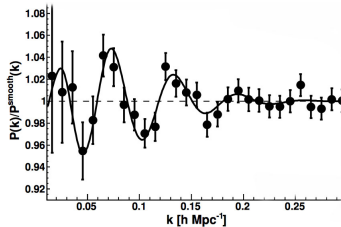


# Expanding the BAO science case

Florian Beutler



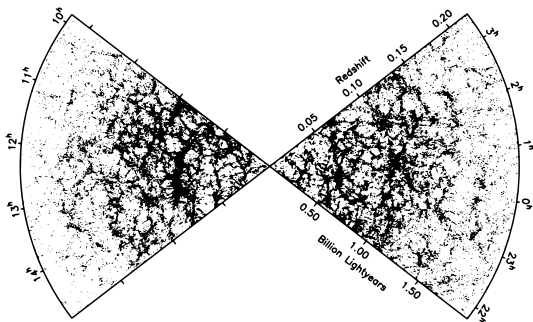
European Research Council  
Established by the European Commission



Royal Society University Research Fellow

- 1 Introduction
  - Galaxy redshift surveys
  - Baryon Acoustic Oscillations (BAO)
- 2 Testing inflation with primordial features (PRR, 1, 2019)
- 3 Neutrinos in the phase of the BAO (Nature Physics, 15, 465, 2019)

# What is a galaxy redshift survey?

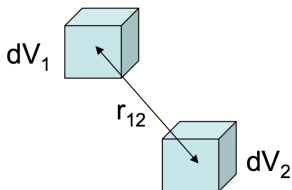


- Measure the position of galaxies (redshift + RA, DEC).
- The CMB tells us a lot about the initial conditions for today's distribution of matter.
- How the initial density fluctuations in the CMB evolved from redshift  $z \sim 1100$  to today depends on  $\Omega_m$ ,  $\Omega_\Lambda$ ,  $H_0$  etc.

# From a point distribution to a power spectrum

- Overdensity-field:

$$\delta(\mathbf{x}) = \frac{\rho(\mathbf{x}) - \bar{\rho}}{\bar{\rho}}$$



- Two-point function:

$$\xi(\mathbf{r}) = \langle \delta(\mathbf{x} + \mathbf{r})\delta(\mathbf{x}) \rangle \begin{cases} \text{homogeneity} \\ \text{isotropy} \\ \text{anisotropy} \end{cases} \left\{ \begin{array}{l} \xi(r) \\ \xi_\ell(r) = \int_{-1}^1 d\mu \xi(r, \mu) \mathcal{L}_\ell(\mu) \end{array} \right.$$

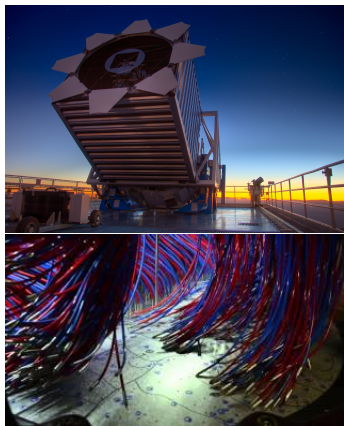
- ...and in Fourier-space:

$$P_\ell(k) = 4\pi(-i)^\ell \int r^2 dr \xi_\ell(r) j_\ell(kr)$$



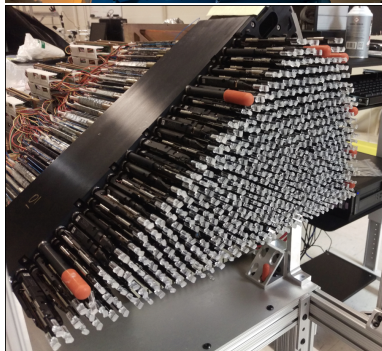
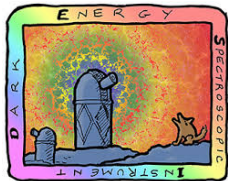
# The BOSS galaxy survey (the past)

- Third version of the Sloan Digital Sky Survey (SDSS-III)
- Spectroscopic survey optimized for the measurement of Baryon Acoustic Oscillations (BAO)
- The galaxy sample includes 1 100 000 galaxy redshifts in the range  $0.2 < z < 0.75$
- The effective volume is  $\sim 6 \text{ Gpc}^3$
- 1000 fibres/redshifts per pointing



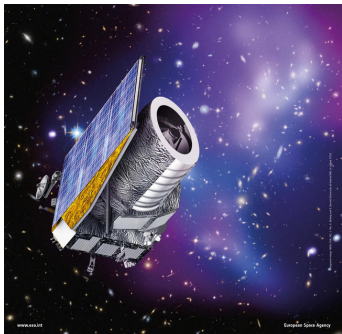
# The DESI galaxy survey (the future)

- Mayall 4m telescope at Kitt Peak, Arizona
- 5000 fibres/pointing
- Will observe 3 types of galaxies (LRGs/ELGs/QSOs) + BGS
- 30 - 40 million galaxies in total
- $z < 1.8$  with galaxies and  $z < 3.5$  with Ly- $\alpha$  forest



# The ESA Euclid mission (the future)

- Launch scheduled for the end of 2022 → L2 point
- Space-based weak lensing + gal. clustering survey over 15 000 deg<sup>2</sup>
- 30 million emission line galaxies over the redshift range 0.7 to 2.0
- Slitless spectroscopy (grism)



# What are Baryon Acoustic Oscillations?

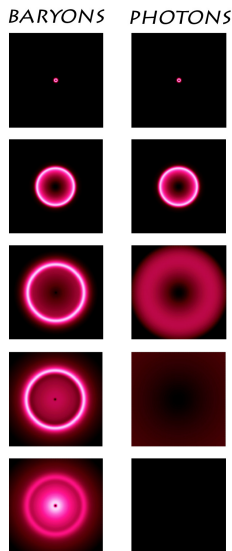
- For the first 380 000 years the evolution eq. of baryon and photon perturbations can be written as

$$\ddot{\delta}_{b\gamma} - c_s^2 \nabla^2 \delta_{b\gamma} = \nabla^2 \Phi$$

with the plane wave solution

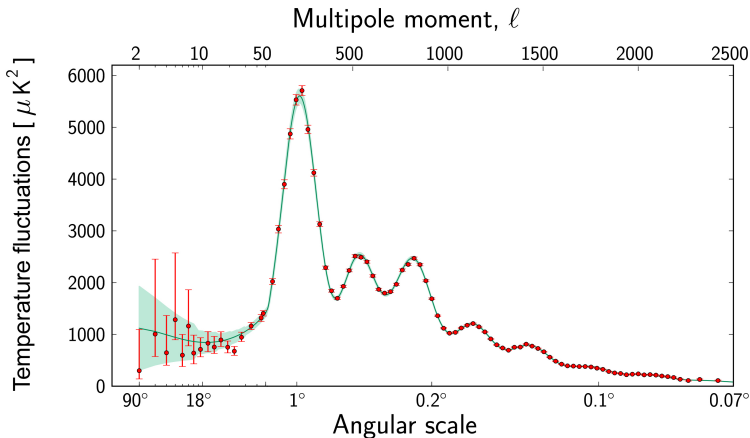
$$\delta_{b\gamma} = A \cos(kr_s + \phi)$$

- Preferred distance scale between galaxies as a relic of sound waves in the early Universe.
- This signal is present at low redshift and detectable in  $\xi(r)/P(k)$  **on very large scales.**



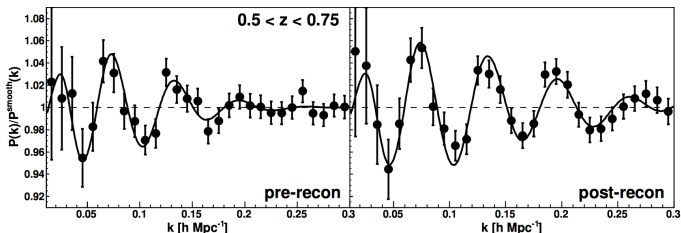
credit: Martin White

# What are Baryon Acoustic Oscillations?



$$r_s(z_d) = 147.34 \pm 0.64 \text{ Mpc} \quad (0.43\%)$$

# Baryon Acoustic Oscillations in BOSS



$$D_V(z = 0.38) r_s^{\text{fid}} / r_s = 1476 \pm 15 \text{ Mpc} \quad (1.0\%)$$

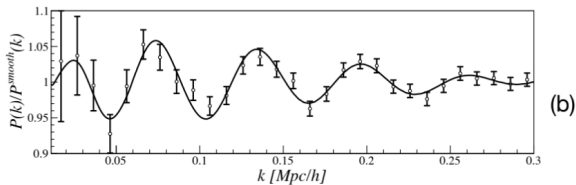
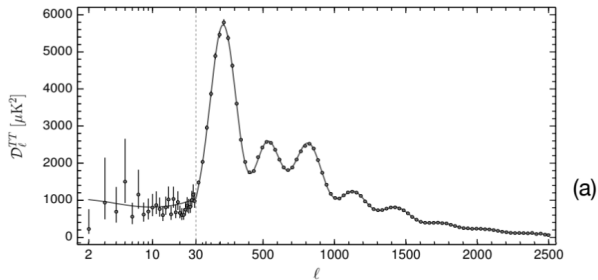
$$D_V(z = 0.61) r_s^{\text{fid}} / r_s = 2146 \pm 19 \text{ Mpc} \quad (0.9\%)$$

$$D_V(z) = \left[ (1+z)^2 D_A^2(z) \frac{cz}{H(z)} \right]^{1/3}$$

$$D_A(z) = \frac{c}{(1+z)} \int_0^z \frac{dz'}{H(z')}$$

$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda + \dots}$$

# Baryon Acoustic Oscillations in BOSS



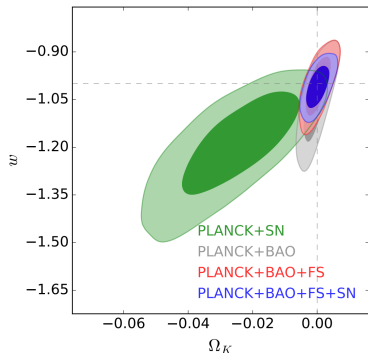
# Baryon Acoustic Oscillations in BOSS

- The BAO signal is located on very large scales and can be captured (mostly) with a linear model.
- In BOSS we used an agnostic broadband marginalisation using a set of polynomial terms and density field reconstruction to boost the signal.
- Due to BAO we now know the distance to  $z = 0.38$  and  $z = 0.61$  with  $\sim 1\%$  uncertainty... **better than our knowledge of  $H_0$ .**



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Alam et al. (2017)

Planck+SN:

$$\Omega_k = 0.025 \pm 0.012$$

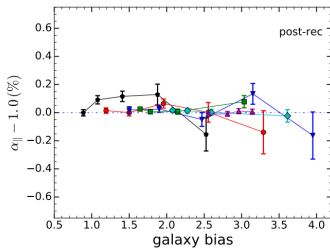
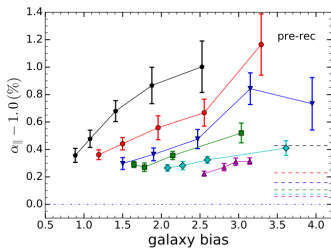
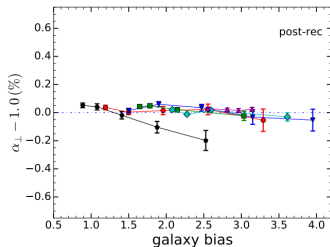
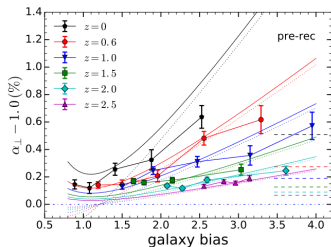
$$w = -1.01 \pm 0.11$$

Planck+SN+BAO:

$$\Omega_k = 0.0003 \pm 0.0027$$

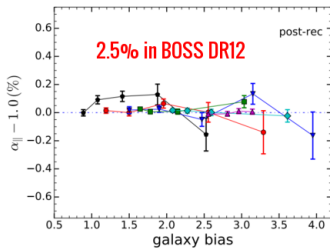
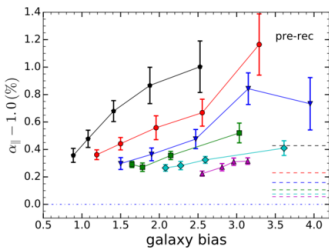
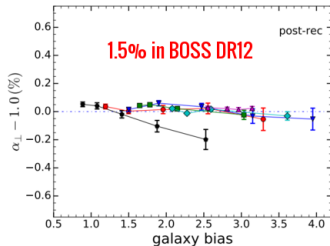
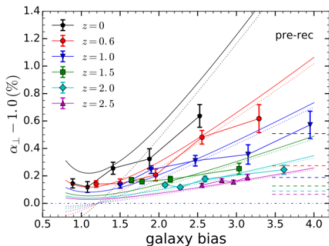
$$w = -1.05 \pm 0.08$$

# Theoretical systematics of BAO



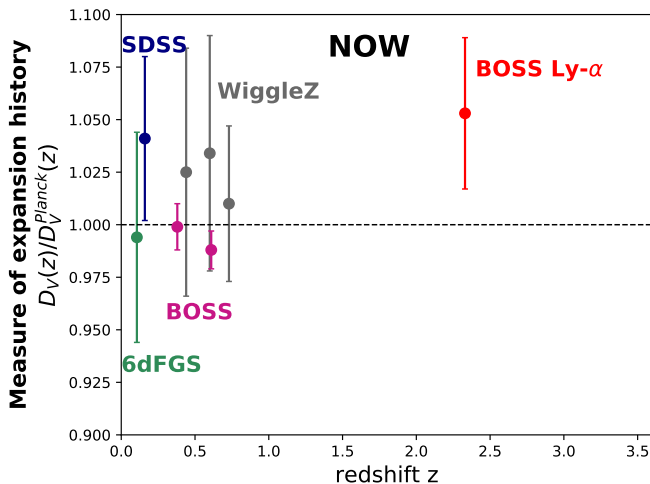
Ding et al. (2018)

# Theoretical systematics of BAO



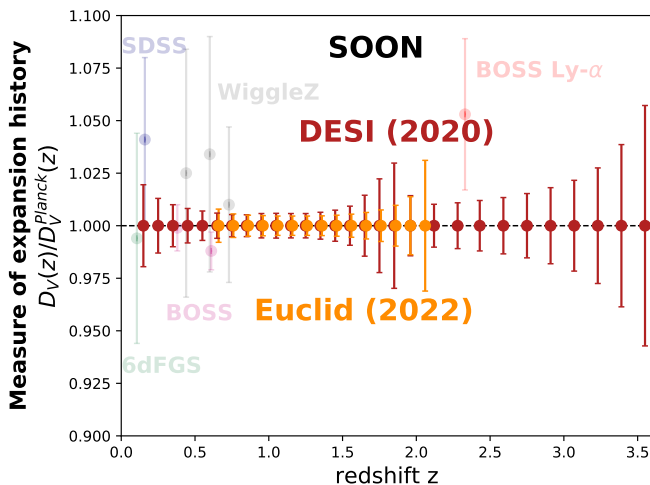
Ding et al. (2018)

# Looking into the (near) future



$$D_V(z) = \left[ (1+z)^2 D_A^2(z) \frac{cz}{H(z)} \right]^{1/3}$$

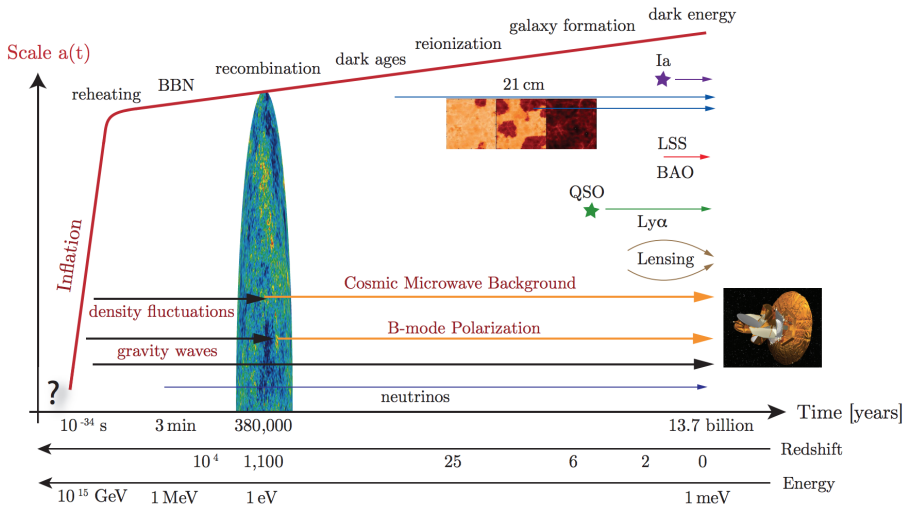
# Looking into the (near) future



$$D_V(z) = \left[ (1+z)^2 D_A^2(z) \frac{cz}{H(z)} \right]^{1/3}$$

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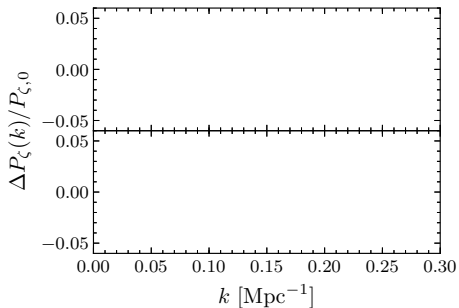
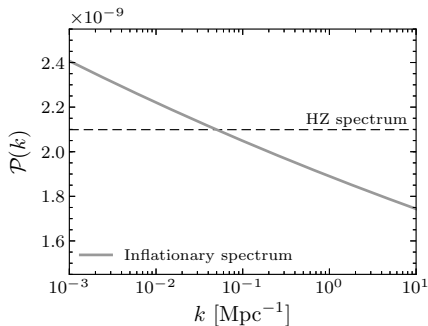
# Inflation in one plot



Baumann (2009)

# Testing inflation through primordial features

## No features

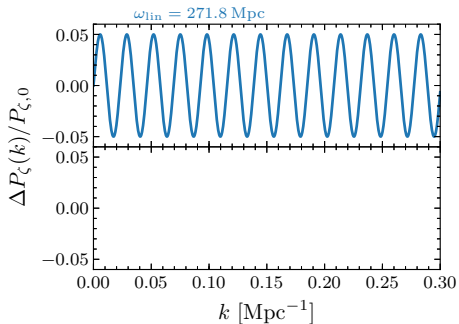
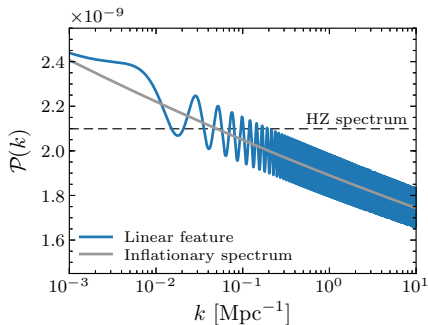


$$P_{\zeta,0}(k) = \frac{2\pi^2}{k^3} \mathcal{P}_{\zeta,0}(k) = \frac{2\pi^2 A_s}{k^3} \left( \frac{k}{k_*} \right)^{n_s-1}$$



# Testing inflation through primordial features

## Linear features

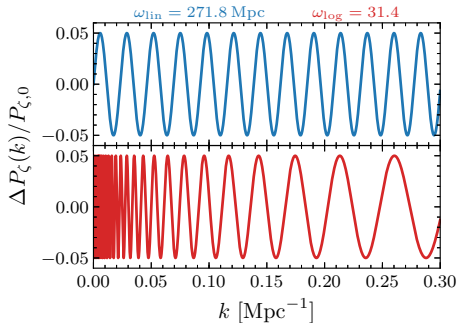
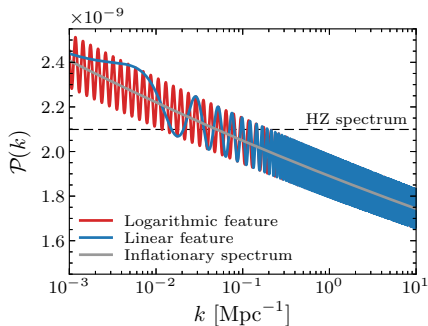


$$\frac{\Delta P_{\zeta}(k)}{P_{\zeta,0}(k)} = A_{\text{lin}} \sin(\omega_{\text{lin}} k + \phi_{\text{lin}})$$

[Sharp Features]  
Starobinsky (1992)  
Adams, Cresswell & Easther (1997)  
...

# Testing inflation through primordial features

## Logarithmic features



$$\frac{\Delta P_{\zeta}(k)}{P_{\zeta,0}(k)} = A_{\text{log}} \sin(\omega_{\text{log}} \log(k/k_*) + \phi_{\text{log}})$$

[Resonant features]

Chen, Easter & Lim (2008)

Silverstein & Westphal (2008)

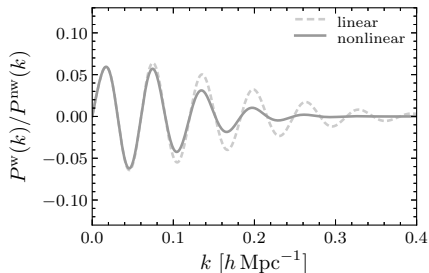
Flauger, McAllister, Pajer & Westphal (2010)

...

## Linear Feature

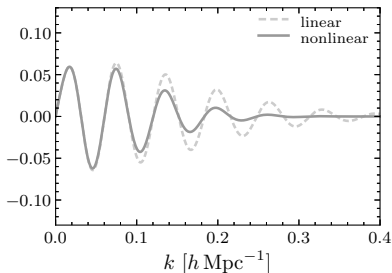
- Damping factor of linear features equal to BAO damping for  $\omega_{\text{lin}} \gtrsim 75 \text{ Mpc}$

$$P(k) = P^{\text{nw}}(k) + e^{-k^2 \Sigma_{\text{nl}}^2 / 2} \left[ P_{\text{BAO}}^{\text{w}}(k/\alpha) \right]$$



## Logarithmic Feature

- Damping factor of log features approx. equal to BAO damping for  $\omega_{\text{log}} \gtrsim 10$



# Feature damping

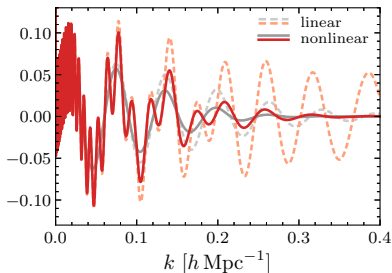
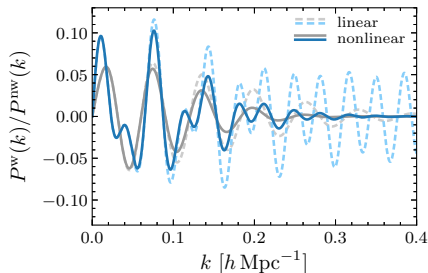
## Linear Feature

- Damping factor of linear features equal to BAO damping for  $\omega_{\text{lin}} \gtrsim 75 \text{ Mpc}$

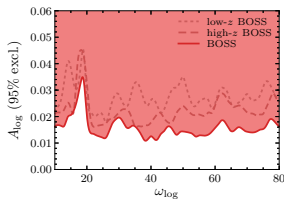
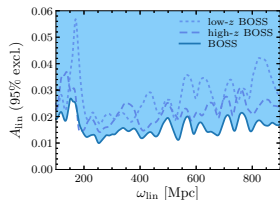
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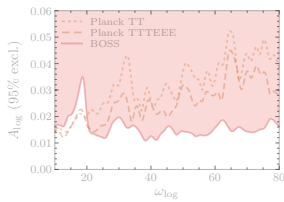
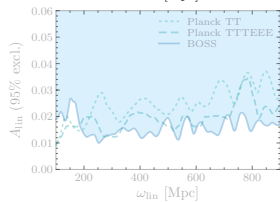
$$P(k) = P^{\text{nw}}(k) + e^{-k^2 \Sigma_{\text{nl}}^2 / 2} \left[ P_{\text{BAO}}^{\text{w}}(k/\alpha) + P_{\text{lin,log}}^{\text{w}}(k) + P_{\text{BAO}}^{\text{w}}(k/\alpha) \delta P_{\zeta}^{\text{lin,log}}(k) \right]$$



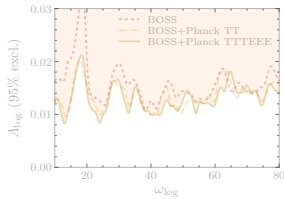
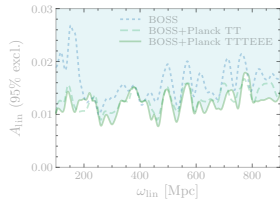
# Feature constraints from BOSS DR12 and Planck



BOSS

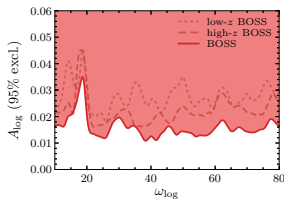
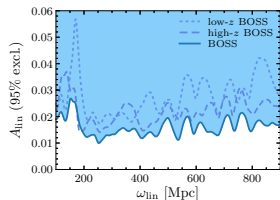


BOSS vs. Planck

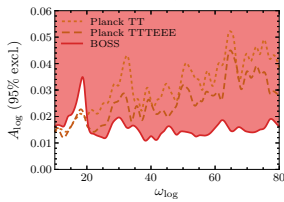
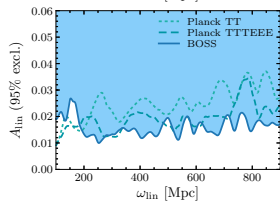


BOSS + Planck

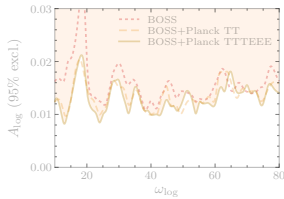
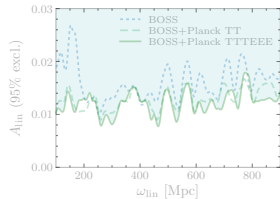
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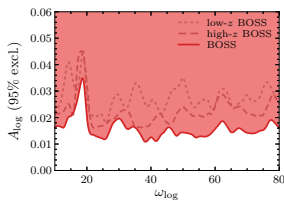
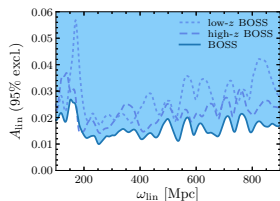


BOSS vs. Planck

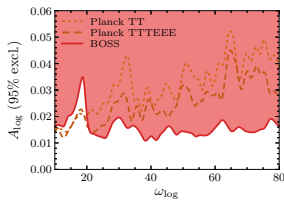
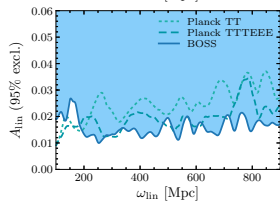


BOSS + Planck

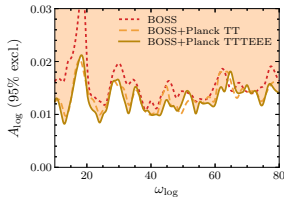
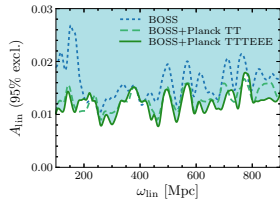
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BOSS

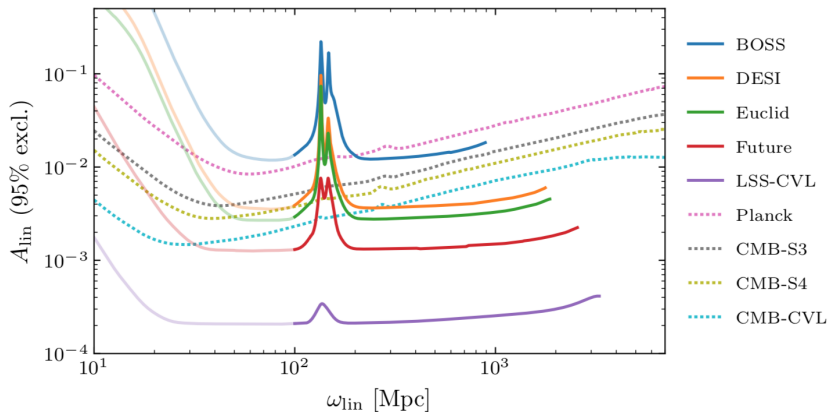


BOSS vs. Planck



BOSS + Planck

# Forecasts for primordial feature constraints



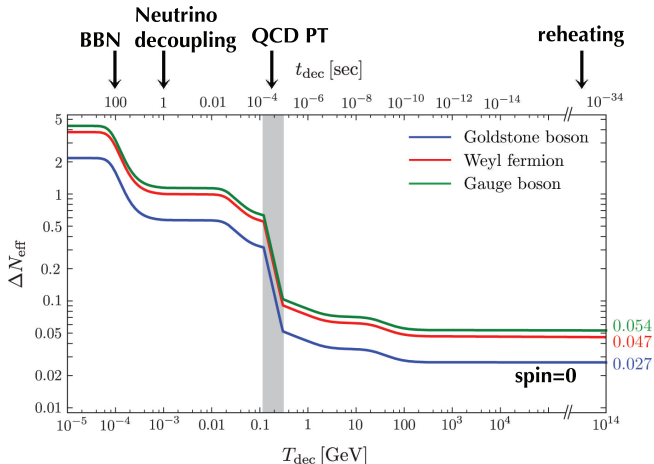
→ LSS dominates on small frequencies, while the CMB can access higher frequencies

→ DESI/Euclid are going to beat even CVL-CMB experiments



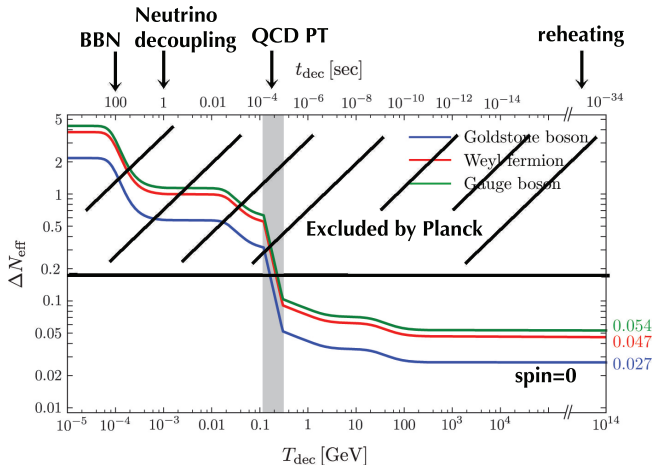
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# Motivation: Neutrinos in the phase of the BAO



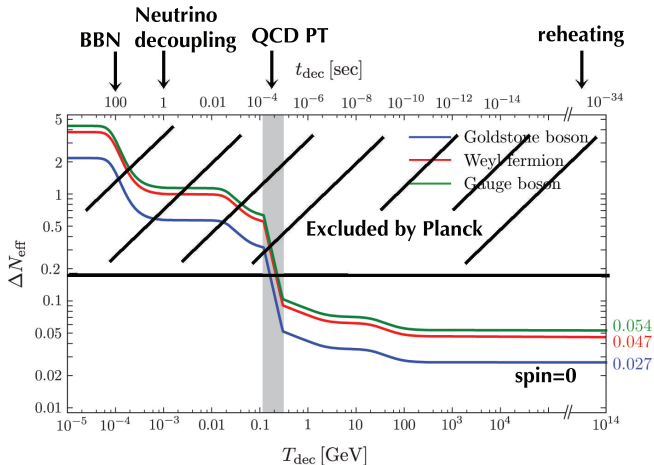
$$\rho_r = \left[ 1 + \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} N_{\text{eff}} \right] \rho_\gamma$$

# Motivation: Neutrinos in the phase of the BAO



$$N_{\text{eff}} = 3.04 \pm 0.18 \quad (\text{Planck})$$

# Motivation: Neutrinos in the phase of the BAO

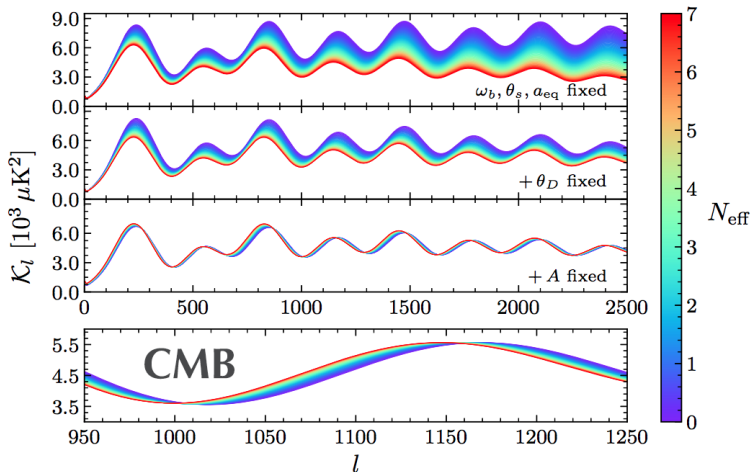


$$\sigma(N_{\text{eff}}) = 0.030 \quad (\text{CMB-S4})$$

$$\sigma(N_{\text{eff}}) = 0.027 \quad (\text{CMB-S4 + Euclid})$$

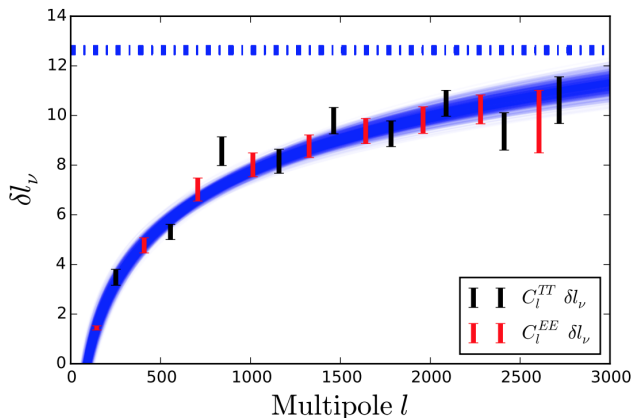
# Neutrinos in the CMB Spectrum

Current constraints are dominated by the damping of the power spectrum (degenerate with helium fraction).



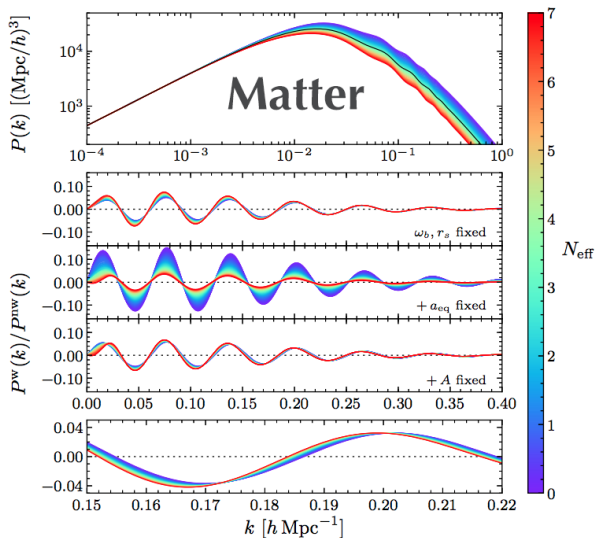
# Phase shift detection in the CMB

The Phase shift has recently been detected in the temperature and polarisation CMB spectrum.



$$N_{\text{eff}} = 2.8^{+1.1}_{-0.4}$$

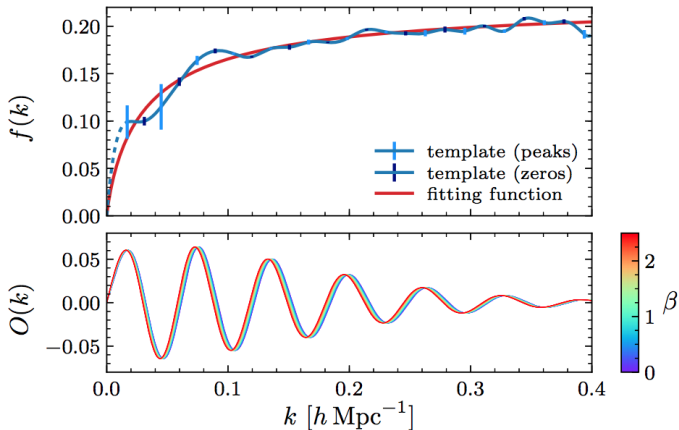
# Neutrinos in the BAO Spectrum



Baumann et al. (2017)

# Neutrinos in the BAO Spectrum

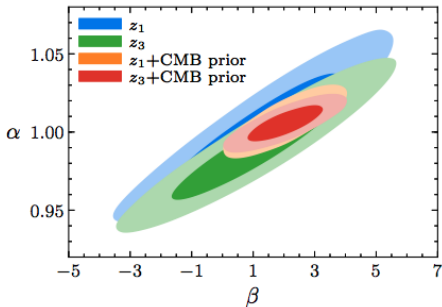
$$O(k) = O_{\text{lin}}(k/\alpha + (\beta - 1)f(k)/r_s^{\text{fid}})e^{-k^2\sigma_{\text{nl}}^2/2}$$





# Neutrinos in the BAO Spectrum

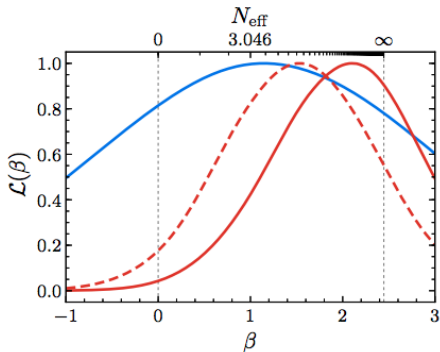
$$O(k) = O_{\text{lin}}(k/\alpha + (\beta - 1)f(k)/r_s^{\text{fid}})e^{-k^2\sigma_{\text{nl}}^2/2}$$



$$\beta(N_{\text{eff}}) = \frac{\epsilon}{\epsilon_{\text{fid}}}$$

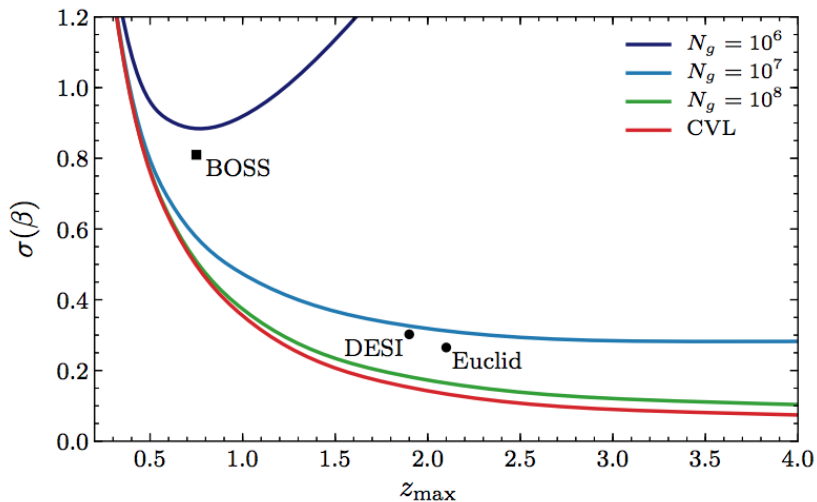
with

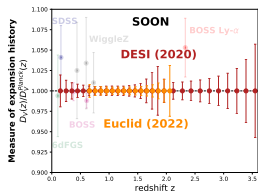
$$\epsilon = \frac{N_{\text{eff}}}{8(11/4)^{4/3}/7 + N_{\text{eff}}}$$



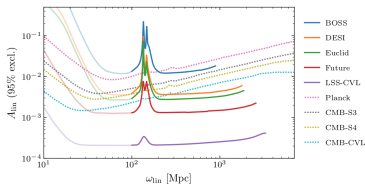
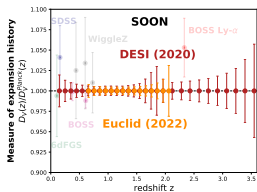
→ Proof of principle!

# Neutrinos in the BAO Spectrum

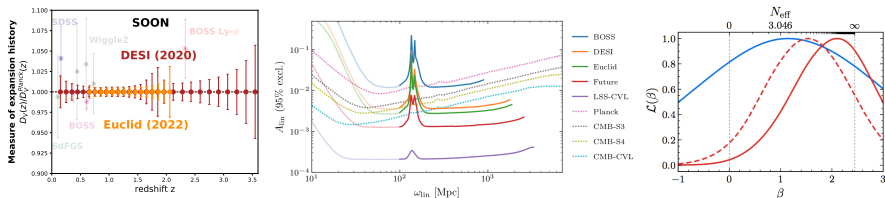




- 1 The next generation of galaxy redshift surveys is just around the corner → with **BAO** as a key science case

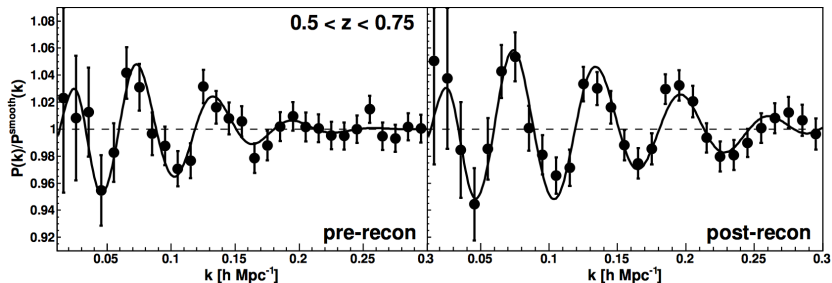


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- 2 The BAO analysis pipeline is **perfectly suited to extract primordial features** to test inflation
- 3 Constraints on primordial features from LSS are **already better than Planck** for a large frequency range



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- 3 Constraints on primordial features from LSS are **already better than Planck** for a large frequency range
- 4 The **phase of the BAO** carries information on  $N_{\text{eff}}$  just as in the CMB  $\rightarrow$  **first (low significance) detection in BOSS**

# Baryon Acoustic Oscillations in BOSS



$$D_A(z) \propto \int_0^z \frac{cdz'}{H(z')}$$
$$H(z) = H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda + \Omega_k(1+z)^2}$$
$$D_V(z) = \left[ (1+z)^2 D_A^2(z) \frac{cz}{H(z)} \right]^{1/3}$$

- Start with linear  $P(k)$  and separate the broadband shape,  $P^{\text{sm}}(k)$ , and the BAO feature  $O^{\text{lin}}(k)$ . Include a damping of the BAO feature:

$$P^{\text{sm,lin}}(k) = P^{\text{sm}}(k) \left[ 1 + (O^{\text{lin}}(k/\alpha) - 1)e^{-k^2 \Sigma_{\text{nl}}^2/2} \right]$$

- Add broadband nuisance terms

$$A(k) = a_1 k + a_2 + \frac{a_3}{k} + \frac{a_4}{k^2} + \frac{a_5}{k^3}$$
$$P^{\text{fit}}(k) = B^2 P^{\text{sm,lin}}(k/\alpha) + A(k)$$

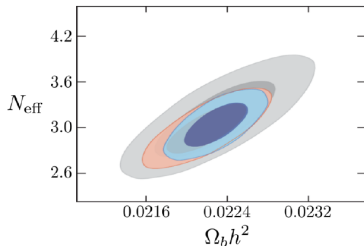
- Marginalize to get  $\mathcal{L}(\alpha)$ .

# Current constraints on $N_{\text{eff}}$

Relic neutrinos make up 41% of the radiation density

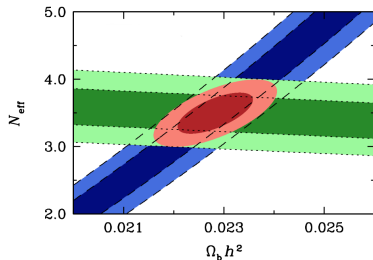
$$\rho_r = \left[ 1 + \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} N_{\text{eff}} \right] \rho_\gamma$$

CMB



$$N_{\text{eff}}^{\text{CMB}} = 3.04 \pm 0.18$$

BBN



$$N_{\text{eff}}^{\text{BBN}} = 3.28 \pm 0.28$$



# Impact of the window function for features search

