Exploring the Dark Universe: constraining the scalar field dark matter model and explaining the Hubble tension as well as the spatial curvature as measured by the final Planck data release

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Over the last 20 years, the Λ cold dark matter (ΛCDM) concordance model has become the standard model of cosmology, given its accordance with many observations, particularly on large cosmic scales and it is characterized by the following two components: cold dark matter (CDM) and Λ, the cosmological constant, which is often interpreted as the simplest realization of dark energy (DE). The physical nature of both components, encompassing the “dark universe,” are two profound open questions in cosmology.

The first part, consisting of the Chapters II and III, explores the scalar field dark matter (SFDM) as an alternative model for DM via its impact on structure formation. To this end, we investigate ΛSFDM cosmologies, which differ from ΛCDM in that CDM is replaced by SFDM, by calculating the evolution of the background universe, as well as linear perturbations, focusing on scalar modes. We consider models with a complex scalar field with a repulsive, quartic self-interaction (SI) in the Thomas Fermi regime, also known as “SFDM-TF,” and models without SI, referred to as fuzzy dark matter (FDM) and compare it to ΛCDM cosmology.

We modify the Boltzmann code Cosmic Linear Anisotropy Solving System (CLASS), to incorporate the physics of complex SFDM, which has as one of its characteristics that its equation of state is maximally stiff in the very early Universe, dominating then over all the other cosmic components, even over radiation. We calculate cosmic microwave background (CMB) and matter power spectra as well as unconditional Press-Schechter halo mass functions for various models, expanding previous literature that were limited either to the background, or to a semi-analytical approach to SFDM density perturbations neglecting the early stiff phase.

Our calculations confirm previous results of recent literature, implying that SFDM models in the Thomas-Fermi regime, where a strong repulsive 2-particle SI is included, have the potential to resolve the “cusp-core” problem, being a valuable alternative to CDM models where $\gtrsim 1$ kpc-size halo cores are disfavored, questioning their ability to explain the small-scale problems on dwarf-galactic scales.

Subsequently, we present DM-only 3D-simulations of halo formation and evolution in ΛSFDM cosmologies, applying fluid approximations for SFDM. Previous literature has presented two fluid approximations for SFDM, as well as simulations of halo formation, where discrepancies were also reported. Therefore, we perform dedicated 3D cosmological simulations for the SFDM model, applying both fluid approximations, as well as for CDM. Our results are very well in accordance with previous works and extend upon them, in that we can explain the reported discrepancies.

We find that the evolution of both SFDM and CDM halos follows a two-stage process. In the early stage, the density profile in the center becomes close to a (n = 1.5)-polytropic core. Consecutively, for CDM halos, the core transitions into a central cusp. In SFDM halos, the additional pressure, due to SI, determines the second stage of the evolution, where the central region follows closely a (n = 1)-polytropic core. Both cores are embedded in a nearly isothermal envelope. We also encounter a new effect, namely a late-time expansion of both polytropic core plus envelope, because the size of the

almost isothermal halo envelope is affected by the decreasing average density of the background universe.

The Chapters IV and V address the exploration of DE, at first, by considering the large-scale problems of ΛCDM, in particular the Hubble tension problem. Cosmological observational programs often compare their data not only with ΛCDM, but also with extensions applying models of dynamical dark energy (DDE), with a time-dependent equation of state (EoS) parameter w. We found a degeneracy in the customary computational procedure for the expansion history, once DDE models are applied. This degeneracy provides an infinite number of cosmological models reproducing the Planck-measured CMB spectrum.

We present a complementary computational approach, which breaks this degeneracy: the "fixed early densities (EDs) approach" evolves cosmological models from the early Universe to the present, in contrast to the customary "fixed H0 approach" which evolves cosmological models in reverse order. We implement a refined procedure, applying both approaches, in an amended version of the code CLASS, where our results reveal that the Chevallier-Polarski-Linder (CPL) model $w(a) = -0.9 + 0.1(1 - a)$ could provide a resolution to the Hubble tension problem.

Moreover, we find that combining both approaches, while requesting to yield consistent results and agreeing with observations across cosmic time, can serve as a kind of consistency check for cosmological models, and will increase the accuracy of inferred cosmological parameters significantly, in particular for ΛCDM extensions. In Chapter V we continue with the exploration of the observed late-time accelerated expansion of the Universe, attributed to DE, by reassessing ΛCDM's flat universe interpretation, where we consider that the Friedmann equation describes the expansion history of FLRW universes in the local reference frame of freely falling comoving observers, which perceive flat, homogeneous and isotropic space in their local inertial system, where special relativity (SR) applies, as a consequence of the equivalence principle. Consequently, the observation of the flatness of space by the measurements of the CMB, confirms us to fulfill the criterion of comoving observers.

We use this fact to propose an extension to ΛCDM, which we would like to put up for discussion, which incorporates the initial conditions of the background universe, comprising the initial matter and radiation content in the early Universe, as well as the initial expansion rate. The observed late-time accelerated expansion is then attributed to a kinematic effect akin to a dark energy component. Choosing the same $\Omega_{m,0} \simeq 0.3$ as ΛCDM, its equation of state $w_{de} \simeq -0.8$. Furthermore, we include the impact on the expansion history caused by the cosmic web of the late Universe, once voids dominate its volume, and find that the initially constant w_{de} becomes time-dependent, evolving to a value of $w_{de} \simeq -0.9$ at the present. While this impact by voids is minor, it is sufficient to provide a solution to the Hubble tension problem, which we already introduced in Chapter IV. We use CLASS to calculate the expansion history and power spectra of our extension and compare our results to concordance ΛCDM and to observations. We find that our model agrees well with current data, in particular with the final data release PR4 of the Planck mission, where it explains the reported spatial curvature of $\Omega_{k,0} = -0.012 \pm 0.010$.