Exploring the dark sector with gravitational waves

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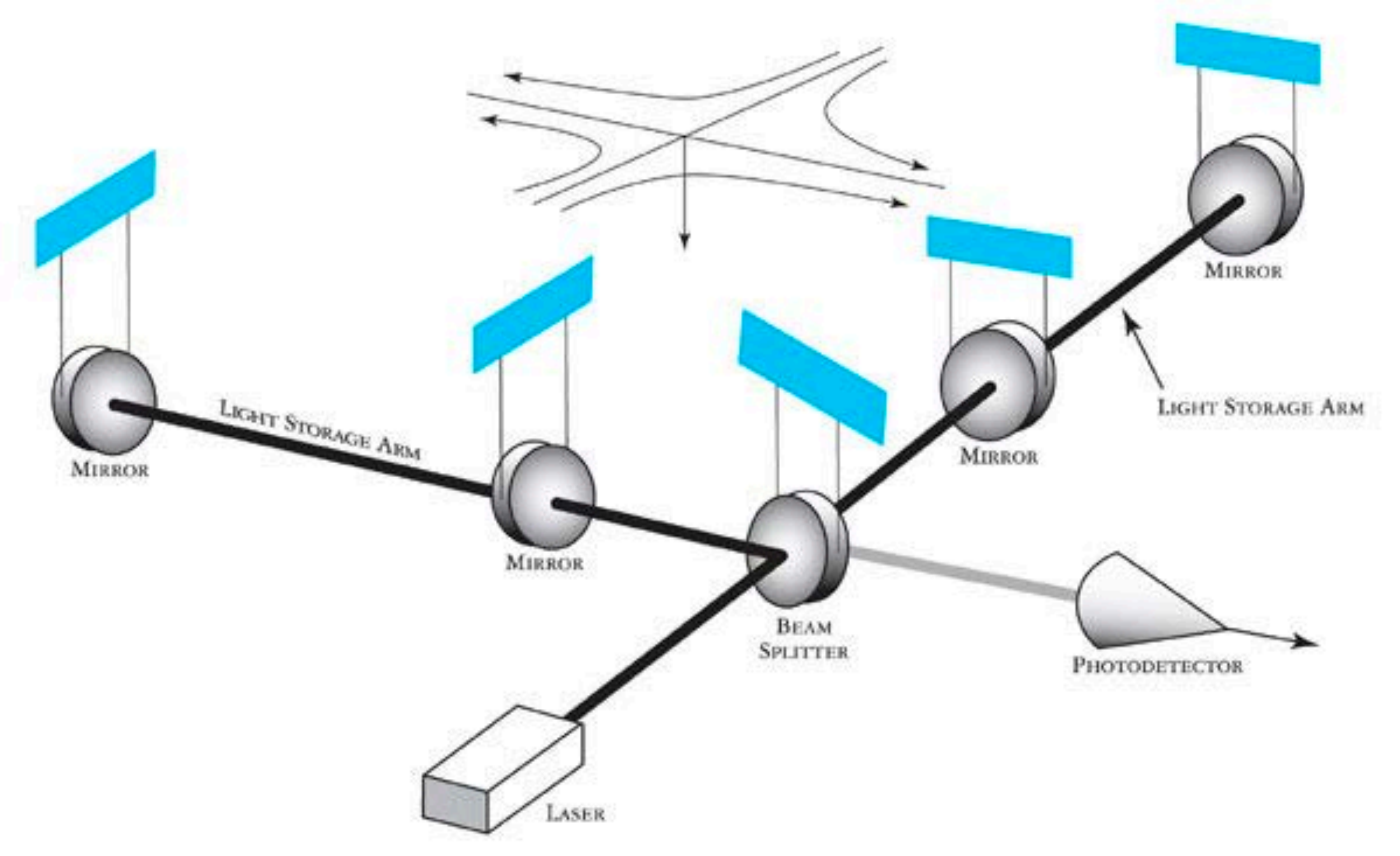
Outline

- Direct searches for dark matter with gravitational-wave (GW) detectors
- Probing gravitational waves from boson clouds around rotating black holes
- Constraints on dark matter from compact objects in binary systems

Background

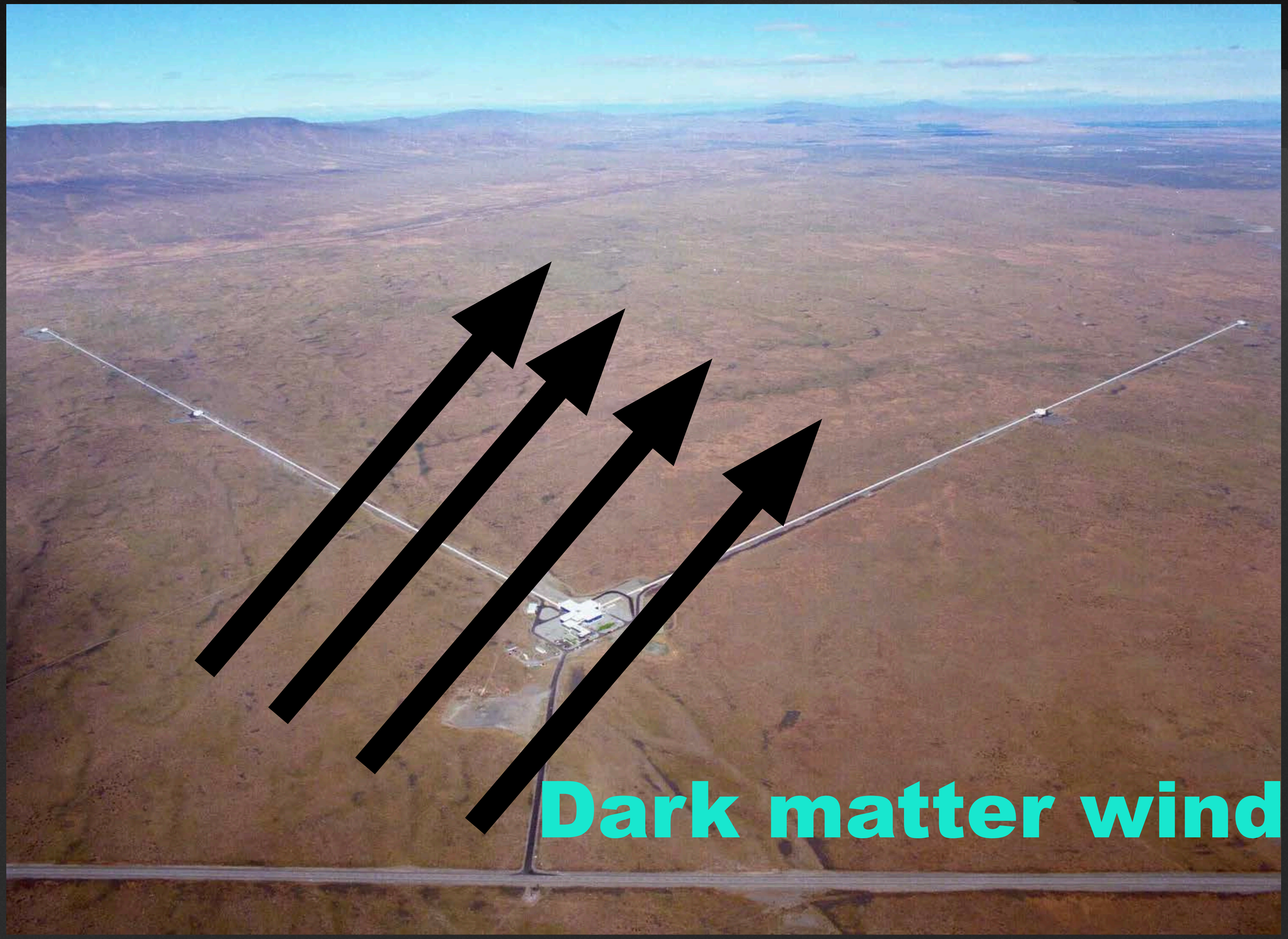
Context

- 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 —> DM mass range $[10^{-14},10^{-12}]$ eV/c^2
- Different DM particles with interact with different standard-model ones, leading to similar but distinguishable signals
- When we do not observe DM we place constraints on the coupling of DM to ordinary particles



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

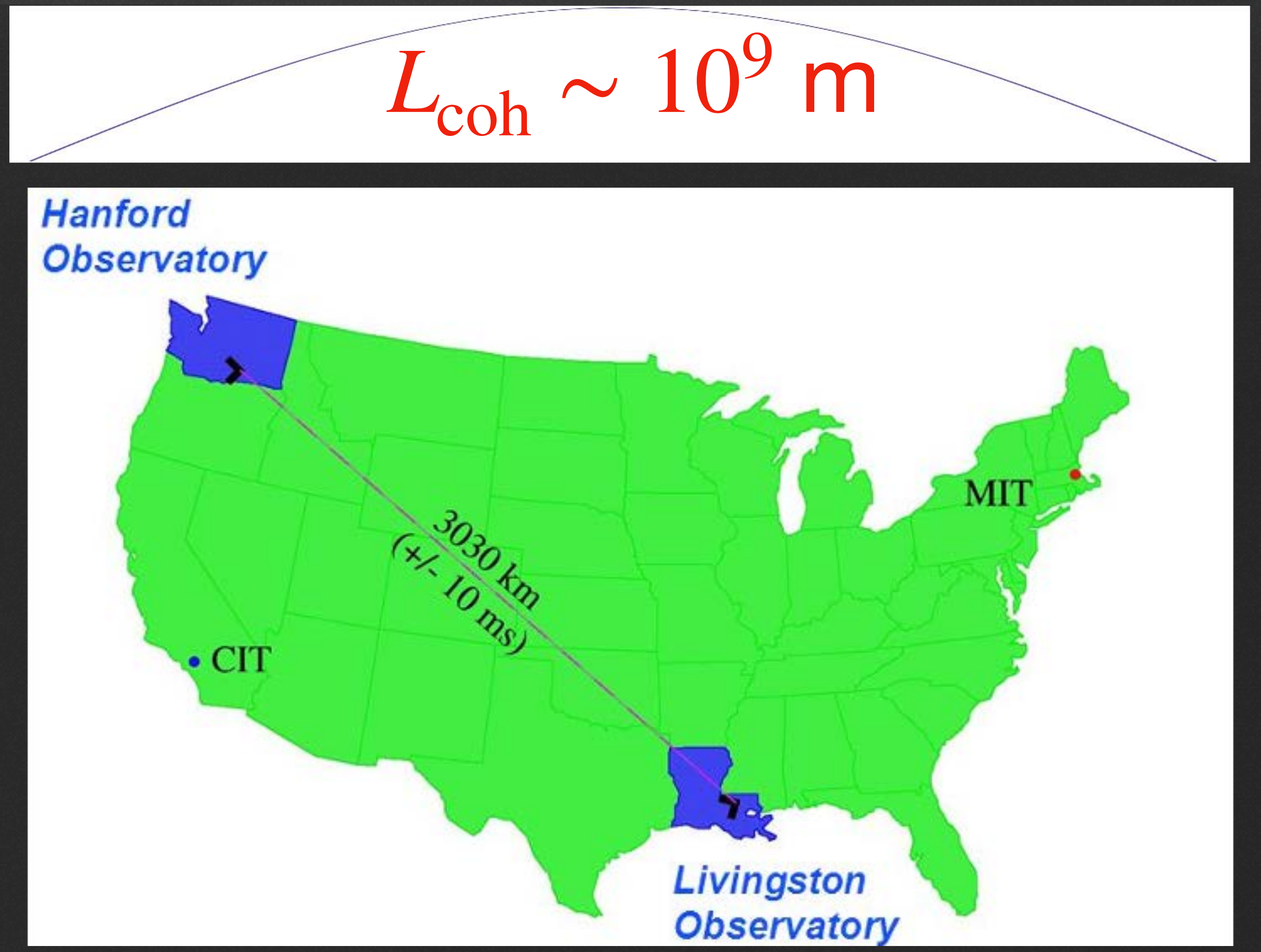
Ultralight dark matter

- 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

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

$$N_o = \lambda^3\frac{\rho_{\rm DM}}{m_A c^2} = \left(\frac{2\pi\hbar}{m_A v_0}\right)^3\frac{\rho_{\rm DM}}{m_A c^2},$$
$$\approx 1.69\times10^{54}\left(\frac{10^{-12}\ {\rm eV}/c^2}{m_A}\right)^4$$

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



Vector bosons: dark photons

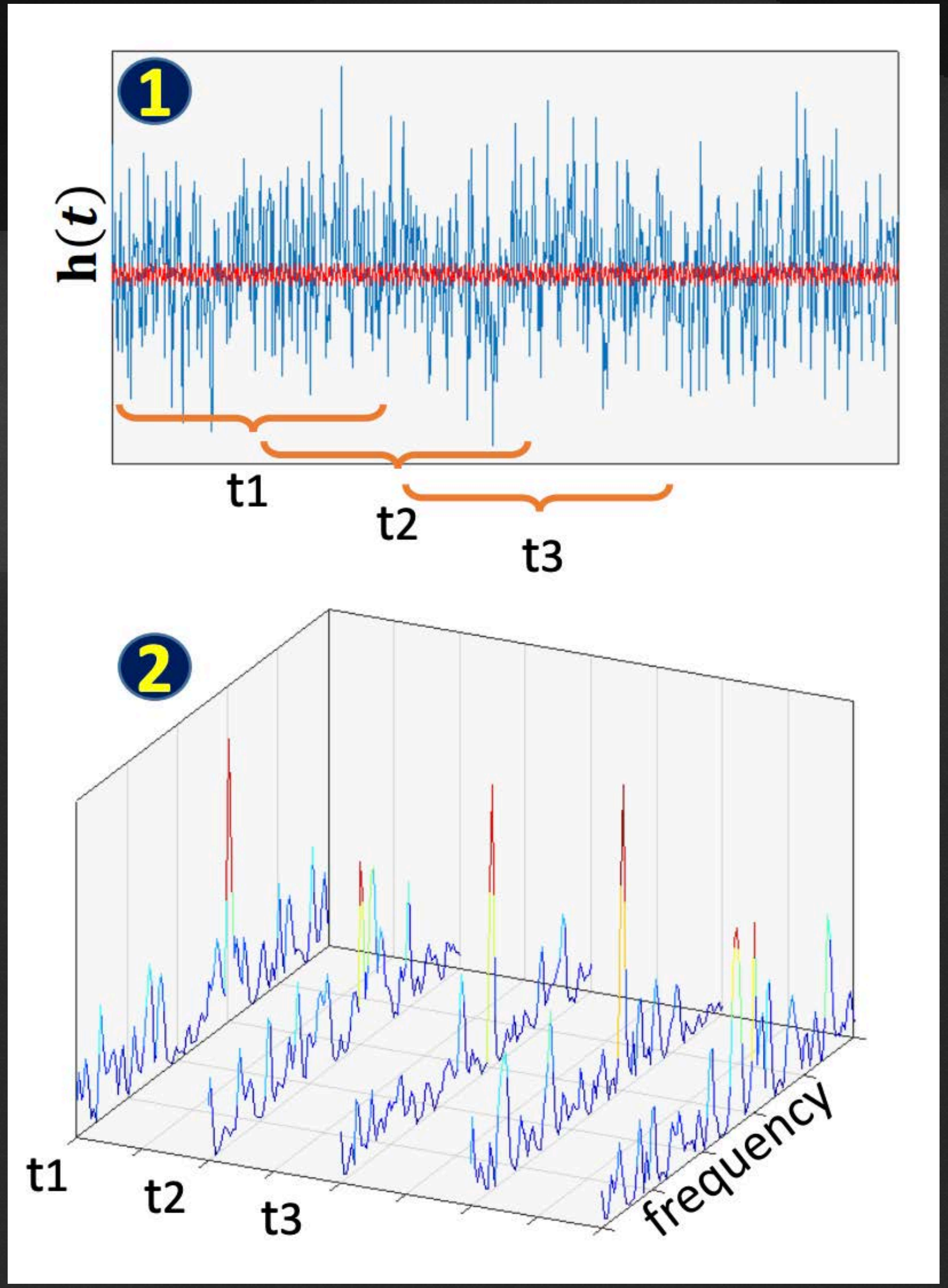
$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} \boxed{+ \frac{1}{2}m_A^2 A^\mu A_\mu - \epsilon_D e J_D^\mu A_\mu,}$$

$\underline{m_A}$: dark photon mass
$\underline{\varepsilon_D}$: 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 —> differential strain from a spatial gradient in the dark photon field
- Apparent strain results from a "finite light travel time" effect

How to search for DM?

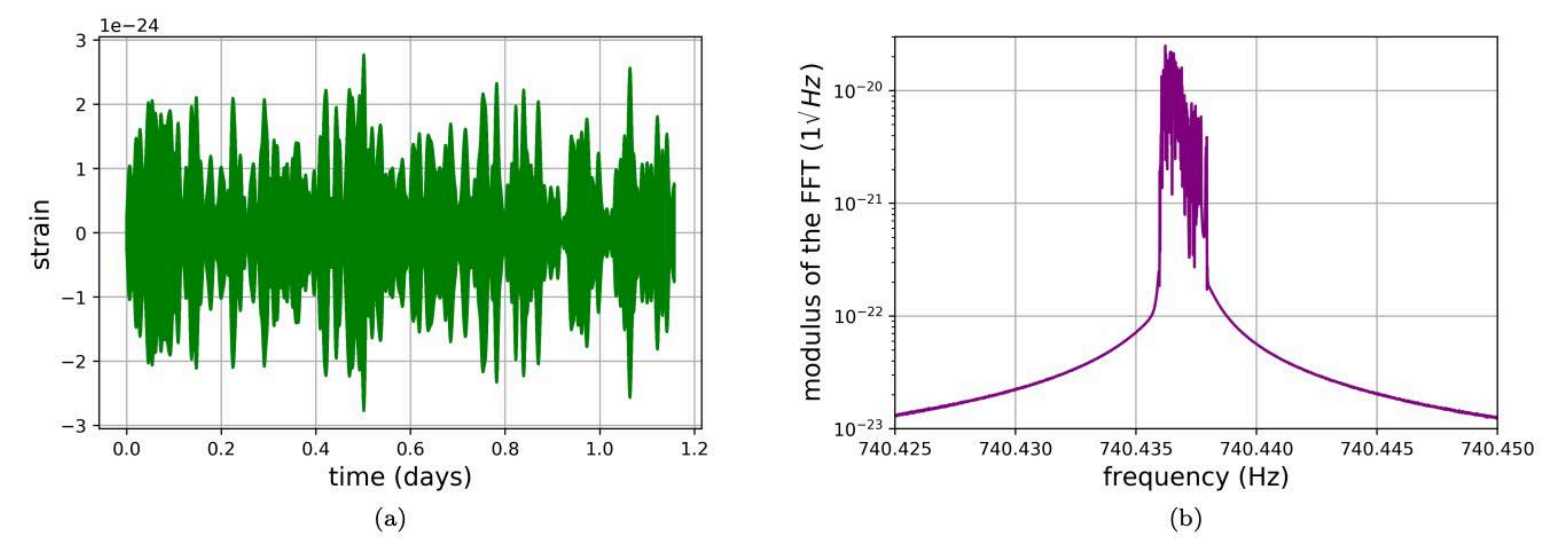
- Ideal technique to find weak signals in noisy data: matched filter
- But, signal has stochastic fluctuations —> matched filter cannot work
- The signal is almost monochromatic —> take Fourier transforms of length $T_{\mathrm{FFT}} \sim T_{\mathrm{coh}}$ and combine the power in each FFT without phase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



Credit: L. Pierini

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

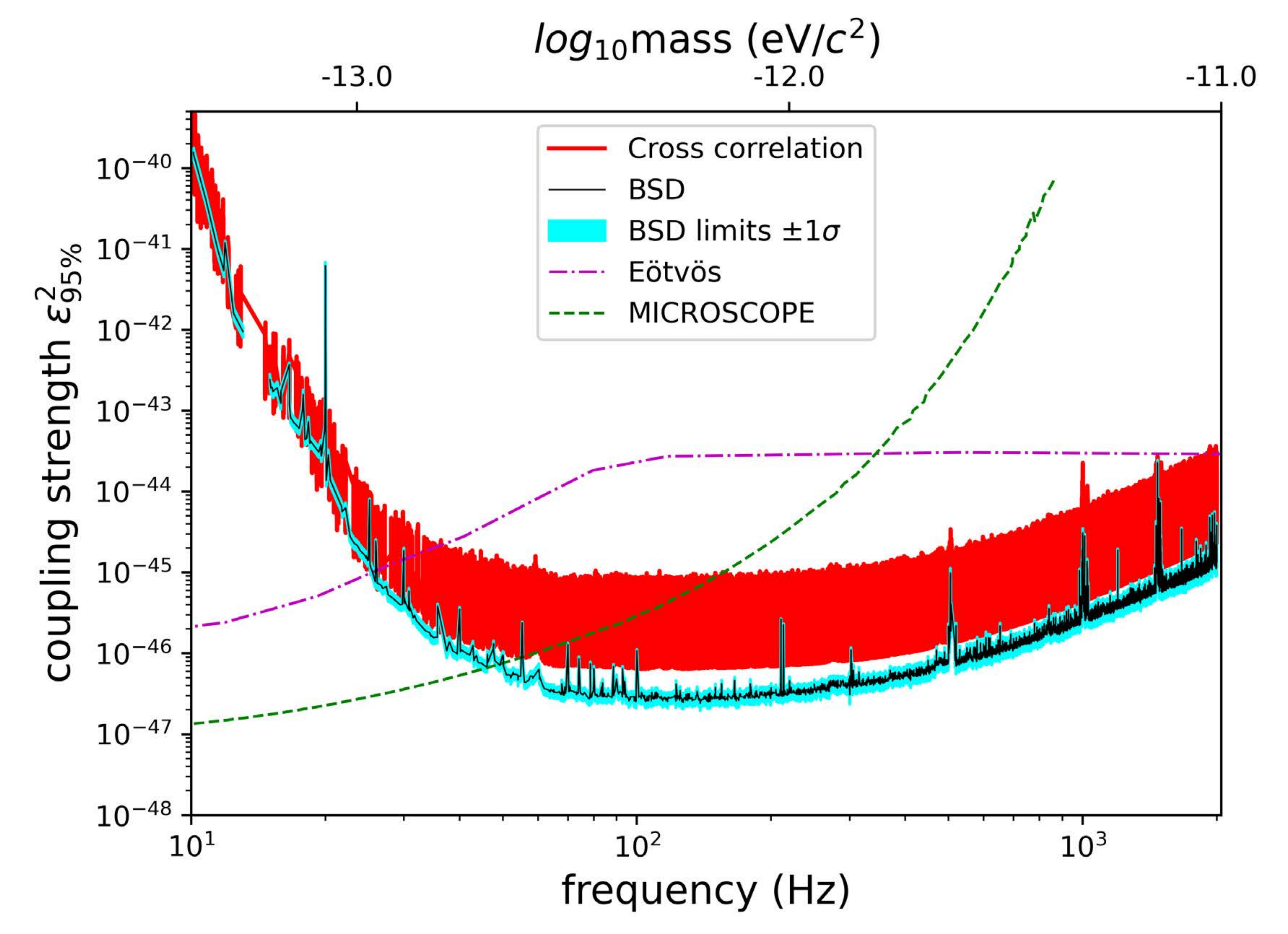


- One day shown, but signal lasts longer than observing run

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

O3 LIGO dark photon search

- Upper limit from two methods (cross correlation and BSD)
- Cross-corr fixes $T_{\mathrm{FFT}} = 1800$ s; excess power matches T_{FFT} to T_{coh}
- Compared to limits from existing torsion balance experiments (Eötvös) and MICROSCOPE satellite
- Limits are generic — can also be applied to other types of DM can be searched for too (dilatons and tensor bosons in particular)



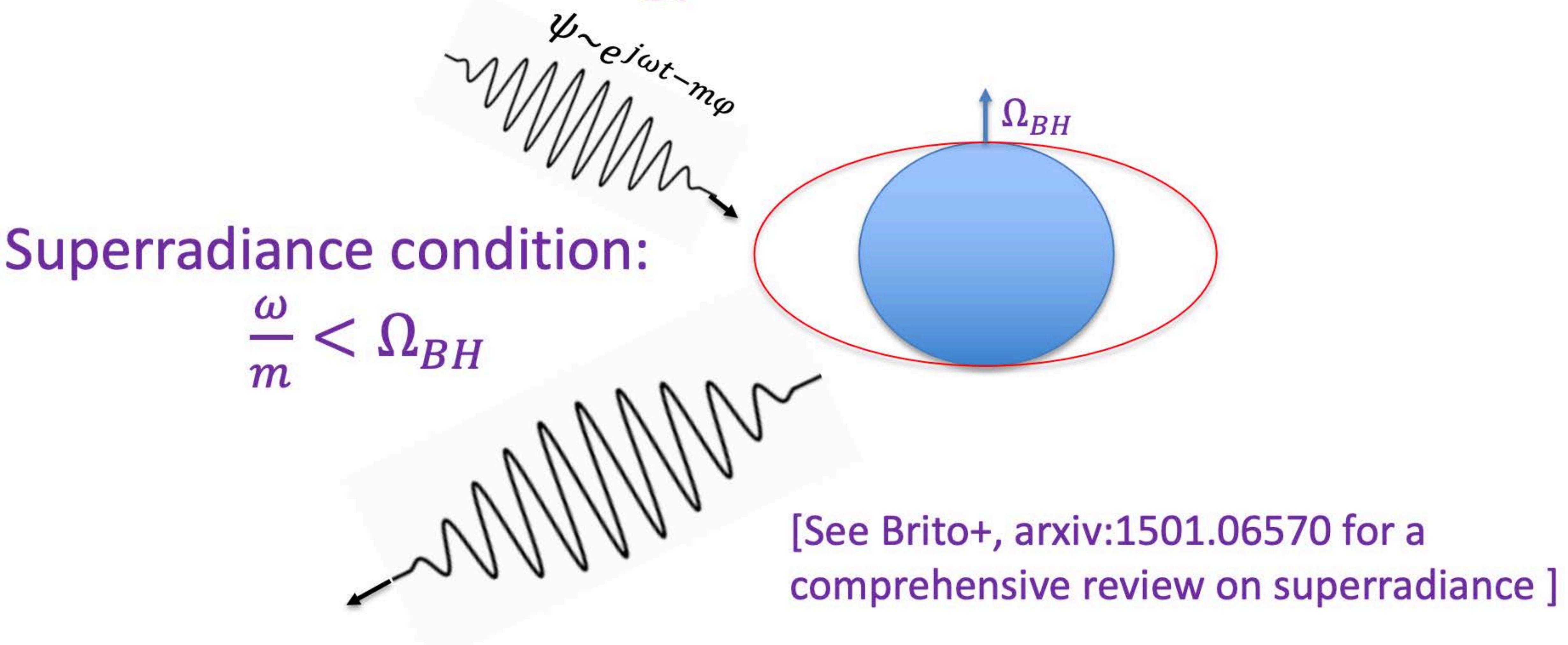
Guo et al. Nat. Commun.Phys. 2 (2019)

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

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



Superradiance condition:

$$\frac{\omega}{m} < \Omega_{BH}$$

[See Brito+, arxiv:1501.06570 for a comprehensive review on superradiance]

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

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

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

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

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)

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

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

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

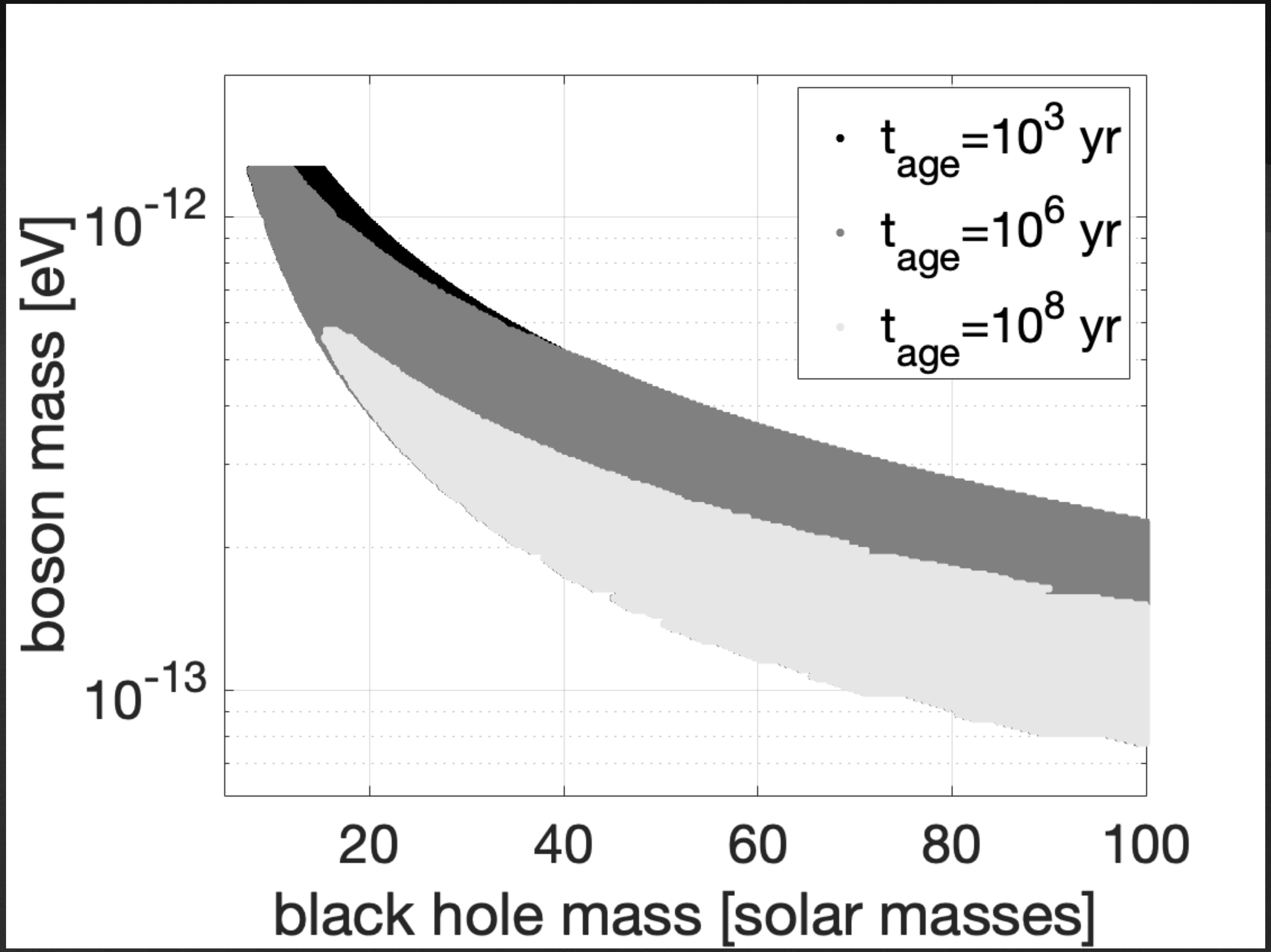
$$h(t) = \frac{h_0}{1 + \frac{t}{\tau_{\rm gw}}}$$

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

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

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

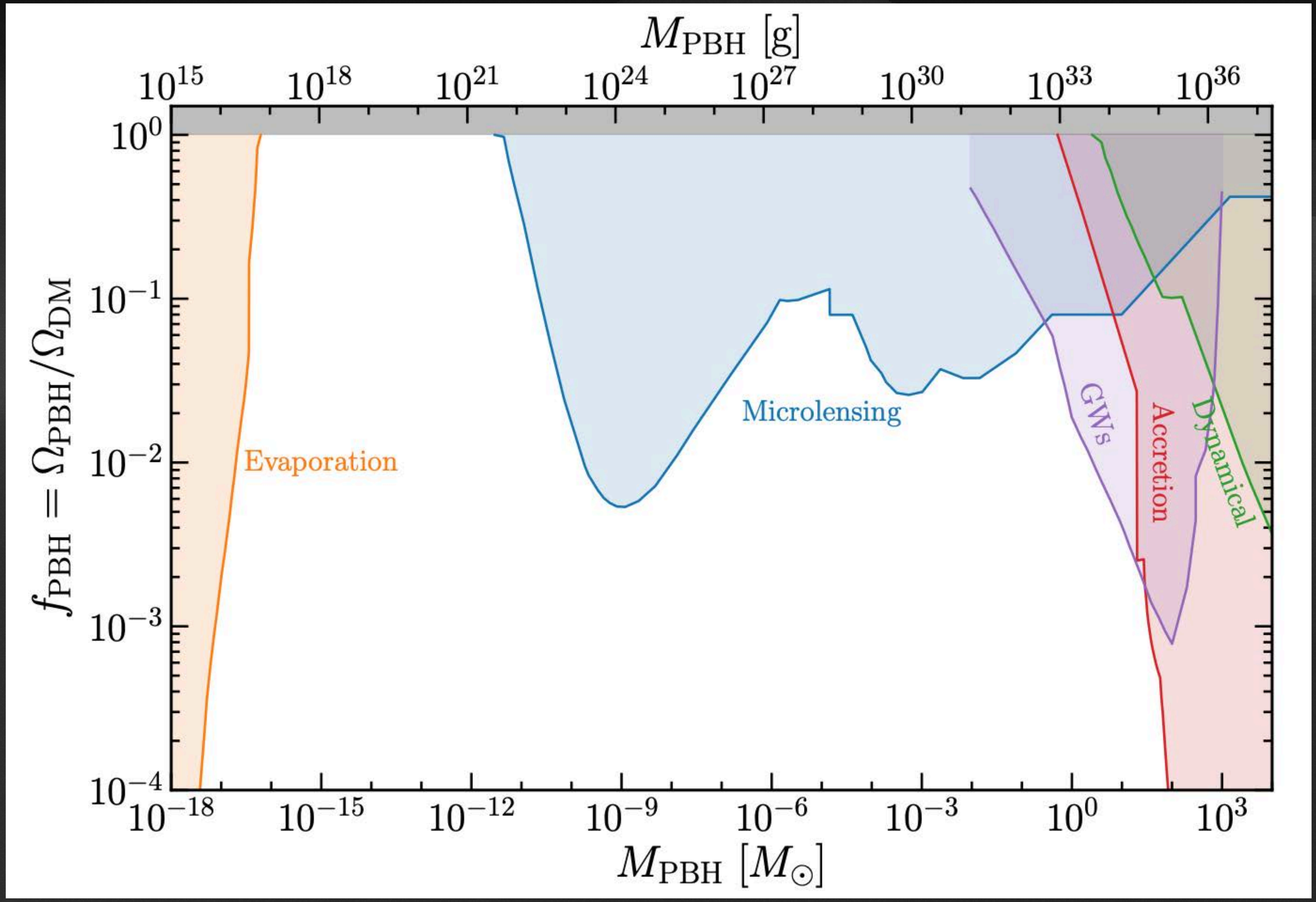


LVK: Phys.Rev.D 105 (2022) 10, 102001

Sub-solar mass compact objects

Primordial Black Holes

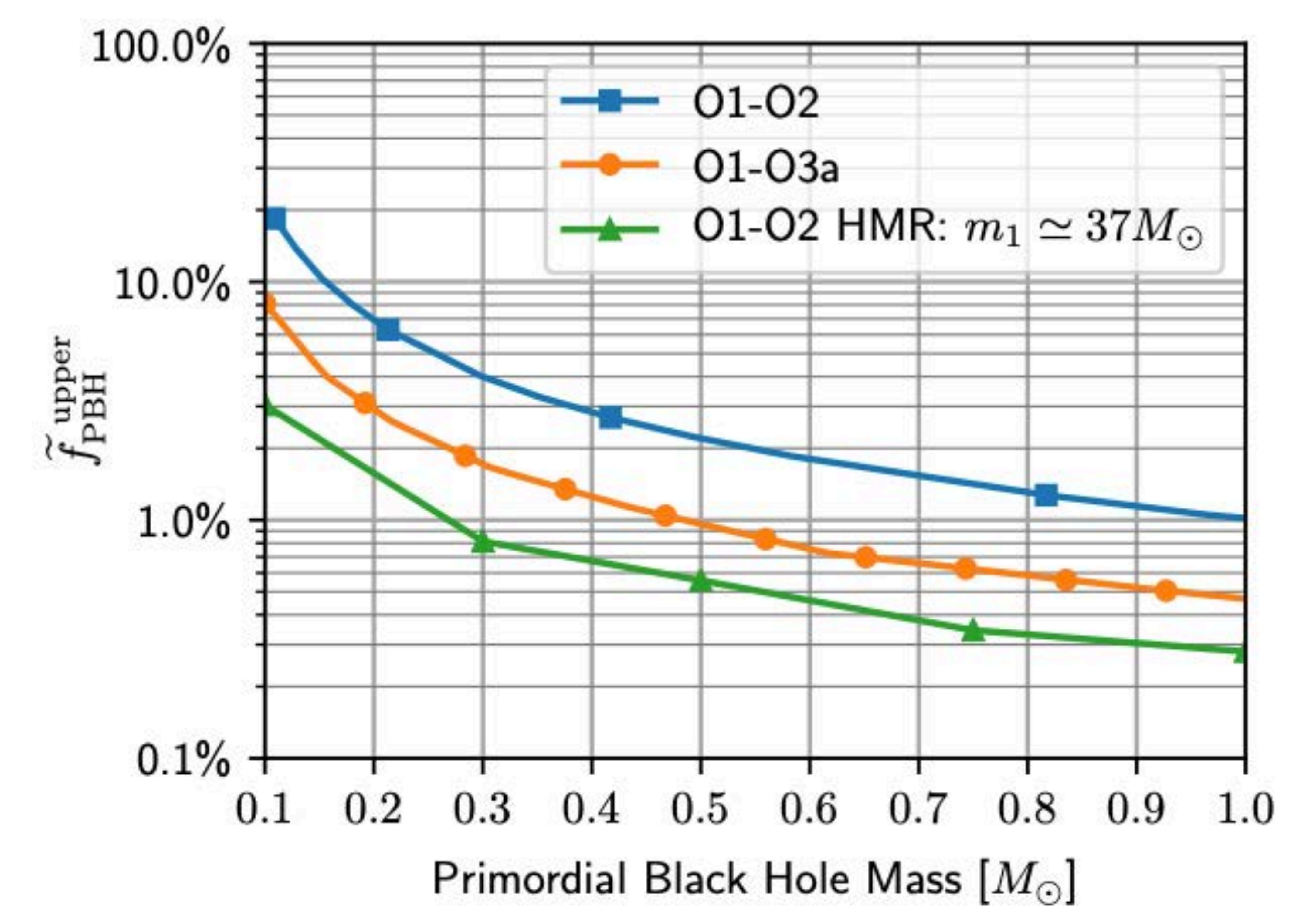
- Low spins of LIGO/Virgo black holes, and merging rate inferences have revived interest in PBHs
- BHs that formed in the early universe can take on a wide range of masses
- Possible links to dark matter



Green and Kavanagh. 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, $\mathcal{O}(0.1 M_\odot)$
- 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



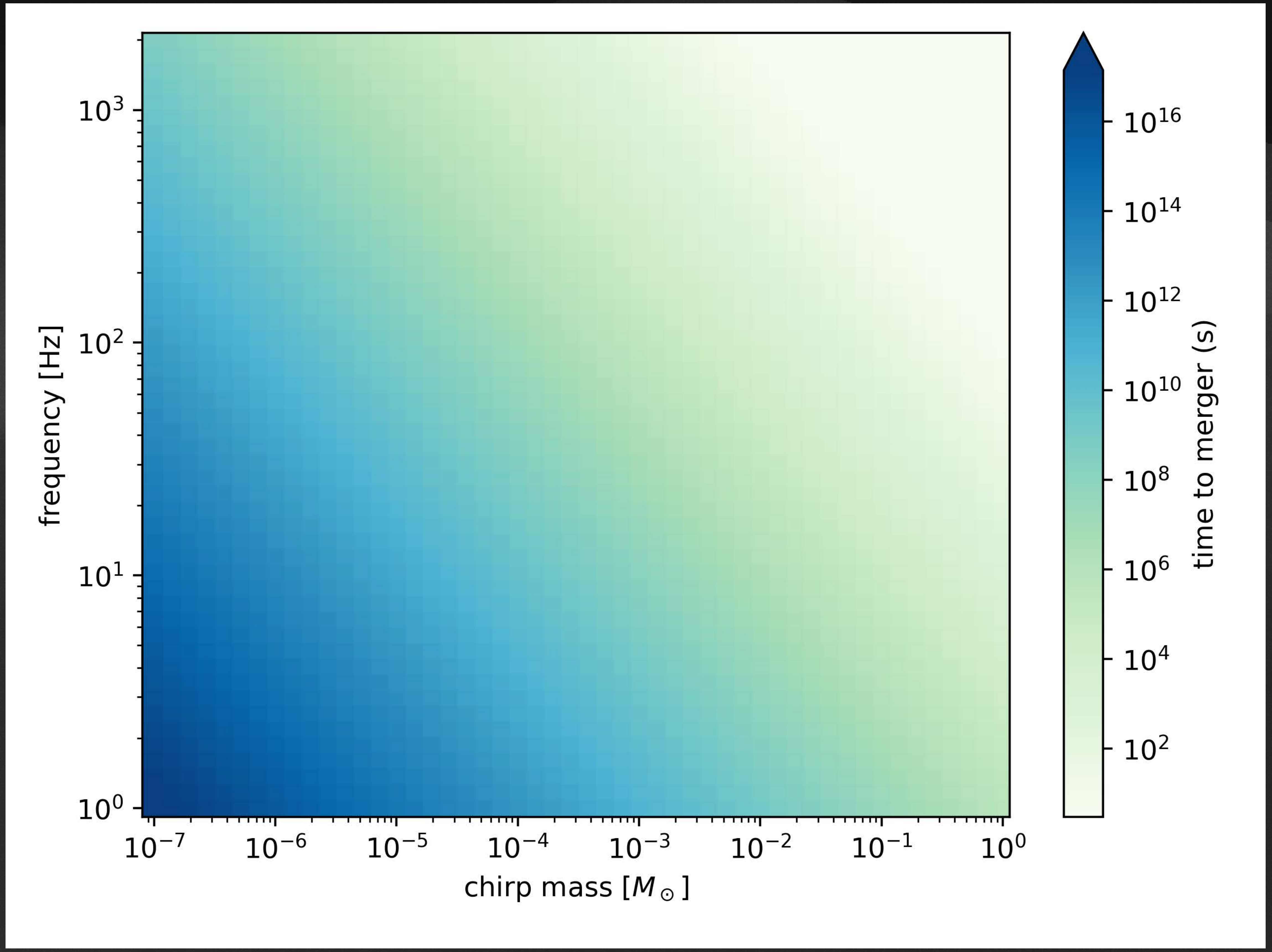
Nitz & Wang: Phys.Rev.Lett. 127 (2021) 15, 151101.
LVK: Phys.Rev.Lett. 129 (2022) 6, 061104
LVK: arXiv: 2212.01477

GWs from inspiraling PBHs

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

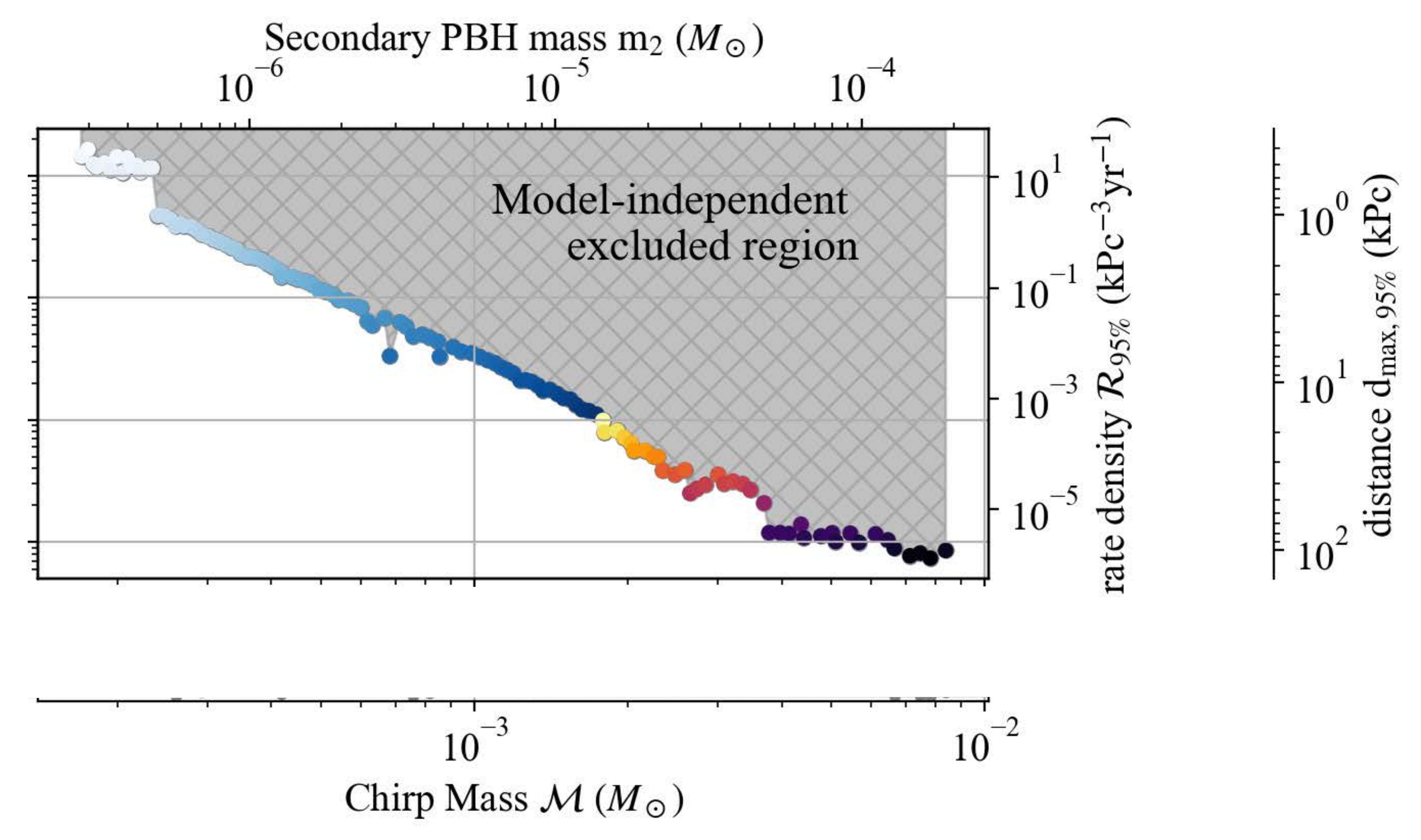
$$\dot{f} = \frac{96}{5}\pi^{8/3}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3} f^{11/3}\left[1 + \dots\right]$$

- 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



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

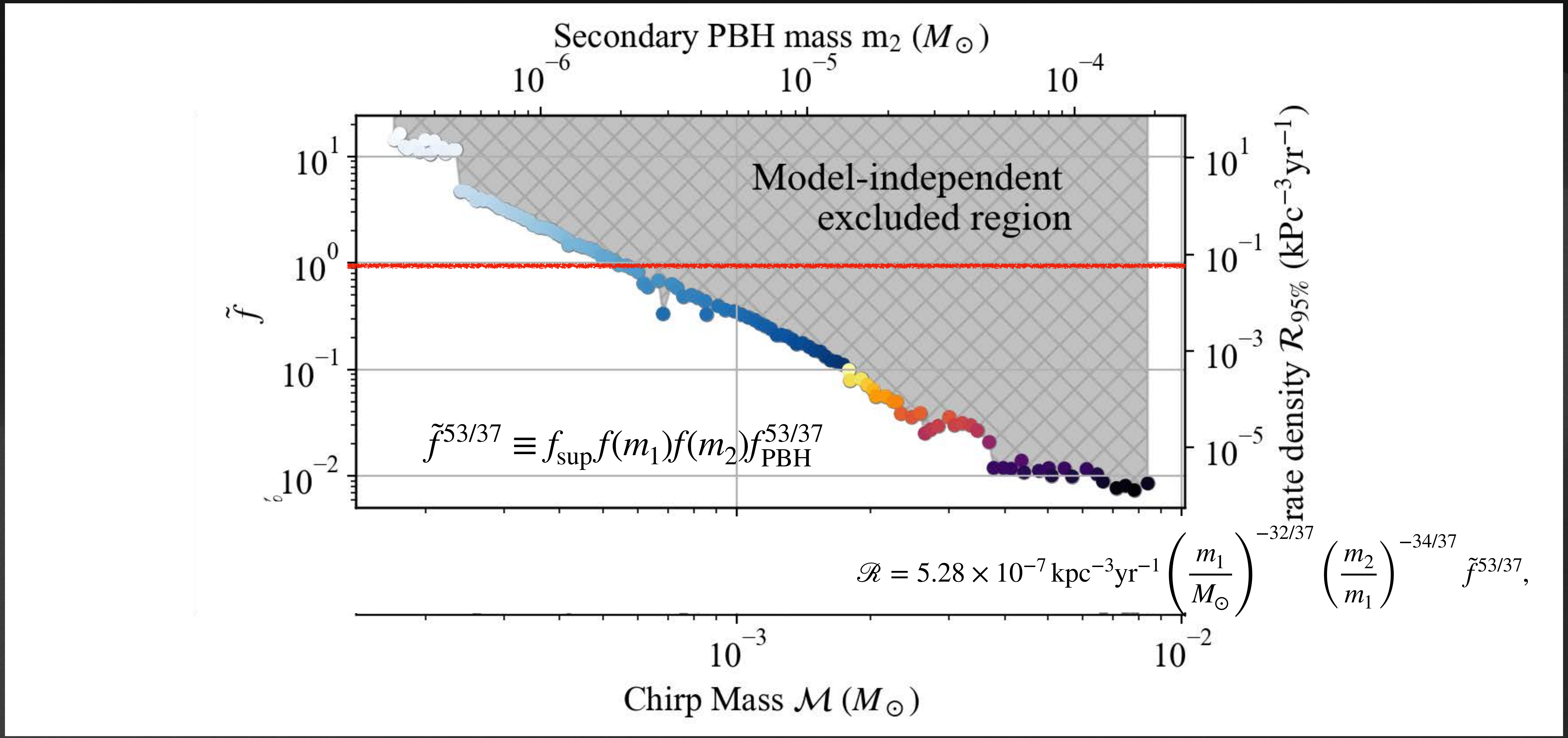
Asymmetric-mass ratio PBHs



- First, we compute the maximum distance at which we could have seen a signal at 95% confidence
- Then, we assume a uniform distribution of sources, and compute a rate density $\mathcal{R} \sim \left[\frac{4}{3}\pi d^3 T_{\mathrm{obs}}\right]^{-1}$

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

Asymmetric-mass ratio PBHs



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

$$\mathscr{R} = 5.28 \times 10^{-7}\,{\rm kpc}^{-3}{\rm yr}^{-1} \left(\frac{m_1}{M_\odot}\right)^{-32/37} \left(\frac{m_2}{m_1}\right)^{-34/37} \tilde{f}^{53/37},$$

$f(m)$: mass function

$f_{\rm PBH}$: fraction of DM that PBHs could compose

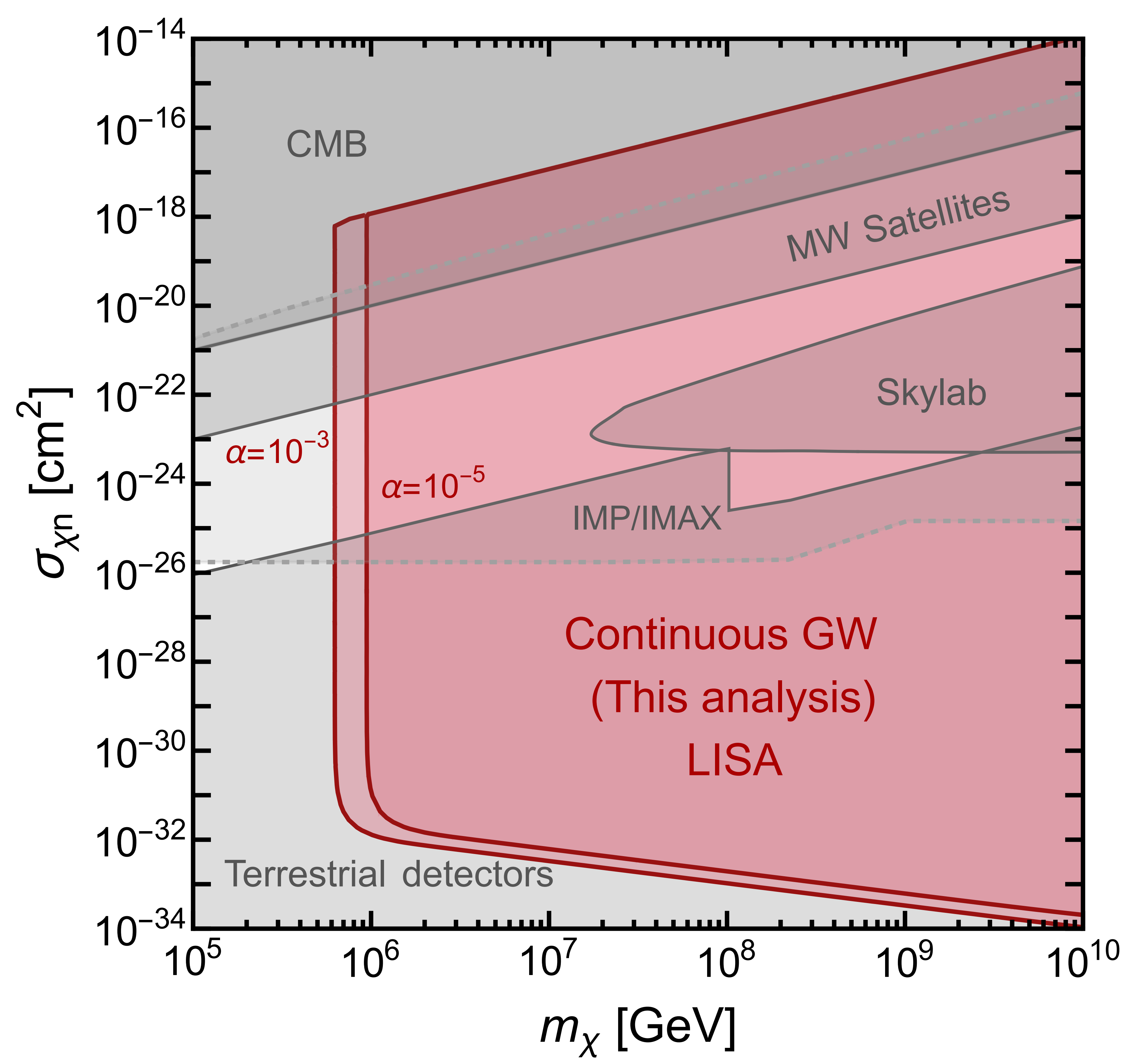
$f_{\rm sup}$: binary suppression factor

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

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

Transmuted Black Holes

- If non-annihilating WIMP DM exists, it could collect around celestial objects formed and induce collapse into BHs
- Using future LISA data, we will be able to set competitive constraints on the cross section of bosonic and fermionic DM for sun-like stars collapsing into inspiraling BHs that could be detectable at ~10 μHz



Bhattacharya, Miller, and Ray (2024): PRD 110.4, 043006.

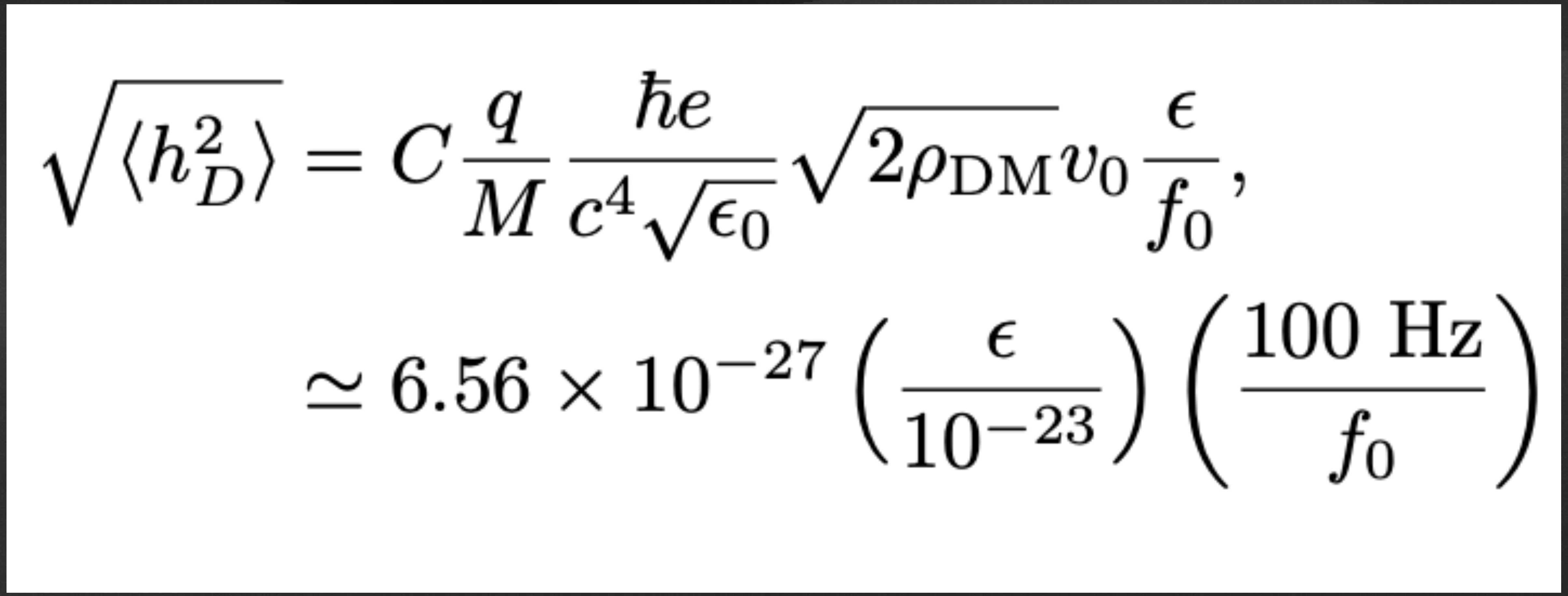
Conclusions

- 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, and (sub-) solar mass black holes
- If you are interested in working on any aspect of dark matter, please send me an email: amiller@nikhef.nl

Backup slides

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

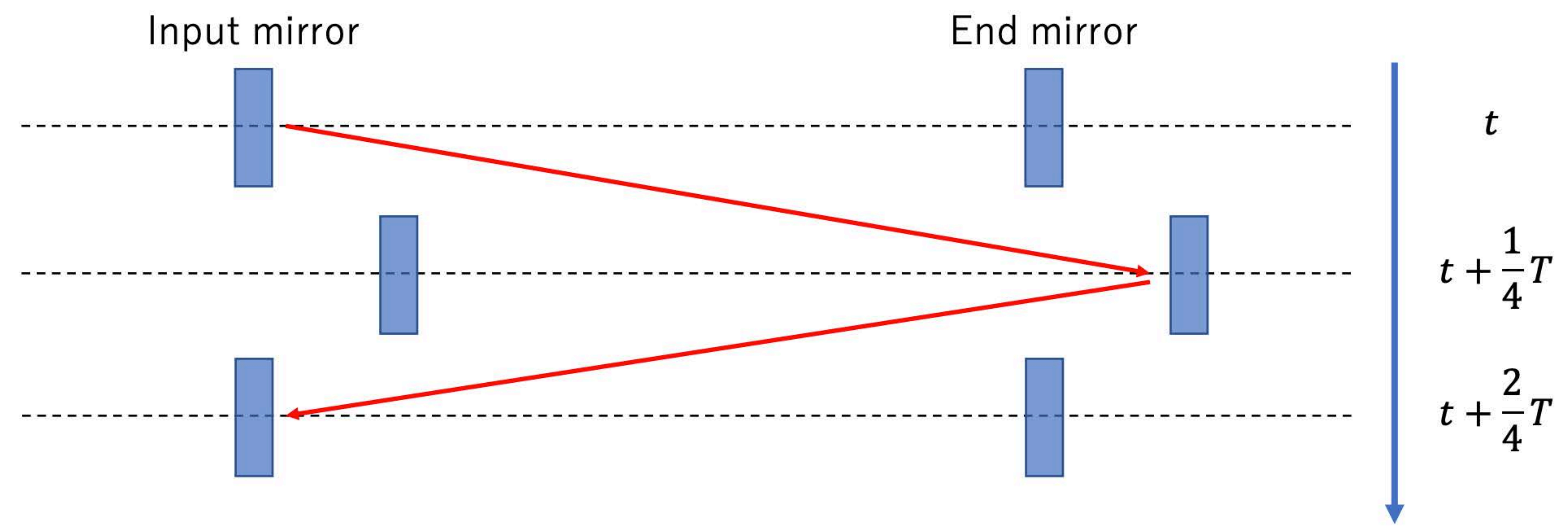


$$\begin{aligned}\sqrt{\langle h_D^2\rangle} &= C\frac{q}{M}\frac{\hbar e}{c^4\sqrt{\epsilon_0}}\sqrt{2\rho_{\mathrm{DM}}}v_0\frac{\epsilon}{f_0},\\ &\simeq 6.56\times 10^{-27}\left(\frac{\epsilon}{10^{-23}}\right)\left(\frac{100\ \mathrm{Hz}}{f_0}\right)\end{aligned}$$

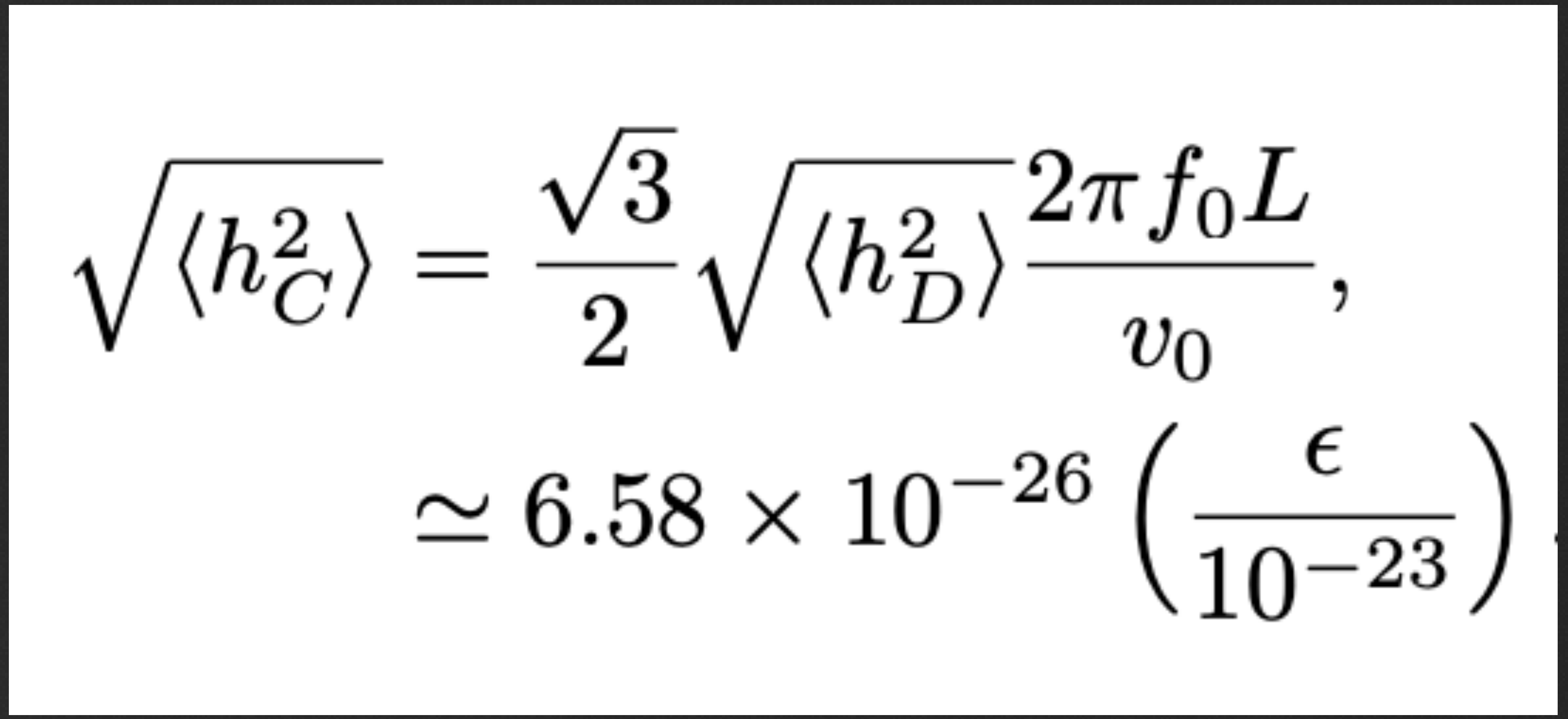
Pierce et al. 2018, Phys. Rev. Lett. 121, 061102

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



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, Phys. Rev. D. 103, L051702

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

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

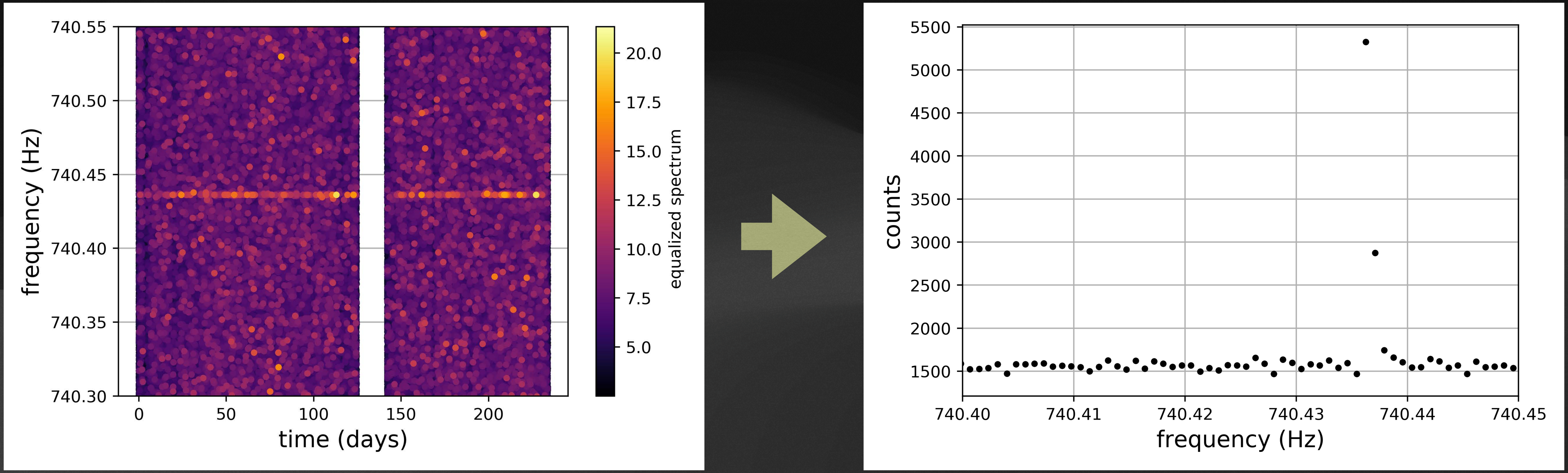
$$\sigma_j^2 = \frac{1}{N_{\mathrm{FFT}}} \left\langle \frac{1}{2P_{1,ij} P_{2,ij}} \right\rangle_{N_{\mathrm{FFT}}}$$

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

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

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

Method: look for 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

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