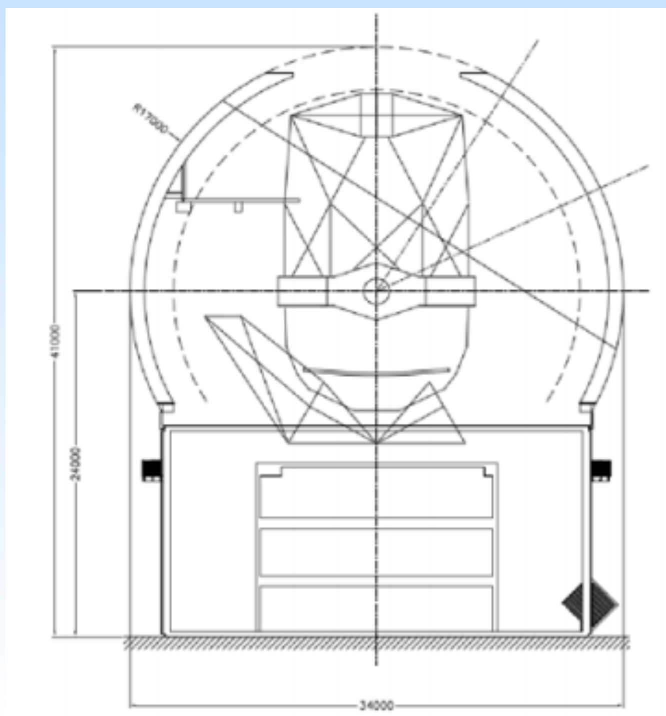
SSSI

The future of ground-based astronomy in the US

Jeffrey Newman, U. Pittsburgh/PITT PACC

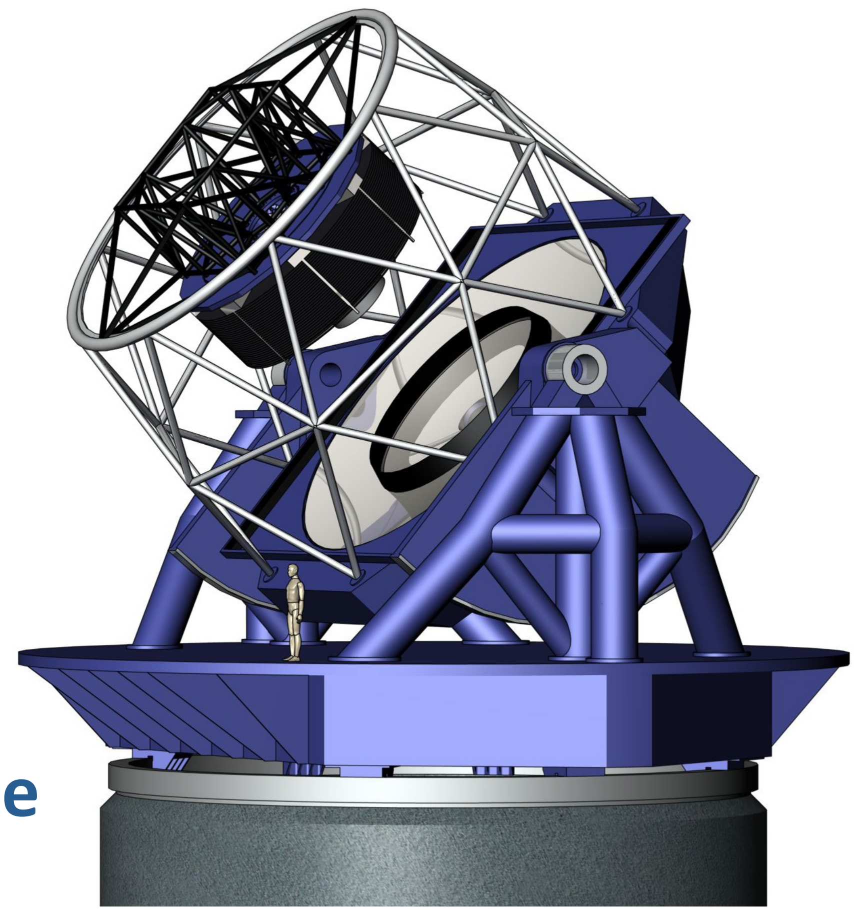


Outline

- Context: DESI, LSST, and ELTs
- Context: basics of spectroscopy
- The Kavli/NOAO/LSST report
- The Cosmic Visions Dark Energy report
- SSSI

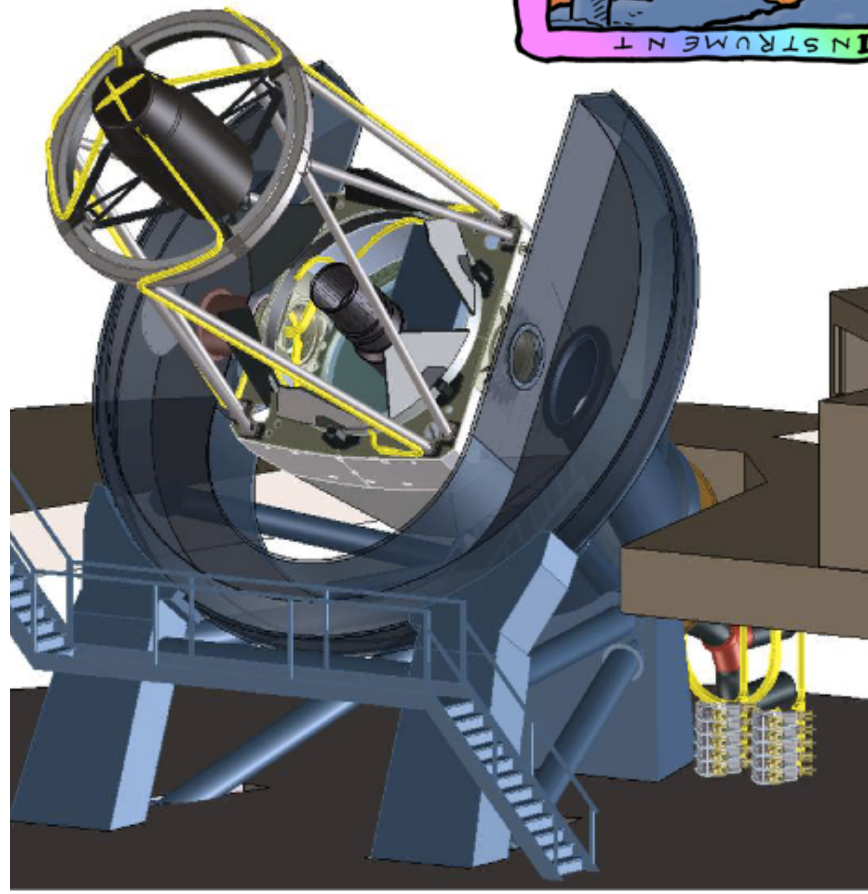
LSST will be the premier ground-based imaging experiment in the next decade

- **8m diameter wide-field telescope, deep imaging in 6 filters**
- **2x15 sec images of 10 sq. deg.**
- **Covers visible sky every 3 nights**
- **10-year survey: >800 visits per pointing**
- **Science enabled:**
  - **Cosmology (dark matter, dark energy, testing GR, etc.)**
  - **Mapping the Milky Way**
  - **Revealing the Transient Universe**
  - **Inventory of the Solar System**



While DESI will be the premier spectroscopic experiment

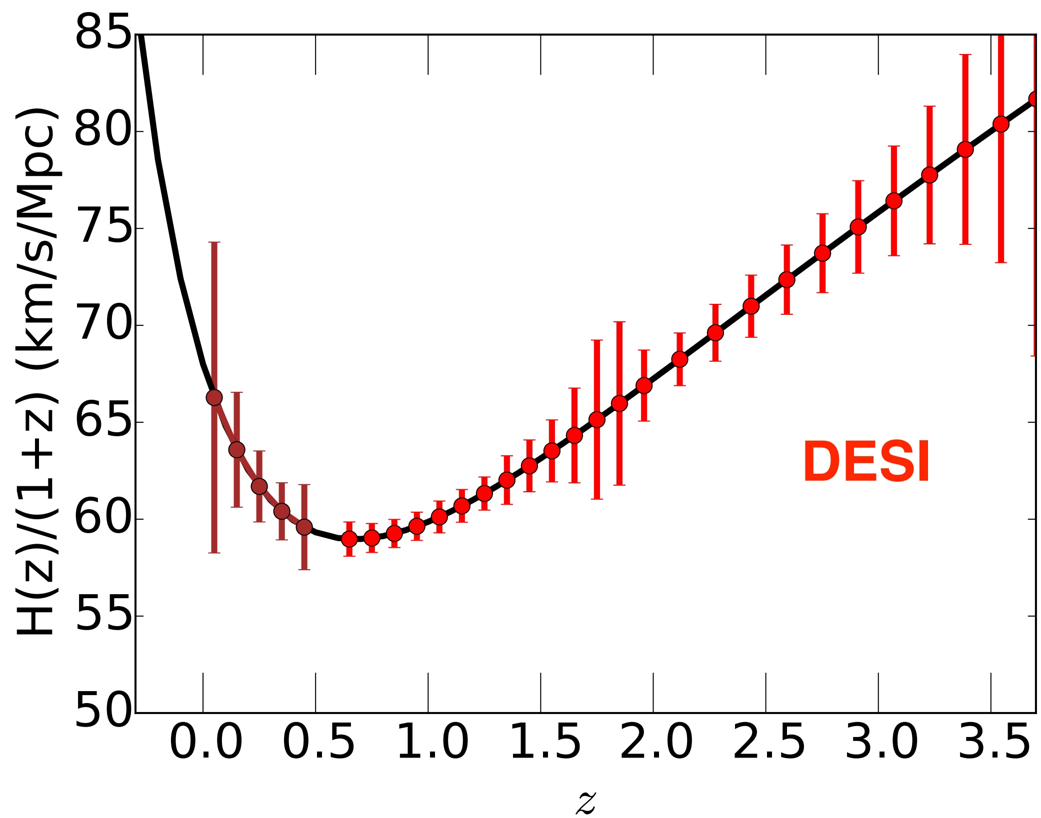
- Adds new full-optical spectrograph to 4m Mayall telescope
- 5000 fibers, 7 sq. deg.
- BAO survey of ~25+million galaxies & QSOs, $0.5 < z < 3.5$, over ~14k square degrees
- "Stage IV" BAO, ~10x better than state of the art, ~2019-2022



Credit: D. Schlegel

By measuring the BAO angular and redshift scales as a function of redshift, constrain the distance-redshift relation / expansion history of the Universe

- **Classical 'standard ruler' test**
- **Measures how the Universe has grown over time**
  - **Depends on amounts & equation of state ($w = P/\rho$) of dark matter and dark energy**

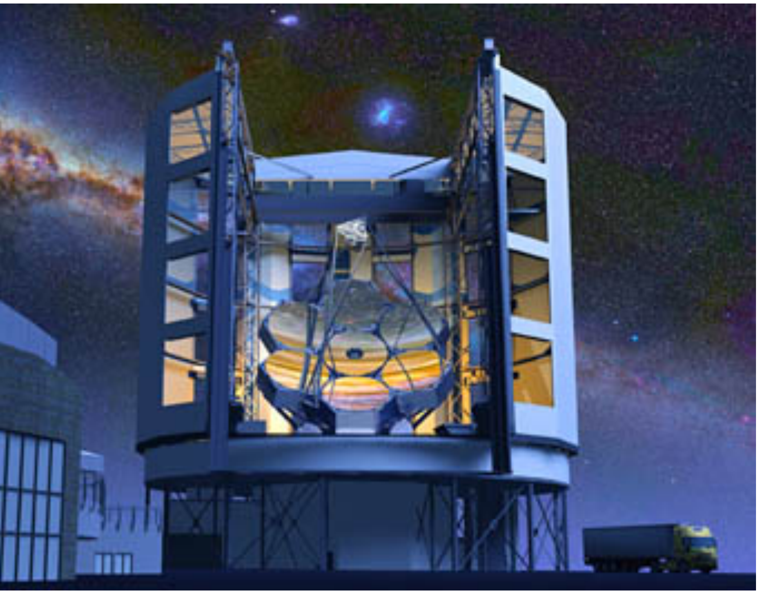
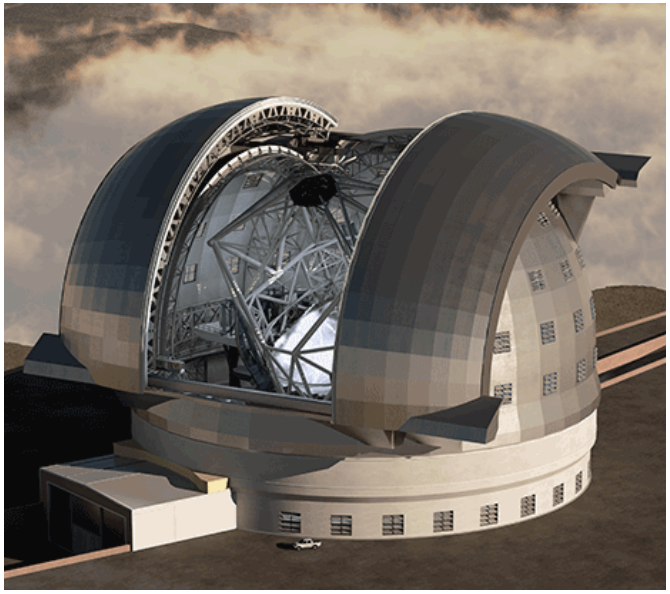
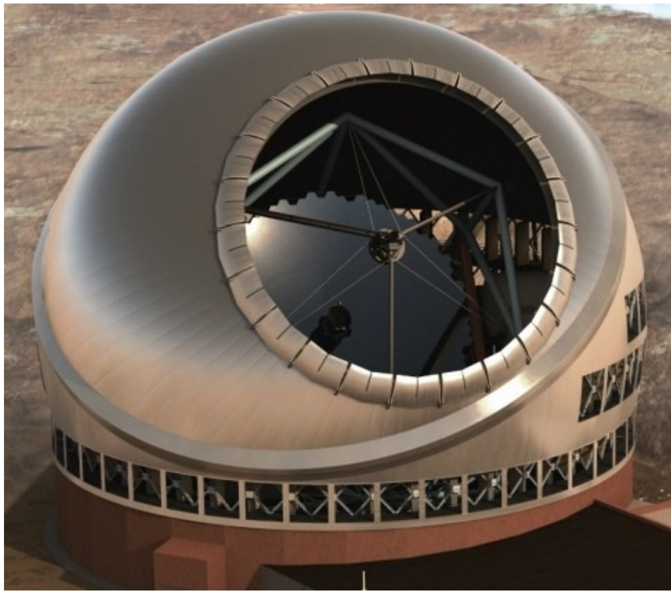


- **Relies on measurements of redshifts and angles: minimal systematics**

Image: DESI FDR report

Extremely Large Telescopes

- 3 major projects ongoing: the European Extremely Large Telescope (~40m diameter), the Giant Magellan Telescope (~25m diameter), and the Thirty Meter Telescope (~30m diameter)
- All have large collecting areas but small fields of view
- None are fully funded, but all are under construction
- Probably at least one will be done by late 2020s, with partial instrument suite

What do we try to measure with telescopes?

1) *Astrometry*: measurements of the positions of objects

- The most ancient form of astronomy; now primarily e.g. for finding asteroids & Kuiper belt objects, some planet searches, and parallax measurements

2) *Photometry*: measurements of the brightnesses (including colors & shapes) of objects

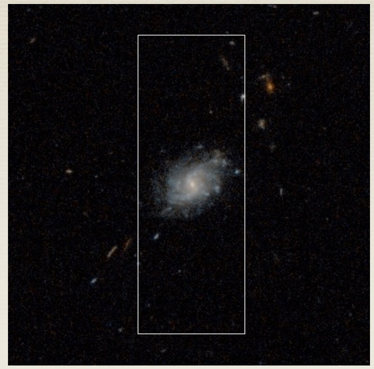
- Dates back to ancient Greeks, who defined the magnitude system
- Both astrometry & photometry rely on *imagers/cameras*

2) *Spectrometry*: measuring the brightness of an object as a function of wavelength

- Provides the greatest amount of information: redshifts, chemical compositions, star formation histories, temperatures, etc.
- Except sometimes in X-ray, relies on *spectrographs*

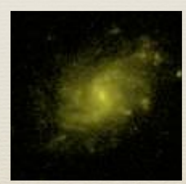
Basics of spectroscopy

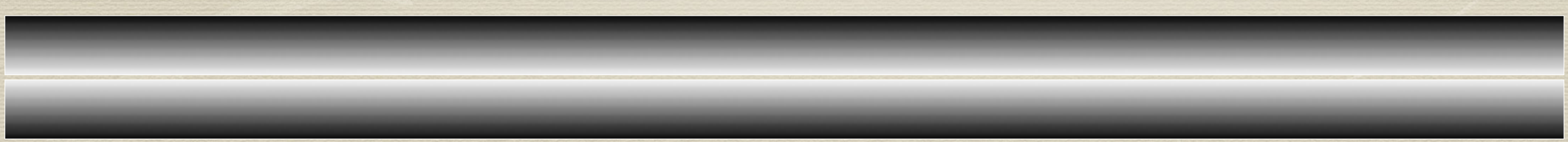
Telescope collects light



Slit or fiber head limits to part of image

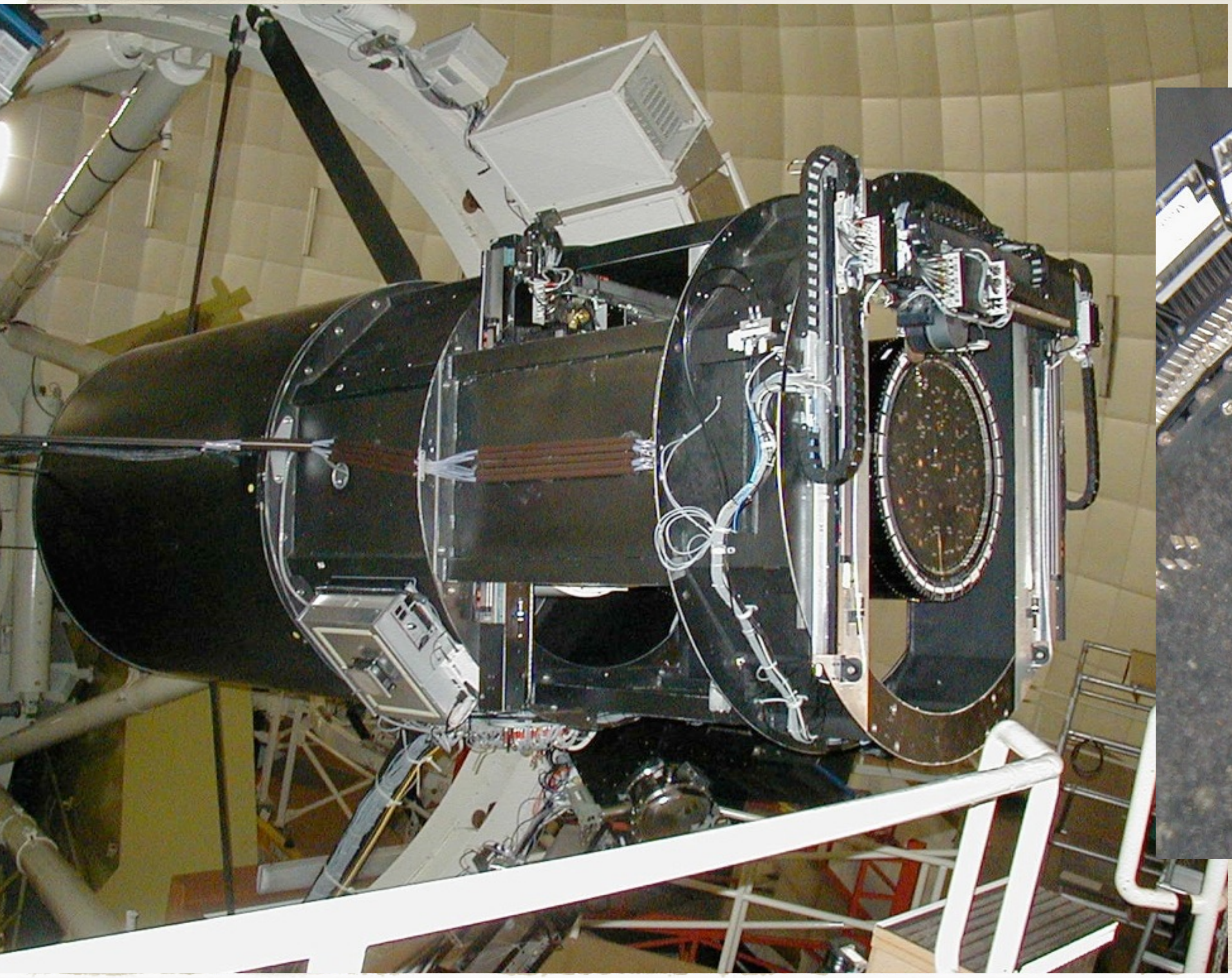
Diffraction grating disperses light





Some basic types of spectrographs

- *Multifiber spectrograph*: positions fibers at the locations of objects in the focal plane (e.g. robotically), carrying light to the spectrograph.



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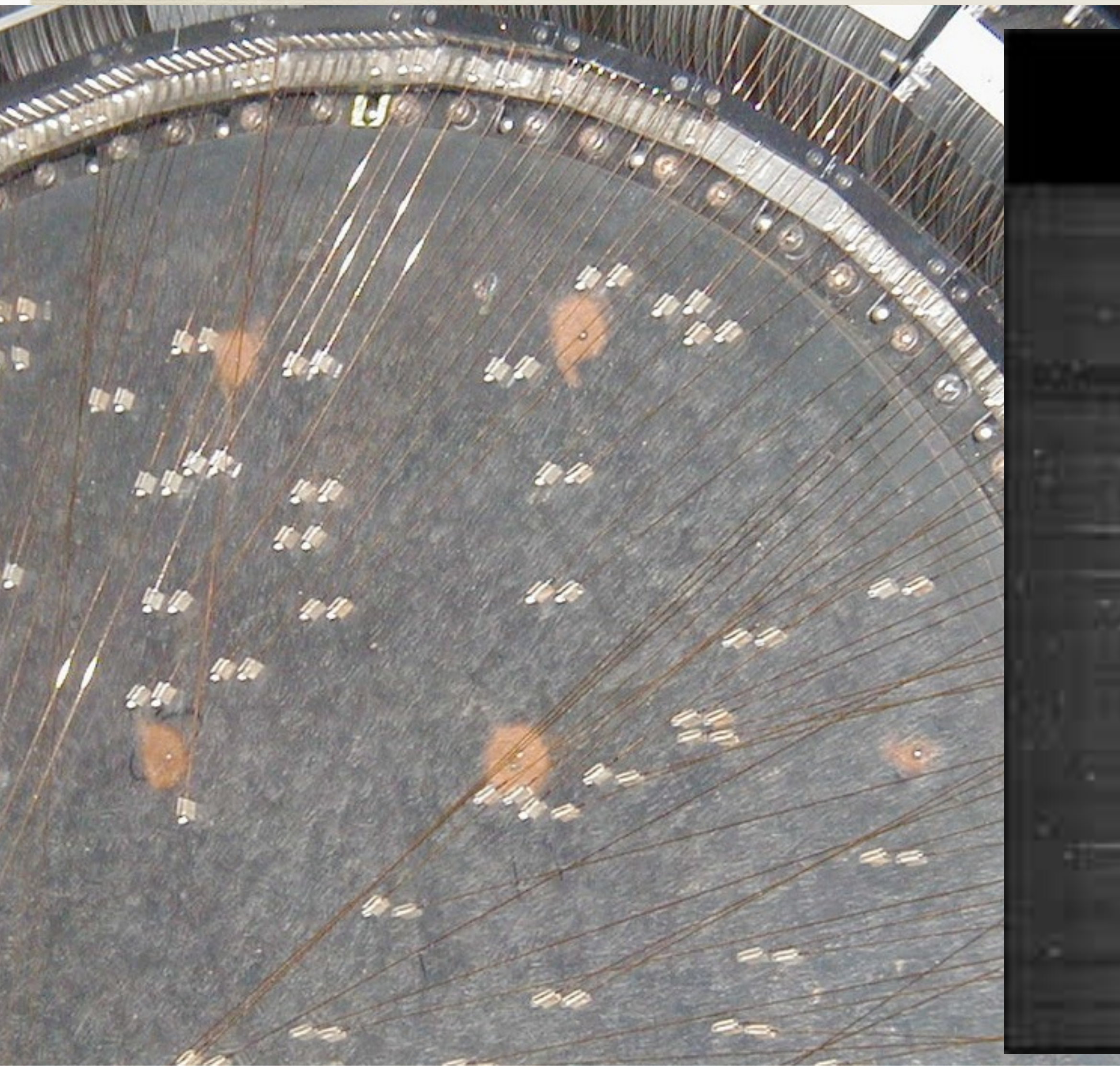
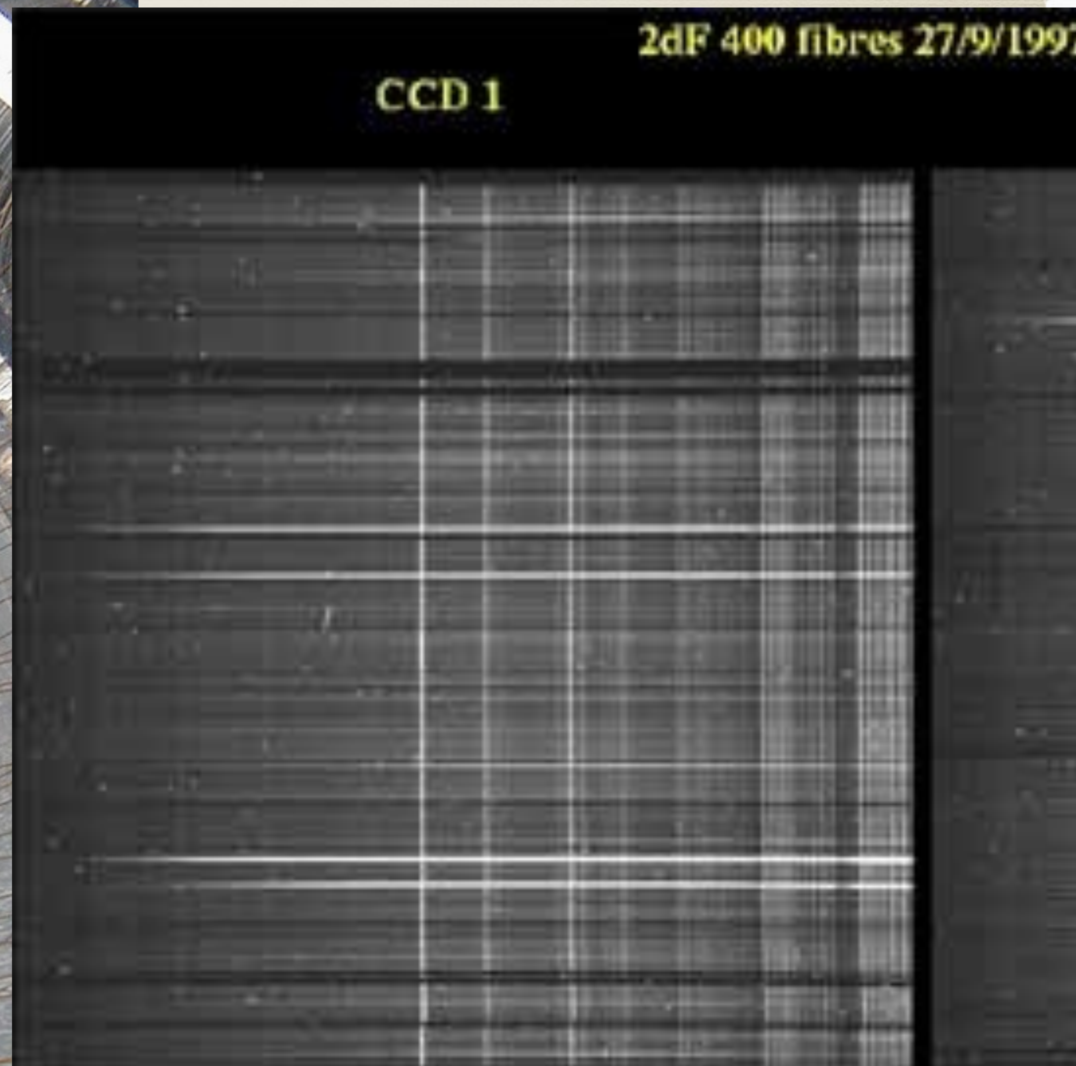
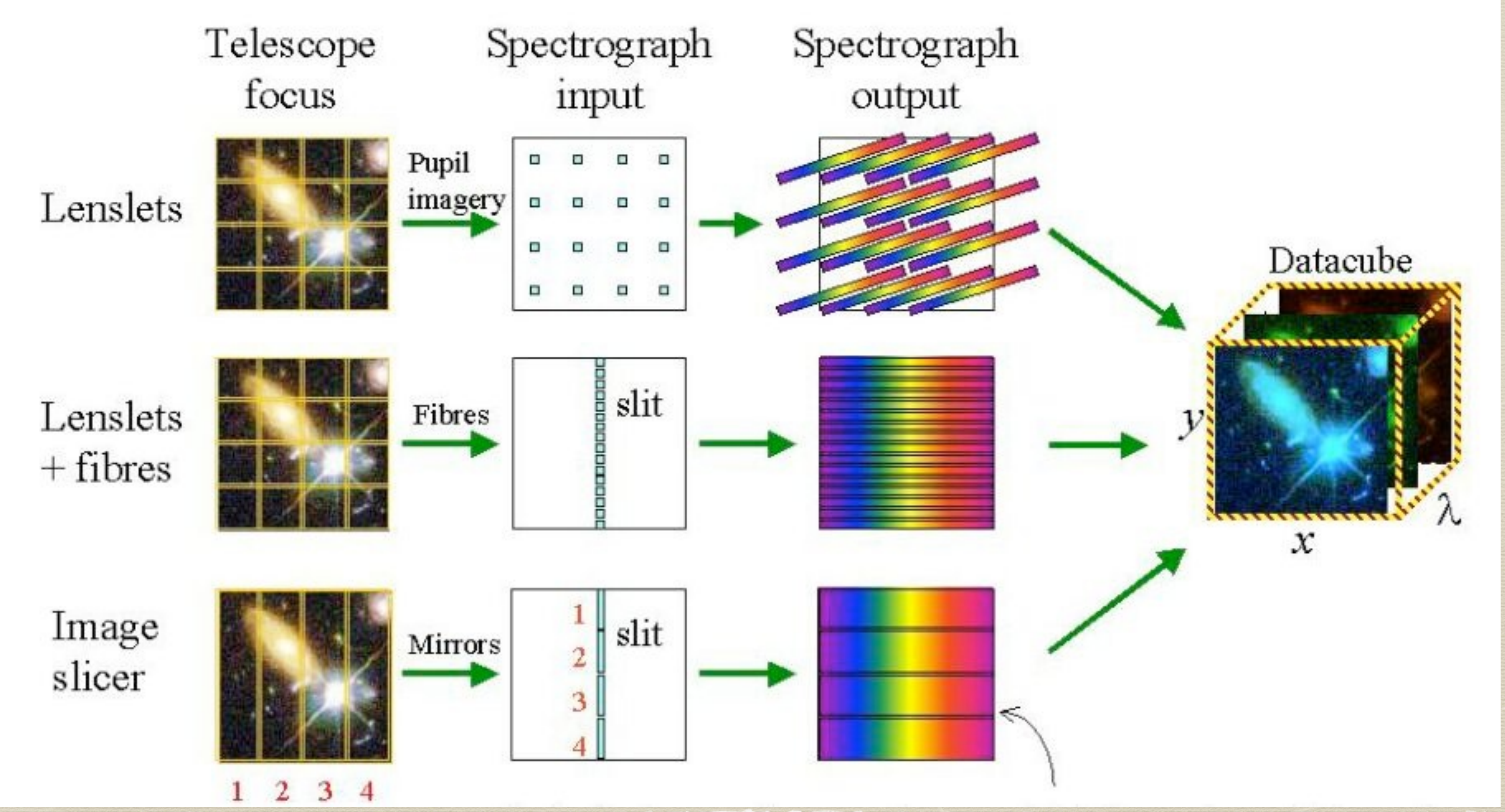




Some basic types of spectrographs

- *Integral Field Unit (IFU)*: obtains a spectrum at every point in its field of view. A hybrid of photometry & spectroscopy: an image at every possible wavelength, or a spectrum at every possible pixel of the image



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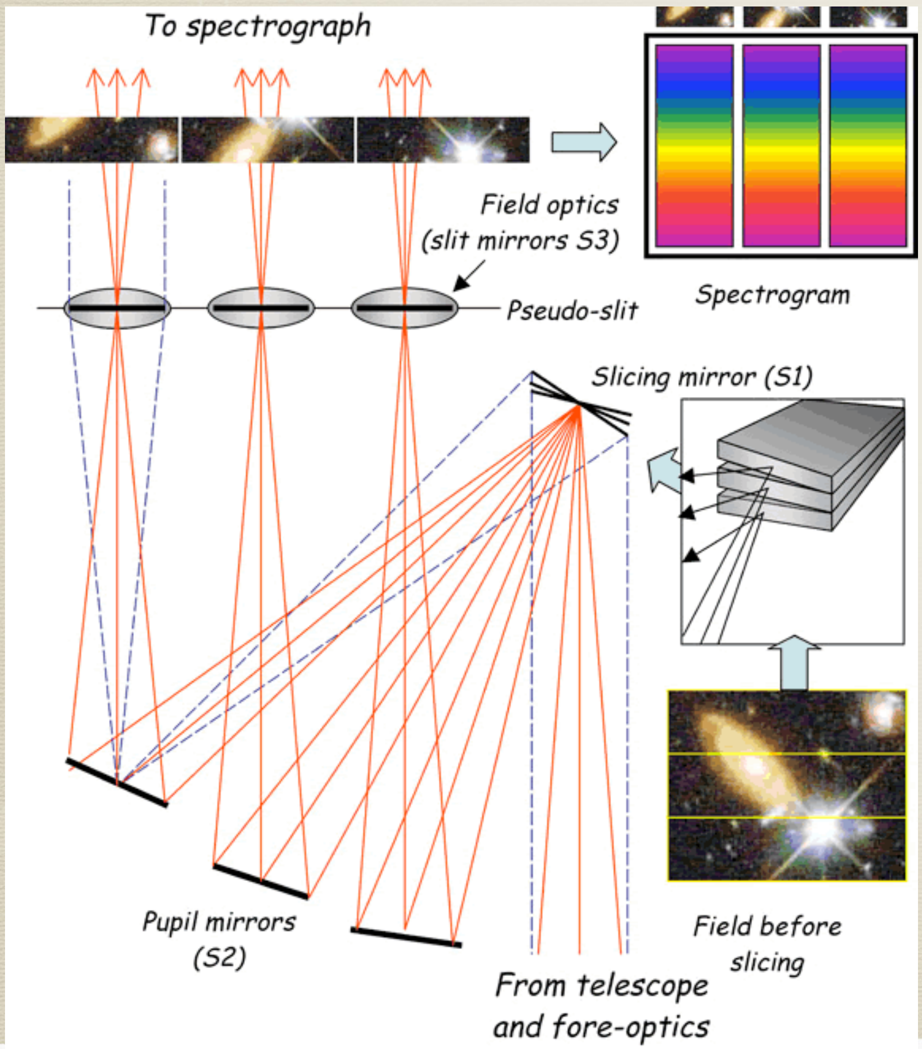
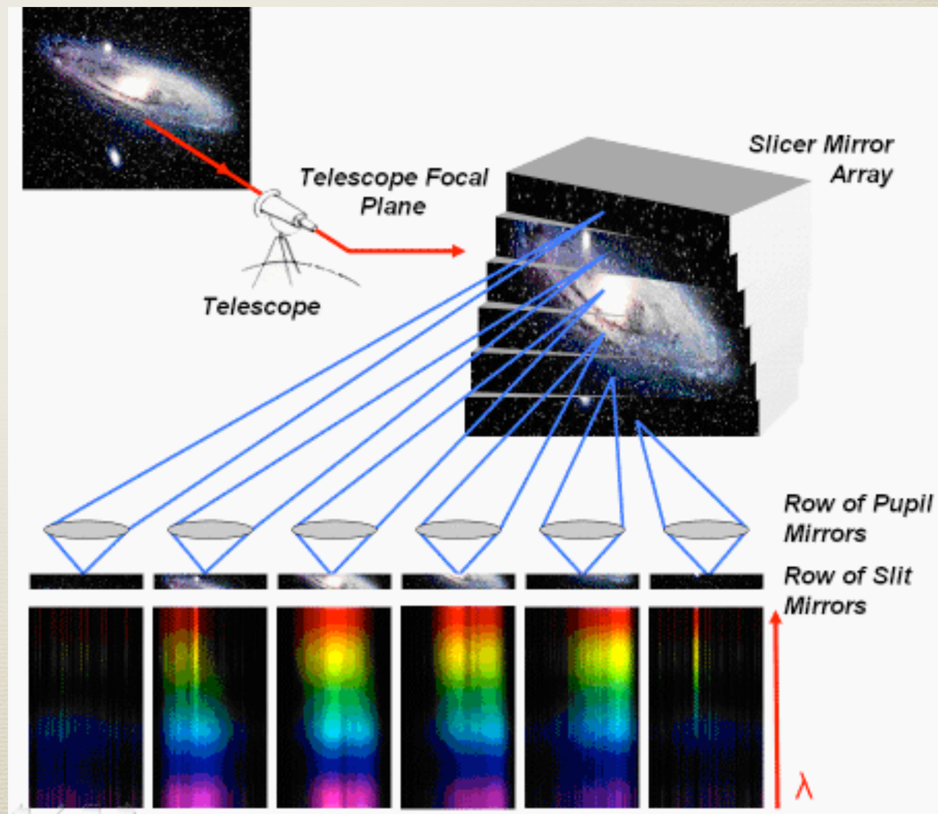




Background: Elmegreen Report

- “A Strategy to Optimize the U.S. Optical and Infrared System in the Era of the Large Synoptic Survey Telescope (LSST)”
- http://www.nap.edu/catalog/21722/optimizing-the-us-ground-based-optical-and-infrared-astronomy-system
- National Research Council report
- Made broad recommendations, but little prioritization

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

Study Process

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)

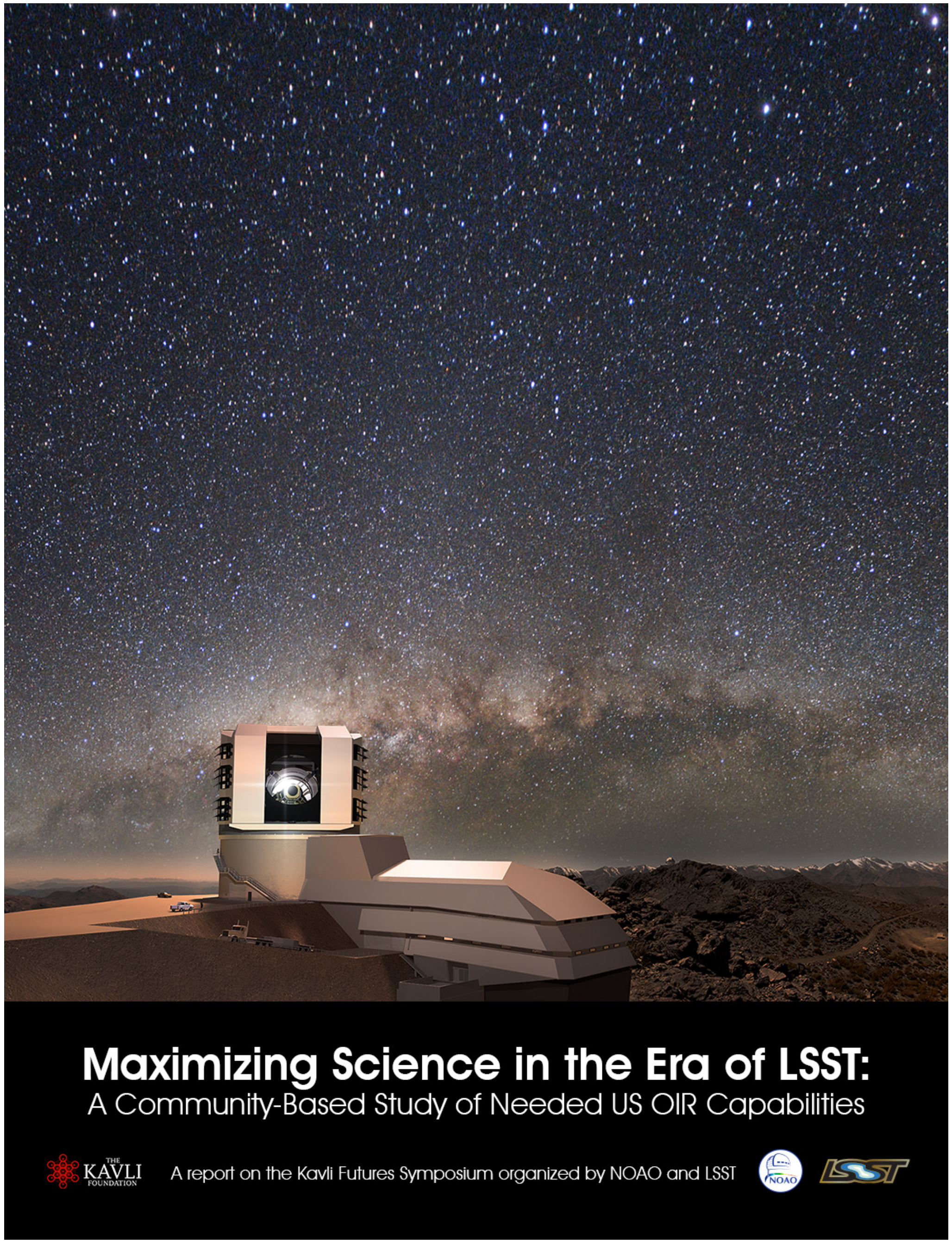
Greg Rudnick (University of Kansas)

Josh Simon (Carnegie Observatories)

David Trilling (Northern Arizona University)

- Winter 2015: Open call for community input on capabilities needed to maximize their LSST science (>100 responses)
- Feb-Mar 2016: Convened 6 study groups
- Mar-Apr 2016: Quantitative studies of needed capabilities
- May 2016: Workshop to discuss and synthesize results and findings
- Summer 2016: Prepare report; released in October

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



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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)

Cover image credit: Y. Beletsky, ESO / Todd Mason, Mason Productions, Inc. / LSST Corporation / P. Marenfeld/NOAO/AURA/NSF

Study Group Topics

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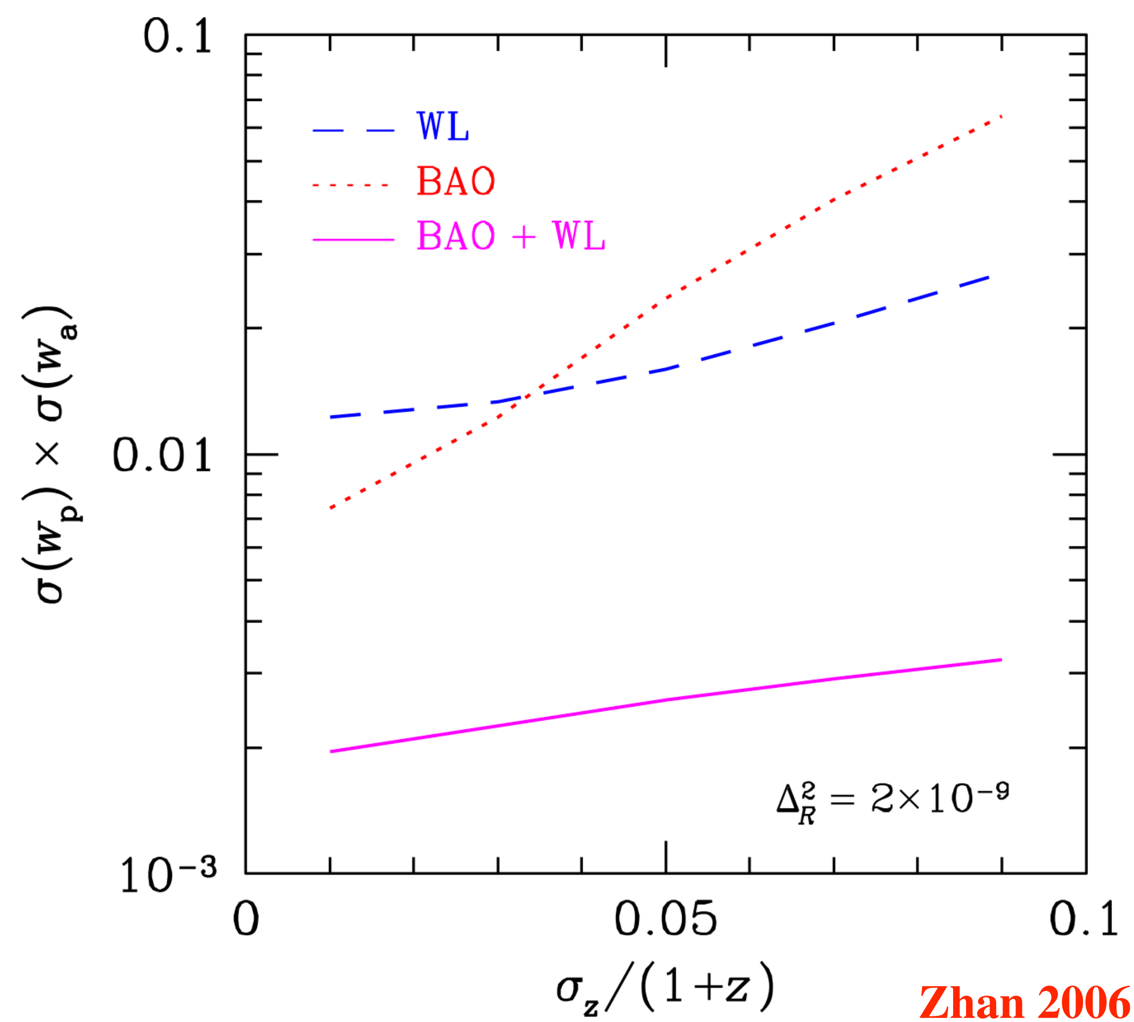
1. Using Small Solar System Bodies to Understand the Evolution of the Solar System
2. Rotation and Magnetic Activity in the Galactic Field Population and Open Star Clusters
3. Probing Galaxy Formation and the Nature of Dark Matter and Gravity in the Local Group
4. Characterizing the Transient Sky
5.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

Cosmology Study Group

Jeffrey Newman (U. Pittsburgh / PITT-PACC), Adam Bolton (NOAO), Will Dawson (LLNL), Mark Dickinson (NOAO), Ryan Foley (UCSC), Elise Jennings (FNAL), Anja von der Linden (SUNY), Eric Linder (DOE), Curtis McCully (LCOGT), Rachel Mandelbaum (CMU), Phil Marshall (SLAC), Tom Matheson (NOAO) Chad Schafer (CMU), Tomasso Treu (UCLA), Ben Weiner (Steward)

A key need for dark energy science: improved photometric redshift training

- **Better training of algorithms using objects with spectroscopic redshift measurements shrinks photo-z errors and improves dark energy constraints, especially for BAO and cluster methods**



Zhan 2006

What qualities do we desire for photo-z training spectroscopy?

- Sensitive spectroscopy of ~30,000 faint objects (to *i*=25.3 for LSST)

  - Needs a combination of large aperture and long exposure times

- High multiplexing

  - Required to get large numbers of spectra

- Coverage of full ground-based spectral window

  - Ideally, from below 4000 Å to ~1.5μm

- Significant resolution (R=λ/Δλ>~4000) at red end

  - Allows secure redshifts from [OII] 3727 Å line at z>1

- Field diameters > ~20 arcmin

  - Need to span several correlation lengths for accurate clustering

- Many fields, >~15

  - To mitigate sample/cosmic variance

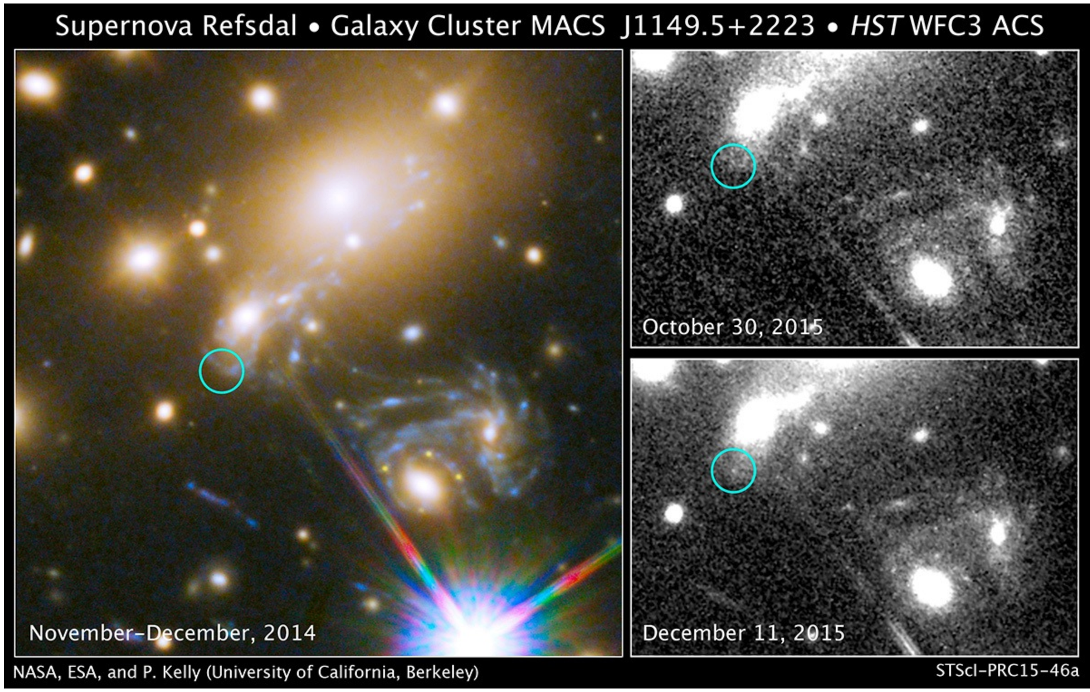
The same sort of spectrograph needed for photo-z's can enhance a variety of cosmological studies

- 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)
- 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

Strong lensing cosmology has different needs

- Strong lens time delays (from lensed QSOs and SNe) depend on cosmological parameters

- Accurate modeling requires **EXTREMELY** accurate positions of images, plus accurate redshifts



- Best done with Adaptive Optics, IFU spectroscopy on 8-40m telescopes
  - R~4000-5000, 1-2.2 micron, 4"x4" FOV, diffraction-limited
  - ~100 hours total observation time for 100 lens systems
  - LSST should provide hundreds of systems with well-measured time delays; follow-up imaging campaigns could enlarge samples
- Multi-object spectroscopy also useful for constraining foreground shear along the line of sight

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**

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

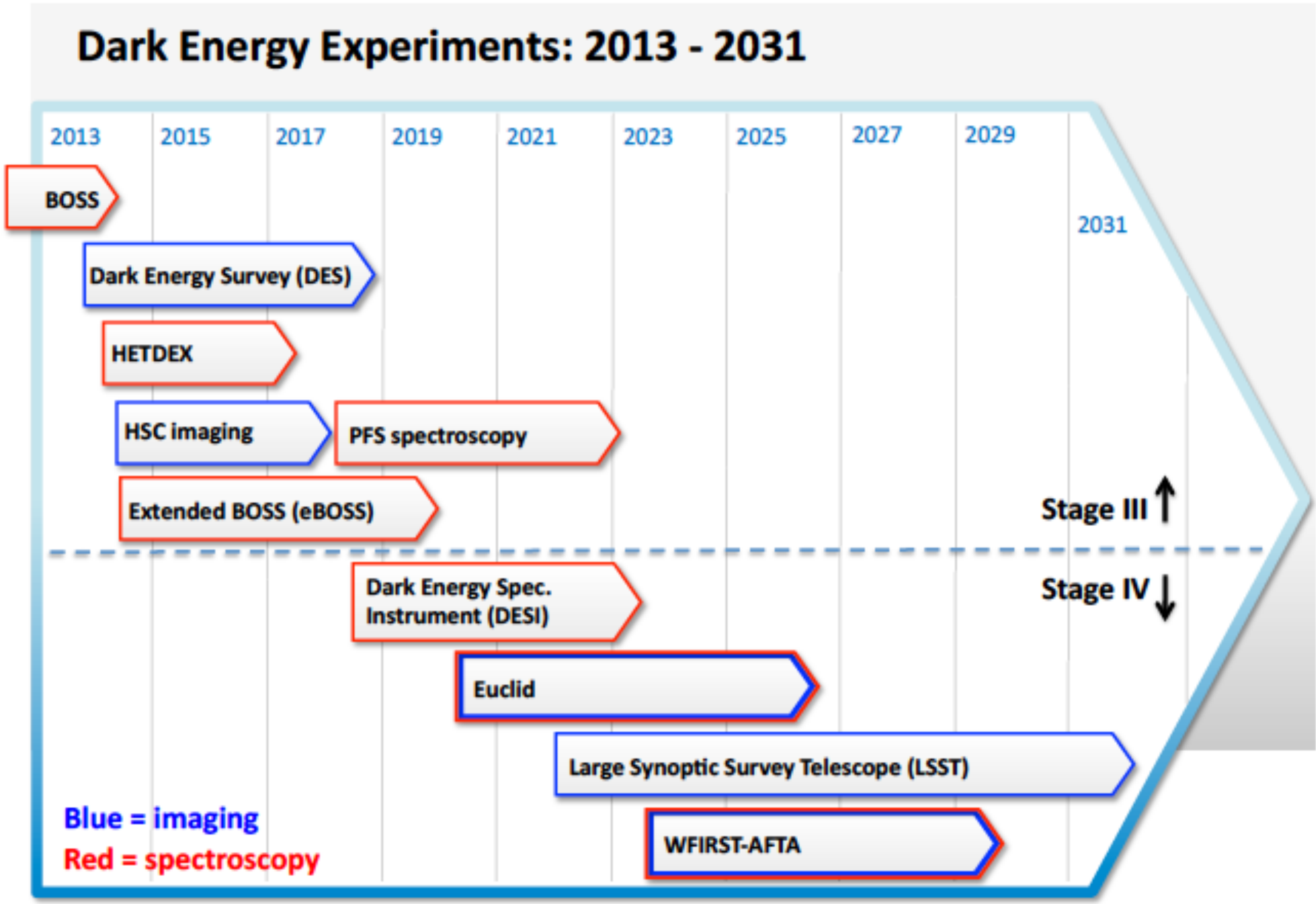
More details on Kavli recommendations for wide-field multi-object spectroscopy (MOS)

- **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, Milky Way structure, reverberation mapping of active galactic nuclei, and studies of stellar rotation and activity.

More details on Kavli recommendations for wide-field MOS (~=SSSI)

- **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**

Context for the DOE Cosmic Visions Report: current and future surveys



Cosmic Visions: Dark Energy

- The Cosmic Visions Dark Energy group was formed by the DOE's Office of High Energy Physics in August 2015: Scott Dodelson (Chair), Katrin Heitmann, Chris Hirata, Klaus Honscheid, Aaron Roodman, Uros Seljak, Anze Slosar, Mark Trodden.
- Two other CV groups (CMB and Dark Matter) coordinate with DOE.
- CMB recently released a first version of their Science Book (1610.02743).
- Dark Energy Cosmic Visions group is still building broad community and developing science case
- Hope to produce a Science Book in 1-2 years for Decadal Survey

Process

Three workshops held to gather input for white papers:

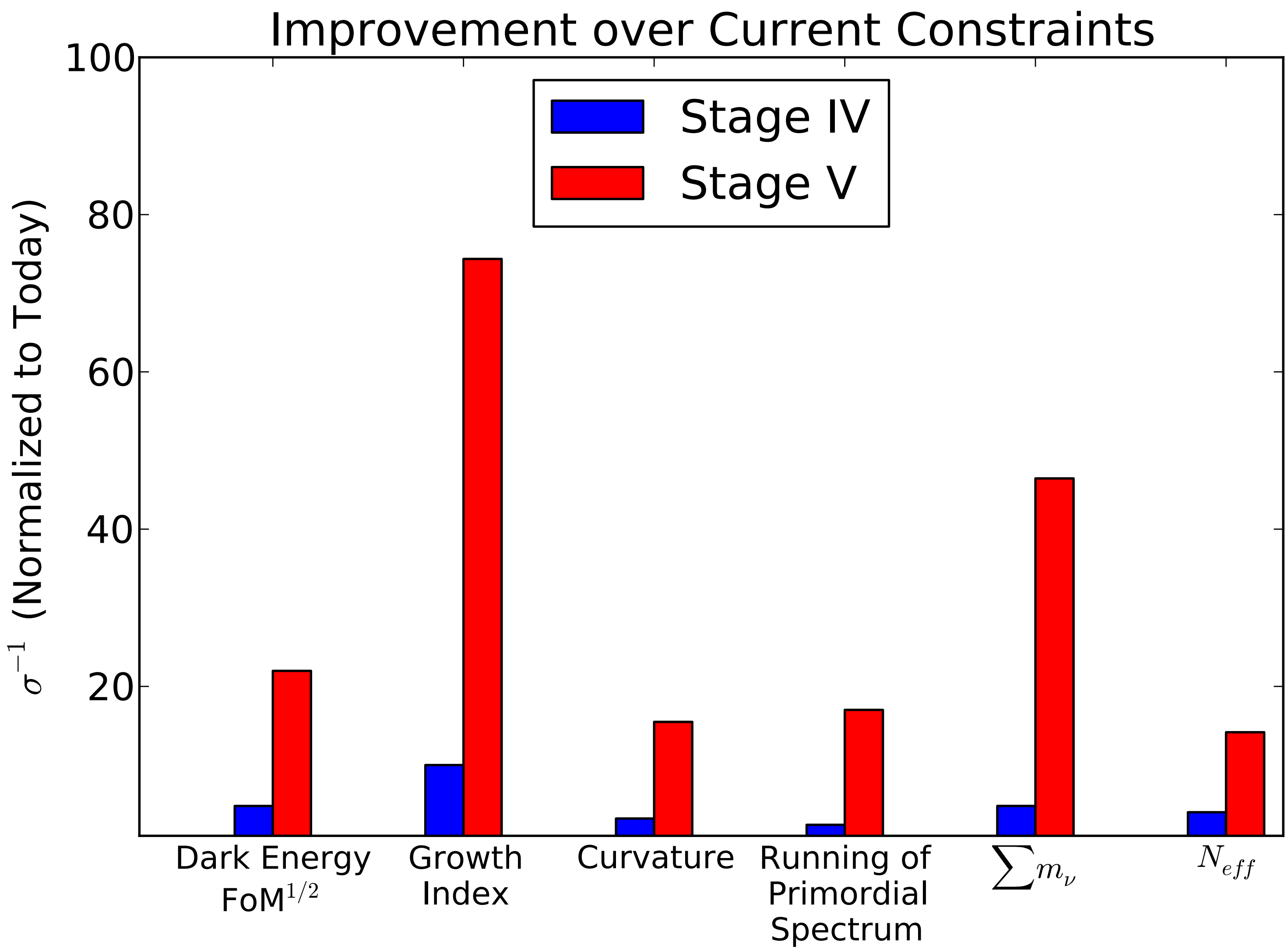
- **Brookhaven, October 1, 2015. Agenda and slides available at https://indico.bnl.gov/categoryDisplay.py?categId=124**
- **Fermilab, November 10, 2015. Agenda and slides available at https://indico.fnal.gov/conferenceOtherViews.py?view=standard\&confId=10639**
- **SLAC, November 13, 2015. Agenda and slides avaiable at https://indico.fnal.gov/conferenceDisplay.py?confId=10842**

Two papers were submitted to the arXiv:

http://arxiv.org/abs/1604.07626

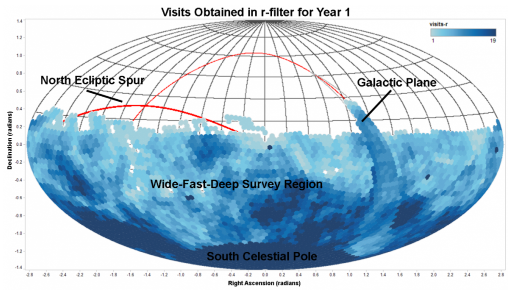
http://arxiv.org/abs/1604.07821

Findings

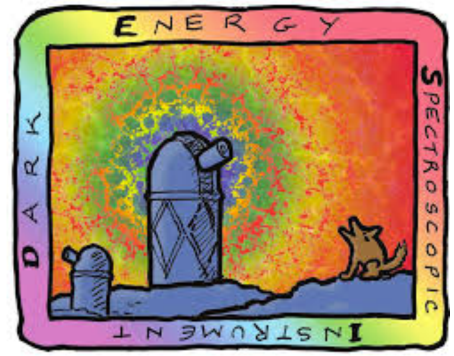


[1] Even after DESI and LSST, there will be a lot of information left in the sky

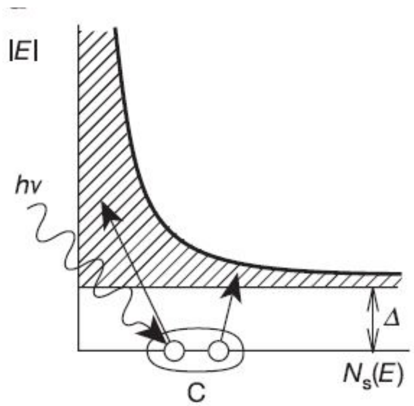
Findings



Southern Spectroscopic Survey Instrument

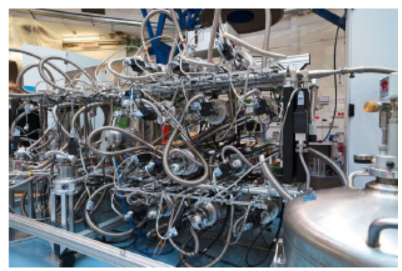


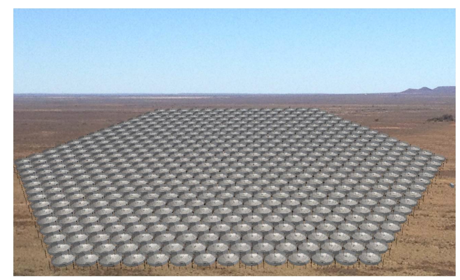
DESI-2



Low Resolution Spectroscopy
aka Hi-Res Photometry

Billion Object Apparatus



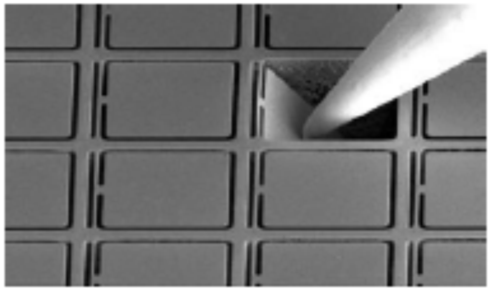


21 cm

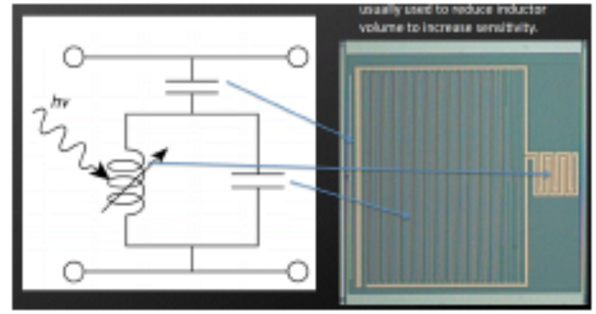
[2] There are multiple ideas for future projects that can mine that information

Findings

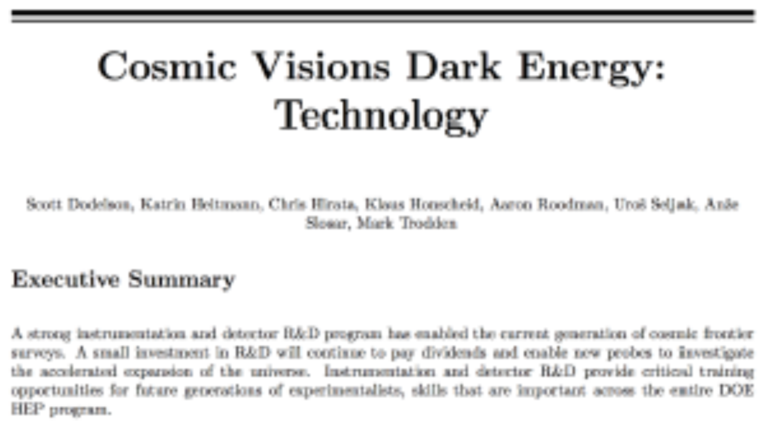
Micro Shutter Arrays developed for JWST



MKIDS Detector Arrays



CV Whitepaper on arXiv 1604.07821



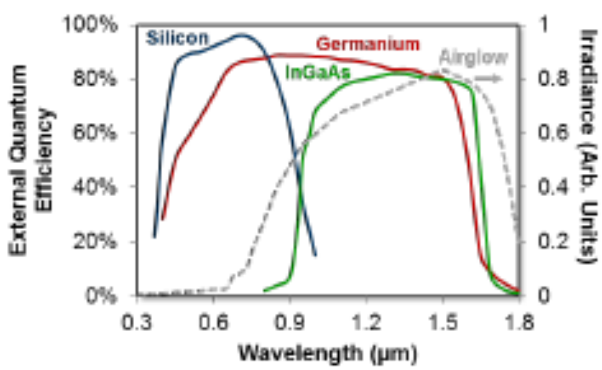
Cosmic Visions Dark Energy: Technology

Scott Dodelson, Katrin Heitmann, Chris Hirata, Klaus Honscheid, Aaron Roodman, Uroš Seljak, Anže Slosar, Mark Trodden

Executive Summary

A strong instrumentation and detector R&D program has enabled the current generation of cosmic frontier surveys. A small investment in R&D will continue to pay dividends and enable new probes to investigate the accelerated expansion of the universe. Instrumentation and detector R&D provide critical training opportunities for future generations of experimentalists, skills that are important across the entire DOE HEP program.

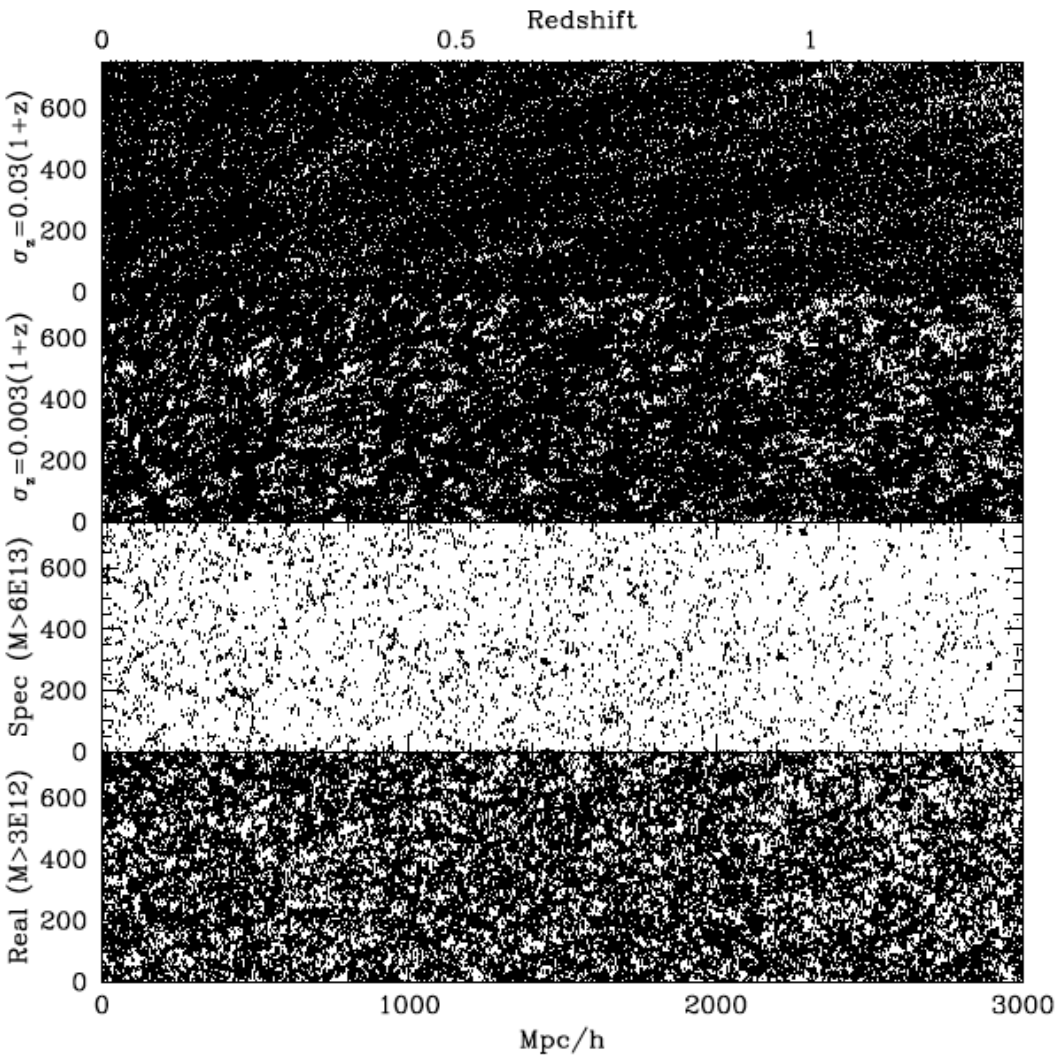
Ge CCDs (MIT LL, LBNL)



C. Leitz

[3] Instrumentation R&D and new technologies will be key for most of these ideas

High-Resolution Photometry



- **Use new detector technologies (still under development) or narrow-band imaging to obtain better redshifts than photo-z's**
- **Challenging to do better than LSST photo-z's; pretty much need to deploy something like this on LSST itself and run for 10 years just to halve redshift errors**

Radio Cosmology: 21 cm/Intensity Mapping

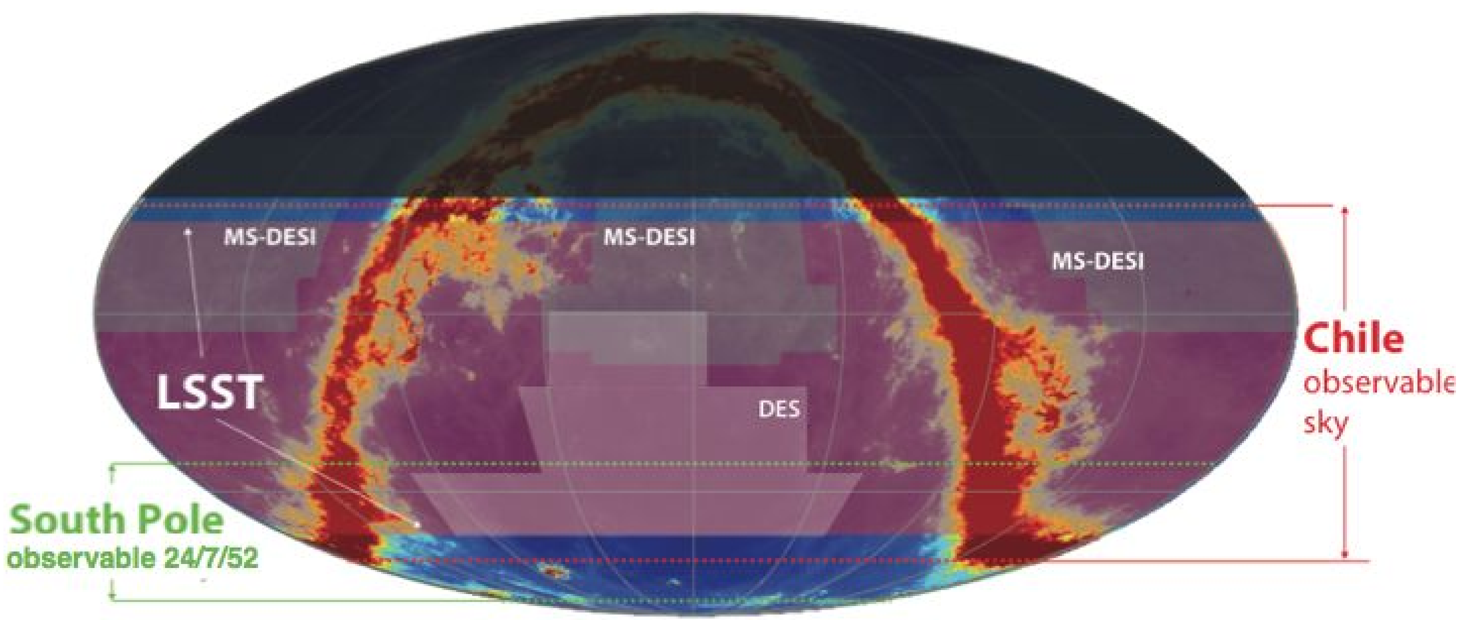
- **Map out the BAO feature using low-resolution (blurred at many-Mpc scales) maps of 21cm radio emission at high redshifts, z>2**
- **DOE role is unclear**
- **Telescopes are cheap to build, but major software challenges in rejecting terrestrial interference**

DESI-2

- DESI will do a 14,000 sq. deg survey of 35 M galaxies & quasars + 10 M stars from 2019-2024
- DESI-2: science with DESI after the planned survey is complete (2025+). Operating costs estimated at $7-8M per year.
  - Modest upgrades to DESI could extend the spectrograph in the red and enable an efficient higher redshift survey
- Possible surveys / science drivers:
  - Dense low redshift survey (e.g. magnitude limited to 21.5) allows precise power spectrum, density & velocity field,
  - High redshift survey at z > 1.5 could be enabled with modest instrument upgrades (requiring new technology)
  - Significant but not huge overlap and cross-correlation science with LSST and CMB-S4
  - Targeted surveys, e.g. gravitational wave follow-up, stellar streams, dense sampling of cluster or lens fields, etc.

Southern Spectroscopic Survey Instrument

- SSSI would be a massively multiplexed (>2500x), wide-field (goal: >1 deg2) optical/IR spectrograph on a 6.5+m telescope
- SSSI provides spectroscopic capabilities matched to LSST and CMB-S4 survey areas and depths; Southern site preferable
- SSSI takes full advantage of current technologies and DESI legacy
- Wide variety of science cases; e.g.: LSST photo-z training, reducing photo-z errors by a factor of 2
- Matches Kavli recommendation



Billion Object Apparatus

- Concept: optical/IR spectrograph on a 10m telescope
  - massively multiplexed (50k-100k fibers)
  - wide-field (1-5 deg^2)
- Primary Objective: complete sampling of linear density field using between 500M and 1B spectroscopic tracers
  - Maximal precision on cosmological constraints with clustering to $z<3.5$
- Feasibility uncertain; no design exists for an instrument like this
- Cost estimates easily get to $1 billion. . .
- If SSSI is deployed on a >10m telescope, could use the same platform for BOA

Road Map for Spectroscopy

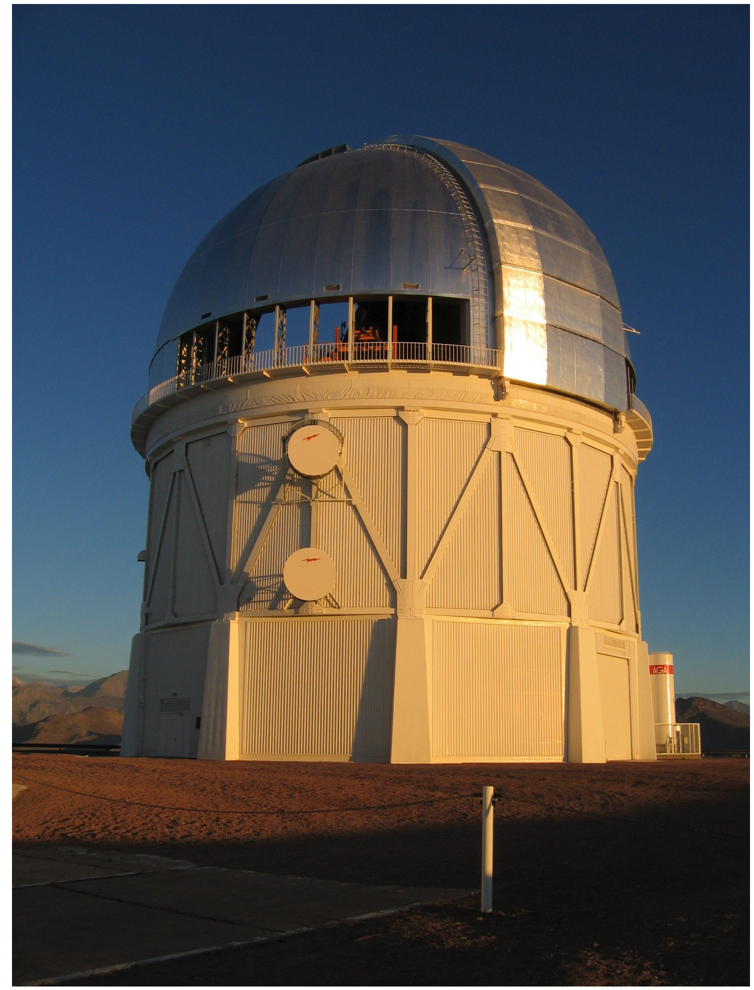
- The proposed spectroscopic surveys build on each other directly
- DESI-2 would be relatively low in cost and could follow DESI immediately in 2024
  - Spectrograph upgrades to add IR arm would enhance capabilities at higher redshifts
  - Moving to Blanco is an option, increasing LSST overlap
- SSSI could reuse DESI spectrographs to reduce costs
  - Earliest possible deployment c. 2026
  - Most efficient option would be to deploy on 11-12m telescope (e.g. MSE or European wide-field concepts)
- BOA would require both a >10m wide-field telescope and significant hardware R&D
  - Earliest possible deployment early 2030s
  - Could utilize telescope originally developed for SSSI

Proposed possible implementation paths for multi-object spectrograph from Kavli report

1. Implement a wide-field MOS on an existing or new Southern-hemisphere telescope: join with DOE on an SSSI?
    1. DESI design could be efficiently deployed at Magellan, costing ~$60M
2. Obtain large amounts of community access to Subaru/PFS + DESI
3. Buy into a proposed new project in the South (ESO wide-field MOS telescope study) or North (Maunakea Spectroscopic Explorer, Telescopio San Pedro Martir)

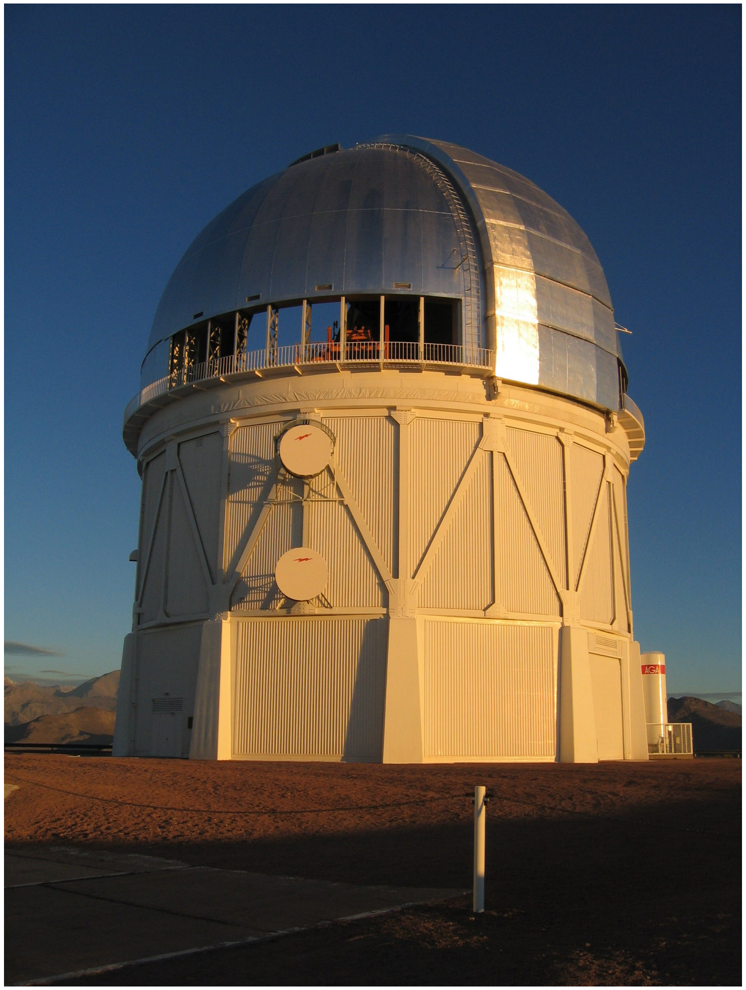
Blanco telescope, Chile

- 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 clone
- DESpec: 5000x, 3 deg^2 FOV with existing corrector, interchangeable w/ DECam:
  - ~40M$



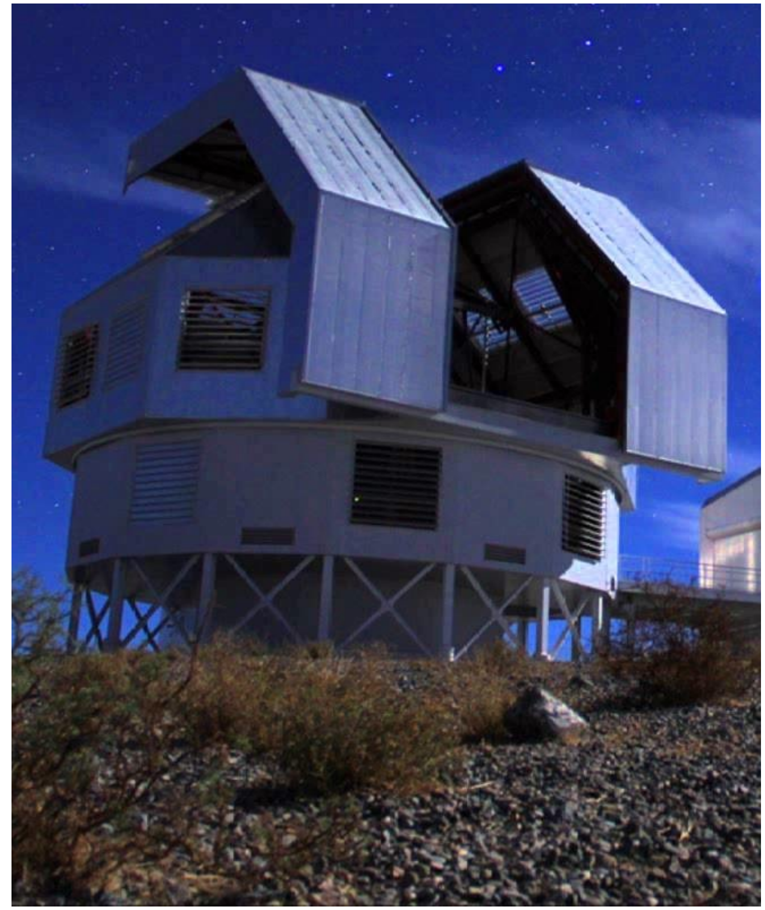
Blanco telescope, Chile

- Pros:
  - Largest field of view w/ DESI move or clone
  - Moving DESI cheapest option for an SSSI; mid-2020s possible
- Cons:
  - Small aperture requires long survey times
  - Earthquake safety of DESI corrector?
  - Kavli/NOAO/LSST report will recommend DECam stay on Blanco at minimum 3 years into LSST survey; would delay SSSI deployment unless DESpec option



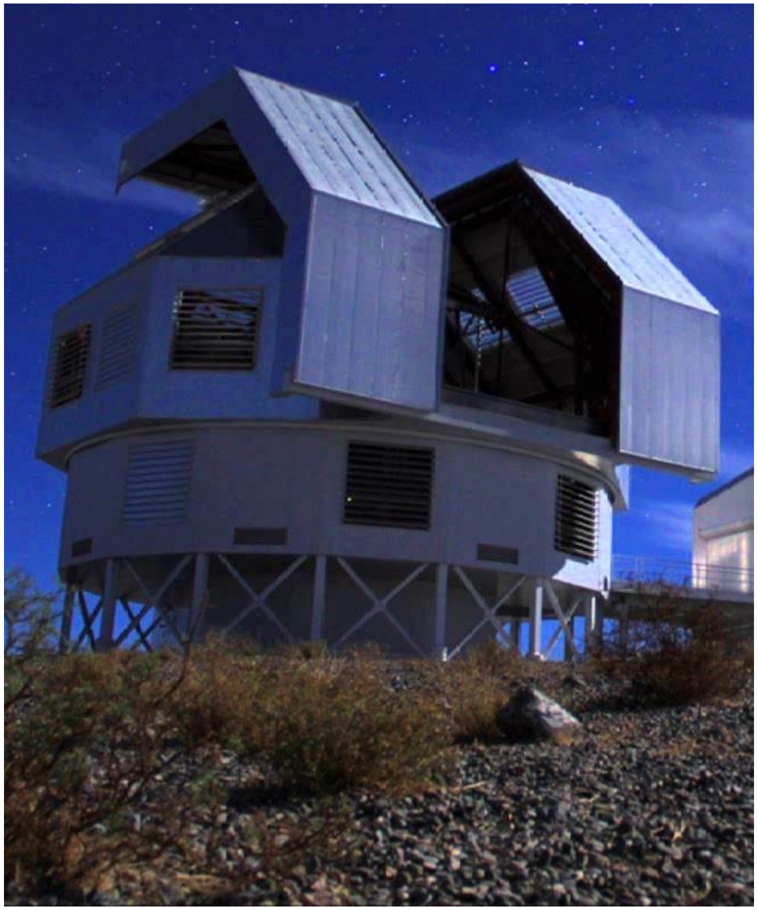
Magellan telescope, Chile

- 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
    - SSSI instrument could form the basis of a SDSS6 survey; potential public/ private partnership



Magellan telescope, Chile

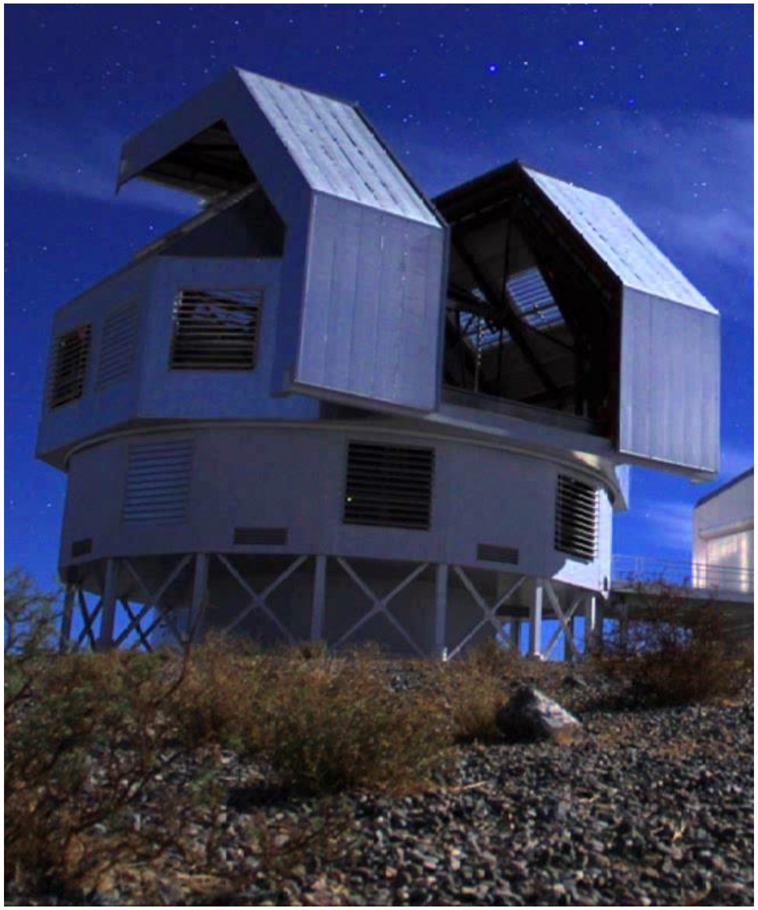
- Pros:
  - Collecting area matches LSST
  - Existing telescope makes earlier schedule possible: mid-2020s?
- Cons:
  - Would prefer even larger aperture, >8m (Kavli/NOAO/LSST)
  - If use an existing Magellan telescope, must navigate politics of Magellan institutions, time access likely limited.
- Build a 3rd Magellan telescope for this? Add $75M+ and additional construction time.



Telescopio San Pedro Mártir, Mexico

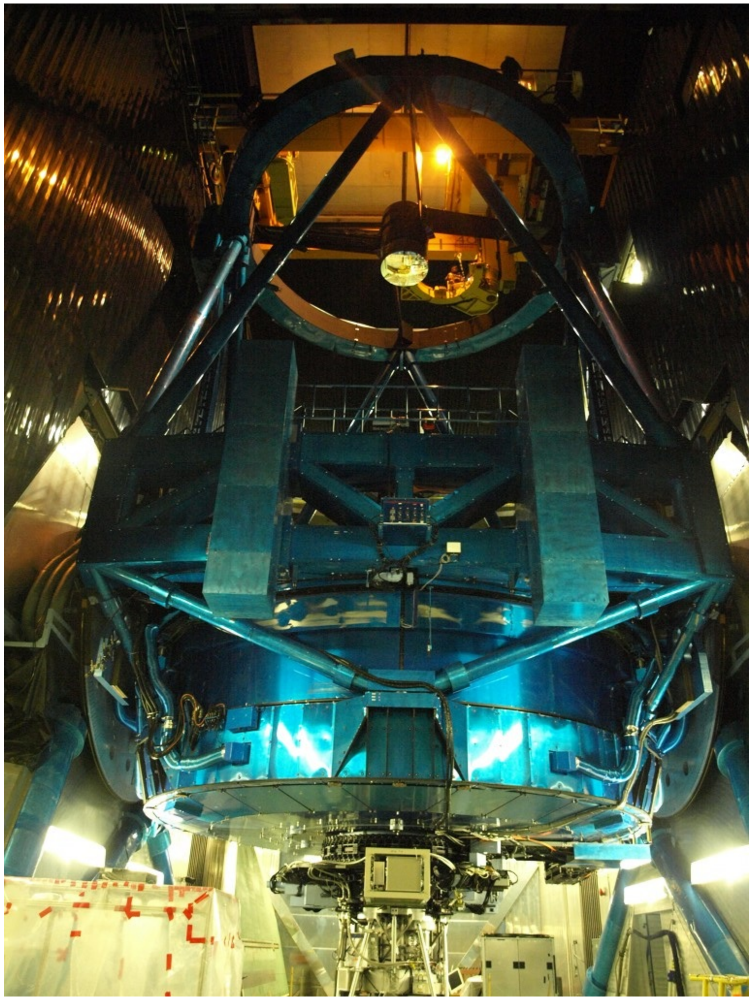
SSSI

- Magellan clone, 6.5m diameter
- Latitude 30N
- Might begin construction 2017 (finish FY23), funding decision imminent
- $74M projected telescope budget, plus ~$75M+(?) for instrument
- Pros:
  - Simpler politics than Magellan, enthusiasm of partners to host an SSSI-like instrument
- Cons:
  - Northern hemisphere
  - Smaller than some other options
  - Not yet certain to be built, time access likely limited.



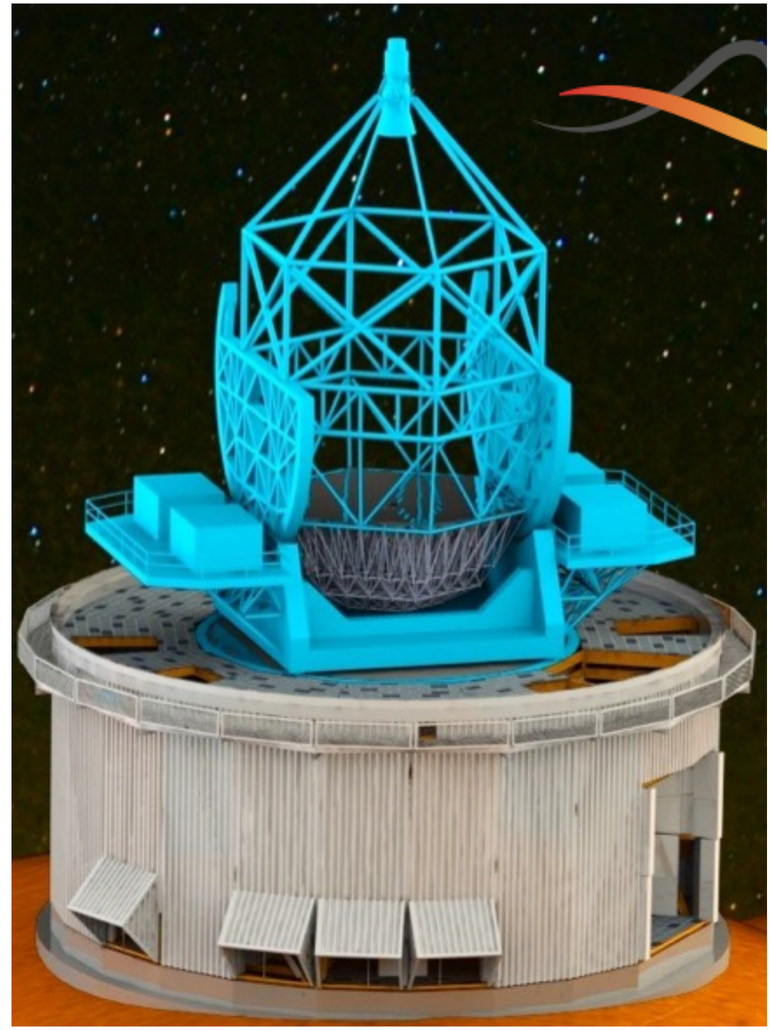
Subaru (+PFS spectrograph), Hawai'i

- 8m diameter, wide-field telescope
- PFS spectrograph, 2400 fibers over 1.3 deg, under construction, commissioning to be completed 2019
- Pros:
  - Enables SSSI without new instrument
- Cons:
  - Northern hemisphere, but can access majority of LSST footprint
  - Limited time access: must compete with other Japanese priorities and potential time allocations for WFIRST
  - Subaru relatively expensive to build + operate



Mauna Kea Spectroscopic Explorer, Hawai'i

- 11m diameter telescope with 1.5 degree field of view, replacing CFHT
- Designed solely for spectroscopy with an SSSI-like (3200-fiber) instrument
- Pros:
  - Large aperture, wide field, very high survey speed
  - Enthusiastic about collaborating
- Cons:
  - Northern hemisphere, but accesses majority of LSST footprint
  - Not yet funded; timescale?
  - Cost to join: $50 million (in-kind via instrument construction?)



- Note: similar telescope concepts for South under ESO discussion.

Budget scenarios

- ~$5-10M:
  - Upgrade DESI in North, or upgrade and move to South
- ~$40M:
  - DESpec on Blanco
- ~$75M+:
  - New instrument for existing or funded 6-10m telescope
  - Join existing or planned facility (PFS, MSE,…)
- ~$125-150M+:
  - New instrument on upgraded Gemini
- ~$250M+:
  - New instrument on new 8m+ in the south
- *Large uncertainties in the larger numbers, depending on design details, partnership arrangements, etc.*
- DES and DESI were/will be ~10 yrs from conception to survey start. LSST ~25 yrs. More ambitious projects will be on-sky well after mid-2020s.

The LSST Dark Energy Science Collaboration

- Particle physics-style collaboration, inaugurated Summer 2012
- More than 500 scientists from >50 institutions (mostly US, France, UK)
- Spokesperson: Rachel Bean, Cornell University (Deputy Spokesperson: JN)
- Developed >200 page 'Science Roadmap' identifying tasks that must be done over the next 4 years to be ready for LSST first light (http://lsst-desc.org/sites/default/files/DESC_SRM_V1.pdf)
- Work on these tasks is going on now!

Getting involved in DESC

- DESC focuses on cosmological measurements related to dark energy, dark matter, neutrino mass, modified gravity, etc.
- Working groups:
- Analysis: Weak Lensing, Large-Scale Structure, Galaxy Clusters, Strong Lensing, Supernovae, Theory & Joint Probes, Photometric Redshifts
- Computational: Cosmological Simulations, Survey Simulations, Computing and Infrastructure
- Technical: Sensor Anomalies, Photometric Correction
- To find out more about DESC and how to join, go to http://lsst-desc.org

Conclusions

- Kavli/NOAO/LSST and Cosmic VIsions reports have one overlap: SSSI
- There is not currently funding for a project of that scale
- Almost certainly will need to be a priority in the coming 2020 Decadal survey to go forward
- Community support will be important if any of the recommendations from the Kavli/NOAO/LSST and Cosmic Visions reports are to succeed!