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Evidence for cosmic acceleration with next-generation surveys: a model-independent approach

Carlos A. P. Bengaly [1,2]★
[1] *Department of Physics and Astronomy, University of the Western Cape, Cape Town 7535, South Africa*
[2] *Département de Physique Théorique, Université de Genève, 24 quai Ernest Ansermet, CH-1211 Genéve 4, Switzerland*

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ABSTRACT

We quantify the evidence for cosmic acceleration using simulations of $H(z)$ measurements from SKA- and Euclid-like surveys. We perform a non-parametric reconstruction of the Hubble parameters and its derivative to obtain the deceleration parameter $q(z)$ using the Gaussian Processes method. This is a completely model-independent approach, so we can determine whether the Universe is undergoing accelerated expansion *regardless* of any assumption of a dark energy model. We find that Euclid-like and SKA-like band 1 surveys can probe cosmic acceleration at over 3 and 5σ confidence level, respectively. By combining them with an SKA-like band 2 survey, which reaches lower redshift ranges, the evidence for a current accelerated phase increases to over 7σ. This is a significant improvement from current $H(z)$ measurements from cosmic chronometers and galaxy redshift surveys, showing that these surveys can underpin cosmic acceleration in a model-independent way.

Key words: cosmology: observations – cosmology: theory – (cosmology:) large-scale structure of the Universe.

1 INTRODUCTION

The evidence of late-time cosmic acceleration is one of the biggest scientific discoveries of the last decades (Riess et al. 1998; Perlmutter et al. 1999). It is ascribed to dark energy that accounts for roughly 68 per cent of the material content of the Universe (Planck collaboration VI 2018). The best candidate to explain this phenomenon is the so-called Cosmological Constant Λ, which is commonly associated with the vacuum density energy of the Universe. Combined with cold dark matter (CDM), responsible for cosmic structure formation, we have the ΛCDM model, i.e. the standard model of cosmology at the present moment. Although the ΛCDM model is able to provide the best explanation for the cosmological observations thus far, it is plagued with coincidence and fine-tuning problems. Since its 'discovery', many attempts have been envisaged to address these issues – see Li et al. (2011) and Clifton et al. (2012) for reviews on this topic. None the less, ΛCDM remains the best candidate we have.

Given the still unknown nature of the current accelerated expansion, it is essential to quantify how well we can detect this phenomenon, since it could rule out the standard model, and even the possibility of the existence of the dark energy paradigm as a whole. Within the context of the standard model, cosmological observations show that the Universe is currently accelerating at roughly 5σ level (Shapiro & Turner 2006; Ishida et al. 2008; Giostri et al. 2012; Rubin & Hayden 2016; Vargas dos Santos, Reis & Waga 2016; Harisadu et al. 2017; Tutusaus et al. 2017; Lin, Li & Sang 2018; Rubin & Heitlauf 2019), albeit this result was recently disputed using the Hubble diagram of Type Ia Supernovae (Nielsen, Guffanti & Sarkar 2016; Ringermacher & Mead 2016; Dam, Heinesen & Wiltshire 2017; Colin et al. 2019a, 2019b; Rameez 2019) and quasars (Lusso et al. 2019; Velten & Gomes 2020; Yang et al. 2019). Other works looked at model-independent probes of cosmic acceleration, thus independent of dark energy, and even General Relativity assumptions, such as kinematic analyses (Rapetti et al. 2007; Cunha & Lima 2008; Carvalho et al. 2011; Lu, Xu & Liu 2011; Nair, Jhingan & Jain 2012; Muthukrishna & Parkinson 2016; Capozziello, D'Agostino & Luongo 2018; Heneka 2018; Jesus, Holanda & Pereira 2018), besides non-parametric approaches (Mortsell & Clarkson 2009; Blake et al. 2011; Harisadu et al. 2018; Velten, Gomes & Busti 2018; Arjona & Nesseris 2019; Gómez-Valent 2019; Jesus et al. 2019; Tutusaus, Lamine & Blanchard 2019). These works found at least moderate evidence ($>2\sigma$) for present time accelerated expansion using existing data.

In this work, we rely on the latter approach to probe the current cosmic acceleration evidence. We adopt a non-parametric method called Gaussian Process for this purpose. We focus on forecasting how well Hubble parameter measurements, $H(z)$, from future redshift surveys mimicking the specifications of Euclid galaxy and SKA intensity mapping – hereafter Euclid-like and SKA-like surveys, respectively. These measurements can be obtained from the Baryonic Acoustic Oscillation scale of the galaxy clustering (see Bengaly, Clarkson & Maartens 2019 for a thorough explanation about this).

Rather than focusing on the *value* of q_0, as many authors do, we shall focus on determining the *uncertainty* of its measurement – and hence how well can we probe the evidence for a positive accelerated phase of the Universe today. To do so, we perform a non-parametric reconstruction of the deceleration parameter $q(z)$, which is a quantity that directly depends on $H(z)$ and its first derivative with respect to the redshift, in order to determine q_0, its current value. We find that these surveys will deliver significant improvement

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★ E-mail: carlosap@on.br

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on q_0 constraints compared to current observational data and that this result is totally independent of the fiducial dark energy model assumed.

2 DATA ANALYSIS

A Gaussian process is a distribution over functions, rather than over variables as in the case of a Gaussian distribution. Therefore, we can reconstruct a function from data points without assuming a parametrization. We do so using the GAPP (Gaussian Processes in PYTHON) code (Seikel, Clarkson & Smith 2012, see also Shafieloo, Kim & Linder 2012) in order to reconstruct $H(z)$ from data (for other applications of GAPP in cosmology, see e.g. Yahya et al. 2013; Busti, Clarkson & Seikel 2014; Cai, Guo & Yang 2016; González 2017; Gómez-Valent & Amendola 2018; Pinho, Casas & Amendola 2018; Bengaly, Clarkson & Maartens 2019; von Marttens et al. 2019; Keeley et al. 2020). We simulate $H(z)$ data assuming the fiducial model,

$$\left[\frac{H(z)}{H_0}\right]^2 = \Omega_{\rm m}(1+z)^3 + (1-\Omega_{\rm m}-\Omega_{\rm DE})(1+z)^2 + \tag{1}$$

$$\Omega_{\rm DE}\exp\left[3\int_0^z \frac{1+w(z')}{1+z'}{\rm d}z'\right], \tag{2}$$

which is valid for a generic dark energy model. We assume the fiducial model to be consistent with Planck 2018 (TT, TE, EE+lowE+lensing) best fit for flat ΛCDM; therefore, $\Omega_{\rm DE} = \Omega_\Lambda = 1 - \Omega_{\rm m}$, $w(z) = w_0 = -1$, and the fiducial values of H_0 and the matter density $\Omega_{\rm m}$ are chosen to be

$$\begin{aligned} H_0 &= 67.36 \pm 0.54\,{\rm km\,s^{-1}\,Mpc^{-1}}, \\ \Omega_{\rm m} &= 0.3166 \pm 0.0084. \end{aligned} \tag{3}$$

We produce the simulated $H(z)$ measurements by the same fashion of Bengaly et al. (2019), whose specifications for SKA- and Euclid-like surveys follow Bacon et al. (2020) and Amendola et al. (2018):

SKA-like intensity mapping survey:

$$\begin{aligned} &\text{Band 1:} && 0.35 < \nu < 1.05\,{\rm GHz}, \\ & && 0.35 < z < 3.06\ N = 10, 15, 20, \\ &\text{Band 2:} && 0.95 < \nu < 1.75\,{\rm GHz}, \\ & && 0.1 < z < 0.5\ N = 5, 10, \\ &\text{Band 1+2:} && N_1 = 10, 15 \text{ and } N_2 = 5; \\ & && N_1 = 20 \text{ and } N_2 = 10, \end{aligned} \tag{4}$$

Euclid-like galaxy survey:

$$\begin{aligned} &\text{Euclid-like only:} && 0.6 < z < 2.0,\ N = 10, 15, 20, \\ &\text{Euclid-like + Band 2:} && N_1 = 10, 15 \text{ and } N_2 = 5; \\ & && N_1 = 20 \text{ and } N_2 = 10, \end{aligned} \tag{5}$$

These prescriptions assume two realistic assumptions for $H(z)$ with Euclid- and SKA-like B1, with $N_1 = 10$ data points and $N_2 = 5$ for SKA-like B2, and an optimistic one with $N_1 = 20$ and $N_2 = 10$. The $H(z)$ measurement uncertainties are taken from the interpolated curves in fig. 10 (left) of Bacon et al. (2020).[1]

The deceleration parameter can be obtained from the GP-reconstructed $H(z)$ for each of these survey configurations according to

$$q(z) = -\frac{\ddot{a}}{aH} = (1+z)\frac{H'(z)}{H(z)} - 1, \tag{6}$$

where $H^{'}(z) \equiv {\rm d}H(z)/{\rm d}z$. Its uncertainty is given by error-propagating $q(z)$ with respect to $H(z)$ such as

$$\left(\frac{\sigma_{\rm q}}{1+q}\right)^2 = \left(\frac{\sigma_H}{H}\right)^2 + \left(\frac{\sigma_{H'}}{H'}\right)^2 - \left(\frac{2\sigma_{HH'}}{HH'}\right), \tag{7}$$

where σ_H and $\sigma_{H'}$ represent the uncertainties of the reconstructed H and $H^{'}$, respectively, and $\sigma_{HH'}$ their respective covariance. Conversely from Bengaly et al. (2019), we did not check the results by other future surveys like MeerKat, DESI, and SKA galaxy survey because the constraints on q_0 would be even more degraded due to the calculation of $H^{'}$. Same applies for $D(z)$ measurements from the angular mode of BAO, which would involve the second derivative computation of this quantity since $H(z) = 1/D^{'}(z)$. A more thorough assessment of the cosmic acceleration using luminosity distance measurements from forthcoming standard candles and sirens surveys will be pursued in the future.

3 RESULTS

3.1 Constraints on q_0

We present the results obtained for Euclid- and SKA-like B1 surveys in Fig. 1. We find that they can probe cosmic acceleration, that is, $q_0 < 0$, at roughly 3.3–3.8σ level, whereas an SKA-like B1 survey will be able to do it at 5.0–5.7σ. This is because an Euclid-like survey is expected to cover of a higher redshift range than an SKA-like B1, so the extrapolation to lower redshift ranges worsens. By combining both SKA-like B1 and Euclid-like surveys with SKA-like B2, as shown in Fig. 2, there is a significant improvement on the q_0 constraints due to its lower redshift coverage. For instance, SKA-like B1+B2 combined can determine $q_0 < 0$ at a 7.0σ level for a realistic configuration, and 9.2σ for an optimistic one, and Euclid-like + B2 can do it at a 7.5σ (9.7σ) level for a realistic (optimistic) configuration, respectively. All these results are summarised in Table 1.

For the sake of comparison, we perform a $q(z)$ reconstruction obtained with real $H(z)$ data from cosmic chronometres (CC) from differential galaxy ages (Jimenez & Loeb 2002; Moresco et al. 2016) and from the radial BAO mode of galaxy clustering. We use the $H(z)$ measurements as compiled by Magana et al. (2018), whose results are presented in Table 1 and Fig. 3. We obtain that they can only determine if the Universe is currently accelerating at just above 1.5σ (2.6σ) level for CC (CC+BAO), and that our results are compatible with previous analysis within 1σ level (Harisadu et al. 2018; Arjona & Nesseris 2019). This demonstrates how Euclid and SKA surveys will largely improve the model-independent assessments of cosmic acceleration evidence.

3.2 Robustness tests

We test how robust are our results with respect to other cosmological models than flat ΛCDM. We thus produce data sets for the optimistic specifications of SKA-like B1 and Euclid-like surveys combined with

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[1] The BAO scales that produce the $H(z)$ measurements are within the regime where foreground removal should be very efficient (Bull et al. 2016; Villaescusa-Navarro, Alonso & Viel 2017).

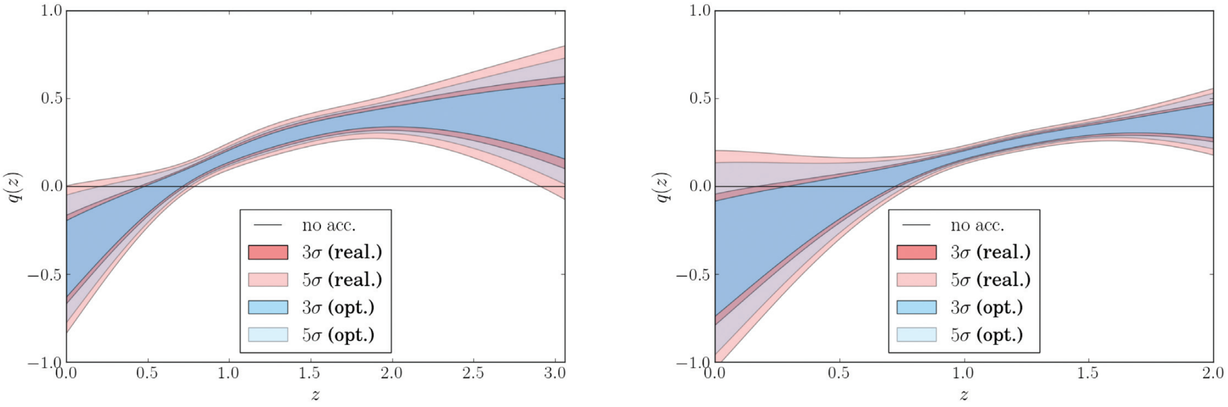

Figure 1. Left-hand panel: Gaussian processes reconstructed $q(z)$ following equations (6) and (7) for an SKA-like B1 survey, assuming the realistic ($N_1 = 10$ and $N_2 = 5$, in blue) and optimistic ($N_1 = 20$ and $N_2 = 10$, in red) specifications. The darker (lighter) shaded curves provide the 3σ (5σ) confidence levels. The black line denotes shows the non-accelerated threshold at $q_0 = 0$. Right-hand panel: Same as the left-hand panel, but valid for an Euclid-like survey.

Table 1. Respectively, the redshift survey, number of data points, the reconstructed q_0 value with its respective uncertainty, and how many σ away we have $q_0 = 0$. We can see that SKA-like B1 and Euclid-like surveys can probe $q_0 < 0$ at over 7σ level when combined with SKA-like B2. Results obtained with real $H(z)$ measurements are presented as well.

Sample	N_1	N_2	q_0	σ_{q_0}	$q_0 < 0\,(\sigma)$
Euclid-like	10	–	−0.416	0.124	3.348
	10	5	−0.464	0.062	7.493
	15	–	−0.413	0.116	3.568
	15	5	−0.463	0.059	7.791
	20	–	−0.411	0.109	3.764
	20	10	−0.467	0.048	9.736
SKA-like	10	–	−0.416	0.083	4.952
	10	5	−0.445	0.063	7.058
	15	–	−0.413	0.078	5.325
	15	5	−0.443	0.059	7.486
	20	–	−0.412	0.073	5.672
	20	10	−0.447	0.049	9.191
CC	30	–	−0.485	0.314	1.541
CC+BAO	30	18	−0.457	0.174	2.631

the SKA-like B2 assuming the following models:

$$\begin{aligned} &\text{w(z)CDM:} \quad w(z) = (-1/2) + (1/2)\tanh[3(z - 1/2)], \\ &\text{k}\Lambda\text{CDM}: \quad \Omega_{\rm k} \equiv 1 - \Omega_{\rm m} - \Omega_{\rm DE} = -0.10, \\ &\text{EdS:} \quad \Omega_{\rm m} = 1, \ \Omega_{\rm DE} = 0, \end{aligned} \tag{8}$$

where the last model, EdS, stands for Einstein-de Sitter model that gives $q_0 = 0.5$, i.e. a non-accelerated model consistent with the cosmic expansion at matter-dominated era. We use it for the sake of determining how well can we rule it out from the standard model, given the precision of this data.

The q_0 constraints obtained for these cases are all consistent with the fiducial model, and with relative uncertainties compatible with the standard model analysis. For an SKA-like B1+B2 survey with optimistic (realistic) configurations, we obtained $q_0^{\rm w(z)CDM} = -0.375 \pm 0.065$ ($q_0^{\rm w(z)CDM} = -0.349 \pm 0.082$), $q_0^{\rm k\Lambda CDM} = -0.344 \pm 0.049$ ($q_0^{\rm k\Lambda CDM} = -0.341 \pm 0.063$), and $q_0^{\rm EdS} = +0.536 \pm 0.072$ ($q_0^{\rm EdS} = +0.530 \pm 0.092$). We present these results in Fig. 4. Hence, we show that we will be able to rule out a non-accelerated model like EdS at over 11σ (8σ) level with a SKA-like survey using $H(z)$ data *alone*. Similar results were obtained for an Euclid-like survey.

We checked if the assumption of a fixed fiducial cosmological model affects our results. We produced Monte Carlo realizations varying the cosmological parameters $\boldsymbol{p} = (\Omega_{\rm m}, H_0)$ according to a Gaussian distribution $\mathcal{N}(\boldsymbol{p}, \sigma_{\boldsymbol{p}})$, where the parameters and their uncertainties are given by equation (3). We found that the measured q_0 values are fully compatible with the uncertainties quoted in Table 1. Finally, we verified how our results change with respect to other GP kernels. For an SKA-like B1+B2 survey assuming a realistic ($N_1 = 10$ and $N_2 = 5$) configuration, for example, we obtained $q_0 = -0.433 \pm 0.076$ and $q_0 = -0.437 \pm 0.070$ for a Matérn(7/2) and Matérn(9/2) kernel, respectively, thus the detection of current cosmic acceleration would be at a 5.6σ (6.2σ) level. As for the optimistic survey specification, again assuming these respective kernels, we found a 7.1σ (8.0σ) evidence positive acceleration instead. So we will still be able to probe cosmic acceleration at over 5σ level even for the most conservative kernels.

4 DISCUSSION AND CONCLUDING REMARKS

The nature of the late-time accelerated expansion of the Universe remains one of the most intriguing phenomenon. Although the Cosmological Constant can account for that and explain the observations with unprecedented precision thus far, it suffers from many theoretical problems. Most of viable alternatives to the Cosmological Constant are also plagued with similar issues. In addition, there are still discussions whether the Universe is truly undergoing an accelerated expansion today depending on how one approaches the available data (Nielsen et al. 2016; Colin et al. 2019a). None the less, all this debate relies on fitting cosmological models with observations. It is essential to quantify the evidence for cosmic acceleration in a model-independent way – it will not tell us the *best* model that describes observations, but it will be able to underpin (or rule out) this phenomenon regardless of the underlying model.

We simulated data for next-generation redshift surveys for this purpose. We produced synthetic $H(z)$ measurements reproducing SKA- and Euclid-like radial BAO measurements, and hence perform a non-parametric reconstruction of the $H(z)$ and $H^{'}(z)$ for the sake of providing $q(z)$, the deceleration parameters – so that its current value, q_0, will tell if the Universe is currently accelerating or not. We found a $\sim 5\sigma$ evidence for this result with a SKA-like B1 survey, and $\sim 3\sigma$ for an Euclid-like one. When combining both

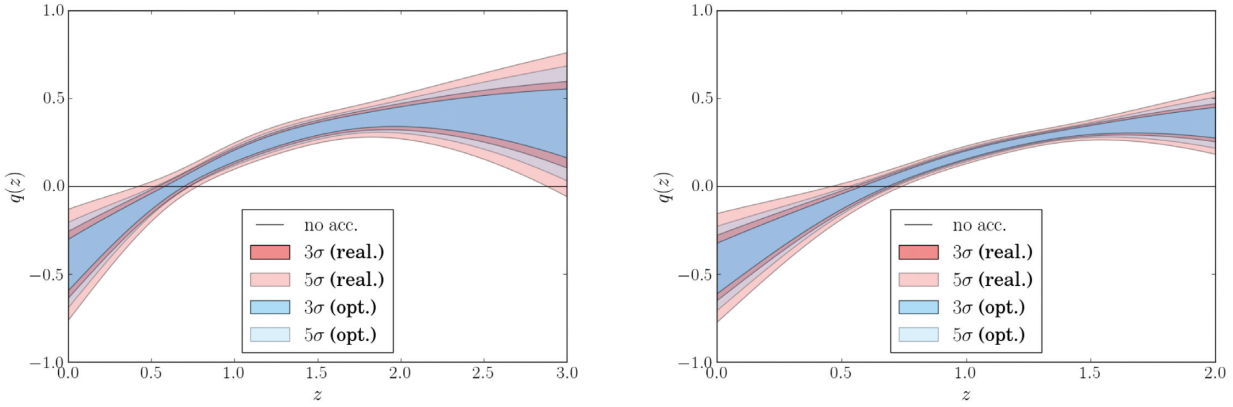

Figure 2. Same as Fig. 1, but including the SKA-like B2 data points.

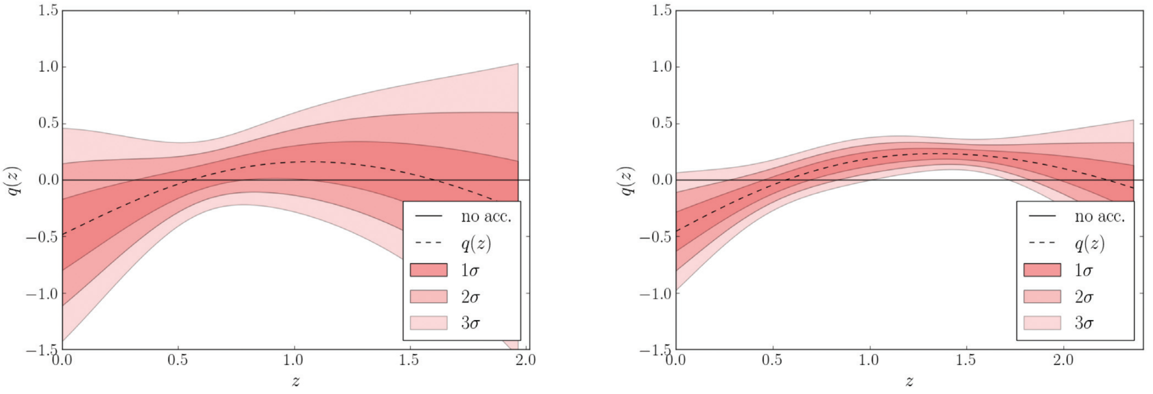

Figure 3. The reconstructed $q(z)$ curves and their 1, 2, and 3σ uncertainties using real $H(z)$ data from CC (left) and CC combined with BAO measurements from galaxy surveys like SDSS and WiggleZ (right).

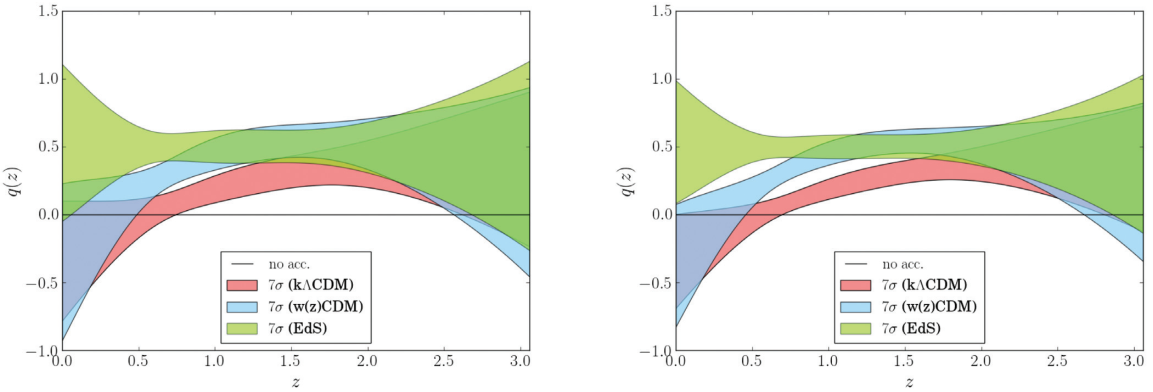

Figure 4. The reconstructed $q(z)$ curves (in 7σ) for SKA-like B1 and B2 surveys combined assuming the kΛCDM (red), w(z)CDM (blue), and EdS (green) models. The left plot displays the results for a realistic survey specification ($N_1 = 10$ and $N_2 = 5$), and the right plot for an optimistic one ($N_1 = 20$ and $N_2 = 10$).

experiments with the SKA-like B2 survey, which will probe a lower redshift threshold, the evidence increases to at least 7σ level. These results are consistent with currently available observations, but *without* the implicit assumption of ΛCDM or any other dark energy model.

These results demonstrate the capability of next-generation redshift surveys on underpinning the evidence for cosmic acceleration in a truly model-independent way, and as powerful probes of late-time Cosmology for the future, along with standard candles and sirens.

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