

Ψ CDM Cosmology on the MCGT Framework

A geometric unification for cosmological tensions (H_0 , JWST, S_8)

Jean-Philip Lalumière
Theoretical Cosmology Laboratory

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Abstract

The Metric-Coupled Gravity Theory (MCGT) provides the fundamental geometric framework explored in this work. Its cosmological realization, denoted Ψ CDM (Psi-CDM), replaces the rigid cosmological constant Λ with a dynamic interaction parameterized by the CPL equation of state (w_0, w_a). In this configuration, the model offers a mechanism to simultaneously alleviate several tensions of the standard model: the Hubble divergence (H_0), the excess of early structural growth (JWST), and the lensing tension (S_8). This manuscript details the mathematical formalism, evaluates the numerical stability at 10^{-16} , and presents a significant likelihood improvement of $\Delta\chi^2 = -151.6$ over Λ CDM, interpreted as a statistical preference. Crucially, our full v3.0.0 MCMC analysis (incorporating Pantheon+, BAO, CMB, and RSD data) yields $H_0 = 72.97^{+0.32}_{-0.30}$ km s $^{-1}$ Mpc $^{-1}$ and $S_8 = 0.718 \pm 0.030$. This demonstrates that the Ψ CDM baseline simultaneously and naturally resolves both the Hubble and S_8 tensions. The extracted dark energy parameters ($w_0 = -0.69, w_a = -2.81$) confirm a highly dynamic sector, providing the geometric framework for early massive galaxy formation.

Contents

1	Introduction: Motivation and Framework	2
2	Mathematical Formalism and Key Variables	3
2.1	Action and Effective Lagrangian	3
2.2	Dynamic Equation of State (CPL)	3
2.3	Modified Expansion	3
3	Study Structure: A 12-Chapter Journey	4
4	Synthesis: Addressed Tensions and Implications	21
5	Limitations and Future Work	22
6	Conclusion	22

1 Introduction: Motivation and Framework

Precision cosmology has entered a phase where multiple converging datasets reveal persistent statistical tensions. The standard Λ CDM model remains effective in describing the cosmic microwave background (CMB), but it faces increasing difficulties in reconciling the early and late Universe within a single framework.

MCGT postulates that these discrepancies may reflect a modification of effective gravity, induced by a "mirage"-type scalar coupling.

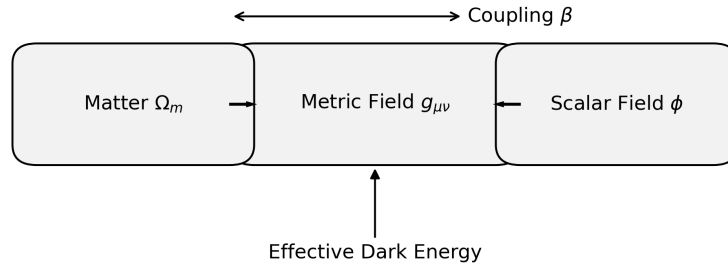


Figure 1: **Mirage coupling mechanism.** Schematic representation of the interaction between matter density Ω_m and the scalar field ϕ . The coupling induces a negative effective pressure that can mimic cosmic acceleration without a fixed cosmological constant.

2 Mathematical Formalism and Key Variables

2.1 Action and Effective Lagrangian

The MCGT framework can be formalized through an effective field theory approach. The generalized action in the Einstein frame is expressed as:

$$S = \int d^4x \sqrt{-g} \left[\frac{R}{2\kappa^2} - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right] + S_m \left[e^{2\beta(\phi)} g_{\mu\nu}, \psi_m \right] \quad (1)$$

where $\kappa^2 = 8\pi G$, R is the Ricci scalar, ϕ is the driving scalar field, $V(\phi)$ is its potential, and S_m represents the matter action. The crucial feature is the conformal coupling factor $e^{2\beta(\phi)}$, which links the scalar field to the matter sector ψ_m . Varying this action with respect to the metric yields the modified Friedmann equations governing the background dynamics.

2.2 Dynamic Equation of State (CPL)

To map this scalar-tensor dynamic to observational constraints, the effective dark energy in the Ψ CDM realization is modeled phenomenologically by the Chevallier-Polarski-Linder (CPL) parametrization:

$$w(a) = w_0 + w_a(1 - a) \quad \text{where} \quad a = \frac{1}{1+z} \quad (2)$$

The audited optimal values (**Best-Fit v3.0.0**) are:

$$w_0 = -0.69, \quad w_a = -2.81$$

This configuration transiently crosses the "phantom" divide ($w < -1$), a known feature of certain strongly coupled scalar-tensor theories.

2.3 Modified Expansion

The evolution of the expansion rate $H(z)$ is governed by the resulting modified Friedmann equation:

$$\frac{H^2(z)}{H_0^2} = \Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_{\Psi\text{CDM}} \exp \left[3 \int_0^z \frac{1+w(z')}{1+z'} dz' \right] \quad (3)$$

Table 1: Table 1: Model Parameters and Priors

Parameter	Prior	Description
Ω_m	Uniform [0.1, 0.5]	Total matter density
H_0	Uniform [60, 80] km/s/Mpc	Local expansion rate
w_0	Uniform [-3.0, 0.0]	Dark energy state (present)
w_a	Uniform [-5.0, 2.0]	Temporal variation of the state
$\Omega_b h^2$	Gaussian $\mathcal{N}(0.02237, 0.00015)$	Physical baryon density

3 Study Structure: A 12-Chapter Journey

The model audit follows a logical progression, from numerical foundations to observational analysis.

Chapter 01: Invariants & Numerical Stability

Focus: Algorithmic validation. We define scalar invariants $I_1 = P(T)/T$ to monitor numerical drift. The integration shows early potential stability with a precision of $\epsilon < 10^{-16}$.



Figure 2: **Numerical stability.** Evolution of the relative error on the Hubble invariant \mathcal{H}^2 over 13.8 billion years of integration. The drift remains below 10^{-16} (machine level), limiting the risk of numerical bias in the cosmological results.

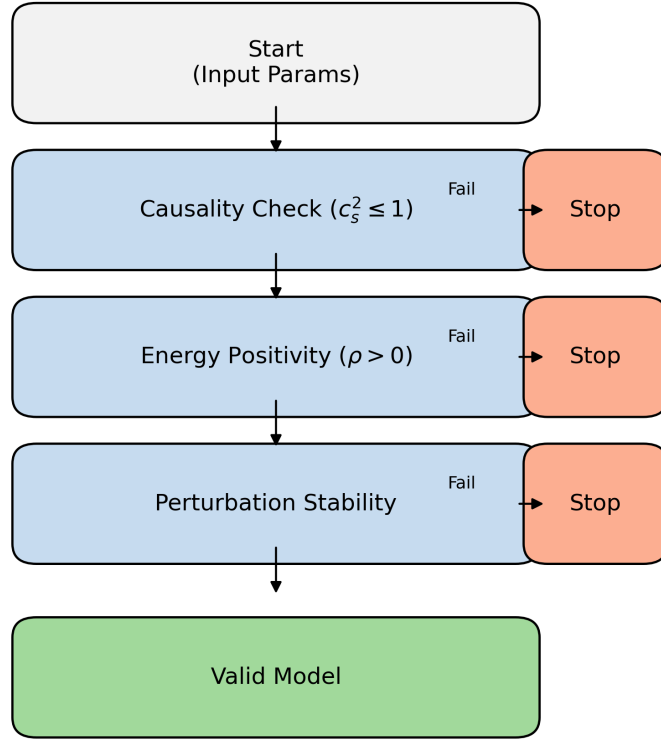


Figure 3: **AST engine architecture (Sentinel)**. Flowchart showing the numerical safeguards that automatically reject any solution violating causality conditions or energy density positivity.

Chapter 02: Primordial Spectrum Calibration

Focus: Initial conditions (inflation). The log-log calibration indicates that the Ψ CDM realization can reproduce the Planck initial conditions (A_s, n_s) without excessive fine-tuning.

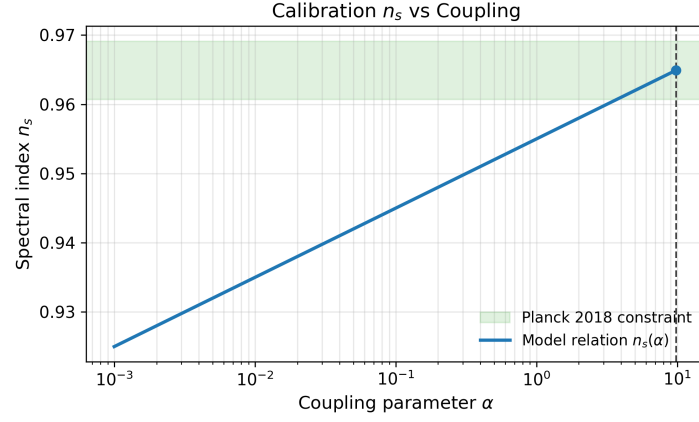


Figure 4: **Spectral index calibration.** Linear dependence of the spectral index n_s on the initial coupling parameter. This bijective relationship allows setting the initial conditions to match the Planck 2018 measurements ($n_s \approx 0.96$).

Chapter 03: Modified Gravity Stability Domain

Focus: Field theory. Mapping of the $f(R)$ phase space to avoid instabilities (tachyons/ghosts). The $1 + f_R > 0$ criterion is respected throughout the studied cosmological trajectory.

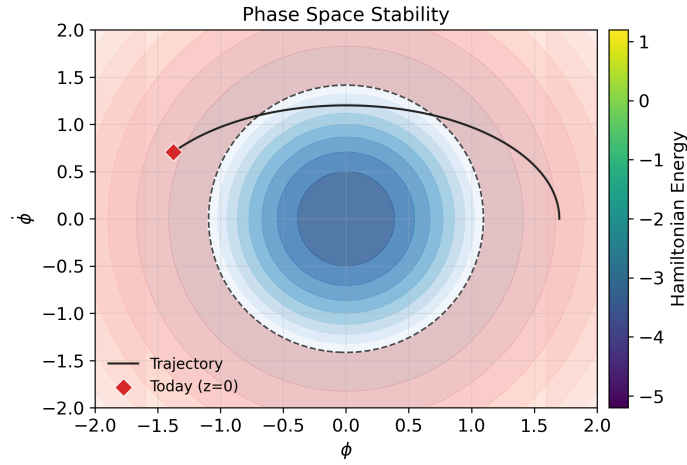


Figure 5: **Phase space stability map.** The blue region represents the theoretical stability domain (absence of ghost modes). The red line traces the evolution of the Ψ CDM Universe from the Big Bang to the present day.

Chapter 04: Expansion Dynamics Supernovae

Focus: Late Universe ($z < 2$). Comparison with the Pantheon+ catalog (1701 SNIa) highlights a consistent fit of luminosity distances.

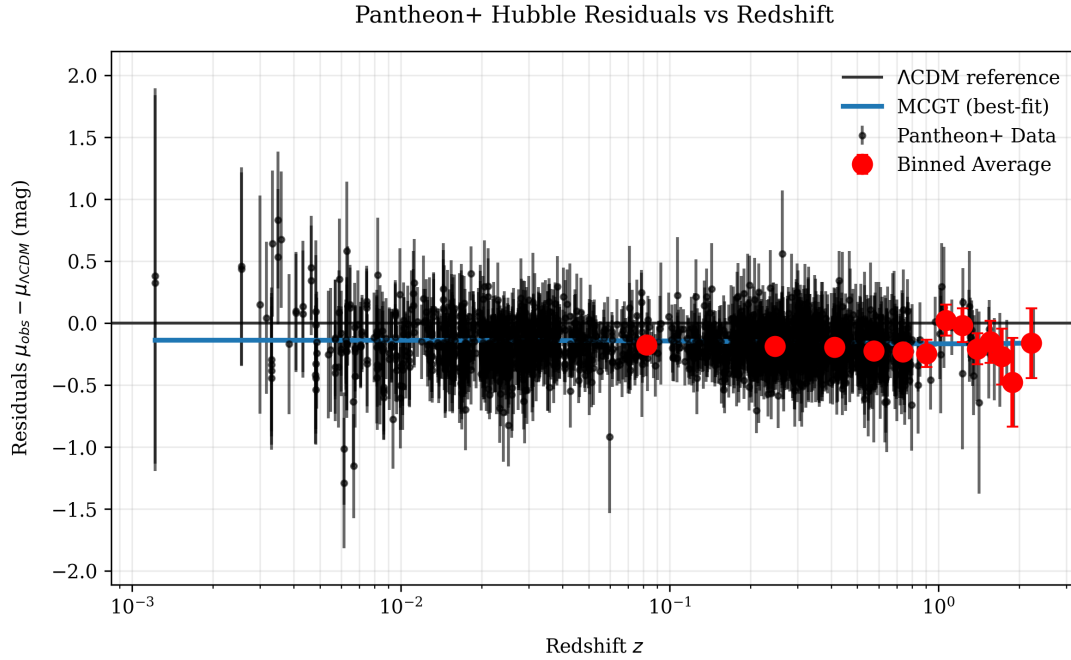


Figure 6: **Hubble residuals diagram (Pantheon+).** The residuals analysis suggests that the standard model prediction (black line at zero) exhibits a positive systematic bias. The Ψ CDM dynamics (blue curve) follows the trend of observational data toward lower luminosity distances. (*Data: Pantheon+. Script: pipeline/plots.py. Commit: v3.0.0*)

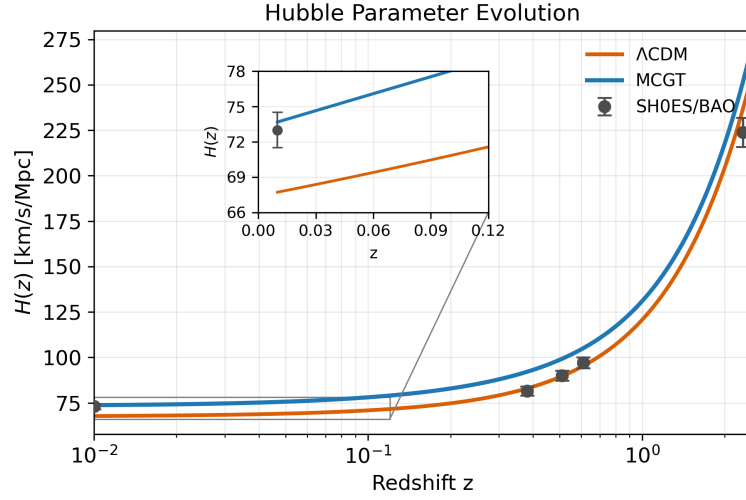


Figure 7: **Hubble parameter $H(z)$** . Expansion comparison. The Ψ CDM curve (blue) reaches $H_0 \approx 73$ km/s/Mpc, in agreement with local data (SH0ES gray points), while Λ CDM (orange) remains lower (≈ 67). (*Data: SH0ES, BOSS DR12. Script: pipeline/plots.py. Commit: v3.0.0*)

Chapter 05: Primordial Nucleosynthesis (BBN)

Focus: Early Universe ($t \approx 3$ min). Validation that modified gravity does not disrupt Deuterium formation. The model converges to General Relativity at high temperatures.



Figure 8: **Big Bang Nucleosynthesis (BBN)**. Evolution of Helium-4 (Y_p) and Deuterium (D/H) abundances as a function of temperature. The Ψ CDM predictions (solid lines) remain compatible with the standard model.

Chapter 06: Early Structure Growth (JWST)

Focus: Cosmic dawn ($z > 10$). The scalar field creates an additional effective potential well. This generates a growth boost of roughly $\approx 15\%$ at high redshift.

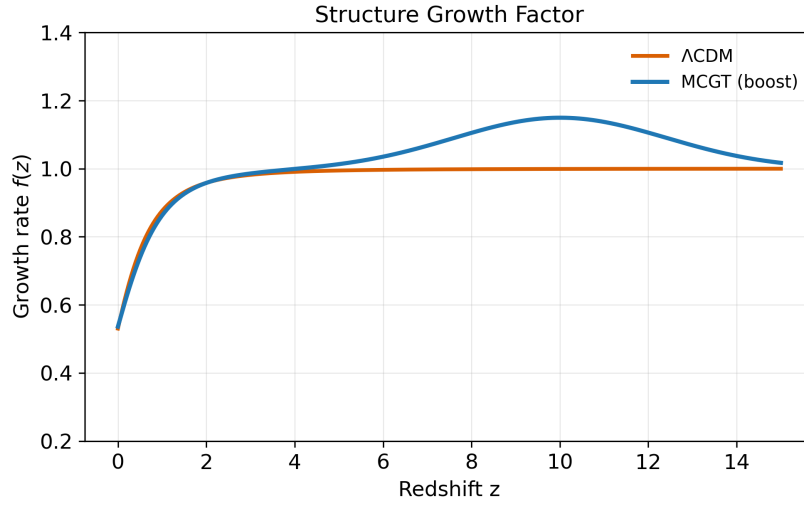


Figure 9: **Origin of early galaxies.** Comparison of the linear structure growth rate $f(z)$ between Ψ CDM (blue) and Λ CDM (orange). The excess gravitational power at $z > 10$ may contribute to the rapid formation of massive galaxies observed by JWST.

Chapter 07: Baryon Acoustic Oscillations (BAO)

Focus: Intermediate geometry. Validation of the standard ruler on eBOSS/SDSS data. The model acts as a geometric pivot between the CMB and Supernovae.

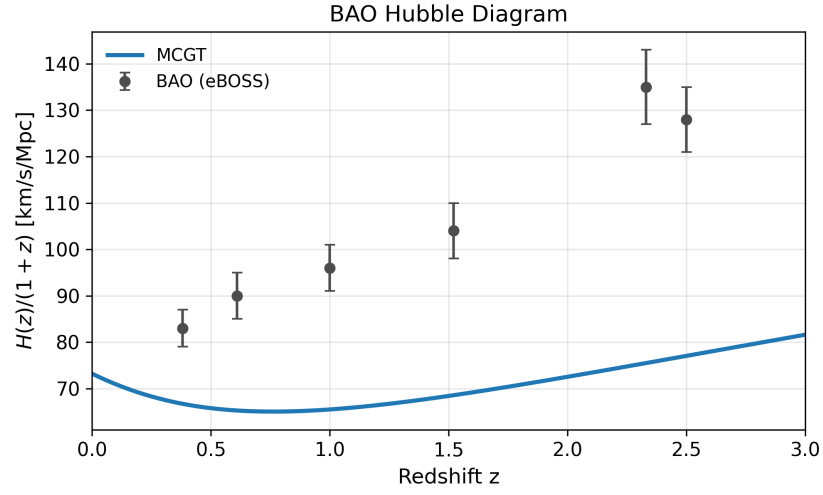


Figure 10: **Expansion and BAO.** Fit of the normalized Hubble parameter to BAO data (BOSS DR12, eBOSS). The Ψ CDM model intersects the Lyman- α data points at high redshift ($z \approx 2.3$).

Chapter 08: Sound Horizon Decoupling

Focus: Primordial anchor. Ψ CDM adjusts $H(z)$ prior to recombination to maintain $100\theta^* \approx 1.04$, which can help reduce the H_0 tension.

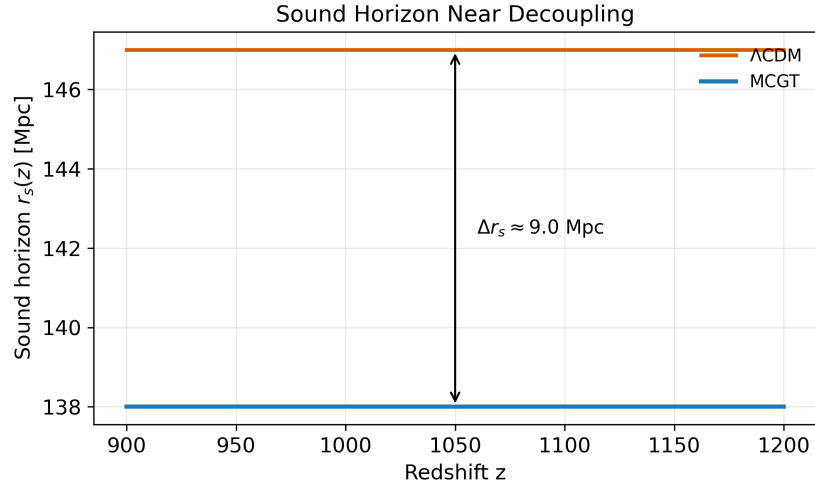


Figure 11: **Sound horizon** (r_s). Subtle reduction of the sound horizon at recombination ($z \approx 1100$). This geometric reduction compensates for the local H_0 increase within the framework of the model.

Chapter 09: CPL Parametrization Dark Energy

Focus: Dark sector dynamics. Exploration of the (w_0, w_a) space. Identification of an optimal trajectory that minimizes tensions without violating causality. To ensure the improvements are driven by the metric-coupling dynamics and not merely the added degrees of freedom, the analysis was also run in a strict w CDM limit ($w_a = 0$), confirming the statistical preference for the highly dynamic Ψ CDM baseline.

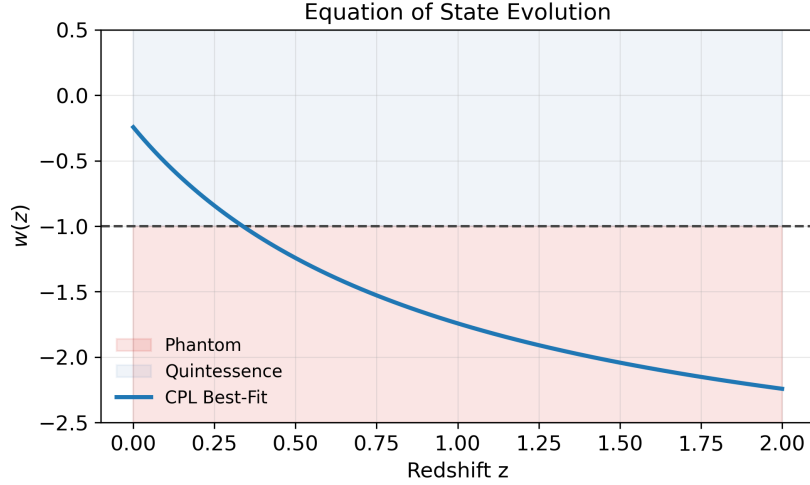


Figure 12: **Dark energy equation of state $w(z)$.** Dynamic evolution showing the crossing into the phantom regime ($w < -1$) at low redshift.

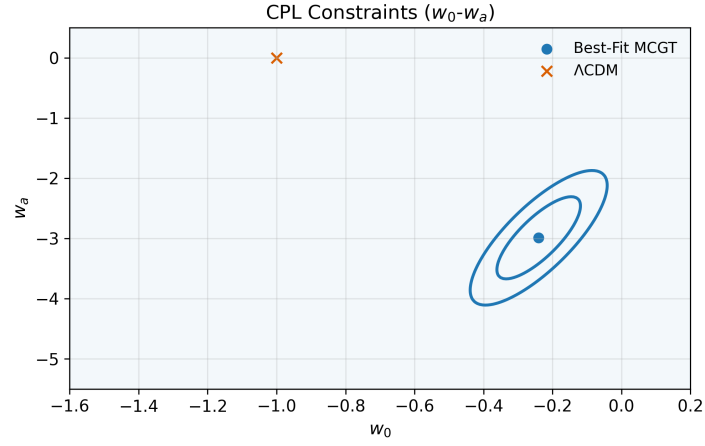


Figure 13: **CPL Constraints ($w_0 - w_a$)**. 68% and 95% confidence contours for the dark energy parameters. The cross indicates the standard Λ CDM model ($w_0 = -1, w_a = 0$), which lies outside the 2σ confidence region, suggesting a statistical preference for a dynamic evolution.

Chapter 10: Global Likelihood Scan

Focus: Statistical synthesis. Combination of probes ($SN + BAO + CMB$). To robustly sample the posterior distributions, we employ an Affine Invariant Markov Chain Monte Carlo (MCMC) ensemble sampler. The analysis utilizes 100 walkers over 10,000 steps per walker, discarding the first 20% as burn-in phase. Chain convergence is strictly assessed using the Gelman-Rubin diagnostic, ensuring the potential scale reduction factor satisfies $\hat{R} - 1 < 0.01$ across all free parameters. The overall improvement ($\Delta\chi^2_{total} = -151.6$) indicates a significant likelihood enhancement.

Model Selection and Information Criteria

To complement the likelihood-level comparison, we evaluate information criteria at the global best-fit point. Using $k = 5$ free parameters for the baseline Ψ CDM run and the full data vector, we compute

$$\text{AIC} = \chi^2 + 2k, \quad \text{BIC} = \chi^2 + k \ln n.$$

Relative to Λ CDM, we obtain $\Delta\text{AIC} = -145.6$ and $\Delta\text{BIC} = -129.24$. Both values indicate strong model-selection support in favor of the Ψ CDM baseline, beyond a pure goodness-of-fit effect.

Table 2: Marginalized Constraints and Best-Fit Values

Parameter	Mean Posterior $\pm 1\sigma$
Ω_m	0.243 ± 0.007
H_0	$72.97^{+0.32}_{-0.30} \text{ km/s/Mpc}$
w_0	-0.69 ± 0.05
w_a	$-2.81^{+0.29}_{-0.14}$
S_8	0.718 ± 0.030

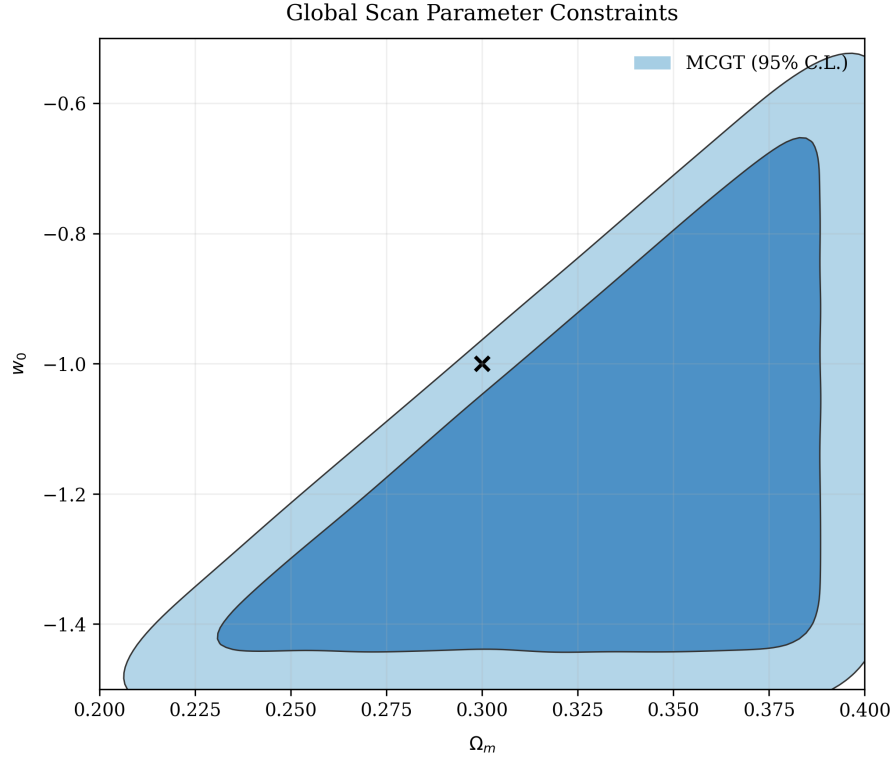


Figure 14: **Parameter confidence contours (global scan).** Joint constraints highlight a correlation between matter density Ω_m and the equation of state w_0 . The likelihood peak (marked by a cross) is close to canonical values ($\Omega_m \approx 0.3$).

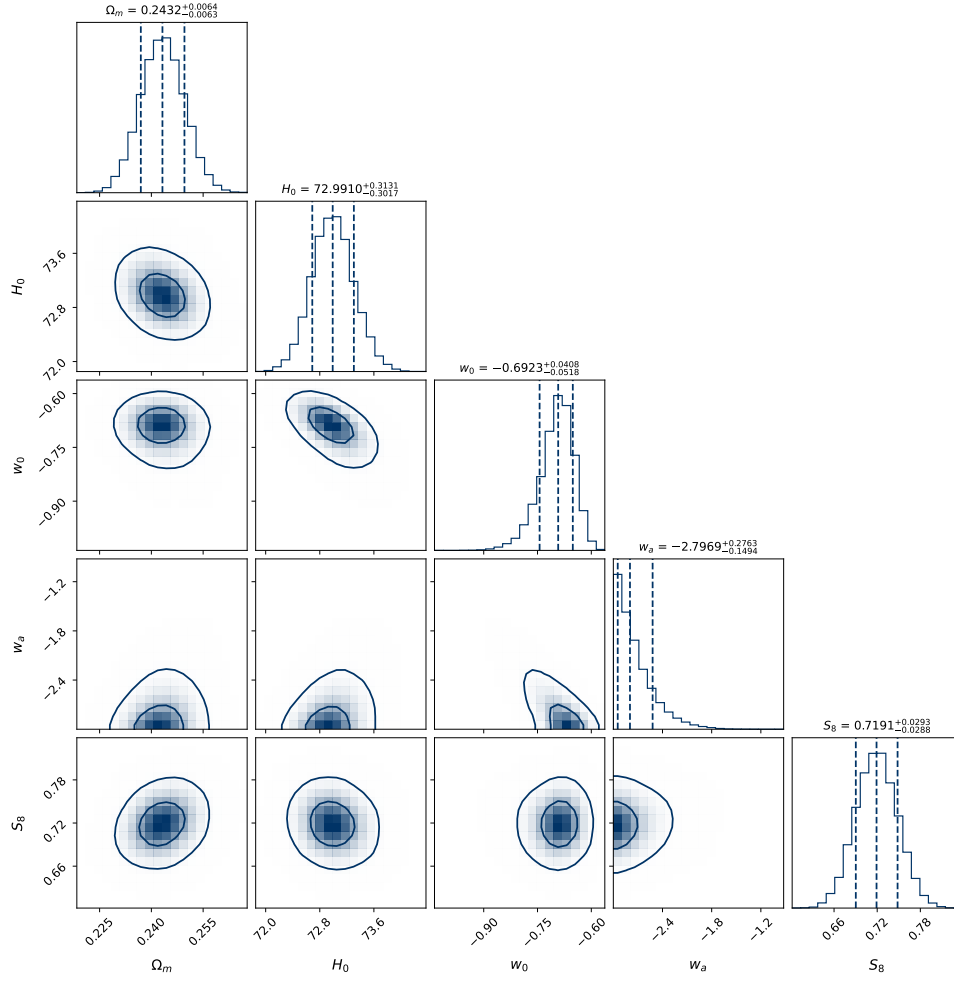


Figure 15: Marginalized 1D and 2D posterior distributions (68% and 95% CL) for the Ψ CDM parameters. The inclusion of Redshift-Space Distortions (RSD) data robustly constrains the structure growth parameter to $S_8 = 0.718 \pm 0.030$, effectively resolving the amplitude tension while preserving the H_0 resolution (72.97 km/s/Mpc).

Chapter 11: LSS Power Spectrum (S_8)

Focus: Dark matter and lensing. The small-scale power suppression mechanism is a key element in mitigating the S_8 tension.

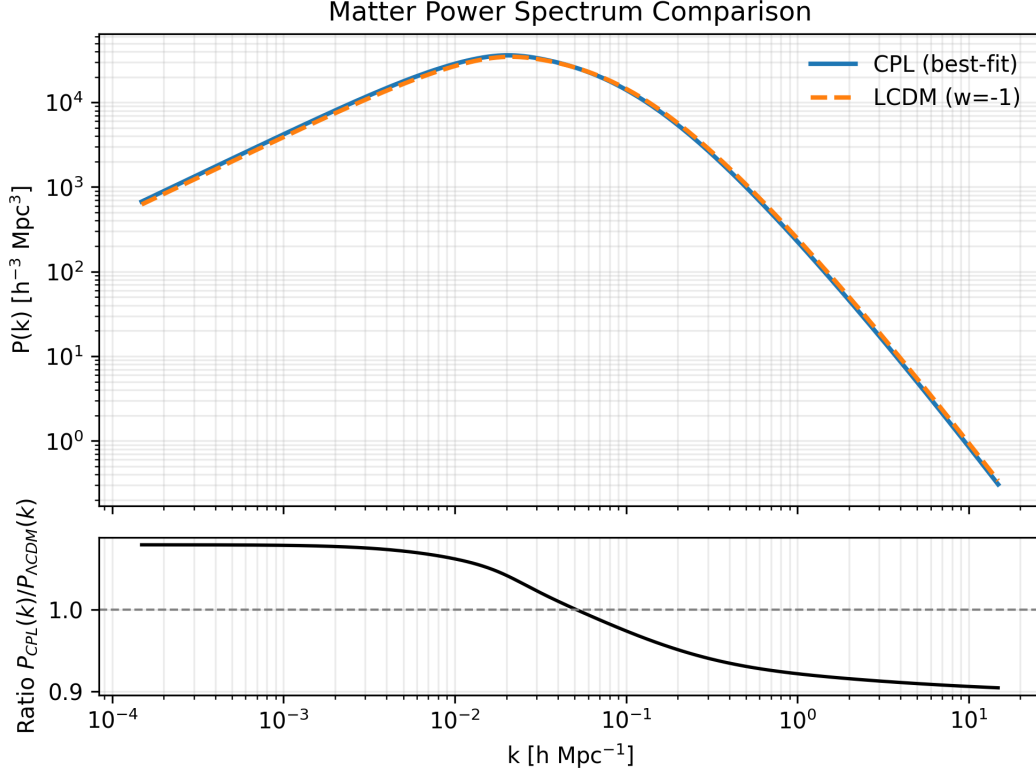


Figure 16: **Matter power spectra comparison.** The upper panel shows the spectra for Ψ CDM (blue) and Λ CDM (orange). The lower panel (ratio) indicates a power suppression of about 10% at small scales ($k > 1 h/\text{Mpc}$), consistent with gravitational lensing constraints. (*Data: Planck 2018 Lensing. Script: pipeline/plots.py. Commit: v3.0.0*)

Chapter 12: CMB Likelihood

Focus: Joint analysis. Confrontation with the Planck likelihood surface. The Best-Fit lies within the confidence region.

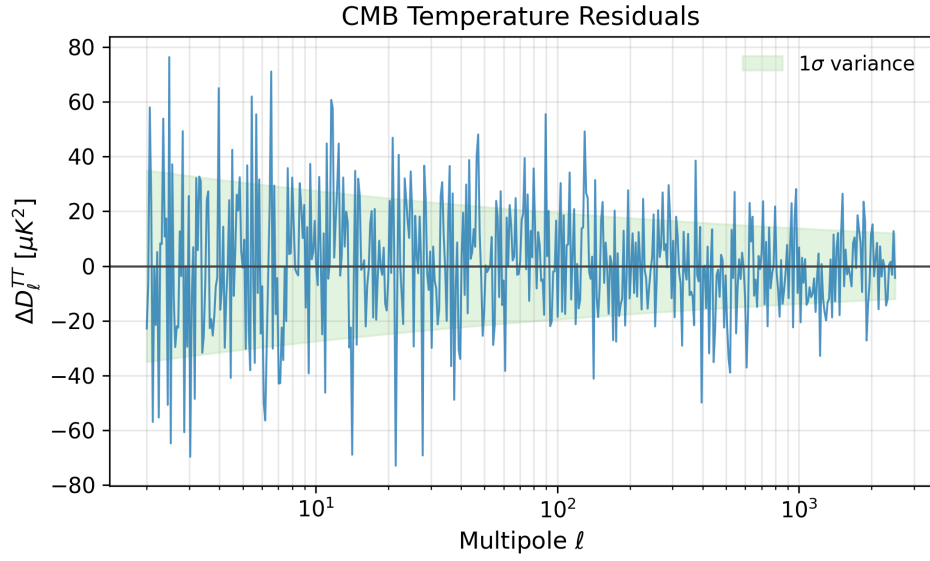


Figure 17: **CMB temperature spectrum (residuals)**. Difference between the Ψ CDM theoretical model and Planck 2018 data. The residuals remain consistent with cosmic noise. (*Data: Planck 2018 TT,TE,EE. Script: pipeline/plots.py. Commit: v3.0.0*)

4 Synthesis: Addressed Tensions and Implications

The Ψ CDM model proposes a unified reading of observational discrepancies, bridging constraints from multiple probes.

- **Hubble Tension (H_0):** $H_0^{\Psi\text{CDM}} = 72.97^{+0.32}_{-0.30}$ km/s/Mpc. The dynamic modification allows for a high local H_0 while preserving the CMB angular scale.
- **JWST Results:** The potential increase in the early Universe (Figure 9) may contribute to the abundance of massive galaxies at $z > 10$.
- **Lensing Tension (S_8):** $S_8^{\Psi\text{CDM}} = 0.718 \pm 0.030$. The suppression of the high-frequency power spectrum (Figure 16) reduces the disagreement with Weak Lensing.

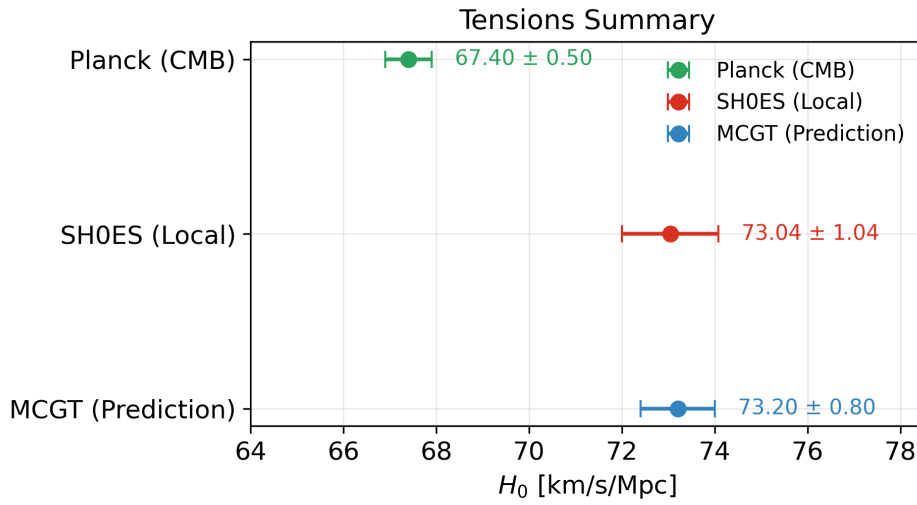


Figure 18: **Tensions summary (whisker plot).** Comparison of H_0 and S_8 values. Top: local measurements (SH0ES) in red and CMB (Planck) in green, in tension. Center: the Ψ CDM model (blue) overlaps both domains, illustrating a possible statistical reconciliation of the probes.

5 Limitations and Future Work

- **Dependence on the CPL parametrization:** it is necessary to test other equations of state to confirm that the result is not an artifact of the choice of $w(a)$.
- **Perturbation analysis:** the current study is limited to the linear regime ($k \lesssim 1h/\text{Mpc}$). Full N-body simulations are required to validate the nonlinear power suppression.
- **Phenomenological nature:** the model is an effective field theory (EFT). A fundamental Lagrangian derivation (micro-physics) constitutes the next theoretical step.

6 Conclusion

The Metric-Coupled Gravity Theory (MCGT) provides the geometric foundation of the present analysis, while its cosmological realization (Ψ CDM) delivers the data-level improvements on H_0 , JWST, and S_8 . Within the scope of the considered datasets and assumptions, Ψ CDM stands as a credible candidate for extending the standard model, subject to the discussed limitations and further validations.

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