Cosmological constraints from full-shape galaxy clustering with DESI DR1

Pauline Zarrouk (CNRS/LPNHE & Sorbonne Université)

On behalf of the DESI collaboration

ADE webinar - 04/03/2025

DARK ENERGY SPECTROSCOPIC INSTRUMENT

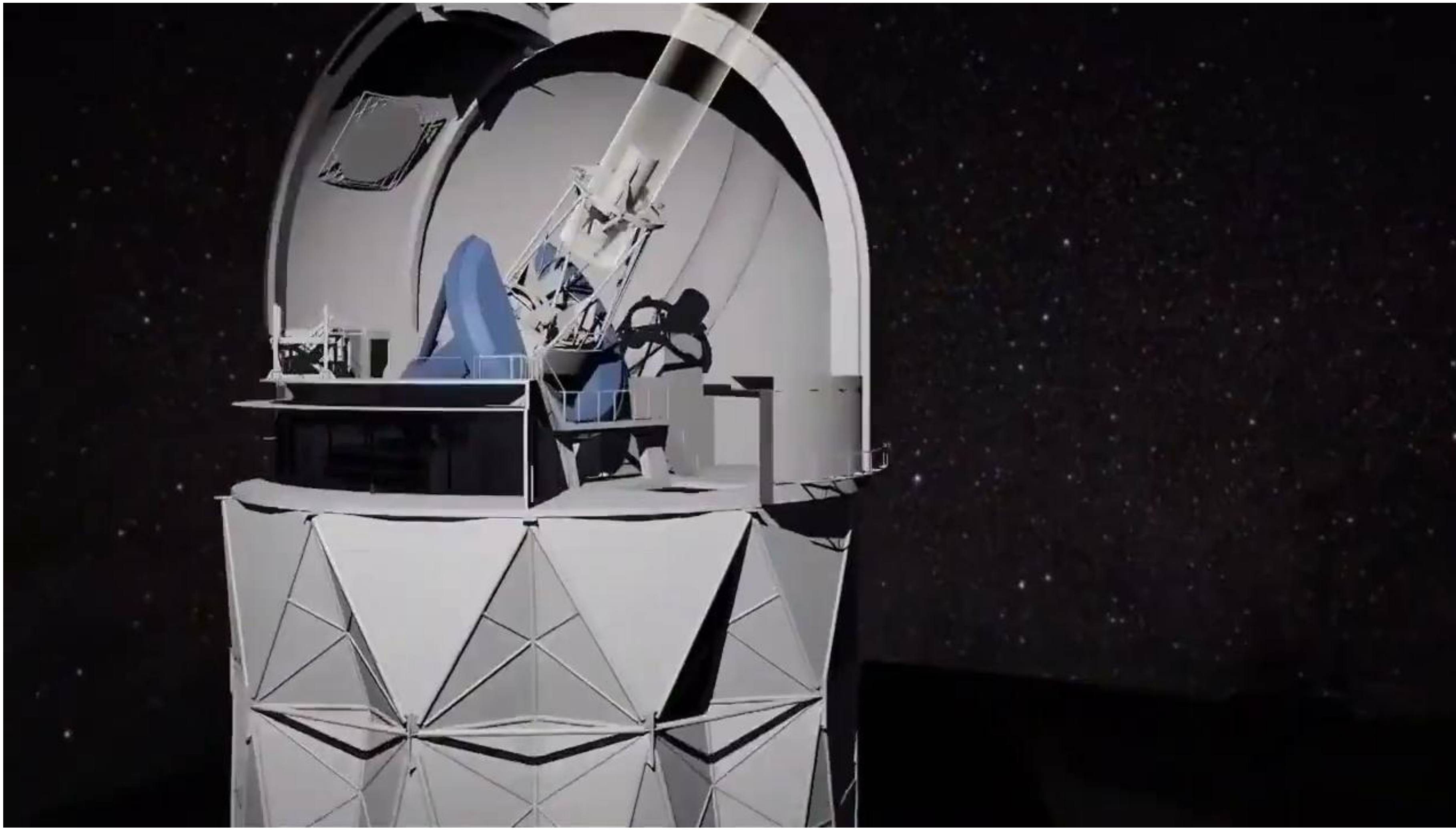
U.S. Department of Energy Office of Science

NSF
NERSC
cea
GOBIERNO DE ESPAÑA — MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD
HEISING-SIMONS FOUNDATION
CONAHCYT
GORDON AND BETTY MOORE FOUNDATION
Science & Technology Facilities Council

Thanks to our sponsors and 72 Participating Institutions!

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

The DESI instrument



Credit: NSF

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

DESI Y5 galaxy samples

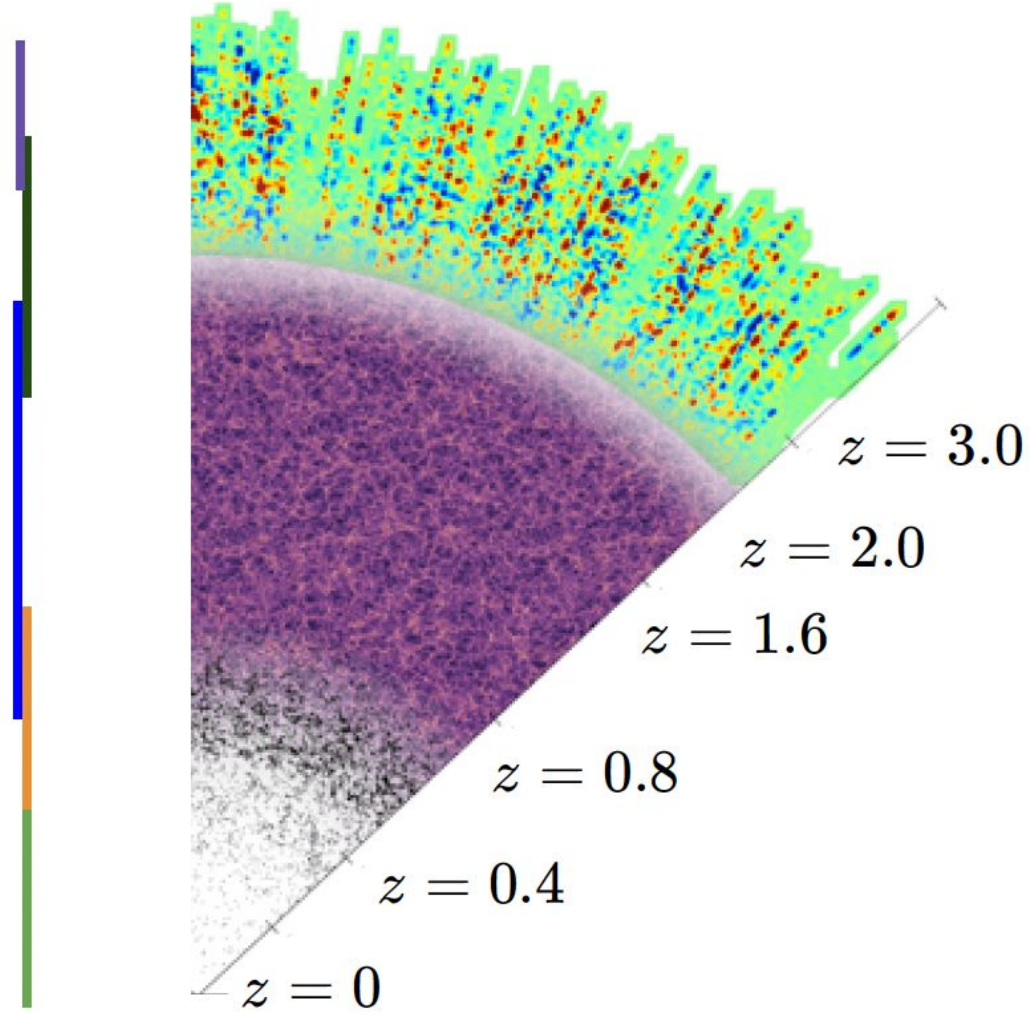
Y5 $\sim$ 40M galaxy redshifts!

QSO: 3M *(SDSS: 500k)*
Lya $1.8 < z$
Tracers $0.8 < z < 2.1$

ELG: 16M *(SDSS: 200k)*
0.6 < z < 1.6

LRG: 8M *(SDSS: 1M)*
0.4 < z < 0.8

Bright Galaxies: 14M *(SDSS: 600k)*
0 < z < 0.4



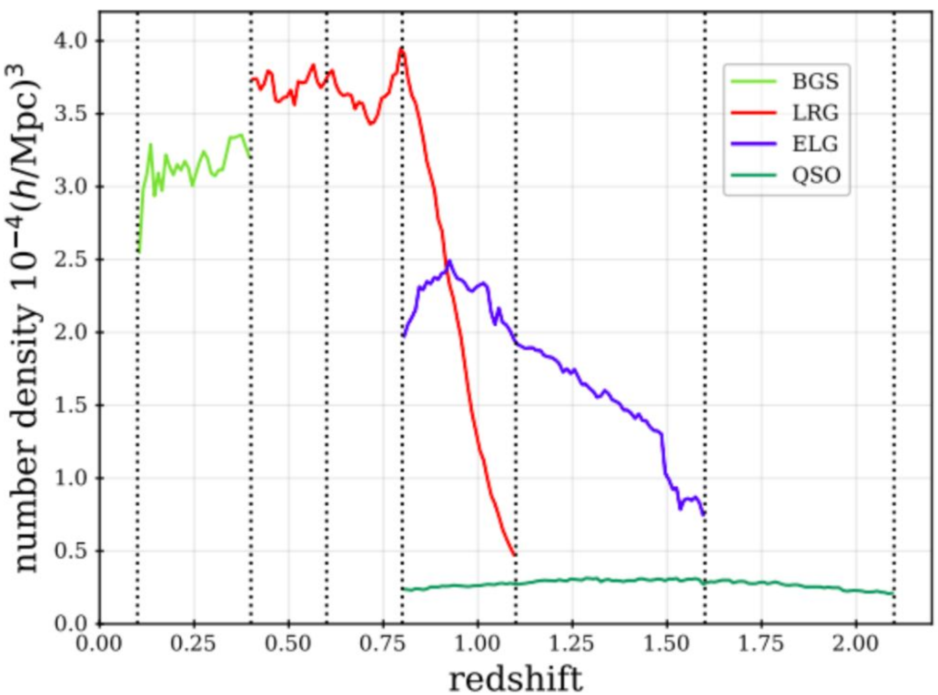
DARK ENERGY SPECTROSCOPIC INSTRUMENT

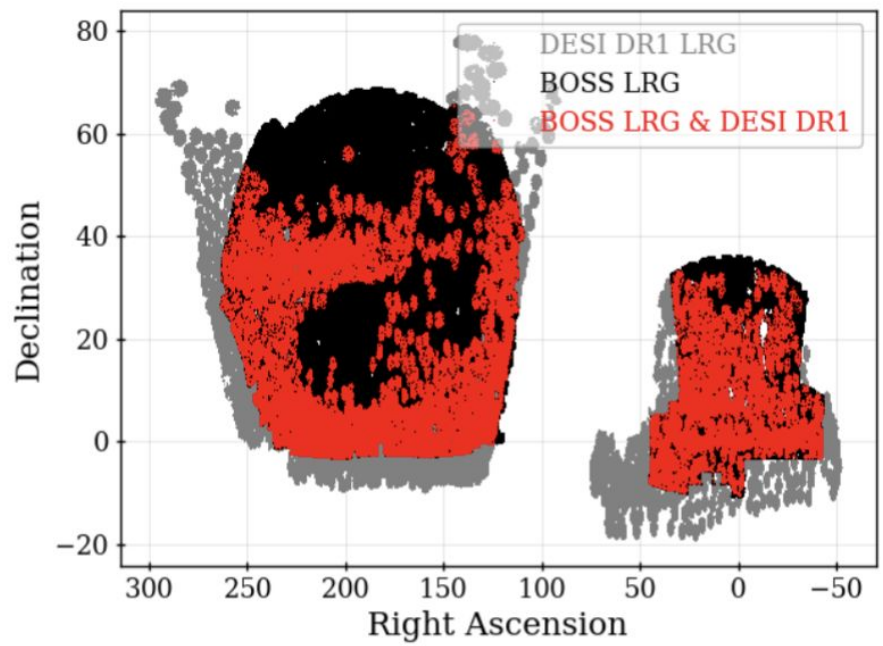
U.S. Department of Energy Office of Science

DESI data release 1 (DR1)

Observations from May 14th 2021 to June 12th 2022

5.7 million unique redshifts at z < 2.1





DESI 2024 II arXiv:2411.12020

For BGS: absolute magnitude-cut $M_r < -21.5$

For ELG, we didn't use the bin 0.8 < z < 1.1 because of low S/N and more significant imaging systematics

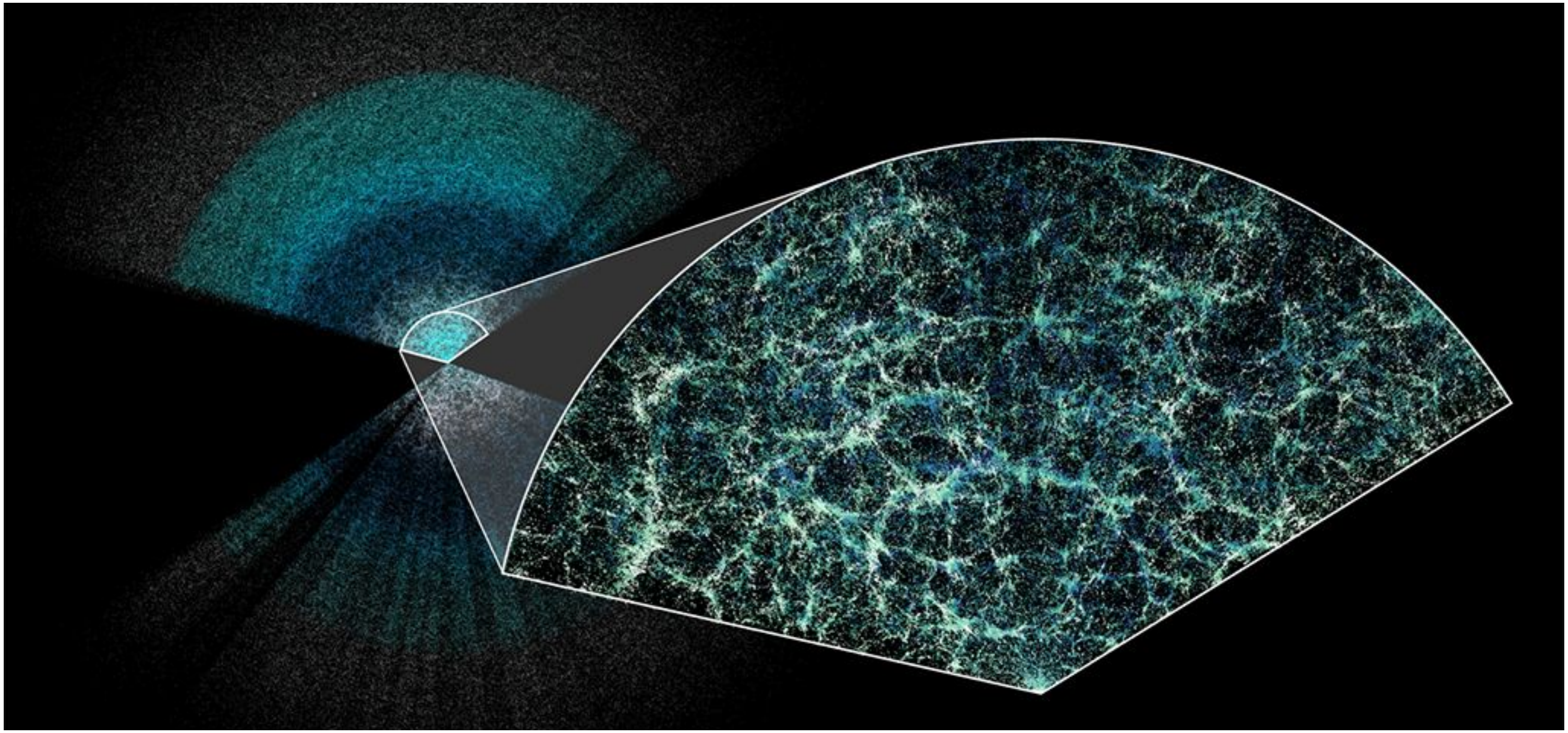
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

DESI data release 1 (DR1)

Observations from May 14th 2021 to June 12th 2022

5.7 million unique redshifts at $z < 2.1$ and **> 420,000 Lyα QSO** at $z > 2.1$



Credit: Claire Lamman / DESI collaboration

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Release of DESI DR1 (FS) results

November 19th 2024

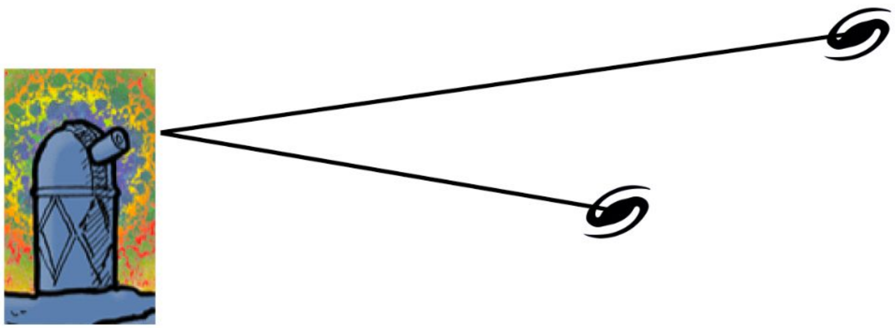
Second batch of DESI DR1 cosmological analyses

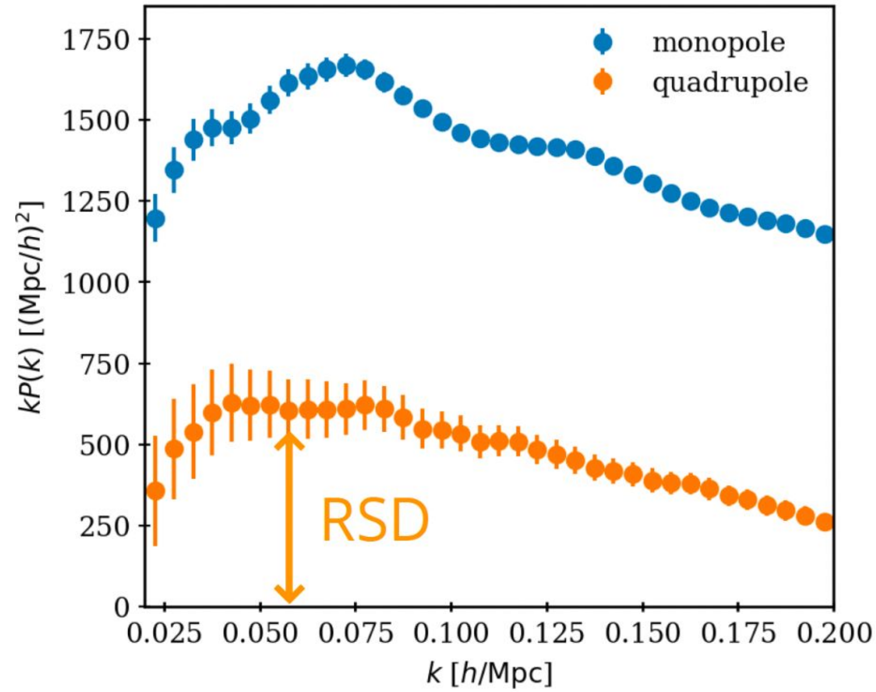
https://data.desi.lbl.gov/doc/papers/

- DESI 2024 I: First year data release
- DESI 2024 II: Sample definitions and two-point clustering statistics
- DESI 2024 III: BAO from Galaxies and Quasars
- DESI 2024 IV: BAO from the Lyman-Forest
- **DESI 2024 V: Full-Shape (FS) measurements of Galaxies and Quasars**
- DESI 2024 VI: Cosmological constraints from BAO measurements
- **DESI 2024 VII: Cosmological constraints from FS measurements**

DESI Press Release
CNRS/IN2P3 Press Release

Galaxy Full Shape in a nutshell



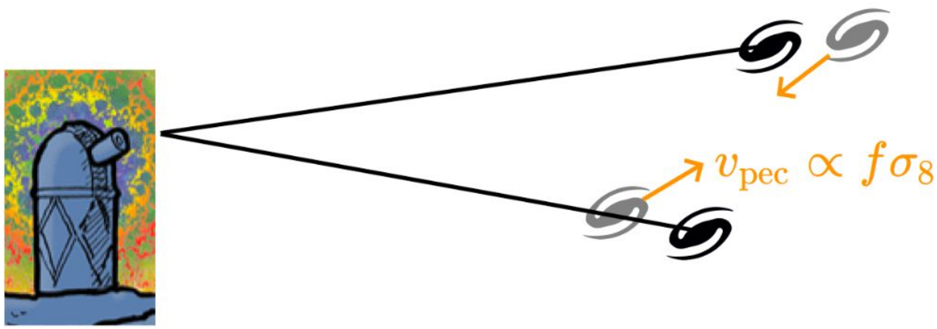


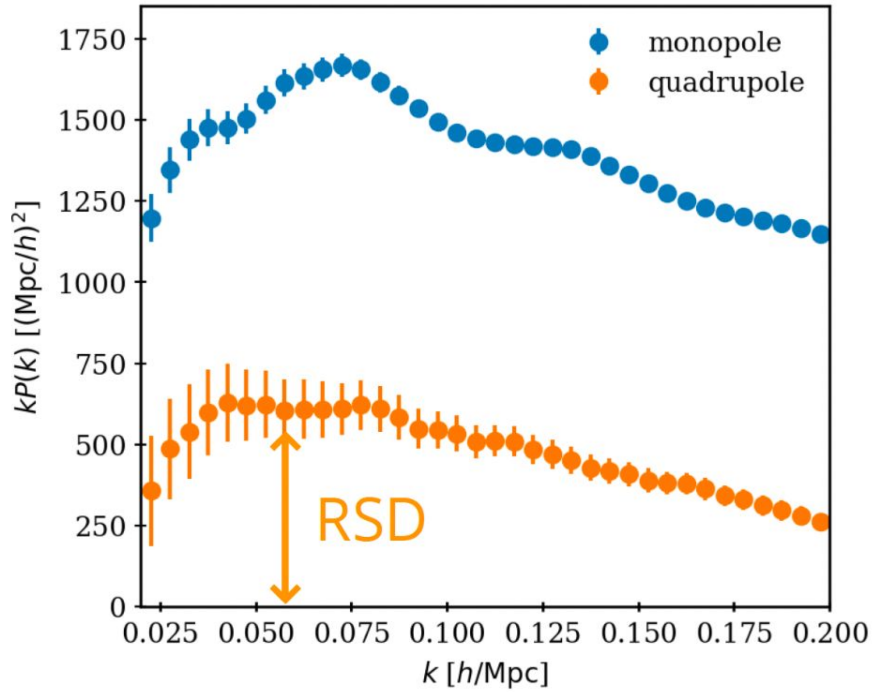
observed redshift = Hubble flow

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Galaxy Full Shape in a nutshell





observed redshift = Hubble flow

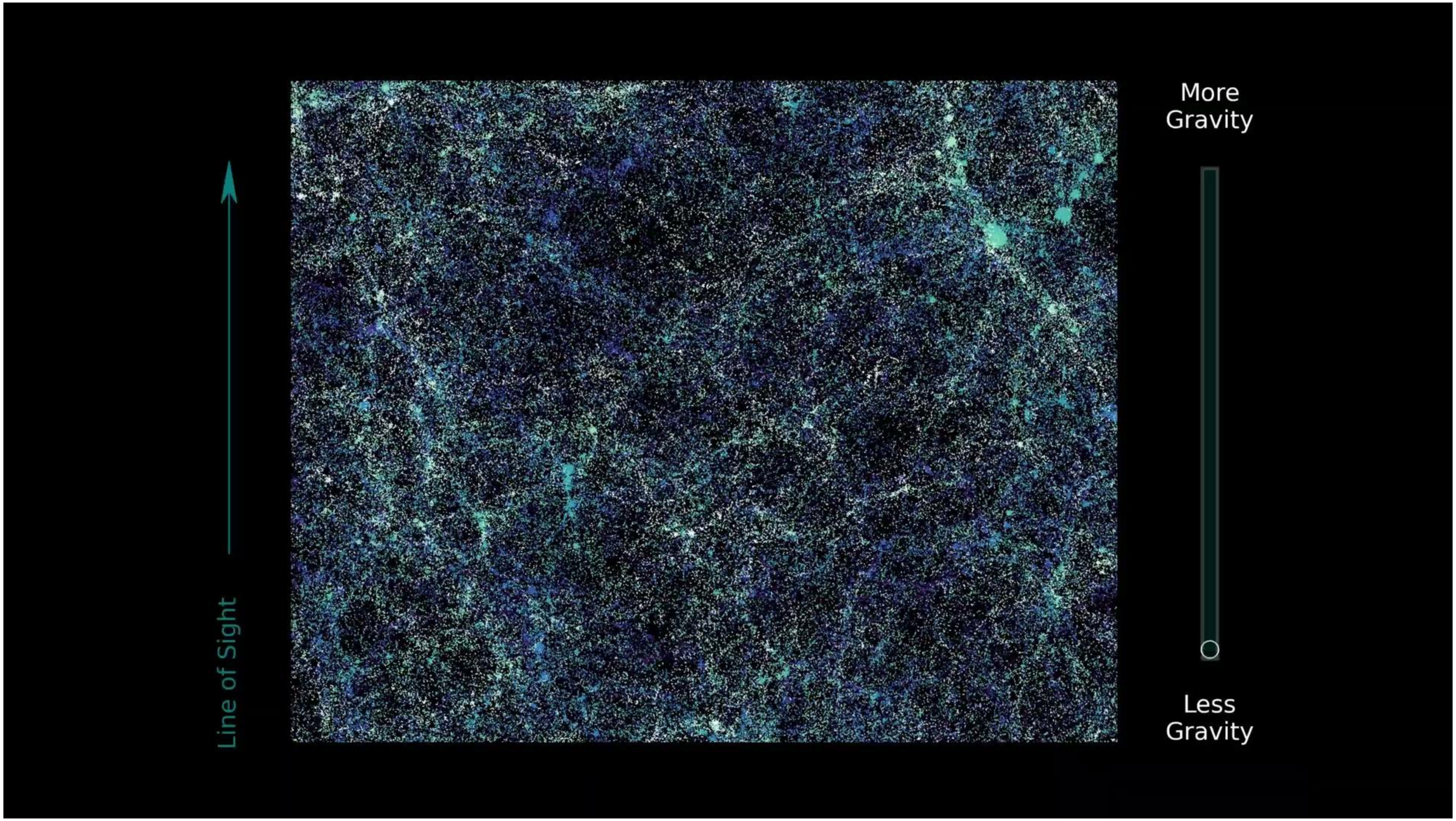
and peculiar velocities (RSD = "redshift space distortions")

Modelling of the **full-shape of the galaxy power spectrum** enables to:

- probe the **growth of structures $f\sigma_8$**
- **test the theory of gravity and dark energy**
- **constrain the sum of neutrino masses**

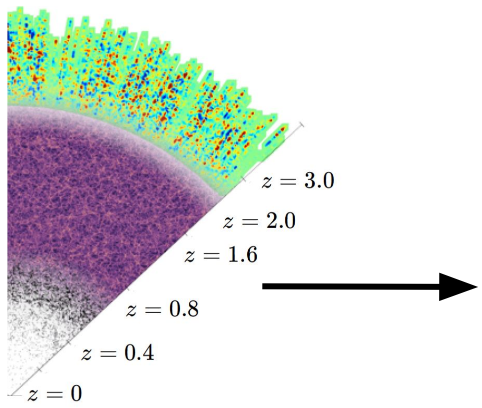
The DESI logo and the text "DARK ENERGY SPECTROSCOPIC INSTRUMENT" and "U.S. Department of Energy Office of Science" stay in the page's top left corner.

Growth of cosmic structures through gravity

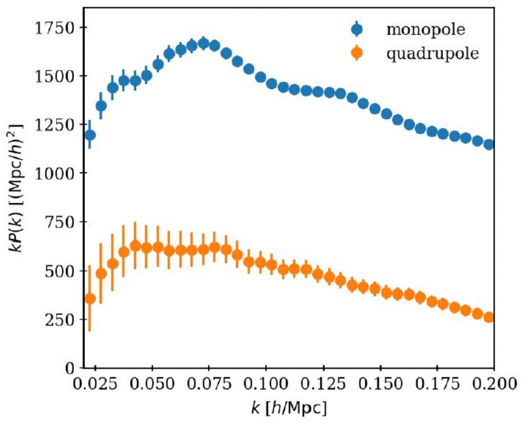


Credit: Claire Lamman and Michael Rashkovetskyi / DESI collaboration

Extract cosmological constraints from the galaxy power spectrum



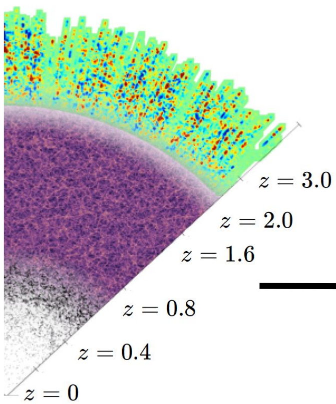
Galaxy 3D maps



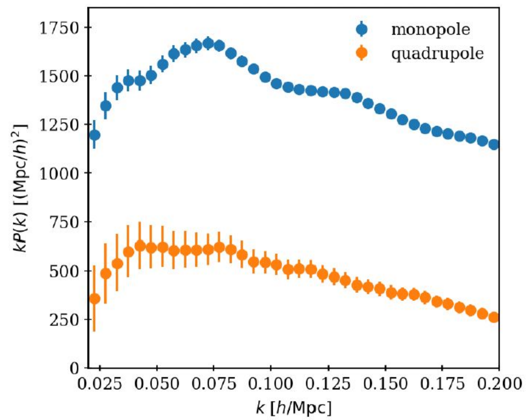
Galaxy power spectrum

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

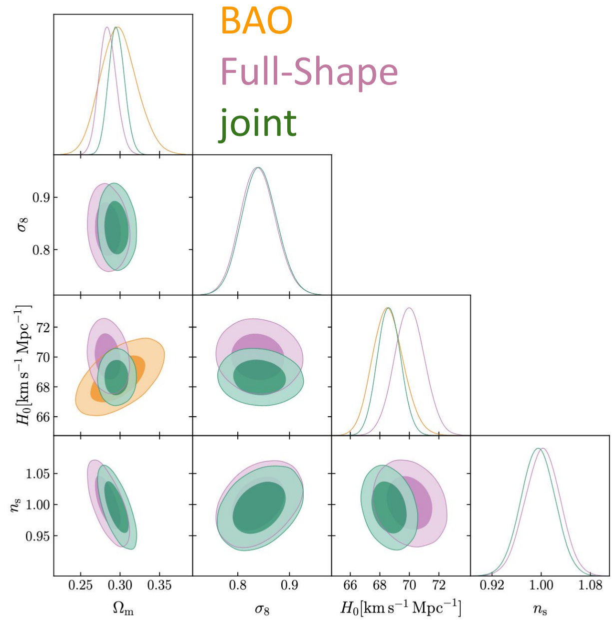
Extract cosmological constraints from the galaxy power spectrum



Galaxy 3D maps



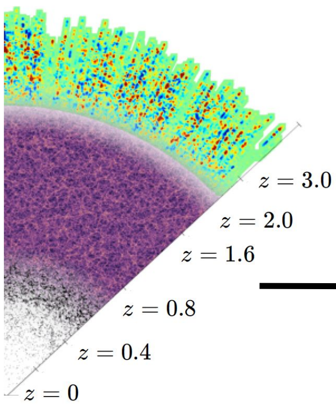
Galaxy power spectrum



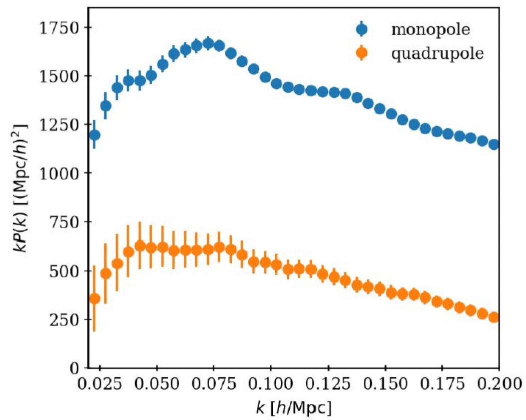
Cosmological model constraints (ΛCDM)

Extract cosmological constraints from the galaxy power spectrum

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

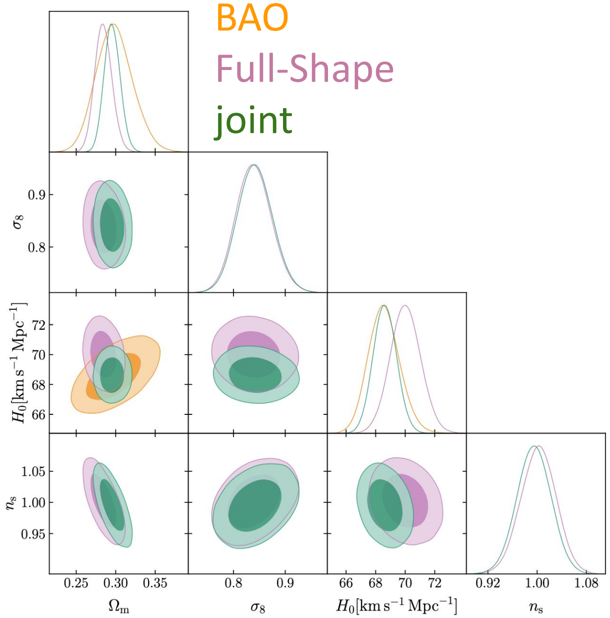


Galaxy 3D maps



Galaxy power spectrum

Full-Modelling
(direct fitting approach)

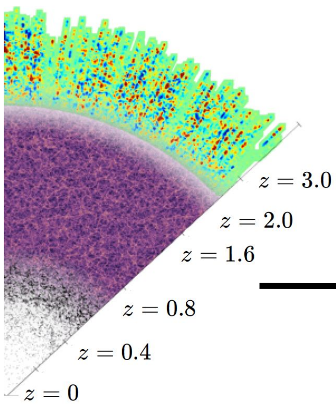


Cosmological model constraints (ΛCDM)

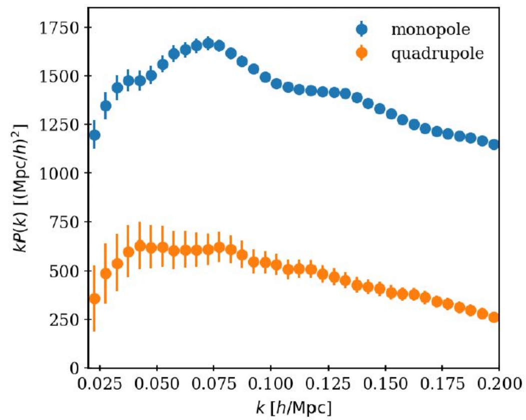
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

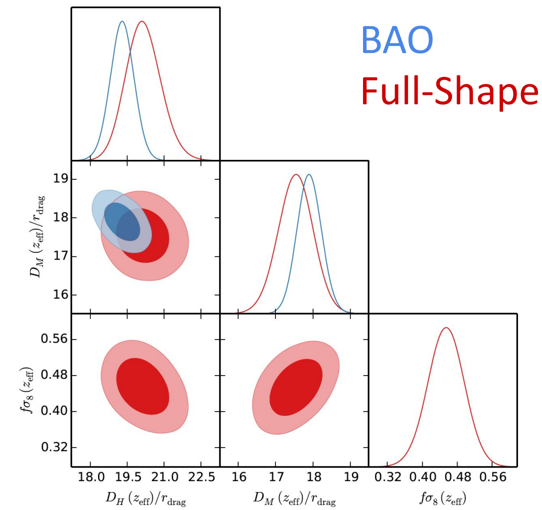
Extract cosmological constraints from the galaxy power spectrum



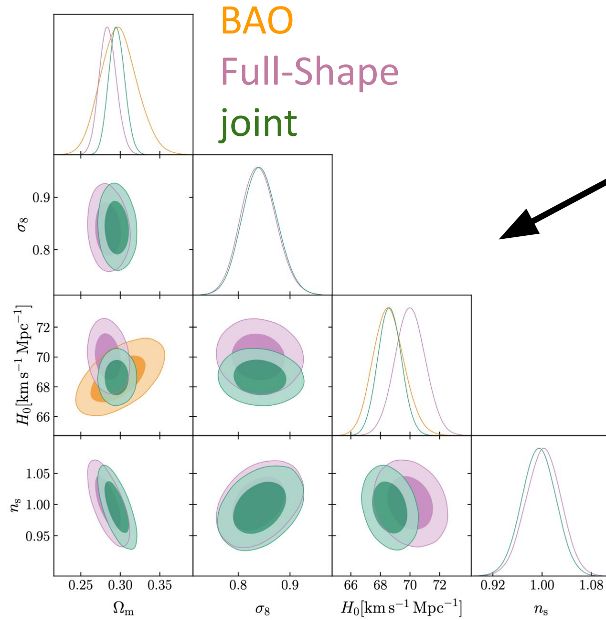
Galaxy 3D maps



Galaxy power spectrum



Compressed parameters

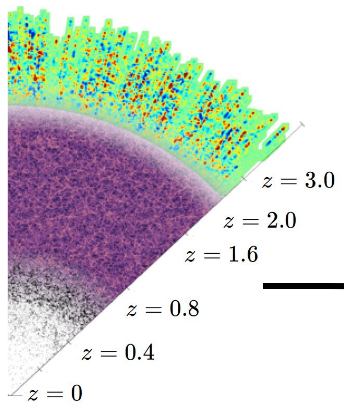


Cosmological model constraints (ΛCDM)

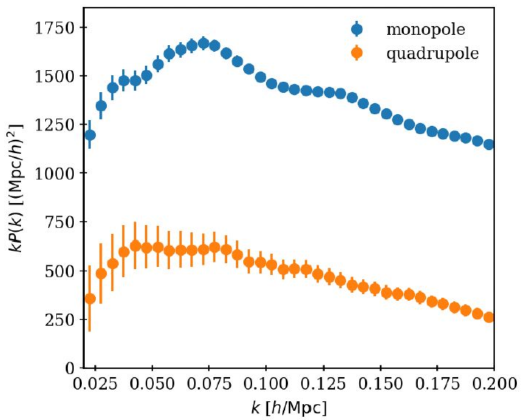
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

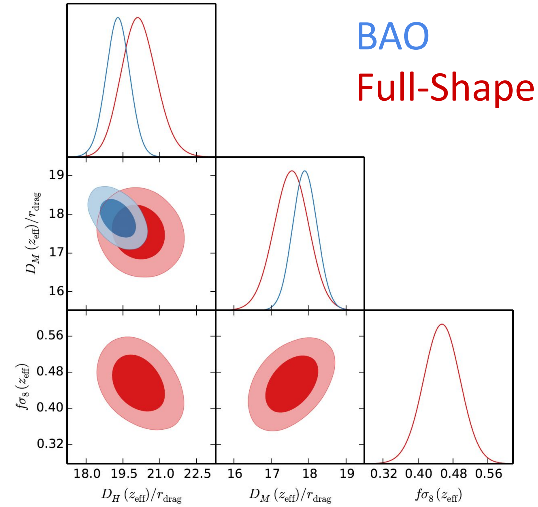
Extract cosmological constraints from the galaxy power spectrum



Galaxy 3D maps

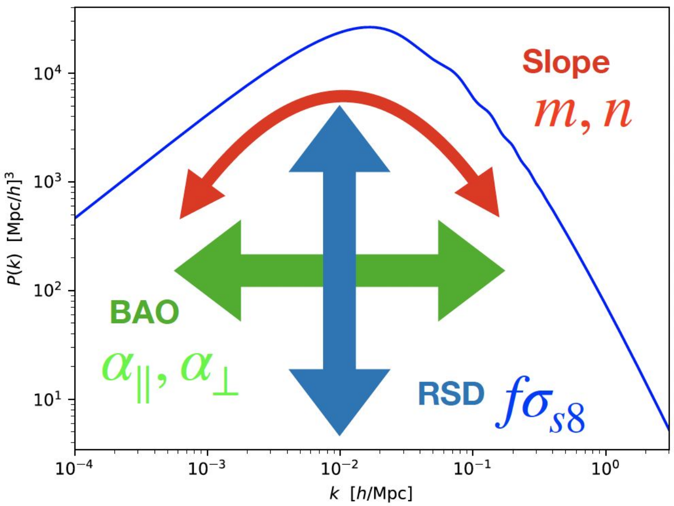


Galaxy power spectrum



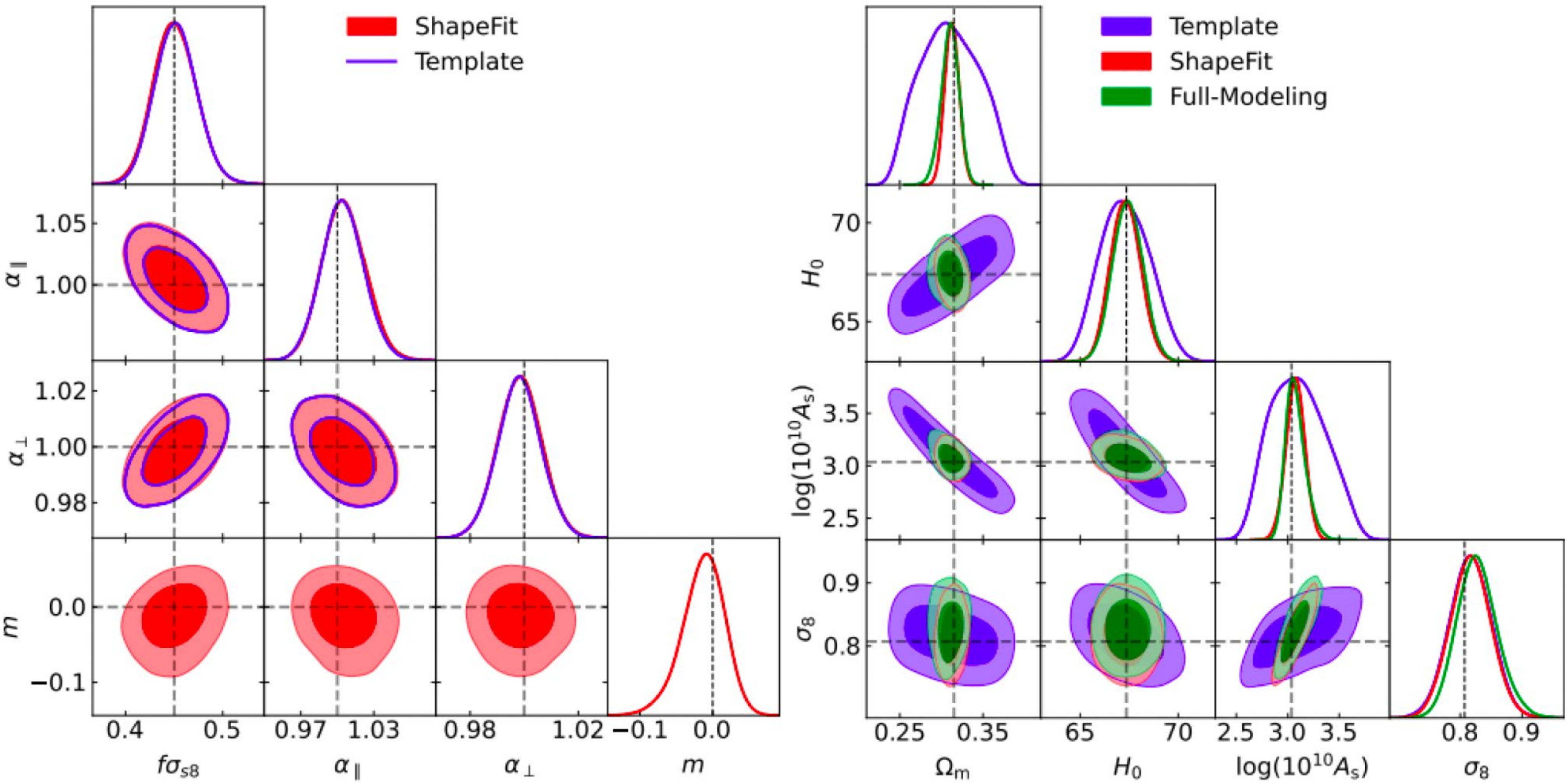
Compressed parameters

ShapeFit
(compressed approach)



DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Comparison of both approaches



Maus et al. 2024a

Modelling the galaxy power spectrum

Three power spectrum Effective Field Theory models considered:

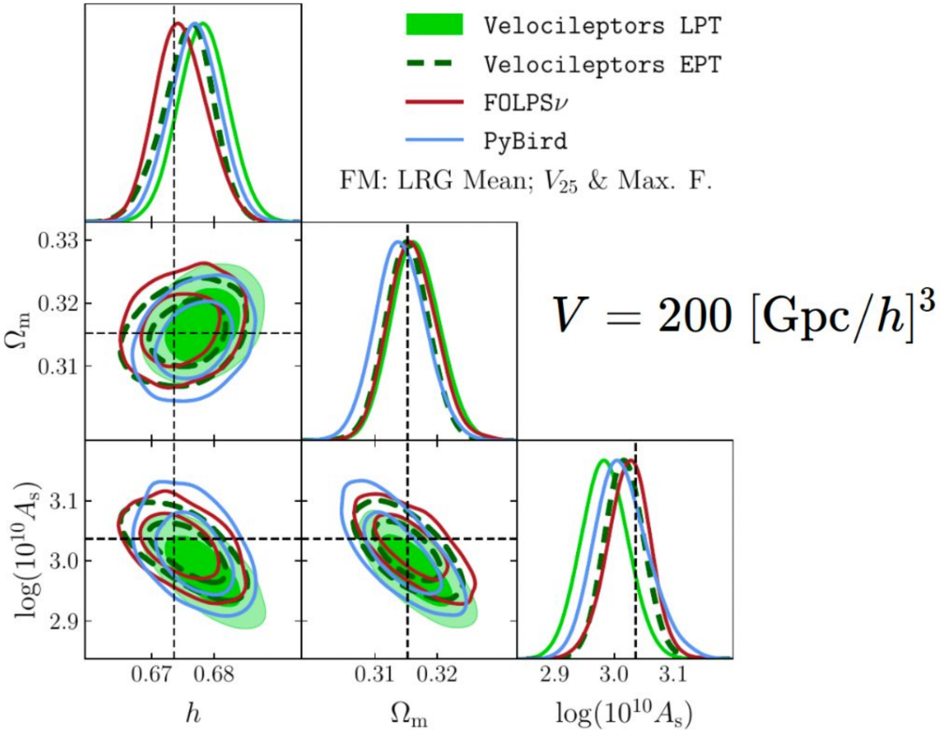
- velocileptors Maus et al. 2024
- folps Noriega et al. 2024
- pybird Lai et al. 2024

One comparison paper:

Maus et al. 2024

One configuration-space model:

- EFT-GSM Ramirez et al. 2024



credit: Mark Maus, Hernan Noriega, Yan Lai

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Modelling the galaxy power spectrum

The **Effective Field Theory** in a nutshell

- model for the multipoles of the power spectrum
- perturbation theory model + counter-terms and stochastic terms
- for the baseline analysis (monopole & quadrupole): 3 galaxy bias parameters, 2 counter-terms, 2 stochastic parameters
- dependence on cosmology into $P_{\rm lin}$, f and Alcock-Paczynski parameters

$$P_{s,g}(k,\mu) = P^{\rm PT}(k,\mu) + (b+f\mu^2)(b\alpha_0 + f\alpha_2\mu^2 + f\alpha_4\mu^4)k^2 P_{s,b_1^2}(k) + \mathrm{SN}_0 + \mathrm{SN}_2 k^2\mu^2 + \mathrm{SN}_4 k^4\mu^4$$

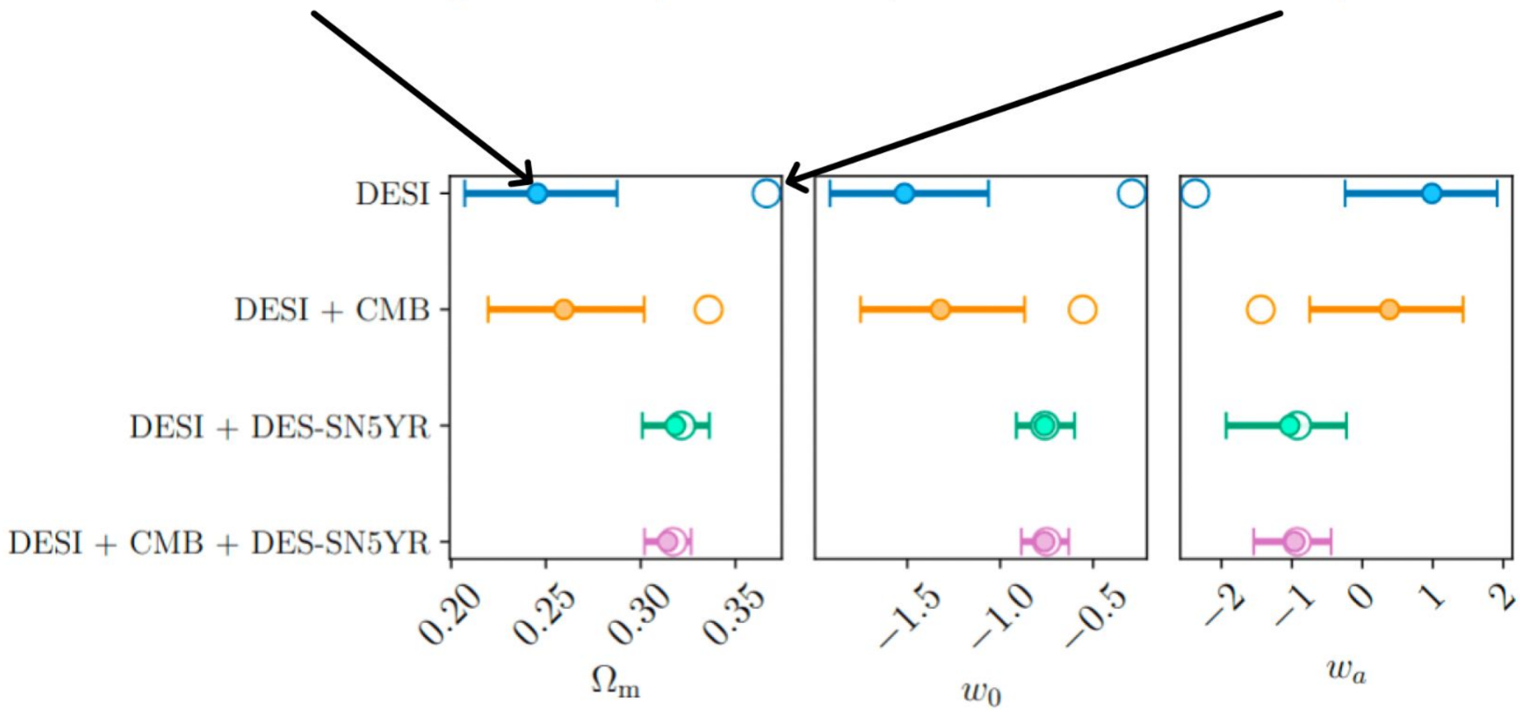
perturbation theory term	counter-terms contribution	stochastic-terms contribution
linear and quasi-linear physics	truncation of perturbative series	small-scale galaxy physics

Projection effects

2 types of projection effects:

- **prior volume effect** when data not constraining enough for the parameter space

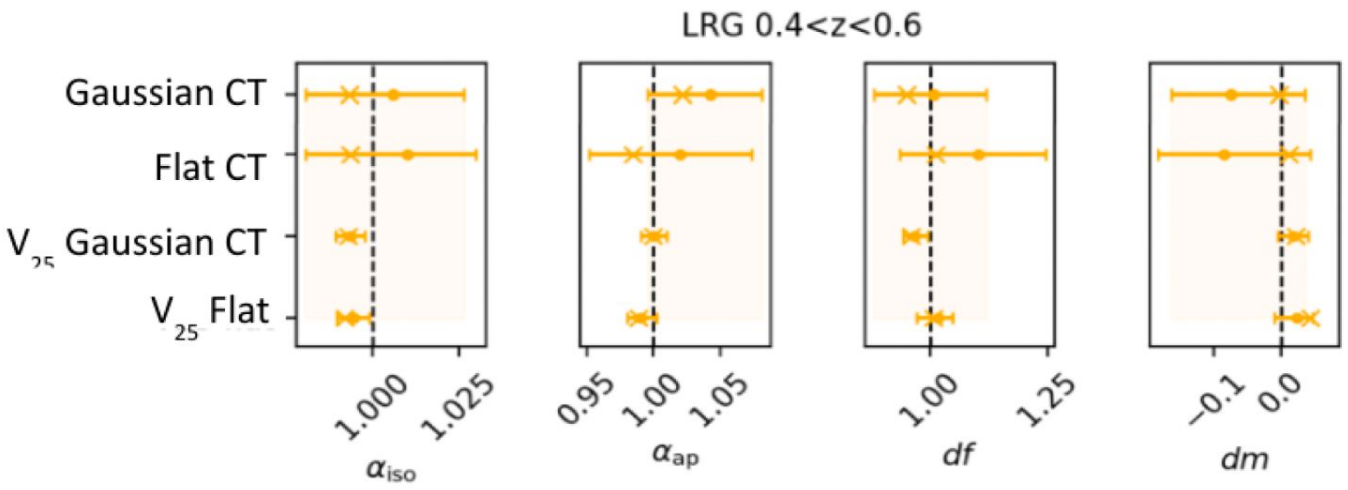
mean and 95% of the marginalised posterior $\neq$ maximum of the posterior (MAP)



Projection effects

2 types of projection effects:

- **prior volume effect** when data not constraining enough for the parameter space
- **prior weight effect** when the prior on a parameter differs from the true value of the data



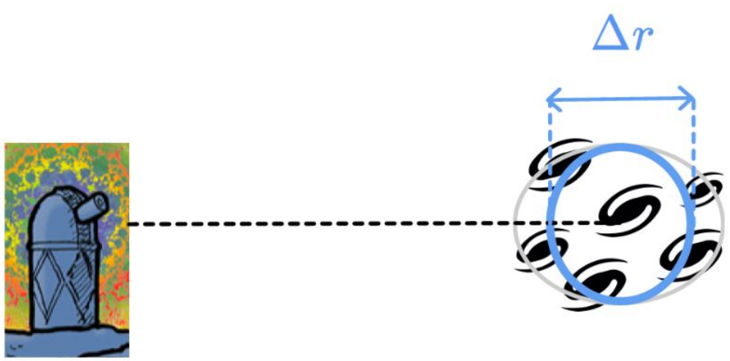
⇒ Difference in MAP values (crosses) between **uninformative flat priors** and **physically-motivated Gaussian priors**: prior weight effect

DARK ENERGY
SPECTROSCOPIC
INSTRUMENT
U.S. Department of Energy Office of Science

Blind analysis

- DESI represents the first galaxy redshift survey data that has been analyzed in a catalogue-based blinded way
- Allow us to mitigate confirmation bias

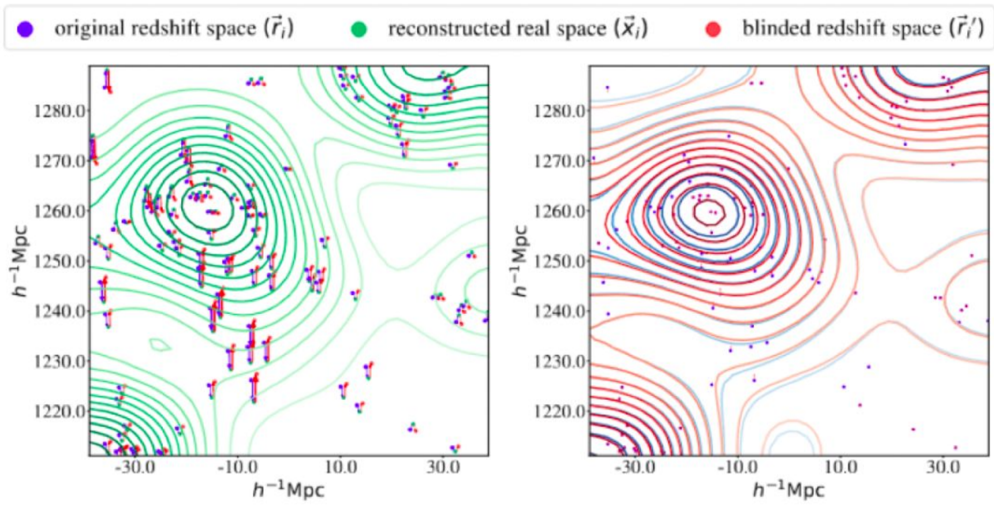
1. geometrical AP-like shift



Same as the BAO blinding

Changes the z-to-distance conversion

2. density-dependent RSD-like shift



Density-dependent shift

Imprints a new RSD shift

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Systematic effects

Study of several potential sources of systematic effects using realistic simulations:

- Theoretical modelling (Maus et al. 2024ab, Lai et al. 2024, Noriega et al. 2024, Ramirez et al. 2024)
- Galaxy-halo connection (Findlay et al. 2024)
- Fiducial cosmology (Gsponer et al. 2024)
- Fibre assignment (Pinon et al. 2024)
- Inhomogeneities in the target selection (Zhao et al. 2024)
- Spectroscopic redshift failures/uncertainties (Yu et al. 2024, Krowleski et al. 2024)
- Covariance matrix: mock-based vs analytic (Forero-Sanchez et al. 2024, Alves et al. 2024, Rashkovetskyi et al. 2024)

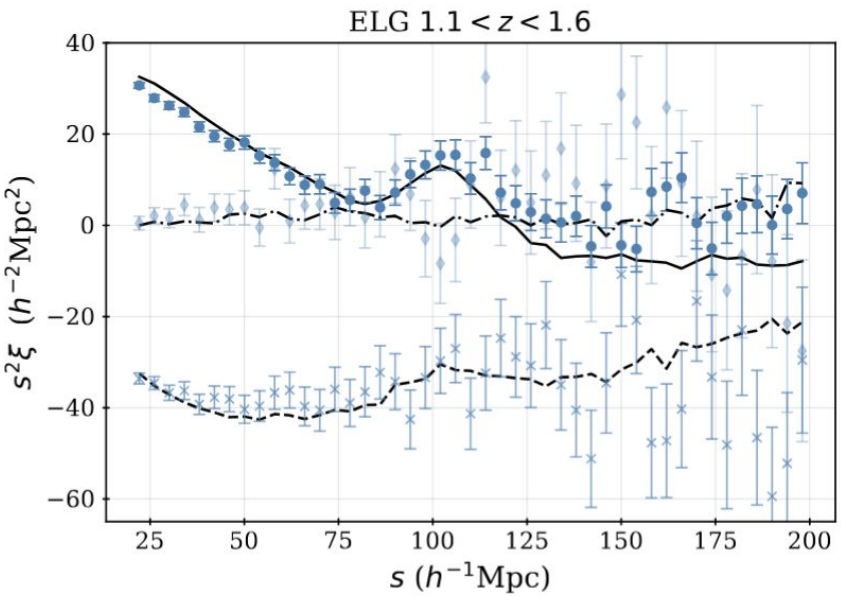
DESI DR1 mock challenge

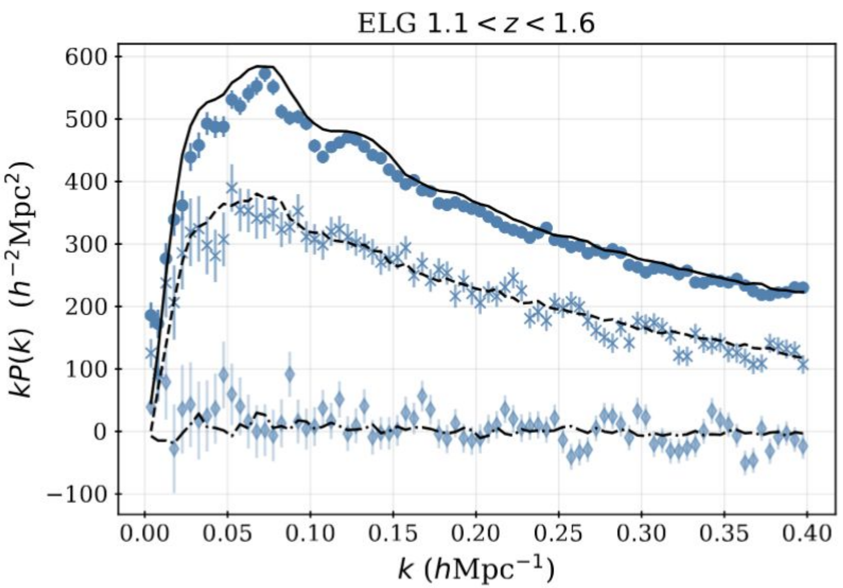
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Two sets of simulations:

N-body simulations for study of systematics

- AbacusSummit N-body simulation (designed for DESI) *(Maksimova et al. 2021)*
- Cubic box 2 $[\mathrm{Gpc}/h]^3$ and cut-sky
- Mass resolution 2 x 10^9 $[M_\odot/h]$
- CompaSO halo catalog M_{halo} > 10.86 $[\log(M_\odot/h)]$ *(Hadzhiyska et al. 2021)*
- HOD based on DESI EDR clustering





DESI 2024 II arXiv:2411.12020

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

DESI DR1 mock challenge

Two sets of simulations:

N-body simulations for study of systematics
- AbacusSummit N-body simulation (designed for DESI) *(Maksimova et al. 2021)*
- Cubic box 2 $[\mathrm{Gpc}/h]^3$ and cut-sky
- Mass resolution 2×10^9 $[M_\odot/h]$
- CompaSO halo catalog $M_{halo} > 10.86$ $[\log(M_\odot/h)]$ *(Hadzhiyska et al. 2021)*
- HOD based on DESI EDR clustering

Approximate mocks for covariance matrix
- 1000 EZmocks per Galactic cap
- Cubic box 6 $[\mathrm{Gpc}/h]^3$ and cut-sky
- Calibrated on DESI DR1 clustering

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

DESI DR1 mock challenge

Two sets of simulations:

N-body simulations for study of systematics

- AbacusSummit N-body simulation (designed for DESI) *(Maksimova et al. 2021)*
- Cubic box 2 $[\mathrm{Gpc/h}]^3$
- Mass resolution 2×10^9 $[M_\odot/h]$
- CompaSO halo catalog $M_{halo} > 10.86$ $[\log(M_\odot/h)]$ *(Hadzhiyska et al. 2021)*
- HOD based on DESI EDR clustering

Approximate mocks for covariance matrix

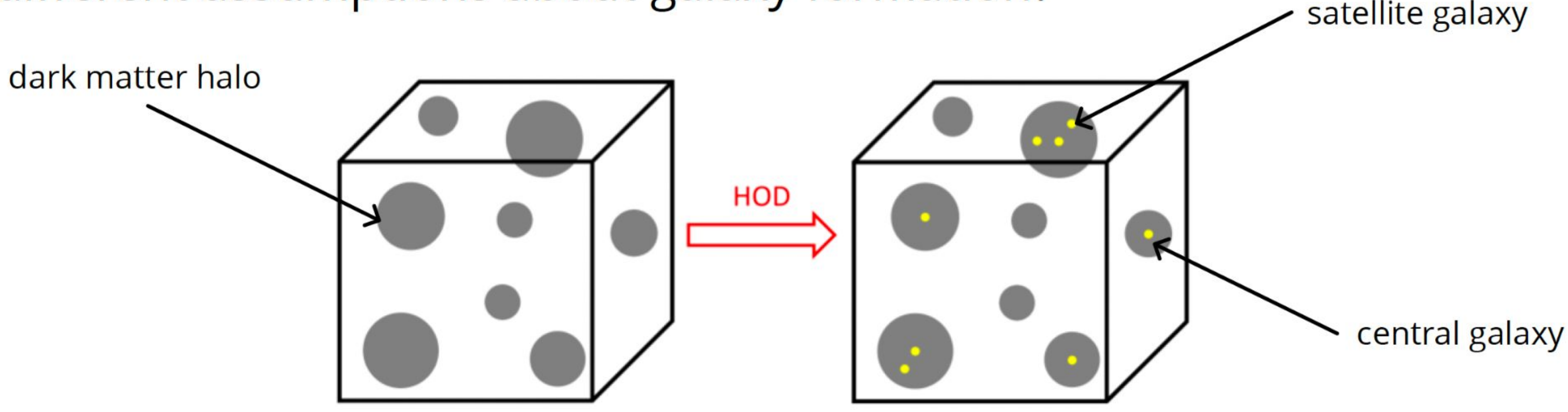
- 1000 EZmocks per Galactic cap
- Cubic box 6 $[\mathrm{Gpc/h}]^3$ and cut-sky
- Calibrated on DESI DR1 clustering

Fibre-assignment procedure applied to both sets of mocks

- for AbacusSummit: realistic and approximate procedure
- for EZmocks: only approximate procedure

Galaxy-halo connection

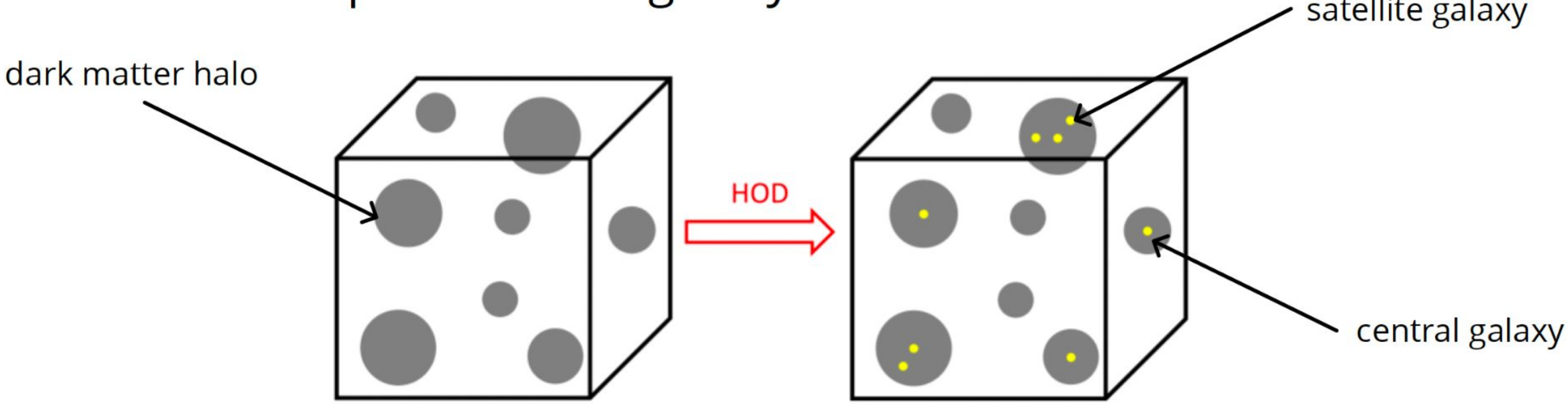
How well do theoretical models capture galaxy clustering under different assumptions about galaxy formation?



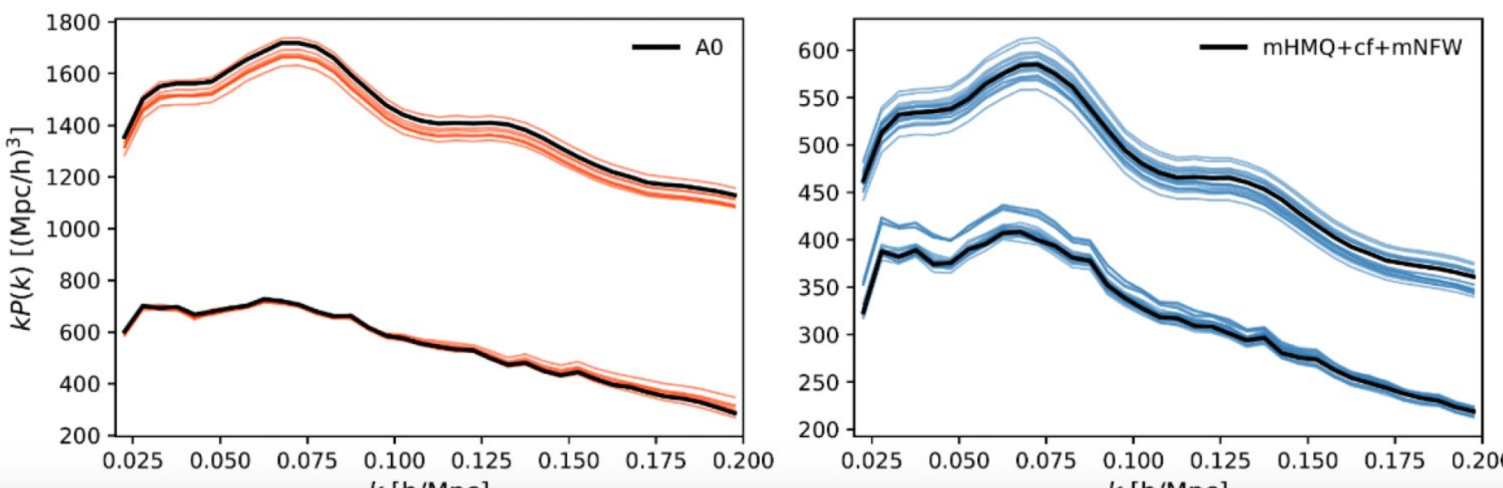
Galaxy-halo connection

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

How well do theoretical models capture galaxy clustering under different assumptions about galaxy formation?



Findlay et al. 2024



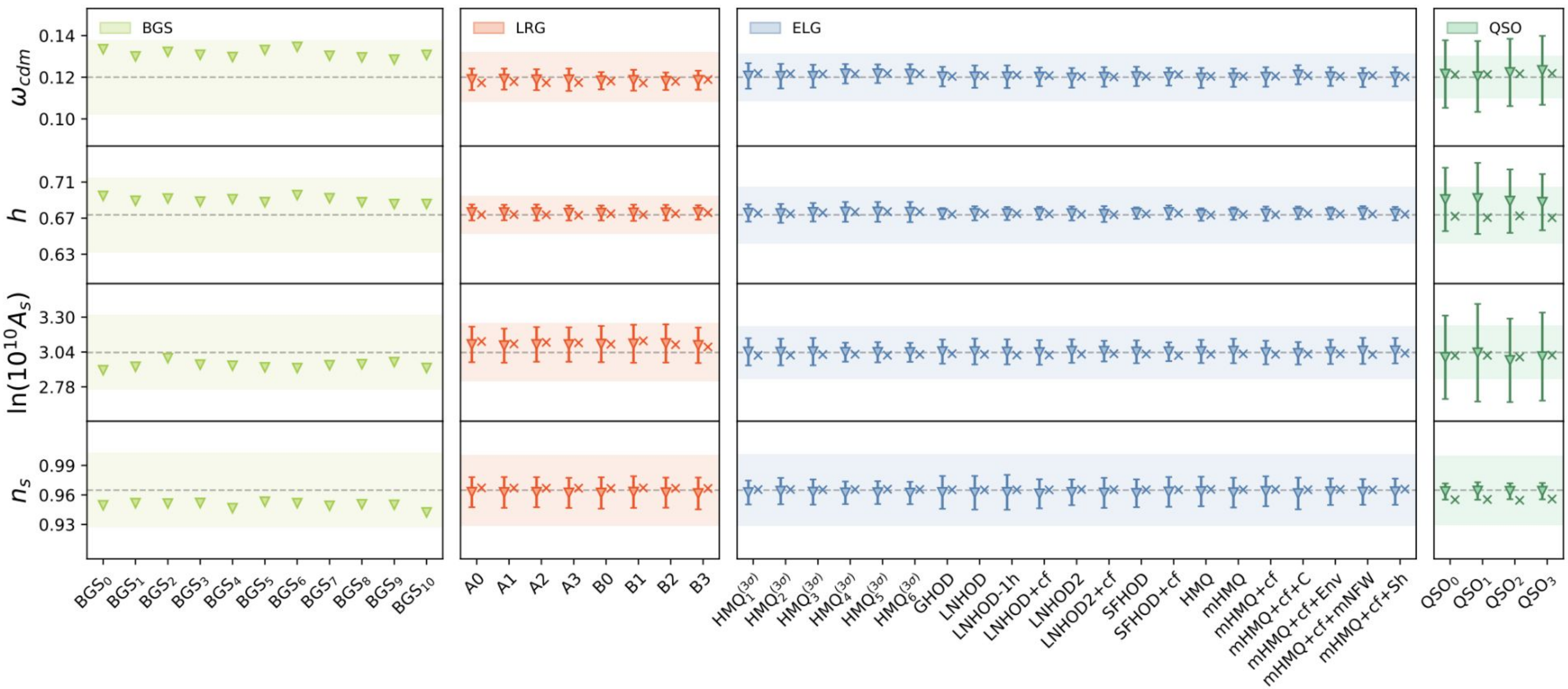
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Galaxy-halo connection

How well do theoretical models capture galaxy clustering under different assumptions about galaxy formation?

Findlay et al. 2024

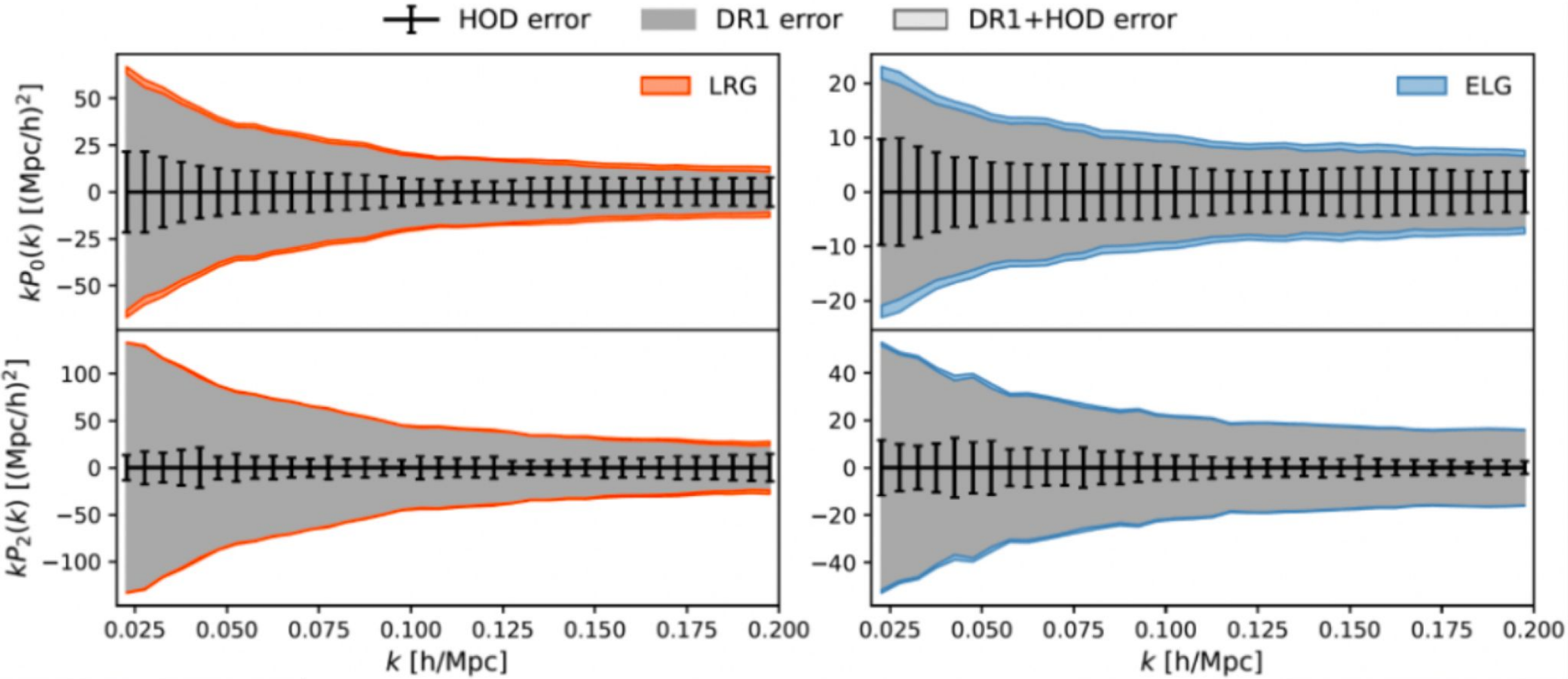


Galaxy-halo connection

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

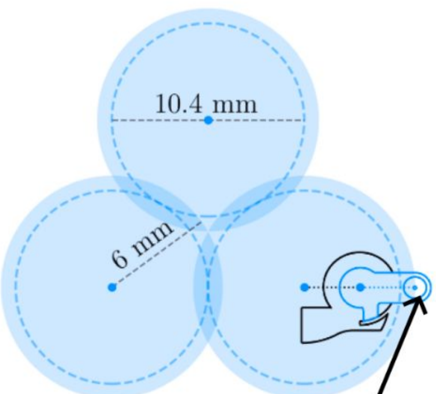
How well do theoretical models capture galaxy clustering under different assumptions about galaxy formation?

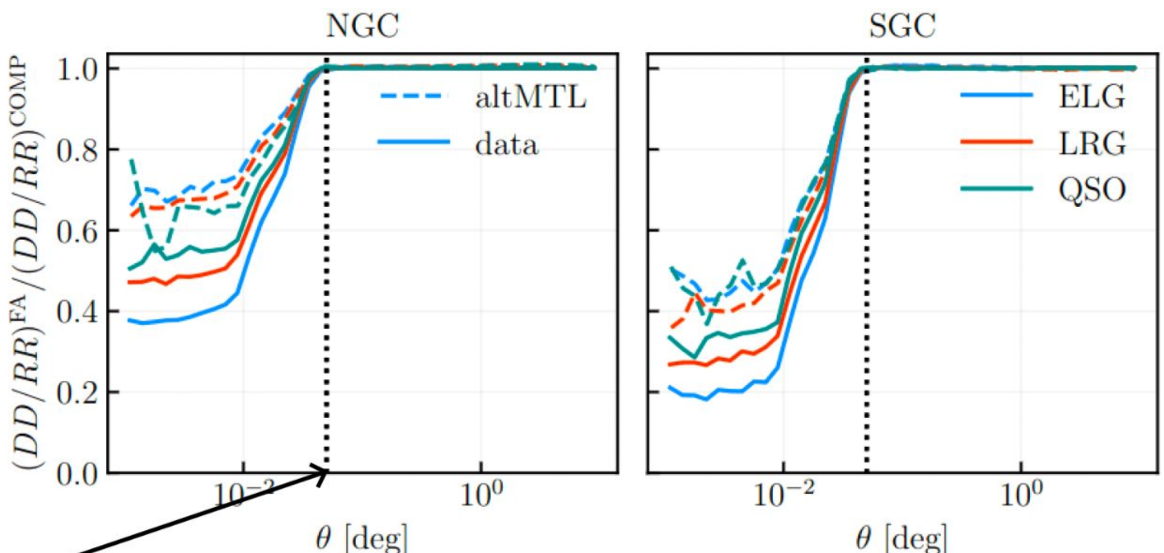
Findlay et al. 2024



Fiber assignment

Groups of galaxies too close to each other cannot all receive a fiber





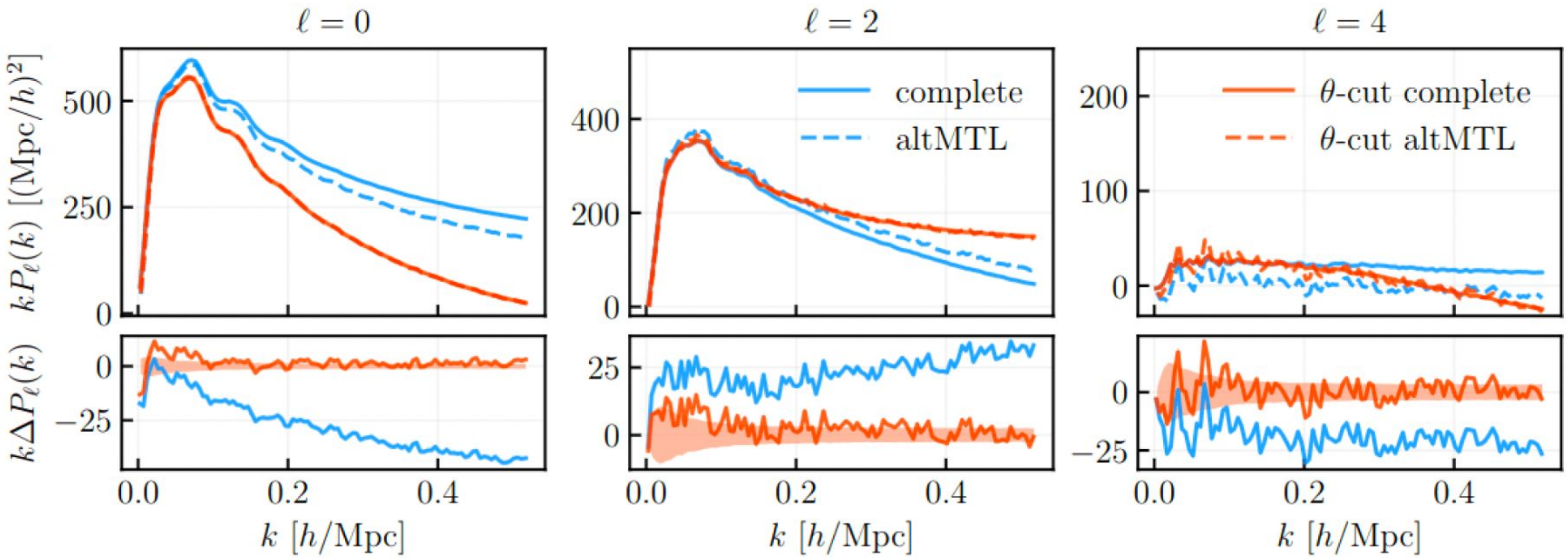
Pinon et al. 2024

$0.05^\circ \simeq$ positioner patrol diameter

Fiber assignment

Impacts power spectrum measurements (altMTL vs complete)

Solution: θ-cut = remove all pairs $< 0.05°$, new window matrix



Pinon et al. 2024

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Systematic effects

Study of several potential sources of systematic effects using realistic simulations:

- Theoretical modelling (Maus et al. 2024ab, Lai et al. 2024, Noriega et al. 2024, Ramirez et al. 2024)
- Galaxy-halo connection (Findlay et al. 2024)
- Fiducial cosmology (Gsponer et al. 2024)
- Fibre assignment (Pinon et al. 2024)
- Inhomogeneities in the target selection (Zhao et al. 2024)
- Spectroscopic redshift failures/uncertainties (Yu et al. 2024, Krowleski et al. 2024)
- Covariance matrix: mock-based vs analytic (Forero-Sanchez et al. 2024, Alves et al. 2024, Rashkovetskyi et al. 2024)

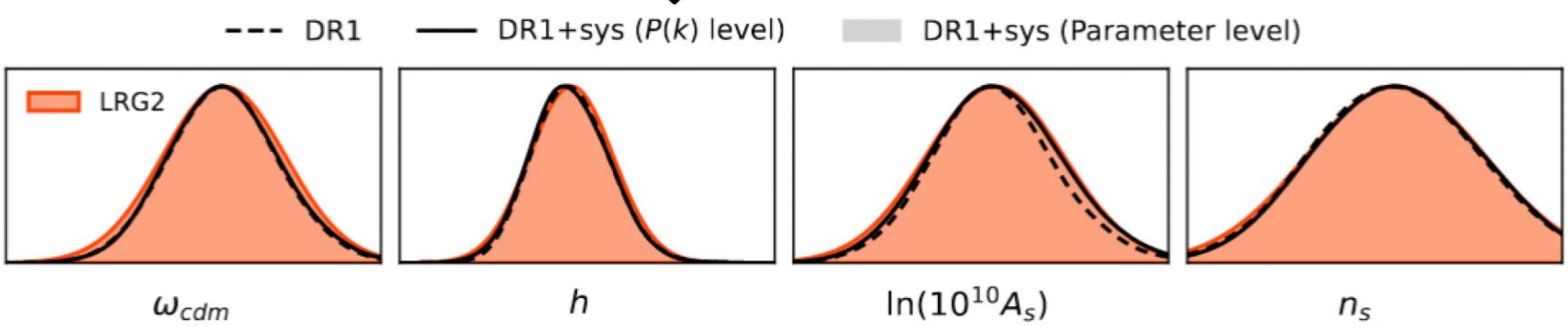
Total systematic error = ⅖ of DR1 statistical error

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Full Shape pipeline - summary

Cosmological parameters (SF)	Priors
$\alpha_{\rm iso}$	$\mathcal{U}[0.8,\ 1.2]$
$\alpha_{\rm AP}$	$\mathcal{U}[0.8,\ 1.2]$
$f/f_{\rm fid}$	$\mathcal{U}[0.0,\ 2.0]$
m	$\mathcal{U}[-0.8,\ 0.8]$
Cosmological parameters (FM)	**Priors**
$\omega_{\rm cdm}$	$\mathcal{U}[0.01, 0.99]$
$\omega_{\rm b}$	$\mathcal{N}[0.02218, 0.00055^2]$
h	$\mathcal{U}[0.2, 1]$
$\ln(10^{10}A_s)$	$\mathcal{U}[1.61, 3.91]$
n_s	$\mathcal{N}[0.9649, 0.042^2]$
Non-cosmological parameters	**Priors**
$(1+b_1)\sigma_8$	$\mathcal{U}[0, 3]$
$b_2\sigma_8^2$	$\mathcal{N}[0, 5^2]$
$b_s\sigma_8^2$	$\mathcal{N}[0, 5^2]$
α_0	$\mathcal{N}[0, 12.5^2]$
α_2	$\mathcal{N}[0, 12.5^2]$
SN_0	$\mathcal{N}[0, 2^2] \times 1/\bar{n}_g$
SN_2	$\mathcal{N}[0, 5^2] \times f_{\rm sat}\sigma_{1\,\rm eff}^2/\bar{n}_g$

- **Observable:** power spectrum monopole and quadrupole
- **Model:** Effective Field Theory
- **Covariance:** mock-based
- **Fitting range:** $0.02 < k\,[h/\mathrm{Mpc}] < 0.2$
- **Fitting parameters:**
  - 5 ΛCDM parameters (FM)
  - 4 compressed parameters (SF)
  - 7 non-cosmological parameters
- **Systematic error:** at the data vector level



DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Full Shape pipeline: what's new!

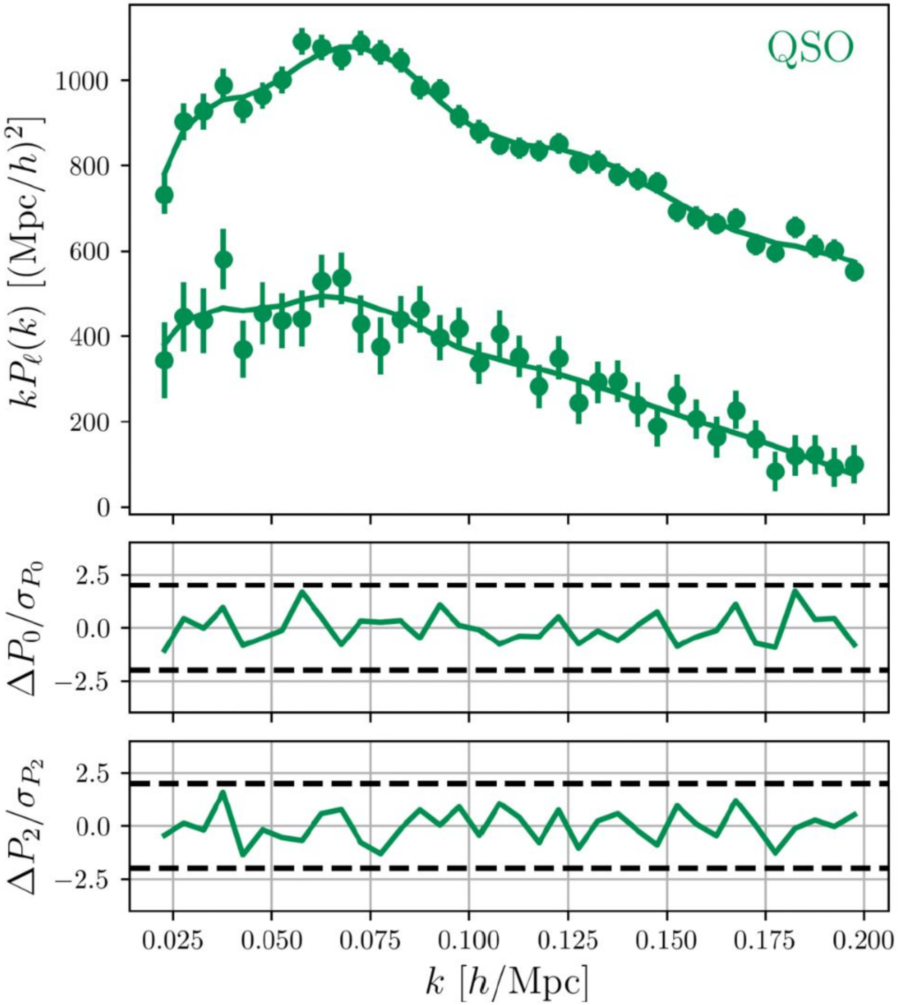
(compared to SDSS)

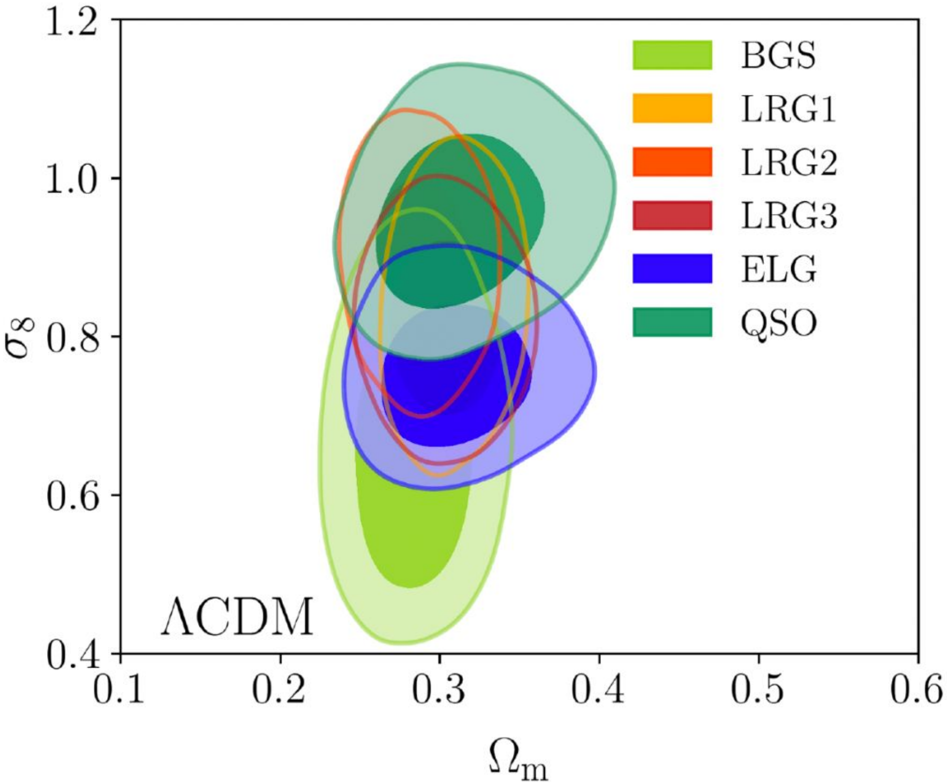
- **Biggest ever spectroscopic dataset** ($N_{\rm tracer}$ and V)
- **Blind analysis** to mitigate observer / confirmation biases (catalogue-level blinding)
- Effective Field Theory models
- Full-Modelling ($\Omega_{\rm cosmo}$) and updated compression approach (ShapeFit)
- Improvements in the treatment of observational systematics (e.g. fiber assignment)
- **Unified Full Shape pipeline** applied to all (discrete) tracer / redshift bins consistently

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

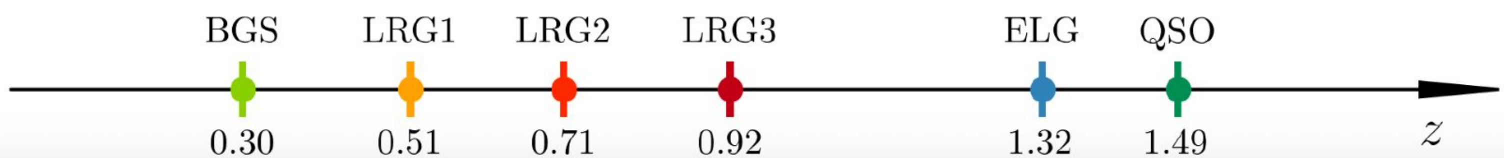
Full Shape + BAO measurements





$\Omega_\mathrm{b}h^2$: BBN from Schöneberg 2024

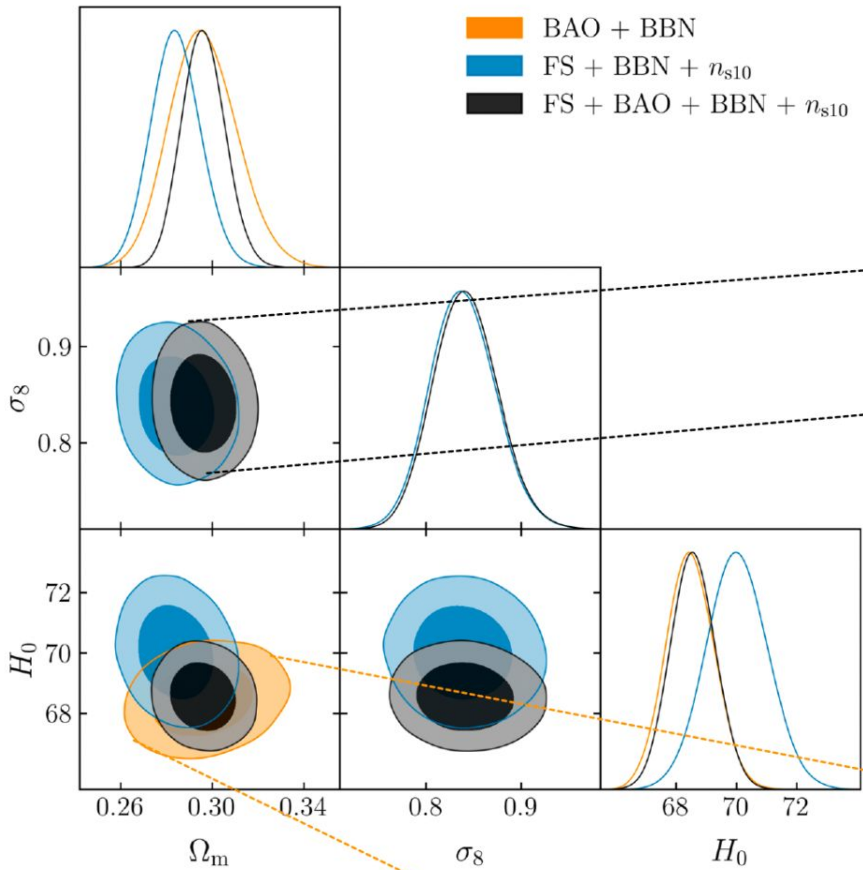
$n_\mathrm{s} \sim \mathcal{G}(0.9649, 0.042^2)$

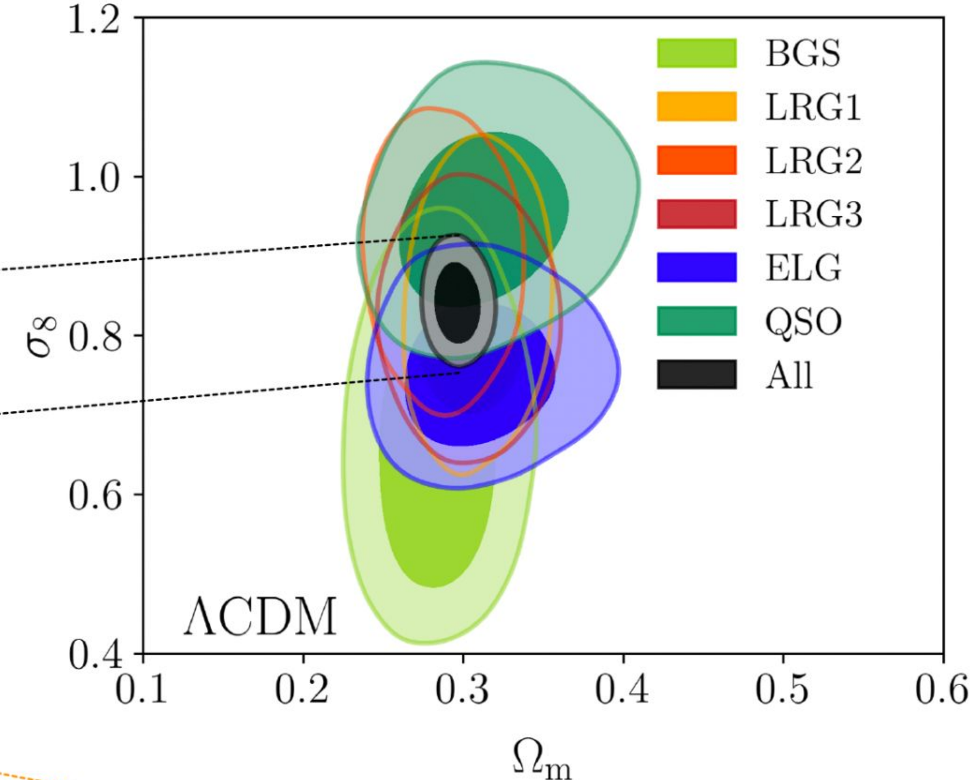


DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Full Shape + BAO measurements



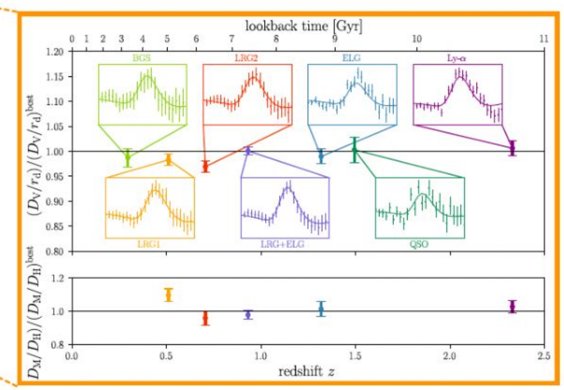


$$\Omega_m = 0.2962 \pm 0.0095 \qquad \mathbf{(3.2\%)}$$

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

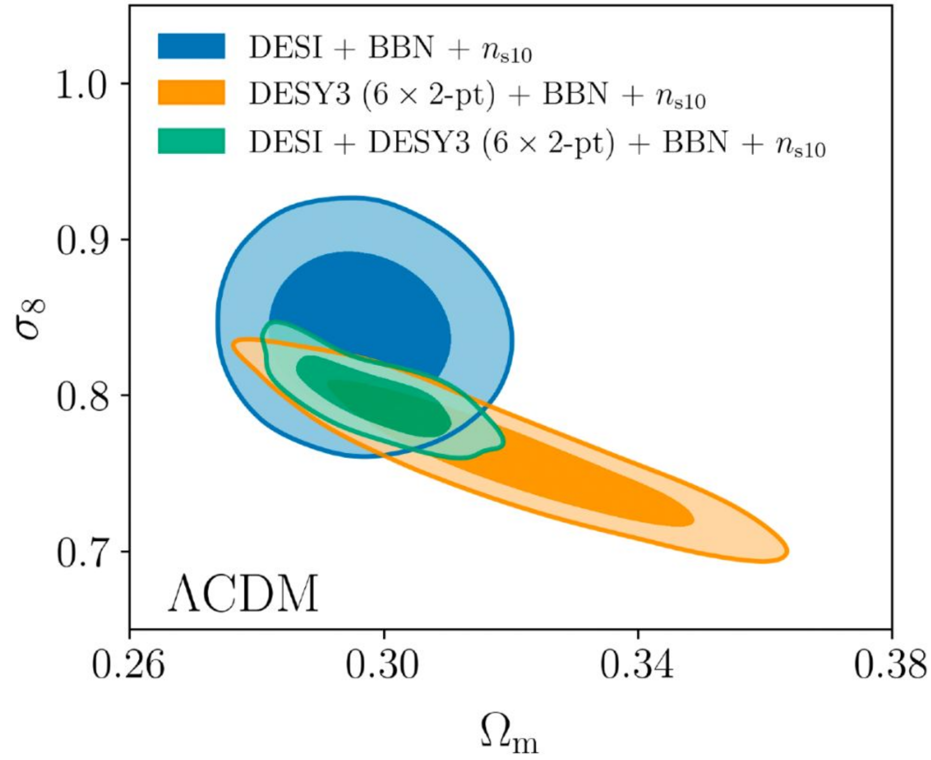
$$H_0 = (68.56 \pm 0.75)\,\mathrm{km\,s^{-1}\,Mpc^{-1}} \qquad \mathbf{(1.1\%)}$$

DESI + BBN + n_{s10}



Combined constraints

- Adding DESI to DESY3 6x2pt* improves σ_8 and Ω_m precision by $\times 2$ (S_8 by 20%)

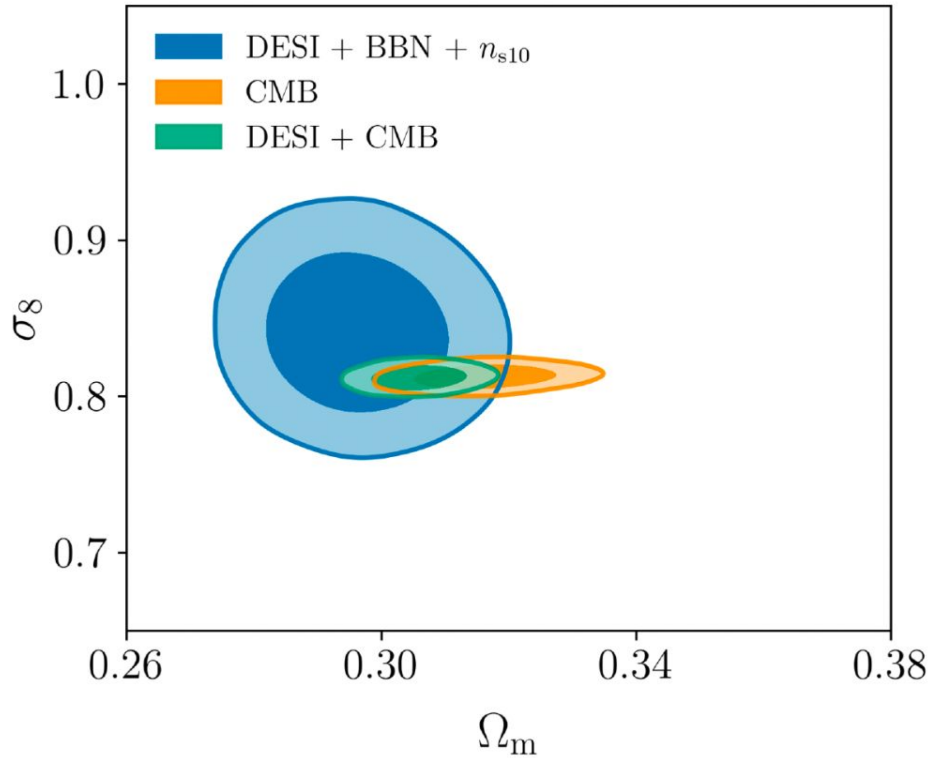


*DES and SPT collaborations 2022
6x2pt = galaxy-galaxy, galaxy-shear, shear-shear, galaxy-CMB lensing, shear-CMB lensing, CMB lensing-CMB lensing

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Combined constraints

- Adding DESI to DESY3 6x2pt improves σ_8 and Ω_m precision by $\times 2$ (S_8 by 20%)
- Adding DESI to CMB improves Ω_m, H_0 and S_8 precision by 30%



Combined constraints

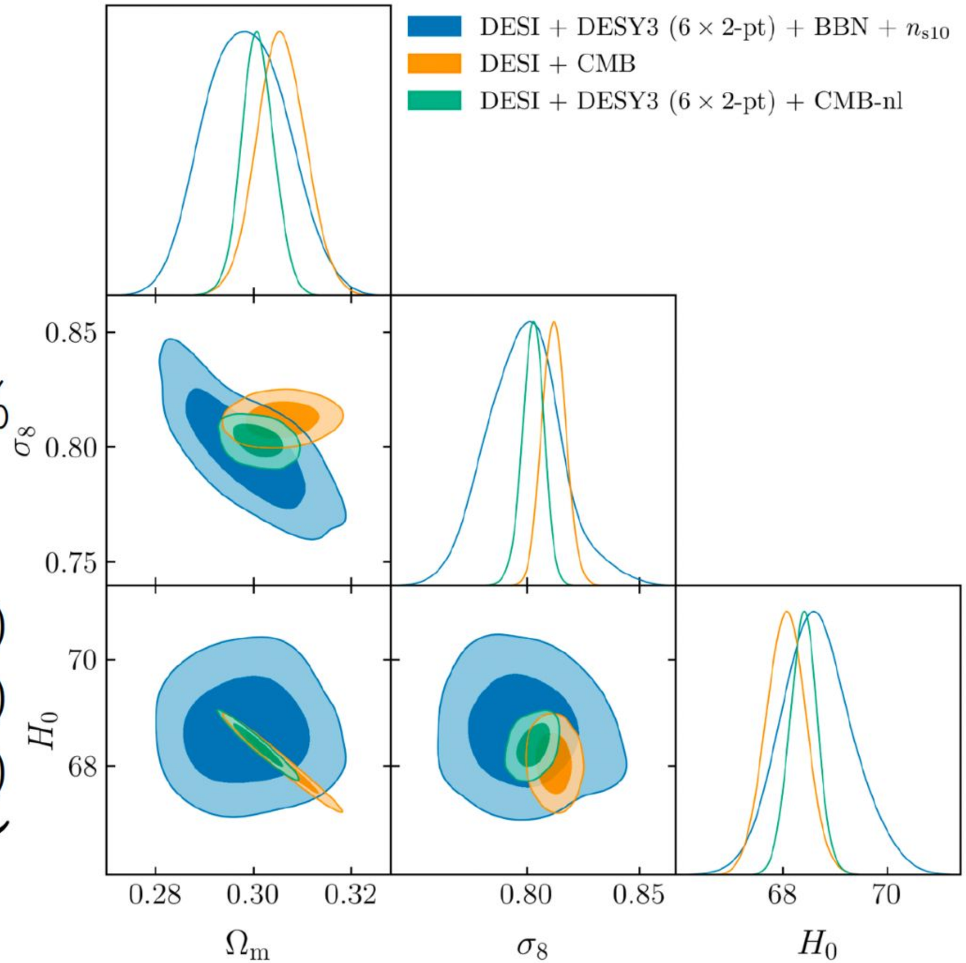
- Adding DESI to DESY3 6x2pt improves σ_8 and Ω_m precision by $\times 2$ (S_8 by 20%)
- Adding DESI to CMB improves Ω_m, H_0 and S_8 precision by 30%

$$\Omega_\mathrm{m} = 0.3009 \pm 0.0034 \quad (\mathbf{1\%})$$

$$\sigma_8 = 0.8028^{+0.0050}_{-0.0045} \quad (\mathbf{0.6\%})$$

$$H_0 = (68.40 \pm 0.27)\,\mathrm{km\,s^{-1}\,Mpc^{-1}} \quad (\mathbf{0.4\%})$$

DESI + DESY3 (6 × 2pt) + CMB-nl



Dynamical Dark Energy - (w_0, w_a)

Dark Energy fluid, pressure p, density ρ

Equation of State parameter $w = p/\rho$

Linked to the evolution of Dark Energy $w(z) = -1 + \frac{1}{3}\frac{d \ln f_{\mathrm{DE}}(z)}{d \ln(1+z)}$

Let's assume the CPL parameterization

$$w(z) = w_0 + \frac{z}{1+z} w_a \qquad \text{(CPL)}$$

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

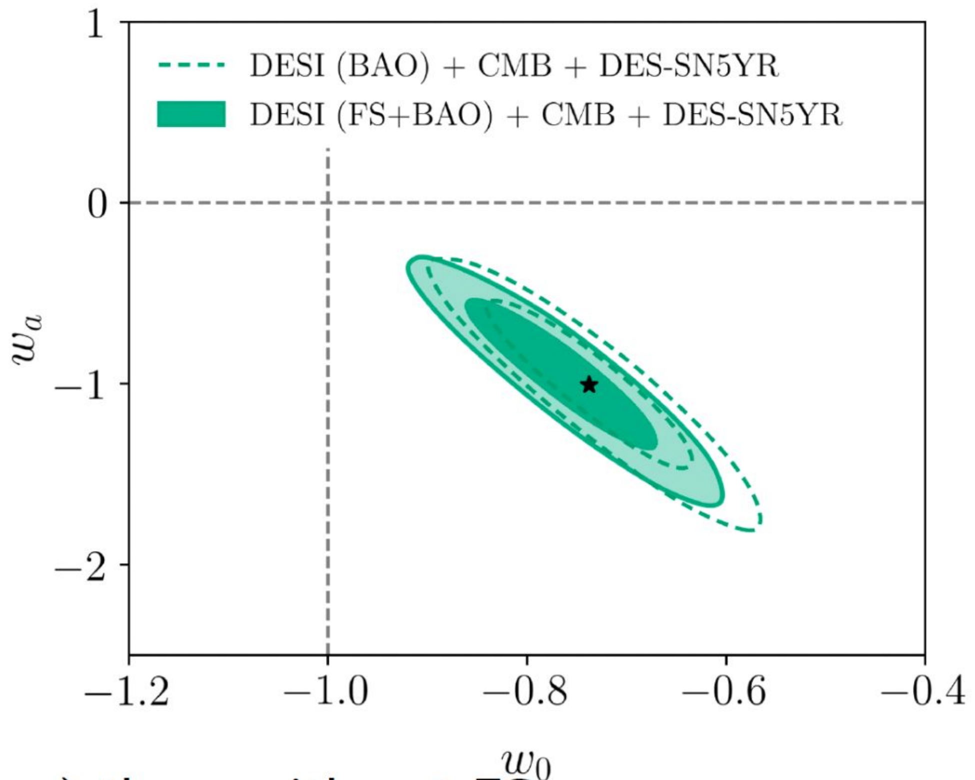
Dynamical Dark Energy - (w_0, w_a)

Combining all DESI + CMB + SN

DESI + CMB + Pantheon+: 2.5σ

DESI + CMB + Union3: 3.4σ

DESI + CMB + DES-SNY5R: 3.8σ



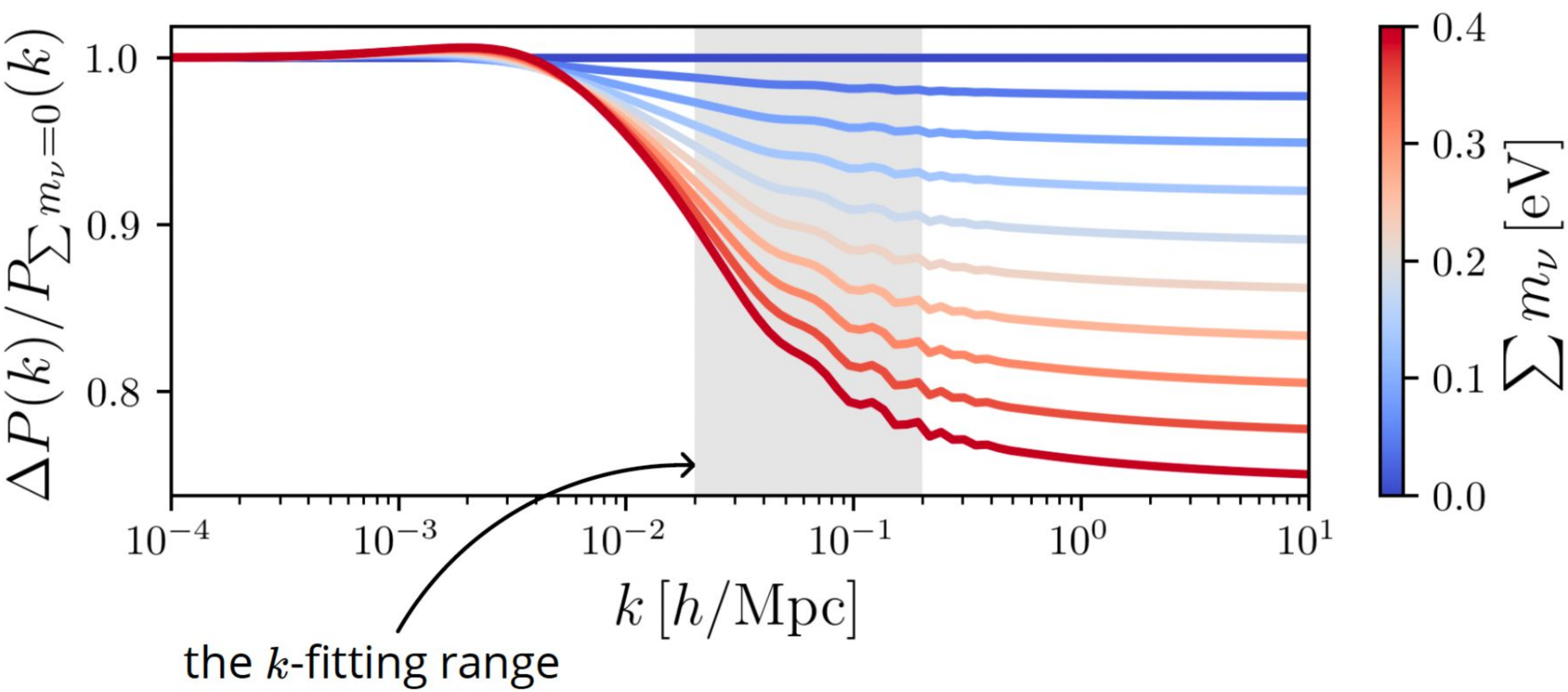
- 20% better constraints in (w_0, w_a) than without FS
- same preference for $w_0 > -1, w_a < 0$
- similar significance for $w_0 w_a$CDM vs ΛCDM

Sum of neutrino masses

Massive neutrinos impact:

i) the expansion history

ii) the growth of structure: $\Delta P(k)/P(k) \propto -\sum m_\nu/\omega_\mathrm{m}$



Sum of neutrino masses

Massive neutrinos impact:

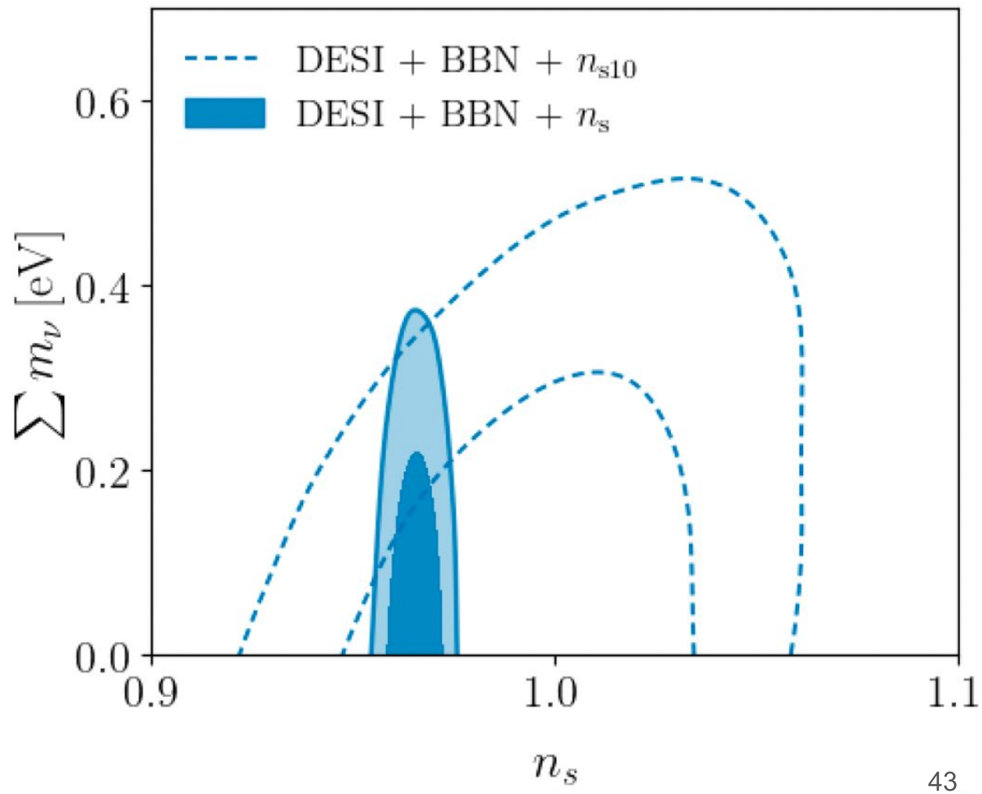
i) the expansion history

ii) the growth of structure: $\Delta P(k)/P(k) \propto -\sum m_\nu/\omega_{\rm m}$

$$\underbrace{\sum m_\nu < 0.409\,\text{eV}\ (95\%)}_{\text{DESI + BBN} + n_{\rm s10}}$$

Taking $n_{\rm s}$ prior from Planck:

$$\underbrace{\sum m_\nu < 0.300\,\text{eV}\ (95\%)}_{\text{DESI + BBN} + n_{\rm s}}$$



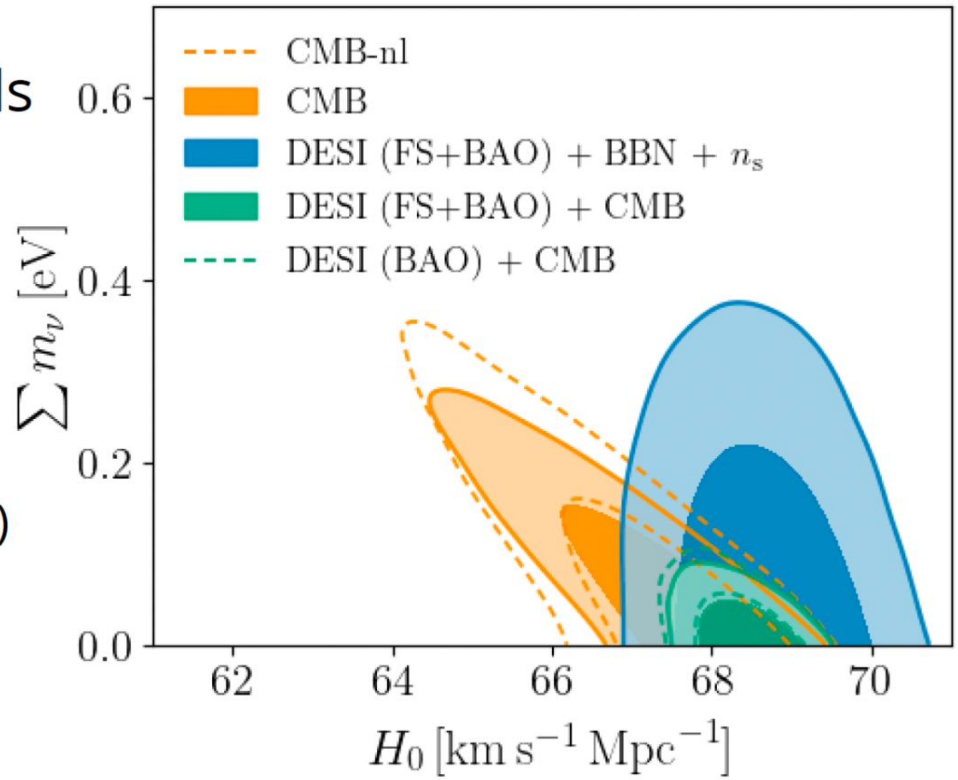
Sum of neutrino masses

Internal CMB degeneracies limiting precision on the sum of neutrino masses

Low preferred value of H_0 yields

$$\underbrace{\sum m_\nu < 0.071\,\mathrm{eV}\ (95\%)}_{\mathrm{DESI+CMB}}$$

(15% better than BAO + CMB: $0.082\,\mathrm{eV}$)



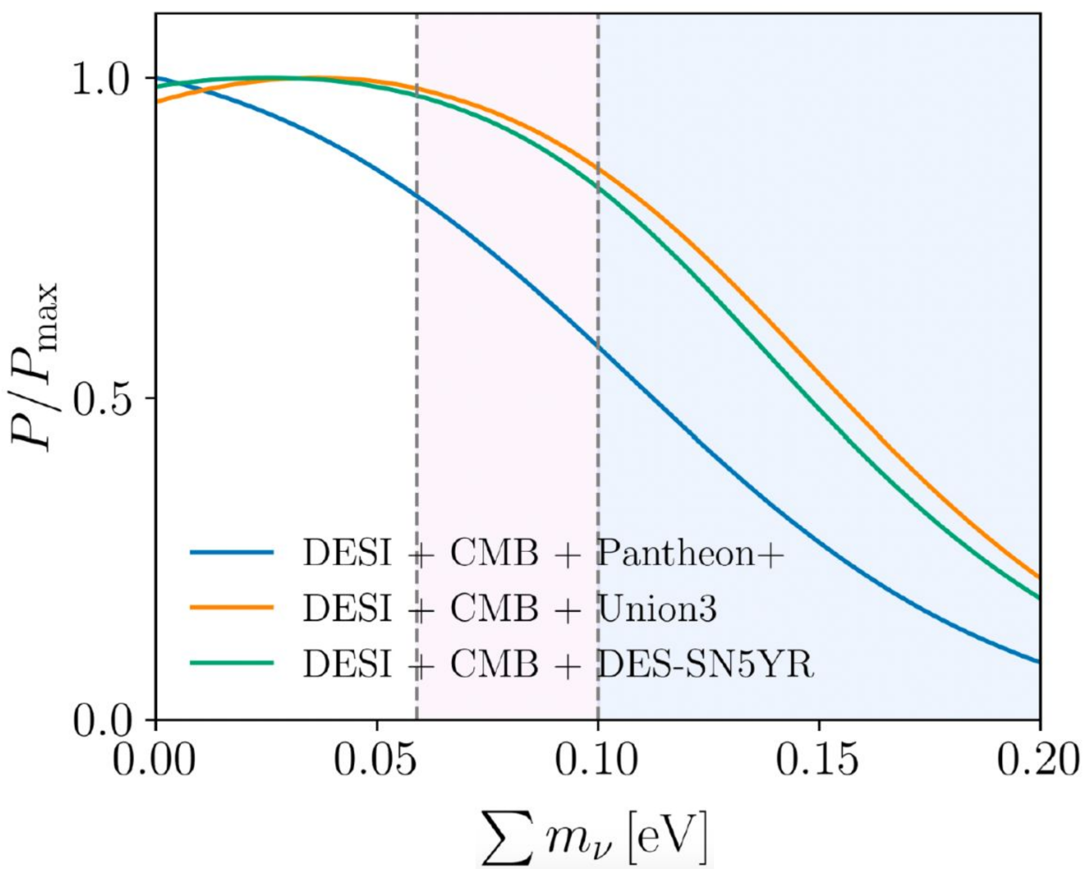
Limit relaxed for more flexible expansion model

e.g. $\sim 0.2\,\mathrm{eV}\ (95\%)$ in $w_0 w_a$CDM, with DES-SN5YR

Sum of neutrino masses

Limit relaxed for more flexible expansion model

e.g. $\sim 0.2\,\mathrm{eV}$ (95%) in $w_0 w_a\mathrm{CDM}$, with DES-SN5YR

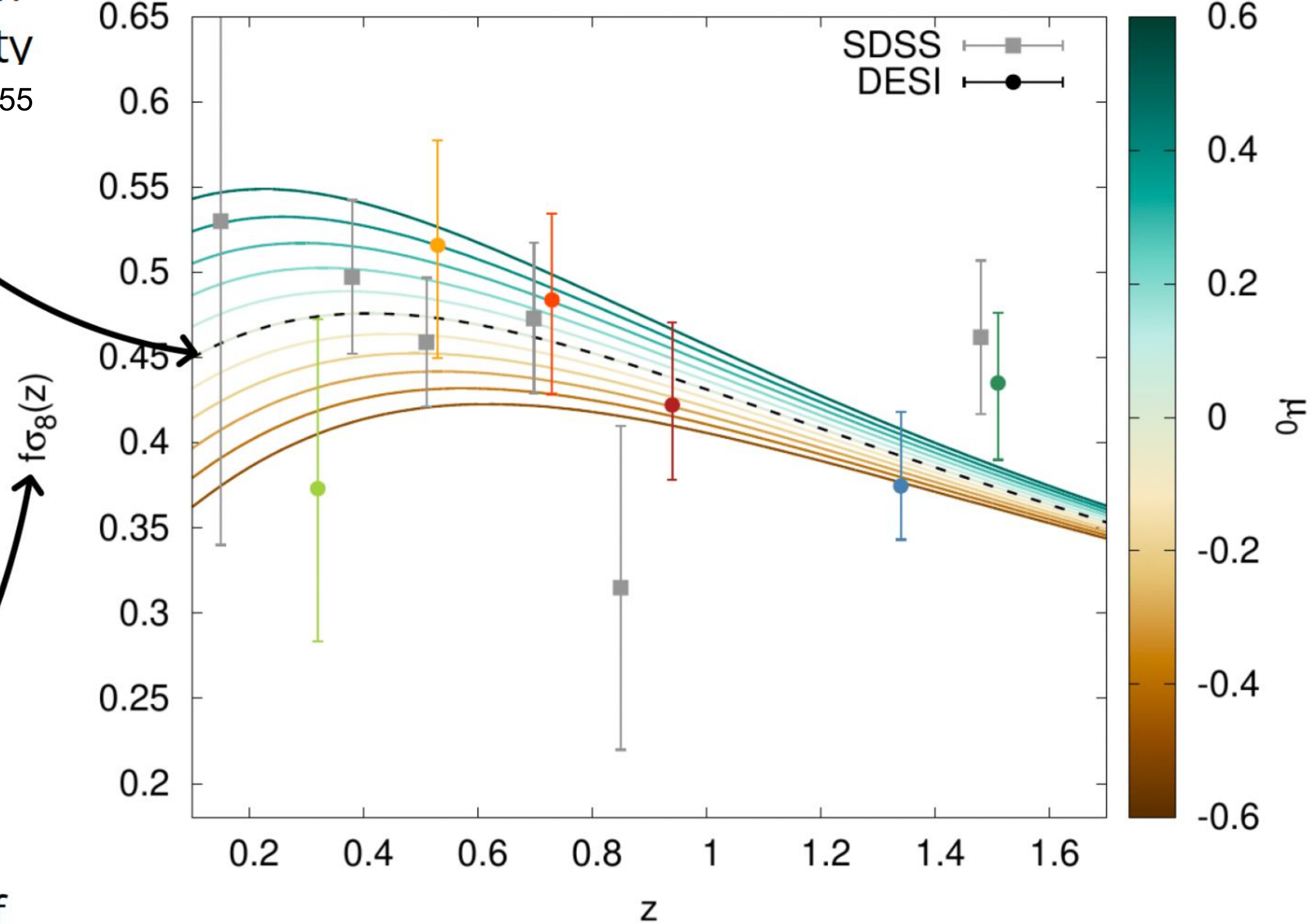


DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

DESI constraints on gravity

prediction from general relativity

$f\sigma_8(z) \sim \Omega_m(z)^{0.55}$



growth rate of structure

⇒ Similar precision on $f\sigma_8$ at $z < 1.5$ between DESI DR1 (1 year of observations) and SDSS (20 years of observations)

Modified gravity

Perturbed FLRW metric

$$ds^2 = a(\tau)^2[-(1+2\Psi)d\tau^2 + (1-2\Phi)\delta_{ij}dx^i dx^j]$$

gravitational potentials

At late times:

(mass) $k^2\Psi = -4\pi G a^2 \mu(a,k) \sum_i \rho_i \Delta_i$

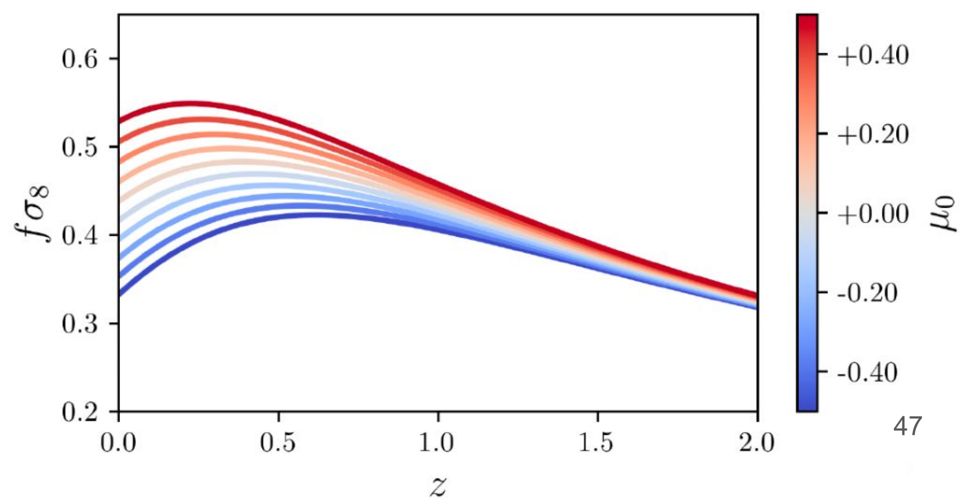
(light) $k^2(\Phi + \Psi) = -8\pi G a^2 \Sigma(a,k) \sum_i \rho_i \Delta_i$

density perturbations

In general relativity, $\mu(a,k) = \Sigma(a,k) = 1$

To test GR, introduce μ_0, Σ_0

$$\begin{cases} \mu(a) = 1 + \dfrac{\Omega_\Lambda(a)}{\Omega_\Lambda}\mu_0 \\ \Sigma(a) = 1 + \dfrac{\Omega_\Lambda(a)}{\Omega_\Lambda}\Sigma_0 \end{cases}$$



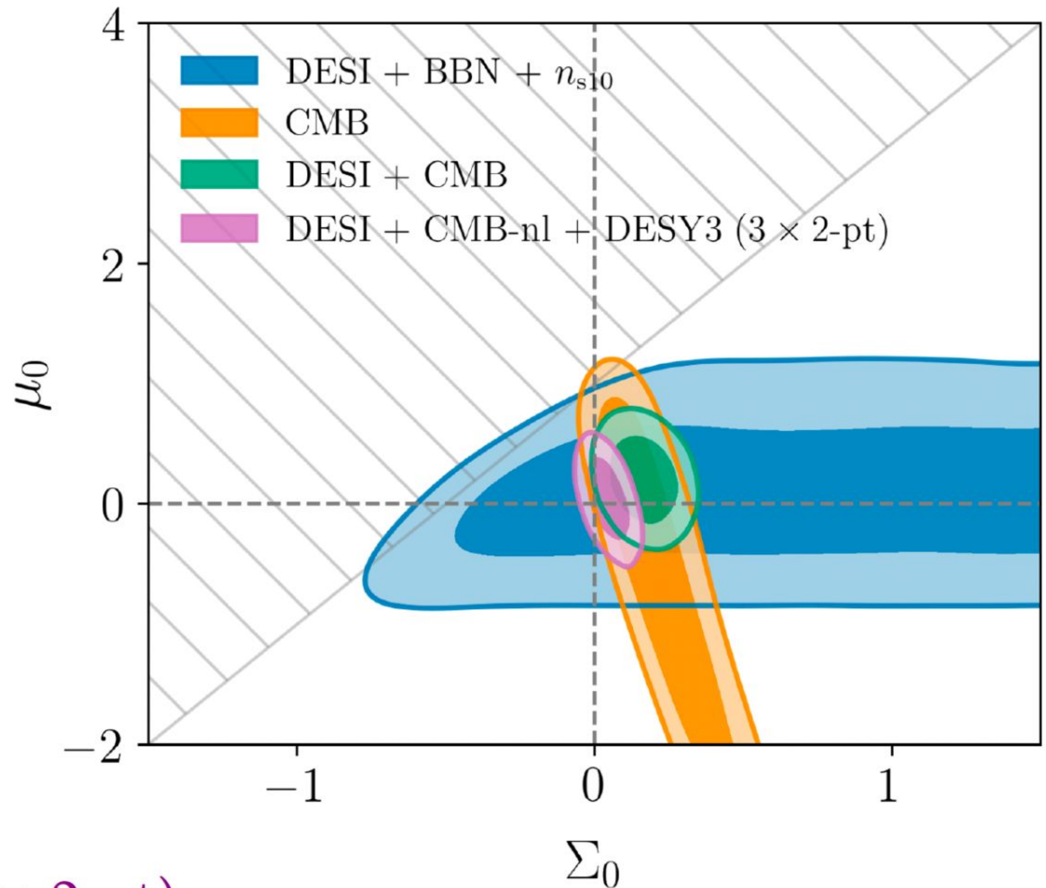
Modified gravity

DESI constrains

$$\underbrace{\mu_0 = 0.11^{+0.45}_{-0.54}}_{\text{DESI + BBN} + n_{s10}}$$

Σ_0 constrained by
- CMB (ISW and lensing)
- galaxy lensing

$$\underbrace{\begin{aligned}\mu_0 &= 0.04 \pm 0.22\\ \Sigma_0 &= 0.045 \pm 0.046\end{aligned}}_{\text{DESI + CMB-nl + DESY3 } (3\times 2\text{-pt})}$$



compared to CMB-nl + DESY3 (3x2pt) only: $\sigma(\mu_0)/2.5$, $\sigma(\Sigma_0)/2$

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Conclusions

Adding Full Shape information to BAO: sensitivity to structure growth

DESI Full Shape favors σ_8, S_8 consistent with Planck

Expansion history: in agreement with previous DESI BAO and CMB results

Still hint of dynamical dark energy, w_0, w_a constraints improved by 20%

Still low $\sum m_\nu$, improved by 15%

Modified gravity μ_0 parameter to be consistent with the zero GR value

DR2 data (Y3 > Y1) on disk, BAO analysis on-going… stay tuned!

APS special session, March 19 2025
https://data.desi.lbl.gov/doc/papers/