Alleviating Cosmological Tensions with the Hadrosymmetric Twin Higgs

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The Hadrosymmetric Twin Higgs (HTH) model provides a natural solution to the little hierarchy problem by incorporating all three generations of quarks in a twin sector. Unlike other Twin Higgs scenarios, such as the Mirror Twin Higgs (MTH), the HTH framework avoids introducing additional light states or radiation and thus remains consistent with stringent bounds on the effective number of relativistic species, $\Delta N_{\rm eff}$. Its particle content and interactions also make it difficult to probe at colliders, highlighting the importance of cosmological tests. In this work, we study the cosmological implications of the HTH model, focusing on the persistent tensions in the Hubble constant (H_0) and the matter clustering amplitude (σ_8). Implementing the HTH sector in a Boltzmann code and confronting it with cosmic microwave background (CMB) data and local H_0 measurements, we find that the scenario reduces the Hubble tension from more than 4σ to about 2.5σ, while also alleviating the σ_8 discrepancy. These results demonstrate that the HTH framework not only addresses naturalness in particle physics but also offers a viable route to mitigating current cosmological tensions, thereby strengthening the link between fundamental theory and precision cosmology.

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I. INTRODUCTION

The Standard Model (SM) of particle physics is one of the most successful and well-established theories in modern physics, yet it leaves unresolved questions, most notably the hierarchy problem. Numerous Beyond Standard Model (BSM) theories have been developed to address this issue, many of which rely on symmetry-based approaches to protect the Higgs mass and predict the existence of new partners for the SM particles. Despite extensive searches, the absence of experimental evidence for such particles at the Large Hadron Collider (LHC) has shifted attention toward models containing new particles neutral under the SM gauge symmetries. Among these, Twin Higgs (TH) models present an appealing solution to the little hierarchy problem by introducing a new twin sector, including particles uncharged under SM gauge interactions [1, 2].

The Higgs sector of the TH models has an approximate global symmetry wherein the SM Higgs boson is a pseudo-Nambu-Goldstone boson (pNGB) of the spontaneous symmetry breaking (SSB) of this global symmetry, which allows the Higgs boson to remain naturally light. However, beyond 5 to 10 TeV, a UV-complete model is necessary because the approximate global symmetry is not radiatively stable. Supersymmetry [3–5] and Composite Higgs models [6–8] are examples of such UV completions. In its most straightforward form, all the SM particles and symmetries are duplicated in the twin sector, known as the Mirror Twin Higgs (MTH) model [1]. This means that a discrete $\mathbb{Z}_2$ symmetry links the particles and symmetries of the SM and TH sectors. Since the particles in the MTH sector carry no charge under SM symmetries, they are difficult to produce at the LHC [9].

However, this model is affected by the bound on the effective SM neutrino degrees of freedom, ΔN_{eff}. The expansion rate of the universe is increased by the existence of additional relativistic degrees of freedom like twin photons and twin neutrinos. However, in a minimal scenario, to evade the little hierarchy problem, just the third generation of twin quarks, charged under twin $SU_C(3)'$ and twin $SU_L(2)'$ gauge symmetries [1] and have almost the same SM coupling values, are required and other features of the twin sectors are not constrained very hard [10, 11]. So, some other varieties of the TH model have been proposed like the fraternal twin Higgs [12], the vector-like twin Higgs [13] and the Hadrosymmetric Twin Higgs [14].

In contrast to the MTH model, in the Hadrosymmetric Twin Higgs (HTH) model, discrete $\mathbb{Z}_2$ symmetry is hardly broken, so the twin sector is not simply a perfect copy of the SM spectrum, and it just contains a mirror copy of the SM hadrons [14]. The twin sector includes all three

[1] The twin particles, couplings, and symmetries are denoted by a prime.

generations of quarks; however, it does not contain any light states or radiation. Furthermore, the twin hypercharge is considered to be a global symmetry instead of a gauge symmetry, which means that the twin photon does not appear in the twin spectrum. As a result, the twin $SU_L(2)'$ gauge bosons possess equal masses.

Since the HTH model does not introduce any additional light particles, it avoids current bounds on $\Delta N_{\rm eff}$. At the same time, its direct collider signatures are extremely elusive [15, 16], making it one of the least experimentally accessible realizations among TH scenarios. This motivates exploring its implications in cosmology, where precise measurements of the expansion history and structure growth offer a complementary probe.

In particular, modern cosmology currently faces two persistent anomalies within the ΛCDM framework. The first is the Hubble tension, a $\sim 4\sigma$ discrepancy between early-time (CMB) and late-time (distance-ladder) determinations of H_0 [17, 18]. The second is the σ_8 tension, a $\sim$ 2–3σ mismatch between the amplitude of matter clustering inferred from large-scale structure surveys and that predicted by the CMB [19, 20]. If not attributable to systematics, these discrepancies may signal physics beyond the standard model of cosmology and or particle physics. There are numerous studies in this area, including modifications to dark energy [21, 22], dark matter [23–27], and even explorations of the physics of the early universe [28–30] (See Ref. [31] for a comprehensive review).

Cosmological extensions of the TH framework are therefore particularly interesting, as recent work has shown that the MTH scenario can simultaneously alleviate both tensions [32]. The authors carried out detailed numerical analyses of twin sector processes, including twin Big Bang nucleosynthesis, twin recombination, and the evolution of perturbations. By fitting the model to CMB and large scale structure data, they showed that the MTH framework not only remains consistent with current cosmological constraints but can also simultaneously alleviate the Hubble and σ_8 tensions.

In this paper, we investigate the cosmological phenomenology of the HTH model. We implement the HTH sector into the publicly available numerical code `CLASS`[2](the Cosmic Linear Anisotropy Solving System) [33] and to perform a Monte Carlo Markov Chain (MCMC) analysis with a Metropolis-Hasting algorithm using the code `MONTEPYTHON-v3`[3] [34, 35] using the Planck 2018 high-ℓ CMB TT, TE, EE + low-ℓ TT, EE + lensing data [36]. Our analysis shows that

[2] https://github.com/lesgourg/class_public
[3] https://github.com/baudren/montepython_public

the HTH framework, originally motivated by particle physics considerations, can also reduce both the Hubble and σ_8 tensions, thereby connecting the resolution of the little hierarchy problem to present-day cosmological observations.

The structure of the paper is as follows. Section II describes the details of the HTH model. Section III presents its cosmological phenomenology. Finally, Section IV summarizes our conclusions.

II. THE MODEL

In this section, we provide a detailed explanation of the HTH model, as introduced in the paper [14]. The Higgs potential of the model demonstrates an approximate $SU(4)$ symmetry. The SM Higgs boson, denoted as H, and the twin Higgs boson, denoted as H', exist within the fundamental representation of the $SU(4)$ symmetry, (H, H'). Following SSB in both sectors,[4] two physical degrees of freedom remain: a pNGB and a radial mode. The pNGB is naturally light and corresponds to the observed boson at the LHC. The mixing between the SM Higgs and the twin Higgs serves as the portal between the two sectors. Consequently, there will be a deviation in the Higgs couplings; to avoid significant discrepancies from the current experimental Higgs branching ratios, v'/v must exceed 3 [9, 12].

Additionally, like other twin Higgs models, the HTH model features an approximate $\mathbb{Z}_2$ symmetry between the Standard Model and twin sectors, which helps to cancel quadratic divergences. To achieve this cancellation, the top quark Yukawa, weak, and color gauge couplings in two sectors should satisfy the following relations respectively [12, 14],

$$\frac{|y_t - y_t'|}{y_t} \sim 0.01, \quad \frac{|g_2 - g_2'|}{g_2} \sim 0.1, \quad \text{and} \quad \frac{|g_3 - g_3'|}{g_3} \sim 0.1, \tag{1}$$

while in the above relations, the cut-off of the twin Higgs sector is set to be around 5 TeV. There are no restrictions on the other Yukawa couplings and hypercharge coupling. Unlike other twin Higgs models, the HTH scenario includes all three generations of quarks but does not feature any light lepton generations within the twin spectrum.

The model's gauge symmetry is expressed as $SU_C(3)' \times SU_L(2)'$, while its twin hypercharge symmetry is a global symmetry rather than gauge symmetry, resulting in all twin weak gauge bosons have similar masses, $m_{W',Z'} = \frac{1}{2} g_2' v'$. So according to this fact and Eq. 1, it is assumed that

[4] The vacuum expectation values (vev) for the SM and twin sectors are represented respectively as: $v \equiv \langle H \rangle$, and $v' \equiv \langle H' \rangle$.

all particles, gauge bosons and quarks, in twin spectrum are heavier than their SM counterparts with a factor v'/v.

The dark hadron spectrum in the HTH model resembles its SM counterpart. According to Eq. 1, due to a slight deviation in the twin QCD coupling (approximately 10%), the twin QCD confinement scale changes only slightly. Based on the two-loop renormalization group running of the strong coupling, the ratio of the confinement scale ($\Lambda'_{\rm QCD}/\Lambda_{\rm QCD}$) varies between 0.2 and 5 [14, 32].

The classification of light and heavy twin quarks is determined by comparing their masses to the twin QCD confinement scale. In the HTH scenario, three light twin quarks are considered, leading to the formation of twin pions within the dark sector. These twin pions, a twin isospin triplet ($\pi'^{\pm}, \pi'^{0}$), are the lightest pNGBs and can have masses well below the twin confinement scale. However, to remain consistent with constraints on the $\Delta N_{\rm eff}$, the twin pion mass must exceed the temperature of Big Bang Nucleosynthesis (BBN), $T_{\rm BBN} \sim \mathcal{O}(\rm MeV)$.

Since the charged twin pions $\pi'^{\pm}$ carry a conserved global $U(1)$ charge, they are stable; however, their relic abundance is expected to be negligible [14]. The twin sector also includes other light and heavy hadronic states, likewise the SM spectrum, such as the twin proton and twin neutron. The twin proton is stable due to baryon number conservation, while the twin neutron remains stable in the absence of light twin-sector leptons. Heavier twin hadrons eventually decay into the stable constituents of the dark sector: twin protons, twin neutrons, and twin pions.

Furthermore, to avoid cosmological overclosure or an early matter-dominated era, the neutral twin pion, π'^{0}, must decay efficiently into SM degrees of freedom before BBN, requiring a lifetime $\tau_{\pi'^0} < \tau_{\rm BBN} \sim 1\,\rm s$. As a pNGB and pseudoscalar, π'^{0} cannot efficiently decay to the SM states via the Higgs portal, since such a decay necessitates both parity and twin isospin violation, leading to strong suppression. To ensure prompt decay before BBN, an additional portal between the twin and SM sectors is required to allow the π'^{0} to decay sufficiently rapidly.

In the mass range $m_{\pi'^0} < 3m_{\pi^0}$, it is necessary to have a UV completion twin-SM portal below the TeV scale, potentially accessible at the LHC. Since the decay requires twin-isospin violation, it is most efficient when the twin pion mixes with the lightest SM pseudoscalar, the π^0. Furthermore, the dominant contribution to the twin pion to SM decay amplitude arises from an off-shell π^0, $\pi'^0 \to \pi^{0*} \to$ SM. As estimated in Ref. [14], for $m_{\pi'^0} < 3m_{\pi^0}$ ($\sim 400\,\rm MeV$), the diphoton mode is expected to be the dominant decay channel for the twin pion.

In the following section, we examine the cosmological implications of the HTH model in light of the features discussed above. We first describe how the HTH framework is implemented in the Boltzmann solver `CLASS`, with particular attention to the decays of twin neutral pions, which govern energy transfer between the twin and visible sectors and impact both the expansion history and structure formation. In contrast to the MTH scenario studied in Ref [32], where light twin states dominate the cosmology, the HTH model contains no such states, making twin hadron dynamics the key driver of its cosmological effects. We then assess whether these features can help to alleviate current cosmological anomalies, the H_0 and σ_8 tensions.

III. COSMOLOGICAL PHENOMENOLOGY OF HTH

As discussed in the introduction, the standard ΛCDM model cannot address the Hubble and σ_8 tensions. This motivates the investigation of BSM scenarios where new degrees of freedom can affect cosmological observables. The HTH model, while originally motivated by naturalness in particle physics, provides a natural testing ground in this context.

To assess its cosmological impact, we implement the HTH framework in the Boltzmann solver `CLASS` [33]. For simplicity, and following the treatment of Ref. [32] in the case of the MTH, we model the twin-sector states (twin neutral pions) as an effective decaying dark matter (DDM) component, while accounting for possible interactions that allow the dark sector to produce visible photons. This approach captures the leading phenomenological effects without relying on the detailed microphysics of the dark hadron spectrum. In background of the `CLASS` code, we used relations describing DDM and its contribution to extra radiation ($\bar{\mathrm{R}}$) given

$$\begin{aligned} \dot{\rho}_{\mathrm{DDM}} + 3H\rho_{\mathrm{DDM}} &= -\gamma_{DDM}\rho_{\mathrm{DDM}}, \\ \dot{\rho}_{\bar{\mathrm{R}}} + 4H\rho_{\bar{\mathrm{R}}} &= \gamma_{DDM}\rho_{\mathrm{DDM}}, \end{aligned} \tag{2}$$

where γ_{DDM} is the decay rate and $\rho_{\bar{\mathrm{R}}}$ represents the produced visible photons by the twin sector. When the decay rate is non-zero ($\gamma_{\mathrm{DDM}} \neq 0$), these produced photons effectively add to the photon radiation content of the universe and enters the cosmological background evolution. As a result, the parameters associated with the decay rate directly affect both the expansion history and the effective radiation fraction of the universe.

Hence, the Boltzmann equations describing the evolution of photon perturbations in HTH model are modified accordingly as,

$$\begin{aligned}
\dot{\delta}_\gamma &= -\tfrac{4}{3}\theta_\gamma + 4\dot{\phi} + a\gamma_{\rm DDM}\frac{\rho_{\rm DDM}}{\rho_\gamma}\left(\delta_{\rm DDM} - \delta_\gamma + \psi\right),\\
\dot{\theta}_\gamma &= k^2\left(\tfrac{\delta_\gamma}{4} - \sigma_\gamma + \psi\right) + an_e\sigma_T\left(\theta_b - \theta_\gamma\right) - a\gamma_{\rm DDM}\frac{3\rho_{\rm DDM}}{\rho_\gamma}\left(\tfrac{4}{3}\theta_\gamma - \theta_{\rm DDM}\right),\\
\dot{\sigma}_\gamma &= \tfrac{4}{15}\left(\theta_\gamma - \tfrac{9}{8}kF_{\gamma 3}\right) - \tfrac{9}{10}an_e\sigma_T\sigma_\gamma + \tfrac{1}{20}an_e\sigma_T\left(G_{\gamma 0} + G_{\gamma 2}\right) - a\gamma_{\rm DDM}\tfrac{\rho_{\rm DDM}}{\rho_\gamma}\sigma_\gamma,\\
\dot{F}_{\gamma l} &= \tfrac{k}{2l+1}\left[lF_{\gamma(l-1)} - (l+1)F_{\gamma(l+1)}\right] - an_e\sigma_T F_{\gamma l}, \qquad l \geq 3,\\
\dot{G}_{\gamma l} &= \tfrac{k}{2l+1}\left[lG_{\gamma(l-1)} - (l+1)G_{\gamma(l+1)}\right] + an_e\sigma_T\left[-G_{\gamma l} + \tfrac{1}{2}\left(F_{\gamma 2} + G_{\gamma 0} + G_{\gamma 2}\right)\left(\delta_{l0} + \tfrac{\delta_{l2}}{5}\right)\right]. \quad (3)
\end{aligned}$$

These equations are expressed in Conformal Newtonian gauge. Here, δ_γ, θ_γ, and σ_γ denote the density perturbation, velocity divergence, and shear stress of photons, respectively. F_γ is the ℓ-th moment of photon temperature perturbations and G_γ is the difference of the two linear polarization components. k is the comoving wavenumber, n_e is the number density of twin electrons, and σ_T is the Thomson scattering cross-section for the twin sector. An overhead dot denotes derivatives with respect to conformal time.

We check the HTH model against the CMB dataset (Planck 2018 high-ℓ CMB TT, TE, EE + low-ℓ TT, EE + lensing), firstly. This can show us if the HTH model has the potential to solve the H_0 and σ_8 tensions or not. We use Bayes's theorem to compute the posterior distributions of the model parameters. Beyond the six standard ΛCDM parameters, $(\Omega_b, \Omega_{DM}, 100\theta_{\rm MC}, \ln 10^{10}A_s, n_s, \tau_{\rm reio})$, the HTH model introduces $(\Omega_{\rm DDM}, \gamma_{\rm DDM})$, with flat priors $\Omega_{\rm DDM} \in [0, 0.1]$ and $\gamma_{\rm DDM} \in [0, 2\times 10^3]$. We consider the decay constant of $\gamma_{\rm DDM}$ is kms^{-1}Mpc^{-1}, the same unit as H_0 in `CLASS`. Convergence of the MCMC chains is verified via the Gelman-Rubin criterion ($R - 1 < 0.01$ for all parameters), with an average acceptance rate of ~ 0.2.

Figure 1 shows the posterior contours for σ_8, Ω_M and H_0. Remarkably, even without additional relativistic species, HTH reduces the Hubble tension from $> 4\sigma$ in ΛCDM to $\sim 2.5\sigma$. This improvement is non-trivial: the model operates under tight CMB photon constraints, leaving minimal freedom for tuning. Thus, the HTH provides a minimal yet impactful modification to the standard cosmology.

Incorporating the local Hubble measurement, $H_0 = 73.04 \pm 1.04, \mathrm{km}, \mathrm{s}^{-1}, \mathrm{Mpc}^{-1}$ [37], yields the HTH* scenario (Figure 1), which does not favor lower H_0 values. Unlike the MTH model, HTH introduces no extra ultra-relativistic degrees of freedom ($\Delta N_{\rm eff} \simeq 0$), a feature that normally limits a model's ability to resolve the Hubble tension. The fact that HTH nonetheless alleviates the tension highlights its genuinely non-trivial cosmological impact. This result can be represented more clear if instead of σ_8 we employ $S_8 = \sigma_8\sqrt{\Omega_M/0.3}$ parametrization as shown in Figure 2.

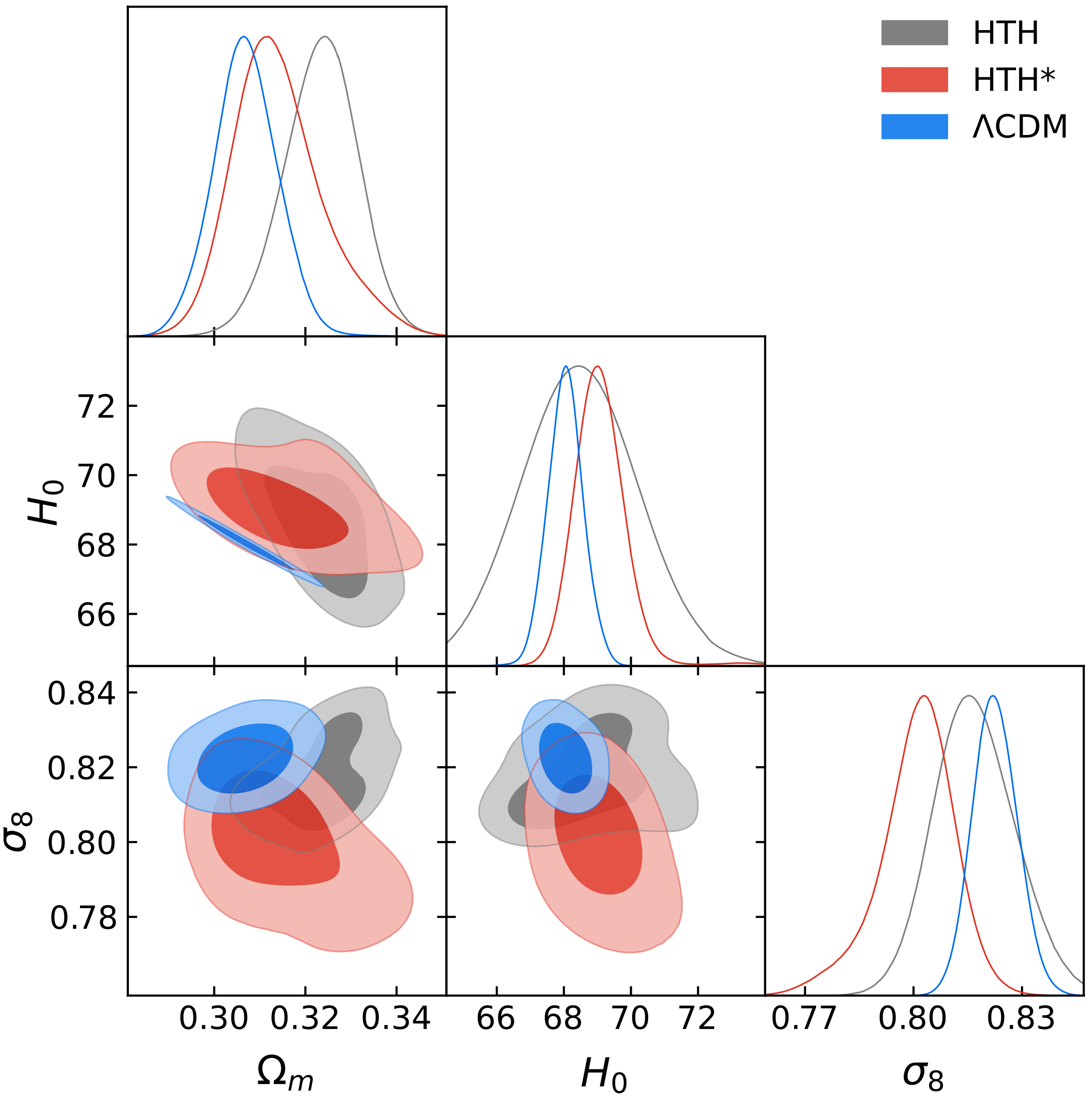

Figure 1: Likelihood contours for the ΛCDM (blue) and HTH (grey) models obtained using only the CMB dataset. The HTH contours are broader due to the additional free parameters. Compared to ΛCDM, the Hubble tension is reduced, and the σ_8 discrepancy is milder. The red contours labeled HTH* include both CMB and local H_0 measurements. In this case, lower H_0 values are excluded, and the σ_8 tension is effectively resolved.

Figure 3 summarizes the posterior mean values and 1-2σ uncertainties for the standard ΛCDM model and the HTH variants: HTH and HTH*. Compared to ΛCDM, the HTH models show small but significant shifts in Ω_b and $\Omega_{\rm cdm}$, reflecting the impact of the decaying dark matter sector. Similarly, $100\theta_s$ and n_s exhibit slight adjustments to accommodate the modified expansion history and perturbation evolution in HTH, while $\tau_{\rm reio}$ and $\ln 10^{10}A_s$ remain broadly consistent

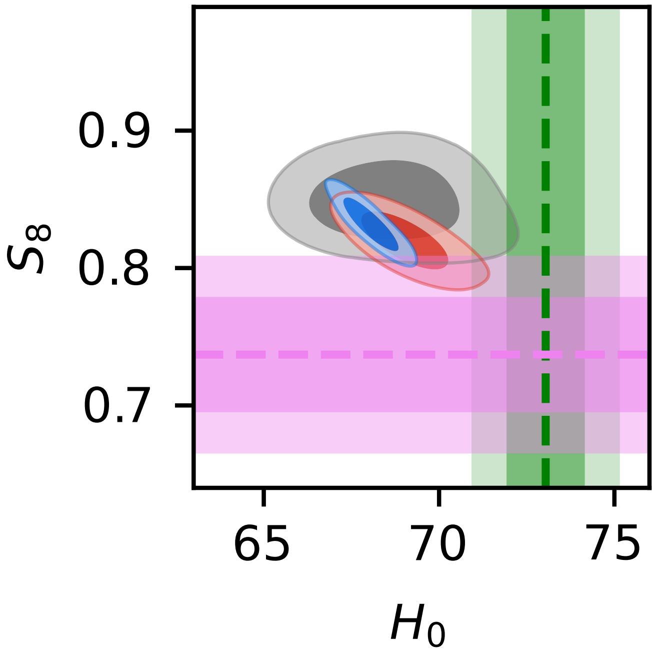

Figure 2: Preferred ranges of $S_8 = \sigma_8\sqrt{\Omega_m/0.3}$ and H_0 for the HTH and ΛCDM models using the Planck 2018 dataset. The HTH* contours include both Planck 2018 data and the local H_0 measurement (73.04 ± 1.04 km/s/Mpc) [37]. For comparison, the SH0ES measurement of H_0 (green) and the KV450 measurement of $S_8 = 0.737^{+0.040}_{-0.036}$ (violet) are also shown [38]. Grey, red, and blue contours correspond to HTH, HTH*, and ΛCDM, respectively.

with standard predictions. Overall, this comparison demonstrates that the HTH models remain fully compatible with current observational constraints, while providing a modest but meaningful reduction in the Hubble tension.

Furthermore, in Appendix A, we consider an extension of the HTH framework in which the twin sector is allowed to contain light leptons (HTH+$\Delta N_{\rm twin}$). This variation reintroduces relativistic degrees of freedom into the spectrum, thereby modifying the expansion history and contributing to $\Delta N_{\rm eff}$. We analyze this case to contrast its cosmological implications with those of the minimal HTH scenario and to illustrate how the presence of light twin states can alter the model's ability to address the H_0 and σ_8 tensions. In Table I, the mean values and the corresponding error bars for the parameters of ΛCDM, HTH, HTH* and HTH+$\Delta N_{\rm twin}$ are reported.

Table I: Cosmological parameters of the ΛCDM, HTH, and HTH+$\Delta N_{\rm twin}$ models inferred from the Planck 2018 dataset, and of the HTH* model inferred from both the Planck 2018 dataset and the local H_0 measurement. Quoted uncertainties represent the 68% (first) and 95% (second) credible intervals.

	ΛCDM	HTH	HTH*	HTH+ΔN_{twin}
$\boldsymbol{\Omega_{cdm}}$	$0.258 \pm 0.007 \pm 0.013$	$0.271 \pm 0.008 \pm 0.011$	$0.262^{+0.007+0.019}_{-0.010-0.016}$	$0.2634 \pm 0.007 \pm 0.012$
$\boldsymbol{\Omega_b}$	$0.04839 \pm 0.0006 \pm 0.0011$	$0.0514 \pm 0.0012 \pm 0.0022$	$0.0507^{+0.0005+0.0031}_{-0.001-0.002}$	$0.0478 \pm 0.0007 \pm 0.0014$
$\boldsymbol{100\theta_s}$	$1.0419 \pm 0.0003 \pm 0.0006$	$1.0439 \pm 0.0010 \pm 0.0022$	$1.0436^{+0.0005+0.0011}_{-0.0004-0.0011}$	$1.04238 \pm 0.0004 \pm 0.0008$
$\boldsymbol{ln(10^{10}A_s)}$	$3.042 \pm 0.014 \pm 0.029$	$3.044 \pm 0.019 \pm 0.036$	$3.030^{+0.028+0.046}_{-0.010-0.084}$	$3.0527 \pm 0.010 \pm 0.030$
$\boldsymbol{n_s}$	$0.966 \pm 0.0040 \pm 0.0082$	$0.9595^{+0.0059}_{-0.0066} \pm 0.012$	$0.957 \pm 0.007 \pm 0.016$	$0.9655 \pm 0.0039 \pm 0.0089$
$\boldsymbol{\tau_{reio}}$	$0.0537 \pm 0.0073 \pm 0.015$	$0.056 \pm 0.009 \pm 0.023$	$0.052^{+0.016+0.025}_{-0.005-0.047}$	$0.0535 \pm 0.0068 \pm 0.013$
$\boldsymbol{10^{-5}\Omega_{ddm}}$	-	$0.48 \pm 0.25 \pm 0.61$	$0.53^{+0.09+0.54}_{-0.24-0.44}$	$0.45 \pm 0.07 \pm 0.16$
$\boldsymbol{10^{+8}\gamma_{ddm}}$	-	$1.68 \pm 0.19 \pm 0.42$	$2.39^{+0.45+0.85}_{-0.39-0.91}$	$3.01 \pm 0.22 \pm 0.42$
$\boldsymbol{\Delta N_{twin}}$	-	-	-	$0.499 \pm 0.031 \pm 0.057$
$\boldsymbol{\Omega_m}$	$0.3067 \pm 0.0071 \pm 0.014$	$0.3236 \pm 0.0070 \pm 0.015$	$0.314^{+0.008+0.022}_{-0.011-0.018}$	$0.3124 \pm 0.0074 \pm 0.016$
$\boldsymbol{H_0}$	$68.1 \pm 0.5 \pm 1.1$	$68.3 \pm 1.0 \pm 2.6$	$69.12^{+0.60+1.49}_{-0.83-2.66}$	$71.3 \pm 0.6 \pm 1.4$
$\boldsymbol{\sigma_8}$	$0.8225 \pm 0.0062 \pm 0.012$	$0.8163 \pm 0.012 \pm 0.020$	$0.80 \pm 0.01 \pm 0.02$	$0.8240 \pm 0.0061 \pm 0.013$

IV. SUMMARY

In this work, we have explored the cosmological implications of the Hadrosymmetric Twin Higgs (HTH) model, a realization of the twin Higgs framework in which the twin sector contains hadronic states but no additional light degrees of freedom. In contrast to the Mirror Twin Higgs (MTH) model, where the discrete $\mathbb{Z}2$ symmetry enforces a full copy of the SM spectrum, the HTH scenario features a hard breaking of this symmetry. As a result, the twin sector is not a perfect replica of the SM but instead contains only a mirror copy of the SM hadrons. In particular, it includes all three generations of twin quarks while excluding light states such as twin photons and twin neutrinos. This structural difference makes the HTH model free from $\Delta N_{\rm eff}$ constraints and highly elusive to collider searches, but potentially relevant in cosmology.

To study the model's impact on cosmological observables, we implemented the HTH sector in the Boltzmann solver `CLASS` and performed a Monte Carlo Markov Chain analysis using `MONTEPYTHON-v3`, confronting the model with Planck 2018 CMB data and local measurements of the Hubble constant. Following a phenomenological approach, we modeled the twin-sector states as an effective decaying dark matter component, allowing for interactions that produce visible photons.

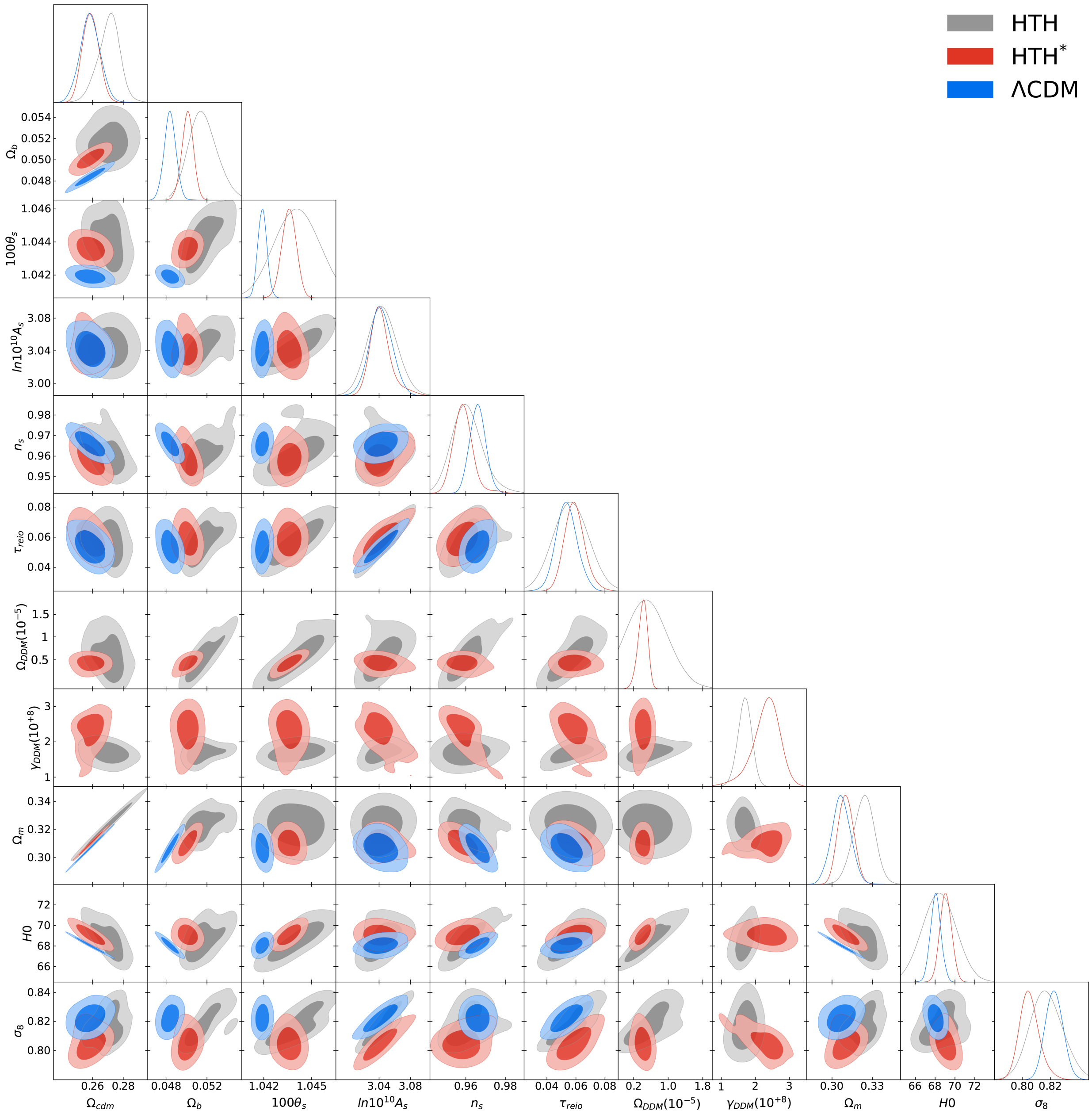

Figure 3: Posterior distributions for all free parameters of the ΛCDM (blue), HTH (grey), and HTH* (red) models.

Our results show that the HTH framework can significantly alleviate the persistent tensions in modern cosmology. In particular, the Hubble tension is reduced from over 4σ in ΛCDM to approximately 2.5σ, while the σ_8 discrepancy is simultaneously mitigated. Including the local measurement of H_0 further restricts the parameter space, leading to a scenario (HTH*) in which the tension in σ_8 is effectively removed.

These findings highlight that the HTH model, while primarily designed to address naturalness in particle physics, also offers a viable mechanism to reconcile current cosmological observations. This underscores the potential of connecting high-energy theoretical models with precision cosmology and motivates further studies of twin-sector phenomenology in both particle physics and cosmology.

Acknowledgments

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Appendix A: The HTH Model and Light Leptons

In this short appendix, we consider an extension of the HTH model in which ultra-relativistic species are included. Although such states are in principle possible within the HTH framework, they are against the original spirit of the model, where extra leptonic degrees of freedom are assumed to be non-propagating in order to satisfy the bound $\Delta N_{\rm eff} \simeq 0$. To obtain a cosmologically viable scenario with $\Delta N_{\rm eff} \neq 0$, a mechanism is required to ensure that these species freeze out before the onset of Big Bang nucleosynthesis. We analyze this extension, denoted HTH+$\Delta N_{\rm twin}$, and find that the results are encouraging. As illustrated in Fig. 4, the Hubble tension can be completely resolved in this setup. The underlying physics is straightforward: ultra-relativistic species modify the early-time cosmology by reducing the sound horizon at recombination, r_s, which is directly connected to the Hubble tension. In particular, the characteristic angular scale of the CMB, θ_s, which is tightly constrained by observations, depends on two physical distances: the comoving distance to the last-scattering surface (sensitive to H_0) and the sound horizon r_s at recombination. Since these are related approximately by $\theta_s \sim r_s H_0$, a reduction in r_s allows for a larger value of H_0 while keeping θ_s nearly unchanged. The Fig. 5 shows that the S_8 anomaly became less significant. The posteriors for all the parameters are shown in Fig. 6.

[1] Z. Chacko, H.-S. Goh, and R. Harnik, *The Twin Higgs: Natural electroweak breaking from mirror symmetry*, Phys. Rev. Lett. **96** (2006) 231802, [hep-ph/0506256].

[2] Z. Chacko, H.-S. Goh, and R. Harnik, *A Twin Higgs model from left-right symmetry*, JHEP **01** (2006) 108, [hep-ph/0512088].

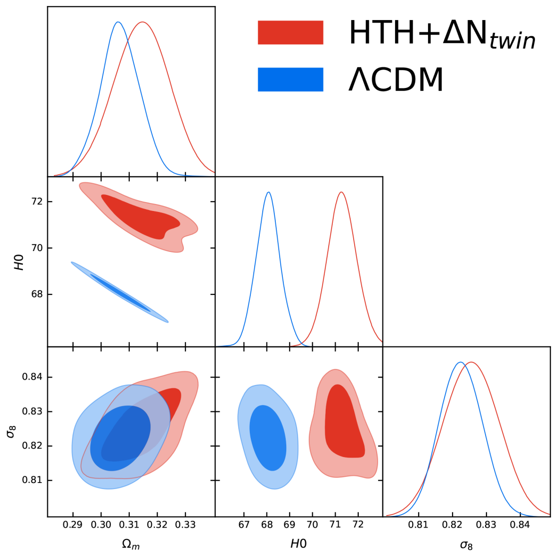

Figure 4: Likelihood distributions for the HTH+$\Delta N_{\rm twin}$ (red) model and ΛCDM (blue) scenario. The addition of ultra-relativistic species clearly alleviates the Hubble tension.

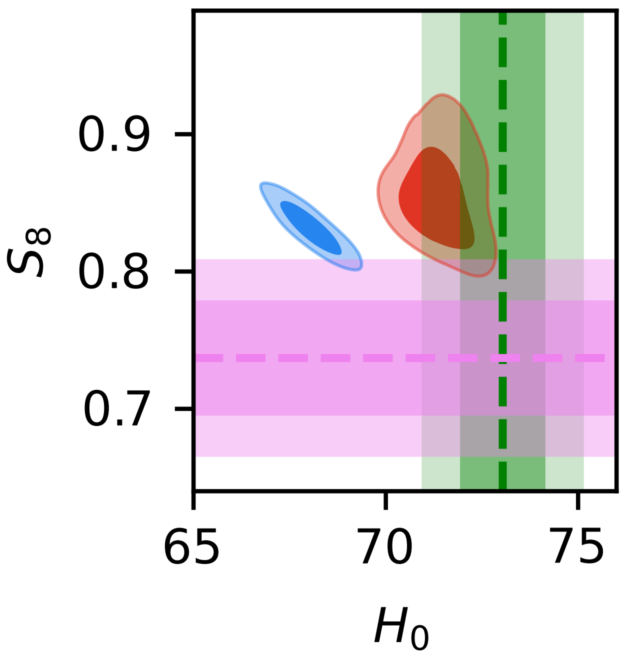

Figure 5: Preferred ranges of $S_8 = \sigma_8\sqrt{\Omega_m/0.3}$ and H_0 for the HTH+$\Delta N_{\rm twin}$ and ΛCDM models. Red and blue contours correspond to HTH+$\Delta N_{\rm twin}$ and ΛCDM, respectively.The local Hubble measurement ($H_0 = 73.04 \pm 1.04$ km/s/Mpc) and KV450 S_8 value are shown for reference [37, 38].

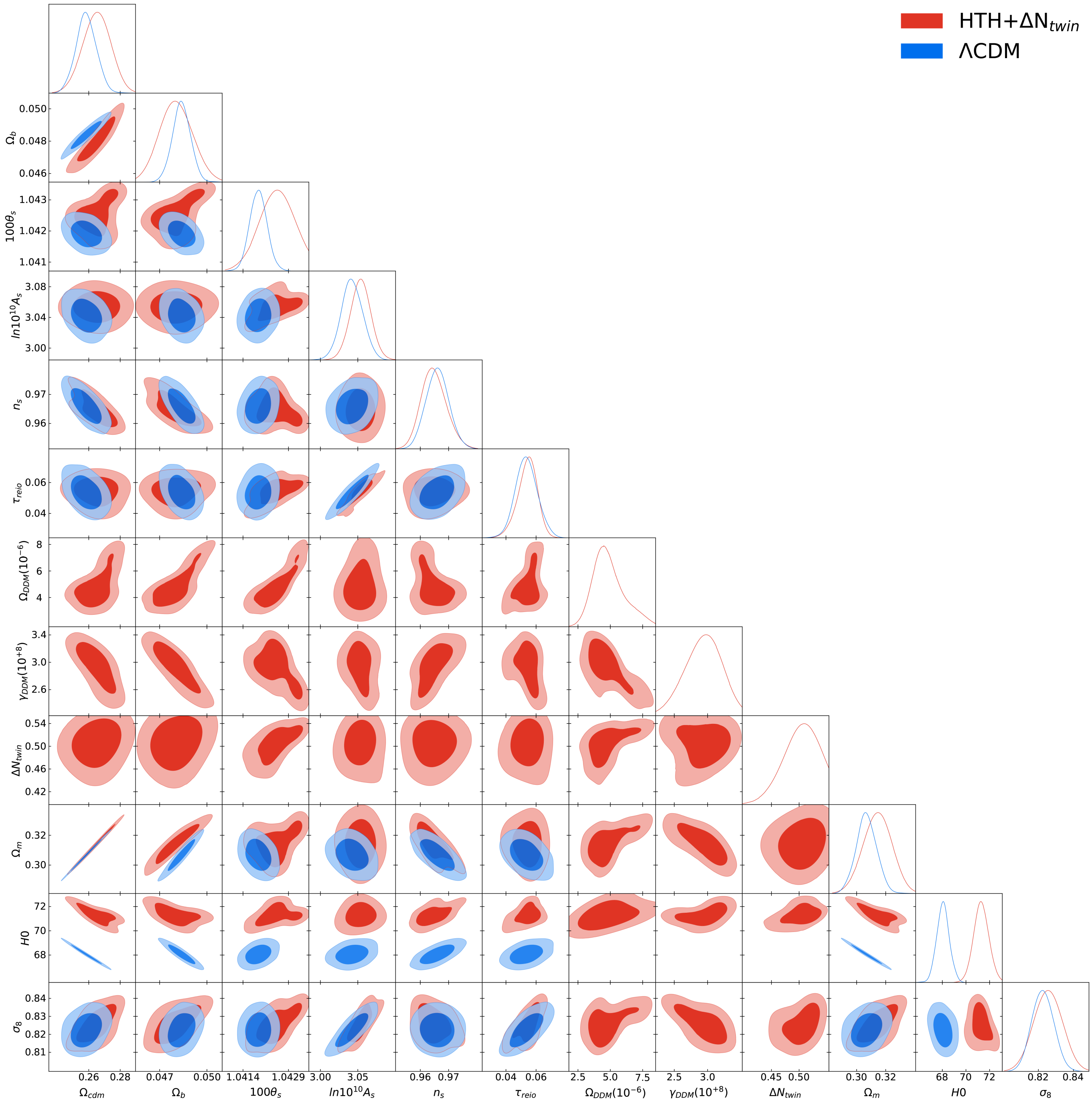

Figure 6: Posteriors for all free parameters of the ΛCDM and HTH+$\Delta N_{\rm twin}$ models, shown in blue and red, respectively.

[3] S. Chang, L. J. Hall, and N. Weiner, *A Supersymmetric twin Higgs*, Phys. Rev. D **75** (2007) 035009, [hep-ph/0604076].

[4] N. Craig and K. Howe, *Doubling down on naturalness with a supersymmetric twin Higgs*, JHEP **03** (2014) 140, [1312.1341].

[5] A. Falkowski, S. Pokorski, and M. Schmaltz, *Twin SUSY*, Phys. Rev. D **74** (2006) 035003, [hep-ph/0604066].

[6] P. Batra and Z. Chacko, *A Composite Twin Higgs Model*, Phys. Rev. D **79** (2009) 095012, [0811.0394].

[7] R. Barbieri, D. Greco, R. Rattazzi, and A. Wulzer, *The Composite Twin Higgs scenario*, JHEP **08** (2015) 161, [1501.07803].

[8] M. Low, A. Tesi, and L.-T. Wang, *Twin Higgs mechanism and a composite Higgs boson*, Phys. Rev. D **91** (2015) 095012, [1501.07890].

[9] G. Burdman, Z. Chacko, R. Harnik, L. de Lima, and C. B. Verhaaren, *Colorless Top Partners, a 125 GeV Higgs, and the Limits on Naturalness*, Phys. Rev. D **91** (2015), no. 5 055007, [1411.3310].

[10] N. Craig, S. Knapen, and P. Longhi, *The Orbifold Higgs*, JHEP **03** (2015) 106, [1411.7393].

[11] N. Craig, S. Knapen, and P. Longhi, *Neutral Naturalness from Orbifold Higgs Models*, Phys. Rev. Lett. **114** (2015), no. 6 061803, [1410.6808].

[12] N. Craig, A. Katz, M. Strassler, and R. Sundrum, *Naturalness in the Dark at the LHC*, JHEP **07** (2015) 105, [1501.05310].

[13] N. Craig, S. Knapen, P. Longhi, and M. Strassler, *The Vector-like Twin Higgs*, JHEP **07** (2016) 002, [1601.07181].

[14] M. Freytsis, S. Knapen, D. J. Robinson, and Y. Tsai, *Gamma-rays from Dark Showers with Twin Higgs Models*, JHEP **05** (2016) 018, [1601.07556].

[15] P. Schwaller, D. Stolarski, and A. Weiler, *Emerging Jets*, JHEP **05** (2015) 059, [1502.05409].

[16] T. Cohen, M. Lisanti, and H. K. Lou, *Semivisible Jets: Dark Matter Undercover at the LHC*, Phys. Rev. Lett. **115** (2015), no. 17 171804, [1503.00009].

[17] A. G. Riess et. al., *Large Magellanic Cloud Cepheid Standards Provide a 1% Foundation for the Determination of the Hubble Constant and Stronger Evidence for Physics Beyond ΛCDM*, Astrophys. J. **876** (2019), no. 1 85, [1903.07603].

[18] **Planck** Collaboration, N. Aghanim et. al., *Planck 2018 results. VI. Cosmological parameters*, Astron. Astrophys. **641** (2020) A6, [1807.06209].

[19] C. Heymans et. al., *KiDS-1000 Cosmology: Multi-probe weak gravitational lensing and spectroscopic galaxy clustering constraints*, Astron. Astrophys. **646** (2021) A140, [2007.15632].

[20] **DES** Collaboration, T. M. C. Abbott et. al., *Dark Energy Survey Year 3 Results: Cosmological Constraints from Galaxy Clustering and Weak Lensing*, Phys. Rev. D **105** (2022), no. 2 023520, [2105.13549].

[21] A. Banihashemi, N. Khosravi, and A. H. Shirazi, *Ginzburg-Landau Theory of Dark Energy: A Framework to Study Both Temporal and Spatial Cosmological Tensions Simultaneously*, Phys. Rev. D **99** (2019), no. 8 083509, [1810.11007].

[22] S. Vagnozzi, *Consistency tests of ΛCDM from the early integrated Sachs-Wolfe effect: Implications for early-time new physics and the Hubble tension*, Phys. Rev. D **104** (2021), no. 6 063524, [2105.10425].

[23] M. A. Buen-Abad, G. Marques-Tavares, and M. Schmaltz, *Non-Abelian dark matter and dark radiation*, Phys. Rev. D **92** (2015), no. 2 023531, [1505.03542].

[24] H. Bagherian, M. Joseph, M. Schmaltz, and E. N. Sivarajan, *Confronting interacting radiation models for the Hubble tension with Lyman-α data*, Phys. Rev. D **111** (2025), no. 4 043513, [2405.17554].

[25] Z. Davari and N. Khosravi, *Can decaying dark matter scenarios alleviate both H0 and σ8 tensions?*, Mon. Not. Roy. Astron. Soc. **516** (2022), no. 3 4373–4382, [2203.09439].

[26] P. Arabameri, Z. Davari, and N. Khosravi, *$k-$Dependent Dark Matter*, 2307.08495.

[27] A. Ashoorioon and Z. Davari, *Dark Matter Cosmology with Varying Viscosity: A Possible Resolution to the S_8 Tension*, Astrophys. J. **959** (2023), no. 2 120, [2303.06627].

[28] M. Kamionkowski and A. G. Riess, *The Hubble Tension and Early Dark Energy*, Ann. Rev. Nucl. Part. Sci. **73** (2023) 153–180, [2211.04492].

[29] V. Poulin, T. L. Smith, and T. Karwal, *The Ups and Downs of Early Dark Energy solutions to the Hubble tension: A review of models, hints and constraints circa 2023*, Phys. Dark Univ. **42** (2023) 101348, [2302.09032].

[30] K. Jedamzik and L. Pogosian, *Relieving the Hubble tension with primordial magnetic fields*, Phys. Rev. Lett. **125** (2020), no. 18 181302, [2004.09487].

[31] **CosmoVerse Network** Collaboration, E. Di Valentino et. al., *The CosmoVerse White Paper: Addressing observational tensions in cosmology with systematics and fundamental physics*, Phys. Dark Univ. **49** (2025) 101965, [2504.01669].

[32] S. Bansal, J. H. Kim, C. Kolda, M. Low, and Y. Tsai, *Mirror twin Higgs cosmology: constraints and a possible resolution to the H_0 and S_8 tensions*, JHEP **05** (2022) 050, [2110.04317].

[33] J. Lesgourgues and T. Tram, *The Cosmic Linear Anisotropy Solving System (CLASS) IV: efficient implementation of non-cold relics*, JCAP **09** (2011) 032, [1104.2935].

[34] B. Audren, J. Lesgourgues, K. Benabed, and S. Prunet, *Conservative Constraints on Early Cosmology: an illustration of the Monte Python cosmological parameter inference code*, JCAP **02** (2013) 001, [1210.7183].

[35] T. Brinckmann and J. Lesgourgues, *MontePython 3: boosted MCMC sampler and other features*, Phys. Dark Univ. **24** (2019) 100260, [1804.07261].

[36] **Planck** Collaboration, N. Aghanim et. al., *Planck 2018 results. VI. Cosmological parameters*, Astron. Astrophys. **641** (2020) A6, [1807.06209].

[37] A. G. Riess et. al., *A Comprehensive Measurement of the Local Value of the Hubble Constant with 1 km s$-$1 Mpc^{-1} Uncertainty from the Hubble Space Telescope and the SH0ES Team*, Astrophys. J. Lett. **934** (2022), no. 1 L7, [2112.04510].

[38] H. Hildebrandt et. al., *KiDS+VIKING-450: Cosmic shear tomography with optical and infrared data*, Astron. Astrophys. **633** (2020) A69, [1812.06076].