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Cosmology and time dependent parameters induced by misaligned light scalar

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We consider a scenario where time dependence on physical parameters is introduced by the misalignment of an ultra-light scalar field. The initial VEV of such field at the early time remains a constant until Hubble becomes comparable to its mass. Interesting cosmological consequences are considered. Light sterile neutrinos hinted by terrestrial neutrino experiments are studied as a benchmark model. We show the BBN constraints can be easily avoided in this scenario, even if reheating temperature is high. The scalar can be naturally light in spite of its couplings to other fields. Parameters of sterile neutrino may remain changing with time nowadays. This can further relax the tension from the recent IceCube constraints.

Introduction. Measurements from cosmology may provide important information or impose strong constraints on possible extensions to the Standard Model (SM). For example, dark matter thermal relic abundance may be used to extract information in the dark sector. Alternatively, if the dark sector contains light particles which have sizable couplings to SM sector, it could be disfavored due to measurements like N_{eff} [1].

On the other hand, a non-trivial evolution of the dark sector during the history of the Universe is able to introduce time dependence to physics parameters, which indicates that conclusions from cosmological measurements may not be applied, in a straightforward manner, to physics measured in our local solar system today.

In this letter, we consider a theory with an ultra-light scalar field ϕ. The VEV of ϕ is assumed to be related to the masses of certain fields, e.g. a fermion ψ. We assume ϕ gets a VEV at the beginning of the Universe [2–4]. When Hubble is larger than m_ϕ, the field value remains approximately unchanged, which will be referred as "early time" in later discussion. The field starts oscillating and its VEV decreases when Hubble becomes smaller than m_ϕ. The time dependence of VEV could have interesting cosmological implications. [1]

This scenario can be applied generically. For example, if the dark matter mass and/or interaction change with time, it may be non-trivial to interpret the calculation of thermal relic abundance to what it implies in our local experiments, such as DM (in)direct detections. This has been considered in the content of O(keV) or heavier sterile neutrino DM [9] [2]. The other possibility is for light dark matter particles having sizable couplings to SM particles. They may be disfavored from cosmological points of view, such as N_{eff} measurements. However, a time dependent mass and interaction of DM induced by ϕ's evolution can easily relax the tensions. Thus such light DM should not be dismissed by simply implementing the cosmological arguments [10, 11]. At last, if the oscillation of the light scalar field in our solar system still plays a role on changing physical parameters, it can introduce time dependence into the experimental results. Searching for that induced by an oscillating dilaton field as DM background, has been studied in [12–15]. Related to neutrino properties, [16] considers the scenario where the scalar field VEV introduces additional mixing among active neutrinos. This can be constrained by the null results from anomalous periodicities measurements in the solar neutrino flux.

In this letter, we are focused on sterile neutrinos with masses O(eV) and mixing angles to active neutrinos at O(0.1). These choices are motivated by the anomalies reported in short distance $\bar{\nu}_\mu \to \bar{\nu}_e$ flavor conversion measurement at the LSND experiment [17–19], as well as other terrestrial neutrino experiments such as MiniBooNE [20]. The preferred parameters of sterile neutrinos are in strong tension with cosmological measurements such as nucleosynthesis and large scale structure [21]. Many efforts have been devoted to reconcile these tensions, for example, by late entropy production [22], additional interactions to sterile neutrino [23], non-trivial neutrino number density dependence in the mass matrix [24], or late time phase transition in the dark sector [25, 26]. A more comprehensive review can found in [27, 28].

In our setup, we introduce a light scalar field ϕ which obtains a VEV as initial condition. We further introduce a coupling between ϕ and sterile neutrino ψ, so that the VEV of ϕ has non-trivial contribution to the Majorana

[1] Other models where certain parameters have non-trivial time dependence have been considered in [5–8]. The change of VEV is either introduced by a phase transition or a chemical potential by populating particles coupled to the scalar field.

[2] Their focus is on heavy sterile neutrino with mass O(keV) or higher. The mixing with active neutrino is large when the Universe if hot in order to produce proper relic abundance, and it becomes small to avoid indirect detections nowadays, such as X/γ-ray line searches.

mass term of ψ. In the current local solar system, ϕ's VEV is much smaller than that during BBN. Thus the mass and mixing of sterile neutrino obtain strong time dependence. We will demonstrate that the constraint from BBN can be efficiently relaxed in this setup.

Introducing ϕ dependence to Fermion mass. We consider the following coupling between a light scalar ϕ and a sterile neutrino ψ

$$L \supset (m_0 + g'^2 \frac{\phi^2}{M})\psi\psi. \tag{1}$$

This particular coupling can be easily realized in a UV model. For example, ϕ may carry a Z_2 parity and its coupling to ψ is induced by integrating out some heavy scalar.

In principle, this model can be further simplified if we do not include the mass term m_0 or do not impose the Z_2 symmetry of ϕ. However, we make these choices in order to avoid the subtlety that ψ becomes much lighter than ϕ when $\langle\phi\rangle$ becomes small during oscillation. Such phenomenon is studied as parametric resonance production and it is considered in [29–32]. Consequently, energy density in ϕ are lost through the production of ψ, which will further back react to the evolution of ϕ. Though this additional subtlety may have important consequences if it happens, this deviates the main focus of this letter.

Cosmological evolution of a light scalar field. Depending on the detailed history of ϕ, it may or may not have a non-zero initial field value away from its minimum before inflation. For simplicity, let us assume the initial field value in the patch of our current Universe before inflation is a universal constant ϕ_{init}.

During inflation the field value will be perturbed away from its universal initial value by quantum fluctuations. The power spectral density is

$$P_\phi(k) = \sigma_\phi^2 = \left(\frac{H_{inf}}{2\pi}\right)^2. \tag{2}$$

Thus the generic value of ϕ randomly fluctuates between $\phi_{inf} \in (\phi_{init} - \frac{H_{inf}}{2\pi}, \phi_{init} + \frac{H_{inf}}{2\pi})$.

If ϕ does not have strong interactions with other fields, its field value remains as a constant after inflation, until Hubble becomes comparable to the mass, i.e. $H_{osc} \simeq m_\phi$. After the oscillation starts, ϕ behaves as matter, and its energy density scales as a^{-3}, where a is the scale factor of the Universe.

This light scalar field may or may not play the role of DM. If ϕ composes O(1) fraction of DM, there is a lower bound on its mass, i.e. 10^{-22} eV [33–36]. This gives a lower bound on the temperature of the Universe at which the scalar field starts oscillating,

$$H_{osc}|_{\min} \simeq \frac{\mathrm{keV}^2}{M_{pl}} \simeq 10^{-22}\mathrm{eV}. \tag{3}$$

This is still before matter-radiation equality. Thus the energy density is properly parameterized by the temperature of the Universe, and H_{osc} can be written as

$$T_{osc} \sim \sqrt{m_\phi M_{pl}}. \tag{4}$$

On the other hand, if ϕ is not the dominant contribution to DM, its mass can be even lower, and it could start oscillating at a later time.

The average energy density of DM as a function of time can be written as

$$\bar{\rho}_{DM}(t) \simeq 10^{-6}\frac{1}{a(t)^3}\mathrm{GeV/cm^3} \simeq 0.6\left(\frac{T(t)}{\mathrm{eV}}\right)^3 \mathrm{eV}^4, \tag{5}$$

Here we take the average DM energy density in the current Universe to be $10^{-6}\mathrm{GeV/cm^3}$. In the last equation, we use the approximation that the temperature of the Universe scales as an inverse linear function of the scale factor, neglecting possible modifications from entropy dumping. To have a consistent cosmology, we require the energy density in ϕ when it starts oscillating to be the same or smaller than that of DM during that time. More explicitly, we have

$$\frac{1}{2}m_\phi^2\phi_{inf}^2 \leq 0.6\left(\frac{T_{osc}}{\mathrm{eV}}\right)^3 \mathrm{eV}^4. \tag{6}$$

If ϕ starts oscillating during radiation dominated era, Eq. (4) is applicable and we get

$$\phi_{inf} \;\leq\; 10^{18}\left(\frac{10^{-22}\mathrm{eV}}{m_\phi}\right)^{1/4}\mathrm{GeV}. \tag{7}$$

Here we emphasize that the calculation above is assuming ϕ evolves as a free field. One may be worried that the existence of particles coupling to ϕ, such as ψ, may contribute as an effective chemical potential of ϕ, thus modifies its evolution when the Universe cools down, e.g. in [6, 24]. However, if the production of ψ is suppressed by either a large mass or small coupling induced by the large VEV of ϕ at the early time, then it has little impact on the evolution of ϕ and it is consistent to treat ϕ as a free field.

N_{eff} during BBN. Let us consider a scenario where ψ has sizable interaction with SM particles. If the properties of this fermion remain the same during the history of the Universe, it can be thermally populated. If its mass during BBN is smaller than MeV, it contributes to ΔN_{eff}, m_0 and its coupling to SM would be strongly constrained.

One typical scenario is light sterile neutrino with large mixing angle. The existence of such sterile neutrino may explain the long-standing experimental anomaly in short distance $\bar{\nu}_\mu \to \bar{\nu}_e$ flavor conversion [17–20]. The experimental results cannot be properly explained if there are only three neutrino flavors. For a recent summary, please see [37]. On the other hand, if sterile neutrinos are added, the measurements favor a squared mass splitting, i.e. Δm^2, around O(1) eV^2 and a mixing angle with active neutrino as $\theta \sim$ O(0.1). [3] The equilibrium of sterile neutrinos with the SM thermal bath can be reached as long as the reheating temperature is only slightly higher than the electron-active neutrino decoupling temperature, i.e. around 1 MeV. This is in tension with the measurements [1] which gives $N_{eff} = 3.15 \pm 0.23$.

On the other hand, if there is a non-trivial dependence on $\langle\phi\rangle$ for the sterile neutrino mass, its mass at the early Universe can be very different from its current value, which matters for terrestrial neutrino experiments. Thus the constraints from the thermal history of the Universe, e.g. N_{eff}, may not be trivially applied.

First, we calculate the local value of $\langle\phi\rangle$ in our solar system. If the de Broglie wavelength of ϕ is smaller than the scale of our galaxy, it behaves as a particle from structure formation point of view. We expect the ratio between local energy density of ϕ to its current average value in our Universe to be the same as that of DM, i.e.

$$\frac{\rho_{\phi,\odot}}{\bar{\rho}_{\phi,0}} \simeq \frac{0.3 \text{ GeV/cm}^3}{10^{-6} \text{ GeV/cm}^3} \simeq 10^5. \tag{8}$$

Thus we can estimate the local VEV of ϕ as

$$\begin{aligned} \rho_{\phi,\odot} &\simeq 10^5 \times \frac{1}{2} m_\phi^2 \phi_{inf}^2 \left(\frac{T_0}{T_{osc}}\right)^3 \\ &\simeq 10^{-6} \times m_\phi^2 \phi_{inf}^2 \left(\frac{\text{eV}}{T_{osc}}\right)^3, \end{aligned} \tag{9}$$

which indicates

$$\frac{\phi_\odot}{\phi_{inf}} \simeq 10^{-3} \times \left(\frac{\text{eV}}{T_{osc}}\right)^{3/2}. \tag{10}$$

For example, if $m_\phi \sim 10^{-22}$ eV, T_{osc} is about keV. This indicates that the VEV of ϕ during the early Universe can be about 8 order to magnitude larger than that locally in our solar system.

In order to obtain some intuition, let us consider some benchmark numbers. First, we would like ψ to obtain a mass larger than at least 10 MeV in order not to be produced in thermal bath if the reheating temperature barely triggers BBN[4], i.e.

$$(m_0 + g'^2 \frac{\phi_{inf}^2}{M}) \simeq g'^2 \frac{\phi_{inf}^2}{M} > 10 \text{ MeV}. \tag{11}$$

Here we assume m_0 is positive and much smaller than $g' \frac{\phi_{inf}^2}{M}$ or else the change on ϕ's VEV during the evolution of the Universe cannot make a difference.

[3] In the following discussion, we only consider one active neutrino and one sterile neutrino. The generalization to multiple species is straightforward.

[4] Later we will see that this is not necessary for sterile neutrino since the the mixing is also largely suppressed when $\langle\phi\rangle$ is large.

Now let us consider two limits, $m_0 \ll g'^2 \frac{\phi_\odot^2}{M}$ and $m_0 \gg g'^2 \frac{\phi_\odot^2}{M}$. When $m_0 \ll g'^2 \frac{\phi_\odot^2}{M}$, the current fermion mass in our solar system is related to that in the early Universe as

$$\frac{m_{\psi,\odot}}{m_{\psi,inf}} = \frac{\langle\phi_\odot\rangle^2}{\langle\phi_{inf}\rangle^2} \simeq 10^{-6} \times \left(\frac{\text{eV}}{T_{osc}}\right)^3. \tag{12}$$

On the other hand, if $m_0 \gg g'^2 \frac{\phi_\odot^2}{M}$, the contribution from the VEV of ϕ in our solar system is negligible, which simply implies m_ψ being larger than that in the scenario where $m_0 \ll g'^2 \frac{\phi_\odot^2}{M}$. Thus in summary, we have

$$\frac{m_{\psi,\odot}}{m_{\psi,inf}} \geq 10^{-6} \times \left(\frac{\text{eV}}{T_{osc}}\right)^3. \tag{13}$$

For sterile neutrino, we need the local ψ mass to be O(1) eV. Then m_ψ, during early time of the Universe, can be easily larger than 10 MeV. More explicitly, if $m_\phi \sim 10^{-22}$ eV and $m_{\psi,\odot}$ is about 1 eV, $m_{\psi,inf}$ can be as large as PeV.

Coupling as a function of $\langle\phi\rangle$. So far, we only consider how $\langle\phi\rangle$ affects m_ψ. At the meanwhile, it also affects the mixing between sterile and active neutrinos. Let us consider a simple supersymmetric theory,

$$W \supset \frac{1}{2} m_0 \Psi^2 + yHL\Psi + \frac{g'}{2M} \Phi^2 \Psi^2 + \frac{1}{2} m_\phi \Phi^2. \tag{14}$$

Here Φ is the supermultiplet containing ϕ, Ψ contains ψ and its superpartner $\tilde{\psi}$. H and L are the higgs and lepton supermultiplets in MSSM.

The mixing angle can be written as $\theta \sim yv/m_\psi$. To fit the anomalies in terrestrial neutrino experiments, we have $m_{\psi,\odot} \sim$ eV and $y \sim 10^{-12}$. However, during the early Universe, m_ψ is much larger than its current value in our solar system, which implies a much smaller mixing angle.

Let us estimate how the suppression on the mixing angle may change the production of sterile neutrinos. The weak interaction (WI) collision rate is $\Gamma_{WI} \sim n\sigma \sim G_F^2 T^2 T^3$, while the oscillation rate goes as $\Delta m^2/T$. One can determine the cross over point as

$$T_{cross} \sim (\Delta m^2/G_F^2)^{1/6}. \tag{15}$$

When temperature is higher than T_{cross}, Quantum Zeno effect is important [23, 38] and the flavor conversion rate can be written as

$$P(\nu_a \to \nu_s) \sim \sin^2 2\theta \times \left(\frac{\Delta m^2}{T\,\Gamma_{WI}}\right)^2. \tag{16}$$

Comparing to Hubble expansion rate, in order to be in equilibrium, one needs

$$T_{high} \leq (\sin^2 2\theta \frac{\Delta m^4}{G_F^2} M_{pl})^{1/9}. \tag{17}$$

Here T_{high} indicates the temperature at which the thermal equilibrium can be reached assuming it is higher than T_{cross}. When the temperature is lower than T_{cross}, Quantum Zeno effect is not important. The averaged conversion probability can be written as

$$\bar{P}(\nu_a \to \nu_s) = \frac{1}{2}\sin^2 2\theta. \tag{18}$$

Then the equilibrium can be reached when

$$T_{low} \geq (G_F^2 M_{pl} \sin^2 2\theta)^{-1/3}. \tag{19}$$

In order to avoid the constraints from N_{eff}, we need $T_{low} > T_{high}$. This indicates

$$(\theta^2 \ \Delta m \ G_F \ M_{pl}) < 1. \tag{20}$$

Taking the approximation that $\Delta m \sim m_\psi$ and $\theta \sim \frac{0.1\mathrm{eV}}{m_\psi}$, we get

$$m_\psi > \mathrm{keV}. \tag{21}$$

In summary, one may resolve the tension between N_{eff} and the preferred parameters of sterile neutrino in two ways. One is to simply raise the sterile neutrino mass to be higher than reheating temperature. One can also suppress the sterile neutrino production rate by reducing its mixing angle to active neutrinos. It turns out that the second choice is more effective. If m_ψ is heavier than keV before/during BBN, sterile neutrinos are not thermally populated even with a high reheating temperature.

Naturalness of ϕ's mass. ϕ being ultra-light is crucial in our scenario. However ϕ has non-trivial coupling to ψ. Thus one needs to check whether it is natural to expect ϕ to have such small mass.

The 1-loop contributions are quadratically divergent

$$\delta m_\phi^2 \sim \frac{g'^2}{16\pi^2}\frac{\langle\phi\rangle^2}{M^2}(\Lambda^2 - m_\psi^2). \tag{22}$$

Here we truncate the quadratic divergences at a scale Λ and assume m_ψ is dominated by ϕ's VEV. Λ is supposed to be the scale where additional physics comes in and cancel the quadratic divergences from ψ's loop. One typical example is to identify Λ as the mass of superpartner of ψ. Before the oscillation of ϕ, we have $m_\psi \simeq g'\langle\phi_{inf}\rangle^2/M$. Thus by requiring naturalness of m_ϕ, Eq. (22) implies

$$(m_{\tilde{\psi}}^2 - m_\psi^2) \ \leq \ 16\pi^2 \frac{m_\phi^2}{m_\psi^2}\langle\phi_{inf}\rangle^2. \tag{23}$$

We require m_ψ to be at least keV before the oscillation of ϕ. If ϕ starts oscillating during the radiation dominated era, one can use Eq. (7) to estimate the misalignment of ϕ. This gives

$$(m_{\tilde{\psi}}^2 - m_\psi^2) \ \leq \ \left(\frac{m_\phi}{10^{-22}\mathrm{eV}}\right)^{3/2}\left(\frac{\mathrm{keV}}{m_\psi}\right)^2 (\mathrm{keV})^2. \tag{24}$$

In order to avoid the constraints from BBN, we need ϕ to start oscillating at temperature below O(MeV). This gives an upper limit to ϕ's mass, i.e. $m_\phi \sim 10^{-16}$ eV. Plugging into Eq. (24) and taking m_ψ to be keV, naturalness requires

$$(m_{\tilde{\psi}}^2 - m_\psi^2) \sim (10 \ \mathrm{MeV})^2. \tag{25}$$

Such degeneracy implies a very small SUSY breaking effects in the dark sector. However this is not impossible to achieve since the dark sector is mostly isolated from SM sector.

Take the superpotential in Eq. (14), for simplicity, let us assume the current sterile neutrino mass in our solar system is dominated by m_0, i.e. $m_0 \sim$ eV. To achieve a mixing angle of O(0.1), we need $y \sim 10^{-12}$. Such tiny coupling between Ψ and SM supermultiplets introduces a SUSY breaking mass to Ψ as

$$(m_{\tilde{\psi}}^2 - m_\psi^2) \sim \frac{y^2}{16\pi^2}(100 \ \mathrm{GeV})^2 \sim (10^{-2}\mathrm{eV})^2. \tag{26}$$

Another possible contribution to the mass splitting between $\tilde{\psi}$ and ψ is from the non-zero VEV of ϕ. Since ϕ is not strictly flat, its displacement away from the origin could contribute a positive vacuum energy and break SUSY. It is straightforward to show that the mass difference between ψ and $\tilde{\psi}$ due to the non-zero VEV of ϕ can be written as

$$(m_{\tilde{\psi}}^2 - m_\psi^2) \sim m_\psi m_\phi, \tag{27}$$

which is much smaller than that in Eq. (25).

At last, the gravity mediated SUSY breaking effects are unavoidable. A low scale SUSY breaking is phenomenologically allowed in scenario of gauge mediation, where $F \sim$ O(10) TeV^2. Such SUSY breaking effects may further introduce a mass splitting between $\tilde{\psi}$ and ψ at O(meV), which indicates

$$(m_{\tilde{\psi}}^2 - m_\psi^2) \sim m_\psi \ \mathrm{meV} \sim (\mathrm{eV})^2, \tag{28}$$

where m_ψ is taken to be keV at the last step.[5]

In summary, SUSY may be introduced to stabilize ϕ's mass, and the superpartner of ψ cannot be too heavy. Such a requirement is not impossible since ψ couples very weakly to the rest of the theory. We emphasize that the naturalness is not a necessary criteria to satisfy, rather a subjective requirement.

Comparing with "late time neutrino mass" models. The idea on time-dependent sterile/active

[5] One may be worried about the gravity mediated SUSY breaking effects directly apply to ϕ. However, ϕ may have an approximate shift symmetry, which is only broken by its small mass term and interaction with ψ. Similar argument has been used in, for example, relaxion models [39].

neutrino mass matrix is not new. Similar ideas have been explored in the "late time neutrino mass" models [25]. Such models consider a possibility that a phase transition happens after BBN and generates both active and sterile neutrinos' masses at late time. Such phase transition is introduced by additional light scalar fields, and it could be triggered by the decrease of thermal masses of the scalar fields. Thus the temperature in dark sector can neither be zero nor equal to that in SM sector, but a little bit lower.

The phase transition spontaneously breaks global symmetries and light/massless goldstone bosons appear in low energy spectrum. In order to fit the anomalies in terrestrial neutrino experiments, the couplings among active neutrino, sterile neutrino and the goldstone modes are not negligible. Thus the active neutrinos will recouple with the dark sector when temperature is low, i.e. $T_{rec} \sim$ O(eV). Furthermore, the mean free paths of neutrinos may also be modified due to their additional interactions with goldstone bosons.

These complications do not happen in our scenario. Since our light scalar field ϕ does not directly talk to active neutrinos, there is no process can induce recoupling between active neutrino and dark sector. The change of field's VEV happens automatically after Hubble becomes smaller than its mass. Thus we do not need the potential of our scalar field to change with time, and the temperature in the dark sector can be simply zero.

Conclusion. In this letter, we study a model to relax the cosmological constraints on O(eV) sterile neutrino with O(0.1) mixing with active neutrino, by introducing a late oscillating light scalar field.

ϕ may be still oscillating in our solar system. If its effects remain important nowadays, e.g. when $m_0 \ll g'\langle\phi_\odot\rangle^2/M$, physical parameters may still change with time. If m_ϕ ranges from 10^{-22} eV to 10^{-16} eV, the period is about seconds to years. This introduces non-trivial time-dependence into experimental results.

Amusingly, the recent result from IceCube [40] disfavors sterile neutrino parameters from global fits [41, 42]. However, it is important to note that IceCube data is mainly in tension with LSND, but remains consistent with MiniBooNE. Given the fact that the operating time of IceCube partially overlaps with that of MiniBooNE but very different from that of LSND, introducing time dependence may resolve this tension. A detailed analysis to include time dependence in global fits could be interesting and we leave it for future study.

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