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Continuous gravitational waves as probes of neutron stars and dark matter

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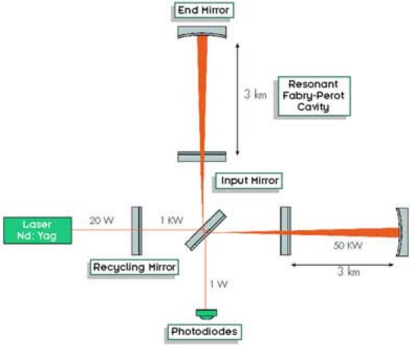
Outline

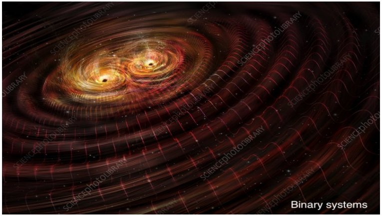
1. Overview
2. Neutron stars
3. Dark matter around black holes
4. Planetary-mass primordial black holes
5. Conclusions

Laser interferometry

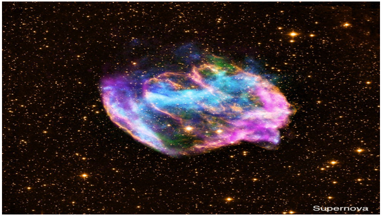


- Gravitational waves will change the positions of objects in their paths
- The mirrors move differently, which induce a differential strain on the detector $h(t)$
- Interferometers are most sensitive to the phase of the modulation, as opposed to the amplitude modulation

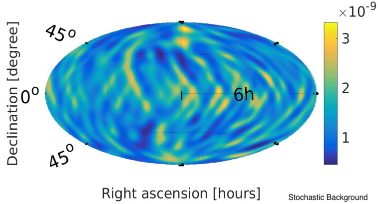
Sources of gravitational waves



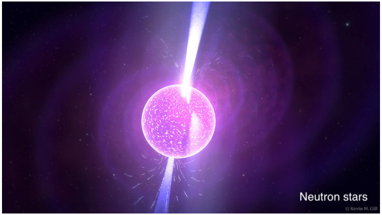
Binary systems



Supernova



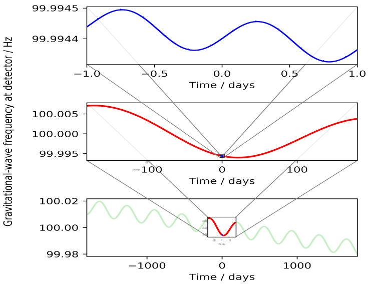
Stochastic Background

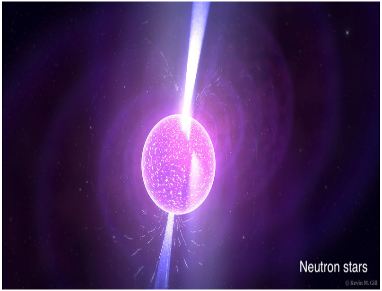


Neutron stars

- Four major sources that LIGO/Virgo search for
- Merging binary systems have already been seen, but the other sources have eluded detection!

Focus here on continuous waves

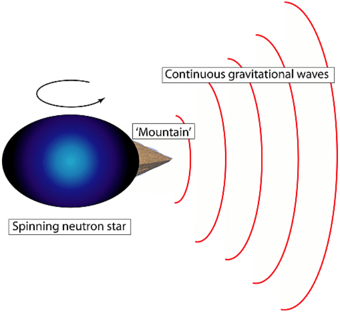




- Quasi-monochromatic, quasi-infinite duration signals
- Searches for both known and unknown neutron stars are difficult and computationally demanding
- From a data analysis point of view, many signals with different underlying physics follow this signal model

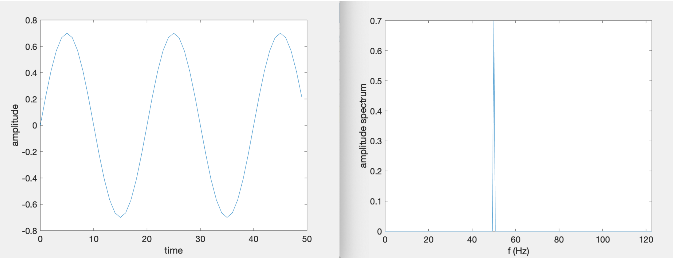
Deformed neutron stars

- Small deformation and rotation → gravitational waves
- Rotate at $\sim 10 - 1000$ Hz [18]
- Small spin-down or spin-up $\dot{f}$ of $\leqslant \mathcal{O}(10^{-8})$ Hz/s
- Model frequency evolution as Taylor series expansion to first or second order
- Reasons for deformations:
    - Crustal strain (starquake, formed at birth)
    - Strong *internal* magnetic field buried during accretion [15]



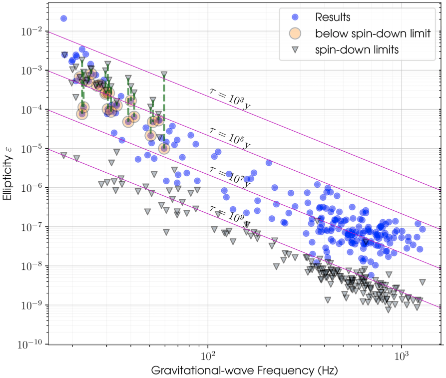
Principles of data analysis for known pulsars

- The position, rotational frequency and frequency change (i.e. spin-down) are known from electromagnetic observations
- Correct the data for the known source parameters → signal becomes truly monochromatic
- Take a single Fourier Transform of all data
- Relatively quick for known pulsars, but cannot be applied in the general case



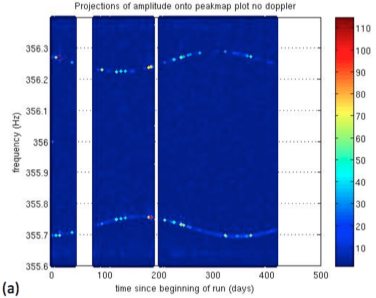
Known pulsar search results

- The goal is to surpass the so-called spin-down limit: probe the case where $< 100\%$ of rotational energy is emitted as gravitational waves
- Results shown for 2nd observing run [1]



Principles of data analysis for unknown pulsars

- Use as long Fourier Transforms lengths as possible!
- Confine signal power into a single frequency bin
- Analyze as much data as possible
- Primary frequency modulation: Doppler shift ($\mathcal{O}(10^{-4}f)$ Hz). Restricts the Fourier Transform to $\mathcal{O}(1000)$ s
- The noise is not Gaussian
- For each Fourier transform: $h(t) \rightarrow h(f)$. This creates a time/frequency spectrogram [7]



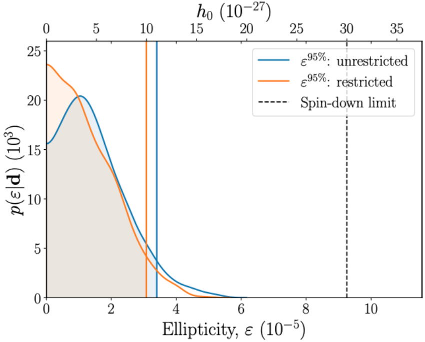
Types of searches

Search type	Description	Sources
targeted	known $\alpha, \delta, f_0, \dot{f}$	Crab, Vela
directed	known α, δ	galactic center
all-sky	nothing known	any

α: right ascension
δ: declination
f_0: pulsar rotation frequency at a reference time t_0
$\dot{f}$: spindown

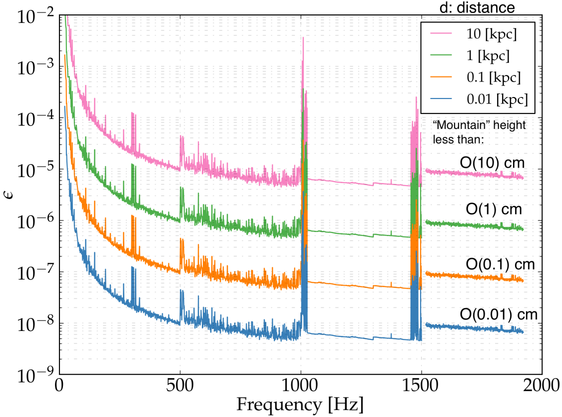
- We “point” to specific locations when analyzing the data
- We also analyze systems in known and unknown binaries [5], and for post-merger remnants [3]

Targeted search for pulsar J0537-6910



- These are posteriors that show the probability that a particular signal with a certain parameters exists, given data [4]
- An amplitude of 0 cannot be excluded → no signal
- Constraints from current observing run (O3)

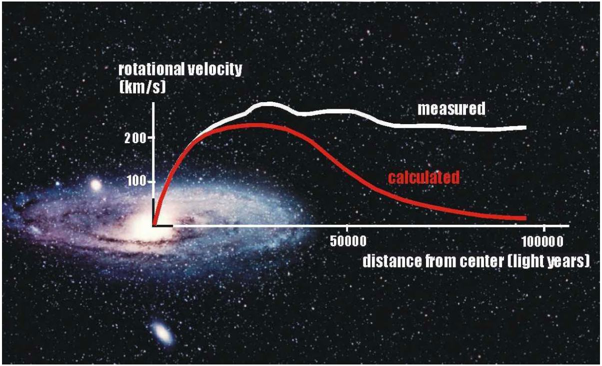
Existing constraints from an all-sky search



- These are upper limits: the minimum deformation, or ellipticity ϵ, we could have seen at 95% confidence
- Deformations with smaller ϵ are easier to form
- LIGO/Virgo's 2nd observing run data [2]

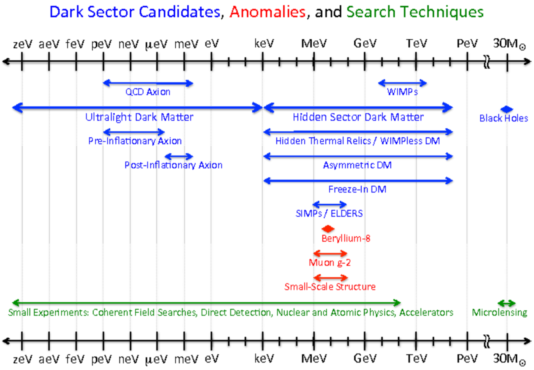
The dark matter problem

- Experiments hint at the existence of dark matter, but its nature remains elusive
- Gravitational waves can probe ultralight dark matter, $\mathcal{O}(10^{-14} - 10^{-11}$ eV/c^2), and ultra-heavy ($\mathcal{O}(M_\odot)$)



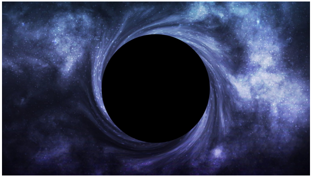
The dark matter context

- Various experiments are sensitive to different dark matter mass regimes
- The frequency sensitivity of ground-based detectors, 10-2000 Hz, fixes the boson masses we can look for



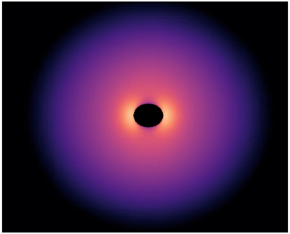
Black hole superradiance

- Near a black hole, quantum fluctuations → bosons pop into existence
- Many bosons fall in, but if the Compton wavelength is comparable to the radius of the black hole, bosons can scatter off it
- Greater effect for black holes with higher spins χ



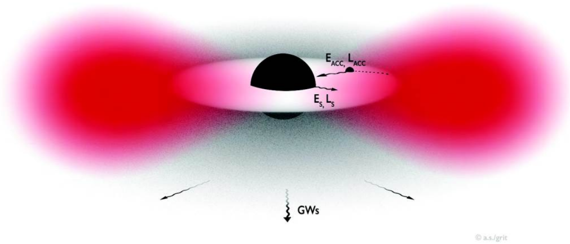
Black hole superradiance

- Energy (mass/spin) extracted from the black hole by scattering bosons → outgoing boson amplitude boosted
- Unlike photons, bosons are massive, so they tend to be bound to black hole → successive scatterings [6]
- A boson "cloud" [13]



Growth of boson clouds

- Clouds are formulated as solutions to Schrodinger-like equations for a scalar field in the Kerr metric: “gravitational Hydrogen atom”
- The lowest, fastest growing state is $l = 1$, $m = 1$



- Superradiance (instability) condition: $\omega_{\text{boson}} < m\Omega_{\text{BH}}$
- No limit on the number of bosons in each state [9]

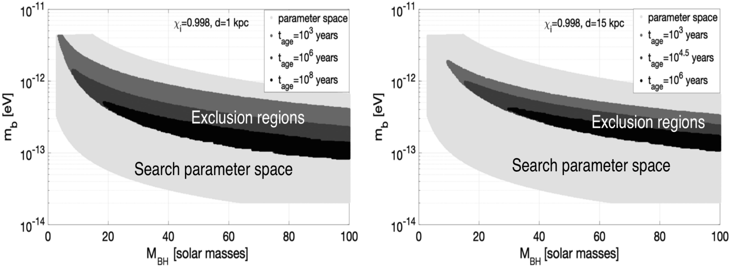
Depletion of scalar boson clouds

- Assume bosons couple to gravity and annihilate into gravitons [8]
- Gravitational waves are emitted from one energy level at a time → monochromatic up to small spinup due to classical self-gravity
- Timescale of depletion $>>$ timescale of cloud growth
- Consider boson mass range $[10^{-14}, 10^{-11}]$ eV

We expect *continuous* gravitational waves!

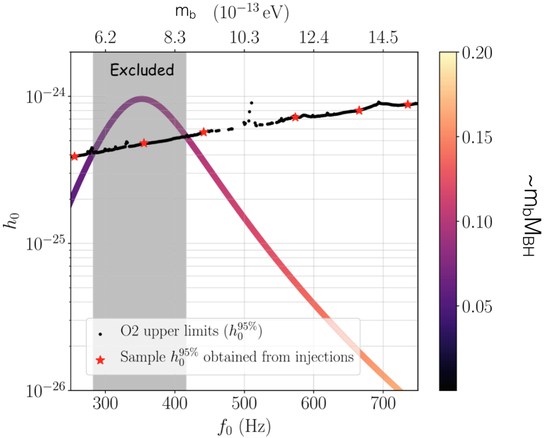
Constraints from an all-sky search

- Reinterpretation of upper limits on ϵ from slide 10: $\epsilon \propto h_0$, the gravitational-wave amplitude [17]
- $h_0, f \rightarrow$ constraints on boson mass m_b and black hole mass M_BH with assumptions on spins χ, distances d, and ages t_age of black holes



- More combinations of m_b and M_BH excluded for younger systems (small t_age) than older ones
- Darker colors are constraints on older systems

Directed search for Cygnus X-1



- Binary parameters and mass/spin known
- Viterbi method used to find the optimal signal path [21]

Primordial black holes (PBHs)

- Black holes that formed in the early universe that can take on a wide range of masses depending on when they formed [10]
- Not predicted by standard model → detection would mean new physics
- PBHs could be linked to dark matter:
  - Dark matter may support cooling mechanisms that allow densely populated regions in space to collapse into PBHs [20]
  - Dark matter may interact with neutron stars and collect inside of them, causing a collapse [14]

How do PBHs form?

- Early universe contained inhomogenities that stopped too dense regions from expanding, causing collapses [11]
- Quantum fluctuations in various inflation theories [12]
- A binary could form if two PBHs form independently but are kept from merging by the gravitational pull of other nearby PBHs [19]
- Also, formation could occur through capture in a PBH halo [22]
- ... many more

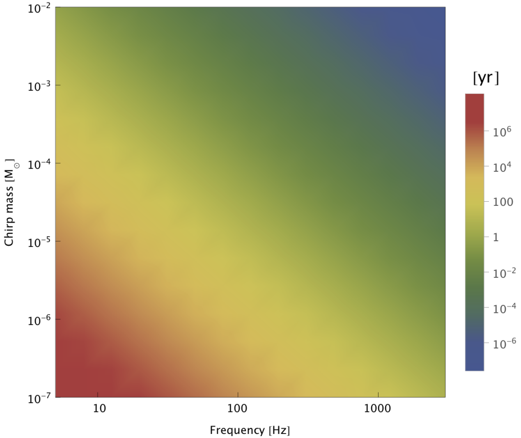
The signal

$$\dot{f}_{\mathrm{gw}} \propto \mathcal{M}^{5/3} f_{\mathrm{gw}}^{11/3} = k f_{\mathrm{gw}}^{11/3} \tag{4.1}$$

$$f_{\mathrm{gw}}(t) = f_0 \left(1 + \frac{8}{3} k f_0^{n-1} (t - t_0)\right)^{-\frac{3}{8}} \tag{4.2}$$

- The inspiral portion of a merger can be modelled as a quasi-circular orbit that loses energy due to gravitational-wave emission
- The approximation holds at distances $> R_{\mathrm{isco}}$
- For chirp masses $\mathcal{M} = [10^{-5}, 10^{-3}] M_{\odot}$, $f_{\mathrm{isco}} > O(M\text{Hz})$
- Timescale of emission varies from $O(\mathrm{yrs})$ to $O(s)$
- Continuous-wave methods applicable
- Methods also applicable to binaries that could be seen by future detectors

How long until PBHs merge?



- Within this frequency range, lighter equal-mass PBHs take longer to merge [16]
- Larger equal-mass PBHs would have formed later

The signal

$$\dot{f}_{\mathrm{gw}} \propto \mathcal{M}^{5/3} f_{\mathrm{gw}}^{11/3} = k f_{\mathrm{gw}}^{11/3} \tag{4.3}$$

$$f_{\mathrm{gw}}(t) = f_0 \left(1 + \frac{8}{3} k f_0^{n-1} (t - t_0)\right)^{-\frac{3}{8}} \tag{4.4}$$

- The inspiral portion of a merger can be modelled as a quasi-circular orbit that loses energy due to gravitational-wave emission
- The approximation holds at distances $> R_{\mathrm{isco}}$
- For chirp masses $\mathcal{M} = [10^{-5}, 10^{-3}] M_\odot$, $f_{\mathrm{isco}} > O(M$Hz$)$
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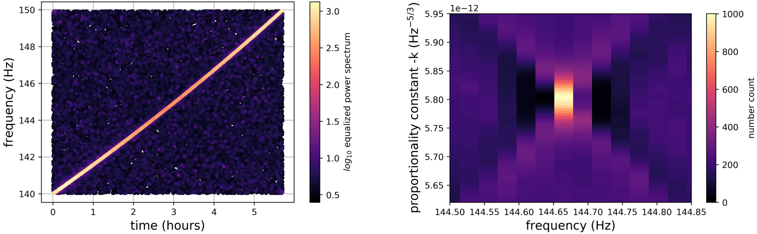
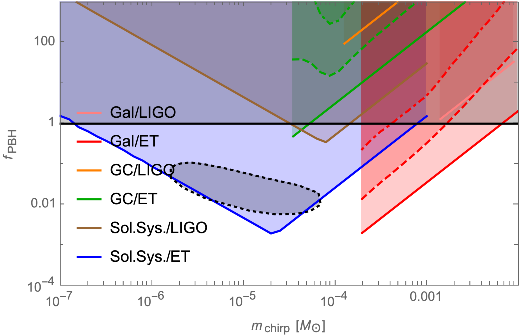
Simulated signal



- Hough Transform maps points in the time/frequency plane to lines in a plane that relates to the frequency and spin-up of the source
- Injection parameters: $h_0 = 4 \times 10^{-23}$, $f_0 = 144.669$ Hz, $\mathcal{M} = 10^{-3} M_\odot$, $k = 5.73 \times 10^{-12}$ Hz$^{-5/3}$

Projected constraints in the current and advanced detector era



- Projected constraints on the fraction of dark matter PBHs could compose for current and future detectors at different distances [16]
- Agnostic and thermal mass functions used
- Oval-dotted lines are constraints from gravitational lensing experiments (OGLE)

Conclusions

- Many interesting physical systems are sources of continuous gravitational waves
- Similar analysis techniques can be employed for a variety of sources
- Current and future searches for boson clouds could be performed over the whole sky, or targeting the remnants of binary mergers

Backup slides

General search scheme

- Choose a Fourier Transform length
- Fourier Transform the strain data, and perform a matched filter (in the case of fully coherent searches), or make a time/frequency spectrogram (in semi-coherent searches)
- Apply a method robust to noise disturbances on the spectrogram to estimate parameters

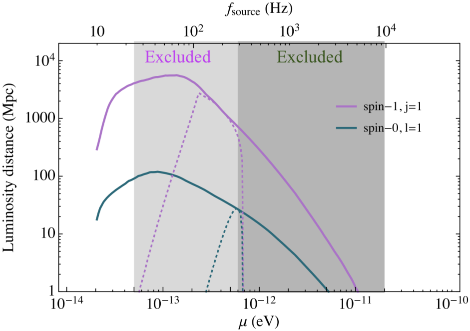
General search scheme

- Look for coincident candidates in each detector
- At this point, many candidates exist and must be discarded in a “follow-up” stage
- Demodulate the signal with the known parameters, and increase the Fourier Transform length
- In the event of no detection, put upper limits with simulations or estimations of theoretical sensitivity

Vector bosons

- Emit gravitational waves with higher amplitudes, but on shorter timescales, than those from scalar bosons
- For shorter signals, spinup becomes important
- Parameter space mostly composed of “transient” continuous wave signals
- Possible targets: merger remnants, x-ray binaries
- Interplay between instability and depletion timescales important

Distance reach



- Assumes monochromatic signal
- Black hole mass chosen as a function of particle mass to give the strongest gravitational-wave signal
- Dotted line: $M_{BH} = 64 M_{sun}$

equations

Ellipticity:

$$\epsilon \equiv \frac{|I_{xx} - I_{yy}|}{I_{zz}}, \tag{5.1}$$

Amplitude of continuous wave:

$$h_0 = \frac{16\pi^2 G}{c^4} \frac{I_{zz}\epsilon f_{\mathrm{rot}}^2}{d}, \tag{5.2}$$

Spindown limit:

$$h_{0,\mathrm{sd}} = \frac{1}{d}\left(\frac{5GI_{zz}}{2c^3}\frac{|\dot{f}_{\mathrm{rot}}|}{f_{\mathrm{rot}}}\right)^{1/2}, \tag{5.3}$$

References I

[1] Abbott, B., Abbott, R., Abbott, T., Abraham, S., Acernese, F., Ackley, K., Adams, C., Adhikari, R., Adya, V., Affeldt, C., et al. (2019a). Searches for gravitational waves from known pulsars at two harmonics in 2015–2017 ligo data. *The Astrophysical Journal*, 879(1):10.

[2] Abbott, B. et al. (2019b). All-sky search for continuous gravitational waves from isolated neutron stars using Advanced LIGO O2 data. *Physical Review D*, 100(2):024004.

[3] Abbott, B. P. et al. (2019c). Search for gravitational waves from a long-lived remnant of the binary neutron star merger GW170817. *The Astrophysical Journal*, 875(2):160.

[4] Abbott, R. et al. (2020). Diving below the spin-down limit: Constraints on gravitational waves from the energetic young pulsar PSR J0537-6910.

[5] Abbott, R. et al. (2021). All-sky search in early O3 LIGO data for continuous gravitational-wave signals from unknown neutron stars in binary systems. *Phys. Rev. D*, 103(6):064017.

[6] Arvanitaki, A., Baryakhtar, M., and Huang, X. (2015). Discovering the qcd axion with black holes and gravitational waves. *Physical Review D*, 91(8):084011.

[7] Astone, P., Colla, A., D'Antonio, S., Frasca, S., and Palomba, C. (2014). Method for all-sky searches of continuous gravitational wave signals using the Frequency-Hough transform. *Physical Review D*, 90(4):042002.

[8] Baumann, D., Chia, H. S., and Porto, R. A. (2019). Probing ultralight bosons with binary black holes. *Physical Review D*, 99(4):044001.

[9] Brito, R., Cardoso, V., and Pani, P. (2015). Black holes as particle detectors: evolution of superradiant instabilities. *Classical and Quantum Gravity*, 32(13):134001.

[10] Carr, B., Clesse, S., Garcia-Bellido, J., and Kuhnel, F. (2019). Cosmic conundra explained by thermal history and primordial black holes. *arXiv preprint arXiv:1906.08217*.

[11] Carr, B., Kohri, K., Sendouda, Y., and Yokoyama, J. (2010). New cosmological constraints on primordial black holes. *Physical Review D*, 81(10):104019.

References II

[12] Carr, B., Kühnel, F., and Sandstad, M. (2016). Primordial black holes as dark matter. *Physical Review D*, 94(8):083504.

[13] Isi, M., Sun, L., Brito, R., and Melatos, A. (2019). Directed searches for gravitational waves from ultralight bosons. *Physical Review D*, 99(8):084042.

[14] Kouvaris, C. and Tinyakov, P. (2011). Constraining asymmetric dark matter through observations of compact stars. *Physical Review D*, 83(8):083512.

[15] Lasky, P. D. et al. (2017). The braking index of millisecond magnetars. *The Astrophysical Journal Letters*, 843(1):L1.

[16] Miller, A. L., Clesse, S., De Lillo, F., Bruno, G., Depasse, A., and Tanasijczuk, A. (2021). Probing planetary-mass primordial black holes with continuous gravitational waves. *Phys. Dark Univ.*, 32:100836.

[17] Palomba, C., D'Antonio, S., Astone, P., Frasca, S., Intini, G., La Rosa, I., Leaci, P., Mastrogiovanni, S., Miller, A. L., Muciaccia, F., et al. (2019). Direct constraints on the ultralight boson mass from searches of continuous gravitational waves. *Physical Review Letters*, 123(17):171101.

[18] Prix, R. (2009). Gravitational Waves from Spinning Neutron Stars. In Becker, W., editor, *Neutron Stars and Pulsars*, volume 357 of *ASSL*, chapter 24, pages 651–685. Springer Berlin Heidelberg.

[19] Raidal, M., Spethmann, C., Vaskonen, V., and Veermäe, H. (2019). Formation and evolution of primordial black hole binaries in the early universe. *Journal of Cosmology and Astroparticle Physics*, 2019(02):018.

[20] Shandera, S., Jeong, D., and Gebhardt, H. S. G. (2018). Gravitational waves from binary mergers of subsolar mass dark black holes. *Physical review letters*, 120(24):241102.

[21] Sun, L., Brito, R., and Isi, M. (2019). Search for ultralight bosons in cygnus x-1 with advanced ligo. *arXiv preprint arXiv:1909.11267*.

[22] Turner, M. (1977). Gravitational radiation from point-masses in unbound orbits-newtonian results. *The Astrophysical Journal*, 216:610–619.