Snowmass2021 - Letter of Interest

MegaMapper: a Massively-Multiplexed Spectroscopic Instrument for Cosmology

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) *[Please specify frontier/topical group]*

Contact Information:
David Schlegel (Lawrence Berkeley National Laboratory) [djschlegel@lbl.gov]

Authors: (long author lists can be placed after the text)

Charles Baltay (Yale), Segev BenZvi (Rochester), Guillermo A. Blanc (Carnegie), Jeff Crane (Carnegie), Regina Demina (Rochester), Xiaohui Fan (Arizona), Simone Ferraro (LBNL), Gaston Gutierrez (FNAL), Klaus Honscheid (OSU), Leopoldo Infante (Carnegie), Juna Kollmeier (Carnegie), John Moustakas (Siena College), John S. Mulchaey (Carnegie), Adam Myers (Wyoming), Jeffrey A. Newman (Pittsburgh), Povilas Palunas (Carnegie), Claire Poppett (LBNL), Solange Ramirez (Carnegie), Lado Samushia (KSU), Eddie Schlafly (LLNL), David Schlegel (LBNL), Hee-Jong Seo (Ohio), Stephen Shectman (Carnegie), Josh Simon (Carnegie), Zachary Slepian (Florida), Marcelle Soares-Santos (U Michigan), Gregory Tarlé (U. Michigan), David Weinberg (OSU), Martin White (UC Berkeley/LBNL), and the MegaMapper team.

Abstract: (maximum 200 words)

The MegaMapper is a massively-multiplexed spectroscopic instrument to be hosted on a large-aperture wide-field telescope in the Southern hemisphere. The instrument is specifically designed to efficiently map the large-scale matter distribution in the high-redshift universe. The MegaMapper will conduct massive spectroscopic surveys of galaxies at $z > 2$ to measure their large-scale distribution, the formation of cosmic structure, and the early cosmic expansion. This data-set will significantly improve current and planned observational constraints on models of Dark Energy, primordial non-Gaussianity, and Inflation, and will provide improved measurements of neutrino masses, the number of relativistic species, and the spatial curvature of the universe. MegaMapper will also map the kinematics of Milky Way halo stars, using them as test particles to probe the nature of small-scale Dark Matter substructures. The MegaMapper instrument design builds upon existing, proven, and cost-effective technologies, reducing the risk and cost of the project.

A wide field-of-view (FOV), highly-multiplexed spectroscopic facility on a large-aperture ground-based telescope has been identified as a key missing tool to advance our understanding of Cosmology and fundamental physics through astrophysical probes [1, 2, 3, 4, 5]. Such a facility is needed to extend galaxy redshift surveys to map large-scale-structure over the largely uncharted cosmic volume available at $z > 2$, and to efficiently map the kinematics of MW stars that are subject to accelerations induced by dark matter substructure in the Galaxy's halo. As outlined in accompanying LOIs submitted to CF4 (Ferraro et al.) and CF3 (Simon et al.), these data sets will improve current and planned observational constraints on models of dark energy, inflation, and dark matter, along with improved measurements of neutrino masses, the number of relativistic species, and the spatial curvature of the universe.

The MegaMapper instrument would be a massively-multiplexed (20,000$\times$) robotic spectroscopic system hosted on a wide-field (3 deg diameter FOV) and large-aperture (6.5 m diameter) telescope at Las Campanas Observatory (LCO) in the Southern hemisphere. The instrument consists of a robotic focal plane assembly (FPA), where 20,000 robots can simultaneously target galaxies and stars with optical fibers. The fibers feed a cluster of 32 DESI spectrographs mounted on a gravity-invariant instrument frame that is supported by the telescope structure. Light is delivered to the FPA by a 5-lens wide-field-corrector (WFC) that provides a telecentric focal surface on the fibers and corrects the effects of atmospheric differential refraction. The conceptual design has been undertaken as a collaboration between the Observatories of the Carnegie Institution for Science to design the telescope, and the Lawrence Berkeley National Laboratory and members of the DESI team to design the instrument.

Robotic Focal Plane Assembly (FPA): The focal plane hosts 20,000 zonal fiber positioner robots, mounted with a pitch of 6.5 mm. The FPA is divided into 32 segments, each feeding 625 fibers to a single spectrograph. Such segmentation has proven critical to the efficient construction, integration, and testing of highly-multiplexed spectrographs like MUSE, VIRUS, and DESI. Each robot contains two precision mechanical gear-motors. One drives rotation about a central axis ("θ"), and the other on a parallel, eccentric axis ("ϕ"), allowing the robot to patrol a planar region. This is the basis of both the DESI and SDSS-V positioner designs. Zonal positioners allow for fast positioning time, high accuracy, and optical telecentricity. DESI completed and currently operates their focal plane of 5,000 positioners, demonstrating that such a system can be mass produced, reliably controlled, precisely positioned (within 3 μm), and reconfigured in a time envelope of less than one minute. Lifetime testing of DESI positioners yielded $> 98\%$ survival at 100,000 moves (the estimated total during calibration + five year survey), and $> 90\%$ survival rate beyond 1,200,000 moves. Ongoing R&D work at LBNL is evolving the DESI design to a smaller version, deployable at the pitch needed for MegaMapper.

DESI-like Spectrograph Cluster: The FPA feeds a cluster of 32 medium-resolution spectrographs that provide full optical wavelength coverage (360-980 nm) [6]. The spectrographs will be identical to those used for DESI and the SDSS-V LVM project [7]. These spectrographs went through extensive design studies, and are optimized to measure redshifts of faint targets in the sky-noise limit. The performance of these spectrographs has been shown to exceed their design goals in delivered optical quality and throughput. We would choose to somewhat increase the number of fibers feeding each spectrograph from 500 (as in DESI) to 625 by decreasing the fiber spacing at the spectrograph slit. This is supported by the as-delivered spot quality in the spectrographs and is being implemented in the SDSS-V LVM units (currently in construction). Each spectrograph is fed by a pseudo-slit with 625 fibers, with dichroics dividing collimated light into three cameras. Each camera has gratings, optics and CCDs that are optimized for its wavelength range in 360–555, 555–656, and 656–980 nm channels. The spectral resolution runs from 2000 on the blue end (at 360 nm) increasing to a resolution of 5500 on the red end (at 980 nm) in order to work between bright sky lines. The as-built efficiences are 70–90% across the full optical range. By the late 2020s both the current DESI spectrographs (10 units), and their twin SDSS-V LVM spectrographs (6 units), will have completed their surveys, and could be deployed as part of the MegaMapper. Another 16 units will need to be built.

Wide-Field Corrector (WFC): MegaMapper will be hosted on a new 6.5 m Magellan-like telescope. The optical design of the existing Magellan telescopes at LCO only provides a 0.5 deg diameter FOV. The 3 deg diameter FOV required for MegaMapper will be delivered on a Cassegrain focal surface at f/3.6 by a 5-lens WFC. The WFC incorporates a lateral displacement atmospheric dispersion corrector (ADC). The first and largest element in the WFC is 1.8 m in diameter, with the other four being ~ 1.5 m. Blanks, as well as polishing and testing procedures for lenses of these sizes are available, and similar lenses are in existence in both astronomical and defense applications. The WFC yields $\leq$ 23 μm rms radius spots ($\leq$ 0.45” FWHM on sky) across the full FOV down to zenith distances of 50°. This image quality is well matched to the median seeing at LCO (0.65”) and the 107 μm (0.95”) fiber diameter of the DESI spectrographs.

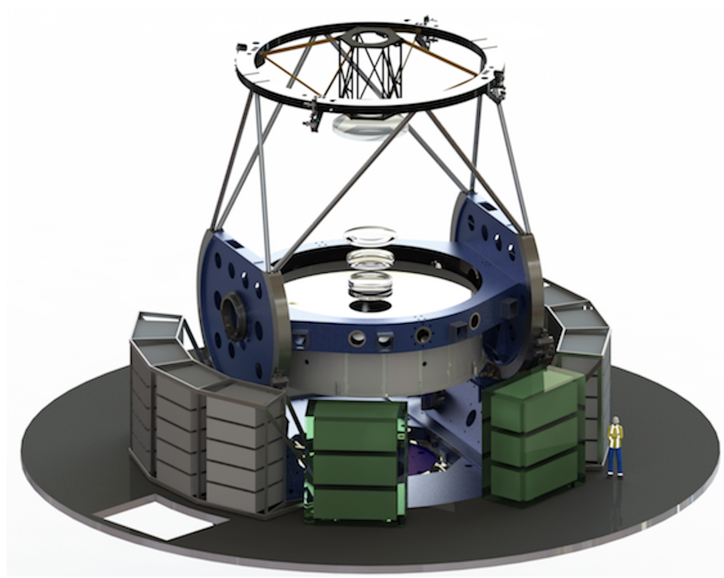

Figure 1: The MegaMapper concept. A cluster of 32 DESI-like spectrographs are mounted on an instrument support structure that rides on the azimuth disk of a wide-field Magellan-like 6.5 m diameter telescope. The clusters are fed by 20,000 robotic fiber positioners deployed across the 3 deg diameter FOV provided by a 5-lens wide-field corrector. *Credit: Jeff Crane, Carnegie Observatories.*

Data System: The MegaMapper data system will be a continuation of the data system as developed by the DESI team and operated on the NERSC high-performance computing platform. The DESI data reduction from the raw pixel level to fully-calibrated spectra and redshift-fitting is state-of-the-art today, and will be maintained and updated at least through the DESI key project from 2021-2025. Poisson-limited spectra for faint targets are achieved through a combination of stability of the spectrographs, stability of the PSF with theta-phi positioners, and a rigorous forward modeling of the spectral extraction and sky-subtraction [14]. The software modifications that will be required for MegaMapper are a training of spectroscopic templates based upon commissioning data.

MegaMapper provides order-of-magnitude improvements in capabilities over present-day and upcoming surveys and instruments such as SDSS-V, DESI, 4MOST, PFS, MOONS, and FOBOS. Optimized as a cosmology instrument, it can outperform next-generation concepts like the Mauna Kea Spectroscopic Explorer (MSE) [8] and ESO’s SpecTel [9, 10], at a fraction of the cost. The MegaMapper concept builds upon tried-and-true, fabricated, and operating designs (i.e., the DESI spectrographs and robotic positioners, and the Magellan telescopes). This strategy significantly reduces the risk of the project, and increases the predictability of cost and schedule.

References

[1] Thomas Matheson, Xiaohui Fan, Richard Green, Alan McConnachie, Jeff Newman, Knut Olsen, Paula Szkody, and W. Michael Wood-Vasey. Spectroscopy in the Era of LSST. *arXiv e-prints*, page arXiv:1311.2496, Nov 2013.

[2] National Research Council. *Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System*. The National Academies Press, Washington, DC, 2015.

[3] Joan Najita, Beth Willman, Douglas P. Finkbeiner, Ryan J. Foley, Suzanne Hawley, Jeffrey A. Newman, Gregory Rudnick, Joshua D. Simon, David Trilling, and Rachel Street. Maximizing Science in the Era of LSST: A Community-Based Study of Needed US Capabilities. *arXiv e-prints*, page arXiv:1610.01661, Oct 2016.

[4] Richard S. Ellis, Joss Bland-Hawthorn, Malcolm Bremer, Jarle Brinchmann, Luigi Guzzo, Johan Richard, Hans-Walter Rix, Eline Tolstoy, and Darach Watson. The Future of Multi-Object Spectroscopy: a ESO Working Group Report. *arXiv e-prints*, page arXiv:1701.01976, Jan 2017.

[5] Christopher W. Stubbs and Katrin Heitmann. Report on LSST Next-generation Instrumentation Workshop, April 11, 12 2019. *arXiv e-prints*, page arXiv:1905.04669, May 2019.

[6] Jerry Edelstein, Patrick Jelinsky, Michael Levi, Gregory Tarle, and David Brooks. The DESI spectrograph system and production. In , volume 10702 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 107027G, Jul 2018.

[7] Juna Kollmeier, S. F. Anderson, G. A. Blanc, M. R. Blanton, K. R. Covey, J. Crane, N. Drory, P. M. Frinchaboy, C. S. Froning, J. A. Johnson, J. P. Kneib, K. Kreckel, A. Merloni, E. W. Pellegrini, R. W. Pogge, S. V. Ramirez, H. W. Rix, C. Sayres, José Sánchez-Gallego, Yue Shen, A. Tkachenko, J. R. Trump, S. E. Tuttle, A. Weijmans, G. Zasowski, B. Barbuy, R. L. Beaton, M. Bergemann, J. J. Bochanski, W. N. Brandt, A. R. Casey, B. A. Cherinka, M. Eracleous, X. Fan, R. A. García, P. J. Green, S. Hekker, R. R. Lane, P. Longa-Peña, S. Mathur, A. Meza, I. Minchev, A. D. Myers, D. L. Nidever, C. Nitschelm, J. E. O'Connell, A. M. Price-Whelan, M. J. Raddick, G. Rossi, R. Sankrit, J. D. Simon, A. M. Stutz, Y. S. Ting, B. Trakhtenbrot, B. A. Weaver, C. N. A. Willmer, and D. H. Weinberg. SDSS-V Pioneering Panoptic Spectroscopy. In *Bulletin of the American Astronomical Society*, volume 51, page 274, September 2019.

[8] Alexis Hill, Nicolas Flagey, Alan McConnachie, Kei Szeto, Andre Anthony, Javier Ariño, Ferdinand Babas, Gregoire Bagnoud, Gabriella Baker, and Gregory Barrick. The Maunakea Spectroscopic Explorer Book 2018. *arXiv e-prints*, page arXiv:1810.08695, Oct 2018.

[9] Luca Pasquini, B. Delabre, R. S. Ellis, J. Marrero, L. Cavaller, and Tim de Zeeuw. ESO Spectroscopic Facility. In Cristina Chiappini, Ivan Minchev, Else Starkenburg, and Marica Valentini, editors, *Rediscovering Our Galaxy*, volume 334 of *IAU Symposium*, pages 242–247, Aug 2018.

[10] Richard Ellis and Kyle Dawson. SpecTel: A 10-12 meter class Spectroscopic Survey Telescope. In , volume 51, page 45, Sep 2019.