A statistical overview of DES SN Ia light curves application to study the Hubble tension

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Introduction

- Dynamic Dark Energy models are focused on describing accelerated expansion of the Universe by considering physics of the early universe, according to the CMB observations.

- The Hubble tension is the discrepancy between the values of H_0 determined from the magnitude-redshift relation and those derived from the Cosmic Microwave Background (CMB). In this work, we analyze Type Ia supernovae (SNe) data to constrain the dark energy EOS, given by $w = \frac{P}{\rho}$.

- In order to alleviate the problem of calculate the expansion rate (Hubble tension), there are some examples of Dark Energy models focused on potential late-time physics, in which the estimation of H_0 implies using observational data. As a proposed model, we present a sigmoid function of *a* and w_0 for w, and by using the recent observations of SN Ia, and compare the results with those obtained from other parametrizations of w.

Friedmann Equations for the Expansion rate (Hubble parameter)

$$H^2 = H_0^2[\Omega_k(1+z)^2 + \Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_\Lambda f(z)], \quad (1)$$

Where Ω_x are the density parameters for curvature (k), matter (m), radiation (r) and dark energy (Λ), respectively, and $f(z)$ is to be determined by the EOS,

$$f(z) = exp\left[\int_0^z \frac{3(1+w(z'))}{1+z'} dz'\right]. \quad (2)$$

Here, $w = \frac{P}{\rho}$, where P is the pressure and ρ the density. The equation of state must satisfy the conservation equation $\dot{\rho} + 3H(\rho + P) = 0$.

Flat geometry is considered: $\Omega_k = 0$.

Sigmoid DE Equation of State (EOS):

$$\boldsymbol{w(a) = w_0 - \frac{(1+w_0)}{1+ e^{\frac{z_a - z}{r}}}} \qquad (3)$$

The Hubble parameter defines the expansion rate of the universe in the FLRW model,

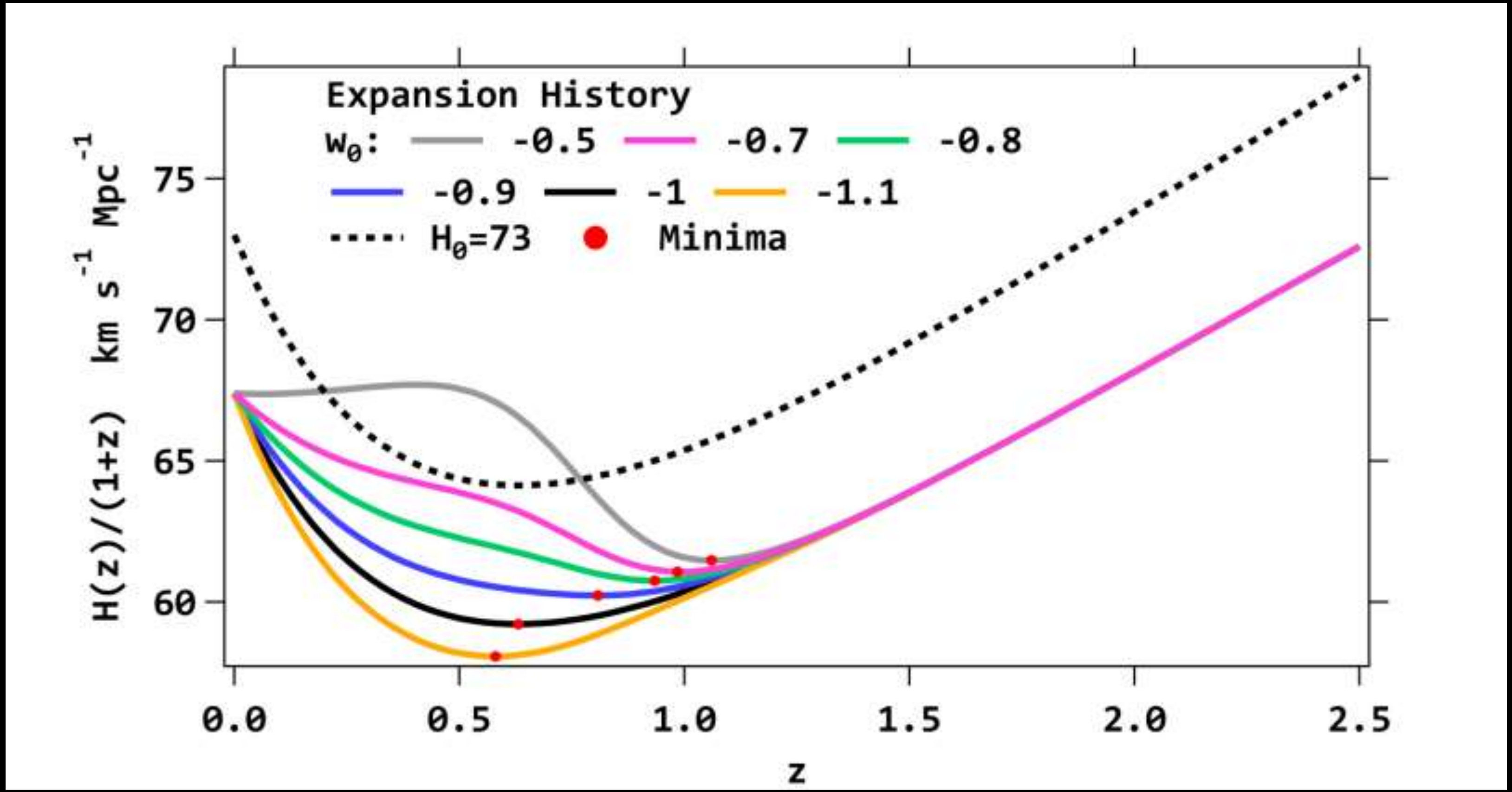
$$\boldsymbol{H(z) = \frac{\dot{a}}{a}}, \qquad (4)$$

With a the cosmological scale factor, related to the cosmological redshift z as

$$\boldsymbol{a = \frac{1}{1+z}}, \qquad \textbf{(5)}$$

Where $a = 1$ for its present value (z=0).

Expansion History Sigmoid Model



Distance modulus: magnitude-redshift relation by luminosity-distance:

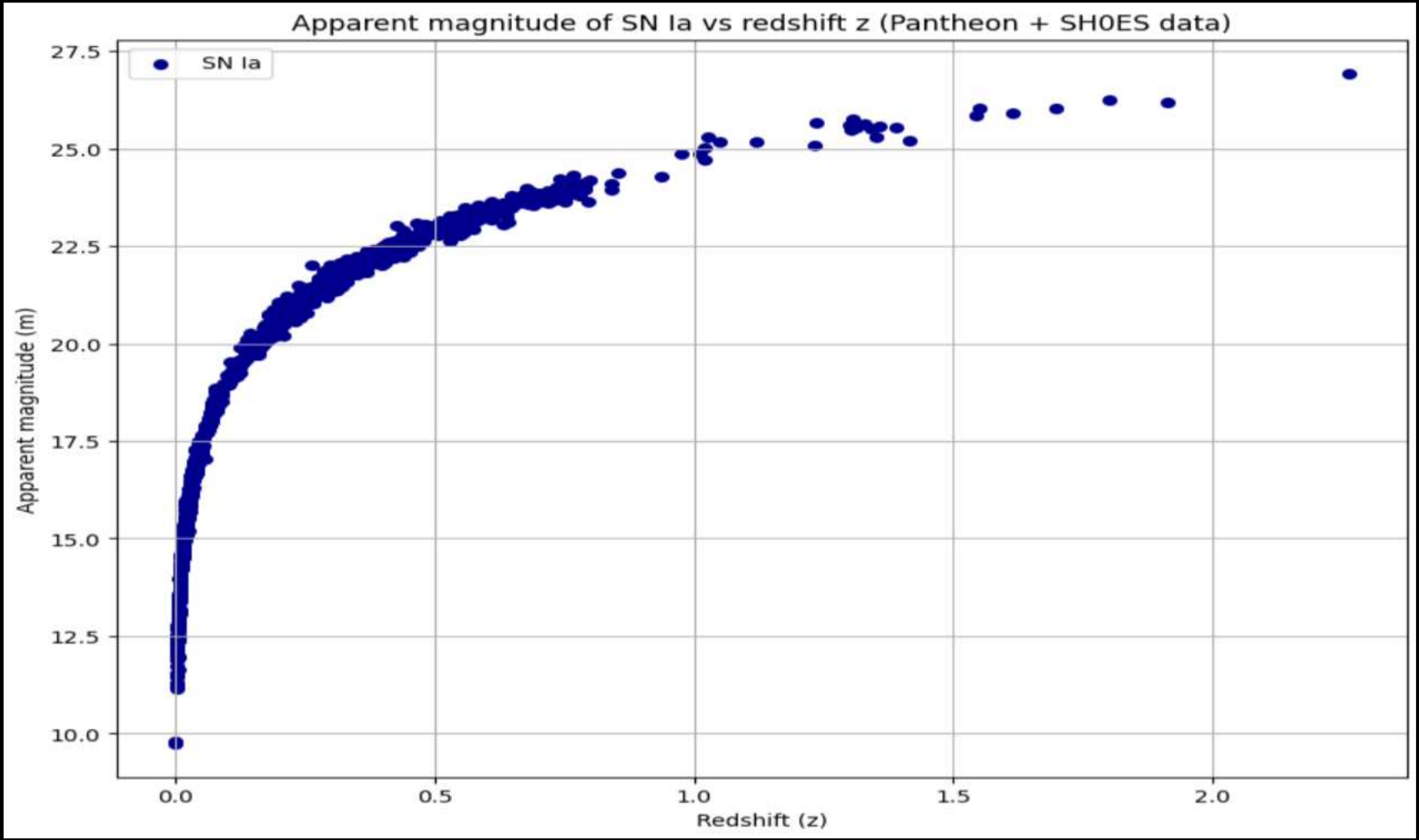
$$m_B - M = 5\ \log[d_L(z)] + 25, \qquad (6)$$

where

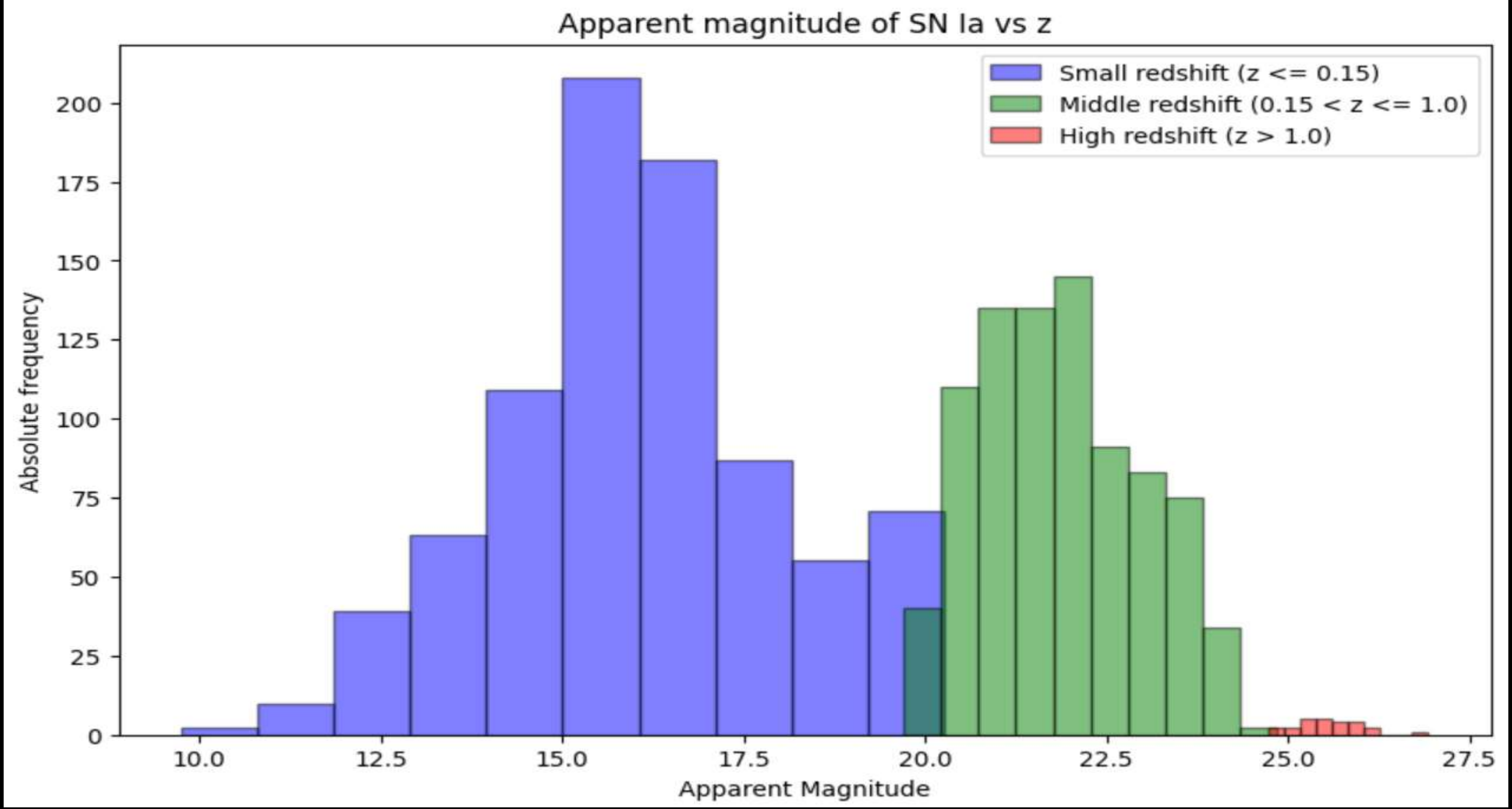
$$d_L(z) = (1 + z) \int_0^z \frac{1}{H(z')} dz'. \qquad (7)$$

Fitting with the sigmoid model: A χ^2 test based on the data and the magnitude values m_B: $\chi^2 = \boldsymbol{R}^{-1}\boldsymbol{C}^{-1}\boldsymbol{R}$, where

$$R_l = m_l - m_B(w_0, w_a, z_a, r, H_0). \qquad (8)$$



Apparent brightness vs redshift for the 1701 SN Ia of Pantheon+ SH0ES data.



Histogram for SN Ia in Pantheon+ data, for different values of redshift and magnitude.

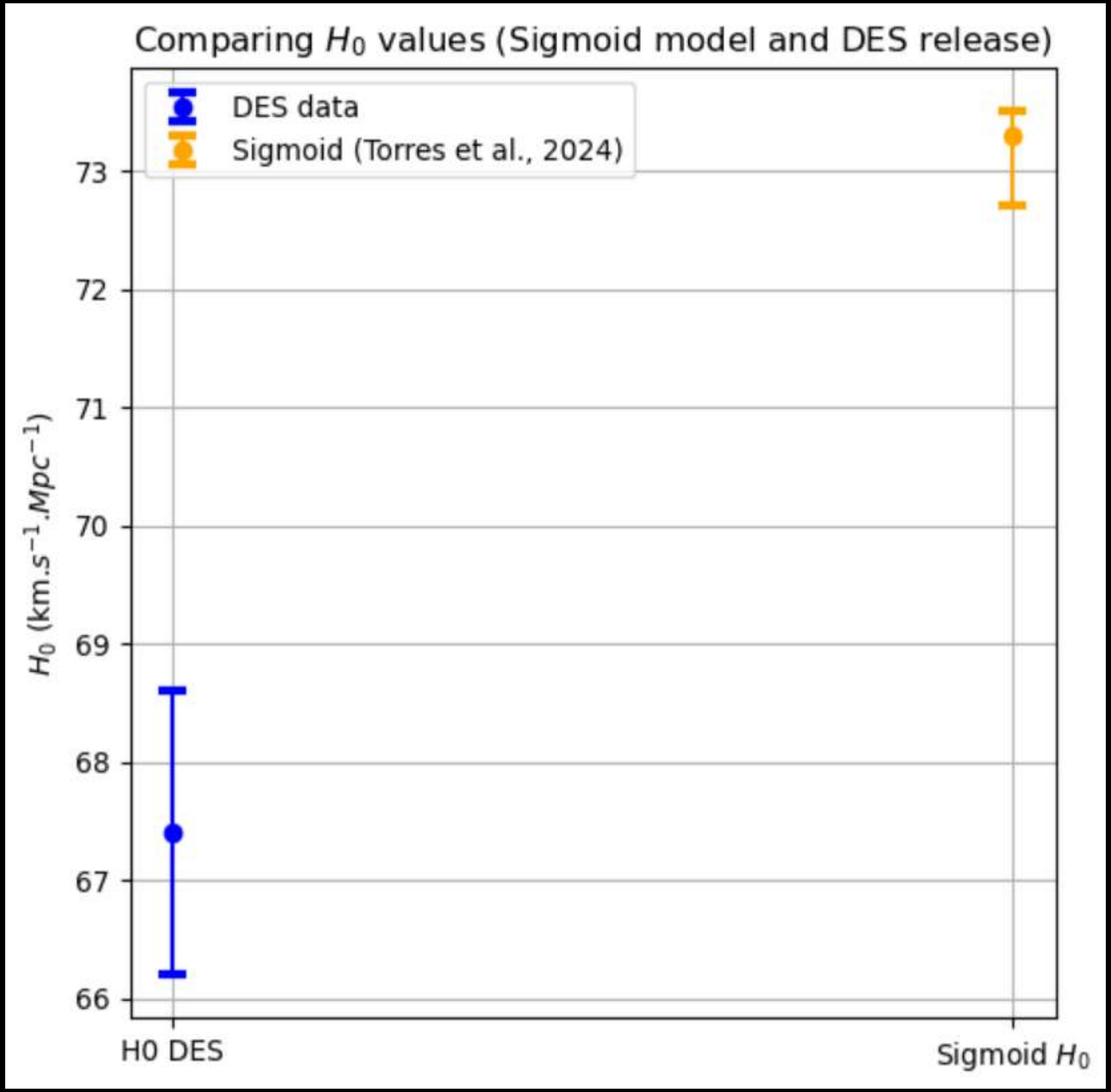
Dark Energy Survey Supernova Program 5YR

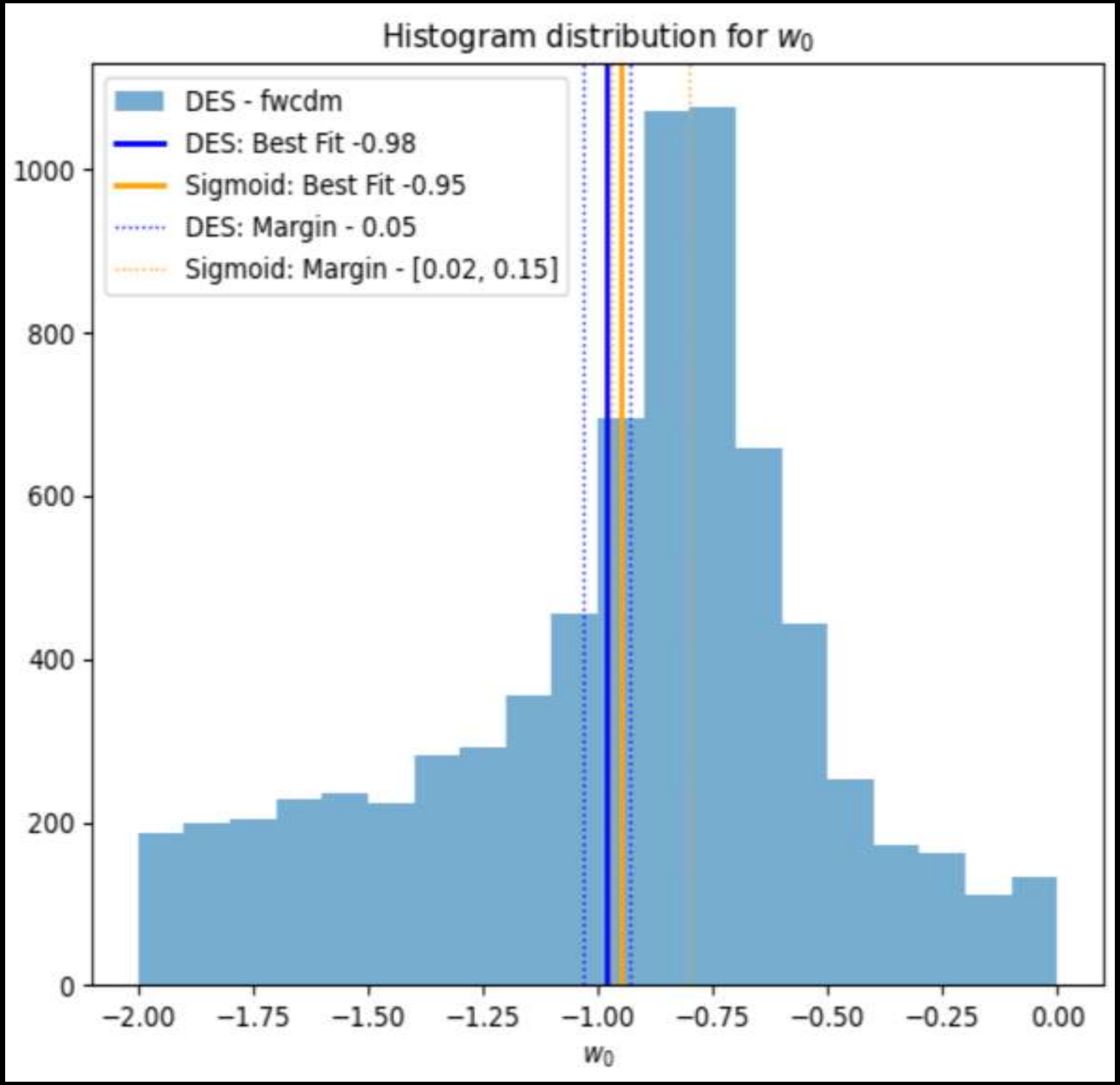
The DES Supernova Program 5-year Data release.

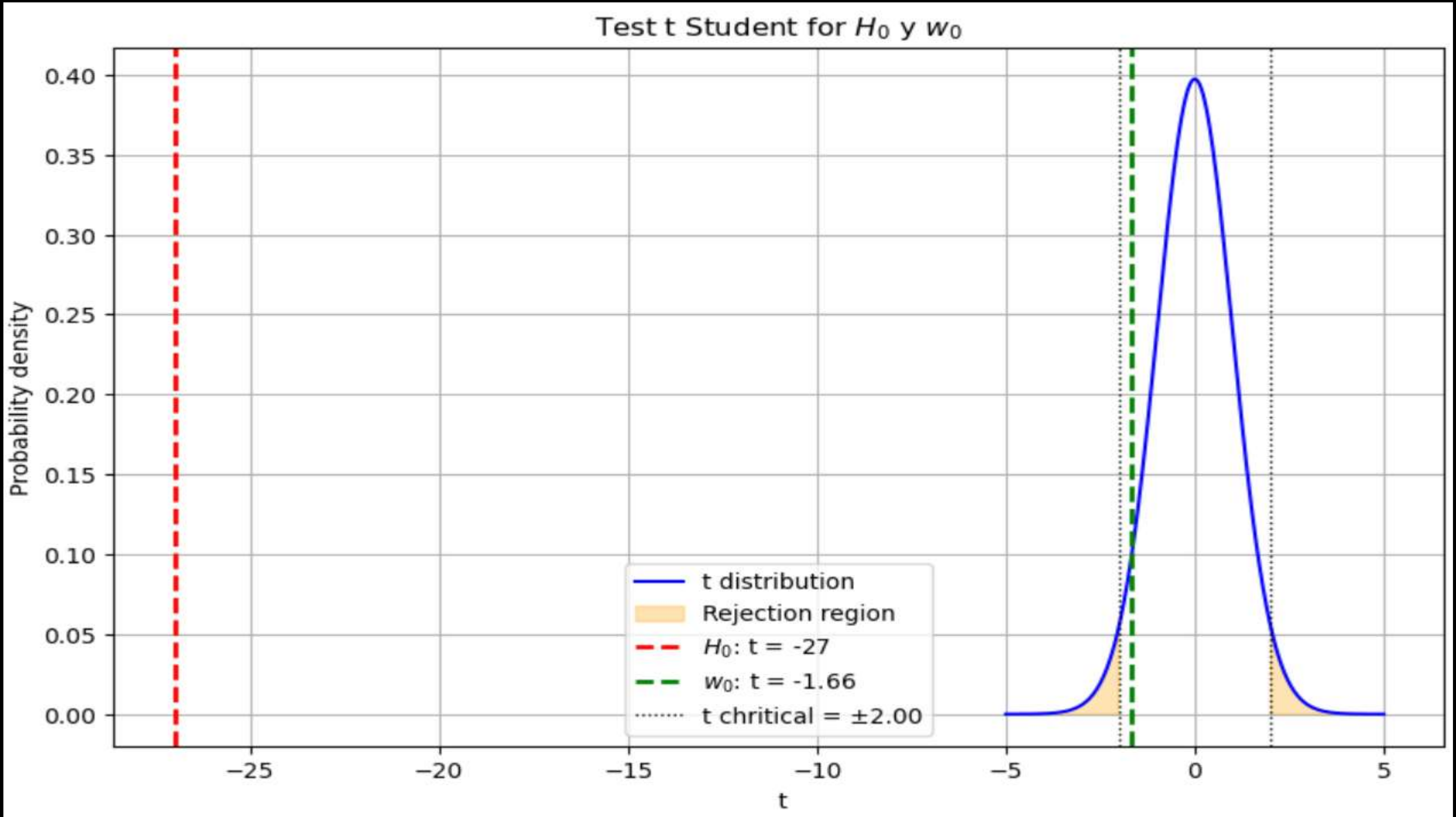
The Dark Energy Survey Supernova Program (DES-SN) consisted on 5 years of observations using the Dark Energy Survey instrument, finding Type Ia Supernovae up to cosmological redshifts $z > 1.1$.

This is the **full public data release** of DES-SN (DES-SN5YR) containing all data products used to compute the cosmological result from the full 5 years of photometrically classified supernovae (SNe) combined with a sample of low-redshift SNe.

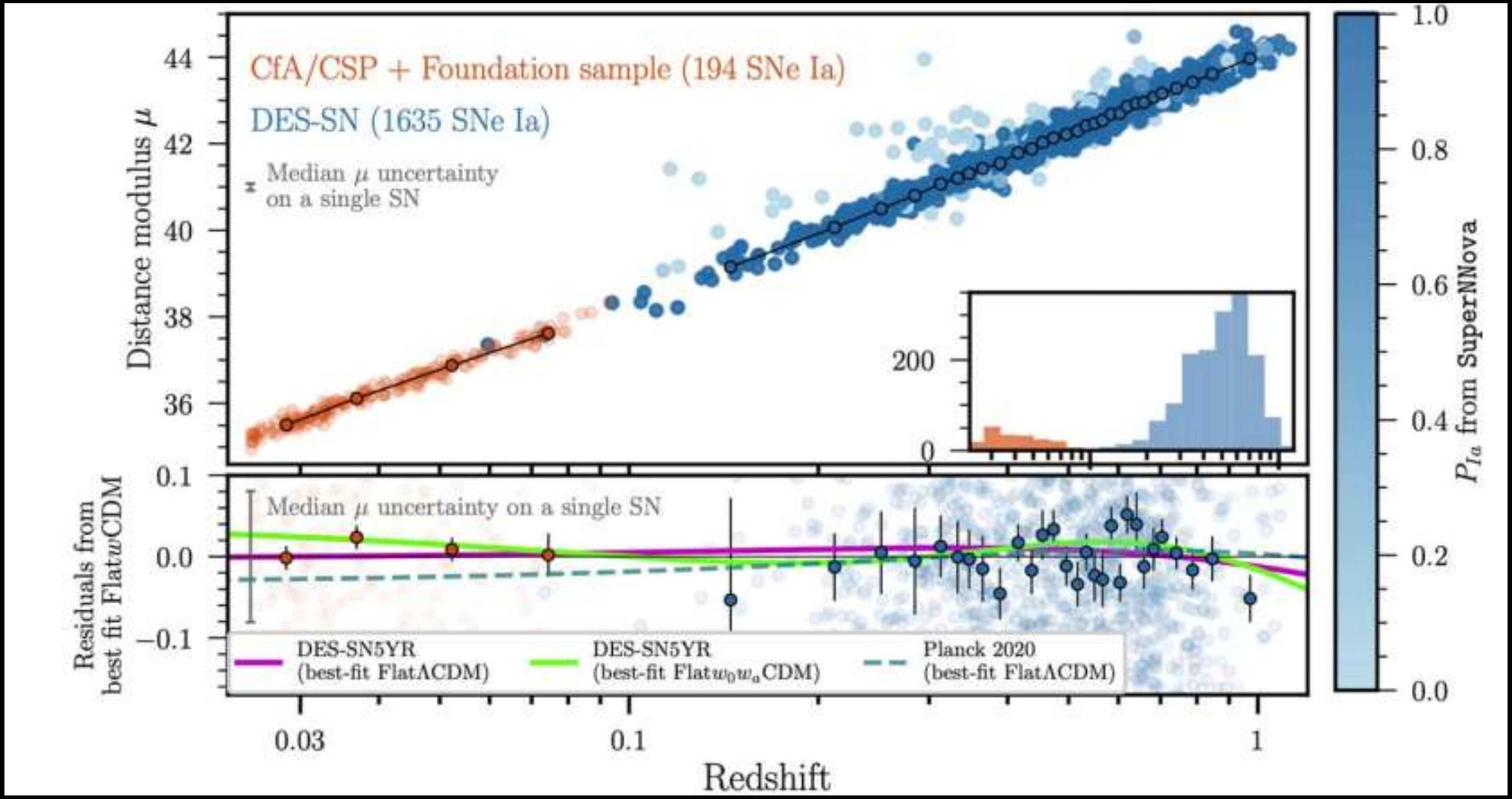
Instructions to download the full data release and its accompanying python utility package can be found below.


Comparing H_0 values (Sigmoid model and DES release)
DES data
Sigmoid (Torres et al., 2024)
H_0 ($km.s^{-1}.Mpc^{-1}$)
73
72
71
70
69
68
67
66
H0 DES
Sigmoid H_0

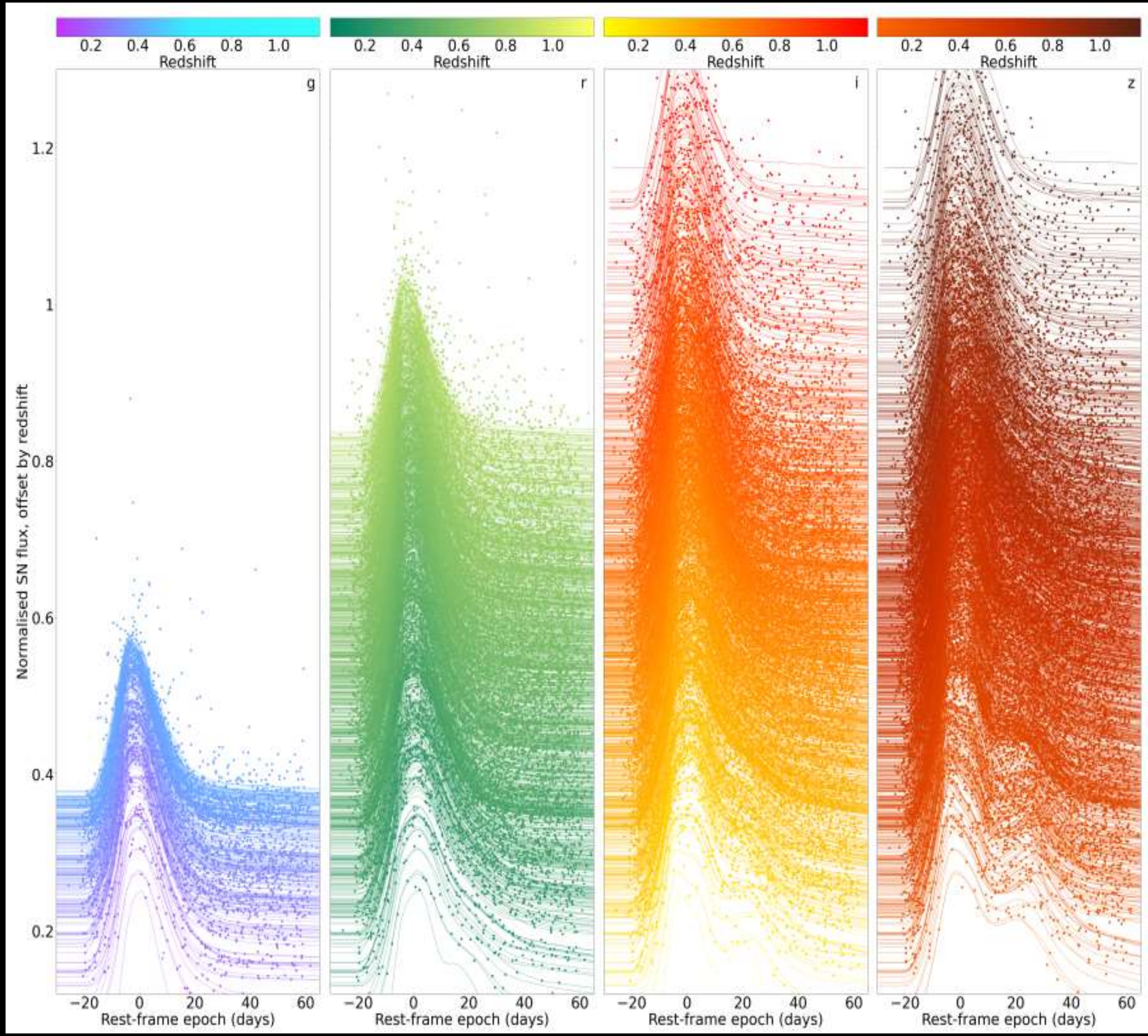

Histogram distribution for w_0
DES - fwcdm
DES: Best Fit -0.98
Sigmoid: Best Fit -0.95
DES: Margin - 0.05
Sigmoid: Margin - [0.02, 0.15]
1000
800
600
400
200
0
−2.00
−1.75
−1.50
−1.25
−1.00
−0.75
−0.50
−0.25
0.00
w_0

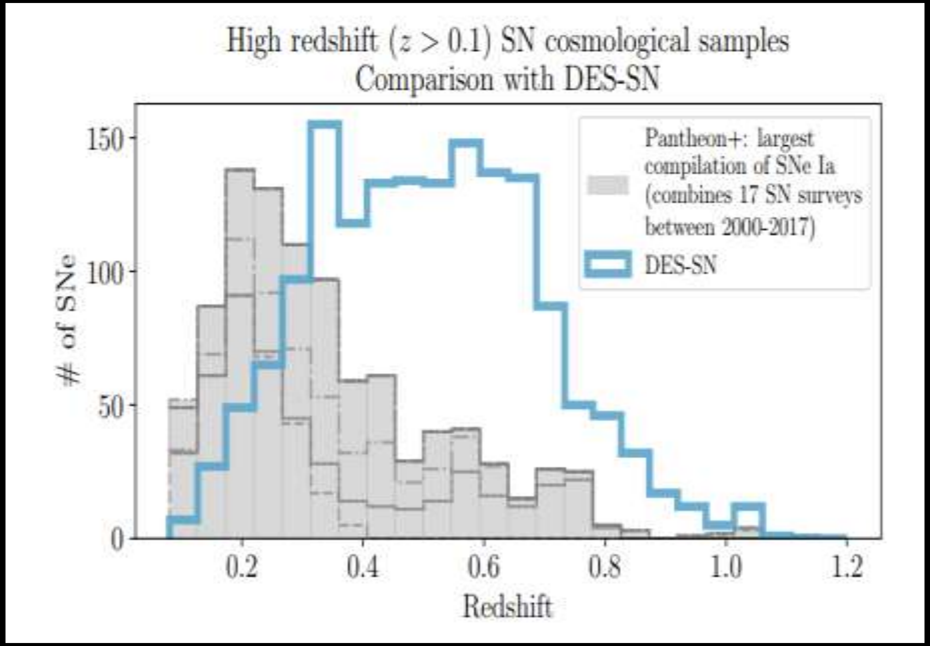

Test t Student for H_0 y w_0
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Probability density
−25
−20
−15
−10
−5
0
5
t
t distribution
Rejection region
H_0: t = -27
w_0: t = -1.66
t chritical = ±2.00

Parameter	DES (Flat wcdm + Planck 2020)	Sigmoid DE Model (Torres et al. 2024)
w_0	$-0.98^{+0.032}_{-0.037}$	$-0.95^{+0.15}_{-0.02}$
H_0	$67.4^{+1.1}_{-1.1}\ km\ s^{-1} Mpc^{-1}$	$73.3^{+0.2}_{-0.6}\ km\ s^{-1} Mpc^{-1}$



DES Collaboration: Abbott et al., 2024





DES Collaboration: Abbott et al., 2024

The significant discrepancy between the H_0 values in DES-SN5YR (67.4 ± 1.1) and the sigmoidal model ($73.3^{+0.2}_{-0.6}$) reflects the well-known H_0 **tension**. This has direct implications for our understanding of this cosmological problem.

Local Implication (Sigmoidal Model):
The sigmoidal model better fits local data, such as measurements from type Ia supernovae and Cepheid variables, which tend to favor higher H_0 values. This model suggests that there may be dynamic evolution in the properties of dark energy, or that local supernovae data capture phenomena not explained by the standard model.

Global Implication (DES):
The value in DES aligns more closely with estimates derived from the Cosmic Microwave Background (CMB), such as those from the Planck satellite. If this discrepancy persists, it could indicate the need for **new physics beyond the standard model** to reconcile local and global expansion scales.

Conclusions

- The H_0 tension suggests the need to explore alternative models (such as the sigmoidal model) or even extend the standard model with new physics.

- The consistency in w_0 indicates that current data support predominantly constant dark energy, though the sigmoidal model leaves open the possibility of smooth evolution.

- The only amount of data is not enough to build a strong discriminant model to solve the Hubble tension.

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Original paper

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ORIGINAL ARTICLE

Evaluating a sigmoid dark energy model to explain the Hubble tension

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Abstract

In this study, we analyze Type Ia supernovae (SNe Ia) data sourced from the Pantheon+ compilation to investigate late-time physics effects influencing the expansion history, $H(z)$, at redshifts ($z < 2$). Our focus centers on a time-varying dark energy (DE) model that introduces a rapid transition in the equation of state, at a specific redshift, z_a, from the baseline, $w_\Lambda = -1$, value to the present value, w_0. The change in the equation of state is implemented as a transition in the DE density scale factor driven by a sigmoid function. The constraints obtained for the DE sigmoid phenomenological parametrization have broad applicability for dynamic DE models that invoke late-time physics. Our analysis indicates that the sigmoid model provides a slightly better, though not statistically significant, fit to the SNe Pantheon+ data compared to the standard Λ cold dark matter (ΛCDM) model. The fit results, assuming a flat geometry and maintaining Ω_m constant at the *2018-Planck* value of 0.3153, are as follows: $H_0 = 73.3^{+0.2}_{-0.6}$ km s^{-1} Mpc^{-1}, $w_0 = -0.95^{+0.15}_{-0.02}$, $z_a = 0.8 \pm 0.46$. The errors represent statistical uncertainties only. The available SN dataset lacks sufficient statistical power to distinguish between the baseline ΛCDM model and the alternative sigmoid models. A feature of interest offered by the sigmoid model is that it identifies a specific redshift, $z_a = 0.8$, where a potential transition in the equation of state could have occurred. The sigmoid model does not favor a DE in the phantom region ($w_0 < -1$). Further constraints to the dynamic DE model have been obtained using CMB data to compute the distance to the last scattering surface. While the sigmoid DE model does not completely resolve the H_0 tension, it offers a transition mechanism that can still play a role alongside other potential solutions.

KEYWORDS
cosmology, dark energy, Hubble tension, Hubble constant, cosmological parameters