



# Dark Odyssey 2020: Gravitational-Wave Probes of Dark Universe (1st CTP Bosan Workshop) January 4-7, 2020

Seoul National University, Int'l Conf Hall 25-1, Korea

## Day 1 (1/4/Sat)

|           |            |                                                                                          |
|-----------|------------|------------------------------------------------------------------------------------------|
| 9:15-9:30 | CTP, Bosan | Opening                                                                                  |
| 9:30-10   | Linqing    | Progress on Gravitational Wave Discovery                                                 |
| 10-10:30  | Masamune   | Gravitational waves in the inhomogeneous Universe                                        |
| Coffee    |            |                                                                                          |
| 11-11:30  | Djuna      | Gravitational probes of exotic compact objects                                           |
| 11:30-12  | Wei        | Looking for primordial black holes in the spectra of GRBs and FRBs                       |
| Lunch     |            |                                                                                          |
| 2:30-3    | TaeHun     | Chair: Jinn-Ouk<br>GRB lensing parallax: Closing the primordial black hole mass window   |
| 3-3:30    | Kyungmin   | Identifying Lensed Gravitational Waves with Deep Learning                                |
| Coffee    |            |                                                                                          |
| 4-4:30    | Tao        | Echoes of 1st-Order Cosmological Phase Transitions in the CMB                            |
| 4:30-5    | Rong-Gen   | Primordial black holes and stochastic gravitational wave induced by scalar perturbations |
| 5-5:30    | Jing       | Probing axions with EHT polarimetric measurements                                        |
| 6-8       | Reception  | (On-site)                                                                                |

## Day 2 (1/5/Sun)

|                |           |                                                                                        |
|----------------|-----------|----------------------------------------------------------------------------------------|
| 9-9:30         | Hyung Won | Gravitational Wave Data Analysis                                                       |
| 9:30-10        | Takahiro  | Constructing gravitational wave templates in extended gravity scenarios                |
| Coffee         |           |                                                                                        |
| Chair: Kathryn |           |                                                                                        |
| 10:30-11       | Tjonnie   | Searching for Dark-Matter Imprints in Gravitational Waves from Merging Compact Objects |

|                 |            |                                                                             |
|-----------------|------------|-----------------------------------------------------------------------------|
| 11-11:30        | Sunghoon   | Probing Dark Matter at LIGO and beyond: Fringe, chirp mass and localization |
| 11:30-12        | Yuko       | Axion like particle search through gravitational messenger                  |
| Lunch&Coffee    |            |                                                                             |
| Chair: Takahiro |            |                                                                             |
| 2:30-3          | Jinn-Ouk   | Induced second-order gravitational waves                                    |
| 3:00-3:30       | Seong Chan | Higgs inflation and PBH                                                     |
| 5-8             | Banquet    | (Bus)                                                                       |

### Day 3 (1/6/Mon)

|                |         |                                                                                                       |
|----------------|---------|-------------------------------------------------------------------------------------------------------|
| Chair: Yue     |         |                                                                                                       |
| 9:15-10        | Kathryn | Spacetime fluctuations in flat space and AdS/CFT                                                      |
| 10-10:30       | Junwu   | Axiverse Strings: A CMB Millikan Experiment                                                           |
| Coffee         |         |                                                                                                       |
| 11-11:30       | Yanou   | Cosmic Archaeology with gravitational waves from (axion) cosmic strings                               |
| 11:30-12       | Andrew  | Searching for the stochastic background with advanced ground based detectors                          |
| Lunch          |         |                                                                                                       |
| Chair: Linqing |         |                                                                                                       |
| 2:30-3         | Yong    | Weyl Symmetry, Inflation and Gravitational Waves                                                      |
| 3-3:30         | Ryan    | Debiasing Cosmic Gravitational Wave Sirens                                                            |
| Coffee         |         |                                                                                                       |
| 4-4:30         | Jiro    | Probing ultralight vector dark matter                                                                 |
| 4:30-5         | Yue     | Searching for Dark Photon Dark Matter with Gravitational Wave Detectors, with LIGO-O1 data and beyond |

# **Progress on Gravitational Wave Discovery**

Linqing Wen (The University of Western Australia)

Abstract

# **Gravitational waves in the inhomogeneous Universe**

Masamune Oguri (University of Tokyo)

The discovery of gravitational waves from a binary black hole merger in 2015 opened up a new window to study the Universe, including the origin of black holes, the nature of dark matter, and the expansion history of the Universe. However, gravitational waves emitted from binary mergers propagate through the inhomogeneous Universe, which can have a considerable impact on observations of gravitational waves, in good or bad ways. I will highlight some examples of the effects of the inhomogeneity on gravitational wave observations, including their possible applications and implications.

## **Gravitational probes of exotic compact objects**

Djuna Croon (TRIUMF)

In this talk I will discuss experimental probes of dark compact objects in the new era of gravitational wave astrophysics. Such proposed objects include scalar (boson) stars, Q-balls, and dark matter clumps inside neutron stars. I will review the properties that will help us distinguish them from astrophysical objects, and the resulting gravitational wave phenomenology. I will also discuss connections with other astrophysical probes, such as gravitational (micro)lensing.

# Looking for primordial black holes in the spectra of GRBs and FRBs

Wei Xue (University of Florida)

The massive compact halo objects (MACHOs) such as primordial black holes or dense mini-halos can gravitational lens the signal of gamma ray bursts (GRB) and fast radio bursts (FRB). I will discuss that most GRB spectra are inappropriate for this kind of lensing searches due to their large sizes. However, FRB lensing, producing a characteristic interference pattern in the frequency spectrum, can probe the MACHOs in the mass range from  $10^{-4}$  to 0.1 solar mass.

## GRB lensing parallax: Closing the primordial black hole mass window

TaeHun Kim (Seoul National University)

The primordial black hole (PBH) comprising full dark matter (DM) abundance is currently allowed if its mass lies between  $10^{-16} M_{\odot} \sim 10^{-11} M_{\odot}$ . This lightest mass range is hard to be probed by ongoing gravitational lensing observations. In this talk, we advocate that an old idea of the lensing parallax of Gamma-ray bursts (GRBs), observed simultaneously by spatially separated detectors, can probe the unconstrained mass range; and that of nearby stars can probe a heavier mass range. In addition to various good properties of GRBs, the astrophysical scale accessible to us –  $r_{\oplus} \sim \text{AU}$  – is just large enough to resolve the GRB lensing by lightest PBH DM.



# Identifying Lensed Gravitational Waves with Deep Learning

Kyungmin Kim (Korea Astronomy and Space Science Institute)

When gravitational waves propagate near massive astrophysical objects such as massive black holes, galaxies, and clusters, they become lensed. The resulting lensed gravitational waves are bent and focussed by the lens, making them easier to identify owing to the increase in their amplitude, and arrive to us at different times as they have travelled different trajectories around the lens. As a consequence, multiple images detectable as repeated near-identical events or superposed gravitational waves with characteristic "beating patterns" occur. Larger lenses will have large potential wells, resulting in large time-delays between the multiple images, while smaller lenses result in short time-delays between lensed gravitational-wave images, resulting in superposed waves. These lensing effects may, in the future, be detectable by the ground-based gravitational-wave detectors such as LIGO, Virgo or KAGRA. We consider lens masses around  $\sim 10^3 - 10^5 M_\odot$  which can produce on the order of millisecond time delays between the arrival times of two lensed gravitational waves. In this talk, I present preliminary results from the implementation of a deep learning method to distinguish lensed gravitational waves radiated from merger of compact binaries and the estimation on the parameters of the source binary system and the lens mass.

# **Echoes of 1st-Order Cosmological Phase Transitions in the CMB**

Tao Liu (The Hong Kong University of Science and Technology)

For cosmological phase transitions such as GUT phase transition and electroweak phase transition, if they are of first order and happened in a preliminary stage of inflation, we show that the gravitational waves generated may leave a scale-dependent imprint in the CMB.

## **Induced second-order gravitational waves**

Jinn-Ouk Gong (Korea Astronomy and Space Science Institute)

We discuss the analytic approach to the induced second-order gravitational waves. We also comment on the gauge invariance and a possible solution to the issue.

## Probing axions with EHT polarimetric measurements

Jing Shu (Institute of Theoretical Physics, Chinese Academy of Science)

With high spatial resolution, polarimetric imaging of a supermassive black hole, like M87★ or Sgr A★, by the Event Horizon Telescope can be used to probe the existence of ultralight bosonic particles, such as axions. Such particles can accumulate around a rotating black hole through superradiance mechanism, forming an axion cloud. When linearly polarized photons are emitted from accretion disk near the horizon, their position angles oscillate due to the birefringent effect when traveling through the axion background. In particular, the supermassive black hole M87★ (Sgr A★) can probe axions with masses  $O(10-20)$  eV ( $O(10-17)$  eV) and decay constant smaller than  $O(10^{16})$  GeV, which is complimentary to black hole spin measurements.

# Gravitational Wave Data Analysis

Hyung Won Lee (Inje University)

After the first detection of gravitational wave on September 14, 2015 by LIGO and Virgo collaboration, there has been, and still are, a lot of interest on gravitational waves. The fact that gravitational waves not only open a new window for observing the Universe but also the technical breakthroughs we had to make to detect the weakest signal in nature is what makes gravitational wave so interesting. The gravitational wave is very weak by nature, and it is enormously difficult to detect. Actually it took more than 20 years of development since the conceptual design to make the first observation. In this talk I want to introduce basics of gravitational wave detection principle using large optical interferometer and how one can extract relevant signal from noisy data for general audience. This talk is based on the two LIGO documents for data extraction (arXiv:1908.1117) and parameter estimation (PRD91042003).

# **Constructing gravitational wave templates in extended gravity scenarios**

Takahiro Tanaka (Kyoto University, Yukawa Institute for Theoretical Physics)

I will discuss the attempts and difficulties of construction of templates of gravitational waves from inspiraling binaries taking into account possible extension of general relativity. After introducing some results which can be used for the actual data analyses, I'd like to explain what kind of theoretical investigation is necessary for the further detailed test of gravity.

# **Searching for Dark-Matter Imprints in Gravitational Waves from Merging Compact Objects**

Tjonnie Li (Chinese University of Hong Kong)

The ability to detect gravitational waves has opened up a novel channel to uncover the nature of dark matter. In particular, when a compact object orbits a black hole admixed in dark matter, it will gravitationally interact with the dark matter distribution surrounding the black hole. This gravitational interaction will exert a slow, accumulative change in the orbit of the compact object. Since the orbit of the compact object is encoded in the gravitational waves it emits, so is the change in the orbit due to dark matter. By analyzing gravitational waves, one can thus measure the matter distribution directly. I present studies that look into the capabilities of present and future gravitational-wave detectors to discern these dark matter imprints.

# **Probing Dark Matter at LIGO and beyond: Fringe, chirp mass and localization**

Sunghoon Jung (Seoul National University)

What can we learn about Dark Matter with Gravitational-Wave(GW) observations at LIGO and future detectors? We first introduce a new GW observable — GW Fringe — that allows LIGO to probe compact dark matter. Secondly, we show that augmenting LIGO with lower mid-frequency detectors can further probe various other dark matter, including axion-like dark matter and cosmic strings. A capability of ideal localization is a bonus of the broadband detection. All these new opportunities utilize the unique chirping nature of GWs from binary mergers. They not only strengthen LIGO science capabilities, but also motivate mid-frequency detections. Most importantly, they are precious new ways to understand the nature of dark matter.



## **Axion like particle search through gravitational messenger**

Yuko Urakawa (Nagoya University; Bielefeld University)

Axion, which was proposed historically to solve the strong CP problem in QCD, is a compelling candidate of dark matter. In this talk, I will explain our recent works which propose a new method to detect the imprint of axion or axion like particle (ALP) through gravitational messenger. First, I will show that the axions can be a prominent source of the GWs through the resonance process that takes place just after the onset of the oscillation. Because of the Chern-Simons coupling, that breaks the parity symmetry, the GWs emitted from the axion can be circularly polarized. Second, I will discuss another ALPs search through the birefringence of the polarized photons due to the coherently oscillating axion. Using the measurement of the polarized photons that had gone through the galaxy gravitational lens system, we have provided a stringent constraint on the ALPS coupling with the photons, that evades the astrophysical uncertainties.

# **Primordial black holes and stochastic gravitational wave induced by scalar perturbations**

Rong-Gen Cai (Institute of Theoretical Physics, Chinese Academy of Science)

Abstract.

## **Effects of asphericity on PBH formation**

Chulmoon Yoo (Nagoya University)

We discuss the effects of asphericity on PBH formation through simulation of full non-linear non-spherical PBH formation.

# **Higgs inflation and PBH**

Seong Chan Park (Yonsei University)

Abstract.

# Spacetime fluctuations in flat space and AdS/CFT

Kathryn Zurek (Caltech)

We consider the uncertainty in the arm length of an interferometer due to metric fluctuations from the quantum nature of gravity, proposing a concrete microscopic model of energy fluctuations in holographic degrees of freedom on the surface bounding a causally connected region of spacetime. This leads to a signal that could be observed in a gravitational wave interferometer.

## **Axiverse Strings: A CMB Millikan Experiment**

Junwu Huang (Perimeter Institute)

Very light axions are a generic prediction of string compactifications. If cosmic strings associated with these axions were produced in the early universe, they quickly approach a so-called scaling solution, such that strings persist in the sky today. I will present some remarkable signals of such strings coupled to photons. In this string background, there is a new Berry phase: a frequency-independent topological polarization rotation of CMB photons equal to the fine structure constant up to a rational number. This manifests itself as a rotation of E-modes in the CMB polarization to B-modes. The current CMB experimental sensitivity to this rotation is about 1%, with many orders of magnitude improvement expected for future experiments. These strings may also be visible in strongly lensed quasar systems. I will show how measuring the undetermined rational number may shed light on the quantization of electric charge in the standard model and how CMB could rule out Grand Unification.

# **Cosmic Archaeology with gravitational waves from (axion) cosmic strings**

Yanou Cui (UC Riverside)

Many motivated extensions of the Standard Model of particle physics predict the existence of cosmic strings. Gravitational waves (GWs) originating from the dynamics of the resulting cosmic string network have the ability to probe many otherwise inaccessible properties of the early universe. In this study we show 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). We also demonstrate that current and planned GW detectors have the potential to detect such GW signals. The potential SGWB from global/axion strings will also be discussed which may provide a new probe for axion-like dark matter models. Furthermore we 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.

## **Searching for the stochastic background with advanced ground based detectors**

Andrew Matas (Max Planck Institute for Gravitational Physics, AEI-Potsdam)

The stochastic gravitational-wave background is a superposition of many different astrophysical and cosmological sources. In this talk I will present observational results for the stochastic background using data from Advanced LIGO's first two observing runs. I will discuss the basic search strategy, and upper limits obtained on isotropic and anisotropic backgrounds, and backgrounds of scalar and vector polarizations. I will also discuss the implications of these results for backgrounds due to compact binary coalescences and cosmic strings. I will discuss prospects for improving these constraints as the detector network approaches design sensitivity. Finally I will comment strategies to understand and mitigate correlated magnetic noise.



# **Weyl Symmetry, Inflation and Gravitational Waves**

Yong Tang (Institute of Theoretical Physics, Chinese Academy of Science)

In this talk, an inflation model with the original Weyl gauge symmetry will be introduced, where the Weyl gauge boson is shown as a dark matter candidate. The Higgs physics will also be modified. Both primordial gravitational wave (GW) and stochastic GW from particle decay will also be discussed.

# Debiasing Cosmic Gravitational Wave Sirens

Ryan Keeley (Korea Astronomy and Space Science Institute)

Lack of knowledge about the background expansion history of the Universe from independent observations makes it problematic to obtain a precise and accurate estimation of the Hubble constant  $H_0$  from gravitational wave standard sirens, even with electromagnetic counterpart redshifts. Simply not knowing the actual background expansion model of the universe (e.g. form of dark energy) can introduce substantial bias in estimation of the Hubble constant. When the statistical precision is at the level of 1% uncertainty on  $H_0$ , biases in non- $\Lambda$ CDM cosmologies that are consistent with current data could reach the 3-sigma level. To avoid model-dependent biases, statistical techniques that are appropriately agnostic about model assumptions need to be employed. In this talk, I demonstrate how model independent statistical methods, specifically Gaussian process regression, can remove bias in the reconstruction of  $H(z)$ , and can be combined model independently with supernova distances. This allows stringent tests of both  $H_0$  and  $\Lambda$ CDM, and can detect unrecognized systematics. This enables us to quantify the redshift systematic control necessary for the use of dark sirens, showing that it must approach spectroscopic precision to avoid significant bias.

## Probing ultralight vector dark matter

Jiro Soda (Kobe University)

The dark matter problem is the most important issue in physics. There are many candidates for the dark matter including WIMPs, neutrinos, black holes, dark photons, and so on. Recently, axion like particles as the dark matter have been actively studied. In particular, ultralight axions may resolve astrophysical small scale problems. One question is if we can extend the scenario to higher spin fields. In this talk, as a first step, I will discuss a possibility of ultralight vector dark matter and assess its detectability.

# Searching for Dark Photon Dark Matter with Gravitational Wave Detectors, with LIGO-O1 data and beyond

Yue Zhao (University of Utah)

If dark matter stems from the background of a very light gauge boson, this gauge boson could exert forces on test masses in gravitational wave detectors, resulting in displacements with a characteristic frequency set by the gauge boson mass. We outline a novel search strategy for such dark matter, assuming the dark photon is the gauge boson of  $U(1)_B$  or  $U(1)_{B-L}$ . We show that both ground-based and future space-based gravitational wave detectors have the capability to make a 5-sigma discovery in unexplored parameter regimes. Furthermore, we use the publicly available data from LIGO's first observing run, O1, to perform the first such dark photon dark matter search. We find that, if a dark photon is the gauge boson of  $U(1)_B$ , LIGO-O1 data has already provided a sensitivity better, in a small mass band, than achieved by prior experiments.