Astro2020 Science White Paper

Galaxy Kinematics and the Future of Dark Energy

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐Formation and Evolution of Compact Objects ☒ Cosmology and Fundamental Physics
☐Stars and Stellar Evolution ☐Resolved Stellar Populations and their Environments
☒Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

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Abstract

Cosmology in the 2020's will see major gains from the combined efforts of WFIRST, Euclid, LSST, and DESI. Constraints on the expansion history of the Universe and on the growth of cosmic structure will both improve by at least an order of magnitude relative to current measurements, and the reach of precision cosmology will extend out to high redshifts (roughly $z<3$). However, despite these great gains, it seems unlikely that the nature of dark energy will be fully understood on the basis of these data. In that epoch of the universe where dark energy dominates -- below redshift 0.5 -- the mainstream cosmological probes will be at or near their fundamental noise limits.

Here we outline a promising new program that can evade these limits and produce compelling constraints on dark energy in the late universe that are complementary to what will be achieved by the existing or planned cosmological probes. We advocate for wide-field surveys of galaxy kinematics, which we argue can be used to dramatically reduce the systematic and statistical errors traditionally associated with weak lensing. We discuss the potential gains for dark energy science, and advocate for the pilot measurements and instrumental development needed to implement it over the next decade.

Introduction

Twenty years after the seminal Ia supernova discovery papers (Perlmutter et al. 1999, Riess et al. 1998), the physical nature of cosmic acceleration remains a mystery. After many subsequent measurements, the focus of inquiry has shifted away from confirmation of the reality of dark energy to investigation into its particular properties. The most constraining current measurements are (mostly) consistent with a cosmological constant (see for example DES collaboration 2018, Alam et al. 2017, Planck Collaboration 2018). However, the theoretical problems with explaining its magnitude and the fact that the early universe appears to have undergone at least one other phase of accelerated expansion not driven by a cosmological constant motivate alternative models. There is at present a wide variety of proposed physical explanations for dark energy, and current data cannot cleanly distinguish between most of the available models (Weinberg et al. 2013).

The next stage of wide-field cosmological surveys will use dedicated ground (LSST, DESI) and space (WFIRST, SPHEREx, Euclid) facilities to improve the precision of measurements of the growth of cosmic structure and the expansion history of the universe by more than an order of magnitude relative to the current state of play. These projects are vital to the future of dark energy studies, and will be a necessary foundation for whatever comes after.

Obtaining better constraints at low redshift ($z<0.5$) is strongly desirable, as this is where the energy density of dark energy dominates, and where the observable effects are qualitatively the strongest. However, redshift surveys will in the 2020s cover the majority of the observable sky in that redshift range with sufficient density to extract most of the usable cosmological information available from the galaxy power spectrum. Meanwhile, weak lensing surveys from LSST, WFIRST, and Euclid will obtain shape measurements for most of the usable galaxy. To go beyond what is possible with these measurements, especially at low redshift, requires new methods.

We argue below that significant gains, complementary with what will be achieved by other surveys, can be made with a program focusing on wide-field surveys of galaxy kinematics. We review the evidence that spatially-resolved kinematics can be used to control for most of the noise in weak lensing measurements, and that these observations are naturally immune to the most important sources of systematic error in weak lensing. We point out the natural synergy with peculiar velocity surveys at low redshift, especially for providing constraints on departures from General Relativity. We explain why existing facilities are, for the most part, not ideally suited to perform these measurements, and describe what is likely to be needed.

Kinematic Lensing

The largest source of uncertainty in WL measurements is the large intrinsic noise in the shapes of galaxies (~0.26), compared to the size of the cosmological shear effect (of order 10^{-2} - 10^{-3}). That is, we do not know the intrinsic shapes of the background galaxies, so WL measurements are necessarily statistical in nature. Several authors (Blain 2002, Morales 2006, Huff et al. 2019) have now explored methods for using galaxy kinematics (variously measured from optical, near infrared, or radio spectroscopy) to constrain the unlensed shapes of galaxies.

This works because the shape, luminosity, and velocity field of disk galaxies are tightly correlated, with the relationship determined by the Tully-Fisher relation (TFR) and simple geometry. Lensing systematically moves galaxies off of this relation, producing apparent rotation along the galactic minor axis and disagreement between the ellipticity of the image and the ellipticity expected from the observed velocity offset from the TFR. This allows the use of spatially-resolved spectroscopy to infer the intrinsic orientation and ellipticity of disk galaxies from their kinematics. While the signal-to-noise ratio per galaxy is small (roughly unity), given the intrinsic scatter in the TFR, it is roughly an order of magnitude *larger* than that of traditional lensing measurements, where the intrinsic shapes are unknown.

Estimates from the COSMOS survey suggest that the number of bright, well-resolved disk galaxies with sufficient optical emission-line strength for kinematic inference is roughly 3 arcmin^{-2}. First quantitative estimates of the potential gains from using this kinematic lensing (KL) technique for WL cosmology show that a KL survey of 5,000 deg^2 with 0.5 galaxy per arcmin^2, a small fraction of the available targets, is likely to be more constraining of the amplitude of structure than a WL mission with characteristics similar to the Large Synoptic Survey Telescope (LSST) (Huff et al. 2019). These estimates do not fully account for the systematic error gains relative to traditional methods, nor for optimal extraction of 3D lensing information, and so represent conservative estimates of the available information.

The nature of the required spectroscopic observations also makes KL more robust to systematic errors than a measurement that relies on imaging alone (Huff et al. 2019, de Burgh-Day et al. 2015). The need for spectroscopy entails that a redshift is obtained for each target, eliminating reliance on photometric redshift estimation. Galaxies bright enough for resolved kinematics are typically bright enough that well-calibrated, unbiased shape measurements are already demonstrated for existing measurement algorithms (Mandelbaum et al. 2015). Finally, the problem of spatially-correlated intrinsic alignments -- normally a significant source of contamination in weak lensing measurements -- is mitigated here, as the intrinsic alignment of each disk is the quantity that is being inferred from the spectroscopy.

In sum, kinematic measurements have the potential to greatly improve over current weak lensing methods, reducing the statistical and systematic errors. And while resolved spectroscopy for 10^7 galaxies seems challenging, a similar quantity of spectra will be collected by planned surveys like SDSS-V and DESI.

Next-Generation Cosmology with Kinematic Lensing

The reduced noise from using galaxy kinematics to control for shape noise opens up several exciting opportunities. Surveying a redshift range similar to LSST yields the statistical gains described above. The reduced systematic error would allow a smaller KL survey to aid in calibrating and mitigating systematics in a larger purely photometric survey, especially those related to intrinsic alignments. The improved redshift determination inherent in KL may allow cluster lensing measurements to mitigate the systematics associated with line-of-sight structure. Recent work also suggests that a KL measurement like that described above could detect the baryon acoustic oscillation feature in the dark matter field (as against the usual measurement from the galaxy density field) (Ding et al. 2019).

The reduction in shape noise also permits lensing measurements to extend to lower redshift. The lensing signal scales roughly as the angular diameter distance to the sources, and the lowest-redshift cross-correlation weak lensing studies (Mandelbaum et al. 2006) obtained several per cent constraints on the clustering of matter at z~0.1. With an order of magnitude reduction in the shape noise, lensing measurements could begin to probe cosmic structures in the same regime where the measurements of the peculiar velocities of individual galaxies are possible.

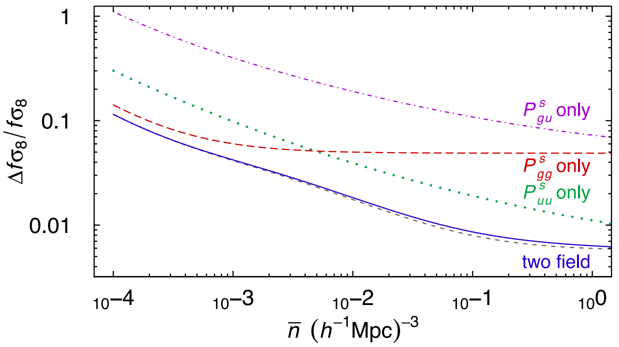

Figure 1. Forecast precision of the growth rate ($f\sigma_8$) from peculiar velocity measurements in the local universe ($z<0.1$) from Koda et al. 2014. Lines show constraints from auto and cross power of the density (g) and velocity (u) fields. Planned surveys like TAIPAN have number densities of 10^{-3}/Mpc, so there is much to be gained here from future work.

Synergy with Peculiar Velocity Surveys

At large scales, the peculiar velocities of galaxies relative to cosmic expansion trace cosmic structure and are a powerful probe of the gravitational potential. In the local universe, independent measures of distance and redshift (such as those afforded by spectroscopy of standard candles) permit direct measurement of the velocity field. In practice, those sufficiently precise standard candles that exist in high enough tracer densities to be useful for peculiar velocities include disk galaxies (via the Tully-Fisher relation), early-type ellipticals (via the Fundamental Plane), and Type Ia supernovae (the rarity of which is made up for by their superior precision as distance indicators).

The impact of a distance determination error on the inferred peculiar velocity grows with redshift, and with typical errors of a few hundred km/s, current measurements cannot reach much further than $z<0.05$ (Springob et al. 2014), holding aside rare exceptional systems like masers and gravitational wave sources.

Inside this range, however, these measurements are the strongest tests available of the large-scale growth of structure in the local universe, and currently-planned surveys like TAIPAN (da Cunha et al. 2017) are still more than an order of magnitude away from exploiting the full potential of this measurement technique (see Figure 1). The cross-correlation of these two probes would be highly constraining, and their combination affords a direct test of the GR metric potentials that is not limited by cosmic variance.

In sum, measurement of galaxy kinematics permits weak lensing measurements to extend to the low-redshift universe where the same spectroscopic observations can also, by exploiting the Tully-Fisher relation, measure the peculiar velocity field. That these complementary observations can be performed in the same volume, and in the regime where the effects of dark energy are largest, makes them a powerful probe next-generation probe of dark energy. Finally, it is worth noting that, the high spectral resolution and broad coverage needed to measure internal galaxy kinematics over even a modest redshift range means that a wide-field survey designed for this purpose would be a fantastically rich source of galaxy evolution science.

Measurement Prospects

We consider as a fiducial goal for this method a survey covering 15,000 deg^2, and obtaining resolved kinematics for 1 galaxies arcmin^{-2}. A simple tomographic weak lensing-only KL measurement with these data is more constraining of the amplitude of large-scale structure, σ_8 than a similar analysis performed with LSST by a factor of 2.5 (after marginalizing over other parameters). Other, greater gains should be expected to come from systematics mitigation and cross-correlation with low-redshift probes as described above.

The measurements we have outlined so far require wide-field surveys that collect spatially-resolved, high-resolution (R>5,000) spectroscopy for millions or tens of millions of galaxies. There are a variety of facilities with hyperspectral imaging capabilities operating today. While many of these could perform small-scale kinematic lensing measurements of the sort envisioned here, there are few facilities on the ground and none in space with the capability to measure kinematic lensing over the wide fields required for competitive cosmology. The number of individual spectra required is in the tens of millions and ranges across thousands of square degrees. Integral field units deployed on modern telescopes typically have comparatively tiny fields of view, and massively multiplexed systems like the Dark Energy Spectroscopic Instrument or the Subaru Prime Focus Spectrograph are designed to place a single fiber on a single target. While multiple offset pointings with such an instrument could be used to achieve some of the gains of spatially-resolved spectroscopy, it is not clear whether they have the fine pointing control and point-spread function control that would be required for weak lensing.

Progress towards establishing the viability of this measurement can be done on small fields with pilot measurements, particularly with cluster lensing on existing instruments. In order to reach the larger survey for combination with local peculiar velocities, additional investment in wide-field hyperspectral imaging capabilities is needed. In the near term, there are promising efforts under way for the fifth iteration of the Sloan Digital Sky Survey which involve robotically-positioned fiber bundles deployable over the very wide SDSS field of view. This is an example of planned instrument capable of measuring KL over a wide enough field that cross-correlation of weak lensing and peculiar velocity measures becomes cosmologically informative. However, no kinematic lensing measurement is currently planned for any survey.

Summary

Cosmic acceleration is likely to remain a significant puzzle beyond the lifetime of currently-planned observations, and so new methods and observables will be needed if we are to have any hope of understanding it. Great gains are likely to be made by measuring both the distribution and motions of matter in the low-redshift universe. We have argued that a science program built around the measurement of internal motions of galaxies in order to measure both weak lensing and the velocity field of the universe at low redshift would be a powerful probe of cosmology that is highly complementary to planned cosmological surveys. We advocate for investment in pilot programs and surveys with existing instruments with a focus on developing methods for accurate KL in the near term. As these mature, we argue for investment in instruments and survey facilities capable of measuring resolved galaxy kinematics to enable KL and peculiar velocity measurements in the low-redshift universe.

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