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A NEW LIMIT ON THE GRAVITON MASS FROM THE CONVERGENCE SCALE OF THE CMB DIPOLE

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ABSTRACT

The clustering dipole in the 2MASS galaxy survey converges on a scale of ~ 400 Mpc to the local peculiar velocity inferred from the Cosmic-Microwave-Background dipole. I show that this limits the graviton mass in Yukawa theories of gravity to less than 5×10^{-32} eV. The new limit is 2.5×10^{8} times tighter than the latest constraint from gravitational waves detected by the LIGO-Virgo-KAGRA collaboration.

1. INTRODUCTION

In General Relativity, gravitational interactions are mediated by a massless gauge boson, the graviton. However, a class of modified gravity theories endow the graviton with a mass, m_g (for a comprehensive review, see de Rham et al. (2017)).

The possible existence of a graviton mass causes a time delay in the propagation of gravitational waves relative to the speed of light, and could also lead to a Yukawa-form for the gravitational potential of a point mass M as a function of distance r,

$$\Phi = -\frac{GM}{r}\exp(-r/\lambda_g), \tag{1}$$

where G is Newton's constant. This is the Green's function solution to the screened Poisson equation,

$$(\nabla^2 - \lambda_g^{-2})\Phi = 4\pi GM\delta^3(\mathbf{r}), \tag{2}$$

with the gravitational acceleration being $\mathbf{g} = -\nabla\Phi$.

The screening length is given by the Compton wavelength of the graviton,

$$\lambda_g = \frac{h}{m_g c} = \left(\frac{400\ \mathrm{Mpc}}{m_g/10^{-31}\ \mathrm{eV}}\right), \tag{3}$$

where h is Planck's constant and c is the speed of light.

Many limits of the graviton mass were derived in the literature based on a variety of data sets (for a comprehensive summary of the limits and related references, see the Particle Data Group (2022)). Most recently, analysis of cosmological gravitational-wave data from the three observing runs of the LIGO-Virgo-KAGRA collaboration (GWTC-3), used the propagation speed limit to derive the constraint, $m_g < 1.27 \times 10^{-23}$ eV (The LIGO Scientific Collaboration et al. 2021). Here, we derive a tighter cosmological constraint.

2. COSMIC DIPOLE CONVERGENCE

Peculiar velocities relative to the Hubble flow, $\mathbf{v}$, are sourced by cosmic density inhomogeneities, with $\mathbf{v} \propto \mathbf{g}$ in the linear regime (Bilicki et al. 2011). The possible screening of gravity on a spatial scale λ_g introduces an exponential cutoff to the gravitational influence of mass concentrations beyond that scale. In that case, the net gravitational acceleration can be written as,

$$\mathbf{g}(\mathbf{r}) = G\int d\mathbf{r}' \frac{\rho_m(\mathbf{r}')\exp(-|\mathbf{r}'-\mathbf{r}|/\lambda_g)}{|\mathbf{r}'-\mathbf{r}|}\left(\frac{1}{|\mathbf{r}'-\mathbf{r}|} + \frac{1}{\lambda_g}\right)\frac{(\mathbf{r}'-\mathbf{r})}{|\mathbf{r}'-\mathbf{r}|}, \tag{4}$$

where $\rho_m(\mathbf{r}')$ is the cosmic matter density at comoving position $\mathbf{r}'$.

The peculiar velocity of the Local Group of galaxies was measured through the dipole anisotropy of the Cosmic Microwave Background (CMB) (Planck Collaboration & Aghanim 2014). The matter perturbations mapped by the 2MASS galaxy survey were shown to converge to the CMB dipole (to within one standard deviation, corresponding to $\sim 10\%$ of the measured CMB dipole) at a distance of ~ 400 Mpc (see Figure 7 in Bilicki et al. (2011)).

3. GRAVITON MASS LIMIT

The requirement that the exponential suppression of a massive graviton would not spoil the 2MASS dipole convergence by more than one standard deviation, sets the constraint $\lambda_g \gtrsim 800$ Mpc based on equation (4). Equation (3) therefore implies,

$$m_g < 5 \times 10^{-32} \text{ eV}, \tag{5}$$

or equivalently $m_g < 8.9 \times 10^{-65}$ g.

This limit is tighter by a factor of 2.5×10^8 than the LIGO-Virgo-KARGA limit (The LIGO Scientific Collaboration et al. 2021), and constitutes the best Yukawa-limit on the graviton mass so far (Particle Data Group 2022).

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