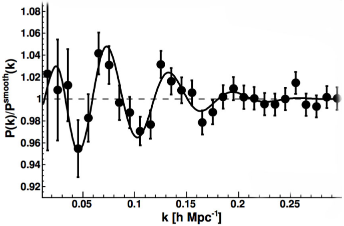
Cosmology with galaxy redshift surveys

Florian Beutler



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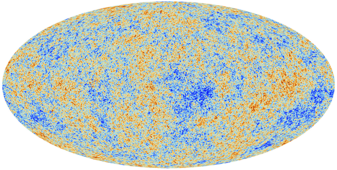
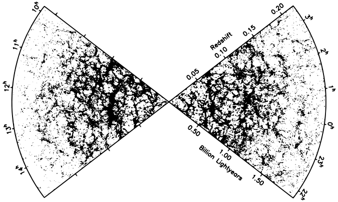
Galaxy redshift survey: the basics



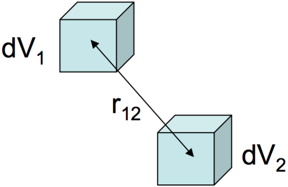


1. Measure the position of galaxies (RA, DEC + redshift).
2. The CMB tells us the initial conditions for today's distribution of matter.
3. How the initial density fluctuations in the CMB evolved from redshift $z = 1100$ to today depends on Ω_m, Ω_Λ, H_0 etc.

From a point distribution to a power spectrum

- Overdensity-field:

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



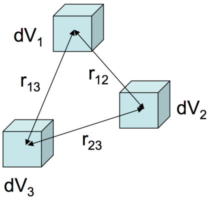
- Two-point function:

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

- ...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:

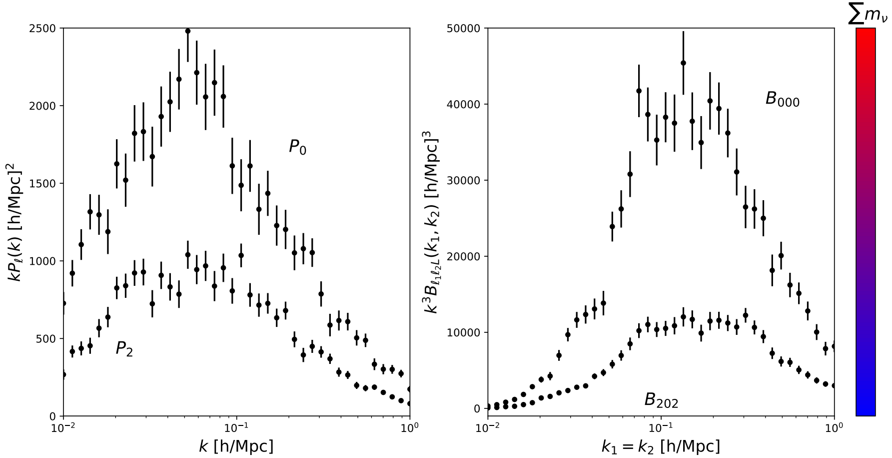
$$\xi(\mathbf{r}_1, \mathbf{r}_2) \overset{\text{homogeneity}}{=} \langle \delta(\mathbf{x} + \mathbf{r}_1)\delta(\mathbf{x} + \mathbf{r}_2)\delta(\mathbf{x}) \rangle \begin{cases} \overset{\text{isotropy}}{=} & \xi_L(r_1, r_2) \\ \overset{\text{anisotropy}}{\longrightarrow} & \xi_{\ell_1\ell_2L}(r_1, r_2) \end{cases}$$

- ...and in Fourier-space:

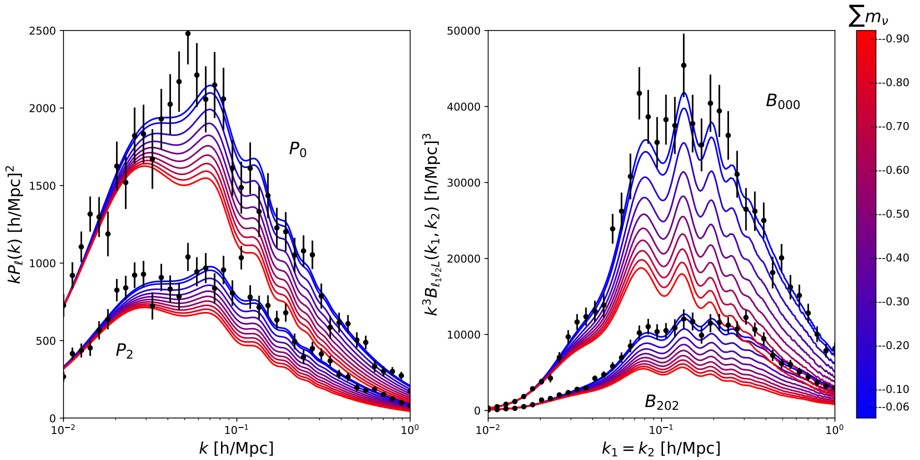
$$B_{\ell_1\ell_2L}(k_1, k_2) = (4\pi)^2(-i)^{\ell_1+\ell_2} \int r_1^2 dr_1 \int r_2^2 dr_2 \xi_{\ell_1\ell_2L}(r_1, r_2) j_{\ell_1}(k_1 r_1) j_{\ell_2}(k_2 r_2)$$

$\longrightarrow$ Public Python/C++ package **Triumvirate**, arXiv:2304.03643
`https://triumvirate.readthedocs.io/en/latest/`

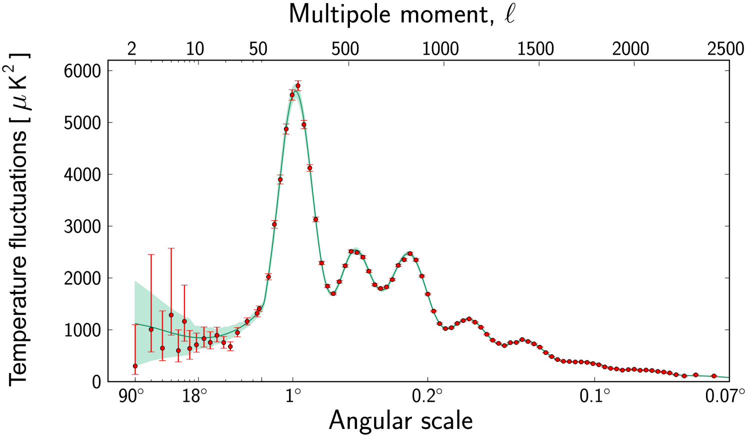
Extracting cosmological information



Extracting cosmological information

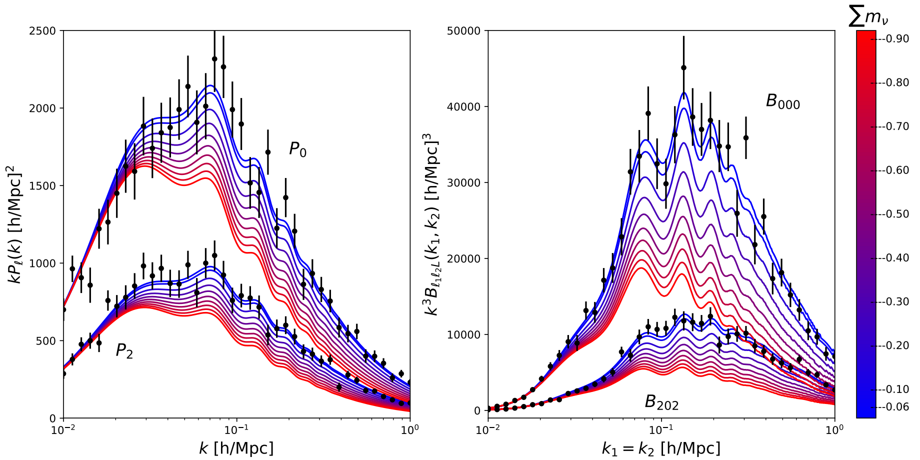


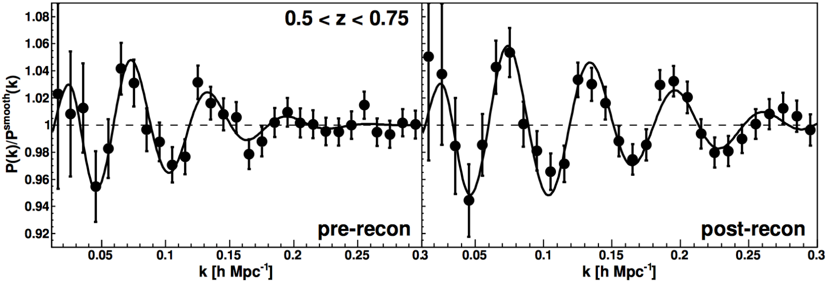
What are Baryon Acoustic Oscillations?



Planck collaboration

What are Baryon Acoustic Oscillations?





- BAO are the most robust observable we can extract from LSS
- The observables are

$$(1+z)D_A(z)/r_d = \int_0^z \frac{cdz'}{r_d H(z')}$$

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

- We require a calibration of the ruler to constrain H_0 (+ cos. model to extrapolate to $z = 0$)

What are redshift-space distortions?

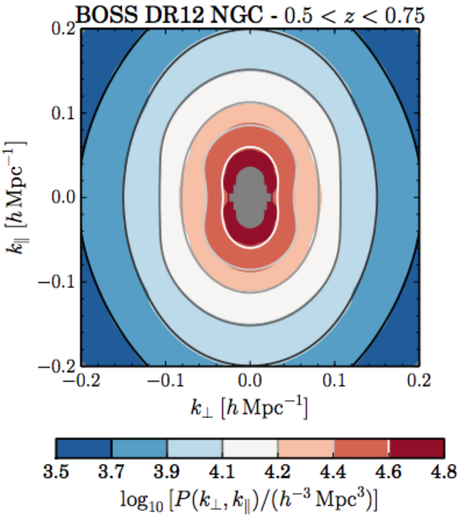
Many more observables, RSD, modified gravity, testing inflation, number of relativistic particles in the early Universe

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

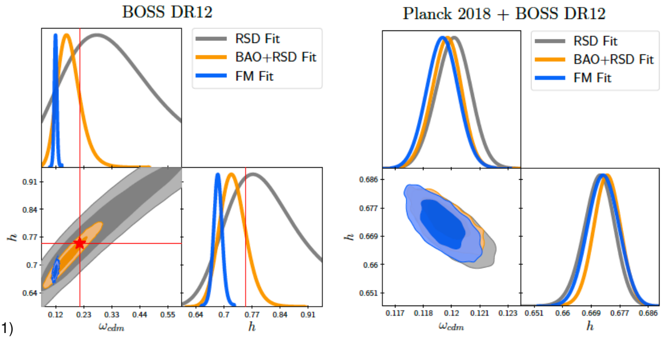
$$\delta_g(k) = b_1\delta_m(k) - \mu^2\nabla\cdot\mathbf{v}$$
$$= \delta_m(k)(b_1 + f\mu^2)$$

→ Introduces a quadrupole
→ Sensitive to cosmology since

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



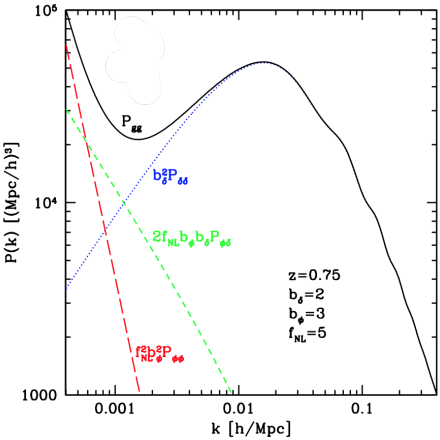
How to extract this information



Brieden et al. (2021)

- The original BOSS analysis extracted BAO and RSD information ($f\sigma_8$, $D_A(z)/r_d$, $H(z)r_d$)
- Recently there was a push for full-shape fits, which can extract additional information from the slope of the power spectrum
- Such information can be extracted from template fits by an extension of 1 or 2 parameters (*ShapeFit*, Brieden et al. 2021)
- How to combine post-recon BAO with a full-shape analysis (Chen et al. 2022)

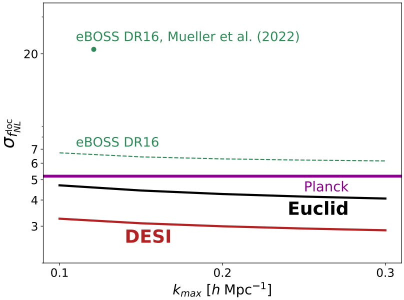
Testing inflation through primordial non-Gaussianity



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

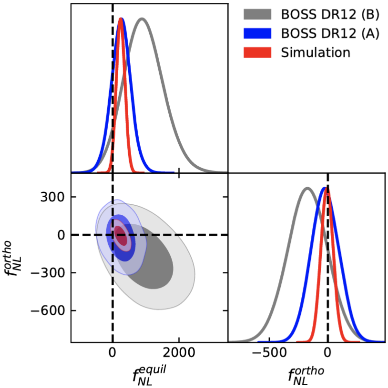
$$\delta_g(k) = \delta_m(k)\left(b_1 + f\mu^2 + \frac{b_\phi f_\mathrm{NL}^\mathrm{loc}\alpha}{k^2}\right) \longrightarrow P_g \propto \frac{b_\phi f_\mathrm{NL}^\mathrm{loc}}{k^2}$$

Dalal et al (2008), McDonald (2008)

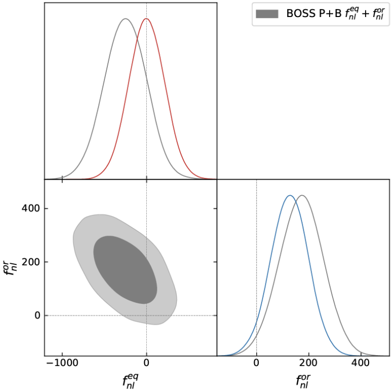


- eBOSS DR16 QSOs: $f_{\rm NL}^{\rm loc} = 12 \pm 21$ (68 C.L.) excluding small k modes and QSOs above $z > 2.2$ (Mueller et al. 2022)
- Theoretical systematics e.g. $b_\phi f_{\rm NL}^{\rm loc}$ degeneracy (Barreira 2022), rel. effects (Castorina & di Dio 2022)
- **SPHEREx** forecasts $\longrightarrow \sigma_{f_{\rm NL}^{\rm loc}} < 0.87$ (with bispectrum 0.23) (Dore et al. 2015)
- BOSS DR12 constraints from the **bispectrum** are $f_{\rm NL}^{\rm loc} = -30 \pm 29$ (68 C.L.) (D'Amico et al. 2022, Cabass et al. 2022)

Non local PNG from BOSS



Cabass et al. (2022),

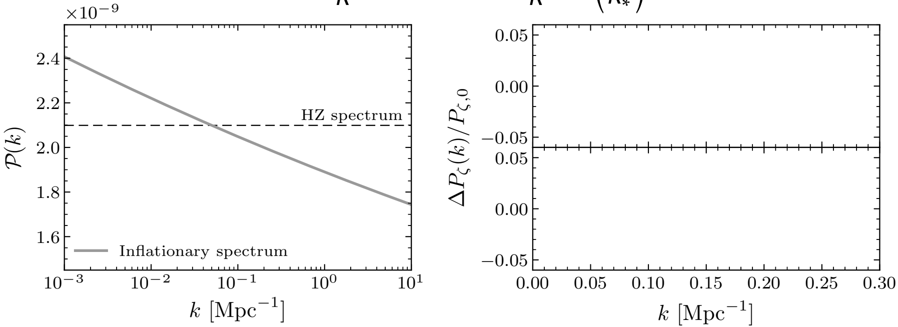


D'Amico et al. (2022)

- Planck 2018: $f_{\rm NL}^{\rm eq} = -26 \pm 47$; $f_{\rm NL}^{\rm ortho} = -38 \pm 24$
- Not yet competitive with the CMB but proof of principle
- **SPHEREx** forecasts $\sigma_{f_{\rm NL}^{\rm eq}} \sim 7$ (Dore et al. 2015)

Testing inflation through primordial features

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



- 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.

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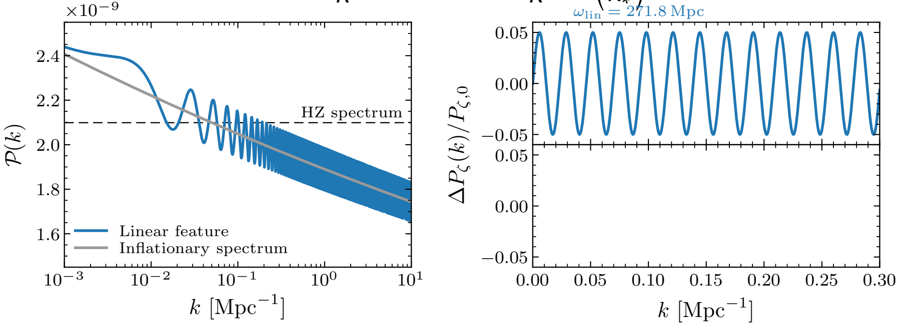

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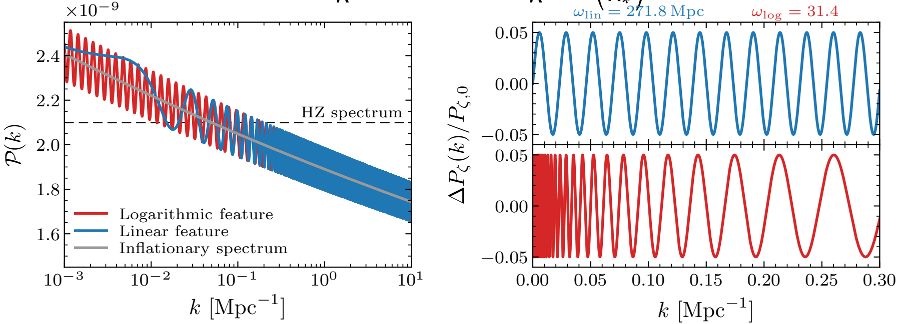

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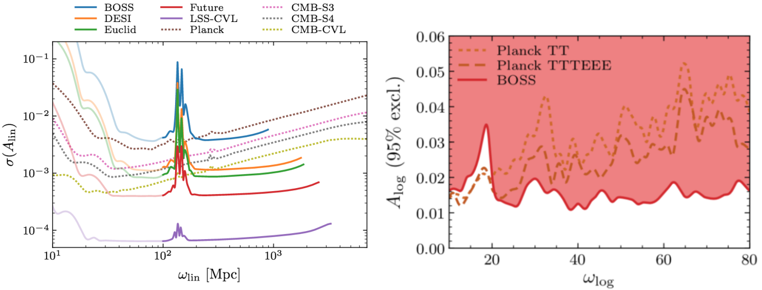
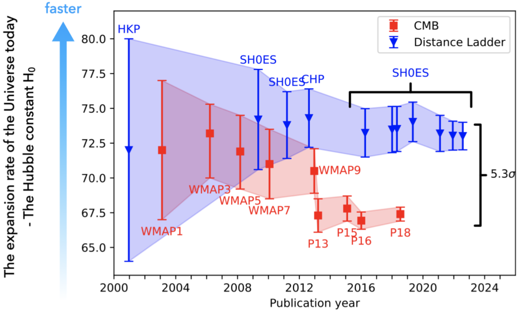


- Here we use a model-independent approach based on

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

- 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

The Hubble tension and LSS



Credit: D'arcy Kenworthy

- The CMB (within LCDM) and local measurements of H_0 are in $> 5\sigma$ tension
- BAO constrain $H(z)r_d$ and D_A/r_d, so we need to calibrate the standard ruler and need to extrapolate to $z = 0 \longrightarrow$ inverse distance ladder
- CMB calibrations allow extending the tension to many models beyond LCDM
- Alternative calibrations use e.g. the baryon density from BBN which agrees well with the Planck constraint

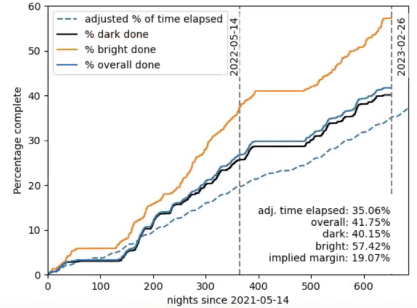
Equality-based constraints: $H_0 = 64.8^{+2.2}_{-2.5}$km/s Mpc (Philcox et al. 2022)

Valentino et al. (2021)

Ongoing survey experiments

DESI

- Mayall 4m telescope at Kitt Peak, Arizona
- 20 - 40 million galaxies over 14 000 deg^2
- In operation since 2020/21

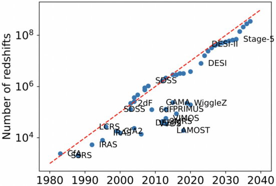


Euclid

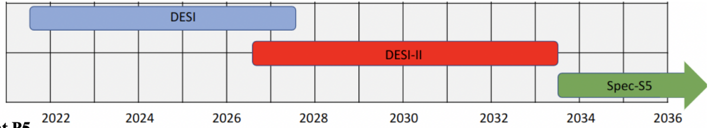
- Launched on July 1st, 2023...
  ...on its way to L2
- 30 million galaxies over 15 000 deg^2
- Slitless spectroscopy (grism)

Spectroscopic surveys in the next decade

- **Dark Energy Spectroscopic Instrument (DESI; primarily z<1.5)**
  - Baryon Acoustic Oscillations (BAO) and Redshift Space Distortions (RSD)
- **DESI-II (primarily z>2)**
  - As powerful as DESI, but at z>2
  - Early dark energy and growth of structure in matter-dominated regime
  - Synergies with other Cosmic Frontier experiments
- **Spec-S5**
  - Primordial physics (more constraining than the CMB in key areas)



Schlegel at P5



Dawson at P5

13

Spec-S5 $\longrightarrow$ 6.5m aperture, 20k fibres

Schelgel et al. arXiv:2209.04322, arXiv:2209.03585, arXiv:1907.11171

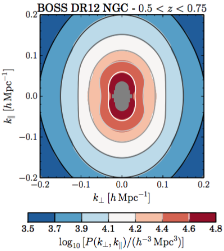
Available data products

- Official BOSS DR12 data release
  https://www.sdss3.org/science/boss_publications.php
- Official eBOSS DR16 data release https://www.sdss4.org/dr16/
- Easy to use Fourier-space products
  https://fbeutler.github.io/hub/deconv_paper.html

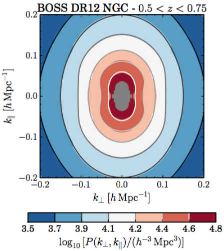
$$\mathcal{L} \propto \exp\left[-\frac{1}{2}(\mathbf{P}_{\mathrm{o}}^{\mathrm{conv}} - \mathbf{WMP}^{\mathrm{true,flat-sky}})^T \mathbf{C}_{\mathrm{conv}}^{-1}(\mathbf{P}_{\mathrm{o}}^{\mathrm{conv}} - \mathbf{WMP}^{\mathrm{true,flat-sky}})\right],$$

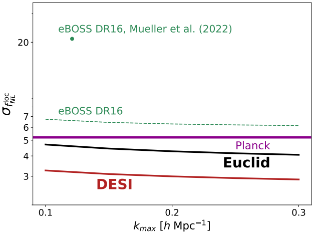
  Following arXiv:2106.06324
- Power spectrum + Bispectrum products
  https://www.ub.edu/bispectrum/page10.html

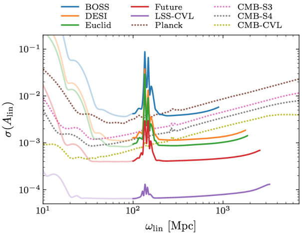
Summary



1. Galaxy surveys offer many observational signatures which can be used to constrain cosmological models (some are more robust than others)



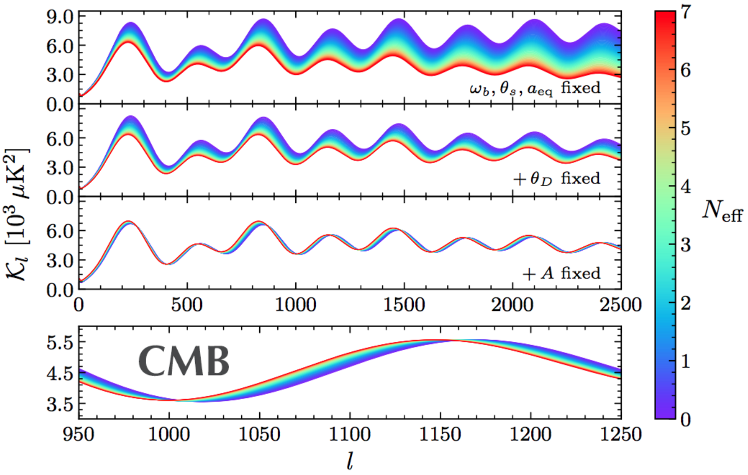




1. Galaxy surveys offer many observational signatures which can be used to constrain cosmological models (some are more robust than others)
2. Stage 4 galaxy redshift surveys (like DESI and Euclid) have the potential to compete with the CMB on several tests of inflation
3. Galaxy survey constraints on the Hubble constant agree well with the CMB (relying on the same physics but different systematics)

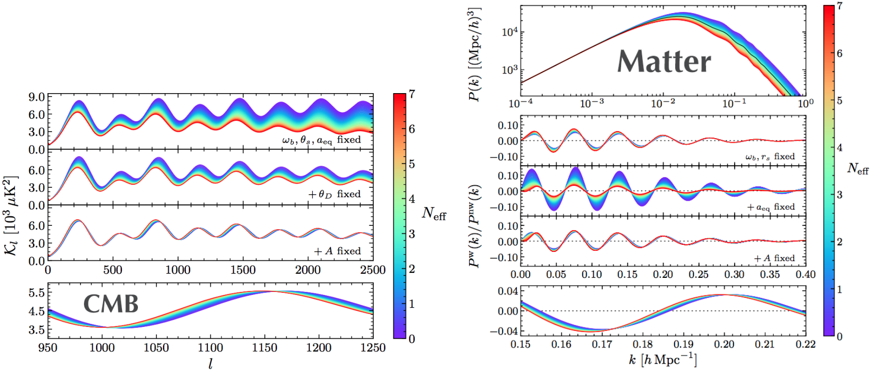
Neutrinos in the CMB Spectrum

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



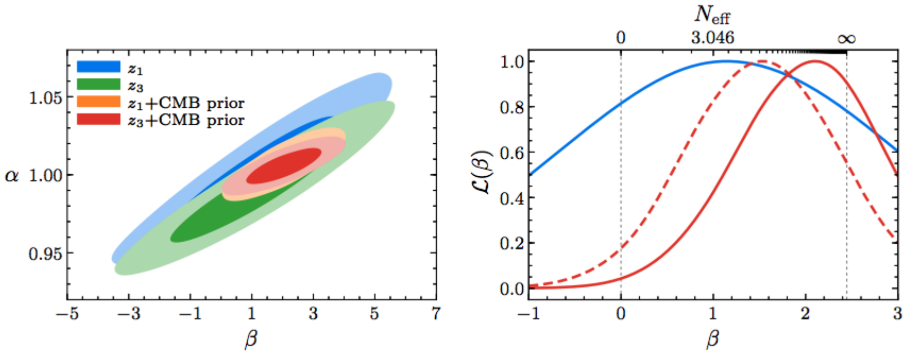
Baumann et al. (2017)

Neutrinos in the BAO Spectrum



Baumann et al. (2017)

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

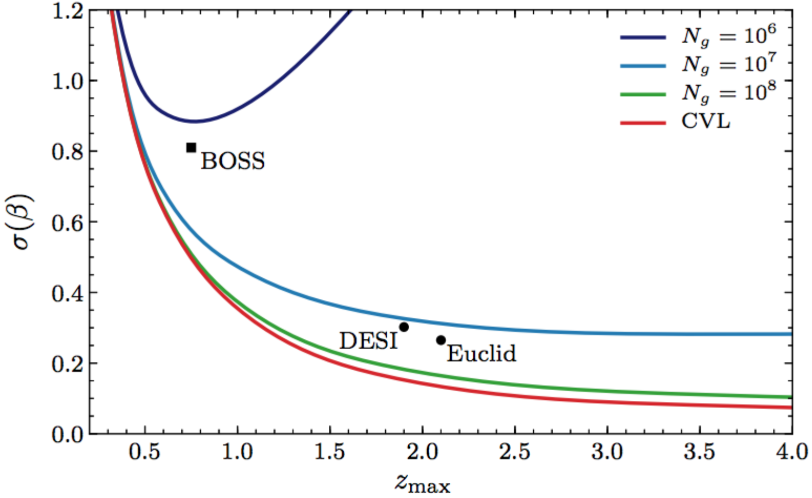


$$\beta(N_{\rm eff}) = \frac{\epsilon}{\epsilon_{\rm fid}} \quad \text{with} \quad \epsilon = \frac{N_{\rm eff}}{8(11/4)^{4/3}/7 + N_{\rm eff}}$$

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

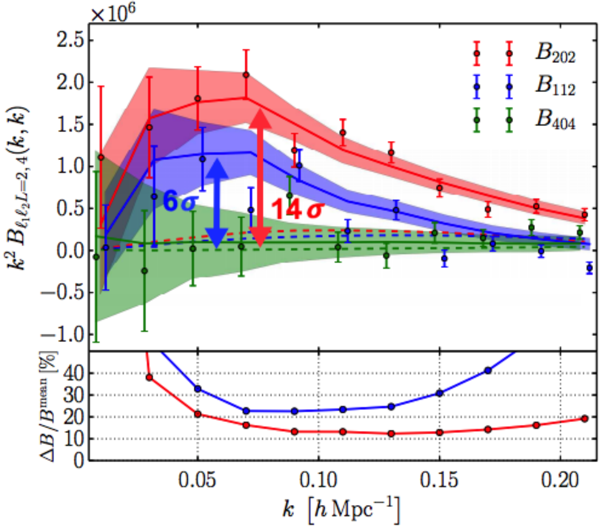
Baumann + FB++ (2019)

Neutrinos in the BAO Spectrum



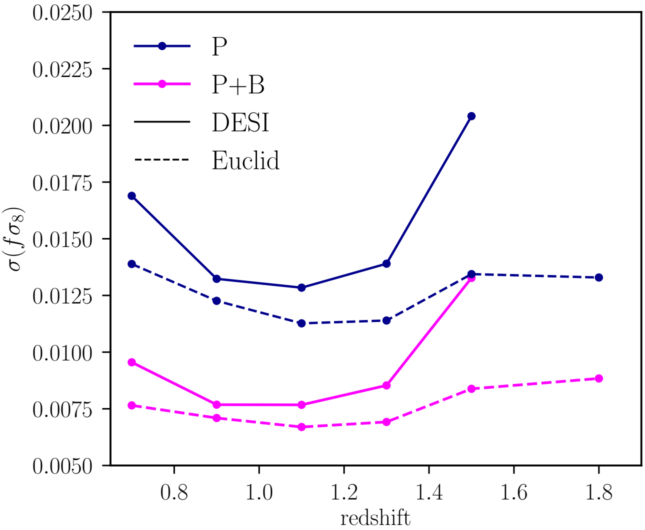
Baumann, FB++ (2019)

First measurement of the anisotropic bispectrum in BOSS

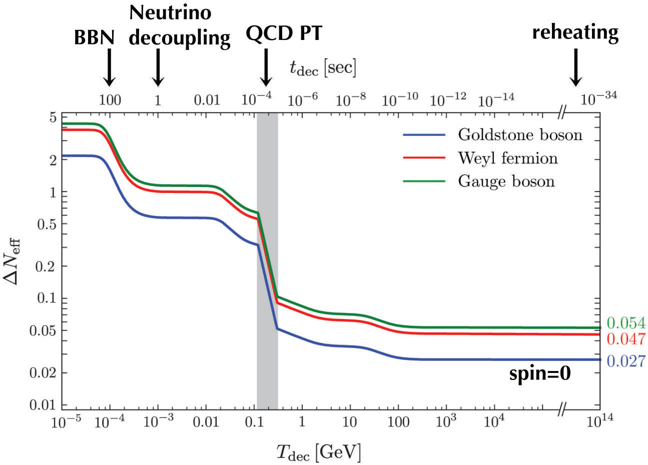


Sugiyama, FB++ (2019)

Bispectrum and RSD forecast (preliminary)



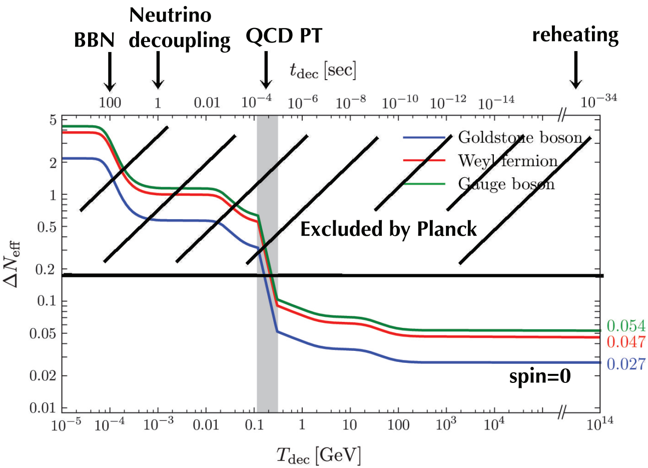
Sugiyama, FB++ (in prep.)



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

Baumann et al. (2017)

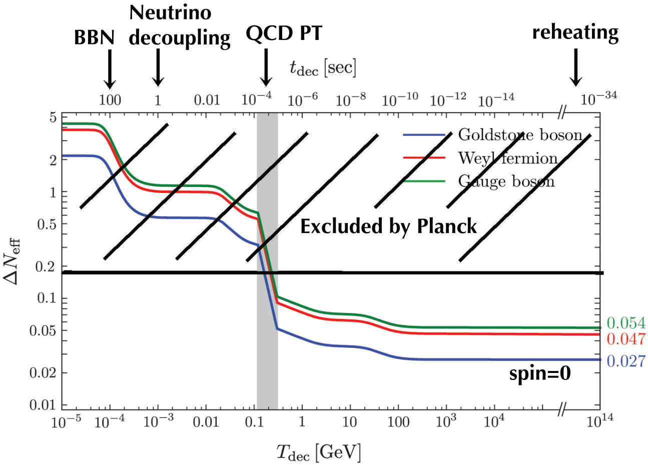
Motivation: Neutrinos in the phase of the BAO



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

Baumann et al. (2017)

Motivation: Neutrinos in the phase of the BAO



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

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

Baumann 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

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

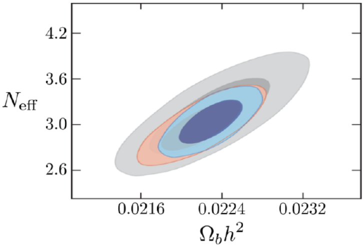
- Marginalize to get $\mathcal{L}(\alpha)$.

Current constraints on $N_{\rm eff}$

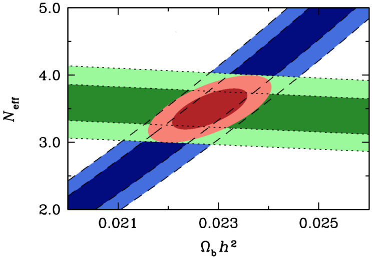
Relic neutrinos make up 41% of the radiation density

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

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

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

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 $B^m_\ell(k_1, k_2, k_3)$. 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 = even (3) $|\ell_1 - \ell_2| \leq L \leq |\ell_1 + \ell_2|$ and (4) $\ell_1 + \ell_2 + L =$ even.