Snowmass2021 - Letter of Interest

Gravitational Wave as a probe of phase transitions during inflation

Thematic Areas: (check all that apply ☐/■)

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
■ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (TF9) Theory Frontier: Astro-Particle Physics and Cosmology

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Abstract: (maximum 200 words)
In a large class of slow roll inflation models, the inflaton tends to travel a large distance in the field space during the inflation. Such an excursion can trigger significant changes in the dynamics of any spectator sector which couples to the inflaton. One plausible scenario is that the evolution of the inflaton triggers a first order phase transition in the spectator sector. We study the properties of the gravitational wave signals produced by a first order phase transition during the inflation era. We show that a standing wave signature can be observed for which the strength of the gravitational wave signal oscillates with its wavelength. We show the range of this signal can be observed either by CMB B modes or directly by terrestrial or space gravitational wave detectors. This oscillation feature of gravitational wave is generic for any approximately instantaneous source during inflation. These results will be published in a set of papers in the near future. We plan to submit a contributed paper to the Snowmass 21 summarizing the findings.

Introduction

Gravitational waves (GWs), once produced, propagate freely through the universe and can bring us the information of their origin as well as the history of the evolution of the universe. There are many proposals, either terrestrial or space based, to detect stochastic GWs [1–15]. Possible sources of the primordial GWs are inflation [16], first order phase transitions [17], and cosmic strings [18].

It is highly plausible that at the very early times there was an inflationary era. The simplest model of inflation is the slow roll model with the inflaton field $\phi(x)$. To produce enough inflation the typical range of the excursion of the inflaton field must be large, even up to $\mathcal{O}(M_{\text{Planck}})$. As such, it may induce significant changes in the dynamics of any spectator fields.This may happen though a direct coupling between the inflaton field to the fields in the spectator sector. Another possibility of induced change is the change of temperature during the inflation. Such changes can lead to dramatic events during the inflation, such as a first order phase transition.

A robust signal of such a first order phase transition is the gravitational wave generated by the bubble collisions. We would like to study the prospect of observing and interpreting such a signal.

Plan of our work

We have already obtained preliminary results. In the coming year, we plan to flesh out the details in a set of publications which will form the basis for a contributed paper to the Snowmass studies.

The peak frequency of the GW signal is given by $f = 10^{11}\ \text{Hz} \times (\beta/H_{\text{inf}})(H_{\text{inf}}/M_{\text{Planck}})^{1/2}(a_\star/a_R)$, where $a_\star$ and a_R are the scale factors corresponding to the completion of the phase transition and the reheating, respectively. β^{-1} characterize the size of the bubble before the collision, and we should require it is within the horizon, $\beta/H_{\text{inf}} \gg 1$. We will show that the GWs produced by bubble collisions in first order phase transition during inflation can provide a unique oscillation signal in the power spectrum. This feature stems from the approximate instantaneous nature of the end of the first order phase transition, which sets in motion a set of gravitational wave modes which oscillate before they exit the horizon.

The strength of the peaks of the GW signal can be estimated as

$$\Omega_{\text{GW}}(f_{\text{today}}) = \Omega_R \times \mathcal{S}(f_p) \times \left(\frac{H_{\text{inf}}}{\beta}\right)^6 \Delta(f_p) \times \frac{\Delta\rho_L}{\rho_{\text{inf}}}\ , \tag{1}$$

where f_{today} is the frequency of in today's universe and f_p is the physical frequency at the time of the bubble collision during inflation. $\Delta(f_p)$ is the spectrum of GW from bubble collisions during first order phase transition in flat space-time, which can be obtained from numerical simulations [19]. $\Delta\rho_L$ is the density of the latent energy of the phase transition and ρ_{inf} is energy density of the inflation sector. Therefore at the peak region Ω_{GW} can be estimated to be around $10^{-7} \times (H_{\text{inf}}/\beta)^6 \times (\Delta\rho_L/\rho_{\text{inf}})$. In Eq. (1), the factor $\mathcal{S}(f_p)$ embodies the oscillatory pattern, and can be written as

$$\begin{aligned}\mathcal{S} \;=\; & \frac{\beta^4}{\omega_p^4}\left\{\frac{1}{2} + \frac{\cos(2\omega_p/H_{\text{inf}})\sin(2\omega_p/\beta)}{4\omega_p/\beta}\right.\\ & \left. + \frac{1}{4\omega_p/\beta}\left(\frac{1-\cos(2\omega_p/H_{\text{inf}} - 2\omega_p/\beta)}{\omega_p/H_{\text{inf}} - \omega_p/\beta} - \frac{1-\cos(2\omega_p/H_{\text{inf}} + 2\omega_p/\beta)}{\omega_p/H_{\text{inf}} + \omega_p/\beta}\right)\right\}\ ,\end{aligned} \tag{2}$$

where $\omega_p = 2\pi f_p$. In the preliminary study we found that at the peak region, the oscillation amplitude of Ω_{GW} can be order one.

The proposed GW observatories like DECIGO and BBO can reach the sensitivity of $\Omega_{\text{GW}} \sim 10^{-15}$ to 10^{-11}. Based on the estimated the strength of the gravitational wave signal, it can potentially be detected by future GW observatories, including DECIGO [3], BBO [7] and SKA [10].

From the shape of the gravitational wave signal, both information of inflation and the phase transition can be measured. We will demonstrate this through several examples, including models with different couplings between the inflaton and the sector which undergoes the phase transition, as well as alternative time evolution of the expansion rate during the inflation. Even though our analysis using a first order phase transition as a model, it should be clear that the signal is generic for any approximately instantaneous GW sources during the inflation.

If the phase transition happened in about 60 e-folds ($N_e = 60$) before the end of inflation, it would have imprint on the CMB spectrum. In particular, we may see large B mode from CMB even in low scale inflation models. We simulate the B mode power spectra induced by first order phase transition using the CLASS package. For N_e= 58, 57 and 56 before the end of inflation, in which we can still see little wiggles induced by the oscillation by the local nature of the bubble collision. However, since the spherical harmonics are not orthogonal to the Fourier modes, we expect the oscillation pattern would be smeared.

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