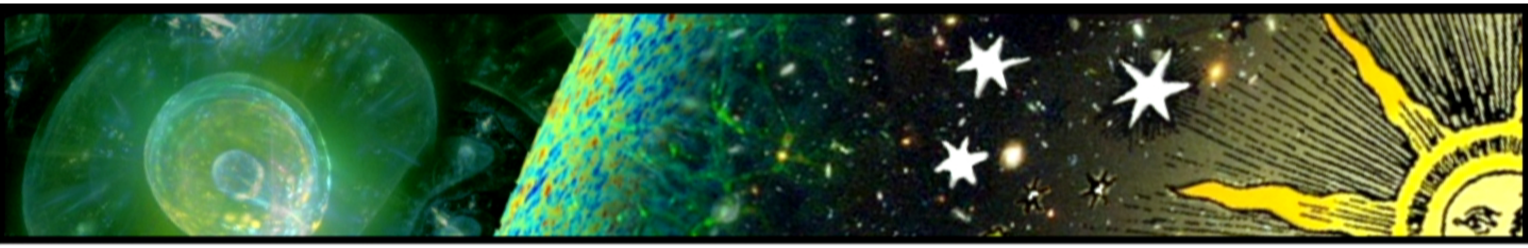
Title: Testing inflation with combined power- and bispectrum

Date: Jul 10, 2013 11:40 AM

URL: http://pirsa.org/13070012

Abstract:



Testing inflation with combined power- and bispectrum

Hiranya V. Peiris
University College London

Science & Technology Facilities Council

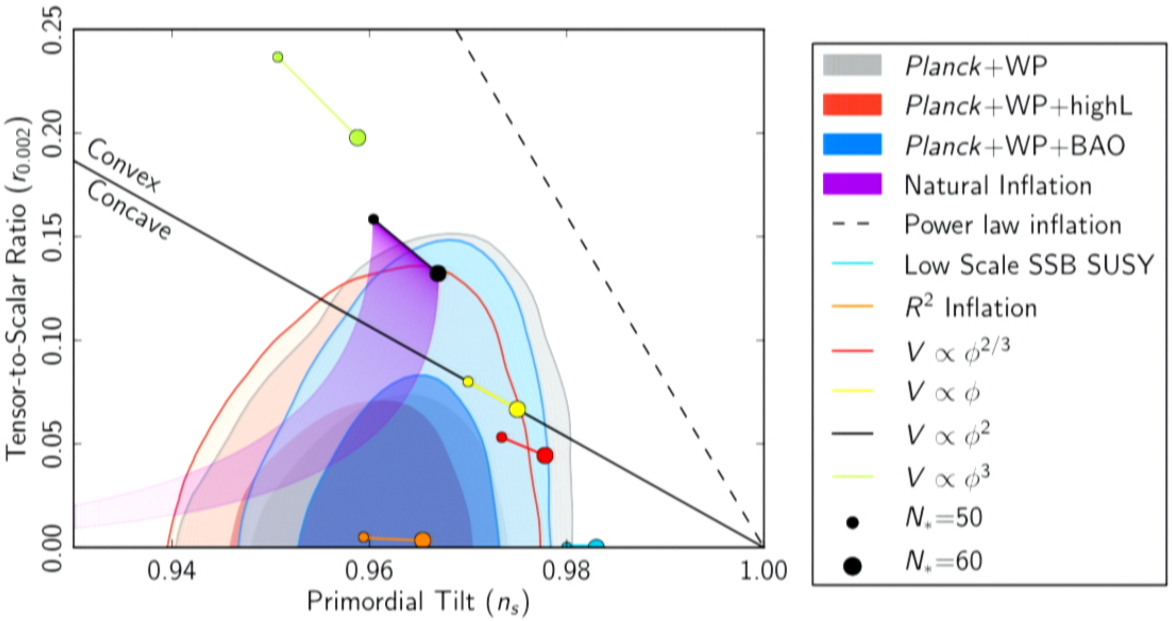
erc
European Research Council

IDEAS

Inflationary models in a post-Planck world

- Exact scale invariance (n_s=1) ruled out at >5σ by a single experiment

- While convex potentials are still allowed, Planck hints that flattened potentials are preferred



Planck+WP: $n_s = 0.9603 \pm 0.0073$ $r_{0.002} < 0.12$ (95% CL)

Inflationary models in a post-Planck world

- Bispectrum now a routine observable, like the spectral index
- Standard bispectrum configurations not detected by Planck; stringent constraints on local/equilateral/orthogonal etc shapes

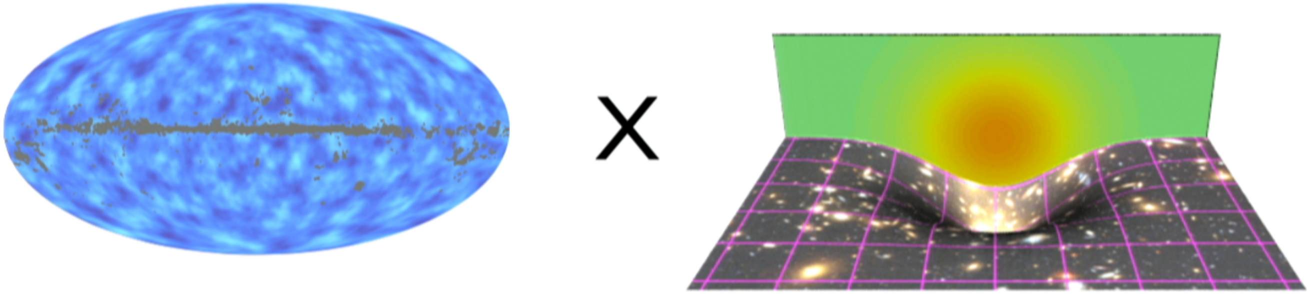
Shape	ISW-lensing subtracted KSW
Local	2.7 ± 5.8
Equilateral	-42 ± 75
Orthogonal	-25 ± 39

DBI	11 ± 69
EFT1	8 ± 73
EFT2	19 ± 57
Ghost	-23 ± 88

Aside: Planck's (non-)PNG measurements

Planck has measured non-primordial NG as predicted by LCDM

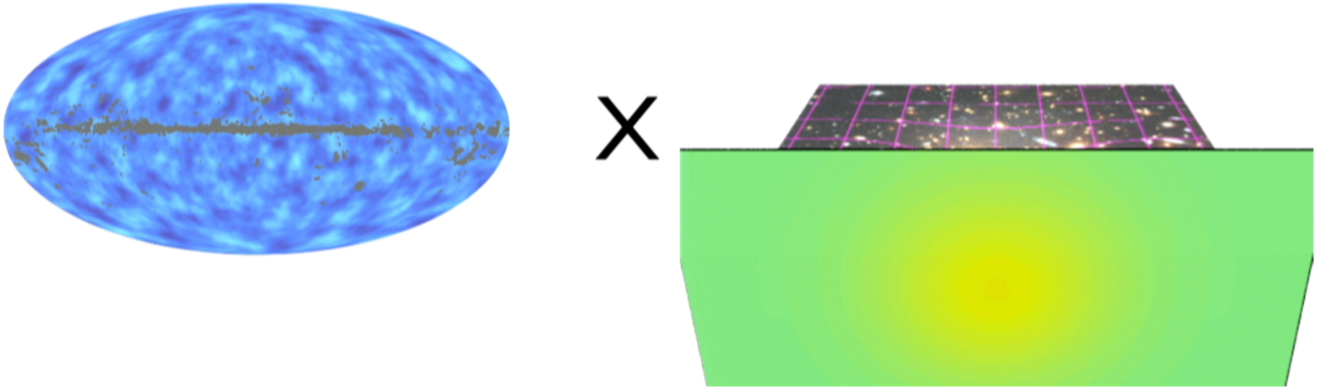
- non-linear effects cause coupling between weak gravitational lensing & ISW from evolving gravitational potential (bispectrum)
- Effect seen in Planck for the first time (significance ~2.5σ).



Aside: Planck's (non-)PNG measurements

Planck has measured non-primordial NG as predicted by LCDM

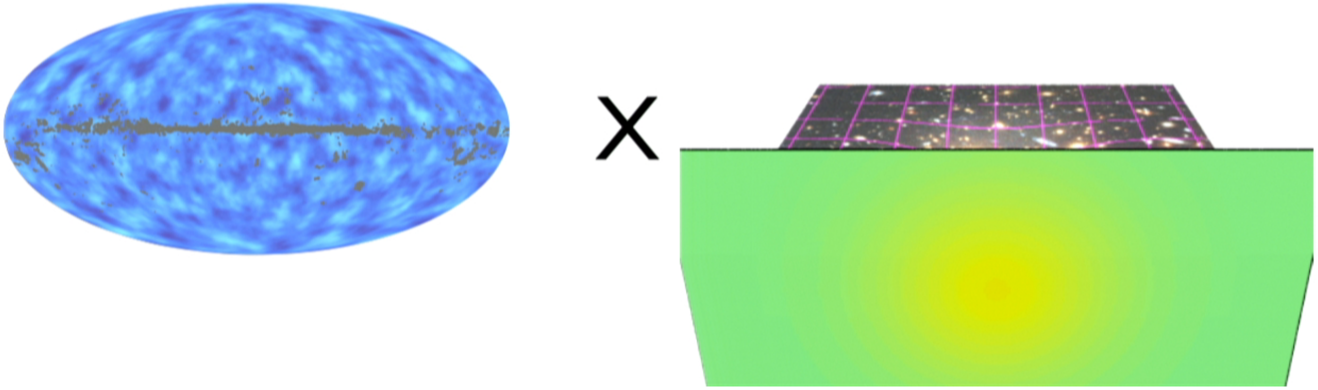
- non-linear effects cause coupling between weak gravitational lensing & ISW from evolving gravitational potential (bispectrum)
- Effect seen in Planck for the first time (significance ~2.5σ).



Aside: Planck's (non-)PNG measurements

Planck has measured non-primordial NG as predicted by LCDM

- non-linear effects cause coupling between weak gravitational lensing & ISW from evolving gravitational potential (bispectrum)
- Effect seen in Planck for the first time (significance ~2.5σ).

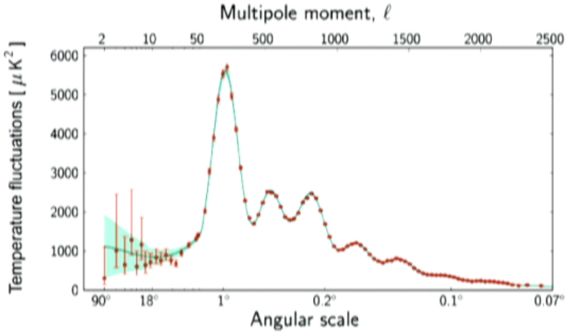


Inflationary models in a post-Planck world

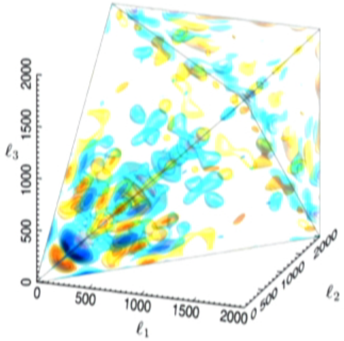
- No NG detection: stalls progress via "bottom up" approach (e.g. reconstruction via measuring EFT observables...).

- "Top down" approach (model-building first) looks more promising.

- Non-generic correlations between 2pt+3pt+... observables provide powerful constraints on such models



+

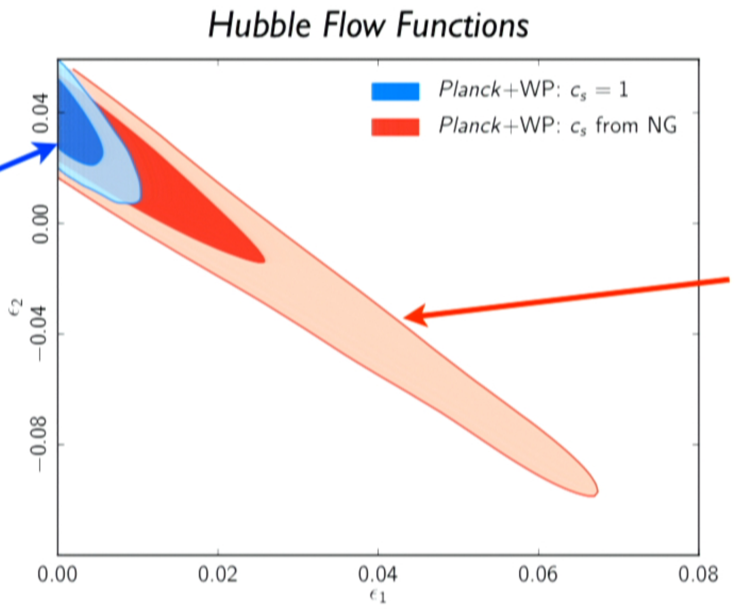


Joint constraints from 2-pt and 3-pt

- Consider general class of inflationary models where Lagrangian is general function of the scalar inflaton field and its first derivative.

- Inflationary sound speed can be $c_s < 1$ (canonical case: $c_s=1$).

- Full parameter set (A_s, ϵ_1, ϵ_2, c_s) assuming constant sound speed degenerate without NG info.



canonical case

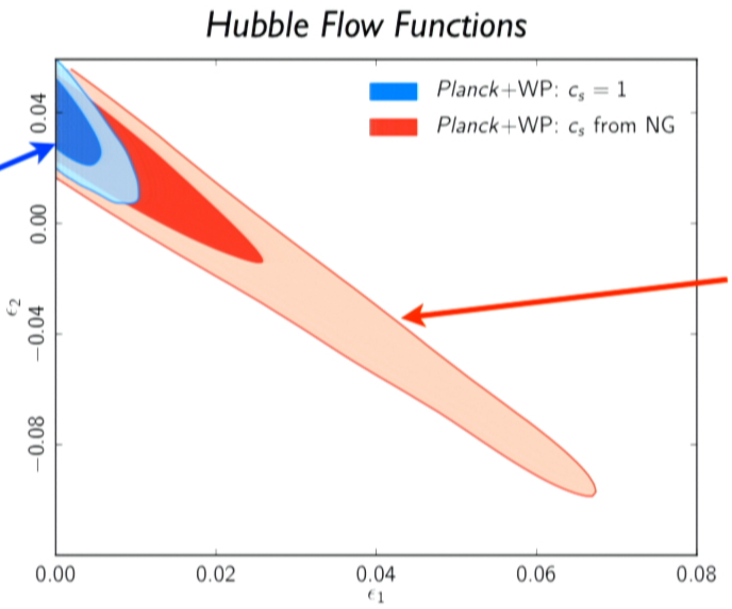
including c_s >0.02 (95% CL) constraint from NG

Joint constraints from 2-pt and 3-pt

- Consider general class of inflationary models where Lagrangian is general function of the scalar inflaton field and its first derivative.

- Inflationary sound speed can be $c_s < 1$ (canonical case: $c_s = 1$).

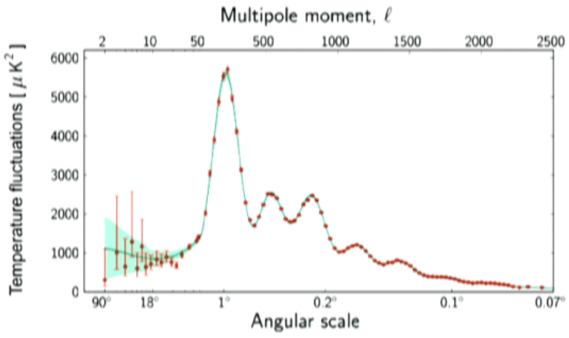
- Full parameter set $(A_s, \epsilon_1, \epsilon_2, c_s)$ assuming constant sound speed degenerate without NG info.



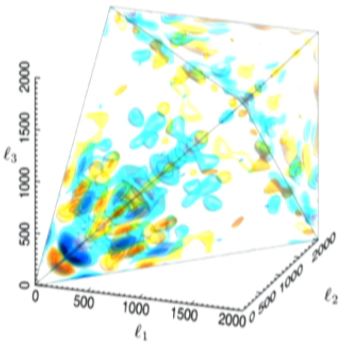
canonical case

including $c_s > 0.02$ (95% CL) constraint from NG

Joint constraints from 2-pt and 3-pt: some other examples



+



- **IR DBI**: DBI model where inflaton moves from IR to UV side, with potential

$$V(\phi) = V_0 - \frac{1}{2}\beta H^2\phi^2$$

where $0.1 < \beta < 10^9$. Planck n_s + f_{NL}(DBI) constrains $\beta < 0.7$ (95% CL).

- **k-inflation**: One class depends on a single parameter γ (Amendariz-Picon et al, 99).

Planck n_s: $0.01 < \gamma < 0.02$ (95% CL);
Planck f_{NL}(equil): $\gamma > 0.05$ (95% CL).
Inconsistent!

Outline

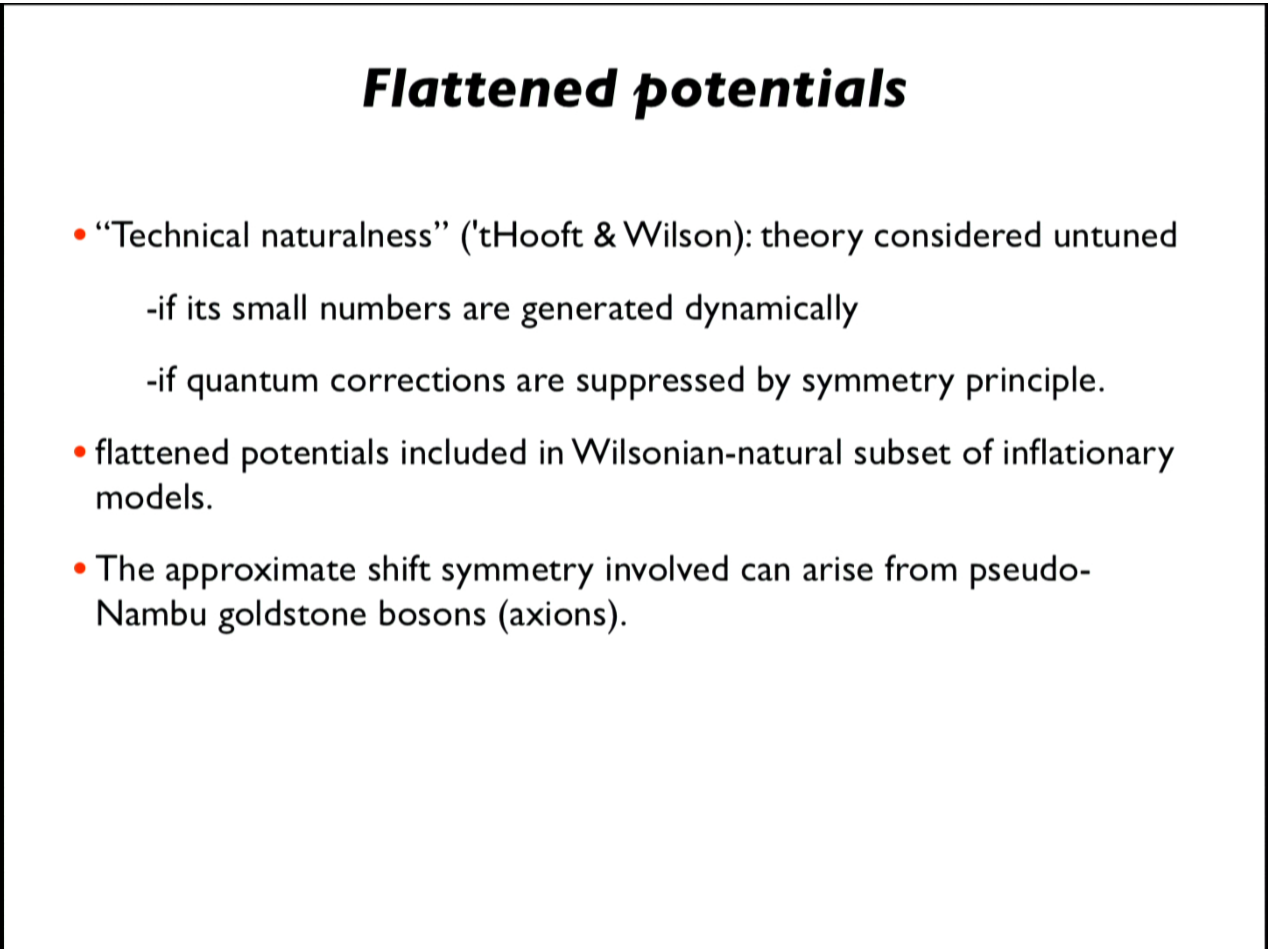
- A case study of the "top down" approach with multiple non-generic observables: constraining monodromy inflation
- NG from LSS surveys: a case study of SDSS photometric quasars

A "top down" case study*: Constraining monodromy inflation

with Richard Easther (Auckland) & Raphael Flauger (IAS Princeton/NYU)

arXiv:1303.2616 (JCAP in press)

*pre-Planck



Flattened potentials

- “Technical naturalness” ('tHooft & Wilson): theory considered untuned

  -if its small numbers are generated dynamically

  -if quantum corrections are suppressed by symmetry principle.

- flattened potentials included in Wilsonian-natural subset of inflationary models.

- The approximate shift symmetry involved can arise from pseudo-Nambu goldstone bosons (axions).

Flattened potentials

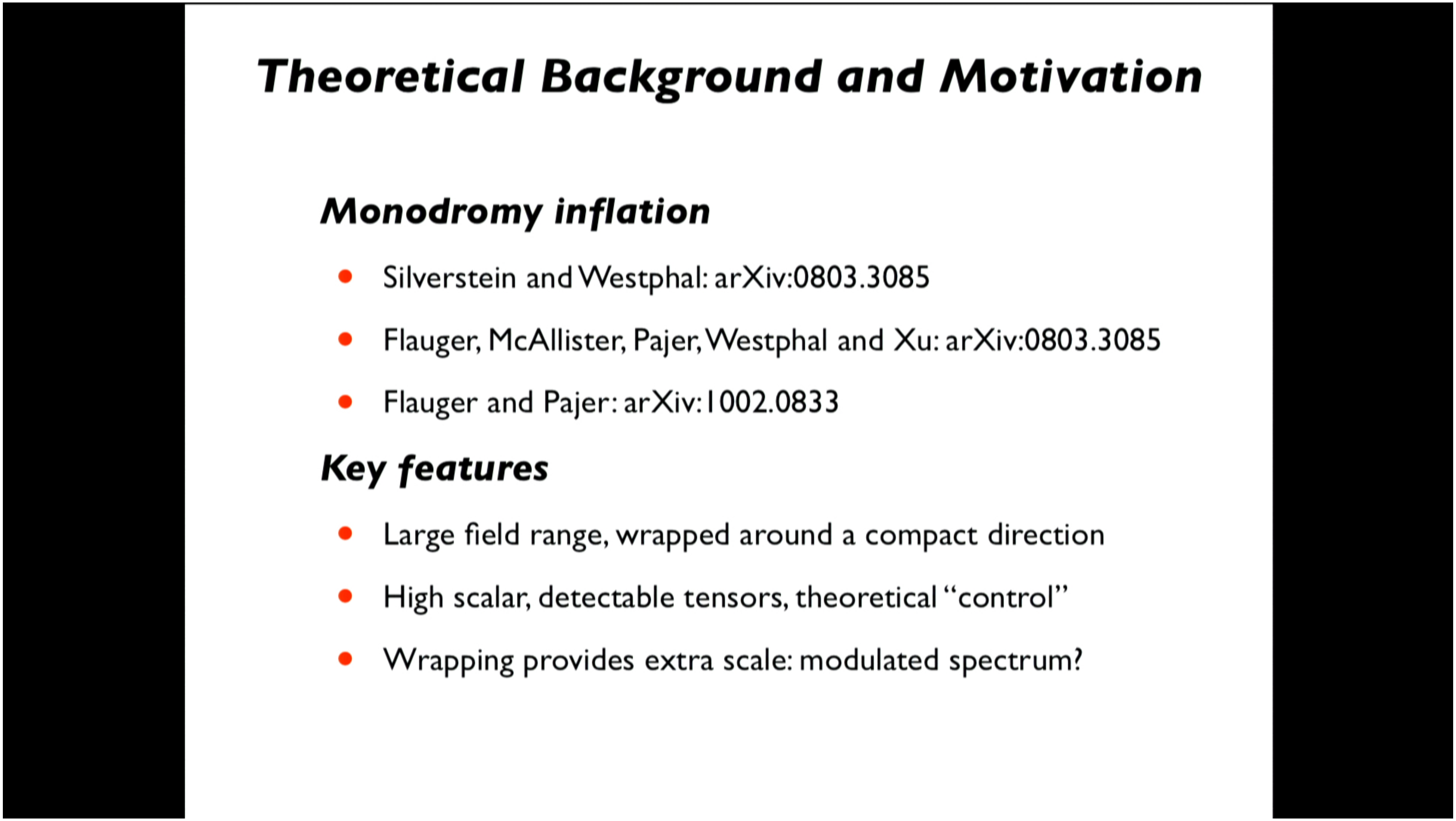
- “Technical naturalness” ('tHooft & Wilson): theory considered untuned

  -if its small numbers are generated dynamically

  -if quantum corrections are suppressed by symmetry principle.

- flattened potentials included in Wilsonian-natural subset of inflationary models.

- The approximate shift symmetry involved can arise from pseudo-Nambu goldstone bosons (axions).



Theoretical Background and Motivation

Monodromy inflation

- Silverstein and Westphal: arXiv:0803.3085
- Flauger, McAllister, Pajer, Westphal and Xu: arXiv:0803.3085
- Flauger and Pajer: arXiv:1002.0833

Key features

- Large field range, wrapped around a compact direction
- High scalar, detectable tensors, theoretical "control"
- Wrapping provides extra scale: modulated spectrum?

Approximation to the potential...

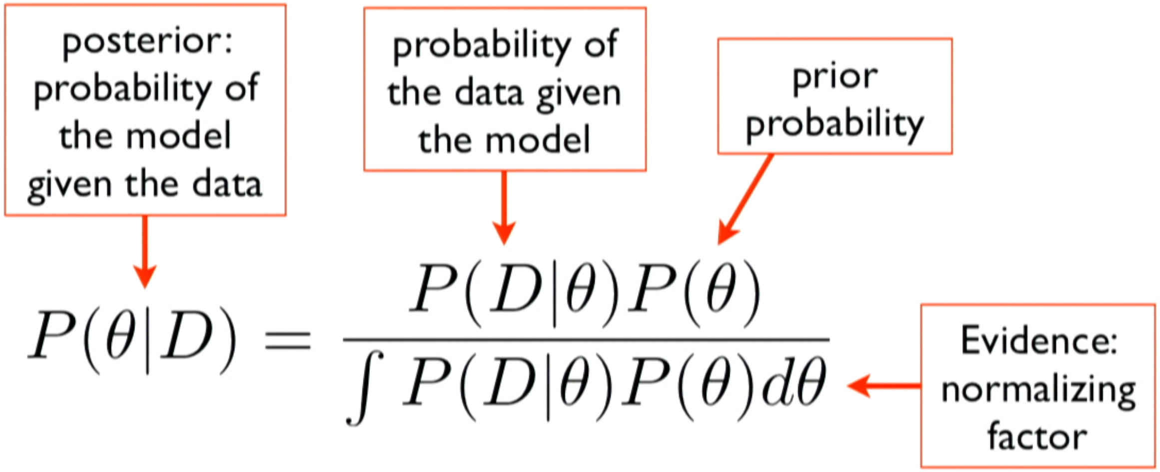
$$V(\phi) = \mu^3 \left[\phi - bf\left(\cos\left(\frac{\phi}{f} + \psi\right) - c\right)\right]$$

- Amplitude of perturbations set by μ
- Axion decay constant f: sub-Planckian, f > few x 10-4
- Modulations: 0 ≤ b < 1 to prevent trapping

Analysis

- Uses MODECODE (Peiris, Easther & others)
  - Directly solves perturbation equations
  - There is also a good approximate solution
- CAMB slowed down by oscillatory spectrum
  - Uses interpolation when it can; not safe here
  - Boosted accuracy settings in CAMB (checked convergence)
- Sampling done by MultiNest
  - Massively parallel; samples prior not posterior

Reminder:
parameter estimation vs model comparison



posterior: probability of the model given the data

probability of the data given the model

prior probability

$$P(\theta|D) = \frac{P(D|\theta)P(\theta)}{\int P(D|\theta)P(\theta)d\theta}$$

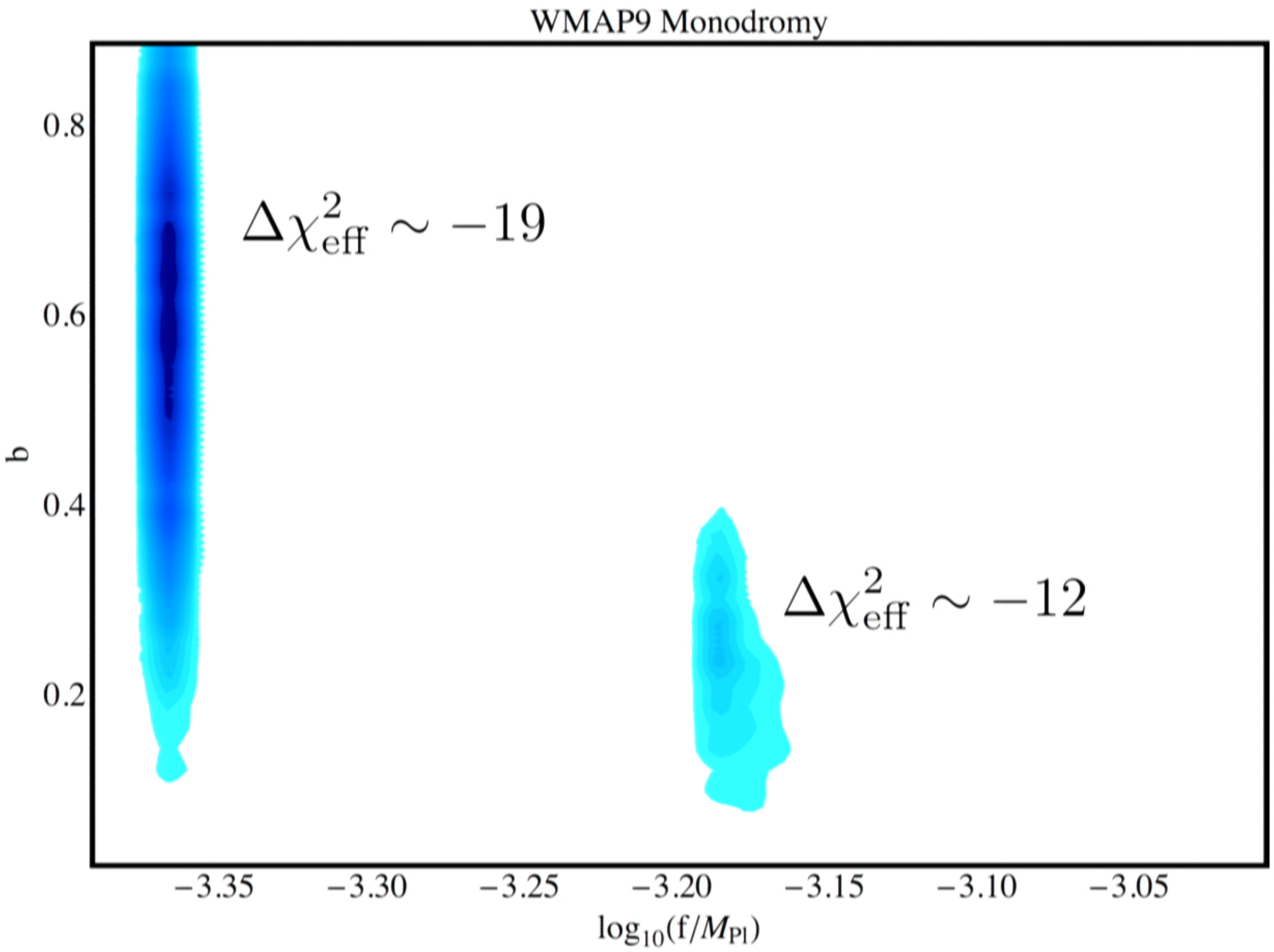
Evidence: normalizing factor

Evidence: model-averaged likelihood

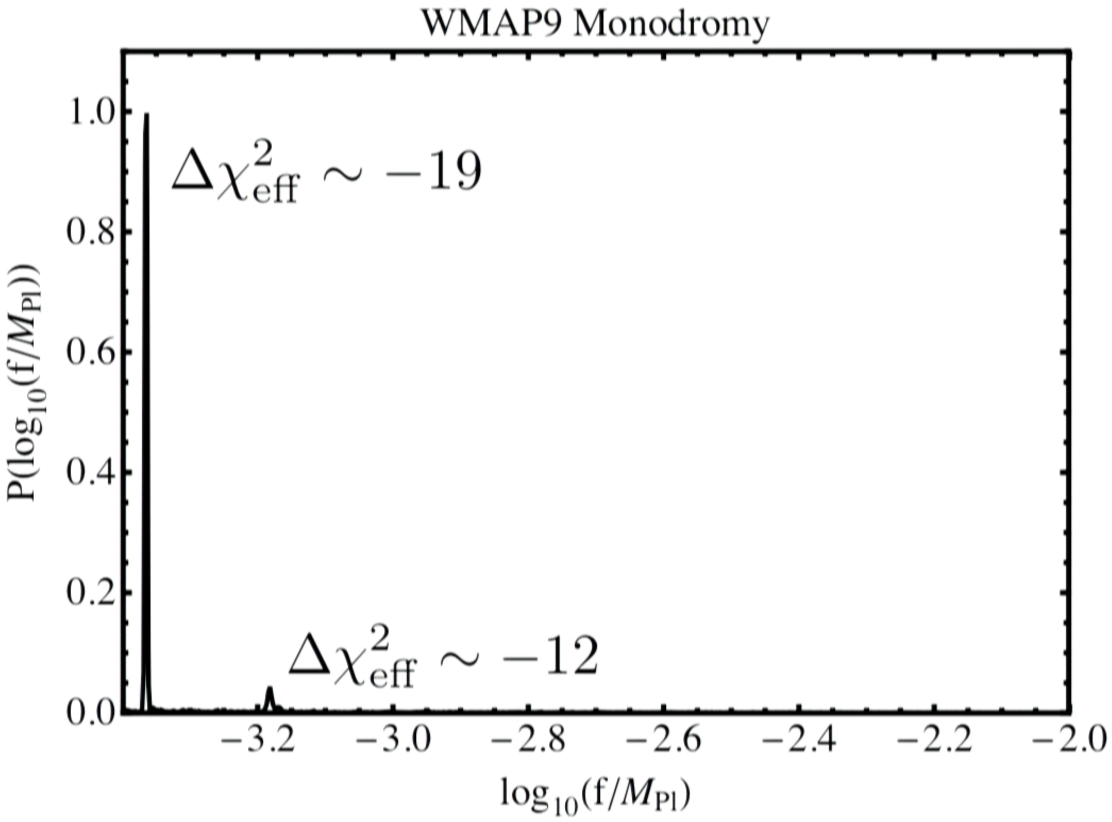
Priors

Inflation	
Mass scale	$-3.615 < \log_{10}(\mu/M_{\rm Pl}) < -3.015$
Axion coupling	$-3.4 < \log_{10}(f/M_{\rm Pl}) < -2.0$
Oscillation amplitude	$0 < b < 0.9$
Phase	$-\pi < \psi < \pi$
Matching	
e-foldings	$N = 55$
Astrophysics	
Baryon fraction	$0.0218859 < \Omega_{\rm b}h^2 < 0.02378859$
Dark matter	$\Omega_{\rm dm}h^2 = 0.1145$
Reionization	$\tau = 0.0874$
Projected acoustic scale	$\theta = 1.040$
Sunyaev-Zel'dovich Amplitude	$A_{\rm SZ} = 0.10078$

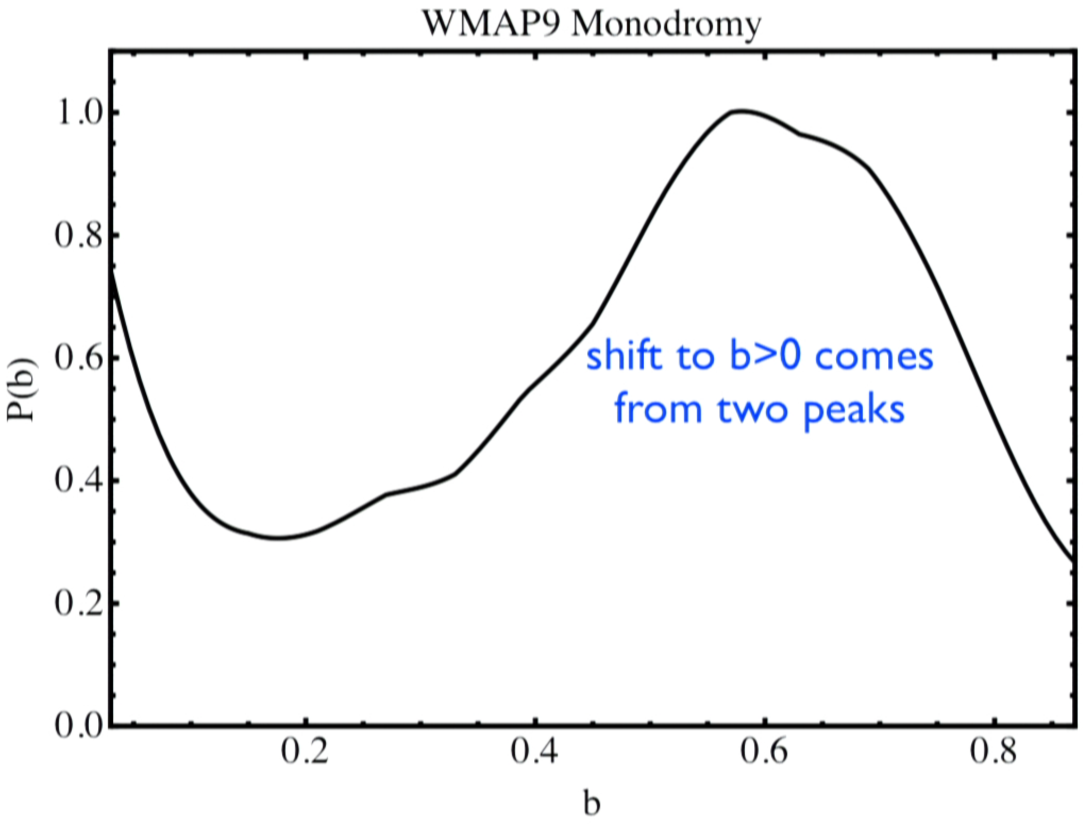
Marginalised posterior



Marginalised posterior

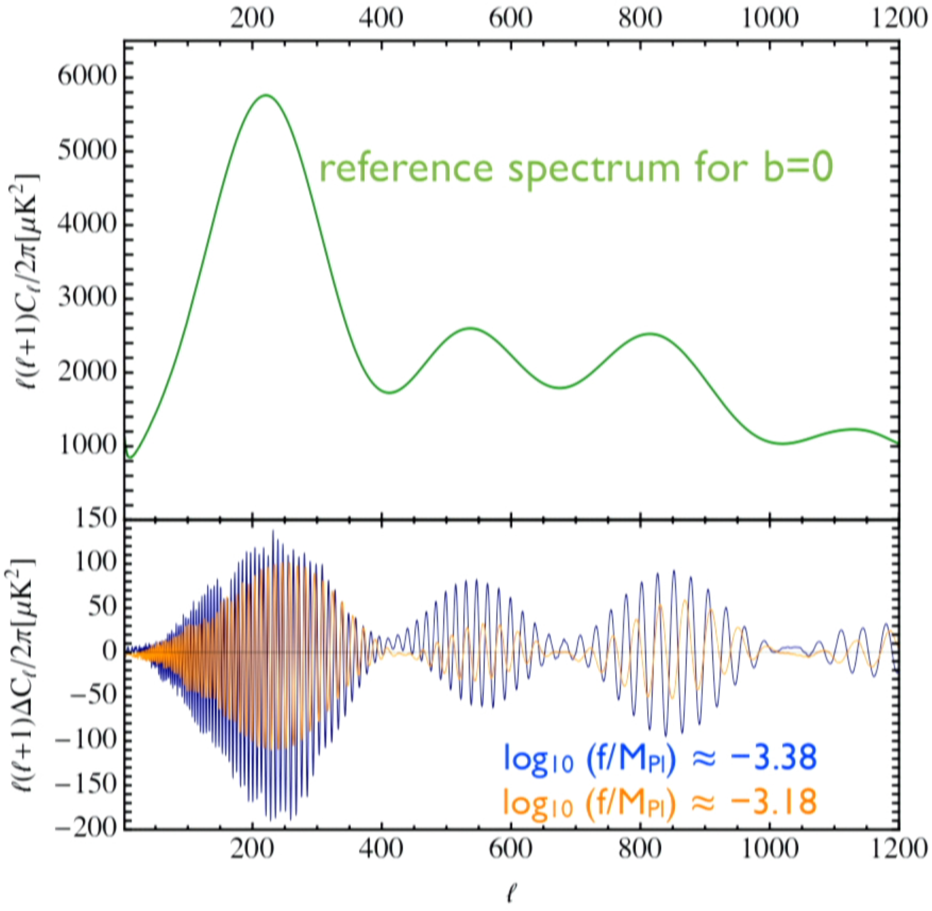


Marginalised posterior

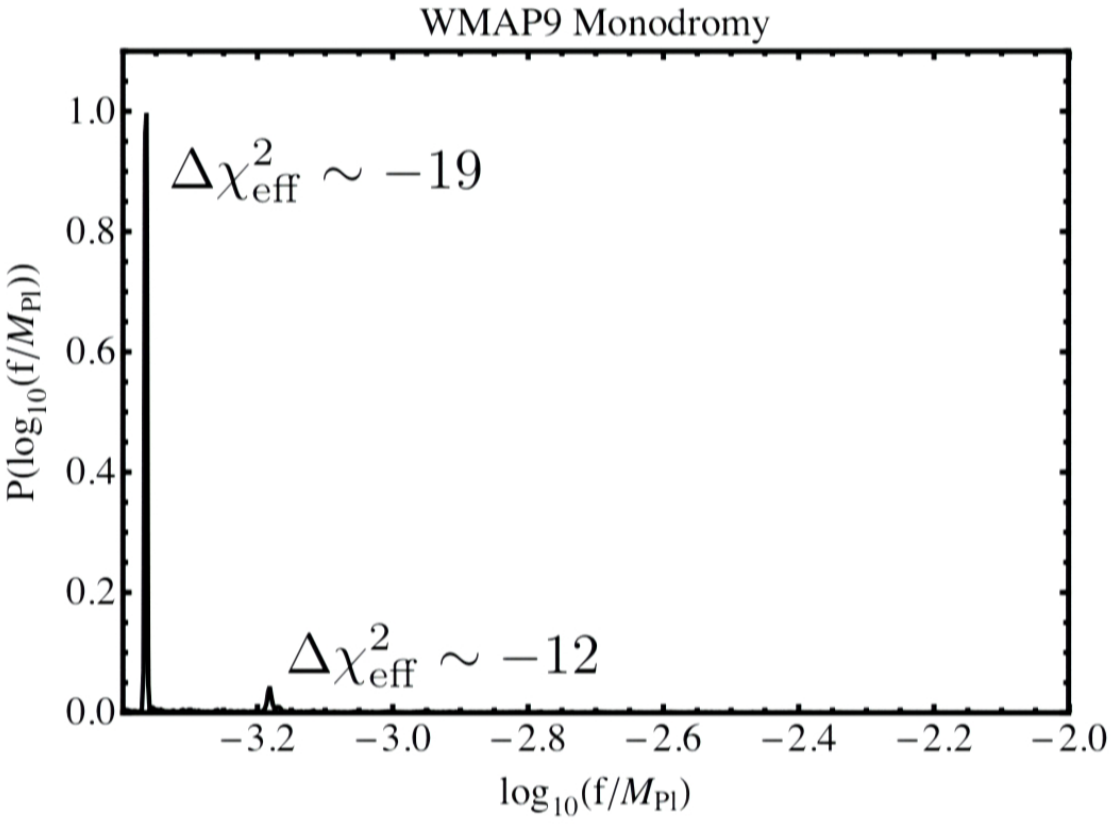


shift to b>0 comes
from two peaks

Effect on power spectrum



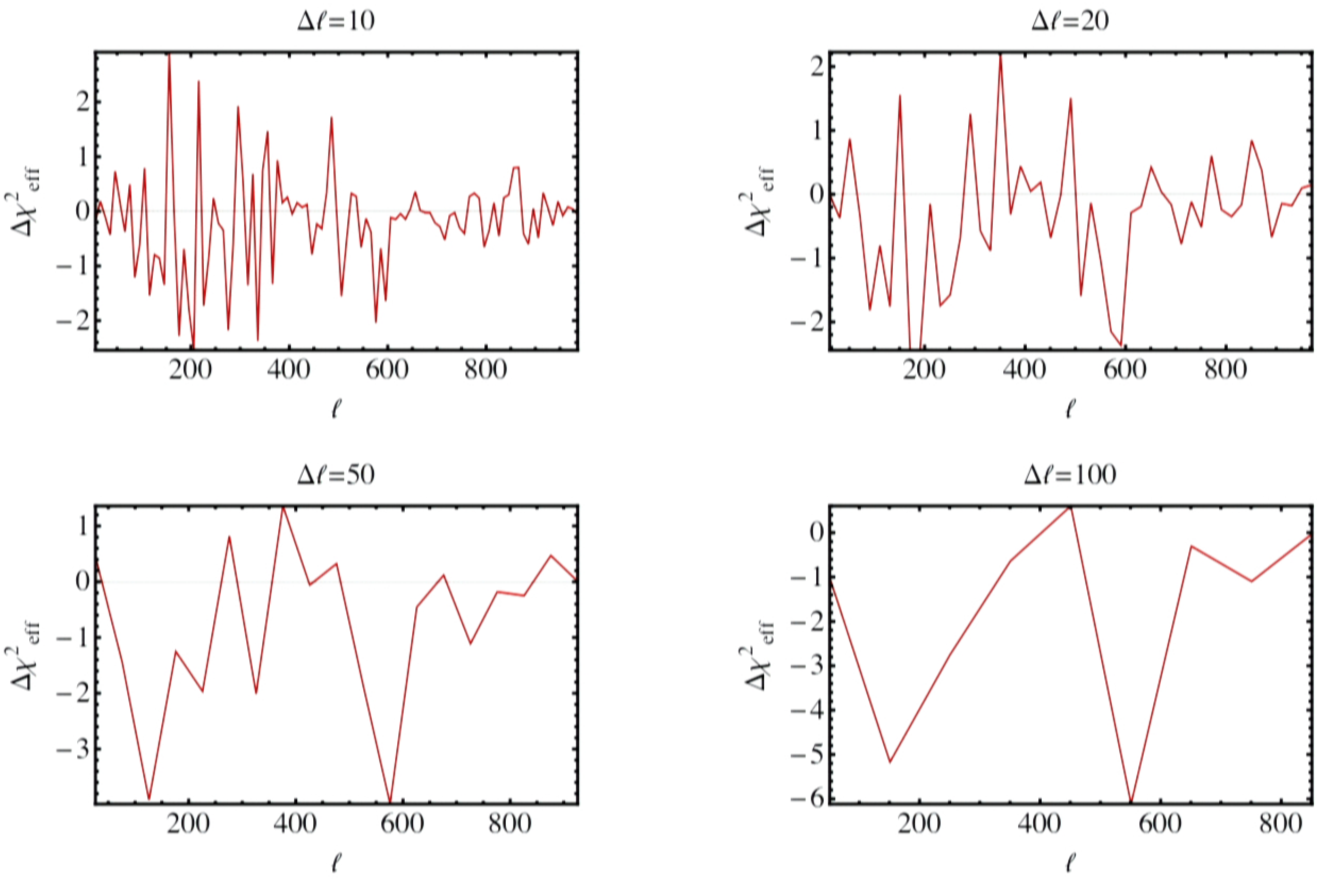
Marginalised posterior



Significance

- Bayesian evidence: 0.6 in favor of modulated model (not significant)
- Maximum likelihood: $-2\,\Delta \ln L \sim 19$ for high peak; 12 for low peak
    - Relative to both b=0 and ΛCDM
    - Significant improvement, but not compelling
    - Both peaks: $-2\,\Delta \ln L \sim 11$ with μ fixed

Locating the improvement...



improvement comes from full l-range where WMAP has S/N

Non-Gaussianity

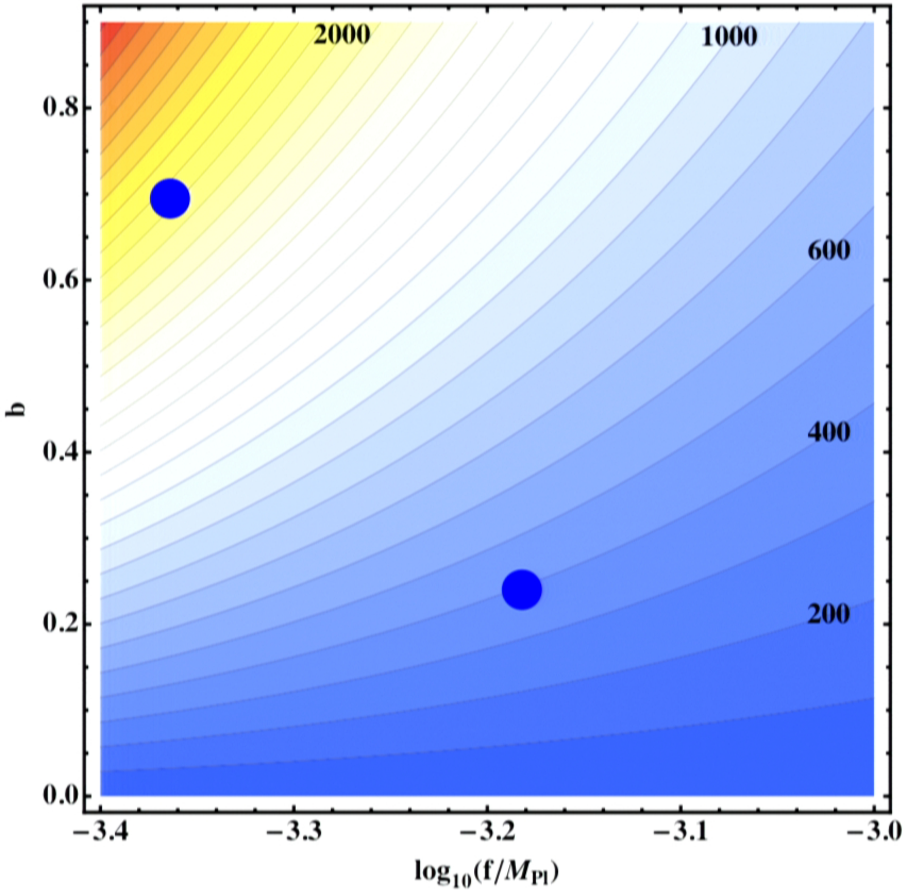
Resonant non-Gaussianity

- Chen, Easther and Lim – arXiv:0801.3295
- Generated inside the horizon
- Considered generic interaction terms for 3-point function

Monodromy

- Flauger, McAllister, Pajer, Westphal & Xu
- Detailed look at non-Gaussianity (also Flauger & Pajer)
- Little "overlap" with standard shapes; not constrained

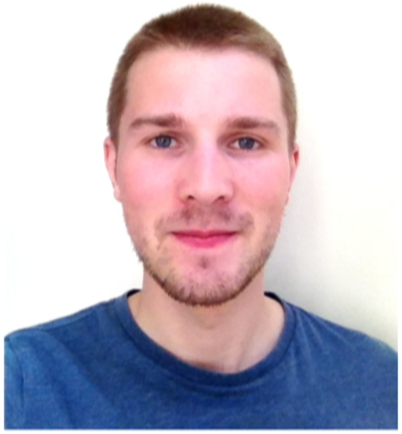
Non-Gaussianity



Post-Planck update

- Large, high frequency oscillation seen in WMAP9
  - Similar analysis by Planck; but not at this frequency
  - WMAP and Planck appear different in several relevant aspects
- Larger than most “anomalies”
  - But not compelling
  - And even if it is “real”, it could be a systematic
- Interesting model, eminently testable through predictions for scalar/tensor spectra + bispectrum...

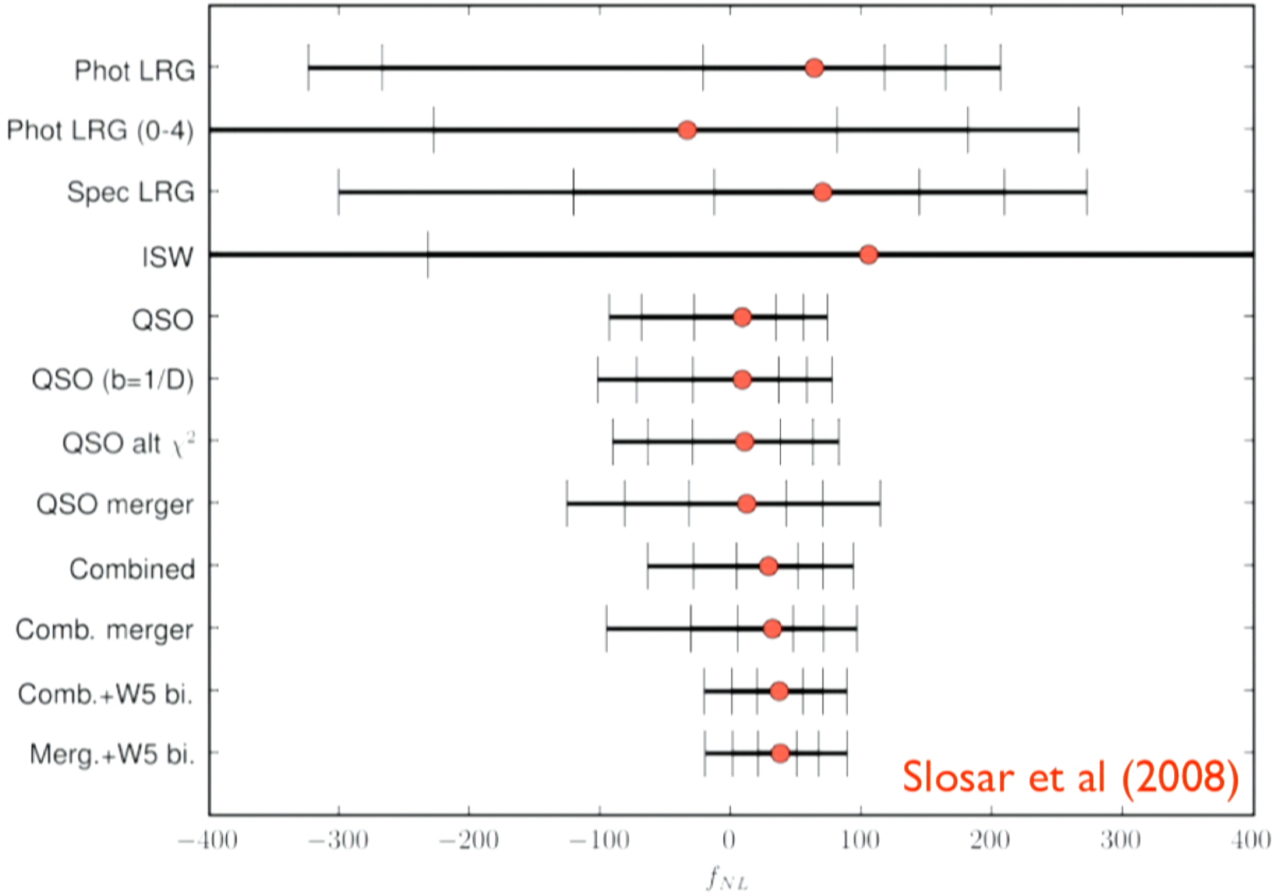
Issues in NG from LSS surveys: A case study of SDSS quasars



with
Boris Leistedt (UCL)
Daniel Mortlock (Imperial)
Aurelien Benoit-Levy (UCL)
Andrew Pontzen (Oxford)

arXiv:1306.0005 (MNRAS accepted)

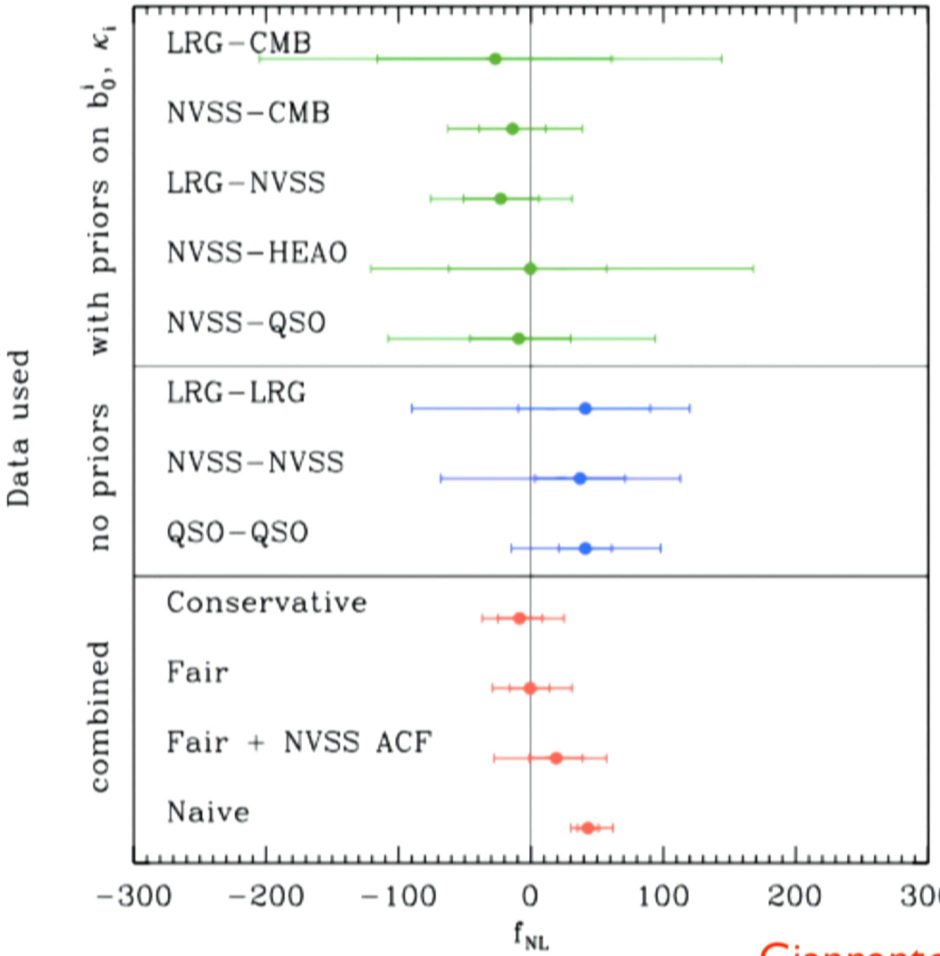
PNG from large scale LSS angular power spectrum



Slosar et al (2008)

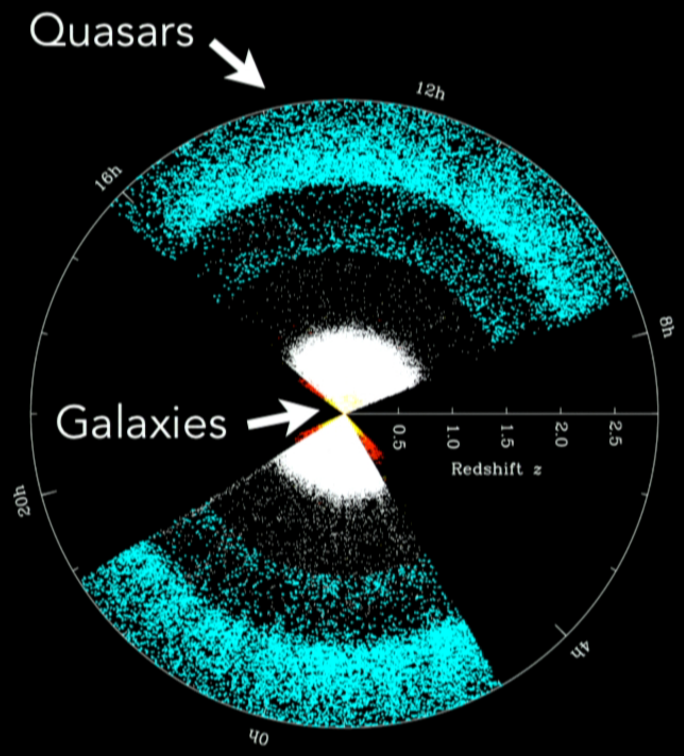
scale-dependent halo bias (Dalal et al 2008)

PNG from large scale LSS clustering



Giannantonio et al (2013)

Cosmology with quasar surveys



Quasars

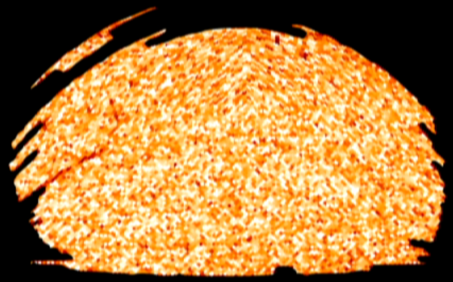
Galaxies

SDSS3 ; Credit: M.Blanton

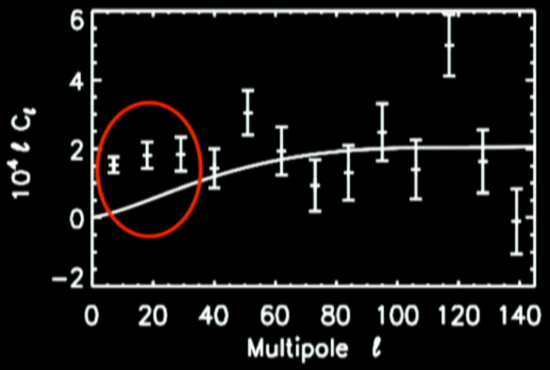
- Quasars are bright, highly biased tracers that span large cosmological volumes
- Probe super horizon / large scale modes: ISW, PNG,...

  e.g. Giannantonio et al. 2006, 2008; Slosar et al. 2008; Xia et al. 2010, 2011, and many others

Purpose of this work



Richards et al (2008) catalogue

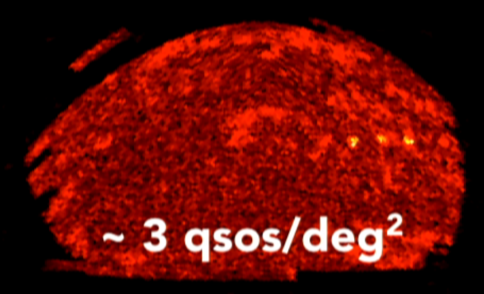


- SDSS photometric quasars: excess clustering power on large scales due to systematics
- Concerns about its use for clustering studies

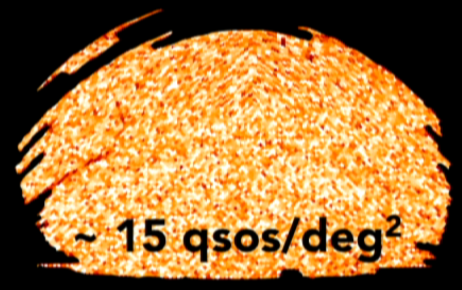
  Pullen and Hirata 2012; Giannantonio et al. 2013
- This work: excess eliminated with appropriate techniques

Photometric Quasars

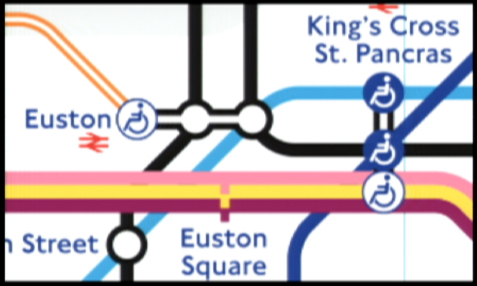
- Spectroscopic catalogues are small, incomplete
- We use UVX sources from the Richards et al (2008) "RQCat" catalogue of SDSS photometric quasars



$z_s < 2.2$ Spec QSOs
from SDSS-DR7



$z_p < 2.2$ UVX Photo QSOs
from RQCat (SDSS-DR6)

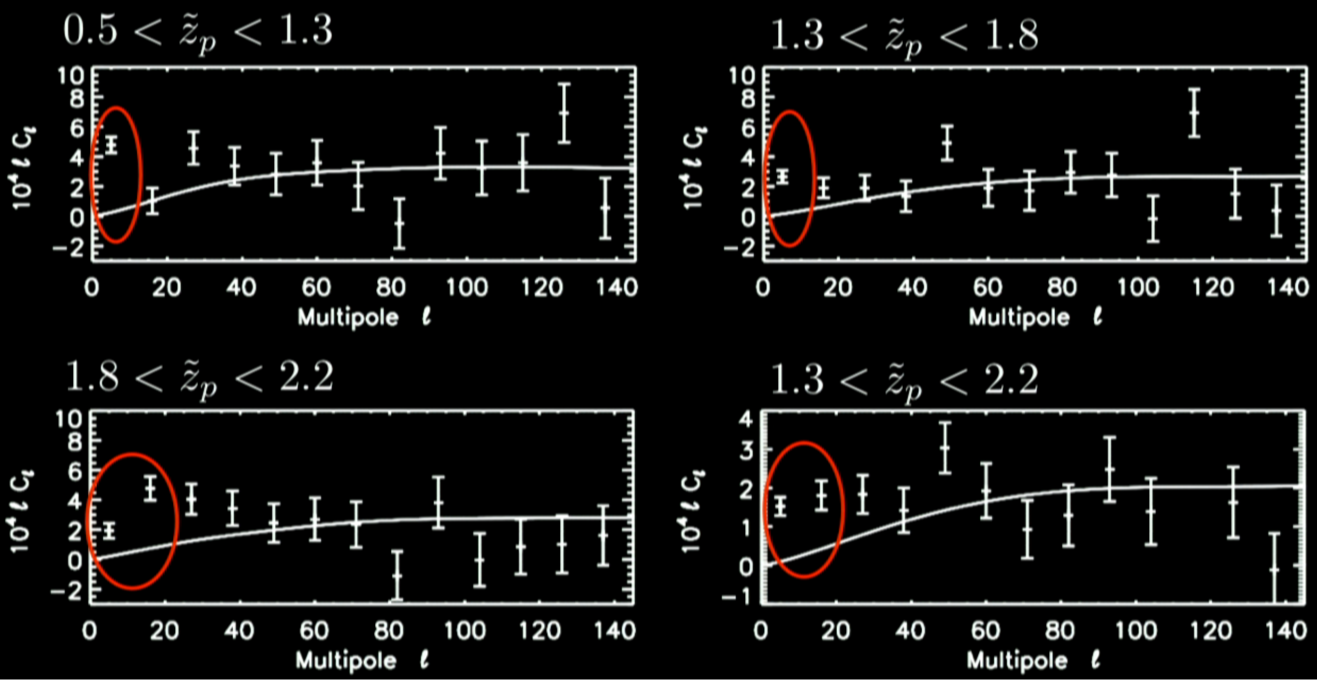


Roadmap

1. SDSS photometric quasars
2. Angular power spectrum estimators
3. Systematics, masks and mode projection
4. Redshift distributions and theory predictions
5. Power spectrum analysis

Angular power spectrum analysis

- RQCat divided into four photometric redshift bins
- SDSS footprint mask : excess power in all samples



Estimating angular power spectra

- Power spectra must be estimated from cut-sky data
- Critical on large-scales due to the cut-induced variance

CMB mask
$f_{\rm sky} > 0.7$

LSS mask
$f_{\rm sky} < 0.2$

The QML and PCL estimators

- Quadratic Maximum Likelihood (QML): optimal, requires a model of the pixel-pixel covariance matrix:

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

↑ Covariance matrix

↑ Theory spectrum

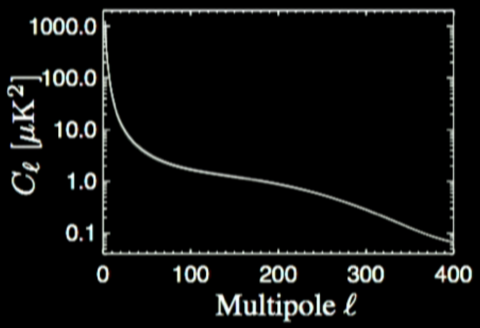
↑ Noise, systematics, ...

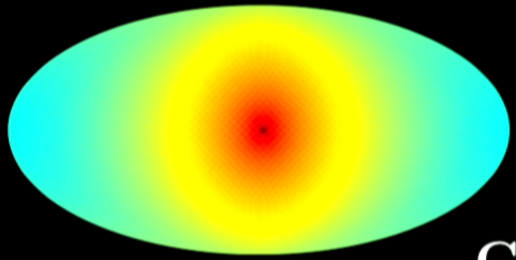
- Pseudo-spectrum estimator (PCL) = QML with diagonal pixel-pixel covariance, i.e. a flat power spectrum

(= uncorrelated pixels)

PCL or QML? CMB vs LSS correlations

CMB

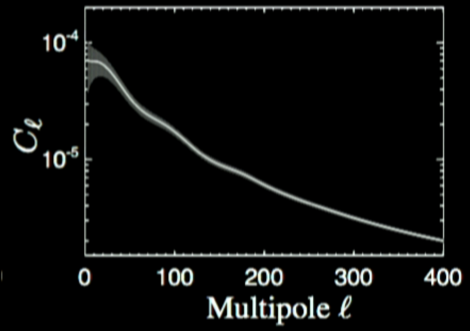


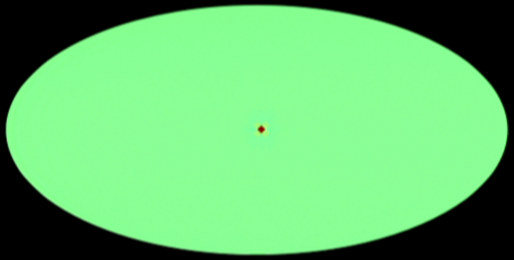


$\mathbf{C}(\theta_{ij})$

with i fixed

LSS





The LSS spectrum is quasi flat => PCL is nearly optimal

in the absence of systematics...

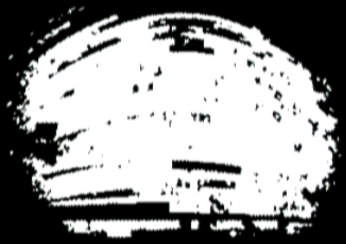
Systematics and stellar contamination

- Spatial variations in calibration and observing conditions ⇒ spatial modulation of QSOs counts
- Imperfect star-quasar separation + spatially dependent due to stellar distribution and systematics

Main systematics for analysing RQCat:

Improved sky masks


Mask 1 (reference)


Mask 2


Mask 3

- Start with the SDSS-DR6 mask
- Remove pixels by thresholding the systematics templates
- Excise regions with missing data

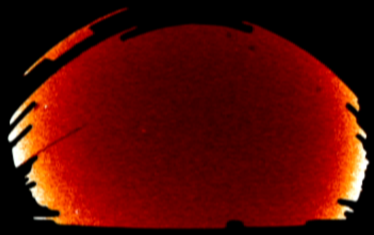
Systematic (unit)	Mask 1	Mask 2	Mask 3
Seeing (arcsec)	2.0	1.6	1.55
Reddening (mag)	0.05	0.05	0.045
Stellar density (stars/deg^2)	562	400	350
Airmass (mag)	1.4	1.3	1.25
Sky brightness (nmgy/arcsec^2)	2×10^{-9}	1.8×10^{-9}	1.75×10^{-9}

Systematics and mode projection

- PCL suboptimal with complex masks and systematics
- QML with mode projection: marginalises over linear contamination models, using systematics templates $\vec{c}_k$

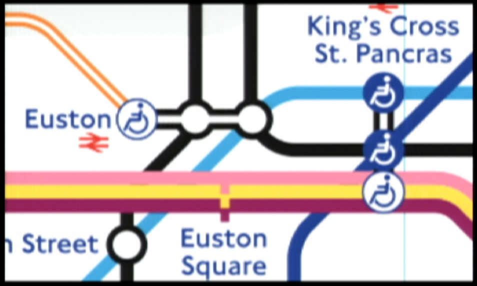
$$\mathbf{C} = \sum_{\ell} \mathcal{C}_\ell \mathbf{P}_\ell + \mathbf{N} + \sum_{k\in \mathrm{sys}} \xi_k \vec{c}_k \vec{c}_k^{\,t} \quad \text{with} \quad \xi_k \to \infty$$

RQCat



stars

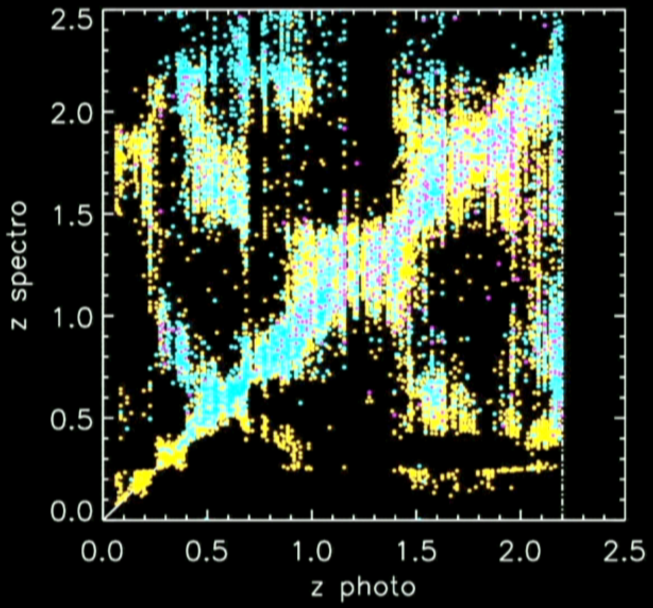
dust extinction



Roadmap

1. SDSS photometric quasars
2. Angular power spectrum estimators
3. Systematics, masks and mode projection
4. Redshift distributions and theory predictions
5. Power spectrum analysis

Photometric redshift estimates

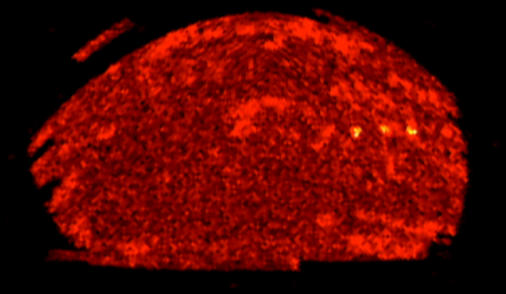


Cross-matching RQCat with
SDSS-DR7, BOSS, and 2SLAQ

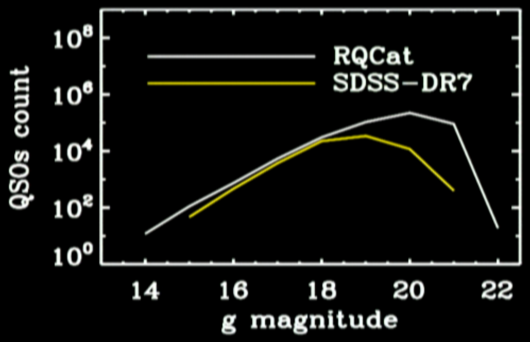
- Quasar photo-z have large fraction of outliers
- Redshift distributions poorly known
- Impacts robustness of theory power spectra

Estimating the redshift distributions

- Cross-match RQCat with SDSS-DR7 spectro QSOs
- Different selection functions ⇒ apply completeness corrections to correct redshift distributions
- Pixel + magnitude dependent corrections



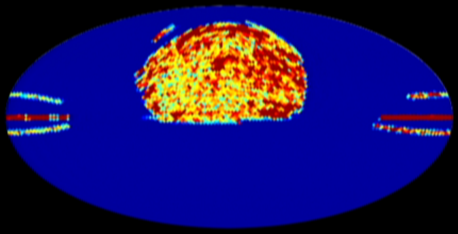
SDSS-DR7 map

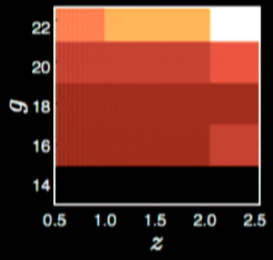


Magnitude distributions

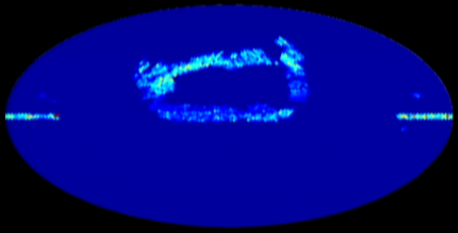
Completeness corrections

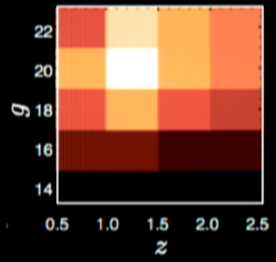
SDSS DR7 cross-matched
with RQCat : 73,175 objects



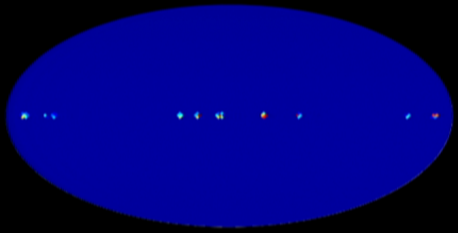


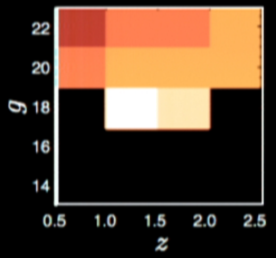
BOSS DR9 cross-matched
with RQCat : 7,914 objects



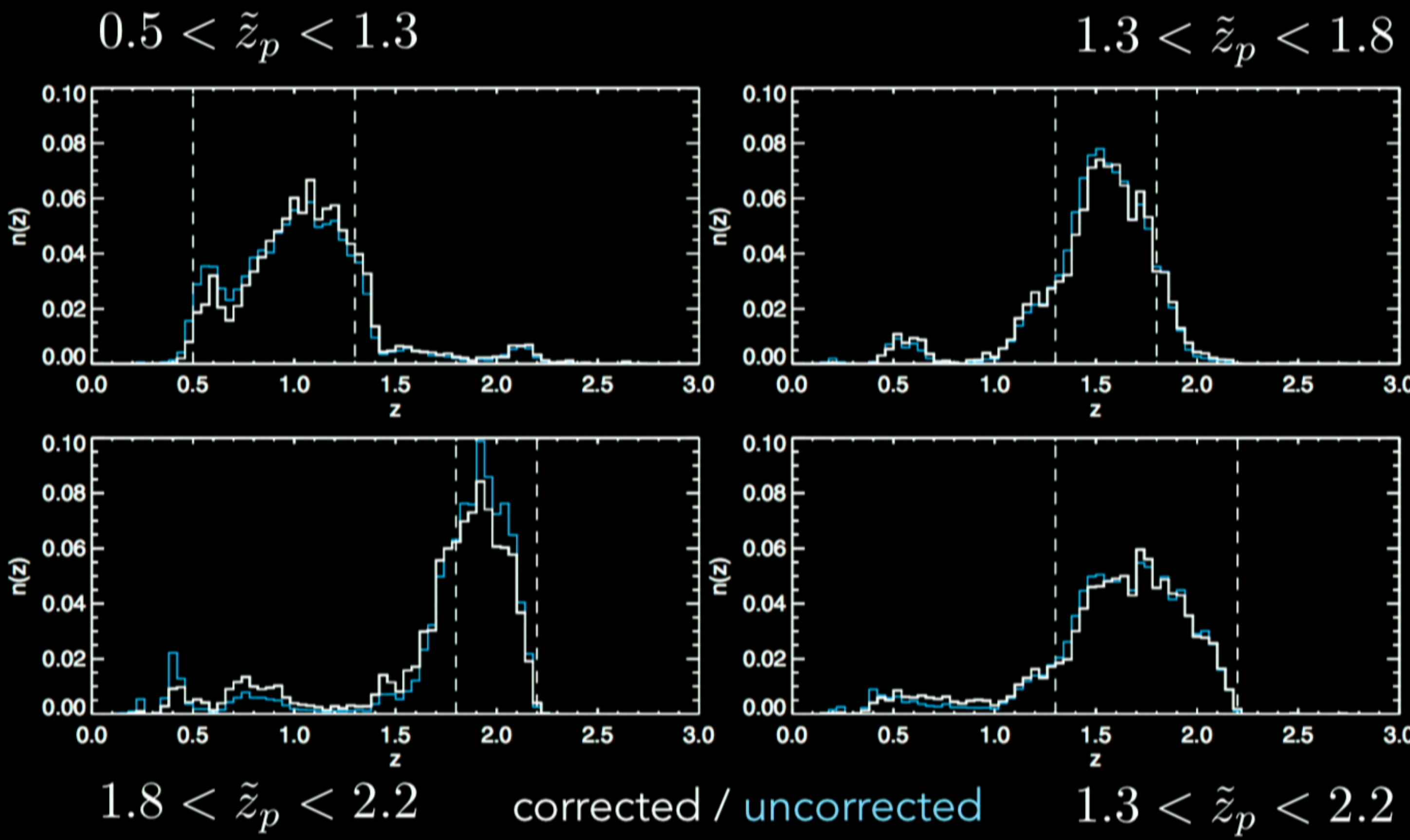


2SLAQ cross-matched
with RQCat : 666 objects





n(z) with completeness corrections



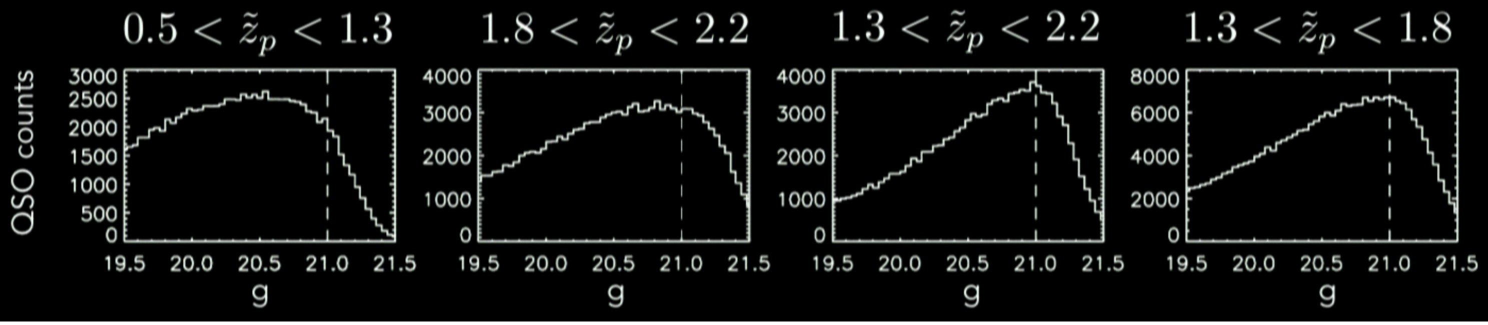
corrected / uncorrected

Estimating magnification effects

Line of sight integral: $C_\ell = \frac{2}{\pi} \int dk k^2 P(k) [W_\ell(k)]^2$

with kernel $W_\ell(k) = \int dz \, [\underbrace{b_g n(z)}_{\text{Linear bias and redshift distribution}} + \underbrace{2(2.5s - 1) f(z)}_{\text{Magnification effects}}] \, D(z) j_\ell(kr),$

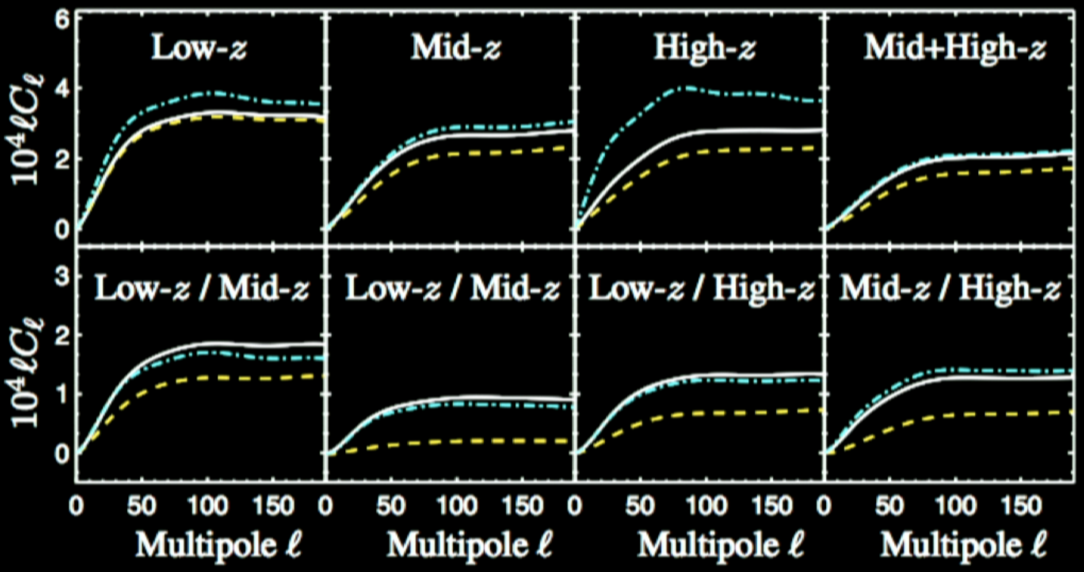
and $s = \frac{d \log N(m)}{dm}$ at g = 21



$0.5 < \tilde{z}_p < 1.3$ $1.8 < \tilde{z}_p < 2.2$ $1.3 < \tilde{z}_p < 2.2$ $1.3 < \tilde{z}_p < 1.8$

Power spectrum theory predictions

- Used CAMB_SOURCES (Challinor and Lewis 2011) with Planck cosmology and corrected n(z) distributions



Solid:
best prediction

Dot-dashed:
completeness corr. neglected

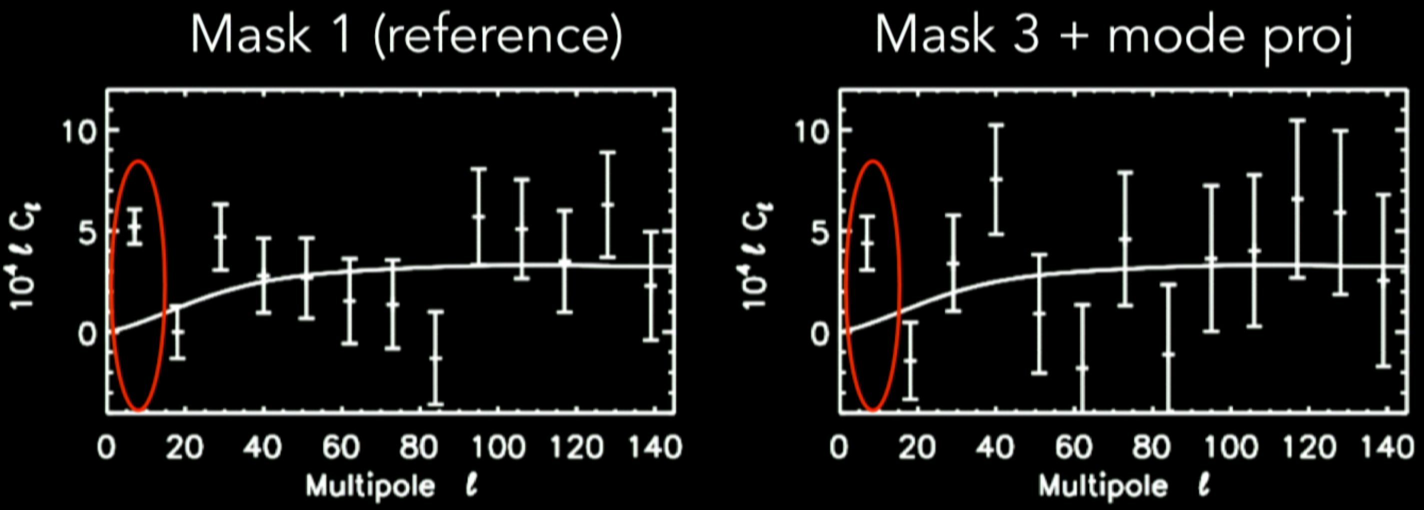
Dashed:
magnification neglected

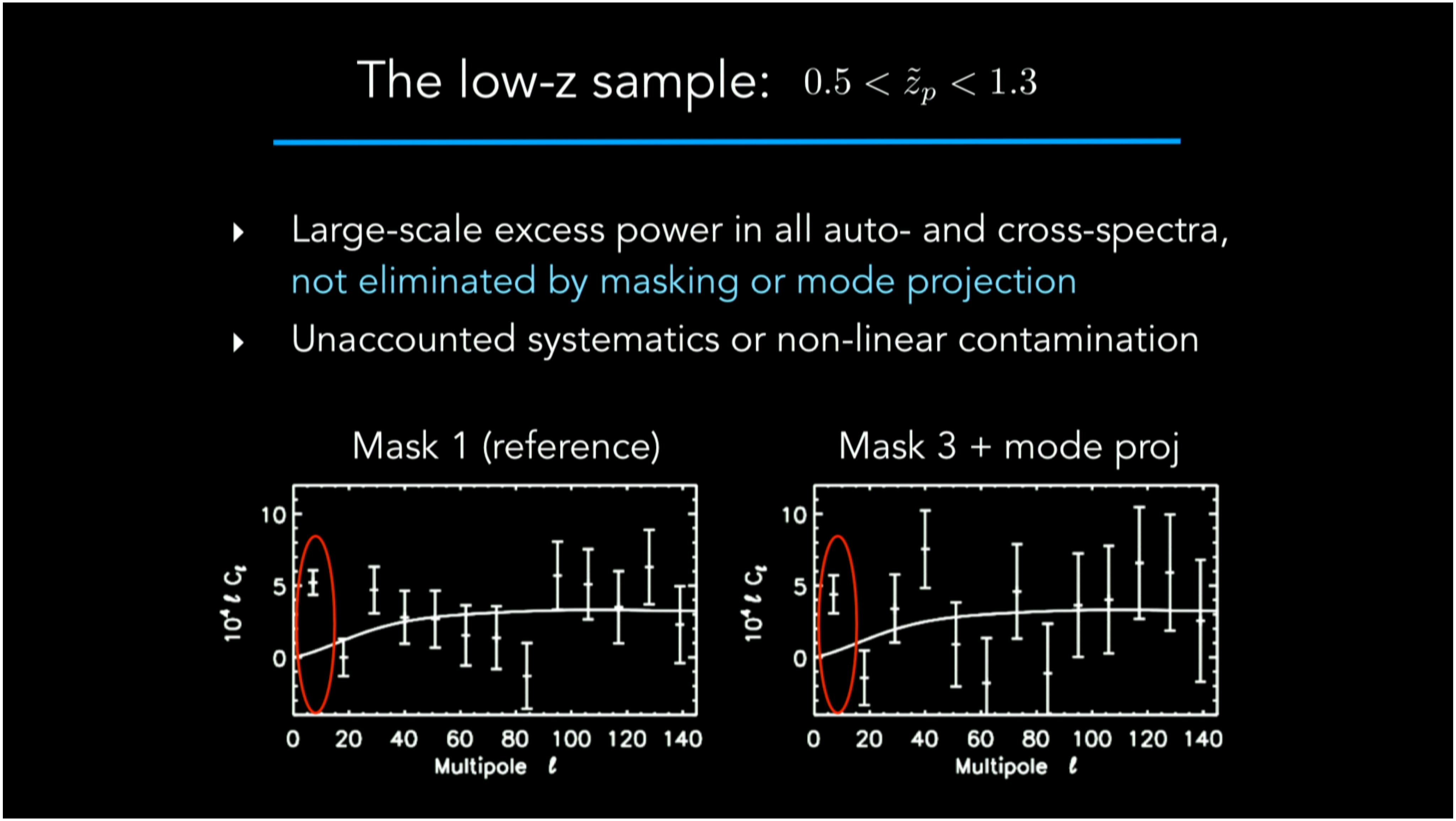
Power spectrum analysis of RQCat

- Ingredients: QML estimator, improved masks, mode projection, robust theory predictions
- Auto- and cross-spectra of RQCat subsamples, + Cross-spectra with systematics templates
- Most spurious correlations eliminated

The low-z sample: $0.5 < \tilde{z}_p < 1.3$

- Large-scale excess power in all auto- and cross-spectra, not eliminated by masking or mode projection
- Unaccounted systematics or non-linear contamination





The low-z sample: $0.5 < \tilde{z}_p < 1.3$

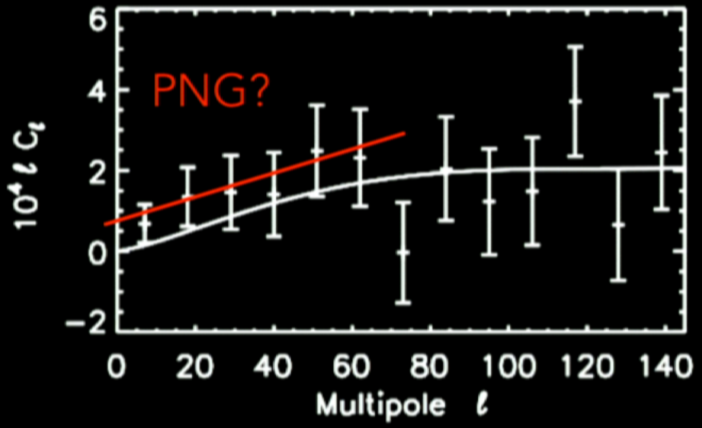
- Large-scale excess power in all auto- and cross-spectra, not eliminated by masking or mode projection
- Unaccounted systematics or non-linear contamination

Mask 1 (reference)

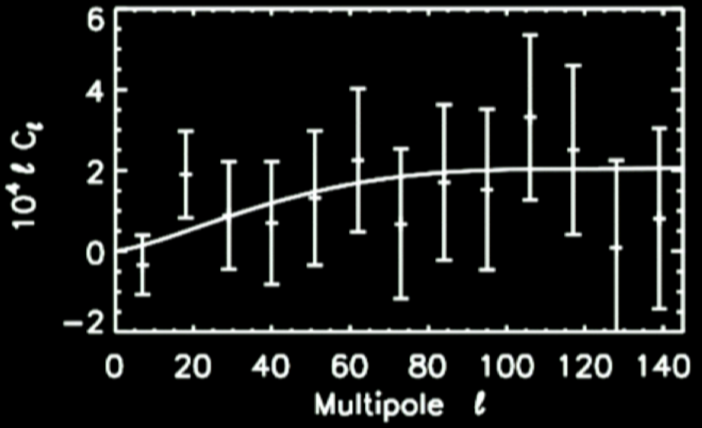
Mask 3 + mode proj

The mid+high-z sample: $1.3 < \tilde{z}_p < 2.2$

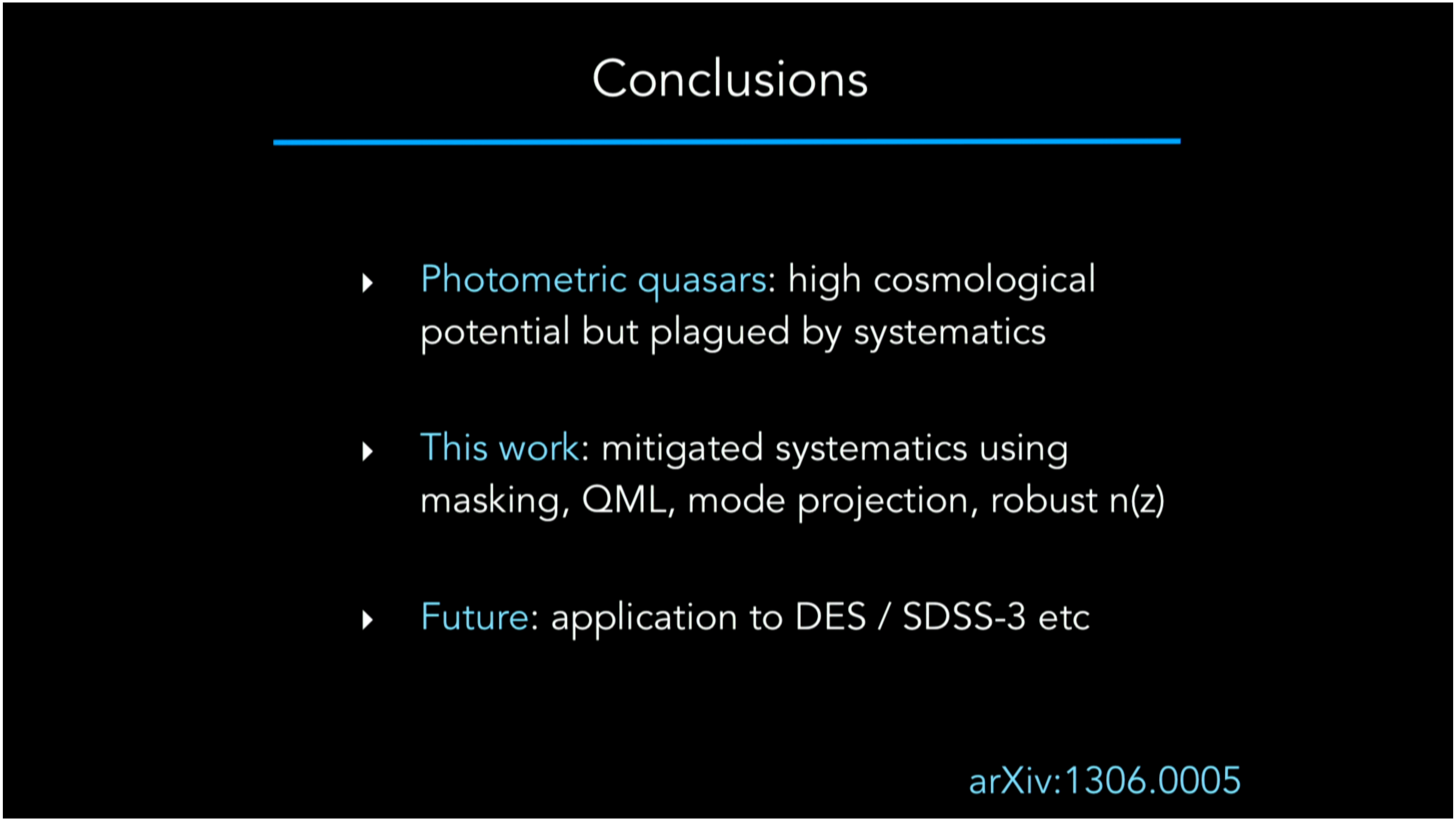
- No statistical anomalies in auto-spectrum with Mask 1, but signatures of systematics found in cross-spectra
- Mask3+mp: systematics within statistical uncertainties



Mask 1 (reference)



Mask 3 + mode proj



Conclusions

- Photometric quasars: high cosmological potential but plagued by systematics
- This work: mitigated systematics using masking, QML, mode projection, robust n(z)
- Future: application to DES / SDSS-3 etc

arXiv:1306.0005


EXIT