Snowmass2021 - Letter of Interest

Direct Detection of Cosmic Acceleration via Redshift Drift

Thematic Areas: (check all that apply □/■)

■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities

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Abstract: Cosmological redshift drift, which directly measures cosmic acceleration, is a direct probe of the expansion history of the Universe that relies only upon simple physics. The best current constraint however is orders of magnitude from a detection because of the stringent requirement of velocity measurements with cm s^{-1} precision and stability over multiyear timescales. Detection of redshift drift is however possible within a decade given a dedicated experiment. High fidelity measurements depend upon two features – (1) the ability to deploy a low-cost, dedicated large-aperture telescope, and (2) the development of hardware for precision radial velocity measurements over long time baselines. There are promising technologies currently within reach in both areas. We advocate for a program to bring these technologies to maturity over the next few years, with the aim of enabling deployment of a facility dedicated to the detection of cosmic acceleration and corresponding constraints on the dark energy equation of state during the coming decade.

During the past 25 years, multiple lines of evidence have led to the now standard paradigm that we live in an accelerating Universe where the rate of cosmological expansion is increasing at late times after the Big Bang. While dark energy dominates the energy budget of the Universe, the nature of dark energy remains almost entirely unknown. At the same time, while the key impact of dark energy is its introduction of accelerating expansion at late times, we have yet to directly observe the acceleration or deceleration of the Universe at any epoch. We argue that the time evolution of the expansion rate can be directly measured with existing technology, and that the potential for such measurements warrants a dedication of resources and effort in the upcoming decade – much as was the case in the past for the development other probes such as CMB, supernovae, BAO, and cosmic shear. Redshift drift measurements complement these other probes, and have the unique advantage that the resulting constraints on the dark energy equation of state become more stringent as the time baseline increases.

Cosmological redshift drift, first discussed nearly 60 years ago [1,2], refers to the change in the observed redshift of an object with time due to acceleration or deceleration in the cosmic expansion rate. Quantitatively $\dot{z} = H_0(1 + z) - H(z)$, which for a standard cosmology corresponds to a redshift change on the order of one part in 10^{11} per year (equivalent to $\sim$cm s^{-1} yr^{-1} velocity precision for detection). While this precision is challenging to achieve, redshift drift is the most direct possible probe of the acceleration history of the Universe. It relies solely on elementary physics, and with a combination of tracer populations (e.g Lyman-forest + radio [3] – see below) can yield measurements from $z \sim 10$ to the present day. Furthermore, as was shown in [4], the uncertainty ellipsoid in the $w_0 - w_a$ plane (where w_0 is the current dark energy equation of state and w_a parameterizes its time dependence) rotates with redshift, with the $z \sim 0.3$ and $z > 2$ constraints being nearly orthogonal. As such, observations spanning a range of redshift reduce the net uncertainty. Redshift drift thus provides a physically simple, completely independent, and complementary approach to other existing probes of the dark energy equation of state.

Realizing the potential of this technique, however, requires dramatically improving upon existing limits. Most current proposals for measuring redshift drift focus on observing either the Lyman-α forest towards distant quasars [5,6] or 21cm absorption lines from distant neutral hydrogen [7,8]. Doublet emission features may offer another alternative [4], though in this case the redshift drift measurement only applies to changes in the spacing between the doublet lines. The best published constraint - based on 21cm radio emission - has an uncertainty several orders of magnitude larger than the expected signal [7]. Liske et al. [6] made the case for measurement of redshift drift with upcoming 30m-class telescopes, finding that the Ly-α approach would enable a detection with a 20-30 year baseline. This motivated a design study for the COsmic Dynamics and EXo-earth experiment (CODEX) for the European Extremely Large Telescope (E-ELT), a precursor to the now-approved second-generation instrument HIRES. Redshift drift is one of the key science cases for this instrument, which is forecast to be on sky by the late 2020s. Given this timescale, a detection of redshift drift by $\sim$2050-2060 is plausible. Calculations for the SKA yield timescales for radio detections of the early 2040s at the earliest [8]. While the above observatory-class facilities have the potential to detect cosmic acceleration by 2050, the US community does not have access to either facility and the timeline of $\sim$30 years is untenable given currently pressing questions on the expansion history of the Universe and the role of dark energy. We advocate both for prioritizing this science within the US research portfolio, and for consideration of dedicated cosmic dynamics experiments. Dedicated experiments can be more cost-effective and deliver results on much shorter timescales than are achievable with these observatory-class facilities.

In the short term, the key to enabling such dedicated experiments will be funding R&D efforts that address the two limiting factors that currently drive the long time baselines. These are (1) the need to deploy sufficiently large aperture telescopes in a cost effective way, and (2) improved spectrographs to enable higher velocity precision and better long-term stability. We specifically advocate for enabling redshift experiments at optical wavelengths, as this is the regime in which there exists the greatest potential for improvement on both fronts.

One solution to the challenge of collecting area is to eschew the construction of large telescopes in favor of arrays of smaller telescopes with equivalent effective aperture. This approach trades (unnecessary) spatial resolution to achieve significant cost savings for a given aperture. We have developed a method for producing large-area-equivalent telescopes by using fiber optics to efficiently link modules of multiple semi-autonomous, small, inexpensive, commercial-off-the-shelf telescopes [9]. This method is enabled both by advances in photonic lantern technologies (which result in $> 95\%$ efficiency in combining the light from the individual telescopes), low-cost telescopes, sensors, and computing (enabling autonomous coordinated operation of a large number of individual telescopes). This design has construction costs which can be more than a factor of 10 lower than equivalent traditional large-area telescopes, and importantly is scalable with time to enable increased aperture as needed. Use of an array also has a unique advantage for calibration, in that a subset of telescopes can be used to obtain observations of velocity reference targets simultaneously with the science observations. A 15m-equivalent dedicated array, which is capable of detecting redshift drift via the Lyman forest in less than a decade, can be constructed for roughly the same cost as a traditional 6-meter telescope. Similarly, a 30m-equivalent array could be deployed for the same cost as a 10m traditional telescope, further decreasing the time required for detection.

The other component required for an effective dedicated experiment is a spectrograph with < 1 cm s^{-1} precision and stability on timescales from years to decades. For comparison, standard spectrographs for exoplanet radial velocity measurements have in recent years achieved regular performance of ~ 10 cm s^{-1} on timescales of days or longer, and have even reached ~ 3 cm s^{-1} through the use of Laser Frequency Comb (LFC) calibrations – albeit with stability timescales of hours or days [10]. The LFC systems can be internally stable to < 0.1 cm s^{-1} on timescales of decades – the limiting factor here is that the spectrographs themselves induce velocity drifts due to thermal expansion, even on the timescales of the observations. A primary reason is that current high-precision radial velocity spectrographs are effectively passive systems. While there may be temperature stabilization of the spectrograph to minimize thermal expansion, there is no active monitoring/correction of path length changes within the spectrographs, which lead to drift in the observed radial velocity measurements. One promising path forward is to follow the example of gravitational wave detectors and use a laser control system to actively stabilize the spectrograph. Such a design uses standard cryogenic, vacuum, and vibration isolation as a starting point. The optical bench of the spectrograph can then be mounted with LIGO-style laser interferometers that provide metrology of the key optical dimensions to an accuracy of $\sim$ 1nm. The metrology is then fed into an active control loop using thermal heating pads bonded to the bench to provide dimensional control at nm level. This approach provides an extreme precision radial velocity spectrograph with the required precision of < 1 cm s^{-1} over timescales from seconds to years.

Together these solutions address the two issues of collecting area and long-term velocity stability that are the primary obstacles to redshift drift detection. A modest investment in development of these technologies over the next few years can enable deployment of a dedicated facility in the second half of the decade and a detection of redshift drift in the 2030s – at least a decade earlier than may be possible with SKA or the ESO-ELT. Such a facility could be deployed at a cost of ∼\$60 million. A facility dedicated to measuring cosmic acceleration would also be capable of measuring other accelerations of comparable magnitude, including hyper-velocity stars and galaxies in nearby clusters, each of which can be used to constrain the dark matter distributions of their host halos.

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