Amaldi Research Center Summer School

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Paestum

Book of Abstracts

Contents

1

The crystallization process in Ta2O5 and TiO2-Ta2O5 amorphous films

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In the current development of optical coatings for high precision instruments like GW interferometers thermal Brownian noise currently pose a limiting factor on the performances obtainable. In particular in the VIRGO experiment, in the 50-300 Hz region, thermal brownian noise act as the dominant contribution.
Since the Brownian noise is commonly attributed to the existence of many local energy minima in the atomic configuration a non-dissipative system like a crystal is expected to improve the mechanical response of the system. For this reason it is thought that the controlled formation of nanocrystallites inside the amorphous coatings could reduce the Brownian noise. The crystallite size and density must however be precisely controlled in order to find a trade-off between the
improvement of the mechanical properties and the formation of light scattering centers.
In this work we studied the crystallization kinetics of Ta2O5 and Ti:Ta2O5 by analyzing the evolution respect to time and temperature of the XRD spectra of our samples obtained treating them either in situ or via rapid thermal annealing. Due to some uncertainity from literature on the Ta2O5 low temperature crystalline phase the kinetics data are also complemented by Raman measurements and ab initio simulations to tackle the problem.

2

GW190521: Search for Echoes due to Stimulated Hawking Radiation from Black Holes

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Being arguably the most massive binary black hole merger event observed to date, GW190521 deserves special attention. The exceptionally loud ringdown of this merger makes it an ideal candidate to search for gravitational wave echoes, a proposed smoking gun for the quantum structure of black hole horizons. We perform an unprecedented multi-pronged search for echoes via two well-established and independent pipelines: a template-based search for stimulated emission of Hawking radiation, or Boltzmann echoes, and the model-agnostic coherent WaveBurst (cWB) search. Stimulated Hawking radiation from the merger is expected to lead to post-merger echoes at horizon mode frequency of ~ 50 Hz (for quadrupolar gravitational radiation), repeating at intervals of ~ 1 second, due to partial reflection off Planckian quantum structure of the horizon. A careful analysis using dynamic nested sampling yields a Bayesian evidence of 7 ± 2 (90\% confidence level) for this signal following GW190521, carrying an excess of $10^{+9}_{-7}\%$ in gravitational wave energy, relative to the main event. Similarly, the reconstructed waveform of the first echo in cWB carries an energy excess of $13^{+16}_{-7}\%$. Accounting for the "look-elsewhere" effects, we estimate a p-value for false detection probability of 5.1×10^{-3} (or 2.6σ) using cWB pipeline, although the verdict on the co-localization of the post-merger echo and the main event in the sky is inconclusive. While the current evidence for stimulated Hawking radiation does not reach the gold standard of 5σ, our findings are in line with expectations for stimulated Hawking radiation at current detector sensitivities. The next generation of gravitational wave observatories can thus draw a definitive conclusion on the quantum nature of black hole horizons.

3

A deep learning approach to detect gravitational waves from binary close encounters

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Gravitational wave (GW) emission from close encounters (CEs) between neutron stars (NSs) and/or black holes (BHs) binary are recently being considered as new potential astrophysical sources for ground-based detectors. CEs are mostly part of three-body systems, constrained by a dense stellar environment. Their GW emission is the result of a dynamical capture, whose waveform is hard to model with respect to quasi-circular isolated inspiral binary systems, already observed by the LIGO/Virgo collaboration. Unmodeled burst search could be a viable method for detecting such systems in data from Advanced LIGO and Virgo observing runs. We propose a deep learning-based approach for CE detection, based on pipeline using convolutional neural networks capable of detecting transient signals associated to CEs. The training of the algorithm is based on simulated timeseries of LIGO and Virgo data, superimposed to stationary-Gaussian background noise. We present preliminary results on the performance of this algorithm, using a one-dimension convolutional neural network, with the ultimate goal of applying to real data.

4

Beyond the long-wavelength approximation: an overview

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In spite of the fact that gravitational-wave (GW) interferometers detect GWs in a very complicated (and very clever) way, the final output (i.e. that used for data analysis, obtained after calibration and other processes) is up to now quite simple: the detected strain is linear in the two GW polarizations, which are multiplied by the corresponding antenna patterns which describe the detector's response to each signal source location in the sky.
The usual antenna patterns do not take into account the transfer function of the interferometers, and as a result they are not frequency-dependent: this is an approximation that works quite well as long at the signal frequencies are well below the LIGO - Virgo free spectral range (FSR) (for the LIGO detectors this frequency is about 37.5 Hz, and for Virgo 50 kHz).
Next-generation detectors, such as Cosmic Explorer (CE) and the Einstein Telescope (ET), are expected to have far longer arms (40 km for CE, 10 km for ET) so that phenomena associated with frequencies around 1000 Hz (like a signal from a core-collapse supernova) are no longer so "low" with respect to the FSR of these detectors (3750 Hz for CE, 15000 Hz for ET).
This means that the transfer function must be taken into account and this produces a frequency dependence of the antenna patterns. However, while the frequency-domain version of the response function has been extensively explored, the time-domain version has not: this time dependence is described in this work.
Moreover, for a fixed frequency the frequency-dependent corrections depend on the source location as seen by each detector. This produces a frequency- and location-dependent systematics that must be taken into account.
In my work I explore the implications of these corrections for data analysis, above all for the next generation of detectors, trying to understand how much the analysis could be biased by using the long-wavelength approximation.

5

Oblique Rotators and General Relativistic Calculations

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Neutron stars are very dense objects found in the universe. These neutron stars can have very high angular velocity about their axis, such fast-spinning neutron stars are also known as pulsars. The rotation axis of a pulsar is defined as the axis around which a star rotates, similarly, we can define an axis called a magnetic axis, which is the axis along which the magnetic field lines originate. In an idealistic scenario, these two axes are not pointed in the same direction, thus forming a finite angle between them. Such stars are called oblique rotators. Pulsars having very high angular velocity can also result in the deformation of the shape of the star thus forming a spheroid. In this talk, I will present how we can model such stars considering general relativistic effects. I will also explain how the magnetic fields, charge density at the surface of the star, and power-loss of such a star varies

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6

Development and performance measurement of position sensors for seismic isolation systems of ETpathfinder prototype GW detector

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Linear Variable Differential Transformers(LVDTs) are the standard, precise, non contact position sensors used in VIRGO and KHAGRA suspension systems which are UHV compatible. The main working principle of this sensor is conversion of linear displacement into an electrical signal through mutual induction. This can be combined with voice coil actuators. Due to their extreme importance in seismic attenuation systems in GW detectors, modelling followed by simulation to achieve the optimal performance is crucial. The goal of the poster presentation is to demonstrate my work on modelling of LVDT designs (used in ETPF) to improve the sensitivity of the sensor. Python interface to finite element methods, pyFEMM, is used. Simulation results for 6 designs will be discussed with the improvements in the linearity and response.

7

A framework for Bayesian inference of gamma-ray burst afterglow properties

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Ever since the joint discovery of GW170817 and GRB170817A, neutron star mergers and their associated gamma-ray burst events have been a focus of study in the field of multi-messenger astronomy. While Bayesian inference is an effective method for performing model comparison and parameter inference, its application is limited by the computational cost of evaluating the likelihood function of any given physical system. In this work, we perform quick parameter estimation on simulated gamma-ray burst X-ray light curves using an interpolated physical gamma-ray burst model, providing a ~90x speed-up per likelihood evaluation. This is achieved by generating a grid of gamma-ray burst afterglow light curves across the parameter space and replacing the likelihood function with a high-dimensional interpolated simulated grid of light curves. I will discuss how this can be used in future work to perform multimessenger Bayesian analysis where the X-ray observations are analysed in conjunction with the gravitational wave strain and the prompt gamma-ray burst emission.

8

Effect of tidal field on the gyroscopic precession around compact astrophysical objects

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A spinning gyro orbiting around a massive compact astrophysical body can capture the general relativistic effects around the central object. If the gyro rotates at some fixed orbit around the star, then the qualitative and quantitative nature of the overall gyro precession frequency can reveal various properties of the central object. If the central object has a companion, then the precession frequency of the gyro will get affected. This work discusses how the tidal field due to a companion object affects the spin precession frequency and orbital angular velocity of a spinning gyro orbiting around a compact astrophysical object. The central object is either a neutron star or a white dwarf. The test gyro is any planetary or asteroid-like object orbiting a neutron star or a white dwarf. Moreover, the companion object that causes the tidal field can be a neutron star, white dwarf or a stellar black hole.

It is seen that the tidal effect significantly affects the spacetime around the central object, which affects the gyro precession frequency and the orbital angular velocity. Slow rotation approximation has been considered for the central object, which creates negligible deformation. The change in the gyro's precession frequency and the orbital angular velocity due to the tidal field increases with an increase in the companion object's mass and decreases as the separation between the central star and the companion star increases. The tidal effect also varies with the stiffness of the equation of state of matter describing the host star. The lower the compactness of the host star, the greater the tidal response; thus, the greater the change in the gyro's precession and angular velocity of the geodesic.

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9

Progress of KAGRA Output mode Cleaner

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Output Mode Cleaner (OMC) is implemented at the AS port to enhance sensitivity of GW detectors, filtering out junk light, including HOMs and RF sidebands, thereby reducing the shot noise. Since it is the last hardware part of GW detectors passing light that carries GW signals, its performance directly affects sensitivity.
As for KAGRA OMC, some problems were found in O3GK. The most significant issue was its low transmissivity. We have improved it from $\sim 80\%$ to $\sim 97\%$ by changing the design and mirrors. Other minor issues have also been fixed. We report on the current status of KAGRA OMC toward O4 and how it will improve the sensitivity of KAGRA.

10

Bayesian Source Fraction Analysis of Ultra-High-Energy Cosmic Rays and the Impact of the Galactic Magnetic Field

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The sources of Ultra-High-Energy Cosmic Rays (UHECRs) have yet to be discovered due to the extensive number of parameters that influence the primary energy and direction. The Galactic Magnetic Field (GMF) strongly influences the deflections of said UHECRs and is a crucial factor in determining UHECR sources. In this work, we build upon the idea of the Bayesian source fraction analysis framework developed by Soiaporn et al. (arXiv:1206.4569) and further extended by Capel and Mortlock (arXiv:1811.06464). The previous analysis framework utilizes Bayesian analysis to associate extragalactic sources from known catalogs to the detected energies and directions of UHECRs measured from the Pierre Auger Observatory. We extend this by introducing the effect of the non-uniform deflections within the GMF using the CRPropa3 simulation code. We further investigate the impact of heavier composition on the inferred source associations. Using the public data from the Telescope

Array experiment, we observe that more source-UHECR associations are present in the Northern Sky as compared to those in the Southern Sky.

11

Squeezed light generation at 1550nm

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We report an experimental generation of squeezed light at 1550nm using a continuous-wave laser. An electric field noise reduction of 1.5 dB below the shot noise was observed. To generate squeezed light, we employed parametric down conversion (PDC) process where 775nm pump light is converted to 1550nm squeezed field. The 775nm pump was produced by second harmonic generation (SHG) in a single pass design. We made an optical parametric oscillator (OPO), the optical resonator where PDC process occurs. Homodyne detection was utilized to measure squeezed light. We plan to generate spatially multimode squeezed light by making a detuned self-imaging cavity. Spatially multimode squeezed light is more robust to mode mismatching than a single-mode squeezed light, so it can be applied to metrology like gravitational detection to reduce the mode mismatch loss.

12

Gravitational wave signals from single-binary black hole encounters in nuclear star clusters

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The next generation of interferometers will be able to detect a great number of signals from different kinds of sources. Among these sources there may be bursts from close encounters between black holes (BHs) in star clusters. In our work, we present a first study of how often single-binary BH encounters can happen in nuclear star clusters (NSCs) as a function of redshift, and whether these encounters are observable by gravitational-wave (GW) detectors. We focus the study on single-binary encounters that are effectively hyperbolic, leaving out the resonant encounters. We find that in NSCs single-binary encounters occur rarely compared to binary mergers, and that the hyperbolic ones most likely produce the strongest GW emission below the observation band of terrestrial GW detectors. While several of them can be expected to occur per year with peak energy in the LISA band, their amplitude is low, and detection by LISA seems improbable.

13

Effects of accreting Primordial Black Holes on the CMB

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Primordial Black Holes (PBHs) maybe formed in the Early Universe during the so called radiation-dominated era, significantly before the appearance of the first nuclei and the first stars. The interest on this dark matter candidate was renewed after the first binary black hole gravitational gave event detected by the LIGO-Virgo Collaboration. In particular it was proposed that PBHs with masses of order ~10 $M_{\odot}$ can make up a substantial fraction of the dark matter. There are many constraints that come from the non-detection of radiation produced by the PBH as a result of the gas accretion process.

The goal of this work is to improve the modelling of PBH accretion in order to obtain more robust constraints on PBH abundance. Existing constraints rely on too simplistic accretion models, e.g., spherical accretion, or on extreme assumptions, e.g., large PBH luminosity. In particular, we already have evidence that astrophysical BHs produce outflows (winds and/or jet), which were never considered in the PBH scenario. Recent works have argued that the formation of outflows can be achieved by a variety of mechanisms, i.e., that they are a phenomenon that arises quite naturally. Moreover, once these outflows formed, they can damp the PBH accretion by a factor few up to one order of magnitude due to mechanical feedback they generate. I will provide an improved modelling of PBH accretion which includes also the possible presence of outflows and their impact on the accretion rate and the energy injection in the surrounding medium.

14

Freely-falling bodies in standing-wave spacetime

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The phenomena of standing waves are well known in a mechanical and electromagnetic setting where the wave has the maximum and minimum amplitude at the antinodes and nodes, respectively. In the context of the exact solution to Einstein's field equations, we analyze a spacetime that represents standing gravitational
waves in an expanding Universe. The study of the motion of free masses is subject to the influence of standing gravitational waves in the polarized Gowdy cosmology with a three-torus topology. We show that antinodes attract freely falling particles and we trace the velocity memory effect.

16

Targeted search and ensemble procedure for the detection of gravitational waves from known pulsars

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We present a multiple test for the targeted search of continuous gravitational waves from an ensemble of known pulsars, combining multidetector single pulsar statistics defined through the 5n-vector method. In order to maximize the detection probability, we describe a rank truncation method to select the most promising sources within the ensemble, based on the p-values computed for single pulsar analysis. We also present the results obtained considering a set of 220 known pulsars and the O3 LIGO and Virgo datasets. No evidence of a GW signal from the ensemble was found, so we set 95% credible upper limit on ensemble parameters.

17

Starscream: A transformer model for the detection of Gravitational-Wave Compact Binary Coalescences

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In recent years there has been been an explosion in the use of artificial neural network transformer models to solve a variety of different problems across many fields. In this paper we take the transformer model archetype and apply it to a well understood problem in Gravitational-Wave data analysis - the detection of Compact Binary Coalescences (CBCs), mergers of black holes and neutron stars. As opposed to Convolutional Neural Networks (CNNs), which have been the prevalent avenue of investigation with Gravitational-Wave machine learning, transformer models use self-attention which enables aggregation of global information than focusing on local feature detection. They also have the advantage of treating time series data sequentially rather than CNNs which view a time series similarly to an image. By examining the attention maps of the transformer model, in contrast to the learned filters of the CNN, we demonstrate a fundamentally different method of analysis which we propose is more suitable for detection.

18

Binary Neutron Star populations in the Milky Way

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Binary neutron star (BNS) systems play a central role in many areas of modern astrophysics. Thanks to high precision of timing measurements of pulsars, BNSs can be considered as cosmic laboratories for gravitational physics. Furthermore, their mergers can be loud sources of gravitational waves, the observation of the electromagnetic counterpart of GW170817 paved the way for new frontiers in multimessenger astrophysics. From the theoretical point of view, there are still many open questions associated to BNSs. What are the processes that most affect the evolution of a BNS? What are the birth spins and magnetic fields of neutron stars and how do they evolve?

In my work, I carried out a detailed analysis of the properties of the BNS population in the Milky Way through an innovative computational approach. I combined cosmological simulation suites, EAGLE and IllustrisTNG, with the state-of-the-art binary-population synthesis code SEVN. I implemented in SEVN detailed prescriptions for the evolution of spins and magnetic fields of neutron stars and I studied the resulting population of BNSs for various common envelope efficiencies and magnetic field decay timescales. After accounting for radio survey selection effects, I compared the results of my simulations with the observed population of Galactic BNSs. I found a best-fit model that agrees with both the radio population of pulsars and the current BNSs merger rate.

In this talk, I present preliminary results on the best-fit model and I discuss the parameters that most affect my results. Finally, I discuss the implications of my results for the forthcoming generation of radio telescopes and gravitational-wave detectors.

19

Multi-messenger observations of black hole-neutron star mergers in the O4 run

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Black hole – neutron star (BHNS) binaries are among the least known objects in the Universe. Only recently were we able to observe them for the first time, and not via the traditional channel of electromagnetic (EM) waves, but through the new window of gravitational waves (GWs). In January 2020, the detectors of the LIGO/Virgo/KAGRA collaboration (LVK) detected two GW signals compatible with BHNS mergers, GW200105 and GW200115, which were then followed by few other candidates. BHNS mergers are expected to produce kilonova (KN) and short gamma-ray burst (SGRB) emission. The former is powered by nuclear-decay of heavy r-process elements, inside the NS material ejected during the merger. The SGRB emission is instead linked to the launch of a relativistic jet, following the formation of an accretion disk around the merger remnant. It is divided into SGRB prompt, due to bulk energy dissipation in the jet, and afterglow, due to the interaction with the ambient medium. Unfortunately, no BHNS GW detection has yet been associated with an EM counterpart, possibly due to either poor sky-localization, or the absence of any emission at all. The increase in the number of observed sources in future observing runs, and the detection of EM signatures, will allow to constrain the properties of this mysterious class of sources, and shed light on aspects such as component BH mass and spin distributions, merger rate densities and formation channels.

For these reasons, predictions of the number of sources detectable during future GW network observing runs, as well as the properties of the expected EM emissions, will be of extreme value in order to organize the EM follow up campaigns to GW events, and enhance the probability of catching these rapidly-fading transients. I am currently working on a related project in collaboration with the University of Milano-Bicocca, which I am going to present. We developed a self-consistent method to compute the GW, EM and joint GW+EM detection rates during the imminent O4 observing run of the LVK network. Our approach is based on simulating a synthetic population of BHNS merging binaries, and inferring the properties of the ejected matter as a function of the binary parameters via numerical-simulation-informed fitting formulae. The core of our work consists in a suite of semi-analitical models to compute the kilonova, SGRB afterglow lightcurves in different frequency bands, and SGRB prompt emission fluxes, as a function of the ejecta properties. Simulating also the GW signal, and imposing appropriate detection thresholds, allows us to finally obtain the GW, EM and joint GW+EM detection rates, considering different observing scenarios. Our work tries to answer fundamental questions such as: do all BHNS mergers produce an EM counterpart? Which counterpart can be detected in wide-area surveys or targeted observations? How long after the merger do we expect to detect the KN and afterglow emissions in a given frequency band? The comparison between our predictions and what will be actually observed during O4 will help dispel the mistery around the properties and evolutionary path of these sources.

20

Detection capabilities of 3G interferometers: prospects for cosmology

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Cosmological parameters can be constrained if simultaneous access to distance and redshift measurements is achieved. Gravitational waves from compact binaries represent the so-called standard sirens, as their waveform provides direct information about the luminosity distance to the source. However, we do need some non gravitational information to break the degeneracy between source mass and redshift and get access to the redshift of the source. In this work, in particular, we focus on dark sirens, where gravitational data comes from binary black hole systems.

Dark sirens approach relies on statistical methods to estimate the redshift. A host galaxy is probabilistically associated to the gravitatinal wave event within the localization volume provided by the detectors. Therefore, an important part of this work is the analysis of distance estimates and detection capabilitites of the future ground based interferometers, especially Einstein Telescope. Large number of binary back hole events are simulated with ET alone and in network with other observatories thanks to a Fisher matrix approach. In particular, we developed a Fiher matrix code in our own group, led by Jan Harms, called GWFish, which has been recently released. It allows us to investigate the parameter estimation capabilitites of future observatories. It has also been tested against a posterior sampling approach, like Bilby, to check the reliability of the Gaussian approximation of the likelihood, with promising results.

As a result, we want to stress the robustness of a Fisher matrix approach and show the encouraging results for distance estimates even for ET alone. Above all, observations by future gravitational waves interferometers could be of great benefit for cosmology.

21

A novel method for the Sky Localisation of Unmodeled Gravitational-Waves using Coherent Null-Energy Maps cleaned with a Spherical Convolutional Auto-encoder

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The MLy Gravitational-Wave Transient Burst detection pipeline has entered an advanced stage of development in preparation for its debut in O4. A crucial part of the desired low-latency detection is the rapid generation of Sky Localisation maps in order to allow the opportunity for multi-messenger follow-up. We apply a coherent reconstruction of a linear combination of detectors using the H_+ and $H_\times$ polarisation components of the signal. In the null-energy formalism, we construct coherent statistics to perform a glitch-robust analysis for unmodelled gravitational-wave transients. A combination of this along with the incoherent null-energy can be used, by applying a minimum threshold, to highlight a maximum credible region of source origin. Maps generated using this method can be produced quickly (<<1s), as is required for the low latency nature of the pipeline. This method produces a noisy sky map, which is then passed through a denoising autoencoder in order to achieve a clean output. Since such sky localisation maps are spherical, we have utilised spherical Convolutional Autoencoder techniques to achieve this.

23

Probing gravitational wave birefringence

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Ezquiaga et al. 2020, showed that the lensing of gravitational waves(GWs) by intervening mass, in the theories beyond general relativity(GR) can mix and alter the speed of GW polarisations. As a result, the individual polarisations would reach detector with a time delay in between. In this study, we follow up on observational prospects of the scrambling of GWs, i.e when the time delay between the (+, ×) polarisations is less than the duration of signal coming from the compact binary coalescences(CBCs). We show that from the low FAR
events detected by LIGO-Virgo one can identify the birefringence caused by beyond GR lensing with the help of Bayesian inference. From the non-observation of birefringence, we additionally put constraints on the beyond-GR lensing cross-section.

24

Prospects for the observation of continuous gravitational waves from spinning neutron stars lensed by the galactic supermassive black hole.

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We study the prospects of detecting continuous gravitational waves (CGWs) from spinning neutron stars, gravitationally lensed by the galactic supermassive black hole. Assuming various astrophysically motivated spatial distributions of galactic neutron stars, we find that CGW signals from a few ($\sim 0 - 6$) neutron stars should be strongly lensed. Lensing will produce two copies of the signal (with time delays of seconds to minutes) that will interfere with each other. The relative motion of the neutron star with respect to the lensing optical axis will change the interference pattern, which will help us to identify a lensed signal. Accounting for the magnifications and time delays of the lensed signals, we investigate their detectability by ground-based detectors. Assuming an ellipticity of $\epsilon = 10^{-7}$ and the spin distribution of known pulsars, lensed CGWs are unlikely to be detectable by LIGO and Virgo in realistic searches involving $\mathcal{O}(10^{12})$ templates. However, third-generation detectors are likely to observe some of them. For the spatial and spin distributions of NSs that we consider, the probability of detecting at least one lensed NS is $\sim 1\% - 44\%$. Such an observation will enable interesting probes of the supermassive black hole and its environment.

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Welcome

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Giancarlo Cella

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Giancarlo Cella

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Michela Mapelli

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Kazuhiro Yamamoto

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Kazuhiro Yamamoto

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Barbara Patricelli

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Barbara Patricelli

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Gianpietro Cagnoli

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Gianpietro Cagnoli

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Michela Mapelli

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Michela Mapelli

37

Kazuhiro Yamamoto

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Paolo Ruggi

39

Elisabetta Cesarini

40

Elisabetta Cesarini

41

Marco Barbieri

42

Marco Barbieri

43

Paolo Ruggi

44

Paolo Ruggi

45

Lorenzo Maccone

46

Lorenzo Maccone

47

Constraints on Compact Dark Matter from Gravitational-Wave Microlensing

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If a significant fraction of dark matter is in the form of compact objects, they will cause microlensing effects in the gravitational-wave signals observable by LIGO and Virgo. From the nonobservation of microlensing signatures in the binary black hole events from the first two observing runs and the first half of the third observing run, we constrain the fraction of compact dark matter in the mass range 10^2–$10^5 M_\odot$ to be less than 50%–80% (details depend on the assumed source population properties and the Bayesian priors). These modest constraints will be significantly improved in the next few years with the expected detection of thousands of binary black hole events, providing a new avenue to probe the nature of dark matter.