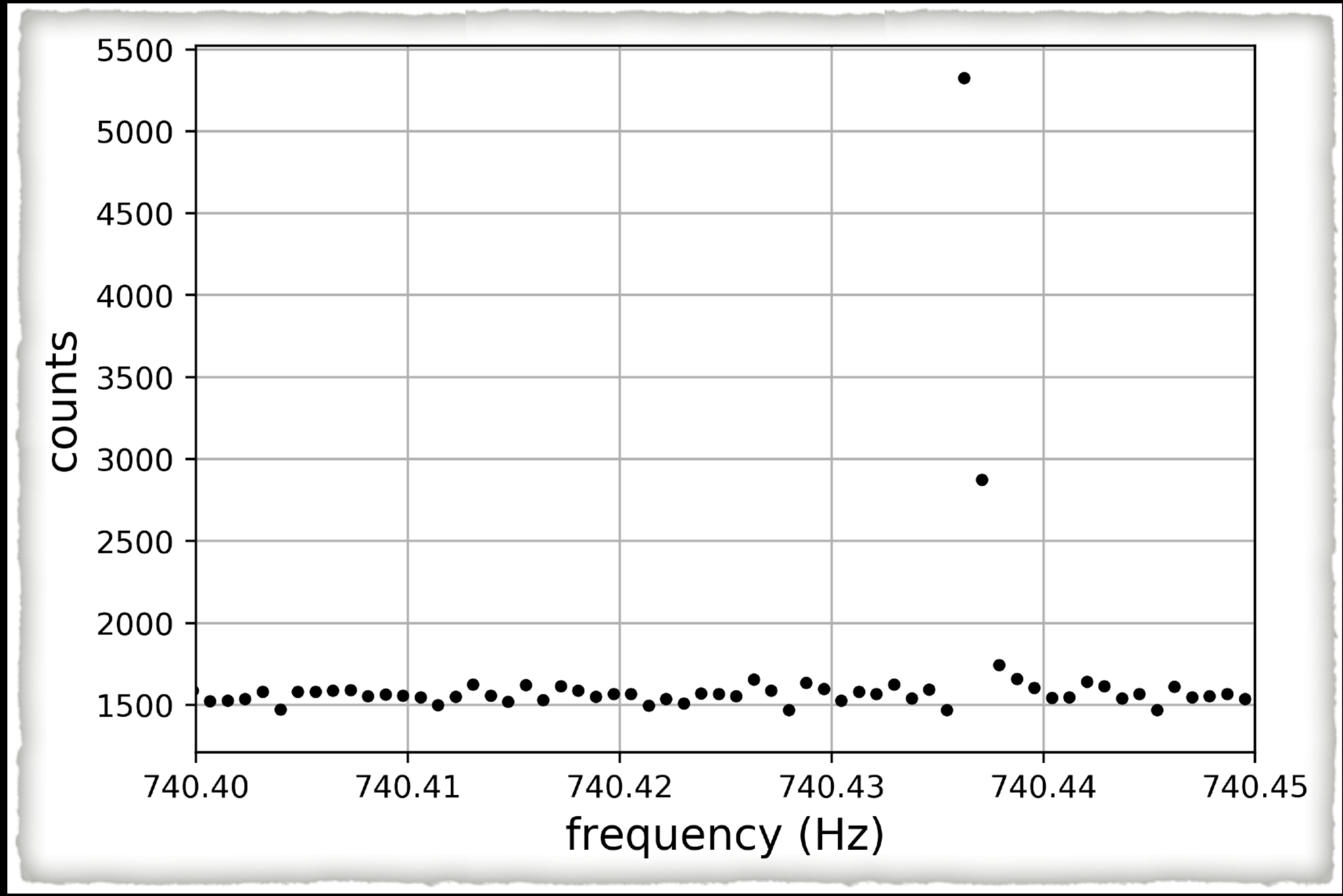
Back-up slides

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

True differential motion

- 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 input mirror to end mirror and back
- Imagine a dark photon field that moves the input mirror 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

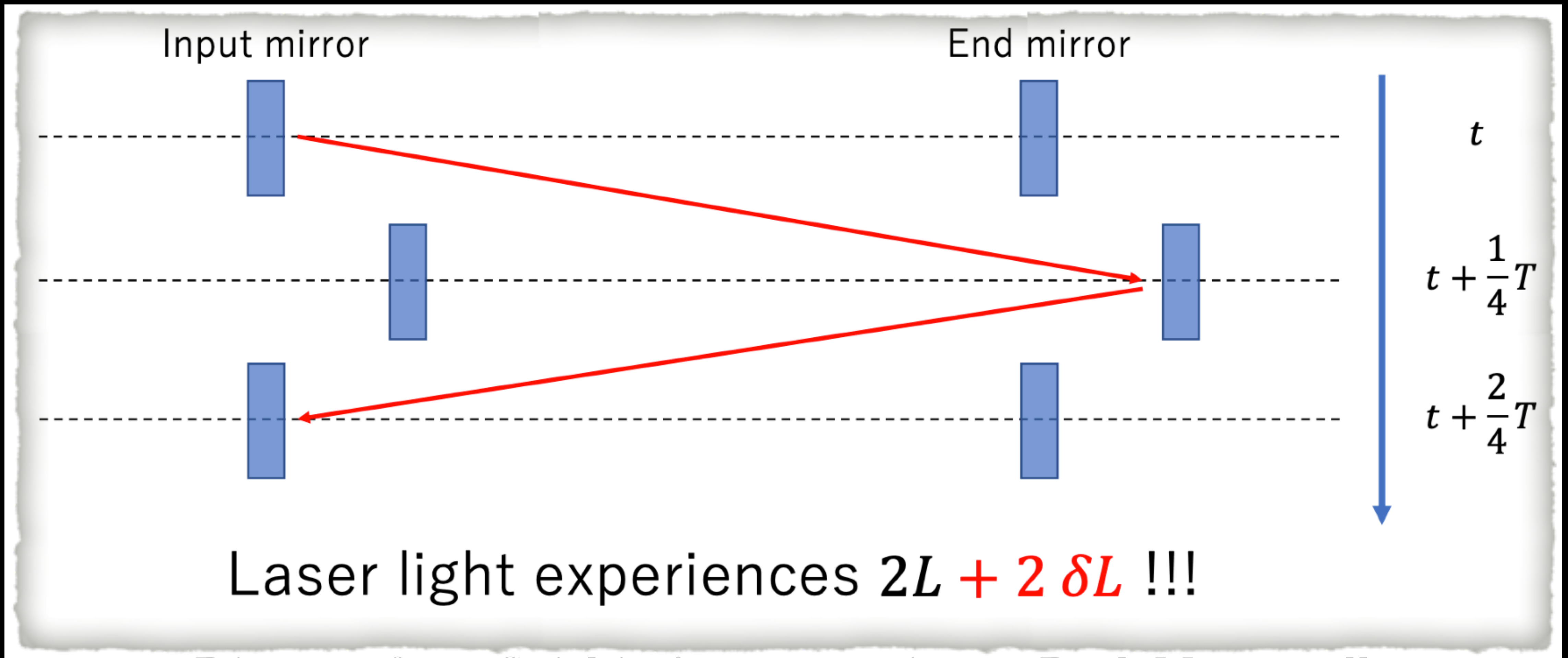


Diagram from Soichiro’s presentation to Dark Matter call

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

Morisaki et al. 2021, Phys. Rev. D. Lett. 103, L05170

Acknowledgements

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