Title: Photometric quasars and primordial non-Gaussianity

Date: Nov 11, 2014 11:00 AM

URL: http://pirsa.org/14110136

Abstract: Quasars are highly biased tracers of the large-scale structure and therefore powerful probes of the initial conditions and the evolution of the universe. However, current spectroscopic catalogues are relatively small for studying the clustering of quasars on large-scales and over extended redshift ranges. Hence one must resort to photometric catalogues, which include large numbers of quasars identified using imaging data but suffer from significant stellar contamination and systematic uncertainties. I will present a detailed analysis of the photometric quasars from the Sloan Digital Sky Survey, and the resulting constraints on the quasar bias and primordial non-Gaussianity. The constraints on $f_{\rm NL}$, its spectral index, and $g_{\rm NL}$, are the tightest ever obtained from a single population of quasars or galaxies, and are competitive with the results obtained with WMAP, demonstrating the potential of quasars to complement CMB experiments. These results take advantage of a novel technique, 'extended mode projection', to mitigate the complex spatially-varying systematics present in the survey in a blind and robust fashion. This work is a new step towards the exploitation of data from the Dark Energy Survey, Euclid and LSST, which will require a careful mitigation of systematics in order to robustly constrain new physics.

Constraining primordial non-Gaussianity with photometric quasars

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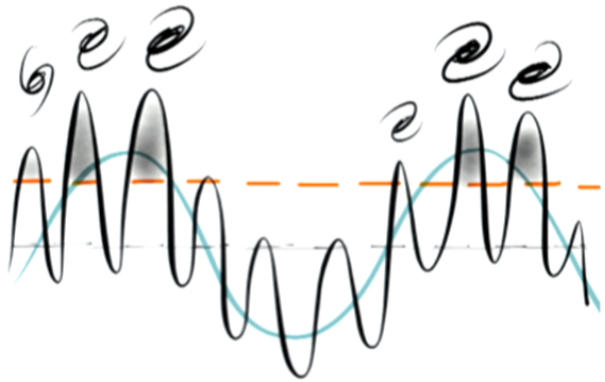
arXiv: 1404.6530 (MNRAS) and 1405.4315 (PRL)
In collaboration with Hiranya Peiris & Nina Roth

Motivation and key concepts

- Early universe physics with galaxy surveys:
  Primordial Non-Gaussianity (PNG)
- Galaxy surveys: many observational systematics
  Can we fully exploit DES / Euclid / LSST ?
- *This work:* (1) blind mitigation of systematics in quasar clustering (2) robust PNG constraints

Road map

Interrupt if you're lost!



1. Primordial non-Gaussianity (PNG in CMB+LSS)
2. Photometric quasars
3. Power spectra and systematics mitigation
4. Constraints on PNG and quasar bias

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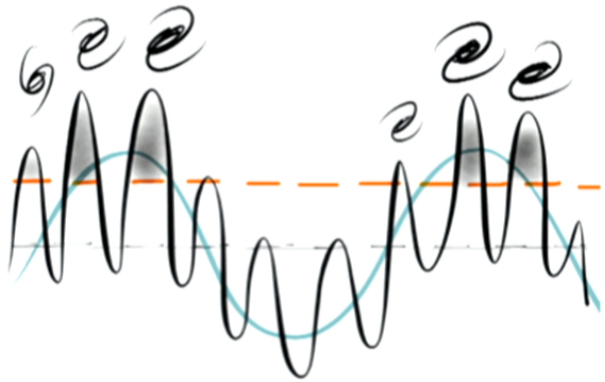

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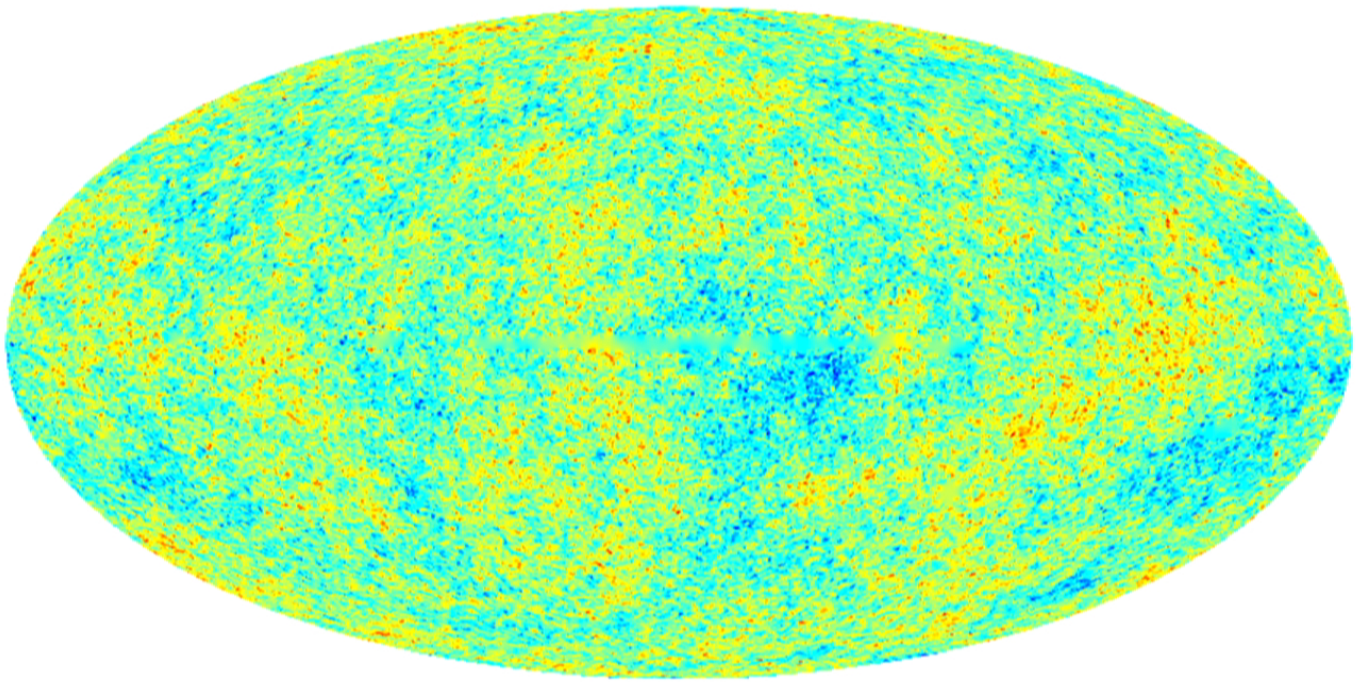
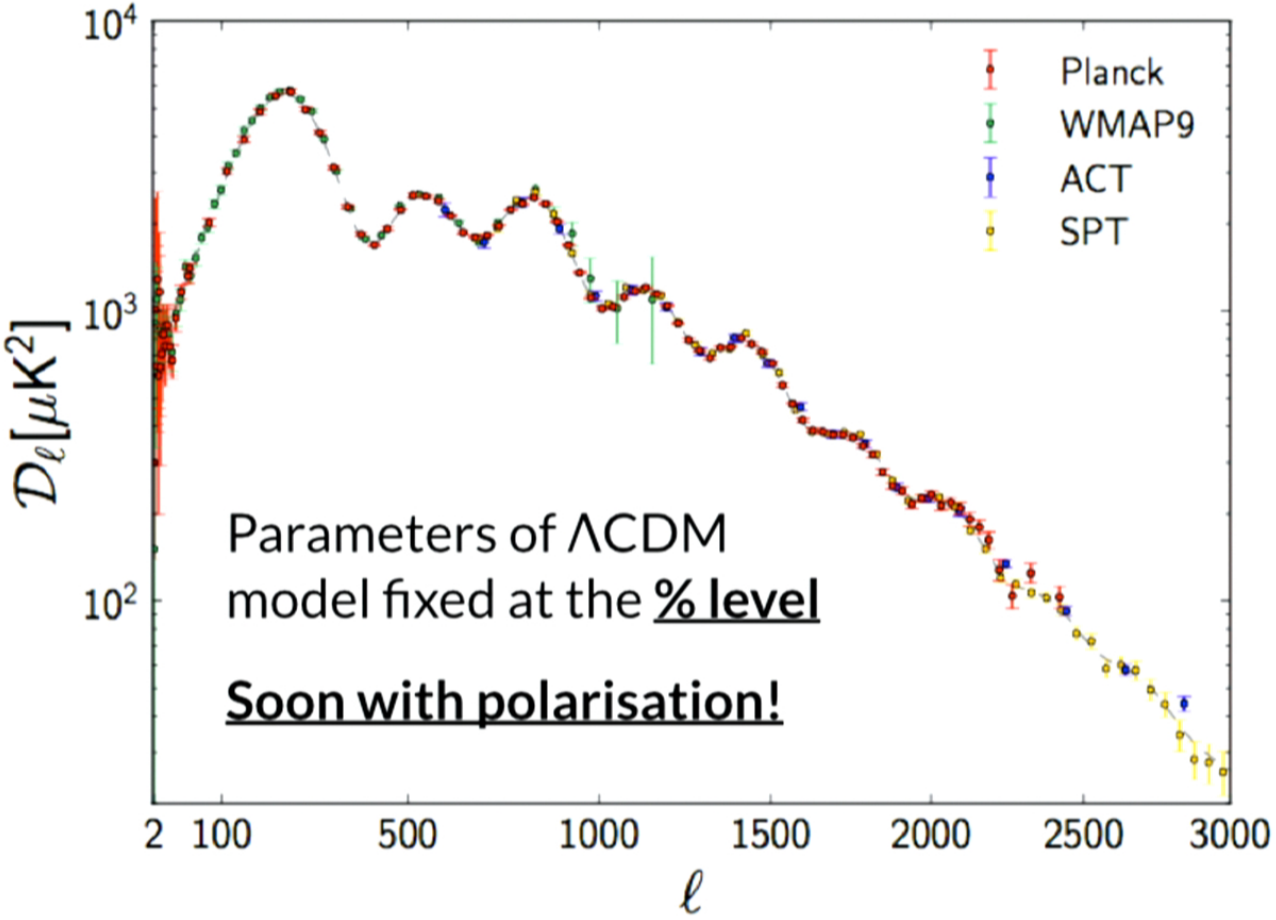
Thanks, Planck!



Post Planck-era



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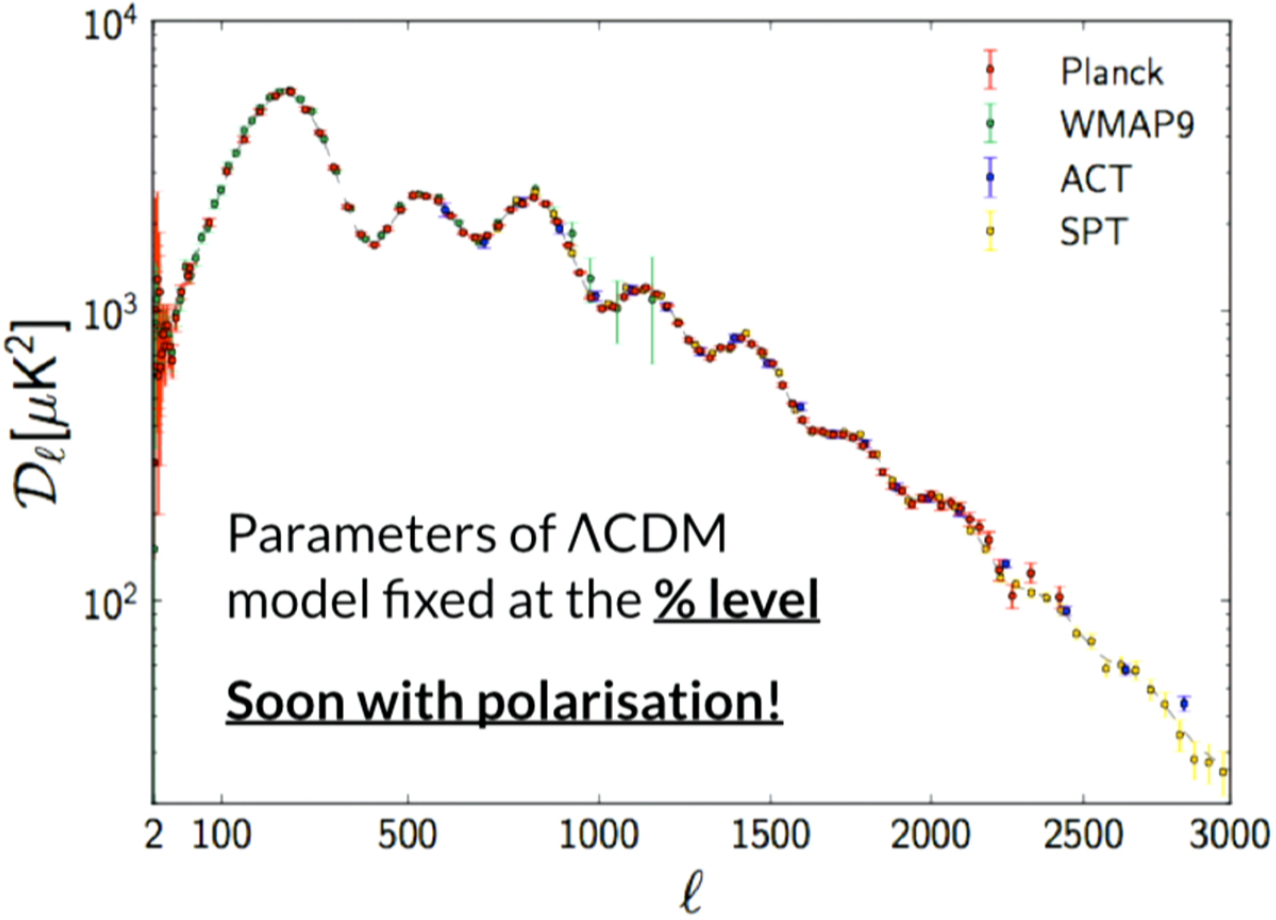

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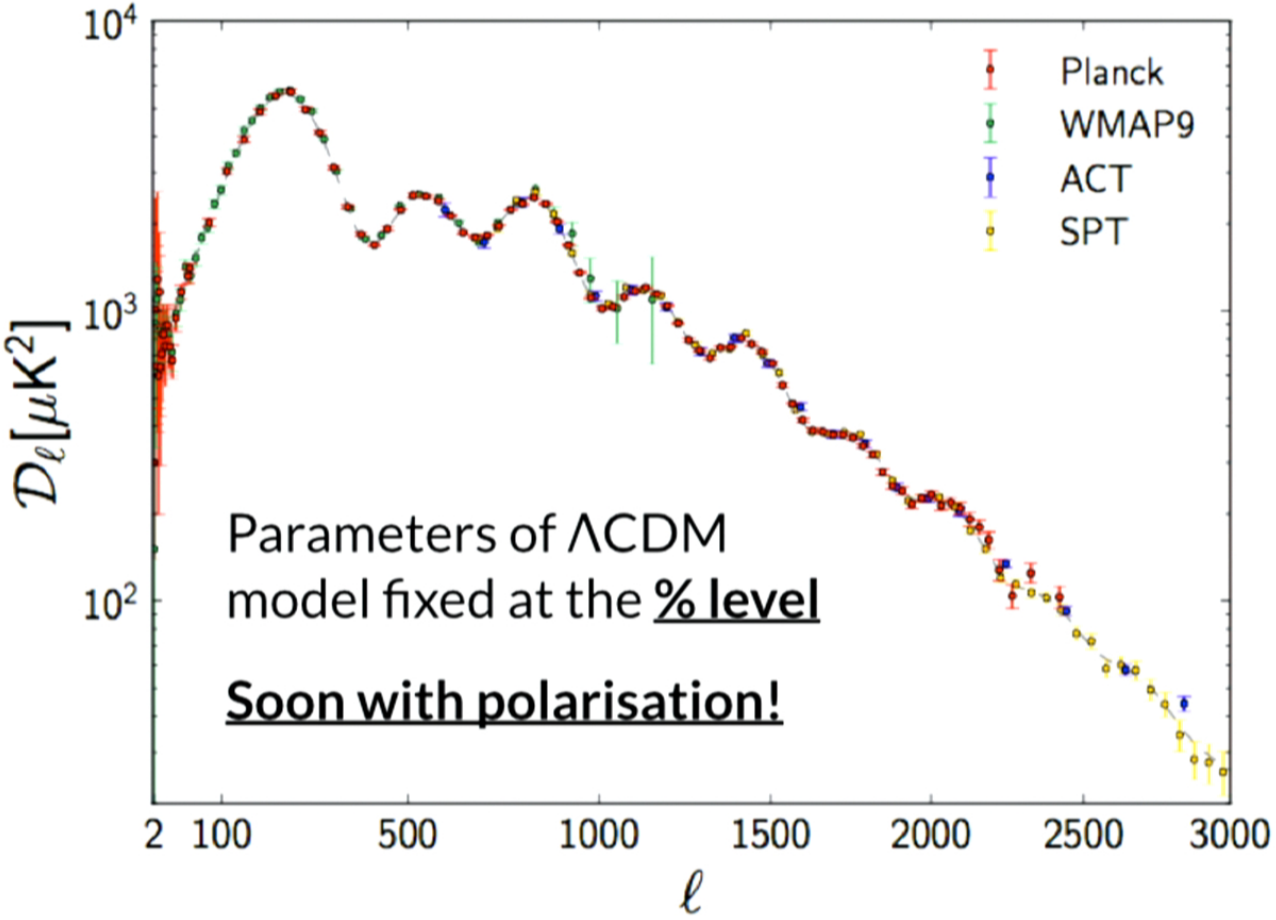


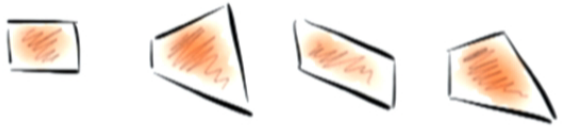
PNG : a window on inflation

- Initial conditions ~**Gaussian**, described by power spectra

  2pt: power spectrum

- Non-Gaussanity: higher order terms

  3pt: bispectrum  ...

  4pt: trispectrum  ...

- Local PNG: $\Phi = \phi + f_{\rm NL}[\phi^2 - \langle\phi^2\rangle] + g_{\rm NL}[\phi^3 - 3\phi\langle\phi^2\rangle]$

  Skewness + kurtosis from "squeezed" configurations

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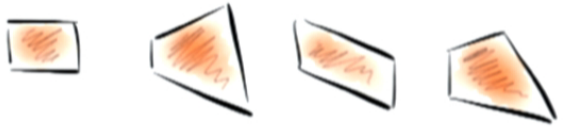
  4pt: trispectrum  ...

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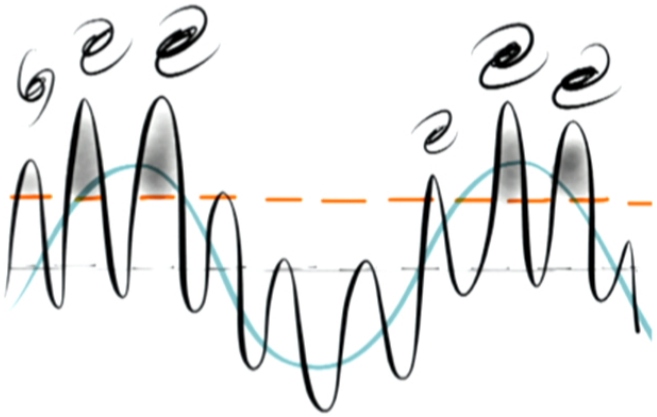
PNG in LSS

- Planck bispectrum constraints: $f_{\rm NL} = 2.7 \pm 5.8$
- # modes LSS >>> # modes CMB
- Different scales than CMB, sensitive to other PNG types



Kaiser effect

PNG enhance **bias** of LSS tracers on large scales

Dalal, Dore *et al* (2007)
Matarrese & Verde (2008)
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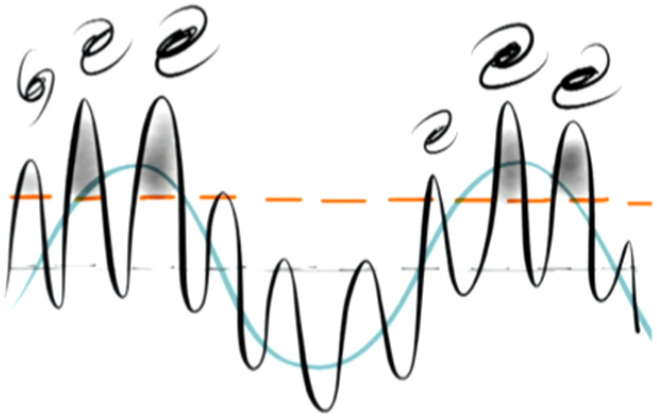

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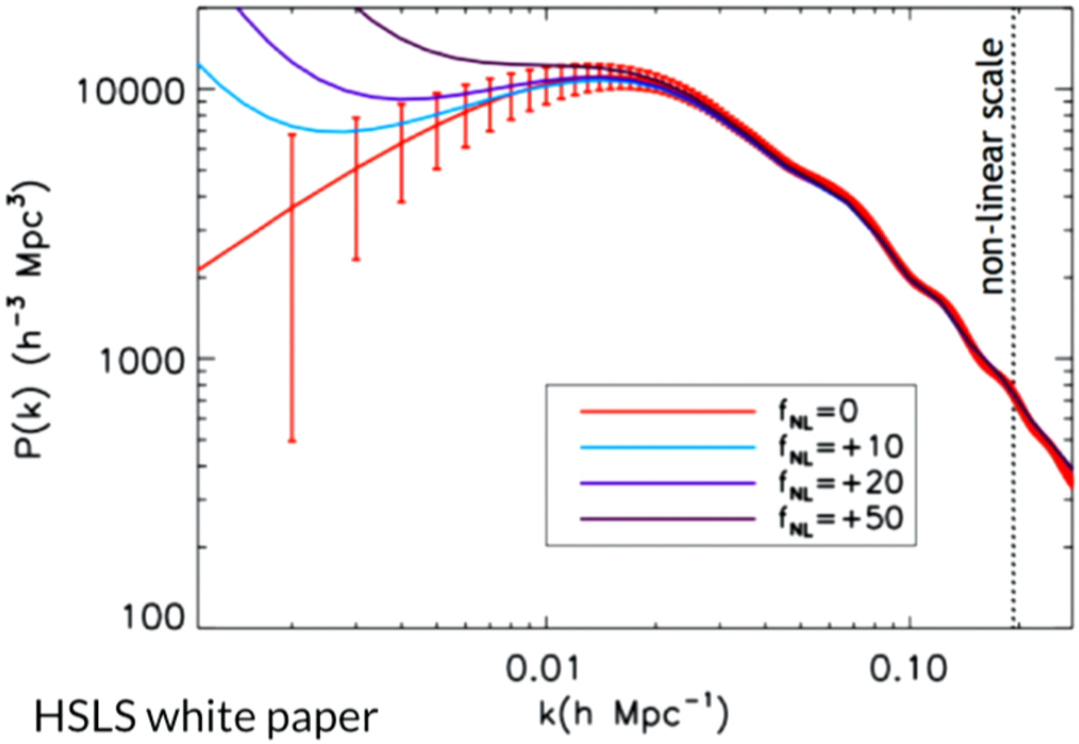
PNG in LSS clustering

LSST: $\sigma(f_{\rm NL}) \sim 1$



HSLS white paper

PNG in LSS clustering

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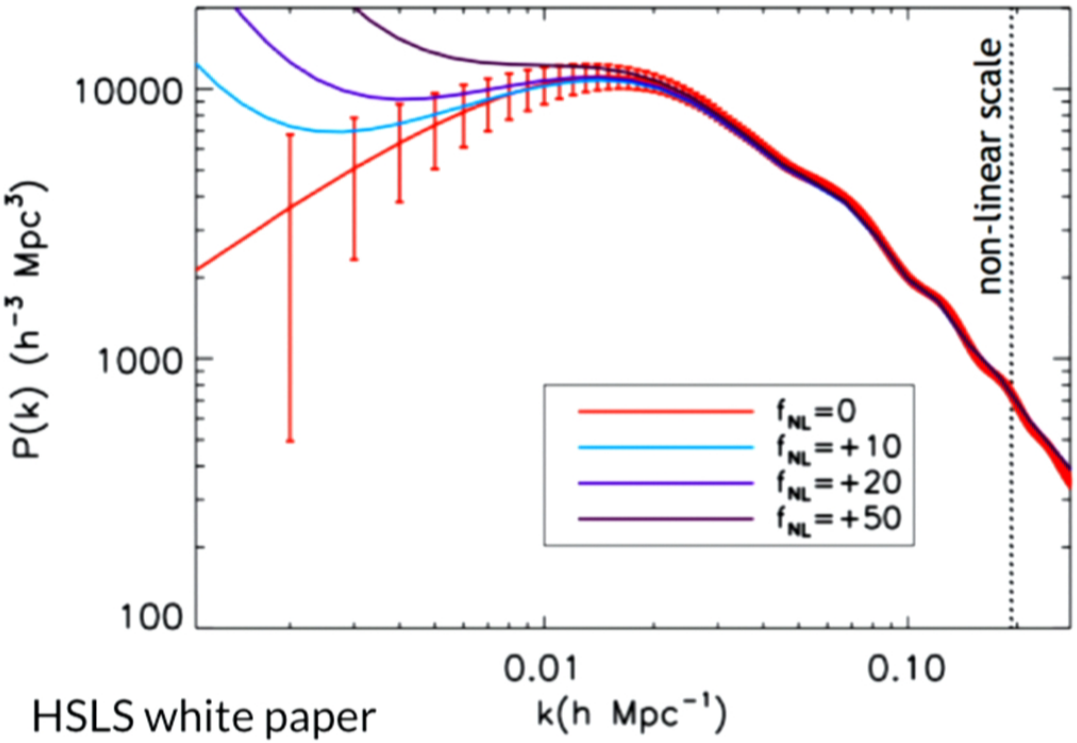

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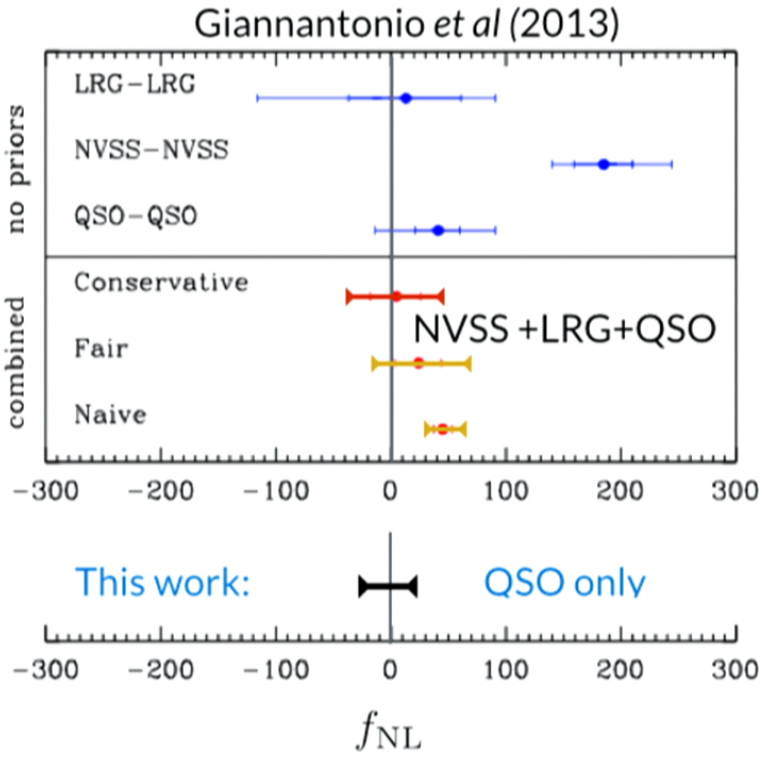
Constraints on PNG from LSS



- Quasars give best PNG constraints
- BUT plagued by systematics…

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Xia *et al* (2010)
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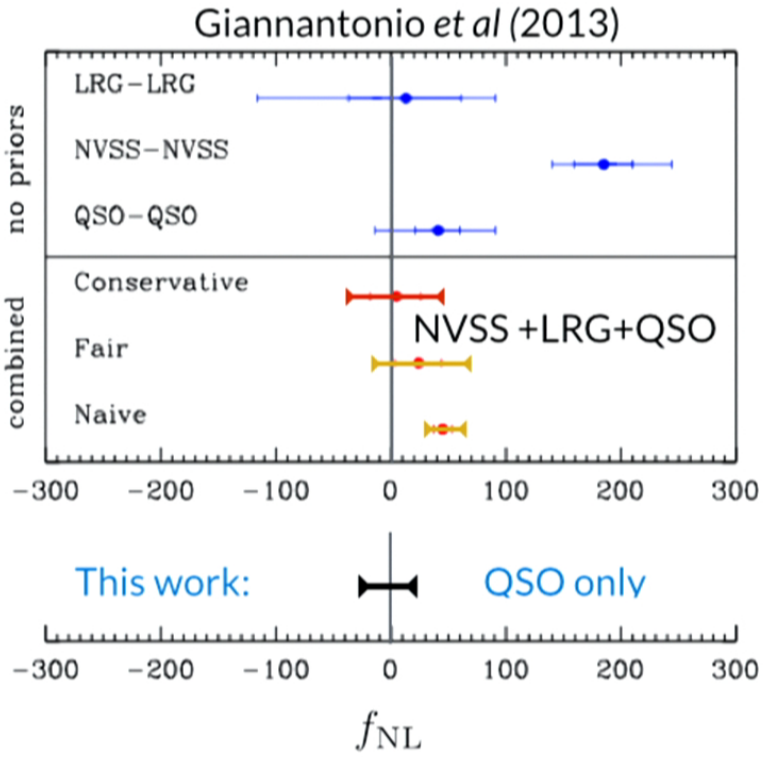

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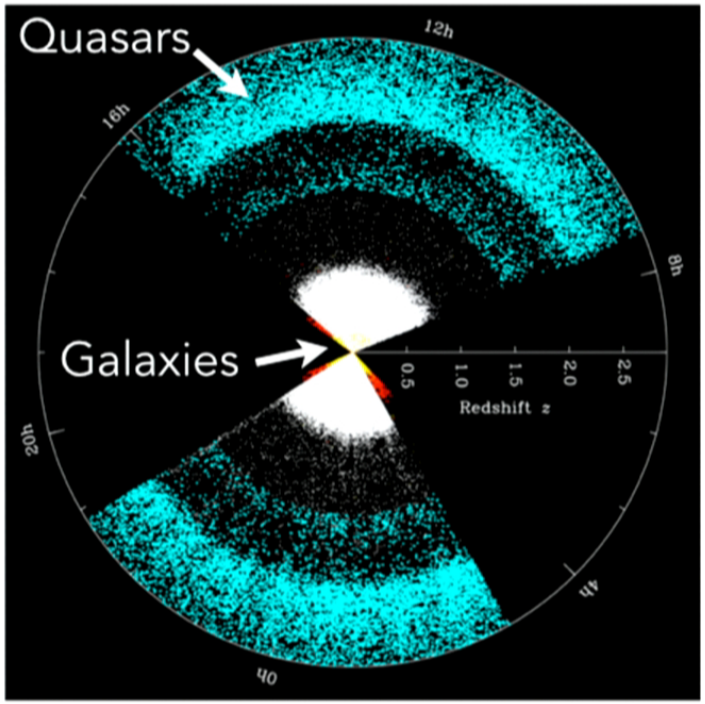
Why are quasars so good for PNG?

- Large volumes + highly biased ⇒ best signal-to-noise

Slosar *et* al (2008), Xia *et al* (2010), Pullen & Hirata (2012), Leistedt *et al* (2013), Giannantonio *et al* (2013) , Ho *et al* (2013), Agarwal *et al (2014)* …



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- ***Option 1:*** spectroscopic surveys: *small, not so deep*
- ***Option 2:*** photometric surveys: *large, deep, but plagued by systematics*

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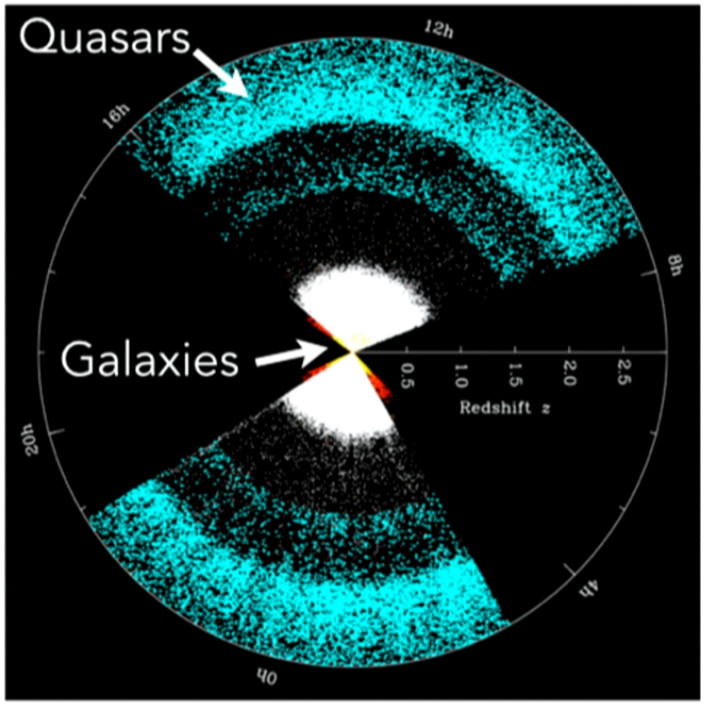

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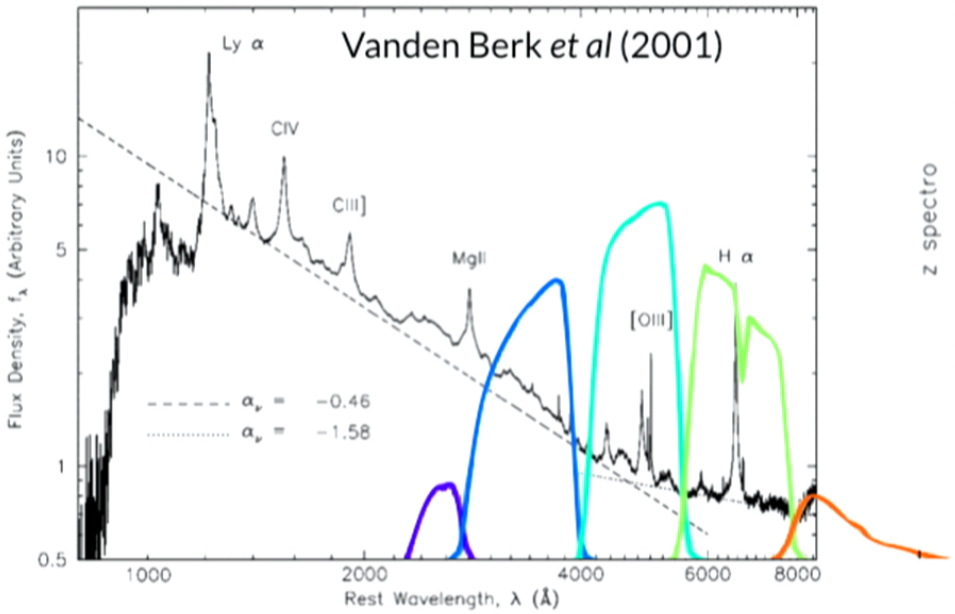
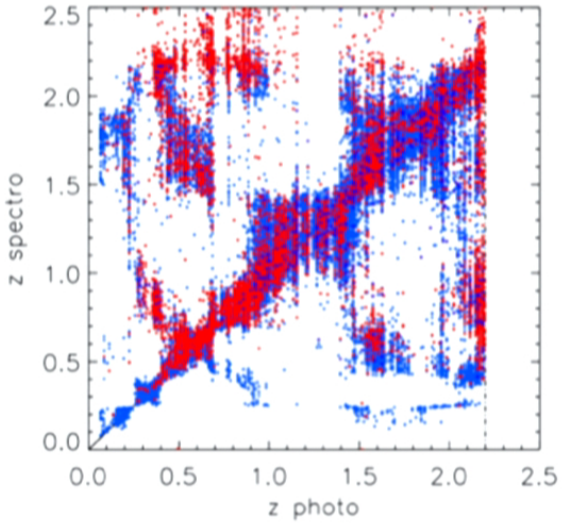
Photometric quasars

- Star/quasar separation + photometric redshift estimation ***with a handful of photometric numbers***





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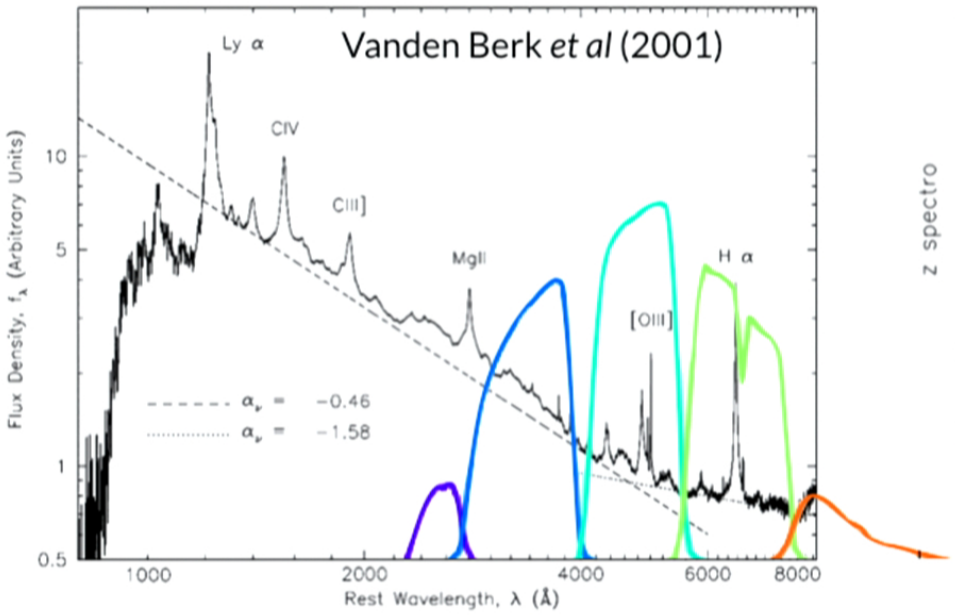

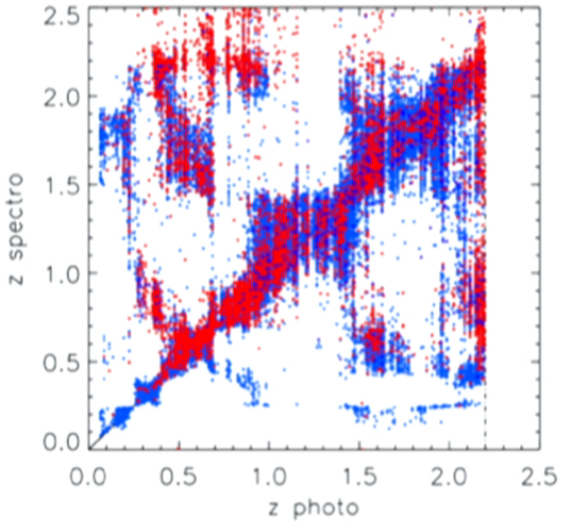

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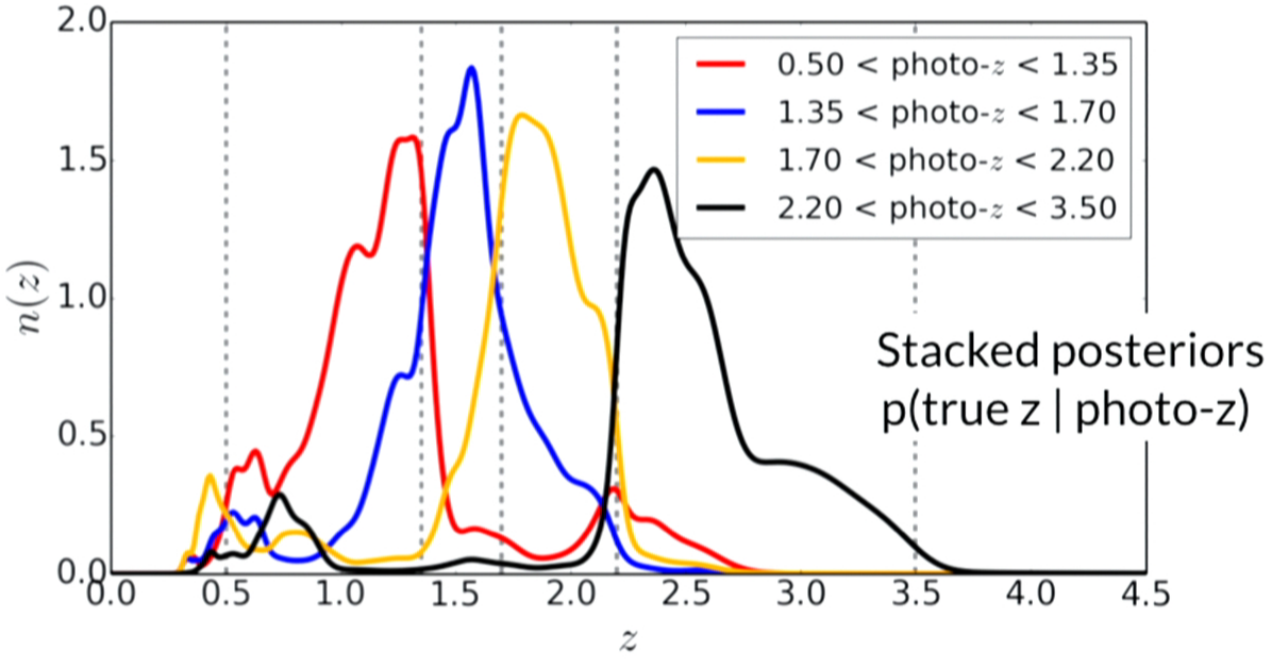
The XDQSOz catalogue

- 1.6 million photometric quasars from SDSS DR8
- p(QSO)>0.8 + divided into 4 samples with photo-z cuts



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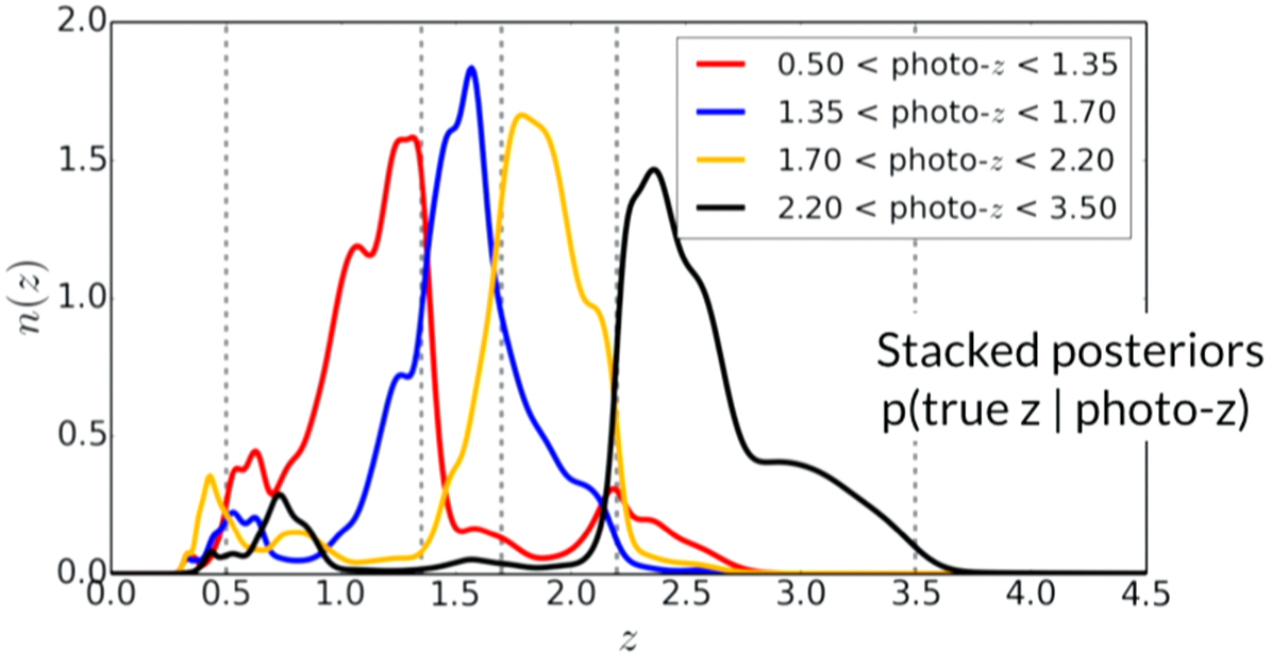
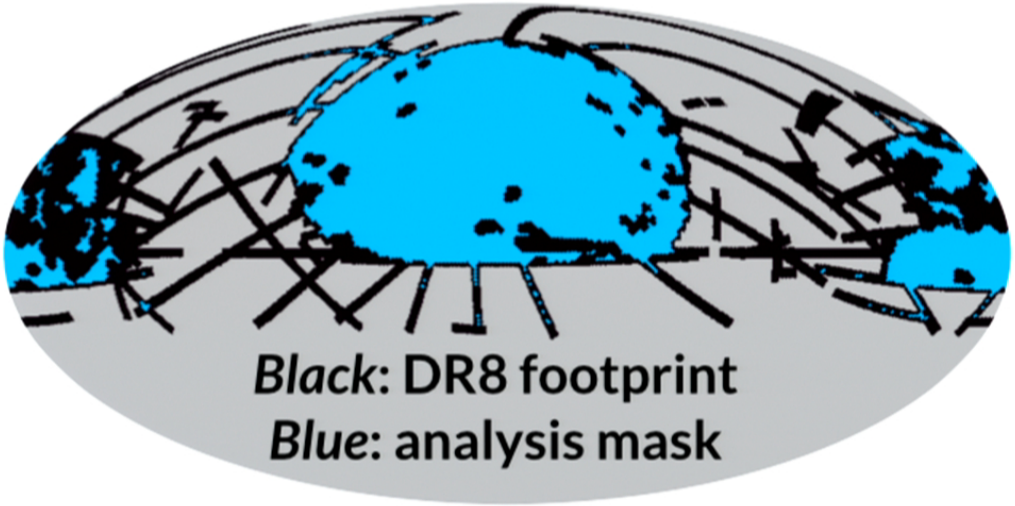
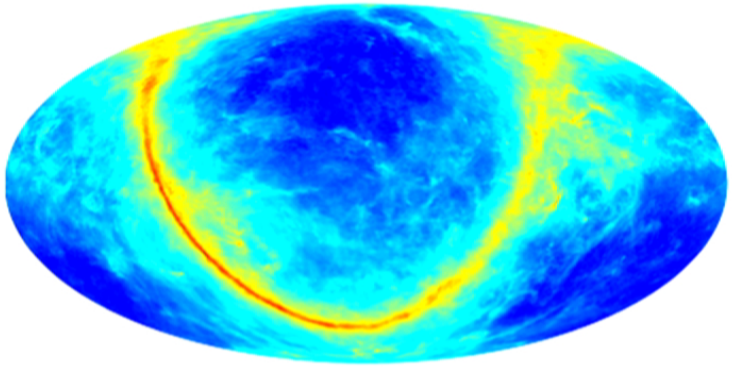


Sky coverage

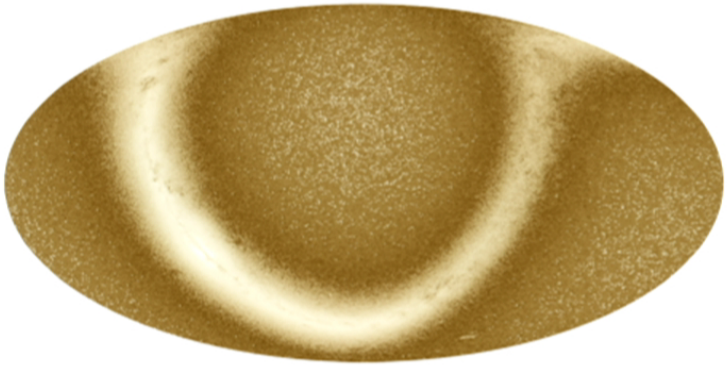


Black: DR8 footprint
Blue: analysis mask

dust



stars



Optimal C_l estimator

- Quadratic maximum likelihood estimator for 10 auto + cross angular power spectra *simultaneously*
- Model of the pixel-pixel covariance matrix:

$$\mathbf{C}_{ij} = \langle x_i x_j \rangle = \sum_\ell \left(\frac{2\ell+1}{4\pi} \right) C_\ell P_\ell(\cos\theta_{ij}) + \mathbf{N}_{ij}$$

Covariance between 2 pixels matrix

Theory spectrum

Noise, systematics, ...

- Why not pseudo spectrum estimator? Because only optimal with flat power spectra and ***no systematics...***

Modelling the clustering of quasars

List of ingredients

- Cosmological parameters (LCDM), shot noise, magnification effects, redshift distributions, RSD
  Use `CAMB_sources` (Challinor & Lewis 2011)
- Quasar bias model: $b^{\rm G}(z) = b_0 + b_0 \left(\frac{1+z}{2.5} \right)^{\gamma}$
- PNG bias: $b^{\rm tot}(k,z) = b^{\rm G}(z) + b^{\rm NG}(k,z)$
- Scaling: $b^{\rm NG}(k,z) = \frac{\beta_f(z) f_{\rm NL} + \beta_g(z) g_{\rm NL}}{\alpha(k,z)} \propto k^{-2}$
- MCMC 'hammer': `emcee` (Foreman-Mackey *et al* 2013)

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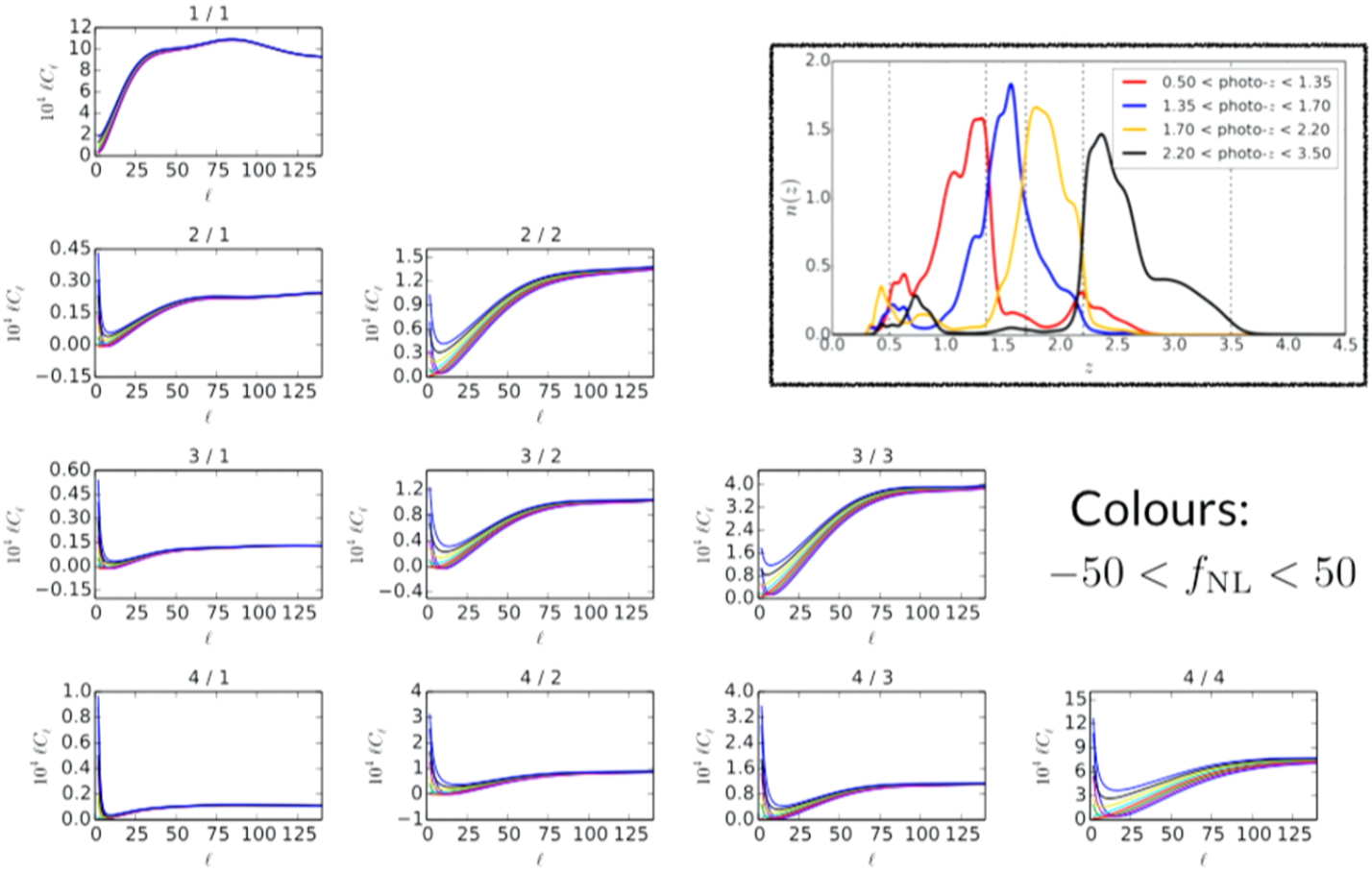
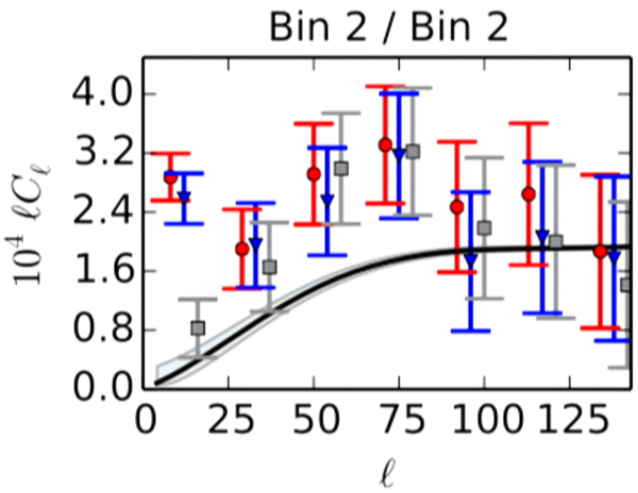
Clustering of XDQSOz quasars



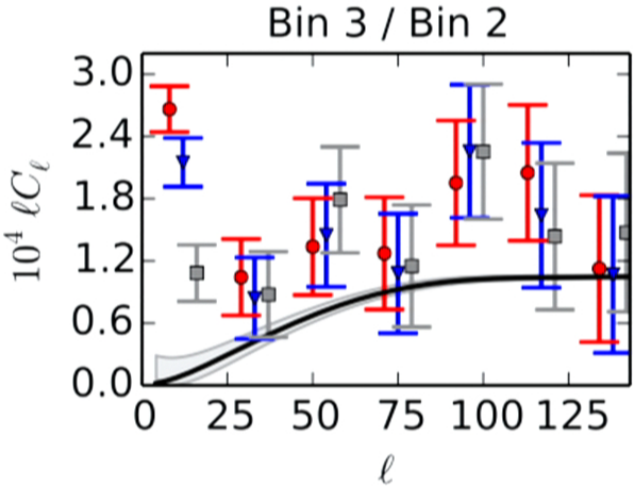
Colours:

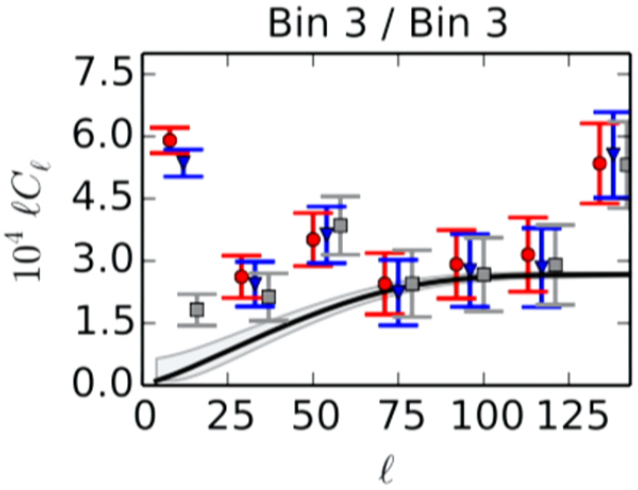
$-50 < f_{\rm NL} < 50$



Raw power spectra

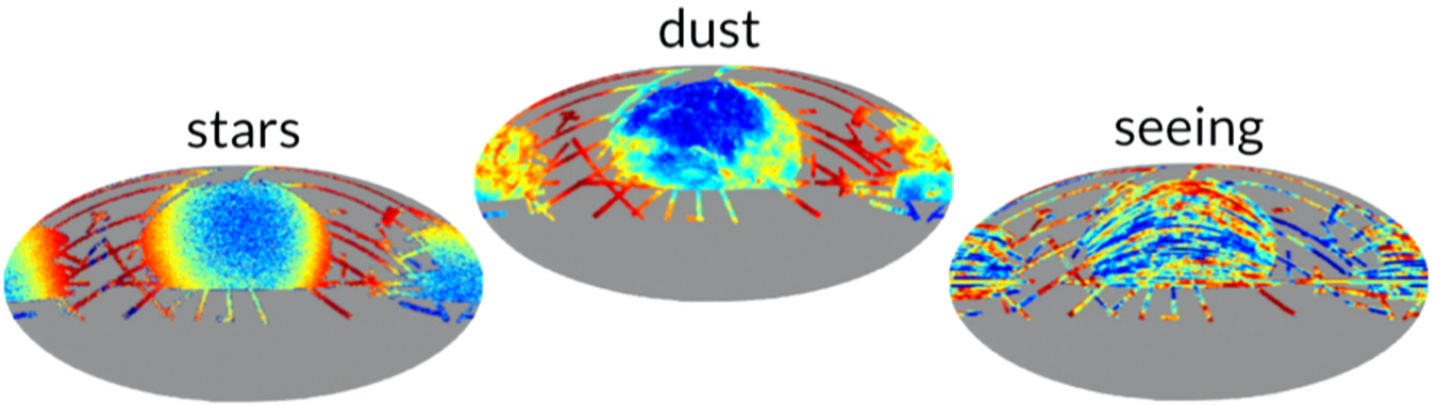
- Evidence for strong systematics in all samples
- Mimic PNG signal

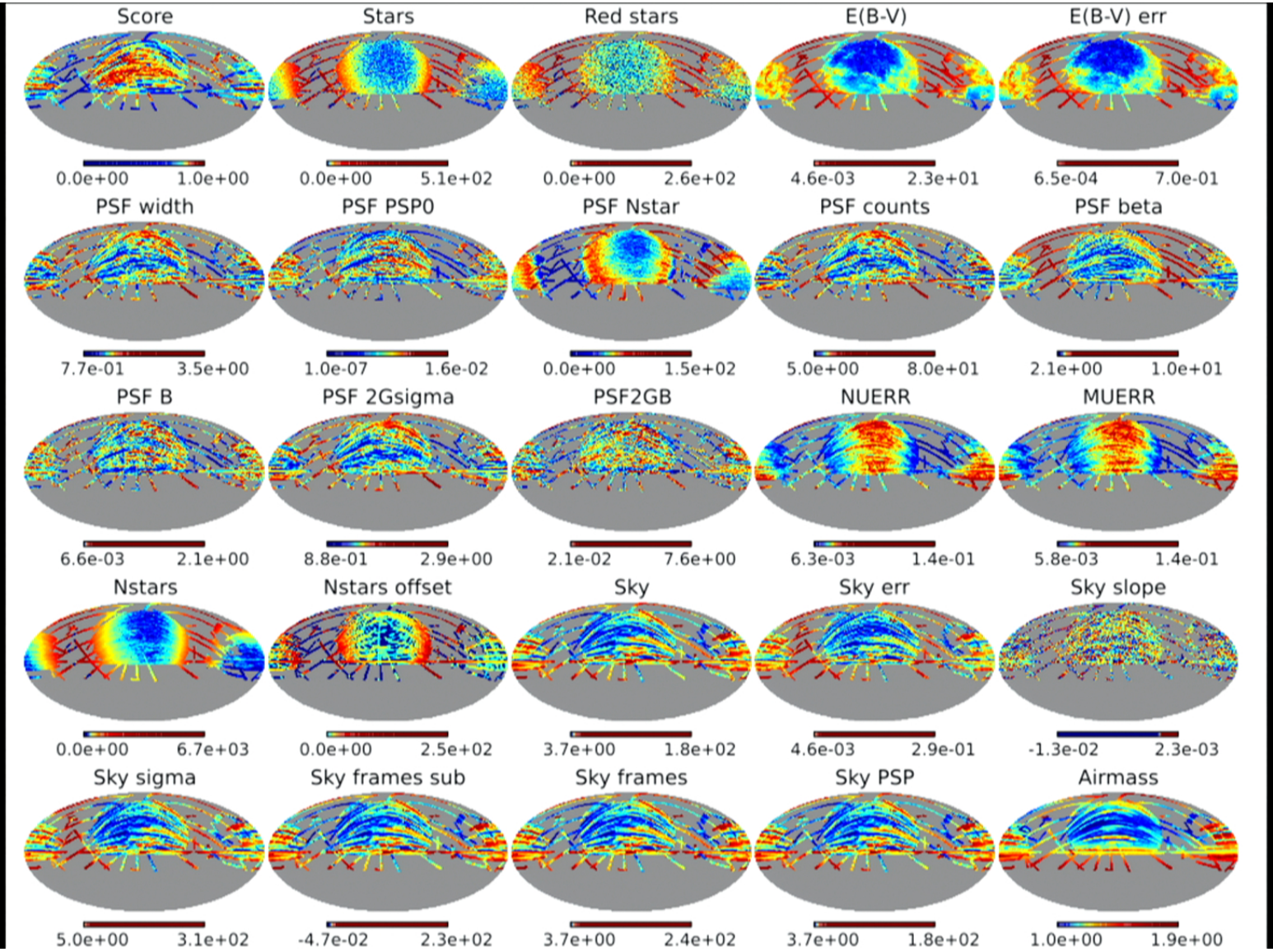




You said systematics?

- Anything that affects point sources or colours
  e.g. dust extinction, seeing, airmass, zero points, …
- Create spatially varying depth & stellar contamination

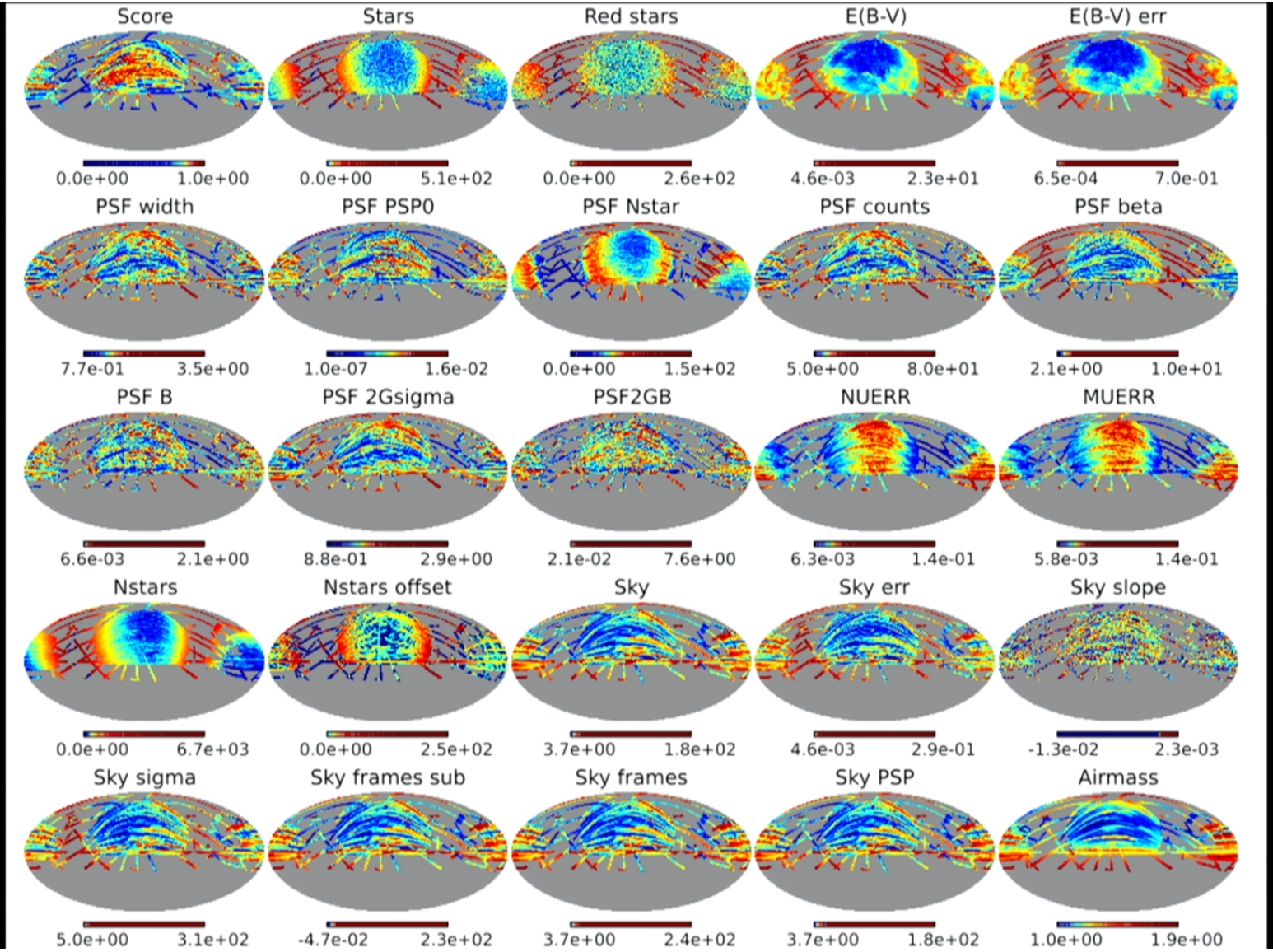



Score
0.0e+00 1.0e+00
Stars
0.0e+00 5.1e+02
Red stars
0.0e+00 2.6e+02
E(B-V)
4.6e-03 2.3e+01
E(B-V) err
6.5e-04 7.0e-01
PSF width
7.7e-01 3.5e+00
PSF PSP0
1.0e-07 1.6e-02
PSF Nstar
0.0e+00 1.5e+02
PSF counts
5.0e+00 8.0e+01
PSF beta
2.1e+00 1.0e+01
PSF B
6.6e-03 2.1e+00
PSF 2Gsigma
8.8e-01 2.9e+00
PSF2GB
2.1e-02 7.6e+00
NUERR
6.3e-03 1.4e-01
MUERR
5.8e-03 1.4e-01
Nstars
0.0e+00 6.7e+03
Nstars offset
0.0e+00 2.5e+02
Sky
3.7e+00 1.8e+02
Sky err
4.6e-03 2.9e-01
Sky slope
-1.3e-02 2.3e-03
Sky sigma
5.0e+00 3.1e+02
Sky frames sub
-4.7e-02 2.3e+02
Sky frames
3.7e+00 2.4e+02
Sky PSP
3.7e+00 1.8e+02
Airmass
1.0e+00 1.9e+00

"If tortured sufficiently,
data will confess to almost ***anything***"

F. Menger

aka confirmation / observer's bias


Score
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E(B-V)
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E(B-V) err
6.5e-04 7.0e-01
PSF width
7.7e-01 3.5e+00
PSF PSP0
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PSF counts
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PSF beta
2.1e+00 1.0e+01
PSF B
6.6e-03 2.1e+00
PSF 2Gsigma
8.8e-01 2.9e+00
PSF2GB
2.1e-02 7.6e+00
NUERR
6.3e-03 1.4e-01
MUERR
5.8e-03 1.4e-01
Nstars
0.0e+00 6.7e+03
Nstars offset
0.0e+00 2.5e+02
Sky
3.7e+00 1.8e+02
Sky err
4.6e-03 2.9e-01
Sky slope
-1.3e-02 2.3e-03
Sky sigma
5.0e+00 3.1e+02
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Sky PSP
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1.0e+00 1.9e+00

Treating systematics

- Suppose we have maps of systematics $\vec{m}_i \quad i = 1, \ldots, \mathrm{N_{sys}}$
- ***Masking or correcting data is dangerous and insufficient***
- Need to **ignore** spatial modes = Bayesian marginalisation = project out weighted data pixels = **mode projection**
- Use "projective" covariance matrix s.t. $\vec{m}_i \mathbf{C}^{-1} \vec{x} = 0$

$$\mathbf{C}^{-1} = \lim_{\alpha_i \to \infty} \left(\underbrace{\mathbf{S}(\{C_\ell\})}_{\text{signal}} + \underbrace{\mathbf{N}}_{\text{noise}} + \overbrace{\sum_i \alpha_i \vec{m}_i \vec{m}_i^t}^{\text{systematics}} \right)^{-1}$$

Extended mode projection

1. Collect all possible systematics

220 templates + pairs ⇒ >20,000 templates

2. Decorrelate set of systematics with SVD

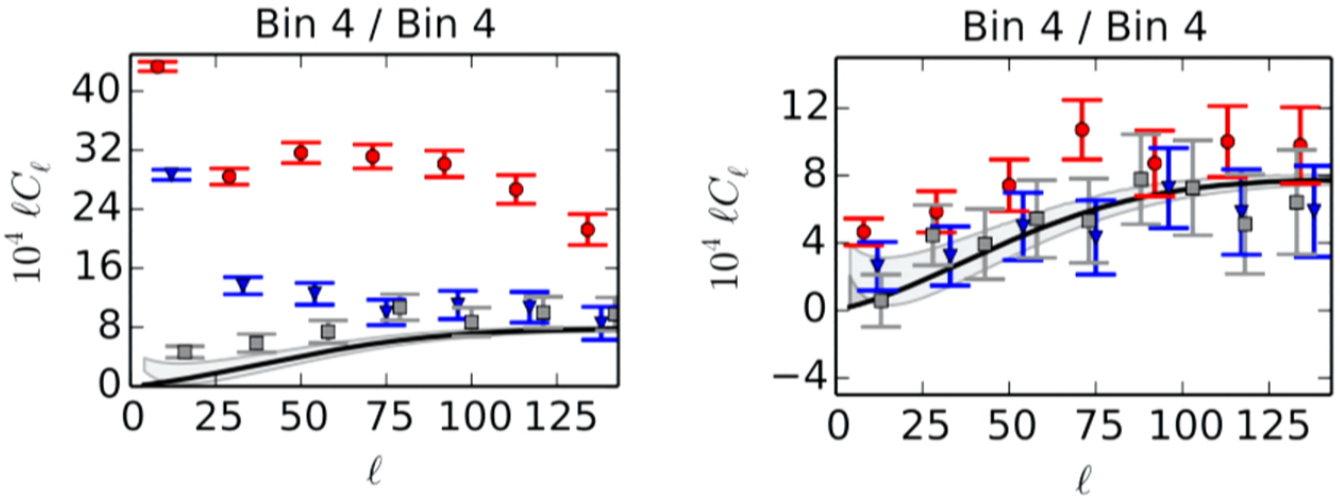
20,000 templates ⇒ 3,700 uncorrelated modes

3. Project out the modes most correlated with data

3,700 null tests; project out modes with chi2>1

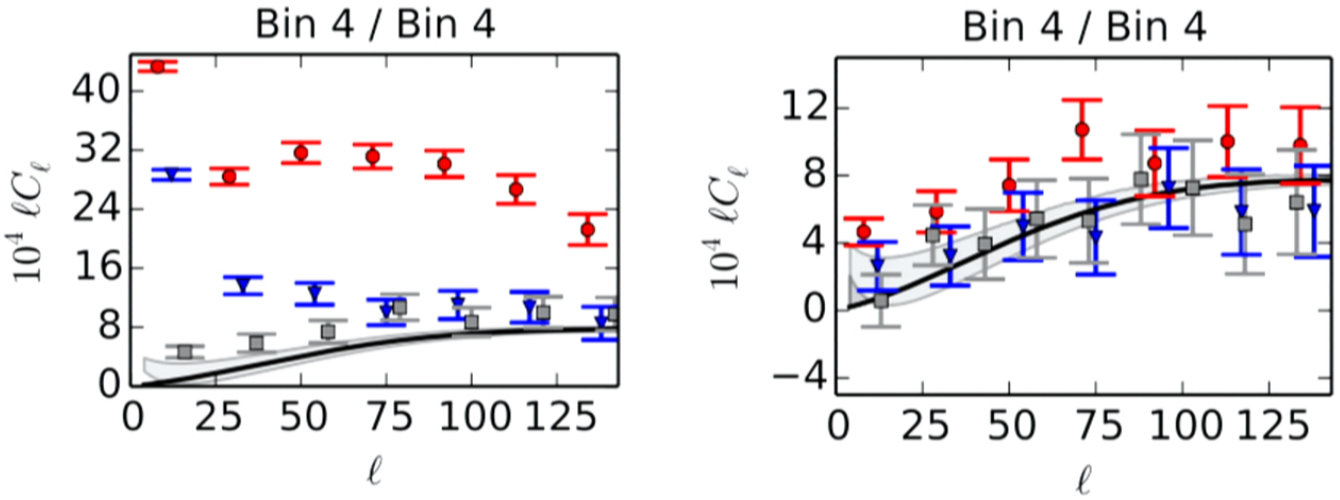
Sacrificing some signal in favour of robustness
⇒ **Blind mitigation of systematics**

Raw spectra vs clean spectra



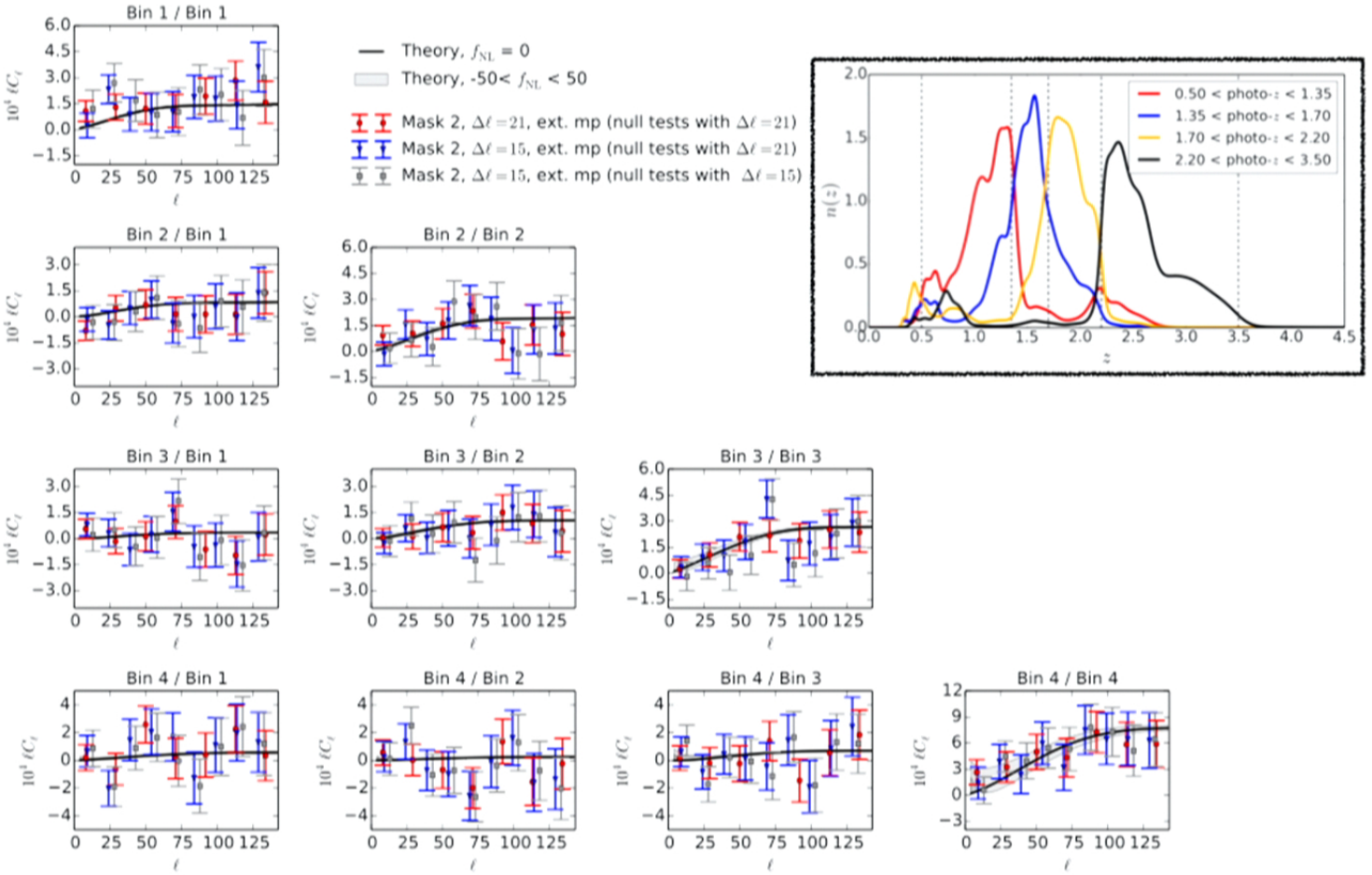
- Project out the templates with reduced chi2 > 1
- Grey band: $-50 < f_{\rm NL} < 50$

Raw spectra vs clean spectra

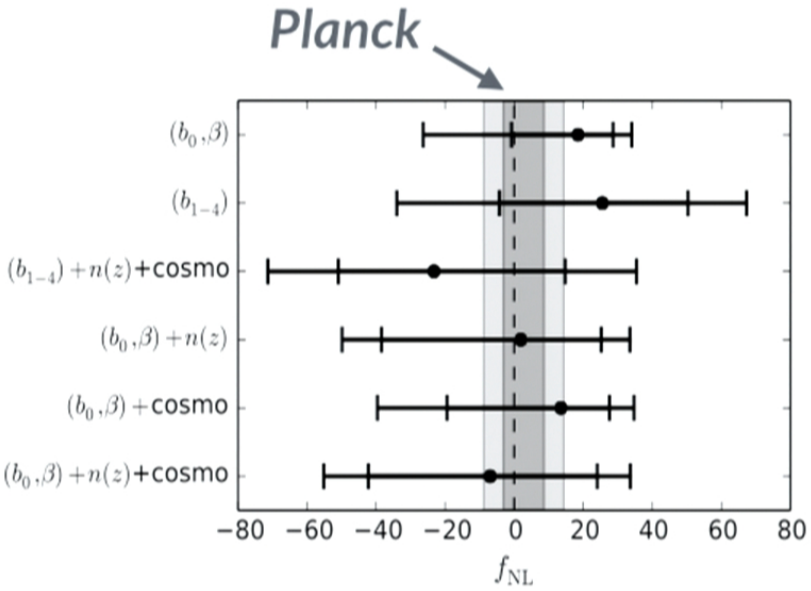


- Project out the templates with reduced chi2 > 1
- Grey band: $-50 < f_{\rm NL} < 50$

Full likelihood



Constraints on fNL



Fixed cosmology & n(z)

$$-16 < f_{\rm NL} < 47 \quad (2\sigma)$$

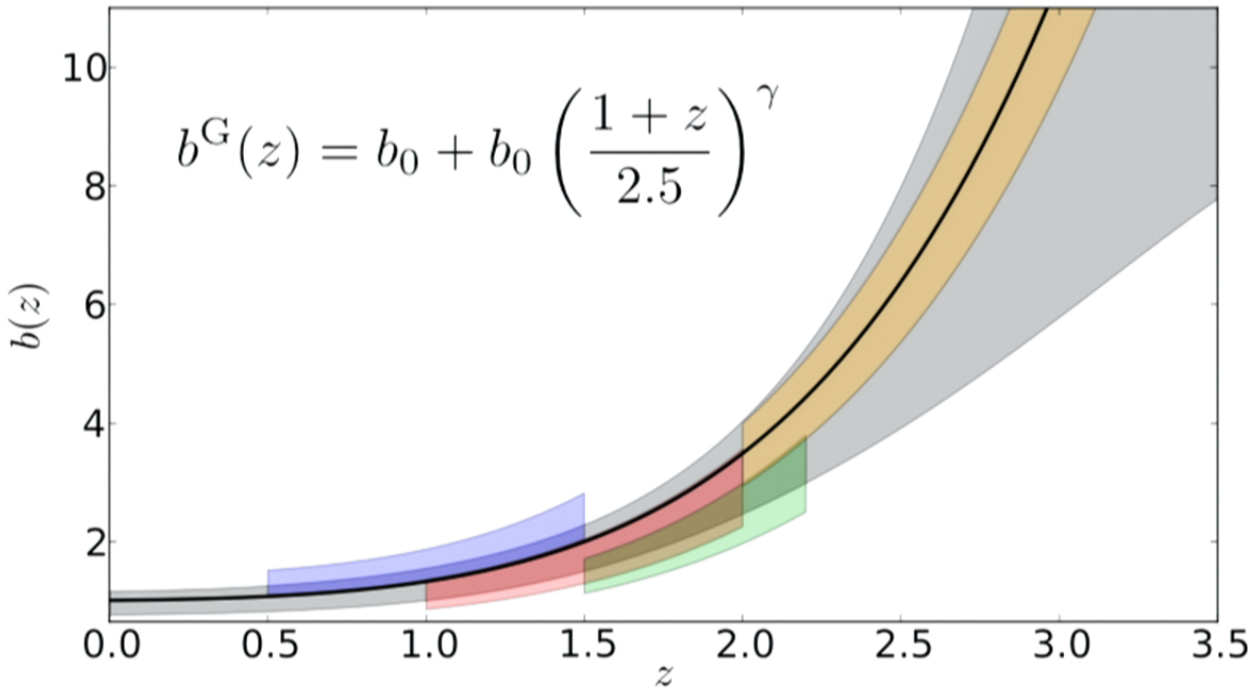
Varying all parameters

$$-49 < f_{\rm NL} < 31 \quad (2\sigma)$$

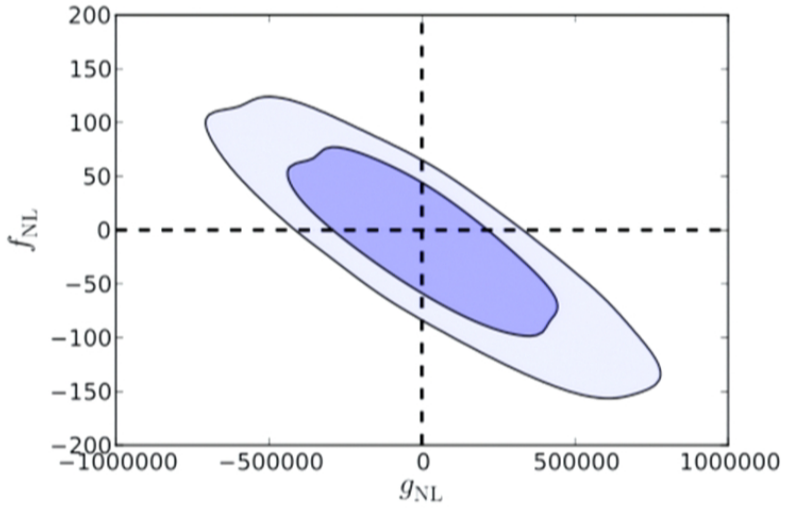
- Competitive with WMAP9 with single LSS tracer
- *Robust to modelling & priors*

Leistedt, Peiris & Roth (1405.4315)

Constraints on the quasar bias



Constraints on gNL



$g_{\rm NL}$ also gives $\Delta b \propto k^{-2}$
=> degenerate with $f_{\rm NL}$
Roth & Porciani (2012)

Hard to constrain from the CMB!

$$-2.7 < g_{\rm NL}/10^5 < 1.9$$

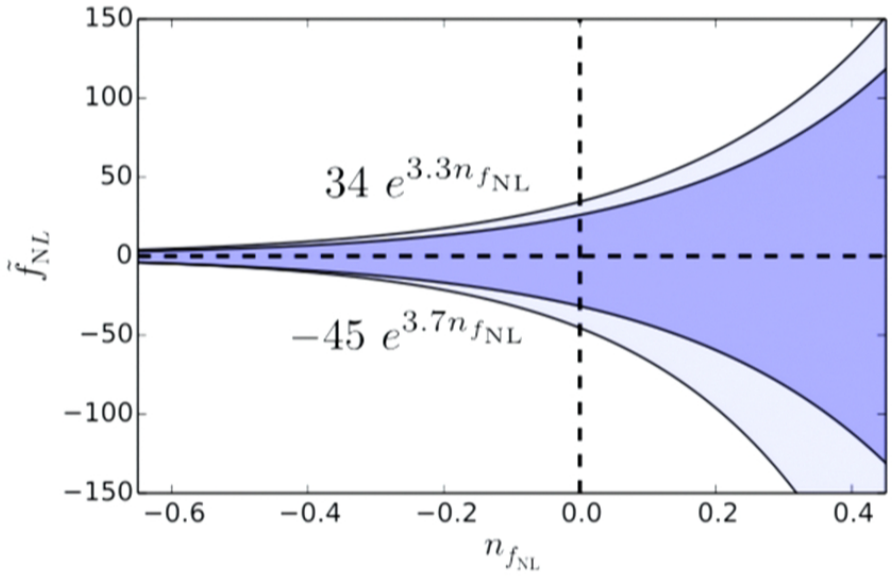
$g_{\rm NL}$ alone

$$-4.0 < g_{\rm NL}/10^5 < 4.9$$
$$-105 < f_{\rm NL} < 72 \quad (2\sigma)$$

$f_{\rm NL} + g_{\rm NL}$

Leistedt, Peiris & Roth (1405.4315)

Constraints on scale-dependent bias



Generalised bias

$$\Delta b(k) \propto k^{-2+n_{f_{\rm NL}}}$$

Giannantonio *et al* (2013)
Agarwal *et al (2014)*
Leistedt, Peiris & Roth (2014)

Single field inflation with a modified initial state, or models with several light fields.

Agullo and Shandera (2012), Dias, Ribeiro and Seery (2013)

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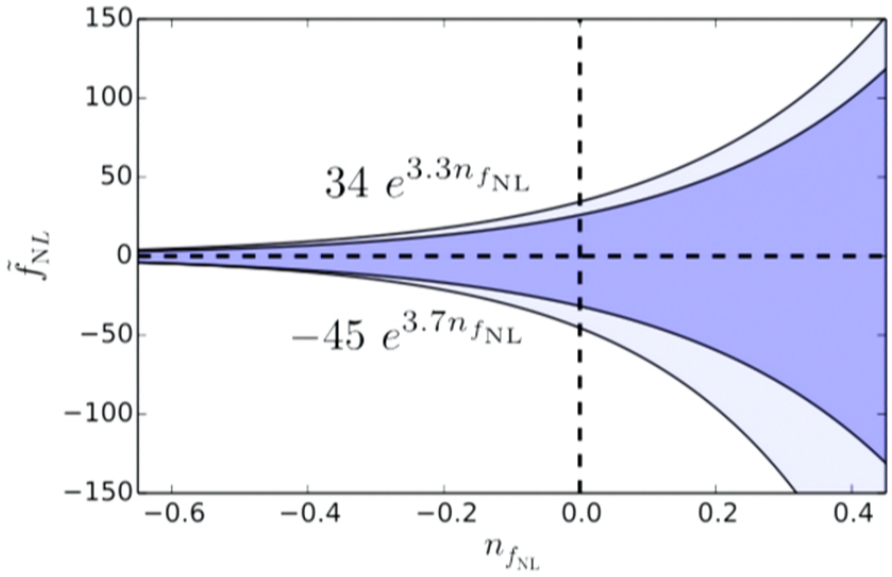

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What about future surveys?

- LSST-like survey: 20 z-bins in 0.5 < z < 3.5
- Fiducial: LCDM, galaxy bias, $f_{\rm NL}^{\rm truth} = 0$

Fisher matrix forecast:

- No systematics: **unbiased** result, $\sigma(f_{\rm NL}) \sim 1$
- With a few real systematics: $f_{\rm NL}^{\rm measured} \sim 30$ (!)
- + mode projection: **unbiased** result, $\sigma(f_{\rm NL}) \sim 5$

Conclusions

- Stringent PNG constraints *using quasars only*
- Extended mode projection: 'blind' mitigation of thousands of systematics
- Future: ***Dark Energy Survey***, Euclid, LSST…

Leistedt & Peiris (1404:6530)
Leistedt, Peiris & Roth (1405.4315)

Conclusions

- Stringent PNG constraints *using quasars only*
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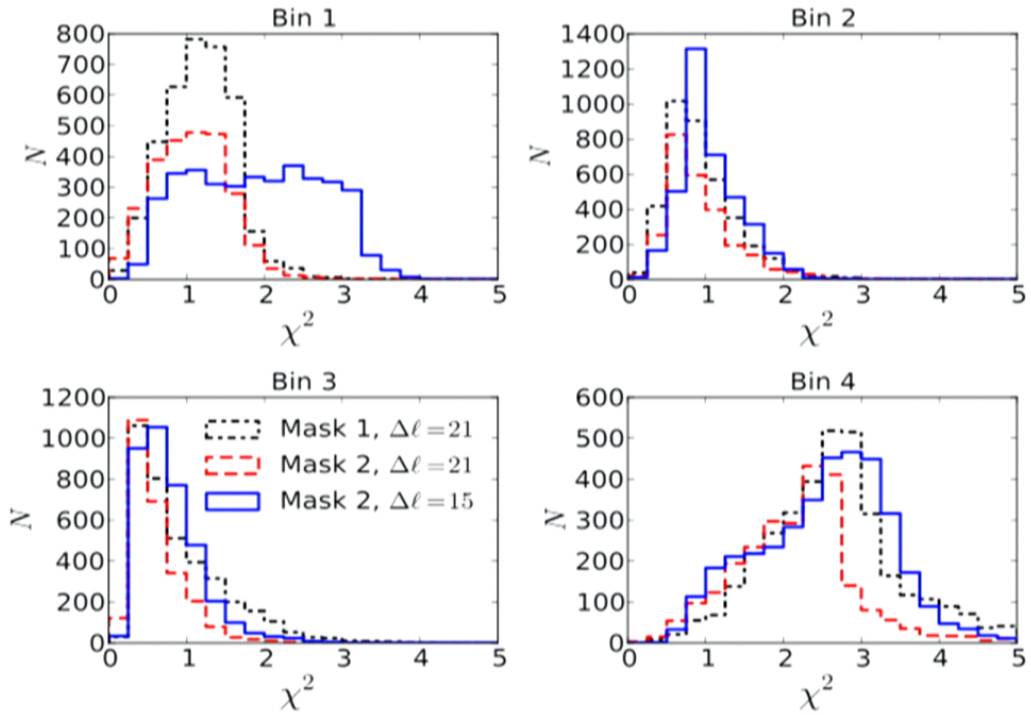
Leistedt & Peiris (1404:6530)
Leistedt, Peiris & Roth (1405.4315)

Null tests



- Cross-spectra of 4 quasar bins x 3,700 systematics
- Project out the templates with reduced chi2 > 1