Snowmass2021 - Letter of Interest

Cosmology and Dark Matter at a cm/s

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

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
□ (CF7) Cosmic Probes of Fundamental Physics
■ (Other) IF2 – Instrumentation Frontier: Photon Detectors

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Abstract: (maximum 200 words)

Direct measurement of cosmic acceleration is a key scientific goal for both cosmology and studying matter and energy, the interactions between them, and the nature of space and time. For cosmology, observing redshift drift could directly establish the Friedmann-Lemaître-Robertson-Walker model. Moreover, it would increase the dark energy figure of merit by a factor of 3 beyond Stage 4 experiments, in combination with cosmic microwave background measurements. The same technology provides unprecedented radial velocity accuracy, enabling mapping the Milky Way gravitational potential to test ultralight axions or fuzzy dark matter, and its detailed structure to constrain dark matter interaction properties and modified gravity screening. Ultrastable interferometers have demonstrated factor 1000 reduction in key systematics, using concepts from high energy physics, putting these science goals within reach in the next decade.

Three key Cosmic Frontier science areas can make great strides in the next decade with the development and application of highly stable and well calibrated interferometric spectroscopy:

- Cosmic redshift drift and direct detection of cosmic acceleration [1;2];
- Constraining ultralight axions/fuzzy dark matter via Milky Way stellar acceleration mapping [3];
- Dark matter interaction properties via Milky Way gravity mapping, e.g. of tidal streams/satellites [4].

Redshifts and Doppler velocities are central measurements for cosmology and for astrophysics respectively. Spectroscopic cosmological redshift precision has been sufficient for standard needs. However, extending this to the time domain – over a Hubble time! – the concept of redshift drift (evolution) over long timescales due to cosmic expansion, has repeatedly been brought up in the literature since it was first introduced by McVittie and Sandage (a theorist and observer working together) in back to back articles in 1962 [5;6].

Just as redshift is a direct measure of cosmic expansion, so redshift drift is a direct measure of cosmic acceleration. The characterization and identification of the origin of current cosmic acceleration is a major goal of cosmic surveys in the 2020s, such as the Vera C. Rubin Observatory's Large Synoptic Survey Telescope (LSST) and the Dark Energy Spectroscopic Instrument (DESI). This cosmic acceleration is due to unknown new energy in the universe – a cosmological constant or dynamical dark energy – or to new laws of gravity beyond Einstein's general relativity – or to a breakdown in the homogeneous and isotropic spacetime governed by the equation of the Friedmann-Lemaître-Robertson-Walker (FLRW) model. Direct measurement of cosmic acceleration can rule out the last possibility by confirming the reality of dynamical acceleration and give incisive new constraints on the properties of the effective dark energy, greatly complementary to those coming from the 2020s experiments under construction. Indeed it could increase their probative power by a factor three, turning them into Stage 5 experiments.

This basically represents an evolution from density/galaxy surveys to velocity surveys to acceleration/gravity surveys. Four key advances make the next decade the time to establish this: 1) Making this into a *differential* measurement by observing not the change in a single emission wavelength but the difference between two nearby, well defined wavelengths in a doublet; 2) Using interferometric spectroscopy, which is itself inherently differential, reducing many instrumental systematics; 3) Recent development of ultrastable interferometers that can control systematics in spurious wavelength drift, point spread function, and calibration a factor at least 1000 times better than conventional spectrographs; 4) Recognition that the optimal science target is at redshift $z \lesssim 0.5$, greatly helping signal to noise, and that this is extraordinarily complementary with high redshift cosmic microwave background measurements to uncover the nature of dark energy.

Such ultrastable spectroscopy is also a key goal of Earth mass exoplanet detection from radial velocities, fusion plasma motions, biomedical Raman spectroscopy, and homeland security remote sensing.

For cosmic redshift drift, the drift is $\Delta z \approx (\Delta t/3\,\mathrm{yr})$ cm/s. This is challenging but a key goal of many science communities and should be achievable during the next decade. Because $\dot{z} = \Delta z/\Delta t = H_0(1+z) - H(z)$, where H is the Hubble expansion and H_0 its current rate, such measurements have great complementarity with high redshift measurements such as the CMB. Measurements at 1% (from observing a relatively small number of "golden" sources) of redshift drift around $z \approx 0.3$ plus the CMB power spectrum could deliver a dark energy figure of merit exceeding 1000. This acceleration experiment serves as well as an independent crosscheck of density or velocity surveys. HEP emission line surveys targeting doublets, such as OII and OIII, are already mature (e.g. BOSS, eBOSS, DESI). The main requirement is number of photons for signal to noise, i.e. time allocations on as large a telescope (10 to 30 meter class) as feasible. Europe is pursuing a different route to this goal, going for brute force with measurements of many 1000s of lines on a

40 meter telescope, but lacking the differential nature of the measurement, the stability of an interferometric spectrograph, and at high redshift $z > 2$ where one loses dark energy leverage and complementarity.

With direct acceleration measurements in the Milky Way, one can determine the dark matter density from the Poisson equation, without assuming spherical symmetry and equilibrium as in the commonly used Jeans analysis. Alternative dark matter scenarios, such as SIDM, WDM and FDM, predict characteristic cutoff scales in the linear power spectrum, which could lead to distinct signatures in the minimal halo mass and abundance of sub-structures, and can be probed by high precision radial velocity measurements down to $\sim$Earth-mass scales[7]. Mapping the gravitational field of the Milky Way, its tidal streams, and satellite galaxies can reveal the full distribution of dark matter – not just where it is but its properties such as nonweak interaction crosssections with dark matter and baryons, and Compton wavelength effects from ultralight dark matter. Other applications could be the peculiar acceleration fields within other galaxies and around galaxy clusters. This technique on an Integral Field Unit (IFU) spectrograph can provide spatial resolution, not only to distinguish between bulk and internal velocity evolution, but also to take advantage of the multiple spatially-resolved measurements of a line, each of which is narrower than the line when spatially-unresolved. Acceleration around galaxies in different environments can provide direct evidence for screening mechanisms in modified gravity.

On the instrumentation side, the interferometric spectrograph, a Michelson interferometer in series with a conventional spectrograph, known as externally dispersed inferometry (EDI), offers great benefits in both improved precision and systematics reduction. Conventional spectrographs have wavelength line spread functions that drift in position and shape under duress from thermal changes to the diffraction grating, fluctuations of air internal and external to spectrograph, a changing pupil, flexure of optical fibers, etc. They also have 1000s of degrees of freedom to control, accounting for each dispersive groove. Any instrumental wavelength drift translates directly into an "insult" in the wavelength accuracy. EDI, as has been used for precision Doppler radial velocimetry and high resolution spectroscopy[8–14], measures the wavelength based on the phase of a fringe, and has only three degrees of freedom – amplitude, period, phase. The insult factor can theoretically be reduced to zero through a technique developed by a HEP theorist and an instrumentalist. One can employ multiple delays in the interferometer to impose essentially a shift symmetry that cancels out any deviations; the delays can be weighted such that the Moiré pattern phase offset from one cancels the next. This technique called crossfading has been demonstrated on telescope data and delivered a factor 1000 reduction in insult.

Direct acceleration measurements can reveal the structure of spacetime, and of dark matter in our Galaxy. Recent developments in both survey strategy and technology have made the next decade ripe for this new window of "gravity surveys". This will finally achieve the long sought goal of direct detection of cosmological acceleration, with its extraordinary complementary with the CMB for Stage 5 level dark energy constraints, as well as mapping astrophysical, "peculiar accelerations" revealing structure and dynamics in the dark matter in the Milky Way galaxy. Gravitational wave interferometers are one clear example of the advantages of using fringe phase shifts for making precision measurements for astrophysics. The synergy of this approach for dark energy and dark matter (and other scientific fields) is truly extraordinary.

One of the attractive features of this technique is that it enhances the planned large facilities with a small (in both space and time footprint and dollars) project. A few million dollars in hardware and a small fraction of nights on premier facilities can deliver major science benefits in foundational explorations of cosmic acceleration and Galactic dark matter, as well as providing an important balance, and connection, between small and large projects as advocated by P5 in 2014.

References

[1] A. G. Kim, E. V. Linder, J. Edelstein, and D. Erskine, Giving cosmic redshift drift a whirl, Astroparticle Physics **62**, 195–205 (2015) [arXiv:1402.6614]

[2] D. Erskine et al., Direct Acceleration: Cosmic and Exoplanet Synergies, arXiv:1903.05656

[3] A. Ravi, N. Langellier, D. F. Phillips, M. Buschmann, B. R. Safdi, R. L. Walsworth, Probing dark matter using precision measurements of stellar accelerations, Phys. Rev. Lett. 123, 091101 (2019) [arXiv:1812.07578]

[4] H. Silverwood, and R. Easther, Stellar Accelerations and the Galactic Gravitational Field, Publ. Astron. Soc. Aust. 36, e038 (2019) [arXiv:1812.07581]

[5] A. Sandage, The Change of Redshift and Apparent Luminosity of Galaxies due to the Deceleration of Selected Expanding Universes, ApJ 136, p. 319 (1962)

[6] G. McVittie, Appendix to The Change of Redshift and Apparent Luminosity of Galaxies due to the Deceleration of Selected Expanding Universes, ApJ 136, p. 334 (1962)

[7] S. Chakrabarti et al., Towards a Direct Measure of the Galactic Acceleration, arXiv:2007.15097

[8] D. J. Erskine, An Externally Dispersed Interferometer Prototype for Sensitive Radial Velocimetry: Theory and Demonstration on Sunlight, PASP **115**, 255–269 (2003).

[9] D. J. Erskine and J. Ge, Novel Interferometer Spectrometer for Sensitive Stellar Radial Velocimetry, in "Imaging the Universe in Three Dimensions: Astrophysics with Advanced Multi-Wavelength Imaging Devices", eds. W. van Breugel and J. Bland-Hawthorn (2000), vol. 195 of *ASP Conf. Series*, pp. 501–507.

[10] P. S. Muirhead, J. Edelstein, D. J. Erskine, J. T. Wright, M. W. Muterspaugh, K. R. Covey, E. H. Wishnow, K. Hamren, P. Andelson, D. Kimber, T. Mercer, S. P. Halverson, A. Vanderburg, D. Mondo, A. Czeszumska, and J. P. Lloyd, Precise Stellar Radial Velocities of an M Dwarf with a Michelson Interferometer and a Medium-Resolution Near-Infrared Spectrograph, PASP **123**, 709 (2011) [arXiv:1103.0004]

[11] D. J. Erskine, J. Edelstein, W. M. Feuerstein, and B. Welsh, High-Resolution Broadband Spectroscopy Using an Externally Dispersed Interferometer, ApJ **592**, L103–L106 (2003).

[12] D. J. Erskine, J. Edelstein, E. H. Wishnow, M. Sirk, P. S. Muirhead, M. W. Muterspaugh, J. P. Lloyd, Y. Ishikawa, E. A. McDonald, W. V. Shourt, and A. M. Vanderburg, High-resolution broadband spectroscopy using externally dispersed interferometry at the Hale telescope: part 1, data analysis and results, Journal of Astronomical Telescopes, Instruments, and Systems **2**, 025004 (2016).

[13] D. J. Erskine, J. Edelstein, E. Wishnow, M. Sirk, P. S. Muirhead, M. W. Muterspaugh, and J. P. Lloyd, High-resolution broadband spectroscopy using externally dispersed interferometry at the Hale telescope: part 2, photon noise theory, Journal of Astronomical Telescopes, Instruments, and Systems **2**, 045001 (2016).

[14] J. Ge, J. van Eyken, S. Mahadevan, C. DeWitt, S. R. Kane, R. Cohen, A. Vanden Heuvel, S. W. Fleming, P. Guo, G. W. Henry, D. P. Schneider, L. W. Ramsey, R. A. Wittenmyer, M. Endl, W. D. Cochran, E. B. Ford, E. L. Martín, G. Israelian, J. Valenti, and D. Montes, The first extrasolar planet discovered with a new-generation high-throughput Doppler instrument, ApJ **648**, 683–695 (2006) [arXiv:astro-ph/0605247]