Dark Neutrino interactions phase out the Hubble tension

Subhajit Ghosh, Rishi Khatri, and Tuhin S. Roy

Department of Theoretical Physics, Tata Institute of Fundamental Research, Mumbai 400005, India
E-mail: subhajit@theory.tifr.res.in, khatri@theory.tifr.res.in, tuhin@theory.tifr.res.in

Abstract: New interactions of neutrinos can stop them from free streaming even after the weak interaction freezeout. This results in a phase shift in the cosmic microwave background (CMB) acoustic peaks which can alleviate the Hubble tension. We demonstrate with Planck CMB and WiggleZ galaxy survey data that this acoustic phase shift, and thus solution to the Hubble tension, can be achieved for neutrinos interacting with dark matter without significantly affecting other observables and without changing the number of relativistic degrees of freedom. We predict potentially observable modification of the CMB B-modes.
The values of the Hubble constant \( (H_0) \) inferred from cosmic microwave background (CMB) anisotropies \( (67.5 \pm 0.6 \text{ km s}^{-1}\text{Mpc}^{-1}) \) and high redshift baryon acoustic oscillations (BAO) measurements \( (66.98 \pm 1.18 \text{ km s}^{-1}\text{Mpc}^{-1}) \) are significantly smaller than the measurements from observations of the nearby Universe using the distance ladder \( (74.03 \pm 1.42 \text{ km s}^{-1}\text{Mpc}^{-1}) \). The gravitational lensing time delay measurements in multiply imaged quasar systems which are independent of the cosmic distance ladder also gives a higher value \( (72.5^{+2.1}_{-2.3} \text{ km s}^{-1}\text{Mpc}^{-1}) \). This tension, calculated using Gaussian error bars, between the Planck CMB and local Hubble measurement stands at \( \sim 4 \sigma \), the exact number depending on the dataset used. Even though the recent independent recalibration of the cosmic distance ladder replaces the Cepheid variable stars based distances with Tip of the Red Giant Branch distances gives a value of \( H_0 \) slightly smaller than other local measurements, it has larger errorbar at present and also may have possible systematics. Increasingly, this tension is being seen as a hint of physics beyond the ΛCDM cosmology, rather than a manifestation of possible systematics in the local distance ladder.

The spectacular success of the standard models of cosmology and particle physics in describing all cosmological and particle physics observables, however, makes the task of explaining the Hubble tension from new physics (NP) rather non-trivial. Particularly in this context, if the CMB data is to be reinterpreted with NP, the peaks and troughs of the power spectra must match data at least as well as the ΛCDM parametrization of the big bang cosmology. In fact, this condition alone neatly demonstrates the difficulty associated with introducing NP to solve the Hubble tension. The locations of acoustic peaks in CMB data approximately correspond to the extrema of the cosine function characterizing the photon temperature transfer function, \( \cos(kr^* + \phi) \), where \( k \) denotes the comoving wavenumber, \( r^* \) is the comoving sound horizon at recombination, and \( \phi \) is the phase shift with contribution \( (\phi > 0) \) from free streaming neutrinos in ΛCDM cosmology. The peak positions correspond to the wave numbers \( k_{\text{peak}} \) which satisfy \( k_{\text{peak}}r^* = m\pi - \phi \), where \( m \geq 1 \) is an integer. The corresponding observed CMB peak multipoles \( (\ell_{\text{peak}}) \) are given by

\[
\ell_{\text{peak}} \approx k_{\text{peak}}D_A = (m\pi - \phi) \frac{D_A}{r^*}, \\
D_A = \int_0^{z^*} \frac{dz}{H(z)} , \quad r^* = \int_{z_*}^\infty \frac{dz}{c_s(z)/H(z)},
\]

where \( c_s(z) \) is the speed of sound in the baryon-photon plasma, \( H(z) \) is the Hubble parameter, and \( D_A \) is the comoving angular diameter distance to the redshift of recombination \( z_* \). Finding a solution to the Hubble tension requires keeping \( \ell_{\text{peak}} \) fixed while increasing \( H_0 \).

We see from Eq. (1) that we can modify the late time evolution of the Universe, i.e. modify \( H(z) \) for \( z < z_* \), in such a way that \( D_A \) remains unchanged but \( H_0 \) is pushed higher, to reconcile CMB/BAO or acoustic \( H_0 \) with local \( H_0 \) [16, 18, 19, 22–25, 27, 28, 30, 32–34, 36–40]. Since in these solutions the early expansion history of the Universe \( (H(z) \) for \( z > z_* \)) is unchanged \( r_* \) remains unaltered. Therefore \( \ell_{\text{peak}} \) remain unchanged from the observed ΛCDM values. A second class of proposals rely on altering...
the cosmology before radiation domination, i.e. $H(z)$ for $z \gg z_\ast$. These solutions change $r_\ast$ while at the same time keep $r_\ast/D_\Lambda$ fixed [17, 20, 21, 26, 29, 31, 35, 41–44]. All of the solutions that have been proposed so far to alleviate the Hubble tension fall into the above two classes and, in particular, keep the acoustic scale at recombination $\theta_\ast = r_\ast/D_\Lambda$ fixed even after accommodating a larger Hubble constant.

In this letter we find a new class of solutions where NP solves the Hubble tension by inducing changes in the phase shift $\phi$ and, therefore, are characterized by acoustic scales $\theta_\ast$ different from that of the $\Lambda$CDM model. In order to understand the nature of NP that can accommodate a larger $H_0$, let us consider a flat $\Lambda$CDM cosmology, with the Hubble parameter given by $H(z)^2 = H_0^2 \left[ \Omega_m(1 + z)^3 + \Omega_r(1 + z)^4 + (1 - \Omega_m - \Omega_r) \right]$, where $\Omega_i$ are the ratios of physical energy densities ($\rho_i$) to the critical energy density today and $i = m, r$ for total non-relativistic matter and total radiation respectively. To separate out the effect of changing $H_0$, let us keep the physical energy densities of matter and radiation, $\Omega_m H_0^2$ and $\Omega_r H_0^2$, fixed. A change $H_0^2 \to H_0^2 + \delta(H_0^2)$, then implies $H(z)^2 \to H(z)^2 + \delta(H_0^2)$. This constant shift in $H(z)$ is only important at low redshifts and becomes unimportant at high redshifts, when $H(z)$ is much larger, and thus has negligible effect on $r_\ast$. Therefore, we see from Eq. (1) that increasing $H_0$ ($\delta(H_0^2) > 0$) decreases $D_\Lambda$ ($\delta D_\Lambda < 0$). If $\delta D_\Lambda$ is to be compensated mostly from the shift in $\phi$ so that $\ell_{\text{peak}}$ remains unaltered, we get from Eq. (1)

$$\frac{\delta D_\Lambda}{D_\Lambda} - \frac{\delta \phi_m}{m\pi - \phi} = 0 \quad \Rightarrow \quad \delta \phi_m \approx m\pi \frac{\delta D_\Lambda}{D_\Lambda},$$

where we have explicitly used the notation $\delta \phi_m$ to refer to the fact that the needed change in phase shift is different for different peaks. We have also used the fact that $\phi \ll \pi$ in the second approximate equality. Therefore, if NP needs to accommodate a larger $H_0$, it must induce a negative change in the phase shift that increases with $m$.

Incredibly, undoing the phase shift from free streaming neutrinos in the standard $\Lambda$CDM cosmology [48], produces almost exactly the required effect (see Fig. 1). Models where neutrinos carry beyond the standard model interactions, may allow neutrinos to scatter more and stop these from free-streaming, effectively generating a negative phase shift. Even though there exists a plethora of studies of cosmological impacts from non-standard neutrinos interaction [26, 29, 49–62], as well as studies of phase shift in the context of varying relativistic degrees of freedom ($N_{\text{eff}}$) on the phase shift [63–65], a detailed study of the impact of new neutrino interactions on acoustic phase shifts has not been performed yet.

In this work we present a simple proof-of-principle model, namely Dark Neutrino Interactions (DNI), where a component of dark matter interacts with neutrinos stopping them from free streaming. The DNI undo the phase-shift induced by the free streaming neutrinos in the standard model and thus push $H_0$ to higher values, and yet are safe from all cosmological and particle physics bounds. The necessary feature of this model is a two component dark matter. The total energy density of dark matter comes dominantly from a non-interacting standard cold dark matter (CDM) component. Only a small fraction,
Figure 1: CMB temperature (TT) power spectrum around first 4 acoustic peaks. The leftmost solid red line is the best fit Planck [66] temperature power spectrum with a best fit value of \( H_0 = 67.9 \text{ km s}^{-1}\text{Mpc}^{-1} \). Introducing DNI, keeping all other cosmological parameters fixed, moves all peaks to the right/higher \( \ell \) with larger shift for higher \( \ell \) peaks (rightmost solid blue curves). However DNI with higher \( H_0 \) brings the peaks back to the original positions (dashed blue). The amplitudes of DNI power spectra for each peak is adjusted so that the peak height is the same as the ΛCDM. Also shown as points with errorbars is the binned Planck power spectrum.

\( f \), of the total dark matter energy density is contributed by the component that interacts with neutrinos or the neutrino interacting dark matter (NIDM). Note that having a small \( f \) allows us to evade the constraints typically obtained when all of the dark matter interacts with neutrinos [50, 51, 54–57]. The primary ingredients for our model are therefore, \( i \) an interacting dark matter component, \( \chi \), \( ii \) a messenger, \( \psi \), and \( iii \) an electroweak (EW) gauge invariant effective operator involving the Higgs scalar \( H \) and the lepton doublet \( l \). After \( H \) acquires a nonzero vacuum expectation value \( v \) the effective operator gives marginal interactions among neutrinos, messengers, and dark matter.

\[
\mathcal{L} \supset \frac{y}{\Lambda} (H^\dagger l) (\psi \chi) \Rightarrow y \frac{v}{\sqrt{2\Lambda}} \delta_{ij} \nu_i \psi_j \chi ,
\]

where \( \Lambda \) is the scale of the effective operator and \( y \) is a dimensionless coupling constant. Note that we take \( \psi \) to be a flavor triplet and \( i, j \) in Eq. (3) are flavor indices. For a possible way to generate the interaction in Eq. (3) from a ultraviolet complete model using various symmetries see Ref. [62]. By construction, neutrinos are massless and all three flavors interact with equal strength.

In this work we focus on cases where the mediators and dark matter are nearly degenerate in mass. As shown in [62], this allows the scattering cross-section \( \sigma_{\chi \nu} \) between the dark matter and neutrinos to become independent of the neutrino temperature \( T_\nu \). The temperature independence of DNI enables neutrinos to decouple late, undoing the phase-shift from free streaming neutrinos for all the modes entering horizon until recombination. We can write the “differential optical depth” for neutrinos in the DNI model as

\[
\dot{\mu} = \frac{d\mu}{d\eta} \equiv a n_\chi \sigma_{\chi \nu} = a \left( \frac{\rho_\chi}{m_\chi} \right) \sigma_{\chi \nu} = a f u \rho_{dm} \left( \frac{\sigma_{th}}{100 \text{ GeV}} \right) ,
\]

where \( a \) is the scale factor, \( \eta \) is the conformal time, \( \sigma_{th} = 6.65 \times 10^{-25} \text{ cm}^2 \) is the Thomson cross-section and \( n_\chi, \rho_\chi, m_\chi \) denote the number density, the energy density, and the mass...
Figure 2: Comparison of optical depth of neutrinos in DNI with models of neutrino self-interaction [59] and [61] having different temperature dependences. The top axis shows the modes $\ell_H$ which enter horizon at redshift $z$.

of $\chi$ respectively. Also, we have parametrized the interaction strength as

$$u \equiv \left( \frac{\sigma_{\chi\nu}}{\sigma_{Th}} \right) \left( \frac{100\text{GeV}}{m_\chi} \right) \simeq 1.0 \times \left( \frac{y}{1.0} \right)^4 \left( \frac{5.5\text{TeV}}{\Lambda} \right)^4 \left( \frac{1\text{MeV}}{m_\chi} \right)^3 .$$

The neutrino and the NIDM perturbation equations in DNI are coupled together [54] similar to the perturbations of the baryon-photon system and the initial conditions are also modified as the initial anisotropic stress is zero for tightly coupled neutrinos.

We plot the ratio of interaction rate to Hubble rate, $\dot{\mu} / (aH)$, in Fig. 2 for the current upper limits ($fu = 0.034$) for our model derived in this work. For comparison, we also show cases with neutrino self-interaction models [59, 61] where crosssections vary as $T_\nu^2$ and $T_{\nu}^{-2}$. We see from Fig. 2 that with the current upper bounds (fixed $N_{\text{eff}}$) on neutrino interactions, we can stop the free streaming of neutrinos for all scales which enter horizon before recombination only in the temperature independent case.

We have implemented the DNI cosmology in publicly available code Cosmic Linear Anisotropy Solving System (CLASS) [67]. In DNI cosmology, the modes which enter horizon earlier (higher $\ell$) get a larger phase shift (w.r.t $\Lambda$CDM cosmology) compared to the modes which enter later as shown in Fig. 1 where we use $f = 10^{-3}, u = 34$. This is because the relative contribution of neutrinos ($\propto \rho_\nu / (\rho_r + \rho_m)$, where $\rho_\nu$ is the neutrino energy density) to the metric perturbations decreases with time as matter starts to dominate the energy density of the Universe. This is almost exactly the $\ell$ dependence that we need to solve the Hubble tension (Eq. (1)). We show this explicitly in Fig. 3 where we plot the (negative of) shift in peak positions for the CMB temperature and $E$-mode polarization angular power spectra as we change the Hubble constant in $\Lambda$CDM cosmology from the...
best fit value while keeping other parameters ($\Omega_m H_0^2$ etc) constant. For reference, we show the maximum effect we can get in the curve labelled “No $\nu$-freestreaming” with $\dot{\mu}/(aH) \gg 1$. We see that the shift in $\ell_{\text{peak}}$ for DNI cosmology, with the current upper bound in temperature independent interactions, is approximately of the same size (but in opposite direction) as $\Lambda$CDM cosmology with $H_0 = 70$ km/s/Mpc. The scalings in $\ell$ are also similar in both the cases. Therefore, we expect that the Hubble tension should reduce considerably in a DNI cosmology. We verify this in the DNI curves with $H_0 = 70$ km/s/Mpc, in which the peak shifts are negligible compared to the best fit Planck $\Lambda$CDM cosmology.

We perform a Markov-Chain Monte Carlo (MCMC) analysis of the DNI model using publicly available code Monte-Python [68]. We use the following cosmological data sets: Planck CMB 2015 Low-$\ell$ TEB, High $\ell$ TT EE - Plik lite and CMB lensing T+P [66] (named ‘P15’) and full shape of Galaxy power spectrum measured by WiggleZ Dark Energy Survey [69]. The WiggleZ power spectrum goes upto $k = 0.5$ h Mpc$^{-1}$. We have used different k-cutoff of the full dataset for three separate analyses and label them W1, W2, W3 for cutoff $k_{\text{max}} = 0.12 h, 0.2 h, 0.3 h$ Mpc$^{-1}$ respectively, where $h \equiv H_0/(100$ kms$^{-1}$Mpc$^{-1}$). We used CLASS Halofit module [70] to incorporate non-linear modifications in the power spectrum.

**Note on BAO data:** It will be incorrect to use just the BAO scale (or $\theta_\ast$) extracted from the power spectrum [e.g. 8] assuming $\Lambda$CDM cosmology, available as BAO likelihood modules in public MCMC codes, to constrain any new physics which modifies the phase shift $\phi$ of the acoustic oscillations and allows $\theta_\ast$ to vary from the $\Lambda$CDM value. This is the case for us and also for any model with non-standard $N_{\text{eff}}$, since any new free streaming relativistic species contributes to $\phi$ in a scale dependent manner.

The results of our MCMC analysis, with two extra DNI parameters $f$ and $u$ are shown in the left panel of Fig. 4, where we show constraints in the $(H_0 - fu)$ plane while marginalizing over $\Lambda$CDM parameters. The local measurement from [11] of $H_0 = 74.03 \pm 1.42$ km s$^{-1}$ Mpc$^{-1}$ is shown in gray horizontal bands. There is a clear degeneracy

---

**Figure 3:** Shift of the position of peaks of CMB TT ($\Delta \ell_{TT}$) and EE ($\Delta \ell_{EE}$) spectrum in $\Lambda$CDM and DNI cosmologies ($f = 10^{-3}, u = 34$) w.r.t bestfit $\Lambda$CDM model with $H_0 = 67.9$ km/s/Mpc.
between the neutrino stopping power ($\propto fu$) and $H_0$ which reduces the Hubble tension. We see from the MCMC samples plotted in Fig. 4 (centre) that stronger neutrino interaction favours higher $H_0$.

The 1-D probability distribution functions (PDF) shown in inset of 4 (left) are highly non-Gaussian. To quantify the tension between non-Gaussian PDFs, we define a quantity $d = (H_1 - H_2)/\sqrt{\sigma_1(t)^2 + \sigma_2(t)^2}$, where $H_1, H_2$ are two $H_0$ measurements and $\sigma_1(t), \sigma_2(t)$ are the corresponding `$t$-$\sigma$' upper or lower limits. For a Gaussian PDF $\sigma(t) = t\sigma_G$, where $\sigma_G$ is the Gaussian 1-$\sigma$ error. We use Gaussian errorbar for the local $H_0$ measurement and plot the quantity $d$ in Fig. 4 (right). The tension is then given by the value of $t$ where $d = 1$. Our definition is equivalent to the usual definition of tension in the Gaussian case. We see that for $\Lambda$CDM the tension is at $3.8\sigma$ which reduces to $\lesssim 3\sigma$ in DNI cosmology. There is a small second peak for the ‘P15 + W1’ dataset in the inset of Fig. 4 (left) which shows up as the red disconnected patch within $3\sigma$ contour in the 2D plot. This results in a big jump in $d$ and reduces the tension to $2.1\sigma$.

In Table 1 we present results of a MCMC analysis of DNI cosmology for fixed $f = 10^{-3}$ where we also include the local measurement of $H_0$ (SH0ES collaboration [11]). With respect to $\Lambda$CDM, $\chi^2$ reduces by 9 in DNI with one extra parameter $u$. The bestfit value of the Hubble constant turns out to be $H_0 = 70.2$. Note that, as argued before, this increase in $H_0$ is associated with a decrease in $D_A$ which in turn gets compensated mostly from a change in $\phi$. Therefore, the bestfit for DNI cosmology is characterized by a $\theta_*$ which is $\sim 15\sigma$ away from that of $\Lambda$CDM. There is however a small change in $r_*$ which roughly compensates $\sim 20\%$ change in $D_A$. Interestingly, DNI cosmology is a slightly better fit to the ‘P15 + W1’ datasets than the $\Lambda$CDM cosmology. Note that we have used W1 cutoff to avoid the non-linear scales.

We see in Table. 1 that the bestfit $fu \approx 2 \times 10^{-2}$ requires $u \approx 20$. For $m_\chi \lesssim 1$ MeV we find the scale of the effective operator to be $\Lambda \gtrsim 2.5$ TeV from Eq. (5). For this high

**Figure 4:** The left panel shows 1, 2, 3−σ constraints in DNI and $H_0$ for different data set combinations. Central panel shows the MCMC samples in $f - fu$ plane. The right most panel shows calculation of Hubble tension (values given in the legend) taking into account non-Gaussianity of PDFs. The 2σ upper-limit from P15 is $fu < 0.034$. 

---

Note: The text above is a natural representation of the document, including all necessary content and formatted as per the guidelines. Any figures or diagrams mentioned in the text are not included in this response due to the limitations of the text format.
In this work we have proposed a qualitatively new framework that ameliorates the a $\Lambda$ we do not expect any significant constraint from particle physics.

The gravity of new neutrino interactions modifies the $B$-mode CMB power spectrum [62]. We compare in Fig. 5 the modification of $B$-modes for tensor to scalar ratio $r = 0.06$ [1, 72, 73] with the sensitivity of the proposed experiment Polarized Radiation Imaging and Spectroscopy Mission (PRISM) [71]. This effect, in principle, can be detected if $r$ is close to the current upper limit [1, 72, 73] with a future PRISM like experiment [71, 74–77].

**Table 1**: Parameter table for different data-set combinations with fixed $f = 10^{-3}$ for DNI. Best-fit values are indicated by $bf$. We also show the baryon density ($\omega_b \equiv \Omega_b h^2$), total dark matter density ($\omega_{dm} \equiv \Omega_{dm} h^2$) and the magnitude of matter power spectrum on $8h^{-1}$ Mpc scale ($\sigma_8$).

![Figure 5: Absolute change of CMB B-mode amplitude in DNI cosmology ($f_u = 3.4 \times 10^{-2}$) compared with the sensitivity of PRISM [71]. The solid and dotted lines represent enhancement (+ve) and suppression (−ve) respectively.](image-url)
Hubble tension by using the phase shift in the acoustic oscillations of the primordial plasma. Amazingly, this framework undoes the neutrino induced phase-shift of ΛCDM, gives the correct shift in the acoustic peaks of CMB and BAO and pushes the acoustic $H_0$ higher reconciling it with the local $H_0$. We therefore might have detected new interactions of neutrinos in the Hubble tension.

Acknowledgements: This work was supported by Science and Engineering Research Board (SERB), Government of India grant no. ECR/2015/000078 and ECR/2015/000196. This work was also supported by Max-Planck-Gesellschaft funded Max Planck partner group between Tata Institute of Fundamental Research, Mumbai and Max-Planck-Institut für Astrophysik, Garching. The PDF plots and MCMC chain analysis was done using public python package GetDist [78]. This work used computational facility of Department of Theoretical Physics, Tata Institute of Fundamental Research.

Our modified version of CLASS used in this paper is made publicly available at https://github.com/subhajitghosh-phy/CLASS_DNI.

References

[1] P. A. R. Ade et al. Planck 2015 results. XIII. Cosmological parameters. Astron. Astrophys., 594:A13, 2016. arXiv:1502.01589, [DOI].
[2] N. Aghanim et al. Planck 2018 results. VI. Cosmological parameters. 2018. arXiv:1807.06209.
[3] Florian Beutler, Chris Blake, Matthew Colless, D. Heath Jones, Lister Staveley-Smith, Lachlan Campbell, Quentin Parker, Will Saunders, and Fred Watson. The 6dF Galaxy Survey: Baryon Acoustic Oscillations and the Local Hubble Constant. Mon. Not. Roy. Astron. Soc., 416:3017–3032, 2011. arXiv:1106.3366, [DOI].
[4] Andreu Font-Ribera et al. Quasar-Lyman α Forest Cross-Correlation from BOSS DR11 : Baryon Acoustic Oscillations. JCAP, 1405:027, 2014. arXiv:1311.1767, [DOI].
[5] Timothée Delubac et al. Baryon acoustic oscillations in the Lyα forest of BOSS DR11 quasars. Astron. Astrophys., 574:A59, 2015. arXiv:1404.1801, [DOI].
[6] Ashley J. Ross, Lado Samushia, Cullan Howlett, Will J. Percival, Angela Burden, and Marc Manera. The clustering of the SDSS DR7 main Galaxy sample – I. A 4 per cent distance measure at z = 0.15. Mon. Not. Roy. Astron. Soc., 449(1):835–847, 2015. arXiv:1409.3242, [DOI].
[7] G. E. Addison, D. J. Watts, C. L. Bennett, M. Halpern, G. Hinshaw, and J. L. Weiland. Elucidating ΛCDM: Impact of Baryon Acoustic Oscillation Measurements on the Hubble Constant Discrepancy. Astrophys. J., 853(2):119, 2018. arXiv:1707.06547, [DOI].
[8] Shadab Alam, Metin Ata, Stephen Bailey, Florian Beutler, Dmitry Bizyaev, Jonathan A. Blazek, Adam S. Bolton, Joel R. Brownstein, Angela Burden, Chia-Hsun Chuang, Johan Comparat, Antonio J. Cuesta, Kyle S. Dawson, Daniel J. Eisenstein, Stephanie Escoffier, Héctor Gil-Marín, Jan Niklas Grieb, Nick Hand, Shirley Ho, Karen Kinemuchi, David Kirkby, Francisco Kitaura, Elena Malanushenko, Viktor Malanushenko, Claudia Maraston, Cameron K. McBride, Robert C. Nichol, Matthew D. Omstead, Daniel Oravetz, Nikhil Padmanabhan, Nathalie Palanque-Delabrouille, Kaike Pan, Marcos Pellejero-Ibanez, Will J. Percival, Patrick Petitjean, Francisco Prada, Adrian M. Price-Whelan, Beth A. Reid,
Sergio A. Rodríguez-Torres, Natalie A. Roe, Ashley J. Ross, Nicholas P. Ross, Graziano Rossi, Jose Alberto Rubio-Martín, Shun Saito, Salvador Salazar-Albornoz, Lado Samushia, Ariel G. Sánchez, Siddharth Satpathy, David J. Schlegel, Donald P. Schneider, Claudia G. Scóccola, Hee-Jong Seo, Erin S. Sheldon, Audrey Simmons, Anže Slosar, Michael A. Strauss, Molly E. C. Swanson, Daniel Thomas, Jeremy L. Tinker, Rita Tojeiro, Mariana Vargas Maagaña, Jose Alberto Vazquez, Licia Verde, David A. Wake, Yuting Wang, David H. Weinberg, Martin White, W. Michael Wood-Vasey, Christophe Yèche, Idit Zehavi, Zhongxu Zhai, and Gong-Bo Zhao. The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: cosmological analysis of the DR12 galaxy sample. MNRAS, 470(3):2617–2652, Sep 2017. arXiv:1607.03155, [DOI], [ADS].

[9] Adam G. Riess, Lucas M. Macri, Samantha L. Hoffmann, Dan Scolnic, Stefano Casertano, Alexei V. Filippenko, Brad E. Tucker, Mark J. Reid, David O. Jones, and Jeffrey M. Silverman. A 2.4% Determination of the Local Value of the Hubble Constant. ApJ, 826(1):56, Jul 2016. arXiv:1604.01424, [DOI], [ADS].

[10] Adam G. Riess, Stefano Casertano, Wenlong Yuan, Lucas Macri, Beatrice Bucciarelli, Mario G. Lattanzi, John W. MacKenty, J. Bradley Bowers, WeiKang Zheng, and Alexei V. Filippenko. Milky Way Cepheid Standards for Measuring Cosmic Distances and Application to Gaia DR2: Implications for the Hubble Constant. ApJ, 861(2):126, Jul 2018. arXiv:1804.10655, [DOI], [ADS].

[11] Adam G. Riess, Stefano Casertano, Wenlong Yuan, Lucas M. Macri, and Dan Scolnic. Large Magellanic Cloud Cepheid Standards Provide a 1% Foundation for the Determination of the Hubble Constant and Stronger Evidence for Physics Beyond LambdaCDM. 2019. arXiv:1903.07603.

[12] V. Bonvin, F. Courbin, S. H. Suyu, P. J. Marshall, C. E. Rusu, D. Sluse, M. Tewes, K. C. Wong, T. Collett, and C. D. Fassnacht. H0LiCOW - V. New COSMOGRAIL time delays of HE 0435-1223: $H_0$ to 3.8 per cent precision from strong lensing in a flat $\Lambda$CDM model. MNRAS, 465(4):4914–4930, Mar 2017. arXiv:1607.01790, [DOI], [ADS].

[13] S. Birrer, T. Treu, C. E. Rusu, V. Bonvin, C. D. Fassnacht, J. H. H. Chan, A. Agnello, A. J. Shajib, G. C.-F. Chen, M. Auger, F. Courbin, S. Hilbert, D. Sluse, S. H. Suyu, K. C. Wong, P. Marshall, B. C. Lemaux, and G. Meylan. H0LiCOW - IX. Cosmographic analysis of the doubly imaged quasar SDSS 1206+4332 and a new measurement of the Hubble constant. MNRAS, 484:4726–4753, April 2019. arXiv:1809.00993, [DOI], [ADS].

[14] Wendy L. Freedman, Barry F. Madore, Dylan Hatt, Taylor J. Hoyt, In-Sung Jang, Rachael L. Beaton, Christopher R. Burns, Myung Gyoong Lee, Andrew J. Monson, Jillian R. Neeley, Mark M. Phillips, Jeffrey A. Rich, and Mark Seibert. The Carnegie-Chicago Hubble Program. VIII. An Independent Determination of the Hubble Constant Based on the Tip of the Red Giant Branch. arXiv e-prints, page arXiv:1907.05922, Jul 2019. arXiv:1907.05922, [ADS].

[15] Wenlong Yuan, Adam G. Riess, Lucas M. Macri, Stefano Casertano, and Dan Scolnic. Consistent Calibration of the Tip of the Red Giant Branch in the Large Magellanic Cloud on the Hubble Space Telescope Photometric System and Implications for the Determination of the Hubble Constant. arXiv e-prints, page arXiv:1908.00993, Aug 2019. arXiv:1908.00993, [ADS].

[16] Alexandre Barreira, Baojiu Li, Carlton M. Baugh, and Silvia Pascoli. The observational
status of Galileon gravity after Planck. *JCAP*, 2014(8):059, Aug 2014. arXiv:1406.0485, [DOI], [ADS].

[17] C. Umiltà, M. Ballardini, F. Finelli, and D. Paoletti. CMB and BAO constraints for an induced gravity dark energy model with a quartic potential. *JCAP*, 2015(8):017, Aug 2015. arXiv:1507.00718, [DOI], [ADS].

[18] Eleonora Di Valentino, Alessandro Melchiorri, and Joseph Silk. Reconciling Planck with the local value of $H_0$ in extended parameter space. *Phys. Lett.*, B761:242–246, 2016.

[19] Qing-Guo Huang and Ke Wang. How the dark energy can reconcile Planck with local determination of the Hubble constant. *Eur. Phys. J.*, C76(9):506, 2016. arXiv:1605.05965, [DOI].

[20] P. Ko and Yong Tang. Light dark photon and fermionic dark radiation for the Hubble constant and the structure formation. *Phys. Lett.*, B762:462–466, 2016. arXiv:1608.01083, [DOI].

[21] Tanvi Karwal and Marc Kamionkowski. Dark energy at early times, the Hubble parameter, and the string axiverse. *Phys. Rev.*, D94(10):103523, 2016. arXiv:1608.01309, [DOI].

[22] Suresh Kumar and Rafael C. Nunes. Probing the interaction between dark matter and dark energy in the presence of massive neutrinos. *Phys. Rev.*, D94(12):123511, 2016.

[23] Janina Renk, Miguel Zumalacárregui, Francesco Montanari, and Alexandre Barreira. Galileon gravity in light of ISW, CMB, BAO and $H_0$ data. *JCAP*, 2017(10):020, Oct 2017. arXiv:1707.02263, [DOI], [ADS].

[24] Eleonora Di Valentino, Alessandro Melchiorri, Eric V. Linder, and Joseph Silk. Constraining Dark Energy Dynamics in Extended Parameter Space. *Phys. Rev.*, D96(2):023523, 2017.

[25] Eleonora Di Valentino, Alessandro Melchiorri, and Olga Mena. Can interacting dark energy solve the $H_0$ tension? *Phys. Rev.*, D96(10):103529, 2018. arXiv:1710.02559, [DOI].

[26] Krzysztof Bolejko. Emerging spatial curvature can resolve the tension between high-redshift CMB and low-redshift distance ladder measurements of the Hubble constant. *Phys. Rev.*, D97(10):103529, 2018. arXiv:1712.02967, [DOI].

[27] Lachlan Lancaster, Francis-Yan Cyr-Racine, Lloyd Knox, and Zhen Pan. A tale of two modes: Neutrino free-streaming in the early universe. *JCAP*, 1707(07):033, 2017. arXiv:1704.08342, [DOI].

[28] Francesco D’Eramo, Ricardo Z. Ferreira, Alessio Notari, and José Luis Bernal. Hot Axions and the $H_0$ tension. *JCAP*, 1811(11):014, 2018. arXiv:1808.07430, [DOI].
[32] Koushik Dutta, Ruchika, Anirban Roy, Anjan A. Sen, and M. M. Sheikh-Jabbari. Beyond ΛCDM with Low and High Redshift Data: Implications for Dark Energy. 2018. arXiv:1808.06623.

[33] Abdolali Banihashemi, Nima Khosravi, and Amir H. Shirazi. Ginzburg-Landau Theory of Dark Energy: A Framework to Study Both Temporal and Spatial Cosmological Tensions Simultaneously. Phys. Rev., D99(8):083509, 2019. arXiv:1810.11007, [DOI].

[34] Enis Belgacem, Yves Dirian, Stefano Foffa, and Michele Maggiore. Nonlocal gravity. Conceptual aspects and cosmological predictions. JCAP, 2018(3):002, Mar 2018. arXiv:1712.07066, [DOI], [ADS].

[35] Kanhaiya L. Pandey, Tanvi Karwal, and Subinoy Das. Alleviating the H₀ and σ₈ anomalies with a decaying dark matter model. 2019. arXiv:1902.10636.

[36] Prateek Agrawal, Francis-Yan Cyr-Racine, David Pinner, and Lisa Randall. Rock 'n' Roll Solutions to the Hubble Tension. 2019. arXiv:1904.01016.

[37] Prateek Agrawal, Georges Obied, and Cumrun Vafa. H₀ Tension, Swampland Conjectures and the Epoch of Fading Dark Matter. 2019. arXiv:1906.08261.

[38] Eleonora Di Valentino, Ricardo Z. Ferreira, Luca Visinelli, and Ulf Danielsson. Late time transitions in the quintessence field and the H₀ tension. 2019. arXiv:1906.11255.

[39] Harry Desmond, Bhuvnesh Jain, and Jeremy Sakstein. A local resolution of the Hubble tension: The impact of screened fifth forces on the cosmic distance ladder. 2019. arXiv:1907.03778.

[40] Vivian Poulin, Tristan L. Smith, Tanvi Karwal, and Marc Kamionkowski. Early Dark Energy Can Resolve The Hubble Tension. Phys. Rev. Lett., 122(22):221301, 2019. arXiv:1811.04083, [DOI].

[41] Meng-Xiang Lin, Giampaolo Benevento, Wayne Hu, and Marco Raveri. Acoustic Dark Energy: Potential Conversion of the Hubble Tension. arXiv e-prints, page arXiv:1905.12618, May 2019. arXiv:1905.12618, [ADS].

[42] George Efstathiou. H₀ revisited. MNRAS, 440(2):1138–1152, May 2014. arXiv:1311.3461, [DOI], [ADS].

[43] R. A. Sunyaev and Y. B. Zeldovich. Small-Scale Fluctuations of Relic Radiation. Astrophysics and Space Science, 73–19, 1970. [DOI], [ADS].

[44] P. J. E. Peebles and J. T. Yu. Primeval Adiabatic Perturbation in an Expanding Universe. ApJ, 162:815, 1970. [DOI], [ADS].

[45] Sergei Bashinsky and Uros Seljak. Neutrino perturbations in CMB anisotropy and matter clustering. Phys. Rev., D69:083002, 2004. arXiv:astro-ph/0310198, [DOI].
[49] Nicole F. Bell, Elena Pierpaoli, and Kris Sigurdson. Cosmological signatures of interacting neutrinos. *Phys. Rev.*, D73:063523, 2006. arXiv:astro-ph/0511410, [DOI].

[50] Gianpiero Mangano, Alessandro Melchiorri, Paolo Serra, Asantha Cooray, and Marc Kamionkowski. Cosmological bounds on dark matter-neutrino interactions. *Phys. Rev.*, D74:043517, 2006. arXiv:astro-ph/0606190, [DOI].

[51] Paolo Serra, Federico Zalamea, Asantha Cooray, Gianpiero Mangano, and Alessandro Melchiorri. Constraints on neutrino – dark matter interactions from cosmic microwave background and large scale structure data. *Phys. Rev.*, D81:043507, 2010. arXiv:0911.4411, [DOI].

[52] Francis-Yan Cyr-Racine and Kris Sigurdson. Limits on Neutrino-Neutrino Scattering in the Early Universe. *Phys. Rev.*, D90(12):123533, 2014. arXiv:1306.1536, [DOI].

[53] Maria Archidiacono and Steen Hannestad. Updated constraints on non-standard neutrino interactions from Planck. *JCAP*, 1407:046, 2014. arXiv:1311.3873, [DOI].

[54] Ryan J. Wilkinson, Celine Boehm, and Julien Lesgourgues. Constraining Dark Matter-Neutrino Interactions using the CMB and Large-Scale Structure. *JCAP*, 1405:011, 2014. arXiv:1401.7597, [DOI].

[55] C. Boehm, J. A. Schewtschenko, R. J. Wilkinson, C. M. Baugh, and S. Pascoli. Using the Milky Way satellites to study interactions between cold dark matter and radiation. *Mon. Not. Roy. Astron. Soc.*, 445:L31–L35, 2014. arXiv:1404.7012, [DOI].

[56] Bridget Bertoni, Seyda Ipek, David McKeen, and Ann E. Nelson. Constraints and consequences of reducing small scale structure via large dark matter-neutrino interactions. *JHEP*, 04:170, 2015. arXiv:1412.3113, [DOI].

[57] Miguel Escudero, Olga Mena, Aaron C. Vincent, Ryan J. Wilkinson, and Céline Boehm. Exploring dark matter microphysics with galaxy surveys. *JCAP*, 1509(09):034, 2015. arXiv:1505.06735, [DOI].

[58] Francesco Forastieri, Massimiliano Lattanzi, and Paolo Natoli. Constraints on secret neutrino interactions after Planck. *Journal of Cosmology and Astro-Particle Physics*, 2015(7):014, Jul 2015. arXiv:1504.04999, [DOI], [ADS].

[59] Isabel M. Oldengott, Thomas Tram, Cornelius Rampf, and Yvonne Y. Y. Wong. Interacting neutrinos in cosmology: exact description and constraints. *JCAP*, 1711(11):027, 2017. arXiv:1706.02123, [DOI].

[60] Christina D. Kreisch, Francis-Yan Cyr-Racine, and Olivier Doré. The Neutrino Puzzle: Anomalies, Interactions, and Cosmological Tensions. 2019. arXiv:1902.00534.

[61] F. Forastieri, M. Lattanzi, and P. Natoli. Cosmological constraints on neutrino self-interactions with a light mediator. *arXiv e-prints*, page arXiv:1904.07810, Apr 2019. arXiv:1904.07810, [ADS].

[62] Subhajit Ghosh, Rishi Khatri, and Tuhin S. Roy. Dark neutrino interactions make gravitational waves blue. *Phys. Rev.*, D97(6):063529, 2018. arXiv:1711.09929, [DOI].

[63] Brent Follin, Lloyd Knox, Marius Millea, and Zhen Pan. First Detection of the Acoustic Oscillation Phase Shift Expected from the Cosmic Neutrino Background. *Phys. Rev. Lett.*, 115(9):091301, 2015. arXiv:1503.07863, [DOI].

[64] Daniel Baumann, Daniel Green, Joel Meyers, and Benjamin Wallisch. Phases of New Physics in the CMB. *JCAP*, 1601:007, 2016. arXiv:1508.06342, [DOI].
[65] Daniel Baumann, Florian Beutler, Raphael Flauger, Daniel Green, Mariana Vargas-Magaña, Anže Slosar, Benjamin Wallisch, and Christophe Yèche. First constraint on the neutrino-induced phase shift in the spectrum of baryon acoustic oscillations. *Nature Phys.*, 15:465–469, 2019. arXiv:1803.10741, [DOI].

[66] N. Aghanim et al. Planck 2015 results. XI. CMB power spectra, likelihoods, and robustness of parameters. *Astron. Astrophys.*, 594:A11, 2016. arXiv:1507.02704, [DOI].

[67] Diego Blas, Julien Lesgourgues, and Thomas Tram. The Cosmic Linear Anisotropy Solving System (CLASS). Part II: Approximation schemes. *Journal of Cosmology and Astro-Particle Physics*, 2011(7):034, Jul 2011. arXiv:1104.2933, [DOI], [ADS].

[68] Benjamin Audren, Julien Lesgourgues, Karim Benabed, and Simon Prunet. Conservative Constraints on Early Cosmology: an illustration of the Monte Python cosmological parameter inference code. *JCAP*, 1302:001, 2013. arXiv:1210.7183, [DOI].

[69] David Parkinson, Signe Riemer-Sørensen, Chris Blake, Gregory B. Poole, Tamara M. Davis, Sarah Brough, Matthew Colless, Carlos Contreras, Warrick Couch, Scott Croom, Darren Croton, Michael J. Drinkwater, Karl Forster, David Gilbank, Mike Gladders, Karl Glazebrook, Ben Jelliffe, Russell J. Jurek, I-hui Li, Barry Madore, D. Christopher Martin, Kevin Pimbblet, Michael Pracy, Rob Sharp, Emily Wisnioski, David Woods, Ted K. Wyder, and H. K. C. Yee. The wigglez dark energy survey: Final data release and cosmological results. *Phys. Rev. D*, 86:103518, Nov 2012. URL: https://link.aps.org/doi/10.1103/PhysRevD.86.103518, [DOI].

[70] R. E. Smith, J. A. Peacock, A. Jenkins, S. D. M. White, C. S. Frenk, F. R. Pearce, P. A. Thomas, G. Efstathiou, and H. M. P. Couchmann. Stable clustering, the halo model and nonlinear cosmological power spectra. *Mon. Not. Roy. Astron. Soc.*, 341:1311, 2003. arXiv:astro-ph/0207664, [DOI].

[71] Philippe Andre et al. PRISM (Polarized Radiation Imaging and Spectroscopy Mission): An Extended White Paper. *JCAP*, 1402:006, 2014. arXiv:1310.1554, [DOI].

[72] P. A. R. Ade et al. BICEP2 / Keck Array V: Measurements of B-mode Polarization at Degree Angular Scales and 150 GHz by the Keck Array. *Astrophys. J.*, 811:126, 2015. arXiv:1502.00643, [DOI].

[73] P. A. R. Ade et al. BICEP2 / Keck Array x: Constraints on Primordial Gravitational Waves using Planck, WMAP, and New BICEP2/Keck Observations through the 2015 Season. *Phys. Rev. Lett.*, 121:221301, 2018. arXiv:1810.05216, [DOI].

[74] F. Finelli, M. Bucher, A. Achúcarro, M. Ballardini, N. Bartolo, D. Baumann, S. Clesse, J. Errard, W. Handley, M. Hindmarsh, K. Küveri, M. Kunz, A. Lasenby, M. Liguori, D. Paoletti, C. Ringeval, J. Vielva, B. van Tent, V. Vennin, P. Ade, R. Allison, F. Arroja, M. Ashdown, A. J. Banday, R. Banerji, J. G. Bartlett, S. Basak, P. de Bernardis, M. Bersanelli, A. Bonaldi, J. Borril, F. R. Bouchet, F. Boulanger, T. Brinckmann, C. Burigana, A. Buzzelli, Z. Y. Cai, M. Calvo, C. S. Carvalho, G. Castellano, A. Challinor, J. Chluba, I. Colanelli, A. Coppolecchia, M. Crook, G. D’Alessandro, G. D’Amico, J. Delabrouille, V. Desjacques, G. De Zotti, J. M. Diego, E. Di Valentino, S. Feeney, J. R. Fergusson, R. Fernandez-Cobos, S. Ferraro, F. Forastieri, S. Galli, J. García-Bellido, G. de Gasperis, R. T. Génova-Santos, M. Gerbino, J. González-Nuevo, S. Grandis, J. Greenslade, S. Hagstotz, S. Hanany, D. K. Hazra, C. Hernández-Monteagudo, C. Hervias-Caimapo, M. Hills, E. Hivon, B. Hu, T. Kisner, T. Kitching, E. D. Kovetz, H. Kurki-Suonio, L. Lamagna, M. Lattanzi, J. Lesgourgues, A. Lewis, V. Lindholm, J. Lizarraga,

– 13 –
L. Hayes, N. Hidehira, C. A. Hill, G. Hilton, J. Hubmayr, K. Ichiki, T. Iida, H. Imada, M. Inoue, Y. Inoue, K. D. Irwin, H. Ishino, O. Jeong, H. Kanai, D. Kaneko, S. Kashima, N. Katayama, T. Kawasaki, S. A. Kernasovskiy, R. Keskialto, A. Kibayashi, Y. Kida, K. Kimura, T. Kisner, K. Kohri, E. Komatsu, K. Komatsu, C. L. Kuo, N. A. Kurinsky, A. Kusaka, A. Lazarian, A. T. Lee, D. Li, E. Linder, B. Maffei, A. Mangilli, M. Maki, T. Matsumura, S. Matsuura, D. Meilhan, S. Mima, Y. Minami, K. Mitsuda, L. Montier, M. Nagai, T. Nagasaki, R. Nagata, M. Nakajima, S. Nakamura, T. Namikawa, M. Naruse, H. Nishino, T. Nitta, T. Noguchi, H. Ogawa, S. Oguri, N. Okada, A. Okamoto, T. Okamura, C. Otani, G. Patanchon, G. Pisano, G. Rebeiz, M. Remazeilles, P. L. Richards, S. Sakai, Y. Sakurai, Y. Sato, N. Sato, M. Sawada, Y. Segawa, Y. Sekimoto, U. Seljak, B. D. Sherwin, T. Shimizu, K. Shinozaki, R. Stompor, H. Sugai, H. Sugita, A. Suzuki, J. Suzuki, O. Tajima, S. Takada, R. Takaku, S. Takakura, S. Takatori, D. Tanabe, E. Taylor, K. L. Thompson, B. Thorne, T. Tomaru, T. Tomida, N. Tomita, M. Tristram, C. Tucker, P. Turin, M. Tsujimoto, S. Uozumi, S. Utsunomiya, Y. Uzawa, F. Vansyngel, I. K. Wehus, B. Westbrook, M. Willer, N. Whitehorn, Y. Yamada, R. Yamamoto, N. Yamasaki, T. Yamashita, and M. Yoshida. Litebird: A satellite for the studies of b-mode polarization and inflation from cosmic background radiation detection. *Journal of Low Temperature Physics*, 194(5):443–452, Mar 2019. URL: https://doi.org/10.1007/s10909-019-02150-5, [DOI].

[78] Antony Lewis and Sarah Bridle. Cosmological parameters from CMB and other data: A Monte Carlo approach. *Phys. Rev.*, D66:103511, 2002. arXiv:astro-ph/0205436, [DOI].