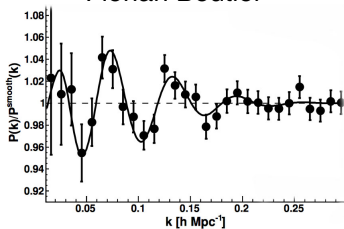


Exploring fundamental physics with galaxy redshift surveys

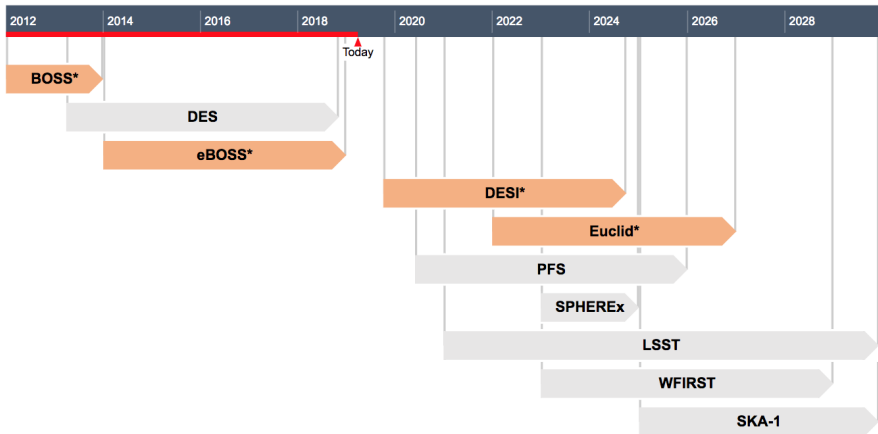
Florian Beutler



Royal Society University Research Fellow

- 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

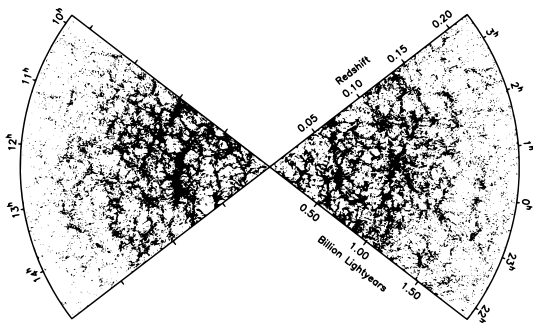
Why should you care?



- DESI will start observing this year!

*Collaboration Member

What is a galaxy redshift survey?

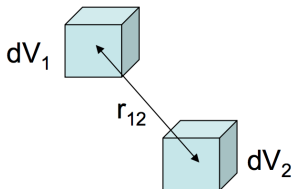


- Measure the position of galaxies (redshift + RA, DEC).
- The CMB tells us a lot about the initial conditions for today's distribution of matter.
- How the initial density fluctuations in the CMB evolved from redshift $z \sim 1100$ to today depends on Ω_m , Ω_Λ , H_0 etc.

From a point distribution to a power spectrum

- Overdensity-field:

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



- Two-point function:

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

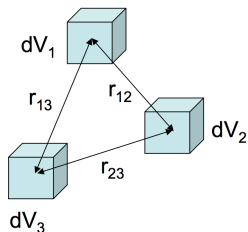
- ...and in Fourier-space:

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

From a point distribution to a bispectrum

- Overdensity-field:

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



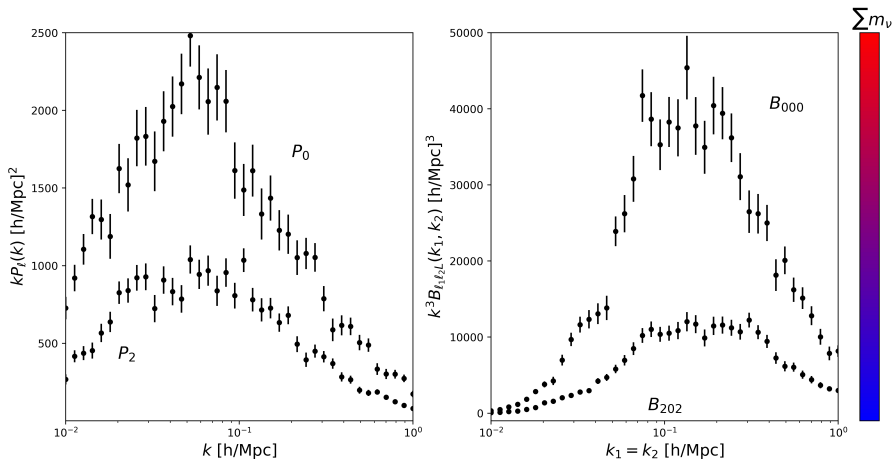
- Three-point function:

$$\xi(\mathbf{r}_1, \mathbf{r}_2) = \langle \delta(\mathbf{x} + \mathbf{r}_1) \delta(\mathbf{x} + \mathbf{r}_2) \delta(\mathbf{x}) \rangle \begin{cases} \text{homogeneity} \\ \text{isotropy} \\ \text{anisotropy} \end{cases} \begin{cases} = & \xi_L(r_1, r_2) \\ \rightarrow & \xi_{\ell_1 \ell_2 L}(r_1, r_2) \end{cases}$$

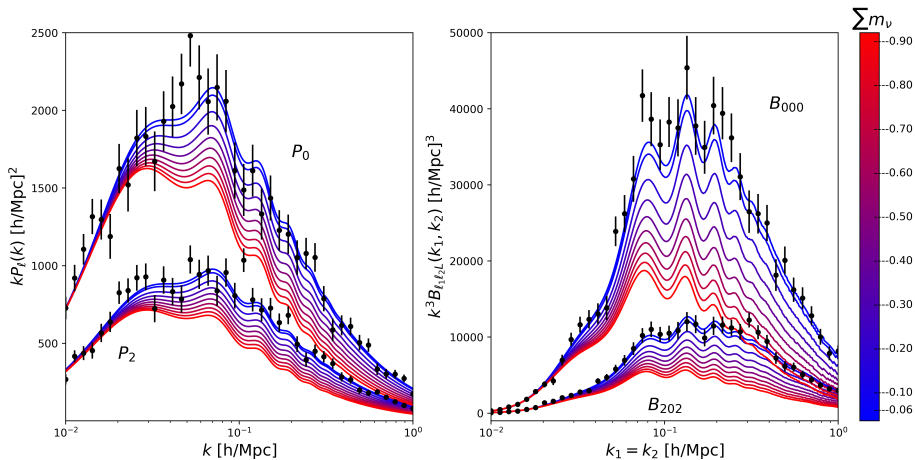
- ...and in Fourier-space:

$$B_{\ell_1 \ell_2 L}(k_1, k_2) = (4\pi)^2 (-i)^{\ell_1 + \ell_2} \int r_1^2 dr_1 \int r_2^2 dr_2 \xi_{\ell_1 \ell_2 L}(r_1, r_2) j_{\ell_1}(k_1 r_1) j_{\ell_2}(k_2 r_2)$$

Extracting cosmological information

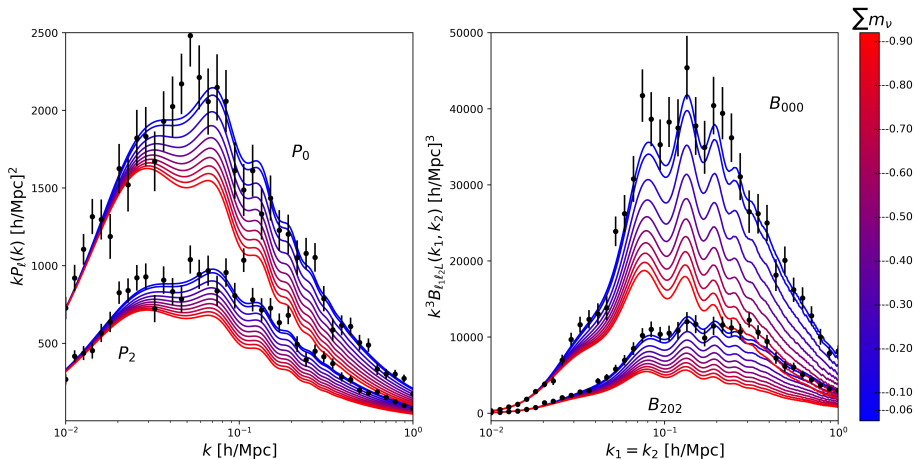


Extracting cosmological information

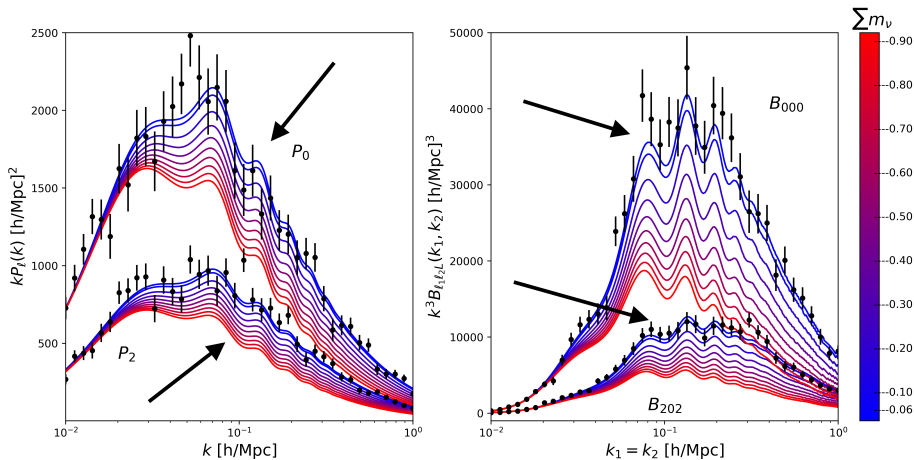


- 1 General introduction to galaxy redshift surveys
 - **Baryon Acoustic Oscillations**
 - Redshift-space distortions
- 2 Testing inflation with primordial non-Gaussianity and primordial oscillations
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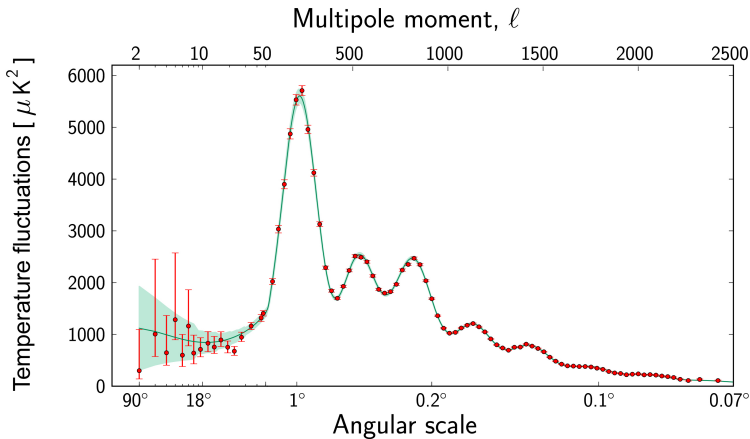
Extracting cosmological information



Extracting cosmological information



What are Baryon Acoustic Oscillations?



What are Baryon Acoustic Oscillations?

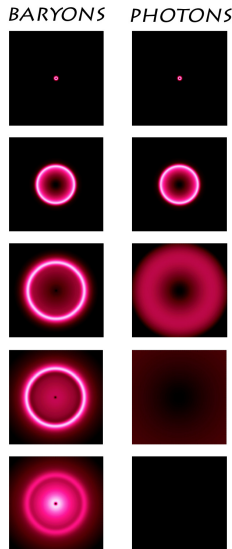
- For the first 380 000 years the evolution eq. of baryon and photon perturbations can be written as

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

with the plane wave solution

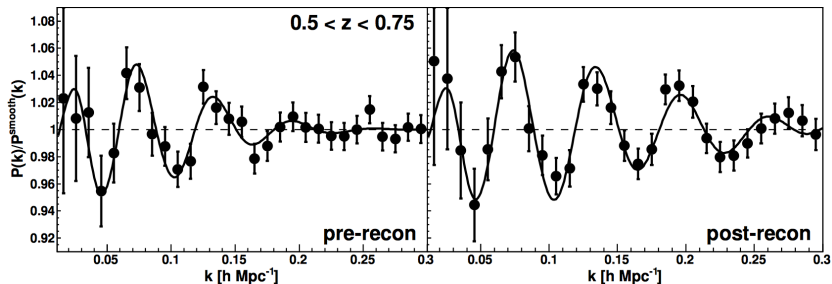
$$\delta_{b\gamma} = A \cos(kr_s + \phi)$$

- 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

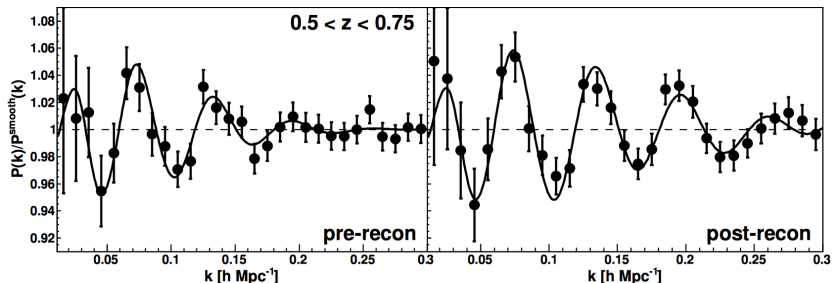
Baryon Acoustic Oscillations in BOSS



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

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

Baryon Acoustic Oscillations in BOSS



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

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

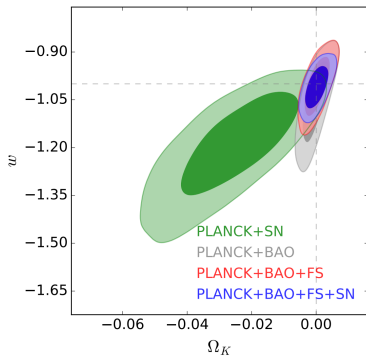
$$D_V(z) = \left[(1+z)^2 D_A^2(z) \frac{cz}{H(z)} \right]^{1/3}$$

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 .**

Baryon Acoustic Oscillations in BOSS

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Alam + Beutler et al. (2017)

Planck+SN:

$$\Omega_k = 0.025 \pm 0.012$$

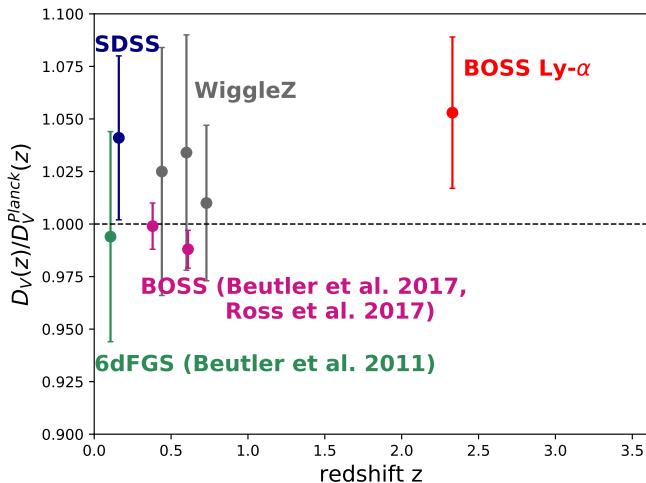
$$w = -1.01 \pm 0.11$$

Planck+SN+BAO:

$$\Omega_k = 0.0003 \pm 0.0027$$

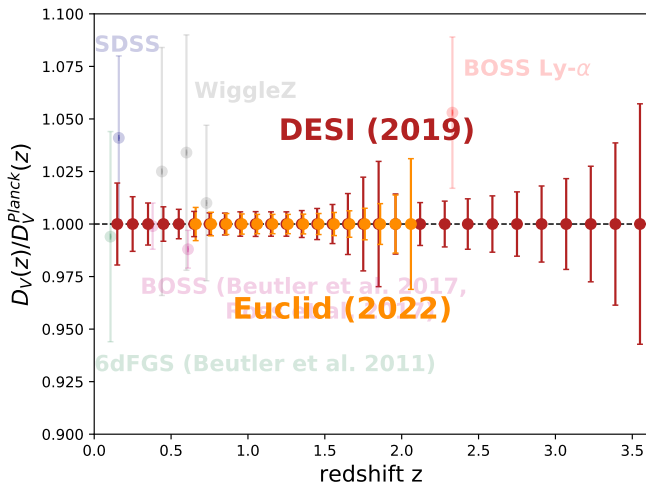
$$w = -1.05 \pm 0.08$$

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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What are redshift-space distortions?

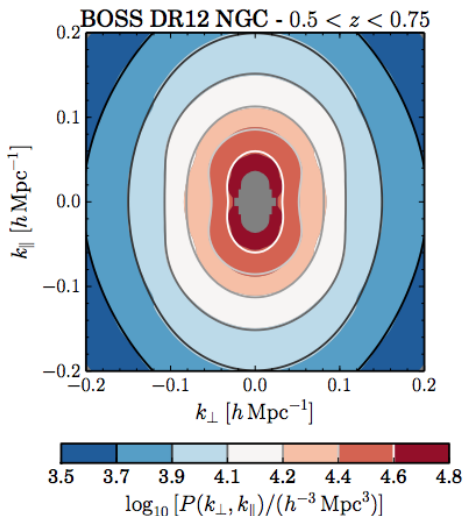
The densities along the line-of-sight are enhanced due to the velocity field

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

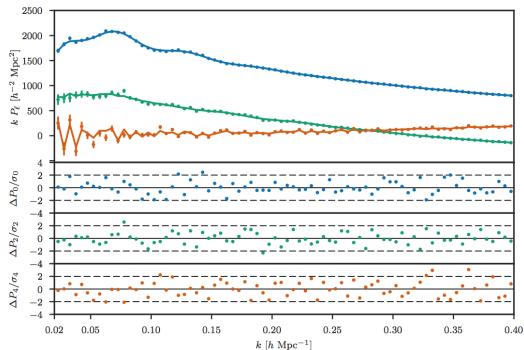
→ Introduces a quadrupole

→ Sensitive to cosmology since

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

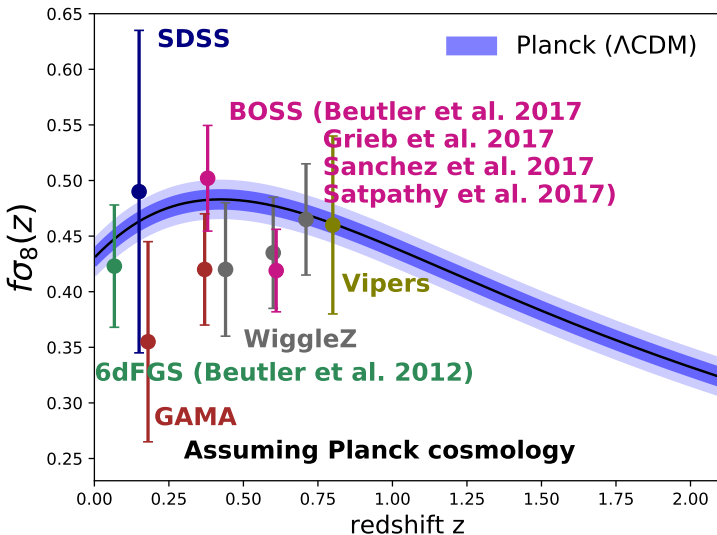


Alam + Beutler et al. (2017)

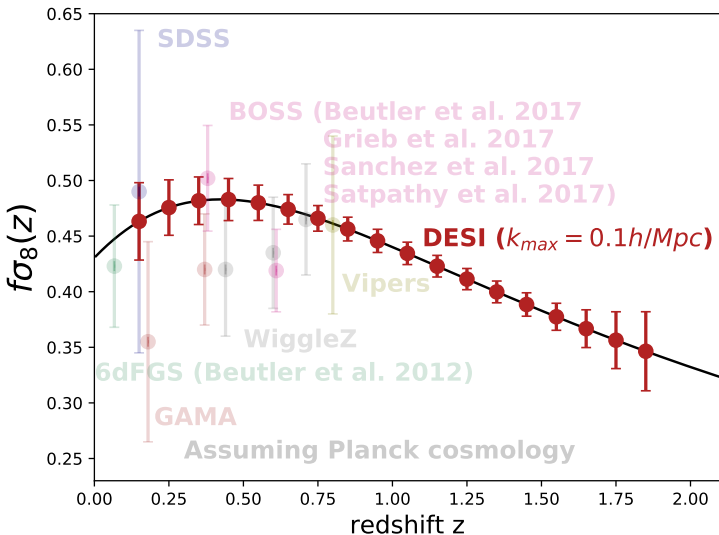


- Can model the power spectrum up to $k_{\text{max}} = 0.4h/\text{Mpc}$ using 9 nuisance (HOD based) parameters.
- We still have to **include the bispectrum** to constrain the nuisance parameters.

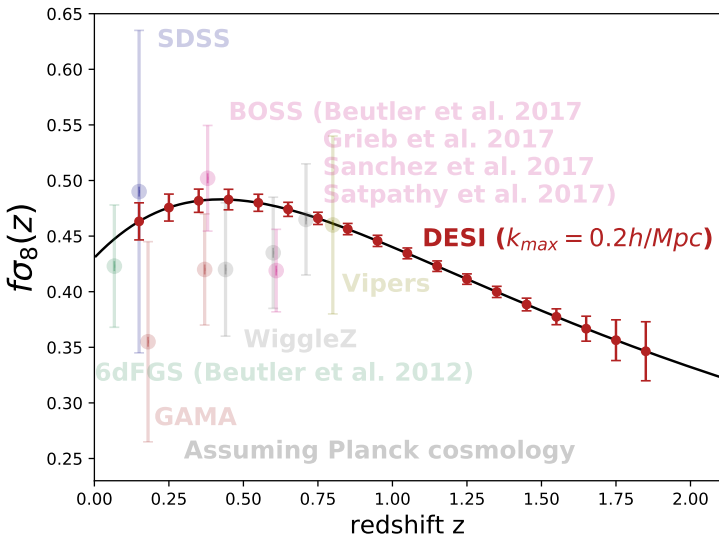
Looking into the (near) future



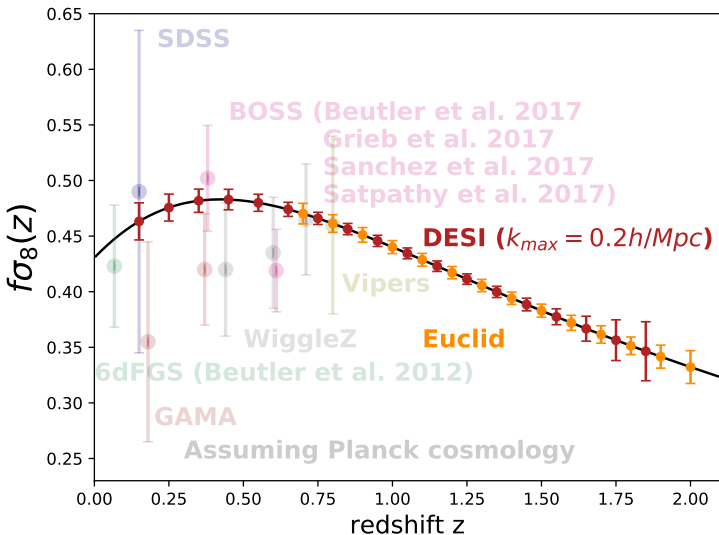
Looking into the (near) future



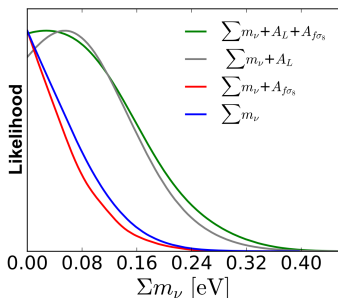
Looking into the (near) future



Looking into the (near) future



Constraining the neutrino mass with BAO & RSD



$$|\Delta m_{31}^2| \approx 2.56 \times 10^{-3} \text{ eV}^2$$

$$\Delta m_{21}^2 \approx 7.37 \times 10^{-5} \text{ eV}^2$$

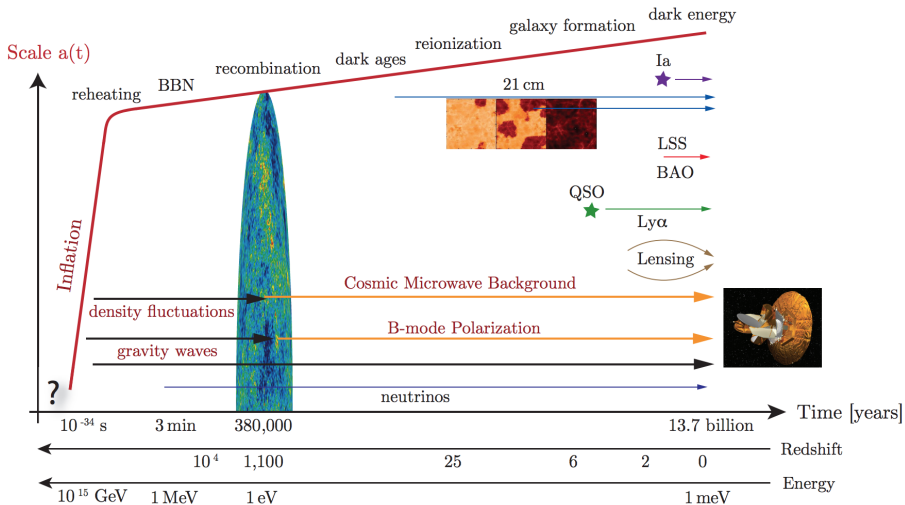
$$0.06 \text{ eV}$$

$$\lesssim \text{Planck} (\Lambda\text{CDM} + \sum m_\nu) + \text{BOSS} < 0.16 \text{ eV}$$

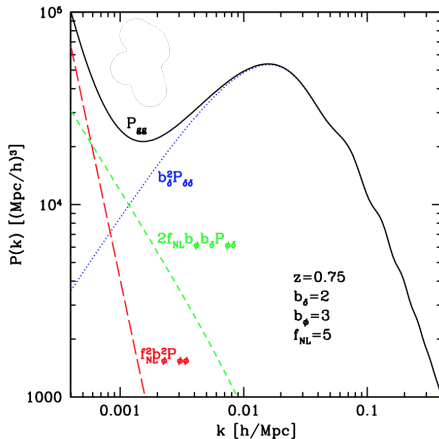
- Neutrino mass hierarchy $\begin{cases} m_{\nu_1} < m_{\nu_2} \ll m_{\nu_3} \rightarrow \min(\sum m_\nu) \approx 0.06 \text{ eV} \\ m_{\nu_3} \ll m_{\nu_1} < m_{\nu_2} \rightarrow \min(\sum m_\nu) \approx 0.1 \text{ eV} \end{cases}$
- **Planck + DESI will yield** $\sigma_{\sum m_\nu} = 0.017 \text{ eV}$
- Tritium β -decay (Troitzk): $m_{\bar{\nu}_e} < 2.05 \text{ eV}$
- KATRIN forecast: $m_{\bar{\nu}_e} \sim 0.2 \text{ eV}$ ($\sum m_\nu \approx 0.6 \text{ eV}$)

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Inflation in one plot



Testing inflation through primordial non-Gaussianity

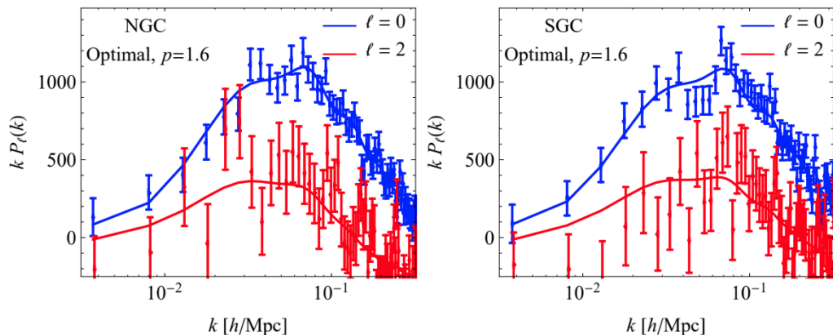


$$\phi_P = \phi + f_{NL}^{loc}(\phi^2 - \langle \phi^2 \rangle)$$

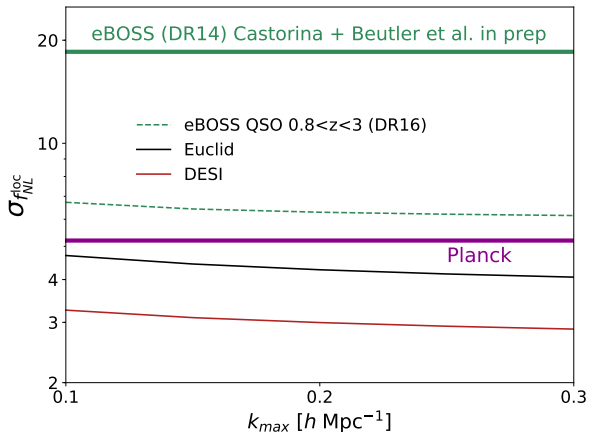
$$\delta_g(k) = \delta_m(k) \left(b_1 + f\mu^2 + \frac{b_{\phi} f_{NL}^{loc} \alpha}{k^2} \right)$$

Primordial non-Gaussianity with LSS (preliminary)

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

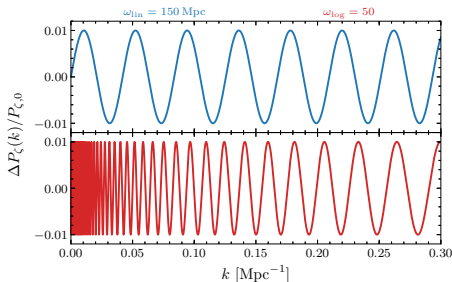


Primordial non-Gaussianity with LSS



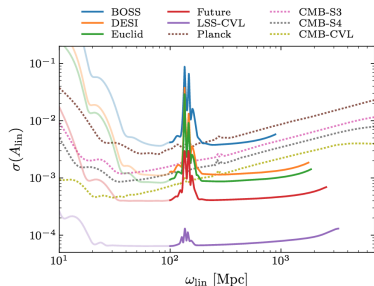
- **No bispectrum information included yet!** $\rightarrow f_{NL}^{equil}, f_{NL}^{ortho}$
- **SPHEREx is now funded** $\rightarrow \sigma_{f_{NL}^{loc}} < 1$ in 2025

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.
- Such features are predicted by many popular inflationary models like monodromy inflation, brane inflation, axion inflation etc.

Testing inflation through primordial features



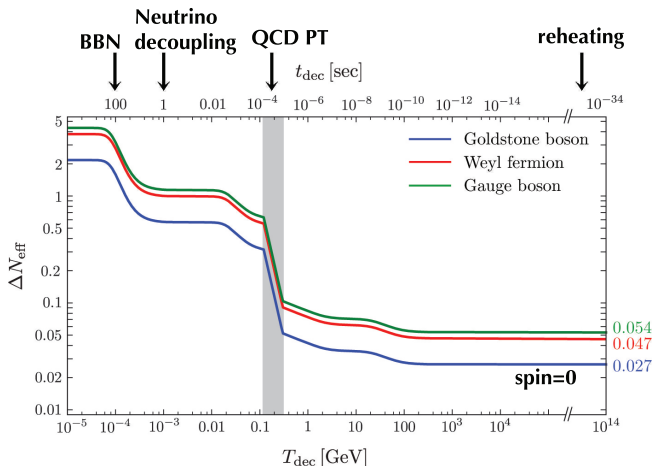
- Here we use a model-independent approach based on

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

- 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

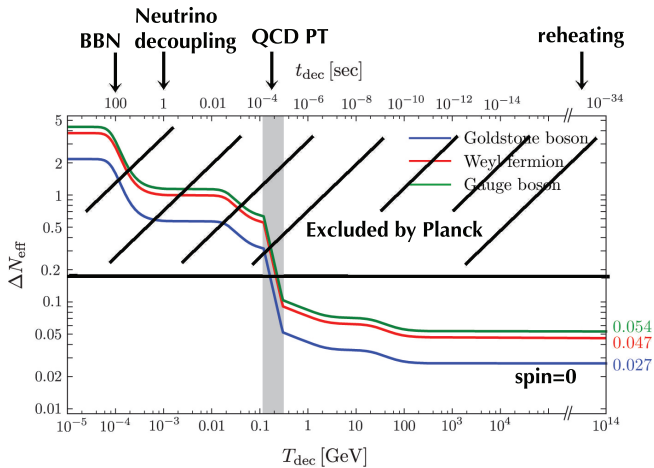
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Motivation: Neutrinos in the phase of the BAO



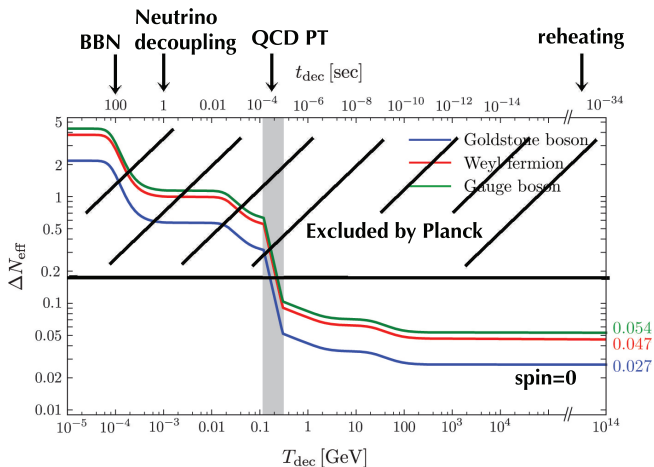
$$\rho_r = \left[1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_{\text{eff}} \right] \rho_\gamma$$

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

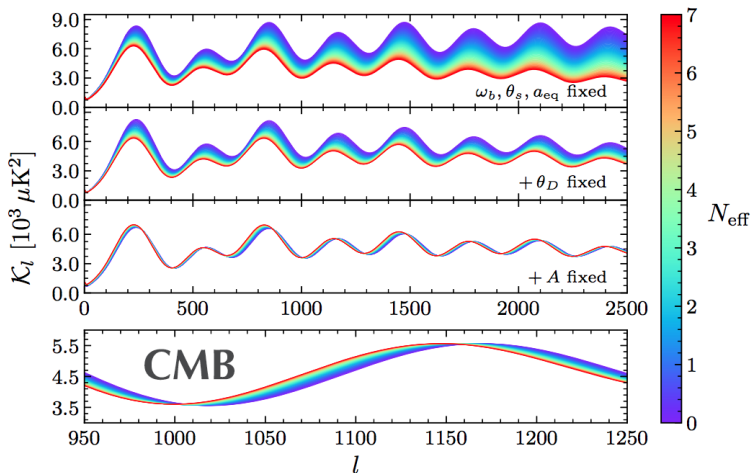


$$\sigma(N_{\text{eff}}) = 0.030 \quad (\text{CMB-S4})$$

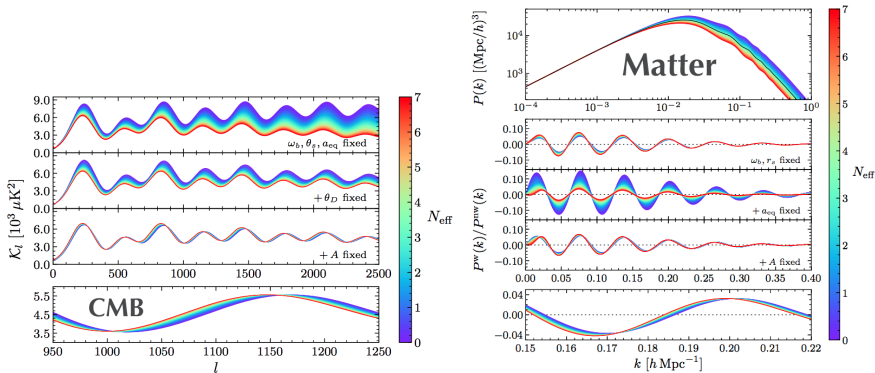
$$\sigma(N_{\text{eff}}) = 0.027 \quad (\text{CMB-S4 + Euclid})$$

Neutrinos in the CMB Spectrum

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

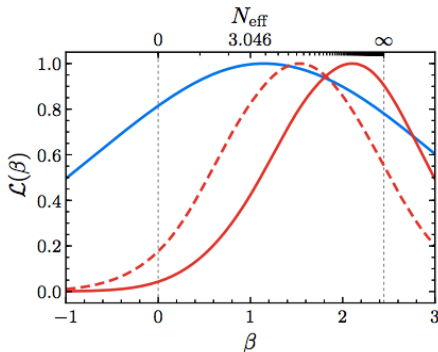
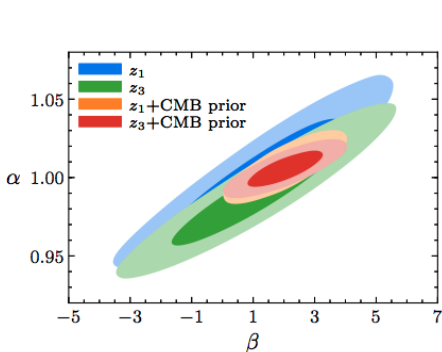


Neutrinos in the BAO Spectrum



Neutrinos in the BAO Spectrum

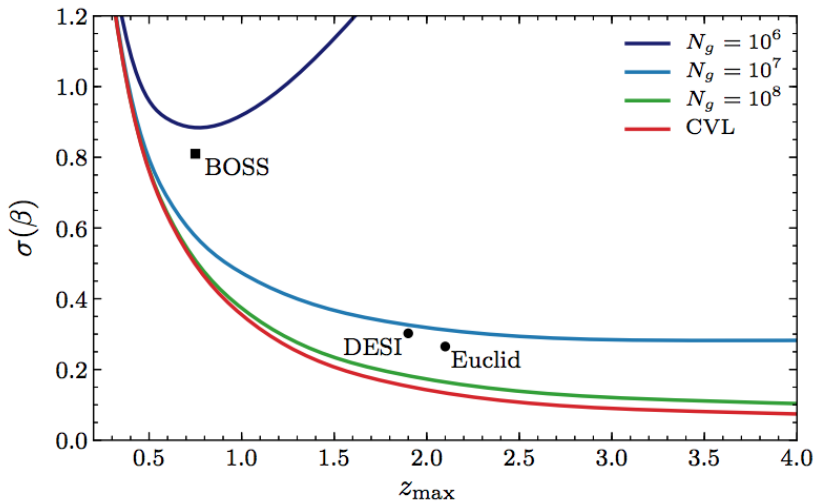
$$O(k) = O_{\text{lin}}(k/\alpha + (\beta - 1)f(k)/r_s^{\text{fid}})e^{-k^2\sigma_{\text{nl}}^2/2}$$



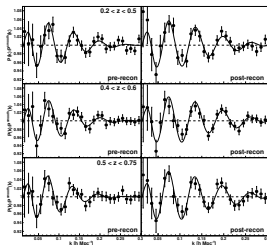
$$\beta(N_{\text{eff}}) = \frac{\epsilon}{\epsilon_{\text{fid}}} \quad \text{with} \quad \epsilon = \frac{N_{\text{eff}}}{8(11/4)^{4/3}/7 + N_{\text{eff}}}$$

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

Neutrinos in the BAO Spectrum

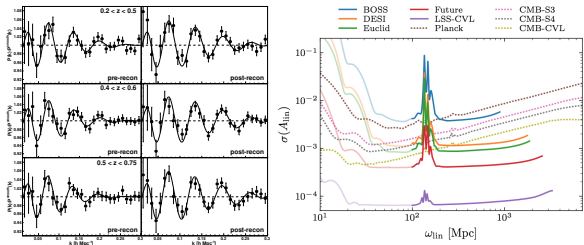


Summary



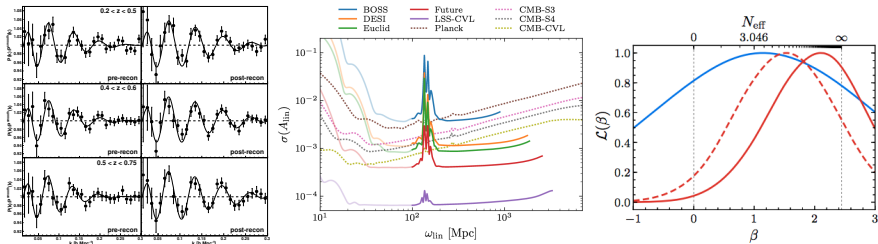
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Summary



- 1 The next generation of galaxy surveys offers unprecedented cosmological constraints using BAO + 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 Constraints on primordial features at high frequencies are **already dominated by LSS data.**

Summary



- 1 The next generation of galaxy surveys offers unprecedented cosmological constraints using BAO + 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 Constraints on primordial features at high frequencies are **already dominated by LSS data**.
- 4 The **phase of the BAO** carries information on N_{eff} just as in the CMB. We have a **low significance detection in BOSS** and will be able to get $\sim 3 - 5\sigma$ detections in DESI and Euclid.

- 1 What is the nature of inflation?
↔ primordial features, primordial non-Gaussianity, primordial grav. waves
 - 2 What is the Neutrino mass scale and are there additional relativistic d.o.f. in the early Universe?
↔ BAO, RSD, CMB lensing, Ly- α forest, weak lensing
 - 3 What is the nature of dark matter and dark energy?
↔ BAO... testing modified gravity with RSD
- Co-chair of the Euclid galaxy clustering working group (since 10/2015)
 - Manager of the spectroscopic visibility mask and sample selection for Euclid (since 03/2016)
 - Member of the DESI institutional board (Since 07/2018) and AI WG lead
 - I led the BOSS DR11, Fourier-space RSD and neutrino mass analysis (Beutler et al. 2014), and the final BOSS, Fourier-space BAO and RSD analysis (Beutler et al. 2017a, 2017b)
 - I led the BOSS-WiggleZ project → first BAO detection in cross-correlation (Beutler et al. 2015)

Further linear corrections

At horizon scales further linear (GR) corrections start to matter:

$$\begin{aligned} \delta_g(k) = & \delta_m(k) \left(b_1 + f\mu^2 \right) - \overbrace{\int_0^r dr' \frac{r-r'}{rr'} \Delta_\Omega(\Phi + \Psi)}^{\text{Lensing}} \\ & + \overbrace{\left(1 - \frac{\dot{\mathcal{H}}}{\mathcal{H}^2} - \frac{2}{r\mathcal{H}} \right) v_{\parallel} + \frac{1}{\mathcal{H}} \dot{v}_{\parallel}}^{\text{Doppler}} + \overbrace{\frac{1}{\mathcal{H}} \partial_r \Psi}^{\text{grav. redshift}} \\ & + \Psi - 2\Phi + \frac{1}{\mathcal{H}} \dot{\Phi} + \frac{2}{r} \int_0^r dr' (\Phi + \Psi) \\ & + \left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + \frac{2}{r\mathcal{H}} \right) \left[\Psi + \int_0^r dr' (\dot{\Phi} + \dot{\Psi}) \right] \left. \vphantom{\int_0^r dr' (\Phi + \Psi)} \right\} \text{Potential} \end{aligned}$$

- 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

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

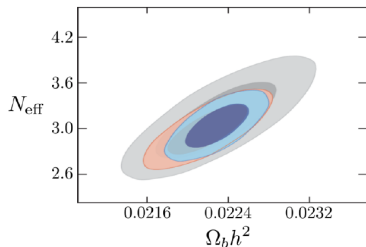
- Marginalize to get $\mathcal{L}(\alpha)$.

Current constraints on N_{eff}

Relic neutrinos make up 41% of the radiation density

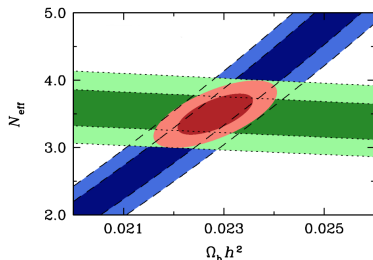
$$\rho_r = \left[1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_{\text{eff}} \right] \rho_\gamma$$

CMB



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

BBN



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

New decomposition formalism for the bispectrum

The estimator is based on the spherical harmonics expansion

$$\begin{aligned}\widehat{B}_{\ell_1 \ell_2 L}(k_1, k_2) &= H_{\ell_1 \ell_2 L} \sum_{m_1 m_2 M} \begin{pmatrix} \ell_1 & \ell_2 & L \\ m_1 & m_2 & M \end{pmatrix} \\ &\times \frac{N_{\ell_1 \ell_2 L}}{I} \int \frac{d^2 \hat{k}_1}{4\pi} y_{\ell_1}^{m_1^*}(\hat{k}_1) \int \frac{d^2 \hat{k}_2}{4\pi} y_{\ell_2}^{m_2^*}(\hat{k}_2) \\ &\times \int \frac{d^3 k_3}{(2\pi)^3} (2\pi)^3 \delta_D(\vec{k}_1 + \vec{k}_2 + \vec{k}_3) \\ &\times \delta n(\vec{k}_1) \delta n(\vec{k}_2) \delta n_L^M(\vec{k}_3)\end{aligned}$$

where $y_L^{M^*}$ -weighted density fluctuation

$$\delta n_L^M(\vec{x}) \equiv y_L^{M^*}(\hat{x}) \delta n(\vec{x})$$

$$\delta n_L^M(\vec{k}) = \int d^3 x e^{-i\vec{k}\cdot\vec{x}} \delta n_L^M(\vec{x})$$

and $y_\ell^m = \sqrt{4\pi/(2\ell+1)} Y_\ell^m$.

Why using this formalism

- This decomposition compresses the data into 2D quantities $B_{\ell_1 \ell_2 L}(k_1, k_2)$ rather than 3D quantities like other decompositions $B_{\ell}^m(k_1, k_2, k_3)$. This reduces the size of the connected covariance matrix.
- This decomposition allows for a self consistent inclusion of the survey window function.
- The RSD information is clearly separated into the L multipoles.
- The complexity of our estimator is $\mathcal{O}((2\ell_1 + 1)N_b^2 N \log N)$.
- Only some multipoles are non-zero: (1) $\ell_1 > \ell_2$ (2) $L = \text{even}$ (3) $|\ell_1 - \ell_2| \leq L \leq |\ell_1 + \ell_2|$ and (4) $\ell_1 + \ell_2 + L = \text{even}$.