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Constraining the Hubble constant and its lower limit from the proper motion of extragalactic radio jets

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ABSTRACT

The Hubble constant ($H_0$) is a measurement to describe the expansion rate of the Universe in the current era. However, there is a 4.4σ discrepancy between the measurements from the early Universe and the late Universe. In this research, we propose a model-free and distance-free method to constrain $H_0$. Combining Friedman–Lemaître–Robertson–Walker cosmology with geometrical relation of the proper motion of extragalactic jets, the lower limit ($H_{0_{\text{min}}}$) of $H_0$ can be determined using only three cosmology-free observables: the redshifts of the host galaxies, and the approaching and receding angular velocities of radio jets. Using these, we propose to use the Kolmogorov–Smirnov test (K–S test) between cumulative distribution functions of $H_{0_{\text{min}}}$ to differentiate cosmology. We simulate 100, 200, and 500 extragalactic jets with three levels of accuracy of the proper motion ($\mu_0$ and $\mu_z$), at 10, 5, and 1 per cent, corresponding to the accuracies of the current and future radio interferometers. We perform K–S tests between the simulated samples as theoretical distributions with different $H_0$ and power-law index of velocity distribution of jets and mock observational data. Our result suggests increasing sample sizes leads to tighter constraints on both power-law index and the Hubble constant at moderate accuracy (i.e. 10 and 5 per cent), while at 1 per cent accuracy, increasing sample sizes leads to tighter constraints on power-law index more. Improving accuracy results in better constraints in the Hubble constant compared with the power-law index in all cases, but it alleviates the degeneracy.

Key words: proper motions – galaxies: jets – cosmological parameters.

1 INTRODUCTION

Approximately a century ago, the Universe was found to be expanding (Hubble 1929). The Hubble parameter, $H(z)$, describes the expansion rate of the Universe. Its value in the current era ($z = 0$), known as the Hubble constant, is denoted by $H_0$. Numerous measurements of the Hubble constant observed from different methods have been proposed to measure the values during the past few decades. For instance, cosmic microwave background, remnant of the big bang in the early Universe, is a standard ruler as a cosmological probe. One of the latest measurements from Planck Collaboration VI (2020) suggested $H_0 = 67.27 \pm 0.60$ km s$^{-1}$ Mpc$^{-1}$. Additionally, the method of the distance ladder, such as Cepheid variables in the late Universe, can be used to constrain the Hubble constant directly. The Supernova H0, for the Equation of State (SH0ES; Riess et al. 2021), which adopted the method of distance ladder, utilized Cepheids to calibrate 42 Type Ia supernovae in the same host galaxies and obtained a value of $H_0 = 73.04 \pm 1.04$ km s$^{-1}$ Mpc$^{-1}$. Other methods such as using baryon acoustic oscillations (e.g. Eisenstein et al. 2005; Cuceu et al. 2019), big bang nucleosynthesis (e.g. Cuceu et al. 2019; Seto & Toda 2021), strong gravitational lensing of quasars (e.g. Wong et al. 2020), water masers (e.g. Herrnstein et al. 1999; Humphreys et al. 2013), and gravitationally lensed supernova (e.g.Refsdal 1964; Vega-Ferrero et al. 2018) were also utilized to measure the Hubble constant.

However, as we obtain more precise measurements, the results conducted from the early Universe further reveal an inconsistency.

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with the Hubble constant from the late Universe. This discrepancy is known as ‘Hubble tension’ and indicates a tension beyond 4.4σ (e.g. Verde, Treu & Riess 2019). The reason for the tension is still under debate. One possible theory is that there may be hints of new physics beyond the Lambda cold dark matter model. For instance, there are popular theories such as the early dark energy (e.g. Poulin et al. 2019), acoustic dark energy (e.g. Yin 2020), or importing sterile neutrino (e.g. Adhikari et al. 2017) trying to tackle this issue. In terms of observation, aside from observing standard candles and standard rulers, several new methods have also been proposed to address this discrepancy for the next generation. For example, since gravitational waves (GWs) act as standard sirens, an independent way to infer luminosity distance from their amplitudes (Schutz 1986), some studies suggested constraining cosmological parameters using GWs in the future (e.g. Abbott 2017; Chen, Fishbach & Holz 2018). Besides, fast radio bursts, radio pulses with millisecond time-scale, can also be used to constrain cosmology thanks to their unique observable quantities, dispersion measure (e.g. Li et al. 2018; Wu, Zhang & Wang 2021), and duration–luminosity relation (e.g. Hashimoto et al. 2019).

Relativistic jets are one of the energetic phenomena that produce piercing matter from regions near compact objects such as black holes and neutron stars. These robust plasma flows are expected to be along the axis of rotation of the host object. Although the relation between the accretion disc and the relativistic jets is still in debate, it is believed that the jets are driven by the tangled magnetic field (e.g. Blandford & Znajek 1977; Hawley & Balbus 2002; McKinney & Gammie 2004). Previous studies revealed that it is possible to extract the information of the Hubble constant from the proper motion of jets (e.g. Lynden-Bell 1977; Taylor & Vermeulen 1997; Qin 1999; Lu & Qin 2021) and with GWs (e.g. Hotokezaka et al. 2019). Therefore, the observation of jets has the potential to help us relieve the Hubble tension.

In this paper, we adopt the method proposed by Qin (1999) (see also Taylor & Vermeulen 1997) to calculate the lower limit of the Hubble constant through the Friedman–Lemaître–Robertson–Walker (FLRW) cosmology and geometrical proper motion of extragalactic radio jets. With only the redshifts, and the receding and approaching angular velocities, the lower limit of the Hubble constant can be determined. The first measurement originated from Taylor & Vermeulen (1997), suggesting $H_{0,\text{min}} = 37 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Qin (1999) adopted a similar method and suggested $27.08 \text{ km s}^{-1} \text{ Mpc}^{-1} < H_{0,\text{min}} < 53.15 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Lu & Qin (2021) made use of an extragalactic radio source, NGC 1052, located at $z = 0.005$. Their results suggested the lower limit of the Hubble constant is $H_{0,\text{min}} = 51.5 \pm 2.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$, which successfully follows the method of Taylor & Vermeulen (1997) in constraining the Hubble constant. Apparently, the latest constraint from proper motion is not enough to relieve the Hubble tension. Therefore, in this paper, we investigate how well $H_0$ can be constrained from $H_{0,\text{min}}$ distributions by simulating samples of observed speeds in nearby bidirectional active galactic nucleus (AGN) jets. Furthermore, we perform Kolmogorov–Smirnov tests (K–S tests; Massey 1951) to compare the cumulative distribution function (CDF) of the mock data to theoretical distribution. K–S test aims to compare whether two distributions are drawn from the same distributions, in order to obtain further information of $H_0$ and power-law index $k$ based on the CDF of $H_{0,\text{min}}$.

The structure of this paper is as follows. We describe the theoretical framework and our method in Section 2. In Section 3, we present the results and distributions of $H_{0,\text{min}}$ from our simulation according to two different cosmologies, and further constrain $H_0$ and $k$ from K–S tests. The conclusion of this study is summarized in Section 4. We assume concordance cosmology with $(\Omega_m, \Omega_{\Lambda}, h) = (0.3, 0.7, 0.7)$, unless otherwise mentioned.
2 METHODOLOGY

According to FLRW cosmology, the Hubble law for a nearby extragalactic source with $z \ll 1$ can be written as follows:

$$\frac{D_h}{1 + z} \approx \frac{cz}{H_0},$$

(1)

where $D_h$ is the luminosity distance and $c$ is the speed of light.

In terms of the geometry, considering a bisymmetric relativistic jet, the proper motion of the receding and approaching jets can be illustrated (e.g. Rees 1966; Behr et al. 1976; Blandford, McKee & Rees 1977; Blandford & Königl 1979; Mirabel & Rodríguez 1994)

$$\mu_{\pm} = \frac{\beta \sin \theta \left(1 + z\right)}{1 \pm \beta \cos \theta} \frac{c}{D_h},$$

(2)

where $\mu_r$ and $\mu_a$ are the proper motions of receding and approaching jets, respectively, $\beta$ is the ratio between the jet velocity and the speed of light ($v/c$), while $\theta$ is the angle between the velocity vector of the approaching jet and the line of sight. Equations (1) and (2) yield (see also Qin 1999; Lu & Qin 2021)

$$H_0 \simeq \frac{2h_0 \mu_r z}{\sqrt{\beta^2 (\mu_a + \mu_r)^2 - (\mu_a - \mu_r)^2}}.$$

(3)

Lastly, since velocity must be smaller than the speed of light ($\beta < 1$), we obtain a relation among the lower limit of the Hubble constant, proper motion, and redshift:

$$H_{0,\min} = Z \sqrt{\mu_a \mu_r}.$$

(4)

We note that there are assumptions that the jets are straight and oppositely directed, and have identical bulk flow speed. If the velocity is higher (especially close to the speed of light), the $H_{0,\min}$ will be close to the true $H_0$ at any fixed $\theta$. Contours of how $\theta$ and $\beta$ will change the fraction of $H_{0,\min}/H_0$ are shown in Fig. 1. In principle, if there is a fraction of the speed of jets that is close to the speed of light, we expect to obtain an $H_{0,\min}$ that is close to $H_0$ from those samples. Therefore, this method provides a model-free and distance-free way to constrain the Hubble constant only from geometry and FLWR cosmology, and may be able to alleviate $H_0$ tension.

We note that due to the relativistic beaming effect (or the Doppler boosting), the receding jets are not easily observed (e.g. Wilkinson et al. 1977; Bridle & Perley 1984; Sparks et al. 1992; Laing & Bridle 2002). For an ideal relativistic jet, the observed luminosity can be expressed as (e.g. Blandford & Königl 1979; Cohen et al. 2007)

$$L_{\text{obs}} = L_{\infty} \beta^{(\alpha - 1)}.$$

(5)
where \( L_{\text{obs}} \) is the observed luminosity and \( L_{\text{int}} \) is the intrinsic luminosity. \( \delta \) is the Doppler factor [\( \delta = \gamma^{-1}(1 - \beta \cos(\theta))^{-1} \)], and \( \gamma \) is the Lorentz factor [\( \gamma = 1/\sqrt{1 - \beta^2} \)]. \( \alpha \) is the spectral index. \( p \) is the Doppler boost exponent (for more detail, see Cohen et al. 2007). Contours of Doppler factor \( \delta \) as a function of \( \gamma \) and \( \theta \) are shown in Fig. 2. For example, in the catalogue of Monitoring Of Jets in Active galactic nuclei with VLBA Experiments (MOJAVE) programme (Lister & Homan 2005; Homan et al. 2021), the two-sided jets account for \( \sim 18 \) per cent of total sources. In this research, we simply assume the samples are those that have two-sided jets.

We propose a new method to test how well we can recover \( H_0 \) and the power-law index, \( k \) (see the explanation in the next paragraph) from the distribution of \( H_{0,\text{min}} \) gave a fixed sample size and a typical measurement error in the future. In this process, in addition to the high Lorentz factor jets, we also utilize lower Lorentz factor jets, in fact, we use the whole distribution to estimate \( H_0 \). In this way, the usable sample size becomes much larger. By conducting the K–S test between mock observational data (fixed \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\) and \( k = -1.5 \)) and the theoretical CDFs (with different prior \( H_0 \) and prior \( k \)), the \( p \)-value, a similarity of two profiles, can be represented as probabilities of \( H_0 \) and \( k \). We simulate a large number of jets, i.e. \( 10^5 \), with \( H_{0,\text{min}} \), as theoretical distributions for each point between \( 65 \) km s\(^{-1}\) Mpc\(^{-1}\) \( < H_0 < 75 \) km s\(^{-1}\) Mpc\(^{-1}\) and \( -1 \) \( < k < -2 \). Fig. 3 shows how the true \( H_0 \) and \( k \) changes the features of CDFs. Figs 4 and 5 show how our idea works. 1 per cent error on the measurement of proper motions and 100 sources are assumed for the mock observational data here. Since the feature of a CDF of \( H_{0,\text{min}} \) changes when \( H_0 \) changes, \( p \)-values from K–S tests will be small when \( H_0 \) of the observational data does not match that of the theoretical one, and vice versa. For example, in the upper panels of Fig. 4, we compare the similarity via the K–S test of the mock observational data (shown in blue curves) and the theoretical curves (the orange, the yellow, and the green curves are assumed \( H_0 = 65, H_0 = 70, \) and \( H_0 = 75 \) km s\(^{-1}\) Mpc\(^{-1}\), respectively). The similarity between mock observational data and the yellow curve is the highest (\( p \)-value is the highest). Therefore, we infer the \( p \)-value as a probability as a function of \( H_0 \) to constrain \( H_0 \). After we conduct K–S tests between the mock observational data and the theoretical CDFs under different \( H_0 \) and \( k \), we are able to constrain \( H_0 \) from the statistical \( p \)-value as a function of \( H_0 \) and \( k \).

For both mock observational data and the theoretical data, we consider a distribution of the velocity following the power-law distribution (e.g. Lister & Marscher 1997; Lister 2003; Cara & Lister 2008; Ajello et al. 2012; Lister et al. 2016; Yuan et al. 2018):

\[
P_v(\gamma) = C \gamma^k,
\]

where \( C \) is a normalized factor, \( k \) is a power-law index. We assume \( k = -1.5 \) for the mock observational data, which is the best fit suggested by superluminal motions (Lister & Marscher 1997). The interval of the velocity is set to be \( 1.01 \leq \gamma \leq 100 \) (e.g. Yuan et al. 2018). The samples are randomly distributed within the spatial

![Figure 5. Similar to Fig. 4 but as a function of \( k \).](image-url)
volume (i.e. population has constant space density) between $0 < z < 0.02$ and $0 < \theta < \pi/2$. Note that for 3-dimensionally oriented two-sided jets, random jet viewing angles in the population $P(\theta, \theta + d\theta) \propto \sin(\theta)d\theta$ (e.g. Law et al. 2009). The effects of Doppler orientation bias may be minimal for $z < 0.02$ and the effects are ignored in the simulation for simplification. The $H_0$ of mock observational data is set to be $70\text{ km s}^{-1}\text{ Mpc}^{-1}$. As a result, we calculate $\mu_x$ and $\mu_y$ for each jet according to equation (2). After the simulation, we construct $H_{0,\text{min}}$ based on equation (4). As for the uncertainty, it depends not only the angular resolution and the distance to the object but also depends strongly on total time coverage and cadence, the brightness temperature of the moving feature, the relative stability of the core (reference point), confusion with nearby jet features, and possible accelerations/non-linear motions (e.g. Lister et al. 2021; Weaver et al. 2022). For simplicity, we simulate $\mu_x$ and $\mu_y$ with the observational uncertainty of 10, 5, and 1 per cent, which is based on the uncertainties in the MOJAVE programme (Homan et al. 2021). In addition, we assume three sets of jets: 100, 200, and 500 jets, which correspond to $\sim 20$, $\sim 40$, and $\sim 100$ per cent of the number of the jets in the MOJAVE programme. Furthermore, there are $\sim 120$ radio galaxies at $z < 0.02$ with jets/lobes structure from 2 Micron All-Sky Survey Redshift Survey (van Velzen et al. 2012). We expect that observing the nearby sources with higher sensitivity radio telescopes will increase the sample size. To estimate errors of $H_{0,\text{min}}$, we conducted each simulation 1000 times by adding randomized errors (i.e. 10, 5, and 1 per cent) to $\mu_x$ and $\mu_y$.

3 RESULTS AND DISCUSSION

Aside from the highest values of $H_{0,\text{min}}$, a comparison of the whole distribution between theoretical and mock data is also meaningful. Hence, we propose to perform the K–S test to confirm if the two distributions are statistically different. By assuming different cosmology and simulating a large enough number of jets (i.e. $10^5$), we perform K–S tests between the mock observational data with the theoretical CDF. Figs 6 to 11 show examples of the $p$-values as a function of $H_0$ and $k$ from K–S tests between mock observational data and theoretical profile under different configurations. As expected, all of the constraints are centred on the value we assume for the mock observational data ($H_0 = 70\text{ km s}^{-1}\text{ Mpc}^{-1}$ and $k = -1$). Figs 6, 7, and 8 demonstrate the constraints of increasing sample sizes under a fixed accuracy (i.e. 1, 5, and 10 per cent, respectively). Figs 9, 10, and 11 demonstrate the constraints of improving accuracy under a fixed sample size (i.e. 500, 200, and 100 jets, respectively). Our result indicates that when $k$ and $H_0$ are close to the real physics in the Universe, $p$-values are higher. However, there is a degeneracy when the accuracy of jets is high. Figs 6 to 8 demonstrate that
if we increase sample sizes, the constraint becomes tighter while the degeneracy remains. Interestingly, we also find that increasing sample sizes leads to tighter constraints on both power-law index and the Hubble constant at moderate accuracy (i.e. 10 and 5 per cent), while at 1 per cent accuracy, increasing sample sizes leads to tighter constraints on power-law index more. According to Figs 9 to 11, improving accuracy results in better constraints in the Hubble constant compared with the power-law index in all cases, but it also alleviates the degeneracy.

In Fig. 12, we show the expected error to be constrained of $H_0$ (the upper panel) and $k$ (the lower panel) under different sample sizes and the accuracy of the measurement. Compared with the uncertainties from the SH0ES (Riess et al. 2021) and Planck (Planck Collaboration VI 2020) measurements, our result indicates that if we can meet the criteria of 1 per cent accuracy, the error of $H_0$ constrained from the K–S tests will be more accurate. It is also clear that at 10 and 5 per cent uncertainties, increasing sample sizes will lead to tighter constraints. However, the constraint saturates at 1 per cent accuracy, which suggests increasing the sample size cannot improve the uncertainties as good as those at 10 and 5 per cent. As can be seen in Fig. 12, $H_0$ can be determined within 1 per cent with 500 jets with 1 per cent accuracy. Besides, increasing the sample size alone to 500 jets with 10 per cent accuracy meets the precision at the SH0ES level. As for the power-law index $k$, increasing sample sizes lead to tighter error compared with improving the accuracy of the proper motion.

We also note that due to the Doppler beaming effect (see the details in Section 2), many receding jets are not easily observable. In our simulations, we simply assume that all jets among our samples have measurable receding jets. The Doppler deboosting effect makes the receding jets dimmer. Improving the integration time and the sensitivity of the telescope will help us to address this issue in the future. Besides, our method requires a large enough sample size to have a meaningful statistical result from the K–S test. For instance, in the MOJAVE programme, there are $\sim$90 jets that are two-sided out of $\sim$500 samples. Many of the samples are only detected one-sided due to the Doppler boosting effect. We suggest three ways to increase the sample size. The first way is to increase the total sample of radio sources. Ongoing and future radio sky surveys such as the Very Large Array Sky Survey (Lacy et al. 2020) are expected to detect 10 million radio sources including radio galaxies (with two-sided jets). The second way is to improve the sensitivity of the telescope. Once the limiting magnitude reaches the brightness of the receding jets, we will be able to measure the proper motions from both jets. For example, for an approaching jet with $\gamma = 3$ and $\theta = \pi/6$, the Doppler factor is $\sim 1.82$. Therefore, the Doppler factor of the receding jet is expected to be $\sim 0.18$. Adopting $p - \alpha = 3$ in equation (5), the receding jet is $\sim 1000$ times fainter than the approaching jet due to the

Figure 7. Same as Fig. 6 but the accuracy is fixed to 5 per cent.
Doppler deboosting effect (and boosting effect for the approaching jet). If the signal-to-noise ratio of the approaching jet is 1000 (e.g. Baczko et al. 2019; Lister et al. 2019), improving the sensitivity to ∼3 to ∼5 times better will be able to detect it. Hovatta et al. (2009) calculated the Doppler factors of quasars, BL Lacertae objects, and radio galaxies. The sources with low Doppler factors are worth further observation on the receding jets when improving sensitivity in the near future. The third way is to monitor the two-sided jets that have not been monitored before. For instance, in the catalogue of FR I radio galaxies (with 219 FR I radio galaxies), FRICAT (Capetti, Massaro & Baldi 2017), many jets are two-sided but only have image data, which suggests those jets have no measurement of proper motions.

In addition, it might be difficult to collect many proper motions of twin jets with high Lorentz factor, especially the receding components. Therefore, we also test whether the method still works under different maximum values of the velocity (γ_{upper}). In our mock observational data, we adopt γ_{upper} = 100. We show how CDF changes under different γ_{upper} in Fig. 13. Regarding H_0 and k, γ_{upper} does not affect the CDF significantly. Here, we gradually reduce the maximum value of the Lorentz factor for the theoretical CDF and conduct K–S tests with the mock observational data. The assumption of the mock observational data is identical to that in Fig. 4, with 100 jets and 1 per cent accuracy. The result is shown in Fig. 14, which suggests that the critical value is at γ_{upper} ∼ 30. Values with γ_{upper} > 30 have p-values higher than 0.05. Once the maximum value of the Lorentz factor is smaller than the critical value, 30, our method fails with p-values smaller than 0.05.

Based on fig. 2 and table 1 of Pracy et al. (2016), there are ∼2200 radio galaxies at z < 0.3. Assuming the ratio of two-sided jets and total jet sample in the MOJAVE programme (∼ 90/ ∼ 500 ∼ 18 per cent), we expect there are 2200 × 18 per cent ∼ 400 two-sided jets in the radio galaxy catalogue. Conducting VLBA to observe such samples will bring the two-sided jets to 500, including the 90 in the MOJAVE programme. In the MOJAVE programme, they monitored 447 AGN jets from 25-yr multi-epoch observations (Homan et al. 2021). Thus, if aiming at these two-sided jets, ∼20 yr of observation at different epochs to measure the proper motion (e.g. ∼ 1 mas yr^{-1} for a jet of β ∼ 0.6 at z ∼ 0.005; ∼ 100 μas yr^{-1} for a jet of β ∼ 0.9 at z ∼ 0.3; Baczko et al. 2019) with VLBA (∼mas resolution) may increase the sample size of two-sided jets to ∼500 in the local Universe. The uncertainties of the proper motions reach ∼ 5 μas level with integration times of 30–50 min (e.g. Lister et al. 2019). Also, the radio galaxies included in Pracy et al. (2016) have criteria with flux density at 1.4GHz > 2.8 mJy. Therefore, MOJAVE VLBA with image rms levels of ∼ 0.1 mJy beam^{-1} is promising to detect and monitor these radio galaxies.
Figure 9. Constraints of $H_0$ and $k$. Three contours show constraints with improving accuracy under the same sample size (500 jets). Outer contours (solid lines) are 0.01 significance while inner contours (dotted lines) are 0.05 significance for each scenario. Planck and SH0ES measurements are shown in 2σ.

Figure 10. Same as Fig. 9 but the sample size is fixed to 200 jets.
Last but not least, if there are too few samples in the nearby Universe, we can extend to higher redshift as long as the approximation of the FLRW metric still works. Moreover, even if the approximation fails at high redshift, if we assume cosmological parameters other than $H_0$, we can extend this method to higher redshifts. For instance, for $\beta = 0.9999$ ($\gamma \sim 70$, $\theta = \pi/2$, the $H_0$ is only $\sim 1$ per cent more than the assumed $H_0$ at $z = 0.05$. We can also revise the redshift distribution based on the distribution from observation for theoretical (simulated) CDFs.

4 CONCLUSION

Based on FLRW cosmology and geometrical relation of the proper motion, the lower limit ($H_{0\text{,min}}$) of the Hubble constant ($H_0$) can be determined only with three cosmology-free observables: redshift, approaching proper motion, and receding proper motion. We propose a new method, performing K–S tests between the observational (mock) data and the theoretical CDF of different $H_0$ and $k$, in order to constrain $H_0$ and $k$. We simulate $10^5$ jets as a numerical distribution of $H_{0\text{,min}}$ and $k$ between $65 \text{ km s}^{-1} \text{Mpc}^{-1} < H_0 < 75 \text{ km s}^{-1} \text{Mpc}^{-1}$ and $-1 < k < -2$ as theoretical distributions and create mock observational data. The result shows that we can simultaneously constrain $H_0$ and $k$. If the values of $H_0$ and $k$ are close to the real Universe, $p$-values are higher. We find that there is a degeneracy between $H_0$ and $k$ when the accuracy is high (e.g. 10 per cent).

Interestingly, we also find that increasing sample sizes leads to tighter constraints on both power-law index and the Hubble constant at moderate accuracy (i.e. 10 and 5 per cent), while at 1 per cent accuracy, increasing sample sizes leads to tighter constraints on power-law index more. Improving accuracy results in better constraints in the Hubble constant compared with the power-law index in all cases, but it also alleviates the degeneracy. In the future, we will be able to alleviate the Hubble tension by the distribution of $H_{0\text{,min}}$ calculated from the proper motion and we could also further constrain $H_0$ and $k$.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.
Figure 12. The errors ($p$-value $>0.05$) under different configurations. The upper panel shows the errors of $H_0$ with different sample sizes and different accuracies compared with the previous error ($2\sigma$ are shown to compare fairly with our $p$-value $=0.05$) of the $H_0$ measurement of SH0ES (Riess et al. 2021) and Planck (Planck Collaboration VI 2020). The lower panel shows the errors of $k$ under different configurations.

Figure 13. Similar to Fig. 3, CDFs of $H_{0\text{min}}$ under different prior $\gamma_{\text{upper}}$.

Figure 14. The $p$-value as a function of $\gamma_{\text{upper}}$. The mock observational data are same as the data presented in Fig. 4.

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Constraining $H_0$ from the proper motion

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