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

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<th>N (per sqdeg)</th>
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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

• 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

**Spectroscopy**

- SDSS 2.5m, N=1000
  - DESI, Mayall 4m, N=5000
  - PFS, Subaru 8.2m, N=2400

- 8-11m class LSST spectroscopic facility
  - 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

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 $\sim40k/sqdeg$

• DESI fiber density is $\sim700/sqdeg$ 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 $\rightarrow$ 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 $k_{\text{max}}$ 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 $r<24 \rightarrow S/N \sim 2$ per angstrom in 0.7” seeing

Map of $2.15<z<2.55$ IGM absorption over 20 arcmin x 15 arcmin (24Mpc/h x 18Mpc/h) from CLAMATO (K-G Lee et al, 2016)
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