Cosmology with DES and DESI

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19/12/2024

Observational Cosmology in Pills

- Standard Model (ΛCDM): flat Universe dominated by Dark Energy (Λ cosmological constant) and Cold Dark Matter

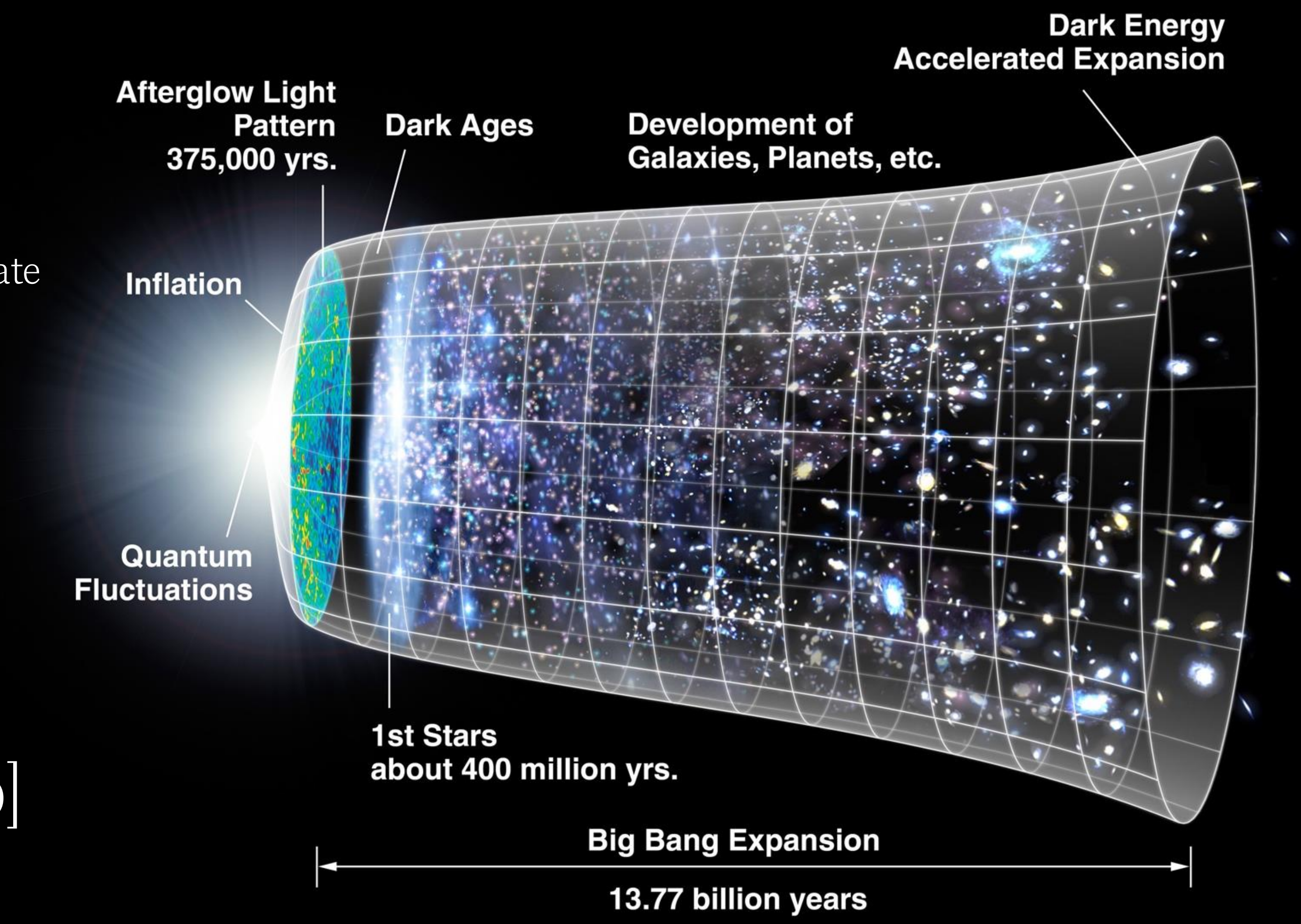
- Cosmological Principle: existence of equivalent coordinate system

- Compatibility with General Relativity

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Described by FLRW metric

$$ds^2 = -c^2 dt^2 + a(t)^2 \left[\frac{dr^2}{1-kr^2} + r^2 (d\theta^2 + \sin^2\theta d\phi^2) \right]$$



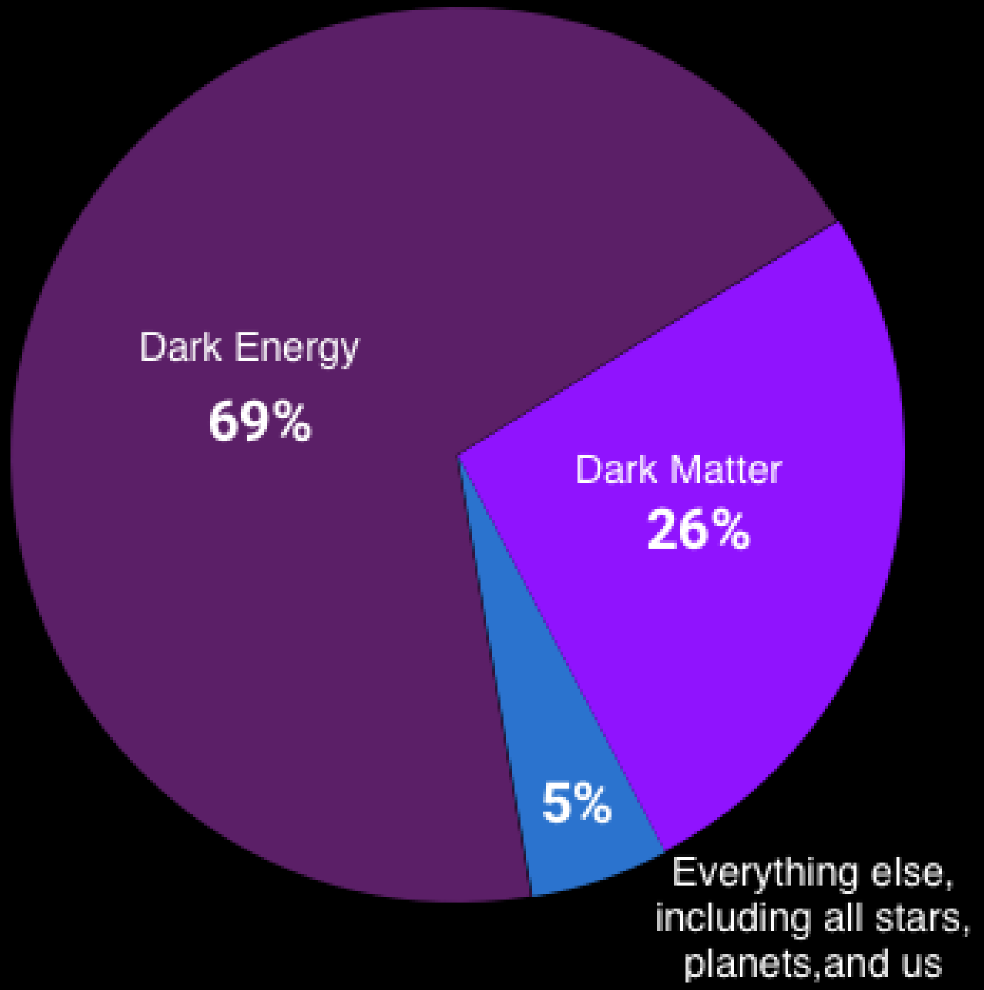
Observational Cosmology in Pills

The Standard Model is in good agreement with different sources as:

- Light element abundances
- Type Ia Supernovae brightness
- Baryon Acoustic Oscillations (BAO) and galaxy clustering
- Weak gravitational lensing
- Cosmic Microwave Background (CMB)

The model relies on six independent Cosmological Parameters:

- Ω_b :baryon density
- Ω_{cdm} :physical dark matter density
- H_0: Hubble constant
- n_s :scalar spectral index
- Δ_R^2 :curvature fluctuation amplitude
- τ: reionization optical depth



Dark Energy

- Most abundant component of the universe
- Unknown nature: it behaves like a negative pressure, being the responsible of the accelerated expansion of the universe
- Compatible properties with vacuum energy
- Current data are described by dark energy being the cosmological constant ($\omega = -1$)

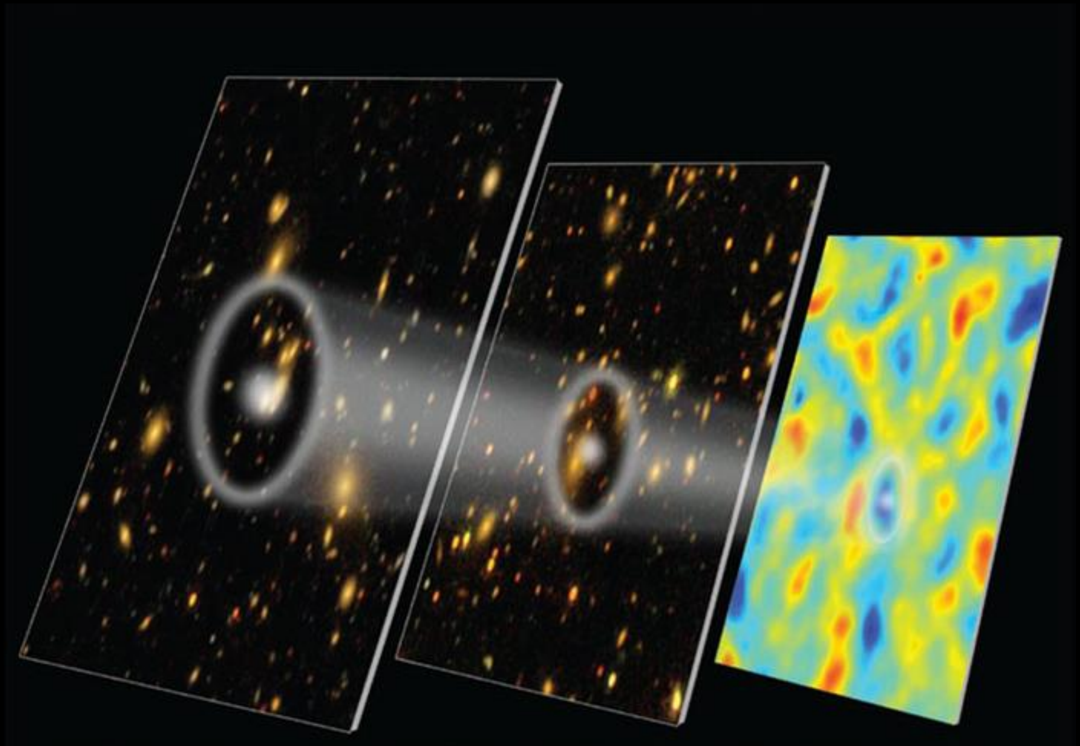
$$\omega = \omega_0 + \omega_a(1-a) = \omega_0 + \omega_a \frac{z}{1+z} \quad \text{(Chevallier-Polarski-Linder)}$$

BAO: geometrical probe and standard ruler that measure the spatial distribution of galaxies

- BAO provide a fixed comoving distance scale
- The apparent angular size and redshift of the BAO feature in the large-scale structure of the Universe, compared with predictions, allow us to infer the rate at which the Universe is expanding and how this rate changes over time

BAO

- Early Universe (z >> 1000): hot plasma with tightly coupled baryons and photons
- Overdensities make overpressures and a sound wave in the gas, wich propagates with velocity $c_s = c/\sqrt{3}$

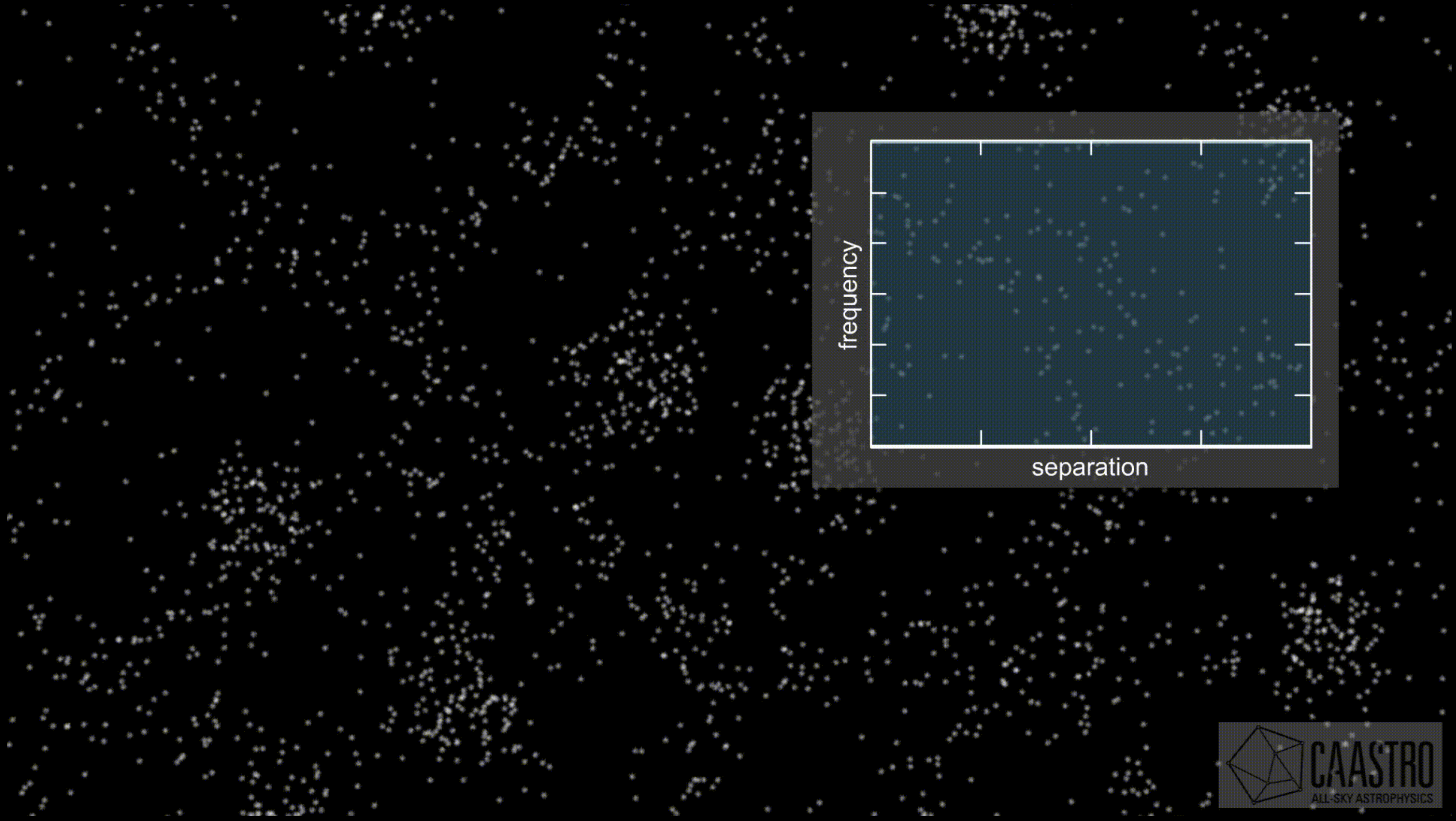


- At z ~ 1100 (t ~ 350 000 yr), temperature is low enough (3000 K) for the formation of hydrogen. Photons decouple and propagate freely (CMB)
- Acoustic waves freeze at a distance given by the acoustic horizon

$$r_d \approx 110 \text{ Mpc } h^{-1}\text{) or 150 Mpc)}$$

- Baryon overdensity attracts dark matter: excess of probability of finding objects at the sound horizon scale!

BAO Detection



http://caastro.org

- Galaxies form in the overdense regions. Mostly, where the initial overdensities were. However, there is a 1% enhancement in the regions 150 Mpc away from these initial overdensities.
- Hence, there should be a small **excess of galaxies 150 Mpc** away from other galaxies, as opposed to 120 or 180 Mpc.
- We can see this as a **single *acoustic peak* in the correlation function of galaxies**.

Dark Energy Spectroscopic Instrument (DESI)

Located at 4-meter Mayall Telescope in Arizona

Upgraded telescope for wide field spectroscopy

Now dedicated to multi-object spectroscopy

First Stage-IV Dark Energy Experiment

Optimized for BAO measurements

10X improvement to w_0w_a figure of merit compared with stage-II Type Ia supernovae measurements

Comprehensive cosmology program

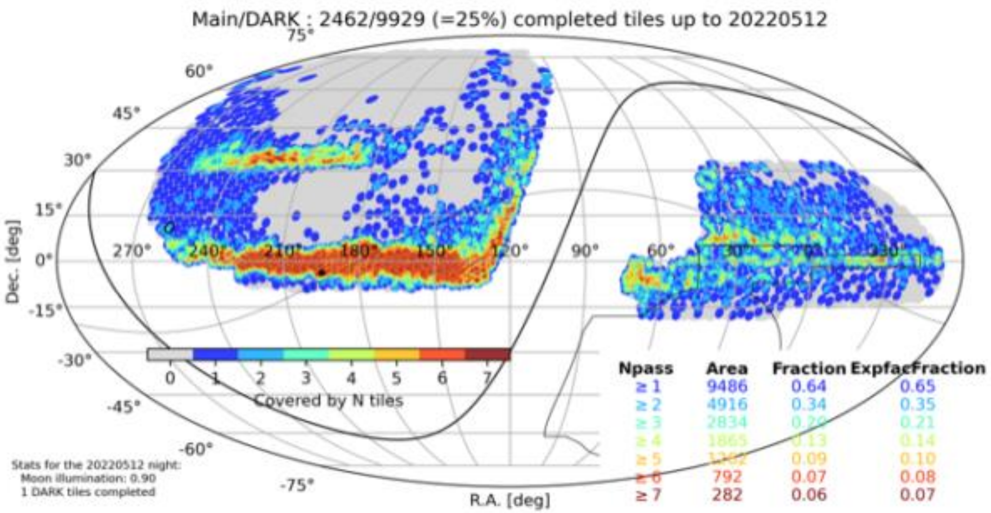
Redshift Space Distortions

Cross-correlations with other surveys

Other wider topics

Large international collaboration: More than 900 scientists, 17 countries, 72 institutions
Lead by LBNL

DESI DR1 BAO Data



- Targets selected from photometric catalogs drawn from three optical surveys (DECaLS, BASS, MzLS)
- 7500 deg^2 covered (over ~ 14200 deg^2)
- ~6 millions unique redshifts, more than twice all the previous spectroscopic surveys together

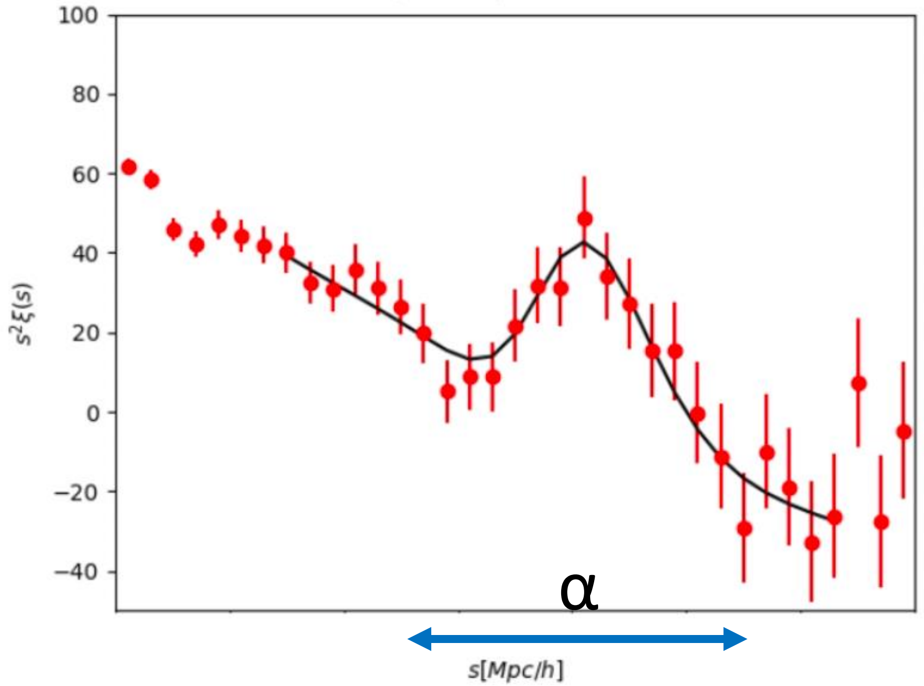
tracer	redshift	$N_{\rm tracer}$	$z_{\rm eff}$	$D_{\rm M}/r_{\rm d}$	$D_{\rm H}/r_{\rm d}$	r or $D_{\rm V}/r_{\rm d}$	$V_{\rm eff}$ ($\rm Gpc^3$)
BGS	$0.1-0.4$	300,017	0.295	—	—	7.93 ± 0.15	1.7
LRG1	$0.4-0.6$	506,905	0.510	13.62 ± 0.25	20.98 ± 0.61	-0.445	2.6
LRG2	$0.6-0.8$	771,875	0.706	16.85 ± 0.32	20.08 ± 0.60	-0.420	4.0
LRG3+ELG1	$0.8-1.1$	1,876,164	0.930	21.71 ± 0.28	17.88 ± 0.35	-0.389	6.5
ELG2	$1.1-1.6$	1,415,687	1.317	27.79 ± 0.69	13.82 ± 0.42	-0.444	2.7
QSO	$0.8-2.1$	856,652	1.491	—	—	26.07 ± 0.67	1.5
Lya QSO	$1.77-4.16$	709,565	2.330	39.71 ± 0.94	8.52 ± 0.17	-0.477	—

DESI Collaboration 2024 (arXiv:2404.03002)

Fitting BAO

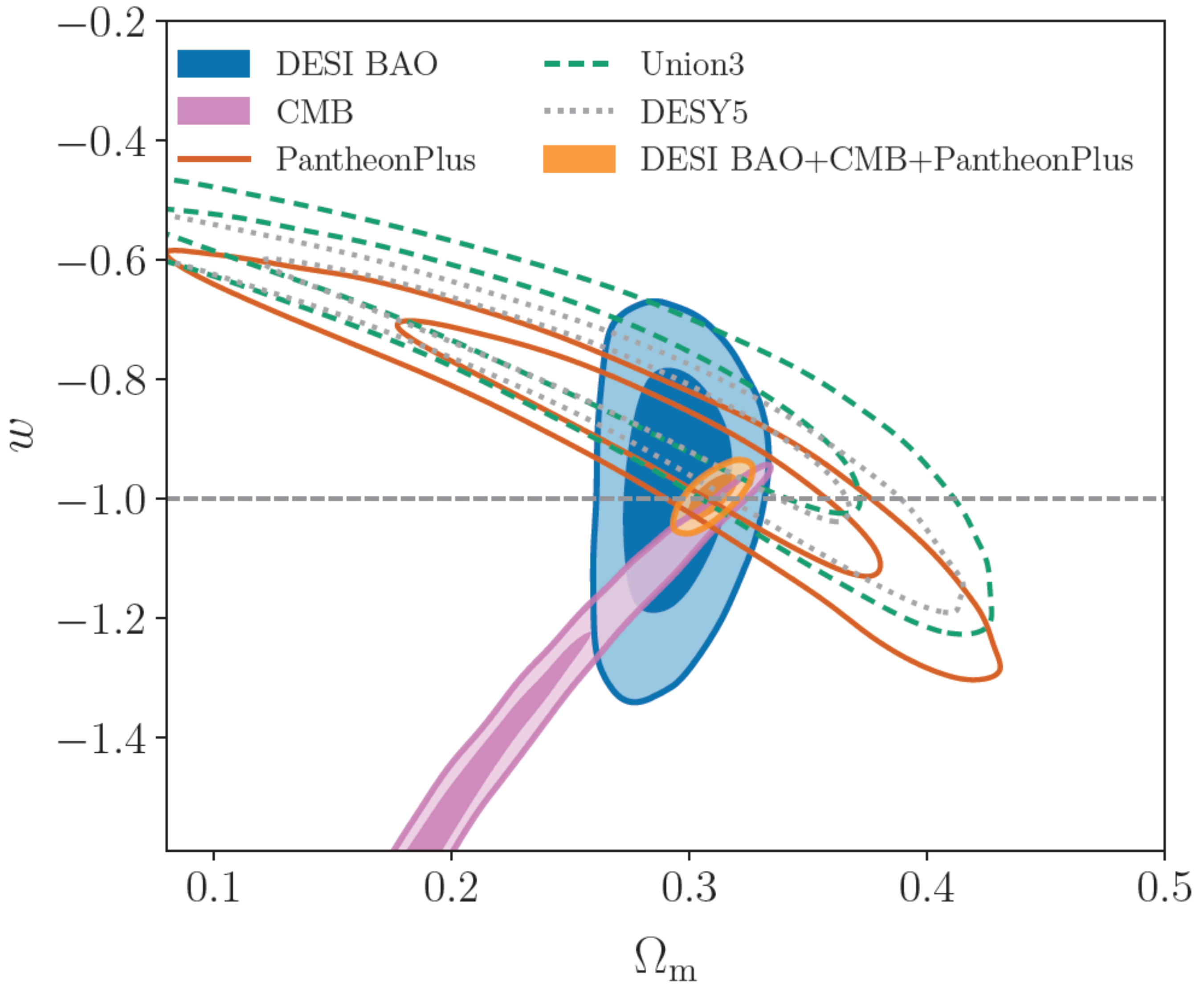
Fit data to the correlation function of a fiducial (model) by rescaling it using alpha parameters

$$\alpha_\perp = \frac{D_A(z) r_d^{\rm fid}}{D_A^{\rm fid}(z) r_d} \quad \alpha_{||} = \frac{H^{\rm fid}(z) r_d^{\rm fid}}{H(z) r_d} \quad \text{or} \quad \alpha_{\rm iso} = (\alpha_{||}\alpha_\perp^2)^{1/3} \quad \alpha_{\rm AP} = \alpha_{||}/\alpha_\perp$$



Results: Dark Energy

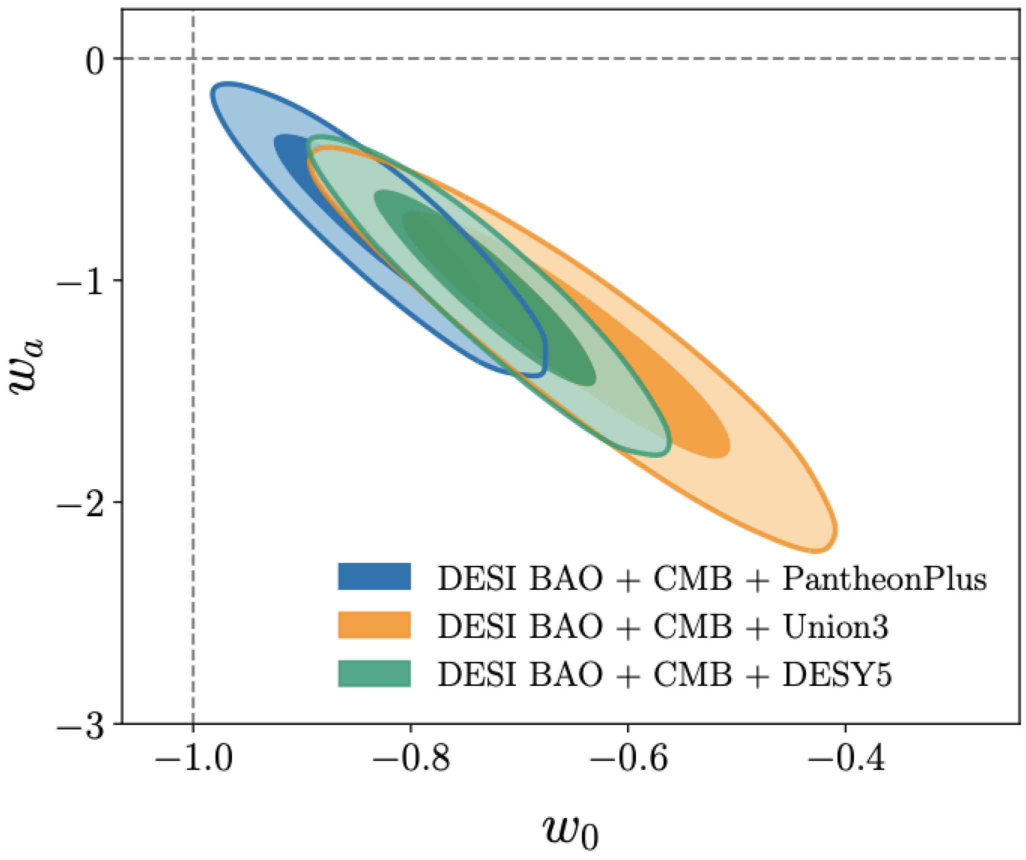
$$\left.\begin{aligned} \Omega_m &= 0.3095 \pm 0.0069 \\ w &= -0.997 \pm 0.025 \end{aligned}\right\}$$ DESI + CMB + PantheonPlus



DESI Collaboration 2024 (arXiv:2404.03002)

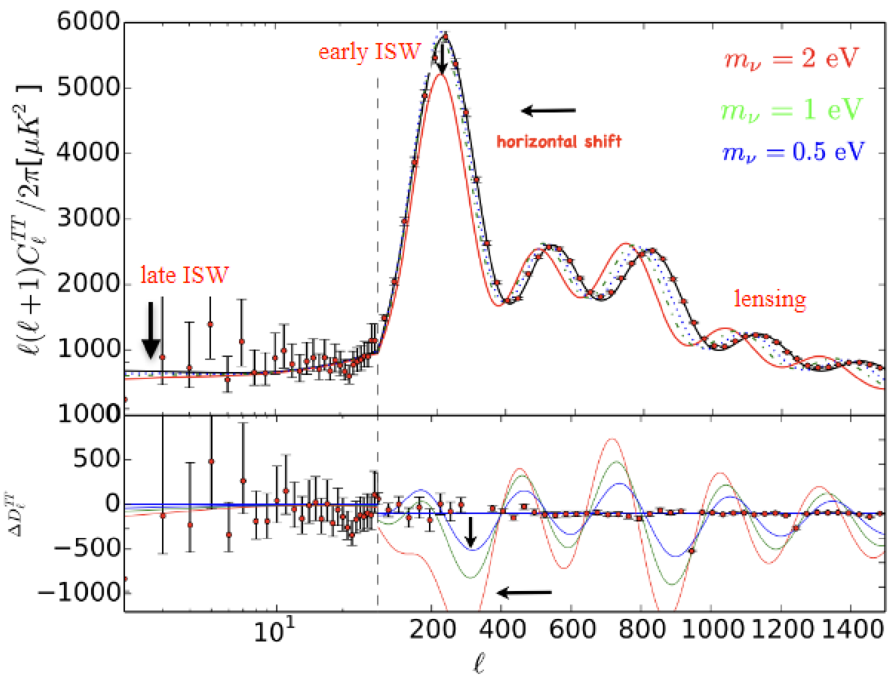
Results: Dark Energy (CPL)

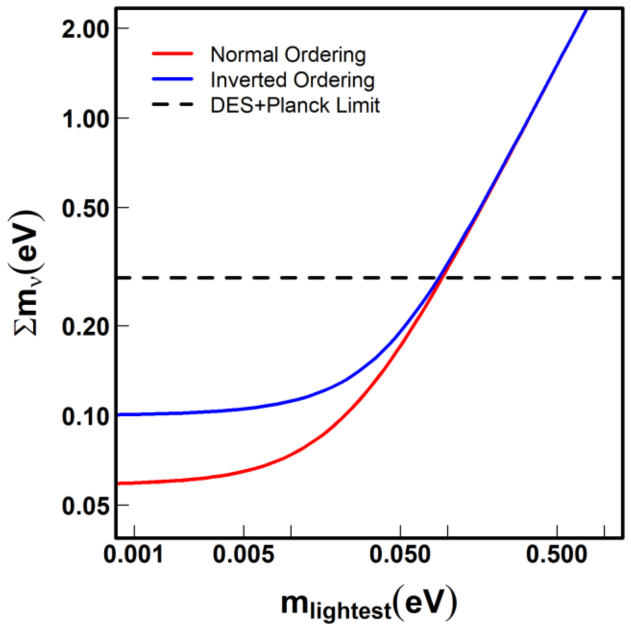
- With $w_0 w_a$CDM we obtain tensions when DESI BAO data are combined with CMB and Supernovae data
- **Preference for w_0 > -1 and w_a < 0**
- $\mathbf{2.6\sigma, 2.5\sigma, 3.5\sigma}$ and $\mathbf{3.9\sigma}$ tension between ΛCDM and our results for different external data combination
- Preferences confirmed by Deviance Information Criterion and Bayesian model-selection analysis



DESI Collaboration 2024 (arXiv:2404.03002)

Results: Sum of neutrino masses





- $\omega_M = \omega_b + \omega_{CDM} + \omega_\nu$ with $\omega_\nu = \sum m_\nu/(93.14eVh^2)$
- **Normal Ordering** (NO): the two smallest mass neutrino eigenstates have the smallest mass splitting ($\sum m_\nu \geq 0.059\ eV$)
- **Inverted Ordering** (IO): the two smallest mass neutrino eigenstates have the biggest mass splitting ($\sum m_\nu \geq 0.10\ eV$)

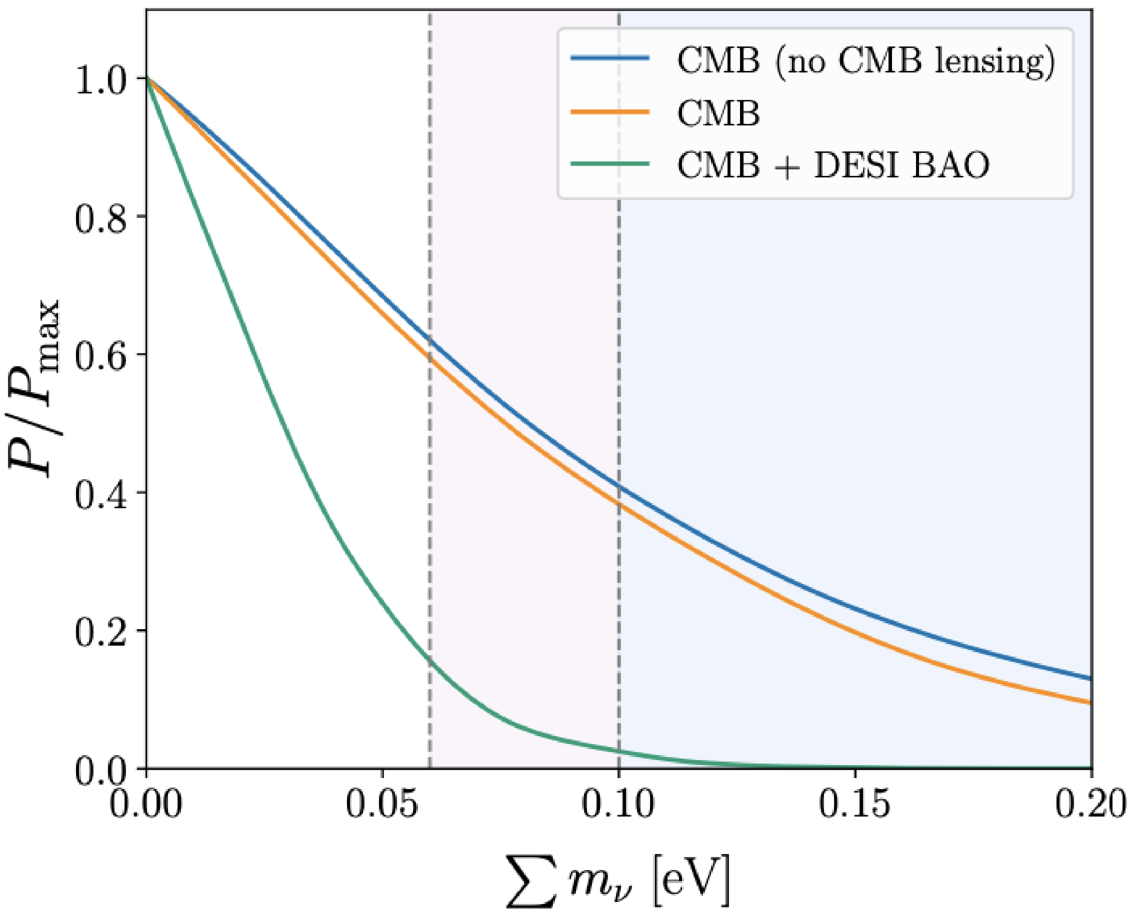
Results: Sum of neutrino masses

- BAO breaks CMB degeneracy between H_0 and Σm_ν
- For ΛCDM: $\sum \boldsymbol{m_\nu} \leq \mathbf{0.21}\ \boldsymbol{eV}$ (CMB+Lensing at 95%)
- For ΛCDM: $\sum \boldsymbol{m_\nu} \leq \mathbf{0.072}\ \boldsymbol{eV}$ (DESI+CMB+Lensing at 95%)

Great constraining power from BAO data

NO is preferred, but results are model dependent

If allowing for w(a): $\boldsymbol{\Sigma m_\nu} < \mathbf{0.195}$ **eV (95%)**



DESI Collaboration 2024 (arXiv:2404.03002)

Results: Number of relativistic species

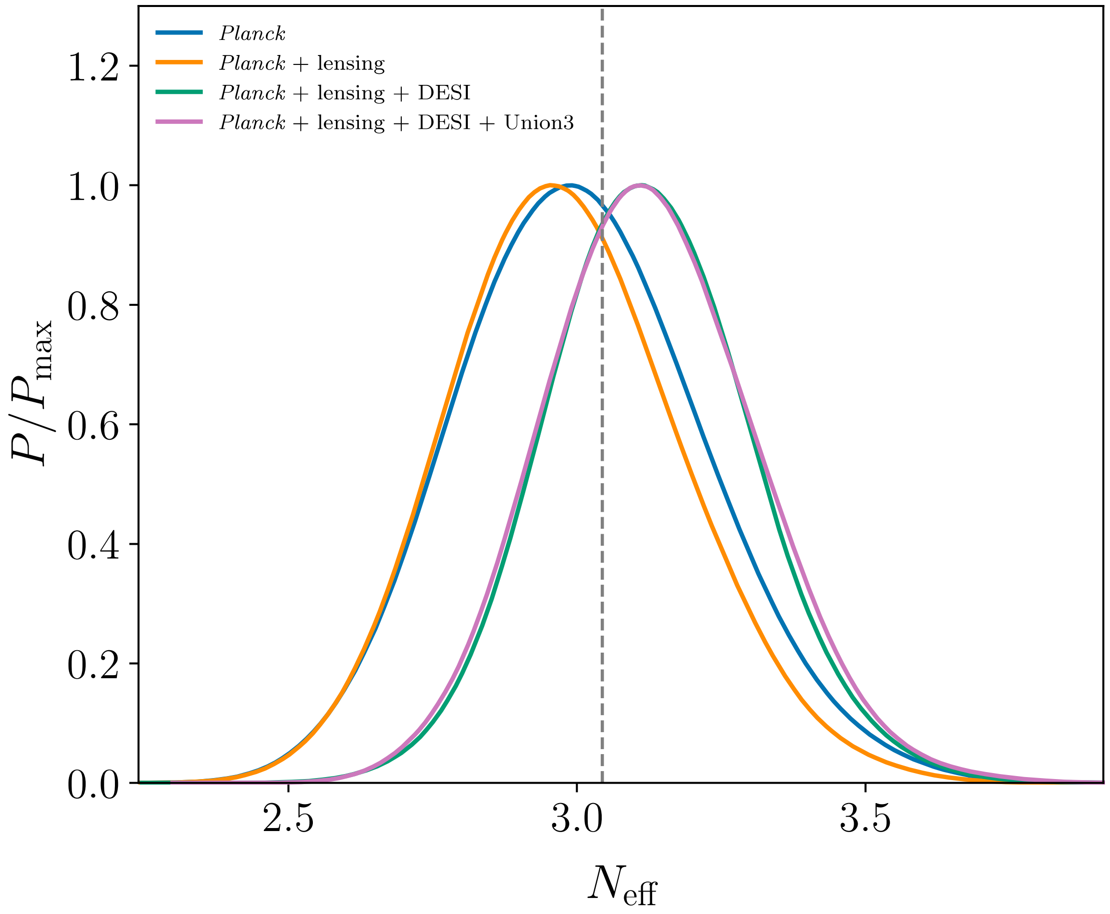
$$\rho_\nu = N_{eff}\frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}}\rho_\gamma$$

- For a standard cosmological model: $\mathbf{N_{eff} = 3.044}$
- Constraints on N_{eff} from CMB exhibit a geometrical degeneracy.
- Increasing N_{eff} correspond to higher H_0 or lower Ω_m

$$N_{eff} = 2.98 \pm 0.20 \text{ (CMB + Lensing)}$$

$$N_{eff} = 3.10 \pm 0.17 \text{ (DESI + CMB + Lensing)}$$

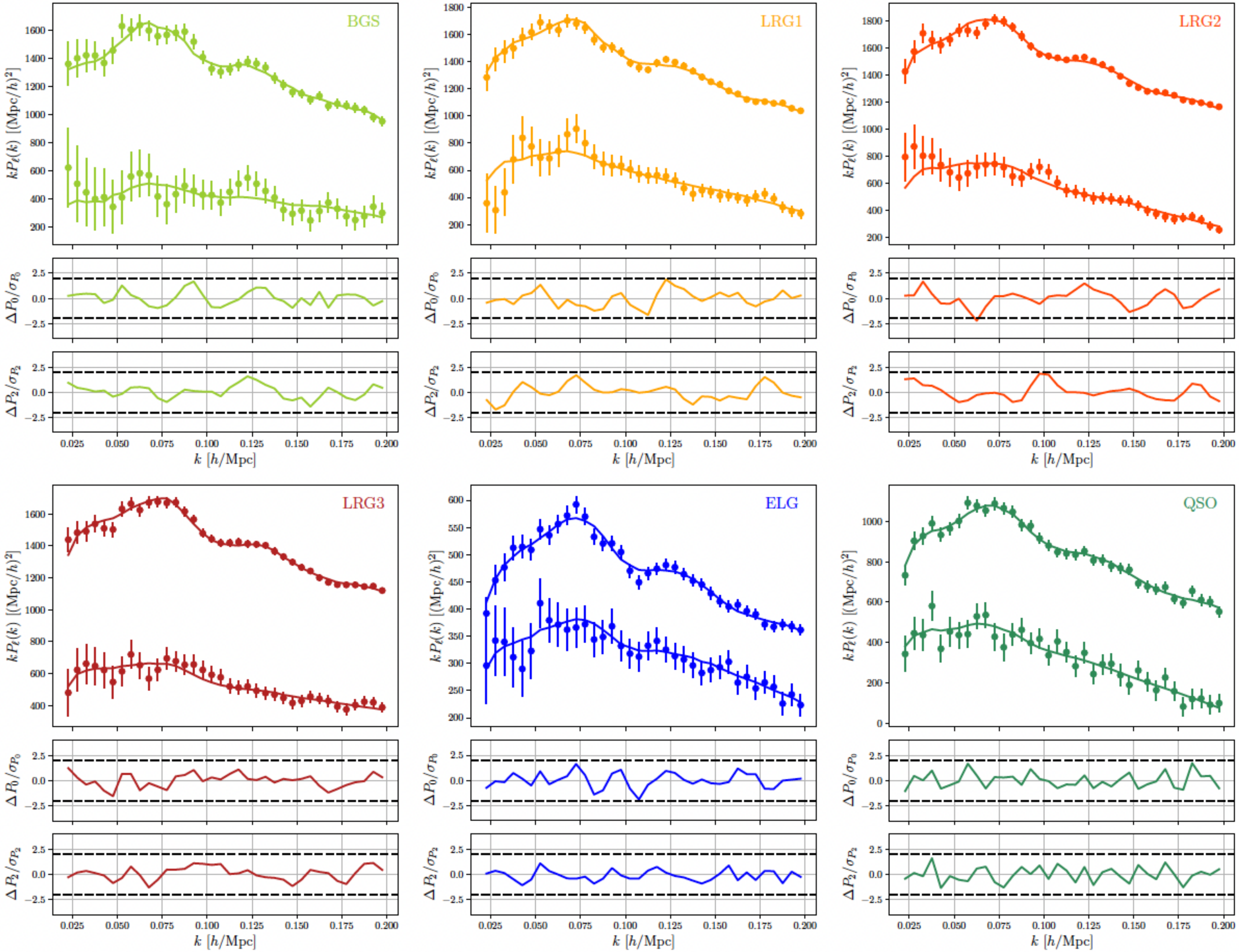
Small shift due to DESI preference for lower Ω_m



DESI DR1 Full-Shape

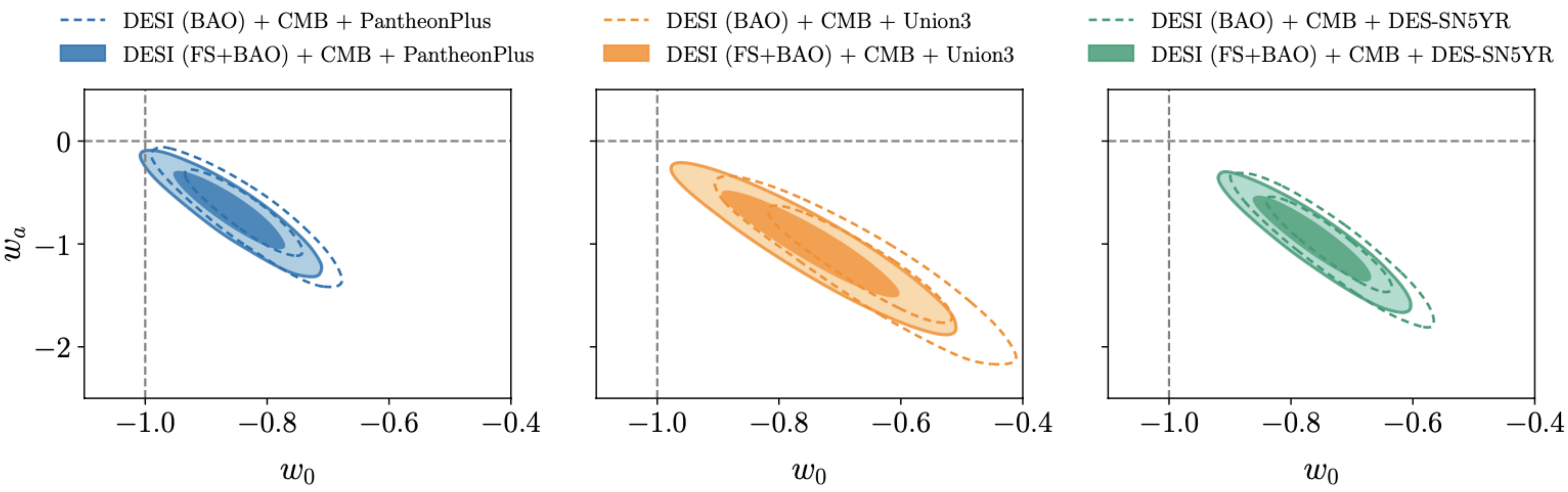
Tracer	redshift range	N_{tracer}	z_{eff}	P_0 $[(h^{-1}\mathrm{Mpc})^3]$	V_{eff} $[\mathrm{Gpc}^3]$
BGS	$0.1-0.4$	300,017	0.295	$\sim 9.2\times10^3$	1.7
LRG1	$0.4-0.6$	506,905	0.510	$\sim 8.9\times10^3$	2.6
LRG2	$0.6-0.8$	771,875	0.706	$\sim 8.9\times10^3$	4.0
LRG3	$0.8-1.1$	859,824	0.930	$\sim 8.4\times10^3$	5.0
ELG2	$1.1-1.6$	1,415,687	1.317	$\sim 2.9\times10^3$	2.7
QSO	$0.8-2.1$	856,652	1.491	$\sim 5.0\times10^3$	1.5

- Full-shape of the clustering signal is considered
- Dependence of the full-shape on z inform us about structure growth and contains information about amplitude and shape of primordial PS
- Monopole, quadrupole and hexadecapole are measured, quantifying information imprinted by RSD
- PS measurements from data and synthetic catalogs (randoms), both masked for bright objects, bad imaging data and fiber assignment



DESI Collaboration 2024 (arXiv:24011.12021)

DE constraints: $w_0 w_a$CDM



$$w_0 = -0.858 \pm 0.061, \quad w_a = -0.68^{+0.27}_{-0.23},$$ DESI (FS+BAO)+CMB +PantheonPlus.

$$w_0 = -0.742 \pm 0.096, \quad w_a = -1.02^{+0.36}_{-0.32},$$ DESI (FS+BAO)+CMB +Union3.

$$w_0 = -0.761 \pm 0.065, \quad w_a = -0.96^{+0.30}_{-0.26},$$ DESI (FS+BAO)+CMB +DES-SN5YR.

DESI Collaboration 2024 (arXiv:24011.12022)

DE constraints: w_0w_aCDM

- Consistent results with BAO-only analysis

- Improvement in constraints of DE EOS: FoM increase by a factor 1.16, 1.22 and 1.15 (respective credible-region areas reduced by about 20%)

- Preference for a departure from ΛCDM values

- $\Delta\chi^2_{MAP} = -8{,}8, -14.5, -17.5$ for the three combinations, that correspond to $2.5\sigma, 3.4\sigma$ and 3.8σ

- Similar preferences founded in BAO-only analysis

$$\left.\begin{array}{l} w_0 = -0.858 \pm 0.061, \\ w_a = -0.68^{+0.27}_{-0.23}, \end{array}\right\} \begin{array}{l} \text{DESI (FS+BAO)+CMB} \\ \text{+PantheonPlus.} \end{array}$$

$$\left.\begin{array}{l} w_0 = -0.742 \pm 0.096, \\ w_a = -1.02^{+0.36}_{-0.32}, \end{array}\right\} \begin{array}{l} \text{DESI (FS+BAO)+CMB} \\ \text{+Union3.} \end{array}$$

$$\left.\begin{array}{l} w_0 = -0.761 \pm 0.065, \\ w_a = -0.96^{+0.30}_{-0.26}, \end{array}\right\} \begin{array}{l} \text{DESI (FS+BAO)+CMB} \\ \text{+DES-SN5YR.} \end{array}$$

Sum of neutrino masses

$$\sum m_\nu < 0.409\,\mathrm{eV} \quad (95\,\%,\ \text{DESI (FS+BAO)+BBN+}n_{s10})$$

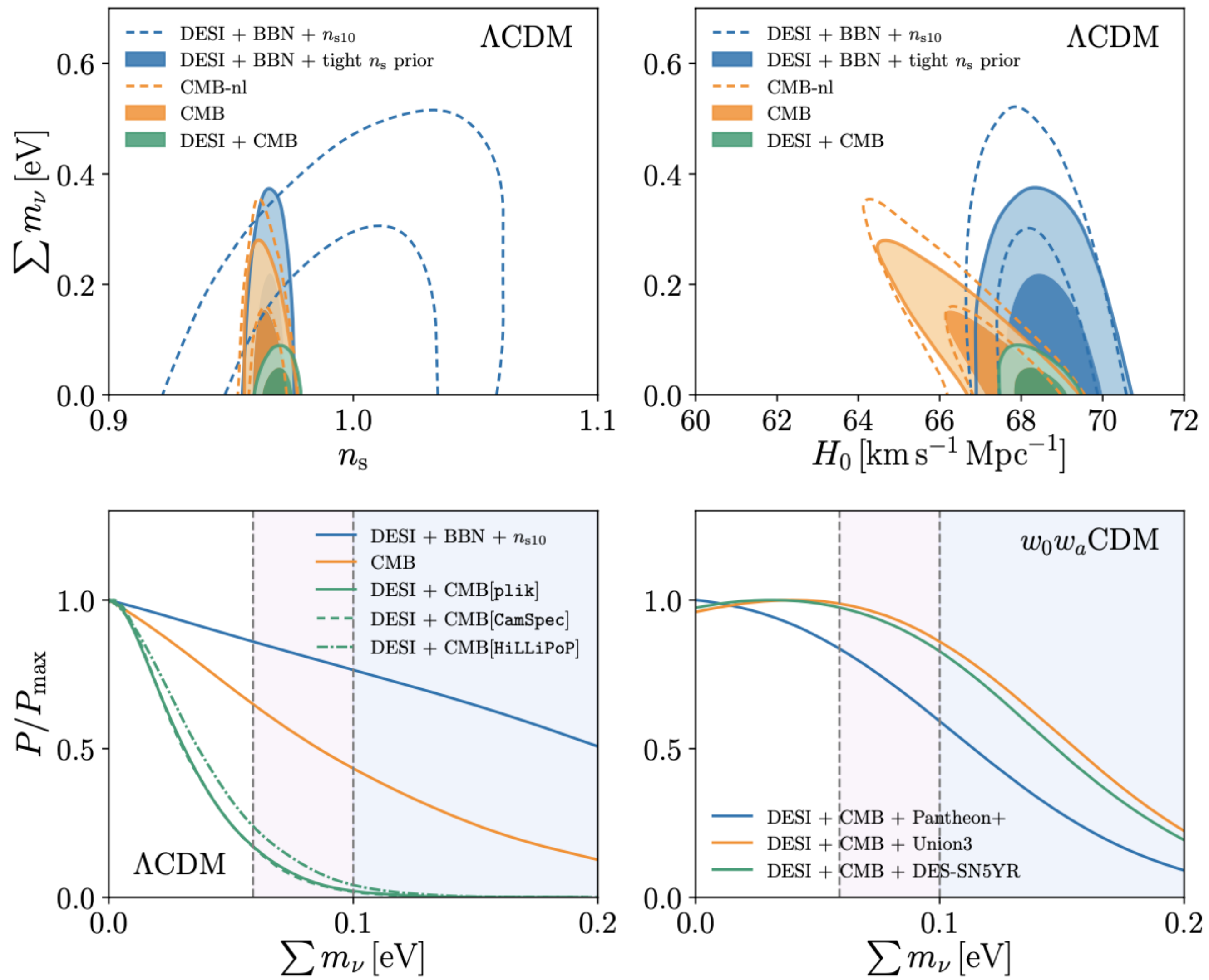
$$\sum m_\nu < 0.300\,\mathrm{eV} \quad (95\,\%,\ \text{DESI (FS+BAO)+BBN+tight } n_s \text{ prior})$$

This is similar to CMB-nl result ($\sum m_\nu < 0.265\ eV$)

$$\sum m_\nu < 0.082\,\mathrm{eV} \quad (95\,\%,\ \text{DESI (BAO only)+CMB}).$$

A different version of ACT likelihood is used

$$\sum m_\nu < 0.071\,\mathrm{eV} \quad (95\,\%,\ \text{DESI (FS+BAO)+CMB})$$



DESI Collaboration 2024 (arXiv:24011.12022)

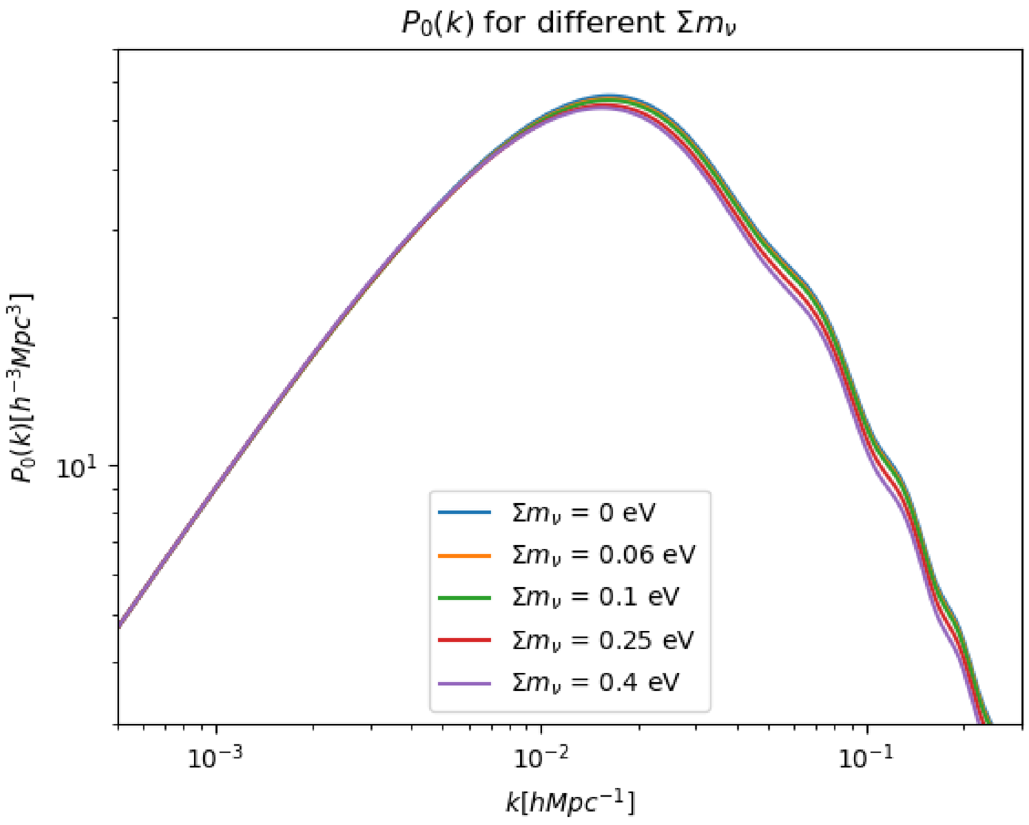
Neutrino mass effects on matter power spectrum

Effects of neutrino masses on P(k)

- Suppression in $P(k)$ on small scales (large k)
- Two main effects:
  - Neutrinos do not cluster below their free-streaming scale
  - CDM and baryon perturbations grow slower in the presence of massive neutrinos

Growth of matter perturbations:

- Above the neutrino free-streaming scale: $\delta_m \propto a$ (purely matter dominated).
- Below the free-streaming scale: $\delta_m \propto a^{1-3\,f_\nu/5}$
- $f_\nu = \Omega_\nu/\Omega_m$



Neutrino mass effects on matter power spectrum

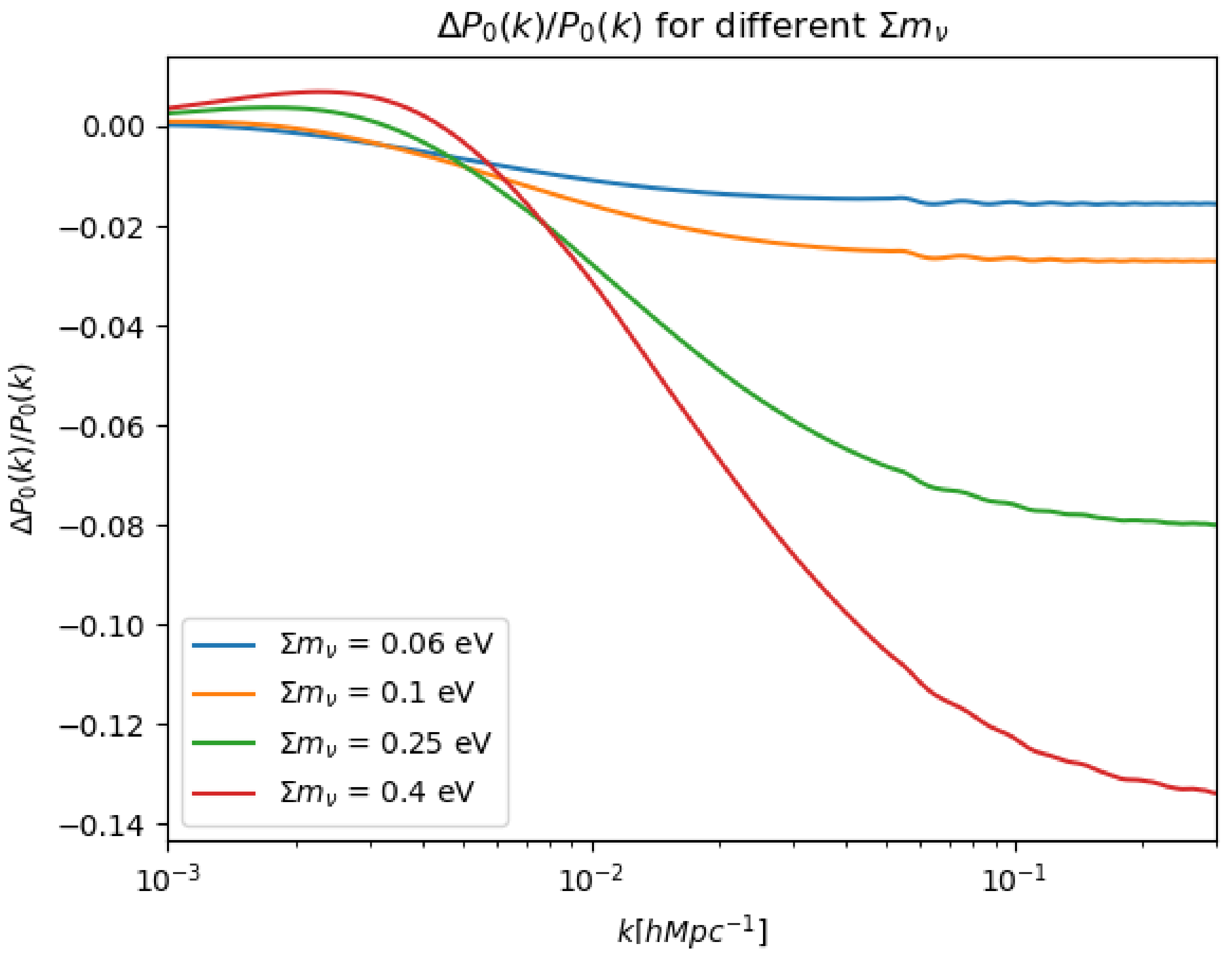
Suppression of $\Delta P(k)/P(k)$:

- $\approx -8f_\nu$ for linear matter perturbations
- $\approx -10f_\nu$ including non-linear effects

Step-like suppression:

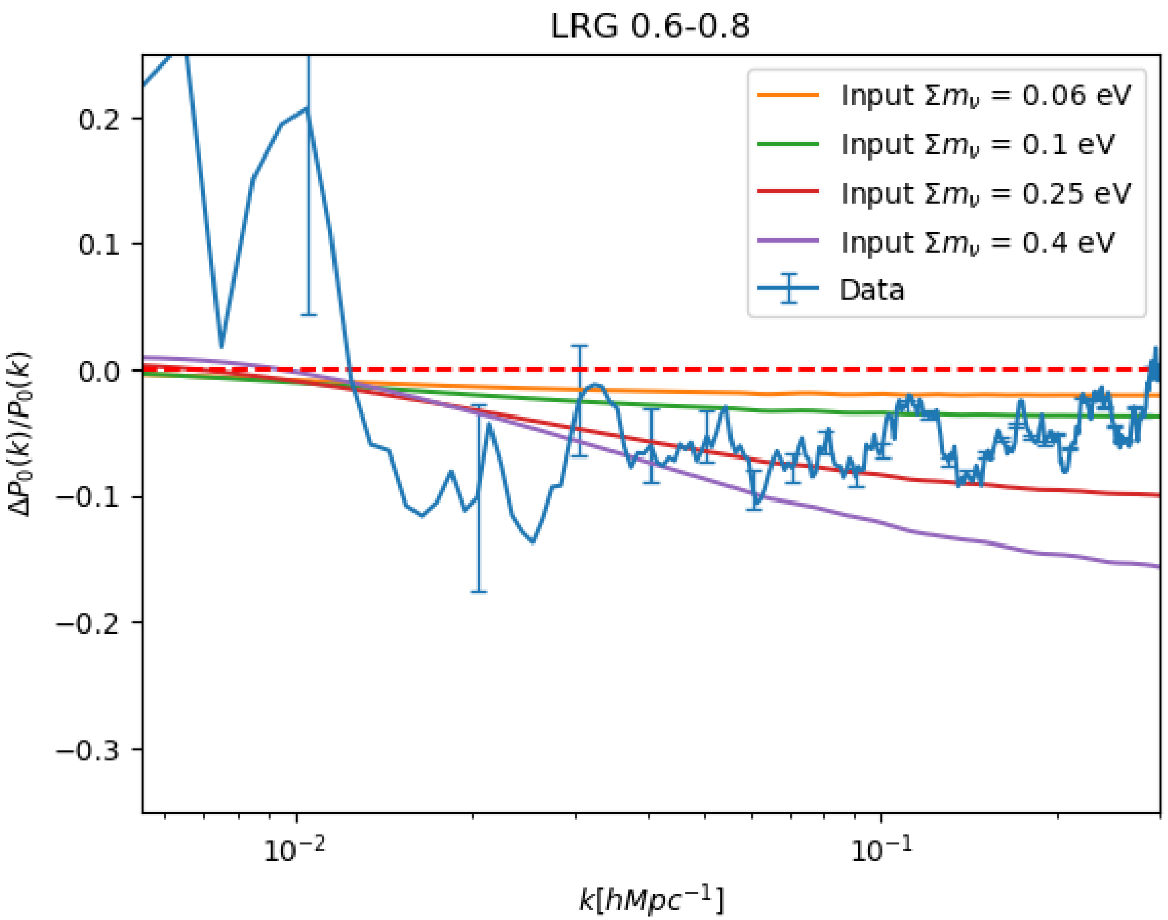
- Since neutrinos with different masses become non-relativistic at different times, it is expected that the suppression of matter power spectrum happens in three steps, according to the free-streaming scale of each neutrino mass eigenstate

- Current cosmological data is sensitive only to the total neutrino mass $\sum m_\nu$



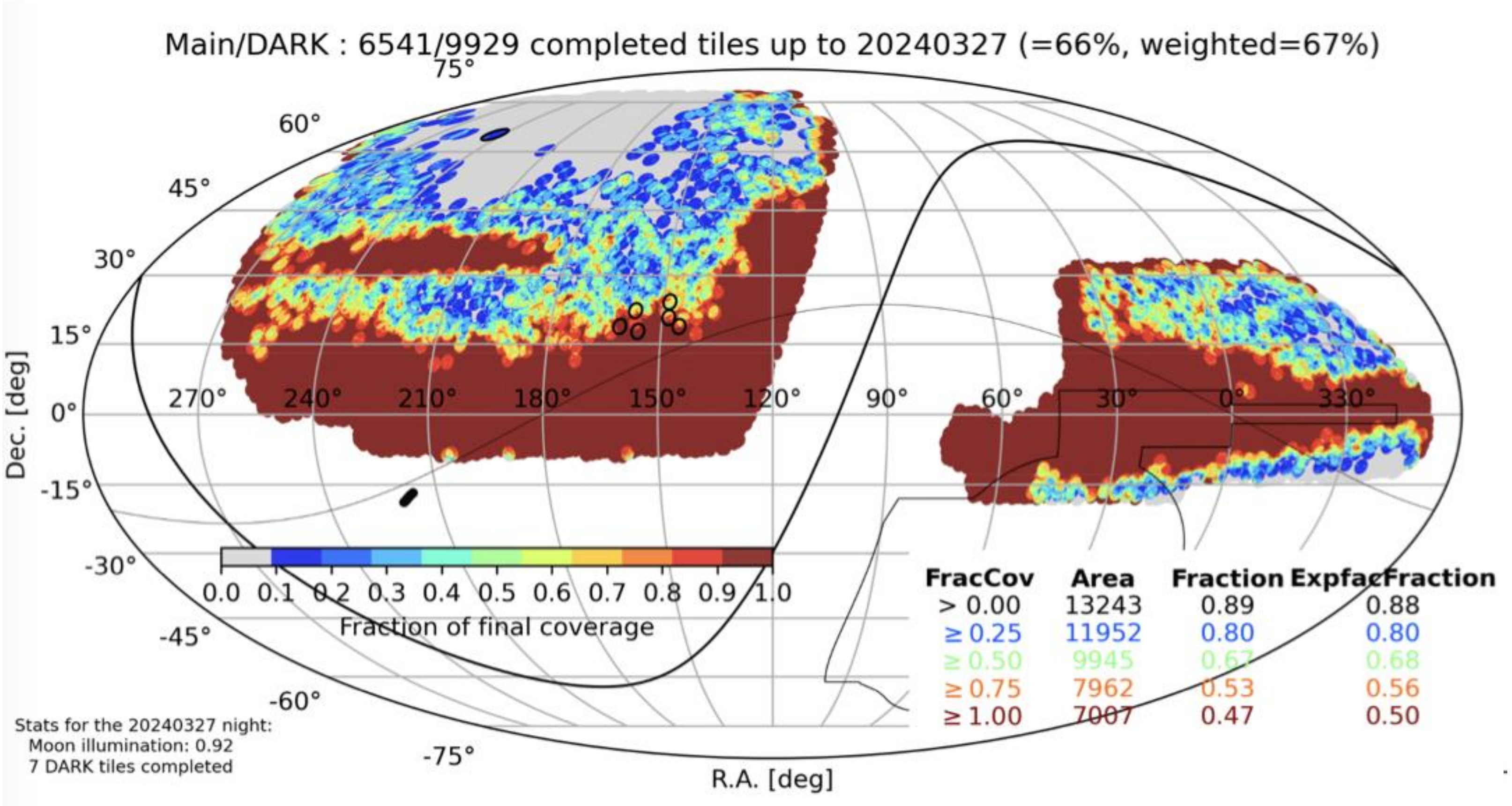
Comparison with theory

- Pretty noisy signal, given also by the small *dk* choice
- Comparison with theoretical expectations underline the presence of the signature
- Even considering all the approximations, signature seems to rule out $\sum m_\nu < 0$ and $\sum m_\nu > 0.4\ eV$ (but not excluded within the error)



And now? Y3!

Includes data taken up to March 31st 2024



- Almost 14 millions redshift collected (more than the twice of Y1 catalog!)
- First results in 2025

Current DESI work and outlook

Now:

- Working on neutrino suppression signature in PS considering more accurate models and analyses (better understanding of the non-linear part, better implementation of the bias, improving fitting model and considering use of scale-cuts, exploration of different binning and fiducial cosmologies better understanding in other potential effects)

- DESI Y3 tasks. Test in Fourier space and maintenance of Y3 covariance scripts with Juan Mena, Uendert Andrade and Otavio Alves. From myself: production of covariances for all redshift bins and pre- and post-reconstruction (Main Contributor).

Near future:

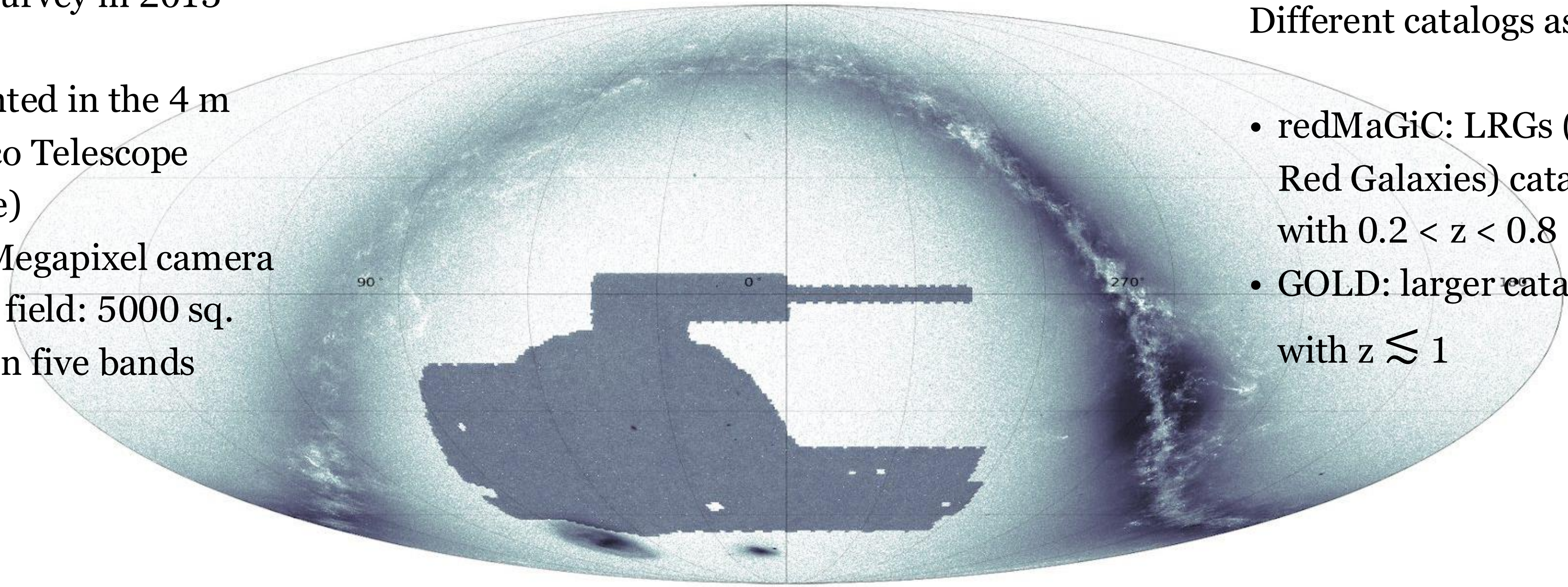
- Contributing to running DESI Y3 inference for future KP papers

- New tests in Fourier space, especially for covariances cross-check

- Contributing to DESI Neutrinos supporting papers (with Williem Elbers and Hernan Noriega)

Dark Energy Survey (DES)

- Full survey in 2013-2019
- Mounted in the 4 m Blanco Telescope (Chile)
- 570 Megapixel camera
- Wide field: 5000 sq. deg. In five bands



Different catalogs as:

- redMaGiC: LRGs (Large Red Galaxies) catalogue with $0.2 < z < 0.8$
- GOLD: larger catalog with $z \lesssim 1$

DES related work

Using Cardinal simulation to test Gold catalog and its derived products (with Chun-Hao To). Redshift distribution and correlation function robustness test for simulations and between sim and Year 6 data

Help on DES Y6 images analysis (about shape and quality of bright object masking, presence of artefacts, and so on)

Helping on new KP paper (with Santi Avila, Anna Porredon, Juan Mena and other folks, now in internal review) with:

- Running chains with simulated data
- Running chains with real data considering CPL parametrization
- Helping with development of tools for quantifying deviations (smaller contribution)

BACKUP SLIDES

Full Modelling vs ShapeFit

Full Modelling

- Detailed theoretical models covering the entire power spectrum or correlation function
- Cosmological parameters (e.g., Ωm, Ωb, h), growth rate (f), bias parameters (b), and others
- High complexity, accounts for non-linearities, redshift-space distortions, and BAO
- High-precision cosmology where detailed analysis is essential

ShapeFit

- Fits specific features rather than the entire shape
- Extension of the classic BAO+RSD approach
- Effective parameters like the BAO scale, overall slope, (m, n) and amplitude
- Lower complexity, focuses on key characteristics, more computationally efficient
- Preliminary analyses and large-scale surveys where computational efficiency is key

Simulations: AbacusSummit and EZmocks

AbacusSummit

- Runned using Abacus N-body code
- base Simulations: $3.3 \cdot 10^9$ particles ($M \sim 10^9 M_{\odot}$)in a 2 Gpc/h box
- Wide z range: 0.1 < z < 3.0
- For this work: 25 base sim, z = 0.8 and Planck 2018 Cosmology
- All cosmologies use $\tau = 0.0544$, most use $\sum m_\nu = 0.06\ eV$

Used for the data

EZmocks

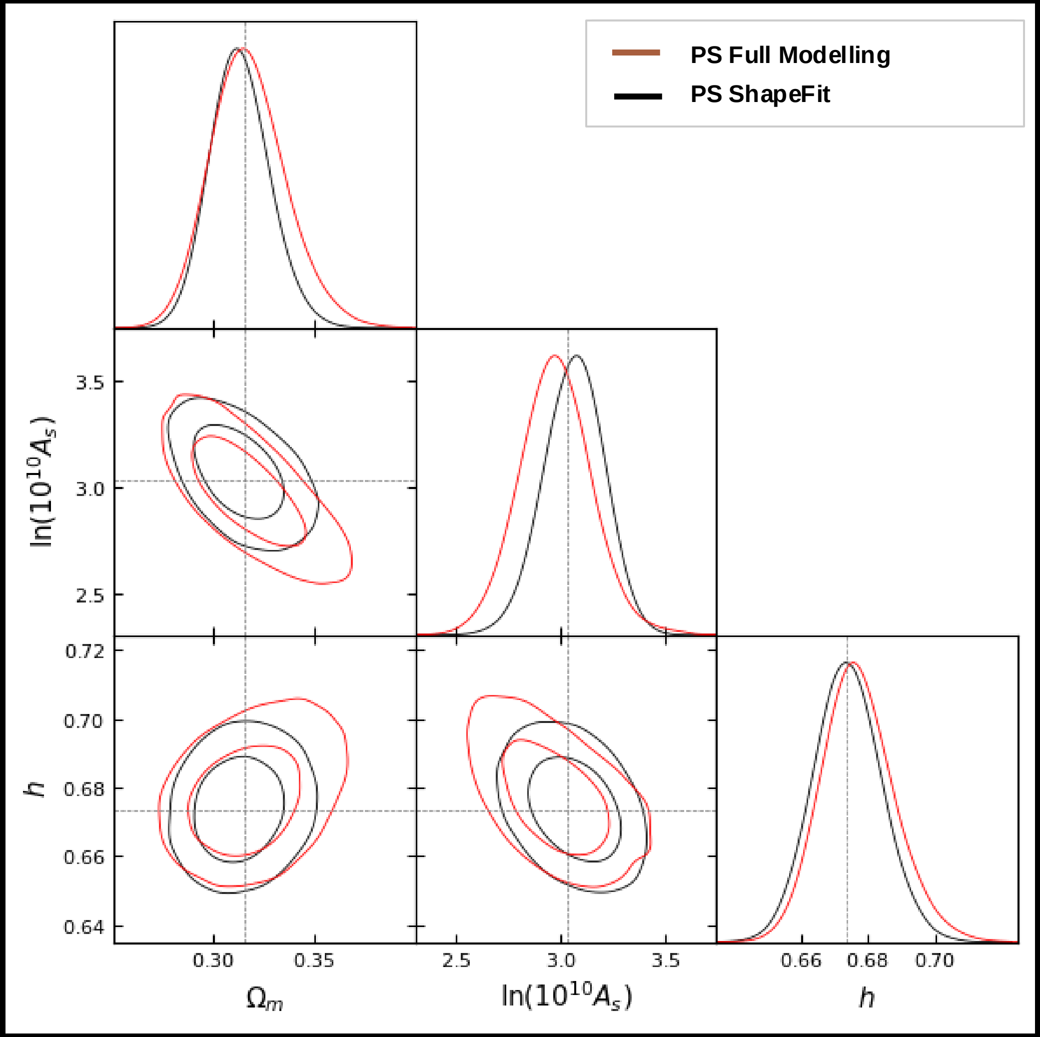
- Effective Zel'dovich approximation mocks
- Based on the Zel'dovich approximation, employ simplified physics
- Widely used in cosmological surveys to estimate statistical errors and study systematic effects
- Provide a fast way to produce large numbers of mocks.
- Accurately capture key large-scale clustering properties

Used for the covariance

Analisys

- Used both PS and CF from LRG mock catalogs (0.8 < z < 1.1)
- MCMC chains runned using **emcee** sampler, with 25 walkers and Gelman-Rubin criterion $\boldsymbol{R-1<0.03}$
- PS and CF show good agreement. A_s is affected by **projection effects**
- Both FM and SF recover cosmological parameters without biases, except for A_s. Valid also in CPL case, with no significant differences between FM and SF

Still a work in progress (degeneration problem, computational time), FM is still preferred



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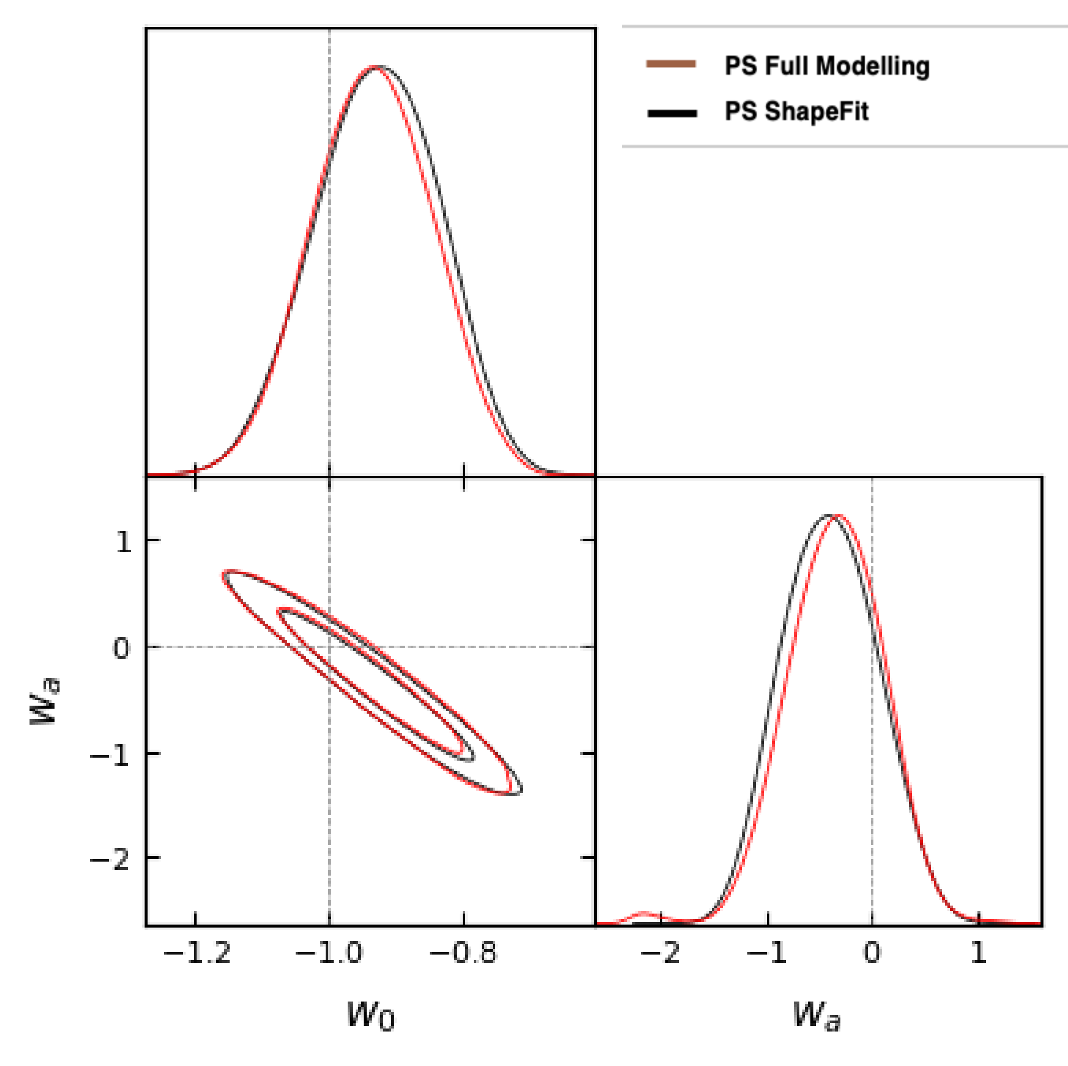


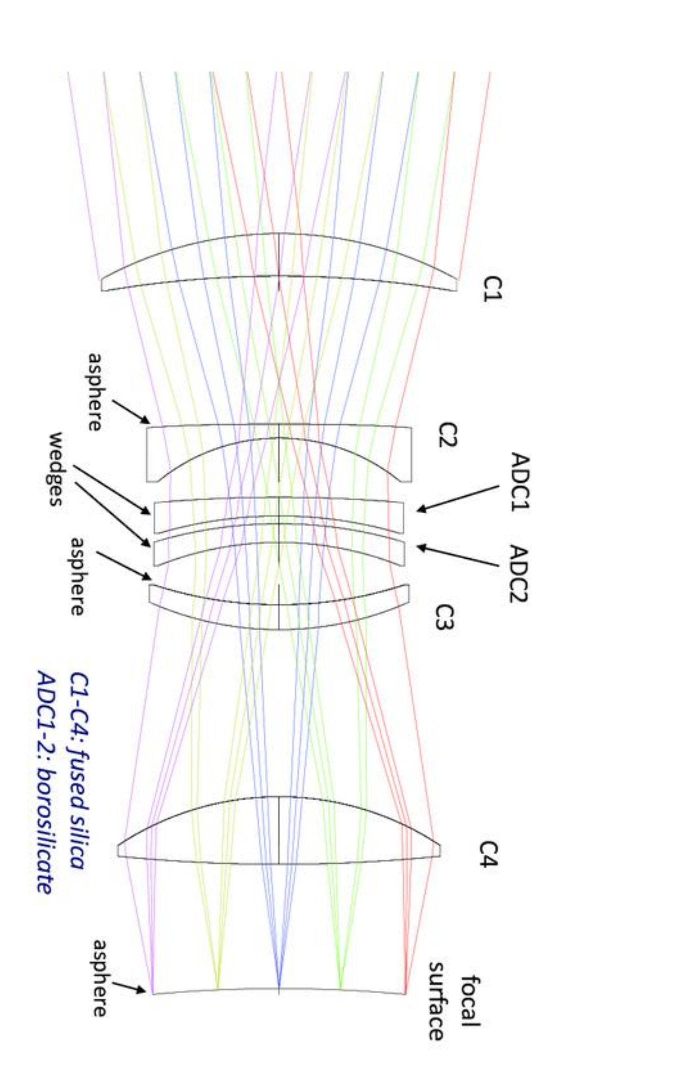
DESI Corrector

DESI Corrector

8 deg^2 wide field of view
6 lenses, each about a meter in diameter
Four have all-spherical surfaces and two have an aspheric surface

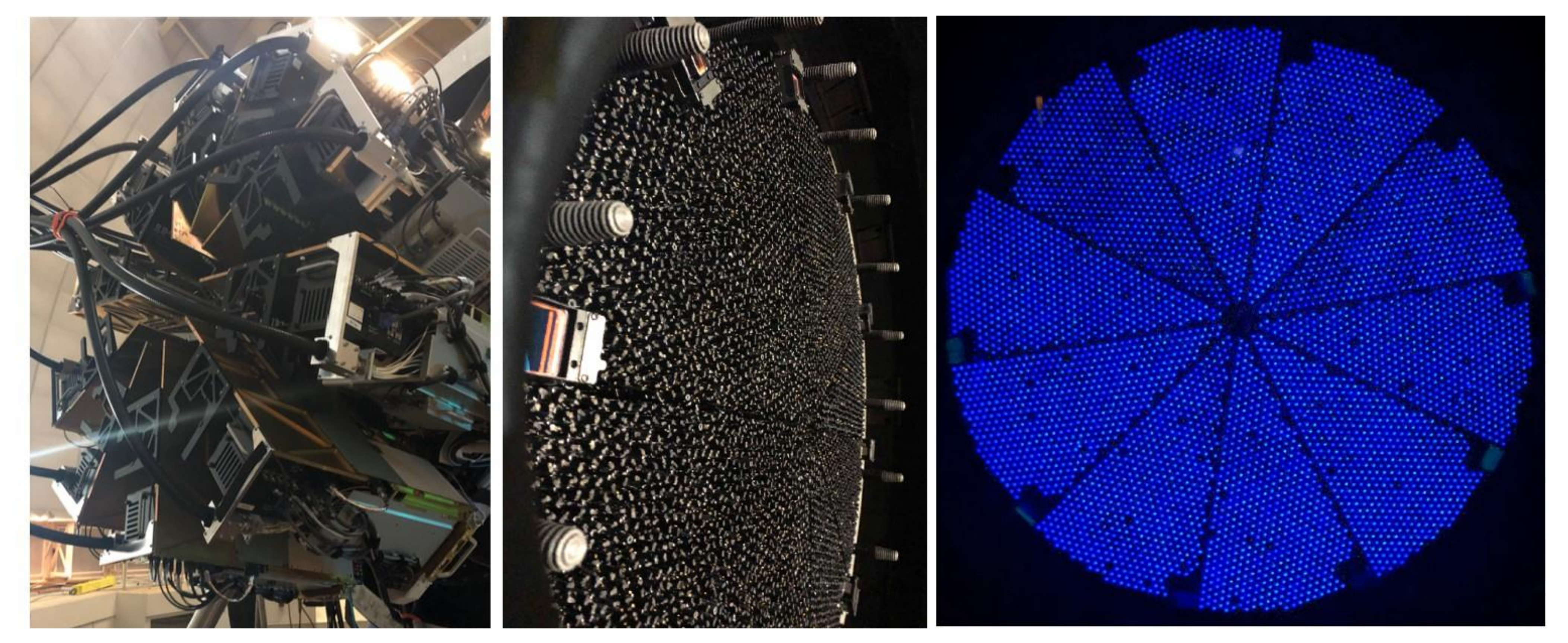
Performance

Coatings are superb
Excellent image quality
Achieved < 0.6" images

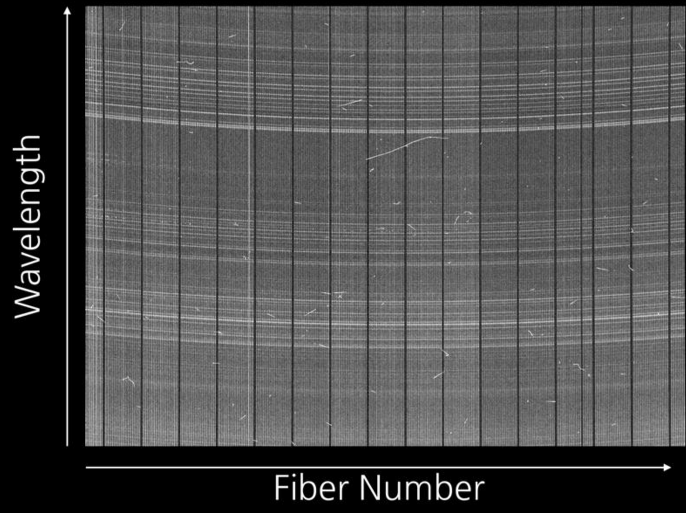


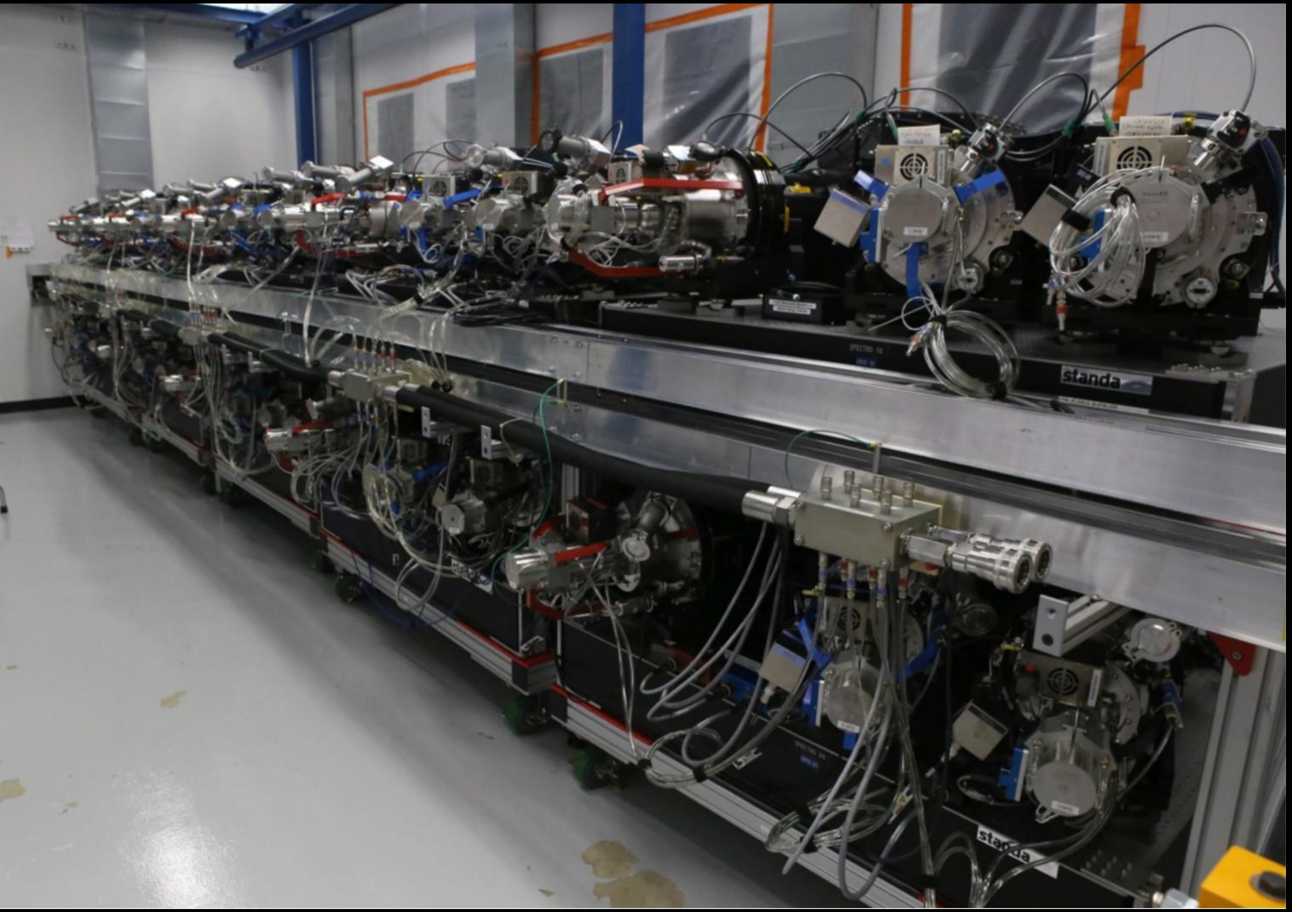
DESI:Focal Plane

5000 robotic positioners, each holding a fiber-optic cable.
Each one is automatically positioned to fix on a preset sequence of individual galaxies and quasars so that the fibers can collect their light.
The movements of these positioners must be carefully choreographed to avoid collisions.



DESI: Spectrographs





10 Multi-Object Spectrographs:
- Wavelength Range: 360 – 980 nm
- 3 channels with separate optics, CCD, cryostats
- 500 fibers
- Resolution: 2000 (blue) – 5500 (NIR)
- 4kx4k CCDs, 60s readout

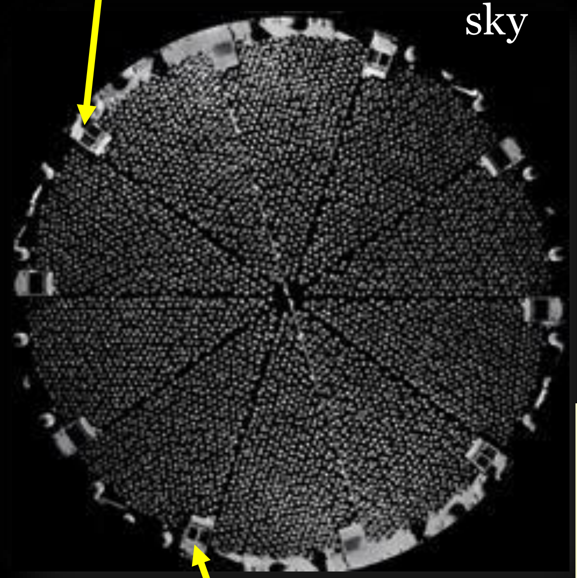
Stable PSF
better than 1 % over many days
Low Read out noise
~ 3 e-
Total Throughput of optical chain is excellent
~40% at 700 nm (total)

DESI: Fibers and GFA Systems

GFA=Guiding, Focus and Alignment

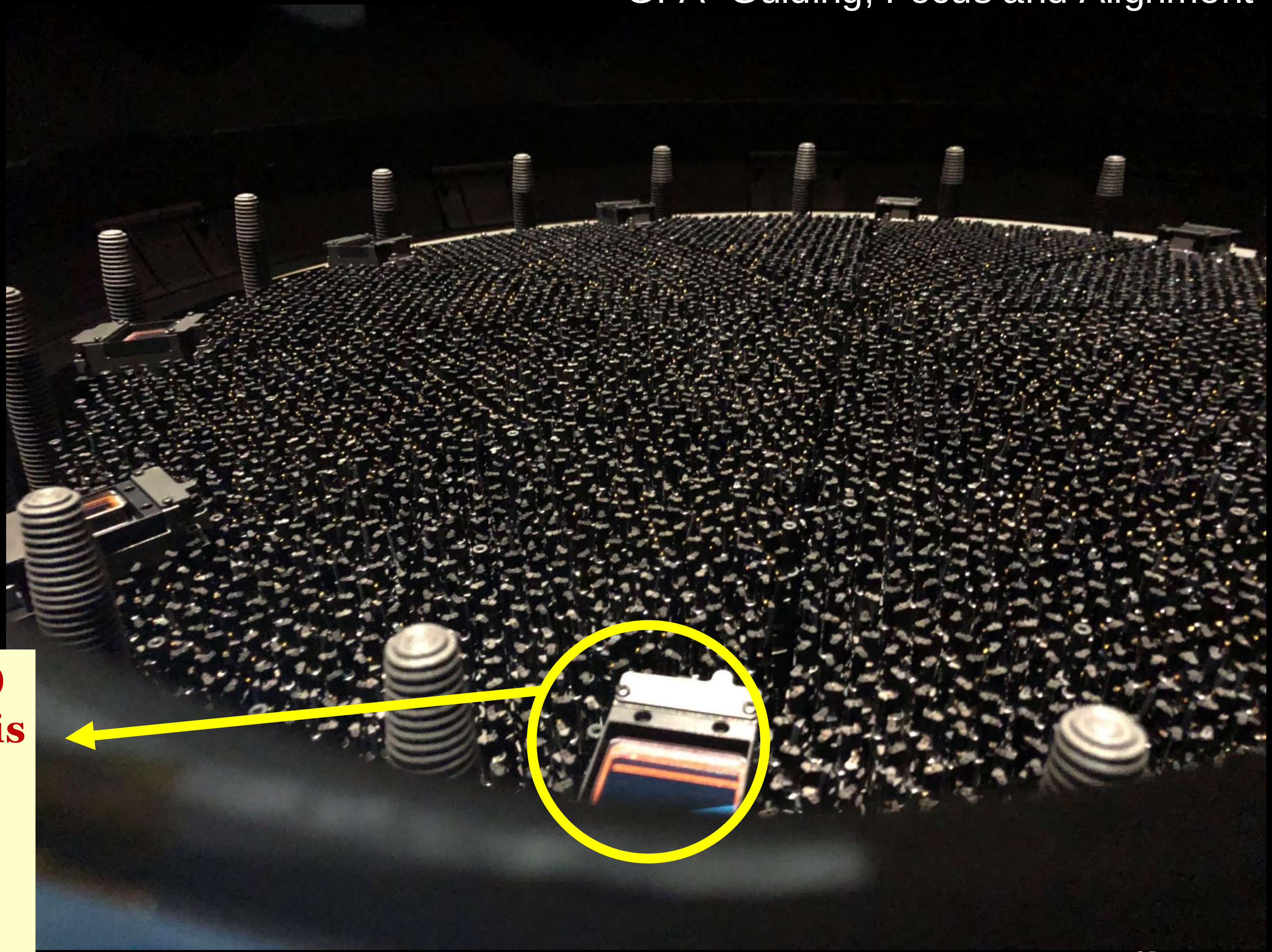
Specification
e2V CCD 230-42
1kx2k, frame transfer
ambient temperature
no shutter
3.4x7.3 arcmin^2 on sky

6 Guide Cameras
r filter



4 Wavefront Cameras
r filter, split thickness

GFA System (10 mini-cameras) is the spanish (Barcelona-Madrid) contribution to the instrument



DARK ENERGY SPECTROSCOPIC INSTRUMENT

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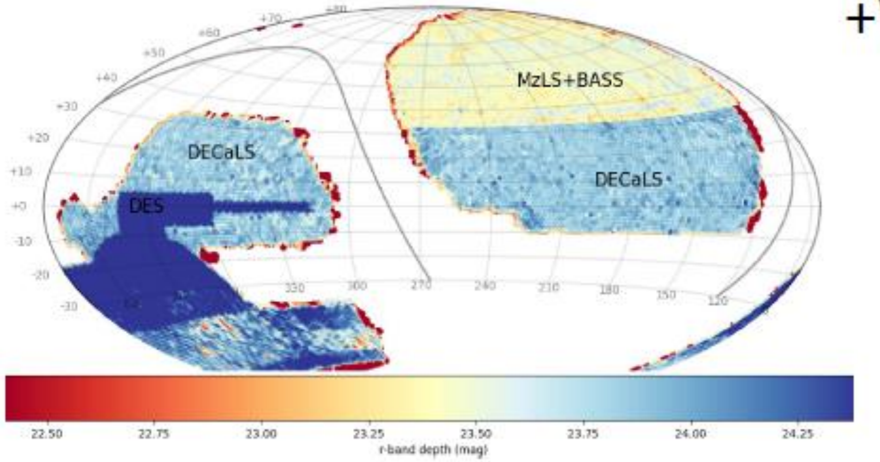
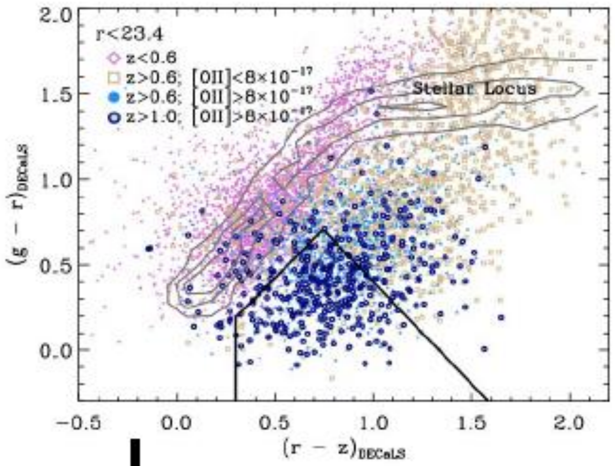
Multi-object Spectroscopy

Imaging Surveys (2014-2019)

+WISE IR sat

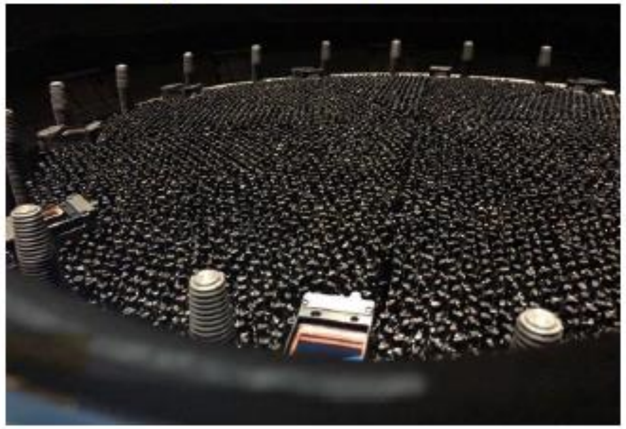


Target Selection

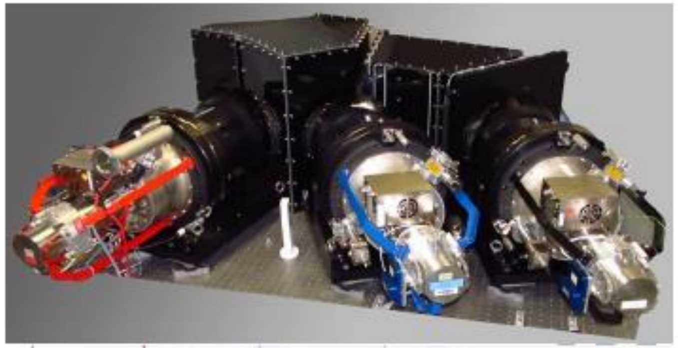


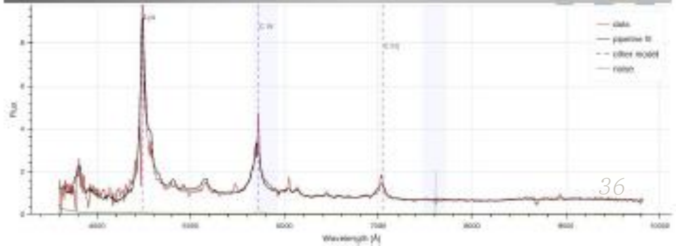
Observation…

…of 5000 objects every ~20mins…



…and measure their redshift





DESI schedule

DESI is ahead of schedule, and this is achieved even with:

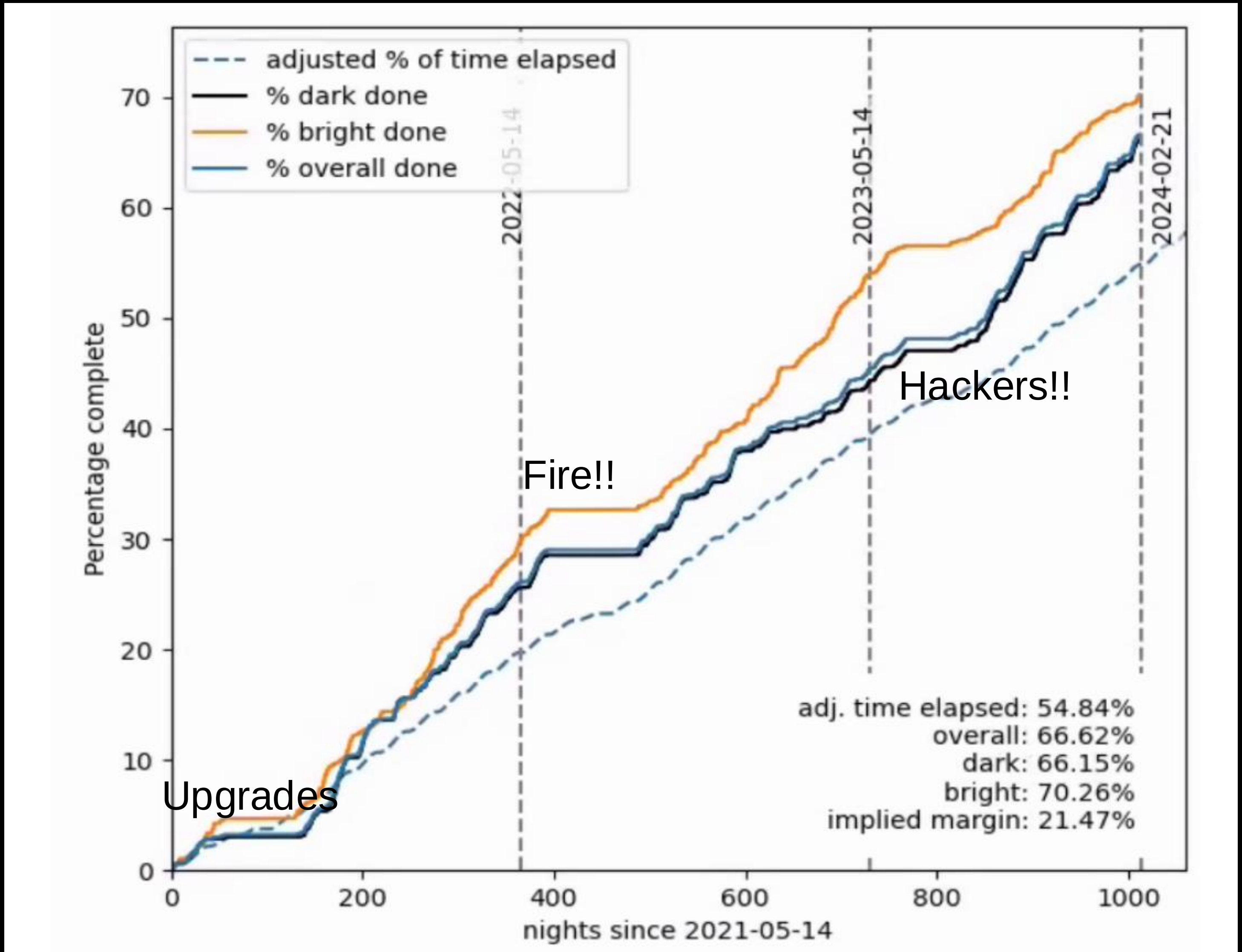
COVID shutdown (March 2020-November 2020)

Contreras fire shutdown (June 2022-September 2022)

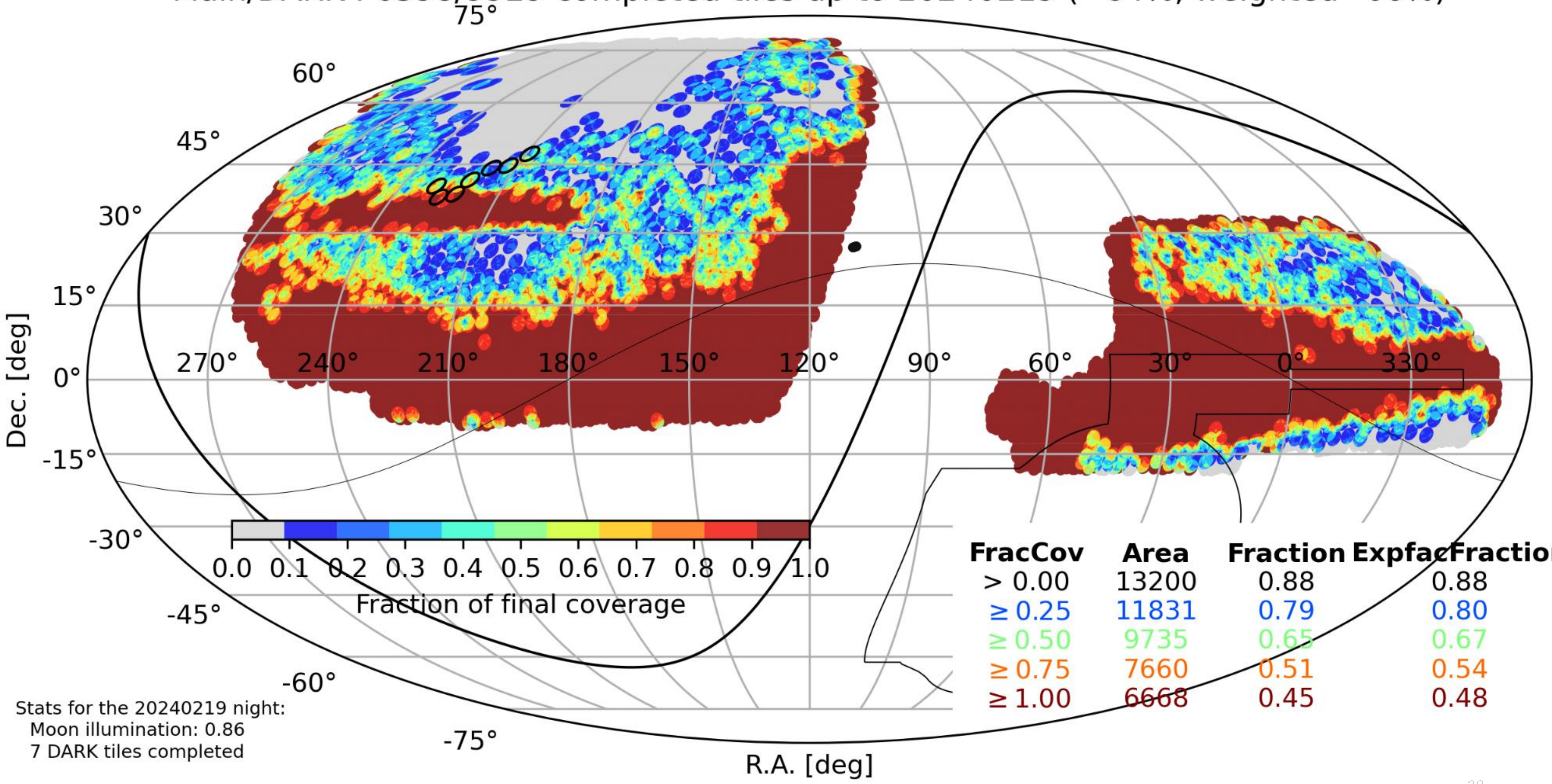
Hackers attack in 2023

The survey is now more than 60% complete
Y3 sample is already taken → Analysis starting now!!

Foreseen samples collection
✓ DESI-Y1 (up to June'22)
DESI-Y3 (up to March'24)
DESI-Y5 (final, 2026)



Main/DARK : 6398/9929 completed tiles up to 20240219 (=64%, weighted=66%)



FracCov	Area	Fraction	ExpfacFraction
> 0.00	13200	0.88	0.88
≥ 0.25	11831	0.79	0.80
≥ 0.50	9735	0.65	0.67
≥ 0.75	7660	0.51	0.54
≥ 1.00	6668	0.45	0.48

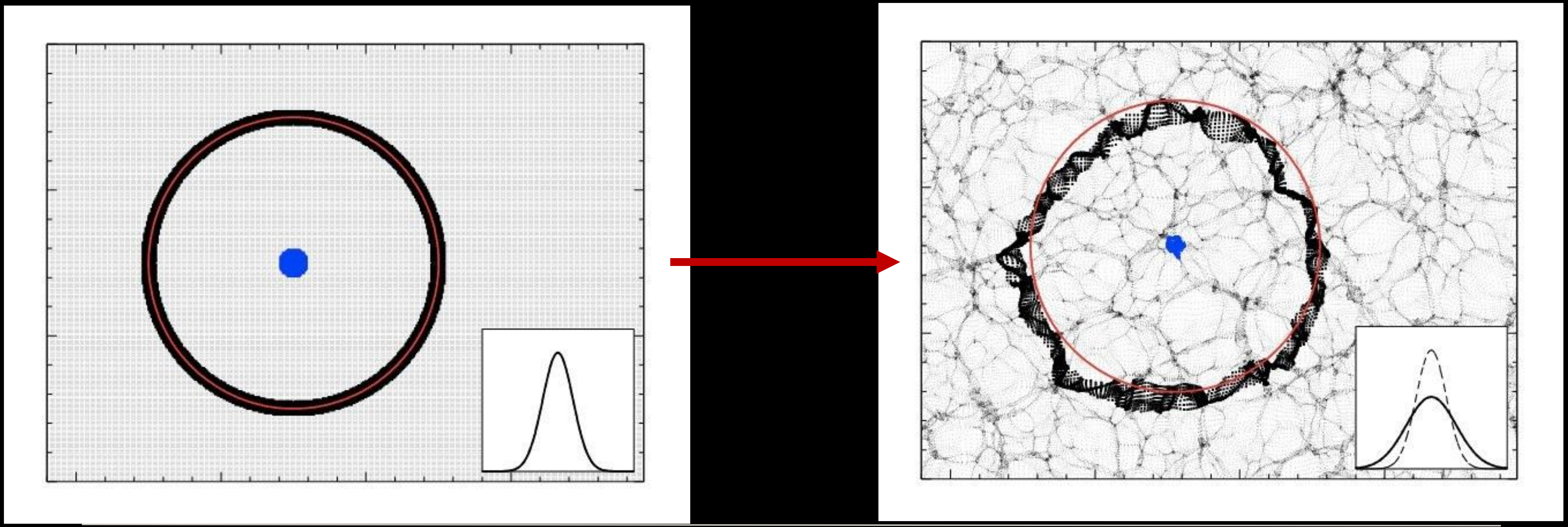
Stats for the 20240219 night:
Moon illumination: 0.86
7 DARK tiles completed

Individual systematic errors

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

Non-linear evolution

Structure growth and peculiar velocities **blur** and **shrink** the ruler, and degrades the precision of the cosmological test

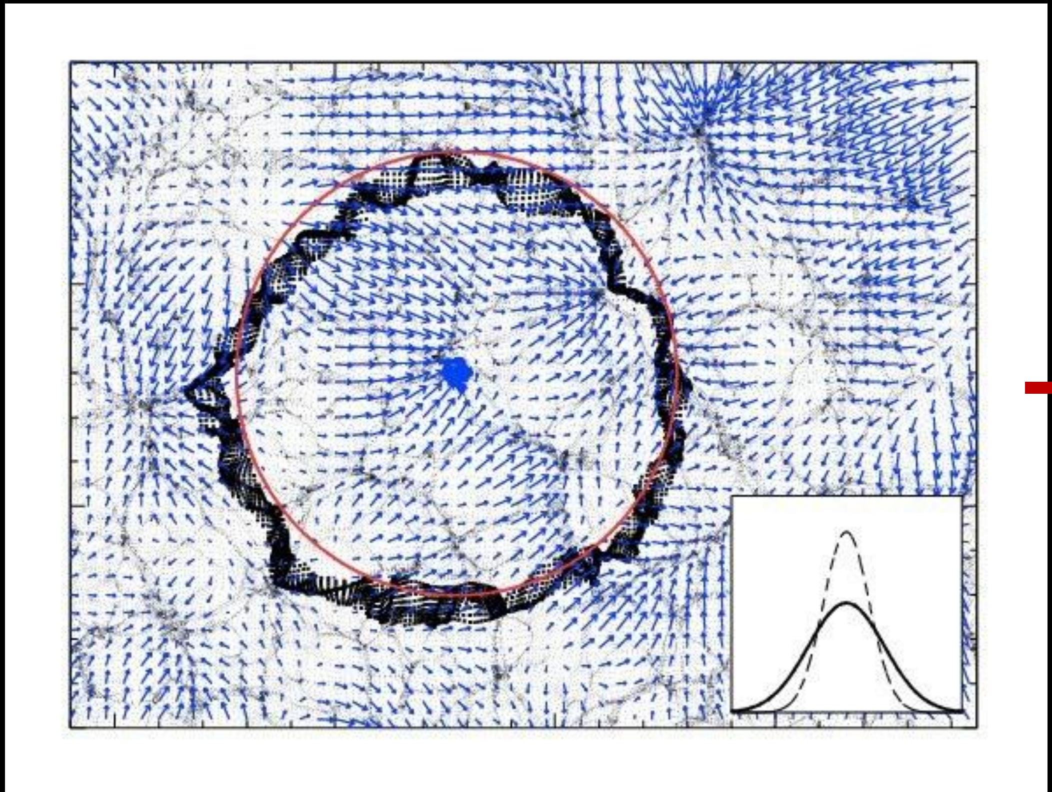


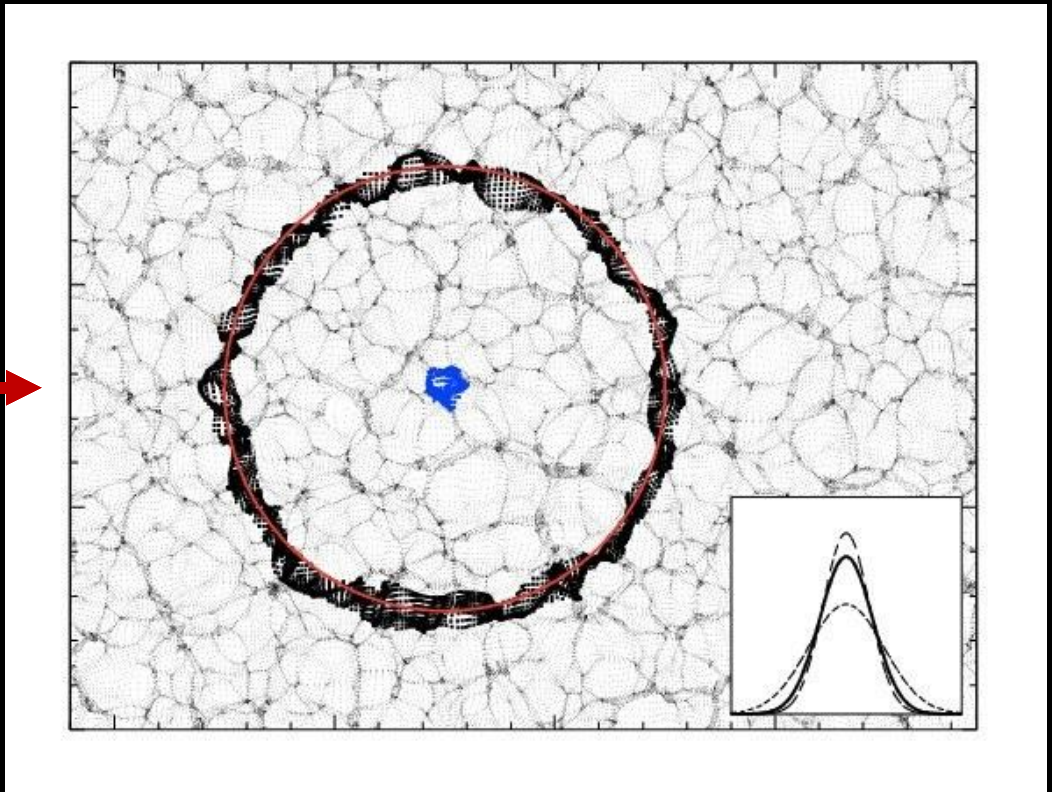
Padmanabhan et al 2012 (http://arxiv.org/abs/1202.0090)

Density field reconstruction

Estimates Zeldovich displacement from observed field, and undoes displacement

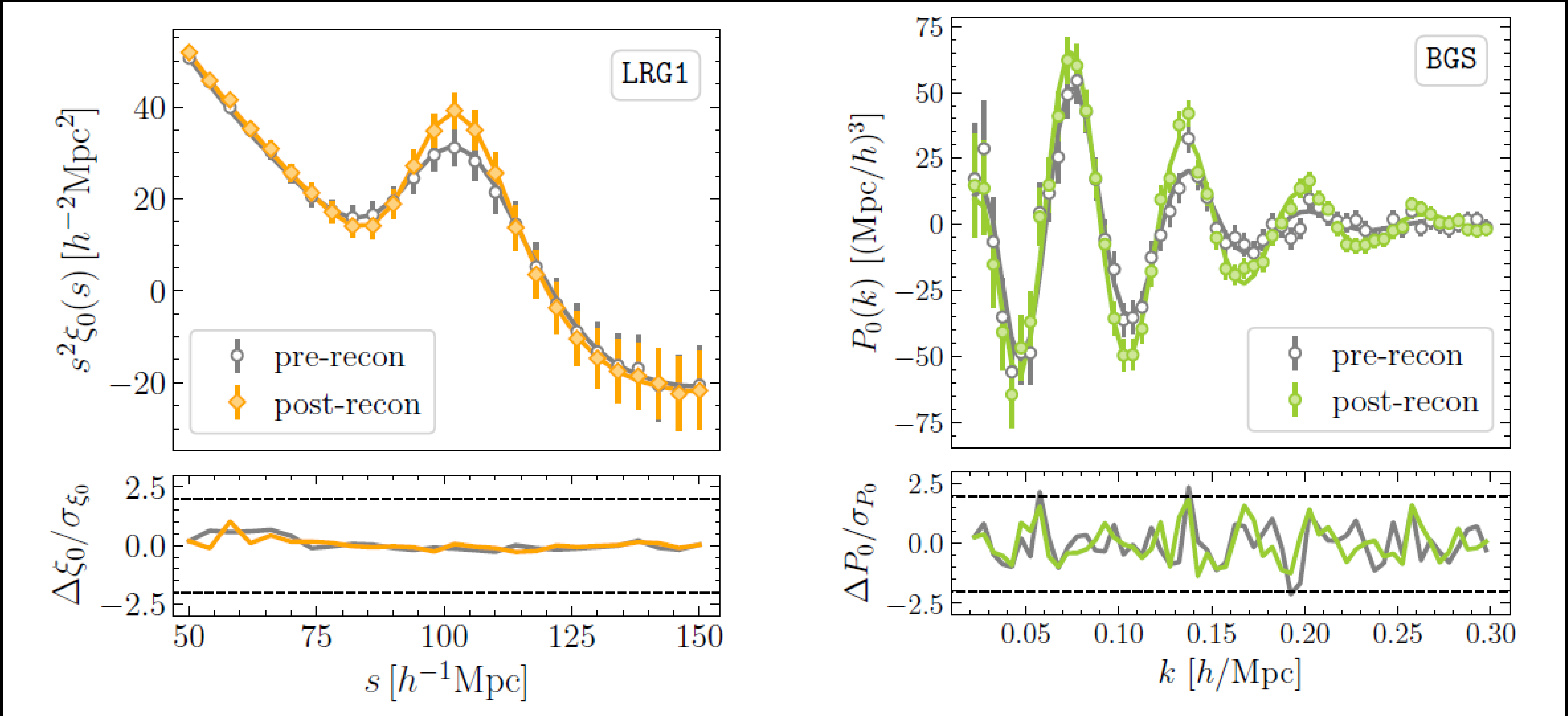
Refurbishes the ruler – **improves both precision and accuracy**





Padmanabhan et al 2012 (http://arxiv.org/abs/1202.0090)

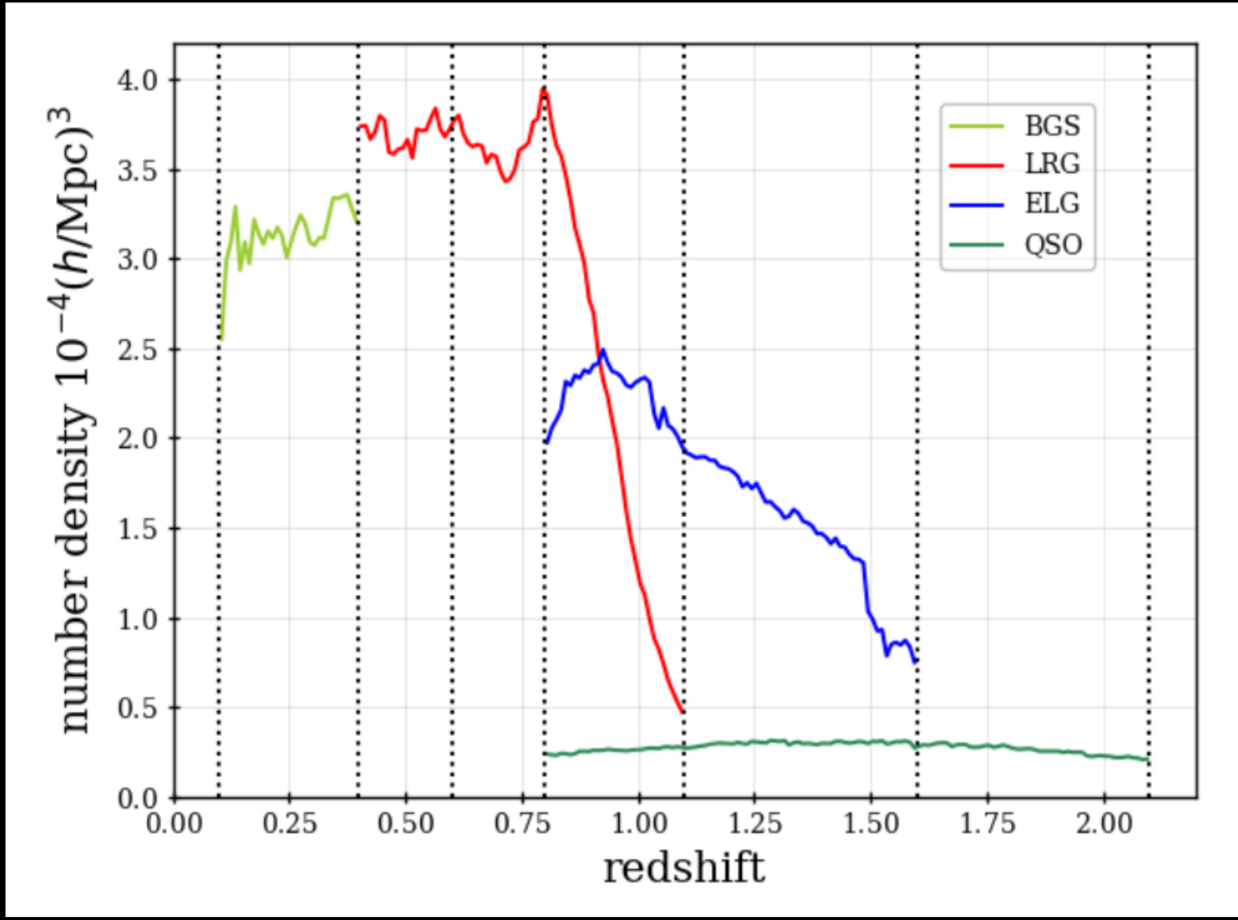
Effect of reconstruction



DESI Collaboration 2024 (arXiv:2404.03005)

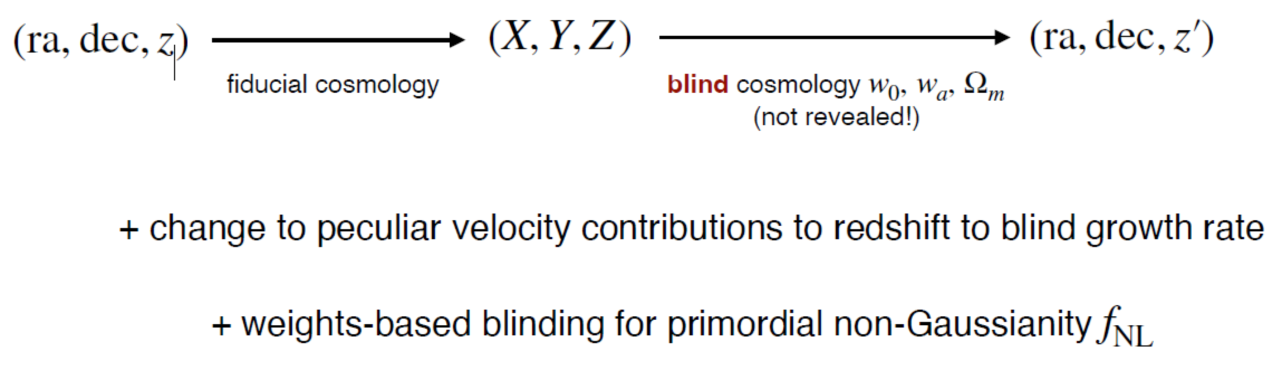
Analysis Procedure

Measure position and redshift of the galaxies, compute the correlation function (or power spectrum) and locate the excess



Effective volume: 18 Gpc^3 (3 times bigger than SDSS)

Fully blinded analysis:

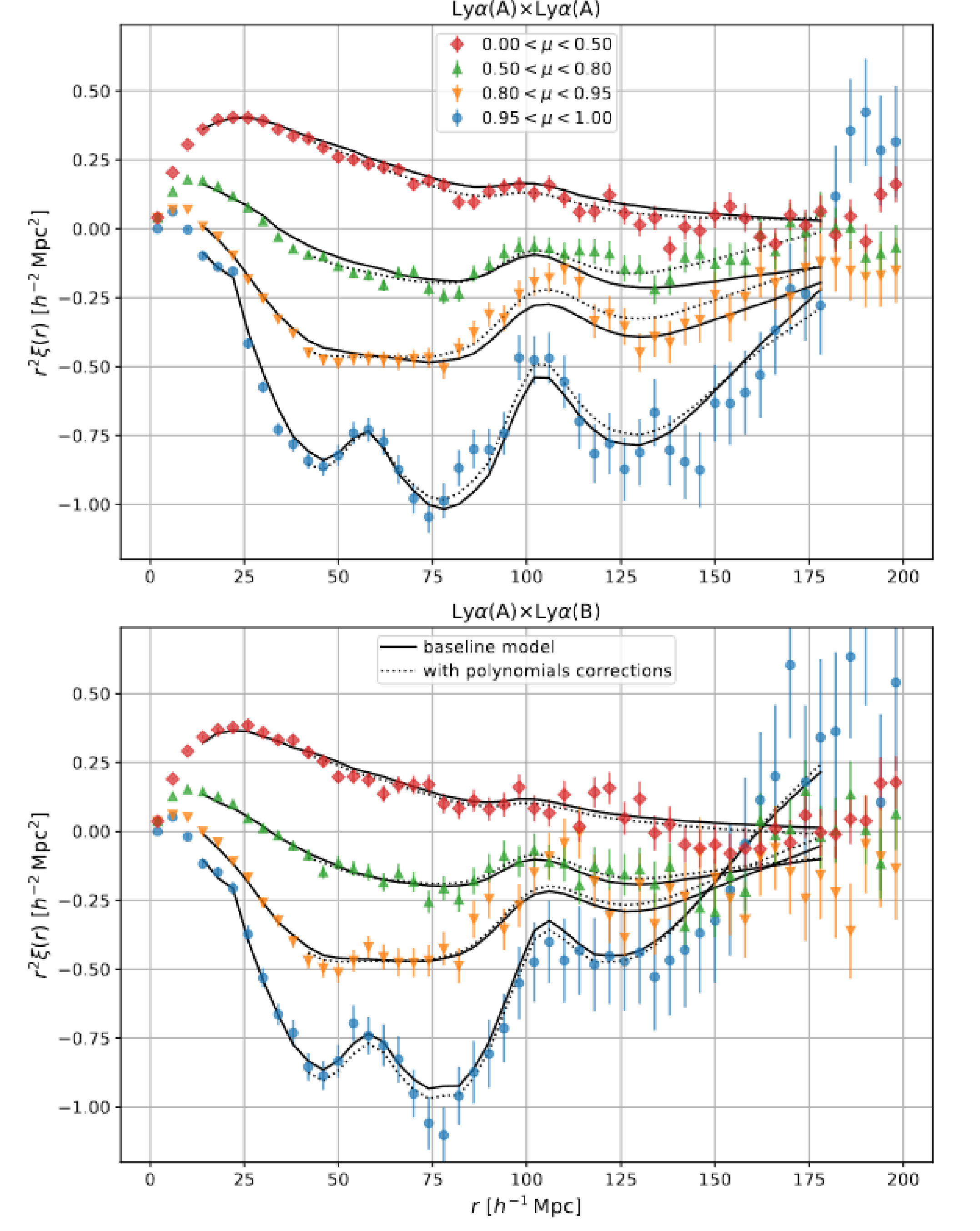


DESI Collaboration 2024 (arXiv:2404.03000)

Lyman-Alpha Forest

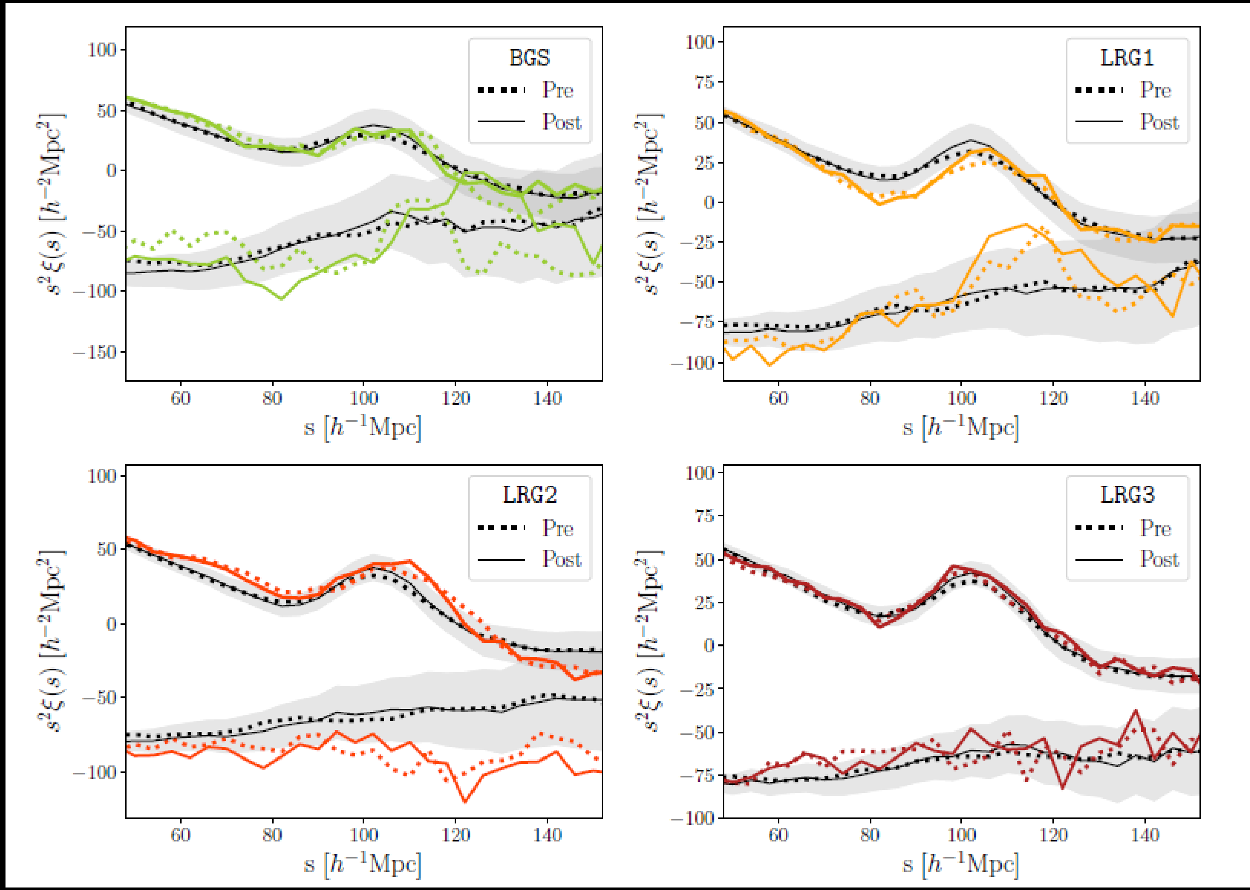
Use absorption lines due to hydrogen clouds between QSO and observer, allowing to measure higher redshifts

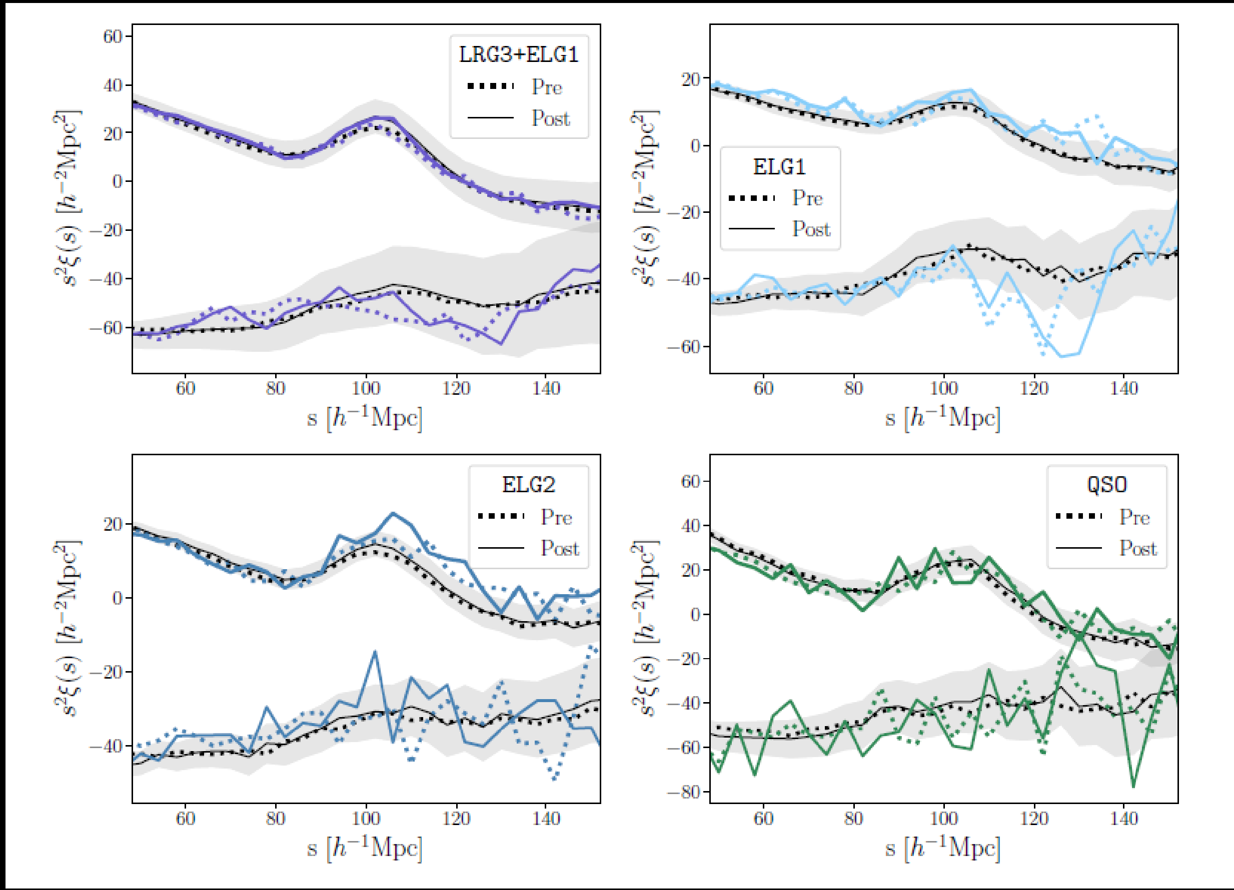
Second Peak (~60 Mpc/h) caused by Silicon lines along the line of sight. Understood and not due to BAO



DESI Collaboration 2024 (arXiv:2404.03001)

Measured Correlation Functions



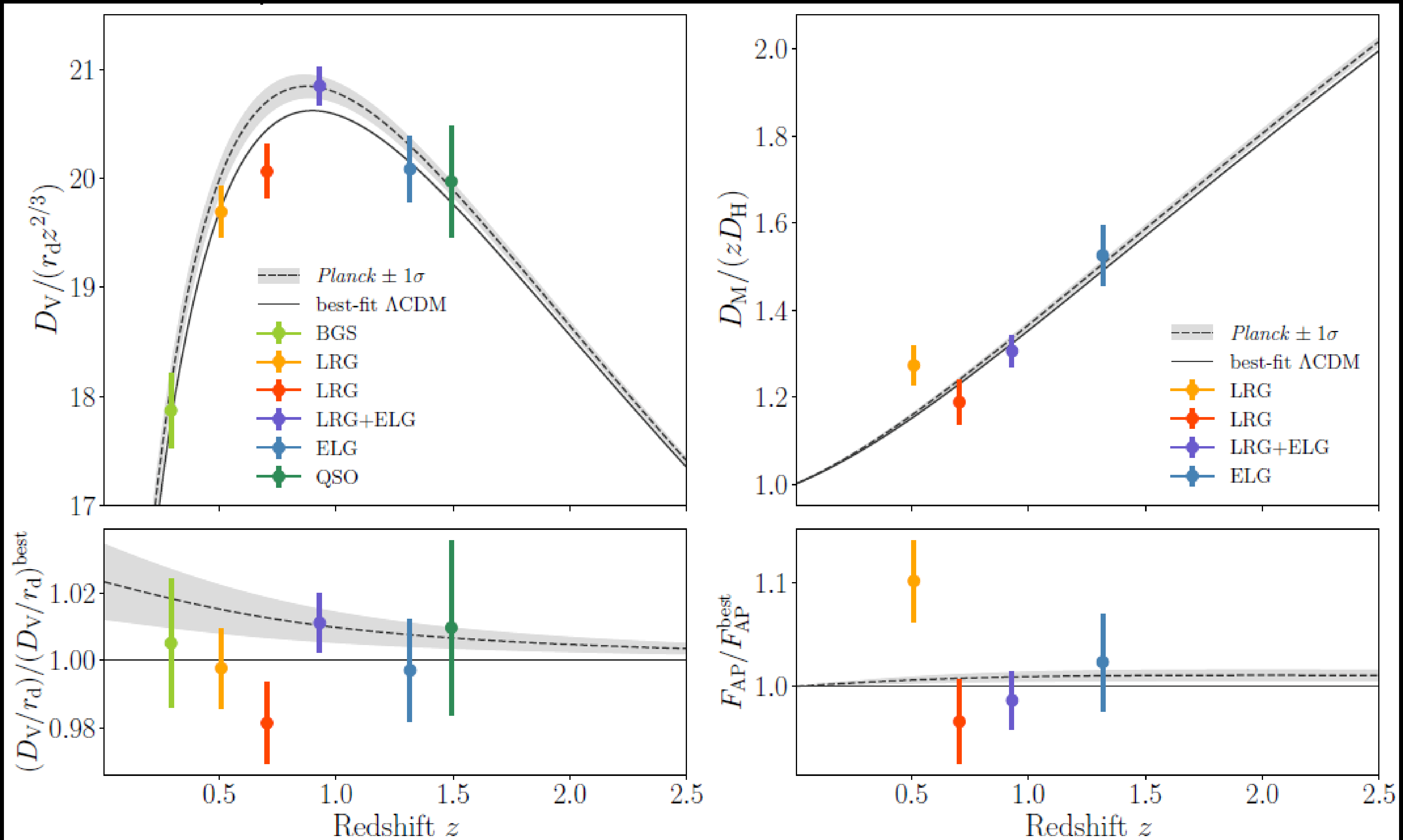


DESI Collaboration 2024 (arXiv:2404.03000)

BAO Results

$$D_V \equiv (zD_M^2 D_H)^{\frac{1}{3}}$$
$$F_{AP} \equiv D_M / D_H$$

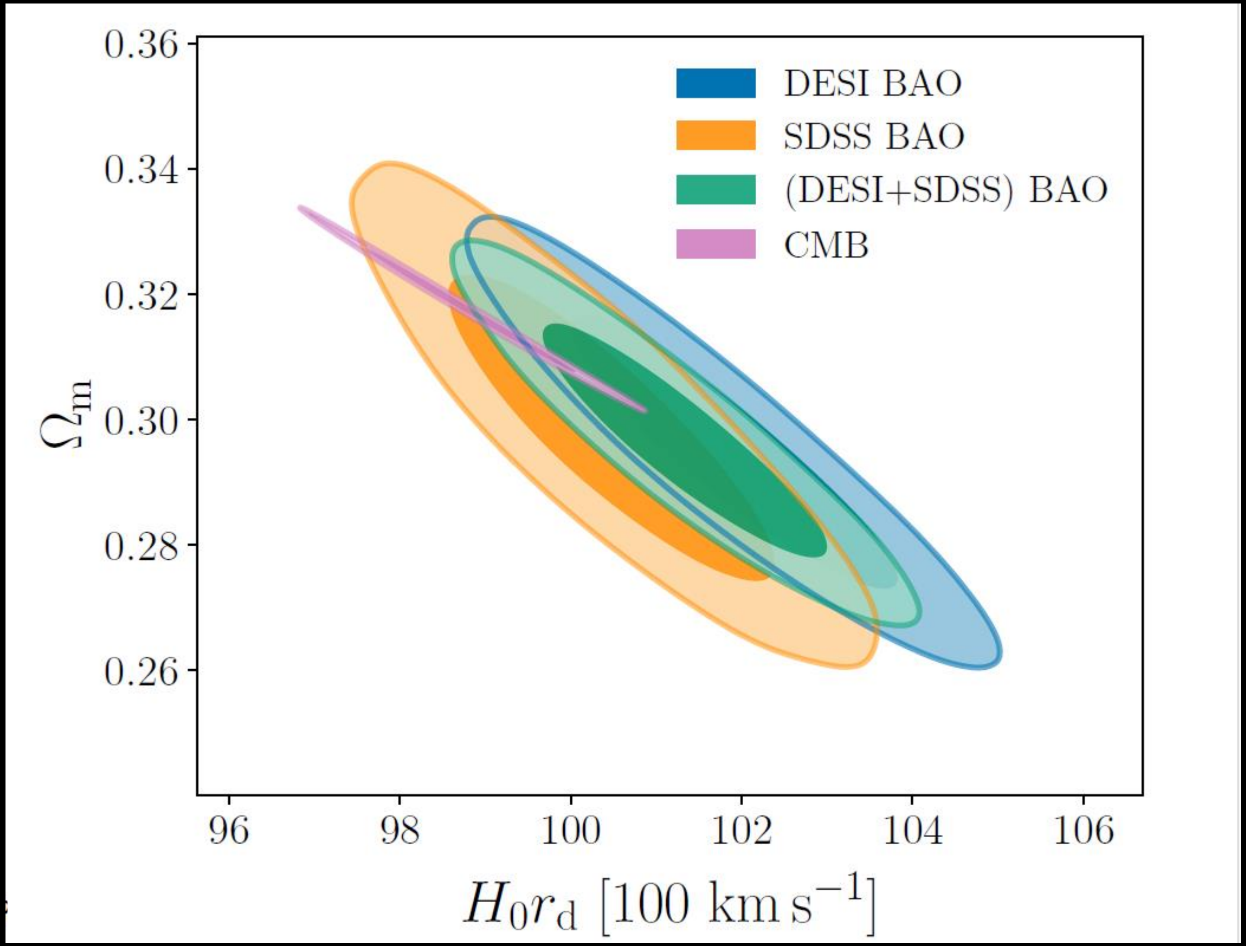
- $\chi^2 = 12.66$ for 10 d.o.f.
- 2 free parameters (Ω_m and $H_0 r_d$)
- Ω_m determines $F_{AP}(z)$ and fixes D_V/r_d shape
- $H_0 r_d$ sets a redshift-independent normalization term for D_V/r_d



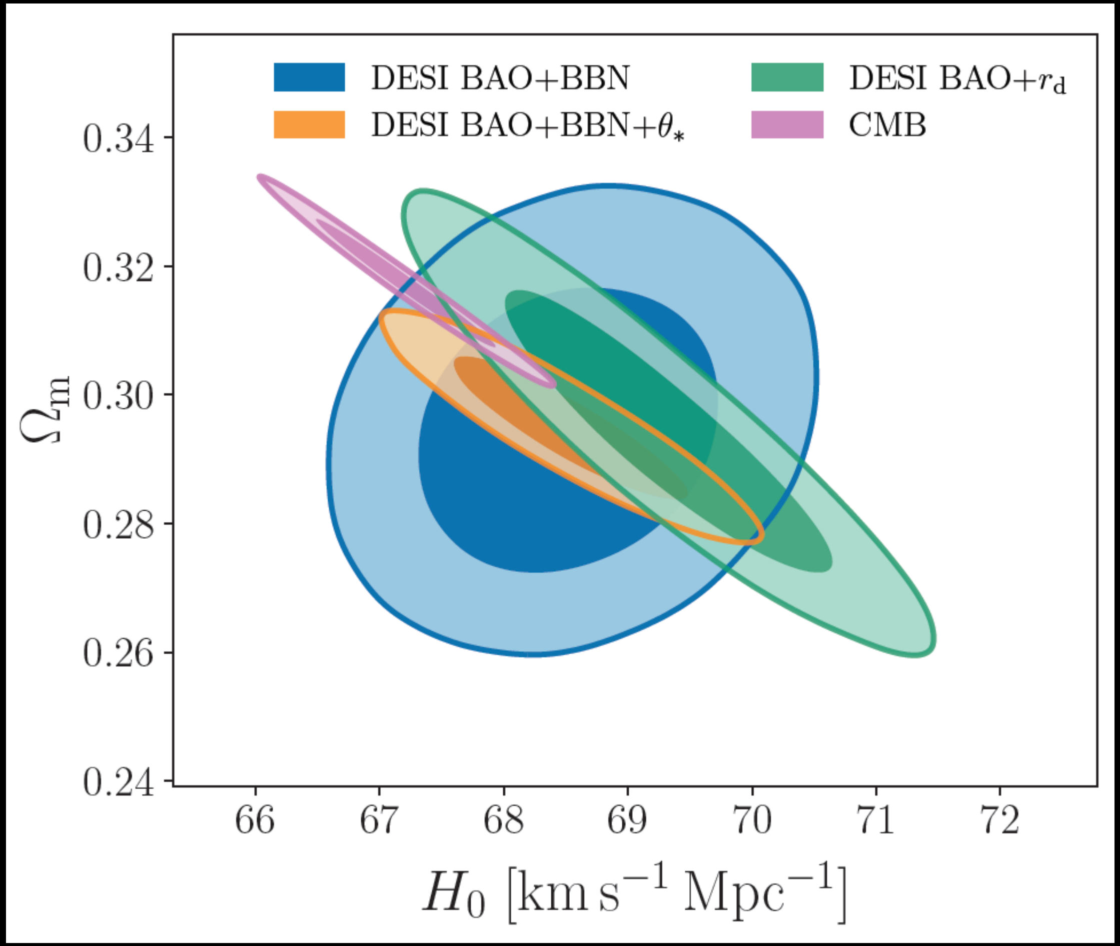
DESI Collaboration 2024 (arXiv:2404.03002)

Results: H_0

Consistent with CMB, slightly higher $H_0 r_d$



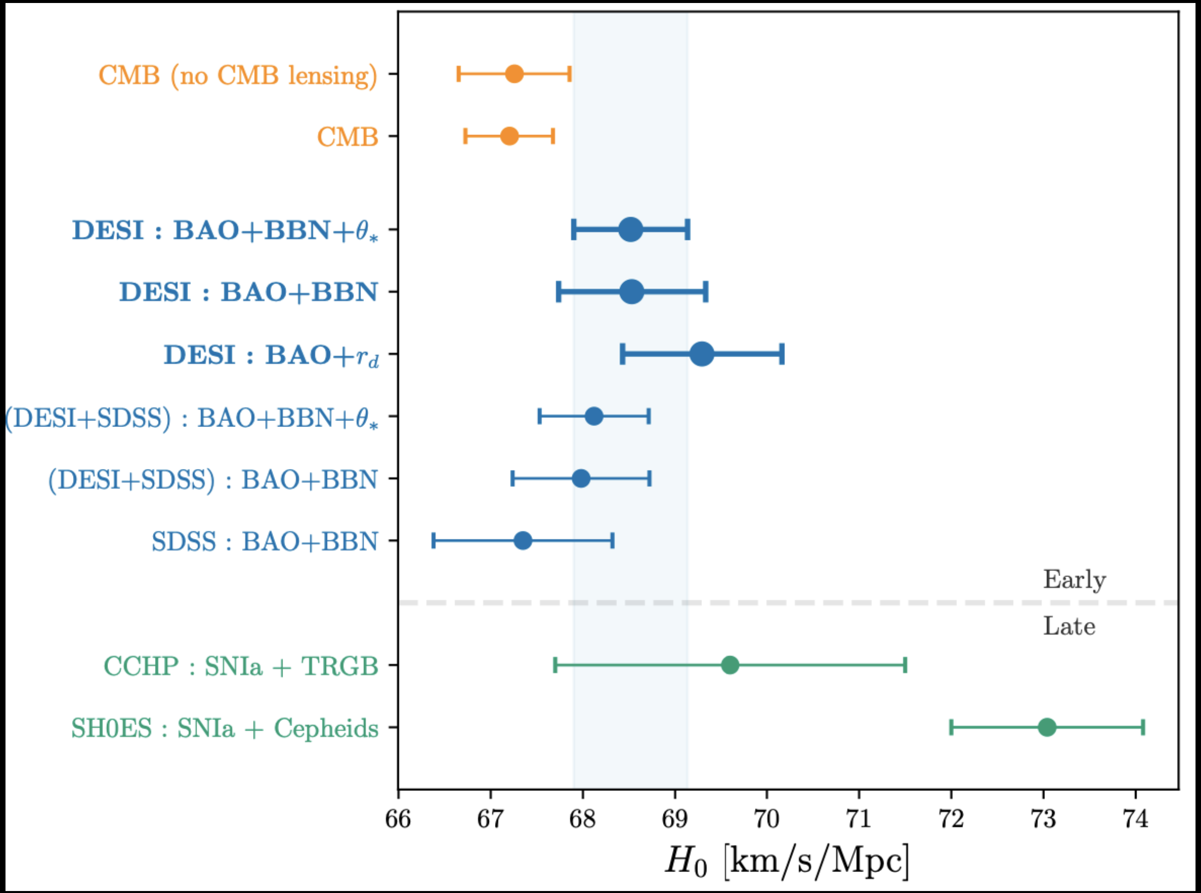
External r_d → slightly larger H_0 but still consistent with CMB



DESI Collaboration 2024 (arXiv:2404.03002)

Results: H_0

- **Tension** between late time and early time measurements ($\sim \mathbf{4-5\sigma}$)
- For DESI + BBN + θ_*: $\boldsymbol{H_0 = 68.52 \pm 0.62}$ km s^{-1} Mpc^{-1}
- For DESI + CMB: $\boldsymbol{H_0 = 67.97 \pm 0.38}$ km s^{-1} Mpc^{-1}
- Slighty higher than Planck, 3.7σ tension with SH0ES result ($\boldsymbol{H_0 = 73.04 \pm 1.04}$ km s^{-1} Mpc^{-1})
- H_0 constraints relaxed if assumption of flat ΛCDM is **relaxed**



DESI Collaboration 2024 (arXiv:2404.03002)

DE constraints: ΛCDM

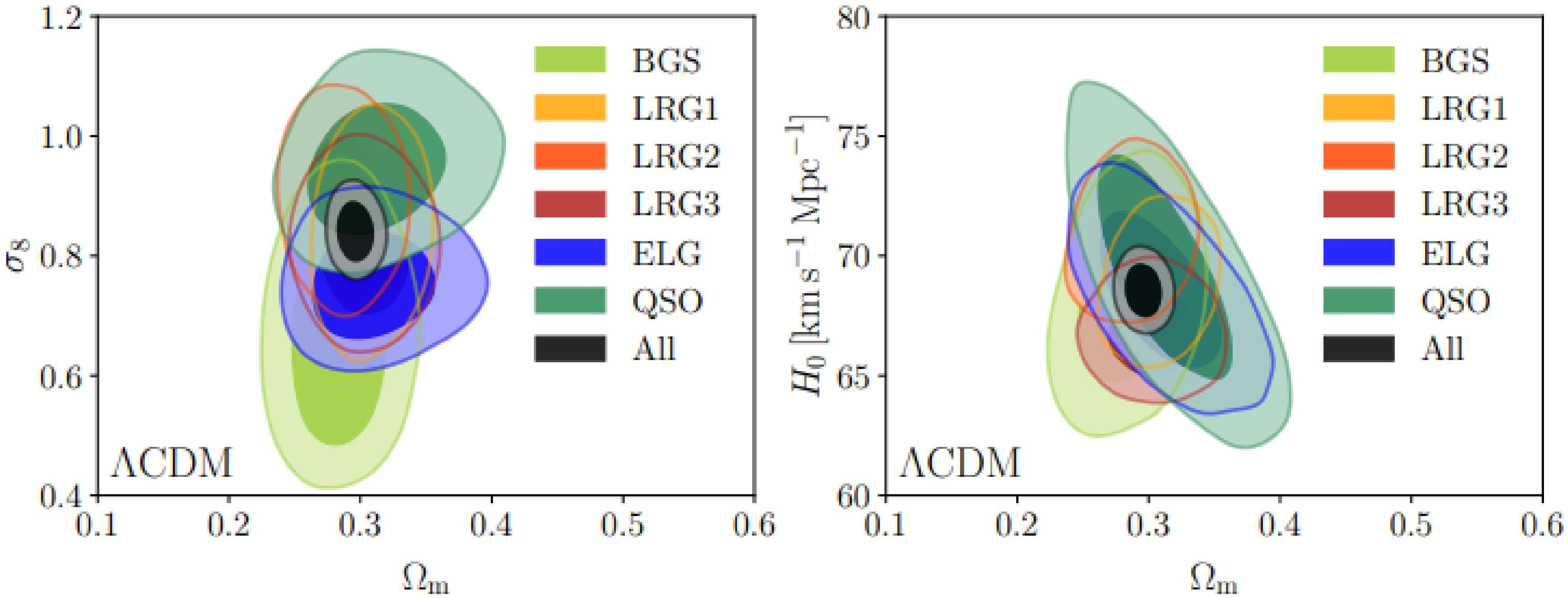
- $\Omega_{de} \equiv 1 - \Omega_m$
- $S_8 \equiv \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.5}$

- Full-shape information lead to an improvement on matter density constraints.

$$\sigma(\Omega_m) = 0.015\ (BAO)$$
$$\sigma(\Omega_m) = 0.0095\ (FS)$$

- Constraint on σ_8 comes from FS, and compatible with CMB result (but with bigger error).

$$\sigma_8 = 0.8133 \pm 0.0050$$



$$\left.\begin{aligned} \Omega_m &= 0.2962 \pm 0.0095, \\ \sigma_8 &= 0.842 \pm 0.034, \\ H_0 &= (68.56 \pm 0.75)\ \mathrm{km\,s^{-1}\,Mpc^{-1}}, \end{aligned}\right\}\ \text{DESI (FS+BAO)+BBN+}n_{s10};$$

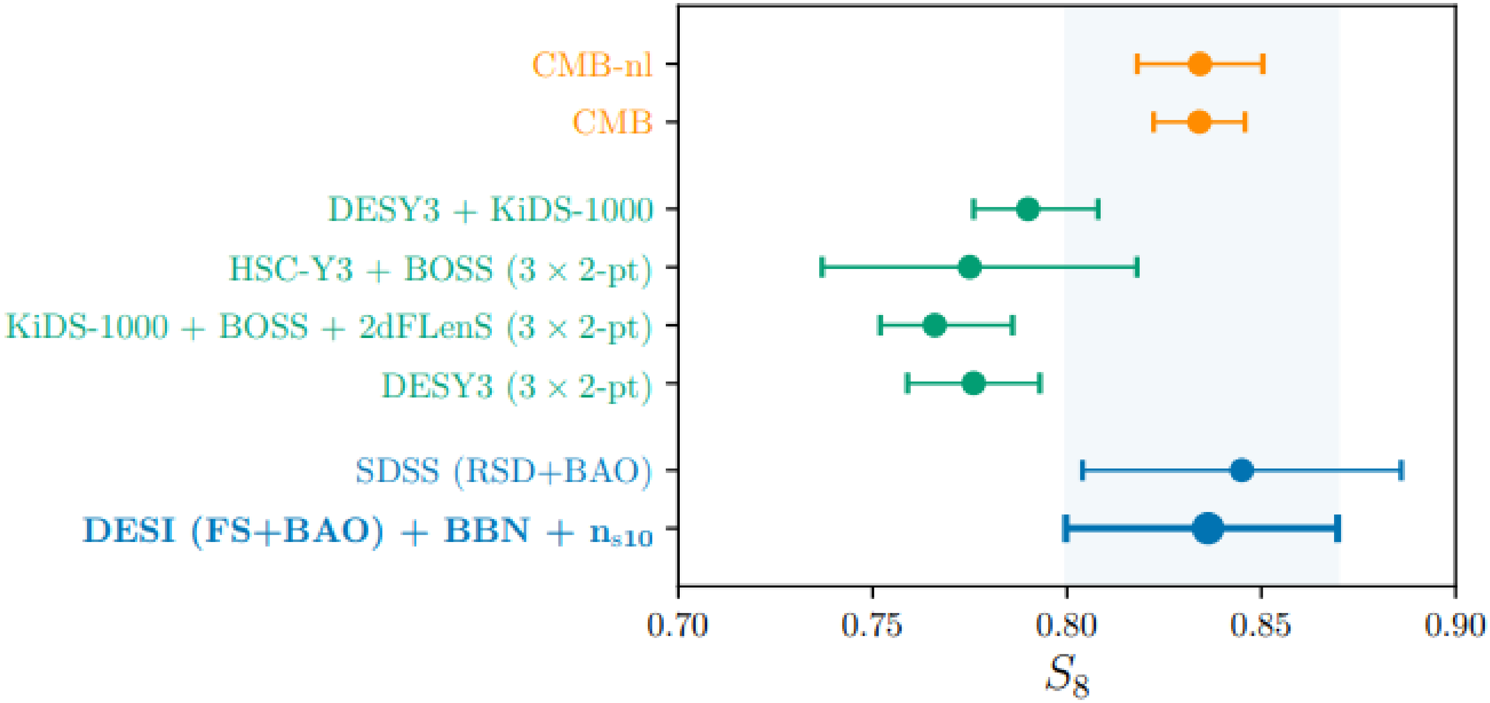
DE constraints: ΛCDM

- Excellent agreement between DESI(FS+BAO) and CMB, slightly higher than results from weak-lensing

  $S_8 = 0.776 \pm 0.017 \; (DESY3)$

- Excellent agreement also with SDSS combined with RSD and BAO

  $S_8 = 0.845 \pm 0.041$



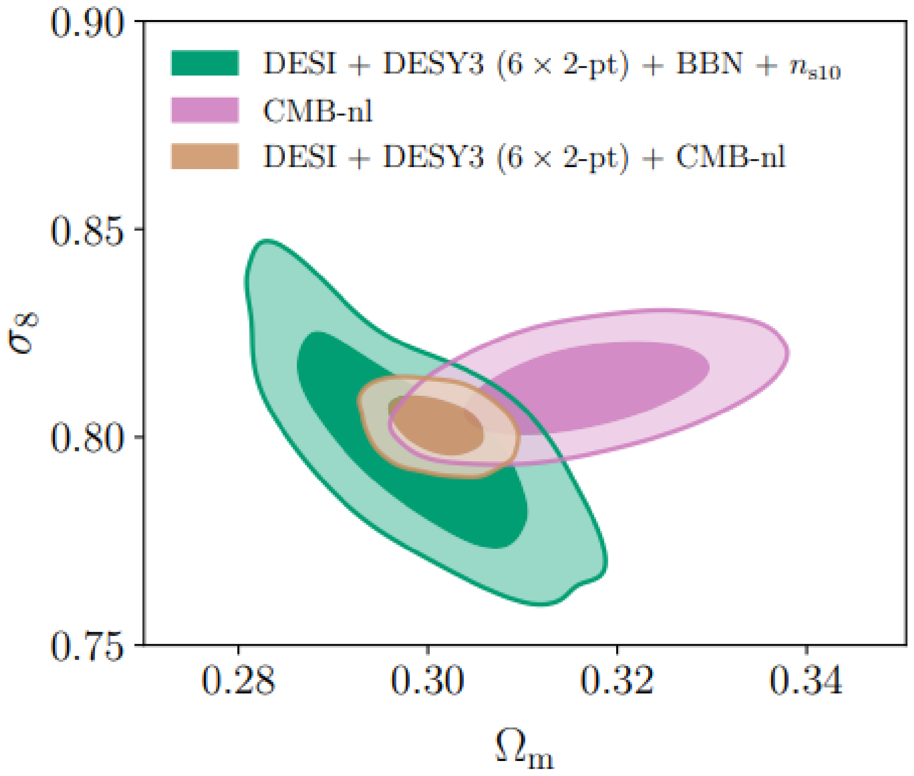
$$S_8 = 0.836 \pm 0.035 \quad \text{(DESI (FS+BAO)+BBN+}n_{s10}\text{)}$$

DE constraints: ΛCDM

- Consinstency with FS+BAO alone
- Uncertanties halved in H_0, error on σ_8 decreases by more than a factor of five
- Contrains improved respect to CMB alone, exception for σ_8 (expected)
- Error on σ_8 increase if we consider CMB-nl

$$\sigma_8 = 0.8086 \pm 0.0071$$

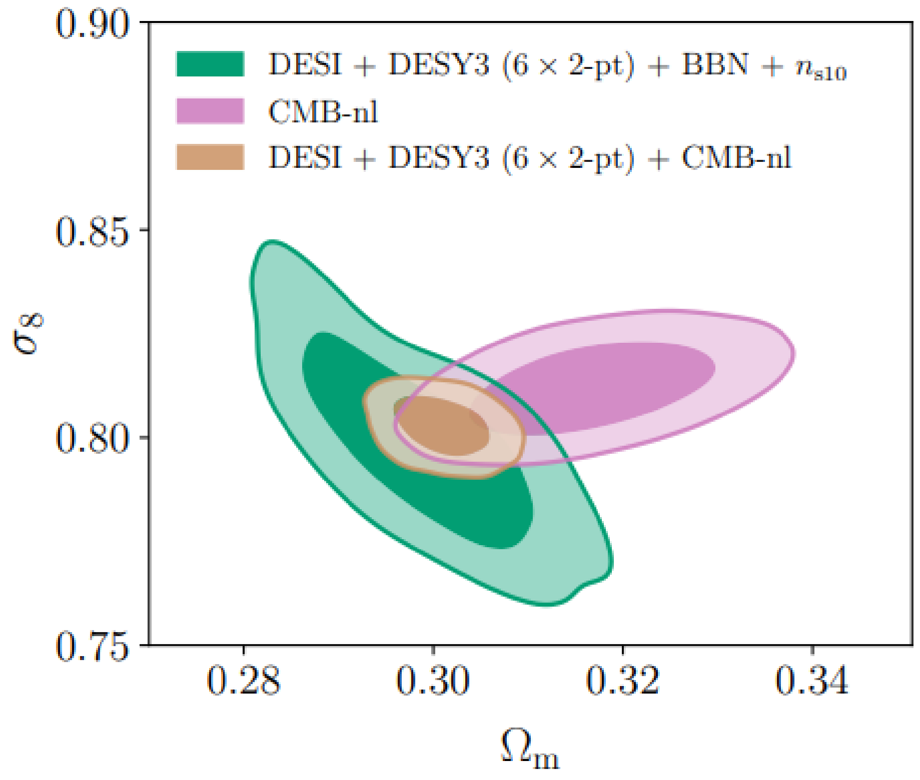
Expected beacuse of CMB lensing is sensitive to this parameter



$$\left.\begin{aligned} \Omega_m &= 0.3057 \pm 0.0050, \\ \sigma_8 &= 0.8121 \pm 0.0053, \\ H_0 &= (68.06 \pm 0.38)\ \mathrm{km\,s^{-1}\,Mpc^{-1}}, \end{aligned}\right\} \text{DESI (FS+BAO) + CMB}$$

DE constraints: ΛCDM

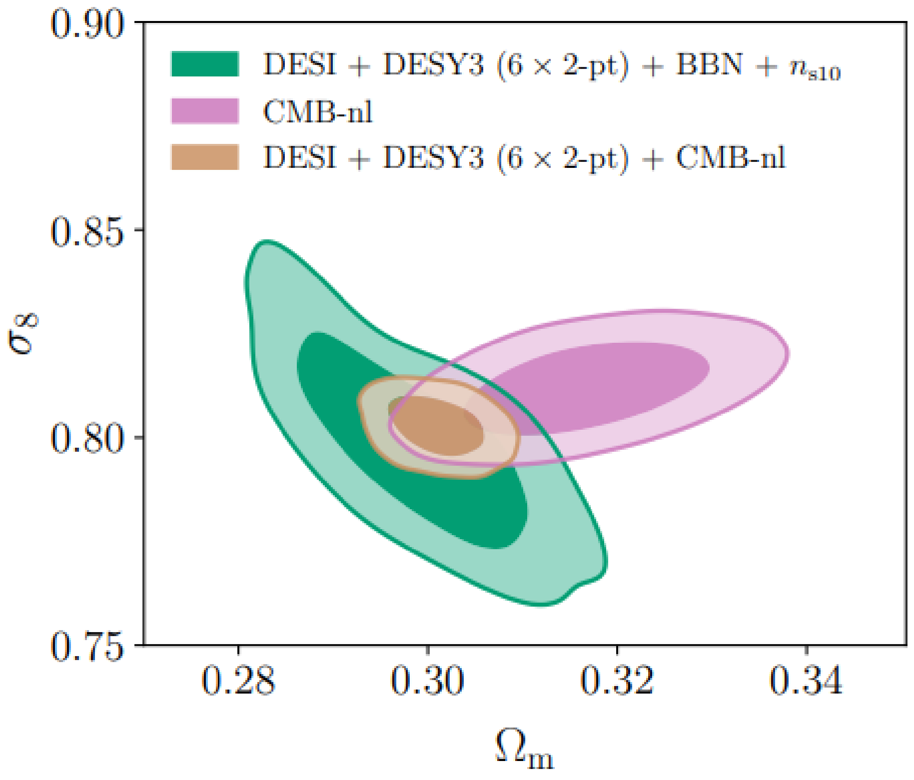
- With 6x2-pt combination the improvement on σ_8 error is about a factor of 2, pulling central value down by one standard deviation
- Pull down is due to lensing information present in DESY3 data
- Addition on 6x2 data doesn't change the precision of DESI's contraints on H_0 and Ω_m
- Improvement in σ_8 and S_8 errors passing from 3x2 to 6x2, indicates CMB lensing information present in DESY3 analysis is significant



$$\left.\begin{aligned} \Omega_m &= 0.2986 \pm 0.0081, \\ \sigma_8 &= 0.799 \pm 0.016, \\ H_0 &= (68.66^{+0.63}_{-0.73})\ \mathrm{km\,s^{-1}\,Mpc^{-1}}. \end{aligned}\right\} \text{DESI (FS+BAO)+BBN+}n_{s10}\text{ + DESY3 }(6\times\text{2-pt}).$$

DE constraints: ΛCDM

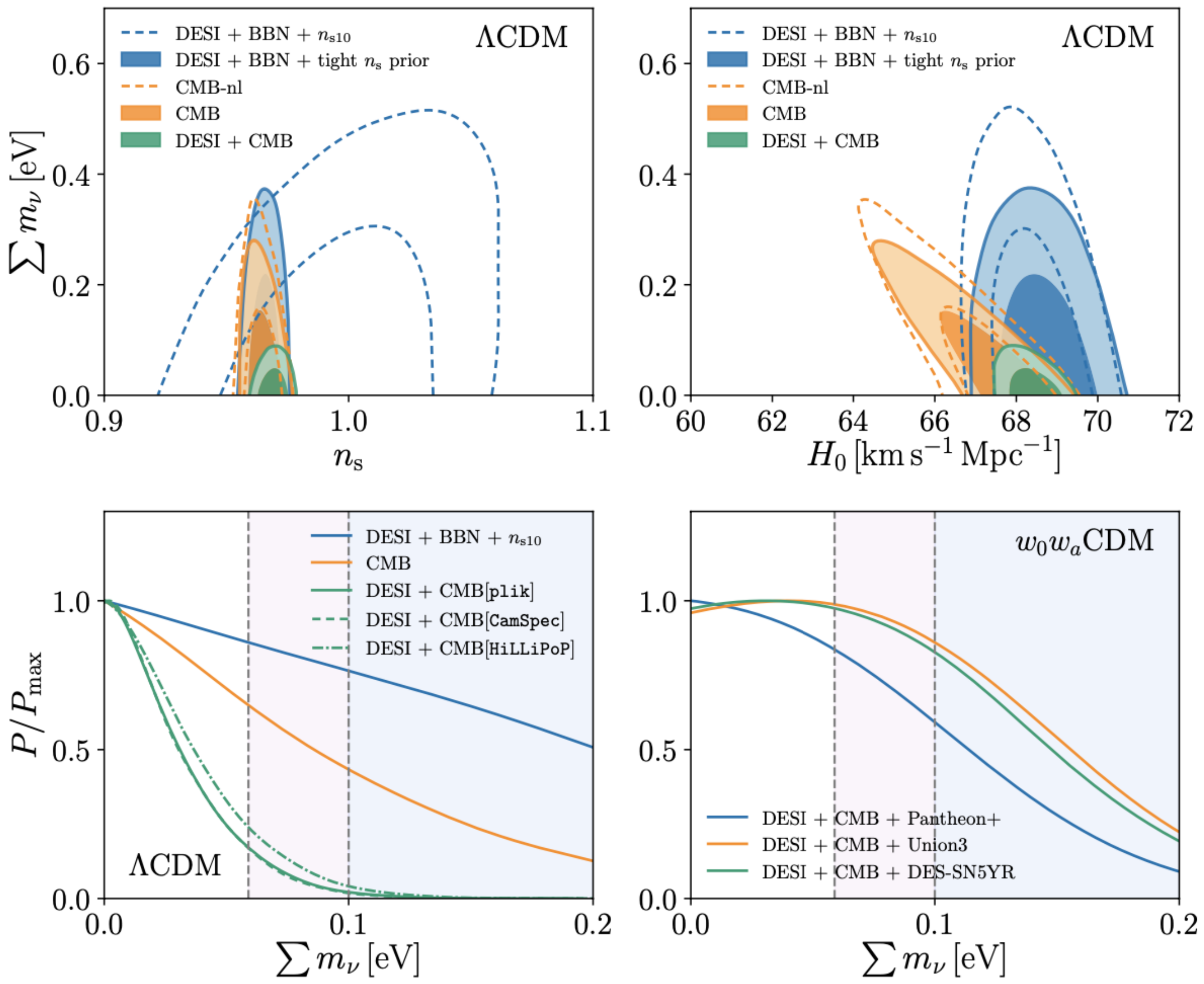
- The addition of CMB-nl to the combination leads to a factor three of improvement in the error.
- Matter density determined with 1% of accuracy, σ_8 and S_8 to 0.6% and $H_0$with 0.4%
- Addition of DESI data improve the measurement of H_0 by 20% compared to CMB-nl+6x2-pt
- DESI alone preferes lower values of H_0, in agreement with CMB measurements: 4.5σ tension with measurements that use Cepheid valiables and nearby SN Ia



$$\left.\begin{aligned} \Omega_{\rm m} &= 0.3009 \pm 0.0034, \\ \sigma_8 &= 0.8028^{+0.0050}_{-0.0045}, \\ H_0 &= (68.40 \pm 0.27)\ {\rm km\,s^{-1}\,Mpc^{-1}}. \end{aligned}\right\} \text{DESI (FS+BAO) + CMB-nl + DESY3 } (6 \times 2\text{-pt}).$$

Sum of neutrino masses

- Posteriors still peaks near 0 for all data combinations
- Compared to the DESI (BAO) analysis, the full-shape information leads to a 15% stronger constraint and a slight increase in the tension. DESI + CMB result remains compatible with the lower bound for the NO at the ~2σ level
- Bounds are obtained for $\sum m_\nu > 0$ prior. Upper limits increase for more restrictive priors
- Consequence of posterior volume in the unphysical range



Sum of neutrino masses

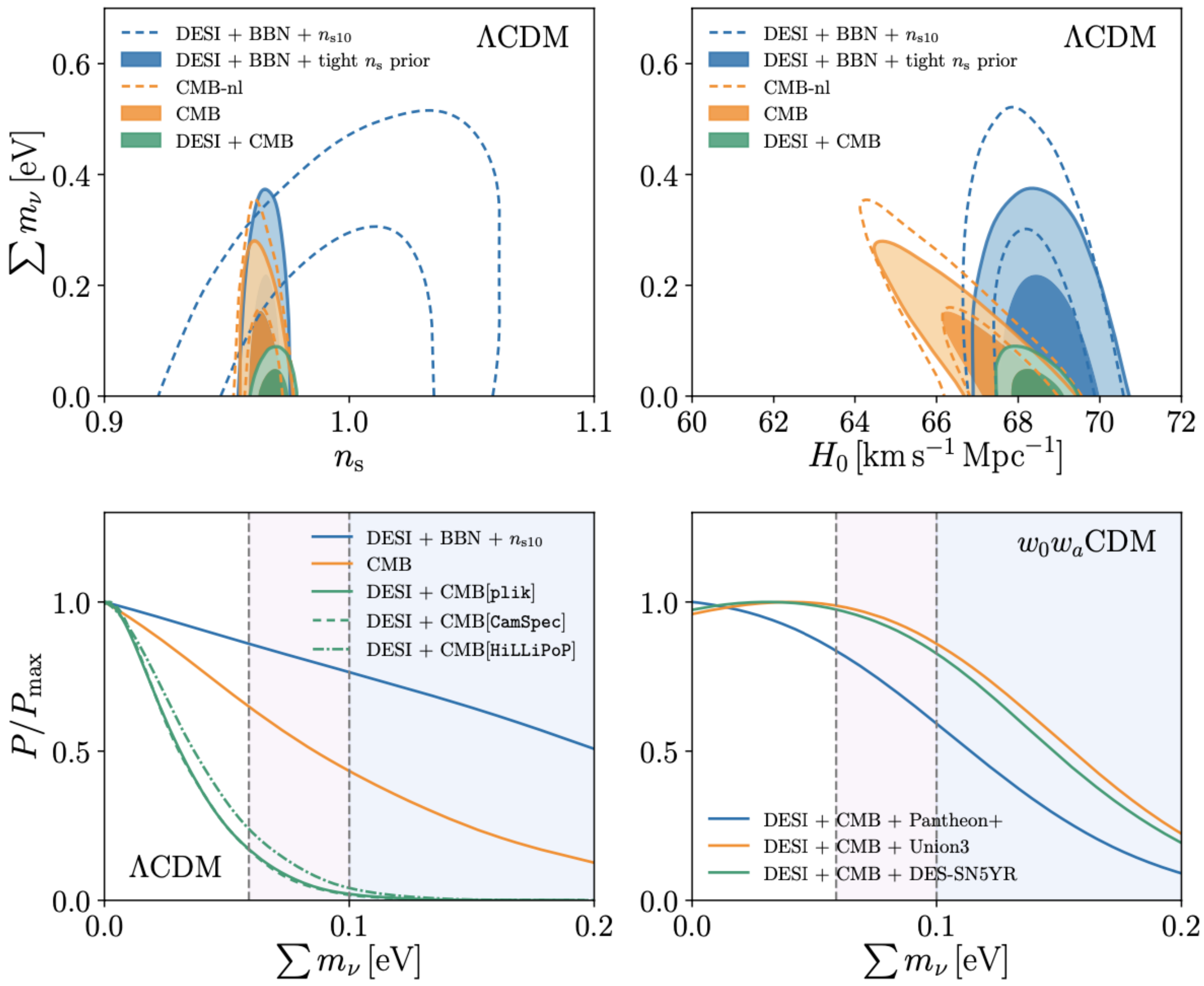
Potential systematic from CMB lensing anomaly

$$\sum m_\nu < 0.069\,\mathrm{eV} \quad (95\,\%,\ \mathrm{DESI\ (FS{+}BAO) + CMB[\texttt{CamSpec}]})$$

$$\sum m_\nu < 0.081\,\mathrm{eV} \quad (95\,\%,\ \mathrm{DESI\ (FS{+}BAO) + CMB[\texttt{HiLLiPoP}]})$$

Constraints depend strongly on the assumed dark energy model

$$\left.\begin{aligned} \sum m_\nu &< 0.196\,\mathrm{eV}\ \ (95\%), \\ w_0 &= -0.753 \pm 0.070, \\ w_a &= -1.02^{+0.37}_{-0.29}, \end{aligned}\right\} \ \mathrm{DESI\ (FS{+}BAO) + CMB + DES\text{-}SN5YR},$$



Number of relativistic species

$$\rho_\nu = N_{eff} \frac{7}{8} \left(\frac{4}{11}\right)^{\frac{4}{3}} \rho_\gamma$$

- For a standard cosmological model: $\mathbf{N_{eff}}$ **= 3.044**
- Constraints on N_{eff} from CMB exhibit a geometrical degeneracy.
- Increasing N_{eff} correspond to higher H_0 or lower Ω_m

$$N_{eff} = 3.18 \pm 0.18 \text{ (DESI(FS+BAO) + CMB)}$$

Small shift due to DESI preference for lower Ω_m

Modified Gravity constraints

- DESI full-shape clustering data are sensitive to the growth of large-scale structure, and can hence constrain deviations from general relativity
- A common and promising approach to testing deviations from general relativity is to add physically motivated phenomenological parameters to the perturbed Einstein's gravitational field equations and test the deviations of such parameters from their GR predicted values

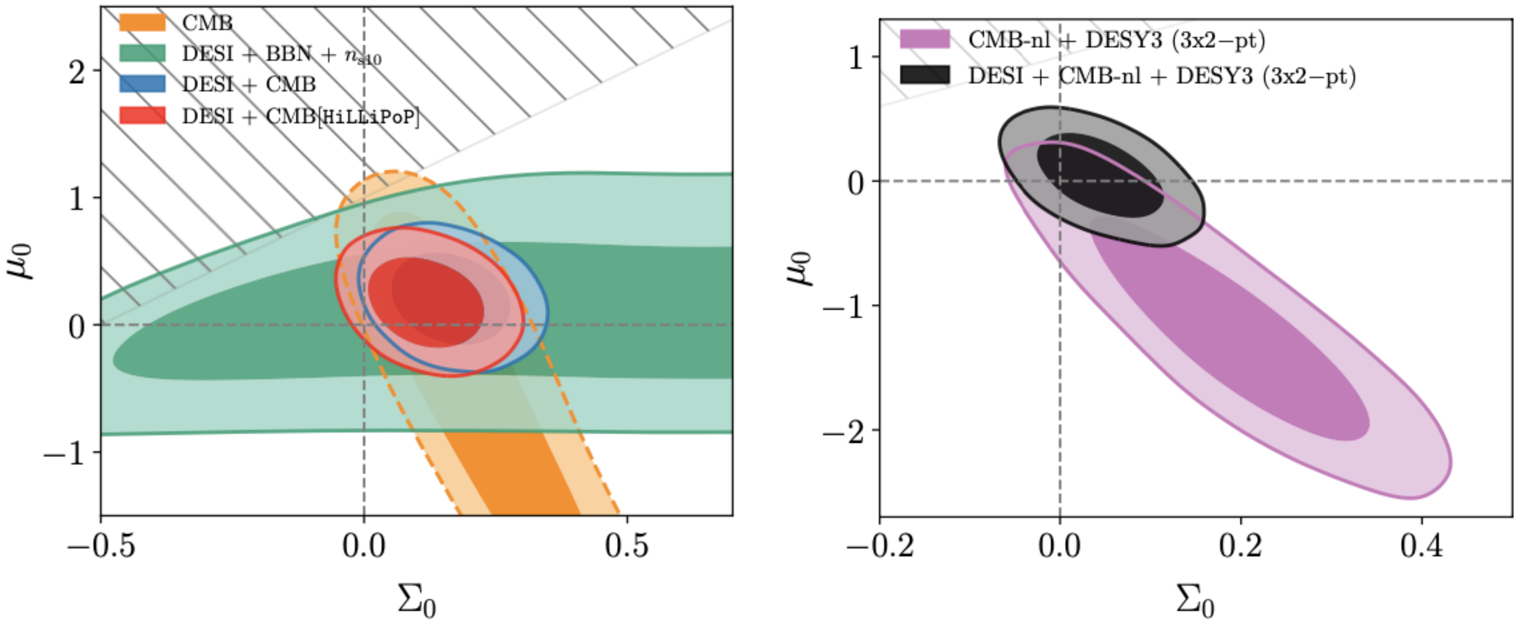
$$\mu(a) = 1 + \mu_0 \frac{\Omega_{\rm DE}(a)}{\Omega_\Lambda}, \qquad \Sigma(a) = 1 + \Sigma_0 \frac{\Omega_{\rm DE}(a)}{\Omega_\Lambda},$$

Modify the strength of gravitational interaction (and the growth rate)

Modify the Weyl potential equation

- Functional form is motivated by the desire to establish a connection between the observed cosmic acceleration and modification to gravity at late times. Time dependence of μ and Σ is set to be proportional to the dark energy density
- Model defined in linear theory. DESI full-shape analysis scale ensure that nonlinearities are small

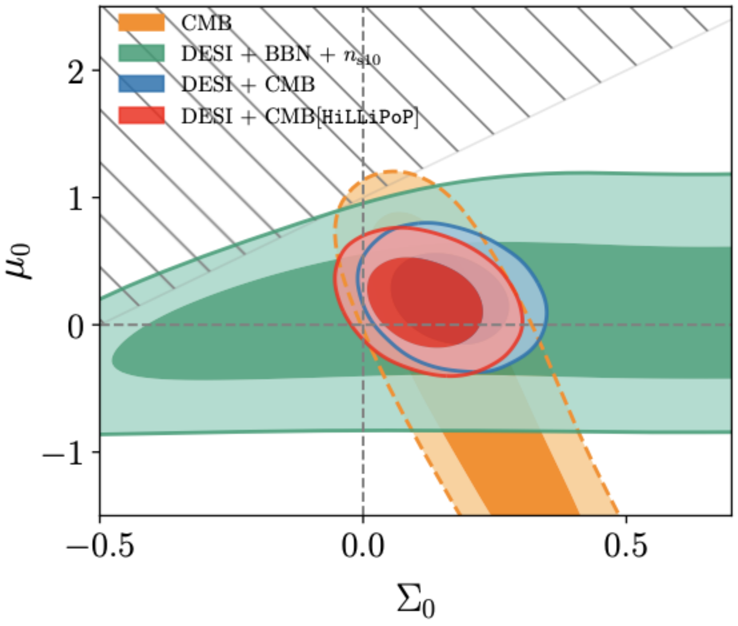
Modified Gravity constraints

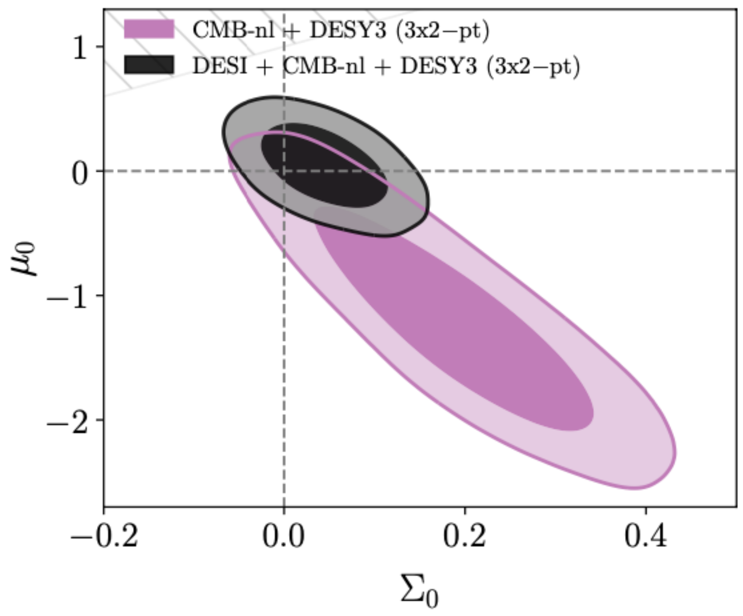


$$\mu_0 = 0.11^{+0.45}_{-0.54} \quad \text{(DESI (FS+BAO)+BBN+}n_{s10}\text{)}$$

- The 68% credible interval still allows possible deviations from 0. Consistency with 0 holds for combinations with external datasets
- Degeneracies broken by datasets combinations, reducing uncertanties on Σ_0

Modified Gravity constraints





$$\left.\begin{aligned} \mu_0 &= 0.04 \pm 0.22, \\ \Sigma_0 &= 0.044 \pm 0.047, \end{aligned}\right\} \begin{aligned} &\text{DESI (FS+BAO)+CMB-nl+} \\ &\text{DESY3 } (3 \times 2\text{-pt}). \end{aligned}$$

- Adding DESI data to CMB-nl and DESY3 (3 × 2-pt) improves the constraints on μ_0 by a factor of 2.5, and those on Σ_0 by a factor of 2
- The use of PR4 Planck likelihood alleviate the tension for the non-zero Σ_0 (anomalous lensing captured from A_{lens} parameter). With PR3 (DESI(FS+BAO) + CMB-nl), tension is around 3σ
- Tension alleviated using recontructed lensing

Theoretical Power Spectra

- Theoretical power spectra calculated with **CAMB** code
- **Planck cosmology** assumed as fiducial
- A three degenerate neutrino mass eigenstates model is adopted
- m_ν set to ***0 eV*** (reference), ***0.06 eV, 0.1 eV, 0.25 eV*** and ***0.4 eV***
- For the ratio, a theoretical PS was calculated for each bin of redshift considered (z=0.1 to z=1.1)
- Calculated for the same *k* range and *dk*

Approximation and simplifications

As this work is still in an embryonic state, until now some simplifications and approximations have been considered

- Synthetic spectra generated with a single value of z instead a broad range
- Effects of non-linearities at large scales not considered
- Effects of different cosmologies not considered and only tests on ΛCDM
- Biases used for scaling the PS, especially for QSO, under discussion
- Still no study on scale cuts or different binning options

Test on data samples

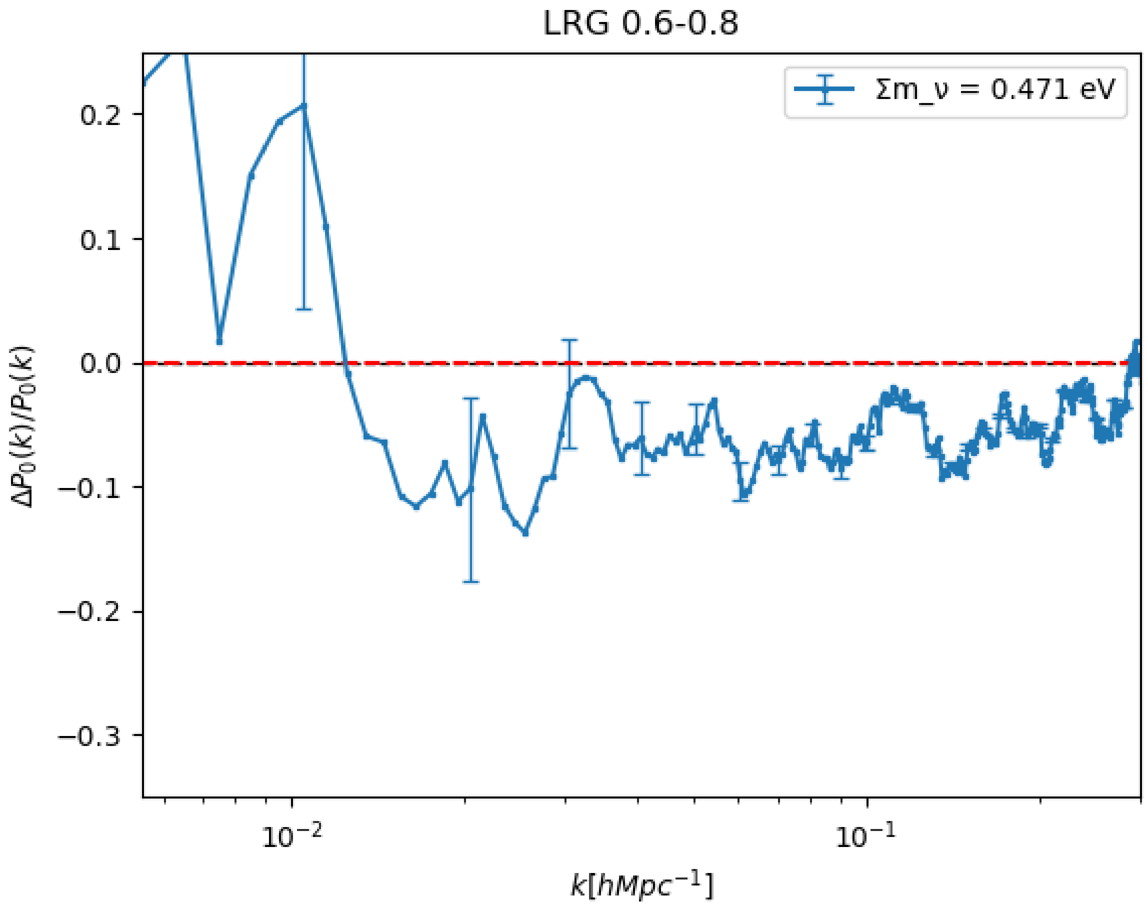
$\Delta P(k)/P(k)$ calculated between data PS and synthetic PS with $m_\nu = 0$

Bias considered for different tracers:

- 2 for LRG
- 1.5 for BGS
- 1.2 for ELG
- 2.1 for QSO
- 1.6 for combined tracer

Growth factor is considered

Almost all tracers show the step!



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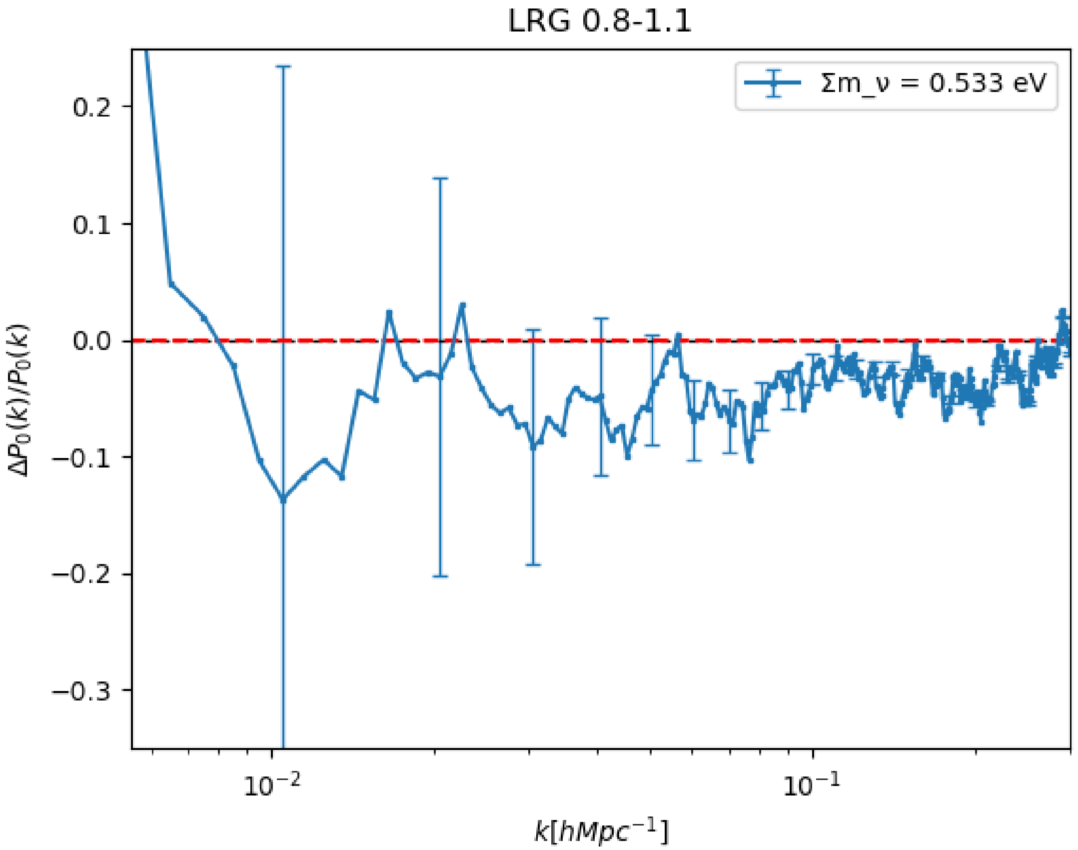
Test on data samples

- $\sum m_\nu$ information obtained fitting the fractional difference via f_ν using **curve_fit** function in python

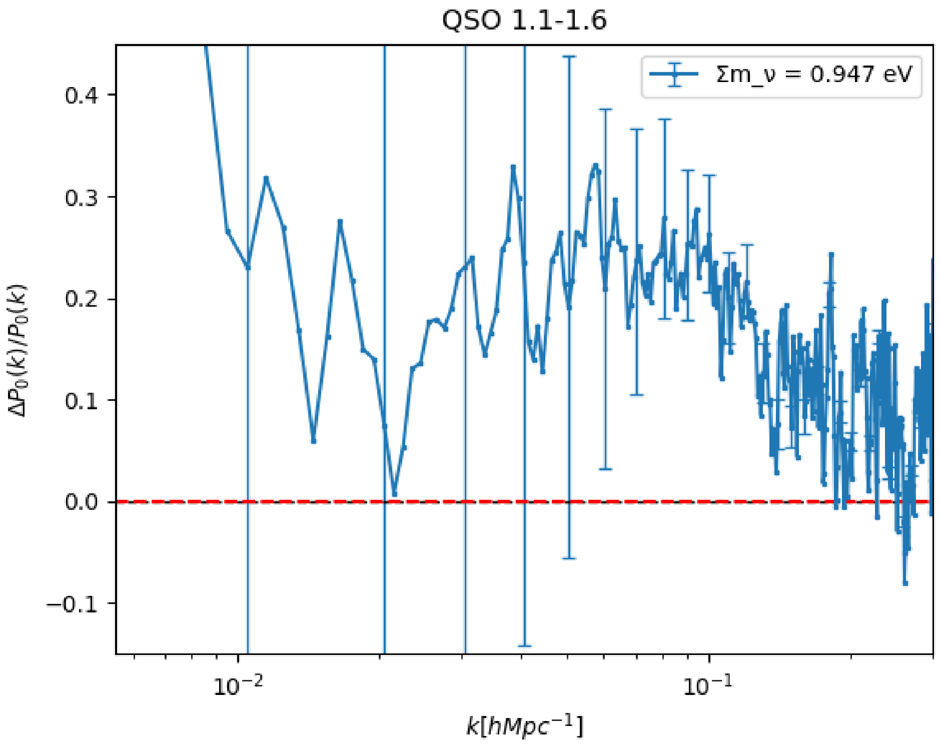
- Very simple model added to the various approximations and simplifications: handle with care!

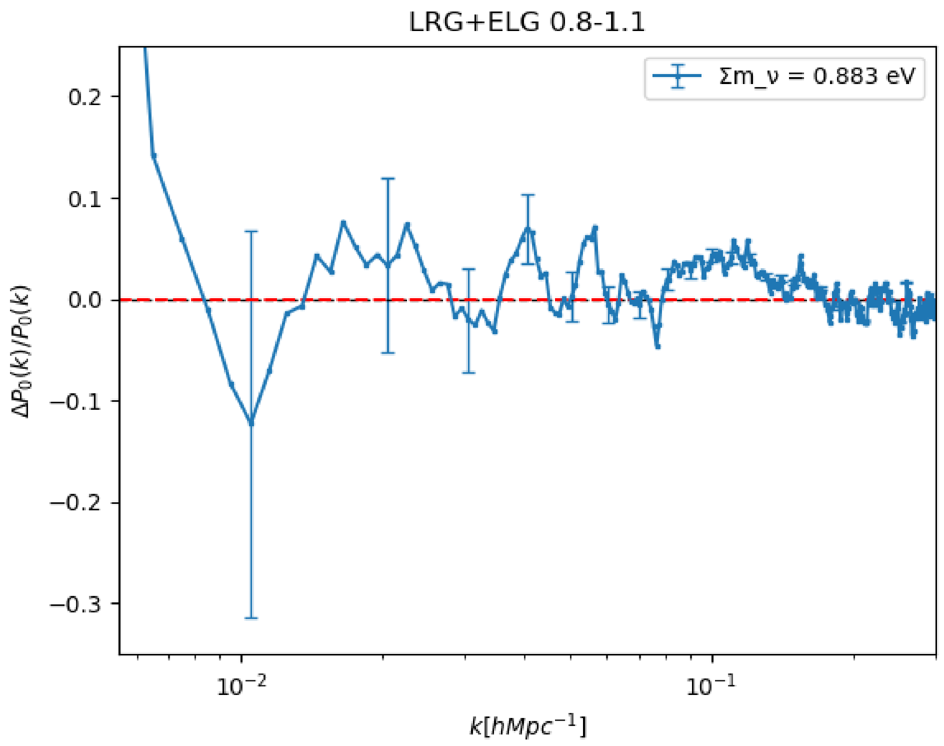
- Fit done in full k range, including large scales (with non-linearities)

- Not so focused on the number, but it seems already not so unreasonable



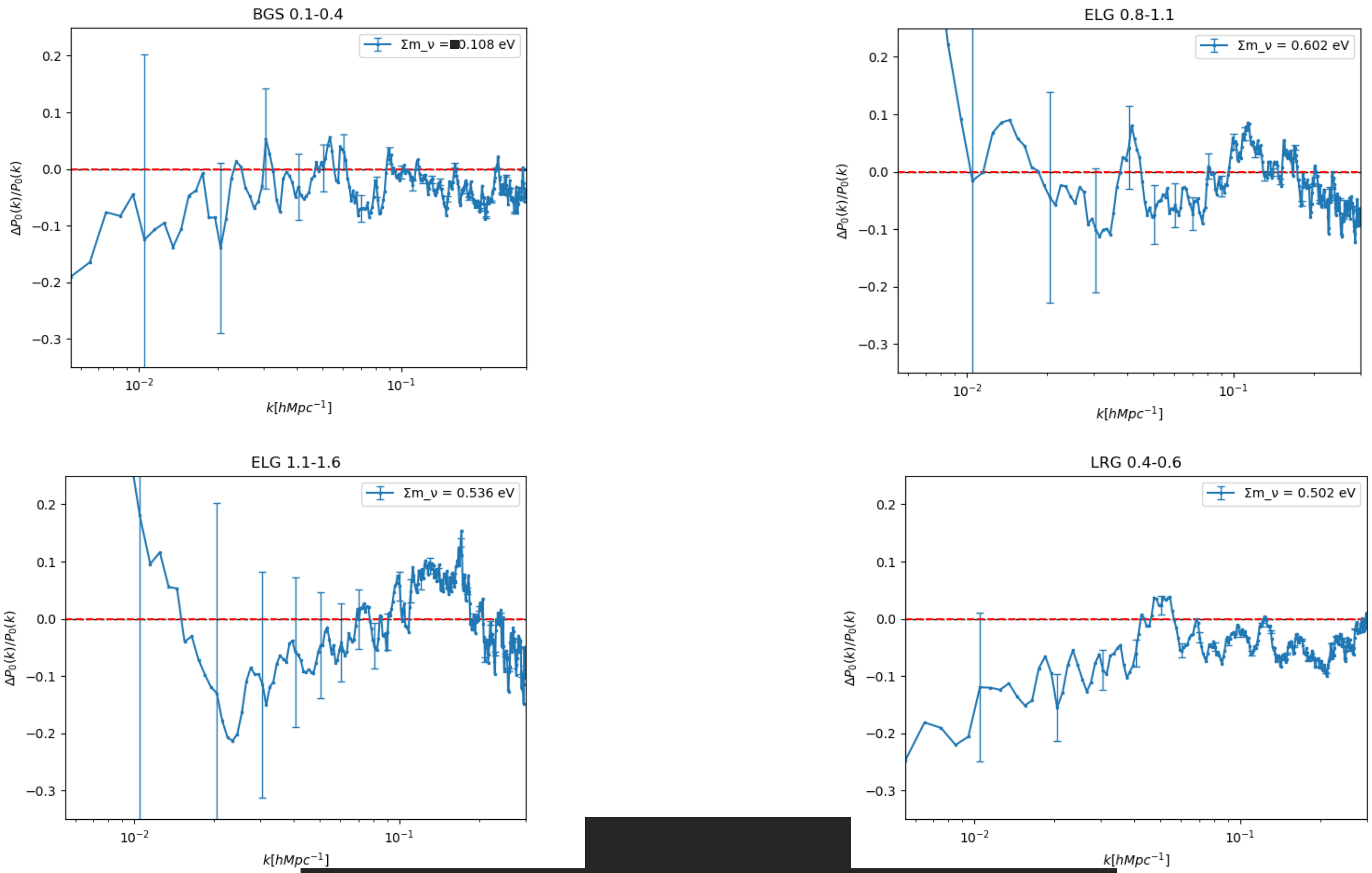
Test on data samples





Most anomalous case: QSO. All positive values (maybe due to bias value?)

Test on data samples



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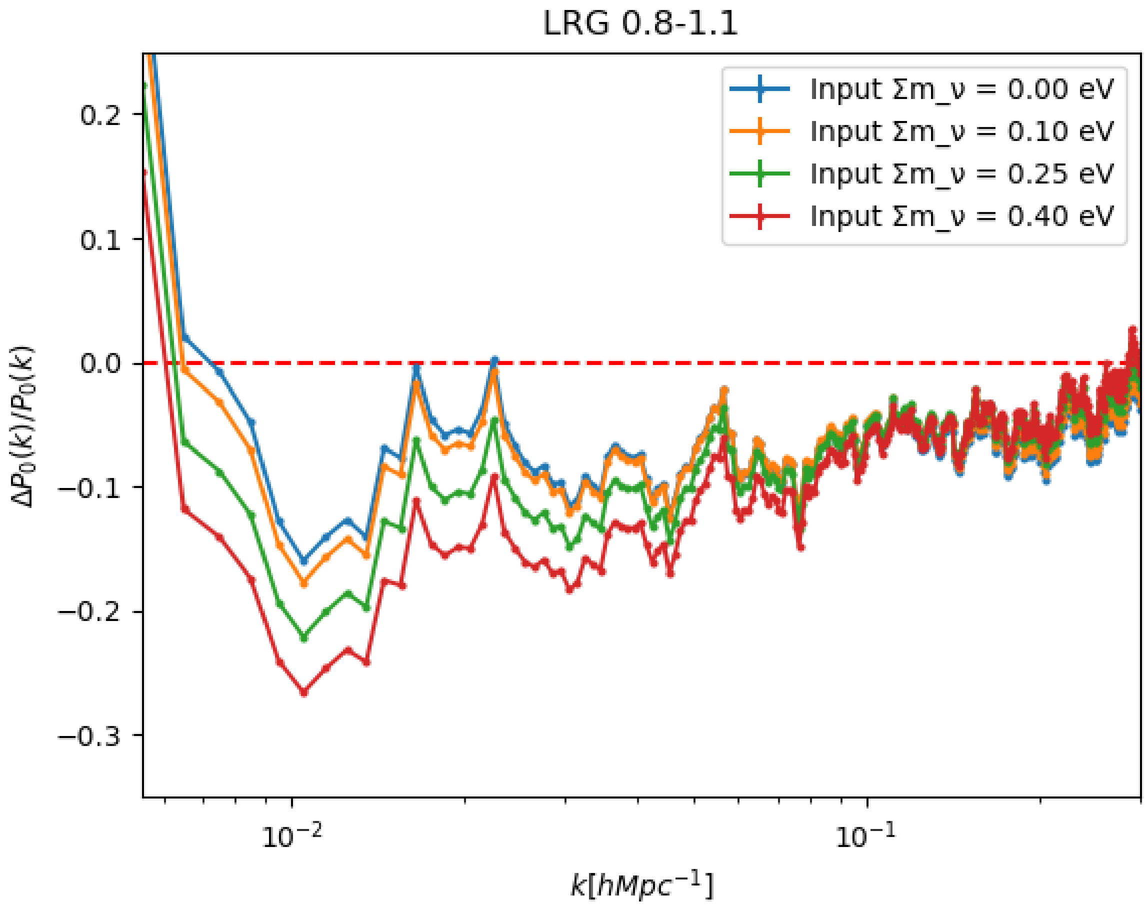
Test on data samples

- We tried to compare PS from data with different synthetic ones considering models with different neutrino masses

- Suppression entity seems to change varying neutrino masses as expected

- Small effect given by the different $\sum m_\nu$ considered in the model



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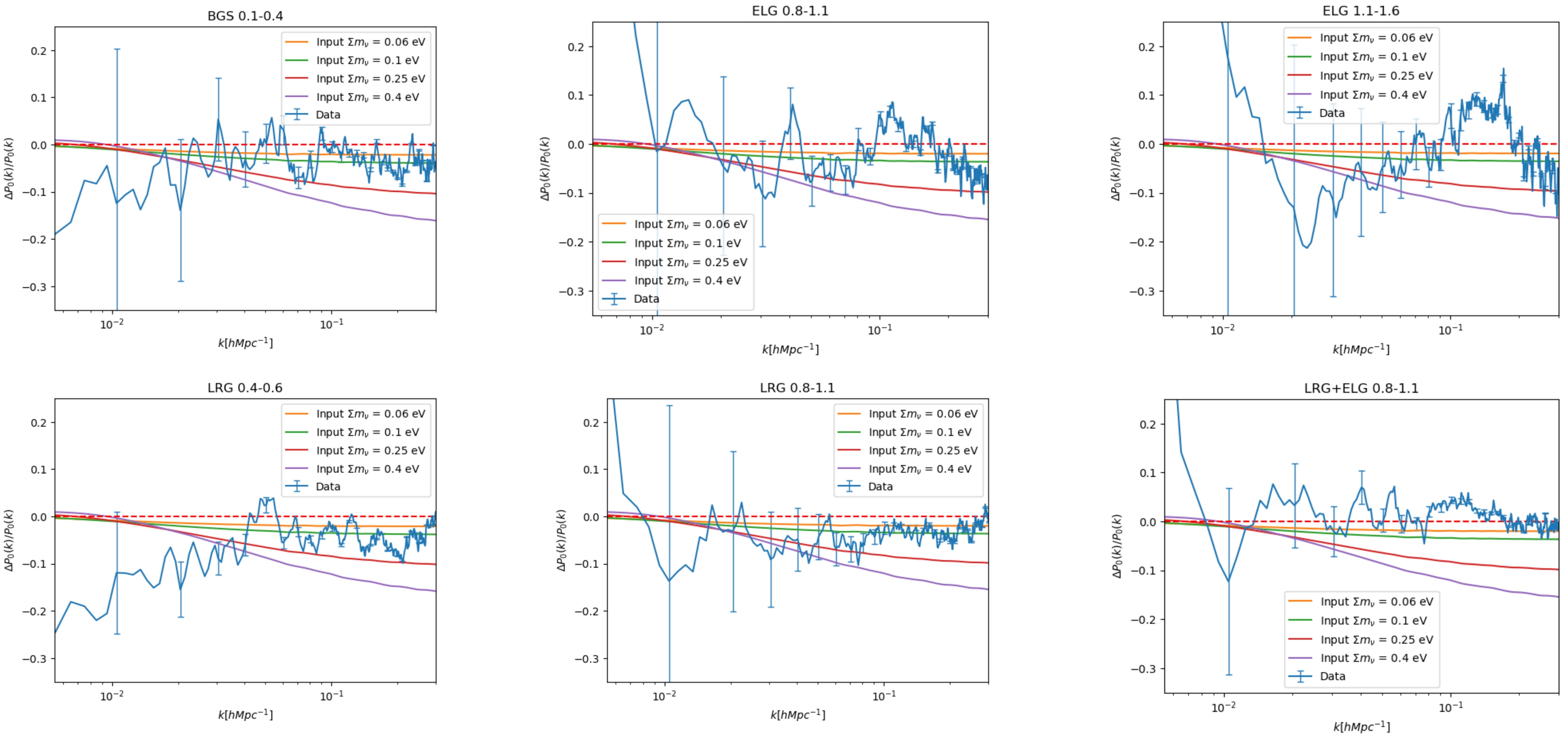
Comparison with theory



External Datasets

CMB

- **Planck** (Temperature and Polarisation auto-spectra likelihoods TT and EE, cross-spectra likelihood TE from PR3 and PR4 release)
- **ACT** (DR6 + PR4 lensing likelihood)

BBN (priors and likelihood)

Supernovae

- **Pantheon+** (1550 SN with $0.001 < z < 2.26$, but we impose $z > 0.01$)
- **Union3** (2087 SN, 1363 in common with Pantheon+)
- **DES Y5** (1635 SN with $0.1 < z < 1.3$)

BAO data from BOSS, eBOSS and SDSS were used for comparison

Cosmological Inference

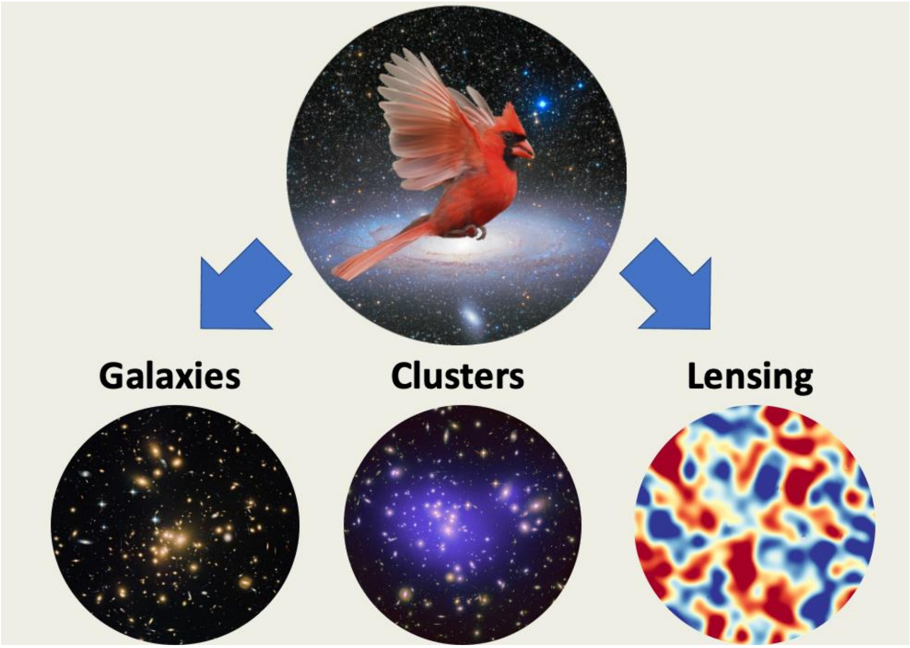
- Likelihoods included in ***cobaya***
- We use the Boltzmann code **CAMB** for theoretical cosmology calculations
- Higher precision settings were used when lensing was included
- Inference performed using **MCMC** sampler in cobaya
- Gelman-Rubin criterion **R-1 < 0.01**
- ***getdist*** used for derive constraints, best-fit calculated using ***iminuit*** algorithm

parametrization	parameter	default	prior
background-only	Ω_m	—	$\mathcal{U}[0.01, 0.99]$
no r_d calibration	$r_\mathrm{d}h$ (Mpc)	—	$\mathcal{U}[10, 1000]$
with r_d calibration	H_0 ($\mathrm{km\,s^{-1}\,Mpc^{-1}}$)	—	$\mathcal{U}[20, 100]$
	ω_b	—	$\mathcal{U}[0.005, 0.1]$
CMB	ω_cdm	—	$\mathcal{U}[0.001, 0.99]$
	ω_b	—	$\mathcal{U}[0.005, 0.1]$
	$100\theta_\mathrm{MC}$	—	$\mathcal{U}[0.5, 10]$
	$\ln(10^{10}A_s)$	—	$\mathcal{U}[1.61, 3.91]$
	n_s	—	$\mathcal{U}[0.8, 1.2]$
	τ	—	$\mathcal{U}[0.01, 0.8]$
extended	Ω_K	0	$\mathcal{U}[-0.3, 0.3]$
	w_0 or w	-1	$\mathcal{U}[-3, 1]$
	w_a	0	$\mathcal{U}[-3, 2]$
	$\sum m_\nu$ (eV)	0.06	$\mathcal{U}[0, 5]$
	N_eff	3.044	$\mathcal{U}[0.05, 10]$

DESI Collaboration 2024 (arXiv:2404.03002)

Cardinal Simulations

- New version of Buzzard simulation
- Provide support to surveys as DES and DESI
- One-quarter sky simulation populated with galaxies out to a z = 2.35
- Uptated subhalo abundance matching (SHAM)
- New color assignment model



The catalog include simulations of catalogues, masks, random catalogues, regions and indices

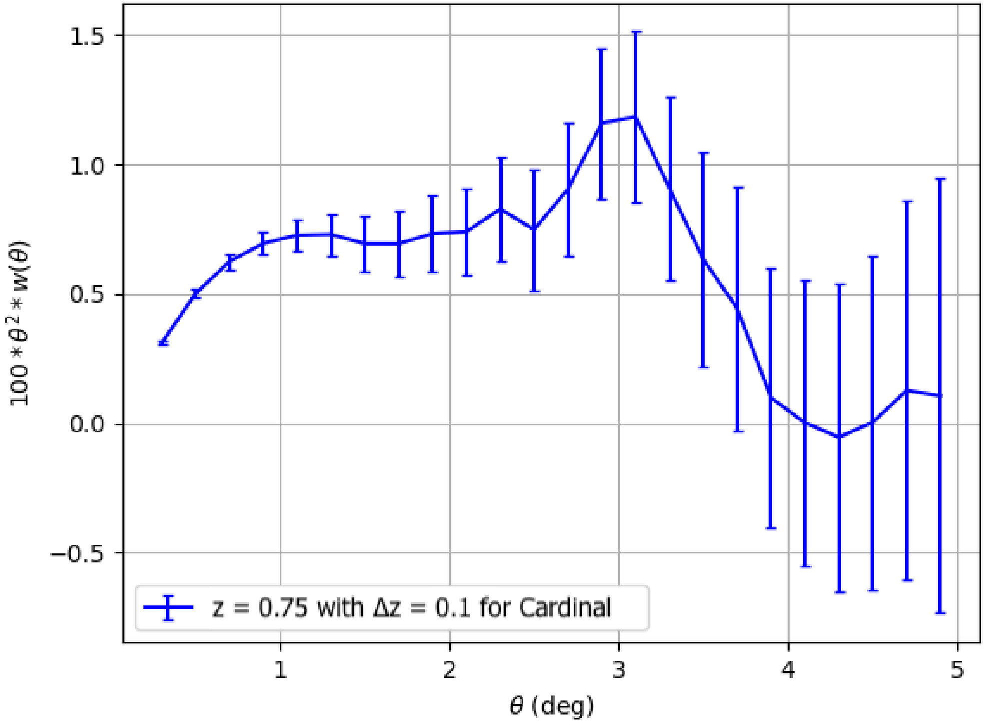
In this case, we work on radMagic-like and GOLD-like catalogs

CF in Cardinal Simulations

Landy - Szalay estimator: $\omega(\theta) = \frac{DD(\theta) - 2DR(\theta) + RR(\theta)}{RR(\theta)}$

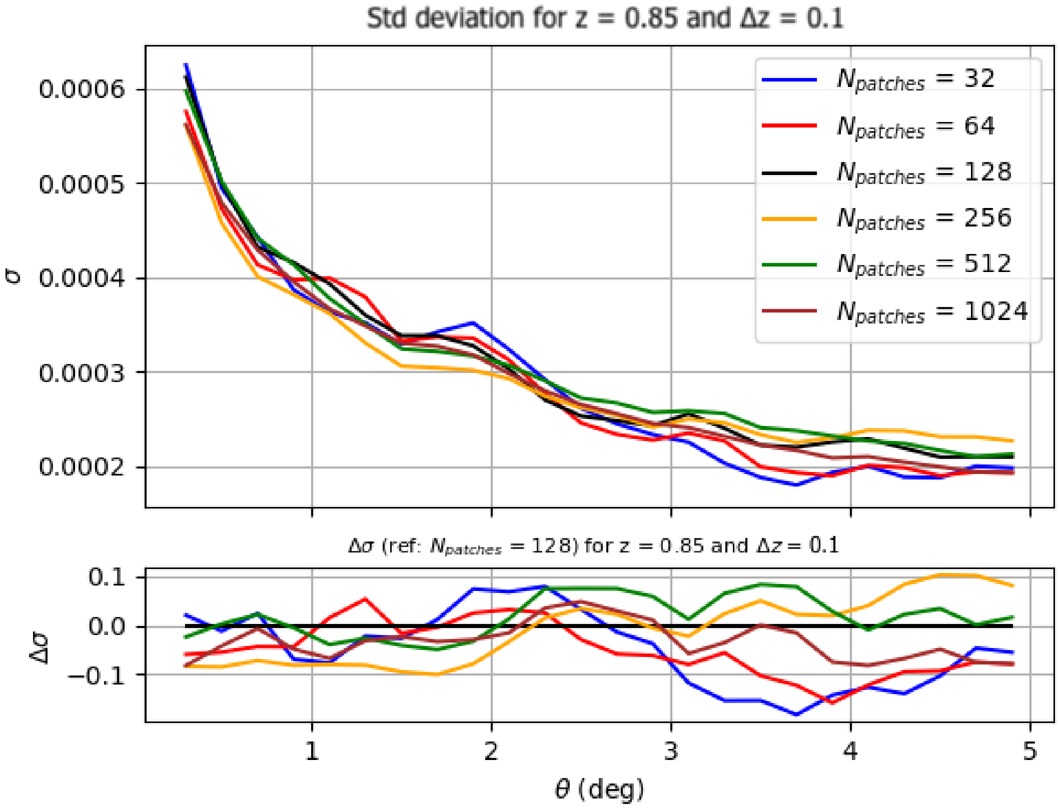
- The angular CF is computed using 25 values of θ between 0 and 5 degrees. We used **NNCorrelation** TreeCorr class in order to compute the count-count two-point correlation, using the jaccknife resampling to compute the CM, using $\boldsymbol{N_{patches}}$ **= 128** as reference value

- We found the CF behavior to be physically consistent, managing to highlight the BAO peak (but not measured, at least at this stage)



CF in Cardinal Simulations

- There is no obvious relationship between the value of the error on the CF (the diagonal of the CM) and the number of patches considered for resampling
- No values of Npatches > 1024 were considered
- Too many regions would create sparsely populated areas of the map, affecting the error calculation.



CF in Cardinal Simulations