“Ups and Downs in Dark Energy”

phase transition in dark sector as a proposal to lessen cosmological tensions

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Based on tensions between the early and late time cosmology, we propose a double valued cosmological constant which could undergo a phase transition in its history. It is named “double-Λ Cold Dark Matter”: $\Lambda\Delta$CDM. An occurred phase transition results in (micro-) structures for the dark sector with a proper (local) interaction. We consider the background data set including BAO distances and Riess et al.’s $H_0$ data point, with and without a prior on $\Omega_m h^2$ we could show our model can lessen the $H_0$ tension by $\Delta \chi^2_{\text{total}} = -7.49$ and $\Delta \chi^2_{\text{total}} = -7.15$ respectively with two more free parameters. We also examine our model to check if we can reduce the $f \sigma_8$ tension. In the presence of Planck 2015 prior on $\Omega_m h^2$ it will be shown that our model is much better than $\Lambda$CDM by $\Delta \chi^2_{\text{total}} = -7.26$ where $H_0$ tension is removed while we do not have any better results for $f \sigma_8$. If we relax the prior on $\Omega_m$ then our model behaves in a very non-trivial way. Our 1 $\sigma$ likelihood has two extrema at $z_t \sim 0$ and one around $z_t \sim 2.25$. The former corresponds to $\Delta \chi^2_{f \sigma_8} = -6.93$ and $\Delta \chi^2_{f \sigma_8} = +0.74$ which means we could only solve $H_0$ tension without any success on $f \sigma_8$ one. However for the latter case, $z_t = 2.25$, we have $\Delta \chi^2_{f \sigma_8} = -5.26$ while $\Delta \chi^2_{f \sigma_8} = -2.89$ and $\Delta \chi^2_{f \sigma_8} = -2.01$. This case shows we can reduce both tensions together which is a hint for our idea that the dark sector underwent a phase transition and it may have (micro-) structures.

I. INTRODUCTION:

The standard model of cosmology, $\Lambda$CDM, is very successful in describing the cosmological data from the early universe [1, 2] as well as the late time observations [3]. Its constitutes are cold dark matter (CDM) and the cosmological constant, $\Lambda$. CDM and $\Lambda$ are responsible for matter structure formation and the late time acceleration phase, respectively. However due to mysterious (dark) nature of its main elements, it is a relevant question to ask if dark matter and dark energy are fundamental or not. On the other hand both theoretically and observationally there are few issues which should be answered in the context of $\Lambda$CDM. One of the outstanding (theoretical) question is the cosmological constant fine-tuning problem [4]. On the other hand, recently, some tensions have been reported between $\Lambda$CDM predictions and the observations. To address these issues there are different approaches which go beyond standard $\Lambda$CDM. We think these tensions can be phrased as follows: a $\Lambda$CDM which its free parameters are fixed by early universe data (mainly CMB) is not consistent (up to few $\sigma$’s) with a $\Lambda$CDM which is constrained by late time observations (i.e. LSS data). A recent work in this direction claims that dynamical dark energy is favored by 3.5 $\sigma$ over $\Lambda$CDM [5]. Their approach is interesting because they look for the dark energy equation of state by reconstructing it directly from the observational data.

The most famous tension is $H_0$ tension which is between measurements of Hubble parameter at $z = 0$ by CMB [1] and supernovae [6–8] where late time direct measurement predicts higher value for $H_0$ in comparison to Planck 2015. This tension was reported in the literature and became worse with the recent measurements [7] although it can be a systematic error in the observations. The other reported tension is $f \sigma_8$ tension where again the measurement of matter density between late time observations [9] and CMB [1] are not compatible. Although in this paper we focus on these two tensions, there are other (mild) tensions e.g. BAO Lyman-α [10], void phenomenon [11] and missing satellite problem [12] where the last two ones are in non-linear regime. On the theory side, there are different strategies to address these tensions but all of them need to go beyond standard model of cosmology. An interesting candidate for this purpose is massive neutrinos but it cannot address both $H_0$ and $f \sigma_8$ tensions together [1]. There are also other ideas trying to solve either $H_0$ or $f \sigma_8$ tensions e.g. interacting dark energy [13, 14], neutrino-dark matter interaction [15], varying Newton constant [16, 17], viscous bulk cosmology [18], massive graviton [19] and many more. Recently, another idea, named $\upsilon\Lambda$CDM, has been studied in the literature to address $H_0$ tension by assuming two different behavior in high and low redshifts [20] which is very similar to [21–23]. This model is based on some theoretical motivations [24, 25]. In $\upsilon\Lambda$CDM, cosmological model switches, at a transition redshift $z_t$, from the standard $\Lambda$CDM model to $R = R_0$ model, where $R$ is the Ricci scalar and $R_0$ is a constant. This feature of $\upsilon\Lambda$CDM model brings us to a new idea to solve the cosmological tensions.

Before discussing this idea let us repeat that it seems all of the cosmological tensions have the same format if we phrase them as: the physics of late time is different from the early universe physics. According to this viewpoint we suggest a new concept/idea in the physics of cosmological models: phase transition in dark sector. In this work we pursue this idea that a phase transition has happened in the dark sector (here we focus on dark energy). The reason for this can be
The temperature the system can go either to almost spin-up or spin-down state if the temperature becomes less than a critical temperature, $T_c$, and for the absolute zero temperature all the spins will be aligned as we have shown in line a in FIG. 1. Physically, it means our system transits from the critical temperature very quickly.

Critical phenomena are revisited in a variety fields of physics, which local interactions of a many-body system result in a global phase transition. Usually, an ordered phase emerges by lowering the free parameter of the model, e.g., temperature, beyond a critical point. For example, Ising model is classic model of critical phenomena, which describes the phase transition from para-magnet to ferro-magnet at Curie temperature. It consists of two-directions magnetic dipoles, i.e., spins, which interacts with each other on a lattice and enforce their neighbors to align with them. In high temperature regime, spins take directions randomly regardless of their neighbors’ directions. Close enough to the critical temperature, however, neighbor interactions result in the emergence of aligned islands. Consequently, there is one dominant direction at low temperature regime.

In the next section we propose a model inspired by Ising model for dark energy which (possibly) experiences a phase-transition. In the section III we constrain our model free parameters with background data. Then in section IV we study our model in the presence of the $f\sigma_8$ data points. We will show how our model can reduce both tensions together. In section V we will conclude and give future perspective on our idea in section VI.

II. $\Lambda$CDM MODEL

We realize a phase transition behavior in dark energy sector by an inspiration from Ising model. In the Ising model two-valued spin is at work and a local interaction between these two spins govern the behavior of the system. By reducing the temperature the system can go either to almost spin-up or spin-down state if the temperature becomes less than a critical temperature, $T_c$, and for the absolute zero temperature all the spins will be aligned as we have shown in line a in FIG. 1. Physically, it means our system transits from the critical temperature very quickly.

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TABLE I: The background dataset. Θ represents the distance of the last scattering surface to us. We also use five BAO volume distances. The additional data point is the Hubble parameter at the present time, H₀, which is reported by analysis of supernovae. We do our χ² with and without a prior on Ωₘh² given by Planck 2015.

| CMB | BAO | BAO | BAO |
|-----|-----|-----|-----|
| CMB first peak [2] | 6dFGS (z = 0.106) [26] | LOWZ (z = 0.320) [28] | DES (z = 0.81) [30] |
| 100Θ = 1.04085 ± 0.00047 | Dᵥ = 456.0 ± 27.0 | Dᵥ = 1264.0 ± 25.0 | Dₐ/rₐ = 10.75 ± 0.43 |

| CMB perturbations [2] | MGS (z = 0.150) [27] | CMASS (z = 0.570) [29] | Local H₀ [7] |
|-----------------------|------------------|------------------|-------------|
| Ωₘh² = 0.1415 ± 0.0019 | Dᵥ = 664.0 ± 25.0 | Dᵥ = 2056.0 ± 20.0 | H₀ = 73.48 ± 1.66 km/s/Mpc |

TABLE II: The best fit values for ΛCDM and ΔCDM for two sets of background data. In both cases, with and without prior on Ωₘh², our model ΔCDM is better by few χ² in comparison to ΛCDM. We also introduced another measure for comparing different models as γ = χ²_min/(N_data - N_model) where N_data is number of data points and N_model is number of free parameters in the model. If a model’s γ is closer to one it means that model is more favored for the same set of the data points. Obviously, in both cases ΔCDM is more favored than ΛCDM by using both χ² and γ measures.

\[
\begin{array}{|c|c|c|}
\hline
\text{model} & \chi^2 & \gamma \\
\hline
\text{ΛCDM} & 4.57 & 1.52 \\
 & H₀ = 72.5^{+2.5}_{-3.0} & \\
 & Ωₘh² = 0.1409 ± 0.0017 & \\
 & Ωₐ = 0.5 ± 0.1 & \\
 & z₁ = 0.00^{+0.14}_{-0.1} & \\
 & \chi^2 = 11.72 & \gamma = 2.34 \\
 & H₀ = 69^{+0.5}_{-1.0} & \\
 & Ωₘh² = 0.1400^{+0.0012}_{-0.0007} & \\
\hline
\end{array}
\]

and the volume distance, \(Dᵥ\),

\[
Dᵥ(z) = \left( \frac{c}{H(z)} \right) (1 + z)^2 Dₐ²(z) \right)^{1/3}.
\]

We will constrain our free parameters by background data points including five BAO volume distances \(Dᵥ(z)\), \(H₀\) and CMB distance. We also repeat our analysis by assuming a prior on \(Ωₘh²\) from perturbation data. We summarized these data points in TABLE I where one can find their original references. We have used mainly the BAO data points which are used by Planck 2015 [2] as well as a recent data point by DES collaboration [30]. For \(H₀\) we use the recent report by Riess et al. [7] which measured a little bit higher value for \(H₀\) from the previous results [6]. The data we have used are summarized in TABLE I.

We did χ² analysis for our model and standard ΛCDM by using all the background data points in TABLE I with and without prior on \(Ωₘh²\). The results are shown in TABLE II. For both cases our model is more consistent with the data in comparison to ΛCDM. In addition for our model in its best-fit predicts \(H₀ = 72.5^{+2.5}_{-3.0}\) km/s/Mpc which produces χ² = 0.35 for both with and without prior on \(Ωₘh²\). This means our model has no inconsistency with local measurements on Hubble parameter [7]. We plotted volume distance versus redshift for our best fits in FIG. 3.

IV. PERTURBATION ANALYSIS: \(f \sigmaₘ TENSION\)

In this section we will consider linear perturbation theory i.e. \(f \sigmaₘ\) and will add corresponding data, see TABLE III. The \(f \sigmaₘ\) is a measurement on the growth of structure \(f(z)\) which satisfies the following equation

\[
\frac{df}{dz} + f \left[ \frac{d \ln E}{dz} - \frac{2}{1+z} \right] - \frac{f^2}{1+z} + \frac{3 \Omegaₐ(m+1)^2}{2 E^2(z)} = 0
\]

and the definition of \(\sigmaₘ(z)\) is as follow

\[
\sigmaₘ(z) = \sigmaₘ(0) \exp \left[ - \int_0^z \frac{f(z')}{1+z'} dz' \right].
\]
As it was mentioned in the introduction, there is a tension between CMB’s and LSS’s prediction for $f \sigma_8$ which is however milder than $H_0$ tension. Here we tried to investigate if our model can lessen this tension or not while we also keep R17 data point for $H_0$. It means, in contrast to many models in the literature, we try to see if we can loose both $H_0$ and $\Theta_{CMB}$ tensions together and not one or another separately. For our analysis we used $f \sigma_8$ data points as reported in TABLE III. The $\chi^2$ analysis results in the best fit of our free parameter written in TABLE IV. As it is clear in TABLE IV the result is more or less same as the case without $f \sigma_8$ results in TABLE II. This means the model prefers to solve $H_0$ tension but leave $f \sigma_8$ without any touch. However if we relax the prior on $\Omega_m h^2$ from Planck’15 then we can see a non-trivial behaviour from our model. This behaviour is shown in FIG. 4 where we have plotted total $\chi^2$ with respect to transition redshift $z_t$. It is obvious there are two different disjoint islands. The best fit values for the parameters and their $\chi^2$ is summarized in TABLE V. The one which is around $z_t \sim 0$ was expected due to the other results. This case solves $H_0$ tension but it does not touch $f \sigma_8$ tension. This case has $\chi^2_{total} = 11.72$ which gives $\Delta \chi^2 = -6.74$ in comparison to standard $\Lambda$CDM. The more interesting case is the case which is still in 1 $\sigma$ likelihood but for $z_t \gtrsim 0.57$. The $\chi^2$ analysis shows slightly smaller value $\chi^2_{total} = 13.20$ as our best fit for this case. This case is worse than the previous one but it is still much better than $\Lambda$CDM by $\Delta \chi^2 = -5.26$. Note that we could not close the 1 $\sigma$ from above in $z_t$ which is understandable. The reason is that when $z_t \gtrsim 0.86$ then there is no low redshift data points above transition redshift. This means all the low redshift data points constrain $H_0$ and $\Omega_m$ while effectively $\Omega_{\Lambda 2}$ is a free parameter which is determined by CMB distance i.e. $\Theta$. This means for any $z_t \gtrsim 0.86$ we always can find a value for $\Omega_{\Lambda 2}$ to be fit with one data point i.e. $\Theta$ while there is no prior on $\Omega_m$. What we see in our model can be related to what has been

| Dataset                         | $f \sigma_8$ Values (z)            |
|---------------------------------|-----------------------------------|
| 6dFGS+SNa [31]                 | $0.428 \pm 0.0465$ (z = 0.92)     |
| SDSS-MGS [32]                  | $0.490 \pm 0.145$ (z = 0.15)      |
| SDSS-LRG [33]                  | $0.3512 \pm 0.0583$ (z = 0.25)    |
| BOSS-LOWZ [34]                 | $0.384 \pm 0.095$ (z = 0.32)      |
| SDSS-CMASS [35]                | $0.488 \pm 0.060$ (z = 0.59)      |
| WiggleZ [36]                   | $0.413 \pm 0.080$ (z = 0.44)      |
| WiggleZ [36]                   | $0.390 \pm 0.063$ (z = 0.60)      |

TABLE III: $f \sigma_8$ Values.

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TABLE IV: The best fit values for $\Lambda$CDM and $\Omega_m h^2$.

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FIG. 3: The volume distance, $D_V(z)$, normalized to Planck 2015 best fit values’ prediction. Note that in addition to above data points, we also have used $H_0$ and $\Theta_{CMB}$ data points in $\chi^2$ calculation. Since we could not plot them here then it is not very obvious that $\Omega$CDM is better than $\Lambda$CDM by looking just at this plot. The results are given in TABLE II.
reported in the literature as a different behaviour than ΛCDM above redshift $z \sim 0.6$ [8]. This makes a degenerate situation which can be broken if we have more data from mid-range redshift $z \sim 2 - 10$. However even in this case if $z_t$ be above all the late time data points then we will have this degenerate situation again. Although the latter case is a little bit worse than the case $z_t \sim 0$ but it has a more interesting property. We plotted volume distance and $f \sigma_8$ versus redshift in FIGS. 5 and 6 respectively.

| $\Lambda$CDM | $\Lambda$CDM $z_t = 0$ | $\Lambda$CDM $z_t = 2.25$ |
|-------------|------------------------|------------------------|
| $H_0 = 69.0$ | $H_0 = 72.5$          | $H_0 = 70.0$          |
| $\Omega_m h^2 = 0.1400$ | $\Omega_m h^2 = 0.1400$ | $\Omega_m h^2 = 0.1223$ |
| $\Omega_{\Lambda_2} = 0.5$ | $\Omega_{\Lambda_2} = 49.8$ |
| $z_t = 0.0$ | $z_t = 2.25$          |
| $\chi^2_{total} = 18.46$ | $\chi^2_{total} = 11.72$ | $\chi^2_{total} = 13.20$ |
| $\gamma = 1.32$ | $\gamma = 0.98$ | $\gamma = 1.10$ |
| $\chi^2_{H_0} = 7.28$ | $\chi^2_{H_0} = 0.35$ | $\chi^2_{H_0} = 4.39$ |
| $\chi^2_{f \sigma_8} = 6.80$ | $\chi^2_{f \sigma_8} = 7.24$ | $\chi^2_{f \sigma_8} = 4.79$ |

TABLE V: The details of $1 \sigma \chi^2$ analysis for both $\Lambda$CDM and $\Lambda$CDM models without any prior on $\Omega_{\Lambda_2} h^2$. In this case we have two local minimums as it is obvious from FIG. 4. The interesting result is that for $z_t = 2.25$ our model can lessen both $H_0$ and $f \sigma_8$ tensions simultaneously. Note that $\Lambda$CDM is more favored than $\Lambda$CDM by using both $\chi^2$ and $\gamma$ measures where $\gamma$ is defined in TABLE II.

FIG. 6: We plotted $f \sigma_8$ with respect to redshift. When we relax the prior on $\Omega_m h^2$, $\Omega_m h^2$ can go down enough, so the $f \sigma_8$ tension as well as $H_0$ tension decreases as expected (c.f. TABLE V). Note that the orange dashed-dotted and green dotted curves are almost on top of each other.

V. CONCLUDING REMARKS

Based on the structure of cosmological tensions, e.g. $H_0$ and $f \sigma_8$, we proposed a dark energy model which says dark sector underwent a phase transition in its history. In this work, our idea has been realized by the simplest scenario: instead of a cosmological constant we have two distinctive values for the cosmological constant and we named our model: $\Lambda$CDM. In addition we supposed inspired by the Ising model we have a cosmological constant we have two distinctive values for the tension decreases as expected (c.f. TABLE V). Note that the orange dashed-dotted and green dotted curves are almost on top of each other.

FIG. 4: In this figure we have plotted the total $\chi^2$ with respect to transition redshift $z_t$ when we do not have any prior on $\Omega_m h^2$. It is clear that we have two distinguishable islands with a minimum at $z_t = 0$ and the other one at $z_t = 2.25$. The former one has less $\chi^2$ which means it fits the data better but it can only solve $H_0$ tension without any success about $f \sigma_8$ one. The latter case, i.e. for $z_t > 0.57$, is more interesting since it can lessen both tensions simultaneously. In this case there is a degeneracy for $z_t$ and $\Omega_{\Lambda_2}$. Since there is no data point above $z > 0.89$ then when $z_t$ is above 0.89 effectively $\Omega_{\Lambda_2}$ should address just one data point i.e. the $\Theta_{CMB}$. This means for any value of $z_t > 0.89$ we can find a proper value for $\Omega_{\Lambda_2}$ with a small deviation in $\chi^2$. Consequently, we cannot close the likelihood for the second part.

FIG. 5: Here we plot the volume distance normalized to Planck 2015 best fit values’ prediction $D_\gamma (z)/D_\gamma^{Planck} (z)$. But this time best fit values of free parameters are calculated by using both background and $f \sigma_8$ data sets TABLES I and III respectively.
(which corresponds to a transition redshift in cosmology). Before the transition redshift the universe switches between $\Lambda_1$ and $\Lambda_2$ while it settles into the standard $\Lambda$CDM model after the transition redshift.

We have checked our model by considering the background cosmological distances i.e. CMB distance to us, BAO’s and $H_0$ measurement. We summarized the results in TABLE II which shows much less $\chi^2$ for our model: $\Delta \chi^2_{\text{total}} = -7.49$ and $\Delta \chi^2_{\text{total}} = -7.15$ with and without a prior on $\Omega_m h^2$. This means our model can remove the $H_0$ tension albeit with two more free parameters. For the next step we examined our model by adding the $f \sigma_8$ data points. This is crucial since we do not know if there is any fundamental idea that can solve both $H_0$ and $f \sigma_8$ tensions together. The result has been summarized in TABLE IV which shows we have less $\chi^2$ when we have a prior on $\Omega_m h^2$ while we could not lessen the $f \sigma_8$ tension. But without any prior on $\Omega_m h^2$ we have a chance to lessen both tensions together as one can see in FIG. 4 and TABLE V. We could show in $1 \sigma \chi^2$ we have a local minimum at $z_t = 2.25$ which can lessen both $H_0$ and $f \sigma_8$ tensions together. This case means a phase transition should be occurred in redshifts above $z_t > 0.57$. This is an interesting results and is in agreement with previous studies on the pure analysis of $H(z)$ data. For example in Figure 10 in [8] it is clear that if one reconstructs $H(z)$ from the data then around $z \sim 0.6$ it starts to deviate from the $\Lambda$CDM predictions however for above this redshift the exact form of $H(z)$ is ambiguous. These results are totally in agreement with what we could get theoretically: to resolve tensions we see a transition in dark energy behavior above $z_t > 0.57$. Even more as it is obvious from FIG. 4 for above $z_t > 0.57$ the results of our analysis are not distinguishable at $1 \sigma$ level. However additional data points for mid range redshifts i.e. $z \sim 2 - 6$ will break this degeneracy.

VI. FUTURE PERSPECTIVES

We think the idea of phase transition in dark sector is a very rich concept both phenomenologically and theoretically. This idea is supported with the way that we understand the cosmological tensions: all of these tensions can be phrased as inconsistencies between early and late time physics and so a phase transitions in mid redshifts can address the different behaviors of the universe in early and late times. A phase-transition in dark energy has a very interesting deep consequence: dark energy has (micro-)structures.

This idea can be checked phenomenologically by checking the bare observations and see if there is a kind of different behaviors for cosmological parameters in different redshifts. For example as we mentioned above the behavior of $H(z)$ is different for low and high redshift as it is reported in [8]. In addition in [5] the behavior of equation of state of dark energy seems is not $w = -1$ and it oscillates. This is also in agreement with our idea where we assume dark energy switches between two different values. However the frequency of oscillations is very larger in our model and we should check our model for lower frequencies too in future works.

In the theoretical side is a vast era of exploration: in this work we focused on the simplest scenario inspired by the Ising model. We will generalize our approach for more precise models e.g. by removing fast phase transition. In addition we can think about other models e.g. Heisenberg model, Potts model and etc. One way to think about this idea is working in a continuum regime which is remained for the future work.

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