# Blind searches for continuous gravitational-wave signals: O3 LIGO-Virgo-KAGRA results and future developments

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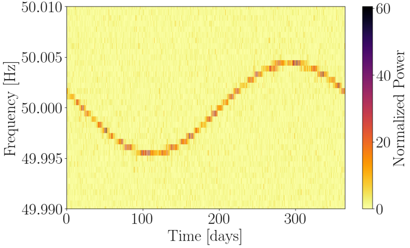
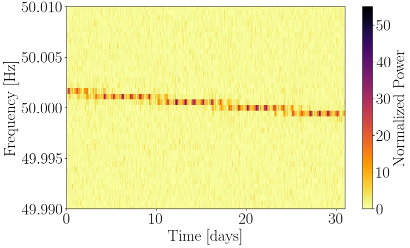
# Introduction

- Continuous waves (CWs) are long-duration quasi-monochromatic gravitational waves (GWs). No direct detection up to date.
- Expected sources are Neutron Stars (NS) presenting a non-axisymmetry (crust deformations, r-modes, free precession).
- More exotic sources: evaporation of boson clouds around spinning black holes, galactic dark matter halos.



# Continuous waves from neutron stars

## Standard CW emission mechanisms

- "Mountains" ($2f_{\rm rot}$): Quadrupolar deformations of the crust.
- r-modes ($\approx \frac{4}{3} f_{\rm rot}$): Coriolis-driven oscillations of the inner fluid.
- Free precession ($\approx f_{\rm rot}$): Misalignment symmetry–rotation axes.

## Amplitude of CWs ("mountains")

$$h_0 = \frac{4\pi^2 G}{c} \frac{I_{\rm z}\epsilon}{d} [2 f_{\rm rot}]^2 \simeq 4.2 \cdot 10^{-26} \left(\frac{\epsilon}{10^{-6}}\right) \left(\frac{f_{\rm rot}}{100 \text{ Hz}}\right)^2 \left(\frac{d}{1 \text{ kpc}}\right)^{-1}$$

- Expected amplitude is orders of magnitude lower than a CBC signal.
- Long integration times are required to unveil these the signal.
- Realistic searches focus on the galactic NS population.

# What could we learn from a CW detection?

## NS physics

- Ellipticity can be sourced by different processes (e.g. magnetic fields, accretion).
- Broad uncertainty on $\epsilon$: $10^{-12}$ to $10^{-5}$ depending on the model.
- Direct measurement provides information about the EoS of a NS.

## NS demographics

- Only $\mathcal{O}(10^5)$ NSs are expected to be active pulsars.
- Pulsars may not be pointing towards us.
- CWs may be required to observe some of the galactic NSs.

## Testing GR

- Long duration $\rightarrow$ Location and polarisation resolved by one detector.
- Beyond-GR polarisations can be measured from a single CW detection.

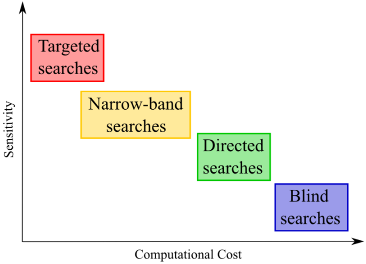
# Searching for CW signals

## Search types according to available information

The more specific the source, the cheaper the search:

- Targeted searches: Source is known and timed via EM observations.
- Blind searches: "Nothing" is assumed about the source.
  - Most expensive kind of search.
  - No specific assumption on the source.

(Sieniawska & Bejger 2019)



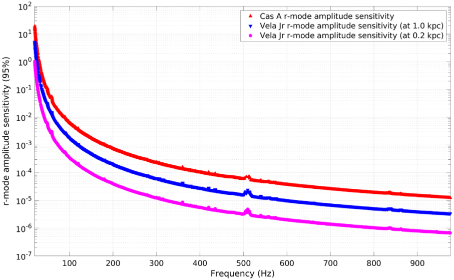

- "Sensitivity" is tied to model accuracy and search method.
- Blind searches use "sub-optimal" search methods to be computationally feasible.
- Incidentally, this makes them more robust to unmodeled physics.

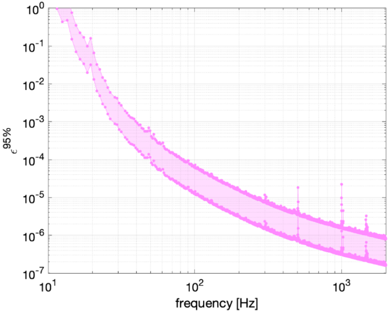
# Blind searches in the O3 LIGO-Virgo-KAGRA observing run

- No confident detection of CW signals (yet).
- Result: Upper limits on $h_0(f)$.
- Physical constraints are derived depending on the emission model.

# Directed searches: [Abbott+ 2021 ApJ 921 80; 2022 PRD 105 082005; PRD 2022 106 042003]

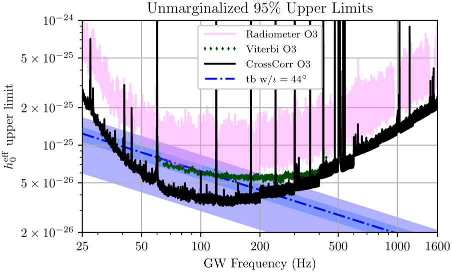
- Search for CW signals from interesting sky positions.
- No evidence for a NS is required.
- Parameter space is selected according to astrophysical information.
- Broad frequency range: sensitive to multiple emission mechanism (mountains, r-modes).
- Targets include supernova remnants or the galactic center.



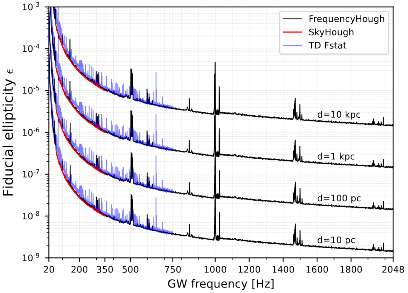
# Directed searches: [Abbott+ ApJL 2022 941 2; PRD 2022 106 062002]

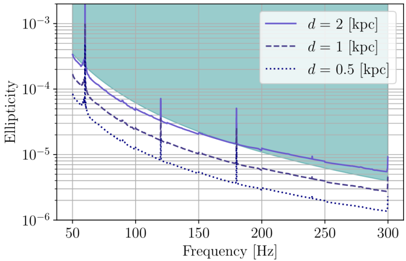
- Sco X-1: Most luminous Low-mass X-ray binary.
- Consistent with a NS accreting from a companion.
- Accretion may produce mountains, leading to CW emission.
- Test-bank for the torque-balance model, which causes NS to spin well below their break-up frequency.




- Upper limits are compatible with reanalysis after correcting erroneous ephemeris [Whelan+ 2023 ApJ 949 117, Killestein+ 2023 MNRAS 520 4].

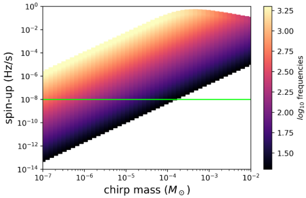
# All-sky searches [Abbott+ PRD 2021 103 064017; PRD 2021 104 082004; PRD 2022 106 102008]




- Most computationally demanding type of search.
- Basic assumption: quasi-monochromatic signal.
- Multiple post-processing and follow-up stages are required to increase the significance of a candidate.
- May be the only way of detecting a subset of unknown galactic NSs.
- Upper limits nearby start to probe realistic equations of state.

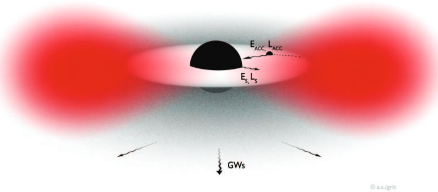
# CWs from other sources

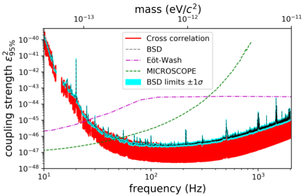



- Planetary and asteroid-mass primordial black hole binaries

  Miller+ 2021 PDU 32 100836; 2022 PRD 105 062008.

- Evaporation of light boson clouds around spinning black holes Brito+ 2017 PRD 96 064050; Abbott+ 2022 PRD 105 102001.




- Direct dark matter interaction with the detectors

  Abbott+ 2022 PRD 105 063030.

# Constraining the nearby abundance of primordial black holes

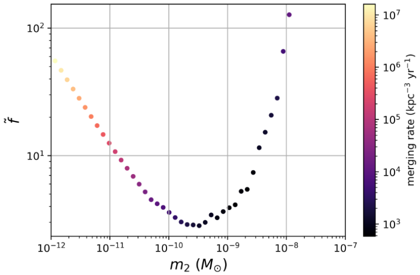



FIG. 17. Constraints on $\tilde{f}$, a quantity that, if less than one, indicates the sensitivity to a given $f_{\rm pbh}$, and inspiraling rate (color) as a function of the secondary mass, with a primary mass $m_1 = 2.5M_\odot$, assuming a monochromatic mass function for $m_1$, no rate suppression, and $f_{\rm pbh} = 1$. These constraints are valid at distances of $\mathcal{O}$(pc).

- All-sky searches make no specific assumptions on the emission mechanism.
- $h_0(f)$ upper limits can be re-interpreted under different physical models.
- O3 all-sky upper limits can be used to limit the fraction of dark matter composed by primordial black holes [Abbott+ PRD 2022 106 102008].
- Non-constraining results so far ($\tilde{f} > 1$), but expected to obtain more interesting results as detectors improve sensitivity.

# Scalar boson-cloud evaporation [Abbott+ PRD 2022 105 102001]

- Evaporation of boson clouds around spinning black holes emits CW with a slight "spin-up" rather than "spin-down".
- For scalar boson clouds, the resulting signal is a standard CW.
- No detection on LIGO-Virgo O3 data.
- Direct detection will allow to map the population of isolated galactic black holes [Zhu+ 2020 PRD 102 063020].

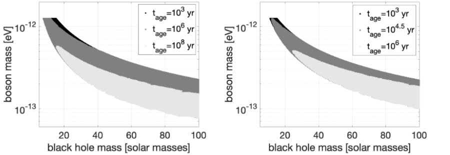



FIG. 6. Exclusion regions in the boson mass ($m_b$) and black hole mass ($M_{BH}$) plane for an assumed distance of $D = 1$ kpc (left) and $D = 15$ kpc (right), and an initial black hole dimensionless spin $\chi_i = 0.9$. For $D = 1$ kpc, three possible values of the black hole age, $t_{age} = 10^3$, $10^6$, $10^8$ years, are considered; for $D = 15$ kpc, $t_{age} = 10^3$, $10^{4.5}$, $10^6$ years are considered.

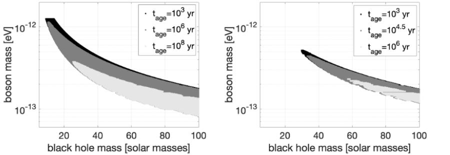
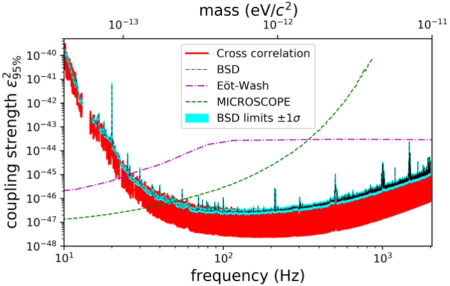



FIG. 7. Same as Fig. 6 but for black hole initial spin $\chi_i = 0.5$. The assumed distance is $D = 1$ kpc (left), and $D = 15$ kpc (right).

# Dark-photon dark matter constraints [Abbott+ 2022 PRD 105 063030]




$$f_0 = \frac{c^2}{2\pi\hbar} m_{\rm dp}$$

$$\Delta f = \frac{1}{2}\left(\frac{v_0}{c}\right)^2$$

- Dark-photon dark matter would couple to baryons and cause oscillations on the mirrors of LIGO/Virgo.
- The detector would measure a quasi-monochromatic signal as it travels through a dark-photon cloud.
- Competitive results cement the role of interferometric detectors to conduct dark matter searches.

# New developments on CW search methods

## Model-wise, the problem is “simple”

- Closed-form model, detection statistics are explicit function calls.
- Easy to parallelize using GPUs: Faster analyses! (months $\rightarrow$ days)

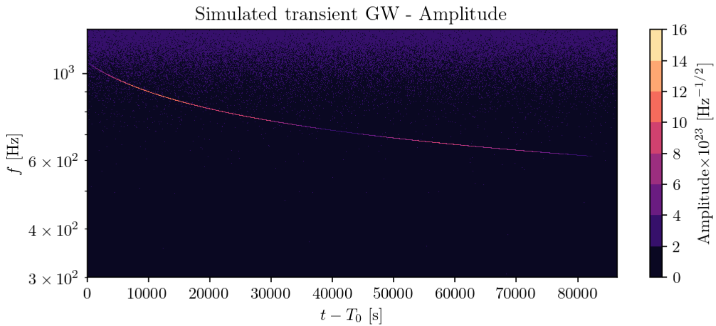
## Actual problems

- Parameter space can become really huge if left untamed.
- Signals are really “weak”: Cannot apply new methods out of the box.

## Possible new avenues

- New sources producing “stronger” CW signals?
- Novel data analysis methods beyond semicoherent searches?

# Searching for CWs from newborn NSs using GPUs
## + Joan-René Mérou (UIB)



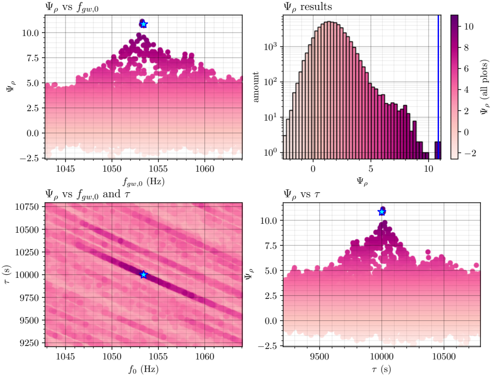

- BNS mergers may produce newborn NSs, which may emit CWs.
- Fast spindown: Must use general torque equation.

$$f(t) = f_0 \left(1 + \frac{t - t_0}{\tau}\right)^{\frac{1}{n-1}}$$

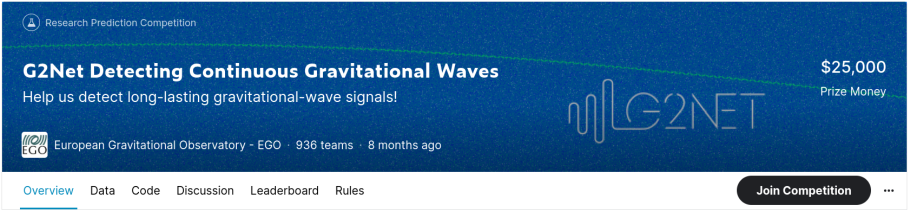
- More complicated parameter space: Non-linearities in the parameters.

# Searching for CWs from newborn NSs using GPUs
+ Joan-René Mérou (UIB)

- We developed an improved version of `ATrHough` [Oliver+ 2019 PRD 99 104067] using `JAX`.
- 60 times faster thanks to JIT + GPU.
- Astrophysical reach limited to a few Mpc.
- Grid search ready to use on upcoming BNS events during O4.



# Kaggle competition, or pursuing blue skies en masse
+ Michael J. Williams, Chris Messenger (U. of Glasgow)




- We ran a **Kaggle competition** to detect CW signals.
- Task: **find CW signals** in artificial data using **any** method of your choice (ML, matched filtering, dynamic programming. . . ).
- Competition lasted for **3 months** and attracted $\sim$ **1000 participants**.
- Total prize of **$25,000**, to be split amongst top three submissions.
- **No definitive ML solution in sight.** Solutions involve a rich variety of approaches.

# Results of the new competition

+ Michael J. Williams, Chris Messenger (U. of Glasgow)

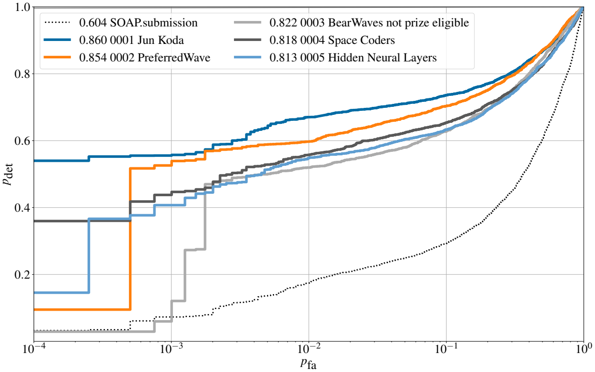
| # | △ | Team | Members | Score | Entries | Last | Solution |
|---|---|---|---|---|---|---|---|
| 1 | ▲ 1 | Jun Koda | | 0.863 | 48 | 8mo | |
| 2 | ▼ 1 | PreferredWave | | 0.855 | 203 | 8mo | |
| 3 | ▲ 2 | BearWaves (not prize eligible) | | 0.826 | 460 | 8mo | |
| 4 | ▼ 1 | Space Coders | | 0.815 | 180 | 8mo | |
| 5 | ▼ 1 | Hidden Neural Layers | | 0.810 | 27 | 8mo | |

## Participation summary

- $\sim 1000$ **participants** submitting solutions during **3 months**.
- Overall good experience. Interesting discussions recorded in the forum.
- Broad pool of participants: Non-professional analysts, students.
- Top-5 leaderboard: Researchers, engineers, AI software developers.

# Quick look at the results (very preliminary!)
## + Michael J. Williams, Chris Messenger (U. of Glasgow)

Comparison metric (AUC-ROC) was selected amongst the ones available in Kaggle.




- **Compare area under ROC curves** with respect to a **baseline uninformed CW search (SOAP)**.
- Top-5 solutions provide better results than an uninformed search.
- Further analysis is ongoing.

# Summary

- Continuous gravitational-waves are a promising avenue to explore the extreme physics of astrophysical objects such as NS.
- Boson cloud evaporation, dark-photon dark matter, and other exotic phenomena, produce similar types of signal on ground-based interferometric detectors.
- Results and new method developments throughout the third observing run of the LIGO-Virgo-KAGRA detectors pave the way towards a first detection as we progress into the era of design sensitivity.