Continuous gravitational waves from unknown neutron stars in binary systems

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Compact Stars in the QCD phase diagram

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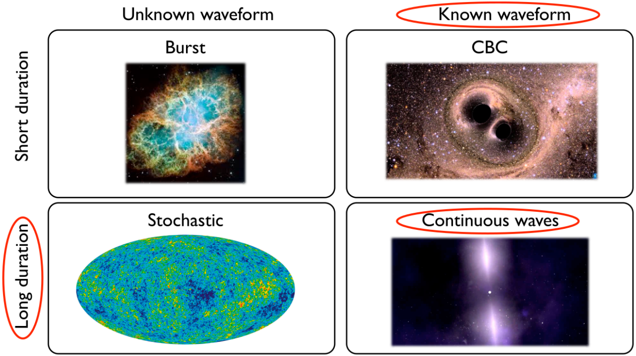
This talk discusses the following paper:
P. B. Covas et al., arXiv:2605.14728 (2026)

Outline

Types of gravitational waves:



- $\sim$ 100 of detections of gravitational waves are all of the same type: **compact binary coalescences** (CBCs).
- Continuous gravitational waves (CWs) are nearly **monochromatic** waves with **virtually infinite duration** but **much weaker gravitational-wave amplitude**.

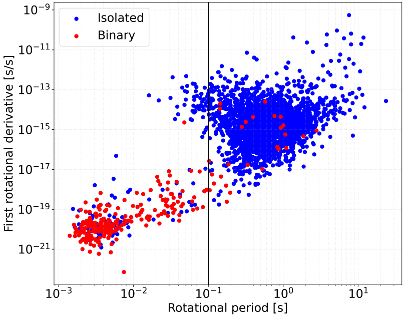
Neutron stars lose rotational energy due to emission of electromagnetic and gravitational radiation, which makes the star increase its rotational period P:

$$\dot{P} = k_B \frac{R^6 B^2}{I} P^{-1} + k_\epsilon I \epsilon^2 P^{-3}.$$

The rotational phase of a neutron star can be described with very good accuracy by a Taylor expansion of a few orders around a reference time:

$$\phi(\tau) = \phi_0 + 2\pi \left[f_0(\tau - \tau_r) + \frac{f_1}{2}(\tau - \tau_r)^2 + \mathcal{O}(\tau - \tau_r)^3 \right].$$

Small fraction of neutron stars detected in our galaxy: ~ 3320 (ver. 1.67 of ATNF catalogue) from the $\sim 10^{8-9}$ expected to exist.

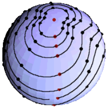


More than half of sources in detector's frequency band in binary systems, with smaller spin-down!

Neutron stars can have asymmetries, due to elastic or magnetic deformations, accretion from companions, ...
If the NS is rotating and has an asymmetry around its rotating axis, it will emit GWs: $h_0 = C_\epsilon \frac{\epsilon I_{zz}}{d} f_{\mathrm{gw}}^2 = 10^{-26} \left(\frac{\epsilon}{10^{-6}}\right) \left(\frac{I_{zz}}{10^{38}\ \mathrm{kg\ m^2}}\right) \left(\frac{f_{\mathrm{gw}}}{100\ \mathrm{Hz}}\right)^2 \left(\frac{1\ \mathrm{kpc}}{d}\right)$.

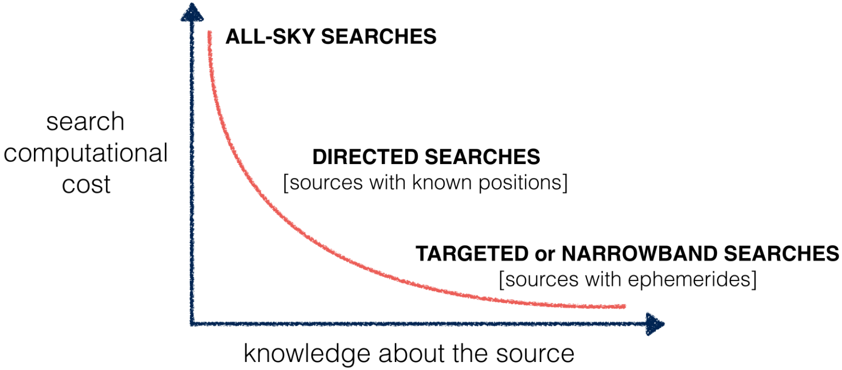
- Non-axysymmetric distortions do not exist in perfect fluid stars, but in realistic neutron stars models such deformations can exist.
- Ellipticity: $\epsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$, where I_{ii} are the principal moments of inertia and the star is rotating around the z axis.
- Maximum theoretical ellipticity highly uncertain (from $\sim 10^{-5}$ to $\sim 10^{-9}$), and it depends on the equation of state (for quark NS: $\sim 10^{-1}$).
- Gravitational wave frequency at twice the rotational frequency for the simplest model.

R-modes (Rossby waves), a **long-lasting oscillation mode produced by the Coriolis force in a rotating fluid:** $h_0 = C_r \frac{\alpha M R^3}{d} f_{\rm gw}^3 = 10^{-26} \left(\frac{\alpha}{2.8\times10^{-4}}\right) \left(\frac{f_{\rm gw}}{100\ \rm Hz}\right)^3 \left(\frac{1\ \rm kpc}{d}\right) \left(\frac{M}{1.4\ \rm M_\odot}\right) \left(\frac{R}{11.7\ \rm km}\right)^3$.



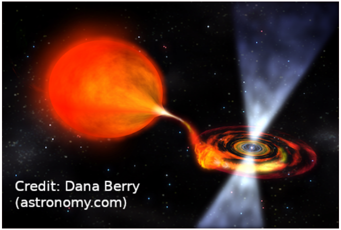
- Unstable to gravitational-wave emission due to the CFS instability. Instability window: regions in the rotational frequency/temperature diagram where the r-modes are unstable. Instability counteracted by dissipative mechanisms such as viscosity.
- Potential large unobserved population of quiescent LMXBs that may be subject to long-lasting ($\sim 10^9$ yr) r-mode emission (called HOFNARs).
- Maximum theoretical r-mode amplitude highly uncertain (from $\sim 10^{-4}$ to $\sim 10^{-6}$).
- Gravitational wave frequency approximately at 4/3 the rotational frequency, depending on the equation of state.

Types of CW searches



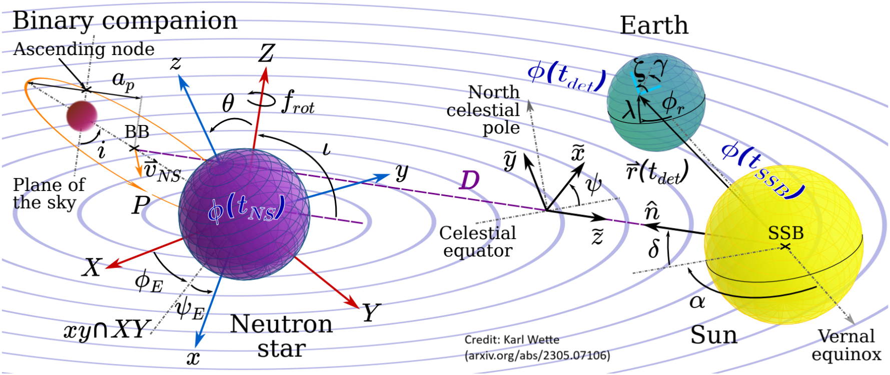
Why search for unknown NS in binary systems?

- Searching for sources in a binary system highly increases the computational cost of the search! Most computationally demanding type of gravitational-wave search.
- More than half of the known pulsar population is in a binary system.
- Accretion gives an additional mechanism to create the required asymmetry or excite an r-mode with a detectable amplitude in the current generation of gravitational-wave detectors.



Trade-off between sensitivity, range of parameter space, and computational cost!

Different frames (neutron star, binary barycenter, solar system barycenter, detector):



Two different types of **parameters** define the CW signal:

Amplitude

Physical parameters:

- Gravitational-wave amplitude: h_0
- Inclination angle: ι
- Polarization angle: ψ
- Initial phase: ϕ_0

or JKS parameters $\mathcal{A}_\mu(h_0, \iota, \psi, \phi_0)$

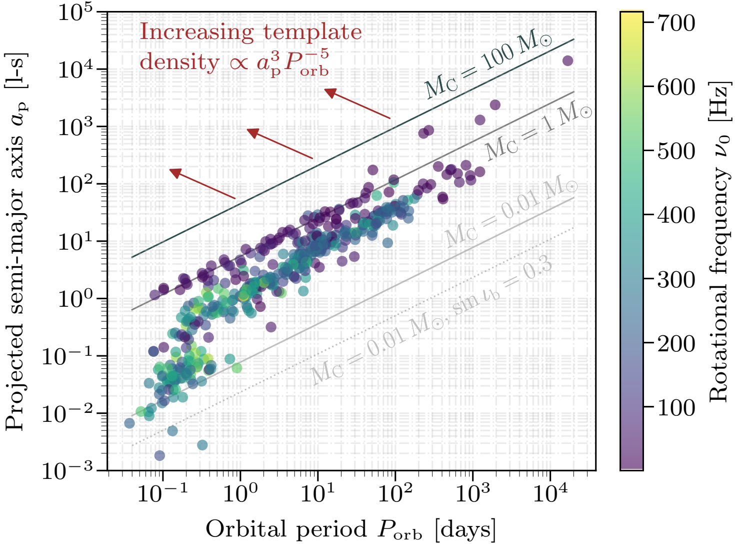
Phase-evolution

- Frequency evolution: f_0, f_1, ...
- Sky position: α and δ
- Keplerian binary orbit: a_p (projected semi-major axis), P_orb (orbital period), t_asc (time of ascension), e (eccentricity), and ω (argument of periapsis)

In a targeted search, **all phase-evolution parameters are known**. For an all-sky search, none of the phase-evolution parameters are known.

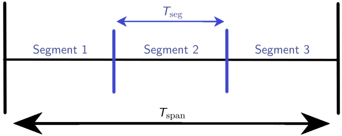
Orbital parameter-space

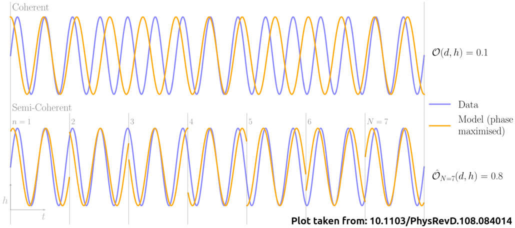
Known neutron stars in binary systems:



Semi-coherent searches

Longer observation time → more templates required for constant mismatch → fully-coherent all-sky CW searches infeasible → use **semi-coherent methods**, breaking up data in smaller segments:



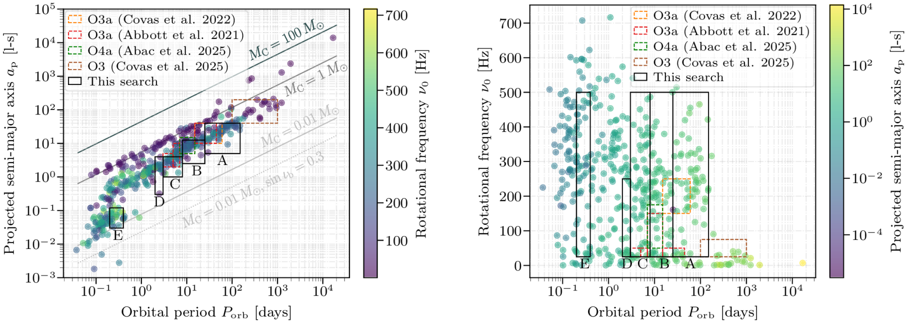


Plot taken from: 10.1103/PhysRevD.108.084014

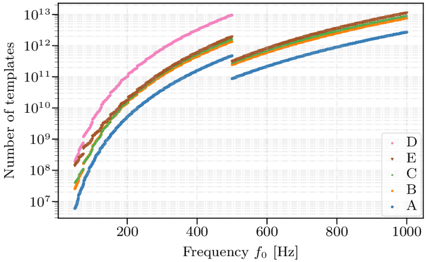
Phase coherence required within each single segment, but not between segments (the 4 amplitude parameters are allowed to vary in each segment)! This reduces the computational cost, but also the sensitivity. **Semi-coherent methods are typically more sensitive than fully coherent matched filtering with a limited computational budget!**

Outline

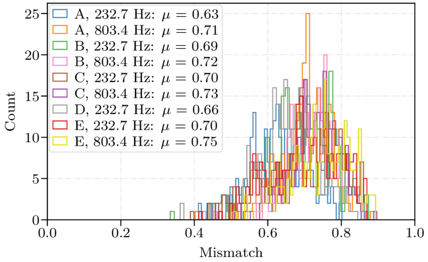
- Used Advanced LIGO O3 data with time-domain cleaning for glitches.
- Employed more sensitive and efficient algorithm + detection statistic.
- Coherent time of $T_{\mathrm{seg}} = 900$ s.
- Breadth vs depth: reduce sensitivity for **wider** search.
- **First search for orbital periods shorter than 0.4 days and gravitational-wave frequencies higher than 520 Hz**



Number of templates for each 0.1 Hz frequency test-band:



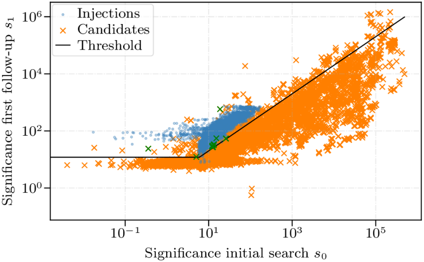
Mismatch histogram for different regions:

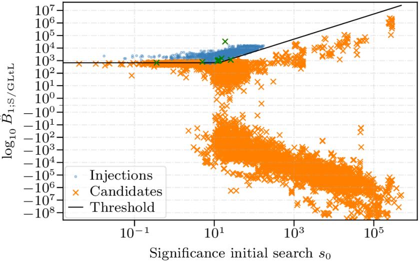


The total number of templates searched is $\sim 6.3 \times 10^{16}$.

The resulting average mismatch produced by our template grid is ≈ 0.7.

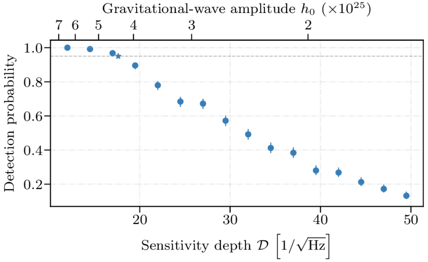
Follow-up based on nested sampling. We increase the coherent time to $T_{\mathrm{seg}} = 2\,700$ s and **re-analyze** 127 500 **candidates**, comparing evolution from initial stage (0) and follow-up stage (1):



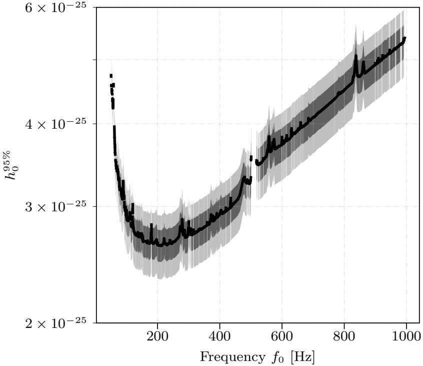


We require that these candidates follow the same behavior as simulated CW signals added to the data, which we used to calibrate this follow-up. **Only 12 candidates survive, none of them can be associated with a real CW signal**

Detection probability in one frequency band:



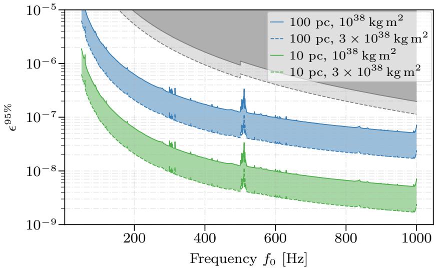
Estimated upper limits on the gravitational-wave amplitude h_0:

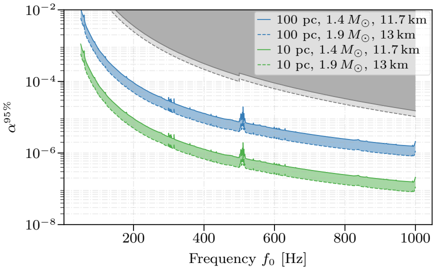


Sensitivity depth (amplitude spectral density / gravitational-wave amplitude: $\sqrt{S_n}/h_0$) is $\sim 18\ \mathrm{Hz}^{-1/2}$.

We convert the estimated h_0 upper limits to other parameters:

Deformation: $h_0 = C_\epsilon \epsilon \frac{I_{zz} f_{\rm gw}^2}{d}$ **R-modes**: $h_0 = C_r \frac{\alpha M R^3 f_{\rm gw}^3}{d}$





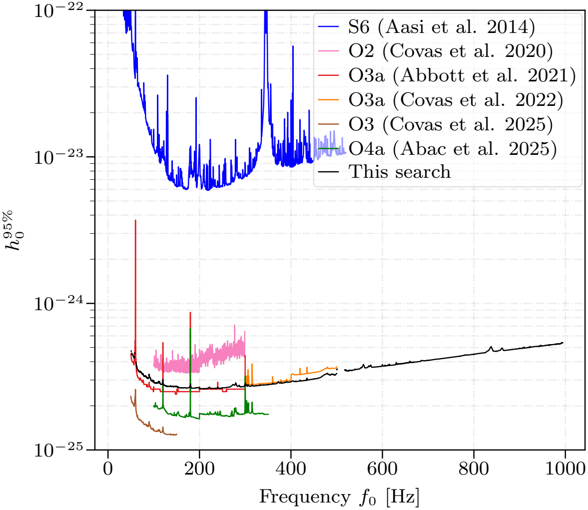
Dashed (solid) lines use $I_{zz} = 3 \times 10^{38}$ (10^{38}) kg m^2.

Dashed (solid) lines use $M = 1.9$ (1.4) $M_\odot$ and $R = 13$ (11.7) km.

Upper shaded gray area separates detectable from non-detectable region.

Distances: 10 pc, 100 pc.

Upper limits of all-sky searches for unknown neutron stars in binary systems:



Additional effects that are usually neglected in all-sky CW searches:

- Spin-wandering.
- Glitches.
- Timing noise.
- Post-Keplerian effects.
- Proper motion.
- Varying gravitational-wave amplitude.
- ...

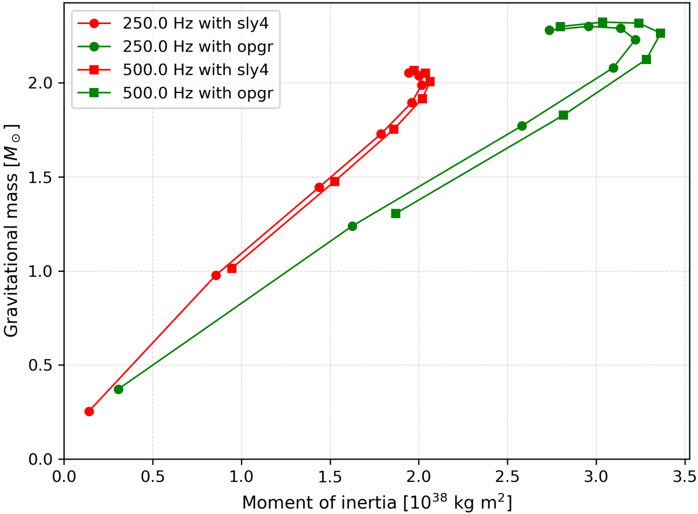
$\sim$ Safely neglected at the first stage of a search with a low coherent time!

Why no CW detections yet?

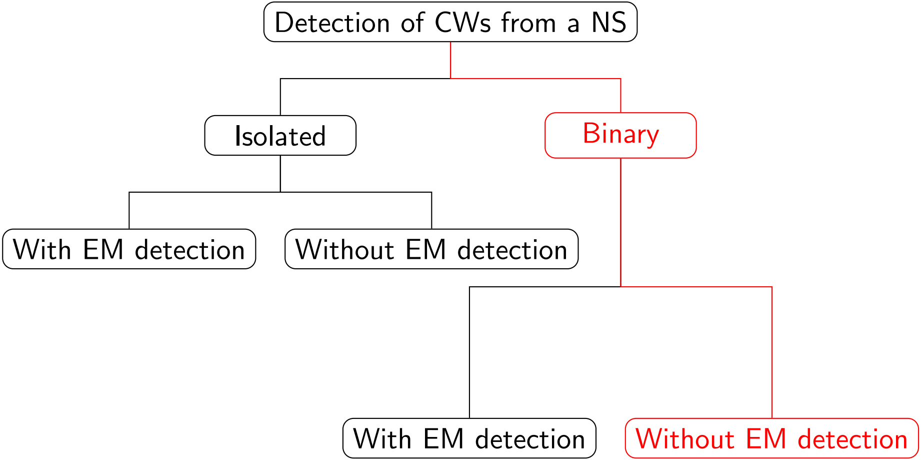
1. Uncertainties on the NS population and their ellipticities / emission mechanisms: smaller amplitudes of CW signals compared to already detected signals!
2. Uncertainties on the signal model: will the CW signal be coherent over long stretches of time? Is the phase of the CW signal coupled to the rotational phase? Does the amplitude change with time?

Outline

Radius can't be measured → We want to **simultaneously measure the mass and the moment of inertia** of the neutron star:



Detection scenarios



Moment of inertia

- The gravitational-wave amplitude is proportional to the moment of inertia: $h_0 = C_\epsilon \frac{I_{zz} \epsilon f_{\rm gw}^2}{d}$, but 2 more unknowns: ϵ and distance d
- We can measure the distance for close sources due to the **parallax effect** (Sieniawska+2022). Distance could also be independently measured due to electromagnetic emission from companion!
- We can disentangle I_{zz} and ϵ with the spin-down f_1 measurement, assuming a braking index n of 5: $I_{zz} = \frac{C'_\epsilon d^2 h_0^2 f_{\rm gw}}{|f_1|}$
- If not all rotational energy is lost through CWs ($n \neq 5$), then we need to measure the second spin-down parameter (Lu+2022): $I_{zz} = \frac{C''_\epsilon d^2 h_0^2 f_{\rm gw}}{f_1 (3-n)}$
- An additional mechanism to measure the moment of inertia is due to a higher-order effect produced by spin-orbit coupling that changes the inclination angle of the binary

Mass

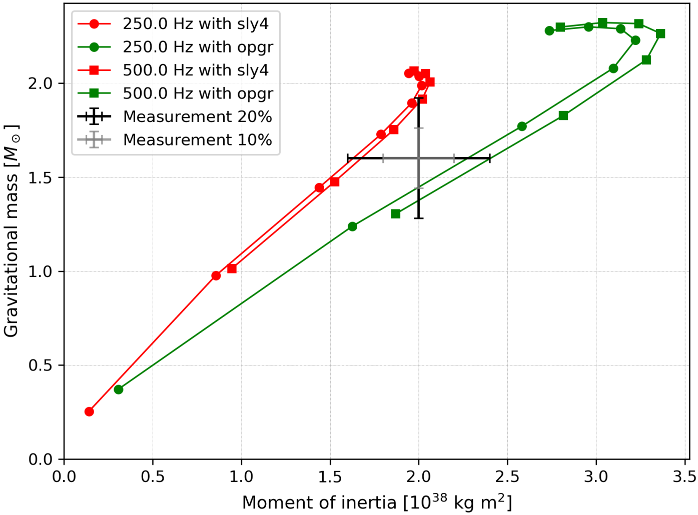
- We can measure the mass of the neutron star by **measuring 2 post-Keplerian parameters**. For example, the rate of periastron advance $\dot{\omega}$ and the Einstein delay γ, which assuming GR are:

$$\dot{\omega} = 3 T_{\odot}^{2/3} \left(\frac{P_{\rm orb}}{2\pi}\right)^{-5/3} \frac{1}{1-e^2} \left(m_{\rm NS} + m_{\rm C}\right)^{2/3},$$

$$\gamma = T_{\odot}^{2/3} \left(\frac{P_{\rm orb}}{2\pi}\right)^{1/3} e \frac{m_{\rm C}\left(m_{\rm NS} + 2m_{\rm C}\right)}{\left(m_{\rm NS} + m_{\rm C}\right)^{4/3}}, \quad \text{where} \quad T_{\odot} = GM_{\odot}/c^3.$$

- An additional mechanism to measure the mass is through the phase comparison of two different harmonics of the CW signal, if they are detected: Ono+2015

Realistic uncertainties due to fitting all parameters simultaneously have not yet been estimated! Could we reach a 10% measurement or lower?



Differences with electromagnetic detection

- Moment of inertia is easier to measure, due to gravitational-wave amplitude. Do not need to detect small-order effect due to spin-orbit coupling
- Gravitational-wave datasets typically have much higher duty cycles
- No dissipative effects (or much smaller) due to the interstellar medium
- Possible biases/uncertainties: ellipticity or/and moment of inertia constant in time?
- A more detailed comparison is needed!

Outline

Conclusions

- No detection of CWs yet, but exciting road ahead.
- Searches for unknown NS are very challenging but present different opportunities for detection.
- There is still **room for improvement in our search methods** (machine learning / GPUs, better detection statistics, more realistic signal models).
- **Widest all-sky binary search to date**.
- Many regions of the parameter space are still unexplored. Big uncertainty on how to decide where to search!

Acknowledgements

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