Probing neutron stars and dark matter with continuous gravitational waves

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Who am I?

- Born & raised in New Jersey
- Collaborate with scientists in China, Japan, US, and all over Europe
- Enjoy nature, travel, hiking and volleyball
- Actively involved in DEI efforts to make physics more inclusive and equitable, and supervising students at all levels

Academic history

2011-2015	2015-2019	Aug.-Nov. 2019	2020-2022	2023-now
The College of New Jersey	University of Florida; Sapienza Università di Roma	ICRR Institute for Cosmic Ray Research University of Tokyo	UCLouvain	Nikhef; Utrecht University
Bachelor, physics	Joint PhD, physics	Visiting researcher	Postdoc #1	Postdoc #2

- Also involved in (not subject in this talk)
  - Machine learning efforts applied to isolated neutron star searches
  - Stochastic background searches for neutron stars
  - Early-warning for binary neutron star inspirals, Einstein Telescope

Joined LIGO/Virgo in 2015

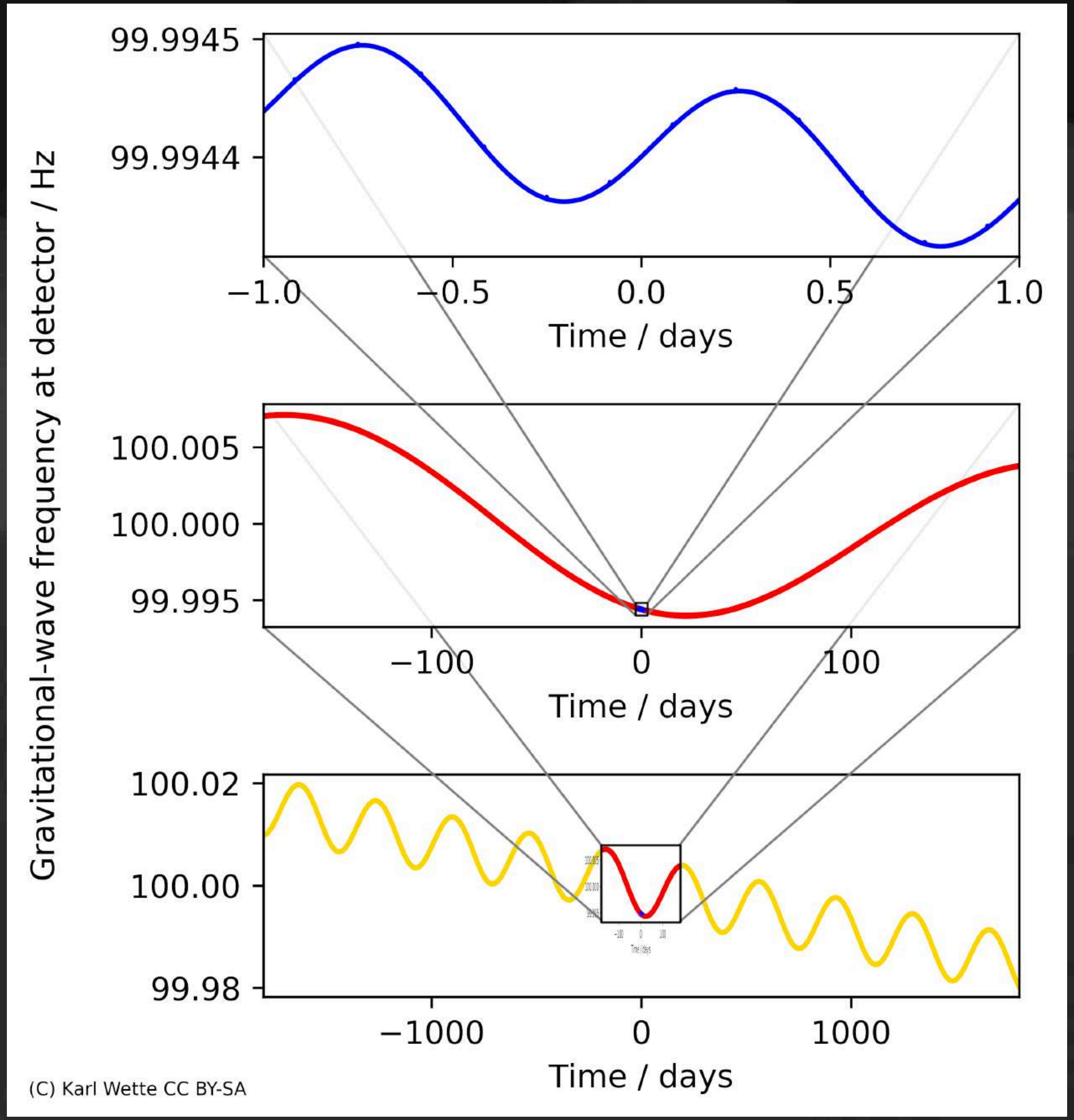
Outline

- Introduction and Motivation
- Gravitational waves (GWs) from neutron stars to probe GeV excess
- Direct detection of ultralight dark matter particles
- GWs from light primordial black holes (PBHs)
- GWs from boson clouds around spinning black holes

Introduction and motivation

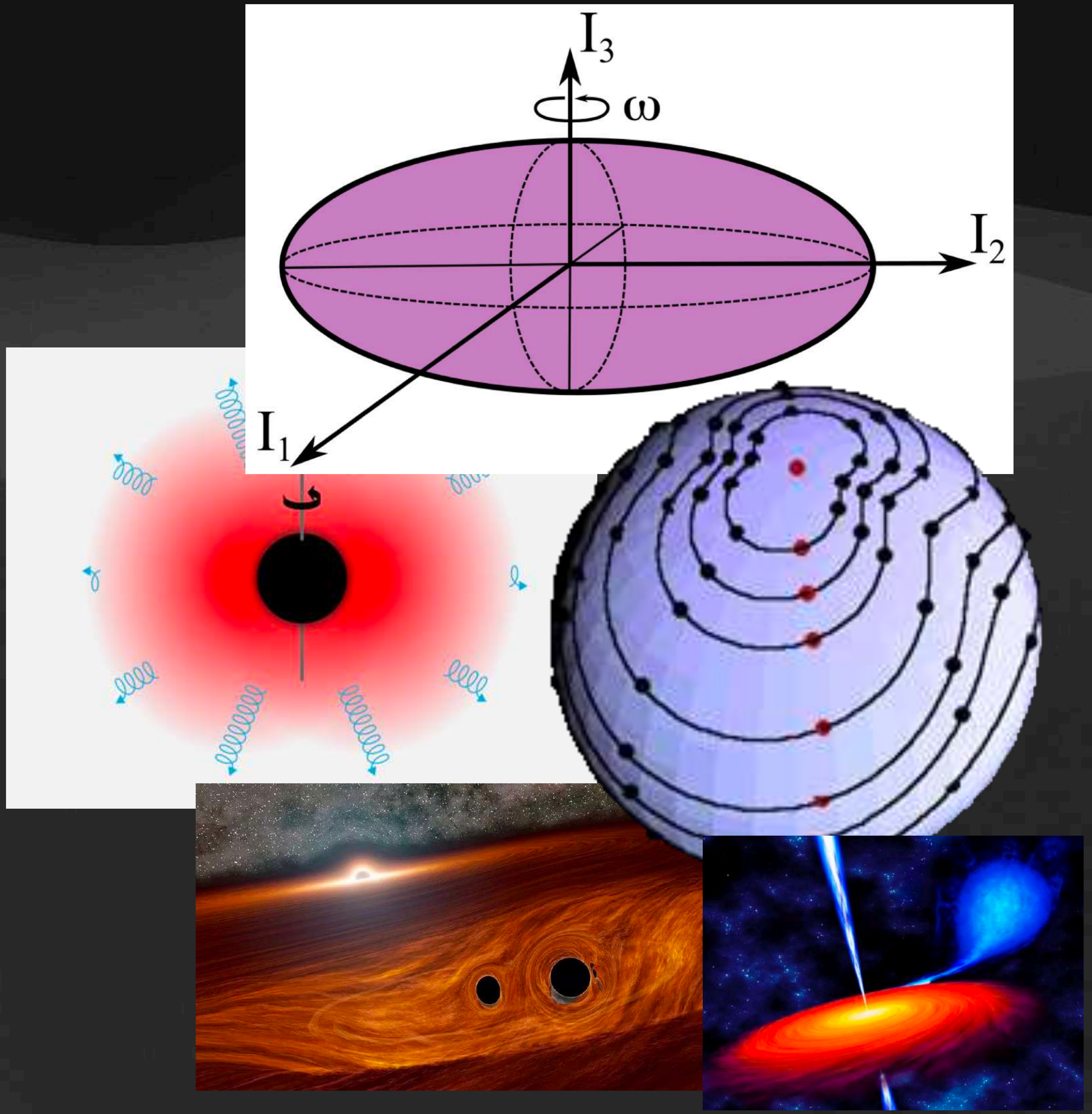
Continuous waves: what and why

- Quasi-monochromatic, persistent signals, subject to Doppler modulations
- The longer we can observe for, the more sensitive we are to these kinds of signals
- A completely new GW signal type: first detection will be another major milestone
- We can keep observing continuous-wave (CW) sources!



The breath of Continuous-wave sources

- SO MANY sources
  - Isolated neutron stars
  - Planetary/asteroid-mass inspiraling PBHs
  - Ultralight dark matter
  - Binary neutron star inspirals (Einstein Telescope)
  - White-dwarf binaries, intermediate-mass black holes (LISA)
- SO MANY algorithms
  - Matched filtering; Machine learning; sideband sums
  - Hough transform; Viterbi Hidden Markov Model; Cross Correlation



How to search for continuous waves?

- When we know the source location and parameters : matched filtering
- When we do not know the source location, nor its parameters, or are looking for exotic physics: semi-coherent methods
  - Break data into chunks of length T_{FFT} , where in each FFT, the signal power is contained to 1 frequency bin
  - Combine the power in these chunks incoherently
- Matched filtering is too computationally heavy and doesn't work well if the signal model is uncertain!

$\Delta f_{\mathrm{Doppler}} = 10^{-4} f$

$N_{\mathrm{sky}} \propto f^2 T_{\mathrm{FFT}}^2$

Computing cost scales as T_{FFT}^6

GWs waves from isolated neutron stars to probe GeV excess

Why probe GeV excess with GWs?

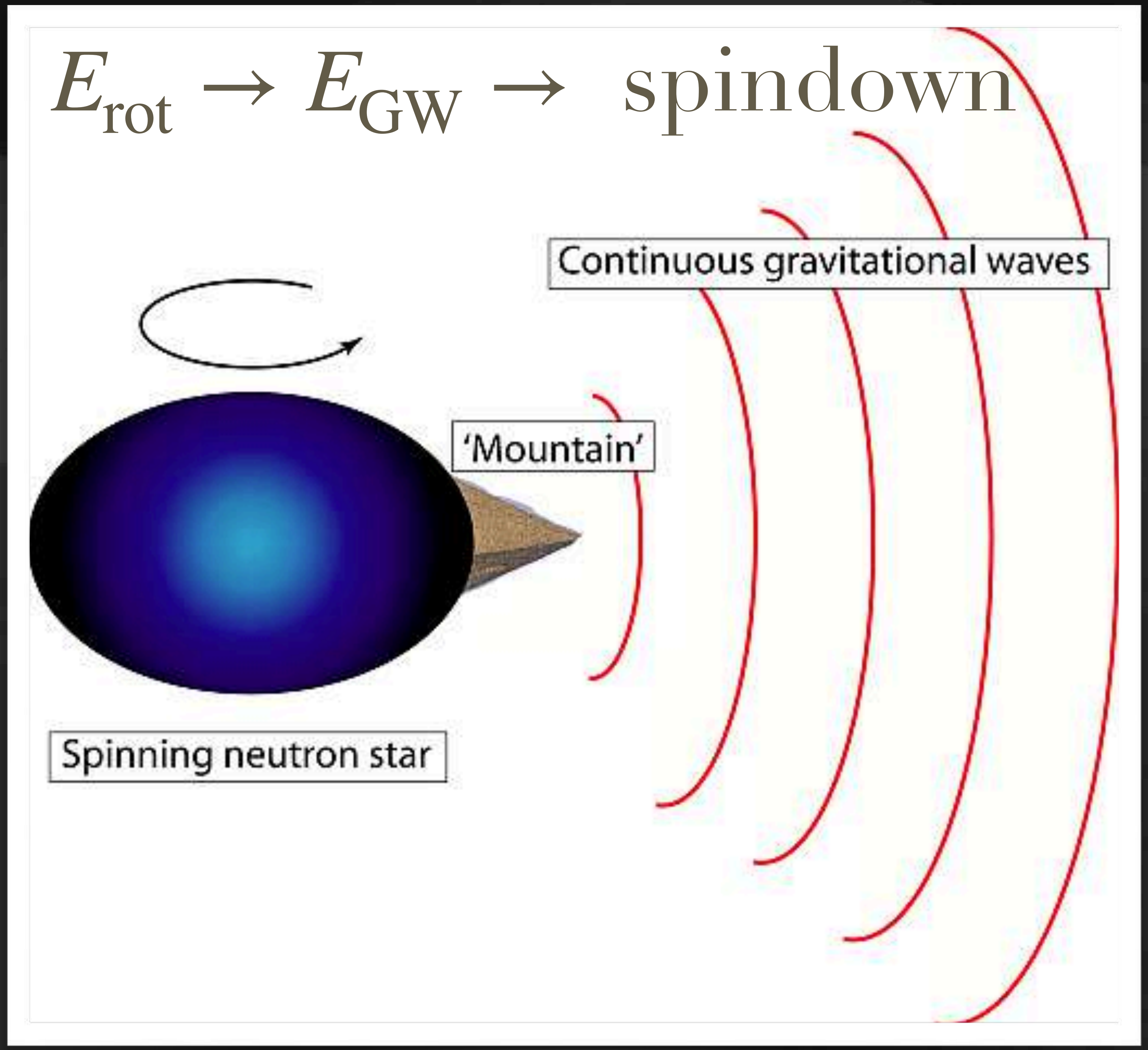
- Gravitational waves (GWs) are ‘smoking gun’ evidence for millisecond pulsars (MSPs) in the galactic center (GC)
    - No interactions with anything between us and sources
    - Would complement electromagnetic probes, but not reliant on them
    - We see ~ 3000 pulsars electromagnetically, but $\mathcal{O}(10^9)$ neutron stars in galaxy
    - Can *exclude* luminosity functions (harder electromagnetically)
- LIGO/Virgo/KAGRA are laser interferometers: they “hear” all GWs, no directional info —> we “point” at the data analysis level

How could isolated neutron stars emit gravitational waves?

- Deviation from spherical symmetry ("Mountain") —> "continuous" GWs

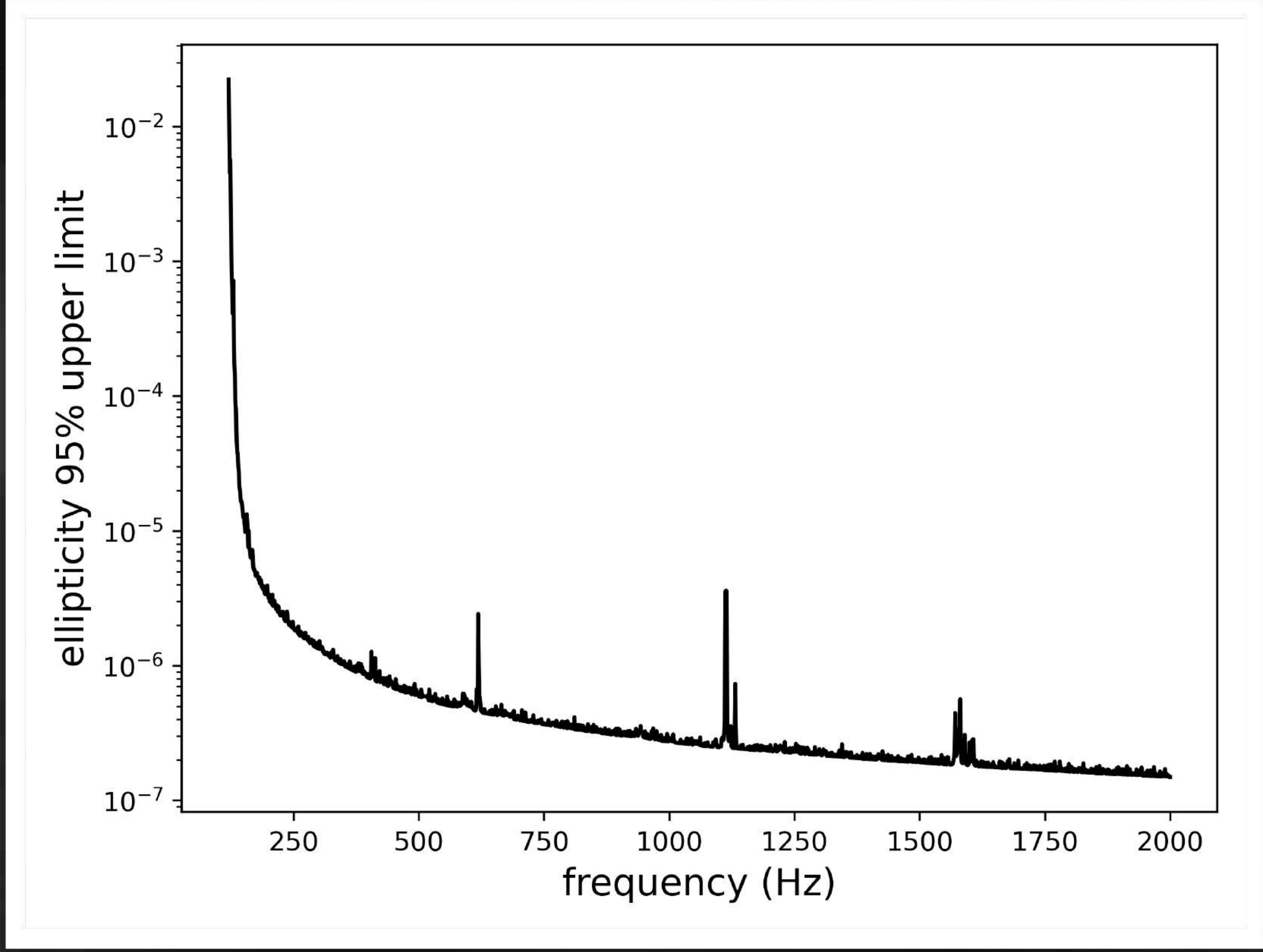
- Size of deformation quantified by *ellipticity*: $\epsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$, could be sustained by *internal* magnetic field

- Height of mountain is $\mathcal{O}(10\text{ km})\epsilon < \mathcal{O}(\mu\text{m})$ —> spin-down is $\mathcal{O}(10^{-10})$ Hz/s —> continuous GWs last **forever**



O3 search for GWs towards galactic center

- MSPs residing near GC could be detected via their GW emission
- For a search towards GC: we do not know the GW frequency, nor the spin-down —> search over these parameters
  - Put constraints on ellipticity at each frequency, for assumed I_{zz}
- Sky localization could be $\mathcal{O}$(arcsec)
- Use upper limits from O3 search to constrain MSP hypothesis



LVK: Phys. Rev. D, 106(10):102008, 2022.

First: Calculate probability of seeing MSPs in most recent data (O3)

- Calculate probability of detecting GWs from a MSP in GC

$$P_{\rm GW} = \int_{f_{\rm min}}^{f_{\rm max}} df P(f) \times \int_{\epsilon_{\rm UL}}^{1} d\epsilon P(\epsilon)$$

ϵ_{UL} : minimum detectable ellipticity in GW search
$P(f)$ and $P(\epsilon)$ are PDFs based on known pulsars

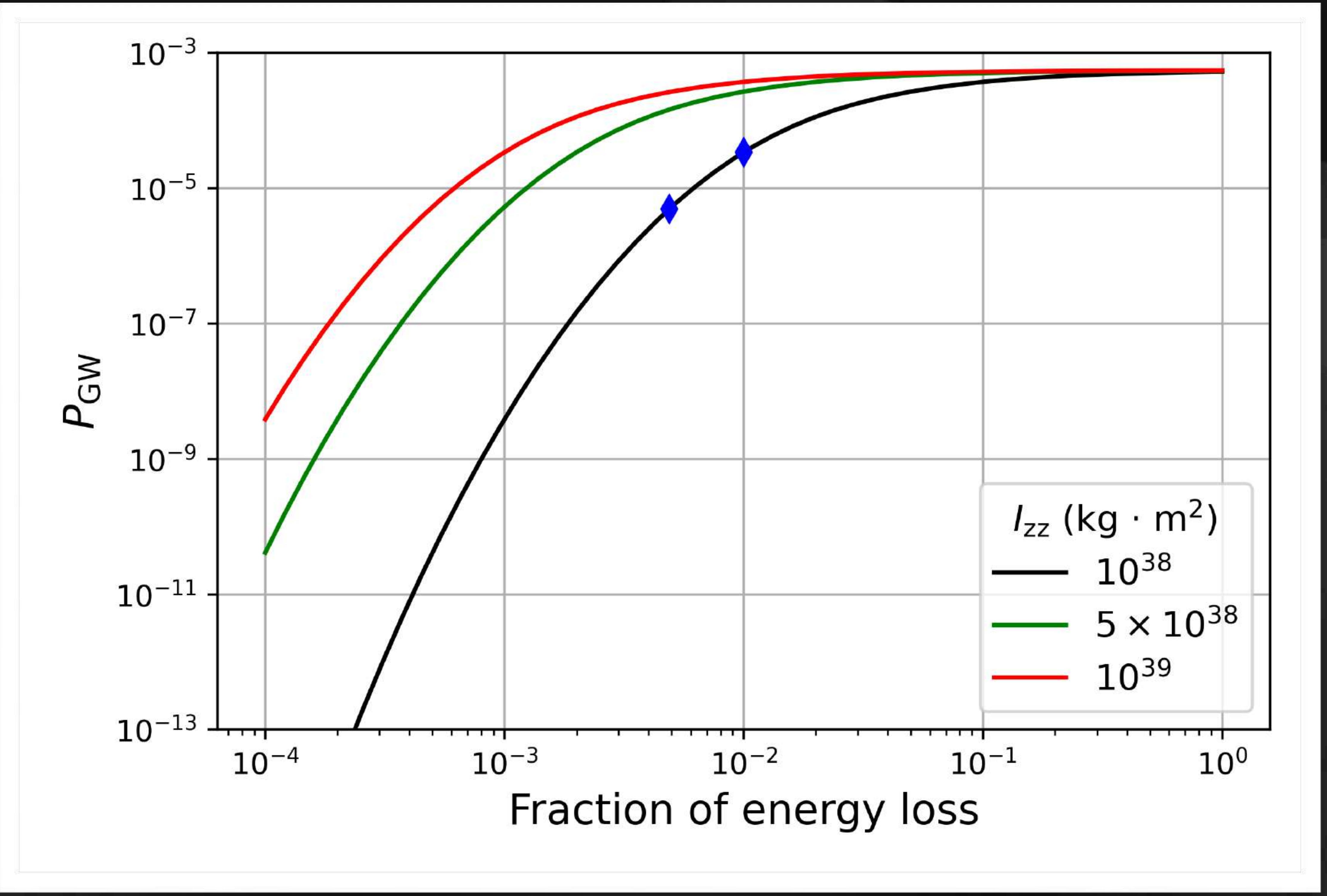
- This is **<u>independent</u>** of any luminosity function to explain the GeV excess

- We take a model-agnostic approach to the ellipticity distribution

  1. Ellipticities are calculated by assuming a fraction (~1%) of the rotational energy is converted into GWs based on parameters from observed pulsars in the Australian Telescope National Facility (ATNF) catalog

P_{GW} varies with model choices

- Probability to detect a GW, as a function of the fraction of rotational energy that we allow to be emitted as gravitational waves.
- Blue diamonds: parameters that we use to exclude luminosity function model (up next)



Miller and Zhao, arXiv:2301.10239

Second: Choose luminosity function

- We use a log-normal distribution, with central value L_0 and width σ_L for the luminosity function of MSPs that could explain the GeV excess [Hooper et al. Journal of Cosmology and Astroparticle Physics 2016.03 (2016): 049.]
- Choose L_0 and $\sigma_L \to N_{\mathrm{MSP}}$ —> exclude a certain choice of L_0 and σ_L if $N_{\mathrm{GW}} = P_{\mathrm{GW}} N_{\mathrm{MSP}} > 1$
- Could use ANY luminosity function

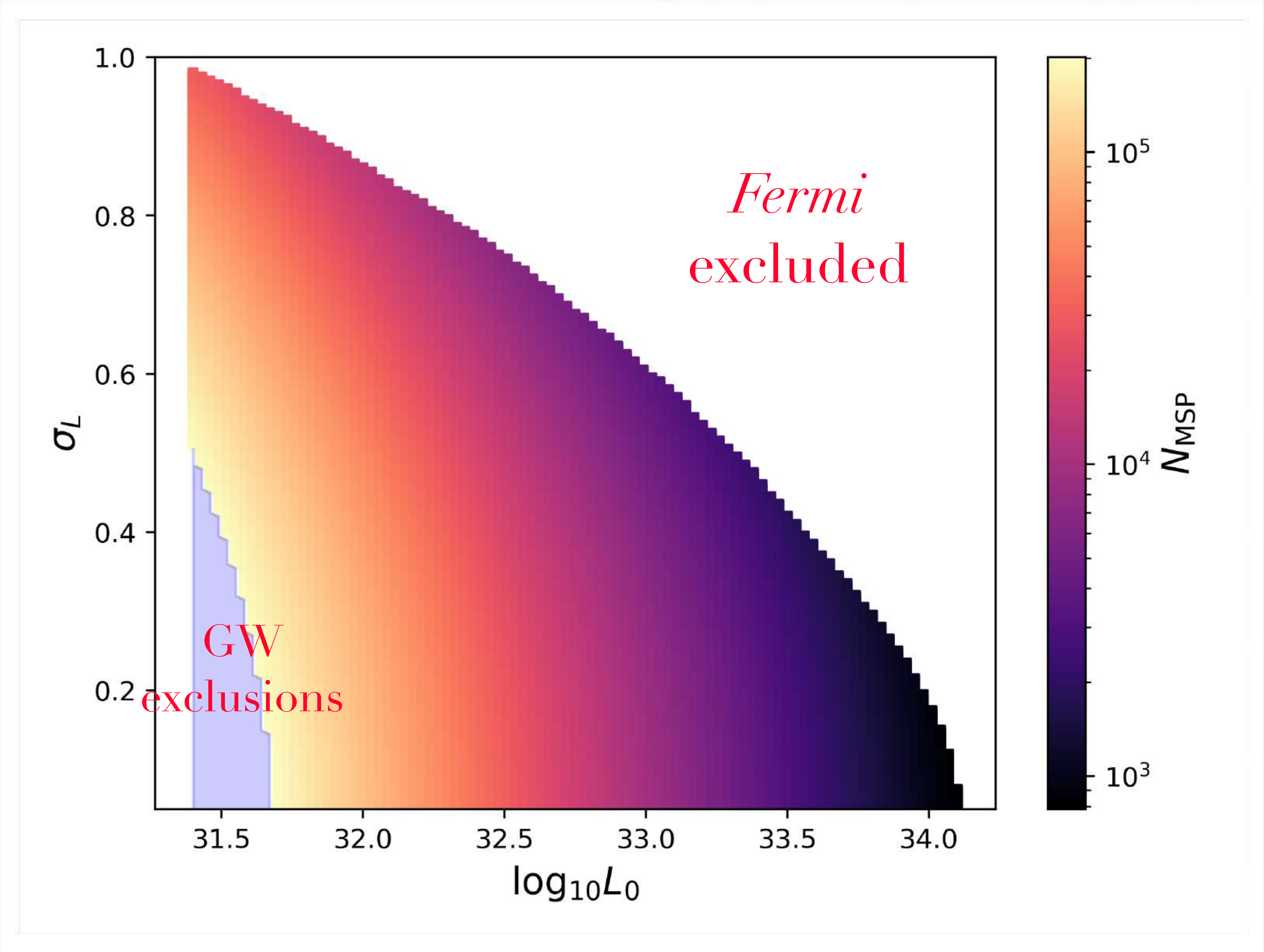
$$P(L) = \frac{\log_{10} e}{\sigma_L \sqrt{2\pi} L} \exp\left(-\frac{(\log_{10} L - \log_{10} L_0)^2}{2\sigma_L^2} \right)$$

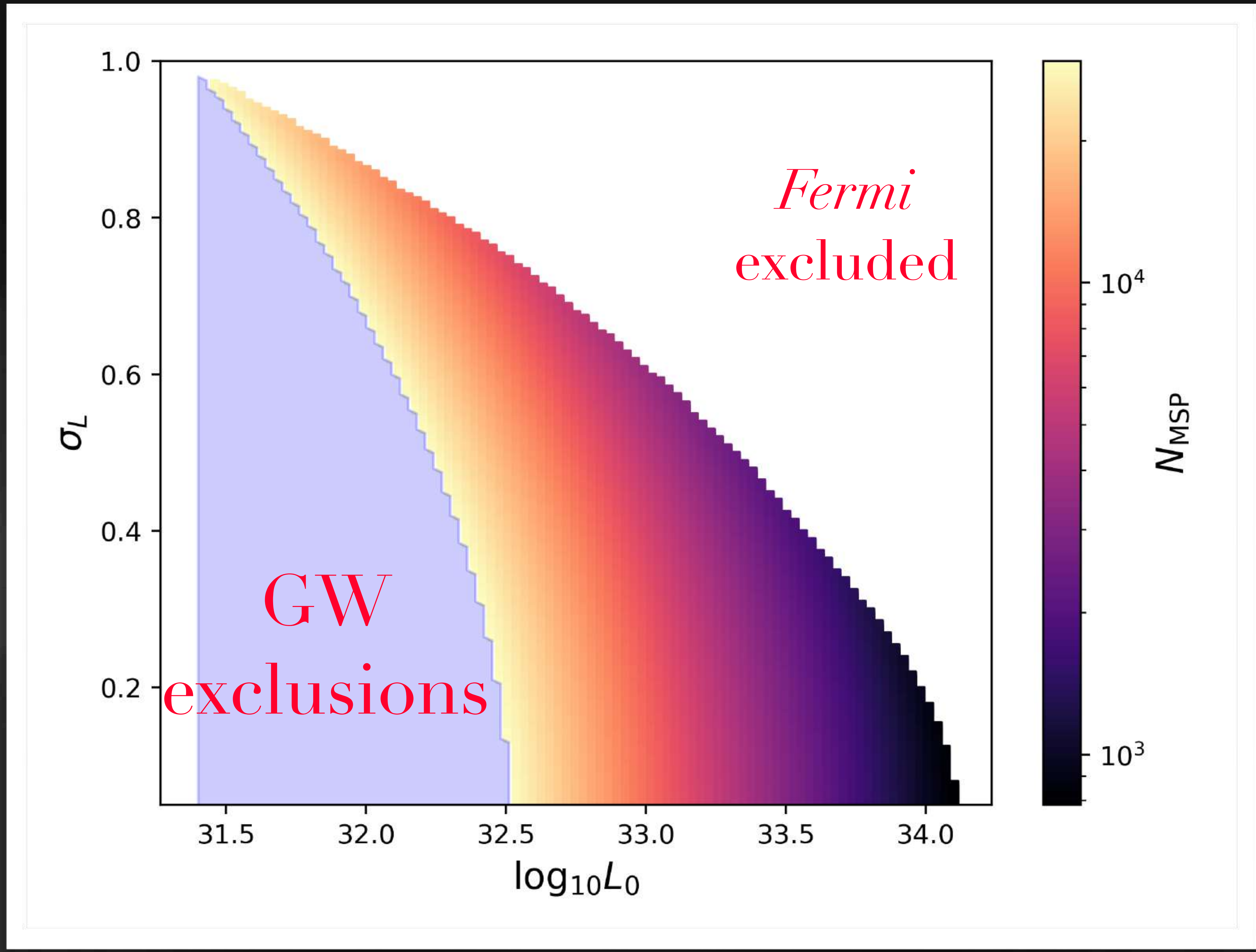
$$N_{\mathrm{MSP}} = \frac{L_{\mathrm{GCE}}}{\int_{L_{\min}}^{\infty} L P(L) dL}$$

$$L_{\mathrm{GCE}} \approx 10^{37} \mathrm{erg/s}$$

Based on *Fermi* flux measurements and model for number density of MSPs

Results: exclusion plots





- Derive source ellipticites from ATNF catalog assuming that GWs are emitted with 0.5% and 1% of the rotational energy of the star

Miller and Zhao, arXiv:2301.10239

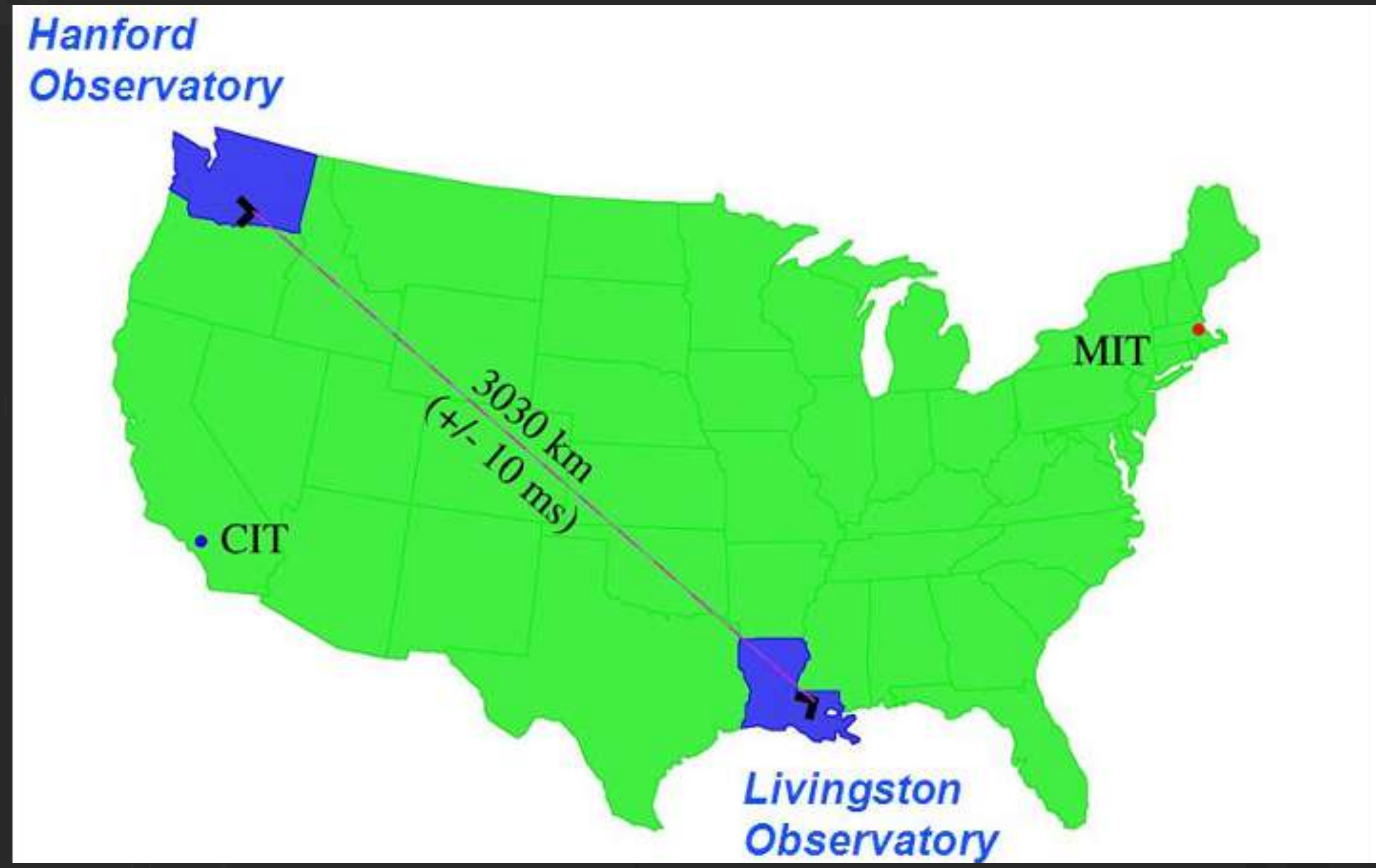
Direct detection of dark matter

Ultralight dark matter: dark photons

- Different types of dark matter could directly interact with interferometer components, leading to a signal that is NOT a GW
- Model as superposition of plane waves, whose velocities follow Maxwell-Boltzmann distribution
  $v_0 \sim$ 220 km/s $\rightarrow \Delta f/f \sim v_0^2/c^2 \sim 10^{-6}$
- Stochastic frequency modulations, $\mathcal{O}(10^{-6}f)$ Hz

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

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



Pierce et al. 2018, Phys. Rev. Lett. 121, 061102
Morisaki et al. 2021, Phys. Rev. Lett. 103, L051702
Vermeulen et al. 2021, Nature 600, pages 424–428

Vector bosons: dark photons

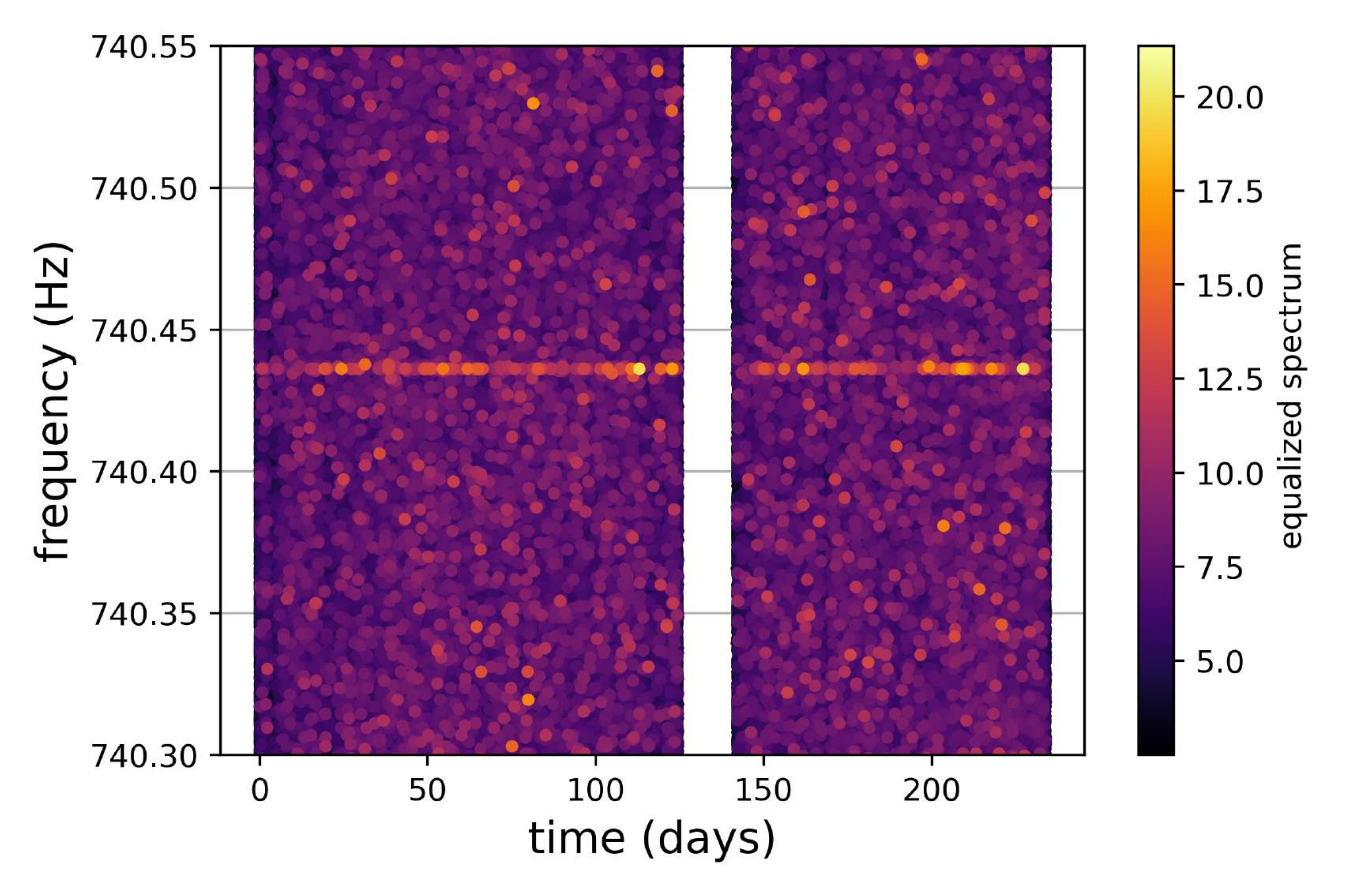
$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \boxed{\frac{1}{2}m_A^2 A^\mu A_\mu - \epsilon_D e J_D^\mu A_\mu},$$

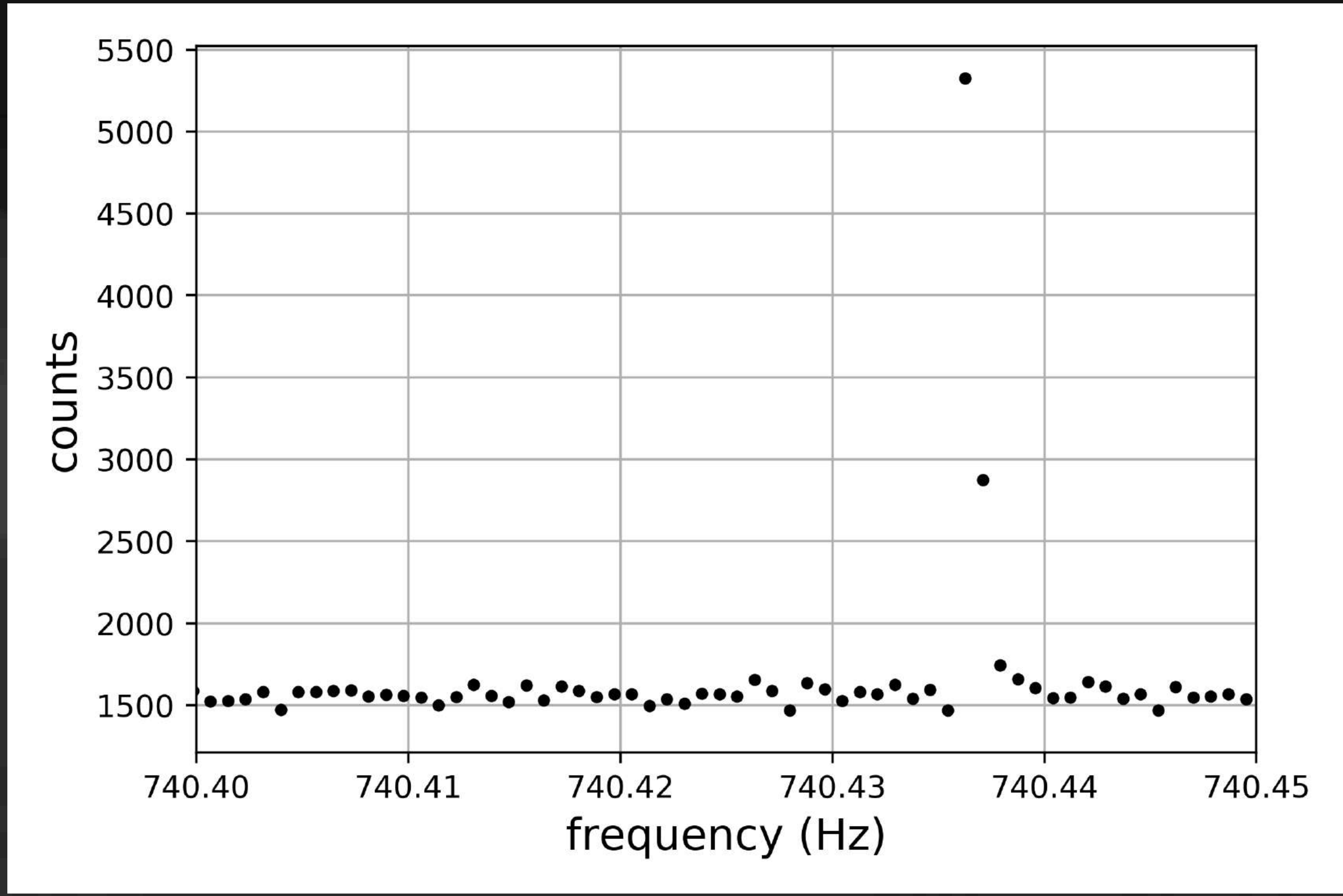
m_A : dark photon mass
ε_D : coupling strength
A_μ : dark vector potential

- Gauge boson of U(1) group that interacts weakly with baryons or baryon-lepton number in materials
- Well-motivated theoretically (arise from misalignment mechanism)
- In the absence of a detection, we put limits on ε_D
- Differential strain from a spatial gradient in the dark photon field
- Apparent strain results from a “finite light travel time” effect

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

Method: Excess power projection



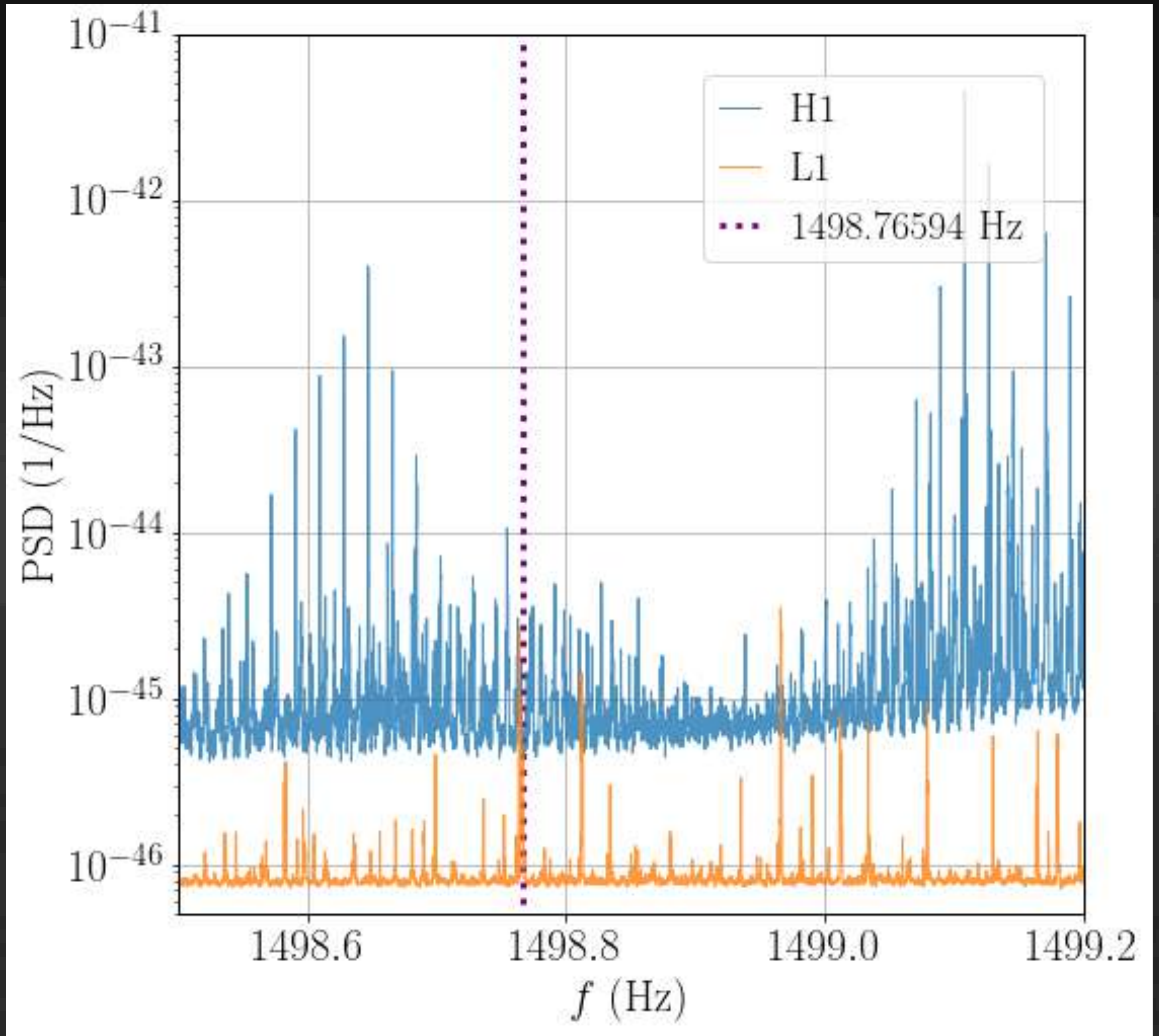


- Choose T_{FFT} to match T_{coh} —> make time/frequency map and project
- O2 Livingston data shown here with a simulated dark photon signal

Miller et al. Phys.Rev.D 103 (2021) 10, 103002

Results: O3 dark photon search

- 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

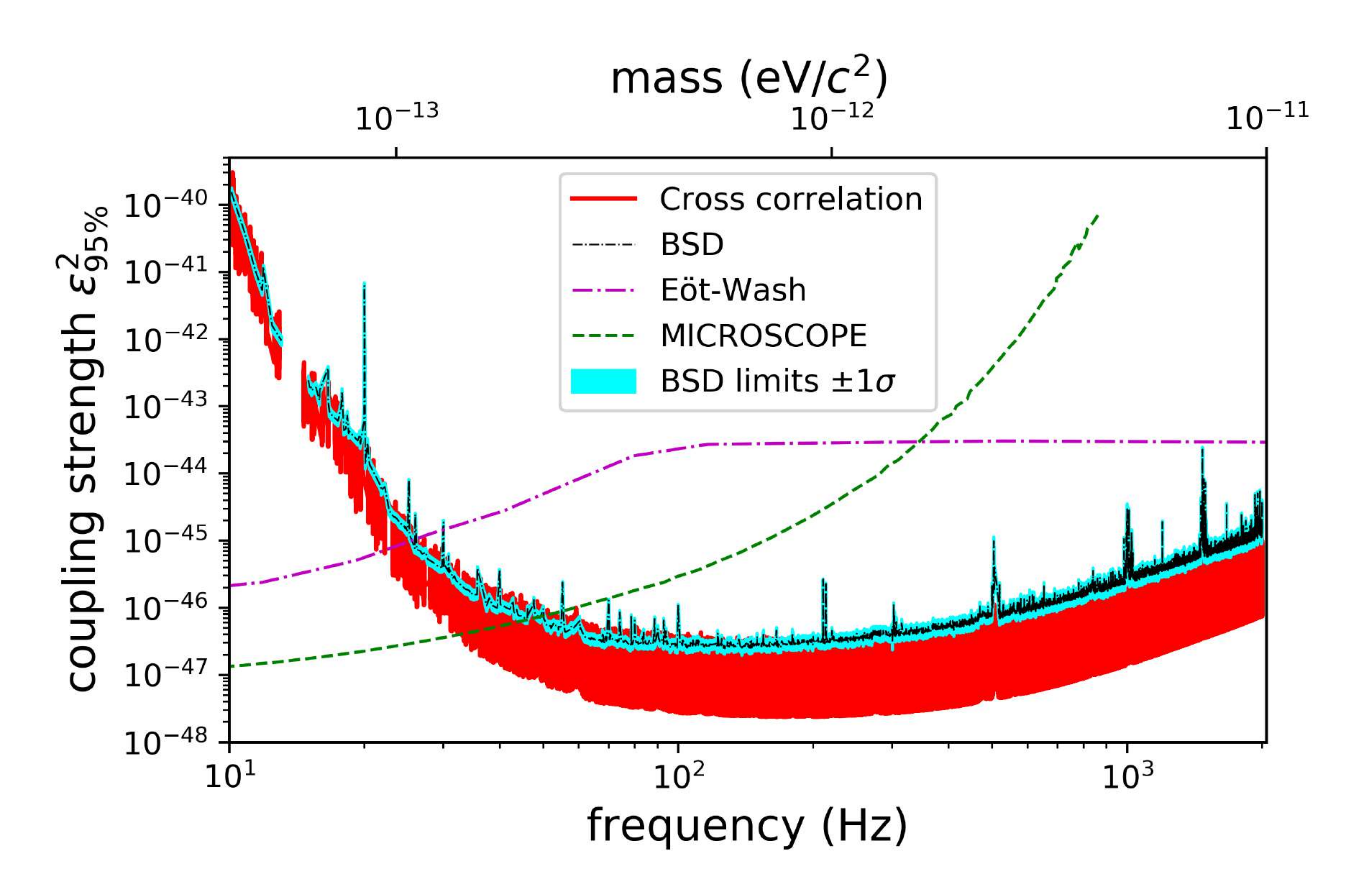


Power spectral density around one outlier (vertical purple line)

LVK 2021: Phys.Rev.D 105 (2022) 6, 063030

Results: O3 dark photon search

- Upper limit from two methods (cross correlation and BSD)
- One fixes $T_{\mathrm{FFT}} = 1800$ s; other matches T_{FFT} to dark matter coherence time
- Compared to limits from existing torsion balance experiments (Eöt-Wash) and MICROSCOPE satellite
- Other types of DM can be searched for too! (Dilations, axions, tensor bosons)



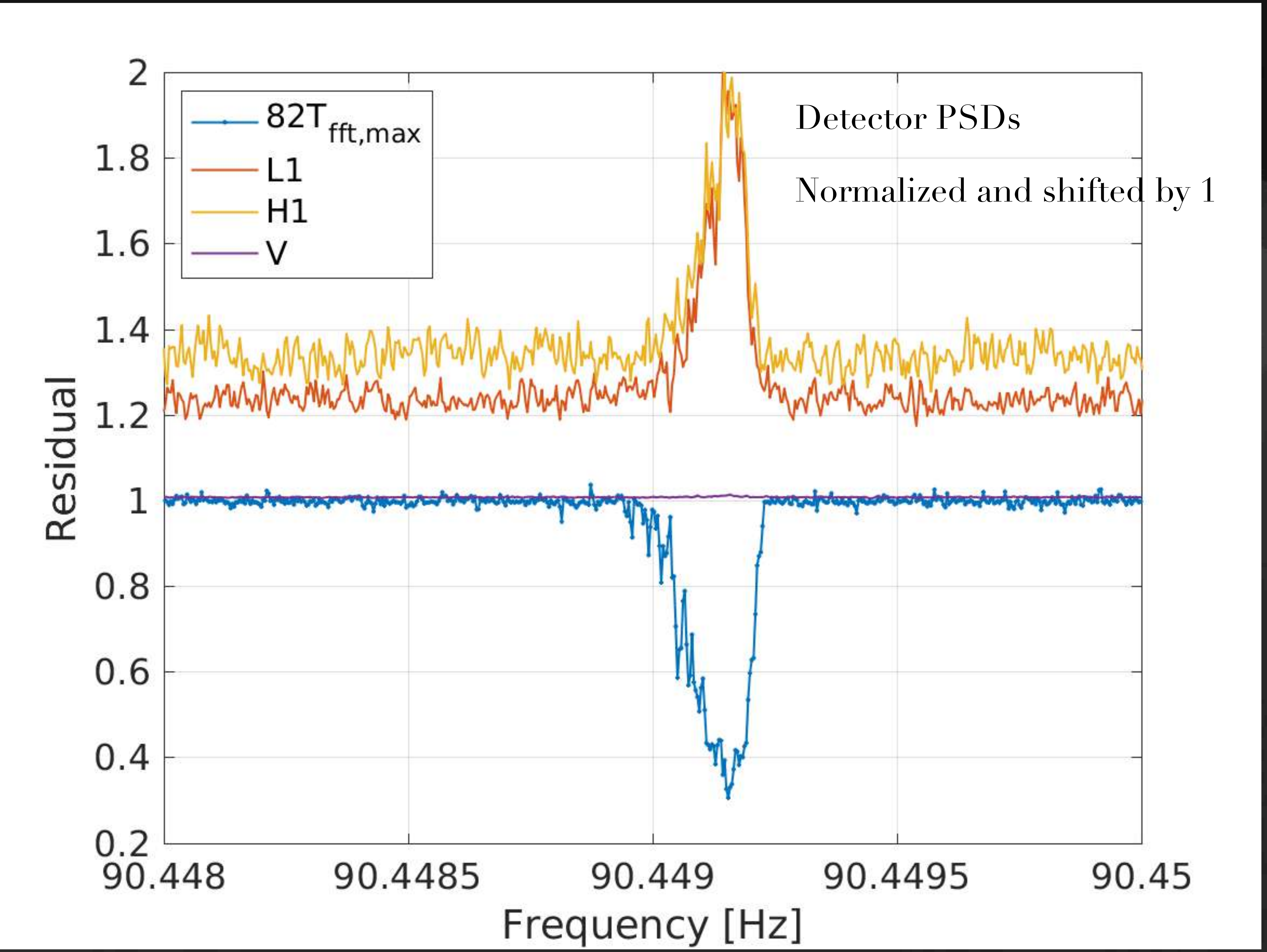
Guo et al. Nat. Commun.Phys. 2 (2019)

LVK 2021: Phys.Rev.D 105 (2022) 6, 063030

Distinguishing DM: Wiener Filter

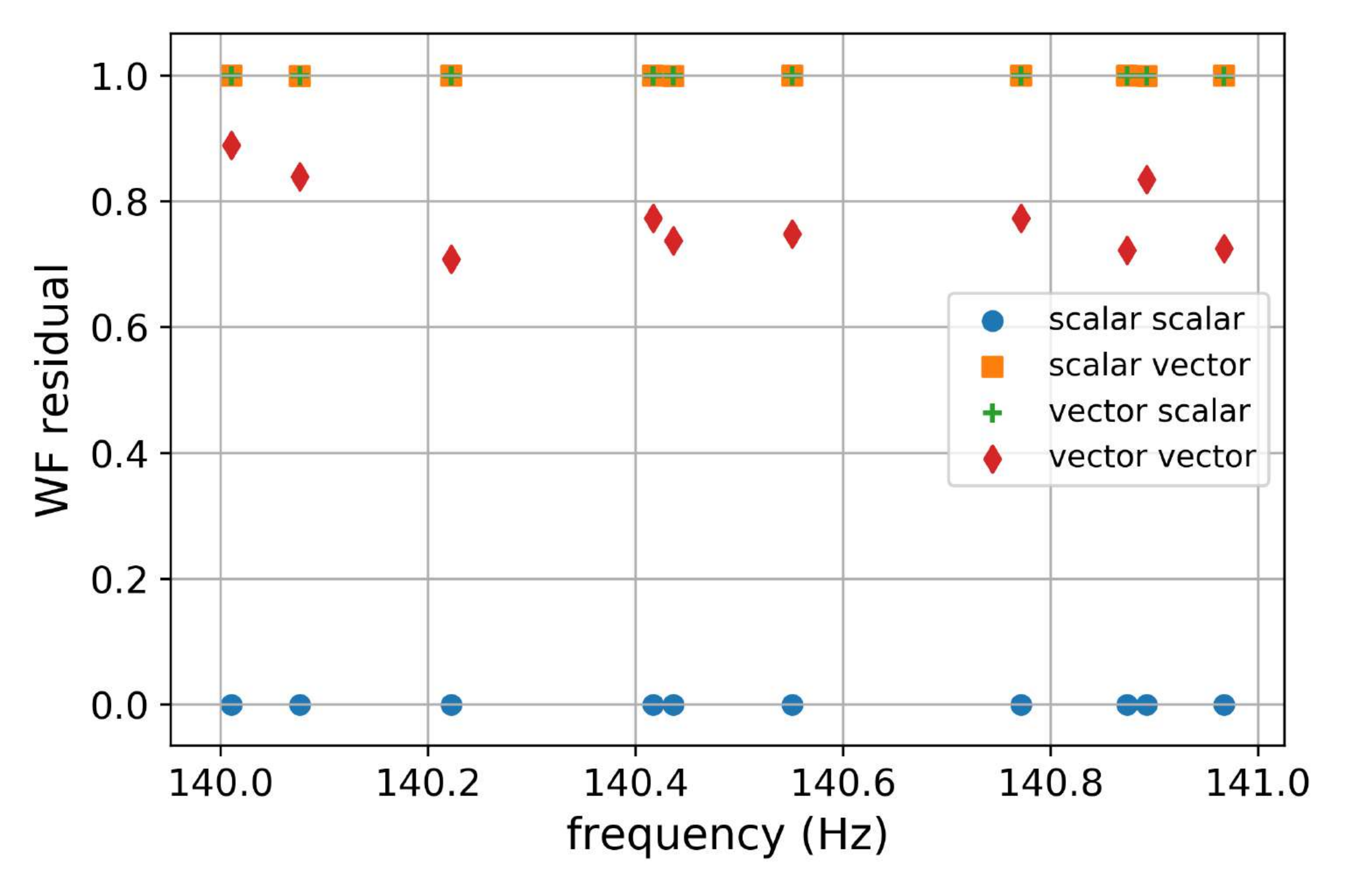
- Filter for random signals
- Minimizes mean square error between modelled random process and observed process
- Normalized (with the PSD of the modelled signal) mean square error between model and data, called "residual" R, calculated over T_{obs}, in chunks of length T_{FFT}
- R~1 —> noise; R~0 —> signal

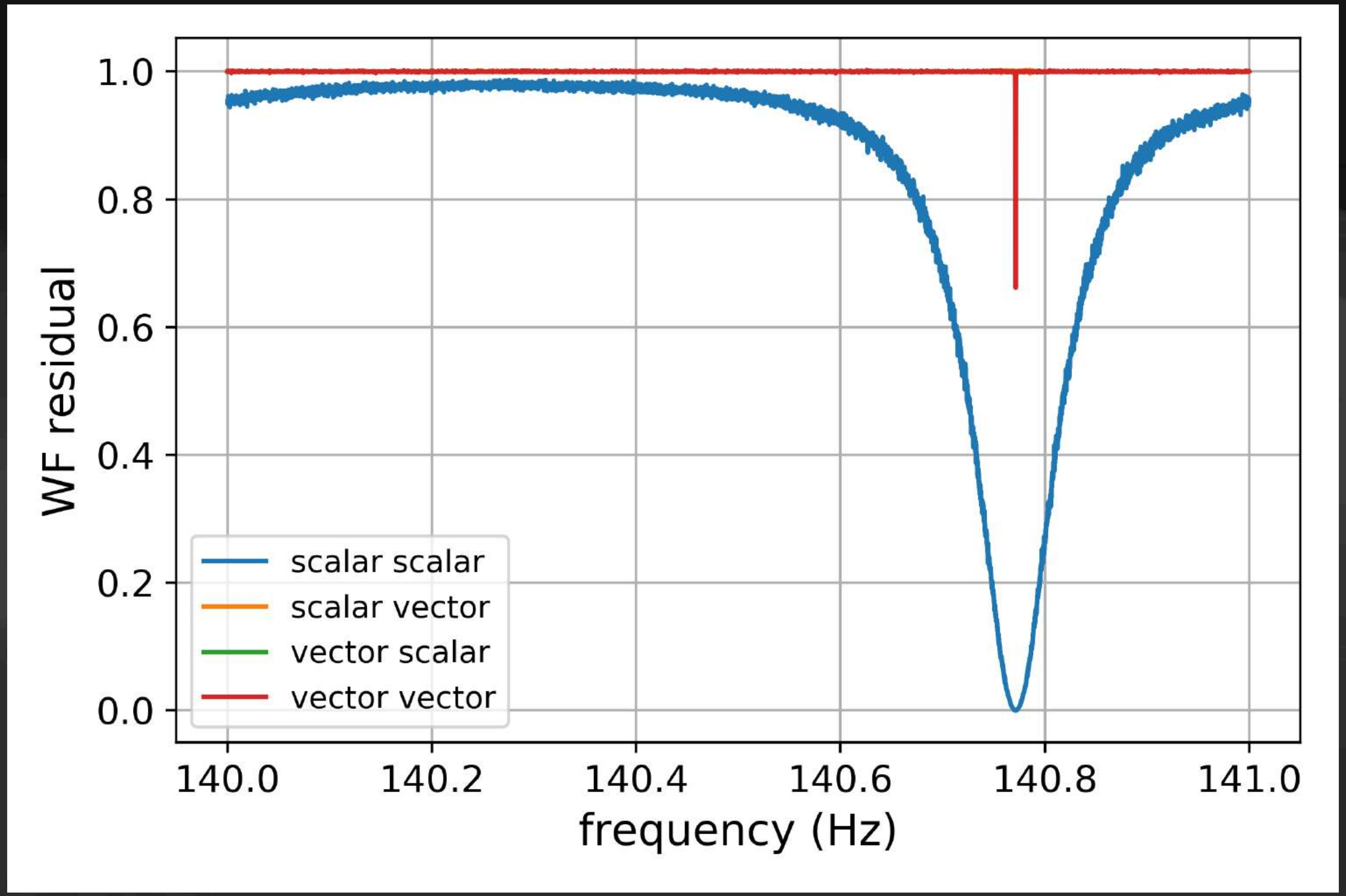
$$R(\omega) = 1 - \frac{\mathbf{P}^{\dagger}_{XY}\bar{\mathbf{P}}^{-1}_{YY}\mathbf{P}_{XY}}{P_{XX}}$$



Miller et al. Phys. Rev. D 105.10 (2022), p. 103035

Distinguishing scalar & vector DM



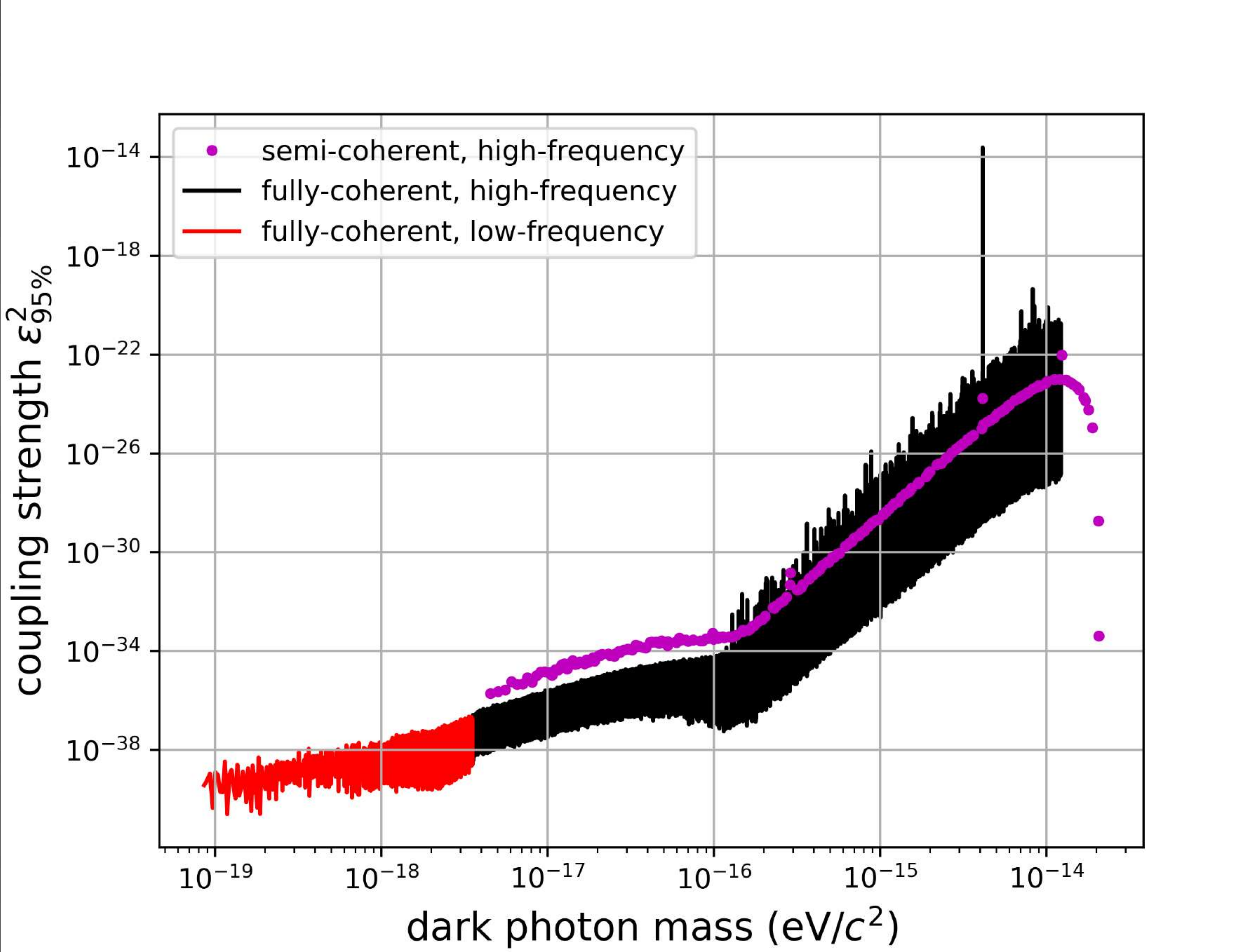


- PSDs different —> Wiener filter residual low when injected signal filtered with same type of DM
- High residuals when injected signal is filtered with wrong DM signal, even at the same frequency
- Vector (dark photon) signal is not that strong —> residuals of ~0.7-0.8
- Detectors are in different places —> their cross powers for different signal types will be different

Miller et al. Phys. Rev. D 105.10 (2022), p. 103035

LISA Pathfinder probes of DM

- Space-based GW detectors will also be sensitive to dark photon dark matter, though at smaller masses
- Same CW techniques applied, since LISA will have same problems of gaps, non-stationary noise, etc. as now
- Not as constraining as existing experiments, but are proof-of-concept

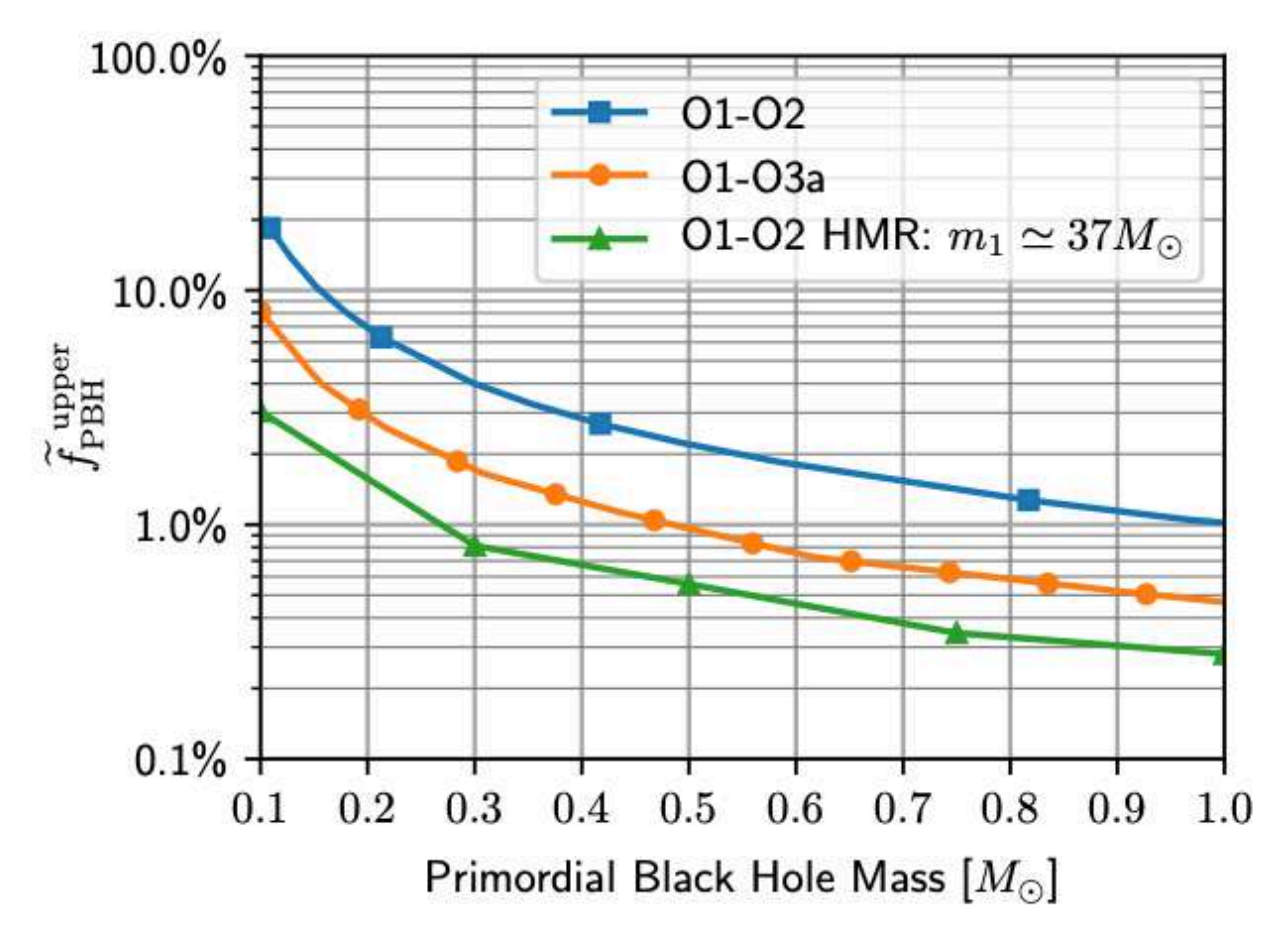


Miller and Mendes. Phys.Rev.D 107 (2023) 6, 063015

GWs from light PBHs

Motivation

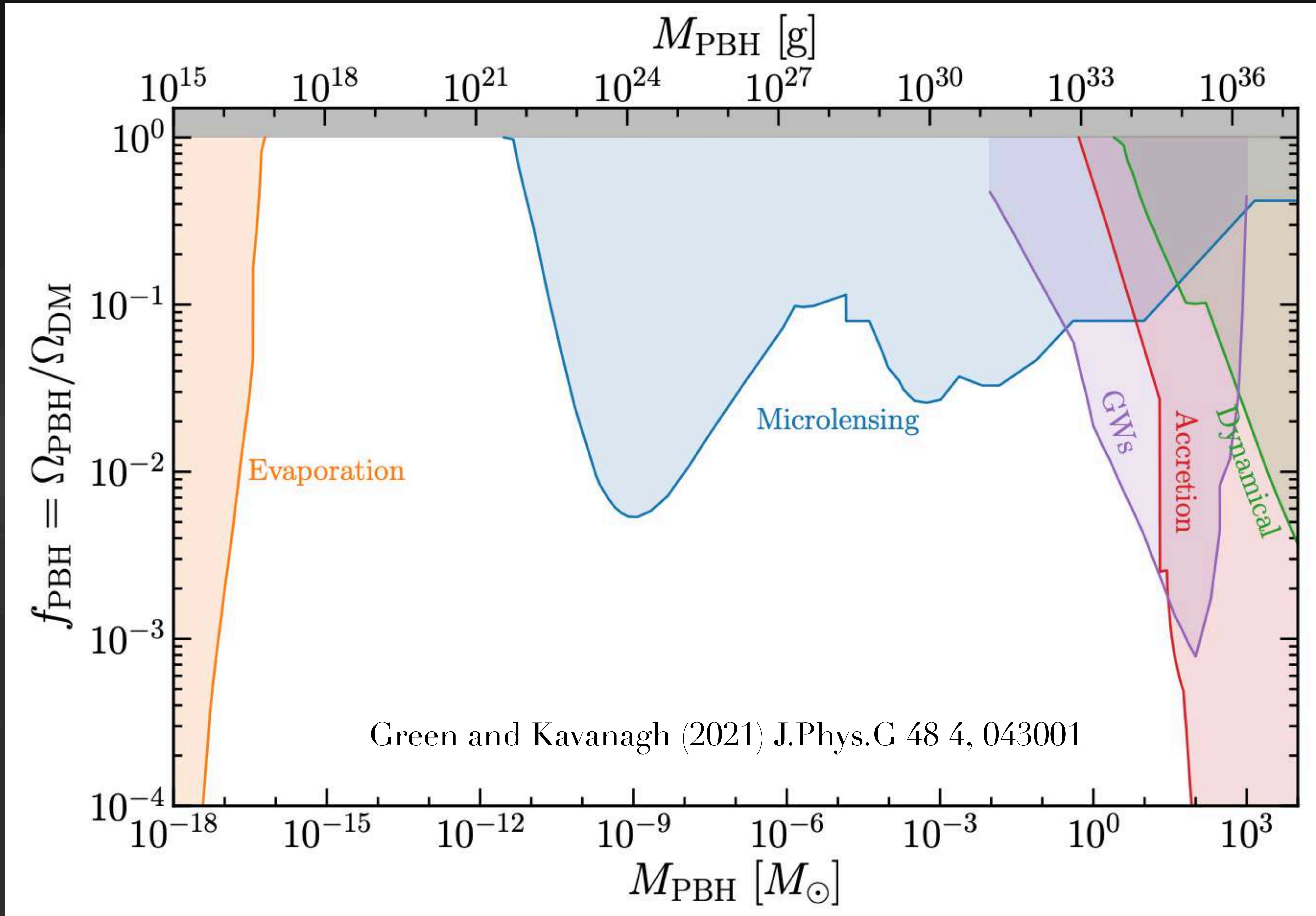
- Many GW efforts to detect PBHs focus on "sub-solar mass" regime, O(0.1 $M_\odot$)
- However, GWs from PBHs with masses $[10^{-7} - 10^{-3}] M_\odot$ have not been searched for
- Matched filtering in this mass range is extremely computationally challenging
- Signal for binaries in this mass range resemble continuous waves, since these systems will inspiral for a very long time and spin up very slowly



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

Current constraints on PBHs

- Asteroid-mass region not well constrained
- Limits based on uniform distribution of PBHs, while GWs could probe clusters of PBHs
- Constraints can be evaded in particular PBH formation models, e.g. if PBHs form in clusters
- Wide range of masses



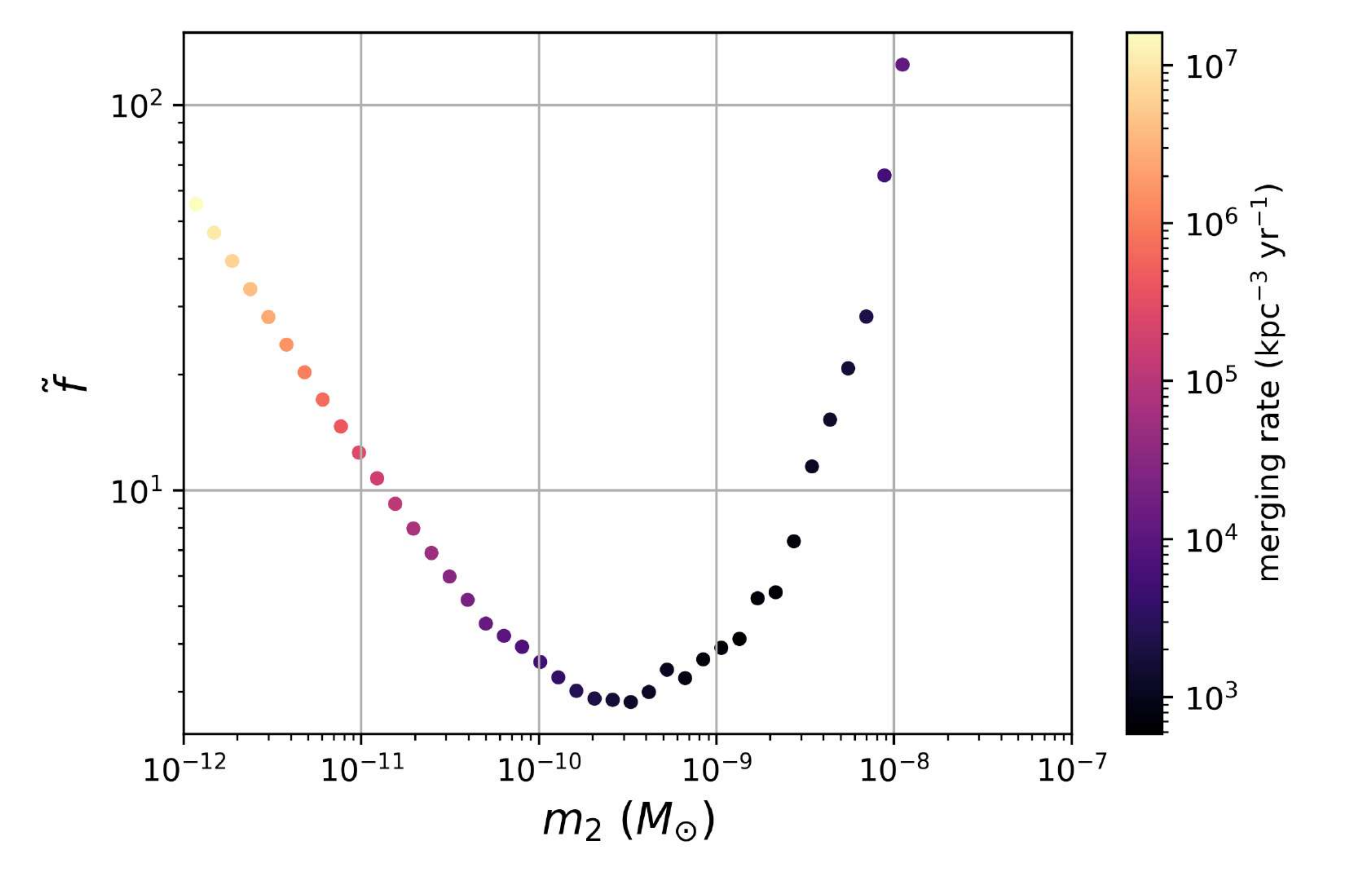
Green & Kavanagh: Journal of Physics G: Nuclear and Particle Physics, 48(4), 043001.

O3 constraints, asteroid-mass PBHs

$$R = 5.28 \times 10^{-7}\,\mathrm{kpc}^{-3}\mathrm{yr}^{-1}\left(\frac{m_1}{M_\odot}\right)^{-32/37}\left(\frac{m_2}{m_1}\right)^{-34/37}\tilde{f}$$

$$\tilde{f}^{53/57} \equiv f_{\mathrm{PBH}}^{53/37} f(m_1) f(m_2)$$

- Sky-avgeraged CW limits $h_0^{95\%}(f) \to d_{\mathrm{bin}}^{95\%}$
- Only allow linear frequency evolution: $f(t) = f_0 + \dot{f}(t - t_0)$
- Maximum $\dot{f}$ searched over ($\sim 1\mu$ Hz/s) —> fixed ranges for $\mathscr{M}, f$
- Distance & no detection —> rates



$$N_{\mathrm{bin}}(f) \simeq \frac{4}{3}\pi d(f)^3 RT,$$

Miller et al. Phys.Rev.D 105 (2022) 6, 062008

R: rate; $m_1 = 2.5 M_\odot$

$N_{\mathrm{bin}}^{\mathrm{tot}}$: number of detected binaries (< 1)

LVK: Phys. Rev. D, 106(10):102008, 2022.

“Transient” continuous waves

- Signal frequency evolution over time follows a power-law and lasts $\mathcal{O}(\text{hours} - \text{days})$

- 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

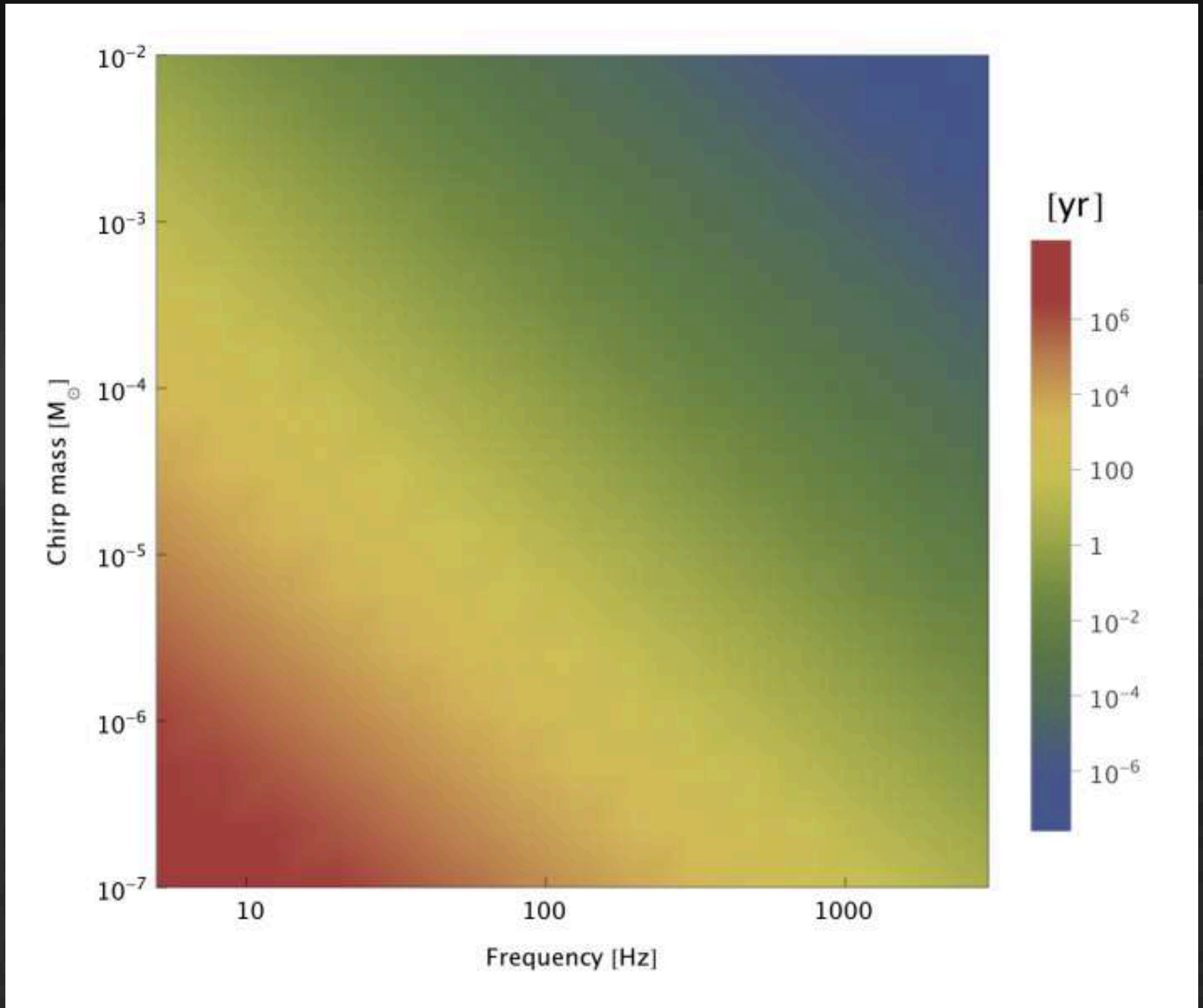
$$\dot{f} = \kappa f^n$$

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

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

GWs from inspiraling PBHs

- $\sim[10^{-7} - 10^{-3}]\ M_\odot$ give rise to signals that are *long lasting*, compared to those detected from $O(M_\odot)$ black holes
- The 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

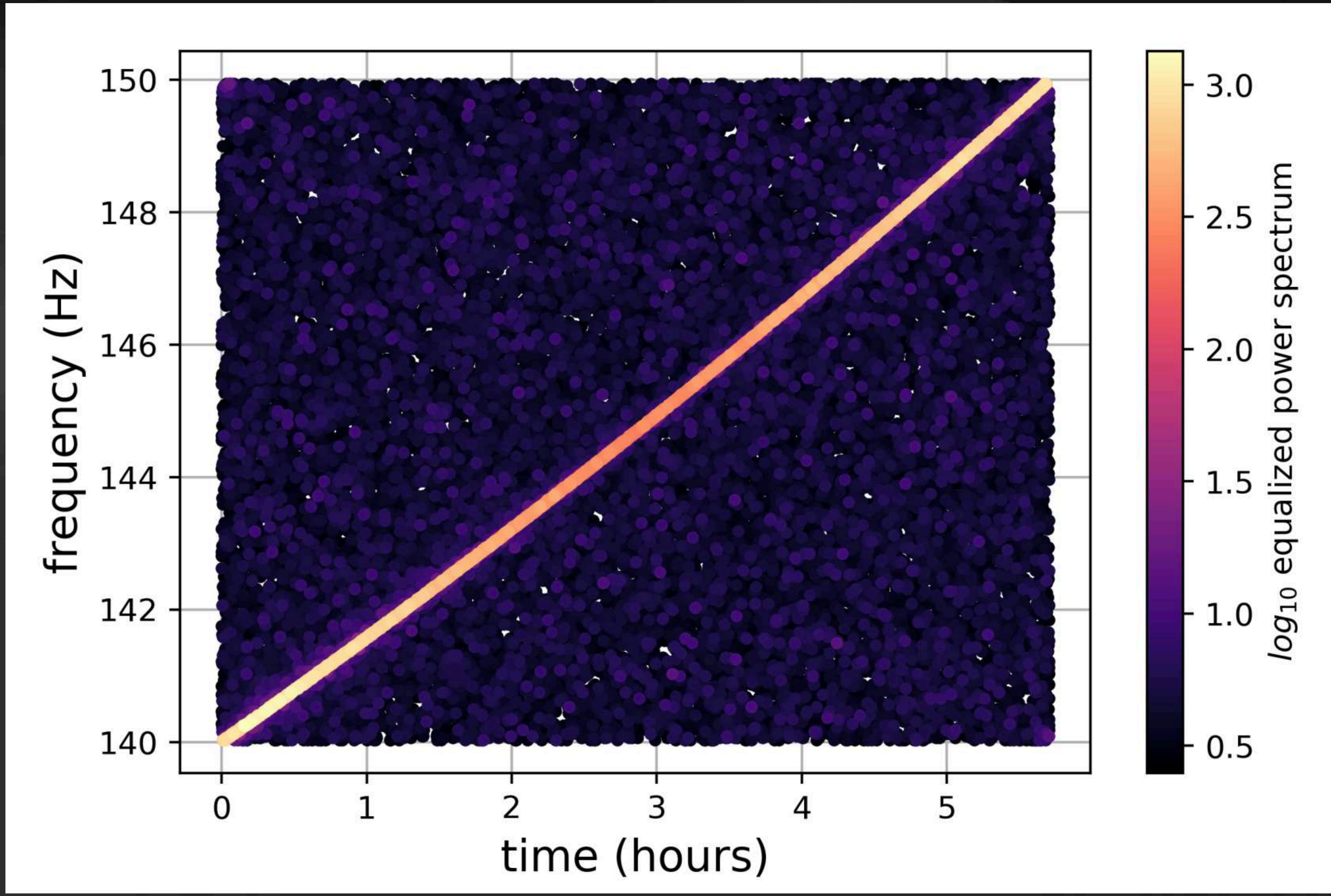


Miller et al. Phys.Dark Univ. 32 (2021) 100836

Generalized Frequency-Hough

- Attempt to detect power-law signals that slowly “chirp” in time
- Input: points in time/frequency detector plane to lines in orbital frequency / chip mass of source plane

$$\dot{f}_{\rm gw} = \frac{96}{5}\pi^{8/3}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3} f_{\rm gw}^{11/3}$$



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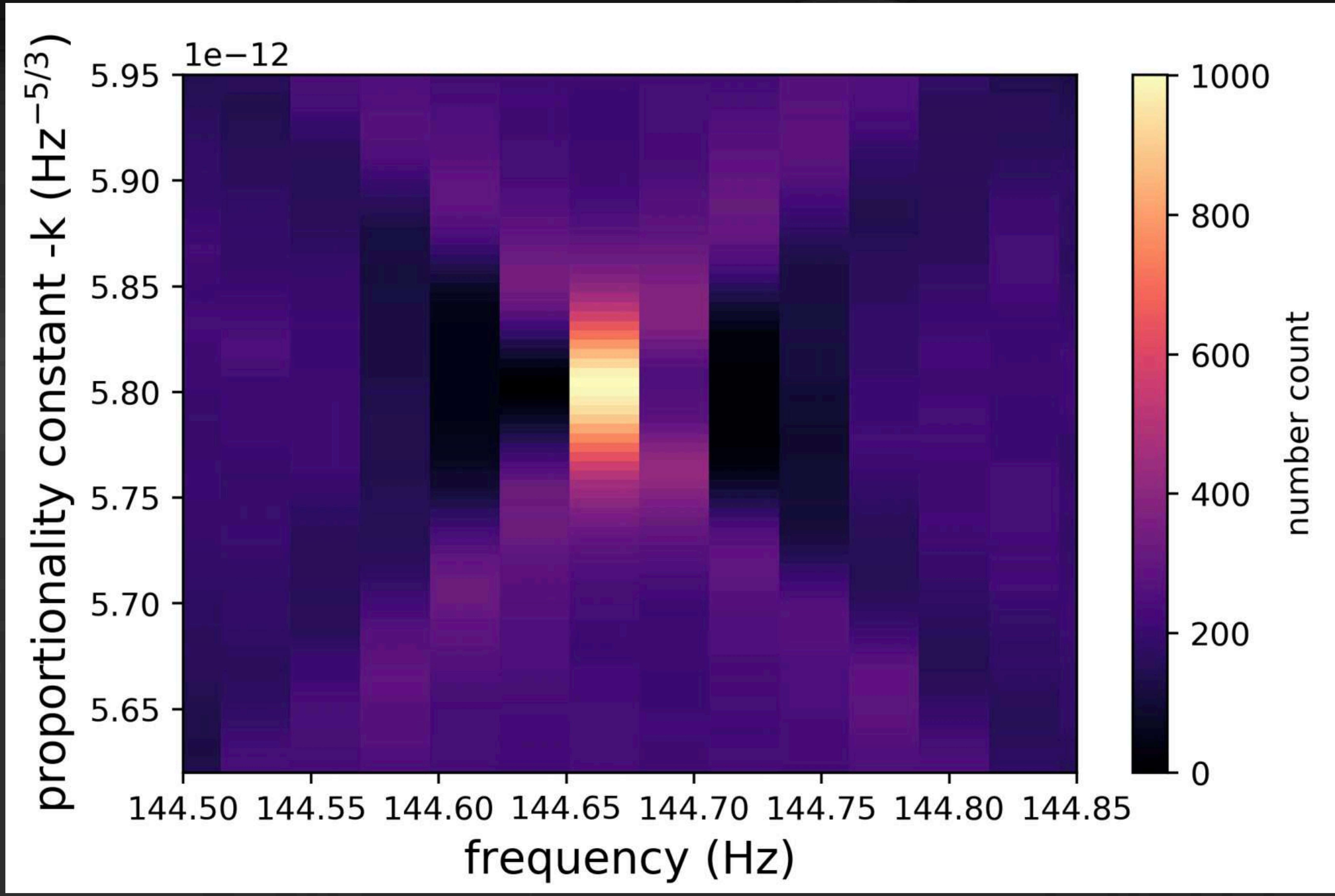
Generalized Frequency-Hough

- Generalization of method to search for isolated neutron stars
- Output: two-dimensional histogram in the frequency/ chirp mass plane of the source



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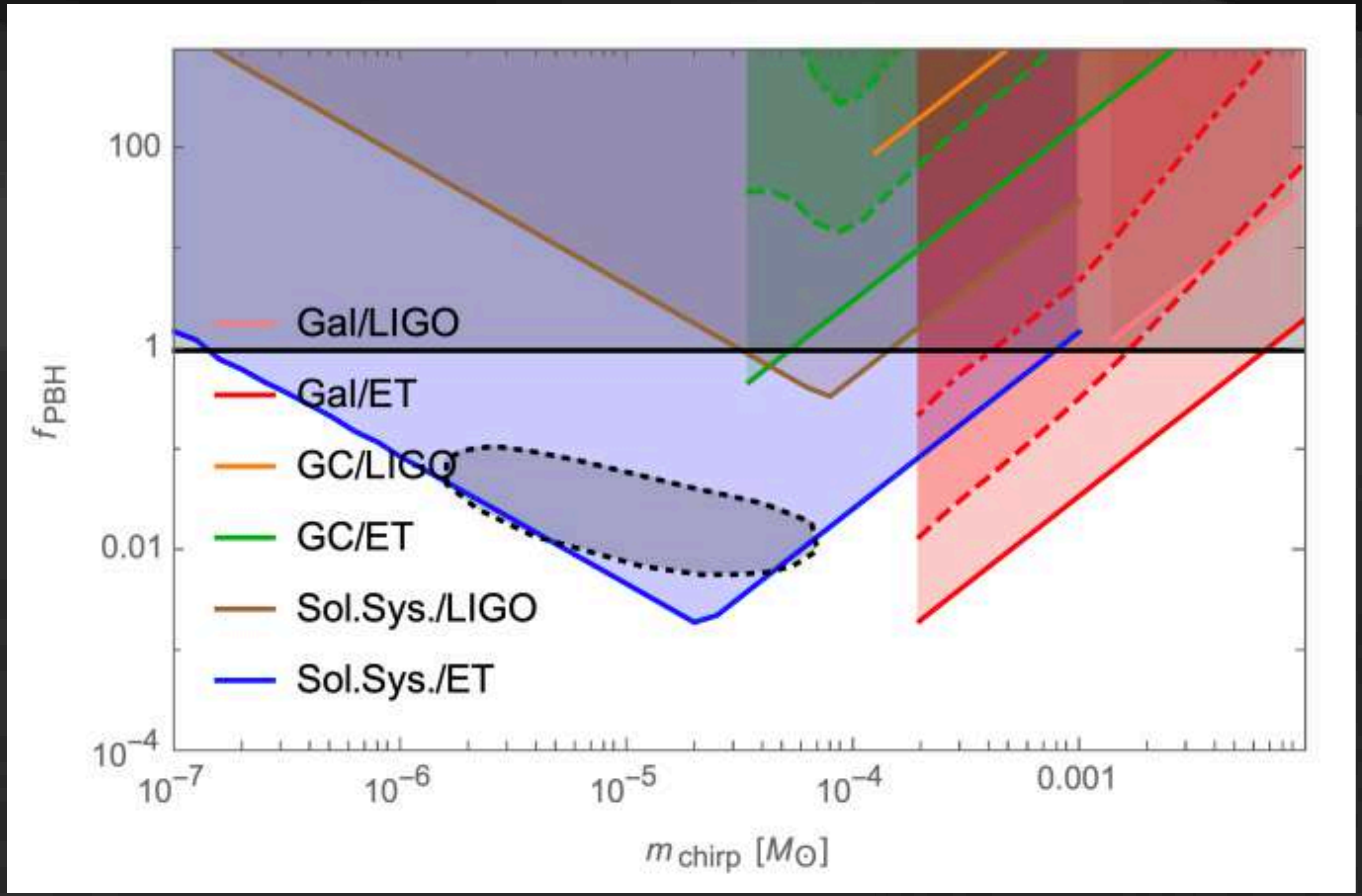
Projected constraints, PBH binaries

- Projected constraints on equal-mass PBHs, for monochromatic and thermal mass functions (solid and dashed lines, respectively)
- Constraint calculated at different distances away from us, at a chosen frequency, for either Einstein Telescope or advanced LIGO sensitivity



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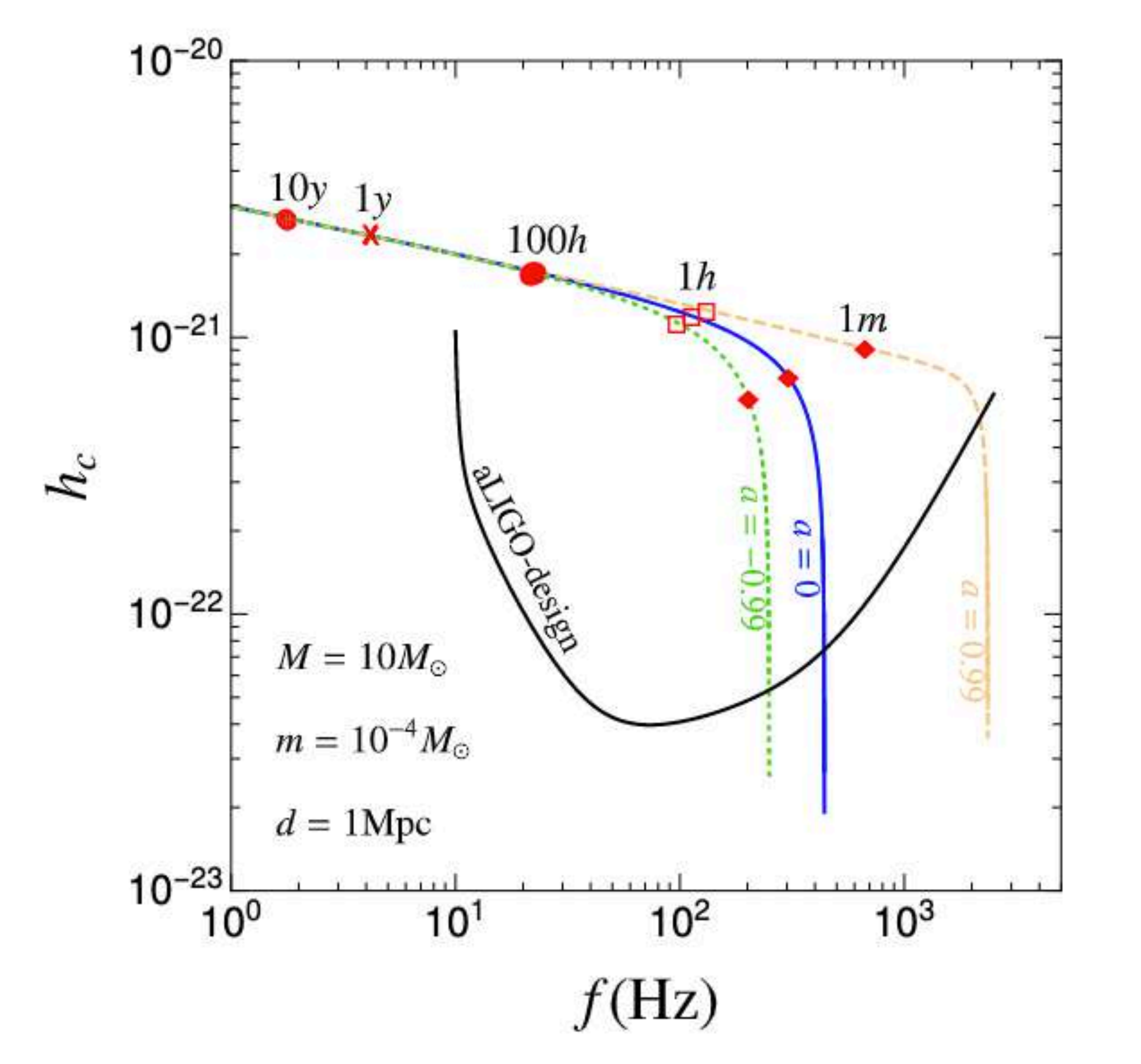
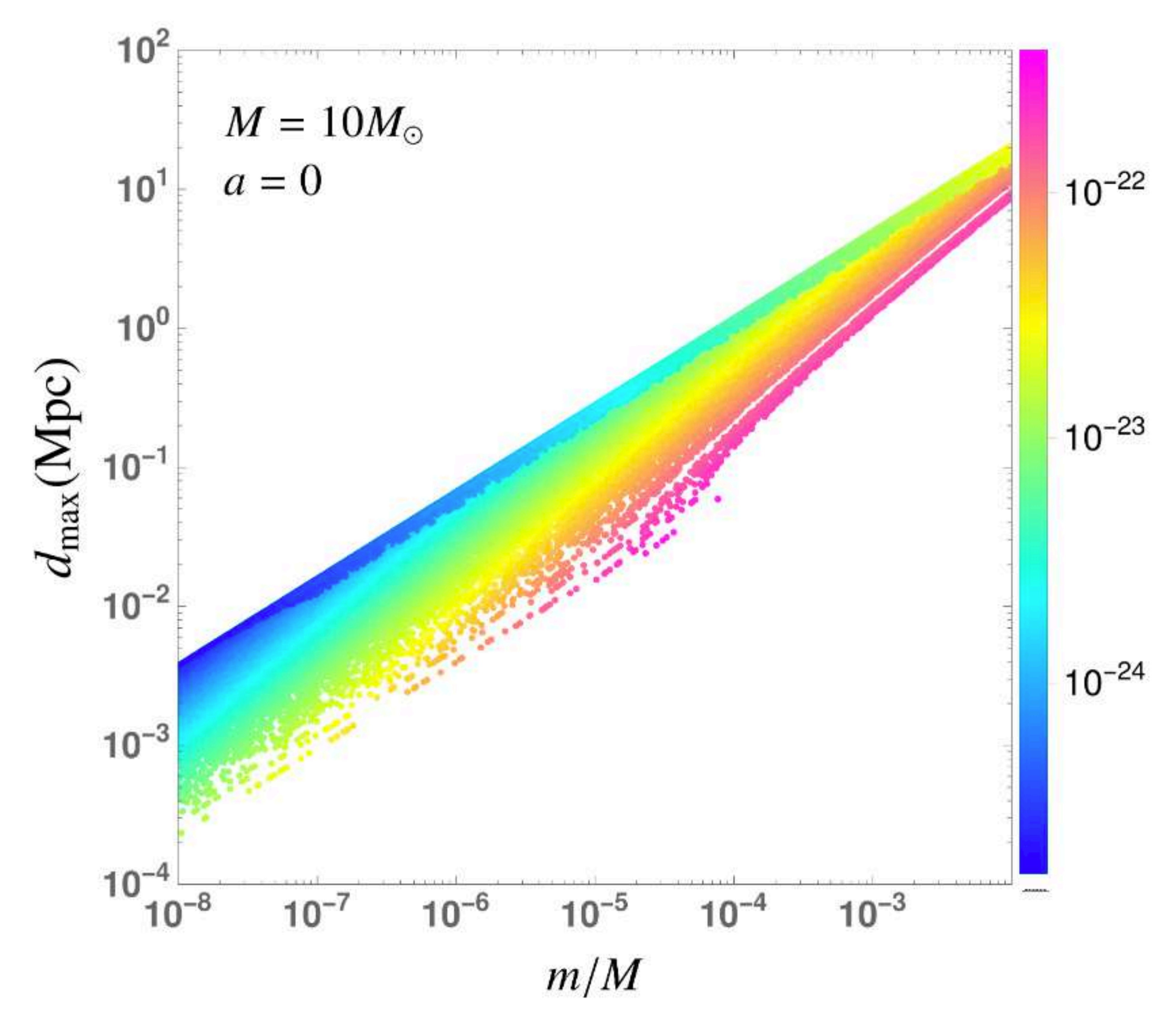
"mini"-EMRI systems



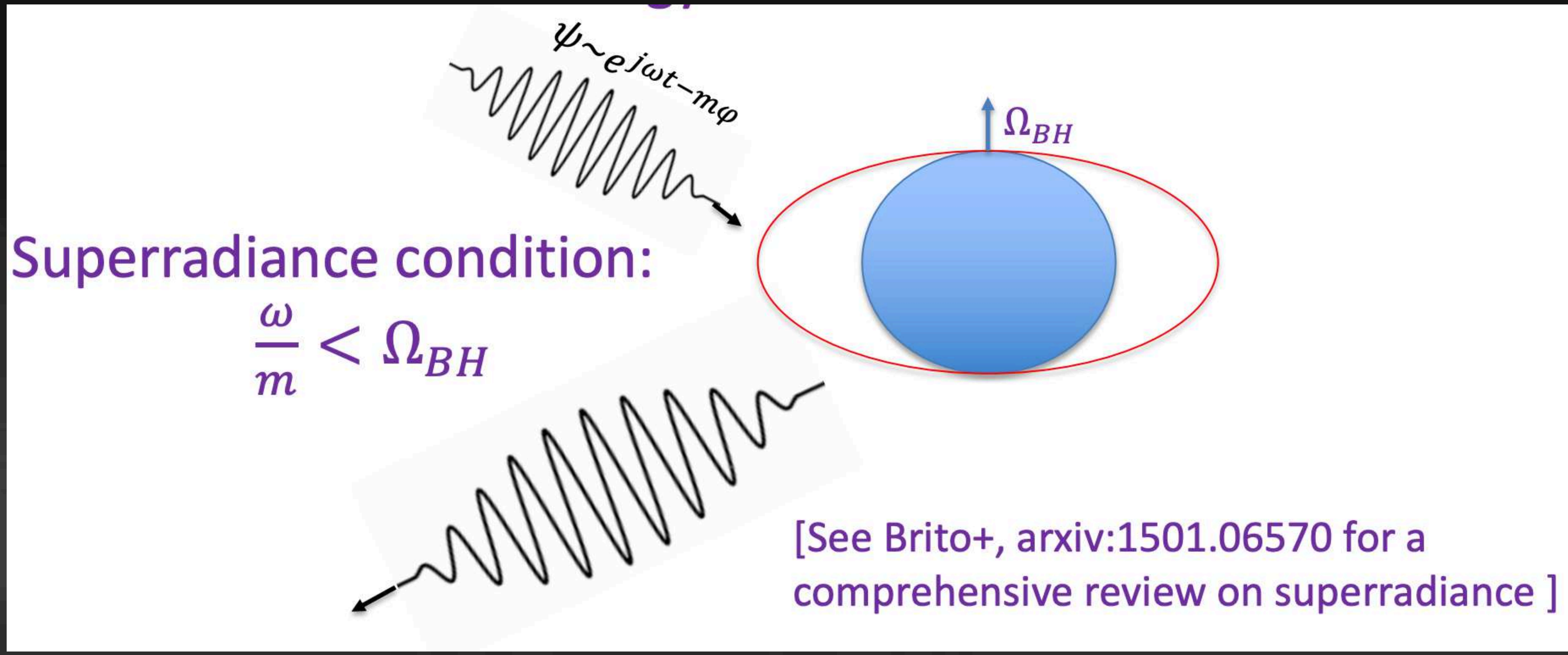


- Generalized Frequency Hough could also probe the existence of mini-EMRI systems — ordinary stellar object + exotic, light companion

GWs from boson clouds around spinning 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



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

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

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

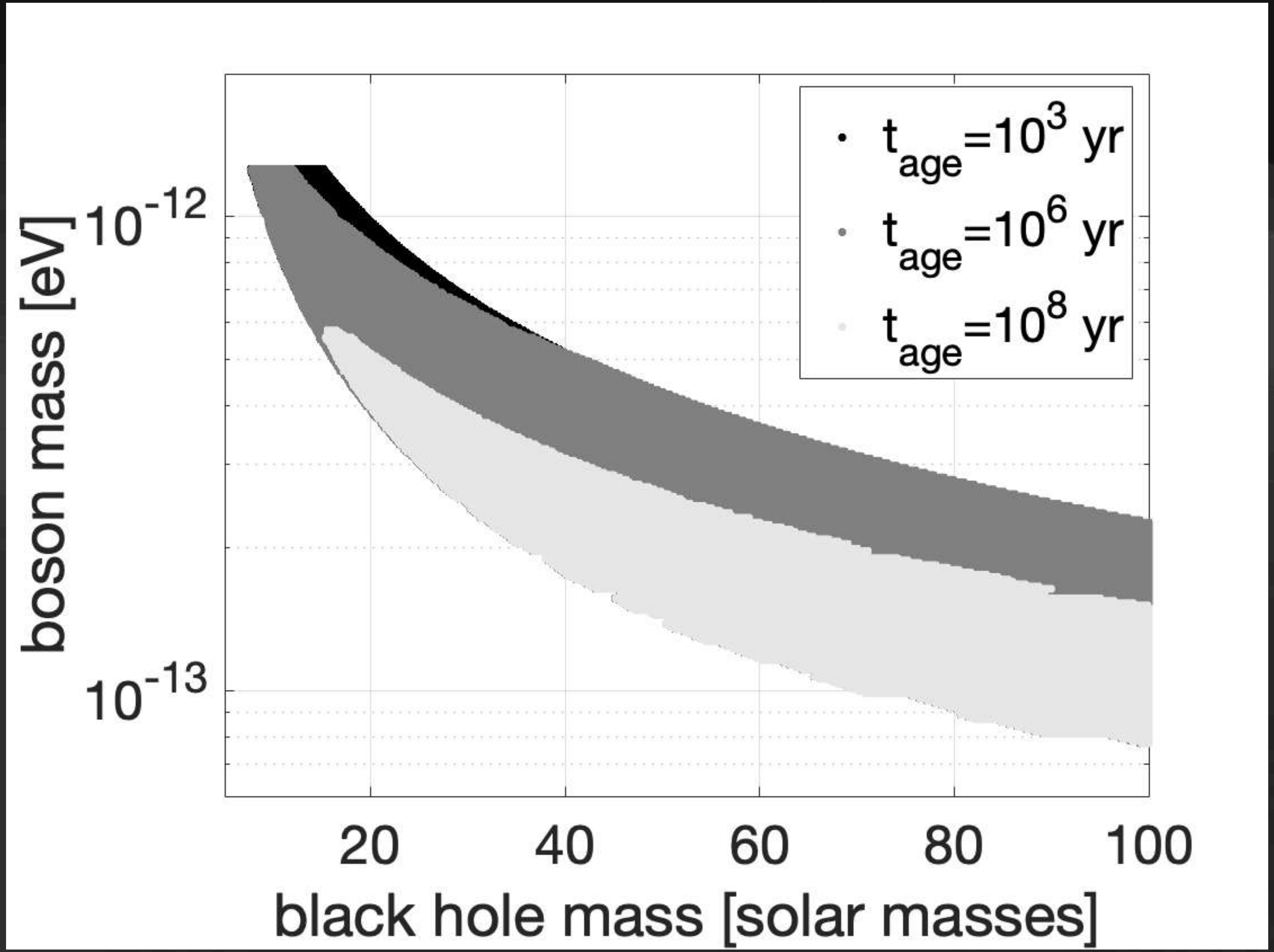
Isi et al. Phys.Rev.D 99 (2019) 8
Brito et al. Phys. Rev. D 96, 064050

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

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

O3 results: Exclusion regions

- Given distance (1 kph), spin (0.9) and age of black hole, we can determine the boson mass/black hole mass pair that would produce an amplitude higher than the value of the upper limit $h_0^{95\%}$
- Bigger distance from us —> smaller excluded region
- At fixed black hole mass, higher boson mass implies higher spin-ups, which are not covered in the search



LVK: Phys.Rev.D 105 (2022) 10, 102001

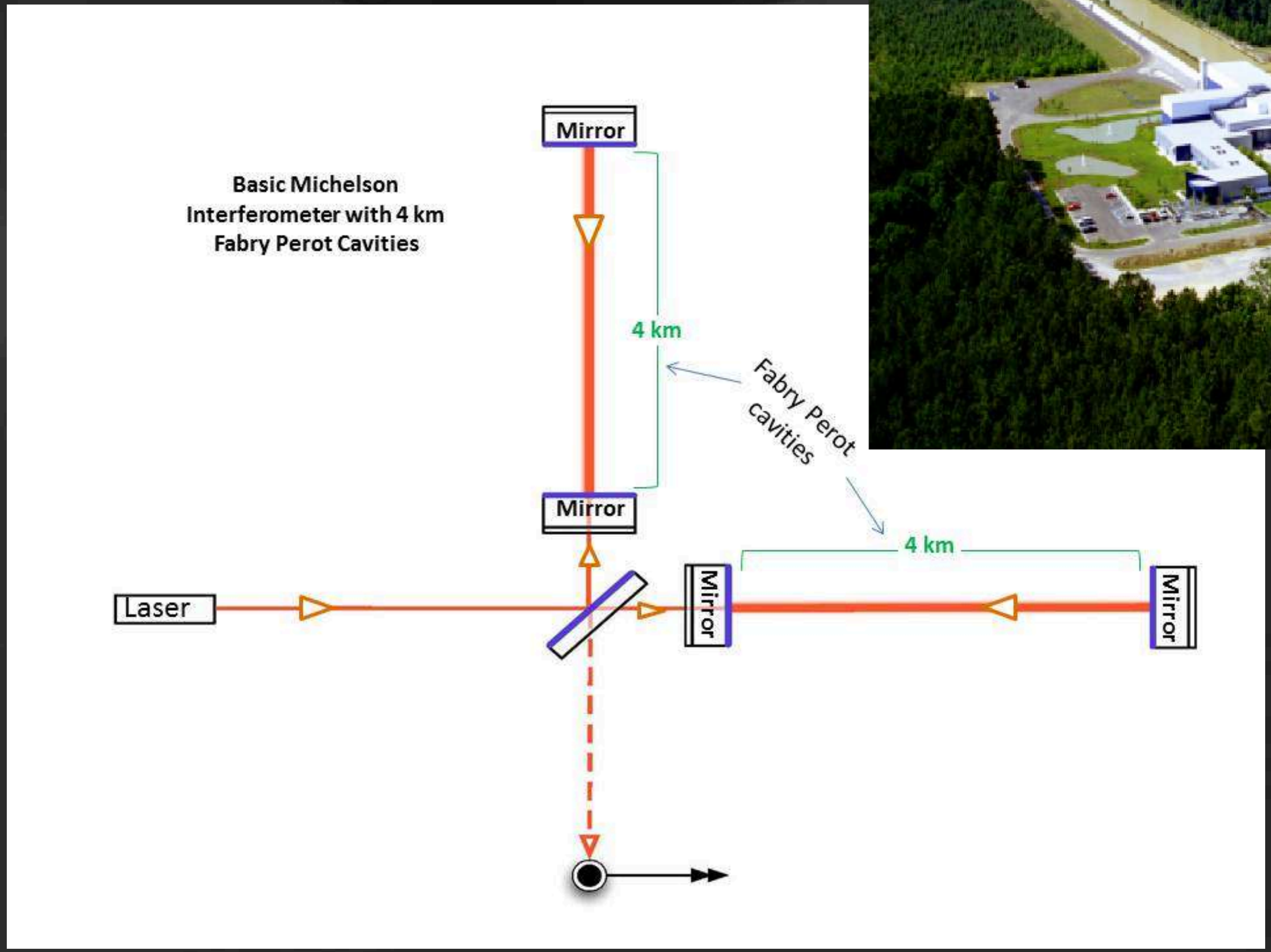
Conclusions

- A simple model of a quasi-monochromatic signal describes so many types of sources
- But, despite its simplicity, unknown source parameters make searches computationally heavy
- GW detectors can probe the existence of dark matter both directly and indirectly
- Many methods have been designed to not lose sensitivity with respect to matched filtering, while also being computationally efficient

Backup slides

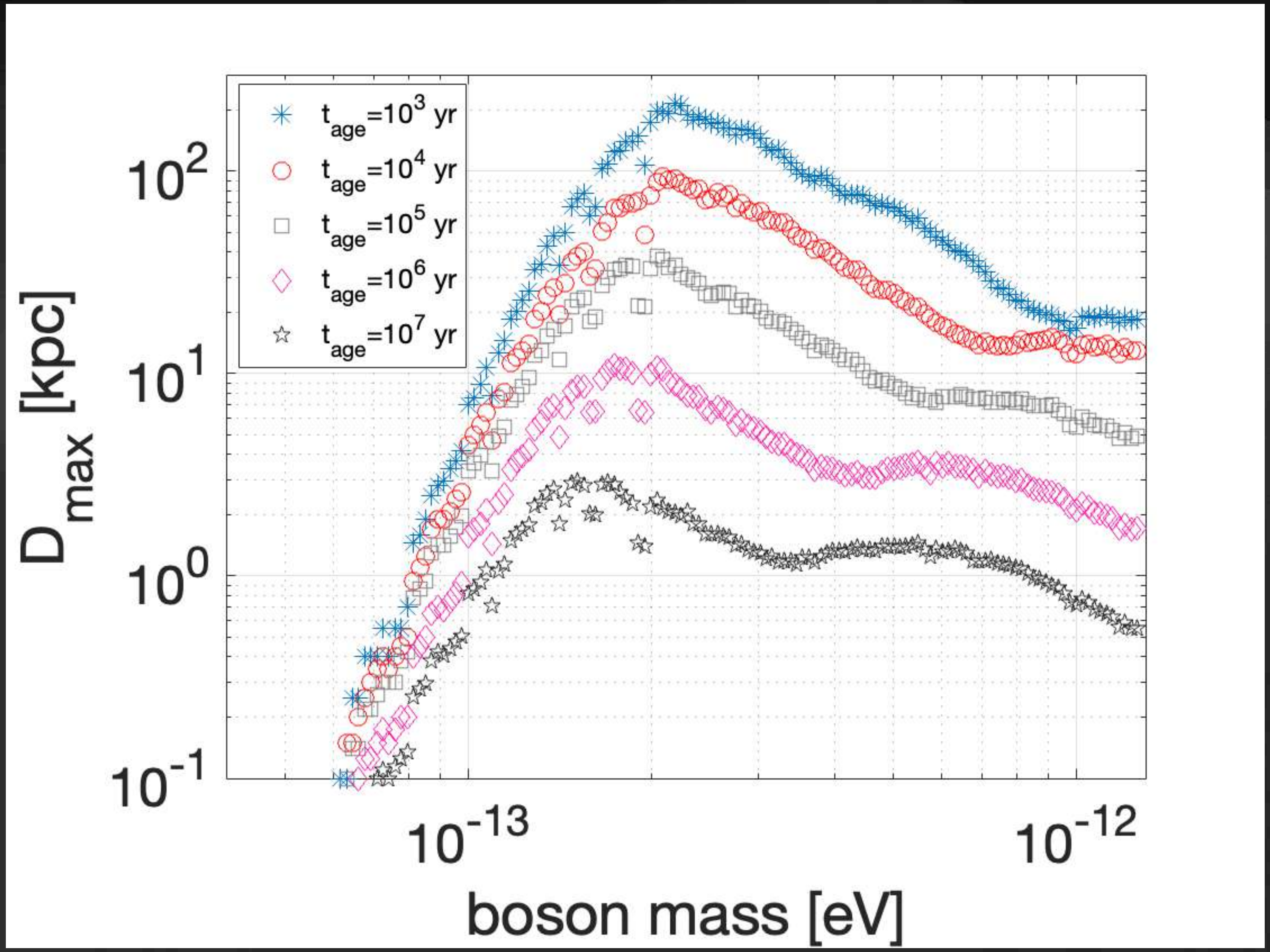
How can we search for dark matter?

- 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
- We care about the *phase* of the signal, and characterize signals by how their phases (or frequencies) change over time



Astrophysical distance reach

- For fixed BH age, calculate at what distance at least 5% of simulated signals would have produced $h_0 > h_0^{95\%}$
- Kroupa mass distribution: $f(m) \sim m^{-2.3}$
- Uniform spins [0.2,0.9] for BH masses between [5,50]M_{sun} and [5,100]M_{sun}
- Constraint reflects ensemble properties of the black hole population



LVK: Phys.Rev.D 105 (2022) 10, 102001

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)

$$f_{\rm gw} \simeq 483\,{\rm Hz}\left(\frac{m_{\rm b}}{10^{-12}\ {\rm eV}}\right) \times\left[1-7\times10^{-4}\left(\frac{M_{\rm BH}}{10M_\odot}\frac{m_{\rm b}}{10^{-12}\ {\rm eV}}\right)^2\right]$$

$$\dot{f}_{\rm gw} \approx 7\times10^{-15}\left(\frac{m_{\rm b}}{10^{-12}\ {\rm eV}}\right)^2\left(\frac{\alpha}{0.1}\right)^{17}\ {\rm Hz/s}.$$

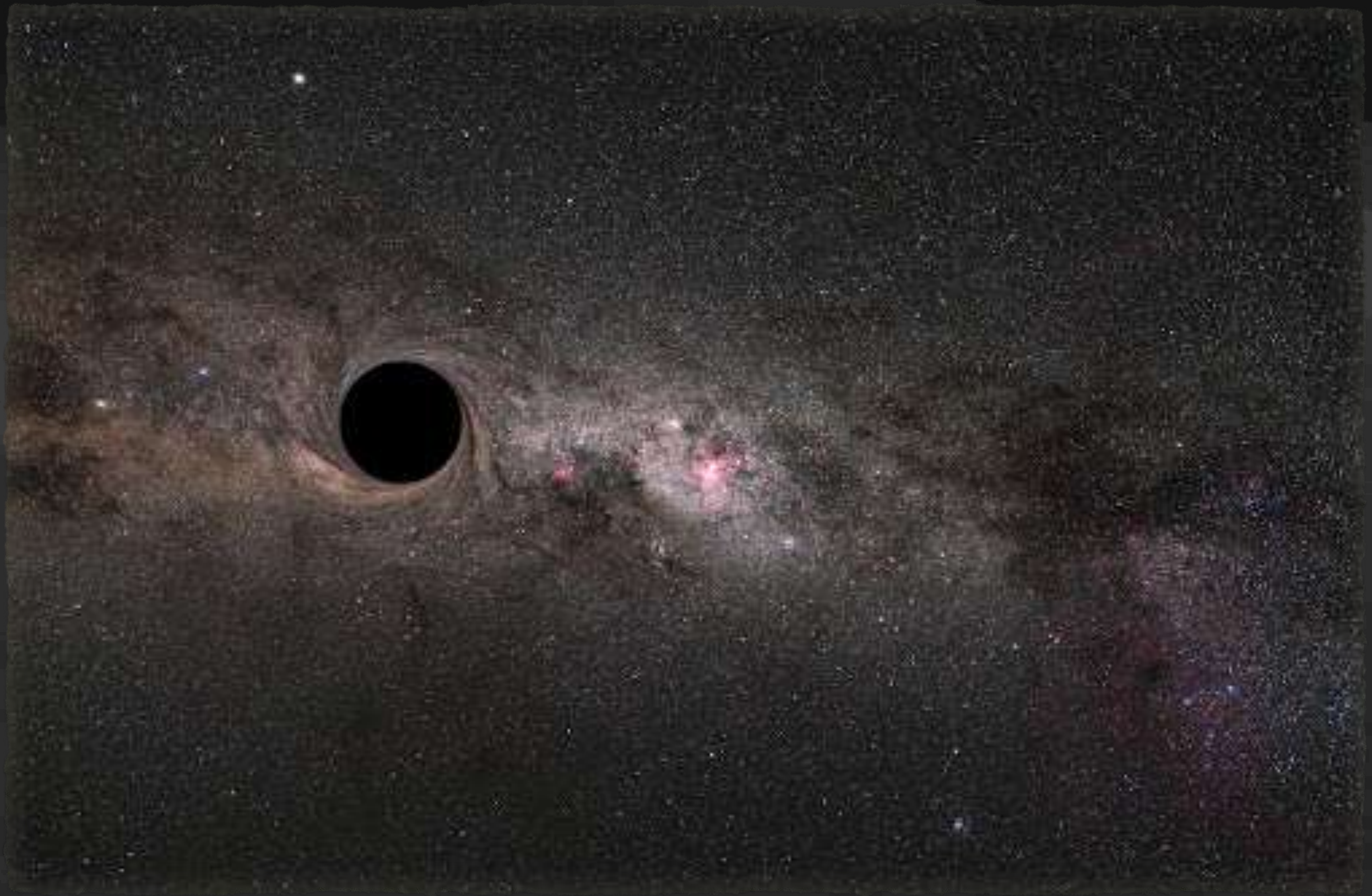
$$h_0 \approx 6\times10^{-24}\left(\frac{M_{\rm BH}}{10M_\odot}\right)\left(\frac{\alpha}{0.1}\right)^7\left(\frac{1\,{\rm kpc}}{r}\right)(\chi_i-\chi_c)$$

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

LVK: Phys.Rev.D 105 (2022) 10, 102001

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



Context

- LIGO, Virgo and KAGRA have looked for gravitational waves from dark matter candidates, e.g. boson clouds around spinning black holes and primordial black holes

- However, the rest of 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

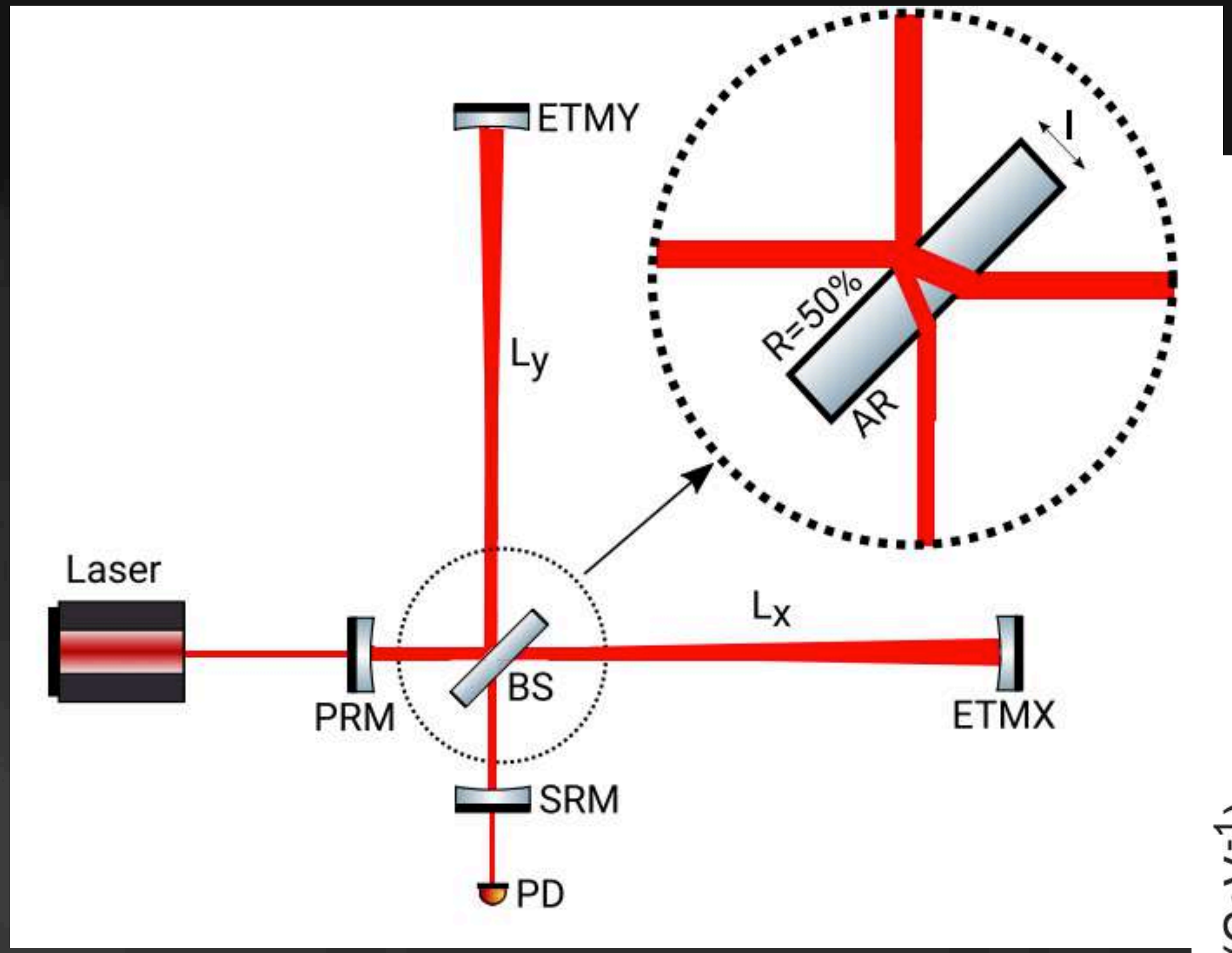
- Other experiments exist to detect particles that could be dark matter as well, e.g. Eöt-Wash torsion balance, MICROSCOPE satellite, ALPS, ADMX,…

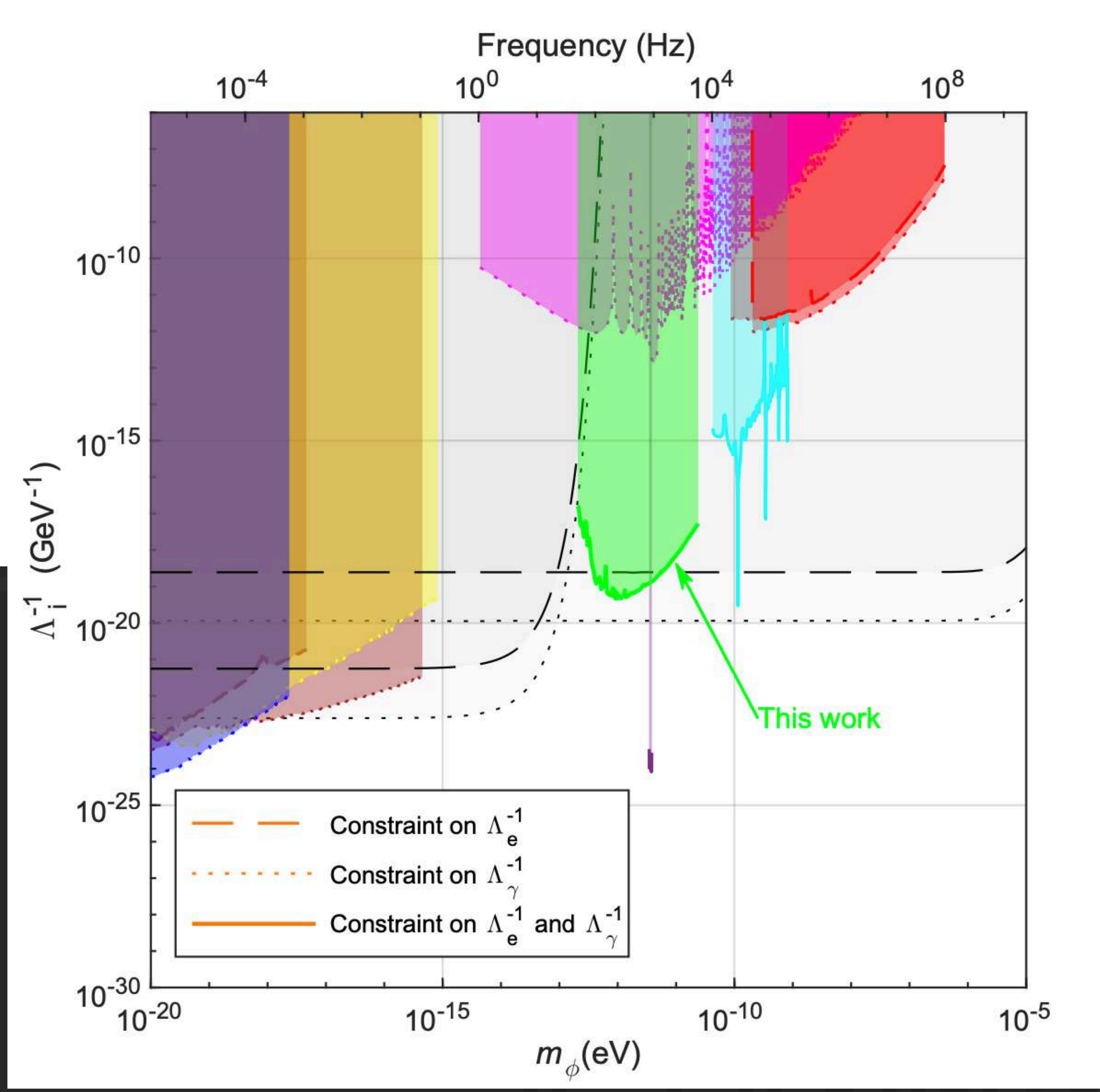
D'Antonio et al. PRD, vol. 98, no. 10, p. 103017
Palomba et al. 2019, PRL, vol. 123, no. 17, p. 171101
Sun et al. 2019 PRD, vol. 101, no. 6, p. 063020

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

Scalar, dilaton dark matter

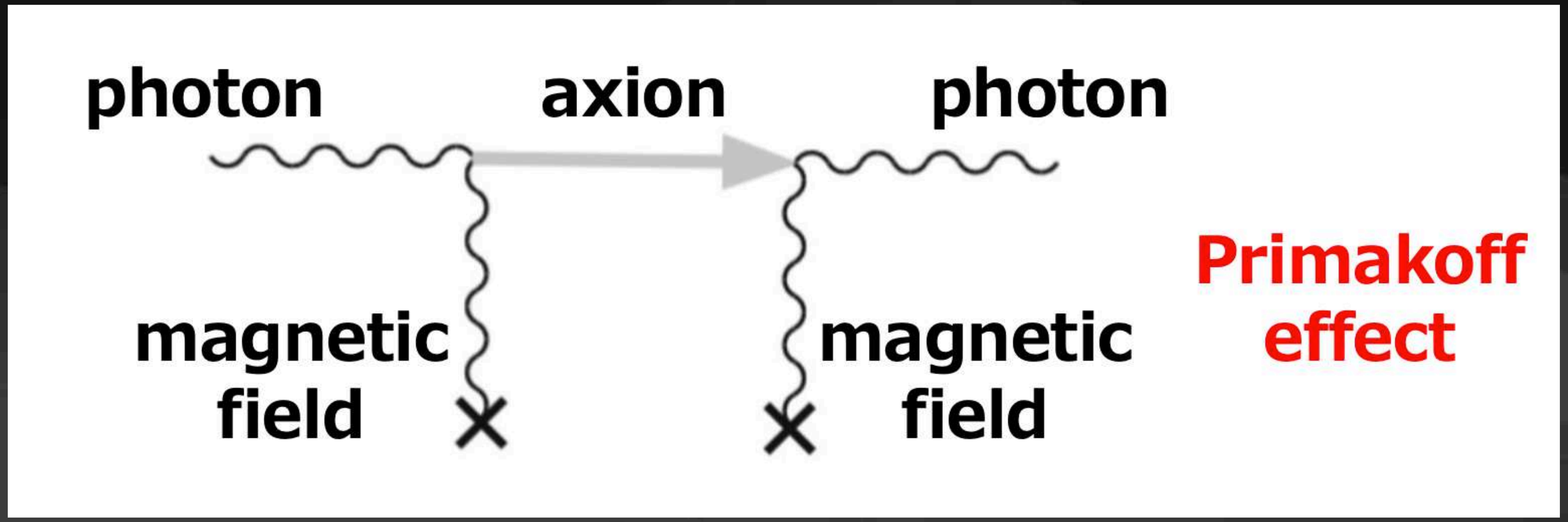
- Couples with strengths Λ_γ and Λ_e to standard model photon and electron fields, respectively
- Physically seen as change in electron mass and atomic Bohr radius
- Leads to changes in size and index of refraction of solids





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



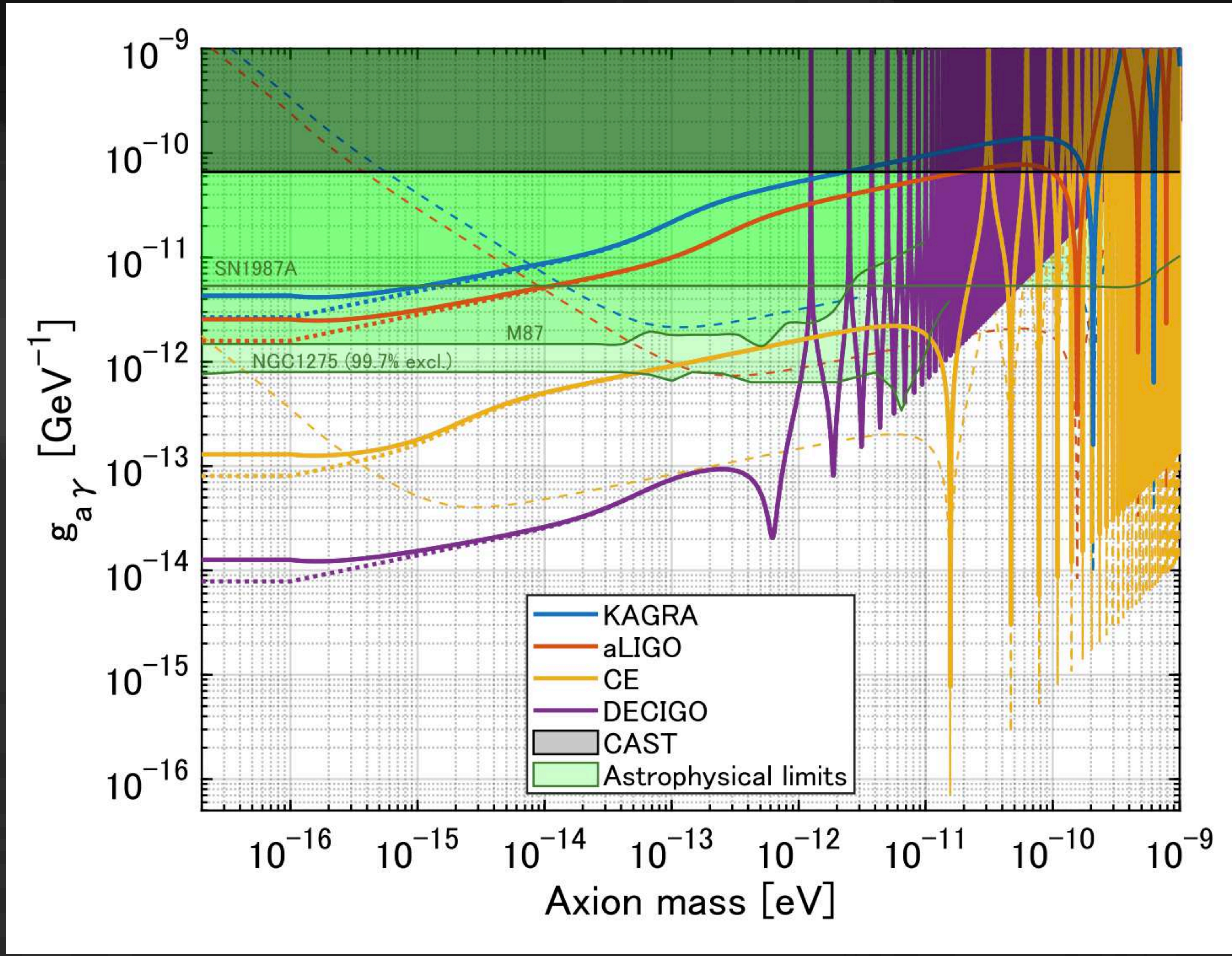
$$c_{\mathrm{L/R}} = \sqrt{1 \pm \frac{g_{a\gamma} a_0 m_a}{k} \sin(m_a t + \delta_\tau)}$$

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 lengths give different resonances for all detectors
- Search in the reflection and the transmission ports of arm cavities.



Nagano et al. (2021) PRD 104, 062008

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

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

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

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

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

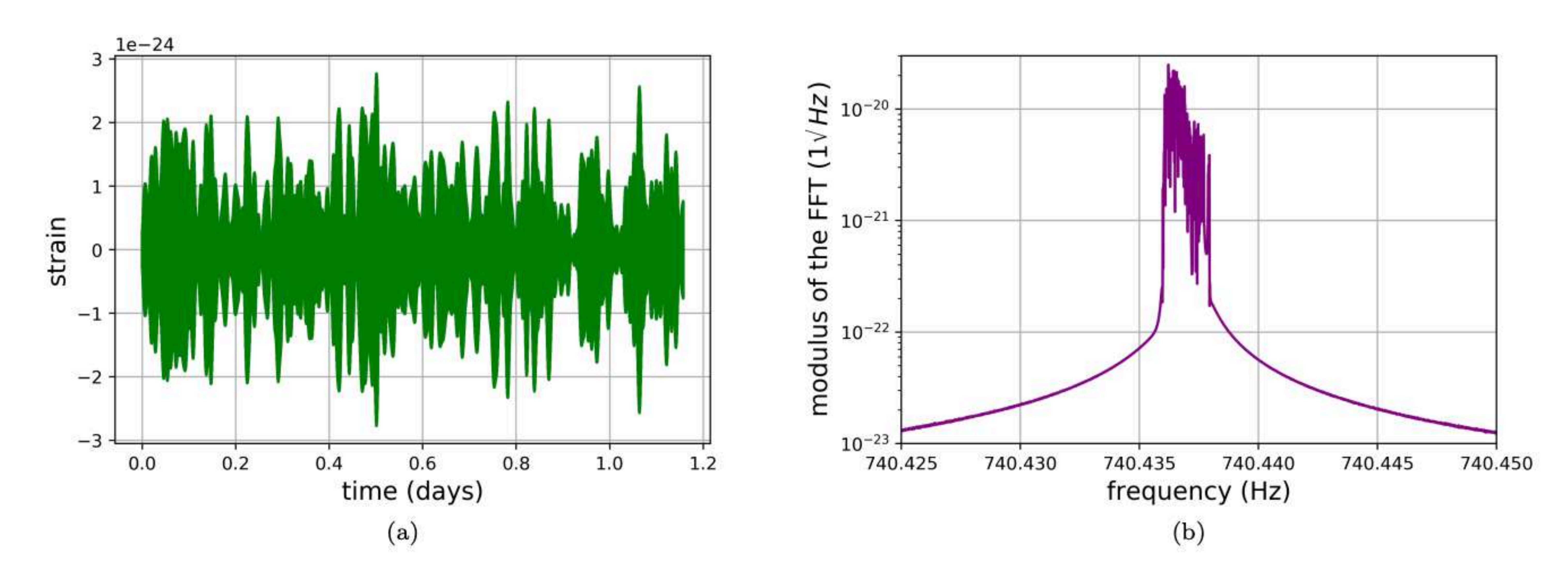
Pierce et al. 2018, Phys. Rev. Lett. 121, 061102

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

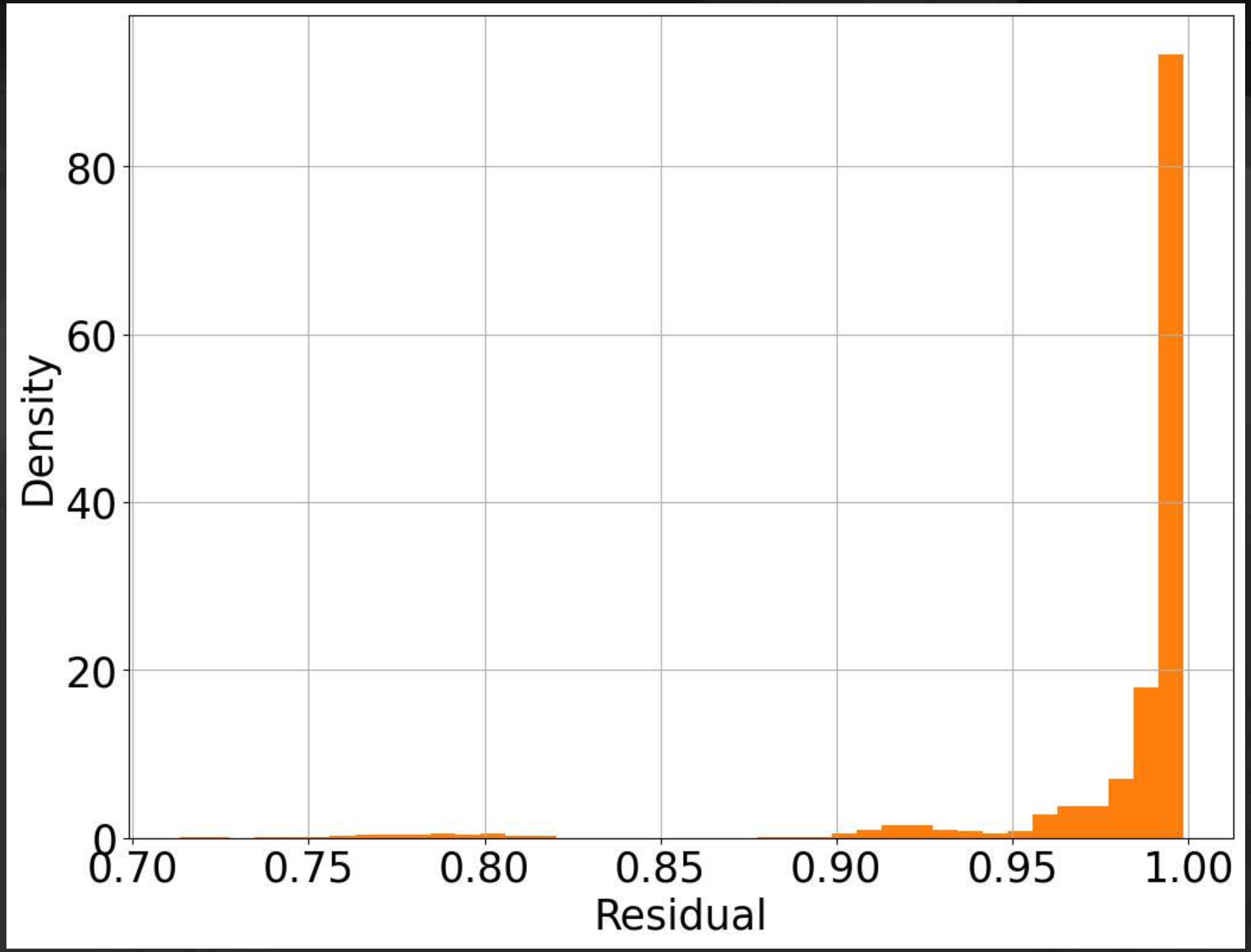


- One day shown, but signal lasts longer than observing run

Miller et al.
Phys.Rev.D 103 (2021) 10, 103002

Residual as a detection statistic

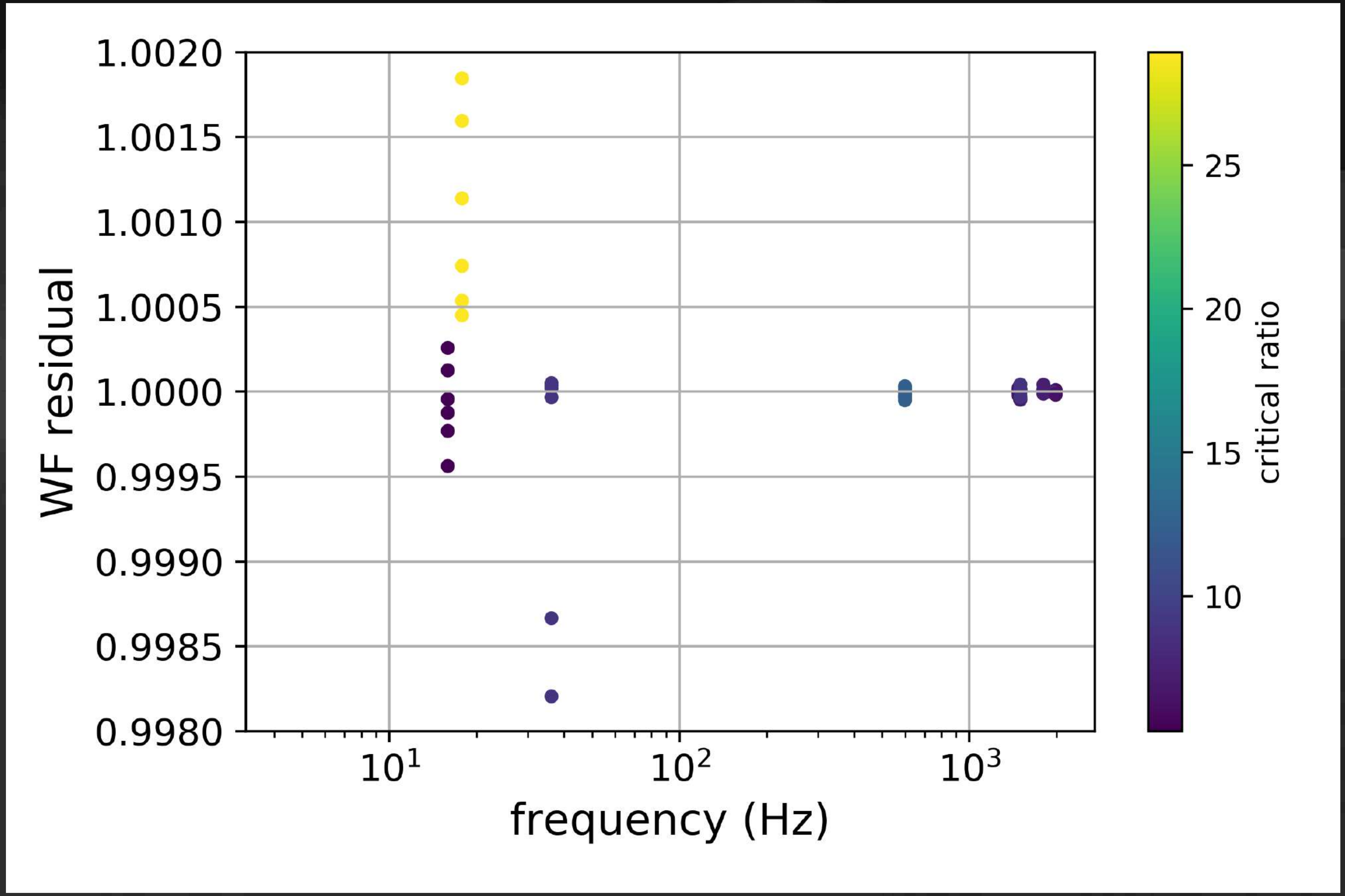
- Background distribution of residual statistic
- 3861 dark-photon templates used to create this plot, that differed from the injected signal.
- $\mu = 0.98; \sigma = 0.037$
- Interesting DM candidates would need $R < 0.7$; we put a threshold $R_{thr} = 0.5 \; --> 13\sigma$



Miller et al. Phys. Rev. D 105.10 (2022), p. 103035

Follow-up of O3 outliers

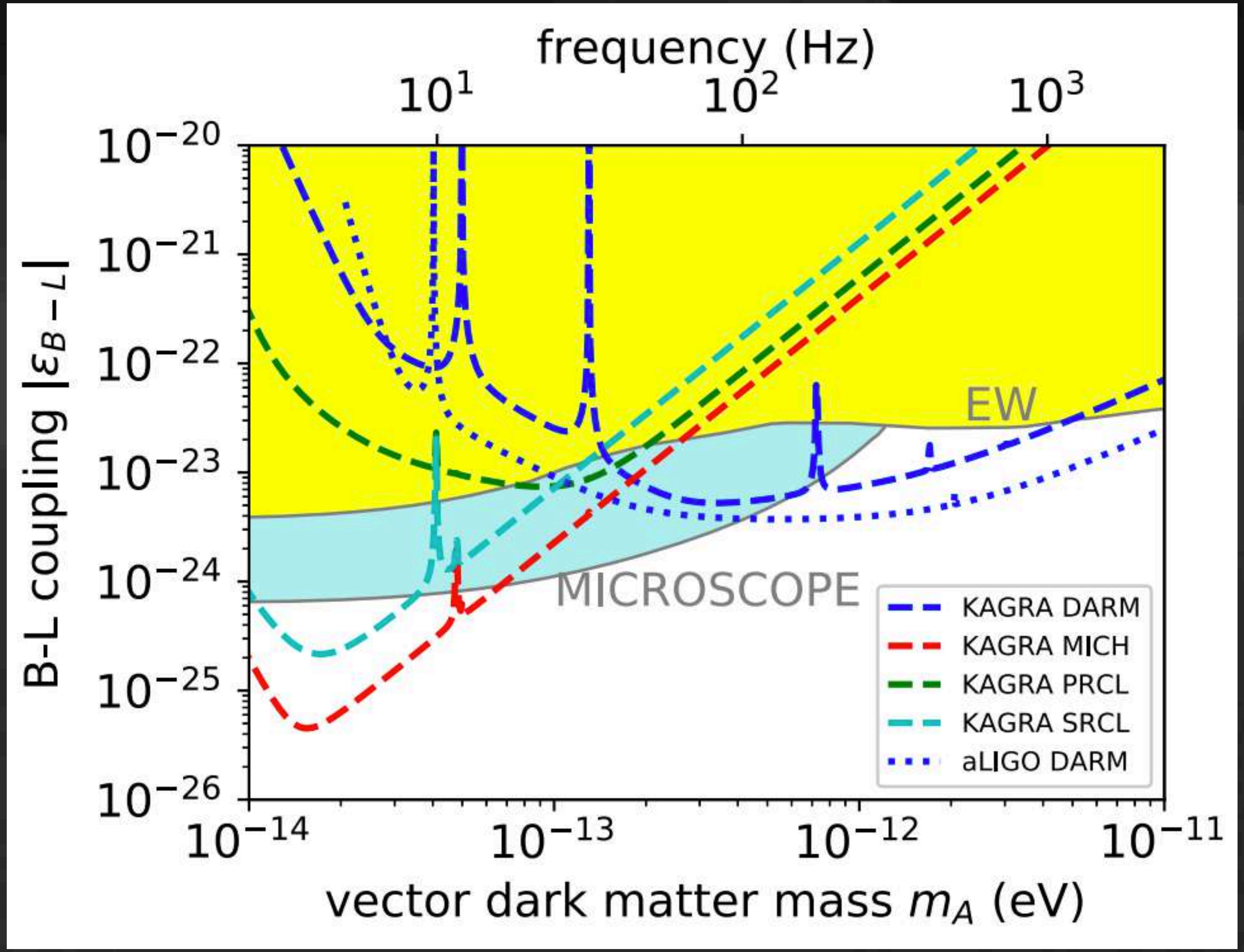
- Wiener filter can be used to confirm or reject outliers arising from cross-correlation or BSD searches
- Model-dependent
- High values of residuals correspond to high critical ratios —> veto is immediate



Miller et al. Phys. Rev. D 105.10 (2022), p. 103035

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

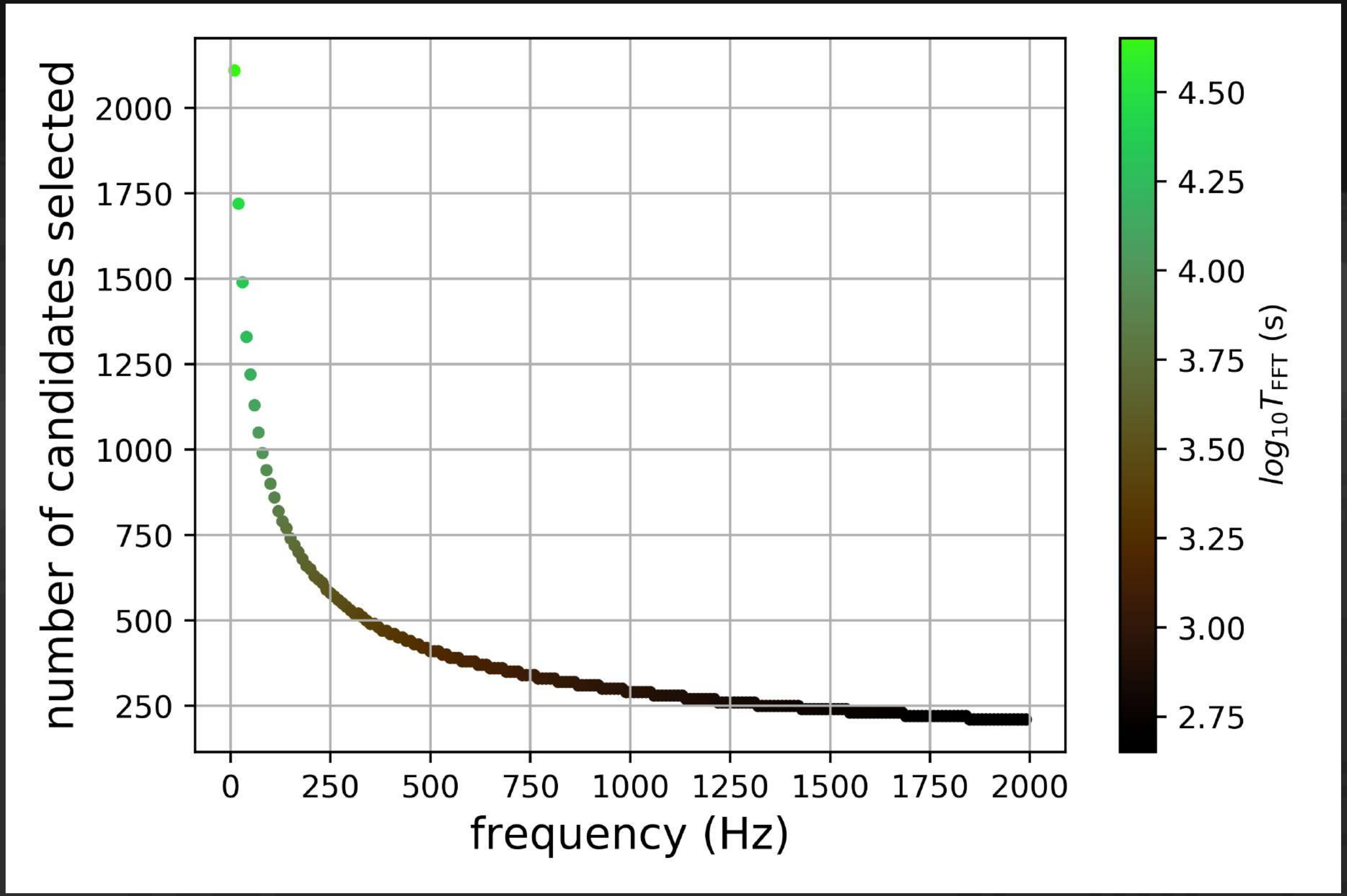


Michamura et al. (2020) PRD 102, 102001

Search method: excess power

- 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 of noise were Gaussian
- 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

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



Number of candidates to select as a function of frequency, with the Fourier Transform time coloured

LVK 2021: Phys.Rev.D 105 (2022) 6, 063030

True differential motion from dark photon field

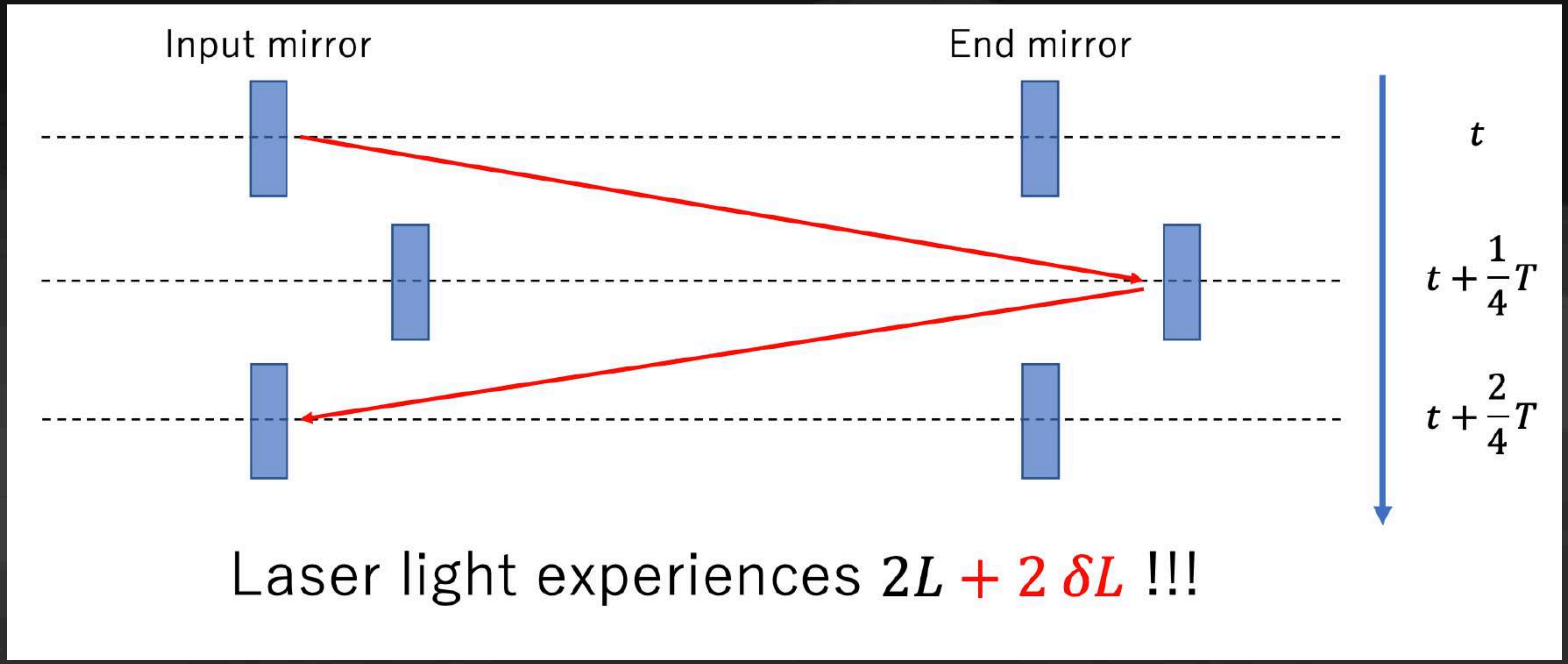
- Differential strain results because each mirror is in a different place relative to the incoming dark photon field: this is a *spatial* effect
- Depends on the frequency, the coupling strength, the dark matter density and velocity

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

Pierce et al. 2018, 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



$$\sqrt{\langle h_C^2\rangle} = \frac{\sqrt{3}}{2}\sqrt{\langle h_D^2\rangle}\frac{2\pi f_0 L}{v_0},$$
$$\simeq 6.58\times 10^{-26}\left(\frac{\epsilon}{10^{-23}}\right)$$

Morisaki et al. 2021, Phys. Rev. Lett. 103, L051702

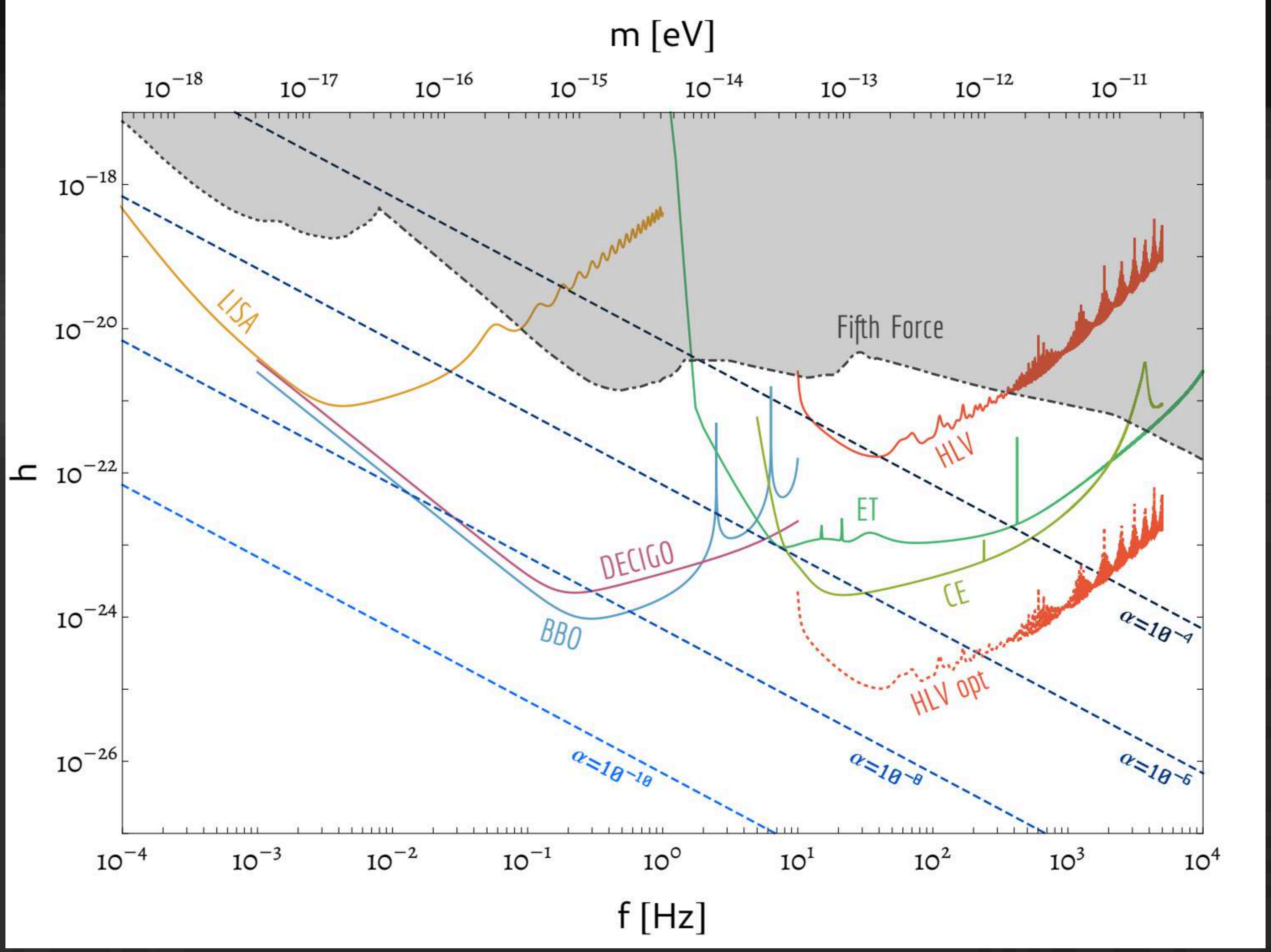
Tensor bosons

- 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

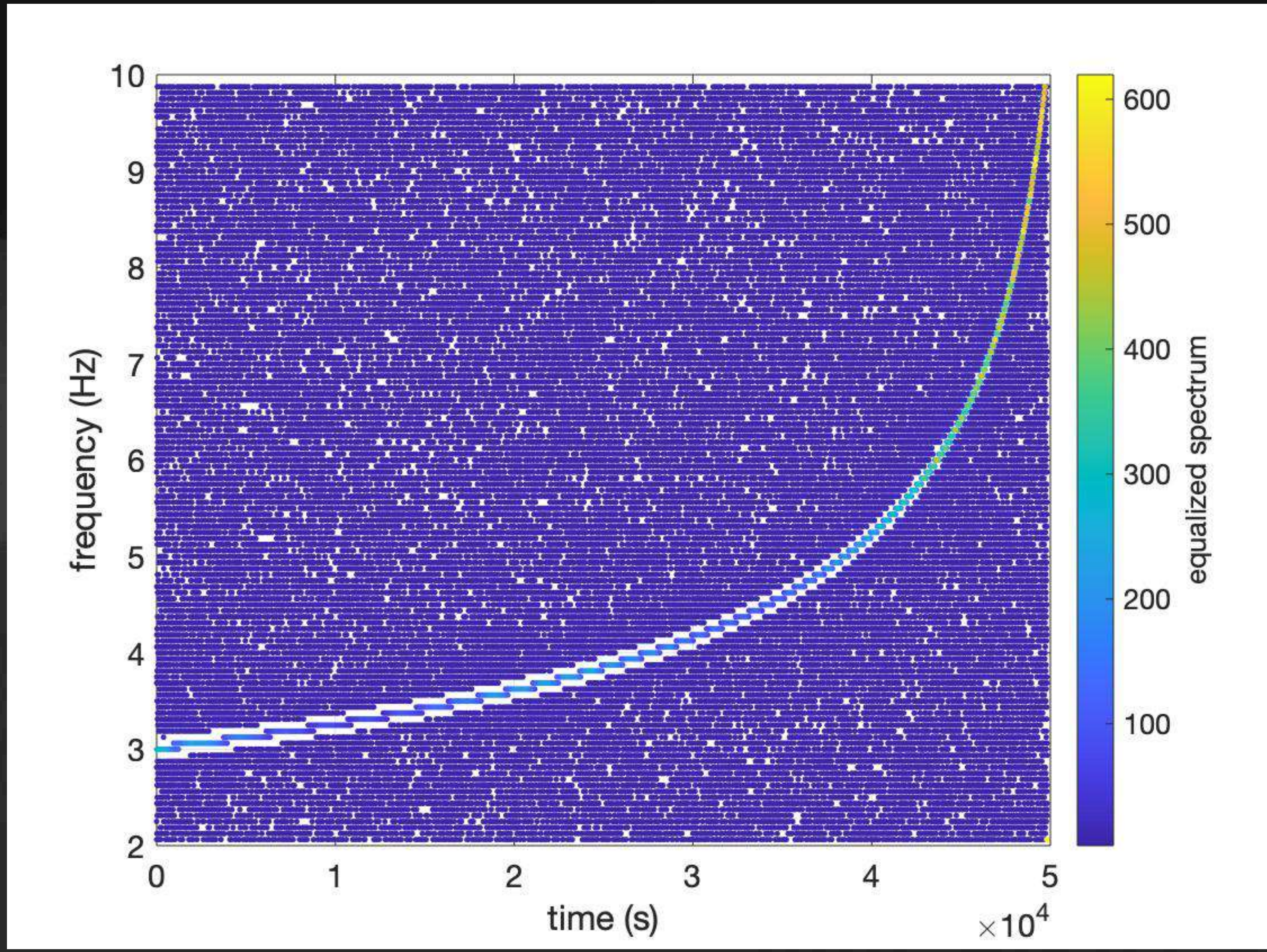
- Current and future detector sensitivities plotted, along with constraints from fifth force experiments
- Depending on theoretical coupling strength, GW interferometers could constrain the existence of tensor boson interactions



Armaleo et al. (2021) JCAP 2021.04: 053

Binary Neutron Star Inspirals

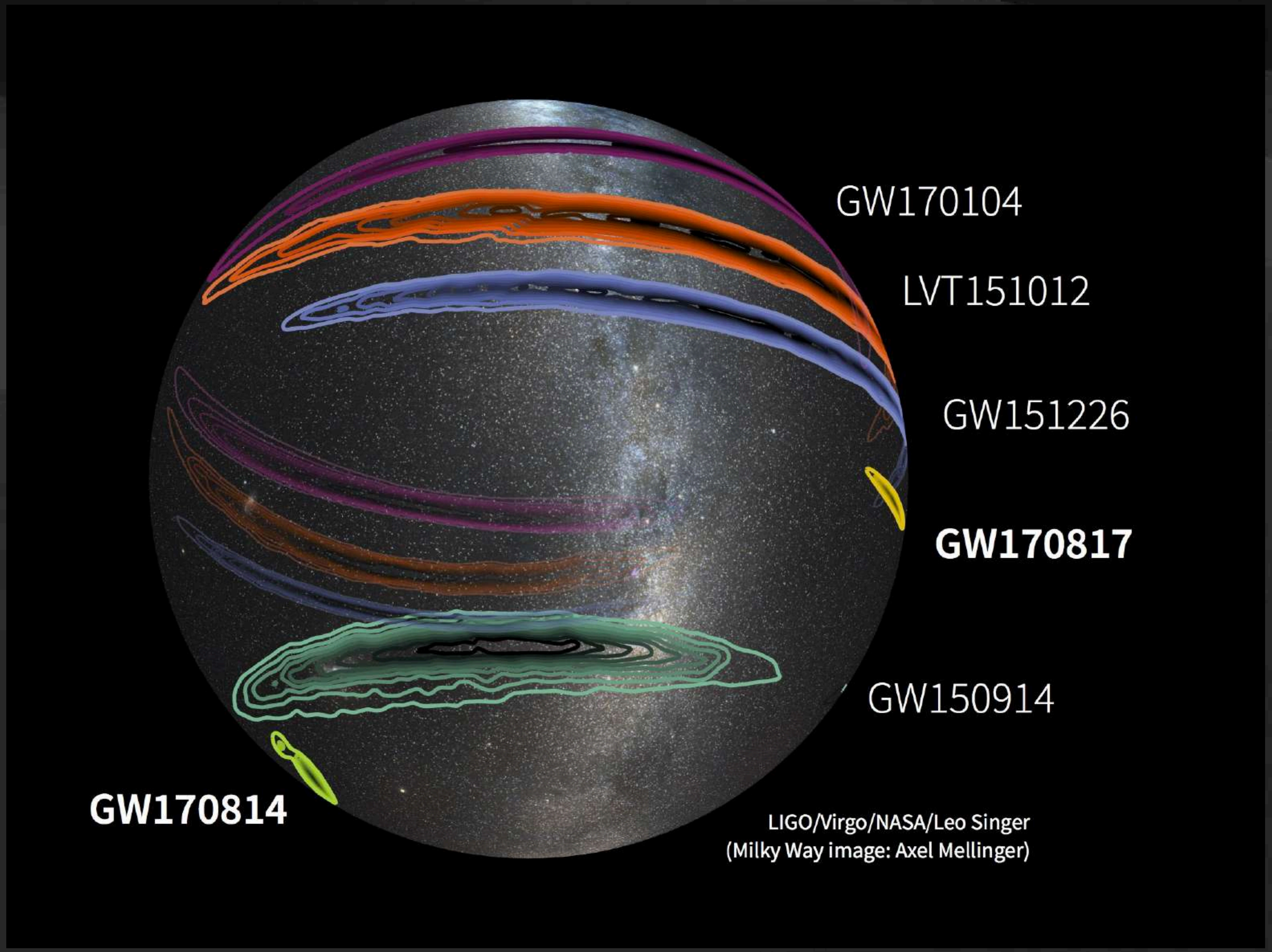
- Inspiraling binary systems will remain within the ET frequency band for a much longer time and overlap (~40-3000x longer for 5 or 1 Hz frequency floors)
- Within this time, assumptions made in matched-filtering analyses, e.g. no gaps, noise stationarity, no glitches, could break down
- Phase mismatch accumulates with longer templates —> need more and more templates for long-lived signals —> very computationally heavy
- Methods used in searches for (transient) CWs could work to provide early-warning sky localization, and could deal with overlapping signals



- Simulated binary neutron star inspiral in white noise up to 1.5 PN, $m_1 = m_2 = 0.9 M_\odot$; $\mathscr{M} = 0.78 M_\odot$

Connection to multi-messengers

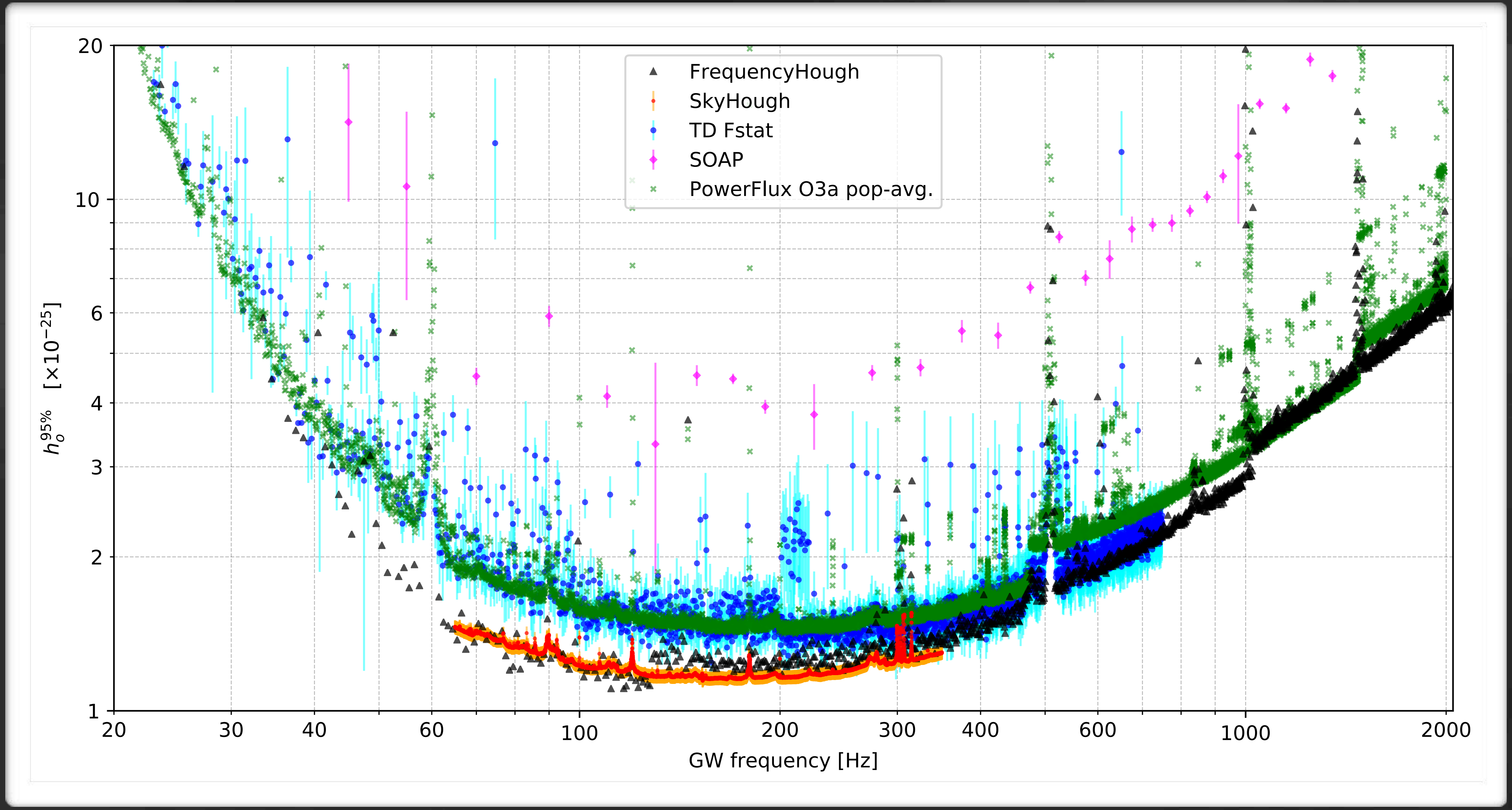
- Binary neutron star inspirals could last for O(hours-days) in future detectors, and are well-modeled by Post-Newtonian expansions
- "Early warning" for astronomers is realistic, given how long these signals could last
- We propose an alternative to matched filtering that could provide early warnings to astronomers, with excellent sky resolution



LVK all-sky search in O3 data

LVK (2021), PRD 104 8, 082004

- Four pipelines used
- These limits represent the minimum detectable amplitude h_0 as a function of gravitational-wave frequency, at 95% confidence
- They are generic, in the sense that they can be interpreted to be for *any* system that follows a linear frequency evolution over time



LVK: Phys. Rev. D, 106(10):102008, 2022.