The standard model of cosmology, ΛCDM, consists of well-known baryons, unknown cold dark matter (CDM) and dark energy, which is represented by the cosmological constant (Λ). Also the gravity is governed by the Einstein general relativity (GR) in the standard model. The vanilla ΛCDM model is a favored one as it fits well almost all of the observations such as cosmic microwave background radiation (CMB) and large scale structure (LSS). However, fundamental questions remain, e.g., what are the natures of dark energy and dark matter? What is responsible for the fine-tuned cosmological constant, in comparison to the vacuum energy density predicted by the particle physics (otherwise known as the cosmological constant problem)?

On the observational side, notable tensions between best fit ΛCDM theoretical predictions [1] and data remain, which include: \( H_0 \) tension [3, 4], \( \sigma_8 \) tension [5], BAO in the Lyman-\( \alpha \) forest [6], void phenomenon [7] and missing satellite problem [8]. While such tensions can be (and often are) due to systematic errors, some may provide clues to the physics beyond the standard models of cosmology and particle physics. As an example, warm dark matter as an idea with some roots in particle physics has been proposed as a solution for missing satellite problem [9]. In the cosmology sector, alternatives such as modified gravity, quintessence, and interacting dark matter-dark energy have been extensively studied (e.g., [10–12]). However, none has been quite as compelling as ΛCDM.

Here we pursue a different perspective on this problem: In spite of (presumable) existence of a huge number of distinct theoretically consistent models, how can Nature only pick one? This leads to an idea described in [13] and based on that a model, über-gravity, introduced in [14] which we will briefly review in the following section. We then study the resulting cosmology and show that it has a rich phenomenology, with the potential to address the \( H_0 \) and BAO in the Lyman-\( \alpha \) forest tensions, as well as distinct predictions for structure formation at low redshifts. The structure of this work is as below: In Sec.(II), we introduce the idea of ensemble average theory of gravity and the corresponding über-gravity model. In Sec.(III), we introduce the cosmological model that follows über-gravity, which we call \( \tilde{\Lambda} \)CDM. In Secs.(IV) and (V), we study the background and perturbation of \( \tilde{\Lambda} \)CDM. Finally in Sec.(VI), we conclude and remark on future directions.

II. UBER-GRAVITY

In this section, we review the idea of the ensemble average theory of gravity and über-gravity in the upcoming two subsections respectively.

A. Ensemble Average Theory of Gravity

The “Ensemble Average Theory of Gravity” [13] suggests that the gravity model is the average over all the theoretically possible models of gravity. For this reason, a recipe has been suggested which is inspired by path integral formalism. This idea has some relationship with the “Mathematical Universe” idea of Tegmark [15]. The same philosophy has been used in the context of particle physics by Arkani-Hamed et al. [16]. In [16], it is assumed that there are different types of standard model of particle physics labeled by their Higgs masses. The idea of taking averaging over all the possible models can give a clue to address hierarchy problems [14, 16]. To implement...
this idea we suggest to work with a Lagrangian which has been defined as [13]

$$\mathcal{L} = \left( \sum_{i=1}^{N} \mathcal{L}_i e^{-\beta \mathcal{L}_i} \right) / \left( \sum_{i=1}^{N} e^{-\beta \mathcal{L}_i} \right), \quad (1)$$

where $\mathcal{L}_i$'s are the theoretically possible Lagrangians and $\beta$ is a free parameter of this model. As is commonly done in statistical physics, we can write this as:

$$\mathcal{L} = -\frac{\partial}{\partial \beta} \ln Z,$$

$$Z = \sum_{i=1}^{N} e^{-\beta \mathcal{L}_i}, \quad (2)$$

where $Z$ is the canonical partition function in the model space. In the next subsection, we will use the idea to make a toy model.

B. Über-Gravity model

In [14], the above idea has been used in the context of gravity and here we will review it very briefly. Let's define the partition function over the all analytic models of gravity as

$$Z = \sum_{f(R)} e^{-\beta f(R)}, \quad (3)$$

where $f(R)$'s are analytic functions of Ricci scalar, $R$. In [14], it has been shown that the final Lagrangian, dubbed über-gravity, is not sensitive to the choice of basis for its main properties. In general, for analytic functions of $f(R)$ we can set basis as $\alpha_n R^n + \lambda_n$ for each $n \in \mathbb{N}$. For simplicity, here we focus on $\alpha_n = 1/R_0^2$ and $\lambda_n = -2\Lambda$, which yields:

$$\mathcal{L}_{\text{über}} = \left( \sum_{n=1}^{\infty} (\tilde{R}^n - 2\Lambda) e^{-\beta (\tilde{R}^n - 2\Lambda)} \right) / \left( \sum_{n=1}^{\infty} e^{-\beta (\tilde{R}^n - 2\Lambda)} \right), \quad (4)$$

where $\tilde{R} = R/R_0$ and $R_0$ is a new free parameter of the model with dimension $[M^2]$ which makes $\beta$ dimensionless. An example of $\mathcal{L}_{\text{über}}$ is shown in Fig. 1.

The über-gravity has the following universal properties: i) for high-curvature regime it reduces to the Einstein-Hilbert (EH) action i.e. $R - 2\Lambda$, ii) for intermediate-curvature regime it predicts a stronger gravity than the EH model, iii) it is vanishing for low-curvature regime ($R < R_0$) and iv) there is a sharp transition at $R_0$, which is not sensitive to choice of the basis and parameters [14]. In this sense, über-gravity is a fixed point in the model space which makes it unique. The main goal of this work is to study the cosmology of our model and for this purpose we need to study the equations of motion. However, for our purpose we need the trace of equation of motion (and we assume the case of steady state i.e. $R$ is evolving very slowly) which is plotted in Fig. 2. In the next section, we will introduce a cosmological model based on the general behavior of the über-gravity.

III. üΛCDM COSMOLOGY

In this section, we propose a cosmological model which is a natural consequence of über-gravity model. According to Fig. 2, we see that the über-gravity leads to a very simple model for the gravity as

$$\text{Gravity} \simeq \begin{cases} R = R_0 & \rho < \rho_{\text{über}} \\ \Lambda\text{CDM} & \rho > \rho_{\text{über}} \end{cases} \quad (5)$$

which we call üΛCDM. In this scenario, if matter density $\rho > \rho_{\text{über}}$ then it sees pure GR with a cosmological constant, while if $\rho < \rho_{\text{über}}$ then the metric is constrained to have constant Ricci scalar i.e. $R_0$, which is a free parameter in our model presented in Eq.(4). We should mention that the above argument does not depend on the radiation content of the universe since the radiation is trace-free and has no contribution to our conclusion based on Fig. 2.

The sharp transition in our model is representative of a fam-
Ily of models that have different physics for early and late time universe. Such models may address the tensions between early and late time observations. In this sense, our model (5) is very similar to vacuum metamorphosis scenario [17] though they are conceptually different and we do not have any claim about the vacuum structure [18].

In the following sections, we study the background and perturbation of this model.

IV. BACKGROUND ANALYSIS

The continuity equation for matter gives \( \rho(t) \propto (1+z)^3 \) which means it is decreasing and the universe is in pure \( \Lambda \)CDM phase, i.e. \( \rho > \rho_{\text{fiber}} \) in (5) for early times. Then there is a transition redshift \( z_0 \) given by \( \rho_{\text{fiber}} \) when the model switches to \( R = R_0 \) phase in (5). For the background we assume a spatially flat FRW metric which gives the following (modified) Friedmann equation for \( z > z_0 \)

\[
E^2(z) = \Omega_m (1+z)^3 + \Omega_\Lambda,
\]

where \( E(z) \equiv H(z)/H_0 \) and \( H_0 \) is Hubble parameter at \( z = 0 \). For \( z < z_0 \) we have

\[
E^2(z) = \frac{1}{2} \bar{R}_0 + (1 - \frac{1}{2} \bar{R}_0)(1+z)^4
\]

where \( \bar{R}_0 = R_0/6H_0^2 \). We assume \( E(z) \) is continuous at \( z = z_0 \) to read \( \bar{R}_0 \) from the following relation

\[
\Omega_m (1+z_0)^3 + \Omega_\Lambda = \frac{1}{2} \bar{R}_0 + (1 - \frac{1}{2} \bar{R}_0)(1+z_0)^4
\]

Furthermore, we assume continuity of \( H'(z) \) or equivalently Ricci scalar which gives us an additional constraint on our parameters

\[
\Omega_m (1+z_0)^3 = \frac{4}{3} (1 - \frac{1}{2} \bar{R}_0)(1+z_0)^4.
\]

Therefore, we see that \( \Lambda \)CDM has three independent free parameters i.e. \( H_0, \Omega_m, \) and \( z_0 \) which is one more than standard \( \Lambda \)CDM’s \( H_0 \) and \( \Omega_m \). Now we are going to constrain \( \Lambda \)CDM with observational data and contrast it with \( \Lambda \)CDM. To do a fair comparison, we should mention that in the following we will find the best fit of \( \Lambda \)CDM with exactly the same datasets which will be used for \( \Lambda \)CDM. As such, the best fit values in \( \Lambda \)CDM may be slightly different from those of Planck 2015 [1].

A. ObservationalDatasets

In the following we report the datasets (data points) used in this work including: CMB, local \( H_0 \), BAO and Lyman-\( \alpha \) forest.

For CMB, we focus on the position of the first peak which gives the distance between us and the surface of last scattering as one indicator [19–21]. This distance is given by 100\( \Theta = 1.04085 \pm 0.00047 \) and we need to use \( r_s = 144.61 \pm 0.49 \) Mpc and \( z_s = 1090.09 \pm 0.42 \) all reported by Planck 2015 TT+lowP data (see Table 4 in [1]). We also add a data point as the value of matter density parameter times the square of Hubble parameter from the CMB perturbations, \( \Omega_m h^2 = 0.1415 \pm 0.0019 \) [1]. The reason for this is that \( \Lambda \)CDM cannot affect the CMB anisotropy power spectrum (up to small secondary effects which are outside the scope of this analysis) since the behavior of \( \Lambda \)CDM and \( \Lambda \)CDM are identical at \( \rho > \rho_{\text{fiber}} \) or high redshifts according to (6). Therefore, we encoded all CMB constraints into two main data points, i.e. distance to the last scattering surface and matter density.

Another data point is given by Riess et al. [3] i.e. \( H_0 = 73.24 \pm 1.74 \) km/s/Mpc, and from now on we refer to it by R16. This is the data point which is in tension with Planck 2015 best-fit \( \Lambda \)CDM model.

The other dataset is the baryonic acoustic oscillation (BAO) measurements: we use the 6dFGS data at \( z = 0.106 \) [22], the SDSS main galaxy (MGS) at \( z = 0.15 \) of [23], Baryon Oscillation Spectroscopic Survey (BOSS) LOWZ [24] at \( z = 0.32 \), and CMASS surveys [25] at \( z = 0.57 \).

In addition to the above datasets, we consider BAO in Lyman-\( \alpha \) forest of quasar spectra by [6] who report two independent quantities at \( z = 2.40 \); line of sight distance as \( D_L/r_d = 8.94 \pm 0.22 \) and angular distance as \( D_M/r_d = 36.6 \pm 1.2 \) where \( D_M = (1+z)D_A \).

A tension between Planck 2015 and Lyman-\( \alpha \) forest BAO has been reported [26] which could potentially be solved with a dynamical dark energy [27]. Here in this work we use the recent analysis [6] which has less tension with Planck 2015. We summarized the datasets in Table I.

In the following, we will report the best fit of our model and standard \( \Lambda \)CDM, first for CMB+BAO+R16 which makes our results comparable with Planck 2015 [1]. Then we will add two Lyman-\( \alpha \) BAO constraints to check if \( \Lambda \)CDM can lessen the reported tension.

B. Results

Our results are summarized in Table II. We used two different combinations of datasets: First we use the data used in Planck 2015 [1], including the distance from last surface scattering and matter density (CMB) and four BAO data points, which we then supplement with R16. Second, we will add Lyman-\( \alpha \) forest BAO data points. We contrast best-fit parameters and goodness of fit between \( \Lambda \)CDM and standard \( \Lambda \)CDM with these datasets [34].

CMB+BAO+R16: \( \Lambda \)CDM best fit values are \( \Omega_m = 0.293^{+0.007}_{-0.009} \) and \( H_0 = 69.4^{+0.8}_{-0.6} \) km/s/Mpc with \( \chi^2 = 7.84 \). The higher value for \( H_0 \) is because we have added R16 to our dataset which drives a higher value for Hubble parameter. Our model best fit occurs at \( H_0 = 71.5^{+1.6}_{-1.5} \) km/s/Mpc, \( \Omega_m = 0.278^{+0.014}_{-0.011} \) and \( z_0 = 0.537^{+0.277}_{-0.375} \) with \( \chi^2 = 4.93 \).

CMB+BAO+R16+Lyα: Adding Lyman-\( \alpha \) BAO data point show tension with \( \Lambda \)CDM as it has been already reported [26] and [27]. By adding these data points the \( \chi^2 \) increases.
significant for both models. ΛCDM’s $\chi^2$ is 19.25 while for ěΛCDM model we have $\chi^2 = 17.11$. The best fit for our model occurs at $\Omega_m = 0.280 \pm 0.013$, $H_0 = 71.2^{+1.8}_{-1.5}$ km/s/Mpc and $z_\odot = 0.413^{+0.305}_{-0.289}$.

We summarize the results in Table II and based on these values we plot background distance quantities: In Fig. 4, the angular diameter distance normalized to Planck 2015 best fit values has been plotted. In addition to our distance to the last scattering surface, we plotted the Lyman-\(\alpha\) forest BAO data point at $z = 2.4$ which shows a 2.5\(\sigma\) tension with both models. In Fig. 5, we plotted the volume distance normalized to Planck 2015 best fit values. We have added BAO data and one should compare this plot with Fig. 14 in [1]. In addition to BAO we transformed local $H_0$ measurement [3] to a distance. Planck 2015 and our best-fit ěΛCDM model are in tension with R16. However the tension almost disappears in ěΛCDM model, while the tension with Lyman-\(\alpha\) $D_V(z)$ measurement is reduced.
V. PERTURBATIONS: THE SET-UP

It is well-known that all $f(R)$ theories of gravity can be written as scalar-tensor theories. Consider the following scalar-tensor action representing the cosmological era after the transition in über-gravity:

$$ S = \frac{1}{16\pi G} \int d^4x \sqrt{-g} \left( R - R_0 \right) + \mathcal{L}_m, \quad (10) $$

where $R$ is the Ricci scalar, $g$ is the trace of the metric $g_{ab}$, $R_0$ is the (constant) value of curvature after the transition, and $\mathcal{L}_m$ is a Lagrange multiplier that is a priori space-time dependent and ensures the constraint $R = R_0$. The equations of motion (EOM) for this action are:

$$ -\frac{g_{ab}}{2} \left( R - R_0 \right) + \xi R_{ab} - \left[ \nabla_a \nabla_b - g_{ab} \square \right] \xi = 8\pi G T_{ab}, \quad (11) $$

$$ R - R_0 = 0. \quad (12) $$

The trace of Eq. (11) can be written using the constraint equation as:

$$ \xi R_0 = 8\pi G T - 3 \square \xi, \quad (13) $$

where $T = g^{ab} T_{ab}$. Using the results for the linear scalar perturbation of Appendix A we can write the Newtonian potential $\psi$ and lensing potential $\phi_L$ in the quasi-static regime ($\nabla^2 \ll H^2$):

$$ \nabla^2 \psi = \frac{16\pi G a^2}{3\xi^0} \delta \rho, \quad (14) $$

$$ \phi_L = \frac{\phi + \psi}{2} = \frac{3}{4} \psi, \quad (15) $$

$$ \left[ \dot{\psi} + \left( H + \frac{\dot{\xi}}{\xi^0} \right) \psi \right]_{,i} = -\frac{16\pi G}{3\xi^0} \rho u_i, \quad (16) $$

where $\rho(\tau) + \delta \rho(x, \tau)$ and $u_i(x, \tau)$ are the CDM density and peculiar velocity, respectively.

In order to solve Equations (13-16), we first need to know the initial conditions for the fields at $z = z_0$. Comparing the action (10) with the Einstein-Hilbert action, we find:

$$ \xi^0(z \geq z_0) = 1 \quad \text{and} \quad \xi^0(z \geq z_0) = 0, \quad (17) $$

which sets the initial condition for the background equation for $\xi^0$ in (13). Having solved for $\xi^0(\tau)$, we can plug into Equation (15) to find Newtonian potential, which in turn governs the geodesic equation for CDM. By comparing Equations (15-16) with Einstein equation, we notice that continuity of matter density and velocity implies that there will be a jump in Newtonian potential, while the lensing potential will remain continuous at $z = z_0$:

$$ \psi(z < z_0) = \frac{4}{3} \psi(z > z_0), \quad (18) $$

$$ \phi_L(z < z_0) = \phi_L(z > z_0), \quad (19) $$

$$ \text{as} \ z \to z_0. \quad (20) $$

Therefore, the rate of structure formation (at the linear level), which is governed by gravitational acceleration, suddenly jumps by 33% at the onset of the transition.

The real story of course, is more complicated. Nonlinear structures are already well in place by $z \sim 0.4$. Inside haloes and their outskirts, the density never goes below $\rho_{\text{uber}}$, implying that GR remains valid. The voids, however, could have underdensities of $\sim 50\%$, and thus have crossed over in the über-era, much earlier [35]. The boost in Newtonian potential can accelerate the emptying of the voids and boost the Integrated Sachs-Wolfe (ISW) effect. Could this provide a means to understand the void phenomenon [7], or the anomalously large ISW effects observed in voids [29] and in general [30]? We defer studying these possibilities to future work, but comment that, due to their nonlinear nature, they can only be satisfactorily addressed using numerical simulations.

VI. CONCLUDING REMARKS

In this work, we show how from the idea of über-gravity a cosmological model is emerged. We call this model üΛCDM, to indicate two distinct phases of cosmological evolution: The era of ΛCDM, and the över-era with a constant Ricci scalar. The universe is in pure ΛCDM and GR when matter density is larger than a critical density, $\rho_{\text{uber}}$. After matter density drops below $\rho_{\text{uber}}$, the universe is in a state with a constant Ricci scalar where we find a suitable solution for Hubble parameter to match the data. This behavior can be seen in a more general context, as a phase transition in gravity, and über-gravity, naturally, provides such a framework to think about such a phase transition. We showed, at the level of background, üΛCDM can be a potential resolution for the tension between high and low redshift $H_0$ measurements, noting that the $H_0$ measured in local universe is computed in the über-era. We also show that in the level of background the üΛCDM model fits with the BAO data better than ΛCDM, albeit marginally.
Furthermore, we provide a preliminary analysis of structure formation in ΛCDM, showing that structure formation will be enhanced in the Πber-era. This is most likely to affect cosmic voids, and could potentially explain anomalies associated with void structure formation. We plan to study this possibility in the future.

Note-I: Recently, LIGO reported detection of gravity wave from a NS-NS binary with its EM counterpart [31]. By using gravitational wave as standard siren (which is completely independent of SNe or CMB) they could measure Hubble parameter, $H_0 = 70.0^{+12.0}_{-10.0}$ km/s/Mpc [32], which as of yet cannot distinguish the models discussed here. Higher statistics of such observations can reduce the errors and shed light on the status of $H_0$ tension in cosmology.

Note-II: During the final stages of this work, Valentino, Linder and Melchiorri submitted a preprint that addressed the cosmic voids, and could potentially explain anomalies associated with void structure formation. We plan to study this possibility in the future.

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Appendix A: Perturbations

In this section, we derive the background and linearly perturbed EOMs of Eqs. (11)-(13). To this end, we expand the EOM to linear order in scalar metric perturbations in the longitudinal gauge:

$$ds^2 = a(\tau)^2[-(1 + 2\psi)d\tau^2 + (1 - 2\phi)d^2x],$$

$$R = R_0,$$

$$\xi = \xi^0(\tau) + \xi^1(x, \tau)$$

$$T_{ab} = \bar{T}_{ab}(\tau) + \delta T_{ab}(x, \tau),$$

$$\bar{T} = \bar{T}(\tau) + \delta T(x, \tau),$$

where $T = T_{ab}g^{ab}$. The background EOMs are:

$$\frac{R_0 a^2}{3} = \frac{\ddot{a}}{a},$$

$$\frac{R_0 a^2}{3} = \frac{8\pi G\bar{T}a^2}{3\xi^0} - \nabla^2 \xi^0 - 2H\xi^0 + \xi_0^0,$$

$$\frac{R_0 a^2}{3} = \frac{16\pi G\bar{T}_0 a^2}{3\xi^0} + 3H(\bar{H} + \xi_0^0) - \frac{2}{3} \nabla^2 \xi^0, \quad (A8)$$

The EOMs at linear order are:

$$\nabla^2 (\psi - 2\phi) = -\psi R_0 a^2 - 3\bar{H}(3\dot{\phi} + \psi) - 3\dot{\phi}, \quad (A9)$$

$$\frac{R_0 a^2}{3} \xi^1 = \frac{8\pi G\bar{T}a^2}{3} \delta T - 2\bar{H}(2\dot{\psi}\xi^0 - \dot{\xi}^1) - \nabla^2 \xi^1 - \xi_0^0(3\dot{\phi} + \psi) - 2\dot{\phi}\xi^0, \quad (A10)$$

$$\frac{R_0 a^2}{3} \xi^1 = \frac{16\pi G\bar{T}_0 a^2}{3} \delta T_0 + 3\xi^1 \bar{H}^2 + \frac{4}{3} \xi_0^0 \nabla^2 \phi - \bar{H}(\bar{H}\psi + \dot{\phi}) - 2\bar{H}(2\dot{\psi}\xi^0 - \dot{\xi}^1) - \frac{2}{3} \nabla^2 \xi^1. \quad (A11)$$

The $\{0i\}$ component of the equation of motion is

$$2\xi^0(\bar{H}\psi_{,i} + \dot{\phi}_{,i}) = 8\pi G\delta T_{0i} - \bar{H}\xi^0_{,i} - \psi_{,i}\xi^0 + \dot{\xi}^0_{,i}. \quad (A12)$$

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[34] Note that the best-fit values of ΛCDM may differ slightly from Planck 2015 [1] due to simplified analysis and different dataset combinations.

[35] This is a particular extreme of the well-known Chameleon screening [28], which is ubiquitous for generic scalar-tensor theories.