11th LISA CosWG Workshop

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Departamento de Física e Astronomia - Universidade do Porto

LISA CONSORTIUM

Book of Abstracts

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Observing Kinematic Anisotropies of the Stochastic Background with LISA

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Next-generation gravitational wave detectors hold the capability to track unresolved gravitational waves bundled into a stochastic background. This composite background contains cosmological and astrophysical contributions, the exploration of which offers promising avenues for groundbreaking new insights into very early universe cosmology as well as late-time structure formation. However, such signatures will be entangled and mixed with instrumental noise & artefacts, making a robust component separation a particularly challenging task, and the object of an intense research effort from the community. A promising diagnostic tool for identifying the origin of SGWB signals bases on exploiting kinematic anisotropies, that is, the deformations of the SGWB angular distribution

induced by the observer motion w.r.t. CMB rest frame. Detection by LISA of such Doppler modulation may act as a smoking-gun for an extragalactic background imprint. This presentation is dedicated to exploring the capability of such detection with LISA and to associated data analysis techniques.

In this talk, I will present the results of our recent publication \[arXiv:2401.14849\], and I will extend to potential further work and improvements. We have developed a full end-to-end pipeline for the extraction of extra-galactic signals, based on kinematic anisotropies arising from the galactic motion, via full-time-domain simulations of LISA's response to the gravitational wave anisotropic sky. Employing a Markov-Chain-Monte-Carlo map-making scheme, multipoles up to $\ell = 2$ are recovered for scale-free spectra that support an interpretation as signals originating from cosmic strings in the case of a high signal-to-noise ratio. We demonstrate that our analysis is consistently beating sample variance and is robust against statistical and systematic errors. The impact of instrumental noise on the extraction of kinematic anisotropies is investigated, we establish a detection threshold of Ω_{GW}
$gtrsim 5 \times 10^{-8}$ (scale-free) in the presence of instrument-induced noise.

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Signals from cosmic strings with gravitational backreaction

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We present results of gravitational backreaction applied to a realistic population of cosmic strings. Backreaction smooths strings and reduces the rate of energy loss, Γ. This smoothing does not give rise to strong cusps, with cusp-like behavior subdominant until at least modes $n \sim 10^6$. Backreaction generally causes strings to self-intersect, but the intersections typically involve only a small fraction of the loop's length; however, we discuss this as a mechanism to possibly unbind loops from galaxies. We close with a discussion of the impact of backreaction on the cosmic string gravitational wave background.

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Accelerating SGWBinner code with the JAX framework

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SGWBinner is a primary tool to investigate the reconstruction of cosmological gravitational wave signals with LISA. Its algorithms are highly developed and most parts of the analysis can be done easily on a laptop, but the final MCMC part is still time consuming. To overcome this situation and accelerate the study of cosmological gravitational wave sources, we have accommodated the JAX framework in the existing code. This provides faster computation of the likelihood function and depending on the template, MCMC becomes a few to ten times faster. As a demonstration, we report the analysis with generalized foreground parameters.

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Gravitational wave lensing in wave-optics: a new approach including polarization effects

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An intriguing aspect of gravitational wave lensing is the emergence wave-effects: interference and diffraction patterns in the waveforms due to finite size effects, occurring when the wave's wavelength is comparable to the Schwarzschild radius of the lens.
These phenomena are particularly interesting because they induce frequency dependent modifications in the waveforms, allowing for a better lens'parameter estimation, especially if the lensing event has an electromagnetic counterpart in the opposite optical regime.
Despite the promising potential of wave-optics effects, our current theoretical tools, based on the diffraction integral, rely on two main assumptions that limit their effectiveness: the eikonal and paraxial approximations on one hand, and the neglect of spin effects on the other.
In this talk I will present our new formalism, based on the established proper time technique, illustrating its robustness as the generalization of the existing framework going beyond all of the limitations mentioned.

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Gravitational waves from a first-order phase transition: sound waves and turbulence

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I will review the production of GWs by the anisotropic stresses of velocity and magnetic fields induced in a first-order phase transition. I will present analytical estimates and numerical simulations that address the production of gravitational waves by sound waves and by MHD turbulence, and show how such an observation by LISA could allow us to understand the nature of the electroweak phase transition and in addition can be used to put constraints on primordial magnetic fields that could persist as intergalactic magnetic fields in the cosmic voids of the large scale structure of the Universe at present time.

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The dark timbre of gravitational waves

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Gravitational wave timbre, the relative amplitude and phase of the different harmonics, can change due to interactions with low-mass halos. We focus on binaries in the LISA range and find that the integrated lens effect of cold dark matter structures can be used to probe the existence of Mv ⊠ 10 M⊠ halos if a single binary with eccentricity e = 0.3–0.6 is detected with a signal-to-noise ratio 100 – 10ˆ4.

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Decay of three-dimensional acoustic turbulence and the resulting power spectrum for cosmological gravitational waves

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A key determinant of the intensity of GWs from a first order phase transition is the lifetime of the acoustic turbulence which follows. We have simulated acoustic turbulence in three dimensions using a highly optimized Python code and study the decay of the shocks and derive simple functional forms for the time evolution of the kinetic energy and the integral length scale at late times using the physical properties of the system. We make a new prediction for the universal shape of the energy spectrum by using its self-similar decay properties and the shape of individual shocks. The obtained model for the spectrum and the decay is used to build an estimate for the GW power spectrum generated by decaying acoustic turbulence under approximations where the expansion of the universe can be neglected. We find that due to the decay the spectrum is modified compared to the non-decaying case by having a convergence in time both in the spectral amplitude and in the

power law of the peak, so that the converged amplitude corresponds to that of the non-decaying case at high wavenumbers after two shock timescale units, and the power law converges to k^4 at times for which the integral length scale has grown to be at least three times the initial one.

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Testing the statistical isotropy of the Universe with stochastic gravitational wave backgrounds

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The anisotropies of stochastic gravitational wave backgrounds (SGWB) of both cosmological and astrophysical origin retain precious information on the geometry and the content of the Universe at early times.
In this talk we present some test of statistical isotropy which can be conducted by observations of SGWB alone and in cross-correlation with other cosmological observables, such as the Cosmic Microwave Background.
In particular, we will focus on some techniques to estimate the monopole, dipole and quadrupole with the LISA-Taiji network, illustrating the constraining power of space-based interferometers.

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Cosmic String Source Modelling with Adaptive Mesh Refinement

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Cosmic strings are topological defects that arise in particle physics models with a spontaneously broken U(1) symmetry, motivated, for example, by the Peccei-Quinn mechanism. Global strings are predicted to radiate massless dark matter axions, massive particles and gravitational waves. If we are to detect these strings via gravitational waves, or to detect axion dark matter in the cosmological post-inflationary symmetry breaking scenario, understanding the magnitude and spectrum of the radiation from strings will be crucial. In this talk, I will detail my work on the analytic modelling of axion string radiation using adaptive mesh refinement simulations and its dependence on parameters such as the string amplitude and the radius of curvature. I will conclude by discussing the applications of these results for axion dark matter and cosmic string gravitational wave predictions.

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From Hubble to Bubble - curvature induced phase transitions after inflation

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The prospect of primordial gravitational waves (GW) offers a promising new window for inflationary cosmology and particle physics. In our study 2309.08530, we investigated the evolution of the potential of a minimal scalar BSM extension at the end of inflation. More specifically, we focused on the transition from the potential-dominated de Sitter epoch to the kinetic dominated period of kination. In this setting, a strong first-order phase transition can take place due to the sign change of the curvature scalar, which the BSM field is non-minimally coupled with. Therefore, an amplified GW spectrum can be produced from the collision of true-vacuum bubbles during kination. With this prescription, we propose a new triggering mechanism for BSM phase transitions that could be potentially observable with future detectors. Finally, I will present a connection of this mechanism with a Higgs-portal dark matter model that we are currently investigating at FCUP.

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Weakly-parametric approach to stochastic background inference in LISA

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Detecting stochastic gravitational wave backgrounds (SGWBs) with the Laser Interferometer Space Antenna (LISA) is one of the mission's scientific objectives. Disentangling SGWBs of astrophysical and cosmological origin is a challenging task, further complicated by the limited instrumental noise knowledge.

Various algorithms for simultaneous fit of noise and signal exist in literature, either leveraging templated inference for both or just one. In this study, we introduce a weakly-parametric approach by implementing an inference based on Gaussian Processes: it can be applied in various contexts with great flexibility both in SGWB and noise modelling.

We assess the effectiveness of our approach for signals with unknown spectral shapes by systematically exploring the model hyperparameters—a milestone towards a more efficient trans-dimensional exploration.

To validate our method, we apply it to the realistic scenario of Extreme Mass Ratio Inspiral (EMRI) backgrounds. Given the complexities of EMRI's gravitational-wave waveform and uncertainties related to the underlying astrophysical population, a completely agnostic modeling approach is recommended.

Our findings show robustly that our algorithm is capable of recovering the injected signal with large and uninformative priors, while simultaneously inferring on the noise level.

In addition, I will present ongoing improvements of the algorithm specifically targeting non-stationary signals originating from anisotropic source distributions, with encouraging results.

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Hierarchical inference of cosmological and population parameters from gravitational wave data with and without electromagnetic counterparts

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Gravitational waves (GWs) from compact binary coalescences are standard sirens that can probe the cosmic expansion history of the late-time Universe if the source redshift is known. Methods for injecting redshift information into the inference process range from the direct detection of electromagnetic counterparts ("bright sirens") to the use of statistical properties inferred either from a catalog of possible hosts or from spectral features in the source-frame mass distribution ("dark sirens").
In this talk, I will present CHIMERA, a new code that combines these methods within a hierarchical Bayesian framework to constrain cosmological and GW population parameters simultaneously. I will discuss the constraints obtained with this code on a set of simulated O4 and O5 GW events and a complete galaxy catalog, showing that a percent-level measurement of H0 could be achieved in O5 using a spectroscopic galaxy catalog. Finally, I will describe the technical improvements we are developing to address the computational limits of the code and to accommodate the large amount of GW data coming from 3G detectors, such as the Einstein Telescope and LISA.

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Characterisation of the power spectrum of acoustically generated gravitational waves with a soft equation of state

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Future space-based interferometers, such as LISA, offer an unprecedented opportunity to detect signals from the stochastic gravitational wave background originating from a first-order phase transition at the electro-weak scale, when elementary particles become massive. The generation of masses can induce a softening of the equation of state of the cosmic fluid and thereby accelerate the expansion rate of the Universe. In this work we study the effect of a softer equation of state on the power spectrum of gravitational waves generated by the sound waves in the plasma during the acoustic phase of the transition. We carry out the analytic calculation assuming that the sound speed and the fluid shear-stress that sources tensor perturbations remain approximately constant during the acoustic phase. The effect of a softer equation of state is twofold: (i) a scale-independent suppression of the power spectrum at all scales, due to the modified propagation of both sound and gravitational waves and (ii) the peak of the spectrum moves to smaller frequencies as the equation of state becomes softer. The power-law scaling of the power spectrum is unaffected by the softening of the equation of state. Our work improves the current estimation of the gravitational waves power spectrum from first order phase transitions and expands the possible scenarios of transitions that can be tested by LISA.

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Gravitational Waves from compressional and vortical modes in strong first order phase transitions

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In many extensions of the Standard Model of particle physics, there would have been first order phase transitions in the early Universe, producing a stochastic background of gravitational waves. This talk reports on large-scale numerical simulations of gravitational wave production at strong phase transitions, seeking to understand the characteristic spectra of the evolving compressional and vortical modes of the fluid.
One transition proceeding by detonation and another by deflagration have been studied.
A flow with similar magnitudes of vortical and compressional modes, as produced by the deflagration, has a very similar form to the mostly compressional flow produced by the detonation. For the first time, saturation of the gravitational wave power spectra due to non-linear decay of the flow is seen.

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Imprints of new physics phenomena: from collider to gravitational waves observables

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Despite the tremendous success of the Standard Model (SM) with its properties remarkably well measured, there is overwhelming phenomenological evidence that strongly suggests the need for physics beyond the current SM, such as explanations for dark matter and neutrino masses. In this presentation we will discuss LISA's potential to reveal further evidence of new physics phenomena through upcoming measurements of the Stochastic Gravitational Wave Background (SGWB) generated from strong first-order phase transitions in the early Universe. As benchmark scenarios, we examine:
1) The impact of supercooling on the SGWB within the millihertz to nanohertz range in generic abelian extensions of the SM governed by classical scale invariance.
2) Phase transitions occurring within a non-abelian dark sector.
3) Colour symmetry restoration at low temperatures within a framework featuring two scalar leptoquarks with thermal vacuum expectation values (if time allows).
Specifically, we explore the conditions that allow these scenarios to be probed at LISA and discuss the potential consequences for collider physics observables. This includes the trilinear Higgs coupling, mixing angles and the mass of new particles.

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TBounce: a new Mathematica tool for cosmological phase transitions and gravitational waves

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The baryon asymmetry problem remains a crucial challenge in particle physics and cosmology. Electroweak baryogenesis, a leading mechanisms to produce the matter-antimatter asymmetry we observe today, requires an extension to the Standard Model to achieve a sufficiently strong first order phase transition.
Besides representing a target for several future-generation colliders, such Beyond the Standard Model (BSM) theories carry the potential to generate - through a thermal phase transition - gravitational waves (GWs) detectable by future space-based detectors, including LISA.
Despite growing interest in the problem, publicly available code to study different BSM scenarios is limited, the prevalent one being CosmoTransitions.
This presentation introduces a fully Mathematica-based paclet to fill the gap, offering a user-friendly and fully-automated tool to derive phase transition and gravitational wave parameters. The paclet exploits the recently developed FindBounce to compute the Euclidean tunnelling action.
Key features include
• simple phase tracing (in progress)
• identification of first order phase transitions
• computation of phase transition parameters (nucleation and percolation temperatures, strength, duration, ⋯)
• derivation of GW spectra from semi-analytical functions found in the literature
Although designed to work with any given thermal potential, the paclet is intended to interface smoothly with DRalgo, a Mathematica package for dimensional reduction and thermal effective field theory computations.
Currently under development, the tool is being tested on a variety of single-field models, including the abelian Higgs, a coupled fluid-field, and a dark photon model.
This presentation will cover preliminary results and future development plans, showcasing the potential for this new paclet to become an invaluable resource in the field of cosmological phase transitions.

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Slow first-order phase transitions

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Strongly supercooled phase transitions cause a period of thermal inflation. Such first-order phase transitions typically generate a strong primary gravitational wave background from bubble collisions. In this talk, I will show that if the transition is also slow it leads to the formation of large inhomogeneities that source a secondary gravitational wave background. For sufficiently slow transitions the secondary background dominates over the primary one. I will also discuss the formation of primordial black holes in such transitions.

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Lensing

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Higgs fizz in the Big Bang: gravitational waves from early universe phase transitions

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