Status of kinematic cosmology with SN Ia:
JLA, Pantheon and future constraints with LSST

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ABSTRACT
In this work we derive state-of-the-art model-independent constraints on cosmology from SN Ia by measuring purely kinematical $(q, j)$ model parameters (where $q$ and $j$ are related to the first and second derivative of the Hubble parameter). For the JLA compilation of SN Ia an agreement within $2\sigma$ of $\Lambda$CDM + GR expectations is found, where best-fitting kinematical parameters are $q = -0.70 \pm 0.18$ and $j = 0.52 (+ 0.58 - 0.60)$. With $q = -0.86 \pm 0.07$ and $j = 1.13 \pm 0.26$ the Pantheon sample shows even better agreement with the ACDM expectation of $j = 1$ than JLA, hinting at less systematics and/or a higher number of SN Ia alleviating tensions. For the future we predict the precision achievable with SN Ia from the LSST deep survey as $\Delta q \sim 0.05$ and $\Delta j \sim 0.1$, which is systematics-limited and could lead to detect both deviations from $\Lambda$CDM + GR (in $j$) or current expansion rates measured (in $q$). In comparison, for standard cosmological parameters we get $\Delta \Omega_m = 0.01$ and $\Delta w = 0.07$ for LSST. Given the high number of SN Ia expected for LSST, kinematical parameters in up to 500 sky regions, each with their own individual Hubble diagram, can be constrained. For each region an individual precision at the 10s of percent level is within reach at current systematics-levels, comparable to present-day full-sky surveys. This will determine anisotropy in cosmic expansion, or the dark energy dipole, at the 10s of percent level at 10s of degree scales.

Key words: cosmological parameters – cosmology: observations – cosmology: theory – supernovae: general

1 INTRODUCTION
Deciphering the cause of accelerated cosmic expansion has been a continuous enterprise over the last 20 years, since its first conclusive evidence by means of supernovae Ia (SN Ia) by Riess et al. (1998) and Perlmutter et al. (1999). More and more cosmological probes have confirmed this picture since, like measurements of the Cosmic Microwave Background (CMB) by the Planck satellite (Ade et al. 2016a), as well as galaxy clustering and the abundance of galaxy clusters (Rapetti et al. 2013; Mantz et al. 2014, 2015). Alongside, different scenarios to explain cosmic expansion have been investigated, the most simple being a cosmological constant $\Lambda$ together with Cold Dark Matter (CDM), with expansion being both isotropic and homogeneous. A wealth of alternative models have been proposed to explain this accelerated expansion, like scalar-tensor models, for example of the Horndeski class (Horndeski 1974). Other models, like Bianchi type I models (Taub 1951), result in a break-down of the standard assumptions of isotropy in a Friedmann-Lemaître-Robertson-Walker (FLRW) framework, while trying to accommodate observations.

Different frameworks, like the testing for hemispherical asymmetries or the fitting of dipolar modulations (Kaluz et al. 2013; Javanmardi et al. 2015; Ade et al. 2016b; Hurier 2016), strive to detect anisotropies in cosmological data. Works on testing the anisotropy with SN Ia data, as for example by Heneka et al. (2014) with a Bayesian model-independent approach related to internal robustness of the dataset, or for example Cai et al. (2013) and Sun & Wang (2018) with standard fitting of cosmological parameters, Wang & Wang (2014) for cosmographic (kinematical) parameters, and Wang & Wang (2018) for a Bianchi-I type metric, found no significant evidence of anisotropies in SN Ia data (within $2\sigma$). Here we aim for a study of kinematical model properties, related to derivatives of the scale factor (see for example Frieman et al. (2008)), as a model-

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independent means of constraining acceleration and changes in acceleration of expansion.

We use both current-day SN Ia from the joint light-curve analysis (JLA) by Betoule et al. (2014) and the Pantheon sample from Scolnic et al. (2017), as well as mock realisations of the upcoming Large Synoptic Telescope (LSST) survey of SN Ia, to measure our kinematical model parameters as a global consistency check with ΛCDM + GR. Furthermore, the upcoming LSST survey of SN Ia (LSST Science Collaboration et al. 2009) will measure around 500,000 SN Ia over a large fraction of the sky. This enables us to test individual Hubble diagrams of SN Ia in different directions, splitting the sky up, with a number of SN Ia in each patch comparable to present-day surveys. Here we will investigate how precise we will be able to measure such Hubble diagrams in different regions, where patch-wise parameter deviations would hint at anisotropies in our cosmology. The use of kinematical parameters will ensure to remain model-independent in our cosmology, while testing global expansion properties and its isotropy.

This paper is organised as follows. In section 2 we describe our kinematical cosmological model and review the framework to derive parameter constraints with the distance moduli of SN Ia. In section 3 we present constraints on kinematical cosmology derived for present-day data, as well as forecast future constraints attainable with LSST. We continue with a forecast of the precision in kinematical model parameters attainable when measuring Hubble diagrams for different sky regions in section 4 and finish in section 5 with our conclusions.

2 KINEMATICAL COSMOLOGICAL MODELS

Dynamical approaches to constraining cosmology aim at deriving cosmological model parameters, as for example the present-day density parameter of dark energy and the dark energy equation of state. In contrast, the kinematical approach relies on in the study of the accelerated background expansion via derivatives of the scale factor \(a\) and therefore presents a model-independent alternative to the dynamical approach. It can be based on weaker assumptions, requiring only that gravity is described by some metric theory and that space-time is isotropic and homogeneous. The FLRW metric and the evolution equations for the scale factor \(a(t)\) are still valid (Friedman et al. 2008).

2.1 The kinematical approach

The kinematical parameters up to third order in a Taylor expansion of the scale factor \(a(t)\) are the Hubble parameter \(H(t)\), the deceleration parameter \(q(t)\) and the \(j\)-parameter \(j(t)\) that measures the change in acceleration (or deceleration). The deceleration parameter, historically defined with a negative sign, measures the cosmic acceleration via

\[
q(t) = \frac{\dot{a}}{a \ddot{a}} = -1 - \frac{H}{a H^2} ,
\]

and in terms of the scale factor it reads

\[
q(a) = -\frac{1}{H} (aH)' ,
\]

where the dot denotes derivatives after time \(t\) and the prime after scale factor \(a\). Models with present-day \(q\)-values \(q_0 < 0\) currently undergo acceleration. The \(j\)-parameter, which represents the change in acceleration as the dimensionless third-order time derivative of \(a\), is given by

\[
j(t) = -\frac{1}{a H^2} \dddot{a} ,
\]

and in terms of the scale factor reads

\[
j(a) = -\frac{(a^2 H^2)''}{2 H^2} .
\]

For a pressure term parametrised via the equation of state that is constant with time, e.g. either matter domination or the domination of a cosmological constant, i.e. in a ΛCDM scenario, we have \(j = 1\); for a time evolving pressure term we have \(j \neq 1\). The ΛCDM, or equivalently \(j = 1\), case presents the zeroth order model around which we are perturbing. The constant \(j\) model captures changes in the accelerated expansion of the Universe at a certain epoch, e.g. for the low redshift Universe with SN Ia. However, for a more realistic treatment a time evolution of \(j\) can also be considered.

For convenience, equation (4) can be rewritten as (Blandford et al. 2004; Rapetti et al. 2007)

\[
a^2 V''(a) - 2j(a) V(a) = 0 ,
\]

where

\[
V(a) = -\frac{a^2 H^2}{2 H_0^2} .
\]

Inserting at present time \(a_0 = 1\) and \(H = H_0\), this yields the solution of equation (5) with the initial conditions \(V(1) = -0.5\) and \(V'(1) = -H_0^2/H_0 - 1 = q_0\). Staying for now with a model that allows for a constant deviation of the \(j\)-parameter from the ΛCDM value of \(j = 1\), equation (5) can then be solved analytically to give

\[
V(a) = -\frac{\sqrt{a}}{2} \left( \left( \frac{p - u}{2p} \right) a^p + \left( \frac{p + u}{2p} \right) a^{-p} \right) ,
\]

with \(p \equiv (1/2) (1 + 8j)\) and \(u \equiv 2(q_0 + 1/4)\).

Requiring a Big Bang solution (corresponding to the existence of a solution to \(V(a) = 0\) in the past as shown in Rapetti et al. (2007)) leads to the exclusion of the following region in the \((q, j)\) parameter space:

\[
j < q + 2q^2 \quad q < -1/4 ,\]

\[
j < -1/8 \quad q > -1/4 .
\]

We will impose these conditions, to exclude regions in parameter space without a Big Bang solution, in our likelihood calculation and parameter estimations in Sections 3 and 4.

2.2 Relating kinematics to dynamics

Here we relate for later comparison the kinematical \(q\)- and \(j\)-parameters to the standard cosmological ones. We define the standard Hubble function \(H\) as \(H^2(a) = \left(\Omega_m a^3 + (1 - \Omega_m) a^{-3(1+w)}\right)\) for the late Universe, with present-day matter-density \(\Omega_m\) and dark energy equation of state \(w\).

We start with the \(q\)-model, i.e. neglecting terms of order \(j\) or higher (therefore describing the kinematic evolution as
a function of the deceleration parameter \( q \) alone with constant acceleration. The effective equation of state \( w \) and the kinematic \( q \)-parameter in this case are connected via

\[
w = -\frac{(1 - 2q)}{3 \left(1 - \Omega_m a^{-3} (H_0/H)^2\right)},
\]

or equivalently

\[
q = 0.5 \left(1 + 3w \left(1 - \Omega_m a^{-3}\right) (H_0/H)^2\right).
\]

At the current epoch this leads to

\[
q_0 = 0.5 \left(1 + 3w (1 - \Omega_m)\right).
\]

We thus can relate the deceleration parameter within a kinematical approach with standard cosmological parameters of the dynamical approach to describing cosmological evolution.

Taking also the change in acceleration with the \( j \)-parameter into account, within the so-called \( q-j \)-model, one finds the relation between kinematical and dynamical parameters

\[
j = -0.5 \left(1 + 3w\right) - 3q (1 + w),
\]

or, equivalently, from Blandford et al. (2004),

\[
j (a) = 1 + \frac{9w (1 + w) (1 - \Omega_m)}{2 (1 - \Omega_m (1 - a^{-3}w))}.
\]

We will make use of these relations in the following to compare results in the kinematical model with standard dynamical ones.

### 2.3 Constraining the \( q-j \)-model with SN Ia

To compare with observational data that are sensitive to the background expansion, like SN Ia, inserting \( V(a) \) from equation (7) into equation (6) gives the evolution of the Hubble parameter as a function of kinematical parameters. The luminosity distance \( d_L \) then reads

\[
d_L = c \int_a^{H_0} \frac{da}{E (a)} = c \int_a^{H_0} \frac{1}{2 \sqrt{V (a)}} da \tag{14}
\]

as \( E (a) = H/H_0 = (1/a) \sqrt{2V (a)} \). The luminosity distance is related to the distance modulus \( \mu \) of a supernova \( i \) at redshift \( z_i \) with apparent magnitude \( m_i \) and absolute magnitude \( M \), for a cosmological model with parameter set \( \theta_j \), via

\[
\mu_{\text{obs},i} = m_{\text{obs},i} - M = 5 \log_{10} d_L (z_i; \theta_j) + 25 + K, \tag{15}
\]

with \( K \) being the so-called K-correction that takes into account that different parts of the source spectrum are observed at different redshifts. The distance modulus is used for cosmological parameter inference, when measured for example with SN Ia (which are assumed to be standard candles of known absolute magnitude). When measuring apparent magnitudes \( m_{\text{obs},i} \) of SN Ia, the distance modulus \( \mu_{\text{obs},i} \) at redshift \( z_i \) is given by

\[
\mu_{\text{obs},i} = m_{\text{obs},i} - M = 5 \log_{10} d_L (z_i), \tag{16}
\]

where \( d_L \) is the luminosity distance.\(^1\)

1 The hat indicates it being in units of \( H_0 \).

With a sample of observed SN Ia light-curves the distance moduli are fitted as

\[
\mu_{\text{obs},i} = m_{\text{obs},i} - (M_B + \alpha x_i - \beta \xi_i + \Delta M + \Delta_B), \tag{17}
\]

with colour and stretch corrections \( c_i \) and \( x_i \), respectively, global best-fitting parameters \( \alpha \) and \( \beta \) for colour and stretch scaling, as well as absolute B-band magnitude \( M_B \) and the mass step function \( \Delta M \) that accounts for correlations of the B-band magnitude with galaxy host mass (Betoule et al. 2014; Jones et al. 2018). For the Pantheon sample, the factor \( \Delta_B \) was included to account for predicted biases from simulations (Scollnic et al. 2017).

To obtain parameter constraints on \( (q, j) \) we minimise, as in the standard cosmological framework, the chi-square function marginalised over absolute magnitude \( M \), K-correction \( K \) and present-day value of the Hubble constant \( H_0 \), which is given by

\[
\chi^2 = S_2 - S_0^2. \tag{18}
\]

The sums \( S_n \) are defined as

\[
S_n = \sum_i \delta m_i^2, \tag{19}
\]

where \( \delta m_i = (m_{\text{obs},i} - m_{\text{th},i}) \) are the magnitude residuals, i.e. the differences between observed apparent magnitudes and theoretically expected ones, and \( \sigma_i \) is the dispersion of distance moduli.

### 3 OBSERVATIONAL CONSTRAINTS ON KINEMATICS

#### 3.1 Results for current datasets: JLA and Pantheon

When deriving constraints for the JLA compilation of 740 SN Ia in the redshift range \( 0.01 < z < 1.3 \) (Betoule et al. 2014),\(^2\) we use the global best-fitting values of \( \alpha = 0.141 \) and \( \beta = 3.101 \) provided and the absolute B-magnitude \( M_B = -19.05 \pm 0.02 \). We account for correlations of B-band magnitude with galaxy host mass with the step function \( \Delta M \), where \( \Delta M = -0.07 \) for stellar masses above \( 10^{10} M_\odot \), and zero otherwise. For the dispersion in distance moduli \( \sigma_i \) we take the errors of absolute magnitude, colour and stretch into account. These stem from uncertainties in the flux measurements, intrinsic scatter, as well as scatter due to peculiar velocities. For the Pantheon sample (Scollnic et al. 2017),\(^3\) which at the moment is the largest combined sample of SN Ia consisting of a total of 1048 SN Ia ranging in redshift from \( 0.01 < z < 2.3 \), we take the observed B-band magnitudes provided as input in our chi-square function. The total error in distance measurements in our treatment of Pantheon takes into account the photometric error, the uncertainty from the mass step correction, distance bias correction, the uncertainty from the peculiar velocity and redshift measurement, as well as the uncertainty from stochastic lensing and

\[\text{http://supernovae.in2p3.fr/sdss_1ns2_jla/ReadMe.html}\]

\[\text{https://archive.stsci.edu/prepds/ps1cosmo/index.html}\]
intrinsic scatter. For both samples the SN Ia light-curve parameters were derived with SALT2 (Guy et al. 2007).

Using the formalism described in the previous section we find best-fitting marginalised values and $1\sigma$ confidence intervals of $q = -0.70 \pm 0.18$ and $j = 0.57^{+0.58}_{-0.60}$ for the JLA sample. The constraints are consistent with the $\Lambda$CDM expectation of $j = 1$ at the $1\sigma$ level for the marginalised parameter value and comply with accelerated expansion for $q < 0$. For the Pantheon sample we find $q = -0.86 \pm 0.07$ and $j = 1.13 \pm 0.26$, in even better agreement with the $\Lambda$CDM expectation of $j = 1$ than the JLA sample, hinting at less systematics and/or a higher number of SN Ia helping to alleviate tensions. The corresponding 1-, 2- and 3-$\sigma$ confidence contours for $q$ and $j$ are shown for the JLA and Pantheon sample as black and blue contours, respectively, in Figure 3 and ??, where the horizontal line indicates the $\Lambda$CDM expectation of $j = 1$. For the comparison with future possible constraints by means of the LSST survey of SN Ia please see the following section and table 1. For comparison we show in Figure A1, appendix A, the confidence contours derived in a standard $\Lambda$CDM scenario for $\Omega_{m,0}$ and $w$ for both the JLA compilation and the LSST mock sample.

3.2 Future constraints with LSST

3.2.1 Creation of LSST mock SN Ia catalogues

To investigate constraints of kinematical parameters that will be possible with upcoming SN Ia surveys, we create mock catalogues for the LSST set of SN Ia, both for the full LSST and the LSST deep field.\(^4\) To do so, we take the predicted redshift distribution for the full LSST and the LSST deep field from LSST Science Collaboration et al. (2009) and calculate the number of SN Ia expected to be observed per year in more than two filters and with a selection cut of signal-to-noise $S/N > 15$. For a ten year period of observations this gives the number counts binned in redshift for LSST deep as shown in the top panel of Figure 1. The bottom panel of Figure 1 shows the number counts binned in redshift for one out of 500 sky patches for the full LSST survey. It becomes for example obvious how the LSST deep survey will tend to probe more SN Ia at higher redshifts as compared to the full survey. Note as well, that the full LSST survey will produce as many SN Ia measurements for 500 sky regions as do present-day full-sky surveys of SN Ia.

A best-fitting cosmology of $\Omega_{m,0} = 0.29$ and $w = -1.0$ (the $\Omega_{m,0}$ value is derived from JLA for the $\Lambda$CDM expectation with $w = -1.0$ fixed) and kinematical best-fitting parameters of $q = -0.57$ and $j = 1.0$ (derived by calculating the corresponding $q$ and $j$ value for our fiducial $\Omega_{m,0} = 0.29$ and $w = -1.0$ with equations (11) and (13)) is assumed, as well as a value of the Hubble parameter $h = 0.7$ throughout the paper. We create mock catalogues by drawing for the chosen fiducial cosmological distance moduli under the expected redshift distribution with a random Gaussian error of 0.05 mag, which is predicted for the LSST deep field, as well as with an error on distance moduli of 0.12 mag for the full LSST field. To underline how exquisite even Hubble diagrams for measurements of 40 deg$^2$ sky regions will be for the full LSST survey, we show in Figure 2 the mock Hubble diagram for one of our 500 sky patches (in blue, with an offset of -1 mag to increase visibility) alongside with the JLA Hubble diagram (in black). We will now discuss in the following sections the precision attainable on kinematical model parameters for both the LSST deep field (section 3.2.2) and for sky patches as part of the full LSST survey in order to test anisotropy of cosmological model parameters in section 4.

3.2.2 $q$-$j$ constraints from LSST deep

Here we constrain the errors on kinematical $q$- and $j$-parameters attainable with the LSST deep survey, using a mock catalogue of SN Ia distance moduli created as described in the previous section.

For the fiducial model of $q = -0.57$ and $j = 1.0$ (the kinematical equivalent of $\Omega_{m} = 0.29$ and $w = -1.0$), we

\(^4\) https://www.lsst.org/lsst_home.shtml
created the LSST deep mock catalogue of distance moduli and then use this catalogue to constrain the likelihood as described in section 2.3. The corresponding confidence contours in Figure 3 (red for LSST deep) show, 1σ errors smaller than Δq ≈ 0.05 and Δ j ≈ 0.1 are within reach with LSST deep (with an assumed error on distance moduli of Δµ = 0.05), even more for the full survey, which will be systematics-limited. This opens up ample possibilities, for example testing modifications of GR in different directions of the sky, as we then can divide our supernovae sample into different sky patches, without losing precision. For marginalisation of the sky, as we then can divide our supernovae sample into different sky patches, without losing precision. For marginalised best-fitting values and confidence contours we find q = −0.58 ± 0.05 and j = 1.03 ± 0.14 for our mock catalogue, assuming fiducial model parameters q = −0.57 and j = 1.0 as well as dispersion of distance moduli Δµ = 0.05. For estimating the standard cosmological parameters (Ω_m, w) from the same mock LSST deep catalogue, we obtain best-fitting values and marginalised 1σ errors of Ω_m = 0.29 ± 0.01 and w = −1.02 ± 0.07. Similar to the kinematical parameters, also the standard cosmological parameters can be measured at significantly higher precision than previously with SN Ia, yielding marginalised errors at the percent level on cosmological standard parameters.

4 DARK ENERGY DIPOLe MEASUREMENT WITH LSST

Over its 10 years of operation the LSST will measure an all-sky sample of about 500,000 SNe Ia, which makes it possible to investigate angular dependence in the redshift-distance relation (LSST Science Collaboration et al. 2009). The detection of an angular dependence would point towards a directionality of the dark energy equation of state, in turn pointing to physics beyond ΛCDM. In the past, for example, residuals with respect to the best-fitting Hubble function or hemispherical best-fits have been measured, as done extensively for different samples of SN Ia as mentioned in the introduction, due to the restriction to a low number of SN Ia in each sky patch and their inhomogeneous distribution. With LSST we will be able to constrain a Hubble diagram for a multitude of directions in the sky and therefore test with SN Ia as standard candles the paradigm of isotropic expansion in cosmology.

Assuming the SN Ia to be roughly isotropically distributed, we divide the sky into 500 patches of 40 deg^2 predicted to be measurable for the LSST survey, with roughly 500 SN Ia per patch. We first assume a systematic error of 0.12 mag as predicted for the full LSST survey. An error on the kinematical model parameters q and j of Δq = 0.3 and Δ j = 0.9 per patch is obtained in this configuration, see the corresponding Fisher contour for one single patch in blue in Figure 3 (top panels). If we assume an error comparable to the LSST deep survey of 0.05 mag to be achievable, constraints are improved with errors at the level of Δq = 0.13 and Δ j = 0.42 per patch, even outperforming full surveys like JLA. For the corresponding Fisher contours see the blue contours, bottom panels, in Figure 3. The error on parameters q and j per patch is driven by the systematic uncertainty on the distance moduli. This means that for an even more accurate testing of isotropy with LSST, systematics would need to be improved on. See also the comparison of constraints on q and j parameters in Table 1.

For comparison, concerning errors on standard dynamical parameters Ω_m,0 and w for an error of 0.12 mag on distance moduli, we derive 1σ errors of ΔΩ_m = 0.04 and Δw = 0.12. This constrains the present-day dark energy dipole at the level of percent to tens of percent. One therefore obtains for standard cosmological parameters, like for dynamical ones, and for each out of 500 sky patches of 40 deg^2, constraints that are competitive with present-day constraints from full SN Ia surveys.

Table 1. Summary of best-fitting (fiducial) values for (q, j)-parameters, with marginalized 68.3 per cent confidence intervals (Δq, Δ j) for SN Ia compilations as indicated.

|     | q fiducial | Δq | j fiducial | Δj |
|-----|------------|----|------------|----|
| JLA | -0.70      | ±0.18 | 0.52       | ±0.38 |
| Pantheon | -0.86 | ±0.07 | 1.13       | ±0.26 |
| LSSTdeep | (−0.57) | ± 0.05 | (1.00) | ± 0.14 |
| LSST500(Δµ=0.12) | (−0.57) | ± 0.30 | (1.00) | ± 0.90 |
| LSST500(Δµ=0.05) | (−0.57) | ± 0.13 | (1.00) | ± 0.42 |

5 CONCLUSIONS AND OUTLOOK

In this work we have shown that with the upcoming full LSST sample of SN Ia the assumption of isotropy can, not only for standard cosmological parameters, but also kinematical parameters, be tested at unprecedented precision. Besides proving the feasibility of testing isotropy of kinematical parameters with LSST, we also estimated present-day best-fitting values for kinematical parameters for the JLA and Pantheon samples of SN Ia. Our results show agreement with the ΛCDM plus GR expectations of j = 1 within 1σ. We observe a tendency with a growing number of SN Ia per sample available, together with the inclusion of extra corrections for distance biases, for estimated parameters to become more consistent with ΛCDM.

To test for constraints on anisotropy achievable with LSST, we divided a LSST mock catalogue of SN Ia in about 500 patches. We then measured the corresponding Hubble diagram for each patch to show the ability to detect deviations in kinematical, on top of standard cosmological parameters, at the tens of percent precision, while limited by the error on the distance modulus due to systematics. For the deep LSST sample of SN Ia that is designed to measure lightcurves with an ~ 0.05 mag error instead of ~ 0.12 mag for the full LSST sample, the kinematical parameters are shown to be measurable with a precision of about Δq ~ 0.05 and Δ j ~ 0.1, on top of an expected ΔΩ_m ~ 0.01 and Δw ~ 0.07 for standard wCDM cosmology. This precise, and hopefully accurate, measurement of the kinematics of our Universe, will enable us to get a model-independent handle on possible deviations from our standard assumptions on having a wCDM cosmology in an isotropic and homogeneous expanding universe. Having up to 500 Hubble diagrams distributed over the sky, each one comparable to, or even outperforming, present-day SN Ia surveys, for example stringent constraints
Figure 3. Constraints on kinematical model parameters ($q, j$) for the JLA (left panels) and Pantheon (right panels) samples of SN Ia (in black) with the best-fit indicated as a black point at $q = -0.70$ and $j = 0.52$ for JLA (left) and at $q = -0.86$ and $j = 1.13$ for Pantheon (right). Forecasted constraints on kinematical model parameters ($q, j$) for one LSST 500 field mock catalogue of SN Ia (blue), assuming an error on the distance indicator of $\Delta \mu = 0.12$ mag (top) and $0.05$ mag (bottom), as well as constraints on the LSST deep field with an expected error of $0.05$ mag (red) are shown alongside. The fiducial model for LSST catalogues $q = -0.57$ and $j = 1.0$ is indicated with a red dot, the $\Lambda$CDM + GR prediction of $j = 1$ with a black horizontal line. Contours indicate the 68.3, 95.4 and 99.7% confidence regions.

on anisotropic models of the Bianchi type can be put in the future. The limit on precision here is set by systematics, demonstrating again the current and future need for tools that statistically select biases in data.

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APPENDIX A: CONSTRAINTS ON STANDARD COSMOLOGICAL PARAMETERS

Here we show in Figure A1 for the JLA compilation of SN Ia (in black) constraints on standard cosmological parameters, for comparison with the corresponding contours in the kinematical model shown in Figures 3, together with forecasted constraints achievable with LSST deep (in red). Parameters are \((\Omega_m, w)\), with best-fitting marginalised values and 1\(\sigma\) confidence intervals of \(\Omega_m = 0.286^{+0.10}_{-0.09}\) and \(w = -0.89^{+0.21}_{-0.20}\) for the JLA sample, showing an agreement within 1\(\sigma\) with the \(\Lambda\)CDM expectation. For the LSST deep mock sample, errors of \(\Delta\Omega_m \sim 0.01\) and \(\Delta w \sim 0.07\) are within reach around the fiducial of \(\Omega_m = 0.29\) and \(w = -1\). Both the kinematical and dynamical approach agree in their conclusions, agreeing with \(\Lambda\)CDM expectations at the 1\(\sigma\)-level.

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