New DESI results weight in on gravity

Cosmological constraints from full-shape galaxy clustering with DESI DR1

Pauline Zarrouk
On behalf of the DESI collaboration

Séminaire - 27/01/2025


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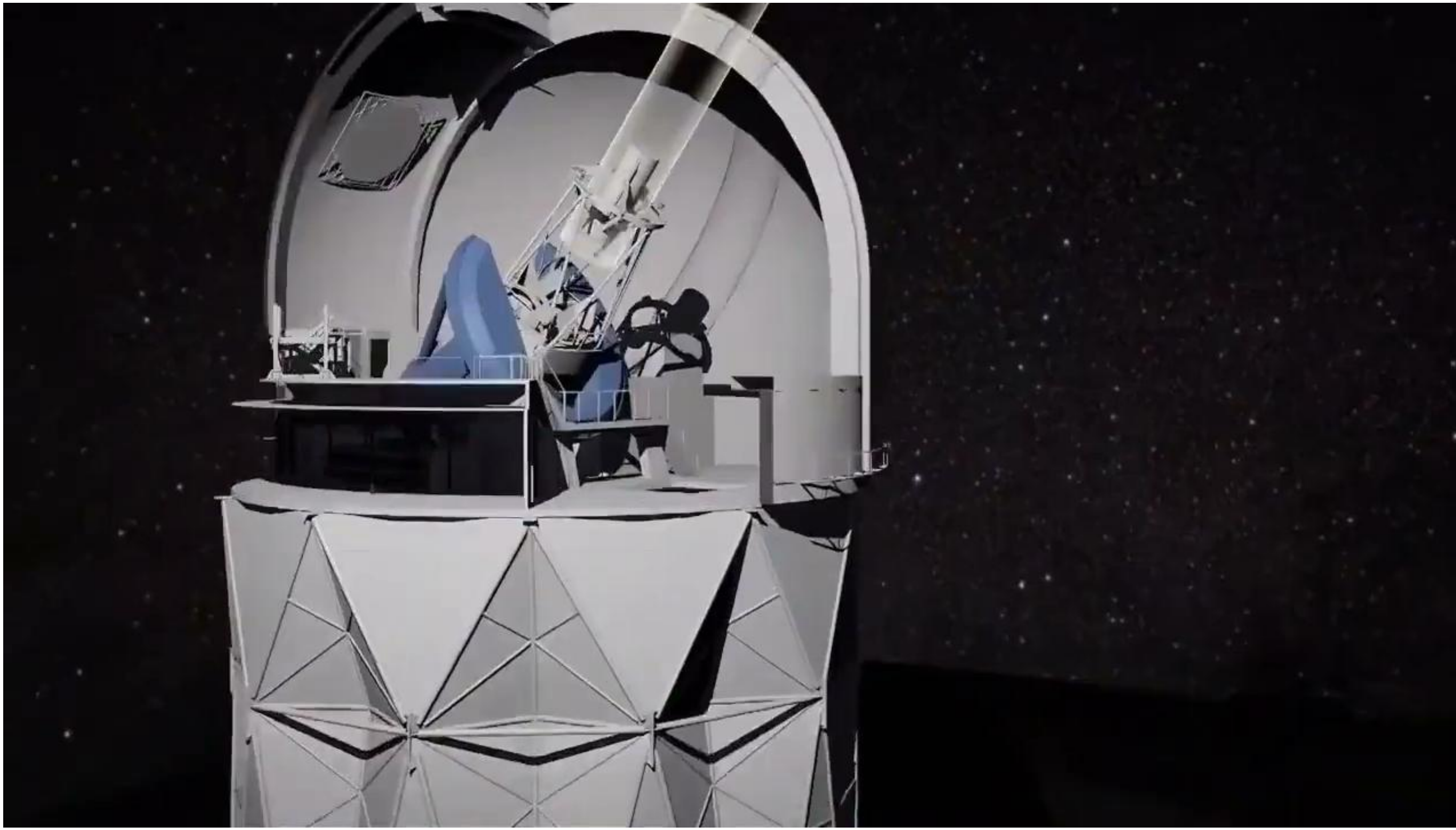
The DESI instrument



Credit: NSF

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DESI Y5 galaxy samples

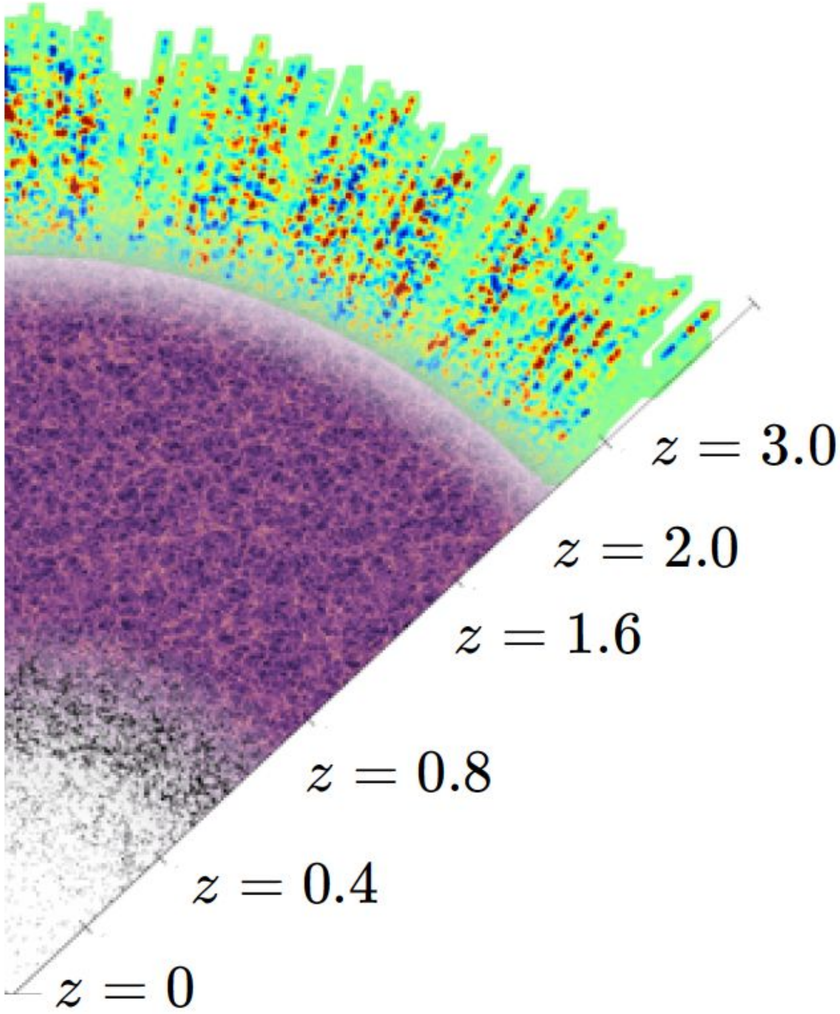
Y5 $\sim$ 40M galaxy redshifts!

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



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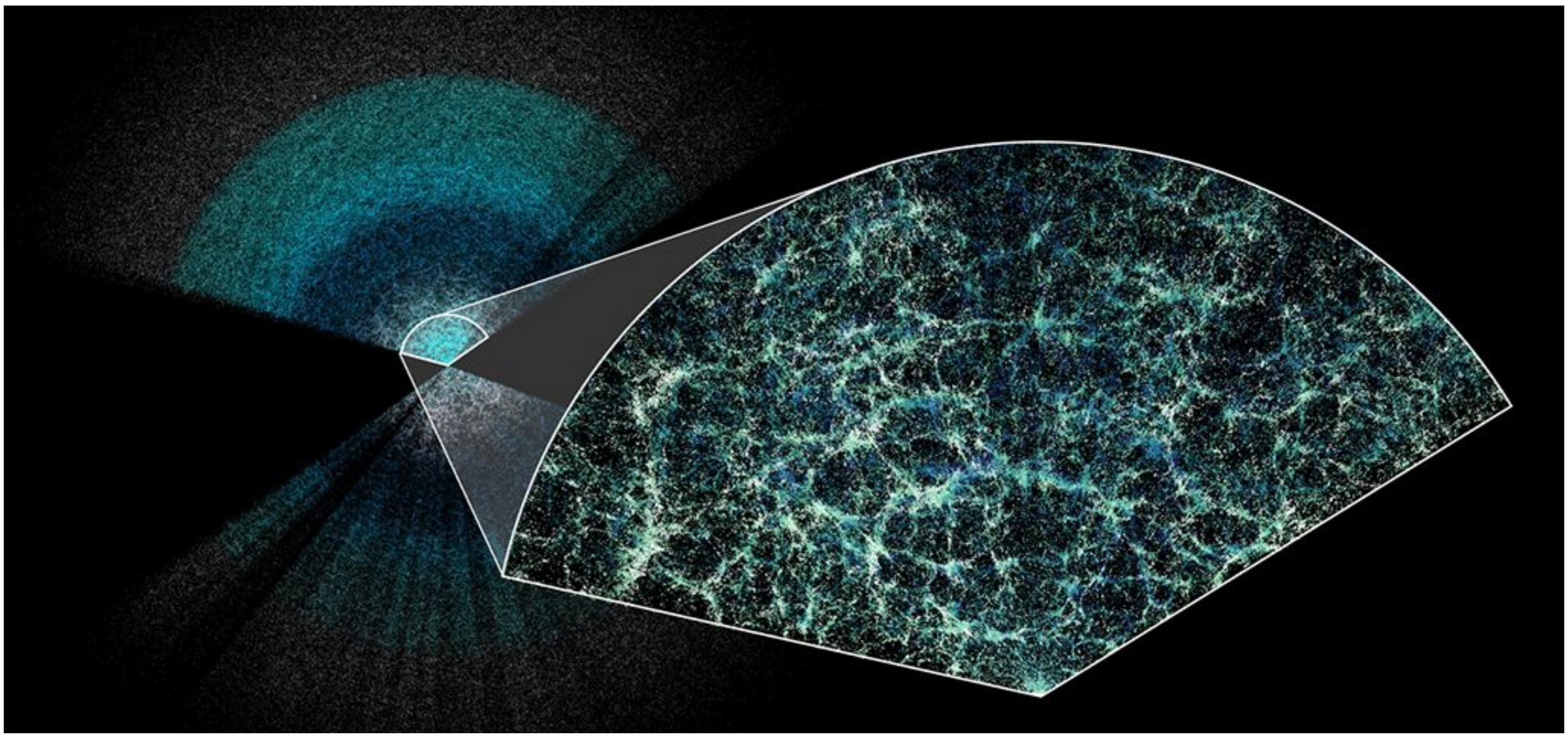
DESI data release 1 (DR1)

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

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Release of DESI DR1 (FS) results

November 19th 2024

Second batch of DESI DR1 cosmological analyses

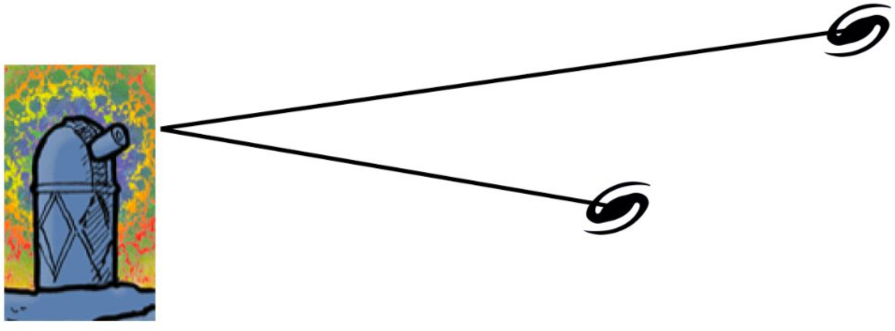
https://data.desi.lbl.gov/doc/papers/

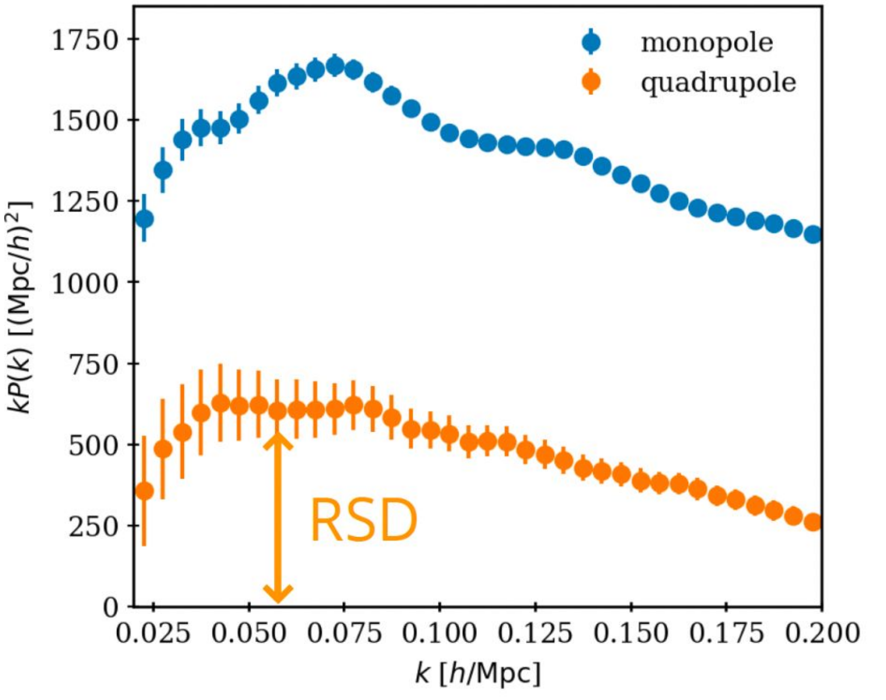
- DESI 2024 I: First year data release
- DESI 2024 II: Sample definitions and two-point clustering statistics
- DESI 2024 III: BAO from Galaxies and Quasars
- DESI 2024 IV: BAO from the Lyman-Forest
- **DESI 2024 V: Full-Shape (FS) measurements of Galaxies and Quasars**
- DESI 2024 VI: Cosmological constraints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

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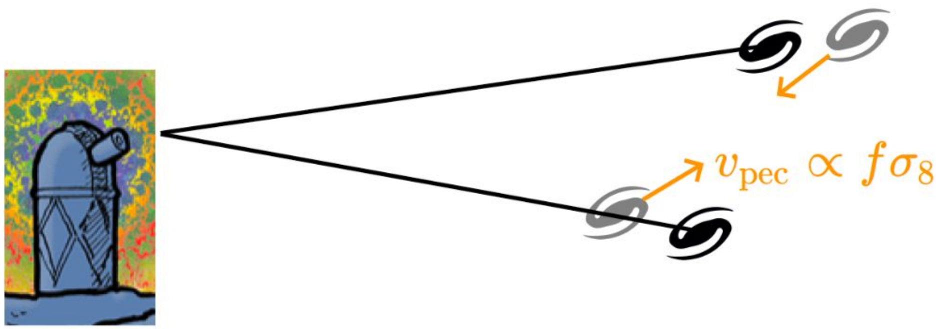
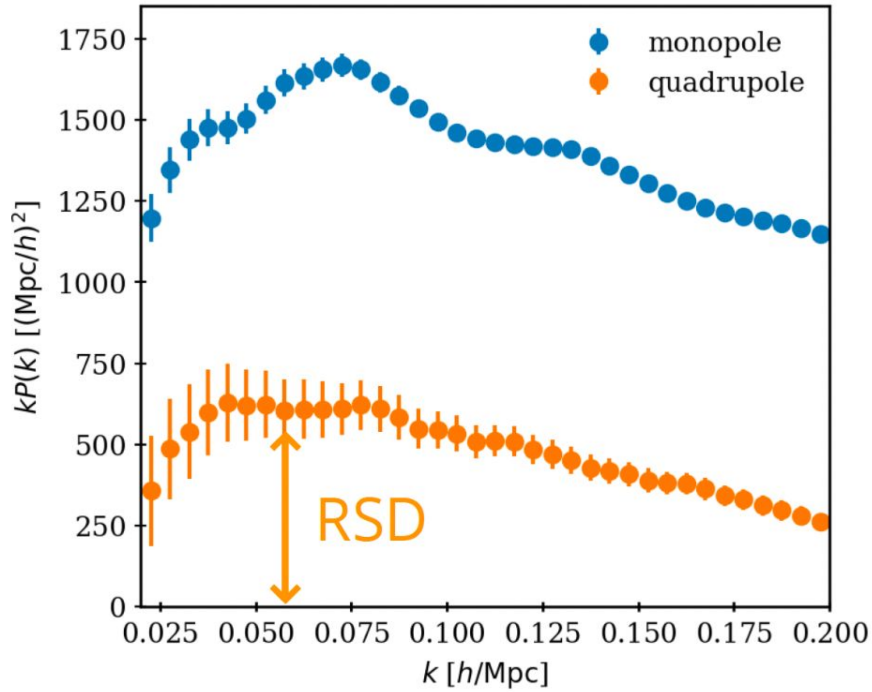


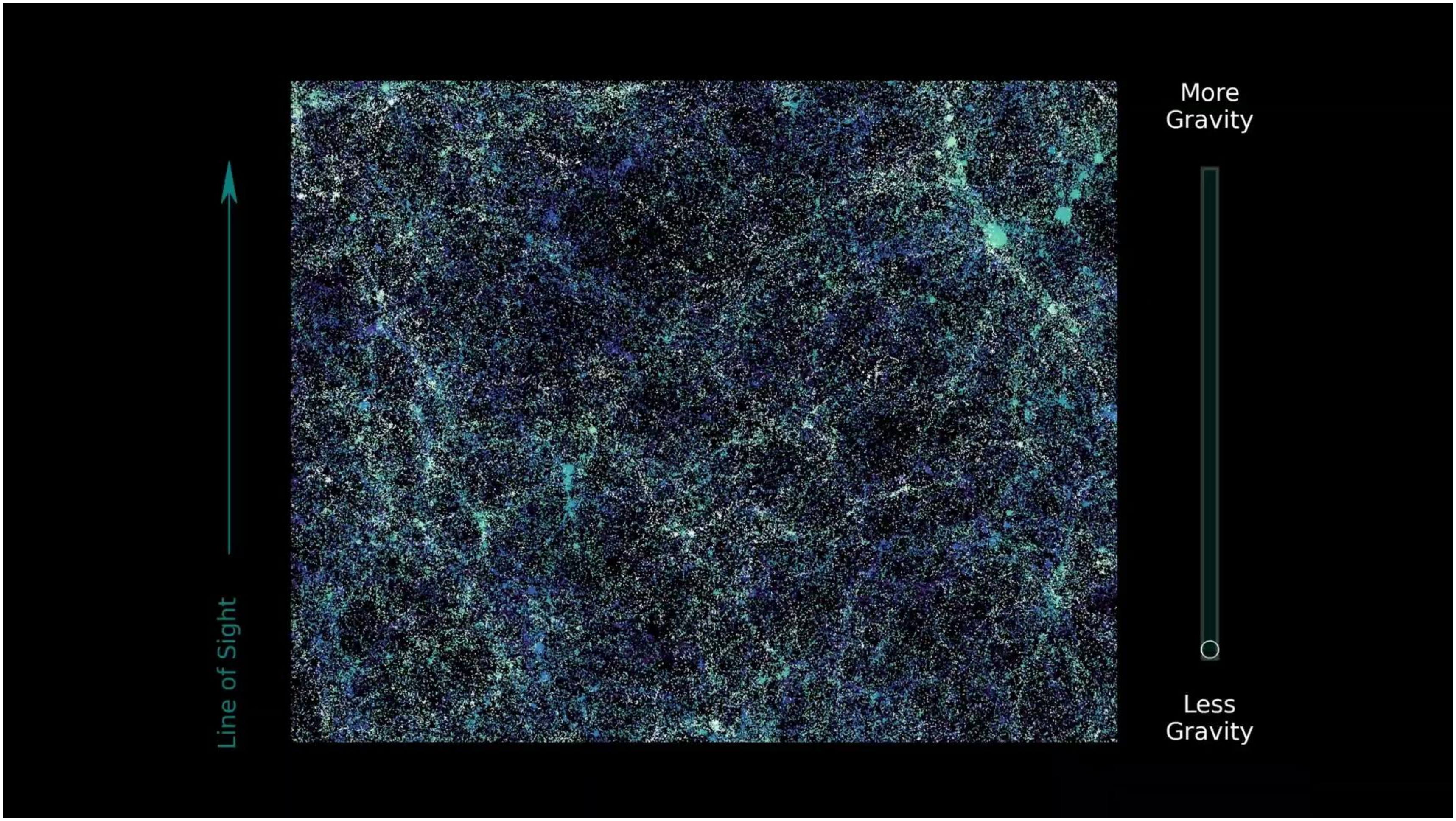


observed redshift = Hubble flow
and peculiar velocities (RSD = "redshift space distortions")

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**

Growth of cosmic structures through gravity



Credit: Claire Lamman and Michael Rashkovetskyi / DESI collaboration

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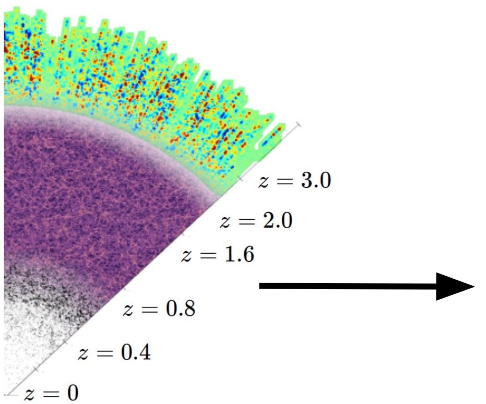
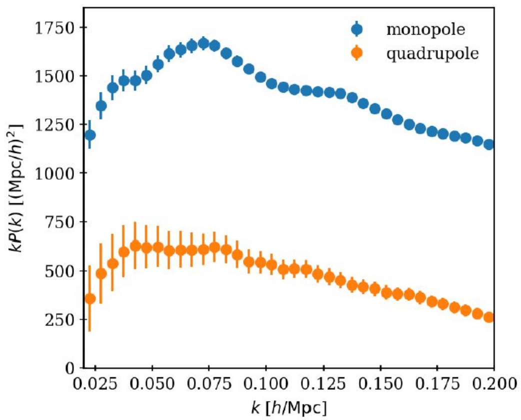
Extract cosmological constraints from the galaxy power spectrum





Galaxy 3D maps

Galaxy power spectrum

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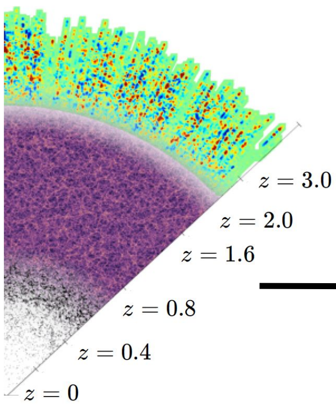
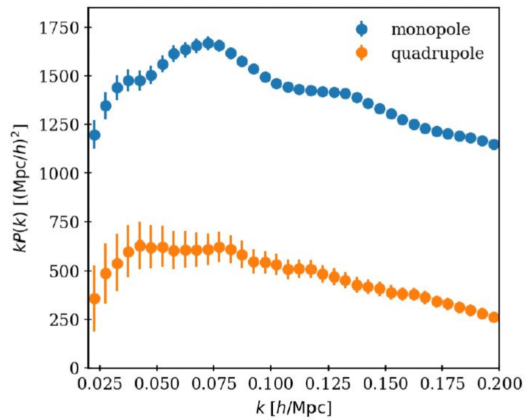
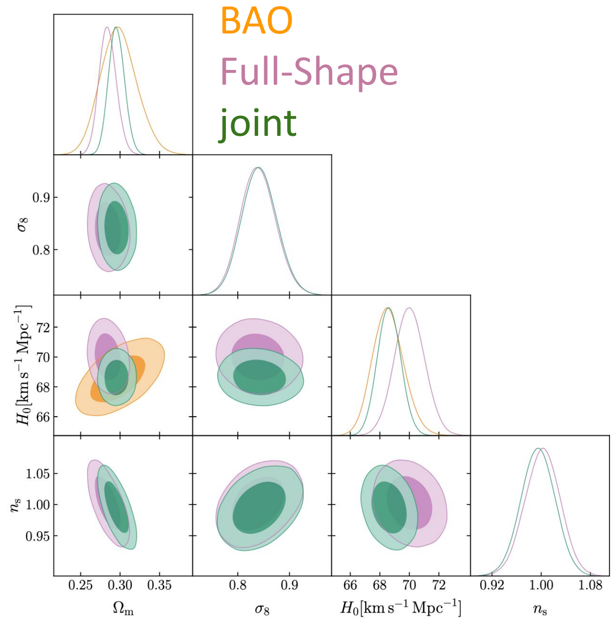


Galaxy 3D maps



Galaxy power spectrum



Cosmological model constraints (ΛCDM)

Extract cosmological constraints from the galaxy power spectrum

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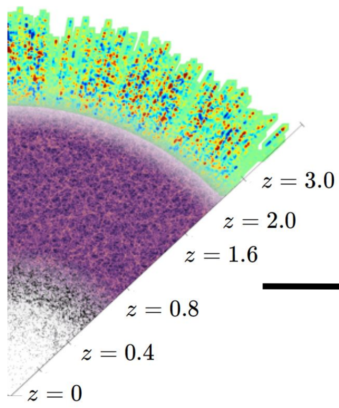

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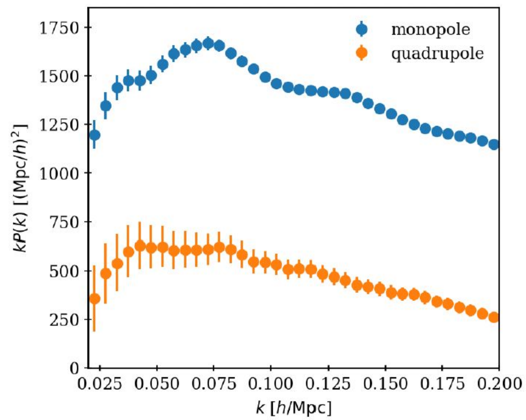
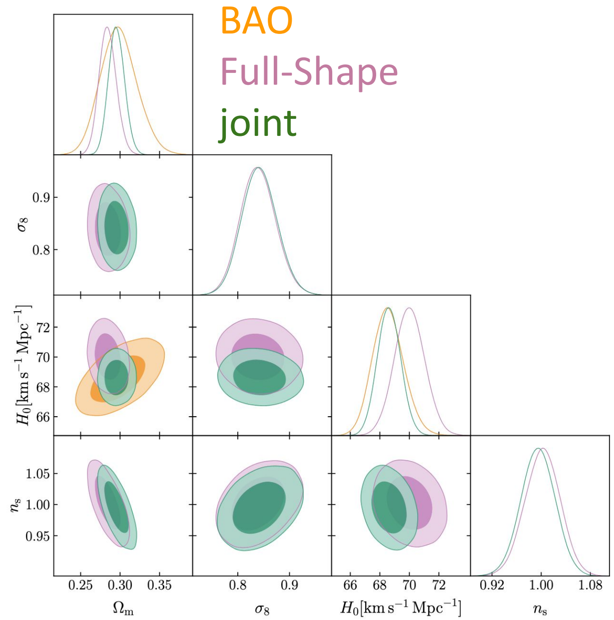


Galaxy power spectrum

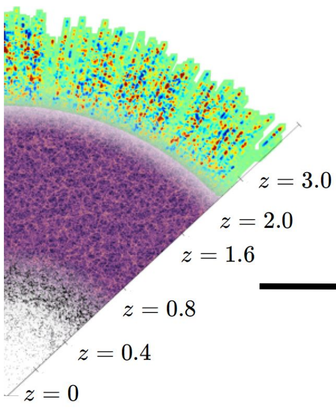
Full-Modelling

(direct fitting approach)

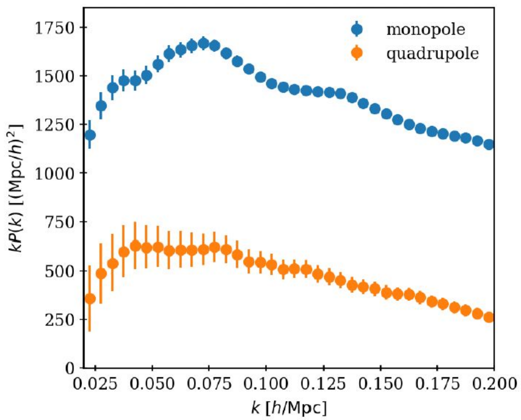


Cosmological model constraints (ΛCDM)

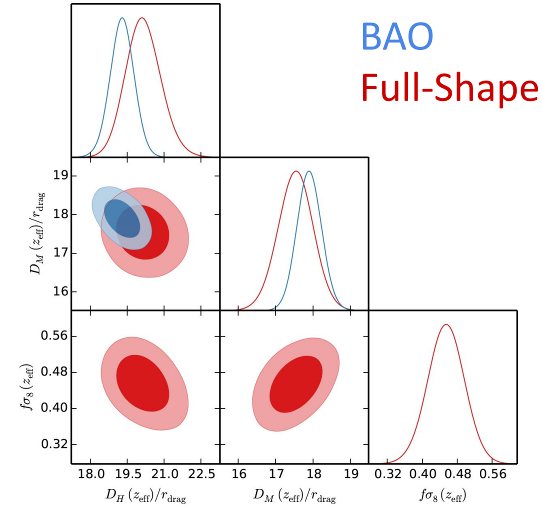
Extract cosmological constraints from the galaxy power spectrum



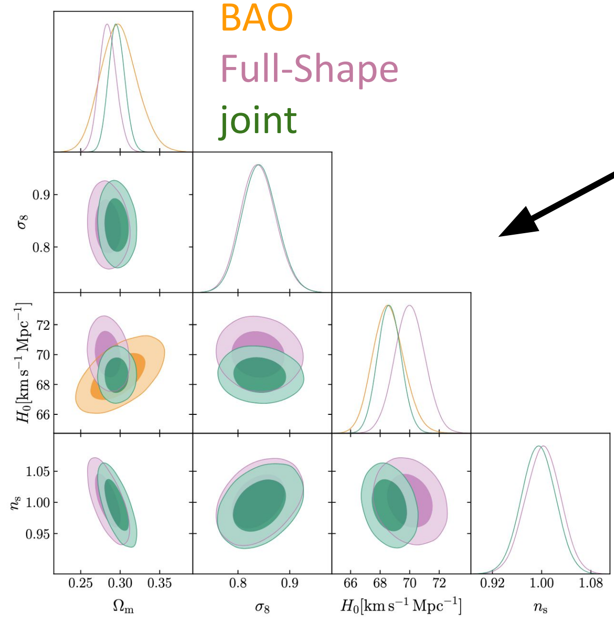
Galaxy 3D maps



Galaxy power spectrum



Compressed parameters



Cosmological model constraints (ΛCDM)

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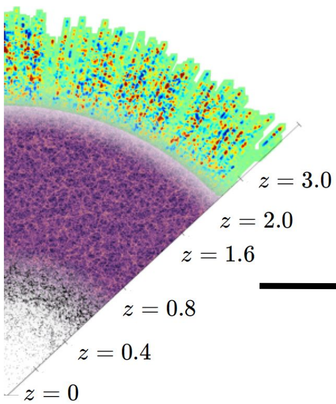
Extract cosmological constraints from the galaxy power spectrum



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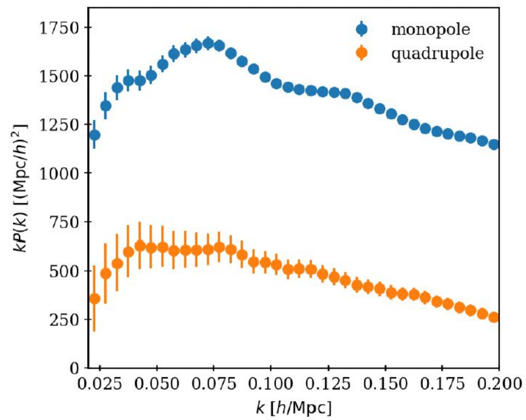
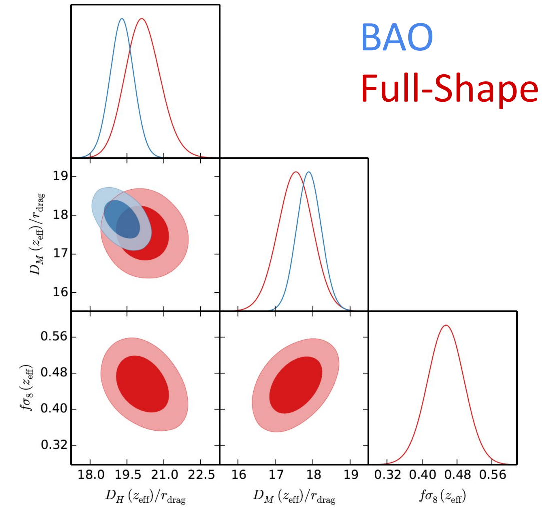
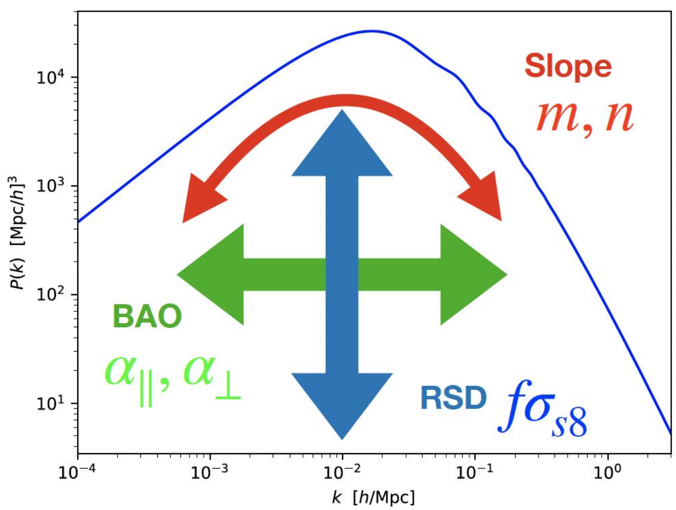


Galaxy power spectrum



Compressed parameters

ShapeFit
(compressed approach)



Comparison of both approaches

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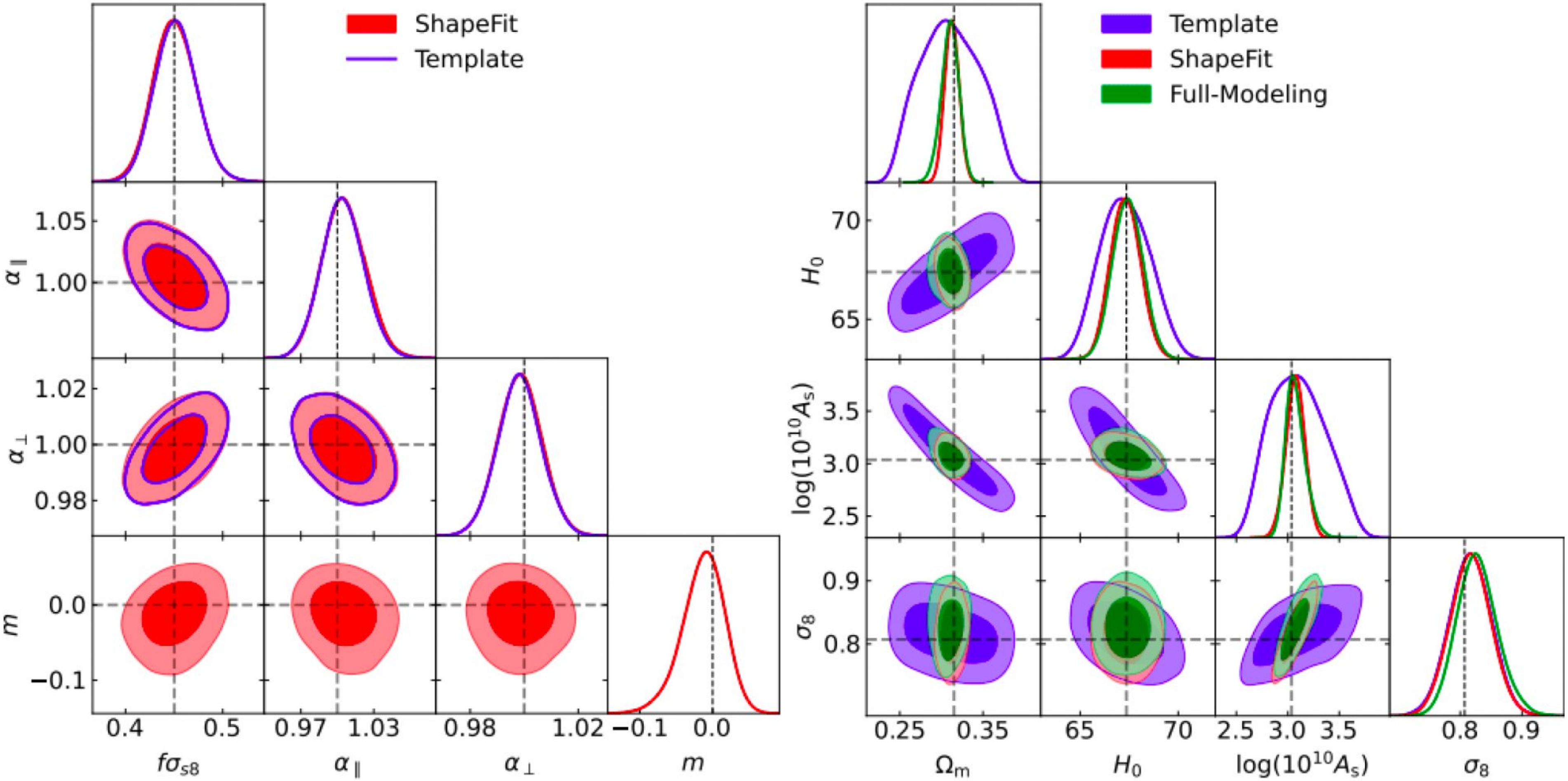

Maus et al. 2024a

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Modelling the galaxy power spectrum

Three power spectrum Effective Field Theory models considered:

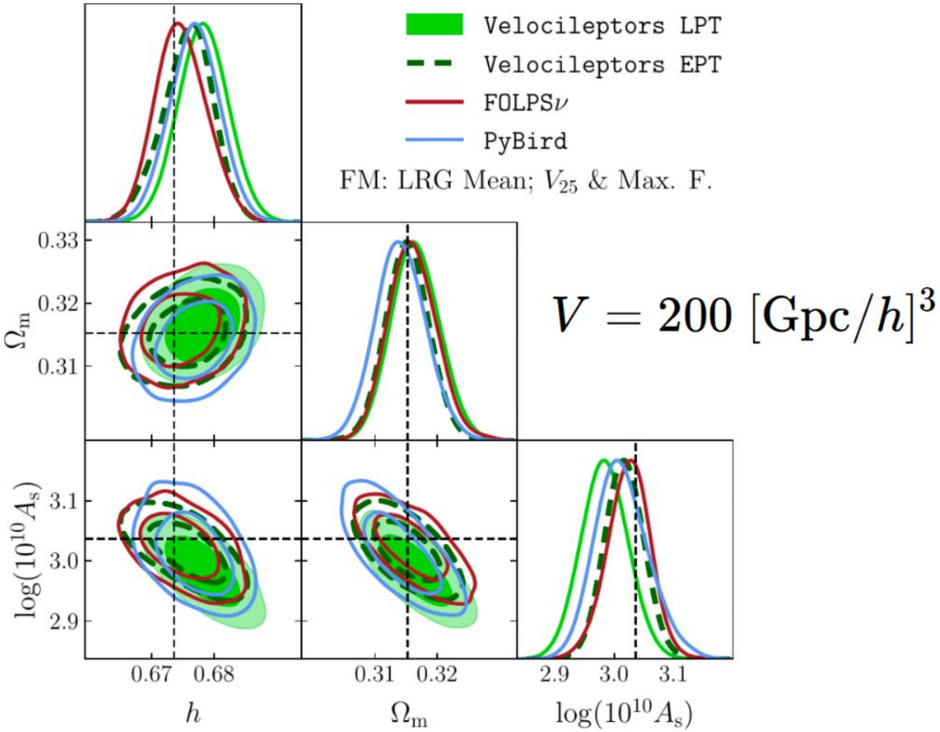
- velocileptors Maus et al. 2024
- folps Noriega et al. 2024
- pybird Lai et al. 2024

One comparison paper:

Maus et al. 2024

One configuration-space model:

- EFT-GSM Ramirez et al. 2024



credit: Mark Maus, Hernan Noriega, Yan Lai

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

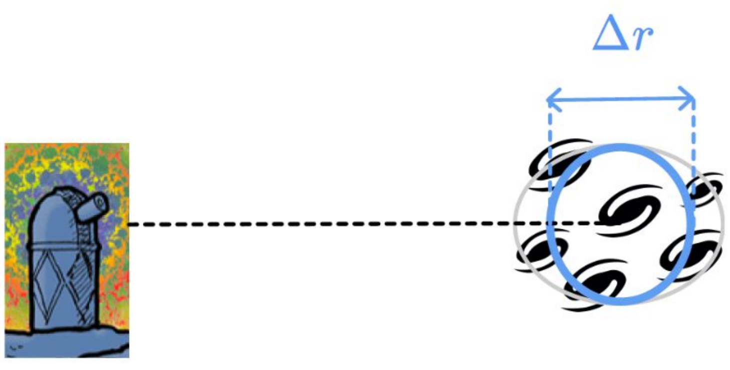
$$P_{s,g}(k,\mu) = P^{\rm PT}(k,\mu) + (b + f\mu^2)(b\alpha_0 + f\alpha_2\mu^2 + f\alpha_4\mu^4)k^2 P_{s,b_1^2}(k) + {\rm SN}_0 + {\rm SN}_2 k^2\mu^2 + {\rm SN}_4 k^4\mu^4$$

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

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

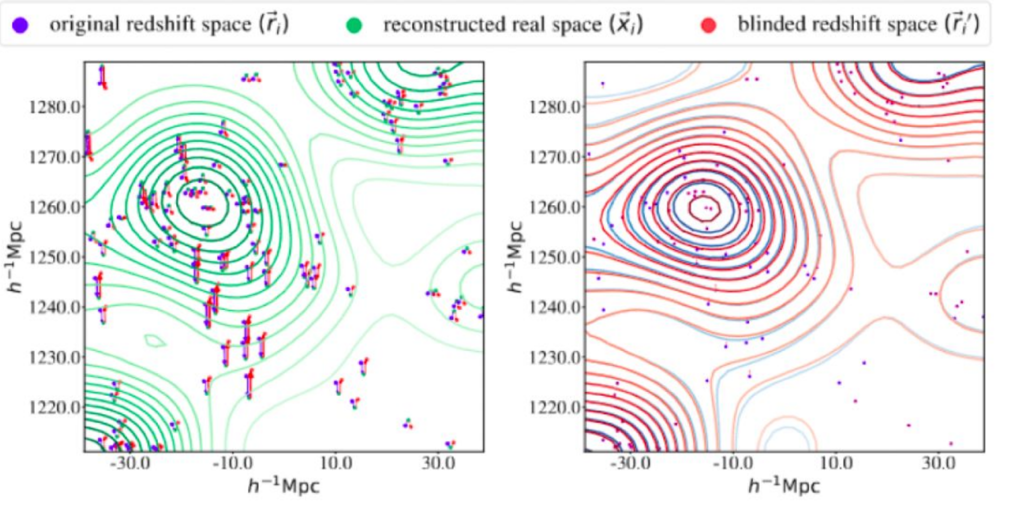
1. geometrical AP-like shift



Same as the BAO blinding

Changes the z-to-distance conversion

2. density-dependent RSD-like shift



Density-dependent shift

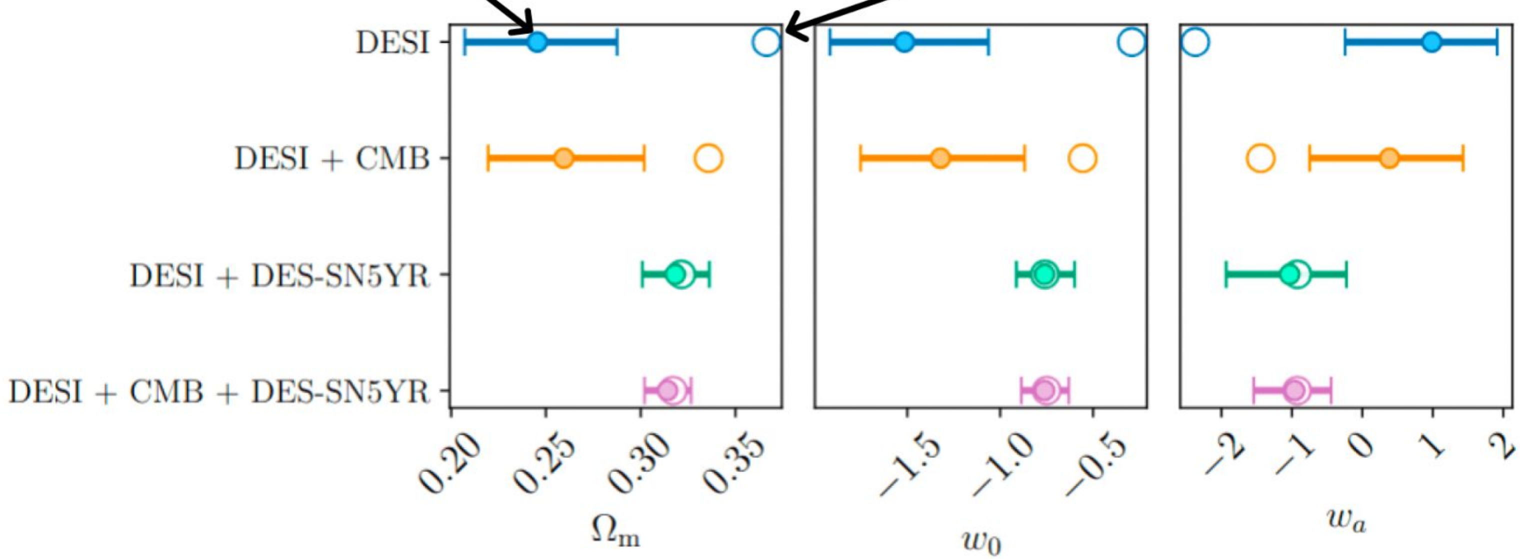
Imprints a new RSD shift

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)



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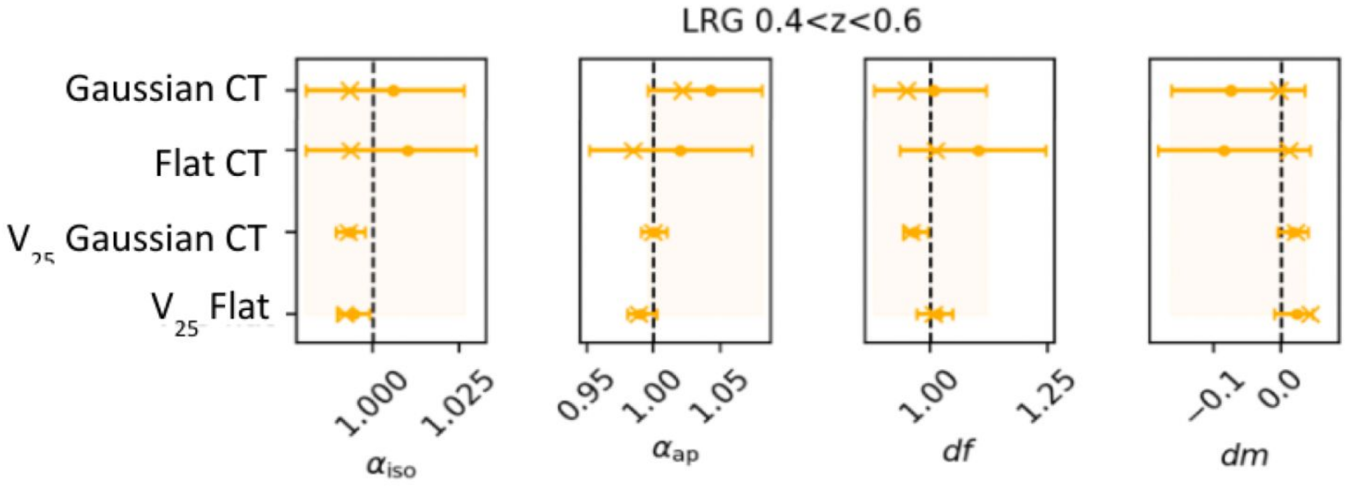
Projection effects

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

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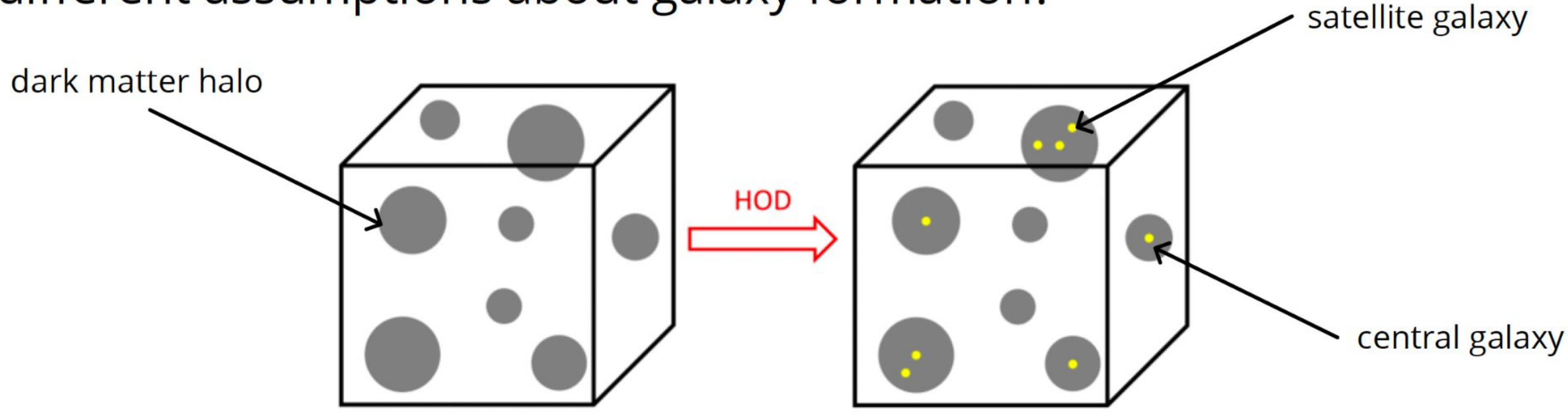
Systematic effects

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)

Galaxy-halo connection

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



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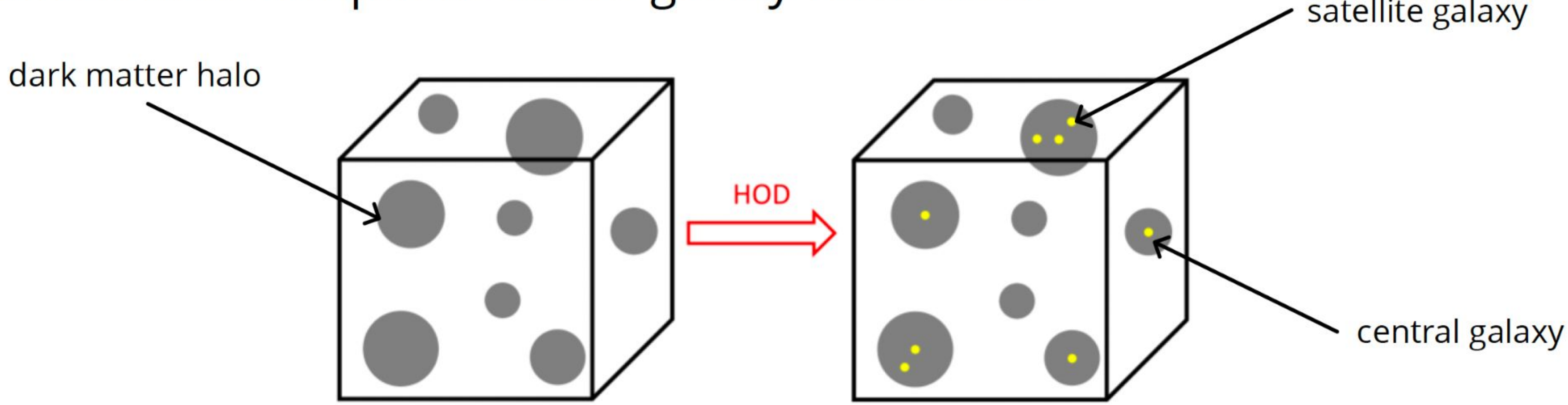
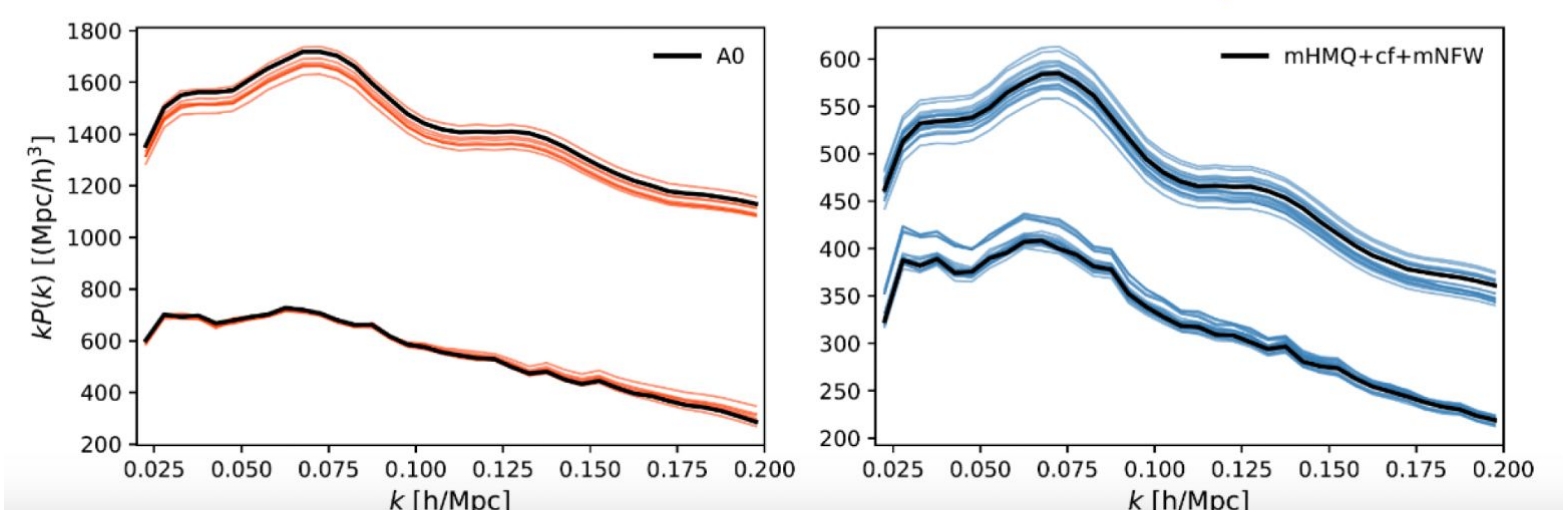


Findlay et al. 2024



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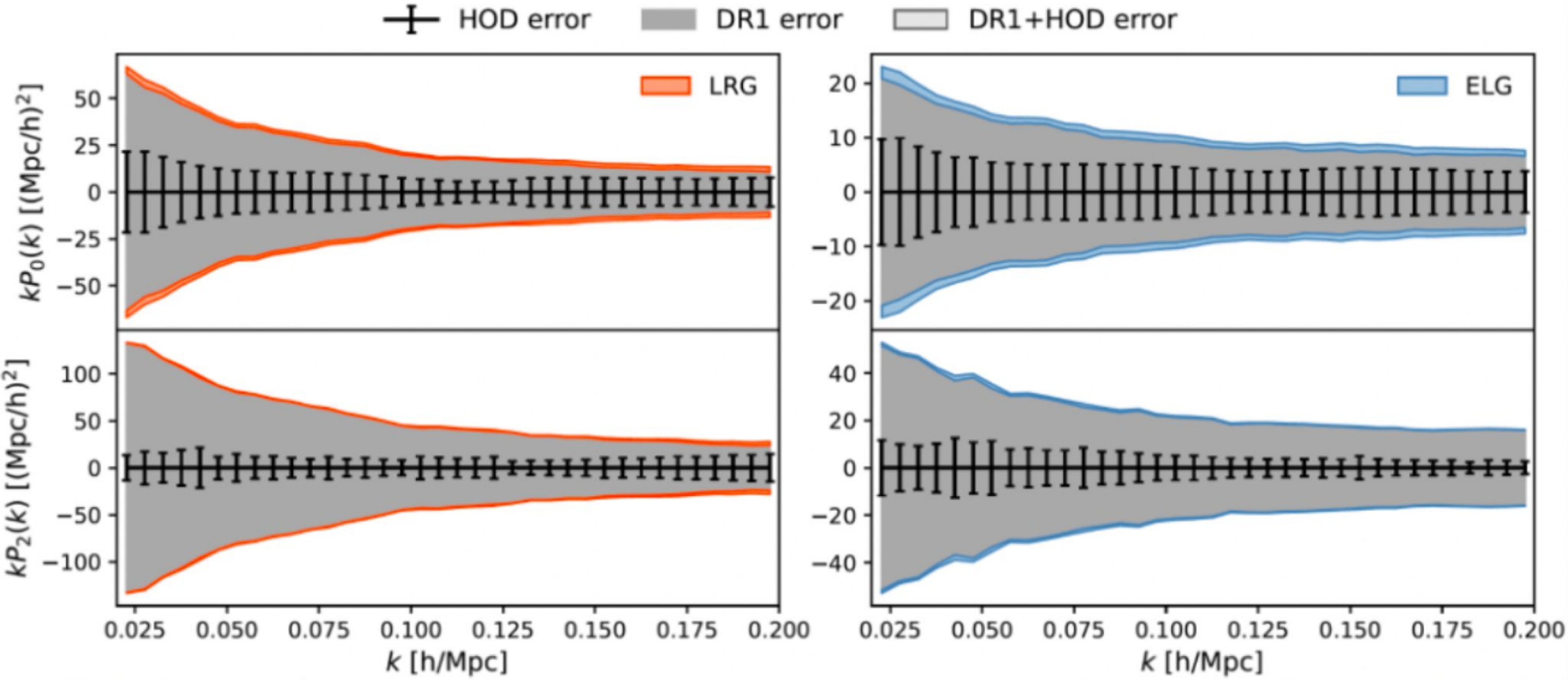

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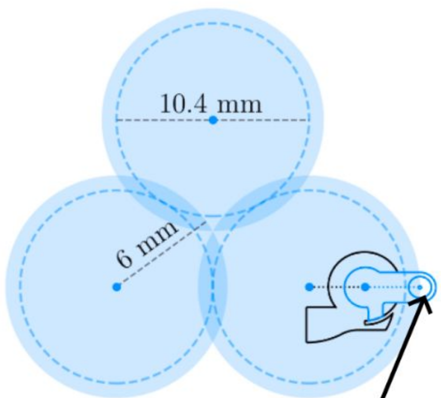
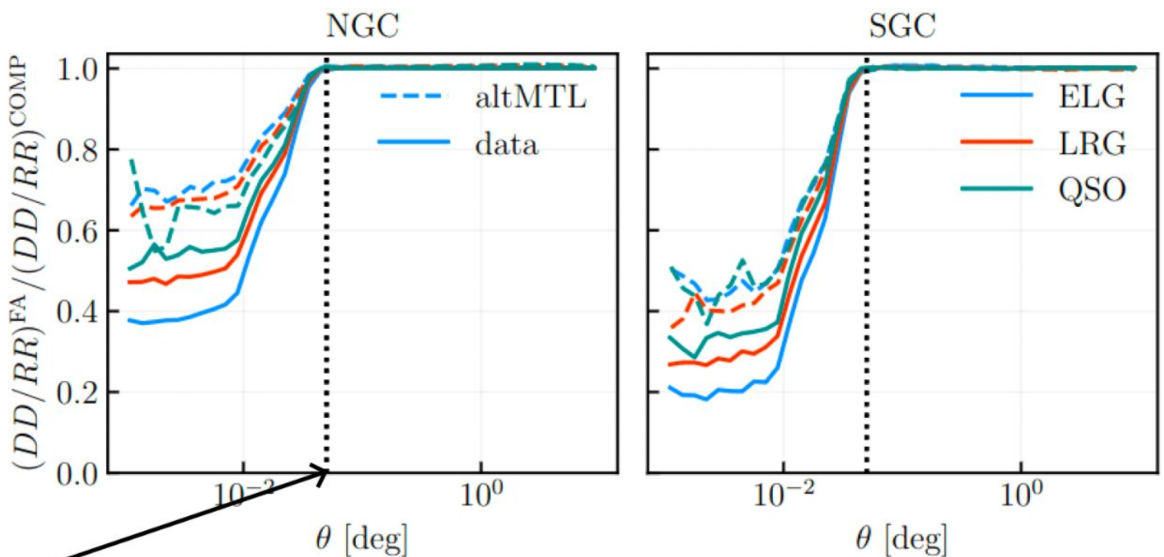
Fiber assignment

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





Pinon et al. 2024

$0.05^\circ \simeq$ positioner patrol diameter

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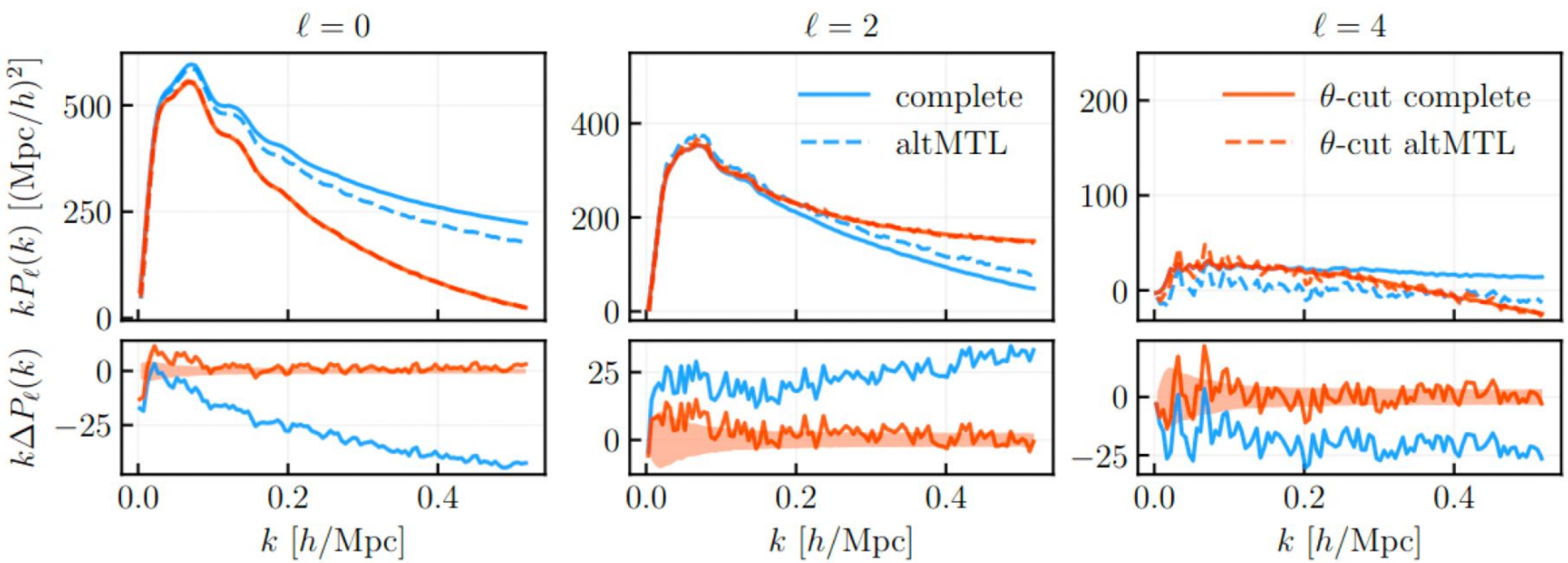
Fiber assignment

Impacts power spectrum measurements (altMTL vs complete)

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



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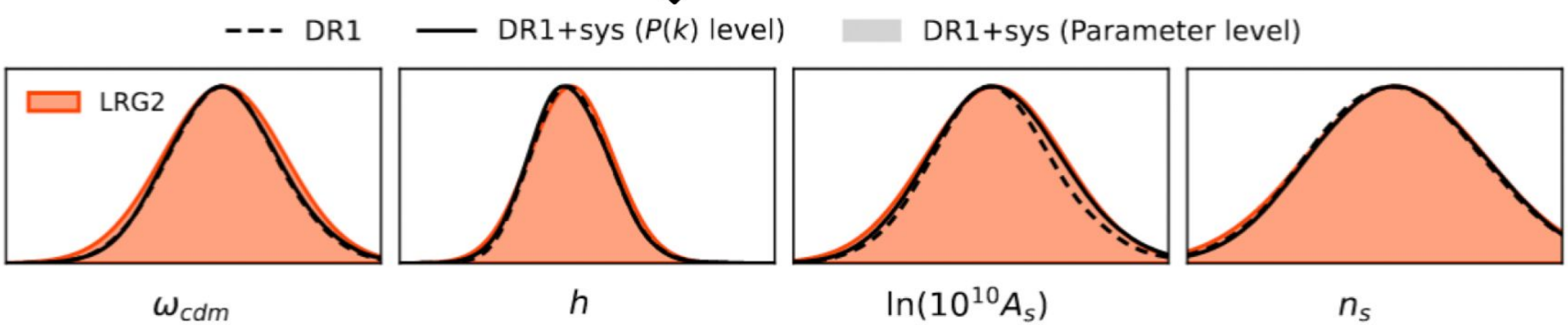
Total systematic error = ⅖ of DR1 statistical error

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	$\mathcal{N}[0, 5^2] \times f_{\rm sat}\sigma_{1\,\rm eff}^2/\bar{n}_g$

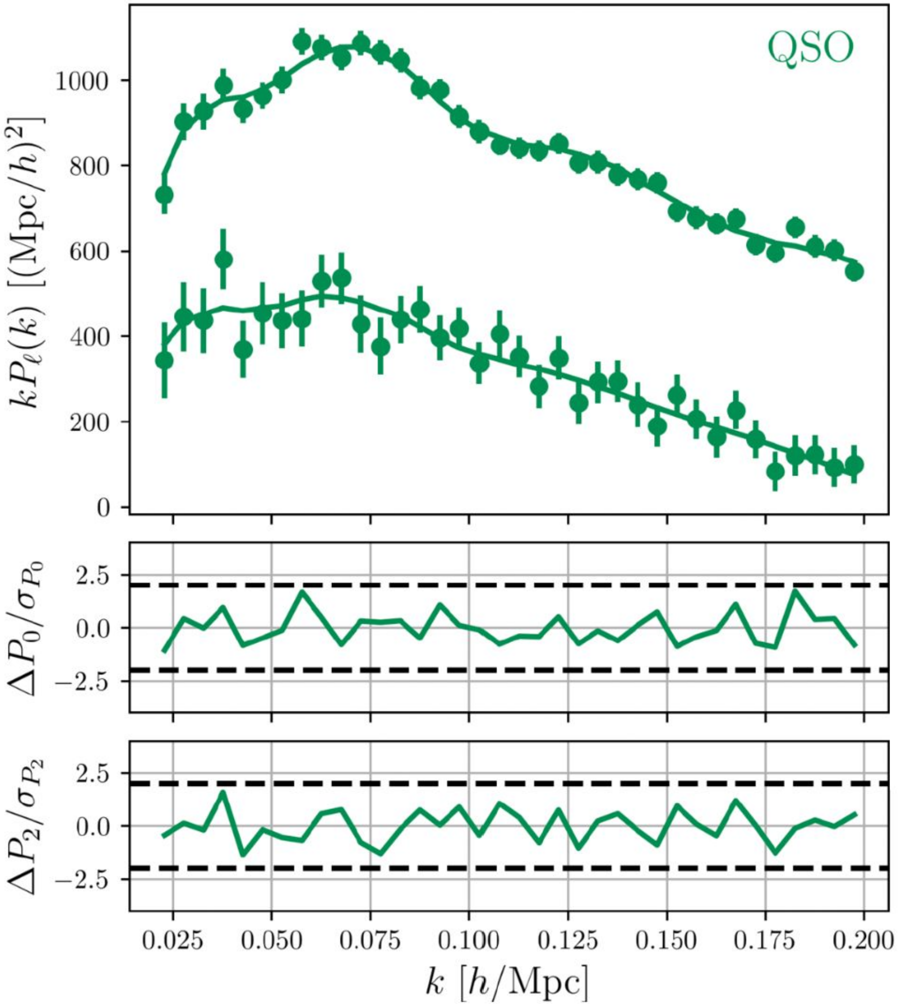
- **Observable:** power spectrum monopole and quadrupole
- **Model:** Effective Field Theory
- **Covariance:** mock-based
- **Fitting range:** $0.02 < k\,[h/\mathrm{Mpc}] < 0.2$
- **Fitting parameters:**
  - 5 ΛCDM parameters (FM)
  - 4 compressed parameters (SF)
  - 7 non-cosmological parameters
- **Systematic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

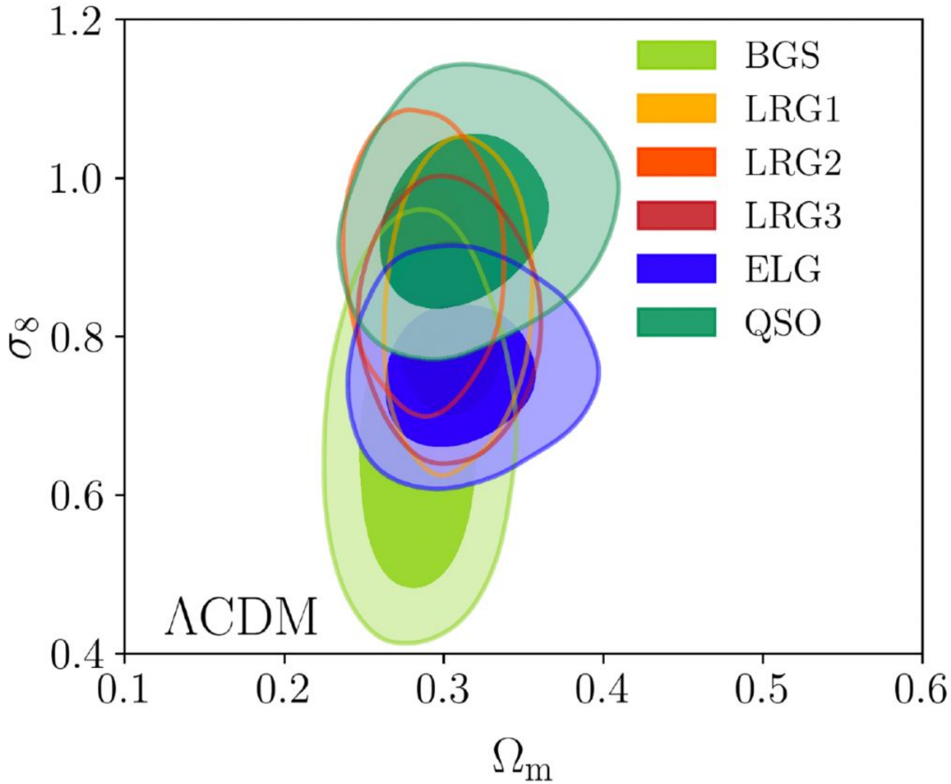


Full Shape pipeline: what's new!
(compared to SDSS)

- **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

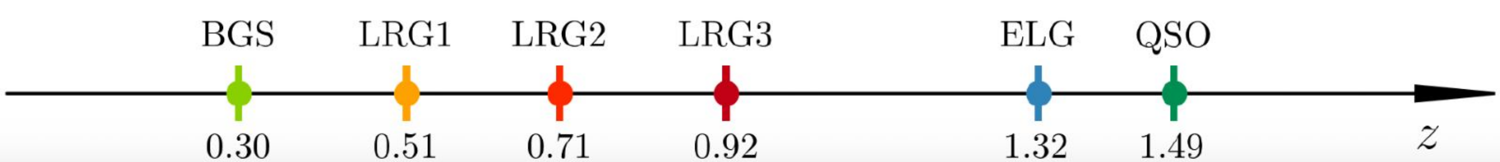
Full Shape + BAO measurements





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

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



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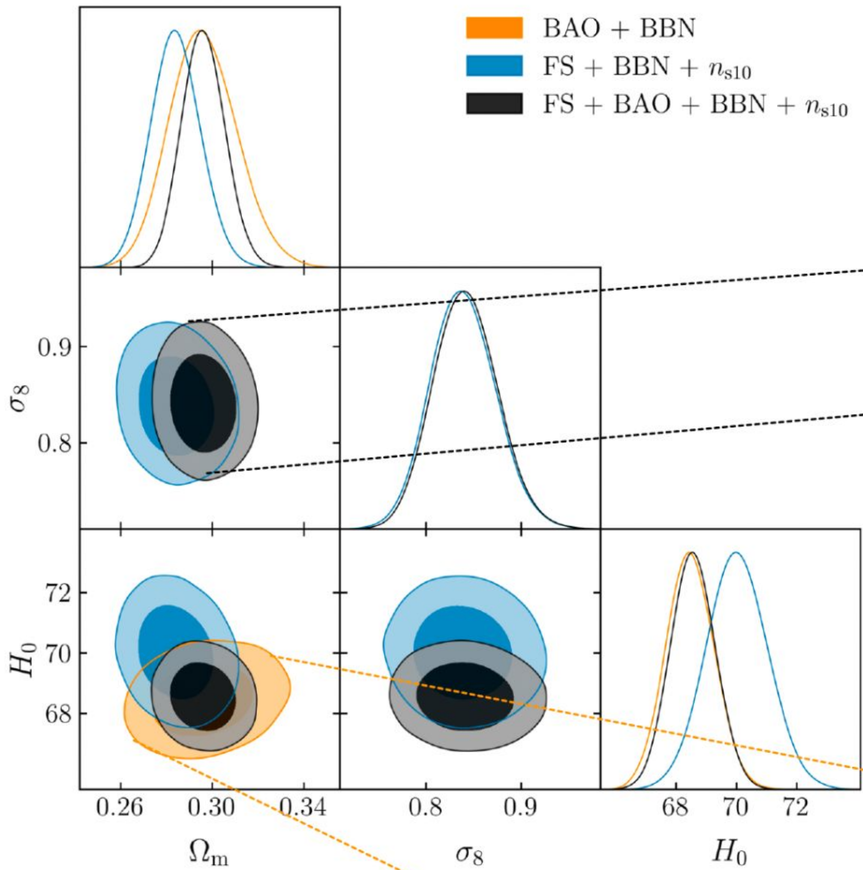
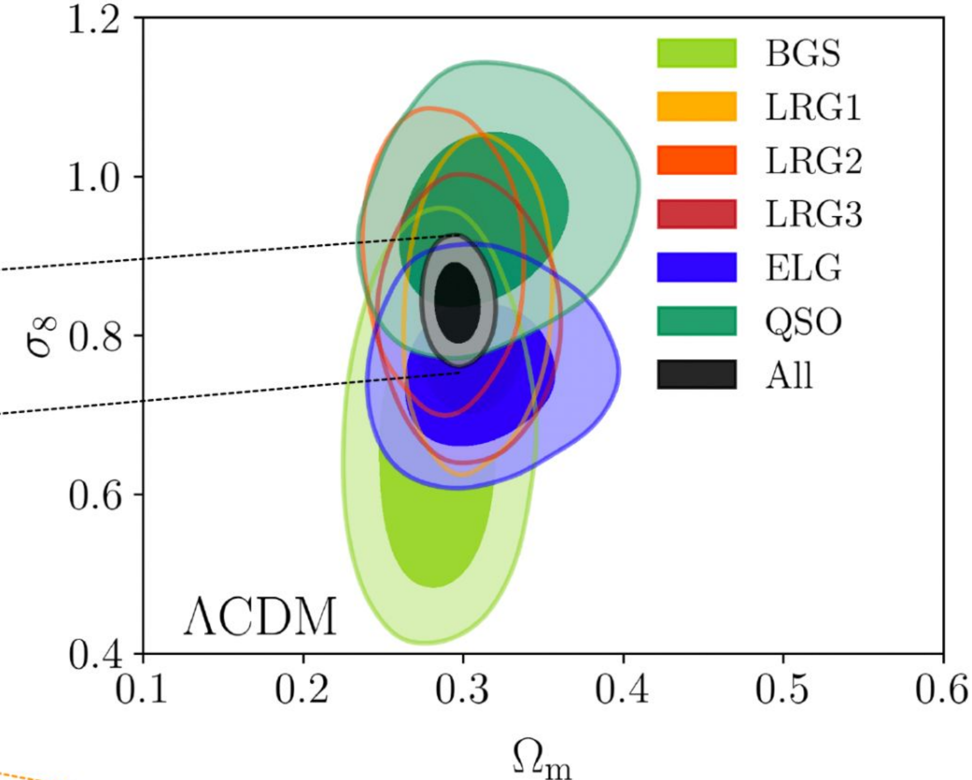
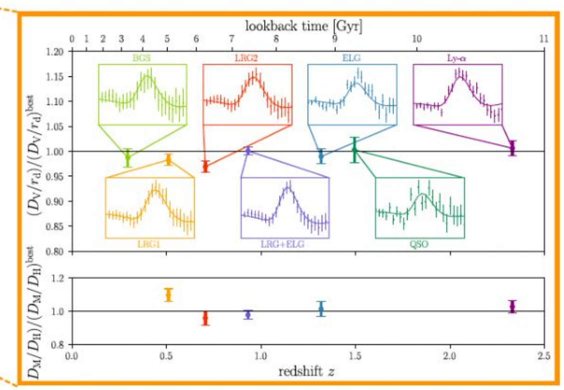
Full Shape + BAO measurements







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

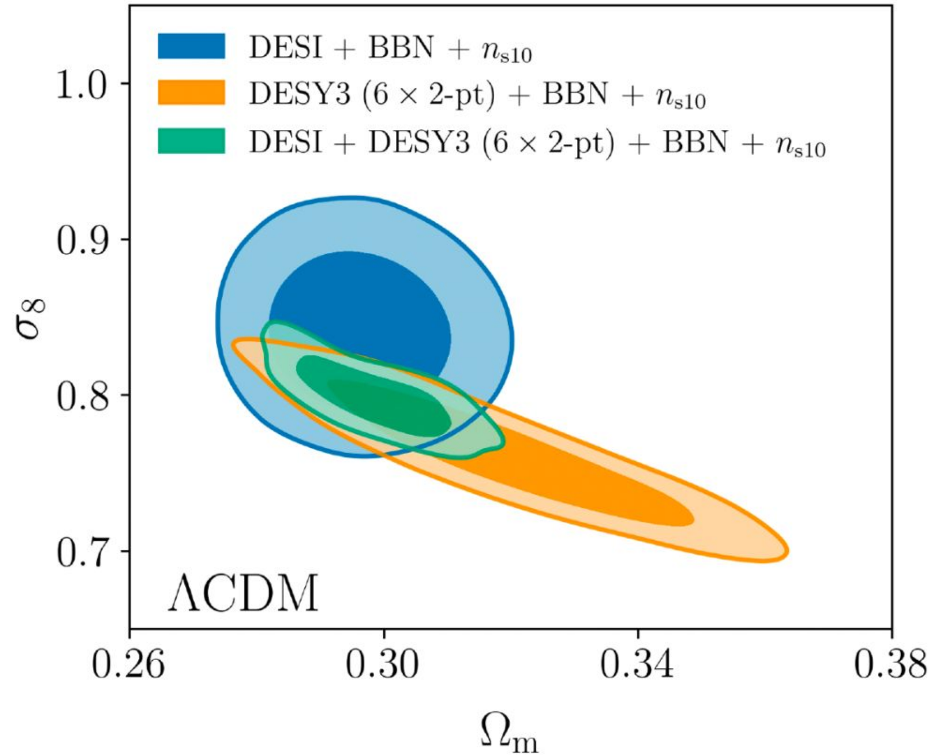
$$\sigma_8 = 0.842 \pm 0.034 \qquad \mathbf{(4.0\%)}$$

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

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

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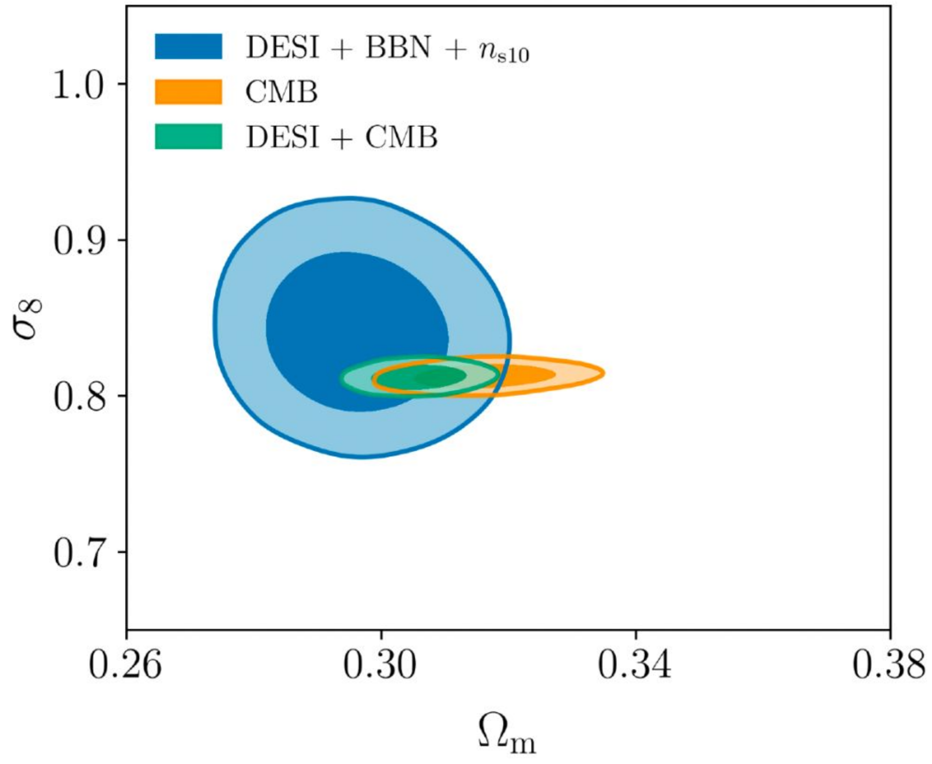
Combined constraints

- 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%



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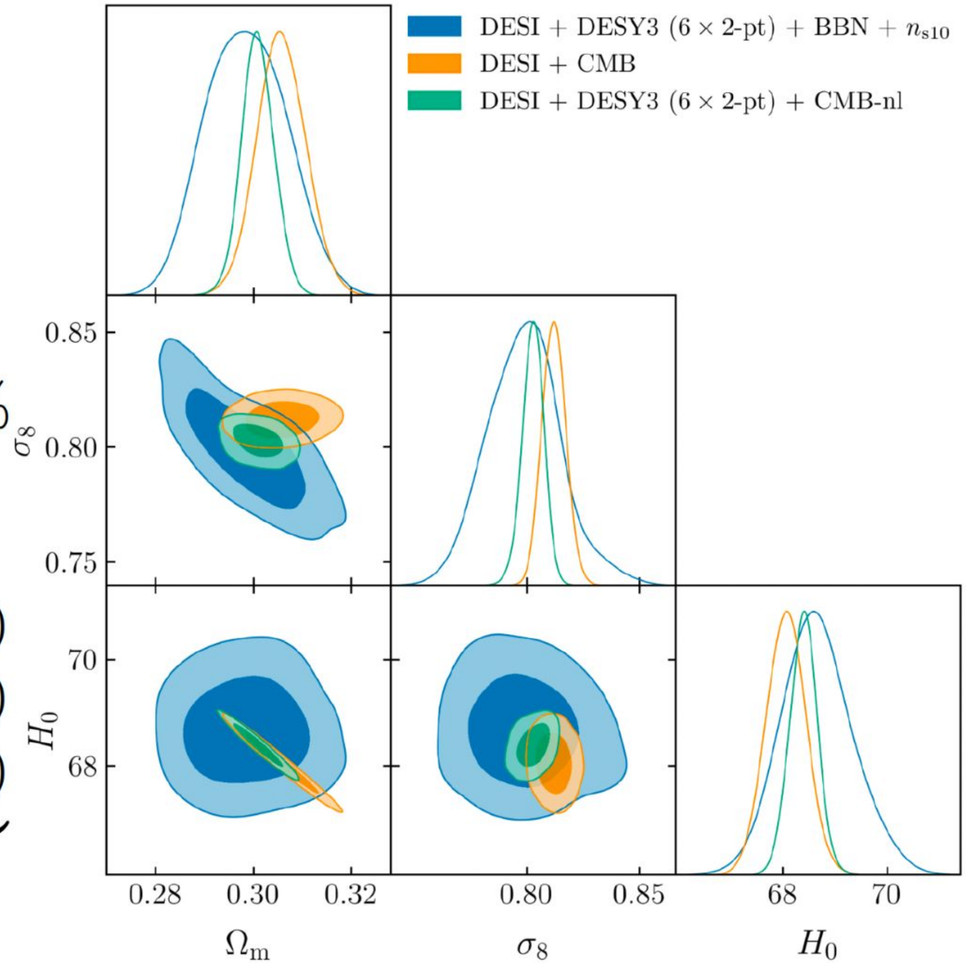
$$\Omega_\mathrm{m} = 0.3009 \pm 0.0034 \quad (\mathbf{1\%})$$

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

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

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 $w(z) = -1 + \frac{1}{3}\frac{d\ln f_{\rm DE}(z)}{d\ln(1+z)}$

Let's assume the CPL parameterization

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

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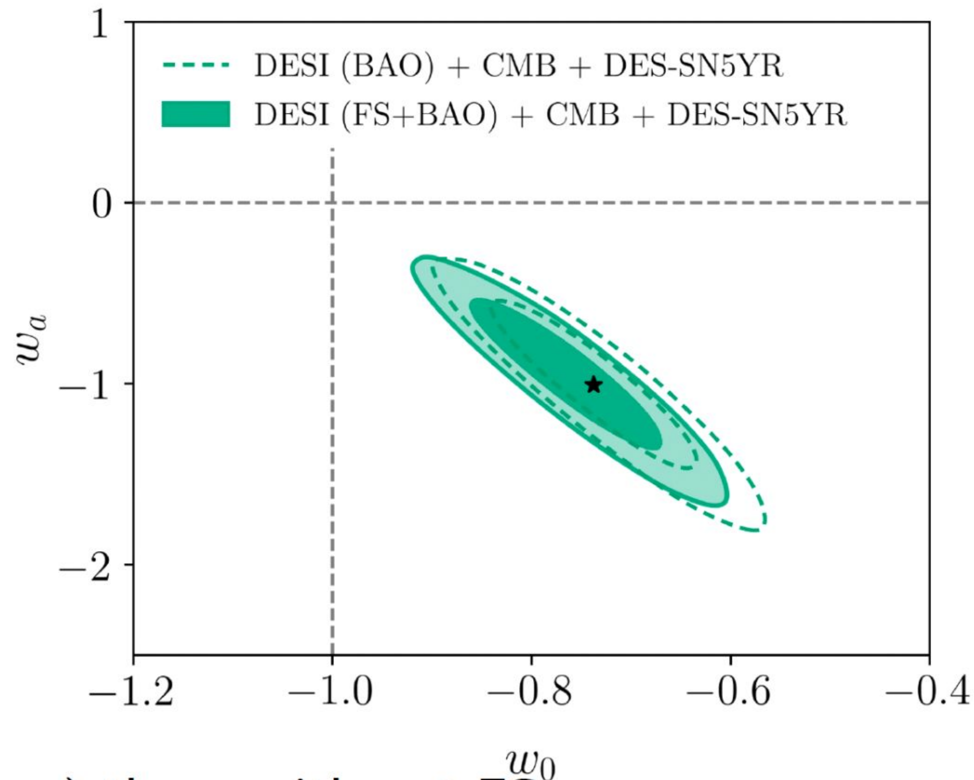
Dynamical Dark Energy - (w_0, w_a)

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

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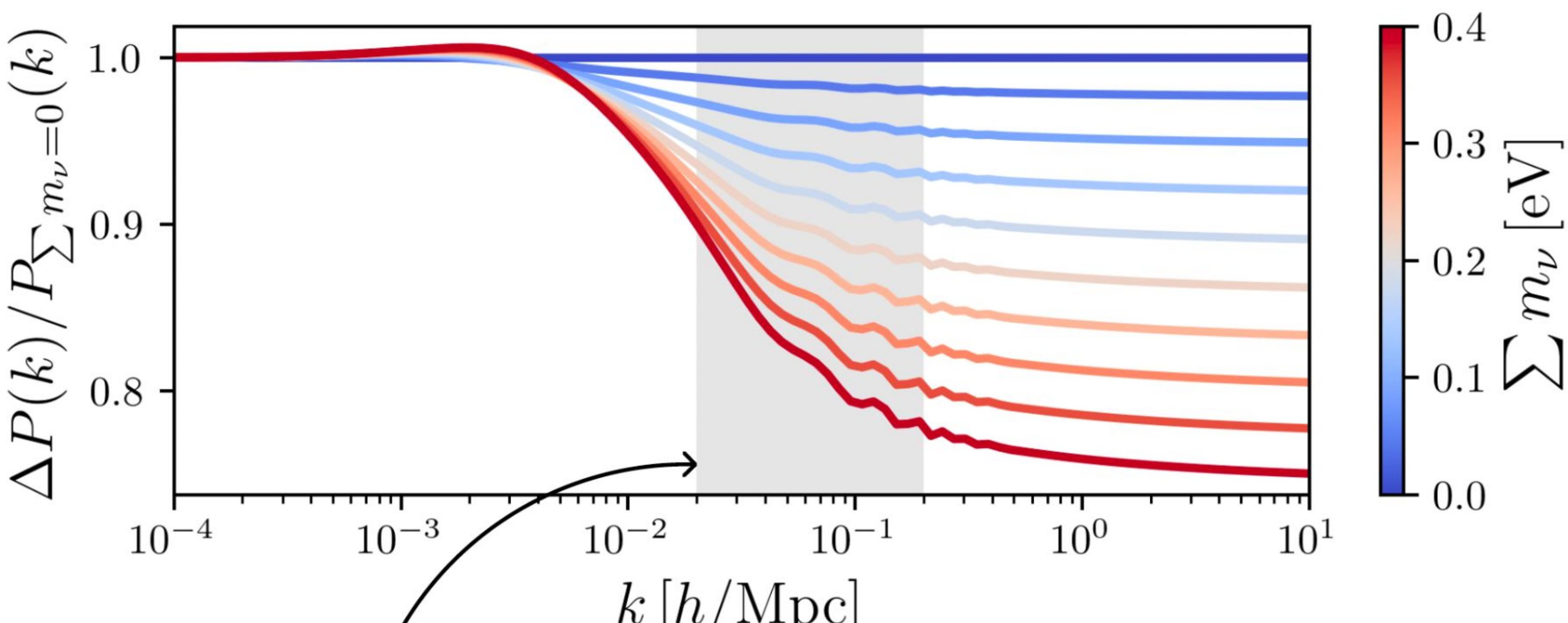
Sum of neutrino masses

Massive neutrinos impact:

i) the expansion history

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



the k-fitting range

Sum of neutrino masses

Massive neutrinos impact:

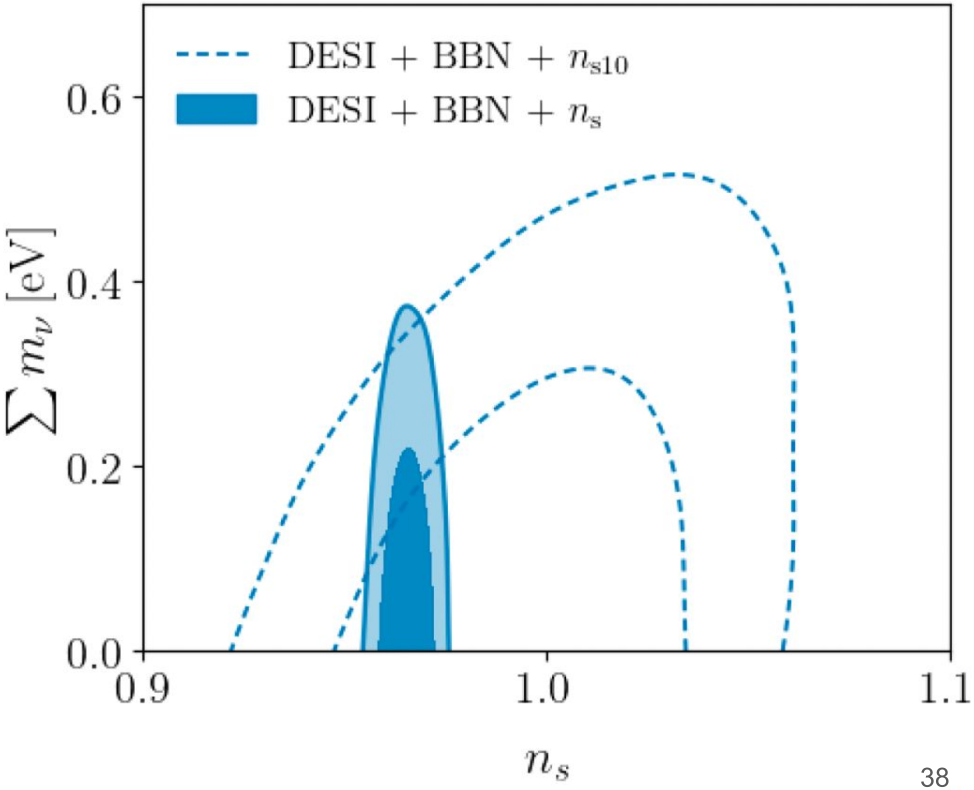
i) the expansion history

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

$$\underbrace{\sum m_\nu < 0.409\,\mathrm{eV}\ (95\%)}_{\mathrm{DESI} + \mathrm{BBN} + n_{\mathrm{s}10}}$$

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

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



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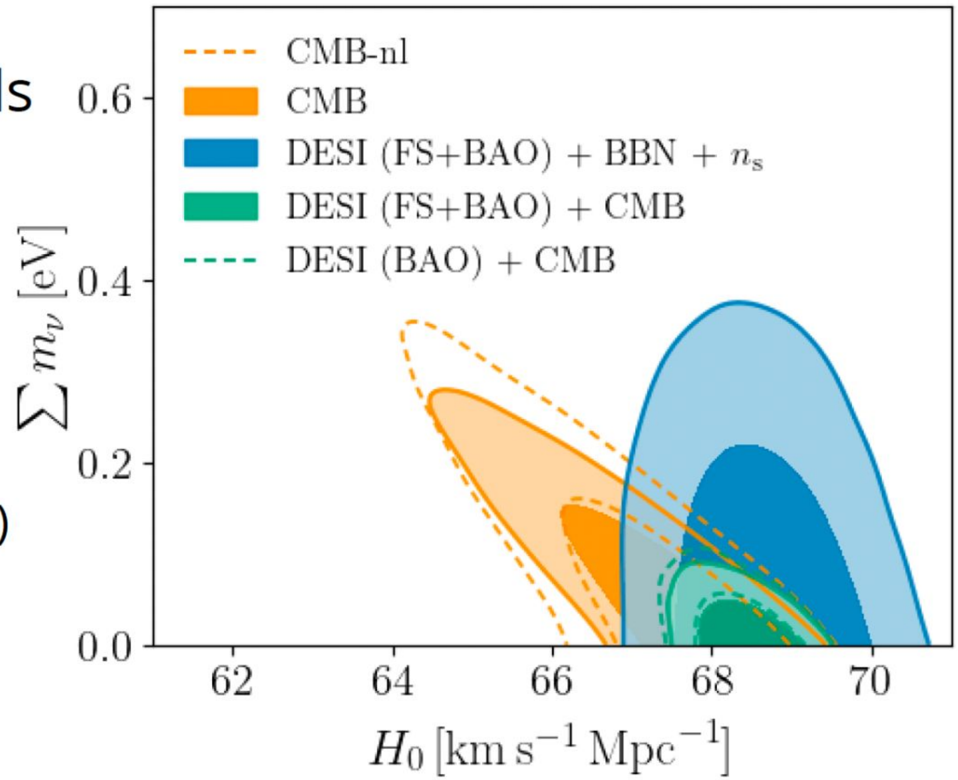
Sum of neutrino masses

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

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Sum of neutrino masses

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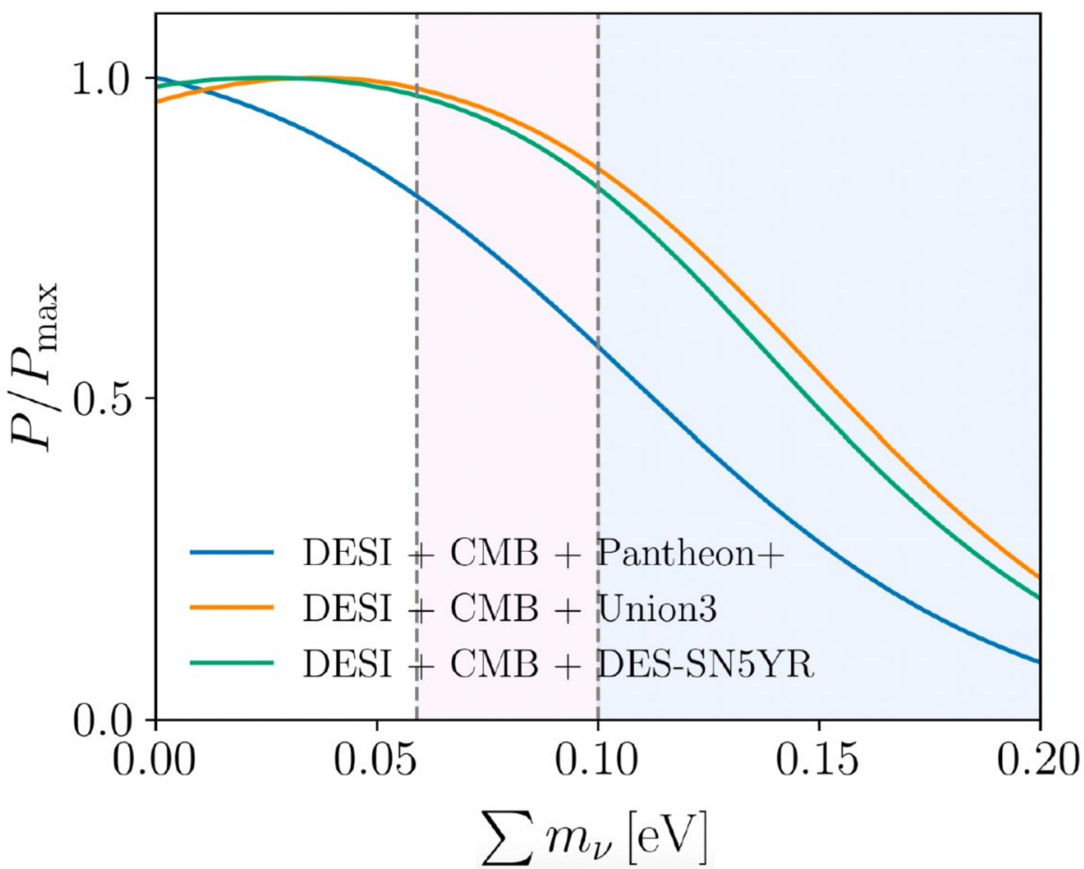

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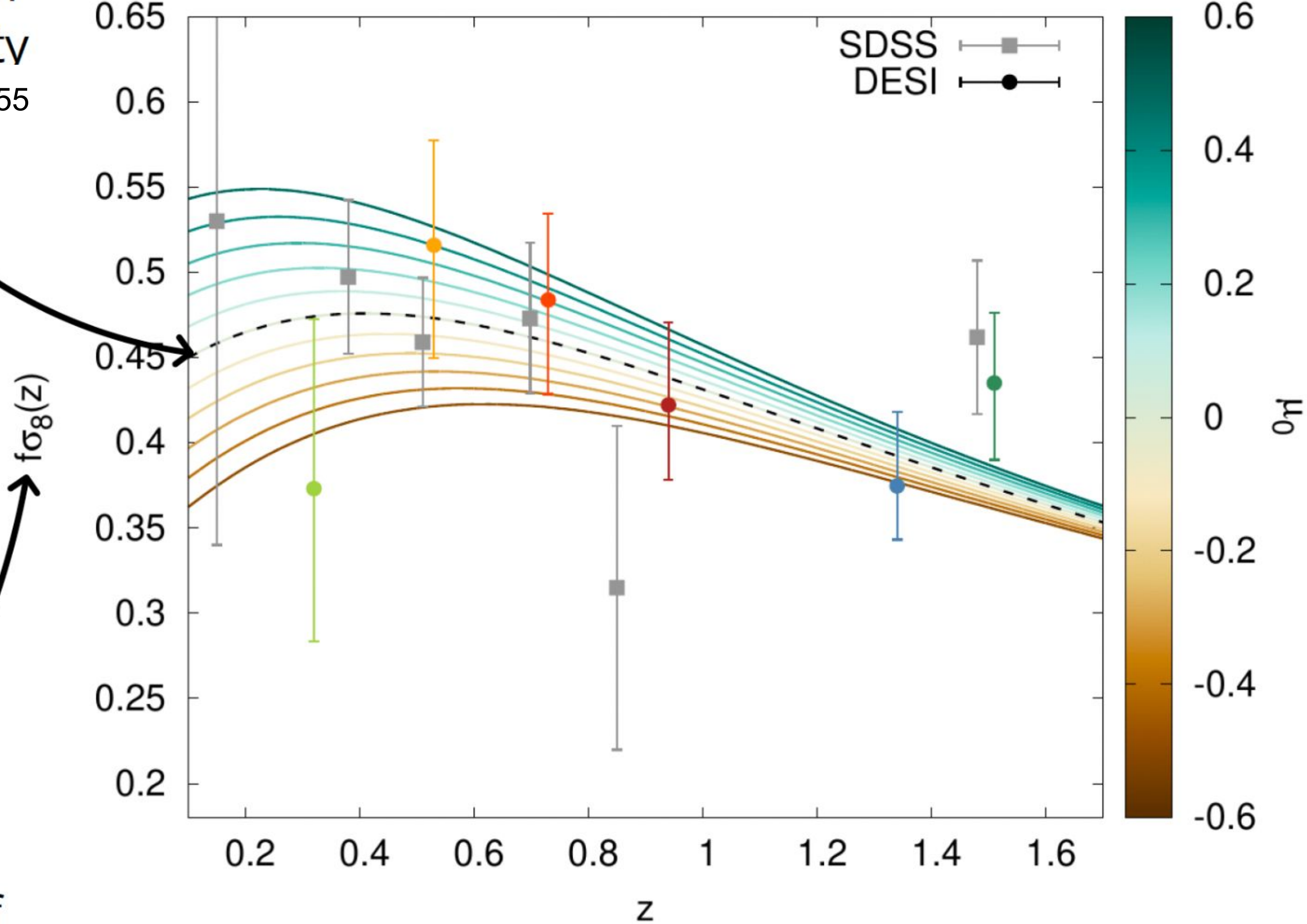
DESI constraints on gravity

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

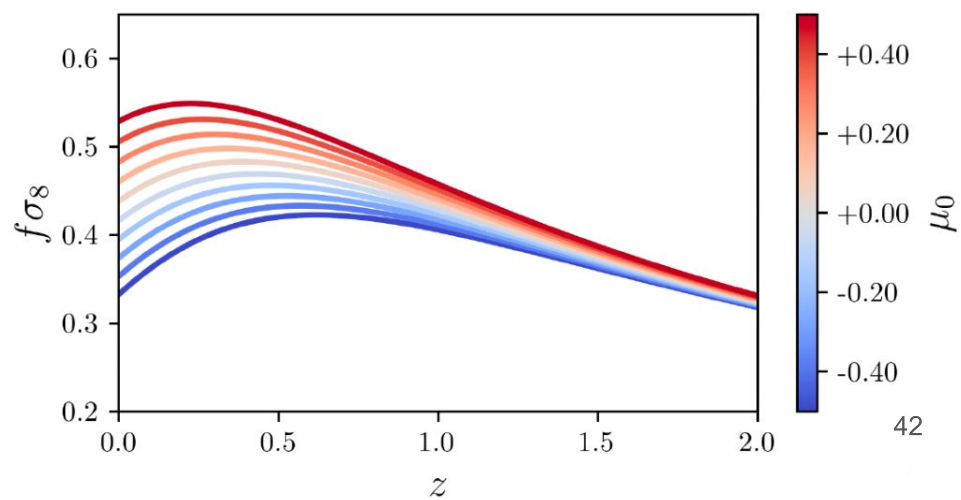
(light) $k^2(\Phi + \Psi) = -8\pi G a^2 \Sigma(a,k) \sum_i \rho_i \Delta_i$

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

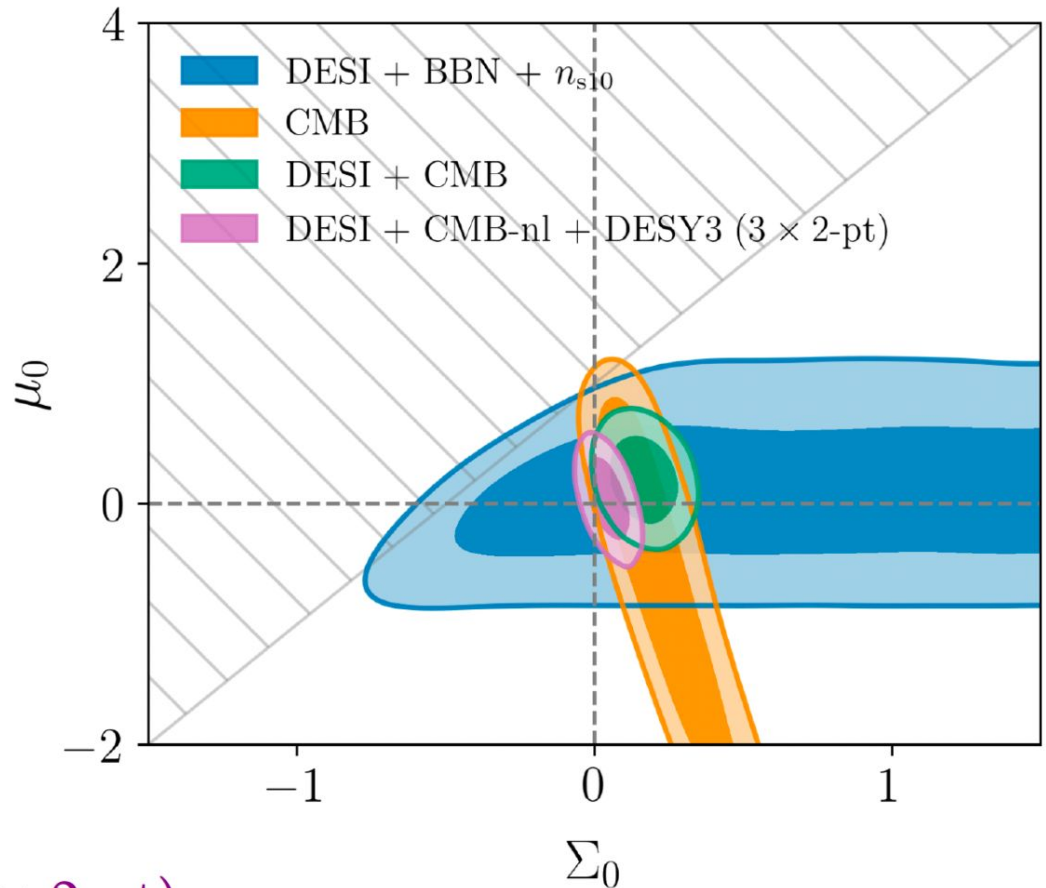
DESI constrains

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

Σ_0 constrained by

- CMB (ISW and lensing)
- galaxy lensing

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



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

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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%

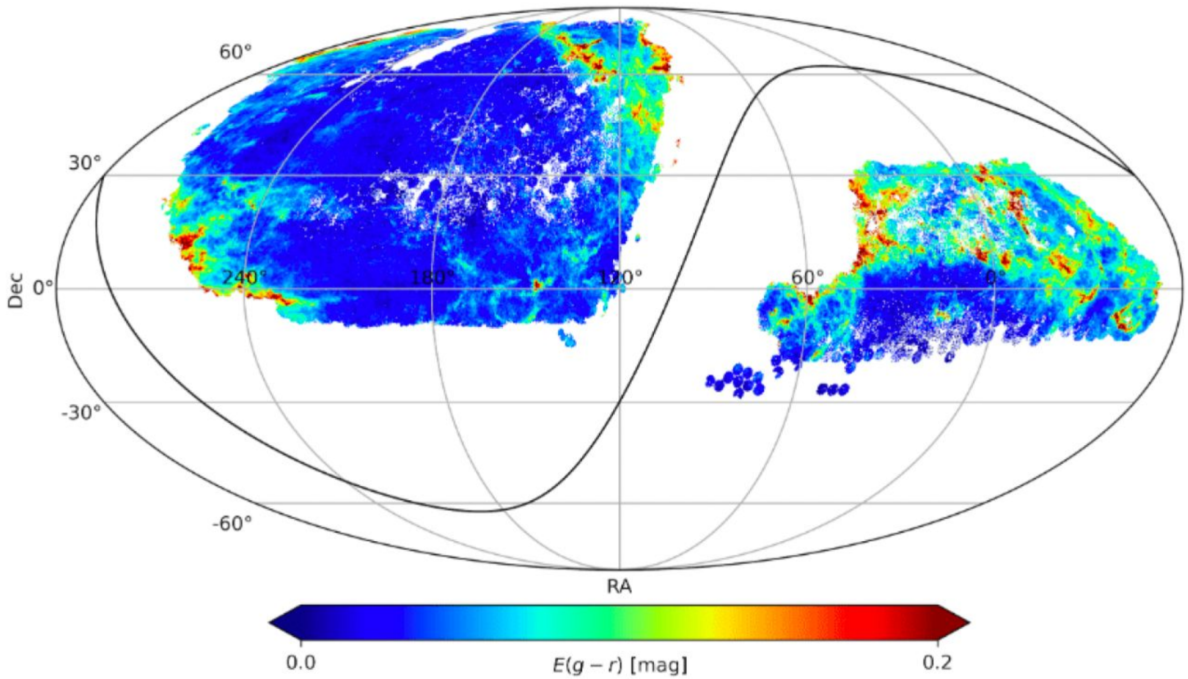
Modified gravity μ_0 parameter to be consistent with the zero GR value

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/

Back up

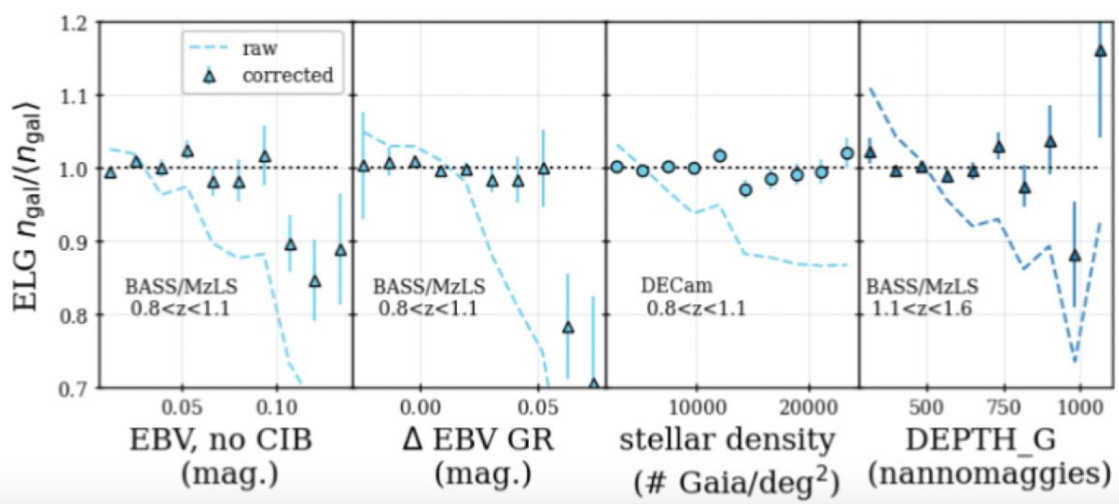
Imaging systematics



stellar redening map from DESI data

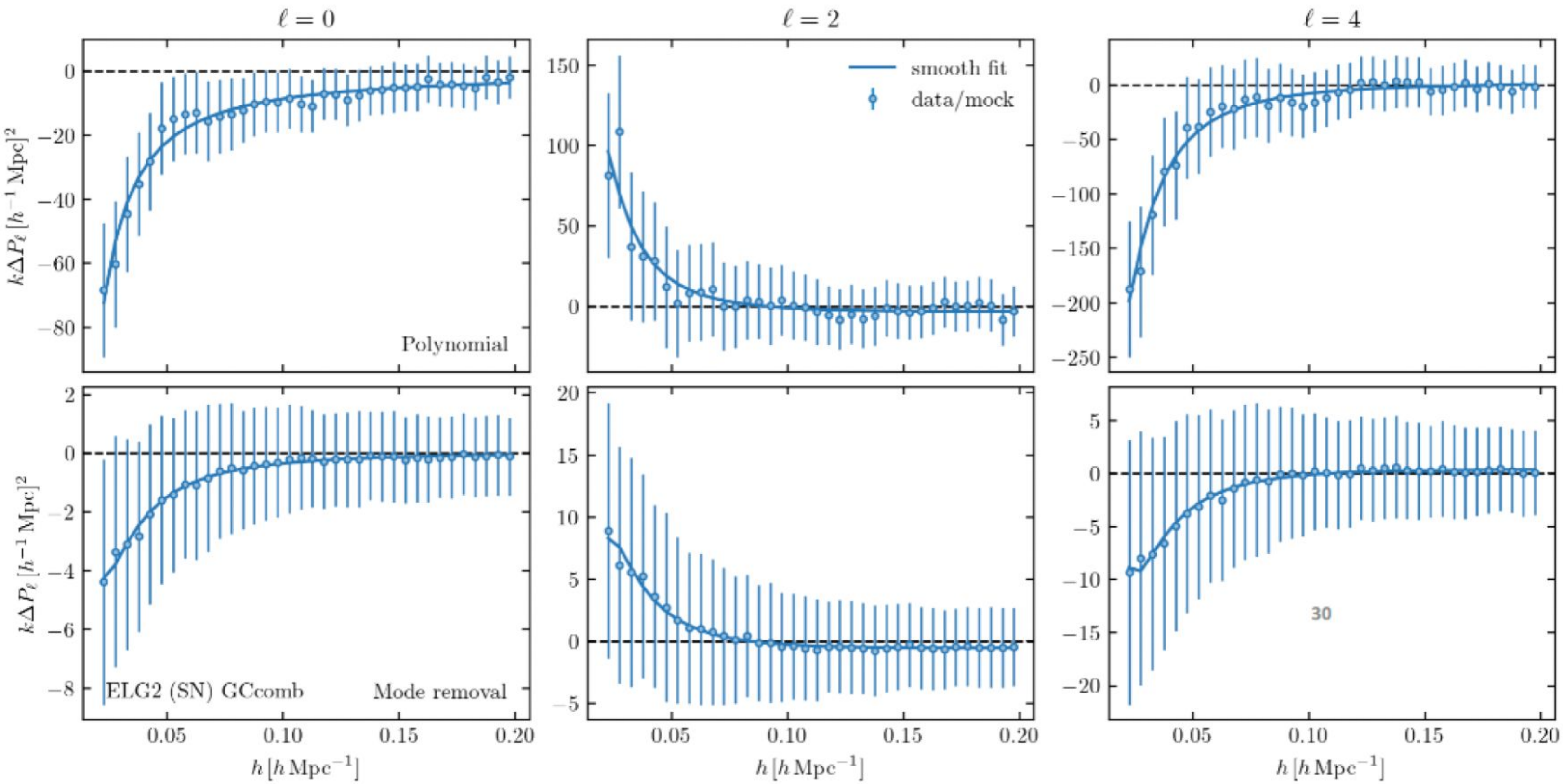
Zhou et al. 2024

variations of angular galaxy density →



Imaging systematics

- Imaging weights (linear for BGS and LRG, Sysnet for ELG, RF for QSO)
- Polynomial correction and mode removal for ELG and QSO



Zhao et al. 2024

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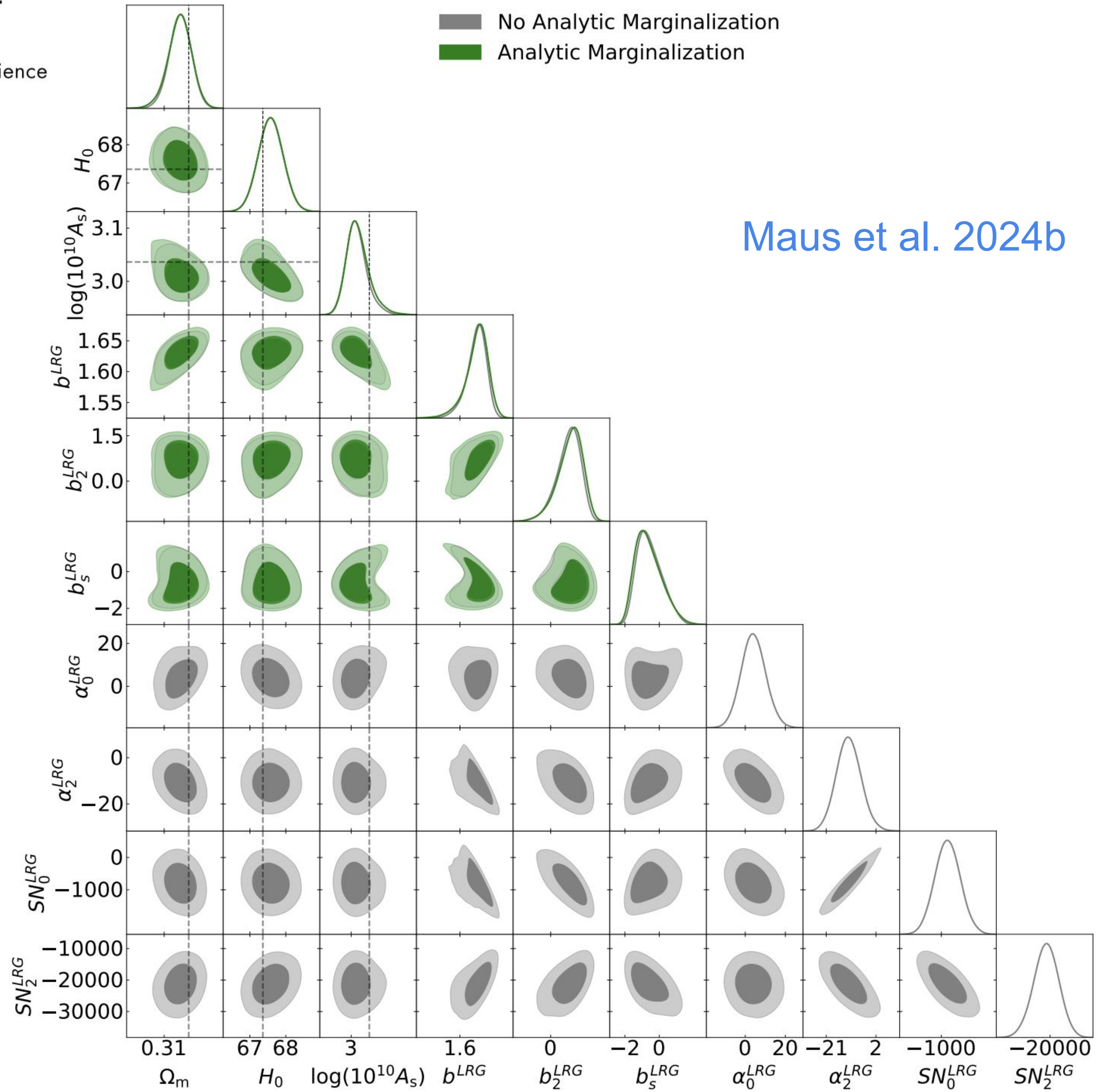

Maus et al. 2024b

Sum of neutrino masses

Impact of the CMB likelihood:

CamSpec and HiLLiPoP-LoLLiPoP based on Planck PR4