

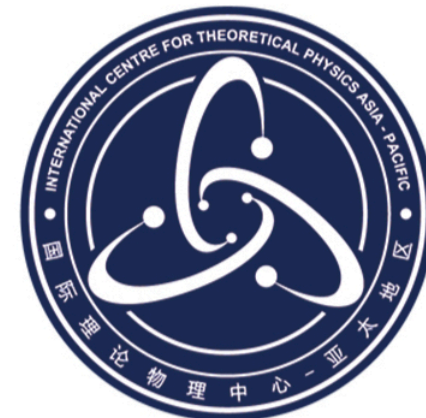
# Prospects of dark matter probes using GW observations

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Paper



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# Outline

- Background
- Types of ultralight dark matter signals
- Search using O4a LIGO/Virgo/KAGRA for ultralight dark matter
- Conclusions



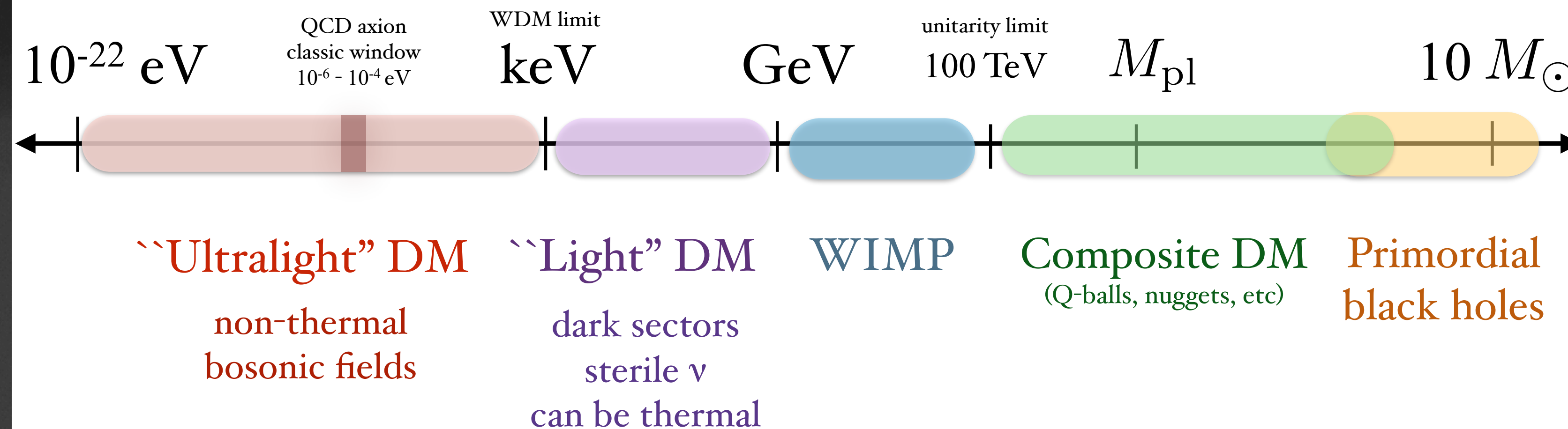
# Background



# Ultralight dark matter

## Mass scale of dark matter

(not to scale)

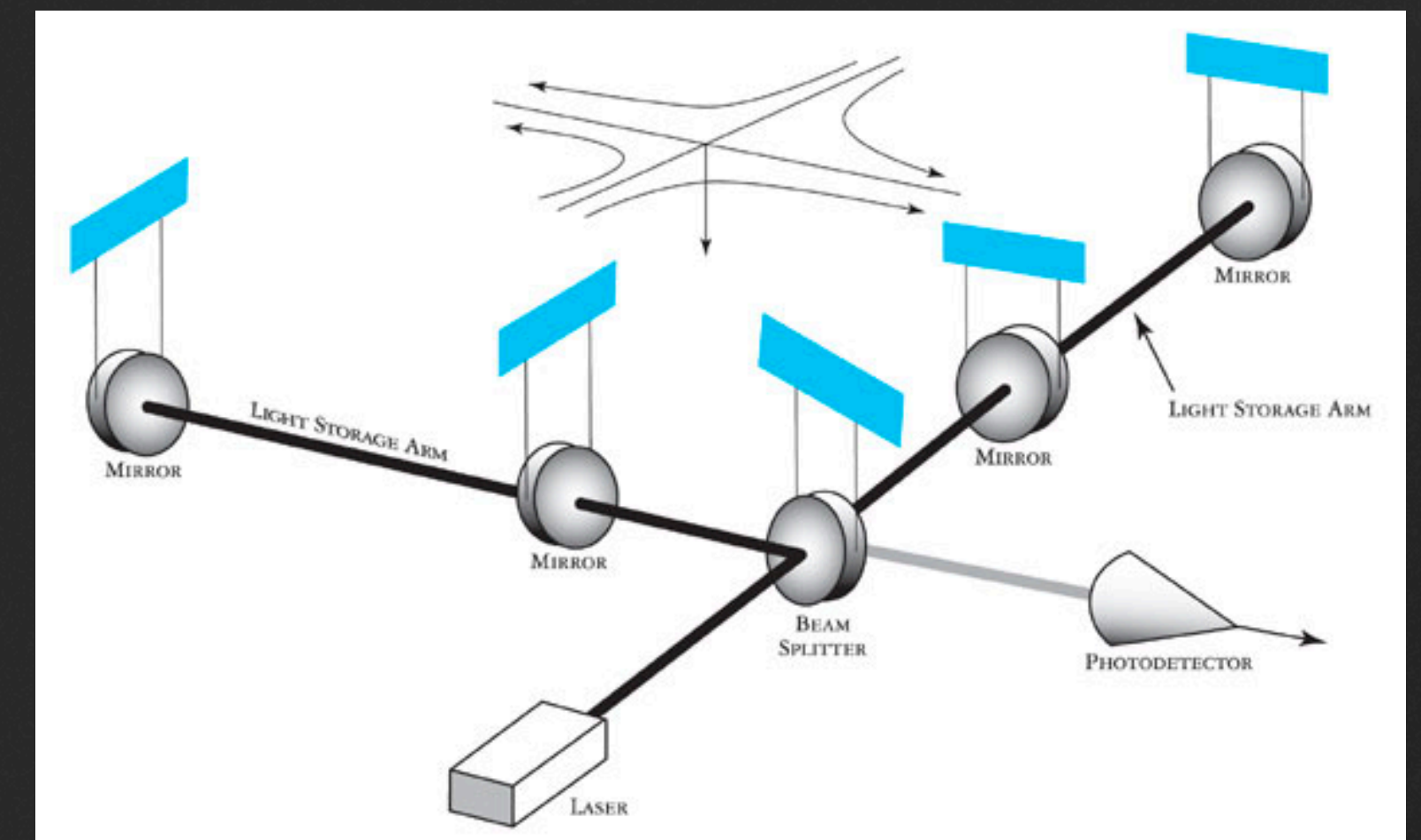


- Potential dark matter spans hundreds of orders of magnitude
- Many models, none are guaranteed to be right or wrong, and often, no *lower bounds* on coupling



# 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?

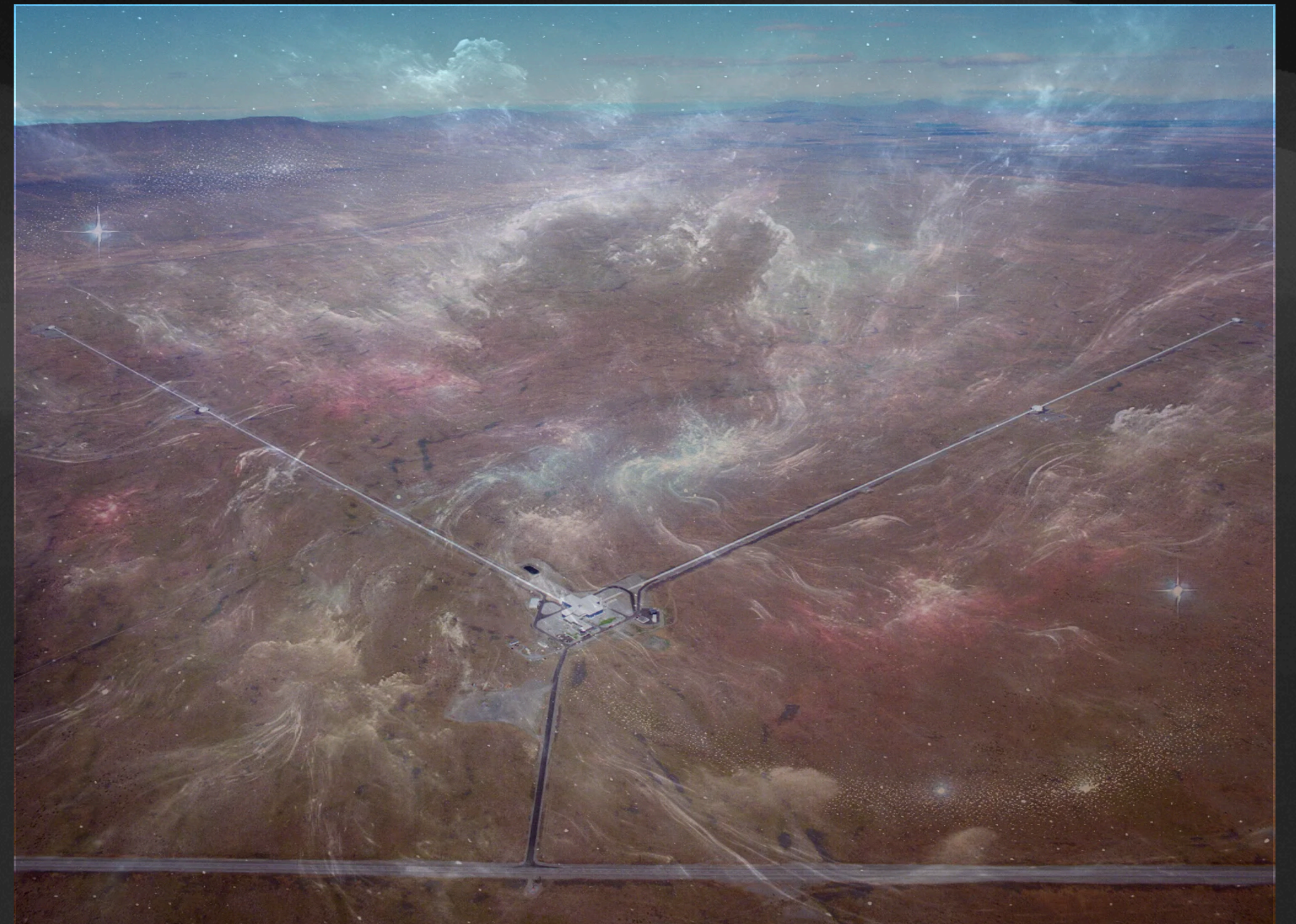




# Ultralight dark matter

- 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  $\rightarrow$  DM mass range  $[10^{-14}, 10^{-12}] \text{ eV}/c^2$
- Different DM particles with interact with different standard-model ones, leading to similar but distinguishable signals

LIGO Hanford in a dark-matter “ether”





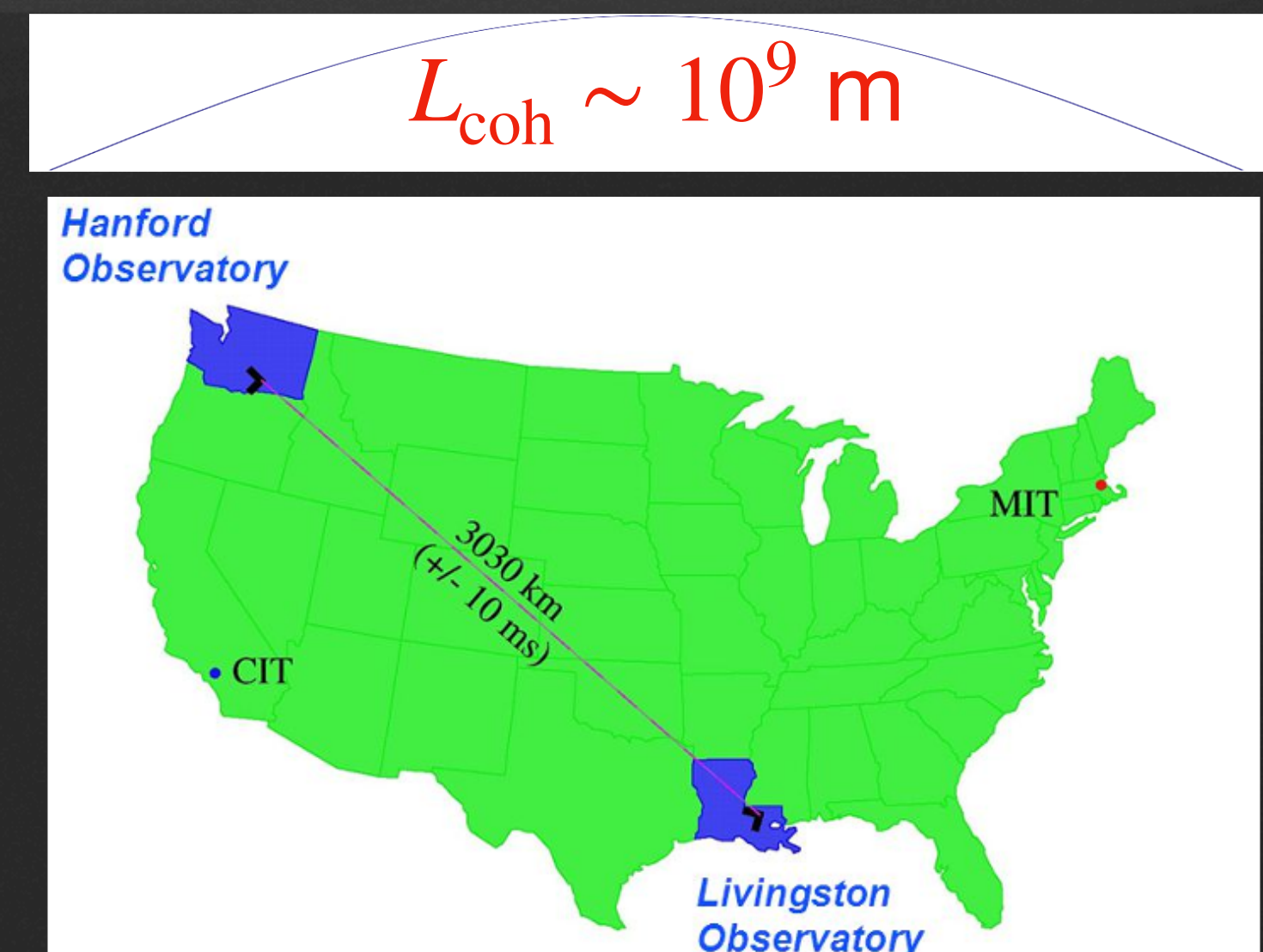
# Ultralight dark matter

- 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  $\Delta f/f \sim v_0^2/c^2 \sim 10^{-6} \rightarrow$  finite wave coherence time

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

$$N_o = \lambda^3 \frac{\rho_{\text{DM}}}{m_A c^2} = \left( \frac{2\pi\hbar}{m_A v_0} \right)^3 \frac{\rho_{\text{DM}}}{m_A c^2},$$

$$\approx 1.69 \times 10^{54} \left( \frac{10^{-12} \text{ eV}/c^2}{m_A} \right)^4$$





# Types of ultralight dark matter



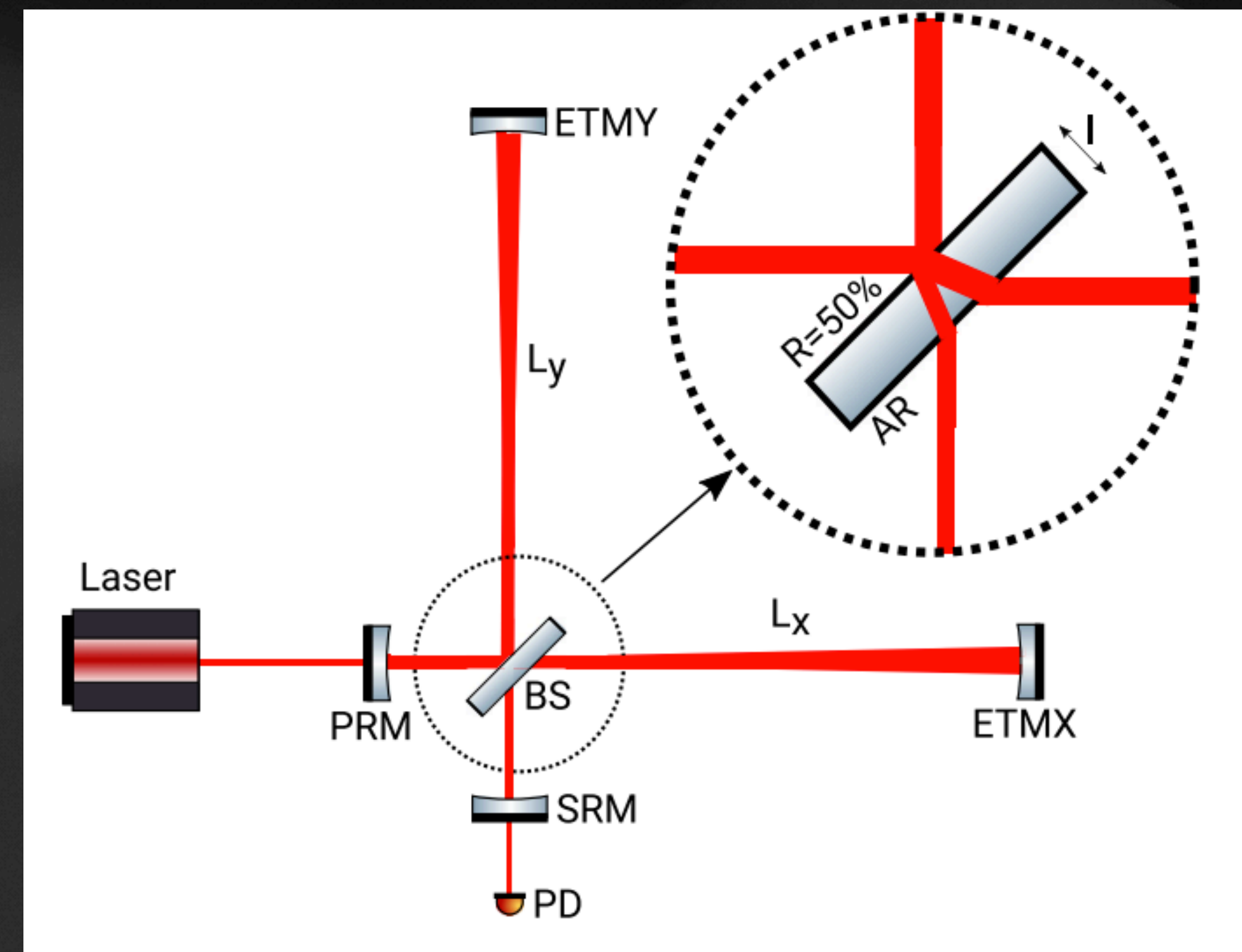
# Types of dark matter

- Scalar dark matter (spin 0): Expand/Contract mirrors
- Dark photon dark matter (spin 1): Accelerate mirrors
- Tensor dark matter (spin 2): Modify gravity



# Scalar dark matter

- Couples with strengths  $\Lambda_\gamma$  and  $\Lambda_e$  to standard model photon and electron fields, respectively
- Causes oscillations in
  - Beamsplitter: splitting occurs far from centre of mass
  - Test masses: Asymmetry from thickness differences





# Vector bosons: dark photons

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

$\underline{m}_A$  : dark photon mass

$\underline{\epsilon}_D$  : 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  $\rightarrow$  differential strain from a spatial gradient in the dark photon field
- Apparent strain results from a “finite light travel time” effect



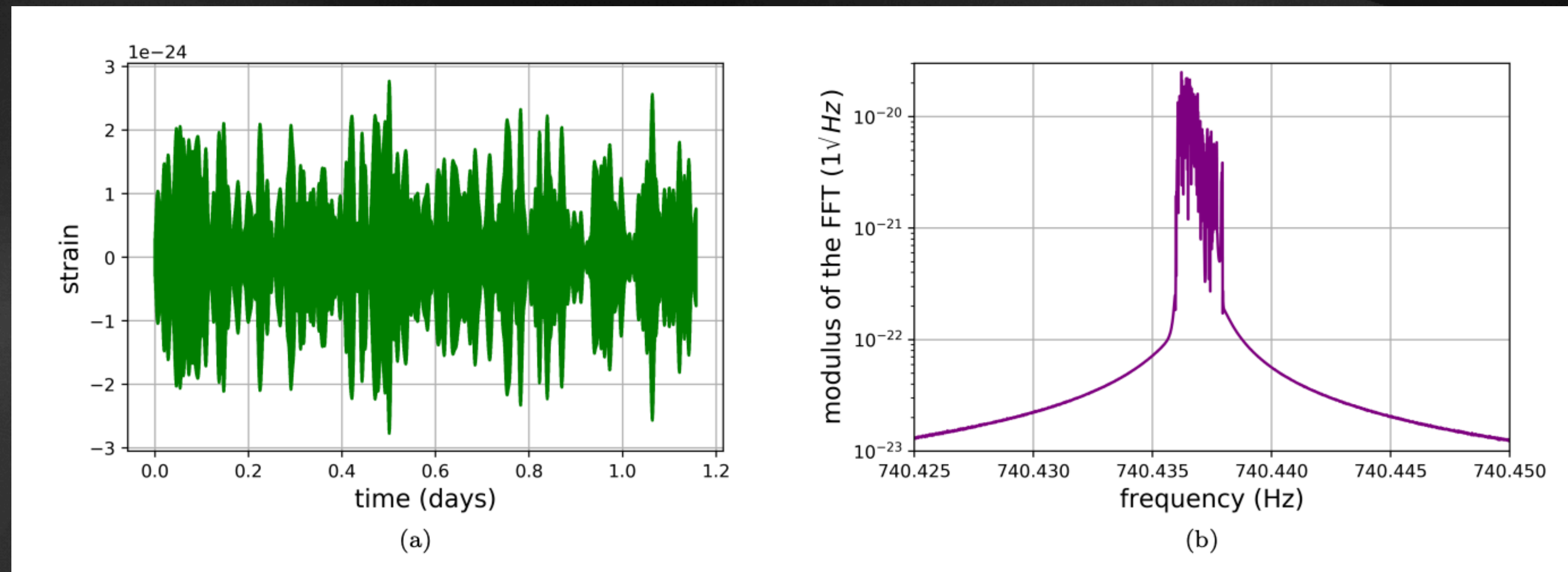
# Tensor bosons

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



# 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



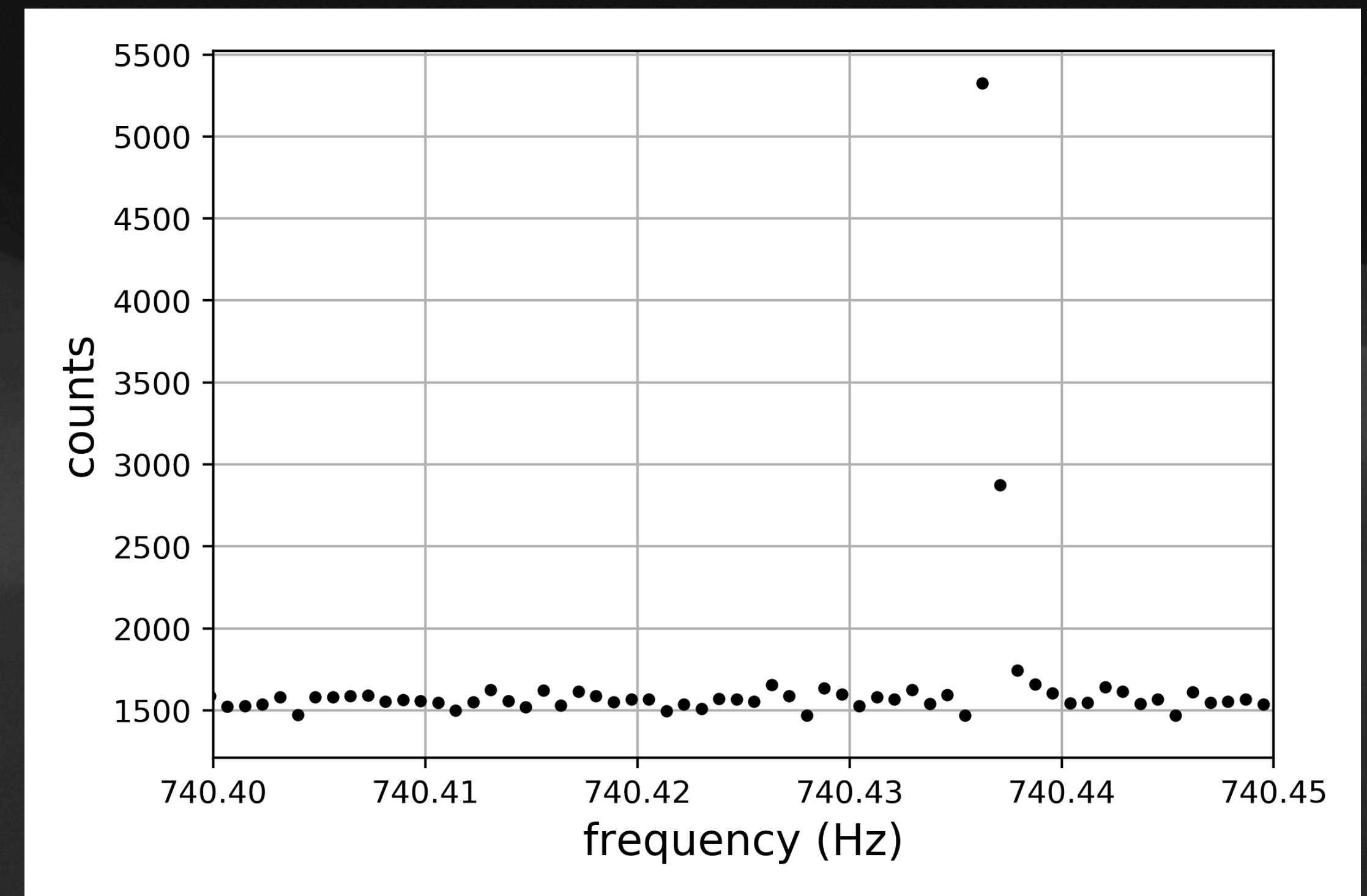
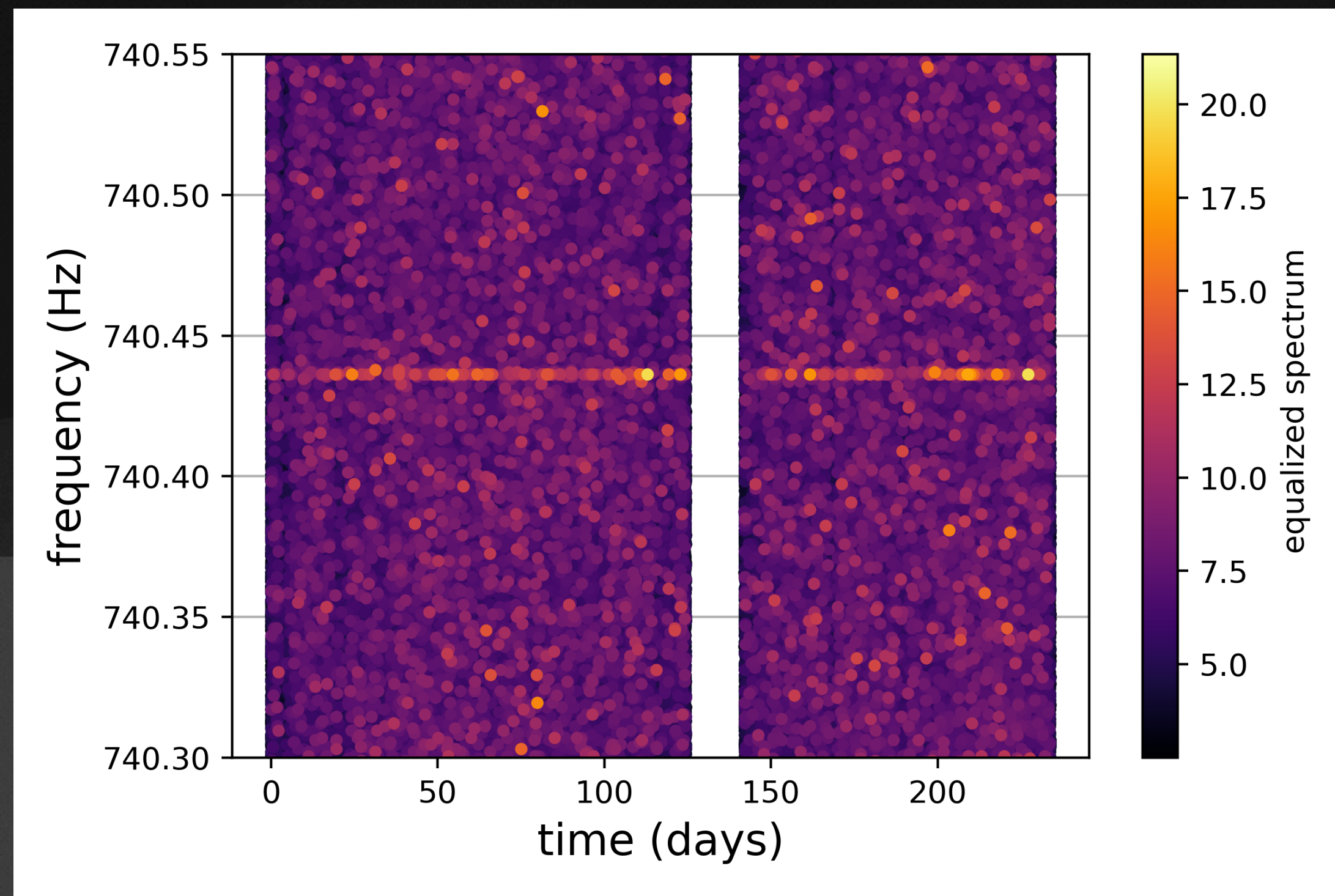
- One day shown, but signal lasts longer than observing run







# Methods



- Cross correlation
- Looking for excess power in time-frequency plane
- Logarithmic Power Spectral Density (PSD)

Pierce et al. 2018, PRL 121, 061102

ALM et al. (2021) PRD 103, 10, 103002

Gottel et al. (2024): PRL. 133, 10, 101001



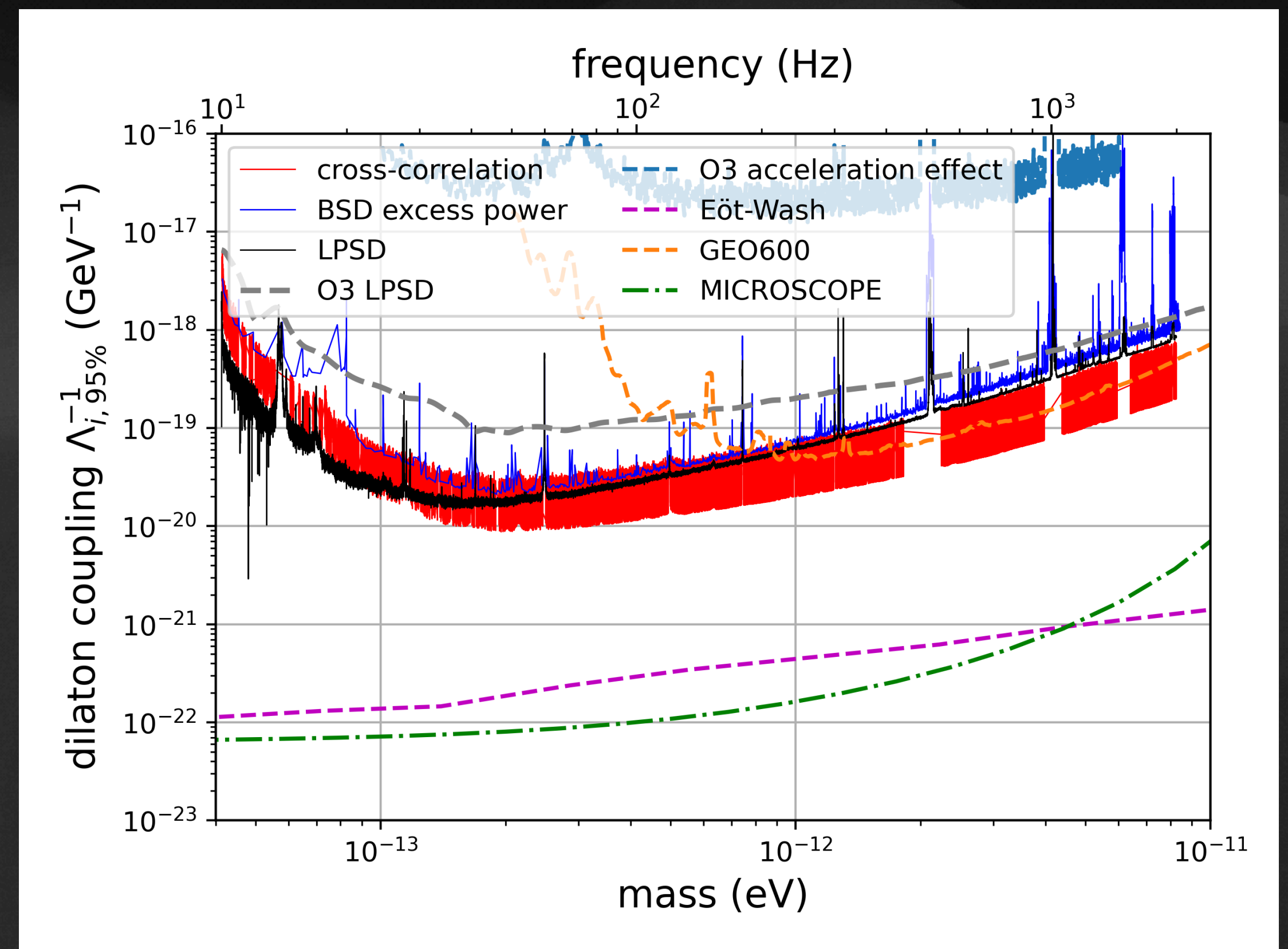
# Results

In a nutshell: we did not find dark matter



# Constraints on scalars

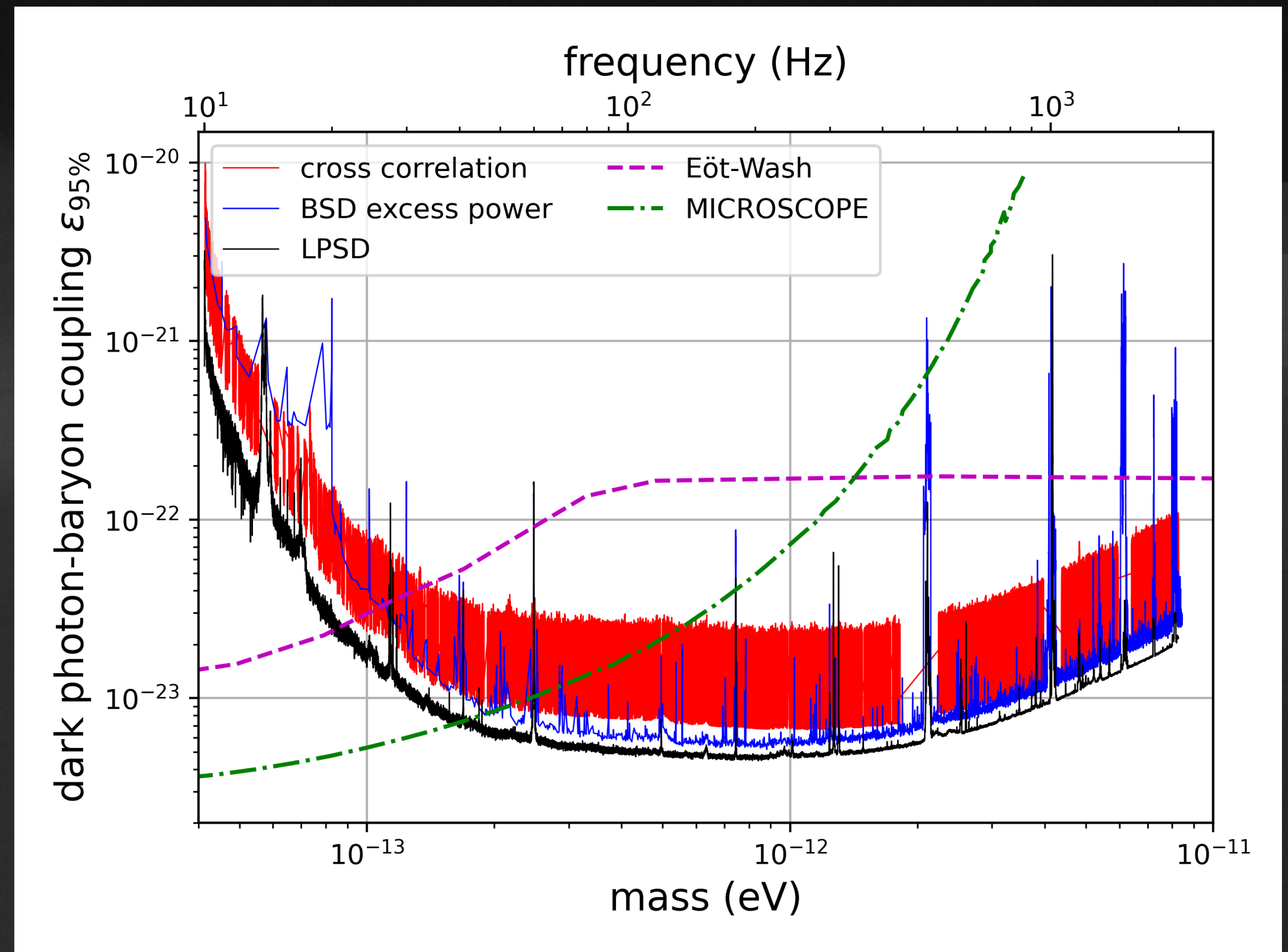
- Direct constraints on coupling constant of scalars to standard model particles
- One order of magnitude improvement over constraints from previous observing runs





# Constraints on vectors

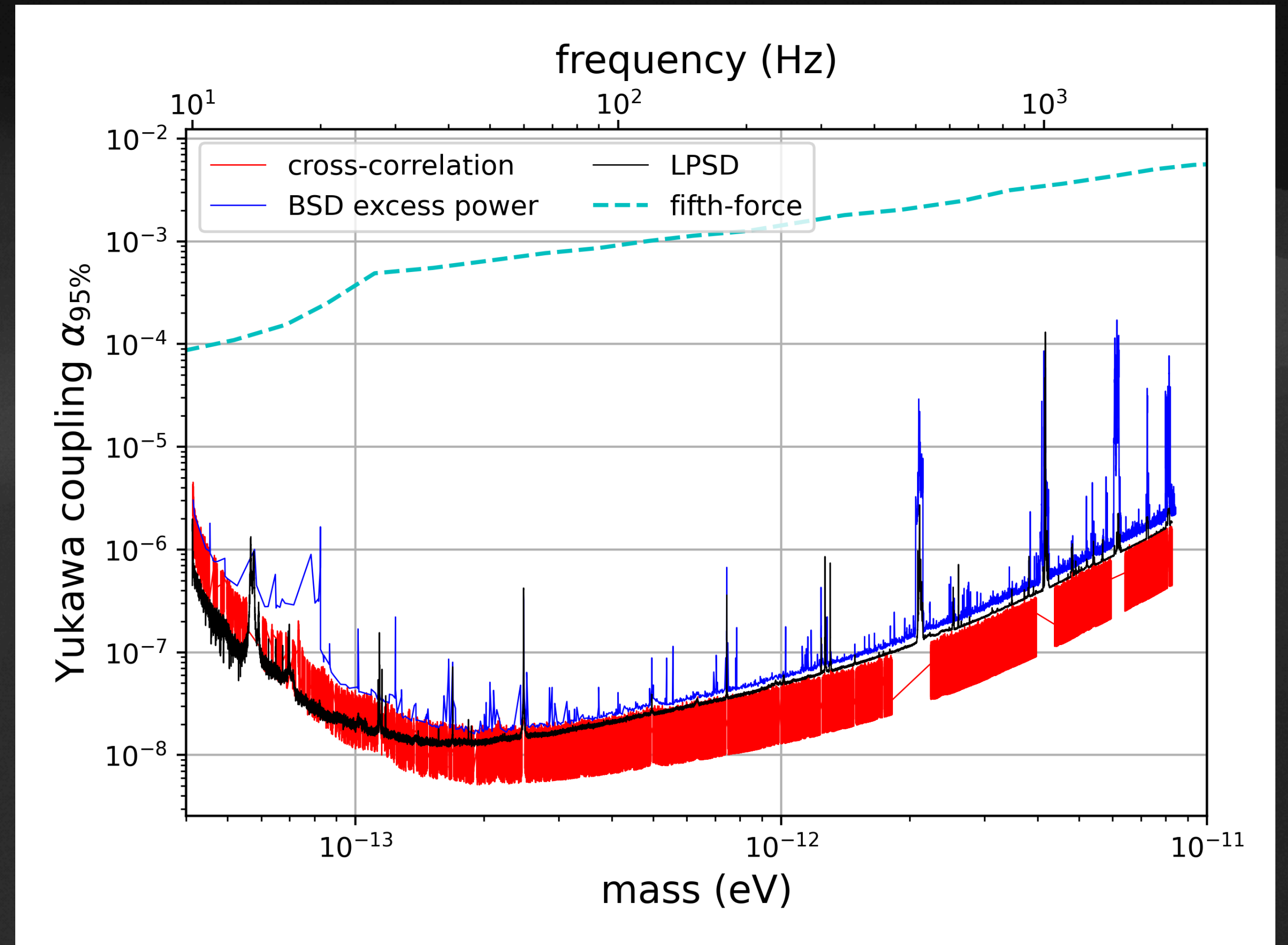
- Here, two effects contribute: spatial and temporal strains
- Cross correlation method is less sensitive to the finite light travel time effect  $\rightarrow$  weaker than the other two methods
- Our limits beat existing ones by  $\sim 1$  order of magnitude





# Constraints on tensors

- Five orders of magnitude better than existing results
- First GW interferometer constraints on tensor bosons





# Prospects

- GW detectors will keep getting better and better —> will drive the limits down. **They can be used as multi-model DM searches — step towards model-independent searches**
- But can we really distinguish amongst which kinds of DM interact with GW detectors?
  - Can we distinguish them from a noise line with finite coherence time?
- Different types of GW IFOs enable probes of different ultralight DM masses coupling to standard-model (SM) particles, but no ‘multi-band’
- Can we design instruments that can maintain GW sensitivity but drastically improve sensitivity to DM/SM coupling?
- Planetary and asteroid-mass PBH binaries can be probed with continuous gravitational waves!!



# Conclusions

- Gravitational wave interferometers can be sensitive to ultralight dark matter coupling to standard model ones
- We have provided best upper limits to-date on 3 dark-matter models
- Any kind of dark-matter model could be constrained if it causes quasi-sinusoidal oscillations of interferometer components



# Acknowledgements

- This material is in part based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation

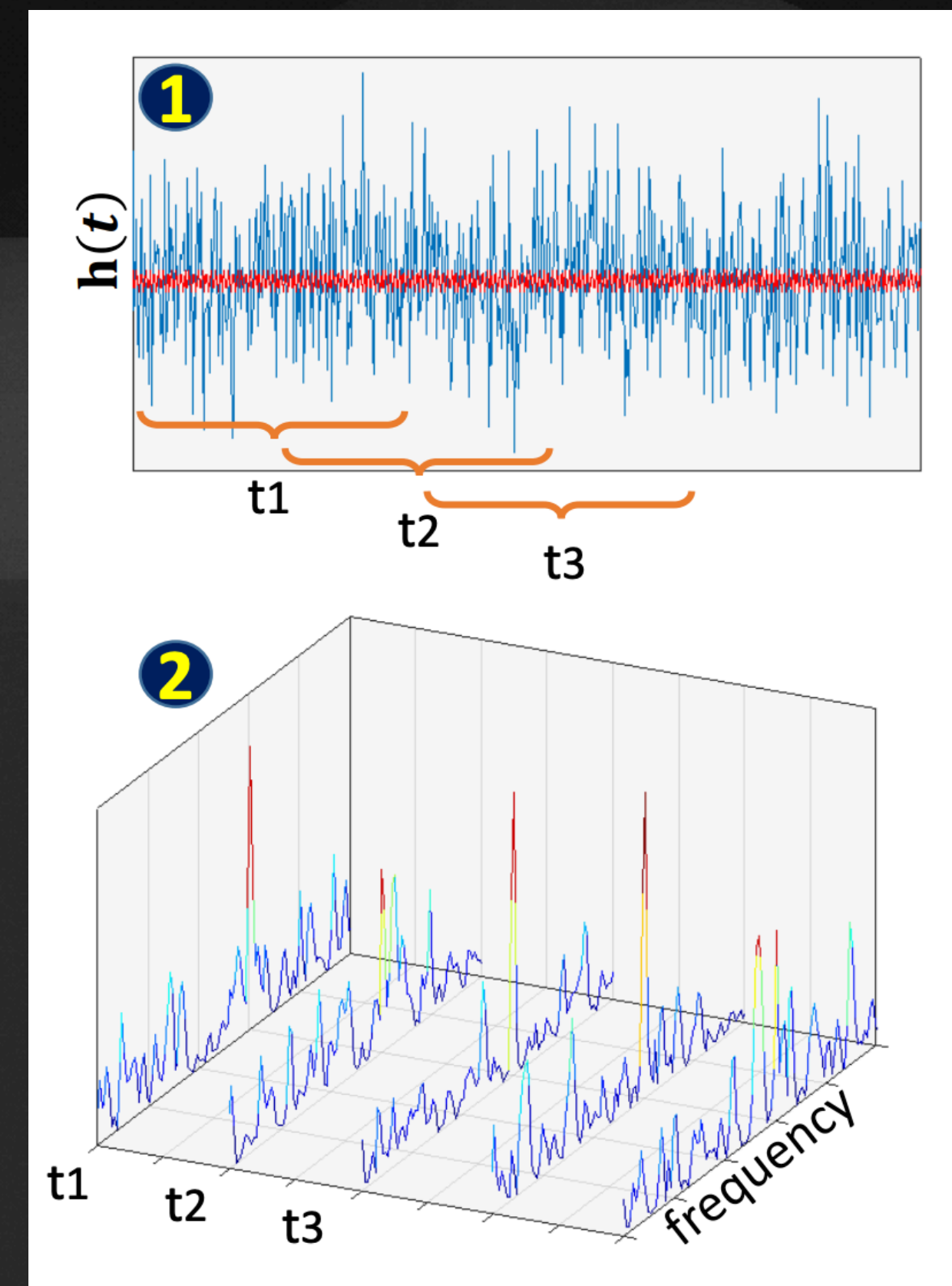


# Back-up slides



# 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



# True differential motion from dark photon field

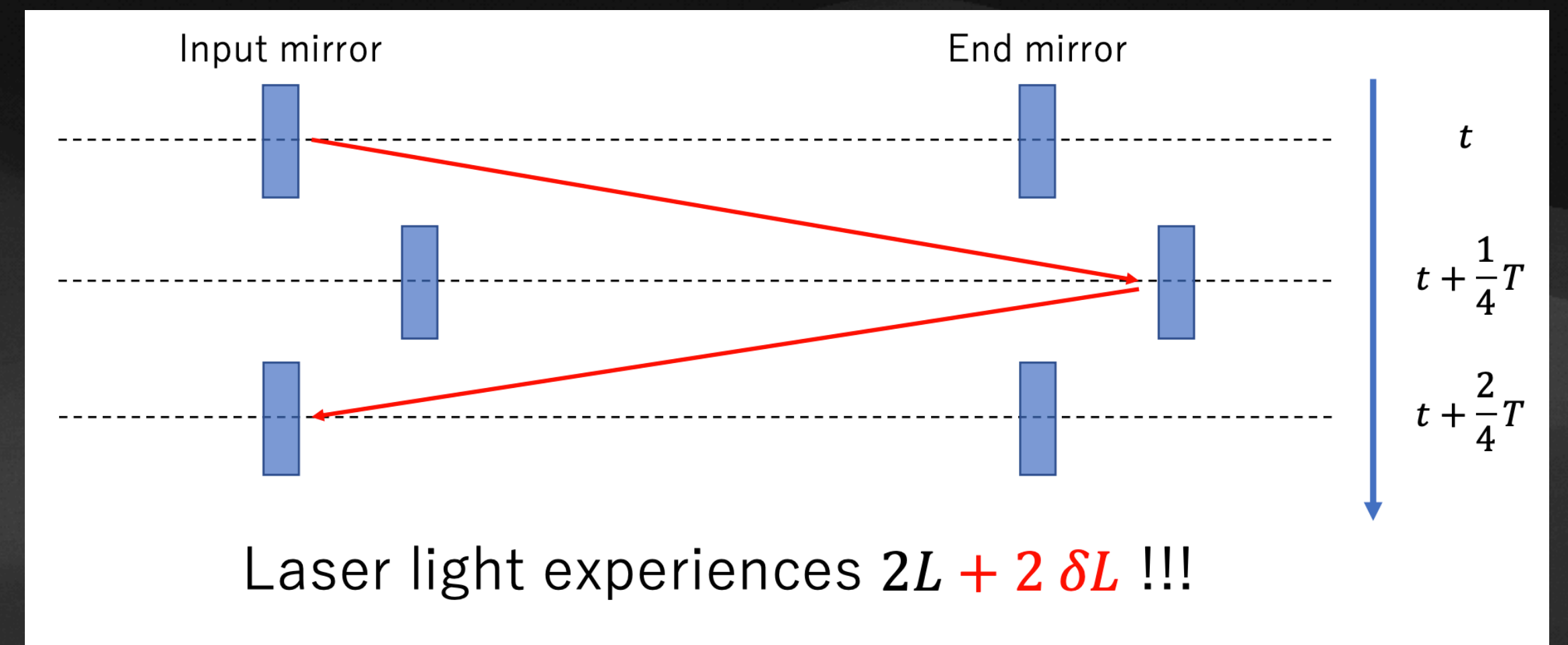
- Differential strain results because each mirror is in a different place relative to the incoming dark photon field: this is a *spatial* effect
- Depends on the frequency, the coupling strength, the dark matter density and velocity

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



# 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



$$\sqrt{\langle h_C^2 \rangle} = \frac{\sqrt{3}}{2} \sqrt{\langle h_D^2 \rangle} \frac{2\pi f_0 L}{v_0},$$

$$\simeq 6.58 \times 10^{-26} \left( \frac{\epsilon}{10^{-23}} \right)$$



# 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  $\gg$  detector separation
- Frequency lags computed to estimate background

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

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

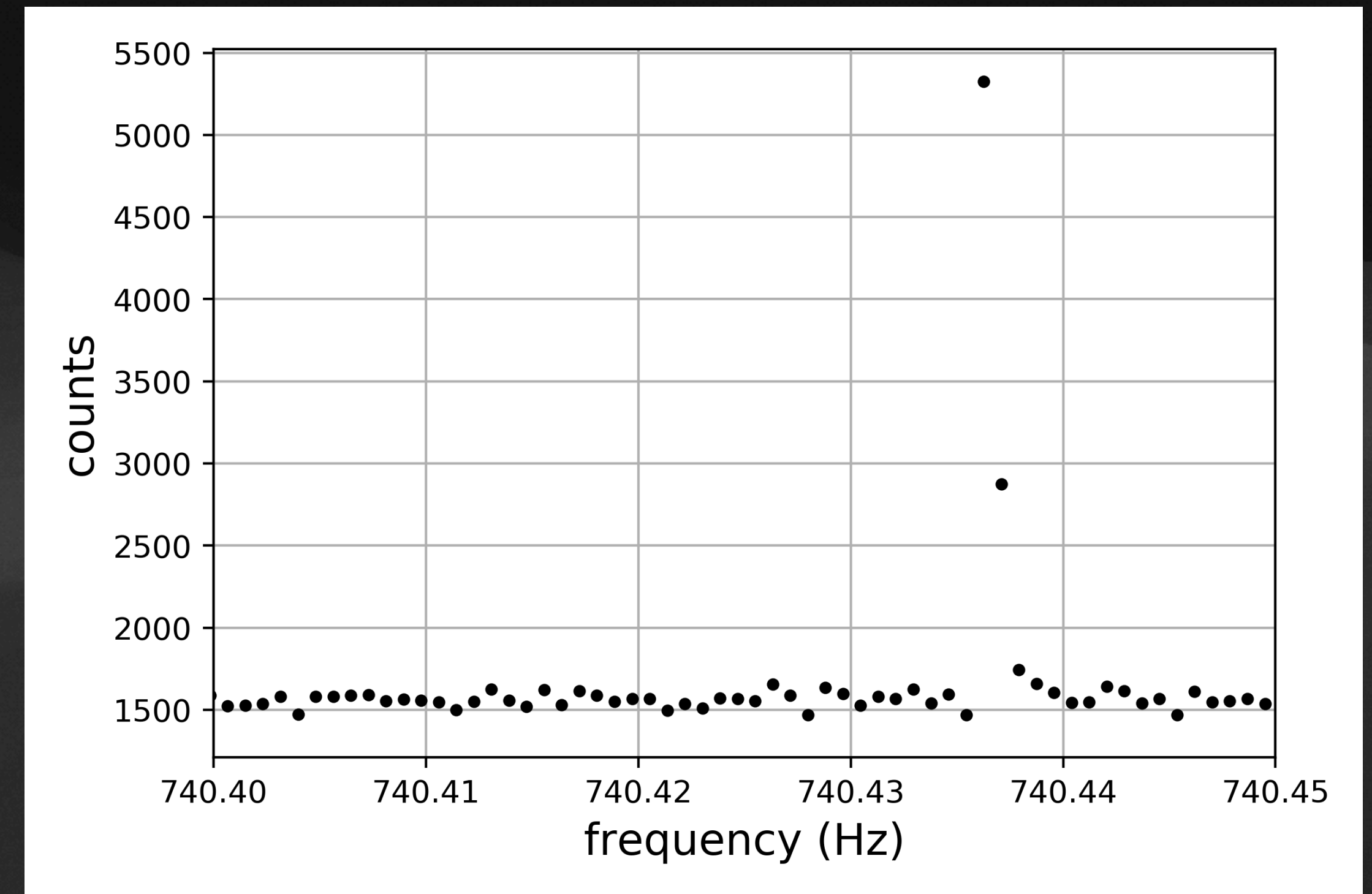
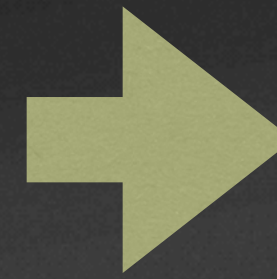
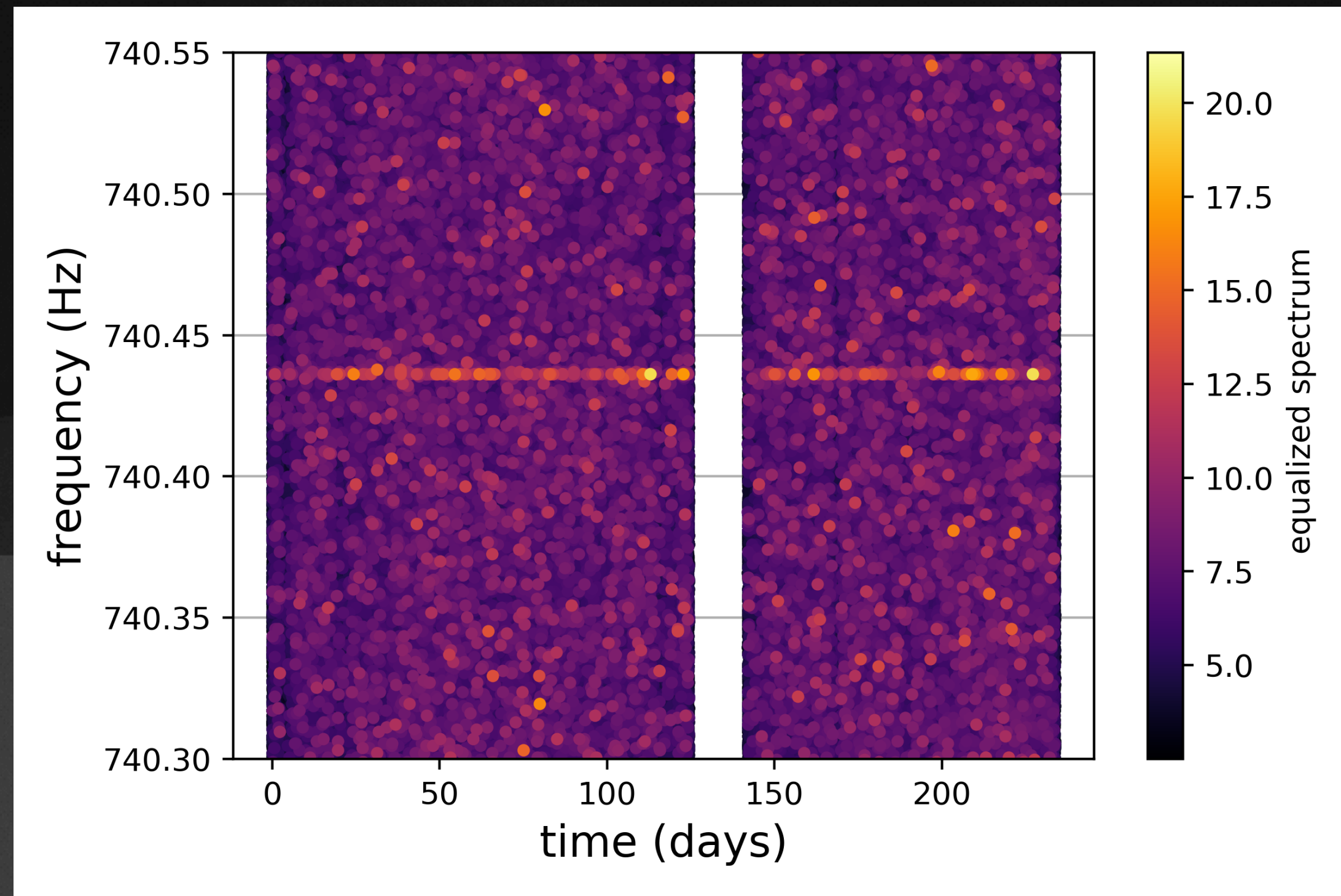
$$\text{SNR}_j = \frac{S_j}{\sigma_j}$$

Pierce et al. (2018), PRL 121, 061102

Guo et al. (2019) Nat. Communications Physics 2.1, 155



# Projection of 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



# LPSD

- Logarithmically-spaced frequencies: Adjust Fourier length in every bin
- Adapted method from computer-music to avoid crippling costs
- Drawback: need long stretches of coincident data,  $\gtrsim 10^5$  s