Wide-field spectroscopy concepts

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(with contributions from Josh Frieman, FNAL)
Starting point: Requirements to address recommendations from both DOE Cosmic Visions report & Kavli/NOAO/LSST report

- High multiplexing
  - Required to get large numbers of spectra
- Coverage of full ground-based spectral window
  - Minimum: 0.37-1 micron, 0.35-1.3 microns preferred
- Significant resolution ($R=\lambda/\Delta\lambda \gtrsim 5000$) at red end
  - Allows secure redshifts from [OII] 3727 Å line at z>1 amongst skylines
- Field diameters > ~20 arcmin
  - >1 degree preferred
- Large telescope aperture
  - Needed to go faint in reasonable time
  - 4-6m (Cosmic Visions) vs. ~8m (Kavli): $50-75M$ instrument
- Southern site preferred to cover full LSST footprint

There are many ways to accomplish this...
Mayall Telescope, Arizona

- 4m diameter
- Latitude 32N
- Could use (possibly upgraded) DESI instrument from mid-2020s
- Pros:
  - Enables wide field spectroscopy without a new instrument
- Cons:
  - Northernmost option, can access $<\frac{1}{2}$ of LSST area
  - Very large amounts of time required to do just the Kavli programs on a 4m
  - Gets worse at the higher airmasses required to reach into LSST footprint from Kitt Peak
Blanco telescope, Chile

- Same telescope used for DES: 4m diameter, currently w/ 3 deg\(^2\) FOV
- Successful experience with DOE/NSF/NOAO partnership
- Clone or move DESI: 5000x multiplexing, ~7 deg\(^2\) FOV
  - ~few M\$ for move or ~60M\$ for a new clone (a new idea from Juna Kollmeier: reuse LVM DESI spectrograph clones?)
- DESpec: 5000x multiplex, 3 deg\(^2\) FOV with existing corrector, interchangeable w/ DECam:
  - ~40M\$
Blanco telescope, Chile

- **Pros:**
  - Largest potential field of view (w/ DESI move or clone)
  - Moving DESI cheapest option for southern wide-field spectroscopy; mid-2020s possible
  - Can reach full LSST footprint
- **Cons:**
  - Small aperture requires long survey times
  - Earthquake safety of DESI corrector?
  - Kavli/NOAO/LSST report recommends DECam stay on Blanco at minimum 3 years into LSST survey; would delay deployment
Magellan telescope, Chile

- Two 6.5 diameter telescopes
- Potential f/3 secondary would match DESI input beam and enable 1.5-2 deg diameter field of view with 3000-6000 positioners
- New secondary would cost ~$few M million, plus ~$75M for instrument
- Magellan institutions with majority of time interested in partnership: successful model with SDSS4/APOGEE-South
- A new instrument could form the basis of a SDSS6 survey; potential public/private partnership
Magellan telescope, Chile

• **Pros:**
  • Larger collecting area vs. 4m
  • Existing telescope makes earlier schedule possible: mid-2020s?

• **Cons:**
  • Would prefer even larger aperture, >8m (Kavli/NOAO/LSST report)
  • If use an existing Magellan telescope, must navigate politics of Magellan institutions; time access likely limited.
  • Could instead build a 3rd Magellan telescope for this: Adds $75M+ to cost and additional construction time.
Gemini telescope, Chile

- 8m telescope, US-led international consortium
- Current FOV is small
- With ~$50M upgrade, could get 1.5 deg FOV, plus ~$75M instrument: WFMOS redux.
- Pros:
  - Larger collecting area; US-led
- Cons:
  - Total cost >~$125M
  - Gemini-South planned to have lead role in LSST transient follow-up. Probably not available before late 2020s.
- Gemini-North might be more available, but is in less optimal hemisphere.
Subaru (+PFS spectrograph), Hawai'i

- 8m diameter, wide-field telescope
- PFS spectrograph, 2400 fibers over 1.3 deg, under construction, commissioning to be completed c. 2019

Pros:
- Enables wide-field spectroscopy without new instrument

Cons:
- Limited time access: must compete with other Japanese priorities and potential time allocations for WFIRST
- Subaru relatively expensive to build + operate: may be costly (Japan LSST buy-in with Subaru time?)
Keck (+FOBOS spectrograph), Hawai'i

- 10m diameter, narrower-field telescope
- FOBOS: proposed 500-object spectrograph
- Designed for high efficiency: could have comparable survey speeds to PFS
- Pros:
  - Large telescope aperture
  - Could enable kinematic weak lensing via mini-IFUs
- Cons:
  - Very limited multiplexing and FOV
  - Limited time available: largest Keck programs to date have been ~100 nights
Maunakea Spectroscopic Explorer, Hawai'i

• 11m diameter telescope with 1.5 degree field of view, replacing CFHT
• Designed solely for spectroscopy with 3249 medium-resolution fibers + 1083 high-resolution

• Pros:
  • Large aperture, wide field, very high survey speed
  • Enthusiastic about collaborating

• Cons:
  • Not yet funded; earliest possible deployment 2026
  • Cost to join: $50 million (in-kind via instrument construction?)

• Note: similar telescope concepts for South under ESO discussion.
New 8m Wide-field Telescope in Chile

- Strawman: 8m+ telescope with >1.5 degree field of view
- Designed *ab initio* for wide-field, highly multiplexed spectroscopy
- Pros:
  - Large aperture, wide field, very high survey speed, access, LSST overlap, ideal location
- Cons:
  - Cost and timescale
Total time required for all Kavli/NOAO/LSST surveys (sorted by telescope aperture; in dark-years). **Leader** for each column shown in red.

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Summary: there exist a range of options for wide-field spectroscopy; capabilities ultimately depend on the budget available

- **~$5-10M**: Upgrade DESI in North, or upgrade and move to Blanco telescope in Chile
- **~$40M+**: Implement DESSpec on Blanco, keep DESI in North
- **~$75M+**: New instrument for existing 6-10m telescope **OR** join existing or planned facility (PFS, MSE, GMT/TMT, **if** instruments meet requirements & enough fiber-m^2^-years are available…)
- **~$125-150M+**: New Magellan clone or Gemini upgrade + instrument
- **~$250M-500M+**: New instrument on new 8-11m in the South. Probably would require international collaboration.
- Strong synergies with DOE science (LSST, dark matter in dwarfs) and NASA via WFIRST (photo-z training, SN hosts): interagency?
- Note: DES and DESI were/will be ~10 yrs from conception to survey start; LSST, >20 yrs. More ambitious projects will be on-sky later.
- Of course, Arjun Dey proposed SWIFT (8m with ~9000x multiplexing) for the 2000 Decadal Survey: we'll soon be overdue!
Some ideas for a name for this concept...

• LASSI = Large Area Spectroscopic Survey Instrument
• SOLS = Source Of LSST [or Large-area] Spectroscopy
• LASS = Large Area Spectroscopic Source
• ILAS = Instrument for Large Area Spectroscopy
• ISLES = Instrument for Spectroscopic Large Etendue Surveys
  • AISLES = Awesome Instrument for Spectroscopic Large Etendue Surveys
• SSSI = Southern Spectroscopic Survey Instrument

• Your idea here! (especially if you have a few $100M to spare...)
How much time would be required to complete surveys from the Najita et al. Kavli/NOAO/LSST report on different platforms?

- This is an attempt to take the largest surveys proposed in the Kavli report and work out how long would be needed to do them

- Common set of assumptions: one-third loss to instrumental effects, weather and overheads; 4m = Mayall/DESI; 8m = Subaru/PFS; all instrumental efficiencies identical; equivalent # of photons will yield equal noise

- See report (available at http://arxiv.org/abs/1610.01661) for details of these surveys

- Will give time in years on each platform; note that this is generally dark time (very faint targets!)
## Key parameters for telescopes and instruments considered (sorted by telescope aperture)

<table>
<thead>
<tr>
<th>Instrument / Telescope</th>
<th>Collecting Area (sq. m)</th>
<th>Field area (sq. deg.)</th>
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Amount of time required for each Kavli/NOAO/LSST survey (sorted by telescope aperture; in dark-years). Leader for each column shown in red.

<table>
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<tr>
<th>Instrument / Telescope</th>
<th>Total time, Photometric Redshift Training (y)</th>
<th>Milky Way halo survey (8000 sq. deg., y)</th>
<th>Local dwarfs and halo streams</th>
<th>Galaxy evolution</th>
<th>Supernova hosts</th>
<th>Total (8000 sq. deg. halo survey, y)</th>
<th>Total (20k sq. deg. halo survey, y)</th>
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Brief descriptions of the Kavli/NOAO/LSST surveys

- Photometric redshift training sample: Minimum of 30,000 galaxies total down to $i=25.3$ in 15 fields >20' diameter
  - 100 hours/pointing on 10m
  - To improve photo-z accuracy for LSST (and study galaxy SED evolution)
  - Highly-complete survey would require ~6x greater exposure time than used here

- Milky Way halo survey: ~125 $g<23$ luminous red giants deg$^{-2}$ over 8,000 (or preferably 20,000) square degrees of sky
  - 2.5 hours/pointing with 8m
  - Allows reconstruction of MW accretion history using stars to the outer limits of the stellar halo. Other objects could be targeted on remaining fibers.
Local dwarfs and halo streams: Local dwarfs were estimated to require 3200 hours on an 8m to measure velocity dispersions of LSST-discovered dwarfs within 300 kpc. Requires FoV ≥ 20 arcmin (1 deg preferred) and minimum slit/fiber spacing < 10 arcsec. Characterizing ~10 halo streams to test for gravitational perturbations by low-mass dark matter halos was estimated to require ~25% as much time on similar instrumentation.
Brief descriptions of the Kavli/NOAO/LSST surveys

- **Galaxy evolution survey:** Minimum of 130,000 galaxies total down to $M=10^{10} \ M_{\text{Sun}}$ at $0.5 < z < 2$ over a 4 sq. deg. field
  - 18 hours per pointing on 8m
  - To study relationship between galaxy properties and environment across cosmic time

- **Supernova host survey:** Annual spectroscopy of ~100 new galaxy hosts of supernovae deg$^{-2}$ with $r<24$ over the ~5 LSST deep drilling fields (10 sq. deg. each)
  - ~8 hours per pointing on 4m
  - Provides redshifts for most of the ~50,000 best-characterized LSST SN Ia (other transients.getHosts could be observed on remaining fibers)
Context: Massively-multiplexed spectroscopy on a large, Southern telescope keeps showing up as a priority


- 2016: DOE-commissioned *Cosmic Visions Dark Energy* report (Dodelson et al.) identified a Southern Spectroscopic Survey facility as one way to enhance and go beyond LSST science in the next decade.

- 2016: NSF-requested NOAO-Kavli-LSST community study *Maximizing Science in the Era of LSST* (Najita, Willman et al.) recommended wide-field, highly multiplexed optical spectroscopy on an 8m+ telescope, preferably in the Southern hemisphere, to address a wide variety of science over the next decade.
Improved photometric redshift training would greatly increase the science gains from LSST

- All LSST probes of dark energy will rely on measuring observables as a function of photometric redshift
- Better training of algorithms via spectroscopic redshifts shrinks photo-z errors and improves dark energy constraints, especially for BAO and clusters
- LSST system-limited photo-z accuracy is $\sim 0.02-0.025(1+z)$ (vs. 0.05(1+z) in similarly deep samples today): difference is knowledge of templates / intrinsic galaxy spectra
- Perfect training set would increase LSST DETF FoM by at least 40%

$\Delta^2_R = 2 \times 10^{-9}$
Basic requirements for LSST photometric redshift training

- >30,000 galaxies down to LSST weak lensing limiting magnitude ($i \sim 25.3$)
- 15 fields at least 20 arcmin diameter widely dispersed over LSST sky to allow sample/cosmic variance & systematics to be mitigated & quantified
- Long exposure times needed to ensure >75% redshift success rates: 100 hours at Keck to achieve DEEP2-like S/N at $i=25.3$
- This would also be a great survey for galaxy evolution, + WFIRST photo-z training needs overlap substantially: could be an interagency project

Newman et al. 2015
The same sort of spectrograph needed for photo-z's can enhance a variety of cosmological studies:

Other dark energy drivers identified in the Kavli report:

• Informing and testing models of intrinsic alignments between physically-nearby galaxies: a major potential weak lensing systematic (requires modest-precision redshifts, ideally over ~40 h⁻¹ Mpc comoving ~≈ 1 deg scales)
• Characterizing large-scale structure (and hence foreground shear) for strong lens systems
• Informing and testing methods of modifying photo-z priors to account for clusters along a given line of sight
• Tests of modified gravity theories using cluster infall velocities
• Tests of dark matter theories using kinematics of galaxies in post-merger clusters (like the Bullet Cluster)
• Testing models of blending effects on photometric redshifts
• Redshifts for SN Ia hosts in LSST deep drilling fields
A survey-optimised instrument with good access to Southern skies is the natural complement to LSST imaging

• Close coupling of photometric and WF spectroscopic surveys pays enormous scientific dividends: SDSS, DES & OzDES, HSC & PFS, DeCALS+DES & DESI,...
  • LSST & ???

• LSST is a *deep, wide, fast* survey. Spectroscopic resources for *deep* (e.g., ELTs) and *fast* (e.g., Gemini-S Octocam) spectroscopic follow-up are being established, but not wide.

• In general, for efficient (i.e., time-limited) multi-object surveys, we need spectroscopic aperture ≥ photometric aperture to have adequate numbers of photons to disperse.

• We need wide-field, highly multiplexed spectroscopy!
Potential Partners

- Elmegreen and Najita/Willman reports identified wide-field spectroscopy as a priority for a broad set of science.
- DOE interest is in cosmology only: could encompass surveys for photo-z training, LSS, characterizing dwarf galaxies for indirect detection, possibly pre-surveys of potential gravitational wave hosts. Most likely to contribute instrumentation in-kind.
- This capability would also be relevant to NASA for WFIRST photo-z training and supernova host spectroscopy
- Private consortia with existing or to-be-built 6-10m telescopes may be interested in partnering for cash or instrument.
- The international community also recognizes and is discussing the potential benefits for such a capability in the LSST era. International partnerships possible and may be necessary for larger-scale implementations of wide-field spectroscopy.
Three example fiducial surveys:

- **Wide**
  - DESI-like high-z survey over 16,000 sq. deg. of LSST footprint not covered by DESI (CMB-S4 area is same size -- a cross-correlation survey would be similar)
  - ~29M spectra total
  - Note: 4MOST will be doing a ~half-DESI-density survey over this area (but no BGS equivalent). Is the extra density/z range worthwhile?

![DESI coverage](image1)

![LSST coverage](image2)
Three example fiducial surveys:

- **Intermediate**
  - Survey of all galaxies to $i \sim 22.25$ over 2700 sq. deg. WFIRST area
  - 42M galaxies total (4.4 per sq. arcmin)
  - 2x DESI exposure time assumed (should yield $\sim 75\%$ redshift completeness, scaling from DEEP2)
  - Dense map of LSS ($\sim 9x$ DESI density)
  - Useful for cross-correlation studies, etc.
  - Could optimize for CMB-S4 rather than WFIRST
Three example fiducial surveys:

- **Deep**
  - >30,000 galaxies over 15 fields at least 20 arcmin diameter each down to LSST weak lensing limiting magnitude ($i \approx 25.3$)
  - Enables photo-z training for LSST
  - 15 fields to allow sample/cosmic variance to be mitigated & quantified
  - Long exposure times needed to ensure >75% redshift success rates: 100 hours at Keck to achieve DEEP2-like S/N at $i=25.3$
<table>
<thead>
<tr>
<th>Instrument/Telescope</th>
<th>Wide</th>
<th>Intermediate</th>
<th>Deep</th>
</tr>
</thead>
<tbody>
<tr>
<td>DESI-South</td>
<td>1.1 years</td>
<td>3.1 years</td>
<td>5.1 years</td>
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<tr>
<td>PFS-South</td>
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<td>Magellan/MAPS</td>
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<td>1.2</td>
<td>1.8</td>
</tr>
</tbody>
</table>

- Notes: Normalizations are optimistic, at least for Wide; the real DESI survey (which is 14k sq deg vs 16k for Wide) is more like 3 years of dark time.
- Time estimates assume that all fibers are assigned to targets and that sky subtraction accuracy scales as photon noise.
- Minimum observation time of 5 min (including 2.5 min overheads) assumed.
- Differences in multiplexing, field sizes, and collecting area are all accounted for; instrumental efficiencies are assumed to be identical.