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# A 5 per cent measurement of the Hubble–Lemaître constant from Type II supernovae

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## ABSTRACT

The most stringent local measurement of the Hubble–Lemaître constant from Cepheid-calibrated Type Ia supernovae (SNe Ia) differs from the value inferred via the cosmic microwave background radiation (*Planck*+ΛCDM) by $\sim 5\sigma$. This so-called Hubble tension has been confirmed by other independent methods, and thus does not appear to be a possible consequence of systematic errors. Here, we continue upon our prior work of using Type II supernovae to provide another, largely independent method to measure the Hubble–Lemaître constant. From 13 SNe II with geometric, Cepheid, or tip of the red giant branch (TRGB) host-galaxy distance measurements, we derive $H_0 = 75.4^{+3.8}_{-3.7}$ km s$^{-1}$ Mpc$^{-1}$ (statistical errors only), consistent with the local measurement but in disagreement by $\sim 2.0\sigma$ with the *Planck*+ΛCDM value. Using only Cepheids ($N = 7$), we find $H_0 = 77.6^{+5.2}_{-4.8}$ km s$^{-1}$ Mpc$^{-1}$, while using only TRGB ($N = 5$), we derive $H_0 = 73.1^{+5.7}_{-5.3}$ km s$^{-1}$ Mpc$^{-1}$. Via 13 variants of our data set, we derive a systematic uncertainty estimate of 1.5 km s$^{-1}$ Mpc$^{-1}$. The median value derived from these variants differs by just 0.3 km s$^{-1}$ Mpc$^{-1}$ from that produced by our fiducial model. Because we only replace SNe Ia with SNe II – and we do not find statistically significant difference between the Cepheid and TRGB $H_0$ measurements – our work reveals no indication that SNe Ia or Cepheids could be the sources of the '$H_0$ tension.' We caution, however, that our conclusions rest upon a modest calibrator sample; as this sample grows in the future, our results should be verified.

**Key words:** supernovae: general – galaxies: distances and redshifts – distance scale.

## 1 INTRODUCTION

In the century since Georges Lemaître (Lemaître 1927) and Edwin Hubble (Hubble 1929) discovered that the Universe is expanding, astronomers have made significant strides in measuring its current expansion rate (known as the Hubble–Lemaître constant, $H_0$). Traditionally, two different approaches have been employed that leverage measurements at opposite extremes of the visible Universe.

(i) With the *distance-ladder method*, relative distances to nearby galaxies in the Hubble flow (i.e. whose motions are mainly due to the expansion of the Universe) are anchored to absolute distance measurements. It is currently comprised of three steps/rungs: (i) geometric distances like Milky Way Cepheid parallaxes from *Gaia* EDR3 (Lindegren et al. 2021; Riess et al. 2021b), detached eclipsing binary stars in the Large Magellanic Cloud (Pietrzyński et al. 2019), or the Keplerian motion of masers in NGC 4258 (Humphreys et al. 2013; Reid, Pesce & Riess 2019) are used to standardize calibrators – e.g. Cepheids or the tip of the red giant branch (TRGB); (ii) nearby Type Ia supernovae (hereafter SNe Ia) can be calibrated by standardized calibrators – e.g. Cepheids (Freedman et al. 2001; Sandage et al. 2006; Riess et al. 2009, 2011, 2016, 2018a, b, 2019, 2021a; Freedman & Madore 2010; Burns et al. 2018; Dhawan, Jha & Leibundgut 2018), TRGB (Madore, Mager & Freedman 2009; Jang & Lee 2017a, b; Freedman et al. 2019; Yuan et al. 2019; Freedman 2021; Anand et al. 2022; Dhawan et al. 2022), or Mira variable stars (Whitelock, Feast & Van Leeuwen 2008; Huang et al. 2020); and (iii) the calibration to nearby SNe Ia is applied to SNe Ia in the Hubble flow. Owing to a series of efforts which have allowed the scientific community to build the cosmic distance ladder over several decades, such as detached eclipsing binary stars in the Large Magellanic Cloud (Pietrzyński et al. 2019), *Gaia* parallaxes (Lindegren et al. 2021; Riess et al. 2021b), Cepheids (Leavitt & Pickering 1912), TRGB (Lee, Freedman & Madore 1993), and SNe Ia in the Hubble flow (SH0ES[1] team), the uncertainty in the local measurement of $H_0$ has improved from $\sim$10 per cent (Freedman et al. 2001) to $\pm$ 1.4 per cent (Riess et al. 2021a) in the

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[1] 'Supernovae, $H_0$ for the Equation of State of Dark Energy'; Riess et al. (2011).

last 20 yr. Using 42 SNe Ia calibrated with Cepheids, Riess et al. (2021a) have derived the most precise estimate of $H_0$ in the late Universe: $73.04 \pm 1.04\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. With the same technique but using 19 SNe Ia calibrated with TRGB, Freedman (2021) obtained $H_0 = 69.8 \pm 0.6$ (stat) $\pm 1.6$ (sys) $\mathrm{km\,s^{-1}\,Mpc^{-1}}$. The difference between the TRGB and Cepheid calibrations is not yet understood (possible systematics in both methods), but it is not clear whether there is any significant difference between TRGB and Cepheid distances for SN Ia hosts. Riess et al. (2021b) compared the only seven hosts in common and found no difference. Also, Anand et al. (2022) reanalysed the TRGB distances with different data to calibrate the zero-point in NGC 4258 and also found no significant difference with Cepheid results ($H_0 = 71.5 \pm 1.8\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$). Moreover, Blakeslee et al. (2021) calibrated surface brightness fluctuations with Cepheids and TRGB, obtaining the same answer for each.

(ii) The alternate method is based on measurements of the early Universe using the sound horizon observed from the cosmic microwave background radiation (CMB; e.g. Fixsen et al. 1996; Jaffe et al. 2001; Bennett et al. 2003; Spergel et al. 2007; Planck Collaboration VI 2020). However, unlike the distance-ladder technique, this method provides only an 'inverse' cosmic distance ladder, calibrated at redshift $z \approx 1100$ and based on the physics of the early Universe extrapolated to $z \approx 0$. Assuming a $\Lambda$ cold dark matter ($\Lambda$CDM) cosmological model, Planck Collaboration VI (2020) derive a value of $H_0 = 67.4 \pm 0.5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. Other works add an intermediate-redshift rung to anchor SNe Ia at $z > 0.1$ and find a consistent value (Macaulay et al. 2019). It is important to note that all the probes from the early Universe assume that the sound horizon calculation from the standard cosmological model is correct. For this reason, Baxter & Sherwin (2021) derive $H_0$ from the CMB without using information from the sound horizon scale. Their result, $H_0 = 73.5 \pm 5.3\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, is consistent with the local measurement but different from the Planck Collaboration VI (2020) value.

The discrepancy between the two approaches, also referred to as the '$H_0$ tension,' has reached a $5\sigma$ level of significance using Cepheids (Riess et al. 2021a) (though only a 1–$2\sigma$ level of significance using TRGB; Freedman 2021; Anand et al. 2022). This tension is difficult to explain by invoking systematic errors, because a multitude of independent methods have confirmed it. For example, Pesce et al. (2020) derived an independent $H_0$ value of $73.9 \pm 3.0\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ using geometric distance measurements to megamaser-hosting galaxies, and Blakeslee et al. (2021) obtained a value of $73.3 \pm 0.7 \pm 2.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ from surface brightness fluctuation distances for 63 bright early-type galaxies (see Di Valentino et al. 2021 for a review). To date, no solution has been found to explain the tension, but a wide variety of ideas have been proposed – e.g. the presence of additional species of neutrinos, early dark energy, decaying dark matter, or a breakdown of the general relativity (see Di Valentino et al. 2021; Riess et al. 2021a for reviews).

In this work, as an independent approach to test the second and third rungs of the distance-ladder method (which rely on SNe Ia), we use Type II supernovae (SNe II; explosions of massive, evolved, hydrogen-envelope stars via core collapse). SNe II display a large range of peak luminosities, but can be calibrated via theoretical (Kirshner & Kwan 1974; Schmidt et al. 1994; Vogl 2020) and empirical methods (Hamuy & Pinto 2002; de Jaeger et al. 2015, 2017b, 2020a; Rodríguez et al. 2019). Using the former, Schmidt et al. (1994) obtained an $H_0$ value of $73 \pm 13\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, while with the latter, values of $69 \pm 16\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (standard candle method, SCM; Olivares E. et al. 2010) and $\sim 71 \pm 8\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (photospheric magnitude method; Rodríguez et al. 2019) have been derived. More recently, by applying a refined version of the SCM (de Jaeger et al. 2020a) and using seven objects with Cepheid or TRGB independent host-galaxy distance measurements, de Jaeger et al. (2020b) demonstrated that SNe II also manifest the '$H_0$ tension' (albeit at a low level of significance). They found an $H_0$ value of $75.8^{+5.2}_{-4.9}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (stat) value, which differs by $1.4\sigma$ from the high-redshift result (Planck Collaboration VI 2020). Finally, using a tailored-expanding-photosphere method (Vogl et al. 2019, 2020), Vogl (2020) obtain a value of $72.3 \pm 2.8\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, where again the uncertainties are only statistical. It is worth noting that the tailored-expanding-photosphere method is currently limited by a small sample size (only six objects) and peculiar-velocity corrections (mean $z = 0.02$), and it is affected by the systematic uncertainties of atmosphere models (Eastman, Schmidt & Kirshner 1996; Dessart & Hillier 2005; Vogl et al. 2019). However, even if this method requires multiple well-calibrated spectra in the first month after the explosion, which is observationally expensive, it is a promising technique as it does not need calibrators. With this method, one can derive absolute SN II distances and therefore measure direct $H_0$ values without the risk of introducing systematic errors from the calibrators.

Here, as in de Jaeger et al. (2020b), we use the SCM to derive precise extragalactic distances, but importantly, we nearly double the number of calibrators (from 7 to 13). This allows us to derive $H_0$ with a precision of $\sim$5 per cent (statistical). Section 2 describes our methodology (data, calibrators, and SCM), and we present our results in Section 3. Section 4 summarizes our conclusions.

## 2 METHOD

### 2.1 Data sample

In this study, we consider the same SN II sample used by de Jaeger et al. (2020b), consisting of 125 objects (89 of which are at $z > 0.01$) from the following surveys: the Lick Observatory Supernova Survey (LOSS; Filippenko et al. 2001), the Carnegie Supernova Project-I (CSP-I; Hamuy et al. 2006), the Sloan Digital Sky Survey-II SN Survey (SDSS-II; Frieman et al. 2008), the Supernova Legacy Survey (SNLS; Astier et al. 2006), the Subaru Hyper-Suprime Cam Survey (SSP-HSC; Aihara et al. 2018; Miyazaki et al. 2012), and the Dark Energy Survey Supernova Program (DES-SN; Bernstein et al. 2012). To this sample, we also add four SNe II for which we have absolute SN host distance measurements: SN 2014bc (Polshaw et al. 2015), SN 2017eaw (Van Dyk et al. 2019), SN 2018aoq (unpublished Lick/KAIT data), and SN 2020yyz (unpublished *Hubble Space Telescope* data and public Zwicky Transient Factory data; Bellm et al. 2019). We refer the reader to de Jaeger et al. (2020b) and references therein for more detailed information regarding the surveys, photometric reduction, and how the magnitudes are simultaneously corrected for Milky Way extinction, *K*-corrected, and *S*-corrected. Note that as in de Jaeger et al. (2020b), all of the CMB redshifts ($z_{\mathrm{CMB}}$) are taken from the NASA/IPAC Extragalactic Database (NED[2]). Then, to account for peculiar velocities, all are corrected (henceforth referred to as $z_{\mathrm{corr}}$) using the model of Carrick et al. (2015). Finally, a residual peculiar-velocity uncertainty of $250\,\mathrm{km\,s^{-1}}$ is added to the total redshift uncertainty in quadrature.

[2]http://ned.ipac.caltech.edu/

**Table 1.** Calibrator sample.

| SN name | Host Galaxy | $\mu$ (mag) | Calibrator | References |
|---|---|---|---|---|
| SN 1999em | NGC 1637 | 30.26 ± 0.09 | Cepheids | de Jaeger et al. (2020b) (updated from Leonard et al. 2003) |
| SN 1999gi | NGC 3184 | 30.64 ± 0.11 | Cepheids | de Jaeger et al. (2020b) (updated from Leonard et al. 2002) |
| SN 2004et | NGC 6946 | 29.21 ± 0.16 | TRGB | From EDD, Anand et al. (2022) |
| SN 2005ay | NGC 3938 | 31.72 ± 0.07 | Cepheids | Riess et al. (2021a) |
| SN 2005cs | NGC 5194/M51 | 29.62 ± 0.09 | TRGB | de Jaeger et al. (2020b) (updated from McQuinn et al. 2017) |
| SN 2008bk | NGC 7793 | 27.80 ± 0.08 | TRGB | From EDD, Anand et al. (2022) |
| SN 2009ib | NGC 1559 | 31.49 ± 0.06 | Cepheids | Riess et al. (2021a) |
| SN 2012aw | NGC 3351 | 29.82 ± 0.09 | Cepheids | de Jaeger et al. (2020b) (updated from Kanbur et al. (2003)) |
| SN 2013ej | NGC 628/M74 | 29.90 ± 0.08 | TRGB | de Jaeger et al. (2020b) (updated from McQuinn et al. (2017)) |
| SN 2014bc | NGC 4258 | 29.387 ± 0.0568 | Geometric | Reid et al. (2019) |
| SN 2017eaw | NGC 6946 | 29.21 ± 0.16 | TRGB | From EDD, Anand et al. (2022) |
| SN 2018aoq | NGC 4151 | 31.04 ± 0.07 | Cepheids | Yuan et al. (2020) |
| SN 2020yyz | NGC 0976 | 31.71 ± 0.15 | Cepheids | Riess et al. (2021a) |

### 2.2 Calibrator sample

This work uses 13 SNe II having absolute distance measurements: one with a geometric distance, seven with Cepheid-derived distances, and five from the TRGB. Among these calibrators, seven were already used (and thus described) by de Jaeger et al. (2020b). We list the remaining six below.

(i) SN 2004et and SN 2017eaw in NGC 6946: de Jaeger et al. (2020b) did not include these objects because they had a large Milky Way extinction, and at that time, the TRGB distance was not reliable (only a few stars). In this work, we add both objects because the colour–magnitude diagram from the Extragalactic Distance Database (EDD[3]) is now well sampled. This means that unlike in Anand, Rizzi & Tully (2018), the break in the stellar luminosity function is now sharper and therefore more reliable. To consider the large Milky Way extinction, we account for it in the distance error by adding 10 per cent of the extinction (0.1 mag) in quadrature. The final distance modulus used is $\mu = 29.21 \pm 0.16$ mag.

(ii) SN 2008bk in NGC 7793: This SN was also removed from de Jaeger et al. (2020b) because its distance was obtained using ground-based observations with only 11 Cepheids. However, a TRGB measurement (Anand et al. 2022) is now available in the EDD. The distance modulus used in this work is $\mu = 27.80 \pm 0.08$ mag.

(iii) SN 2014bc ($\mu = 29.387 \pm 0.0568$ mag; Reid et al. 2019) in NGC 4258 using the Keplerian motion of masers.

(iv) SN 2018aoq ($\mu = 31.04 \pm 0.07$ mag; Yuan et al. 2020) in NGC 4151 using Cepheids.

(v) SN 2020yyz ($\mu = 31.71 \pm 0.157$ mag; Riess et al. 2021a) in NGC 0976 using Cepheids.

The TRGB luminosities are converted into distance moduli using a zero-point calibration of $-4.01$, which is the average of many recent measurements as compiled by Li, Casertano & Riess (2022, see their table 3) and an uncertainty of 0.04 mag. Additionally, the Cepheid distances have been revised and updated from Riess et al. (2021a). It is important to note that because it is not clear whether there is any significant difference between TRGB and Cepheid distances for SN Ia hosts (see Section 1), here we use TRGB and Cepheid distance measurements together to increase the total number of calibrators and decrease the statistical error in $H_0$. Also, in Section 3.1, we show that the mean SN II luminosity from TRGB and Cepheids is consistent (differing by $\sim 0.3\sigma$), which supports the use of both calibrators together. A summary of all the calibrators available in this work and their distances can be found in Table 1.

[3] https://edd.ifa.hawaii.edu/

### 2.3 Empirical SN II standardization

SNe II are not standard candles, but they are standardizable using theoretical or empirical methods. Here, we follow the methodology of de Jaeger et al. (2020b) and use the SCM, which leverages the correlation between SN II luminosity and two observables: (i) the photospheric expansion velocity and (ii) colour. Intrinsically brighter SNe II have more-rapidly expanding photospheres and are bluer (see figs 7 and 8 of de Jaeger et al. 2020a). Therefore, for each SN, the corrected magnitude is written as

$$m_{\rm corr} = {\rm m} + \alpha \log_{10}\left(\frac{v_{{\rm H}\,\beta}}{\bar{v}_{{\rm H}\,\beta}}\right) - \beta(c - \bar{c}), \quad (1)$$

where $m$ is the apparent magnitude in a given passband at 43 d after the explosion, $c$ is the colour, $v_{{\rm H}\,\beta}$ is the velocity measured using H $\beta$ absorption from an optical spectrum, and the overbars are used to denote averaged quantities. The nuisance parameters $\alpha$ and $\beta$ are discussed below. For more details, we refer the reader to equations (1), (2), and (3) of de Jaeger et al. (2020a).

### 2.4 $H_0$ from SNe II

This section describes how $H_0$ can be derived from SNe II using the SCM. As the methodology is the same as that used by de Jaeger et al. (2020a), only a brief description is presented here.

As defined by Riess et al. (2011),

$$\log_{10} H_0 = \frac{M_i + 5\,a_i + 25}{5}, \quad (2)$$

where $a_i$ is the intercept of the SN II magnitude–redshift relation (translated to $z = 0$) measured from the Hubble-flow sample and $M_i$ is the absolute SN II $i$-band magnitude (at 43 d) derived using our calibrator sample. Therefore, the approach is to fit a joint model which combines the calibrator and Hubble-flow samples to constrain $M_i$ and to determine $a_i$. Simultaneously, our model evaluates how close the calibrators are to the mean absolute magnitude, and, given a value of $H_0$, how close the absolute magnitudes of the Hubble-flow SNe II are to the mean absolute magnitude.

However, as the SNe II are not standard candles, we also need to standardize their apparent magnitudes by deriving $\alpha$ and $\beta$ from equation (1). Our model thus has five free parameters: $\alpha$, $\beta$, $H_0$, $M_i$, and $\sigma_{\rm int}$, where $\sigma_{\rm int}$ is the usual uncertainty added to account for

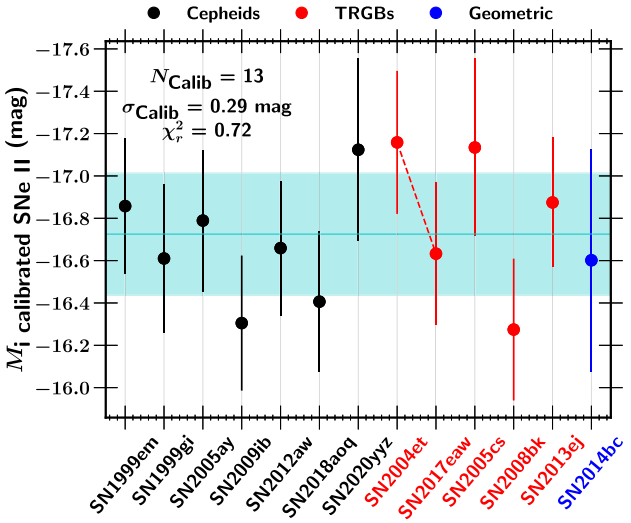


**Figure 1.** Absolute *i*-band magnitude 43 d after the explosion for the 13 calibrators based on Cepheid (black), TRGB (red), or geometric (blue) distances. We also present the standard deviation obtained after applying the SCM, represent it by the cyan filled region. A dashed line connecting SN 2004et and SN 2017eaw has been plotted to indicate that they are located in the same host galaxy. Note that the uncertainties include the intrinsic scatter ($\sigma_{\rm int} = 0.29$ mag) as well as the reduced $\chi^2_r$.

unmodelled, intrinsic SN II scatter. As in de Jaeger et al. (2020a), we use the PYTHON package EMCEE developed by Foreman-Mackey et al. (2013) with 300 walkers, 2000 steps, and with uniform priors for $\alpha$, $\beta \neq 0$, $H_0 > 0$, and $M_i < 0$, and scale-free for $\sigma_{\rm int} > 0$ with $p(\sigma_{\rm int}) = 1/\sigma_{\rm int}$.

## 3 RESULTS

### 3.1 Calibrators

Following de Jaeger et al. (2020a), who demonstrated that the best passband to minimize the intrinsic dispersion among SNe II in the Hubble diagram is the *i* band, we use the same band and show, in Fig. 1, the absolute magnitudes of all 13 calibrators. The calibrators have a weighted average absolute magnitude of −16.71 mag, with a dispersion of $\sigma_{\rm cal} = 0.29$ mag – similar to those obtained by de Jaeger et al. (2020a) (−16.69 and 0.24 mag, respectively) and as expected, larger in scatter than that obtained using SNe Ia and 42 calibrators (0.13 mag; Riess et al. 2021a). Although the method to standardize SNe II is not as strong as the one used for SNe Ia, the dispersion increases to 0.80 mag when the SCM is not applied, demonstrating its utility.

It is interesting to compare the average absolute magnitude obtained for both types of calibrators. For our five TRGBs, we find an average absolute magnitude of $-16.81 \pm 0.33$ mag, while for our seven Cepheids $-16.68 \pm 0.25$ mag. The absolute magnitude for the TRGB is slightly larger than, but fully consistent with, the Cepheids. Small-number statistics may explain the difference, as in de Jaeger et al. (2020a) the difference was $\sim 1\sigma$ with two TRGBs and five Cepheids, while in this work it is just $\sim 0.3\sigma$.

### 3.2 Hubble–Lemaître constant

To minimize the effect of peculiar velocities, we select only SNe II with $z_{\rm corr} > 0.01$ in our Hubble-flow sample ($N = 89$). With the 13 calibrators described in Section 2.2, we obtain a median value of $H_0 = 75.4^{+3.8}_{-3.7}$ km s$^{-1}$ Mpc$^{-1}$, where the quoted uncertainties are statistical only. This value is consistent with the one derived by de Jaeger et al. (2020b) with seven calibrators ($H_0 = 75.8^{+5.2}_{-4.9}$ km s$^{-1}$ Mpc$^{-1}$); however, with the addition of six calibrators, we reduce the statistical uncertainty by 25 per cent (5.0 versus 6.7 per cent; see de Jaeger et al. 2020b). As expected and seen in Fig. 2, the other free-fitting parameters ($\alpha$, $\beta$, $M_i$, and $\sigma_{\rm int}$) are only slightly different with respect to de Jaeger et al. (2020b), as we use the same Hubble-flow sample and add six new nearby objects. Note that the intrinsic scatter derived for the SNe II in the Hubble flow and the nearby SNe II is consistent (0.28 versus 0.29 mag).

Regarding the '$H_0$ tension,' our result is consistent with the local measurement from SNe Ia ($73.04 \pm 1.04$ km s$^{-1}$ Mpc$^{-1}$; Riess et al. 2021a), and shows a discrepancy of $2.2\sigma$ with the early-Universe value ($H_0 = 67.4 \pm 0.5$ km s$^{-1}$ Mpc$^{-1}$; Planck Collaboration VI 2020). If we use only the Cepheids to measure $H_0$ ($N = 7$), we obtain $H_0 = 77.6^{+5.2}_{-4.8}$ km s$^{-1}$ Mpc$^{-1}$, while using only TRGB ($N = 5$), we find $H_0 = 73.1^{+5.7}_{-5.3}$ km s$^{-1}$ Mpc$^{-1}$. There is no meaningful difference between our results derived from TRGB or from Cepheids.

A summary of our data, $H_0$ fit, and residuals is shown in Fig. 3, where we see only the second and third rungs of the distance-ladder method that have been tested in this work. The second rung allows us to calibrate and derive the SN II absolute *i*-band magnitude using 13 calibrators (geometric, Cepheids, and TRGB), while the third rung uses SNe II in the Hubble flow to constrain $H_0$.

### 3.3 Systematic uncertainties

In this section, we investigate possible sources of systematic errors in our measurement. For this, we look at the effect of different cuts and calibrators on $H_0$. We summarize all the results in Table 2.

First, because peculiar velocities can systematically affect $H_0$ measurements (Boruah, Hudson & Lavaux 2021; Sedgwick et al. 2021), we investigate what changes in the associated uncertainty in the recession velocities have on our determination of $H_0$. We find that changing the error to 150 km s$^{-1}$ instead of 250 km s$^{-1}$ only changes the value by 0.2 per cent ($75.3^{+4.0}_{-3.7}$ km s$^{-1}$ Mpc$^{-1}$). Then, we investigate what changes if we cut our Hubble-flow sample at $z_{\rm corr} > 0.023$ (Riess et al. 2021a). With this cut, our Hubble-flow sample decreases to 47 SNe II and we find a value of $77.6^{+4.7}_{-4.5}$ km s$^{-1}$ Mpc$^{-1}$ – an increase of 2.9 per cent with respect to our fiducial model. If we apply a less-restrictive redshift cut and use all the SNe II ($z_{\rm corr} > 0.0$), a decrease of 1.3 per cent is seen ($H_0 = 74.4^{+3.7}_{-3.3}$ km s$^{-1}$ Mpc$^{-1}$). Finally, we investigate what changes if we use uncorrected CMB-frame redshifts rather than redshifts corrected for peculiar velocities. In this case, $H_0$ decreases by 0.5 per cent to $75.0^{+3.8}_{-3.6}$ km s$^{-1}$ Mpc$^{-1}$. The effect on $H_0$ seen when applying different redshift cuts can be explained by peculiar velocities that are not perfectly corrected or by small-number statistics of the Hubble-flow sample (the largest difference is seen when the sample is reduced to 47 objects).

Secondly, we investigate the effect of the calibrators on $H_0$. Using only Cepheids or TRBGs as calibrators causes the largest differences relative to the fiducial model. We find a difference of 2.9 per cent ($77.6^{+5.2}_{-4.8}$ km s$^{-1}$ Mpc$^{-1}$) and 3 per cent ($73.1^{+5.7}_{-5.6}$ km s$^{-1}$ Mpc$^{-1}$) with only Cepheids and only TRGBs, respectively. The small discrepancy between the TRGB and Cepheid values could hint that there might be a systematic difference between the TRGB and Cepheid methods, as possibly seen with SNe Ia (see Freedman 2021; Riess et al. 2021b; Anand et al. 2022). However, our TRGB and Cepheid values are consistent, differing by $<1.0\sigma$. Also, both values are in the range of other local measures (Di Valentino et al. 2021) and statistically

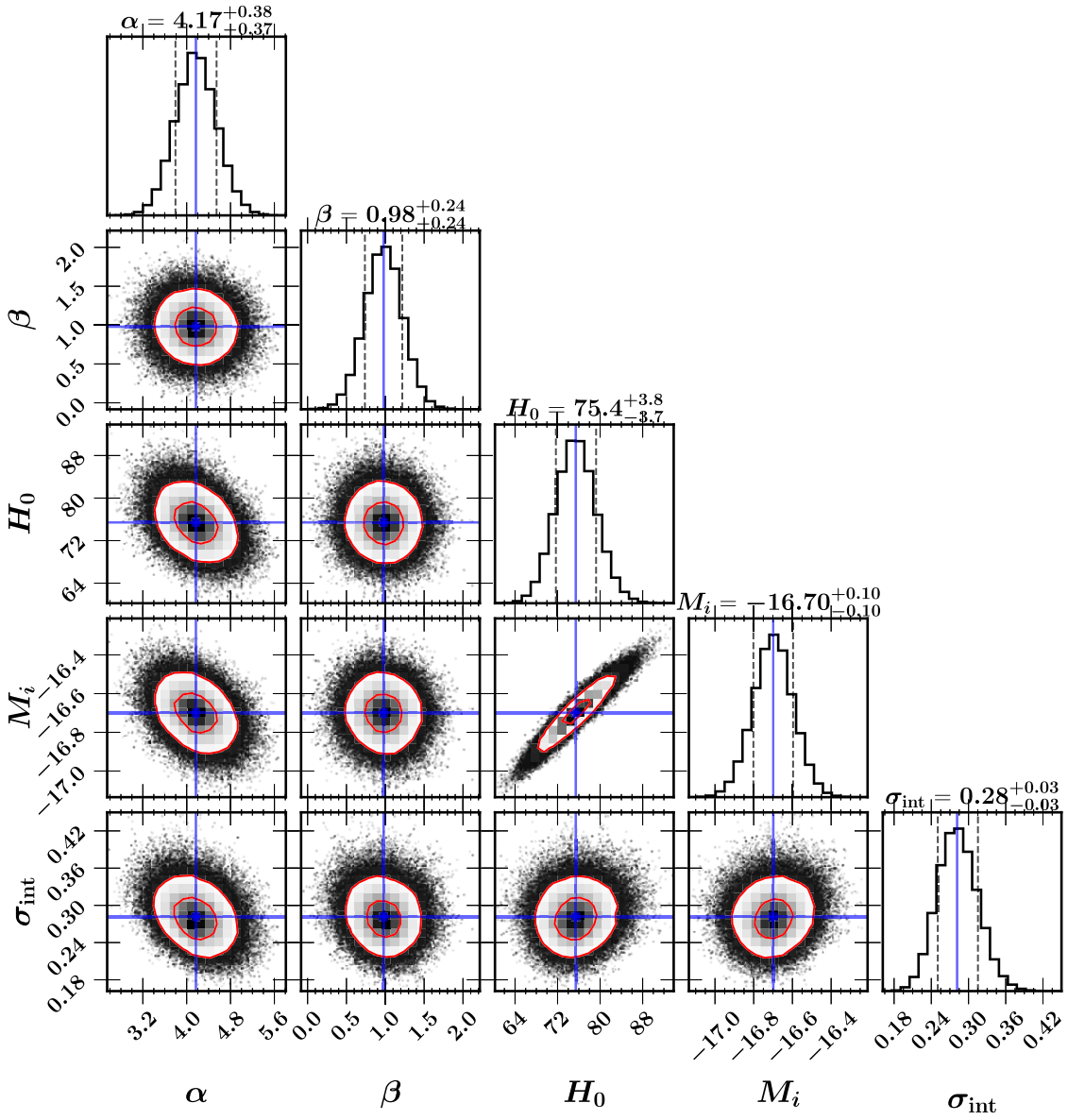


**Figure 2.** Corner plot showing all 1D and 2D projections of our fitted parameters: $\alpha$, $\beta$, $H_0$, $M_i$, and $\sigma_{\rm int}$. Data points shown in grey and red contours are given at $1\sigma$ and $2\sigma$ (which corresponds in two dimensions to the 39 and 86 per cent of the volume). For each parameter, the median value and the 16th and 84th percentile differences are shown.

inconsistent with the *Planck*+ΛCDM value, suggesting that neither points to the source of the tension.

Finally, two SNe II (SN 2004et and SN 2017eaw) with TRGB distance measurements have a large Milky Way extinction. If we remove them from our calibrator sample, $H_0$ increases to $77.0^{+4.4}_{-4.3}$ km s$^{-1}$ Mpc$^{-1}$ (difference of 2.2 per cent). We expect to find a higher value than in our fiducial model because after removing two TRGB distance measurements, the Cepheid calibrator sample size represents $\sim$ 63 per cent (versus $\sim$ 53 per cent) of all the calibrators. As the Cepheid $H_0$ value is larger than the TRGB $H_0$ value, our $H_0$ value excluding those two SNe II from the TRGB sample will move towards a higher value than our fiducial model.

Finally, we investigate the effect of the different surveys. Using only the CSP-I sample or removing it only affects our fiducial $H_0$ measurement by 0.5 per cent. The major differences are seen when only the low-$z$ KAIT sample is used or removed, producing a difference of 3.0 and 1.2 per cent, respectively. The largest difference could be explained by a small number of SNe II in the Hubble flow (19) or by intrinsic SN II differences. However, no significant differences are seen in the magnitude, velocity, and colour distributions of the CSP-I and KAIT surveys. Finally, excluding the two low-$z$ samples (CSP-I and KAIT) increases the $H_0$ value to $77.2^{+4.8}_{-4.4}$ km s$^{-1}$ Mpc$^{-1}$, a difference of 2.4 per cent.

All 13 $H_0$ measurements from the aforementioned analysis variants are consistent with our fiducial model. The median and standard deviation of all the variants are $75.1 \pm 1.5$ km s$^{-1}$ Mpc$^{-1}$, which corresponds to only 0.3 km s$^{-1}$ Mpc$^{-1}$ lower than our fiducial value (only $\sim$8 per cent of the statistical uncertainty). Following the conservative approach of Riess et al. (2019), our systematic uncertainty is calculated as the standard deviation of our variants. From the 13 variants presented in Table 2, we obtain a systematic uncertainty of $\sim$1.5 km s$^{-1}$ Mpc$^{-1}$ ($\sim$ 2 per cent). Includ-

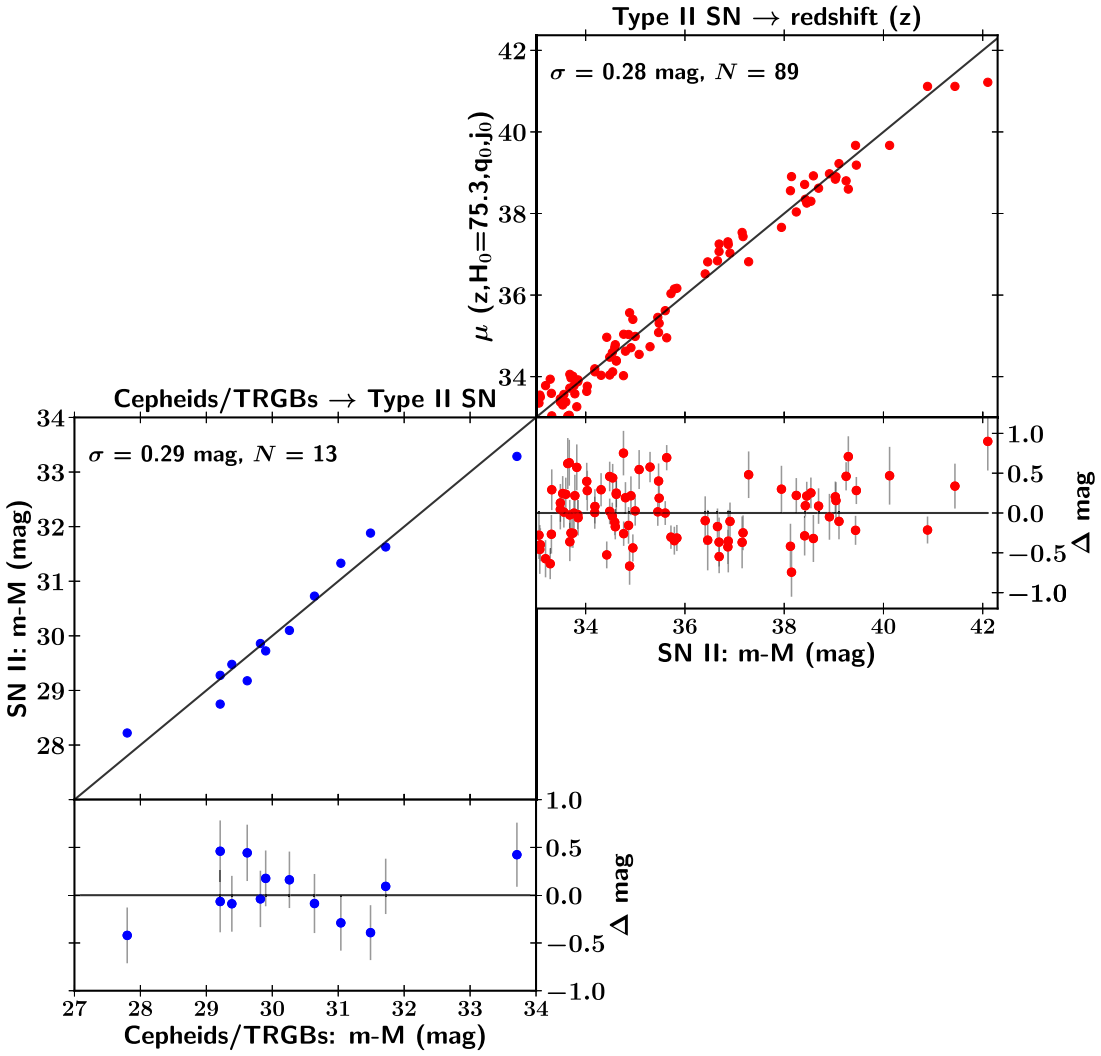


**Figure 3.** Figure similar to the SNe Ia figure of Riess et al. (2021a), representing the last two rungs of the distance ladder: Cepheid- and SN-based (bottom left), and SN- and redshift-based (top right). Blue dots represent the SNe II with geometric, Cepheid, or TRGB distances to estimate $M_i$. Red dots are the SNe II in the Hubble flow used to derive $H_0$.

ing both statistical and systematic uncertainties, our $H_0$ value is $75.4^{+3.8\ (\mathrm{stat})}_{-3.7\ (\mathrm{stat})} \pm 1.5\ (\mathrm{sys})\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. This is the most precise $H_0$ value obtained from SNe II with the SCM. Taking into account both sources of uncertainties, our value differs by $2.0\sigma$ from the high-redshift results (Planck Collaboration VI 2020) and by only $0.6\sigma$ from the local measurement (Riess et al. 2021a).

### 3.4 Bootstrap simulation

We perform a bootstrap resampling of the set of calibrators, with replacement (see Fig. 4), to study the calibrator effects on $H_0$. With 13 calibrators, we explore a total of 5200 300 possibilities (25!/13!12!) and obtain a median value of $75.5 \pm 3.7\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. The peak of the distribution is consistent with the original value and the local measurements using SNe Ia (Riess et al. 2021a), but almost does not overlap with the *Planck*+ΛCDM value. Only 1.4 per cent of the 5200 300 $H_0$ samples are smaller than $67.9\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, which corresponds to *Planck*+ΛCDM value $+1\sigma$. Finally, as in de Jaeger et al. (2020b), our distribution also extends to large $H_0$ values (85–95 $\mathrm{km\,s^{-1}\,Mpc^{-1}}$), and this behaviour is driven by the faintest calibrators (SN 2009ib, SN 2018aoq, and SN 2008bk).

## 4 CONCLUSIONS

In this work, we test the second and the third rungs of the SN Ia distance ladder. For this purpose, we use SNe II to provide an independent measurement of $H_0$. With 13 objects having geometric, Cepheid, or TRGB host-galaxy distance measurements, we derive $H_0 = 75.4^{+3.8}_{-3.7}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, where the quoted uncertainties are statistical only.

By analysing 13 variants to our fiducial model, we also investigate the possible sources of systematic error. We find that all 13 $H_0$ measurements are consistent with our fiducial model, and the median value only differs by $0.3\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. From our 13 variants, we obtain a standard deviation of $\sim 1.5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ ($\sim$2 per cent), which we interpret as an estimate of the systematic error in the SCM. Combining systematic and statistical uncertainties, we derive a value of $75.4^{+3.8}_{-3.7}$ (stat) $\pm 1.5$ (sys) $\mathrm{km\,s^{-1}\,Mpc^{-1}}$. Our value is consistent with the local measurement (Riess et al. 2021a) and differs by $2.0\sigma$ from the high-redshift results (Planck Collaboration VI 2020). Therefore, this demonstrates that there is no evidence that SNe Ia are the source of the '$H_0$ tension'; the third rung of the cosmic distance ladder, yielded by SNe Ia and SNe II, is consistent.

**Table 2.** Free-parameter values for different sample choices.

| Sample | Cali | $N_{cali}$ | $\sigma_{cali}$ (mag) | $N_{SNe}$ | $\alpha$ | $\beta$ | $H_0$ (km s$^{-1}$ Mpc$^{-1}$) | $M_i$ (mag) | $-5\,a_i$ (mag) | $\sigma_{int}$ (mag) | $\Delta H_0$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fiducial | C+T+G | 13 | 0.29 | 89 | $4.17^{+0.38}_{-0.37}$ | $0.98^{+0.24}_{-0.24}$ | $75.4^{+3.8}_{-3.7}$ | $-16.70^{+0.10}_{-0.10}$ | $-1.09^{+0.04}_{-0.04}$ | $0.28^{+0.03}_{-0.03}$ | ... |
| Peculiar-Velocity Variants | | | | | | | | | | | |
| $v_{pec} = 150$ | C+T+G | 13 | 0.29 | 89 | $4.15^{+0.38}_{-0.36}$ | $0.98^{+0.24}_{-0.25}$ | $75.3^{+4.0}_{-3.7}$ | $-16.70^{+0.10}_{-0.10}$ | $-1.08^{+0.04}_{-0.04}$ | $0.29^{+0.03}_{-0.03}$ | 0.2 per cent |
| $z_{cmb}$ | C+T+G | 13 | 0.29 | 89 | $4.11^{+0.37}_{-0.37}$ | $1.04^{+0.25}_{-0.24}$ | $75.0^{+3.8}_{-3.6}$ | $-16.70^{+0.10}_{-0.10}$ | $-1.08^{+0.04}_{-0.04}$ | $0.28^{+0.03}_{-0.03}$ | 0.5 per cent |
| $z_{corr} > 0.023$ | C+T+G | 13 | 0.29 | 47 | $4.36^{+0.53}_{-0.51}$ | $0.57^{+0.35}_{-0.34}$ | $77.6^{+4.7}_{-4.5}$ | $-16.80^{+0.12}_{-0.12}$ | $-1.25^{+0.05}_{-0.05}$ | $0.28^{+0.04}_{-0.04}$ | 2.9 per cent |
| $z_{corr} > 0.0$ | C+T+G | 13 | 0.29 | 116 | $4.24^{+0.34}_{-0.34}$ | $1.08^{+0.23}_{-0.23}$ | $74.4^{+3.7}_{-3.4}$ | $-16.64^{+0.10}_{-0.10}$ | $-1.00^{+0.03}_{-0.03}$ | $0.27^{+0.03}_{-0.03}$ | 1.3 per cent |
| Calibrator Sample Variants | | | | | | | | | | | |
| $z_{corr} > 0.01$ | C | 7 | 0.24 | 89 | $4.12^{+0.44}_{-0.43}$ | $0.88^{+0.25}_{-0.24}$ | $77.6^{+5.2}_{-4.8}$ | $-16.64^{+0.13}_{-0.13}$ | $-1.09^{+0.04}_{-0.04}$ | $0.28^{+0.03}_{-0.03}$ | 2.9 per cent |
| $z_{corr} > 0.01$ | T | 5 | 0.33 | 89 | $4.07^{+0.40}_{-0.40}$ | $1.04^{+0.28}_{-0.28}$ | $73.1^{+5.7}_{-5.3}$ | $-16.77^{+0.16}_{-0.16}$ | $-1.09^{+0.04}_{-0.04}$ | $0.29^{+0.03}_{-0.03}$ | 3.0 per cent |
| $-$04et, 17eaw | C+T+G | 11 | 0.28 | 89 | $4.11^{+0.39}_{-0.38}$ | $0.92^{+0.24}_{-0.25}$ | $77.0^{+4.4}_{-4.3}$ | $-16.65^{+0.12}_{-0.12}$ | $-1.09^{+0.04}_{-0.04}$ | $0.28^{+0.03}_{-0.03}$ | 2.2 per cent |
| Hubble-Flow Sample Variants | | | | | | | | | | | |
| Only CSP-I | C+T+G | 13 | 0.29 | 37 | $4.20^{+0.48}_{-0.47}$ | $0.98^{+0.32}_{-0.31}$ | $75.1^{+4.1}_{-3.9}$ | $-16.65^{+0.10}_{-0.10}$ | $-1.02^{+0.05}_{-0.05}$ | $0.27^{+0.04}_{-0.04}$ | 0.5 per cent |
| No CSP-I | C+T+G | 13 | 0.29 | 52 | $4.33^{+0.49}_{-0.48}$ | $0.96^{+0.31}_{-0.31}$ | $75.0^{+4.4}_{-4.1}$ | $-16.75^{+0.11}_{-0.11}$ | $-1.13^{+0.05}_{-0.05}$ | $0.28^{+0.05}_{-0.05}$ | 0.5 per cent |
| Only KAIT | C+T+G | 13 | 0.32 | 19 | $4.87^{+0.69}_{-0.67}$ | $1.29^{+0.40}_{-0.39}$ | $73.2^{+4.6}_{-4.5}$ | $-16.66^{+0.11}_{-0.10}$ | $-0.98^{+0.09}_{-0.08}$ | $0.26^{+0.09}_{-0.13}$ | 3.0 per cent |
| No KAIT | C+T+G | 13 | 0.29 | 70 | $4.00^{+0.40}_{-0.38}$ | $0.83^{+0.26}_{-0.26}$ | $76.3^{+4.0}_{-3.8}$ | $-16.70^{+0.10}_{-0.10}$ | $-1.11^{+0.04}_{-0.04}$ | $0.27^{+0.03}_{-0.03}$ | 1.2 per cent |
| CSP-I+KAIT | C+T+G | 13 | 0.29 | 56 | $4.36^{+0.43}_{-0.43}$ | $1.14^{+0.28}_{-0.28}$ | $74.4^{+4.1}_{-3.9}$ | $-16.65^{+0.10}_{-0.11}$ | $-1.01^{+0.05}_{-0.05}$ | $0.28^{+0.04}_{-0.04}$ | 1.3 per cent |
| 'high-$z$' | C+T+G | 13 | 0.29 | 33 | $4.11^{+0.53}_{-0.52}$ | $0.68^{+0.35}_{-0.35}$ | $77.2^{+4.8}_{-4.4}$ | $-16.78^{+0.12}_{-0.11}$ | $-1.22^{+0.06}_{-0.06}$ | $0.26^{+0.05}_{-0.05}$ | 2.4 per cent |

*Note.* Effect of systematic errors on the best-fitting values using the SCM and different samples. The fiducial line corresponds to the values obtained in Section 3.2, i.e. $z_{corr} > 0.01$, 13 calibrators, and 89 SNe II in the Hubble flow. We try different cuts in redshift ($z_{corr}$), surveys (e.g. only/no CSP-I, only/no KAIT, only CSP-I+KAIT, only high-$z$), calibrators [Cepheids (C) and/or TRGBs (T) and/or geometric (G)], and also remove some calibrators (e.g. $-$04et and $-$17eaw for SN 2004et and SN 2017eaw). The median value with the 16th and 84th percentile differences for each parameter are given together with their statistical uncertainties. The last column, $\Delta H_0$, corresponds to the percentage difference from the fiducial model.

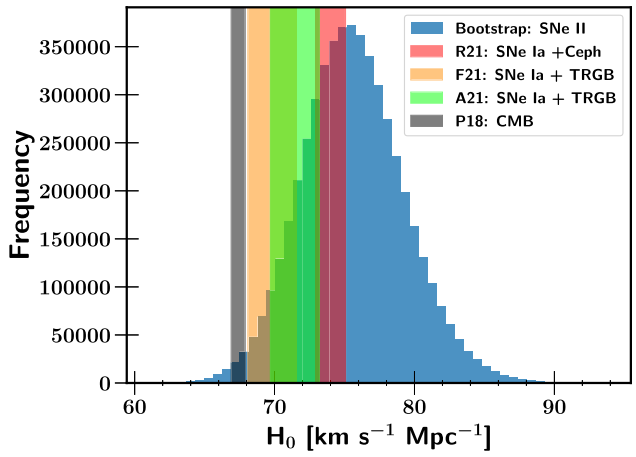


**Figure 4.** Histogram of our bootstrap resampling of the set of calibrators, with replacement. This histogram consists of 51 bins and contains a total of 5200 300 simulations. An average value of $75.5 \pm 3.7$ km s$^{-1}$ Mpc$^{-1}$ is derived. The red, orange, lime, and black filled regions correspond to the $H_0$ values obtained (respectively) by Riess et al. (2021a), Freedman (2021), Anand et al. (2022), and Planck Collaboration VI (2020). Only 1.4 per cent of the 5200 300 $H_0$ values are smaller than $67.4 + 0.5$ km s$^{-1}$ Mpc$^{-1}$ (Planck Collaboration VI 2020).

We also perform a bootstrap simulation to study the calibrator effects on $H_0$. The peak of our distribution is consistent with the local measurements using SNe Ia (Riess et al. 2021a) but almost does not overlap with the *Planck*+$\Lambda$CDM value. Only 1.4 per cent of the 5200 300 $H_0$ values are smaller than 67.9 km s$^{-1}$ Mpc$^{-1}$ which corresponds to the *Planck*+$\Lambda$CDM value $+1\sigma$.

Finally, with the availability of two sources of calibration, Cepheids or TRGB, we investigate the role of either in the '$H_0$ tension.' With seven Cepheids or five TRGB, we derive consistent values which differ by $<1.0\sigma$ (difference of 4.5 km s$^{-1}$ Mpc$^{-1}$ between Cepheids and TRGB). Both values are also in the range of several other local measures (Di Valentino et al. 2021). Thus, despite the larger uncertainties of our values, we find no indication of Cepheids or TRGB as the source of the '$H_0$ tension.' This is in good agreement with the results from Blakeslee et al. (2021), Kourkchi et al. (2022), Anand et al. (2022), and Riess et al. (2021a), who found no significant difference in $H_0$ between the use of Cepheids and TRGB.

With upcoming studies, we will increase the number of SNe II in the Hubble flow and reduce the systematic uncertainties due to peculiar velocities. Also, as shown in this paper, with a larger number of calibrators, we will be able to reduce our statistical uncertainty. Finally, having more Cepheid and TRGB distance measurements will allow us to better test the second rung of the distance ladder and see whether there is a systematic difference between both calibrators.

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*Software:* ASTROPY (Astropy Collaboration 2013), MATPLOTLIB (Hunter 2007), NUMPY (Harris et al. 2020), SCIPY (Virtanen et al. 2020), triangle v0.1.1. Zenodo. 10.5281/zenodo.11020.

## DATA AVAILABILITY

The majority of the data have already been published and can be found in Poznanski et al. (2009) (KAIT-P09), D'Andrea et al. (2010) (SDSS-SN), de Jaeger et al. (2017a) (HSC), de Jaeger et al. (2019) (KAIT-d19), and de Jaeger et al. (2020a) (DES-SN). CSP-I and SNLS data will be shared on reasonable request to the corresponding author.

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