A Window into the Dark Sector with Gravitational Waves

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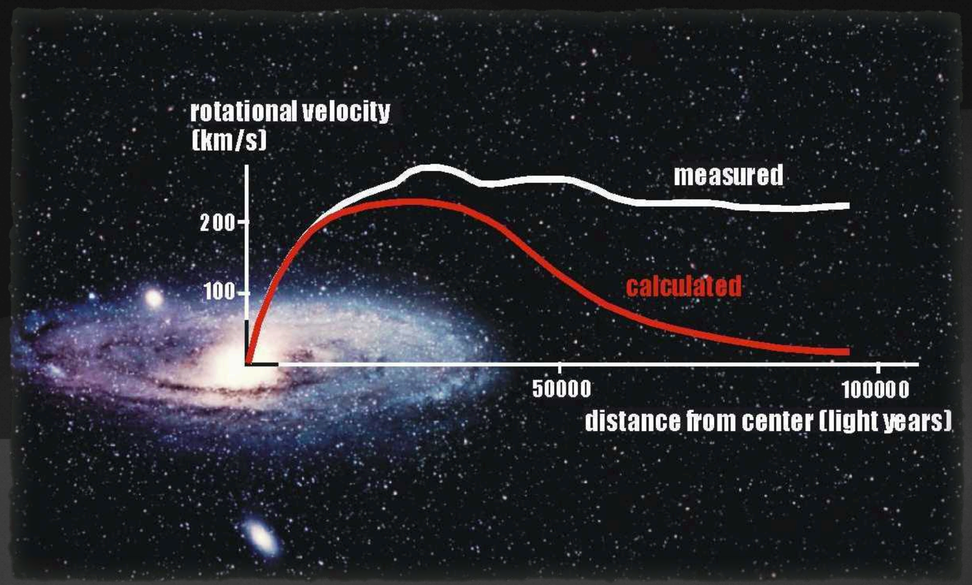


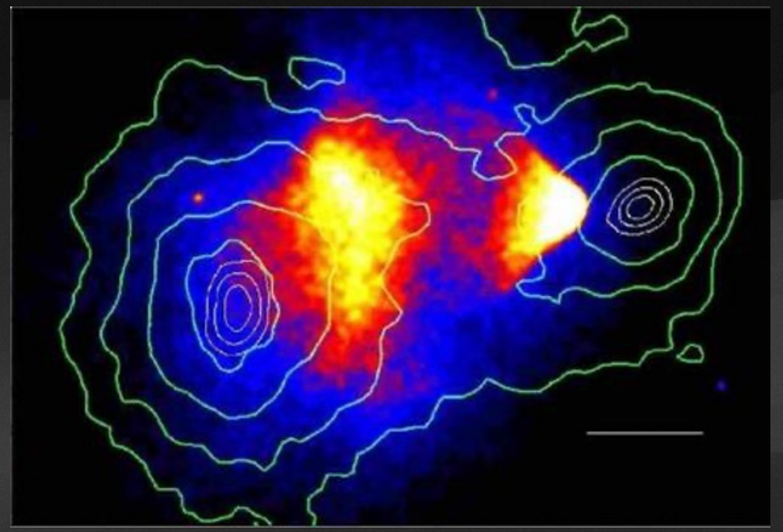
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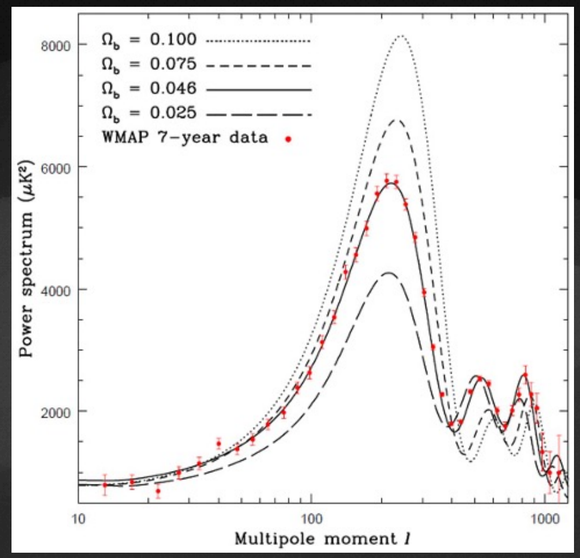
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Evidence for dark matter

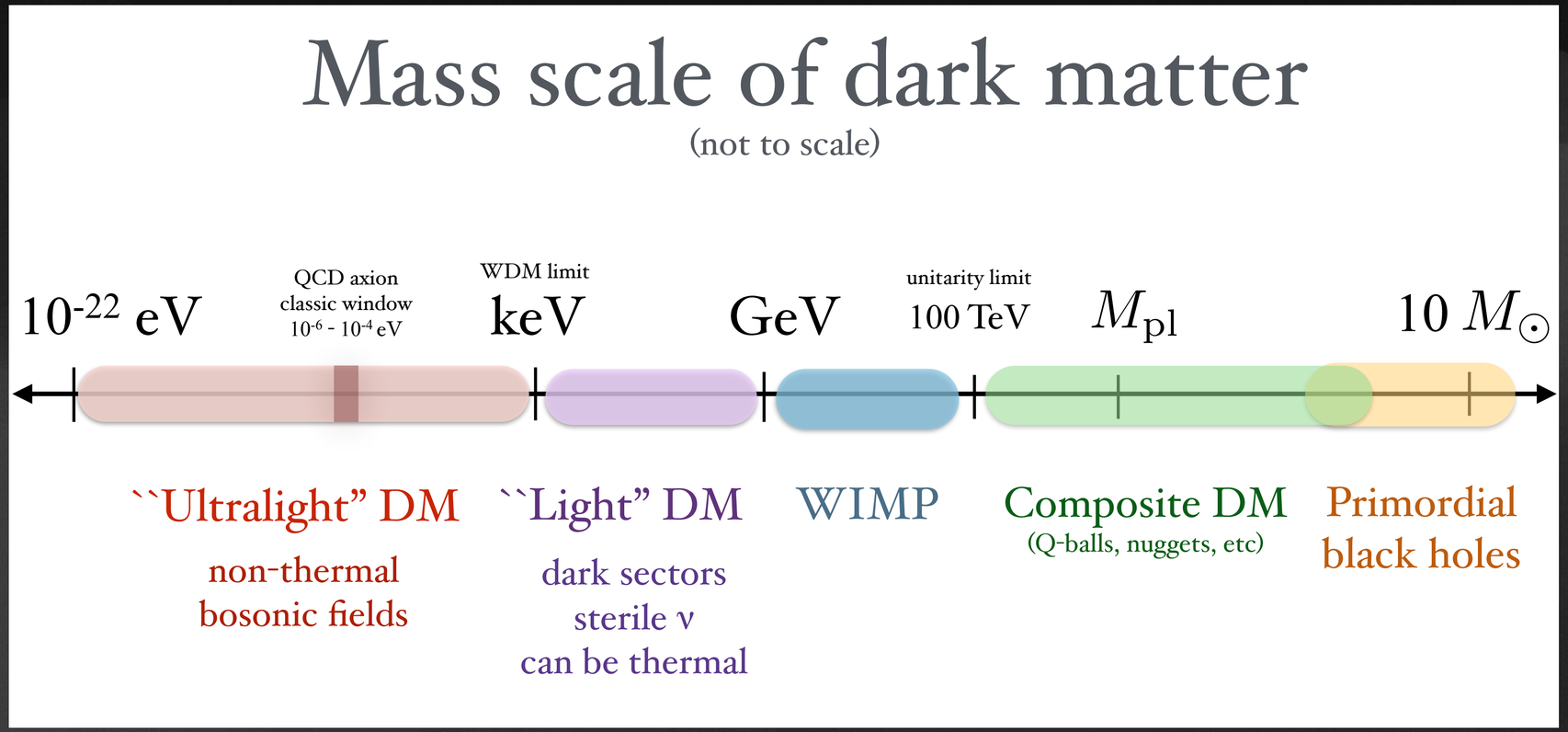






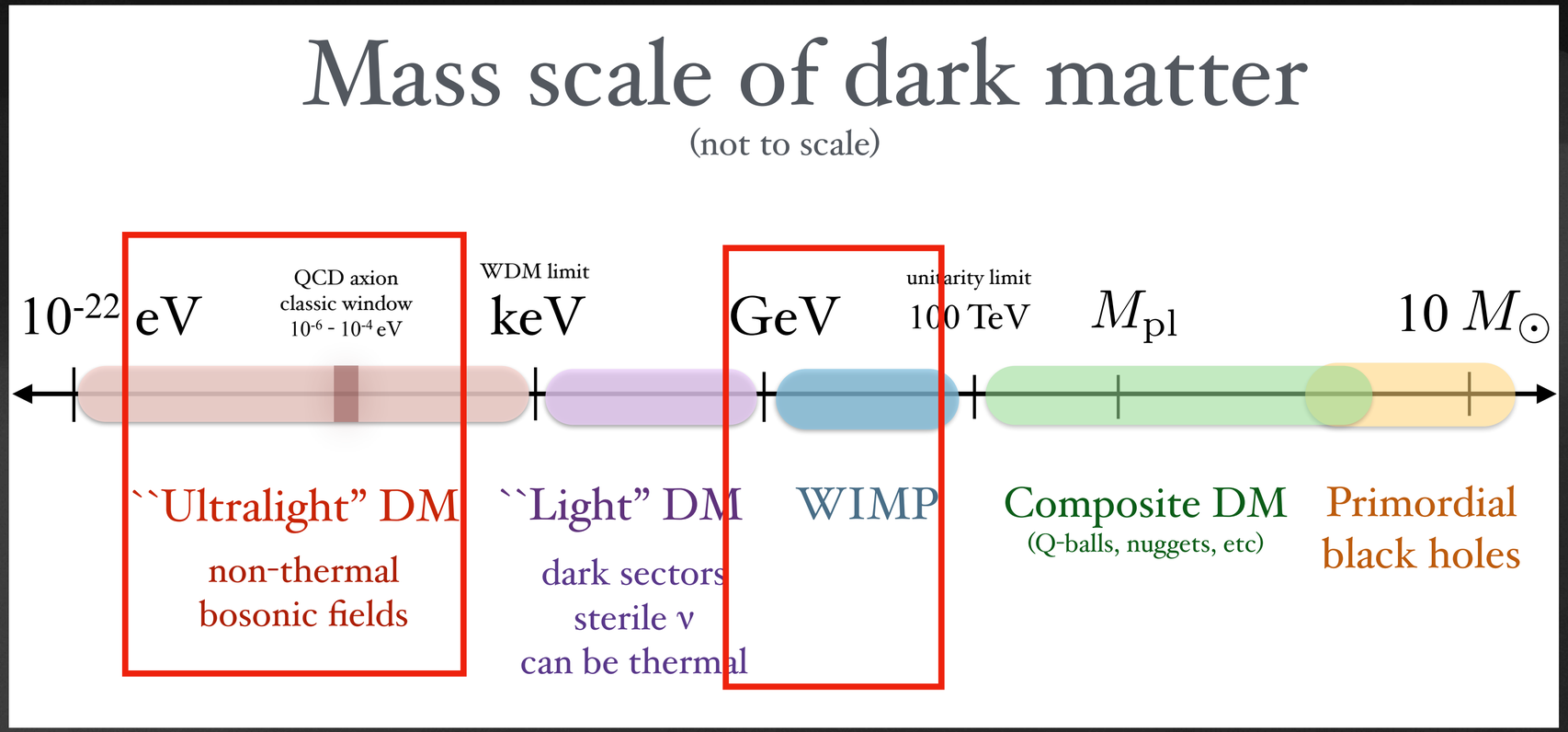
- Galaxy rotation curves: stars move too fast based on visible matter distribution
- Bullet cluster: dark matter gravitationally lenses light around it in this cluster
- CMB anisotropy power spectrum: dark matter needed to explain anisotropies

What could dark matter be?



- 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

What could dark matter be?



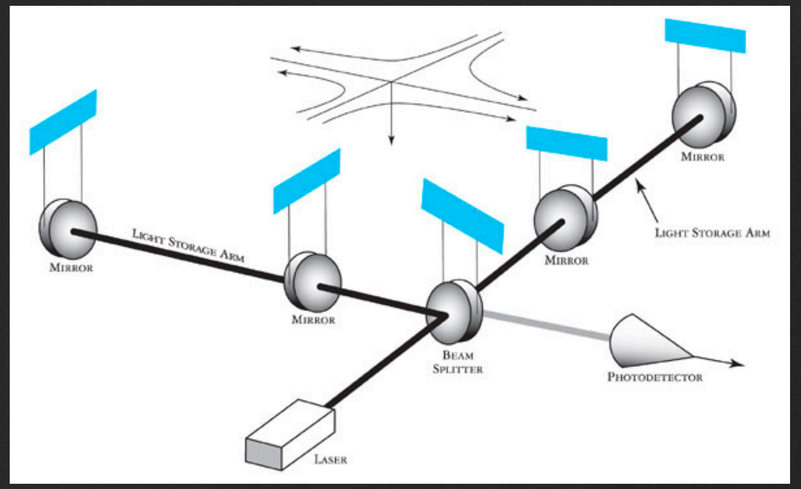
- Potential dark matter spans hundreds of orders of magnitude
- Many models, none are guaranteed to be right or wrong, and often, no *lower bounds* on coupling

Direct Ultralight Dark-Matter Detection

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 differential length change of the interferometer arms can be detected as a “signal”
- Can we use interferometers to detect dark matter?



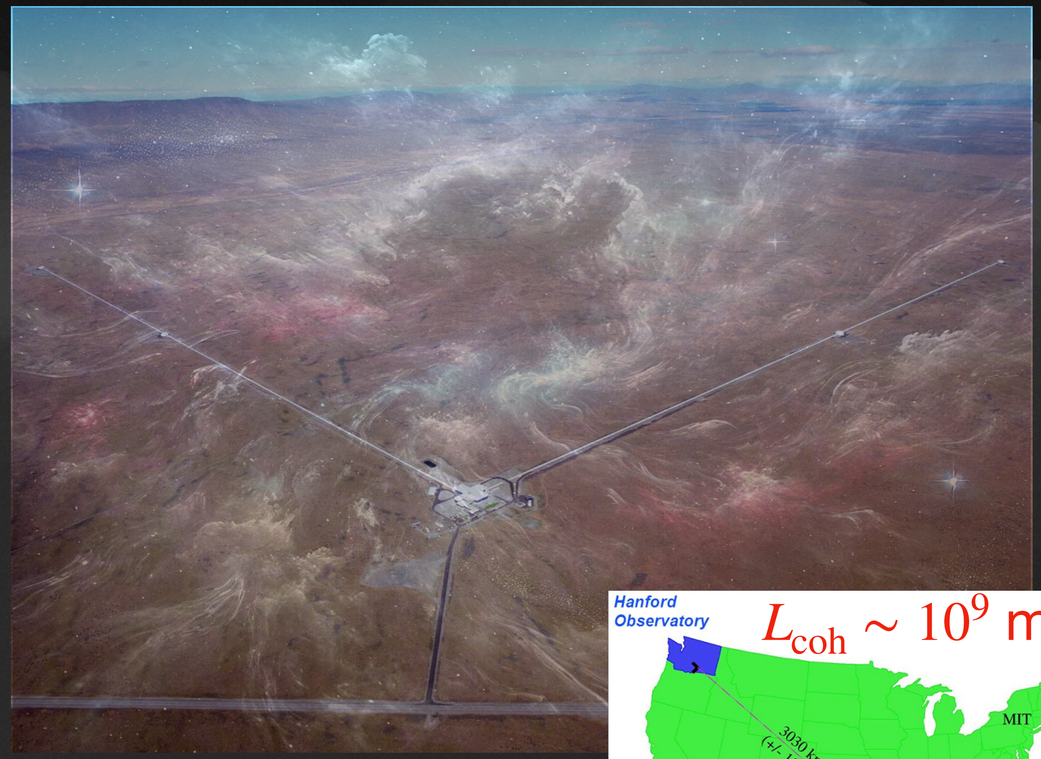


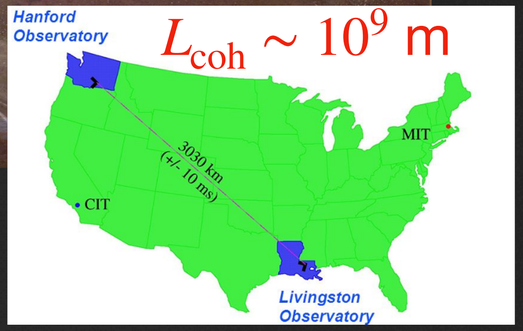
Ultralight dark matter

- The interferometers sit in a wind of DM
- LIGO is sensitive to signals at frequencies between [10,2000] Hz —> DM mass range $[10^{-14},10^{-12}]$ eV/c^2
- Different DM particles will interact with different standard-model ones, leading to similar but distinguishable signals
- DM induces stochastic frequency modulation $\Delta f/f \sim v_0^2/c^2 \sim 10^{-6}$ —> finite wave coherence time

$$T_{\rm coh} = \frac{4\pi\hbar}{m_A v_0^2} = 1.4\times10^4\ {\rm s}\left(\frac{10^{-12}\ {\rm eV}/c^2}{m_A}\right)$$

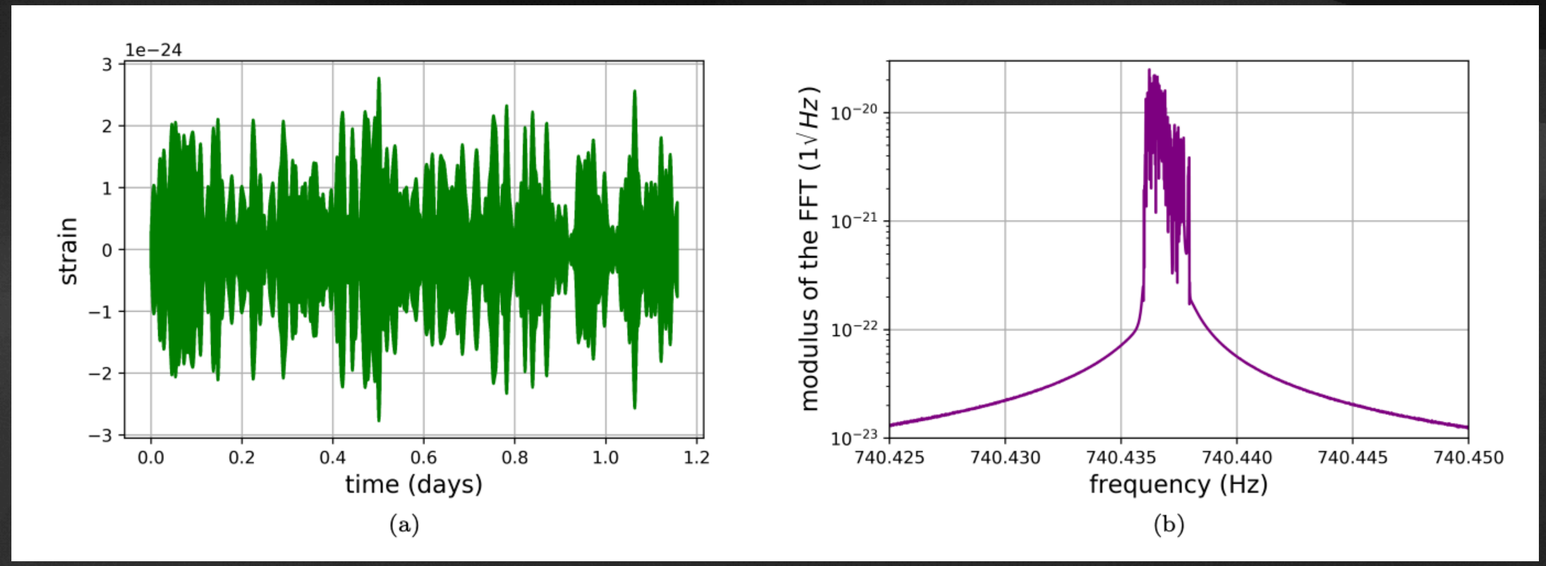
LIGO Hanford in a dark-matter "ether"





What the signal looks like

- Example of simulated dark photon dark matter interaction
- Power spectrum structure results from superposition of plane waves, visible when $T_{\mathrm{FFT}} > T_{\mathrm{coh}}$



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

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

Types of dark matter

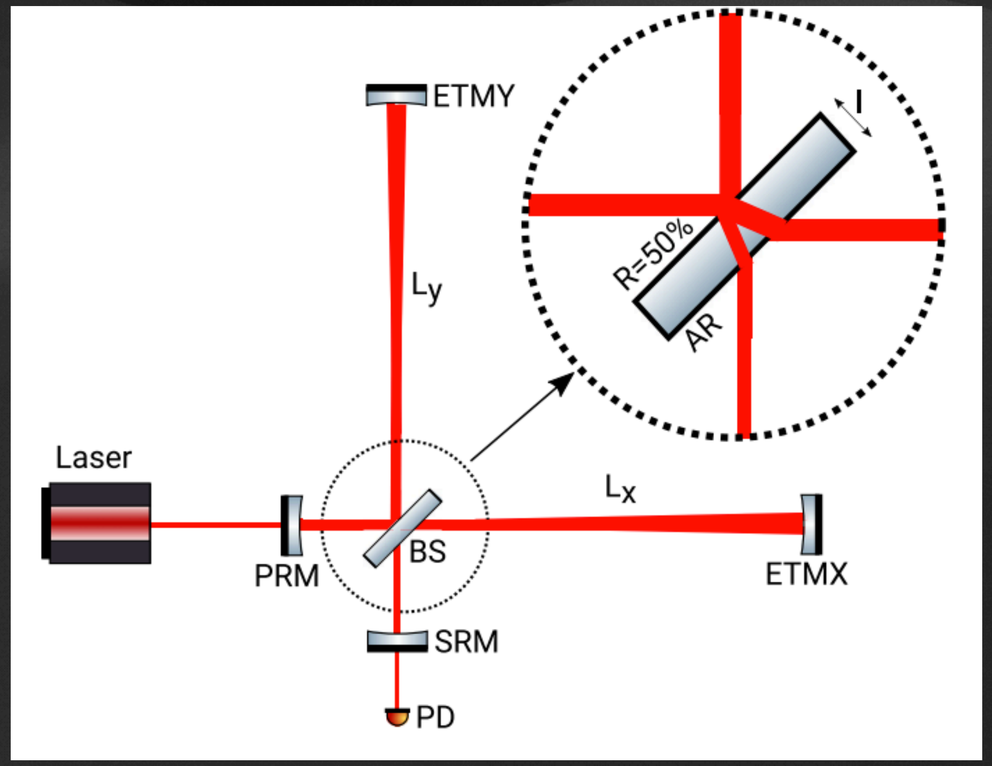
- Scalar dark matter (spin 0): Expand/Contract mirrors
- Dark photon dark matter (spin 1): Accelerate mirrors
- Tensor dark matter (spin 2): Modify gravity

Slide inspired by Goettel, A.

Scalar dark matter

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

- Scalar field ϕ couples with strengths Λ_γ and Λ_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



Slide inspired by Goettel, A.

Vector bosons: dark photons

m_A : dark photon mass
ε_D : coupling strength
A_μ : 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
- First search done for these particles on O1 data

Pierce et al. 2018, PRL 121, 061102

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

Tensor bosons

$$\mathcal{L} = -\frac{1}{4}\chi^{\mu\nu}\mathcal{E}_{\mu\nu,\alpha\beta}\chi^{\alpha\beta} - \frac{1}{8}\left(\frac{m_{\mathrm{DM}}c}{\hbar}\right)^2\left(\chi_{\mu\nu}\chi^{\mu\nu} - \chi^2\right) - \frac{\alpha}{2cm_{\mathrm{Pl}}}\sqrt{\frac{\hbar}{c}}\chi_{\mu\nu}T^{\mu\nu}$$

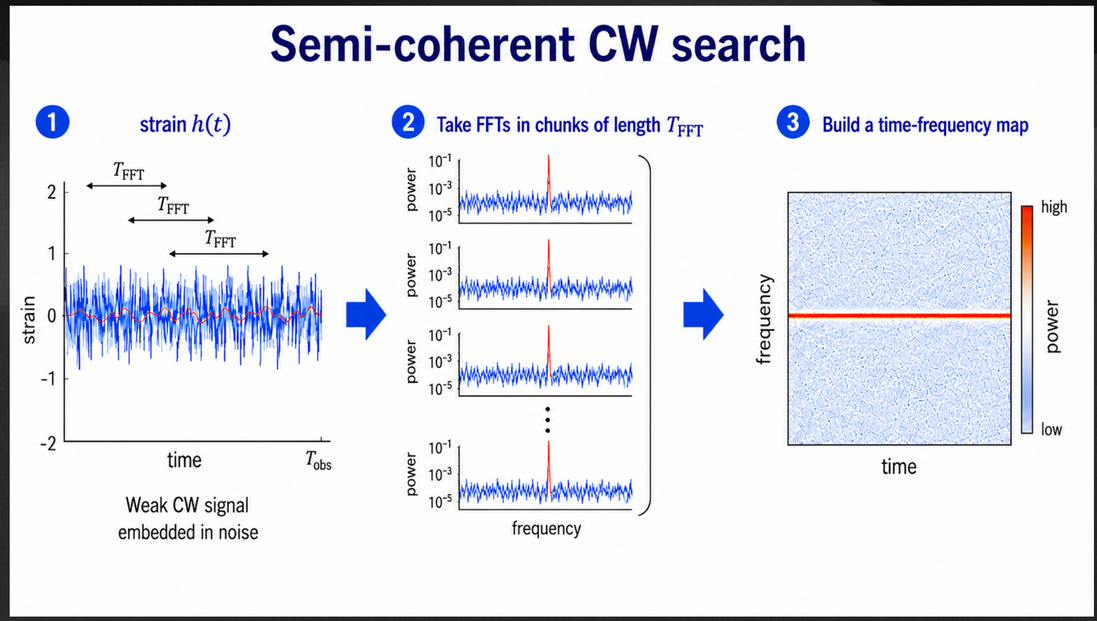
$\underline{m_{DM}}$: dark-matter mass
$\underline{\alpha}$: coupling strength
$\chi_{\mu\nu}$: tensor field

- Arise as a modification to gravity, even though it acts as an additional dark matter particle
- Stretches spacetime around mirrors, just like gravitational waves
- Will appear as a Yukawa-like fifth force modification of the gravitational potential

Armaleo et al. (2021) JCAP 2021.04: 053

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 $T_{\rm FFT} \sim T_{\rm coh}$ and combine the power in each FFT without phase information
- 3 methods used: cross correlation, BSD excess power, and LPSD
- Computationally cheap!



Pierce et al. 2018, PRL 121, 061102

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

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

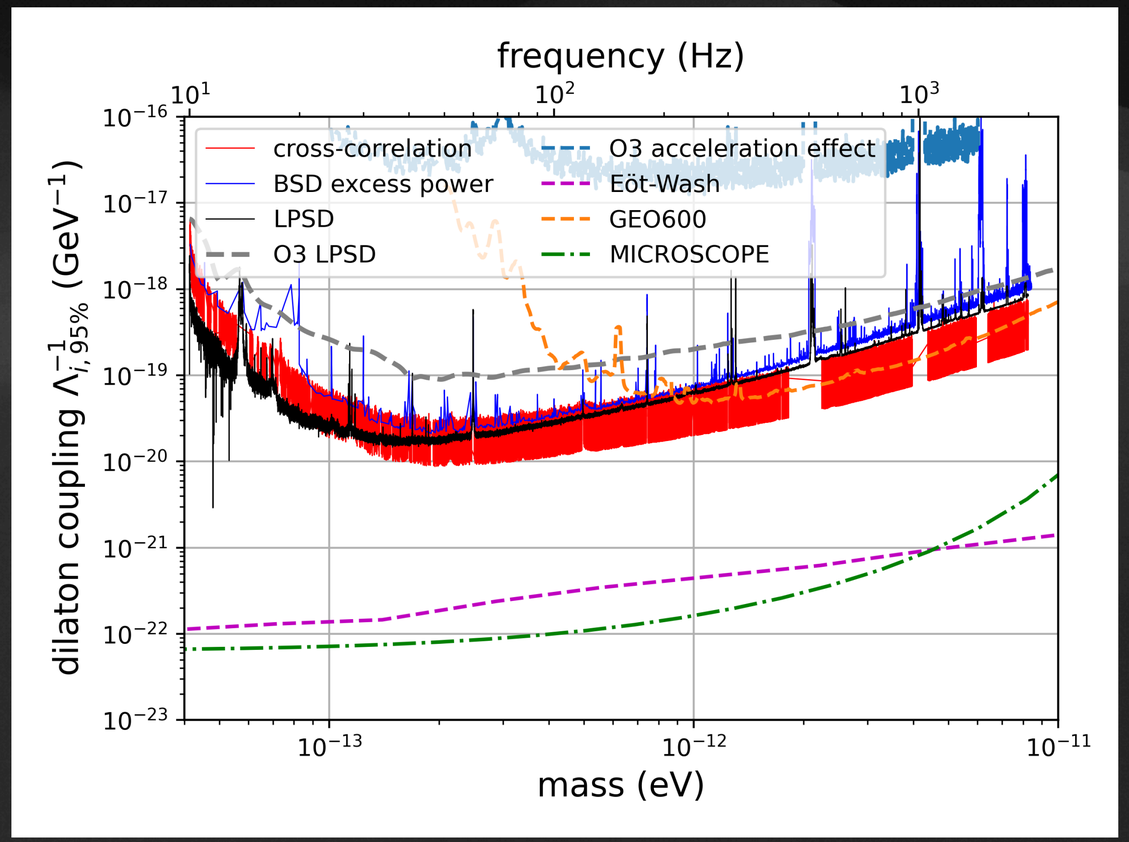
Goettel et al., (2024), PRL 133 (10), 101001

Search for dark matter in LIGO O4a data

LVK (2026): PRL 137.13, p. 131001

Constraints on scalars

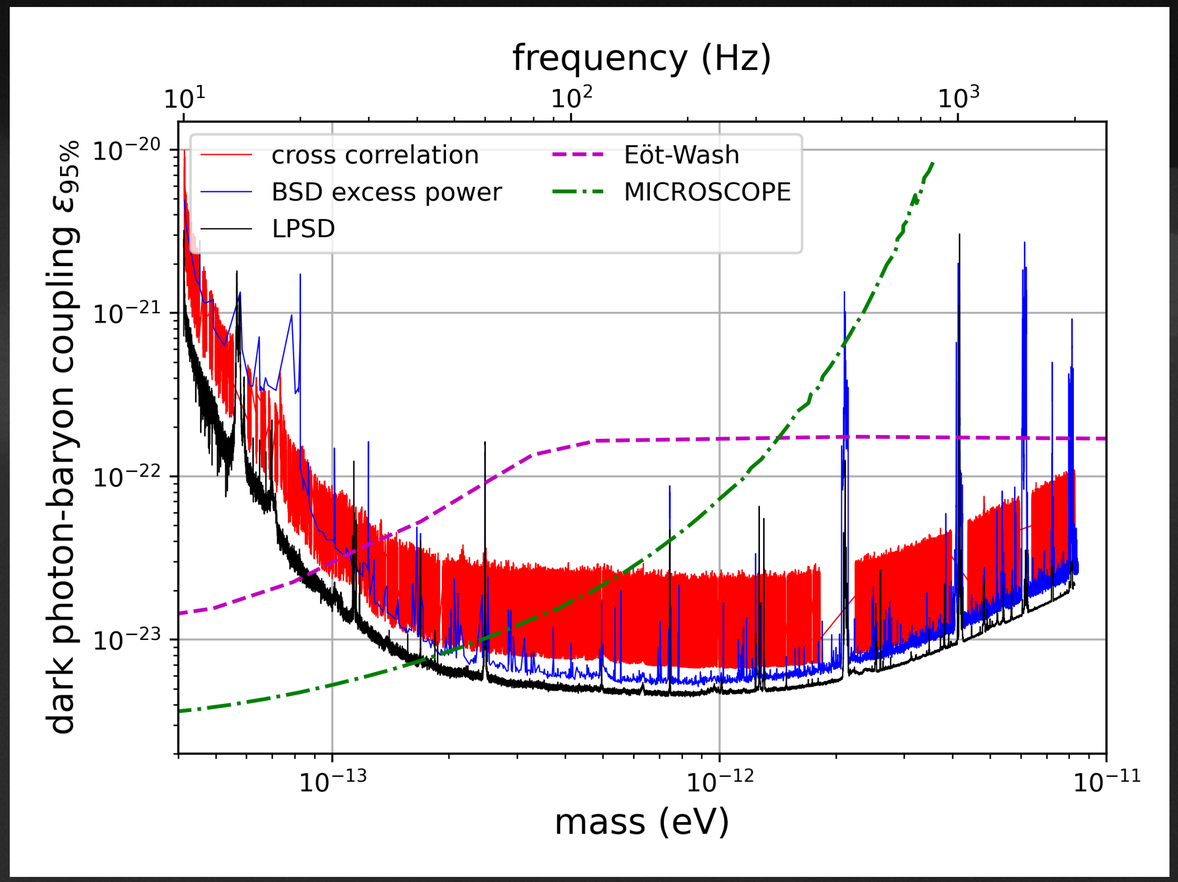
- Direct constraints on coupling constant of scalars to standard model particles
- One order of magnitude improvement over constraints from previous observing runs



LVK (2026): PRL 137.13, p. 131001.

Constraints on vectors

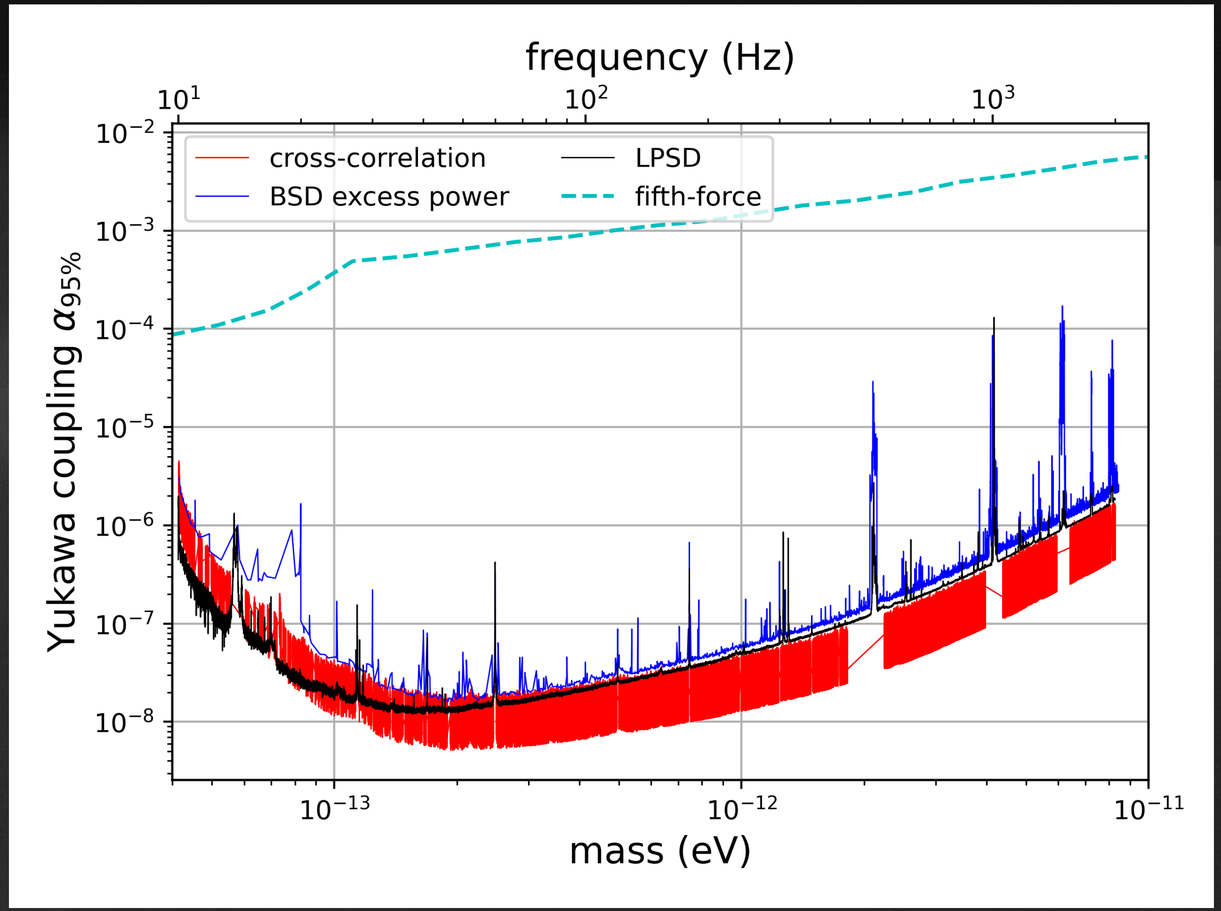
- Here, two effects contribute: spatial and temporal strains
- Cross correlation method is less sensitive to the finite light travel time effect —> weaker than the other two methods
- Our limits beat existing ones by ~1 order of magnitude



LVK (2026): PRL 137.13, p. 131001.

Constraints on tensors

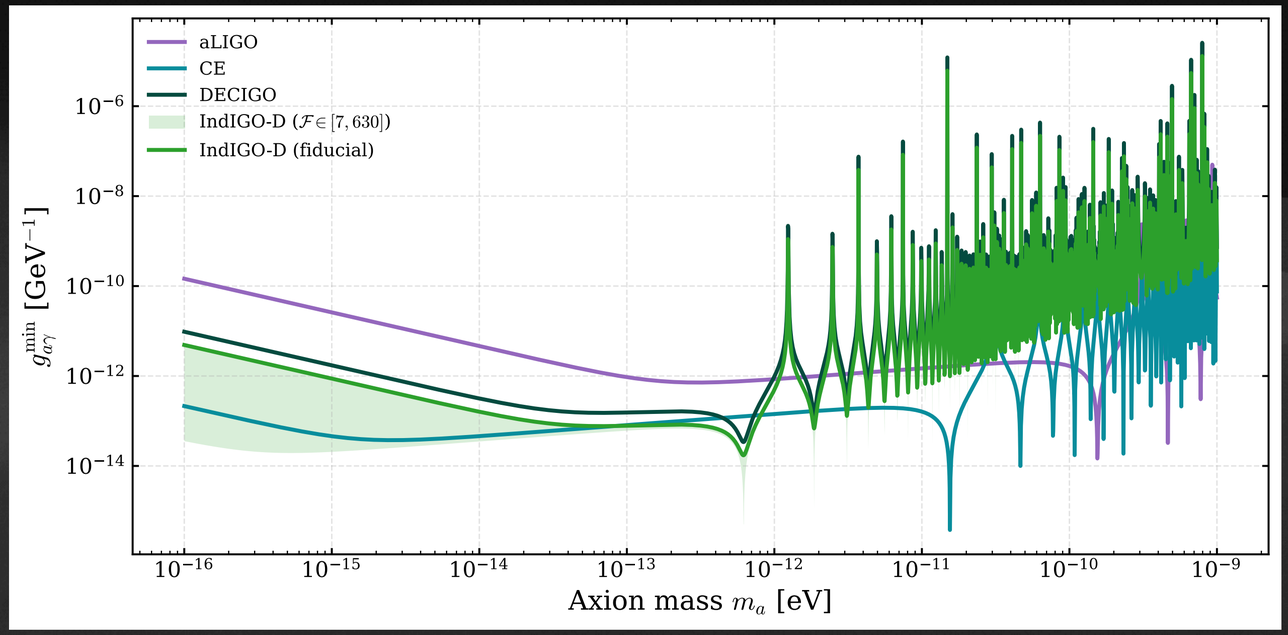
- Five orders of magnitude better than existing results
- First GW interferometer constraints on tensor bosons



LVK (2026): PRL 137.13, p. 131001.

GW detectors as probes of axions

- Axions can alter the phase velocities of left- and right- circularly polarized light
- Use optics that measure polarizations of the laser light after it is transmitted at end mirrors to search for axions
- Can be done with KAGRA, and in the future decihertz detector INDIGO-D
- Resonances when wavelength of axion matches wavelength of cavity



$$H_a(m_a) \equiv \frac{i}{k}\frac{1}{m_a}\frac{4r_1 r_2 \sin^2(m_a L/2)}{1 - r_1 r_2 e^{-i2m_a L}}\left(-e^{-im_a L}\right),$$

$m_a L \ll 1$: $H_a(m) \propto m$

$m_a = \pi/L$: resonance with peak enhanced by $r_1 r_2/(1 - r_1 r_2)$

$m_a L = \pi(2N - 1)$: repeated peaks under a envelope of $H_a(m) \propto 1/m$

Nagano et al., PRL123,111301(2019)

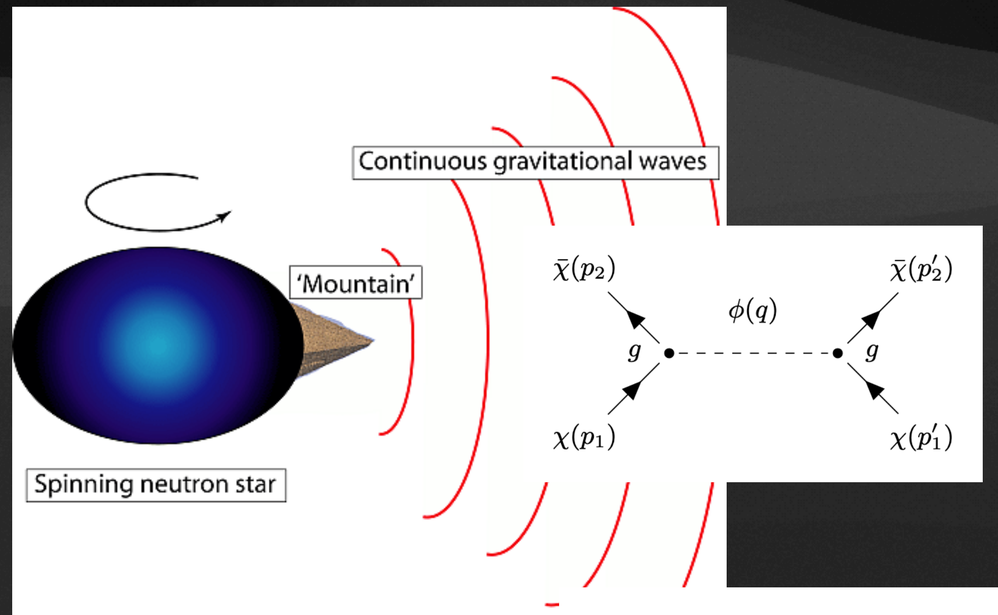
Hoque, **ALM**, Mukherjee (2026): arXiv:2608.15240 (accepted, PRD)

Dark-matter admixed neutron stars

Mahapatra, **ALM** and Das (2026): arXiv: 2606.05082

Dark-matter admixed neutron stars as sources of continuous waves

- Neutron stars can capture dark matter, forming a two-component system of baryonic matter and DM
- Consider fermionic dark matter with repulsive Yukawa self-interactions, with mass m_χ, coupling g, and mediator mass m_ϕ; $\rho = \rho(m_\chi, m_\phi, g)$
- Stronger self-interactions increase the star's moment of inertia relative to considering only baryonic matter
- "Dark mountains" can form from an asymmetry in the dark-matter mass distribution of the star



$$I_{zz} = \int \rho(x^2 + y^2)\, dV$$

$$h_0 = \frac{4\pi^2 G}{c^4} \frac{\varepsilon I_{zz} f_{\mathrm{GW}}^2}{d}$$

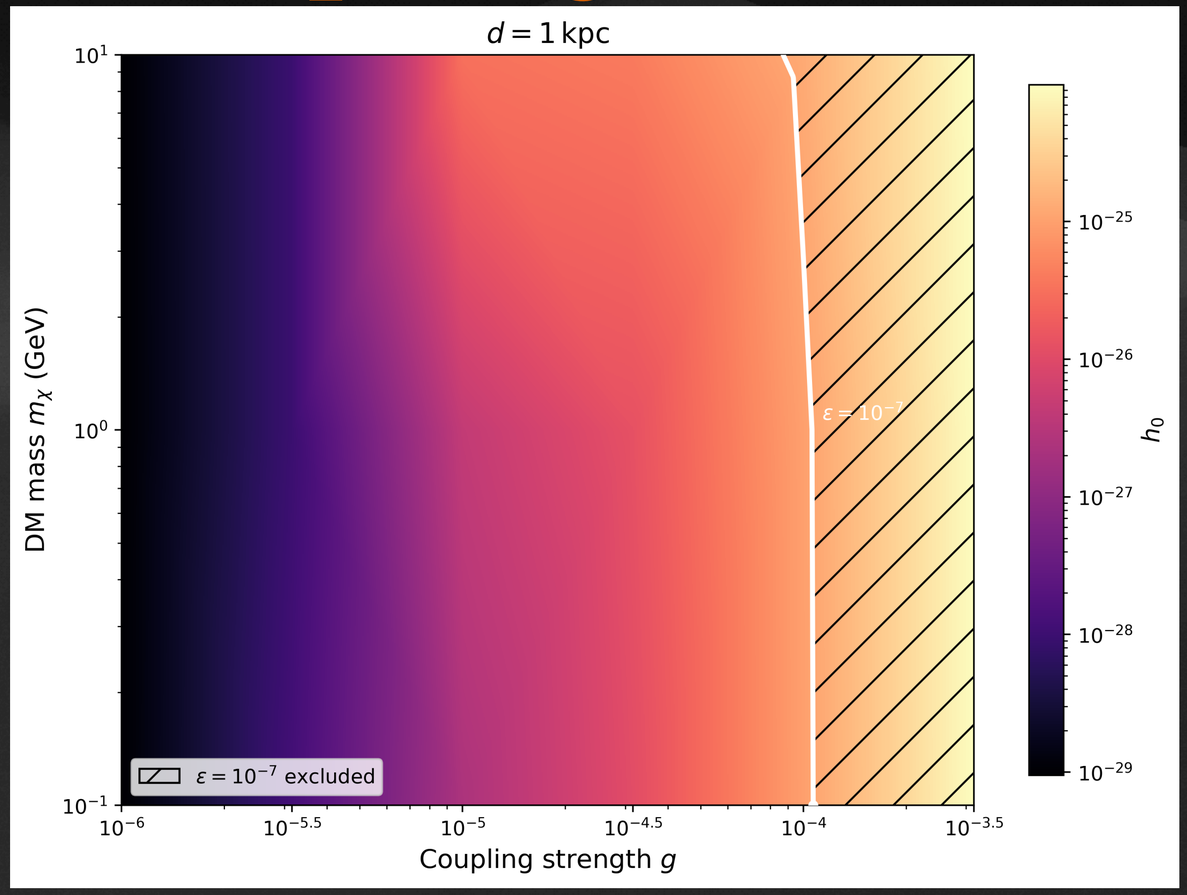
$$\varepsilon = \frac{|I_{xx} - I_{yy}|}{I_{zz}}$$

Mahapatra, **ALM** and Das (2026): arXiv: 2606.05082

$$h_0 = \frac{4\pi^2 G}{c^4} \frac{\varepsilon I_{zz} f_{GW}^2}{d}$$

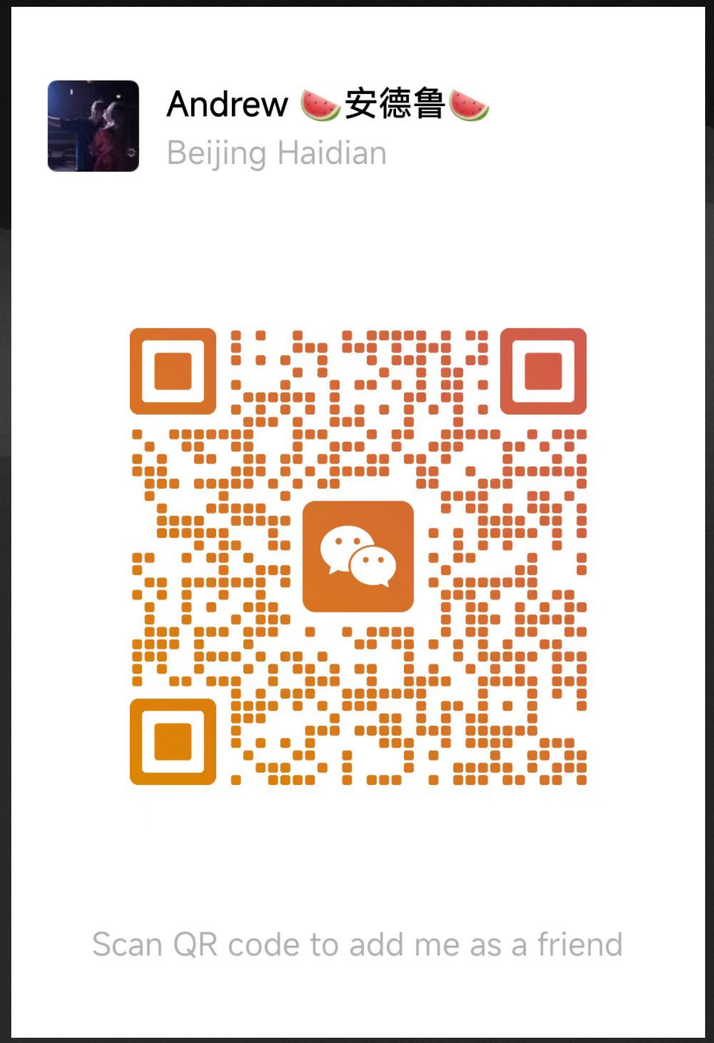
O4a constraints on DM mass and coupling

- Dark matter changes moment of inertia I_{zz}
- Upper limits on h_0 —> constraints on I_{zz} for fixed ellipticity and source distance
- $I_{zz} = I_{zz}(m_\chi, m_\phi, g)$ —> can exclude DM parameters



Conclusions: where are we at?

- Ground-based detectors provide stringent limits on particle DM
- But we have only constrained a few models.. there are in principle many other kinds of DM that could interact with GW detectors
- Interesting in knowing more about GW probes of dark matter? See this recent review (arXiv:2503.02607; IJMP D)
- Interested in working on GW probes of dark matter? Send me an email: andrew.miller.ligo@ucas.ac.cn



Backup slides

Methods: Cross correlation

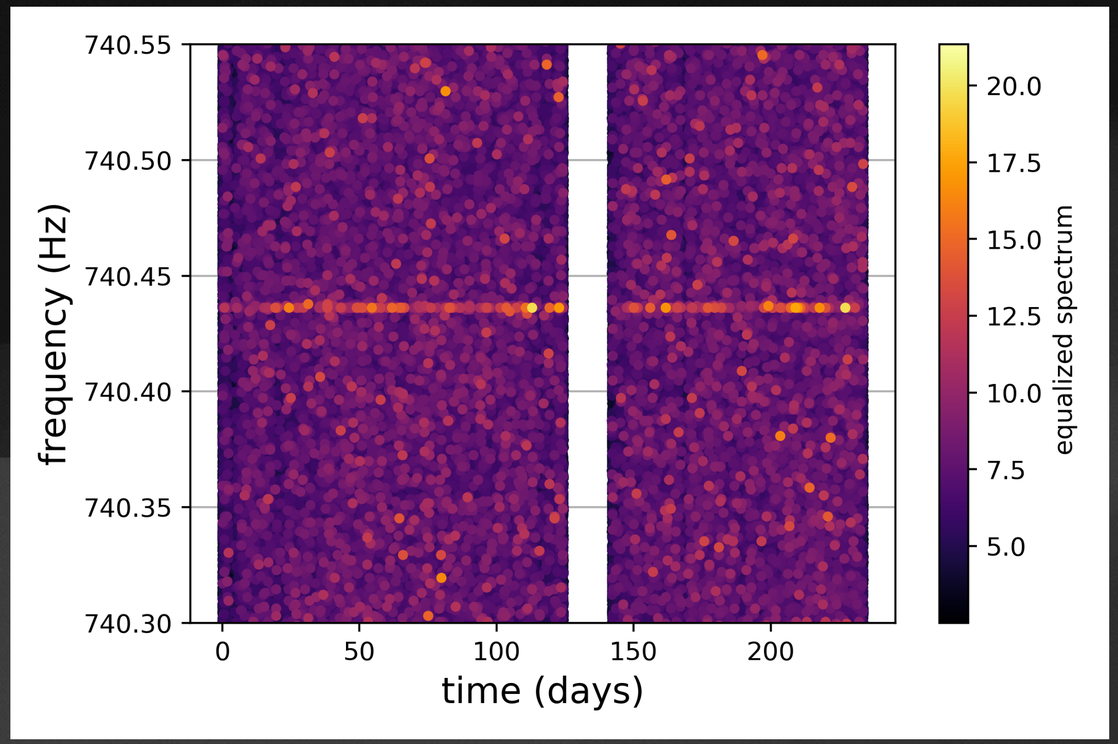
- Use syncronized 1800 s SFTs (5696 SFTs in O4a)
- SNR computed per frequency bin
- Negative, real SNR for dark photon/tensor boson
- Postive, real SNR for dilatons
- SNR sign depends on overlap reduction function, which is constant of -0.9 or 1
- Background modelling: frequency lags
- No candidates above threshold at 1% FAP

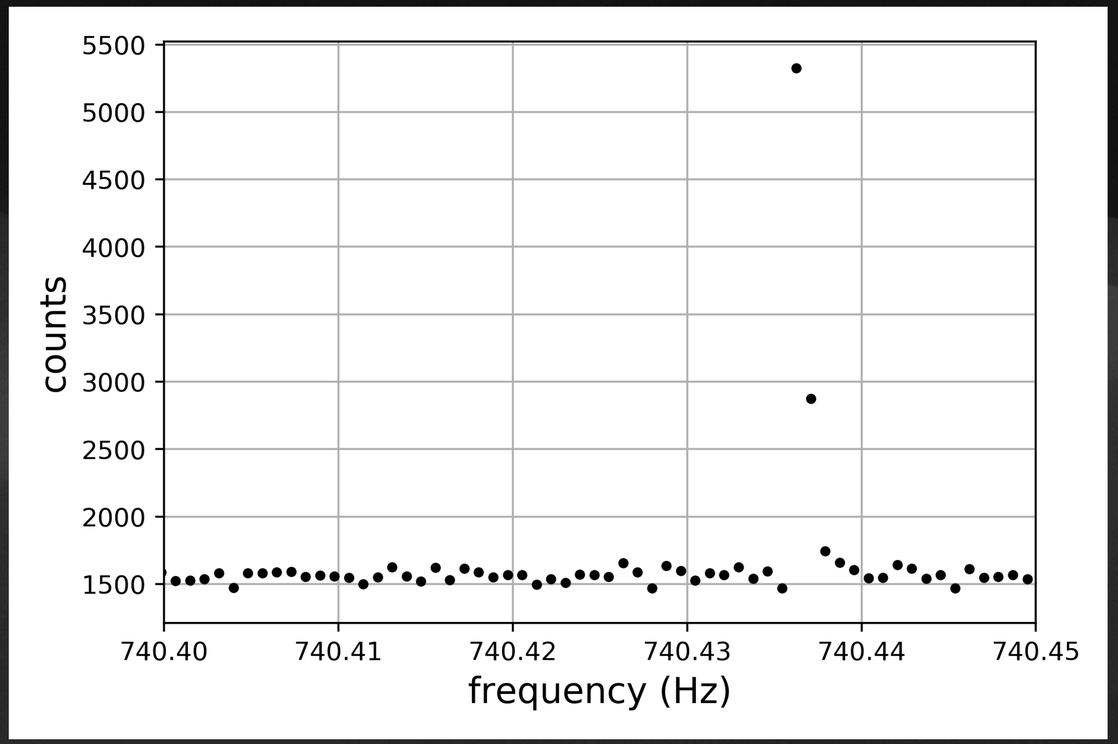
$$S_j = \frac{1}{N_{\mathrm{FFT}}} \sum_{i=1}^{N_{\mathrm{FFT}}} \frac{z_{1,ij} z^*_{2,ij}}{P_{1,ij} P_{2,ij}}$$

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

Pierce et al. 2018, PRL 121, 061102

Methods: BSD excess power





- Using BSD framework, vary the coherence length every 1 Hz to match the DM coherence time
- Looking for excess power in time-frequency plane; Sum peaks at each frequency
- Follow up done in two ways: increase TFFT to see if the candidate's CR falls off or not

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

Methods: LPSD

- Optimal binning is log spaced b/c $\frac{\Delta f}{f} \sim 10^{-6}$
- Log f bins from FFTs is O(N^2) operation
- Adapted method used in Computer Music to use frequency-dependent FFT length to cleverly compute log spaced FFT bins
- Fit PSD with a spline; model the residuals with a skew-normal (SN) distribution
- Likelihood ratio test to find excess power: compare likelihoods of noise-only vs. signal hypothesis



$$r(\mu) = \log P - \log(B + \mu\beta)$$

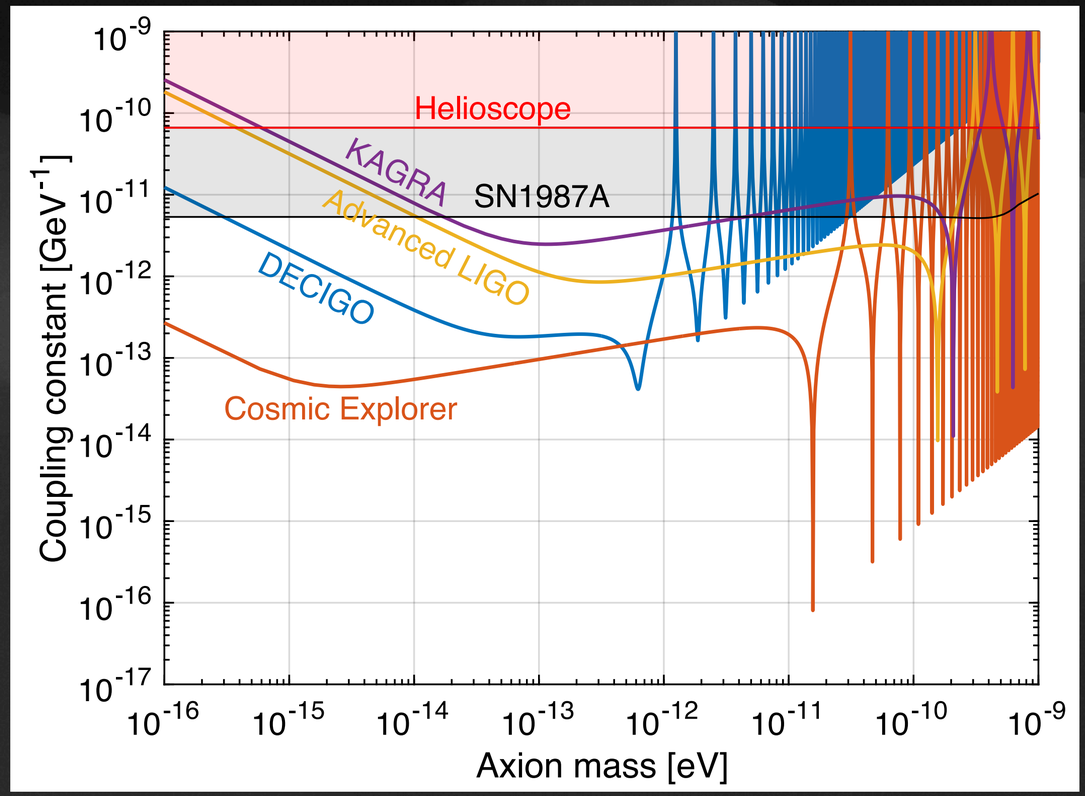
expected background PSD B
Measured PSD P
μ : DM sig amplitude
β: conversion b/t amplitude and how DM appears in detector

$$\mathcal{L}(\mu) = \prod_{\text{IFO}} \prod_{\text{seg}} p_{\text{SN}}[r_{\text{IFO,seg}}(\mu)]$$

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

Next up: full O4 analysis

- Considering the same three DM models + axions
- Using auxiliary channel data to search for dark matter
- New methods also analyze KAGRA data



O4a constraints on dark-mountain size

- First constraints on dark mountains
- Ellipticity dictates how tall the mountains to be
- Stronger couplings —> smaller mountains can be constrained

