Multi-messenger Continuous Gravitational Waves

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Book of Abstracts

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Deep Einstein@Home all-sky search for continuous gravitational waves in LIGO O3a public data

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We present the results of the volunteer computing project Einstein@Home all-sky search for continuous gravitational waves in the LIGO O3 public data. This is the most sensitive search to date for the probed waveforms, with frequencies in the 20-800 Hz range and spin-downs between -2.6 x 10^-9 Hz s^-1 and 2.6 x 10^-10 Hz s^-1.

Neutron stars 1 / 2

Neutron star crust deformations, solar system mountains, and gravitational waves

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“Mountains”, or non-axisymmetric deformations of rotating neutron stars, efficiently radiate gravitational waves. We consider analogies between neutron star mountains and surface features of solar system bodies. Both neutron stars and moons, such as Europa or Enceladus, have thin crusts over deep oceans while Mercury has a thin crust over a large metallic core. Thin sheets may wrinkle in universal ways. Europa has linear features, Enceladus has “Tiger” stripes, and Mercury has lobate scarps. Neutron stars may have analogous features. The innermost inner core of the Earth is anisotropic with a shear modulus that depends on direction. Possible anisotropies in the neutron star crust material could produce mountains as the star is spun up or down.

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Universal relations to measure neutron star properties from targetedr-mode searches

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R-mode oscillations of rotating neutron stars(NS) are promising candidates for continuous gravitational wave (GW) observations.In a recent work, we showed that imposing recent constraints on the NS EOS, the r-mode frequency range can increase upto 25% for the most promising candidate PSR J0537-6910 depending on the range of compactness. We also derived universal relations of the NS parameters, compactness and dimensionless tidal deformability with the r-mode frequency. In

another subsequent publication, we investigate how these universal relations can be used to infer various NS intrinsic parameters following a successful detection of the r-modes. In particular, we show that for targeted r-mode searches in LVK data, these universal relations along with the "I-Love-Q" relation can be used to estimate both the moment of inertia and the distance of the NS thus breaking the degeneracy of distance measurement for continuous gravitational wave(CGW) observations. We also discuss that with a prior knowledge of the distance of the NS from electromagnetic observations, these universal relations can also be used to constrain the dense matter equation of state (EOS) inside NS. We quantify the accuracy to which suchmeasurements can be done using the Fisher information matrix for a broad range of possible, unknown parameters, for both thea-LIGO and Einstein Telescope (ET) sensitivities.

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A novel neural-network architecture for continuous gravitational waves

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The high computational cost of wide-parameter-space searches for continuous gravitational waves (CWs) significantly limits the achievable sensitivity. This challenge has motivated the exploration of alternative search methods, such as deep neural networks (DNNs). Previous attempts to apply convolutional image-classification DNN architectures to all-sky and directed CW searches showed promise for short, one-day search durations, but proved ineffective for longer durations of around ten days. In this paper, we offer a hypothesis for this limitation and propose new design principles to overcome it. As a proof of concept, we show that our novel convolutional DNN architecture attains matched-filtering sensitivity for a targeted search (i.e., single sky-position and frequency) in Gaussian data from two detectors spanning ten days. We illustrate this performance for two different sky positions and five frequencies in the $20-1000\mathrm{Hz}$ range, spanning the spectrum from an ''easy" to the ''hardest" case. The corresponding sensitivity depths fall in the range of $82-86/\sqrt{\mathrm{Hz}}$. The same DNN architecture is trained for each case, taking between $4-32\mathrm{hours}$ to reach matched-filtering sensitivity. The detection probability of the trained DNNs as a function of signal amplitude varies consistently with that of matched filtering. Furthermore, the DNN statistic distributions can be approximately mapped to those of the $\mathcal{F}$-statistic under a simple monotonic function.

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Continuous gravitational waves from unknown neutron stars in binary systems

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Unknown neutron stars in binary systems might be one of the best sources of continuous gravitational waves (yet to be detected), due to their millisecond rotation rates, the accretion from their companion which can source the required asymmetry, and the vast unexplored parameter space. These searches have a prohibitive computational cost due to the large number of dimensions that need to be explored and the huge amount of data needed to achieve detectable signal-to-noise ratios. In this review talk we will present a summary of the different algorithms that have been used to carry out these searches, and we will review the different search results up to date.

Astro / 6

Fast optical photometry of Sco X-1 with SiFAP2@TNG

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Millisecond pulsars are ideal targets to probe the strong interaction at supranuclear densities and search for continuous gravitational wave sources. Either the rotation of their magnetic field or the infall of matter lost by a companion star is assumed to power their electromagnetic emission. Recently, we exploited the fast optical photometer SiFAP2 at 3.6m INAF's Telescopio Nazionale Galileo to discover optical pulsations from two millisecond pulsars surrounded by an accretion disk. Thanks to the much higher photon counting statistics of an optical telescope compared to high energy instruments, this has opened the intriguing possibility of searching for weak pulsed signals from accreting neutron stars at an unprecedented sensitivity. Being the best candidates for a continuous gravitational wave detection, the brightest accreting neutron stars (e.g., Sco X-1 and Cyg X-2) are the prime targets. I will discuss the properties of the optical millisecond pulsars discovered so far, the first preliminary results of an optical pulsation search from Sco X-1 as well as prospects for the near and mid-term future.

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Continuous Waves - a review so far

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Finding continuous waves from spinning neutron stars and other long-lived sources is a highly challenging data analysis problem. We need to dig extremely weak signals out of large data sets while covering huge unknown parameter spaces. I will review past efforts of the LVK collaboration and wider community and the current state of the field at the start of O4.

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F-statistic analyses with lalpulsar and PyFstat

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The F-statistic is one of the standard methods for CW searches. We will look at its general motivation from both Frequentist and Bayesian perspectives, its frequency-domain implementation in lalpulsar, and the practical aspects of both coherent and semicoherent searches based on it. We will then use the python package PyFstat for some interactive practical examples.

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Not-so-blind searches for young, isolated, nearby gravitars

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Blind searches for continuous gravitational-wave signals (CWs) survey broad regions in the parameter-space in order to find currently unknown sources with possibly no electromagnetic counterpart. As a result, these searches are amongst the most computationally expensive searches in the current gravitational-wave data-analysis landscape.
In this work, we revisit the detectability prospects of a theoretical, nearby population of young, isolated, CW-driven neutron stars (gravitars) using the current and future generation of ground-based gravitational-wave detectors. We construct specific search setups following the expected properties of this population, which result in a sensitivity improvement with respect to typical all-sky searches.

Neutron stars 1 / 11

Modelling magnetically formed neutron star mountains

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With the onset of the era of gravitational-wave astronomy, the search for continuous gravitational waves, which remain undetected to date, has intensified in more ways than one. Rapidly rotating neutron stars with non-axisymmetrical deformations of their crusts are the main targets for CGW searches. The extent of this quadrupolar deformation (commonly referred to as mountains of the neutron star) is measured by the maximum ellipticity that can be sustained by the crust of a neutron star and it places an upper limit on the CGW amplitudes emitted by such systems. In this paper, following the example set by [1] and [2], we calculate the maximum ellipticity of a neutron star crust generated by the Lorentz force exerted on it by the star's internal magnetic fields. We focus on three different scenarios for different configurations of the star's magnetic fields to calculate the size of the neutron star mountain formed using the scheme devised by [1]. We show that the fiducial ellipticity of the star is enhanced in the presence of strong magnetic fields and it is further enhanced when components of the magnetic field are trapped in the crust. This promising result allows us to estimate the increased size of the neutron star mountains which will be vital when the imminent first detection of continuous gravitational waves happens.

References

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[2] J A Morales and C J Horowitz. "Neutron star crust can support a large ellipticity". In: Monthly Notices of the Royal Astronomical Society 517.4 (Oct. 2022), pp. 5610–5616. doi: 10.1093/mnras/stac3058. url: https://doi.org/10.1093%5C%2Fmnras%5C%2Fstac3058.

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Gravitational waves from magnetar glitches and anti-glitches

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In this talk, I will introduce a simple toy model that can simultaneously explain magnetar glitches and anti-glitches. It is based on the idea of mass ejection from the magnetar and how its magnetic field plays an important part in sustaining the mass quadrupole required for gravitational wave emission. I will use astrophysical arguments to argue that the continuous gravitational waves emitted will be transient in nature and I will comment on whether they will be detectable with future decihertz detectors, like DECIGO and the Big Bang Observer.

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GWLab

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The GWLab is a virtual laboratory for gravitational wave analysis. The first element of GWLab is a continuous wave search model based on the Viterbi search method. Users can carry out a continuous wave search through an online interface at gwlab.org.au. The aims of this GWLab module are to lower the barrier to entry for continuous wave searches as well as enabling easy data provenance and data sharing. GWLab is a project of the Astronomy Data and Computing Services Gravitational Wave Data Centre. This talk will overview GWLab and invite feedback on its development.

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A new method to search for long-duration gravitational wave signals

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Spinning neutron stars are sources of long-duration continuous waves (CWs) that may be detected by interferometric detectors. We focus on glitching pulsars with abrupt spin-ups and long term spin-down, which imprint in CWs as transient signals from weeks to months. Standart method for identifying transient signals is the match-filtering, which combines a coherent detection statistics

over time intervals of different duration. We propose a new method, where the most information from an initial search is considered in order to set up the post-following transient searches. In this method we localise a long-duration signal (longer than a few hours) when the start time and duration of the signal are unknown. We apply the method to search for transient CWs from the frequently glitching pulsar PSR J0537-6910 in the absence of parallel electromagnetic observations of the glitches.

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How to search for continuous gravitational waves while allowing the frequency to wander: selected results using O3 LIGO data

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Rotating neutron stars offer great potential as targets for continuous gravitational wave (CW) searches. However their spin frequency may display stochastic fluctuations over time, due to X-ray flux (and hence accretion torque) variability or timing noise. It is crucial to accommodate for this spin-wandering" in (at least some) CW search algorithms. One approach is to deploy a hidden Markov model (HMM) which postulates that the CW frequency executes a random walk. In this presentation, I will provide an introduction to the HMM search method, and the outcome of three CW searches employing said method using data from LIGO's third observing run O3. These searches targeted the low-mass X-ray binary Scorpius X-1, 20 accreting millisecond X-ray pulsars, and the millisecond pulsar J0437−4715.

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The importance of neutron star oscillation modes in constraining the neutron star EoS and nuclear parameters from GW observations of binary and isolated neutron stars.

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Detection of Gravitational wave events involving neutron stars (NS) provides an excellent scenario for understanding the NS interior. In a binary system, the excitation of NS oscillation modes, such as rotational r-mode and fundamental f-mode, can draw energy from the orbital energy and introduce a phase shift in the observed GW waveform. The ignorance of such dynamical mechanisms can bias the inferred NS properties and hence the NS equations of state (EoS). We investigate how much bias one would expect due to ignorance of such dynamical oscillations on the NS properties and the nuclear parameters constrained over a population of binary neutron star mergers with the current and future GW detectors. Furthermore, the oscillation modes can be excited in isolated NSs, and their detection can reveal the NS interior. Assuming that the NS f-mode is excited during the pulsar glitches, we try to constrain the NS EoS and the nuclear parameters from the future detection of NS f-modes from potential glitch candidates.

Astro / 17

Measuring the magnetic dipole moment and magnetospheric fluctuations of SXP 18.3 with a Kalman filter

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X-ray flux and pulse period fluctuations of accretion-powered pulsars in the Small Magellanic Cloud and elsewhere convey important information about the disk-magnetosphere interaction. In this talk, we present a novel signal processing framework based on the canonical magnetocentrifugal accretion torque and a linear Kalman filter to generate time-dependent estimates of the state variables associated with magnetocentrifugal accretion, namely the mass accretion rate, the Maxwell stress at the disk-magnetosphere boundary, and the radiative efficiency of the accretion. The parameter estimation scheme maximizes the Kalman filter likelihood to infer the underlying static physical parameters, including the magnetic dipole moment μ. We present new results for the Small Magellanic Cloud X-ray transient SXP 18.3 and discuss implications of the parameter estimation platform for (i) a population-wide analysis of magnetic dipole moments μ in the Small Magellanic Cloud; and (ii) searches for continuous gravitational radiation from low-mass X-ray binaries.

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Targeted searches for continuous gravitational waves

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With help from Pulsar timing solutions, it becomes possible to target individual pulsars for their continuous gravitational wave (CW) emission. Such targeted searches are the most sensitive among the various types of CW searches. In the event of a non-detection, the constraints on the gravitational wave strain at twice the spin frequency of the pulsar translate to a constraint on the ellipticity - a quantitative measure of the asymmetry of the pulsar. This talk highlights how pulsar observations aid CW searches, describe two methods - a frequentist and a new Bayesian one, and shows results from recent targeted searches at AEI, Hannover.

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Application of matched-filtering to analysis of nearly periodic gravitational wave signals

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Basic mathematical concepts of gravitational-wave data analysis will be introduced. In particular statistical principles of detection of signals in noise and estimation of their parameters are presented. Derivation of the matched-filtering statistic for signal consisting of a linear combination of several functions of unknown parameters will be presented. The case of amplitude and frequency modulated signal with application to continuous gravitational
wave signals will be discussed in detail.

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I shall present codes to for detections and parameter estimation of three types of gravitational wa
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1.  Monchromatic signal.

2.  Signal from r-mode instabilities in a known  pulsar.

3.  Postmerger signal after binary neutron star merger and ringdown signal
    after binary black hole merger.
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Continuous gravitational waves from Galactic neutron stars: demography, detectability and prospects.

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Surveying the sky in search of continuous gravitational waves (CWs) emitted by unknown neutron stars (NSs) is by now a well established practise. The elusiveness of such signals pushes the involved academic community to refine its search techniques and strategies as well as to review the assumptions made on an astrophysical basis.

We discuss both points and study the prospects for detection of CWs from Galactic NSs making use of a synthetic population, generated by evolving stellar remnants in time according to different models, making this the first "ab-initio" approach devoted to the topic.
We consider the most recent constraints set by all-sky searches for CWs and use them for our detectability criteria.
We track the parameter space occupied by our synthetic signals so as to understand how to invest the limited computational resources in order to maximise the chances of detection.
We discuss prospects in view of 3rd-generation detectors and briefly treat the case of recycled NSs.

Our results show that NSs whose ellipticity is solely caused by magnetic deformations cannot produce any detectable signal, not even by 3rd-generation detectors.
Currently detectable sources show a strong correlation between magnetic field and ellipticity. We find that if low magnetic field isolated neutron stars are very rare, then the highest possible ellipticity values must be realised in nature in order to have a detectable source.
Computational cost might be saved in all-sky surveys by restricting the searches to $\pm 15^{\circ}$ of the galactic plane and by limiting the frequency derivative range as a function of frequency, generally below 600 Hz.

According to our models, 3rd-generation detectors as Einstein Telescope and Cosmic Explorer constitute an enhancement of possible detectable sources of a factor up to ≈ 250.
CWs from recycled NSs will likely remain elusive to detection by current detectors but should be detectable with the next generation of detectors.

arXiv:2303.04714

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Tidal oscillations of neutron stars in eccentric binary systems

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The finite size of neutron stars in binary systems has an observable effect on the binary evolution due to tidal interactions. These tidal interactions in circular binaries result in an adiabatic evolution, where the frequency of tidal excitations coevolves with the orbital frequency. However, in case the orbit is eccentric, there is a periodic sharp pulse of external tidal force, which results in an independent oscillation of the neutron star on its eigenfrequencies, with the energy being drained from the orbit. This provides an opportunity to measure the f-mode frequency independently from the tidal deformability in such systems. We investigate tidal excitations in eccentric binary systems and study whether they have an observable effect on the orbit. We find that gravitational wave signals from tidal oscillations have low signal-to-noise ratio. The observation of the orbital phase shift caused by these tidal oscillations, on the other hand, might be feasible with the current detector network. Since this phase shift highly depends on the f-mode frequency of the neutron stars, the observation of such an effect might be used to constrain the neutron star equation of state through the measurement of the f-mode frequency.

Future GW detectors / 22

Detectability of continuous gravitational waves with future interferometers

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Detection of continuous waves will open a new frontier in multi-messenger astronomy. I summarize detection prospects for the four main scenarios - pulsar searches, Sco X-1 type directed searches, Cas A type directed searches, and all sky surveys. I include developments in gravitational wave interferometry from now to Einstein Telescope and Cosmic Explorer, and contemporary electromagnetic observatories such as the Square Kilometre Array.

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Properties of a multi-template search for a transient signal

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We focus on long, but not infinite duration continuous wave signals and investigate the statistical properties of the detection statistic in the presence of a transient signal searched with a template grid set up for an always-ON continuous signal. We show how this affects the signal-to-noise ratio in real data in the presence of the noise. Based on this research, we propose a search scheme useful when there are no electromagnetic observations to inform on the time of occurrence of the signal.

Astro / **24**

The TRAPUM Survey for New Gamma-ray Pulsars

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TRAnsients and PUlsars with MeerKAT (TRAPUM) is a large survey project using the new MeerKAT radio interferometer to search for new pulsars in the Southern sky. TRAPUM performs targeted searches of parts of the sky that are most likely to host previously unknown pulsars: globular clusters; nearby galaxies; supernova remnants, pulsar wind nebulae and other TeV sources; and unidentified gamma-ray sources detected by the *Fermi* Large Area Telescope (LAT). In this talk, I will present TRAPUM's survey of *Fermi*-LAT gamma-ray sources, and the 21 new millisecond pulsars (MSPs) that we have discovered, nearly half of which are in exotic "spider" binary systems with low-mass, irradiated companion stars. I will describe how detection and timing of gamma-ray pulsations in the *Fermi*-LAT data immediately provides us with 14-year ephemerides for these new MSPs, enabling follow-up searches for continuous gravitational waves in public LIGO data, and often revealing complex long-term orbital period variations due to activity in companion stars. I will also describe how we are obtaining pulsar mass measurements from our new spider binaries via optical modelling to constrain the maximum neutron star mass and equation of state.

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Making sense of narrow spectral artifacts

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Narrow spectral noise artifacts can degrade the sensitivity of continuous wave searches, creating spurious outliers or casting doubt on nearby signal candidates. This tutorial will review some basics of CW detector characterization and walk participants through investigating example artifacts from O3. The tutorial is intended to give participants a better understanding of how LIGO line lists are compiled, what challenges arise in characterizing these artifacts, and what kinds of detector characterization investigations can help to strengthen or dismiss a continuous wave candidate signal.

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Radio monitoring of the pulsars as potential continuous GW sources

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The rotational history of the neutron star underlying a radio pulsar can be tracked by performing repeated observations of the time of arrival of its pulses, via a procedure called "pulsar timing". This presentation introduces the basics of this kind of experiments, and their applicability in the aim of enhancing the sensitivity of the GW detectors to a sample of continuous GW sources.

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Broad parameter space searches and machine learning

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One of the key sources for LIGO-Virgo-Kagra is rapidly spinning neutron stars. These long duration and weak signals introduce many computational challenges including analysing large volumes of data and a wide parameter spaces. When searching for continuous signals with no prior knowledge of its frequency evolution, typical matched filtering approaches become computationally infeasible leading to a need for different analysis techniques. I will introduce one search called SOAP which covers a broad parameter space and discuss how machine learning can be used to aid with these searches.

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A precision orbital ephemeris for Sco X-1

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The low-mass X-ray binary Sco X-1 remains the key target for CWG searches, given that it by far outstrips other candidates in terms of expected strain. Efficient searches require the orbit of the NS to be well-constrained. We have been exploiting optical emission lines that trace the binary companion star in the system for over 20 years now. These Bowen fluorescence lines have been an important probe of binary parameters in a number of XRBs, but in the case of Sco X-1 our focus has been to provide a robust and precise ephemeris for the binary orbit of the neutron star. We will review the technique to highlight how we have not just improved the precision over time, but also have addressed some of the possible systematics of the method and ensure that robust parameter uncertainties can be derived. Whilst this has allowed us to obtain very precise timings for the overall phasing of the neutron star orbit, other parameters relevant to CWG searches (asini, e, …) remain difficult to constrain accurately. We discuss these limitations as well as prospects for continuing to keep the ephemeris accurate during O4 and beyond.

Neutron stars 2 / 29

MATINS: a new 3D code for the magnetothermal evolution of isolated neutron stars

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Isolated Neutron Stars (NS) are intriguing sources of continuous gravitational waves (GW) that have yet to be detected. To emit GWs, a star typically requires a mass-energy distribution that deviates from axial symmetry with respect to its rotational axis. This deviation often stems from the non-axisymmetric distribution of magnetic energy, which arises from the coupled magnetic and thermal evolution of the star. Understanding the magneto-thermal evolution of NSs over time is also crucial for comprehending their spectral and temporal properties and shedding light on the origins of different NS populations.

To achieve these goals, a comprehensive numerical study is necessary, involving the analysis of heat diffusion and magnetic evolution equations, as well as detailed calculations of the star's microphysical properties, such as neutrino emissivity, heat conductivity, and electric conductivity. Additionally, to account for non-axisymmetric effects, a 3D solution of the equations becomes essential. These effects are particularly significant as they contribute to the formation of a non-axisymmetric temperature distribution on the stellar surface, leaving an observable imprint on the object's light curve.

In this talk, I present the implementation of our new code, MATINS, a 3D magneto-thermal evolution code designed to solve the coupled magnetic and thermal evolution equations for isolated NSs with the most detailed microphysical description currently available.

Future GW detectors / 30

A high frequency GW detector to look for CW GWs from BH superradiance

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I will present a new concept of a resonant, high frequency GW detector which operates on the basis of optical levitation. This detector will be sensitive to galactic BH superradiance signals, especially those from axions at the GUT scale. I will describe the working principle, the experimental progress, and the projected sensitivity of this detector to continuous GWs.

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Sequential simulation-based inference for gravitational waves

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The current and upcoming generations of gravitational wave experiments represent an exciting step forward in terms of detector sensitivity and performance. Key upgrades at the LIGO, Virgo and KAGRA facilities will see the next observing run (O4) probe a spatial volume around four times larger than the previous run (O3), and design implementations for e.g. the Einstein Telescope, Cosmic Explorer and LISA experiments are taking shape to explore a wider frequency range and probe cosmic distances.

In this context, however, a number of imminent data analysis problems face the gravitational wave community. It will be crucial to develop tools and strategies to analyse (amongst other scenarios) signals that arrive coincidentally in detectors, longer signals that are in the presence of non-stationary noise or other shorter transients, as well as noisy, potentially correlated, coherent stochastic backgrounds. With these challenges in mind, we develop PEREGRINE, a new sequential simulation-based inference approach designed to study broad classes of gravitational wave signal.

In this talk, I discuss the need of the hour for flexible, simulation-efficient, targeted inference tools like PEREGRINE before demonstrating its accuracy and robustness through direct comparison with established likelihood-based methods. As an example, we show that we are able to fully reconstruct the posterior distributions for every parameter of a spinning, precessing compact binary coalescence using one of the most physically detailed and computationally expensive waveform approximants (SEOBNRv4PHM). Crucially, we are able to do this using only 2% of the waveform evaluations that are required in e.g. nested sampling approaches, highlighting our simulation efficiency as the state-of-the-art when it comes to gravitational waves data analysis.