# Searches for dark matter signals with gravitational-wave detectors

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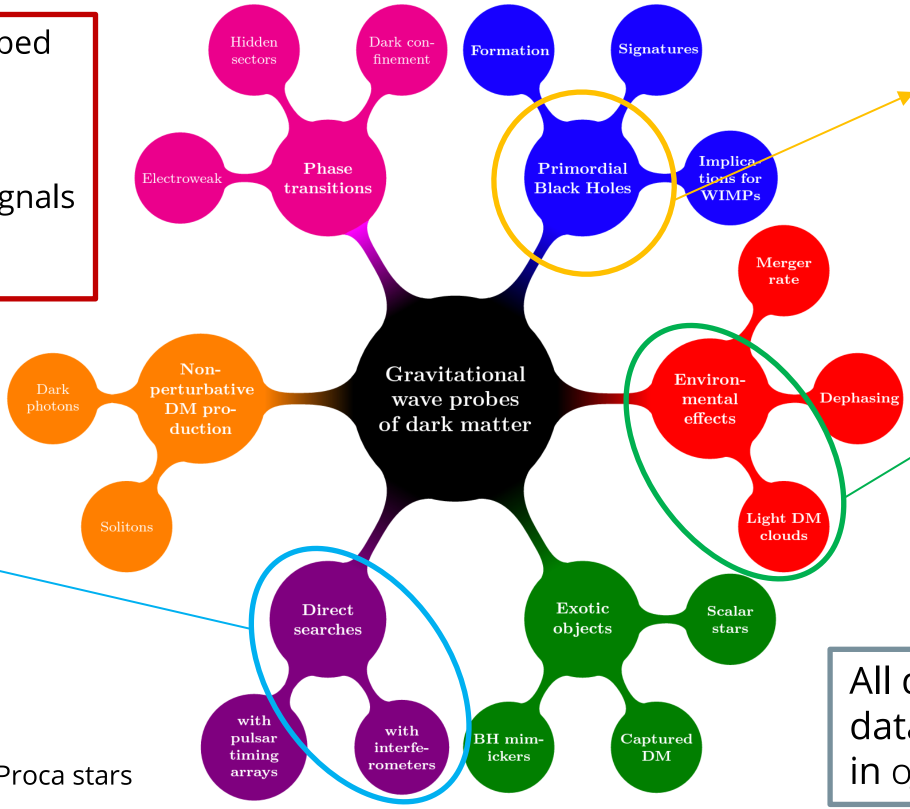
# Dark matter and GW detectors

Many scenarios can be probed using GW detectors:

we are interested in quasi-monocromatic long-lived signals

[see OJP 2022 arXiv:2202.01088]



Inspiral phase or very low masses

Boson clouds around black holes

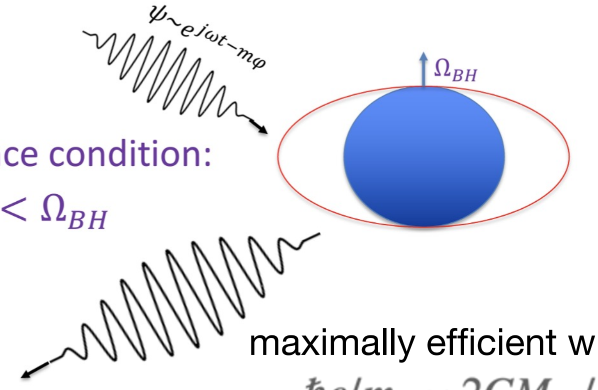
Vector bosons interacting with the detector

See also:
Calderón-Bustillo et al. PRL, 2021 – Proca stars
Ng et al. PRL, 2021 – BHBC mergers
…

Credit: Bertone et al. 2020

All developed from the BSD data framework described in OJP et al. 2019 CQG 36 015008

# Boson clouds: scalar bosons



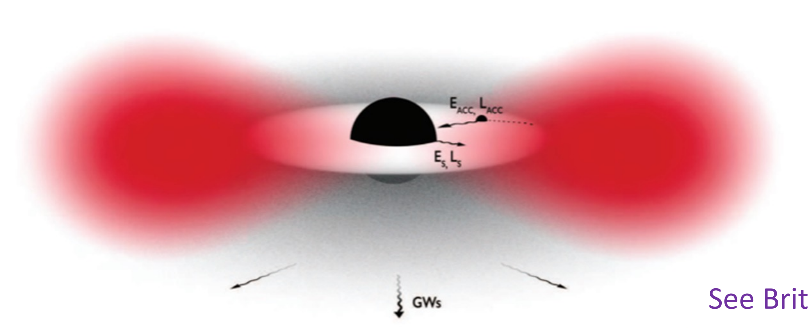
Superradiance condition:

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

wave is scattered off
a rotating black hole

maximally efficient when

$$\hbar c/m_b \sim 2GM_{bh}/c^2$$



Credit: Ana Sousa Carvalho

See Brito's talk

- field bosons condensate, occupying the same (quantum) state with huge occupation numbers
- This process (~days) subtracts energy to the BH momentum → the BH slows down

$$\tau_{\rm inst} \approx 20 \left(\frac{M_{\rm BH}}{10 M_\odot}\right) \left(\frac{\alpha}{0.1}\right)^{-9} \left(\frac{1}{\chi_i}\right) \text{days},$$

- The superradiance stops and the cloud dissipate through GWs (~years)

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

# The boson cloud signal characterization

- The BH-boson cloud system resembles the hydrogen atom = *gravitational atom*

fine structure constant

$$\alpha = \frac{GM_{\rm BH}}{c^3}\frac{m_b}{\hbar}$$

- The strain amplitude decays as

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

- The GW frequency is twice the field frequency

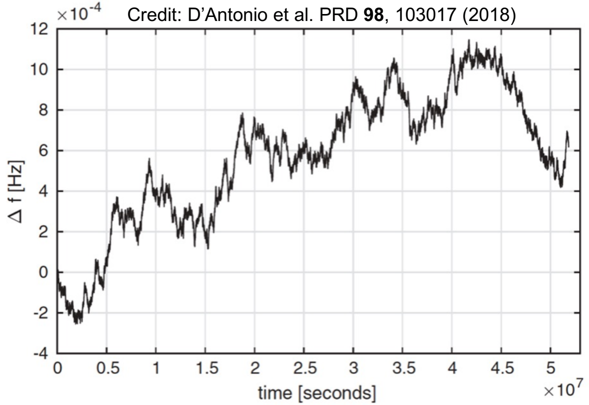
$$f_{\rm gw} \simeq 483\ {\rm Hz}\left(\frac{m_{\rm b}}{10^{-12}{\rm eV}}\right)\left[1 - 7\times10^{-4}\left(\frac{M_{\rm BH}}{10M_\odot}\frac{m_{\rm b}}{10^{-12}{\rm eV}}\right)^2\right]$$

- A small spin-up due to annihilation is present

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

(when self interaction is negligible!)

We do not consider the effect due to transition levels


Credit: D'Antonio et al. PRD **98**, 103017 (2018)

# Searches with Earth-based interferometers

- In the Advanced LIGO-Virgo sensitivity band: 10–2000 Hz → $10^{-14}$–$10^{-11}$ eV

- The first all-sky survey for persistent, quasi-monochromatic GW signals emitted by ultralight scalar boson clouds around spinning BHs:

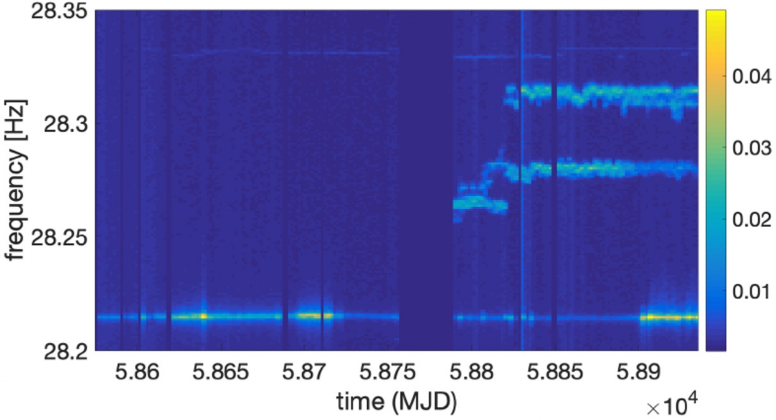
*«All-sky search for gravitational wave emission from scalar boson clouds around spinning black holes in LIGO O3 data»* - R. Abbott et al. - PRD 105, 102001(2022)

- Frequency range 20–610 Hz.
- A small range around zero considered for the spin-up.
- O3 observing run of Advanced LIGO.

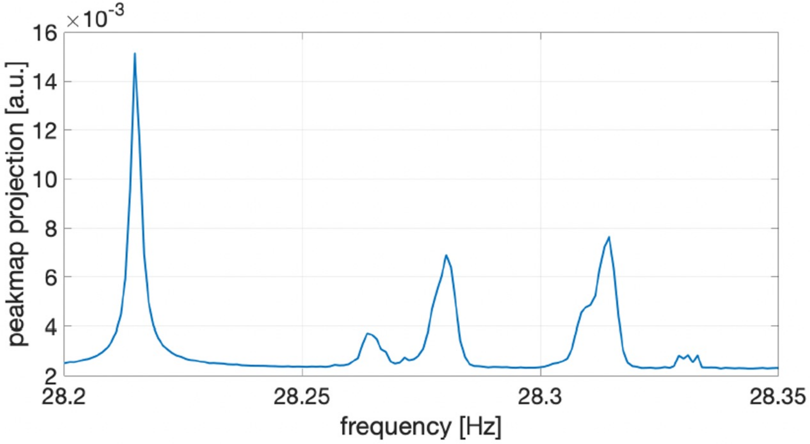
See also this directed search:
Isi et al. PRD 99, 084042 (2019)

# Search method

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



from time series (BSD) → map of the most significant time-frequency peaks (multiple FFT lengths, for robustness)



Correct the peakmap for the considered sky position (Doppler) → check important peaks in the projection.

Check for coincidences in 2 detectors, follow up the most significant candidates:

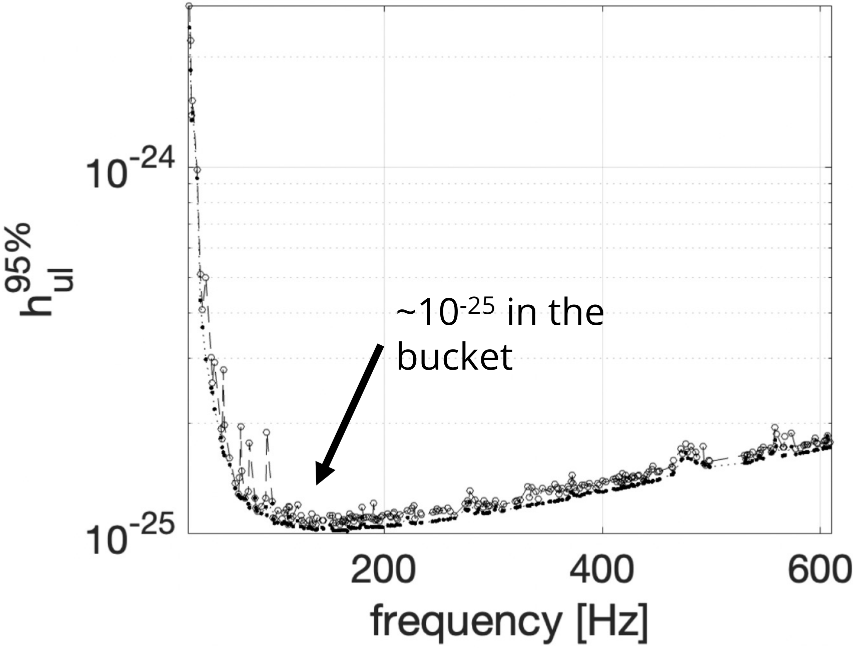
- FrequencyHough – tuned for standard monochromatic signals
- Viterbi – more robust against deviations

# Results: upper limits

- No potential candidate remains after the follow-up

→ upper limits on the signal strain

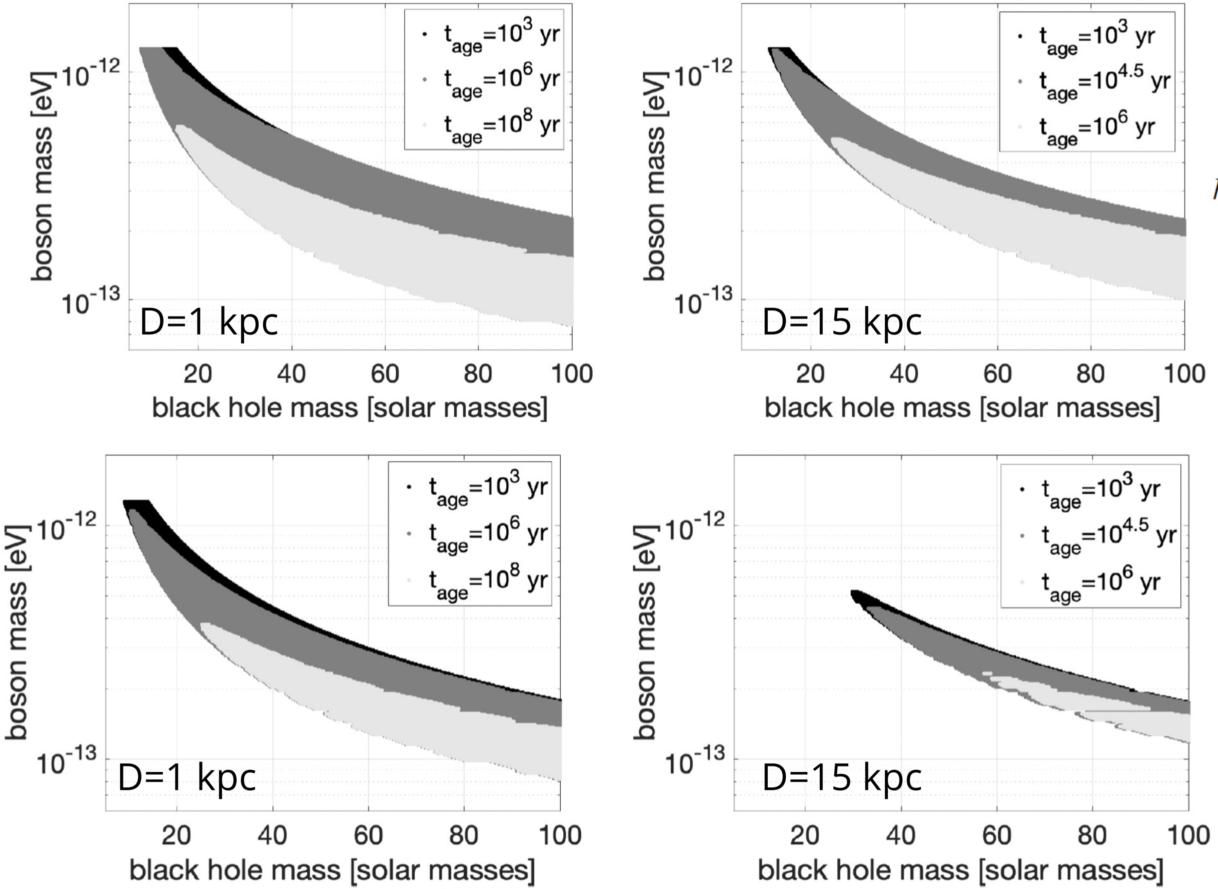
- Astrophysical implications:
  - exclusion regions in the BH-boson mass plane
  - distance reach of the search: how far we can exclude the presence of an emitting system given the null detection results



~$10^{-25}$ in the bucket

# Exclusion regions

See also Palomba et al. PRL 123, 171101 (2019)



BH spin = 0.9

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

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

For each BH spin, distance and age

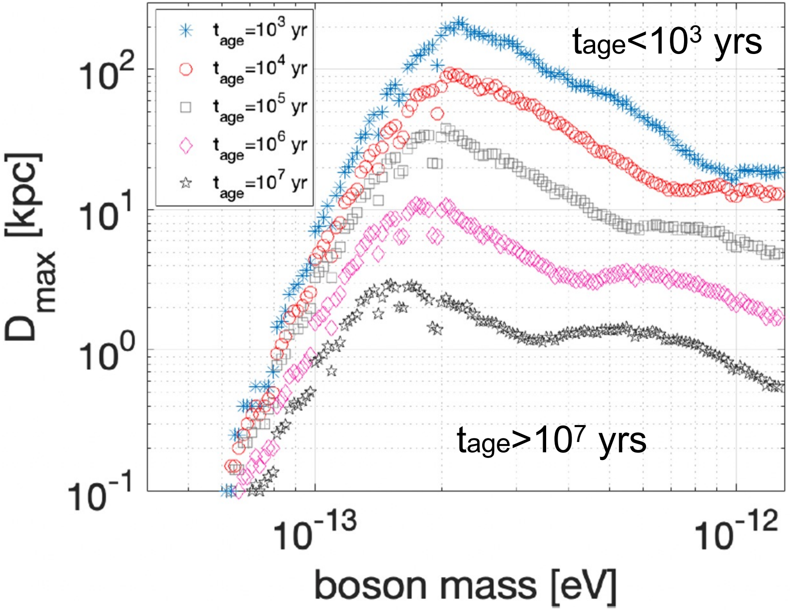
↓

we exclude some BH-boson masses combination

BH spin = 0.5

# Astrophysical reach of the search

maximum distance at which a given BH–boson cloud system, with a certain age, is not emitting CWs, as a function of the boson mass



Simulating a BH population with:

- Kroupa mass distribution [5, 100] $M_\odot$
- uniform spin distribution [0.2, 0.9].

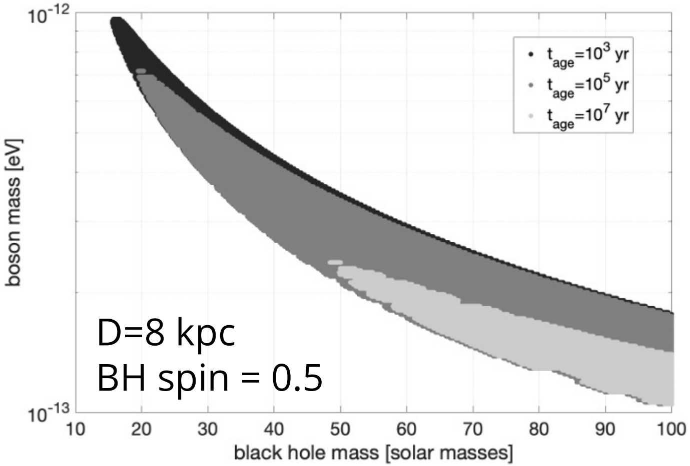
The maximum distance corresponds to the distance at which at least 5% of the simulated signal have $h_0 > h_{ul}$ → are detected.

Similar behavior for a simulated BH population of [5, 50] $M_\odot$.

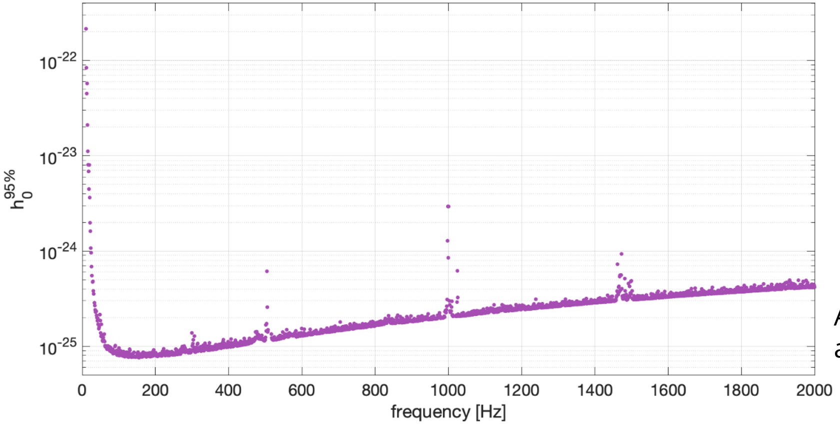
Results depend on the ensemble properties of the simulated BH population.

# Galactic center environment DM or NSs?

- Very active and densely populated place.
- GeV excess measured by Fermi-LAT: DM annihilation or NS population?
- Semi-coherent method + spin-up range → boson cloud exclusion regions



D=8 kpc
BH spin = 0.5

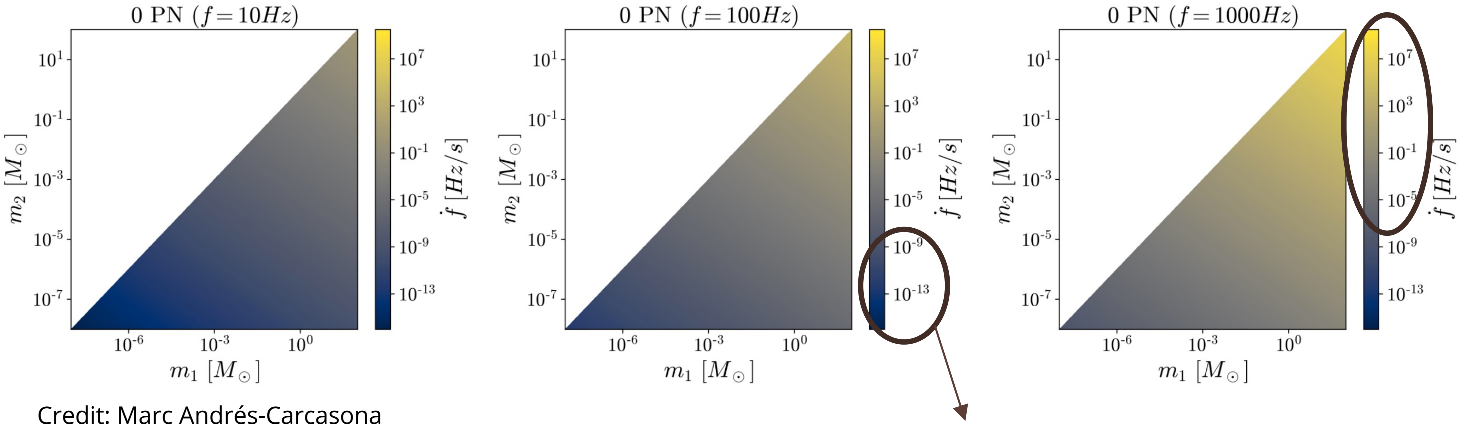


Abbot et al.
arXiv:2204.04523

# Primordial BHs and dark compact objects

- We are interested in certain combinations:
  - Low chirp masses (although low strains)
  - Inspiral phase in the detector band

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



Credit: Marc Andrés-Carcasona

High spin-up

- Long-transient methods

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

- Ad hoc methods

Low spin-up

- Standard CW methods might be already useful

$$f_0 + (t - t_0)\dot{f}_{\rm gw}$$

See also this search for CDO in the Solar System:
C.J.Horowitz et al. Phys. Let. B 800, (2020), 135072

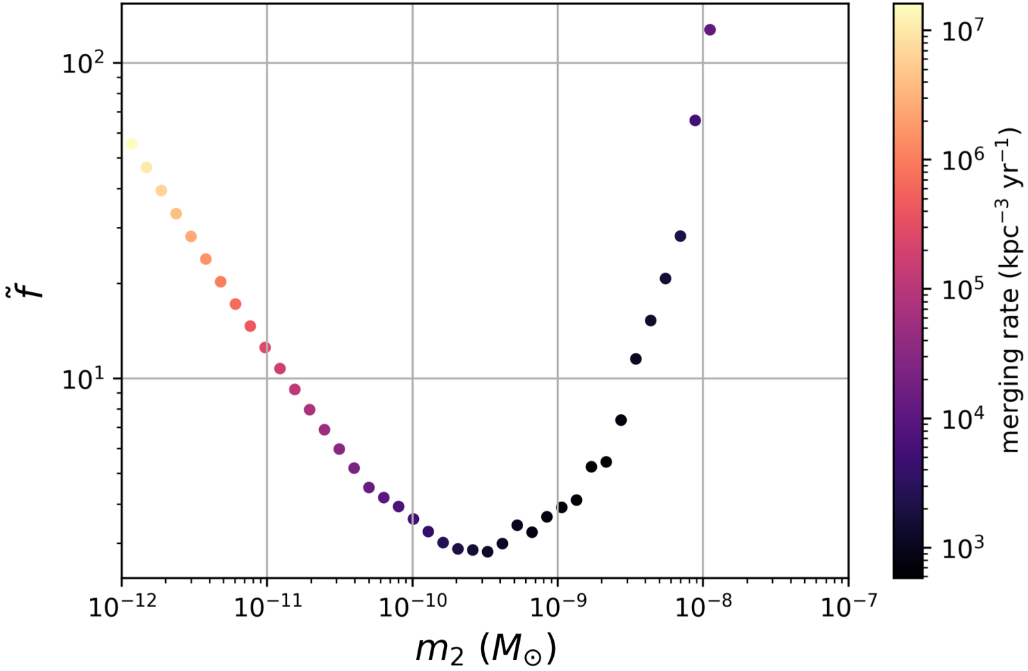
# Constraints on PBH dark matter from all-sky NS surveys

All-sky search for continuous gravitational waves from isolated neutron stars using LIGO-VIRGO O3 data - arXiv:2201.00697

All-sky results can be re-interpreted: merging rates and abundances of planetary- and asteroid-mass PBHs.

Binary PBH: akin to a CW with positive spin-down parameter (spin-up).

Current results cannot constrain the nearby PBH population



# Direct detection of dark matter: vector bosons

- Direct detection of ultralight dark matter signals via their interactions with GW interferometers (baryons/baryons minus leptons in the materials - fused silica)
- Treated as a “classical field”
- The interaction with the detector could cause a differential strain:
  - A spatial gradient is present → relative acceleration between the objects due to the different field amplitude

$$\sqrt{\langle h_D^2 \rangle} = C\frac{q}{M}\frac{e\epsilon}{2\pi c^2}\sqrt{\frac{2\rho_{\mathrm{DM}}}{\epsilon_0}}\frac{v_0}{f_0} = 6.28\times10^{-27}\left(\frac{\epsilon}{10^{-23}}\right)\left(\frac{100\ \mathrm{Hz}}{f_0}\right)$$

  - Additional effect due to the finite light travel time

$$\sqrt{\langle h_C^2 \rangle} = \frac{\sqrt{3}}{2}\sqrt{\langle h_D^2 \rangle}\left(\frac{2\pi f_0 L}{v_0}\right) \simeq 6.21\times10^{-26}\left(\frac{\epsilon}{10^{-23}}\right)$$

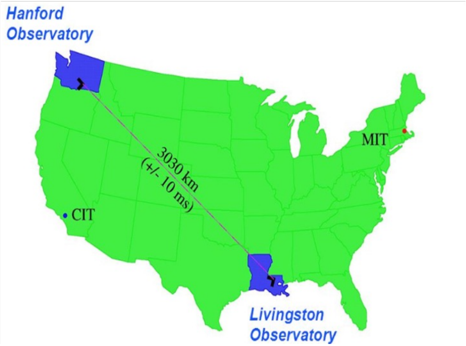
- We call these dark photons, although the interaction model is a bit different (no small mixing-induced coupling to EM currents here)
- No detection → limits on coupling $\varepsilon$

# The signal

The time-dependent force acting on the test masses, produces a strain oscillating at the same frequency and phase as the DM field

$f_0 = m_A c^2/(2\pi\hbar) \longrightarrow \frac{\Delta f}{f_0} = \frac{1}{2}\frac{v_0^2}{c^2} \approx 2.94 \times 10^{-7}$ + Doppler effect (~1e-8)

(Maxwell-Boltzmann spreading)



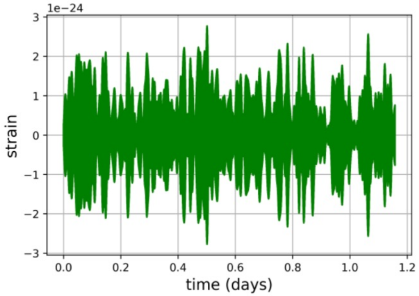
The coherence time >> detectors separation

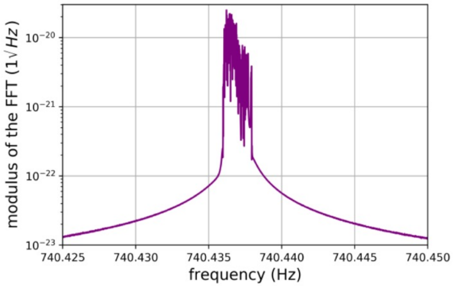
→ we can look for coincidences

$$L_{\text{coh}} = \frac{2\pi\hbar}{m_A v_0} = 1.6 \times 10^9 \text{ m} \left(\frac{10^{-12} \text{ eV}/c^2}{m_A}\right)$$

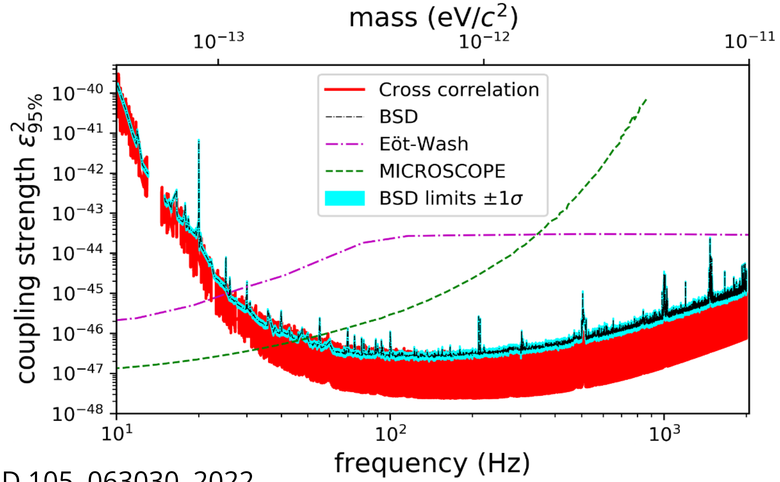
# Methods

- Cross-correlation:
  - Analyze detector data simultaneously, look for identical signals in both detectors.
  - Fixed coherence time.





- Excess power (BSD):
  - Analyze each detector's data separately, including Virgo.
  - Coherence time as a function of the boson mass considered.
  - Look for strong, coincident candidates.



Abbott et al., PRD 105, 063030, 2022

# Yes…

- Earth based interferometers can be used to look for dark matter candidates
- We derive interesting constraints, although no detection has been claimed

# …but

- In boson clouds: self interaction? Second order effects (gravitons from excited energy levels?)
- Tensor case?
- Ensemble of boson clouds signals?
- PBHs during the inspiral phase?
- Other ideas?