Spectroscopic Roadmap

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Outline

- Background and Motivation
- Possible Path for Spectroscopic Programs
- Challenges and Complementarity to Small Programs

DESI in 2024

- Will have completed 14,000 sqdeg spectroscopic survey
- Spectra of ~30M objects
  - Primary science of BAO to $z<3.5$
  - Redshift space distortions, full-power, etc.
  - Redshifts for subsample of LSST sources
  - Possible cross-correlation calibration of photo-z
- Very capable instrument in 2024
  - Low redshift, magnitude-limited sample?
  - New sample of targets at high redshift?
  - Supplemental LSST spectroscopy?

LSST in 2024-2032

- Designed to meet cosmology goals independent of supplemental data
- Potential to enhance LSST astronomy and cosmology beyond core goals with comprehensive spectroscopy
- Cosmology drivers for spectroscopy
  - Transient science
  - Evolution of structure
  - Dark matter and gravity
  - Photo-z training
  - Galaxy clusters
  - Strong lens systems
  - …

Recommendation for Wide-field Spectroscopy

- Consistent across multiple studies
  - Kavli, Cosmic Visions, Elmegreen
- Motivated by enhancement of LSST science
  - 8m-class telescope
  - DESI-like resolution
  - DESI-like wavelength coverage at minimum
  - Extension to 1.3-1.5 microns desirable
  - Minimum field of view 20 arcmin; >1 degree preferred
  - High multiplexing, >2500x
- What is appropriate timeframe?
- 6-meter or 30-meter as alternative?

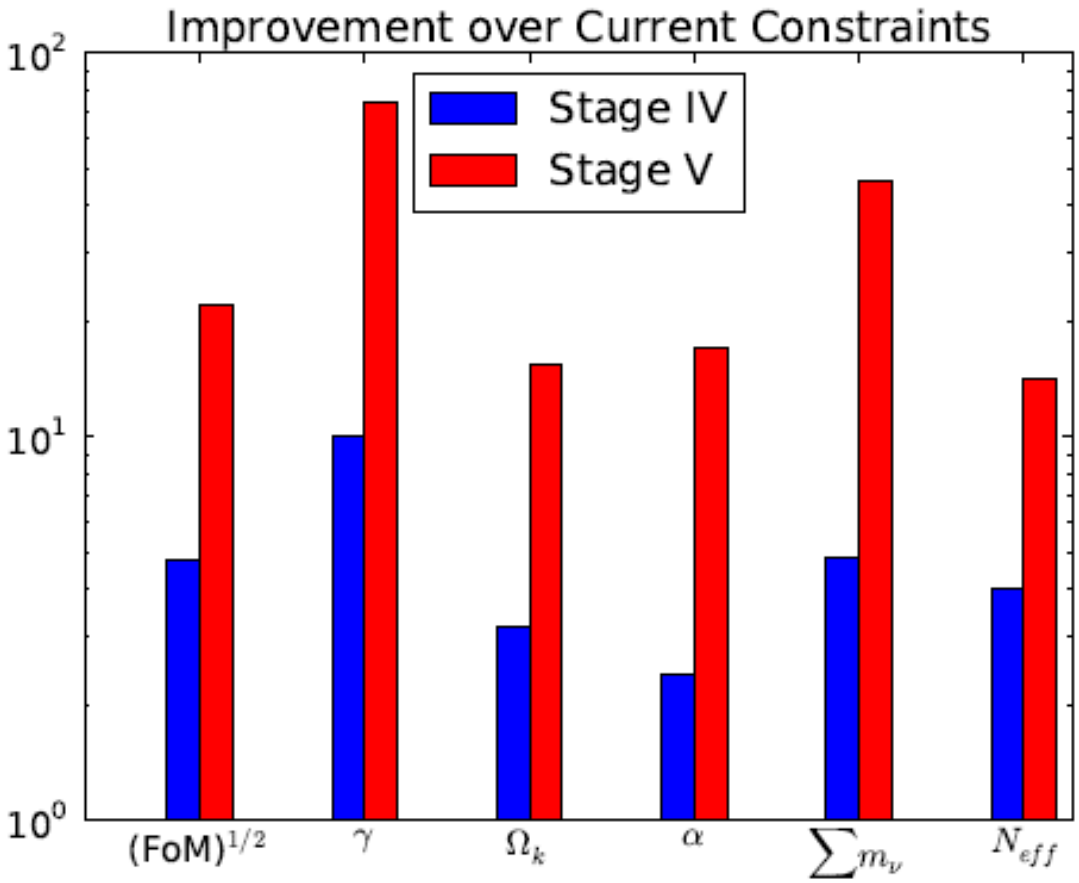
Scope and Budget for Coordinated LSST Spectra

- $5-10M: Upgrade DESI in North or move to Blanco
- ~$40M: Clone DESI for Blanco in Chile
- ~$75M: Provide new instrument for existing or planned (e.g. MSE, TMT, GMT) telescope
- $125-150M: New Magellan clone and instrument
- $250-500M: New instrument on new 8-11-meter telescope in Chile (requires multi-agency and international collaboration)

- Note: DESI is 10 years from conception to survey. Expect delivery time to scale with complexity.

Dedicated Spectroscopic Program in 2032

- Following DESI and LSST: Possible for major advances in standard cosmological model from massive spectroscopic program
- Illustrative and optimistic: need specific constraints for spectroscopic survey
- Not shown here: follow-up surprises from Stage-IV



Modes Available After DESI

- 20k/sqdeg galaxies to z<1.75
  - 200M modes with new sample
  - Access non-linear regime
  - kmax=0.38 (z=0.5); kmax=0.6 (z=1.5)
- 20k/sqdeg galaxies at 1.75<z<3.25
  - 150M modes with new sample
  - New BAO, kmax=0.36 (z=2), kmax=0.47 a(z=3)
- 40k galaxies/sqdeg → full power spectrum to kmax=0.35 and z<3.25

Redshift	kmax	Modes (Millions)	N (per sqdeg)	N (nonlinear)
0.25<z<0.75	0.19	1.75	500	2000
0.75<z<1.25	0.25	7.37	1500	6000
1.25<z<1.75	0.30	17.47	3000	12000
1.75<z<2.25	0.36	31.97	4000	
2.25<z<2.75	0.41	50.67	6000	
2.75<z<3.25	0.47	73.33	7000	
3.25<z<3.75	0.53	99.75	9000: extremely difficult	

Spectroscopy of a Billion Objects

- DESI - science reach still not statistically limited
  - Lack mixed bias tracers and high density sampling at high redshift
  - Room to improve RSD at small scales (k>0.2)
- Statistics for future optical spectroscopic survey
  - More modes to explore
  - Can increase mix of tracer bias
  - Measure clustering to non-linear scales at z<1.5
  - Measure clustering to linear scales at 1.5<z<3.25
- Can now probe z>2.1 Lyman-alpha forest with LBGs (e.g. Lee et al. 2017)
- Galaxy evolution and Milky Way science drivers to reach 1B spectra
  - e.g. ESO Future of Multi-Object Spectroscopy Working Group Report
  - https://arxiv.org/ftp/arxiv/papers/1701/1701.01976.pdf

- Consider comprehensive program to saturate information content through clustering to z=3.25 in tandem with galaxy science/stellar spectroscopy

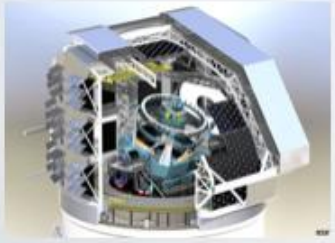
A Family Tree for Spectroscopy

Imaging

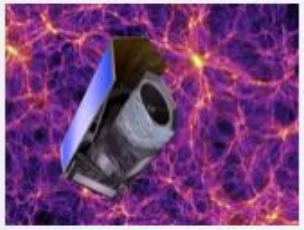
SDSS 2.5m, 7 deg^2 FOV

DECam, Blanco 4m,

HSC, Subaru 8.2m,
1.5 deg^2 FOV



LSST 6.5m (effective),
9.5 deg^2 FOV



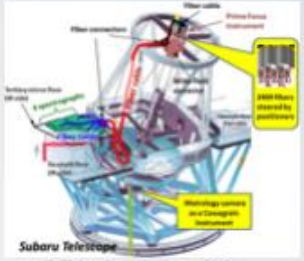
Euclid 1.2m (space),
0.5 deg^2 FOV

WFIRST 2.4m (space),
0.34 deg^2 FOV

Spectroscopy

SDSS 2.5m, N=1000

DESI, Mayall 4m,
N=5000



PFS, Subaru 8.2m,
N=2400

8-11m class LSST
spectroscopic facility

Billion Object Apparatus

Possible Path for Spectroscopy

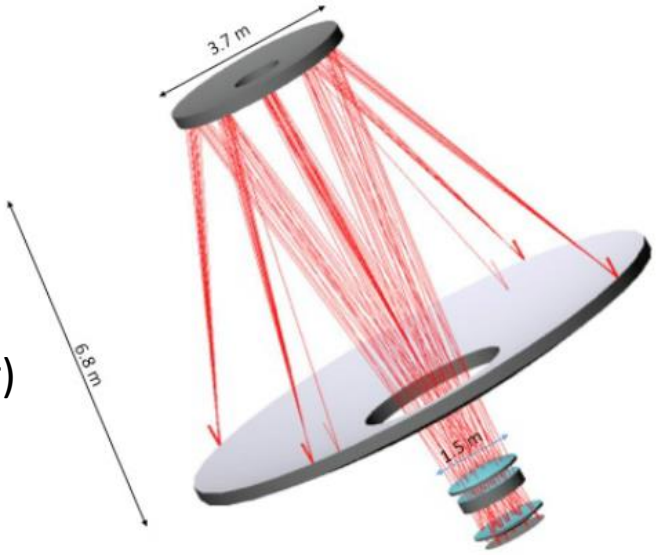
- The roadmap!
  - DESI → DESI-II → LSST-coordinated spectroscopic facility → Dedicated spectroscopic survey facility
  - Continuous coverage
  - Shared technologies
- DESI-II
  - Pursue new clustering regimes
  - Cover subset of immediate LSST needs in 2024-2026 timeframe
- Dedicated facility for LSST spectroscopy
  - Instrument with ~5000-fiber spectrograph
  - Coordinate with LSST imaging over final 5-6 years
  - Pursue multiple cosmology/astronomy programs
  - Instrument spectrographs with IR coverage
  - Generalize design for upcoming large telescope for massive multiplexing
- Billion Object Apparatus
  - Inherit telescope and/or spectrographs from LSST spectroscopic program
  - Massive upgrade to 50k-100k fiber spectrograph at completion of LSST
  - Dedicated spectroscopic survey to $z<3.5$

Achieving the Multiplex Limit

- Traditionally, 'survey etendue' $A\Omega$ is defined as the product of telescope collecting area and FOV
- At high density surveys, more appropriate metric is related to multiplex factor
  - As long as the surface density of fibers is less than the surface density of targets, optimize the product of telescope area and number of fibers: A*N
- Target density to achieve Stage V is ~40k/sqdeg
- DESI fiber density is ~700/sqdeg with 6 millimeter patrol radius

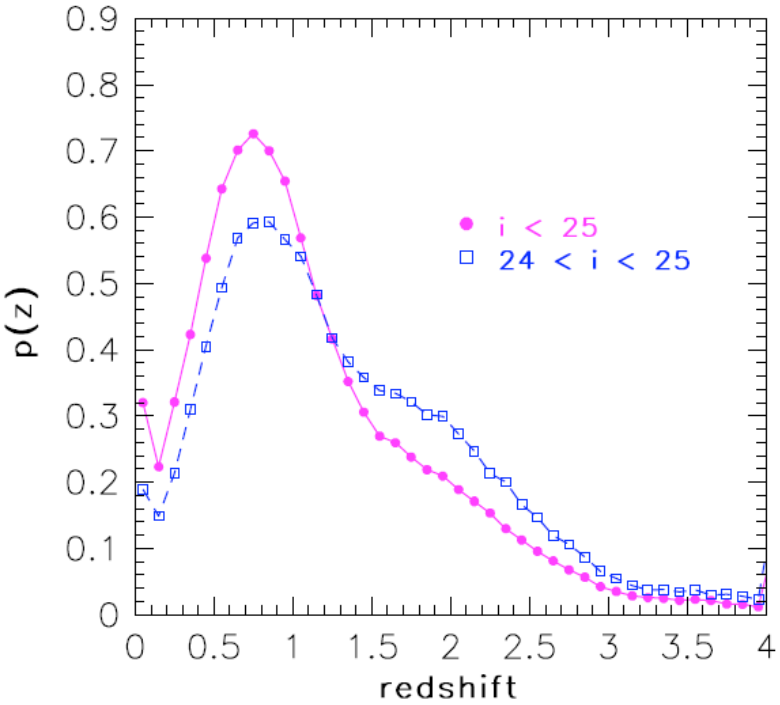
Possible Telescope Design

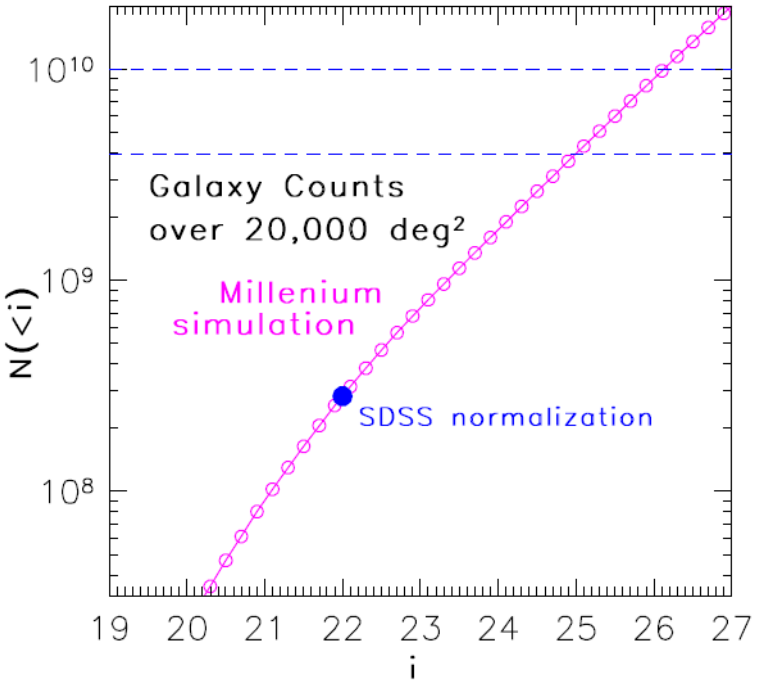
- Design for Cass focus on 10-m class telescope
  - “Fiber Design” Pasquini et al., 2016
- 2.5 degree diameter FOV (4.9 sqdeg)
- F/3 beam
  - 145 micron/arcsec platescale
  - Well matched to SDSS fibers (180 micron diameter)
- 1.3 meter focal plane diameter
  - 2.6X DESI focal plane area
  - Well-matched to LSST spectroscopic facility
  - Could host 13,000 fibers using DESI positioners
  - Increase to 50,000 fibers if decrease patrol radius from 6→3 millimeter
- 50,000 fibers over 4.9 sqdeg
  - Goal of 40k targets/sqdeg
  - Require average 4 visits per coordinate
  - ~12,000 observations for 14,000 sqdeg
- **See also MSE discussion in parallel session**



Magnitude Limited Sample

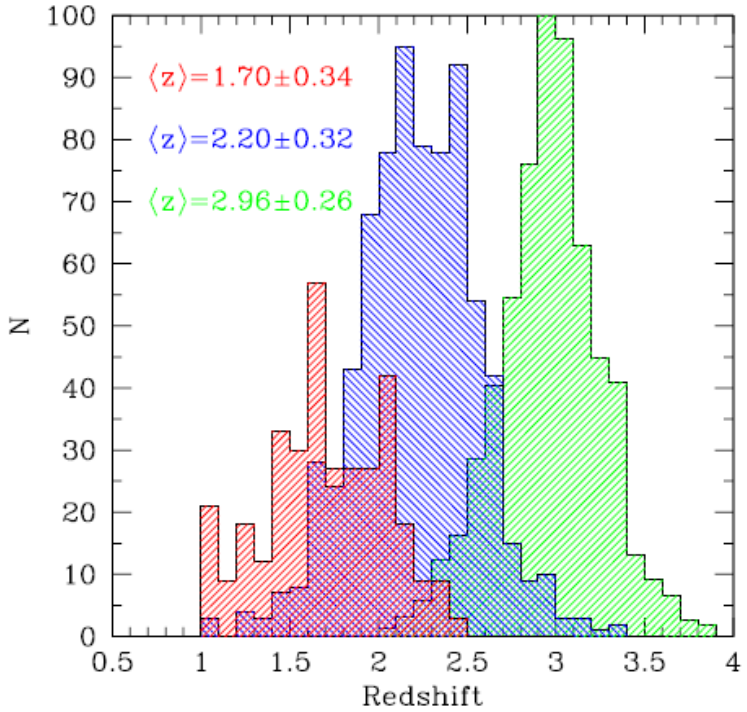
- VVDS survey at i<22.5 with 8m class telescope
  - Better spectral resolution and wavelength coverage required
- Magnitude-limited sample favors z<1.0, saturate low-z modes
- Tune magnitude limit to desired number density
  - 15k/sqdeg at i<22.0
  - 20k/sqdeg at i<22.5
- Need fainter targets and color selection to sample z>1

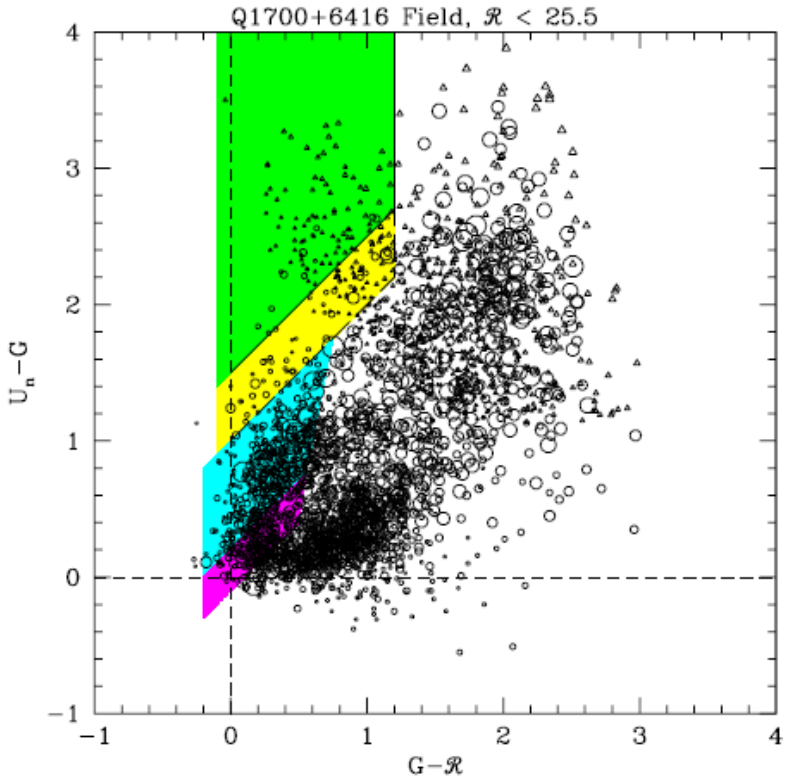




Sample selection (1.0<z<3.25)

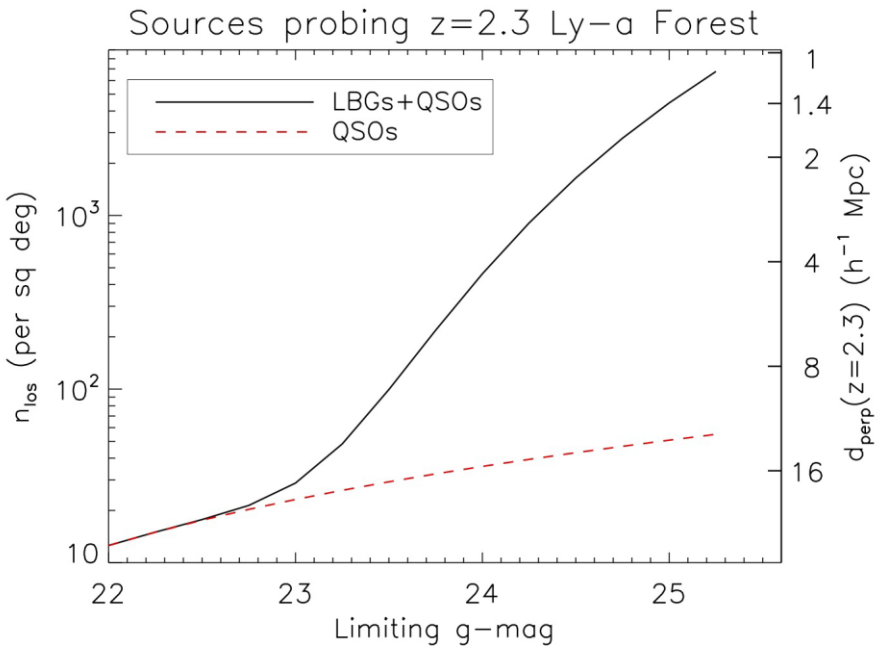
- Prior galaxy science programs → star forming samples with 10-m telescope
- e.g. Steidel et al, LRIS on Keck I
  - Lyman-break galaxies selected on (U-G) versus (G-R)
  - R=1000
  - Redshifts from UV interstellar lines
  - 1.5 hour exposures
- Revisit redshift distributions for r<24.5

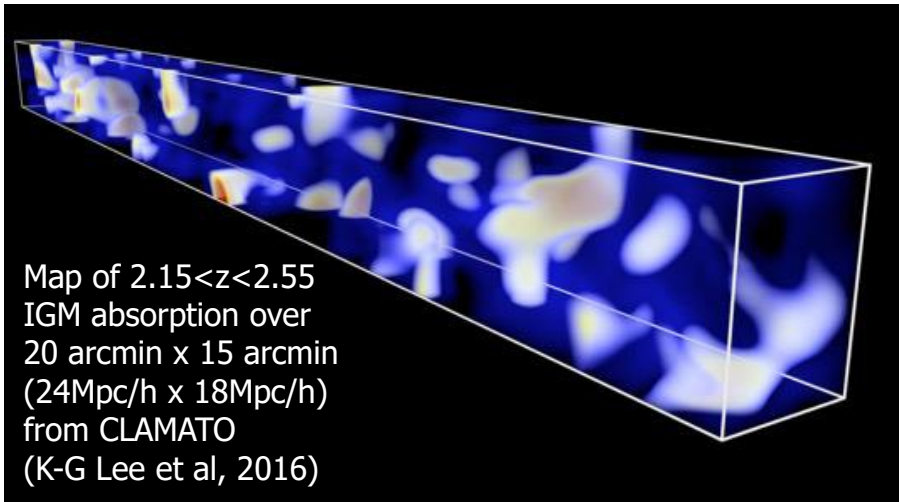




Lyman-alpha Absorption Tomography at z>2

- Likely too few direct tracers at z>2 to reach kmax goal
- ~2500 sightlines per sq deg at r < 24.5
- Sightline separations of 2-3 Mpc/h → full 3D mapping down to non-linear scales through IGM absorption
- K-G Lee et al 2014 showed that S/N = 2-3 per angstrom sufficient for tomographic reconstruction
- Ongoing CLAMATO survey over 1 sq deg on Keck-I/LRIS
  - (http://clamato.lbl.gov)
  - 2hr exposure for r<24 → S/N~2 per angstrom in 0.7" seeing





Challenges & Complementarity to Small Programs

- Science drivers
- Target selection and spectral quality
- Instrumentation
- Partnerships and timescale

Science Drivers

- DESI and DESI-II
  - What will r<19.5 program reveal about small-scale clustering?
  - What will be limits of LRG/ELG/quasar programs at z>0.4?
  - What is optimal use for DESI in 2024?
- Coordinated LSST Spectroscopy
  - What is scope of full spectroscopic portfolio, including astronomy?
  - Over what timescale is spectroscopy needed?
- Dedicated Spectroscopic Survey
  - Spectroscopic program needs cosmological model space beyond mode-counting.
  - Need theoretical infrastructure for small scales and higher-order statistics (Dark energy figure of merit obsolete by 2030)
  - Combination of numerical work and analytical models for scales <10 Mpc
  - Novel probes and other measurement techniques to consider?

- Simulations, theory, and new windows can all be pursued now with an impact for spectroscopic surveys on much longer time scales

Target Selection and Spectral Quality

- Coordinated LSST Spectroscopy
  - What resolution and wavelength coverage is needed for astro/cosmo
  - What exposure depths are required?
  - What is best fit of aperture and multiplexing? Is it well-matched to 50k fiber upgrade?
- Dedicated Spectroscopic Survey
  - Approximate selections presented for proof of concept
  - How to optimize low redshift selection?
  - How to optimize high redshift selection?
  - What resolution and exposure depth required to reach desired completeness?

- Requires continued observation with next-generation facilities such as PFS and MSE

Instrumentation Challenges

- IR coverage essential to explore high redshift
  - [OII] visible to z<2.5 with 3500<lambda<13,000 \AA
  - New germanium CCD's being developed at Lincoln Labs/LBNL
- Multiplexing
  - Increase number and density of fibers in focal plane
  - Are fibers and positioners most appropriate?
- Scale production of spectrographs for tens of thousands of fibers
  - How to build, test and maintain ~100 spectrographs
  - Gain efficiency with more dense sampling on CCD
- Ground layer adaptive optics
  - Simulated studies of HST imaging reveal optimal sensitivity for high z galaxies around 0.6" seeing
- Potential for new technology development now toward any of these goals

Programmatics

- Coordinated LSST spectroscopy well-motivated but nearing state of urgency
  - Decadal survey concludes in 2020, leaving only three years to beginning of LSST
- How to define cosmological drivers for Stage V before Stage IV begins?
  - Theory not developed to match possible survey scope
  - Need updated Dark Energy Task Force
- US Partners
  - Being discussed in DOE Cosmic Visions
  - Science beyond cosmology → NSF + NASA
- Global partners essential

Summary

- Spectroscopic potential exists beyond DESI in series of staged experiments
- Challenges to long term spectroscopic program include timing, theoretical framework, and technology developments
- This workshop
  - Long-term strategy for spectroscopy
  - Short term programs to enhance LSST, DESI, and long term vision