Multi-object spectroscopy for LSST

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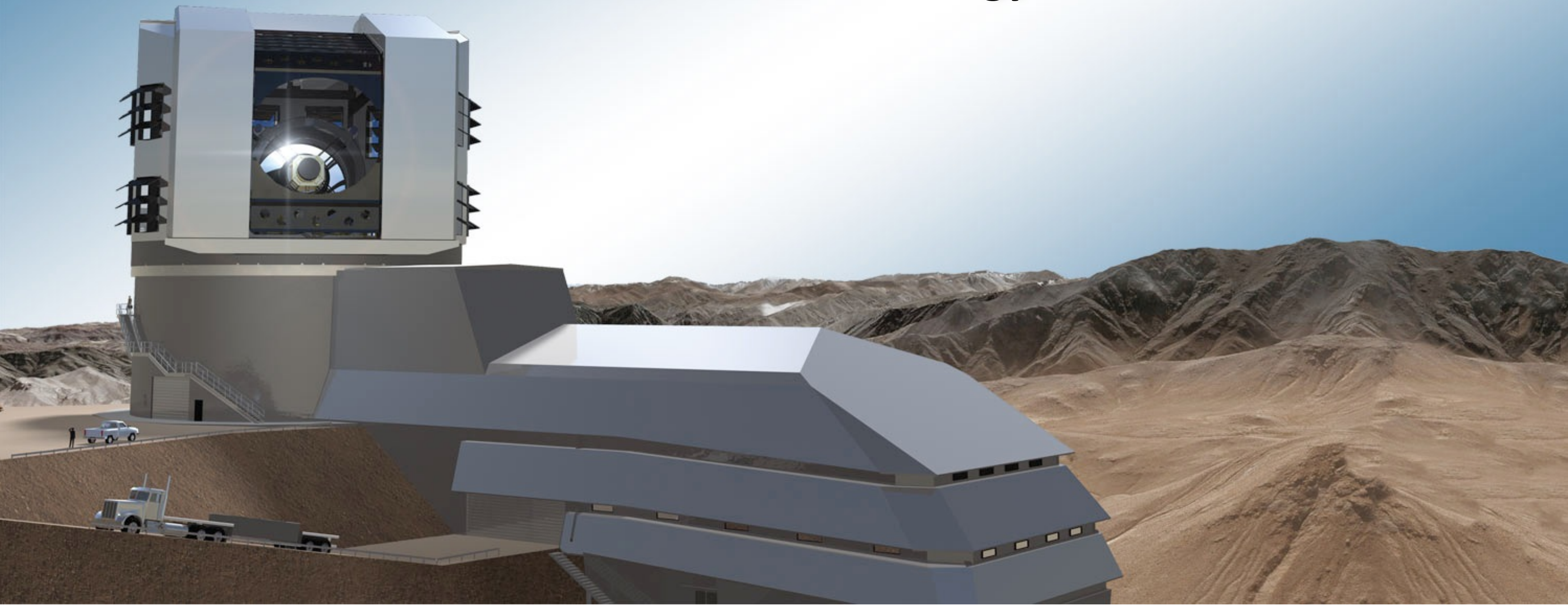
LSST Dark Energy Science Collaboration



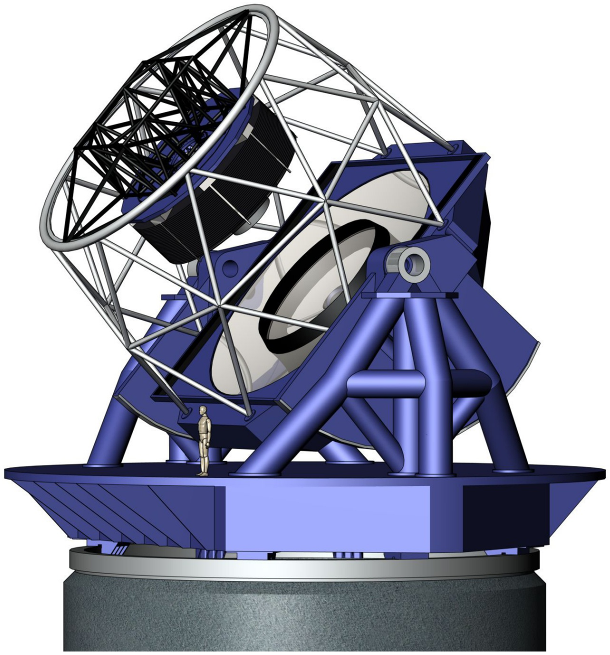
Outline

- A (very) brief introduction to LSST
- Overview of MOS applications:
  - What LSST can do for MOS surveys
  - What MOS surveys can do for LSST
- A few specific cases:
  - Photometric redshift training
  - Photometric redshift calibration
  - Supernova + transient hosts in deep drilling fields

- See Snowmass white papers on *Cross-Correlations* and *Spectroscopic Needs for Imaging Dark Energy Experiments* and NOAO white paper on *Spectroscopy in the Era of LSST* (http://

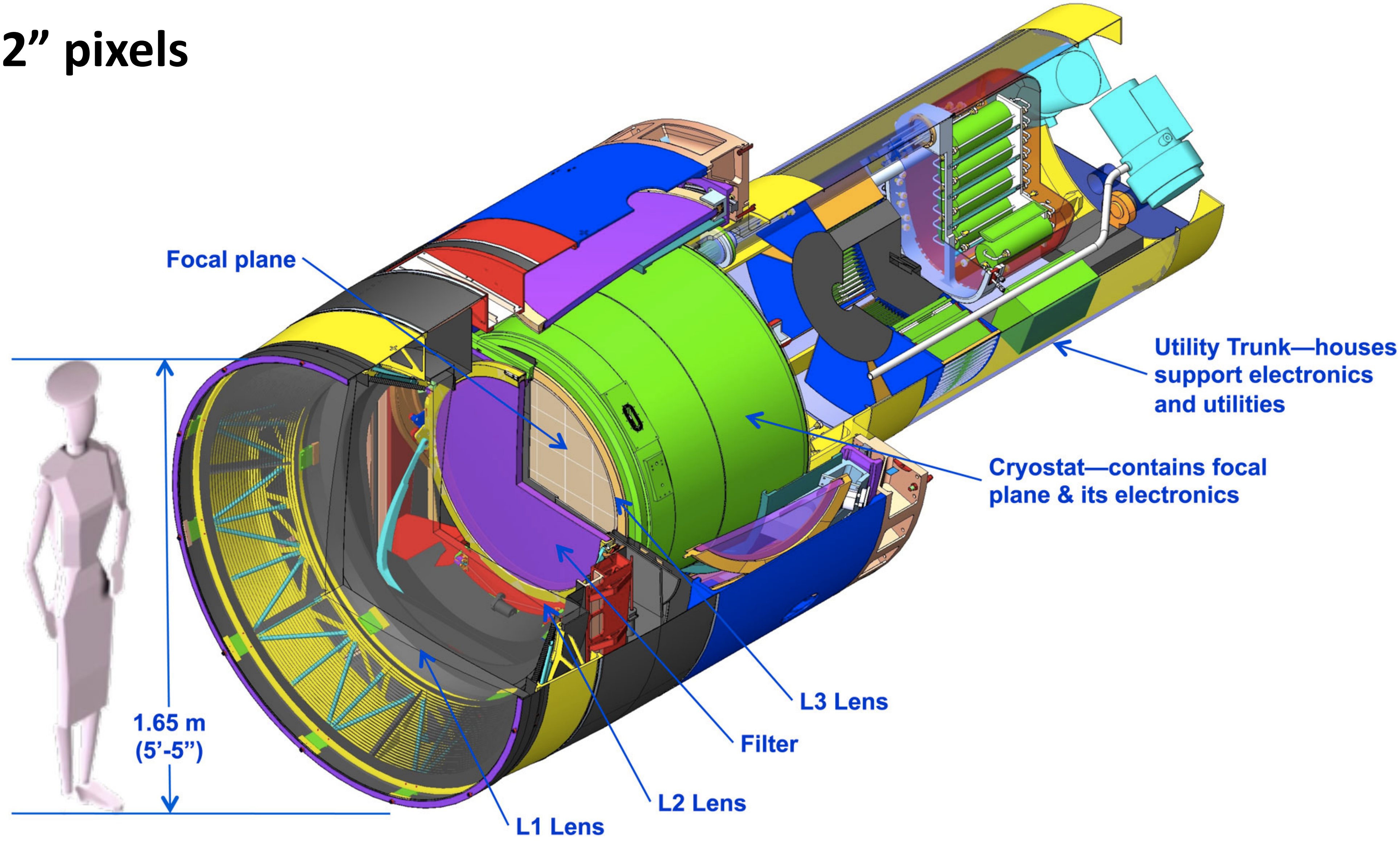
A brief review of LSST

- 8m diameter (6.7m effective), f/1.23 telescope, deep imaging in 6 filters (*ugrizy*)
- 2x15 sec images of 9.6 sq. deg. at a time
  - 900 visits per night, cover visible sky every 3 nights
- 10-year total survey: combine >800 visits per pointing for extremely deep imaging over 50% of sky
- Science enabled:
  - Cosmology (dark matter, dark energy, testing GR, etc.)
  - Mapping the Milky Way
  - Revealing the Transient Universe
  - Inventory of the Solar System



3.2 gigapixel camera. 9.6 deg^2 FoV

0.2” pixels

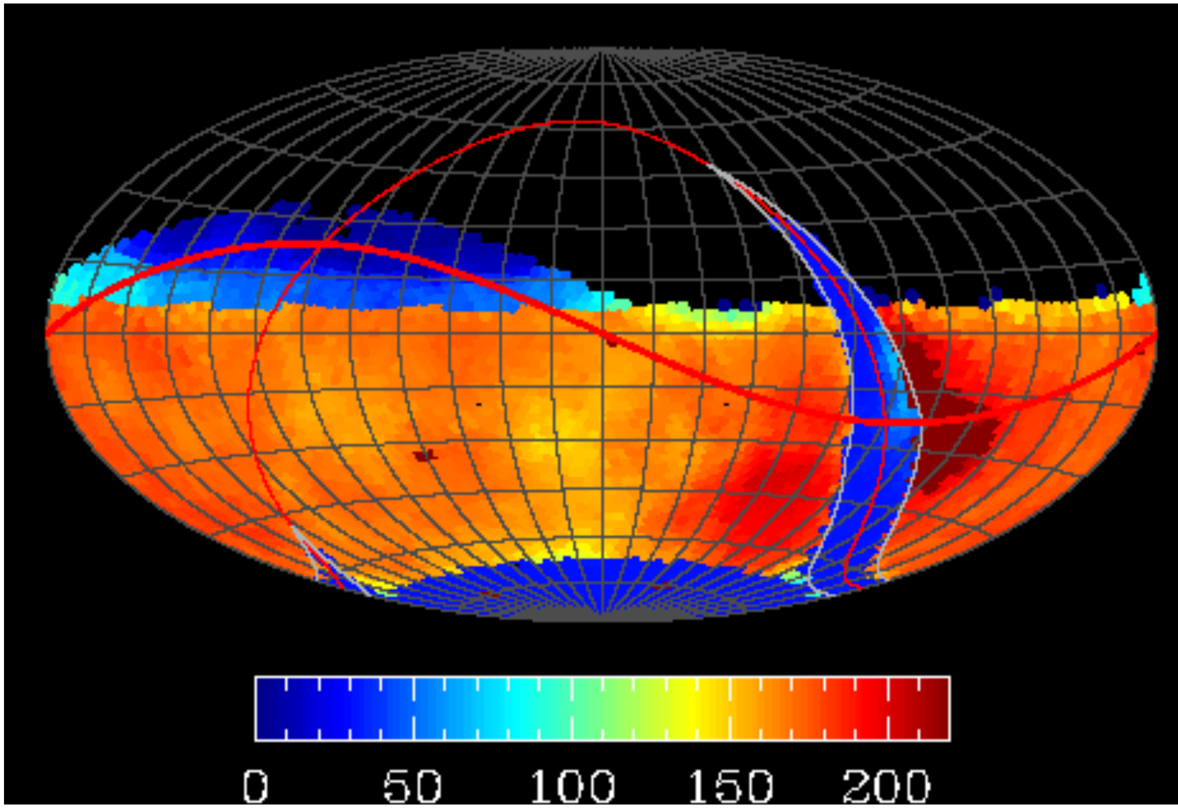


Camera ¾ Section

LSST: A dedicated 10-year survey

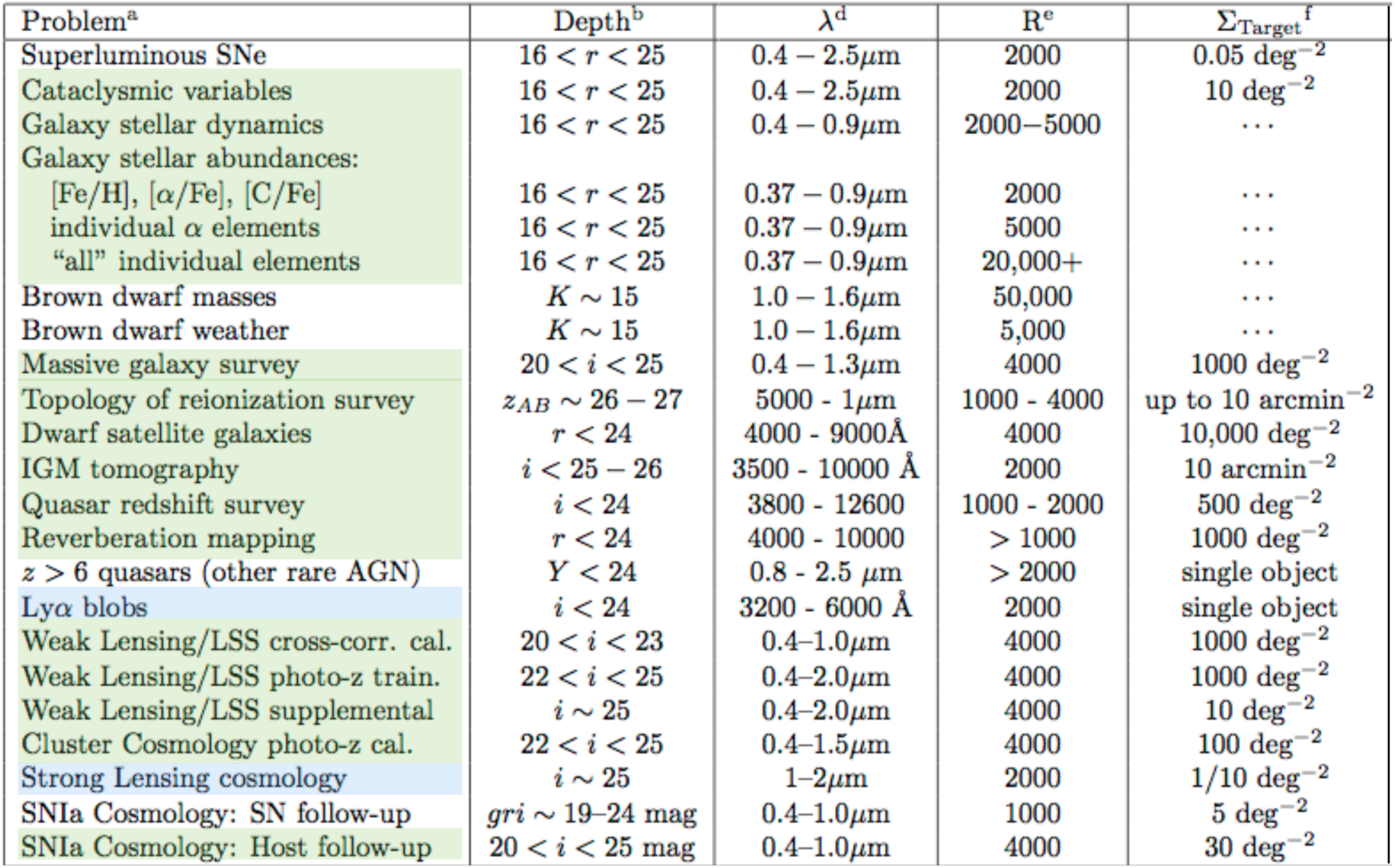
- 5σ point-source depth (1 visit): 23.9 (*u*), 25.0 (*g*), 24.7 (*r*), 24.0 (*i*), 23.3 (*z*), 22.1 (*y*)
- Depth at end of the survey: 26.3 (*u*), 27.5 (*g*), 27.7 (*r*), 27.0 (*i*), 26.2 (*z*), 24.9 (*y*)

- 40 trillion observations of 40 billion objects
- Status: construction start approved by NSF & DOE
- 'First stone' laid next month
- Survey start late 2022
- Provides base imaging for ~all subsequent Southern surveys!



Needs for (multi-object) spectroscopy

- **Matheson et al. white paper analyzed spectroscopic use cases:**

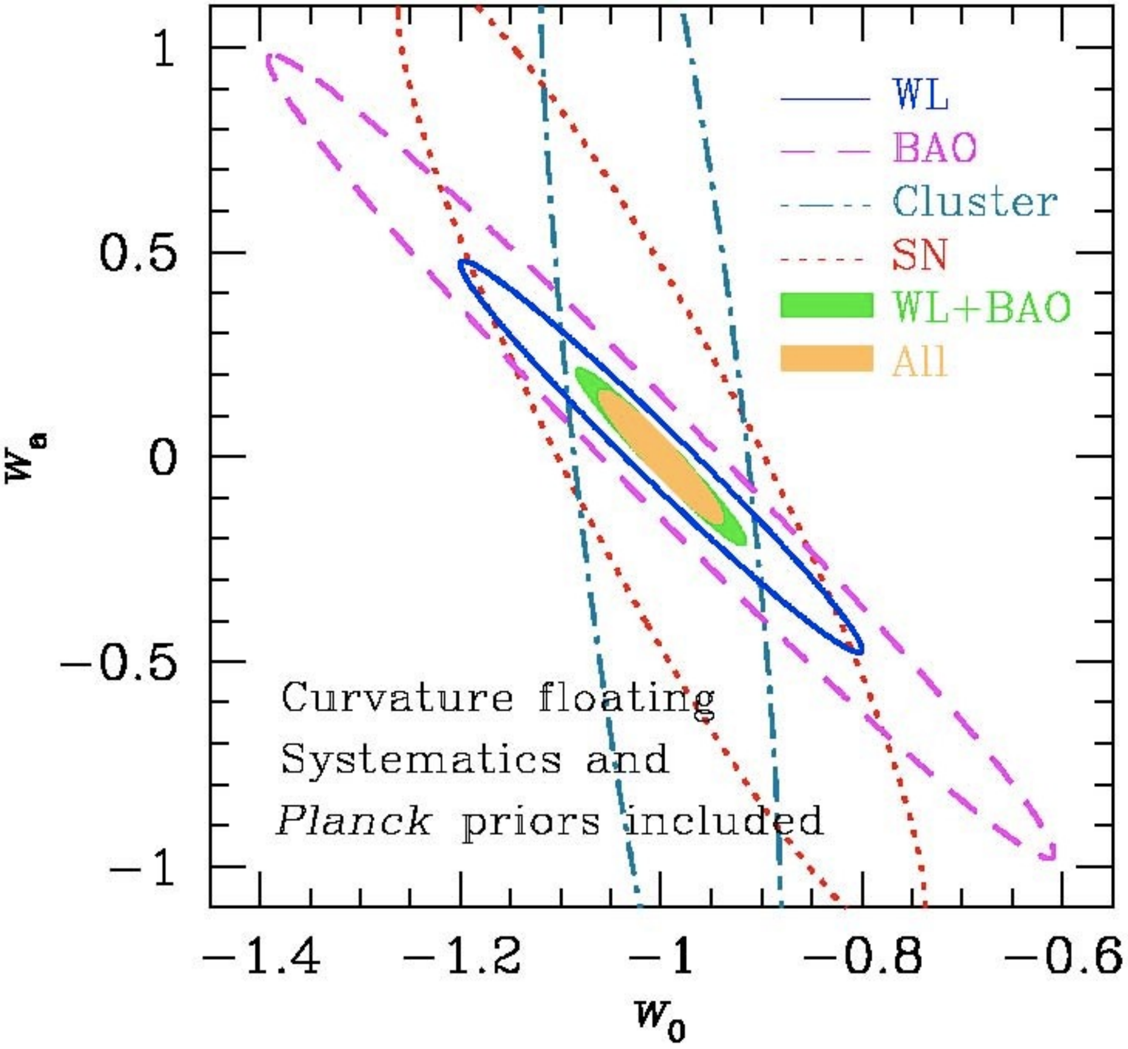


Problem[a]	Depth[b]	λ[d]	R[e]	Σ_{Target}[f]
Superluminous SNe	$16 < r < 25$	$0.4 - 2.5\mu m$	2000	$0.05\ \mathrm{deg}^{-2}$
Cataclysmic variables	$16 < r < 25$	$0.4 - 2.5\mu m$	2000	$10\ \mathrm{deg}^{-2}$
Galaxy stellar dynamics	$16 < r < 25$	$0.4 - 0.9\mu m$	2000–5000	…
Galaxy stellar abundances:				
[Fe/H], [α/Fe], [C/Fe]	$16 < r < 25$	$0.37 - 0.9\mu m$	2000	…
individual α elements	$16 < r < 25$	$0.37 - 0.9\mu m$	5000	…
"all" individual elements	$16 < r < 25$	$0.37 - 0.9\mu m$	20,000+	…
Brown dwarf masses	$K \sim 15$	$1.0 - 1.6\mu m$	50,000	…
Brown dwarf weather	$K \sim 15$	$1.0 - 1.6\mu m$	5,000	…
Massive galaxy survey	$20 < i < 25$	$0.4 - 1.3\mu m$	4000	$1000\ \mathrm{deg}^{-2}$
Topology of reionization survey	$z_{AB} \sim 26 - 27$	5000 - $1\mu m$	1000 - 4000	up to 10 arcmin^{-2}
Dwarf satellite galaxies	$r < 24$	4000 - 9000Å	4000	$10{,}000\ \mathrm{deg}^{-2}$
IGM tomography	$i < 25 - 26$	3500 - 10000 Å	2000	$10\ \mathrm{arcmin}^{-2}$
Quasar redshift survey	$i < 24$	3800 - 12600	1000 - 2000	$500\ \mathrm{deg}^{-2}$
Reverberation mapping	$r < 24$	4000 - 10000	> 1000	$1000\ \mathrm{deg}^{-2}$
$z > 6$ quasars (other rare AGN)	$Y < 24$	0.8 - 2.5 μm	> 2000	single object
Lyα blobs	$i < 24$	3200 - 6000 Å	2000	single object
Weak Lensing/LSS cross-corr. cal.	$20 < i < 23$	$0.4–1.0\mu m$	4000	$1000\ \mathrm{deg}^{-2}$
Weak Lensing/LSS photo-z train.	$22 < i < 25$	$0.4–2.0\mu m$	4000	$1000\ \mathrm{deg}^{-2}$
Weak Lensing/LSS supplemental	$i \sim 25$	$0.4–2.0\mu m$	4000	$10\ \mathrm{deg}^{-2}$
Cluster Cosmology photo-z cal.	$22 < i < 25$	$0.4–1.5\mu m$	4000	$100\ \mathrm{deg}^{-2}$
Strong Lensing cosmology	$i \sim 25$	$1–2\mu m$	2000	$1/10\ \mathrm{deg}^{-2}$
SNIa Cosmology: SN follow-up	$gri \sim 19–24$ mag	$0.4–1.0\mu m$	1000	$5\ \mathrm{deg}^{-2}$
SNIa Cosmology: Host follow-up	$20 < i < 25$ mag	$0.4–1.0\mu m$	4000	$30\ \mathrm{deg}^{-2}$

Green = MOS, **Blue = IFU**

LSST constrains dark energy in many ways… all will rely on redshift information

- 4 major probes of dark energy: weak lensing, baryon acoustic oscillations, cluster counts, & type Ia supernovae & (plus strong lensing, etc.)
- For all of these, we want to measure observables as a function of redshift
- With a 5000-fiber spectrograph on a 10m telescope, >50,000 years to measure redshifts for LSST "gold" weak lensing sample (4 billion galaxies)!
- By necessity, LSST will use photo-z's

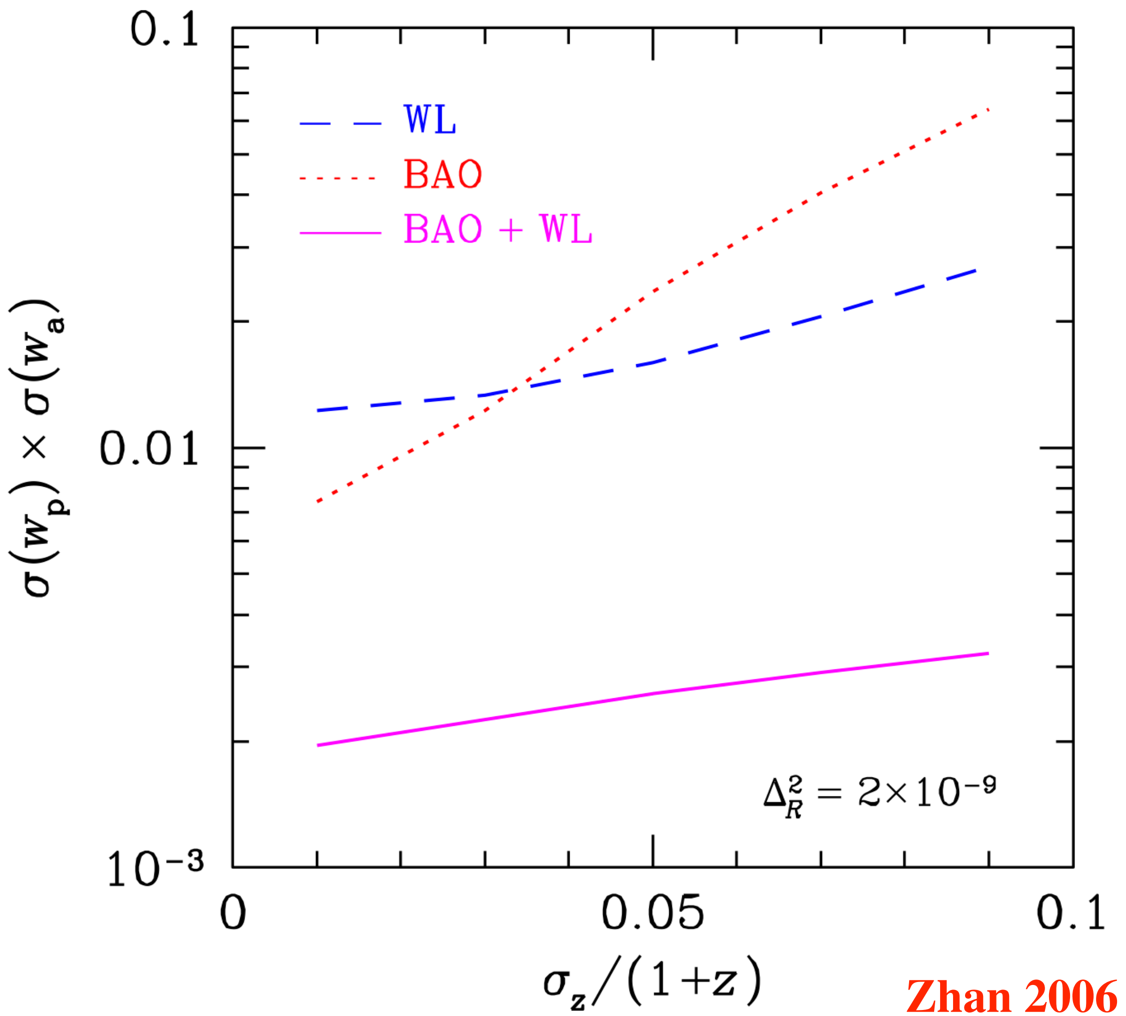


LSST Science Book

Two ways we need MOS for photo-z work: training and calibration

- **Training**: Reducing errors in photo-z's by improved templates or larger set of training data with z's

- Better-trained algorithms yield smaller RMS errors: improves DE constraints, esp. for BAO and clusters

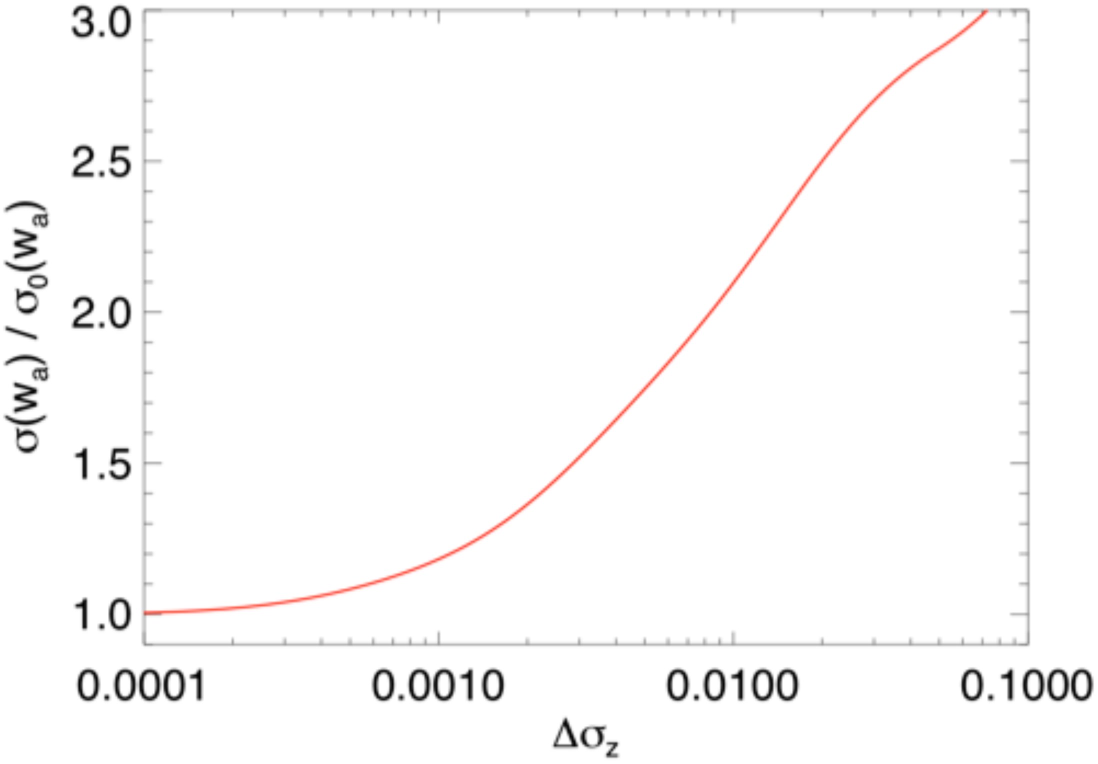


Zhan 2006

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

Two ways we need MOS for photo-z work: training and calibration

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



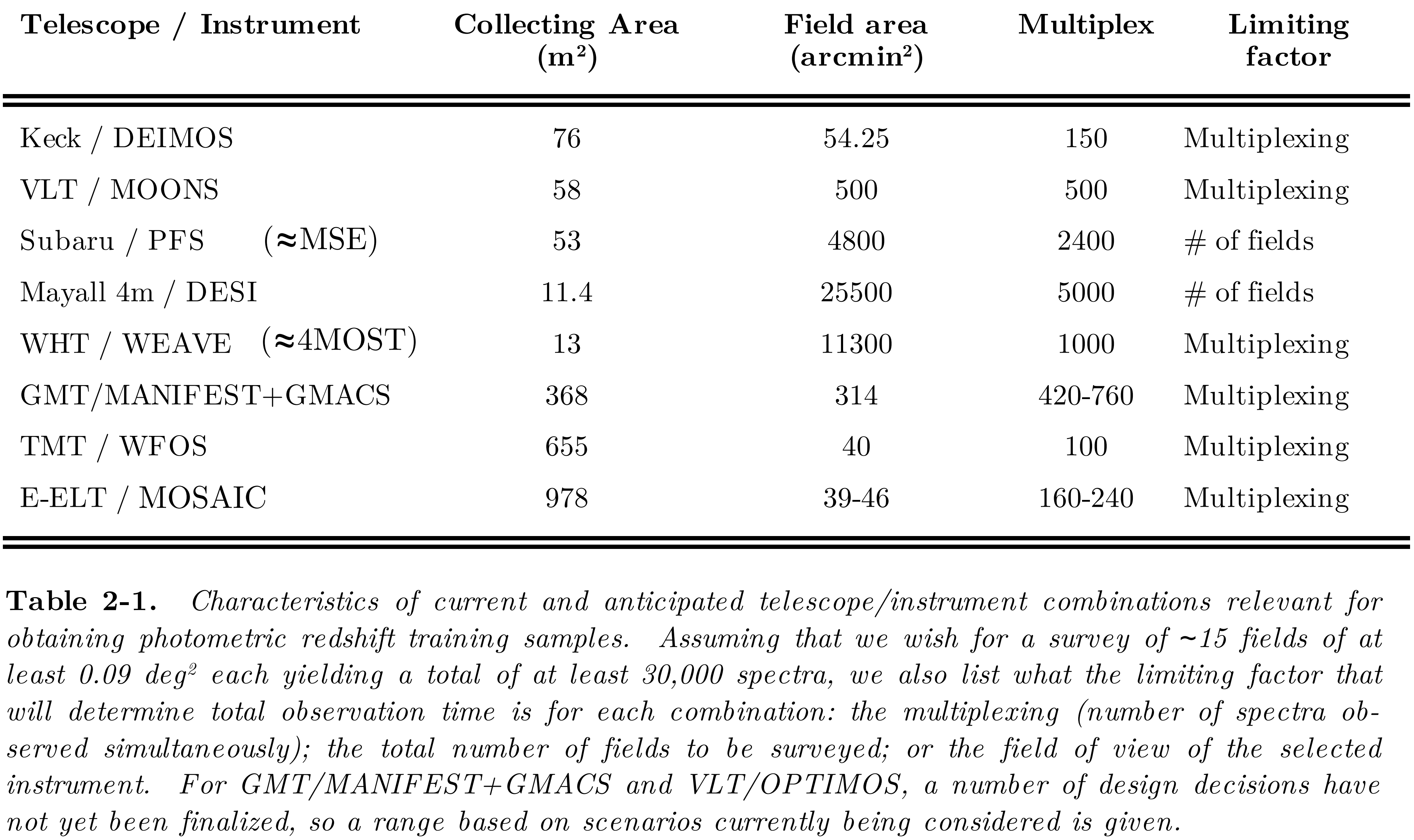
Newman et al. 2013

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

Minimum requirements for training spectroscopy

- Sensitive spectroscopy of >~30,000 faint objects (to *i*=25.3)
  - 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
- If all of these are achieved, AND highly-secure redshifts are measured for >99% of targets, the training set can also calibrate LSST at the needed accuracy.

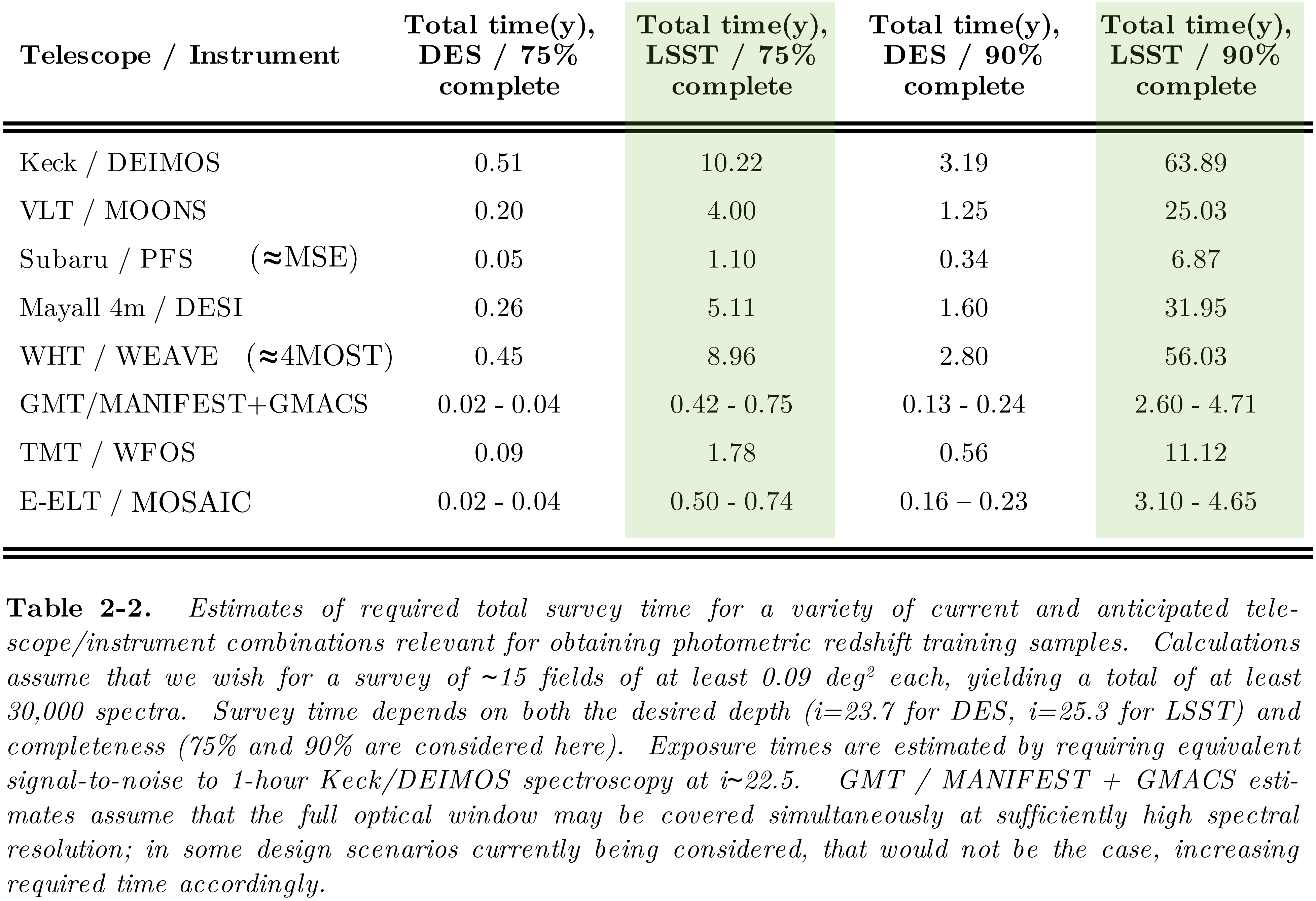
Summary of (some!) potential instruments



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 (≈MSE)	53	4800	2400	# of fields
Mayall 4m / DESI	11.4	25500	5000	# of fields
WHT / WEAVE (≈4MOST)	13	11300	1000	Multiplexing
GMT/MANIFEST+GMACS	368	314	420-760	Multiplexing
TMT / WFOS	655	40	100	Multiplexing
E-ELT / MOSAIC	978	39-46	160-240	Multiplexing

Table 2-1. *Characteristics of current and anticipated telescope/instrument combinations relevant for obtaining photometric redshift training samples. Assuming that we wish for a survey of ∼15 fields of at least 0.09* deg^2 *each yielding a total of at least 30,000 spectra, we also list what the limiting factor that will determine total observation time is for each combination: the multiplexing (number of spectra observed simultaneously); the total number of fields to be surveyed; or the field of view of the selected instrument. For GMT/MANIFEST+GMACS and VLT/OPTIMOS, a number of design decisions have not yet been finalized, so a range based on scenarios currently being considered is given.*

Time required for each instrument



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	10.22	3.19	63.89
VLT / MOONS	0.20	4.00	1.25	25.03
Subaru / PFS (≈MSE)	0.05	1.10	0.34	6.87
Mayall 4m / DESI	0.26	5.11	1.60	31.95
WHT / WEAVE (≈4MOST)	0.45	8.96	2.80	56.03
GMT/MANIFEST+GMACS	0.02 - 0.04	0.42 - 0.75	0.13 - 0.24	2.60 - 4.71
TMT / WFOS	0.09	1.78	0.56	11.12
E-ELT / MOSAIC	0.02 - 0.04	0.50 - 0.74	0.16 – 0.23	3.10 - 4.65

Table 2-2. *Estimates of required total survey time for a variety of current and anticipated telescope/instrument combinations relevant for obtaining photometric redshift training samples. Calculations assume that we wish for a survey of ~15 fields of at least 0.09 deg^2 each, yielding a total of at least 30,000 spectra. Survey time depends on both the desired depth (i=23.7 for DES, i=25.3 for LSST) and completeness (75% and 90% are considered here). Exposure times are estimated by requiring equivalent signal-to-noise to 1-hour Keck/DEIMOS spectroscopy at i~22.5. GMT / MANIFEST + GMACS estimates assume that the full optical window may be covered simultaneously at sufficiently high spectral resolution; in some design scenarios currently being considered, that would not be the case, increasing required time accordingly.*

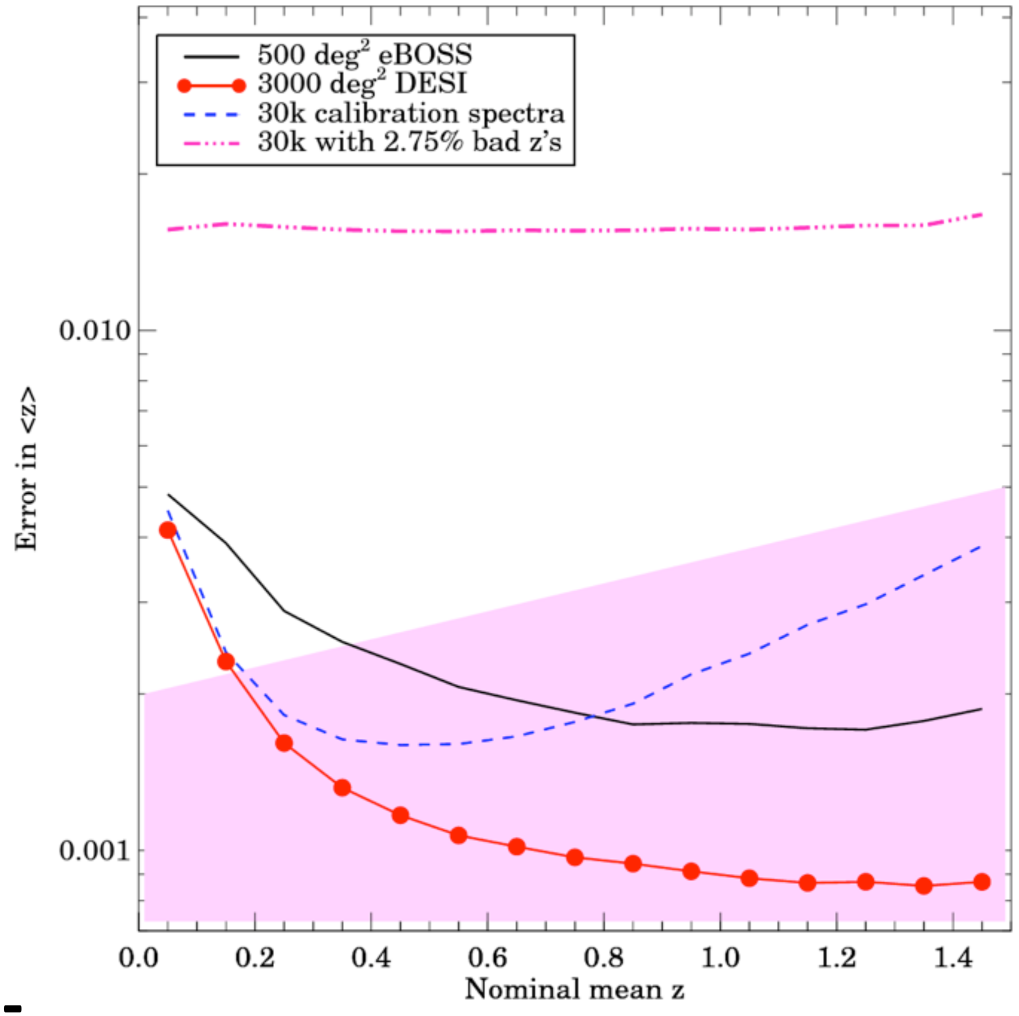
Wide-field MOS surveys enable photo-z calibration via cross-correlations

- Galaxies of all types cluster together: trace same dark matter distribution

- Enables reconstruction of *z* distributions via spectroscopic/ photometric cross-correlations (Newman 2008)

- For LSST calibration, require >100k objects over >100 deg^2, spanning full z range

- >500 degrees of overlap with DESI-like survey would meet LSST science requirements (>3000 sq deg of overlap expected).

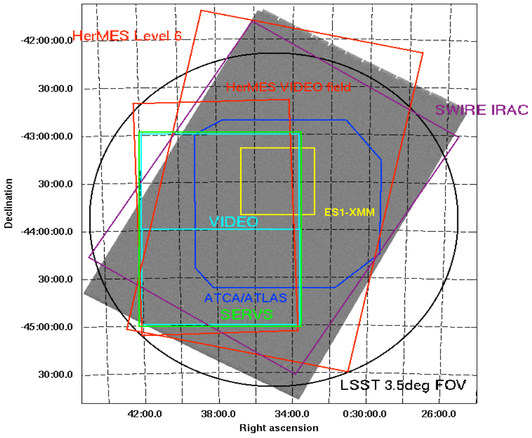


Snowmass White Paper: Spectroscopic Needs for Imaging DE Experiments

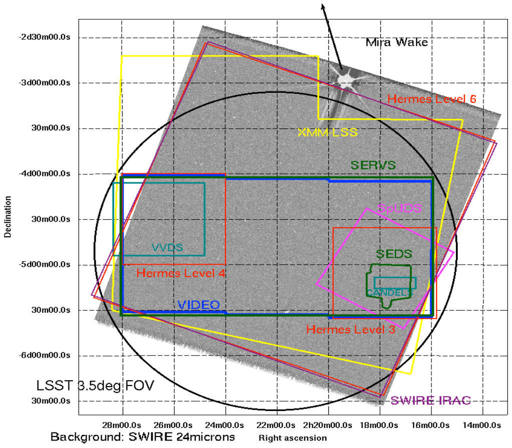
A key opportunity: the LSST Deep Drilling Fields

- 10% of LSST time will be spent on 20-40 "Deep Drilling" fields
- Approx. final co-added depths: *ugri*~28.5, *z*=28.0, *y*=27.0 (vs. *u*~26.3, *gri* ~27.5, *z*=26.2, *y*=24.9 over full area*)*
- Some possibilities: Jupiter/Neptune trojans, SMC, LMC, Milky Way pole+anticenter, an open cluster, a nearby galaxy cluster (Fornax?)
- Most would be blank extragalactic fields (4 selected already).
- Should be well-suited for MOS follow-up: will have high density of transients / hosts

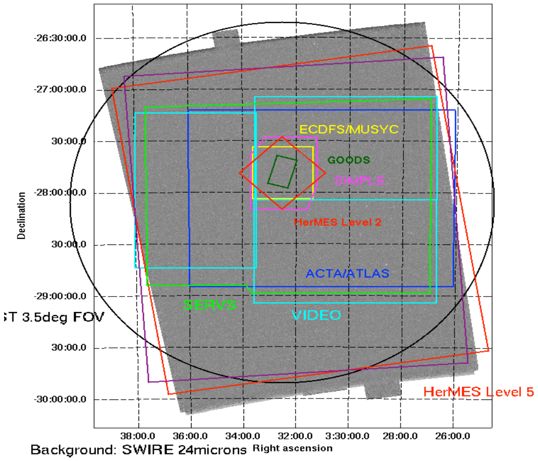
ELAIS-S1



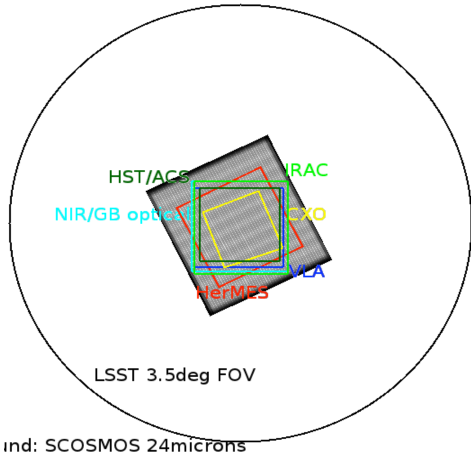
XMM-LSS



Extended CDF-S



COSMOS



Images: M. Lacy

Future MOSes can make currently infeasible projects 'easy'

- The most useful LSST supernovae will be those found in the deep drilling fields (best light curves)
- >30,000 SNe Ia over ~300 square degrees
- 8 hours on DESI should yield redshifts for ~70% of hosts to r~24 (assuming sky subtraction scales well)
  - ~60 nights total on DESI to get redshifts for most of the Ia's - allows typing and cosmological analyses
- This would take >600 nights with VLT/VIMOS, or >2000 nights with Keck/DEIMOS

Conclusions

What can LSST do for MOSes?

- **Should provide the base imaging for many future MOS surveys, will identify many millions of interesting targets**

What can MOSes do for LSST?

- **LSST Galactic, transient, and dark energy studies ALL will benefit from MOS follow-up/training/calibration**

- **Minimum LSST photo-z training survey, ~75% complete:**
  - **15 pointings, ~30k spectra to $i = 25.3$, ~0.5 years on a 20-40m telescope (can do galaxy evolution science simultaneously)**
- **Spectroscopic/photometric cross-correlations can calibrate photo-z's even using only spectra of bright galaxies & QSOs**

- **See Snowmass white papers on *Cross-Correlations* and *Spectroscopic Needs for Imaging Dark Energy Experiments* and NOAO white paper on *Spectroscopy in the Era of LSST* (http://arxiv.org/abs/1309.5384, 1309.5388, 1311.2496) for much more!**

Spectroscopic training set requirements

- Goal: make δ_z and $\sigma(\sigma_z)$ so small that systematics are subdominant
- Many estimates of training set requirements (Ma et al. 2006, Bernstein & Huterer 2009, Hearin et al. 2010, LSST Science Book, etc.)
- General consensus that roughly 20k-30k extremely faint galaxy spectra are required to characterize:
  - Typical z_{spec}-z_{phot} error distribution
  - Accurate catastrophic failure rates for all objects with $z_{phot} < 2.5$
  - Characterize all outlier islands in z_{spec}-z_{phot} plane via targeted campaign (core errors easier to determine)
- Those numbers of redshifts are achievable with planned telescopes & instruments, if multiplexing is high enough

What qualities do we desire in our training sets?

- **Sensitive spectroscopy of faint objects (to i=23.7 for DES, 25.3 for LSST)**

  - Need a combination of large aperture and long exposure times; >20 Keck-nights (=4 GMT-nights) equivalent per target, minimum

- **High multiplexing**

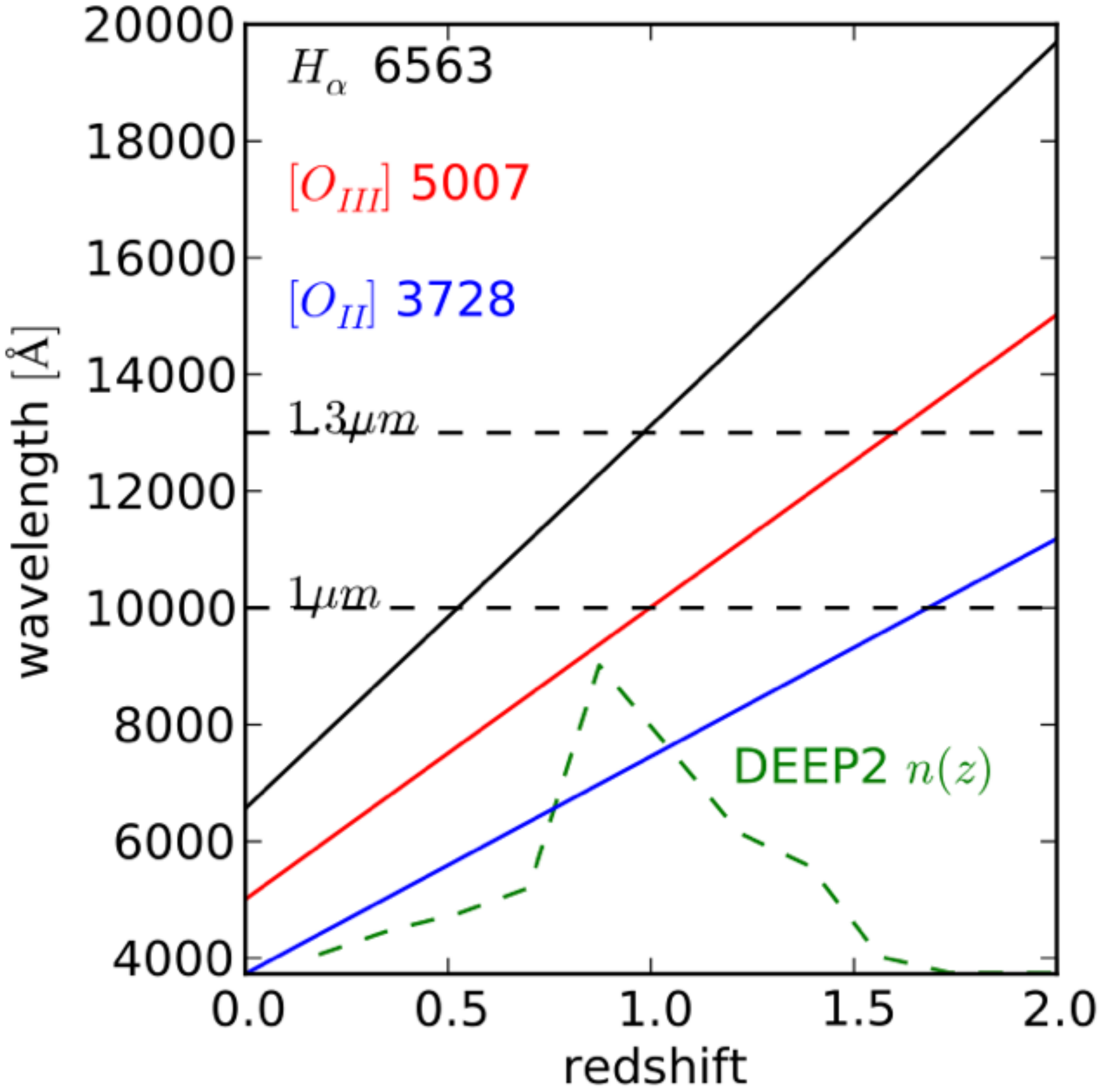
  - Obtaining large numbers of spectra is infeasible without it

What qualities do we desire in our training sets?

- **Coverage of full ground-based window**

  - Ideally, from below 4000 Å to ~1.5μm

    - Require multiple features for secure redshift

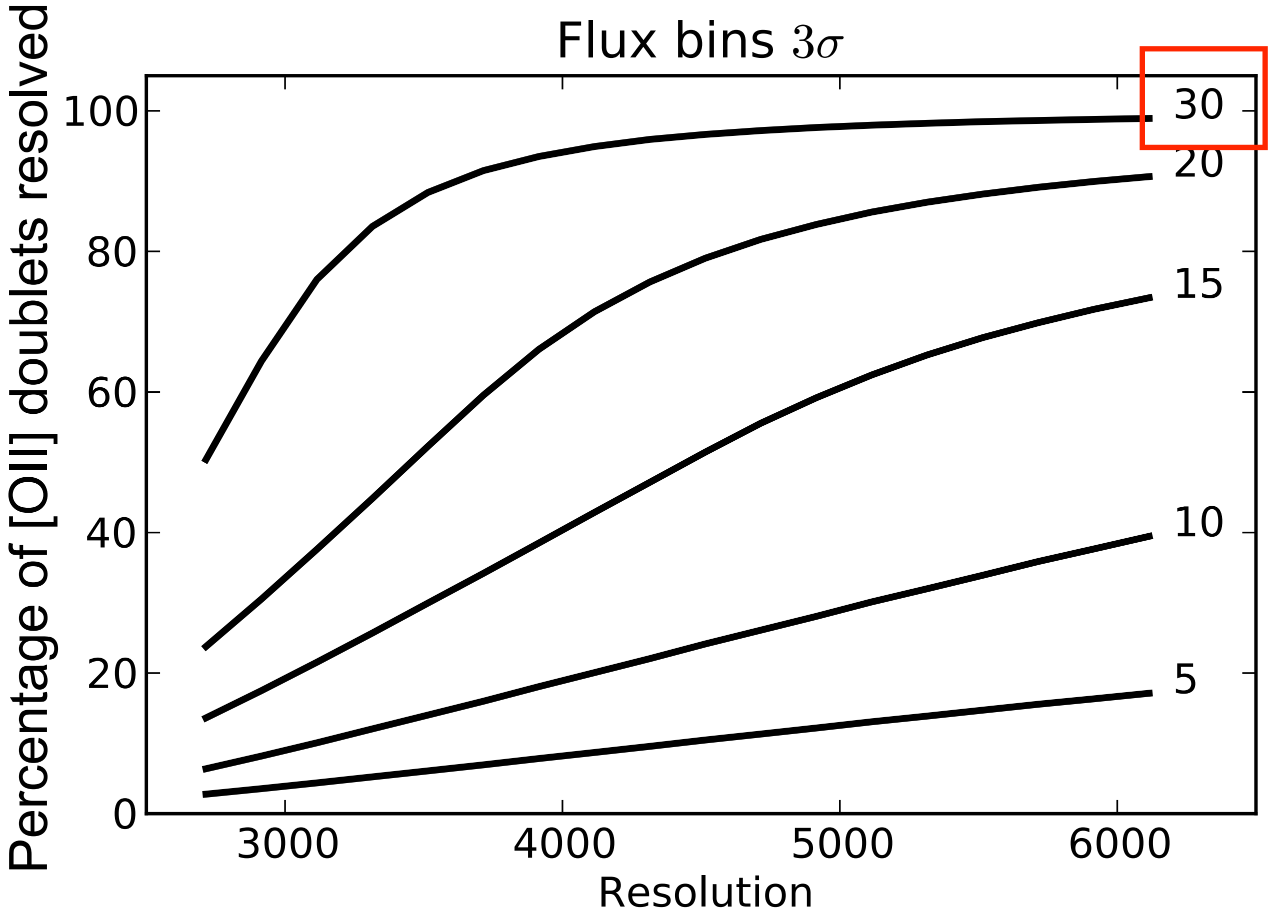


Comparat et al. 2013, submitted

What qualities do we desire in our training sets?

- **Significant resolution (R>~4000) at red end**

  - Allows redshifts from [OII] 3727 Å doublet alone, key at *z*>1



Comparat et al. 2013, submitted

What qualities do we desire in our training sets?

- **Field diameters > ~20 arcmin**

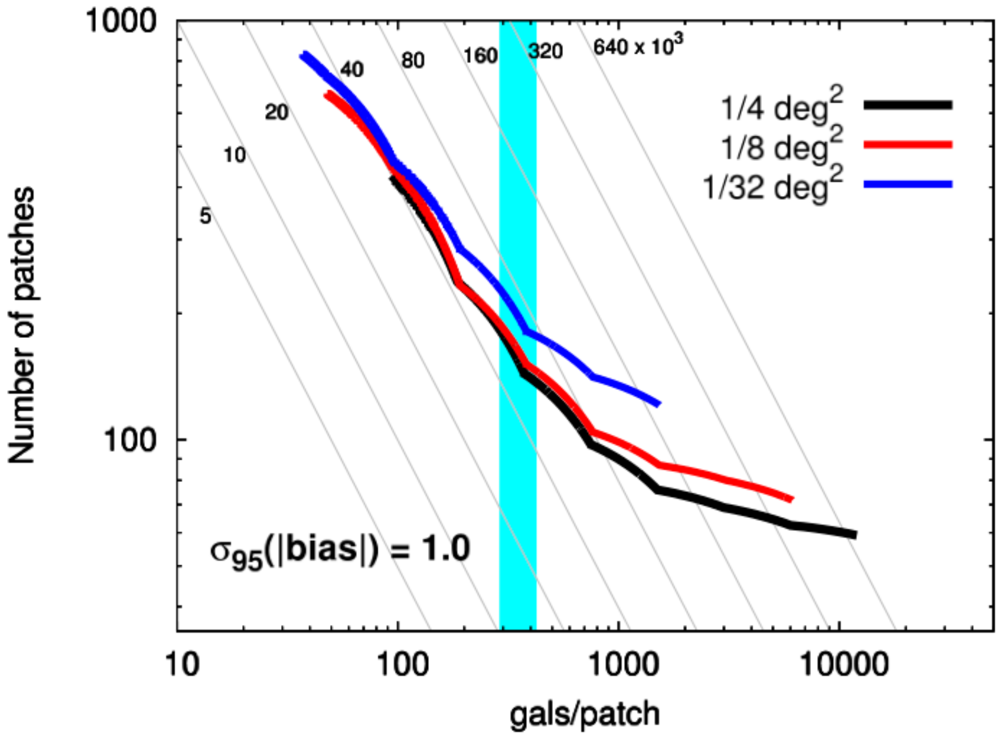
  - Need to span several correlation lengths for accurate clustering measurements (key for synergistic galaxy evolution science and for cross-correlation techniques)

  - $r_0 \sim 5\ h^{-1}$ Mpc comoving corresponds to ~7.5 arcmin at z=1, 13 arcmin at z=0.5

- **Many fields**

  - Minimizes impact of sample/ cosmic variance.

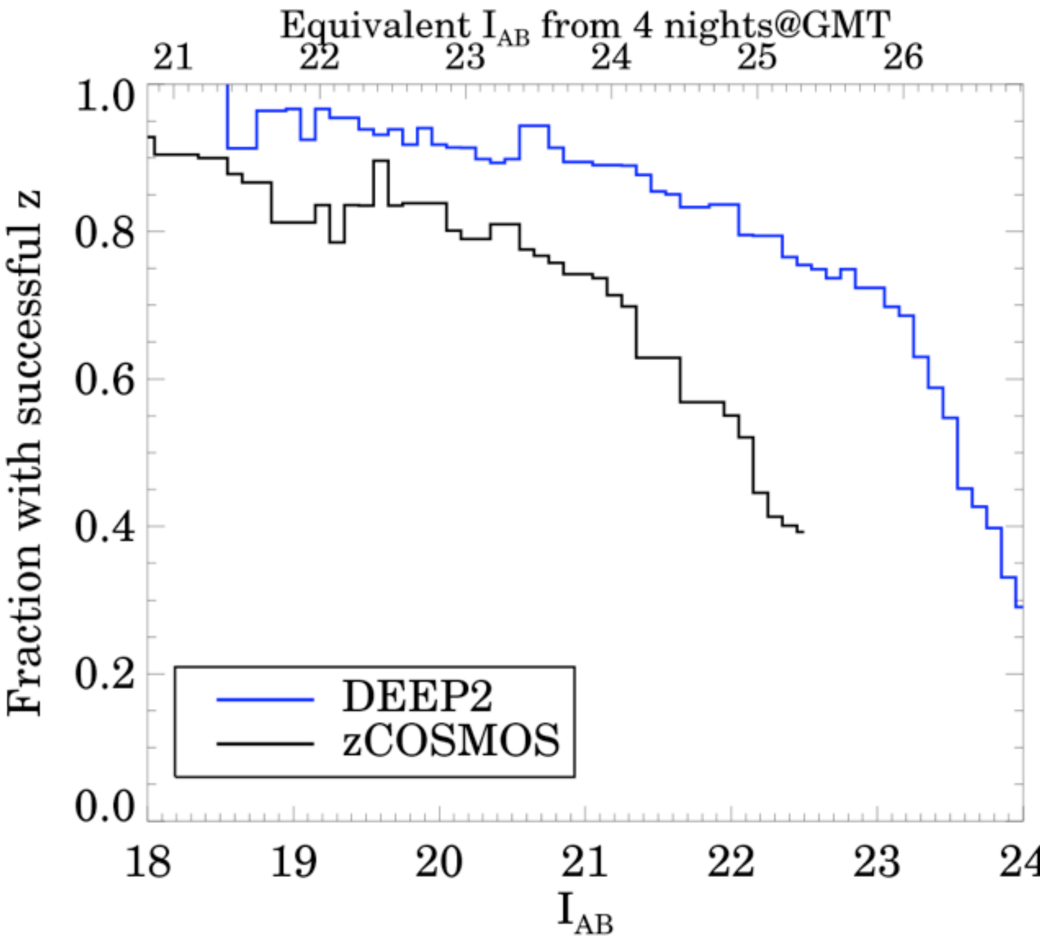
    - e.g., Cunha et al. (2012) estimate that 40-150 ~0.1 deg^2 fields are needed for DES for sample variance not to impact errors (unless we get clever)



Cunha et al. 2012

Biggest concern: incompleteness in training/calibration datasets

- In current deep redshift surveys (to i~22.5/R~24), 25-60% of targets fail to yield secure (>95% confidence) redshifts
- Redshift success rate depends on galaxy properties - losses are systematic, not random
- Estimated need 99-99.9% completeness to prevent systematic errors in calibration from missed populations, for direct calibration of redshift distributions from training set

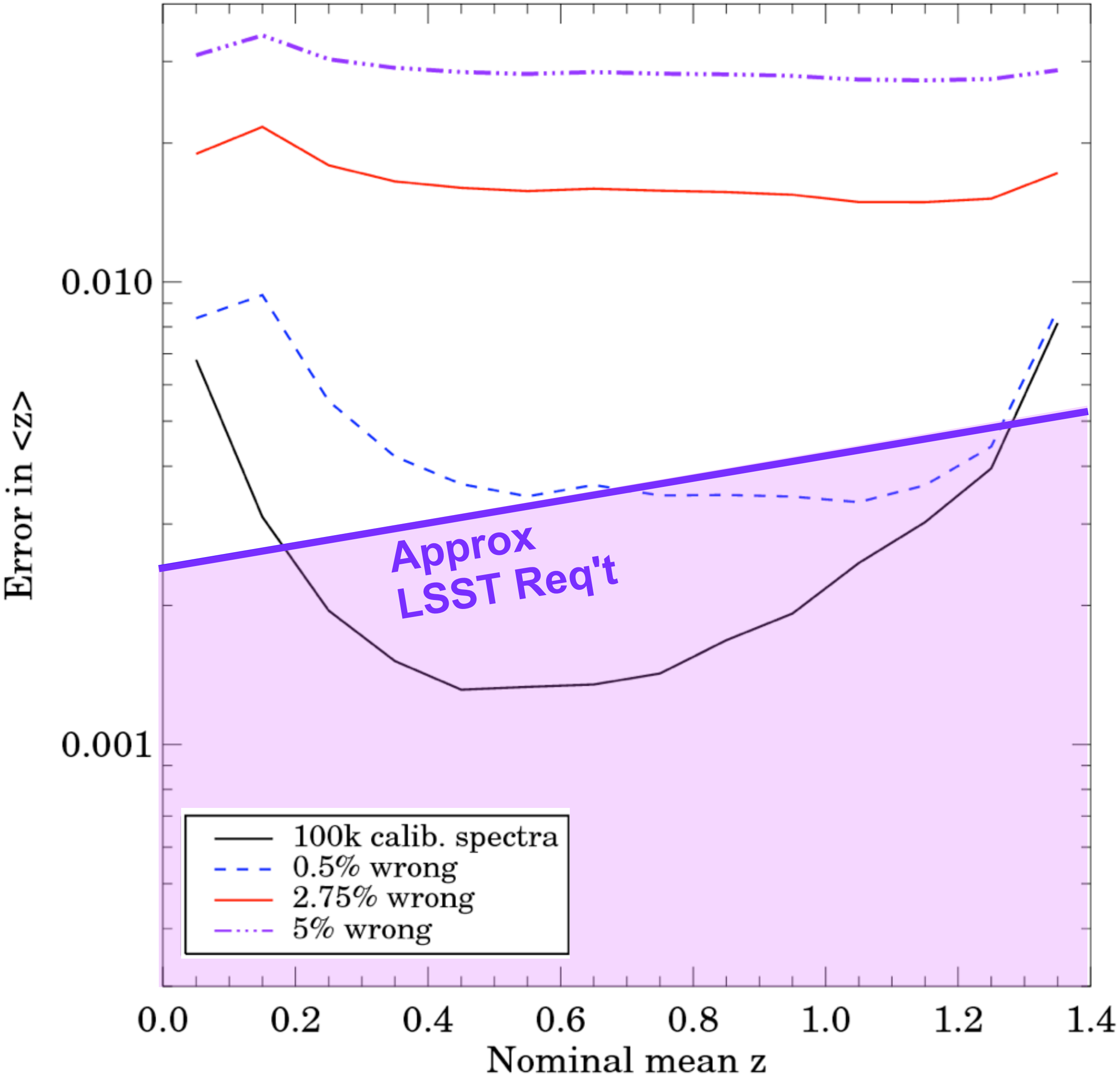


Data from DEEP2 (Newman et al. 2013) and zCOSMOS (Lilly et al. 2009)

Note: even for 100% complete samples, current false-z rates would compromise calibration accuracy

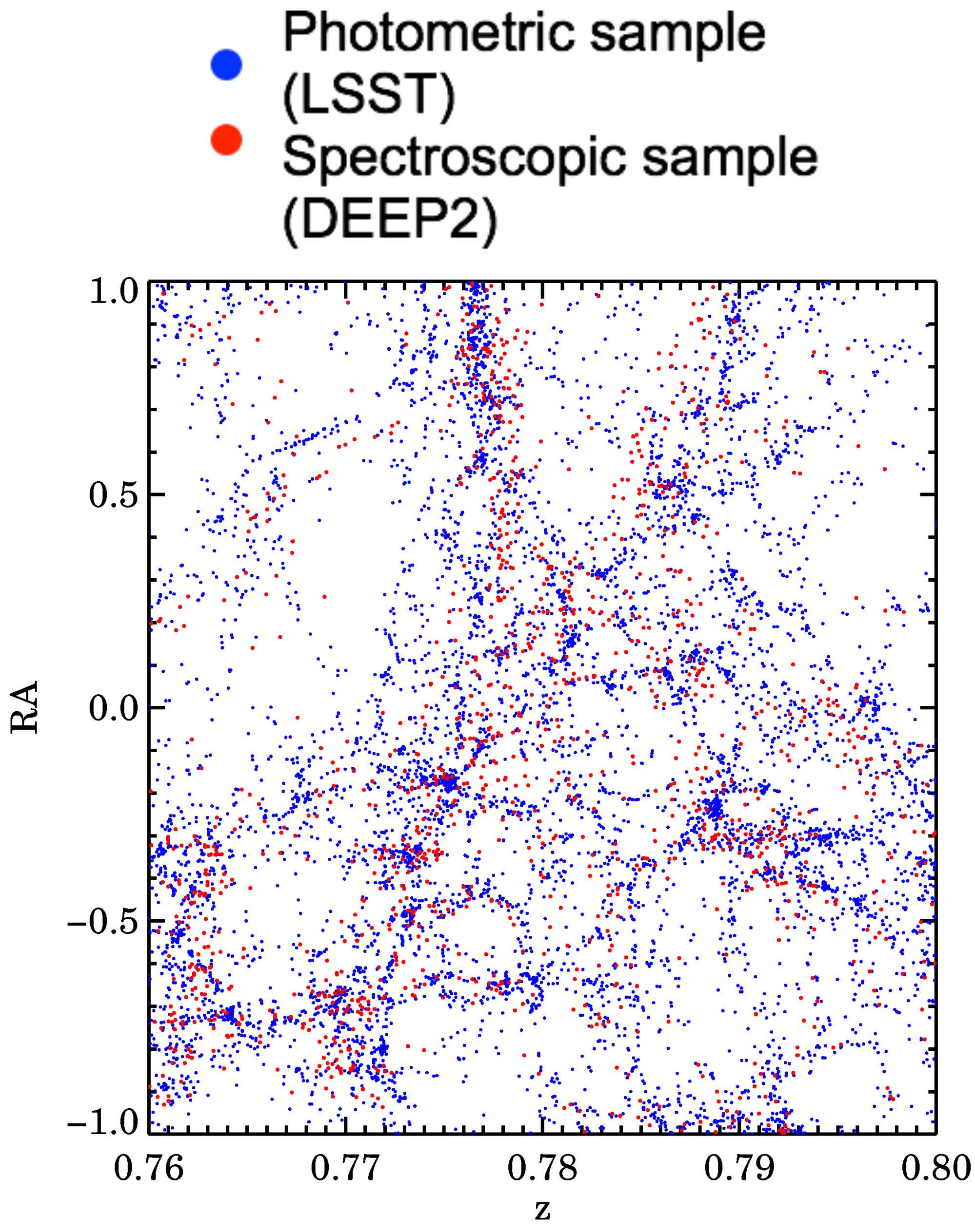
- **Only the highest-confidence redshifts should be useful for precision calibration: lowers spectroscopic completeness further when restrict to only the best**

Based on simulated redshift distributions for ANNz-defined DES bins in mock catalog from Huan Lin, UCL & U Chicago, provided by Jim Annis



Cross-correlation methods: exploiting redshift information from galaxy clustering

- **Galaxies of all types cluster together: trace same dark matter distribution**
- **Galaxies at significantly different redshifts do not cluster together**
- **From observed clustering of objects in one sample vs. another (as well as information from autocorrelations), can determine the fraction of objects in overlapping redshift range**
- **Do this as a function of spectroscopic *z* to recover *p(z)***

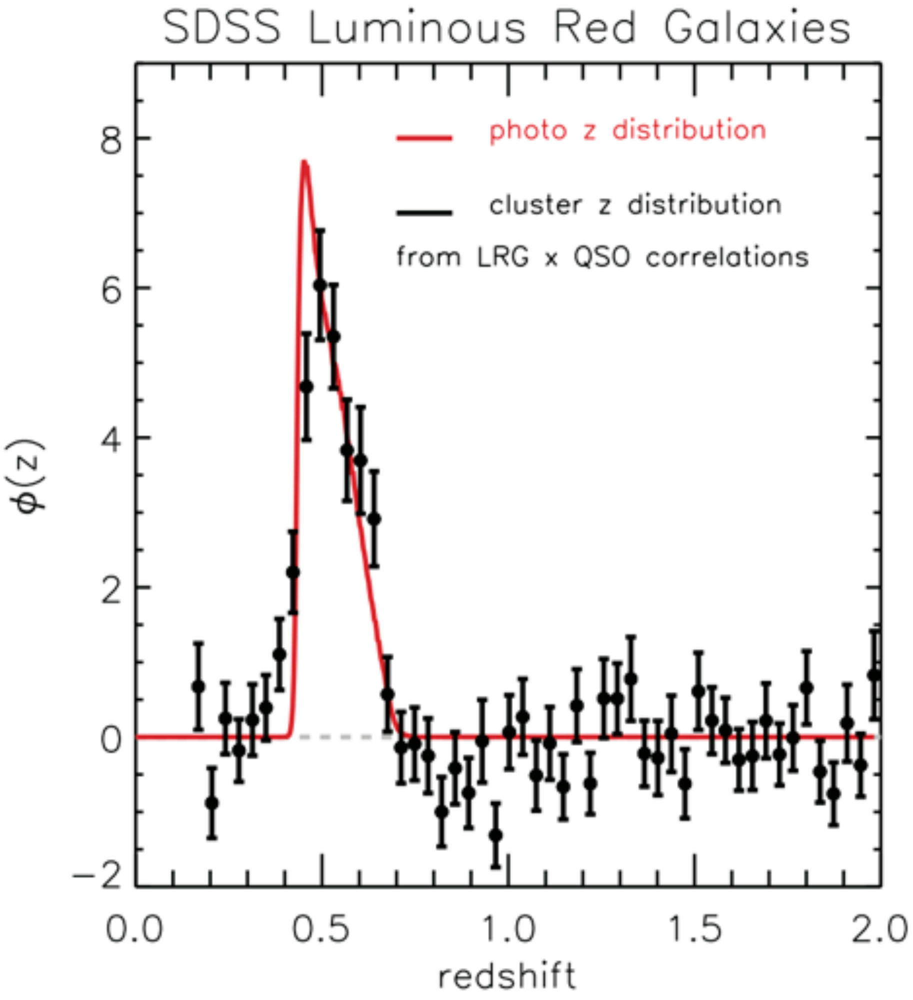


Higher-resolution information can be obtained by cross-correlating with spectroscopic samples

- **Key advantage: spectroscopic sample can be systematically incomplete and include only bright galaxies!**
- **See: Newman 2008, Matthews & Newman 2010, 2011**

Red: Photo-z distribution for LRGs in SDSS

Black: Cross-correlation reconstruction using only SDSS QSOs (rare at low z!)



Menard et al. 2013

Higher-resolution information can be obtained by cross-correlating with spectroscopic samples

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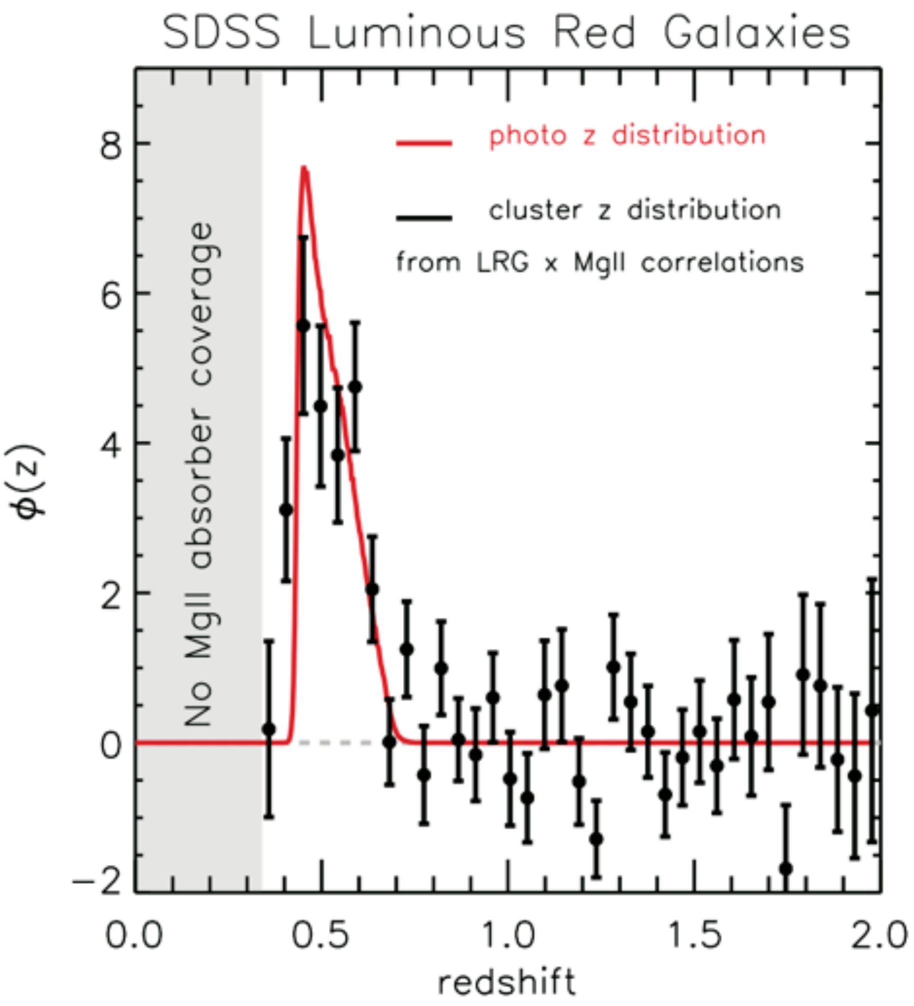
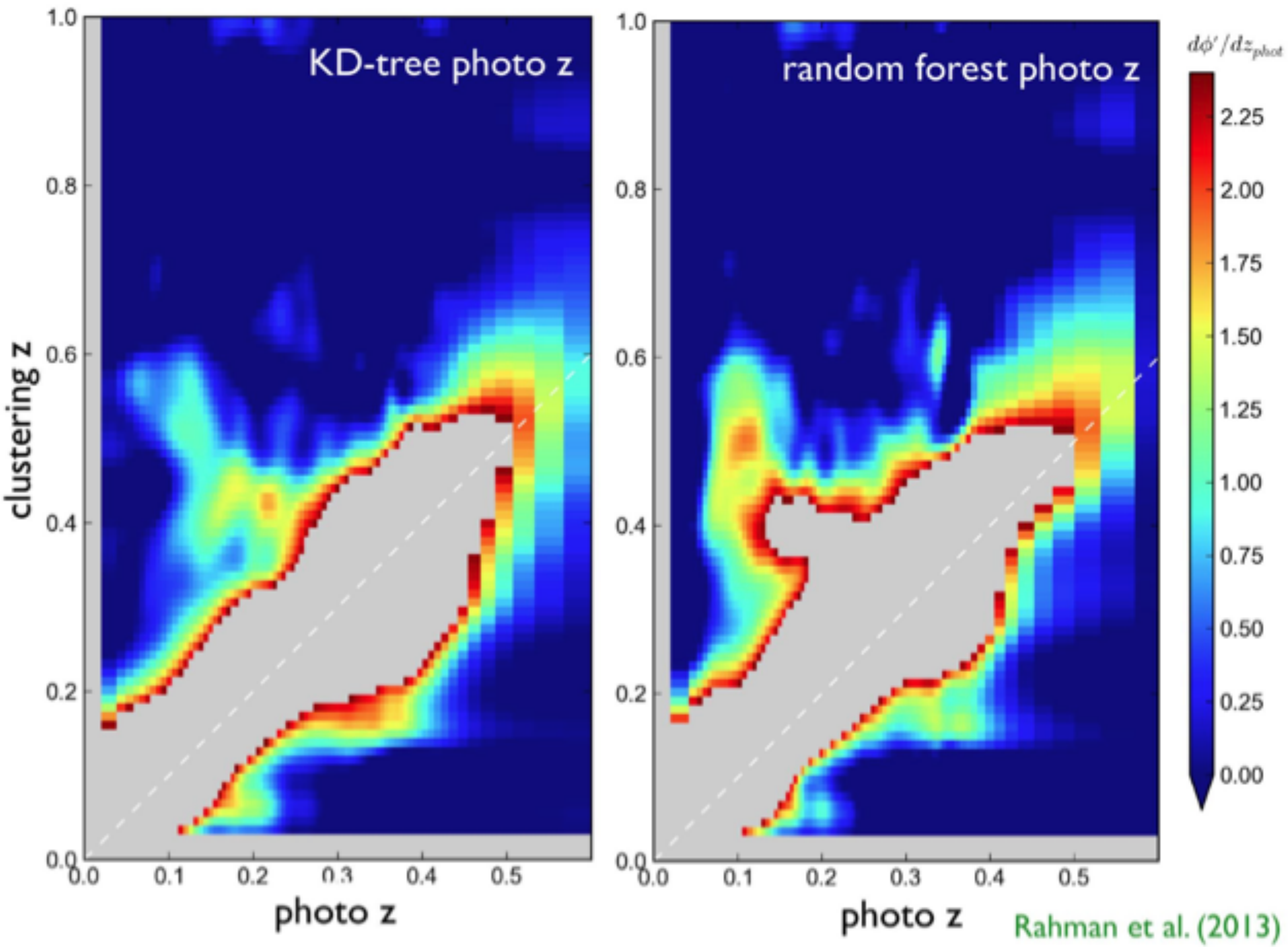
Red: Photo-z distribution for LRGs in SDSS

Black: Cross-correlation reconstruction using only SDSS Mg II absorbers (even rarer!)



Menard et al. 2013

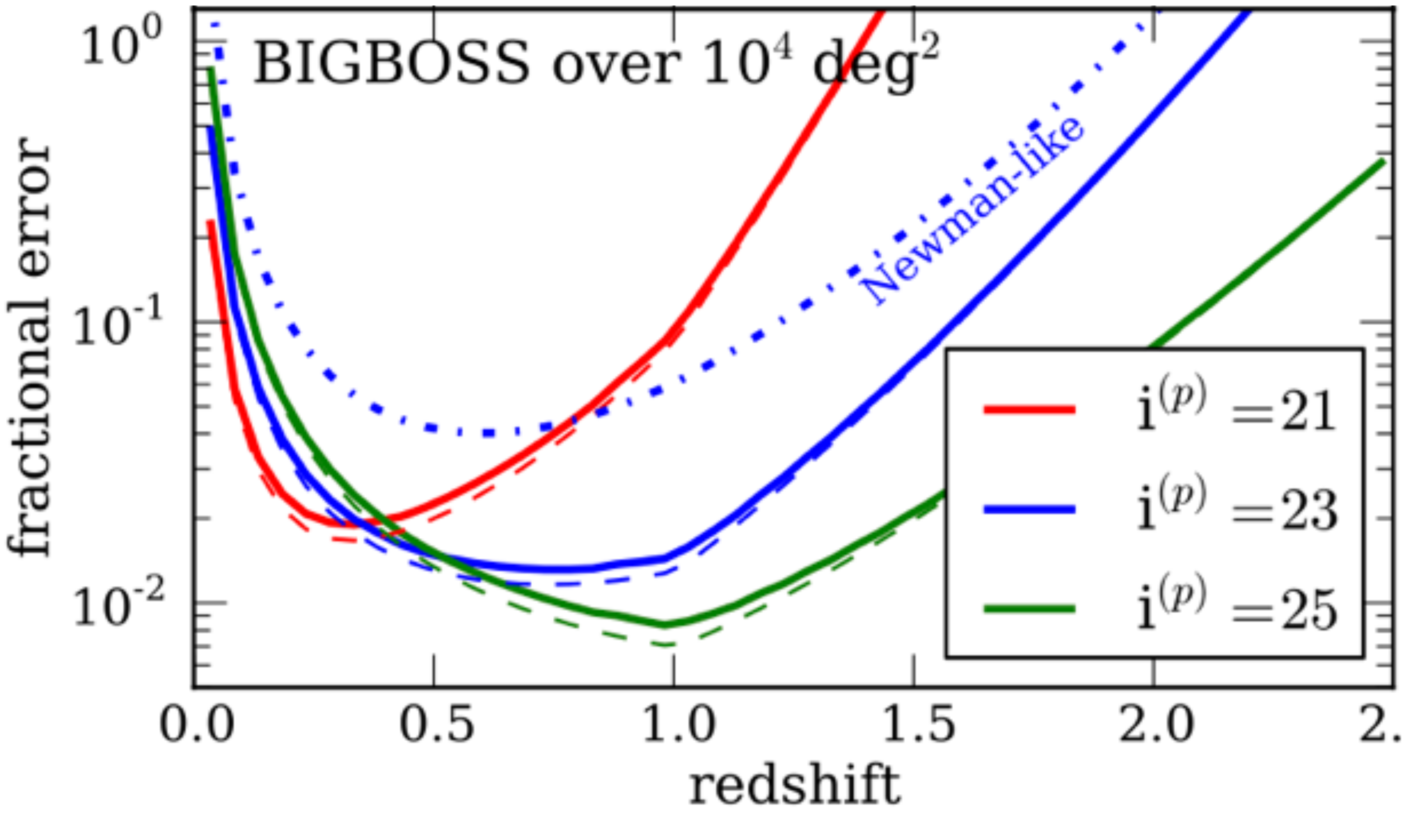
Cross-correlation methods are now being used to test SDSS photo-z's



Rahman et al. (2013)

Note: cross-correlation forecasts above are pessimistic!

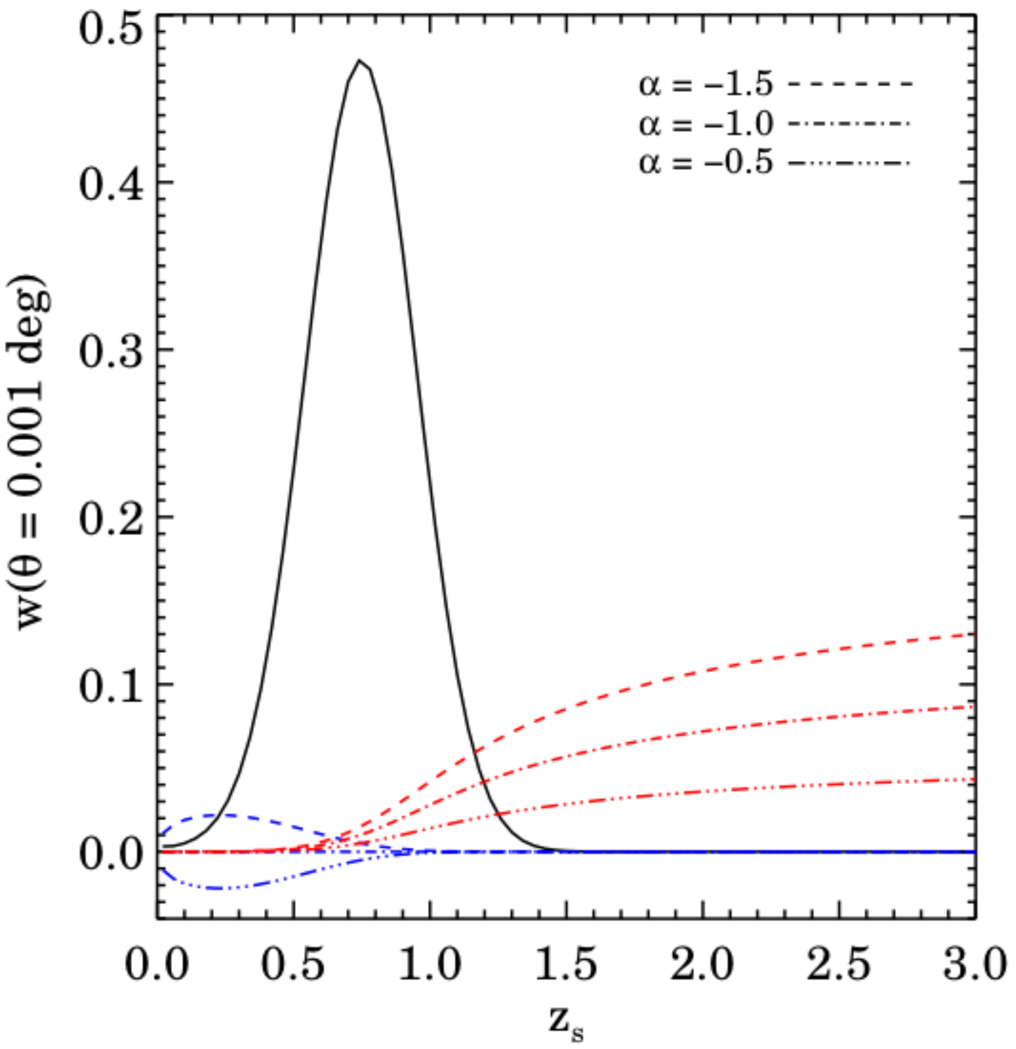
- McQuinn & White (2013): Application of optimal estimators to cross-correlation analysis



- Makes maximum use of information on linear scales, avoids integral constraint error
- Obtain errors 2-10x smaller than Newman 2008 / Matthews & Newman 2010

Biggest concern right now: disentangling cross-correlations from clustering and lensing magnification

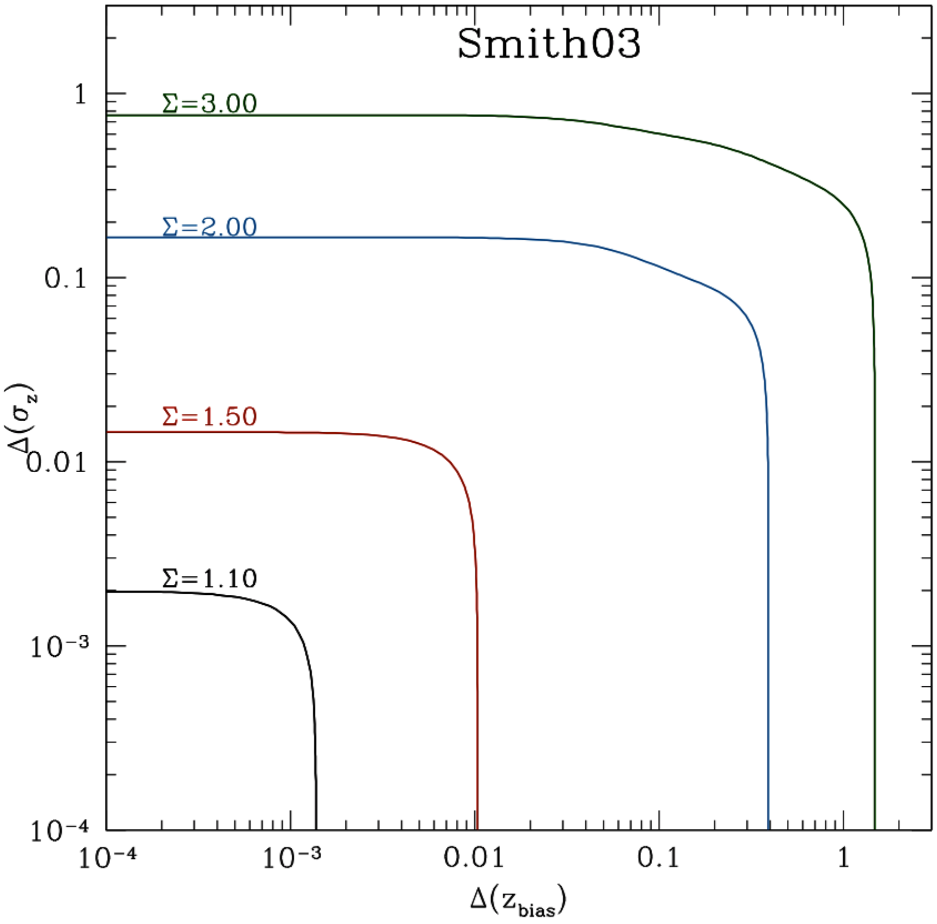
- *Black*: cross-correlations between photo-z objects (z=0.75 Gaussian) and spectroscopic sample as a function of *z*
- *Blue*: observed cross-correlation due to spectroscopic objects lensing photometric ones
- *Red*: observed cross-correlation due to photometric objects lensing spectroscopic ones
- Weak/CMB lensing could help us predict the red curves



Matthews & Newman 2014, in prep.

DE systematic errors from uncertainty in photo-z calibration

- Estimates based on Gaussian error models: photo-z bias, $\delta_z = \langle z_p - z_s \rangle$, and uncertainty in scatter, $\sigma(\sigma_z) = \sigma(\mathrm{RMS}(z_p - z_s))$, must be below ~0.003 - 0.01 for photo-z systematics to be subdominant in lensing/BAO (looser requirements come from better P(k) predictions)

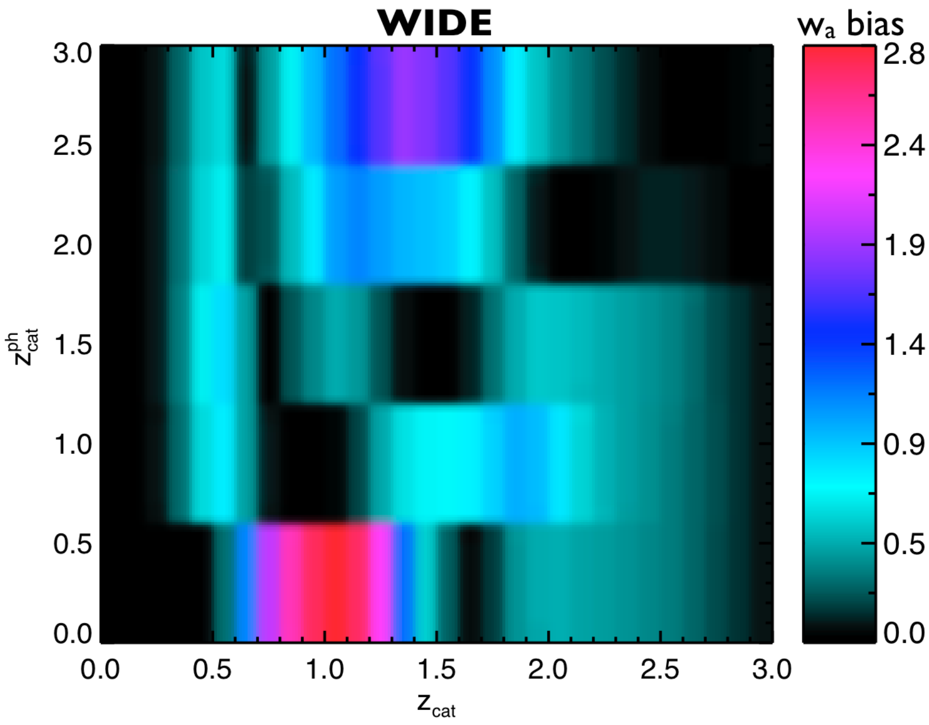


Hearin et al. 2010

- More realistic: need to consider catastrophic, non-Gaussian outliers. Can't be eliminated (e.g. HST shows 2% of faint DEEP2 objects are blends)
- If drop all galaxies with z<0.3 or z>2.1, random lensing errors only 20% worse , but systematics much less (Hearin et al. 2010)

Systematic errors from photo-z catastrophic outliers

- More realistically: need to consider catastrophic, non-Gaussian outliers
- Can't be eliminated entirely:
    - ~2% of DEEP2 targets were actually galaxies at different *z* blurred together from ground
    - Can be difficult to distinguish one spectral break from another: degeneracies
- Some sorts of catastrophic errors worse than others
- If drop all galaxies with z<0.3 or z>2.1, lensing errors only 20% worse (Hearin et al. 2010)



Hearin et al. 2010