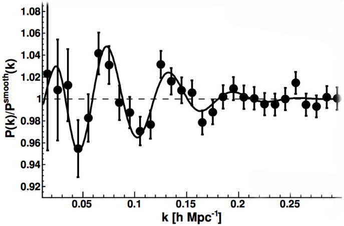
Cosmology with Euclid and the Dark Energy Spectroscopic Instrument (DESI)

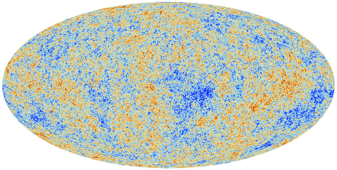
Florian Beutler



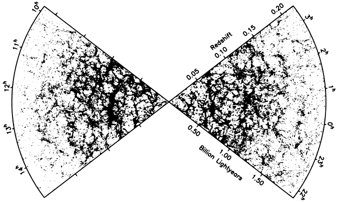
European Research Council
Established by the European Commission
THE ROYAL SOCIETY
THE UNIVERSITY OF EDINBURGH

Royal Society University Research Fellow

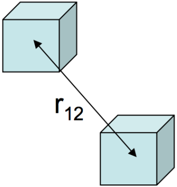
What is a galaxy redshift survey?



$\Longrightarrow$



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:

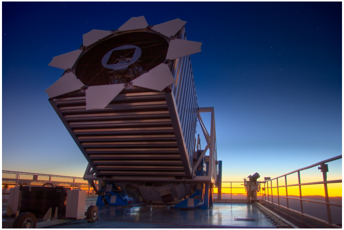
$$\xi(\mathbf{r}) \overset{\text{homogeneity}}{=} \langle \delta(\mathbf{x}+\mathbf{r})\delta(\mathbf{x}) \rangle \begin{cases} \overset{\text{isotropy}}{=} & \xi(r) \\ \overset{\text{anisotropy}}{=} & \xi_\ell(r) = \int_{-1}^{1} d\mu\, \xi(r,\mu)\mathcal{L}_\ell(\mu) \end{cases}$$

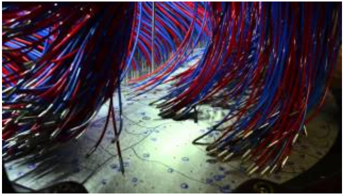
- ...and in Fourier-space:

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

The BOSS galaxy survey

- Third version of the Sloan Digital Sky Survey (SDSS-III), 2.5m mirror
- 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

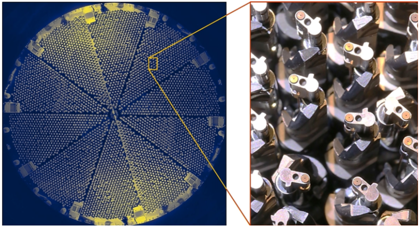


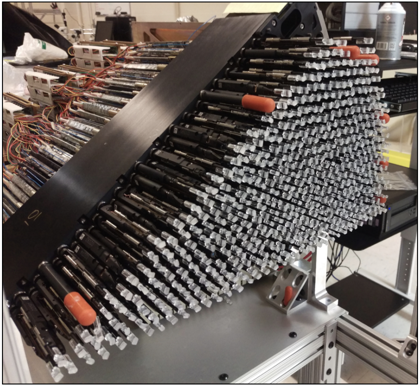


The DESI galaxy survey

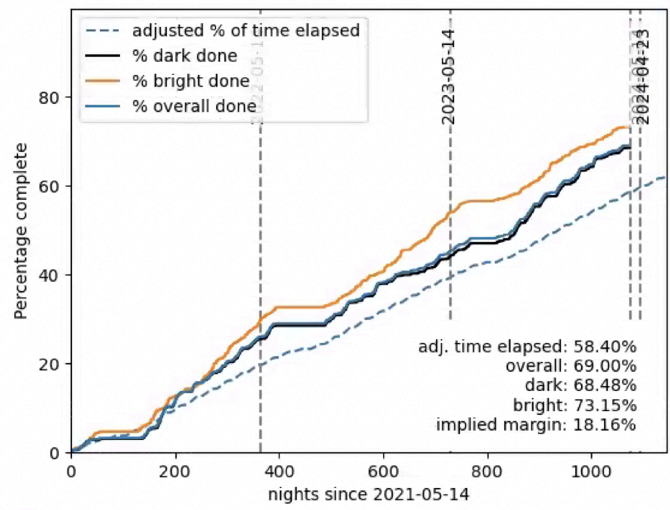
- Mayall 4m telescope at Kitt Peak, Arizona
- 5000 fibres/redshifts per pointing
- 13.6 million flux-limited sample of galaxies at $z < 0.4$ (BGS)
- 23.7 million color-selected galaxies at $0.4 < z < 1.5$ (LRGs & ELGs)
- 2.8 million Quasars at $z > 0.8$
- Ly-α forest at $2 < z < 3.5$

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





DESI schedule



DESI schedule

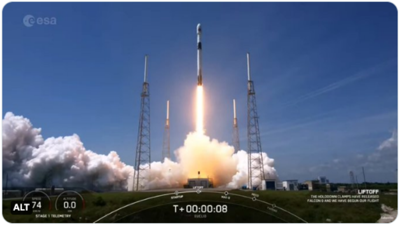
The ESA Euclid mission

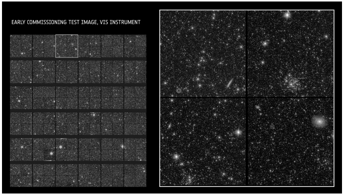
- Launched in July 2023 → L2 point
- Space-based weak lensing + gal. clustering survey over 15 000 deg^2
- 30 million emission line galaxies over the redshift range 0.7 to 2.0
- Slitless spectroscopy (grism)

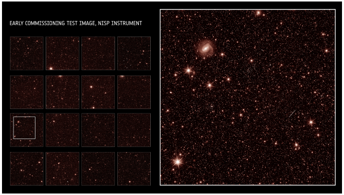
ESA's Euclid mission
@ESA_Euclid

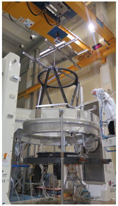
🚀 Liftoff for the #DarkUniverse 🕵️ detective that aims to shed light on the nature of #DarkMatter & #DarkEnergy

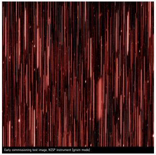
👏 #ESAEuclid



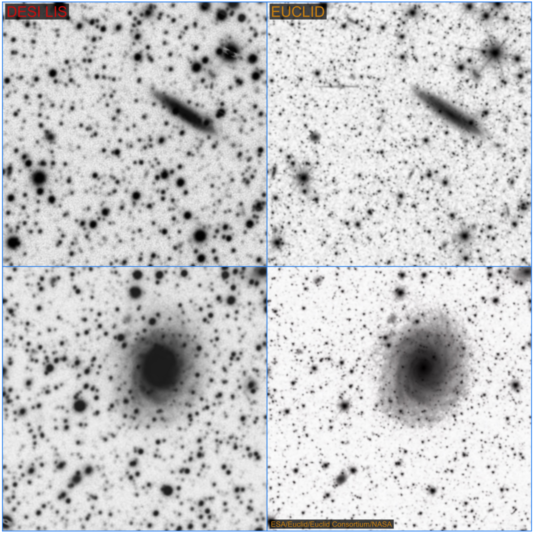








Euclid first images



DESI (4m) Euclid (1.2m)

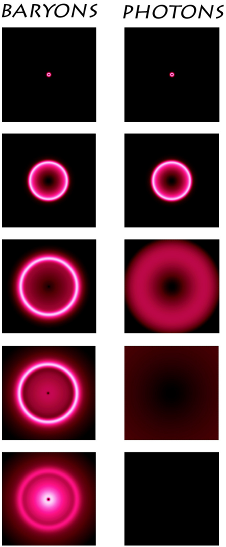
What are Baryon Acoustic Oscillations?

The evolution eq. of baryon and photon perturbations in the radiation dominated era can be written as

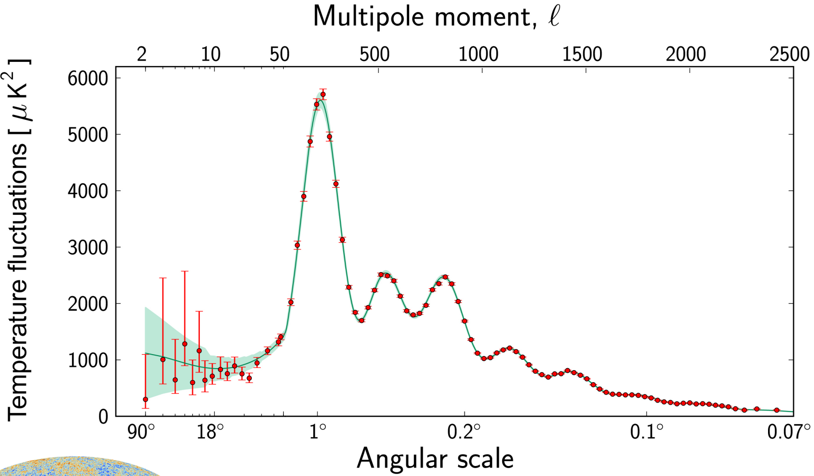
$$\ddot{\delta} + 2H\dot{\delta} + \left(\frac{c_s^2 k^2}{a^2} - 4\pi G\overline{\rho}\right)\delta = F$$

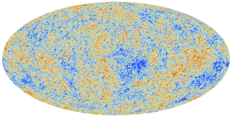
Note that this is a forced and damped harmonic oscillator ($m\ddot{x} + b\dot{x} + kx = F$) with the plane wave solution $\delta \propto A\cos(\omega t - \phi)$, where $\omega^2 = c_s^2 k^2/a^2 - 4\pi G\overline{\rho}$.

- Preferred distance scale between galaxies as a relict of sound waves in the early Universe.
- Can be used as a standard ruler.
- The systematic errors are far below the current statistical errors.

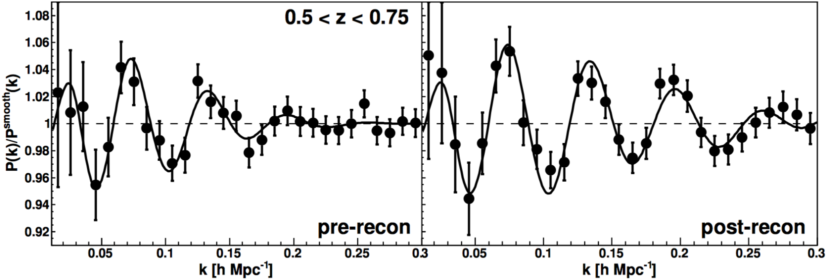


credit: Martin White





Planck collaboration

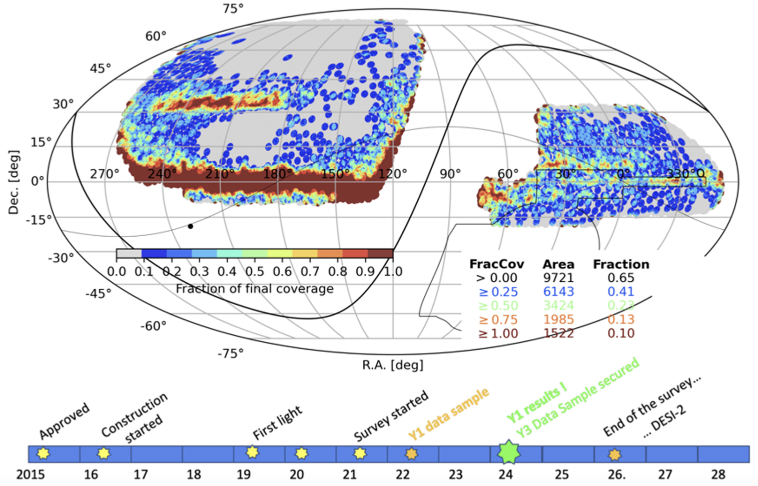


- BAO are the most robust observable we can extract from LSS
- The observables are

$$\frac{D_M(z)}{r_d} = \int_0^z \frac{c dz'}{r_d H(z')}$$

$$\frac{D_H(z)}{r_d} = \frac{c}{H(z) r_d} = c\left[H_0 r_d \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda + \Omega_k(1+z)^2}\right]^{-1}$$

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

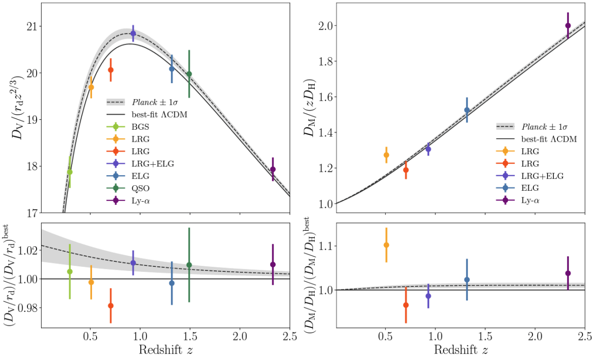


- 5.7 million unique redshifts (3 times as big as SDSS) after just 1 year

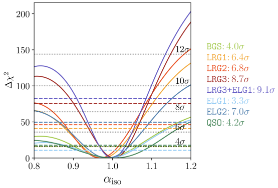
DESI 2024

DESI 2024: redshift distribution

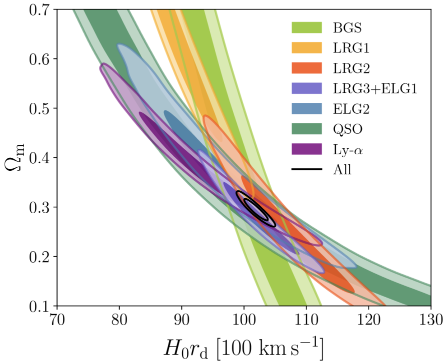
$$D_V(z) = \left[z D_M^2(z) D_H(z) \right]^{1/3}$$



- With BAO we can map the expansion history for the past 11 billion years
- The aggregate distance precision for DESI Y1 is 0.52% (already better than 2 decades of SDSS)



$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + (1-\Omega_m)}$$



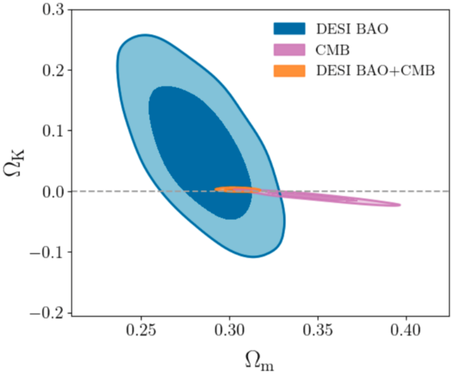
$$\Omega_m = 0.295 \pm 0.015$$

$$H_0 r_d = 101.8 \pm 1.3[10^2 \mathrm{km\,s^{-1}}]$$

DESI 2024

DESI 2024: Curvature Ω_K

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_K(1+z)^2 + (1-\Omega_m-\Omega_K)}$$

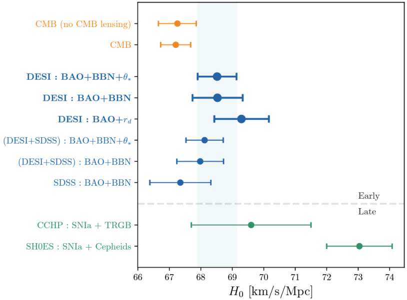


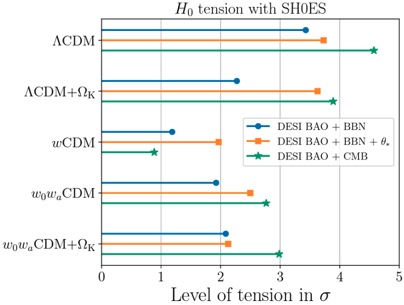
- DESI: $\Omega_K = 0.065^{+0.068}_{-0.078}$
- CMB: $\Omega_K = -0.0102 \pm 0.0054$
- CMB+DESI: $\Omega_K = 0.0024 \pm 0.0016$

*CMB = Planck [plik] temp. + pol. + (Planck PR4 + ACT DR6) CMB lensing

DESI 2024

DESI 2024: Hubble tension

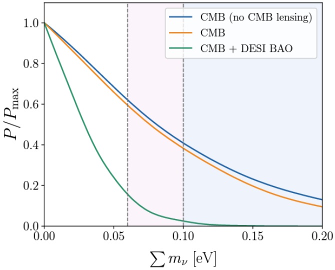


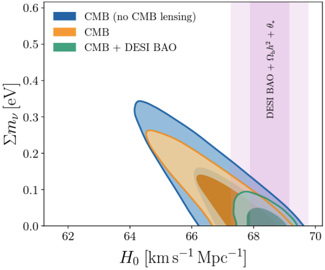


- DESI + BBN gives a 1.2% constraint on H_0 ($68.53 \pm 0.80\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$)
- 3.4σ tension with SH0ES (no CMB involved!)

DESI 2024

DESI 2024: Constraining the neutrino mass





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

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

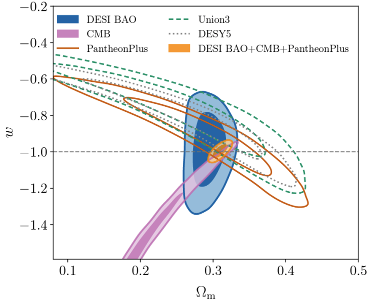
$$0.059\,\mathrm{eV} \lesssim \mathrm{CMB}\left(\Lambda\mathrm{CDM} + \sum m_\nu\right) + \mathrm{DESI\ BAO} < 0.072\,\mathrm{eV}\ (95\%)$$

- Neutrino mass hierarchy $\begin{cases} m_{\nu_1} < m_{\nu_2} \ll m_{\nu_3} \rightarrow \textbf{min}\left(\sum m_\nu\right) \simeq 0.059\,\mathrm{eV} \\ m_{\nu_3} \ll m_{\nu_1} < m_{\nu_2} \rightarrow \textbf{min}\left(\sum m_\nu\right) \simeq 0.1\,\mathrm{eV} \end{cases}$
- KATRIN: $m_{\bar{\nu}_e} < 0.8\,\mathrm{eV}$ (90%)
- Fixing $\sum m_\nu = 0.059\,\mathrm{eV}$ results in $\Delta\chi^2 = 3.8$
- Prior dependence: $\sum m_\nu > 0.059\,\mathrm{eV} \rightarrow \sum m_\nu < 0.113\,\mathrm{eV}$ (95%)

DESI 2024, PDG (2018), KATRIN 2022

DESI 2024: ωCDM

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + (1-\Omega_m)(1+z)^{3(1+\omega)}}$$



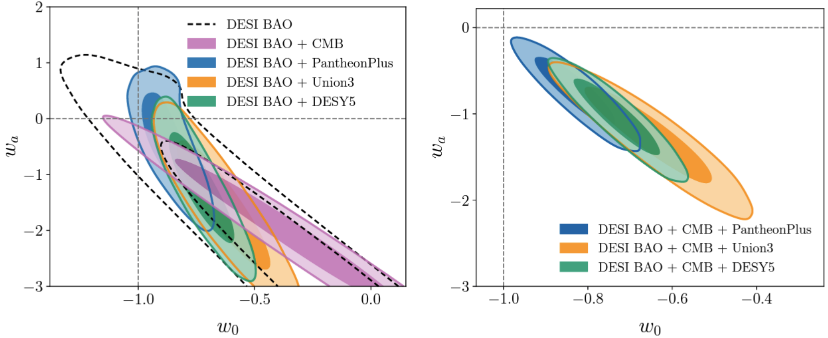
$$\left.\begin{aligned}\Omega_m &= 0.293 \pm 0.015\\ \omega &= -0.99^{+0.15}_{-0.13}\end{aligned}\right\}\quad \text{DESI BAO}$$

$$\left.\begin{aligned}\Omega_m &= 0.3095 \pm 0.0069\\ \omega &= -0.997 \pm 0.025\end{aligned}\right\}\quad \text{DESI BAO + CMB + PantheonPlus}$$

DESI 2024

DESI 2024: $\omega_a\omega_0$CDM with $\omega(z) = \omega_0 + \omega_a \frac{z}{1+z}$

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + (1-\Omega_m)(1+z)^{3(1+\omega_0+\omega_a)}e^{-3\omega_a\frac{z}{1+z}}}$$



- DESI + CMB has 2.6σ tension with ΛCDM
- This can increase when including SN datasets (between 2.5 and 3.9σ)

DESI 2024

Much more to come (soon)

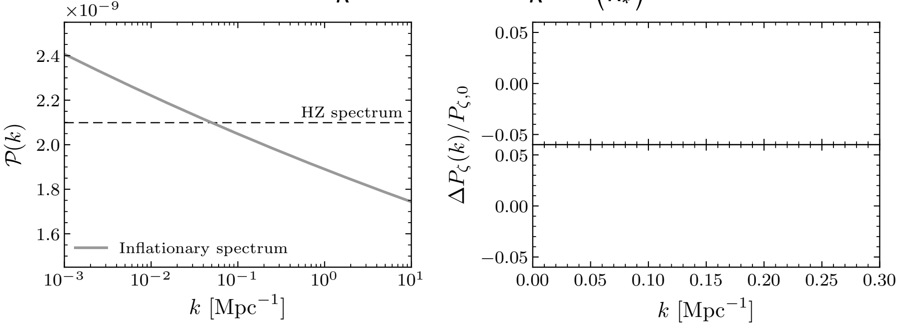
Full-shape power spectrum analysis of DESI Y1:

- Contains additional observables (redshift-space distortions, additional AP information, primordial non-Gaussianity, relativistic effects, primordial features etc.)
- Can have significant non-linear clustering contributions (small scales) and hence much harder to model
- Can contain significant imaging systematics (large scales) which are difficult to remove

→ The final DESI Y5 catalog will be 3 times bigger than Y1

Testing inflation through primordial features

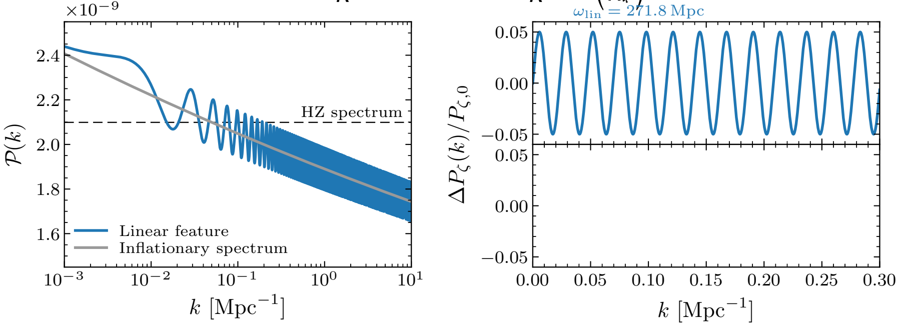
$$P_{\zeta,0}(k) = \frac{2\pi^2}{k^3}\mathcal{P}_{\zeta,0}(k) = \frac{2\pi^2 A_s}{k^3}\left(\frac{k}{k_*}\right)^{n_s-1}$$



- 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

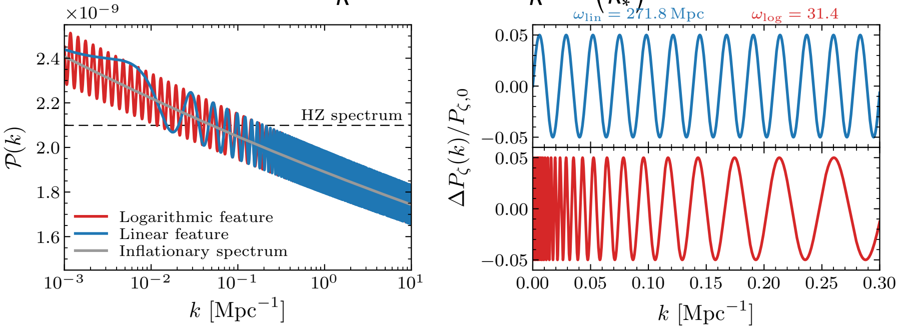
$$P_{\zeta,0}(k) = \frac{2\pi^2}{k^3}\mathcal{P}_{\zeta,0}(k) = \frac{2\pi^2 A_s}{k^3}\left(\frac{k}{k_*}\right)^{n_s-1}$$



- 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.

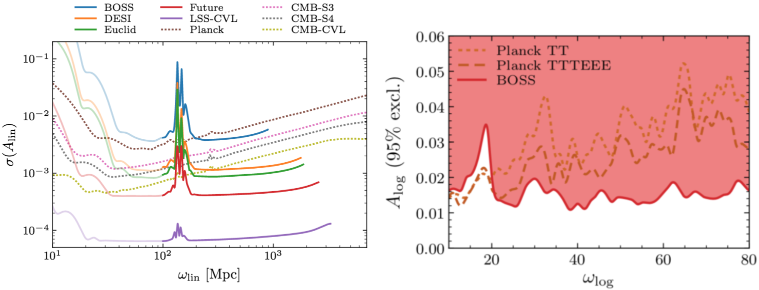
Testing inflation through primordial features

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



- 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



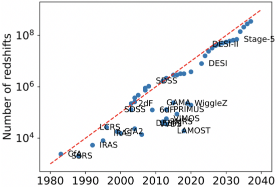
- Here we use a model-independent approach based on

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

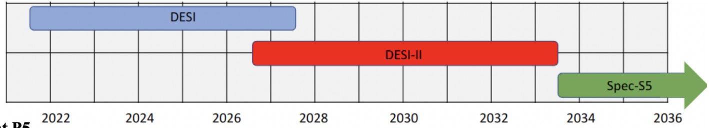
- LSS is more powerful than the CMB on small frequencies, while the CMB can access much higher frequencies
- DESI is going to provide constraints which cannot be accessed even by a CVL CMB experiment

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



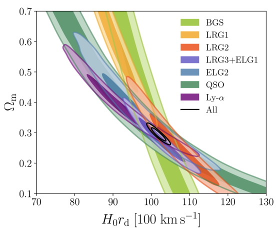
Dawson at P5

13

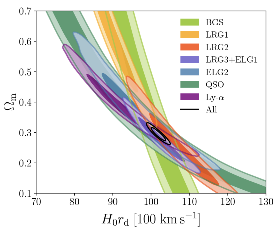
Spec-S5 (MegaMapper) ⟶ 6.5m aperture, 20k fibres

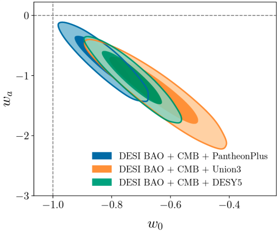
Schelgel et al. arXiv:2209.04322, arXiv:2209.03585, arXiv:1907.11171

Summary

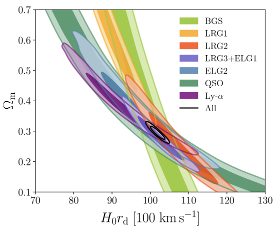


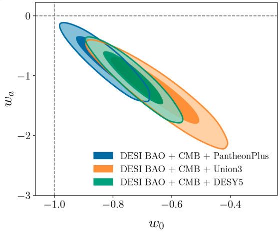
1. DESI and Euclid will provide excellent LSS datasets over the next decade with the DESI Y1 BAO results already public

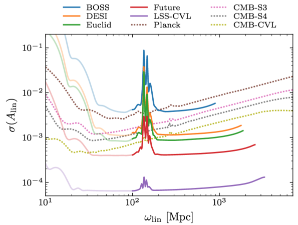




1. DESI and Euclid will provide excellent LSS datasets over the next decade with the DESI Y1 BAO results already public
2. Some tension with LCDM when allowing time dep. dark energy and the upper limits of the neutrino mass getting closer to the minimum mass provided by Neutrino oscillation experiments







1. DESI and Euclid will provide excellent LSS datasets over the next decade with the DESI Y1 BAO results already public
2. Some tension with LCDM when allowing time dep. dark energy and the upper limits of the neutrino mass getting closer to the minimum mass provided by Neutrino oscillation experiments
3. Many more results to come this summer (Full-shape P(k) analysis, primordial features etc.)
4. DESI Y3 data collection is now completed and the first results will be published next year
5. The final DESI dataset will be 3x larger than Y1 (2026 onwards)