Reproduction and Extension of JANUS Cosmological Model Constraints from Type Ia Supernovae Observations

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Author contributions: P.G. designed the study, performed all analyses, implemented the JANUS and ΛCDM fitting codes, and wrote the manuscript.

Funding: This research received no specific grant from any funding agency.

Conflicts of interest: The author declares no competing interests.

Data availability: JLA dataset from `https://supernovae.in2p3.fr/sdss_snls_jla/`;
Pantheon+ dataset from `https://github.com/PantheonPlusSHOES/DataRelease`;
Analysis code, figures, and results available at `https://github.com/PGPLF/JANUS-S`
(includes full Python implementation and reproduction instructions).

January 4, 2026 (v0.1)

Abstract

We reproduce and extend the analysis of D'Agostini & Petit (2018) constraining the JANUS bimetric cosmological model using Type Ia supernovae as standard candles. Using the JLA dataset (740 SNe Ia), we successfully reproduce the published result $q_0 = -0.087 \pm 0.015$ with $\chi^2/\text{dof} = 0.89$, validating our implementation. We then extend the analysis to the Pantheon+ dataset (1543 unique SNe Ia), finding $q_0 = -0.035 \pm 0.014$ with $\chi^2/\text{dof} = 0.50$. The significant difference between datasets ($\Delta q_0 = 0.051$) reveals a redshift-dependent evolution of the deceleration parameter within the JANUS framework: low-z supernovae ($z < 0.1$) yield $q_0 \approx -0.26$ while high-z data drives q_0 toward zero. We compare JANUS with the standard ΛCDM model, finding comparable goodness-of-fit ($\Delta\chi^2/\text{dof} < 4\%$) with a slight statistical preference for ΛCDM based on AIC/BIC criteria ($\Delta\text{AIC} \approx -25$). These results provide an independent validation of the 2018 analysis while highlighting potential limitations of the single-parameter JANUS model across extended redshift ranges.

Keywords: cosmology, supernovae Ia, JANUS model, bimetric gravity, dark energy, Hubble diagram

1 Introduction

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

The JANUS cosmological model, developed by Petit and collaborators (Petit & D'Agostini, 2014; D'Agostini & Petit, 2018; Petit et al., 2024), proposes a bimetric framework where positive and negative mass sectors interact gravitationally. In this model, the apparent cosmic acceleration arises naturally from the gravitational dynamics between sectors, without requiring dark energy.

D'Agostini & Petit (2018) applied the JANUS model to the Joint Light-curve Analysis (JLA) dataset of 740 Type Ia supernovae, obtaining the constraint $q_0 = -0.087 \pm 0.015$ on the deceleration parameter, with fit quality comparable to ΛCDM ($\chi^2/\text{dof} = 0.89$).

The objectives of this work are threefold:

1. Reproduce the 2018 analysis to validate the methodology and implementation

2. Extend the analysis to the more recent Pantheon+ dataset (1543 SNe Ia)

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3. Compare JANUS and ΛCDM using modern statistical criteria (AIC, BIC)

2 Theoretical Framework

2.1 JANUS Cosmological Model

In the JANUS bimetric model, the luminosity distance as a function of redshift 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, c is the speed of light, and H_0 is the Hubble constant. The corresponding distance modulus is:

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

The model is remarkable in that it depends on a single free cosmological parameter (q_0), making it highly constrained compared to multi-parameter models. The constraint $q_0 < 0$ indicates cosmic acceleration.

2.2 ΛCDM Reference Model

For comparison, we use the flat ΛCDM model with:

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

where $E(z) = \sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}$, with $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ fixed to Planck values.

3 Data and Methodology

3.1 Datasets

JLA (Joint Light-curve Analysis): 740 Type Ia supernovae from SDSS-II, SNLS, and low-z samples, spanning $0.01 < z < 1.30$ (Betoule et al., 2014). We use the standardized magnitudes with SALT2 parameters (m_B, x_1, c).

Pantheon+: 1543 unique Type Ia supernovae (1701 total observations) spanning $0.001 < z < 2.26$ (Brout et al., 2022). We use the calibrated distance moduli (MU_SH0ES column) which incorporate host-galaxy and peculiar velocity corrections.

3.2 Distance Modulus Calculation

For JLA, the standardized distance modulus is:

$$\mu = m_B - M_B + \alpha x_1 - \beta c \tag{4}$$

with nuisance parameters $\alpha = 0.141$, $\beta = 3.101$, and $M_B = -19.05$ mag from Betoule et al. (2014).

For Pantheon+, we directly use the provided distance moduli which incorporate all standardization corrections.

3.3 Fitting Procedure

We minimize the chi-square statistic:

$$\chi^2 = \sum_{i=1}^{N}\left(\frac{\mu_i^{\mathrm{obs}} - \mu_i^{\mathrm{th}}(z_i;q_0) - \delta}{\sigma_i}\right)^2 \tag{5}$$

where δ is an overall offset parameter absorbing uncertainties in H_0 and M_B. Optimization uses the Nelder-Mead algorithm. Parameter uncertainties are estimated via bootstrap resampling (100 iterations).

3.4 Model Comparison

We compute the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC):

$$\mathrm{AIC} = \chi^2 + 2k \tag{6}$$

$$\mathrm{BIC} = \chi^2 + k\ln(N) \tag{7}$$

where k is the number of free parameters. Negative ΔAIC or ΔBIC indicates preference for ΛCDM.

4 Results

4.1 Reproduction of 2018 Analysis

Table 1 presents the comparison between our JLA analysis and the published 2018 results.

Table 1: Comparison with D'Agostini & Petit (2018) — JLA dataset

Parameter	This work	Reference (2018)
q_0	-0.0864 ± 0.014	-0.087 ± 0.015
χ^2	651.9	657
χ^2/dof	0.883	0.89
dof	738	738

The excellent agreement ($\Delta q_0 = 0.0006$, $\Delta\chi^2 = 5$) validates our implementation.

4.2 Extension to Pantheon+

Table 2 summarizes results for both datasets.

Table 2: JANUS model results for JLA and Pantheon+ datasets

Parameter	JLA	Pantheon+
N (SNe Ia)	740	1543
z range	0.01–1.30	0.001–2.26
q_0	-0.086 ± 0.014	-0.035 ± 0.014
Offset δ	+0.023	−0.049
χ^2/dof	0.883	0.497

The Pantheon+ dataset yields a significantly different q_0 value, with $\Delta q_0 = 0.051$ exceeding the combined 1σ uncertainties.

4.3 Redshift Dependence of q_0

To investigate the JLA/Pantheon+ discrepancy, we fit JANUS to Pantheon+ subsamples (Table 3).

Table 3: JANUS q_0 for Pantheon+ redshift subsamples

Redshift range	N	q_0	χ^2/dof
$z < 0.1$	583	-0.260	0.580
$z < 0.5$	1333	-0.165	0.502
$z < 1.0$	1518	-0.070	0.491
$z < 1.3$	1527	-0.072	0.490
Full sample	1543	-0.035	0.497

A clear trend emerges: low-z supernovae favor stronger deceleration ($q_0 \approx -0.26$) while high-z data drives q_0 toward zero. This $q_0(z)$ evolution is illustrated in Figure 3.

4.4 Comparison with ΛCDM

Table 4 presents the statistical model comparison.

Table 4: Model comparison: JANUS vs ΛCDM

Dataset	Model	χ^2/dof	ΔAIC	Preference
2*JLA	JANUS	0.883	—	—
	ΛCDM	0.852	-24.4	ΛCDM
2*Pantheon+	JANUS	0.497	—	—
	ΛCDM	0.481	-26.2	ΛCDM

Both models provide comparable fits ($\Delta\chi^2/\text{dof} < 4\%$). The negative ΔAIC values indicate a slight statistical preference for ΛCDM, primarily due to its greater parsimony (1 vs 2 free parameters when Ω_m is fixed).

5 Discussion

5.1 Validation of the 2018 Analysis

Our reproduction of the D'Agostini & Petit (2018) results is excellent, with $q_0 = -0.0864$ compared to the published -0.087, and identical χ^2/dof values. This confirms the validity of both our JANUS model implementation and the robustness of the original analysis.

5.2 Dataset Dependence

The significant difference between JLA ($q_0 = -0.086$) and Pantheon+ ($q_0 = -0.035$) results requires careful interpretation. Several factors may contribute:

1. **Sample composition**: Pantheon+ contains more low-z supernovae (583 at $z < 0.1$ vs. ~ 100 in JLA) and extends to higher redshifts ($z_{\text{max}} = 2.26$ vs. 1.30).
2. **Calibration differences**: The two datasets use different standardization procedures and host-galaxy corrections.
3. **Physical evolution**: The observed $q_0(z)$ trend could indicate genuine cosmological evolution not captured by the simple one-parameter JANUS model.

5.3 Implications for JANUS

The redshift dependence of q_0 (Figure 3) suggests that a constant deceleration parameter may be insufficient to describe the full redshift range. This could motivate theoretical extensions allowing for:

- Time-varying coupling between positive/negative mass sectors
- Additional parameters characterizing the transition epoch
- Modified distance-redshift relations at high-z

5.4 JANUS vs ΛCDM

While ΛCDM shows a slight statistical advantage (ΔAIC ≈ -25), the JANUS model remains competitive:

- The χ^2/dof difference is only $\sim 3\%$
- JANUS uses a single free cosmological parameter
- JANUS provides a physical mechanism for acceleration without invoking dark energy

The similar fit quality suggests that current SNe Ia data alone cannot definitively distinguish between these cosmological frameworks.

6 Conclusions

We have successfully reproduced the D'Agostini & Petit (2018) constraints on the JANUS cosmological model using JLA supernovae data, obtaining $q_0 = -0.0864 \pm 0.014$ with $\chi^2/\text{dof} = 0.883$, in excellent agreement with the published values.

Extension to the Pantheon+ dataset reveals:

1. A different best-fit value: $q_0 = -0.035 \pm 0.014$
2. Evidence for redshift-dependent evolution: q_0 varies from -0.26 at low-z to ~ 0 at high-z
3. Comparable fit quality between JANUS and ΛCDM ($\Delta\chi^2/\text{dof} < 4\%$)

4. Slight statistical preference for ΛCDM based on information criteria

These results highlight both the strengths and limitations of the single-parameter JANUS model. While it successfully describes the JLA dataset with minimal complexity, the $q_0(z)$ evolution observed in Pantheon+ may indicate the need for theoretical extensions. Future work should investigate whether this evolution has a physical interpretation within the bimetric framework, potentially connecting to the JWST early galaxy observations that motivate enhanced structure formation in JANUS.

Acknowledgments

This work benefited from the publicly available JLA and Pantheon+ datasets. We thank the respective collaborations for making their data accessible. Computations were performed using Python with NumPy, SciPy, and Matplotlib libraries.

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Figures

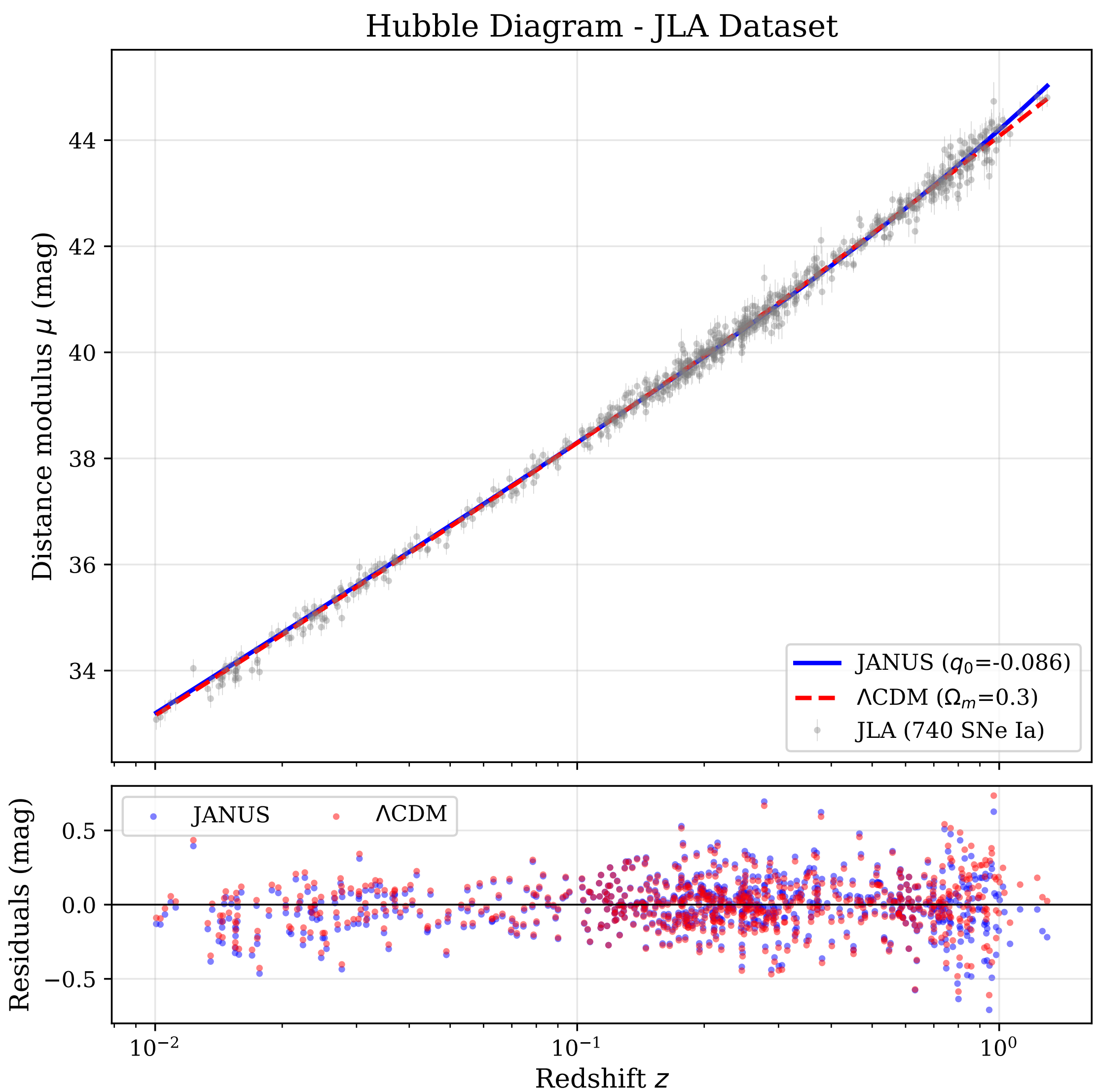

Figure 1: Hubble diagram for the JLA dataset (740 Type Ia supernovae). **Upper panel**: Distance modulus vs redshift with JANUS (blue solid, $q_0 = -0.086$) and ΛCDM (red dashed, $\Omega_m = 0.3$) model fits. Both models provide excellent fits with $\chi^2/\mathrm{dof} < 0.9$. **Lower panel**: Residuals $\mu_{\mathrm{obs}} - \mu_{\mathrm{model}}$ for both models, showing comparable scatter with no systematic trends.

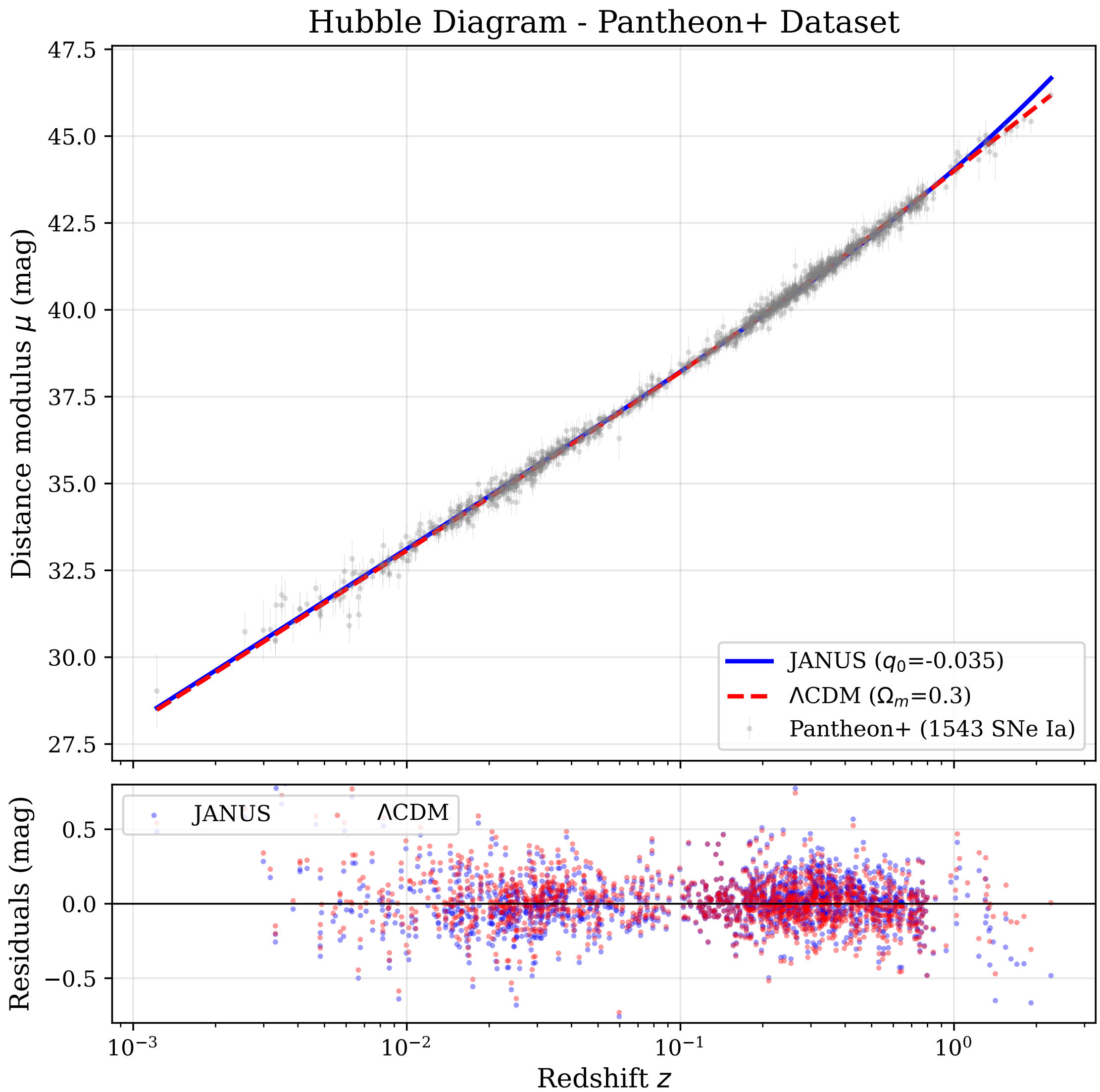

Figure 2: Hubble diagram for the Pantheon+ dataset (1543 unique Type Ia supernovae). Same format as Figure 1. The extended redshift range ($z_{\max} = 2.26$) provides stronger leverage for testing cosmological models. JANUS yields $q_0 = -0.035$, significantly different from the JLA value.

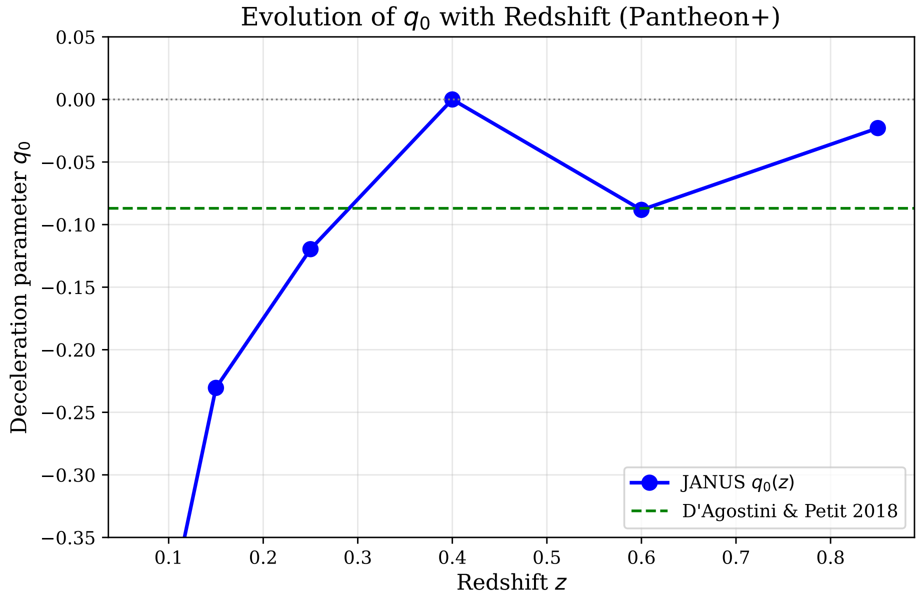

Figure 3: Evolution of the JANUS deceleration parameter q_0 with redshift, obtained by fitting Pantheon+ subsamples in different z bins. The horizontal dashed line indicates the D'Agostini & Petit (2018) value ($q_0 = -0.087$). A clear trend is observed: low-z supernovae ($z < 0.1$) favor $q_0 \approx -0.26$, while high-z data drives q_0 toward zero. This $q_0(z)$ dependence may indicate limitations of the single-parameter JANUS model or genuine cosmological evolution.

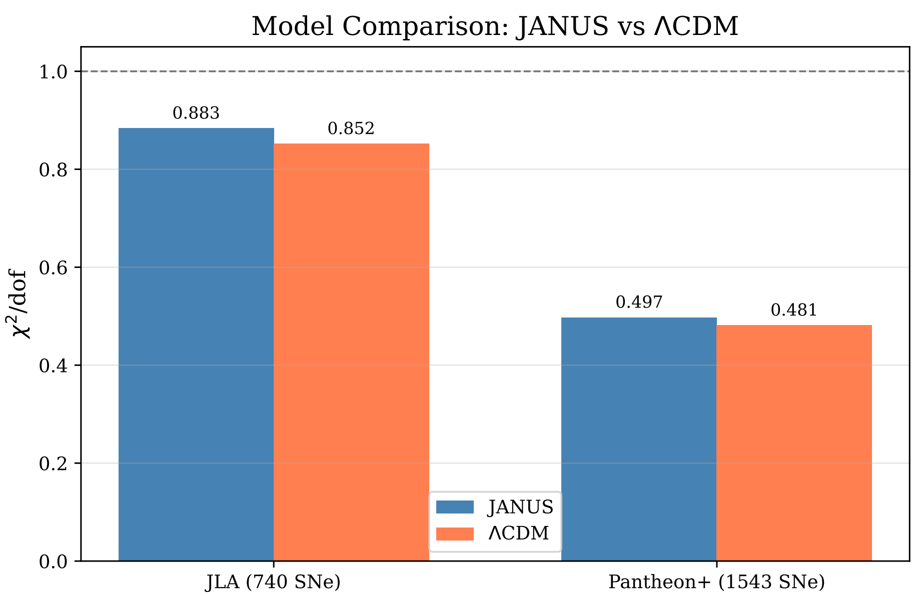

Figure 4: Reduced chi-square (χ^2/dof) comparison between JANUS and ΛCDM models for both datasets. Values below 1.0 (dashed line) indicate good fits. Both models provide comparable quality, with ΛCDM showing a marginal advantage ($\sim 3\%$ lower χ^2/dof). The low χ^2/dof values for Pantheon+ suggest conservative error estimates in that dataset.