Status and perspectives of Continuous Gravitational Wave searches

Ornella Juliana Piccinni

1 INFN, Sezione di Roma, I-00185 Roma, Italy;
* Correspondence: ornella.piccinni@ligo.org;

Abstract: The birth of gravitational wave astronomy has been triggered by the detection of the first signal produced by the merger of two compact objects. The following discoveries by the Earth-based network of advanced interferometers had a significant impact in many fields of science: astrophysics, cosmology, nuclear physics and fundamental physics. However, Compact Binaries Coalescence signals are not the only type of gravitational waves detectable by LIGO, Virgo, and KAGRA. An interesting family of yet undetected signals, and the ones that I will consider in this review, are the so-called continuous waves, paradigmatically exemplified by the gravitational radiation emitted by galactic, fast-spinning isolated neutron stars with a certain degree of asymmetry in its mass distribution. In this work, I will review the status and the latest results from Advanced detectors data.

Keywords: Continuous gravitational Waves; Neutron stars; Dark Matter; LIGO; Virgo; KAGRA

1. Introduction

To date the LIGO and Virgo intereferometric detectors [1,2] have been able to detect up to 90 gravitational wave (GW) events from the coalescence and merger of two compact bodies, either a pair of black holes (BHs) or neutron stars (NSs) or a mixed NS-BH system. Each confirmed detection, starting from the first event in September 2015, has added a big piece of information about our comprehension of Nature. However there is still a huge pile of missing pieces to be added to the puzzle before having a complete picture of the actual components of our Universe. Indeed we are at the beginning of the newborn gravitational wave astronomy. Resuming all the information we have collected so far, we have been able to prove, among other things, the existence of GWs, BHs in binaries, the formation of heavy elements in NSs mergers, only by considering the class of transient signals also known as compact binary coalescence events. Any system is able to generate gravitational waves if its mass distribution is not symmetric, i.e. whenever a mass quadrupole moment is on. In particular, other astrophysical systems are able to emit GW detectable by Earth interferometers like LIGO, Virgo and KAGRA [3]. Although the emitted signal is very difficult to catch in the data, their discovery would certainly be of wide interest for full the scientific community. In this review I will focus on the discussion of the prospect of detection for a particular subset of GW signals called continuous waves (CWs). In Sec. 2, I will provide some information about the physical systems that can emit this particular feature. In Sec. 3 I will provide an up-to-date list of the data analysis techniques used for this type of problem. Finally, in Sec. 4 I will report the latest observational results, while conclusion are given in Sec 5.

2. Sources of continuous gravitational waves

The detection of continuous gravitational wave signals represents one of the next milestones to reach in gravitational-wave astronomy, both within the LIGO-Virgo-KAGRA collaboration and by external independent groups. Long-lasting signals, persistent over the full observing run, or in its shorter duration version, the so-called long...
CW transients, are typically emitted by fast spinning asymmetric NSs, both in accreting systems or as newborn isolated sources. To this canonical list of sources, recent studies have reported the possibility to observe also the continuous gravitational emission by potential dark matter (DM) candidates. Other potential sources of CWs are Boson stars [4,5] and Thorne–Żytkow Objects [6], although no associated search in advanced detector data has been carried out yet.

In this section, I will review the main emission models proposed in the literature. Previous reviews about CW signals and searches can be found in [7–12] or in the more general GW reviews [13,14].

2.1. Neutron stars

The physical condition of NS matter is unique, making these fascinating compact objects precious laboratories for subatomic physics [15,16]. High density and pressure are reached as the inner core is approached, growing from a value comparable with terrestrial atomic nuclei in the NS crust \( p_0 \sim 2.5 \times 10^{14} \text{ g/cm}^3 \), up to values one order of magnitude bigger in the inner core. Surface magnetic fields can reach values up to \( 10^{15} \text{ Gauss} \) or up to \( 10^{17} \text{ Gauss} \) for strongly magnetized NSs, also known as magnetars [17,18].

Given the extreme condition of NS matter, the equation of state (EOS) is not completely known, since superfluidity, superconductivity [19,20], exotic states or quantum effects could be present [21–24]. The actual NS composition is still unknown. In particular, when quark contributions become non-negligible at higher densities [25], de-confined quark matter can be present, although how this phase transition occurs is still unclear.

In a different scenario, NS inner core can be composed by hyperons [26], Bose–Einstein, pion or kaon condensates [27–29], and more. It is clear then it does not exists an easy answer to the question “what is the NS core made of?”. Furthermore, some of the above-mentioned status of matter are considered as simultaneously present inside the compact object. The NS matter EOS directly reflects on the star observable global parameters like the mass and radius. Theoretical and observational efforts, including GWs, are ongoing to measure the NS masses and radii [30–34]. To set constraints on the EOS mass and radius of a NS should be measured simultaneously and some assumptions on the pulse profiles should be made (see e.g. [35]). NS masses are typically measured from pulsar observations, while radius measurements are more challenging and strongly depend on the X-ray emission model assumed. To date, the NS measured masses lie in the range \( [1.1 \sim 2.2] M_\odot \), with the most massive source being the millisecond pulsar J0740+6620 with \( 2.14 M_\odot \) [36]. Direct measurements of radii do not exist, however estimates can be done for instance by combining the measured flux and temperature with the source distance. Current estimates report NS radii in the range \( [9 \sim 13] \text{ km} \) [37–39]. Further improvements on the NS radius and mass estimates derived from the NICER mission [40,41]. The detection of the first NS merger event GW170817 by LIGO and Virgo [42], followed by the electromagnetic (EM) gamma-ray burst GRB170817 [43], and the optical transient signal of a kilonova (AT 2017gfo) [44], provided a new tool for NS mass and radius estimates [45], extending the possible NS mass range. Other GW events involving potential NS have been reported to date: GW190425 [46] with a progenitor mass of \( [1.12 \sim 2.52] M_\odot \) and GW190814 [47] involving a compact object with a mass \( 2.50 \sim 2.67 M_\odot \). No EM counterpart has been observed by the two events, and the possibility that these are the smallest BHs to date, instead of the most massive NSs, cannot be excluded.

The formation of a NS could happen through two main channels: (i) core-collapse supernova explosions (CCSN), forming a very hot proto-neutron star, followed by a cooler stable NS [48], (ii) after a binary NS merger involving at least one progenitor NS [49]. In these two scenarios, fast-rotating and highly magnetized young NS (in particular magnetars) could be formed.

Fast-spinning NSs are expected to emit GWs continuously if they are asymmetric with respect to their rotation axis [50,51]. Potential targets for Earth-based detectors
are galactic sources. The energy released, as the star spins, is almost monochromatic and with a frequency proportional to the star’s spin frequency. Four different scenarios are considered possible for the observation of CW, namely (i) very hot newborn NSs, right after the formation i.e. after merger and core-collapse supernova, rotating at a frequency close to its Keplerian limit; (ii) young NSs like stable supernova remnants during the initial spin-down phase; (iii) accreting low mass X-ray binaries (LMXBs) emitting thermal X-ray radiation and characterized by a small spin-up (iv) fast-spinning pulsars i.e. old millisecond pulsars with small spin down. Different emission models are considered (see [50]), these include the CW emission due to the presence of non-axisymetries in rigid rotating triaxial bodies, rotating about one of its principal axis (equivalent to a biaxial rotor not spinning about one of the principal axes); oscillation of the star; or more complicated scenarios such as free precessing systems or heterogeneous stars (when multiple phases of component matter are simultaneously present, including superfluidity).

If from one side some of the GW emission mechanisms are well understood, the actual factors which cause the asymmetry in the star are still under debate. Indeed the asymmetry could be triggered by the presence of residual crustal deformations (e.g., after a fast cooling of the NS crust causing its breaking), the presence of a strong inner magnetic field not aligned with the star’s rotation axis, or the presence of magnetic or thermal “mountains” (see [12] for a review). The maximum ellipticity (i.e., deformability) the star can sustain depends on both the NS EOS and the breaking strain of the crust [10]. I briefly review the two main emission mechanisms happening in NSs and how these reflect on the expected CW signal amplitude.

**Ellipticity driven emission:** the GW amplitude for a NS with asymmetries, can be expressed in terms of the product between the moment of inertia $I_3$ along the spin axis and the star’s degree of asymmetry, also known a ellipticity $\epsilon$:

$$h_0 = \frac{16\pi^2 G}{c^4} \frac{I_3 \epsilon f_{\text{spin}}^2}{r}$$  \hspace{1cm} (1)

where $f_{\text{spin}}$ is the star spin frequency of a source at a distance $r$. Most of the observed NSs have rotation frequencies below 1kHz, i.e. in the sensitivity range of ground-based interferometers such as Advanced LIGO/Virgo. The ellipticity is given by $\epsilon = \frac{I_2 - I_1}{I_3}$ assuming $I_1 \neq I_2$. Most of the parameters entering in Eq. 1 can be somehow constrained by astronomical observations, while the less constrained parameter is the ellipticity $\epsilon$ for which only theoretical maxima estimates exist [52–57]. Current estimates lie in the $10^{-7} - 10^{-5}$ range, except for an estimated fiducial ellipticity $\sim 10^{-9}$ possibly sustained by millisecond pulsars [55]. According to theoretical models, the ellipticity in a spinning NS can be sustained by the presence of strong internal magnetic fields and/or elastic stresses in the crust or core. For the case of elastic stresses, the maximum sustained ellipticity is related to the crustal breaking strain as [38]

$$\epsilon < 2 \times 10^{-5} \left( \frac{u_{\text{break}}}{0.1} \right)$$  \hspace{1cm} (2)

with estimated values of $u_{\text{break}} = 0.1$ much larger than standard terrestrial materials [59]. However these constraints strongly depend on the actual EOS (see e.g. [10]). For quadrupolar deformations on spherically symmetric stars due to magnetic fields [60–62], the ellipticity is given by the ratio of the magnetic energy and the GW energy. The actual deformation strongly depends on the magnetic field morphology. Indeed, poloidal fields will oblate the star, while toroidal fields tend to prolate the star. In the best-case scenario when the magnetic field is purely poloidal the ellipticity will be positive and will depend on the average $B$ field as

$$\epsilon \approx 10^{-12} \left( \frac{B}{10^{12} G} \right)^2$$  \hspace{1cm} (3)
In a realistic scenario both the poloidal and toroidal components will contribute to the \( B \) field (for a detailed discussion see [12,50]). Given the uncertainty connected to the estimation of \( \varepsilon \) and the moment of inertia \( I \), typically the deviation from axisymmetry is constrained in terms of the quadrupole \( Q_{22} \) (assuming that the \( l = m = 2 \) mode dominates) [53]

\[
Q_{22} = \sqrt{\frac{8\pi}{15}} \varepsilon I
\]  

(4)

**R-mode emission:** a different emission channel for CW radiation is given by the Rosby (r-)modes oscillations in rotating stars. R-mode emission is provided by the Chandrasekhar-Friedman-Schutz instability, leading to the rapid growth of the r-mode amplitude until a saturation amplitude is reached and the growth of the mode stops [63]. These amplitudes are damped by the viscosity of the star. Given these two opposite effects, where the amplitude increases with the spin of the star and is suppressed by the viscosity, dependent on the temperature, an instability window is defined in the angular velocity-temperature plane [64]. Typically NS are unstable to r-modes except at extreme temperatures. At very low temperatures the shear viscosity dominates the damping, while at very high temperatures the bulk viscosity takes the lead in the r-mode suppression. Given this strict relation with the inner physics of NS during r-mode emission, constraints on the GW observable properties are interesting tools for the study of the EOS [50,65]. A typical value constrained in CW searches for r-modes is the r-mode amplitude \( \alpha \), connected with the GW strain \( h_0 \) as:

\[
h_0 = \frac{16}{27} \sqrt{\frac{2}{5\pi^2}} \frac{G}{c^5} M R^3 \frac{\chi^2 f_{gw}^{3/2} \alpha}{r}
\]  

(5)

where the dimensionless constant \( \tilde{f} \) is connected to the source density and EOS [63]. \( M \) and \( R \) are the NS mass and radius. The GW frequency \( f_{gw} \) is given by the oscillation angular frequency \( \omega \) which is related to the rotation angular velocity as \( \omega = -4/3\Omega \). If relativistic corrections and other effects due to the rotation are considered [66,67], the relation between the GW frequency and the star spin frequency can be parametrized as [50,65]:

\[
f_{gw} = \frac{4}{3} \chi f_{spin}
\]  

(6)

Strong ellipticities are also expected to be present in LMXBs, due to an asymmetric accretion process producing, for instance, thermal gradients in the crust [52]. In these systems, a spinning NS is accreting matter from a companion, forming a circumstellar accretion disc around it and emitting strong X-ray radiation. These systems represent interesting targets for CW searches [68], given that when the accretion torque balances the GW torque, LMXBs become very stable GW emitters. In particular, the GW amplitude of LMXB is proportional to the square root of the X-ray flux. For this reason, very bright sources like Scorpius X-1 (Sco X-1) or XTE J1751-305 represent ideal targets. It has been observed that all the NSs in LMXB systems have maximum spinning frequencies below their Keplerian breakup limit. This suggests that this limit is strongly related to the gravitational wave torques [69,70], due to oscillations or asymmetries, although it could be due to the interaction of the accreting disk with the NS magnetic field [71]. The search for CW from accreting sources is complicated mainly by two factors [68]: (i) the source is spun up by the companion during the accretion, causing a spin-wandering effect [72] (ii) an additional Doppler effect by the binary orbital motion is present [73]. Eventually, variations in the matter accretion rate directly reflect into irregular spinning frequency. To make these searches even more complicated, often the spin frequency is


not known, as for the case of Sco X-1.

The CW class of signal is then a good benchmark to study the state of matter at higher densities. In addition to this aspect, CW detection can be used to test general relativity. According to general relativity, only two tensor polarization states exists for GWs. When more generic metric theories of gravity are assumed, the number of polarizations increase up to six, allowing for two scalar and two vector additional modes. In particular, for the Brans–Dicke theory of gravity[74], an additional scalar polarization state is predicted to be present along with the two tensor polarizations predicted by GR.

As discussed in [75–77] it is possible to put constraints on these extra polarizations using searches for CW from known pulsars. Indeed the detector response function to a given polarization depends on the direction of propagation of the GW along the two detector arms. Given the long duration nature of GWs, different antenna patterns will produce a different sidereal amplitude modulation. This means that all the relevant information to distinguish between the polarizations is encoded in the sidereal-day-period amplitude modulation of the signal. This is true only if the signal phase evolution for non-GR polarizations is equal to that assumed for GR.

2.1.1. The role of the frequency

Following [8], it is possible to extract some information about the main CW emission mechanism happening in a NS, by looking at the gravitational wave frequency measured in a detection. In particular it is known that the gravitational wave frequency is related to the star spin frequency according to $f_{\text{gw}} = k(f_{\text{spin}} + f_{\text{prec}})$. Here $k$ is a proportionality factor dependent on the model considered. In the simplest case of no precessing ($f_{\text{prec}} = 0$) rigid rotating bodies, with asymmetries supported by elastic and/or magnetic stresses, $k = 2$, hence $f_{\text{gw}} = 2f_{\text{spin}}$. In r-mode oscillations scenarios the estimated emitted frequency is $f_{\text{gw}} \sim 4\frac{3}{2}f_{\text{spin}}$, although deviations from this number are expected when relativistic corrections are included and/or different EOS are considered. In this case, the GW amplitude of the r-mode signal is parametrized in terms of the r-mode amplitude $\alpha$ and it explicitly depends on the mass and radius of the NS and on the star EOS.

In between these two scenarios lie all the possible emission models connected with free precession, where dual harmonic emissions can be present at once and twice the star spinning frequency for a biaxial rotor. More complicated cases are expected for a triaxial freely precessing body and these are typically not considered in current CW searches. Recent works report the possibility to have a dual harmonic emission also in the case of a superfluid core pinned to the crust and not aligned with the principal axes of the moment of inertia [78]. More complicated cases, including the possibility to have emission from a deferentially rotating two-component star, are also considered in the literature, where also in this case a multiple harmonic emission is expected.

For the case of CWs emitted by low-mass X-ray binaries systems (e.g. Sco X-1), accreting matter from a companion star, the relation between the spin frequency and the GW frequency is expected to be $f_{\text{gw}} = 2f_{\text{spin}}$.

Historically single harmonic models have been the ones considered in CW searches, although the latest works also use more model-robust approaches. In particular, most of the modeled searches are tracking single harmonics at twice the rotating frequency, while less stringent constraints are used in more model-robust searches, including simultaneous dual harmonic or spin-wandering tracking and narrow-band searches. Lately, the interest in the so-called long duration transient has increased, as well the possibility to look for CW signals from glitching pulsars. In both cases, the emitted frequency is no longer considered as fully monochromatic but opportune deviations are taken into account, namely the high spin-down rate in long transients and the sudden frequency change expected for glitching pulsars. It is also possible that glitches trigger an increased GW emission [79], with sudden spin-up events and then relaxing back to the spin-down scenario following an exponential decrease.
As the star spin, its angular momentum will be radiated away e.g. via GW emission, decreasing its frequency as
\[ \dot{f} = K f^n \] (7)
where the negative constant \( K \) and the braking index \( n \) depend on the energy loss mechanism as \( n = f \dot{f} / f^2 \). The spin-down process is more complicated than the simple power law in Eq. 7, and in general, it is possible that the energy loss is due to a simultaneous contribution from both the gravitational and magnetic dipole emission. For a spin-down fully dominated by a gravitational emission \[80\], i.e. a gravitar, \( n = 5 \) (or \( n = 7 \) if the GW emission happens via r-mode), while \( n = 3 \) for magnetic dipole emission. An estimate of the age of the source can be expressed as
\[ \tau = - \left[ \frac{f}{(n-1)f_0} \right] \left[ 1 - \left( \frac{f}{f_0} \right)^{(n-1)} \right] \] (8)
where \( f_0 \) is the star birth rotation frequency. For old sources (with \( f \ll f_0 \) the age is simplified as
\[ \tau \approx - \left[ \frac{f}{(n-1)f} \right] \] (9)

2.1.2. Strain amplitude limits

It is possible to identify promising targets for CWs by computing some limits based on the information about the source. These quantities constraint the maximum GW emission a given system can emit. Three main limits are used in CW searches: the spin-down limit, the age-based limit and the torque balance limit.

**Spin-down limit**: generally for known pulsars with precisely measured \( f_{\text{spin}} \) and \( \dot{f}_{\text{spin}} \), it is possible to define the so-called spin-down limit on the maximum detectable strain \[51\]. If all the energy loss during the spin-down is released in form of GW, by equating the GW power emission to the time derivative of the rotational kinetic energy one gets for a source at a distance \( r \):
\[ h_{sd}^0 = \frac{1}{r} \sqrt{\frac{5 G I_3}{2 c^3 f_{gw}}} \frac{|f_{gw}|}{f_{gw}} = 2.5 \times 10^{-25} \left( \frac{1 \text{kpc}}{r} \right) \left( \frac{1 \text{kHz}}{f_{gw}} \right) \left( \frac{|f_{gw}|}{10^{-10} \text{ Hz/s}} \right) \left( \frac{I_3}{I_0} \right). \] (10)
where \( I_0 = 10^{38} \text{ kg m}^2 \). This gives an optimistic idea on how strongly a known pulsar can emit CWs.

**Age based limit**: an alternative way to check the goodness of a potential CW target is to look at the so-called indirect age-based limit. Similar to the spin-down limit, assuming that all the energy lost is radiated away with GWs, it is possible to express the spin-down limits in terms of the age of the star \( \tau \) using Eq. 8 and a braking index \( n = 5 \) for the ellipticity case \[81\]
\[ h_{age}^0 = 2.27 \times 10^{-24} \left( \frac{1 \text{kpc}}{r} \right) \left( \frac{1 \text{kyr}}{\tau} \right)^{1/2} \left( \frac{I_3}{I_0} \right)^{1/2} \] (11)

**Torque balance limit**: Empirical upper limits can be defined also for the accreting binaries case. Assuming that the GW emission is completely balanced by the angular momentum added via accretion, the so-called torque-balance limit can be derived \[82\]. Assuming that the maximum accretion luminosity is fully radiated as X-rays

---

1 Given the proportionality between \( f_{gw} \) and \( f_{spin} \), here \( f \) can indicate any of the two frequencies.
this provides an estimate on the mass accumulation rate, hence the limit can be written in term of the observable X-ray flux $F_X$ and the star spin frequency (GW frequency)

$$h_{0}^{\mathrm{tb}} = 5 \times 10^{-27} \left( \frac{F_X}{F_\star} \right)^{1/2} \left( \frac{R}{10 \text{ km}} \right)^{1/2} \left( \frac{r_m}{10 \text{ km}} \right)^{1/4} \left( \frac{1.4M_\odot}{M} \right)^{1/4} \left( \frac{700 \text{ Hz}}{f_{gw}} \right)^{1/2}$$ (12)

with $F_\star = 10^{-8}$ erg cm$^{-2}$ s$^{-1}$. $M$ and $R$ are the NS mass and radius and $r_m$ is the lever arm, usually equal to $R$ or to the Alfven radius, i.e. the radius corresponding to the inner edge of the accretion disk.

2.2. Dark matter candidates

A CW-like signature is expected to be emitted also by several potential DM candidates [83]. During the last years, interferometric detector data are being used to look for evidence of DM, both in terms of GW, emitted by systems made up of particles from the dark sector, and as direct DM detectors, assuming a certain coupling model with the detector itself. For a review of all the DM candidates that can be investigated using GWs detectors, see [84]. A good fraction of DM particles could be represented by ultra-light bosons, including dark photons or Quantum-Chromo-Dynamics axions [85–88] In this section, I review three main scenarios involving DM candidates, where a persistent CW-like signal is expected to be present and whose signal is actively searched by the CW community: boson clouds around spinning BHs, vector bosons in form of dark photons, compact dark objects (CDO) or primordial black holes (PBHs). The latest observational results will be discussed in Sec. 4.2.

**Boson clouds.** Ultralight bosons condensates can clump around spinning BHs through superradiance [86,87,89]. The same effect is somehow expected also for rotating NS [90,91], although it is not clear if the GW emission is loud enough to be detected by currently operating detectors. The BH-boson cloud system can be approximated by the hydrogen atom model when the axion’s Compton wavelength is comparable to the size of a BH, turning this system into a gravitational atom. When scalar field bosons are present nearby the spinning BH, these can interact with the BH and condensate around them all occupying the same (quantum) state and reaching huge occupation numbers after an exponential growth. The axion or axion-like particle scattering on the BH can extract angular momentum decreasing the BH spin. When the BH spin is low enough the superradiance process stops and the cloud evaporates via axion annihilation to gravitons. During this depletion phase or when transitioning between levels of the gravitational atom, the system generates a quasi-monochromatic and long-duration signal that can be searched with CW methods. The most interesting scenario for Earth-based detectors like LIGO, Virgo and KAGRA is the annihilation process. Indeed the signal produced in this case is in the detector sensitivity band for boson masses in the $10^{-13} - 10^{-12}$ eV range. If the boson self-interaction is negligible, the gravitational-wave signal frequency depends mainly on the mass of the boson, and weakly on the mass and spin of the BH. When self-interaction is considered, the approximation of the signal with a CW-like shape is no longer valid, and opportunely modifications should be taken into account [92]. In particular, if the self-interaction is stronger than the gravitational binding energy, the system undergoes a bosenova collapse of the bosonic cloud, resulting in a burst of GWs [86]. In general the annihilation signal cannot be modeled if any assumption on the BH population is done. Indeed it depends on the mass, spin, distance, and age of the BH.

Let us briefly review the main characteristic of the signal emitted by BH-boson clouds as in [85,86,89,93,94]. When the superradiant condition is satisfied, i.e. when the boson angular frequency is less than the BH’s outer horizon angular frequency, scalar field start to clump into the BH. This effect is maximized when the the particle’s
reduced Compton wavelength $\lambda_b = \frac{\hbar c}{m_b}$ is comparable to the BH Schwarzschild radius $R = \frac{2GM_{BH}}{c^2}$. This superradiant instability phase has a typical duration of

$$\tau_{\text{inst}} \approx 20 \left( \frac{M_{BH}}{10M_\odot} \right) \left( \frac{\alpha}{0.1} \right)^{-9} \left( \frac{1}{\chi_i} \right) \text{days}, \quad (13)$$

dependent on the BH mass $M_{BH}$ and dimensionless spin $\chi_i$. Taking back the analogy with the hydrogen atom, $\alpha$ is the fine-structure constant in the gravitational atom

$$\alpha = \frac{GM_{BH} m_b}{\hbar c^3}, \quad (14)$$

As long as the BH spin is above the critical spin $\chi_c \approx \frac{4\alpha}{\chi+i}$, the cloud will continue to grow and the BH will decrease a bit its mass and its spin. Once equilibrium has been reached, the boson cloud mass is dissipated and on a timescale $^2$

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

The GW amplitude decays in time as $(1 + t/\tau_{\text{gw}})^{-1}$ from a starting strain amplitude determined mainly by the BH and boson masses (entering in the definition of $\alpha$) and the BH initial spin

$$h_0 \approx 3 \times 10^{-24} \left( \frac{\alpha}{0.1} \right)^7 \left( \frac{\chi_i - \chi_c}{0.5} \right) \left( \frac{M_{BH}}{10M_\odot} \right) \left( \frac{1\text{kpc}}{r} \right), \quad (16)$$

During this emission phase, the GW emitted frequency, which is twice the frequency of the field, is also dependent on the two-component masses as

$$f_{\text{gw}} \approx 483 \text{ Hz} \left( \frac{m_b}{10^{-12}\text{eV}} \right) \left[ 1 - 7 \times 10^{-4} \left( \frac{M_{BH}}{10M_\odot} \right) \left( \frac{m_b}{10^{-12}\text{eV}} \right)^2 \right] \quad (17)$$

During the depletion phase, a small spin-up is present due to the loss of mass. Indeed, during the cloud formation phase, a large spin-down rate is present, although the expected signal strain is still too low to be detected. This drift changes when the cloud starts to evaporate. The actual spin-up rate during the depletion phase is strongly dependent on the boson self-interaction constant. For simplicity we consider the case a negligible self-interaction, when the spin-up due to annihilation is the dominant drift:

$$f_{\text{gw}} \approx 7 \times 10^{-15} \left( \frac{m_b}{10^{-12}\text{eV}} \right)^2 \left( \frac{\alpha}{0.1} \right)^{17} \text{Hz/s} \quad (18)$$

When the self-interaction starts to be non-negligible, the spin-up rate is enhanced by two contributes, one from the bosons energy level transition and a second from the change in the self-interaction energy as the cloud depletes. At this point the signal is expected to be shorter or with a smaller amplitude. For a more general discussion on the role of the boson self-interaction parameter see [92]. In current CW searches the main contribution to the GW emission considered for these models are those from the main growing state, since second fastest growing state emission is weaker than the first level one and is not fully quadrupolar.

Analogous to the standard CW case in NS, Doppler modulations should be considered when looking for the signal in the detector data (see 4.2 for the latest observing results from this field).

\[\text{for } m = 1 \text{ and for } \alpha \ll 0.1\]
**Ultralight vector bosons: dark photons.** DM particles are expected to interact with other DM particles in the same way as standard matter interacts with the EM force mediated by the photon. The equivalent force mediator for the dark sector the dark photon. According to current theories, the dark photon is not expected to couple directly to SM particles although a small mixing-induced coupling to EM currents can be present [95,96]. Here we focus on an ultralight DM candidate with masses as low as \( \sim 10^{-22} \) eV, which behaves as a classical field interacting coherently with the atoms of the test masses. In particular we assume that the dark photon is a vector boson coupled to the baryon or baryons minus leptons number \( U(1)_B / U(1)_{B-L} \). In practice, if sufficiently light, the dark photon has a high phase-space density, hence it behaves as a coherently oscillating classic field impinging an oscillating force on dark charged objects [97–99]. The same type of oscillation is expected for the tensor boson case [100].

The mass of the dark photon could be provided either by a dark Higgs boson or via the Stuckelberg mechanism [95,96,101]. Different production mechanisms have been proposed for the dark photon, such as misalignment mechanism associated with the inflationary epoch, light scalar decay or by cosmic strings [102,103]. Several attempts to set constraints on this type of DM are present in literature [98,104,105]. The dark photon DM field oscillations act as a time-dependent EP-violating force acting on the test masses and producing a change in the relative length of the detector’s arms. There exist two main signatures when test bodies interact with the dark photon fields: a spatial gradient is present, producing a relative acceleration between the objects due to the different field amplitude; given the EP-violation of this force, test masses of different materials will experience different accelerations. For all Earth-based detectors, an additional effect due to the finite light travel time should be considered [106,107].

I briefly review the main characteristics of the expected signal from dark photons while search results are discussed in Sec. 4.2. The Lagrangian of the massive vector field \( A^\mu \), which couples to \( B \) or \( B-L \) current \( J_D^\mu (D = B \) or \( B-L \) \) as DM is given (in natural units) by

\[
\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F_{\mu\nu} + \frac{1}{2} m_D^2 A^\mu A_\mu - \epsilon_D e q_{D,i} A^\mu_{D,i} \tag{19}
\]

where \( F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, m_A \) is the mass of the vector field, and \( \epsilon_D \) is the coupling constant normalized to the EM one. The dark photon field \( A_\mu \) can be approximated as a plane wave with a characteristic momentum \( k \approx m_A v_D / h \), within a coherence time \( T_{coh} \approx 2\pi h (m_A v_D)^{-1} \). The local amplitude \( A_{\mu,0} \) of the dark electric gauge field is obtained assuming an energy density, \( 1/3 m_A^2 A_{\mu,0} A^\mu_{\mu,0} \), equal to that of the local DM \( \rho_{DM} = 0.4 \text{ GeV/cm}^3 \). The time-dependent force acting on the test masses, produces a strain oscillating at the same frequency and phase as the DM field [97,107–110]. In this non relativistic scenario the contribution from the magnetic dark field is negligible if compared to the electric dark field [3]. The dark photon DM background field will generate an acceleration on each \( i \)-th test object as:

\[
\ddot{a}_i(t, x_i) = \frac{F_i(t, x_i)}{M_i} \approx \epsilon_D e q_{D,i} A(t, x_i^2) \tag{20}
\]

where \( M_i \) and \( q_{D,i} \) are the total mass and dark charge of the test mass located at \( x_i \).

This acceleration will cause a differential relative displacement between pairs of test masses along different axes that can be converted into a strain by integrating Eq. 20 twice over time. Following [107,111] the gravitational wave strain will have two contributes, one due to the deviation of the arm length due to the dark force acting on the mirrors (\( h_D(t) \)), and a second one due to the finite light traveling time in the arm (\( h_C(t) \)). These

---

3 Hence the time derivative of the time component of \( A_\mu \) is negligible relative to \( \ddot{A} \)
two contributions can be averaged over random polarization and propagation directions and their strain in SI units can be written as:

\[
\sqrt{\langle h_D^2 \rangle} = C \frac{q}{M} \frac{c e D}{2 \pi c^2} \sqrt{\frac{2 \rho_{\text{DM}}}{e} v_0} = 6.28 \times 10^{-27} \left( \frac{\epsilon}{10^{-23}} \right) \left( \frac{100 \text{ Hz}}{f_0} \right)
\]

(21)

\[
\sqrt{\langle h_E^2 \rangle} = \sqrt{3} \sqrt{\frac{2}{2} \langle h_D^2 \rangle} \left( \frac{2 \pi f_0 L}{v_0} \right) \approx 6.21 \times 10^{-26} \left( \frac{\epsilon}{10^{-23}} \right)
\]

(22)

The quantity \(C\) is a geometric factor dependent on the position and orientation of the interferometer with respect to the DM wind. The signal frequency is then determined by the dark photon mass \(f_0 = m_A c^2 / (2 \pi \bar{h})\) corresponding for Earth-based detectors to dark photon masses in the range \(10^{-14} - 10^{-11} \text{ eV}/c^2\). Given that the velocity of dark photon particles follows a Maxwell-Boltzmann distribution, the GW frequency will be broadened as:

\[
f_{\text{gw}} = f_0 + \Delta f
\]

(23)

where

\[
\frac{\Delta f}{f_0} = \frac{1}{2} \frac{v_0^2}{c^2} \approx 2.94 \times 10^{-7}
\]

(24)

Also for the dark photon DM case the Doppler shift due to Earth’s rotation is present, although the frequency shift due to this effect is an order of magnitude smaller than the one from the Maxwell-Boltzmann spreading.

**Compact dark objects and primordial black holes.** The actual formation channel for CDOs is still an open question. One option, proposed in [112], is to assume that these objects can be trapped inside normal matter via non-gravitational interactions, for instance the Sun or even the Earth [113]. If also a second CDO is trapped inside the same object, these can form a binary CDO emitting GWs with a long lifetime for low mass objects. According to [112] the number of collisions between CDOs and the Sun is not negligible for CDO masses \(\sim 10^{-10} M_\odot\). The GW signal emitted by a pair of CDOs is equivalent to the GW signal far from the coalescence of a pair of PBHs. Also PBHs can be constituent of a fraction of the DM in the Universe depending on their formation channels (see [114–117] for the latest reviews about PBHs as DM candidates). In particular the origin of most of the sub-solar and planetary mass BHs is likely to be primordial, although speculations on alternative formation channels exist, e.g. created from NSs by accumulation of DM and subsequent collapse into a BH [118]. For the context of CW signals, PBHs as well as more generic CDOs, represent new potential targets. Indeed, the GW signals emitted by these systems, when the two compact objects are far away from the coalescence, are modeled as monochromatic and are analogous to CW-like signals. This approximation is valid until the inspiral orbital do not reach the inner-most stable orbit and it is typically modelled as a power law. For the masses considered \((\leq 10^{-5} M_\odot)\), this approximation is always valid in the detector sensitivity band. In addition, if the chirp mass is small enough, the frequency can be modeled exactly as the linear frequency Taylor expansion used for standard CW searches. This means that, for instance, a pair of PBHs inspiralling far from the coalescence with chirp masses below \(10^{-5} M_\odot\) would emit a GW signal indistinguishable from those arising from non-axisymmetric rotating NSs spinning up. Let us now consider the type of emission that could be released by these systems. We can assume that the two far from the coalescence orbiting PBHs/CDOs can be approximated as a two-body problem of two-point mass objects in a circular orbit, losing energy as the inspiralling goes on. The signal model discussed in this section is widely described in classical handbook of gravitational wave science [119–121] as well as in [112,122–124]. The expected signal
strain amplitude is equivalent to that of the GW signal from a circular BH binary inspiral at a distance \( r \) identified by a chirp mass \( M \) with a time to the coalescence \( \tau = t_c - t \):

\[
h_0(t) = \frac{4c}{r} \left( \frac{G M}{c^3} \right)^{5/3} (\pi f_{gw}(t))^{2/3}
\]

(25)

The amplitude is time dependent and scales with the GW frequency, equivalent to twice the system orbital frequency. The gravitational wave frequency emitted is dependent on the system chirp mass \( M \) as

\[
f_{gw}(\tau) = \left( \frac{5}{\tau} \right)^{3/8} \left( \frac{G M}{c^3} \right)^{-5/8}
\]

(26)

In this case the expected signal frequency variation (the spin-up) due to the change in distance of the inspiralling system is given by:

\[
f_{gw} = \frac{96}{5} \pi^{8/3} \left( \frac{G M}{c^3} \right)^{5/3} f_{11/3}^{gw},
\]

(27)

Eq. 26 is derived integrating the expression for the spin-up. For the low mass considered, the frequency evolution can be simplified assuming that the observing time \( T_{obs} \) is bigger than \( \tau \) and for assuming a small chirp mass. This means that the PBH/CDO spin-up rate \( f_{gw} \) can be treated as a constant. In this case the expected signal can be linearized as \( f_{gw}(t) \sim f_0 + (t - t_0) \dot{f}_{gw} \) which coincide with the standard NS case (see Eq.29). On the other hand, if the spin-up is too high, this approximation is no longer valid and the frequency evolution should be modeled as a power-law as discussed in [124]. Also for this system the signal undergoes a daily modulation at the detector which should be considered in the analyses.

3. Type of searches

Different methods for the search of CW signals have been developed. The variety of methods reflects the different ways it is possible to look for these long-lasting signals, giving priority to the sensitivity of the pipeline or its robustness to the signal model.

3.1. The signal at the detector

CWs are by definition all those quasi-monochromatic GW signals characterized by a long duration, ranging from hours to years, and deeply buried in detector noise. When the CW signal reaches the detector, several modulation effects occur. The strain measured at the detector for a triaxial rotor is given by

\[
h(t) = h_0 \left[ F_+ (t, \alpha, \delta, \psi) \frac{(1 + \cos^2 i)}{2} \cos \Phi(t) + F_\times (t, \alpha, \delta, \psi) \cos i \sin \Phi(t) \right]
\]

(28)

here \((\alpha, \delta)\) are the right ascension and declination of the source in the sky, \(\psi\) is the polarization angle, \(F_+ / \times\) are the detector response to the two \(h_+ / \times\) polarizations and \(i\) the inclination of the rotation axis to the line of sight and \(\Phi(t)\) is the GW phase. In a more general formalism where a dual-harmonic emission is assumed, the strain at the detector has two components \(h_{21}\) and \(h_{22}\), representing the emission at \(f_{gw} = f_{\text{spin}}\) and \(f_{gw} = 2f_{\text{spin}}\), respectively (see e.g Eqs. (1) and (2) in [125]). The two harmonics are typically represented by the two amplitudes \(C_{21}\) and \(C_{22}\). Equation 28 is equivalent to the \(h_{22}\) component only, i.e. by setting \(C_{21} = 0\) and given \(C_{22} = h_0/2\). The phase of the
The gravitational wave signal is related to the frequency components \((f, \dot{f}, \ddot{f}, \ldots)\) at a given reference time \(t_0\) as

\[
\phi(t) = \phi_0 + 2\pi \left[ f(t - t_0) + \frac{\dot{f}}{2!}(t - t_0)^2 + \ldots \right]
\]

where \(\phi_0\) is an initial phase. The signal phase is modulated mainly by the Doppler, due to relative motion between the detectors and the source and other relativistic effects such as the Einstein and Shapiro delays. The frequency at the detector will be spread with respect to the emitted frequency as:

\[
f(t) = \frac{1}{2\pi} \frac{d\Phi(t)}{dt} = f_0(t) \left( 1 + \frac{\vec{v}(t) \cdot \hat{n}}{c} \right)
\]

where \(\vec{v}\) is the velocity vector of the detector, while in the \(\hat{n}\) is the unit vector pointing to the source direction, both expressed in the Solar System Barycenter (SSB) reference frame.

The phase modulation due to the Doppler Effect, apart from an irrelevant constant, can be obtained by integrating Eq. 30 as:

\[
\phi_d(t) = 2\pi \int_{t_0}^{t} f_0(t') \frac{\vec{v}(t') \cdot \hat{n}}{c} dt' \approx \frac{2\pi}{c} p_n(t) f_0(t)
\]

The pure signal strain at the detector, assuming the utopian situation where no noise is present, is depicted in Fig. 1. The figure on the left reproduces a signal as it is received at the detector, and it is visibly modulated both in frequency and in amplitude. Even after the removal of the main modulation effects, namely the Doppler and the spin-down of the source, the power spectrum reported on the right side is very different to the one produced by a purely sinusoidal signal. In the right plot, five peaks are visible and those are due to the Earth sidereal modulation. This last effect produces a splitting of the signal power among five frequencies \(f_0, f_0 \pm f_\oplus, f_0 \pm 2f_\oplus\), where \(f_\oplus\) is the Earth sidereal frequency. When the signal is buried in the detector data, it is not possible to appreciate the signal morphology by eye since it is several orders of magnitude lower than the typical data strain amplitude. For this reason, effective data analysis methods are needed to root out the signal from the noise. Some of these methods are reported in Sec. 3.2.
3.2. Search methods

Given the long-lived and weak nature of CW signals, it is intuitive to think that the
more data are used in the analysis the more signal power is integrated, increasing the
signal-to-noise ratio. For this reason many matched filtering methods have been de-
veloped to look for sources like know pulsars, where all the parameters about the source are
known. Matched filtering techniques provide the optimal detection statistics, once the
model is assumed as completely known. Typically source parameters are available from
EM observations, i.e. the source sky position and its rotational parameters are known.
In this case the so-called “targeted” searches are done using matched filtering. Several
implementation of the matched filtering techniques, also known as coherent searches,
exists based on different detection statistics or algorithms \(5\)-vector\cite{126,127} method,
\(F/B/G\) statistic \cite{128–132}, time-domain heterodyne-based pipelines (Bayesian and
Band-Sampled-Data) \cite{133–135}). In targeted searches the phase of the CWs is locked to
the rotational phase of the crust of the star and is completely defined by its EM obser-
vation. When this assumption is relaxed “narrow-band” searches are performed. This
is possible for instance when there is a differential rotation between the rigid crust and
superfluid parts of the star. In these searches a small region around the expected signal
parameters is investigated. In general a narrow-band search for a given target is less
sensitive than its respective targeted case due to the increased number of trials factors.
Many of these pipelines have been generalized to investigate a wider parameter
space. As the knowledge about the source parameters decreases, the parameter space that
is left to investigate explodes, making impractical the use of fully coherent searches\cite{136}.
For this reason many semi-coherent techniques have been developed\cite{137,138}. In a
typical semi-coherent search chunks of data are first analyzed coherently (e.g. using
matched-filter) and then combined incoherently. These searches are suitable in the
case when no EM counterpart is present, like blind all-sky search surveys for NS or
DM candidates, or when the true nature of the source is not completely known, for
instance directed searches pointing to interesting sky regions or supernova remnants
hosting potential young NS. Semi-coherent methods include the FrequencyHough \cite{139–
141}, the SkyHough \cite{142–144}, the Time-Domain \(F\)-statistic \cite{128,145,146}, Weave \cite{147},
PowerFlux \cite{148,149}, and Einstein@Home based on the global correlation transform
method \cite{150–152}. A comparison of methods for the detection of gravitational waves
from unknown NSs is given in \cite{153}.

Loosely coherent methods, like the Falcon pipeline \cite{154–156}, have been de-
volved to manage the huge computing cost of blind all-sky searches while keeping the
robustness to a wide family of signals, allowing for a small phase mismatch in the
evolution of a perfect sine wave. A different approach can be used if one wants to go
deep with the sensitivity in an all-sky search but keep the focus on a specific narrow
frequency band as described in \cite{157}. Semi-coherent or incoherent methods can be
used when no assumption on the source frequency evolution is made or it is typically
different than the standard Taylor expansion in time like in Eq. 29. These include the
hidden Markov model Viterbi tracker \cite{158–160}, the Sidereal Filter \cite{161} and cross-
correlation based methods like CrossCorr \cite{162} STAMP \cite{163}, SOAP \cite{164} or Radiometer
\cite{165}. Some of these methods – CrossCorr method \cite{166}, Viterbi/F-statistic method
\cite{167}, the 5-vector binary method \cite{168} and the method in \cite{73} have been adapted
for the low-mass X-ray binary searches such as Sco-X1, where also the orbital modu-
lation needs to be considered and a stochastic spin wandering, including spin-up, is
assumed. Methods specifically tailored for all-sky searches for unknown binaries are the
BinarySkyHough \cite{169} and TwoSpect \cite{170}. Different flavours of the above-mentioned
techniques have been adapted for the case of long-transient CW signals \cite{171–177} and
glitching pulsars \cite{178,179}, ensemble of pulsars \cite{132,180,181} or DM candidates \cite{182–
184}. Furthermore, several methods have been developed for the search of CW signals
using machine learning \cite{185–191}. For the latest review on CW methods and searches
see \cite{7,9,11}. 


In general all these pipelines produce the so-called search candidates, i.e. potential astrophysical signals that need to be investigated in detail. These candidates undergo a series of post-processing veto steps and then, the most interesting ones, are followed up with different techniques in order to clearly establish their significance, e.g. [191–202].

A good fraction of these candidates is vetoed if found near known instrumental artifacts, also known as spectral lines, typically present in the detectors [203]. Multiple approaches exist for this part of the analysis to discard or pass the outliers to the follow-up stage, as described in [7]. Sometimes the assessment of the real origin of an outlier is the most difficult (and time-consuming) part of the analysis, but in general for most of the follow-up techniques the final goal is to check if the outlier significance follows an expected theoretical trend. This is achieved, for instance, by checking if the outlier signal-to-noise ratio grows as more data are used to analyze that candidate or increasing the coherence time or by using machine learning techniques (see Sec. 4 in [7]). If all the outliers are discarded from being real astrophysical signals during the follow-up stage, no CW signal detection can be claimed. In this case, typically upper limits on the signal strain are provided. These curves usually span the full frequency range investigated in the search. For a given confidence level, the upper limit curve determines a watershed on the signal amplitude $h_0$ above which it is possible to exclude the existence of CW signals. These curves are estimated using a tremendous number of simulated signals added to the data or via less computationally expensive methods based on analytically derived or scaling formulas (the most famous being the sensitivity depth [200,204], see also [205,206]). In addition to giving an estimate of how deep a given search can look for a CW signal, upper limits are often used to set astrophysical constraints on some related quantities according to the type of search performed. Typical constraints derived from upper limit curves are those on the ellipticity of the spinning NS (or the quadrupole $Q_{22}$) or the $r$-mode amplitude $a$. In searches looking for DM candidates these limits can be converted e.g. coupling constant, mass exclusion regions, merging rates and abundances.

According to population studies, an order of $10^6$ NSs are expected to exist in our Galaxy. Only a small fraction of the expected population has been detected electromagnetically or has an associated EM counterpart [207]. Furthermore a good fraction of these sources is in a binary systems as reported by the ATNF catalog [208]. Information provided by astronomers is used to constrain the investigated parameter space. In this sense, CW searches have a strong multi-messenger approach. EM information is fundamental for the search of known pulsars, but it provides interesting inputs for the search of new sources, like supernova remnants potentially hosting a NS, as well as updated information about these sources. In particular, the detection of CWs from a particularly interesting sky region or source represents a real discovery; given the long-lasting nature of the signal EM observation following the detection could be carried out for a long time. On the other hand, the discovery of EM dark sources, including DM candidates, will provide a new tool for the study of a new population of astrophysical sources, as well as contribute to solving many of the open questions about our Universe.

4. Recent results

Since the beginning of the Advanced detector era, the interest with respect to CW sources has increased, as probed by the increasing number of publications on this topic over the years. Boosted by the enhancement of the sensitivity of the detectors, a completely new family of searches has taken place, showing the strong versatility of the search methods developed for CW searches. I briefly review the most recent search results for CW signatures in Advanced detector data from the latest three observing runs. The latest O3 dataset started on April 1, 2019, 15:00 UTC and finished on March 27, 2020, 17:00 UTC. In the following we refer to the period 1 April 2019 - 1 Oct 2019 as O3a, while the second part of O3, O3b, starts on the 1st November 2019 after a month-long commissioning break. During the Advanced detector era, other two previous runs took
place. The first observing run (O1) started on September 11, 2015 and finished January 19, 2016. The second observing run (O2) lasted from November 30, 2016 to August 25, 2017. During O1 only the two LIGO interferometers were taking data, while during O2 Advanced Virgo joined the run at the beginning of August 2017.

4.1. Results from known sources (pulsars, LMXBs, supernova remnants)

In this section I review the latest results for searches of CW from known sources or sources with an EM counterpart even if not completely identified, such as the central compact objects in supernova remnants.

**Known pulsars:** Targeted searches are the most sensitive methods to look for persistent signals from known pulsars. These searches strongly rely on the EM information available about the source. Indeed, in these searches the GW phase evolution is completely determined by the EM observations of the rotational parameters of the star. This in principle gives a full picture of the GW emission model happening in the star. A slightly different method, known as narrow-band, is sometimes applied if the coupling between the GW and EM signal phase evolution is relaxed. This allows for a more general scenario and typically a small region around the expected GW frequency and spin-down is investigated. The latest extensive search for CW from known pulsars is reported in [209]. In this work 236 pulsars have been analyzed, among which the Crab and the Vela pulsars, using LIGO and Virgo O3 data combined with O2 data. Several pulsars glitched during the considered runs and some have sufficient information from EM observations on their orientation to restrict their priors. The ephemerides come from the observations from the CHIME, Hobart, Jodrell Bank, MeerKAT, Nancay, NICER and UTMOST observatories. The search was run using three independent pipelines: the Time-domain Bayesian method [133,134], the F/G/D-statistic method [77,128,131] and the 5-vector method [126,127]. The Bayesian and F/G/D-statistic methods searched for the standard single harmonic emission from the $l = m = 2$ mass quadrupole mode with a frequency at twice the pulsar rotation frequency. In addition, these pipeline assumed a dual harmonic emission scenario, i.e. the $l = 2; m = 1, 2$ modes with a GW frequency at once and twice the rotation frequency [78,210]. To complete the search, the 5-vector method limited the search to the single harmonic scenario but at the $l = 2; m = 1$ mode only, hence assuming a GW frequency at the star rotation frequency. Furthermore, the D-statistic, has been used to test the dipole radiation as predicted by Brans-Dicke theory [74,77]. No GW detection has been reported and upper limits on the strain are given in Fig. 2. Blue stars indicate the upper limit of a given pulsar, those with upper limits below the spin-down limit (see Eq. 10) are marked with yellow circles. Grey triangles mark the spin-down limit of each pulsar. From the figure, 23 out of the 236 pulsars have strain amplitudes lower than the limits calculated from their electromagnetically measured spin-down rates. Among these, 90 millisecond pulsars have a spin-down ratio less than 10, like J0437-4715 and J0711-6830, with spin-down ratios of 0.87 and 0.57 respectively. For the Crab and Vela pulsars these limits are factors of ~ 100 and ~ 20 lower than their spin-down limits, respectively. Nine of these 23 pulsars beat their spin-down limits for the first time. The pulsar with the smallest upper limit on $h_0$ was J1745-0952 with $4.72 \times 10^{-27}$. The best $Q_{22}$ upper limit was achieved by J0711-6830 with $4.07 \times 10^{29}$ kg m$^2$, equivalent to a limit on the ellipticity of $5.26 \times 10^{-9}$. This result is lower than the maximum values predicted for a variety of NS equations of state [57]. Concerning the dual harmonic search, the most constraining upper limit for $C_{21}$ was $7.05 \times 10^{-27}$ for J2302 + 4442. The stringent $C_{22}$ upper limit was $2.05 \times 10^{-27}$ for J1537 − 5312. A previous search using O1 and O2 data on 222 pulsars is given in [211]. In that search the percentage of GW emission making up the spin-down luminosity for Crab and Vela pulsars was less than 0.017% and 0.18% respectively. In the latest search [209] these numbers decrease to 0.009% for Crab but increased for Vela up to a maximum of 0.27%. This result is due to the presence of a significant noise line in the LIGO Hanford detector at twice Vela’s rotational frequency. The search in [211] is an
improvement of the result of the previous 'CW pulsar catalog' collecting the results of targeted searches for 200 pulsars in O1 data [212].

Test for non-GR polarizations are also provided for the 23 pulsars investigated in [209], checking for the additional non-negligible scalar radiation originated from the time dependent dipole moment [77]. No deviation from GR has been reported and the stringent upper limit for dipole radiation is obtained for the millisecond pulsar J0437-4715. A previous test on GR from known pulsar searches, not assuming any particular alternative theory of gravity, is given in [213] using O1 data.

A separate dual harmonic search has been performed on the same dataset (O2+O3) for the energetic young pulsar and frequent glitcher PSRJ0537-6910 in [214]. No CW signal has been detected in this search but, for the first time, the spin-down limit for this type of emission on this source has been surpassed. Results show that gravitational waves from the $l = m = 2$ mode contribute to less than 14% of the spin-down energy budget. The same target has been investigated by other two searches, tuned for $r$-modes oscillations, using ephemerides from NICER [215] in O3 [216] and O1+O2 [217] data. As discussed in Sec. 2.1, the relation between the gravitational-wave frequency and the star spin frequency in $r$-mode emission scenarios, strongly depend on the NS structure.

For this reason both searches assumed the frequency evolution model proposed in [218]. Searches for $r$-mode emission from PSRJ0537-6910 are motivated by the fact that this pulsar shows a trend in the inter-glitch behavior that suggest an effective braking index close to $n = 7$ at long times after the glitch [219,220]. A braking index of 7 is expected for a spin-down dominated by the $r$-mode emission. Amplitude upper limits in [216] improve existing results by a factor of up to 3, placing stringent constraints on theoretical models for $r$-mode driven spin-down in PSR J0537-6910. Another search for $r$-mode emissions for the Crab pulsar is reported in [221], providing for the first time upper limits beating the spin-down limit for this source/type of emission in O1 plus O2 data.
Five sources have been the target of a previous single and dual harmonic search for known pulsars [125]. These pulsars have been analyzed in the data from the first two and the first half of the third observing run of advanced detectors (O1+O2+O3a). The targets included three recycled pulsars (J0437-715, J0711-6830, and J0737-3039A) and the two young famous pulsars Crab and Vela. For Crab, Vela and J0711-6830 also a narrow-band search has been performed using the 5-vector narrow-band method [222,223]. Results from this work constrain the equatorial ellipticities of some of the targets to be less than $10^{-8}$ and, for the first time, it is reported an upper limit below the spin-down limit for a recycled pulsar. This latter aspect is interesting since the evolutionary history of a recycled pulsar is connected to an early accretion phase from a binary companion, very different to the case of young and more slowly spinning pulsars. Another set of seven recycled pulsars is investigated in [224]. The timing information is provided by the Arecibo 327 MHz Drift-Scan Pulsar Survey and the search is performed on O1+O2+O3a data. All the targets, except for the millisecond pulsar J0154+1833, are in binary systems. An interesting source is the double-neutron-star system PSR J1411+2551. The stringent constraint on the ellipticity is $1.5 \times 10^{-8}$ for PSR J0154+1833. Data from Fermi-LAT observations have been used in the search for CW from single harmonic emission from PSR J0952-0607 [225] and dual-harmonic emission from PSR J1653-0158 [226], using data from O1 and O2. The results of the search for CW signals from ten sources, associated with TeV sources observed by the High Energy Stereoscopic System (H.E.S.S.) are reported in [227]. All the sources are associated with isolated NSs and with estimated distances up to 7 kpc. In particular, two targets are γ-ray pulsars while eight H.E.S.S. sources are pulsar wind nebulae powered by known pulsars. The ephemerides for each pulsar are provided by the Australian Telescope National Facility (ATNF) pulsar catalogue. The search is performed using O2 data and tracks, with a hidden Markov model, the three GW frequencies expected to be at once, twice and 4/3 of the source spin frequency in a narrow band of 1 Hz around each multiple. The latest results from the O3 fully coherent narrow-band search can be found in [228]. The search looks for CW from 18 pulsars using the 5-vector and F-statistic narrow-band pipelines. For seven of these pulsars the upper limits are lower than their spin-down limit. These results overcome the corresponding ones from the narrow-band search in O3a [125] improving the upper limits by a factor $\sim$ 35% for the Crab pulsar, and $\sim$ 10% for Vela and J0711-6830 pulsars even if the parameter space investigated in this search is 6.5, 1.2 and 7.1 times larger. Results from an additional search for long-duration transient gravitational waves after pulsar glitches are also reported in [228]. Six targets have been investigated by the long-transient search, performed using the transient F-statistic method [173,229]. For these six sources, showing a total of nine glitches, independent long-transient search is performed after each glitch. None of these targets, neither from the narrow-band or long-transient search, produced an outlier significant enough to be considered as a signal, although two marginal outliers are reported for the last glitch of J0537-6910. The transient F-statistic method has been applied for the search of long-duration transients after glitches in the Vela and Crab pulsars in O2 data [230]. Previous narrow-band searches using O2 and O1 data are given in [231,232].

**Supernova remnants:** another family of interesting targets with EM counterparts but without precise timing of the pulsations are the supernova remnants. Supernova remnants may host young neutron stars, excellent targets for the search of CW. Given the lack of information on the spin frequency of the central compact object inside the nebula, directed searches are performed. In these searches the only information assumed as known is the source sky position, while the remaining parameters ($f_{gw}$, $f_{gw}$, ... ) are investigated in a wide range. The choice of the parameter space to investigate is only limited by the computing cost of the search, and this may vary from each pipeline. With a limited amount of computing power, some regions may have a higher priority over the full GW sensitivity band [233,234]. No CW detection is reported from these sources.
Searches for supernova remnants in LIGO-Virgo O3a data are reported in [235,236]. To date results in [235] are the most stringent for the source targeted: Cassiopeia A (Cas A), G11.7-2.1 and Vela Jr. (G266.2-1.2) supernova remnants. Both sources are extremely young, with inferred lower estimate ages of ~ 300 years for Cas A, and ~ 700 years for Vela Jr. With these assumptions, these targets have a corresponding indirect age-based limit (see Eq. 11) of ~ 1.2 × 10^{-24} for the central compact object in Cas A, assuming a distance of 3.3 kpc, and 1.4 × 10^{-23} for Vela Jr. if located at 0.2 kpc. The search is based on the semi-coherent Weave method [147]. No gravitational wave signal is detected in the analyzed band and the best sensitivity to the signal strain amplitude reached in this search is ~ 6.3 × 10^{-26} for Cas A and ~ 5.6 × 10^{-26} for Vela Jr., well below their age-based upper limit. A comparative plot is shown in Fig. 3 showing also the upper limits provided by the searches in [235–237]. In the search reported in [236], three complementary pipelines have been used: the Band-Sampled-Data directed pipeline, the single harmonic Viterbi and the dual harmonic Viterbi pipelines. Each pipeline used different signal models and methods of identifying noise artifacts. In particular the two Viterbi pipelines are robust to sources with spin wandering. This search targets a total of 15 supernova remnants, including Cas A, Vela Jr. and G347.3-0.5. These three targets have been analyzed also in the Einstein@Home search in [238] using O1 data. The most interesting candidates of this search have been followed up in O2 data, along with new sub-threshold candidates of the same O1 search [237]. A full deep search for CWs from G347.3-0.5 in the frequency band below 400 Hz in O2 LIGO data is provided in [239]. This choice is justified by the existence of a sub-threshold candidate at around 369 Hz survived from the search in [237]. The same candidate has been further investigated with a MCMC method in O2 data [193]. Any significant result has been reported from this search in O2 data hence upper limits are provided, improving those from the same search in O1 data and those from the more robust single harmonic Viterbi tracker in O3a [236].

For the closest target Vela Jr. the best upper limit in [236] is 8.2 × 10^{-26} for the BSD pipeline. This results is more constraining than those set by [237,238], however it is less stringent than the results in [235] by a factor of 30% (see Fig. 3). It should be noted that the searches in [237,238] used O1 and O2 data, while the searches in [235,236] used data from detectors with improved sensitivity (O3a). However the O1 search in [237,238] use a coherent integration duration ~ 20 – 150 times longer than the one in the BSD search in [236], while the Weave search in [235] used a coherence length 10 – 70 times longer. This guarantees a starting sensitivity gain of a factor 1.7-2.9 and 2.1-3.5 for [235] and [237,238], respectively. On the other hand, the use of longer coherence times corresponds to an increase in the computing power needed for the search, as it scales at least as the fourth power of the coherence time. This makes clear that different approaches are needed when wide parameter space searches are performed, choosing the right balance between computing cost, robustness and sensitivity.

Previous searches for CW from some of the targets in [236] are presented in [240,241] using LIGO O2 data, although using respectively a fully coherent method and a less sensitive but model robust Viterbi tracker. A previous fully coherent O1 search is given in [242], listing among the targets the also the extrasolar planet candidate Fomalhaut b suggested to be a nearby old NS. This latter is investigated in [243] using a hidden Markov model Viterbi tracker.

**Low-mass X-ray binaries and Sco-X1:** A significant fraction of observed known NS is in a binary system. Among these, LMXBs are of particular interest for CW searches. Indeed, the presence of a GW torque could explain why the maximum observed spinning frequency 716 Hz for PSR J1748-2446ad is well below the centrifugal break-up frequency, estimated at ~ 1400 Hz. These systems are typically formed by a NS (or stellar-mass BH)

---

[1] The ranges are due to fact that the coherence time used in [236] changes in each 10Hz frequency band.
and a low mass (\( \leq 1 M_\odot \)) stellar companion. A recent search for CWs from 20 accreting millisecond X-ray pulsars in O3 data is given in [244]. Five of these 20 accreting pulsars have been already analyzed with the same method in O2 data[245]. The search relies on the EM observation of the spin frequencies and orbital parameters of the system happening during the active outburst phase. The algorithm uses a hidden Markov model (implemented via Viterbi) to track spin wandering[158], and combines its results with the J-statistic to account for the orbital phase modulation[167]. For each target the search looks for a CW signal in sub-bands around \( \{1, 4/3, 2\} f_{\text{spin}} \). One of the targets, SAX J1808.4-3658, went into outburst during O3a. Given that, according to some models, CWs are only emitted during this outburst phase [246], an opportunistic search for SAX J1808.4-3658 is also provided in [244]. No significant candidates are reported from this search. However, upper limits have been placed on the GW strain amplitude with 95% confidence level. The strictest constraint is \( 4.7 \times 10^{-26} \) from IGR J17062-6143. The stringent constraints on the ellipticity for the \( f_{\text{gw}} = 2f_{\text{spin}} \) case is \( \epsilon_{95\%} = 3.1 \times 10^{-7} \) for IGR J00291+5934 source. The corresponding upper limit on the r-mode amplitude (\( f_{\text{gw}} = \frac{4}{3} f_{\text{spin}} \)) is \( \alpha_{95\%} = 1.8 \times 10^{-5} \) for the same source.

To date several searches have targeted Sco X-1 [247–250] in advanced detector data. The latest results using O3 data are reported in [251]. Sco-X1 is a very interesting candidate for CW searches since it is the brightest extra-Solar x-ray source in the sky which means that it is potentially an optimal source of GWs[252,253]. The system is composed by a 1.4 \( M_\odot \) NS and a 0.7 \( M_\odot \) companion star [254]. Although being a known source, no EM measurement of the rotation frequency and frequency derivative exist for Sco-X1. In addition to these uncertainties, some of the binary parameters are unknown, making the search for this source very computationally challenging. To date no CW is reported for this source, while the torque-balance limit (see Eq. 12) has been beaten for the first time in [247], using CrossCorr method[166,255] in O2 data. The best constrain are as low as \( 7.06 \times 10^{-26} \) assuming a NS spin inclination \( \iota = 44^\circ \pm 6^\circ \) [254,256]. To date none of the searches beats the limit, if an isotropic prior on \( \iota \) is made, as reported in Fig. 4. A different method has been used in the latest search for Sco-X1 in O3 [251].
Figure 4. GW strain upper limits at 95% confidence as a function of frequency. No assumption on the $\iota$ angle is done for the curves in figure. The curves are for the CrossCorr O1 search [250](black line), the CrossCorr O2 search [247](brown line), the Radiometer O3 search [257] (light pink line), and the O3 hidden Markov model search [251](green line). The indirect torque-balance upper limits (see Eq. 12), for the $r_m = R$ case (red solid line) and for $r_m$ equal to the Alfven radius (dashed red line), are also plotted. Figure taken from [251].

This method although being less sensitive than the cross-correlation search provides a complementary tool to CrossCorr results. The upper limits from the O3 search are on average $\sim$ 3 times lower than those from the O2 hidden Markov model search [249] and 13 lower than the same search in O1 data [248]. Previous searches using O1 data and the hidden Markov model and CrossCorr methods are reported in [248,250]. In O3 the lowest $h_{95}^0$% for a hidden Markov model tracked signal are $4.56 \times 10^{-26}$, $6.16 \times 10^{-26}$, and $9.41 \times 10^{-26}$ for circular ($\iota = 0^\circ$), electromagnetically restricted ($\iota = 44^\circ$) and unknown polarizations, respectively. Also for the hidden Markov model search the torque balance limit is beated for a fixed $\iota$ below 200 Hz and for $r_m$ equal to the NS radius or the Alfven radius [248].

By beating the torque balance limit for $r_m$ at the Alfven radius, is possible to identify some exclusion region over the mass-radius-magnetic field combination for some equations of state models (see [247] for a discussion). Constraints in the mass-radius plane are also possible when $r_m$ equals the NS radius.

4.2. Results from unknown sources (all-sky, spotlight surveys, dark matter candidates)

In the absence of EM driven information, wide parameter space searches for unknown sources allow scouring the whole sky in search for EM silent sources. These searches include blind all-sky surveys for isolated NS and NS in binary systems. It is also usual to look for CWs from a specific and over-populated region in the sky, like the Galactic Center or some globular clusters. In these cases sometimes the information provided by EM observations is not enough to distinguish the exact population of the analyzed region and GW could help in this direction. Finally, through gravitational waves, we could also look for DM candidates.

All-sky surveys. The latest results for all-sky surveys using LIGO-Virgo O3 data are reported in [258] and a summary of the results can be found in Fig. 5. Four different analysis methods are used to look for signals from isolated non-axisymmetric NSs:
the FrequencyHough [139], Sky-Hough [142], Time-Domain F-statistic [128,259], and SOAP [164], for the first time applied in an all-sky CW search. The frequency investigated ranges from $10$ to $2048$ Hz and from $-10^{-9}$ to $10^{-9}$ Hz/s for the first frequency derivative, each pipeline covers a subset of this parameter space except for the FrequencyHough. The frequency range is wide enough to cover most of the expected sources: young and energetic NS, millisecond pulsars and signals from r-mode oscillations. Although not directly searched by none of the pipelines, the search results are generic and, independently of the emitting source, are valid for any quasi-monochromatic, persistent signal characterized by the parameters investigated in this search following the linear phase evolution in Eq. 29. Constraints the rate and abundance of inspiraling planetary-mass and asteroid-mass PBHs are also discussed in this search.

### No CW observation

The latest search, run using O3a data [269,270] placed upper limits on the strain at $2.4 \times 10^{-25}$ in the 100-200 Hz frequency range. This is the first all-sky search using Advanced Virgo data. A previous search using the PowerFlux pipeline on O3a data [149], provided an upper limit on the strain for the most favorable orientation of $6.3 \times 10^{-26}$, improving previous results from O2 data. If compared with the population averaged upper limit, the lowest 95% C.L. in O3a is $1.4 \times 10^{-25}$, less constraining than the full O3 search in [258] (see Fig. 5). Results from this search have been used to constrain the rate and abundance of inspiraling PBHs in [260]. To date only the O2 Falcon search beats the upper limits in [258], although the frequency derivative range is at least $10^3$ smaller, making the results in [258], de facto the most stringent limits for sources with spin-down as low as $-1 \times 10^{-8}$ Hz/s in the 20 – 2000 Hz frequency range. Upper limits on the ellipticity are also derived in [258]. The search is able to detect nearby sources, within 100 pc, with ellipticities above $3 \times 10^{-7}$ emitting at 200 Hz, or even ellipticities as low as $\sim 2 \times 10^{-9}$ for sources spinning at the highest frequencies. For sources located as far as the Galactic Center region (8-10 kpc) the search is able to detect signals with ellipticities bigger than $\sim 3 \times 10^{-6}$ for frequencies above 1500 Hz. Probing very small ellipticities with such a wide parameter space search, certainly goes in the right direction for a detection. Indeed, ellipticities below $10^{-7}$ are in the expected range of sustainable strains in NS crusts [52,54,56–58]. Previous searches performed using O2 data are given in [261–265] and O1 searches can be found in [266–268].

No CW detection is reported neither from all-sky searches for unknown NSs in binary systems. The latest search, run using O3a data [269,270] placed upper limits on the strain at $2.4 \times 10^{-25}$ for NSs in binary systems spanning orbital periods of 3 - 45 days. The search, carried out using the BinarySkyHough pipeline, is the update of the all-sky binary survey presented in [271], improving the results by a factor of 1.6. A good fraction of known NS is in a binary system. Despite this, no other all-sky search, specifically tailored for unknown binaries, has been carried out in advanced detector data. The main reason for this lack is due to the huge computing cost associated with these searches, significantly overcoming the already computationally demanding all-sky searches for isolated NS. However according to [272], for some combinations of the binary period and semi-major axis parameters, results from wide parameter space searches for unknown isolated sources are also valid for the binary case.

### Spotlight surveys: the Galactic Center and Terzan 5

Directed searches targeting interesting sky regions like the Galactic Center and the globular cluster Terzan 5 have been carried out in advanced detector data. Indeed, concerning the Galactic Center, a significant population of up to hundreds or even thousands of NSs is expected to exist [273,274]. Moreover, the true composition of this region, showing an extended gamma-ray emission from its center [275–277], is still under debate and could be explained for instance by the presence of an unresolved population of millisecond pulsars [278–282]. To date, the latest search for CW from the Galactic Center looks for signals

---

5 except for the SOAP pipeline that covers the additional small region [1000;2048] Hz in frequency and $[10^{-5};10^{-8}]$ Hz/s in spin-up
in the frequency range \([10 - 710]\) Hz in O2 data \([283]\). The search looks for CW signals from NS located within 25-150 parsecs from the Galactic Center. The spin-down range covered in this search range from \(-1.8 \times 10^{-9}\) Hz/s to \(3.7 \times 10^{-11}\) Hz/s. The search uses a semi-coherent method based developed in the Band-Sampled-Data framework. No continuous wave signal has been detected and upper limits on the gravitational wave amplitude are presented. To date, this search reports the most stringent upper limit at 95% confidence level for frequencies below 500 Hz, with a minimum strain of \(\sim 1.4 \times 10^{-25}\) at 160 Hz. A previous search for CW from the Galactic Center and Terzan 5 is reported in \([284]\) using O1 data. The search, based on a loosely coherent method, looks for signals emitting at frequencies in the range \([475 1500]\) Hz and with frequency time derivatives in the range \([-3.0; 0.1]\) \(\times 10^{-8}\) Hz/s. O3 data have been already used to make a lower sensitivity search for an unresolved GW emission from the Galactic Center region using stochastic GW searches methods \([257]\). An older search for this region has been performed in the fifth LIGO scientific run \([285]\). Updated results using specifically tailored CW methods in O3 data are in preparation.

**Dark matter candidates - ultralight bosons and CDOs.** Methods for the search of CW from NSs can be easily adapted to any kind of GW signal with features similar to the standard NS case. An emerging family of searches is the one for DM candidates. This branch of investigations through CW tools is very immature when compared e.g. with known pulsars searches. Nevertheless, some searches have been carried out in advanced detector data. In sec. 2.2, the major DM systems investigated in CW searches have been described: boson clouds around spinning BHs, ultralight vector bosons and CDOs.

The first all-sky survey for persistent, quasi-monochromatic GW signals emitted by ultralight scalar boson clouds around spinning BHs is reported in \([286]\). The search analyzed the frequency range \([20; 610]\) Hz of the O3 observing run of Advanced LIGO. According to the expected spin wandering signal model from boson clouds, a small range around the \(f_{GW}\) parameter has been considered. The main search has been carried out using the method in \([182]\) and the most interesting candidates have been followed up with a FrequencyHough based method and the Viterbi method. No potential CW candidate remains after the follow-up and upper limits on the signal strain are provided at 95% confidence level. The minimum value is \(1.04 \times 10^{-25}\) in the most sensitive frequency region of the detectors \(\sim 130\) Hz. These upper limits on the strain can be
translated into exclusion regions in the BH-boson cloud mass plane, after assuming some parameters of the BH population: the age of the source, its distance and its spin. Along with these exclusion regions, it is possible to derive the 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 (see Figure 6). In other words, these maximum distances tell us how far we can exclude the presence of an emitting system according to the null detection results obtained by the search. These constraints have been computed simulating a BH population with masses in the range \([5 - 100]\ M_\odot\) and a uniform spin distribution in the range \([0.2; 0.9]\). The maximum distance corresponds to the distance at which at least 5\% of the simulated signal produces a strain amplitude higher than the upper limits of the search, meaning that would have been detected. The paper in [286] also report the same figure but for a BH population with maximum masses of 50\ M_\odot. These constraints strongly depend on the ensemble properties of the simulated BH population. The plot in Fig. 6 shows that the presence of systems younger than \(10^3\) yrs is disfavoured within the Galaxy, if formed by bosons with masses above \(1.2 \times 10^{-13}\) eV, for the considered BH mass distribution. Older systems, which produce a smaller strain amplitude, are more difficult to constraint.

The search in [286] is the first of this type, all-sky type and optimized for frequency wandering signals, although it is possible to compute the same exclusion regions of the BH / scalar boson mass parameter space also using upper limits from blind all-sky searches for spinning NSs as in [93]. A previous directed search for boson clouds from Cygnus X-1 was performed in O2 data in [287] using the same Markov model Viterbi method applied for the follow-up of the all-sky boson cloud O3 search [286].

Another potential candidate for CW signals, in the subset of the ultralight DM particles with masses \(10^{-14} - 10^{-11}\) eV/c\(^2\) is a vector boson, the dark photon, which directly couples to GW interferometers (see Sec. 2.2). The latest O3 LIGO-Virgo data all-sky search for CW signature from this type of system in provided in [111]. The boson mass range probed by this search is \([2 - 4] \times 10^{-13}\) eV/c\(^2\) corresponding to the detectors frequencies [10 - 2000] Hz. The search applies two complementary methods. One pipeline is based on a cross-correlation method[97] and already used in a previous dark photon DM O1 search [108]. The second is a semi-coherent method [184] based on
the Band-Sampled-Data framework[135] and adapted from the one used in the latest O3 BH-boson cloud search [182,286]. No evidence of DM signatures has been found and upper limits on the signal strain are derived. These limits can be converted into upper limits on the coupling factor of the interaction between the dark photon and the baryons in the detector. These constraints surpass the ones provided by existing DM experiments, such as the Eöt-Wash torsion balance[288] and MICROSCOPE[289], and improve previous O1 results by a factor ~ 100.

Searches for CW signatures from a pair of CDOs or PBHs far from the coalescence are also possible. The only actual search for systems with a frequency and amplitude evolution described by Eq.s 26 and 25 has been performed in O1 data [112]. How these CDOs can be formed is still under debate, one option is to assume that these objects can be trapped by normal matter, for instance a planet or even the Sun. Once these objects are formed, binaries can form if orbiting close enough to each other. CDOs emitting GWs from the inspiral phase inside a solar system object should be very dense and in a very close binary orbit. The search in [112] searches for CW signals from CDOs orbiting near the center of the Sun in the GW frequency range 50-550 Hz. No signal is claimed and upper limits are provided. These limits are converted into upper limits on the mass of CDOs. For almost the full frequency range investigated these limits are below $10^{-9} M_\odot$ with a minimum value of $5.8 \times 10^{-10} M_\odot$ at 525.5 Hz.

Constraints on the rates and abundances of nearby planetary- and asteroid-mass primordial BHs are provided in [258] and [260]. These constraints are mapped from the upper limits strain results of the O3a Powerflux search and the O3 FrequencyHough search with minimal modelling assumptions on the PBH population. As anticipated in the previous paragraph, the search in [258] targets CW from unknown NS, but the results can be generalized for the case of CDOs or PBHs far from the coalescence as far as they follow a linear frequency evolution. In principle this search is able to probe GW signals below 250 Hz from inspiralling PBHs binaries with chirp masses smaller than $O(10^{-5}) M_\odot$. The constraints obtained from the latest full O3 search in [258] are more stringent than those presented in [260] from the O3a search thanks to the use of a longer observing time. Unfortunately, none of these results are stringent enough to be able to constraint the merging rate of PBHs, but will certainly be interesting for future third generation of detectors [290,291].

5. Conclusion

During the last years we have witnessed the huge impact that GW science had on our understanding of the Universe. Each detection has provided an interesting tool to test what already is known, but mostly the unknown, about these fascinating compact objects able to emit GWs. The main actors in these scenes have been the well known CBC events, either as a pair of BHs or a system involving at least a NS. We have witnessed the birth of the so-called multi-messenger astronomy, an incredibly powerful way to depict the details of a binary NS merger through EM, neutrino and particle astronomy. But this is just the beginning, indeed the increase in the detectors’ sensitivity, expected for the upcoming fourth observing run, along with the improvement of existing pipelines, will certainly bring to the discovery of even more fascinating and unexpected phenomena.

In this scenario, CW signals can be the next surprise in GW astronomy. A CW detection from NS could provide evidence for star deformations and shed light on the NS structure and their thermal, spin, and magnetic field evolution. On the other hand, if the CW detection happens to be in the case of a DM candidate like from a boson cloud around spinning BH, this will lead to the first direct evidence of the existence of DM, solving one of the most intriguing open problems of astrophysics.

Unfortunately, to date any search has been able to find strong evidence of GW emission from CW sources. However, an increasing number of known pulsars is surpassing their spin-down limit. The lowest constraints on the equatorial ellipticities are
very close to realistic expectations for normal EOS. A comment is probably necessary to explain why, even using the most sensitive pipelines for CW searches, any GW has been observed from these sources. It is not unlikely that the assumed models are not well representative of the realistic emission scenario happening for CW, in particular for NS. This is the main reason why, along with improvements in the pipelines sensitivity, many approaches tend to improve the pipelines robustness with respect to the model. The final answer to this long-debated issue of the existence (or not) of CW signals is probably behind the corner and the upcoming O4 run is expected from a wide community of scientists to finally solve this unanswered question. Even if no detection happens during O4, a new generation of detectors – Einstein Telescope, Cosmic Explorer, LISA and more [290–295] – will start their observation in the future, providing even more interesting detection scenarios.

Funding: This work was supported by the L’Oréal-UNESCO fellowship for Women in Science.

Acknowledgments: I thank the Continuous Wave working group and the LIGO-Virgo-KAGRA Collaboration for the material used in this review.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>NS</td>
<td>Neutron Star</td>
</tr>
<tr>
<td>EOS</td>
<td>Equation Of State</td>
</tr>
<tr>
<td>DM</td>
<td>Dark Matter</td>
</tr>
<tr>
<td>BH</td>
<td>Black Hole</td>
</tr>
<tr>
<td>PBH</td>
<td>Primordial Black Hole</td>
</tr>
<tr>
<td>GW</td>
<td>Gravitational waves</td>
</tr>
<tr>
<td>EM</td>
<td>Electromagnetic</td>
</tr>
<tr>
<td>LMXB</td>
<td>Low-Mass X-ray Binary</td>
</tr>
<tr>
<td>O1</td>
<td>Observing Run 1</td>
</tr>
<tr>
<td>O2</td>
<td>Observing Run 2</td>
</tr>
<tr>
<td>O3</td>
<td>Observing Run 3</td>
</tr>
</tbody>
</table>

References


1070. Lockitch, K.H.; Friedman, J.L.; Andersson, N. Rotational modes of relativistic stars: Numerical results.


1074. Mastrano, A.; Melatos, A.; Reisenegger, A.; Akgün, T. Gravitational wave emission from a magnetically deformed non-barotropic neutron star.


1080. Ushomirsky, G.; Cutler, C.; Bildsten, L. Deformations of accreting neutron star crusts and gravitational wave emission.

1081. Shapiro, S.L.; Teukolsky, S.A. Black holes, white dwarfs, and neutron stars: the physics of compact objects; 1983.


1084. Ushomirsky, G.; Cutler, C.; Bildsten, L. Deformations of accreting neutron star crusts and gravitational wave emission.


108. Guo, H.K.; Riles, K.; Yang, F.W.; Zhao, Y. Searching for dark photon dark matter in LIGO O1 data. *Communications Physics* 2019, 2. doi:10.1038/s42005-019-0255-0.


270. Tenorio, R.; Collaboration, L.S.; Collaboration, V. An all-sky search in early O3 LIGO data for continuous gravitational-wave signals from unknown neutron stars in binary systems, 2021, [arXiv:gr-qc/2105.07455].

