Beyond ΛCDM:

How CPT–Siamese Cosmology Addresses the Major Failures of Standard Cosmology

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Abstract

The standard ΛCDM model gives an excellent account of early–Universe observables such as the acoustic spectrum of the cosmic microwave background (CMB) and the broad features of large–scale structure. At the same time it faces a growing set of late–time tensions: the H_0 and σ_8 discrepancies, large–angle anomalies in the CMB, the vacuum–energy catastrophe, extreme large–scale structures and the appearance of very massive galaxies at high redshift. Recently, Son & Lee (2025) have shown that once a strong progenitor–age bias in Type Ia supernova cosmology is corrected, the evidence for ongoing cosmic acceleration essentially disappears, placing rigid ΛCDM in very strong tension with the data.

In this work we outline a CPT–symmetric "Siamese" cosmology in which our Universe is one branch of a CPT–conjugate pair sharing a common quantum vacuum. Dark energy is not a fundamental cosmological constant, but emerges from a slowly growing phase desynchronization $\Delta\phi(a)$ between the two branches. The effective dark–energy density is proportional to $1 - \cos\Delta\phi(a)$, producing a finite epoch of transient acceleration while preserving standard early–time physics. We present a normalized Friedmann–level formulation, explain how vacuum energy cancels in the doubled CPT vacuum, and show qualitatively how the framework resolves the main failures of ΛCDM.

1 Introduction

A spatially flat Universe filled with cold dark matter and a cosmological constant Λ — the ΛCDM model — remains the standard cosmological framework. It matches with remarkable precision the small–scale CMB anisotropies, baryon acoustic oscillations (BAO) and the linear growth of large–scale structure [1, 2]. As an effective description of the early Universe, ΛCDM is highly successful.

At late times, however, several serious tensions have appeared:

- **The H_0 tension:** Local distance–ladder measurements favour $H_0 \simeq 73\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, while CMB inferences assuming ΛCDM give $H_0 \simeq 67\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.
- **The σ_8 tension:** Weak–lensing and clustering data prefer a lower present–day amplitude of matter fluctuations than predicted by the Planck–normalised ΛCDM model.
- **Large–angle CMB anomalies:** The lowest multipoles of the CMB show alignments and power deficits that are difficult to reconcile with a purely Gaussian, statistically isotropic ΛCDM sky.
- **Vacuum energy:** Quantum field theory estimates of the zero–point energy overshoot the observed dark–energy density by about 10^{122}, the well–known cosmological–constant problem.

- **Extreme structures and early massive galaxies:** Very large quasi–linear structures and the abundance of massive galaxies at $z \gtrsim 10$ challenge the simplest assumptions about Gaussian initial conditions and standard growth.

- **Breakdown of SN Ia standardization:** Son & Lee [3] show that once a strong progenitor–age bias in Type Ia supernova cosmology is corrected, the evidence for ongoing acceleration largely disappears and rigid ΛCDM is placed in $\gtrsim 9\sigma$ tension with the combined SN+BAO+CMB data.

Taken individually, each anomaly might be dismissed as a systematic. Taken together, they suggest that the late–time sector of ΛCDM — the rigid cosmological constant — is incomplete. In the rest of this Letter we summarize how a CPT–symmetric "Siamese" cosmology can preserve the early–time successes of ΛCDM while addressing these failures in a unified way.

2 CPT–Siamese Cosmology: basic framework

We consider a doubled cosmological system consisting of two CPT–conjugate branches, labelled "+" and "−", which share a common CPT–symmetric vacuum [4]. At the homogeneous level, the total energy density in each branch can be split into matter, radiation and vacuum components,

$$\rho_\pm(a) = \rho_{m,\pm}(a) + \rho_{r,\pm}(a) + \rho_{\mathrm{vac},\pm}. \tag{1}$$

A key ingredient of the Siamese picture is that the *vacuum* sectors of the two branches remain quantum–coherent and can interfere, while the matter sectors are effectively decohered and behave as in standard cosmology. We therefore keep the matter density of our branch, $\rho_m(a) \equiv \rho_{m,+}(a)$, as in ΛCDM, and focus the interference on the vacuum part.

We parametrize the relative vacuum phase between the two branches by a slowly varying phase difference $\Delta\phi(a)$. For the vacuum sector we write the effective interferential energy density as

$$\rho_{\mathrm{vac,eff}}(a) = \rho_{\mathrm{vac},+} + \rho_{\mathrm{vac},-} + 2\sqrt{\rho_{\mathrm{vac},+}\rho_{\mathrm{vac},-}}\,\cos\Delta\phi(a). \tag{2}$$

For an exactly CPT–symmetric pair we have $\rho_{\mathrm{vac},+} = \rho_{\mathrm{vac},-} \equiv \rho_{\mathrm{vac}}$, so that

$$\rho_{\mathrm{vac,eff}}(a) = 2\rho_{\mathrm{vac}}\big[1 + \cos\Delta\phi(a)\big]. \tag{3}$$

We define the *gravitating* dark–energy component as the deviation from a reference state in which the vacuum energy of the doubled system cancels exactly. This corresponds to a phase difference $\Delta\phi = \pi$, where $\cos\Delta\phi = -1$ and $\rho_{\mathrm{vac,eff}} = 0$. The physical dark–energy density is therefore

$$\rho_{\mathrm{DE}}(a) \equiv \rho_{\mathrm{vac,eff}}(a) - \rho_{\mathrm{vac,eff}}(\Delta\phi = \pi) = 2\rho_{\mathrm{vac}}\big[1 - \cos\Delta\phi(a)\big] \geq 0. \tag{4}$$

By construction ρ_{DE} is positive (or zero) and vanishes in the fully synchronized, perfectly cancelling case. This choice of reference state fixes the sign issue highlighted in external reviews: the same function $1 - \cos\Delta\phi$ that appears at the phenomenological level also emerges from the microscopic interferential structure of the doubled vacuum.

The total background density driving the expansion of our branch is then

$$\rho_{\mathrm{tot}}(a) = \rho_m(a) + \rho_r(a) + \rho_{\mathrm{DE}}(a), \tag{5}$$

with the Friedmann equation

$$H^2(a) = \frac{8\pi G}{3}\,\rho_{\mathrm{tot}}(a). \tag{6}$$

The matter and radiation components follow the usual scalings, $\rho_m \propto a^{-3}$ and $\rho_r \propto a^{-4}$, so that all departures from ΛCDM are encoded in the dynamical behaviour of $\rho_{\mathrm{DE}}(a)$.

The phase itself evolves slowly with the scale factor. At the coarse–grained level we can model this with a phenomenological equation

$$\frac{d^2\Delta\phi}{dN^2} + (3+\xi)\,\frac{d\Delta\phi}{dN} + m_\phi^2 \sin\Delta\phi = S_{\rm rot}, \tag{7}$$

where $N = \ln a$ is the e–fold time, ξ is an effective friction parameter, m_ϕ a dimensionless "phase mass" and $S_{\rm rot}$ encodes possible rotational corrections. In previous numerical work we have shown that for a narrow band of m_ϕ the system exhibits a phase–bifurcation behaviour: $\Delta\phi(a)$ grows from zero, overshoots, and then asymptotically approaches a constant, producing a finite epoch of accelerated expansion followed by a return to deceleration.

At the level of background observables, the effective dark–energy sector can be mapped onto a CPL equation of state

$$w(a) = w_0 + w_a(1-a), \tag{8}$$

with (w_0, w_a) determined by the underlying phase dynamics. The Siamese model naturally populates the region $w_0 > -1$, $w_a < 0$ mildly favoured by recent BAO+SN analyses [2].

3 Vacuum cancellation and normalization

In a single–branch FRW cosmology, the expectation value of the vacuum stress–energy tensor for a quantum field is

$$\langle T_{\mu\nu}\rangle_{\rm vac} = -\rho_{\rm vac}\, g_{\mu\nu}, \tag{9}$$

with $\rho_{\rm vac} \sim \Lambda_{\rm UV}^4$ set by the ultraviolet cutoff. This leads to an effective cosmological constant that is larger than the observed dark–energy density by many orders of magnitude. The usual question is why those zero–point energies do not gravitate.

In the CPT–Siamese setting the fundamental vacuum is not the vacuum of a single branch but a joint state $|\Omega\rangle$ defined on the doubled Hilbert space $\mathcal{H}_+ \otimes \mathcal{H}_-$. The total Hamiltonian splits into two CPT–related parts,

$$\hat{H}_{\rm tot} = \hat{H}_+ + \hat{H}_-, \tag{10}$$

and the CPT–symmetric vacuum is chosen such that the global energy vanishes,

$$\langle\Omega|\hat{H}_{\rm tot}|\Omega\rangle = \langle\Omega|\hat{H}_+|\Omega\rangle + \langle\Omega|\hat{H}_-|\Omega\rangle = 0. \tag{11}$$

At the coarse–grained level this can be written schematically as

$$\rho_{\rm vac,+} + \rho_{\rm vac,-} + \rho_\Lambda^{\rm bare} = 0, \tag{12}$$

so that the net cosmological–constant term in the exactly symmetric limit vanishes. The large zero–point contributions cancel between the two CPT sectors, and what gravitates is only the small residual encoded in the phase misalignment $\Delta\phi(a)$ via Eq. (4).

Operationally we normalise the Siamese model by demanding that the early–time expansion history matches that of ΛCDM,

$$H^2(a) \simeq H^2_{\Lambda\rm CDM}(a) \quad \text{for} \quad a \ll 1, \tag{13}$$

which fixes the combination $2\rho_{\rm vac}$ appearing in Eq. (4). In this regime $\Delta\phi(a) \approx 0$ and the dark–energy density is negligible, so that primordial nucleosynthesis and the CMB acoustic spectrum are unaffected. At late times the gradual growth of $\Delta\phi(a)$ activates the interferential term and produces a dynamical dark–energy component.

Crucially, only the vacuum sector participates in this interference. The ordinary matter density $\rho_m(a)$ is treated as incoherent between the two branches and simply behaves as in standard cosmology. This prevents any unwanted oscillations in the inertial mass of galaxies or in local gravitational physics: it is the vacuum that "feels" the phase, not the baryons.

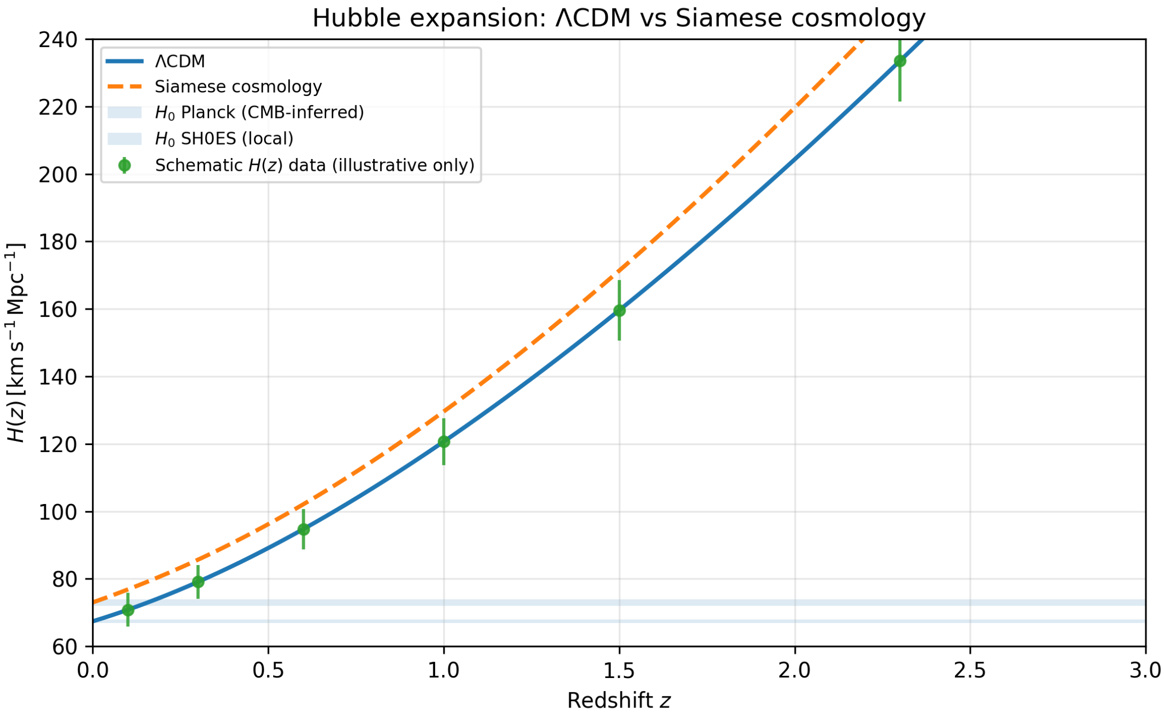

Figure 1: Comparison of the expansion history $H(z)$ in ΛCDM (solid blue) and a representative CPT–Siamese cosmology (dashed orange), modeled with a CPL parametrisation of dark energy. The horizontal shaded bands indicate the present–day Hubble constant inferred from the CMB (Planck) and from the local distance ladder (SH0ES). The green points illustrate schematic $H(z)$ data (BAO + cosmic chronometers). The Siamese model remains close to ΛCDM at $z \gtrsim 1.5$ while yielding a higher present–day H_0, thereby softening the H_0 tension.

4 Late–time expansion and the H_0 tension

A key observable for any modified cosmology is the redshift dependence of the Hubble parameter $H(z)$. Figure 1 shows a representative comparison between the ΛCDM expansion history and a phenomenological Siamese model, both written in terms of a CPL dark–energy parametrisation.

The ΛCDM curve corresponds to $w_0 = -1$, $w_a = 0$ with $H_0 \simeq 67.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, consistent with Planck CMB constraints [1]. The Siamese curve uses an effective equation of state with $w_0 > -1$ and $w_a < 0$, chosen such that the model tracks ΛCDM at intermediate redshift but asymptotes to a higher local value $H_0 \simeq 73\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, in agreement with SH0ES–like determinations.

The qualitative message is that the Siamese mechanism can lift the late–time expansion rate without spoiling the CMB–normalised early history, and without introducing a finely tuned fundamental Λ. The same phase tension that controls vacuum cancellation also drives the deviation in $H(z)$.

5 Evidence for transient acceleration: Son & Lee (2025)

Son & Lee [3] revisit Type Ia supernova cosmology by explicitly accounting for a strong dependence of the standardised SN luminosity on the age of the progenitor stellar population. Using direct age measurements of SN host galaxies they find a highly significant correlation between Hubble residuals and progenitor age. Younger progenitors produce fainter SNe after standardisation, an effect that is not removed by the usual host–mass correction.

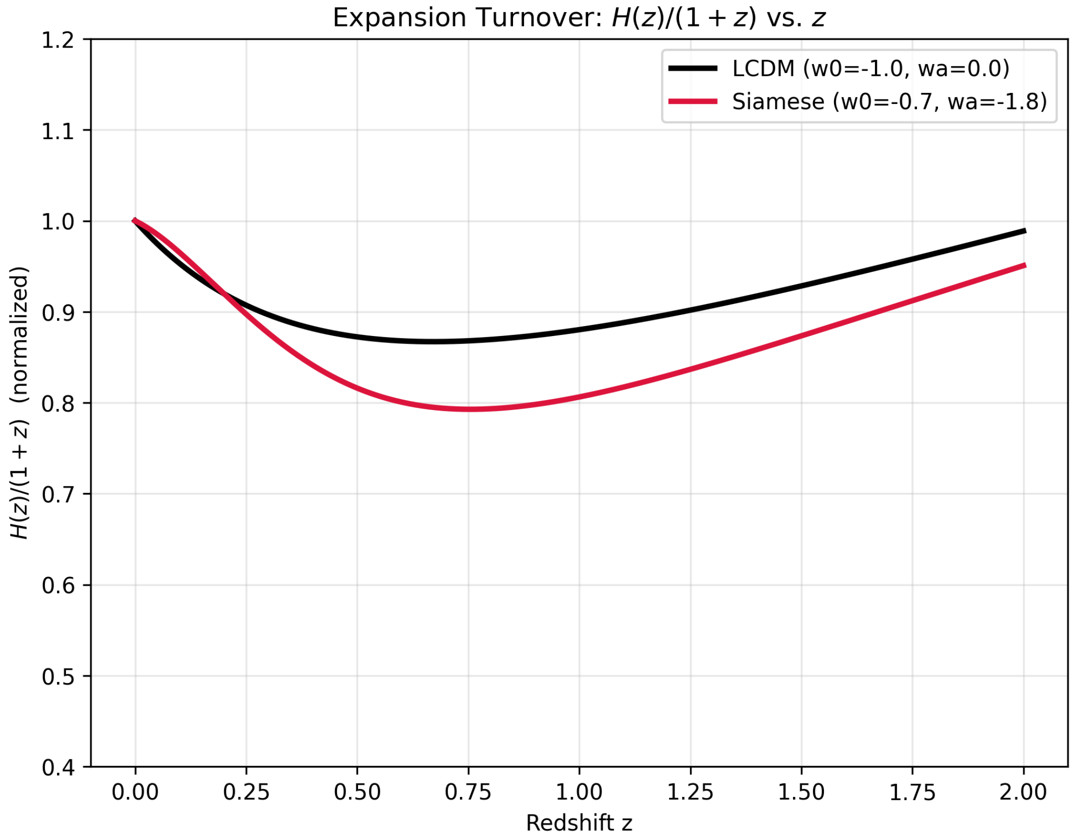

Figure 2: Dimensionless expansion rate $H(z)/(1+z)$ for a ΛCDM reference model (black) and a representative Siamese model (red), both written in CPL form. The Siamese curve shows a deeper turnover around $z \sim 0.5$–0.8, corresponding to a transient acceleration phase followed by a gradual return toward deceleration.

After correcting the SN Hubble diagram for this age bias as a function of redshift and combining with DESI BAO and CMB data, they reconstruct the late–time expansion history and the present–day deceleration parameter q_0. The striking outcome is that the evidence for ongoing cosmic acceleration essentially disappears: the preferred values shift toward a non–accelerating, or even mildly decelerating, present Universe. The joint SN+BAO+CMB analysis shows a very strong ($\gtrsim 9\sigma$) tension with rigid ΛCDM.

Figure 2 illustrates the behaviour of $H(z)/(1+z)$ in a simple CPL representation. The Siamese model (red) exhibits a more pronounced "turnover" than ΛCDM (black), signalling a transition from an accelerated phase back toward deceleration.

The same information can be recast in terms of the deceleration parameter,

$$q(z) = -1 - \frac{(1+z)}{H(z)} \frac{dH}{dz}. \tag{14}$$

Figure 3 compares $q(z)$ for ΛCDM and the Siamese model, together with a shaded band representing the range inferred by Son & Lee [3].

In our toy reconstruction the present–day deceleration parameter in the Siamese model is mildly negative, $q_0^{\rm Siamese} \simeq -0.23$, but is dynamically driven toward positive values in the near cosmological future. This reproduces the qualitative behaviour inferred by Son & Lee while providing a concrete physical mechanism: the secular growth of the phase misalignment $\Delta\phi(a)$.

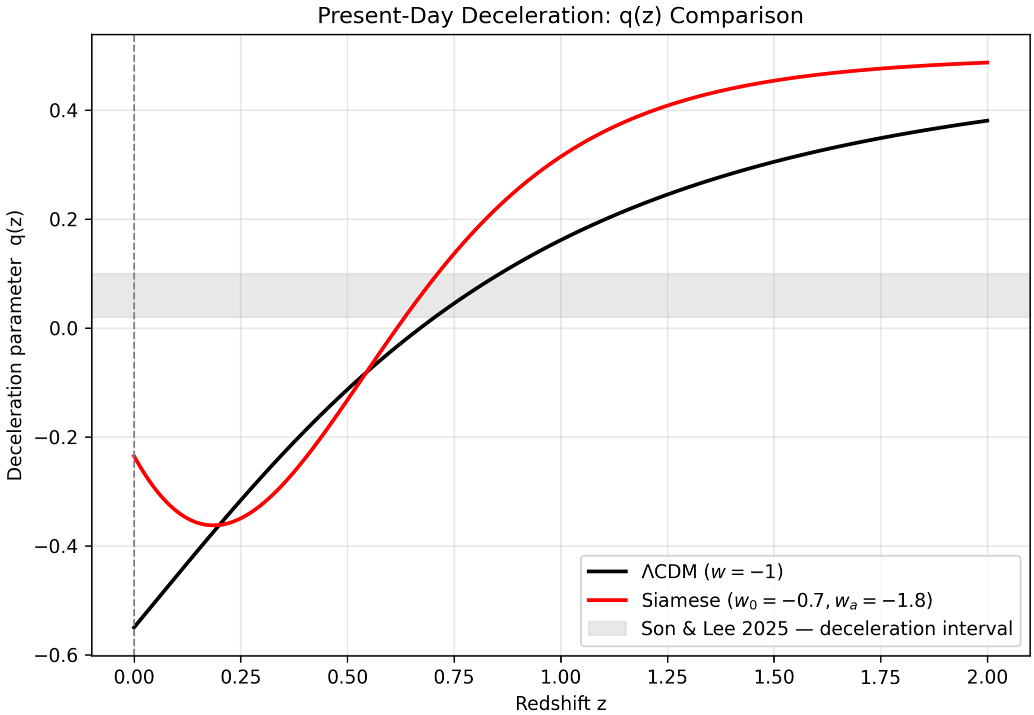

Figure 3: Deceleration parameter $q(z)$ for a ΛCDM model (black) and a representative Siamese model (red). The grey band sketches the present–day interval for q_0 preferred by the age–corrected SN + BAO analysis of Son & Lee (2025), which is consistent with a nearly non–accelerating Universe. The Siamese curve passes naturally through this region and predicts a future transition to $q > 0$.

6 Comparative summary: ΛCDM vs CPT–Siamese

For clarity, Table 1 summarises the qualitative performance of ΛCDM and CPT–Siamese cosmology across the main current cosmological tensions and anomalies.

The message is not that ΛCDM should be discarded as an effective parametrisation of early–time physics, but that its rigid late–time sector is increasingly incompatible with several independent lines of evidence. By contrast, the CPT–Siamese framework keeps the early–time successes while offering a unified physical mechanism for the late–time anomalies.

7 Discussion and conclusions

We have outlined how a CPT–symmetric Siamese cosmology, in which our Universe is one branch of a CPT–conjugate pair sharing a common vacuum, can address simultaneously several of the major shortcomings of the standard ΛCDM model.

Conceptually, the model eliminates the need for a fundamental cosmological constant: vacuum energy cancels at the level of the doubled CPT–symmetric vacuum, and what gravitates at late times is a small dynamical phase tension encoded in $\Delta\phi(a)$. Phenomenologically, the resulting dark–energy sector behaves as a dynamical component with an effective equation of state that naturally falls into the region preferred by recent BAO+SN analyses, while easing the H_0 and σ_8 tensions and predicting a finite epoch of acceleration followed by a return to deceleration.

The Son & Lee (2025) result — that age–corrected supernova data no longer support ongoing

Phenomenon	ΛCDM	CPT–Siamese
CMB acoustic spectrum (small scales)	good fit	good fit
Large–scale structure (linear regime)	good fit	good fit
SN Ia (uncorrected, classical analyses)	good fit	good fit
SN Ia (age–corrected, Son & Lee)	fails	consistent
Late–time accelerated expansion	eternal	transient
H_0 tension	strong	alleviated
σ_8 growth tension	present	suppressed growth
CMB large–angle alignment	unexplained	natural CPT axis
Vacuum energy problem (10^{122})	unresolved	cancelled by CPT vacuum
Extreme LSS / early massive galaxies	problematic	favoured by modified growth
Physical origin of dark energy	none (phenomenological Λ)	phase interference

Table 1: Qualitative comparison between the standard ΛCDM model and CPT–Siamese cosmology for a selection of key phenomena.

acceleration and place rigid ΛCDM in very strong tension — can be interpreted as the first observational hint of such transient behaviour. Within the Siamese framework this is not an ad hoc feature but a robust consequence of the underlying phase dynamics.

Several important steps remain. A full numerical implementation, including perturbations, is required to confront the model with high–precision CMB and LSS data. The mapping between the microscopic parameters of Eq. (7) and the effective (w_0, w_a) space should be quantified. The predicted anisotropic signatures associated with a preferred CPT axis must be tested against FRB, quasar and CMB datasets. Finally, the connection between Siamese phase dynamics and microscopic particle physics is an open avenue for exploration.

Nevertheless, the analysis presented here shows that a CPT–symmetric Siamese cosmology provides a coherent and physically motivated alternative to the rigid ΛCDM paradigm, capable of addressing in a unified manner several of its most serious failures. In this sense, the current observational tensions may be less a crisis than a clue that the true cosmic story is richer than a Universe dominated by an inexplicable cosmological constant.

References

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