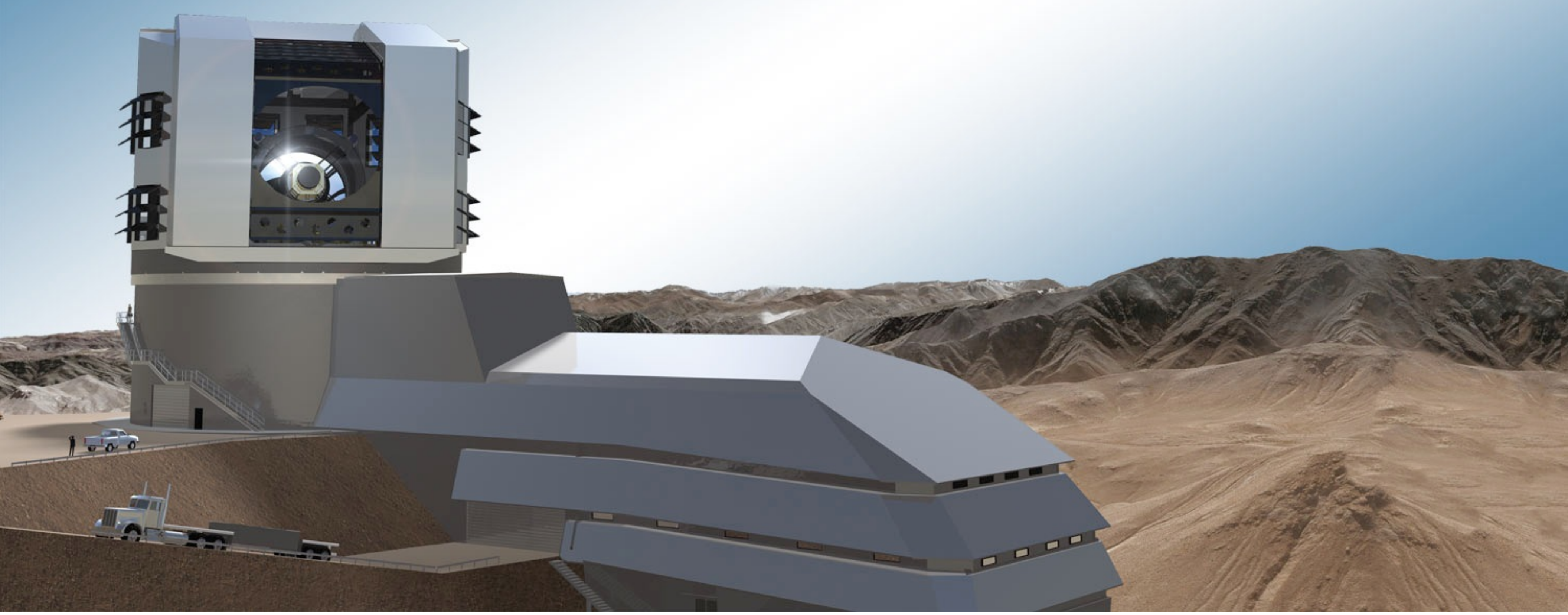
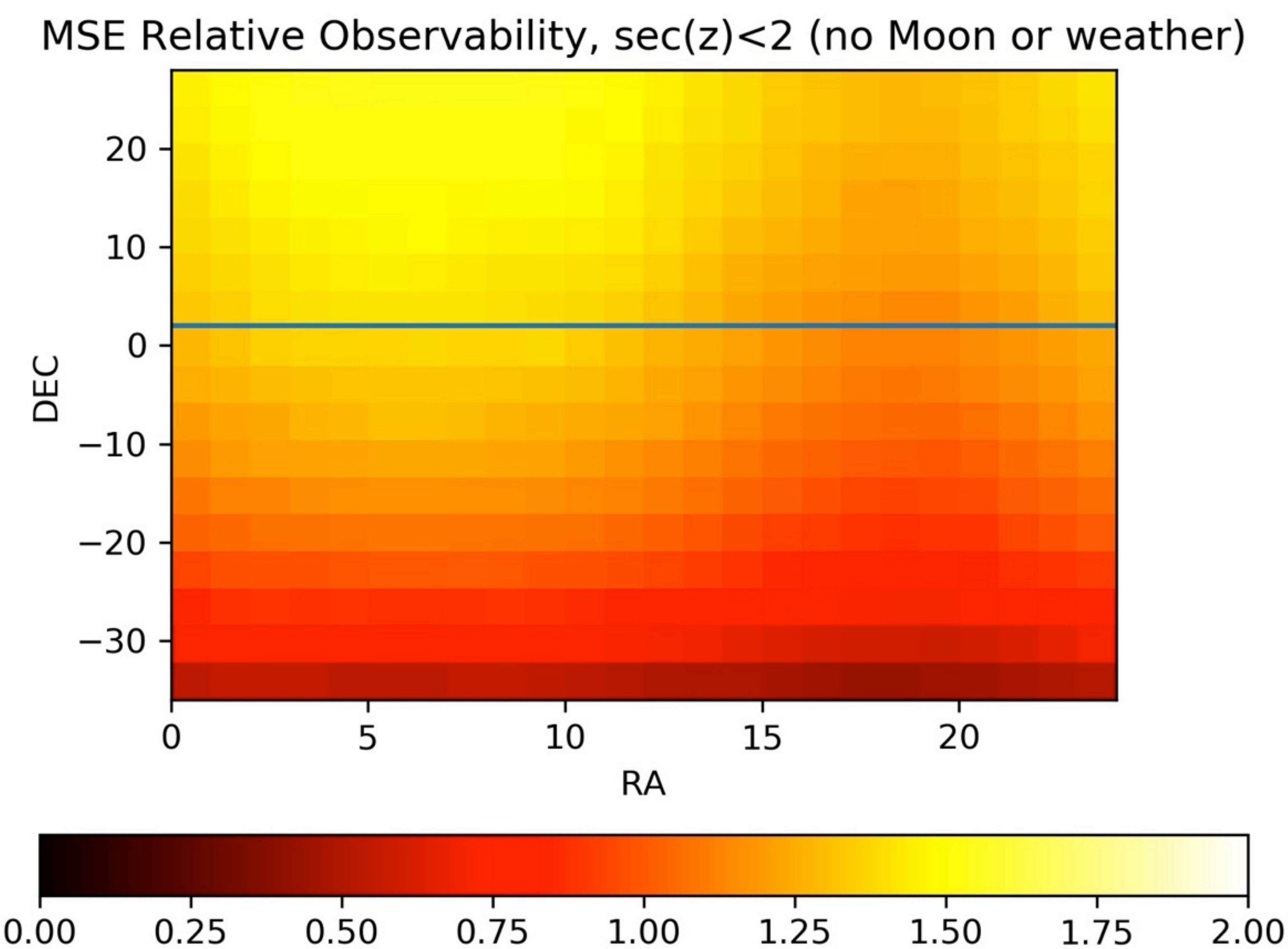
# Southern spectroscopy in the post-LSST era

Jeffrey Newman, U. Pittsburgh / PITT-PACC



# I will define 'Southern' broadly




- **Observing to dec ~ -20 or so isn't too bad from Mauna Kea**

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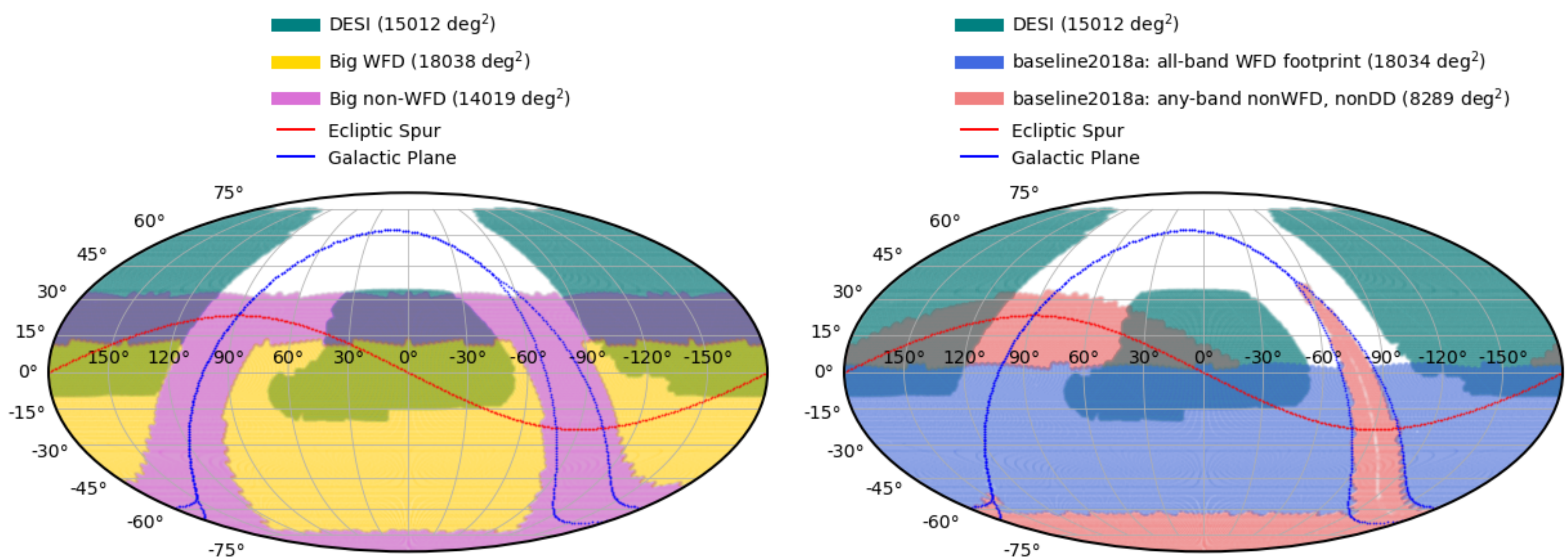
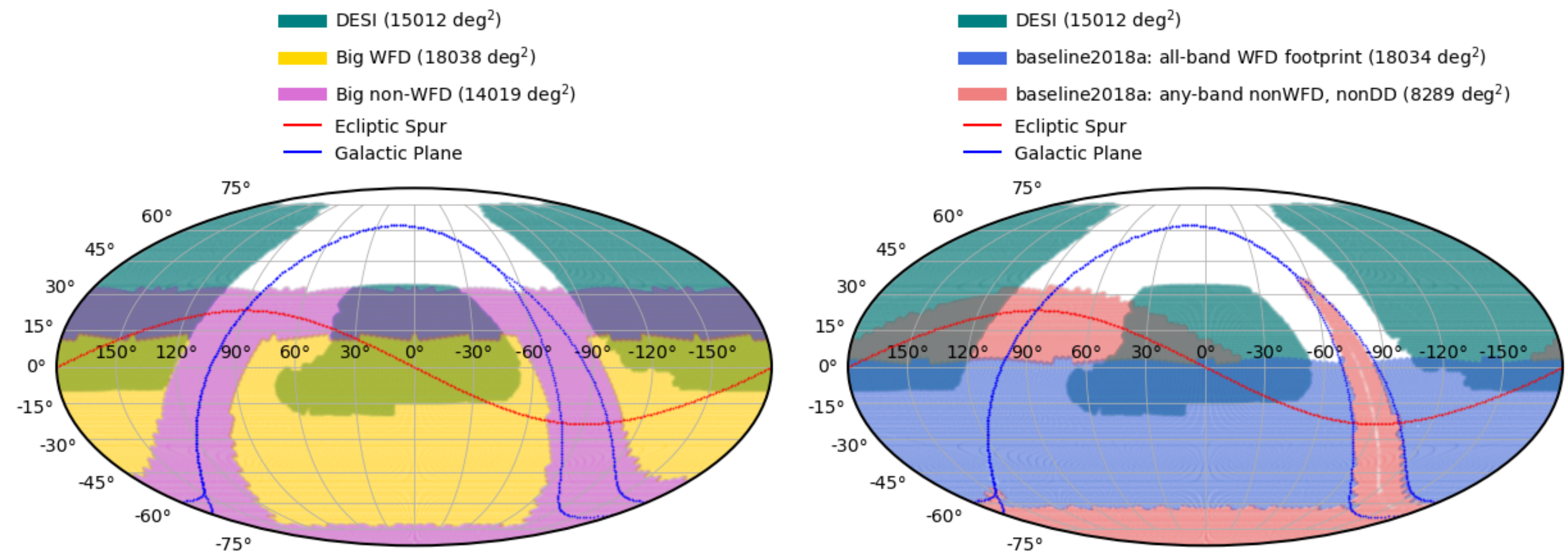



Figure 1: *Left:* Our proposed Big Sky footprint: yellow fields denote our recommended expanded WFD footprint while the purple fields represent the mini-surveys in the extended footprint. *Right:* Footprint from `baseline2018a` for WFD (blue) and all the mini-surveys aside from the DDFs (coral red). Both plots show overlap the DESI footprint (aqua green), demonstrating that our Big Sky footprint significantly increases the overlap with DESI (5912 deg$^2$ for WFD and 4538 deg$^2$ for non-WFD) vs. `baseline2018a` (3739 deg$^2$ for WFD and 2233 deg$^2$ for non-WFD).

- **Reasonable to expect 4000-6000 sq. deg. of overlap with DESI; could push a bit lower in Dec**

# I will define 'Southern' broadly

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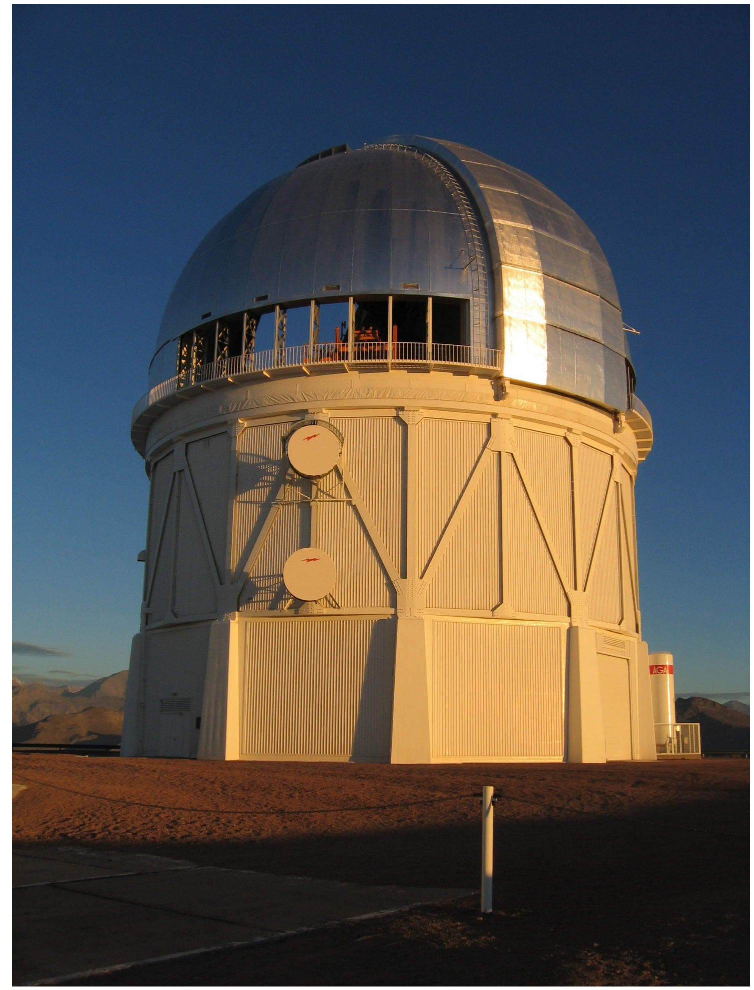
- **Kitt Peak is further south than the southernmost point in South Carolina...**

# Mayall Telescope / DESI, Kitt Peak

- 4m diameter
- Latitude 32N
- 5000-fiber positioners covering 7 sq. deg. field of view, feeding spectrographs covering 360 nm to 980 nm
- Fixed spectral resolution ranging from 2000 (blue) - 5000 (red)

# Blanco telescope, Chile (plus new spectrograph)

- Same telescope used for DES: 4m diameter, currently w/ 3 $deg^2$ FOV
- Could clone or move DESI: 5000x multiplexing, ~7 $deg^2$ FOV
  - ~few M$++ for move or ~75M$ for clone
- DESpec design: 5000x multiplex, 3 $deg^2$ FOV using existing corrector, interchangeable w/ DECam:
  - ~40M$

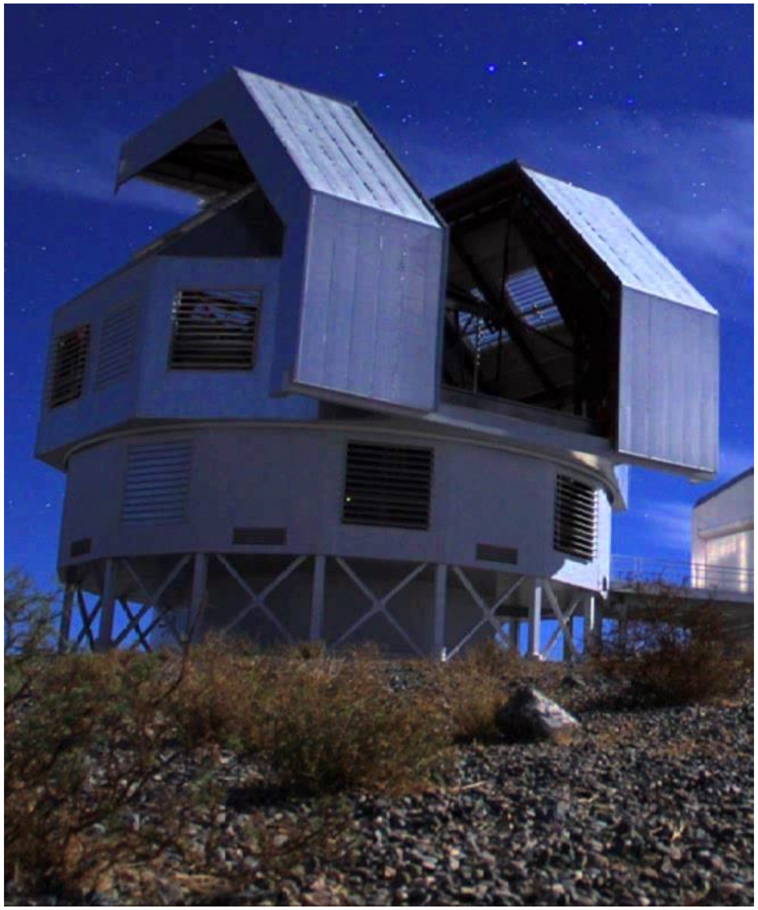


# William Herschel Telescope / WEAVE, La Palma, Spain

- 4.2m telescope at latitude 28N
- 2 deg FoV
- 960 fibers (or 20 mini-IFUs or 1 large IFU)
- 1 hour reconfiguration time!
- R~5000 or 20000
- 370-960 nm in medium-resolution mode
- Commissioning spring 2020

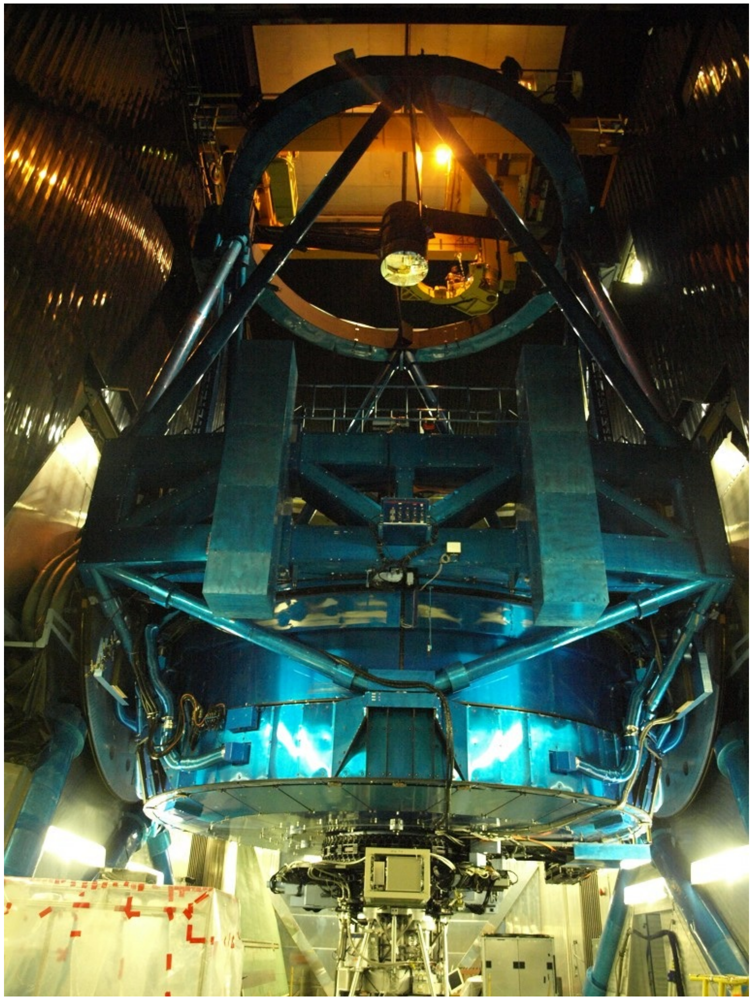
# Magellan telescopes, Chile (plus new spectrograph and/or telescope)

- Two existing 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 DESI-like positioners
- New secondary would cost ~$few M million, plus ~$75M+ for instrument
- My understanding is that it would be possible to design a new facility with up to ~4 sq. deg. field of view and ~20,000 fiber positioners, using an extra Magellan mirror



# Subaru/PFS, Hawai'i

- 8m diameter, wide-field telescope at latitude 20N
- PFS spectrograph will have 2400 fibers over 1.3 deg
- Fixed resolution and coverage; 380nm to 1260nm at a resolution of 2300-4300
- Start of 300-night Sumire survey planned for 2021

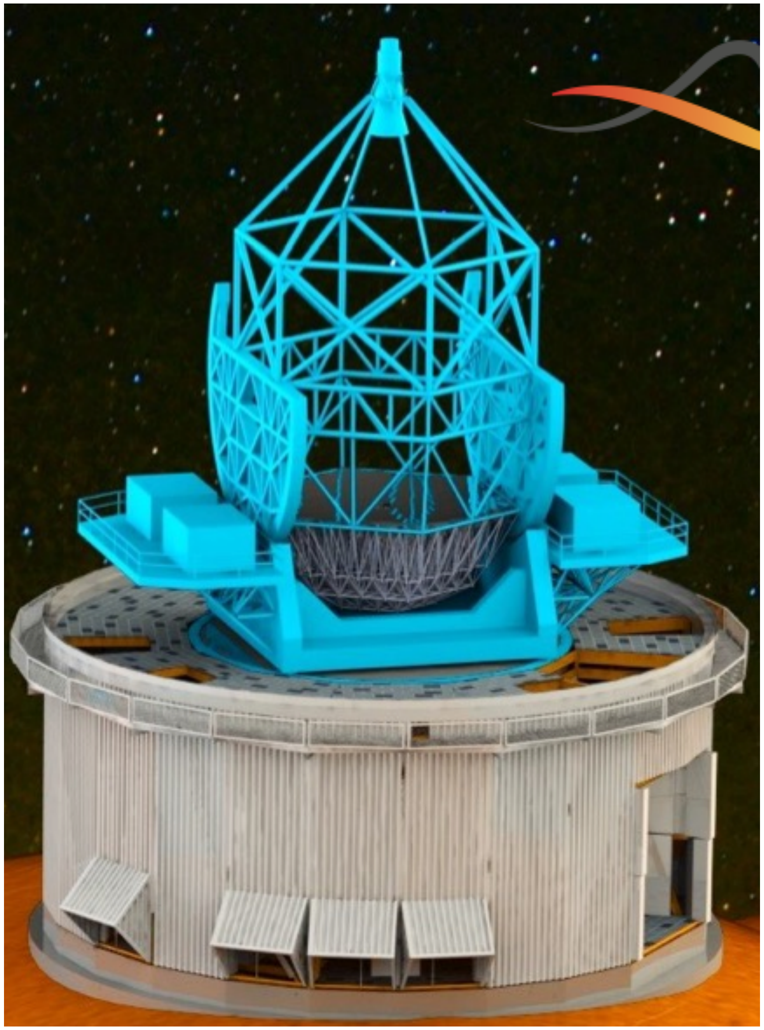


# Keck (+FOBOS spectrograph), Hawai'i

- 10m diameter, narrower-field telescope
- FOBOS: proposed spectrograph with up to 1800 fibers
- 310-1000 nm coverage, R ~ 3500
- 20 arcmin diameter field of view
- Designed for high efficiency: could have comparable survey speeds to PFS

# The Maunakea Spectroscopic Explorer, Hawai'i

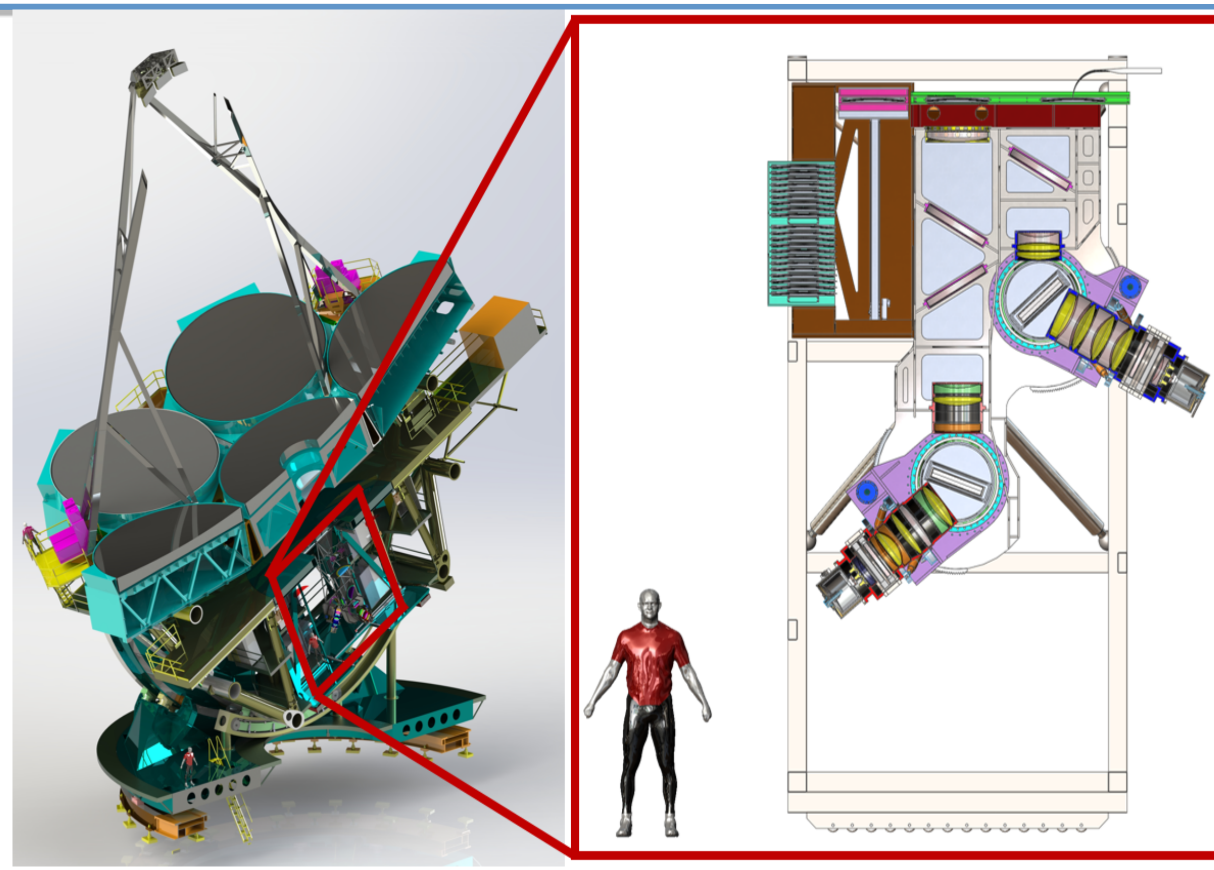
- **11m diameter telescope with 1.5 degree field of view, replacing CFHT**
- **Designed solely for spectroscopy**
- **3249 fibers feed medium-resolution spectrographs,  1083 high-resolution**
- **360-1320 nm, R~2500-3500 continuous wavelength coverage**
- **R~6000 spectroscopy up to 1.8 microns possible with coverage gaps**



- **Similar "SpecTel" telescope concept for South under ESO discussion.**

# GMT / GMACS + MANIFEST, Chile

- 24.5m diameter telescope
- Relatively large field of view for an ELT: up to 20 arcmin
- In slit mode, GMACS instrument has resolution 500-6000 and 7.5 arcmin FoV
- Can couple to MANIFEST fiber feed system to access full field of view; ~1000 fibers (can do 100x10-fiber IFUs)
- Resolution ~3x greater in fiber mode (with 0.3" fibers)

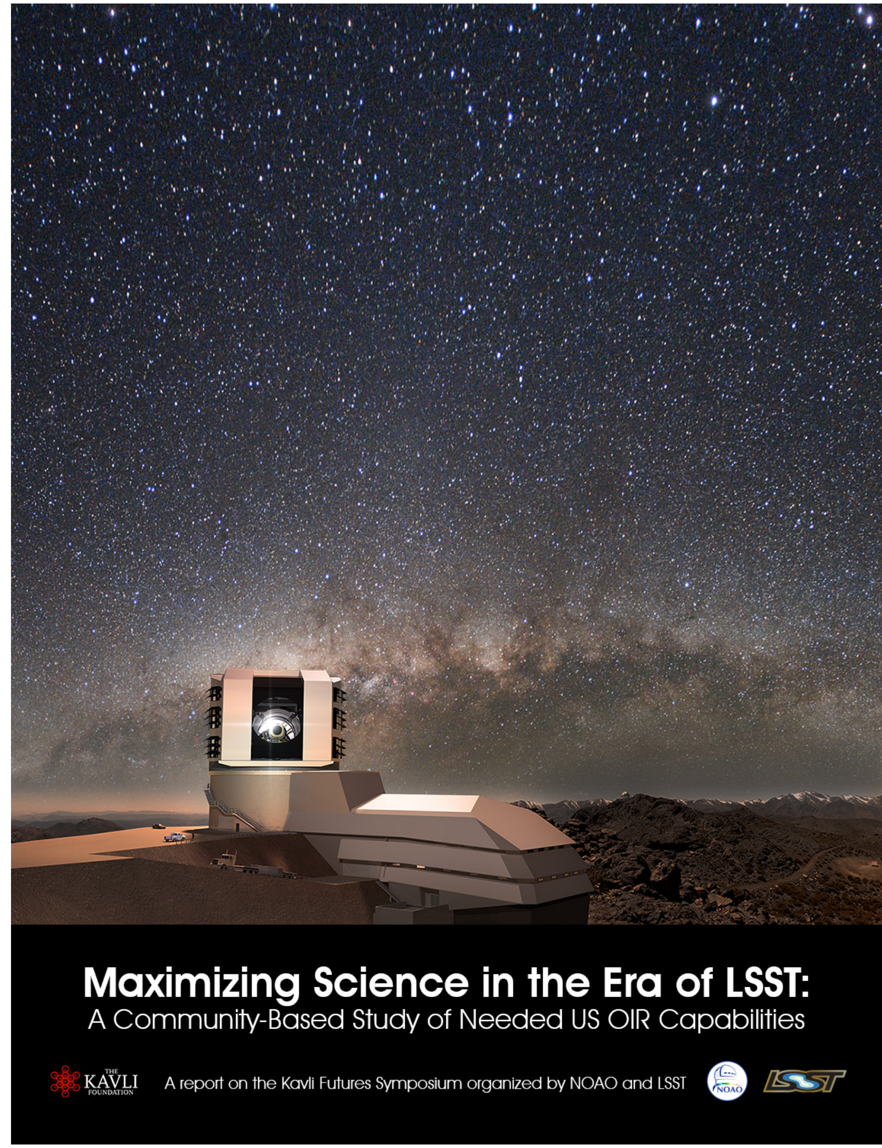


# Scenarios considered for the DESI - LSST Instrument for Spectroscopic Hypersurveys

- Consider 3 scenarios for LSST-based spectroscopy:
  - DELISH: place DESI-size positioners in LSST focal plane. Can accommodate 3800 positions in that area.
  - DELISH Aggressive: place 35,000 fiber positioners in LSST focal plane. ~1 object per square arcmin .
  - DELISH BOA (Billion Object Apparatus): 500,000 fiber positioners
    - Can target the 14 $r < 24$ objects per sq. arcmin across a whole LSST pointing, simultaneously
    - Can obtain 5 hours' exposure time for ~all r<24 objects across the whole 20k sq. deg. LSST footprint in a 10 year survey (assuming 180 dark nights/year, 6 hours open shutter time per dark night after weather losses + overheads)
    - 14/arcmin$^2$ * (3600 arcmin$^2$/deg$^2$) * 20k sq. deg. = 1.01 billion spectra

# Relative efficiencies: how much time would be required to complete the surveys from the Kavli/NOAO/LSST report on different platforms?

- The Najita, Willman et al. report explored the ground-based OIR needs to conduct science with LSST, based on a set of use cases
- This is an attempt to estimate the time required for the largest surveys from the report
- 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; ignoring differences in seeing/image quality and fiber/slitlet size. Only medium-resolution fibers included. Assuming full spectral range can be covered simultaneously (likely not true for EELT).
- See report (available at http://arxiv.org/abs/1610.01661 ) for details of these surveys
- Will give time required in years on a given platform; note that the need is generally all for dark time (very faint targets!)
- Costs based on TSIP + inflation: $1k/m²/night



# 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**

- **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/hosts could be observed on remaining fibers)**

# Brief descriptions of the other Kavli/NOAO/LSST surveys

- **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.**

- **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.**

# Brief descriptions of the other Kavli/NOAO/LSST surveys

- **Galaxy evolution survey: Minimum of 130,000 galaxies total down to $M=10^{10}$ $M_{Sun}$ 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**

# Key parameters for telescopes and instruments considered (sorted by telescope aperture)

| Instrument / Telescope | Collecting Area (sq. m) | Field area (sq. deg.) | Multiplex | Targets per sq. deg. |
|---|---|---|---|---|
| 4MOST | 10.7 | 4.000 | 1,400 | 350 |
| Mayall 4m / DESI | 11.4 | 7.083 | 5,000 | 706 |
| WHT / WEAVE | 13.0 | 3.139 | 1,000 | 319 |
| DELISH | 32.4 | 9.600 | 3,800 | 396 |
| DELISH Aggressive | 32.4 | 9.600 | 35,000 | 3,646 |
| DELISH BOA | 32.4 | 9.600 | 500,000 | 52,083 |
| Subaru / PFS | 53.0 | 1.250 | 2,400 | 1,920 |
| VLT / MOONS | 58.2 | 0.139 | 500 | 3,600 |
| Keck / DEIMOS | 76.0 | 0.015 | 150 | 9,954 |
| Keck / FOBOS | 76.0 | 0.087 | 1,800 | 20,637 |
| ESO SpecTel | 87.9 | 4.9 | 3,333 | 679 |
| MSE | 97.6 | 1.766 | 3,249 | 1,839 |
| GMT/MANIFEST + GMACS | 368 | 0.087 | 420 | 4,815 |
| TMT / WFOS | 655 | 0.007 | 100 | 14,458 |
| E-ELT / Mosaic Optical | 978 | 0.009 | 200 | 22,500 |
| E-ELT / MOSAIC NIR | 978 | 0.009 | 100 | 11,250 |

# Amount of time required for each survey from the Kavli/NOAO/ LSST report (sorted by telescope aperture; in dark-years).

| Instrument / Telescope | Total time, Photometric Redshift Training (y) | Milky Way halo survey (8000 sq. deg., y) | Local dwarfs and halo streams | Flare stars | Galaxy evolution | Supernova hosts |
|---|---|---|---|---|---|---|
| 4MOST | 5.4 | 12.6 | 10.1 | 3.2 | 4.21 | 0.05 |
| Mayall 4m / DESI | 5.1 | 6.7 | 9.5 | 3.0 | 1.11 | 0.03 |
| WHT / WEAVE | 6.0 | 13.3 | 8.3 | 2.6 | 4.88 | 0.06 |
| DELISH | 1.8 | 1.7 | 3.3 | 1.0 | 0.51 | **0.01** |
| DELISH Aggressive | 1.8 | 1.7 | 3.3 | 1.0 | **0.06** | **0.01** |
| DELISH BOA | 1.8 | 1.7 | 3.3 | 1.0 | **0.02** | **0.01** |
| Subaru / PFS | 1.1 | 8.2 | 2.0 | 0.6 | 0.50 | 0.04 |
| VLT / MOONS | 2.7 | 67.0 | 1.9 | 4.2 | 2.18 | 0.29 |
| Keck / DEIMOS | 6.8 | 473.1 | 8.3 | 29.6 | 5.56 | 2.04 |
| Keck / FOBOS | 0.8 | 81.7 | 1.4 | 5.1 | 0.46 | 0.35 |
| ESO SpecTel | 0.7 | **1.3** | 1.2 | 0.4 | 0.22 | **0.01** |
| MSE | 0.6 | 3.1 | 1.1 | **0.3** | 0.20 | **0.01** |
| GMT/MANIFEST + GMACS | **0.5** | 16.9 | **0.3** | 1.1 | 0.41 | 0.07 |
| TMT / WFOS | 1.2 | 119.6 | 2.1 | 7.5 | 0.97 | 0.51 |
| E-ELT / Mosaic Optical | 0.5 | 51.8 | 0.9 | 3.2 | 0.32 | 0.22 |
| E-ELT / MOSAIC NIR | 0.8 | 43.4 | 0.8 | 2.7 | 0.65 | 0.19 |

**Note: both optical & NIR modes on E-ELT/MOSAIC needed to cover desired wavelength range**

## Total time required for <u>all</u> surveys from the Kavli/NOAO/LSST report (sorted by telescope aperture; in dark-years).

| Instrument / Telescope | Total (no halo survey, dark-years) | Total (8000 sq. deg. halo survey, dark-years) | Total (20k sq. deg. halo survey, dark-years) | Approx. cost per year |
|---|---|---|---|---|
| 4MOST | 22.9 | 35.5 | 54.4 | \$3,900,000 |
| Mayall 4m / DESI | 18.7 | 25.4 | 35.5 | \$4,200,000 |
| WHT / WEAVE | 21.9 | 35.1 | 55.0 | \$4,700,000 |
| DELISH | 6.7 | 8.5 | 11.1 | \$12,000,000 |
| DELISH Aggressive | 6.3 | 8.0 | 10.6 | \$12,000,000 |
| DELISH BOA | 6.2 | 8.0 | 10.6 | \$12,000,000 |
| Subaru / PFS | 4.3 | 12.5 | 24.8 | \$19,000,000 |
| VLT / MOONS | 11.2 | 78.2 | 178.8 | \$21,000,000 |
| Keck / DEIMOS | 52.2 | 525.3 | 1234.9 | \$28,000,000 |
| Keck / FOBOS | 8.1 | 89.9 | 212.5 | \$28,000,000 |
| ESO SpecTel | 2.5 | **3.8** | **5.6** | \$32,000,000 |
| MSE | **2.3** | 5.4 | 10.1 | \$36,000,000 |
| GMT/MANIFEST + GMACS | **2.3** | 19.2 | 44.5 | \$130,000,000 |
| TMT / WFOS | 12.2 | 131.8 | 311.2 | \$130,000,000 |
| E-ELT / Mosaic Optical | 5.2 | 57.0 | 134.7 | \$240,000,000 |
| E-ELT / MOSAIC NIR | 5.1 | 48.5 | 113.5 | \$240,000,000 |

# Scaling of redshift errors for narrow-band imaging

- Centroid error for a feature is approximately:

$$\Delta\lambda \sim= \frac{\text{FWHM}}{\text{S/N of detection}}$$

- Allows simple rescaling of expected *z* errors
- FWHM $\propto$ 1/R
- S/N $\propto$ (object flux) ×(efficiency × total exposure time x collecting area)$^{1/2}$ *
- S/N $\propto$ $(1/R)^{1/2}$ for narrow-band imaging
- S/N ~independent of R for spectroscopy if features are resolved**
- S/N $\propto$ $(1/R)^{1/2}$ if features are diluted by resolution (BG $\propto$ $R^{-1}$)**

* assuming background-limited

** assuming background-limited, pixel scale resolves FWHM, and background is not resolved into individual lines

# Scaling of redshift errors for narrow-band imaging

- Example scenarios, scaling from LSST photo-z's:
  - LSST is equivalent to R~6; if split LSST observing amongst N filters, but total time and efficiency are unchanged:
    - FWHM $\propto (6/N)$, S/N $\propto (6/N)^{1/2}$
    - Perfect template photo-z error would be $\sim(6/N)^{1/2} \times 0.02\ (1+z)$
    - Note: if spend 10 years on 10% of LSST area, drop errors by a further factor of ~3 (as 10x greater exposure time): $\sim 0.001(1+z)$ errors for a 30-band survey
  - Place a spectrograph with 16% efficiency and resolution R on LSST and run for 10 years
    - FWHM $\propto (6/R)$, S/N $\propto (0.16*6)^{1/2}$ (as no longer divide time amongst 6 bands) $\times (6/R)^{1/2}$ (from BG)
    - Perfect template redshift error would be $\sim(6/R)^{1/2} \times 0.02\ (1+z)$
    - NB: only get this for ~5000 objects at a time..

# Scaling of redshift errors for narrow-band imaging

$$\Delta\lambda \sim= \frac{\text{FWHM}}{\text{S/N of detection}}$$

- Spectroscopy scaled from DEEP2 errors (R=6000, 10m, 1 hour exposures, $\sigma_z$~0.000033@i=22.5, assume identical efficiency if on LSST):
  - DEEP2: R=1000 × LSST, area = 2.2 × LSST, exposure time = 0.12 × LSST, flux = 13.2 × LSST
  - Redshift error predicted for 10-year LSST survey would be $\sim(6/R)^{1/2} \times 0.015\,(1+z)$

# Scaling of redshift errors for narrow-band imaging

$$\Delta\lambda \sim= \frac{\text{FWHM}}{\text{S/N of detection}}$$

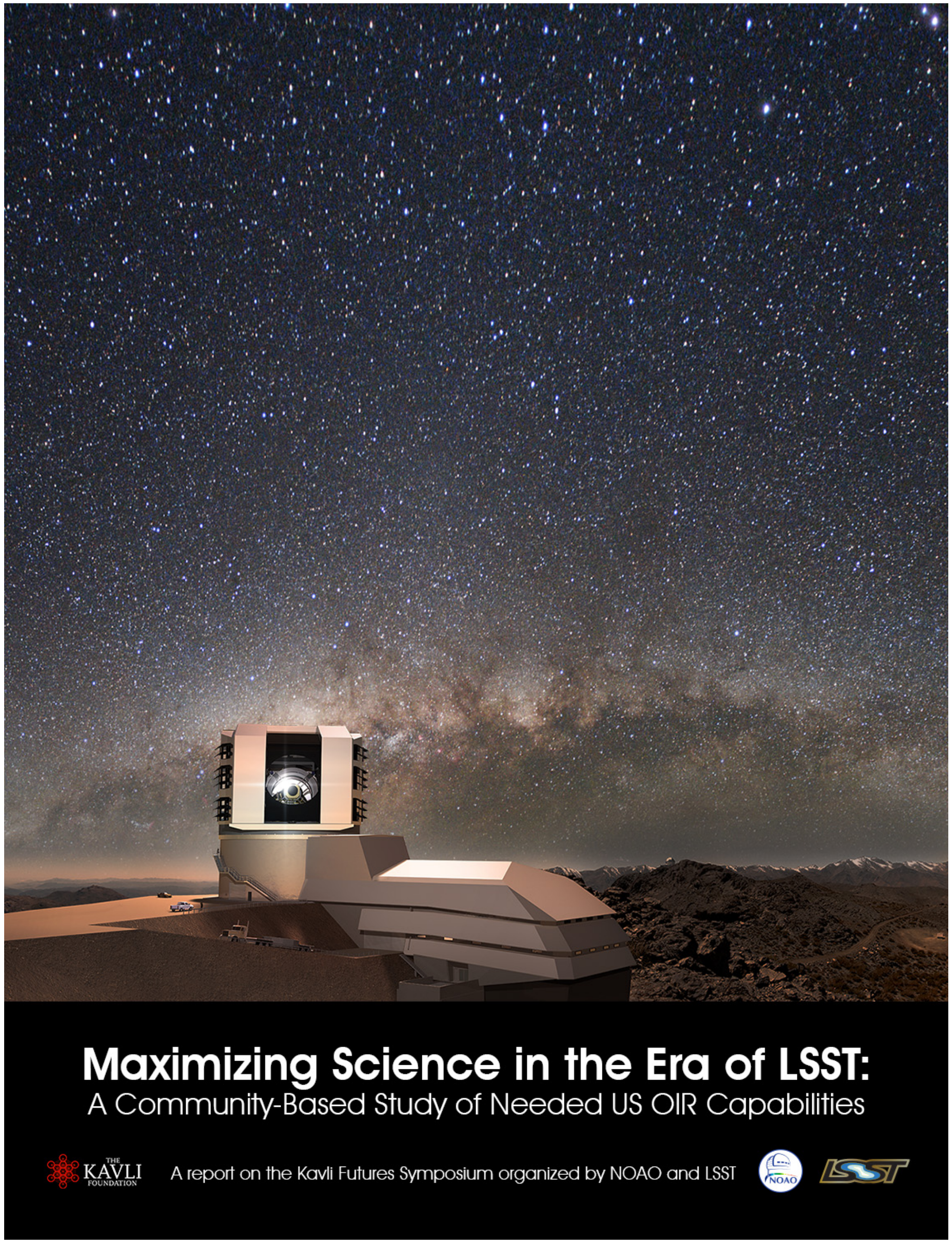
- Spectroscopy scaled from zCOSMOS errors (R=600, 8m, 1 hour exposures, $\sigma_z \sim 0.00036$@i=22.5, assume identical efficiency if on LSST):
  - zCOSMOS: R=100 × LSST, area = 1.4 × LSST, exposure time = 0.12 × LSST, flux = 13.2 × LSST
  - Redshift error predicted for 10-year LSST survey would be $\sim(6/R)^{1/2} \times 0.015\,(1+z)$

# The Kavli/NOAO/LSST report

- NSF asked NOAO + LSST to work together to produce a report:
  - organized around 6-8 science cases with quantitative requirements
  - to assess and prioritize potential O/IR System resources (e.g., telescopes, instruments, and software infrastructure) that can fulfill the needs for these cases
  - to identify high priority future investments

- Intended to provide inputs to federal and private funding sources & observatories
- Kavli Foundation provided funding to enable the report
- Led by Joan Najita and Beth Willman

# Report is available at https://arxiv.org/abs/1610.01661



# Maximizing Science in the Era of LSST: A Community-Based Study of Needed US OIR Capabilities

*A report on the Kavli Futures Symposium organized by NOAO and LSST*

*Joan Najita (NOAO) and Beth Willman (LSST)*
*Douglas P. Finkbeiner (Harvard University)*
*Ryan J. Foley (University of California, Santa Cruz)*
*Suzanne Hawley (University of Washington)*
*Jeffrey Newman (University of Pittsburgh)*
*Gregory Rudnick (University of Kansas)*
*Joshua D. Simon (Carnegie Observatories)*
*David Trilling (Northern Arizona University)*
*Rachel Street (Las Cumbres Observatory Global Telescope Network)*
*Adam Bolton (NOAO)*
*Ruth Angus (University of Oxford)*
*Eric F. Bell (University of Michigan)*
*Derek Buzasi (Florida Gulf Coast University)*
*David Ciardi (IPAC, Caltech)*
*James R. A. Davenport (Western Washington University)*
*Will Dawson ((Lawrence Livermore National Laboratory)*
*Mark Dickinson (NOAO)*
*Alex Drlica-Wagner (Fermilab)*
*Jay Elias (NOAO)*
*Dawn Erb (University of Wisconsin-Milwaukee)*
*Lori Feaga (University of Maryland)*
*Wen-fai Fong (University of Arizona)*
*Eric Gawiser (The State University of New Jersey, Rutgers)*
*Mark Giampapa (National Solar Observatory)*
*Puragra Guhathakurta (University of California, Santa Cruz)*
*Jennifer L. Hoffman (University of Denver)*
*Henry Hsieh (Planetary Science Institute)*
*Elise Jennings (Fermilab)*
*Kathryn V. Johnston (Columbia University)*
*Vinay Kashyap (Harvard-Smithsonian CfA)*
*Ting S. Li (Texas A&M University)*
*Eric Linder (Lawrence Berkeley National Laboratory)*
*Rachel Mandelbaum (Carnegie Mellon University)*
*Phil Marshall (SLAC National Accelerator Laboratory)*
*Thomas Matheson (National Optical Astronomy Observatory)*
*Søren Meibom (Harvard-Smithsonian CfA)*
*Bryan W. Miller (Gemini Observatory)*
*John O'Meara (Saint Michael's College)*
*Vishnu Reddy (University of Arizona)*
*Steve Ridgway (NOAO)*
*Constance M. Rockosi (University of California, Santa Cruz)*
*David J. Sand (Texas Tech University)*
*Chad Schafer (Carnegie Mellon University)*
*Sam Schmidt (UC Davis)*
*Branimir Sesar (Max Planck Institute for Astronomy)*
*Scott S. Sheppard (Carnegie Institute for Science/Department of Terrestrial Magnetism)*
*Cristina A. Thomas (Planetary Science Institute)*
*Erik J. Tollerud (Space Telescope Science Institute)*
*Jon Trump (Penn State, Hubble Fellow)*
*Anja von der Linden (SUNY)*
*Benjamin Weiner (Steward Observatory)*

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# Study Group Topics

**Study Organizing Committee (SOC):**

**Joan Najita** (Co-chair, NOAO)

**Beth Willman** (Co-chair, LSST/University of Arizona)

**Douglas Finkbeiner** (Harvard)

**Ryan Foley** (University of Illinois)

**Suzanne Hawley** (University of Washington)

**Jeff Newman** (University of Pittsburgh)

**Greg Rudnick** (University of Kansas)

**Josh Simon** (Carnegie Observatories)

**David Trilling** (Northern Arizona University)

1. Using Small Solar System Bodies to Understand the Evolution of the Solar System
2. Rotation and Magnetic Activity in the Galactic Field Population and Open Star Clusters
3. Probing Galaxy Formation and the Nature of Dark Matter and Gravity in the Local Group
4. Characterizing the Transient Sky
5. The Co-Evolution of Baryons, Black Holes, and Cosmic Structure
6. **Facilitating Cosmology Measurements with LSST**

# Kavli Study Recommendations

***Critical resources in urgent need of a clear development path***

- Develop or obtain access to a highly multiplexed, wide-field optical multi-object spectroscopic capability on an 8-m or larger class telescope, preferably in the Southern Hemisphere

***Critical resources that have a potential development path***

- Deploy a broad wavelength coverage, moderate resolution (R = 2000 or larger) OIR spectrograph on Gemini South (via existing Gemini Gen 4 #3 instrument call)

- Ensure the development and early deployment of an alert broker[s], scalable to LSST, and provide access to a diverse suite of facilities for alert triage and urgent follow-up

# Kavli Study Recommendations

## ***Critical resources that exist today***

- Support into the LSST era high-priority OIR capabilities that are currently available, e.g. Blanco/DECam and Gemini/NIFS, among others.  (Solar System and Stars science cases for DECam require ~3 years each)

## ***Infrastructure resources and processes in urgent need of development***

- Support development of observatory infrastructure that enables efficient deployment of follow-up programs

- Regularly review computing needs and support for analysis and discovery tools

- Continue community planning and development

# More details on Kavli recommendations for wide-field MOS

- **MOS called out as a requirement for:**
  - Photometric redshift training
  - Investigations of potential systematics in cosmological measurements:
    - intrinsic alignment effects on weak lensing
    - biases of photo-z's around galaxy clusters
    - blending effects on photo-z's
    - effects of foreground mass distribution in strong lens systems
  - Also for studies of galaxy evolution, local dwarf galaxy stellar spectroscopy (cf. Guhathakurta talk), Milky Way structure (cf. Li talk), reverberation mapping of active galactic nuclei (cf. Trump talk), and studies of stellar rotation and activity (cf. Buzasi talk). chair).

# More details on Kavli recommendations for wide-field MOS

- Proposed characteristics:
  - 8m-class telescope
  - R~5000 in the red and R~2500 in blue
  - Minimum wavelength coverage 0.37-1 micron, extension to 1.3-1.5 microns desirable
  - Minimum field of view 20 arcmin; >1 degree preferred
  - High multiplexing, >2500x

# More details on Kavli recommendations for wide-field MOS

- Possible ways to implement:
  1. Implement a wide-field MOS on an existing or new Southern-hemisphere telescope
  2. Obtain large amounts of community access to PFS + DESI
  3. Buy into a proposed new project in the South (ESO SpecTel) or North (MSE)