Gravitational Wave Probes of Physics Beyond Standard Model

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Book of Abstracts

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Gravitational waves from bubble collisions in first order phase transitions

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We will discuss energy budget of first order phase transitions and identify models capable of supporting extreme supercooling necessary to feature bubble collisions as the main source of gravitational waves. We will also review new semi-analytical calculation of the spectrum appropriate in such strong transitions.

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Challenges and Opportunities of Ultra-High-Frequency Gravitational Wave Detection

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The first direct detections of gravitational waves by the LIGO and VIRGO collaborations have opened up new avenues to explore the Universe. Currently operating and planned gravitational wave detectors mostly focus on the frequency range below 10 kHz, where signatures from known astrophysical sources are expected to be discovered. However, based on what happens with the electromagnetic spectrum, there should be interesting physics to be discovered at every scale of gravitational wave frequencies. In particular, any discovery of gravitational wave signatures at frequencies higher than 10 kHz would correspond either to exotic astrophysical objects (such as primordial black holes or boson stars) or to cosmological events in the early Universe, such as phase transitions, preheating after inflation, oscillons, cosmic defects, etc. Hence, the search for ultra-high-frequency gravitational waves is a promising and challenging search for new physics and it provides a unique opportunity to test many theories beyond the Standard Model that could not be tested otherwise. In this talk, I will briefly review the state of the art of ultra-high-frequency gravitational wave physics, both from the theoretical point of view - summarising the most promising known sources and their features - and from the experimental point of view - presenting the state of the art in terms of experimental proposals in this frequency range and what are the possible ways forward.

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Model-independent energy budget of gravitational waves from a cosmological first-order phase transition

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Cosmological first-order phase transitions are predicted by many new physics models and could have facilitated the generation of the baryon asymmetry. Gravitational waves are a promising tool to study phase transitions in the early universe. In this talk, I focus on the energy budget of such phase transitions, which is an important factor in the prediction of the gravitational wave spectrum. Formerly, this analysis was based mostly on simplified models, such as the bag equation of state. I'll present a model-independent computation of the energy budget, which only depends on the speed of sound in the broken and symmetric phase and a newly defined phase transition strength parameter. I compare our new approach to approximations found in the literature and show that the new, model-independent analysis is typically accurate to the percent level, whereas the former approaches can deviate significantly from the full numerical result.

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Dark neutrino interactions make inflationary CMB B-modes blue and phase out Hubble tension

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New interactions of neutrinos with a subdominant component of dark matter can prevent them from free streaming. As a result, the inflationary gravitational waves escape the damping by neutrinos and, with respect to the standard LCDM cosmology, there is enhancement of primordial gravitational wave amplitude and CMB B-modes on small scales. The effect on the CMB scalar acoustic oscillations is the absence of neutrino induced phase shift that is present in the standard LCDM cosmology with free streaming neutrinos. The dark neutrino interaction therefore shifts the acoustic oscillation features in the CMB temperature and E-mode polarization power spectra thus pushing the CMB inferred value of the Hubble constant higher, alleviating the Hubble tension. The inflationary CMB B-modes, if measured precisely with future experiments, are therefore a potential probe of new interactions beyond the standard model and can test this solution to the Hubble tension.

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Searching for gravitational wave bursts from cosmic string cusps with the Parkes Pulsar Timing Array

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Cosmic strings are one of the gravitational wave (GW) sources that can be probed by pulsar timing arrays (PTAs). In this work, we develop a detection algorithm for the GW burst from a cusp on a cosmic string and apply it to a Parkes PTA data release. We find four events with a false alarm probability of less than 1\%. However further investigation shows that all of these are likely to be spurious. As there are no convincing detections, we place upper limits on the GW amplitude for different event durations. From these bounds we place limits on the cosmic string tension, that are independent from other bounding techniques. Finally, we discuss the physical implications of our results and the prospect of probing cosmic strings in the era of Square Kilometre Array.

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Nonlinear gravitational-wave memory from cusps and kinks on cosmic strings

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The nonlinear memory effect is a fascinating prediction of general relativity (GR), in which oscillatory gravitational-wave (GW) signals are generically accompanied by a monotonically-increasing strain which persists in the detector long after the signal has passed. This effect is directly accessible to GW observatories, and presents a unique opportunity to test GR in the dynamical and nonlinear regime. We have recently calculated, for the first time, the nonlinear memory signal associated with GW bursts from cusps and kinks on cosmic string loops, which are an important target for current and future GW observatories. In this talk I will describe the resulting analytical waveforms for the GW memory from cusps and kinks, and the corresponding "memory of the memory" and other higher-order memory effects. These are among the first memory observables computed for a cosmological source of GWs, with previous literature having focused almost entirely on astrophysical sources. Surprisingly, we find that the cusp GW signal diverges for sufficiently large loops, and argue that the most plausible explanation for this divergence is a breakdown in the weak-field treatment of GW emission from the cusp. This shows that previously-neglected strong gravity effects must play an important role near cusps, although the exact mechanism by which they cure the divergence is not currently understood. I will argue that one possible resolution is for these cusps to collapse to form primordial black holes (PBHs).

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Gravitational waves from metastable cosmic strings

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Cosmic strings, which form during cosmological U(1)-symmetry-breaking phase transitions, represent an intriguing potential source of stochastic gravitational waves from the early Universe. While most studies thus far have focused on stable cosmic strings whose stability is guaranteed by the topology of the underlying vacuum structure, many Grand Unified Theories (GUTs) actually predict the formation of a metastable cosmic-string network that collapses after a finite lifetime in consequence of GUT monopole pair production. In this talk, I will discuss the theoretical description of such a network and its individual components as well as the resulting consequences for the emitted spectrum of primordial gravitational waves. Remarkably, the gravitational-wave signal from metastable cosmic strings may well explain the common-spectrum process recently observed in the 12.5-year NANOGrav pulsar timing data, while at the same time, and in contrast to stable cosmic strings, predicting a signal at higher frequencies still within the reach of current-generation ground-based interferometers. On their way to design sensitivity, existing gravitational-wave experiments will therefore have a realistic chance to probe particle physics processes at energies close to the GUT scale via the observation of gravitational waves from metastable cosmic strings.

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Turbulent production of gravitational radiation from cosmological phase transitions

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The generation of primordial magnetic fields and its interaction with the primordial plasma during cosmological phase transitions is turbulent in nature. I will describe and discuss results of direct numerical simulations of magnetohydrodynamic (MHD) turbulence in the early universe and the resulting stochastic gravitational wave background (SGWB). In addition to the SGWB, the primordial magnetic field will evolve up to our present time and its relics can explain indirect observations of weak magnetic fields coherent on very large scales. I will apply the numerical results to magnetic fields produced at the electroweak and the QCD phase transitions and show that these signals may be detectable by the planned space-based Laser Interferometer Space Antenna (LISA) and by Pulsar Timing Array (PTA). The detection of these signals would lead to the understanding of the underlying physics of cosmological phase transitions, which can have consequences on the baryon asymmetry problem and on the origin seed of observed magnetic fields coherent over very large scales at the present time.

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Reliable predictions for cosmological phase transitions

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A first-order phase transition in the early universe would have given rise to a stochastic gravitational wave background which may be observable today. In this talk, I will focus on the crucial problem of making reliable predictions in the face of infrared Bose enhancements at high temperature. Such enhancements break the alignment between the loop and coupling expansions, and typically lead to several orders of magnitude uncertainty in the gravitational wave amplitude. In this context, I will give an overview of recent works analysing the reliability of the coupling expansion at high temperature, both on its own terms and in comparison with nonperturbative lattice simulations. The results offer concrete encouragement for the prospect of learning about particle physics from gravitational wave experiments, and I will finish by commenting on open questions and future directions.

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LIGO-Virgo observations and primordial black holes

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Since the dawn of gravitational wave (GW) astronomy, there has been increasing interest towards primordial black holes (PBHs). PBHs form binaries very efficiently at the time they decouple from the Hubble flow, and their present merger rate is high, assuming that they comprise a non-negligible fraction of dark matter. In this talk I will review the recent progress regarding the implications of LIGO-Virgo observations on PBHs.

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Cosmological bubble friction in local equilibrium

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In first-order cosmological phase transitions, the asymptotic velocity of expanding bubbles is of crucial relevance for predicting observables like the spectrum of stochastic gravitational waves, or for establishing the viability of mechanisms explaining fundamental properties of the universe such as the observed baryon asymmetry. In these dynamic phase transitions, it is generally accepted that subluminal bubble expansion requires out-of-equilibrium interactions with the plasma which are captured by friction terms in the equations of motion for the scalar field. This has been disputed in works pointing out subluminal velocities in local equilibrium arising either from hydrodynamic effects in deflagrations or from the entropy change across the bubble wall in general situations. We argue that both effects are related and can be understood from the conservation of the entropy of the degrees of freedom in local equilibrium, leading to subluminal speeds for both deflagrations and detonations. The friction effect arises from the background field dependence of the entropy density in the plasma, and can be accounted for by simply imposing local conservation of stress-energy and including field dependent thermal contributions to the effective potential. We illustrate this with explicit calculations of dynamic and static bubbles for a first-order electroweak transition in a Standard Model extension with additional scalar fields.

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Cosmic Archaeology with gravitational waves from (axion) cosmic strings

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In this talk I will discuss two important aspects of cosmology and particle physics that can be probed with GW signals from cosmic strings: probing the pre-BBN primordial dark age and axion physics. Gravitational waves (GWs) originating from the dynamics of a cosmic string network have the ability to probe many otherwise inaccessible properties of the early universe. In particular, I will discuss how the frequency spectrum of a stochastic GW background (SGWB) from a cosmic string network can be used to probe Hubble expansion rate of the early universe prior to Big Bang Nucleosynthesis (BBN), during the "primordial dark age". Furthermore I will show that in contrary to the standard expectation, cosmic strings formed before inflation could regrow back into horizon and leave imprints, with GW bursts potentially being the leading signal. In relation to axion physics I will also demonstrate the detection prospect for SGWB from global/axion strings which may provide a new probe for axion-like dark matter models, considering various scenarios of cosmic history. Finally I will briefly discuss the prospect of using frequency domain information to disentangle a cosmologically sourced SGWB such as from cosmic strings vs. astrophysics sourced SGWB, particularly highlighting the impact of a midband GW experiment.

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Neutrino Mass, Leptogenesis, GUT

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I discuss how the origin of neutrino mass and baryon asymmetry may lead to gravitational wave signal from cosmic strings. In some cases of symmetry breaking patterns from GUT, cosmic strings may come with magnetic monopoles or domain walls, making the gravitational wave spectrum richer. We may learn how the GUT is broken if the gravitational wave signal can be mapped out for a wide range of frequencies.

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The Stochastic Gravitational Wave Background from Cosmic String Networks

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In this talk we will review the different ingredients that go into the
calculation of the stochastic gravitational wave background from cosmic strings and explain how one can extract the relevant information by performing large scale cosmological simulations of Nambu-Goto strings. Finally, we will also discuss
how current efforts to take into account gravitational backreaction can impact on the gravitational wave signals from strings.

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Towards an all-orders calculation of the electroweak bubble wall velocity

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In this talk, I discuss work where we calculate the velocity of the Higgs condensate bubble wall during a first-order electroweak phase transition in the early Universe. The interaction of particles with the bubble wall can be accompanied by the emission of multiple soft gauge bosons. When computed at fixed order in perturbation theory, this process exhibits large logarithmic enhancements which must be resummed to all orders when the wall velocity is large. In this work, we perform this resummation both analytically and numerically at leading logarithmic accuracy. The numerical simulation is achieved by means of a particle shower in the broken phase of the electroweak theory. The two approaches agree to the 10% level. For fast-moving walls, we find the scaling of the thermal pressure exerted against the wall to be P~γ^2T^4. This is impactful for baryogenesis, gravitational wave radiation and the generation of other cosmic relics.

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From dimensional reduction to droplets: understanding strong first-order phase transitions

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In many extensions of the Standard Model, the electroweak transition is first order - in some cases, strongly so. The ensuing phase transition would result in collisions of bubbles of the new Higgs phase. These collisions, and the associated interactions of sound waves in the plasma, are substantial sources of gravitational waves. For a phase transition at or around the electroweak scale, these

gravitational waves may be detectable by future missions such as LISA. They can indirectly provide a probe of particle physics beyond the Standard Model, complementary to future colliders.

However, concrete predictions of the resulting gravitational waves will require good understanding both of the particle physics models themselves, as well as the non-equilibrium physics of the transition. In other words, we need accurate studies of the phase diagrams in the underlying particle physics theories, as well as good predictions of the expected gravitational wave signal from simulations. These feed into one another, forming a so-called 'pipeline'.

The stronger the phase transition, the better the chance of being detected (or constrained) by future missions like LISA. However, strong transitions are also the most poorly understood. In this talk I will discuss some recent results from different points along the 'pipeline', with a focus on the consequences for strong first-order phase transitions.

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Gravitational waves and quantum gravity

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We will review recent results about the search for a cosmological imprint of quantum gravity in gravitational-wave physics.Tight constraints and a chance of detection for some models may come from modified dispersion relations, the luminosity distance of standard sirens and the stochastic gravitational-wave background.

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Bridging the microhertz gap with asteroids

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The science case for a broad program of gravitational wave (GW) detection across all frequency bands is exceptionally strong. At present, there is a dearth of coverage by existing and proposed searches in the GW frequency band lying between the peak sensitivities of PTAs and LISA, roughly 0.1-100 microhertz. In this talk, I will outline a conceptual mission proposal to access this band. I will demonstrate that a few carefully chosen asteroids which orbit in the inner Solar System can act as excellent naturally occurring gravitational test masses despite the environmental noise sources. As such, a GW detector can be constructed by ranging between these asteroids using optical or radio links. At low frequencies, I will discuss how gravity gradient noise arising from the combined motion of the other ~1e6 asteroids in the inner Solar System sharply cuts off the sensitivity of this proposal. Sensitivity in the middle of this band is mostly limited by various solar perturbations to the asteroid test masses, while the high-frequency sensitivity is limited by noise in the ranging link. The projected strain-sensitivity curve that I will present indicates significant potential reach in this frequency band for a mission of this type.

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The gravitational memory of supernova neutrinos

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When a burst of neutrinos from a core collapse supernova passes by the Earth, it causes a permanent change in the local space-time metric, called the gravitational memory. Long considered unobservable, this effect will be detectable in the future, for a galactic supernova, at upcoming deci-Hertz gravitational wave interferometers. I present a new phenomenological description of the memory and its application to different core collapse scenarios. Using this model, I discuss the detectability of the supernova neutrino memory and its physics potential in the context of multi-messenger astronomy.

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TBA

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Probing particle physics and cosmology with cosmic strings and GWs

In this talk we will first review the LIGO-Virgo O3 constraints on cosmic strings, both from the stochastic GW background (SGWB) and from a burst search. We will then go beyond the standard cosmic string scenario, and discuss (i) the effects of possible particle emission from cusps and kinks, both on the loop distribution as well as on different observables (the stochastic GW background as well as the gamma-ray background) (ii) current carrying strings, and the formation of vortons which can act as a dark matter component. Finally, we will comment on how the SGWB from cosmic strings can be used to probe particle physics, and also cosmology, beyond the standard models, and at energy scales much above those of particle accelerators.

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TBA

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Inflation after PLANCK

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I will review the current status of inflation and discuss how one can improve it using new observational probes.

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Audible Axions from NANOGrav to the lattice

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The dynamics of axions after inflation can give rise to an observable stochastic gravitational wave background. I will present new results for the GW spectrum from a lattice simulation of an axion-dark photon system in a radiation dominated universe, and furthermore show that this signal could explain the recently observed excess in the NANOGrav data.

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Classical vs. quantum divide of gravitons in cosmology

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Gravity and matter are universally coupled, and this unique universality provides us with an intriguing way to quantifying quantum aspects of space-time in terms of the number of gravitons. In particular, I will provide a limit on the number of gravitons if we trace out the matter degrees of freedom. I will obtain the universal bound on the number of gravitons. Since the number of gravitons also signify the number of bosonic states they occupy, the number of gravitons will place an indirect constraint on the gravitational entropy of the system. Based on these observations, I will ascertain how the primordial Universe and the subsequent phase transitions in the Universe will capture the essence of classical gravity and gravitational waves and whether there is a possibility of detecting the quantum feature of the graviton in a laboratory.

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Gravitational waves from inflation

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Inflation is an epoch in the very early universe, characterised by a nearly exponential expansion. It provides an explanation for the origin of cosmic structure and it is in excellent agreement with current observations. The particle physics description of inflation is, however, still largely unknown. Primordial gravitational waves have the potential to shed new light on this epoch. In this talk I will discuss gravitational wave production during inflation and highlight our future prospects for testing inflation using all available primordial gravitational wave probes, from the cosmic microwave background all the way to interferometers.

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Recent progress in cosmological collider physics

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Heavy particles can be produced on shell during inflation and leave distinct signals in the correlations of density fluctuations. These signals can be searched for in the future CMB/LSS/21cm observations. In this talk I will introduce the basics of this cosmological collider program. I will then describe some recent works along this direction with fun physics and visibly large signals, including seeing heavy neutrinos, probing CP violations, missing energies, and a scenario of Cosmological

Higgs Collider where the high-energy Higgs interactions can be measured from the primordial non-Gaussianity.

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Black holes, gravitational waves, and avenues to new physics

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I will begin by reviewing the possibility that primordial black holes may make up the dark matter. I will then describe an array of analyses that can be done with CMB data and galaxy surveys to look for the effects of Hubble-scale gravitational waves and also to seek chirality in the gravitational-wave background.

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Primordial Blackholes and Cosmological Gravitational Waves

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Transmuted black holes and neutrinos from gravitational wave sources

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My talk will be composed of two parts. During the first part, I will be talking about formation of transmuted black holes via particle dark matter accumulation in compact stars. Stellar objects catastrophically accrete non-annihilating dark matter, and the small dark core subsequently collapses, eating up the host star and transmuting it into a black hole. The wide range of allowed dark matter masses allows a smaller effective Chandrasekhar limit and thus smaller mass black holes. We point out several avenues to test our proposal, focusing on the redshift dependence of the merger rate. We show that redshift dependence of the merger rate can be used as a probe of the transmuted origin of low mass black holes. During the second part of the talk, I will briefly talk about the search of neutrinos from various gravitational wave sources: binary neutron star merger and neutron star - black hole merger.

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Constraining non-GR gravity scenarios with observations of gravitational waves

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Many gravitational theories beyond general relativity have been proposed over the years as a physical explanation of the dark sector. All such theories affect the emission, propagation and detection of

gravitational waves. In this talk, I will discuss some proposed scenarios and how the GW170817/GRB170817A simultaneous detection of gravitational and electromagnetic waves from the same source limits the allowed parameter space.

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TBA

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The search for a SGWB in LIGO, Virgo and KAGRA

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Space Gravitational Wave Antenna DECIGO

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The band 0.1-10Hz is just between the frequency regimes probed by the ground-based detectors (LIGO, Virgo, KAGRA,..) and the proposed space detectors (LISA, TianQin, Taiji). I briefly introduce the Japanese plan DECIGO targeting this band and then discuss its targets, including primordial stochastic background and compact binaries.

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AION/AEDGE

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Prospect of detecting gravitational waves and probing gravity with pulsar timing arrays.

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Low-frequency gravitational waves cannot be detected with ground-based detectors. While GW observations at frequencies in the micro- to mHz regime are planned with spaced-based detectors, even lower frequencies, such as at nHz frequencies, can be

detected with pulsar timing arrays (PTAs). The talk summarises the PTA experiments, describes the current status and prospects, and also indicates how gravity tests are enable by detections.

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LISA

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Cosmic Explorer - a next-generation gravitational-wave detector

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Advanced LIGO and Virgo have detected dozens of gravitational waves, emitted from binary neutron stars and binary black holes. Third-generation observatories - such as Cosmic Explorer and the Einstein Telescope - will provide a significant boost in sensitivity and detect thousands of binary mergers per month, both from the local universe and from cosmological distances. In this talk I will review some of their key science goals. These include: measuring structure and composition of neutron stars' interiors; detecting the mergers of primordial black holes at high redshifts, testing general relativity and looking for dark matter particles.

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Searching for Primordial Gravitational Waves with CMB-S4

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Observations of the temperature anisotropies of the cosmic microwave background radiation have been key to our understanding of the early universe. The cosmic microwave background also contains invaluable information about the early universe that can be revealed through precision observations of the polarization anisotropies. Perhaps most strikingly, measurements of the polarization anisotropies may reveal the imprint of primordial gravitational waves. In this talk I will review the implications of a detection of primordial gravitational waves and will discuss the expected sensitivity for and the status of the next generation ground-based CMB experiment CMB-S4.

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Keynote Seminar

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Black hole archaeology with gravitational waves

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Gravitational waves from binary mergers encode not only the properties of individual non-luminous objects, but also of their astrophysical populations. With the growing dataset we can study for the first time how black hole properties are distributed. In this talk I will demonstrate how such studies can be used to learn about particle and nuclear physics in giant stars. The key insight is that due to an instability in stellar cores, a wide range of progenitor stellar masses leaves no black hole remnant. The unpopulated space in the stellar graveyard is known as the black hole mass gap (BHMG). The effects of new physics can dramatically alter the late stages of stellar evolution, resulting in shifts of the BHMG. I will give several examples, and demonstrate how these predictions can be tested using the growing catalogue of gravitational wave observations.

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Probing cosmic superstrings with gravitational waves

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We discuss the stochastic gravitational wave background generated by cosmic superstring networks and show that heavier string types may leave distinct signatures on this spectrum. We show that these signatures may be within the reach of present and upcoming gravitational wave detector (particularly of pulsar timing arrays). This demonstrates that approximating the gravitational wave spectrum generated by cosmic superstring networks using the spectrum generated by ordinary cosmic strings with reduced intercommuting probability (which is often done in the literature) leads, in general, to weaker observational constraints on the tension of fundamental strings and to a loss of information about the underlying string theory.

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Generation of GWs from freely-decaying kinetic turbulence

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We present new results on the gravitational wave signal from kinetic turbulence in the aftermath of a first order phase transition in the early universe