Unveiling the presence of Continuous Gravitational Waves in the Advanced Detector Era

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SAPIENZA
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11th Iberian Gravitational Waves meeting

https://www.uv.es/igwm2021/program.html

INFN
Istituto Nazionale di Fisica Nucleare

LIGO
VIRGO

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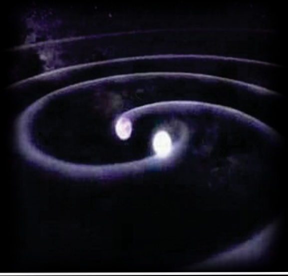
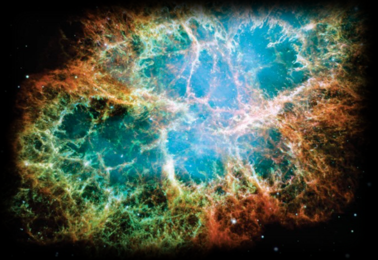
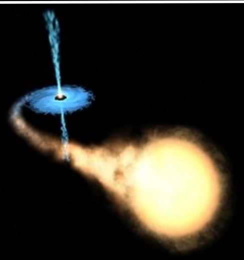
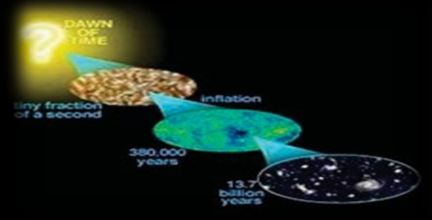
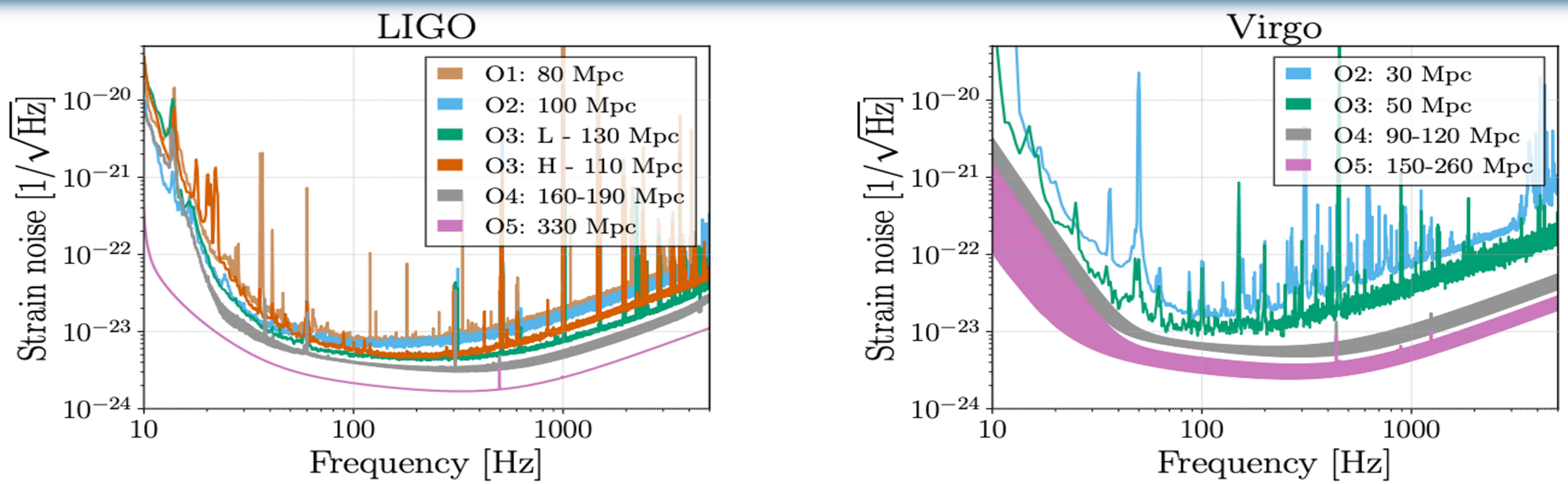
OUTLINE

- Recap on Gravitational-Wave (GW) sources
- GW Advanced detector sensitivity progression
- Continuous-Wave (CW) signals
- How to perform a search for CWs?
- CW search highlights from the third advanced LIGO-Virgo detector run
- Synergies with Multi-messenger astronomy
- Future Prospects

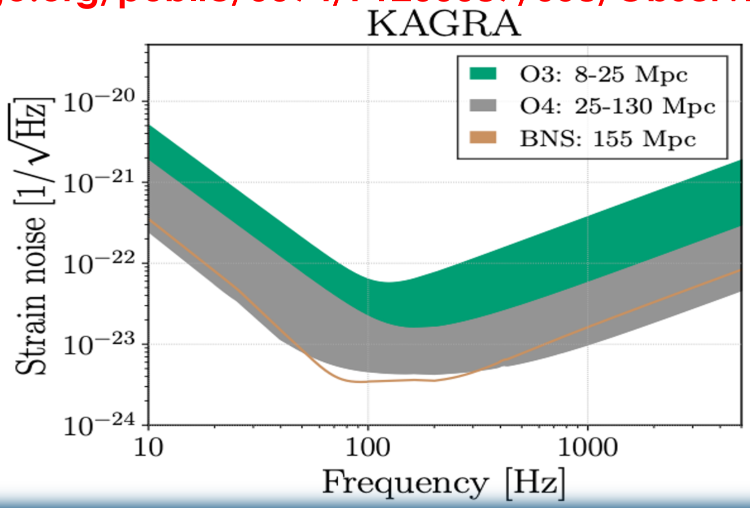
Recap on GW sources

		Two Black Holes (BHs)	Two Neutron Stars (NSs)	BH-NS
Compact Binary Coalescing systems *(CBC)*, well modeled waveforms		✓	✓	✓
Supernovae, GRBs (*bursts*), unmodeled waveforms; short-duration GW events in coincidence with signals in electromagnetic (EM) radiation/neutrinos			X	
Fast-spinning NSs in our galaxy (either <u>isolated</u> or in <u>binary systems</u>); monochromatic waves; modeled waveform			X	X
Cosmological GW (*stochastic background*); A background of primordial and/or astrophysical GWs; unmodeled waveform			X	

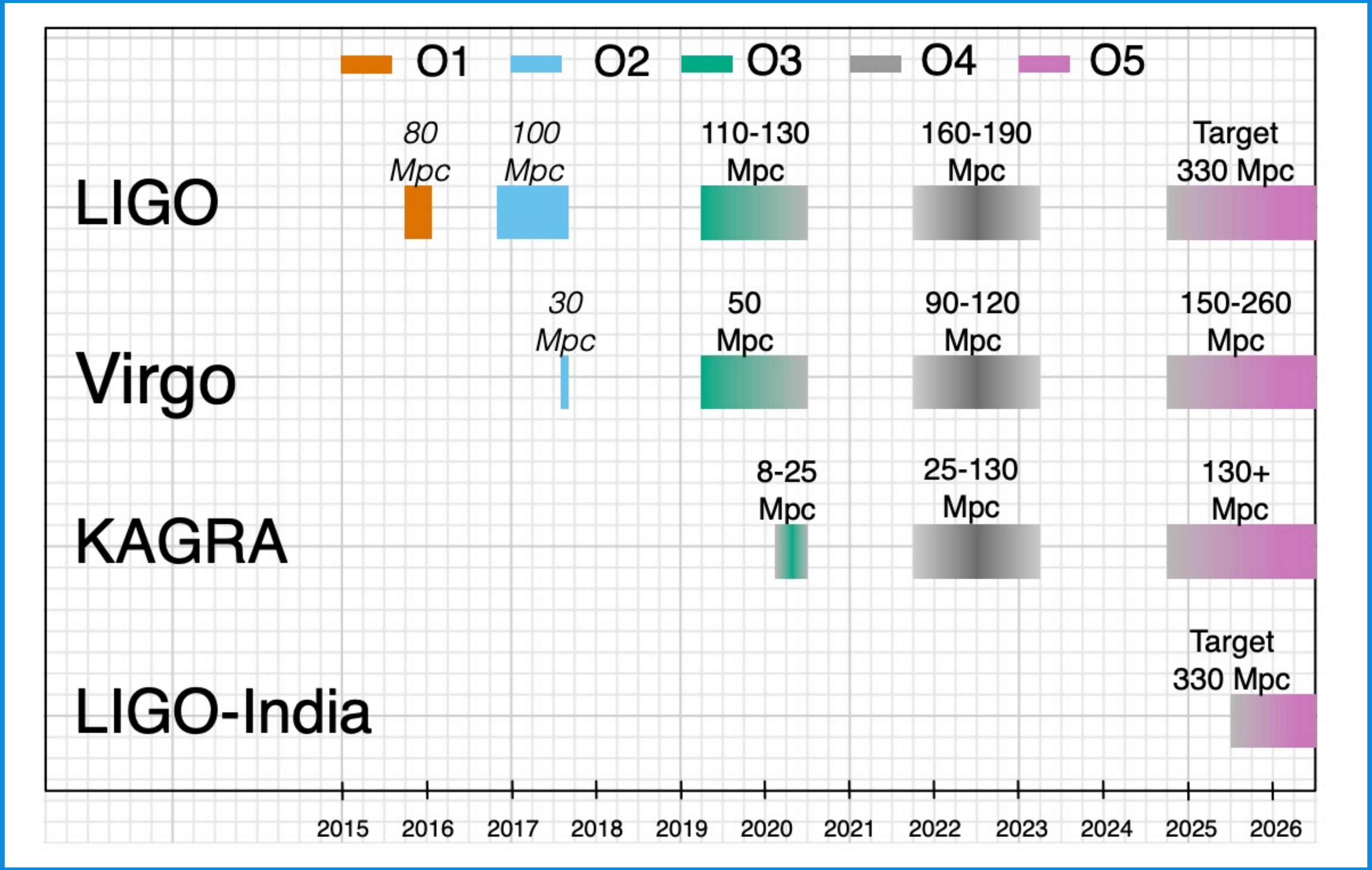
GW Advanced detector sensitivity progression.I



https://dcc.ligo.org/public/0094/P1200087/058/ObservingScenarios.pdf



GW Advanced detector sensitivity progression.II



https://dcc.ligo.org/public/0094/P1200087/058/ObservingScenarios.pdf

CW signals.I

- Quasimonochromatic waves with a slowly decreasing intrinsic frequency, which are expected to be emitted by
  - *Rapidly rotating NSs with non-axisymmetric deformations*
  - *Short periodic signals (from ~hours-days) from NS r-modes*
  - *Clouds of ultra-light bosons that could form around Kerr black holes as a consequence of superradiance*

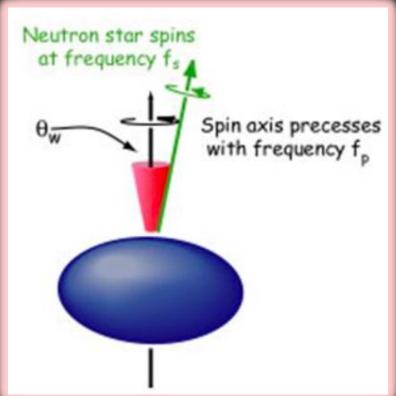
- Constant amplitude, weak (weaker than transient GW events), but persistent over years of data taking:
  - *Signal duration >> observation time*
  - *Due to the weakness of CWs, we have to integrate for a longer time to increase the signal-to-noise-ratio ~$O(T^{1/2})$*

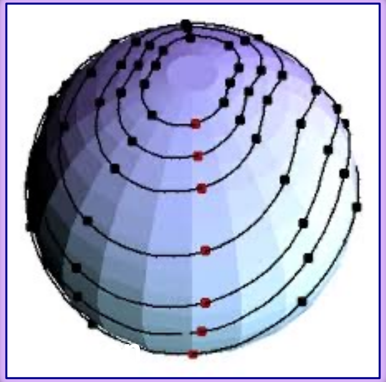
- Sensitivity increases with observation time

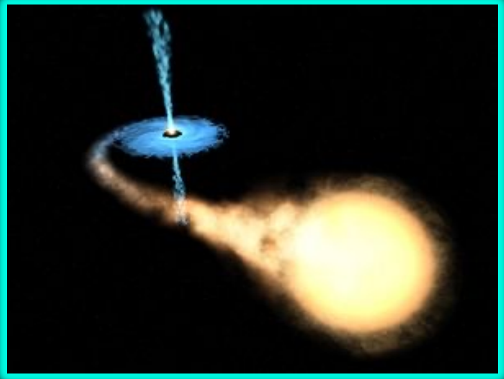
- Computation cost scales with a high power of the observation time

CW signals.II

- More than 3000 observed NSs (mostly pulsars) and $\mathcal{O}(10^8 - 10^9)$ expected to exist in the Galaxy
- To emit CWs a NS must have a certain degree of non-axisymmetry due to
  - deformation caused by elastic stresses or magnetic field not aligned to the rotation axis ($f_{GW} = 2\ f_{rot}$)
  - free precession around rotation axis ($f_{GW} \sim f_{rot} + f_{prec}$; $f_{GW} \sim 2 f_{rot} + 2\ f_{prec}$)
  - excitation of long-lasting oscillations (*e.g.* *r*-modes; $f_{GW} \sim 4/3\ f_{rot}$)
  - deformation due to matter accretion (*e.g.* LMXB; $f_{GW} \sim 2\ f_{rot}$)







http://en.wikipedia.org/

CW signals.III:
CWs from rotating NSs

The measured strain amplitude h_0 on Earth is given by

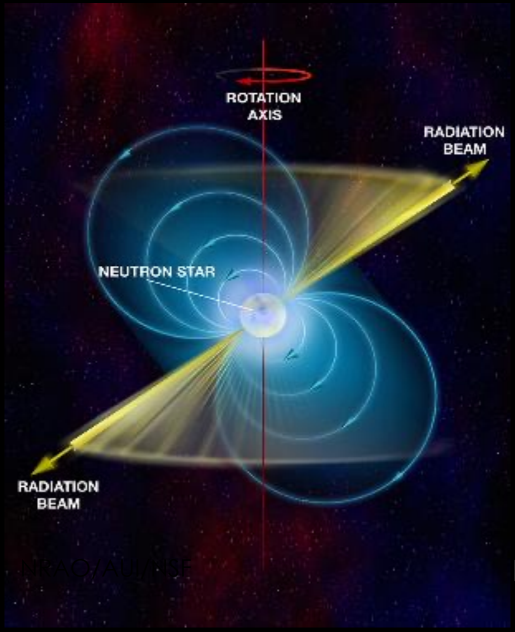
$$h_0 = \frac{4\pi^2 G}{c^4}\frac{I_{zz} f^2 \varepsilon}{d} \Rightarrow h_0 = 4\cdot 10^{-25}\left(\frac{\varepsilon}{10^{-5}}\right)\left(\frac{I_{zz}}{10^{45}\,\mathrm{g\,cm^2}}\right)\left(\frac{f_r}{100\ \mathrm{Hz}}\right)^2\left(\frac{1\ \mathrm{kpc}}{d}\right)$$

with d distance to the source, $\varepsilon = (I_{xx}-I_{yy})/I_{zz}$ being the equatorial non-axisymmetry and I_{ab} the moments of inertia

MAXIMUM DEFORMATION

- Normal NS ⟶ $\varepsilon \leq 10^{-5}$
- Hybrid (hadron-quark core) ⟶ $\varepsilon \leq 10^{-3}$
- Extreme quark stars ⟶ $\varepsilon \leq 10^{-1}$

PRD 87, 129903 (2013)]



CW signals.IV:
The spindown limit

A rotating NS spins down losing energy:

$\varepsilon = \epsilon$

- $\dot{E}_{rot} \propto I_{zz} f_{rot} \dot{f}_{rot}$ ROTATIONAL ENERGY LOSS
- $\dot{E}_{GW} \propto I_{zz}^2 f_{rot}^6 \epsilon^2$ GRAVITATIONAL ENERGY LOSS
- If we assume that all of the loss of energy of a spinning NS is caused by GW emission, i.e., that the observed star spindown, which is the decrease of the rotation period, is due to GWs, we get

$$\dot{E}_{rot} = \dot{E}_{GW} \Longrightarrow \epsilon_{sd} \propto \sqrt{\frac{1}{I_{zz}} \frac{|\dot{f}_{rot}|}{f_{rot}^5}}$$

- From h_0 we can also express a theoretical upper limit for the GW amplitude:

$$h_{sd} \propto \frac{1}{r} \sqrt{I_{zz} \frac{|\dot{f}_{rot}|}{f_{rot}}}$$

Going below the spindown limit means we are putting a constraint on the fraction of spindown energy due to the emission of GWs

CW signals.V:
Signal characteristics

- A CW signal is not exactly monochromatic, but it has a spindown due to the loss of energy (in a few cases a spinup may be present)

$$f_0(t) = f_0 + \dot{f}_0(t-t_0) + \frac{\ddot{f}_0}{2}(t-t_0)^2 + \ldots$$

- Due to both the Earth orbital and rotational motions, we have that the signal frequency is Doppler shifted, depending on the direction of the source in the sky, and –if the signal is in an binary system– we have a further Doppler modulation due to the orbit motion of the companion

$$f(t) = \frac{1}{2\pi}\frac{d\Phi(t)}{dt} = f_0(t)\left(1 + \frac{\vec{v}\cdot\hat{n}}{c}\right), \quad \vec{v} = \vec{v}_{orb} + \vec{v}_{rot}$$

- Due to the variation of the source direction in the detector frame, a sidereal day variation of the signal phase and amplitude is present
- Glitches (i.,e., sudden variations of the rotational frequency of the star) can also occur

CW signals.VI:
CWs from spinning NSs in binary systems

- A CW signal from a source in a binary system is frequency-modulated by the source orbital motion, which in general is described by five unknown Keplerian parameters
- Accretion from a companion may cause an asymmetrical quadrupole moment of inertia of the spinning NS
- In some cases the accretion is asymmetric due to the sporadic observation of X-ray pulsations
- This asymmetry can lead to GW emission through various mechanisms:
  - *temperature-dependent electron capture onto nuclei in the crust [ApJ 501, L89 (1998)]*
  - *magnetic funneling of accreted material [ApJ 623, 1044 (2005)]*
  - *sustained instability of rotational r-modes [ApJ 516, 307 (1999)]*
- The most rapidly observed accreting NSs do not spin at very high frequencies, and this seems to suggest that their accretion torques are balanced by GW emission torque [ApJ 501, L89 (1998)]
- Maximal Doppler modulation due to the source orbital motion depends on orbital parameters

$$\Delta M = \frac{a_p \Omega}{1 - e}$$

How to perform a search for CWs?

The way to search for CWs depends on how much about the source is known. There are three main different types of searches:

- TARGETED/narrowband searches for observed NSs. The source parameters (sky location, frequency & frequency derivatives) are assumed to be known with great/enough accuracy (*e.g.* the Crab and Vela pulsars) => $\mathcal{O}$(laptop)

$$h_{0_{min}} \approx 10\sqrt{\frac{S_n(f)}{T_{coh}}}$$

- DIRECTED searches, where sky location is known while frequency and frequency derivatives are unknown (*e.g.* Cassiopeia A, SN1987A, Scorpius X-1, galactic center, globular clusters) => $\mathcal{O}$(cluster)

$$h_{0_{min}} \approx \alpha\sqrt{\frac{S_n(f)}{T_{coh}}}$$

- ALL-SKY searches for unknown pulsars => computing challenge (grid/cloud infrastructures)

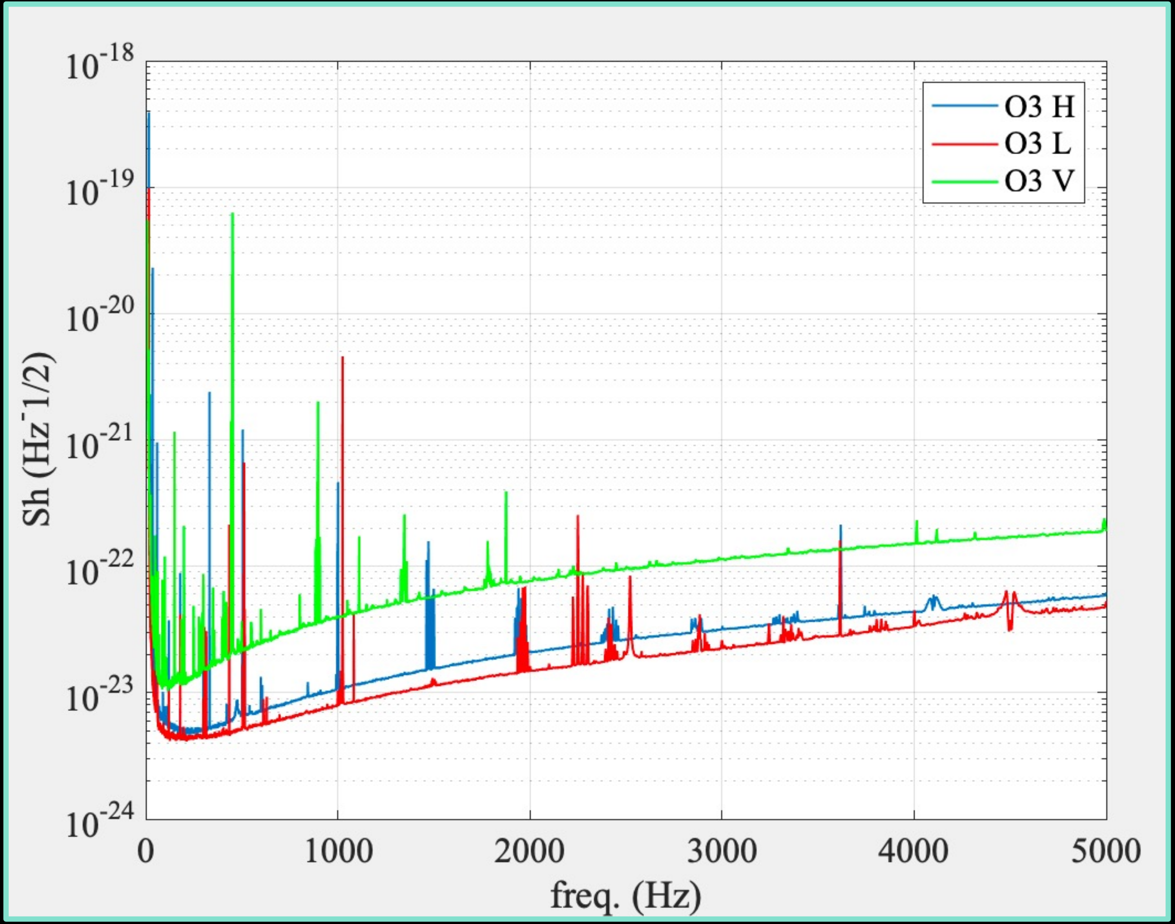
$$h_{0_{min}} \approx \frac{\Lambda}{N^{1/4}}\sqrt{\frac{S_n(f)}{T_{coh}}}$$

CW search highlights from the third advanced LIGO-Virgo detector run

The third advanced LIGO-Virgo detector run O3

O3 observing run:
April 1, 2019 – March 27, 2020

Commissioning break:
October 1-31, 2019



GW constraints on the equatorial ellipticity of millisecond pulsars

ApJL 902 L21 (2020); https://arxiv.org/abs/2007.14251

- CW search from 5 radio pulsars
- Used data set: 6 months of O3 (April 1 – October 1, 2019); O2 (Nov. 30, 2016 – August 25, 2017) and O1 (Sept. 12, 2015 – Jan. 19, 2016)
- For the 1st time we matched (for PSR J0437-4715) or surpass (for PSR J0711-6830) the indirect limits on GW emission from recycled pulsars inferred from their observed spindowns, and constrain their equatorial ellipticities to be less than 10^{-8}

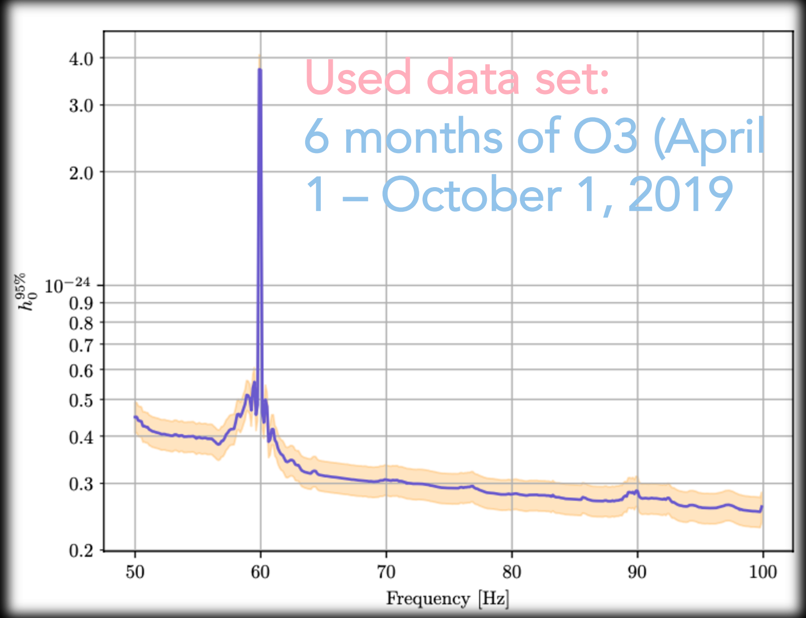
Pulsar	f_{rot} (Hz)	$\dot{f}_{rot}$ ($Hz\,s^{-1}$)	$\dot{f}^{int}_{rot}$ ($Hz\,s^{-1}$)	distance (kpc)	Spin-down luminosity (W)
Young pulsars					
J0534+2200 (Crab)	29.6	-3.7×10^{-10}	…	2.0 ± 0.5 [a]	4.5×10^{31}
J0835−4510 (Vela)	11.2	-2.8×10^{-11} [b]	…	$0.287^{+0.019}_{-0.017}$ [c]	6.9×10^{29}
Recycled pulsars					
J0437−4715	173.7	-1.7×10^{-15}	-4.1×10^{-16}	0.15679 ± 0.00025 [d]	2.8×10^{26}
J0711−6830	182.1	-4.9×10^{-16}	-4.7×10^{-16}	0.110 ± 0.044 [e]	3.4×10^{26}
J0737−3039A	44.1	-3.4×10^{-15}	…	$1.15^{+0.22}_{-0.16}$ [f]	5.9×10^{26}

- Targeted searches that assume a tight coupling between the GW and EM signal phase evolution for two recycled pulsars
- Targeted and narrowband searches for PSR J0711-6830, Crab and Vela

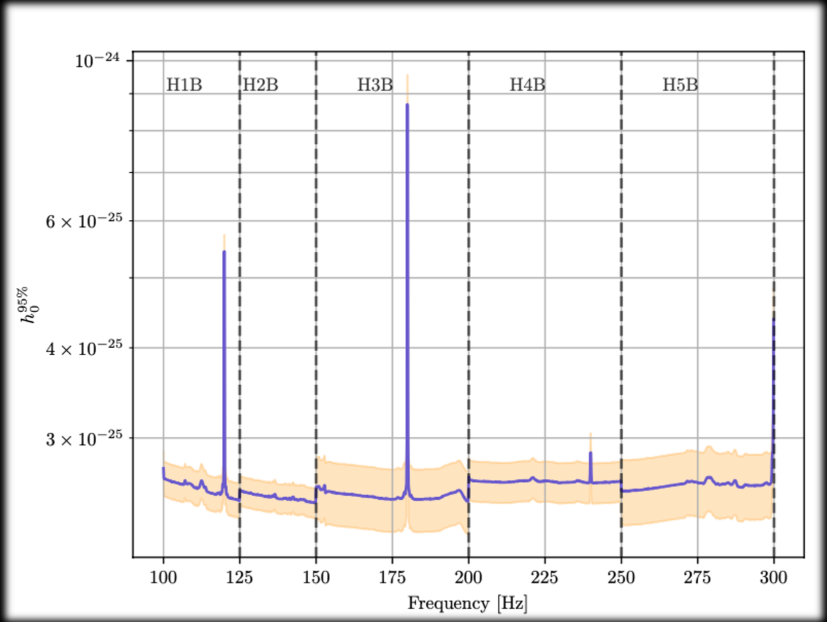
All-sky search for CWs from unknown NSs in binary systems

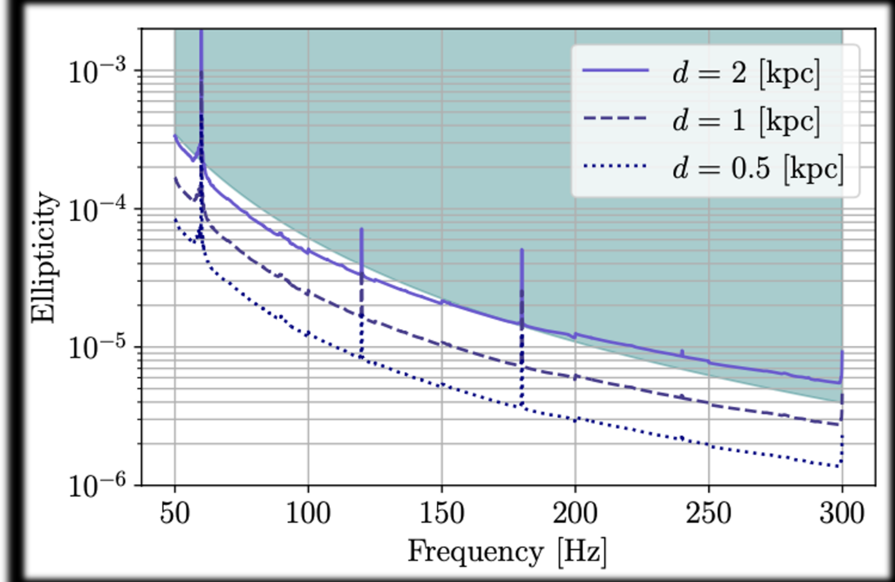
PRD 103, 064017 (2021); https://arxiv.org/abs/2012.12128

- Search frequency region: [50-300] Hz
- Binary orbital parameters are split into four regions, including Orbital period: [3 – 45] days; Projected semimajor axis: [2 – 40] ls
- Search sensitivity estimated in terms of the GW amplitude corresponding to the interpolated 95% detection efficiency using a simulated population of signals



Used data set:
6 months of O3 (April 1 – October 1, 2019





No detection can be claimed

Constraints on GWs from the energetic young X-ray pulsar PSR J0537-6910

ApJL 913, L27 (2021); https://arxiv.org/abs/2012.12926

- PSR J0537-6910 has the largest spindown luminosity of any pulsar and is highly active with regards to glitches
- Used data set: O2, O3 of LIGO and Virgo
- Timing ephemeris obtained using NICER data
- Search at both once and twice f_{rot} = 62 Hz

- No detection can be claimed
- Our constraints reach below the GW spindown limit (for the 1st time for this pulsar) by more than a factor of 2 and limit GWs to account for less than 14% of the spindown energy budget
- Equatorial ellipticity limited to less than ~ $3x10^{-5}$

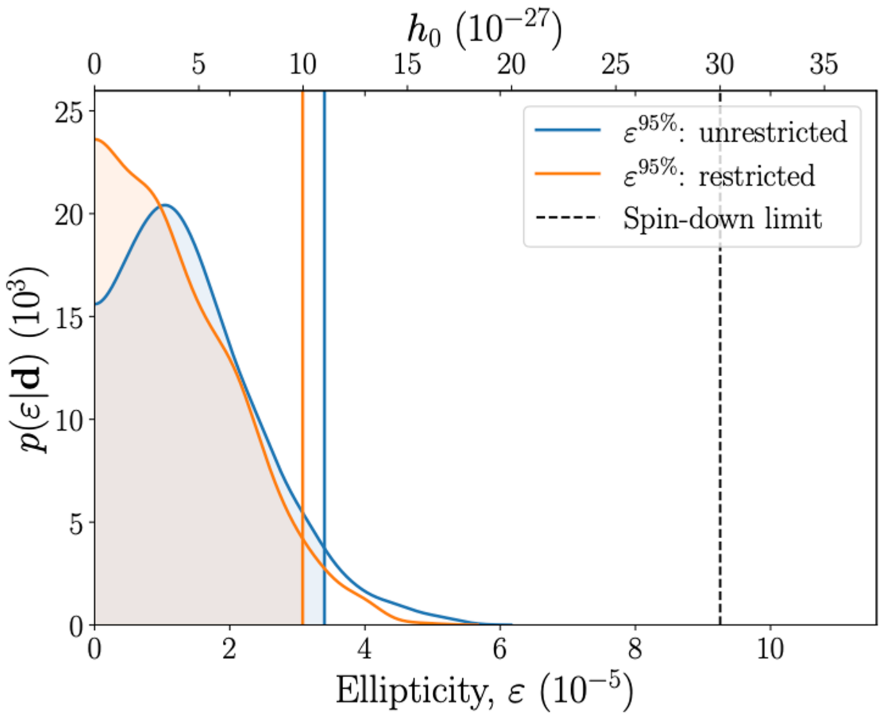
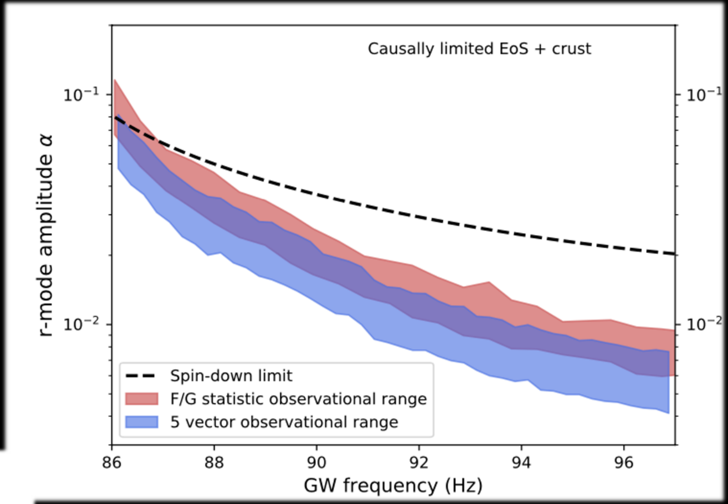


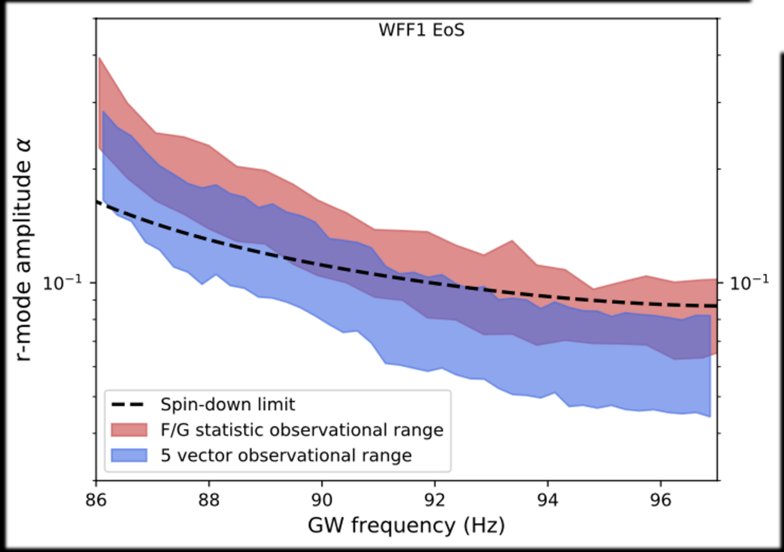
Figure 4. Posterior probability distribution for ellipticity and h_0 for the analyses with unrestricted and restricted priors on the pulsar orientation. The 95% credible upper limits are shown as vertical colored lines, while the spin-down limit is given by the vertical dashed black line.

Constraints on GW emission due to r-modes in the glitching pulsar PSR J0537-6910

ApJ (submitted); https://arxiv.org/abs/2104.14417

- Search frequency region: [86-97] Hz
- Used data set: full O3 (April 1, 2019 – March 27, 2020)
- Timing ephemeris obtained using NICER data
- Results improved on previous amplitude upper limits from r-modes in J0537-6910 by a factor of up to 3
- We place stringent constraints on theoretical models for r-mode driven spin-down in PSR J0537-6910, especially for higher frequencies at which our results reach below the spindown limit defined by energy conservation





$$\alpha = \sqrt{\frac{5}{8\pi}\frac{c^5}{G}\frac{h_0}{(2\pi f)^3}\frac{d}{MR^3\tilde{J}}} \approx 0.017\left(\frac{90\ \mathrm{Hz}}{f}\right)^3\left(\frac{h_0}{10^{-26}}\right)$$

r-mode amplitude leading to GWs with amplitude h_0

CW search from young supernova remnants

ApJ (submitted); https://arxiv.org/abs/2105.11641

- Search for 15 young supernova remnants
- Used data set: 6 months of O3 (April 1 – October 1, 2019)
- Search frequency region: [10 – 2000] Hz
- The best 95% confidence constraints placed on the signal strain are 7.7×10^{-26} for G39.2–0.3 and 7.8×10^{-26} for G65.7+1.2 at 200 Hz
- The most stringent constraints on the ellipticity ($<\sim 10^{-7}$) and *r*-mode amplitude ($<\sim 10^{-5}$) are reached at ~ 400 Hz for the closest target G **266.2–1.2/Vela Jr**

Source	Minimum t_{age} (kyr)	D (kpc)	T_{coh} (hours)	f (Hz)	$\dot{f}$ (Hz/s)
G1.9+0.3	0.10	8.5	1.0	[31.56, 121.7]	$[-3.858 \times 10^{-8}, 3.858 \times 10^{-8}]$
G15.9+0.2	0.54	8.5	1.0	[44.03, 657.1]	$[-3.858 \times 10^{-8}, 3.858 \times 10^{-8}]$
G18.9–1.1	4.4	2	1.9	[31.02, 1511]	$[-1.507 \times 10^{-8}, 1.507 \times 10^{-8}]$
G39.2–0.3	3.0	6.2	2.8	[62.02, 459.2]	$[-1.968 \times 10^{-8}, 1.968 \times 10^{-8}]$
G65.7+1.2	20	1.5	4.7	[35.10, 1128]	$[-3.149 \times 10^{-9}, 3.149 \times 10^{-9}]$
G93.3+6.9	5.0	1.7	1.9	[30.00, 1668]	$[-1.335 \times 10^{-8}, 1.335 \times 10^{-8}]$
G111.7–2.1	0.30	3.3	1.0	[25.71, 365.1]	$[-3.858 \times 10^{-8}, 3.858 \times 10^{-8}]$
G189.1+3.0	3.0	1.5	1.4	[26.13, 2000]	$[-1.968 \times 10^{-8}, 1.968 \times 10^{-8}]$
G266.2–1.2	0.69	0.2	1.0	[18.36, 839.6]	$[-3.858 \times 10^{-8}, 3.858 \times 10^{-8}]$
G291.0–0.1	1.2	3.5	1.0	[31.97, 1460]	$[-3.858 \times 10^{-8}, 3.858 \times 10^{-8}]$
G330.2+1.0	1.0	5	1.1	[36.57, 1039]	$[-3.858 \times 10^{-8}, 3.858 \times 10^{-8}]$
G347.3–0.5	1.6	0.9	1.0	[21.74, 1947]	$[-3.858 \times 10^{-8}, 3.858 \times 10^{-8}]$
G350.1–0.3	0.60	4.5	1.0	[31.96, 730.1]	$[-3.858 \times 10^{-8}, 3.858 \times 10^{-8}]$
G353.6–0.7	27	3.2	10	[77.86, 318.3]	$[-2.295 \times 10^{-9}, 2.295 \times 10^{-9}]$
G354.4+0.0	0.10	5	1.0	[25.72, 121.7]	$[-3.858 \times 10^{-8}, 3.858 \times 10^{-8}]$

Constraints on dark photon dark matter using O3

PRL (submitted); https://arxiv.org/abs/2105.13085

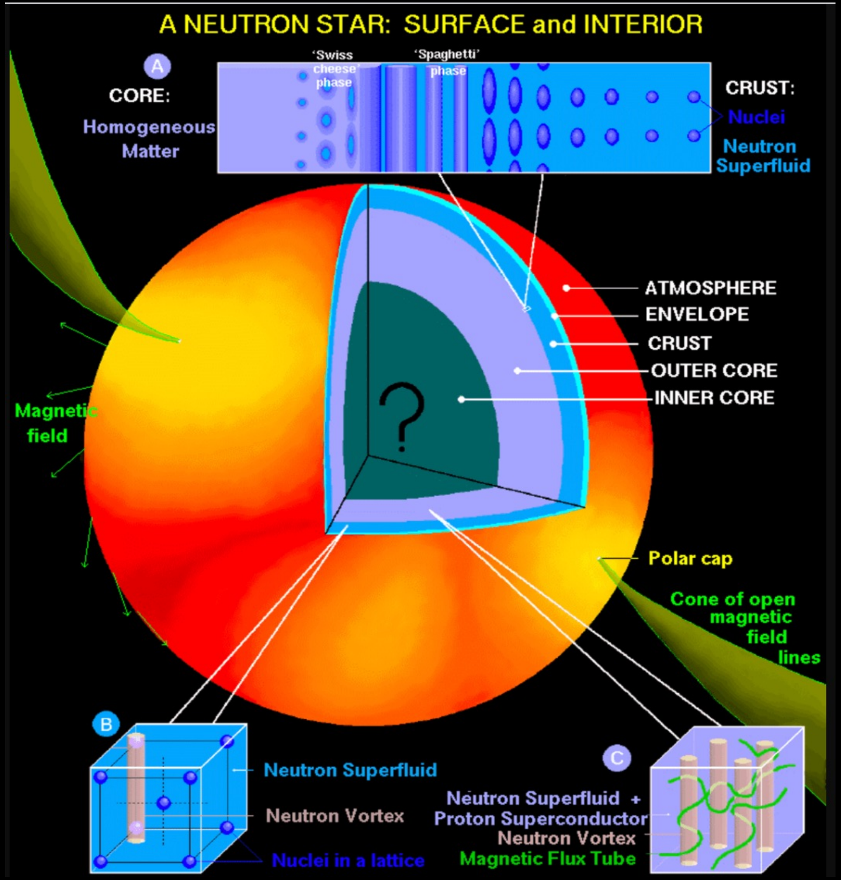
We present a search for dark photon dark matter that could couple to gravitational-wave interferometers using data from Advanced LIGO and Virgo's third observing run. To perform this analysis, we use two methods, one based on cross-correlation of the strain channels in the two nearly aligned LIGO detectors, and one that looks for excess power in the strain channels of the LIGO and Virgo detectors. The excess power method optimizes the Fourier Transform coherence time as a function of frequency, to account for the expected signal width due to Doppler modulations. We do not find any evidence of dark photon dark matter with a mass between $m_{\mathrm{A}} \sim 10^{-14} - 10^{-11}$ eV/c^2, which corresponds to frequencies between 10-2000 Hz, and therefore provide upper limits on the square of the minimum coupling of dark photons to baryons, i.e. $U(1)_{\mathrm{B}}$ dark matter. For the cross-correlation method, the best median constraint on the squared coupling is $\sim 1.31 \times 10^{-47}$ at $m_{\mathrm{A}} \sim 4.2 \times 10^{-13}$ eV/c^2 ; for the other analysis, the best constraint is $\sim 1.2 \times 10^{-47}$ at $m_{\mathrm{A}} \sim 5.7 \times 10^{-13}$ eV/c^2. These limits improve upon those obtained in direct dark matter detection experiments by a factor of ~ 100 for $m_{\mathrm{A}} \sim [2-4] \times 10^{-13}$ eV/c^2.

Synergies with Multi-messenger astronomy

- EM observations alone cannot help to understand NS composition (highly condensed matter, crystalline structure, viscosity,…)

- Information on NS quadrupolar deformation (ellipticity) will be very valuable to understand whether NSs are composed by only neutrons, quarks, exotic matter, and so on

- Other NS properties (the range of NS masses, radii, sky locations, maximum NS spin frequency, population models, cold dense matter EOS properties)

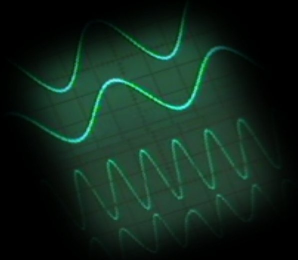


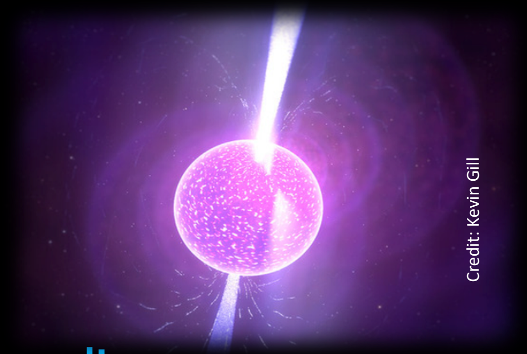
Credit: Dany P Page, Phys.org

- Detecting deviations from General Relativity (speed of GWs, existence of other polarizations)

What do we need to facilitate the CW detection?

- UPDATED EPHEMERIS as fully coherent searches for CWs from known pulsars rely on coherent phase models and wrong ephemeris can introduce phase errors, which would result in a loss of signal-to-noise ratio
- RADIO OBSERVATORIES able to monitor the vast majority of radio pulsars, mainly those with high spindown, which translates into a strong CW emission (e.g. PSRs J1952+3252 and J1913+1011)
- GAMMA/X-RAY observations
- NEW PULSAR DISCOVERIES (in all of EM bands)
- ROBUST ALGORITHMS able to detect both our standard signal models and the unexpected!
- … and of course (more) SENSITIVE GW DETECTORS





Credit: Kevin Gill

Future Prospects

- Finish analyzing O3 data
- Optimizing search algorithms (porting to GPUs/Machine Learning)
- Improve Follow-up methodologies (to be more computationally efficient)
- Getting ready for O4+ and the 3rd generation GW detectors (e.g., Einstein Telescope and LIGO Cosmic Explorer)

QUESTIONS ARE WELCOME