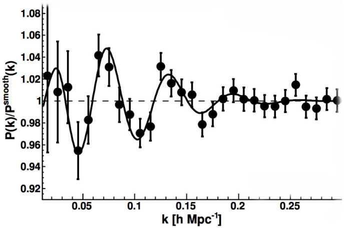
Cosmology with the Euclid and Dark Energy Spectroscopic Instrument (DESI)

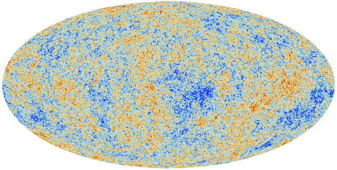
Florian Beutler



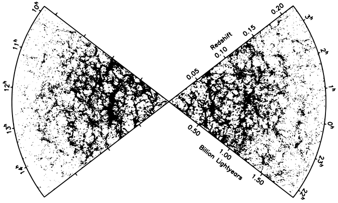
European Research Council
Established by the European Commission
THE ROYAL SOCIETY
THE UNIVERSITY OF EDINBURGH

Royal Society University Research Fellow

What is a galaxy redshift survey?



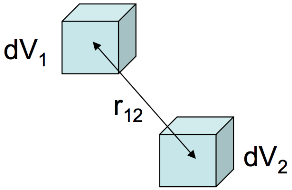
$\Longrightarrow$



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 1100 to today depends on Ω_m, Ω_Λ, H_0 etc.

- Overdensity-field:

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



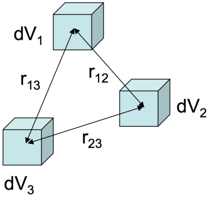
- Two-point function:

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

- ...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:

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

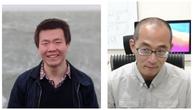
- Three-point function:

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

- ...and in Fourier-space:

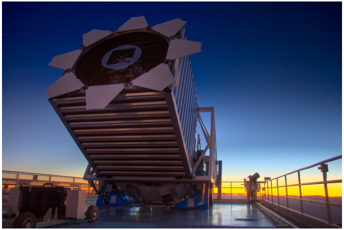
$$B_{\ell_1\ell_2L}(k_1, k_2) = (4\pi)^2(-i)^{\ell_1+\ell_2}\int r_1^2 dr_1 \int r_2^2 dr_2 \xi_{\ell_1\ell_2L}(r_1, r_2) j_{\ell_1}(k_1r_1) j_{\ell_2}(k_2r_2)$$

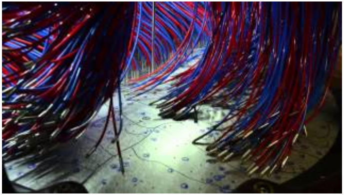
$\longrightarrow$ **Triumvirate**, JOSS:5571
`https://triumvirate.readthedocs.io/en/latest/`



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

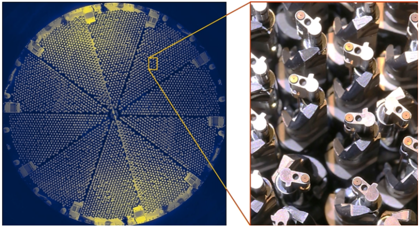


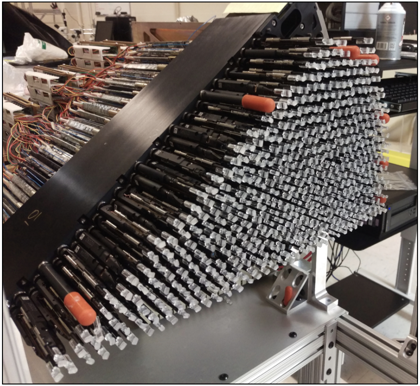


The DESI galaxy survey

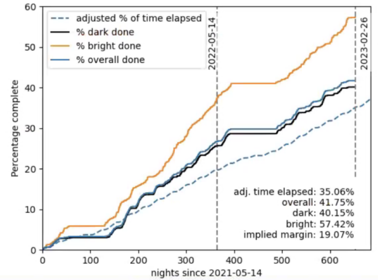
- Mayall 4m telescope at Kitt Peak, Arizona
- 5000 fibres/redshifts per pointing
- 13.6 million flux-limited sample of galaxies at $z < 0.4$ (BGS)
- 23.7 million color-selected galaxies at $0.4 < z < 1.5$ (LRGs & ELGs)
- 2.8 million Quasars at $z > 0.8$
- Ly-α forest at $2 < z < 3.5$

4m Mayall at Kitt Peak, Arizona. Twin to the Blanco, CTIO





DESI schedule



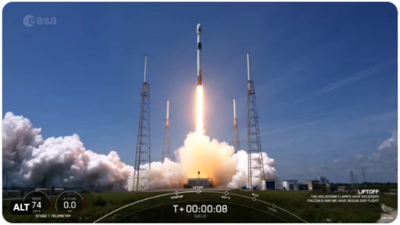
The ESA Euclid mission

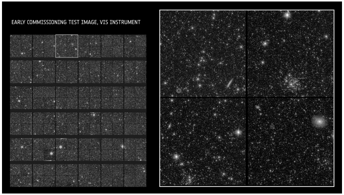
- Launched in July 2023 → L2 point
- Space-based weak lensing + gal. clustering survey over 15 000 deg^2
- 30 million emission line galaxies over the redshift range 0.7 to 2.0
- Slitless spectroscopy (grism)

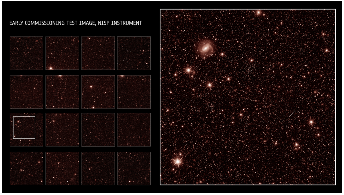
ESA's Euclid mission
@ESA_Euclid

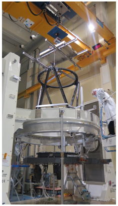
🚀 Liftoff for the #DarkUniverse 🕵️ detective that aims to shed light on the nature of #DarkMatter & #DarkEnergy

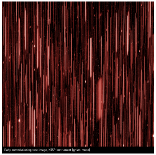
👏 #ESAEuclid



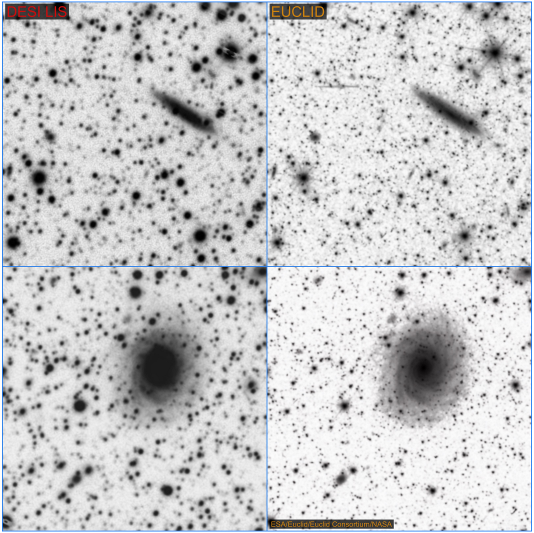






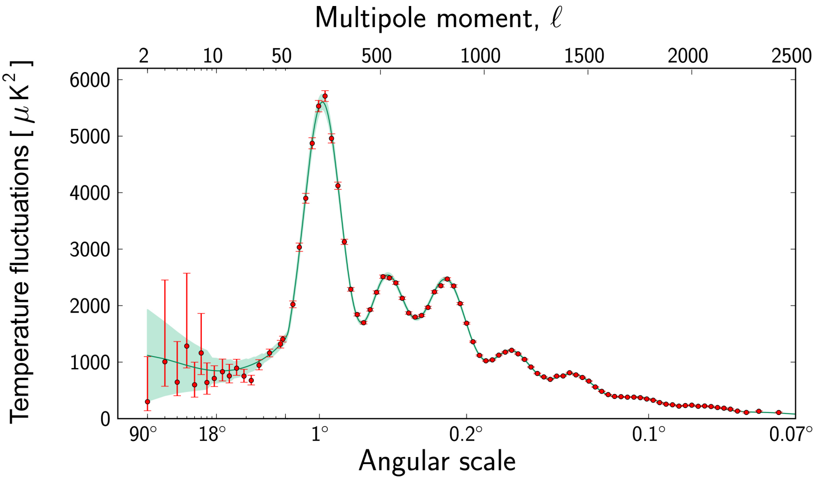


Euclid first images

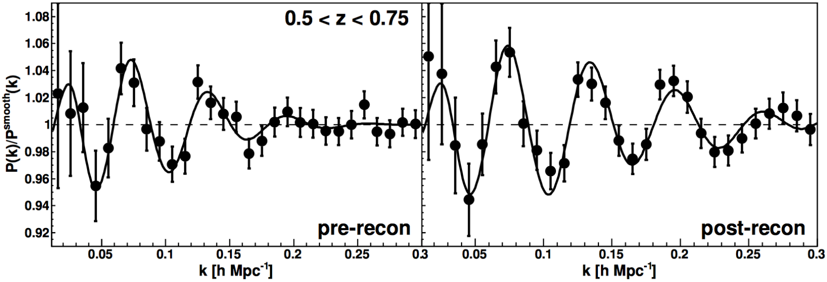


DESI (4m) Euclid (1.2m)

What are Baryon Acoustic Oscillations?



Planck collaboration



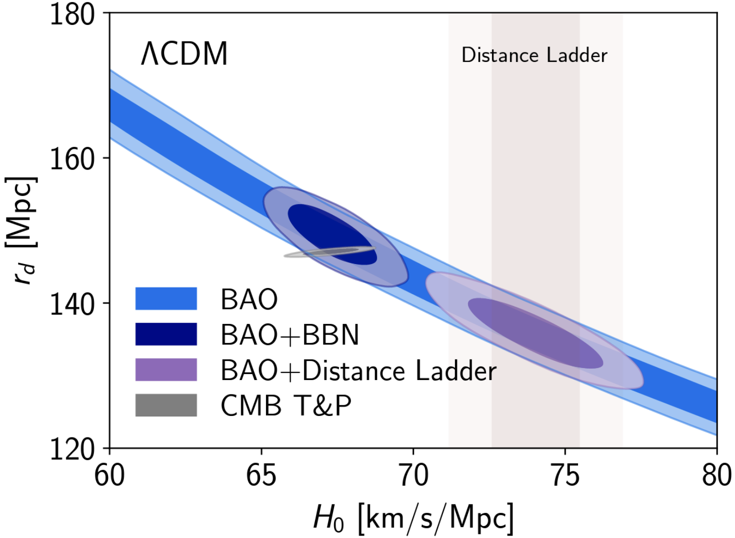
- BAO are the most robust observable we can extract from LSS
- The observables are

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

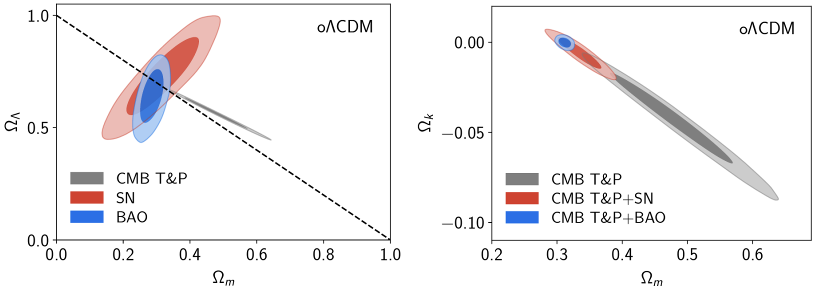
$$H(z)r_d = H_0 r_d \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda + \Omega_k(1+z)^2}$$

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

BAO and H_0



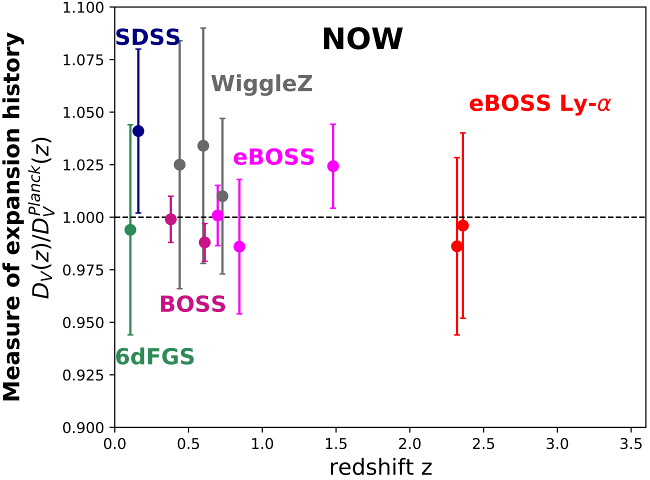
Alam et al. 2020



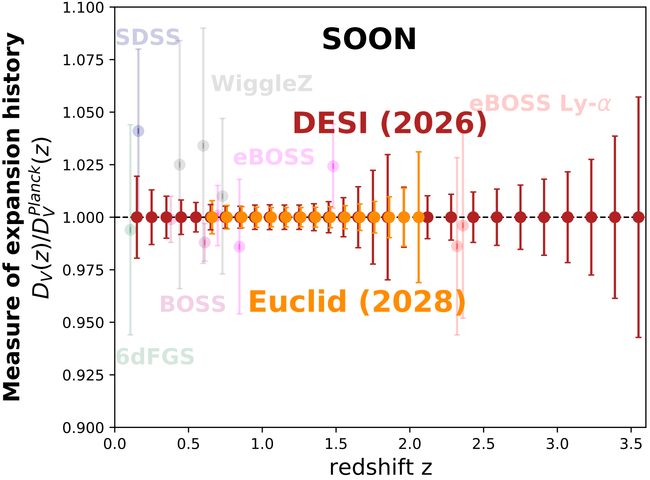
- Planck: $\Omega_k = -0.044^{+0.019}_{-0.014}$
- Planck+BAO: $\Omega_k = -0.0001 \pm 0.0018$

Alam et al. (2020)

Looking into the (near) future



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



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

DESI first results

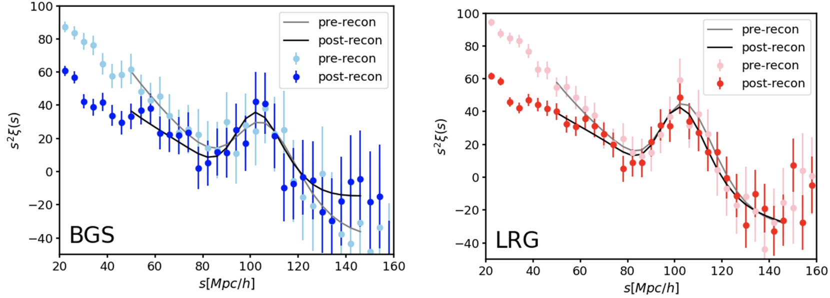


Table 3. BAO key fitting results for DESI-M2 LRGs and BGS.

Sample	Reconstruction	BAO Detection Significance	$\alpha + \Delta\alpha$	$\min(\chi^2)$/dof
DESI-M2 LRG	Pre-recon	5.170	0.987 ± 0.016	15.619 / 20
	Post-recon	5.050	1.000 ± 0.017	13.463 / 20
DESI-M2 BGS	Pre-recon	2.337	0.980 ± 0.040	13.172 / 20
	Post-recon	2.963	1.001 ± 0.026	16.724 / 20

- 2 months of data (unblinded), no cosmological analysis
- 110k galaxies in BGS and 260k in the LRG sample
- Forecasting 0.29% error on the BAO between $0.4 < z < 1.1$

Moon et al. (2023)

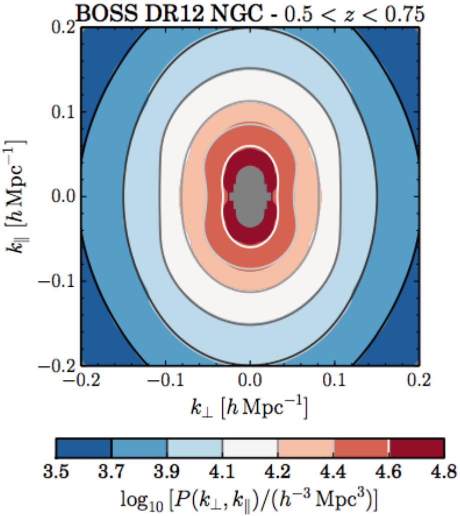
What are redshift-space distortions?

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

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

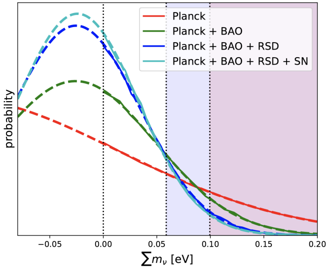
→ Introduces a quadrupole
→ Sensitive to cosmology since

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



Alam et al. (2017)

Constraining the neutrino mass with BAO & RSD



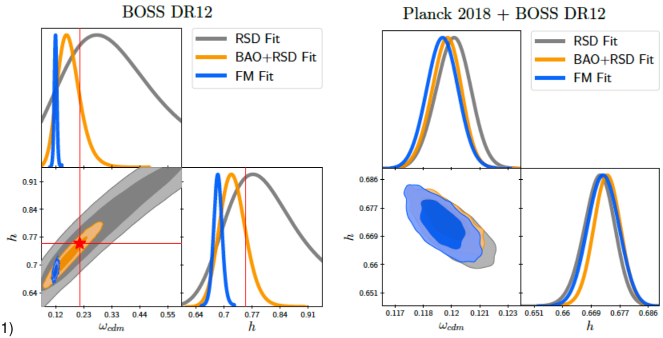
$|\Delta m^2_{31}| \simeq 2.56\times10^{-3}\,eV^2$
$\Delta m^2_{21} \simeq 7.37\times10^{-5}\,eV^2$

$$0.06\,eV \lesssim \text{Planck}\left(\Lambda\text{CDM} + \sum m_\nu\right) + \text{BOSS/eBOSS} + \text{SN} < 0.099\,eV$$

- 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 (2020), PDG (2018), Font-Ribera++ (2014), Wolf (2008)

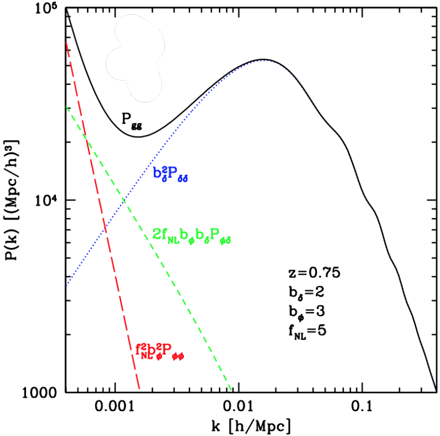
How to extract this information



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 fits to the full-shape power spectrum using EFTofLSS to extract additional information from the slope
- 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

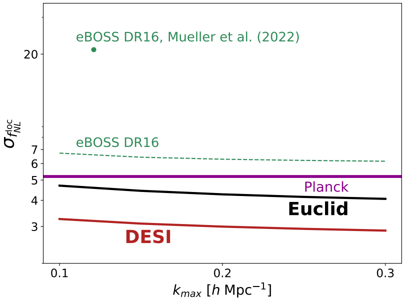


$$\phi_{\rm p}(x) = \phi_G(x) + f_{\rm NL}^{\rm loc}(\phi_G^2(x) - \langle\phi_G^2(x)\rangle)$$

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

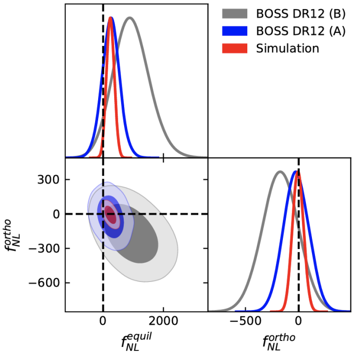
Dalal et al (2008), McDonald (2008)

Primordial non-Gaussianity with LSS

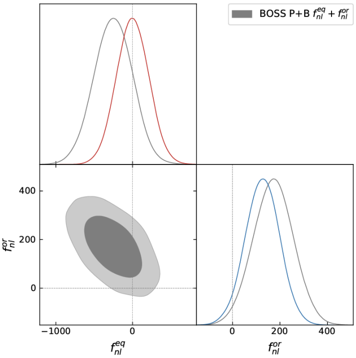


- eBOSS DR16 QSOs: $f_{\rm NL}^{\rm loc} = 12 \pm 21$ (68 C.L.) excluding small k modes and QSOs above $z > 2.2$ (Mueller et al. 2022)
- Theoretical systematics e.g. $b_\phi f_{\rm NL}^{\rm loc}$ degeneracy (Barreira 2022), rel. effects (Castorina & di Dio 2022)
- **SPHEREx** forecasts $\longrightarrow \sigma_{f_{\rm NL}^{\rm loc}} < 0.87$ (with bispectrum 0.23) (Dore et al. 2015)
- Single-field models generally predict $f_{\rm NL}^{\rm loc} \sim O(\epsilon) \ll 1$ (Maldacena 2003, Creminelli & Zaldarriaga 2004)

Non local PNG from the BOSS bispectrum



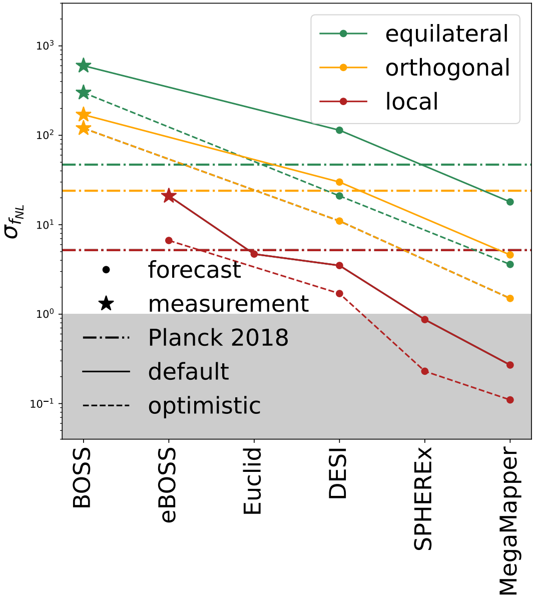
Cabass et al. (2022)



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
- These non-Gaussian templates arise in e.g. the EFT of inflation and test the slow-roll nature of inflation

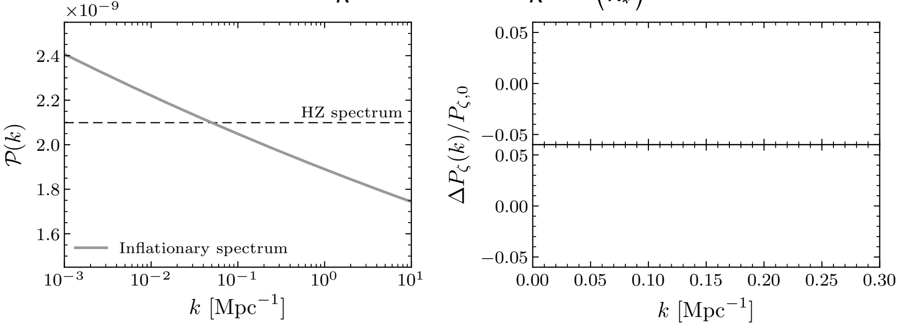
How far can we go?



Dore et al. (2014), Mueller et al. (2020), Braganca et al. (2023), Cabass et al. (2022), D'Amico et al. (2022)

Testing inflation through primordial features

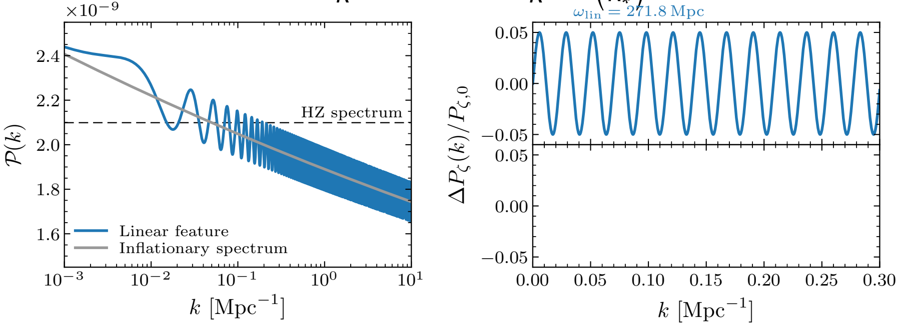
$$P_{\zeta,0}(k) = \frac{2\pi^2}{k^3}\mathcal{P}_{\zeta,0}(k) = \frac{2\pi^2 A_s}{k^3}\left(\frac{k}{k_*}\right)^{n_s-1}$$



- 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.

Testing inflation through primordial features

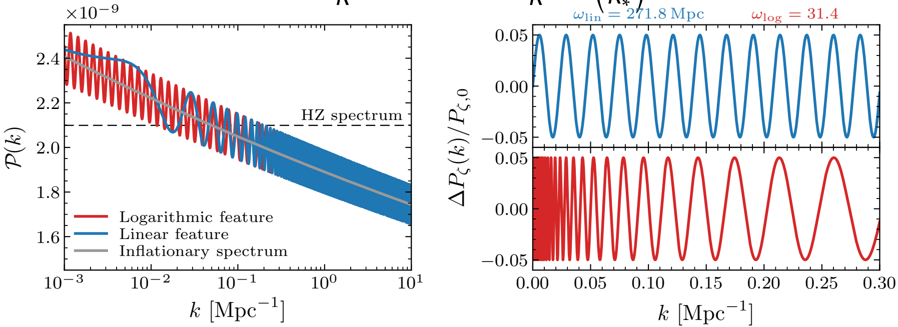
$$P_{\zeta,0}(k) = \frac{2\pi^2}{k^3}\mathcal{P}_{\zeta,0}(k) = \frac{2\pi^2 A_s}{k^3}\left(\frac{k}{k_*}\right)^{n_s-1}$$



- 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.

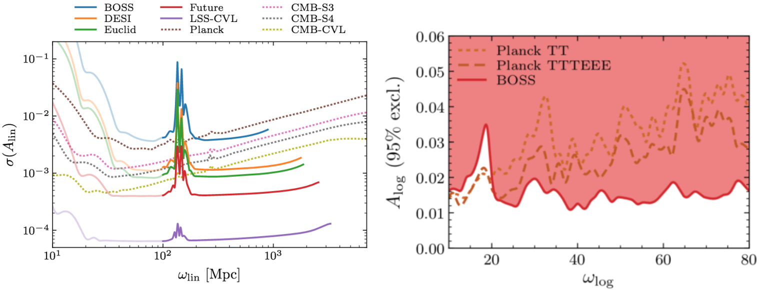
Testing inflation through primordial features

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



- 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.

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

Further linear corrections

$$\delta_g(k) = \delta_m(k)\left(b_1 + f\mu^2\right)$$

- Detecting some of these terms can test theories which modify the Euler equation ($\frac{1}{\mathcal{H}}\partial_r\Psi = \frac{1}{\mathcal{H}}\dot{v}_{||} + v_{||}$) (Bonvin & Fleury 2018)
- Most of these terms are strongly suppressed in the std. 2-pt correlators (e.g. $(\mathcal{H}/k)^2 \sim 10^{-5}$ at $k = 0.1h/$Mpc in the power spectrum)

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

Further linear corrections

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

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

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

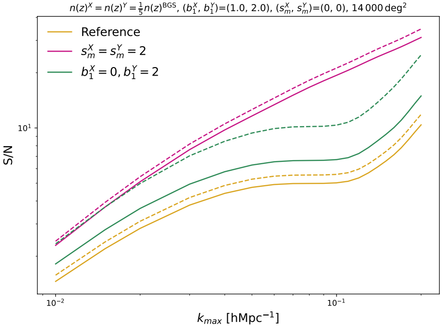
- Detecting some of these terms can test theories which modify the Euler equation ($\frac{1}{\mathcal{H}}\partial_r\Psi = \frac{1}{\mathcal{H}}\dot{v}_\parallel + v_\parallel$) (Bonvin & Fleury 2018)
- Most of these terms are strongly suppressed in the std. 2-pt correlators (e.g. $(\mathcal{H}/k)^2 \sim 10^{-5}$ at $k = 0.1h/\text{Mpc}$ in the power spectrum)

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

DESI-BGS forecasts for relativistic effects

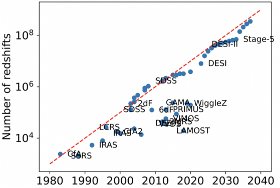
$$P_1(k,z) \overset{(\mathcal{R}^X=\mathcal{R}^Y)}{=} i\Delta b_1 \frac{\mathcal{H}}{k}\left(f\mathcal{R} + \frac{3}{2}\Omega_m\right) D^2 P(k)\,,$$

$$\mathcal{R} = 1 - b_e - f - \mathcal{H}^{-1}\partial_t \ln f - (2 - 5s_m)\left(1 - \frac{1}{\mathcal{H}r}\right)$$

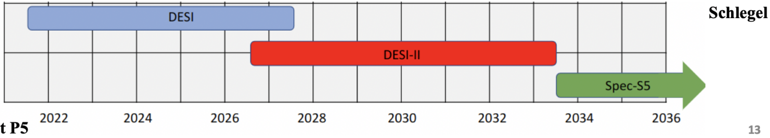


$$\left(\frac{S}{N}\right)^2 = \frac{1}{4\pi^2}\sum_i^{z_{\rm bins}} V(z_i)\int_{k_{\rm min}}^{k_{\rm max}} dk\, k^2 \frac{\left|P_1^{XY}(k,z_i)\right|^2}{\sigma^2_{P_1}(k,z_i)}$$

- **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

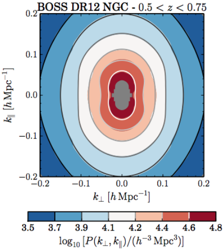


Dawson at P5

Spec-S5 (MegaMapper) ⟶ 6.5m aperture, 20k fibres

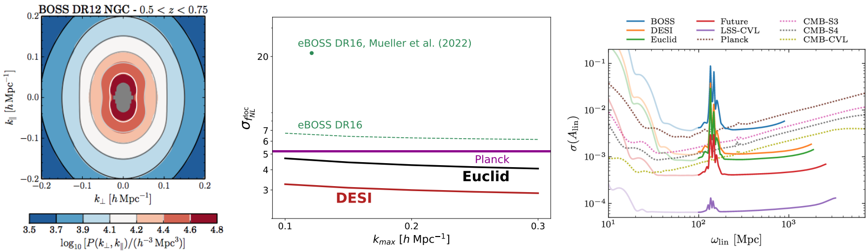
Schelgel et al. arXiv:2209.04322, arXiv:2209.03585, arXiv:1907.11171

Summary



1. DESI and Euclid are the first stage 4 experiments to take data and the first DESI data release is expected in 2024
2. Galaxy surveys offer many observational signatures (BAO, RSD, rel. effects) which offer powerful test for LCDM

Summary



1. DESI and Euclid are the first stage 4 experiments to take data and the first DESI data release is expected in 2024
2. Galaxy surveys offer many observational signatures (BAO, RSD, rel. effects) which offer powerful test for LCDM
3. DESI and Euclid have the potential to compete with the CMB on several tests of inflation (PNG, primordial features)

Euclid timeline