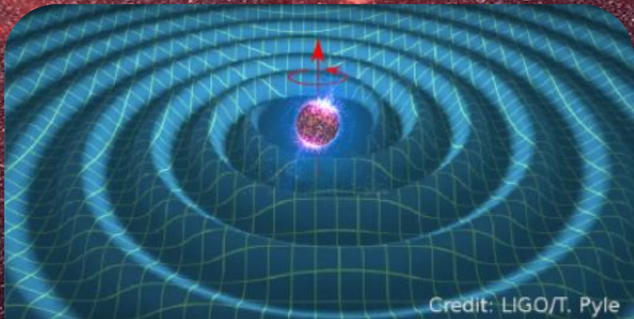
LIGO–Virgo–KAGRA webinar

Searching for continuous gravitational waves from unknown sources

24 February 2022



https://dcc.ligo.org/G2200241/public

Searching for Continuous Gravitational Waves from Unknown Sources

1. <u>Introduction</u>
   Brynmor Haskell
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2. <u>All-sky searches</u>
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3. <u>Boson cloud searches</u>
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   Postdoctoral researcher
   INFN Rome (Italy)/IFAE (Spain)

4. <u>Direct dark matter detection</u>
   Andrew Miller
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   Université catholique de Louvain (Belgium)

<u>Moderation:</u> David Keitel (University of the Balearic Islands, Spain)

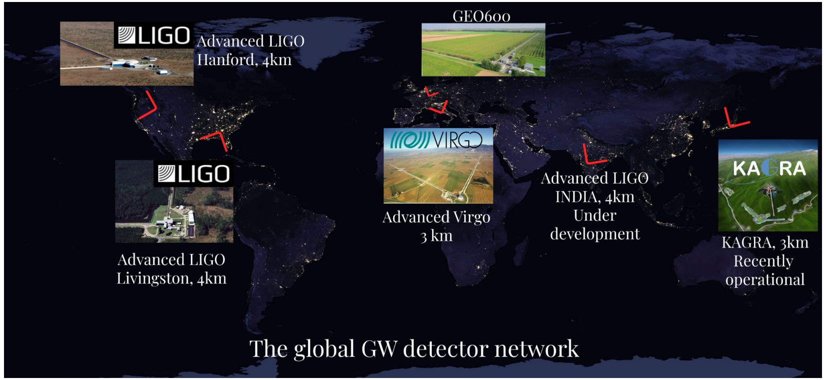
<u>Panelists:</u> William East (Perimeter Institute, Canada)
Andrzej Królak (IMPAN, Poland)
Cristiano Palomba (INFN Rome, Italy)

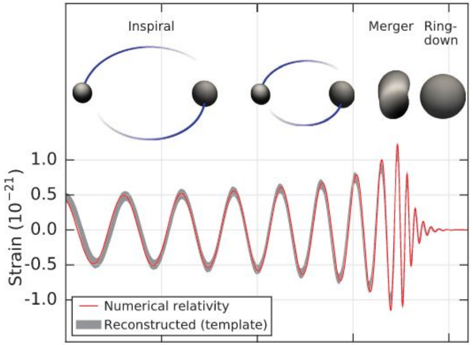



Introduction

Continuous Gravitational Waves

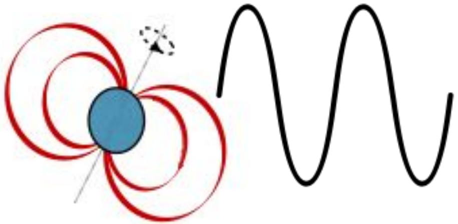
- Compact binary coalescence: “chirp signal” **DETECTED**





[B. P. Abbott et al. PRL 116, 061102, 2016]

- Continuous waves: long lived quasi monochromatic signals (e.g. from rotating neutron stars).



- Signals generally weaker, but signal to noise grows with observation time:

$$SNR \propto \sqrt{T}$$

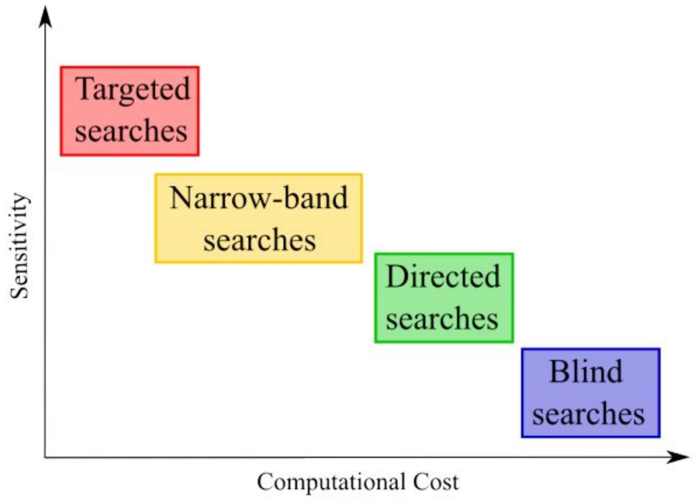
Continuous wave searches

- Searches can be targeted, if the source is <u>**known**</u> and its parameters measured from EM observations.

- Directed searches assume knowledge of the position of the source.

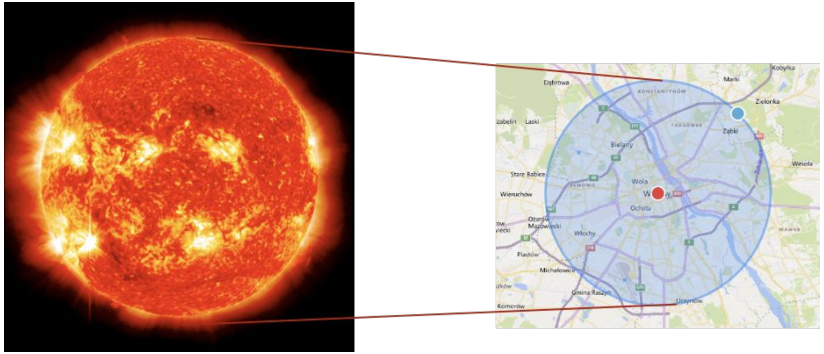
- For <u>**unknown**</u> sources we perform all-sky searches with minimal assumptions, or spot-light searches in regions with interesting astrophysical populations (such as the galactic center).

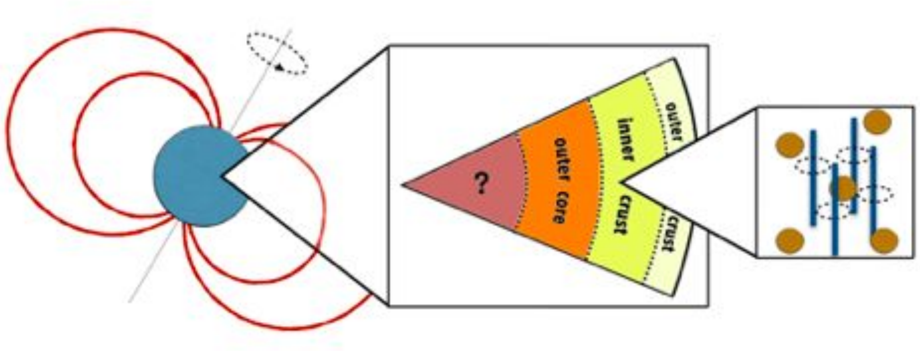
- Analysing long segments of data coherently is computationally challenging, semicoherent strategies must be adopted to compensate the loss in sensitivity.



[Sieniawska & Bejger, Universe 5, 11217, 2019]

Neutron star structure





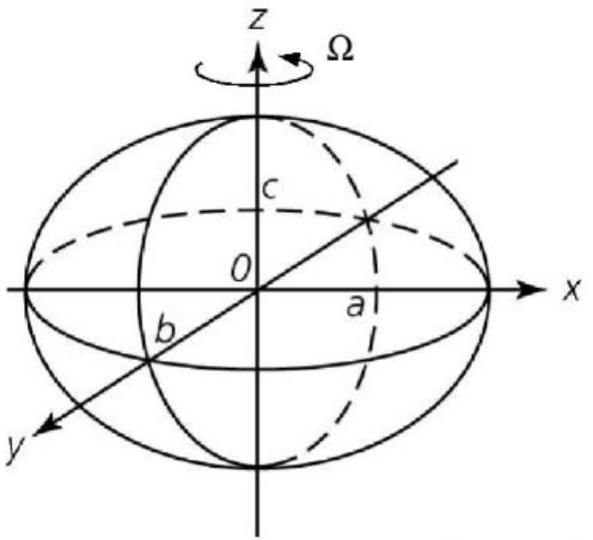
- The strong gravity of a Neutron Star ensures it is *almost* a perfect sphere.
- Crustal strains and magnetic fields can support small deformations.
- A quadrupolar deformation in a rotating star can lead to GW emission.

CWs from Neutron Stars

- Mountain size described in terms of ellipticity: $\epsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$

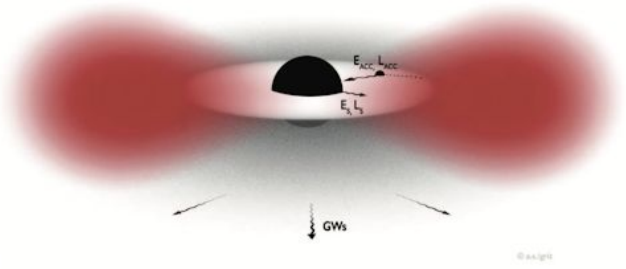
- Theoretical limits on the size: $\epsilon \lesssim 10^{-6}$
- Strongest emission at frequency $\omega = 2\Omega$

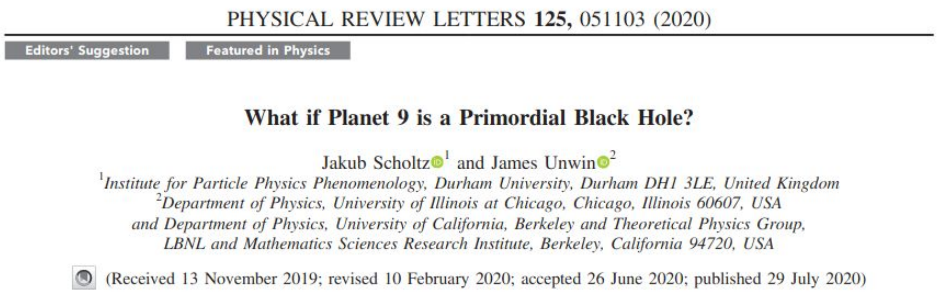
- We expect to be sensitive to sources in our galaxy
- Gravitars: spun down entirely by GWs, ‘dark’ in EM.



CW signals from dark matter

- Superradiant scattering of ultralight bosons around rotating BHs can lead to the creation of macroscopic clouds.
- The cloud dissipates as bosons annihilate and emit GWs.
- The signal is quasi monochromatic.




PHYSICAL REVIEW LETTERS **125,** 051103 (2020)

Editors' Suggestion   Featured in Physics

What if Planet 9 is a Primordial Black Hole?

Jakub Scholtz[1] and James Unwin[2]

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(Received 13 November 2019; revised 10 February 2020; accepted 26 June 2020; published 29 July 2020)

- Planetary Mass Primordial Black Holes may also constitute a fraction of the DM.
- PBH binaries will also produce a signal that is quasi-monochromatic.

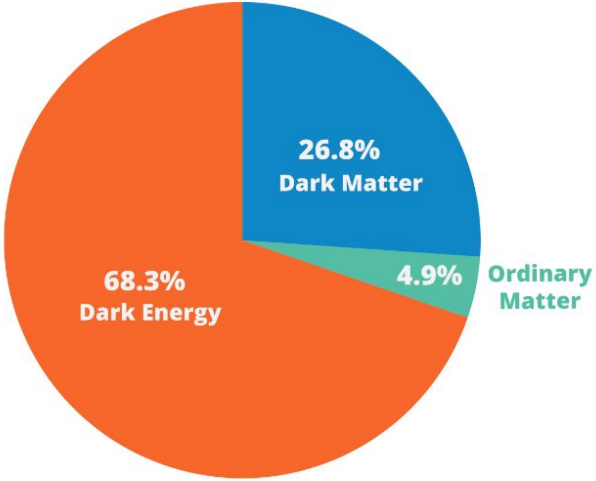
Direct detections of dark matter

- Interferometers can be used as particle physics experiments.

- Ultralight bosons can interact directly with the detectors
e.g. by modifying the coupling constants or mass of the electron.

- The DM particles affect detectors as a monochromatic oscillation.

- CW methods can be used for a **DIRECT** detection.



CWs from unknown sources: all-sky searches

Signal model

Two sets of parameters:

- Amplitude: source orientation & nominal GW amplitude.
- Phase-evolution: source spindown, sky position, orbital parameters (if binary system).

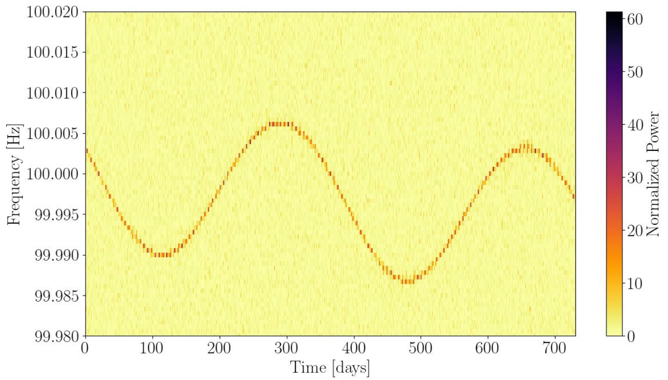
Amplitude parameters are dealt with analytically.

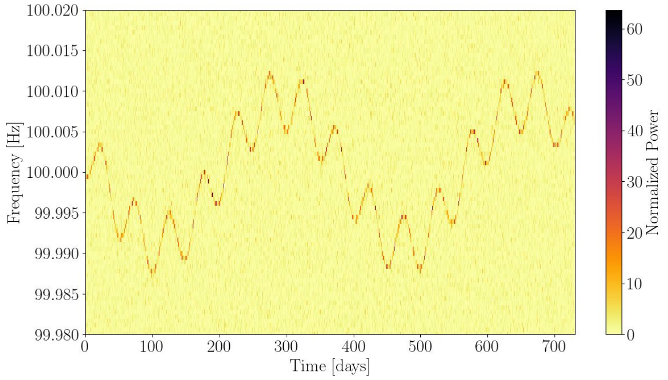
Phase-evolution parameters numerically searched over:

1. Compute instantaneous frequency @ detector frame.
2. Accumulate detection statistic along time-frequency track.

Isolated NS: $$f(t) = [f_0 + (t - t_{\mathrm{ref}}) f_1] \left(1 + \frac{\vec{v}(t)}{c} \cdot \hat{n}\right)$$

Binary NS: $$f(t) = f_0 \left(1 + \frac{\vec{v}(t)}{c} \cdot \hat{n} - a_{\mathrm{p}} \Omega \cos\left[\Omega (t - t_{\mathrm{asc}})\right]\right)$$





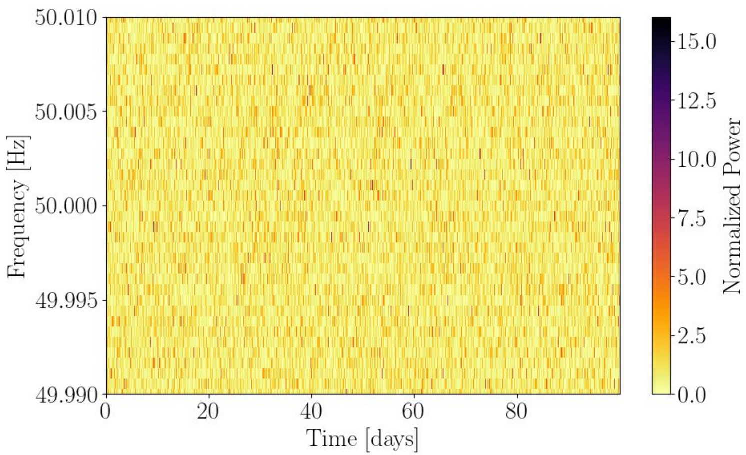
Search strategy

As opposed to CBC, CW signals are expected to be long (~months–years) lasting for the full observing run.

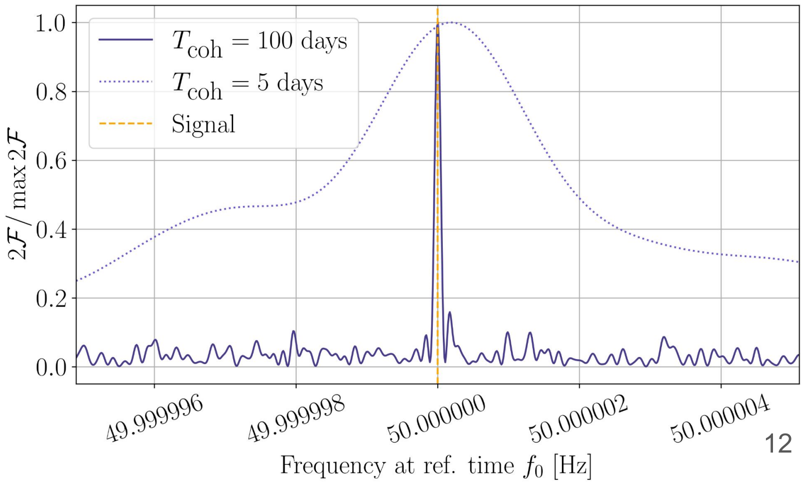
Matched-filtering ("fully-coherent search") is unfeasible for unknown sources → Too many templates.

Semicoherent searches: matched-filter short segments (~hours–days) and combine the results.

- More sensitive than matched-filtering at a fixed computing cost!
- Incidentally, search becomes more robust to unmodeled physics (e. g. NS glitches).



Search over frequency →



All-sky searches for CWs in O3 data

We look for a long-lasting quasi-monochromatic signal modulated according to a certain Doppler pattern. If nothing is found, we estimate the weakest signal we could have detected with our search (h_0).

Upper bounds on h_0 are interpreted under different models:

- maximum ellipticity of nearby neutron stars within a certain distance.
- maximum fraction of DM that nearby population of planetary-mass PBHs could compose.

Two types of searches are presented:

- CWs from unknown isolated NSs:
  All-sky search over frequency and spindown parameters.
  R. Abbott et al. Phys. Rev. D 104, 082004 (2021) & R. Abbott et al. arXiv:2201.00697 [gr-qc]

- CWs from unknown NSs in binary systems:
  All-sky search over frequency and circular orbital parameters.
  R. Abbott et al. Phys. Rev. D 103, 064017 (2021)

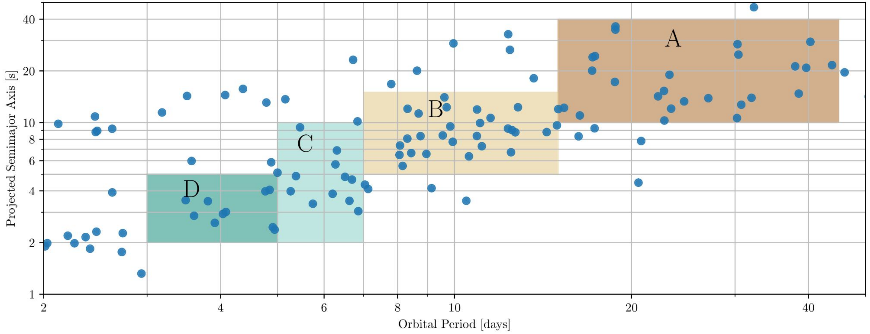
CWs from unknown NSs in binary systems

NSs in binary systems could be subject to physical mechanisms allowing for the build up of crust asymmetries (e.g. accretion from a companion).

Search conducted on early O3 advanced LIGO data using BinarySkyHough.

Structure of the search:

- Run BinarySkyHough.
- Cluster neighboring candidates and select top 5 clusters in each 0.125 Hz band.
- Veto candidates overlapping with instrumental artifacts of known origin.
- Follow-up surviving candidates using an MCMC.



All-sky search on two frequency bands:

- L = 50 – 100 Hz → A, B, C, D
- H = 100 – 300 Hz → B

t_{asc} covered along its entire range.

EM binary NSs have low spindown values:

- Do not search explicitly over spindown.
- Search still sensitive up to $|f_1| \sim 6 \cdot 10^{-11}$ Hz/s

Results

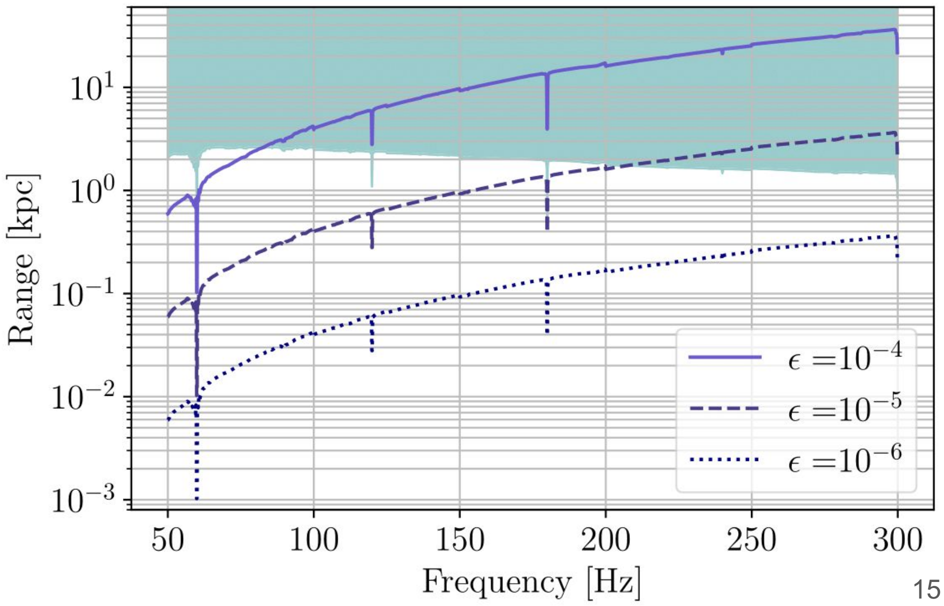
Most candidates are deemed inconsistent with an astrophysical signal after follow-up.

Small fraction of candidates is consistent with a side-band of the 60 Hz power-line artifact.

We estimate the sensitivity of the search and translate it into constraints upon the ellipticity of nearby binary NSs.

- Ellipticity is constrained to < (10^{-4}–10^{-5}) @ (1–2) kpc, depending on frequency.
- Results start to probe the regime of exotic equations of state (~10^{-5}), but still a while until realistic ones (10^{-7}–10^{-6}).

Regions	LA	LB	LC	LD	H1B	H2B	H3B	H4B	H5B
Initial Clusters	2000	2000	2000	2000	1000	1000	2000	2000	2000
Vetoed by Identified Line	366	359	359	373	44	0	32	30	30
Surviving Clusters	1634	1641	1641	1627	956	1000	1968	1970	1970
Fraction (%)	81.7	82.05	82.05	81.35	95.6	100	98.4	98.5	98.5
Surviving Outliers after $2\hat{\mathcal{F}}_{\mathrm{th}}$ veto	73	72	71	71	7	6	8	3	0



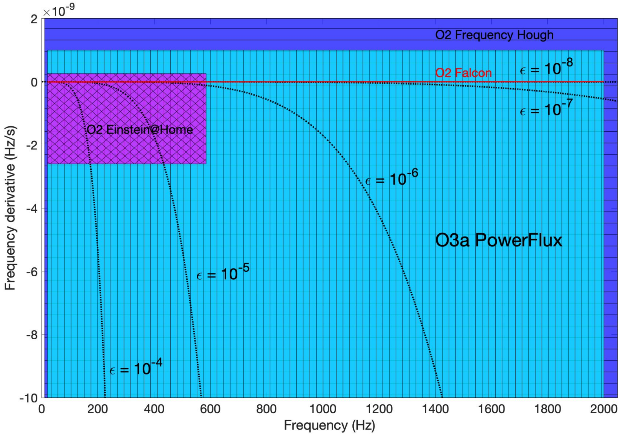
CWs from isolated NSs

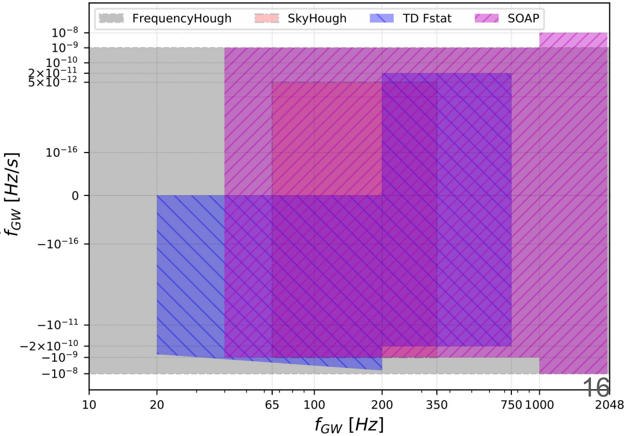
A variety of searches with different scopes were conducted on O3 data:

- PowerFlux search on early O3 aLIGO data.
- FrequencyHough search on full O3 aLIGO + aVirgo.
- SkyHough & Time-domain *F*-statistic search on full O3 aLIGO.
- SOAP search on full O3 aLIGO.

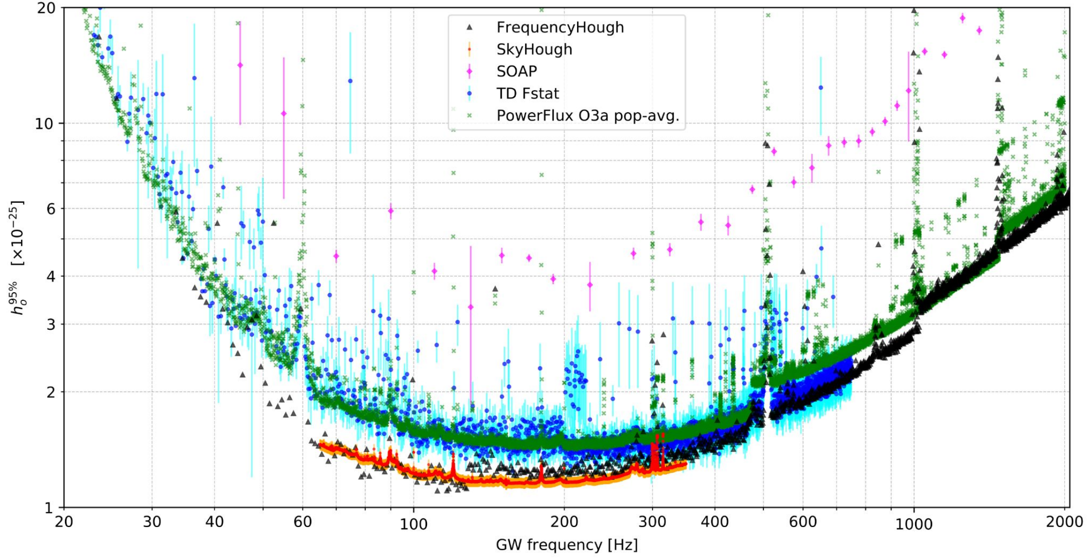
PowerFlux, FrequencyHough, SkyHough and Time-domain *F*-statistic assume a similar frequency-evolution model to that specified a few slides back.

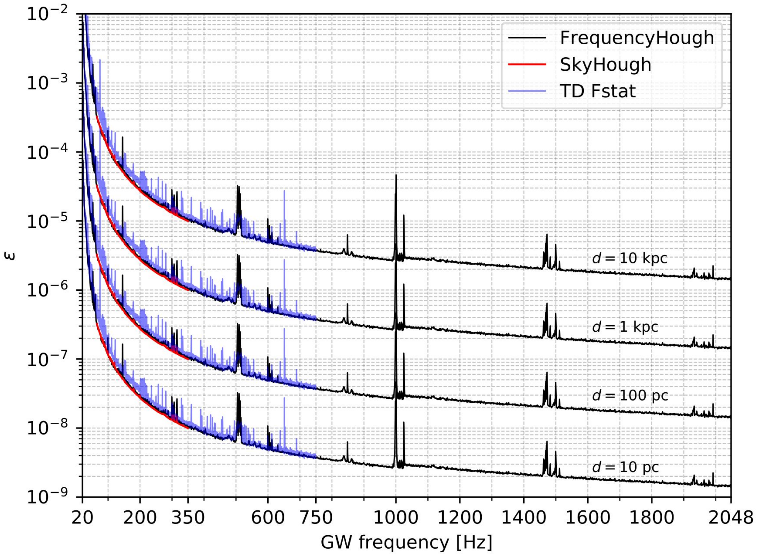
SOAP is an unmodeled search based on the Viterbi algorithm.
It is designed as an early-alert search and is robust to deviations from a quasi-monochromatic emission model (e.g. timing noise, glitches).
This results in a less sensitive although much more affordable and robust all-sky search.





Results





No outliers can be associated to an astrophysical origin.

We estimate the sensitivity of the search and translate it into constraints upon the ellipticity of nearby NSs.

Results within a kpc start to probe ellipticities in the range of realistic equations of state.

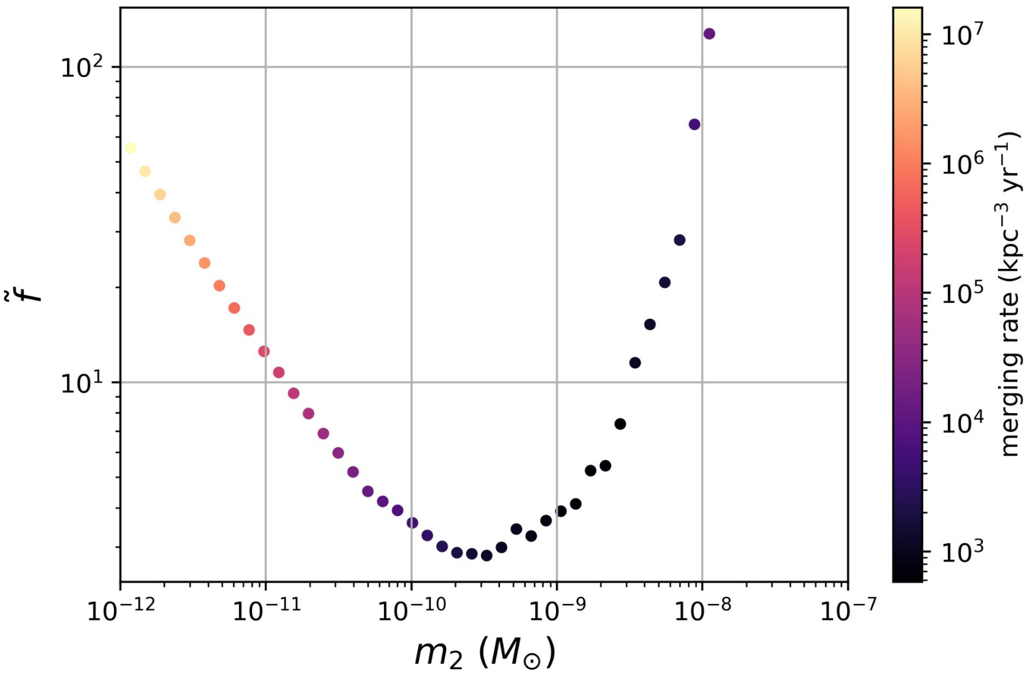
Alternatively, these upper bounds can be reinterpreted under other physical models.

Constraints on PBH dark matter

Results can be re-interpreted in terms of the merging rates and abundances of planetary- and asteroid-mass PBHs.

Binary PBH: Low-mass system, inspiral phase is akin to a CW with positive spindown parameter (spinup).

Current results cannot constrain the nearby PBH population ($\tilde{f} > 1$),
future detectors will be able to provide physical constraints.



Searches for DM candidates

Astrophysical evidence for dark matter

The majority of the matter in the universe is dark matter, which doesn't absorb, emit, or scatter light of any wavelength → check its gravitational influence.

Title: Galaxy rotation under the influence of dark matter. Credit: Ingo Berg

orbital speeds of stars in galaxies such as our own Milky Way and Andromeda (M31)

Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

the curious case of the bullet cluster

+clusters of galaxies, anisotropies of the cosmic microwave background, large scale structure formation, …

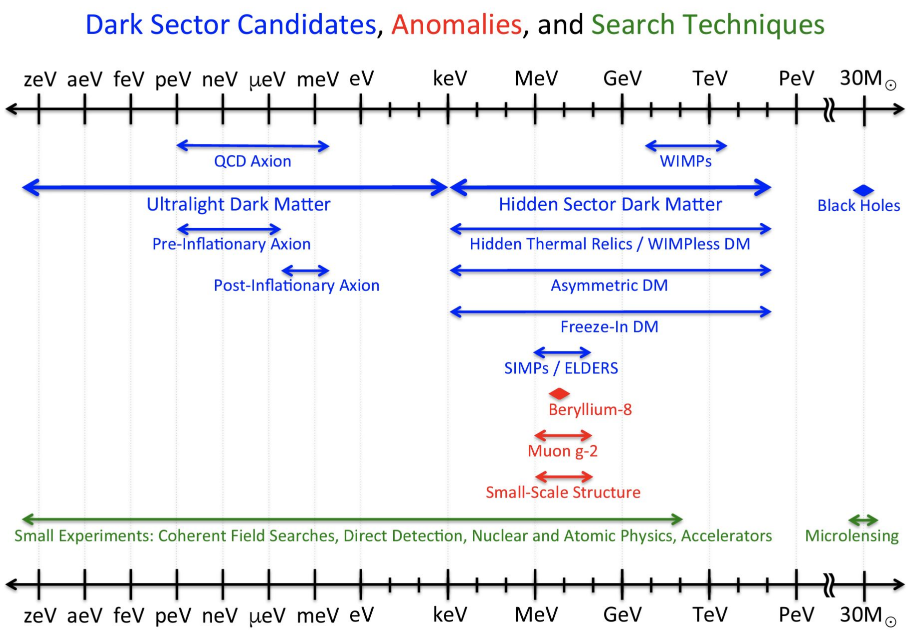
Dark matter identikit

- Constitutes the 85% of matter
- barely interacts with ordinary matter
- Could be heavy or ultralight

WIMPs, Axion or axion-like particles, dark photons, Sterile Neutrinos, etc.

Can form macroscopic objects: primordial black holes, boson clouds, boson stars, MACHOs etc.

Today we focus on ultralight dark matter in the range: 10–2000 Hz ←→ 10^{-14}–10^{-11} eV

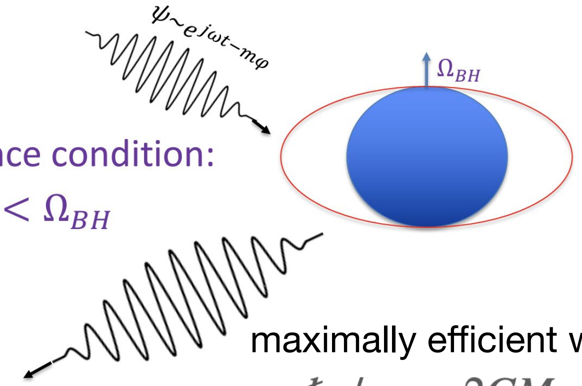


Battaglieri M. et al. arXiv:1707.04591 ; FERMILAB-CONF-17-282-AE-PPD-T

Searching for DM with GWs: boson clouds

Boson clouds

Credit: C. Palomba



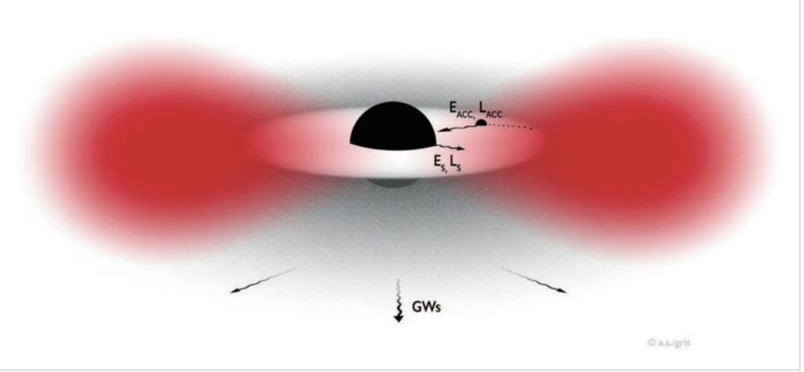
Superradiance condition:

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

wave is scattered off a rotating black hole

maximally efficient when

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



- We need: boson angular frequency < BH's outer horizon angular frequency
- Bosons condensate around the BH, occupying the same (quantum) state with huge occupation numbers.
- This process (~days) extracts energy from the BH momentum → The BH slows down.
- The superradiance stops and the cloud dissipates through GWs (~years).

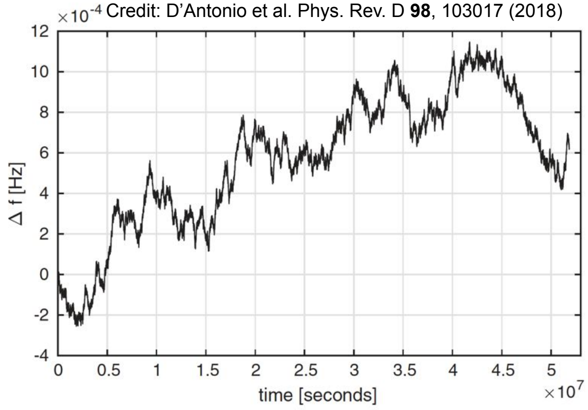
The boson cloud signal characterization

- The BH–boson cloud system resembles the hydrogen atom: *gravitational atom.*

fine structure constant

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

- The strain amplitude depends on this constant, spin and distance and decays as $h(t) = \frac{h_0}{1 + \frac{t}{\tau_{\rm gw}}}$.
- The GW frequency is twice the field frequency and depends on m_b and M_{BH}.
- A small spin-up due to annihilation is present (assuming a small self-interaction).



Searches with Earth-based interferometer

- The emitted frequency, which is dependent on the ultra-light scalar boson field mass, is expected to be in the Advanced LIGO-Virgo sensitivity band.

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

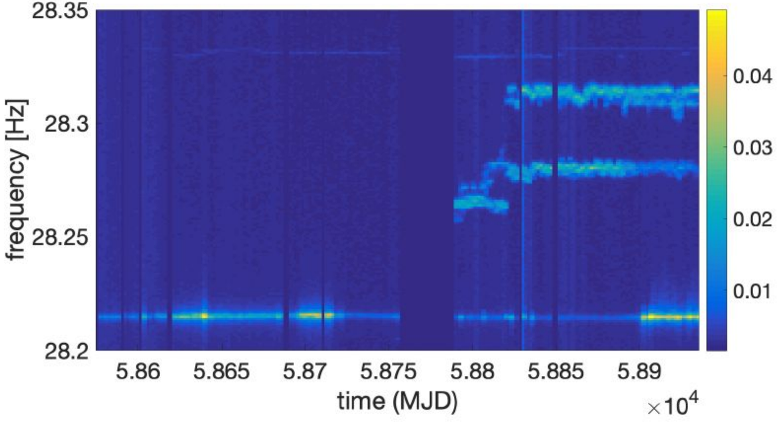
«All-sky search for gravitational wave emission from scalar boson clouds around spinning black holes in LIGO O3 data» - R. Abbott et al. - arXiv:2111.15507

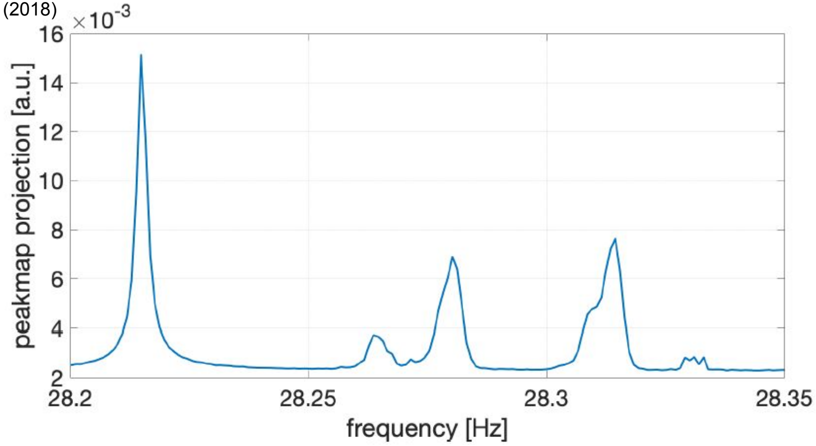
- The search analyzed the frequency range 20–610 Hz of the O3 observing run of Advanced LIGO.

- A small range around the spin-up parameter has been considered.

Search method

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





from BSD time series → 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.

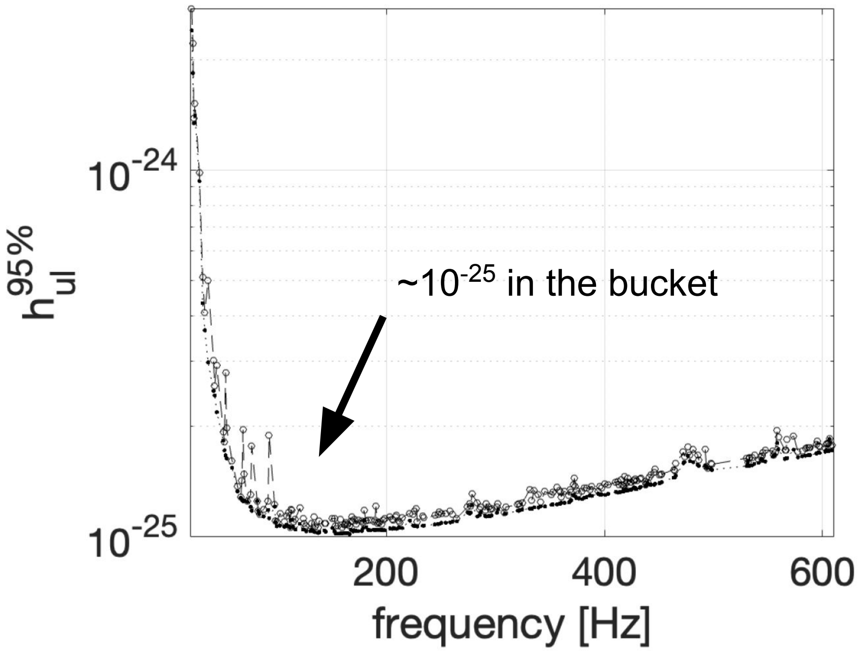
Check for coincidences in 2 detectors, follow up the most significant candidates:

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

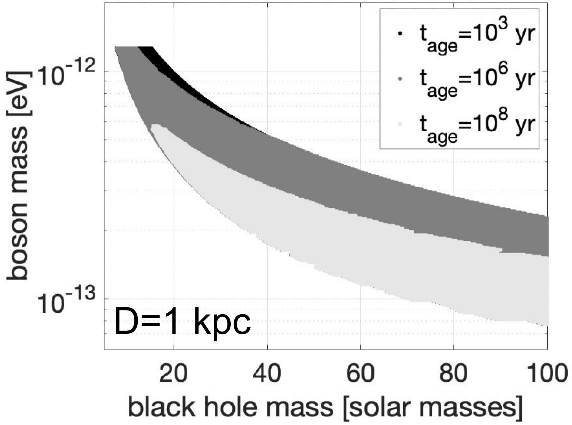
Results: upper limits

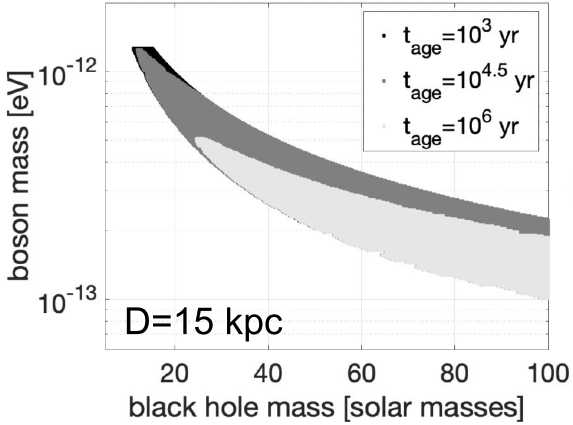
- No potential candidate remains after the follow-up
  → upper limits on the signal strain

- 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



Exclusion regions





BH spin = 0.9

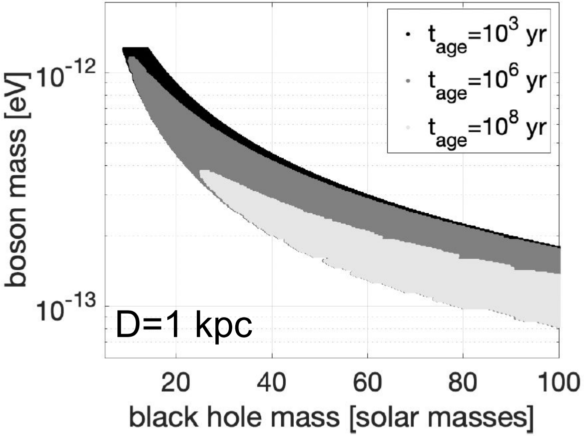
$$h_0 \approx 6 \times 10^{-24} \left(\frac{M_{\rm BH}}{10 M_\odot}\right) \left(\frac{\alpha}{0.1}\right)^7 \left(\frac{1\,{\rm kpc}}{D}\right) (\chi_i - \chi_c)$$

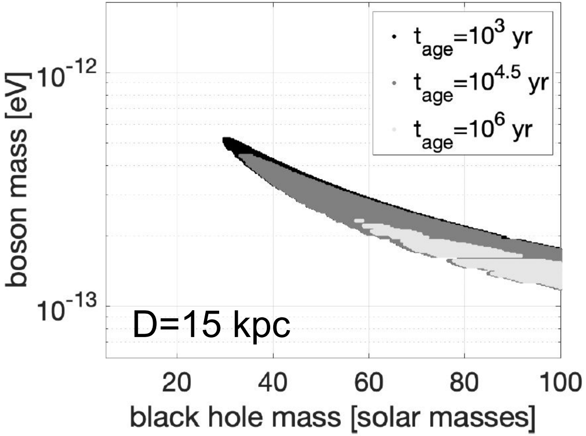
$$h(t) = \frac{h_0}{1 + \frac{t}{\tau_{\rm gw}}}$$

assuming a BH population with given spin, distance and age

↓

we exclude some BH-boson masses combination

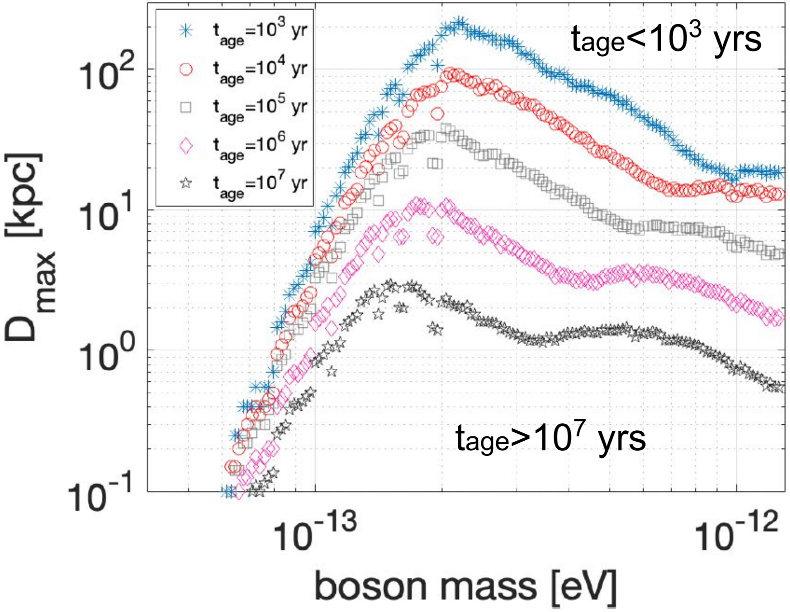




BH spin = 0.5

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

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

Direct detection of dark photon DM with GW detectors

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, now we focus on direct detection of ultralight dark matter signals via their interactions with GW detectors (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,…

Ultralight dark matter

- Fixed dark matter energy density ρ_{DM} → huge occupation number N_0 → overlapping wavefunctions that can be modelled as a superposition of plane waves.
- Could be generated non-thermally via the misalignment mechanism in the early universe.
- Forms coherently oscillating field at quasi-fixed frequency with finite coherence time (viralized during galaxy formation).
- Velocities follow a Maxwell-Boltzmann distribution, centered about virial velocity v_0, the velocity at which dark matter orbits center of galaxy.

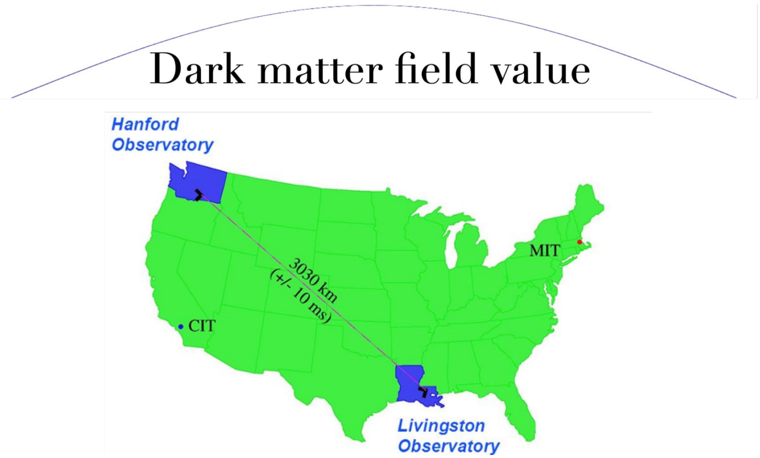
$$N_o = \lambda^3 \frac{\rho_{\rm DM}}{m_A c^2} = \left(\frac{2\pi\hbar}{m_A v_0}\right)^3 \frac{\rho_{\rm DM}}{m_A c^2},$$
$$\approx 1.69 \times 10^{54} \left(\frac{10^{-12}\ \mathrm{eV}/c^2}{m_A}\right)^4$$

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

Ultralight dark matter signals

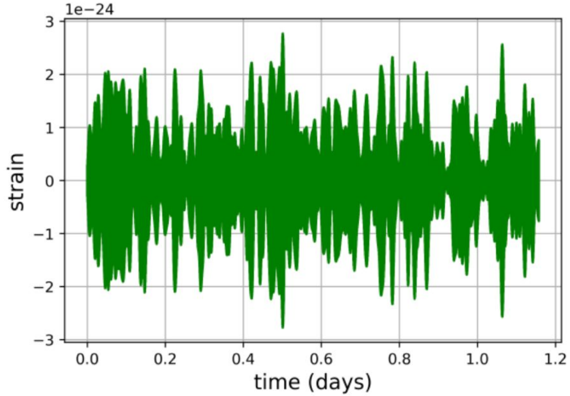
- Coherence length >> separation between detectors, leading to correlated signals.
- The signal imprinted in our detectors will be quasi-monochromatic, with stochastic frequency variations of $O(v_0^2/c^2)f \sim 10^{-6}\, f$ Hz .

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

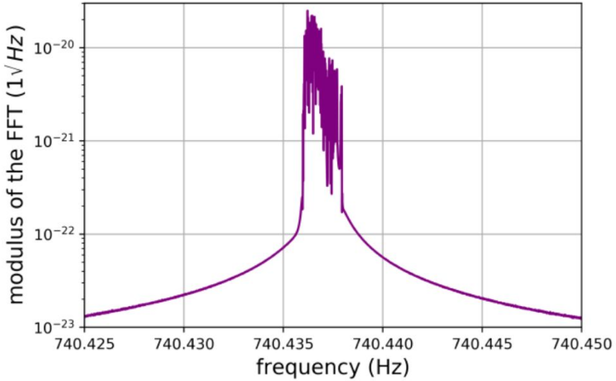


Credit: Y. Zhao

The signal and analysis strategy



(a)

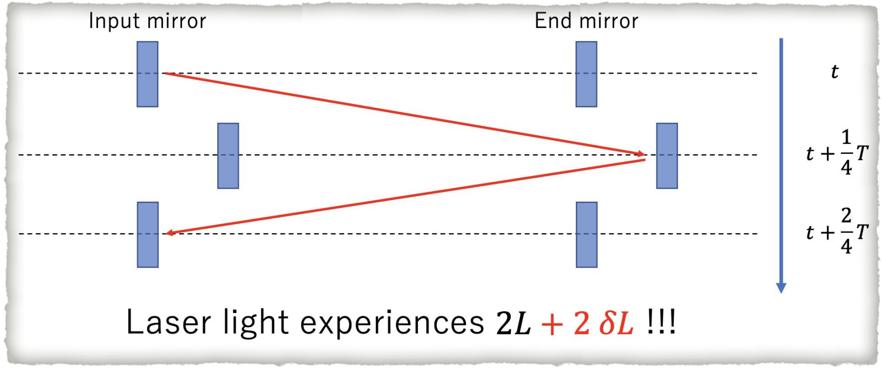


(b)

- Example of simulated dark photon dark matter interaction.
- Power spectrum structure results from superposition of plane waves.
- Principle of data analysis: break dataset into smaller chunks to confine this frequency modulation to one frequency bin, then sum power incoherently .
- One day shown, but signal lasts longer than observing run.

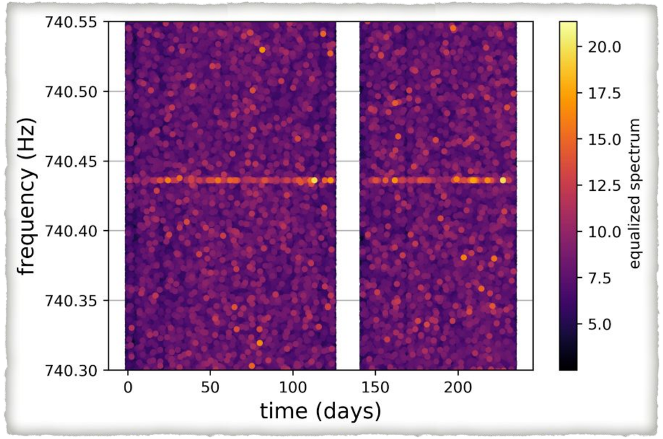
Physics of Dark Photons

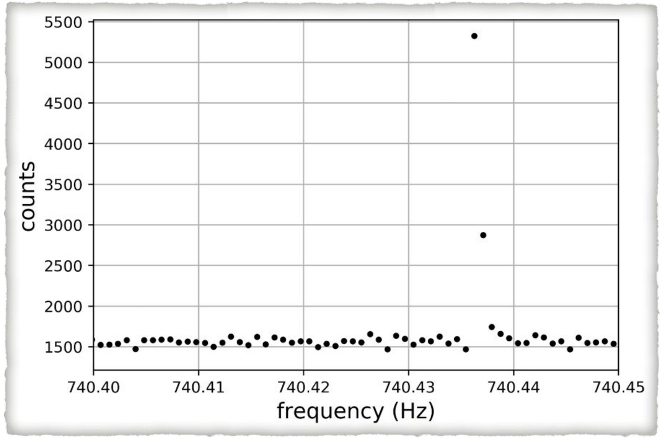
- Vector particle that weakly interacts with protons and/or neutrons in materials and causes “dark” electric force on test masses
- Differential strain from a spatial gradient in the dark photon field.
- Differential strain from temporal effect: light takes a finite amount of time to travel between the mirrors.
- No detection → limits on coupling ε.



Methods

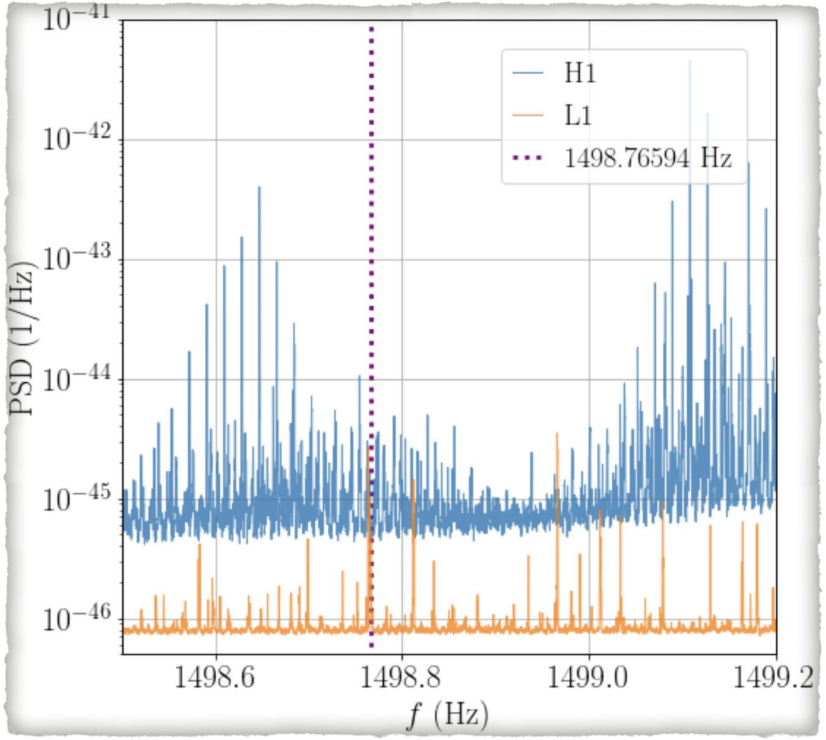
- Cross-correlation:
  - Analyze detector data simultaneously, look for identical signals in both detectors.
  - Fix FFT length to be 1800 s.
- Excess power (BSD): analyze each detector's data separately.
  - Change FFT length as a function of the boson mass considered.
  - Look for strong, coincident candidates.





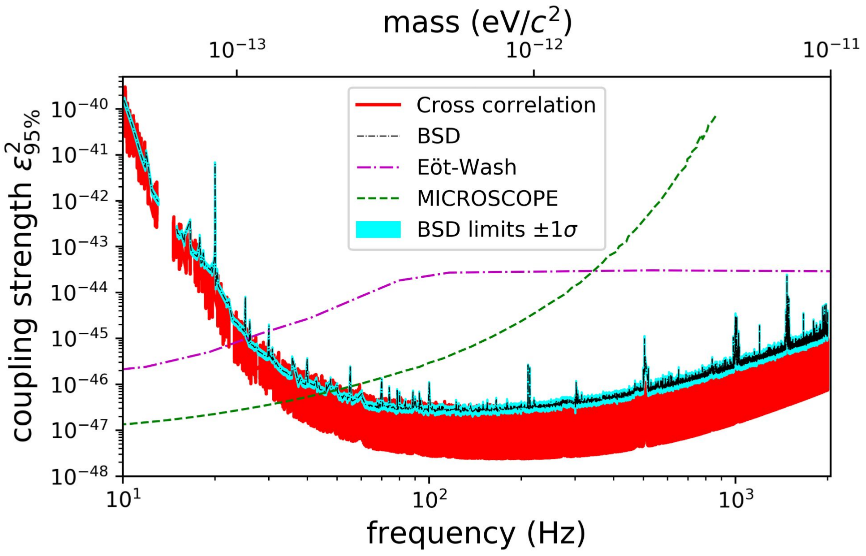
Results: outliers

- Both methods returned only a handful of outliers.
- Outliers vetoed by analyzing the noise around the frequencies of those candidates.
- Example of large comb that caused a strong outlier in H1 and L1.



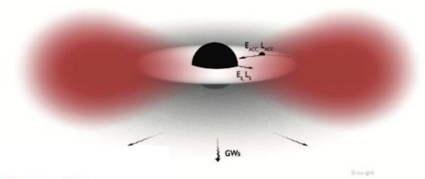
Results: upper limits

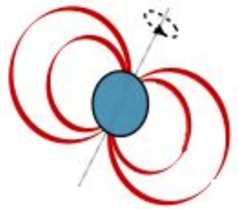
- All outliers vetoed in excess power method; only 4 sub-threshold outliers consistent with Gaussian noise expectation for cross-correlation.
- Both common and differential motion strains considered when calculating these limits.
- Improvement by 2-4 orders of magnitude compared to existing experiments.

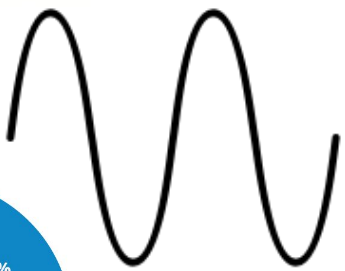


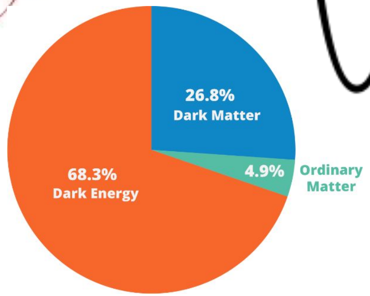
Summary

- CW searches probe a variety of physical sources: neutron stars, PBH binaries, boson clouds, direct DM interaction,…
- O4 run will start at the end of this year.









- O3a all-sky binary CWs: Phys. Rev. D 103, 064017 (2021)
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- O3a all-sky isolated CWs: Phys. Rev. D 104, 082004 (2021)
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- O3 boson clouds search:
  arxiv.org/abs/2111.15507 | www.ligo.org/science/Publication-O3BosonClouds/
- Direct detection DM search:
  arxiv.org/abs/2105.13085 | www.ligo.org/science/Publication-O3DarkPhotons/