Dark matter at kHz gravitational-wave frequencies

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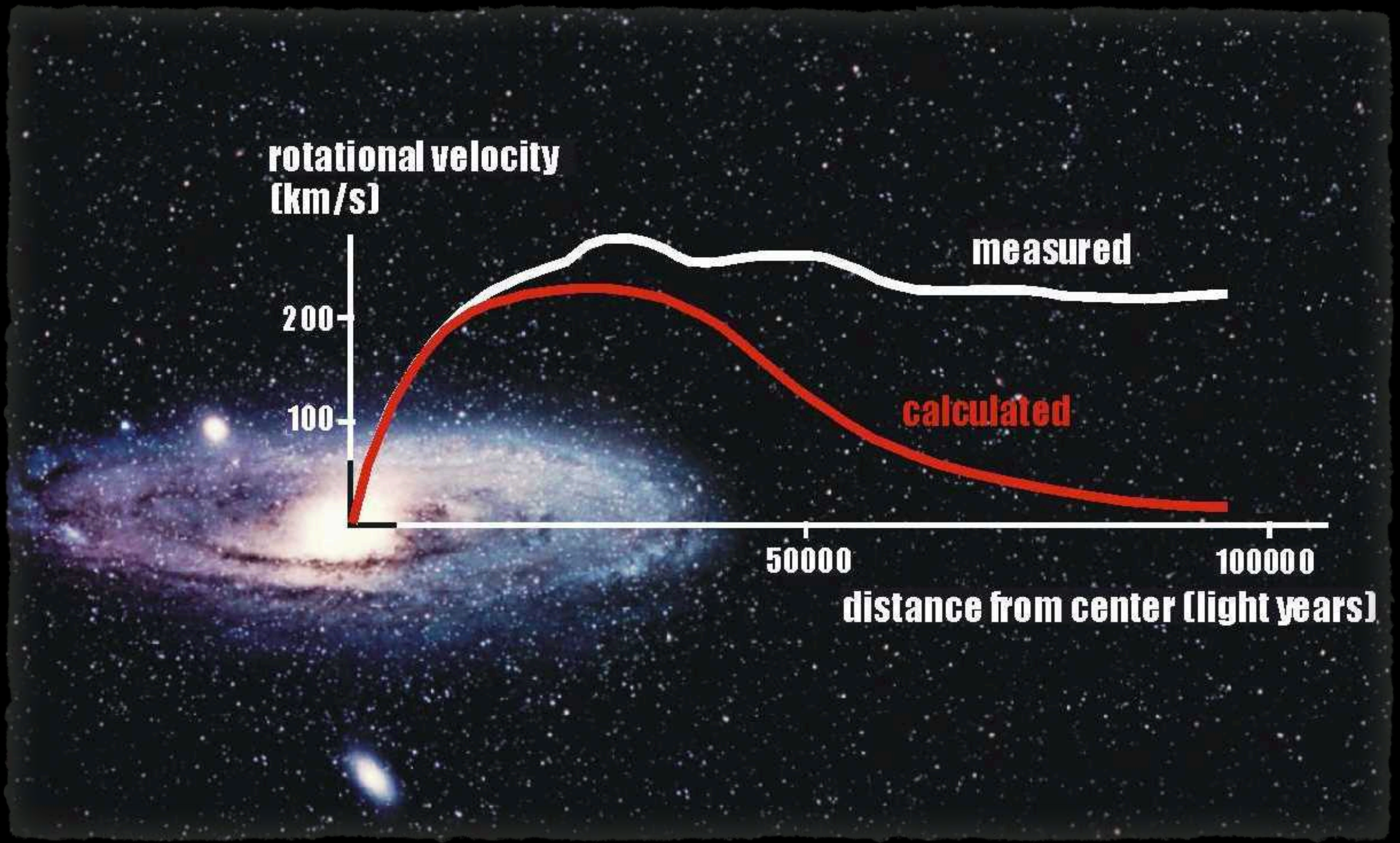
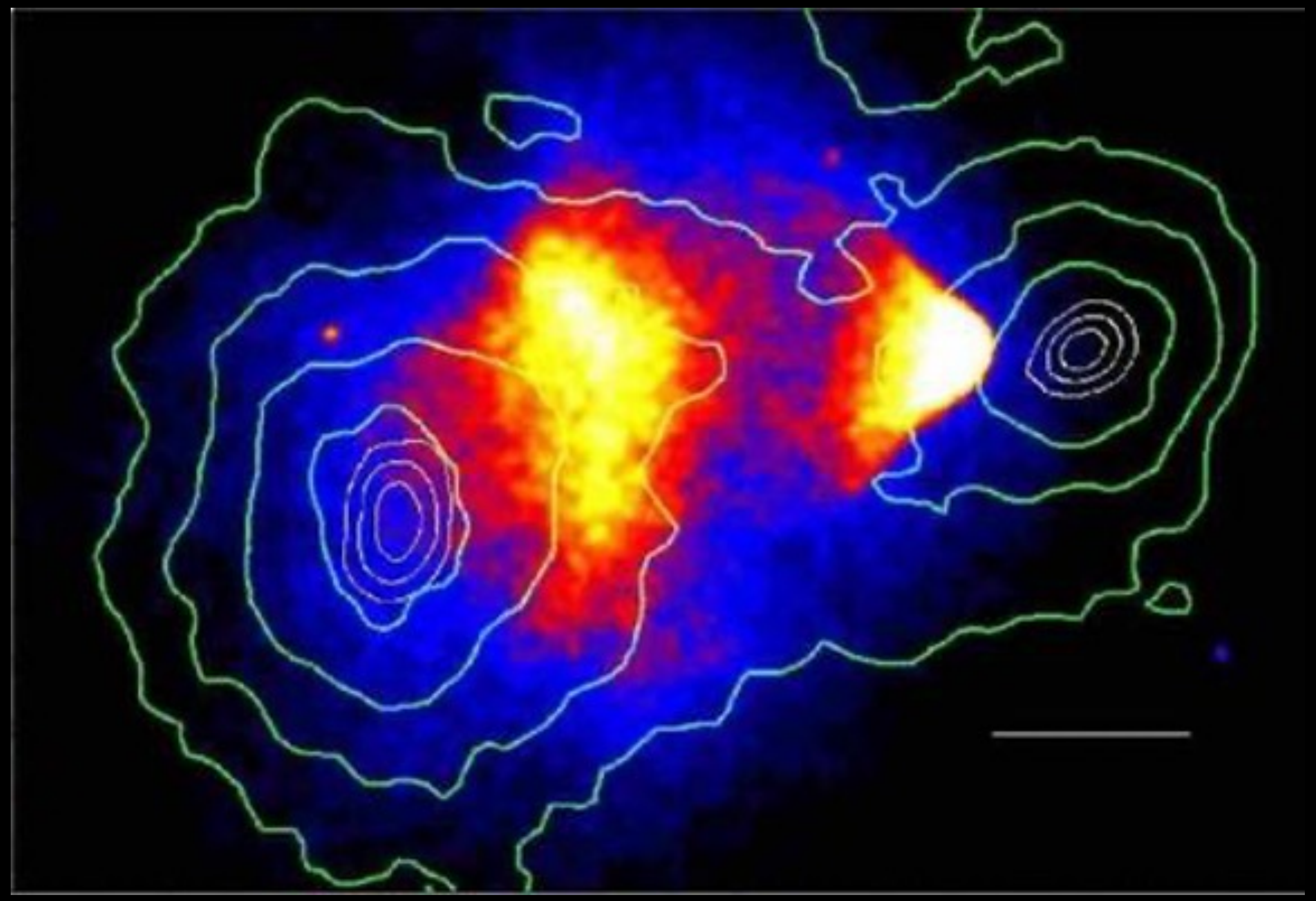
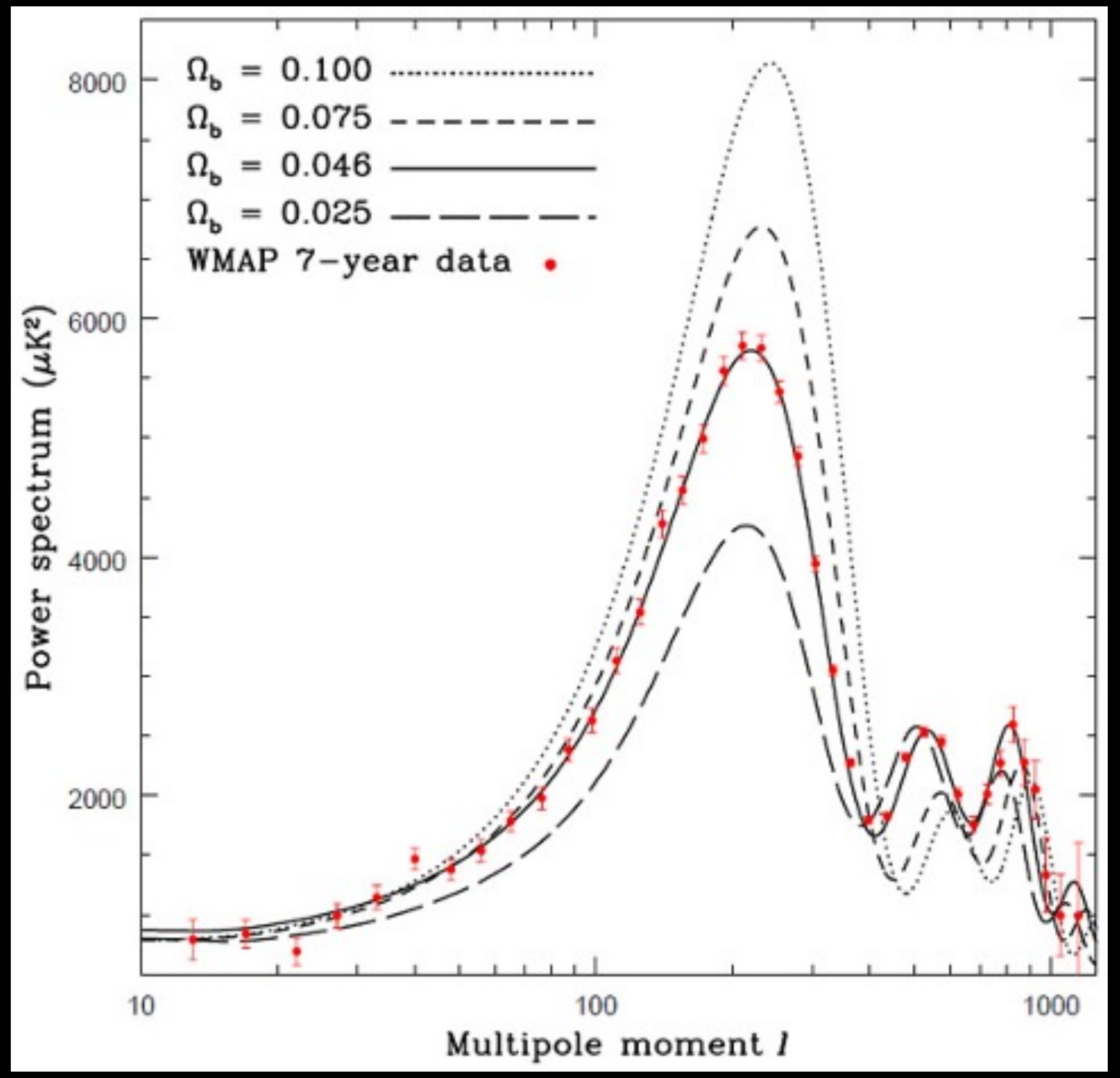
Why do we need dark matter?

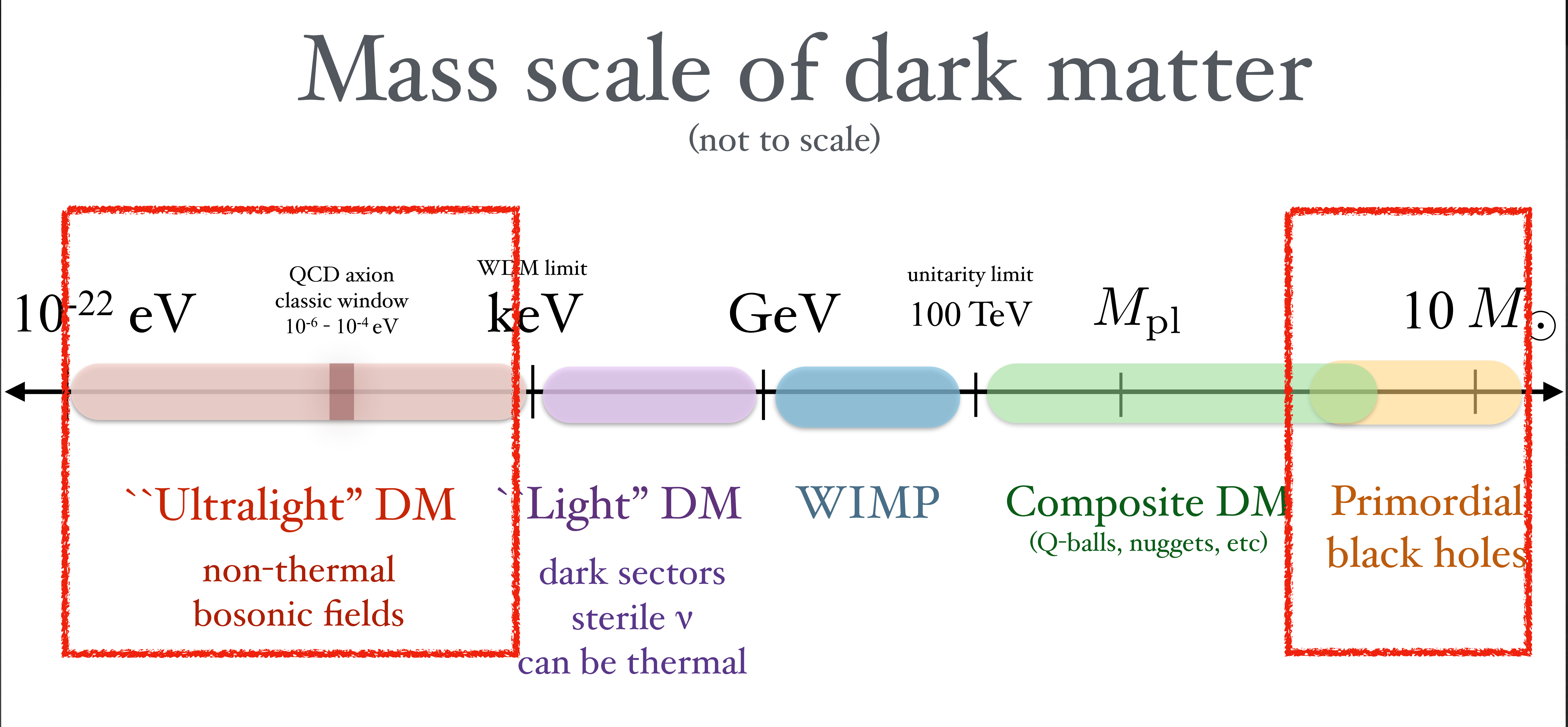






- Galaxy rotation curves: stars move too fast based on visible matter distribution
- Bullet cluster: dark matter gravitationally lenses light around it in this cluster
- CMB anisotropy power spectrum: dark matter needed to explain anisotropies

What could dark matter be?



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

How can GW detectors probe dark matter at kHz frequencies?

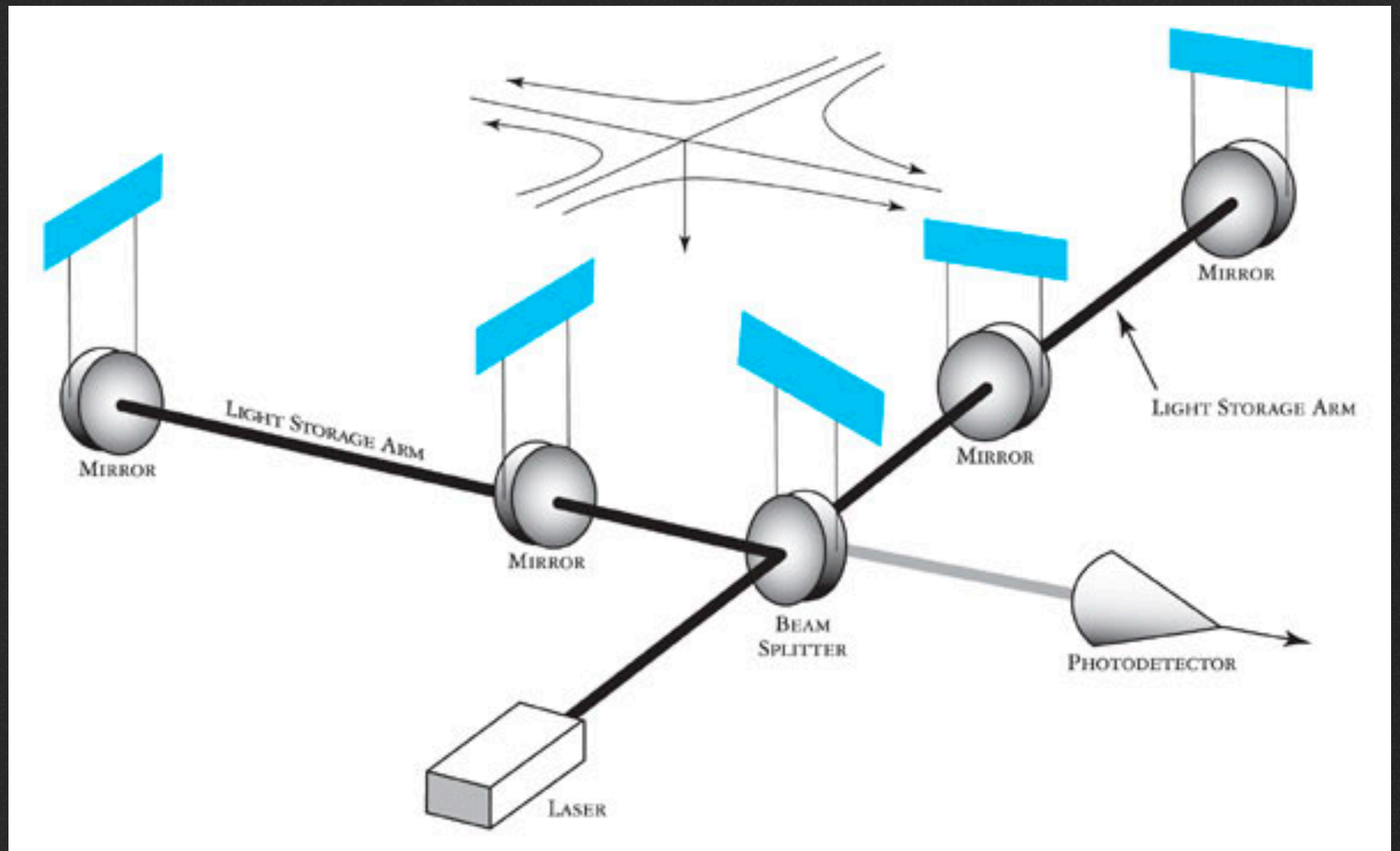
kHz DM sources of GWs

- Ultralight particle dark matter in particular mass ranges could couple to the standard-model particles in the interferometers
- Boson clouds around rotating black holes would give off quasi-monochromatic GWs due to the annihilation of bosons into gravitons
- Sub-solar-mass primordial black-hole binaries would still be inspiraling at kHz frequencies; lighter masses would generate long-lived signals

Ultralight particle dark matter

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?

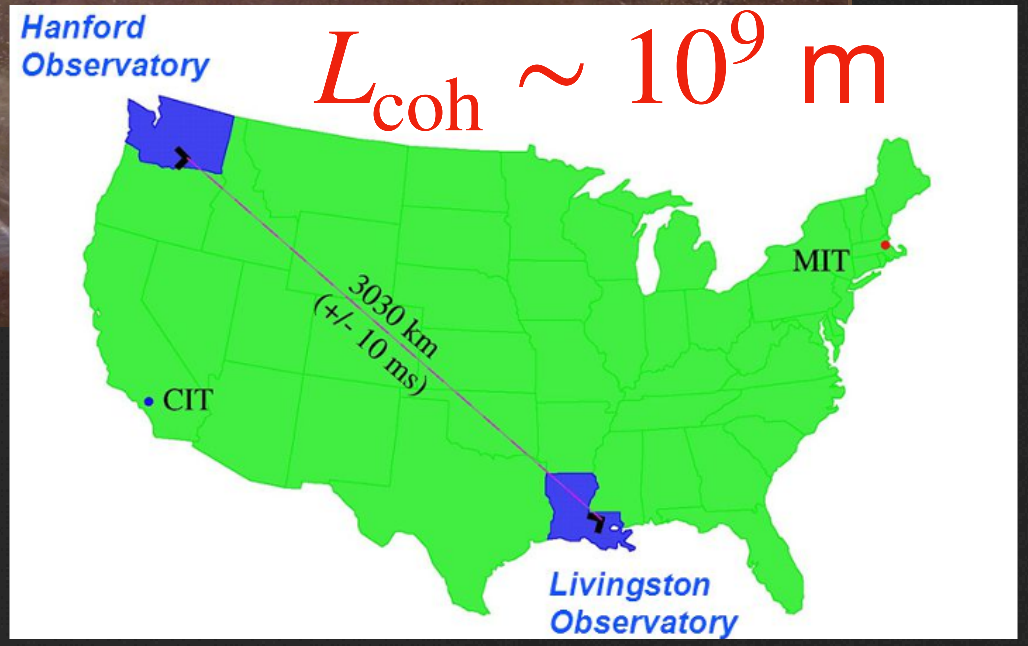


Ultralight dark matter

- The interferometers sit in a wind of DM
- 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 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

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

LIGO Hanford in a dark-matter "ether"



Types of dark matter

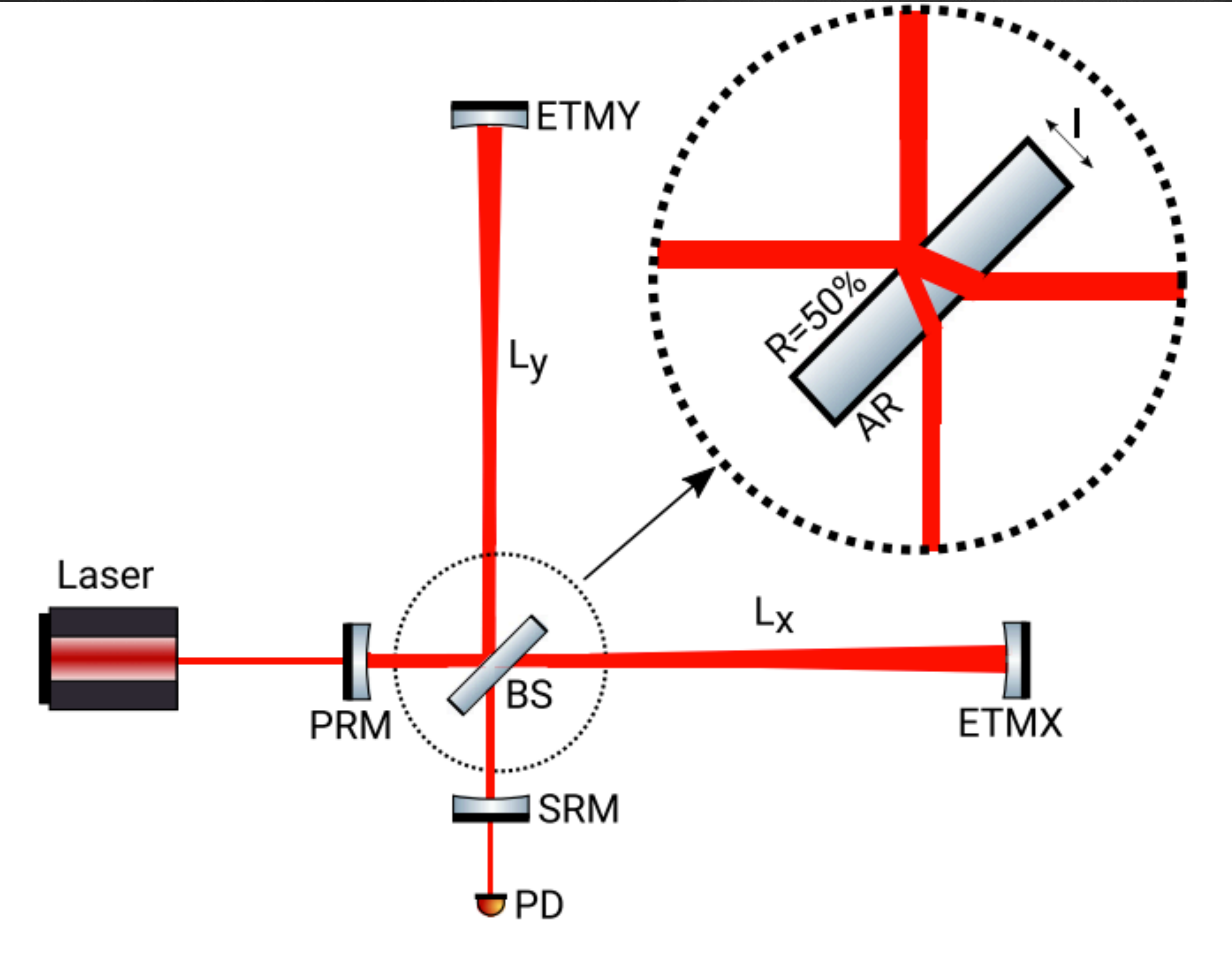
- Scalar dark matter (spin 0): Expand/Contract mirrors
- Dark photon dark matter (spin 1): Accelerate mirrors
- Tensor dark matter (spin 2): Modify gravity

Slide inspired by Goettel, A.

Scalar dark matter

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

- 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



Grote and Stadnik, Physical Review Research 1.3 (2019): 033187.

Slide inspired by Goettel, A.

Vector bosons: dark photons

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

m_A : dark photon mass
ε_D : coupling strength
A_μ : 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 —> 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

Tensor bosons

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

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

What's unique about the kHz regime?

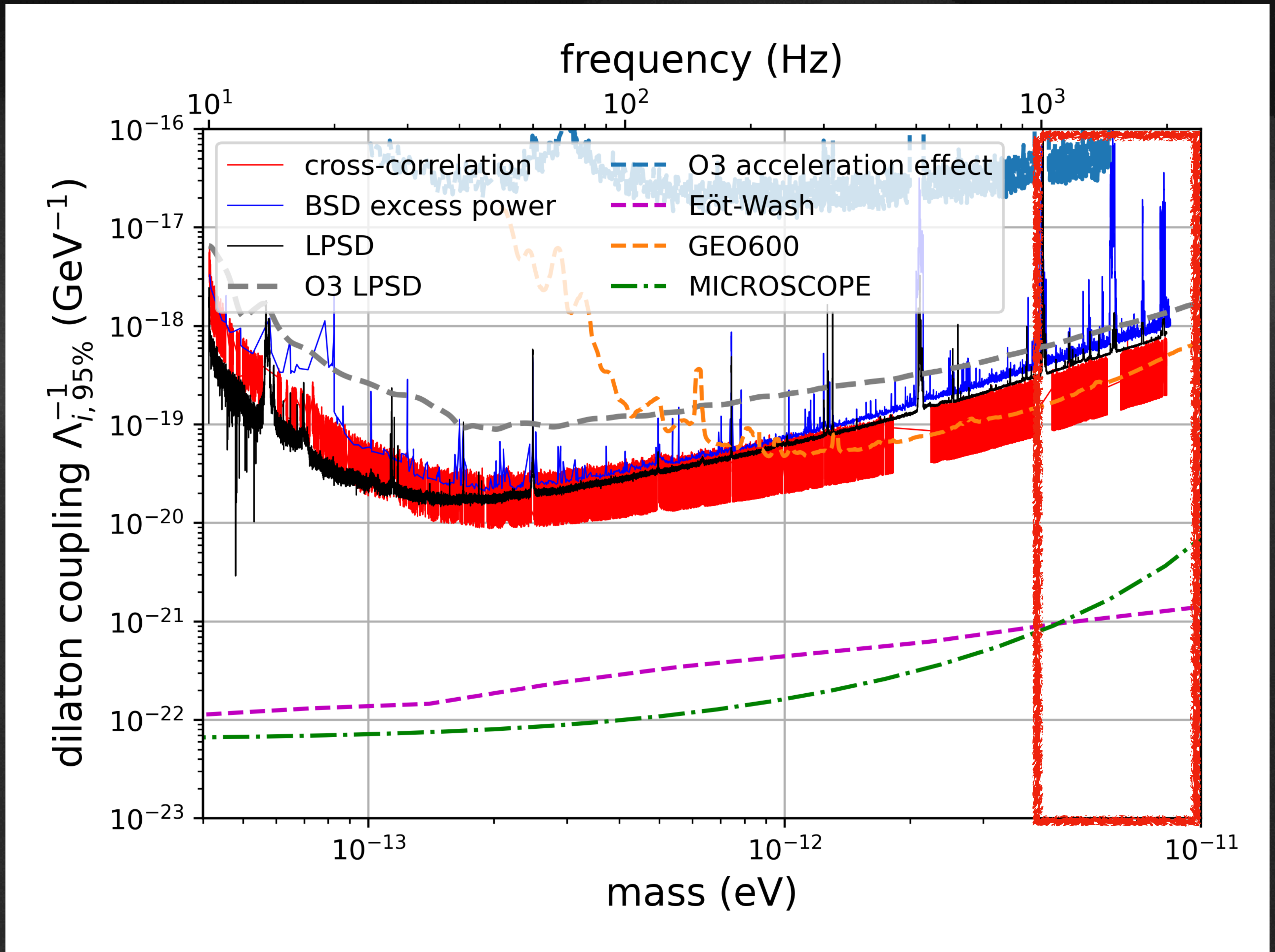
- The kHz regime sits at the high end of frequencies accessible by LVK
- At such frequencies, the DM signal coherence time is shorter —> shorter FFTs —> less absolute sensitivity
- From 1-2 kHz, LVK lose sensitivity
- We are sensitive to smaller DM couplings

O4a Search Results

arXiv:2510.27022

Constraints on scalars

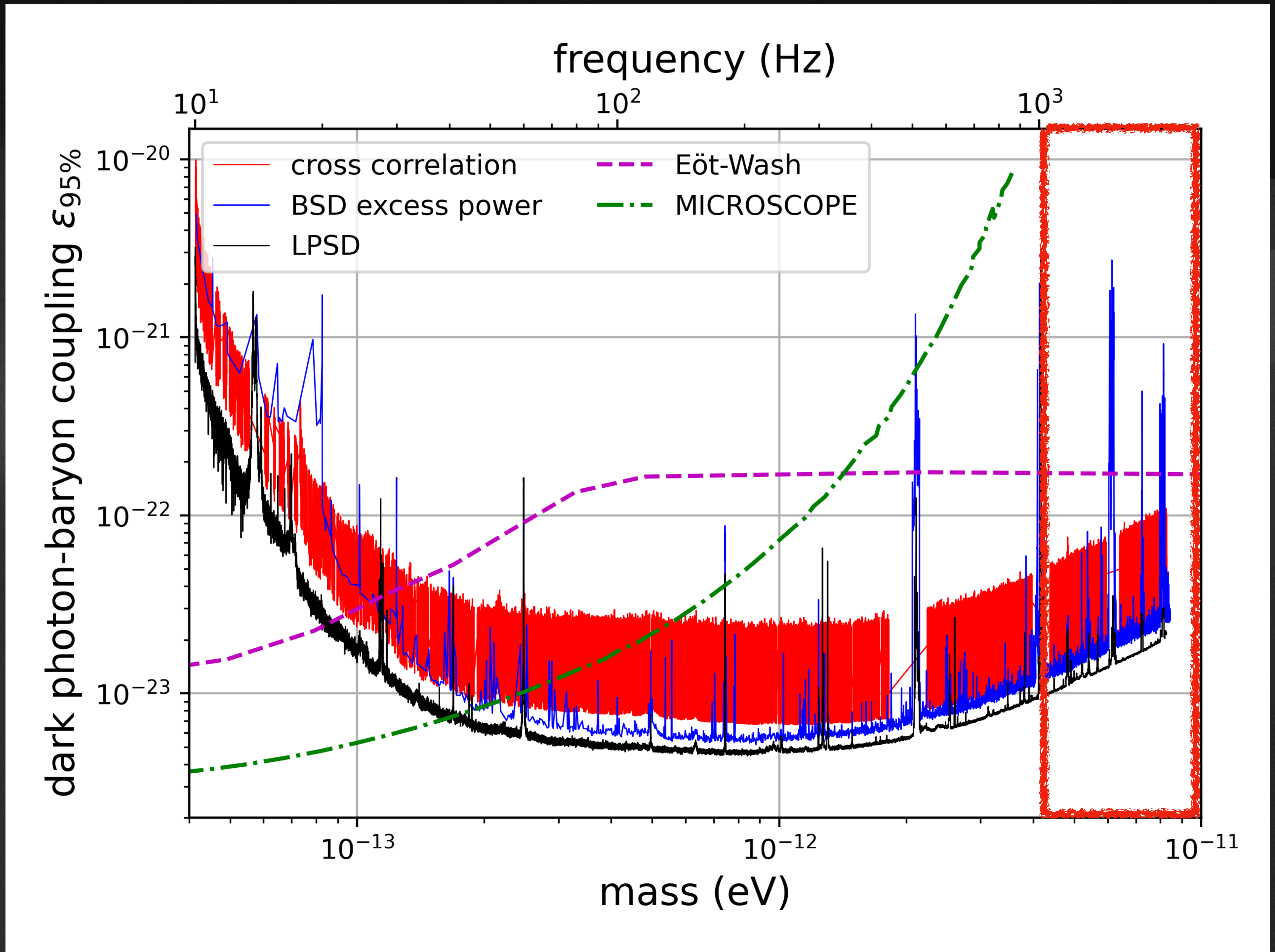
- Direct constraints on coupling constant of scalars to standard model particles
- One order of magnitude improvement over constraints from previous observing runs



LVK (2025): arXiv:2510.27022

Constraints on vectors

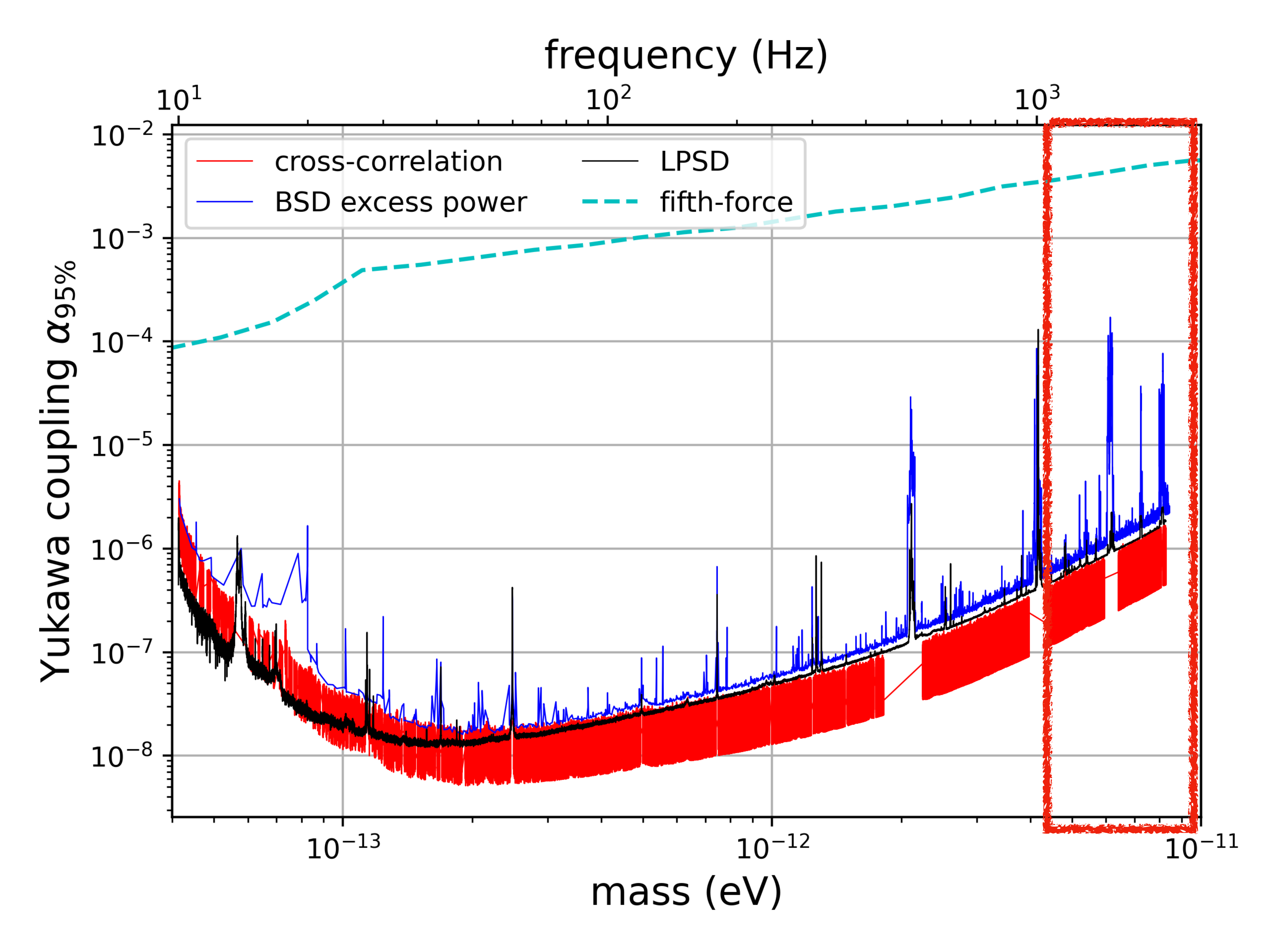
- Here, two effects contribute: spatial and temporal strains
- Cross correlation method is less sensitive to the finite light travel time effect —> weaker than the other two methods
- Our limits beat existing ones by ~1 order of magnitude



LVK (2025): arXiv:2510.27022

Constraints on tensors

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

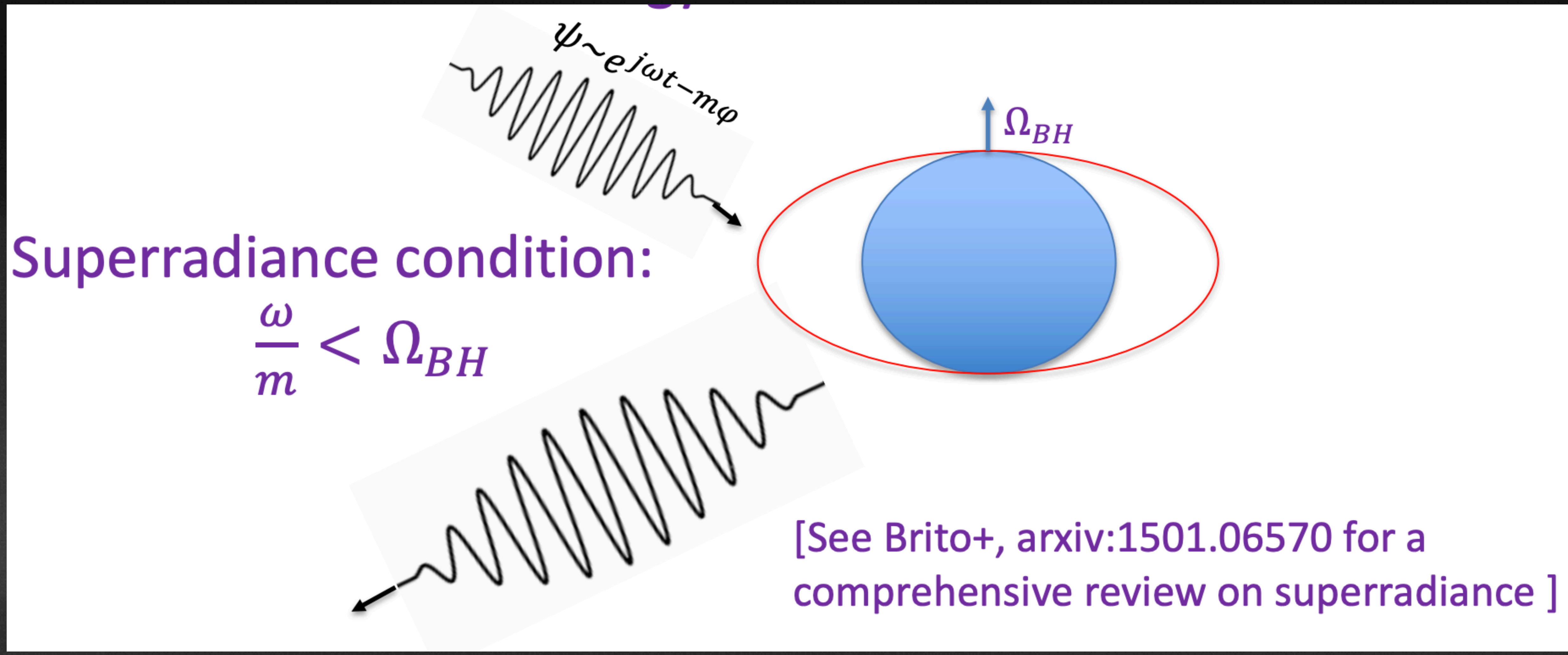


LVK (2025): arXiv:2510.27022

GWs from boson clouds around rotating black holes

Ultralight scalar boson clouds

- After cloud forms, annihilation of bosons into gravitons energy level by energy level —> quasi-monochromatic CWs
- Growth timescale << annihilation time scale for scalar boson clouds
- LVK performed all-sky search for boson clouds around rotating BHs



$$\tau_{\rm inst} = 27 \left(\frac{M_{\rm BH}}{10 M_\odot}\right) \left(\frac{\alpha}{0.1}\right)^{-9} \left(\frac{1}{\chi_i}\right) \text{ days},$$

$$\tau_{\rm gw} = 6.5 \times 10^4 \left(\frac{M_{\rm BH}}{10 M_\odot}\right) \left(\frac{\alpha}{0.1}\right)^{-15} \left(\frac{1}{\chi_i}\right) \text{ years.}$$

$$\alpha = \frac{G M_{\rm BH}}{c} \frac{m_b}{\hbar}$$

Brito et al. (2017), PRD 96, 064050
Isi et al. (2019), PRD 99, 8

Boson cloud signal

- Quasi-monochromatic, long-lasting signal with a small spin-up (in the weak self-interacting limit)
- In the intermediate/strong self-interacting limits, other spin-up terms become important, weakening and shortening the signal
- LIGO/Virgo/KAGRA performed an all-sky search for boson clouds in the most recent data (O3) and a directed search for two remnants of BBH mergers (O4a)

LVK: PRD 105 (2022) 10, 102001
LVK (2025): arXiv: 2511.19911

$$f_{\rm gw} \simeq 483\,{\rm Hz}\left(\frac{m_{\rm b}}{10^{-12}\ {\rm eV}}\right) \times\left[1 - 7\times 10^{-4}\left(\frac{M_{\rm BH}}{10M_\odot}\frac{m_{\rm b}}{10^{-12}\ {\rm eV}}\right)^2\right]$$

$$\dot{f}_{\rm gw} \approx 7\times 10^{-15}\left(\frac{m_{\rm b}}{10^{-12}\ {\rm eV}}\right)^2\left(\frac{\alpha}{0.1}\right)^{17}\ {\rm Hz/s}.$$

$$h_0 \approx 6\times 10^{-24}\left(\frac{M_{\rm BH}}{10M_\odot}\right)\left(\frac{\alpha}{0.1}\right)^7\left(\frac{1\,{\rm kpc}}{r}\right)(\chi_i-\chi_c)$$

$$h(t) = \frac{h_0}{1+\frac{t}{\tau_{\rm gw}}}$$

D'Antonio et al. [with **ALM**] (2018), PRD 98, 103017
Palomba et al. [with **ALM**] (2019): PRL 123, 171101

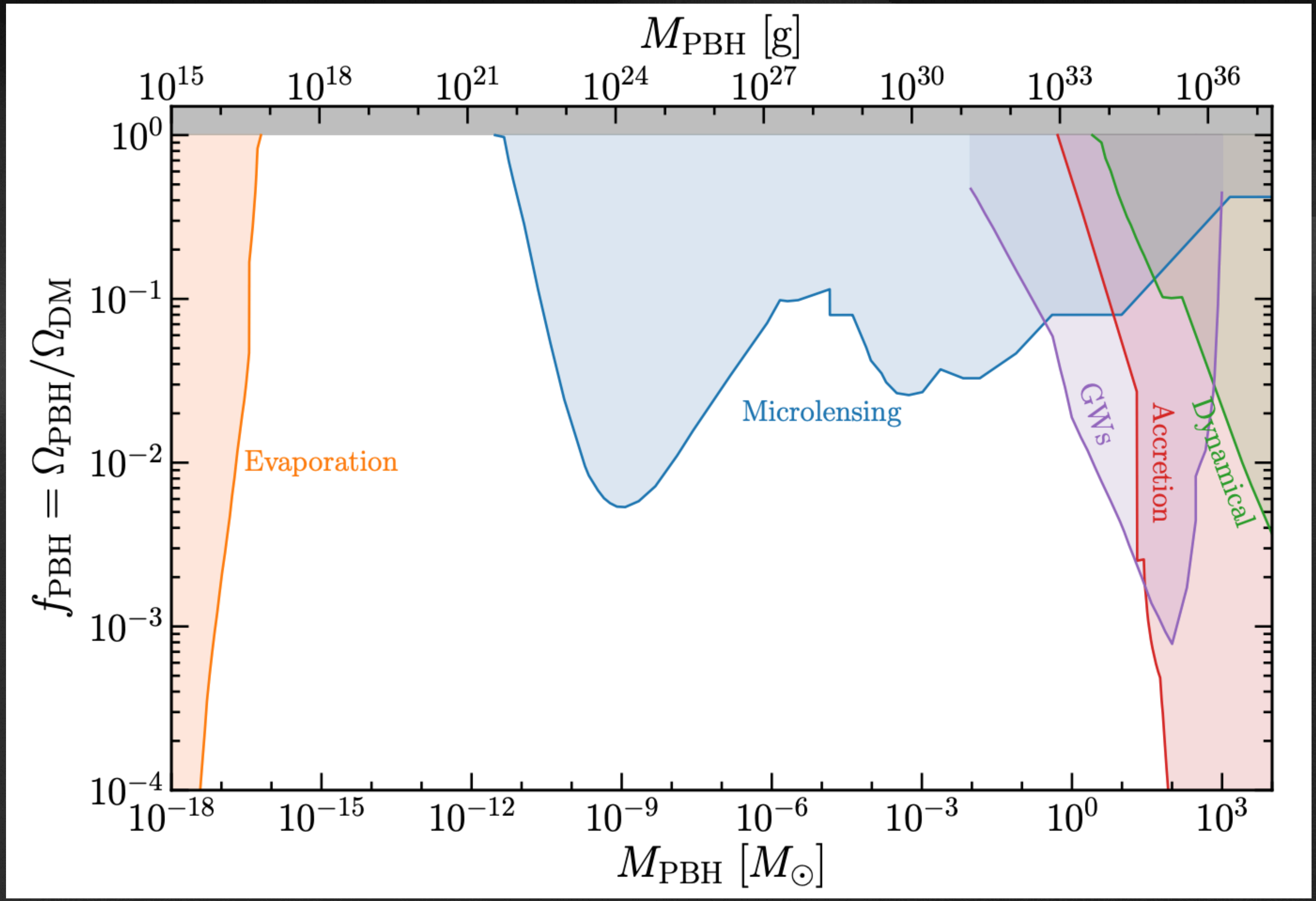
What's unique about the kHz regime?

- We are sensitive to boson masses between $[2{,}4] \times 10^{-12}$ eV
- At these high frequencies, the Doppler shift becomes more prominent: for a monochromatic signal, $f_{\mathrm{gw}} = f_0(1 + \vec{v} \cdot \hat{n}/c)$
- Larger Doppler shifts —> more sky points required to search over —> better sky localization ; BUT, higher computational cost
- As of yet: no search for GWs from annilhating boson clouds around rotating BHs above ~600 Hz

GWs from sub-solar mass inspiraling compact objects

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



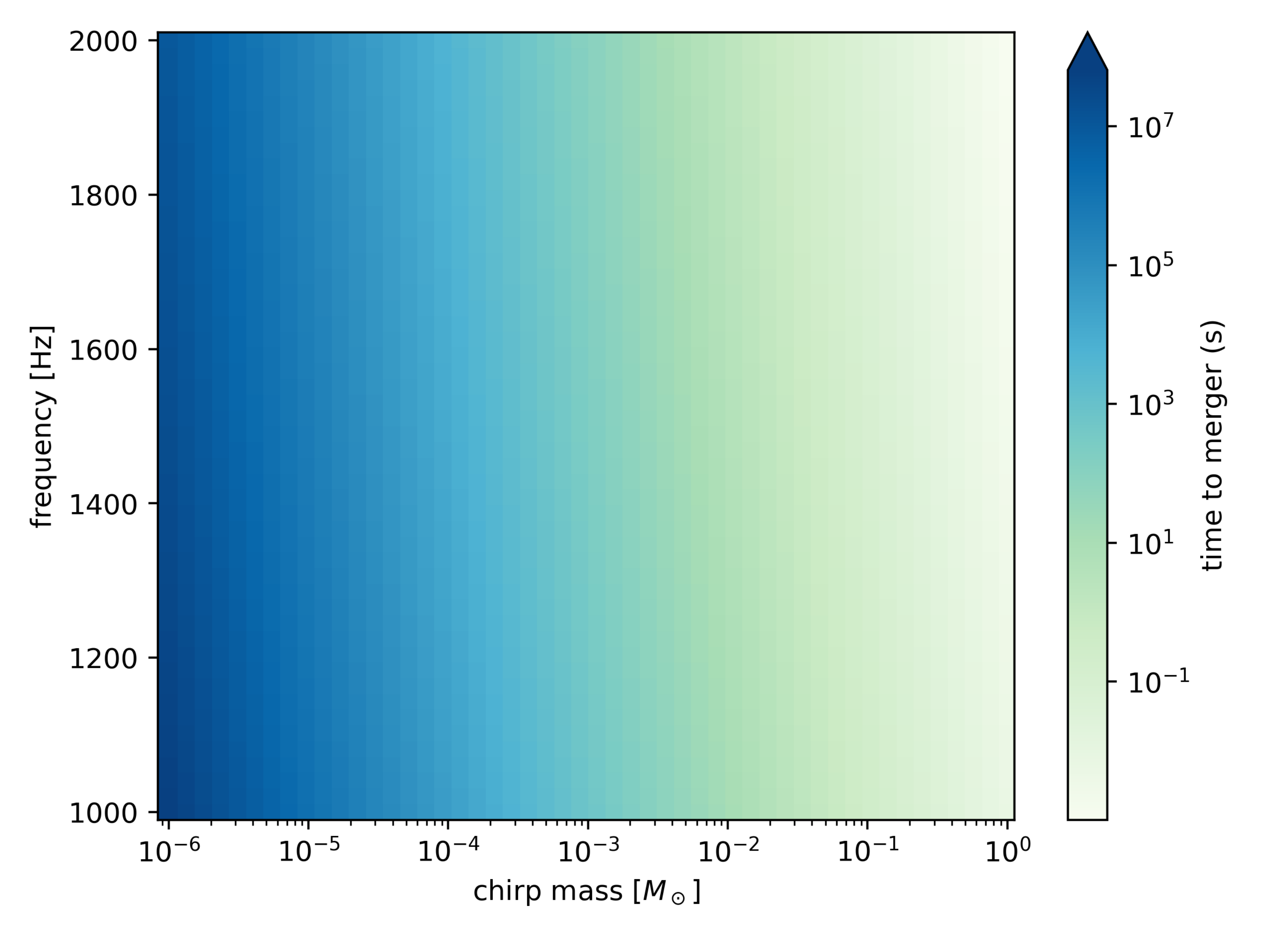
Green and Kavanagh (2021). Journal of Physics G: Nuclear and Particle Physics 48.4, 043001.

GWs from inspiraling PBHs

- The phase evolution of two objects far enough away from merger can be described by quasi-Newtonian circular orbits

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

- We analyze GW data looking for the phase evolution of the signal, characterized entirely by the chirp mass $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$ and signal frequency



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

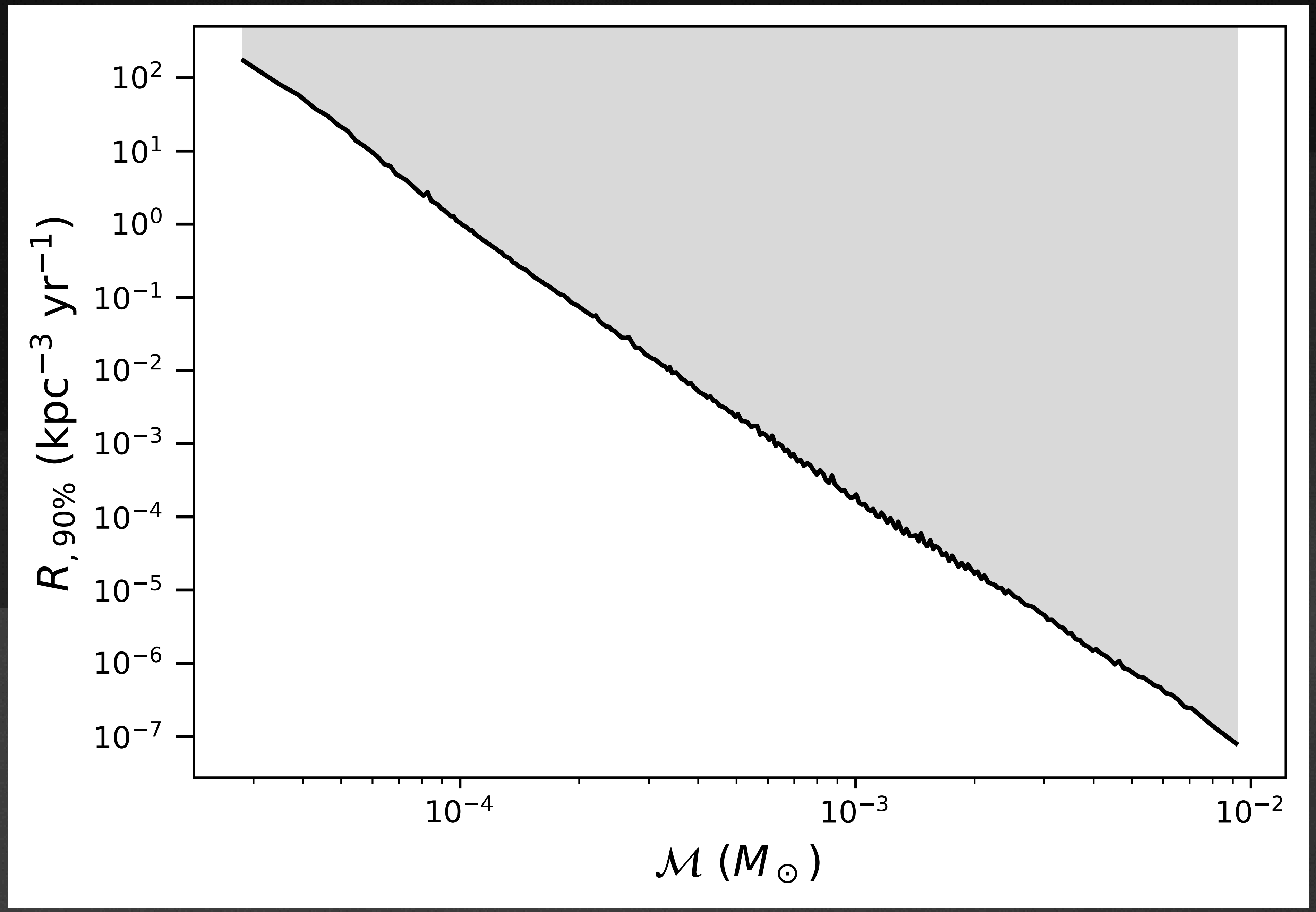
What's unique about the kHz regime?

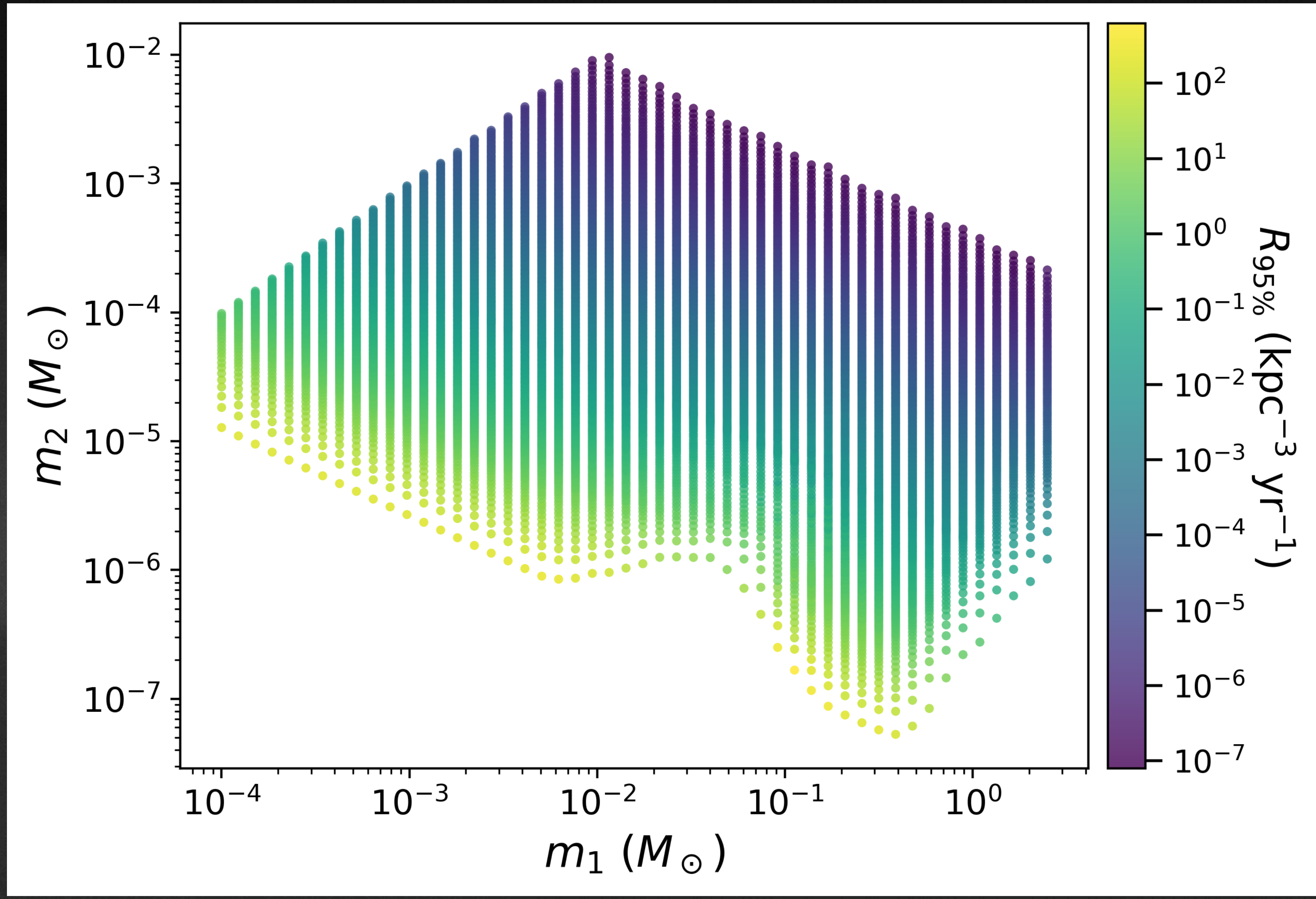
- At kHz frequencies, sub-solar-mass ultra-compact objects are closer to merger than at other frequencies
- Merger frequencies lie outside of the band
- The techniques that we use to look for objects with chirp masses $\mathscr{M} \lesssim 10^{-2} M_\odot$ require long-lived signals with orbits that don't quicken too much
- So, at kHz frequencies, we search for binaries of $\mathscr{M} \in [10^{-5},\ 10^{-4}] M_\odot$
  - Long and slow enough inspiral, but strong enough to be seen within the galaxy

O4a Search Results

arXiv: 2511.19911

O4a constraints on rate density



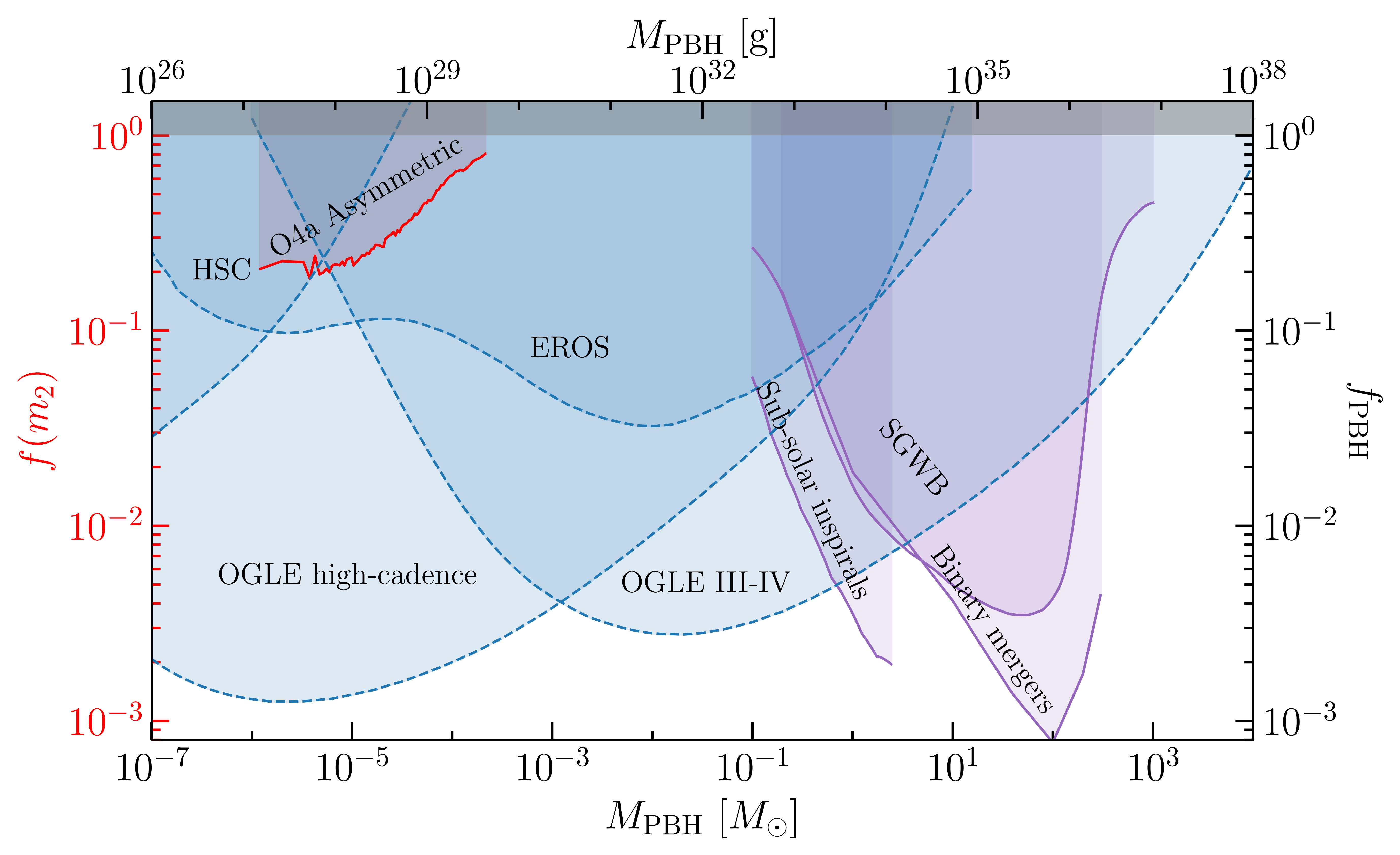


- Rate density constraints at 90% confidence level
- kHz constraints arise from $\mathscr{M} \in [3 \times 10^{-5},\ 2 \times 10^{-4}] M_\odot$
- Independent of PBHs; assume only ultra-compact binaries

LVK (2025): arXiv: 2511.19911

O4a constraints on PBH abundance

- Constraints on secondary mass m_2 assuming a primary mass $m_1 = 2.5 M_\odot$, motivated by the QCD phase transition;
- kHz range don't provide physical constraints in this plot
- Valid for specific type of mass functions and are thus highly model dependent
- Our limits complement those from microlensing experiments



LVK: PRL 123, 161102 (2019); LVK: PRL 129, 061104 (2022); LVK: MNRAS 524, 5984 (2023); Nitz and Wang PRL 127, 151101 (2021); Nitz and Wang PRD106, 023024 (2022); LVK: arXiv:2510.26848 (2025)

LVK (2025): arXiv: 2511.19911

Conclusions

- Dark matter can be probed directly via its interactions with GW detectors without the need to design new instruments!
- Gravitational waves can probe BSM particles forming clouds around rotating black holes, but the kHz regime has not been explored
- Planetary-mass compact binaries can be probed with pattern recognition techniques, but constraints on PBHs arising from kHz frequencies are weak
- See my recent review (arXiv:2503.02607, *IJMP D*) for more details on GW probes of DM
- If you are interested in working on any aspect of dark matter, please send me an email: andrew.miller.ligo@ucas.ac.cn

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

Back-up slides

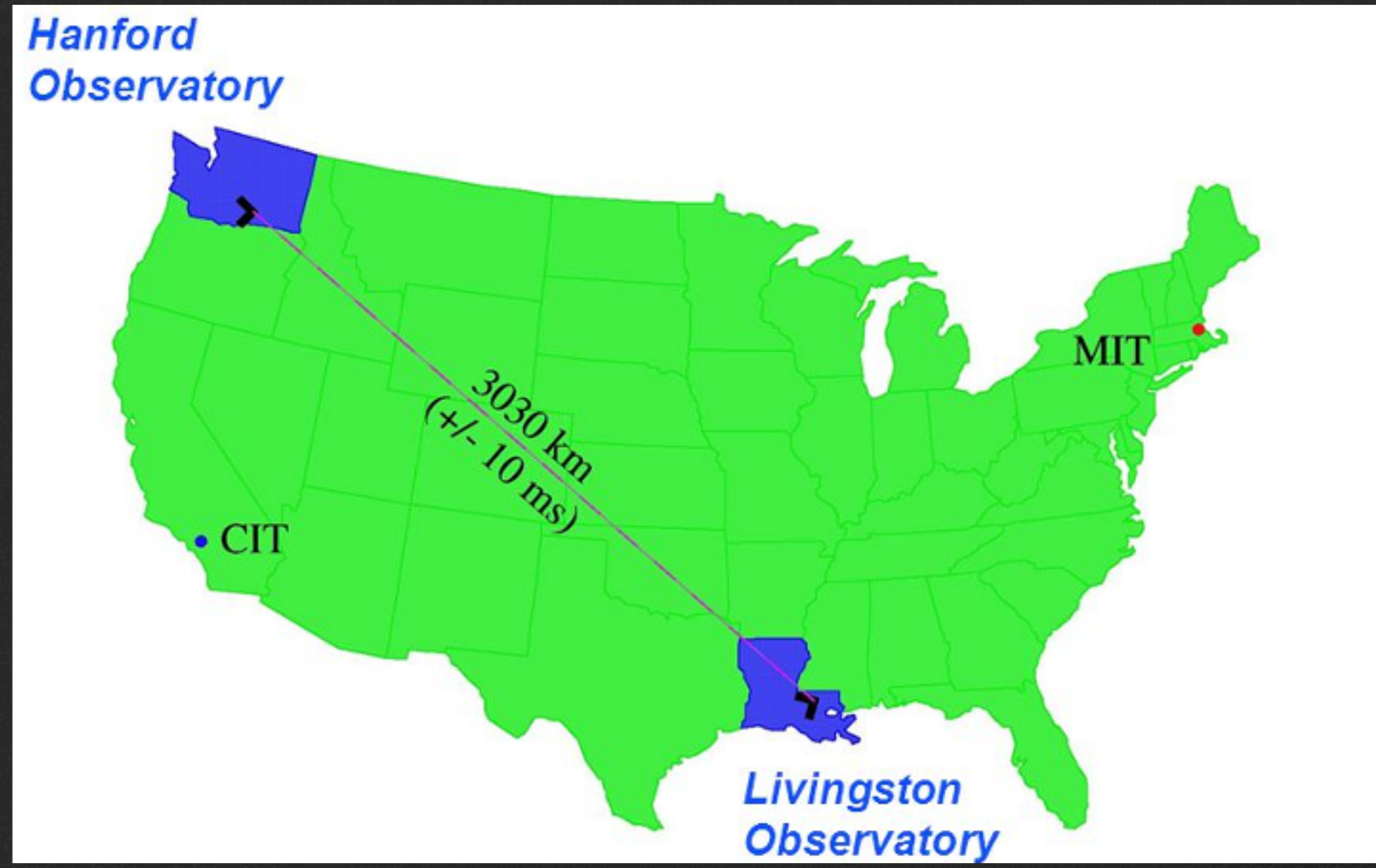
Ultralight dark matter

- 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

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

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

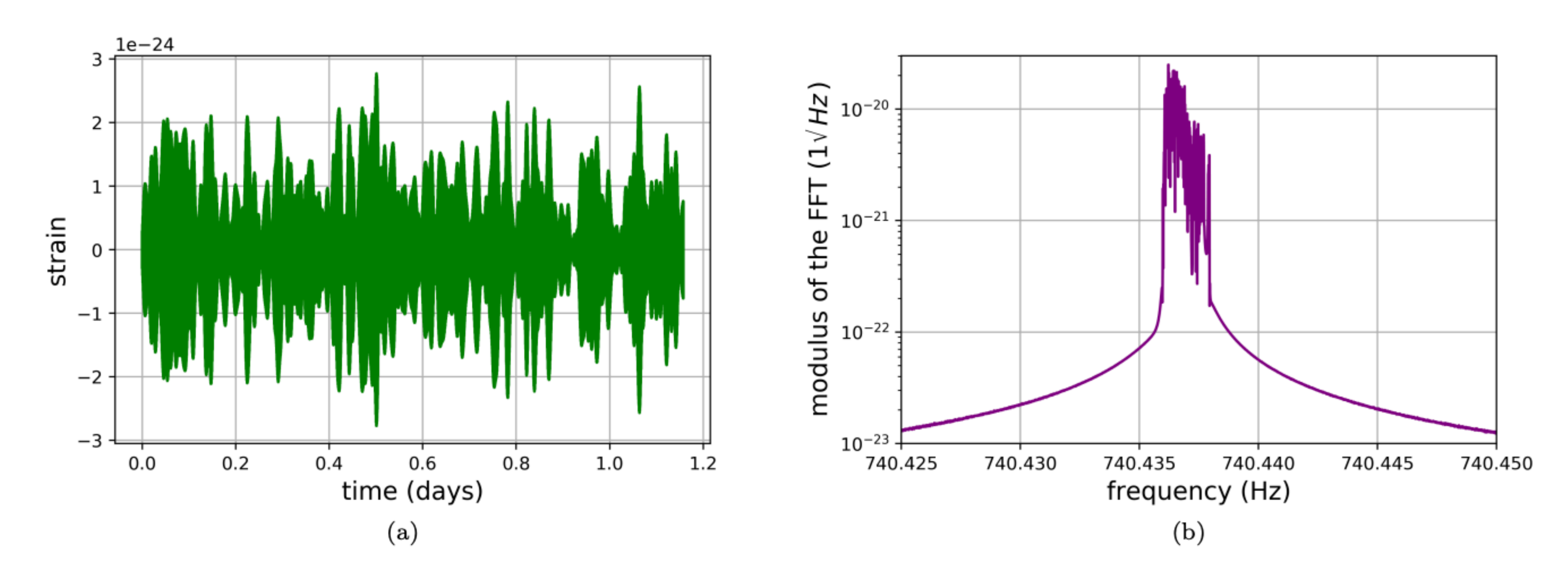
$$L_{\rm coh} \sim 10^9 \text{ m}$$



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 $T_{\text{FFT}} > T_{\text{coh}}$
- 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

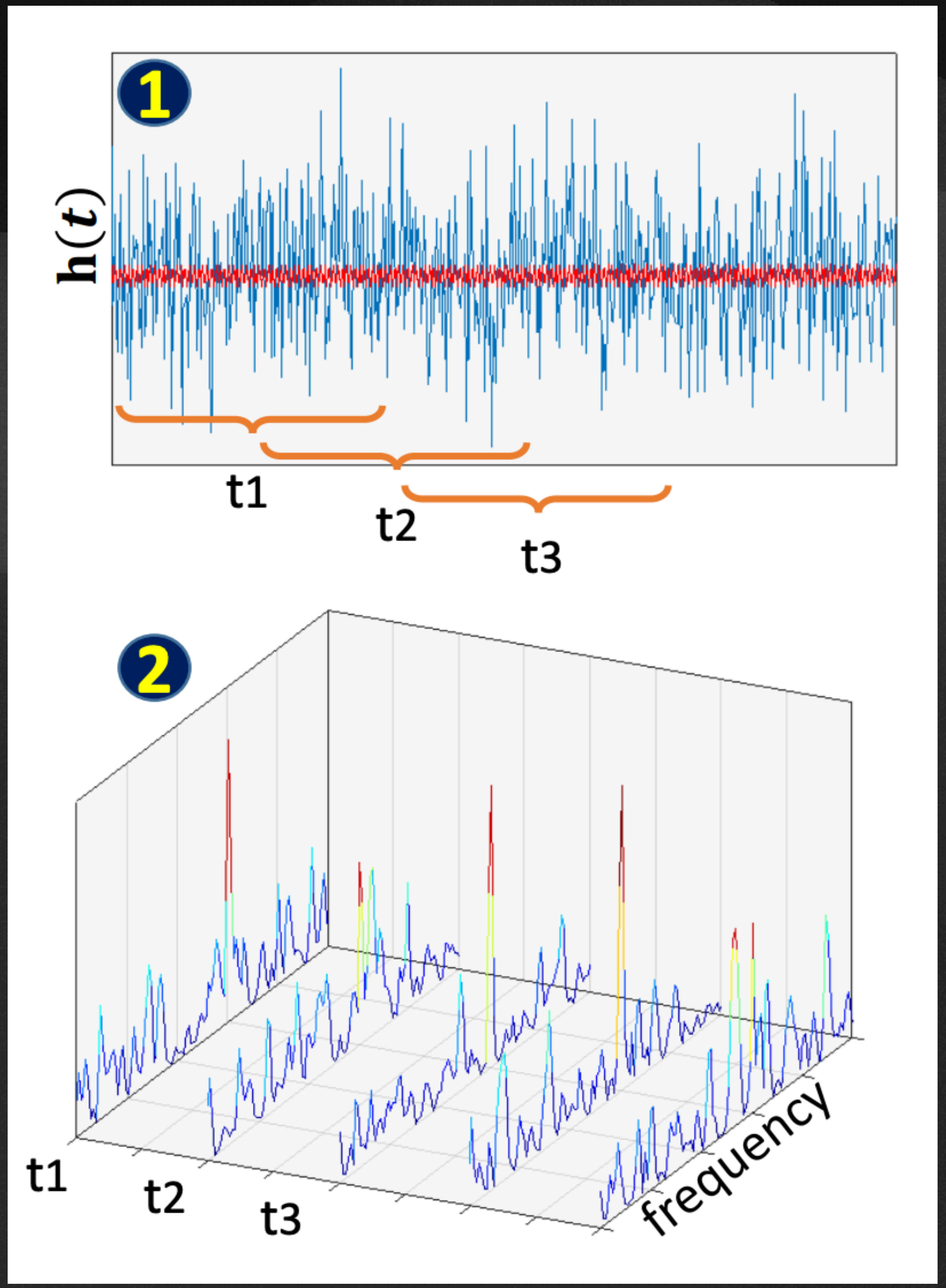


- One day shown, but signal lasts longer than observing run

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

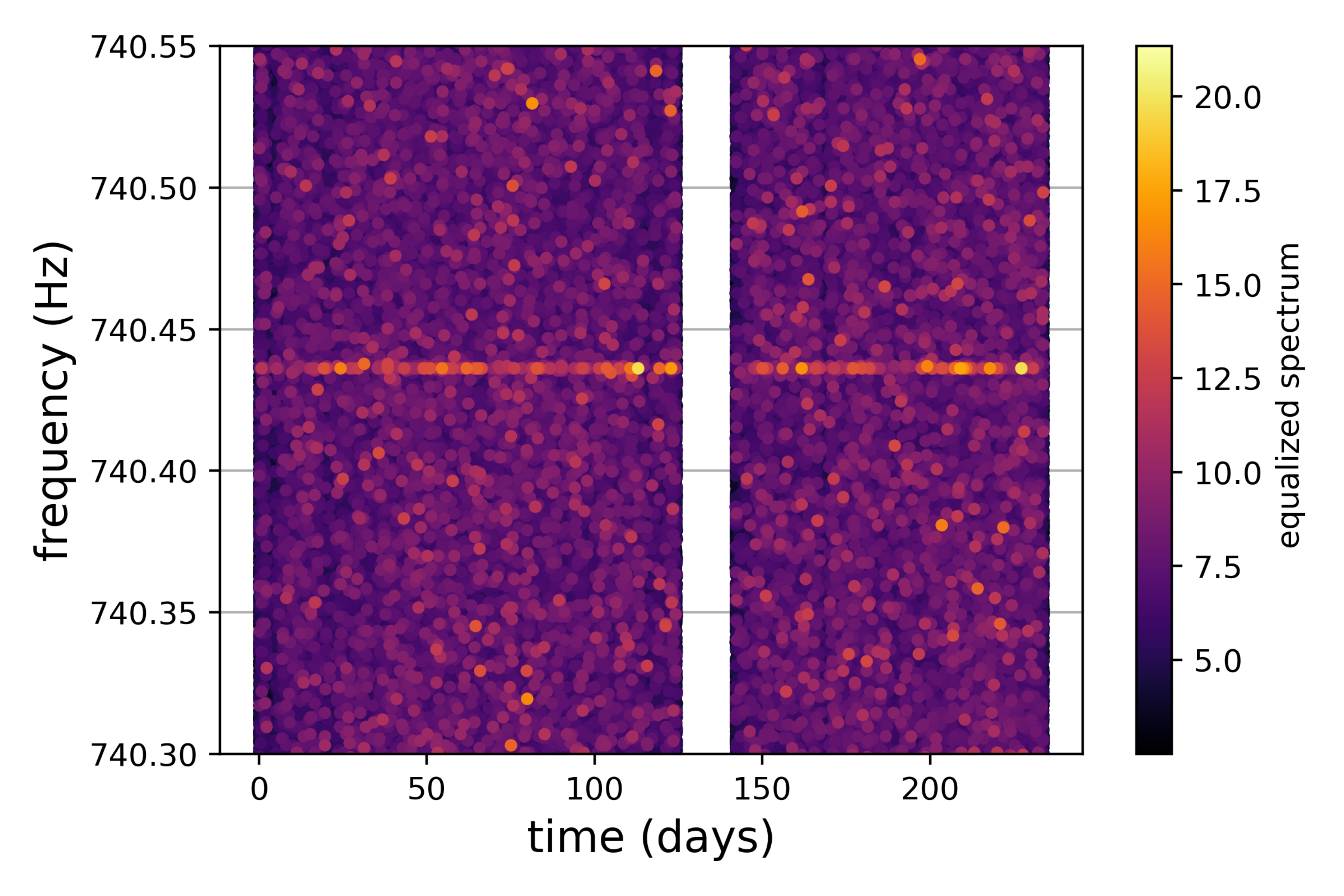
How to search for DM?

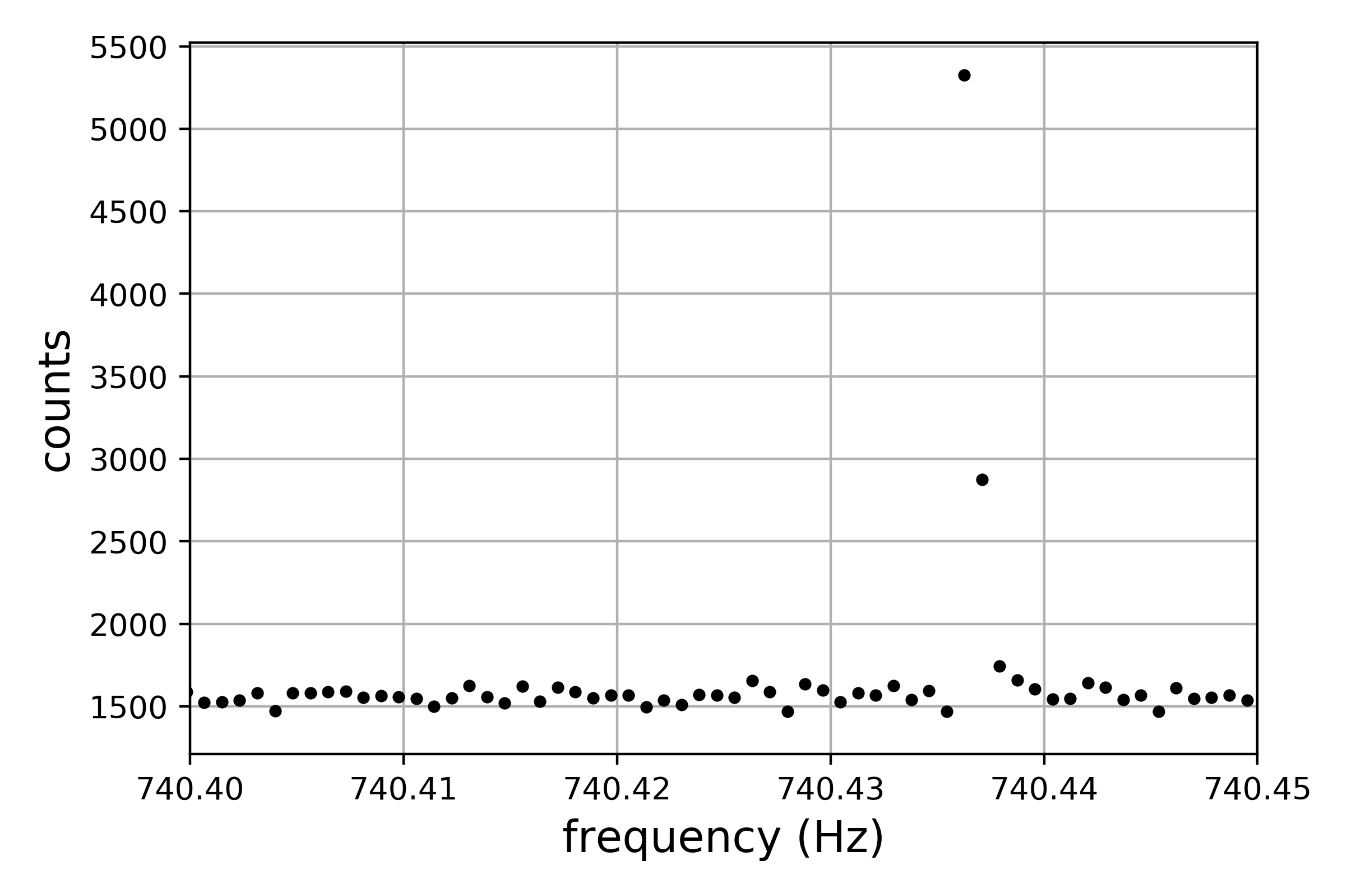
- Ideal technique to find weak signals in noisy data: matched filter
- But, signal has stochastic fluctuations —> matched filter cannot work
- The signal is almost monochromatic —> take Fourier transforms of length $T_{\mathrm{FFT}} \sim T_{\mathrm{coh}}$ and combine the power in each FFT without phase information



Credit: L. Pierini

Methods





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

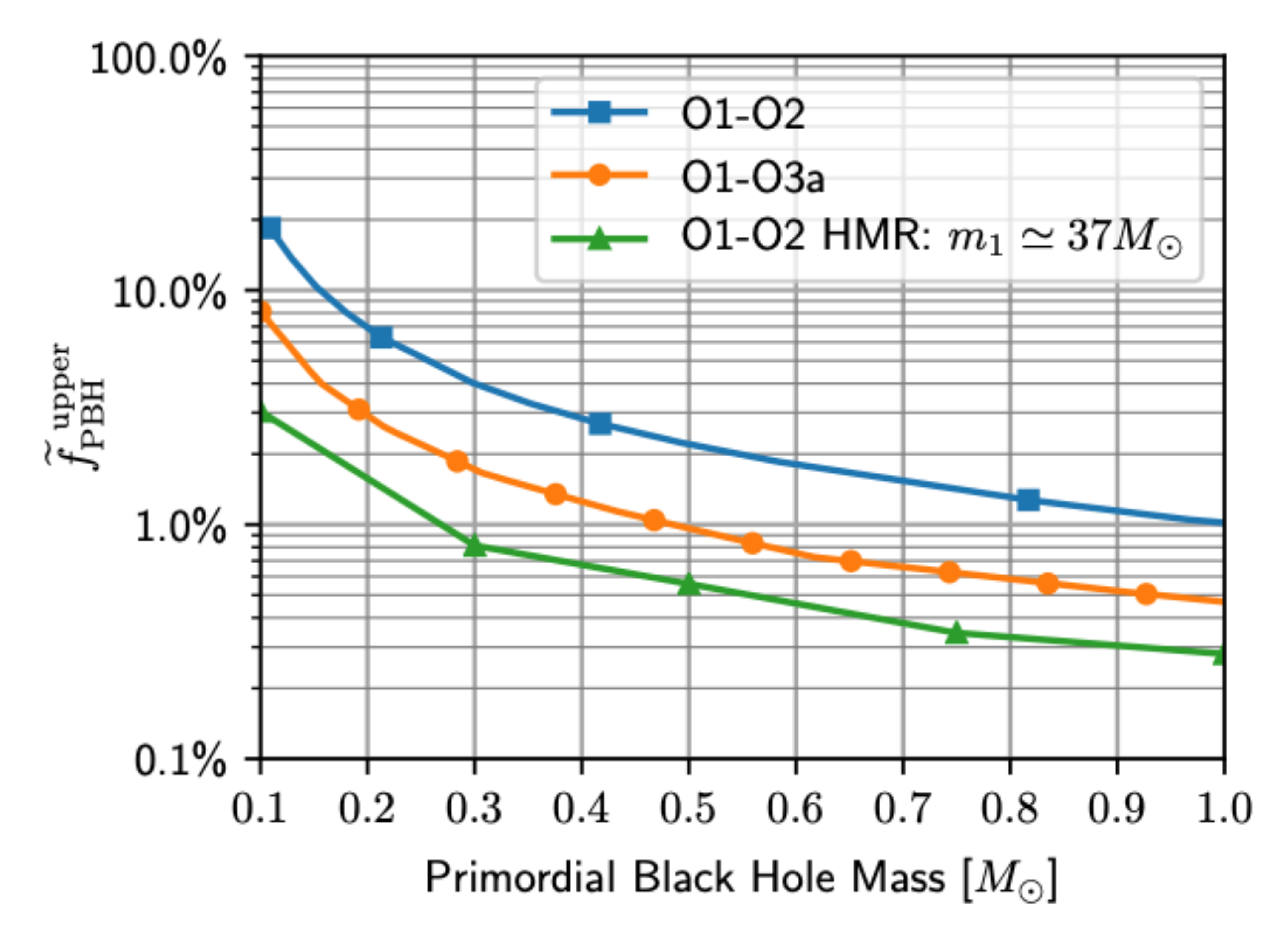
Pierce et al. 2018, PRL 121, 061102

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

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

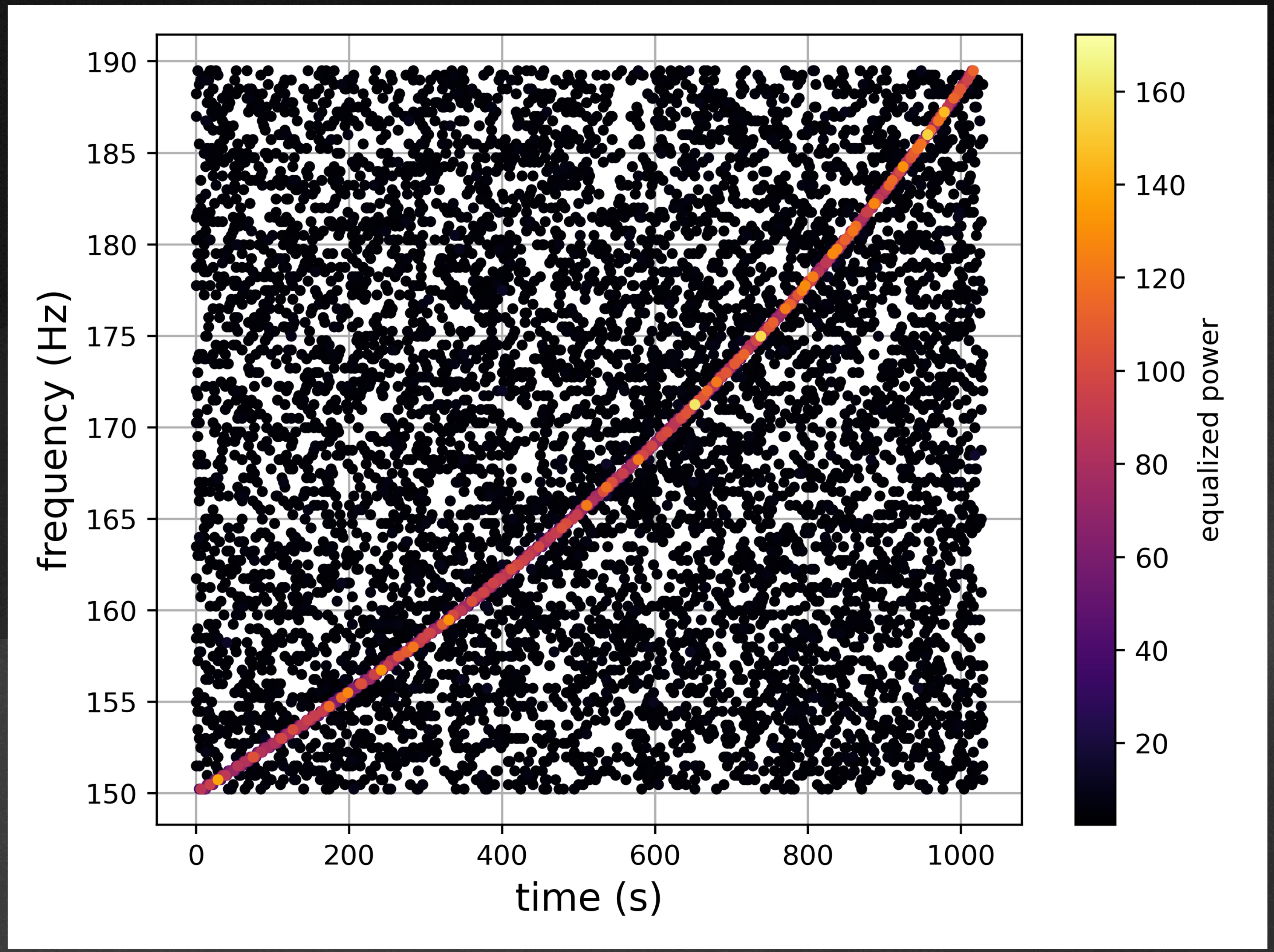
Motivation

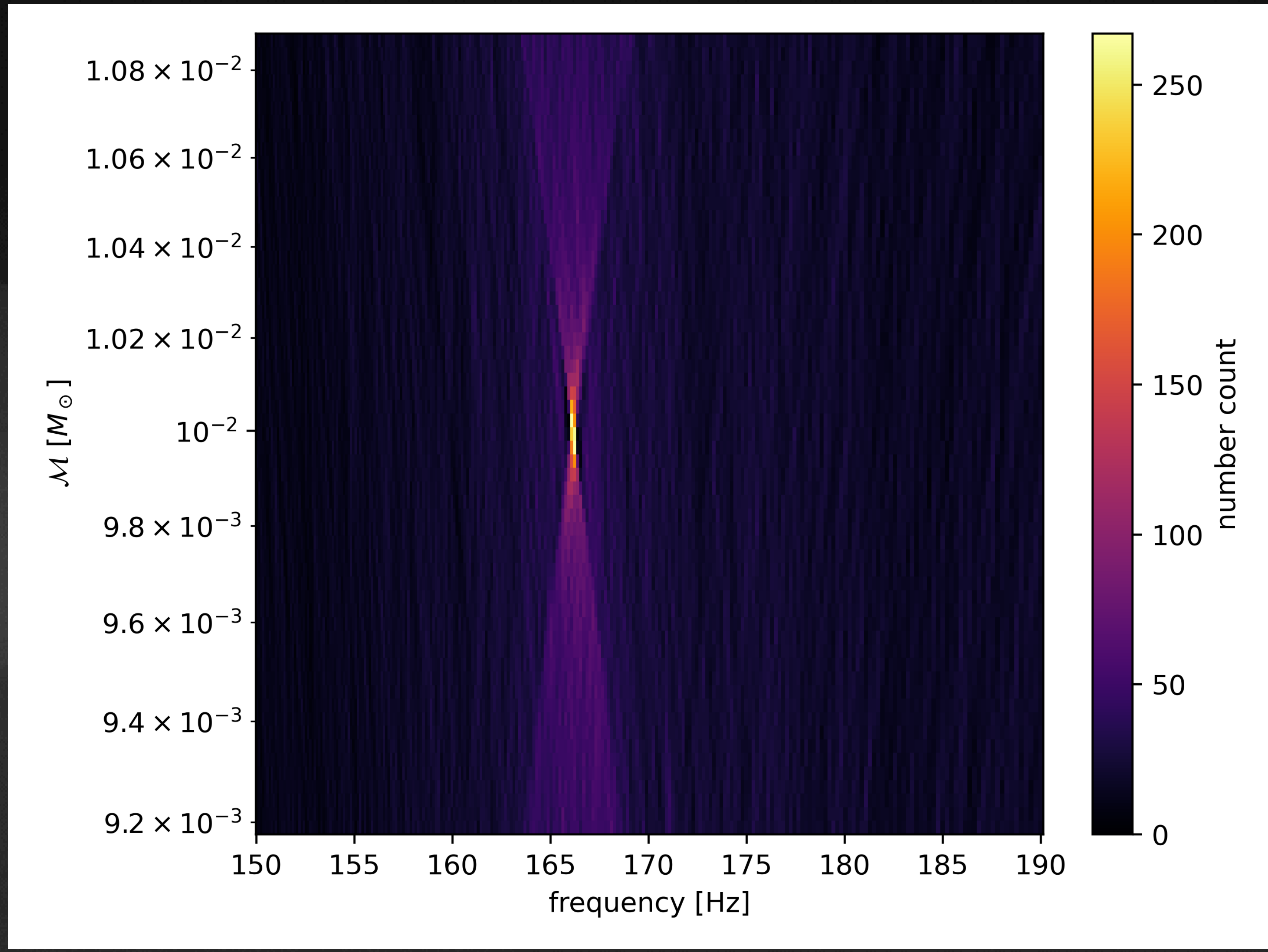
- Many GW efforts to detect PBHs focus on "sub-solar mass" regime, $\mathcal{O}(0.1M_{\odot})$
- However, GWs from $[10^{-7},10^{-2}]M_{\odot}$ PBH binaries have not yet been searched for
- Matched filtering in this mass range is extremely computationally challenging
    - Signals are long-lasting at LIGO frequencies—> many more templates needed for the same m_1, m_2 system if the system inspirals for longer



Nitz & Wang (2021): PRL 127 15, 151101.
LVK (2022): PRL 129 6, 061104
LVK (2023): MNRAS, 524, 4, 5984-5992

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

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

ALM et al. (2024) PRD 110.8: 082004.