# Shedding light on dark matter with gravitational waves: searches in the first part of the fourth observing run of LIGO-Virgo-KAGRA

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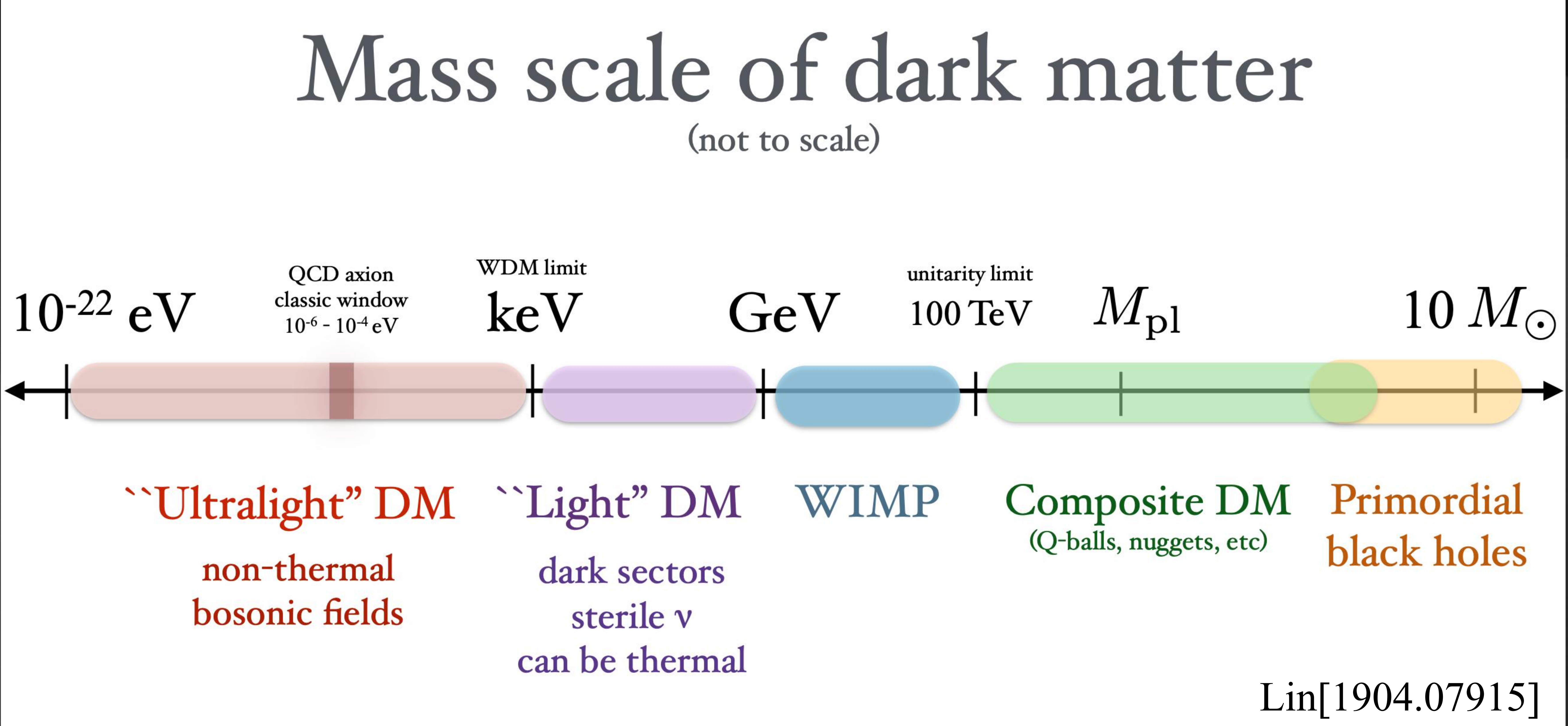
# Outline

- Background
- Ultralight dark matter searches
- Light primordial black hole searches
- Conclusions

# Background

# Dark Matter Candidates

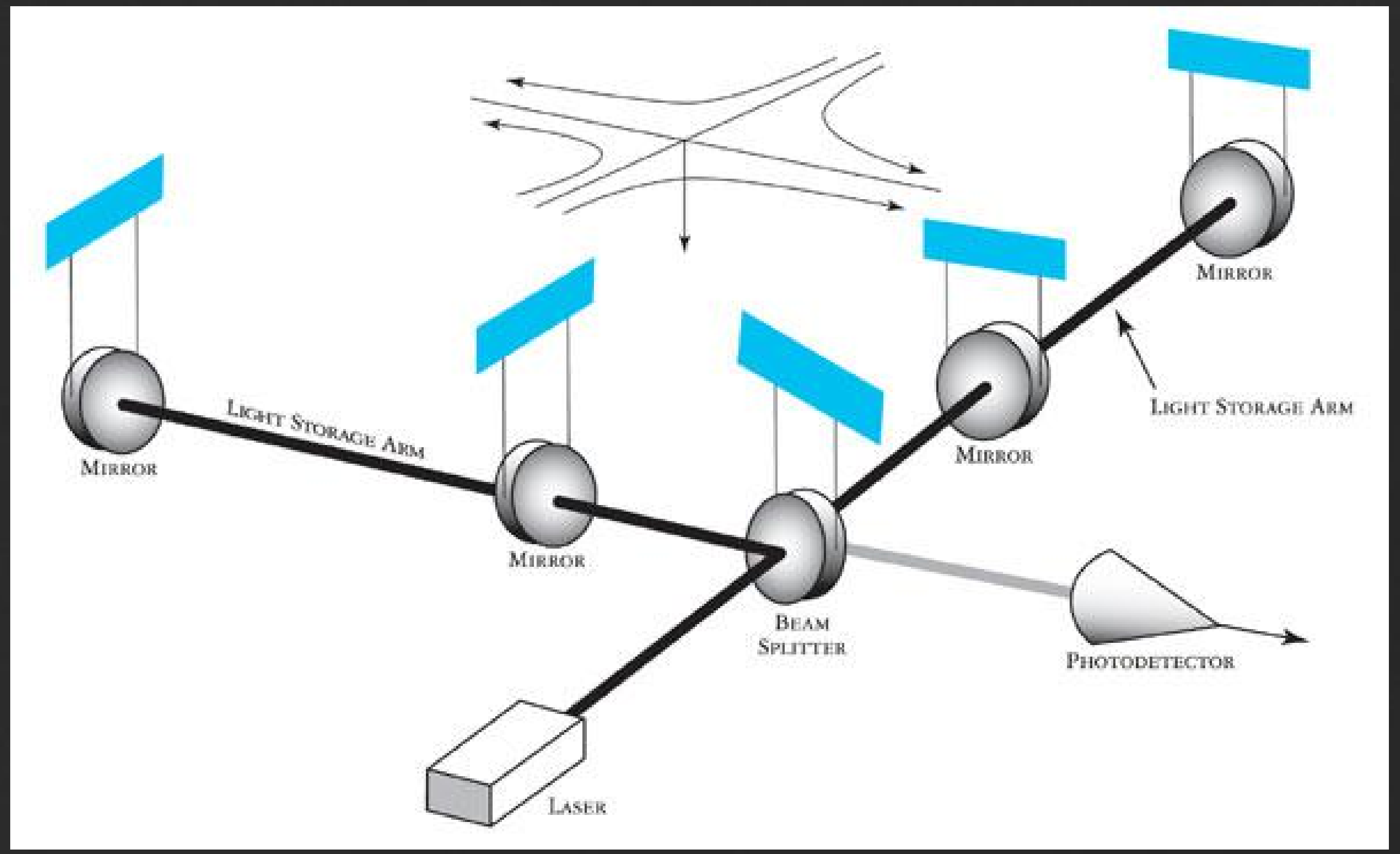



All can be detected with GW: Miller[2503.02607], Bertone et al SciPost[1907.10610]

# Ground-based GW Detectors

O4a: 2023-05-24 to 2024-01-16

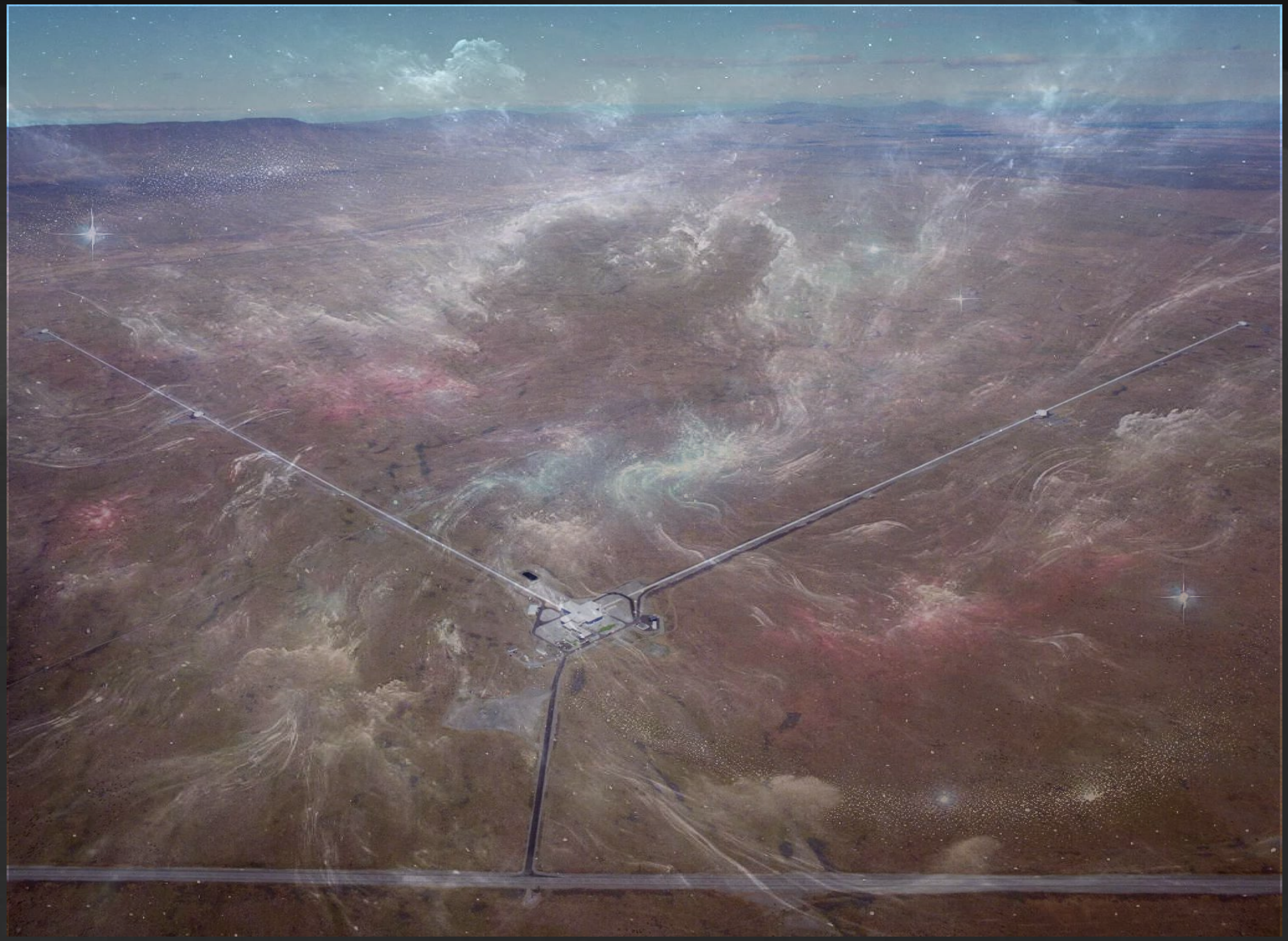
- LIGO, Virgo and KAGRA are km-long size interferometers designed to measure the displacement of test masses (mirrors) in the audio band (10-2000) Hz
- These are precision instruments that measure a *strain* $h \sim \Delta L/L$
  - Detection principle: anything that causes a change in length of the interferometer 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 —> DM mass range $[10^{-14}, 10^{-12}]$ eV/$c^2$
- Different DM particles interact with different standard-model ones, leading to similar but distinguishable signals

LIGO Hanford in a dark-matter "ether"



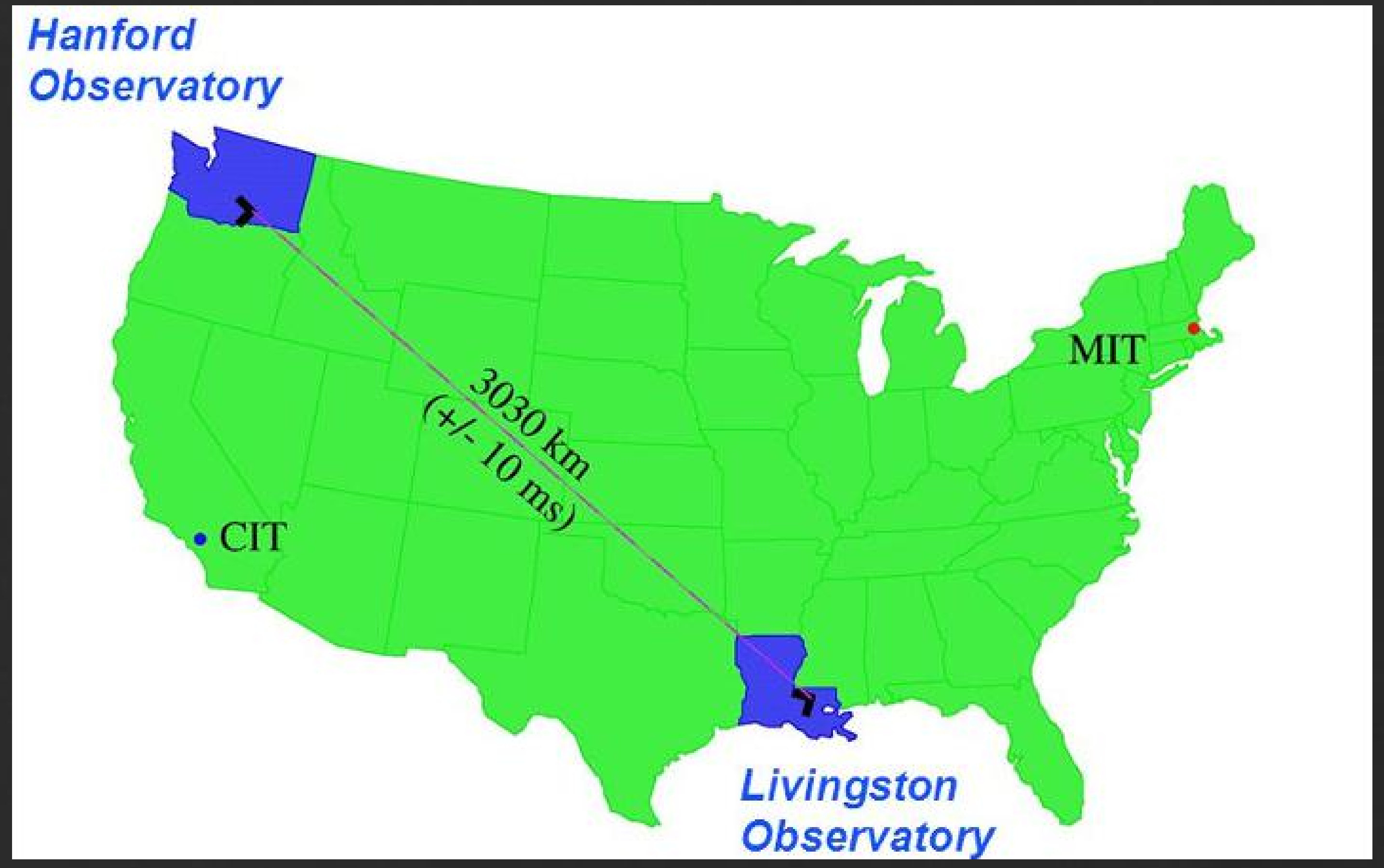
# Ultralight dark matter

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

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

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

$$L_{\text{coh}} \sim 10^9 m$$




Pierce et al. 2018, PRL 121, 061102

# Types of ultralight dark matter

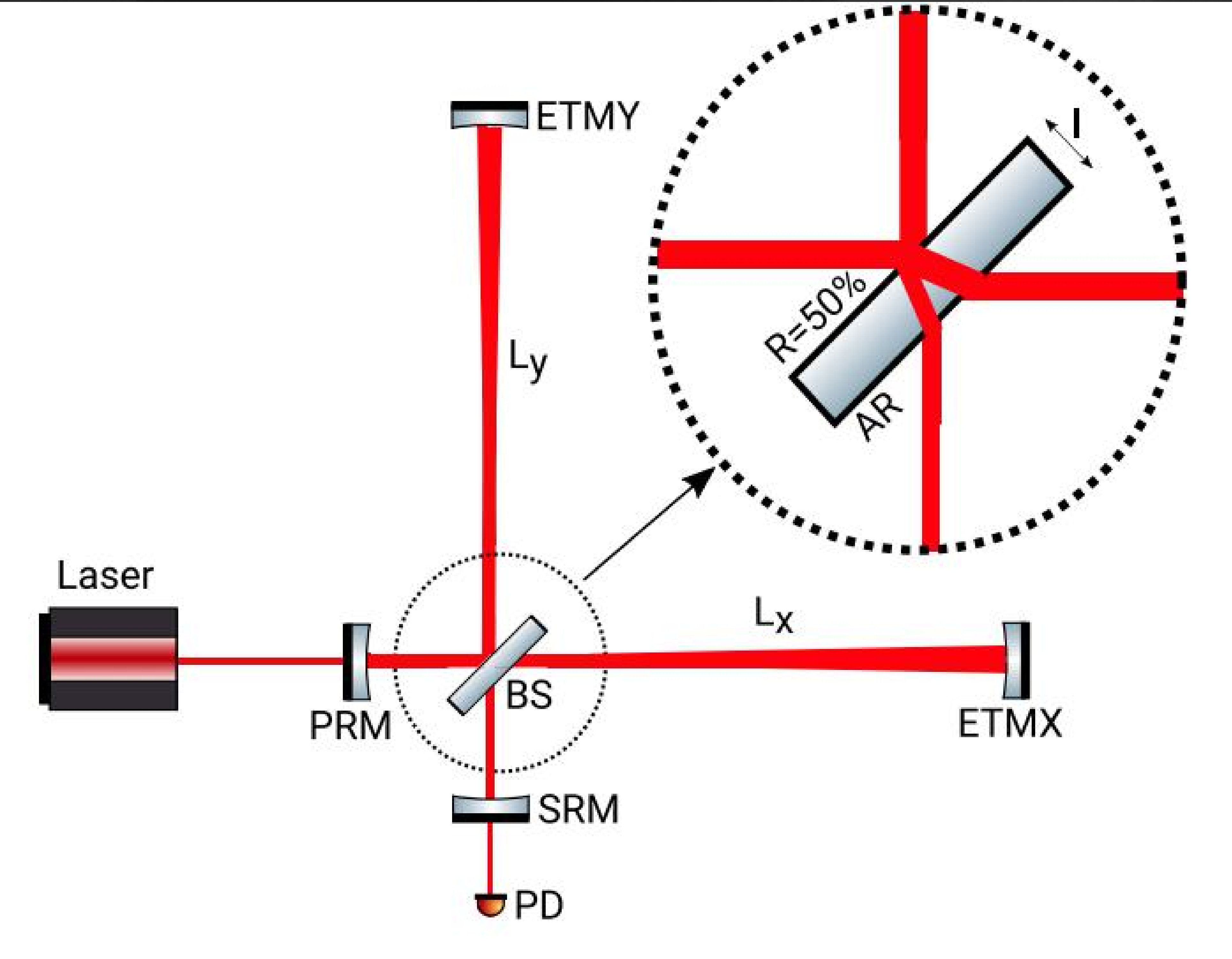
- Scalar dark matter (spin 0): Expand/Contract mirrors
- Dark photon dark matter (spin 1): Accelerate mirrors
- Tensor dark matter (spin 2): Modify gravity

Slide inspired by Goettel, A.

# Scalar dark matter

- Couples with strengths $\Lambda_\gamma$,$\Lambda_e$ 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

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




Vermeulen et al, Nature[2103.03783]



Slide inspired by Goettel, A.

# Vector bosons: dark photons

$m_A$ : dark photon mass
$\varepsilon_D$ : coupling strength
$A_\mu$ : dark vector potential

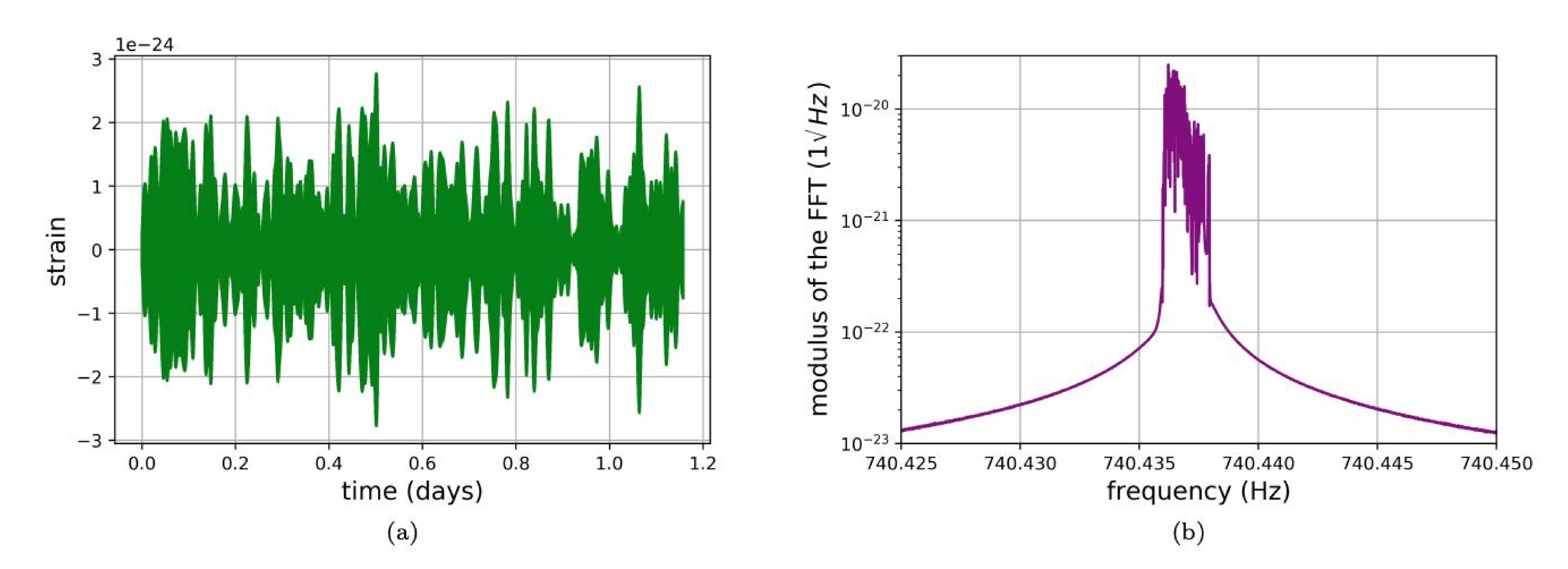
$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_A^2 A^\mu A_\mu - \epsilon_D e J_D^\mu A_\mu,$$

- 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

Pierce et al. 2018, PRL 121, 061102

# 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




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

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

# Methods

# 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

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

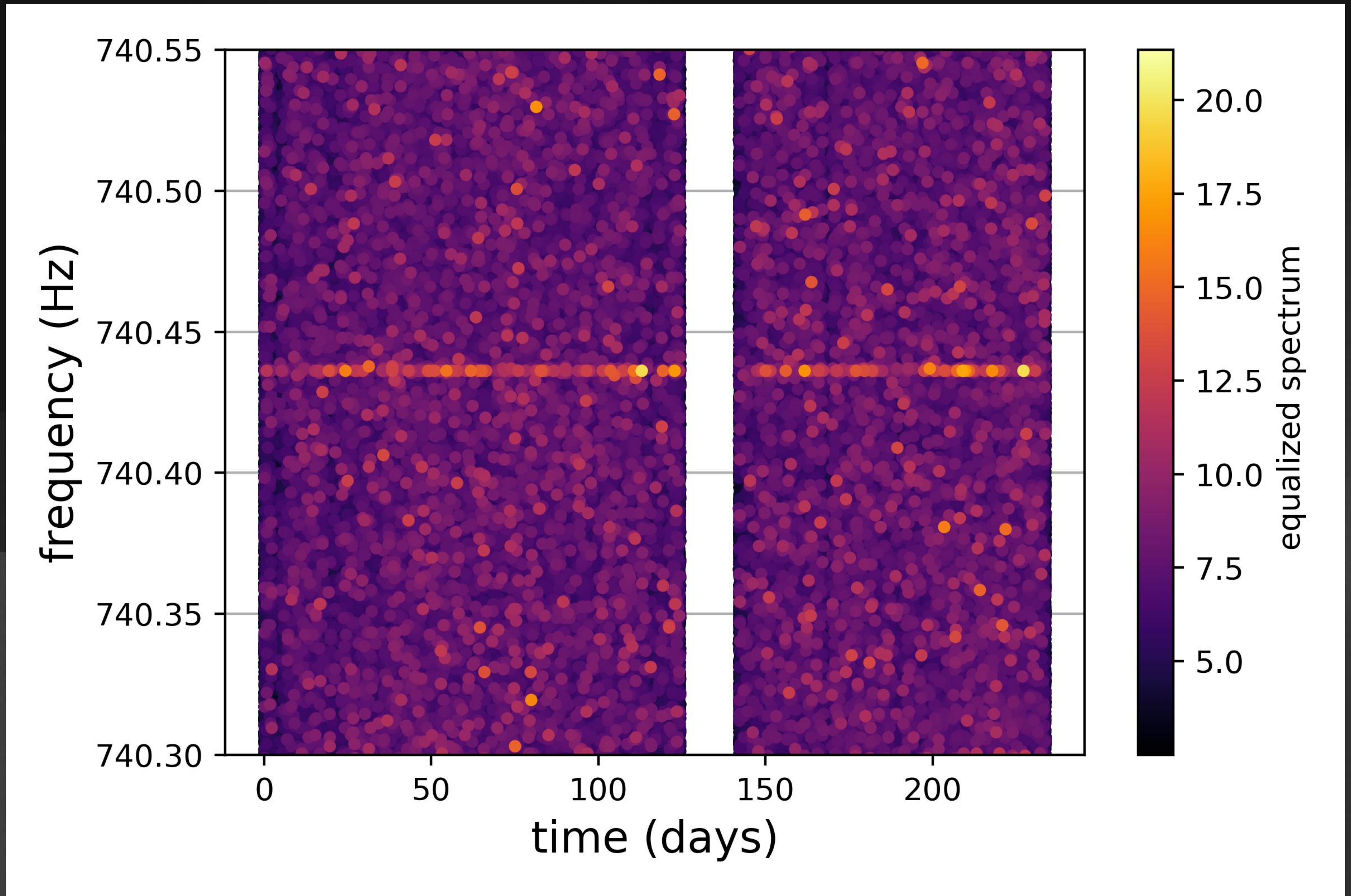
$$\sigma_j^2 = \frac{1}{N_{\mathrm{FFT}}} \left\langle \frac{1}{2 P_{1,ij} P_{2,ij}} \right\rangle_{N_{\mathrm{FFT}}}$$

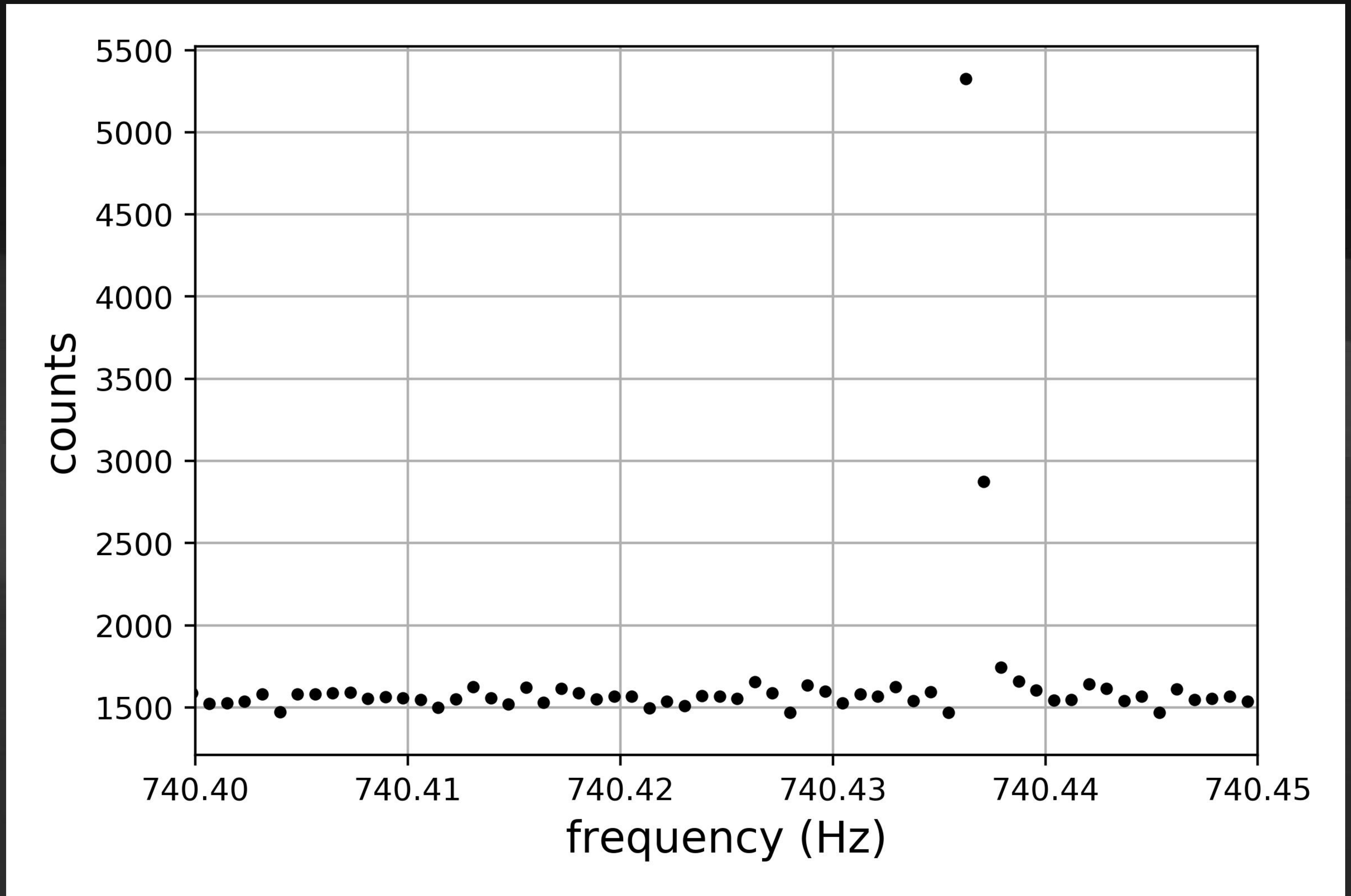
$$\mathrm{SNR}_j = \frac{S_j}{\sigma_j}$$

Pierce et al. (2018), PRL 121, 061102
Guo et al. (2019) Nat. Communications Physics 2.1, 155

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

# 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

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

# 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

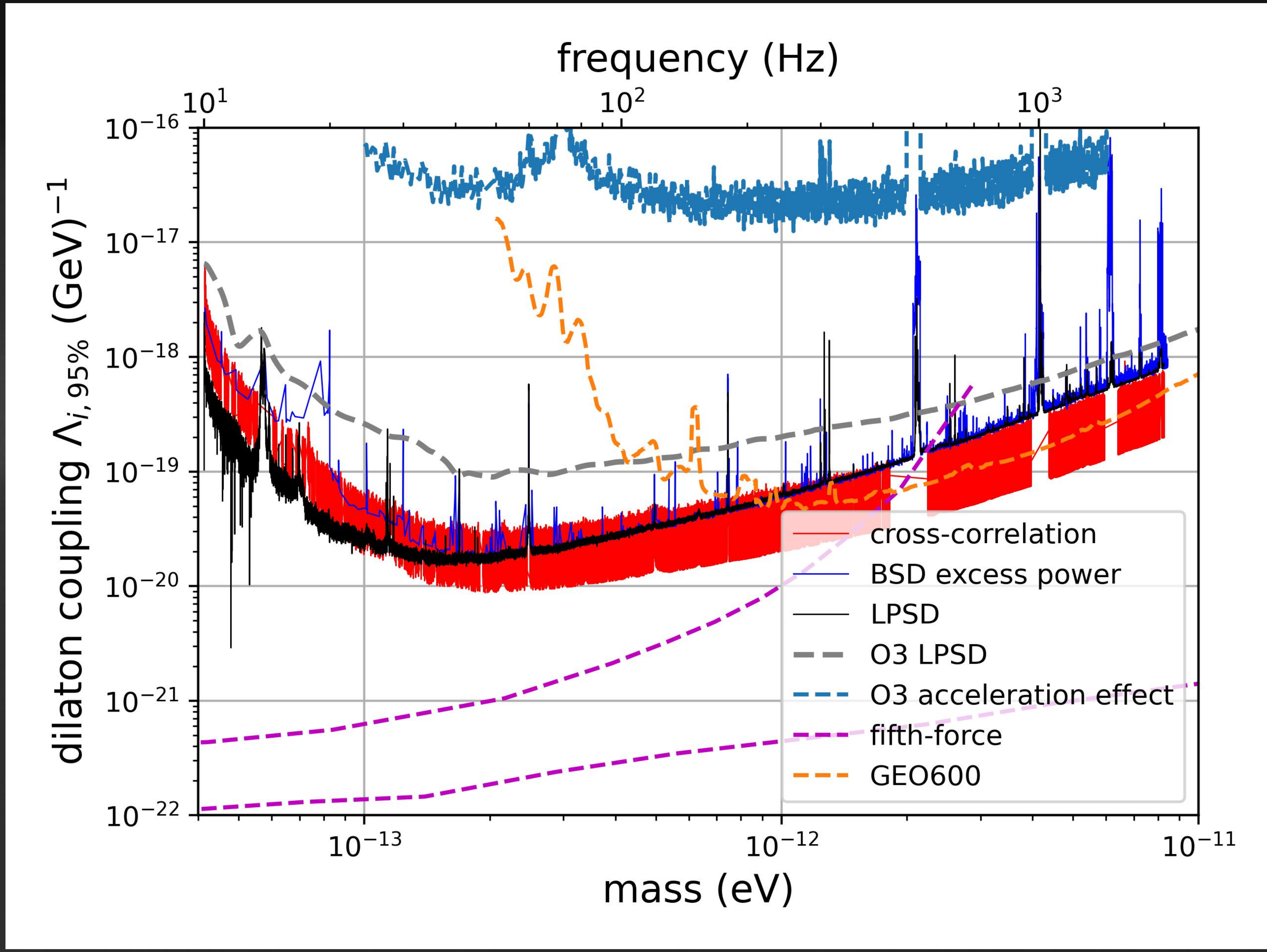
Gottel et al. (2024): PRL. 133, 10, 101001

Gottel and Raymond (2025): arXiv:2503.03293

# Results

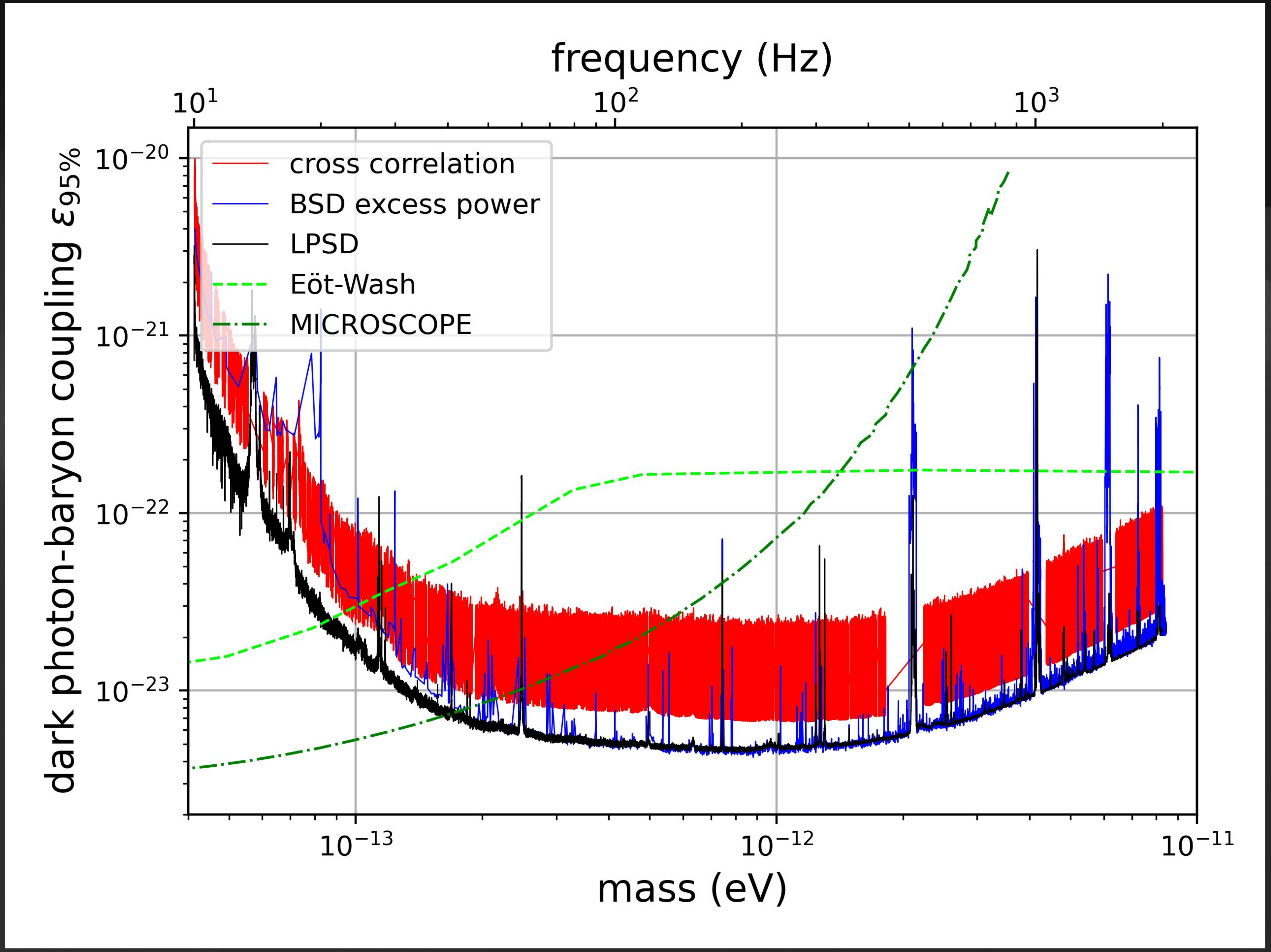
# Constraints on scalars

- Direct constraints on coupling constant of scalars to standard model particles
- One order of magnitude improvement over constraints w.r.t O3 and GEO results



# Constraints on vectors

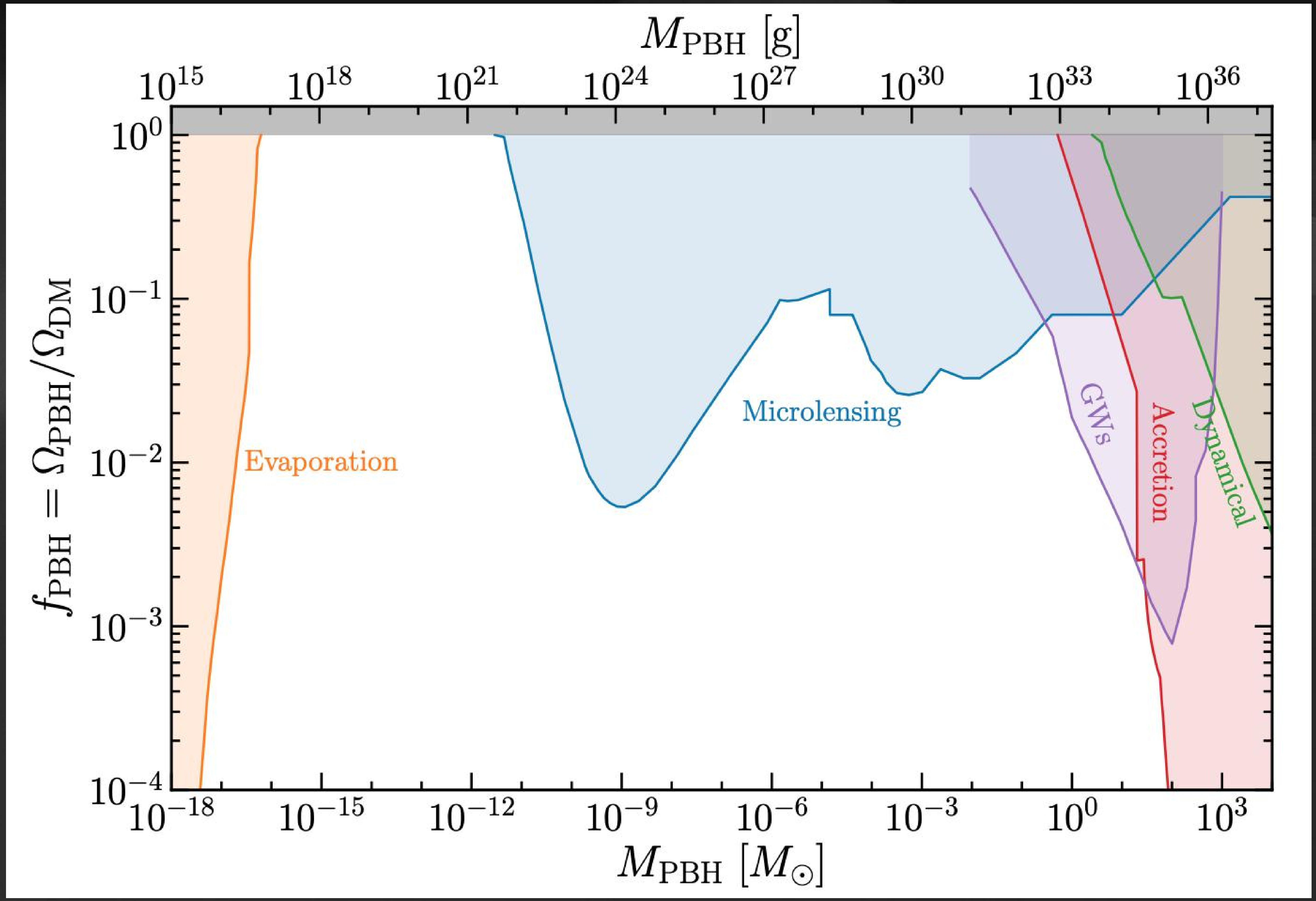
- Here, two effects contribute: spatial and temporal strains
- Cross correlation method is less sensitive to the finite light travel time effect —> weaker than the other two methods
- Our limits beat existing ones by ~1 order of magnitude



# Light PBH Searches (O3a)

# Primordial Black Holes

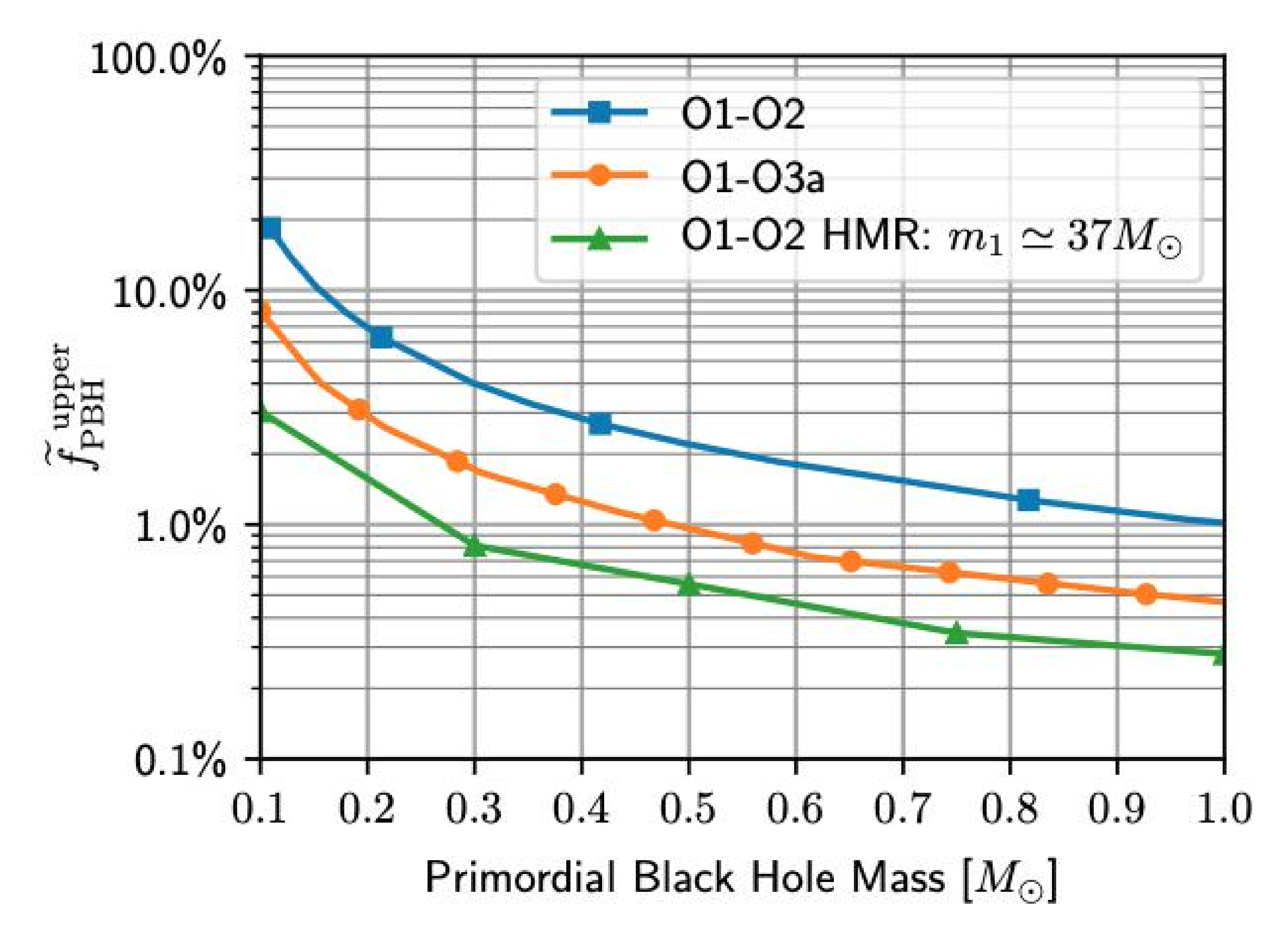
- Low spins of LIGO/Virgo black holes, and merging rate inferences have revived interest in PBHs
- BHs that formed in the early universe can take on a wide range of masses
- Possible links to dark matter




Green and Kavanagh. Journal of Physics G: Nuclear and Particle Physics 48.4 (2021): 043001.

# Motivation

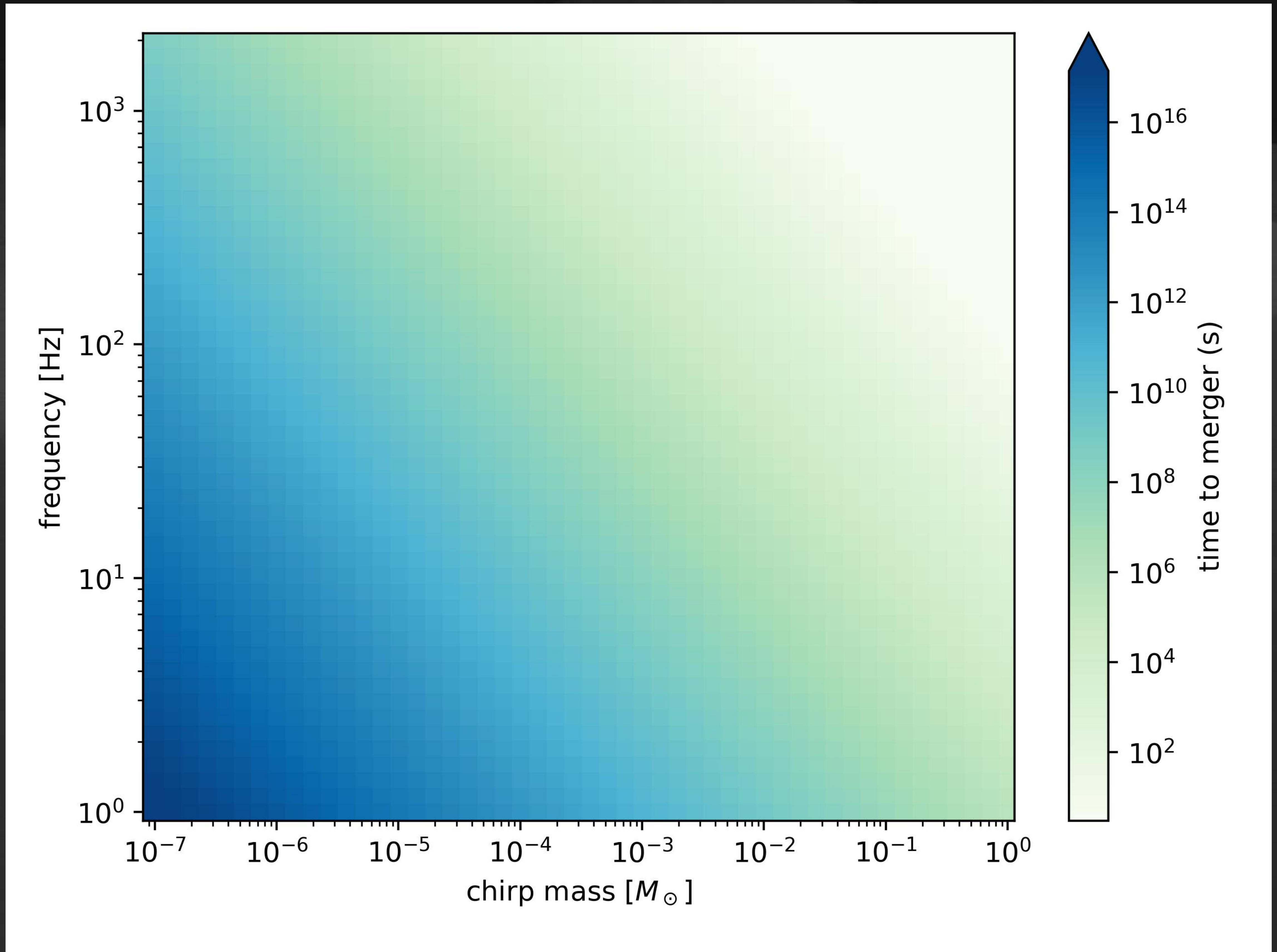
- Many GW efforts to detect PBHs focus on “sub-solar mass” regime, O(0.1 $M_\odot$)
- However, GWs from PBHs with masses [$10^{-7}$ - $10^{-3}$]$M_\odot$ have not been searched for
- Matched filtering in this mass range is extremely computationally challenging
- Signals for binaries in this mass range resemble continuous waves




Nitz & Wang: Phys.Rev.Lett. 127 (2021) 15, 151101.
LVK: Phys.Rev.Lett. 129 (2022) 6, 061104
LVK: arXiv: 2212.01477

# GWs from inspiraling PBHs

- ~[$10^{-7}$ - $10^{-3}$] $M_\odot$ give rise to signals that are *long lasting*, compared to those detected from O($M_\odot$) black holes
- The GW frequency evolution of these binaries can be described as quasi-Newtonian circular orbits
- Techniques used in GW data analysis for quasi-monochromatic or power-law signals can also be applied to detect PBHs
- Matched filtering in this mass range is extremely computationally challenging




ALM et al. Phys.Dark Univ. 32 (2021) 100836

# "Transient" continuous waves

- Signal frequency evolution over time follows a power-law and lasts $\mathcal{O}(\mathbf{hours} - \mathbf{days})$
- Can describe gravitational waves from the inspiral portion of a light-enough binary system, or from a system far from coalesces

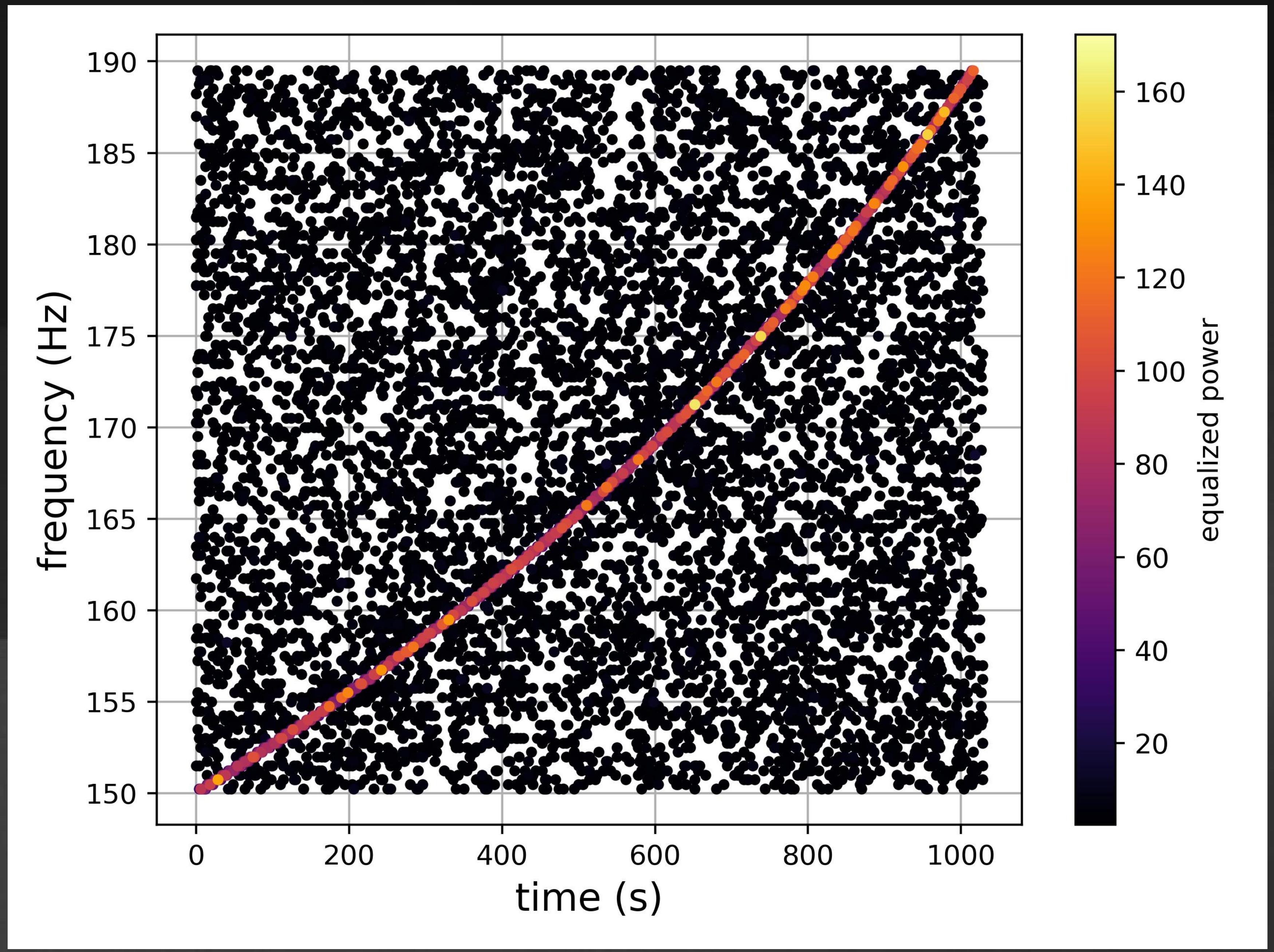
- Gravitational waves from quasi-Newtonian orbit

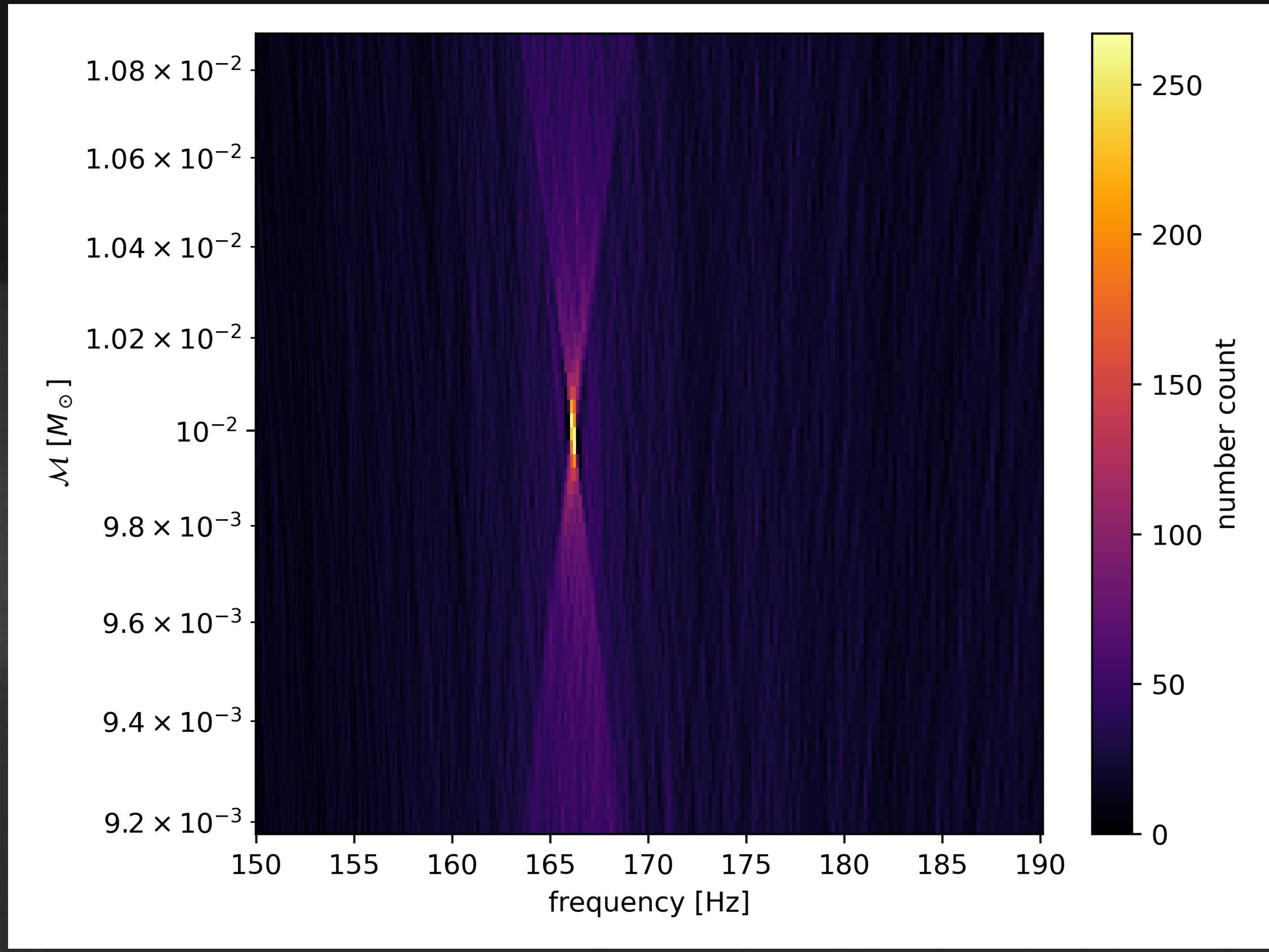
$$\dot{f} = \kappa f^n$$

$$\dot{f} = \frac{96}{5}\pi^{8/3}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3} f^{11/3}[1 + \ldots]$$

$\mathcal{M}$: chirp mass
$f$: frequency
$\dot{f}$: spin-up

# Generalized Frequency-Hough



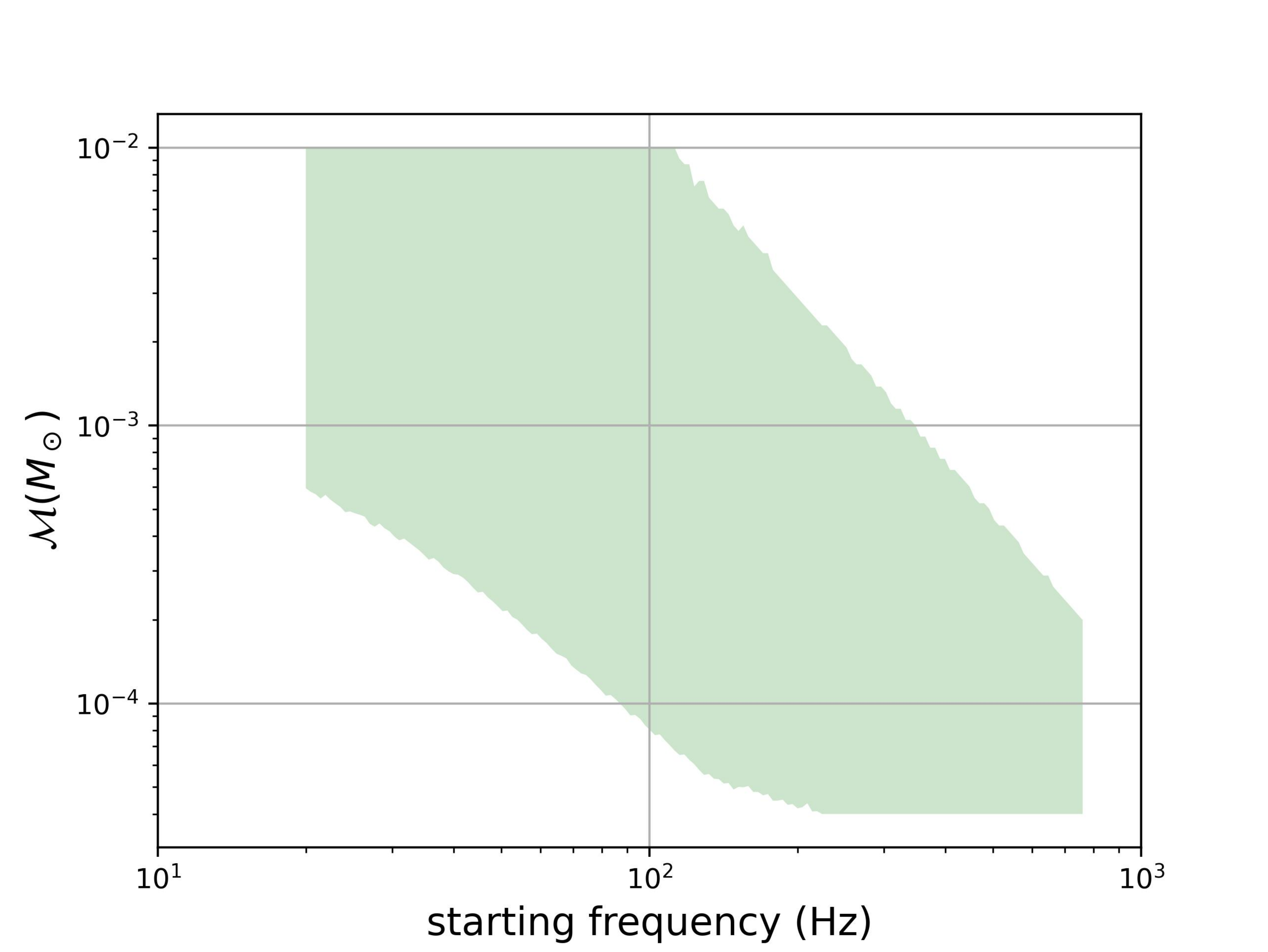




- Detect power-law signals that slowly "chirp" in time
- Input: points in time/frequency detector plane ; look for power-law tracks
- Output: two-dimensional histogram in the frequency/chirp mass plane of the source

Miller et al. Phys.Dark Univ. 32 (2021) 100836

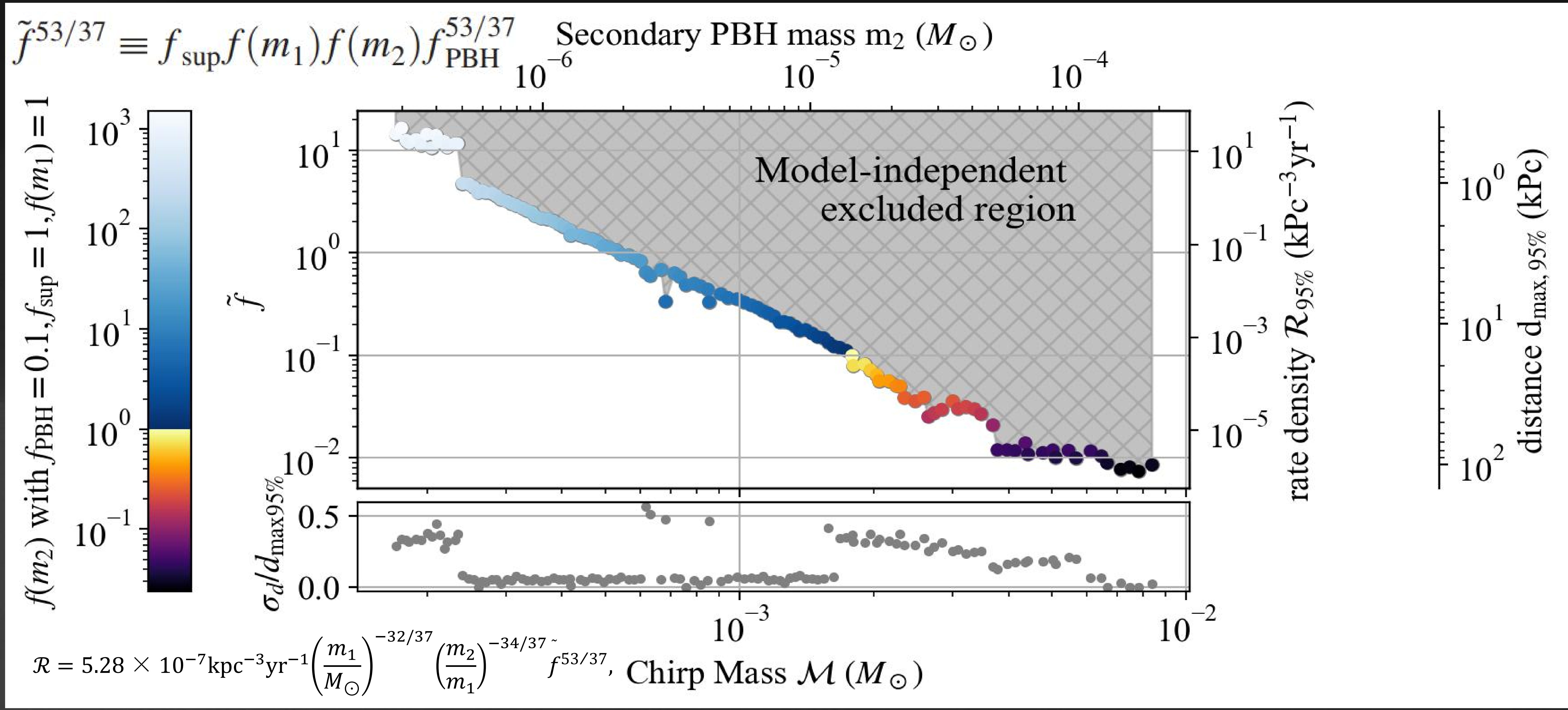
# Parameter Space

- Constructed by considering equal-mass systems with: $\mathcal{M} \in [4 \times 10^{-5}, 10^{-2}] M_{\odot}$; $T_{\mathrm{dur}} \in [1h,\ 7d]$
- Sensitive to asymmetric mass-ratio systems $q = m_2/m_1 \approx \eta \in [10^{-7}, 10^{-4}]$ for $m_1 \sim \mathcal{O}(M_{\odot})$ as long as: $|f_{0PN}(t) - f_{3.5PN}(t)| \leq \frac{1}{T_{\mathrm{FFT}}}$,
- We found ~300 candidates at $7\sigma$ but these were due to noise disturbances




ALM et al., PRL 133.11 (2024): 111401

# O3a constraints on asymmetric-mass ratio PBHs




- Merger rates enhanced for PBHs in asymmetric mass ratio binaries
- We can constrain $\tilde{f}$, or assuming $m_1 = 2.5M_\odot, f(m_1) \sim 1, f_{\rm sup} = 1$, we can put upper limit on $f(m_2)$



ALM et al., PRL 133.11 (2024): 111401

# Conclusions

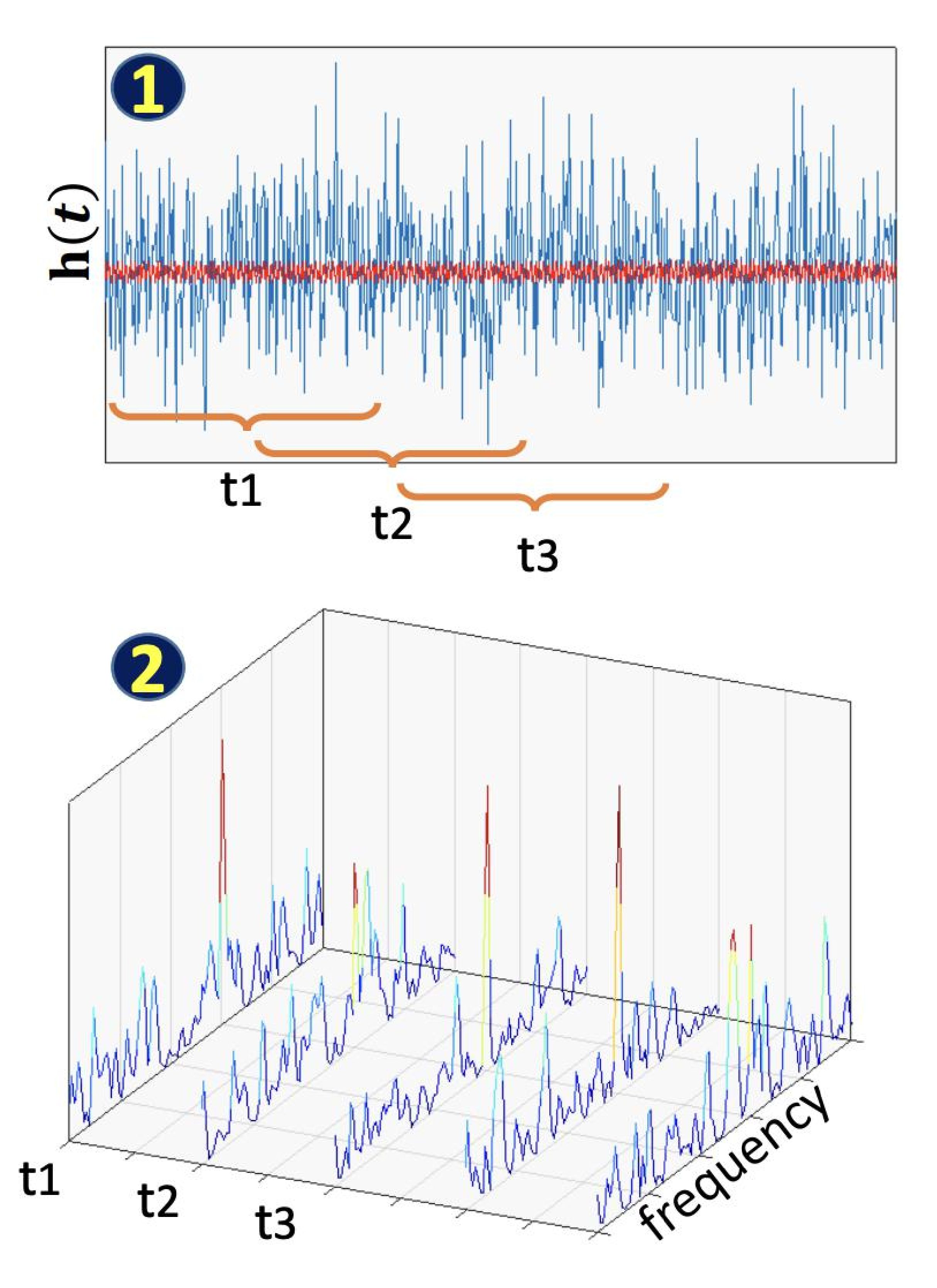
- Gravitational wave interferometers can be used to search for particle and macroscopic dark matter
- Improved search results for ultralight dark matter models
- Searches performed for very light primordial black holes
- Any kind of dark-matter model could be constrained if it causes quasi-sinusoidal 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 $T_{\mathbf{FFT}} \sim T_{\mathbf{coh}}$ and combine the power in each FFT without phase information




Credit: L. Pierini

# True differential motion from dark photon field

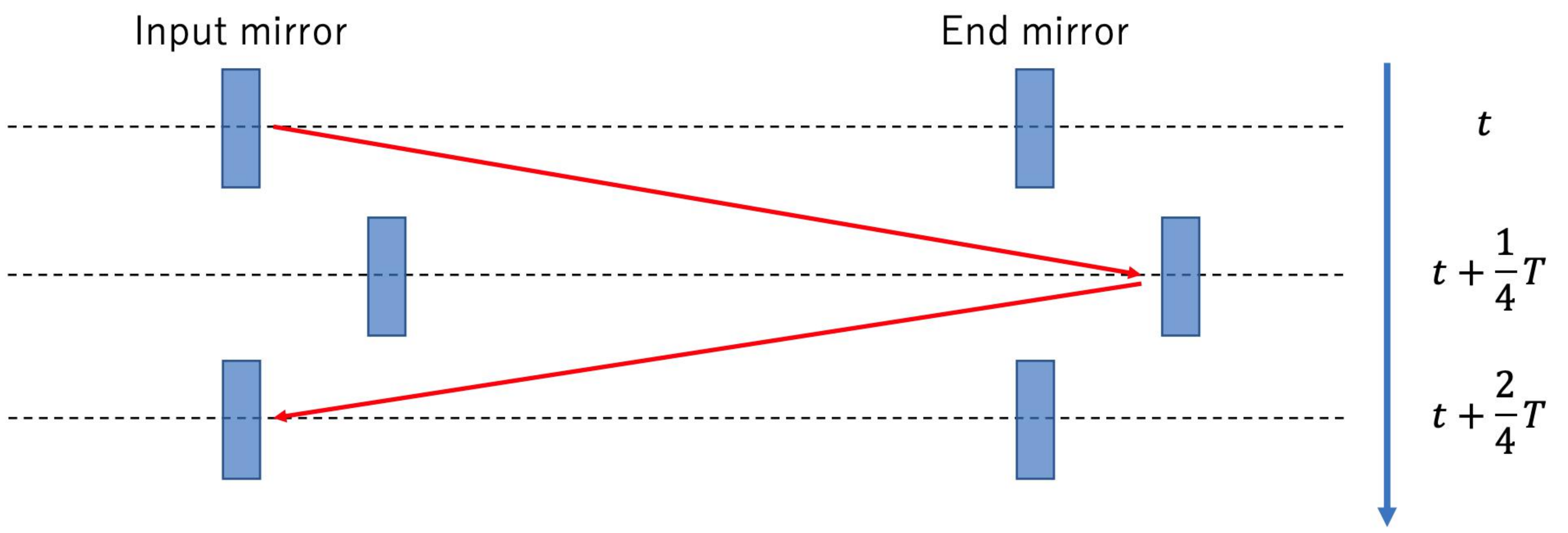
- Differential strain results because each mirror is in a different place relative to the incoming dark photon field: this is a *spatial* effect
- Depends on the frequency, the coupling strength, the dark matter density and velocity

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

Pierce et al. (2018), PRL 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), PRD 103, L051702

# 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: $h(t) = \frac{\alpha\sqrt{\rho_{\mathrm{DM}}}}{\sqrt{2}mM_p}\cos(mt + \phi_0)\Delta\epsilon$
- 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

Armaleo et al. (2021) JCAP 2021.04: 053