Wide-Field Spectroscopic Follow-Up

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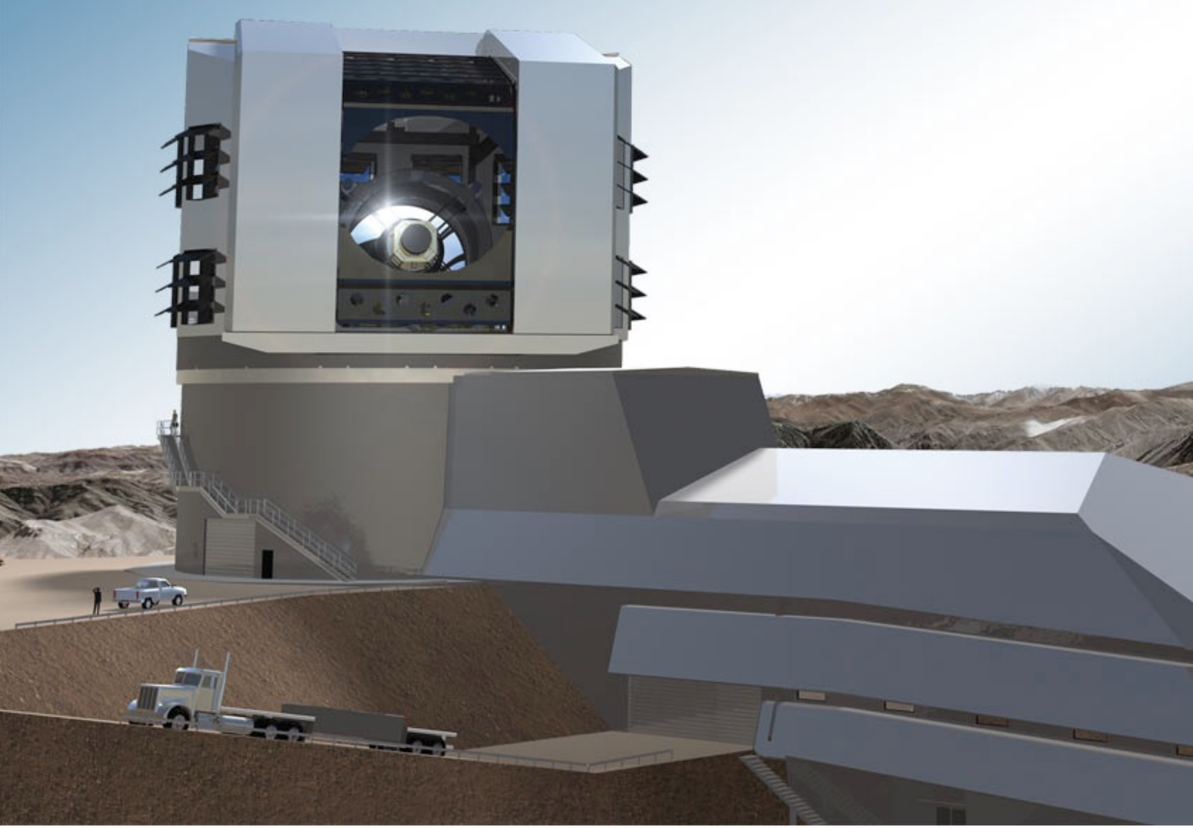


- **See Snowmass white papers on *Cross-Correlations* and *Spectroscopic Needs for Imaging Dark Energy Experiments* for more details!**

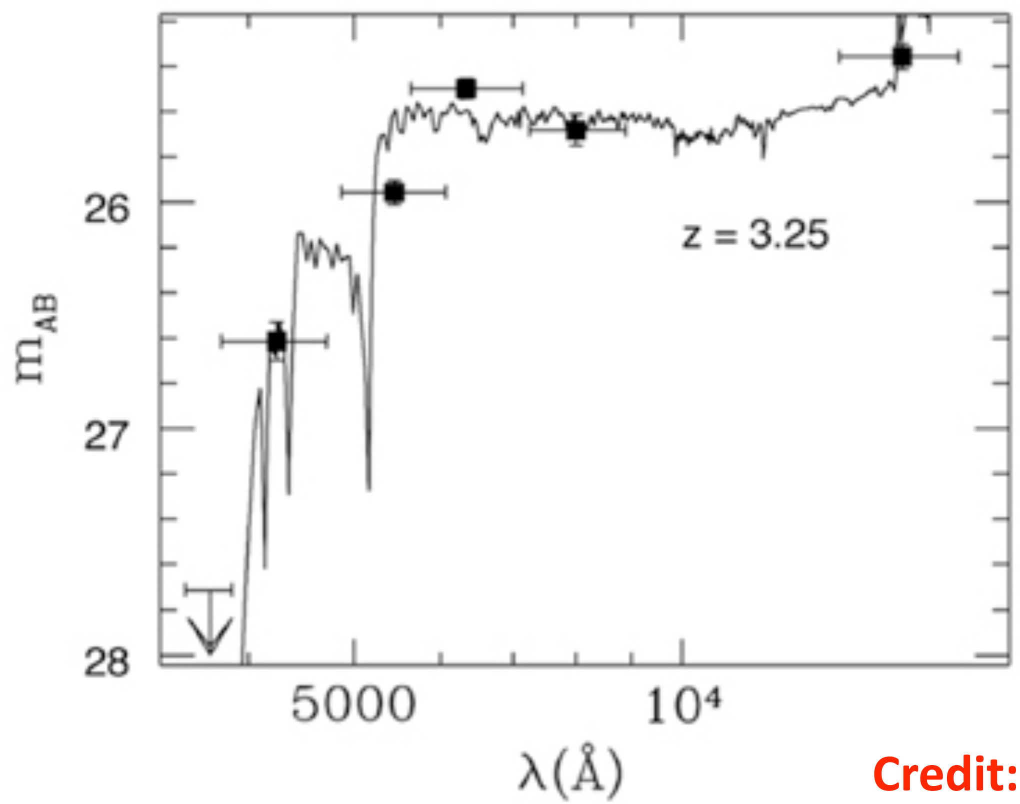
Outline

- Training photometric redshifts for DES and LSST
  - Potential systematics from training sets
- Mitigating systematics with wide-area surveys: cross-correlation techniques for photo-z calibration
- Another role for DESI: Supernova host redshifts

- See Snowmass white papers on *Cross-Correlations* and *Spectroscopic Needs for Imaging Dark Energy Experiments* (http://arxiv.org/abs/1309.5384, 1309.5388) for much more!

Spectroscopy provides ideal redshift measurements – but is infeasible for large samples

- At LSST "gold sample" (i<25.3) depths, ~180 hours on a 10m telescope to determine a redshift (70% of time) spectroscopically
- With a next-generation, 5000 fiber spectrograph on a 10m telescope, still >50,000 telescope-years to measure redshifts for LSST "gold" weak lensing sample (4 billion galaxies)!



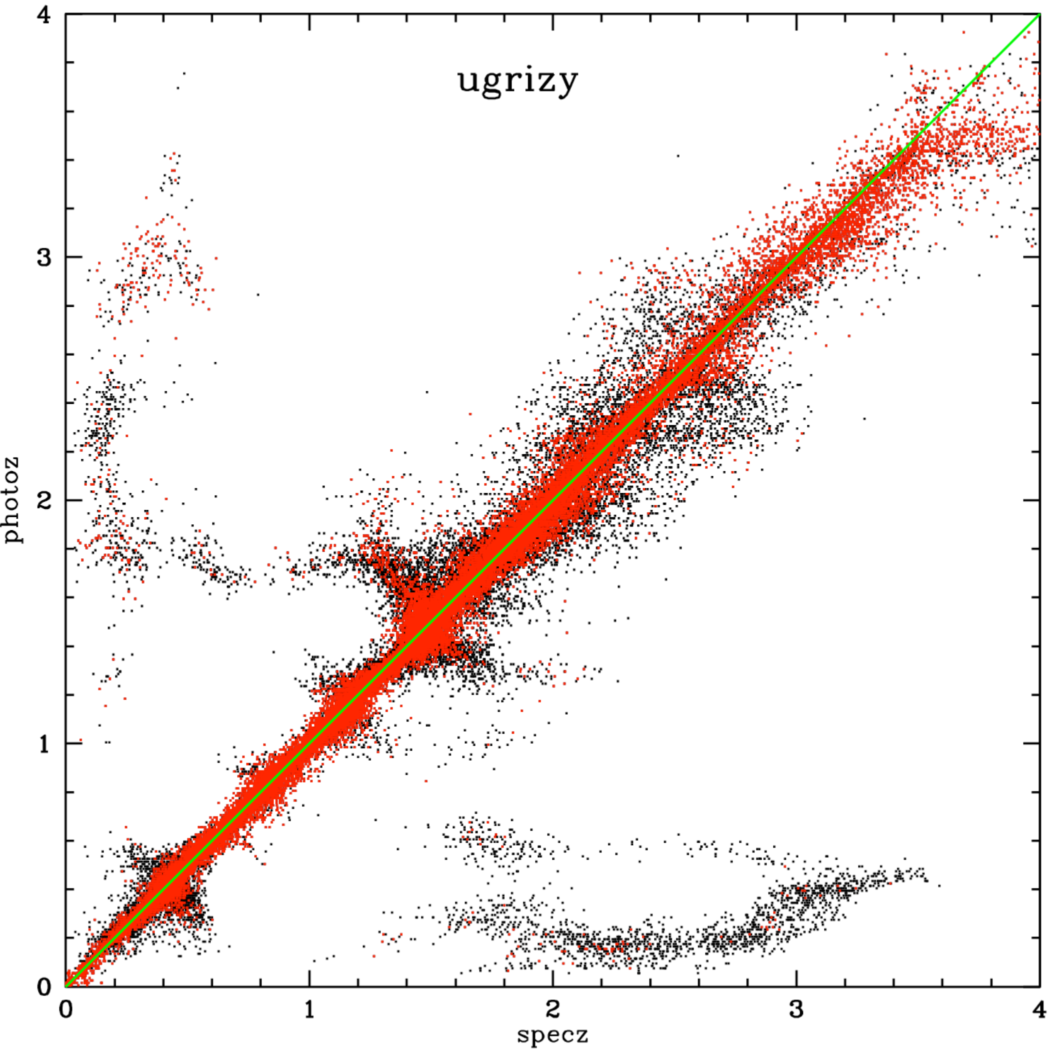
Credit: ESO

Two basic Photo-z methods: Template fitting and training-based; each has advantages & disadvantages

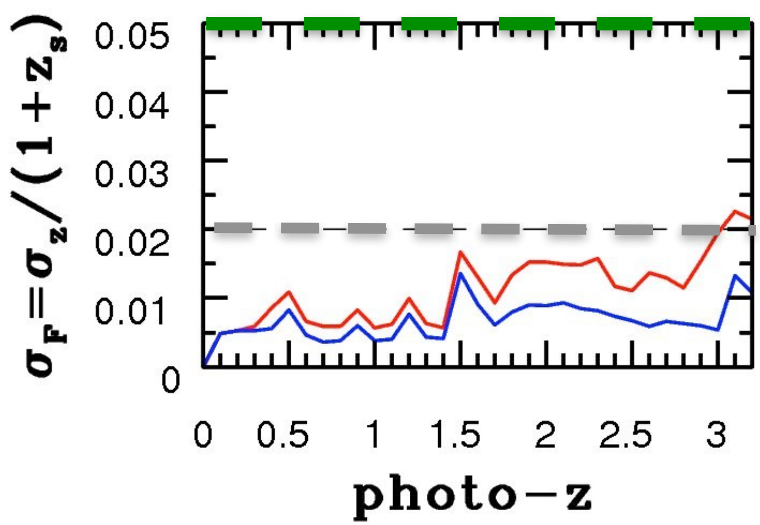
- **Template fitting**: use galaxies with known *z* + imaging to determine set of underlying galaxy spectral energy distributions (SEDs) and relative photometric calibrations
  - Can then determine *p(z | ugrizy)*
  - For high accuracy, needs spectra of galaxies spanning full range of possible properties

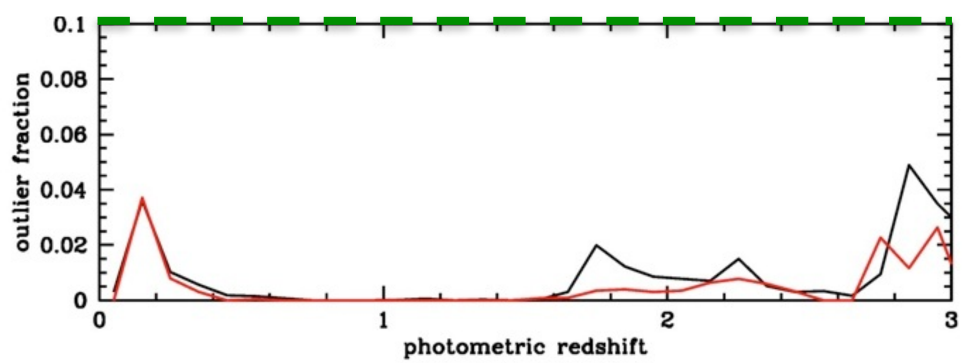
- **Training-based:** Use set of galaxies with known redshift and well-understood sampling to determine relations between *z* and colors
- Training set MUST span full range of properties & z of galaxies
  - Pro: Takes advantage of progress in machine learning & stats
  - Con: Sensitive to systematic incompleteness in training sets - extrapolate poorly

Example: expected photo-z performance for LSST *ugrizy*



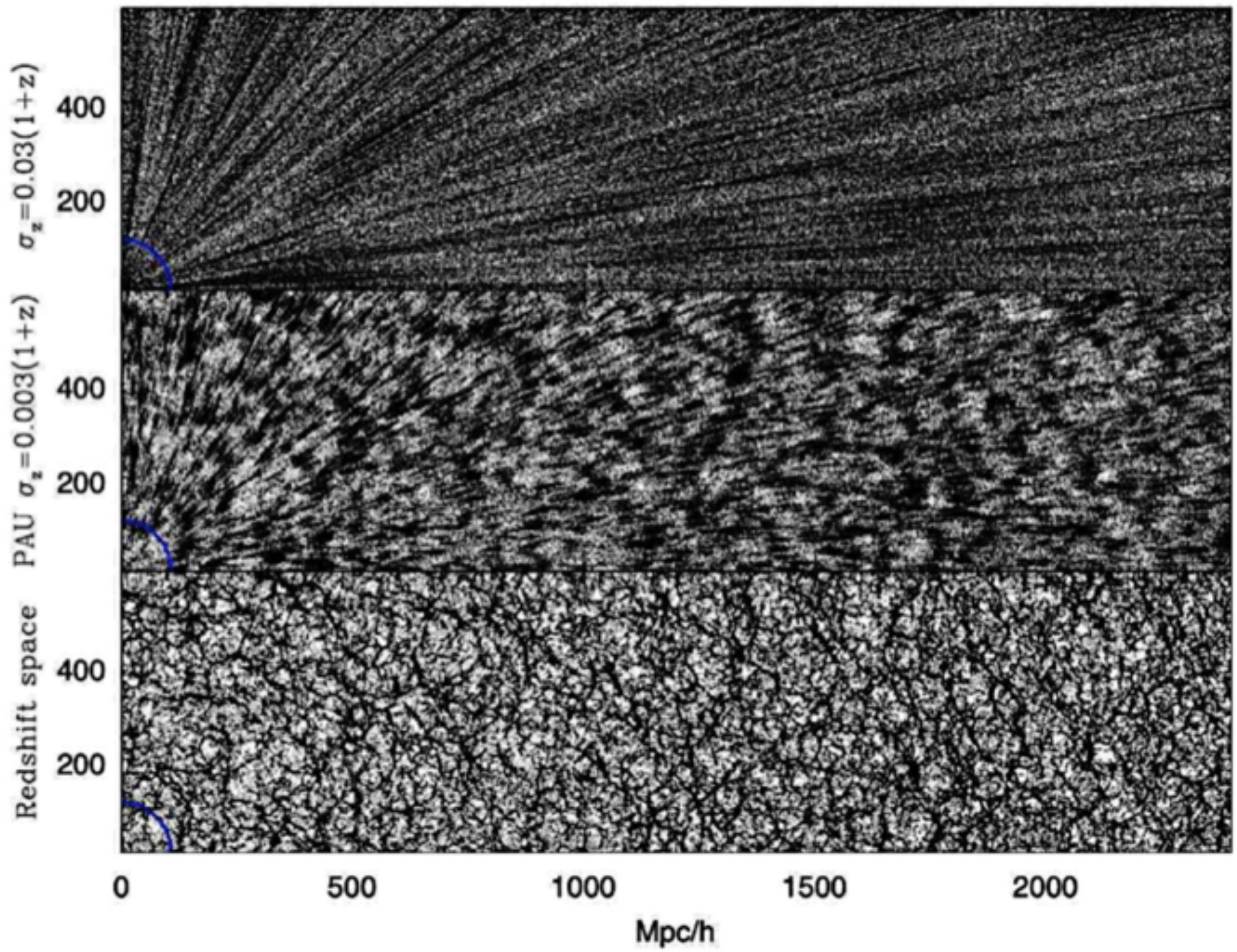
Green: Requirements on actual performance; grey: requirements on performance <u>with perfect template knowledge</u> (as in these sims)





Two spectroscopic needs 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**



Benitez et al. 2009

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

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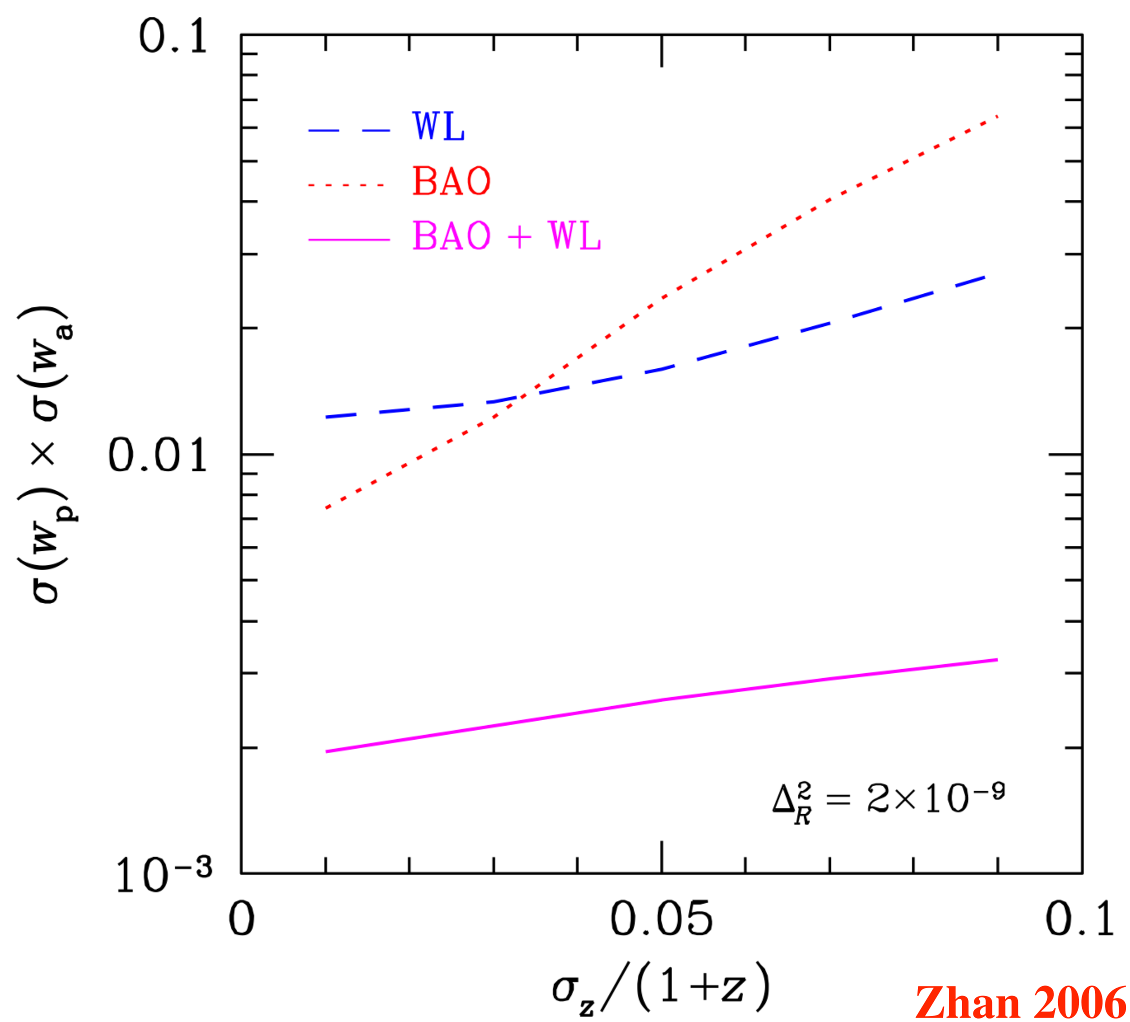
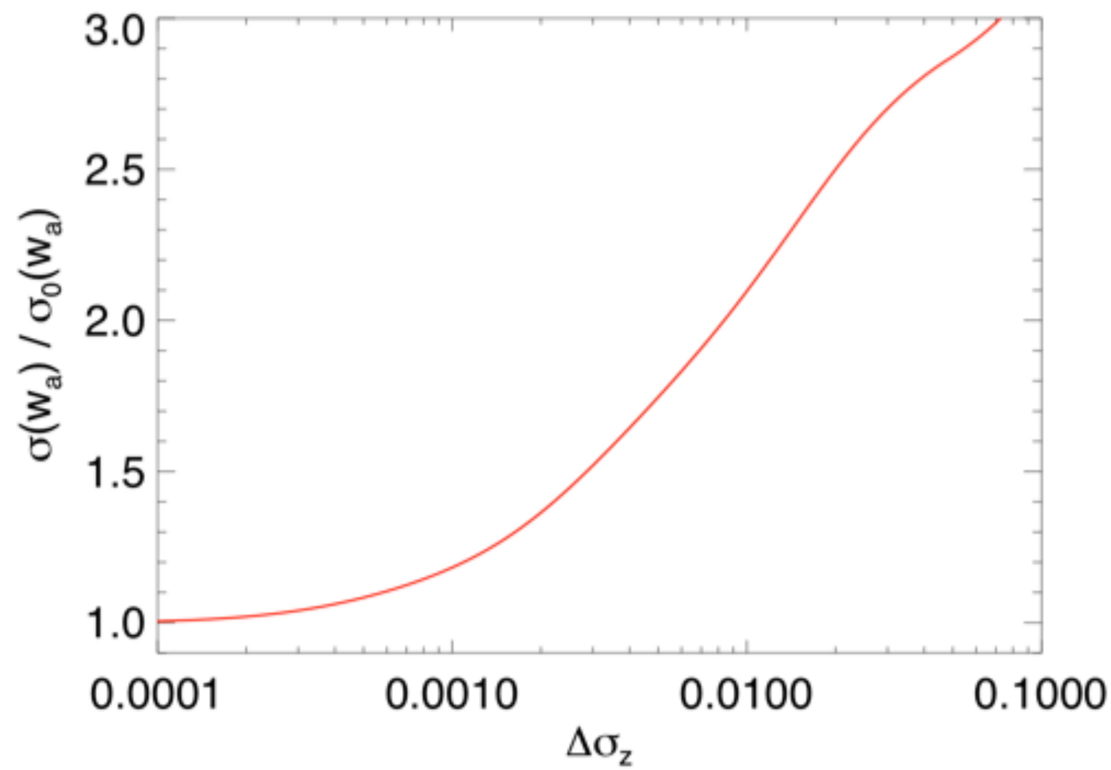


Zhan 2006

- 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

- 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

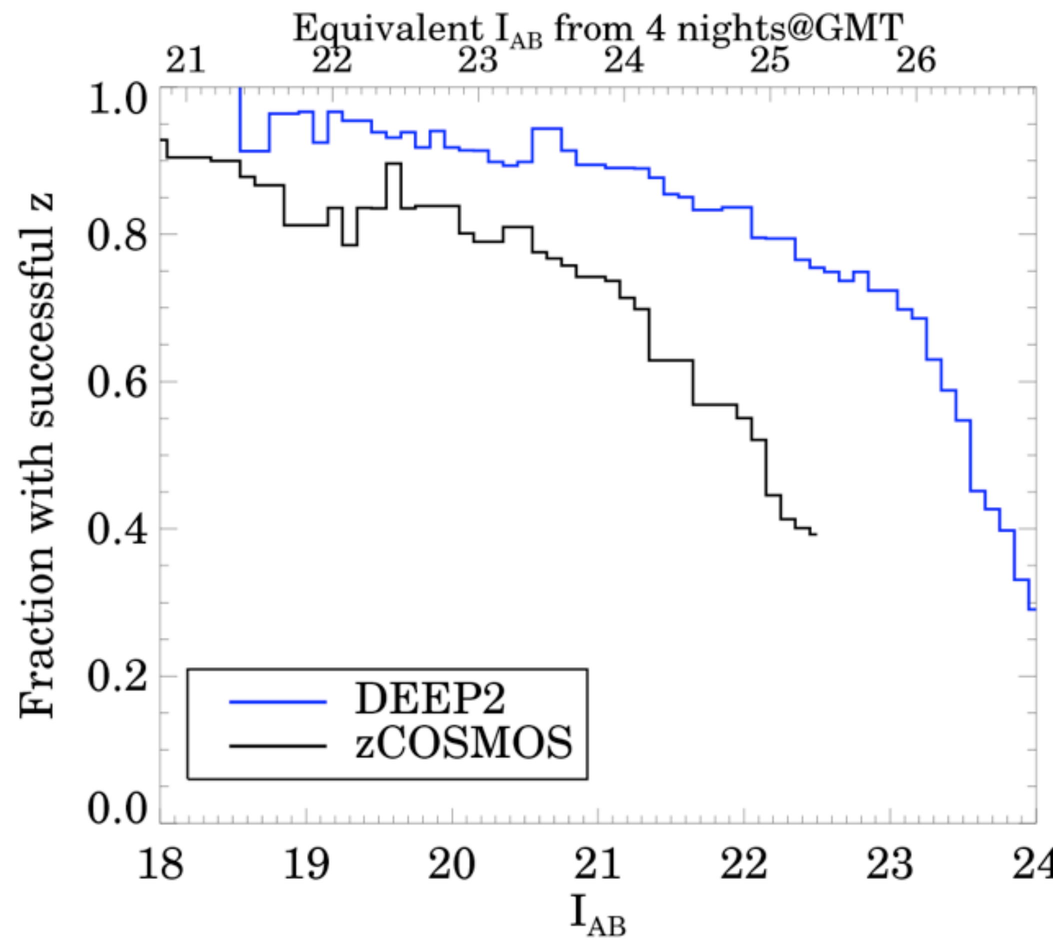
  – *uncertainty in* bias, $\sigma(\delta_z) = \sigma(\langle z_p - z_s \rangle)$, and *uncertainty in* scatter, $\sigma(\sigma_z) = \sigma(\mathrm{RMS}(z_p - z_s))$, must both be <~0.002(1+*z*) for Stage IV surveys

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

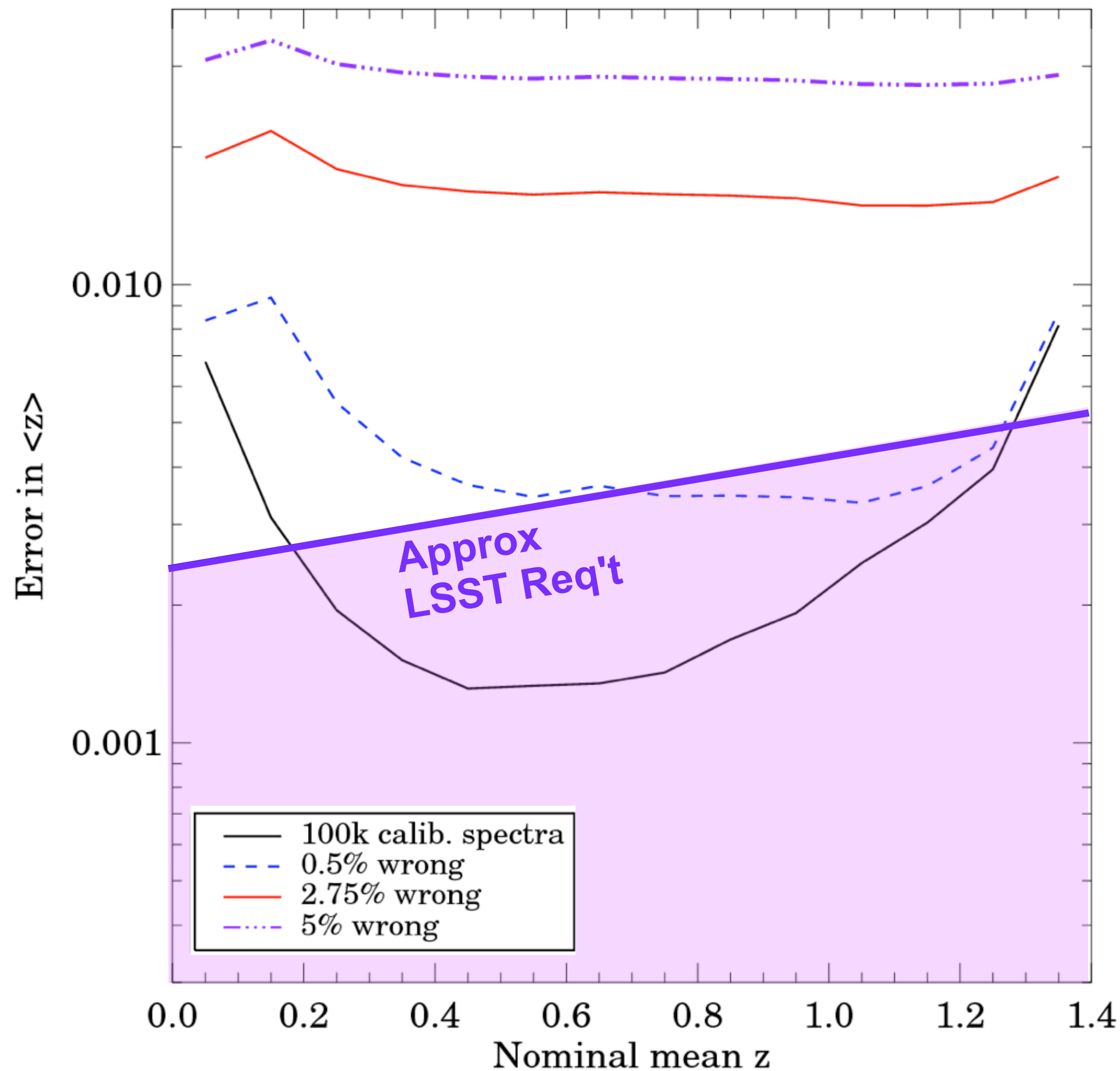
- Estimated need 99-99.9% completeness to prevent systematic errors in calibration from missed populations, for direct calibration of redshift distributions from training set



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

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

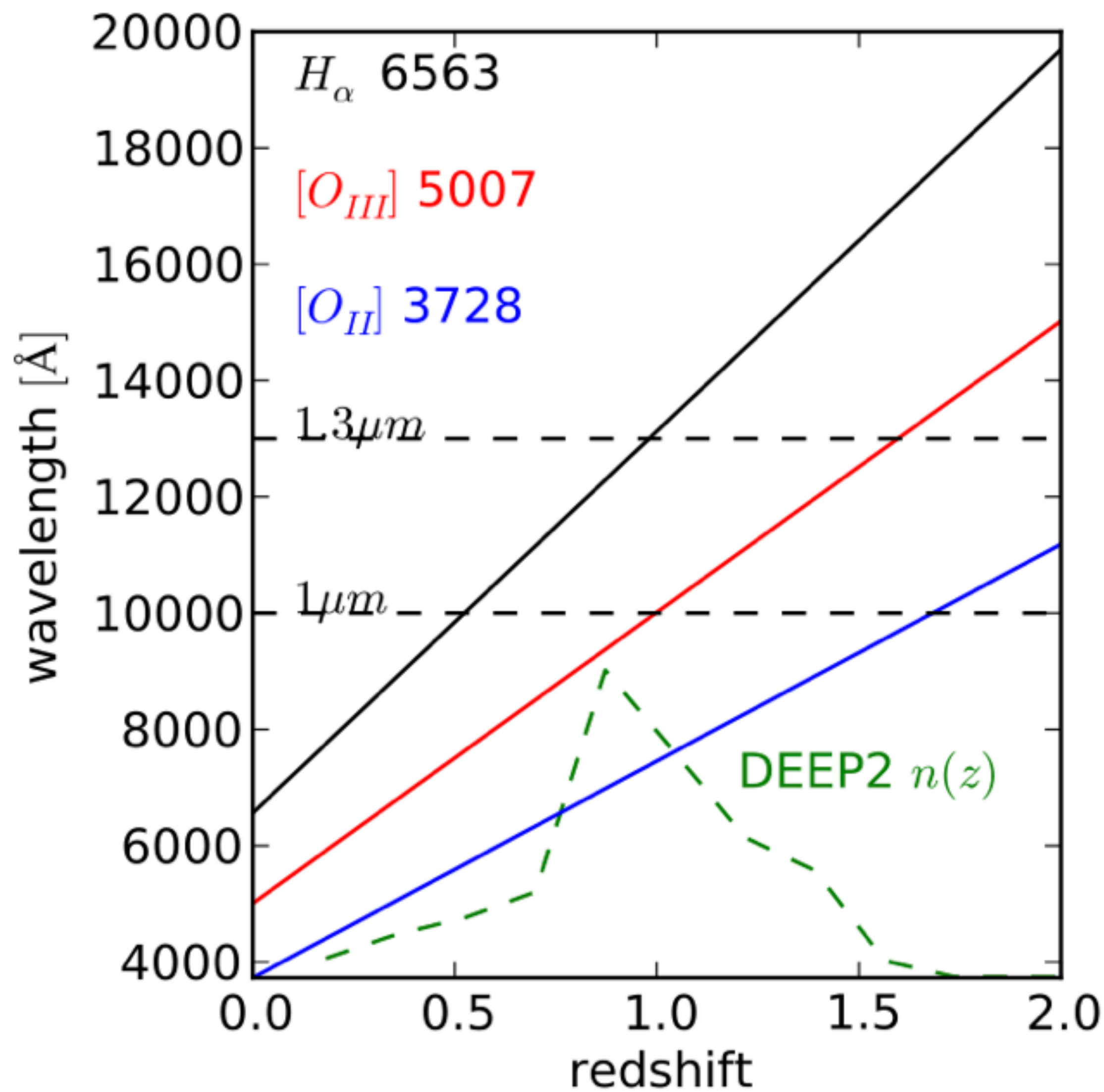
  - Obtaining large numbers of spectra is infeasible without it

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

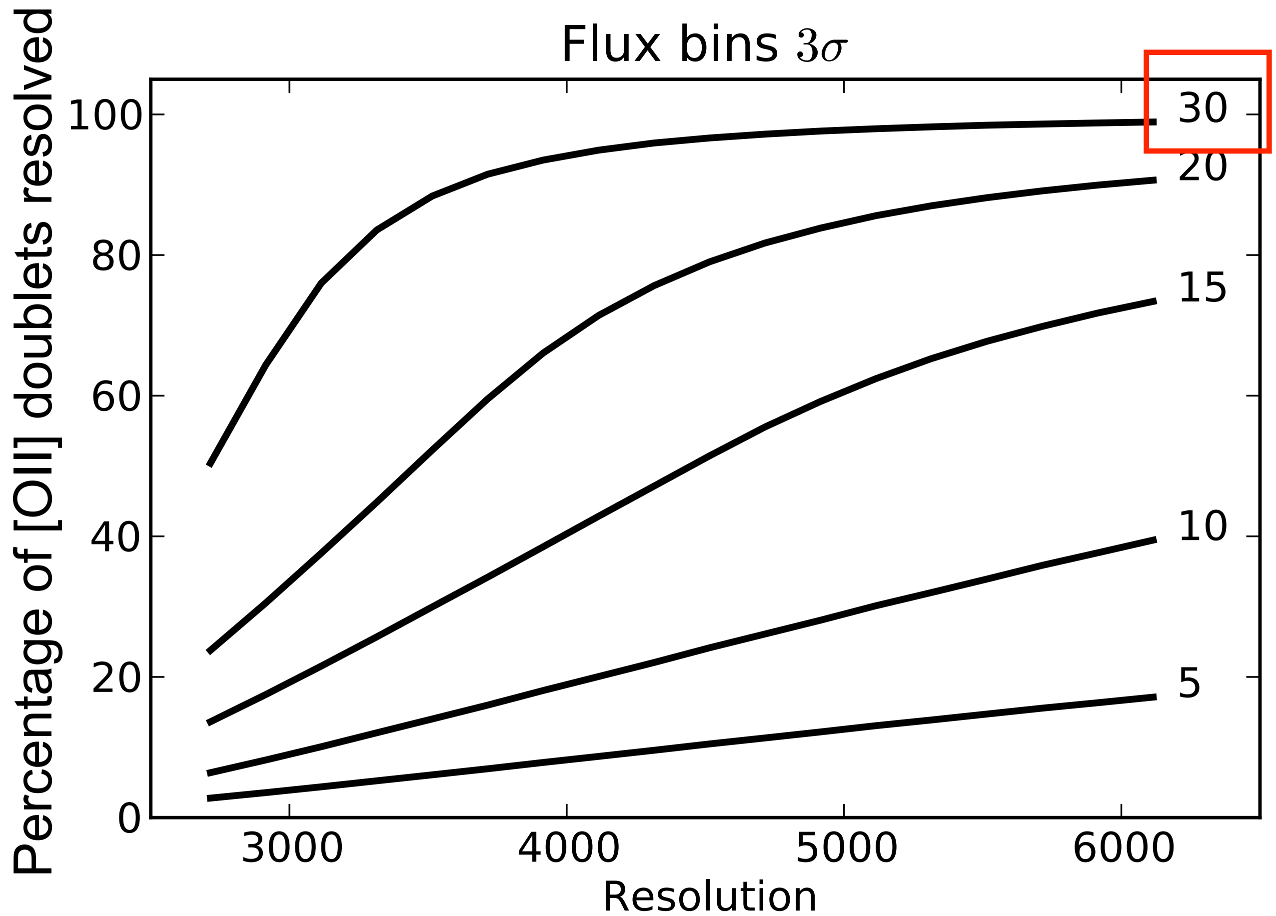


Comparat et al. 2013, submitted

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**

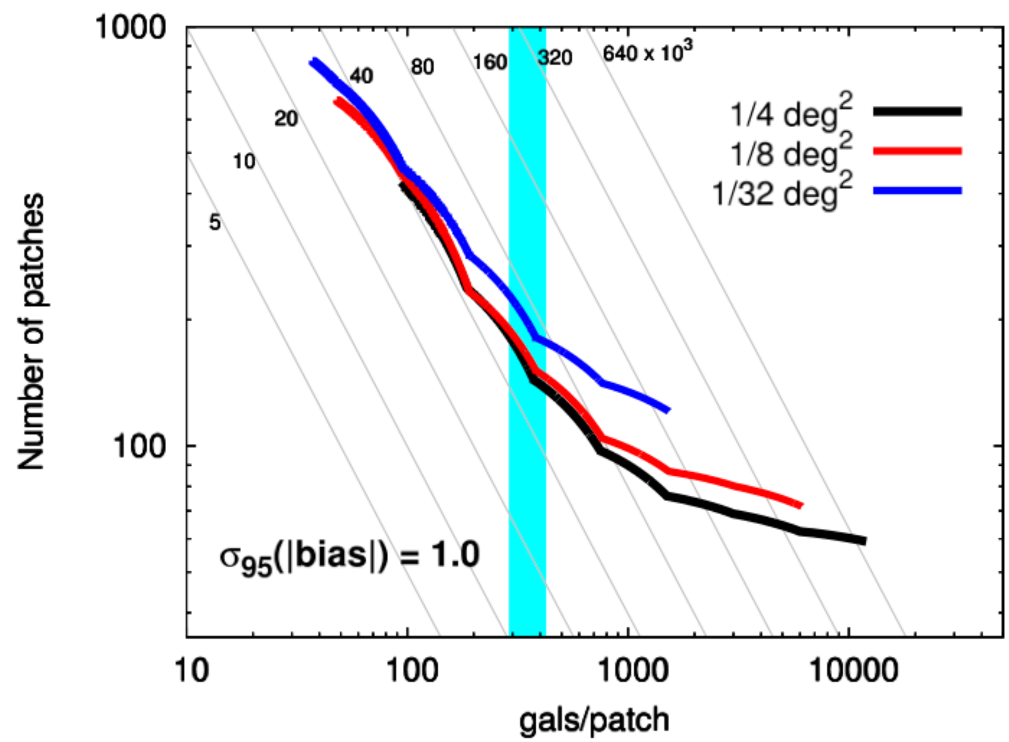
  - Need to span several correlation lengths for accurate clustering measurements (key for synergistic galaxy evolution science and for cross-correlation techniques)

  - $r_0 \sim 5\ h^{-1}$ 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

Estimated time requirements for training sets

- **DES / 75% complete:**

  ➡ 0.05 - 0.45 years (c. 2018), 0.02+ years (c. 2022+)

- **DES / 90% complete:**

  ➡ 0.34 - 1.6 years (c. 2018), 0.13 years (c. 2022+)

- **LSST / 75% complete:**

  ➡ 1.1 - 5.1 years (c. 2018), 0.42+ years (c. 2022+)

- **LSST / 90% complete:**

  ➡ 6.9 - 32 years (c. 2018), 2.6+ years (c. 2022+)

Depending on telescope/spectrograph properties, time required is determined by # of fields (15), # of spectra observable simultaneously (if multiplexing is low), or telescope field of view (if <<20' diameter). See Tables 2-1 & 2-2 of white paper.

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

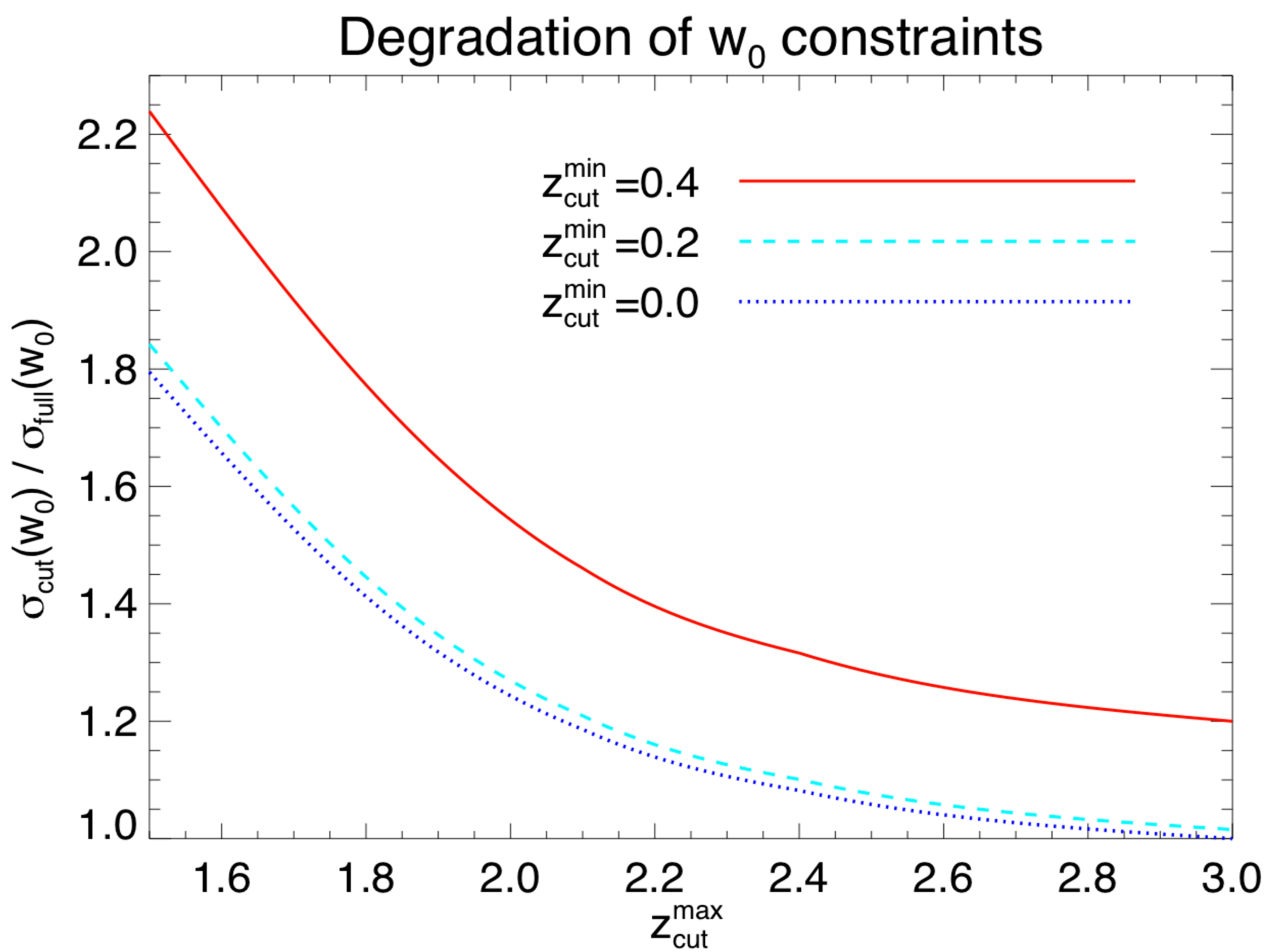
Table 2-1. *Characteristics of current and anticipated telescope/instrument combinations relevant for obtaining photometric redshift training samples. Assuming that we wish for a survey of ~15 fields of at least 0.09 deg^2 each yielding a total of at least 30,000 spectra, we also list what the limiting 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	0.05	1.10	0.34	6.87
Mayall 4m / DESI	0.26	5.11	1.60	31.95
WHT / WEAVE	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 / OPTIMOS	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.*

3 Ways to address spectroscopic incompleteness and enable calibration – all may be feasible



I. **Throw out objects lacking secure photo-*z* calibration**

- **ID regions in e.g. *ugrizy* space where redshift failures occurred**
- **Eliminating a fraction of sample has modest effect on FoM**
  - **Not yet known if sufficiently clean regions exist**

3 Ways to address spectroscopic incompleteness and enable calibration – all may be feasible

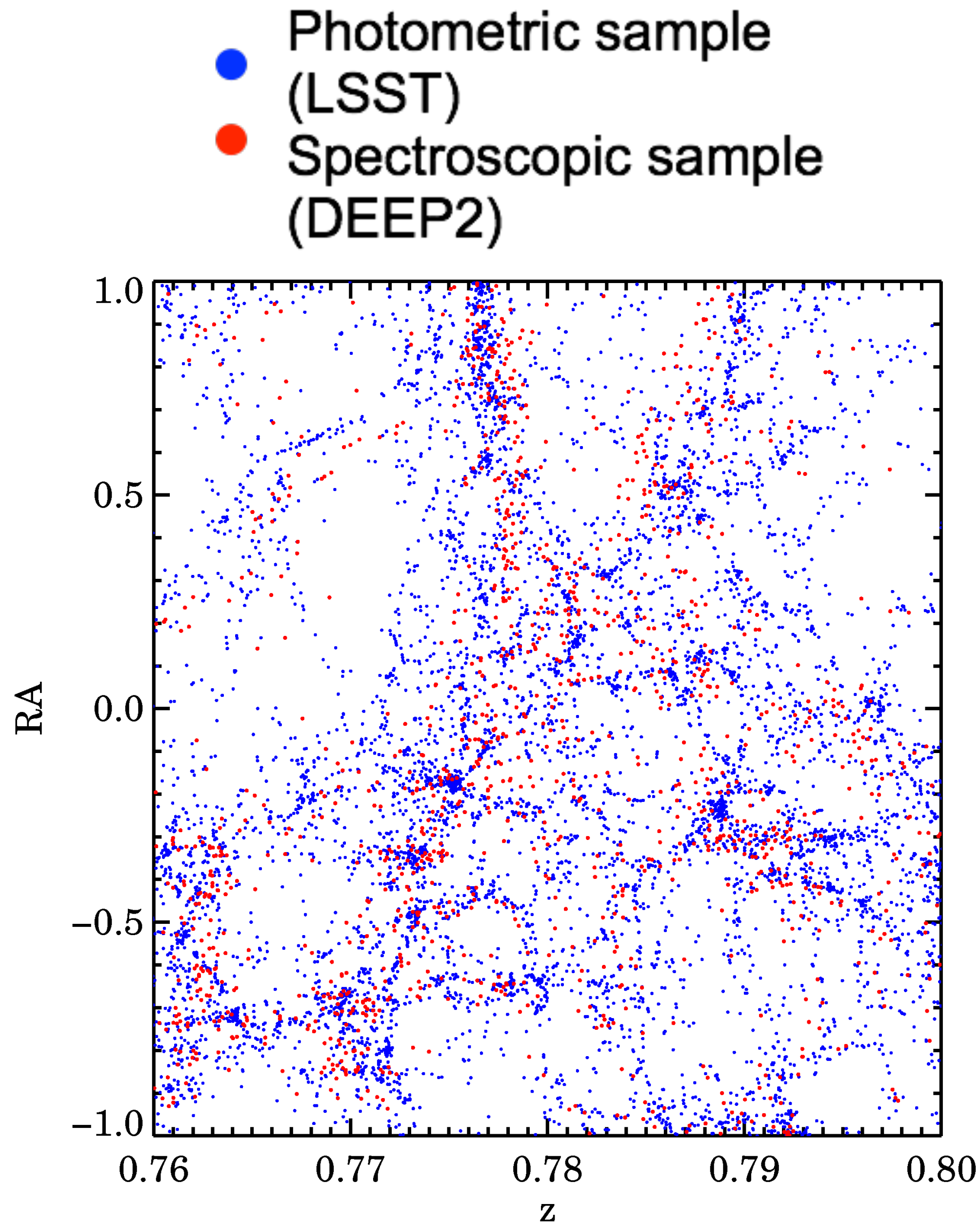
II. **Incorporate additional information**

- **Longer exposure/wider wavelength range spectroscopy (JWST, etc.) for objects that fail to give redshifts in first try**
  - Not yet known if will yield sufficient completeness
- **Develop comprehensive model of galaxy spectral evolution constrained by redshifts obtained**
  - **See Carlos Cunha's talk**
  - **A major research program, not there now**

III. **Cross-correlation techniques**

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)***

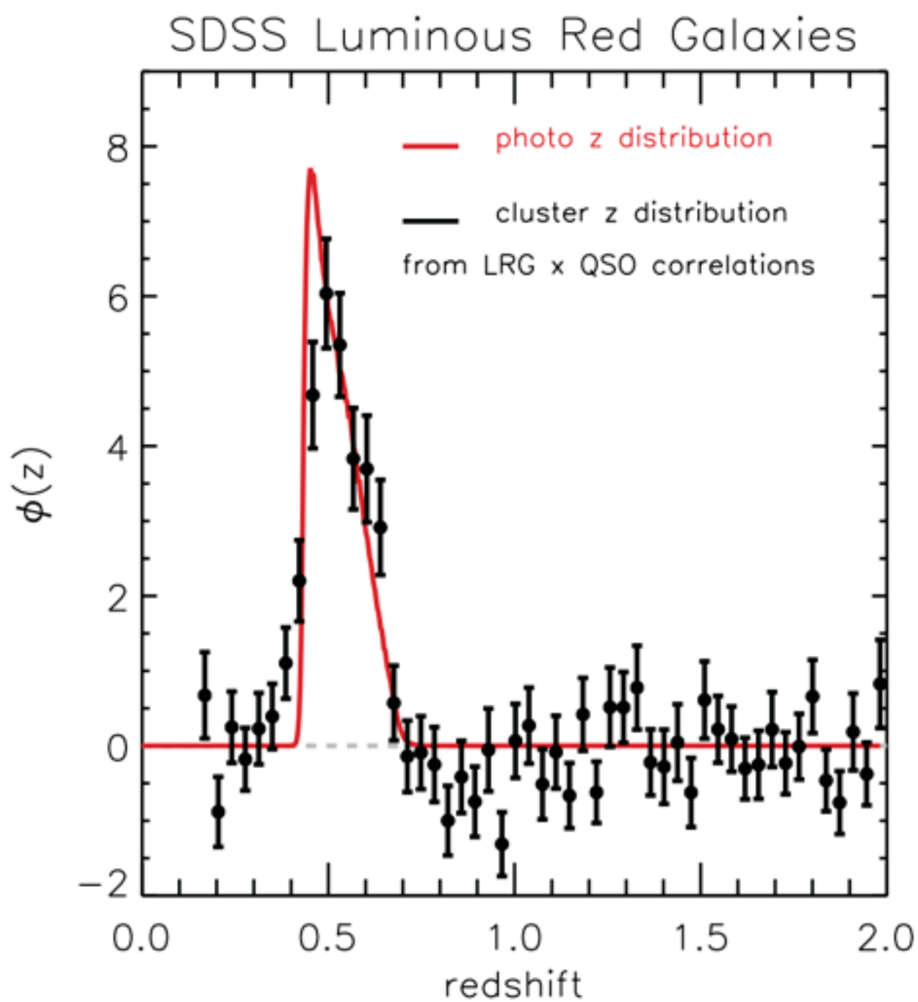


Higher-resolution information can be obtained by cross-correlating with spectroscopic samples

- **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

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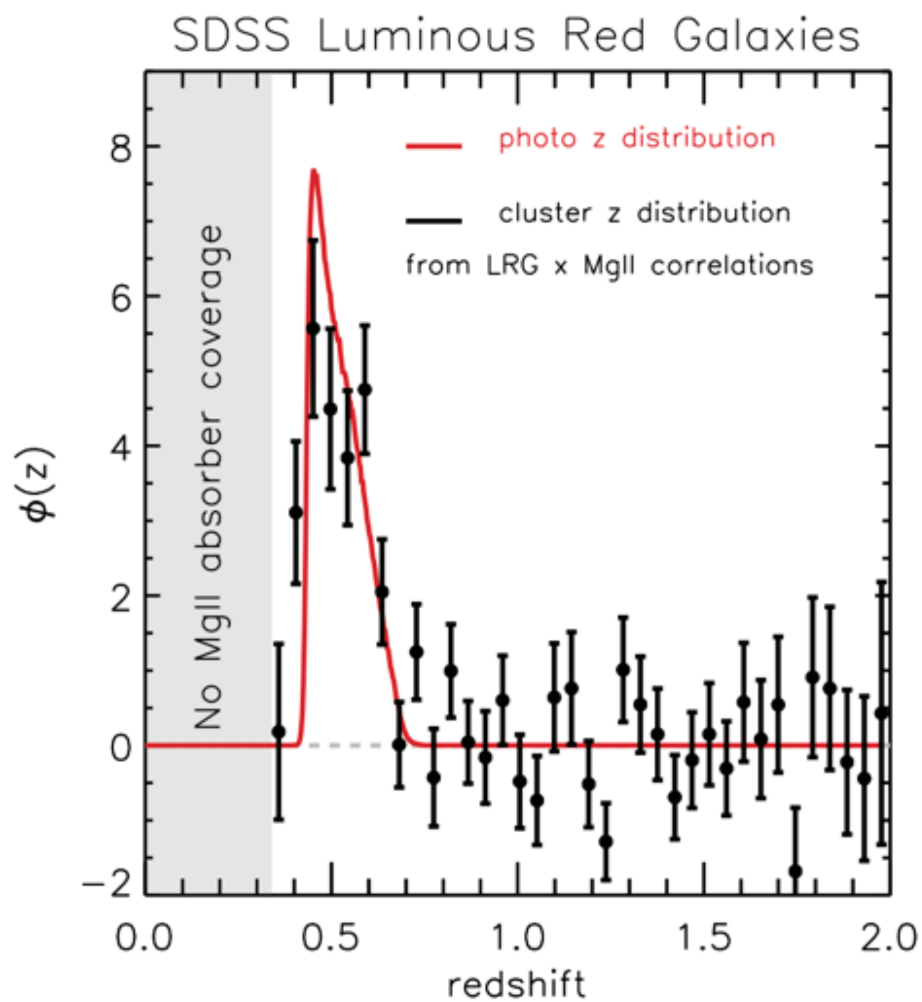
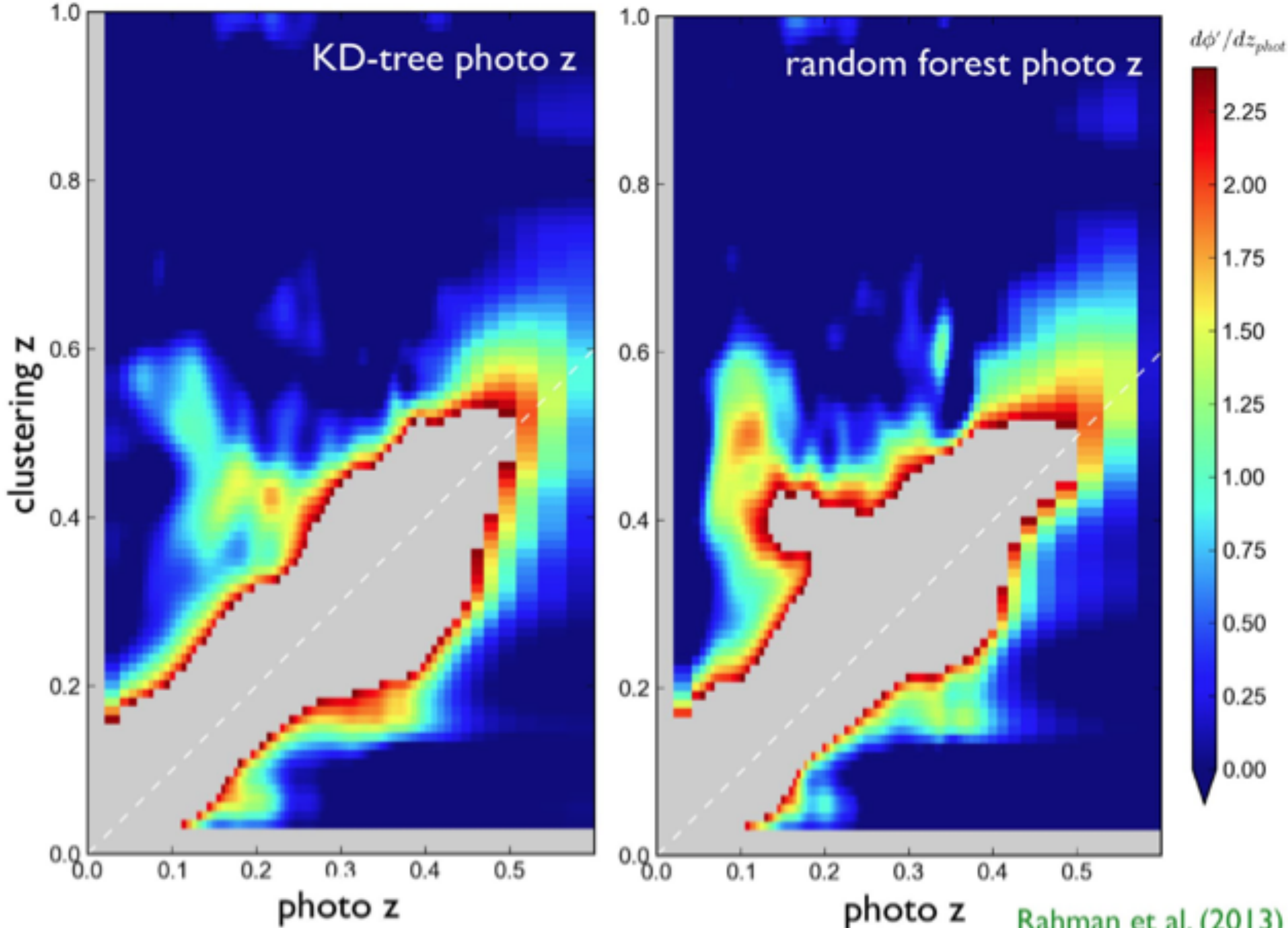
Red: Photo-z distribution for LRGs in SDSS

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)

Relevant planned projects: eBOSS and DESI

- Uses BOSS spectrograph on SDSS telescope 1000 fibers, 7 sq. deg.
- BAO survey of ~650k galaxies & ~850k QSOs, 0.5 < z < 1.5, over 7500 square degrees (~500 sq. deg. overlap with DES)
- Stage III BAO, 2014-c. 2020

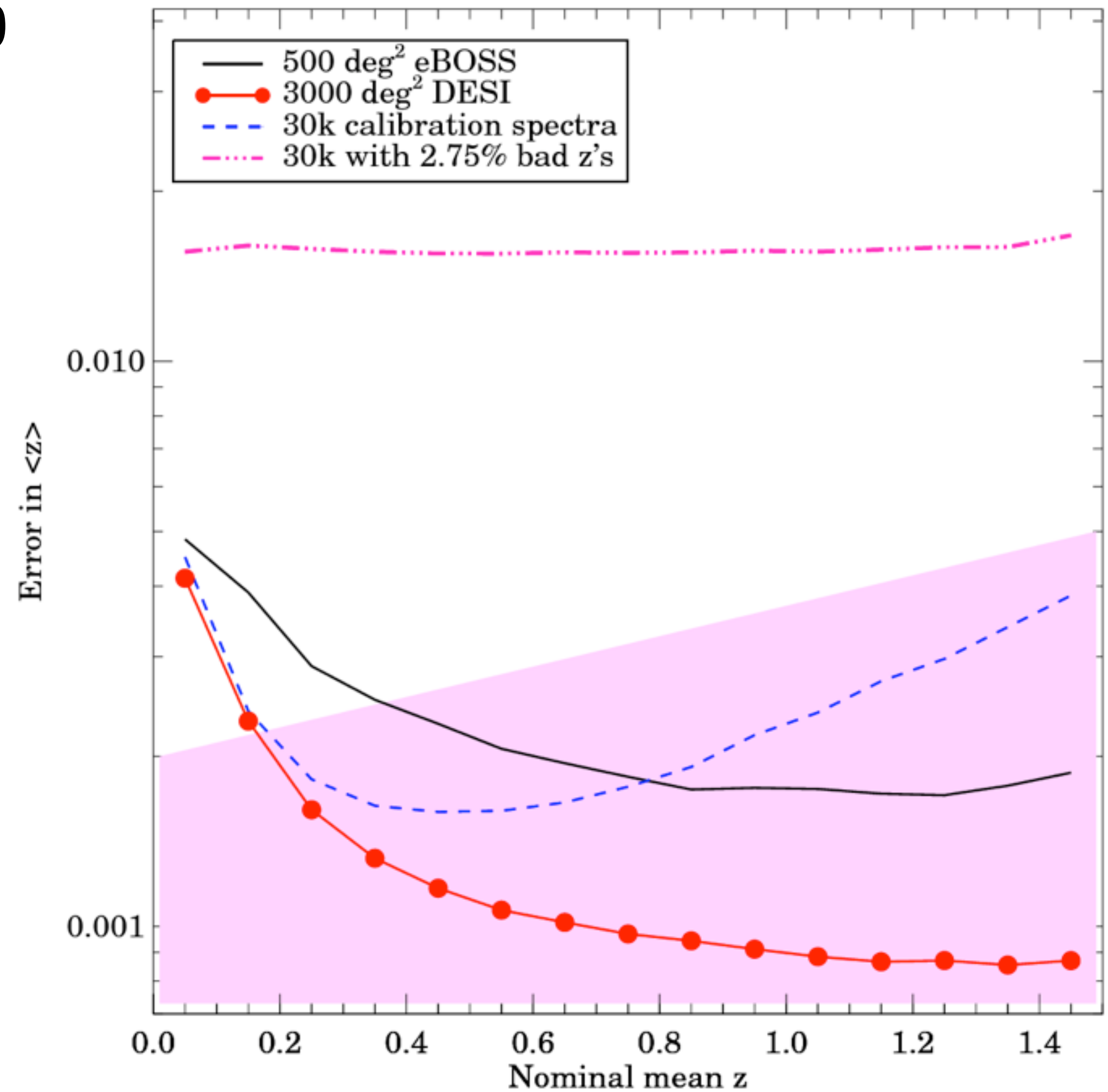
- Add new full-optical spectrograph to 4m Mayall telescope
- 5000 fibers, 7 sq. deg.
- BAO survey of ~20+million galaxies & QSOs, 0.5 < z < 3.5, over ~14k square degrees
- Stage IV BAO, ~2018-2021

DESI can be relevant for deep surveys, too

- Compare DESI vs Subaru/PFS:
  - 5000 fibers vs 2500
  - 4m aperture vs 8m
- Getting the same number of photons on the same number of objects will take ~2x longer survey time with DESI
  - >2x the observing time may be available!

Spectroscopic requirements for cross-correlation methods

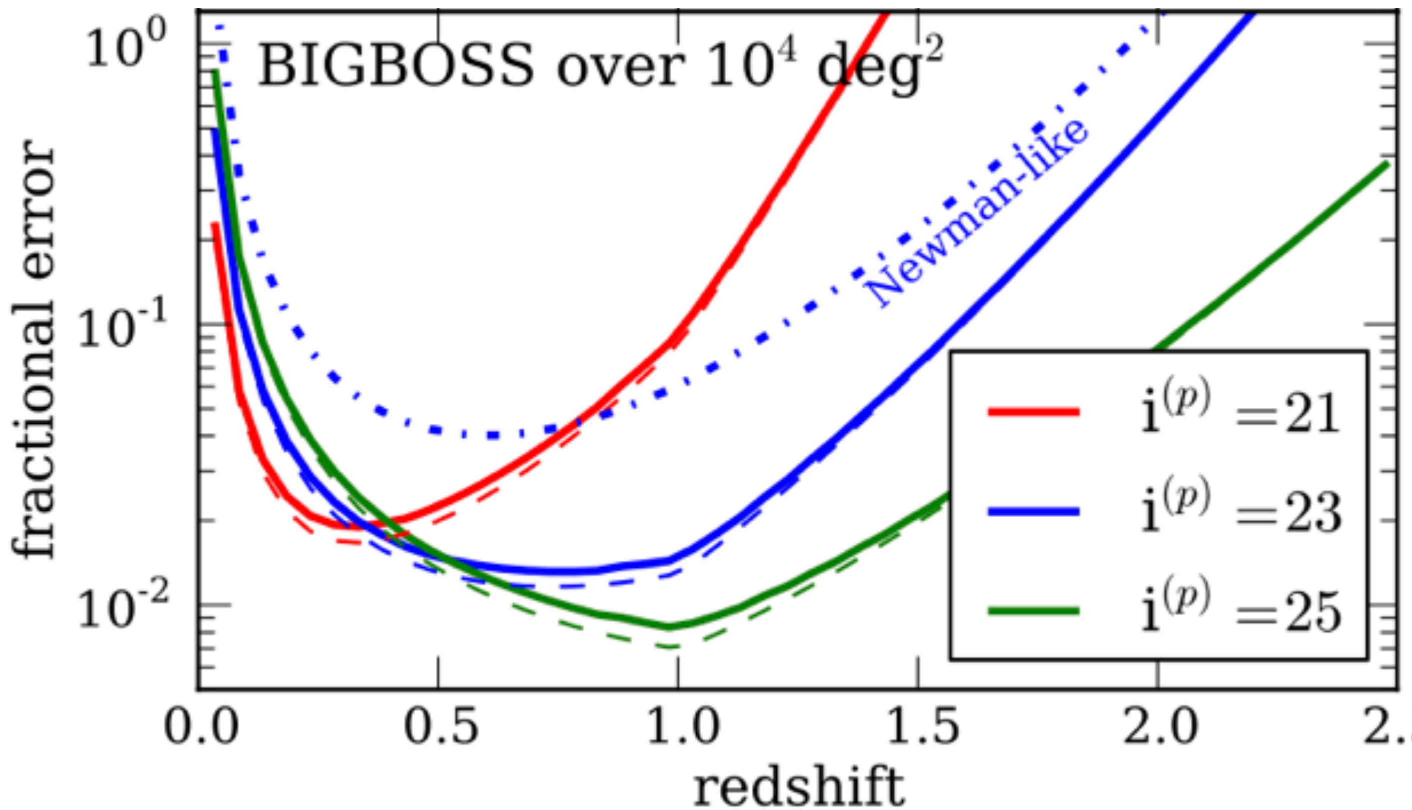
- Want >100k objects over >100 sq. degrees, spanning redshift range of photometric sample
- >500 square degrees of overlap with DESI-like survey sufficient for needs
- Expected ~3000 deg^2 overlap between DESI and LSST is comparable to 100% complete sample of 100k spectra with no false z's!
- The cross-correlations will simultaneously provide information on galaxy evolution



Snowmass White Paper: Spectroscopic Needs for Imaging DE Experiments

Note: those forecasts are pessimistic!

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

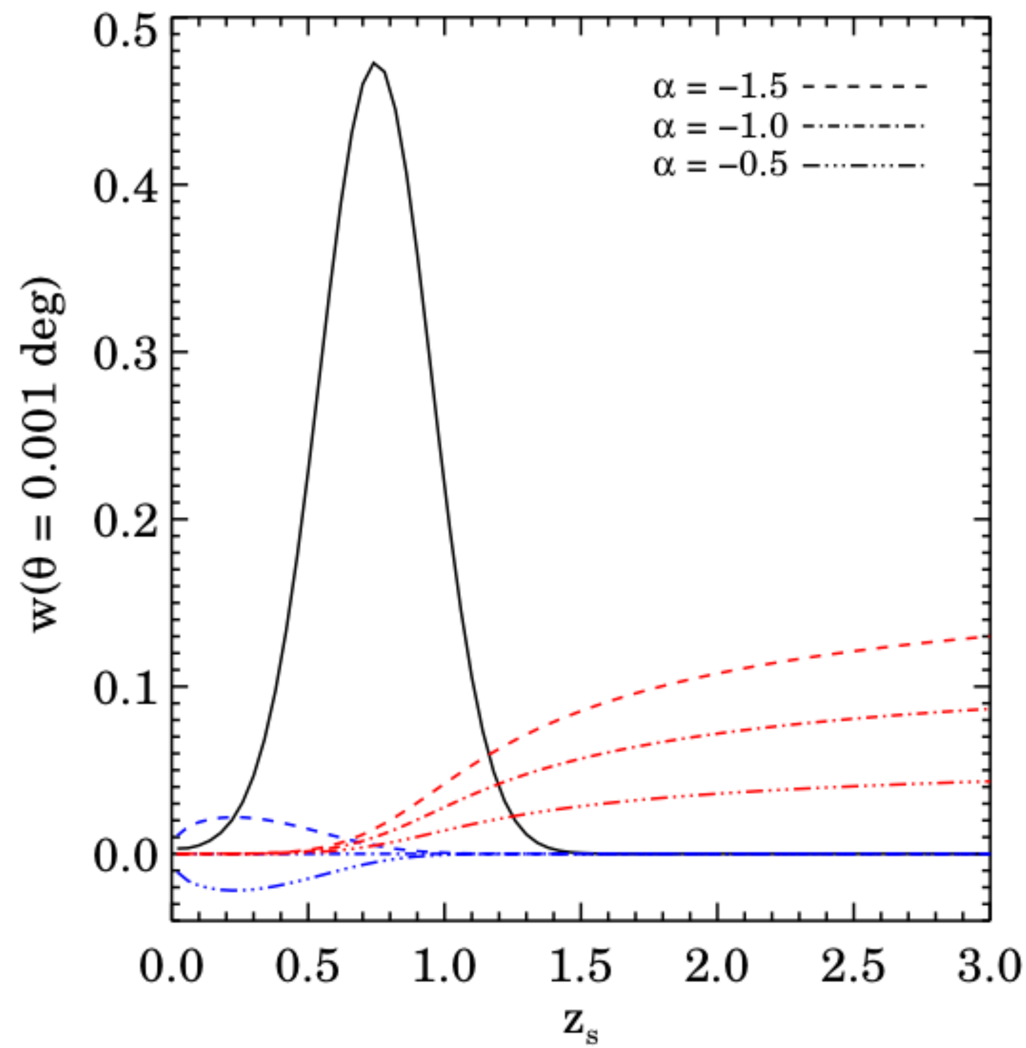


• Makes maximum use of information on linear scales, avoids integral constraint error

• 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.

DESI can otherwise hard projects 'easy'

- The most useful LSST supernovae will be those found in 20-30 repeatedly-imaged 'deep drilling' fields
- >30,000 SNe Ia spread out over 300 square degrees found over 10 years
- Mapping from Keck/DEIMOS experience, 8 hours on DESI should yield redshifts for ~70% of hosts to r~24
  - ~60 nights total on DESI to get redshifts for ~70% of the supernovae - allows typing and cosmological analyses
- This would take >600 nights with VLT/VIMOS, or >2000 nights with Keck/DEIMOS

Conclusions

- Photo-z's are critical for dark energy experiments
- Incompleteness or incorrect redshifts in spectroscopic samples will cause systematic errors in photo-z applications
- Cross-correlation methods can calibrate photometric redshifts even using incomplete samples of only bright galaxies & QSOs
- Minimum LSST photo-z training survey, ~75% complete:
  - 15 widely-separated pointings, ~30,000 spectra to i = 25.3, ~0.4 years on a 20-40m telescope (can do galaxy evolution science simultaneously)
- eBOSS and especially DESI are extremely useful for cross-correlation calibration
- See Snowmass white papers on *Cross-Correlations* and *Spectroscopic Needs for Imaging Dark Energy Experiments*, http://arxiv.org/abs/1309.5384, 1309.5388