Dark Energy and Inflation Midterm Report

Precision measurements from a Stage-V dark energy and inflation experiment will transform the universe into the ultimate laboratory for studying fundamental physics. After the completion of DESI, LSST, and CMB-S4, a Stage-V program will need to characterize the distribution of matter using 1) the largest volumes possible to optimize cosmological measurement precision, 2) a large range of spatial scales for sensitivity to a full suite of cosmological parameters, and 3) the broadest possible range in redshift to fully measure the evolution of the cosmos.

An ambitious program of spectroscopic and intensity mapping surveys in the 2030-2040 timeframe will sharpen our understanding by

- probing artifacts from an early epoch of accelerated cosmic expansion (inflation) and exploring its underlying physics,
- investigating theories of late time acceleration (Dark Energy), including possible time variation of the equation of state and modified theories of gravity,
- constraining the neutrino mass scale, and
- unveiling new degrees of freedom produced at high energies in the early universe.

These topics correspond to physics that emerges at cosmological scales, scales that are primarily accessible via cosmic surveys. The potential for these future surveys is unprecedented and requires investment into R&D now to develop enabling instrumentation.

Dark Energy and Inflation: Primary Research Directions and Key Challenges

The three Primary Research Directions for a Stage-V facility each have two clear Key Instrumentation Challenges, as follows:

1) **Optical-infrared spectroscopy out to redshift z~4 at very high density**
    - **a)** Cost-effective infrared detectors with comparable performance to Silicon CCDs are required to explore new redshifts not accessible with DESI. New Germanium CCDs hold this promise as an alternative to InGaAs and HgCdTe CMOS detectors.
    - **b)** New designs for fiber positioners are required for a large increase in multiplexing power over DESI, thus leading to substantially larger sample sizes to span all spatial scales in galaxy clustering.

2) **21-cm intensity mapping of large scale structure out to redshift z~6**
    - **a)** High redshift galaxy surveys with the 21cm line require improvements in instrument calibration and stability to enable foreground removal. This includes hardware development such as direct, sub-ps synchronized digitization at each of the ~1000 dishes separated by up to a km.
    - **b)** The raw data of a next generation 21cm experiment would amount to 2 Zettabytes over a 5 year survey, necessitating real-time calibration feedback loops and data reduction for manageable datasets. To enable

such architecture, new network technologies need to be developed that can process tens of petabytes of raw data per second by performing timestream channelization, corner-turning and FFT image synthesis over fixed network path with modest power consumption. These technologies are synergistic with streaming DAQ development for collider applications.

3) **mm-wave spectral line intensity mapping of large scale structure to z~6**
    - **a)** A cosmological survey using intensity mapping of mm-wave spectral lines will need compact filled arrays of spectrally resolving on-chip detectors such as kinetic inductance detectors. Fabricating these detectors requires advancing fabrication techniques using superconducting thin-films (similar to those used for CMB detectors) to achieve significant improvements detector fabrication rates and yields.
    - **b)** Taking advantage of recent industry advances with multi-tone microwave readout (e.g. System on Chip hardware, very wide band digitizers) will be needed to readout a mm-wave spectrometer array with appropriate sensitivity for cosmology (~1M channels).

In what follows, we describe the data required for the key science drivers in a Stage-V experiment, the observational facilities (Primary Research Directions) that could produce these samples, and the Key Instrumentation Challenges that require a comprehensive R&D program.

Discovery Space for Stage-V Cosmic Surveys

Following the completion of DESI, LSST, and the upcoming CMB surveys, there are two clear regimes of discovery space for a Stage-V program in dark energy and inflation. The first is at scales of a few Mpc at low redshifts, where the Universe transitions from a decelerating regime governed by matter to an accelerating regime governed by an unexplained physical mechanism. It is in this accelerating regime where tests of dark energy models are likely to be most effective. The second regime is at high redshifts where the large volume allows precise tests of inflation, neutrino mass, early Universe physics, and non standard models of dark energy. The discovery space for these science drivers is presented in Figure 1.

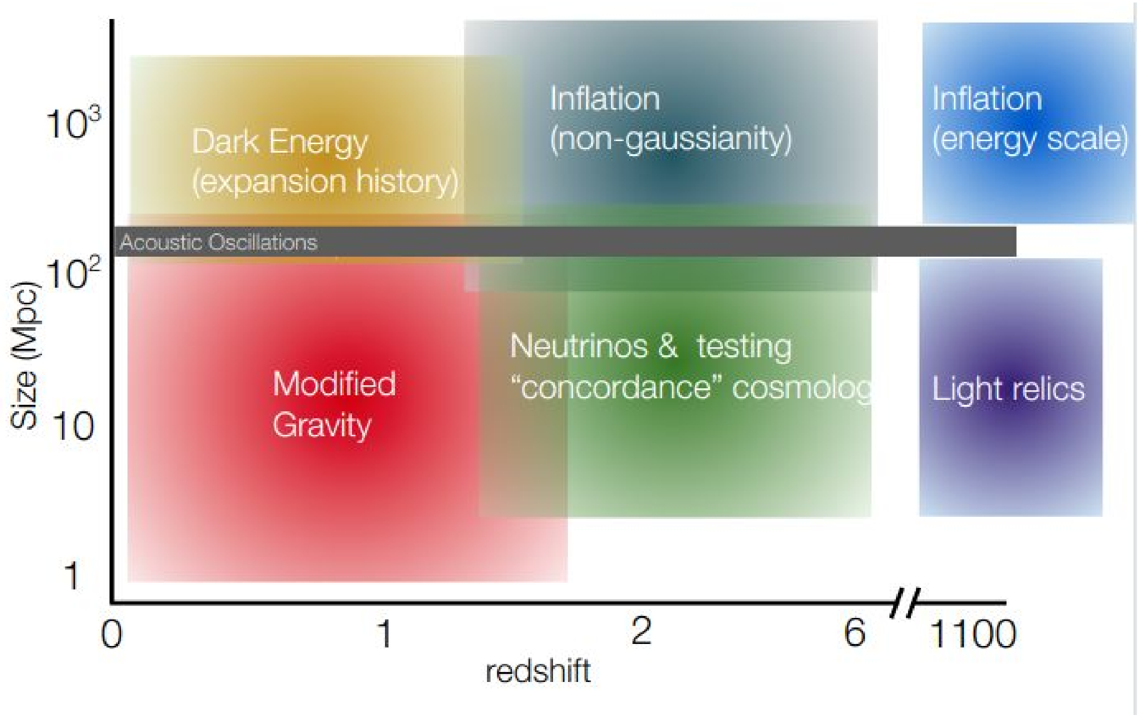

Figure 1: Key cosmological science drivers as a function of redshift (x-axis) and scale of clustering (y-axis).

Growth of structure in the accelerating epochs: The baryon acoustic oscillation (BAO), weak lensing, and supernovae Ia measurements from Stage-IV experiments will lead to major advances in understanding the time-evolving nature of dark energy. However, there will be a vast reservoir of information on cosmic expansion history remaining to be tapped through spectroscopic observations of clustering at small scales and lower redshifts (lower left corner of Figure 1). Precise Stage-V measurements of structure growth over the last nine billion years have the potential to illuminate the physics underlying dark energy or whether General Relativity must be modified to explain the current acceleration of cosmic expansion. Clustering on these small scales is the next frontier for high precision measurements of structure growth as a tool to explore the dynamic nature of dark energy during the time when dark energy is most prevalent.

DESI will obtain sub-percent precision measurements of cosmic expansion history using the BAO distance scale over the redshift interval $0<z<1.5$. At the highest redshifts in this interval, the standard cosmological model predicts a universe that is decelerating according to a matter-dominated energy content. At the lowest redshifts in this interval, the universe is shown to accelerate according to a dark-energy dominated energy content. DESI will have sufficiently high SNR on large scales to effectively saturate information on the BAO distance scale out to $z<1.5$. However, the number density of DESI galaxy targets is not sufficient to fully characterize the small-scale modes shown in Figure 1. With theoretical advances, this 'quasilinear' regime will be explored with techniques such as three-point statistics, forward modeling of the density field, and advanced modeling of the galaxy-halo connection. These theoretical advances will allow fundamentally new insight into dark energy and modified gravity. To extract the information on structure growth in this regime over the largest possible volume will require an order of magnitude increase in density over DESI.

Physics in the matter-dominated epochs: The cosmic expansion of the universe underwent two unexplained epochs of acceleration. We attribute the current acceleration to dark energy. In the very first moments, we attribute the acceleration to one or more inflationary fields. The signature of inflation remains in the largest scales of galaxy clustering, best probed over the large volumes available at high redshift (top central region of Figure 1). Exploration of clustering at $z>1.5$ at smaller scales (bottom central region of Figure 1) will also lead to vast improvements on the precision of BAO distance scale and structure growth measurements. In turn, these measurements will open a new frontier in testing models of early Dark Energy, curvature, and neutrino mass.

Substantial improvements in cosmological constraints using clustering at $z>1.5$ will be possible after the completion of the DESI Stage-IV spectroscopic program. For example, improvements of more than an order of magnitude will be possible in exploring non-Gaussianity in the primordial power spectrum. Whether by single object spectroscopy or intensity mapping, it is possible to obtain sample sizes that are equivalent to a two order of magnitude increase relative to DESI. A clear path therefore exists for a Stage-V experiment to extract critical information on inflation, the BAO distance scale, and structure growth at redshifts $z>1.5$.

Given these science drivers, the primary techniques for Stage-V exploration of the cosmos each have a Priority Research Direction (PRD), discussed below.

Priority Research Direction: Optical-Infrared spectroscopic cosmic surveys

Over the period 2020-2025, DESI will obtain optical spectra of tens of millions of galaxies and quasars to measure the clustering of matter as a probe of fundamental physics. The key enabling technologies for DESI are large-format Silicon CCDs hosted by three-channel spectrographs and robotic positioners that place fiber optics into the path of spectroscopic targets. Based on these two technologies, the DESI survey was optimized to obtain nearly cosmic-variance limited measurements of the BAO scale to $z<1.5$. The galaxy samples required to obtain high precision measurements of the redshift-distance relationship reach typical number densities of 3-5 $[\mathrm{Mpc}/h]^{-4}$, or roughly 1500 good redshifts per square degree. Clustering at higher redshifts will be explored through quasar spectra, primarily through absorption at $z>2$ due to the Lyman-alpha transition in neutral hydrogen. Even with Lyman-alpha forest observations, DESI will be shot-noise limited on all scales at $z>1.5$.

A Stage-V galaxy survey is motivated in part by the pursuit of dark energy science and models of modified gravity with measurements of the structure growth rate at $z<1.5$. The range of scales characterized as quasi-linear evolves with increasing redshift, from approximately 5 h^{-1}Mpc at $z=0.5$ to approximately 3 h^{-1}Mpc at $z=1.5$. To incorporate advanced models that optimally constrain the rate of structure growth on these scales, we estimate that a sampling of the density field to a SNR=0.5 at a scale half that of the quasi-linear clustering regime is required. Such a sample will enable modeling of astrophysical nuisance parameters and allow significant strides in modeling the dynamic nature of dark energy or modified gravity. Roughly 20,000 galaxies per square degree are required to achieve this precision on the clustering amplitude. Over a 14,000 square degree footprint, a Stage-V program would produce 280 million spectra, corresponding to 7% of the LSST gold sample. Reaching this number density for a spectroscopic survey requires an order of magnitude increase in multiplexing capability relative to DESI, a 10-12 meter class telescope to allow target selection one magnitude fainter than DESI, and infrared detectors for robust redshift estimation through detection of multiple features over the redshift interval $1<z<1.5$ (middle panel of Figure 2).

Precision measurements of clustering at redshifts $z>1.5$ further motivate a Stage-V galaxy survey. Massive spectroscopic samples at these redshifts would advance modeling of early dark energy, curvature, inflation, and neutrino physics. These objectives are best pursued with Lyman-alpha emitting galaxies and Lyman-break galaxies that are plentiful over the approximate redshift interval $1.5<z<4$. LSST imaging will provide a sample of candidate galaxies for these studies based on dropouts identified at blue wavelengths in multiband photometry. A sample of 10,000 galaxies deg^{-2} at $g<24.5$ over a 14,000 deg^2 can be identified with LSST imaging, leading to a density that is two orders of magnitude larger than the quasar density of DESI. These high redshift galaxies also illuminate the foreground neutral hydrogen that produces the Lyman-alpha forest, thus allowing continuous sampling of the low bias and low contrast density field. A program of this scale would contain most of the cosmological information from the linear regime. At a minimum, an order of magnitude increase in survey speed over DESI is required to saturate the large-scale modes for inflation and BAO over these redshifts. Another order of magnitude in survey speed would be required to probe smaller scales and sample the Lyman-alpha forest. Over a 14,000 square degree footprint, a Stage-V program of this scale would produce around 140 million spectra, corresponding to about 3% of the LSST gold sample. Infrared detectors would enable galaxy measurements over $1.5<z<2.0$ (bottom panel of Figure 2) which are impossible with DESI. Infrared detectors would also allow robust redshift estimation through [OII] emission to validate Lyman-alpha detections at redshifts $2<z<2.6$.

The two key technologies for a Stage-V galaxy survey are therefore Germanium CCDs and new fiber positioner designs. The challenges that demand immediate R&D are as follows:

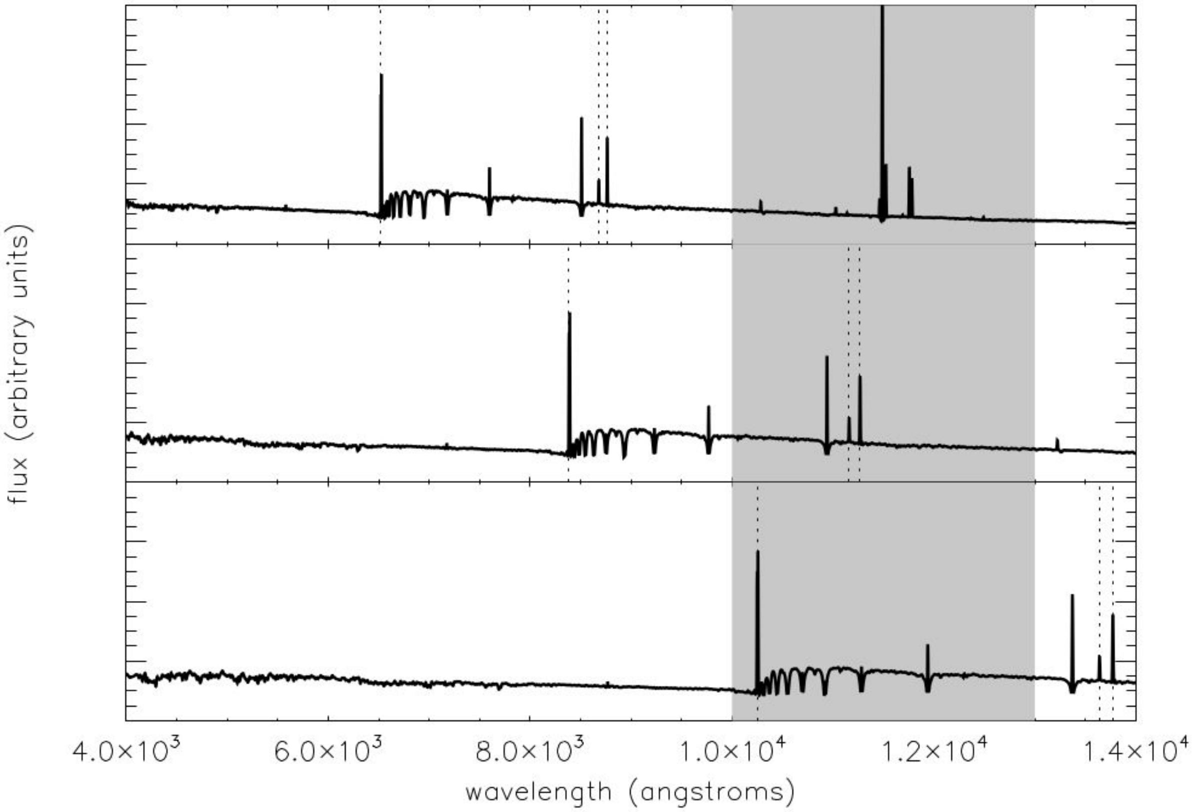

Figure 2: Spectra of emission line galaxies at redshifts z=0.75 (top panel), z=1.25 (middle panel), and z=1.75 (bottom panel). The location of [OII] and [OIII] emission lines is identified by the dashed lines. The coverage at redder wavelengths enabled by Germanium CCDs is shown in the shaded region, demonstrating what spectral features can be accessed at higher redshifts with infrared detectors.

Germanium CCDs: Silicon CCD development activities for dark energy science were performed at the Lawrence Berkeley National Laboratory (LBNL) in partnership with DALSA Semiconductor. Over a ten-year period, these deep-depletion CCDs advanced from an early prototype to a device that can be manufactured in bulk with few cosmetic defects and nearly optimal sensitivity across the wavelength range 3,600 < λ < 10,000 Å. These detectors are the enabling technology in the DES, BOSS, and eBOSS dark energy experiments and are being instrumented in the DESI spectrographs. Scientists at Fermi National Accelerator Laboratory (FNAL) and Brookhaven National Laboratory (BNL) have developed systems to efficiently test, characterize, and identify science-grade devices.

As demonstrated in Figure 2, the effective band-gap around 1 eV limits Silicon CCDs to galaxy redshifts at z<1.6. At higher redshifts, singly-ionized oxygen ([OII]), the primary spectroscopic feature used to determine redshift, is moved out of the bandpasses accessible by Silicon and into the IR. Enormous, relatively unexplored volumes will still be available at these higher redshifts even after DESI is completed. Detectors with sensitivity at wavelengths longer than 10,000 Å will allow us to extend galaxy surveys to higher redshifts.

While infrared InGaAs and HgCdTe CMOS detectors have been used in ground- and space-based observatories, these detectors are expensive, require substantial cooling, and suffer from low yield in the fabrication process. Calibration of the pixelated amplifiers is a considerable challenge and an impediment to data quality for long term surveys. Germanium CCDs offer a potentially attractive alternative to access longer wavelengths. Germanium CCDs can be processed with the same tools used to build silicon imaging devices, show promise for read noise and sensitivity comparable to that of Silicon detectors, and offer a high quantum efficiency to wavelengths as red as 1.4 microns when cooled to 77 K. This increase in wavelength coverage will allow a spectroscopic identification of [OII] emission lines to $z = 2.6$, a factor of two increase in volume over what is accessible in the DESI galaxy sample.

An investment in Germanium CCD development and a collaboration with new CCD industrial partners offers several synergies:

Light Source Applications: A number of properties make Germanium sensors an excellent choice for photon science applications at Synchrotrons like the APS and NSLS-II. Germanium's higher stopping power allows for a much higher quantum efficiency at higher x-ray energies, extending the usable range from 20keV for Silicon to almost 100keV for Germanium. Today a number of beamlines for x-ray fluorescence and absorption spectroscopy are already utilizing pixelated germanium detectors for their reliable performance across a large energy range. Methods under development for Germanium CCDs could replace the Li-doped n-type contacts often used in Ge x-ray detectors with a much thinner layer, thereby significantly reducing the dead layer thickness. Germanium CCDs could enable much smaller pixels resulting in increased count rate capability while at the same time resulting in a more compact and more cost effective detector. Furthermore, the imaging capabilities of these devices could extend the effective energy range for x-ray diffraction and imaging experiments.

Dark matter searches: a new skipper CCD design on Silicon with ultra-low readout noise shows promise for single photon detection. Several methods for direct detection of dark matter using Silicon detectors would benefit from the increased sensitivity to rare events offered by these new CCDs. To pursue this research requires a partnership with a new industrial partner for the delivery of Silicon wafers, thus leading to a significant increase in detector volume and sensitivity to dark matter detection.

Cross-agency collaboration: Germanium is 2.3x denser than Si, so is sensitive to higher energy x-rays than Silicon at a fixed detector thickness. With better energy resolution and much higher position resolution, Germanium CCDs can offer improved performance over hard x-ray detectors used in space-based missions. Low-noise, visible detectors such as Silicon Skipper CCDs can satisfy the needs for faint exoplanet characterization with a space-based instrument. The development of Germanium and a new foundry partner for CCD production therefore open opportunity for collaborative effort with NASA labs.

Robotic Fiber Positioners: Robotic fiber positioners have been an integral part of the advancement in spectroscopic surveys from Stage III to Stage IV Dark Energy Experiments. The survey speed of current spectroscopic facilities and three potential Stage-V spectroscopic facilities (in bold) are presented in Table 1. The key technology to increase survey speed in the future is the size of the fiber positioners. The fiber positioners for DESI consist of 5000 individual robots placed at a 10.4 mm pitch between neighboring units. With 6.5 mm positioners, MegaMapper would have ten times the survey speed as DESI with only a modest primary mirror. Positioners at a 5 mm pitch instrumented into the proposed 11.4-meter SpecTel telescope would offer a factor of 100 improvement in survey speed over that of DESI.

A significant technological hurdle for a stage V spectroscopic program can be retired with 5-6 mm pitch fiber positioners that can be constructed cost-effectively en masse. Several conceptual designs exist and are being explored now. A prototyping and comparative review of these designs would confirm their feasibility and allow cost modeling for mass production. Demonstrating the urgency of prototyping, the DESI project developed four independent designs over a five year period. After down-selection based upon cost and performance, it was still five years before a fully populated focal plane was possible.

Instrument	Primary Mirror Area	# fibers	Relative Survey Speed
BOSS	3.68 m^2	1000	1
DESI	9.5 m^2	5000	14.3
PFS	50 m^2	2400	36.3
MSE	78 m^2	3249	76.3
MegaMapper (6.5 mm positioners)	28 m^2	20,000	153
SpecTel (DESI positioners)	88 m^2	15,000	359
SpecTel (6.5 mm positioners)	88 m^2	38,400	919
SpecTel (5.0 mm positioners)	88 m^2	60,000	1435

Table 1: Survey speeds for multi-fiber spectrographs as measured by the product of the telescope clear aperture, number of fibers, and losses from mirror reflections. This speed assumes a dedicated program, which would not be possible in all cases. MSE, SpecTel, and MegaMapper are proposed experiments under consideration in the NAS decadal survey.

Priority Research Direction: 21-cm intensity mapping cosmic surveys

The first 21cm radio telescopes sensitive enough to form spatially unresolved maps of large scale structure to measure the expansion history at high redshift (z~1-2) are expected to produce their first results in the 2020-2025 timeframe. The CHIME experiment and others are driving the field in demonstrating the technology and analysis techniques required for cosmological results for key Dark Energy science goals. 21cm experiments form essentially spectroscopic surveys across enormous survey areas, leveraging developments in digital technology in the radio along with the low spatial resolution of compact radio arrays. Current 21cm experiments probe intermediate redshift ranges (z=0.8-2.5) that overlap with DESI and other optical surveys. Because neutral hydrogen is ubiquitous in the Universe, higher redshift surveys are not inherently more difficult than their lower redshift counterparts. As a result, future arrays can be designed for redshifts z=2.5-6 (200MHz - 400MHz) where the neutral hydrogen line naturally extends beyond traditional optical surveys. Above redshift z=6 (<200MHz) the signal becomes dominated by astrophysical effects. Overlap with optical surveys increases below redshift 2.5 (>400MHz) and could be used to round out the surveys to cosmic variance limits. The resulting science possible from high redshift 21cm measurements of Large Scale Structure live in redshift range z~2-6, and at scales 10^{-3} to ~0.5 h^{-1}Mpc, naturally probing inflation, unconventional Dark Energy, and neutrinos.

To achieve a redshift z=2.5-6 survey of large scale structure with a 21cm interferometer requires a compact array of 1000+ elements, outfitted with radio receivers, a timing network, digital and perhaps GPU-based correlators, the ability to remove bright foregrounds that swamp the cosmological signal of interest, and a compute infrastructure to handle the 200+PB of data and more for simulations.

A DOE-led 21cm experiment has been proposed to fulfill this promise in a single experiment. Packed Ultrawide-band Mapping Array (PUMA) is composed of 32,000 6-m dishes covering a hexagonal closed-packed lattice with a 50% fill factor. The array is designed to span 200-1100MHz (z=0.3-6) in a single instrument. Its main scientific goals include physics of dark energy and modified gravity (expansion history and growth across cosmic time), physics of inflation (primordial non-Gaussianity and primordial features) and two synergistic astrophysical themes (Fast Radio Burst and pulsars followup). A descoped configuration with 5000 dishes can still do significant science. Bringing this experiment to reality will require targeted R&D in a variety of areas that also overlap with traditional DOE strengths.

A full N^2 correlation of 1000+ interferometric elements across a wide bandwidth would result in data rates exceeding 1000s of PB/day. This can be reduced to as low as 100Tb/day or about 200 PB total by co-adding across elements that have the same physical spacing between antennas. Such co-addition can be done efficiently using a technique called FFT correlation, which in addition to the data rate savings also decreases the computational and therefore cost and power intensity since it scales algorithmically as N logN rather than N^2. It will therefore be absolutely required for the future experiments. However, it requires signals from individual antennas to be phase and gain calibrated across the band, which is currently not feasible. Our priority research directions deal with two enabling technologies.

Key Challenges:

Direct digitization at the focus synchronized across the antenna array: Today, signals are amplified at the foci of receiver, but transported by long analog links to the central processing location. This leads to differential temperature dependence in phases and gain from individual elements. *Digitization of the analog signals at the focus* of each telescope would allow improvements in complex gain stability and enable rigorous real-time feedback required for co-adding (described above). This may also allow direct correlation with calibration signals deployed on calibration drones, digitally shape the bandpass of the instrument to remove frequency dependence and hence aid in removing foregrounds, and measure cross-talk between dishes. This is an area with a great degree of commercial overlap: low cost digitizers operating in the gigahertz regime with up to 14-bit resolution are readily available; low cost programmable logic devices capable of interfacing with a high-speed ADC can provide digital filtering to the frequency range of interest and interfacing to high speed networks; and the availability of integrated RF / ADC / FPGA devices in the near future may provide a path to very compact high-performance receivers. However, simply distributing a clock signal from a central location suffers from the same drifting phase dependencies. Instead, one must deploy *precision clock distribution* techniques that actively monitor delays and maintain sub-ps synchronization. Although this level timing synchronization has been demonstrated, the solution is not cost effective at this scale. Designing a low-cost solution by leveraging timing solutions already deployed at DOE beam facilities informed by requirements from radio demonstrations ties this R&D effort to a core DOE strength.

Network architectures: 21cm interferometers implement a portion of the telescope optics in network and software. Instead of light-rays propagating through optical lenses, signals from each telescope in the array are streamed through the massive network and coherently combined to form an image of the sky. Total data rates after digitizaton exceeds petabytes per second that need to be efficiently analyzed in a distributed architecture. Such architecture is characterized by fixed data paths and standard signal processing operations, such as FFTs and corner-turns. The evolution in accelerator experiments from triggered data acquisition to streaming data acquisition has great synergistic possibilities for co-development. Both are characterised by branched network topology with fixed data packet routes and massive data rates.

Other Key Technologies:

Precision management of individual components: Current generation of experiments have found that differences in the telescope beam patterns between elements causes the real-time reduced to be less efficient than anticipated. Moreover, the beam patterns remain difficult to measure in advance, so they cannot yet even estimate how much signal the experiments are losing. The differences in beam patterns and response across the instrument bandwidth stem from differences in the dish shape, differences in the receiver chains (amplifiers, filters, and signal transmission), and lack of real-time feedback on changes between elements due to thermal drifts, etc. To realize an efficient co-adding scheme, we require the ability to mass produce identical sensitive receivers (telescopes, amplifiers, signal transmission) with excellent uniformity. This requires evolving new fabrication techniques such as fiberglass dishes to a more advanced state, and facility infrastructure to measure and ensure uniformity.

Improved Calibration techniques: The biggest issue facing current experiments is the inability to remove bright foreground emission from the Milky Way Galaxy. Although it is in principle easy to filter based on its smooth dependence on frequency, frequency dependence in the instrument response hampers this subtraction, and in fact current experiments do not yet have a detection specifically because they cannot yet remove this foreground emission. In particular, the instrument beam and the instrument gain must be known to ~1% or better. Although the field is tackling this challenge in a variety of ways, more work needs to be done towards improved calibration. One example are *Unmanned aerial vehicle for primary beam calibration:* one mechanism for mapping beams is to transmit radio signals from sources deployed on drones or other aerial platforms. Advances for this technology could include digital signals generated to be correlated with the dishes for improved signal-to-noise.

Intensive simulation, pipeline, and analysis: Current 21cm interferometers are the first generation of imaging telescopes theoretically capable of detecting cosmological neutral hydrogen at large scales. These initial instruments are discovering tradeoffs between sensitivity, sky coverage, computational tractability, and calibration ability that were not fully appreciated during their design phases many years ago. As a result, more realistic assumptions can now be used to optimize the design of the instrument, calibration strategy, and data analysis. This requires development of massive time- and map-based simulations, the ability to inject ‘known unknowns’ such as timing jitter, non-uniformity, gain changes, and calibration uncertainties, and a full analysis pipeline to cosmological parameters to estimate the effects of these systematics.

Priority Research Direction: mm-wave intensity mapping cosmic surveys

The third PRD is an intensity mapping cosmic survey using the signal from rotational CO transitions and the [CII] fine structure lines. This approach, like the 21-cm technique (PRD-2), measures the emission from all objects along the line of sight. For sufficiently narrow detection bands, the total measured flux is dominated by CO/[CII] line-emission coming from galaxies within a narrow slice in redshift. The large angular scale fluctuations of the measured intensity map provides a measurement of the galaxy 2D power spectrum at that redshift. Measuring a broad range of detection bands provides a spatial-spectral data cube that corresponds to a biased tracer of the 3D underlying dark matter density field. Like a 21-cm galaxy survey, a Stage-V mm-wave intensity mapping survey is sensitive to both non-gaussianity from inflation and high redshift cosmology through the BAO feature. Such a survey is both independent of and complementary to a 21-cm survey and cross-correlation between the two measurements will yield results that are scientifically compelling and robust to astrophysical assumptions (e.g. foregrounds, star-formation uncertainties).

At high redshifts, the CO/[CII] lines are shifted to mm wavelengths, frequencies that are difficult to detect using traditional technologies. Members of the mm/sub-mm astrophysics community are actively developing technologies for mm-wave intensity mapping using detectors similar to those used in CMB experiments. Instruments in progress, which will make the first proof-of-concept measurements of these lines, include TIME (CO/CII), AIM-CO and COMAP (CO), and Starfire (CII). Near-future projects in the US, planned for CCAT-Prime and the South Pole Telescope, will deploy larger integral field unit (IFU) spectrometers to carry out initial cosmological measurements using this technique and will serve as pathfinders for an eventual Stage-V cosmic survey. Recent advances with large arrays of superconducting detectors (such as used for CMB) will provide the technical foundation for advancing this new probe of cosmology to the level needed for a Stage-V cosmic survey.

Technology development for submm intensity mapping

A Stage-V cosmic survey of large scale structure over the redshift range $3<z<6$ using mm-wave intensity mapping requires hundreds of pixel years on a 6-10 meter submm telescope. A project of this scale can be accomplished if each pixel has a significant fractional bandwidth populated by spectral channels with a resolving power of a few hundred. At wavelengths spanning the mm-wave and submm-wavelength, existing technology (grating spectrometers, Fourier transform and etalon instruments, submm mixers) cannot easily scale to the needed focal plane density and bandwidths. New technologies with compact on-chip spectrometers will be necessary. Several groups (e.g., micro-SPEC, SuperSpec, W-SPEC, DSHIMA) are pioneering this technology using microwave Kinetic Inductance Detectors (mKIDs) with prototype instruments having a few pixels currently being fielded. A Stage V cosmic survey will require a few-thousand pixel IFU, which efficiently fills the focal plane of a contemporary 6-10 meter telescope. Such a focal plane requires nearly half a million detectors and corresponding readout channels. Expanding the mKID on-chip spectrometer technology to the pixel density required for a survey-class instrument will require significant improvements in fabrication yield, testing and readout. There is substantial overlap between the mm-wave spectrometer technology and current state-of-the-art CMB detectors and the facilities and expertise used for executing CMB-S4 provide a solid technical basis for carrying out the needed R&D for a mm-wave Stage-V cosmic survey. The principle technical advancement is increasing the detector density relative to what has been successfully implemented for CMB. Where CMB-S4 will deploy 500k detectors on 21 telescopes, a Stage-V mm-wave cosmic survey will deploy 500k detectors on a single focal plane. There are two key challenges to achieving this goal:

Key Challenges

Detector Fabrication: The increased detector density favors using mKID detectors, which unlike Transition Edge Sensors, are athermal sensors. The latter places stringent requirements on fabrication processes and materials synthesis to insure tight control of materials properties to maximize yield while minimizing unwanted noise (e.g. from Two-Level System fluctuators). Moreover, the required resolving power of a few hundred corresponds to more narrow optical bandpasses relative to what has been demonstrated for CMB experiments. These more narrow bandpasses also require tighter process control during detector fabrication.

Detector Readout: The intrinsic advantage of mKID technology is their inherent multiplexability. However, the channel count and channel density needed for Stage-V cosmology requires more than an order of magnitude increase in detector count compared to current state-of-the-art and will require investment in further developing the needed multi-tone microwave readout.

Specifically, mKID readout for Stage V cosmology needs new electronics that takes advantage of recent industry advances (System on Chip hardware, very wide band digitizers).