# Mode-Projection Tests for LSST

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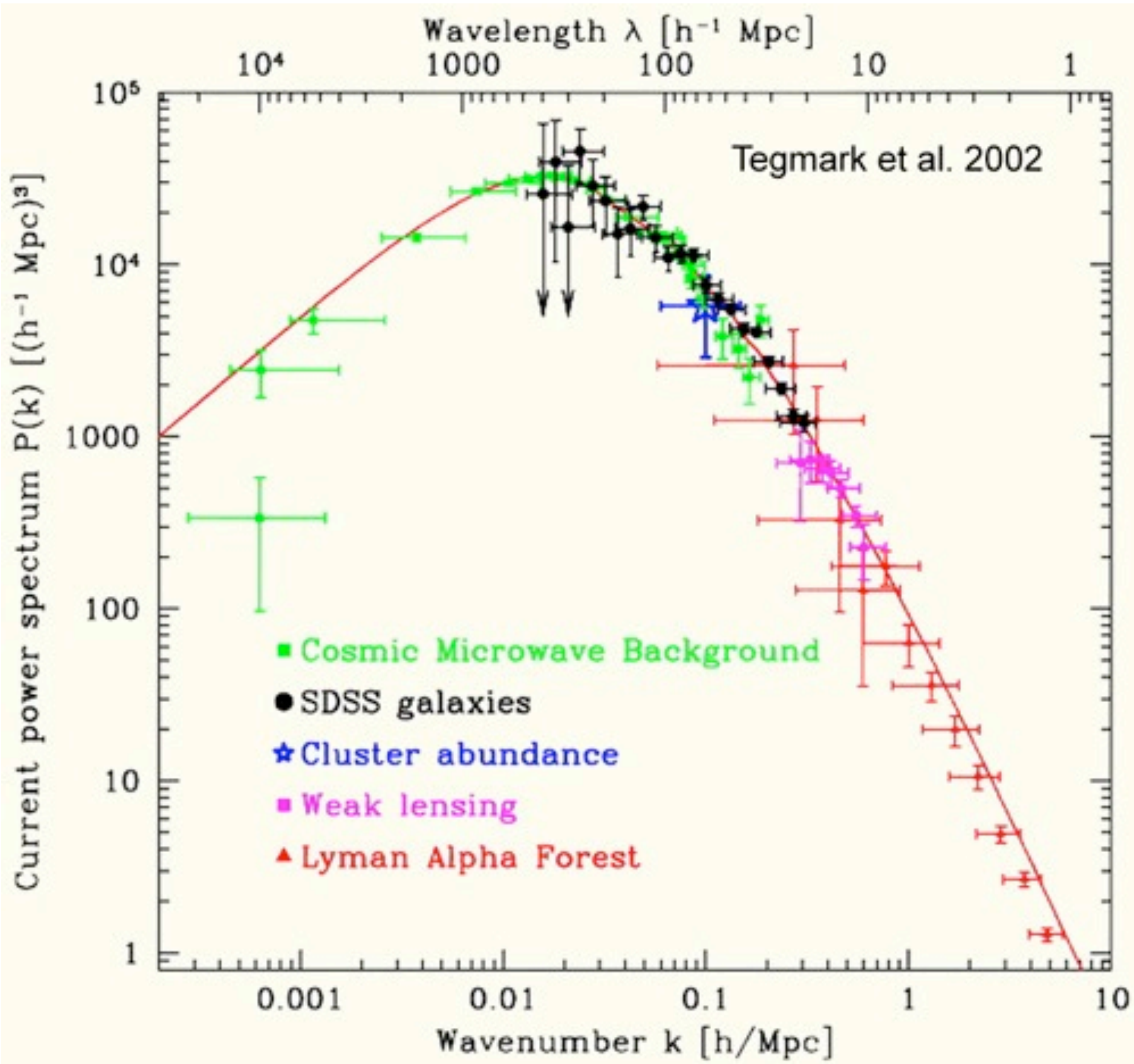
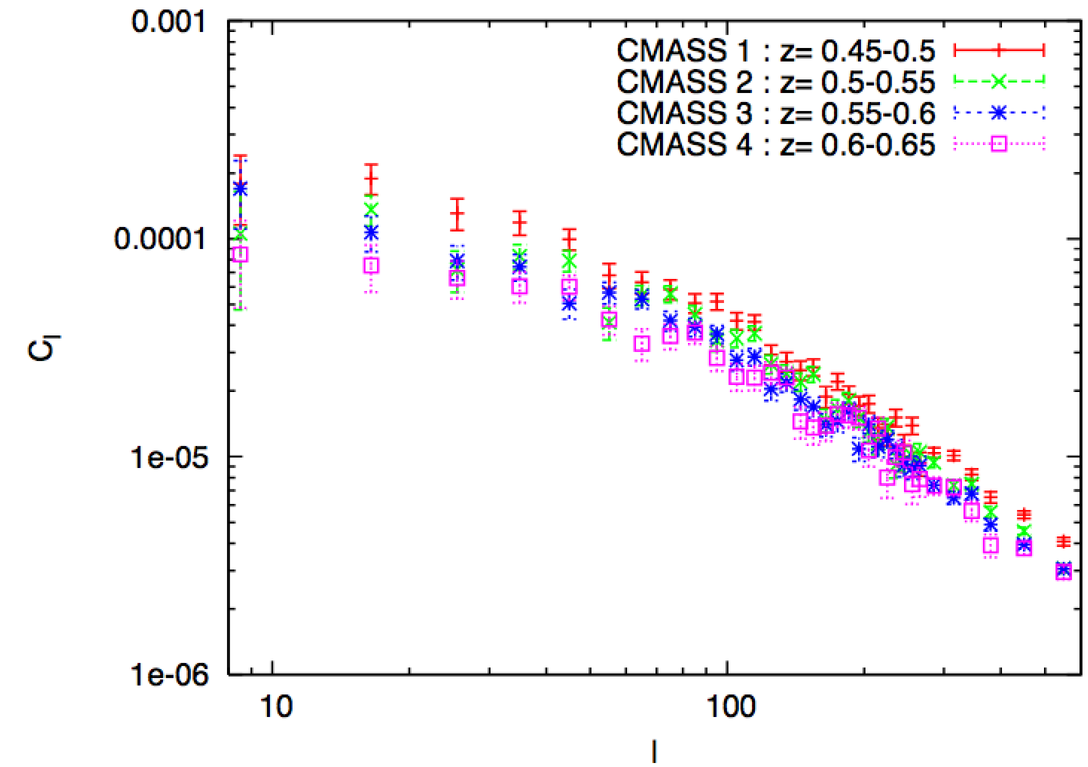
# Power Spectrum




Credit: Ho et al. 2012

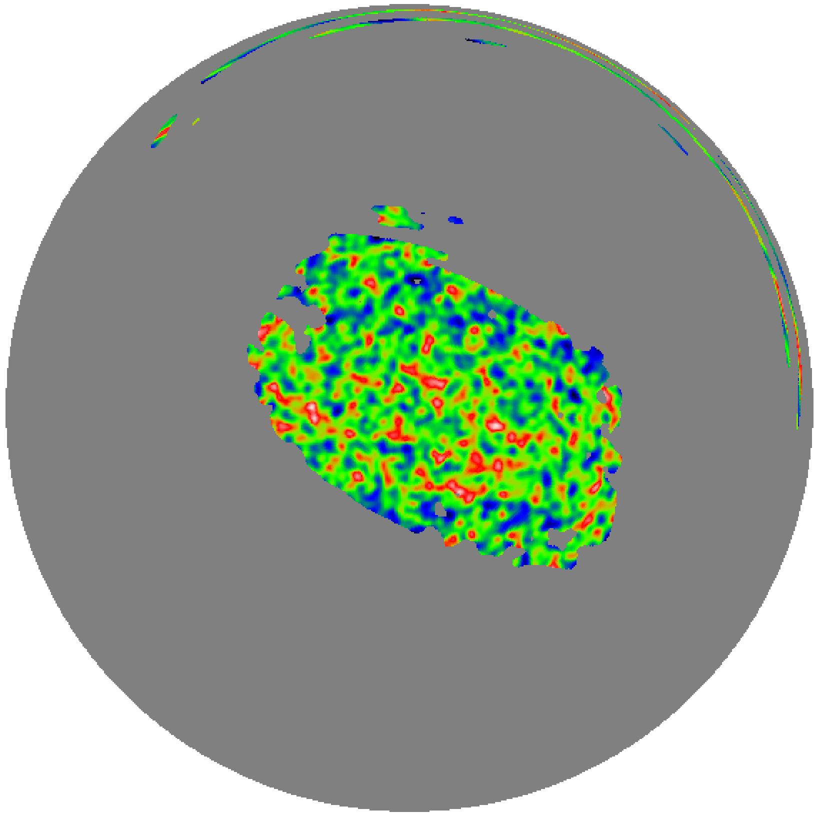



$C_\ell$ - angular power spectrum

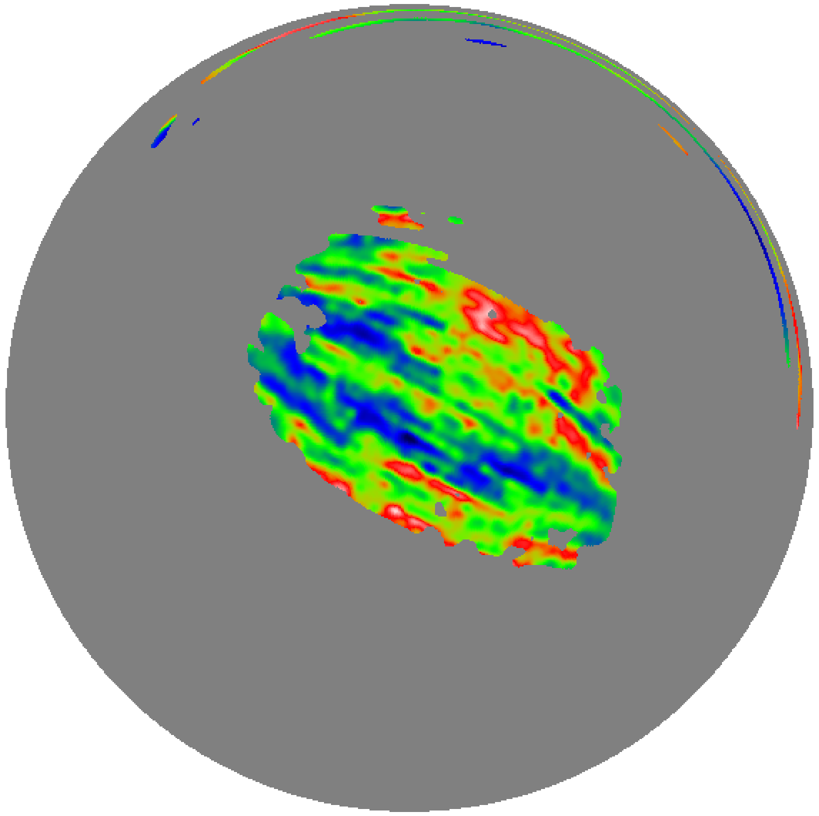
$=$ radial projection of $P(k)$

# Seeing

z01

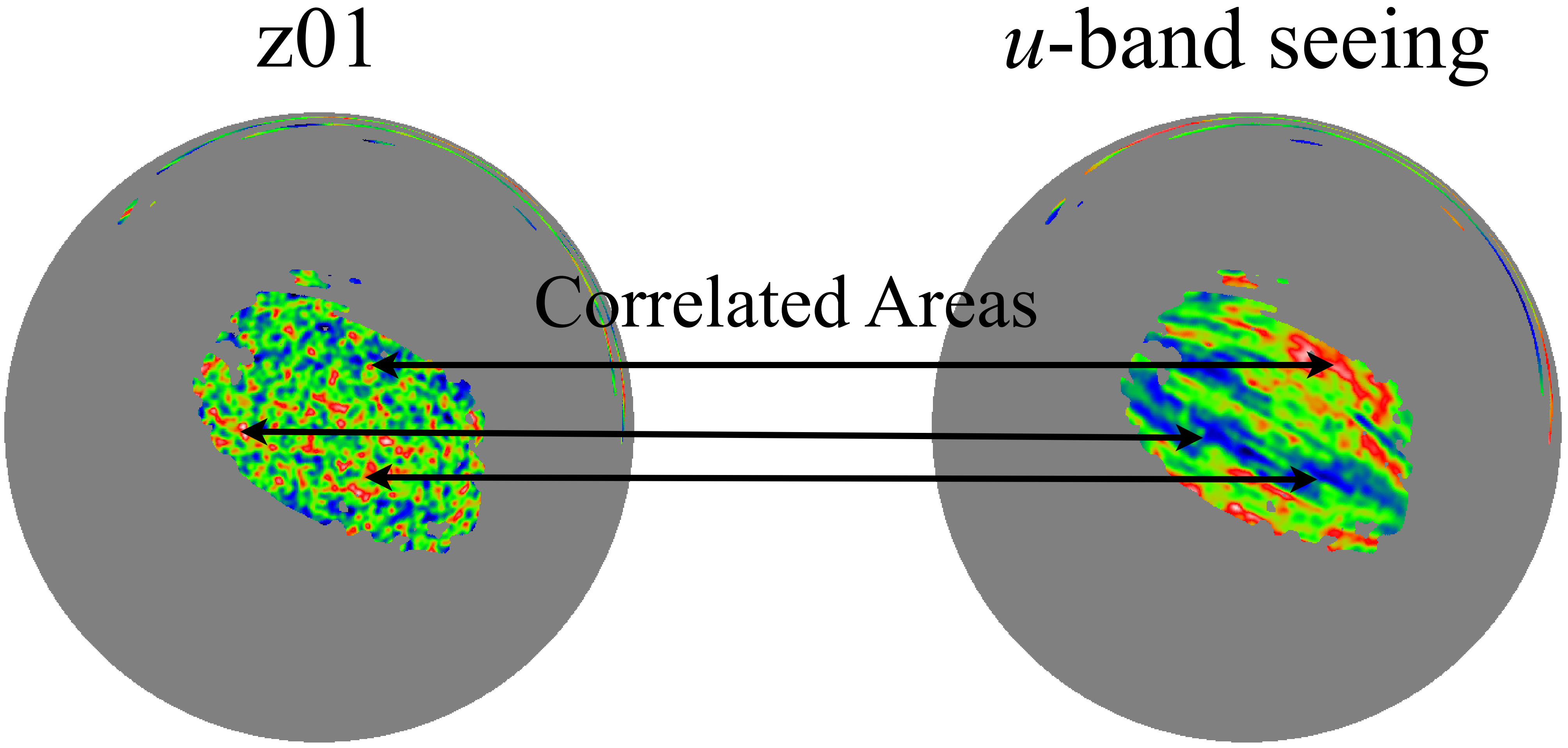


*u*-band seeing



- Seeing - the FWHM of the point-spread function in a pixel.
- Affects photometric noise, de-blending of sources, and star-galaxy separation.

# Seeing

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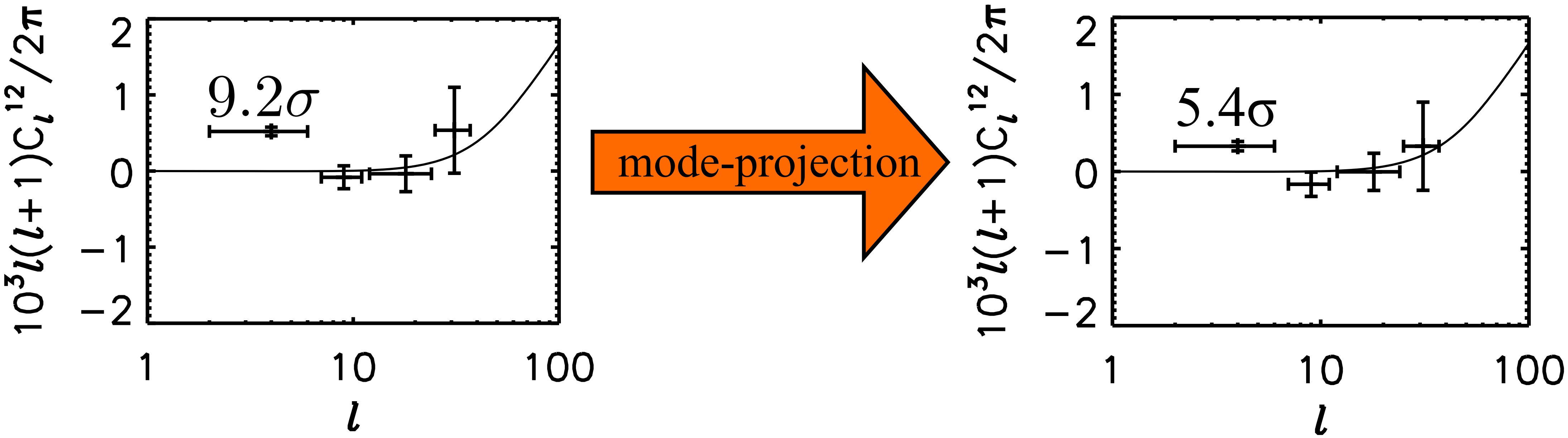
# Photometric Quasars




Still too high!

Credit: Pullen and Hirata 2013

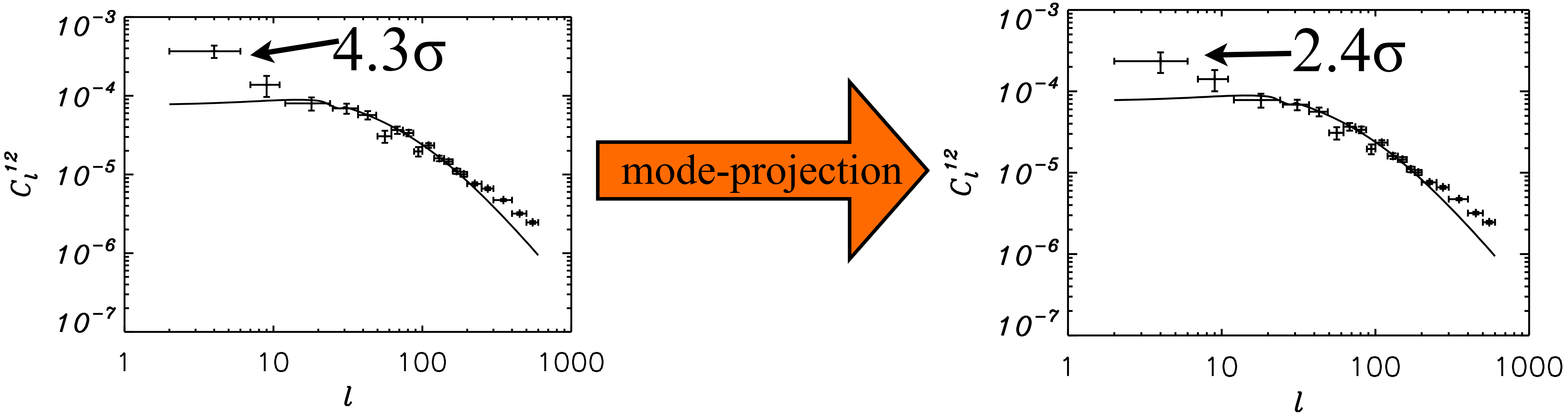
- Excess cross-correlation contaminates $f_{\rm NL}$ and implies systematics.
- We perform *mode-projection* - boosts the expected noise of contaminated modes to remove them from the estimator.
- Mode-projecting the seeing map reduces the cross-correlation by 4σ; stellar contamination was also a culprit.

Tegmark et al. 1997, Bond et al. 1998, Halverson et al. 2001

# Going Forward

- SDSS DR6 quasar maps had 2% contamination; < 0.6% is needed for $f_{\rm NL} < 10$.
- LSST's multiple viewings will beat down some systematic errors (e.g. seeing) on small scales, but not others (e.g. stellar contamination).
- More masking (Leistedt et al. 2013), cross-correlating between surveys (Giannantonio et al. 2013) seem to help.
- Ho & Agarwal (Ho et al. 2013) show that contaminated angular modes can be removed directly.
- I am currently testing these methods for the LSST survey.

# CMASS Galaxies




- CMASS galaxies from BOSS survey exhibit stellar contamination on large scales.

- It appears that unknown contaminants may be present.

- *Next steps: (1) Identify methods to remove unknown systematics after mode-projection and (2) determine LSST multiple scans response using Stripe 82 data.*

Ho et al. 2012

# How to remove systematics?

- We avoid fitting cross-correlation amplitudes, which can cause spurious modes and oversubtraction.
- Instead we mode-project templates related to various systematics.
- Mode projection makes the estimator *exactly* insensitive to a given systematic template by effectively increasing the contaminated mode's noise.

$$\mathbf{x}^{\rm obs} = \mathbf{x}^{\rm true} + \sum_{i=sys} \lambda_i \mathbf{\Psi}_i$$

$$\mathbf{C} = \mathbf{C}^{\rm true} + \sum_{i=sys} \zeta_i \mathbf{\Psi}_i \mathbf{\Psi}_i^T$$

A number large enough so increasing it further does not affect the estimate.

# Non-Gaussianity

- In LSS, non-Gaussianity causes the clustering bias to shift at large scales.
- Quasars are the best tracers for this due to high redshifts and high bias.
- Systematics Test: Cross-correlate quasar maps from different redshifts.

$$\Phi_{\rm NG} = \phi_G + f_{\rm NL}(\phi_G^2 - \langle \phi_G^2 \rangle)$$

$$(Planck\!: f_{\rm NL} = 2.7 \pm 5.8)$$

$$\Delta b(k) \propto f_{\rm NL}/k^2$$

Planck Collaboration 2013, Dalal et al. 2008, Slosar et al. 2008, Xia et al. 2011

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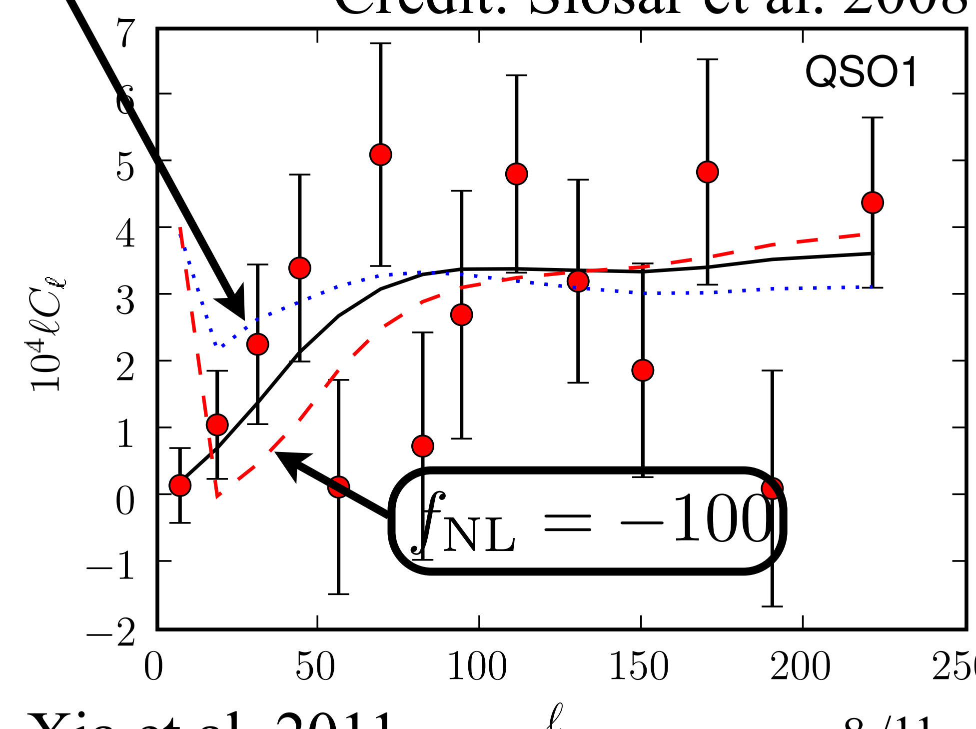
$f_{\rm NL} = 100$

Credit: Slosar et al. 2008




Planck Collaboration 2013, Dalal et al. 2008, Slosar et al. 2008, Xia et al. 2011

# Scale-dependent bias

- Nongaussian perturbations are seen in many models of primordial cosmology.
- It mixes large (halos) and small (< galaxy) scale clustering
- It makes scale-dependent bias.
- Big effect on large scales!
- Photometric quasars are best due to large, high-redshift samples.

**Decomposed Curvature Perturbation**

Nongaussian

$$\Phi = \phi + f_{\rm NL}(\phi^2 - \langle \phi^2 \rangle)$$

Gaussian

$$\Delta b(M,k) \propto \frac{f_{\rm NL}(b-p)}{k^2 T(k) D(z)}$$

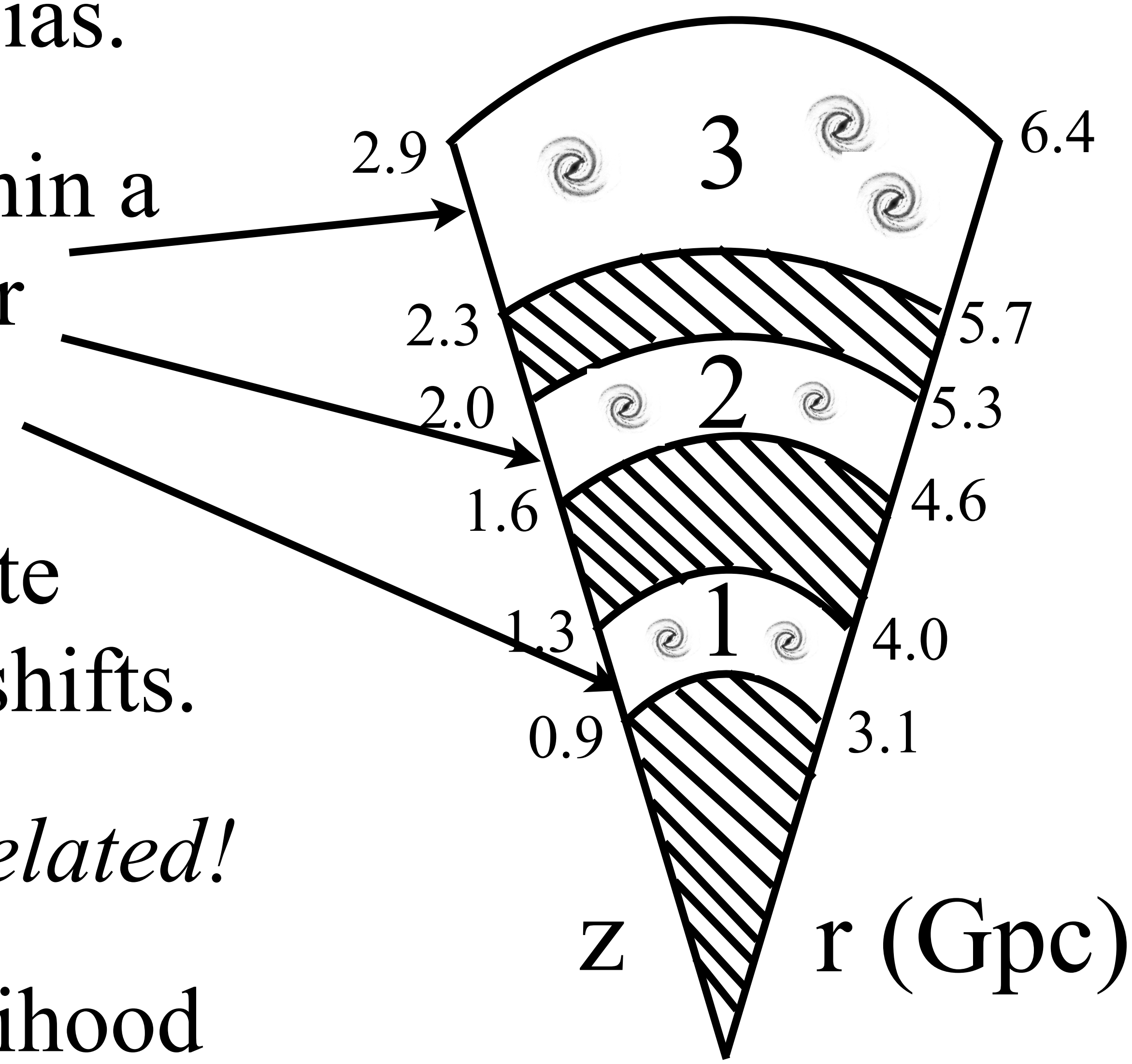
$$p = \begin{cases} 1 & \text{galaxies} \\ 1.6 & \text{quasars} \end{cases}$$

# Quasar Clustering

- Quasars are the best tracers for this due to high redshifts and high bias.
- We choose 3 redshift slices within a larger SDSS *photometric* quasar sample (Richards et al. 2008).
- Systematics Test: Cross-correlate quasar maps from different redshifts.
- *Quasar maps should be uncorrelated!*
- Use a quadratic maximum likelihood (QML) estimator for $C_\ell$.

Tegmark et al. 1996, Padmanabhan et al. 2003

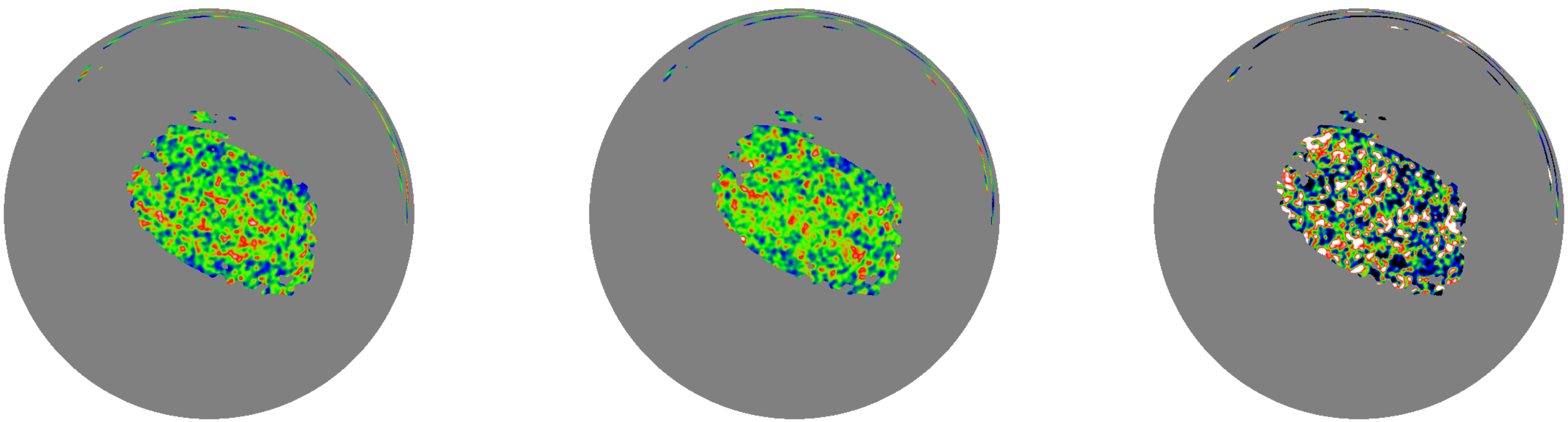
SDSS Sample




redshift slices

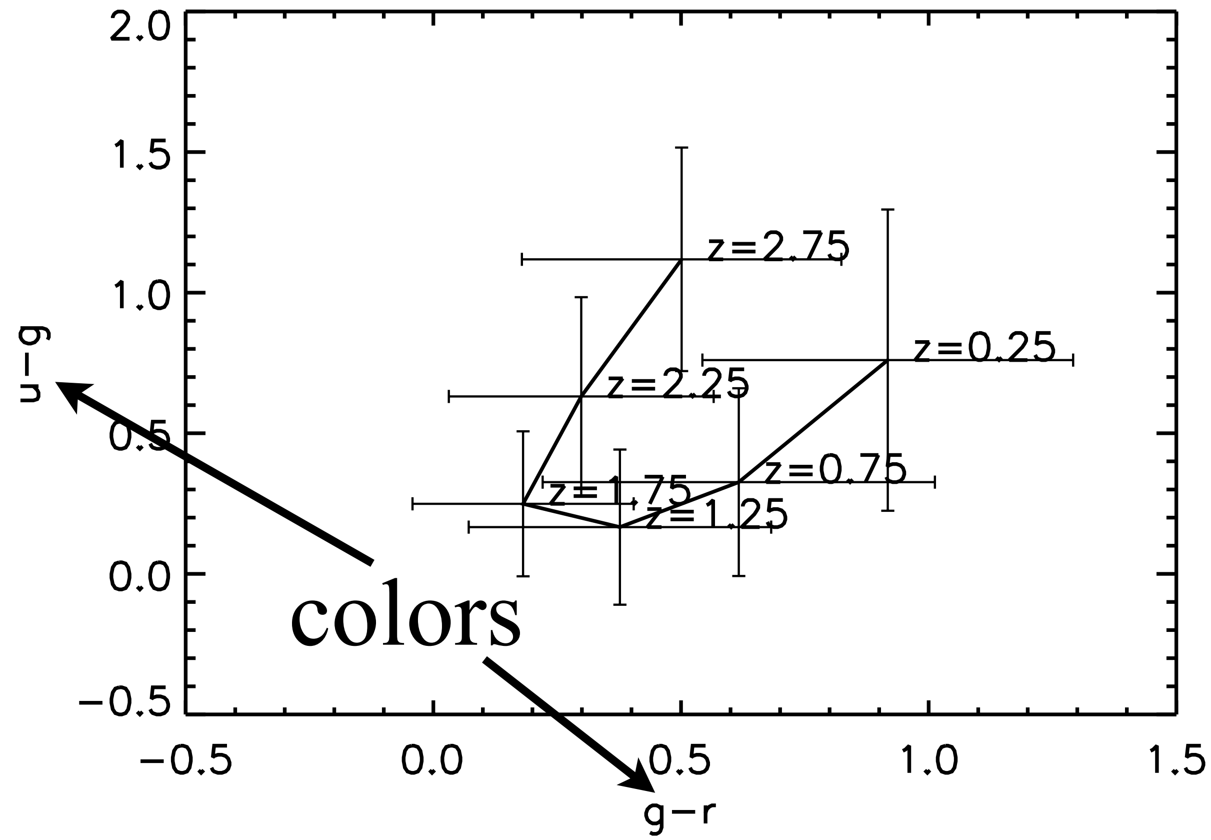
# Quasar Maps

$z \in [0.9, 1.3]$ $z \in [1.6, 2.0]$ $z \in [2.3, 2.9]$



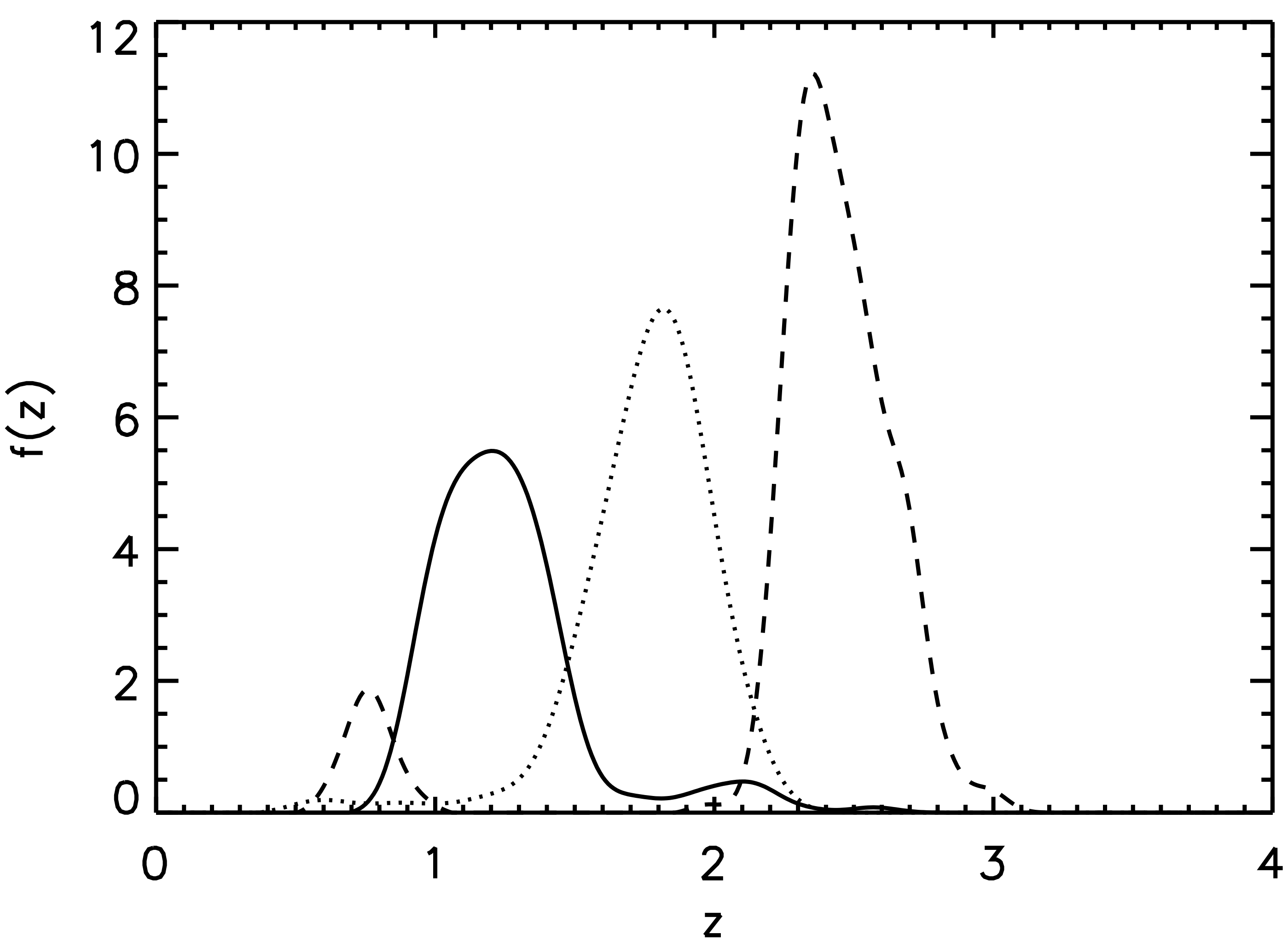
| Label | $z_{\rm p}$ | $z_{\rm mean}$ | $N_{qso}$ |
|---|---|---|---|
| z01 | 0.9–1.3 | 1.230 | 75,835 |
| z02 | 1.6–2.0 | 1.731 | 91,356 |
| z03 | 2.3–2.9 | 2.210 | 10,806 |

# Photometric Redshifts




- Colors from apparent magnitudes vary with redshift, allowing redshifts to be estimated fast.
- Redshift errors are large ( $\sim 0.1$).

# Redshift Distribution



# Template Properties

| Systematic (units) | $\overline{\Psi}$ | $\sigma_{\Psi}$ | $\zeta$ | z01 slope | z02 slope | z03 slope |
|---|---|---|---|---|---|---|
| ebv (mag) | 0.0251 | 0.0109 | $10^7$ | +0.415±0.424 | -0.249±0.351 | -5.84±2.98 |
| star | $+2.96 \times 10^{-7}$ | 0.658 | $10^6$ | +0.0149±0.0070 | +0.0121±0.0058 | +0.130±0.049 |
| rstar | $+3.67 \times 10^{-6}$ | 1.38 | $10^6$ | $(+2.60 \pm 3.35) \times 10^{-3}$ | $(+7.29 \pm 2.77) \times 10^{-3}$ | $(+3.89 \pm 23.58) \times 10^{-3}$ |
| ugr (mag) | +0.0176 | 0.0354 | $10^9$ | -0.0453±0.1306 | -0.276±0.108 | +0.438±0.919 |
| gri (mag) | $+6.59 \times 10^{-3}$ | 0.0282 | $10^9$ | -0.0852±0.1639 | $(-8.98 \pm 135.61) \times 10^{-3}$ | -0.322±1.154 |
| riz (mag) | $+1.84 \times 10^{-3}$ | 0.0211 | $10^7$ | +0.201±0.219 | +0.401±0.181 | -0.0270±1.5419 |
| uerr (mag) | -0.0164 | 0.0207 | $10^5$ | -0.480±0.223 | -0.0589±0.1847 | -2.54±1.57 |
| airu (mag) | 1.15 | 0.0921 | $10^6$ | -0.0583±0.0502 | -0.0700±0.0415 | -0.0838±0.3532 |
| seeu (arcsec) | 1.54 | 0.175 | $10^6$ | -0.176±0.026 | -0.124±0.022 | -0.198±0.186 |
| seer (arcsec) | 1.35 | 0.164 | $10^6$ | -0.162±0.028 | -0.112±0.023 | -0.130±0.198 |
| skyu (maggies/arcsec$^2$) | 22.2 | 0.230 | $10^6$ | $(-3.25 \pm 20.10) \times 10^{-3}$ | +0.0265±0.0166 | -0.170±0.141 |
| skyi (maggies/arcsec$^2$) | 20.3 | 0.216 | $10^6$ | $(-9.28 \pm 21.40) \times 10^{-3}$ | +0.0464±0.0177 | -0.0936±0.1506 |
| mjd (days) | 52505 | 552 | $10^2$ | $(+3.4 \pm 8.4) \times 10^{-6}$ | $(+1.92 \pm 0.69) \times 10^{-5}$ | $(+1.52 \pm 0.59) \times 10^{-4}$ |
| cam1 | $+1.19 \times 10^{-9}$ | $2.85 \times 10^{-3}$ | $10^6$ | -2.08±1.62 | +1.45±1.34 | +1.33±11.42 |
| cam2 | $-7.11 \times 10^{-10}$ | $2.85 \times 10^{-3}$ | $10^6$ | -0.324±1.622 | -0.697±1.342 | +0.125±11.416 |
| cam3 | $-8.42 \times 10^{-10}$ | $2.85 \times 10^{-3}$ | $10^6$ | +0.977±1.622 | +1.72±1.34 | +7.87±11.42 |
| cam4 | $-1.46 \times 10^{-9}$ | $2.85 \times 10^{-3}$ | $10^6$ | +4.44±1.62 | -4.73±1.34 | +8.80±11.42 |
| cam5 | $-2.92 \times 10^{-9}$ | $2.85 \times 10^{-3}$ | $10^6$ | -3.32±1.62 | -1.97±1.34 | -7.72±11.42 |
| ref | -0.0596 | 0.439 | $10^6$ | $(-2.59 \pm 10.53) \times 10^{-4}$ | $(+5.00 \pm 8.71) \times 10^{-3}$ | +0.0299±7.41 |

# Power Reductions

z01 x z02

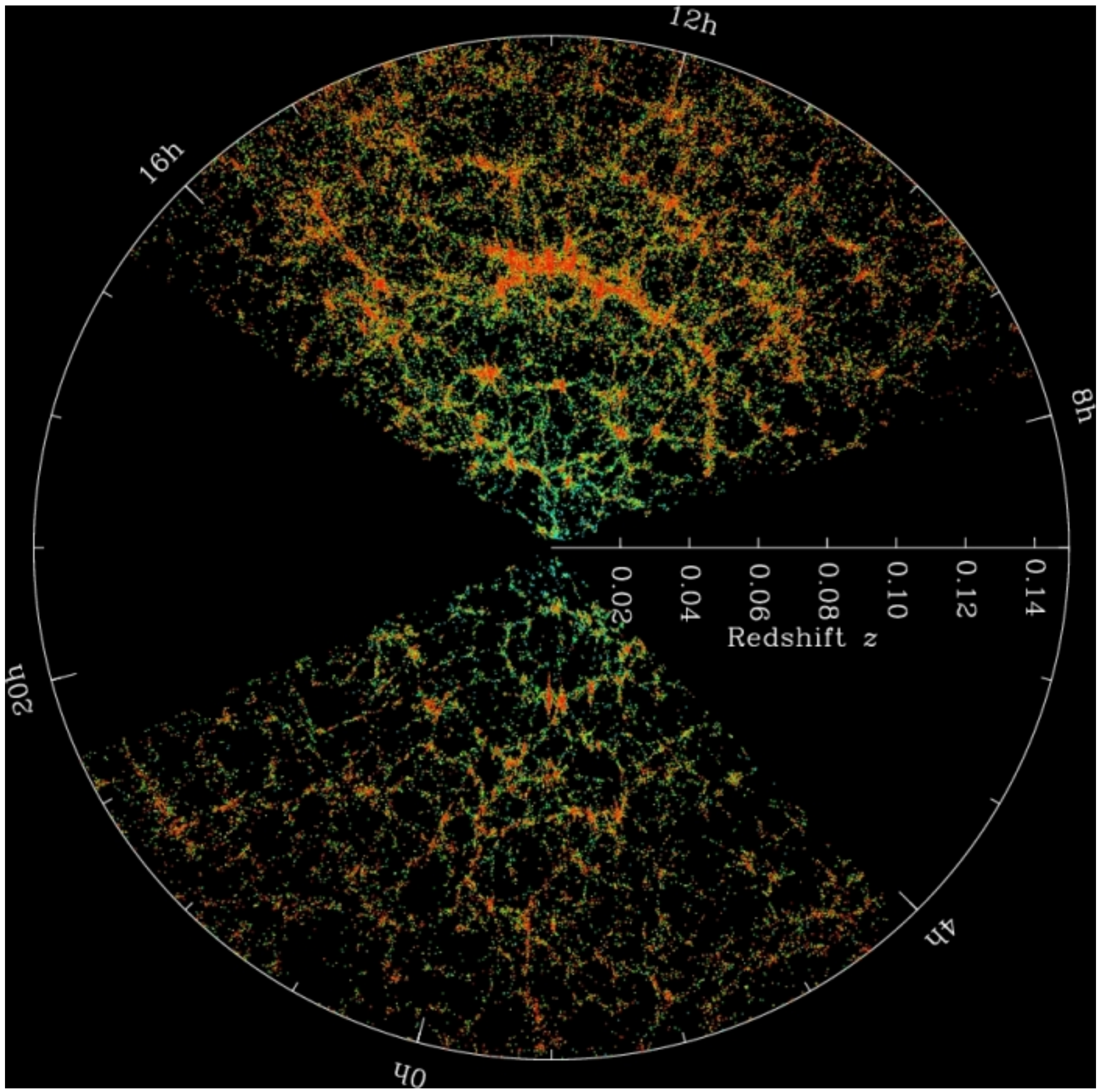
| Systematic | $10^4 C_\ell^{12}$ | ΔSNR ($\sigma$) |
|---|---|---|
| Red stellar contamination | $1.59 \pm 0.19$ | -0.8 |
| $(g-r)$ vs. $(u-g)$ | $1.60 \pm 0.19$ | -0.8 |
| $(i-z)$ vs. $(r-i)$ | $1.57 \pm 0.19$ | -0.9 |
| Air mass ($u$ band) | $1.66 \pm 0.19$ | -0.5 |
| Seeing ($u$ band) | $1.06 \pm 0.19$ | -3.6 |
| Seeing ($r$ band) | $1.16 \pm 0.19$ | -3.1 |

z01 x z03

| Systematic | $10^5 C_\ell^{12}$ | ΔSNR ($\sigma$) |
|---|---|---|
| Stellar contamination | $5.5 \pm 2.8$ | -0.7 |
| Seeing ($u$ band) | $6.6 \pm 2.8$ | -0.3 |
| Seeing ($r$ band) | $6.7 \pm 2.8$ | -0.3 |

Seeing, stellar contamination seem to be the dominant systematics.

# LSS Surveys




Credit: SDSS

SDSS - Sloan Digital Sky Survey

- A catalog of galaxies, quasars, etc. within a given distance/area interval.
- Traces large-scale structure (LSS) back in time.

  *Dark Energy, Star Formation*
- Carries an imprint from very early structure.

  *Inflation*