Precise peculiar velocities from gravitational waves accompanied by electromagnetic signals and cosmological applications

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Abstract

Peculiar velocities are a precious tool to study the large-scale distribution of matter in the local universe and test cosmological models. However, present measurements of peculiar velocities are based on empirical distance indicators, which introduce large error bars. Here we present a new method to measure the peculiar velocities, by directly estimating luminosity distances through waveform signals from inspiralling compact binaries and measuring redshifts from electromagnetic (EM) counterparts. In the future, with the distance uncertainty of GW events reducing to **0.1** per cent by future GW detectors, the uncertainty of the peculiar velocity can be reduced to **10** km/s at 100 mega parsecs. We find that dozens of GW events with EM counterparts can provide a Hubble constant H_0 uncertainty of **0.5%** and the growth rate of structure with a **0.6%** precision in the third-generation ground-base GW detectors, which can reconcile the H_0 tension and determine the origins for cosmic accelerated expansion.

Introduction

Recently, Advanced LIGO and Virgo discovered the first binary neutron stars inspiralling signal GW170817, accompanied by electromagnetic (EM) counterparts, heralding the new era of gravitational-wave multi-messenger astronomy. When using GWs and EM counterparts to measure the distance-redshift relation, the redshifts should be entirely due to the cosmic expansion. However, in the local universe, large-scale structure induces peculiar motions so that the measured redshifts contain contributions from peculiar velocities.
Meanwhile, the horizon of Advanced LIGO and Virgo for the BNS or NS-BH merger is only a few hundreds Mpc. If we take the typical value of peculiar velocity $v_{\rm pec} = 400$ km s^{-1}, and Hubble constant $H_0 = 70$ km s^{-1} Mpc^{-1}, the peculiar velocity can contribute about 30% of the measured redshift at a distance of 20 Mpc. Therefore, the effect of peculiar velocities on GW astronomy is crucial in local universe. However, previous works using GW sirens do not consider this effect seriously.

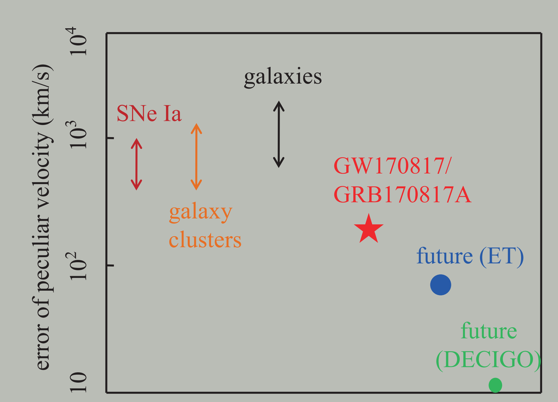

Figure: Measurement accuracy of the peculiar velocity at 100 Mpc for different methods.

At present, there are two ways to measure peculiar velocities. The first is to measure peculiar velocities directly by obtaining distances to individual galaxies and their redshifts. The second method measures the peculiar velocities statistically based on redshift space distortion. Unfortunately, the peculiar velocities derived from both methods have large uncertainties.

Method

Here we propose a robust method to measure the peculiar velocities with high accuracy using GWs and EM counterparts. Based on the observed redshift z and the luminosity distance d_L derived from GW waveform signal, the radial peculiar velocity $v_{\rm p}$ can be calculated by

$$v_{\rm pec,r} = cz - H_0 d_L, \qquad (1)$$

Method

where c is the speed of light and H_0 is the Hubble constant. Because of the H_0 tension, we should provide an independently measured H_0 to calculate $v_{\rm pec,r}$. If H_0 is measured precisely in the future, $v_{\rm pec,r}$ can be derived directly from equation (1).
Our method, called $v - v$ comparison method, is performed by comparing the radial peculiar velocities from GW observations with those reconstructed from the galaxy survey.
In the linear density perturbation regime, the peculiar velocity ($\vec{v}_{\rm pec}$) can be expressed as

$$\vec{v}_{\rm pec}(\vec{x}) = \frac{H_0 f_0}{4\pi}\int {\rm d}^3\vec{x}'\delta_{\rm m}(\vec{x}',t_0)\frac{(\vec{x}'-\vec{x})}{|\vec{x}'-\vec{x}|^3}, \qquad (2)$$

where f_0 is the present day growth rate of structure.
The Point Source Catalogue redahift (PSCz) is used and the peculiar velocity field is reconstructed assuming $\beta = 1$. Since the true value of β is uncertain, we need to constrain β and H_0 simultaneously by comparing the peculiar velocities from equation (3) with measured peculiar velocities. The predicted velocities in GW location are calculated by applying a Gaussian kernel of radius R_j (5 Mpc in our paper) to the predicted 3D velocity $\mathbf{v}_{\rm rec}(\mathbf{x}_j)$ specified at the position of the PSCz galaxies. We have

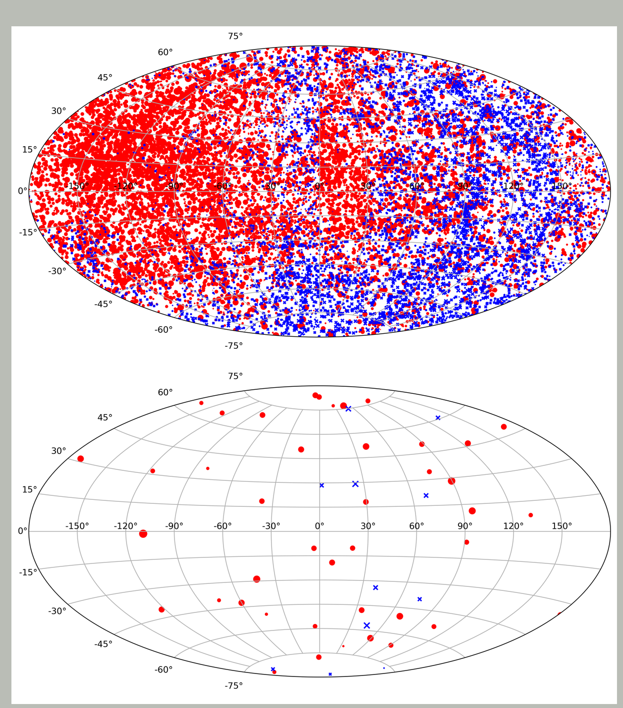

Figure: Peculiar velocities of PSCz galaxies and mock GW events projected in Galactic coordinates.

$$\mathbf{v}_{\rm smo}(\mathbf{x}_i) = \frac{\sum_{j=1}^{N'}\mathbf{v}_{\rm rec}(\mathbf{x}_j)\exp\left(-\frac{(\mathbf{x}_j-\mathbf{x}_i)^2}{2R_j^2}\right)}{\sum_{j=1}^{N'}\exp\left(-\frac{(\mathbf{x}_j-\mathbf{x}_i)^2}{2R_j^2}\right)}. \qquad (3)$$

Then the predicted radial peculiar velocities are

$$v_{{\rm model},i} = \mathbf{v}_{\rm smo}(\mathbf{x}_i)\cdot\mathbf{x}_i. \qquad (4)$$

We construct a mock GW catalogue to compare measured peculiar velocities with PSCz survey. The errors are given by

$$\left(\frac{\sigma_{v_{{\rm pec,r},i}}}{H_0 d_L}\right)^2 = \left(\frac{\sigma_{H_0}}{H_0}\right)^2 + \left(\frac{\sigma_{d_L}}{d_L}\right)^2. \qquad (5)$$

Method

For the third-generation detectors, such as Einstein Telescope (ET), we adopt $\frac{\sigma_{H_0}}{H_0}\sim$ **1%** and $\frac{\sigma_{d_L}}{d_L}\sim$ **1%**.

Result

The ability of our method depends on the measurement accuracies of the Hubble constant H_0 and luminosity distance d_L. For BNSs, the distance accuracy by Advanced LIGO can reach 10%. The main uncertainty comes from the errors of the distances measured by GW detectors.

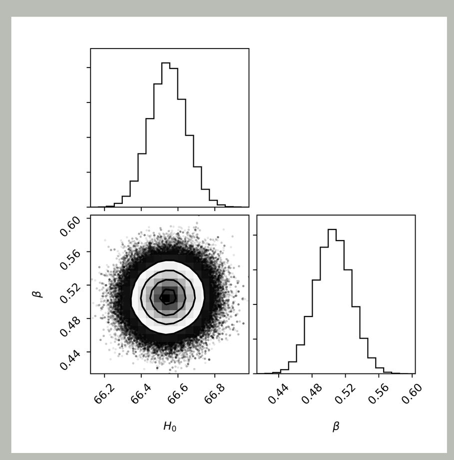

Figure: Constraints on β and H_0 using $v - v$ comparison method from mock GW catalogue.

For the third-generation detectors, such as ET, BBO and DECIGO, the distance uncertainties could be as low as 1% and 0.1% in local universe, respectively. In the future, the uncertainty of the H_0 can also be decreased to **0.1%**, together with the uncertainty of d_L decreased to **0.1%**, the errors of peculiar velocities can be determined to $\sim$ **10** km/s at 100 Mpc.

Summary

The peculiar velocities measured by our method would be powerful cosmological tools in the future. Although our method may be limited by the reconstructed peculiar velocity field, future galaxy surveys can give high-quality peculiar velocity field.

Main References

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