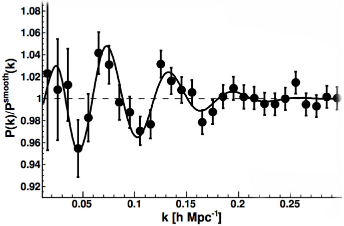
Exploring fundamental physics with galaxy redshift surveys

Florian Beutler

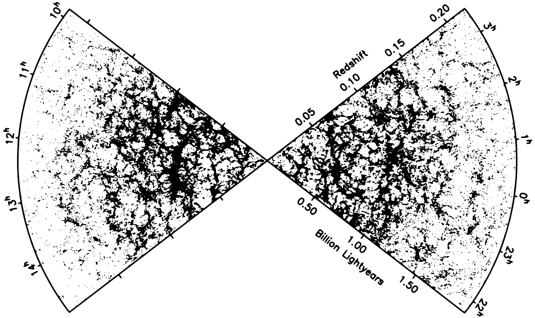


Royal Society University Research Fellow

Outline of the talk

1. General introduction to galaxy redshift surveys
   - Baryon Acoustic Oscillations
   - Redshift-space distortions
2. Testing inflation with primordial non-Gaussianity and primordial oscillations
3. Neutrinos in the phase of the BAO

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

- If the underlying distribution is Gaussian, all of the information is in the 2-point function

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

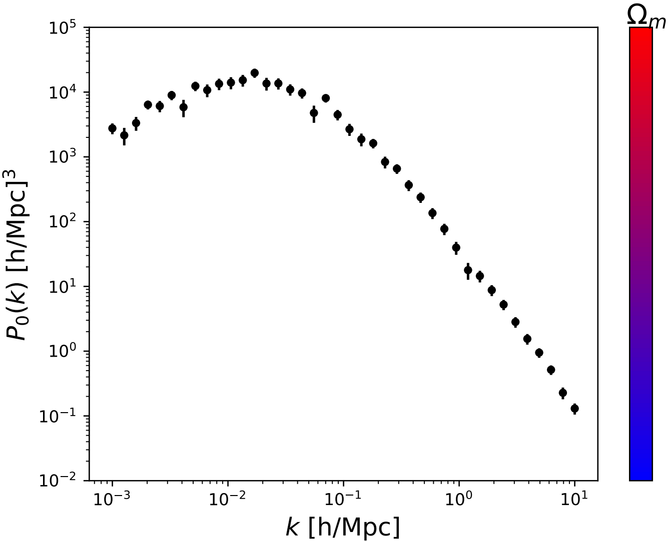
$$\xi(\mathbf{r}) \overset{\text{homogeneity}}{=} \langle\delta(\mathbf{x}+\mathbf{r})\delta(\mathbf{x})\rangle \begin{cases} \overset{\text{isotropy}}{=} & \xi(r), \\ \overset{\text{anisotropy}}{=} & \xi_\ell(r) = \int_{-1}^{1} d\mu\, \xi(r,\mu)\mathcal{L}_\ell(\mu), \end{cases}$$

$$P_\ell(k) = 4\pi(-i)^\ell \int_0^\infty r^2 dr\, \xi_\ell(r) j_\ell(kr)$$

with $\mu = \mathbf{r}\cdot\hat{\mathbf{n}}/r$.

- The actual **observed** galaxy distribution is not isotropic nor Gaussian.

Extracting cosmological information



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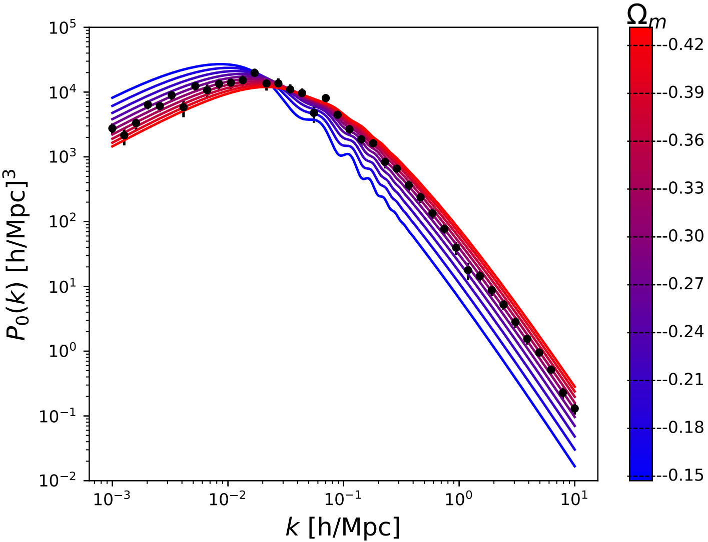
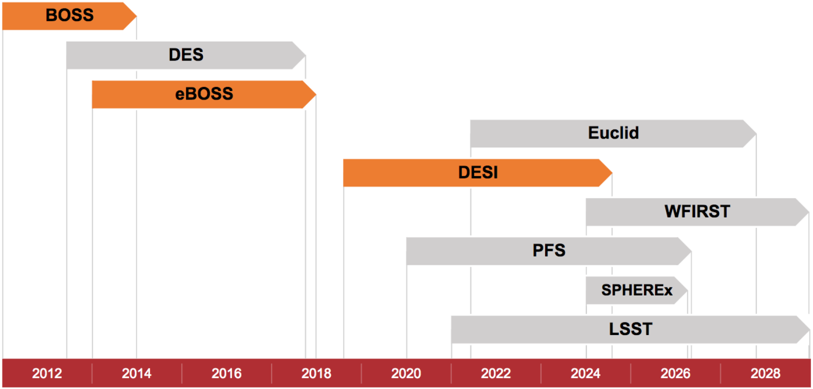
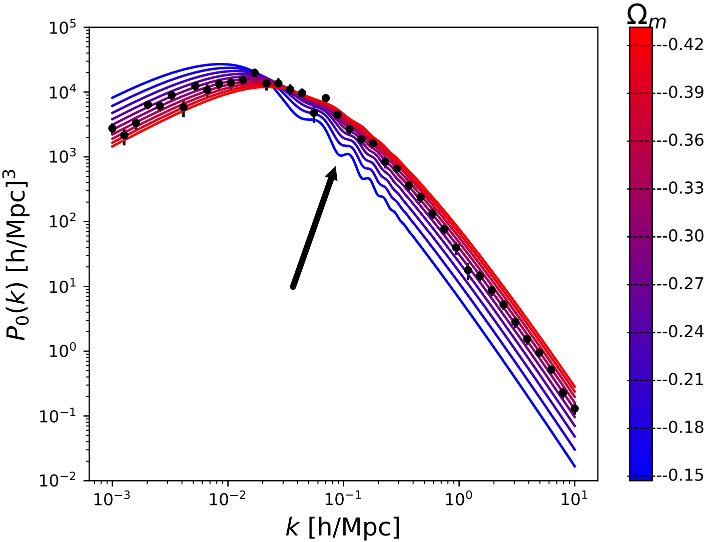


Timeline



- DESI will start observing this year!
- SPHEREx has just been approved

Extracting cosmological information



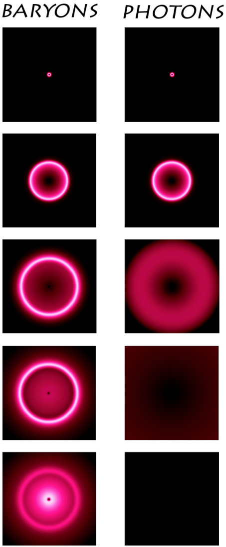
- For the first 300 000 years the evolution eq. of baryon and photon perturbations can be written as

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

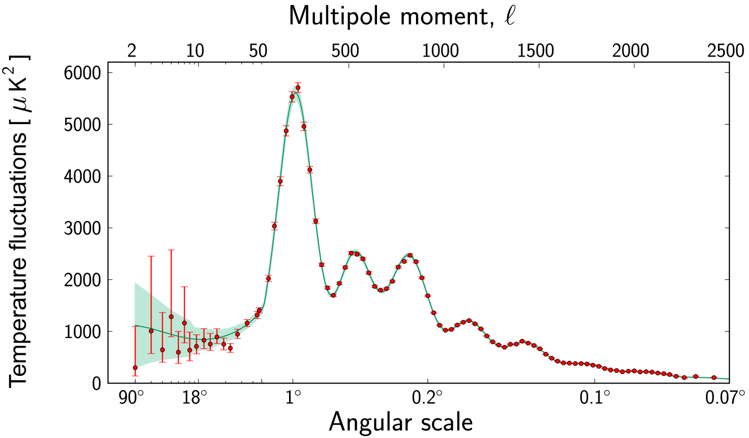
with the plane wave solution

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

- 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**.

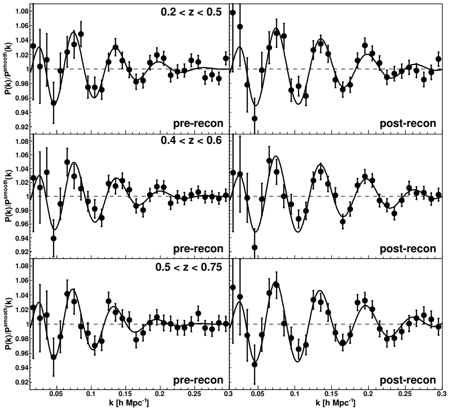


credit: Martin White

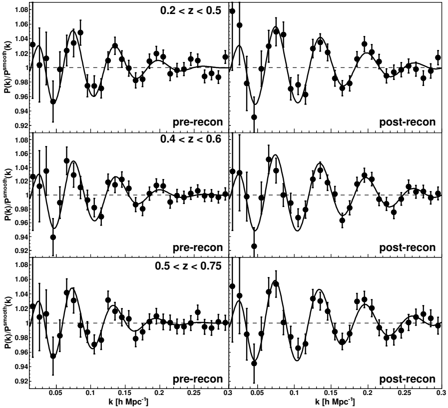


Planck collaboration

Baryon Acoustic Oscillations in BOSS



Baryon Acoustic Oscillations in BOSS



$$D_V(z = 0.38)\, r_s^{\rm fid}/r_s \propto D_A^2/H = 1476 \pm 15 \text{ Mpc} \qquad (1.0\%)$$

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

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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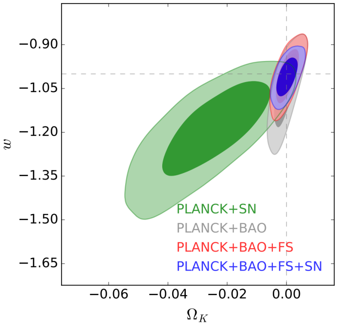


Alam + Beutler et al. (2017)

Planck+SN:

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

Planck+SN+BAO:

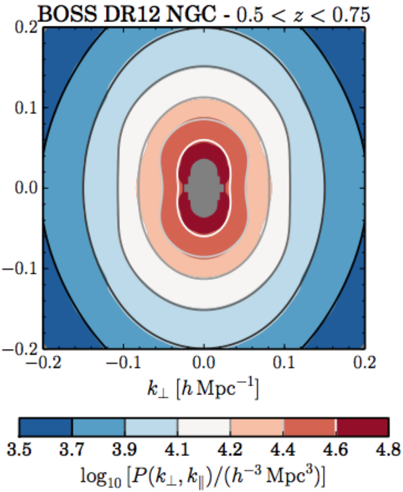
$$\Omega_k = 0.0003 \pm 0.0027$$
$$w = -1.05 \pm 0.08$$

The densities along the line-of-sight are enhanced due to the velocity field

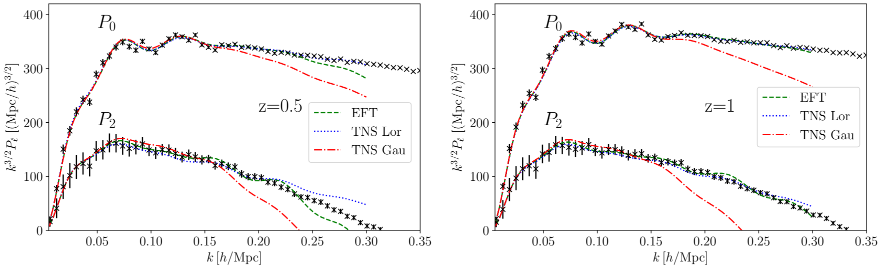
$$\delta_g(k) = b_1\delta_m(k) - \mu^2\nabla\cdot\mathbf{v}$$
$$= \delta_m(k)(b_1 + f\mu^2)$$

→ Introduces a quadrupole
→ Sensitive to cosmology since

$$f = \frac{\partial \ln D}{\partial \ln a} \approx \Omega_m^{0.55}$$



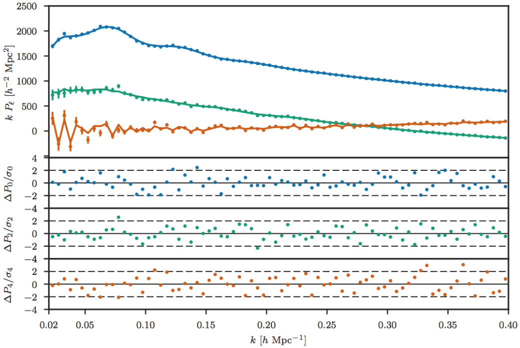
Alam + Beutler et al. (2017)



- The TNS model works up to $k_{\rm max} \sim 0.2h/$Mpc at $z = 0.5$.
- EFTofLSS works up to similar scales (but generally leads to better cosmological constraints).
- EFT can predict the bispectrum with (almost) no additional nuisance parameters.

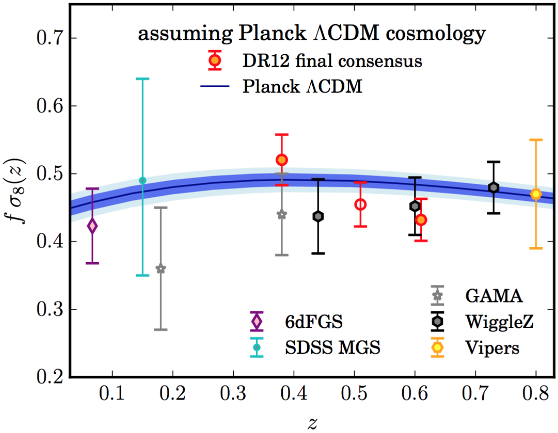
Bose + Beutler et al. in prep.

Broadband modelling - Distribution function model



- Can model the power spectrum up to $k_{\mathrm{max}} = 0.4h/\mathrm{Mpc}$ using 9 nuisance (HOD based) parameters.
- We still have to **include the bispectrum** to constrain the nuisance parameters.

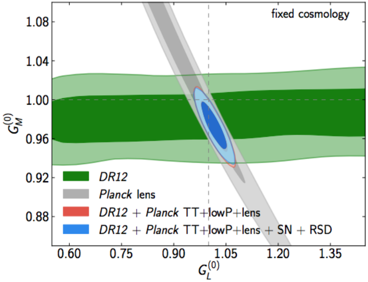
Hand + Beutler et al. (2017)

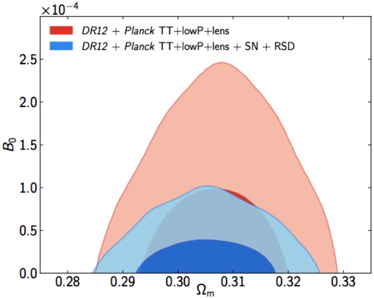


$$[f\sigma_8](z = 0.38) = 0.502 \pm 0.041 \pm 0.024 \qquad (9.5\%)$$

$$[f\sigma_8](z = 0.61) = 0.419 \pm 0.036 \pm 0.009 \qquad (8.9\%)$$

Alam + Beutler et al. (2017)





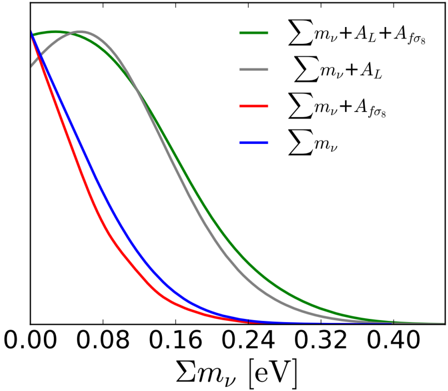
$$\nabla^2 \Psi = 4\pi G a^2 \rho \Delta G_M (z = \text{linear.})$$
$$\nabla^2 (\Psi + \phi) = 8\pi G a^2 \rho \Delta G_L (z = \text{linear.})$$

LSS constraints:

$$B_0 = \frac{2H_0^2 \lambda_1^2}{c^2} < 7.7 \times 10^{-5}$$

$$G_M = 0.980 \pm 0.096$$
$$G_L = 1.082 \pm 0.060$$

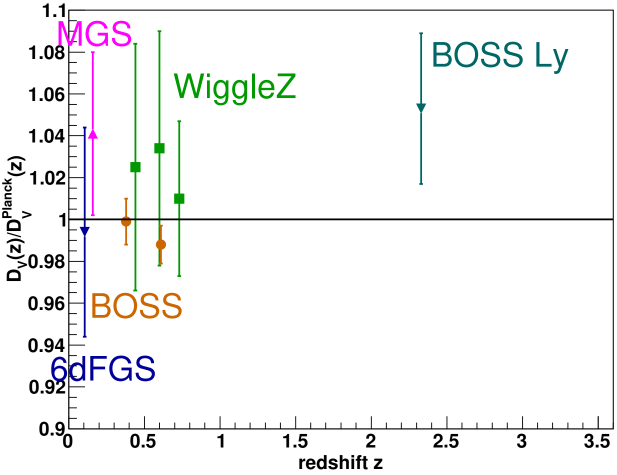
Mueller + Beutler et al. (2017)



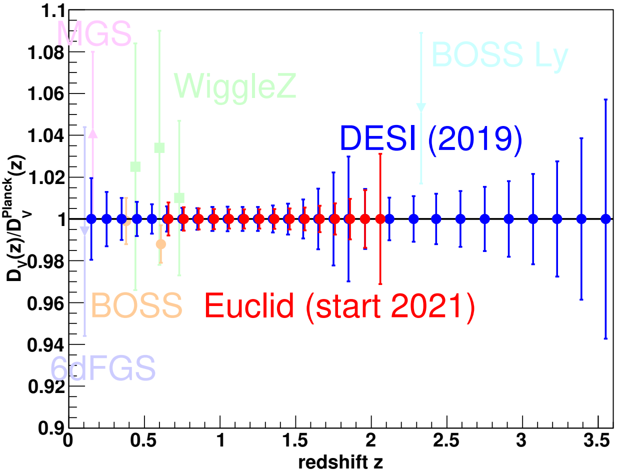
$$\Lambda CDM + \sum m_\nu < 0.16\, eV$$

Alam + Beutler et al. (2017)

Looking into the (near) future



$$D_V \propto D_A^2/H(z)$$



$$D_V \propto D_A^2/H(z)$$

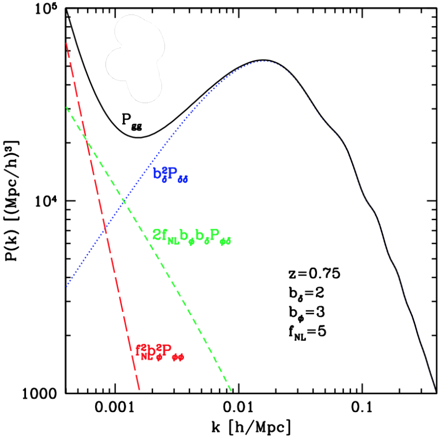
1. Testing inflation with signatures in the primordial power spectrum.
2. Measuring the cosmic neutrino background with the phase of the BAO.

Testing inflation with signatures in the primordial power spectrum

Castorina + Beutler et al. in prep., Beutler et al. in prep.

1. We can search for primordial non-Gaussianity
2. We can search for features in the primordial power spectrum
3. We can try to measure curvature $\Omega_k \leftrightarrow$ e-folds (prob. very difficult since the expected signal is $\Delta\Omega_k \sim 10^{-4}$)

Testing inflation through primordial non-Gaussianity



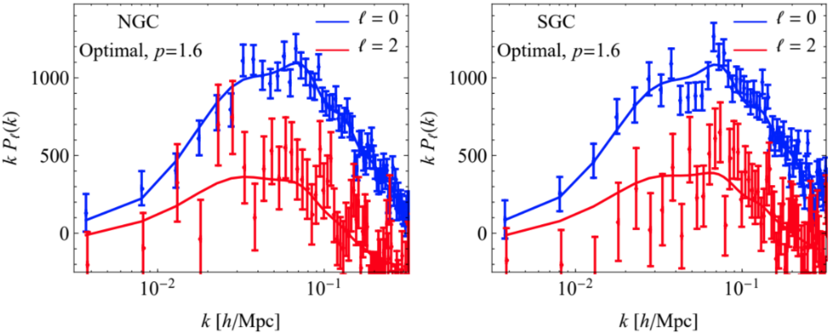
$$\phi_{\rm p} = \phi + f_{\rm NL}^{\rm loc}(\phi^2 - \langle\phi^2\rangle)$$

$$\delta_g(k) = \delta_m(k)\left(b_1 + f\mu^2 + \frac{b_\phi f_{\rm NL}^{\rm loc}\alpha}{k^2}\right)$$

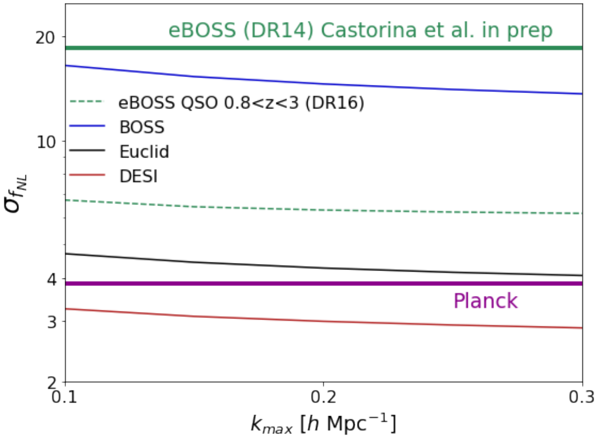
McDonald 2008

Primordial non-Gaussianity with LSS (preliminary)

- The CMB bispectrum yields $f_{\rm NL}^{\rm loc} = 0.8 \pm 5.2(/1.3)$ (Planck col.)
- eBOSS DR14: $\sim 150\,000$ Quasars at $0.8 < z < 2.2$
- eBOSS provides the currently best LSS constraint $f_{\rm NL}^{\rm loc} = -8^{+18}_{-19}$ using $1/3$ of the final eBOSS sky coverage and excluding $z > 2.2$

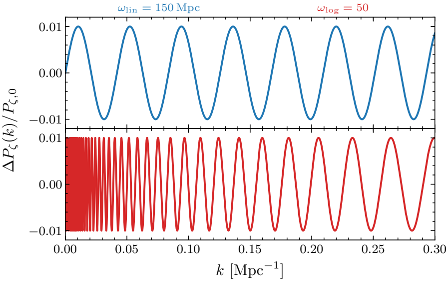


Castorina + Beutler et al. in prep.



- **No bispectrum information included yet!**
- **SPHEREx is now funded** $\rightarrow \sigma_{f_{\rm NL}} < 1$ **in 2025**

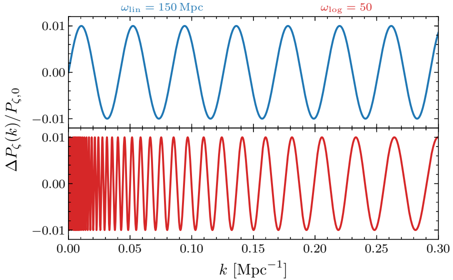
Testing inflation through primordial features



- Feature(s) in the inflationary potential can introduce features in the primordial power spectrum, which might still be detectable today.
- Sharp features can lead to linear oscillations, while periodic features lead to log-oscillations.
- As BAO has shown, features in the power spectrum can be measured very accurately.

Beutler et al. in prep.

Testing inflation through primordial features

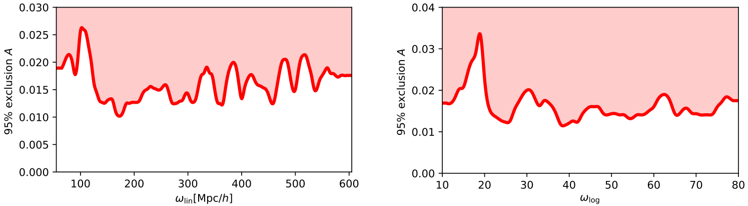


- Here we use a model-independent approach based on

$$\frac{\Delta P_\zeta}{P_\zeta} = \begin{cases} A^{\cos}\cos\left[\omega_{\log}\log\left(\frac{k}{0.05}\right)\right] + A^{\sin}\sin\left[\omega_{\log}\log\left(\frac{k}{0.05}\right)\right], \\ A^{\cos}\cos\left[\omega_{\rm lin}k\right] + A^{\sin}\sin\left[\omega_{\rm lin}k\right] \end{cases}$$

- LSS is more powerful than the CMB on small frequencies, while the CMB can access much higher frequencies
- LSS can improve over Planck by a factor of 2 - 10, depending on frequency (Chen et al. 2016)

Beutler et al. in prep.



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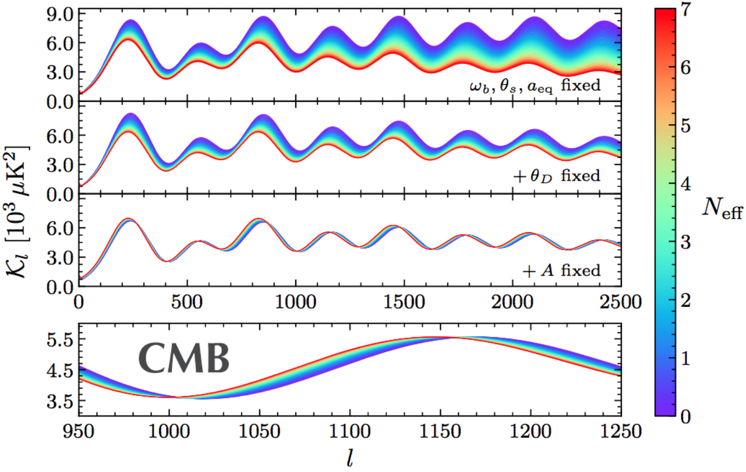
Beutler et al. in prep.

Measuring the cosmic neutrino background with the phase of the BAO

Baumann + Beutler et al. (2019), Nature Astronomy

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



Baumann et al. (2017)

Neutrinos in the BAO Spectrum

The oscillations have been imprinted during radiation domination

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

with solutions (Φ sourced by γ, DM, baryons)

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

- The gravitational sources on the right only impact A, but they cannot change the phase (Bashinsky & Seljak 2003, Baumann et al. 2015).
- Any fluctuation in the grav. potential which travels faster than the baryon-photon plasma can generate a phase shift (free streaming neutrinos $c_\nu > c_\gamma$).

Evolution of density perturbations

The oscillation have been imprinted during radiation domination

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

with solutions (Φ sourced by γ, DM, baryons + ν)

$$\begin{aligned}\delta_{b\gamma} &= A\cos(kr_s) + \delta B\sin(kr_s) \\ &= A\cos(kr_s + \phi)\end{aligned}$$

- The gravitational sources on the right only impact A, but they cannot change the phase (Bashinsky & Seljak 2003, Baumann et al. 2015).
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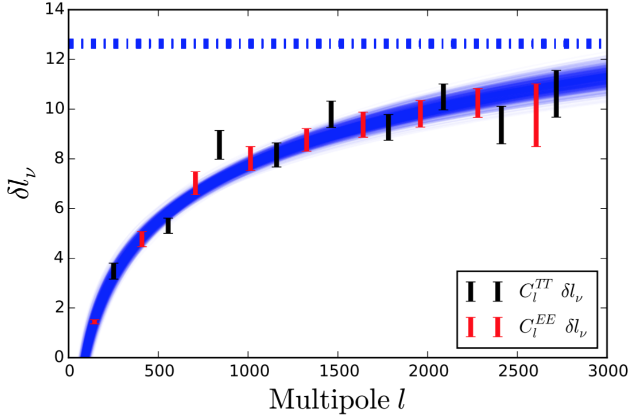
Phase shift detection in the CMB

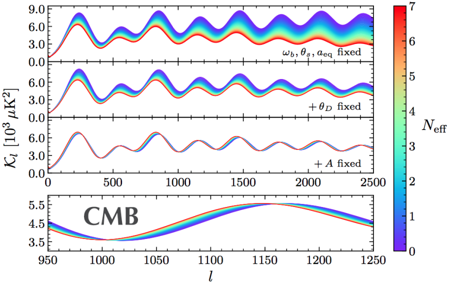
The Phase shift has recently been detected in the temperature and polarisation CMB spectrum.



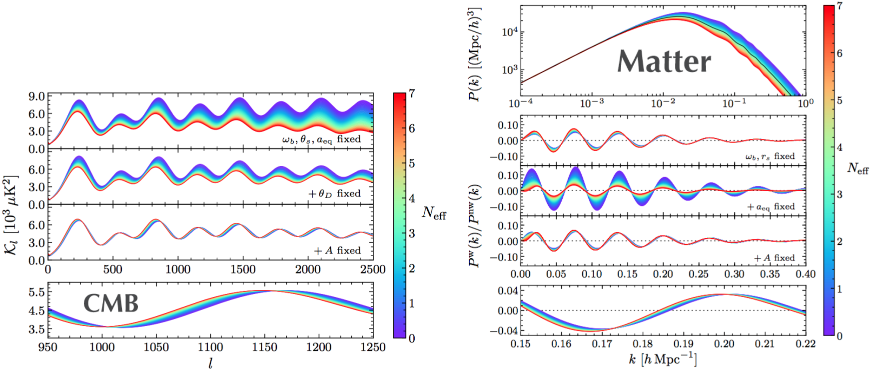
$$N_{\rm eff} = 2.8^{+1.1}_{-0.4}$$

Follin et al. (2015)

Neutrinos in the BAO Spectrum

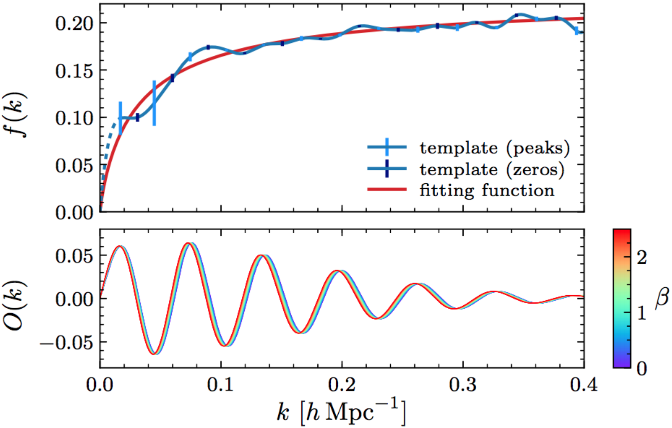


Neutrinos in the BAO Spectrum



Baumann et al. (2017)

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



Baumann + Beutler et al. (2019)

Neutrinos in the BAO Spectrum

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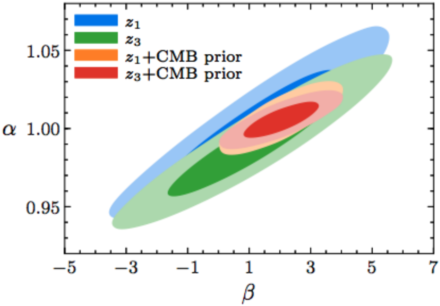
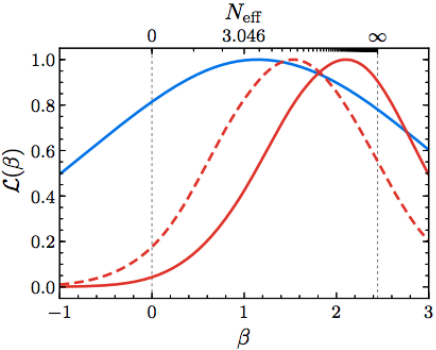


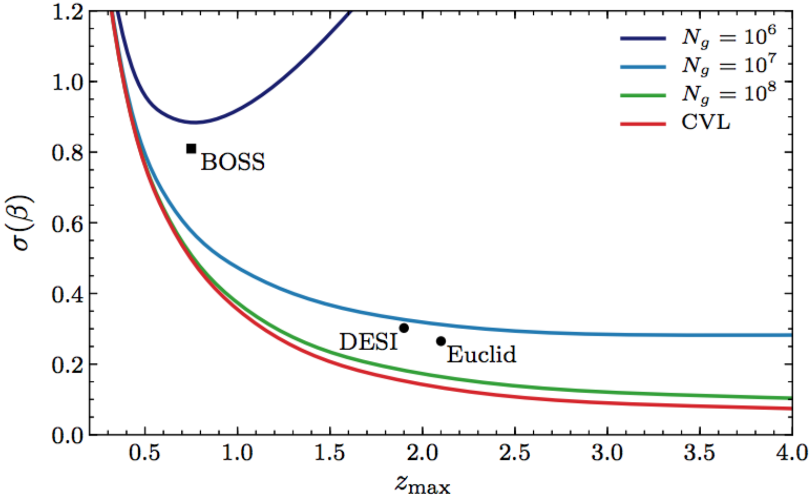


$$\beta(N_{\mathrm{eff}}) = \frac{\epsilon}{\epsilon_{\mathrm{fid}}} \quad \text{with} \quad \epsilon = \frac{N_{\mathrm{eff}}}{8(11/4)^{4/3}/7 + N_{\mathrm{eff}}}$$

→ This is a proof of principle for extracting information on light relics from galaxy clustering data.

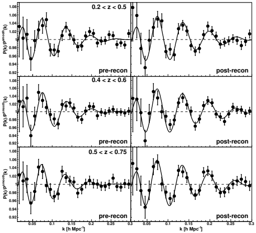
Baumann + Beutler et al. (2019)

Neutrinos in the BAO Spectrum



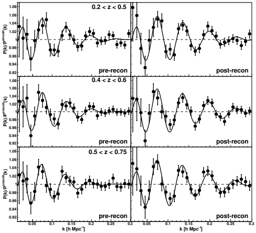
Baumann + Beutler et al. (2019)

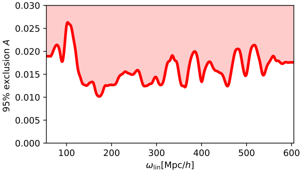
Summary



1. The next generation of galaxy surveys offers unprecedented cosmological constraints using BAO and RSD **and DESI will start this year**.

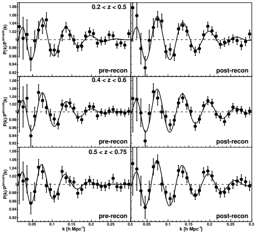
Summary

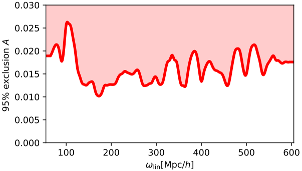


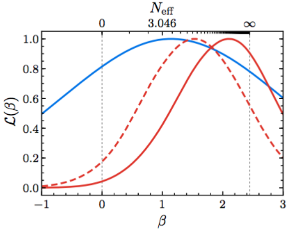


1. The next generation of galaxy surveys offers unprecedented cosmological constraints using BAO and RSD **and DESI will start this year**.
2. LSS can constrain inflationary models competitive with the CMB using both **primordial non-Gaussianity** and **primordial features**.

Summary







1. The next generation of galaxy surveys offers unprecedented cosmological constraints using BAO and RSD **and DESI will start this year**.
2. LSS can constrain inflationary models competitive with the CMB using both **primordial non-Gaussianity** and **primordial features**.
3. The **phase of the BAO** carries information on $N_{\rm eff}$ just as in the CMB. Indirect observable of the cosmic neutrino background.
4. We have a **low significance detection in BOSS** and will be able to get $\sim 3 - 5\sigma$ detections in DESI and Euclid.
5. First use of the BAO feature beyond its application as a standard ruler.

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

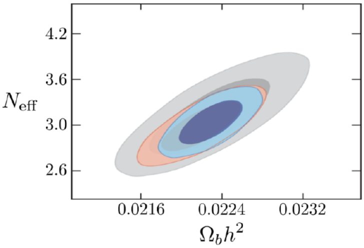
$$A(k) = a_1 k + a_2 + \frac{a_3}{k} + \frac{a_4}{k^2} + \frac{a_5}{k^3}$$
$$P^{\rm fit}(k) = B^2 P^{\rm sm,lin}(k/\alpha) + A(k)$$

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

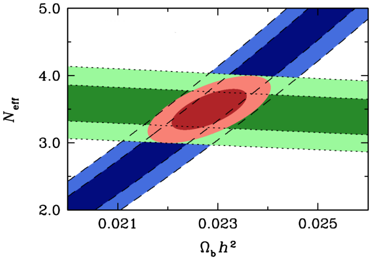
Relic neutrinos make up 41% of the radiation density

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

CMB



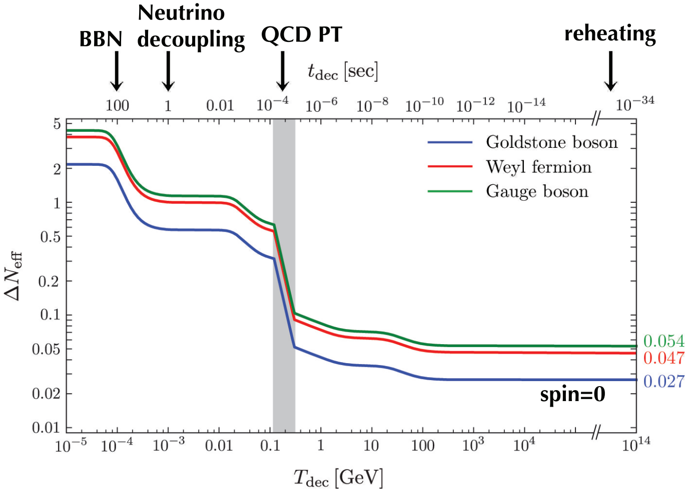
BBN



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

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

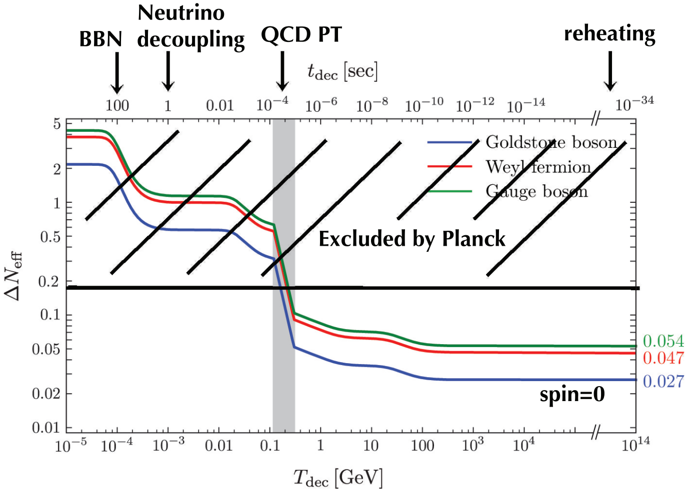
Planck (2015), Cooke et al. (2015)



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

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

Motivation



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

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