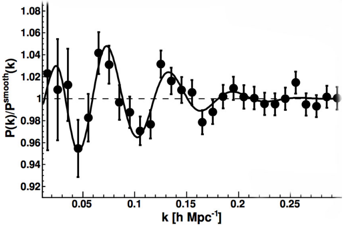
Exploring fundamental physics with galaxy redshift surveys

Florian Beutler



THE ROYAL SOCIETY

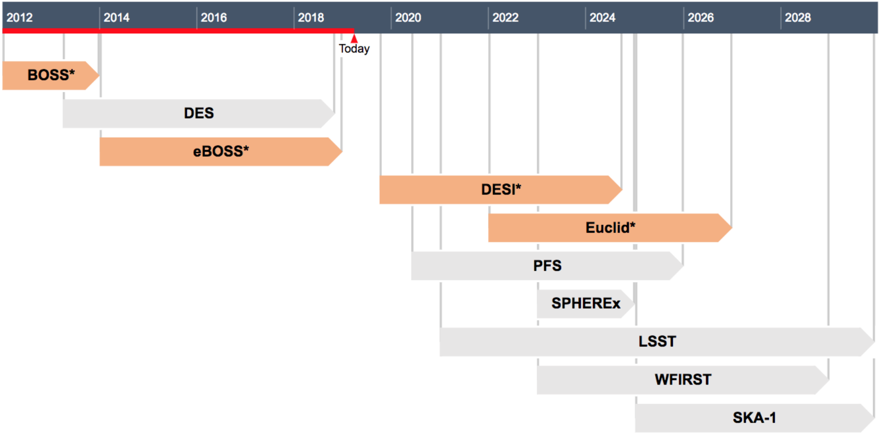
ICG Portsmouth

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

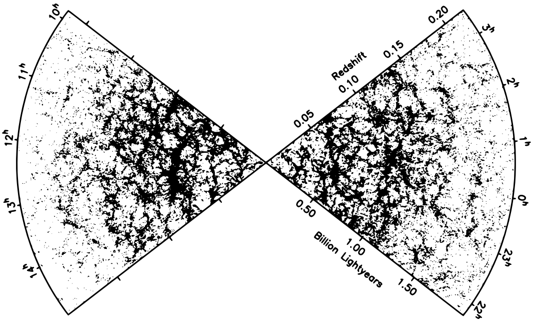
Why should you care?



- DESI will start observing this year!

*Collaboration Member

What is a galaxy redshift survey?

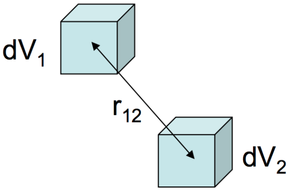


- Measure the position of galaxies (redshift + RA, DEC).
- The CMB tells us a lot about the initial conditions for today's distribution of matter.
- How the initial density fluctuations in the CMB evolved from redshift $z \sim 1100$ to today depends on Ω_m, Ω_Λ, H_0 etc.

From a point distribution to a power spectrum

- Overdensity-field:

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



- Two-point function:

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

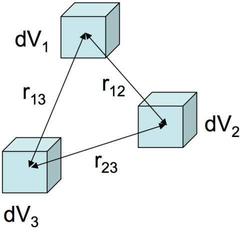
- ...and in Fourier-space:

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

From a point distribution to a bispectrum

- Overdensity-field:

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



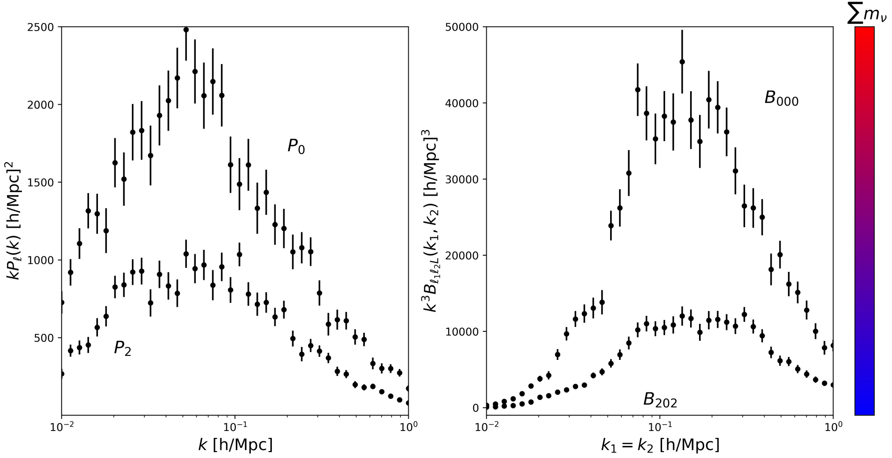
- Three-point function:

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

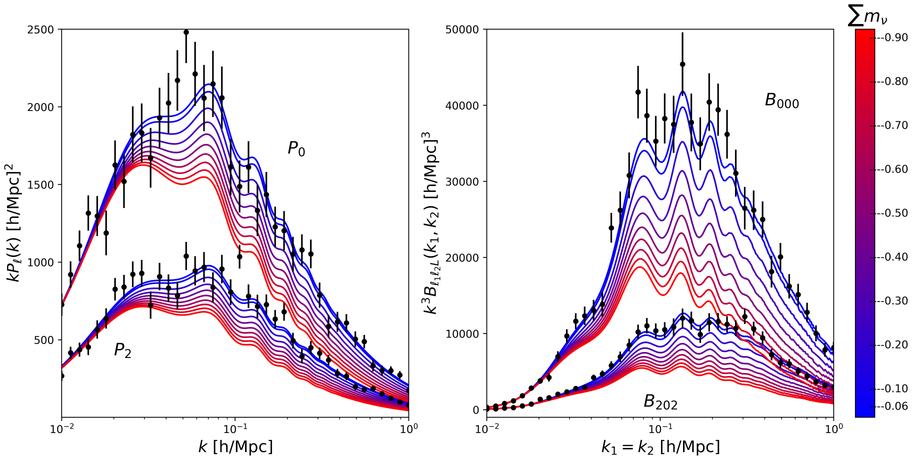
- ...and in Fourier-space:

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

Extracting cosmological information



Extracting cosmological information



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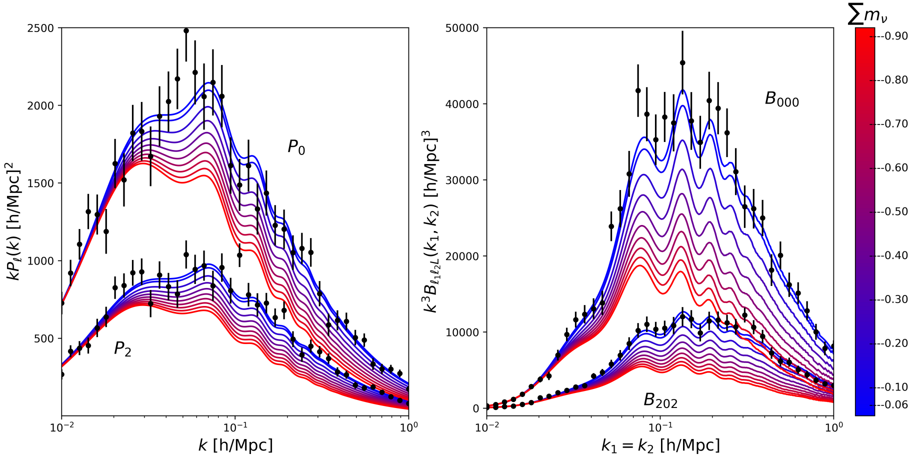
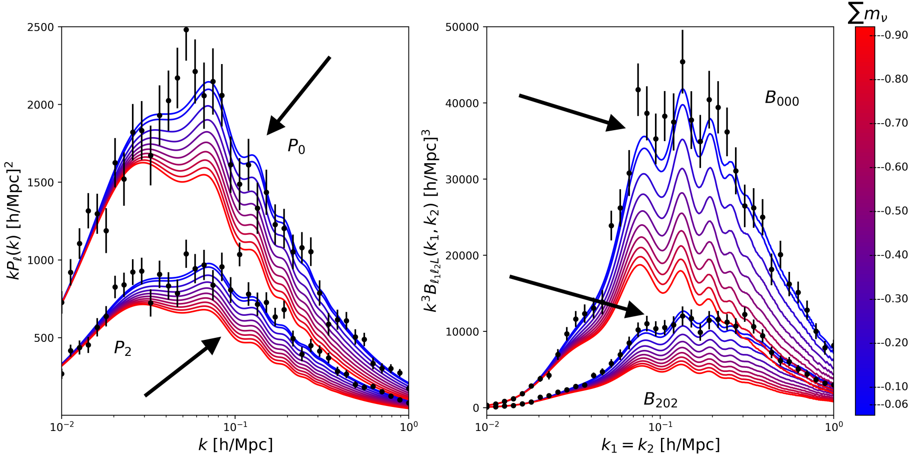
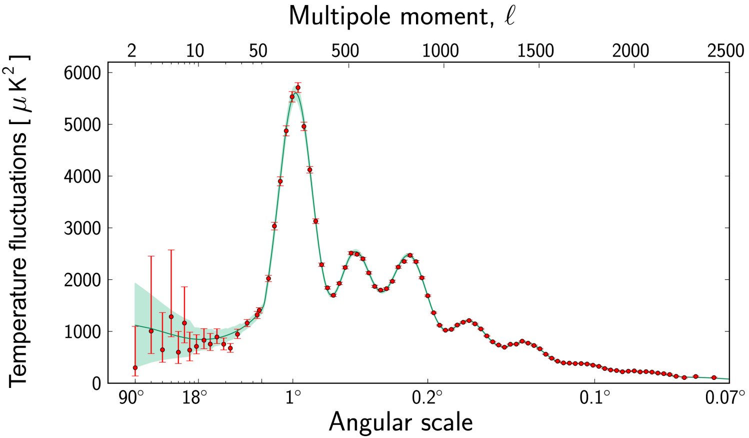
Extracting cosmological information



Extracting cosmological information



What are Baryon Acoustic Oscillations?



Planck collaboration

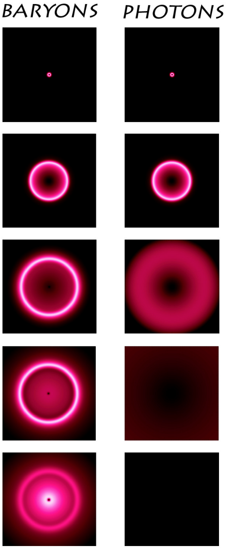
- For the first 380 000 years the evolution eq. of baryon and photon perturbations can be written as

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

with the plane wave solution

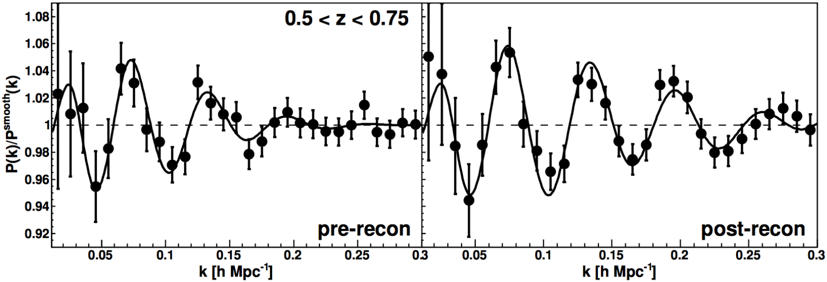
$$\delta_{b\gamma} = A\cos(kr_s + \phi)$$

- 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

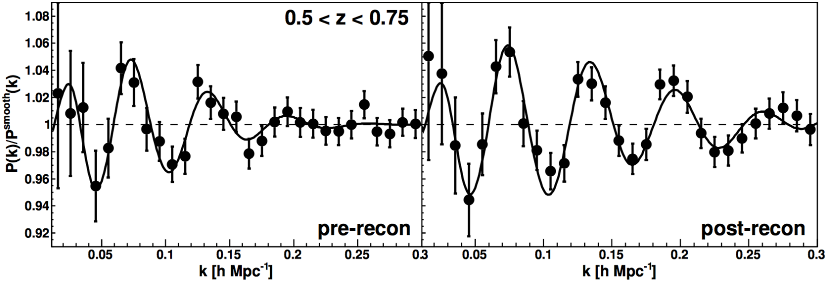


$$D_A(z) = \int_0^z \frac{cdz'}{H(z')}$$

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

Beutler et al. (2017)

Baryon Acoustic Oscillations in BOSS



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

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

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

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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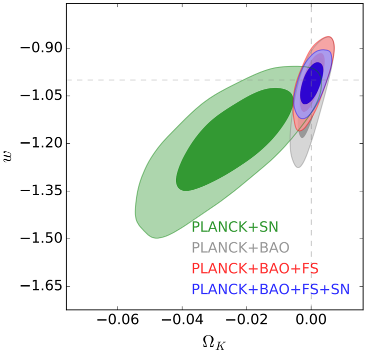


Alam + Beutler et al. (2017)

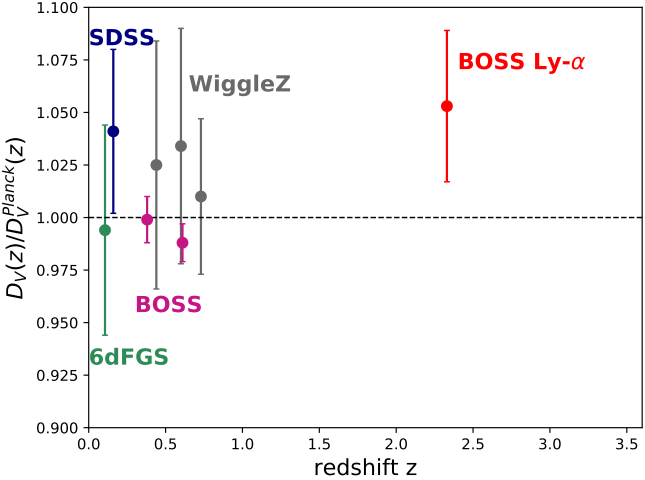
Planck+SN:

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

Planck+SN+BAO:

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

Looking into the (near) future



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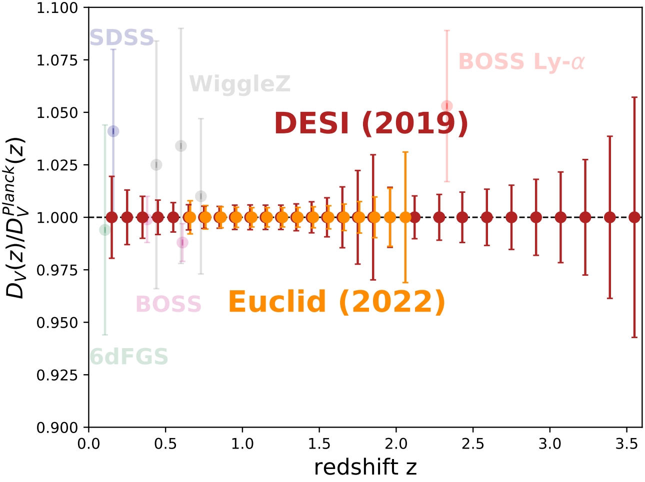

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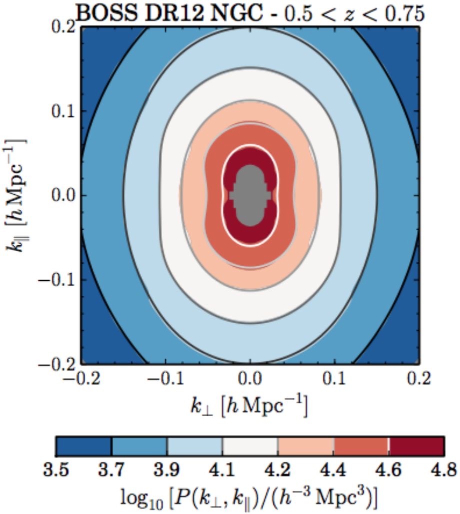
The densities along the line-of-sight are enhanced due to the velocity field

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

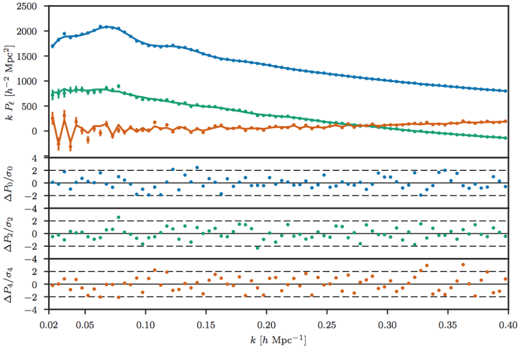
→ Introduces a quadrupole
→ Sensitive to cosmology since

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



Alam + Beutler et al. (2017)

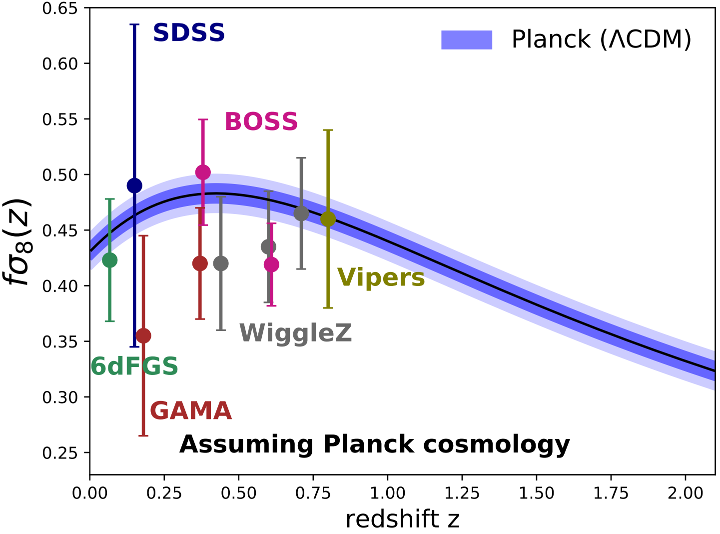
Broadband modelling - Distribution function model



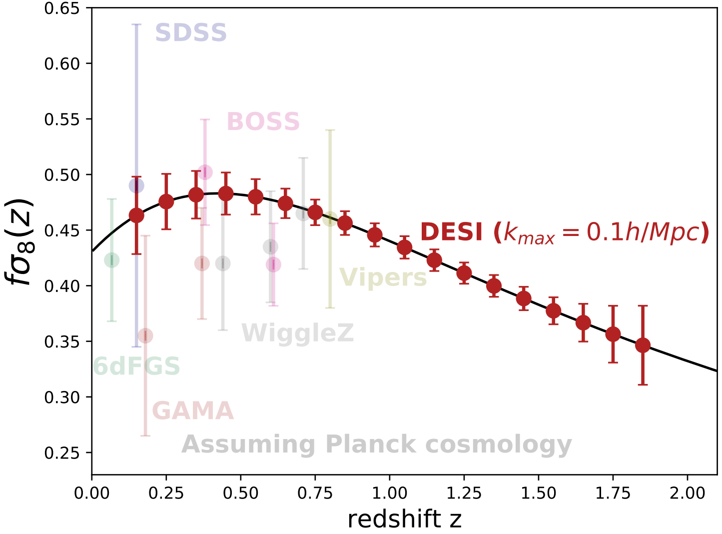
- Can model the power spectrum up to $k_{\mathrm{max}} = 0.4h/\mathrm{Mpc}$ using 9 nuisance (HOD based) parameters.
- We still have to **include the bispectrum** to constrain the nuisance parameters.

Hand + Beutler et al. (2017)

Looking into the (near) future



Looking into the (near) future



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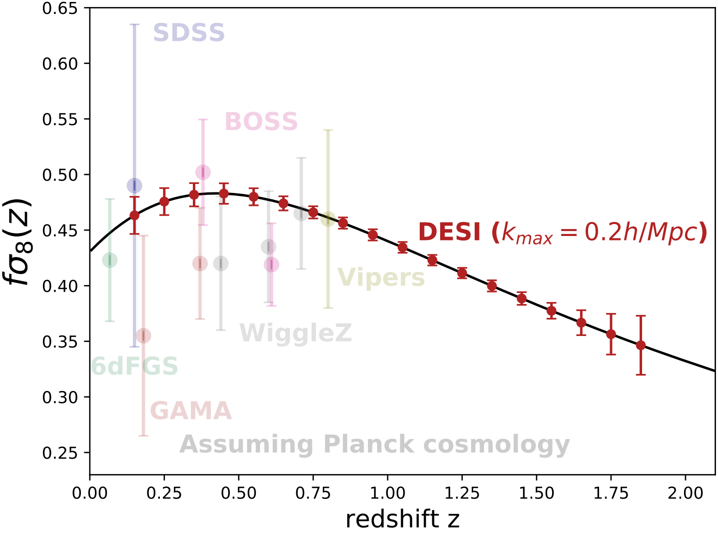

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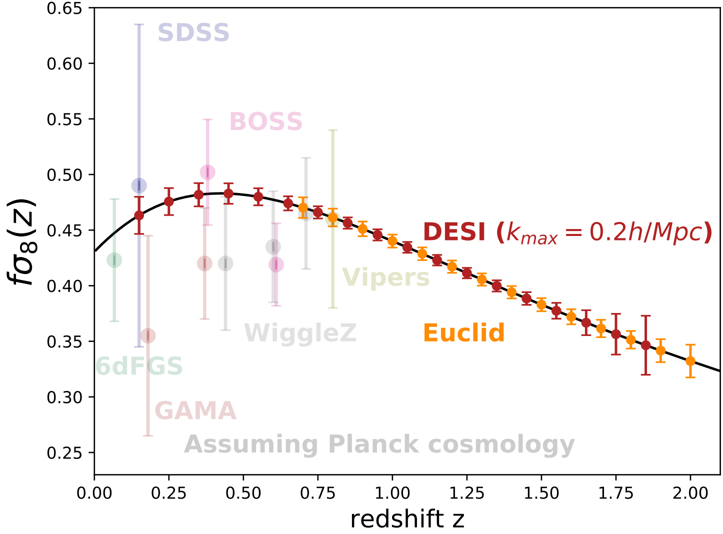
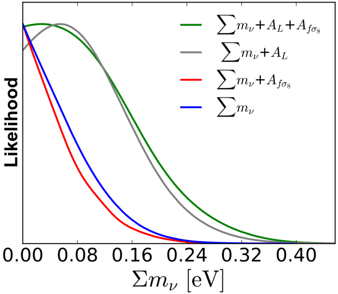


Constraining the neutrino mass with BAO & RSD



$|\Delta m^2_{31}| \simeq 2.56\times10^{-3}\,\mathrm{eV}^2$
$\Delta m^2_{21} \simeq 7.37\times10^{-5}\,\mathrm{eV}^2$

$0.06\,eV \lesssim \text{Planck}\left(\Lambda\text{CDM} + \sum m_\nu\right) + \text{BOSS} < 0.16\,eV$

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

Alam + Beutler et al. (2017), PDG (2018), Font-Ribera et al. (2014), Wolf (2008)

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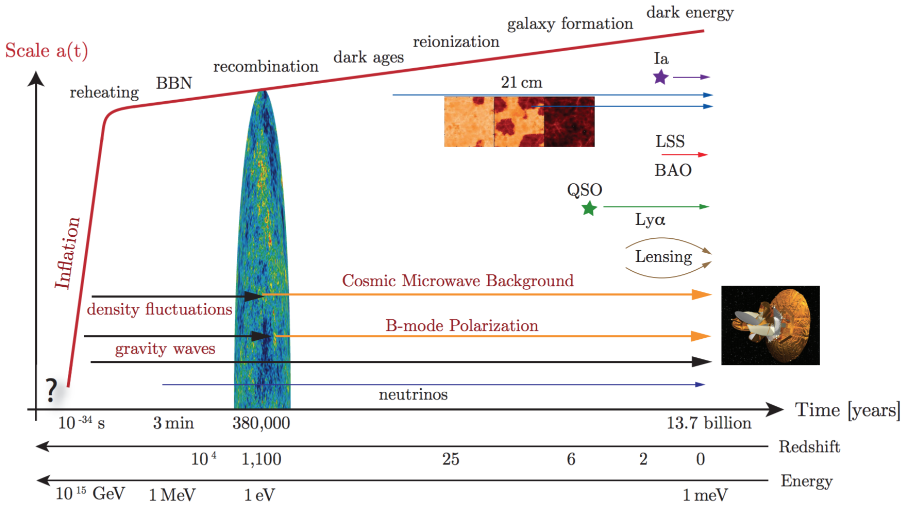
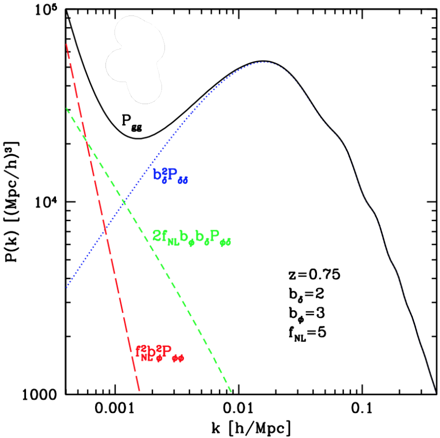
Inflation in one plot



Baumann (2009)

Testing inflation through primordial non-Gaussianity

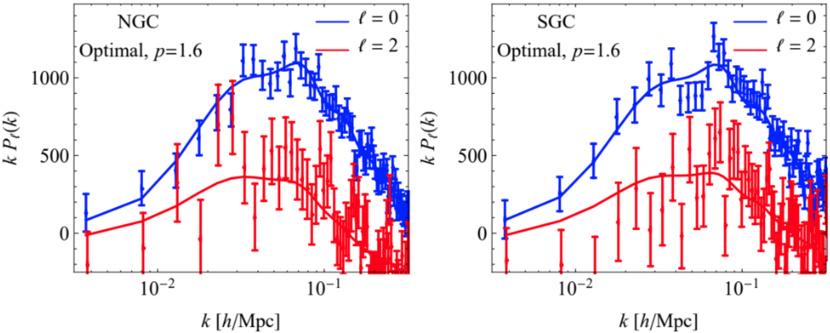


$$\phi_\mathrm{p} = \phi + f_\mathrm{NL}^\mathrm{loc}(\phi^2 - \langle\phi^2\rangle)$$

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

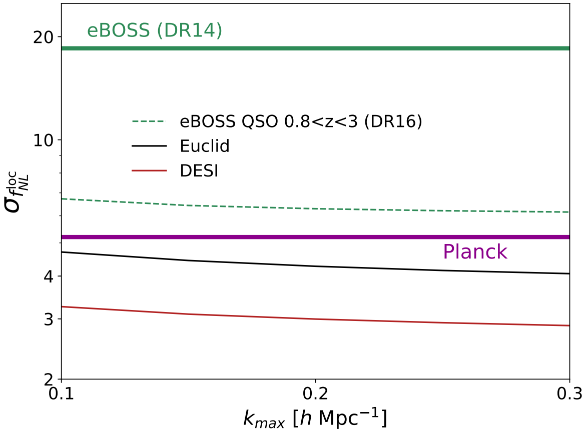
McDonald (2008)

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

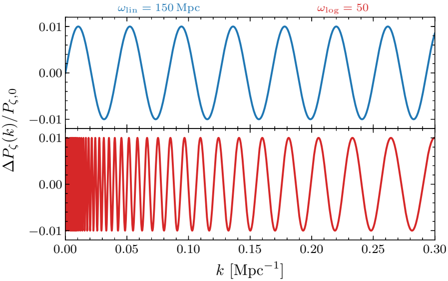


Castorina + Beutler et al. in prep.

Primordial non-Gaussianity with LSS



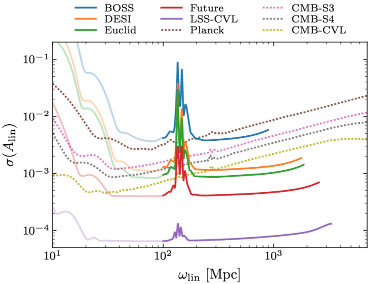
- **No bispectrum information included yet!** $\rightarrow f_{\rm NL}^{\rm equil}, f_{\rm NL}^{\rm ortho}$
- **SPHEREx is now funded** $\rightarrow \sigma_{f_{\rm NL}^{\rm loc}} < 1$ **in 2025**



- 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.

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
- DESI is going to provide constraints which cannot be accessed even by a CVL CMB experiment

Beutler et al. in prep.

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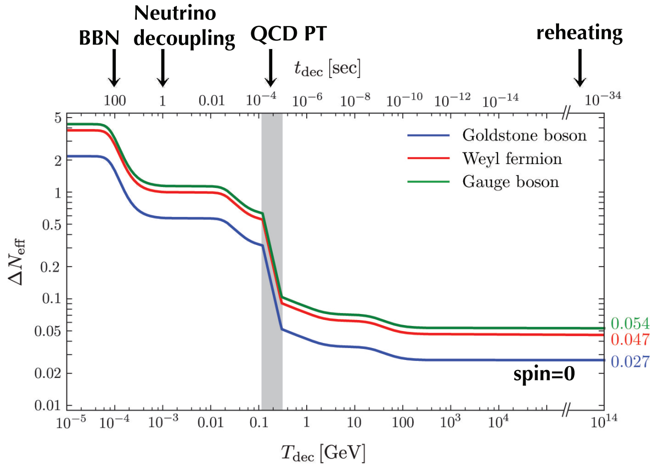
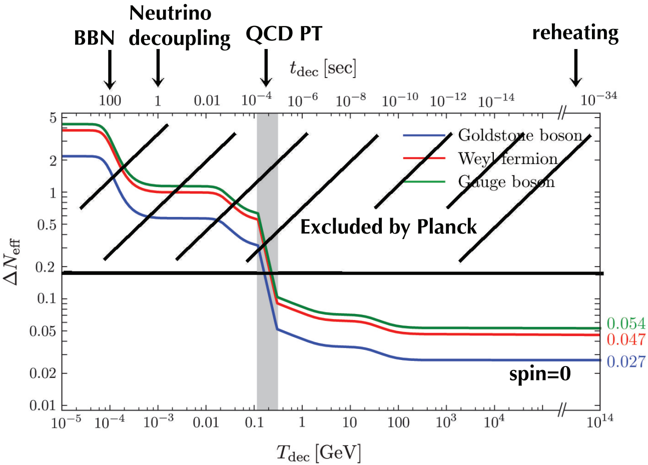
Motivation: Neutrinos in the phase of the BAO



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

Baumann et al. (2017)

Motivation: Neutrinos in the phase of the BAO



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

Baumann et al. (2017)

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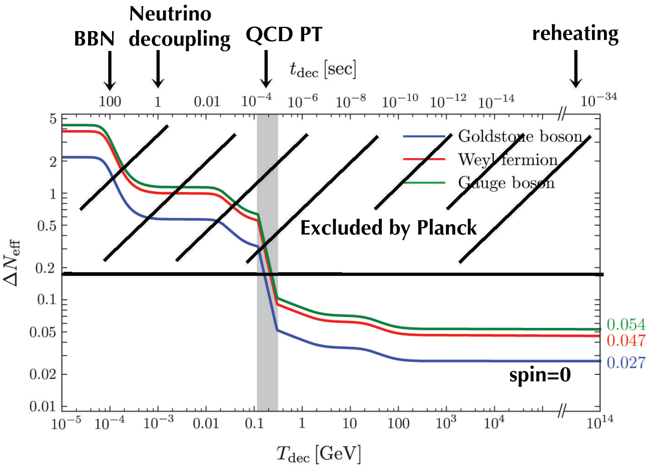


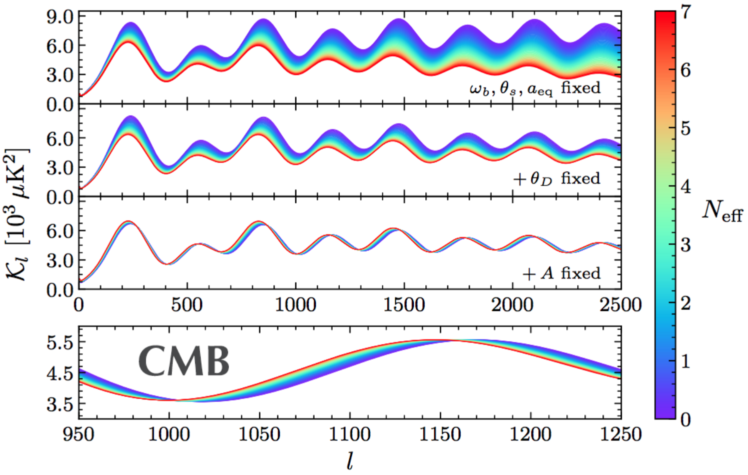
$\sigma(N_{\rm eff}) = 0.030$ (CMB-S4)

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

Baumann et al. (2017)

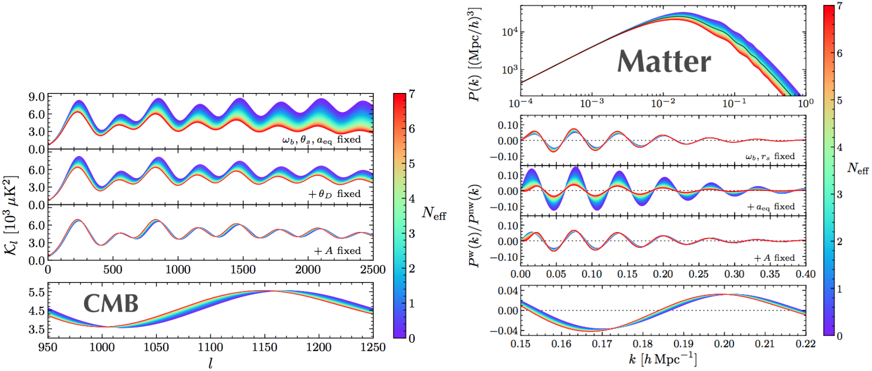
Neutrinos in the CMB Spectrum

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



Baumann et al. (2017)

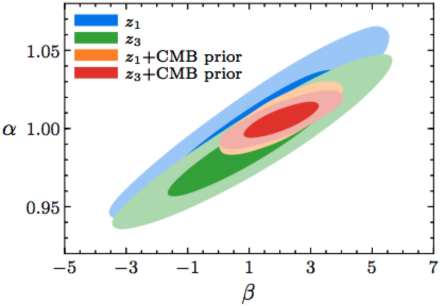
Neutrinos in the BAO Spectrum

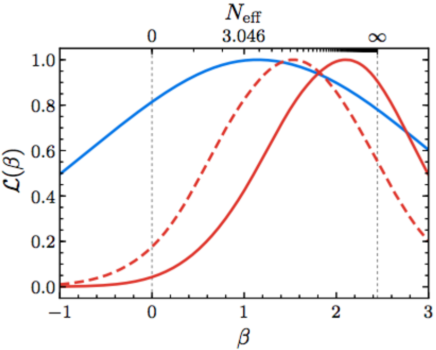


Baumann et al. (2017)

Neutrinos in the BAO Spectrum

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



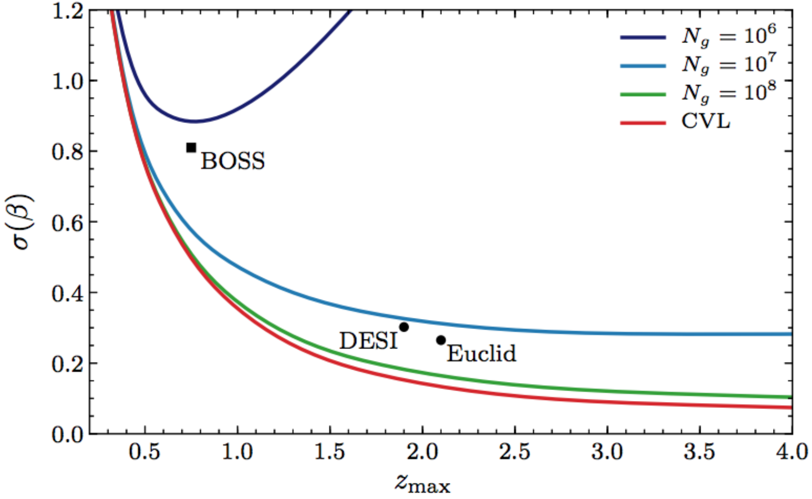


$$\beta(N_{\rm eff}) = \frac{\epsilon}{\epsilon_{\rm fid}} \qquad \text{with} \qquad \epsilon = \frac{N_{\rm eff}}{8(11/4)^{4/3}/7 + N_{\rm eff}}$$

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

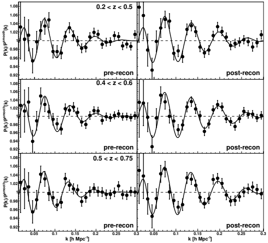
Baumann + Beutler et al. (2019)

Neutrinos in the BAO Spectrum



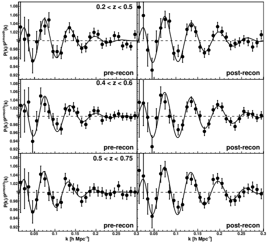
Baumann + Beutler et al. (2019)

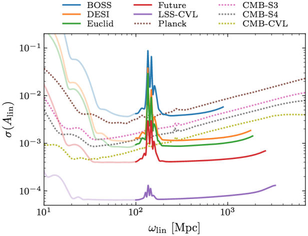
Summary



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

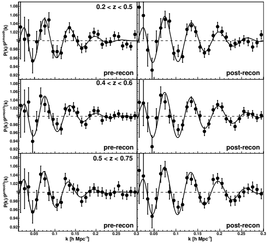
Summary

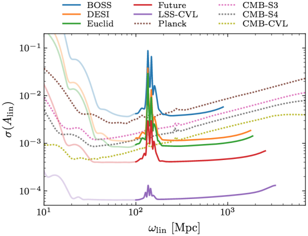


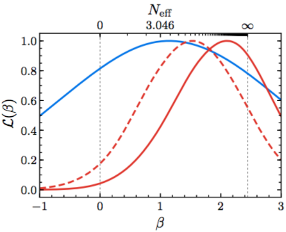


1. The next generation of galaxy surveys offers unprecedented cosmological constraints using BAO + RSD and **DESI will start this year**.
2. LSS can constrain inflationary models competitive with the CMB using both **primordial non-Gaussianity** and **primordial features**.
3. Constraints on primordial features at high frequencies are **already dominated by LSS data**.

Summary







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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 $N_{\rm eff}$ 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.

Research agenda

1. What is the nature of inflation?
   $\hookrightarrow$ 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?
   $\hookrightarrow$ BAO, RSD, CMB lensing, Ly-α forest, weak lensing
3. What is the nature of dark matter and dark energy?
   $\hookrightarrow$ 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 $\rightarrow$ first BAO detection in cross-correlation (Beutler et al. 2015)

Further linear corrections

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

$$\delta_g(k) = \delta_m(k)\left(b_1 + f\mu^2\right) - \overbrace{\int_0^r dr' \frac{r-r'}{rr'}\Delta_\Omega(\Phi+\Psi)}^{\text{Lensing}}$$

$$+ \overbrace{\left(1 - \frac{\dot{\mathcal{H}}}{\mathcal{H}^2} - \frac{2}{r\mathcal{H}}\right)v_\parallel + \frac{1}{\mathcal{H}}\dot{v}_\parallel}^{\text{Doppler}} + \overbrace{\frac{1}{\mathcal{H}}\partial_r\Psi}^{\text{grav. redshift}}$$

$$\left.\begin{aligned} &+\Psi - 2\Phi + \frac{1}{\mathcal{H}}\dot{\Phi} + \frac{2}{r}\int_0^r dr'(\Phi+\Psi) \\ &+\left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + \frac{2}{r\mathcal{H}}\right)\left[\Psi + \int_0^r dr'(\dot{\Phi}+\dot{\Psi})\right] \end{aligned}\right\} \text{Potential}$$

Yoo et al. (2010), Bonvin & Durrer (2011), Challinor & Lewis (2011)

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

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

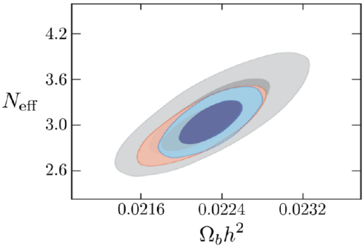
- Marginalize to get $\mathcal{L}(\alpha)$.

Current constraints on $N_{\rm eff}$

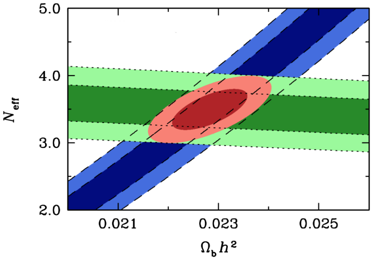
Relic neutrinos make up 41% of the radiation density

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

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)

New decomposition formalism for the bispectrum

The estimator is based on the spherical harmonics expansion

$$\widehat{B}_{\ell_1\ell_2L}(k_1,k_2) = H_{\ell_1\ell_2L}\sum_{m_1m_2M}\begin{pmatrix}\ell_1 & \ell_2 & L\\ m_1 & m_2 & M\end{pmatrix}$$
$$\times\frac{N_{\ell_1\ell_2L}}{I}\int\frac{d^2\hat{k}_1}{4\pi}y_{\ell_1}^{m_1*}(\hat{k}_1)\int\frac{d^2\hat{k}_2}{4\pi}y_{\ell_2}^{m_2*}(\hat{k}_2)$$
$$\times\int\frac{d^3k_3}{(2\pi)^3}(2\pi)^3\delta_{\rm D}\left(\vec{k}_1+\vec{k}_2+\vec{k}_3\right)$$
$$\times\,\delta n(\vec{k}_1)\,\delta n(\vec{k}_2)\,\delta n_L^M(\vec{k}_3)$$

where y_L^{M*}-weighted density fluctuation

$$\delta n_L^M(\vec{x}) \equiv y_L^{M*}(\hat{x})\,\delta n(\vec{x})$$
$$\delta n_L^M(\vec{k}) = \int d^3x e^{-i\vec{k}\cdot\vec{x}}\delta n_L^M(\vec{x})$$

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 $B_{\ell_1\ell_2L}(k_1,k_2)$ 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 $\mathcal{O}((2\ell_1+1)N_b^2N\log N)$.
- Only some multipoles are non-zero: (1) $\ell_1 > \ell_2$ (2) L = even (3) $|\ell_1-\ell_2| \leq L \leq |\ell_1+\ell_2|$ and (4) $\ell_1+\ell_2+L =$ even.