DEEP2 and Beyond: Studying the Universe with Surveys

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Feb. 2007

Outline

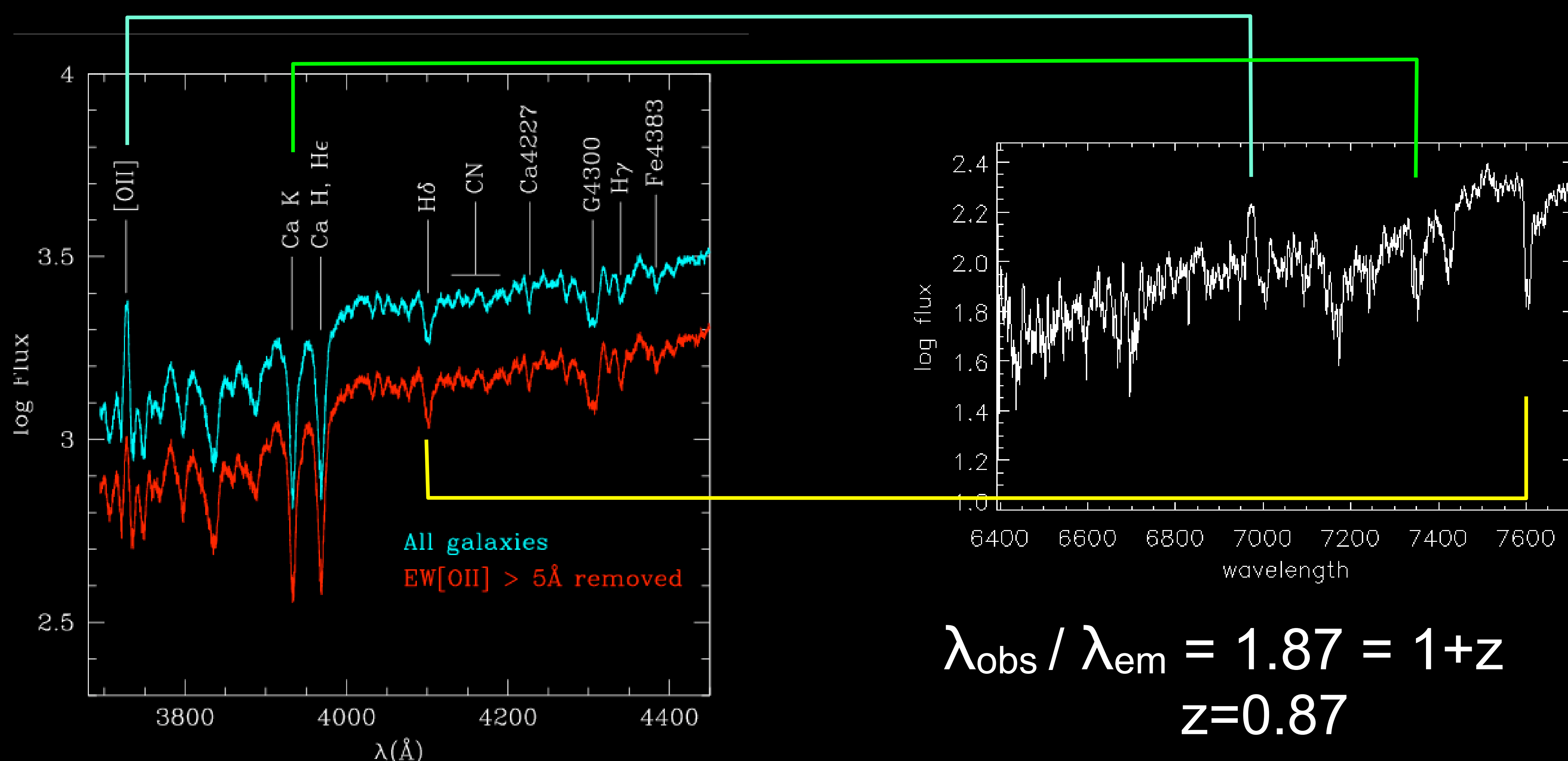
I. The DEEP2 Galaxy Redshift Survey
II. Testing for variations in the Fine Structure Constant
III. Calibrating Dark Energy experiments with Redshift Surveys
IV. The power of serendipity

Things I won't talk about

95% of the results from DEEP2 (e.g. studies of galaxy evolution, tests of dark energy models)

Measuring Redshifts

The *redshift* ($z \equiv \Delta\lambda/\lambda$) of an object measures how much the Universe has expanded since light left it (size of Universe ∝ $1/(1+z)$). The distance (or lookback time) to an object is a monotonic function of z.

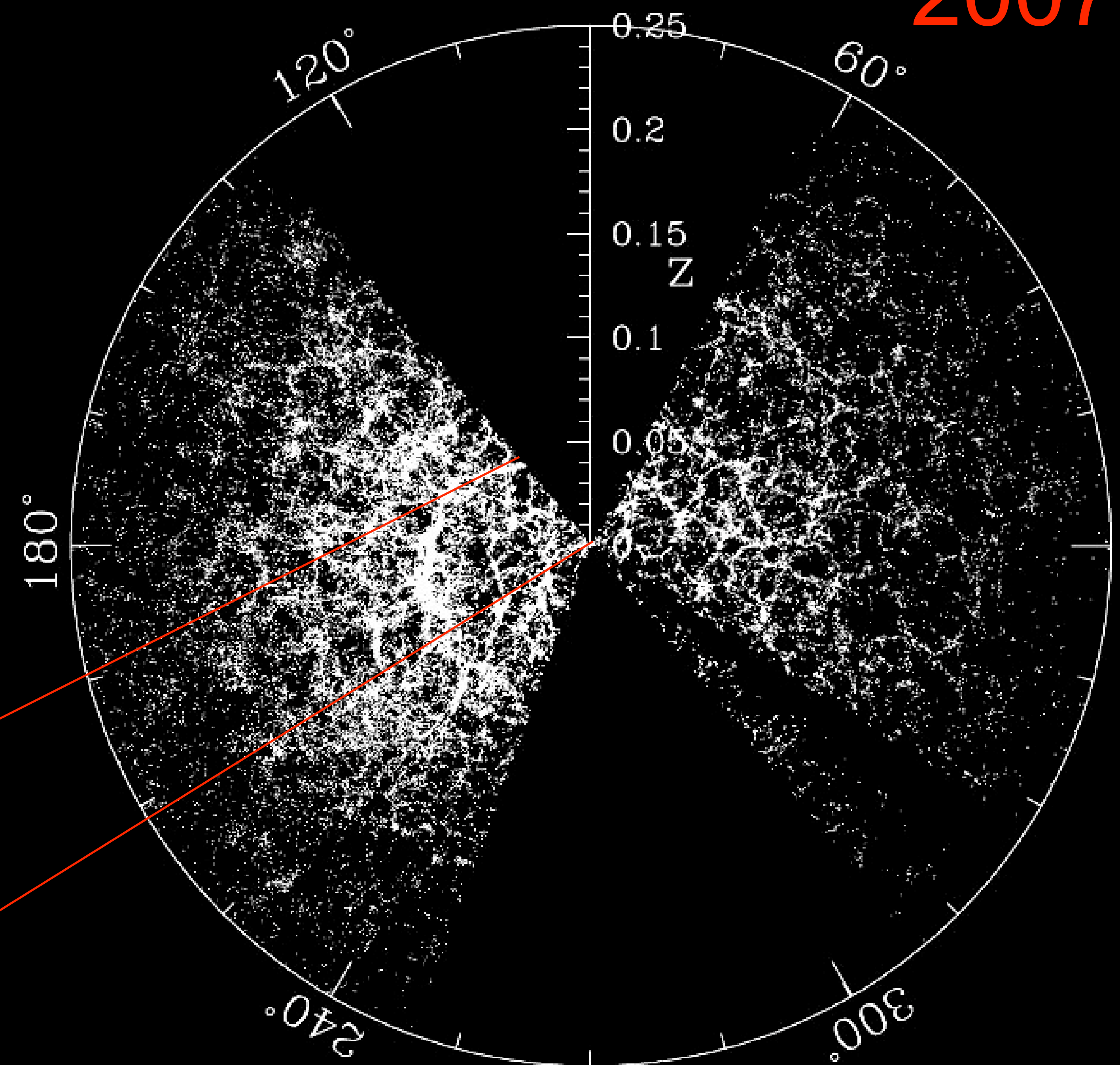


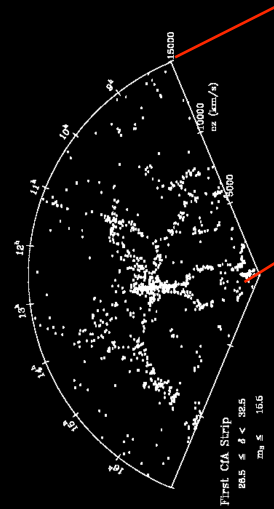
$$\lambda_{obs} / \lambda_{em} = 1.87 = 1+z$$

$$z=0.87$$

Local redshift surveys

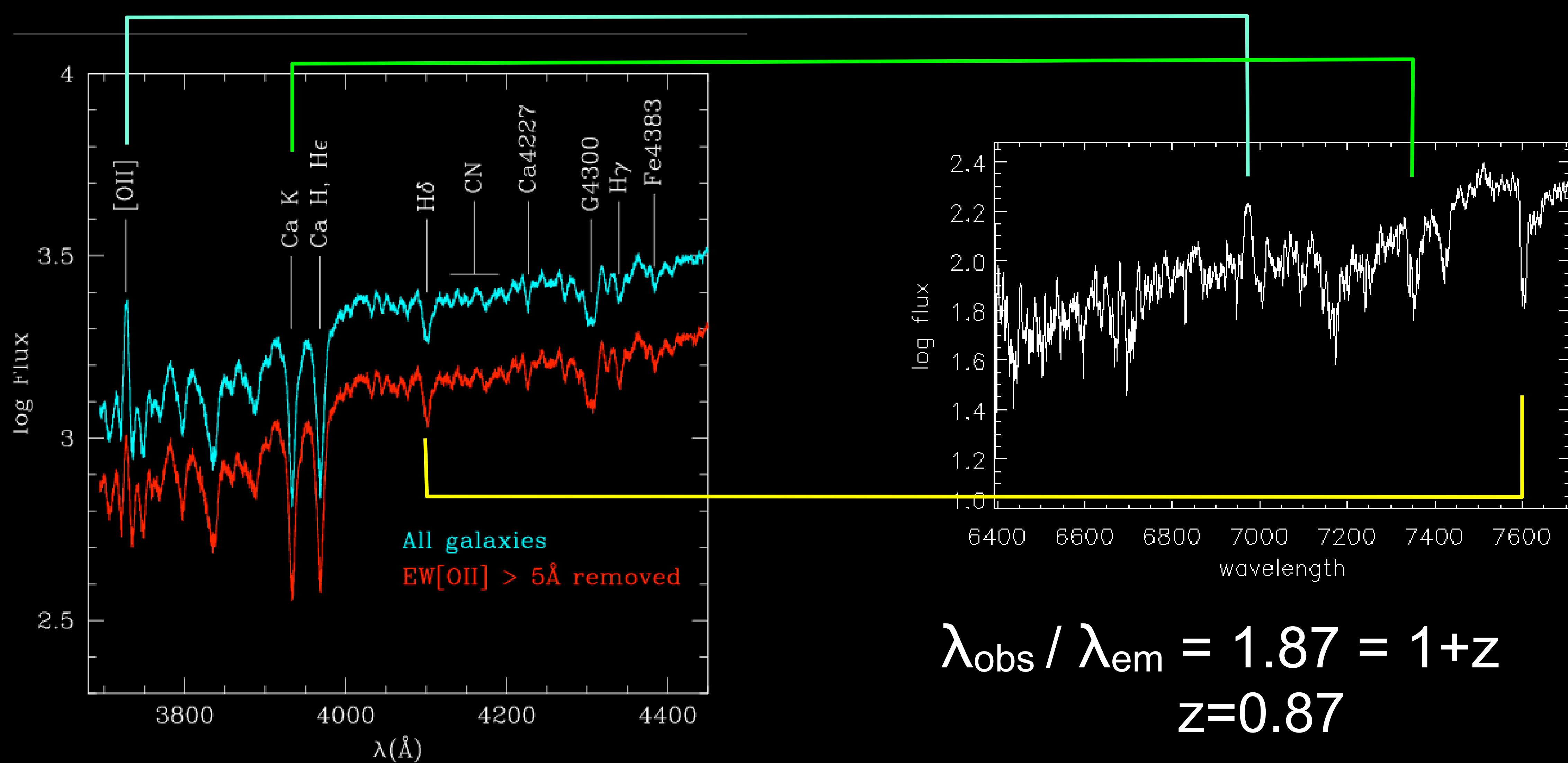
Over the past ~25 years, surveys of the local Universe have progressed from mapping out 2500 galaxies in a thin slice of sky (Davis et al.'s CfA1) to $\sim 10^6$ over one-fourth of the sky (Sloan Digital Sky Survey)





Other information from redshift surveys

A redshift survey tries to map out and measure statistics of the “large-scale structure” traced by some class of objects (e.g. galaxies); but the same data can be used to measure the demographics of galaxy properties.



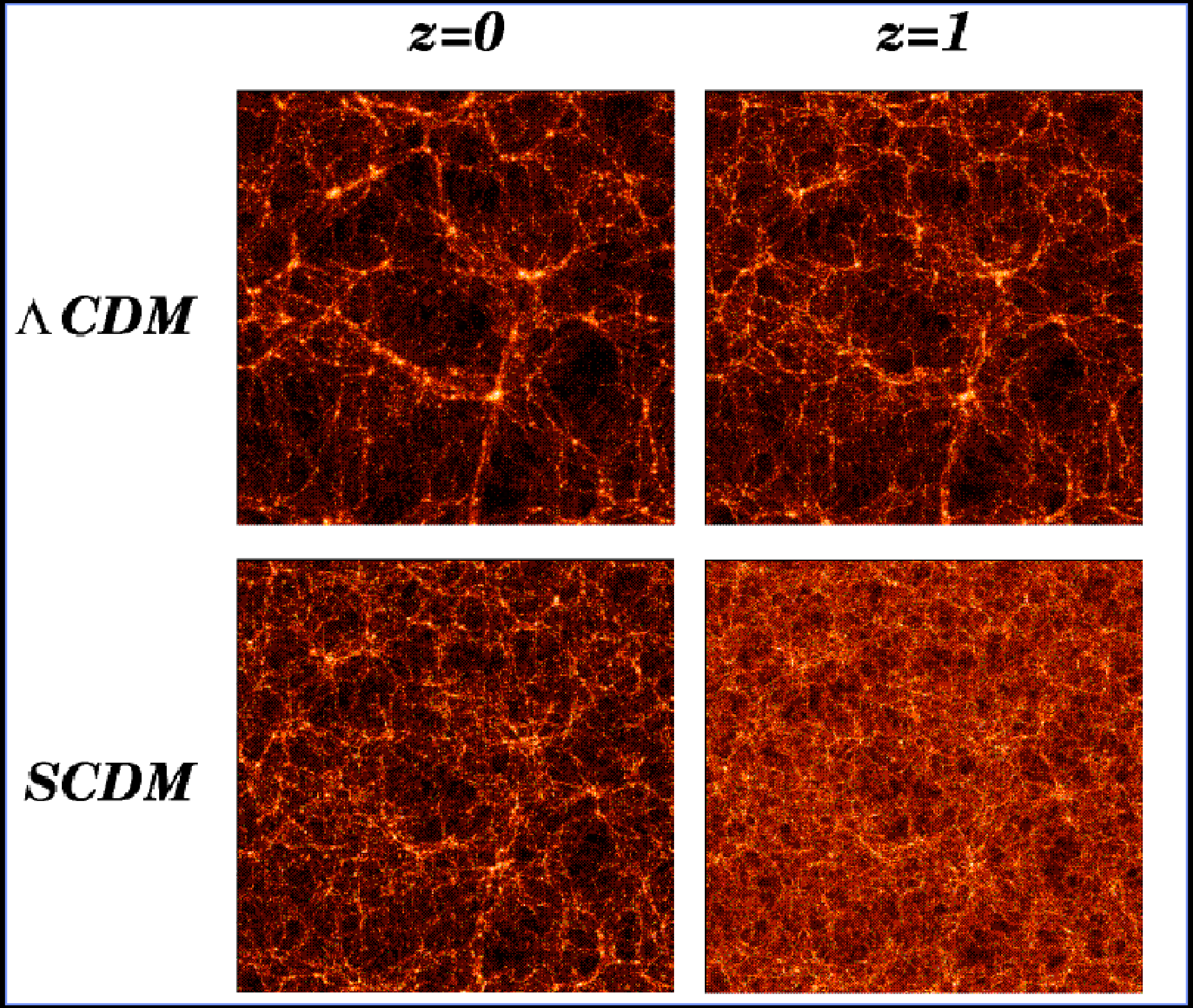
$\lambda_{obs} / \lambda_{em} = 1.87 = 1+z$

$z=0.87$

Surveys of *distant* galaxies can constrain both cosmology and galaxy evolution

The evolution of the pattern of filaments and voids traced out by galaxies - the large-scale structure - is strongly dependent on the underlying cosmology.

By comparing the universe at high redshift to z=0, one can perform many unique cosmological tests and simultaneously study galaxy formation and evolution.



DEEP2: A Redshift Survey at *z*~1

DEEP2 (= DEEP Extragalactic Evolutionary Probe 2) studies both galaxy properties and large-scale structure at z~1.

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M. Davis (PI)
J. Newman
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Steward Obs.

A. Coil
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A. Metevier
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N. Konidaris
J. Harker
G. Graves

Princeton

C. Conroy

Harvard

D. Finkbeiner

U. Pitt.

A. Connolly

U. Hawaii

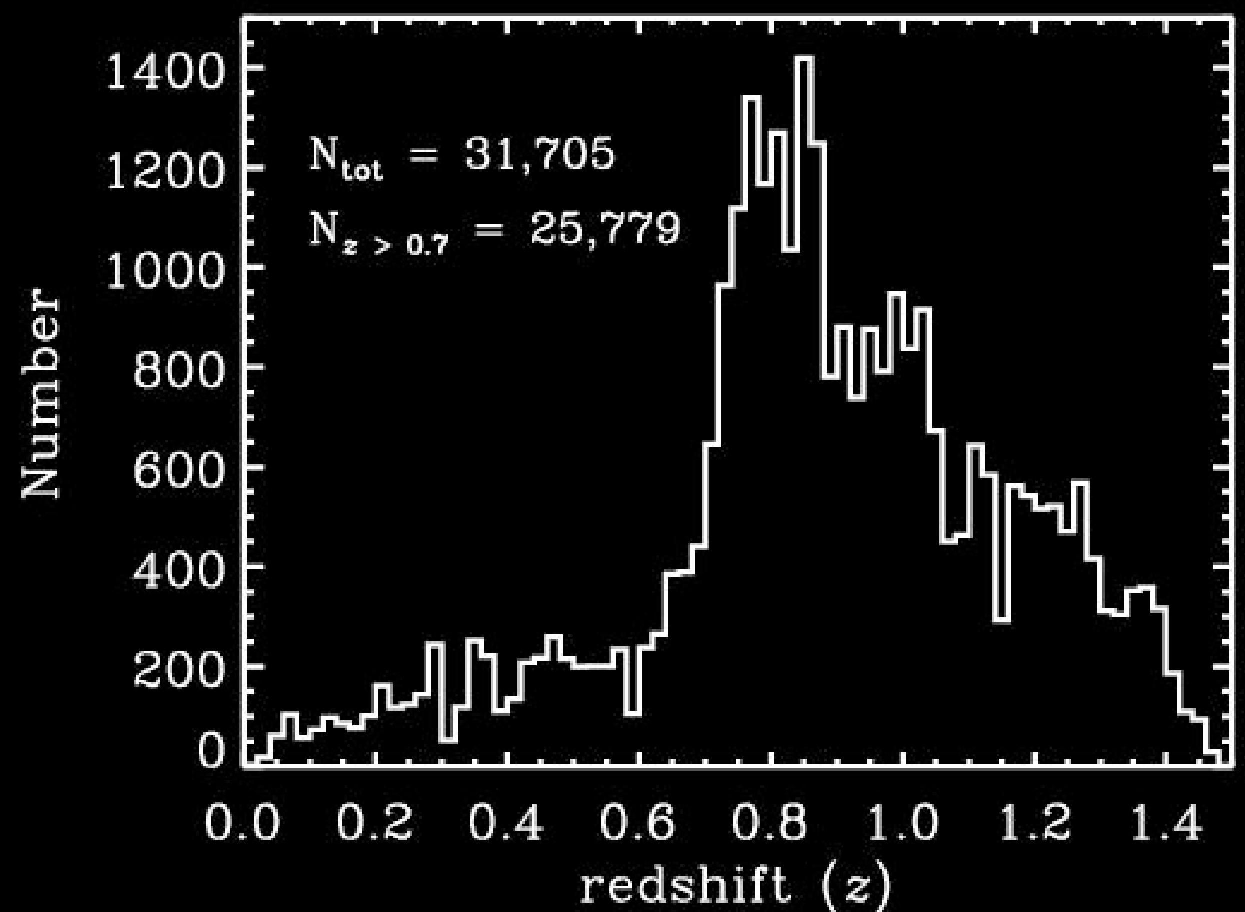
N. Kaiser

U. Virginia

R. Schiavon

Vital statistics of DEEP2

DEEP2 is obtaining spectra of >50,000 galaxies within four $0.5^\circ \times < 2^\circ$ patches of sky in order to measure redshifts and determine their properties. We focus on the redshift range $0.7 < z < 1.4$. DEEP2 constitutes a ~50× larger dataset than previous high-z surveys.



These galaxies are ~300× fainter than those which local surveys study: only the largest telescopes on Earth can be used for this.

z=0.7-1.4
≡6.0-8.5 Gyr ago

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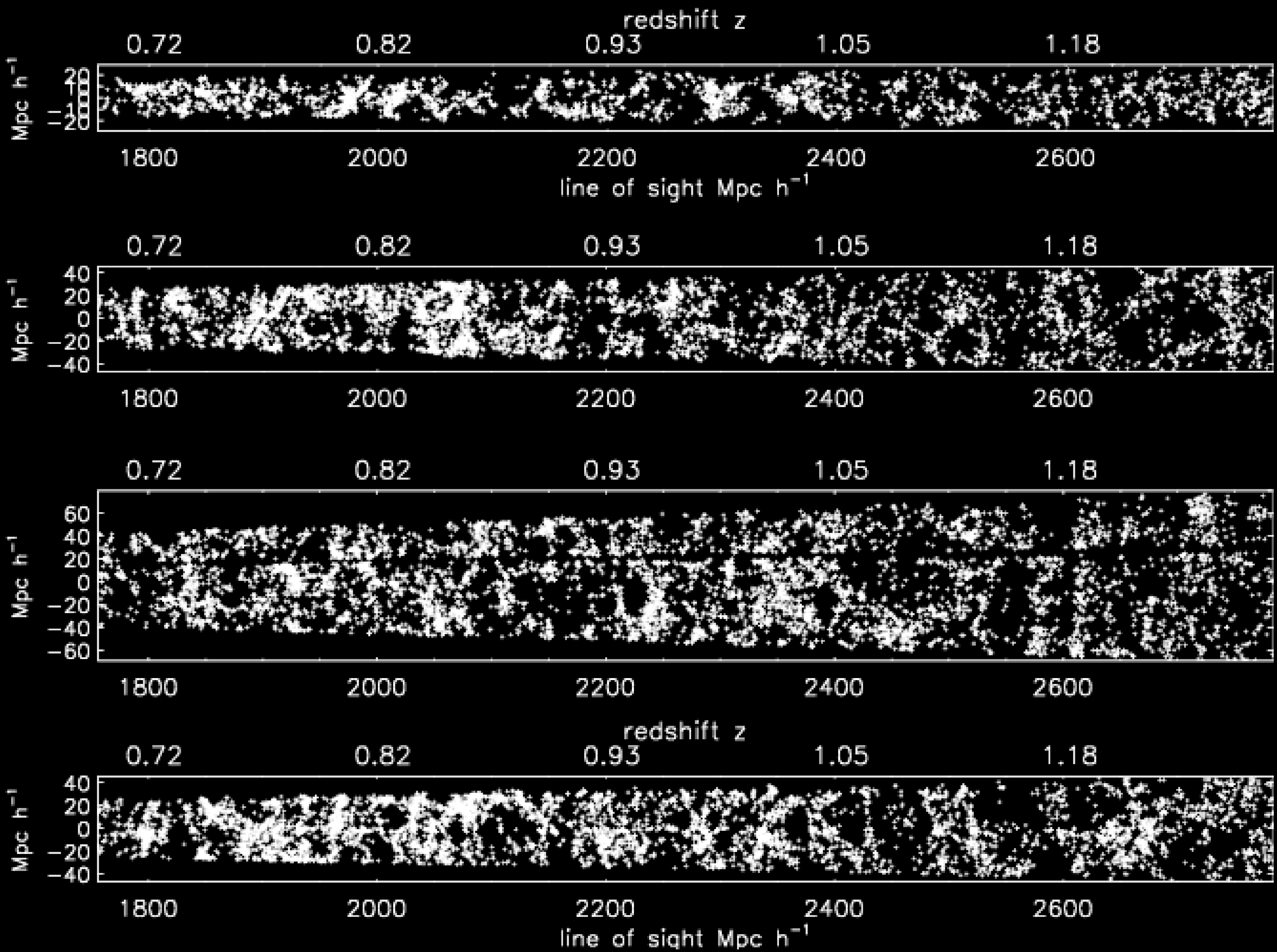
DEEP2 has been made possible by DEIMOS, a new instrument at Keck

A massive (10 ton) new instrument, the DEIMOS spectrograph (PI: Faber), was designed specifically for DEEP2. A grant of 80 nights' observing time from the University of California has brought DEEP2 to fruition.

Redshift Maps in 4 Fields: z=0.7-1.3



DEEP2 has now obtained >95% of planned data.

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Are the fundamental constants of Nature the same everywhere in the Universe and over all times?

DEEP2 data can be used to answer questions not considered when the survey was designed. For instance, we have now used DEEP2 to test for variation in the Fine Structure Constant, α.

A Quick Review

The fine-structure constant is

$$\alpha = \frac{e^2}{\hbar c}$$ (cgs units)

It is the dimensionless coupling constant of QED--i.e., it determines the strength of electromagnetism.

Its measured value at the present day is 1/137.03599911.

Why test for changes in α?

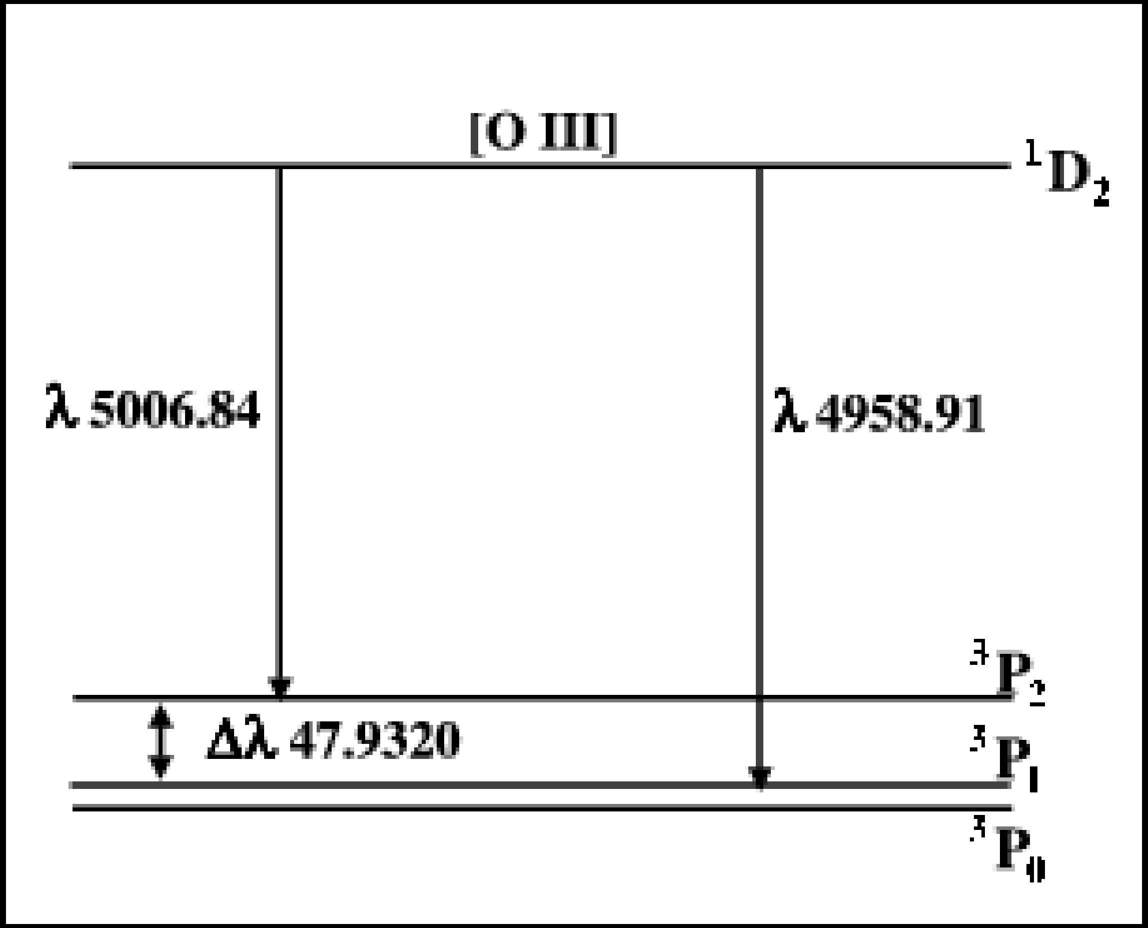
- α provides one of the easiest ways to test the universality of physical laws.
- Temporal and/or spatial variation in α is predicted by some theories with large extra dimensions and dark energy scenarios.
- There have been recent claims that significant evolution has been detected.
- Most methods of testing for evolution in α are likely dominated by unknown systematics (e.g. different groups get significantly different results using the same basic method).

Recent measurements disagree

Sample	Method	Median z	$d\alpha/dt/\alpha$ (year^{-1})	σ ($d\alpha/dt/\alpha$)
Webb et al. 2001	Many-multiplet	~1.5	**1.14E-15**	**2.9E-16**
Murphy et al. 2004	Many-multiplet	1.75	**6.40E-16**	**1.4E-16**
Quast et al. 2004	Many-multiplet	1.15	5.08E-17	4.2E-16
Srinand et al. 2004	Many-multiplet	1.55	-6.50E-17	6.2E-17
Tzanavaris et al. 2004	MM + 21cm	0.5	-1.30E-15	1.5E-15
Chand et al. 2004	Si absorption	~2.5	-8.68E-16	2.5E-15
Levshakov et al. 2005	Fe absorption	1.839	-3.73E-17	5.9E-17
Prestage et al. 1995	Lab measurement	0 (140d)	3.70E-14	Upper limit
Fujii et al. 2003	Oklo natural reactor	~0.1	**-4.40E-17**	**4.0E-18**
Lamoreaux & Torgerson	Oklo natural reactor	~0.1	**-2.25E-17**	**5.5E-18**
Darling 2004	OH 18cm lines	0.247	4.98E-16	1.3E-15
Bahcall et al. 2003	Oxygen emission	0.37	-2.99E-14	1.7E-14

Oxygen emission lines provide lower nominal precision than absorption line/many-multiplet or natural reactor methods, but the (astro)physics is much simpler. It is this type of measurement which we can perform with DEEP2.

Physics of [OIII]



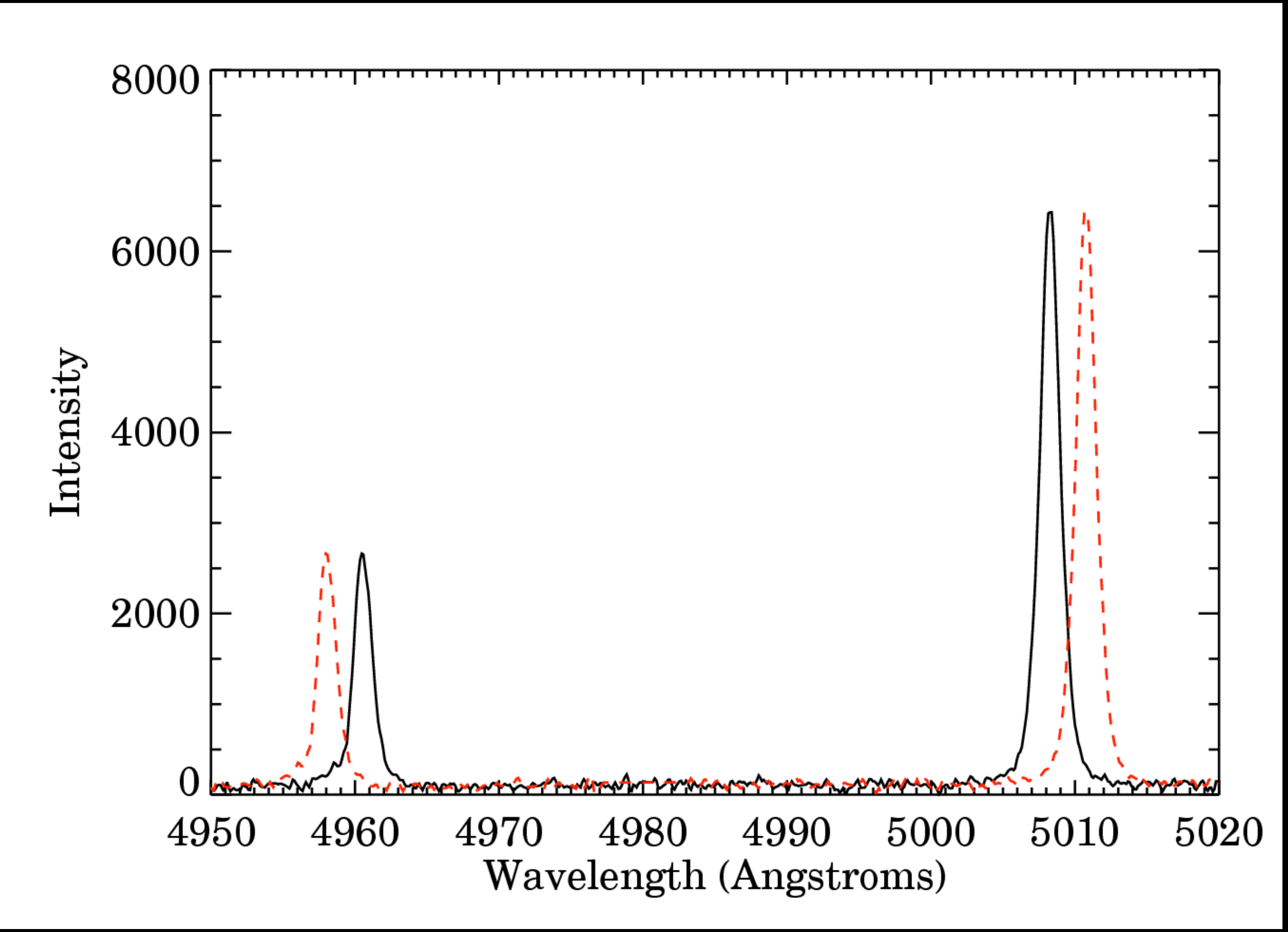
In astronomical notation, "[OIII]" denotes a forbidden transition of twice-ionized Oxygen. When excited to the right electron configuration, these ions will randomly emit a photon of wavelength either 4959 or 5007 Å. Because the transition is forbidden, absorption by other oxygen ions is negligible.

Physics of [OIII] and α

Because of this, the [OIII] 4959 & 5007 Å emission lines must have line profiles proportional to each other (regardless of isotopal ratios, gas density or distribution, etc). This is not true of absorption lines used to study α.

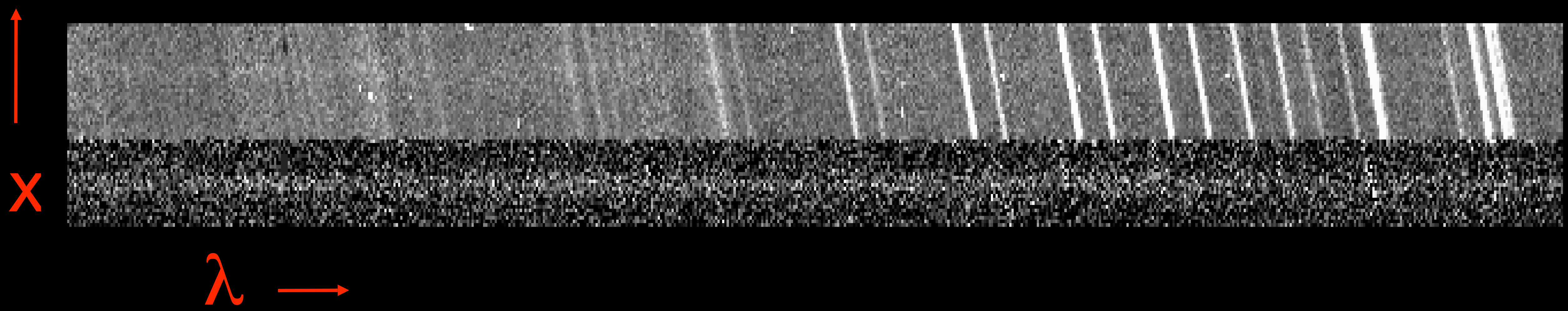
Furthermore, to <~1%,
$\alpha^2 \propto (\lambda_2-\lambda_1)/(\lambda_2+\lambda_1)$ for these lines, as the splitting arises from fine structure directly.

Effect of changing α



Shown is the effect of a 5% change in α applied to an actual spectrum - we can detect evolution ~1/800 this large!

Taking advantage of contamination



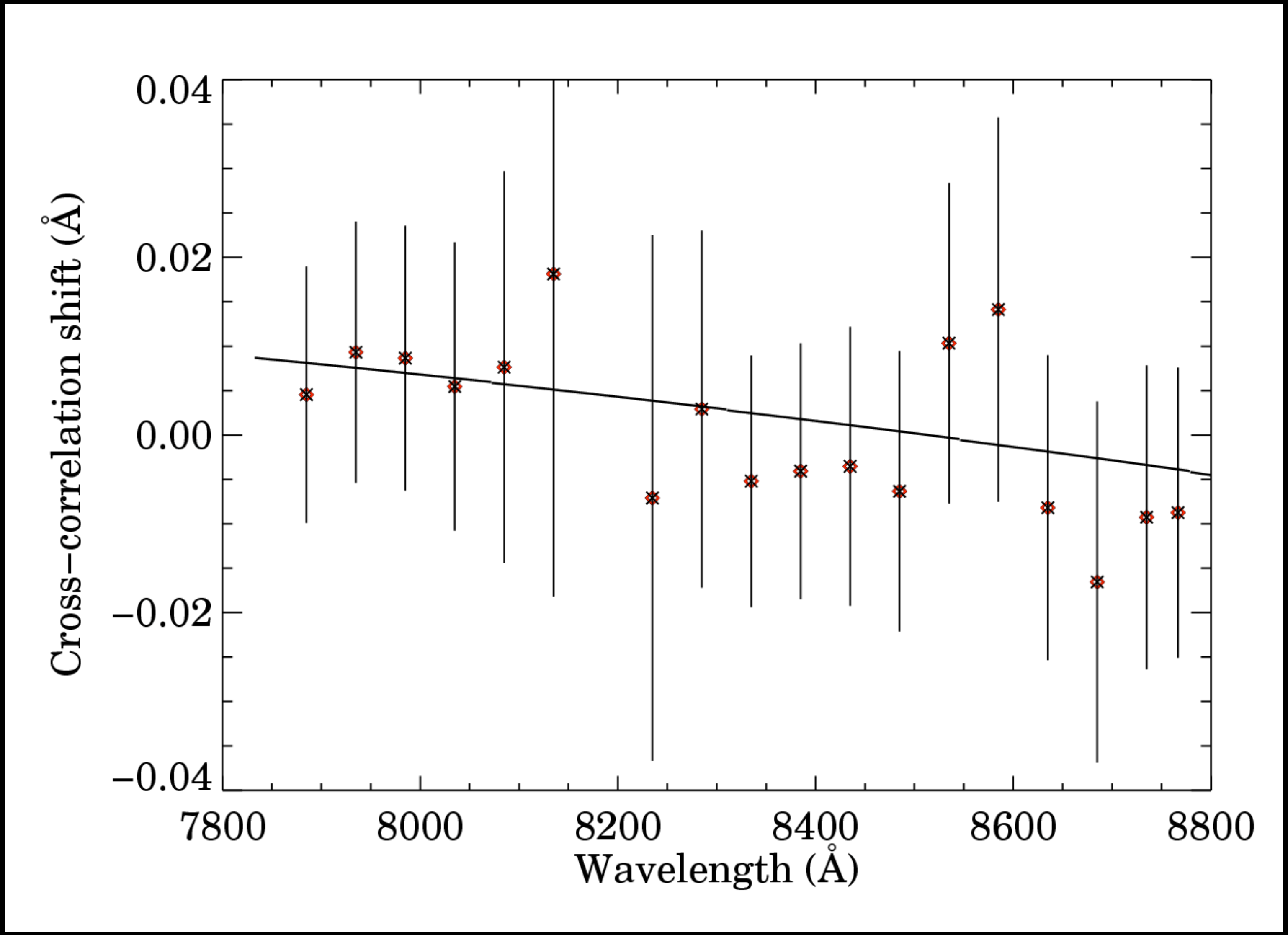
On top is shown part of a raw spectrum from our instrument: it is dominated by emission from the night sky (especially OH emission lines), not the galaxies we study.

Below, we show the same spectrum, processed to remove the night sky “background”. Although they get in the way of studying galaxies, the night sky lines are critical to the calibrations we need to study α.

We must control systematic wavelength calibration errors…

Temperature fluctuations, focus changes, etc., can alter the relationship between pixel & wavelength from when we calibrated it with arclamps in the afternoon.

We remedy this by cross-correlating the sky spectrum from each slit vs. a high-quality template and solve for shift vs. wavelength.



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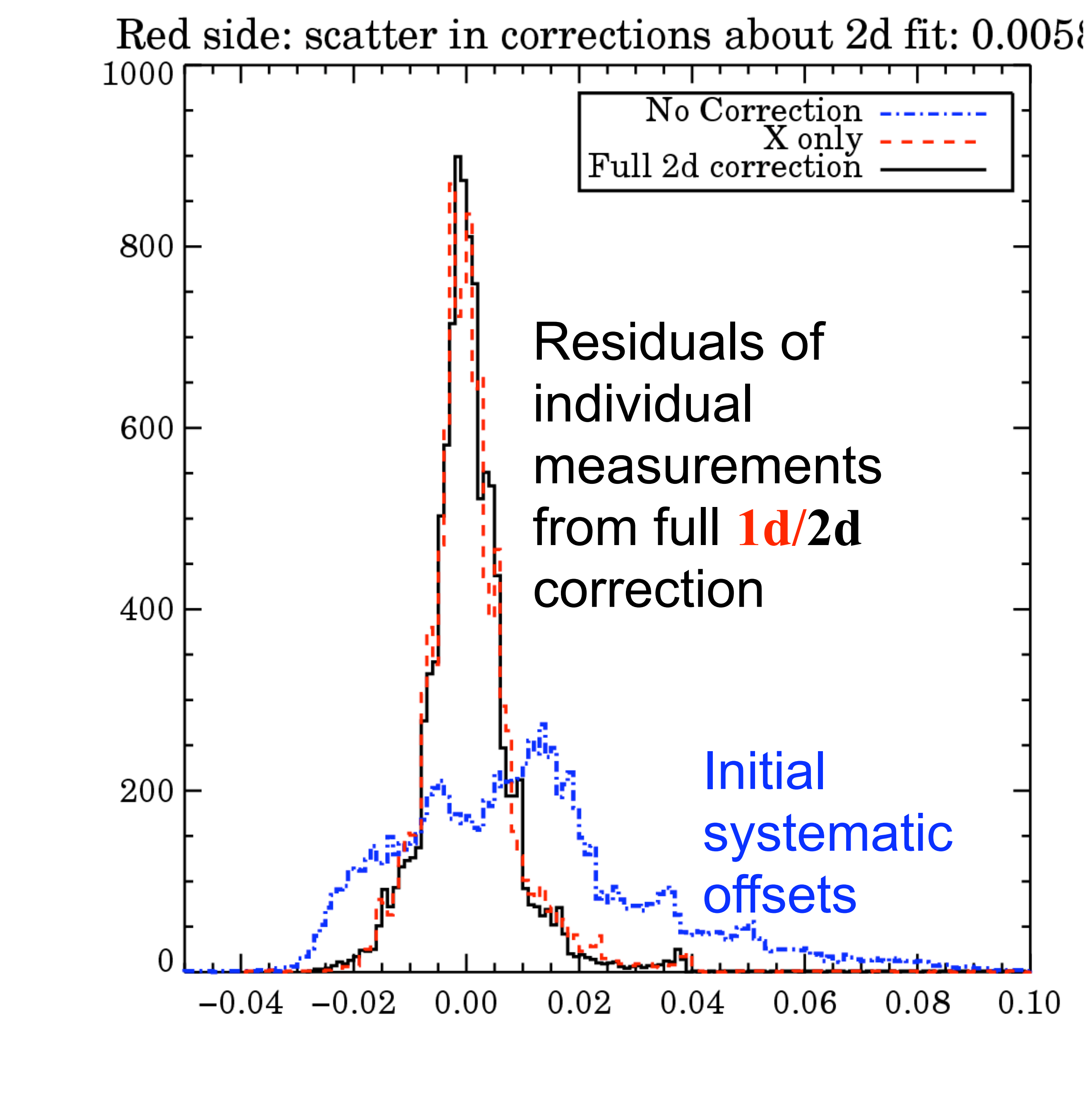
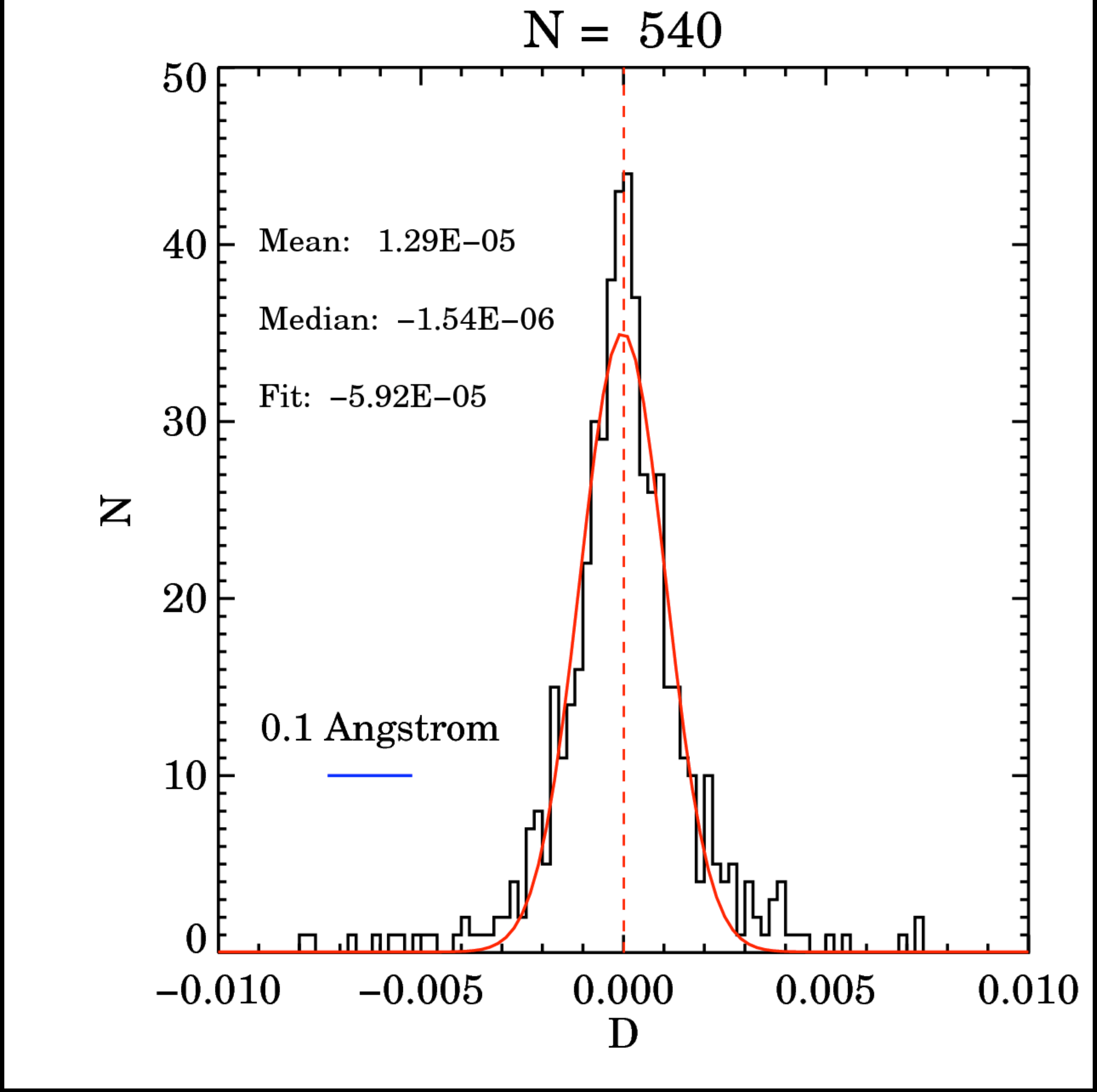
Combining data from many slits helps

RMS residual of single-slit fits about the global solution for all slits is ~0.006-0.008Å - dominated by the individual measurement uncertainties. Actual errors should be ~1/10 as large (as >100 slits in fit).



Corrected wavelength errors are dwarfed by centroid errors-- we're limited by S/N of emission lines.

We detect no change in α from *z*=0 to *z*=0.7



Start with the simplest thing: combine all galaxies with *z*>0.6 into one bin, and measure <D>=<$\Delta\alpha^2/\alpha^2$>.

Newman et al. 2007, *in prep.*

We measure $\Delta\alpha/\alpha$ = -8.08 $\times 10^{-6}$ +/- 1.91 $\times 10^{-5}$ at median z=0.72

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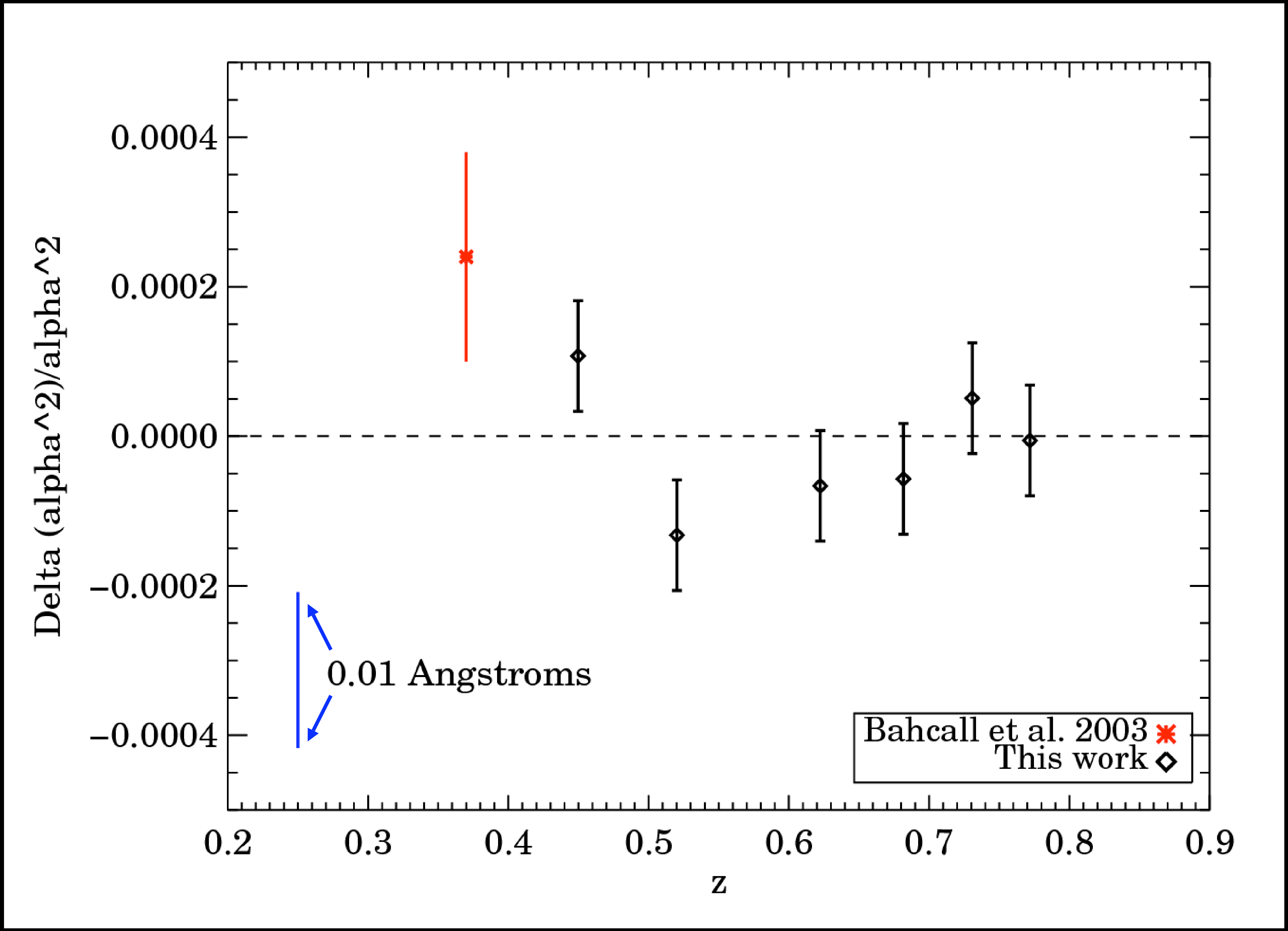
We also detect no significant slope, dα/dt



We measure dα/dt = 9.55×10^{-15} +/- 2.58×10^{-14} yr^{-1}

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DEEP2 vs. previous measurements

Sample	Method	Median z	dα/dt/α (year^{-1})	σ (dα/dt/α)
Webb et al. 2001	Many-multiplet	~1.5	**1.14E-15**	**2.9E-16**
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This work (slope)	**Oxygen emission**	**0.72**	**9.55E-15**	**2.6E-14**
This work (vs. z=0)	**Oxygen emission**	**0.72**	**-1.35E-15**	**3.2E-15**

Nominal precision does not approach QSO absorption-line measurements. However, [OIII] method is much simpler and should be more robust.

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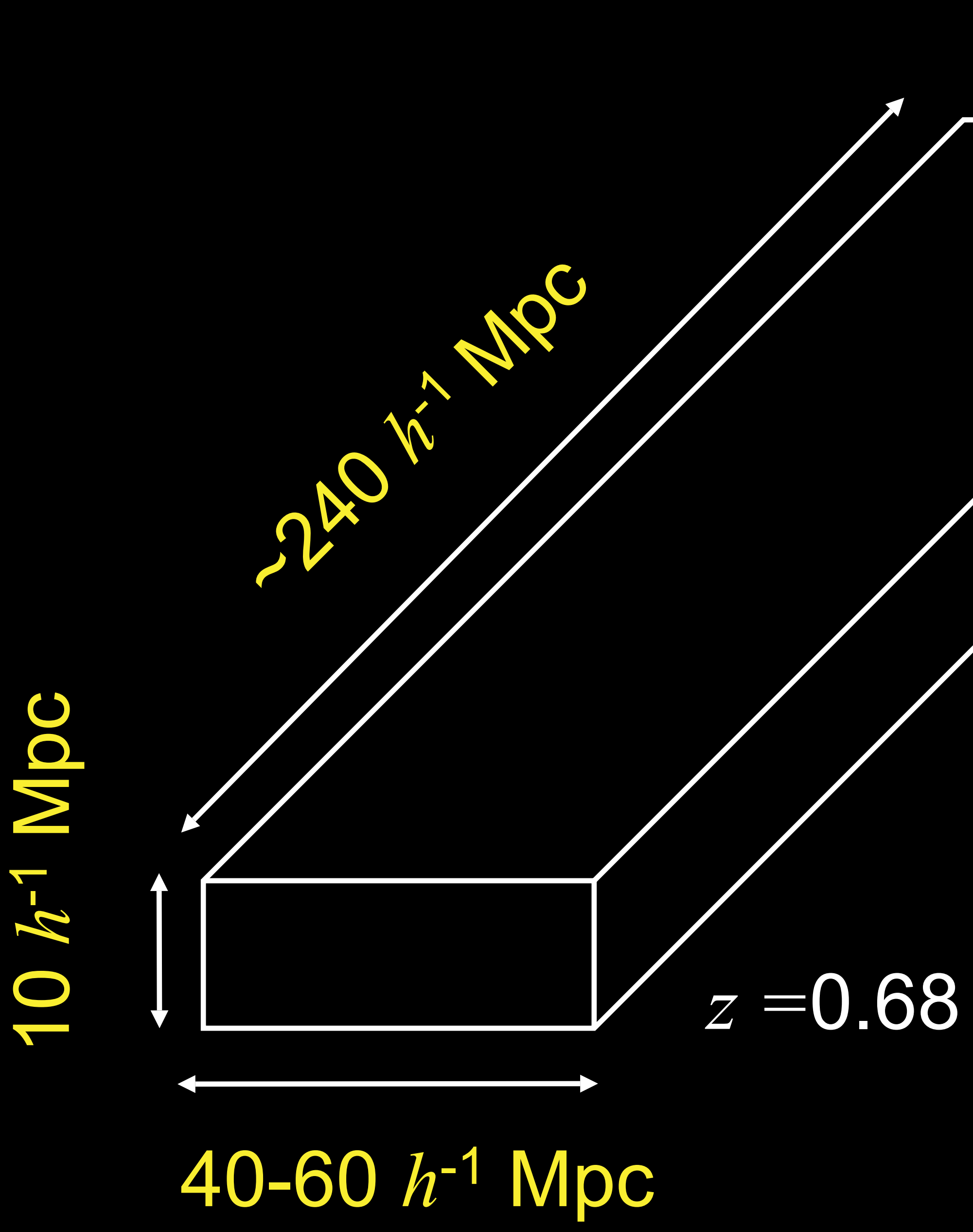
The Future

Number of [OIII]-emitting galaxies needed to rule out (or confirm) the many-multiplet detections at 99% confidence:

[OIII] Photons per galaxy → / Resolution ↓	1 x DEEP2	3 x DEEP2	10 x DEEP2
2500 (0.5xDEEP2)	192000	64000	19200
5000 (1xDEEP2)	96000	32000	9600

Cf. 540 objects (~1% of full sample) in DEEP2 measurement. However, future surveys will likely target bright emission-line galaxies over a narrower redshift range - just what is needed!

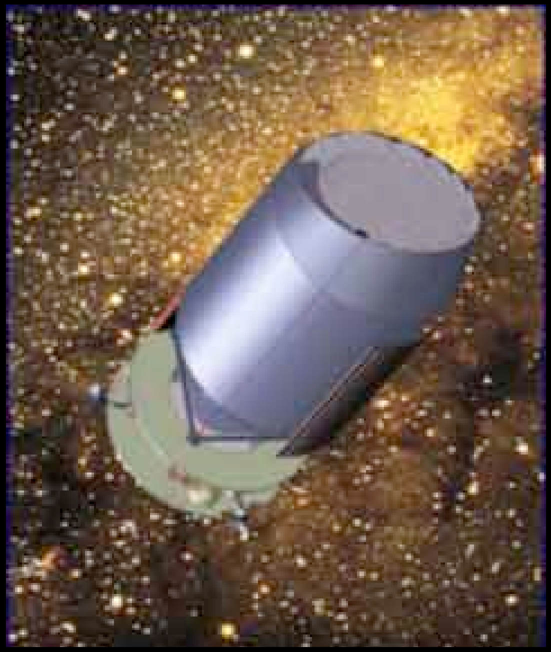
Testing for spatial variation

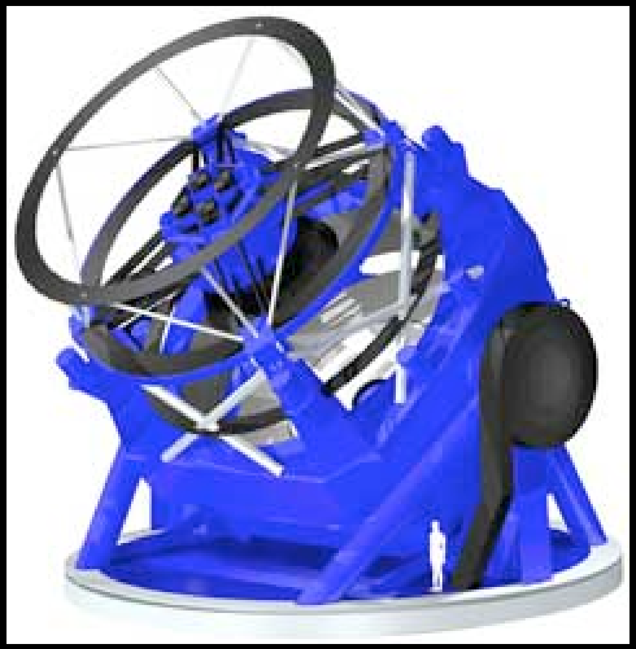


We can test for **spatial variation** in α by measuring the differences in <$\Delta\alpha^2/\alpha^2$> amongst **similar volumes** in the 4 DEEP2 fields **at the same redshifts**.

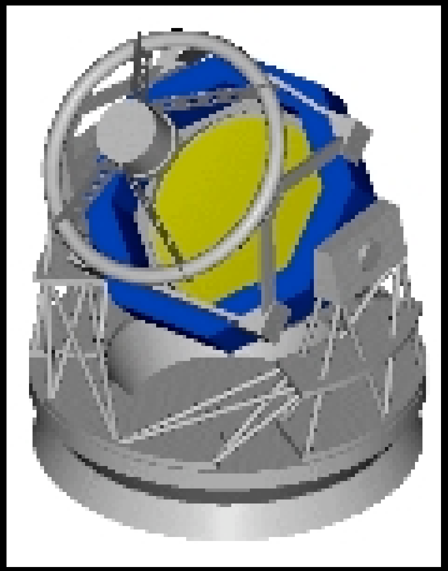
We set a 95% upper limit on Gaussian spatial fluctuations at ~1000-3000 Mpc separations: $\sigma\,(\Delta\alpha/\alpha) < 9.0\times10^{-5}$

Calibrating Photometric Redshifts beyond Spectroscopic Limits





Dark Energy Survey



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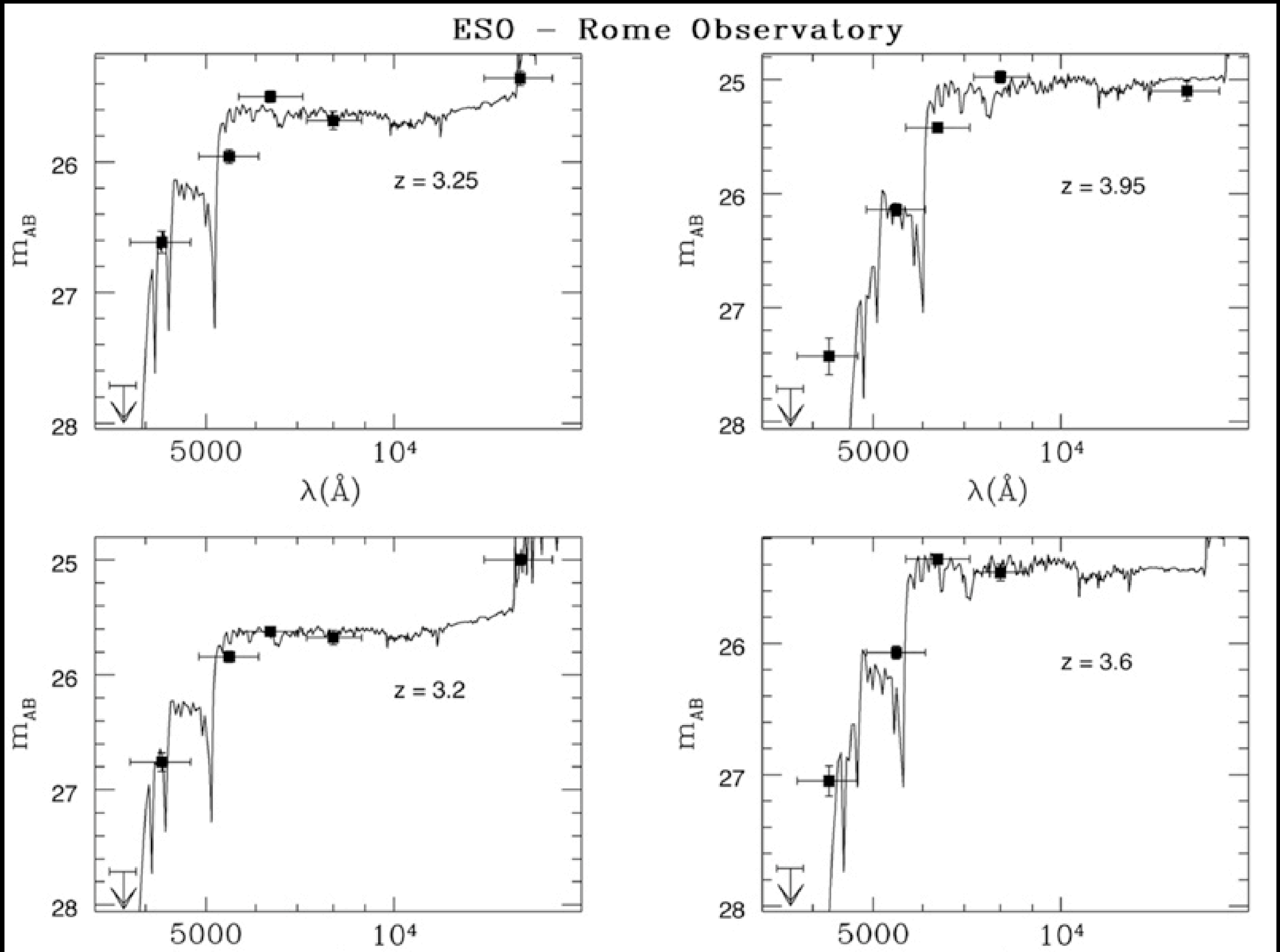
Photometric measurements can be used to estimate *z*



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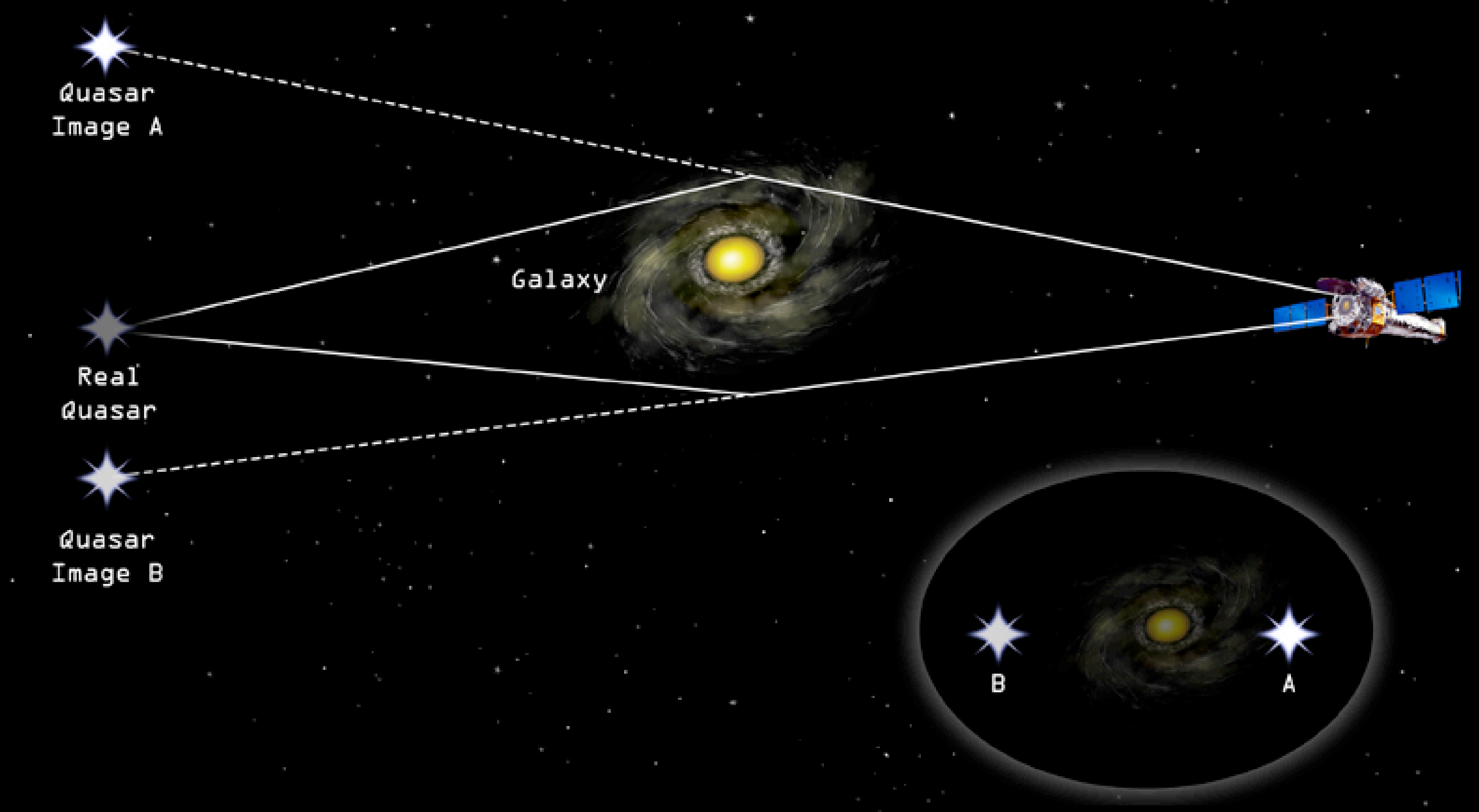
Dark energy probes require precision redshifts... e.g., lensing



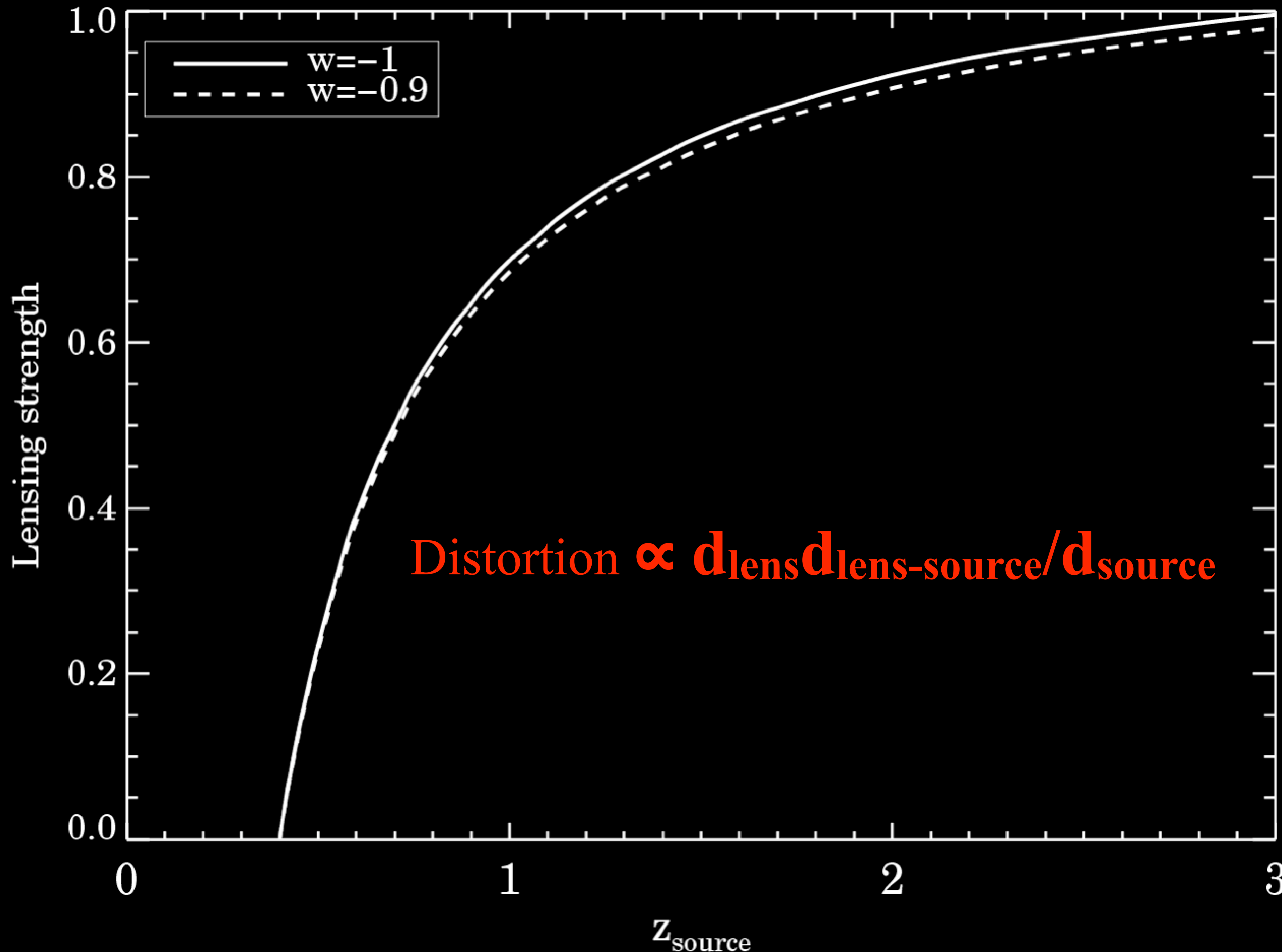
Credit:
Chandra

The strength of gravitational lensing depends on the geometry of the lens system and the amount of mass deflecting light.

Strong gravitational lensing

Weak gravitational lensing

The amount of lensing distortion at a given *z* depends on distance



Distortion $\propto$ $\mathbf{d_{lens} d_{lens\text{-}source} / d_{source}}$

A difficult problem

- Future DE experiments plan to use photo-z's for objects far too faint to get spectroscopic redshifts for *en masse*

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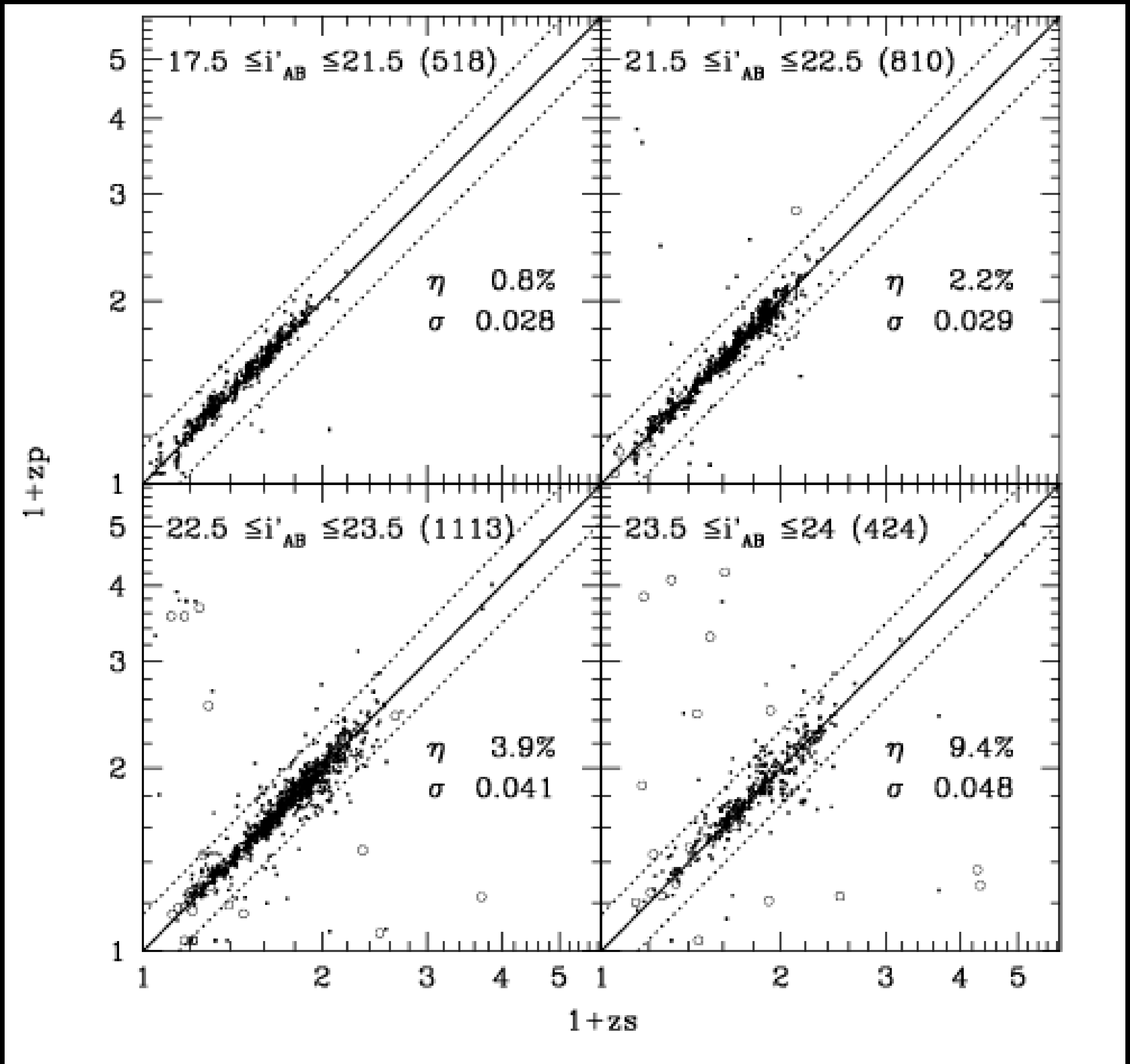
- Future DE experiments plan to use photo-z's for objects far too faint to get spectroscopic redshifts for *en masse*

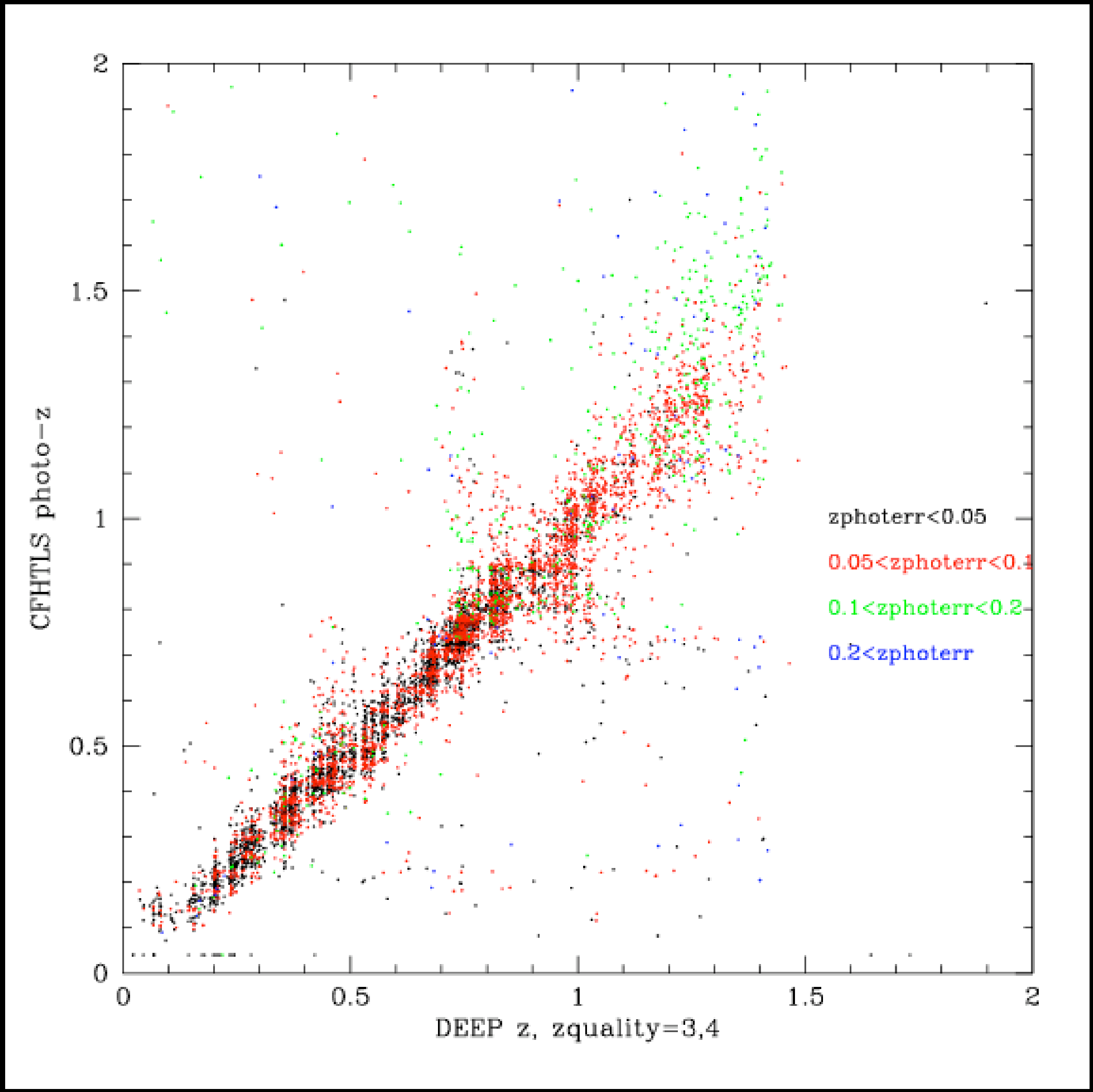
- High-z/faint spectroscopic redshift survey samples are **far** from complete

- Photo-z calibrations for brighter galaxies may not apply directly to fainter galaxies at same z (smaller galaxies start star formation later - so they have different spectra than brighter galaxies).

How can we test photo-z's for faint galaxies if we can't get complete sets of spectroscopic redshifts?

Conventional photo-*z* calibrations

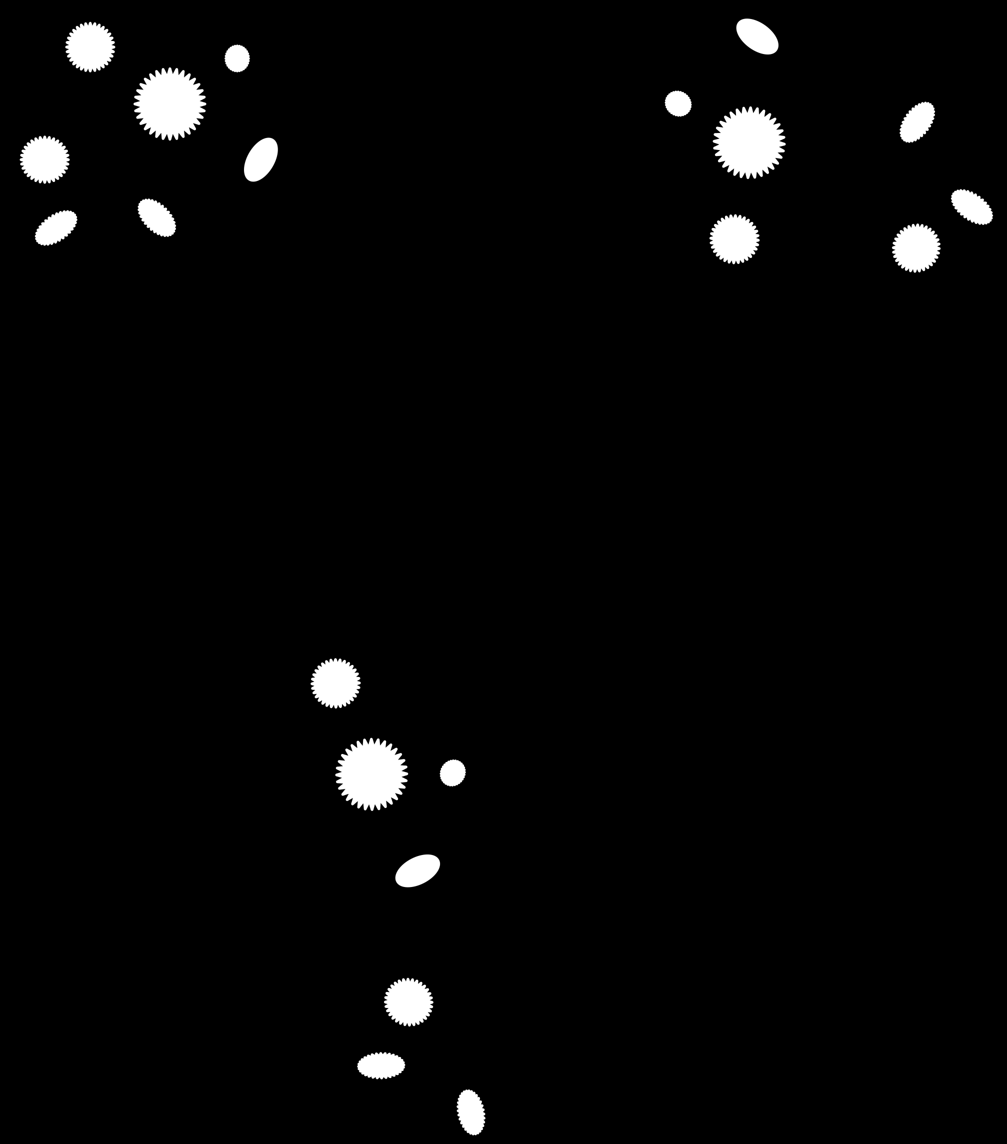




Ilbert et al. 2006

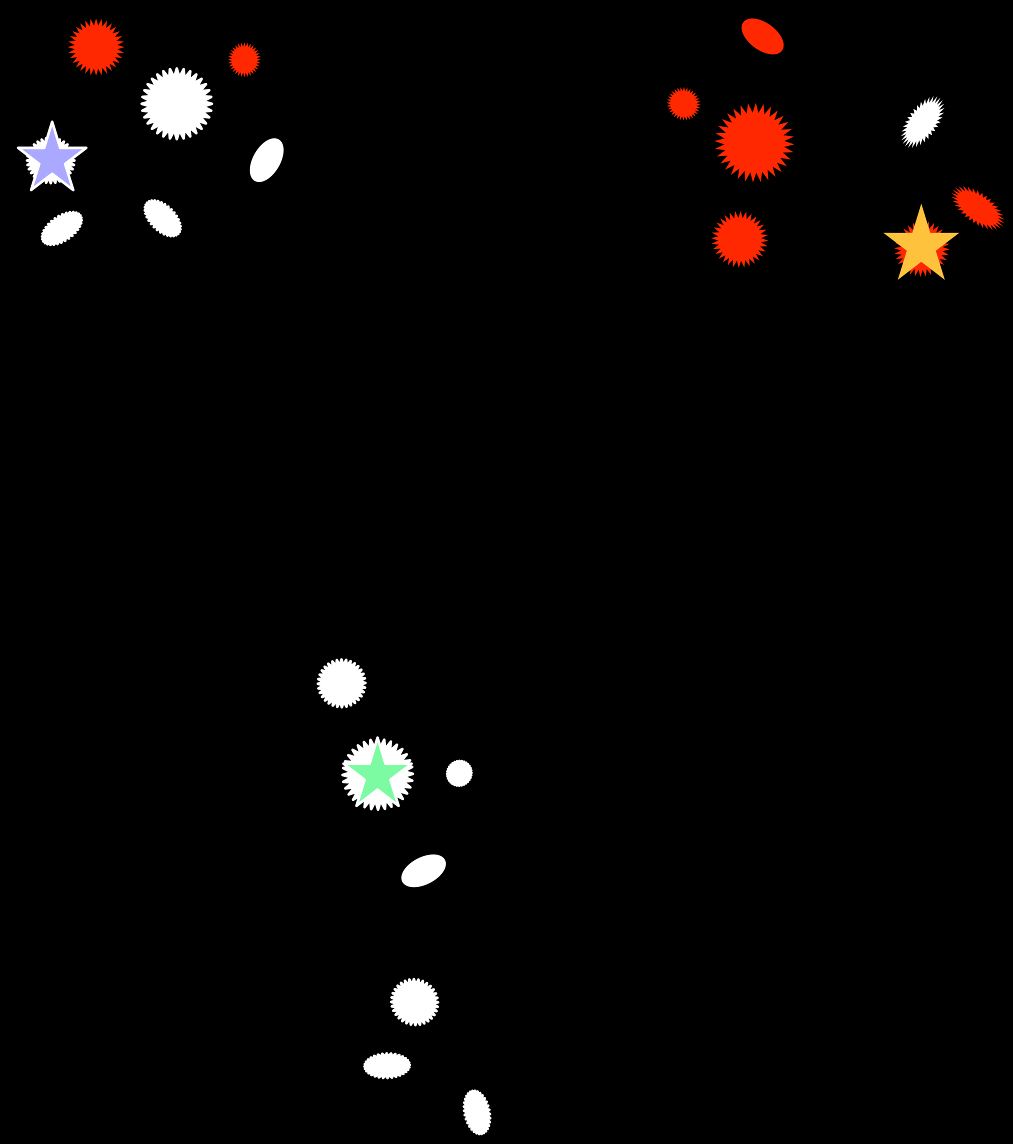
courtesy B. Weiner

Calibrating photometric redshifts using galaxy correlations

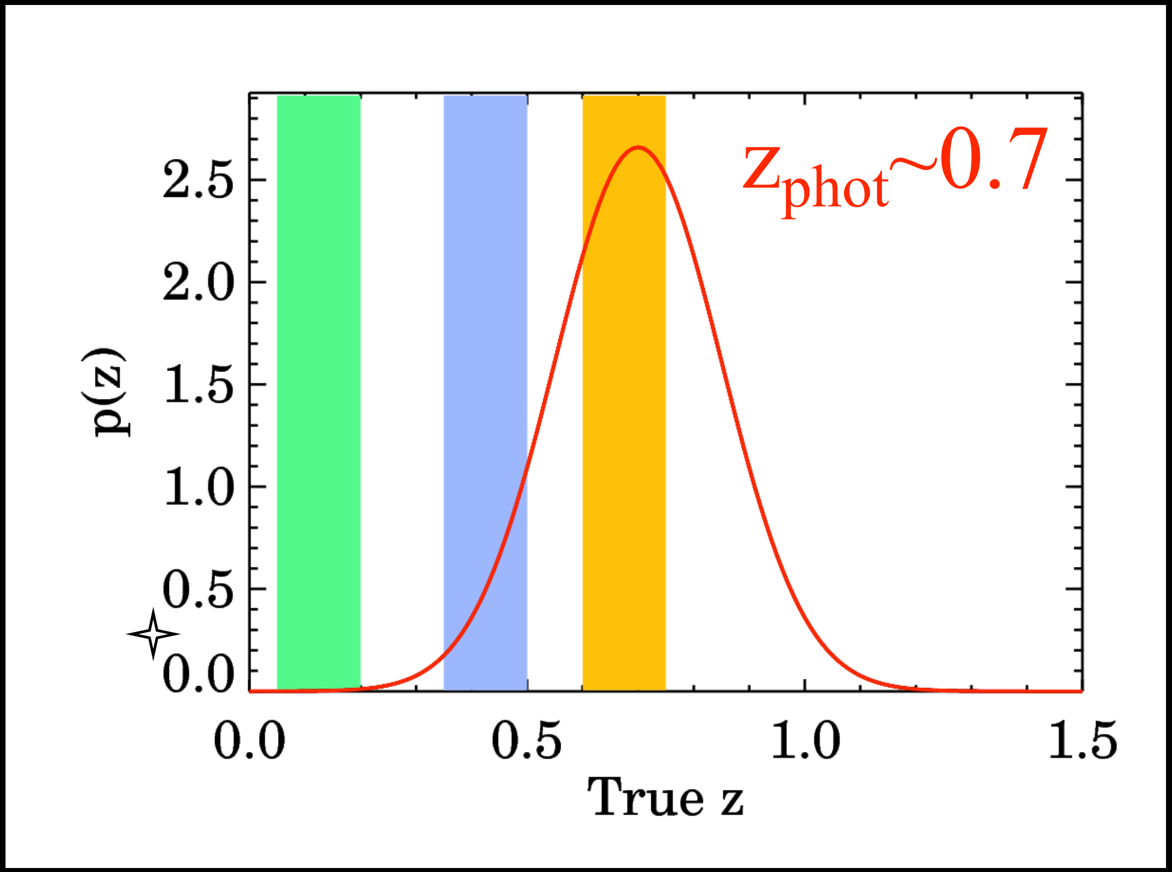


Both because dark matter halos cluster with each other and because more galaxies are found in more massive halos, all populations of galaxies cluster with each other - both in 3D and in projection on the sky.

Correlation statistics can tell us about redshift distributions



Consider objects in some photo-*z* bin, in a region where there is another set of objects with spectroscopic *z*'s.



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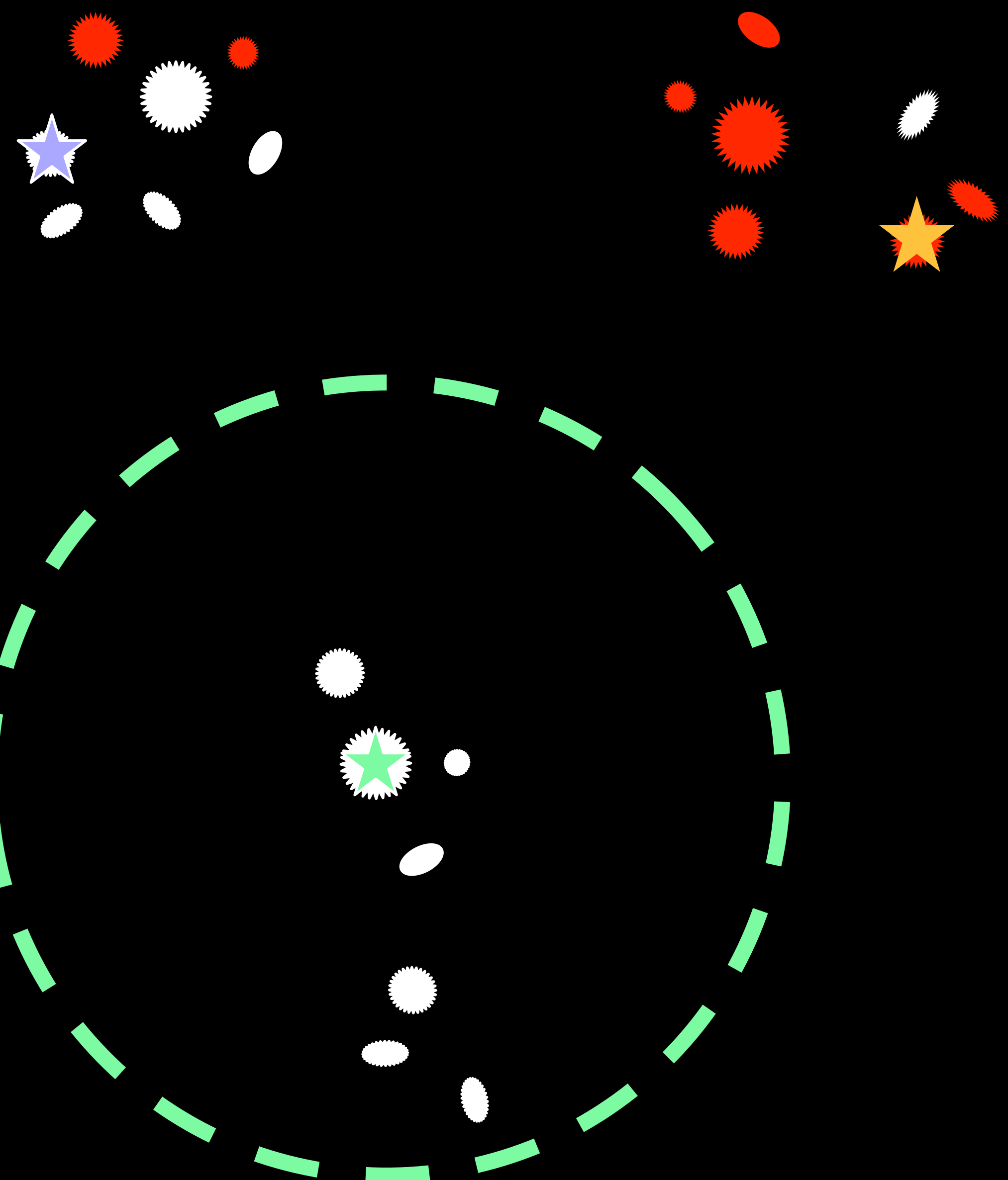
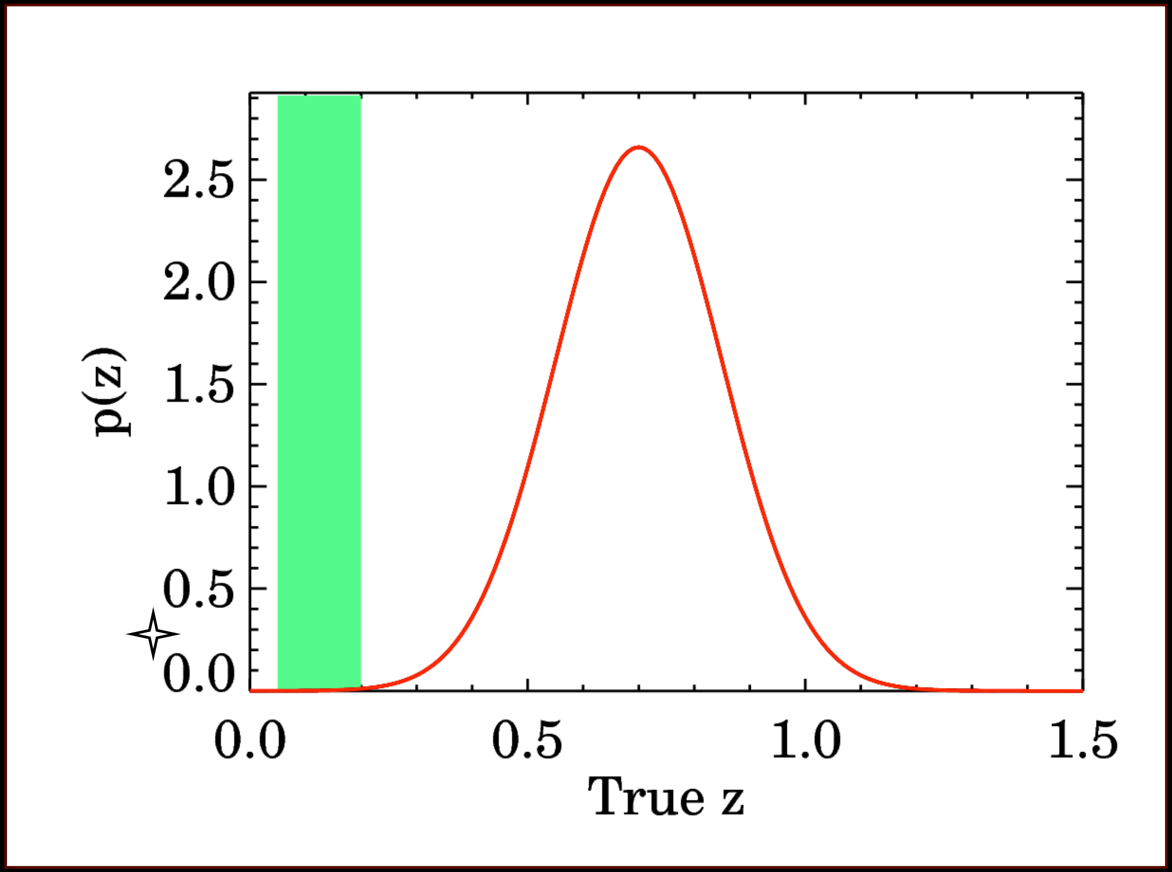
No overlap in *z* :

If none of the photo-z objects are in fact at the same *z* as a spectroscopic object, they will not cluster with it on the sky.





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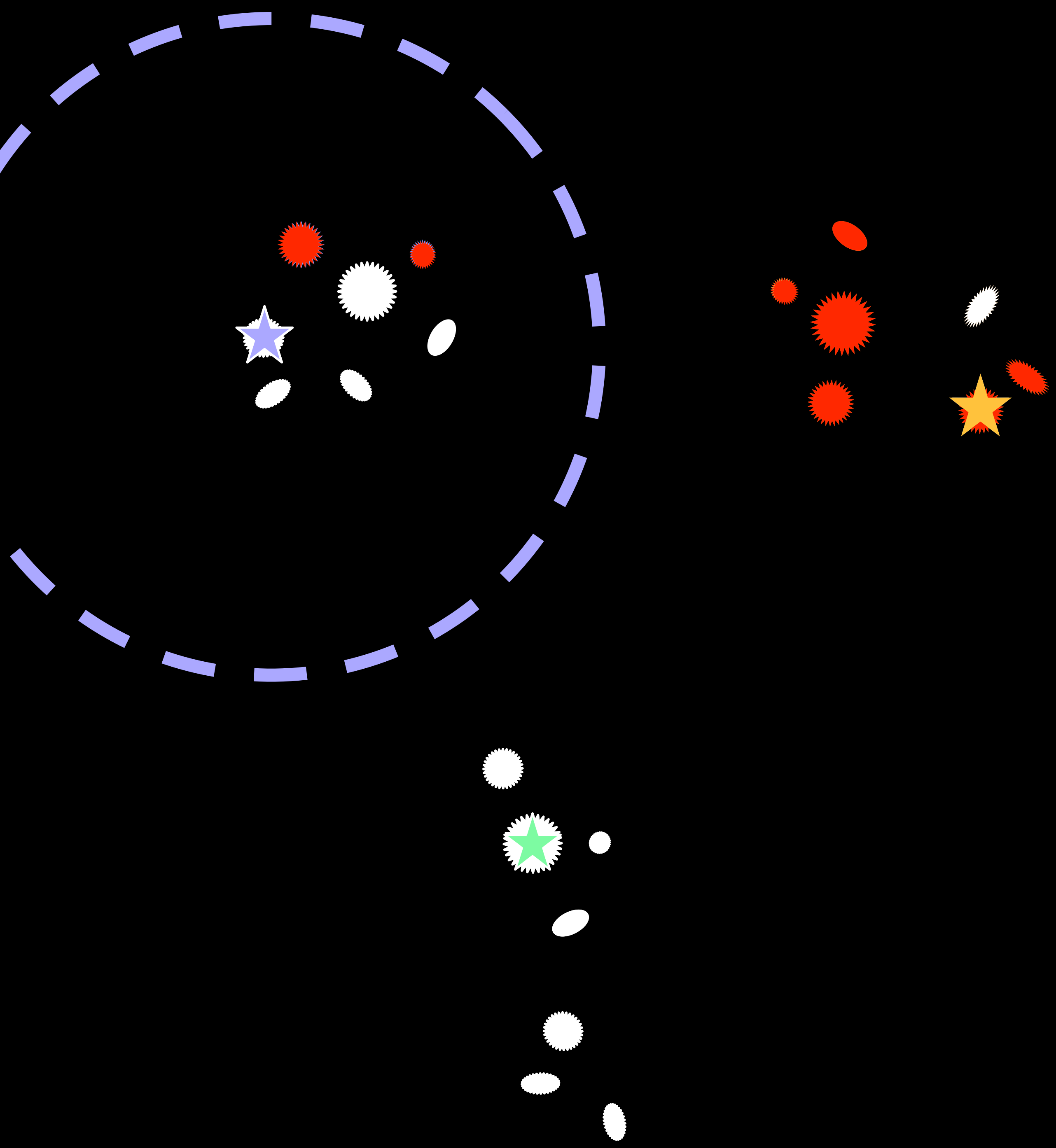
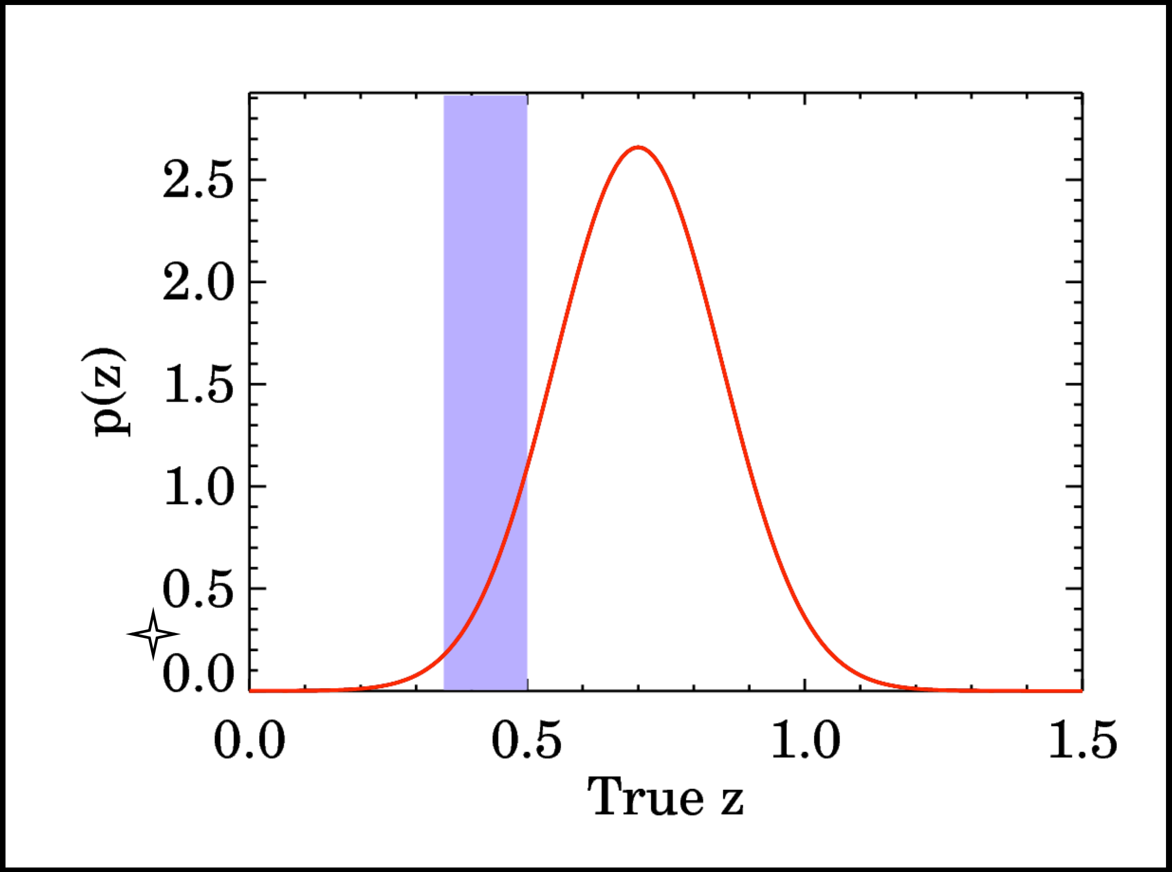
Some overlap in *z* :

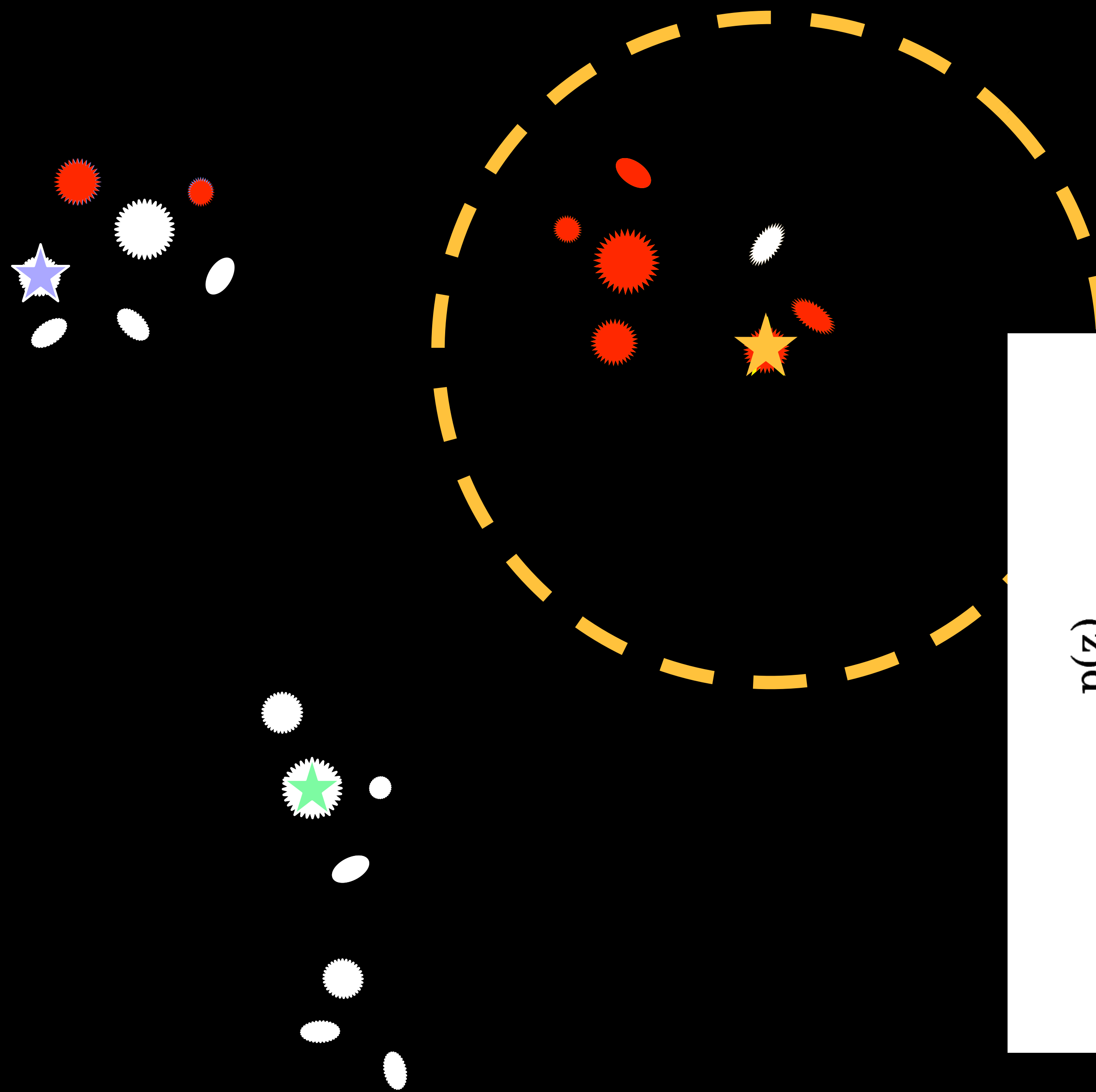


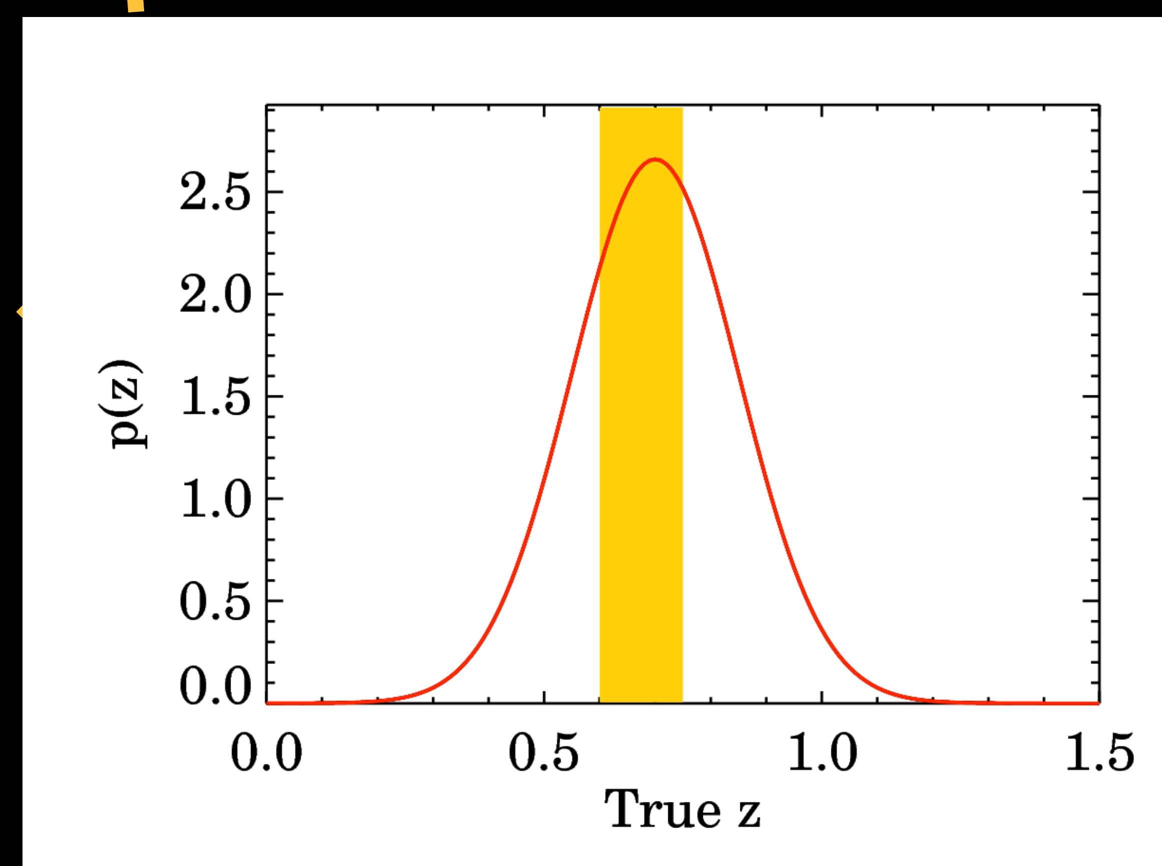
Those photo-*z* objects which are close in *z* to a spectroscopic object will yield a clustering signal.



Maximal overlap in *z* :

The cross-correlation is stronger at redshifts where a greater fraction of the photo-*z* objects truly reside.





Two-point correlation statistics

The simplest clustering observable is the two-point correlation function, the excess probability over random that a second object will be found some distance from another:

$$dP = n\,(1 + \xi(r))\,\mathrm{d}V$$

where $\xi(r)$ denotes the real-space two-point autocorrelation function of this class (which has average density n) at separation r.

$\xi(r)$ is the Fourier transform of the power spectrum. It is described well by a power law,

$$\xi(r) = (r/r_0)^{-\gamma}$$

where $r_0 \sim$ 3-5 h^{-1} Mpc, depending on galaxy type, and $\gamma \approx 1.8$.

Angular cross-correlations

For galaxies in a small spectroscopic bin (e.g. $\Delta z = 0.01$) we can measure the excess clustering on the sky of photometric galaxies about a spectroscopic galaxy, defined by:

$$dP_{sp}(\theta) \sim \Sigma_{\mathbf{p}} \, (1 + w_{sp}(\theta)) \, d\Omega \, ,$$

where $w_{sp}(\theta) \sim \int \xi_{sp}(y) \, p(z) \, dz$, and $y = (l^2 + D^2 \theta^2)^{1/2}$

Additional observables

In addition to $w_{sp}(\theta) \sim \int \xi_{sp}(y)\, p(z)\, dz$,

we can measure the correlation function for spectroscopic galaxies: ξ_{ss}

And the angular autocorrelation for photometric galaxies:

$$w_{pp} \sim \int \xi_{pp}(y)\, p(z)^2\, dz$$

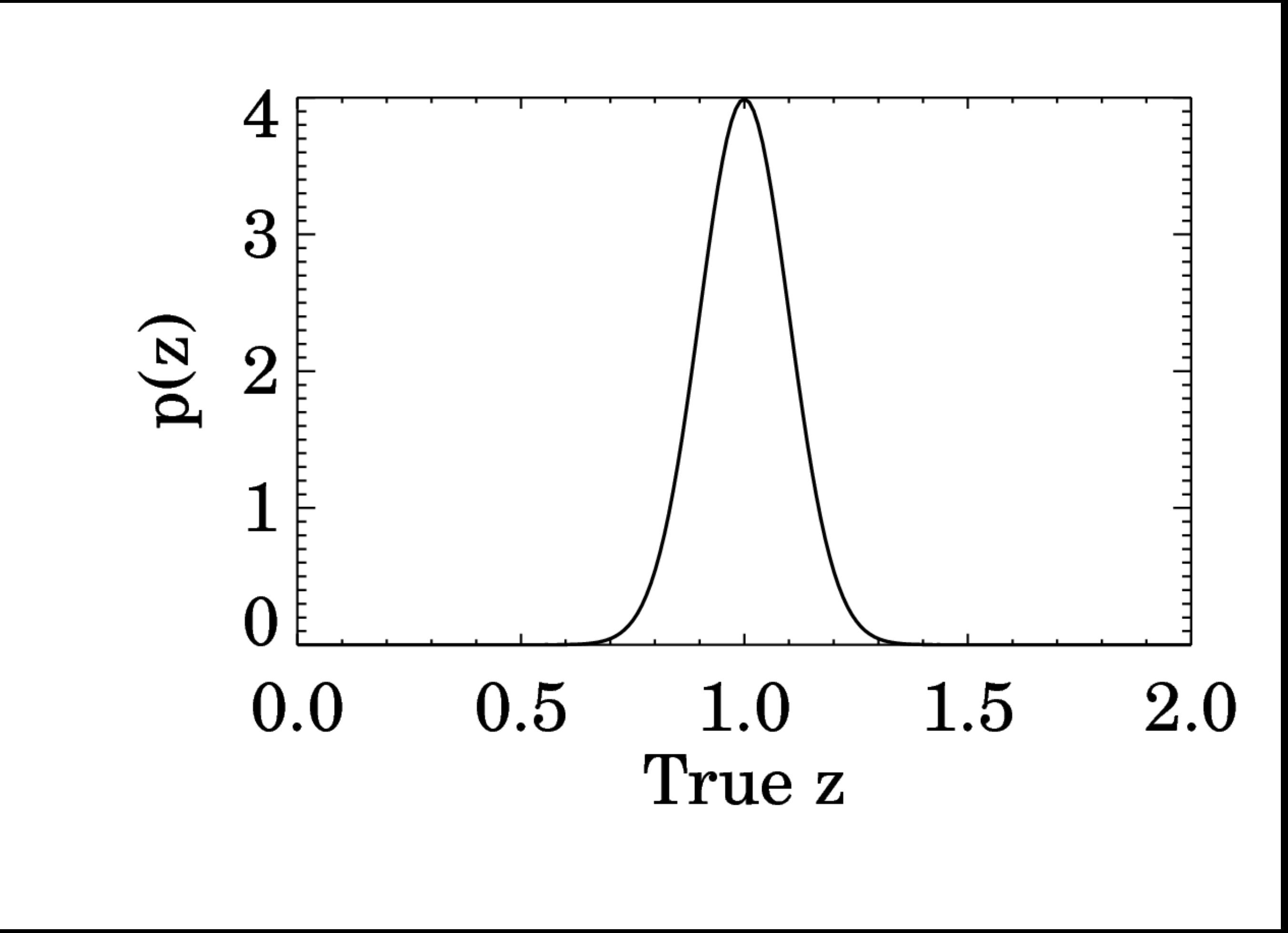
For simple biasing, $\xi_{sp} = (\xi_{ss}\, \xi_{pp})^{1/2}$,

providing enough information to solve separately for ξ_{sp} and $p(z)$

Assumptions for the following:

1) We have a spectroscopic sample of galaxies with well-measured redshifts. For starters, assume it has a flat redshift distribution (constant dN_s/dz), e.g. 25k galaxies/unit z.

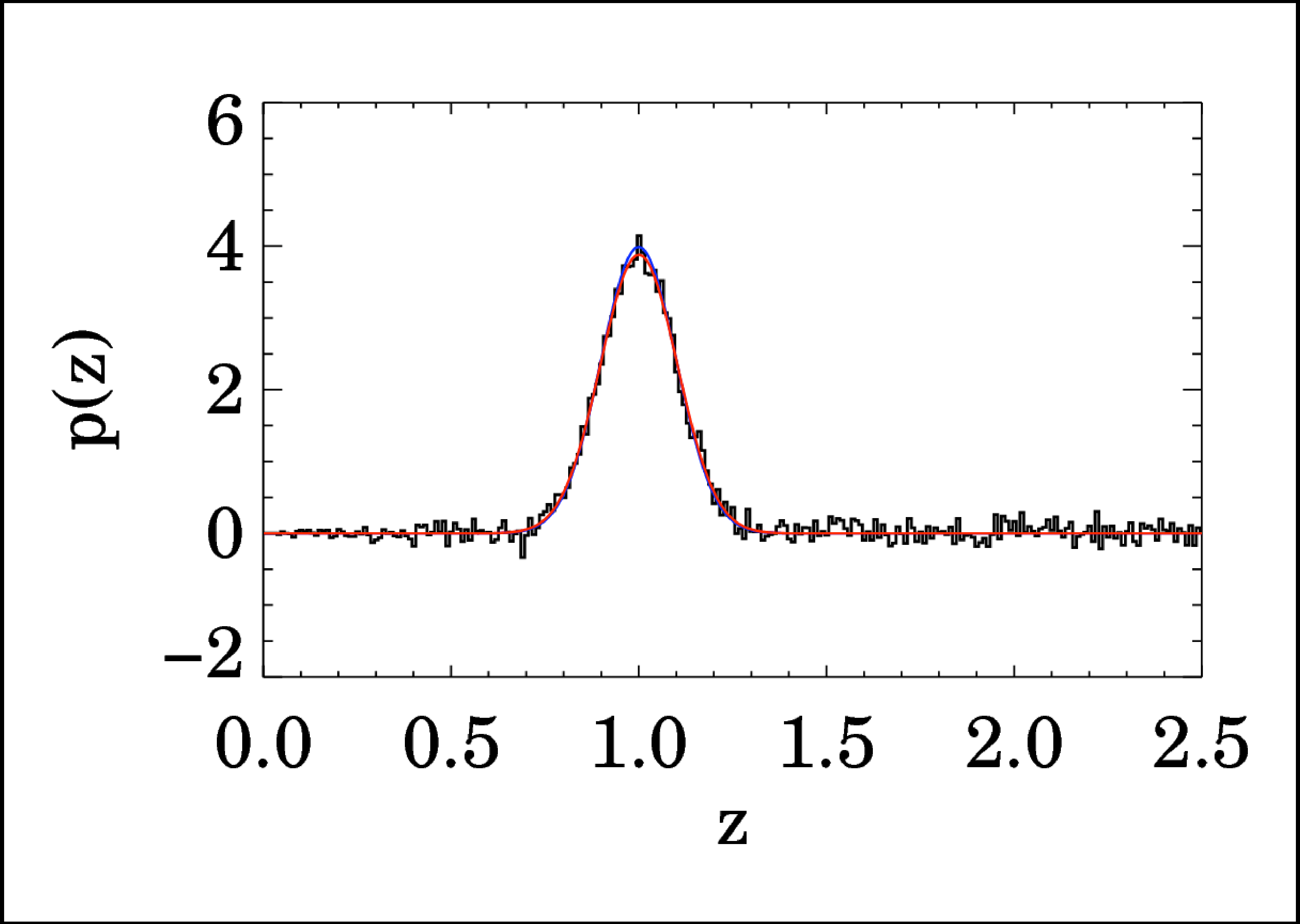
2) We want to measure the redshift distribution $p(z)$ for a sample of galaxies in one photometric redshift bin with true distribution a Gaussian with mean z=1 and sigma σ_z. For a standard scenario, we take surface density Σ_p =10/sq. arcmin and σ_z ~ 0.1 . *



Assumptions (continued)

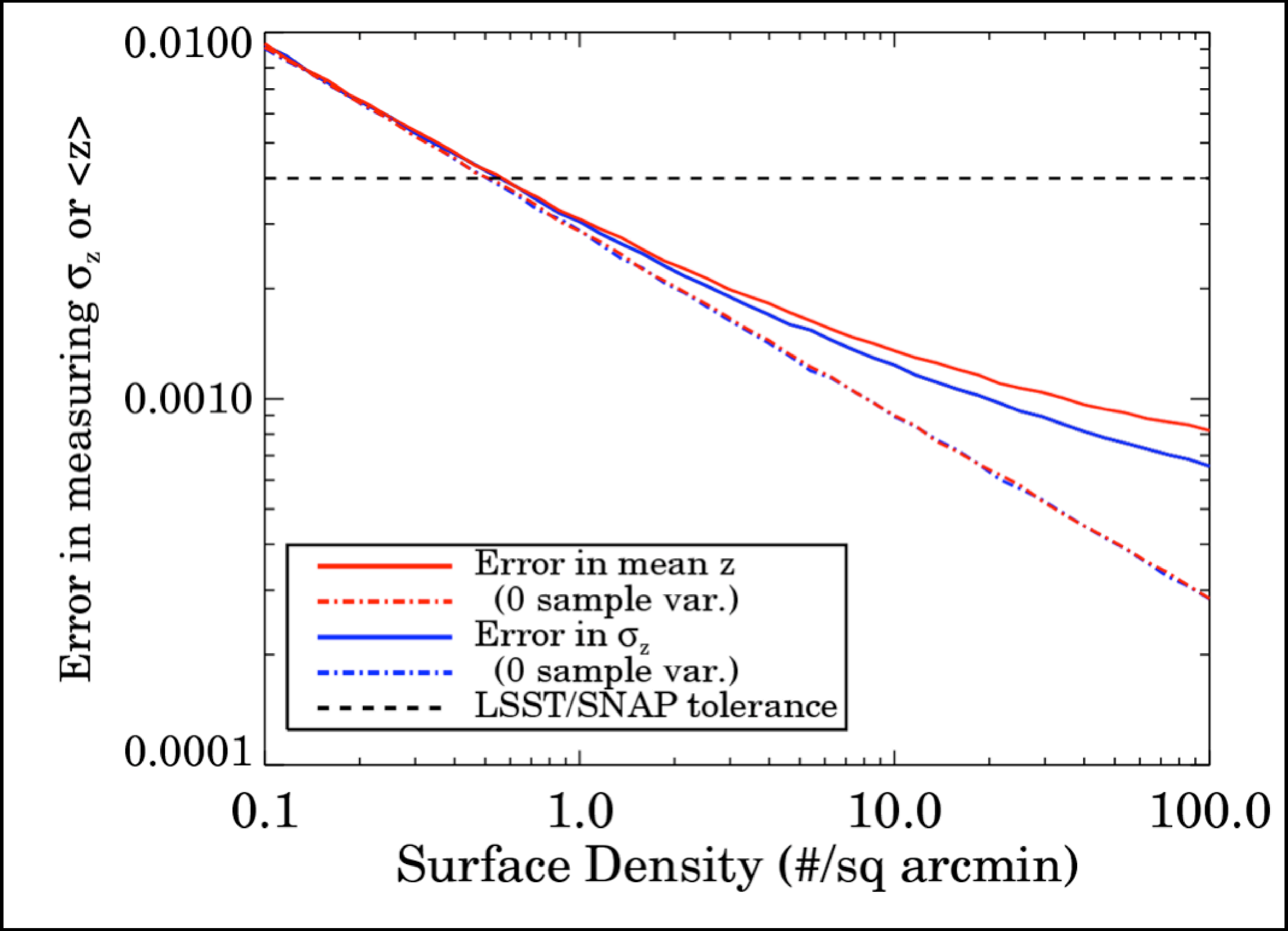
3) We can ignore gravitational lensing, which can also cause correlations (can be removed iteratively).
4) The clustering of the photometric sample is independent of z . *
5) We measure correlations within a 10 h^{-1} Mpc comoving radius (trade-off of useful area vs. nonlinearities). *
6) Sample variance has been removed to first order using the observed fluctuations in dN_s/dz . *

Monte Carlo simulations



Generate realizations with realistic correlation measurement errors in bins and do Gaussian fits to inferred *p(z)* in each

Scaling with Σ_p



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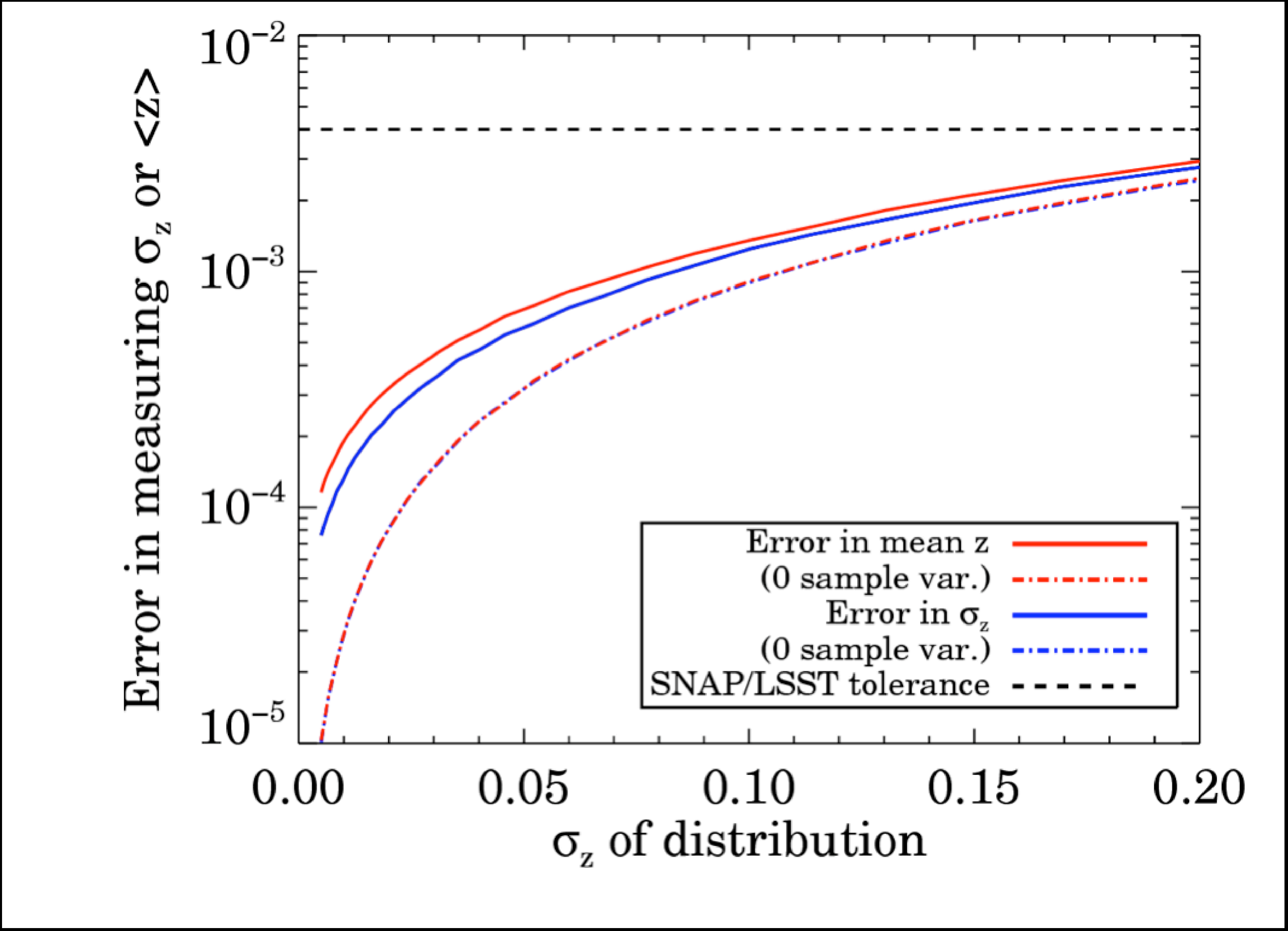
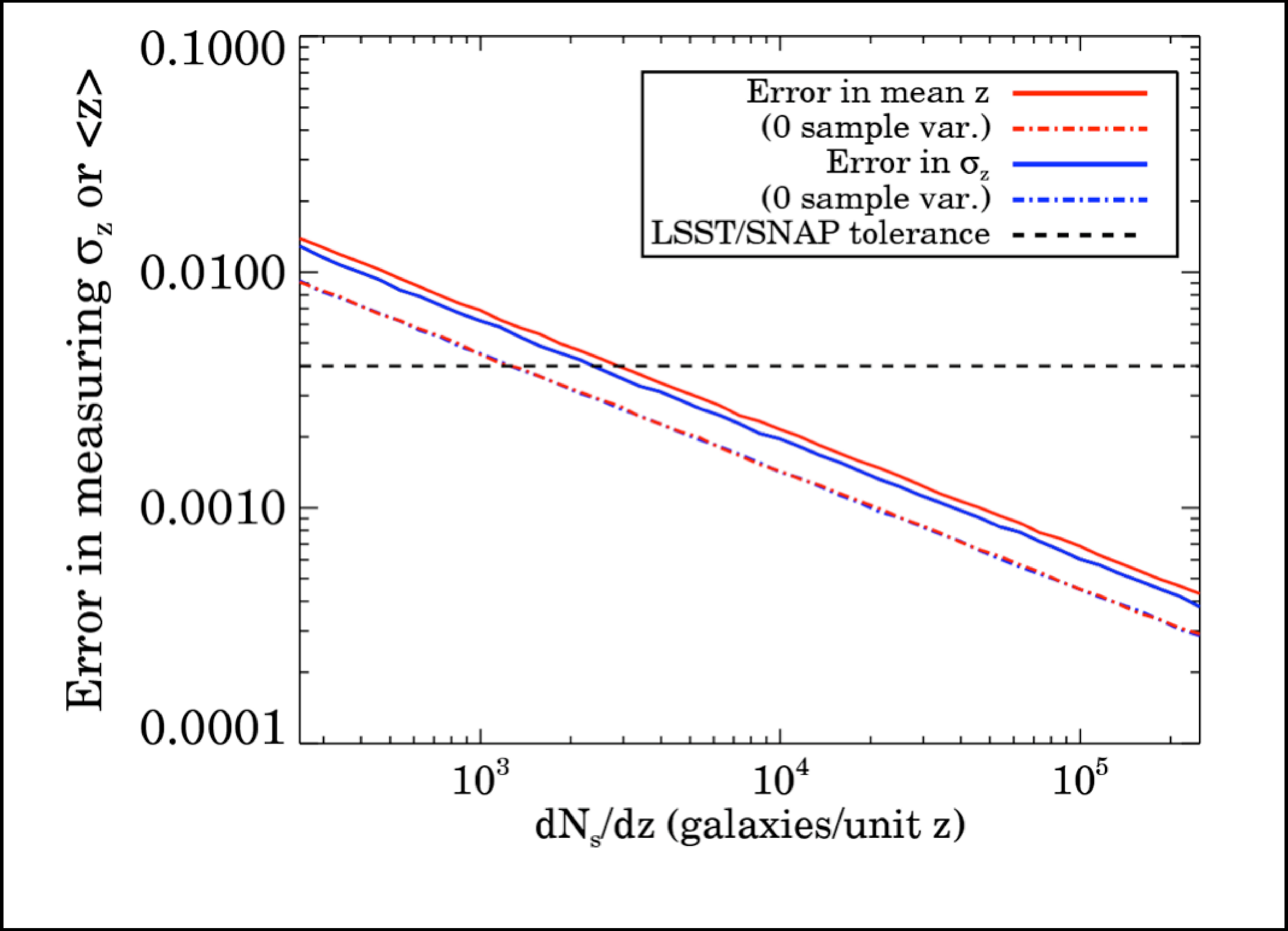
Scaling with σ_z



Scaling with dN_s/dz



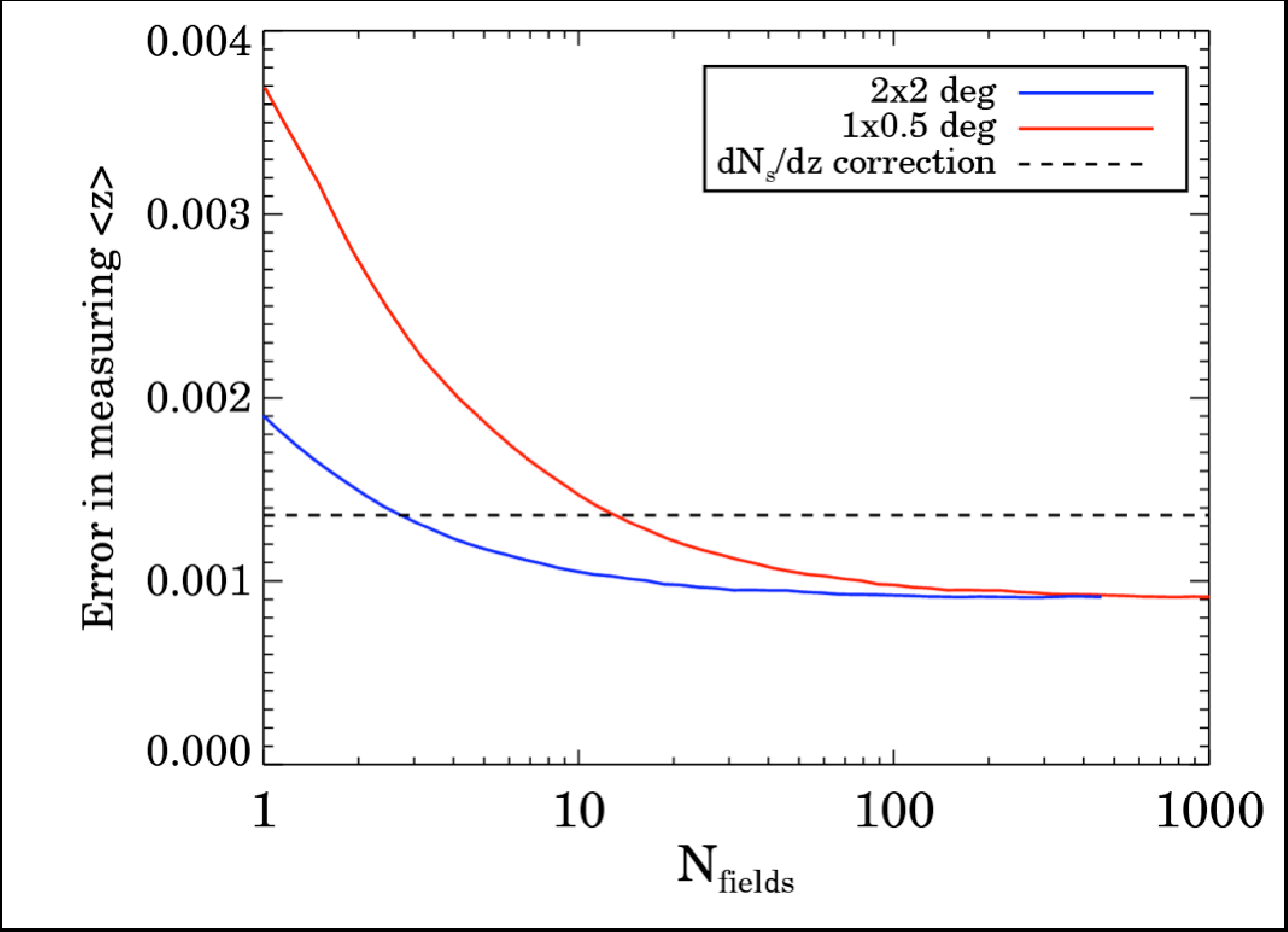
Net scaling:

For both the uncertainty in the mean *z* of the photometric galaxies or the uncertainty in σ_z, we get:

$$\sigma \sim 1.5 \times 10^{-3} \; (\sigma_z/0.1) \, ((\mathrm{d}N_s/dz) \, / \, 25{,}000)^{-0.5} (\Sigma_p/10)^{-0.3}$$

If $p(z)$ is made up of multiple, nonoverlapping Gaussian peaks each containing f_{peak} of the probability, errors scale as $f_{peak}^{-1/2}$.

Observing in many independent fields can reduce the impact of sample variance



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Dominant Errors:

Random errors:

$\mathbf{1.5 \times 10^{-3}}$ $(\sigma_z/0.1)\,((\mathrm{d}N_s/dz)\,/\,25{,}000)^{-0.5}(\Sigma_p/10)^{-0.3}$

Assuming no bias evolution though it exists:

$< \mathbf{1.5 \times 10^{-3}}$ $(db/dz\,/\,b)/0.3\;(\sigma_z/0.1)^2$

Systematic errors in ξ_{ss}:

$< \mathbf{8.0 \times 10^{-4}}$ $(\sigma_{sys}/0.02)\;(\sigma_z/0.1)$

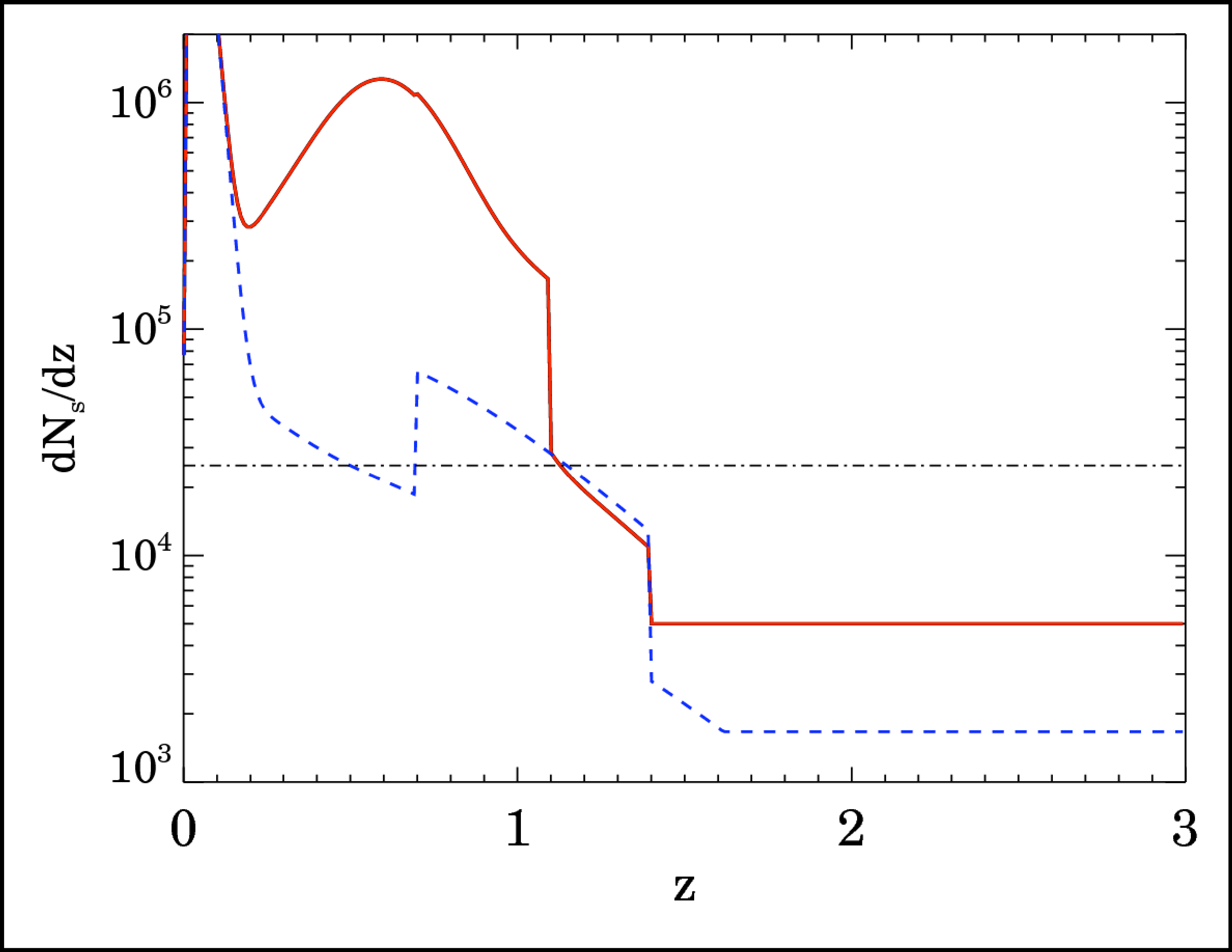
Errors in assumed cosmology:

$< \mathbf{4.7 \times 10^{-4}}$ $(\sigma_z/0.1)^2\;(\Delta\Omega_m/0.03)$

Field-to-field zero point variations:

$< \mathbf{2.3 \times 10^{-4}}$ $(\sigma_{zp}/0.01)\,(N_{patch}/4)^{-0.5}\;(\sigma_z/0.1)$

Near-future prospects

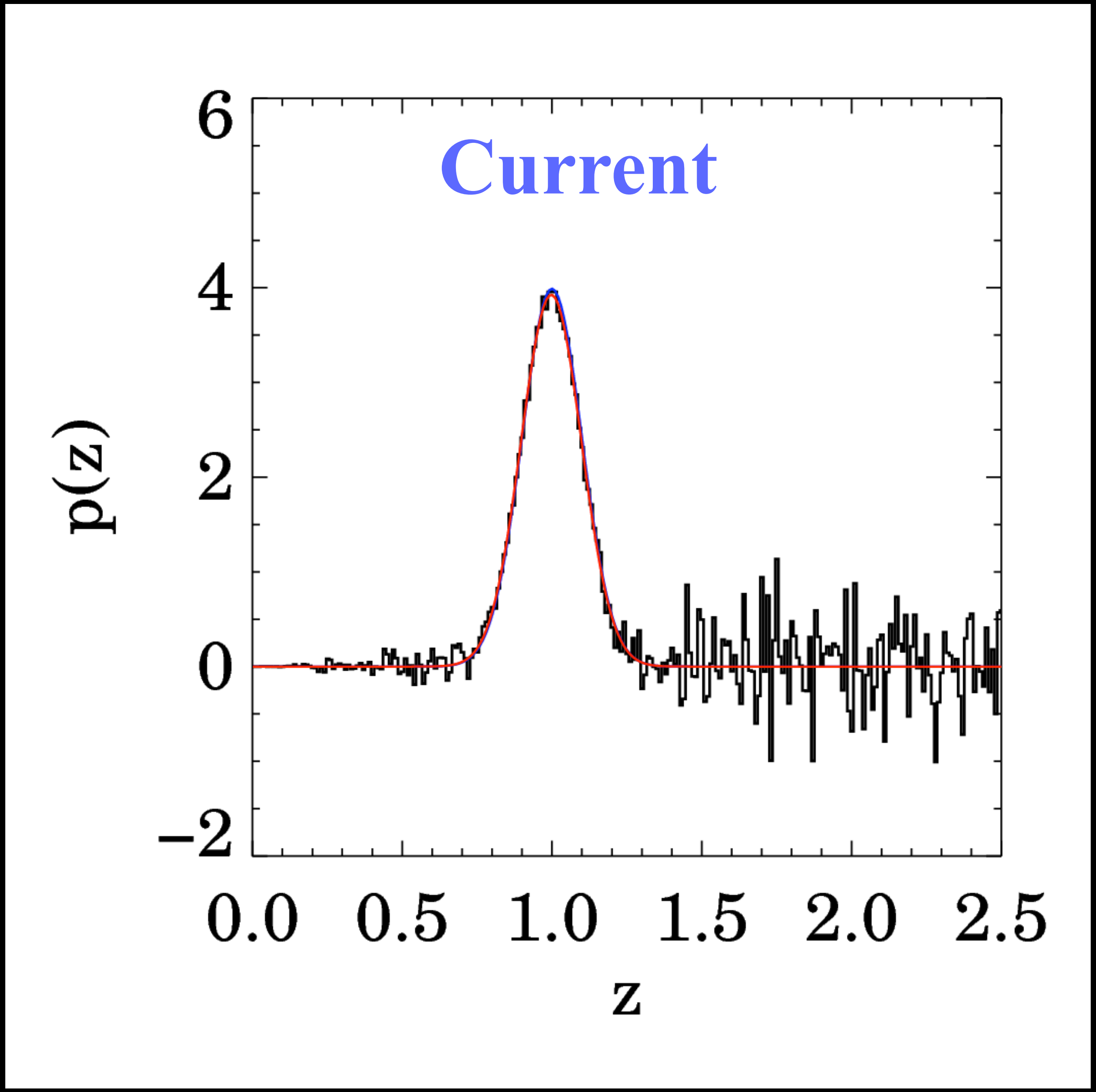


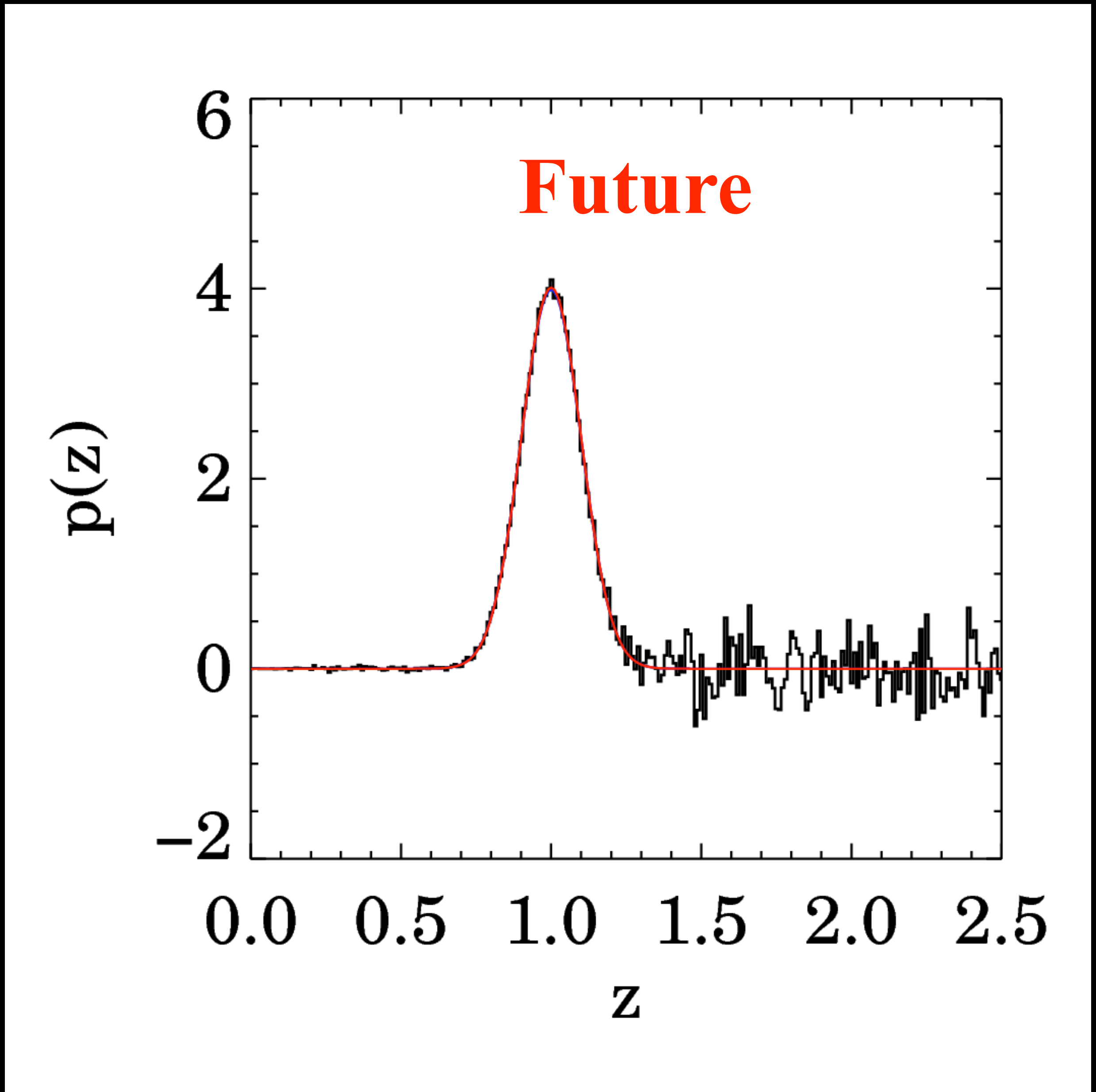
Blue: SDSS + AGES + VVDS + DEEP2+1700 galaxies/unit *z* at high *z*

Red: add *z*COSMOS + PRIMUS + WiggleZ + 5000 galaxies/unit *z* at high *z*

Monte Carlo realizations for real surveys

Redshift samples will be 3-10x larger than today at most *z*, with correspondingly smaller errors:





The All-wavelength Extended Groth strip International Survey

— Spitzer MIPS, IRAC

— DEEP2 spectra and Caltech / JPL K_s imaging

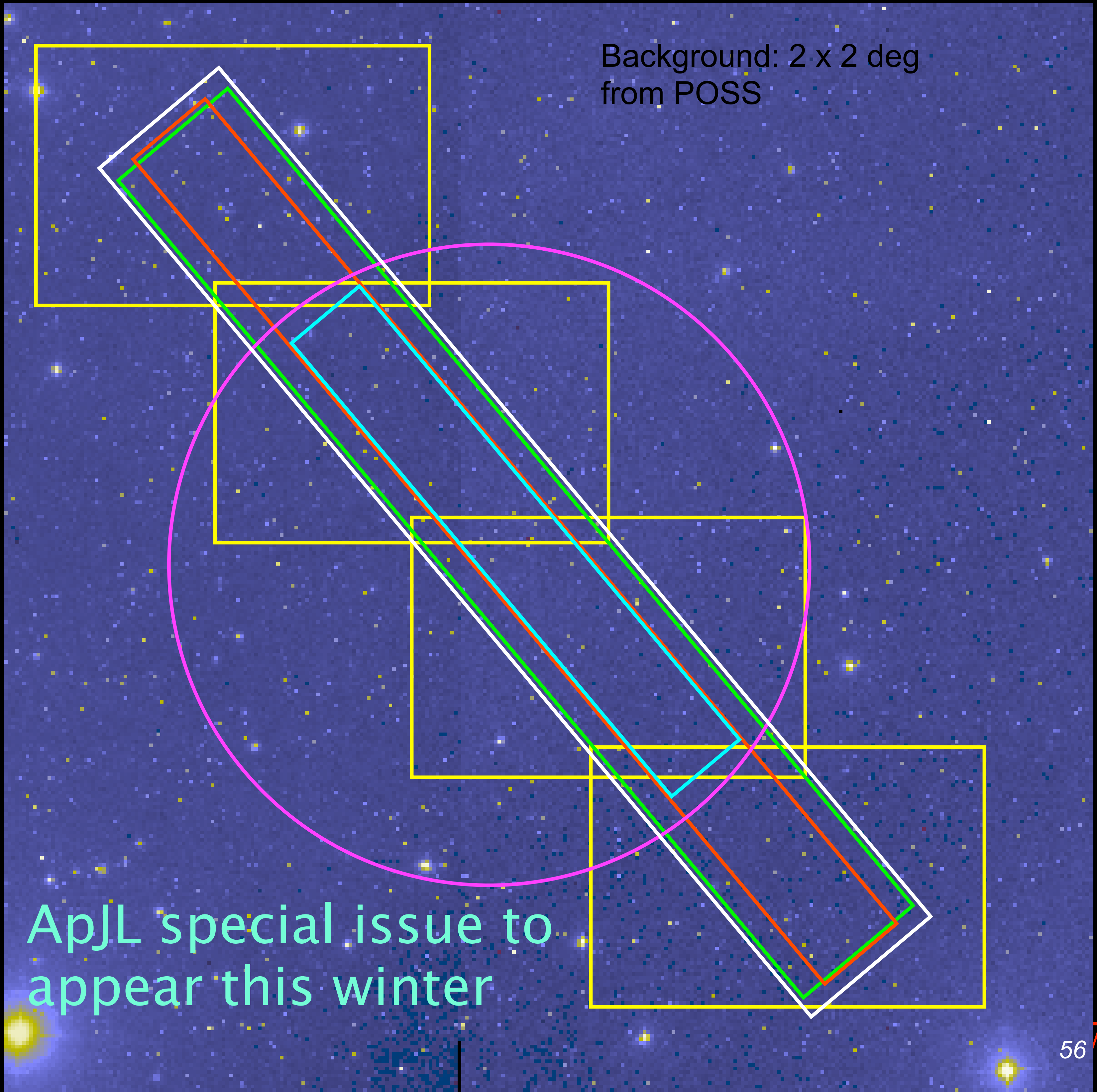
— HST/ACS V,I (Cycle 13)

— DEEP2/CFHT B,R,I

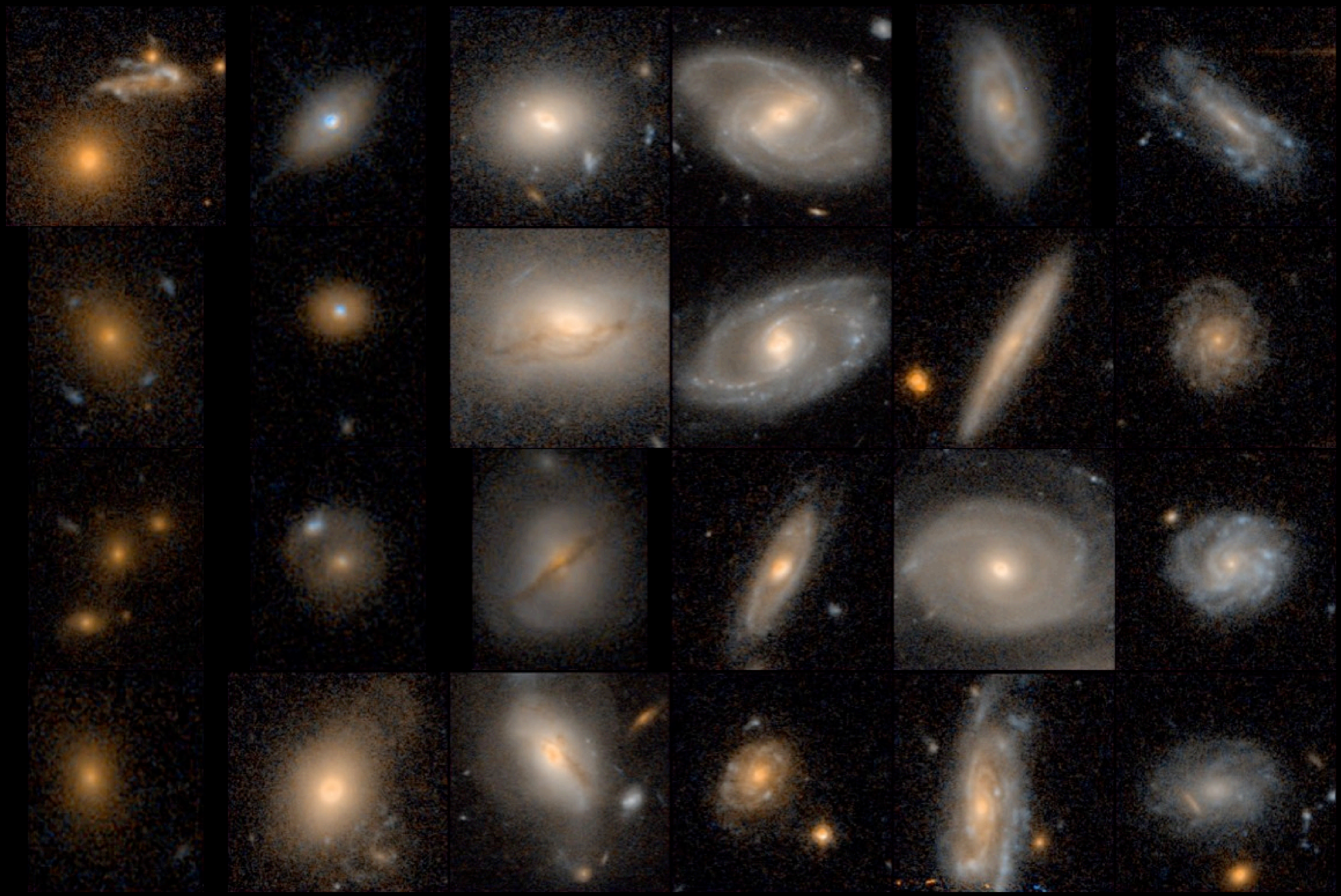
— GALEX NUV+FUV

— Chandra/ACIS

Plus VLA, CFHTLS SCUBA, etc….



In AEGIS, we are seeing the ancestors of modern galaxies



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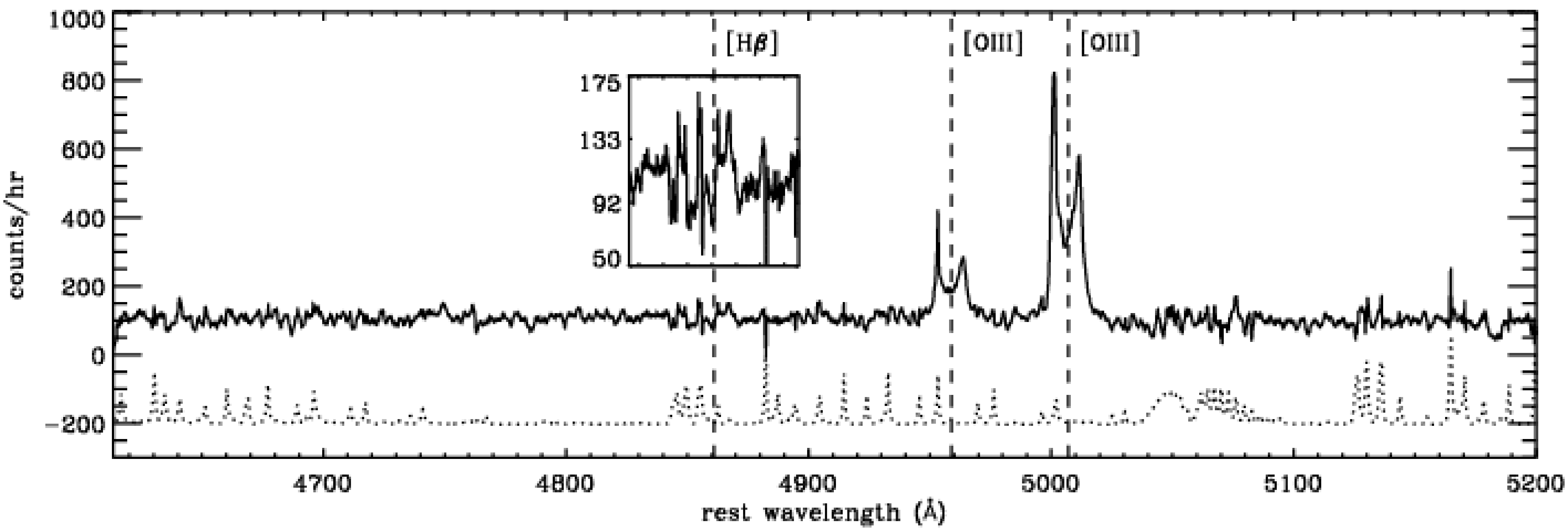
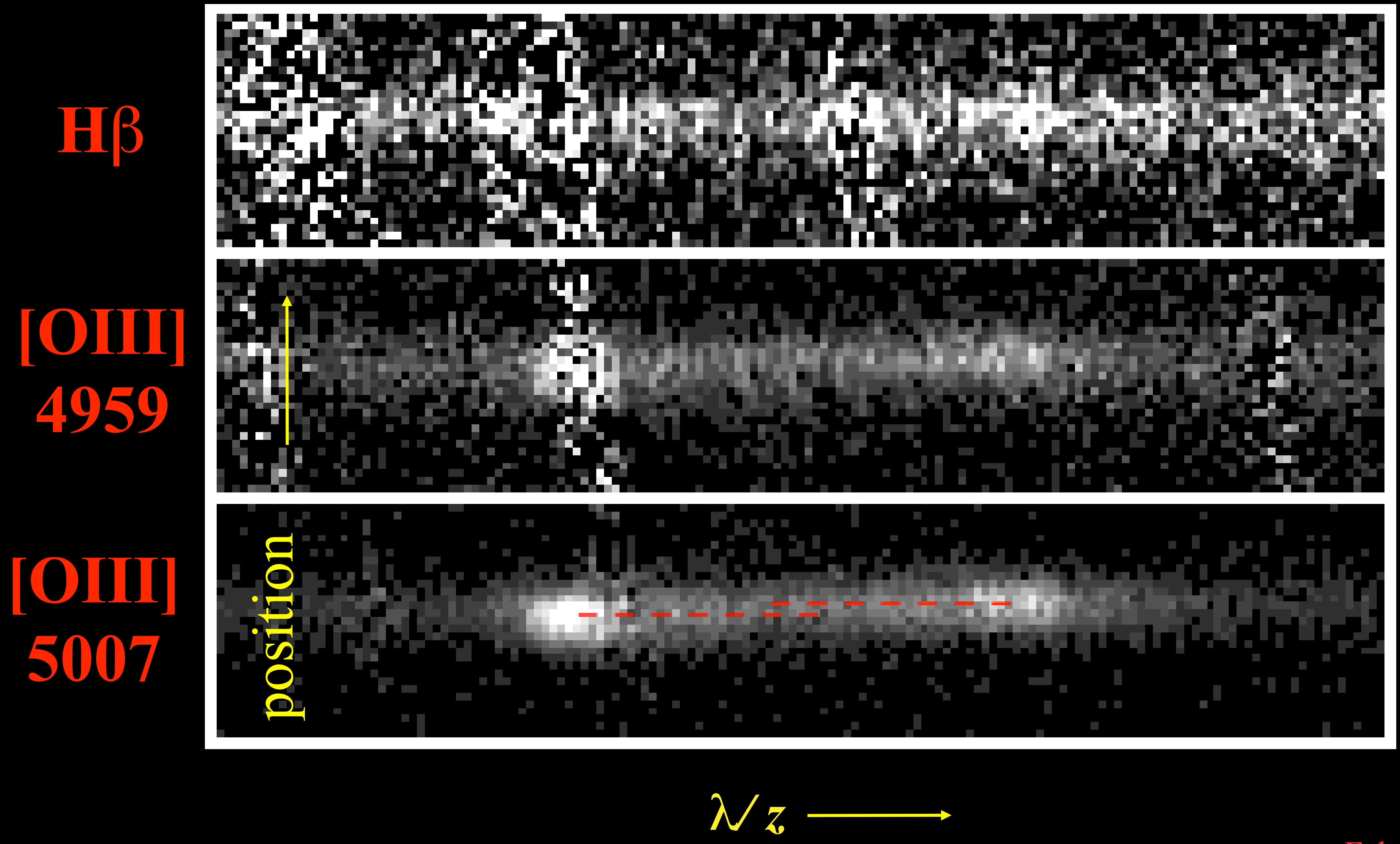
Though it is difficult to connect them one-to-one

By combining area with depth, AEGIS allows us to discover rare objects…



Gerke et al. 2007

Like a spectroscopically identified, dual AGN



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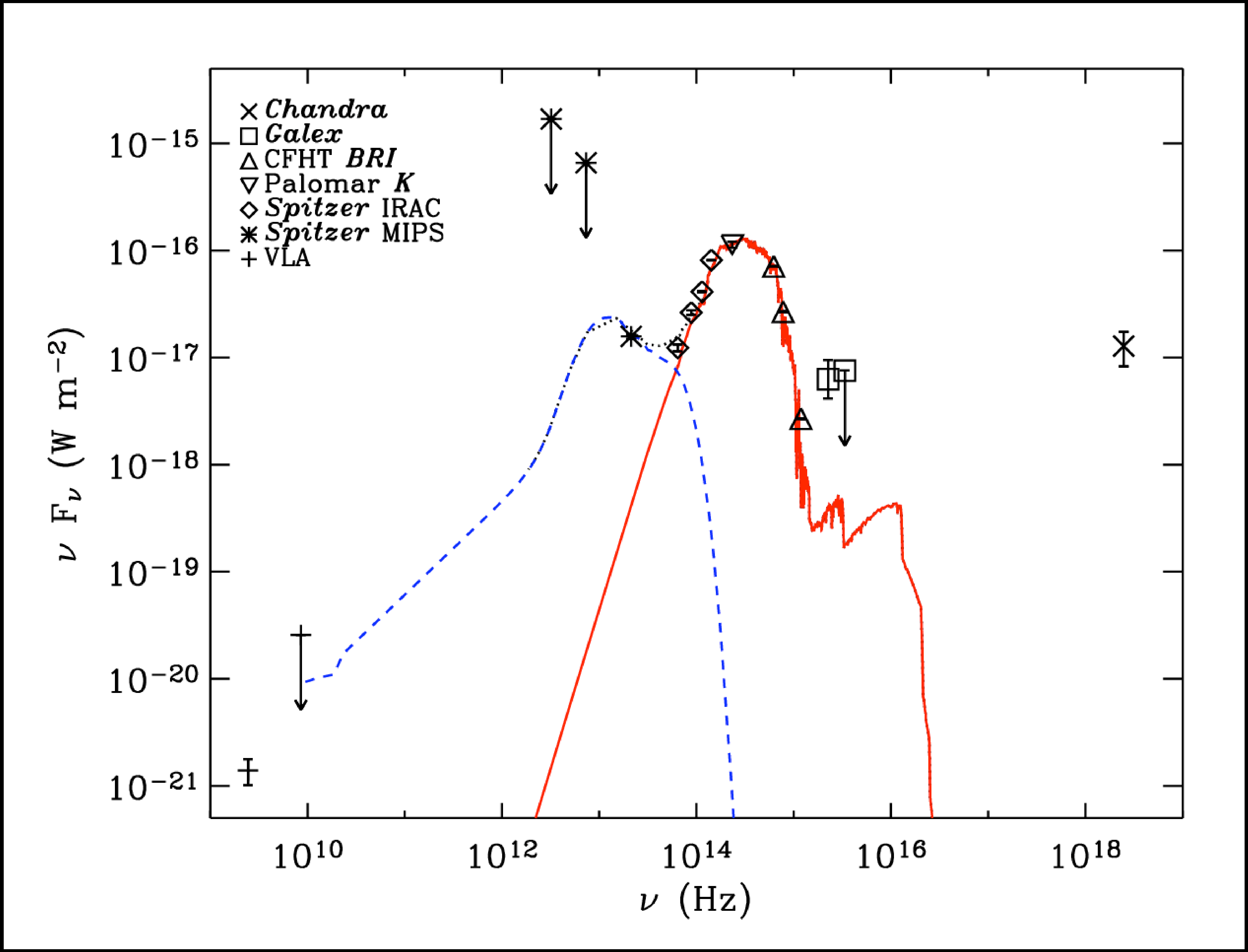
We have measured its spectrum over 9 decades in frequency…



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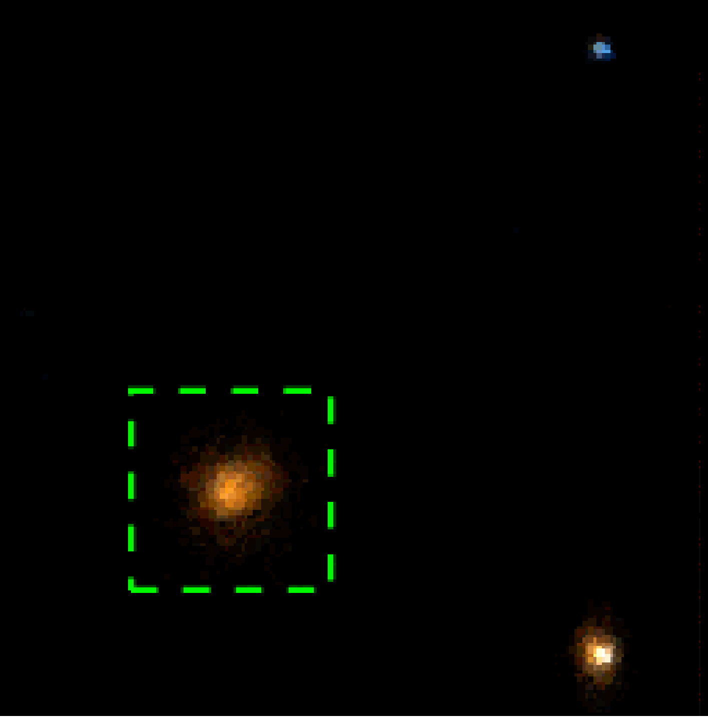
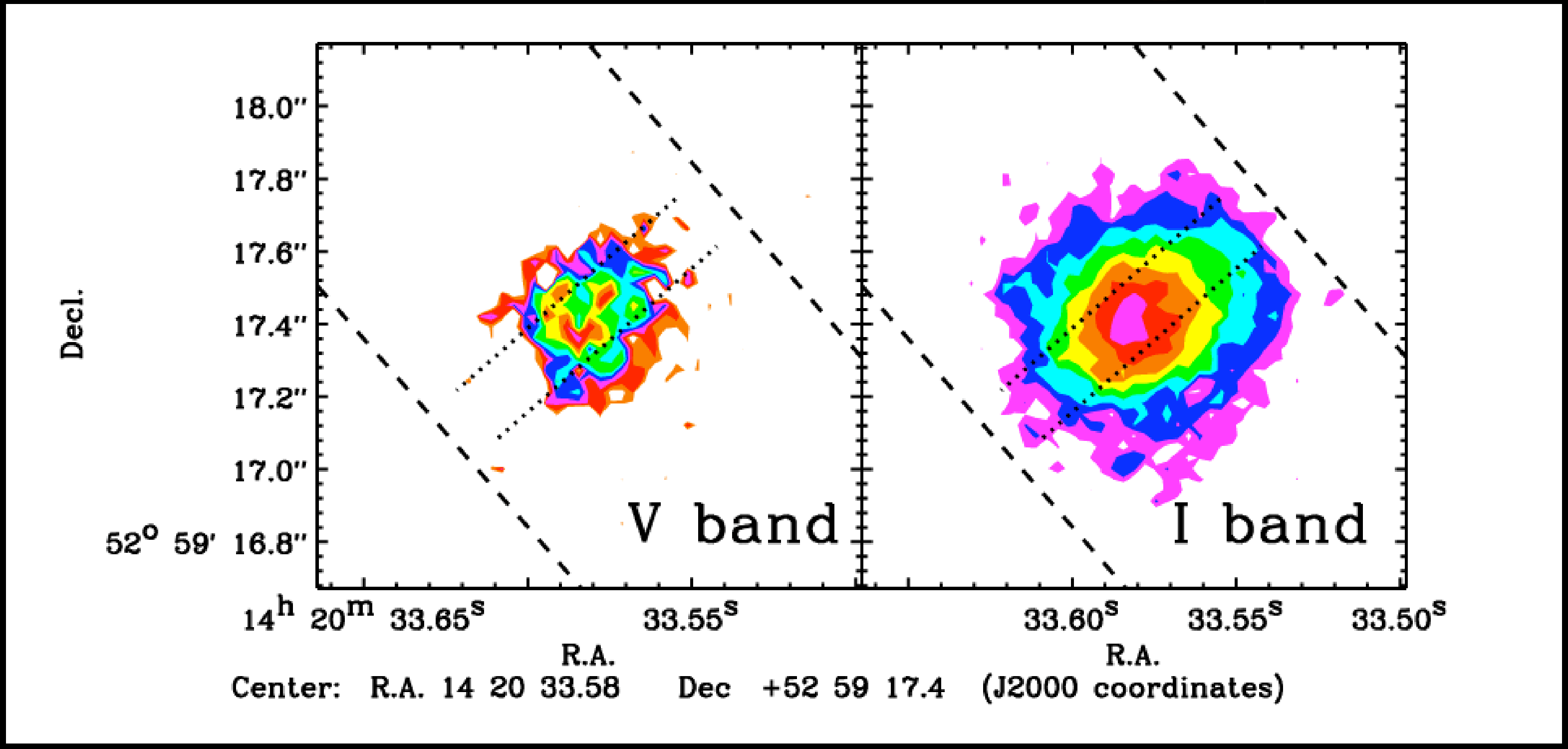
And have high-resolution *HST* imaging





Conclusions

- It is possible to test for variations in the fine-structure constant using galaxy [OIII] emission--much simpler (astro)physics than metal absorption lines.
- DEEP2 finds no evidence for time variation in α to z~0.7, or for spatial variation over scales of ~2 Gpc, but error bars are ~10 times too large to address claimed detections with QSO metal absorption lines.
- Using cross-correlation techniques, photometric redshift distributions may be determined to the accuracy required by future dark energy experiments, even without faint spectra.
- There are many more results from DEEP2 and AEGIS still to come!

DEEP2 Data Release 2: **http://deep.berkeley.edu/DR2**