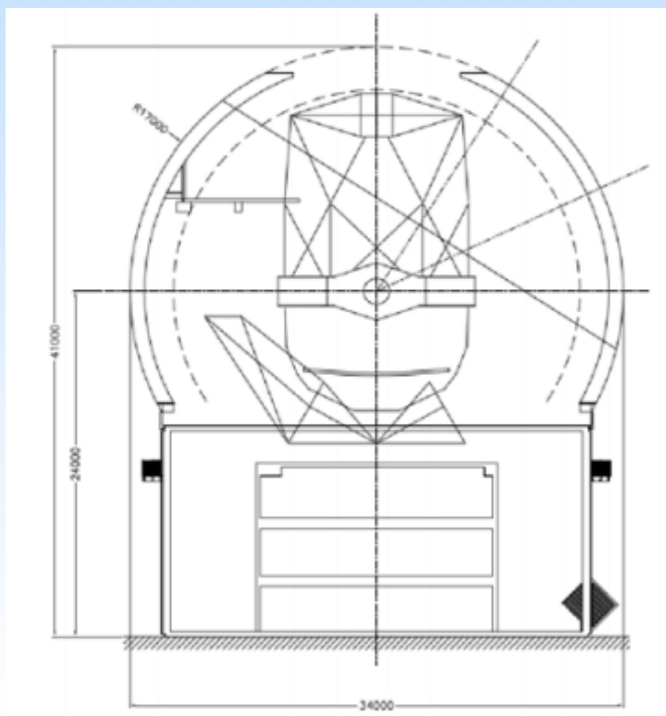
Spectroscopic Support for LSST Science: A Dark Energy Perspective

Jeff Newman, U. Pittsburgh/PITT PACC
(with contributions from Josh Frieman, FNAL)



Context: Massively-multiplexed spectroscopy on a large, Southern telescope keeps showing up as a priority

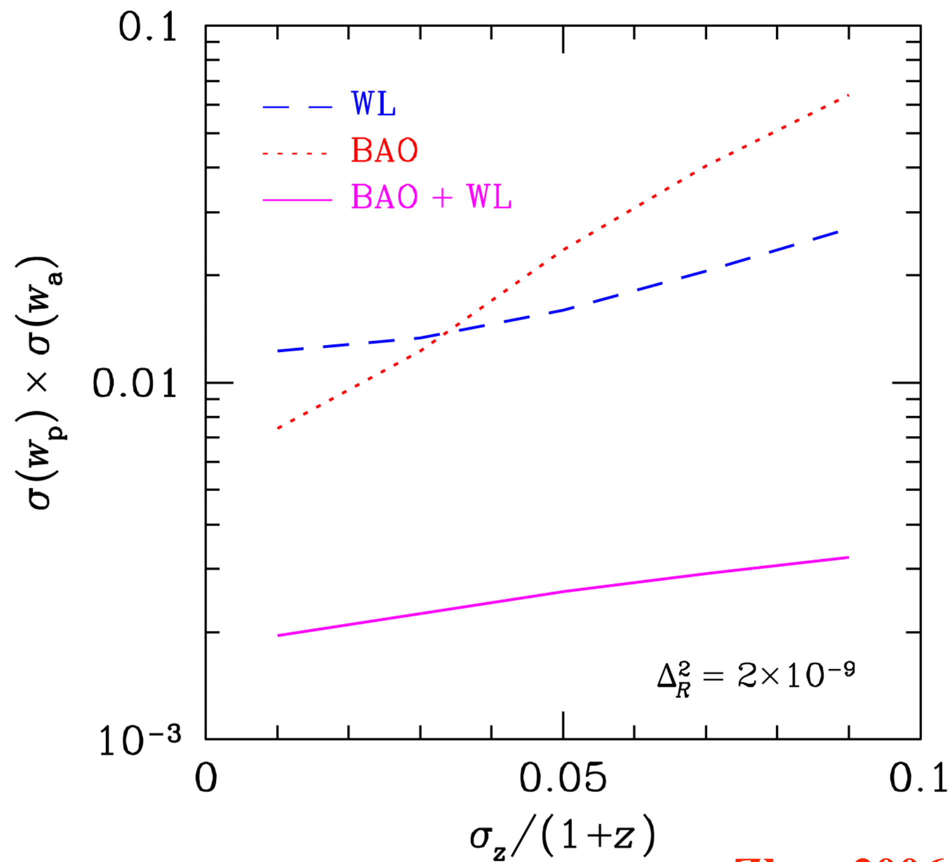
- **2015: NSF-commissioned NRC report *A Strategy to Optimize the US Optical and Infrared System in the Era of LSST* (Elmegreen et al.) recommended wide-field, highly multiplexed spectroscopy on an intermediate-to-large aperture telescope in the southern hemisphere.**
- **2016: DOE-commissioned *Cosmic 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+.**

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 a Large-Area Spectroscopic Survey Instrument: A LASSI

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**



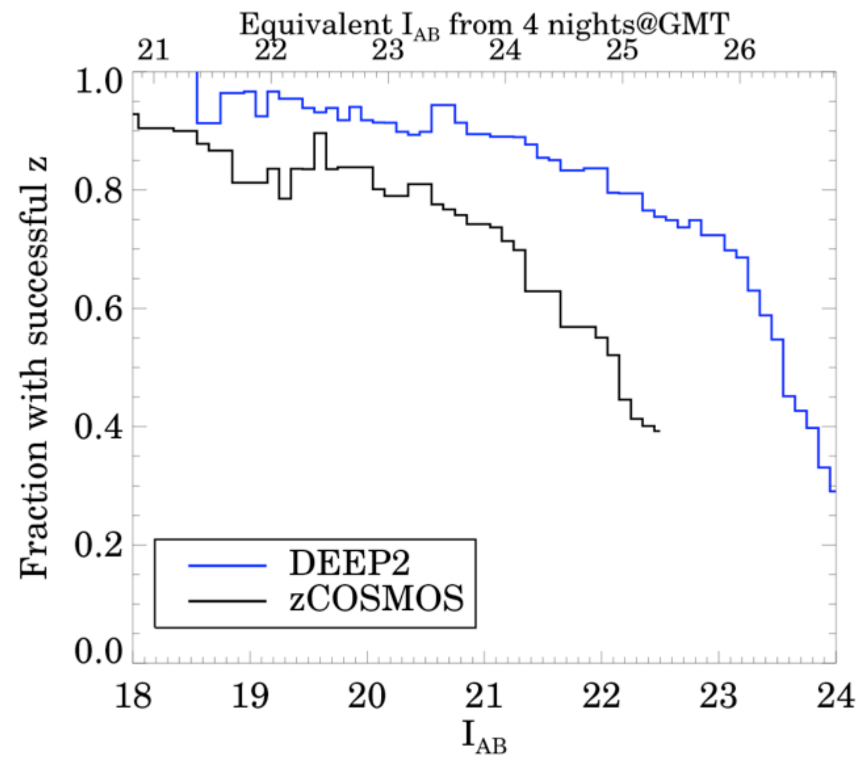
Zhan 2006

- **LSST system-limited photo-z accuracy is ~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%**

Basic requirements for LSST photometric redshift training

LASSI

- >30,000 galaxies down to LSST weak lensing limiting magnitude (*i*~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

Instrument requirements to address both Cosmic Visions & Kavli recommendations: based on photo-z

LASSI

- 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 ($R=\lambda/\Delta\lambda>\sim 5000$) at red end
  - Allows secure redshifts from [OII] 3727 Å line at z>1
- Field diameters > ~20 arcmin
  - >1 degree preferred
- Large telescope aperture
  - Needed to go faint in reasonable time
  - 4-6m (Cosmic Visions/LASSI) vs. ~8m (Kavli)

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

LASSI

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

Summary of (some!) potential instruments

LASSI

Telescope / Instrument	Collecting Area (m^2)	Field area ($arcmin^2$)	Multiplex	Limiting factor
Keck / DEIMOS	76	54.25	150	Multiplexing
VLT / MOONS	58	500	500	Multiplexing
Subaru / PFS	53	4800	2400	# of fields
Mayall 4m / DESI	11.4	25500	5000	# of fields
WHT / WEAVE	13	11300	1000	Multiplexing
VISTA / 4MOST	10.7	14400	1400	Multiplexing
GMT /MANIFEST+GMACS	368	314	420-760	Multiplexing
TMT / WFOS	655	40	100	Multiplexing
E-ELT / MOSAIC	978	39-46	160-240	Multiplexing
Keck / FOBOS	76	314	500	Multiplexing
MSE	98	6360	3200	# of fields
Magellan / MAPS	32	6360	5000	# of fields
TMT/WFOS-fiber pess	655	113	1000	Field of view
TMT/WFOS-fiber opt.	655	201	2000	Field of view

Updated from Newman et al. 2015, *Spectroscopic Needs for Imaging Dark Energy Experiments*

Time required for each instrument

LASSI

Telescope / Instrument	Total time(y), DES / 75% complete	Total time(y), LSST / 75% complete	Total time(y), DES / 90% complete	Total time(y), LSST / 90% complete
Keck / DEIMOS	0.51	10.2	3.2	64
VLT / MOONS	0.20	4.0	1.3	25
Subaru / PFS	0.05	1.1	0.34	6.9
Mayall 4m / DESI	0.26	5.1	1.6	32
WHT / WEAVE	0.45	9.0	2.8	56
VISTA / 4MOST	0.39	7.8	2.4	48
GMT/MANIFEST+GMACS	0.02 - 0.04	0.42 - 0.75	0.13 - 0.24	2.6 - 4.7
TMT / WFOS	0.09	1.8	0.56	11
E-ELT / MOSAIC	0.02 - 0.04	0.50 - 0.74	0.16 – 0.23	3.1 - 4.7
Keck / FOBOS	0.12	2.3	0.72	14
MSE	0.03	0.60	0.19	3.7
Magellan / MAPS	0.09	1.8	0.56	11
TMT/WFOS-fiber pess.	0.01	0.25	0.08	1.55
TMT/WFOS-fiber opt.	0.01	0.14	0.04	0.87

Updated from Newman et al. 2015, *Spectroscopic Needs for Imaging Dark Energy Experiments*

Conclusions

- Photo-*z* training is a key driver for the need for spectroscopy to complement LSST: greatly enhances LSST cosmology constraints (comparable to a second LSST!)
- Benefits from an LASSI for cosmology extend well beyond photo-z training
- Kavli report identified LASSI as a critical complement to LSST for studies of cosmology, stars, Milky Way structure, local dwarf galaxies, and galaxy evolution
- Photo-z training was only ~13% of the total time needed on a LASSI-like spectrograph, just from Kavli projects: high demand for this!
- Of course, a higher-multiplex BOA on a larger telescope would be even better...
- For more details, see presentations at https://kicp-workshops.uchicago.edu/FutureSurveys/presentations.php and https://indico.hep.anl.gov/indico/conferenceOtherViews.py?view=standard&confId=1035

Conclusions

LASSI

- **Many needs for wide - field, highly-multiplexed spectroscopy to exploit LSST...**

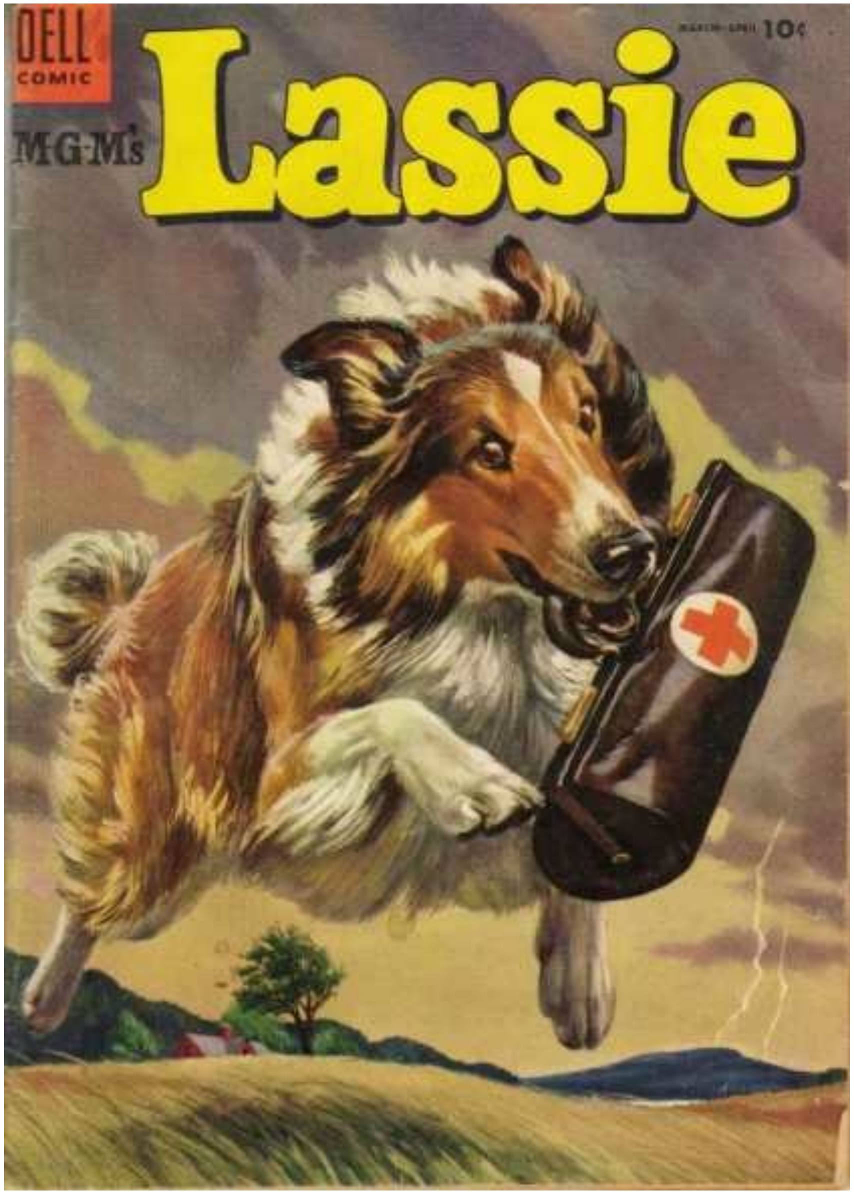
Conclusions

LASSI

- **Many needs for wide - field, highly-multiplexed spectroscopy to exploit LSST...**
- **LASSI can save the day!**

Conclusions

- Many needs for wide - field, highly-multiplexed spectroscopy to exploit LSST...
- LASSI can save the day!



Some other ideas for a name for this concept...

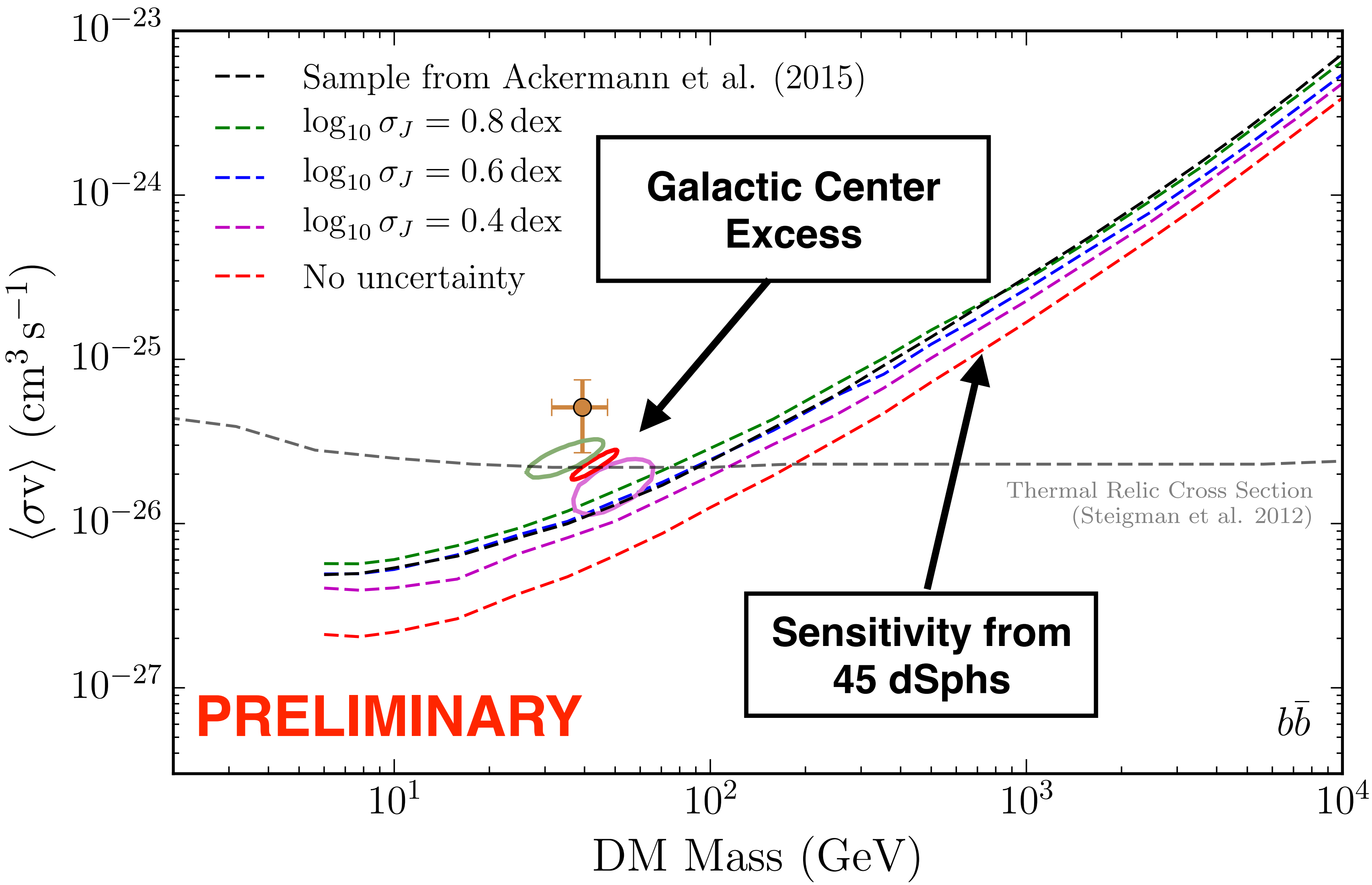
- **SOLS = Source Of LSST [or Large-Area] Spectroscopy**
- **SAULS = Survey Apparatus Used for Large Surveys (for those who like Berkeley delis...)**
- **LASS = Large Area Spectroscopic Source**
- **ILAS = Instrument for Large Area Spectroscopy**
- **ISLES = Instrument for Spectroscopic Large Etendue Surveys**

LASSI capabilities would depend on the budget available

LASSI

- ~$5-10M: Upgrade DESI in North, or upgrade and move to Blanco telescope in Chile
- ~$40M+: Implement DESpec on Blanco, keep DESI in North
- ~$75M+: New instrument for existing or funded 6-10m telescope OR join existing or planned facility (PFS, MSE, GMT/TMT if instruments meet requirements & enough fiber-years etc. are available…)
- ~$125-150M+: New Magellan clone + instrument, or instrument on upgraded Gemini (but Gemini-S will likely be largely dedicated to LSST transient follow-up...)
- ~$250M-500M+: New instrument on new 8-11m in the south. Probably would require international collaboration.
- DES and DESI were/will be ~10 yrs from conception to survey start; LSST, ~25 yrs. More ambitious projects will be on-sky later.

Improving indirect-detection dark matter searches with LASSI

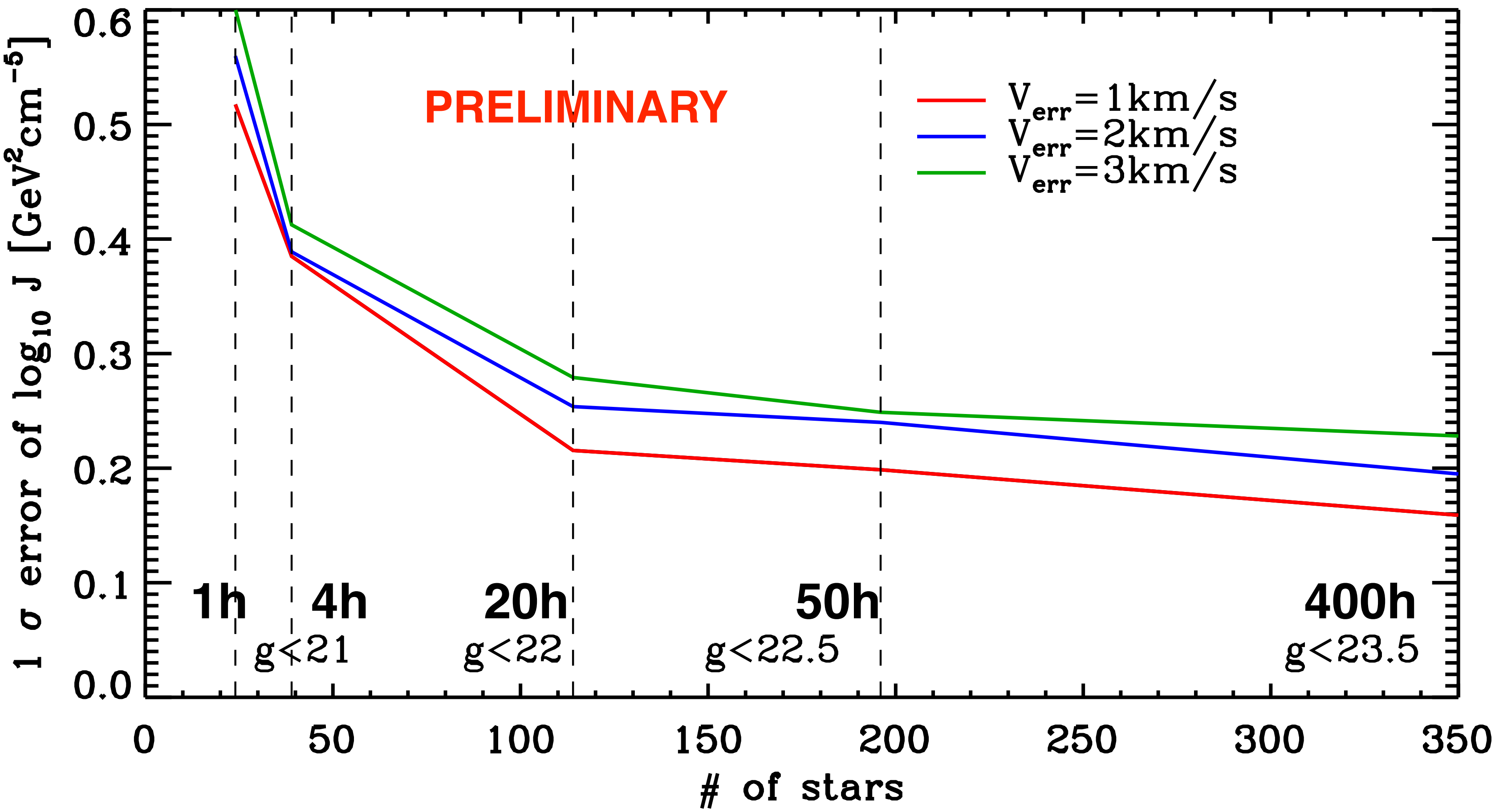


Wang, Drlica-Wagner, Li, & Strigari, in prep.

- **Better estimates of astrophysical J factors improve sensitivity of gamma-ray DM searches**

Improving indirect-detection dark matter searches with LASSI

LASSI



Magnitudes & exposure times are for Reticulum 2 & 6.5m telescope

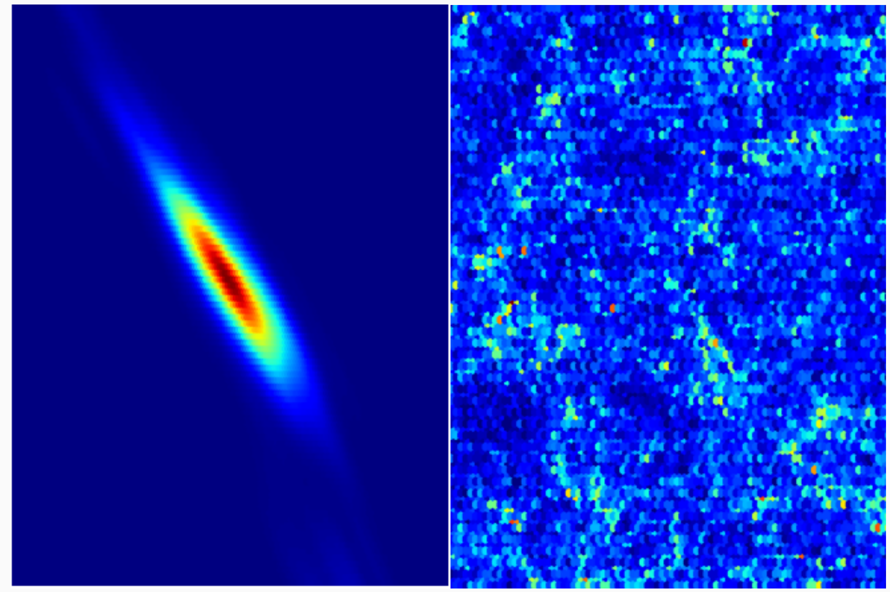
- Long exposures for many stars per dwarf are needed to reduce J-factor errors: an LASSI can help make this possible.

Wang, Drlica-Wagner, Li, & Strigari, in prep.

Gravitational wave cosmology with LASSI

LASSI

- **By mid-2020s, >2 gravitational wave sources per day will be detected, with localizations to ~90 Mpc along the line of sight and ~1 deg² on sky**
- **In combination with dense galaxy map, can identify over density most likely to host the GW event**
- **Enables cosmological constraints by comparing standard-siren distances to redshifts**
- **LASSI would be well-suited to producing such maps at low z**



Left: HLV spatial localization- $40° \times 30°$, red $\times 10$ more likely than light blue. Right: mock galaxy catalog, $M_i < -21, z \leq 0.2$. (Buzzard v1.1)

Annis, Soares-Santos, & Brout, in prep.

LASSI-like capabilities were also identified as critical for a variety of science cases in Kavli study

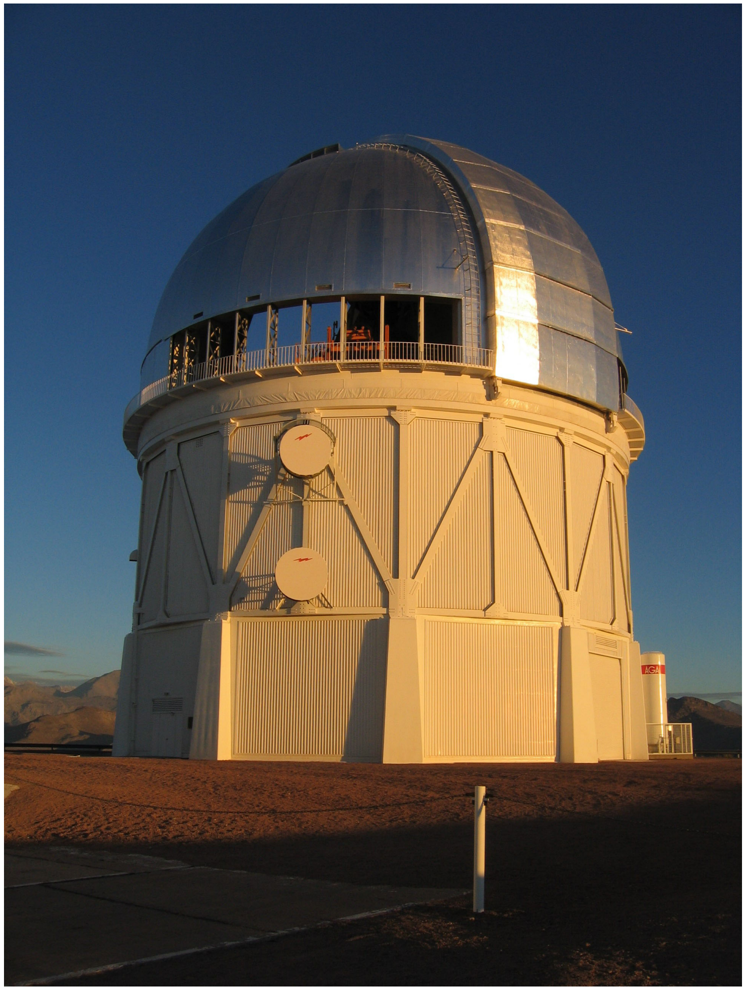
LASSI

- Galaxy evolution: survey of ~100,000 galaxies to *z*=2 to study connection between galaxy properties and environment in LSST deep drilling fields
  - Requires ~1 year of time on a Subaru/PFS-like spectrograph
- Milky Way structure: spectroscopy of ~1,000,000 stars to study the build-up of the Milky Way's stellar halo
  - Requires ~1.5 years of time on a Subaru/PFS-like spectrograph
- Local dwarf galaxies: studies of stellar properties and kinematics
  - Requires >2 years of time on a Subaru/PFS-like spectrograph
- Understanding stars: studies of stellar activity and rotation
  - Requires ~2 years of time on a Subaru/PFS-like spectrograph
- Can also contribute to transient science by targeting LSST transients on spare fibers during other surveys, and supernova cosmology by obtaining redshifts for past photometric SN hosts

Blanco telescope, Chile

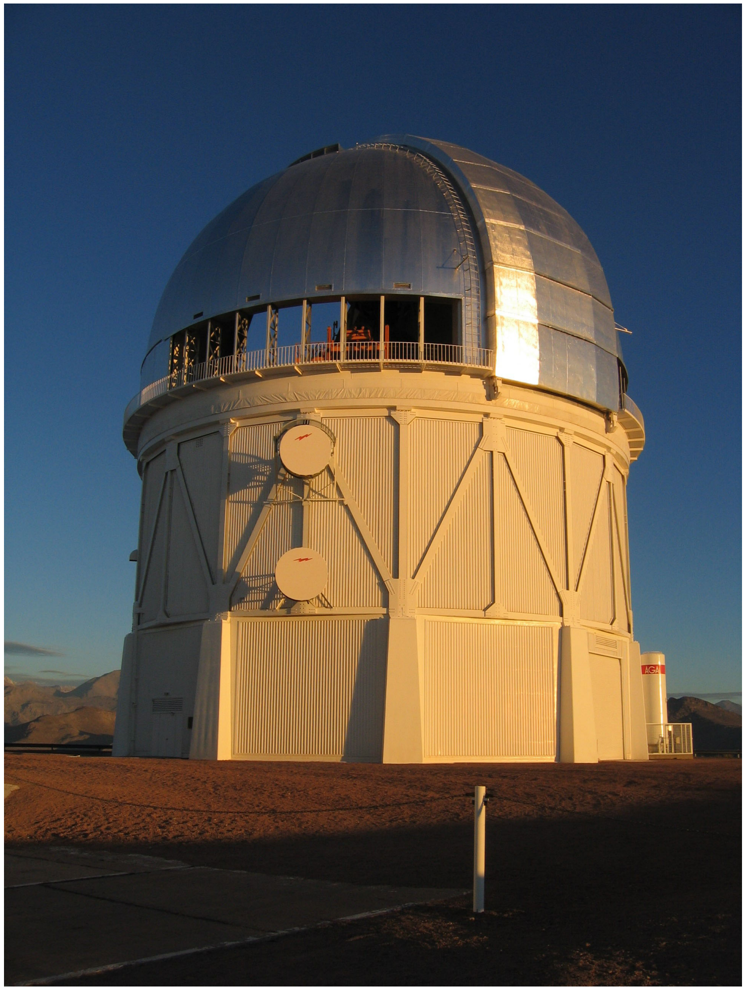
LASSI

- 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 multiplex, 3 deg^2 FOV with existing corrector, interchangeable w/ DECam:
  - ~40M$



Blanco telescope, Chile

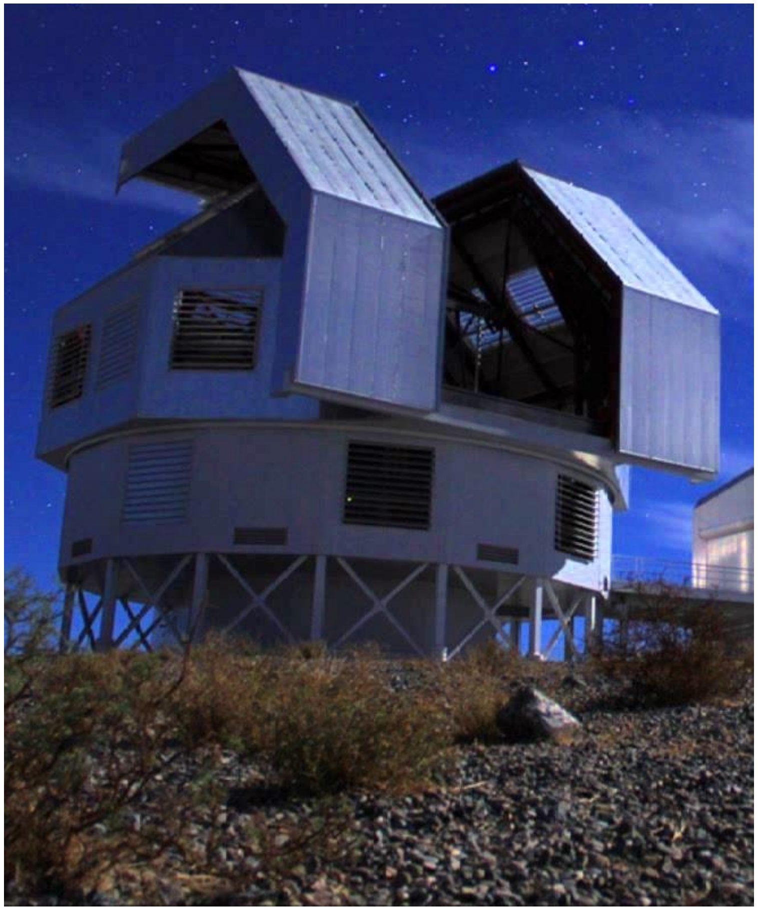
- **Pros:**
  - **Largest field of view w/ DESI move or clone**
  - **Moving DESI cheapest option for an LASSI; mid-2020s possible**
- **Cons:**
  - **Small aperture requires long survey times**
  - **Earthquake safety of DESI corrector?**
  - **Kavli/NOAO/LSST report will recommend DECam stay on Blanco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



Magellan telescope, Chile

LASSI

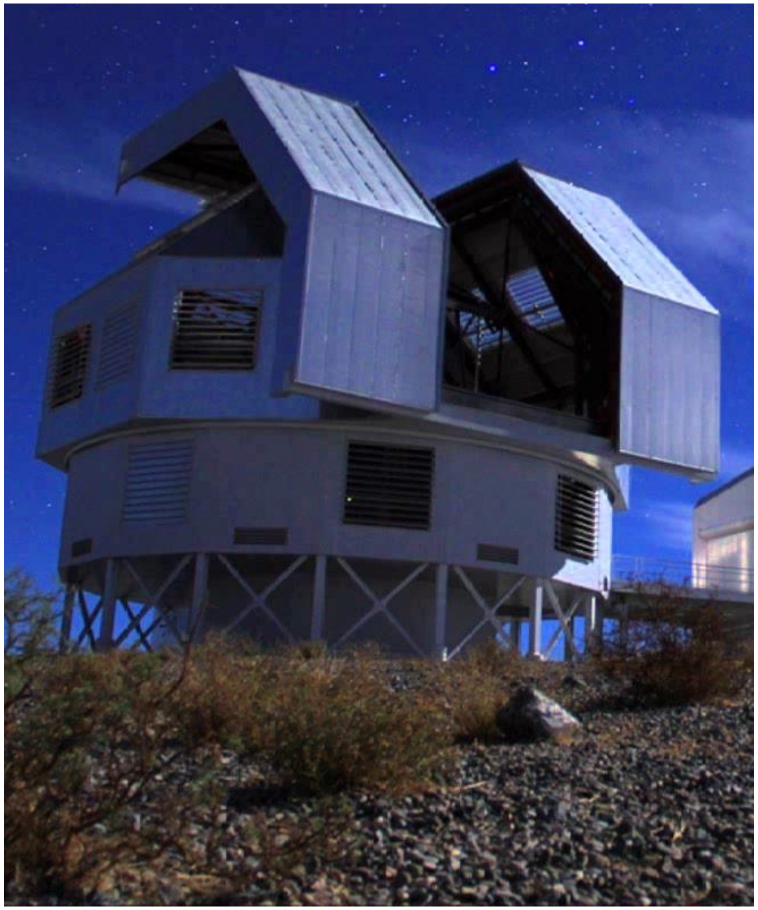
- Two 6.5 diameter telescopes
- Potential f/3 secondary would match DESI input beam and enable 1.5-2 deg diameter field of view with 3000-6000 positioners
- New secondary would cost ~$few M million, plus ~$75M+(?) for instrument
- Magellan institutions with majority of time interested in partnership: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



Magellan telescope, Chile

LASSI

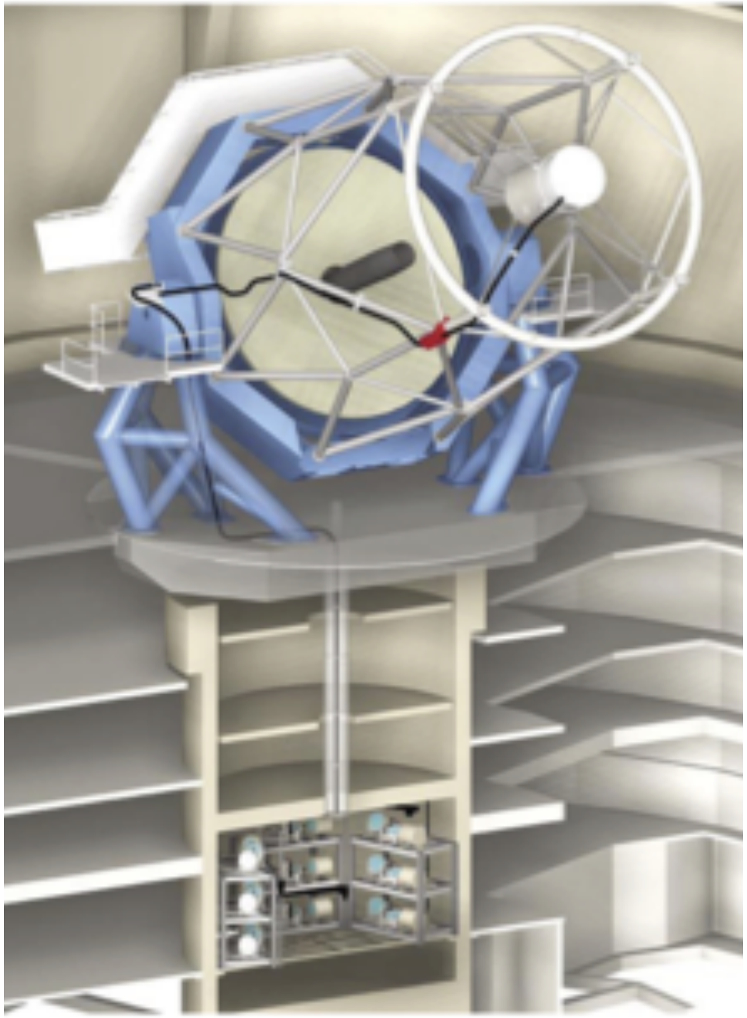
- Pros:
  - Larger collecting area
  - Existing telescope makes earlier schedule possible: mid-2020s?
- Cons:
  - Would prefer even larger aperture, >8m (Kavli/NOAO/LSST)
  - If use an existing Magellan telescope, must navigate politics of Magellan institutions, time access likely limited.
- Build a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



Gemini telescope, Chile

LASSI

- 8m telescope, US(NSF)-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 in wrong hemisphere.



Mayall Telescope, Arizona

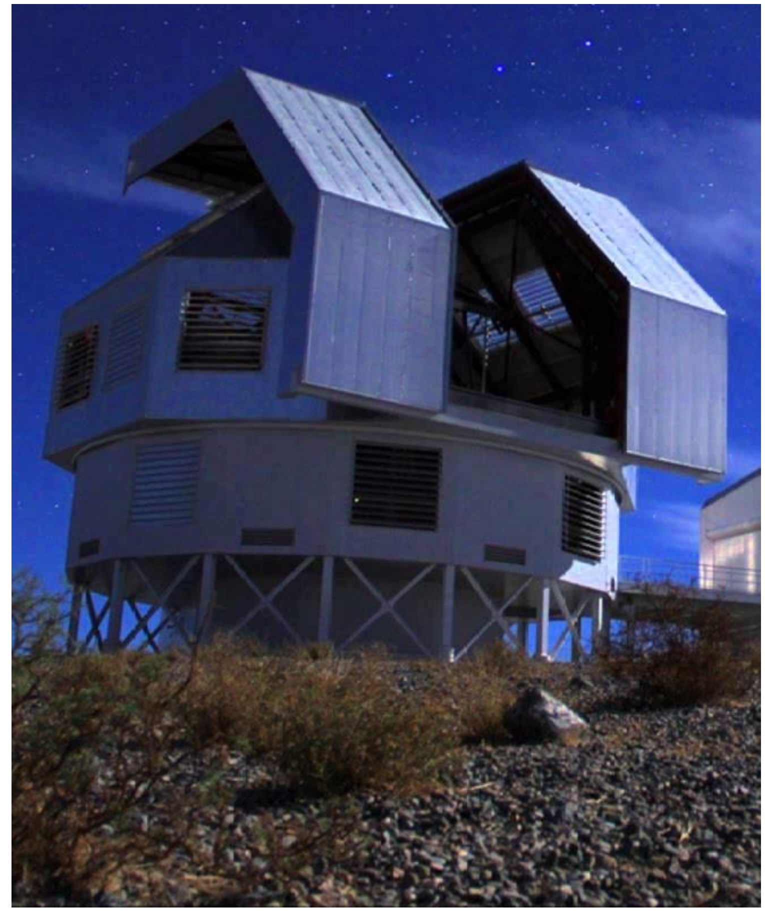
LASSI

- 4m diameter
- Latitude 32N
- Could use (possibly upgraded) DESI instrument from mid-2020s
- Pros:
  - Enables LASSI science without new instrument
- Cons:
  - Northernmost option, can access <<½ of LSST area
  - Very large amounts of time required to do LASSI program on 4m
  - Gets worse at the higher airmasses required to reach into LSST footprint from Kitt Peak

Telescopio San Pedro Mártir, Mexico

LASSI

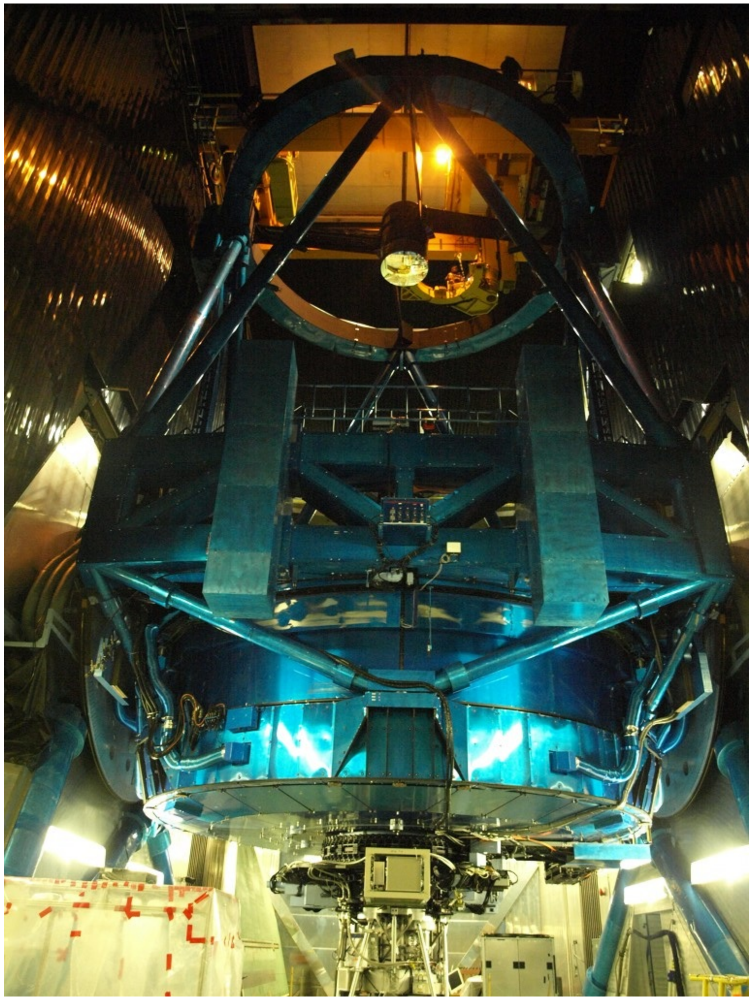
- Magellan clone, 6.5m diameter
- Latitude 30N
- $74M projected telescope budget, plus ~$75M+(?) for instrument
- Pros:
  - Simpler politics than Magellan, enthusiasm of partners to host an LASSI-like instrument
- Cons:
  - Northern hemisphere
  - Smaller than some other options
  - Not yet certain to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



Subaru (+PFS spectrograph), Hawai'i

LASSI

- 8m diameter, wide-field telescope
- PFS spectrograph, 2400 fibers over 1.3 deg, under construction, commissioning to be completed 2019
- Pros:
  - Enables LASSI 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

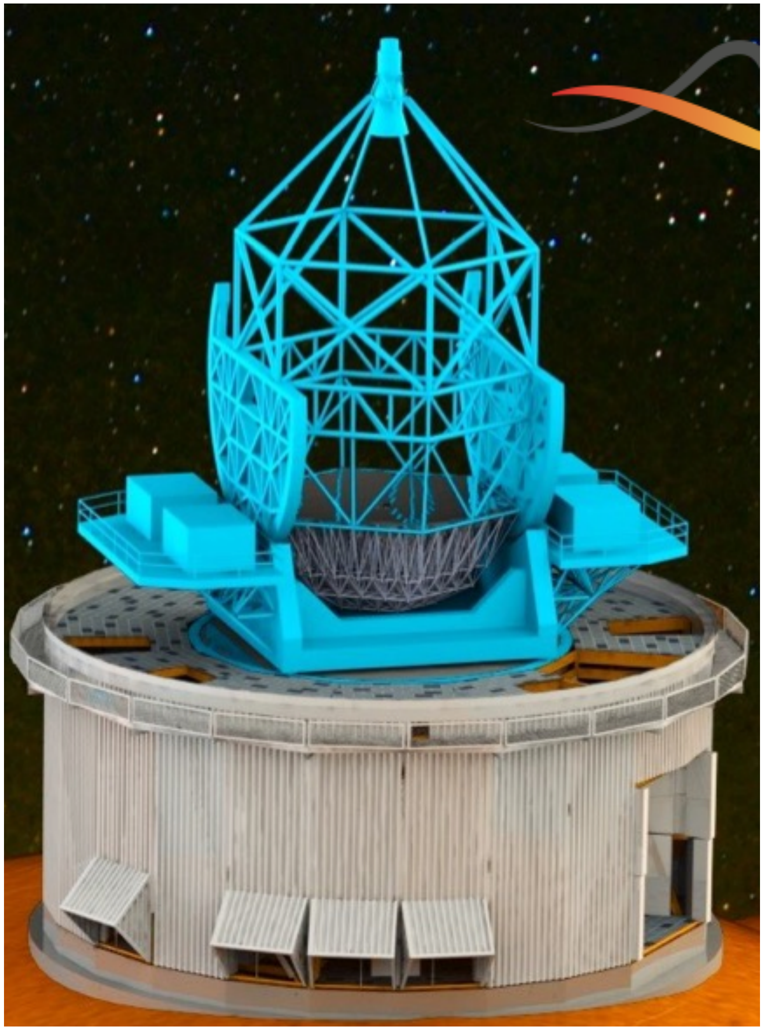


Keck (+FOBOS spectrograph), Hawai'i

- 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:
  - Northern hemisphere, but accesses majority of LSST footprint
  - Very limited multiplexing and FOV
  - Limited time available: largest Keck programs to date have been ~100 nights

Mauna Kea Spectroscopic Explorer, Hawai'i

- 11m diameter telescope with 1.5 degree field of view, replacing CFHT
- Designed solely for spectroscopy with an LASSI-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.

New 8m WF Telescope in Chile

- Strawman: 8m+ telescope with >1.5 degree field of view
- Designed *ab initio* for WF, highly multiplexed spectroscopy
- Pros:
  - Large aperture, wide field, very high survey speed, access, LSST overlap
- Cons:
  - Cost and timescale

Potential Partners

LASSI

- Astronomy community has identified LASSI-like instrument as a priority, but will want to enable non-cosmic science.
- DOE focus is on cosmology only
- LASSI would be relevant to NASA for WFIRST photo-z training
- 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 LASSI.

Three example fiducial surveys:

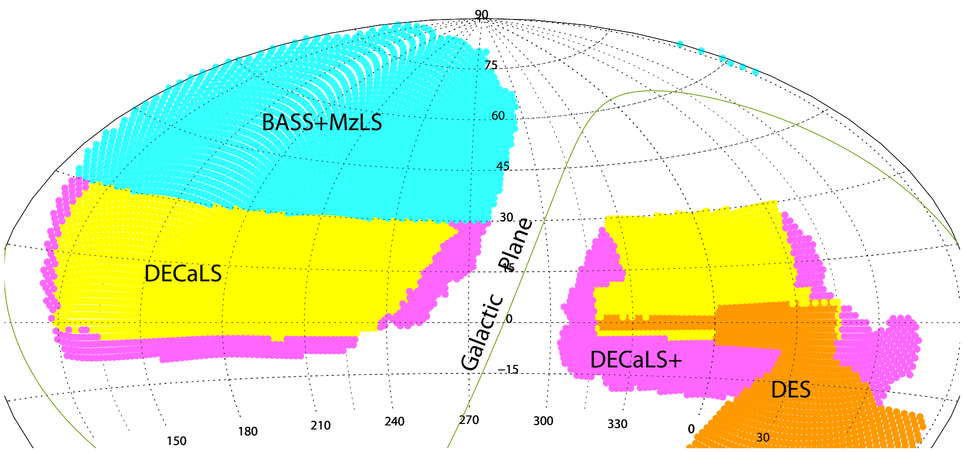
- **Wide**

  - 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)

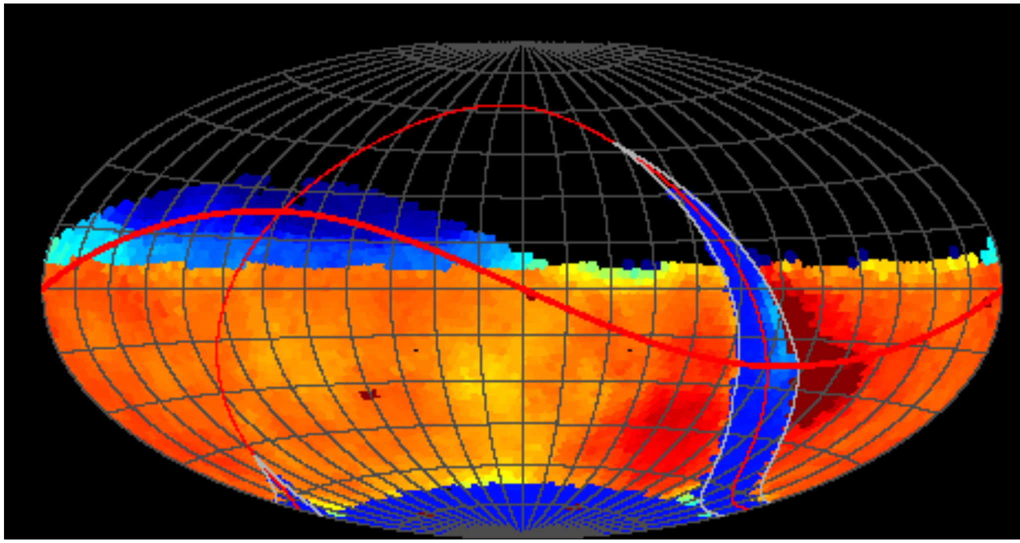
  - ~29M spectra total

  - 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

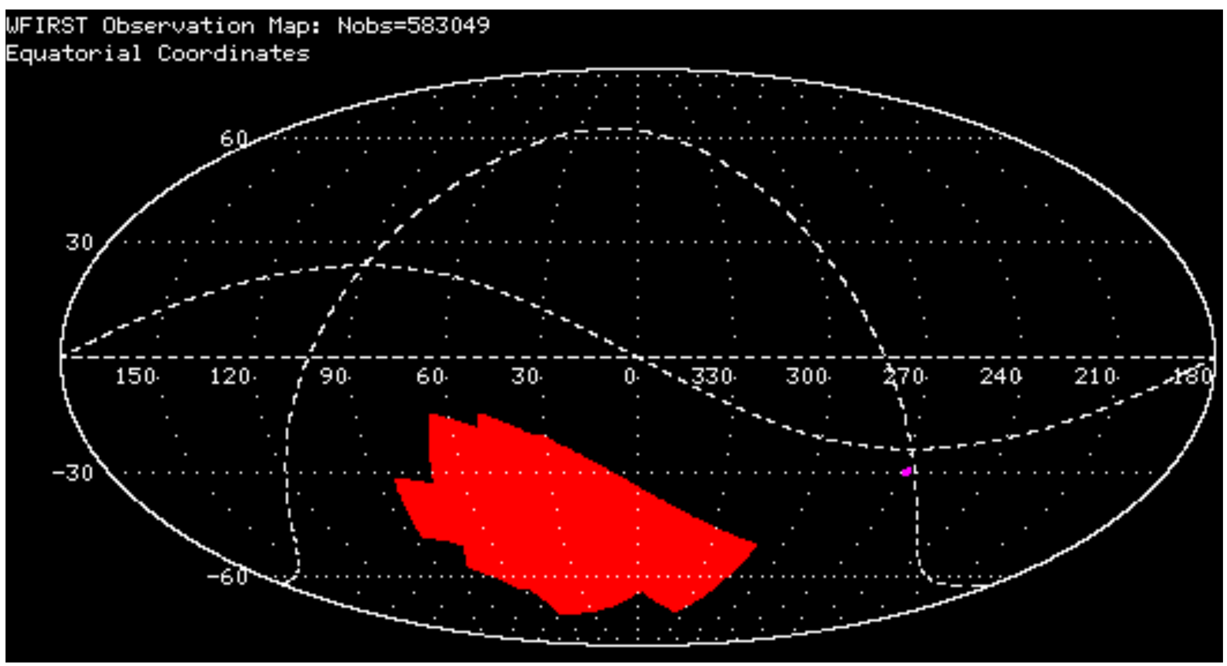


LSST coverage



Three example fiducial surveys:

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



Three example fiducial surveys:

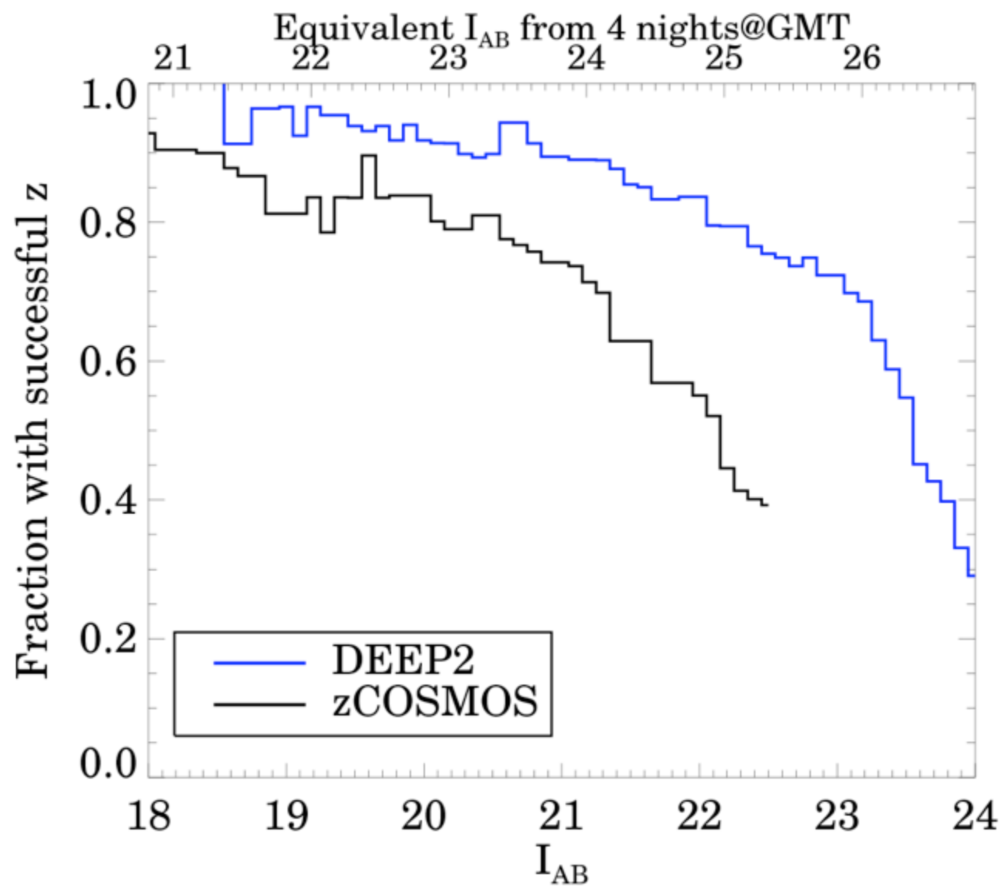
- **Deep**

  - >30,000 galaxies over 15 fields at least 20 arcmin diameter each down to LSST weak lensing limiting magnitude (*i*~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



Number of dark years required for each survey on each instrument/telescope

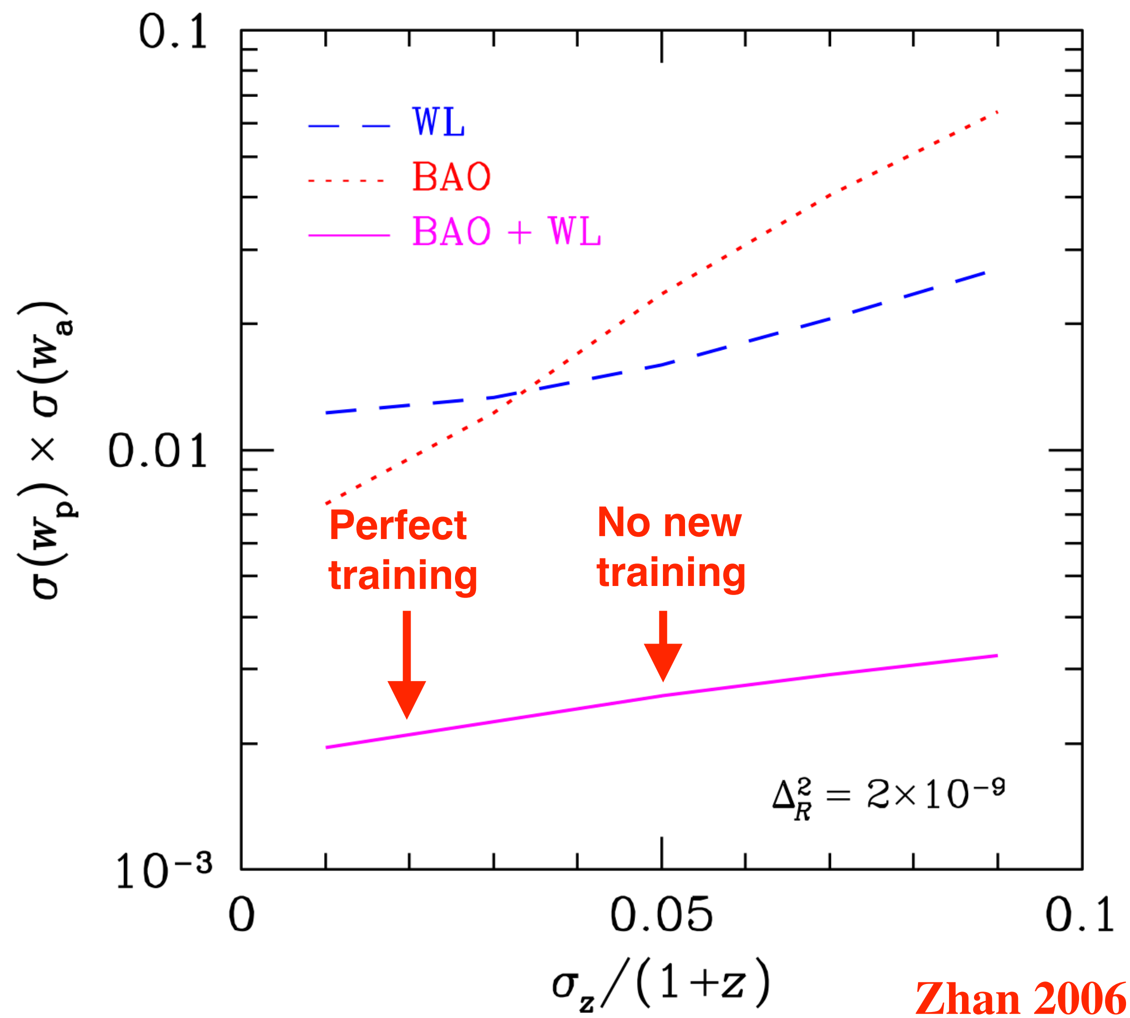
LASSI

	Wide	Intermediate	Deep
DESI-South	1.1 years	3.1 years	5.1 years
PFS-South	0.7	1.7	1.1
MSE-South	0.4	0.8	0.6
Magellan/MAPS	0.7	1.2	1.8

- 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.

Two spectroscopic needs for photo-z work: training and calibration

- **Better training of algorithms using objects with spectroscopic redshift measurements shrinks photo-z errors and improves DE constraints, esp. for BAO and clusters**



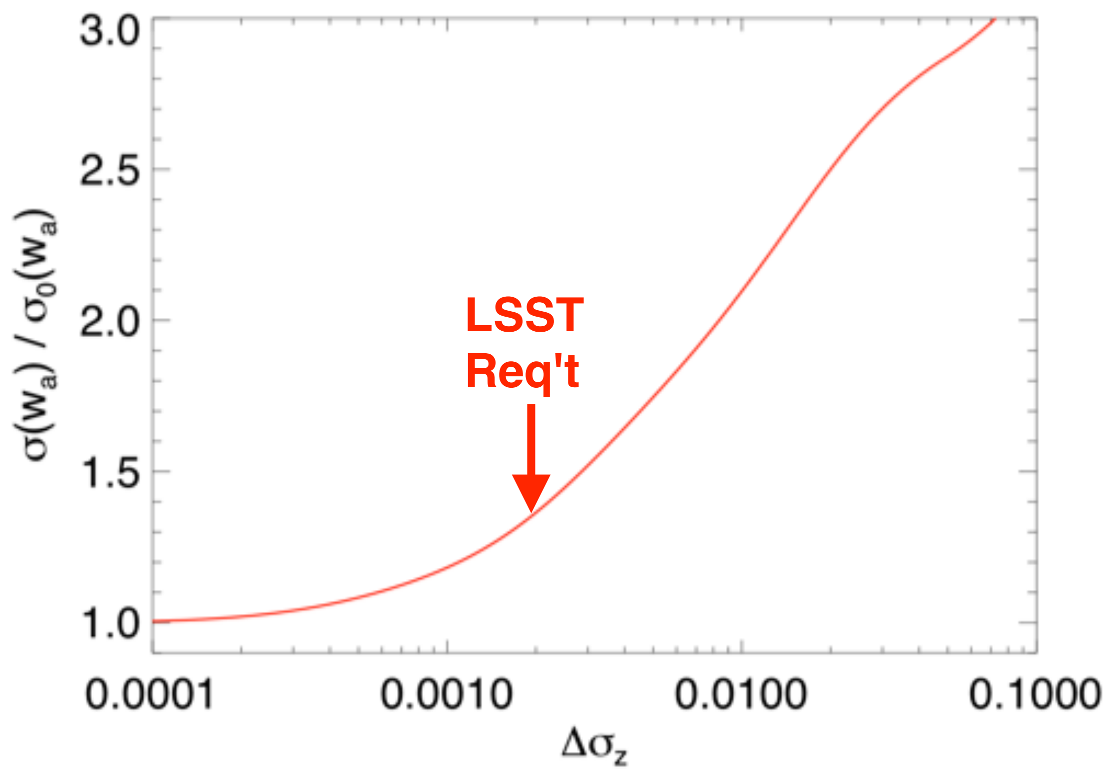
Zhan 2006

  - **Training datasets will contribute to calibration of photo-z's. ~Perfect training sets can solve calibration needs.**

Two spectroscopic needs for photo-z work: training and calibration

LASSI

- For weak lensing and supernovae, individual-object photo-*z*'s do not need high precision, but the calibration must be accurate - i.e., bias and errors need to be extremely well-understood



Newman et al. 2013

  - *uncertainty in* bias, $\sigma(\delta_z) = \sigma(<z_p - z_s>)$, and in scatter, $\sigma(\sigma_z) = \sigma(RMS(z_p - z_s))$, must both be <~0.002(1+*z*) for Stage IV surveys