First Measurement of Neutrinos in the BAO Spectrum

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Abstract

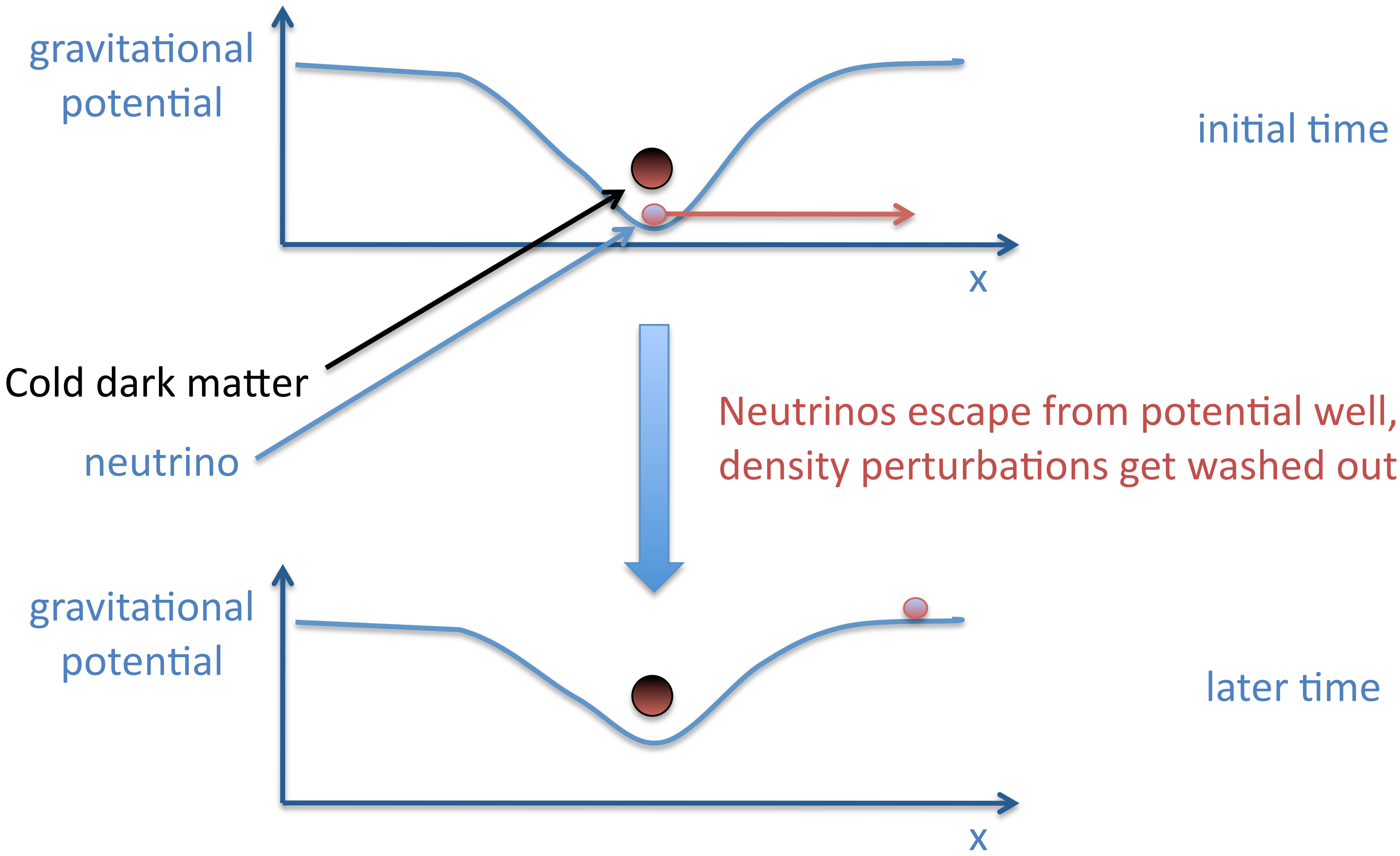
The existence of the cosmic neutrino background is a fascinating prediction of the hot big bang model. These neutrinos were a dominant component of the energy density in the early universe and, therefore, played an important role in the evolution of cosmological perturbations. In particular, fluctuations in the neutrino density produced a distinct shift in the temporal phase of sound waves in the primordial plasma, which has recently been detected in the cosmic microwave background (CMB). In this paper, we report on the first measurement of this neutrino-induced phase shift in the spectrum of baryon acoustic oscillations (BAO) of the BOSS DR12 data. Constraining the acoustic scale using Planck data, and marginalizing over the effects of neutrinos in the CMB, we find evidence for a non-zero phase shift at greater than 95% confidence. We also demonstrate the robustness of this result in simulations and forecasts. Besides being a new measurement of the cosmic neutrino background, our work is the first application of the BAO signal to early universe physics and a non-trivial confirmation of the standard cosmological history.

Cosmo club, Saclay **April 24, 2018**

Context

Free-Streaming

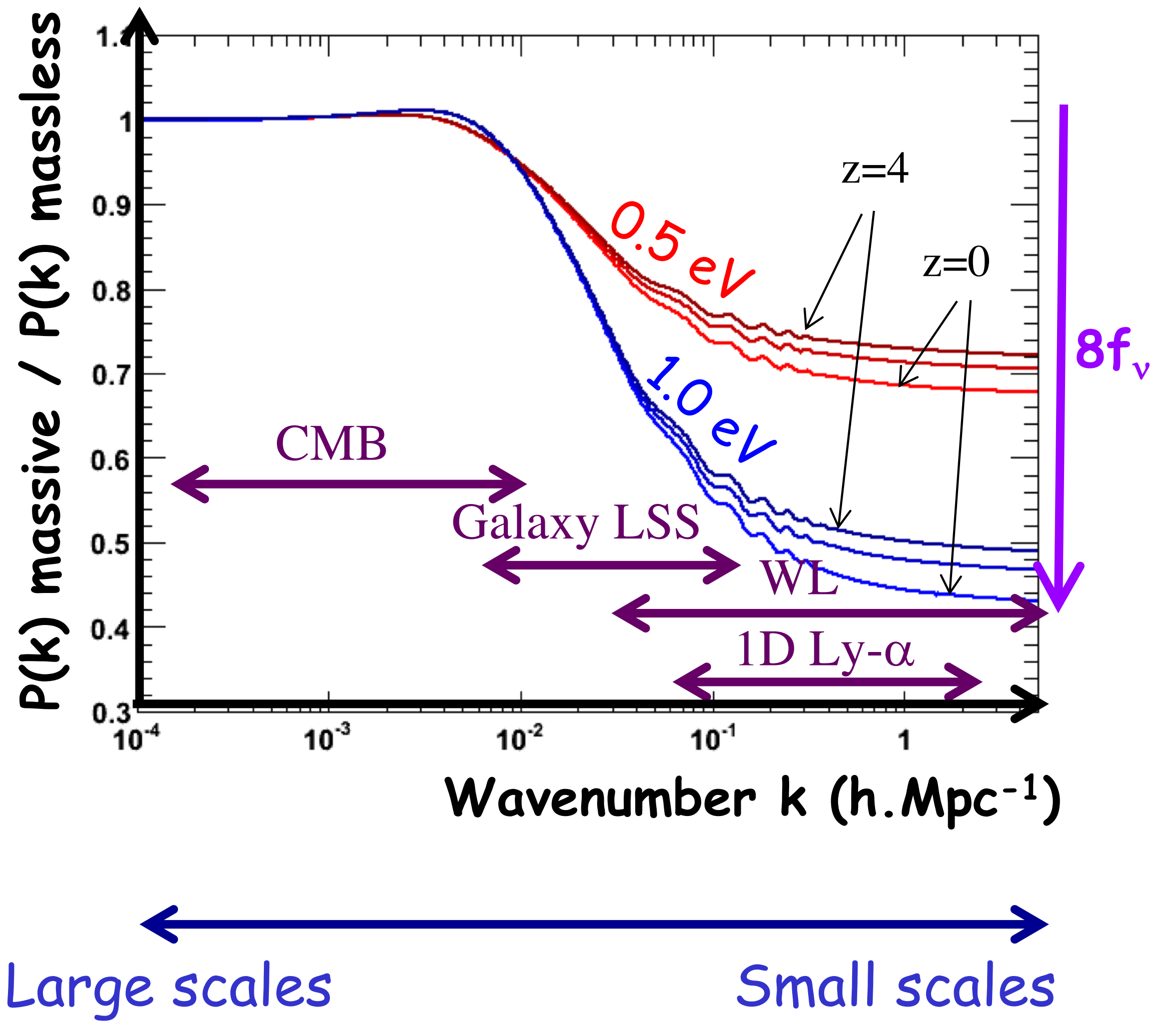
Velocity dispersion large wrt size of potential well



Neutrinos escape from potential well, density perturbations get washed out

Impact of ν on matter power spectrum

- Impact in CMB-alone only for non-relativist neutrinos ⇒ ~1-2 eV limit



- Free-streaming:
  - Wash out the fluctuations
  - Suppression of small scales in P(k)

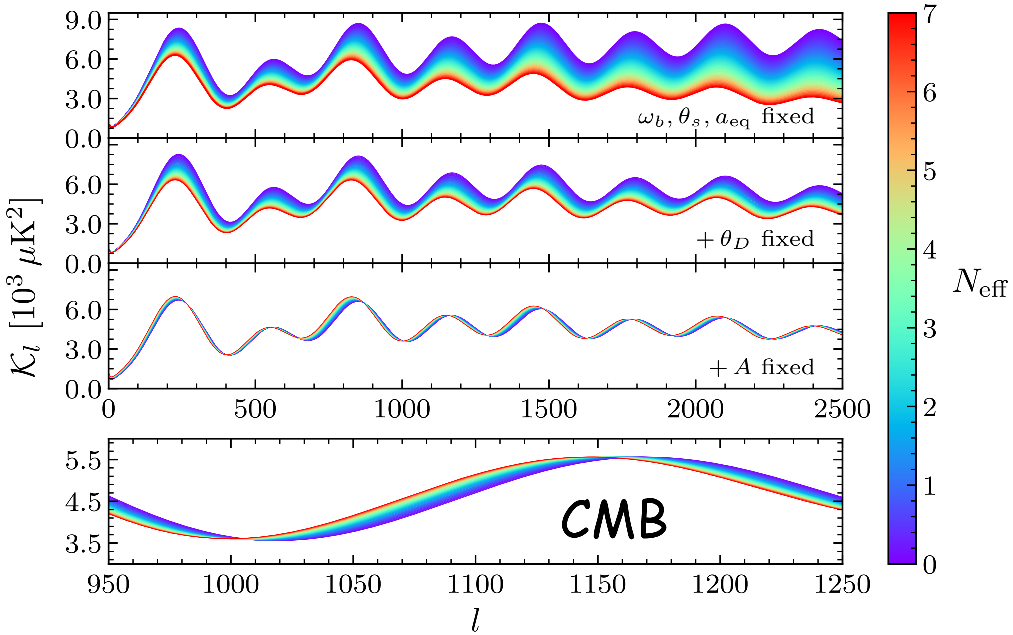
- Suppression factor ⇔ Σm_ν

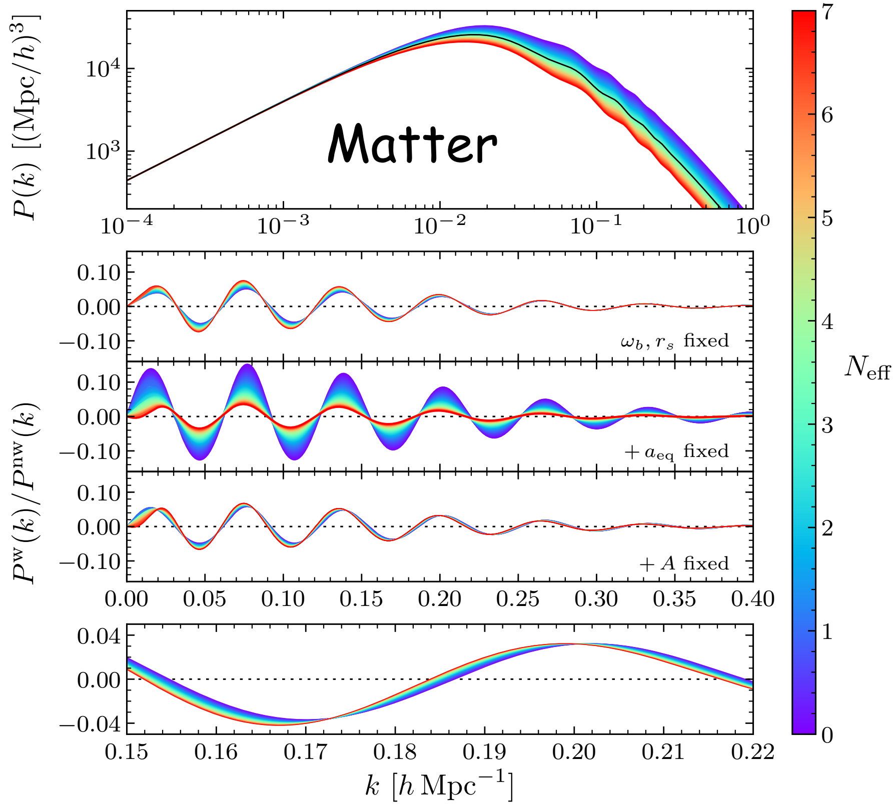
- All probes directly sensitive to free-steaming through the damping of P(k)
  - Galaxy Power spectrum
  - Weak lensing
  - Ly-a absorption along the line of sight
  - CMB-lensing

We propose to "detect" CνB with a different approach

CMB/Matter and N_{eff}

Baumann et al. 2017

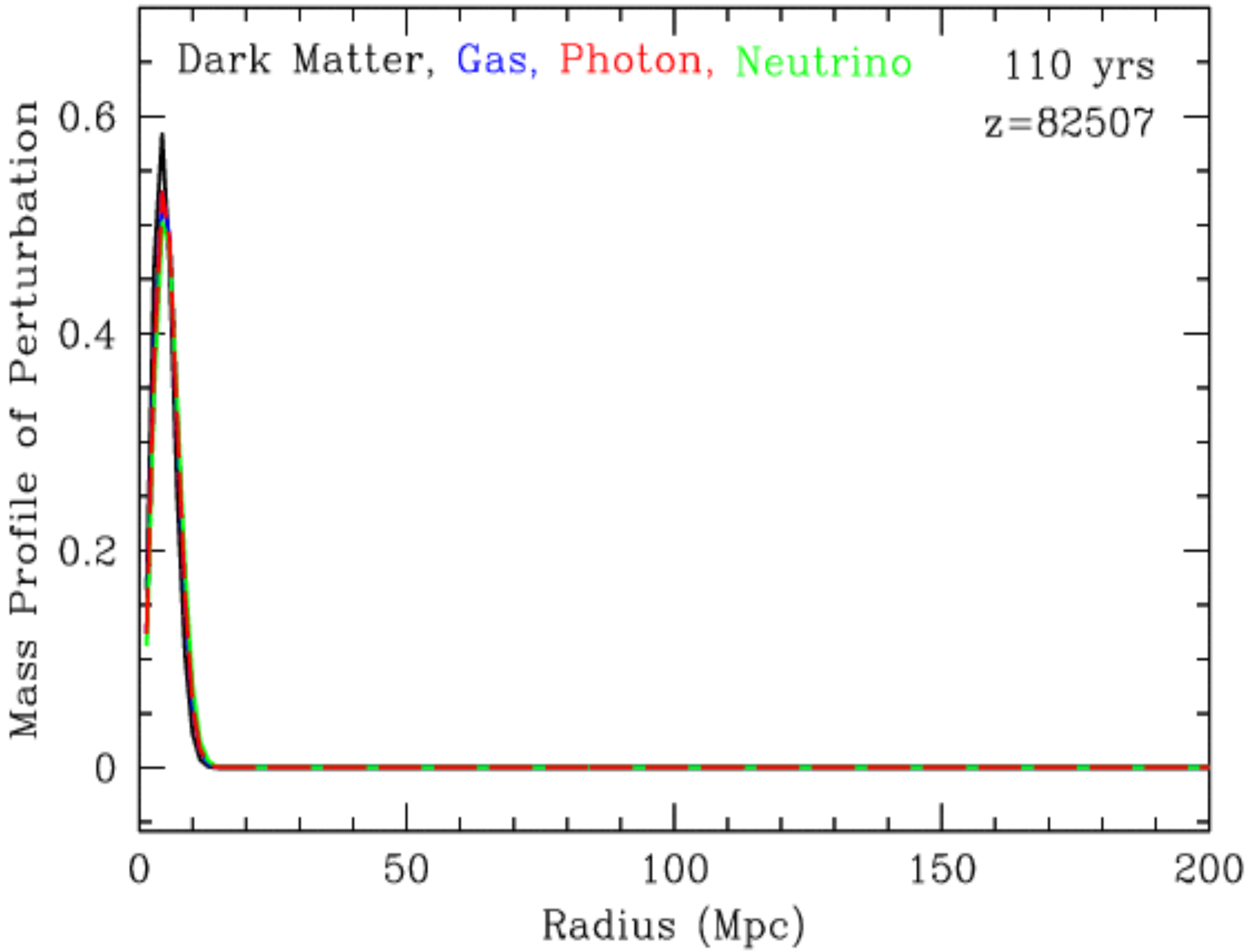




- Any fluctuation in the grav. potential which travels faster than the baryon-photon plasma can generate a phase shift (free streaming neutrinos $c_\nu > c_s \sim c/sqrt(3)$) (see Bashinsky & Seljak 2004).

- Both for CMB and BAO once the amplitude effects are fixed, we see a tiny phase shift as a fct of N_{eff} that we want to measure….

Neutrinos in BAO



Eisenstein et al.

- Free-streaming neutrinos overtake the photons, and pull them ahead of the sound horizon.

First observation with CMB

Follin, Knox et al. 2015

Two distinct N_{eff}:

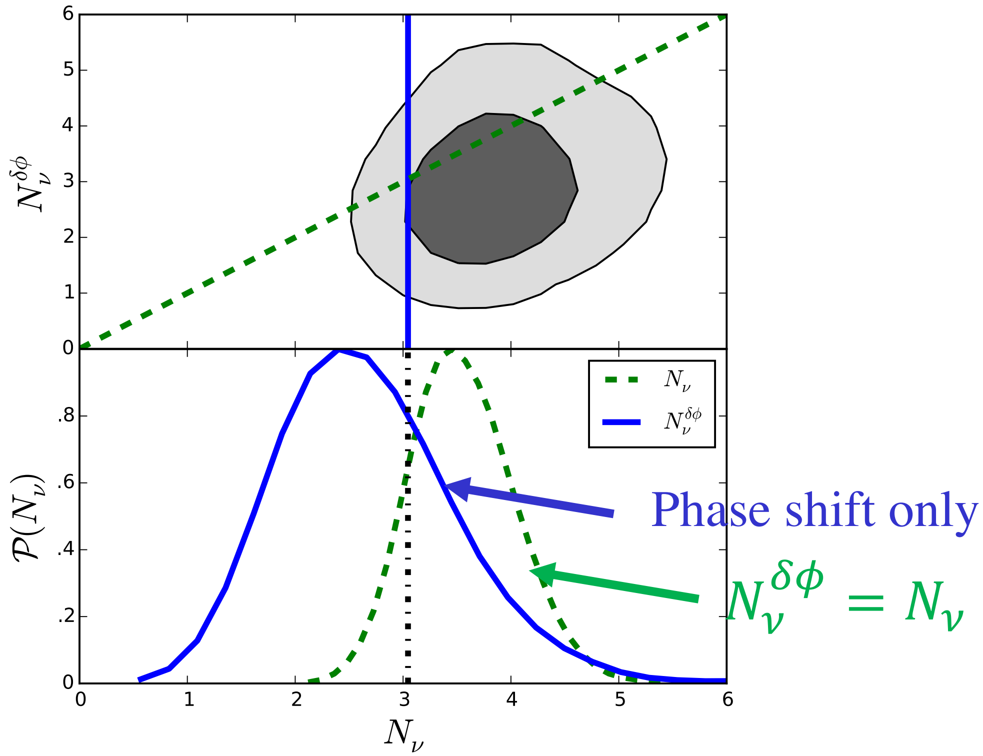
- N_ν sensitive to the wash out of the fluctuations
- $N_\nu^{\delta\phi}$ sensitive to the phase shift

Standard constraint on N_{eff}

$$N_\nu = 3.3^{+0.7}_{-0.2}$$

Constraint with phase shift on N_{eff}

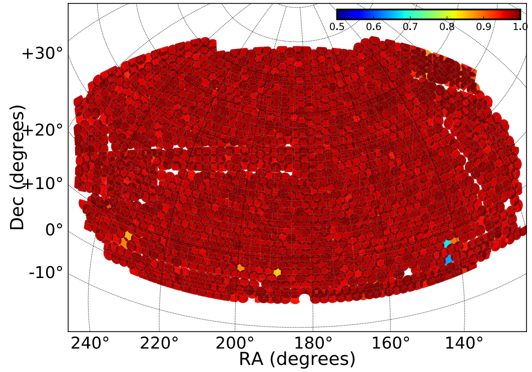
$$N_\nu^{\delta\phi} = 2.3^{+1.1}_{-0.4}$$

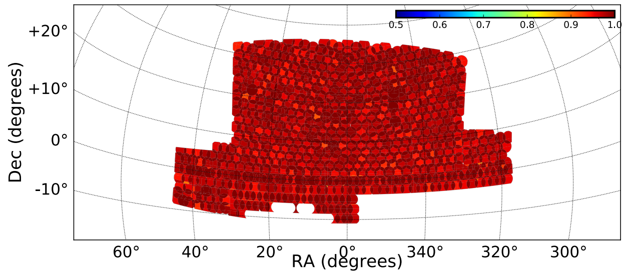


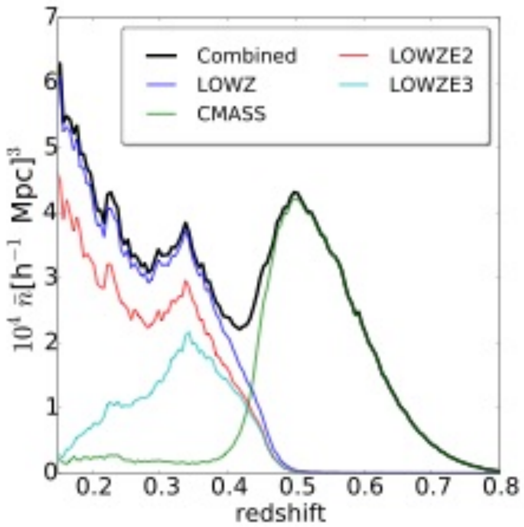
- **First observation of $N_\nu^{\delta\phi}$ in CMB with Planck 2013 at 4.5σ**

First measurement of Neutrinos in the BAO Spectrum

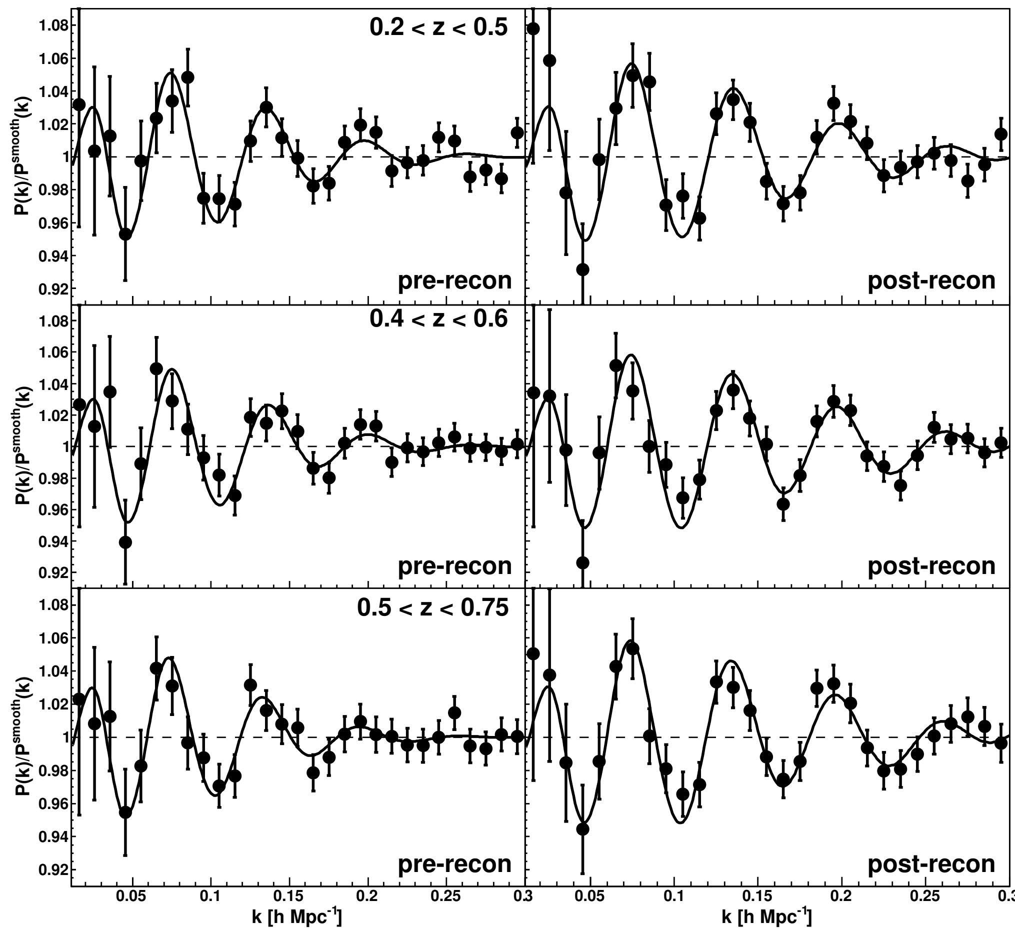
Data: BOSS DR12





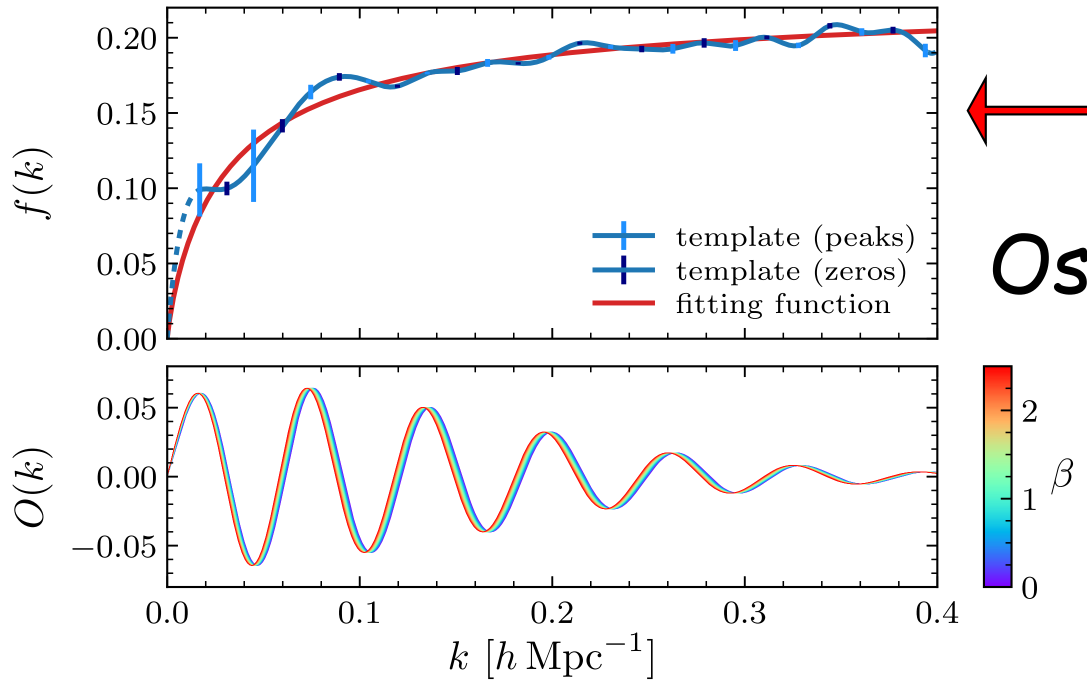


Beutler et al. 2017



- 1.2M LRGs
- Surface: ~10 000 deg^2
- 2 independent redshift bins

Phase shift and template

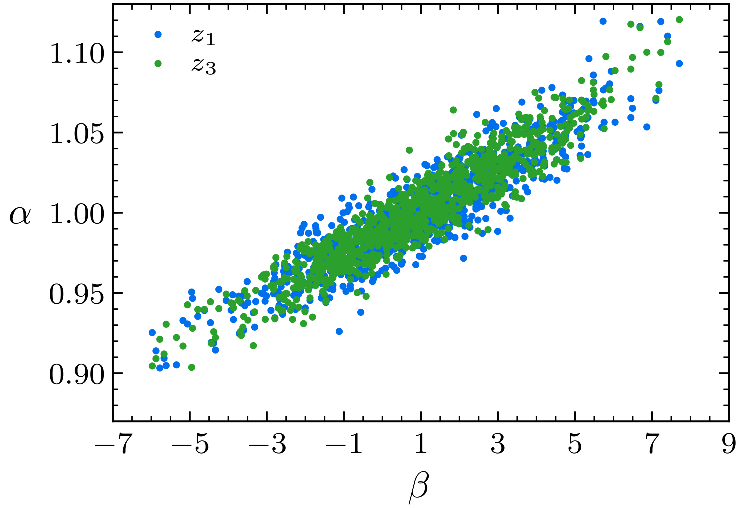


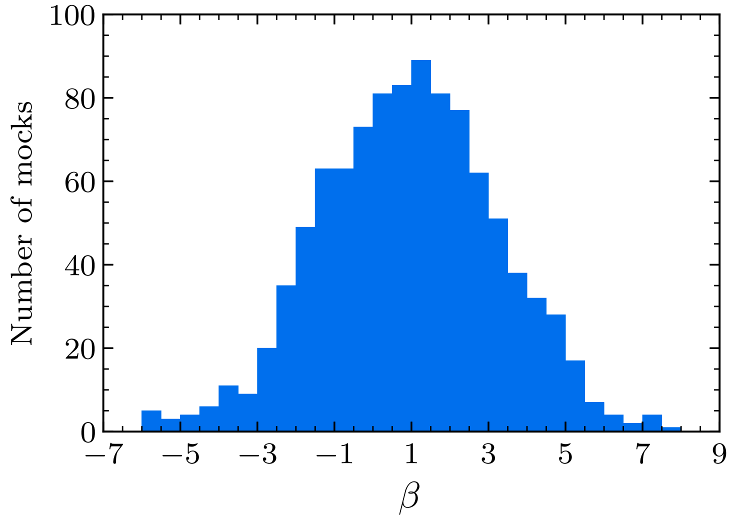
$\text{Oscil}(k/\alpha + (\beta-1) f(k)/r_s)$

- α : BAO scale. β : phase shift
  β simple function of N_{eff} , β = 0, 1 → N_{eff} = 0, 3.046

- Phase shift measured with CLASS :
  Slight dependence of β as a function of k (second order effect and well controlled)

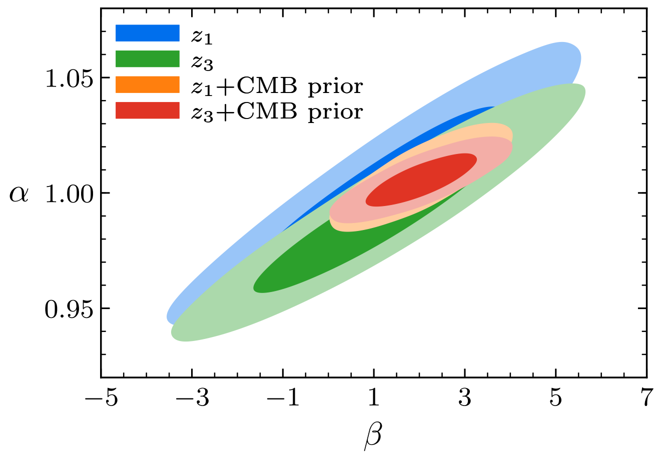
Validation with mocks

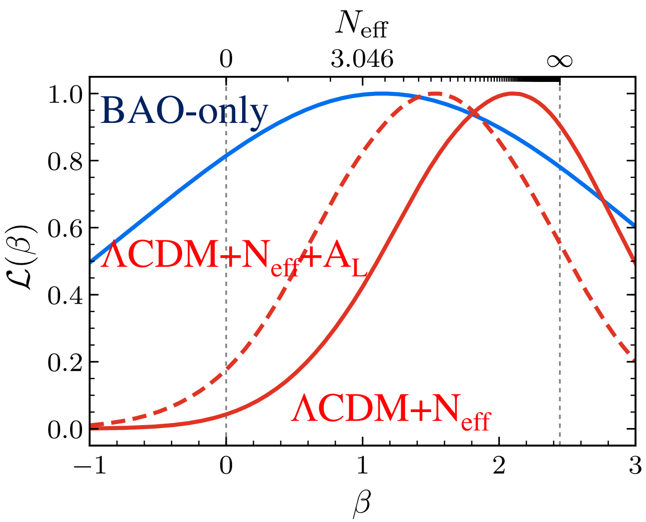




- 1000 MultiDark-patchy mocks - Two redshift bins
- α : BAO scale. β : phase shift
- Strong correlation between α and β
- No bias but large errors with BAO alone…
- Error on β is 2.3
- Need to introduce a prior on α to improve β constraint

Results





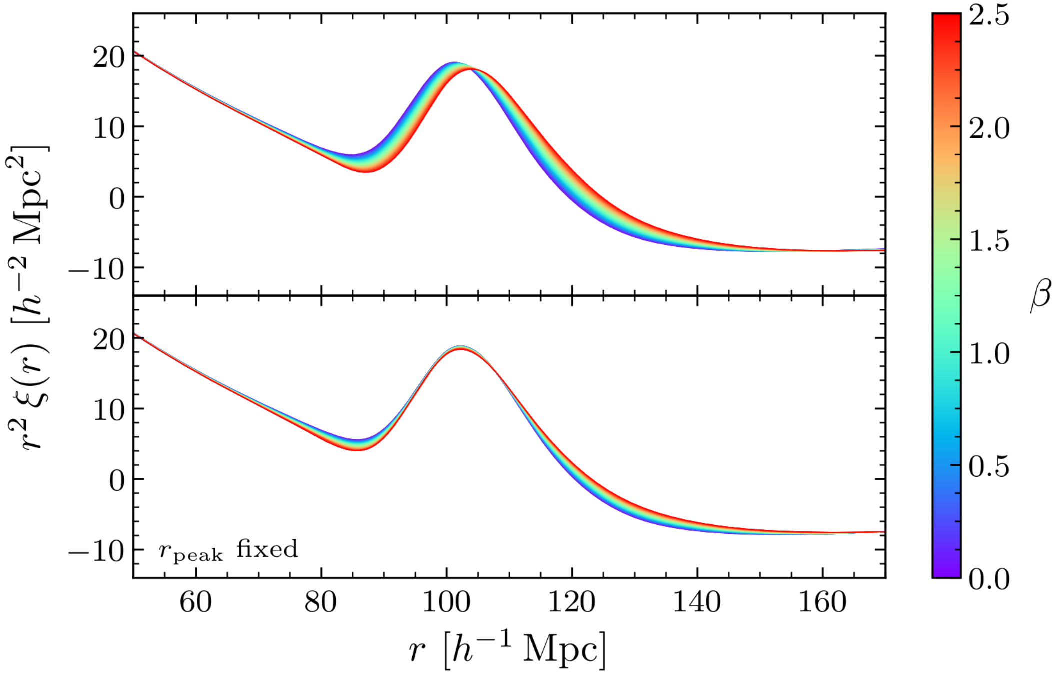
Prior Cosmology	β
None (BAO-only)	1.2 ± 1.8
ΛCDM+$N_{\rm eff}$	2.05 ± 0.81
ΛCDM	1.97 ± 0.73
ΛCDM+$N_{\rm eff}$ (TT-only)	1.6 ± 1.1
ΛCDM (TT-only)	1.87 ± 0.89
ΛCDM+$N_{\rm eff}$+A_L	1.53 ± 0.83
ΛCDM+A_L	1.49 ± 0.76

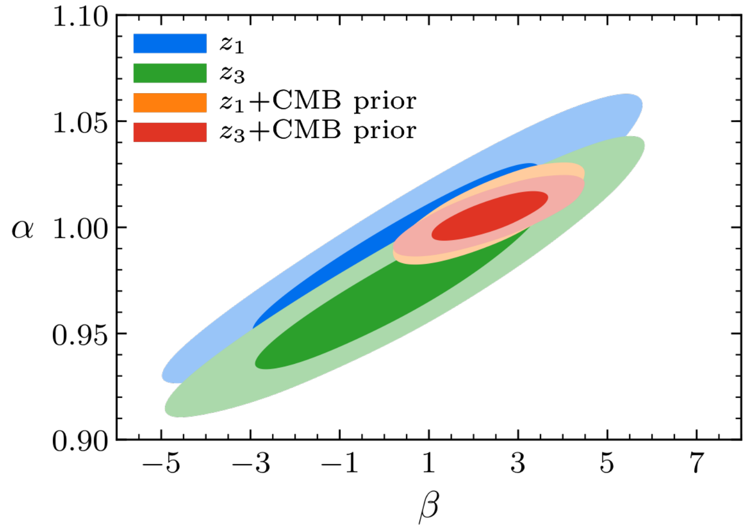
- Very loose constraint on β with BAO alone

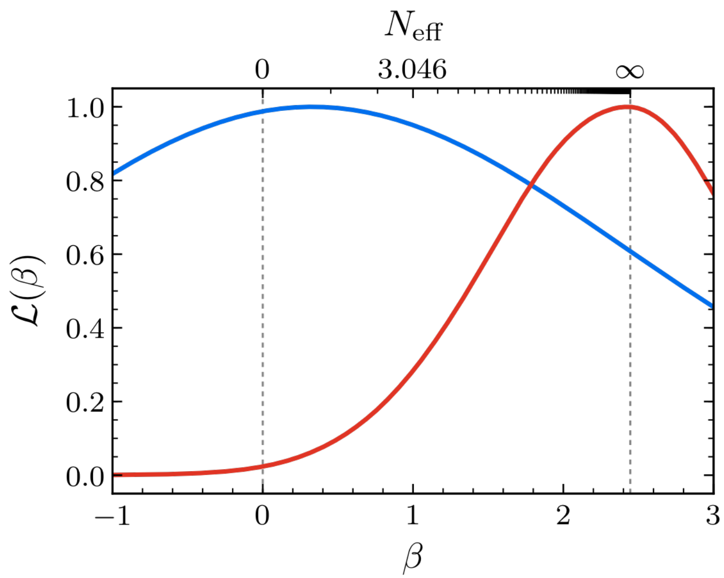
- By adding Planck, we constrain α and improve β
- To be conservative we combine with Planck (including correlations with N_{eff}) but without using Planck N_{eff} value

- β<0 (N_{eff} <0) is rejected at 95 C.L.
  $\rightarrow$ **First measurement of CνB in BAO**

Configuration space

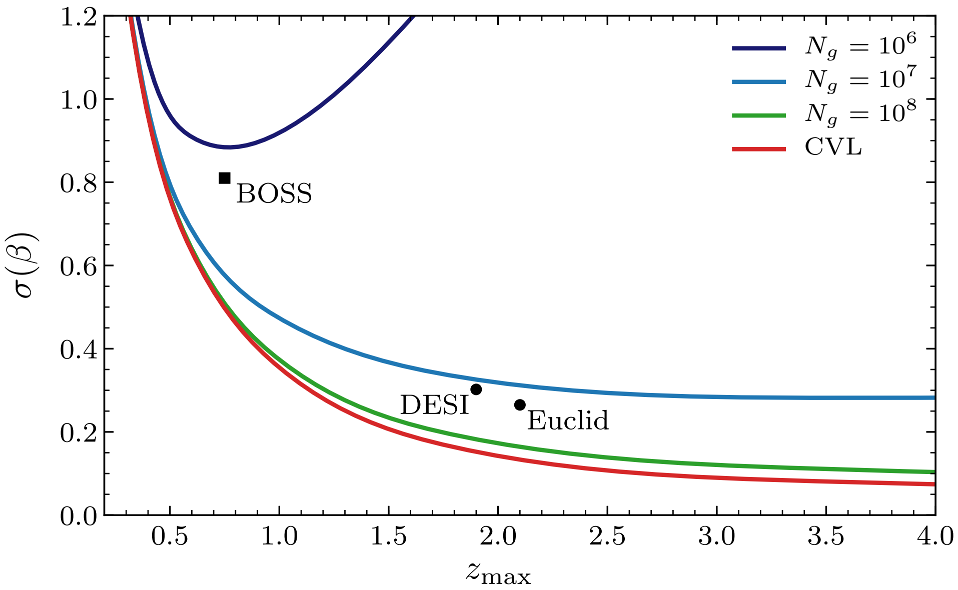






- ➢ Broadening of the BAO peak
- ➢ More difficult because of degeneracy with parameters describing the “broad band”
- ➢ Fairly good agreement

Summary and prospects



- This article is a proof of principle with real data

- Caveats: need a prior on α and to assume flat ΛCDM

- With DESI, higher redshift $\rightarrow$ higher k_{max} $\rightarrow$ more oscillations $\rightarrow$ break degeneracy between α and β alone

Additional Slides

Origin of the shift

2.1 Preliminaries

We will take the initial BAO power spectrum to be

$$P_{\rm in}^{\rm w}(k) = T^{\rm w}(k) P_{\rm in}^{\rm nw}(k)\,, \quad T^{\rm w}(k) \equiv A\Big[\sin(kr_s)\,\mathcal{D}_\alpha(k) + \beta\,\cos(kr_s)\,\mathcal{D}_\beta(k)\Big]\,, \tag{2.1}$$

where r_s is the BAO scale, A is a constant proportional to the baryon fraction $f_b \equiv \rho_b/\rho_m$ and $\mathcal{D}_{\alpha,\beta}(k)$ are envelope functions[5] that encode the damping of the oscillations on small scales. The superscripts 'w' and 'nw' stand for "wiggle" and "no-wiggle", respectively. The no-wiggle power spectrum, $P_{\rm in}^{\rm nw}(k)$, describes the initial conditions for the dark matter in the absence of baryons and the total power spectrum is $P_{\rm in}(k) = P_{\rm in}^{\rm w}(k) + P_{\rm in}^{\rm nw}(k)$. We will refer to the sine contribution in (2.1) as the "neutrinoless BAO feature" and the cosine contribution as the "phase shift". The parameter β determines the size of the initial phase shift, e.g. it is proportional to $N_{\rm eff}$ in a theory with extra relativistic species. We are especially interested in the behavior for $k \to \infty$ where the phase shift is a constant [13, 14]. The real-space correlation function is

$$\xi_{\rm in}^{\rm w}(r) = A\int \frac{k^2{\rm d}k}{2\pi^2}\,\frac{\sin(kr)}{kr}\,\Big[\sin(kr_s) + \beta\cos(kr_s)\Big]\,P_{\rm in}^{\rm nw}(k)\,. \tag{2.2}$$

The integration over modes with large momenta will be suppressed due to the rapidly oscillating integrand, unless $r \sim r_s$, in which case the oscillations cancel between $\sin(kr)$ and $\sin(kr_s)$ or $\cos(kr_s)$. To describe the limit $k \to \infty$, we are therefore led to consider the behavior of the correlation function near $r = r_s$.