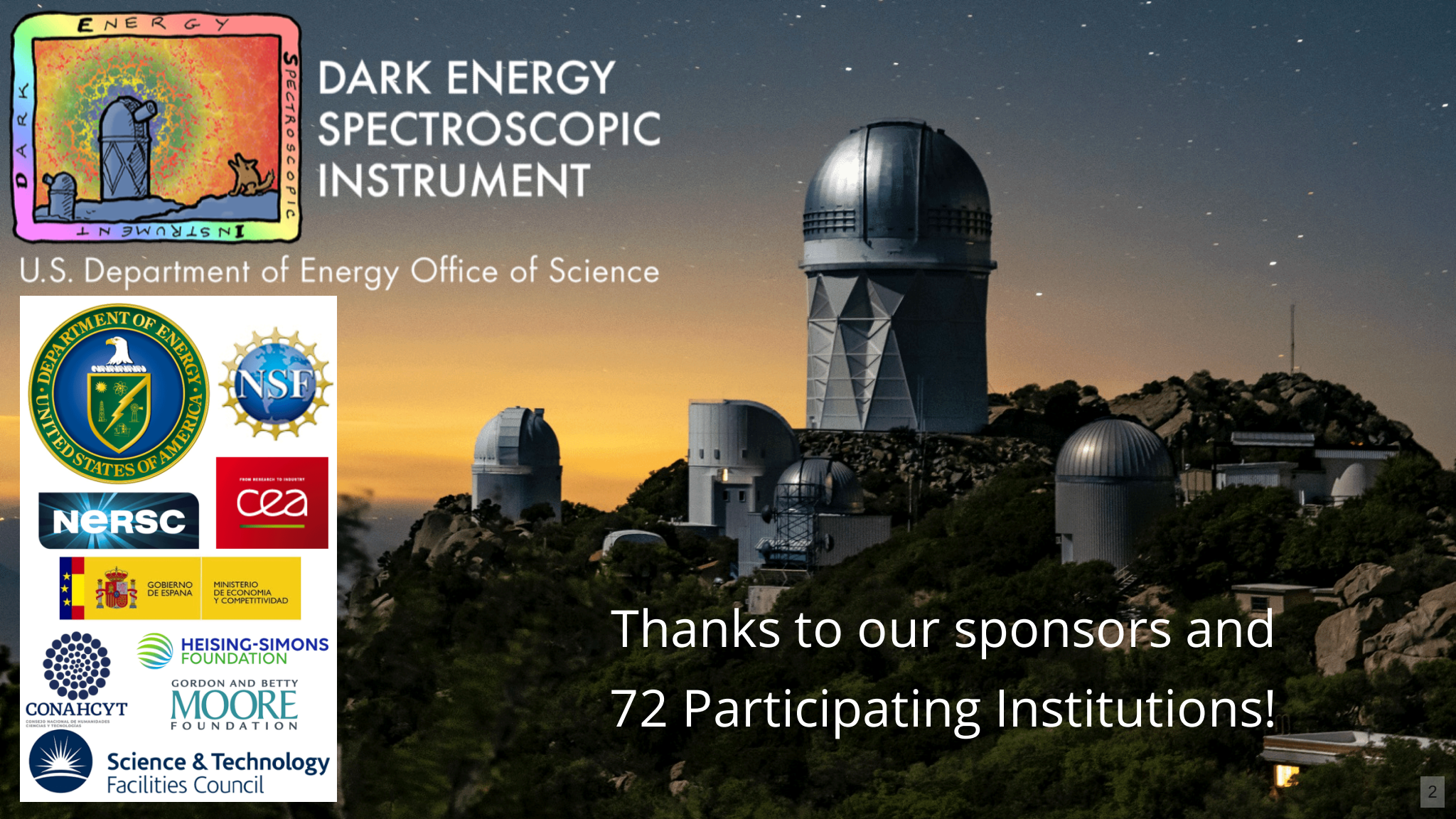
DESI DR2: Full-Shape Clustering and CMB Lensing Cross-Correlation



Arnaud de Mattia
CEA Paris-Saclay, Irfu

ADE
November 2026

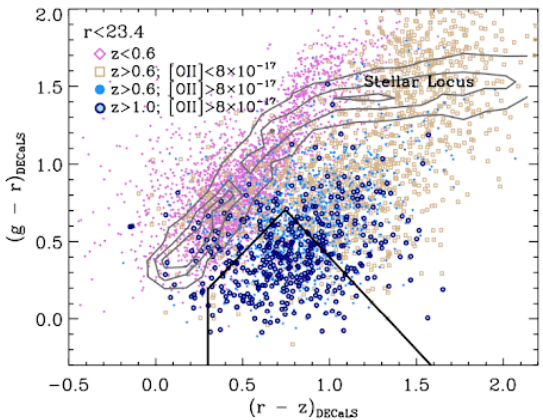

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science
Thanks to our sponsors and
72 Participating Institutions!

DARK ENERGY SPECTROSCOPIC INSTRUMENT

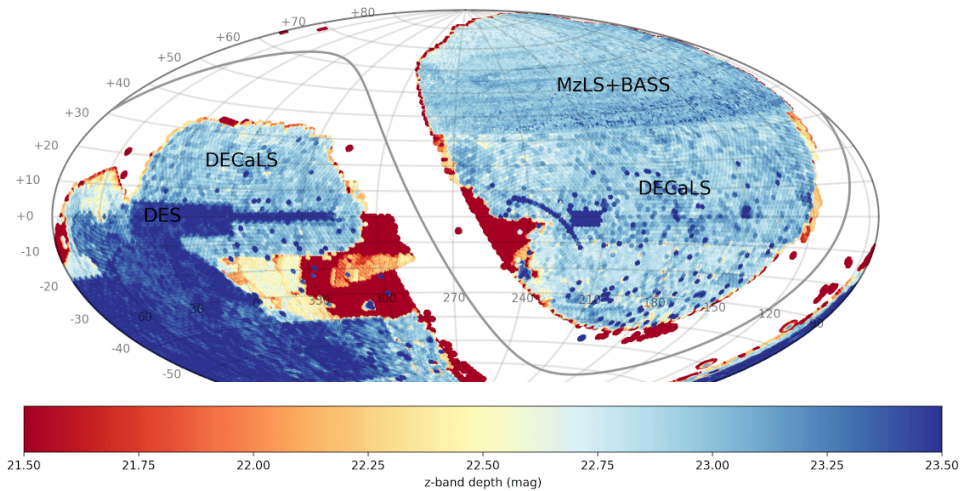
U.S. Department of Energy Office of Science

From images to redshifts

target selection

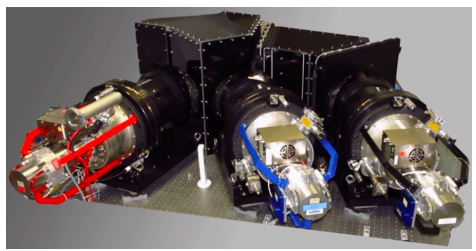


imaging surveys (2014 - 2019) + WISE (IR)

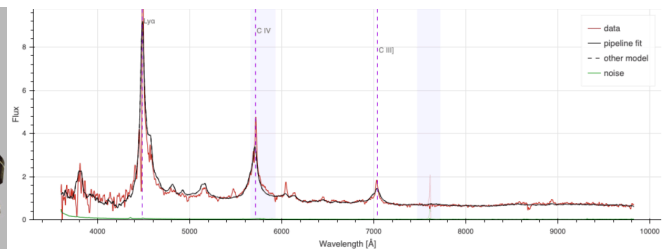


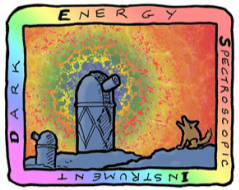
spectroscopic observations





spectra and redshift measurements





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DESI run 1 galaxy samples

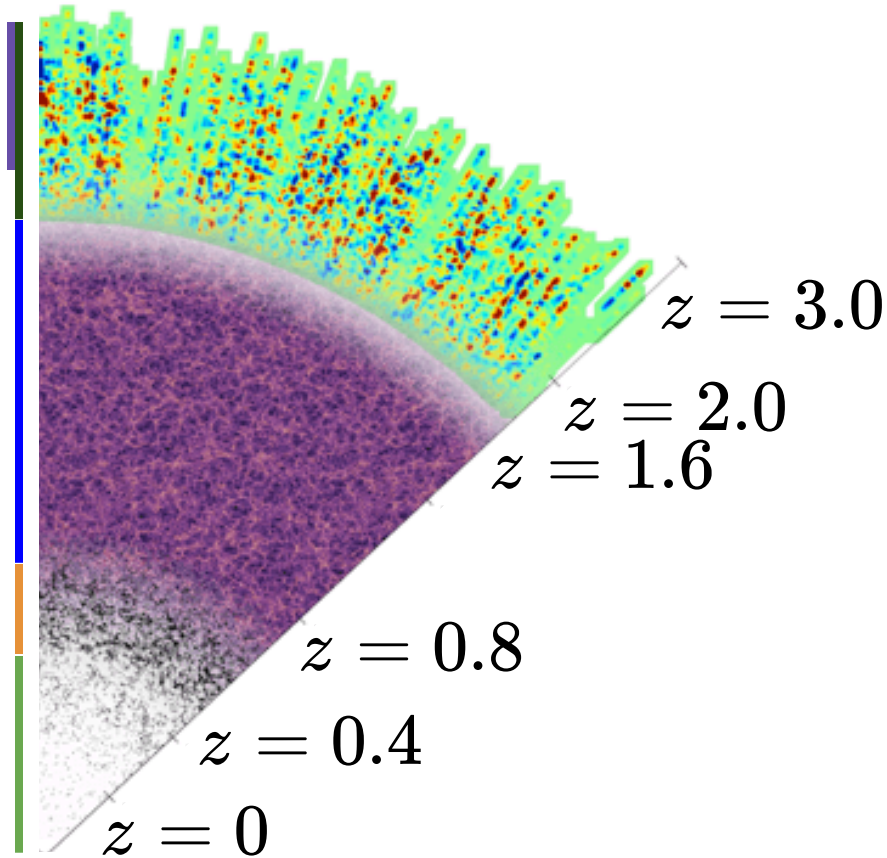
8 years $\sim$ 63M galaxy redshifts over 17k deg^2

QSO: 3.4M *(SDSS: 500k)*
Lyα 1.8 < z
Tracers 0.8 < z < 2.1

ELG: 30M *(SDSS: 200k)*
0.6 < z < 1.6

LRG: 14M *(SDSS: 1M)*
0.4 < z < 1.1

BGS: 17M *(SDSS: 600k)*
0 < z < 0.4

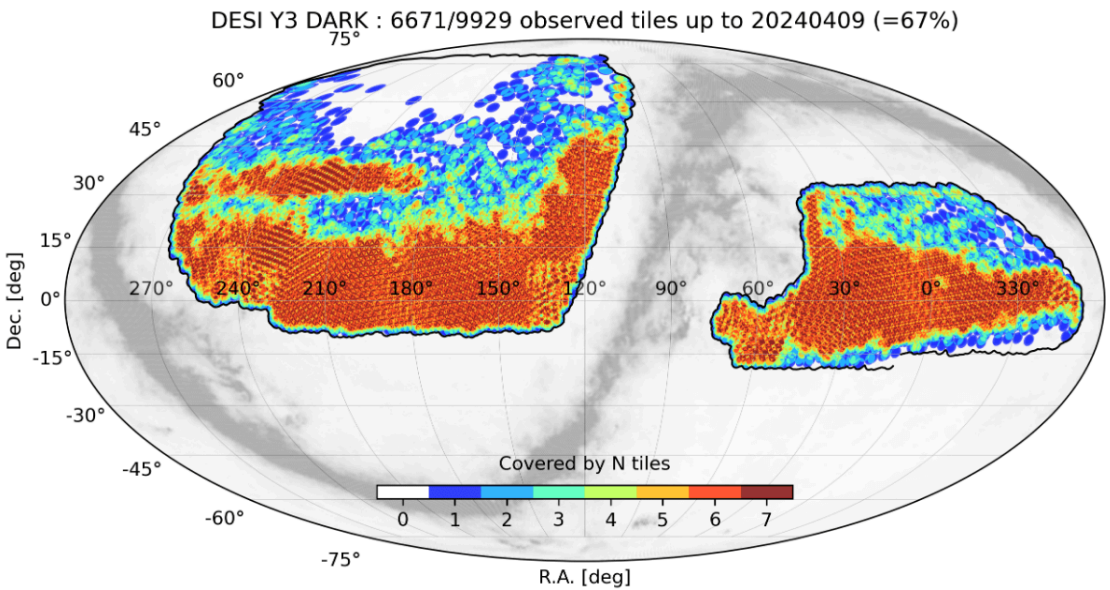


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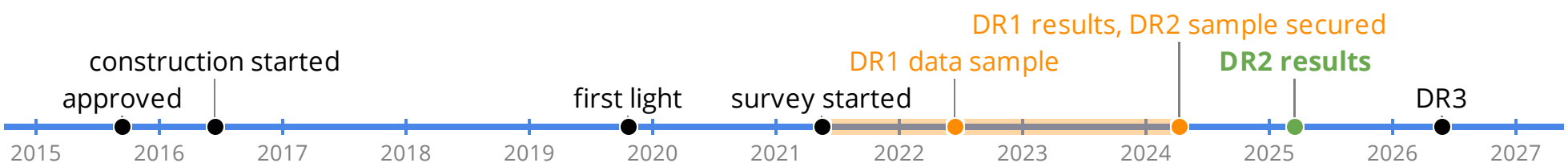
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DESI data release 2 (DR2)

Observations from May 14th 2021 to April 9th 2024



- 30M galaxy and QSO redshifts in **3 years**
- **14M** used in the DR2 analysis (6M in DR1)
- **820,000 Lyα QSO** at $z > 2.09$ (420,000 in DR1)
- **> 2× increase in number of tracers**



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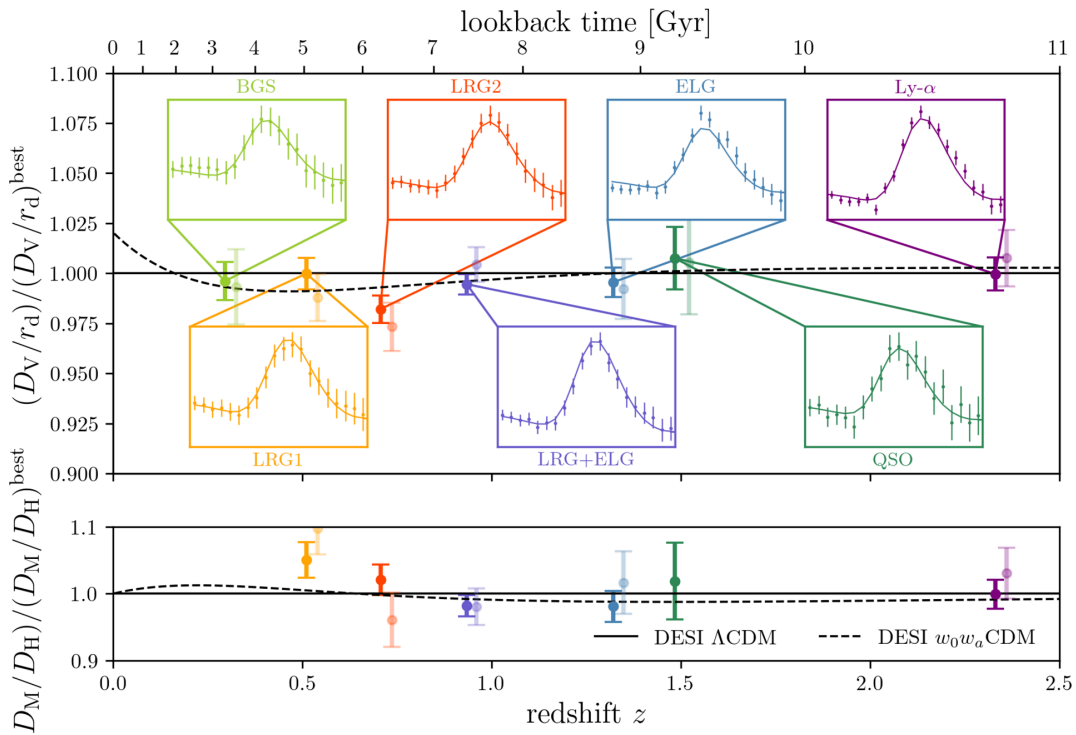
DESI DR2 BAO

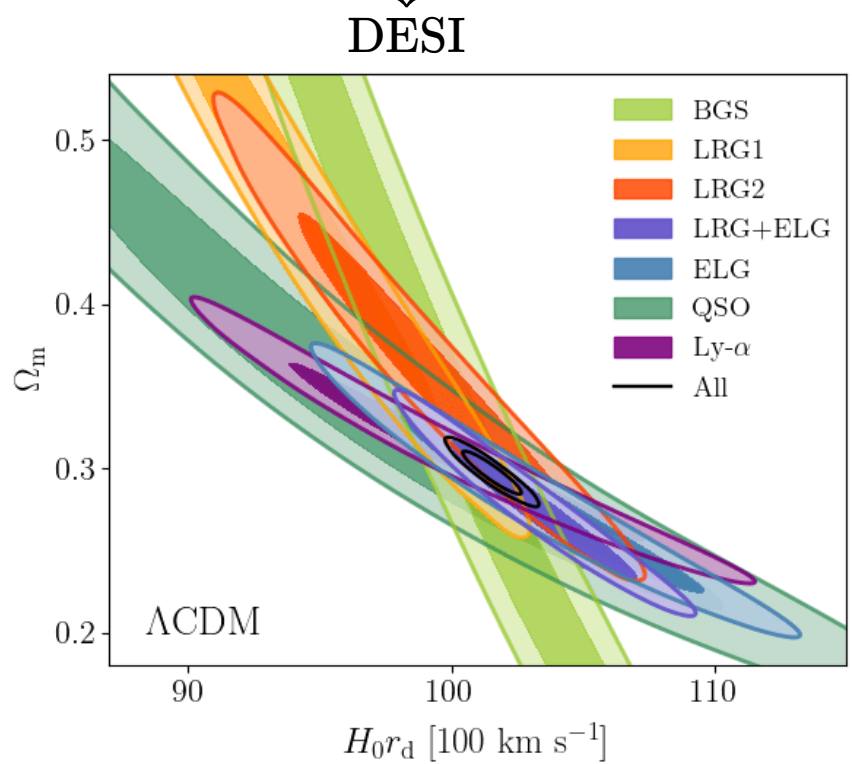
$$\Omega_{\rm m} = 0.2975 \pm 0.0086 \quad (\mathbf{3.0\%})$$

$$H_0 r_{\rm d} = (101.54 \pm 0.73)\,[100\,{\rm km\,s^{-1}}] \quad (\mathbf{0.7\%})$$

DESI

DESI DR2 BAO measurements



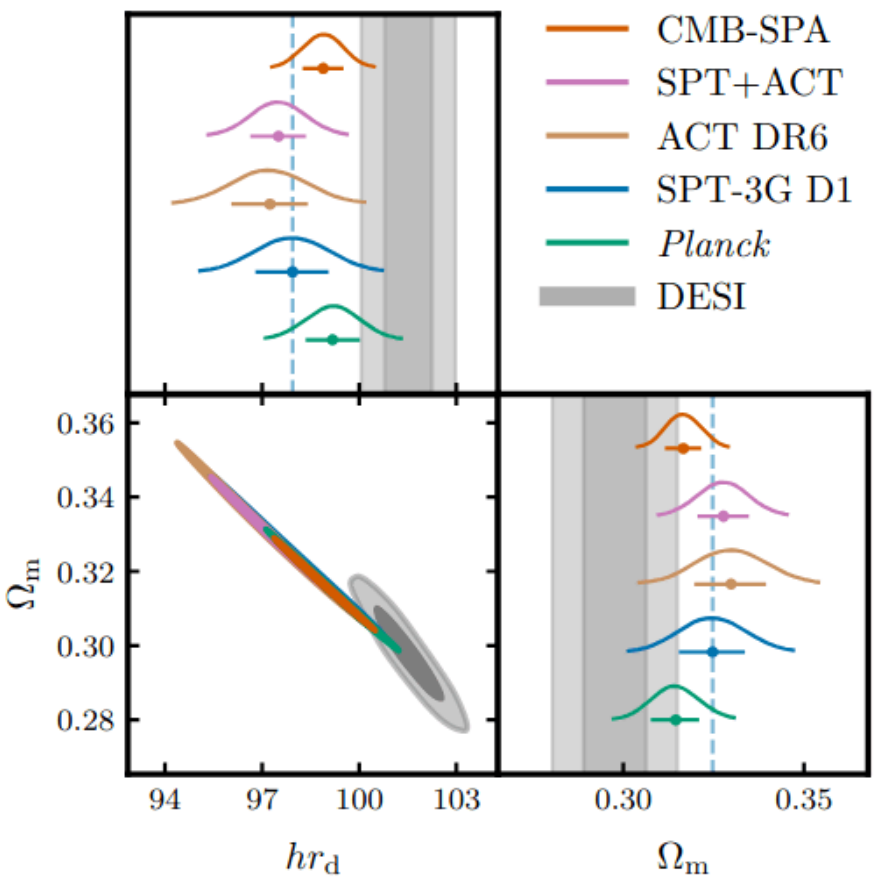


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BAO vs CMB

SPA = SPT+Planck+ACT



	$100\,\Omega_m$	hr_d [Mpc]	Distance to DESI
CMB-SPA	31.66 ± 0.50	98.89 ± 0.63	$2.8\,\sigma$
SPT+ACT	32.77 ± 0.72	97.51 ± 0.87	$3.7\,\sigma$
SPT+*Planck*	31.89 ± 0.54	98.63 ± 0.67	$3.0\,\sigma$
ACT DR6	33.0 ± 1.0	97.2 ± 1.2	$3.1\,\sigma$
SPT-3G D1	32.47 ± 0.91	97.9 ± 1.1	$2.5\,\sigma$
Planck	31.45 ± 0.67	99.18 ± 0.84	$2.0\,\sigma$
DESI	29.76 ± 0.87	101.52 ± 0.73	

Camphuis+25

We conclude that there is a growing discrepancy in the ΛCDM parameter values favored by CMB and BAO data, even though ΛCDM provides an excellent fit to CMB and BAO data separately. The magnitude of this effect is borderline statistically significant, which motivates the collection of more precise data as well as the search for a cosmological model that better fits both types of data simultaneously.

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Dark Energy Equation of State

DESI DR2 papers (2025) → with SN updates (2026)

Combining all DESI + CMB + SN

$$\underbrace{w_0 = -0.838 \pm 0.055 \qquad w_a = -0.62^{+0.22}_{-0.19}}$$

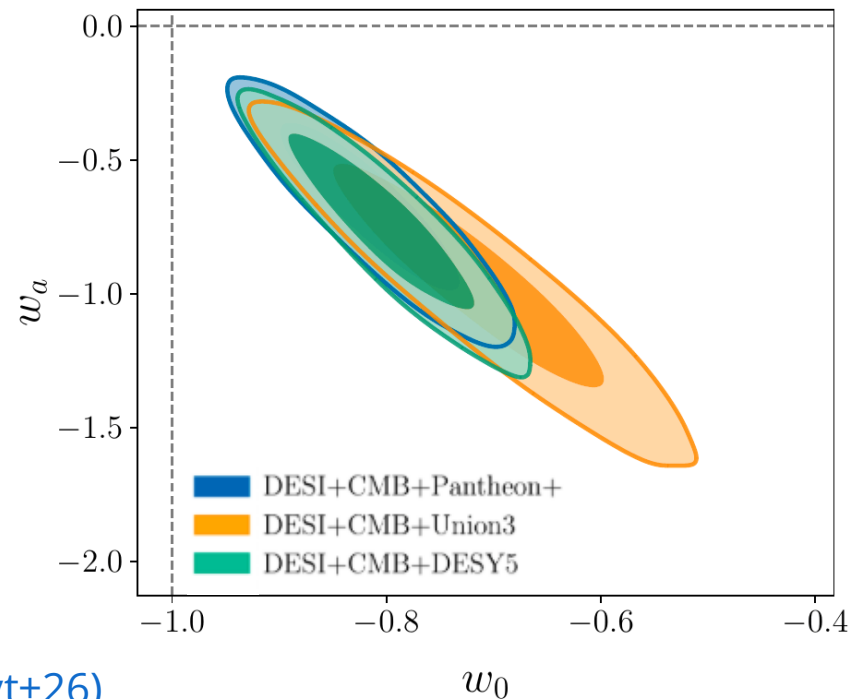
$\text{DESI} + \text{CMB} + \text{Pantheon+} \implies 2.8\sigma \rightarrow \mathbf{3.2\sigma}$

$$\underbrace{w_0 = -0.667 \pm 0.088 \qquad w_a = -1.09^{+0.31}_{-0.27}}$$

$\text{DESI} + \text{CMB} + \text{Union3} \implies 3.8\sigma \rightarrow \mathbf{3.4\sigma}$

$$\underbrace{w_0 = -0.752 \pm 0.057 \qquad w_a = -0.86^{+0.23}_{-0.20}}$$

$\text{DESI} + \text{CMB} + \text{DES-SN5YR} \implies 4.2\sigma \rightarrow \mathbf{3.3\sigma}$



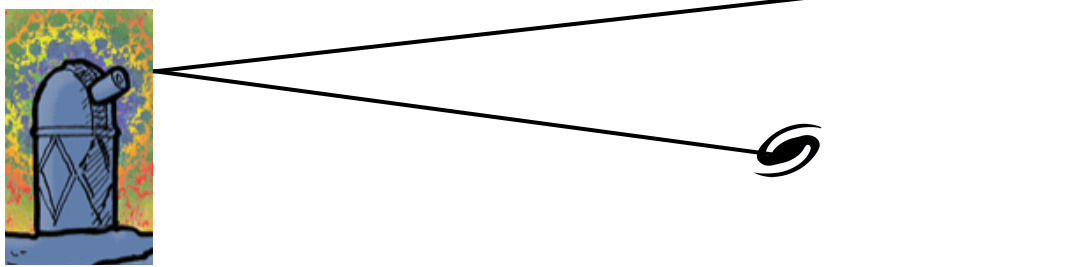
- Pantheon+ and Union3.1: new host galaxy masses (Hoyt+26)
- DESY5-Dovekie: re-calibration, numerical fixes (Popovic+25)

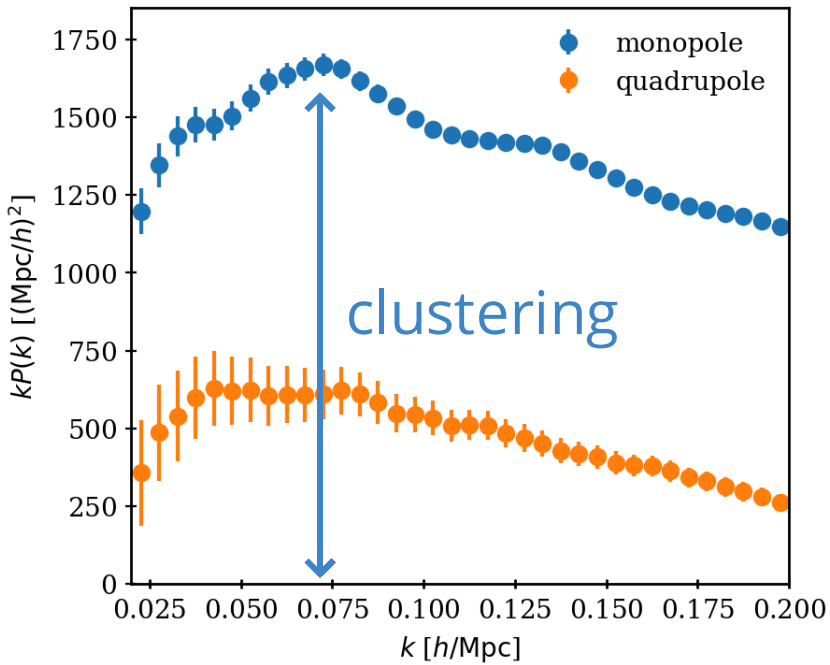
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Full Shape measurements

We fit the "full shape" (FS) of the galaxy power spectrum multipoles



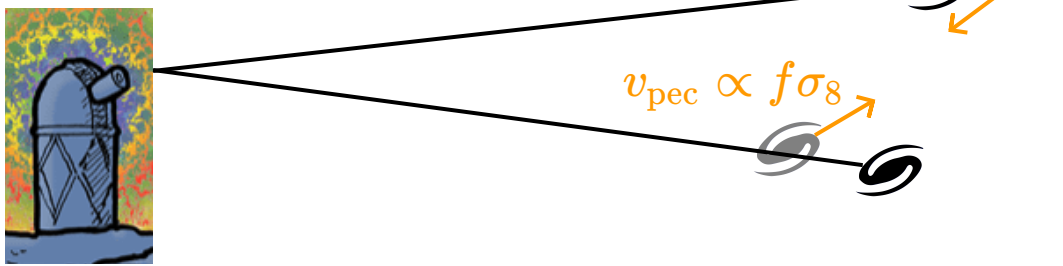


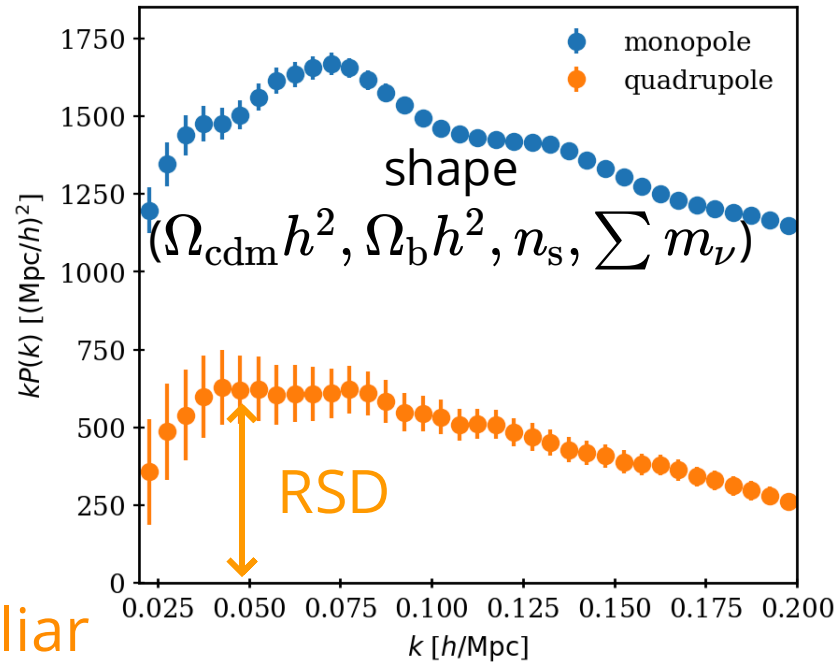
DARK ENERGY SPECTROSCOPIC INSTRUMENT

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Full Shape measurements

We fit the "full shape" (FS) of the galaxy power spectrum multipoles





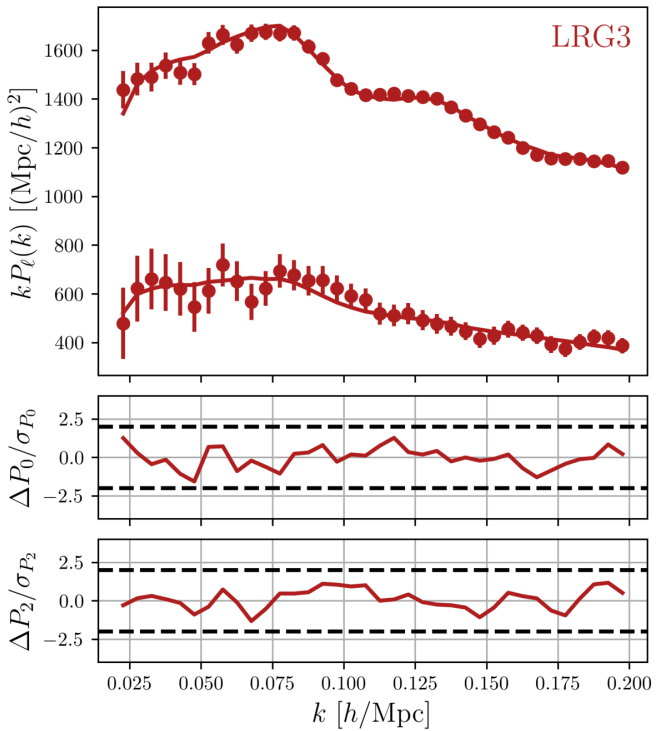
observed redshift = Hubble flow and peculiar velocities (RSD = "redshift space distortions")

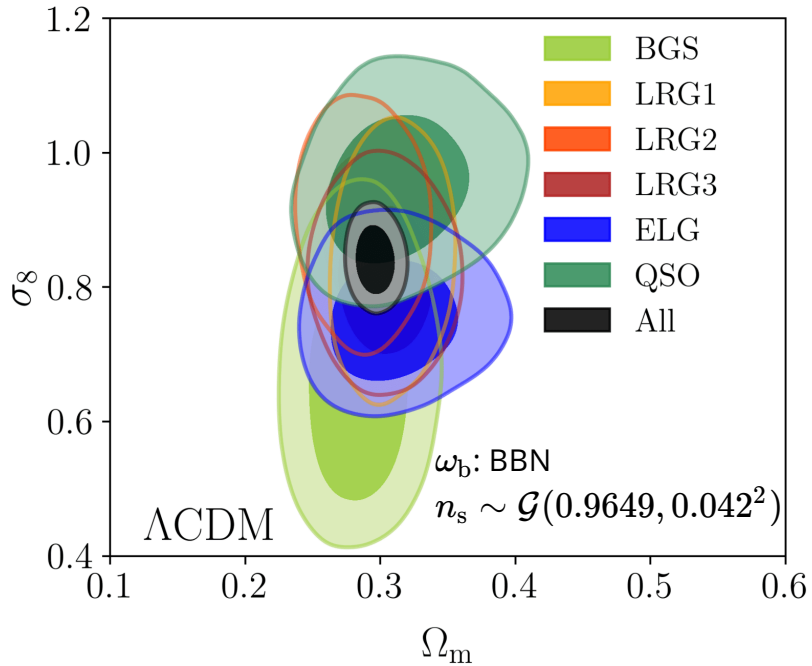
growth of structure $f\sigma_8$ sensitive to the theory of gravity and dark energy

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DR1 Full Shape + BAO





$$\Omega_m = 0.2962 \pm 0.0095 \quad (\mathbf{3.2\%})$$

$$\sigma_8 = 0.842 \pm 0.034 \quad (\mathbf{4.0\%})$$

$$H_0 = (68.56 \pm 0.75)\,\mathrm{km\,s^{-1}\,Mpc^{-1}} \quad (\mathbf{1.1\%})$$

Growth of structure: S_8 consistent with the CMB, **no deviation from GR in μ_0**

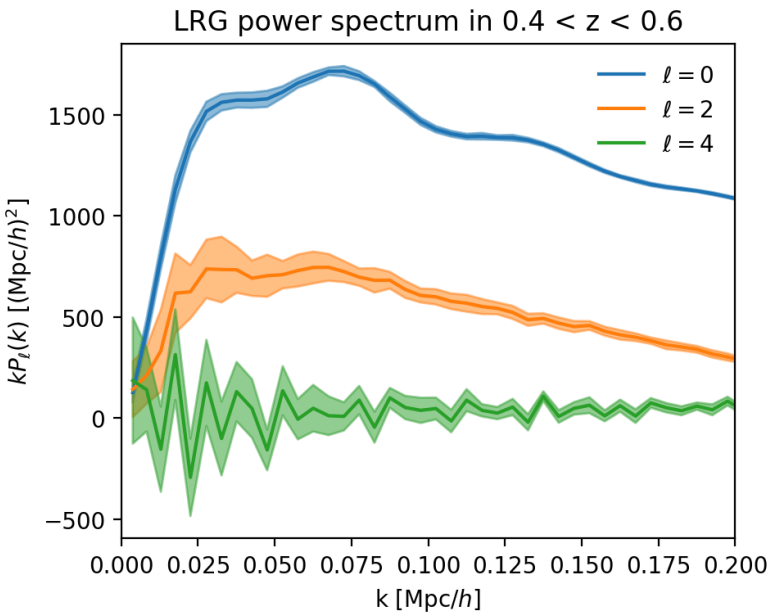
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DR2 Full Shape analysis

jaxpower

To the power spectrum $\propto |\delta(\mathbf{k})|^2$...



projection on $\mathcal{L}_\ell(\hat{k} \cdot \hat{z})$

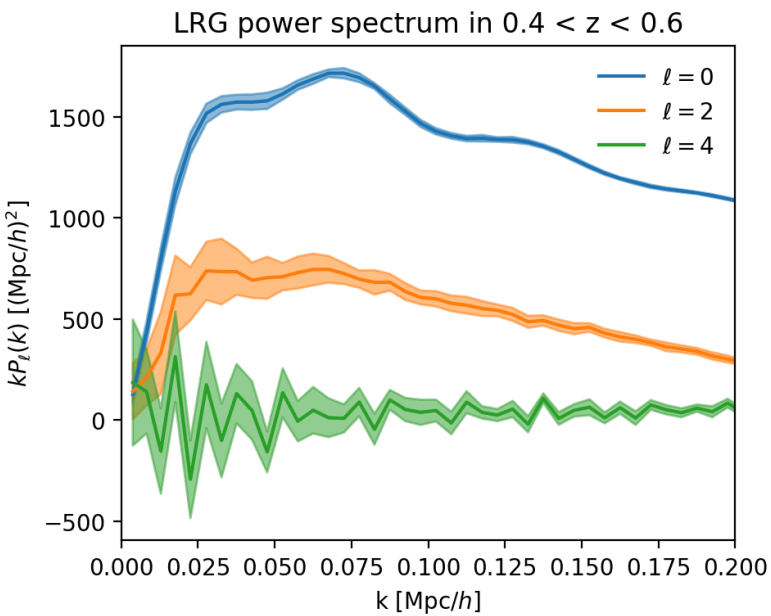
DARK ENERGY SPECTROSCOPIC INSTRUMENT

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DR2 Full Shape analysis

jaxpower

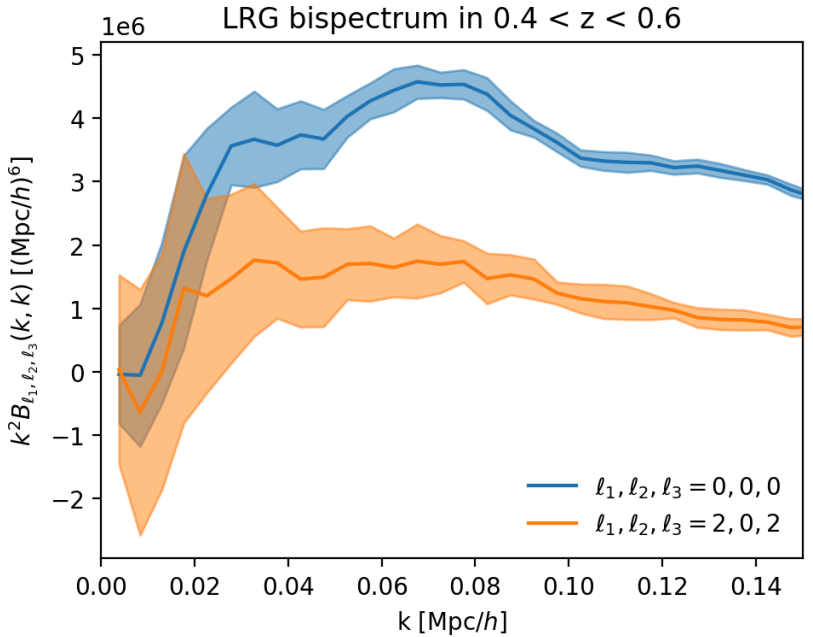
... we're adding the bispectrum $\langle \delta(\mathbf{k_1})\delta(\mathbf{k_2})\delta(\mathbf{k_3}) \rangle$! Sugiyama+18 "TripoSH" basis



projection on $\mathcal{L}_\ell(\hat{k} \cdot \hat{z})$

+

non-linearity of clustering



projection on:

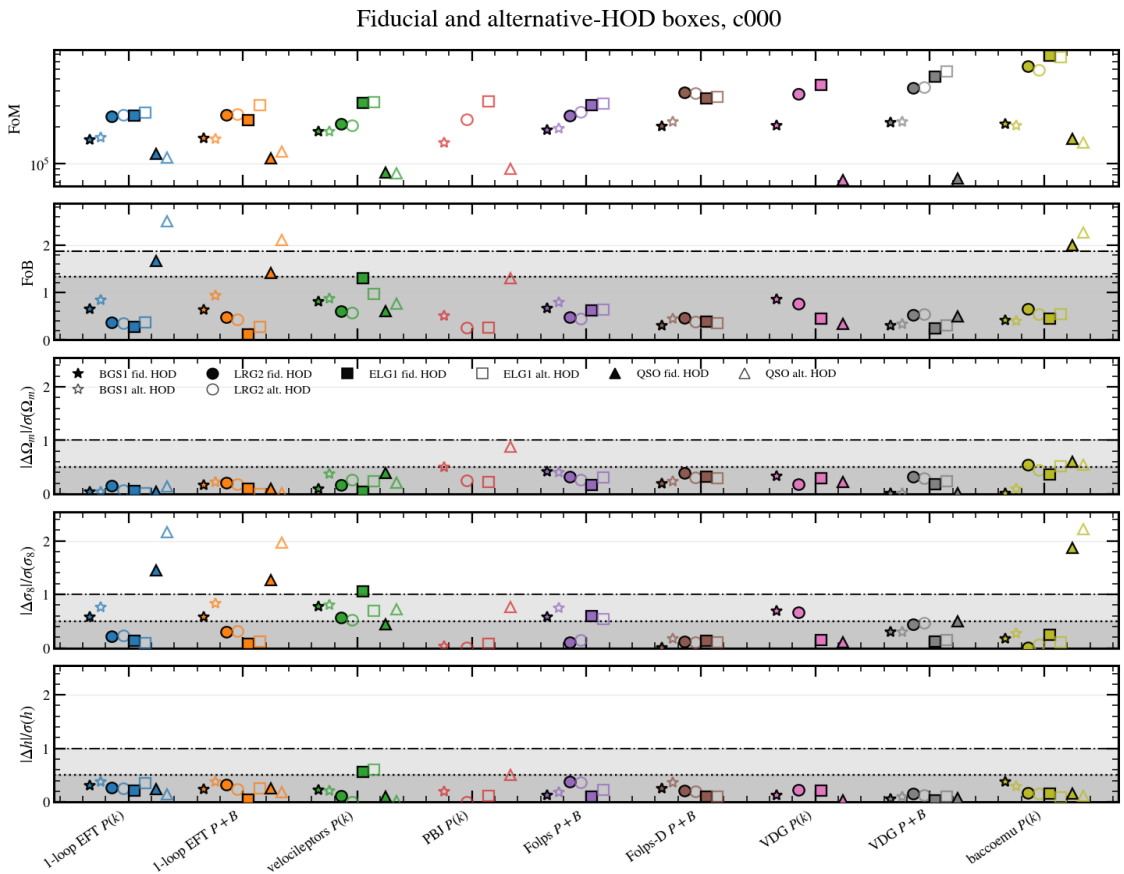
$$S_{\ell_1\ell_2L}(\hat{r}_1, \hat{r}_2, \hat{n}) = H^{-1}_{\ell_1\ell_2L} \sum_{m_1,m_2,M} \begin{pmatrix} \ell_1 & \ell_2 & L \\ m_1 & m_2 & M \end{pmatrix} y_{\ell_1 m_1}(\hat{r}_1) y_{\ell_2 m_2}(\hat{r}_2) y_{LM}(\hat{n}$$

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DR2 mock challenge

PRELIMINARY



- **Data**: mean of 25 Abacus boxes, fiducial and alternative HOD
- **Models** for P and $P+B$: 1-loop EFT, velocileptors, PBJ, Folps(-D), VDG, baccoemu
- **Requirement**: bias $< 0.5\sigma$ per parameter (σ of a single box), figure of bias < 0.87 (grey bands)
- Projection effects under control
- **Key Paper: FolpsEFT and VDG $P+B$**

Credit: M. Pellejero-Ibañez

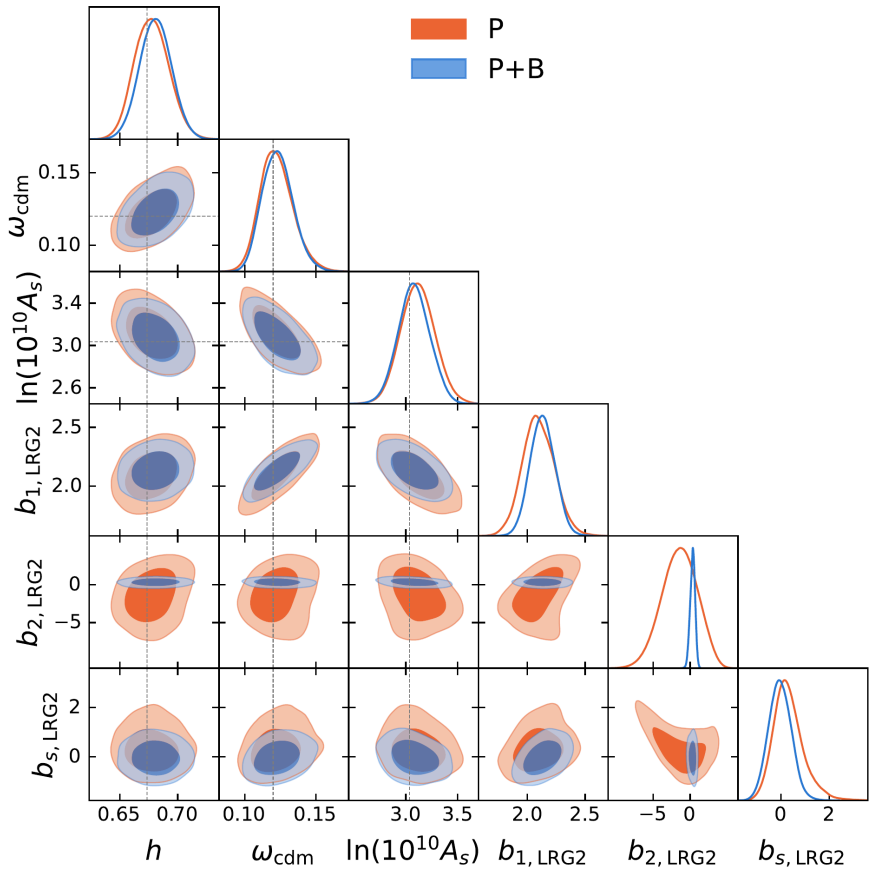
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What does B constrain?

desilike

PRELIMINARY



- Fits of P vs. $P + B$, LRG 0.6 < z < 0.8 (dashed: fiducial cosmology)
- **B pins down the nonlinear bias**: $\sigma(b_2)$ reduced by ~10 times
- Cosmology $(h, \omega_{\rm cdm}, \ln(10^{10} A_s))$: ~9% gain in precision
- **DR2 Full Shape: expected > 30% improvement on $\sigma(\sigma_8)$ compared to DR1**

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Why is Full Shape challenging?

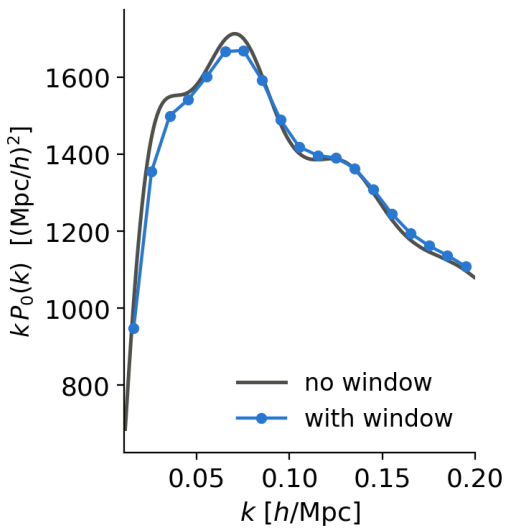
Full shape of the galaxy power spectrum (and now bispectrum!) sensitive to:

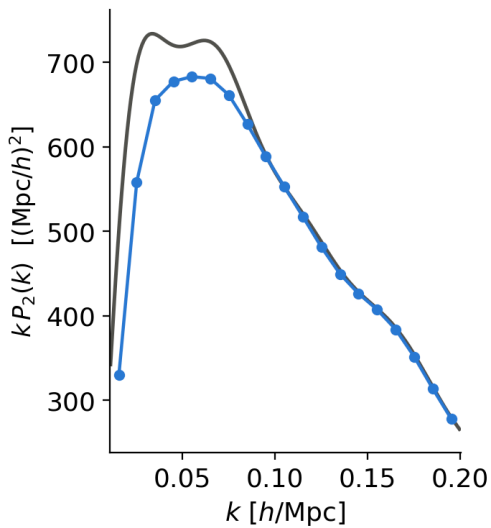
- the survey geometry

"window matrix"

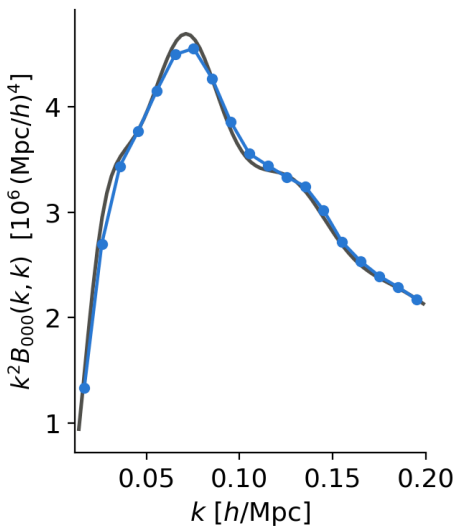
$$\langle P_o(k) \rangle = W(k, k') P_t(k')$$

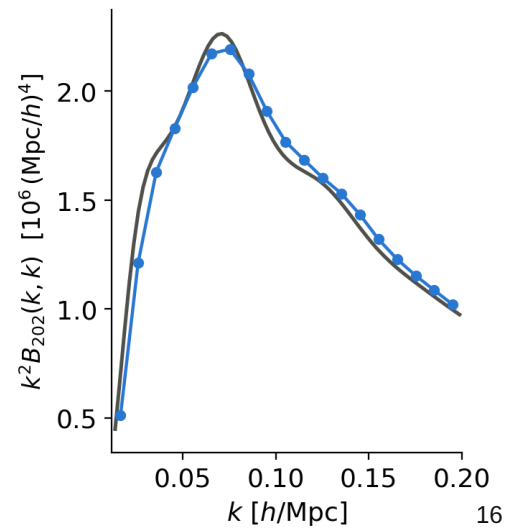
power spectrum

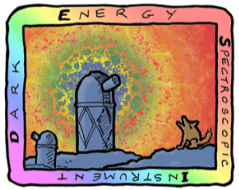




bispectrum







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Why is Full Shape challenging?

Full shape of the galaxy power spectrum (and now bispectrum!) sensitive to:

- the survey geometry
- (mis)specification of the selection function $\bar{n}$ = "observational systematics"
  1. **photometry:** "how many targets are selected depending on observing conditions" (e.g. Rosado-Marin+25)
  2. **fiber assignment:** "not all targets receive a fiber" (e.g. Bianchi+25, Pinon+25)
  3. **spectroscopy:** "not all redshifts are measured reliably" (e.g. Krolewski+25) and "uncertainty on the redshift measurement" (e.g. Yu+25)

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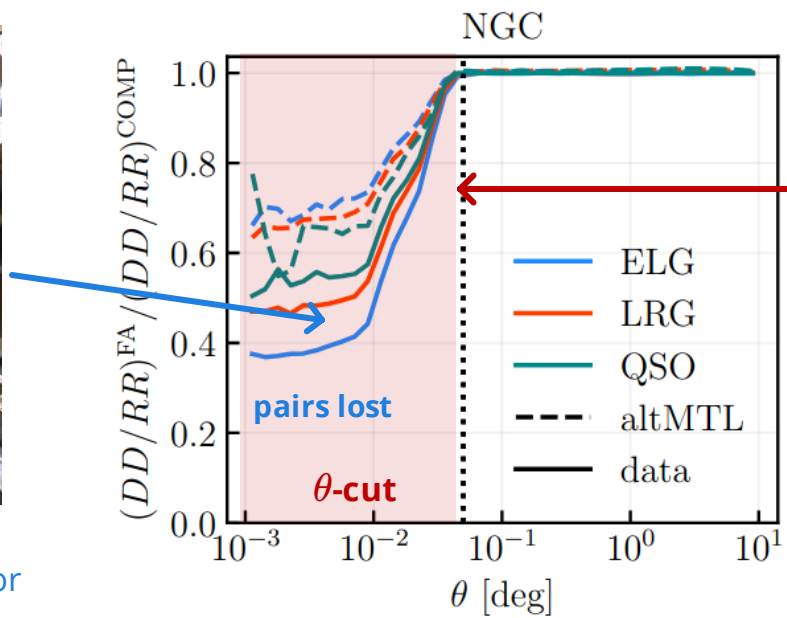
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Fiber assignment (θ-cut)

Close pairs ($\lesssim 0.05°$, the positioner patrol diameter) cannot all receive a fiber: pairs are lost at small separation



Fiber positioners, patrol radius 6 mm: close targets compete for the same positioners



Pinon+25

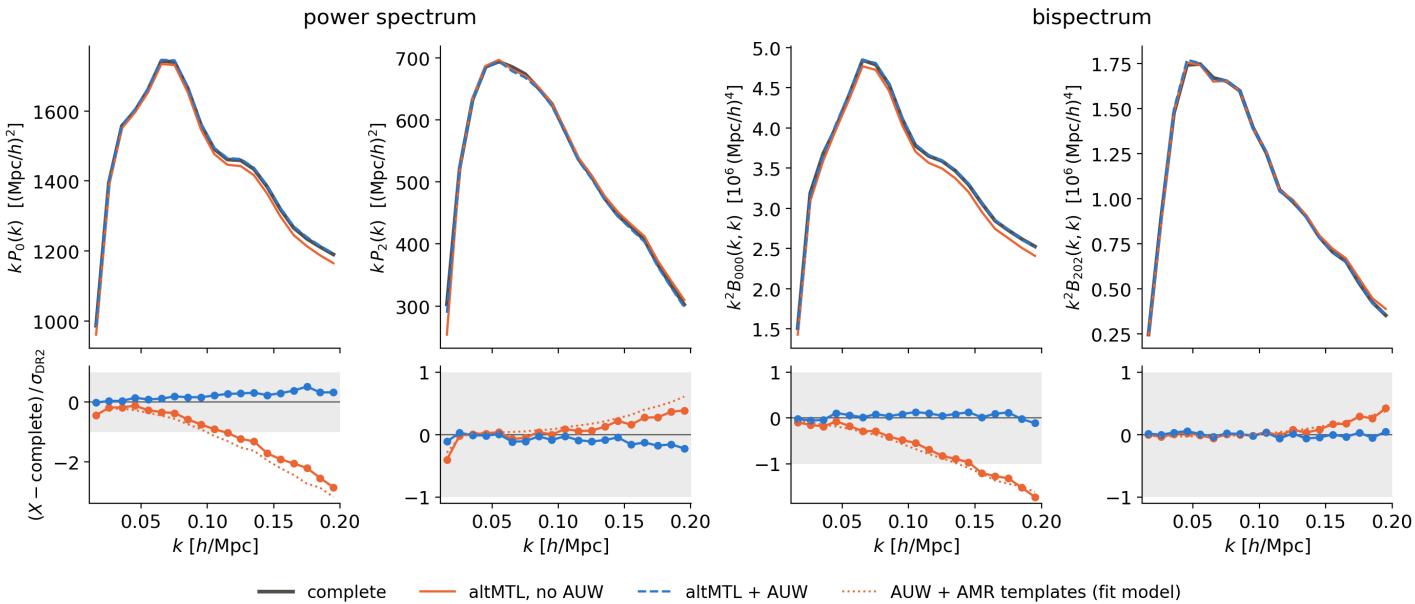
θ-cut = remove *all* pairs $< 0.05°$, and model it in the window matrix

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Fiber assignment (θ-cut)

- Close pairs ($\lesssim 0.05°$, the positioner patrol diameter) cannot all receive a fiber: pairs are lost at small separation
- **DR2: angular upweighting (AUW)** of close pairs, instead of the θ-cut



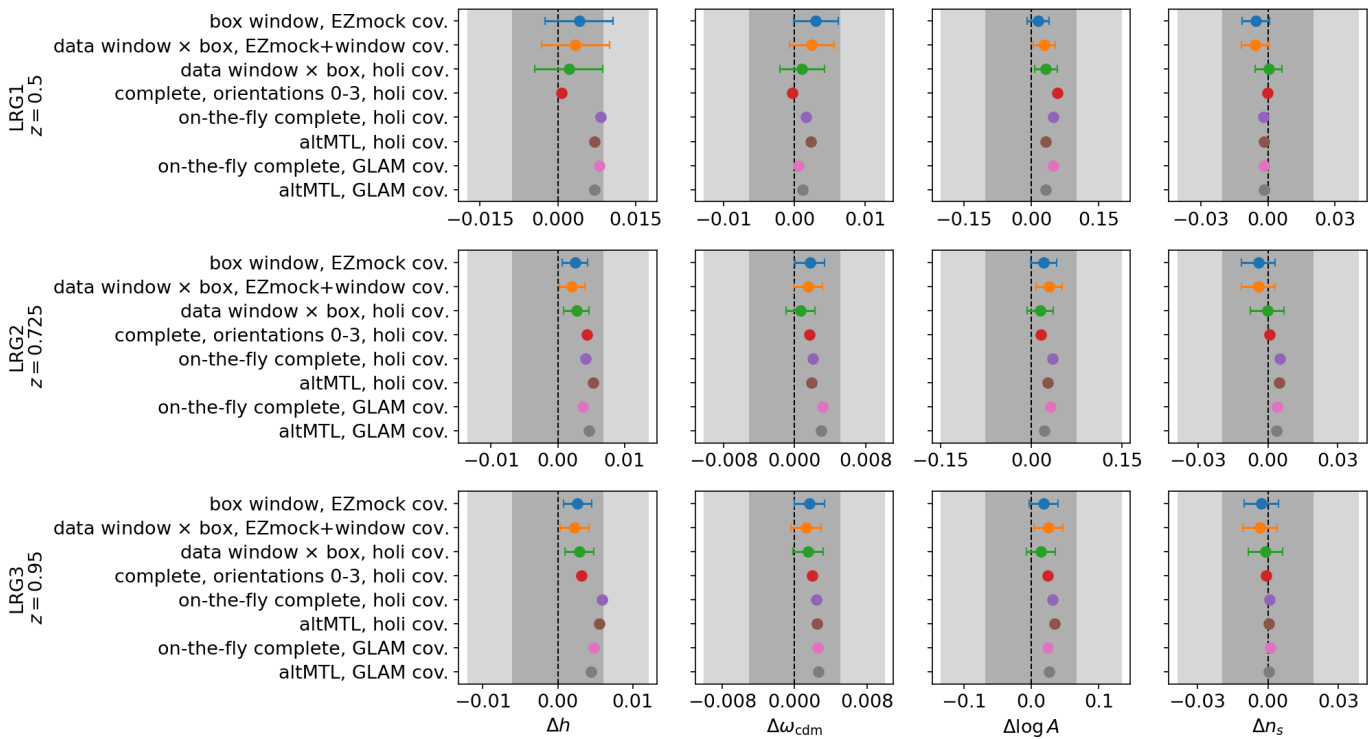
LRG 0.6 < z < 0.8, mocks with fiber assignment (altMTL) vs. without (complete)

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Validation on realistic mocks

PRELIMINARY



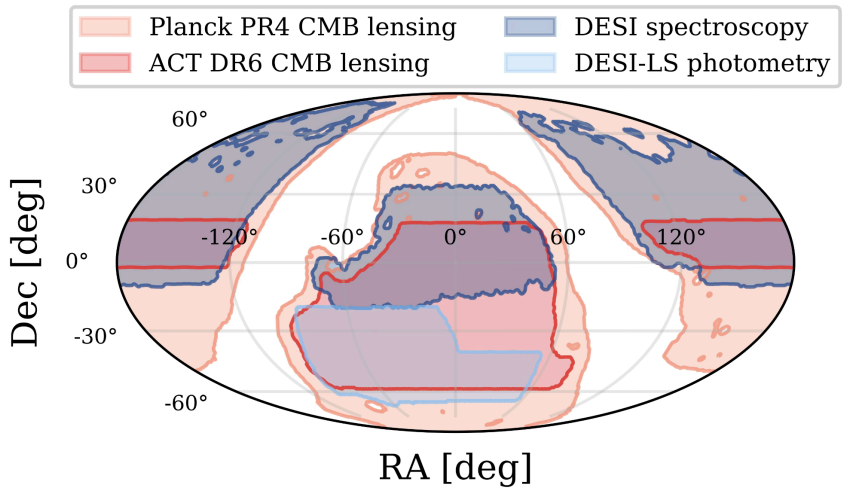
- Joint fits of $P + B$ to the mean of 25 mocks
- Tests: survey window, fiber assignment, integral constraints, covariance
- **Shifts small compared to the statistical error** (shaded: $\pm 0.5\sigma$, $\pm 1\sigma$)

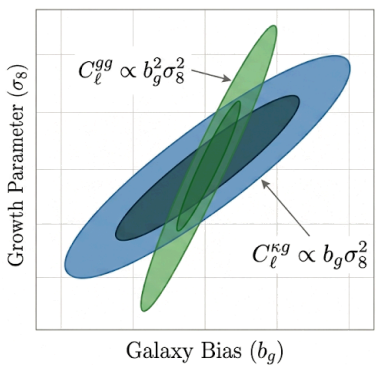
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DESI DR2 × CMB lensing

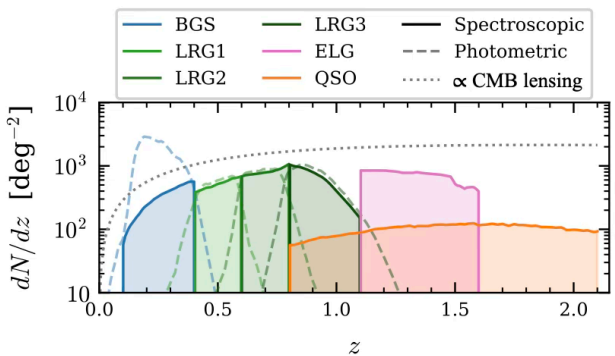
- **CMB lensing** κ: projected matter; cross-correlation with DESI galaxies recovers the redshift evolution, robust against galaxy systematics
- **Joint analysis**: DESI DR2 3D clustering (BGS to QSO) + $C_\ell^{\kappa g}$ with ACT DR6 and Planck PR4 lensing
- **Model**: Lagrangian PT / hybrid EFT, analytic covariance





Breaks the $b - \sigma_8$ degeneracy

$$C_\ell^{gg} \propto b^2\sigma_8^2$$
$$C_\ell^{\kappa g} \propto b\,\sigma_8^2$$

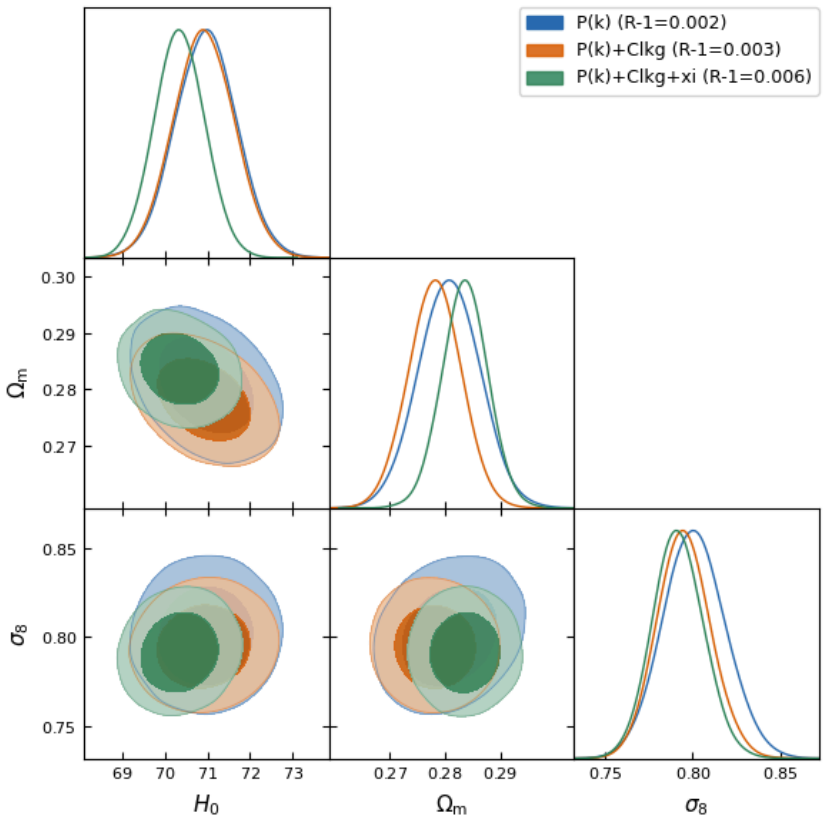


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Constraining power to expect

PRELIMINARY, BLINDED



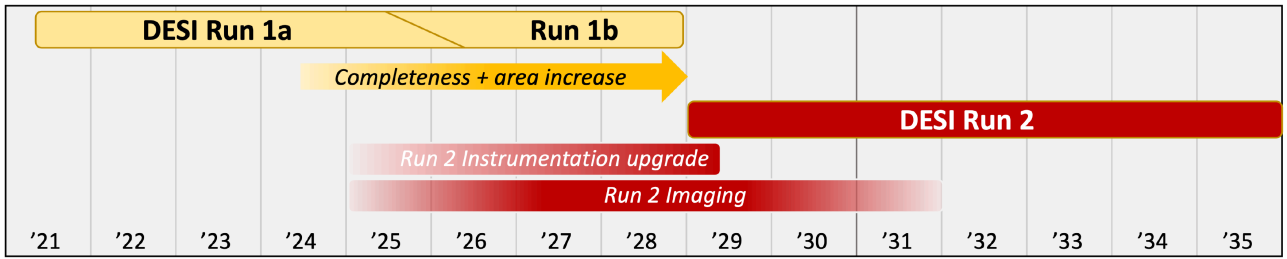
- Model validated on lightcone mocks
- Extragalactic CMB foregrounds mitigated to $< 0.2\sigma$
- Projection effects under control
- $\simeq 20\%$ **gain on** $\sigma(\sigma_8)$ **from** $C_\ell^{\kappa g}$

Adapted from G. Farren (DESI CMBx), Cosmic Rhythms, Sep. 2026

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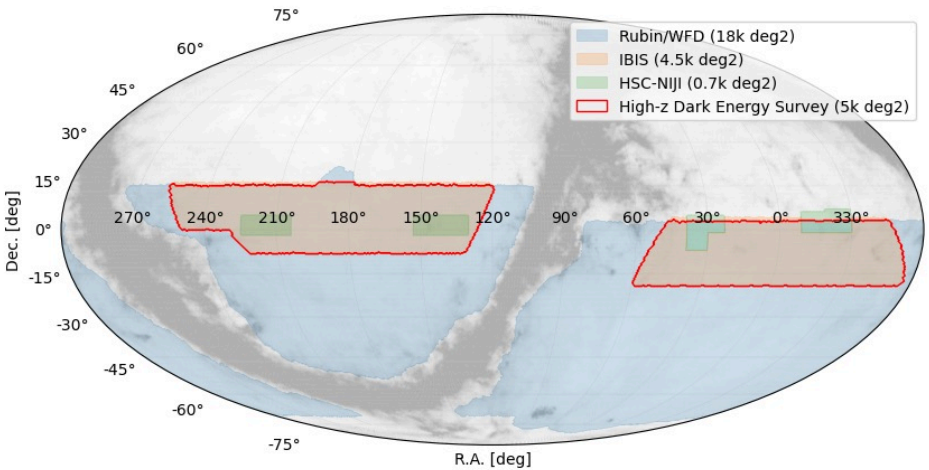
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DESI Run 2 (2029 – 2035)

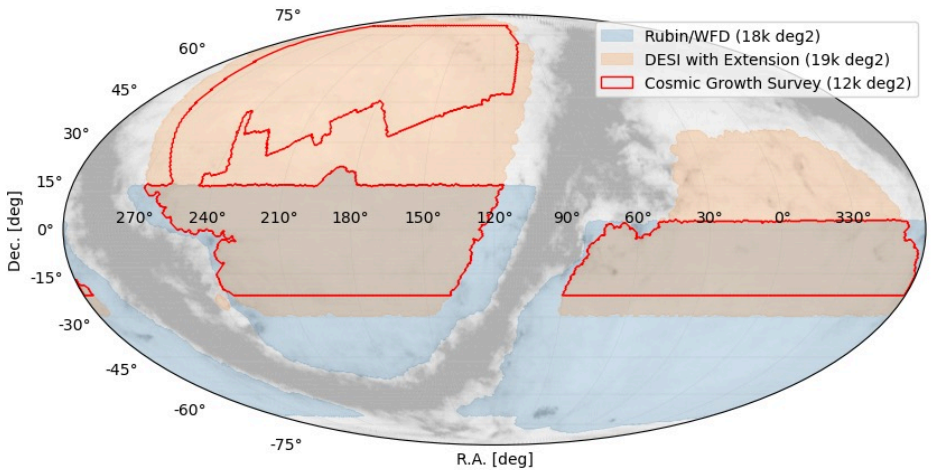


Instrument upgrades

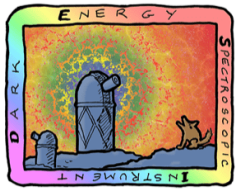
- Blue channel: MAS skipper CCDs, read noise 3.6 e^- → < 1 e^-
- Mirror cooling
- Collimator actuators



High-z Dark Energy Survey: $2 < z < 3.5$, 5000 deg², LAEs + LBGs → **6 sub-percent BAO**



Cosmic Growth Survey: $z < 0.85$, 12000 deg², dense XLGs → **~3 times better $\sigma(f\sigma_8)$**

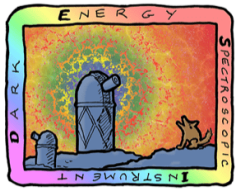


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Conclusions

- **DESI**: Run 1 extended to 8 years (~ 63 M extragalactic redshifts); DESI Run 2 from 2029
- **DR2 BAO**: "discrepancy" with CMB (lower Ω_m, higher H_0); preference for time-varying dark energy when combined with CMB and SN
- **Full Shape**: DR1 FS + BAO constrains σ_8 and modified gravity (consistent with GR); DR2 adds the **bispectrum**: expected > 30% improvement on $\sigma(\sigma_8)$ compared to DR1
- $\times$ **CMB lensing**: joint P + $C_\ell^{\kappa g}$ analysis of DR2, $\simeq 20\%$ gain on $\sigma(\sigma_8)$
- $\times$ **galaxy lensing**: KIDS, DECADE, DES
- See **Eric's talk on Ly-α Full Shape**, and **Domitille's talk on DR2 PNG**



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Why is Full Shape challenging?

Full shape of the galaxy power spectrum and bispectrum sensitive to:

- **the survey geometry**

observed density of galaxies

$$F(\mathbf{r}) = n_g(\mathbf{r}) - \bar{n}(\mathbf{r}) = \bar{n}(\mathbf{r})\delta_g(\mathbf{r})$$

selection function

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Why is Full Shape challenging?

Full shape of the galaxy power spectrum (and now bispectrum!) sensitive to:

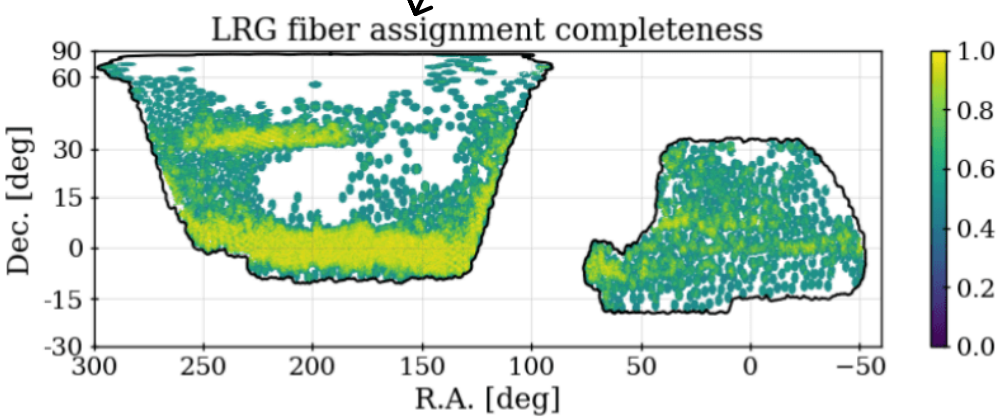
- **the survey geometry**

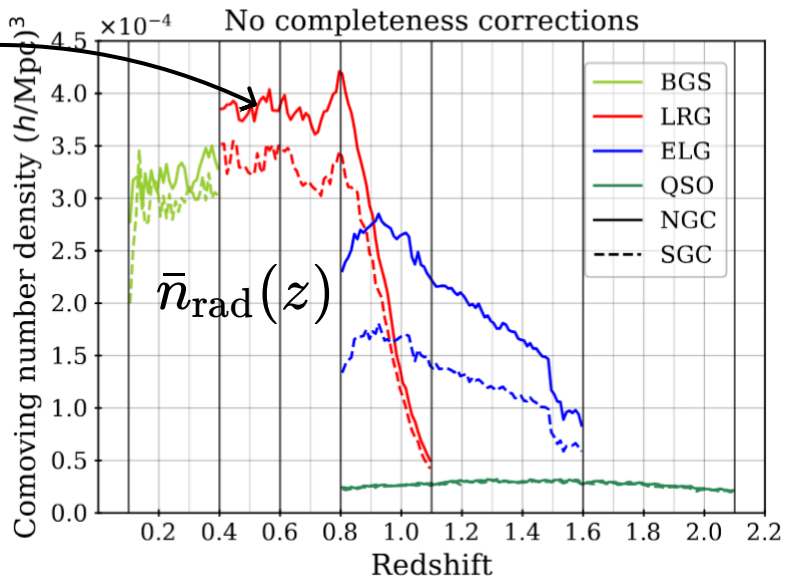
observed density of galaxies

$$F(\mathbf{r}) = n_g(\mathbf{r}) - \bar{n}(\mathbf{r}) = \bar{n}(\mathbf{r})\delta_g(\mathbf{r})$$

selection function

$\bar{n}_{\rm sky}(\mathrm{R.A.}, \mathrm{Dec.})$





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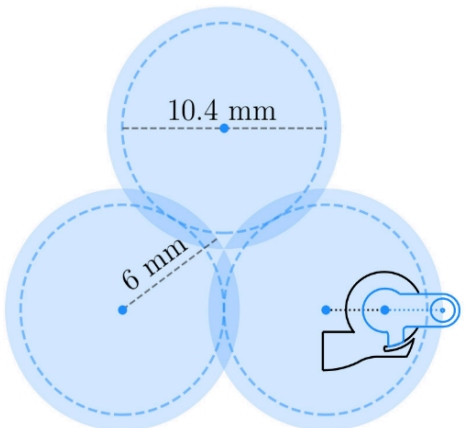
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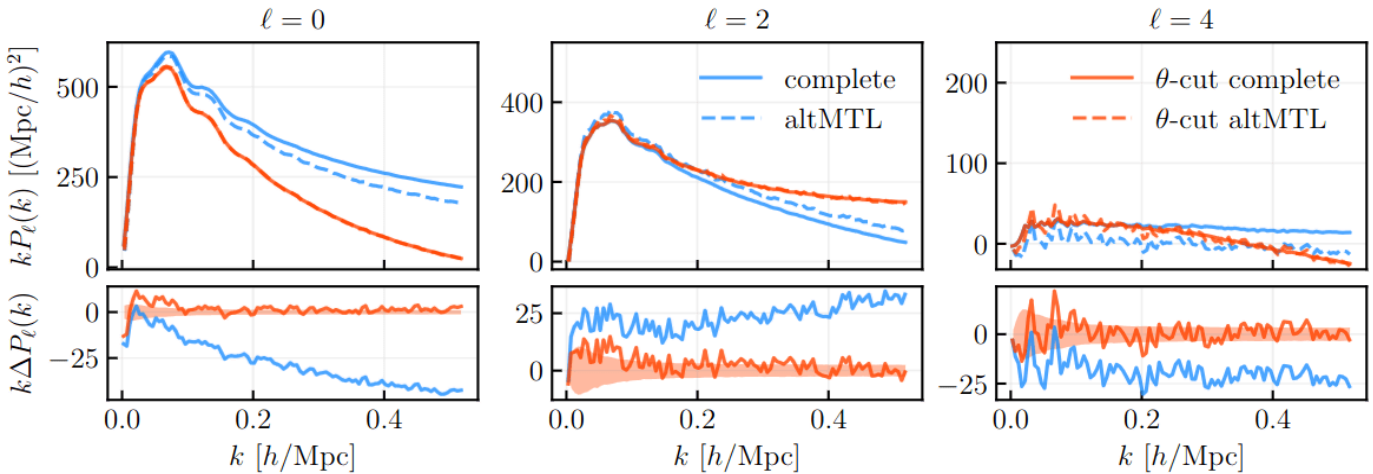
Fiber assignment (θ-cut)



Mathilde Pinon

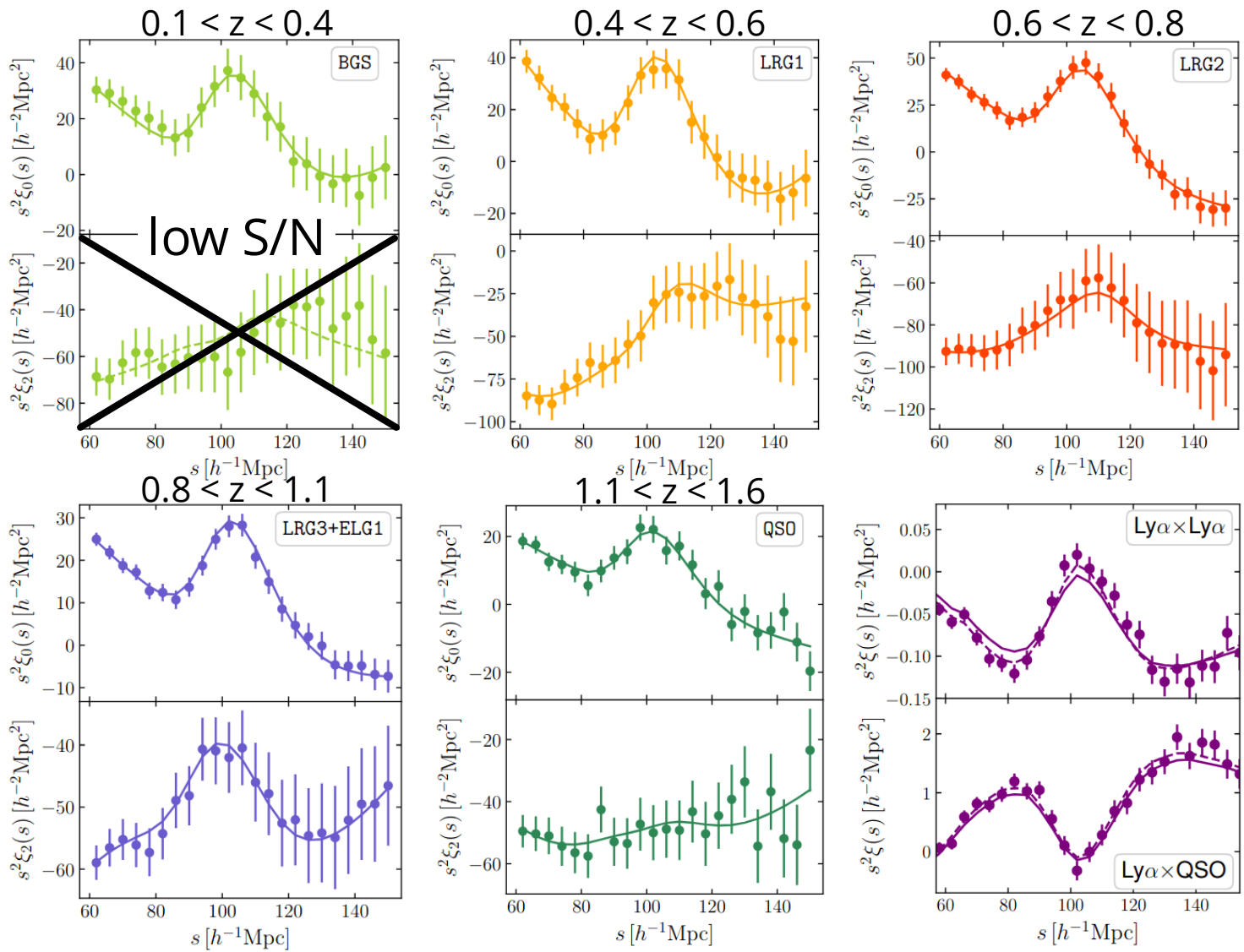
Close pairs ($\lesssim 0.05°$, the positioner patrol diameter) cannot all receive a fiber: pairs are lost at small separation





θ-cut = remove all pairs $< 0.05°$, and model it in the window matrix

Pinon+25

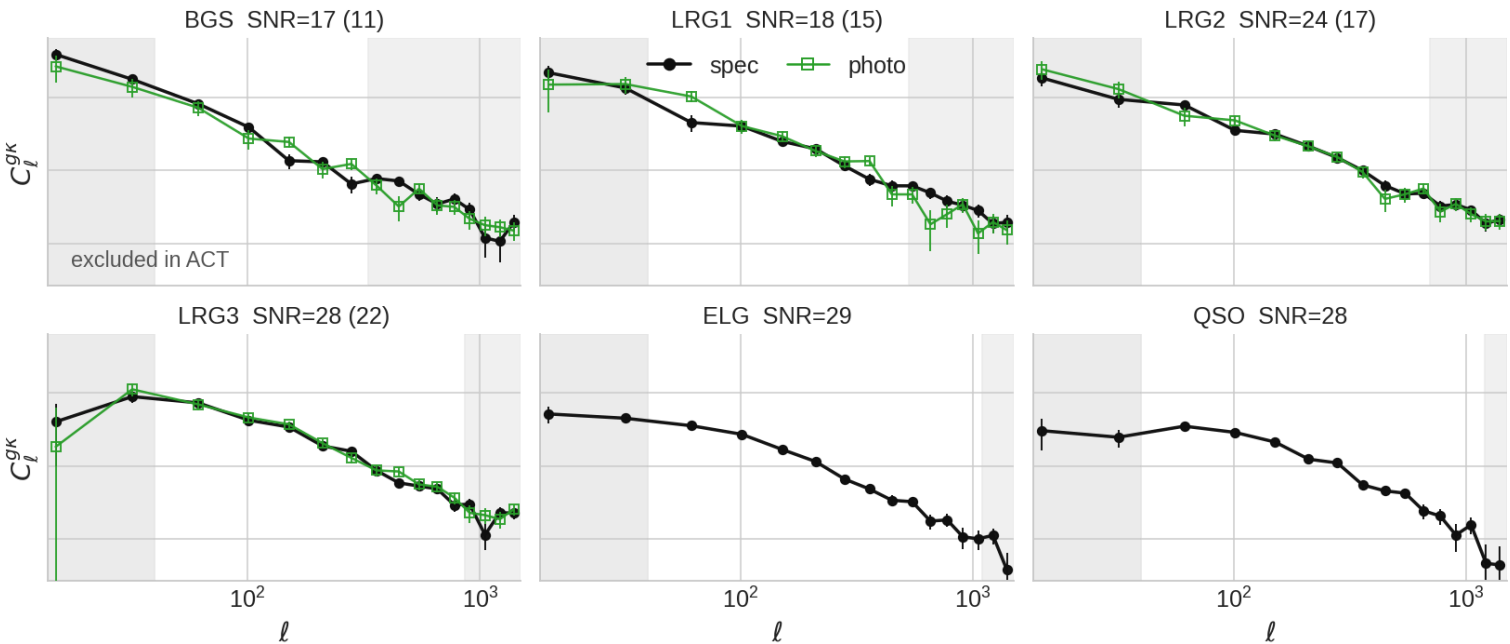

0.1 < z < 0.4
BGS
low S/N
0.4 < z < 0.6
LRG1
0.6 < z < 0.8
LRG2
0.8 < z < 1.1
LRG3+ELG1
1.1 < z < 1.6
QSO
Lyα×Lyα
Lyα×QSO
$s^2\xi_0(s)\,[h^{-2}\mathrm{Mpc}^2]$
$s^2\xi_2(s)\,[h^{-2}\mathrm{Mpc}^2]$
$s^2\xi(s)\,[h^{-2}\mathrm{Mpc}^2]$
$s\,[h^{-1}\mathrm{Mpc}]$

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Cross power spectra

PRELIMINARY, BLINDED



Signal-to-noise 15 - 30 per spectroscopic sample

ACT and Planck cross-spectra co-added for visualisation only

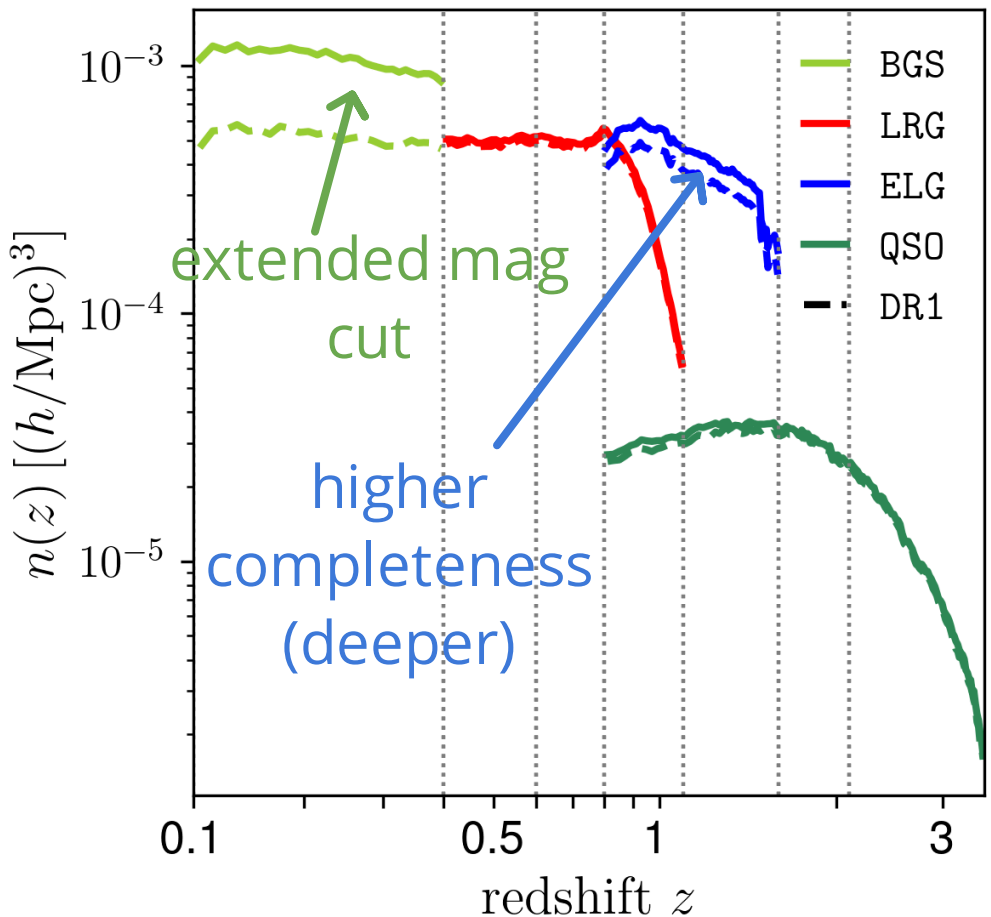
Adapted from G. Farren (DESI CMBx), Cosmic Rhythms, Sep. 2026

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DESI data release 2 (DR2)

- 30M galaxy and QSO redshifts in **3 years of operation**
- **14M** used in the DR2 analysis (6M in DR1)
- Including **820,000 Lyα QSO** at $z > 2.09$ (420,000 in DR1)
- **$> 2\times$ increase in number of tracers**

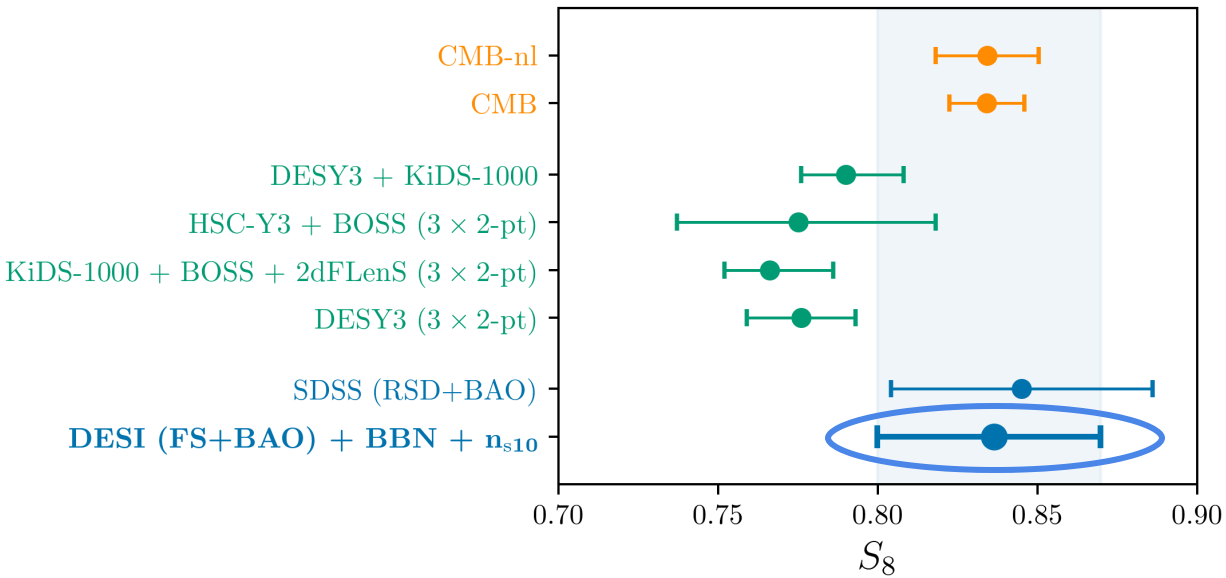


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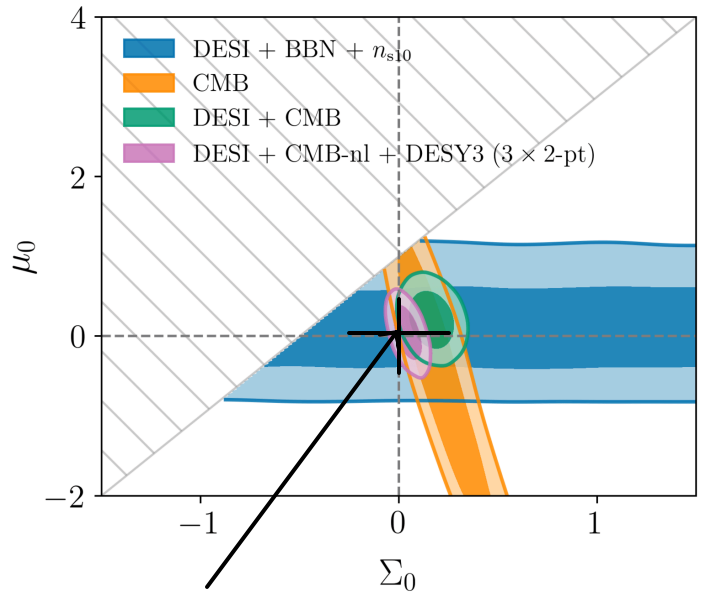
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Full Shape Analysis

In November 2024: DR1 Full-Shape results (probing the growth of structure)



$$S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$$



General Relativity

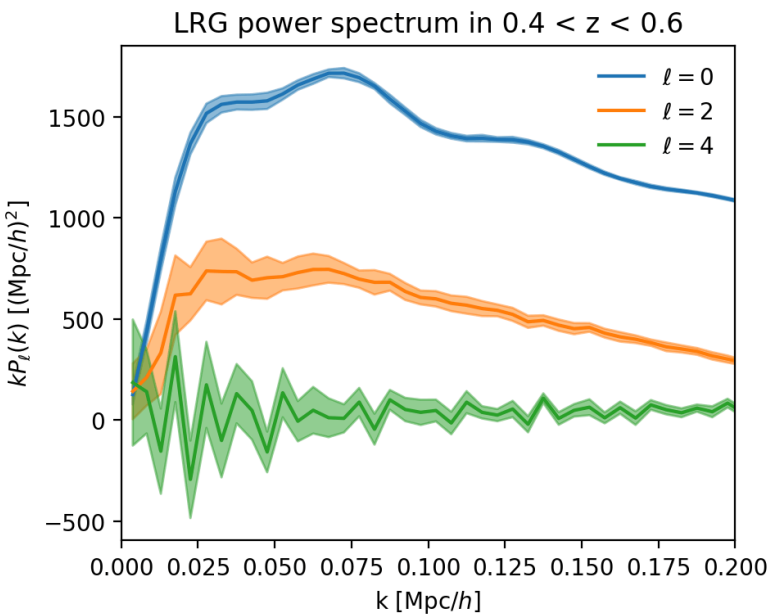
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DR2 Full Shape analysis

jaxpower

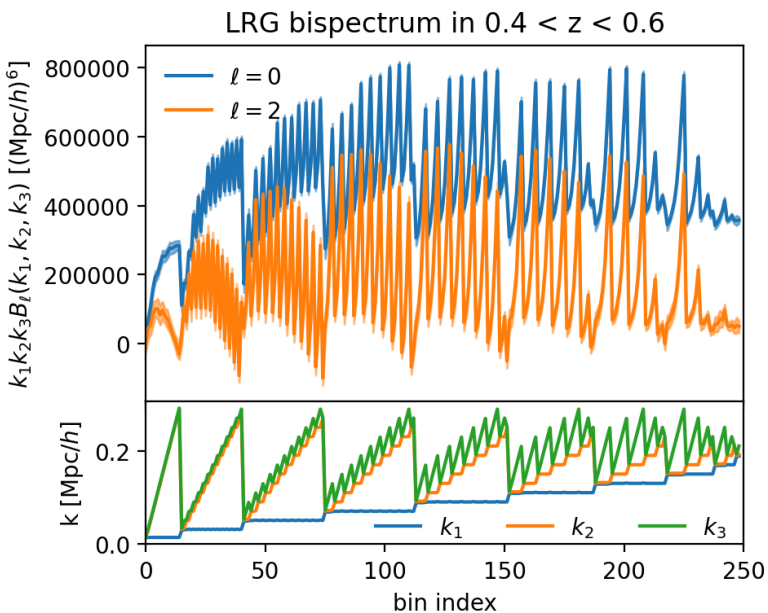
... we're adding the bispectrum $\langle \delta(\mathbf{k_1})\delta(\mathbf{k_2})\delta(\mathbf{k_3})\rangle$! Scoccimarro15 basis



projection on $\mathcal{L}_\ell(\hat{k}\cdot\hat{z})$

+

non-linearity of clustering



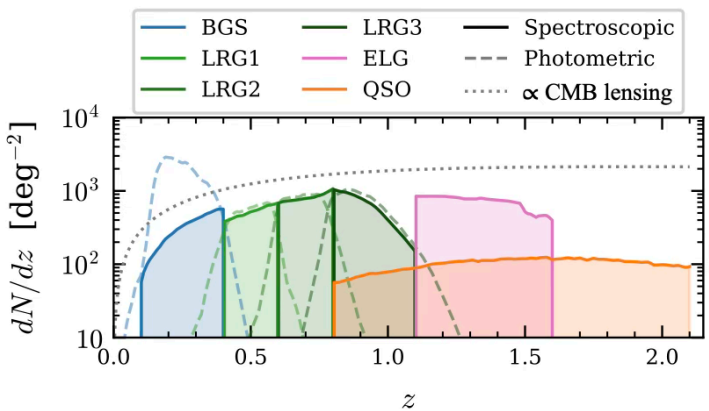
projection on $\mathcal{L}_\ell(\hat{k}_3\cdot\hat{z})$

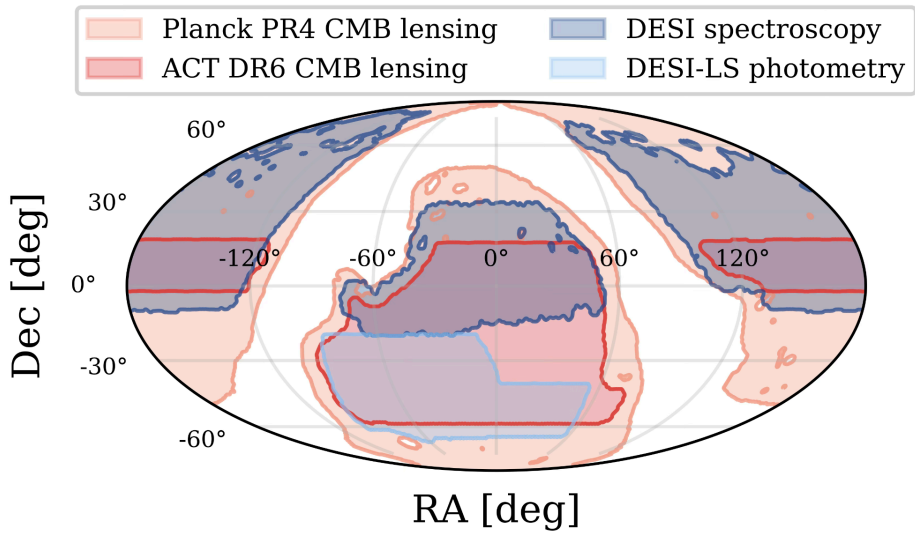
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DESI DR2 × CMB lensing

- **Joint analysis**: 3D clustering of DESI DR2 tracers (BGS to QSO) + 2D cross-correlation $C_\ell^{\kappa g}$ with ACT DR6 and Planck PR4 lensing
- **Photometric samples** (BGS, LRG) on the Legacy Imaging footprint, without spectroscopy
- **Model**: Lagrangian PT / hybrid EFT, analytic covariance, for P_ℓ + $C_\ell^{\kappa g}$ + post-recon. BAO



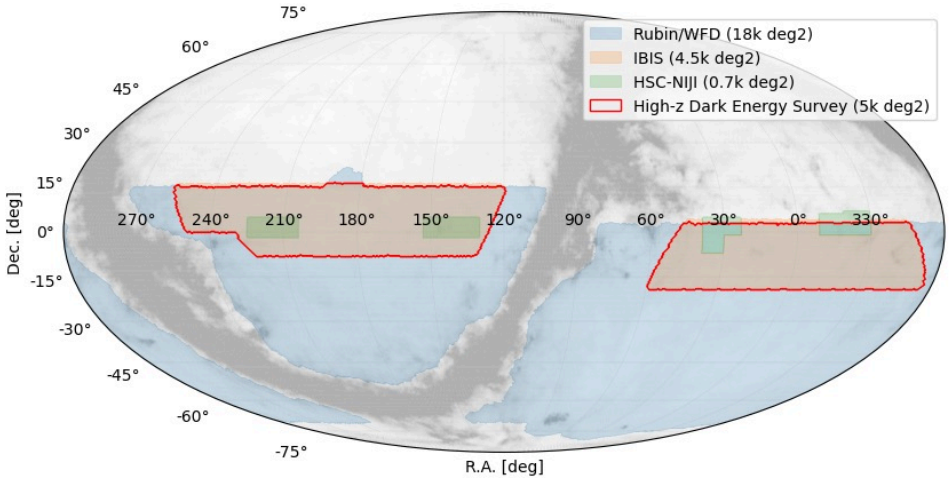


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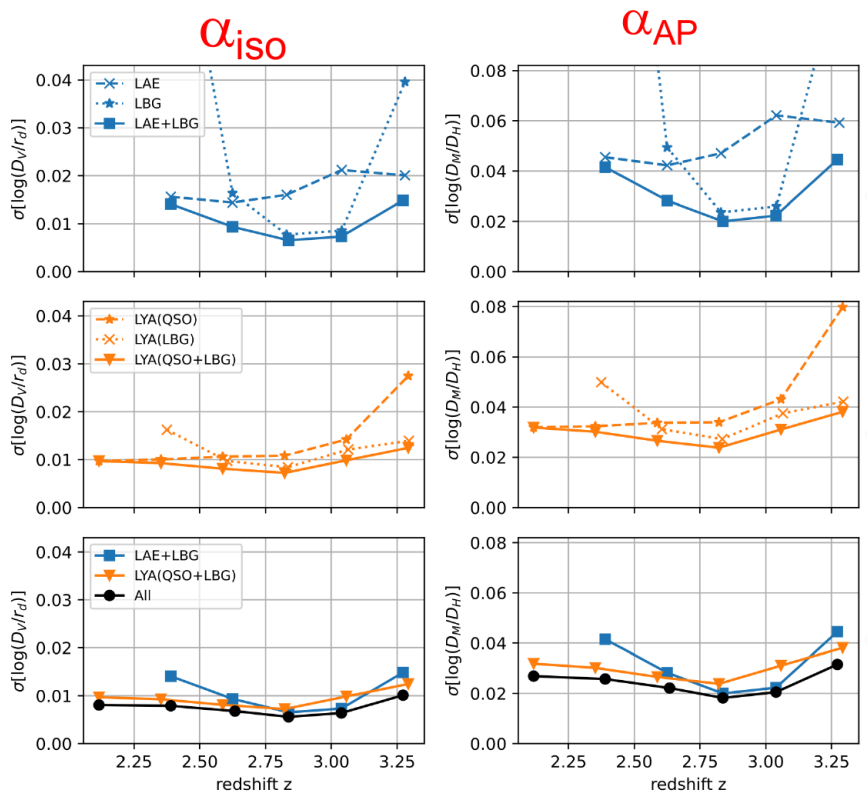
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Run 2: High-z Dark Energy Survey



- 5000 deg², $2 < z < 3.5$: **Ly-α emitters** (~800 deg⁻²), **Lyman break galaxies** (~900 deg⁻²), **Ly-α forest (quasars)**
- Targets from Rubin/LSST (u, g, r) + medium bands (IBIS, POLU, Niji)
- **6 sub-percent BAO measurements**, $\sigma(f_{\rm NL})$ ~ 2-3, $\sum m_\nu$ at $\geq 3\sigma$

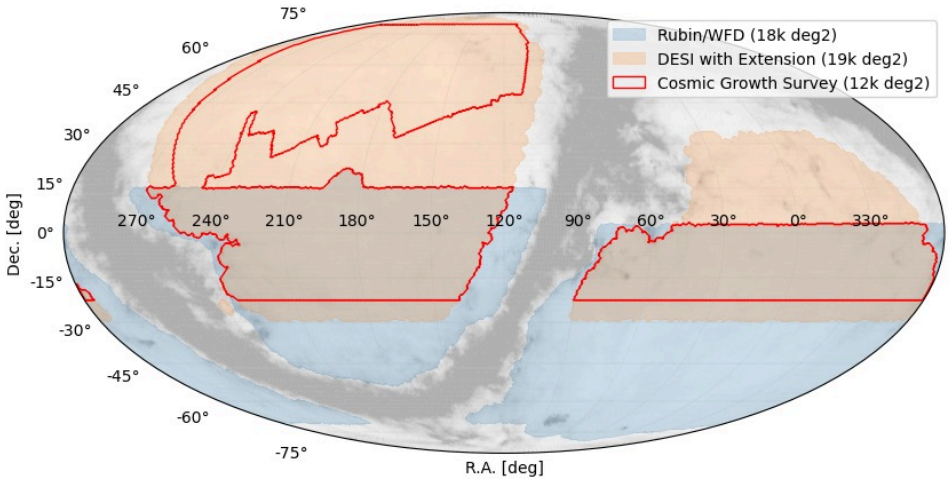


BAO precision forecasts

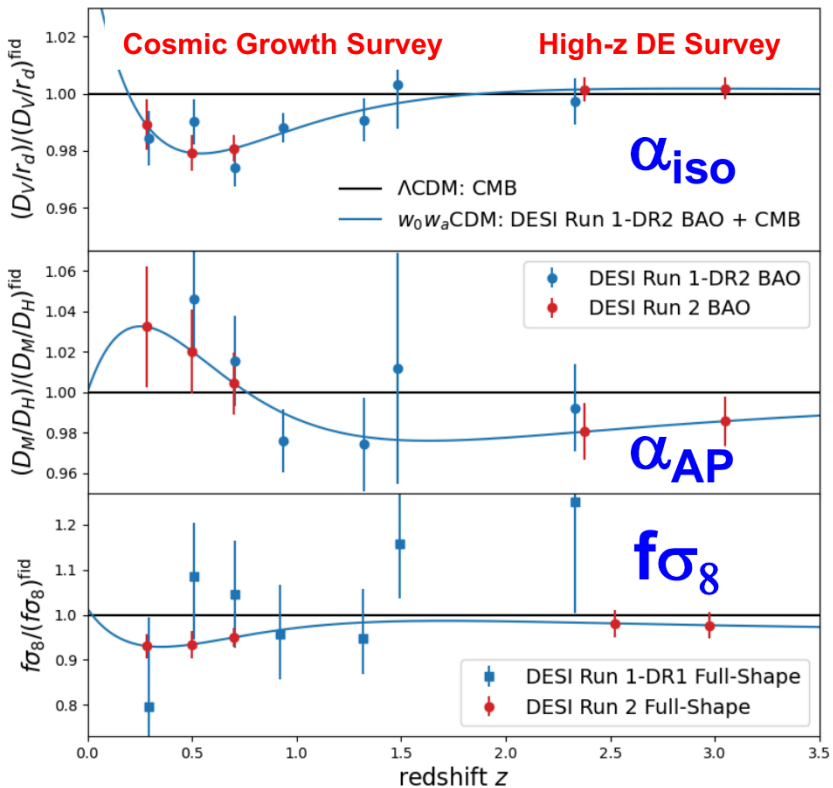
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Run 2: Cosmic Growth Survey



- 12000 deg², **Extreme emission Line Galaxies** (XLGs: Hα, [OIII]), ~1500 deg^{-2}, 0.07 < z < 0.85
- At z ~ 0.3: 3 times the density of BGS, bias ~3 times smaller: **~3 times better** $\sigma(f\sigma_8)$
- **Independent BAO (10-20% gain), dense sample** for small scales and multi-tracer



Run 2 forecasts (red) vs. DESI DR1 / DR2 (blue)