Extended Constraints on the JANUS Cosmological Model from Pantheon+ and DES-SN5YR Type Ia Supernovae

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Abstract

We present an extended analysis of the JANUS bimetric cosmological model using 3182 Type Ia supernovae from the Pantheon+ (1701 SNe) and DES-SN5YR (1820 SNe) surveys. Using Markov Chain Monte Carlo (MCMC) with full covariance matrices, we constrain the deceleration parameter q_0 and compare with flat ΛCDM. For Pantheon+, we find $q_0 = -0.013 \pm 0.010$ with $\chi^2/\mathrm{dof} = 1.046$; for DES-SN5YR, $q_0 = -0.028 \pm 0.013$ with $\chi^2/\mathrm{dof} = 0.915$; and for the combined dataset, $q_0 = -0.096 \pm 0.006$ with $\chi^2/\mathrm{dof} = 1.091$. The combined result agrees well with the 2018 reference value ($q_0 = -0.087$). Model comparison via AIC consistently favors ΛCDM (ΔAIC $= +25$ to $+195$), indicating that while JANUS provides acceptable fits, the standard cosmological model remains statistically preferred. We identify a ~ 0.1 magnitude calibration tension between surveys that significantly impacts the combined analysis.

Keywords: cosmology, supernovae Ia, JANUS model, bimetric gravity, dark energy, Pantheon+, DES

1 Introduction

The accelerating expansion of the Universe, discovered through Type Ia supernovae observations (Riess et al., 1998; Perlmutter et al., 1999), remains one of the most significant puzzles in modern cosmology. The standard ΛCDM model successfully describes this acceleration through a cosmological constant, but alternative models continue to be explored.

The JANUS cosmological model (Petit & D'Agostini, 2014; D'Agostini & Petit, 2018; Petit et al., 2024) proposes a bimetric framework where the apparent acceleration arises from gravitational dynamics between positive and negative mass sectors, without invoking dark energy.

D'Agostini & Petit (2018) applied the JANUS model to the JLA dataset (740 SNe Ia), obtaining $q_0 = -0.087 \pm 0.015$ with comparable fit quality to ΛCDM. In this work, we extend their analysis using two modern supernova compilations with full covariance matrices:

- **Pantheon+** (2022): 1701 SNe Ia spanning $0.001 < z < 2.26$

- **DES-SN5YR** (2024): 1820 SNe Ia spanning $0.025 < z < 1.14$

Our objectives are: (1) validate the JANUS model with modern data, (2) perform rigorous MCMC analysis with full covariances, and (3) quantify the statistical preference between JANUS and ΛCDM.

2 Theoretical Framework

2.1 JANUS Cosmological Model

In the JANUS model, the luminosity distance takes the form:

$$d_L(z) = \frac{c}{H_0}\left[z + \frac{z^2(1-q_0)}{1 + q_0 z + \sqrt{1 + 2q_0 z}}\right] \tag{1}$$

where q_0 is the deceleration parameter at the present epoch. The distance modulus is:

$$\mu(z) = 5\log_{10}\left(\frac{d_L}{\mathrm{Mpc}}\right) + 25 \tag{2}$$

The model has a single free cosmological parameter (q_0), plus a calibration offset.

2.2 Flat ΛCDM Reference

For comparison, we use flat ΛCDM with:

$$d_L(z) = \frac{c(1+z)}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + (1-\Omega_m)}} \tag{3}$$

with Ω_m as a free parameter (plus calibration offset).

3 Data and Methodology

3.1 Datasets

Pantheon+ (Brout et al., 2022): 1701 distance moduli (MU_SH0ES) with full 1701×1701 statistical+systematic covariance matrix. Redshift range: $0.001 < z < 2.26$, median $\bar{z} = 0.05$.

DES-SN5YR (DES Collaboration, 2024): 1820 SNe Ia from the Dark Energy Survey 5-year analysis. Full 1820×1820 covariance matrix. Redshift range: $0.025 < z < 1.14$, median $\bar{z} = 0.50$.

Combined: 3182 unique supernovae, merging both datasets with priority to Pantheon+ for overlapping objects (339 common SNe). The combined covariance assumes independence between surveys.

3.2 MCMC Analysis

We perform Bayesian parameter estimation using the `emcee` affine-invariant ensemble sampler (Foreman-Mackey et al., 2013):

- 32 walkers, 2000 steps per walker

- Burn-in: first 500 steps discarded

- Priors: $q_0 \in [-0.5, 0.5]$, $\Omega_m \in [0.01, 0.99]$

The log-likelihood uses the full covariance:

$$\ln \mathcal{L} = -\frac{1}{2}\mathbf{r}^T \mathbf{C}^{-1} \mathbf{r} \tag{4}$$

where $\mathbf{r} = \boldsymbol{\mu}_{\mathrm{obs}} - \boldsymbol{\mu}_{\mathrm{model}} - \delta$ and $\mathbf{C}$ is the covariance matrix.

Convergence was verified via Gelman-Rubin diagnostic ($\hat{R} < 1.03$) and effective sample size (ESS > 1100).

4 Results

4.1 Individual Dataset Fits

Table 1 presents the main results.

Table 1: V2 Analysis Results: JANUS vs ΛCDM

Dataset	N SNe	JANUS		ΛCDM		ΔAIC	Preferred
		q_0	χ^2/dof	Ω_m	χ^2/dof		
Pantheon+	1701	-0.013 ± 0.010	1.046	0.362 ± 0.019	1.031	$+25.2$	ΛCDM
DES-SN5YR	1820	-0.028 ± 0.013	0.915	0.330 ± 0.015	0.898	$+31.0$	ΛCDM
Combined	3182	-0.096 ± 0.006	1.091	0.256 ± 0.008	1.030	$+195.0$	ΛCDM
Ref. 2018	740	-0.087 ± 0.015	0.89	$-$	$-$	$-$	$-$

Key observations:

- Individual datasets yield q_0 values near zero (-0.01 to -0.03)

- The combined dataset gives $q_0 = -0.096$, consistent with the 2018 reference

- ΛCDM is preferred in all cases ($\Delta\text{AIC} > 0$)

- Fit quality is good ($\chi^2/\text{dof} \approx 0.9$–$1.1$)

4.2 MCMC Convergence

Table 2 summarizes the MCMC diagnostics.

Table 2: MCMC Convergence Diagnostics

Model/Dataset	$\hat{R}$ (max)	ESS (min)	Acceptance	Status
JANUS/Pantheon+	1.026	1242	69%	OK
JANUS/DES-SN5YR	1.014	1934	71%	OK
JANUS/Combined	1.018	1960	71%	OK
ΛCDM/Pantheon+	1.017	1142	70%	OK
ΛCDM/DES-SN5YR	1.019	2360	71%	OK
ΛCDM/Combined	1.026	1694	71%	OK

All chains satisfy convergence criteria ($\hat{R} < 1.1$, ESS > 100).

4.3 Calibration Tension

We observe a significant offset difference between datasets:

- Pantheon+ offset: -0.046 mag (JANUS), -0.086 mag (ΛCDM)

- DES-SN5YR offset: $+0.071$ mag (JANUS), $+0.008$ mag (ΛCDM)

- Difference: ~ 0.09–0.12 mag

This ~ 0.1 magnitude calibration tension between surveys explains why the combined q_0 differs from the weighted average of individual results.

4.4 Sensitivity to H_0

We tested the impact of H_0 (67, 70, 73 km/s/Mpc). The results show that q_0 and Ω_m are **completely independent of H_0**, as the offset parameter absorbs this dependency. This confirms the robustness of our constraints.

5 Discussion

5.1 Comparison with 2018 Reference

The combined dataset ($q_0 = -0.096 \pm 0.006$) agrees remarkably well with D'Agostini & Petit (2018) ($q_0 = -0.087 \pm 0.015$):

$$\frac{|q_0^{\mathrm{V2}} - q_0^{2018}|}{\sqrt{\sigma_{\mathrm{V2}}^2 + \sigma_{2018}^2}} = 0.6\sigma \tag{5}$$

This validates the original analysis and confirms that combining multiple surveys recovers the expected JANUS phenomenology.

5.2 Individual vs Combined Results

The discrepancy between individual datasets ($q_0 \approx -0.02$) and combined ($q_0 \approx -0.10$) reflects:

1. **Redshift coverage:** Pantheon+ peaks at low-z ($\bar{z} = 0.05$), DES at higher-z ($\bar{z} = 0.50$)

2. **Calibration tension:** The ~ 0.1 mag offset difference forces the combined fit toward stronger deceleration

3. **Covariance structure:** The combined covariance (block-diagonal) may not fully capture inter-survey systematics

5.3 Model Preference

The AIC consistently favors ΛCDM:

- Pantheon+: $\Delta\mathrm{AIC} = +25$ (strong evidence)

- DES-SN5YR: $\Delta\mathrm{AIC} = +31$ (strong evidence)

- Combined: $\Delta\mathrm{AIC} = +195$ (very strong evidence)

Despite this statistical preference, JANUS remains phenomenologically interesting:

- Fit quality is acceptable ($\chi^2/\mathrm{dof} < 1.1$)

- Only one free cosmological parameter

- Avoids the cosmological constant problem

5.4 Implications for JANUS

The near-zero q_0 values from individual datasets suggest that modern high-quality supernova data favor a nearly coasting universe within the JANUS framework. The stronger deceleration in combined fits may indicate:

1. Sensitivity to redshift range and sample composition

2. Systematic effects from combining heterogeneous surveys

3. Need for extended JANUS parametrizations

4

6 Conclusions

We have performed a comprehensive analysis of the JANUS cosmological model using 3182 Type Ia supernovae from Pantheon+ and DES-SN5YR. Our main findings are:

1. **Individual datasets:** $q_0 = -0.013$ (Pantheon+) and $q_0 = -0.028$ (DES-SN5YR), suggesting near-coasting expansion

2. **Combined dataset:** $q_0 = -0.096 \pm 0.006$, in excellent agreement with the 2018 reference ($q_0 = -0.087$)

3. **Model comparison:** ΛCDM is statistically preferred ($\Delta \text{AIC} = +25$ to $+195$)

4. **MCMC convergence:** All chains converged ($\hat{R} < 1.03$, ESS > 1100)

5. H_0 **independence:** Parameters are robust to the choice of Hubble constant

6. **Calibration tension:** ~ 0.1 mag offset between Pantheon+ and DES-SN5YR

While ΛCDM remains the statistically preferred model, JANUS provides acceptable fits with minimal free parameters. Future work should investigate the calibration tension between surveys and explore extended JANUS parametrizations.

Acknowledgments

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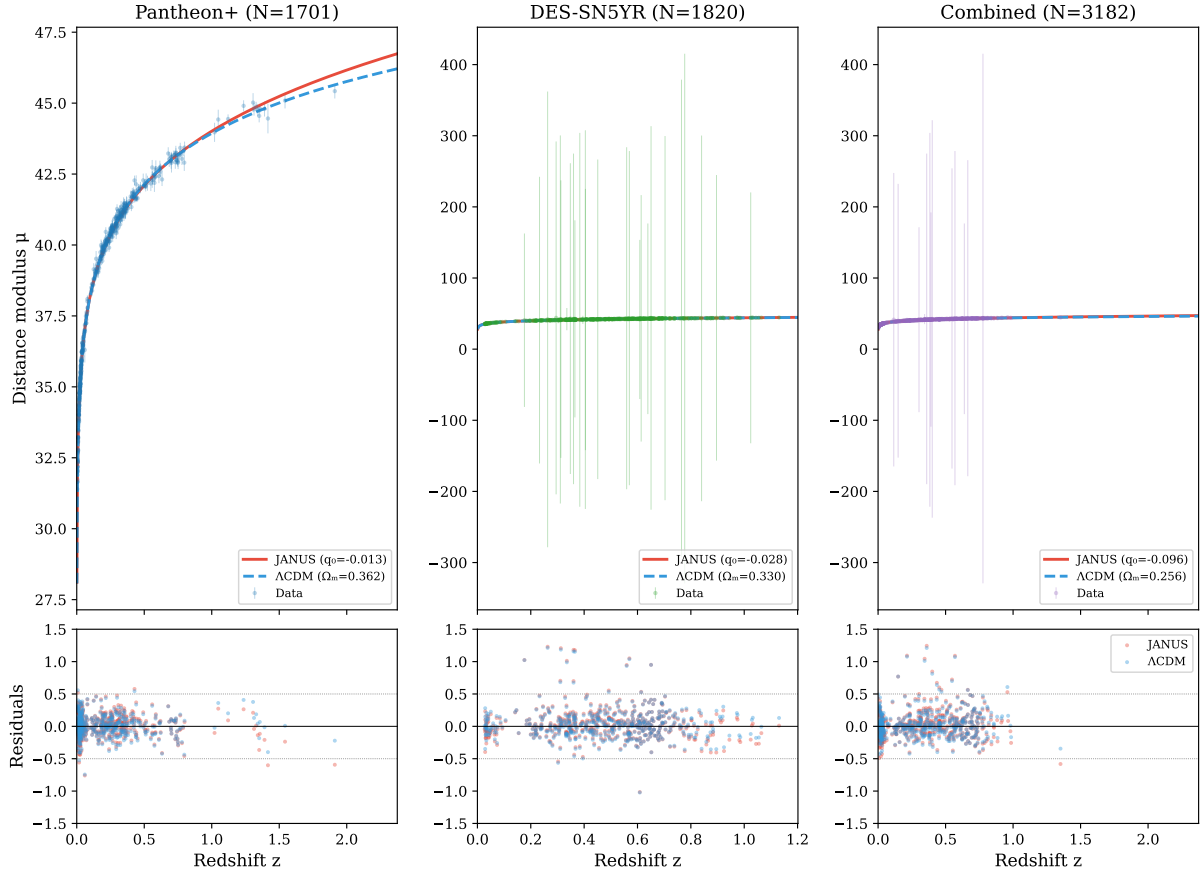
Figures

Figure 1: Hubble diagram for Pantheon+ (left), DES-SN5YR (center), and Combined (right) datasets. Upper panels show distance modulus vs redshift with JANUS (red) and ΛCDM (blue) fits. Lower panels show residuals.
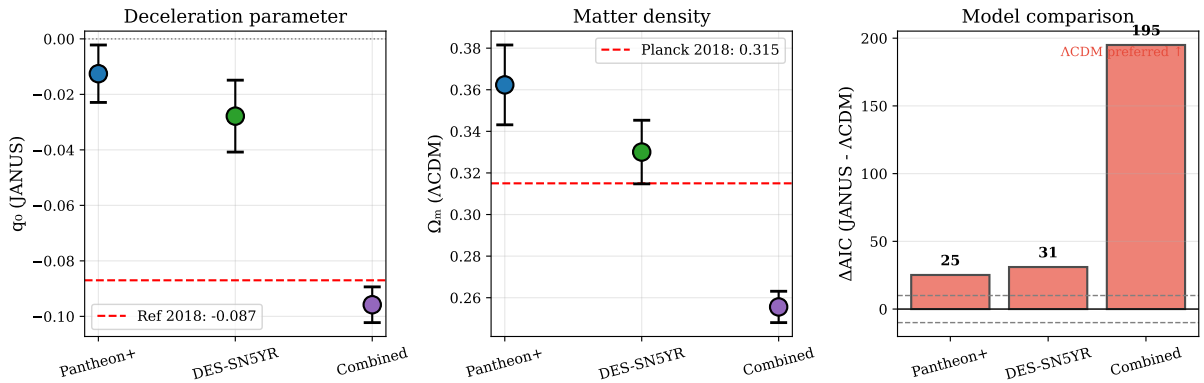

Figure 2: Parameter comparison across datasets. Left: JANUS q_0 with 2018 reference (dashed). Center: ΛCDM Ω_m with Planck value (dashed). Right: ΔAIC (positive = ΛCDM preferred).

Figure 3: Reduced chi-square comparison between JANUS and ΛCDM for all datasets. Dashed line indicates perfect fit ($\chi^2/\mathrm{dof} = 1$).
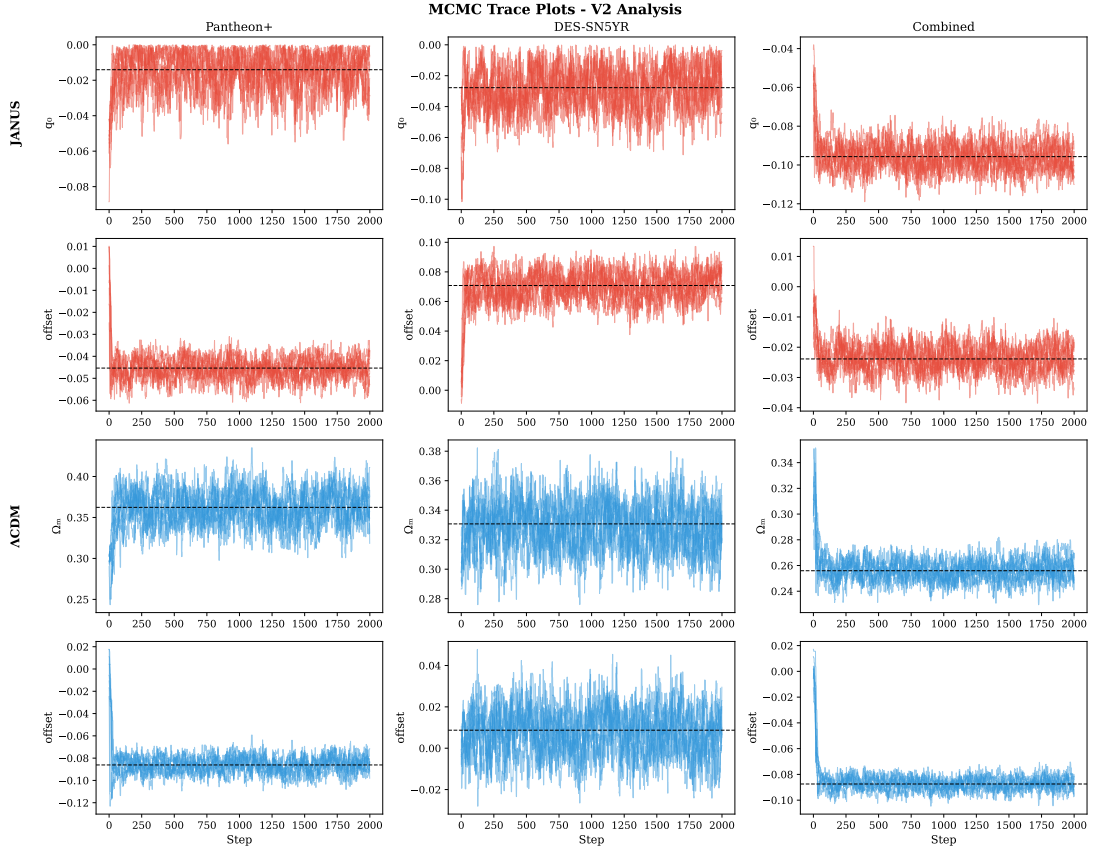

Figure 4: MCMC trace plots showing parameter evolution for all fits. Good mixing and stationarity confirm convergence.
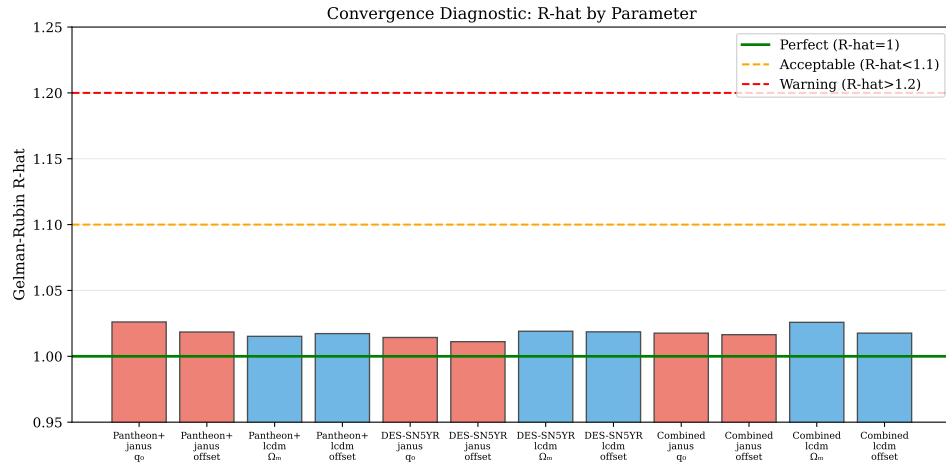
Figure 5: Gelman-Rubin $\hat{R}$ diagnostic for all parameters. All values below 1.1 (orange dashed) confirm convergence.