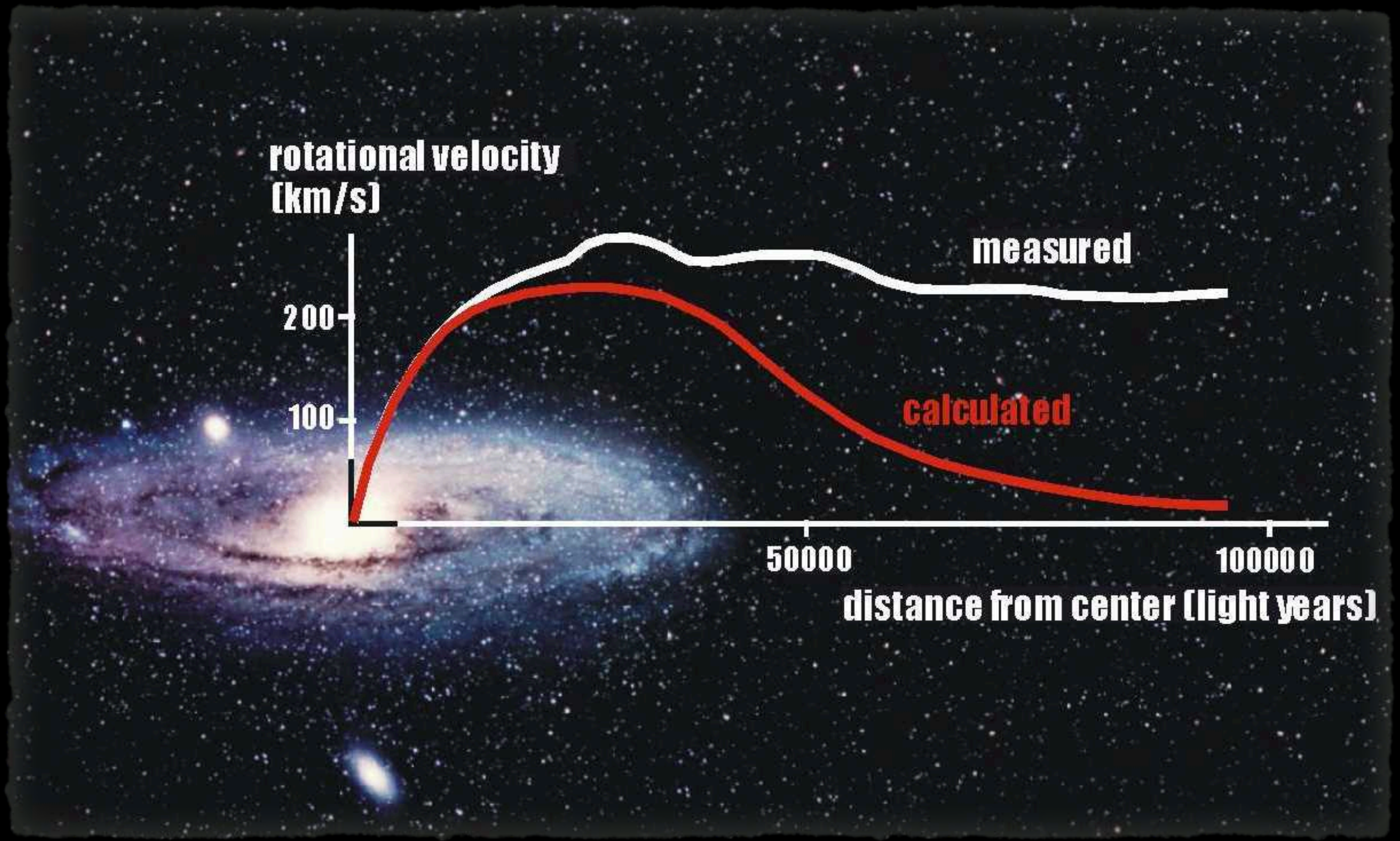
Direct detection of dark matter with gravitational-wave interferometers

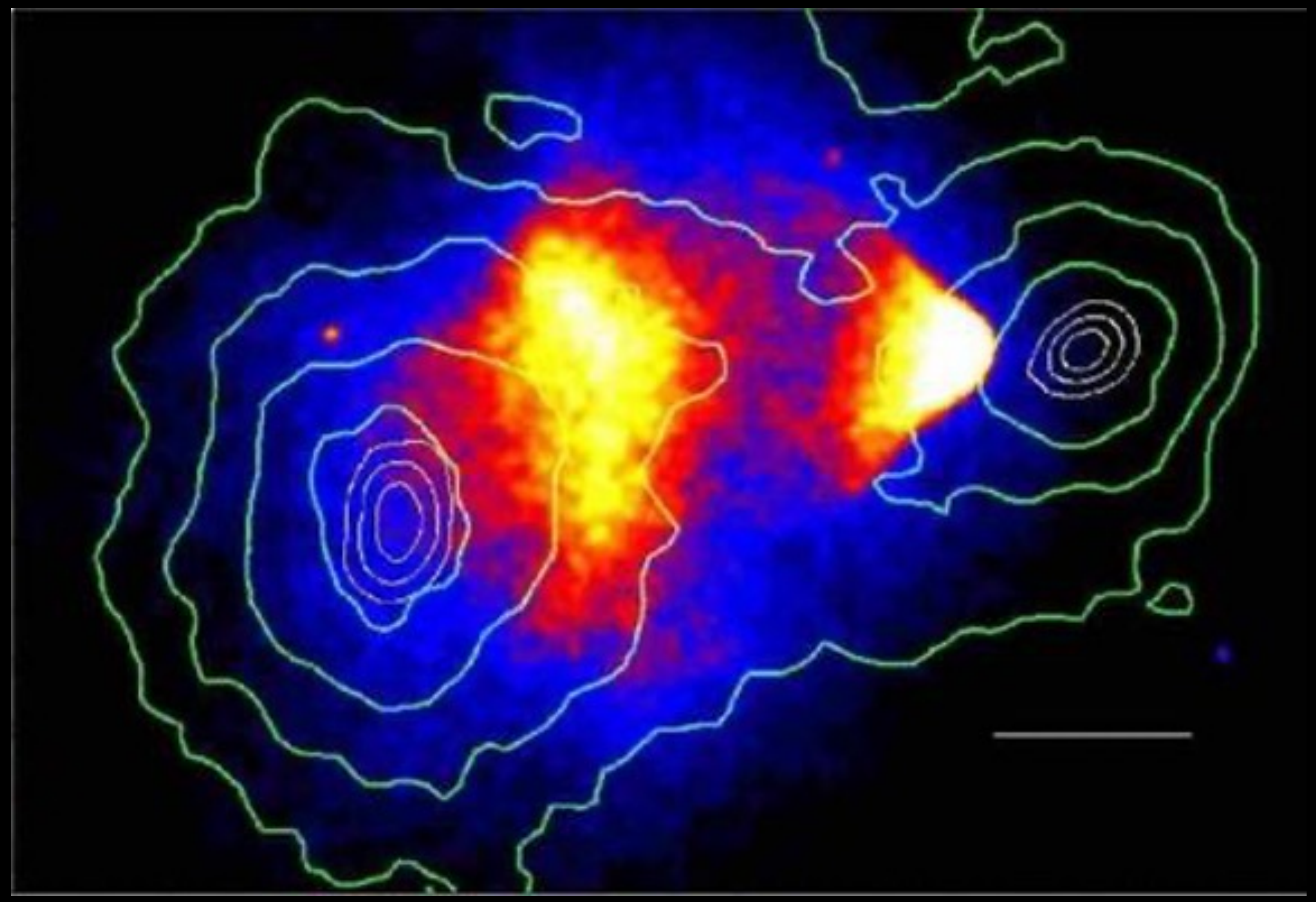
Andrew L. Miller

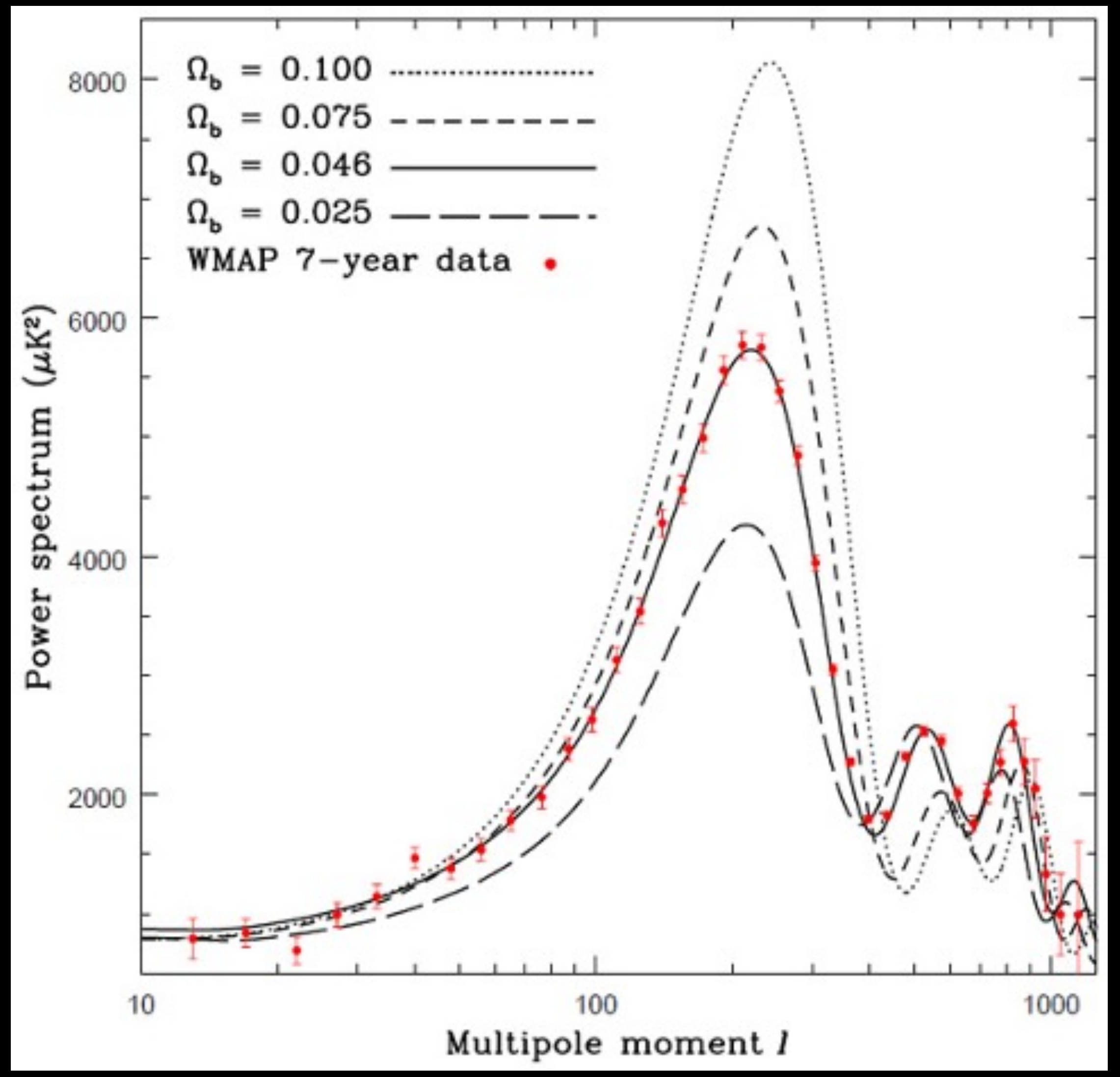
Outline

- Background and motivation
- Types of dark matter particles
- Search results and projected sensitivities
- Conclusions

Why do we need dark matter?



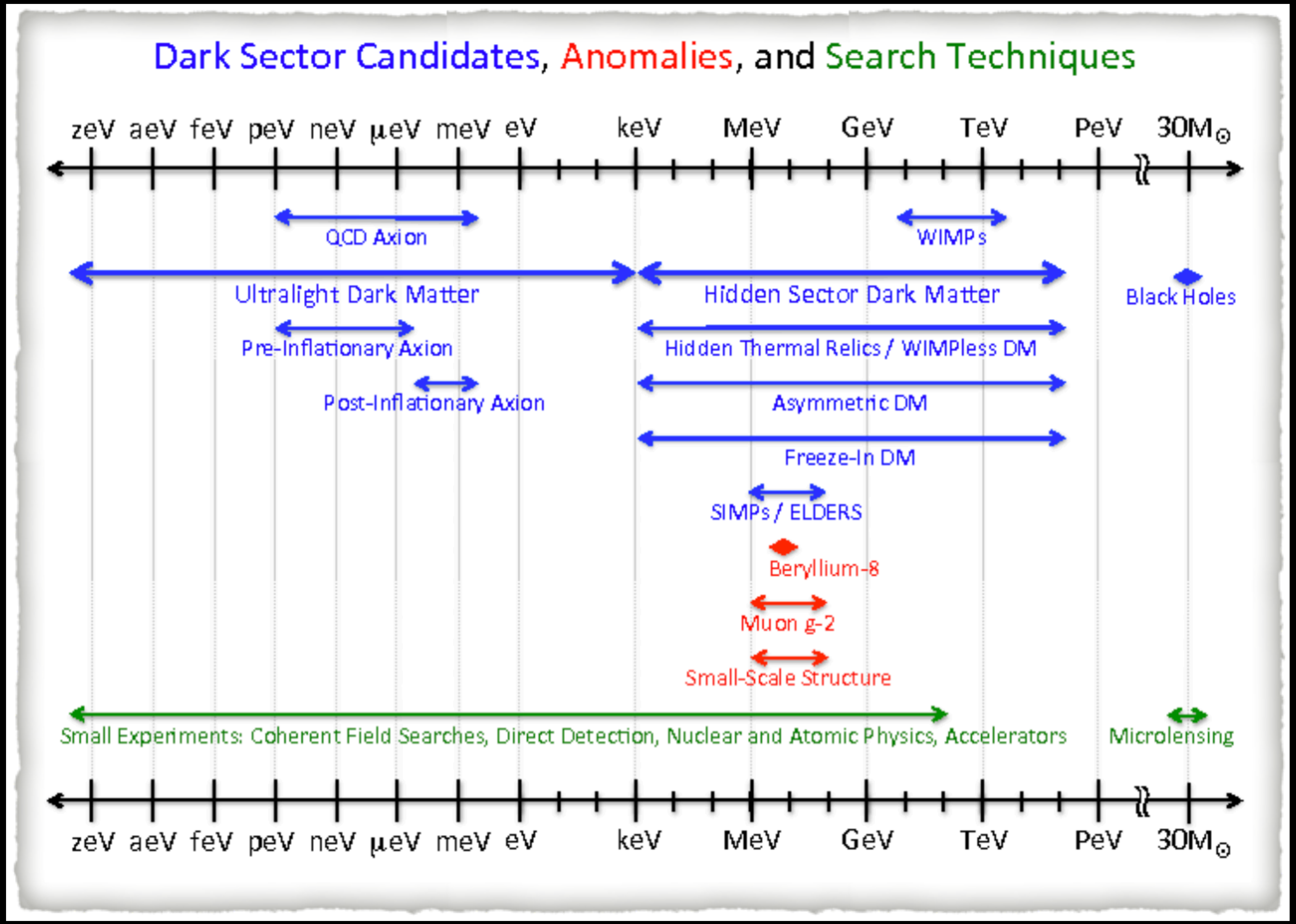




- Galaxy rotation curves: stars move too fast based on visible matter distribution
- Bullet cluster: dark matter gravitationally lenses light around it in this cluster
- CMB anisotropy power spectrum: dark matter needed to explain anisotropies

What could dark matter be?

- Mass could span almost one hundred of orders of magnitude!
- Could be heavy, e.g. WIMPs
- Could be ultralight
- Could be primordial black holes
- We 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

- LIGO, Virgo and KAGRA have looked for GWs 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,…

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

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

Ultralight dark matter

- Fixed dark matter energy density ρ_{DM} —> huge occupation number N_0—> overlapping wavefunctions that can be modelled as superposition of plane waves
- Could be generated nonthermally via the misalignment mechanism in the early universe
- Forms coherently oscillating field at quasi-fixed frequency
- Produced with very small kinetic energies, but becomes virialised during the formation of galactic structures, giving these particles the finite coherence time
- Velocities follow a Maxwell-Boltzmann distribution, centered about the virial velocity $v_0 \sim$ 220 km/s, the velocity at which dark matter orbits the center of the galaxy

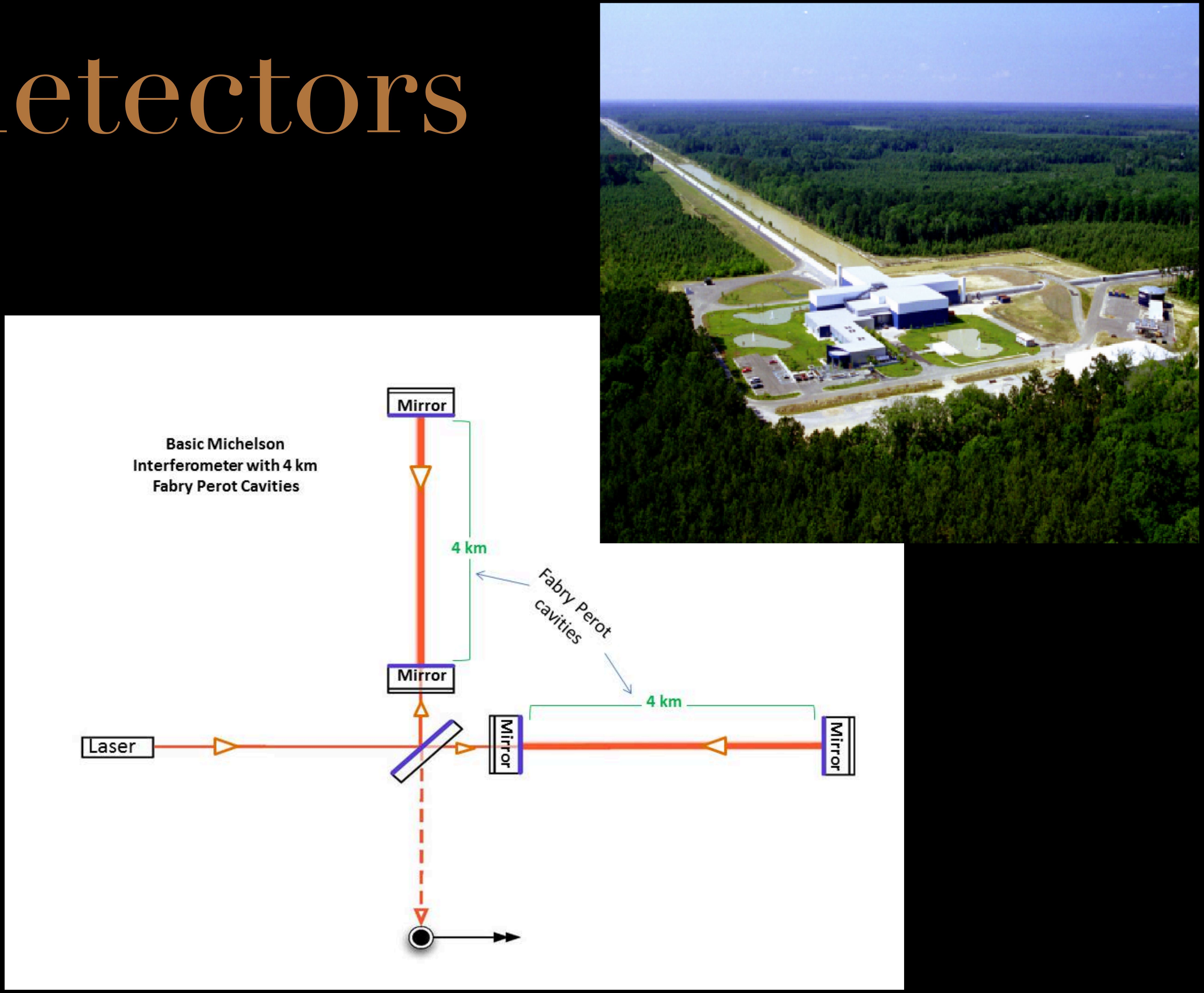
$$N_o = \lambda^3 \frac{\rho_{\mathrm{DM}}}{m_A c^2} = \left(\frac{2\pi\hbar}{m_A v_0}\right)^3 \frac{\rho_{\mathrm{DM}}}{m_A c^2}$$
$$\approx 1.69 \times 10^{54} \left(\frac{10^{-12}\ \mathrm{eV}/c^2}{m_A}\right)^4$$

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

Preskill et al. 1983 Phys. Lett. B 120, 127
Grote and Stadnik 2019 Phys. Rev. Research, vol. 1, 033187

GW detectors

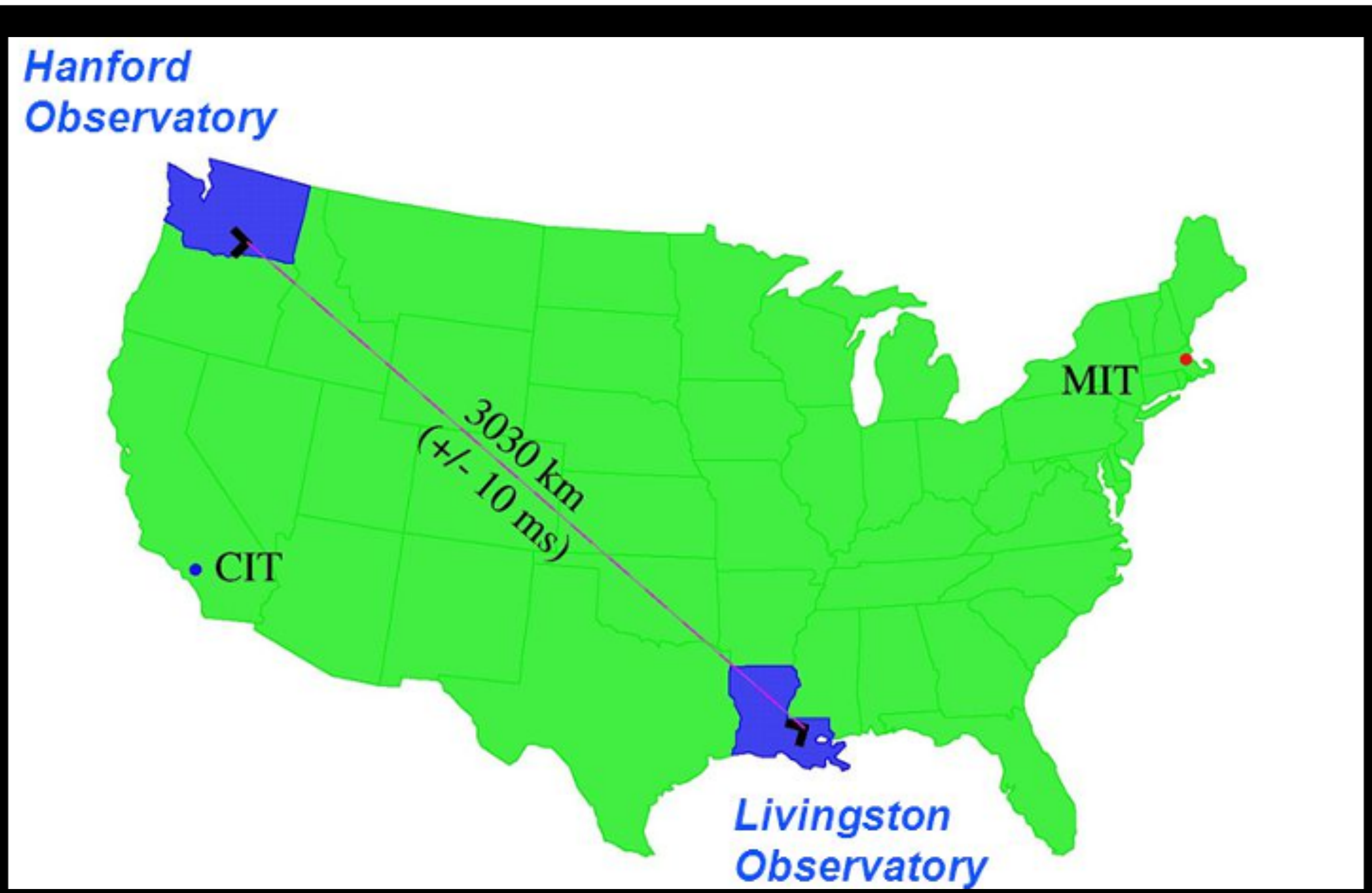
- Laser interferometers look for small displacements, which change the path length of laser light that shines down each arm
- Amazing sensitivity to extremely small displacements (1/100 the width of a proton)
- Look for strain $h \sim \Delta L/L$ and phase difference



Ultralight dark matter signals

$$L_{\mathrm{coh}} = \frac{2\pi\hbar}{m_A v_0} = 1.6 \times 10^9\ \mathrm{m} \left(\frac{10^{-12}\ \mathrm{eV}/c^2}{m_A} \right)$$

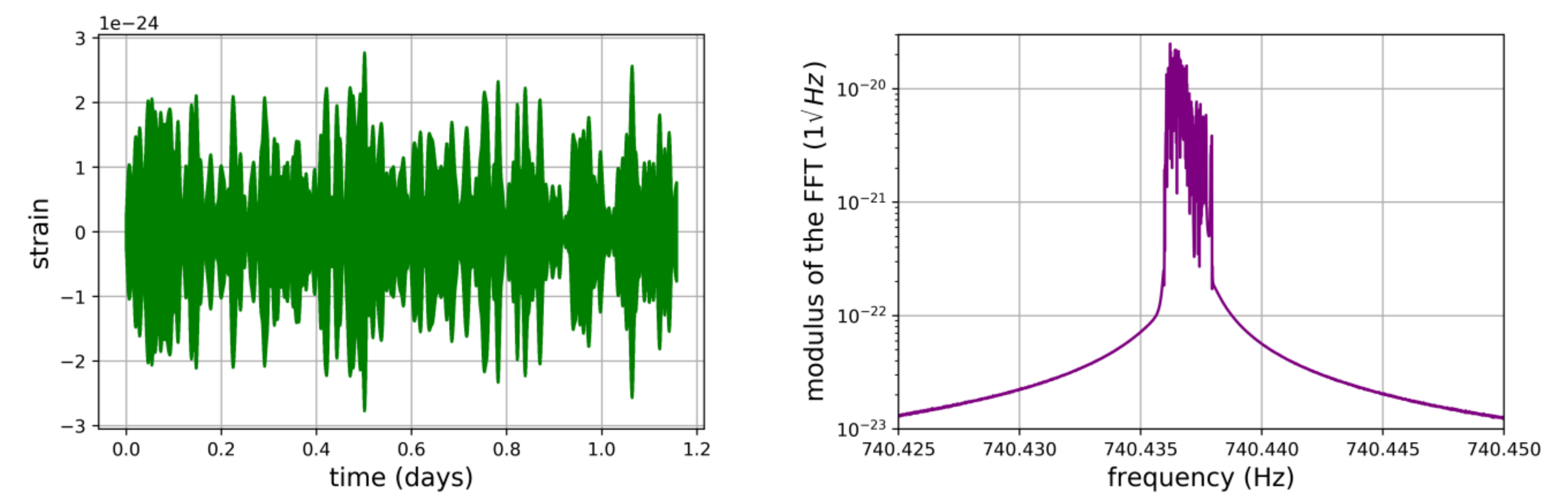
- Coherence length >> separation between detectors, leading to correlated signals
- The signal imprinted in our detectors will be quasi-monochromatic, with stochastic frequency variations of $\mathcal{O}(v_0^2 f) \sim \mathcal{O}(10^{-6} f)$ Hz if $T_{\mathrm{obs}} > T_{\mathrm{coh}}$



Pierce et al. (2019) PRD 99, 075002

The signal and analysis strategy

- Example of simulated dark photon dark matter interaction
- Power spectrum structure results from superposition of plane waves, visible when $T_{\mathrm{FFT}} > T_{\mathrm{coh}}$
- Principle of data analysis: break dataset into smaller chunks of length $T_{\mathrm{FFT}} \sim T_{\mathrm{coh}}$ to confine this frequency modulation to one frequency bin, then sum power incoherently



(a) (b)

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

Miller et al. 2020, PRD 103, 103002

Types of dark matter

- Scalar, dilaton dark matter
- Axion (-like) particles
- Vector dark matter (dark photons)
- Tensor dark matter

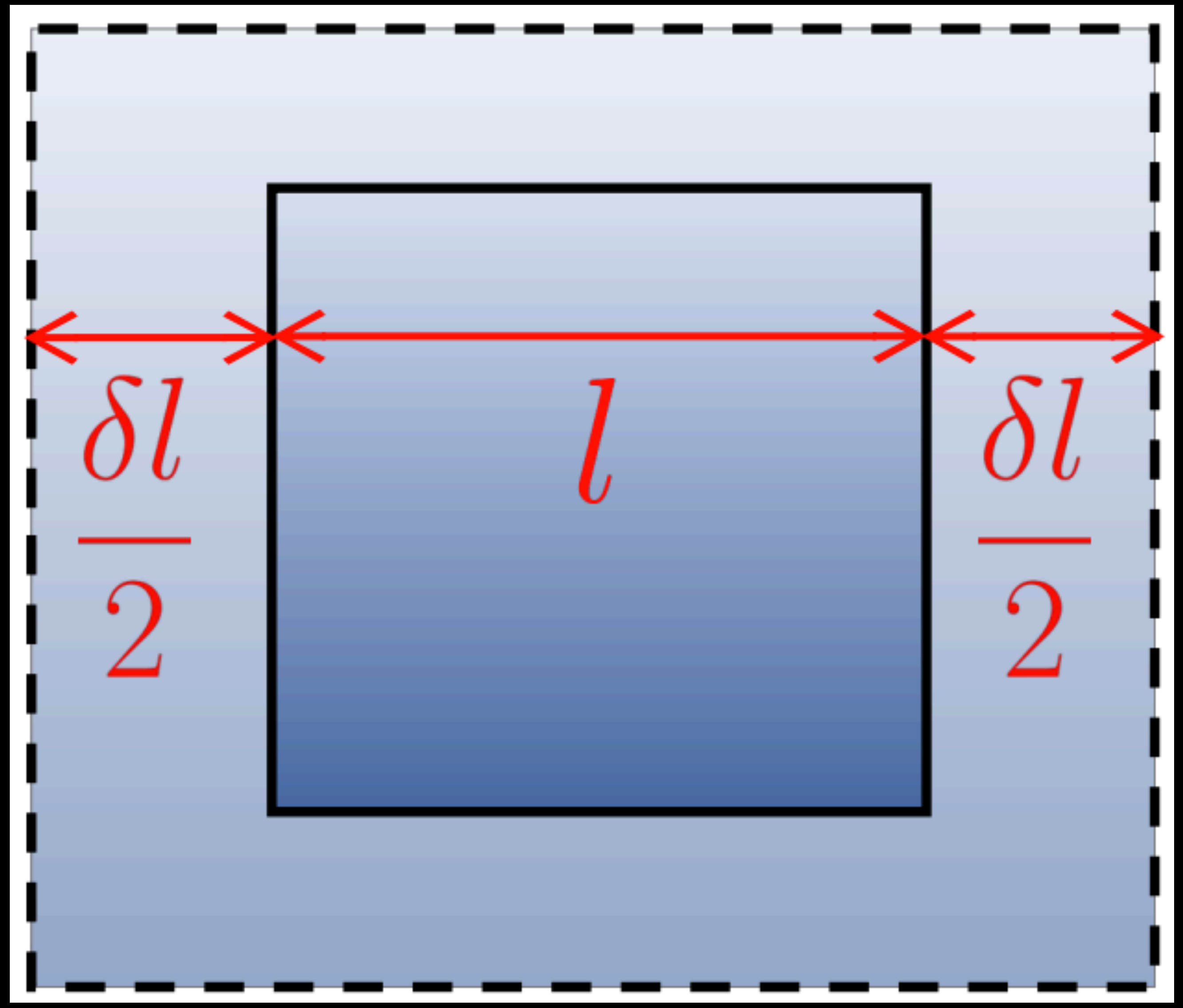
Scalar, dilaton dark matter

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

$$\mathcal{L}_{\text{int}} \supset \frac{\phi}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} - \frac{\phi}{\Lambda_e} m_e \bar{\psi}_e \psi_e$$

$$\frac{\delta\alpha}{\alpha} = \frac{\phi}{\Lambda_\gamma}$$

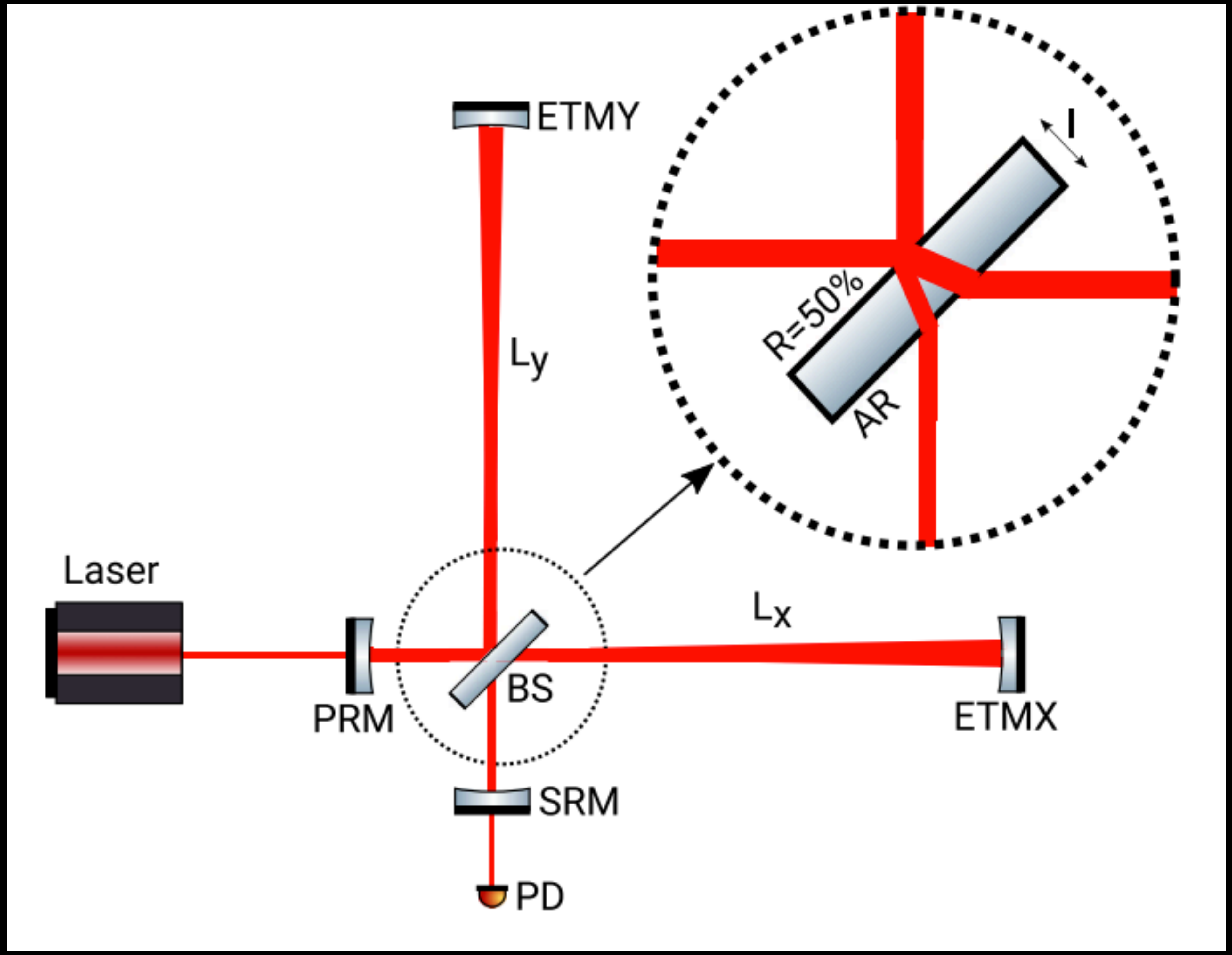
$$\frac{\delta m_e}{m_e} = \frac{\phi}{\Lambda_e}$$



Preskill et al. 1983 Phys. Lett. B 120, 127
Grote and Stadnik 2019 Phys. Rev. Research, vol. 1, 033187

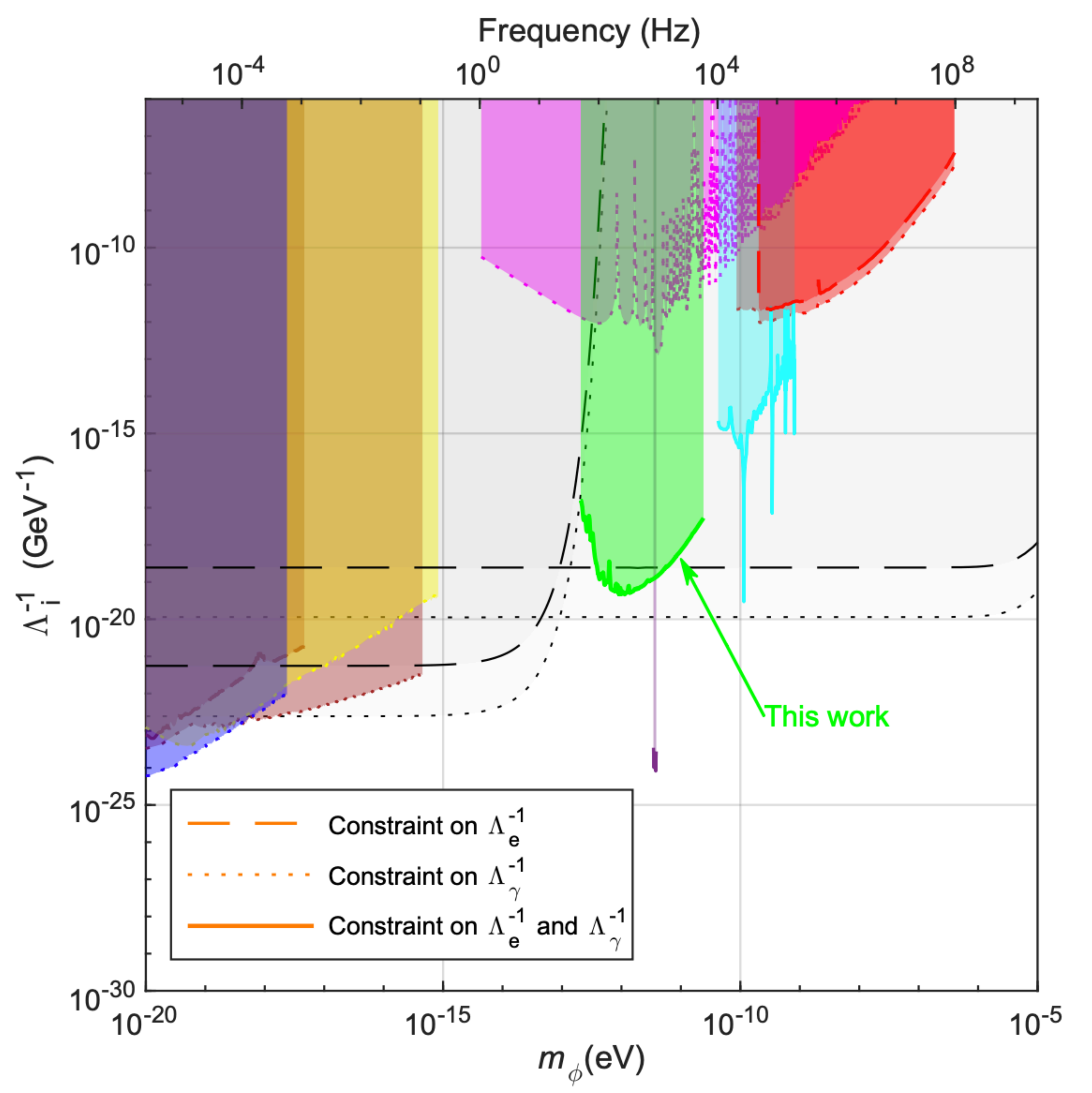
Observable effects of scalar dark matter

- GEO600 most sensitive, since interferometers are not sensitive to common mode motion induced by scalar dark matter
- Freely-suspended beam splitter would oscillate about its center of mass due to time-varying size changes induced by scalar dark matter, shifting the surface that reflects laser light back and forth
- Time-varying index of refraction would change optical path length across beam splitter too, though smaller effect
- $\delta(L_x - L_y) \approx \sqrt{2}(n\delta l + l\delta n)$



Searching for scalar dark matter

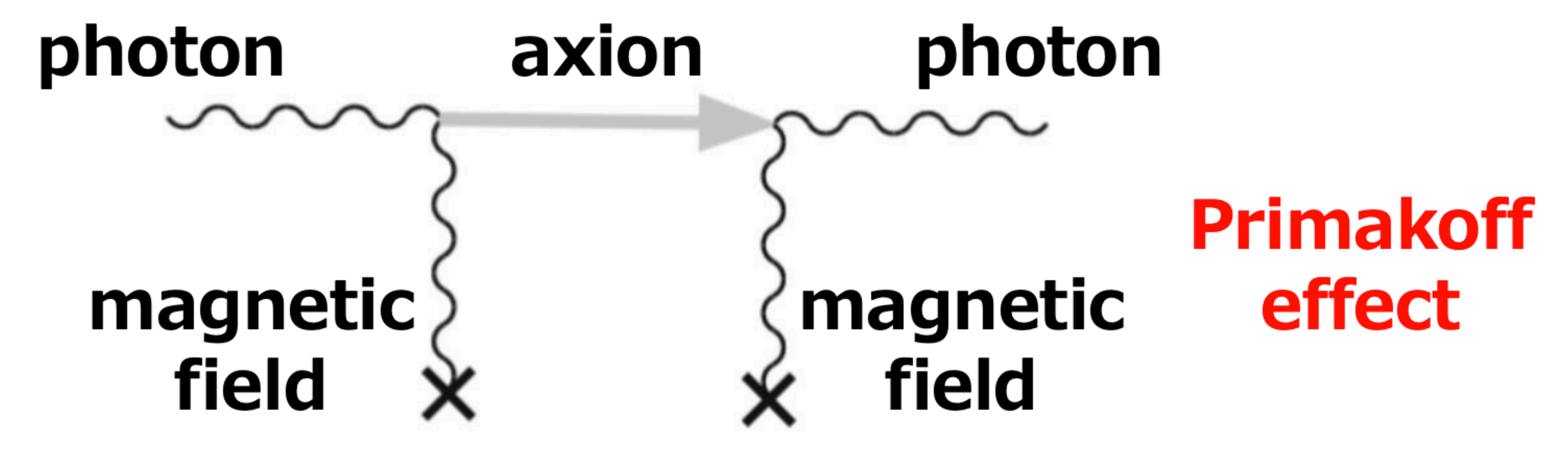
- Search performed on GEO600 data between 50-8192 Hz on seven segments each of 10^5 seconds
- Spectral estimation method (LPSD): varies the FFT length as a function of dilaton mass at every log(frequency)
- Average estimates of signal power spectrum (average the FFTs)
- Constrained scalar, dilaton/modulus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

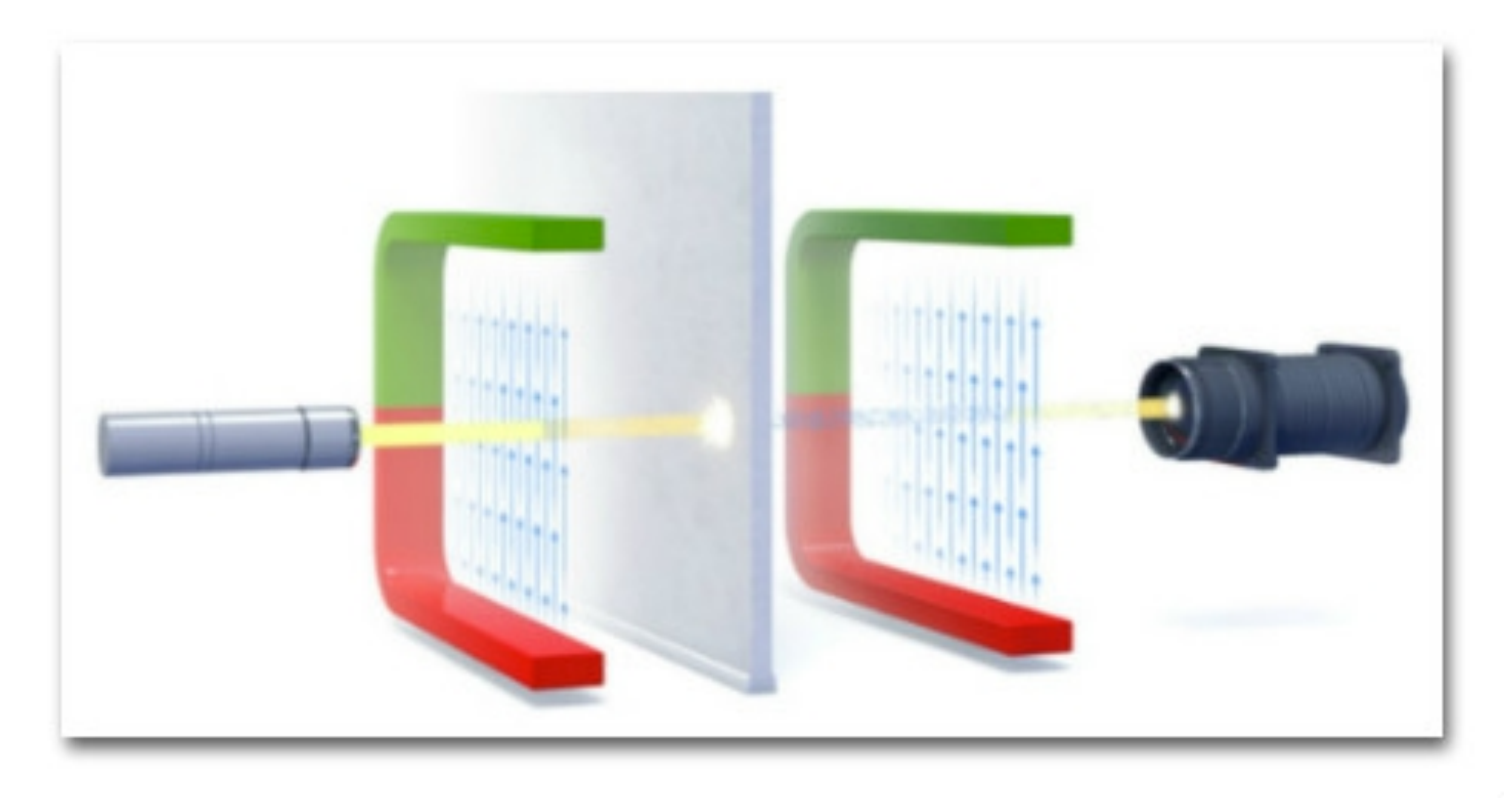


Vermeulen et al. (2021) arXiv: 2103.03783

Axions

- Pseudo-scalar particle originally introduced to solve strong CP problem (QCD axion)
- Various axion-like particles (ALPs) predicted by string theory and supergravity
- Many experiments to search for ALPs through axion-photon coupling Especially by using magnetic fields





- “Light shining through wall” (LSW) Experiments

Axions modulate photon polarizations

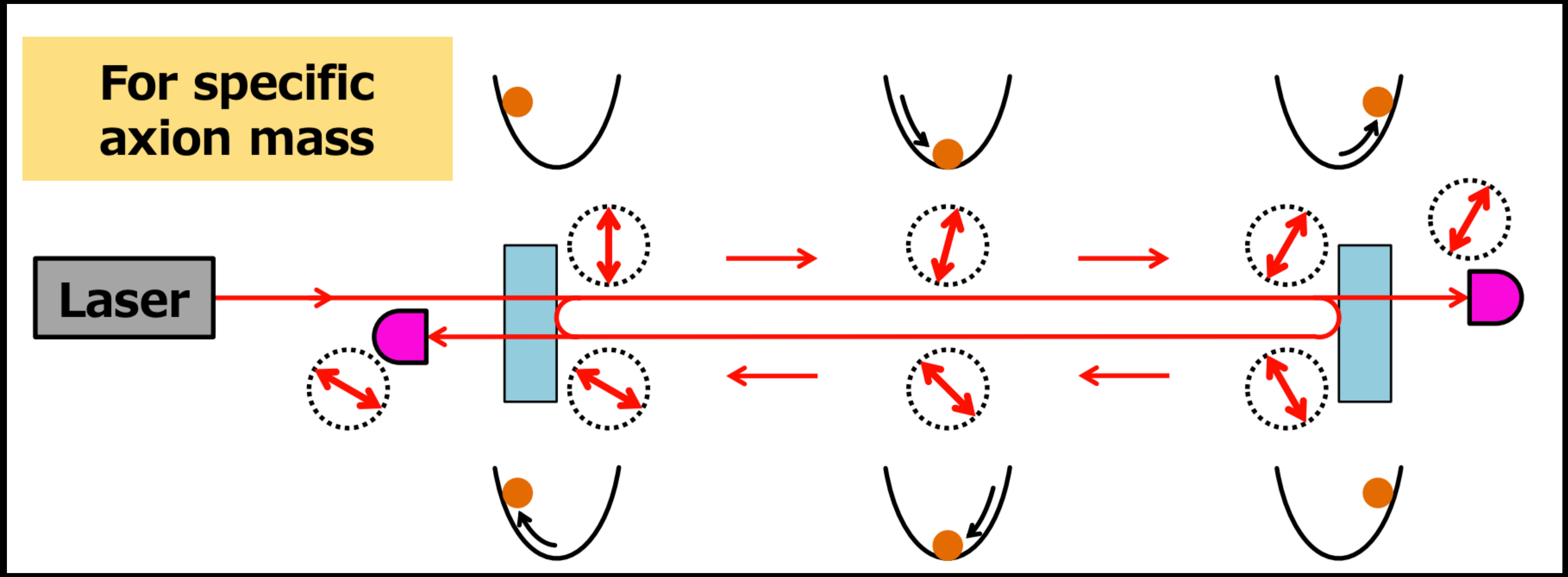
- Axions could couple to photons
- Left- and right- circularly polarized light will travel at different speeds in the presence of an axion field
- No need for external magnetic field
- Longer arms improve sensitivity
- Polarization flip at the mirrors enhances signal strength if round-trip time equals odd-multiples of axion oscillation period

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

coupling constant

axion field

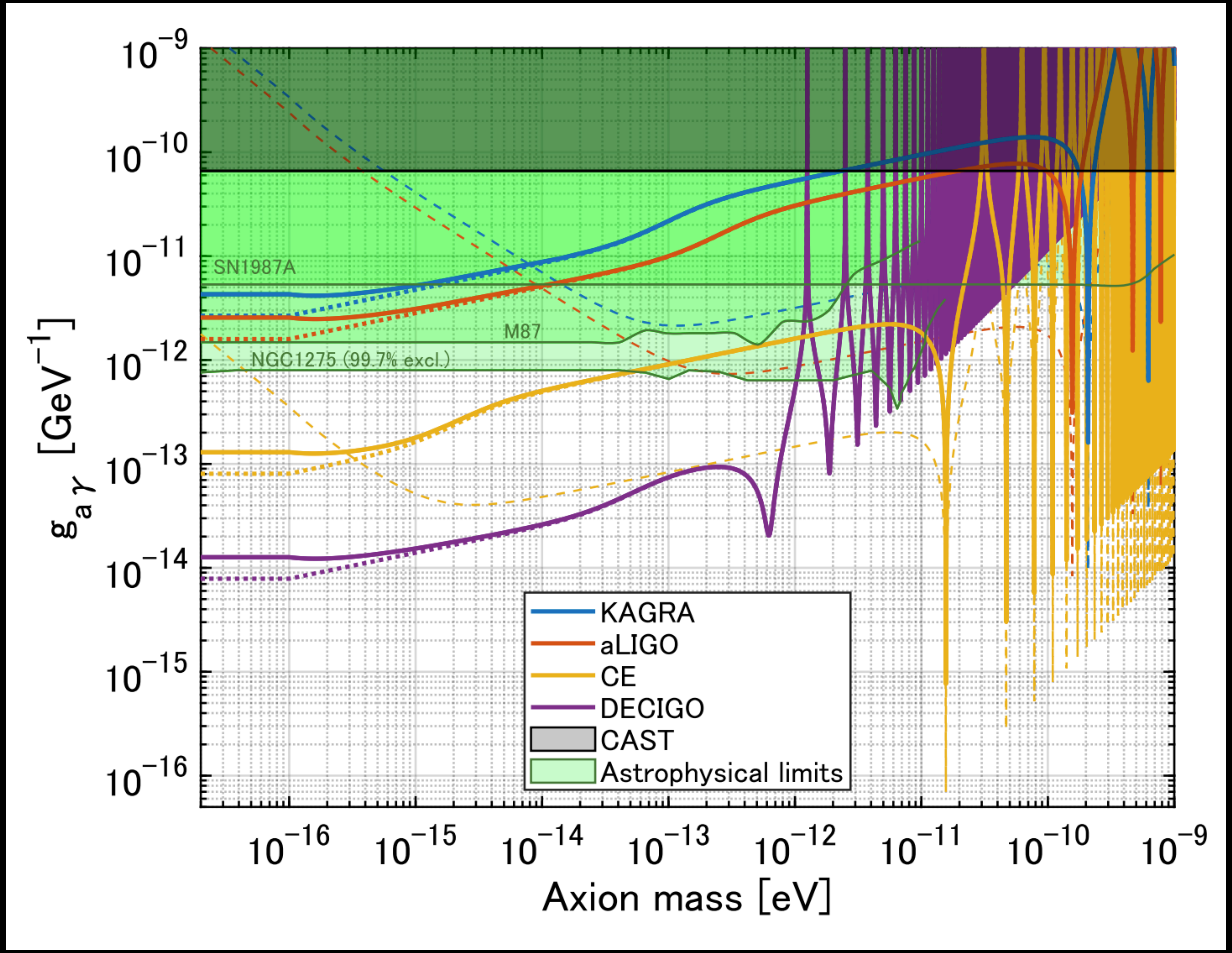
axion mass



Nagano et al. (2019) PRL 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 length gives different resonances for all detectors
- Search in the reflection and the transmission ports of FP cavities.



Nagano et al. (2021) PRD 104, 062008

Vector bosons: dark photons

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

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

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

- Dark photon coupling to protons / neutrons contribute to two differential arm strains:

  1. Differential strain from a spatial gradient in the dark photon field

  2. Apparent differential strain from common-mode motion of the mirrors

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

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

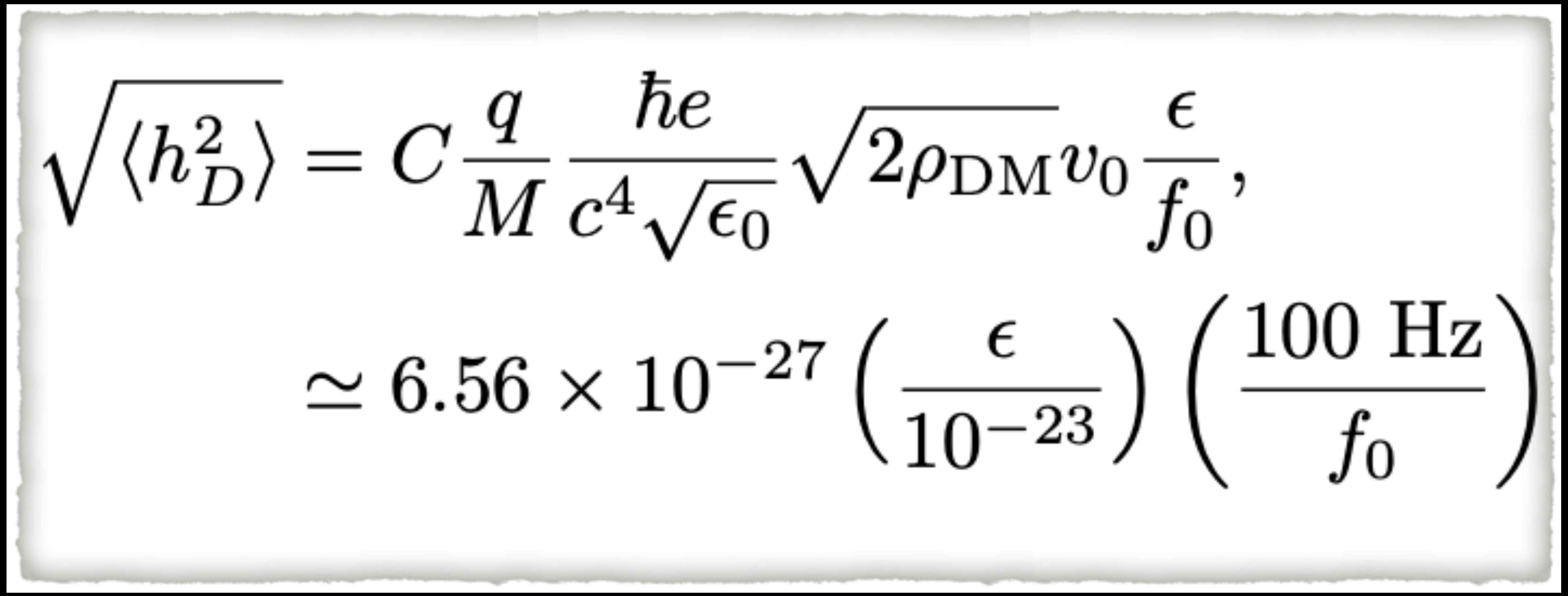
m_A: mass of dark photon
f_0: frequency of dark photon

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

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

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

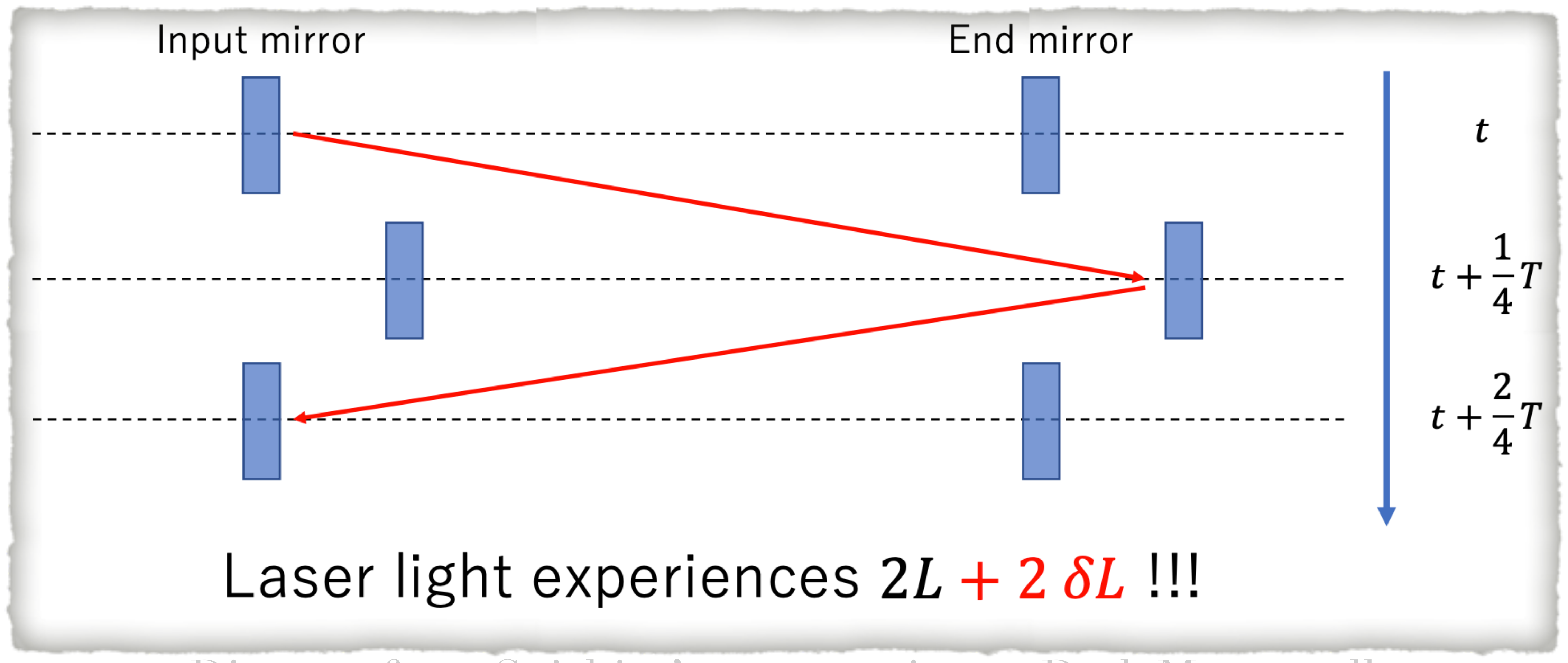


$$
\begin{aligned}
\sqrt{\langle h_D^2\rangle} &= C\,\frac{q}{M}\,\frac{\hbar e}{c^4\sqrt{\epsilon_0}}\sqrt{2\rho_{\mathrm{DM}}}\,v_0\,\frac{\epsilon}{f_0}, \\
&\simeq 6.56\times 10^{-27}\left(\frac{\epsilon}{10^{-23}}\right)\left(\frac{100\ \mathrm{Hz}}{f_0}\right)
\end{aligned}
$$

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 $2L + 2\,\delta L$!!!

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. Lett. 103, L051702

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

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

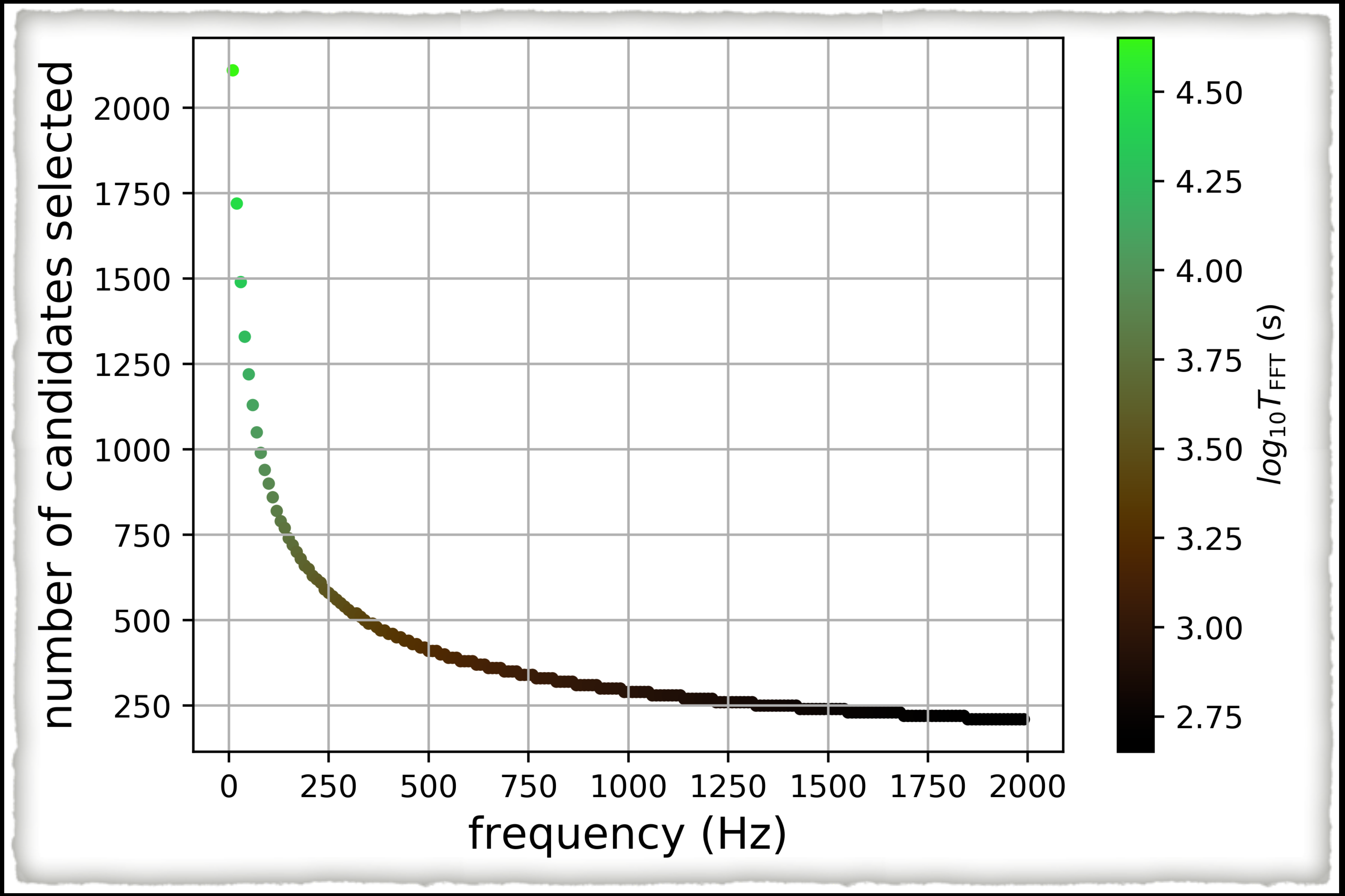


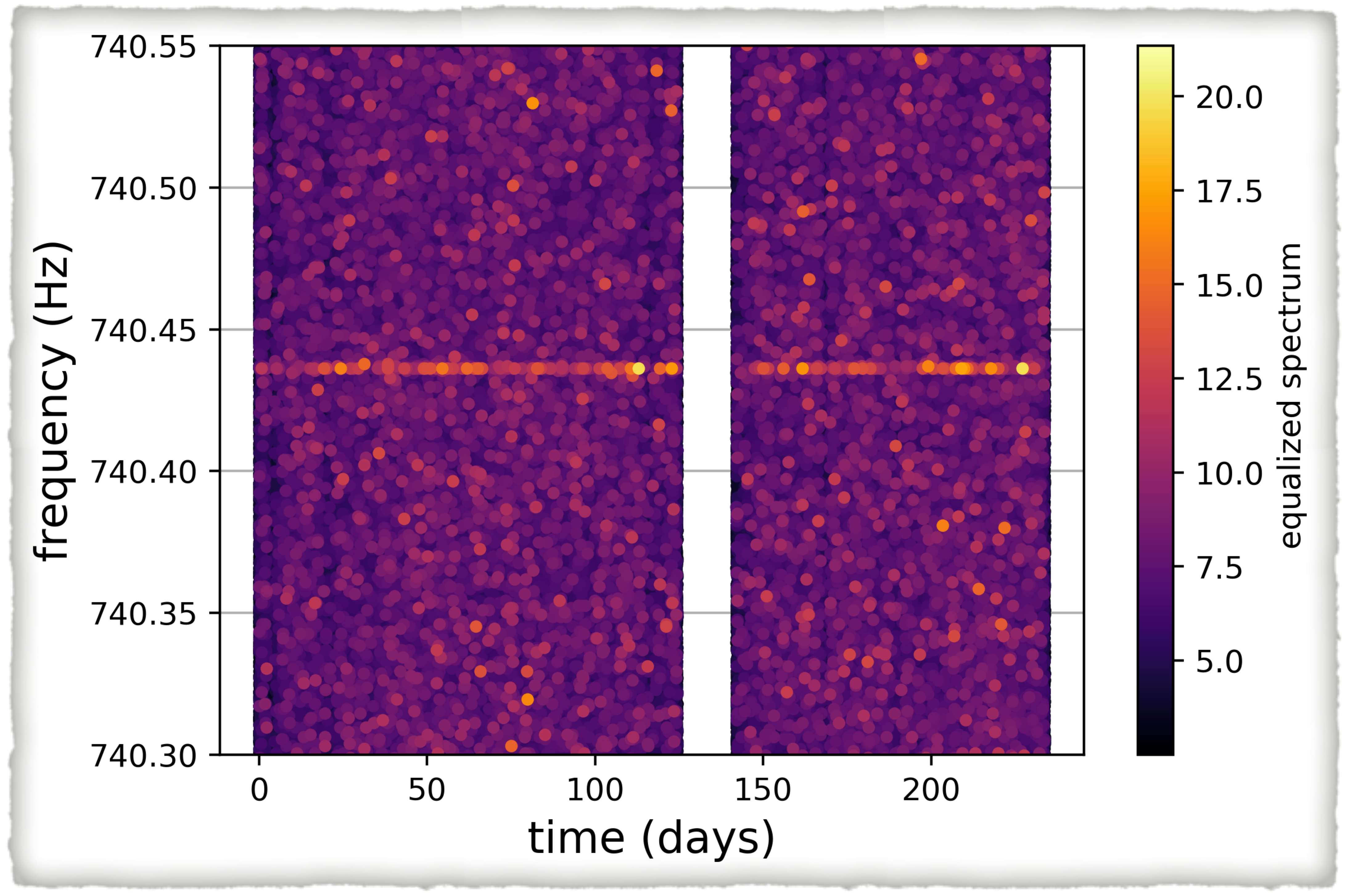
Figure 1: number of candidates to select as a function of frequency, with the Fourier Transform time coloured

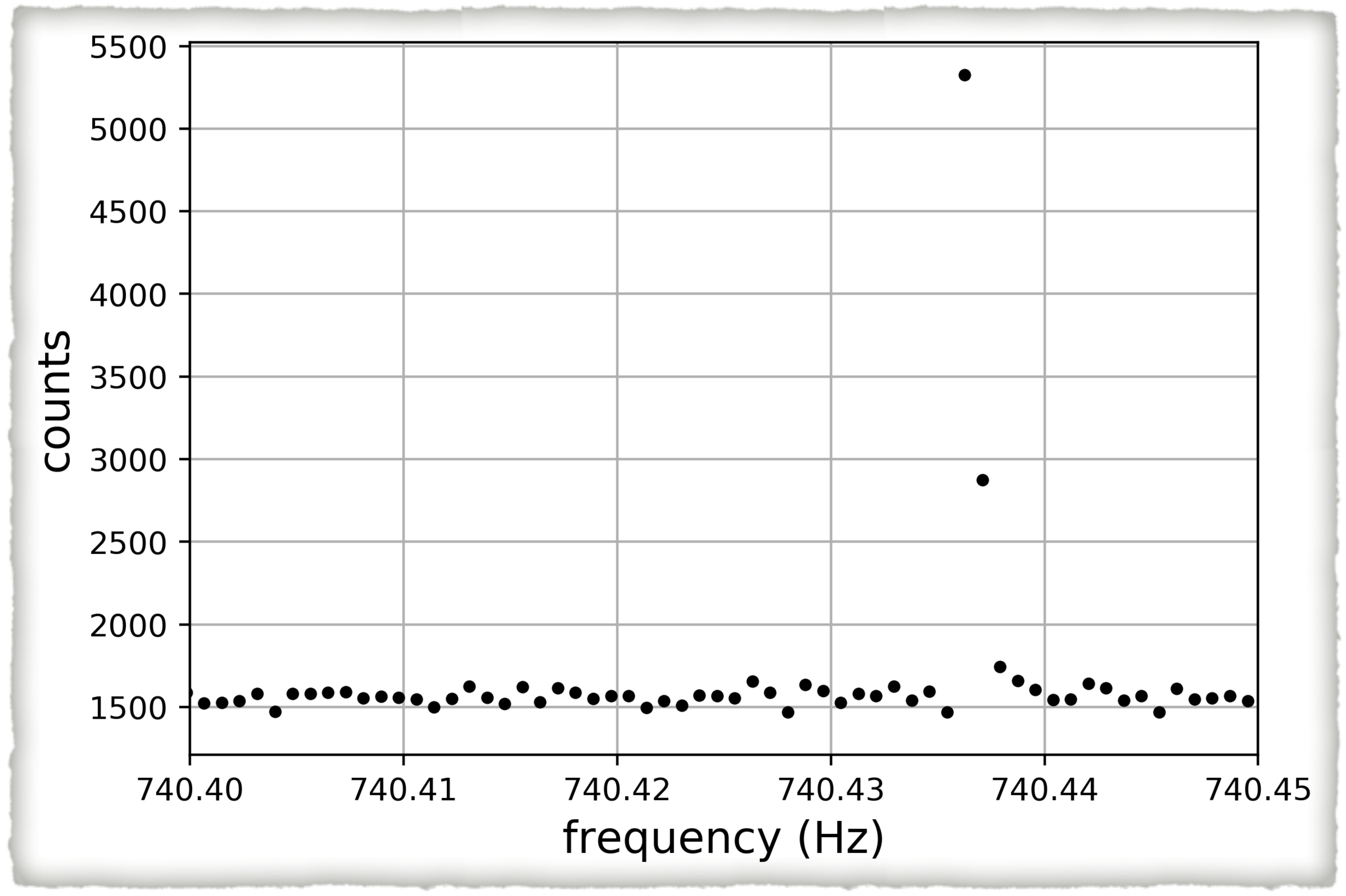
Miller et al. 2020, PRD 103, 103002

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

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

Excess power projection

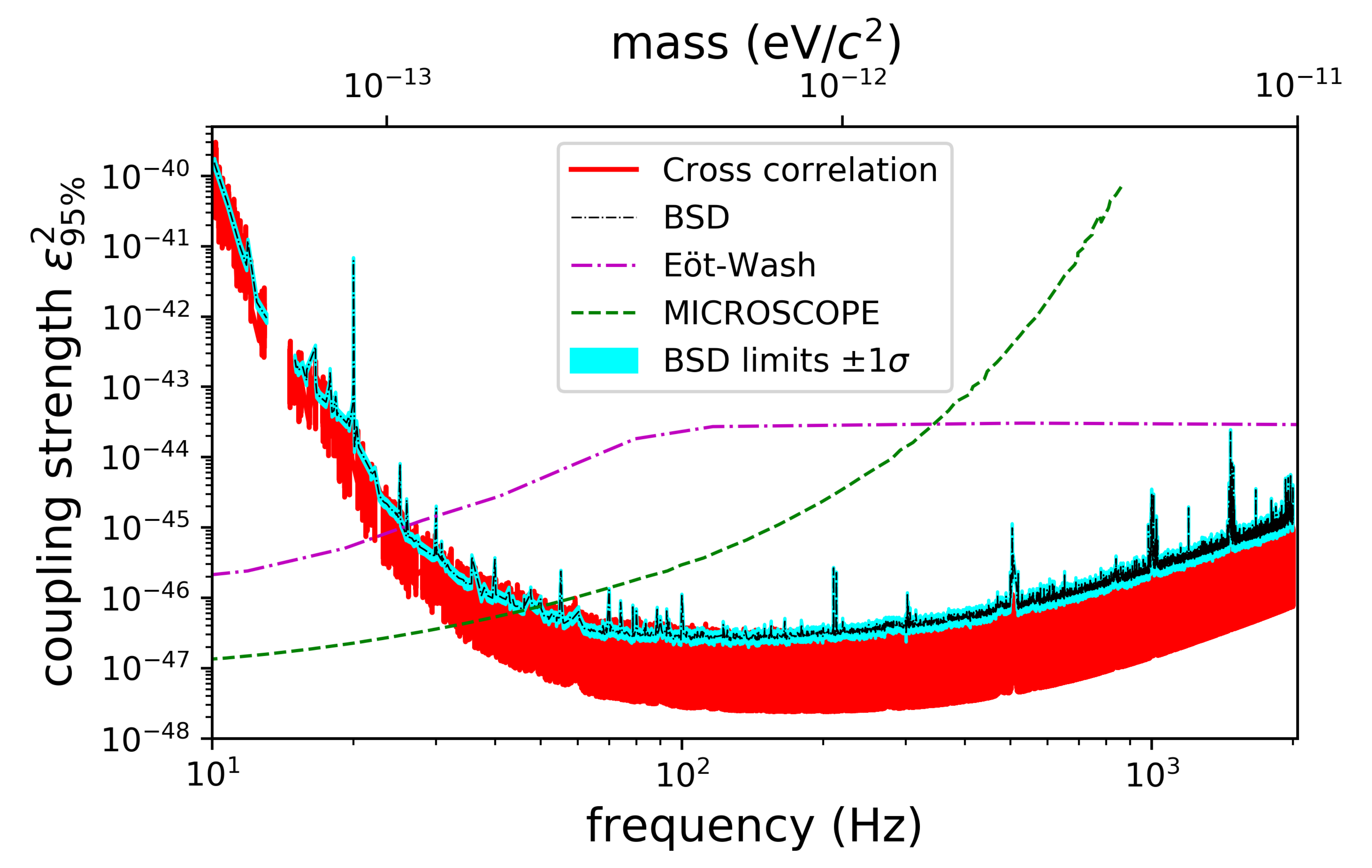




- Carefully choose T_{SFT} —> peakmap and project
- O2 Livingston data shown here with a simulated dark photon signal

Results: O3 dark photon search

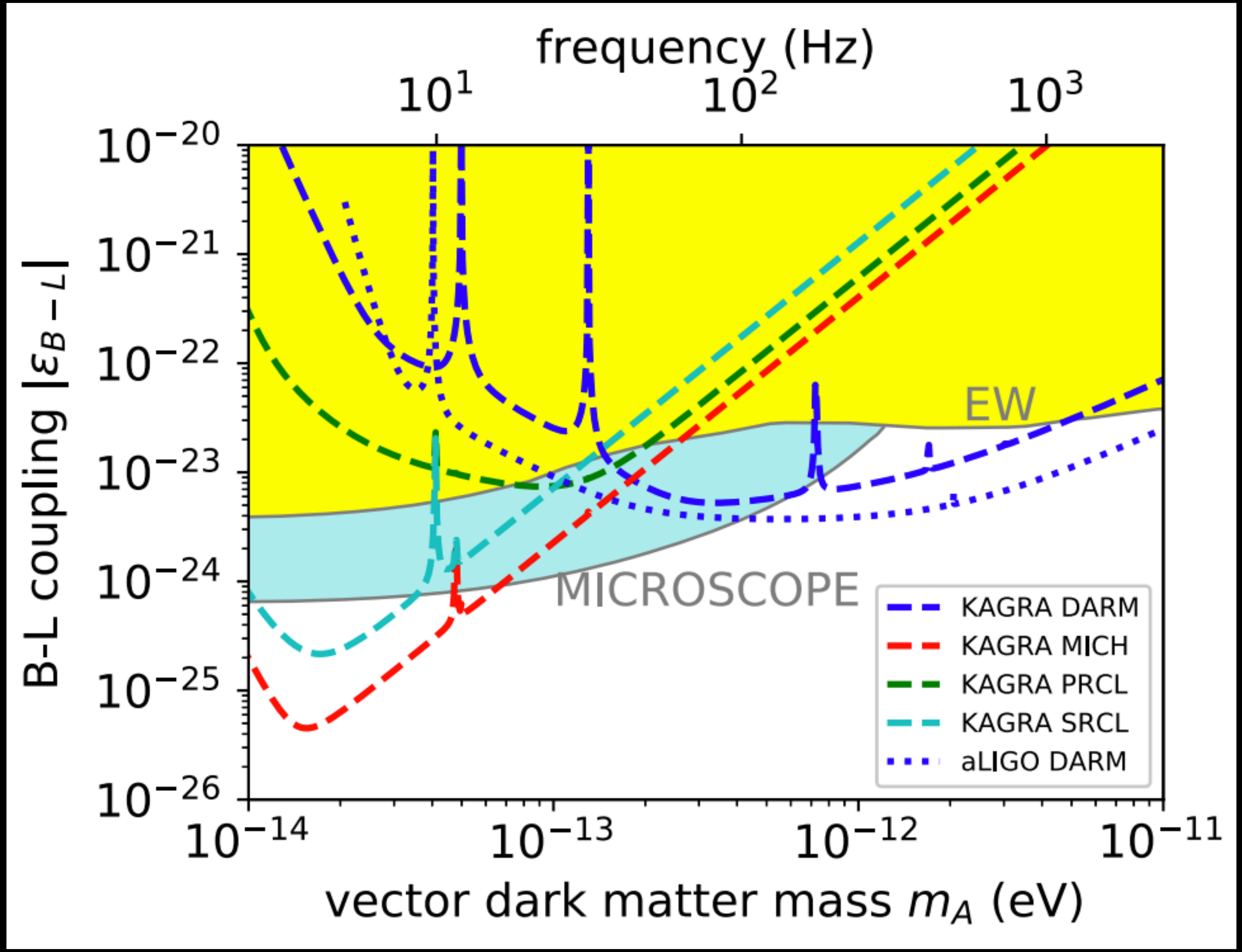
- All outliers vetoed in excess power method; only 4 sub-threshold outliers consistent with Gaussian noise expectation for cross-correlation
- Feldman-Cousins approach used to set upper limits, which assume our detection statistics follow a Gaussian distribution
- Both common and differential motion strains considered when calculating these limits



Abbott et al. (LVK) 2021: arXiv 2105.13085

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



Michamura et al. (2020) PRD 102, 102001

Tensor bosons

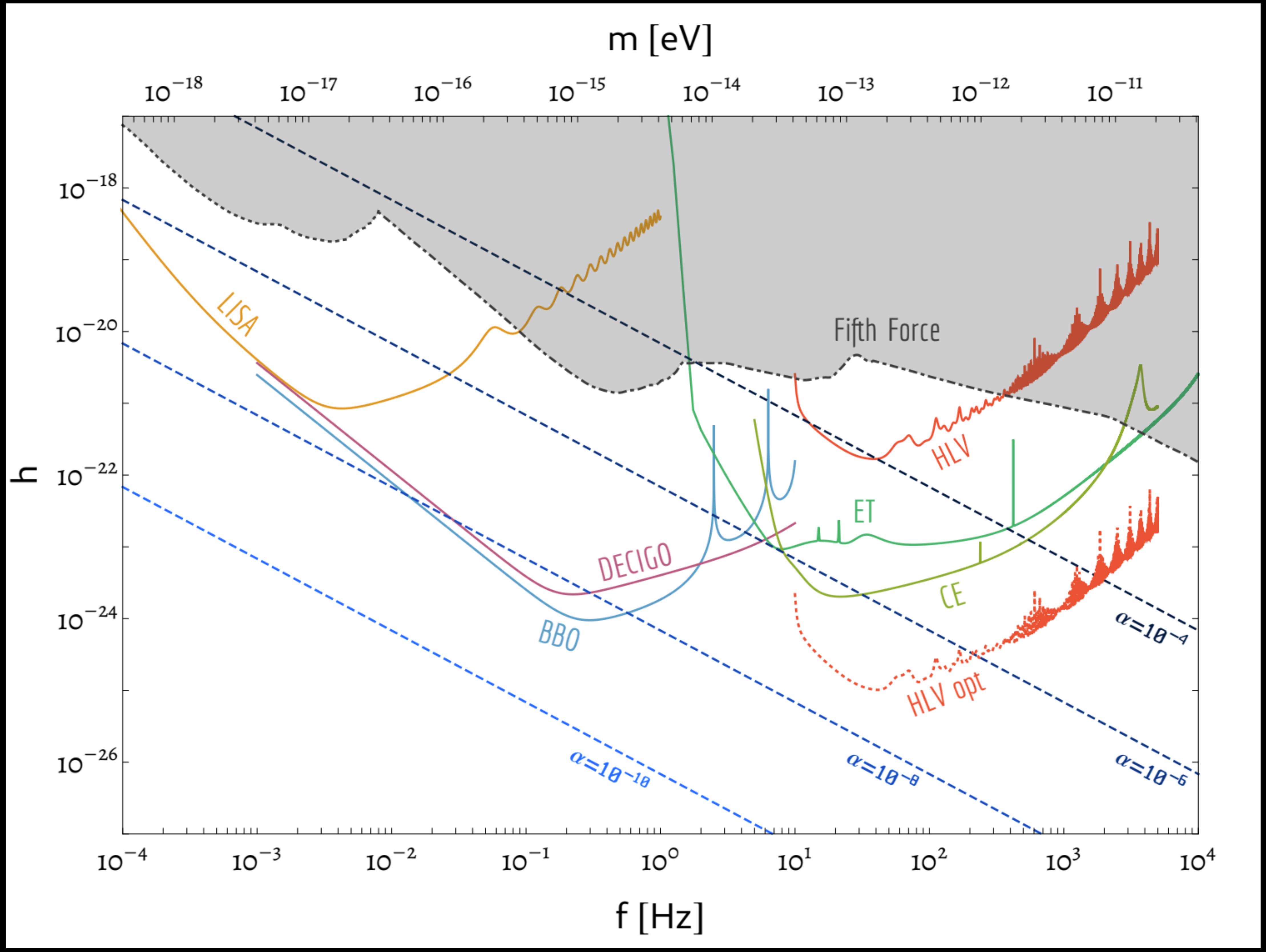
- Arise as a modification to gravity, even though it acts as an additional dark matter particle
- Metric perturbation couples to detector: $h(t) = \dfrac{\alpha\sqrt{\rho_{\mathrm{DM}}}}{\sqrt{2}mM_p}\cos(mt + \phi_0)\Delta\epsilon$
- Self-interaction strength α determines how strong metric perturbation is
- $\Delta\epsilon$ encodes the five polaraizations of the spin-2 field
- Will appear as a Yukawa-like fifth force modification of the gravitational potential

Armaleo et al. (2021) JCAP 2021.04: 053

Projected sensitivity towards tensor bosons

- Current and future detector sensitivities plotted, along with constraints from fifth force experiments

- Depending on theoretical coupling strength, GW interferometers could constrain the existence of tensor boson interactions



Armaleo et al. (2021) JCAP 2021.04: 053

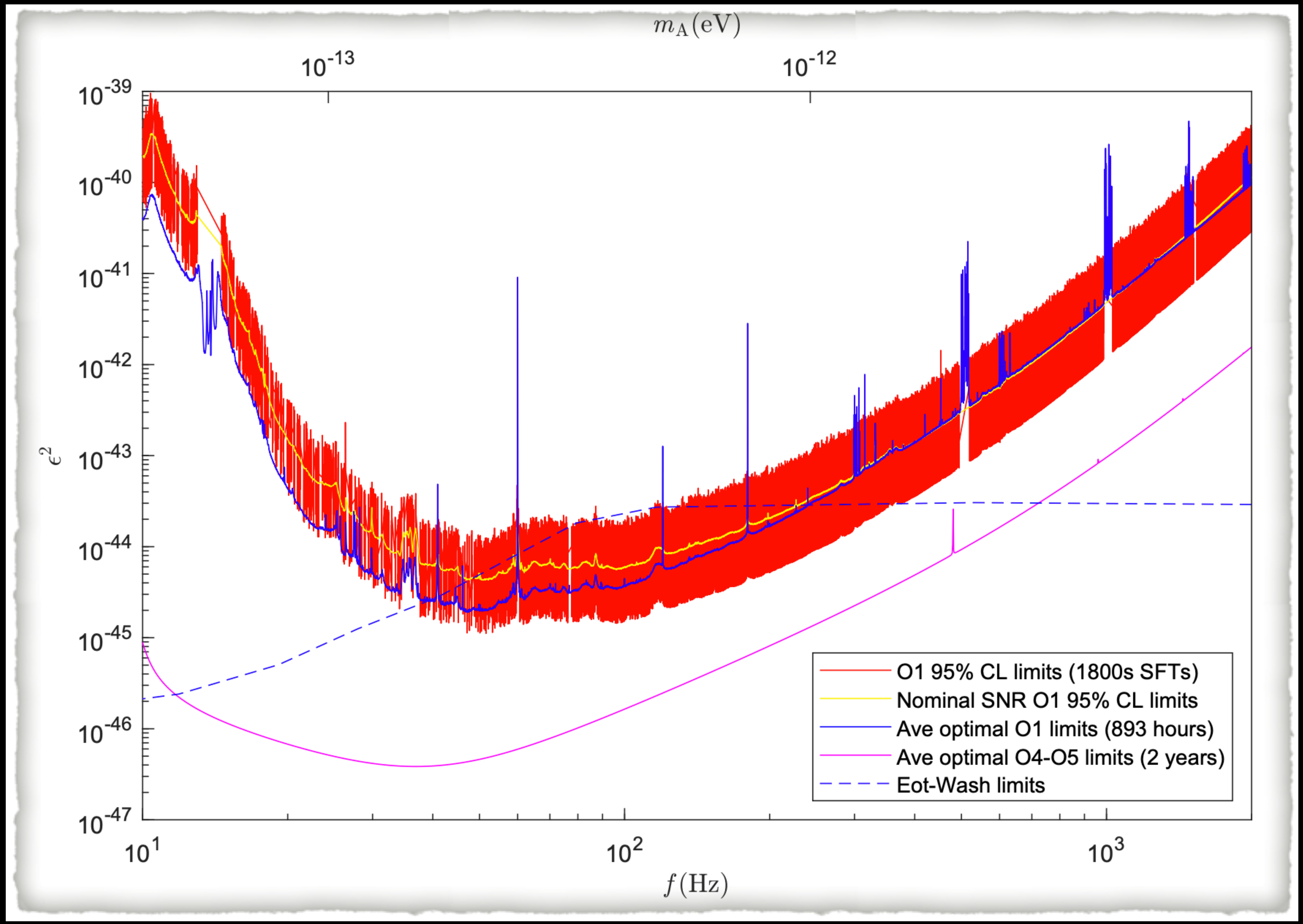
Conclusions

- Upper limits from multiple searches for dark matter improve upon existing ones from direct dark matter detection experiments
- In the case of vector dark matter, accounting for the common motion of the arms is primarily responsible for improvements relative to existing experiments
- 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

O1 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 Nature Communications Physics 2

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

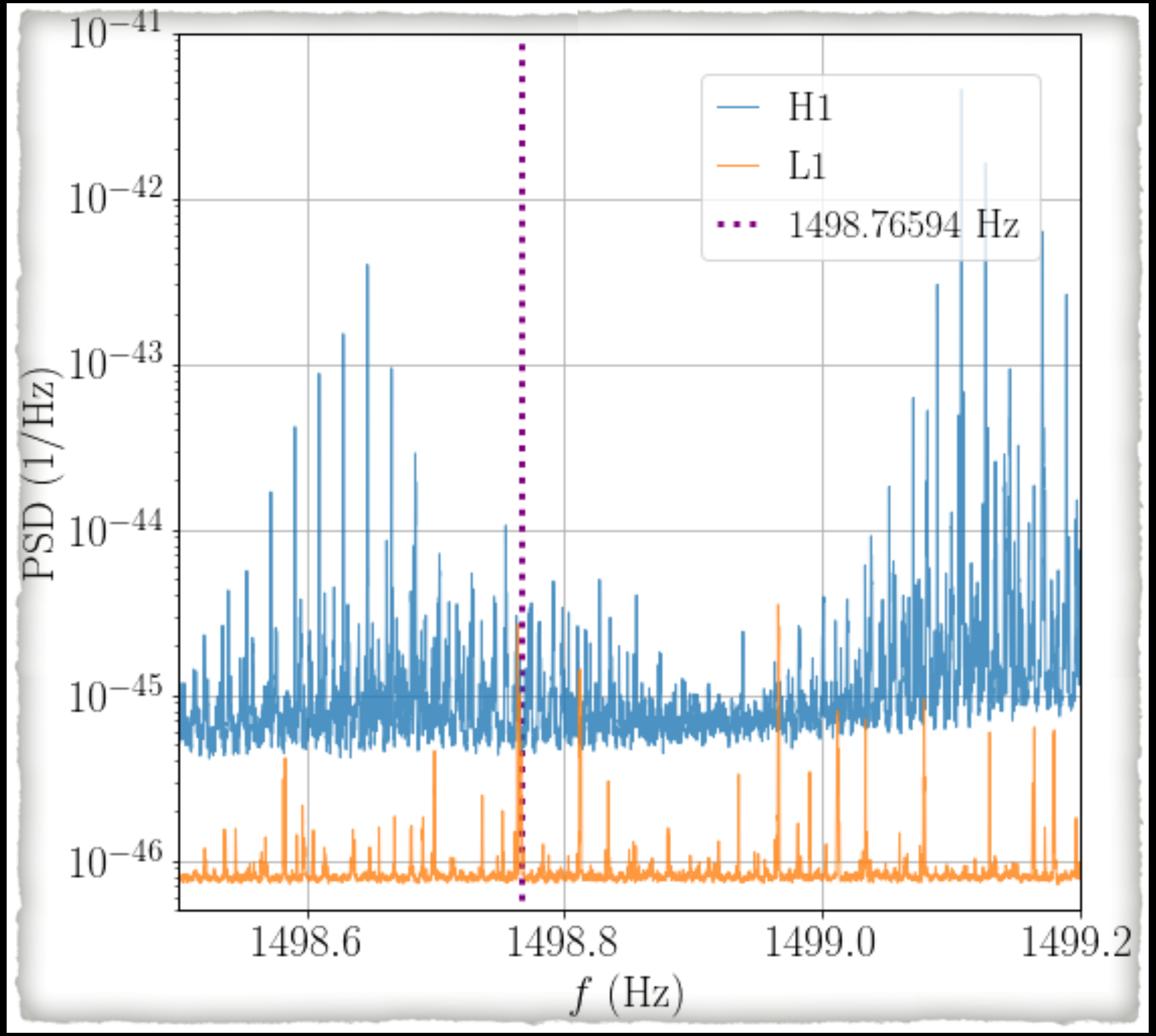


Figure 2: PSD around one outlier, given by the vertical purple line