The search for continuous gravitational waves from young supernova remnants (SNRs) in the first part of the fourth LIGO-Virgo-KAGRA (LVK) O4a Observing Run

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Background and Motivation

- While the LIGO-Virgo-KAGRA (LVK) collaboration has detected more than 290 transient gravitational-wave events from compact binary mergers (https://gracedb.ligo.org/; https://www.ligo.caltech.edu/news/ligo20250320), continuous gravitational waves (CWs) have yet to be observed. The fourth observing run (O4) offers unprecedented sensitivity, providing the best opportunity so far to achieve this goal.
- CWs are long-duration, nearly monochromatic signals. They arise from time-varying mass quadrupole moments caused by small deviations from perfect axial symmetry in a spinning neutron star (NS). Such signals are expected to be several orders of magnitude weaker than those from mergers (see Piccinni 2022, Riles 2023, Wette 2023 for recent reviews).
- Detecting CWs would mark a major milestone in astrophysics, providing direct insights into NS structure and dynamics (see **Fig. 1**). Such a detection could constrain asymmetries and crustal deformations, inform the equation of state of ultra-dense matter, shed light on energy loss mechanisms and magnetic field configurations.
- CW observations could uncover hidden NSs or pulsars, invisible to traditional astronomical searches, which often rely on detecting electromagnetic pulsations. CW detection would therefore provide *independent channel* to reveal these hidden objects, expanding our view of the diverse NS population.

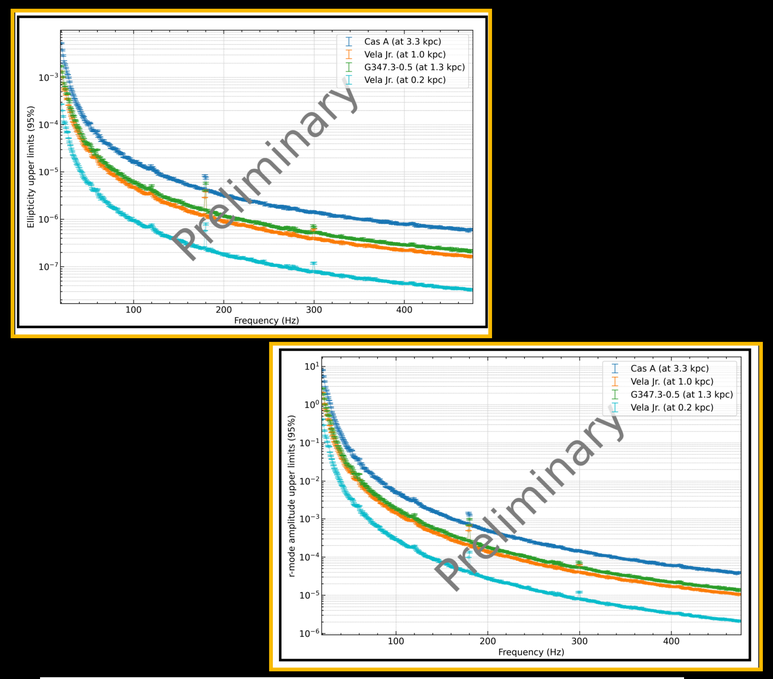

Fig. 1: Preliminary ellipticity and r-mode upper limits for O4a data using the Weave pipeline on 3 CCO-hosting SNRs (Abbott+2025). See Methodoly and Results.

Targets

- Young core-collapse supernova remnants (SNRs), known or expected to house NSs, are excellent targets for the search of CWs.
- In the absence of pulsations, a young NS may manifest itself as (**Fig. 2**):
  (a) *central compact object (CCO)* detected in X-rays near the center of its hosting SNR, as in Cas A;
  (2) a point-like source powering a *pulsar wind nebula (PWN)*, as in DA 495 and IC 443, the synchrotron bubble inflated by the relativistic wind of the NS as it interacts with its surrounding SNR or interstellar medium, and typically observed in radio and/or X-ray energies;
  (3) a compact engine, yet-to-be-discovered, evident through its impact on its surroundings, as for the youngest known SNR 1987A in the LMC.

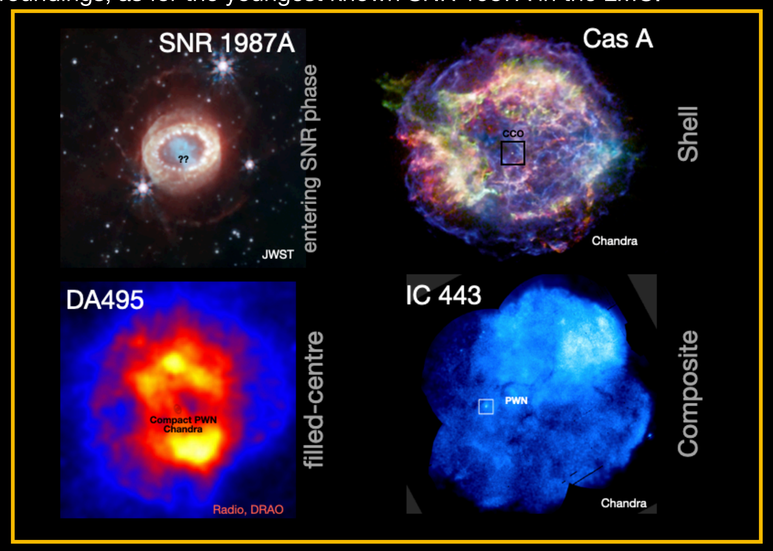

Fig. 2: Example SNRs from our target list

- A CW search in the ~10 Hz–2 kHz would reveal indirectly the presence of objects with spin periods in the~1–200 ms range since the CW frequency is approximately twice the spin frequency of the hidden star, and does not typically exceed that value. Such a search could help reveal the fastest and youngest spinning NSs. This range of rotation period values overlaps with the known pulsation periods of many young rotation-powered pulsars as well as that of the 3 known pulsars in the CCOs family.
- The SNRs list consists of a total of 15 targets drawn originally from the list used in the O3a searches (Abbott et al. 2021, 2022) with updates. In particular, we include SNR 1987A (given the evidence of a compact object or PWN within), exclude G354.4+0.0 (now believed to be an HII region), and focus on the SNRs potentially housing young NSs. Their age and distance estimates have been updated since O3a to reflect the values in SNRcat (2025 version, snrcat.physics.umanitoba.ca; Ferrand & Safi-Harb 2012). These estimates affect the search parameters for each of the pipelines used for our search.

Methodology

- O4a data span from May 24, 2023 to January 16, 2024.
  Five pipelines were used: BSD, SHV and DHV (semi-coherent methods), Weave, and PyStoch (new for O4a):
- ⋆ BSD (Piccinni et al. 2018) is the directed Band-Sampled Data pipeline based on the Frequency Hough tranform.
- ⋆ SHV is the single-Harmonic Viterbi and DHV is the Dual-Harmonic Viterbi pipelines, both based on a hidden Markov model tracking scheme (Sun et al. 2018, 2019). Viterbi takes into consideration the uncertainties associated with the star's stochastic spin evolution, with one of them tracking two harmonics of the star's spin frequency simultaneously.
- ⋆ Weave, used for 3 CCO-hosting SNRs (Cas A, Vela Jr, G347.3-0.5; **Fig. 3**), is a semi-coherent method, based on the F-statistic (Jaranowski et al. 1998). Weave sums matched-filter detection-statistic values over time segments spanning the observation.
- ⋆ PyStoch (Ain et al. 2018) adapts stochastic background mapping, analyzes cross-correlated and folded data in the 20–1726 Hz band. In this search, PyStoch estimates the optimal signal-to-noise ratio as a function of frequency for a specific sky location.
- ⋆ These methods use selected SNRs and frequency ranges and are complementary to each other.

Results and Next Steps

- Upper limits will be placed using all 5 pipelines; as a result we will derive limits on any associated NS ellipticity and r-mode amplitudes (LVK Collaboration 2025).
- **Fig. 2** shows a preliminary sensitivity plot for 3 CCO-hosting SNRs using Weave, and **Fig 1** shows the preliminary equatorial ellipticity and r-mode upper limits (95% efficiency). This result represents the most sensitive wide-band directed searches for CWs from SNRs to date.

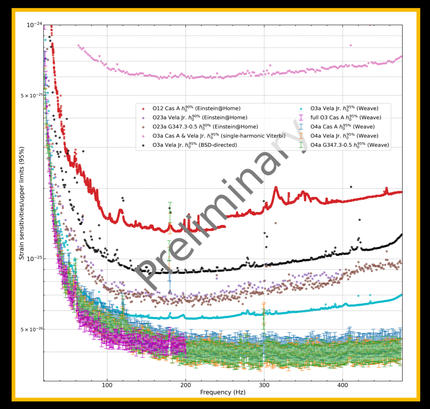

Fig. 3: Preliminary Weave upper limit results for CCO-hosting SNRs

References: Abbott , R. et al. 2021, ApJ, 921, 80; Abbott, R. et al. 2022, Phys.Rev. D, 105, 082005; Ain, A. et al. 2018, Phys. Rev. D, 98, 024001; Ferrand, G. & Safi-Harb, S. 2012, Adv. Sp. Res. 49, 1313 (snrcat.physics.umanitoba.ca); Jaranowski, P. et al. 1998, Phys. Rev. D, 58, 063001; LVK Collaboration 2025 (in preparation); Piccinni, O. J. et al. 2018, Classical and Quantum Gravity, 36, 015008; Piccinni, O. J. et al. 2022, Galaxies, 10, 72; Riles, J. 2023, Living Reviews in Relativity, 26, 3; Sun, L. et al. 2018, Phys. Rev. D, 97, 043013; Sun et al. 2019, Phys. Rev. D, 99, 123010; Wette, K. 2023. Astroparticle Physics, 153, 102880.

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