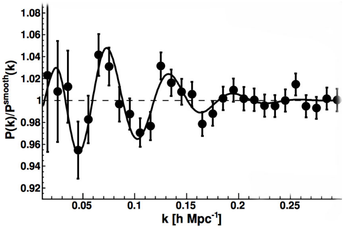
Expanding the BAO science case

Florian Beutler

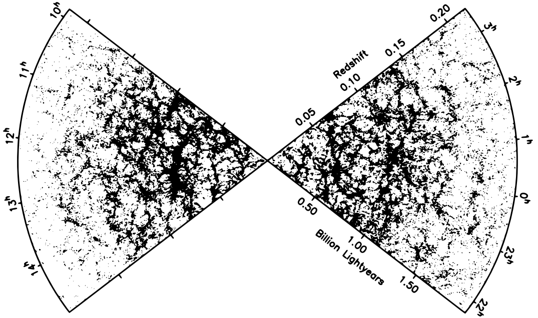


Royal Society University Research Fellow

Outline of the talk

1. General introduction to galaxy redshift surveys & BAO
2. Testing inflation with primordial features (**arXiv:1906.08758**)
3. Neutrinos in the phase of the BAO (**arXiv:1803.10741**)

What is a galaxy redshift survey?

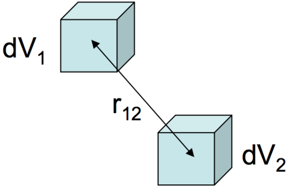


- Measure the position of galaxies (redshift + RA, DEC).
- The CMB tells us a lot about the initial conditions for today's distribution of matter.
- How the initial density fluctuations in the CMB evolved from redshift $z \sim 1100$ to today depends on Ω_m, Ω_Λ, H_0 etc.

From a point distribution to a power spectrum

- Overdensity-field:

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



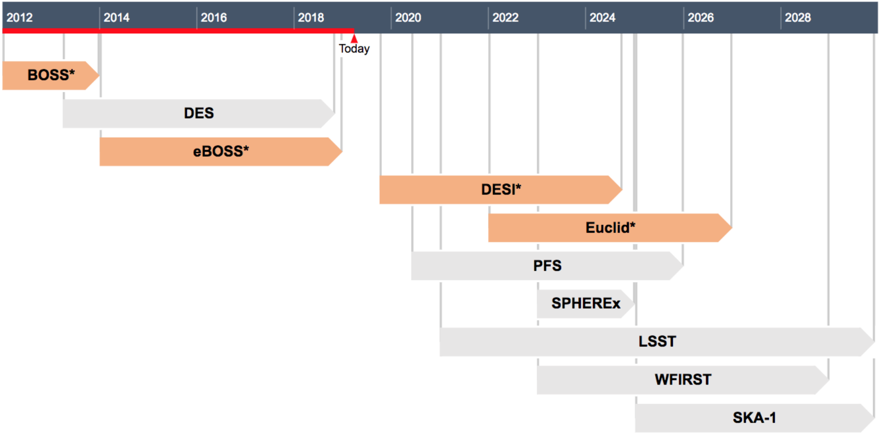
- Two-point function:

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

- ...and in Fourier-space:

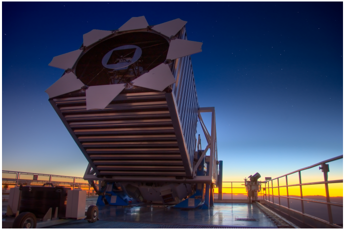
$$\boxed{P_\ell(k) = 4\pi(-i)^\ell \int r^2 dr\, \xi_\ell(r) j_\ell(kr)}$$

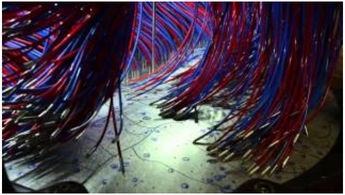
Why should you care?



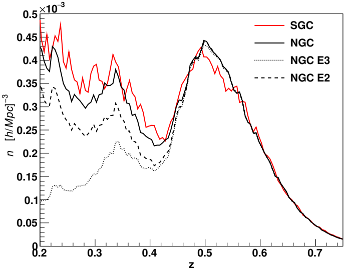
The BOSS galaxy survey

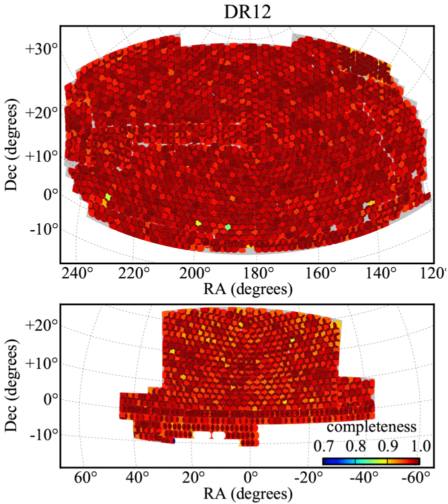
- Third version of the Sloan Digital Sky Survey (SDSS-III)
- Spectroscopic survey optimized for the measurement of Baryon Acoustic Oscillations (BAO)
- The galaxy sample includes 1 100 000 galaxy redshifts in the range $0.2 < z < 0.75$
- The effective volume is $\sim 6\,\mathrm{Gpc}^3$
- 1000 fibres/redshifts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





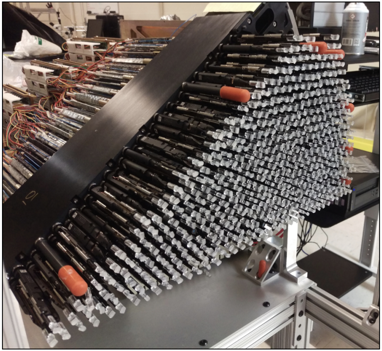
- The final data release (DR12) covers about 10 000 deg^2
- The survey is divided in a north galactic patch (NGC) and a south galactic patch (SGC).





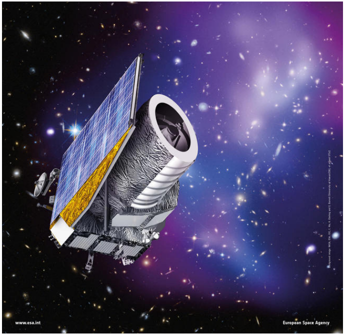
The DESI galaxy survey

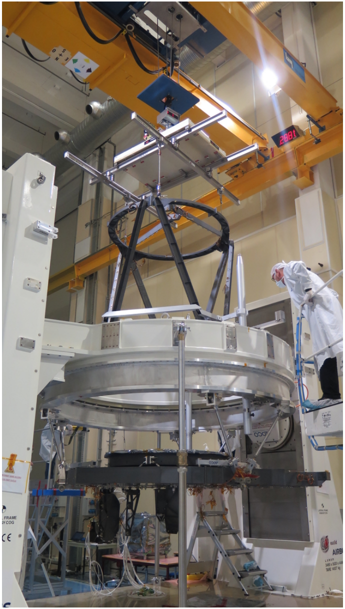
- Mayall 4m telescope at Kitt Peak, Arisona
- 5000 fibres/pointing
- Will observe 3 types of galaxies (LRGs/ELGs/QSOs) + BGS
- 30 - 40 million galaxies in total
- z < 1.8 with galaxies and z < 3.5 with Ly-α forrest



The ESA Euclid mission

- Launch scheduled for summer 2022 $\rightarrow$ L2 point
- Space-based weak lensing + gal. clustering survey over 15 000 deg^2
- 30 million emission line galaxies over the redshift range 0.7 to 2.0
- Slitless spectroscopy (grism)





What are Baryon Acoustic Oscillations?

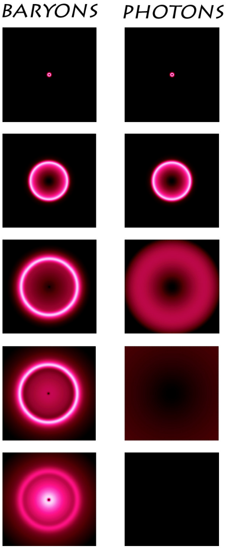
- For the first 380 000 years the evolution eq. of baryon and photon perturbations can be written as

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

with the plane wave solution

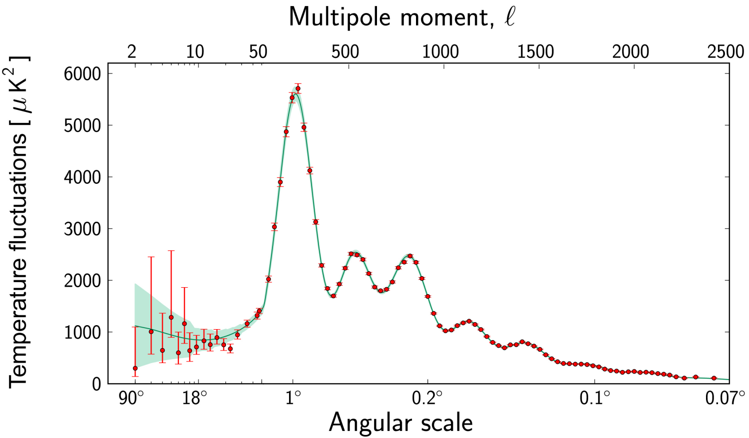
$$\delta_{b\gamma} = A\cos(kr_s + \phi)$$

- 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?

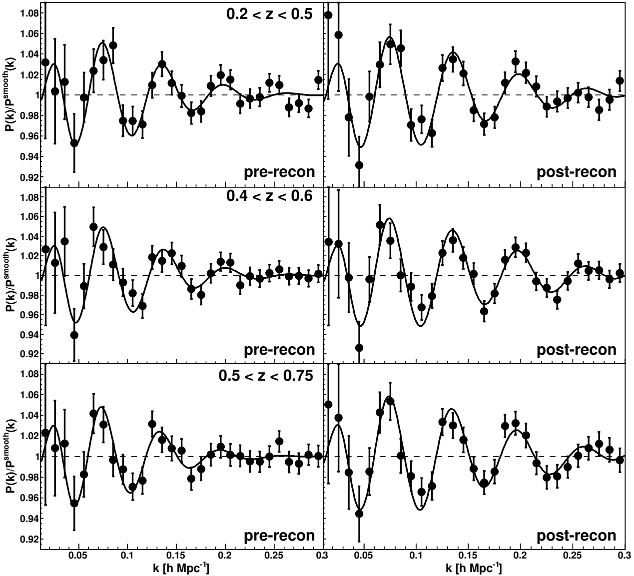


$$r_s(z_*) = 144.75 \pm 0.66\,\text{Mpc} \quad (0.46\%)$$

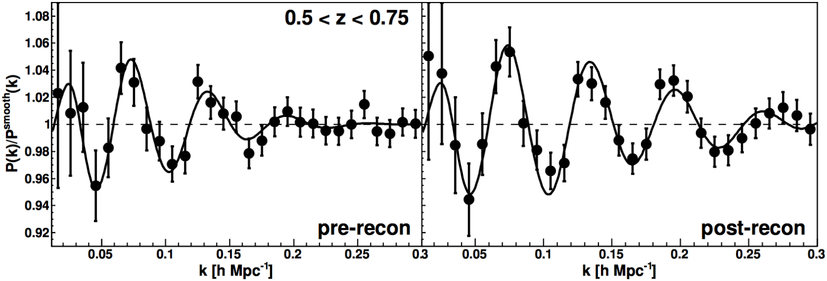
$$r_s(z_d) = 147.34 \pm 0.64\,\text{Mpc} \quad (0.43\%)$$

Planck collaboration

Baryon Acoustic Oscillations in BOSS



Beutler et al. (2017)



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

$$H(z) = H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda + \Omega_k(1+z)^2}$$

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

Beutler et al. (2017)

Fitting the BAO

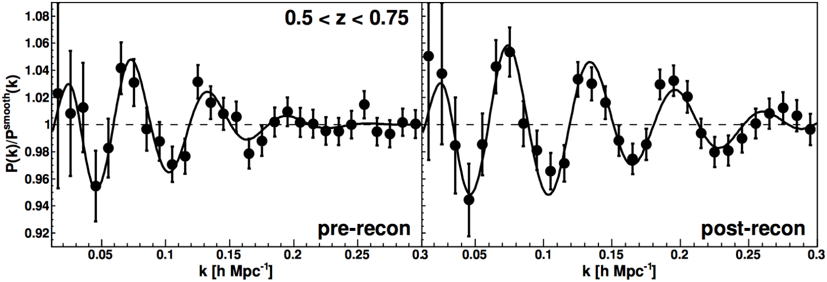
- Start with linear $P(k)$ and separate the broadband shape, $P^{\rm sm}(k)$, and the BAO feature $O^{\rm lin}(k)$. Include a damping of the BAO feature:

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

- Add broadband nuisance terms

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

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



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

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

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

Beutler et al. (2017)

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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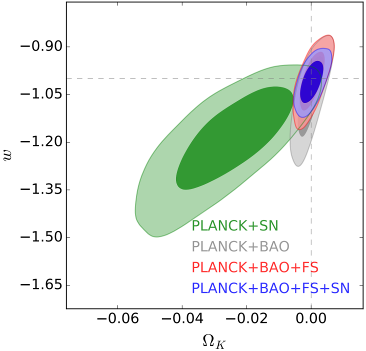


Alam et al. (2017)

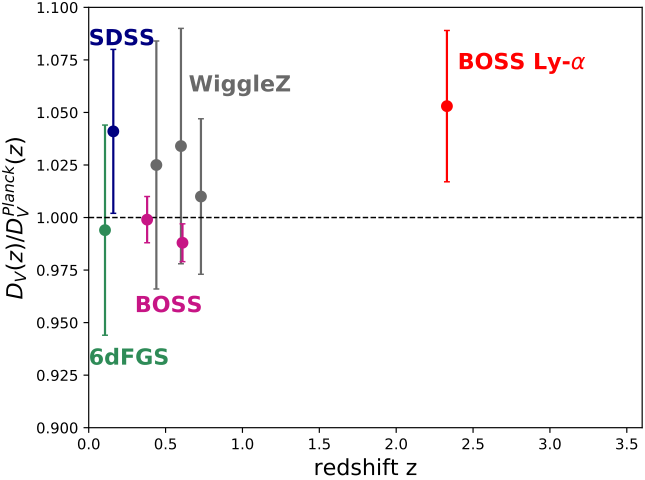
Planck+SN:

$$\Omega_k = 0.025 \pm 0.012$$
$$w = -1.01 \pm 0.11$$

Planck+SN+BAO:

$$\Omega_k = 0.0003 \pm 0.0027$$
$$w = -1.05 \pm 0.08$$

Looking into the (near) future



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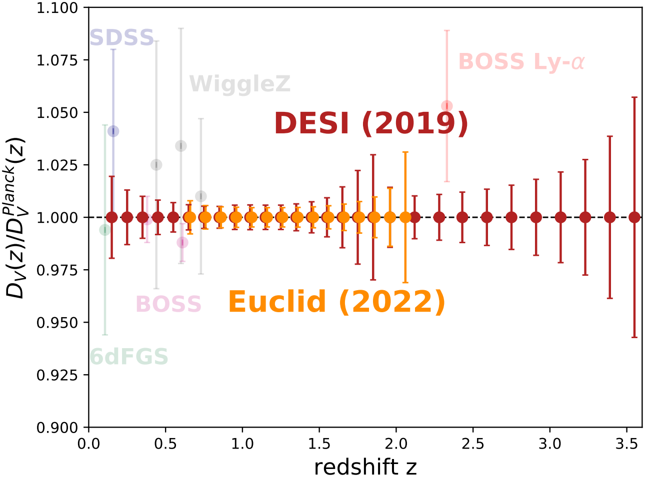

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Outline of the talk

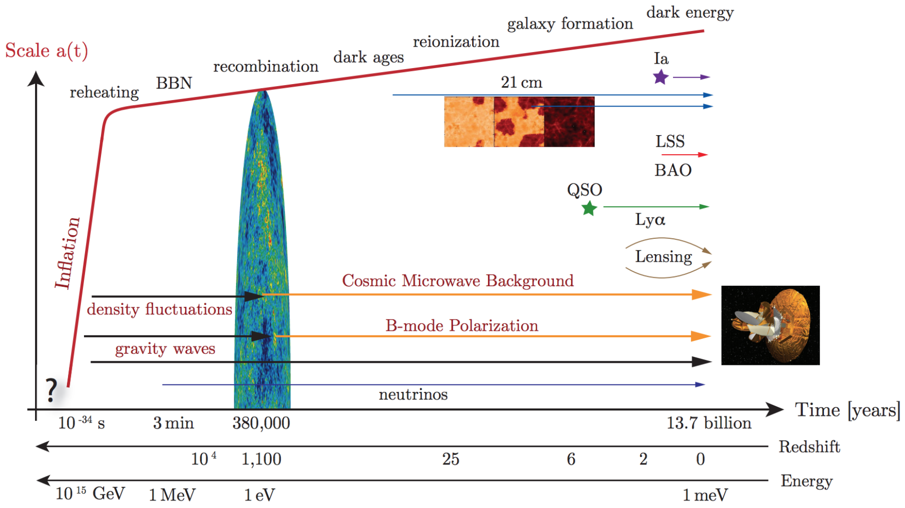
1. General introduction to galaxy redshift surveys & BAO
2. Testing inflation with primordial features (**arXiv:1906.08758**)
3. Neutrinos in the phase of the BAO (**arXiv:1803.10741**)

Primordial Features from Linear to Nonlinear Scales

Florian Beutler, Matteo Biagetti, Daniel Green, Anze Slosar and Benjamin Wallisch

ArXiv: 1906.08758

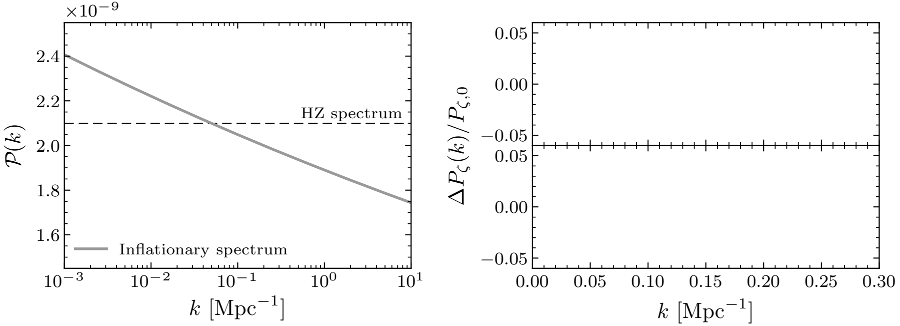
Inflation in one plot



Baumann (2009)

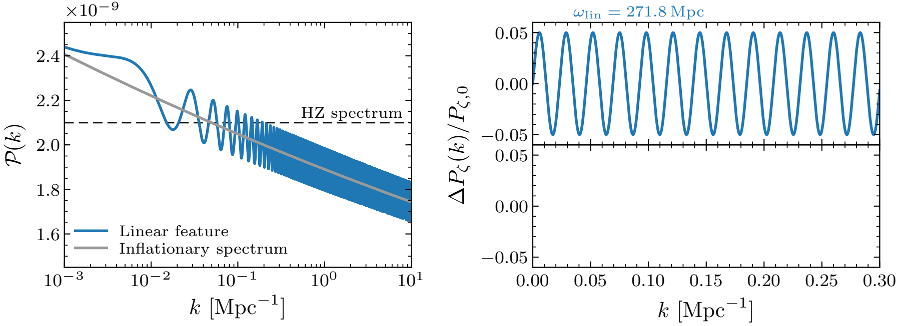
Testing inflation through primordial features

No features



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

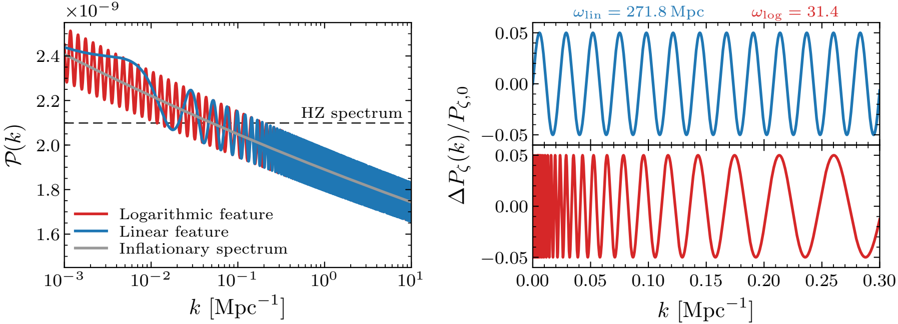
Linear features



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

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

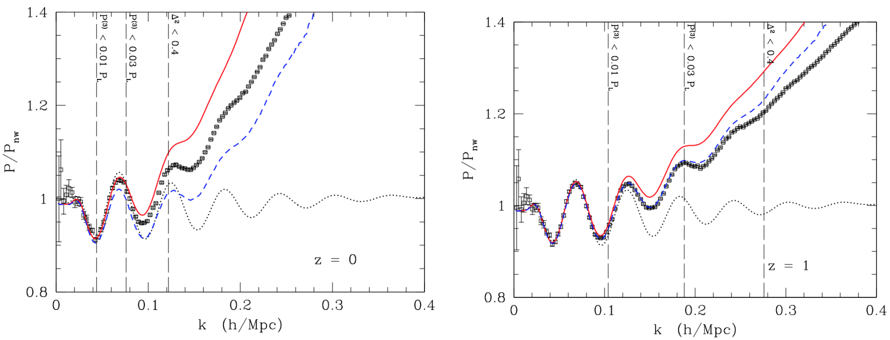
Logarithmic features



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

[Resonant features]
Chen, Easther & Lim (2008)
Silverstein & Westphal (2008)
Flauger, McAllister, Pajer & Westphal (2010)
. . .

Non-linear gravitational evolution



Carlson et al. in (2009)

Feature damping

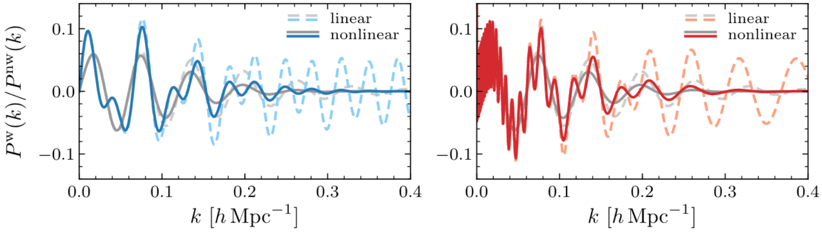
Linear Feature

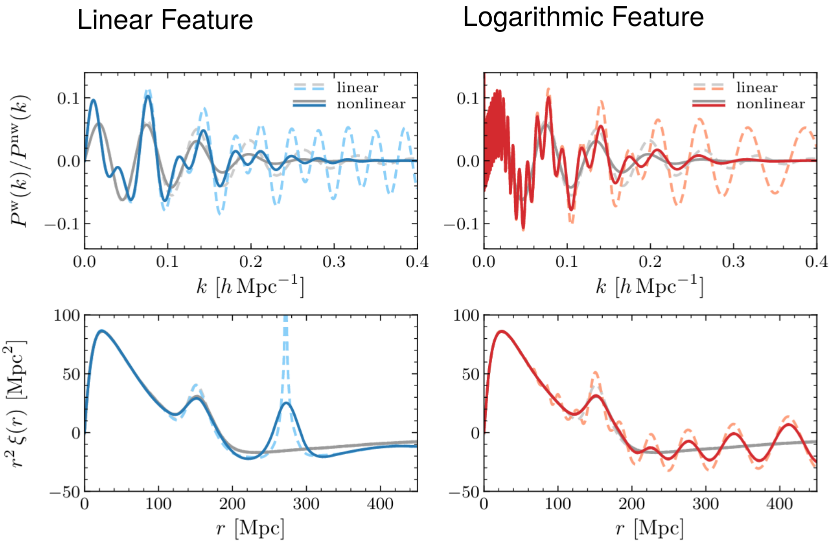
- Damping factor of linear features equal to BAO damping for $\omega_{\rm lin} \gtrsim 75\,$Mpc

Logarithmic Feature

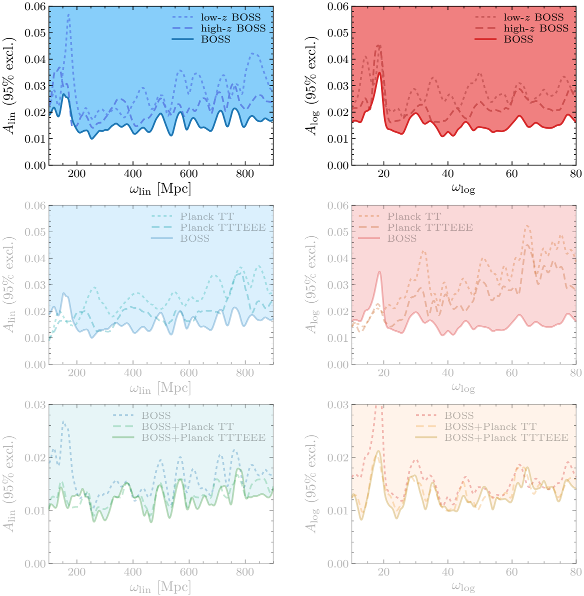
- Damping factor of log features approx. equal to BAO damping for $\omega_{\rm log} \gtrsim 10$

$$P(k) = P^{\rm nw}(k) + e^{-k^2\Sigma^2_{\rm nl}/2}\left[P^w_{\rm BAO}(k) + P^w_{\rm lin,log}(k) + P^w_{\rm BAO}(k)\delta P^{\rm lin,log}_{\zeta}(k)\right]$$




Linear Feature
Logarithmic Feature
linear
nonlinear
$P^{\rm w}(k)/P^{\rm nw}(k)$
$k\ [h\,{\rm Mpc}^{-1}]$
$r^2\,\xi(r)\ [{\rm Mpc}^2]$
$r\ [{\rm Mpc}]$

Feature constraints from BOSS DR12 and Planck

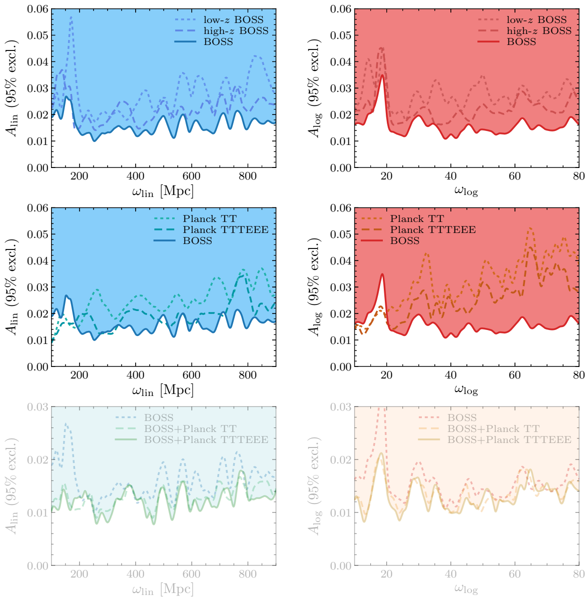


BOSS

BOSS vs. Planck

BOSS + Planck

Feature constraints from BOSS DR12 and Planck



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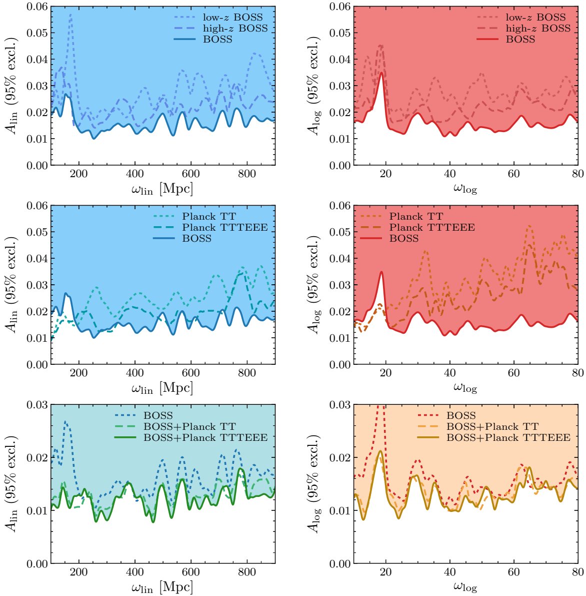
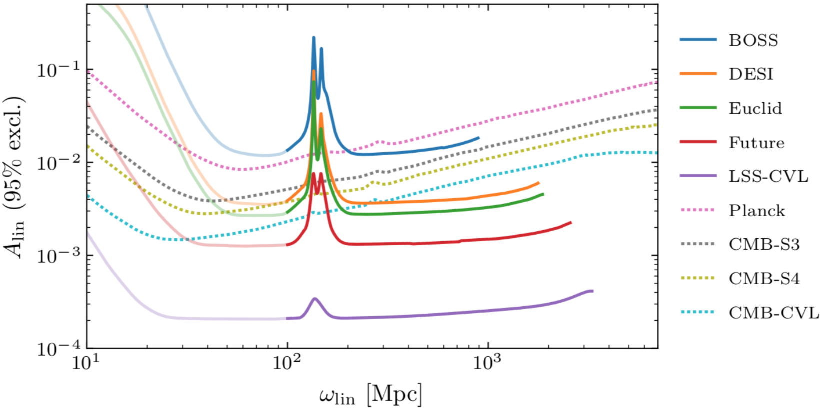


BOSS

BOSS vs. Planck

BOSS + Planck

Forecasts for primordial feature constraints



- LSS is more powerful than the CMB on small frequencies, while the CMB can access much higher frequencies
- DESI is going to provide constraints which cannot be accessed even by a CVL-CMB experiment

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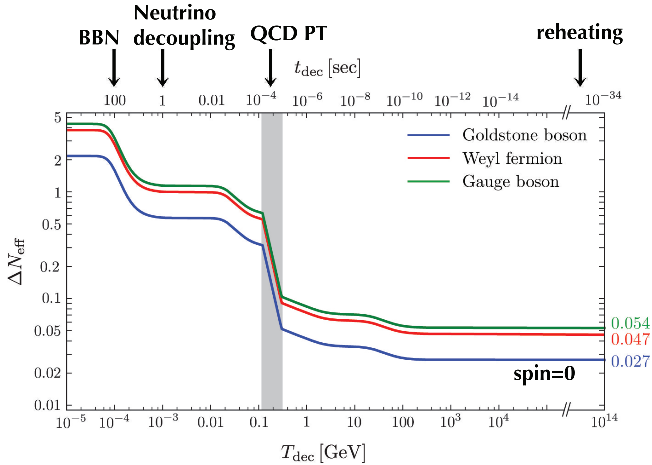
1. General introduction to galaxy redshift surveys & BAO
2. Testing inflation with primordial features (**arXiv:1906.08758**)
3. Neutrinos in the phase of the BAO (**arXiv:1803.10741**)

First Measurement of Neutrinos in the BAO Spectrum

Daniel Baumann, Florian Beutler, Raphael Flauger, Daniel Green, Mariana Vargas-Magana, Anze Slosar, Benjamin Wallisch, Christophe Yeche

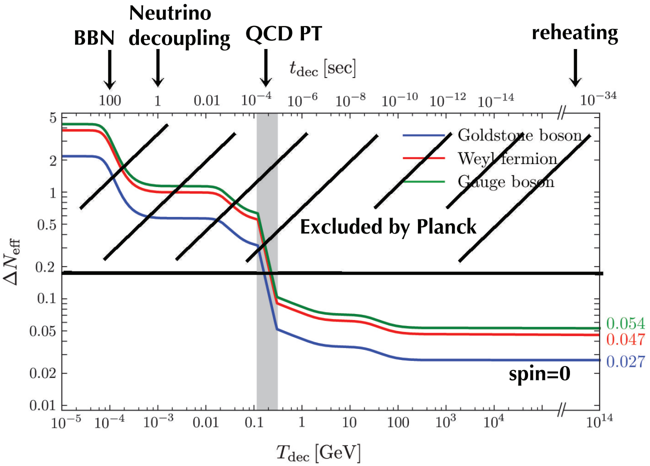
Nature Physics, 15, 465 (2019)

Motivation: Neutrinos in the phase of the BAO



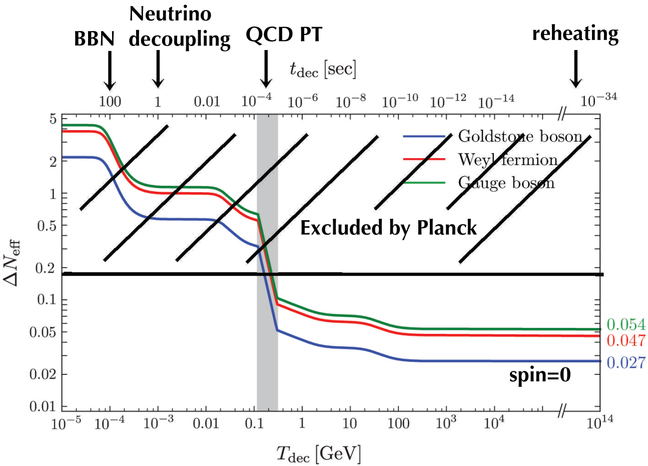
$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

Baumann et al. (2017)



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

Baumann et al. (2017)



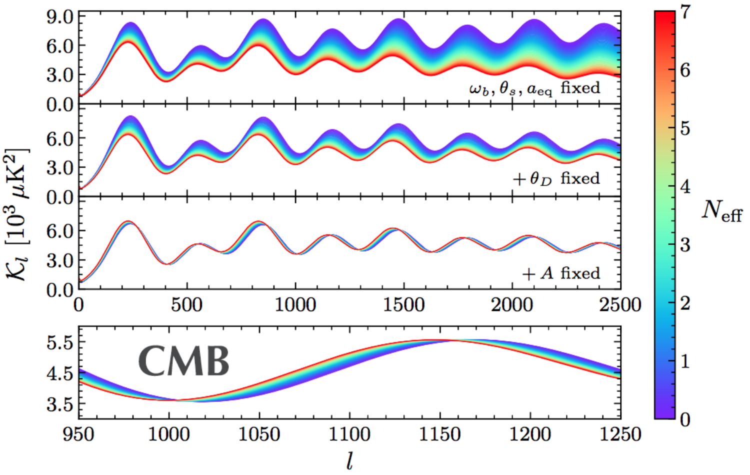
$\sigma(N_{\rm eff}) = 0.030$ (CMB-S4)

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

Baumann et al. (2017)

Neutrinos in the CMB Spectrum

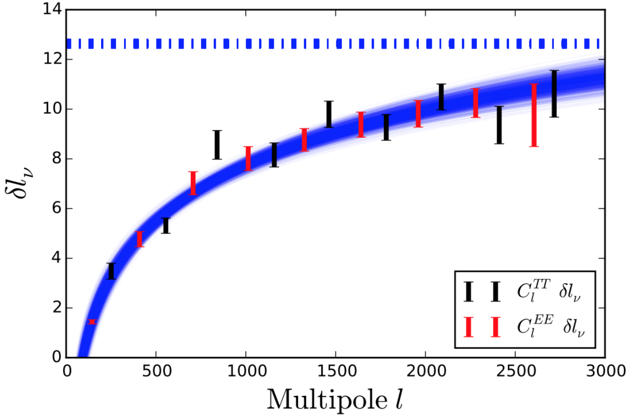
Current constraints are dominated by the damping of the power spectrum (degenerate with helium fraction).



Baumann et al. (2017)

Phase shift detection in the CMB

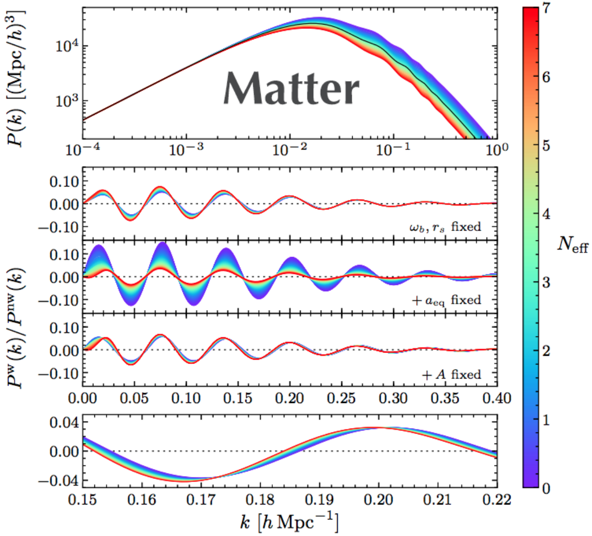
The Phase shift has recently been detected in the temperature and polarisation CMB spectrum.



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

Follin et al. (2015)

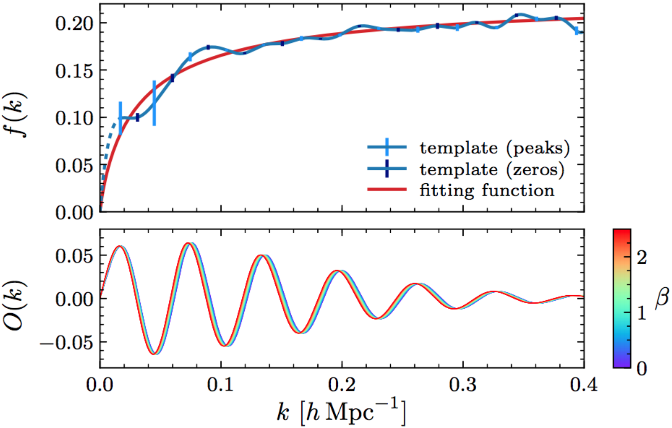
Neutrinos in the BAO Spectrum



Baumann et al. (2017)

Neutrinos in the BAO Spectrum

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



Baumann et al. (2019)

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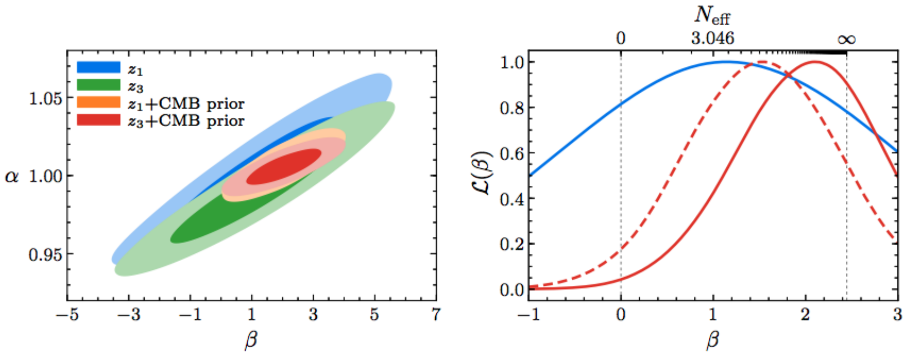
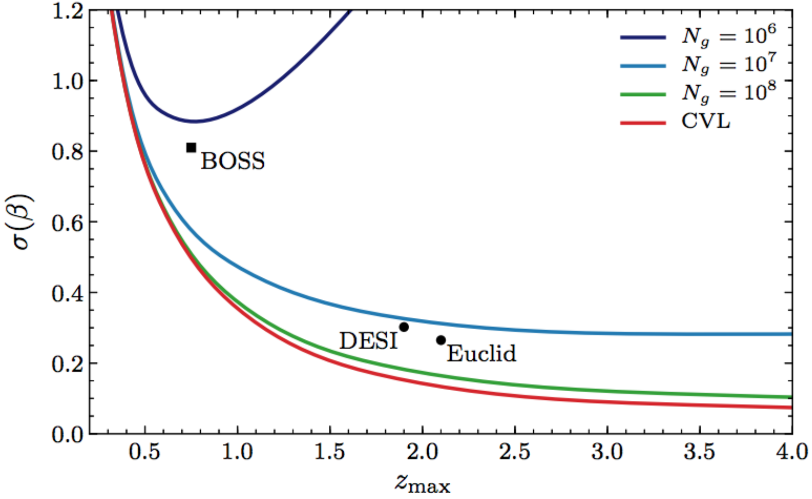


$$\beta(N_{\rm eff}) = \frac{\epsilon}{\epsilon_{\rm fid}} \qquad \text{with} \qquad \epsilon = \frac{N_{\rm eff}}{8(11/4)^{4/3}/7 + N_{\rm eff}}$$

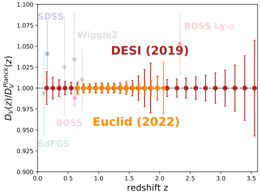
→ Proof of principle!

Baumann et al. (2019)

Neutrinos in the BAO Spectrum

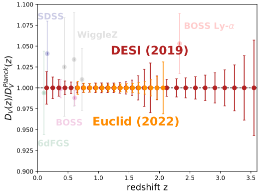


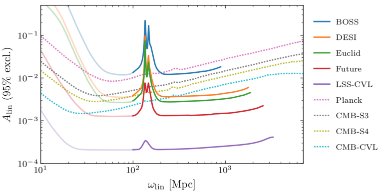
Baumann et al. (2019)



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

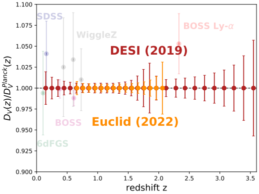
Summary

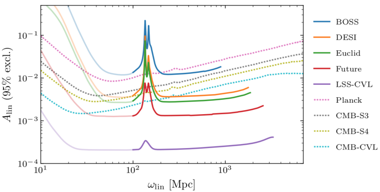


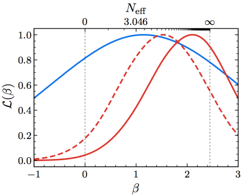


1. The next generation of galaxy redshift surveys is just around the corner → with **BAO as a key science case**
2. The BAO analysis pipeline is **perfectly suited to extract primordial features** to test inflation
3. Constraints on primordial features from LSS are **already better than Planck** for a large frequency range

Summary





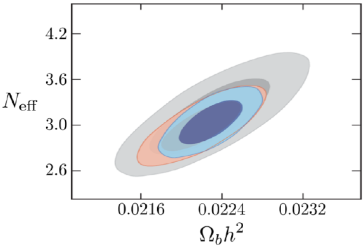


1. The next generation of galaxy redshift surveys is just around the corner $\rightarrow$ with **BAO as a key science case**
2. The BAO analysis pipeline is **perfectly suited to extract primordial features** to test inflation
3. Constraints on primordial features from LSS are **already better than Planck** for a large frequency range
4. The **phase of the BAO** carries information on $N_{\rm eff}$ just as in the CMB $\rightarrow$ **first (low significance) detection in BOSS**

Relic neutrinos make up 41% of the radiation density

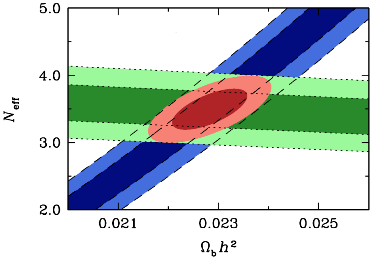
$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\mathrm{eff}}\right]\rho_\gamma$$

CMB



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

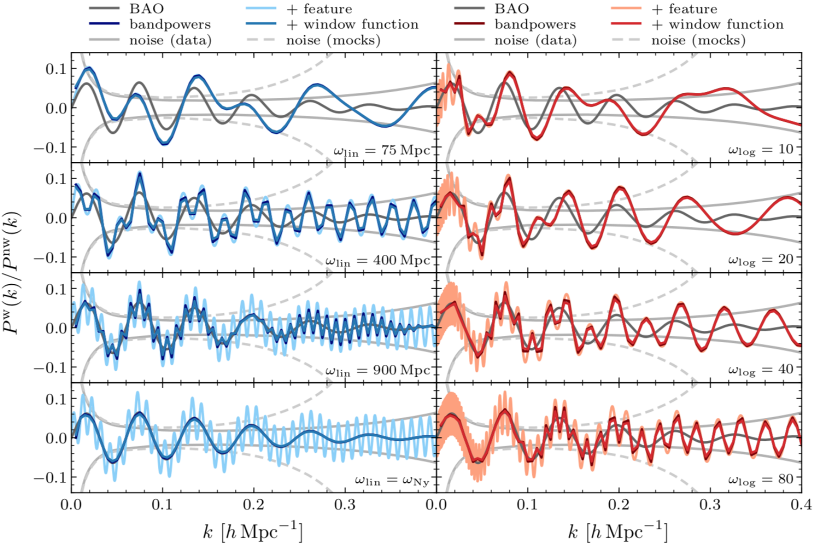
BBN



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

Planck (2015), Cooke et al. (2015)

Impact of the window function for features search



Beutler et al. (2019)