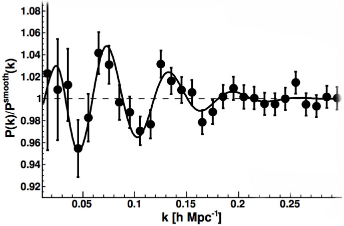
Cosmology with the Euclid and Dark Energy Spectroscopic Instrument (DESI)

Florian Beutler



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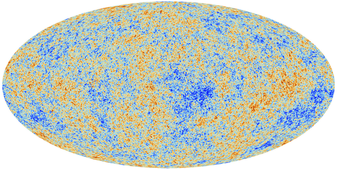
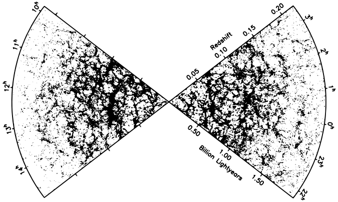


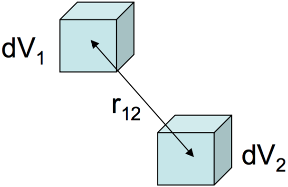
$\Longrightarrow$



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:

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

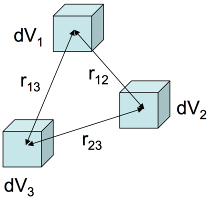
- ...and in Fourier-space:

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

From a point distribution to a bispectrum

- Overdensity-field:

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



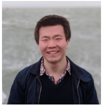
- Three-point function:

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

- ...and in Fourier-space:

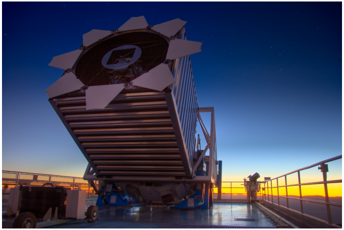
$$\boxed{B_{\ell_1\ell_2L}(k_1, k_2) = (4\pi)^2(-i)^{\ell_1+\ell_2} \int r_1^2 dr_1 \int r_2^2 dr_2 \, \xi_{\ell_1\ell_2L}(r_1, r_2) j_{\ell_1}(k_1 r_1) j_{\ell_2}(k_2 r_2)}$$

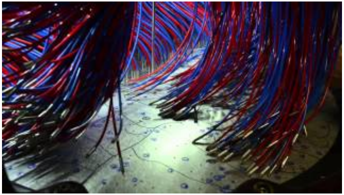
$\longrightarrow$ **Triumvirate**, JOSS:5571
`https://triumvirate.readthedocs.io/en/latest/`



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

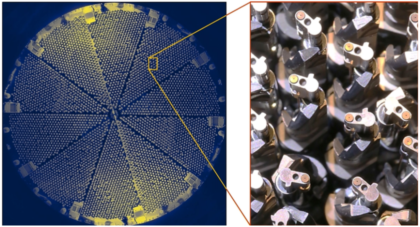


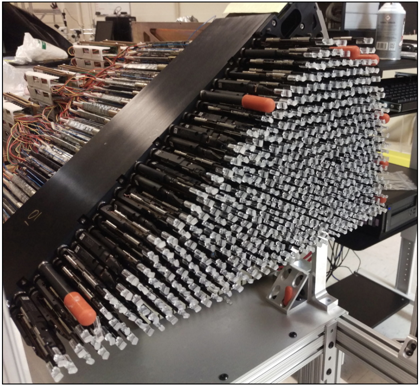


The DESI galaxy survey

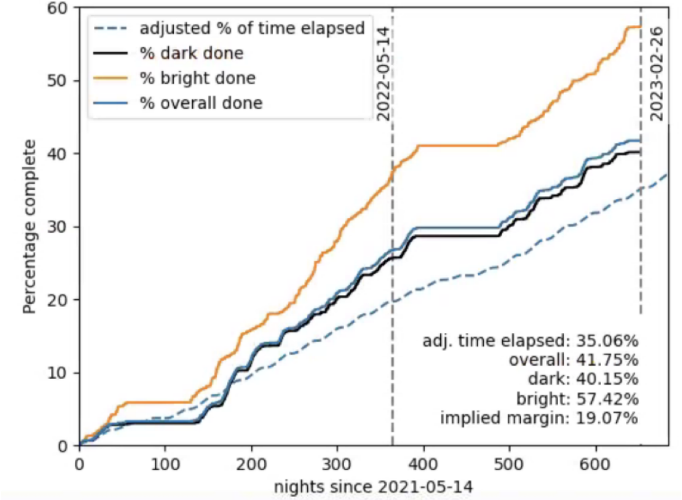
- Mayall 4m telescope at Kitt Peak, Arizona
- 5000 fibres/redshifts per pointing
- 13.6 million flux-limited sample of galaxies at $z < 0.4$ (BGS)
- 23.7 million color-selected galaxies at $0.4 < z < 1.5$ (LRGs & ELGs)
- 2.8 million Quasars at $z > 0.8$
- Ly-α forest at $2 < z < 3.5$

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





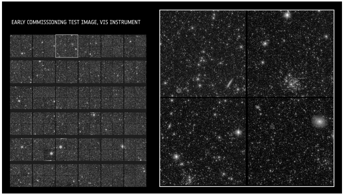
DESI schedule

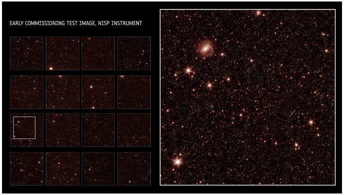


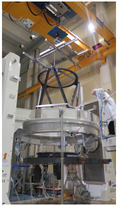
DESI schedule

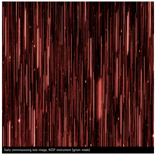
The ESA Euclid mission

- Launched in July 2023 $\longrightarrow$ 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)

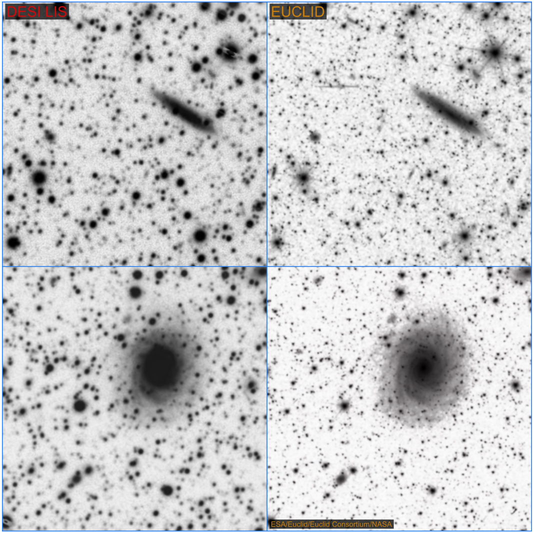




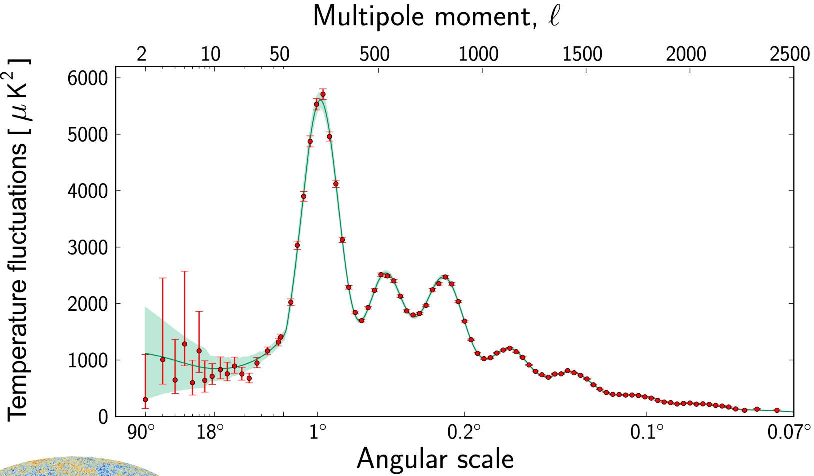


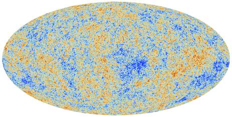


Euclid first images



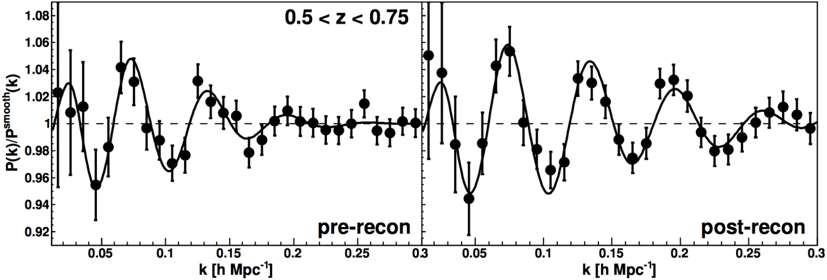
DESI (4m) Euclid (1.2m)





Planck collaboration

Baryon Acoustic Oscillations in BOSS

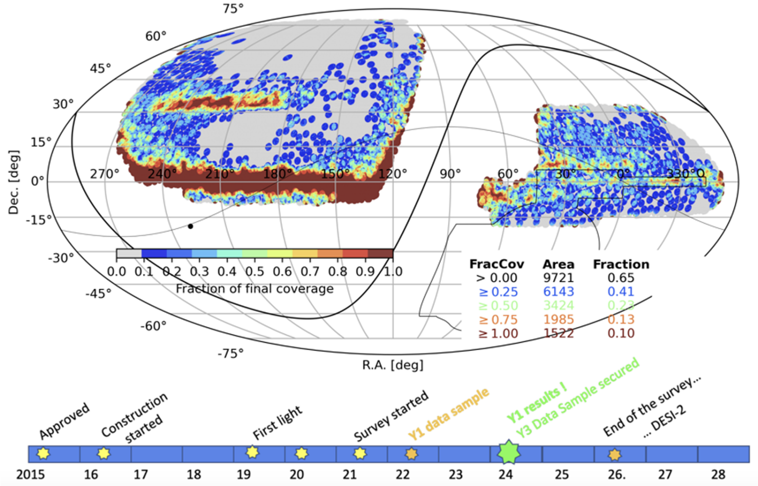


- BAO are the most robust observable we can extract from LSS
- The observables are

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

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

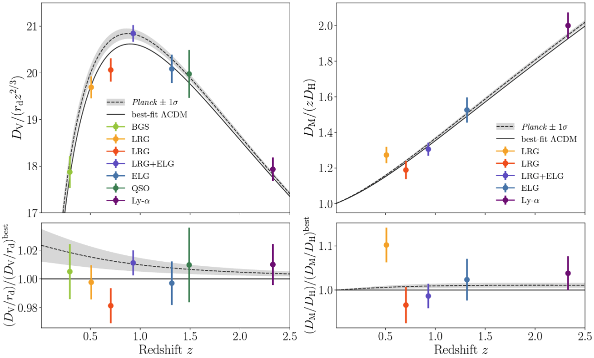
- We require a calibration of the ruler to constrain H_0 (+ cos. model to extrapolate to $z = 0$)



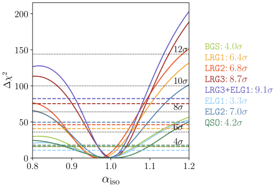
- 5.7 million unique redshifts (3 times as big as SDSS) after just 1 year

DESI 2024

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

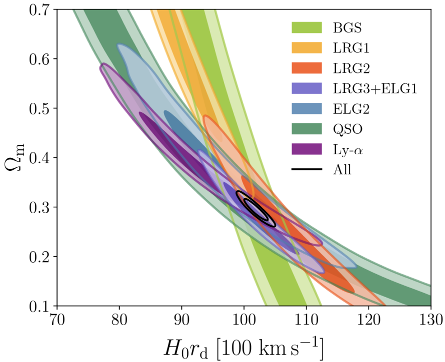


- With BAO we can map the expansion history for the past 11 billion years
- The aggregate distance precision for DESI Y1 is 0.52% (already better than 2 decades of SDSS)



DESI 2024: ΛCDM

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



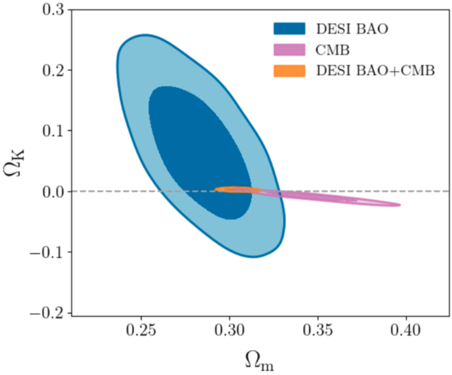
$$\Omega_m = 0.295 \pm 0.015$$

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

DESI 2024

DESI 2024: Curvature Ω_K

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

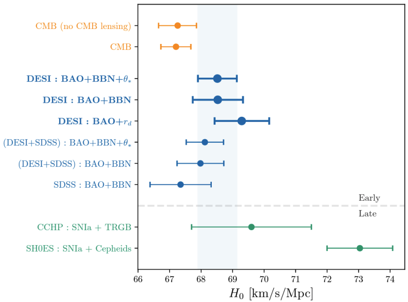


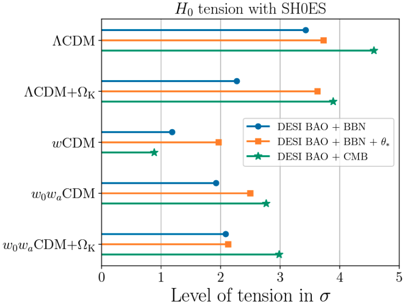
- DESI: $\Omega_K = 0.065^{+0.068}_{-0.078}$
- CMB: $\Omega_K = -0.0102 \pm 0.0054$
- CMB+DESI: $\Omega_K = 0.0024 \pm 0.0016$

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

DESI 2024

DESI 2024: Hubble tension

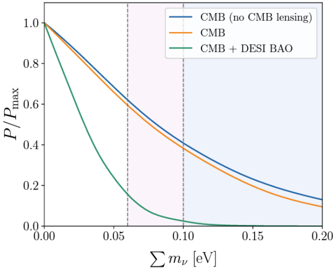


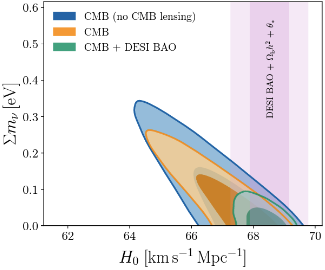


- DESI + BBN gives a 1.2% constraint on H_0 ($68.53 \pm 0.80 \mathrm{km\,s^{-1}\,Mpc^{-1}}$)
- 3.4σ tension with SH0ES (no CMB involved!)

DESI 2024

DESI 2024: Constraining the neutrino mass





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

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

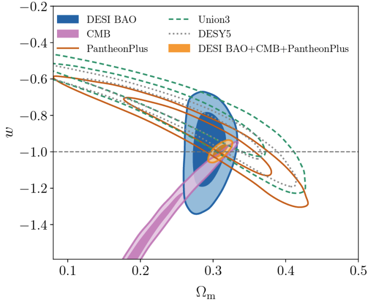
$$0.059\,\text{eV} \lesssim \text{CMB}\left(\Lambda\text{CDM} + \sum m_\nu\right) + \text{DESI BAO} < 0.072\,\text{eV (95\%)}$$

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

DESI 2024, PDG (2018), KATRIN 2022

DESI 2024: ωCDM

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

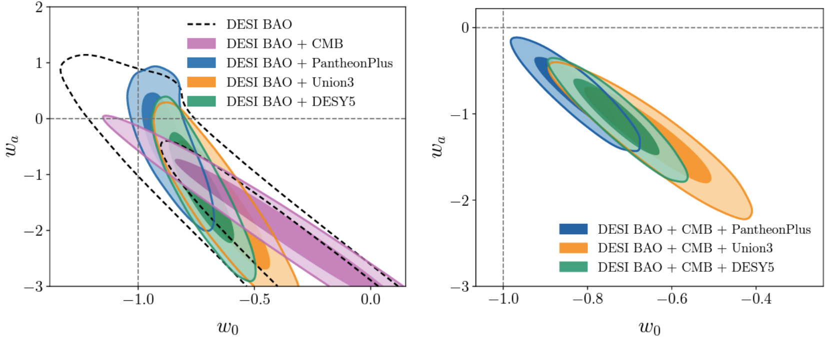


$$\left.\begin{aligned} \Omega_m &= 0.293 \pm 0.015 \\ \omega &= -0.99^{+0.15}_{-0.13} \end{aligned}\right\} \quad \text{DESI BAO}$$

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

DESI 2024

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



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

DESI 2024

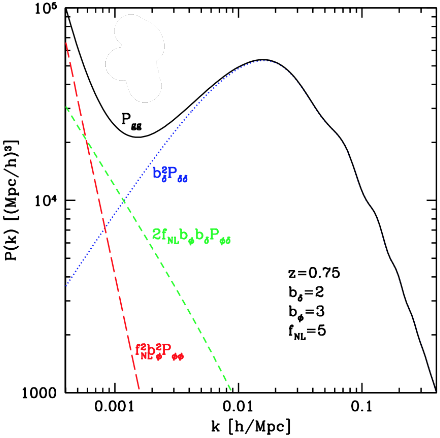
Much more to come (soon)

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

$\rightarrow$ The final DESI Y5 catalog will be 3 times bigger than Y1

Testing inflation through primordial non-Gaussianity

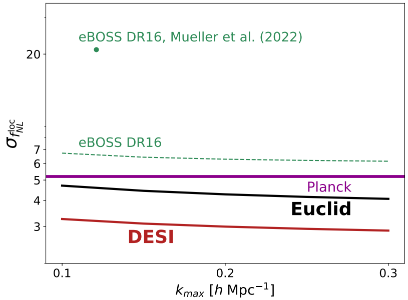


$$\phi_\mathrm{p}(x) = \phi_G(x) + f_\mathrm{NL}^\mathrm{loc}(\phi_G^2(x) - \langle\phi_G^2(x)\rangle)$$

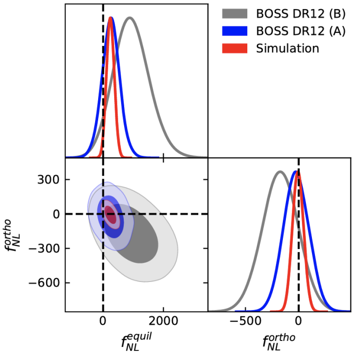
$$\delta_g(k) = \delta_m(k)\left(b_1 + f\mu^2 + \frac{b_\phi f_\mathrm{NL}^\mathrm{loc}\alpha}{k^2}\right) \rightarrow P_g \propto \frac{b_\phi f_\mathrm{NL}^\mathrm{loc}}{k^2}$$

Dalal et al (2008), McDonald (2008)

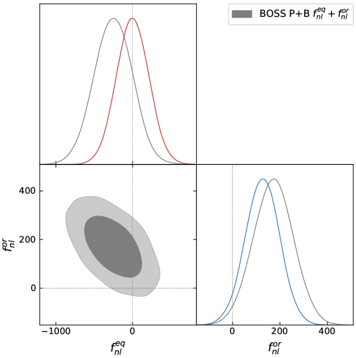
Primordial non-Gaussianity with LSS



- 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)



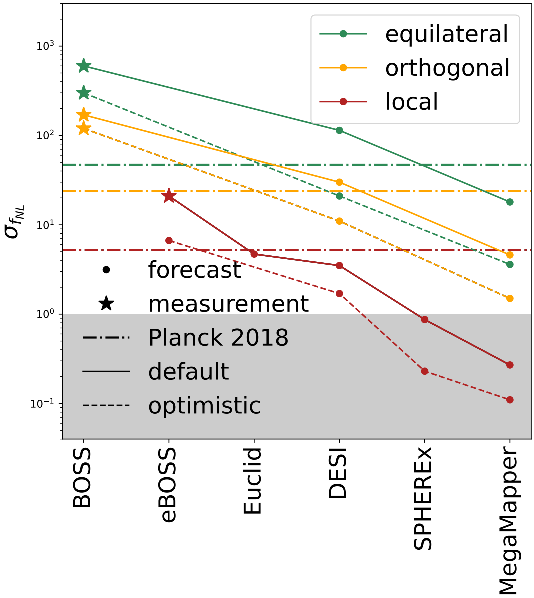
Cabass et al. (2022)



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

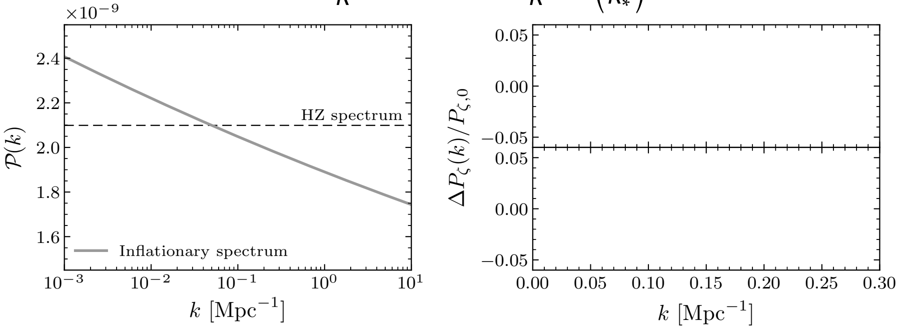
How far can we go?



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.

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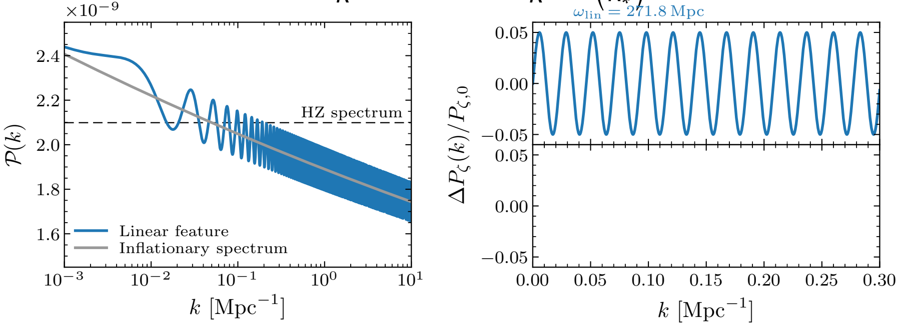

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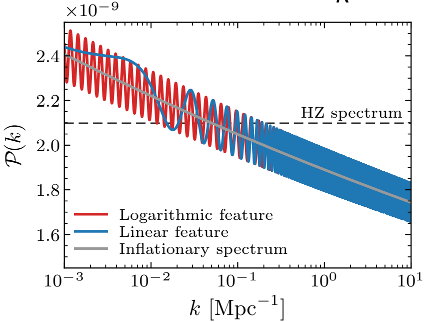

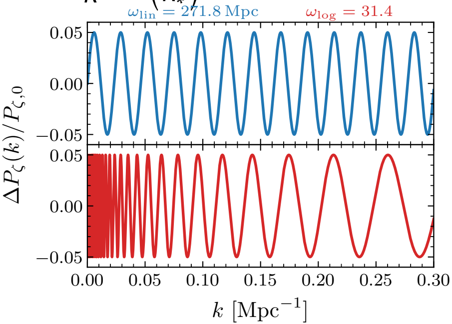

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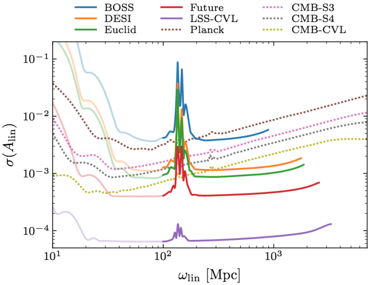
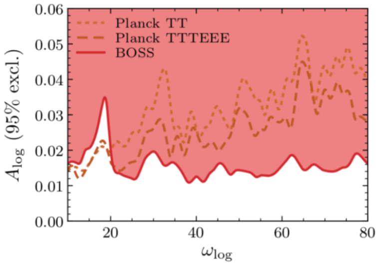




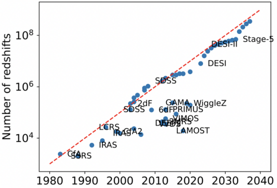
- Here we use a model-independent approach based on

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

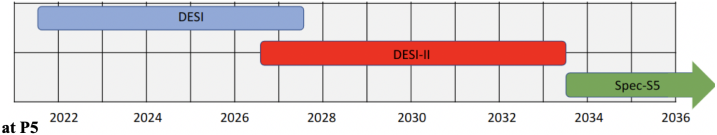
- LSS is more powerful than the CMB on small frequencies, while the CMB can access much higher frequencies
- DESI is going to provide constraints which cannot be accessed even by a CVL CMB experiment

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



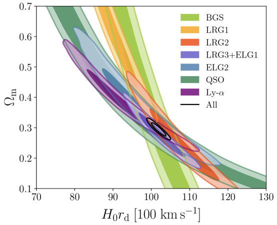
Dawson at P5

13

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

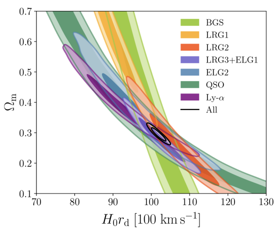
Schelgel et al. arXiv:2209.04322, arXiv:2209.03585, arXiv:1907.11171

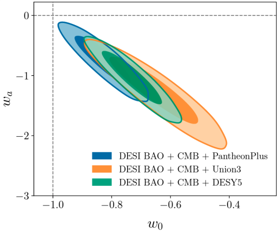
Summary



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

Summary





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

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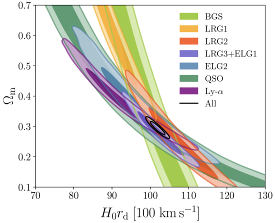
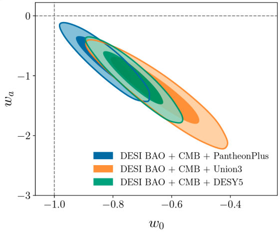
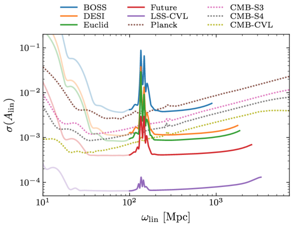






1. DESI and Euclid will provide excellent LSS datasets over the next decade with the DESI Y1 BAO results already public
2. Some tension with LCDM when allowing time dep. dark energy and the upper limits of the neutrino mass getting closer to the minimum mass provided by Neutrino oscillation experiments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

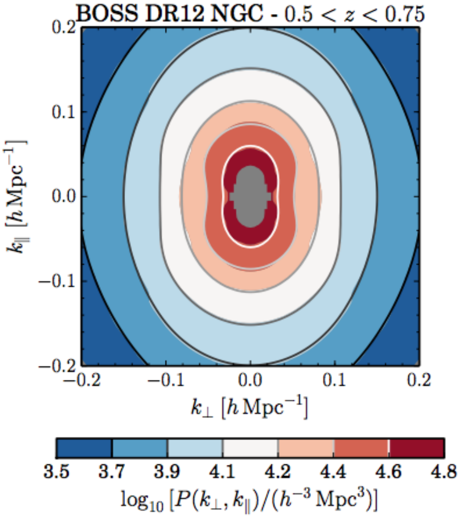
What are redshift-space distortions?

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

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

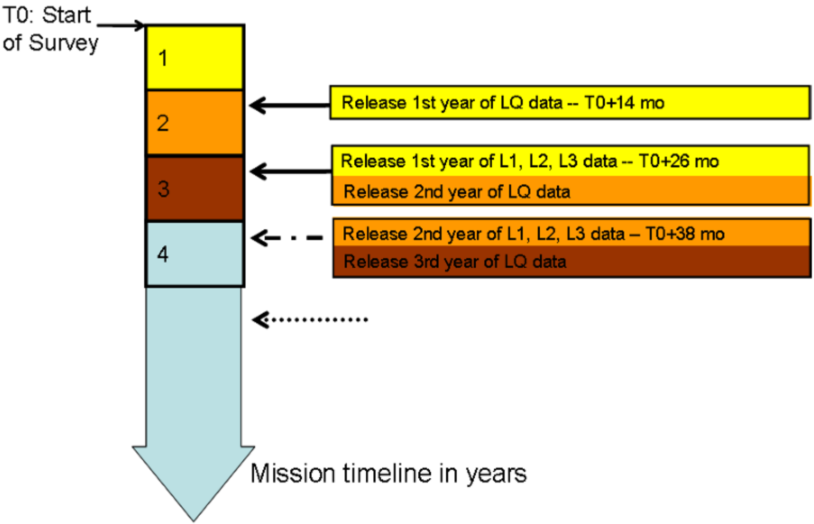
→ Introduces a quadrupole
→ Sensitive to cosmology since

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



Alam et al. (2017)

Euclid timeline



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 $k = 0.1h/\mathrm{Mpc}$ in the power spectrum)

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

Further linear corrections

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

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

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

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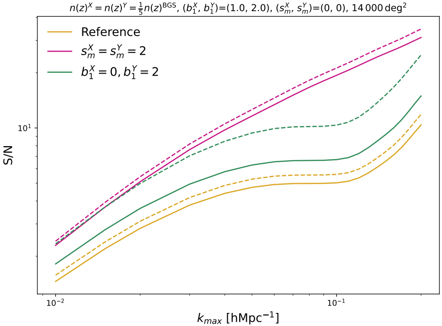
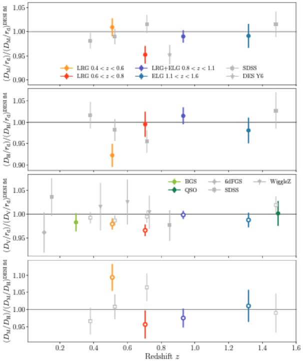
DESI-BGS forecasts for relativistic effects

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

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

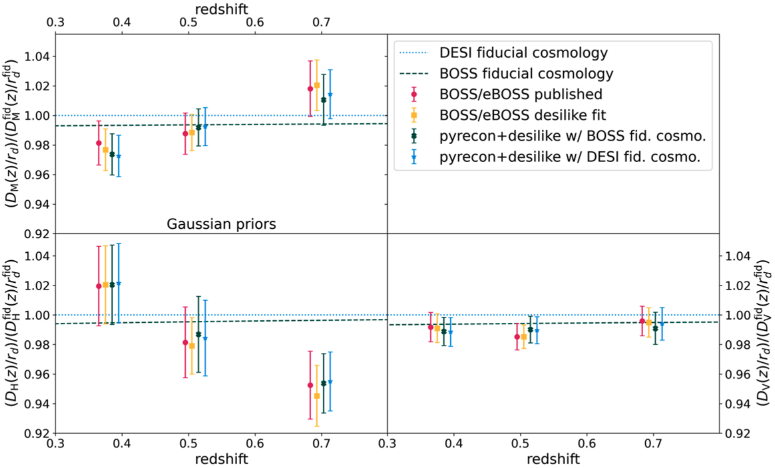


$$\left(\frac{S}{N}\right)^2 = \frac{1}{4\pi^2}\sum_i^{z_{\rm bins}} V(z_i)\int_{k_{\rm min}}^{k_{\rm max}} dk\, k^2 \frac{\left|P_1^{XY}(k,z_i)\right|^2}{\sigma^2_{P_1}(k,z_i)}$$



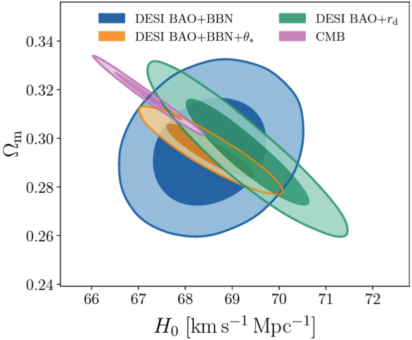
- The correlation with the $z \sim 0.7$ LRG redshift bins is ≤ 0.2 and the tension is around $2.7 - 3\sigma$
- There are small differences in the analysis framework
- The analysis was blinded
- We conclude that this difference is consistent with a statistical fluctuation

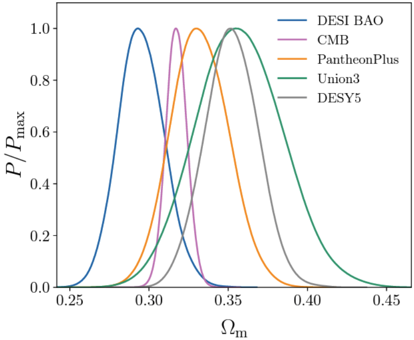
DESI 2024: Reanalysis of BOSS/eBOSS



DESI 2024

DESI 2024: Ω_m



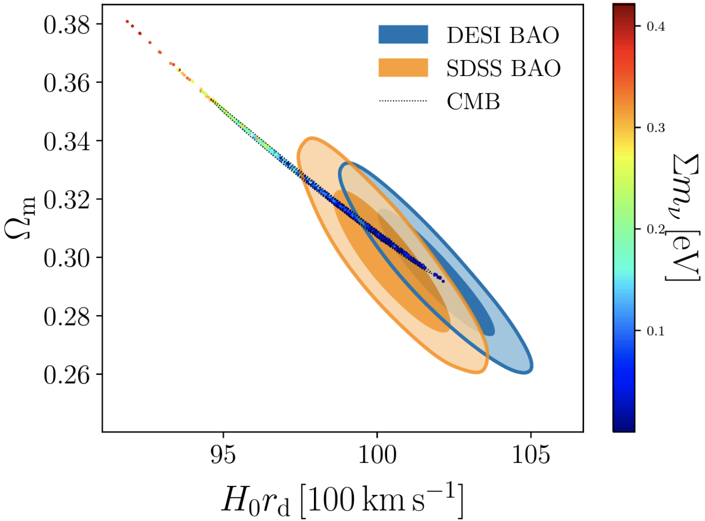


$$\left.\begin{aligned} \Omega_m &= 0.3069 \pm 0.0050, \\ H_0 &= (67.97 \pm 0.38)\mathrm{km s^{-1} Mpc^{-1}} \end{aligned}\right\}$$

DESI BAO + CMB

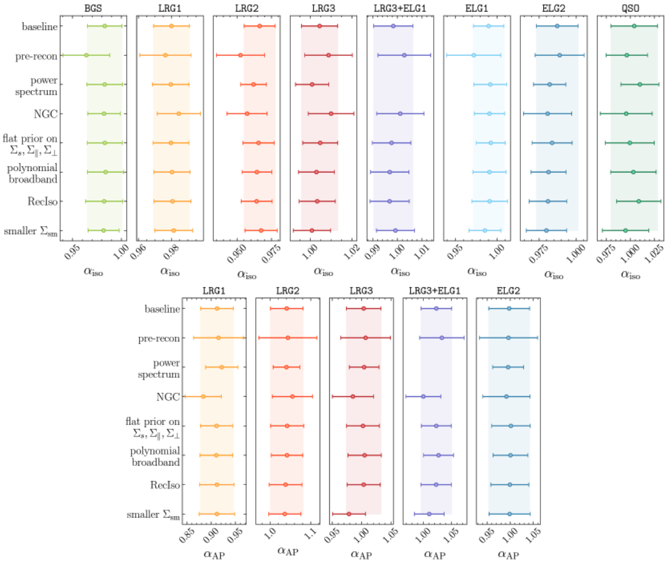
DESI 2024

DESI 2024: DESI vs. CMB



DESI 2024

DESI 2024: BAO systematics tests



DESI 2024

model / dataset	Ω_m	H_0 [km s^{-1} Mpc^{-1}]	Σm_ν [eV]	N_{eff}
ΛCDM+$\sum m_\nu$				
DESI+CMB	0.3037 ± 0.0053	68.27 ± 0.42	< 0.072	—
ΛCDM+N_{eff}				
DESI+CMB	0.3058 ± 0.0060	68.3 ± 1.1	—	3.10 ± 0.17
wCDM+$\sum m_\nu$				
DESI+CMB	0.282 ± 0.013	$71.1^{+1.5}_{-1.8}$	< 0.123	—
DESI+CMB+Panth.	0.3081 ± 0.0067	67.81 ± 0.69	< 0.079	—
DESI+CMB+Union3	0.3090 ± 0.0082	67.72 ± 0.88	< 0.078	—
DESI+CMB+DESY5	0.3152 ± 0.0065	67.01 ± 0.64	< 0.073	—
wCDM+N_{eff}				
DESI+CMB	0.281 ± 0.013	$71.0^{+1.6}_{-1.8}$	—	2.97 ± 0.18
DESI+CMB+Panth.	0.3090 ± 0.0068	67.9 ± 1.1	—	3.07 ± 0.18
DESI+CMB+Union3	0.3097 ± 0.0084	67.8 ± 1.2	—	3.06 ± 0.18
DESI+CMB+DESY5	0.3163 ± 0.0067	67.2 ± 1.1	—	3.09 ± 0.18
w_0w_aCDM+$\sum m_\nu$				
DESI+CMB	$0.344^{+0.032}_{-0.026}$	$64.7^{+2.1}_{-3.2}$	< 0.195	
DESI+CMB+Panth.	0.3081 ± 0.0069	68.07 ± 0.72	< 0.155	—
DESI+CMB+Union3	0.3240 ± 0.0098	66.48 ± 0.94	< 0.185	—
DESI+CMB+DESY5	0.3165 ± 0.0069	67.22 ± 0.66	< 0.177	—
w_0w_aCDM+N_{eff}				
DESI+CMB	$0.346^{+0.032}_{-0.026}$	$63.9^{+2.2}_{-3.3}$	—	2.89 ± 0.17
DESI+CMB+Panth.	0.3093 ± 0.0069	67.5 ± 1.1	—	2.93 ± 0.18
DESI+CMB+Union3	0.3245 ± 0.0098	65.9 ± 1.3	—	2.91 ± 0.18
DESI+CMB+DESY5	0.3172 ± 0.0067	66.6 ± 1.1	—	2.92 ± 0.18

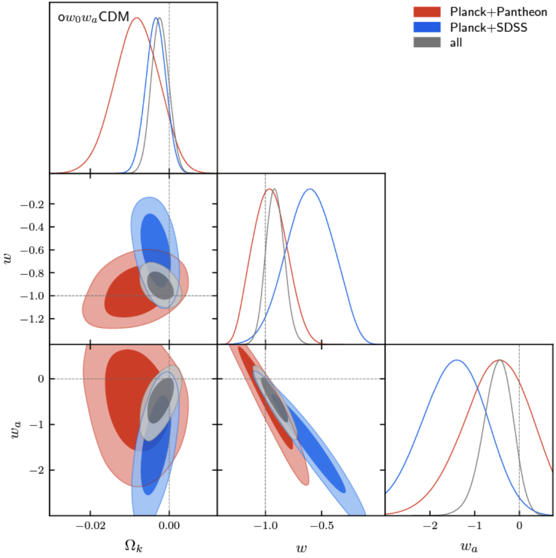
DESI 2024

DESI 2024: BAO systematics budget

Systematic	Error (in percent)	Comments
Theoretical	0.1 ($\alpha_{\rm iso}$), 0.2 (α_{AP})	Includes fitting methodology and choices, as well as expected impacts from galaxy bias and cosmology misestimation
Observational		
a. Imaging	Not detected	Tested on the data, with the largest change being 0.3% seen for the ELG1, and the rest being 0.1%.
b. Spectroscopic	Not detected	Tested with the mocks on the clustering level.
c. Fiber assignment	Not detected	The test was finalized after unblinding.
HOD	0.2	Only one detected statistically significant pair Limited by statistical precision of mocks Note : some of this error is already included in the theory budget
$N_{\rm eff}$	0.2 ($\alpha_{\rm iso}$)	Bias for $N_{\rm eff} = 3.7$
Fiducial $D_A(z)$	< 0.1	May require iteration post-unblinding if best-fit is far from fiducial Upper limit based on statistical precision
Reconstruction	Not detected	No significant effects from different
		algorithms etc.
Covariances	Not detected	Based on comparisons between analytic and mock covariances

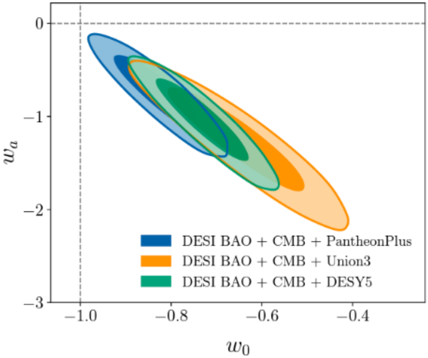
DESI 2024

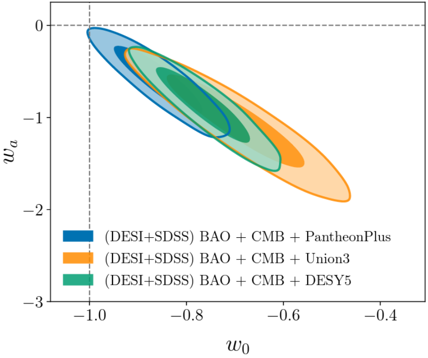
BOSS/eBOSS $w_0 w_a$CDM



Alam et al. 2020

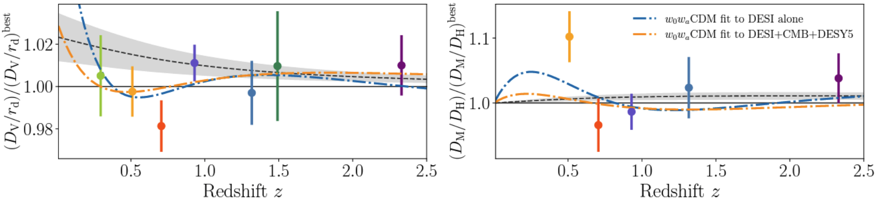
DESI vs. SDSS for $\omega_0\omega_a$CDM





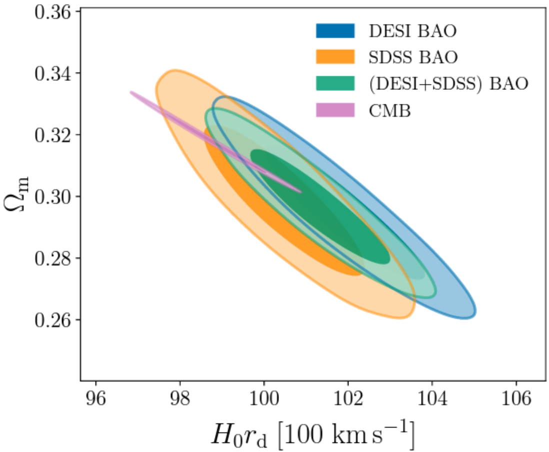
DESI 2024

DESI 2024: $w_0 w_a$CDM models



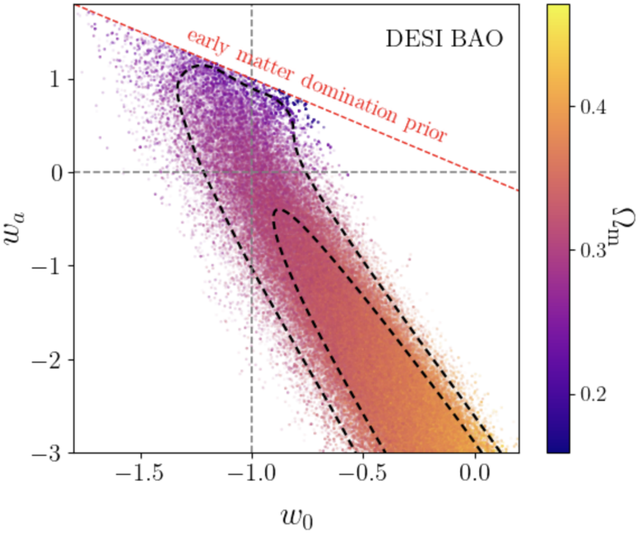
DESI 2024

DESI and SDSS are consistent



DESI 2024

The impact of $w_0 w_a$ prior



DESI 2024