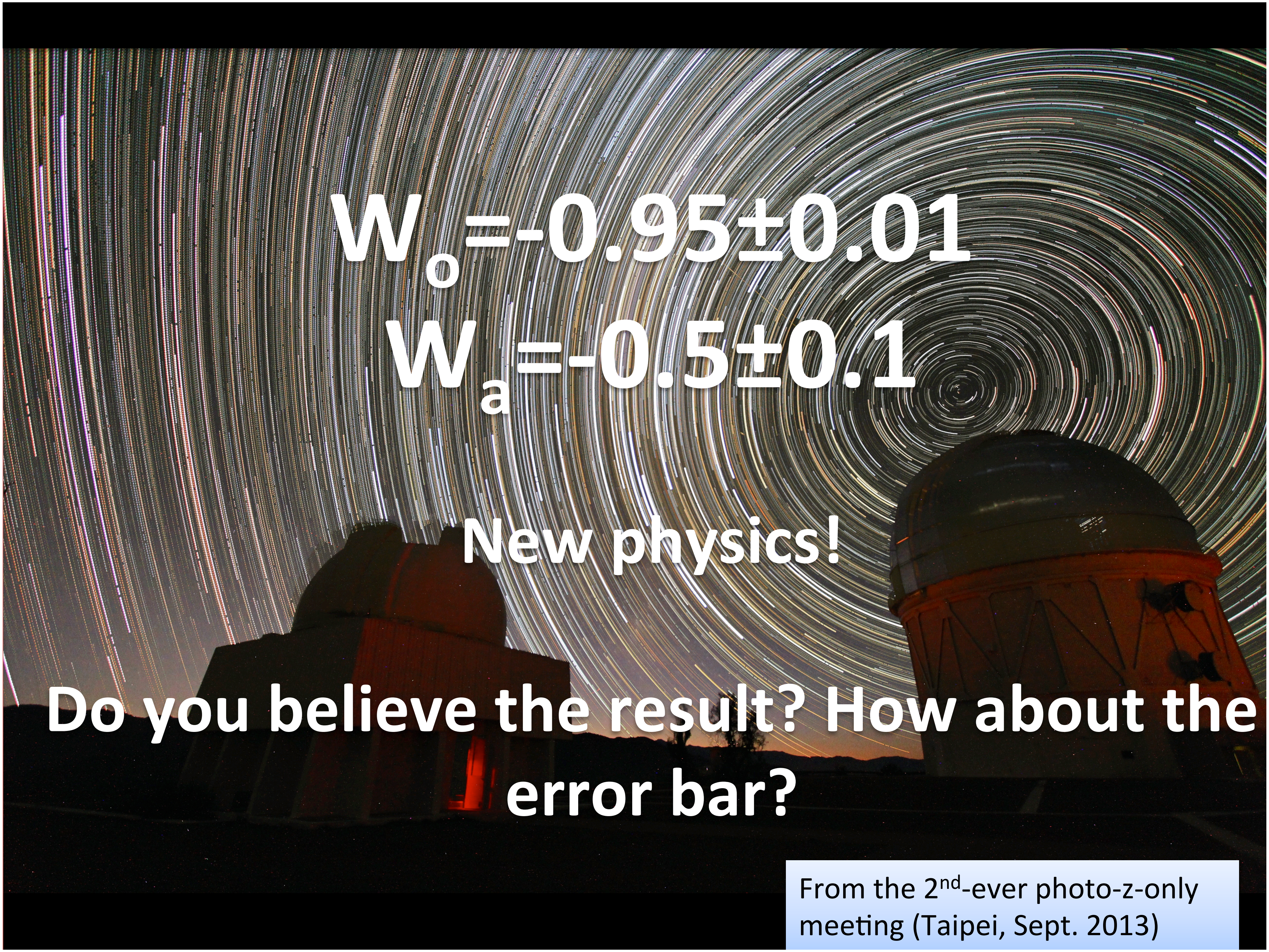
STANFORD UNIVERSITY

KIPAC
KAVLI INSTITUTE FOR PARTICLE ASTROPHYSICS AND COSMOLOGY

Photometric redshifts: The long road ahead

Carlos Cunha
Stanford University

DES/LSST joint meeting, March 26, 2014


W_o=-0.95±0.01
W_a=-0.5±0.1
New physics!
Do you believe the result? How about the error bar?
From the 2nd-ever photo-z-only meeting (Taipei, Sept. 2013)

Study of photo-zs = study of galaxies

- **Regular photo-zs** are a technique of galaxy classification.

- Cross-correlation methods: power spectrum + **Halo Occupation Distributions**

Study of photo-zs = study of galaxy formation

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- We don't trust photo-zs so we can't use them to study galaxies.
- We don't trust photo-zs so we need large spectroscopic samples selected on the photometry of our survey to check that the photo-zs are okay.
- We are not awarded to time to get the large spec-z samples because TACs only award time for galaxy formation proposals.
- Yet, the results of those studies don't trickle down to photo-z studies, nor do our results influence galaxy formation studies.

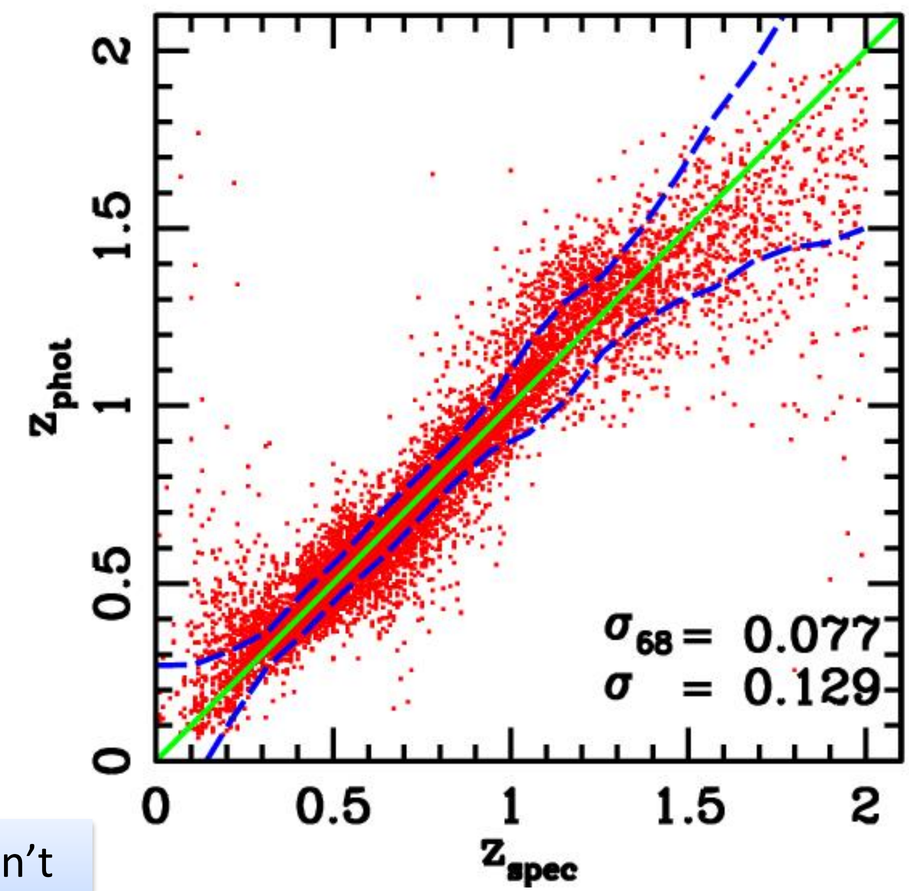
Lightning review of photo-z's

Photo-zs are often not very good.

Three steps before getting to the cosmology:

- **Get photo-zs;**
- **Estimate photo-z errors and cull outliers;**
- **Calibrate error distribution, e.g. $P(z_s|z_p)$.**

Because you don't trust photo-zs

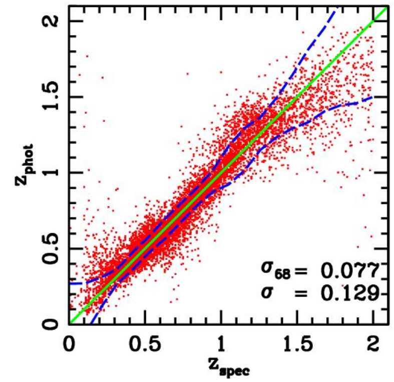


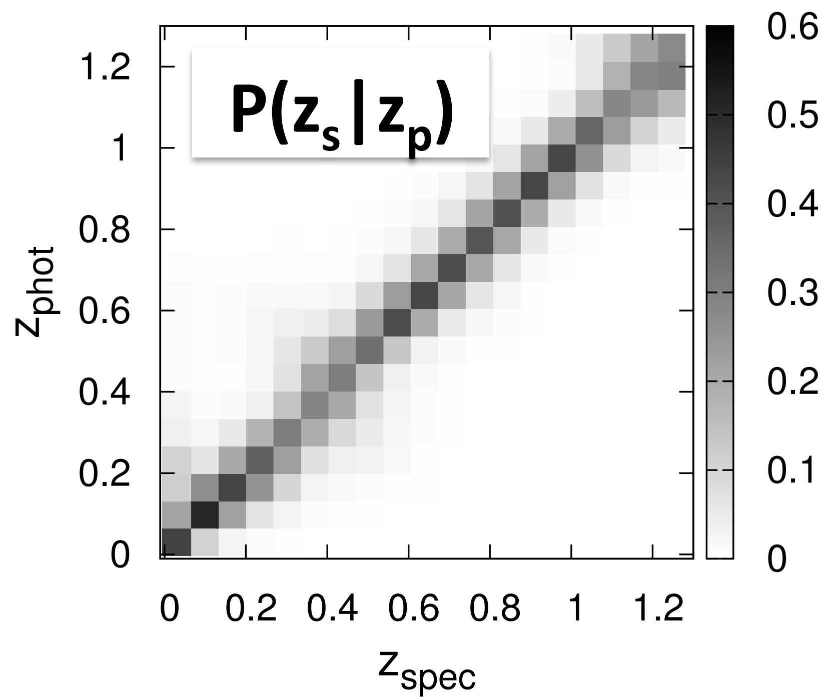
Basics of photo-z's

Photo-zs are often not very good.

Three steps before getting to the cosmology:

- **Get photo-zs; spectra recommended**
- **Estimate photo-z errors and cull outliers; spectra recommended**
- **Calibrate error distribution, e.g. $P(z_s|z_p)$. spectra required**





Need spectra, so what?

Good spectroscopic samples are hard to come by. **Issues**

- **Selection in observables:** typically have many more bright samples than faint samples.
- **Selection in non-observables:** sample selected for a different purpose with different bands (e.g. DEEP2 survey).
- **Shot-noise:** samples are small.
- **Sample variance:** surveys are pencil-beam.
- **Angular variation of photometric depth.**
- **Spectroscopic failures:**
  - Can't get spectra for certain galaxies.
  - Wrong spectroscopic redshifts.

Spec-zs needed!

- Having large, complete spectroscopic samples would solve every photo-z problem.
- **Common issue:** Probably neither DES nor LSST will have sufficient spectroscopic samples for direct photo-z calibration by the time the surveys are well underway.
- **Bare minimum (if no spec-zs):** Correct estimation of photo-z uncertainties and propagation into cosmology.

Living with insufficient spec-zs

Stage I: Acceptance

Can we get by without calibration?

- Difficult to do because of **modeling uncertainties**. We don't know how much we know about galaxies.
- Spectroscopic samples are **incomplete** and we don't know what is being missed.
- **Significant angular variations** in photo-z quality imply that global error statistics are insufficient.

Living with insufficient spec-zs

Stage II: Face your fears (or get someone else to do it for you)

- **Quantify knowledge of galaxy formation.**
  - My ideal: cosmology-style error bananas for a few parameters.
  - Not easy. Physical parameters, SEDs, or color space. Lots of existing surveys with different selection (more on this later).
  - If successful, can use the results for more successful spec-z proposals.
- **Better spectroscopic simulations** to understand incompleteness in existing spec-z samples (e.g. SPOKES).
- **We do have colors.** Can't afford to not use all of this information. Models have to, at the very least, reproduce global properties of observables (e.g. color, mag. distributions – for different surveys). The better the colors, the more stringent this check becomes.

Opportunities for collaboration

- Everyone must push for spectra.
- Quantifying galaxy formation models.
  - Developing success metrics.
  - Comparing to existing surveys.
  - And then making better proposals for spectra.
  - Includes: optimizing targeting strategy to minimize cost (e.g. Carrasco & Brunner 2013, VanderPlas & Connoly 2009) – still need to connect to cosmology.
- DES + eBOSS: testbed for cross-correlations.
- Adding CMB lensing.
- Reducing direct calibration requirements (with cross-correlations, lucky patches, …).
- **Sharing simulation resources and algorithms**. Quick photometric simulations needed for monte carlo studies and galaxy parameter estimation. Modular architecture is key.
  - DES: wide-area N-bod/HOD?yspectro-photometric
  - LSST: photon-by-photon

Code work

- **Training set methods**
  - How to handle variable observing conditions. Angle-dependent solution needed.
  - Don't extrapolate.
  - Require dedicated spectra.
- **Template-fitting methods**
  - No code can be flexible enough.
  - Priors are difficult to implement correctly due to photometry errors and incompleteness.
  - Do not check/enforce global constraints on observable properties (thereby throwing away valuable information).
  - Slow.

Code work

- Training set methods
  - Slow.

Better: Use simulations.

- Combine speed of training sets, extrapolation power of models, global constraints.

- Compare different surveys consistently.

- Simulation parameters directly comparable to galaxy evolution studies

Quantifying knowledge of galaxy formation

- In terms of physical parameters:
  - Good: Most general, and easiest to connect to galaxy formation studies.
  - Bad: Often not self-consistent: SEDs often implicitly assumed for K-corrections and other derivations.
  - Existing physical models have fundamental limitations.
- In terms of SEDs.
  - Good: Small number of SEDs covers most space (e.g. Yip et al, Blanton et al.)
  - Bad: Discrete set. Difficult to perturb.
- In terms of colors: PLEASE, NO!
  - Can't redshift colors.
  - Difficult to map from one survey to another.

Quantifying knowledge of galaxy formation

- In terms of physical parameters:
  - Good: Most general, and easiest to connect to galaxy formation studies.
  - Ba … K-
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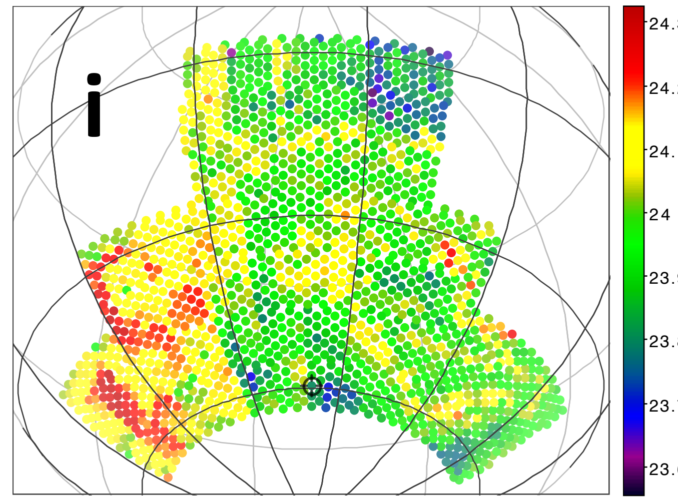
  - Ex
- In ter
  - Go … nton et
    al.
  - Ba
  - W … feed
    ba
- In ter
  - Ca
  - Di

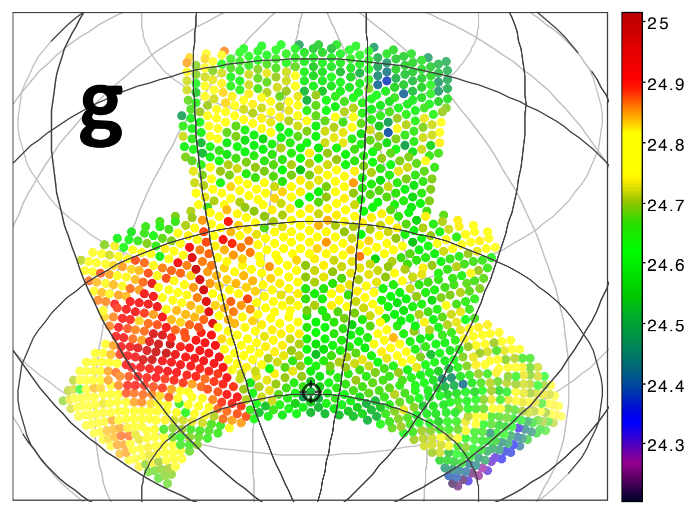
The good news: We only worry about photometric properties, so resolution of SEDs doesn't have to be too high (though it has to be higher than you might think).

Eternal dichotomy: SEDs vs. priors: local galaxies are representative until what redshift?

Strong angular dependence of photo-z scatter

DES 5yr
mag – limits





Conclusion

- Mistrust of photo-zs implies enormous costs to verify that photo-zs are okay.

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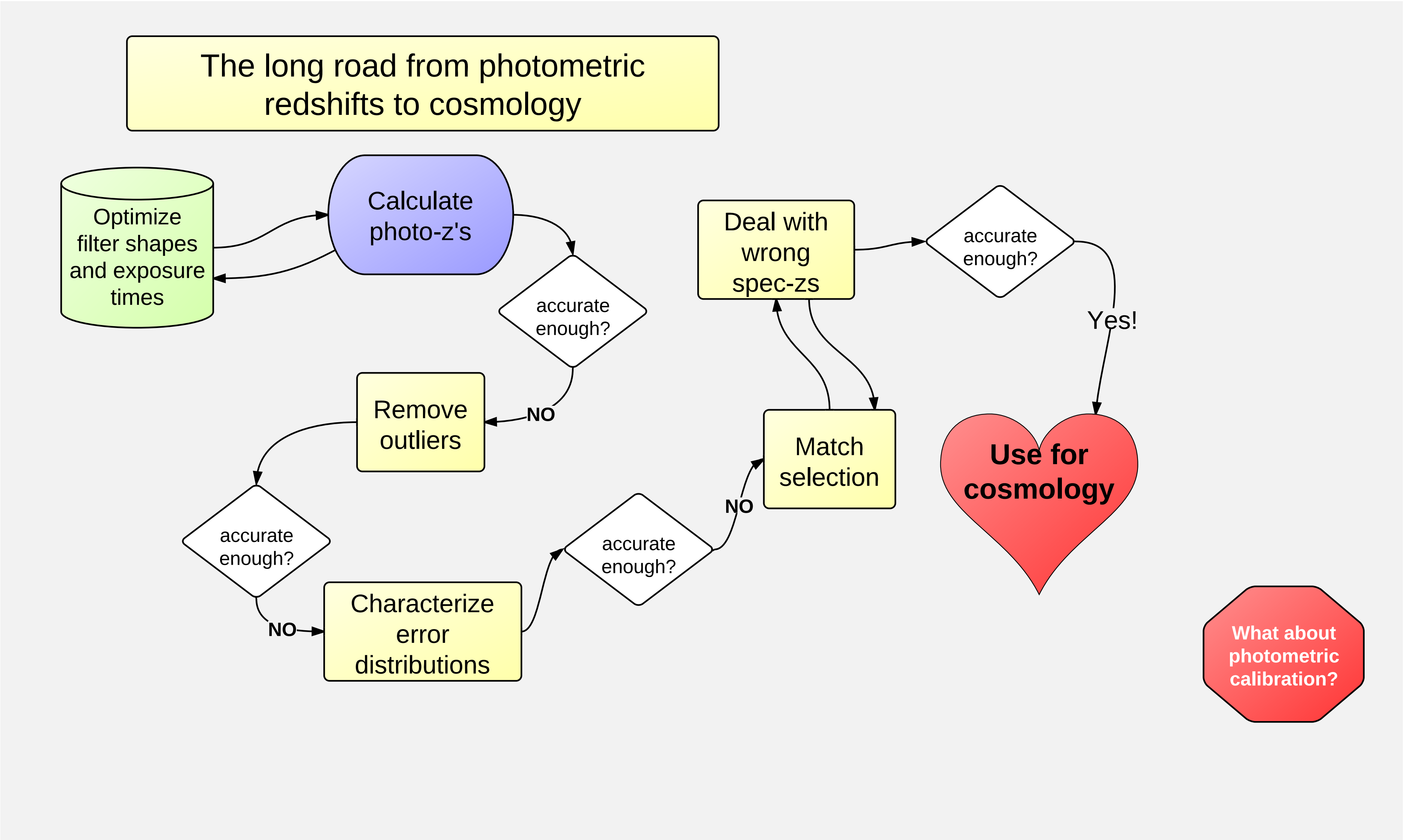
- But galaxy formation studies require redshifts.
- Both have to be done simultaneously.

Conclusion

- Mistrust of photo-zs implies enormous costs to verify that photo-zs are okay.
- We cannot trust photo-zs because we don't trust our understanding of galaxy populations and distributions.
- But galaxy formation studies require redshifts.
- Both have to be done simultaneously.
- Simulations are the best framework with which to assess our state of knowledge (and I'll only trust cosmological results from LSST when we can produce a photometric simulation that closely resembles observations).

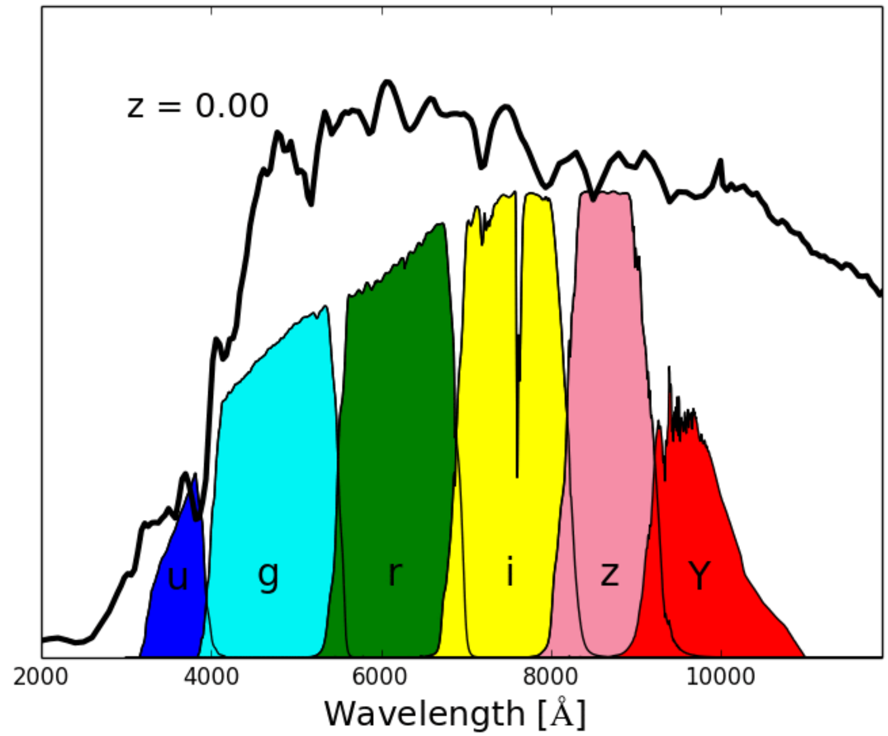
Other issues

- photometry errors.
- …
- …
- …
- …


The long road from photometric redshifts to cosmology
Optimize filter shapes and exposure times
Calculate photo-z's
accurate enough?
NO
Remove outliers
accurate enough?
NO
Characterize error distributions
accurate enough?
NO
Match selection
Deal with wrong spec-zs
accurate enough?
Yes!
Use for cosmology
What about photometric calibration?

Basics of photo-zs

- Probe strong spectral features (4000 Å break)
- Flux in each filter depends on galaxy's type and redshift.



Terminology:

magnitude = A – log(flux)
color = magnitude - magnitude

Need spectra, so what?

Good spectroscopic samples are hard to come by. **Solutions**

- **Selection in observables: e.g. Weights** (Lima, Cunha et al 2008)
- **Selection in non-observables: Don't do it.**
- **Shot-noise: need many galaxies**
- **Sample variance: need lots of area.**

Cunha et al. 2012a

- **Spectroscopic failures:**
  - **Can't get spectra for certain galaxies.**
  - **Wrong spectroscopic redshifts.**

Cunha et al. 2012b

Weights

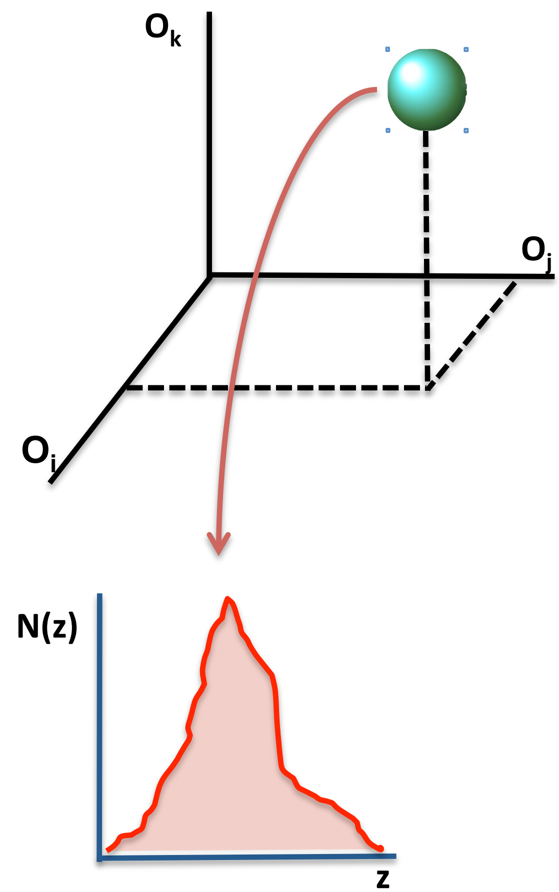
Match distributions of observables in **training** (spectroscopic or simulated) sample and **photometric** sample by assigning **weights** to training set galaxies.

$$Weight \propto \frac{\rho_{photo}}{\rho_{train}} \quad \text{where} \quad \rho_i = \frac{N_i}{V}$$

N_i : number of galaxies within ball of volume V.

The radius of the ball is determined by the distance to 100th nearest neighbor in the training set in space of observables (colors and magnitudes).

Assumption: Training set is **locally** representative of photometric set.
Is that true? Yes, **if** differences in selection are only in observable space.



The Dark Energy Survey

- Study Dark Energy using 4 complementary techniques:
  I. Cluster Counts
  II. Weak Lensing
  III. Baryon Acoustic Oscillations
  IV. Supernovae

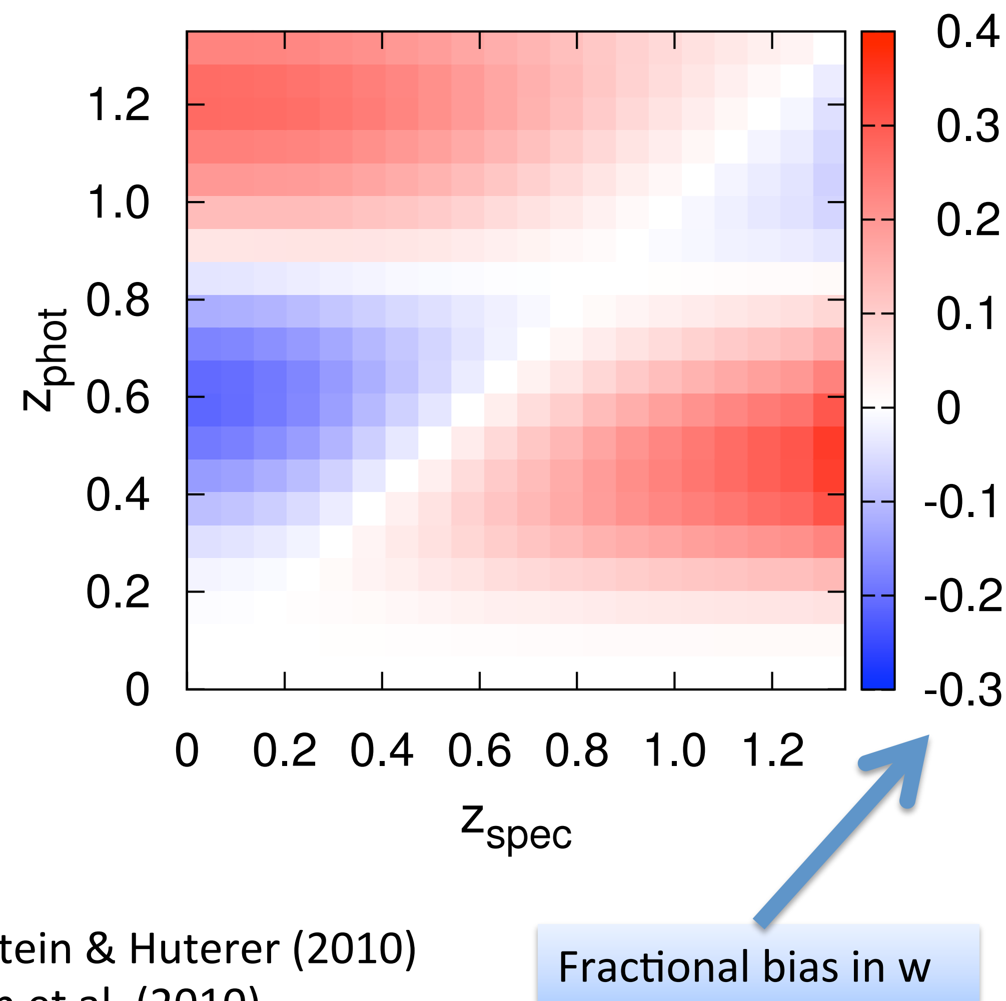
- Two multiband surveys:
  Main: 5000 deg^2 ≈ 5 (h^{-1}Gpc)^3
  300 million galaxies
  g, r, i, z, Y to 24th mag
  SNe: 15 deg^2 repeat

- Build new 3 deg^2 FoV camera and Data management sytem in Blanco 4-m telescope
  Survey 2012-2017 (525 nights)
  Camera available for community use the rest of the time (70%)

www.darkenergysurvey.org

Biases in w from error in $P(z_s|z_p)$ estimation

- Fixed **0.01** error in $\mathbf{P(z_s|z_p)}$ estimation, i.e, **$\Delta P(z_s|z_p)$ =0.01** at a single bin.
- For DES shear-shear analysis.



Bernstein & Huterer (2010)
Hearin et al. (2010)
Cunha et al. 2012a

Biases due to sample variance

Sample variance

For typical existing spectroscopic samples, sample variance is significantly larger than shot noise.

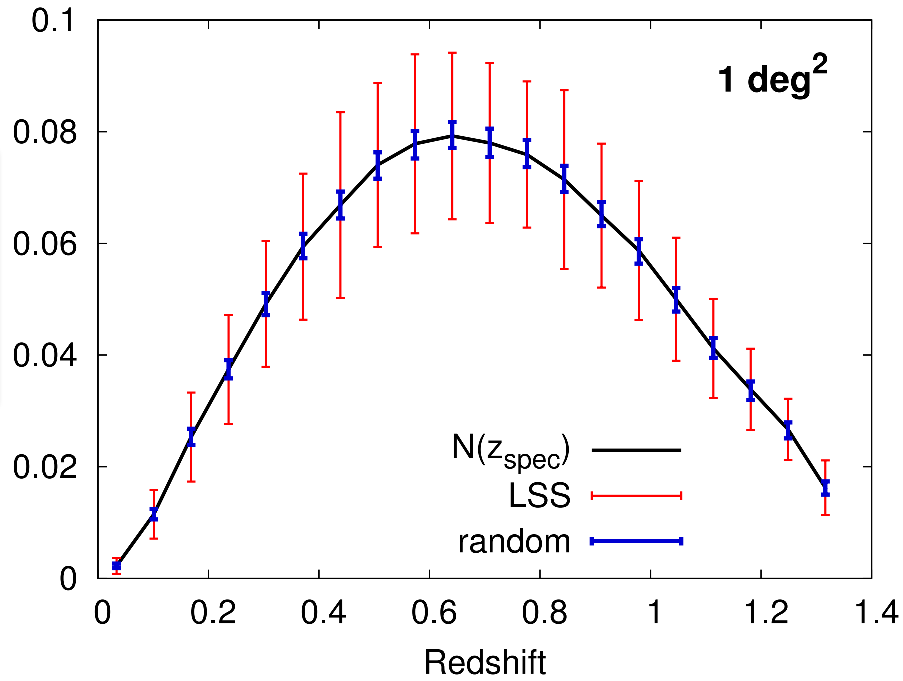


Figure 1. Normalized spectroscopic redshift distribution for the full data. The red (light gray) error bars show the 1-σ variability in the redshift distribution for contiguous 1 deg^2 angular patches. The blue (dark gray) error bars show the variability in the redshift distribution assuming random samples of with the same mean number of objects as the 1 deg^2 patches. We assume that only a 25% random subsample of each patch is targeted for spectroscopy, yielding about 1.2×10^4 galaxies per patch on average.

Cunha, Huterer, Busha & Wechsler
arXiv: 1109:5691

Sample variance in photo-zs and zspecs

Example:

Distribution of galaxies in photometric sample:

z_{phot}

1	1	2
1	6	1
2	1	1

z_{spec}

Distribution of galaxies in calibration sample:

z_{phot}

1	1	4
1	6	2
2	1	2

z_{spec}

LSS fluctuation!!!

Sample variance in photo-zs and zspecs

photometric sample:

1	1	2
1	6	1
2	1	1

calibration sample:

1	1	4
1	6	2
2	1	2

$P(z_p|z_s)$

0.25	.125	0.50
0.25	0.75	0.25
0.50	.125	0.25

=

0.25	.125	0.50
0.25	0.75	0.25
0.50	.125	0.25

$P(z_s|z_p)$

0.25	0.25	0.50
.125	0.75	.125
0.50	0.25	0.25

≠

.167	.167	.667
.111	.667	.222
0.4	0.2	0.4

Colums: z_{phot}

Rows: z_{spec}

Sample variance in photo-zs and zspecs

photometric sample:

1	1	2
1	6	1

calibration sample:

1	1	4
1	6	2

Conclusion:

$P(z_s|z_p)$ is sensitive to z_{spec} fluctuations, but **$P(z_p|z_s)$** is not. Conversely, only **$P(z_p|z_s)$** is sensitive to z_{phot} fluctuations.

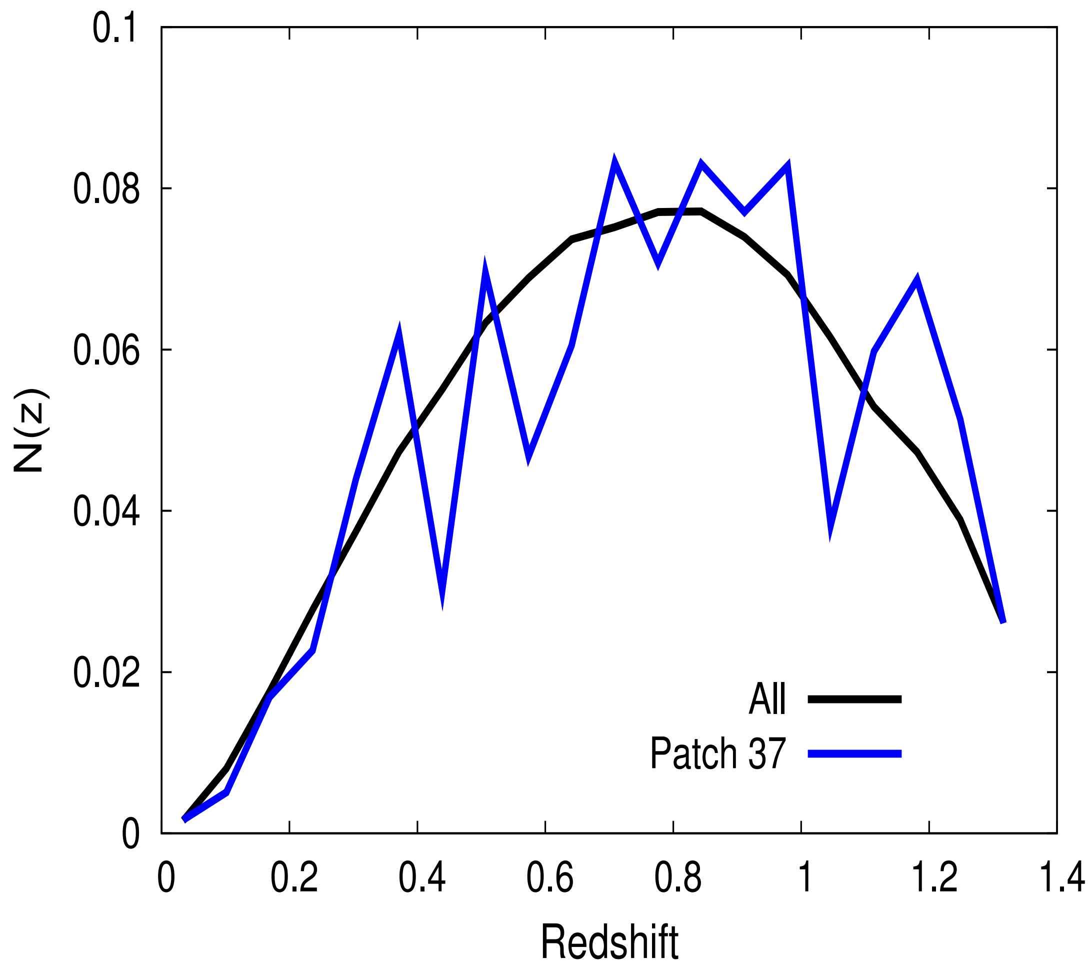
$P(z_s|z_p)$

.125	0.75	.125
0.50	0.25	0.25

$\neq$

.111	.667	.222
0.4	0.2	0.4

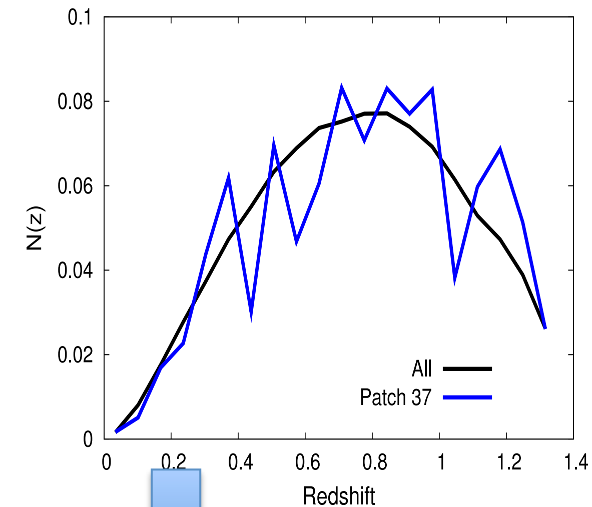
Example: Patch 37



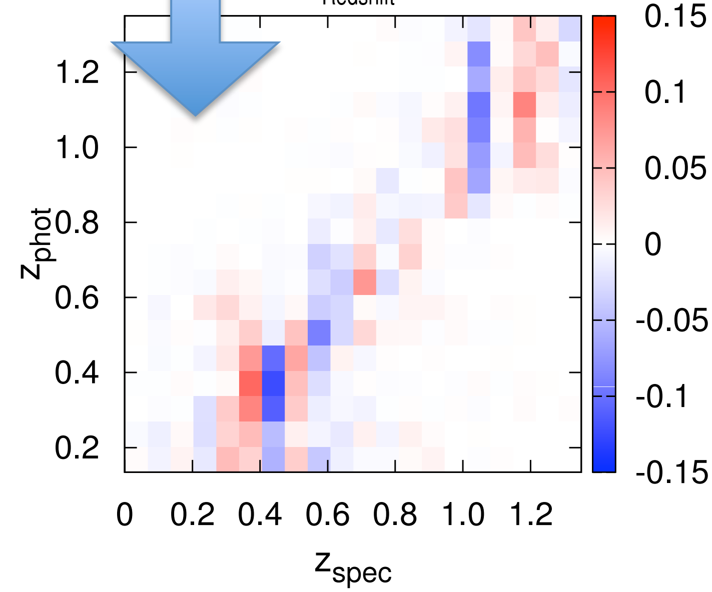
Example: Patch 37

An example:

- Errors in $N(z_{spec})$ translate into errors in the error matrix estimation.



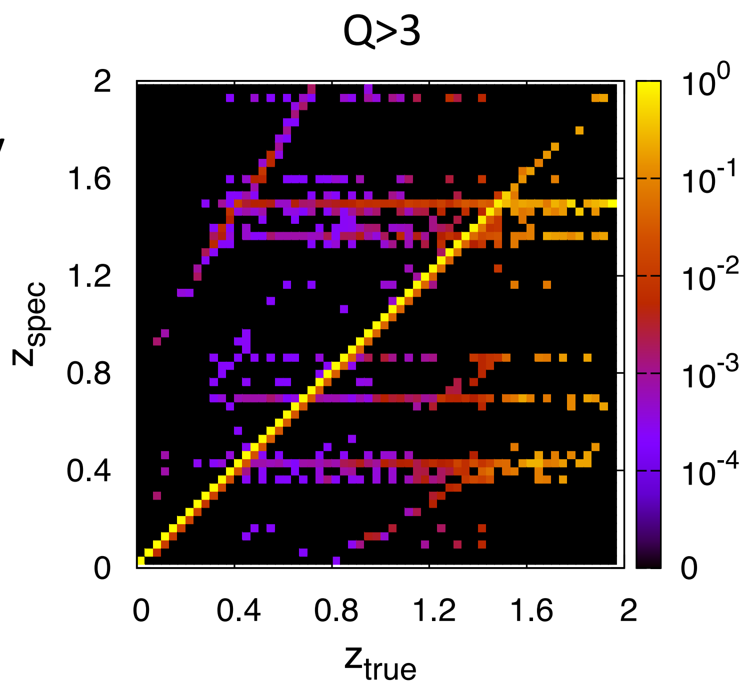
$$\Delta P(z_s|z_p) = P(z_s|z_p)_{phot} - P(z_s|z_p)_{train}$$



Spectroscopic failures (wrong redshifts)

Issues:

- When spec-z's are wrong, they're really wrong.
- A small speck of wrong redshifts is enough to mess up cosmological constraints.



Sample used in the plot has 98.6% correct redshifts and constitutes 60% of total sample.

Q: cross-correlation parameter (measures redshift confidence)

Case study: Simulations of

DES photometry + VVDS-like spec-z's

Cunha, Huterer, Lin, Busha, Wechsler et al, 2012b

Conclusions

- **Incompleteness:**
  - **Does not introduce cosmological biases** if selection matching is performed.
  - Statistical constraints suffer with reduction of sample size.

- **Wrong redshifts:**
  - Cause severe biases.
  - Need better than 99% correct redshifts.
  - If 99% accuracy not possible, need to calibrate spectroscopic error distribution $P(z_{true}|z_{spec})$ with deeper sample/better instrument.

- **Moral of the story:** Focus has to be on accuracy of derived redshifts.

How can we get so many spectra?

<u>Existing instruments:</u>

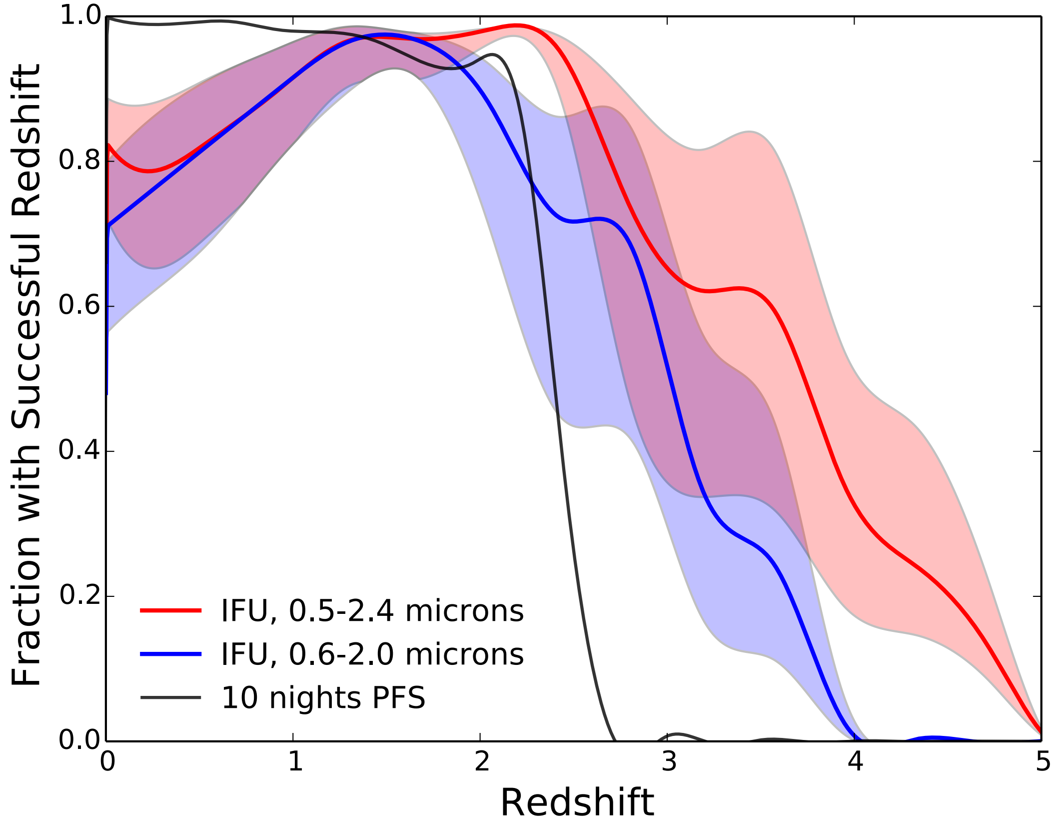
- VLT (8-m)
- Magellan (6.5 m)
- Gemini (8-m)
- Keck (10-m)

<u>Planned:</u>

- PFS on Subaru (8 m)
- ngCFHT (8 m)
- IFU on WFIRST (2.5 m)
- GMACS (24.5 m)

Why an IFU on WFIRST?

- About 3000 sq degrees.
- few $\times 10^4$ low-res spectra
- Extending LSST calibration beyond z~2 can improve FoM by 30-40%.



In collaboration with S. Perlmutter, J. Newman and C. Hirate