The DESI survey and its cosmological Implications

Antoine Rocher
Rafaela Gsponer
Postdocs
Ecole Polytechnique Fédérale de Lausanne

On behalf of the DESI collaboration

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

EPFL

Credit : DESI collaboration

CosmoFONDUE – 2025 June 12th - Geneva


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT
U.S. Department of Energy Office of Science
DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA
NSF
NERSC
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MINISTERIO DE ECONOMIA Y COMPETITIVIDAD
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2

Dark Energy Spectroscopic Instrument

- DESI is a state-of-the-art spectroscopic instrument installed at the **Mayall 4-meter telescope at Kitt Peak National Observatory.**
- First **Stage-4 spectroscopic survey** on sky
  - measures the 3D distributions of galaxies
  - 1/3 sky 14000 deg^2
- **40M redshifts at the end of the survey (5 years)**
  x13 previous spectroscopic surveys

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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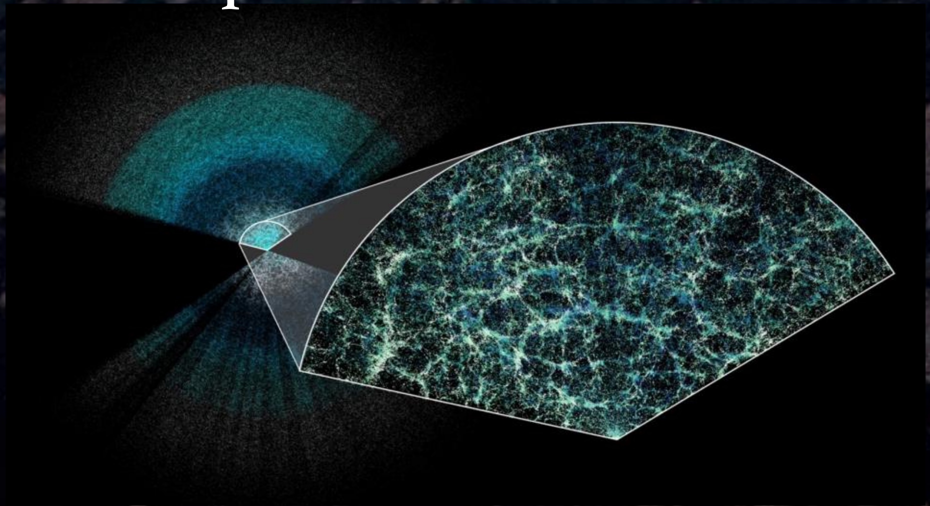
Dark Energy Spectroscopic Instrument

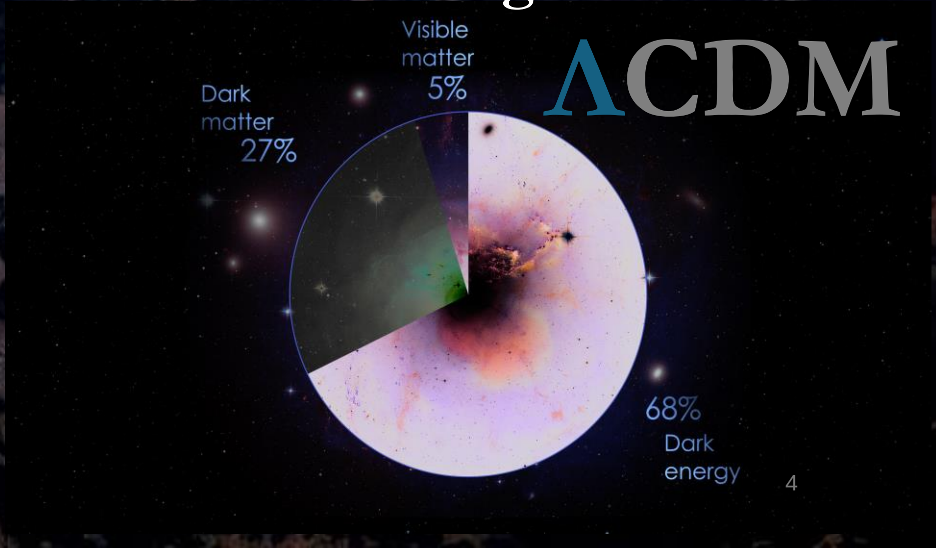
Key questions:

- **Expansion history of the Universe**
  => Constraint Dark Energy with BAO
- **How does the structure form?**
  => Test of gravity (GR)
- **Primordial physics, inflation (f_{nl})**
- **Neutrino mass, dark matter models…**

+ many other science cases

Map the Universe in 3D to constrain the cosmological model





Credit : DESI collaboration/Claire Lamman

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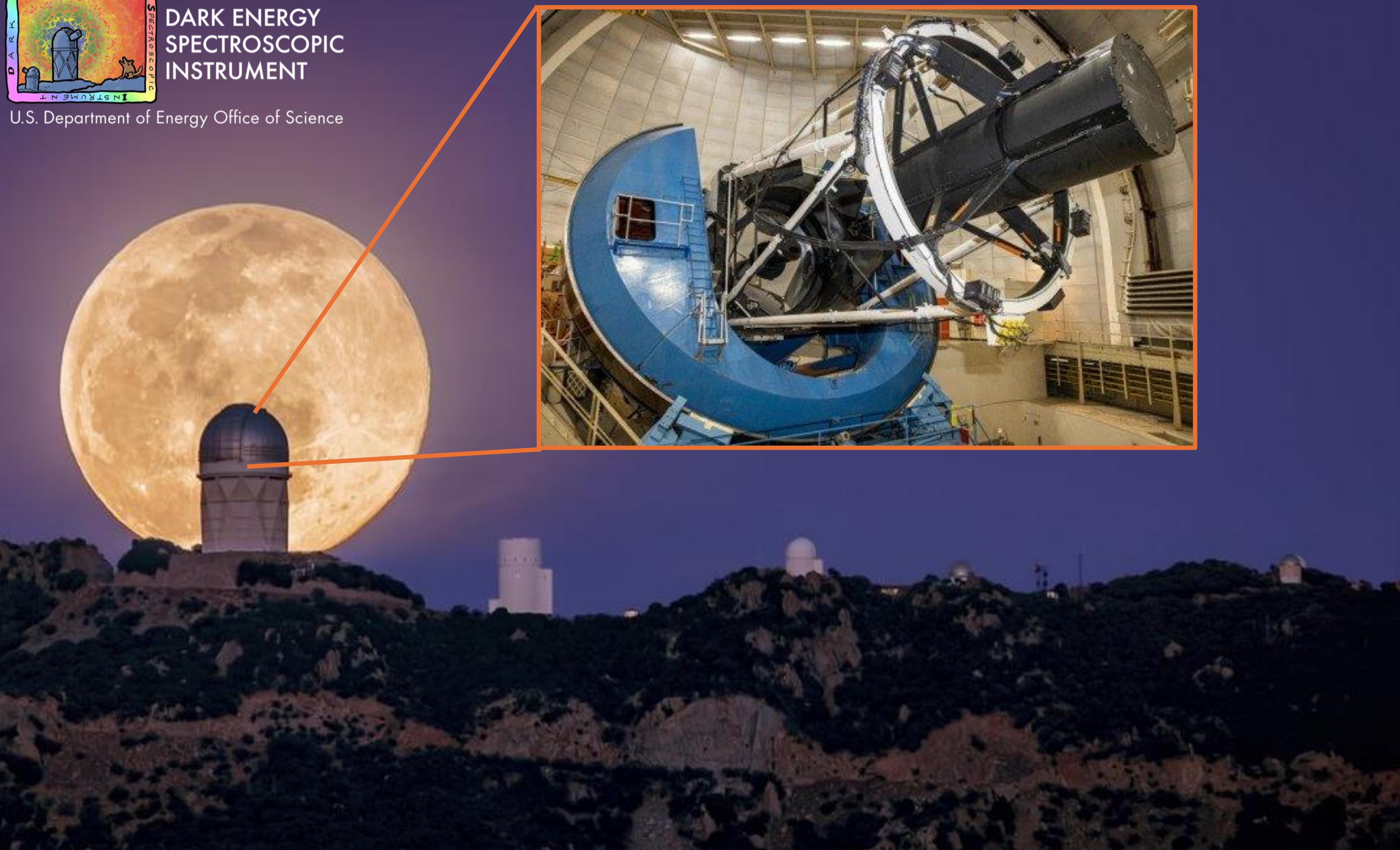

DESI is a state-of-the-art instrument installed at the Mayall 4-meter telescope at Kitt Peak National Observatory.

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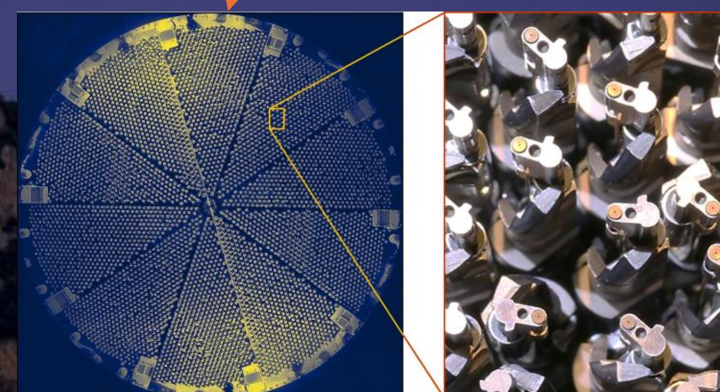
Focal plane is populated with 5000 robotics fibers



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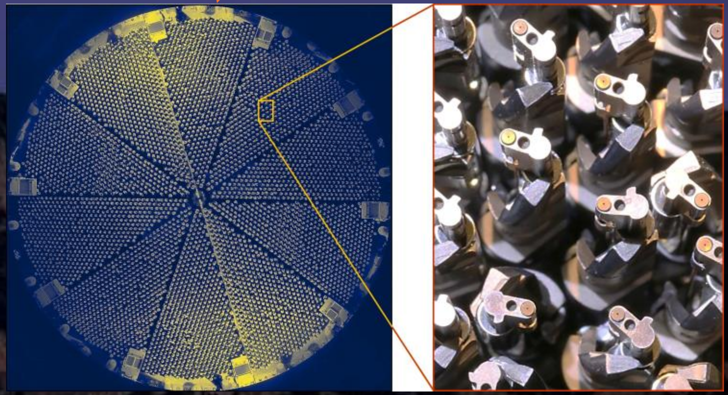
Focal plane is populated with 5000 robotics fibers

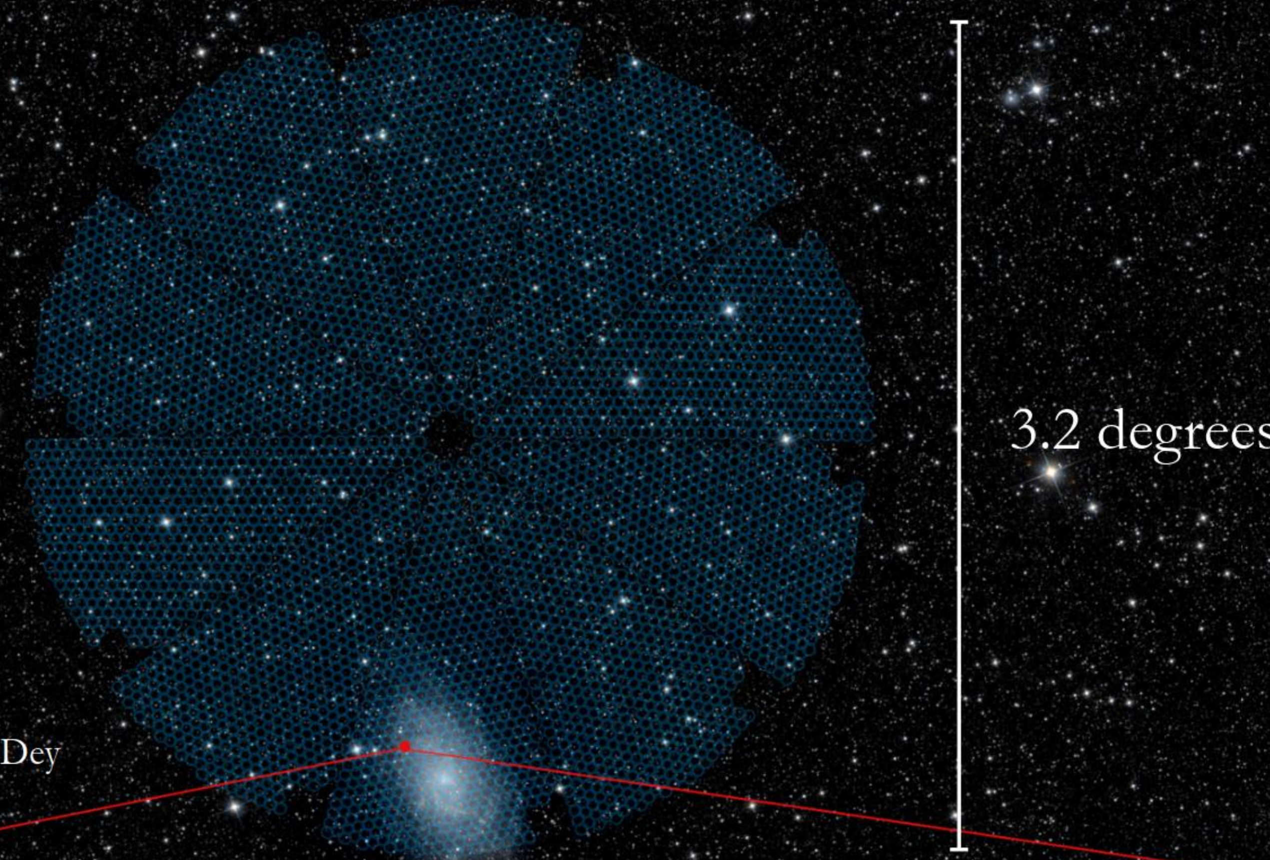
That feed 10 spectrographs
λ ~ 360-980 nm

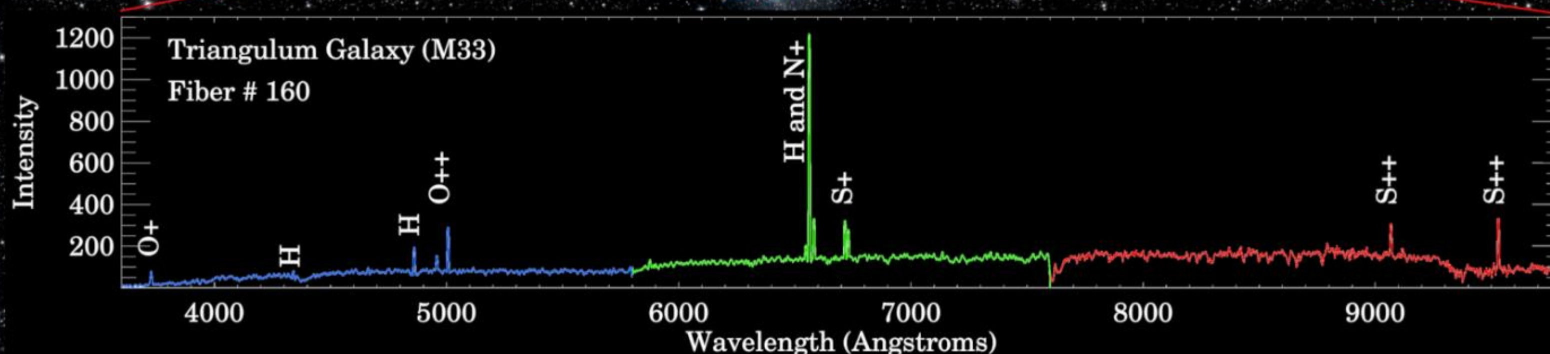


DESI is a state-of-the-art instrument installed at the Mayall 4-meter telescope at Kitt Peak National Observatory.

These fibers allow DESI to map an area of the sky larger than 30 full moons—simultaneously.

Full Moon (to scale)





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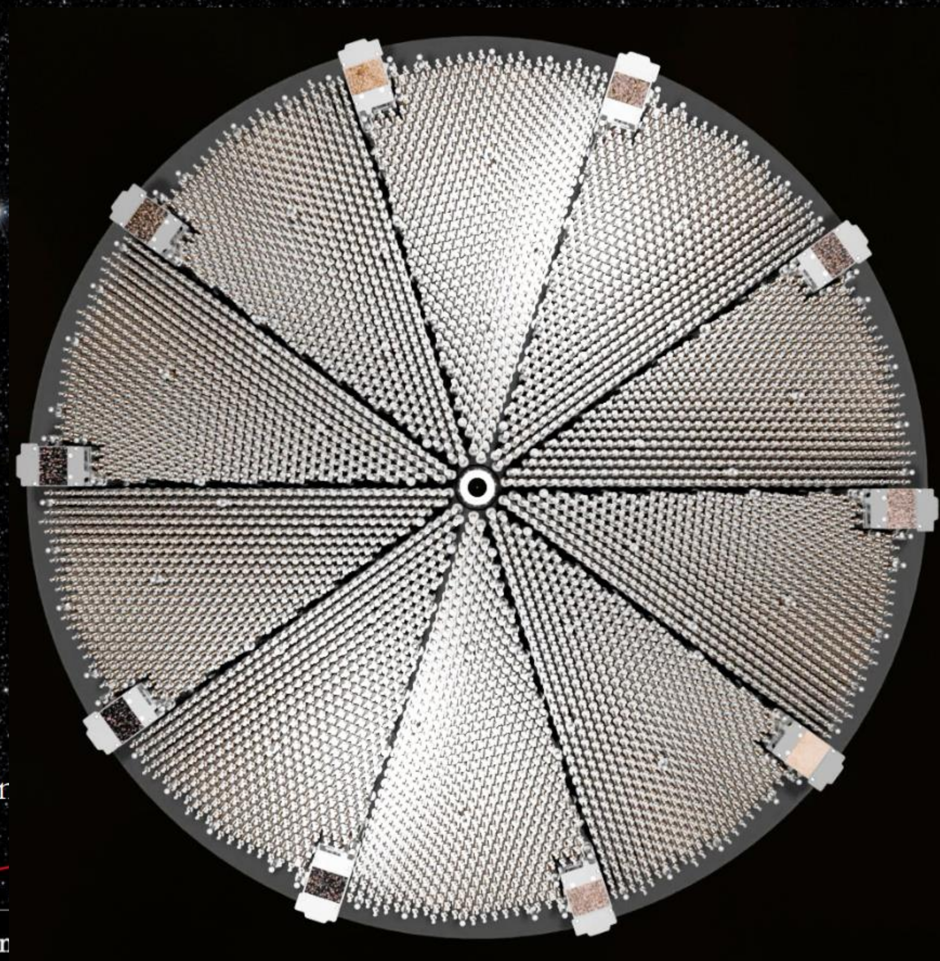
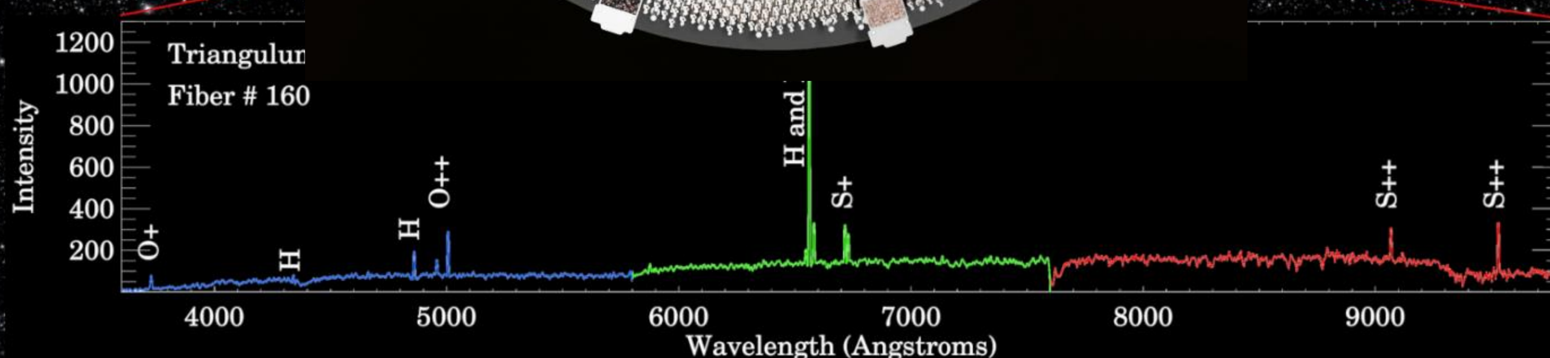
Full Moon
(to scale)



3.2 degrees

Credit: Arjur
(NOIRLab)



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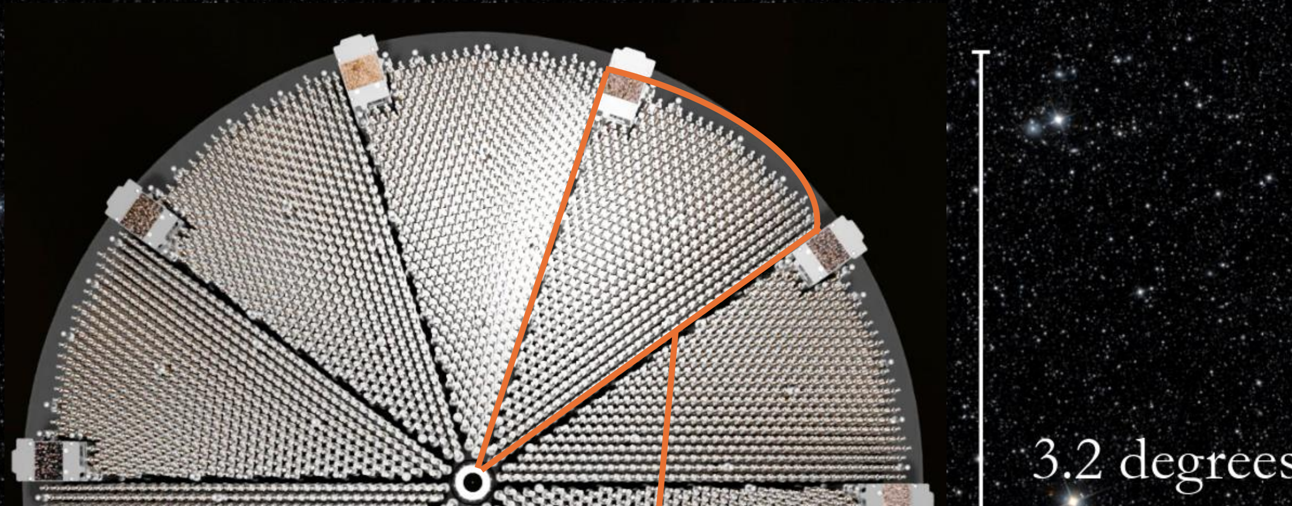

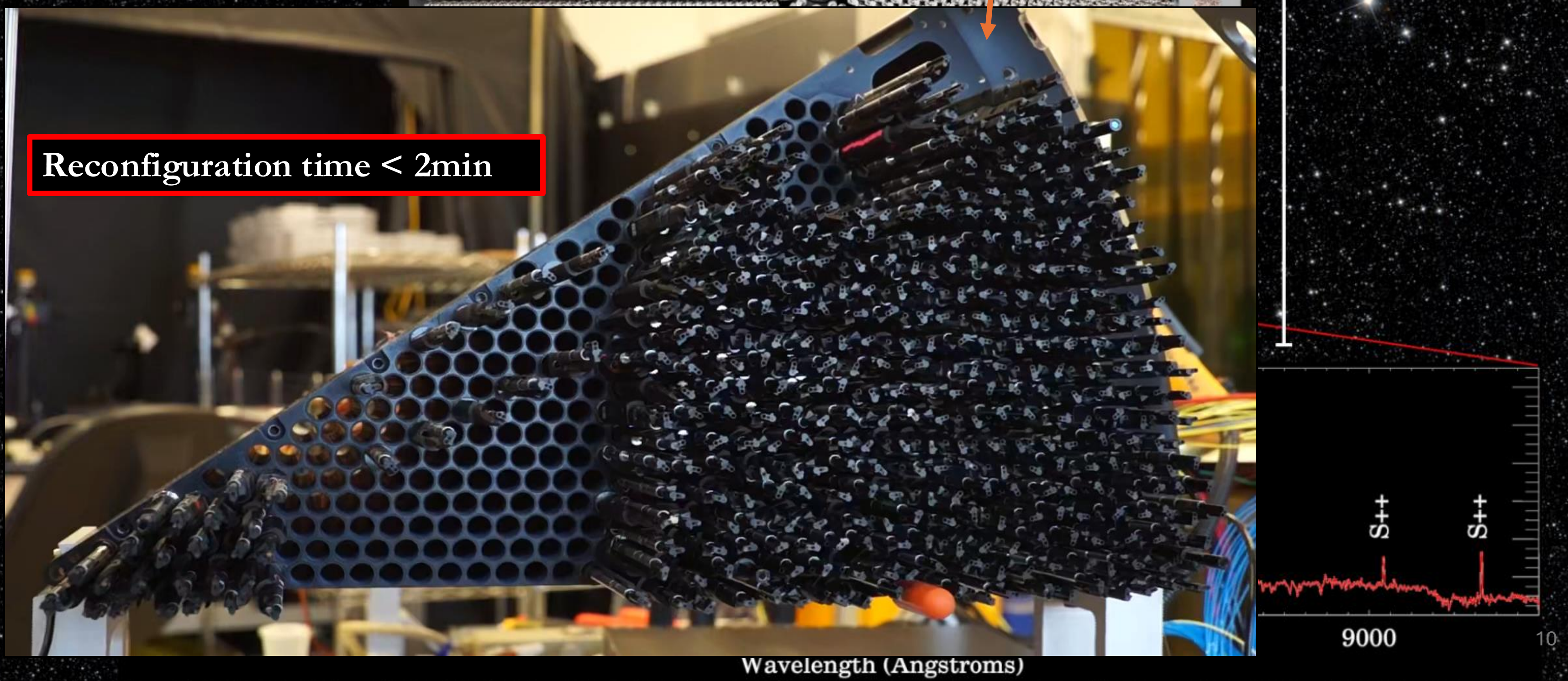

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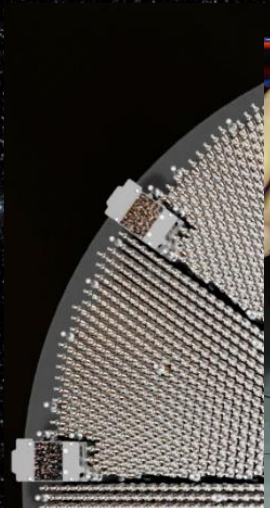
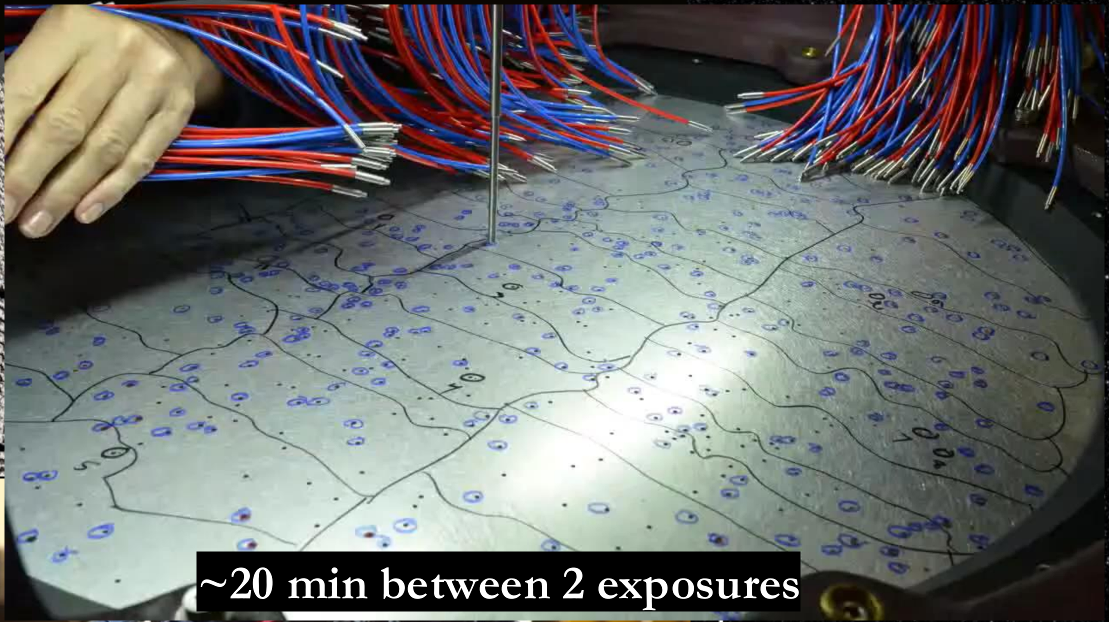
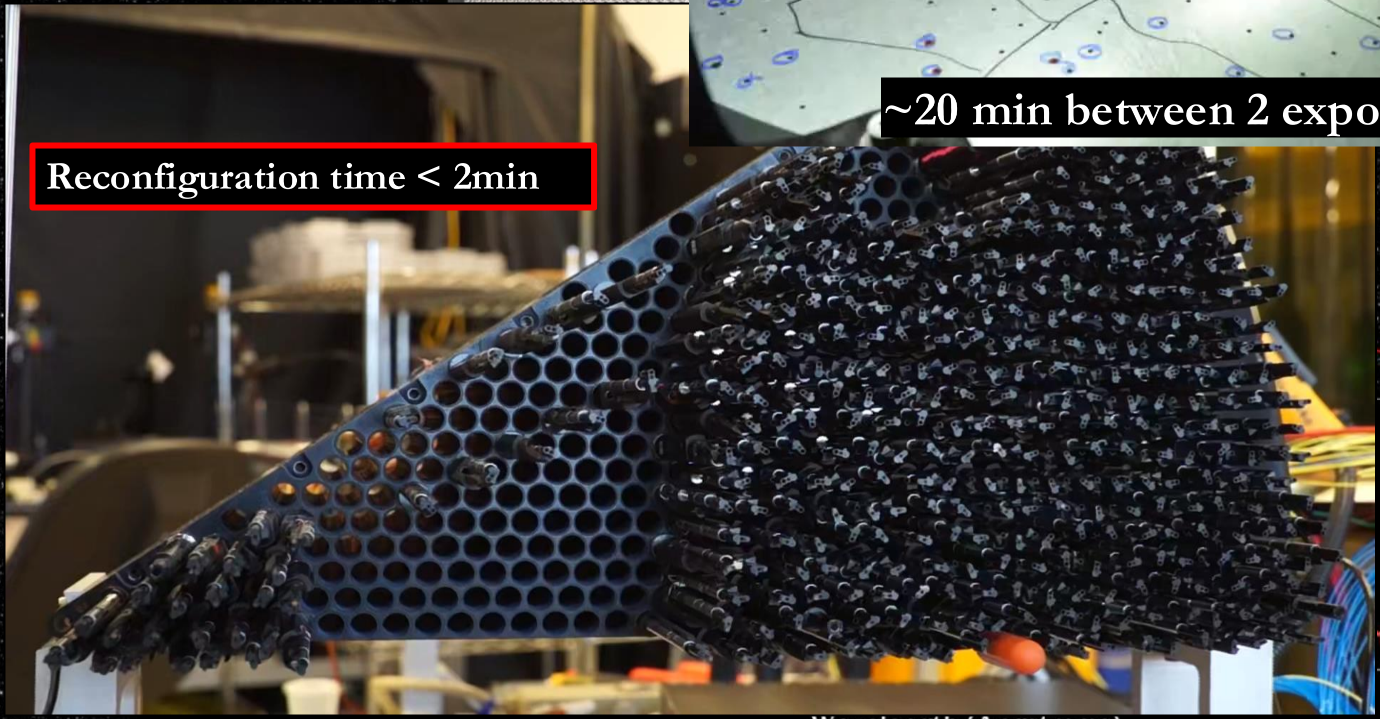
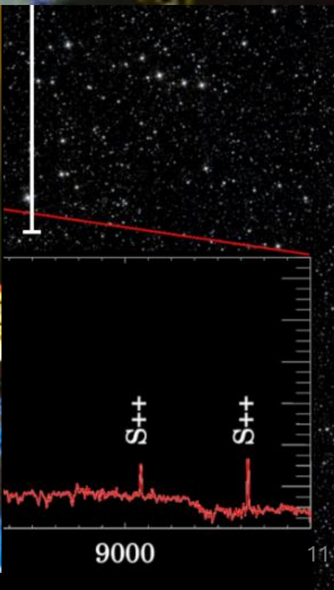
SDSS

Full Moon
(to scale)









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The DESI main survey

4 different tracers to probe the Universe z < 3.5

Dark time survey

3M Quasars (QSOs)
0.8<z<2.6

+ Ly-α z > 2.1

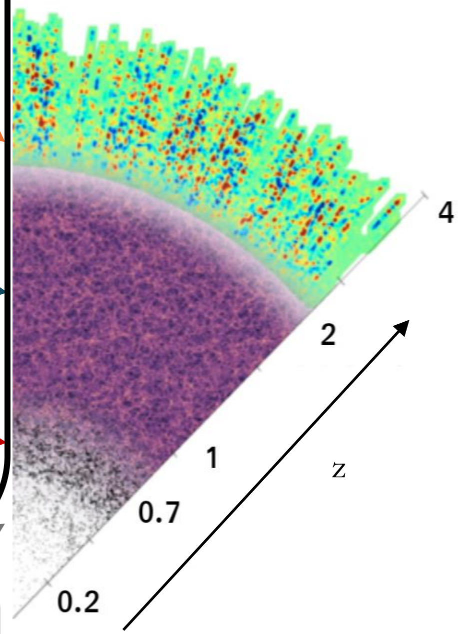
17M Emission line galaxies (ELGs)
0.6<z<1.6

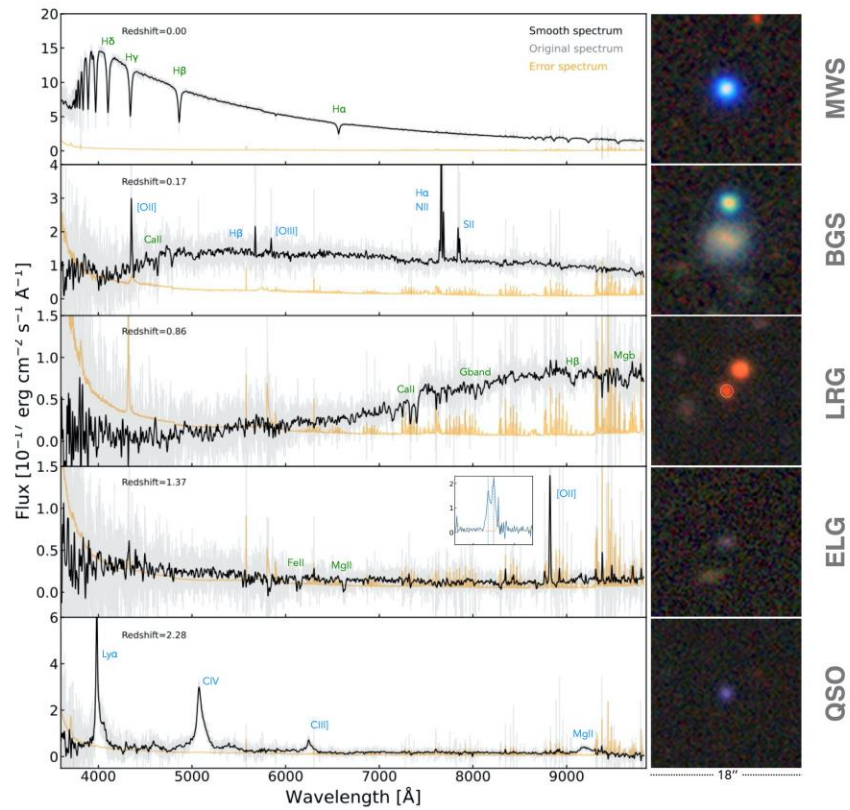
8M Luminous red galaxies (LRGs)
0.4<z<1.1

13.5M Bright galaxies
0<z<0.5

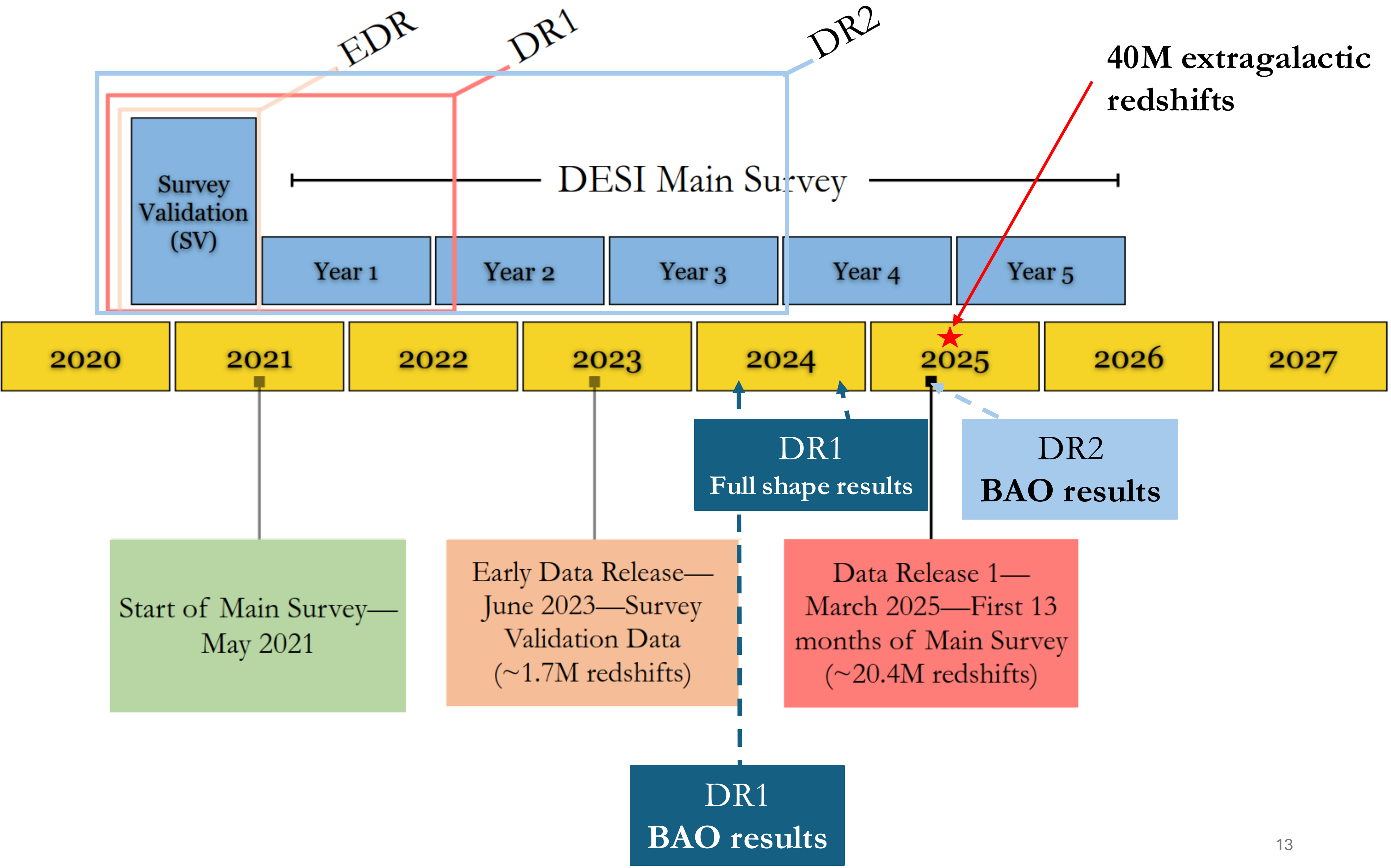
+ Milky way Stars

Bright time survey





DESI Timeline



DESI DR1 contains the **most detailed 3D map of the universe** ever, spanning 12 billion years of cosmic time.

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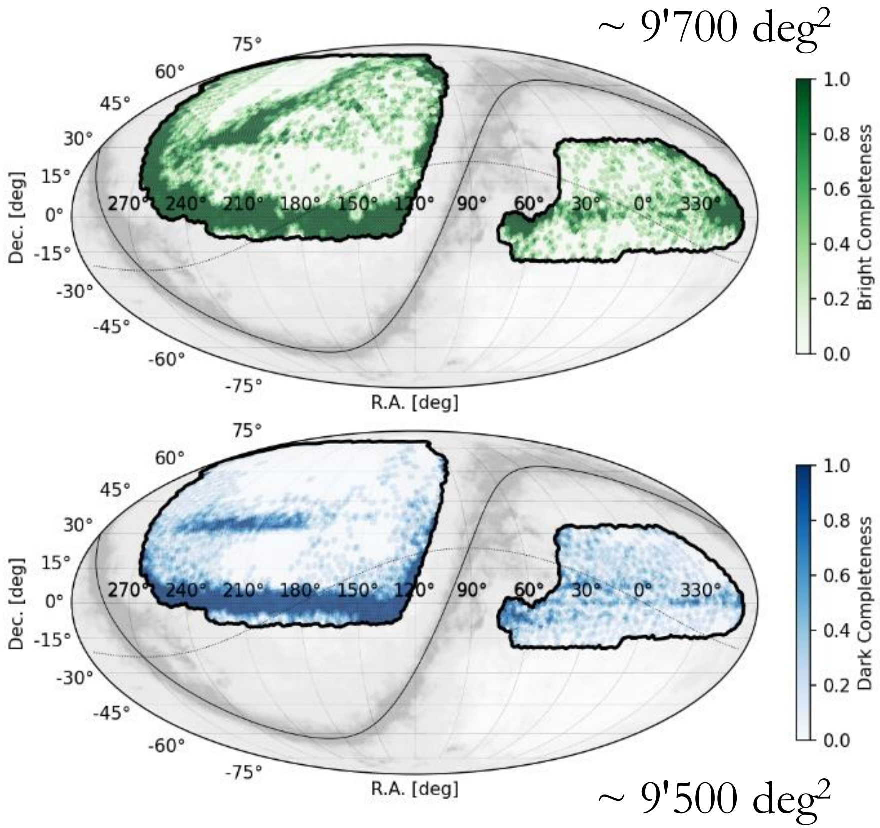

DR1 Main-Survey Completeness
—Bright Program: 41% (4 passes)
—Dark Program: 29%

Main Survey :
- **13.1M galaxies**
- **1.6M quasars**
- **4M stars**

+ Survey Validation (1.7M objects)

Total: 20.4M redshifts

Redshifts for the BAO analysis

Tracer	DR1
BGS	300,043
LRG	2,138,627
ELG	2,432,072
QSO	1,223,391
Total	6,094,133

Publicly available: https://data.desi.lbl.gov/doc/releases/dr1

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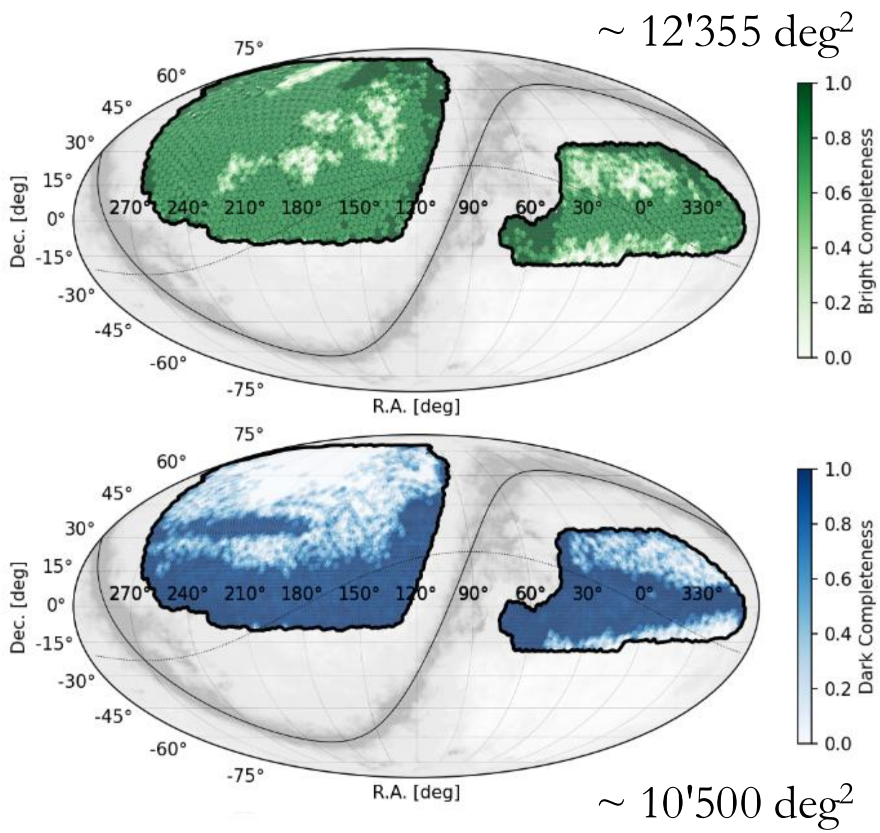
DESI DR2 will contain two-thirds of the 5-year survey data and ~50M redshifts, two times more than DR1!



DR2 Main-Survey Completeness
—Bright Program: 73% (5 passes)
—Dark Program: 67%

Main Survey (internal release):
- **31M galaxies**
- **2.8M quasars**
- **12.3M stars**

\+ Survey Validation (1.7M objects)

Total: 46.1M redshifts

Redshifts for the BAO analysis

Tracer	DR1	**DR2**
BGS	300,043	**1,188,526**
LRG	2,138,627	**4,468,483**
ELG	2,432,072	**6,534,844**
QSO	1,223,391	**2,062,839**
Total	6,094,133	**14,254,692**

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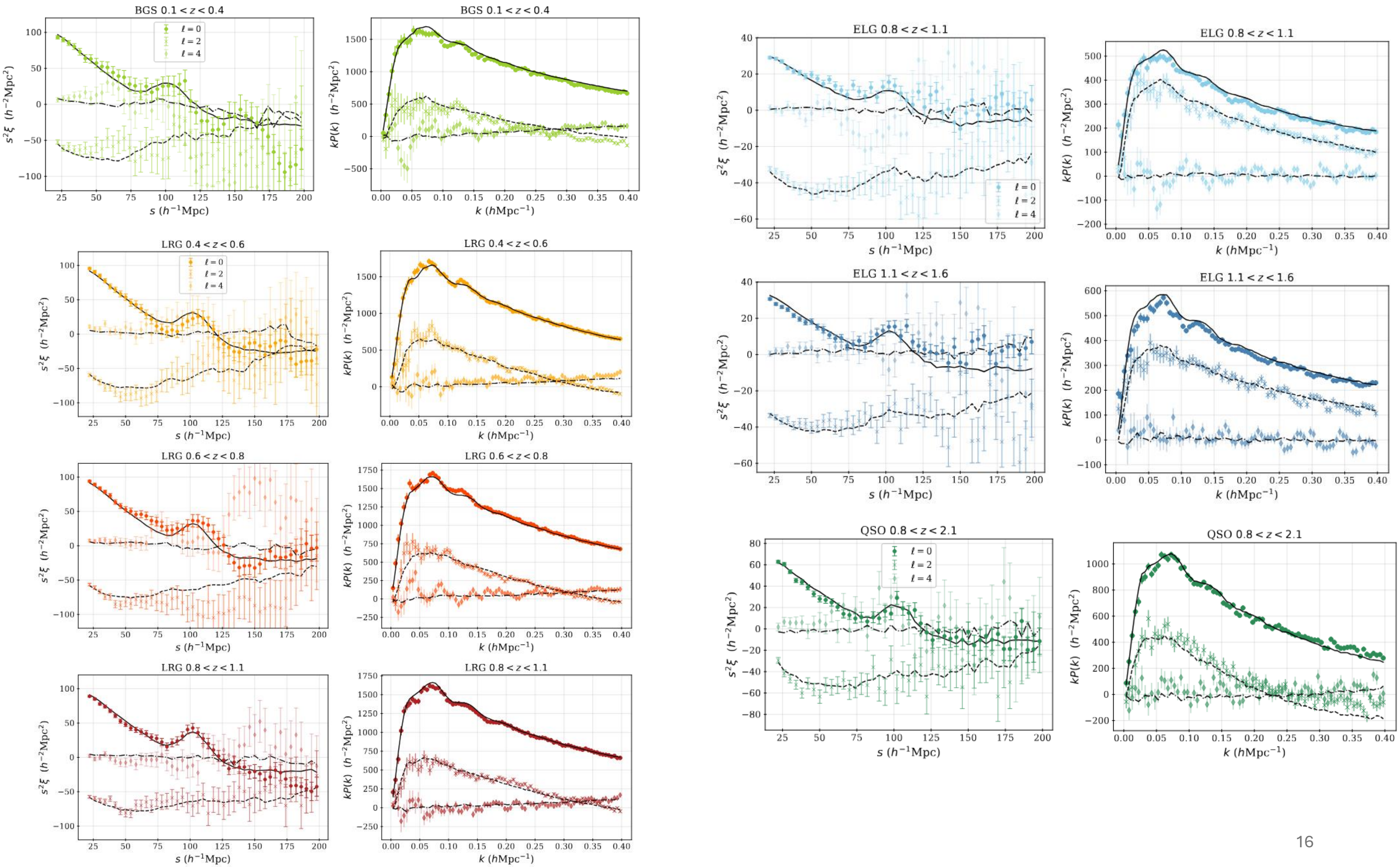
DESI 2024 II: Sample Definitions, Characteristics, and Two-point Clustering Statistics

arxiv: 2411.12020v1



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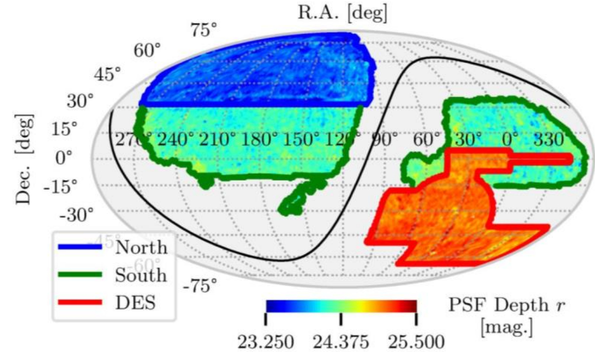
Main observational systematic sources

arxiv: 2411.12020v1

Chaussidon et al 2022



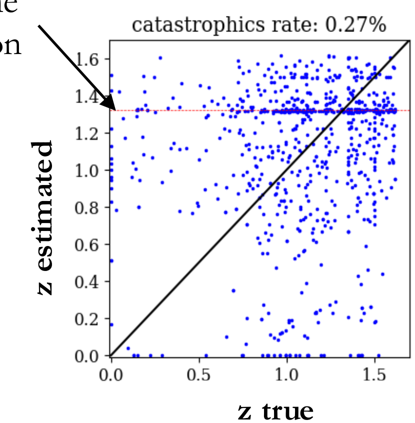
Systematic errors from the target selection (imaging systematics):

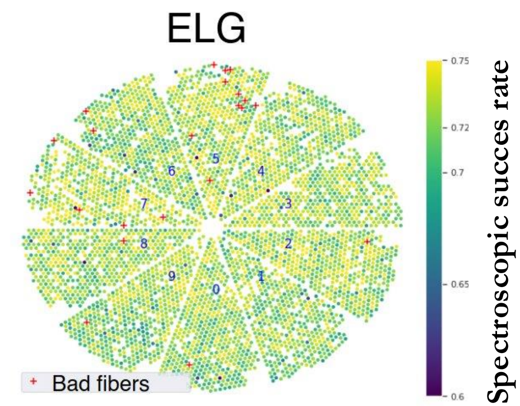
- Target density variations due to photometric properties

Yu et al. 2024
Krolewski et al. 2024

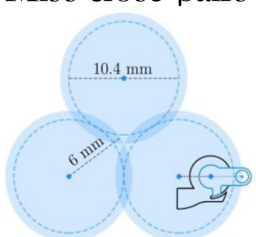
- **Systematic errors from spectroscopic operations:**
  - Change in spectroscopic success rate (SSR) due to instrumentation or observing conditions

[OII] line confusion

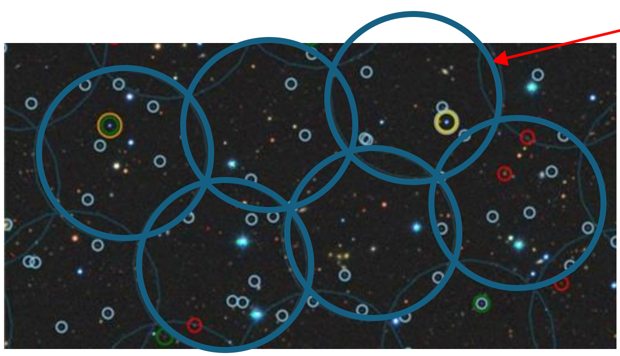




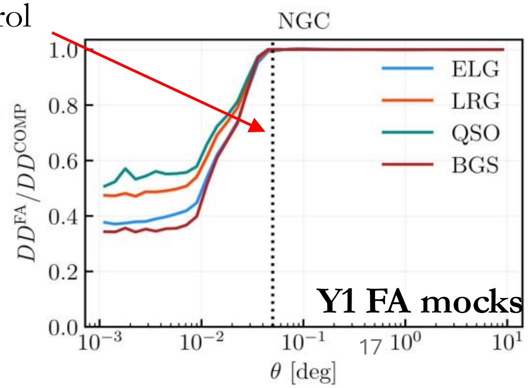
- **Fiber assignment effects:**
  - Miss close pairs of objects



Pinon et al 2024



Fiber patrol radius



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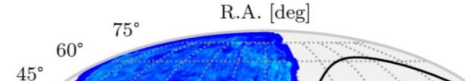
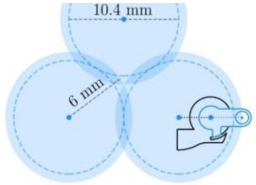
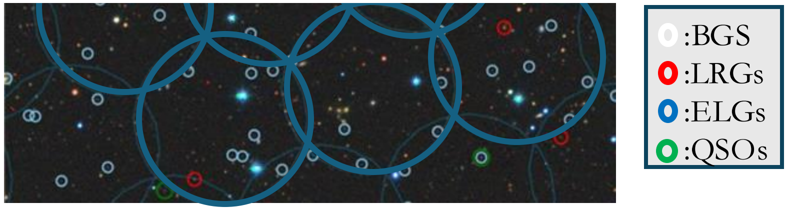


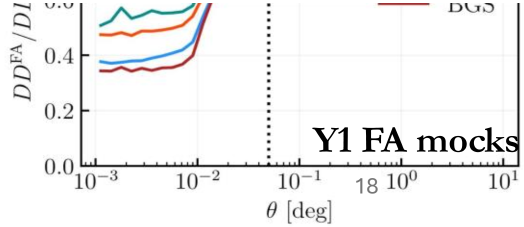
Ref.	Topic	Section
[12]	DESI LSS catalogs	Sections 2.3, 4, 5.1 and 8
[14]	Catalog-level blinding	Section 2.4
[15]	Catalog-level blinding method for $f_{\rm NL}$ measurements	Section 2.4
[22]	Incompleteness due to fiber assignment	Section 5
[23]	Removing scales affected by fiber assignment incompleteness	Section 5
[13]	Alternative realizations of DESI fiber assignment	Section 5.2
[16]	Improved Galactic extinction maps from DESI Observations of stars	Section 6
[17]	Forward modelling imaging systematics for DESI LRGs	Section 6
[18]	Correcting for imaging systematics in DESI ELGs	Section 6
[20]	DESI spectroscopic systematics	Section 7
[21]	Correcting for spectroscopic systematics in DESI ELGs	Section 7
[31]	Comparison between analytical and mock-based covariance matrices	Section 10.2
[29]	Analytic covariance matrices for correlation functions	Section 10.2
[30]	Analytic covariance matrices for power spectra	Section 10.2
[24]	Simulations of DESI LSS	Section 11

Table 1. The list of the papers supporting this paper and the corresponding sections where their results are discussed.

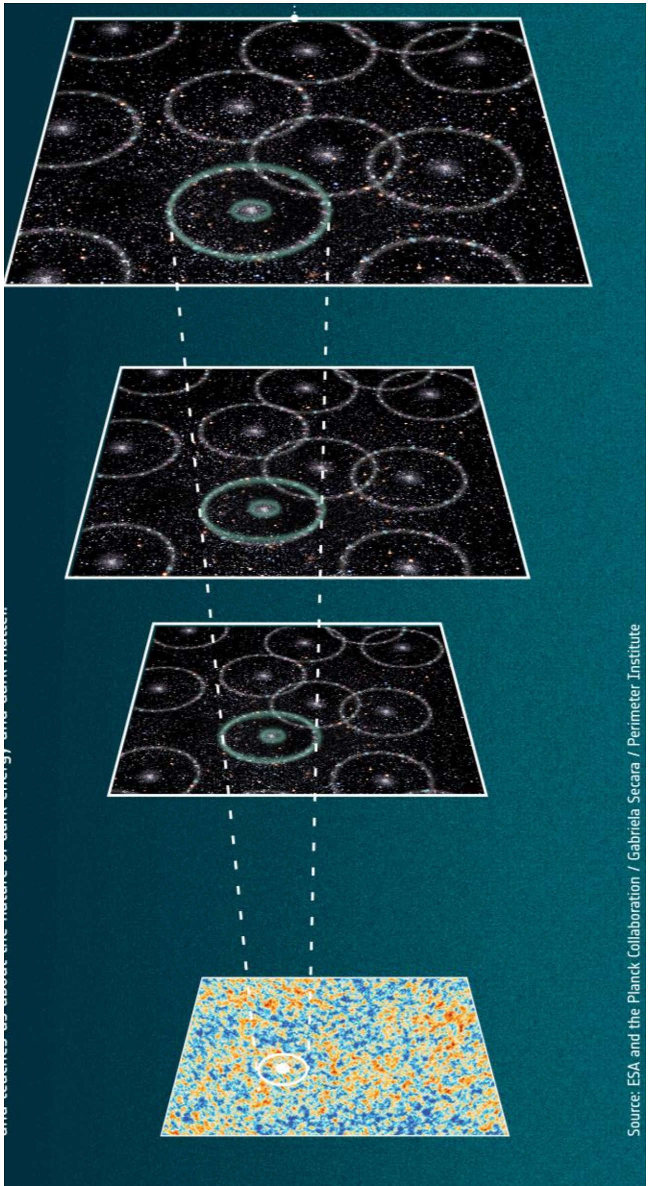


Pinon et al 2024

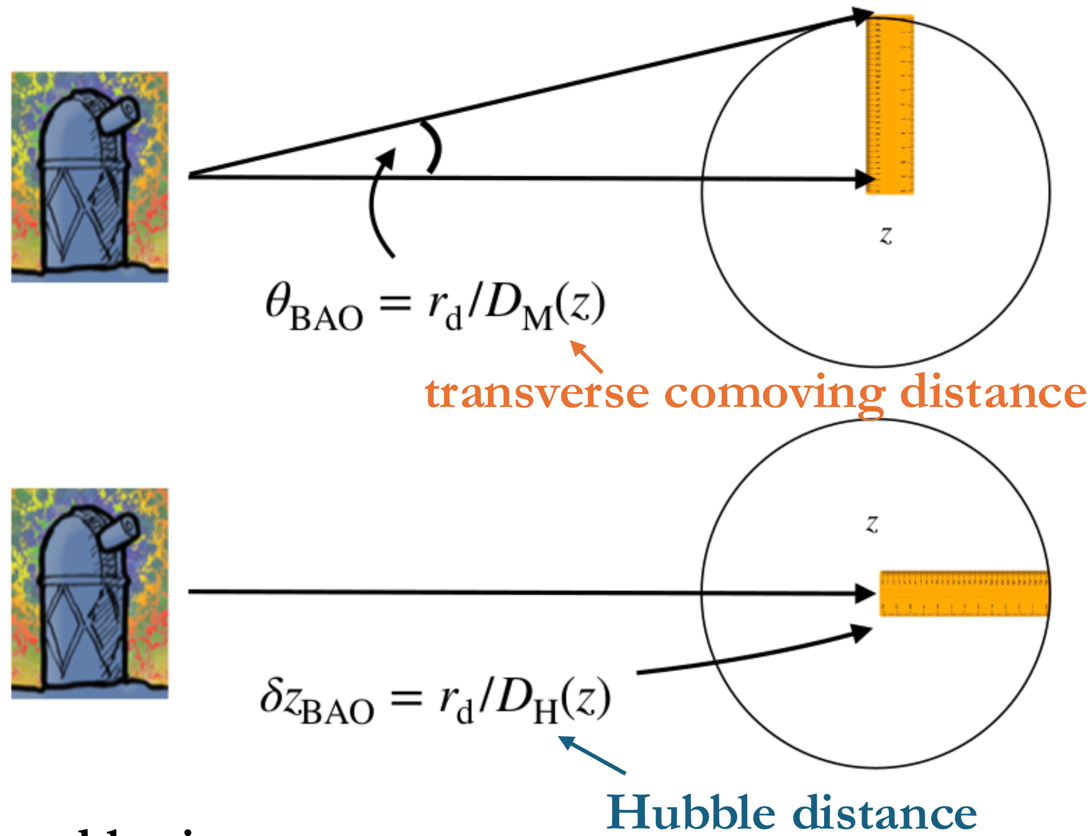




Full-shape & BAO in a Nutshell



BAO → Expansion (Dark Matter, Dark Energy)



sound horizon r_d

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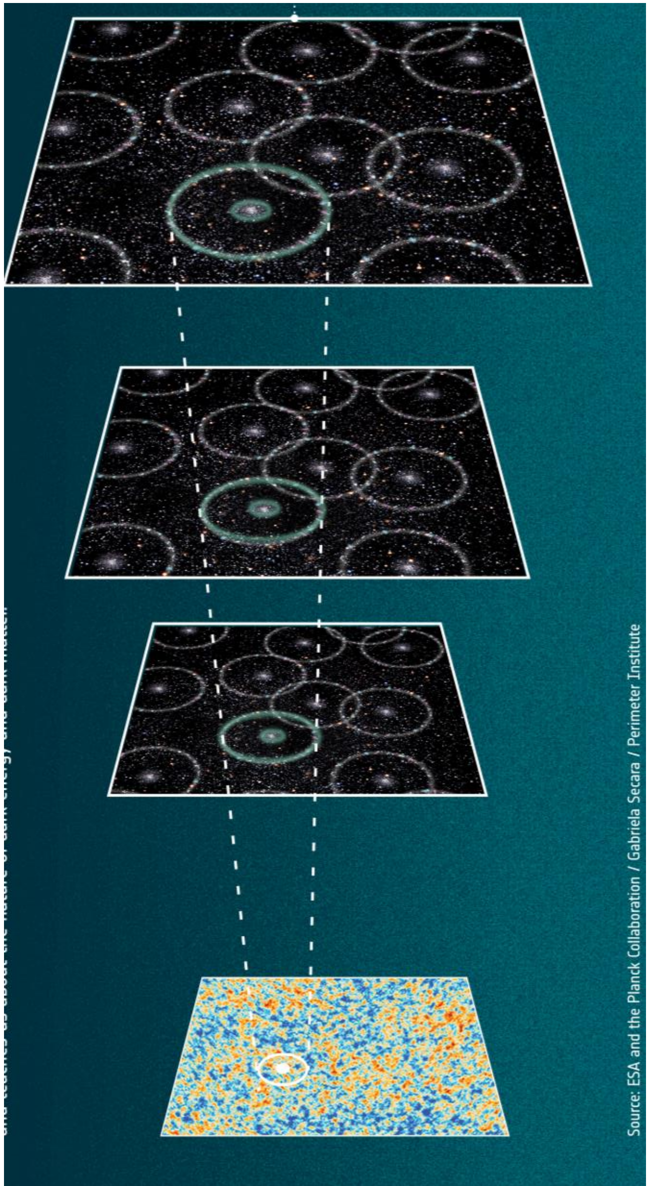
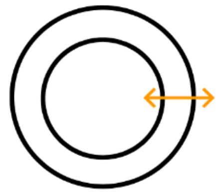


BAO → Expansion (Dark Matter, Dark Energy)

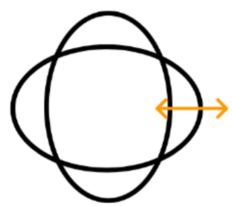
isotropic measurement

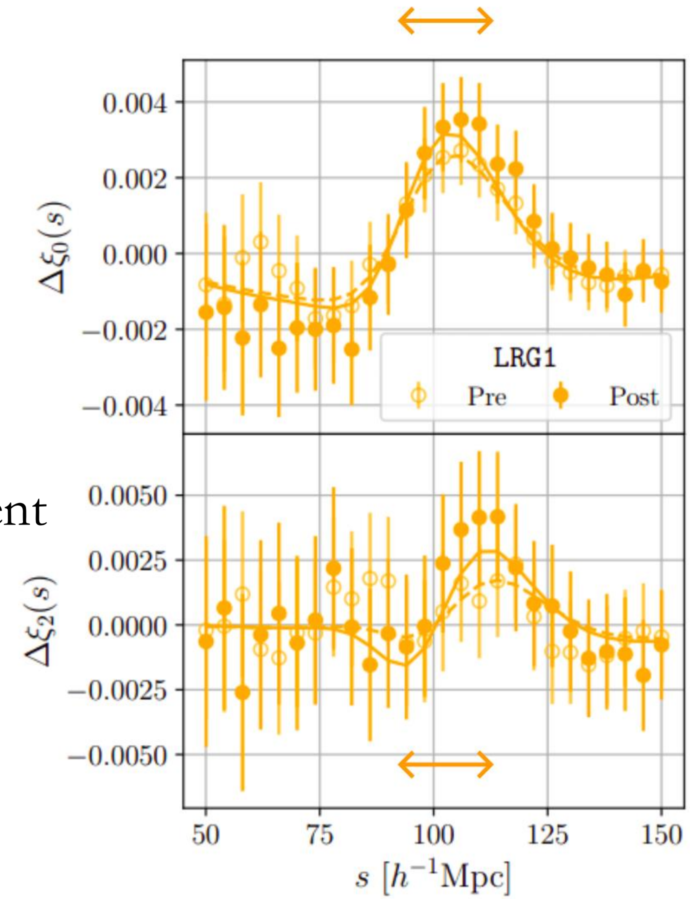
$$\propto (D_{\rm M}^2(z) D_{\rm H}(z))^{1/3}/r_{\rm d}$$



anisotropic measurement

$$\propto D_{\rm M}(z)/D_{\rm H}(z)$$





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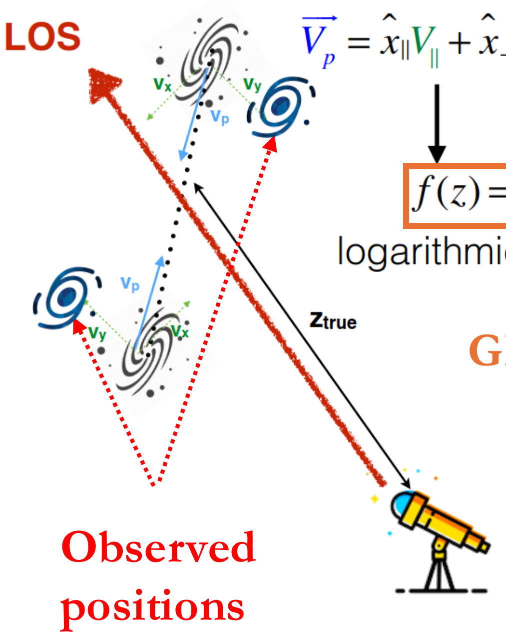
Full-shape & BAO in a Nutshell

Peculiar velocities impact the measurement of the redshift and create **anisotropies in the galaxy distribution**

(Kaiser 1987)

$$\delta_{\mathrm{RSD}}(\overrightarrow{k}, a) = [1 + f(a) u_k^2]\, \delta(\overrightarrow{k}, a)$$

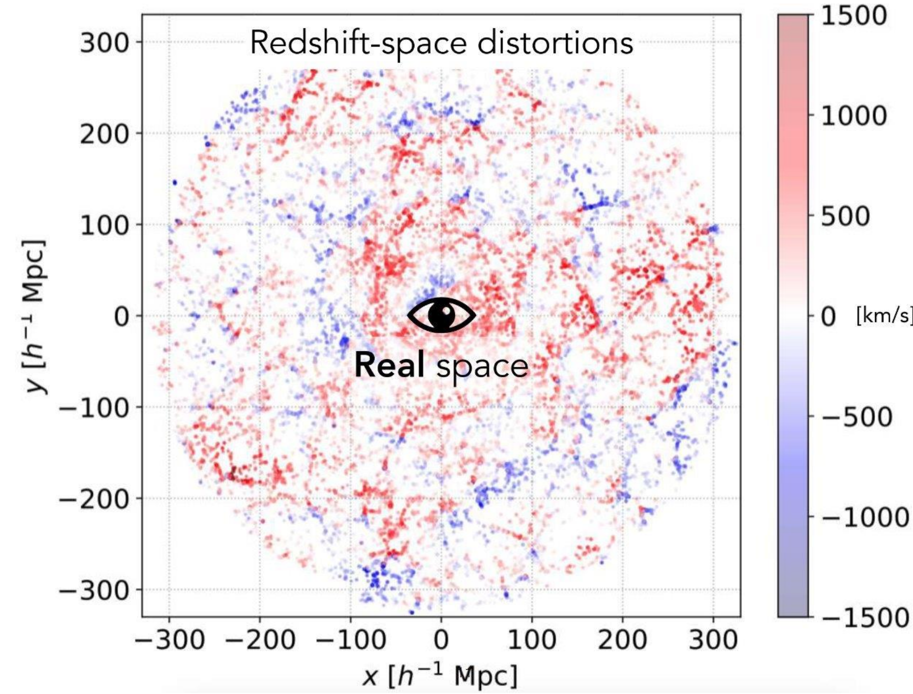


$$\overrightarrow{V}_p = \hat{x}_{\parallel} V_{\parallel} + \hat{x}_{\perp} V_{\perp}$$

$$f(z) = \Omega_m(z)^{\gamma}$$

logarithmic growth of structure

GR predict $\gamma \approx 0.55$



$$z_{obs} = z_{true} \oplus z_{pec} \equiv \left[(1 + z_{true}) \times (1 + z_{pec})\right] - 1$$

Credit : J. Bautista

1. Hubble flow
2. Coherent with growth of structure

Enhancement / reduction of the clustering along the line-of-sight (LOS)

Credit : H. Gil-Marin

Full-shape & BAO in a Nutshell

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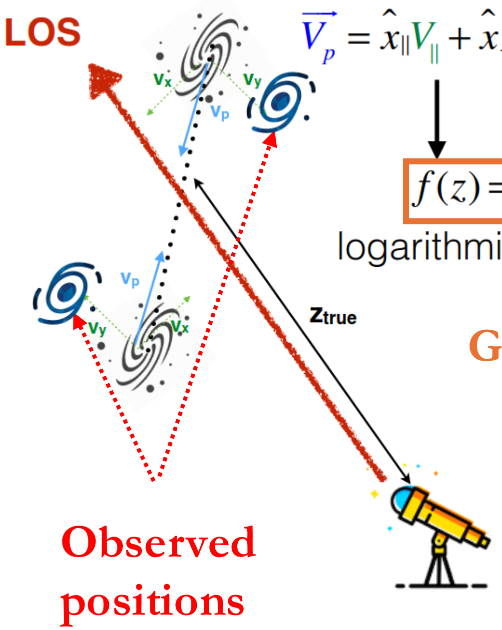

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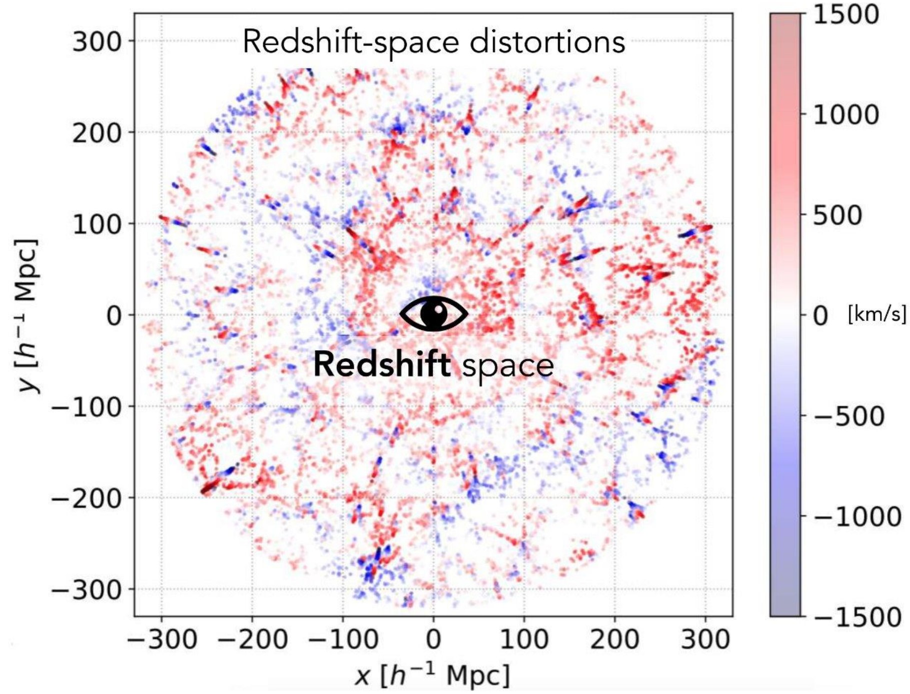

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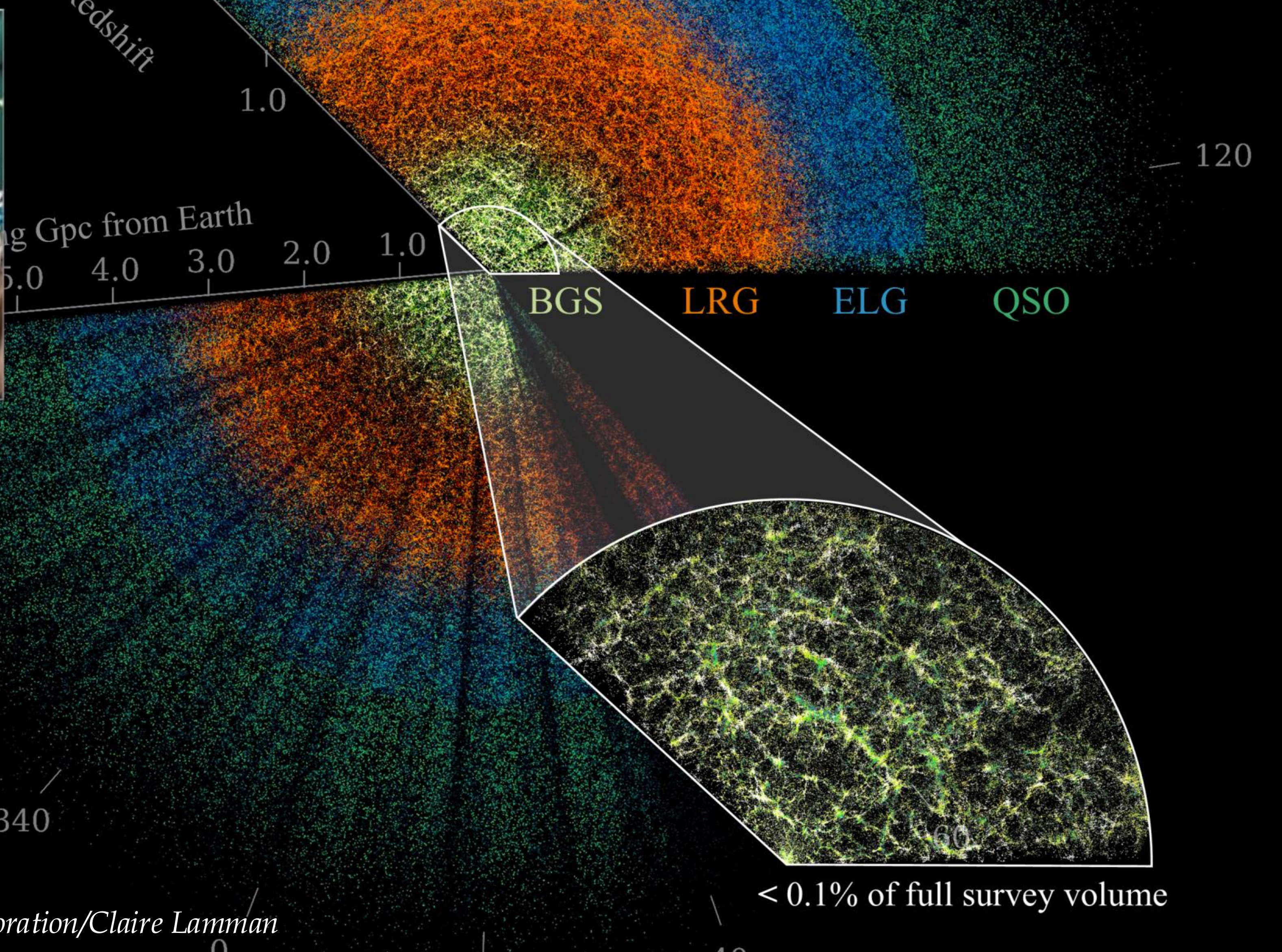
Cosmological implication of DESI DR1 and DR2



Credit : DESI collaboration/Claire Lamman

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Full-shape DR1: Modified Gravity

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

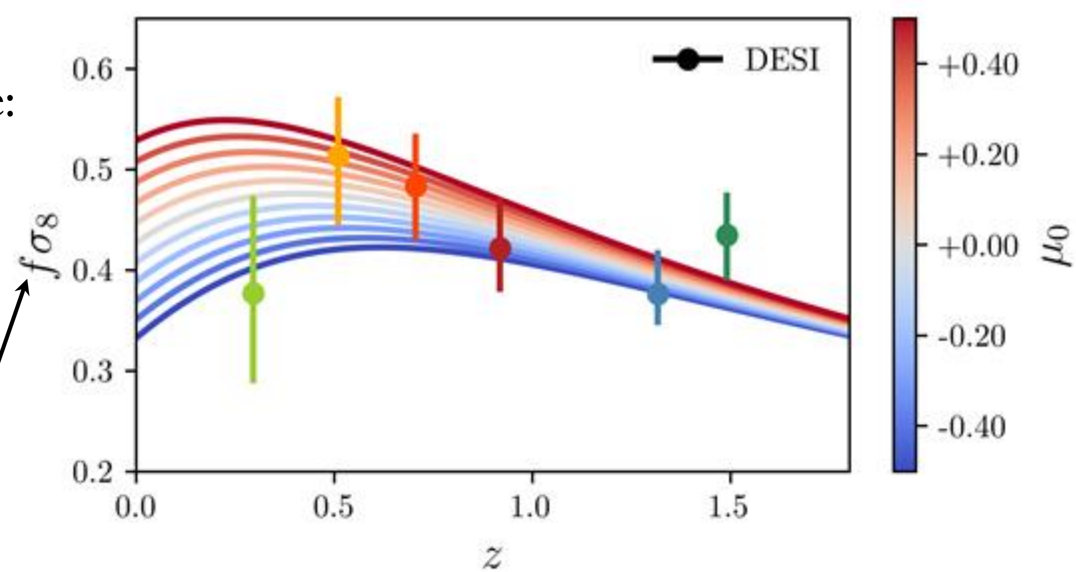
At late times:

$$k^2\Psi = -4\pi G a^2 \mu(a,k)\Sigma_i \rho_i \Delta_i$$
$$k^2(\Phi+\Psi) = -8\pi G a^2 \Sigma(a,k)\Sigma_i \rho_i \Delta_i$$

In GR: $\mu(a,k) = \Sigma(a,k) = 1$

Choose the following time dependence:

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



Growth rate of structure

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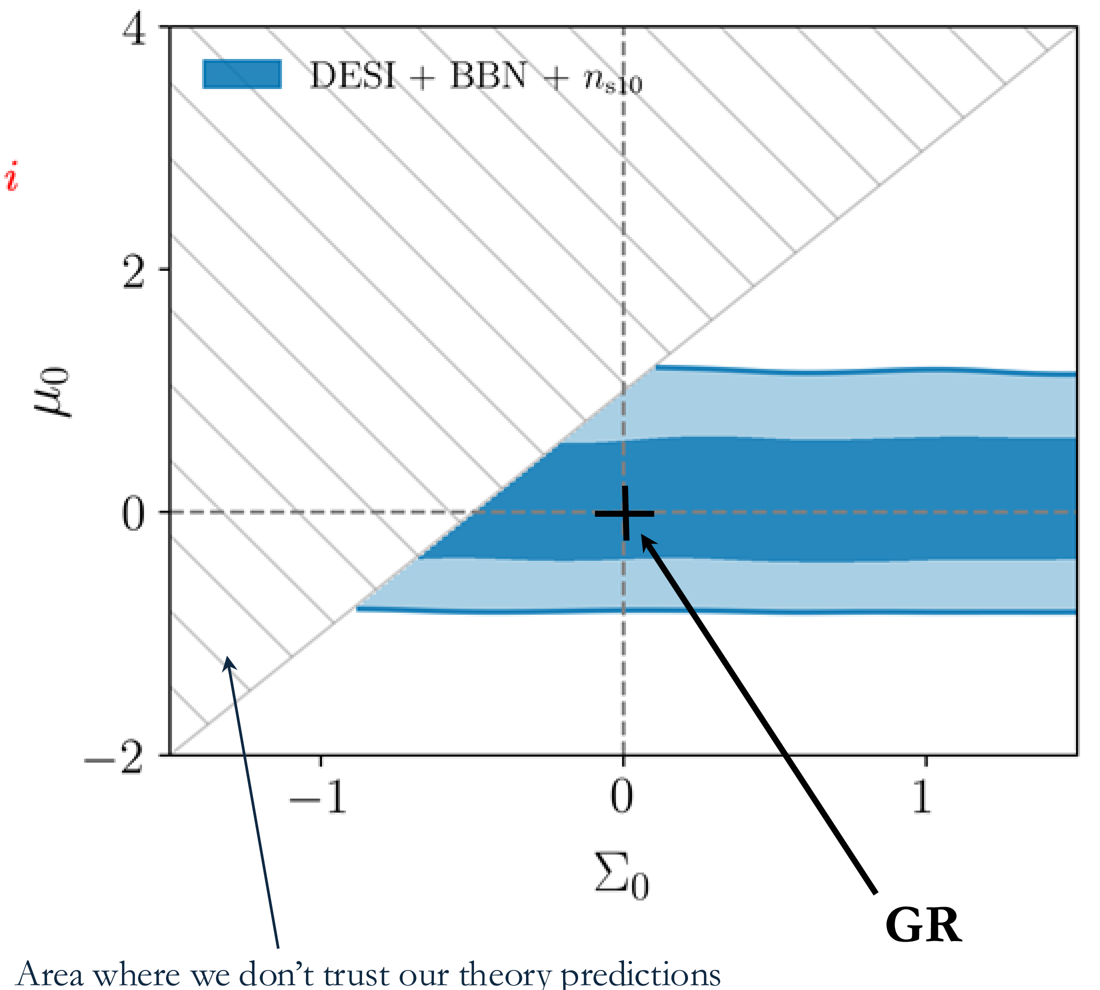
Full-shape DR1: Modified Gravity

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

Describes the motion of massive particles in a gravitational field:
→ can be directly constrained by DESI

$$\mu_0 = 0.11^{+0.45}_{-0.54}$$



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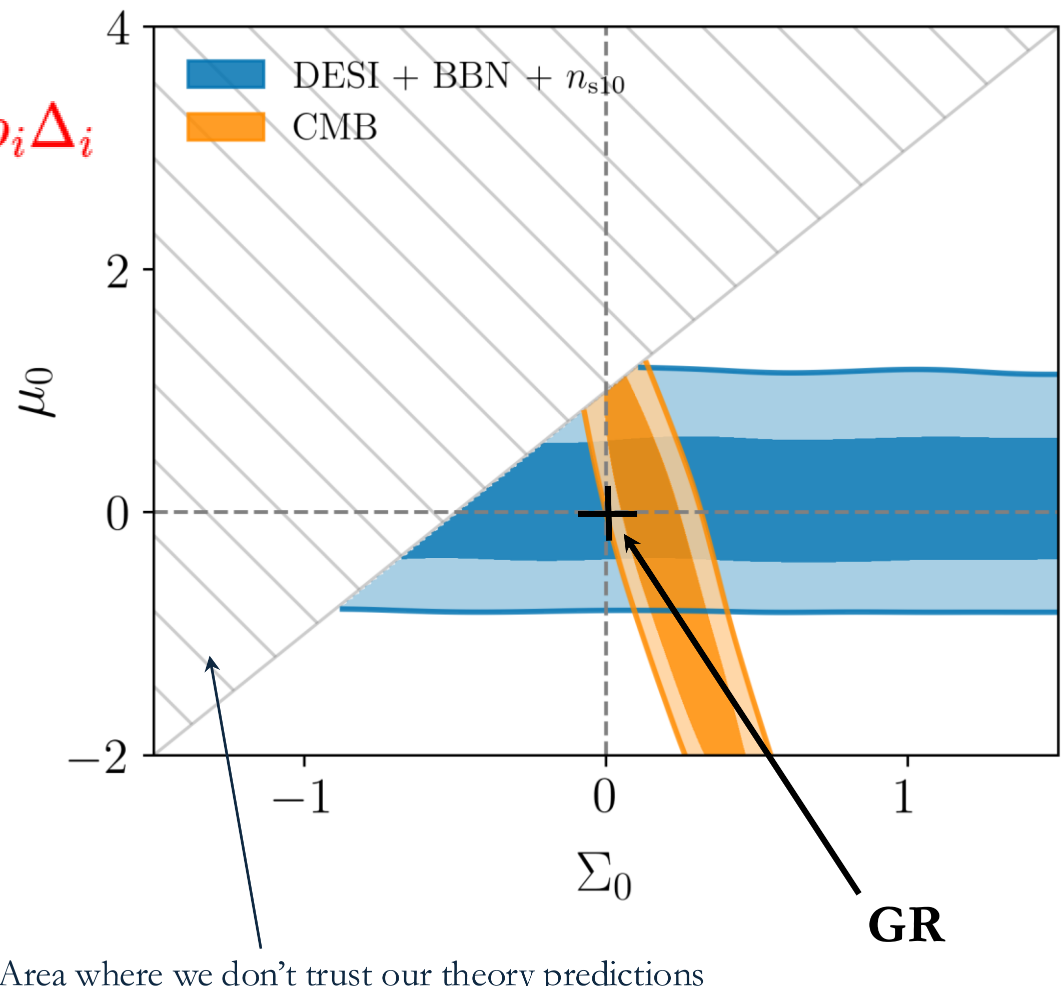
Full-shape DR1: Modified Gravity

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

Describes the motion of massive particles in a gravitational field:
→ can be constrained by lensing and ISW

$$\Sigma_0 = 0.25^{+0.12}_{-0.18}$$

Slight departure from GR related to CMB lensing anomaly



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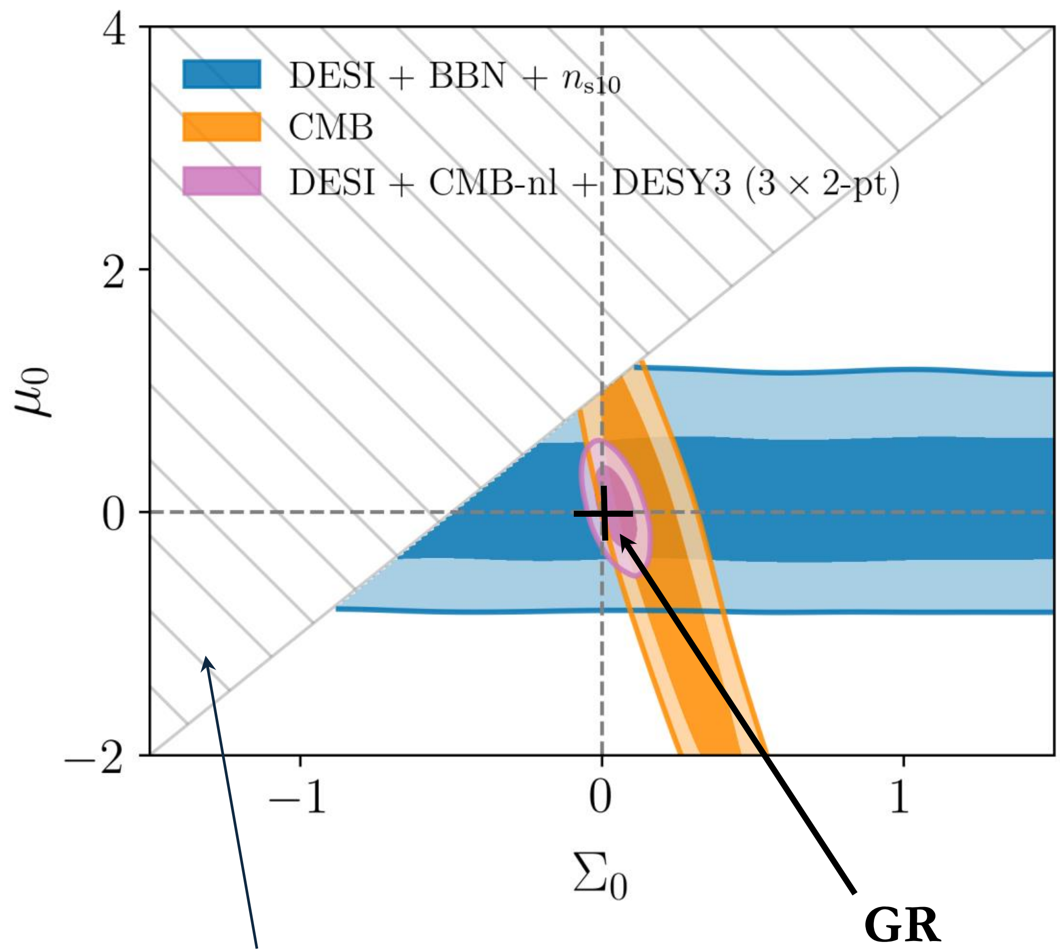
Full-shape DR1: Modified Gravity

Combination of clustering and lensing:

DESI +CMB-nl+DESY3

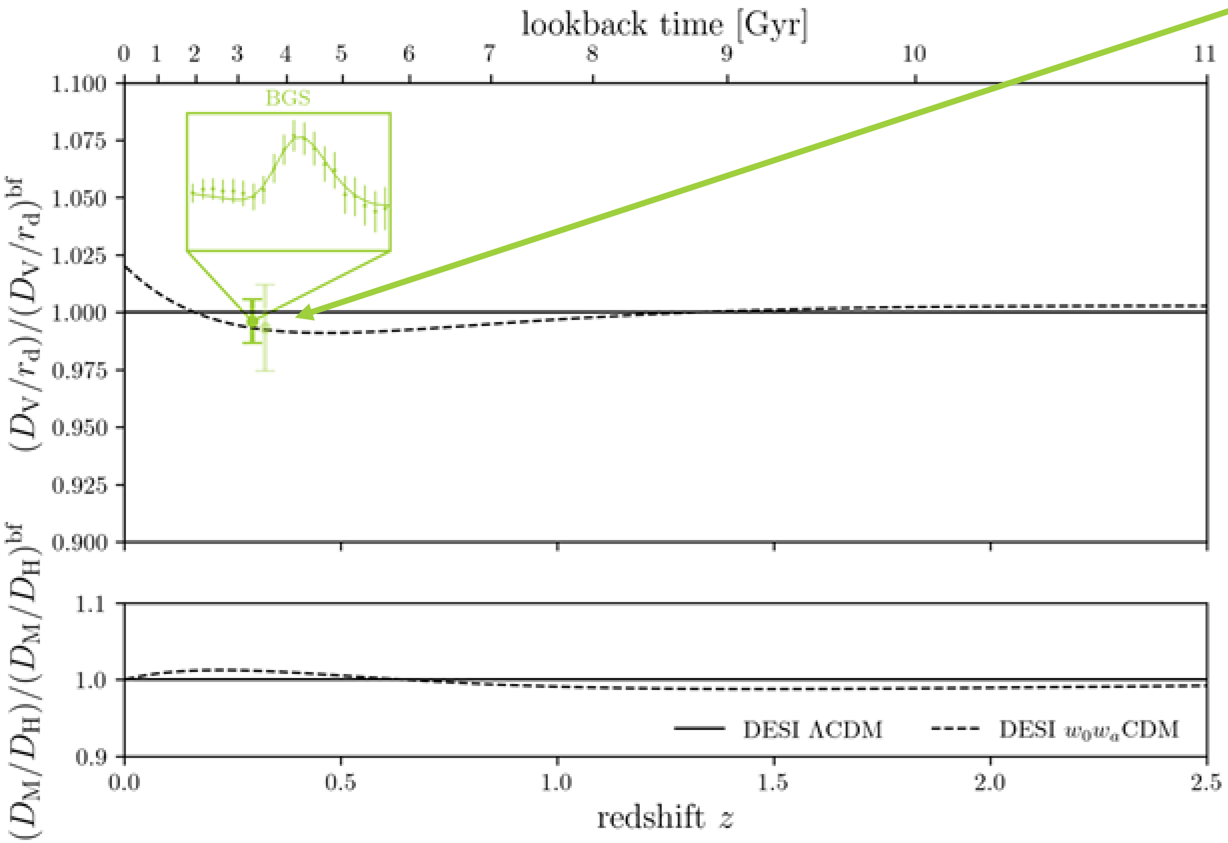
$$\begin{cases} \mu_0 = 0.04 \pm 0.22 \\ \Sigma_0 = 0.044 \pm 0.047 \end{cases}$$

Suggest consistency with GR

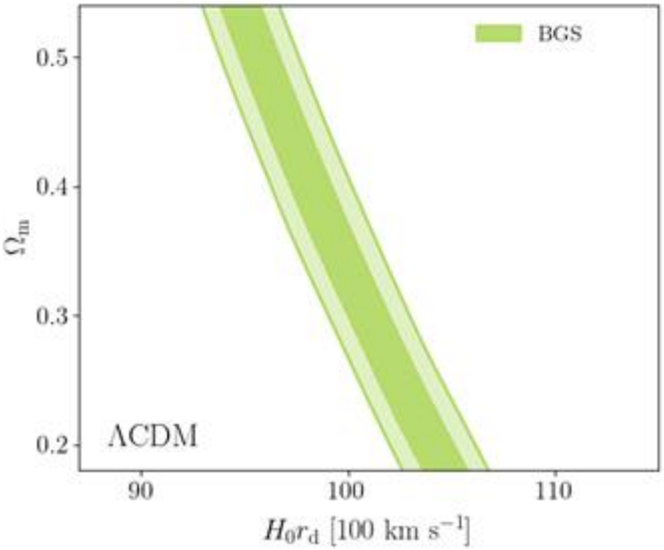


BAO: From DR1 to DR2

Only isotropic BAO fit



bf: DESI + CMB + DESY5



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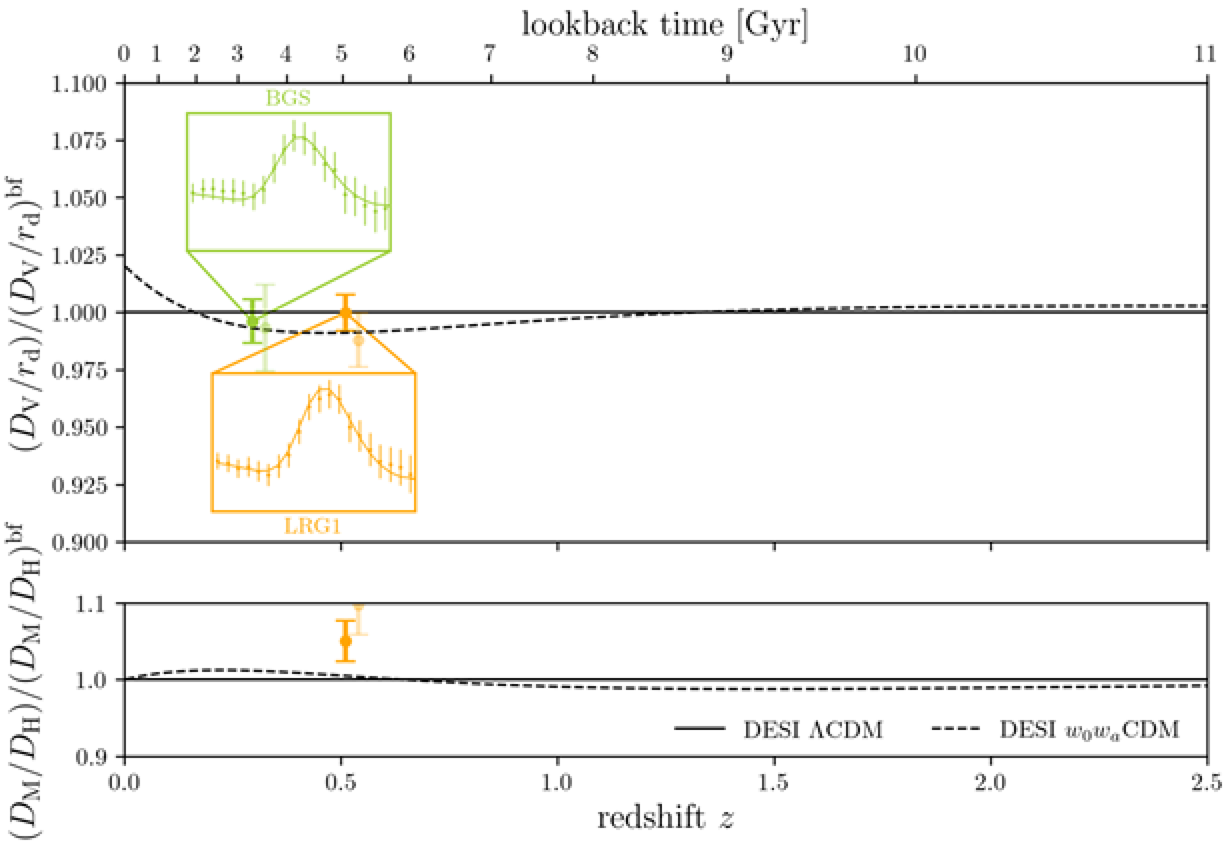
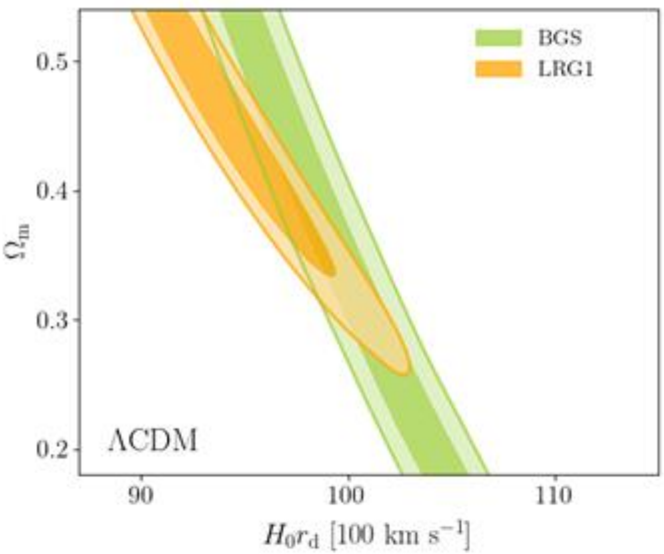
BAO: From DR1 to DR2

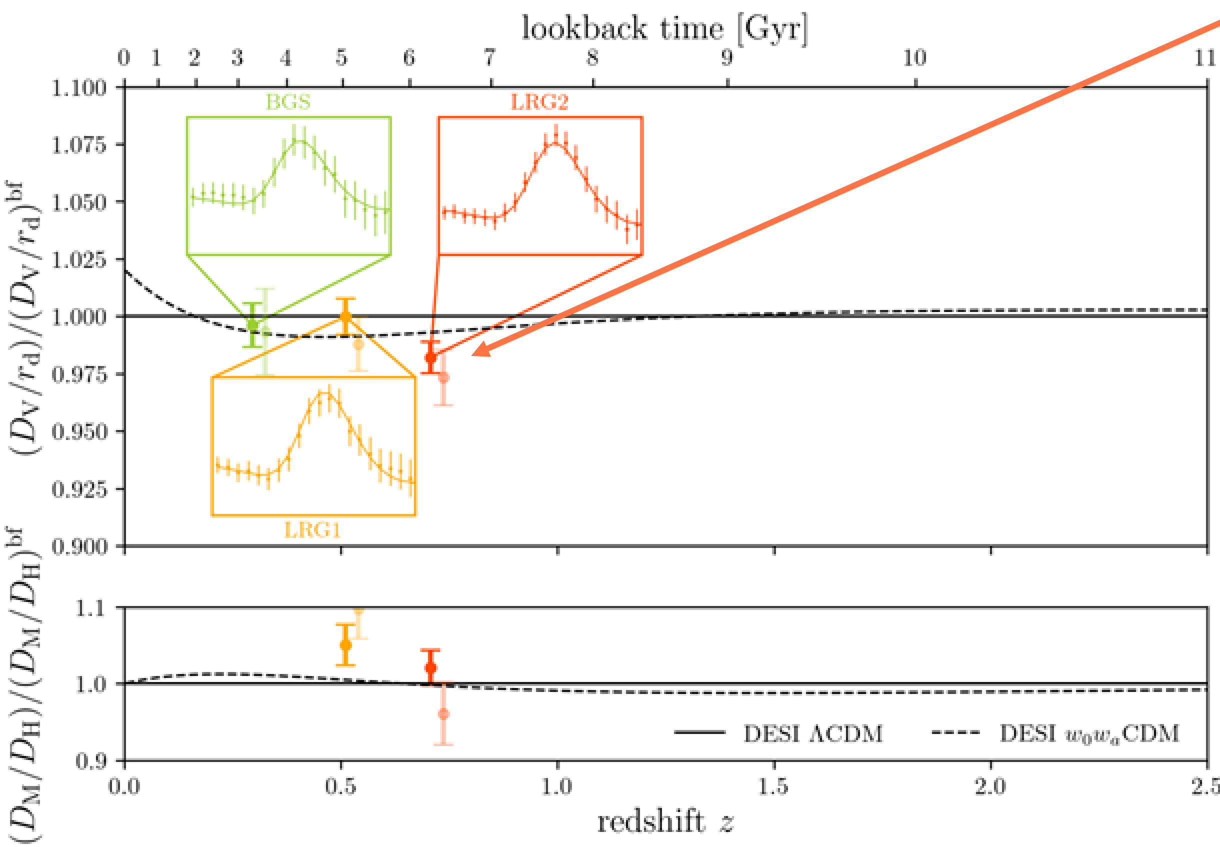


bf: DESI + CMB + DESY5

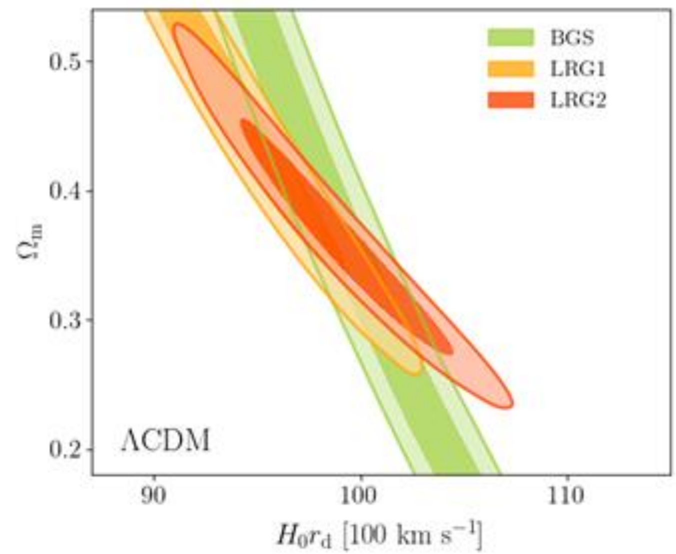


BAO: From DR1 to DR2

Tension with SDSS is reduced to 2.6σ



bf: DESI + CMB + DESY5



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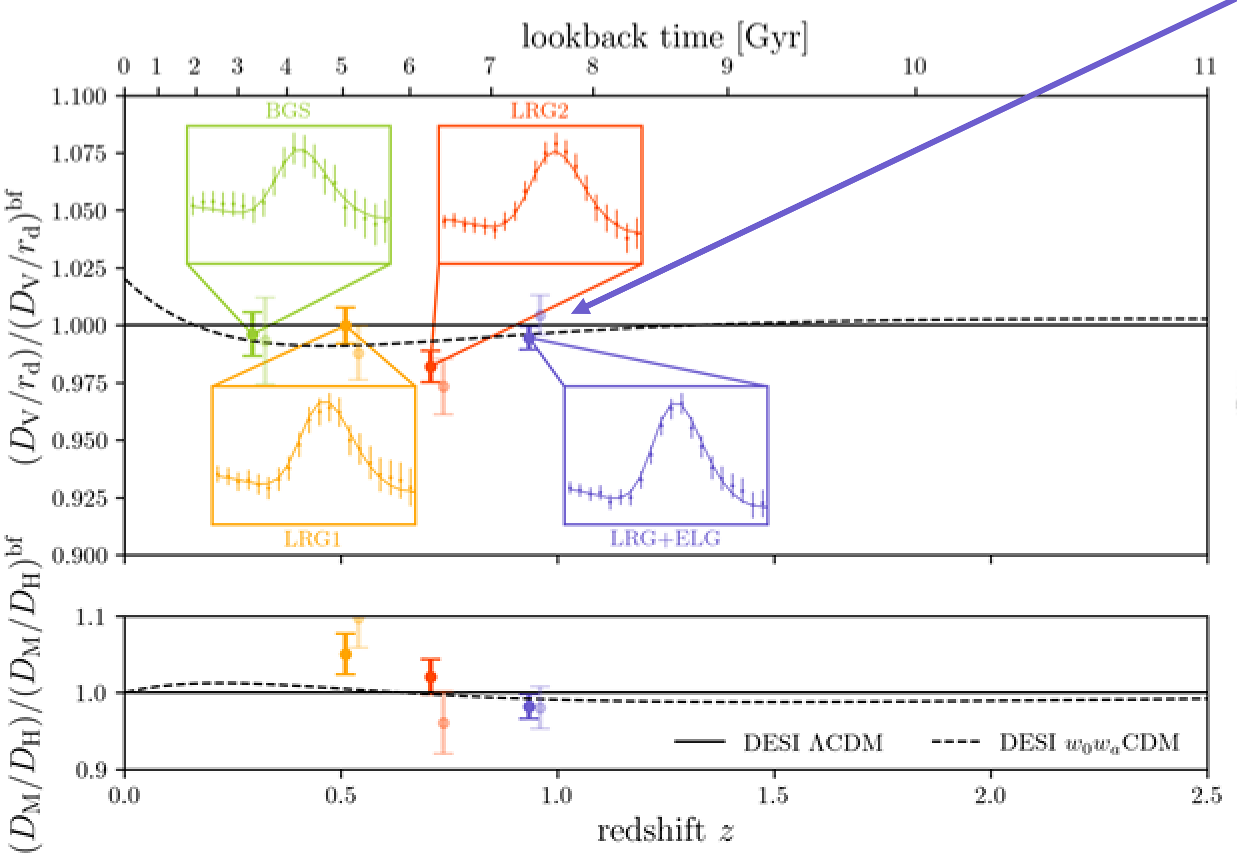
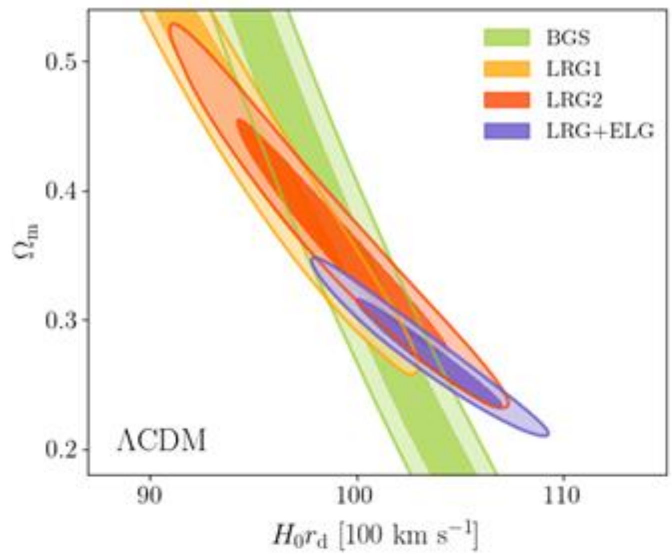
BAO: From DR1 to DR2



bf: DESI + CMB + DESY5

Combination of LRG3 and ELG, yielding our tightest BAO measurement (15σ)



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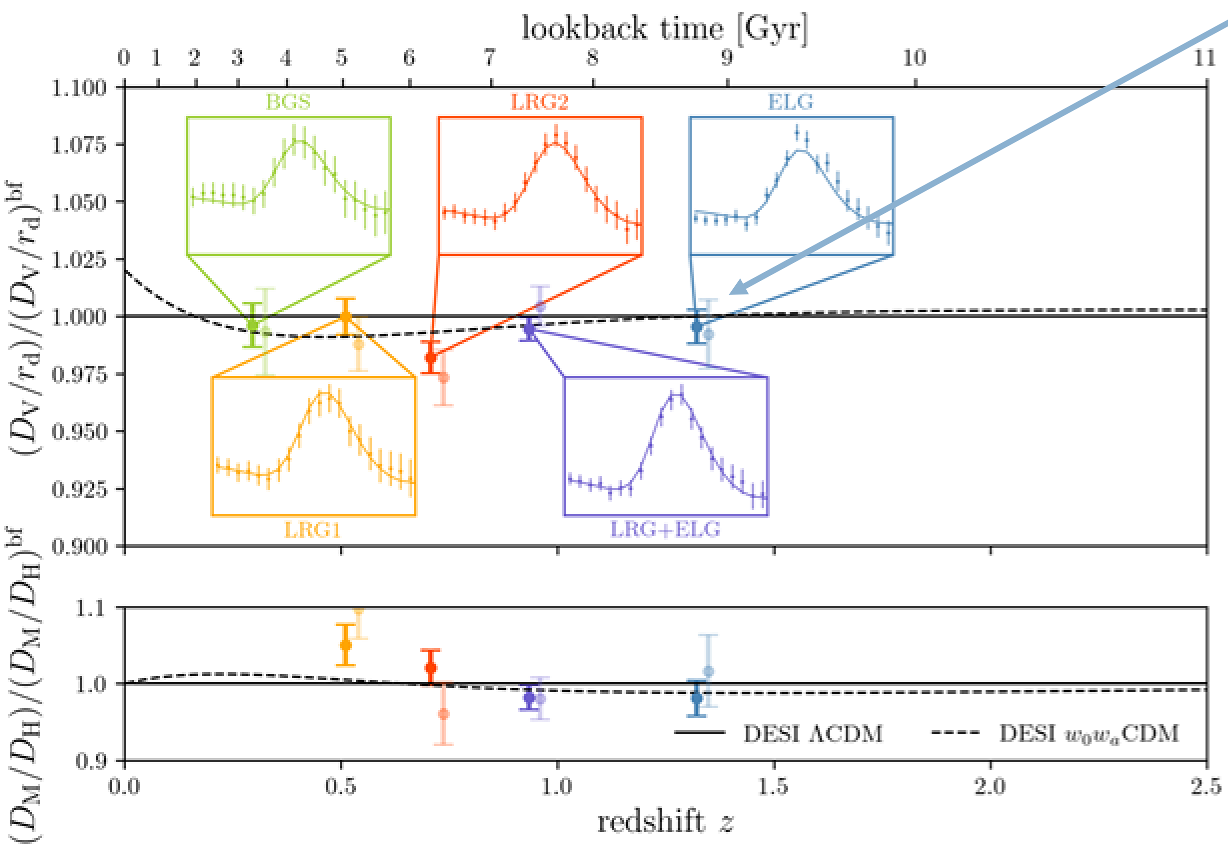
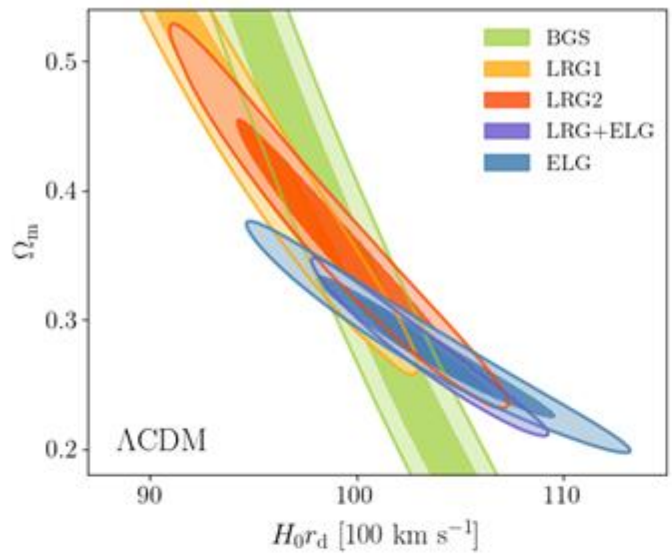
BAO: From DR1 to DR2

Error bars are reduced by a factor of two

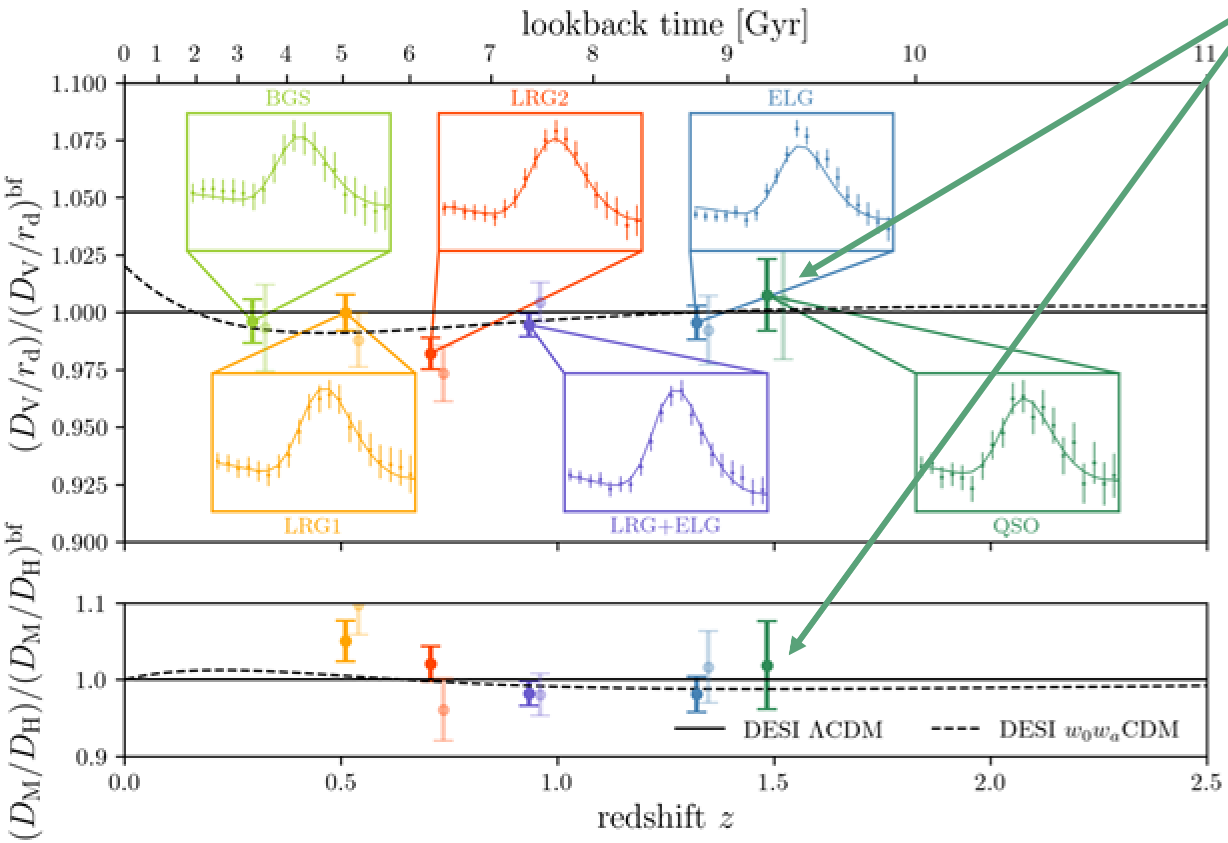




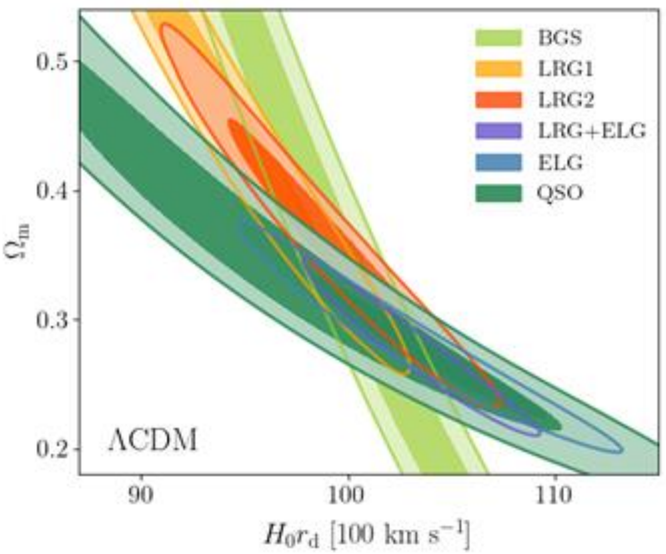
bf: DESI + CMB + DESY5

BAO: From DR1 to DR2

New 2D BAO fits for QSO



bf: DESI + CMB + DESY5



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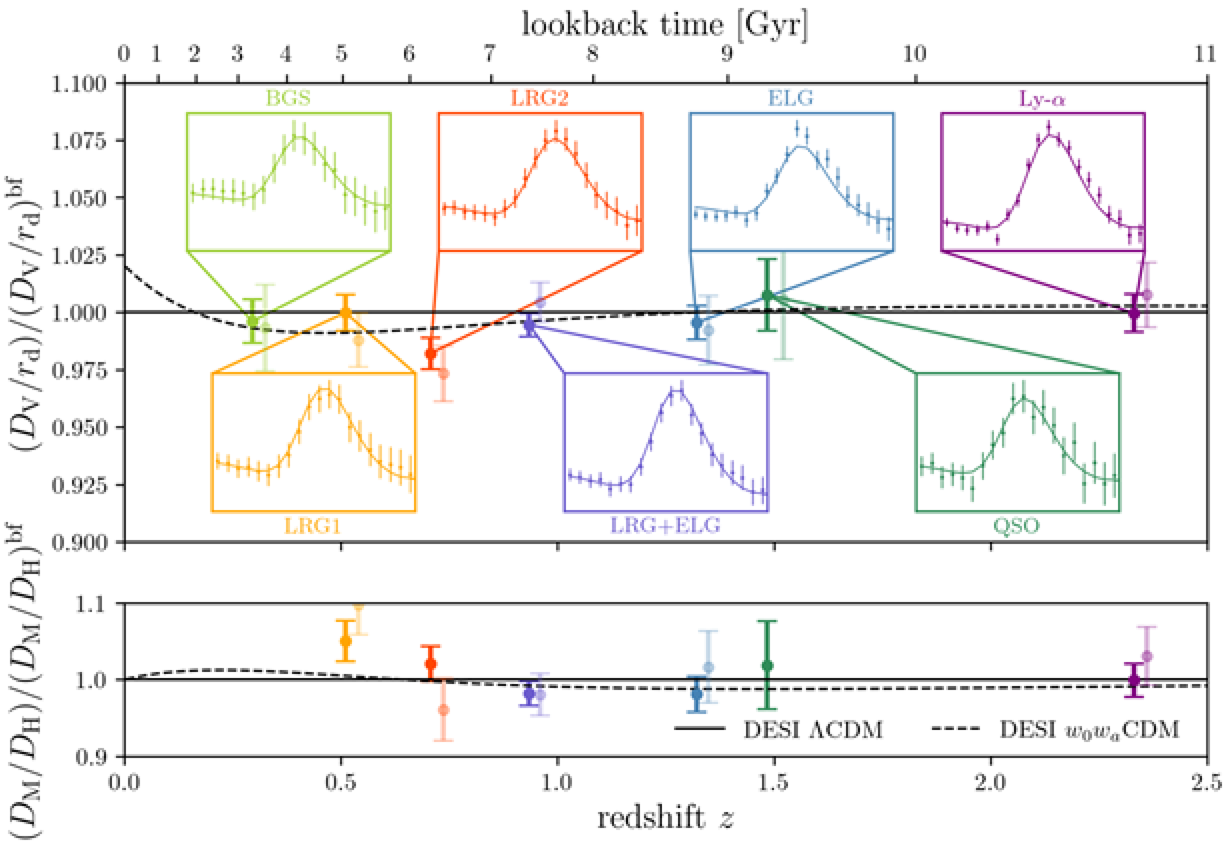
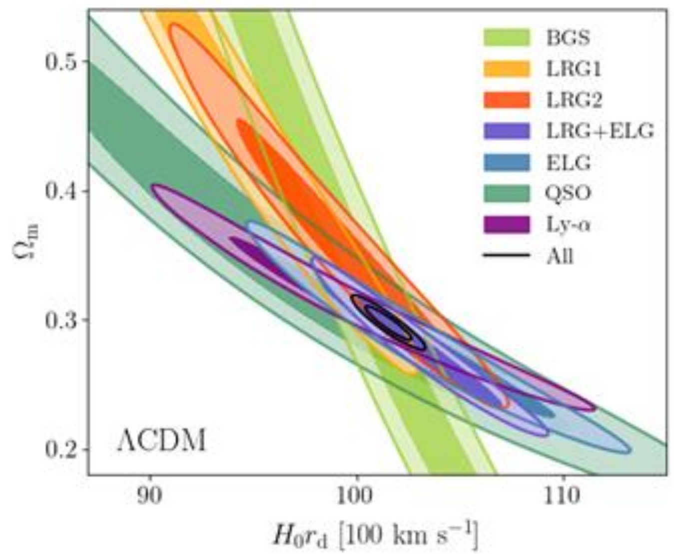
BAO: From DR1 to DR2

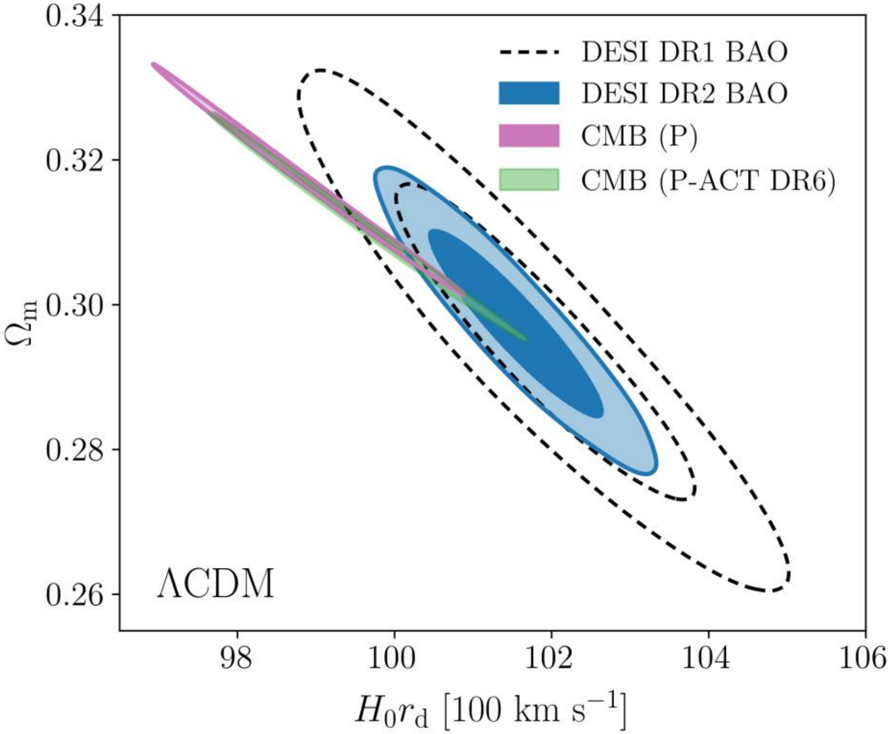


bf: DESI + CMB + DESY5

Agreement & complementarity between tracers



BAO: From DR1 to DR2



$$\text{DESI DR2} \begin{cases} \Omega_m & = 0.2975 \pm 0.0086 \\ hr_d & = (101.54 \pm 0.73)\ \text{Mpc} \end{cases}$$

DR1 → DR2: 40% improvement in precision on Ω_m and hr_d

On the consistency between CMB (including the new ACT results) and DESI, see *arXiv:2504.18464*

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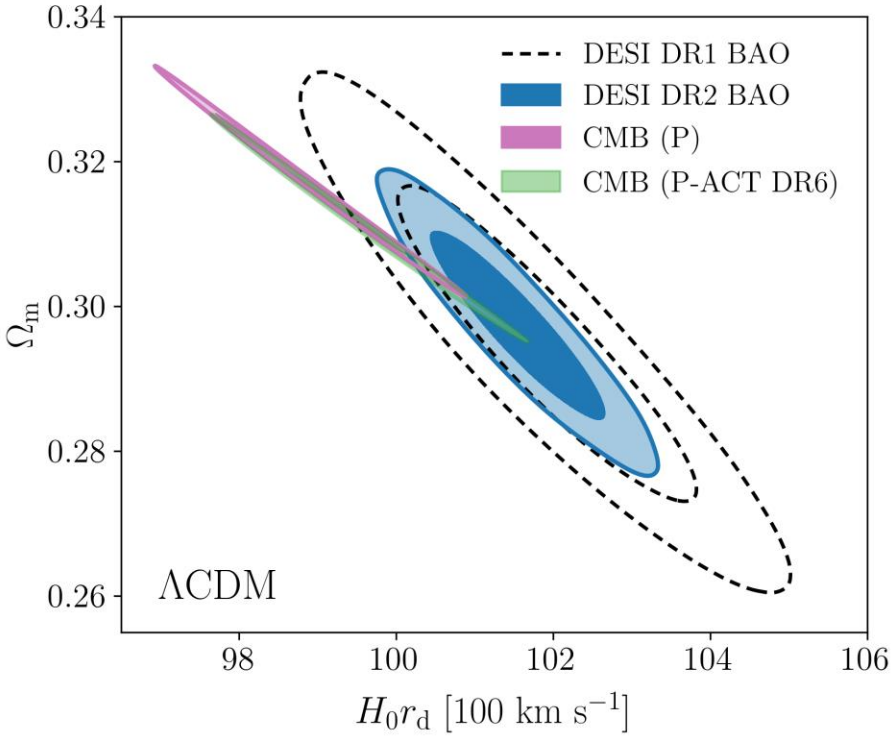
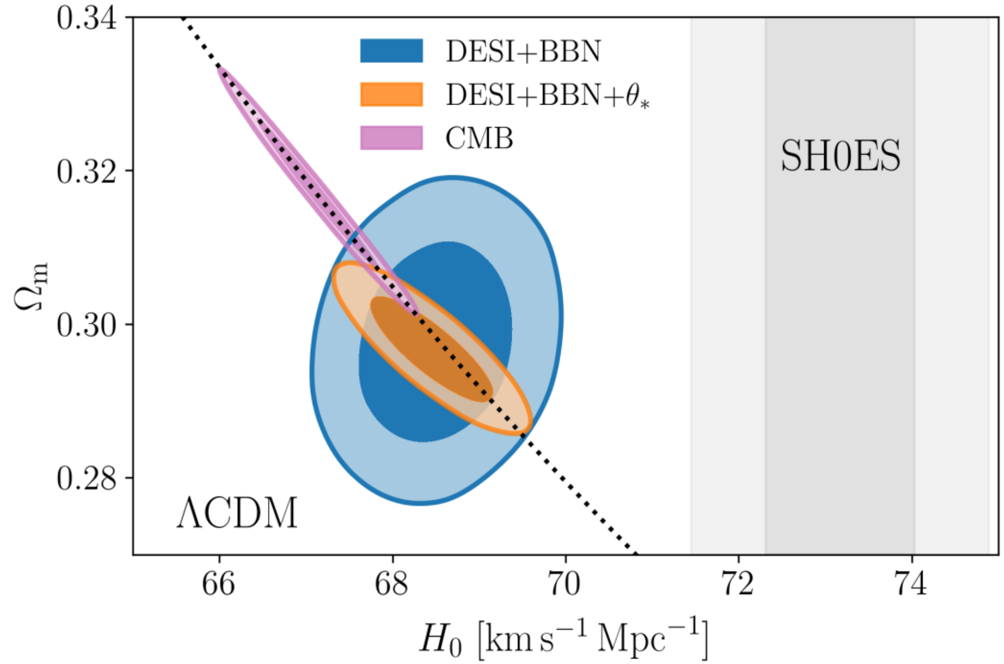
BAO: From DR1 to DR2





$$\text{DESI DR2} \begin{cases} \Omega_m &= 0.2975 \pm 0.0086 \\ hr_d &= (101.54 \pm 0.73)\ \text{Mpc} \end{cases}$$

DR1 → DR2: 40% improvement in precision on Ω_m and hr_d

BBN prior on ω_b:

$$H_0 = (68.51 \pm 0.58)\ \text{km/s/Mpc}$$

Adding prior on *angular acoustic scale* θ_* :

$$H_0 = (68.45 \pm 0.47)\ \text{km/s/Mpc}$$

On the consistency between CMB (including the new ACT results) and DESI, see [arXiv:2504.18464]

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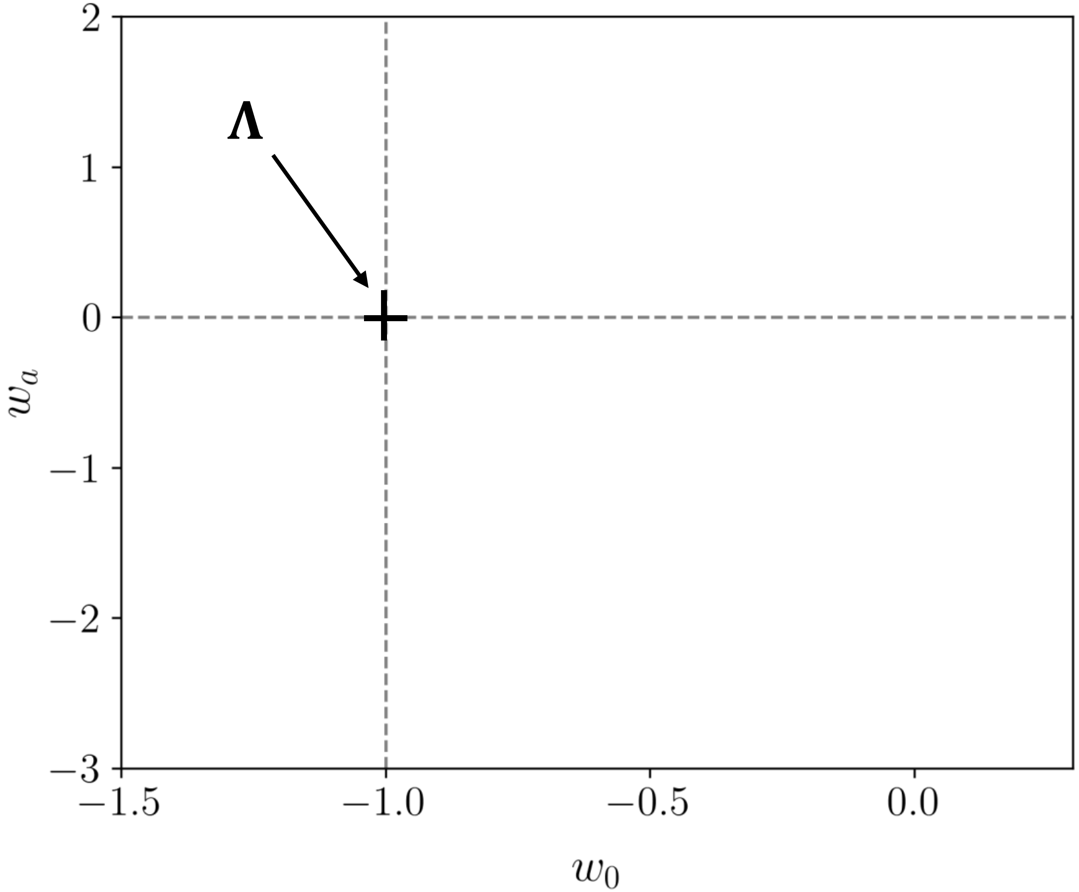
Dark Energy Equation of State



We model a varying DE equation of state through:

$$w(a) = w_0 + w_a(1 - a)$$

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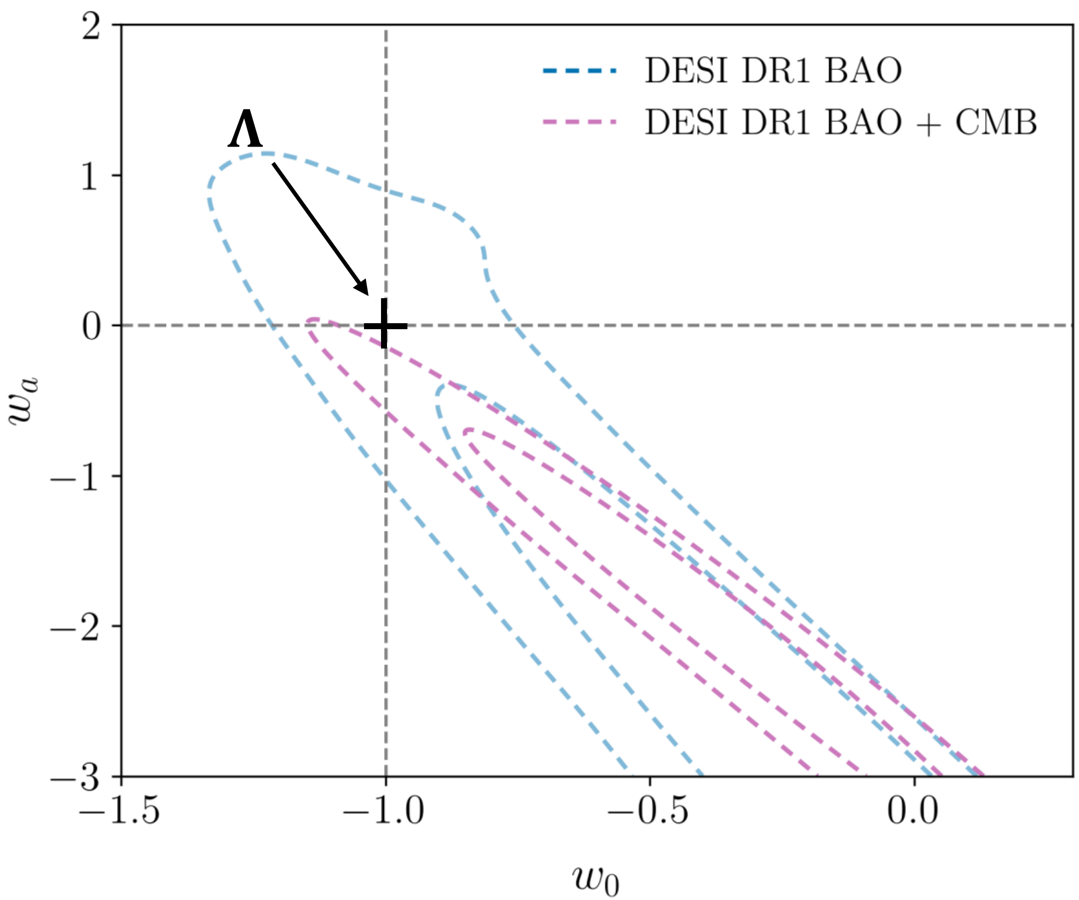
Dark Energy Equation of State



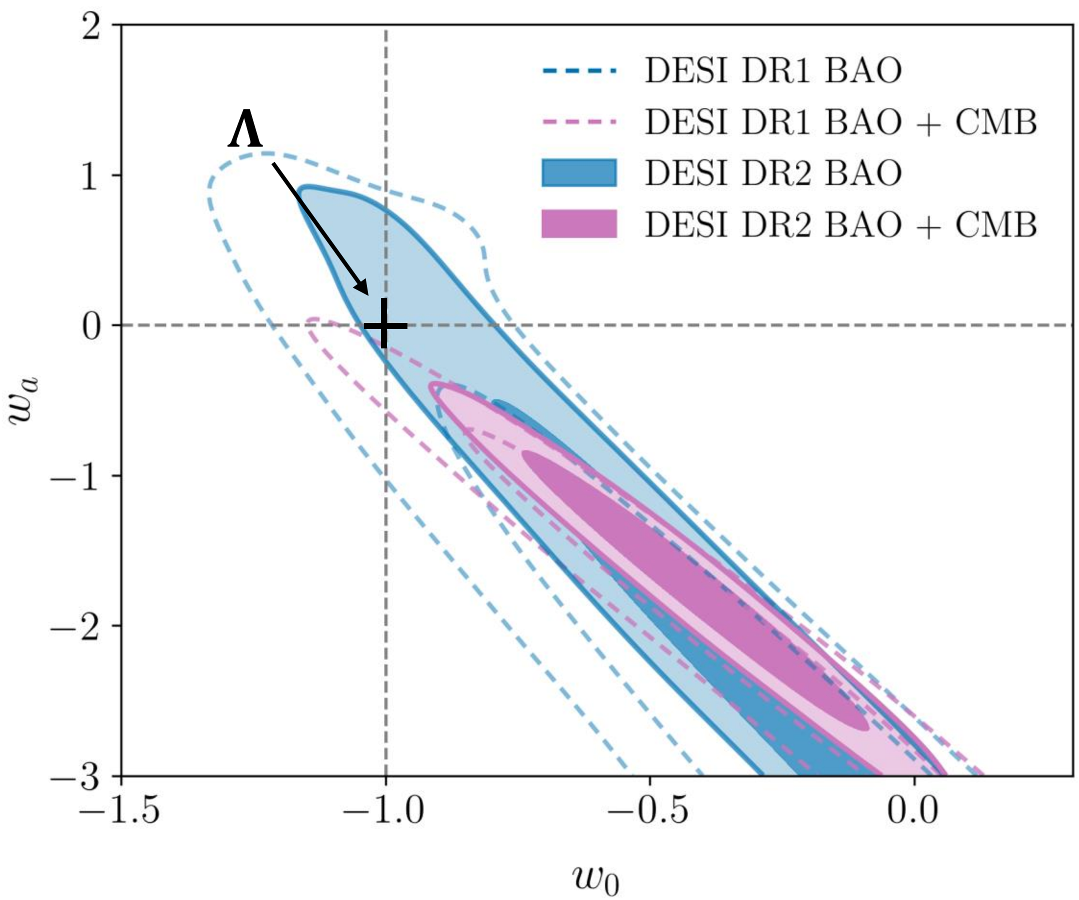
We model a varying DE equation of state through:

$$w(a) = w_0 + w_a(1-a)$$

$$w_0 = -0.45^{+0.34}_{-0.21} \quad w_a = -1.79^{+0.48}_{-1.00}$$

DR1: DESI + CMB ⇒ 2.6σ

Dark Energy Equation of State



We model a varying DE equation of state through:

$$w(a) = w_0 + w_a(1 - a)$$

$w_0 = -0.45^{+0.34}_{-0.21}$ $w_a = -1.79^{+0.48}_{-1.00}$

DR1: DESI + CMB ⇒ 2.6σ

$w_0 = -0.42 \pm 0.21$ $w_a = -1.75 \pm 0.58$

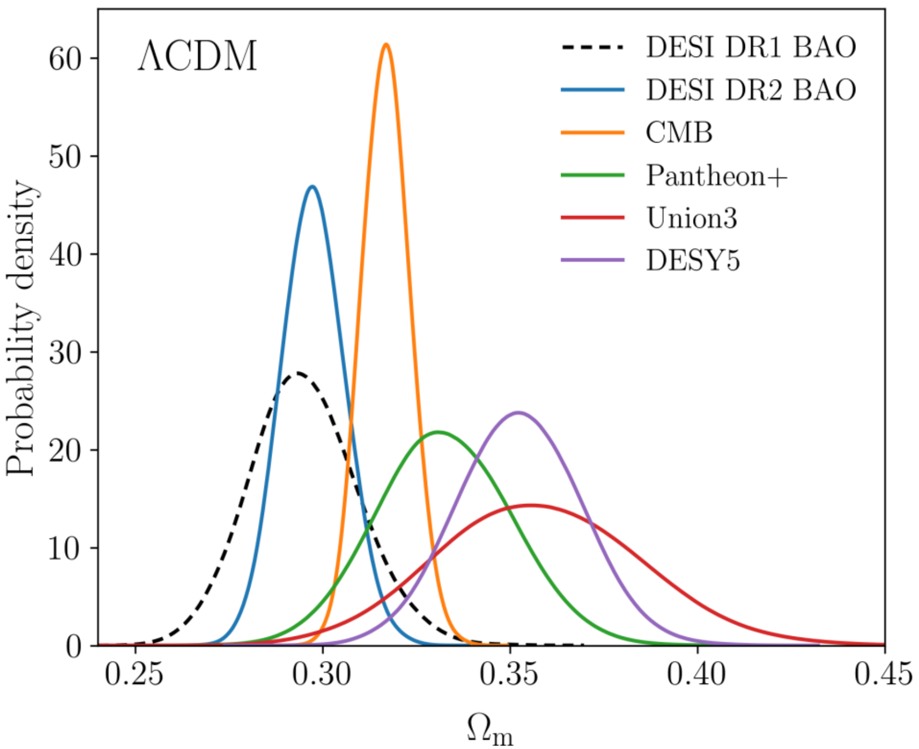
DR2: DESI + CMB ⇒ 3.1σ

Dark Energy Equation of State

In **ΛCDM**:

→ DESI BAO predicts slightly lower values of $\boldsymbol{\Omega}_m$ than Planck

→ SN data sets predict higher values of $\boldsymbol{\Omega}_m$ than Planck



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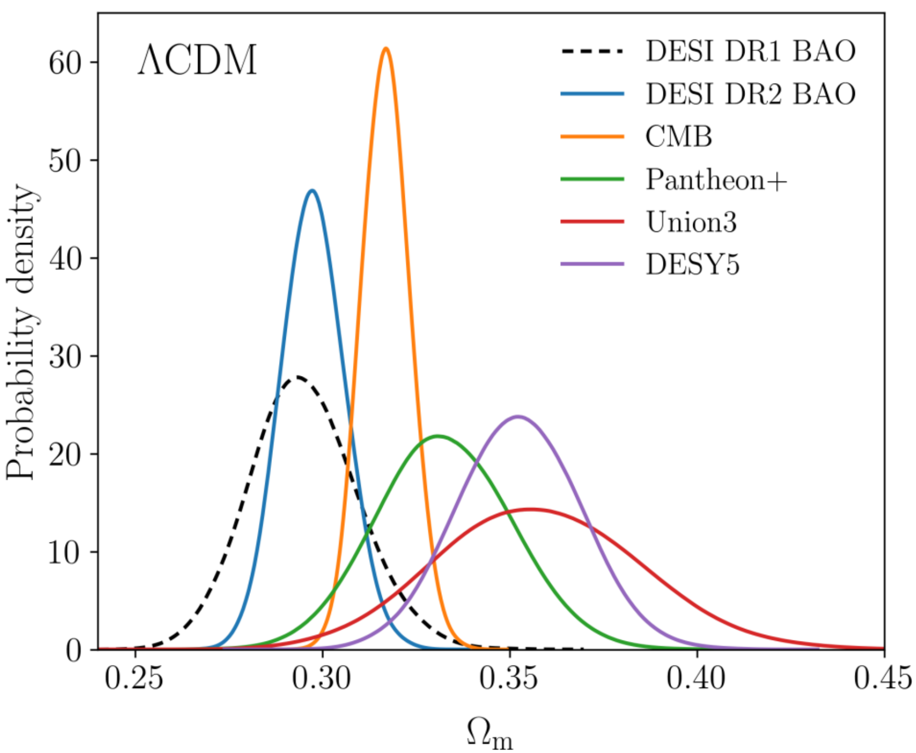
Dark Energy Equation of State

In **ΛCDM**:

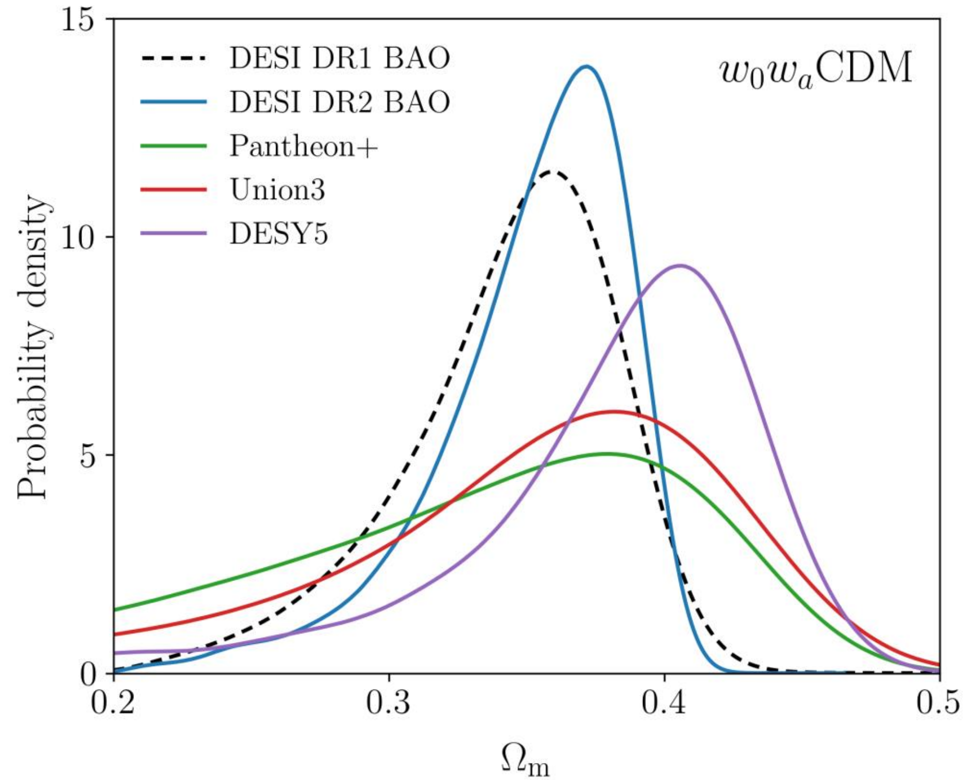
→ DESI BAO predicts slightly lower values of $\mathbf{\Omega}_m$ than Planck

→ SN data sets predict higher values of $\mathbf{\Omega}_m$ than Planck



In **w0waCDM**:

→ Prediction of $\mathbf{\Omega}_m$ from DESI BAO consistent with SNe Ia data sets



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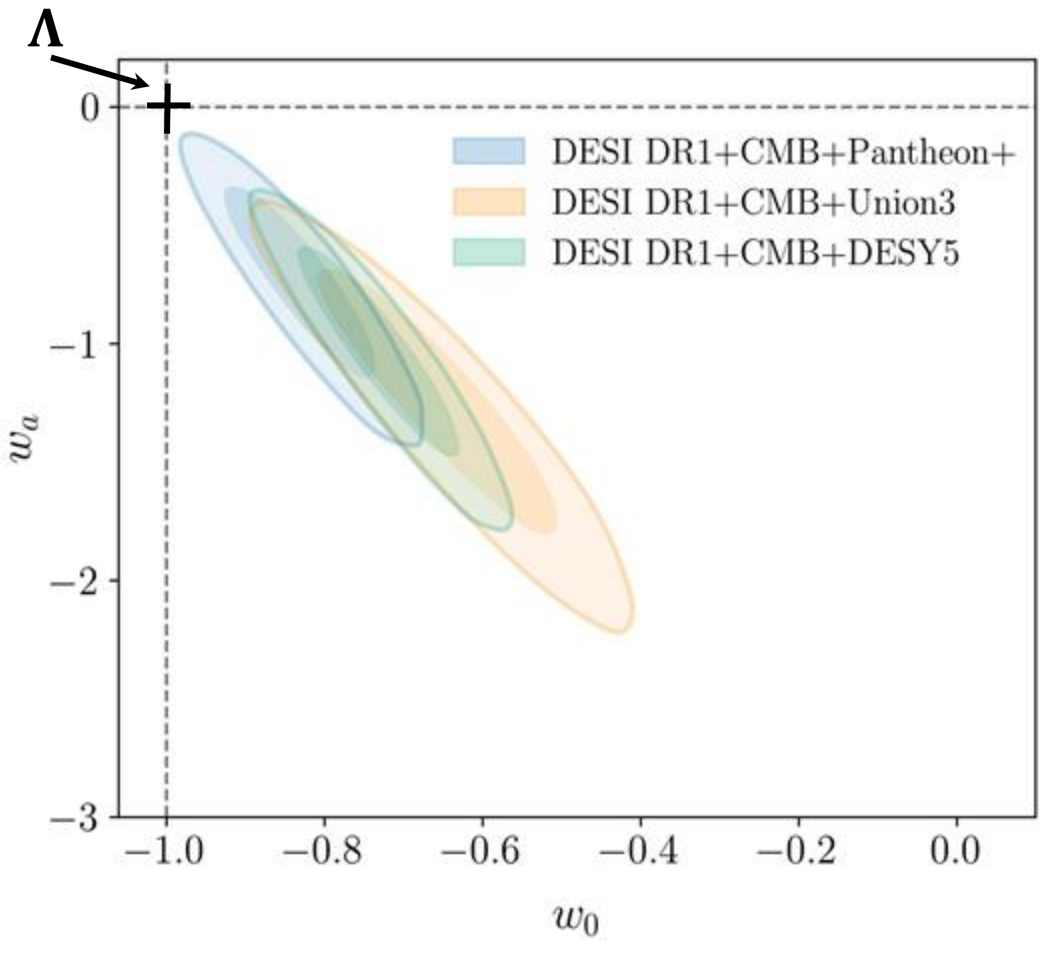
Dark Energy Equation of State



Combining DESI + CMB + SN:

$w_0 = -0.827 \pm 0.063 \quad w_a = -0.75^{+0.29}_{-0.25}$

DR1: DESI + CMB + Pantheon+ ⇒ 2.5σ

$w_0 = -0.64 \pm 0.11 \quad w_a = -1.27^{+0.40}_{-0.34}$

DR1: DESI + CMB + Union3 ⇒ 3.5σ

$w_0 = -0.727 \pm 0.067 \quad w_a = -1.05^{+0.31}_{-0.27}$

DR1: DESI + CMB + DESY5 ⇒ 3.9σ

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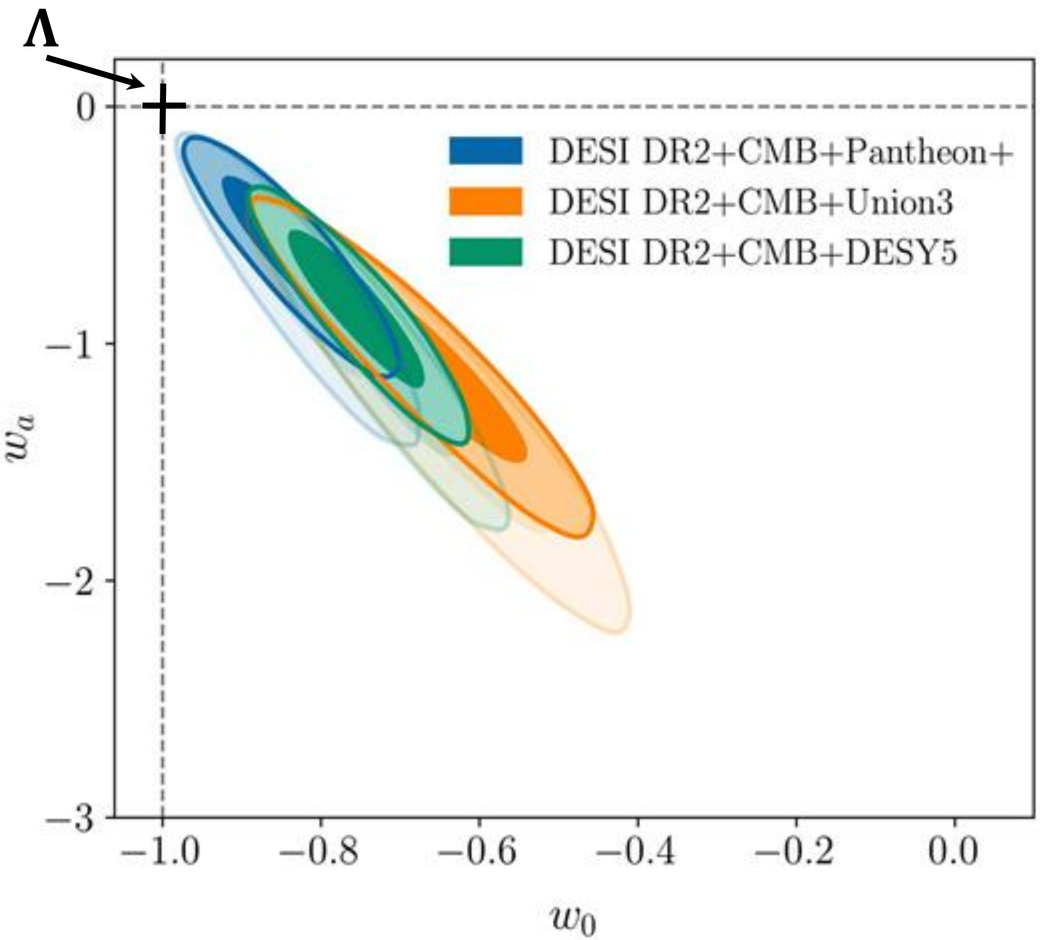
Dark Energy Equation of State



Combining DESI + CMB + SN:

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

DR1: DESI + CMB + Pantheon+ ⇒ 2.8σ

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

DR1: DESI + CMB + Union3 ⇒ 3.8σ

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

DR1: DESI + CMB + DESY5 ⇒ 4.2σ

Extended DE Study

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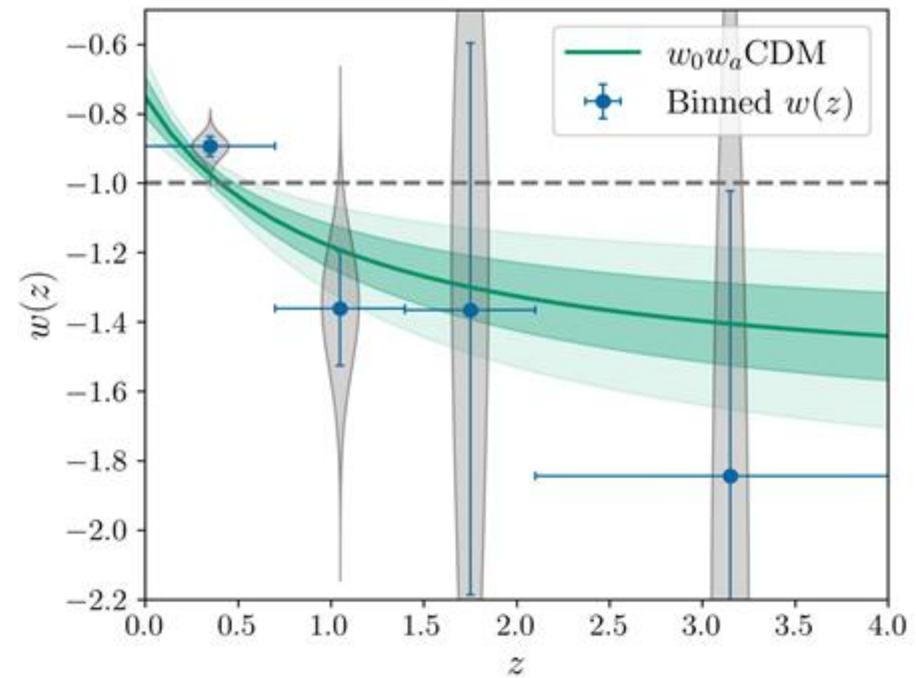
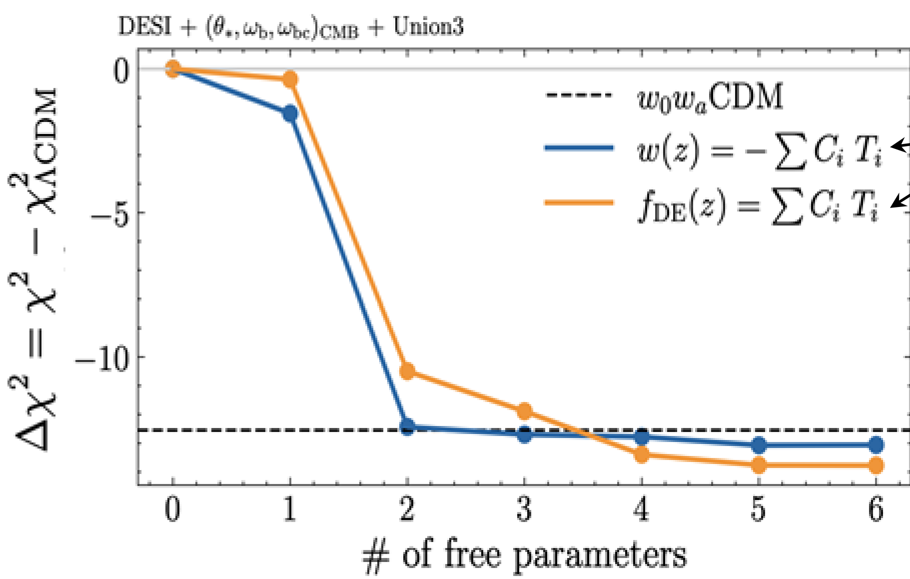
Non-parametric way of determining w(z) through **binning**:

→ comparison of different redshift intervals without the assumption of a specific functional form





Chebyshev Polynomial

Testing **different parameterisation** of either w(z) or $\rho_{DE}(z)$:

→ alternative 2 parameter models with different functional forms
→ introduction of additional degree of freedom

For more details, see arXiv:2503.14743

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Futur prospects

Credit : DESI collaboration

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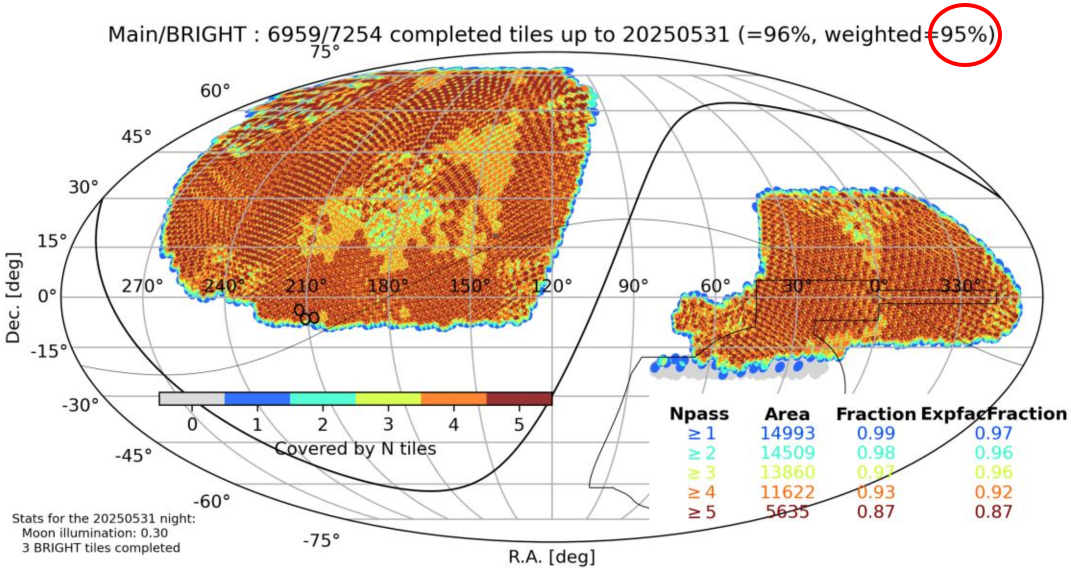
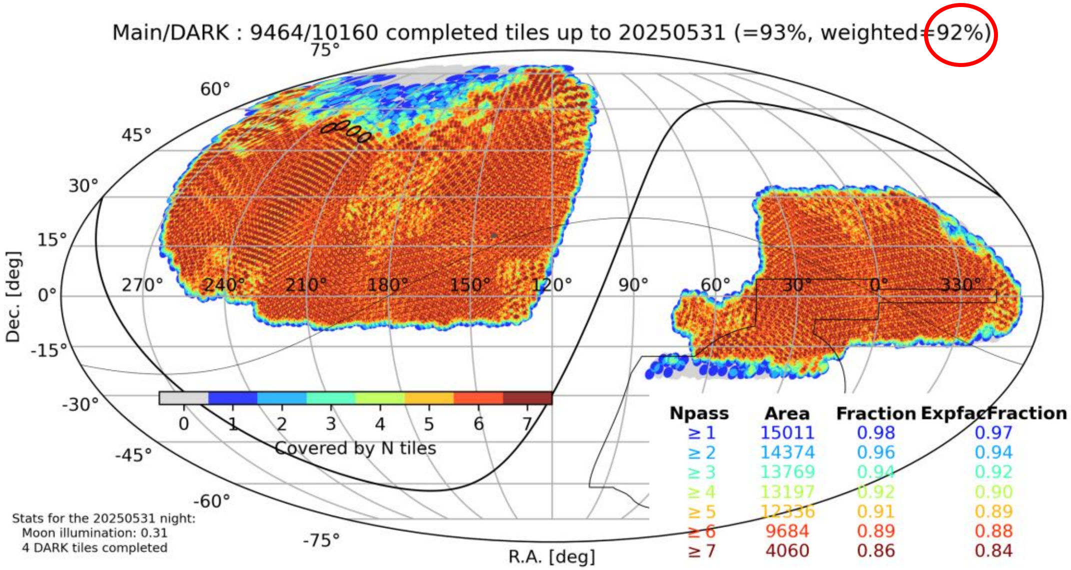
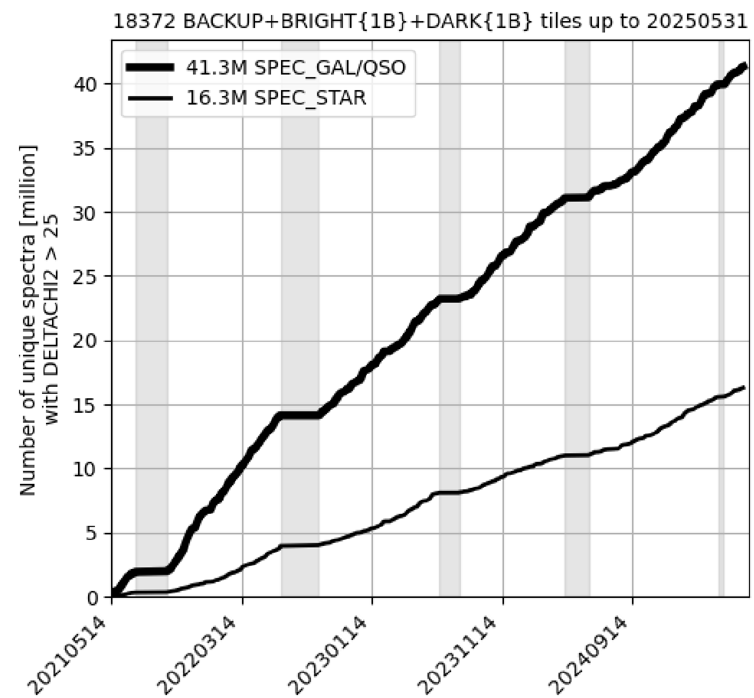
DESI survey status







Main Survey almost finished after 4 years of observations !

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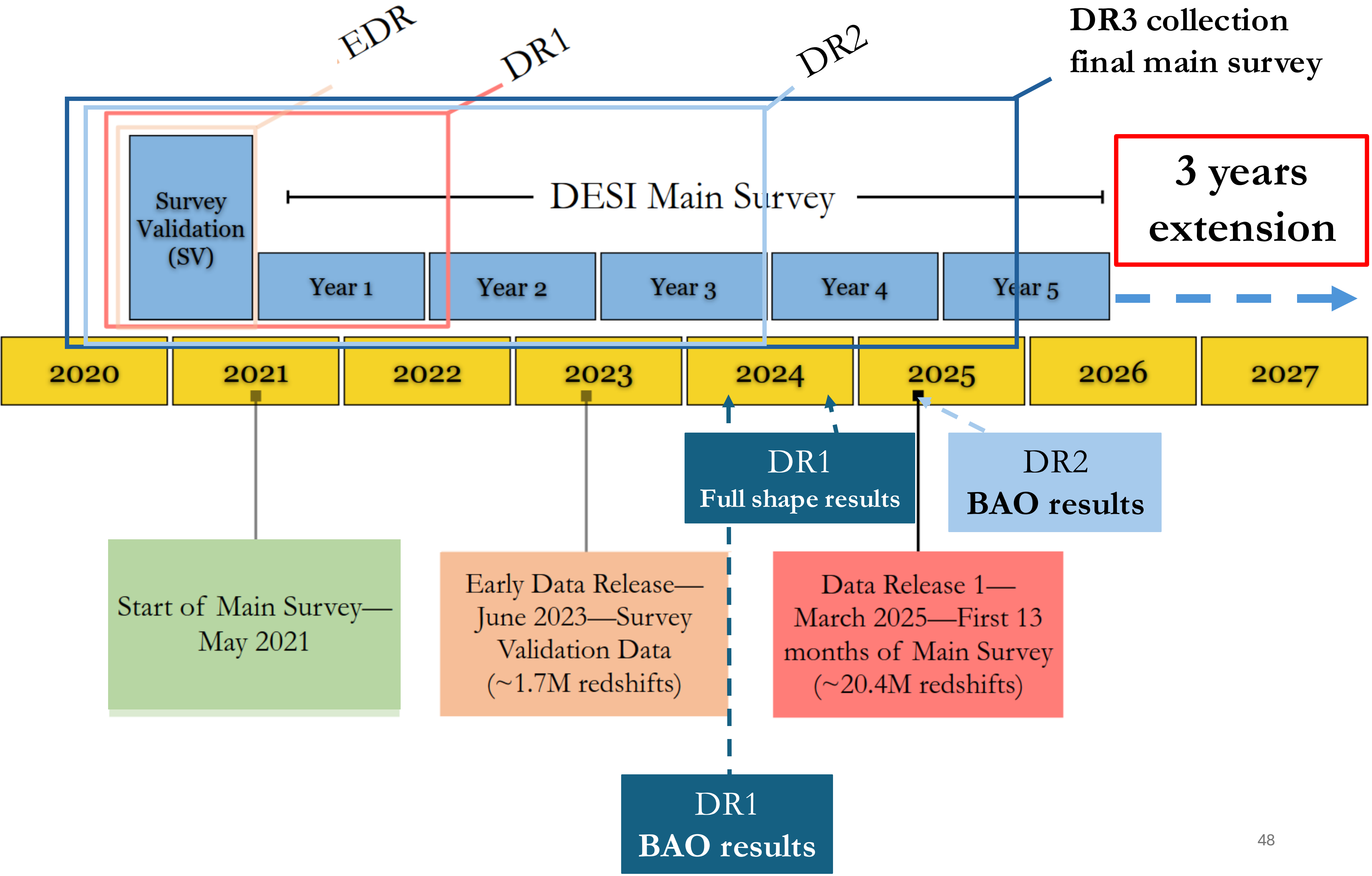
DESI Timeline



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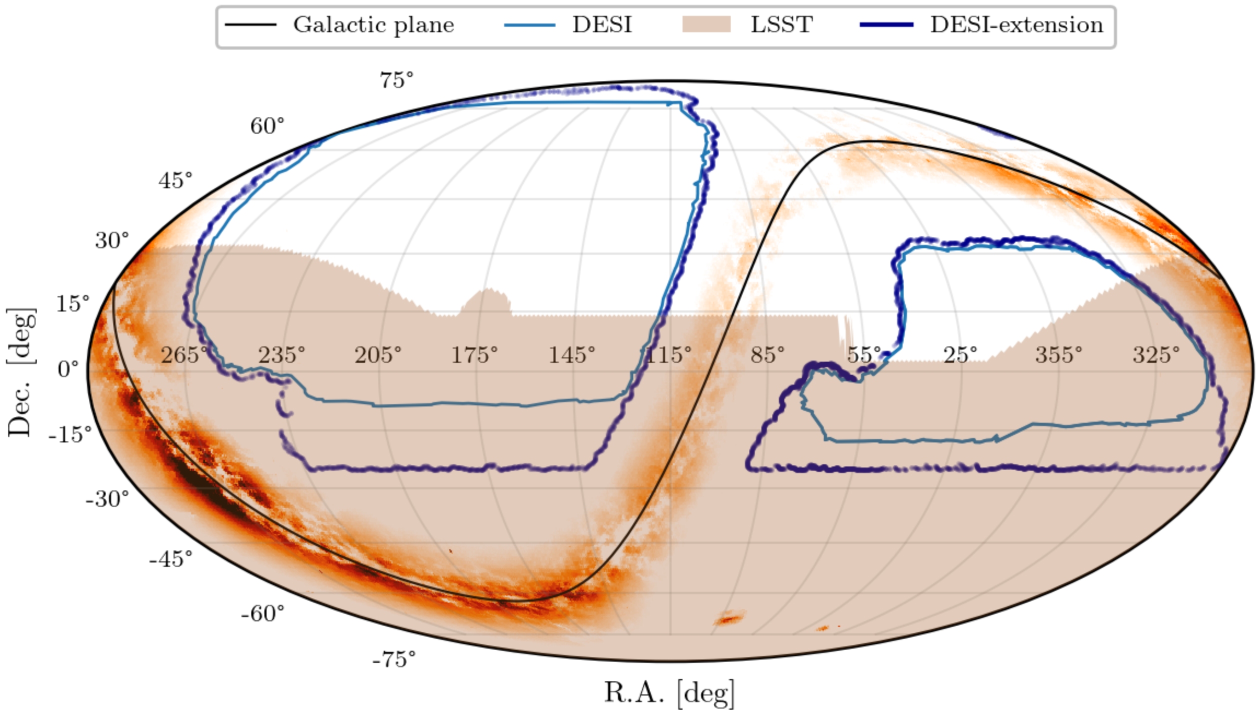
DESI Extension

5 => **8 year survey** (until 2029)



Increase sky area 14'000 => **17'000 deg^2**

Bigger Overlap with LSST

Expected ~60M extragalactic redshifts

~~3M~~ 3.6M Quasars (QSOs) **0.8<z<2.6**

+ Ly-α **z > 2.1**

~~17M~~ 21M Emission line galaxies (ELGs) **0.6<z<1.6**

~~8M~~ 10M Luminous red galaxies (LRGs) **0.4<z<1.1**

~~13.5M~~ 16M Bright galaxies **0<z<0.5**

+ ~5M New sample of LRGs **Luminous Galaxies Extension (LGE)**

Increased density (+50%)

0.4<z<1.1

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Lots of new science to discover with DESI !

- Full-shape MG constraints compatible with GR
- DR2 is fully consistent with DR1 with error bar smaller by almost ~2x
- DESI + CMB prefer dynamical DE at 3.1σ
- Including SN data strengthens this to 2.8σ - 4.2σ

APPENDIX

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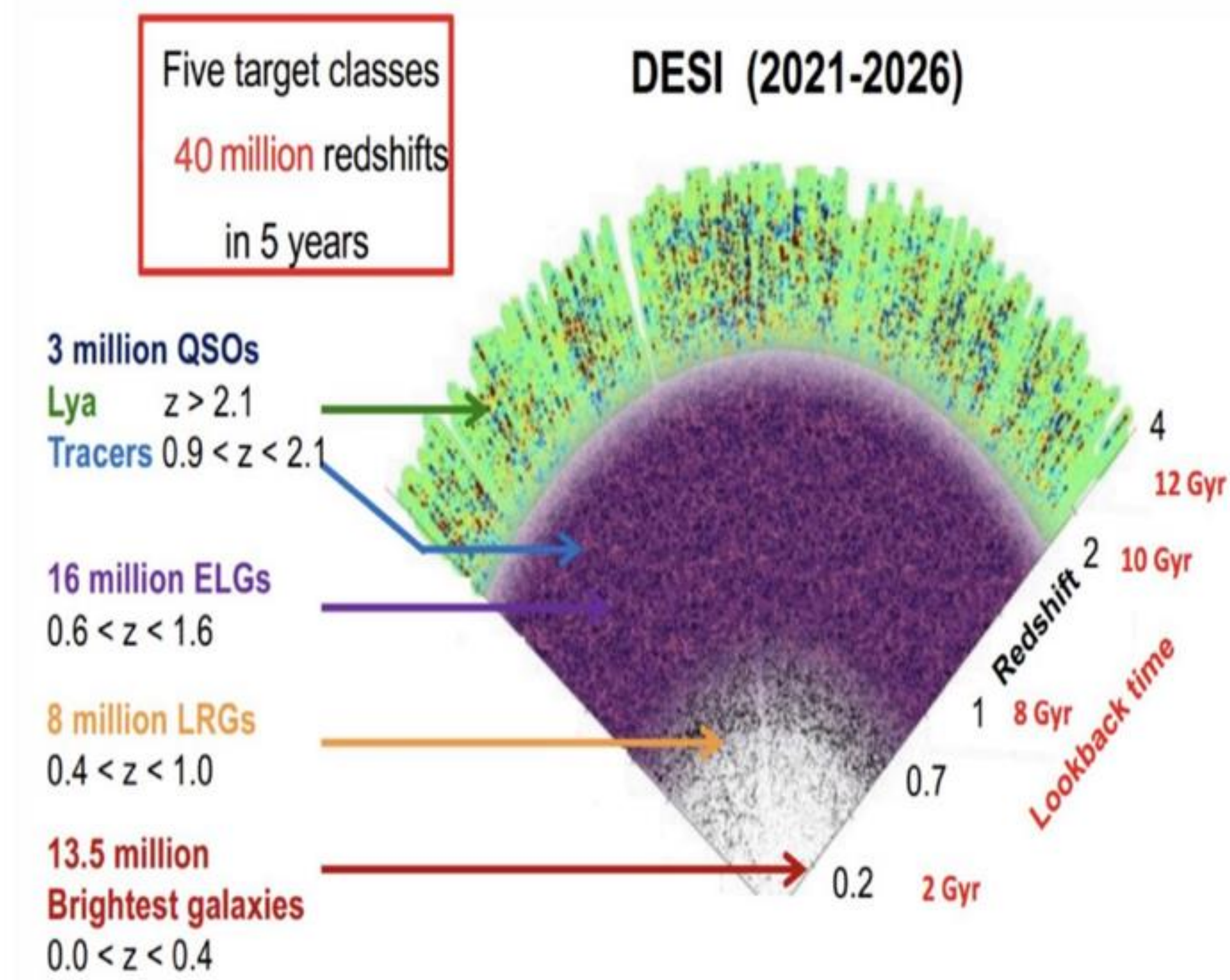
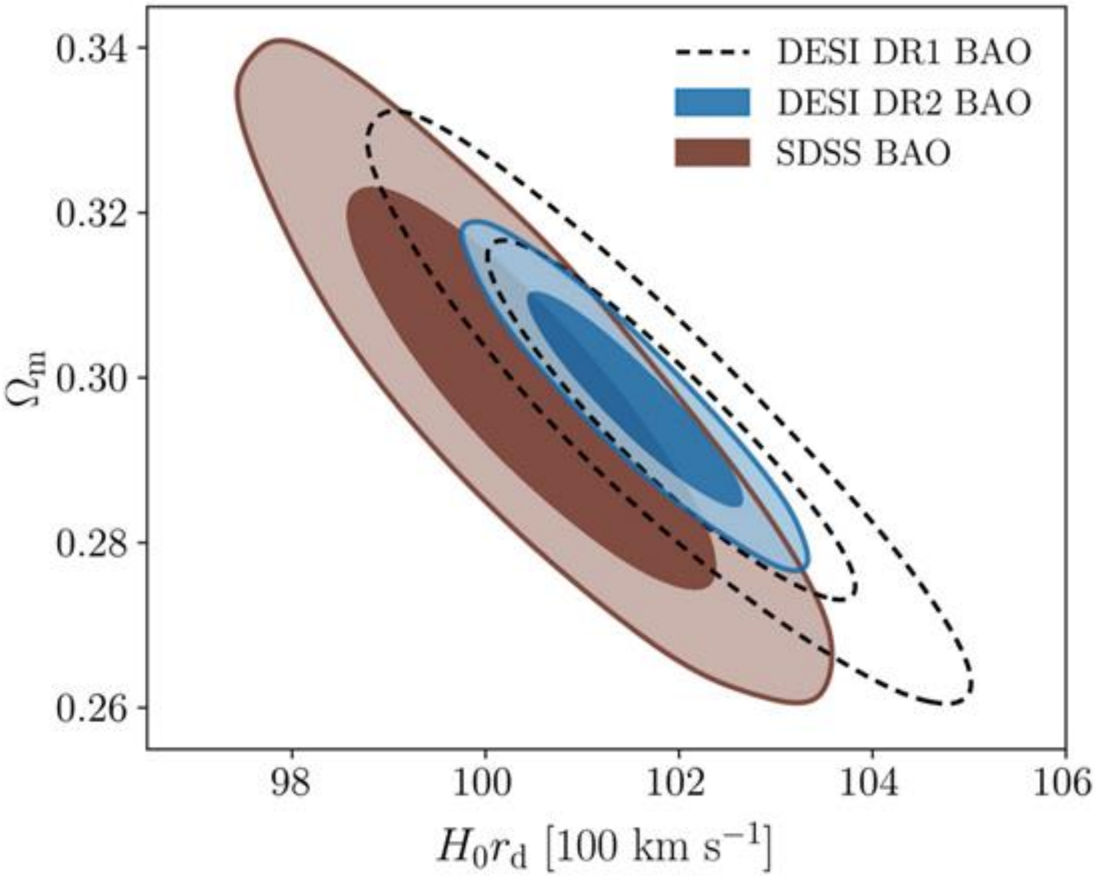
Redshifts for the BAO analysis

Tracer	DR1	**DR2**
BGS	300,043	**1,188,526**
LRG	2,138,627	**4,468,483**
ELG	2,432,072	**6,534,844**
QSO	1,223,391	**2,062,839**
Total	6,094,133	**14,254,692**



Consistency with SDSS



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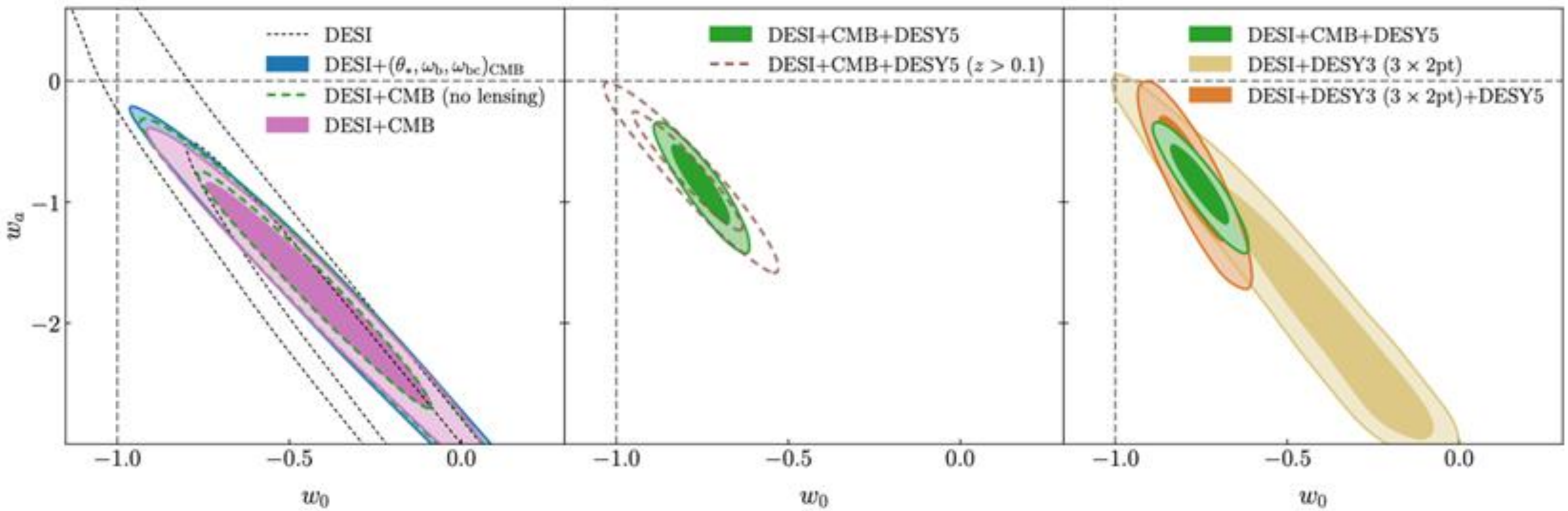
DR2: Level of Significance for the different data sets

Datasets	$\Delta\chi^2_{\mathrm{MAP}}$	Significance	Δ(DIC)
DESI	−4.7	1.7σ	−0.8
DESI+$(\theta_*, \omega_\mathrm{b}, \omega_\mathrm{bc})_\mathrm{CMB}$	−8.0	2.4σ	−4.4
DESI+CMB (no lensing)	−9.7	2.7σ	−5.9
DESI+CMB	−12.5	3.1σ	−8.7
DESI+Pantheon+	−4.9	1.7σ	−0.7
DESI+Union3	−10.1	2.7σ	−6.0
DESI+DESY5	−13.6	3.3σ	−9.3
DESI+DESY3 (3×2pt)	−7.3	2.2σ	−2.8
DESI+DESY3 (3×2pt)+DESY5	−13.8	3.3σ	−9.1
DESI+CMB+Pantheon+	−10.7	2.8σ	−6.8
DESI+CMB+Union3	−17.4	3.8σ	−13.5
DESI+CMB+DESY5	−21.0	4.2σ	−17.2

TABLE VI. Summary of the difference in the effective χ^2_{MAP} value (defined as twice the negative log posterior at the maximum posterior point) for the best-fit w_0w_aCDM model relative to the best ΛCDM model with $w_0 = -1$, $w_a = 0$, for fits to different combinations of datasets as indicated. The third column lists the corresponding (frequentist) significance levels given 2 extra free parameters, and the final column shows the results for $\Delta(\mathrm{DIC}) = \mathrm{DIC}_{w_0w_a\mathrm{CDM}} - \mathrm{DIC}_{\Lambda\mathrm{CDM}}$. As a rule of

Robustness of the Dark Energy results

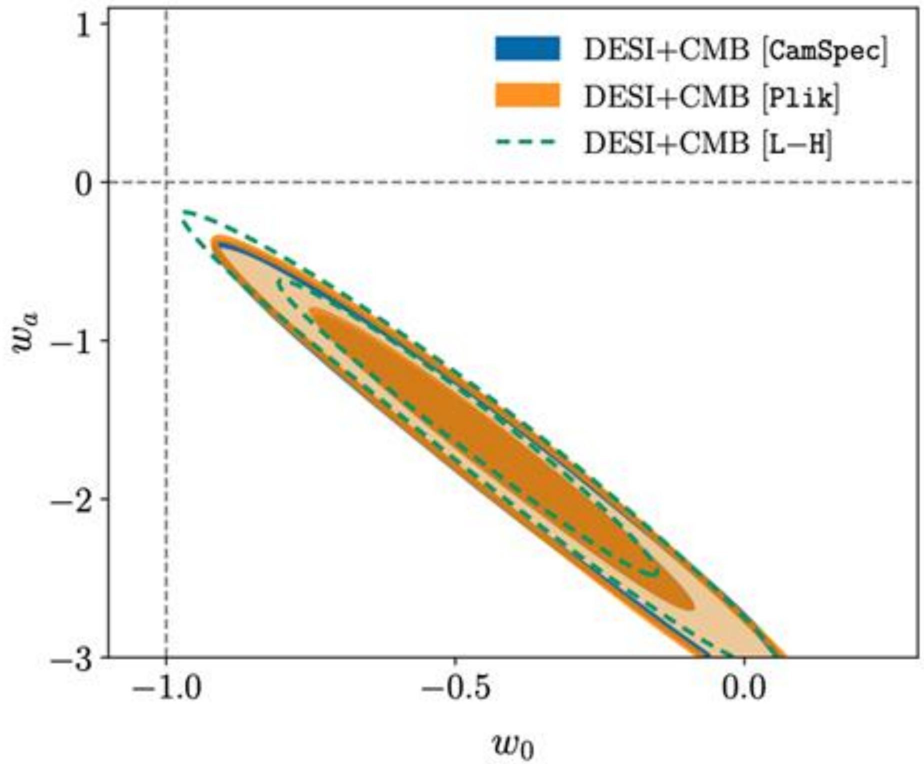


Different level of CMB information:
→ **CMB-derived priors** (late-time dark energy independent)
→ full **CMB information** (with or without lensing)
→ tighten constraints on w0wa through fixing $\mathbf{\Omega}_m$

DESY5 calibration:
→ remove **samples for z > 0.1**
→ best fit still lies in the lower quadrant

Replacing the CMB with DESY3:
→ constraints on w0wa **purely depending on low-z probes**

Robustness of the Dark Energy results



Results are robust to different CMB likelihoods

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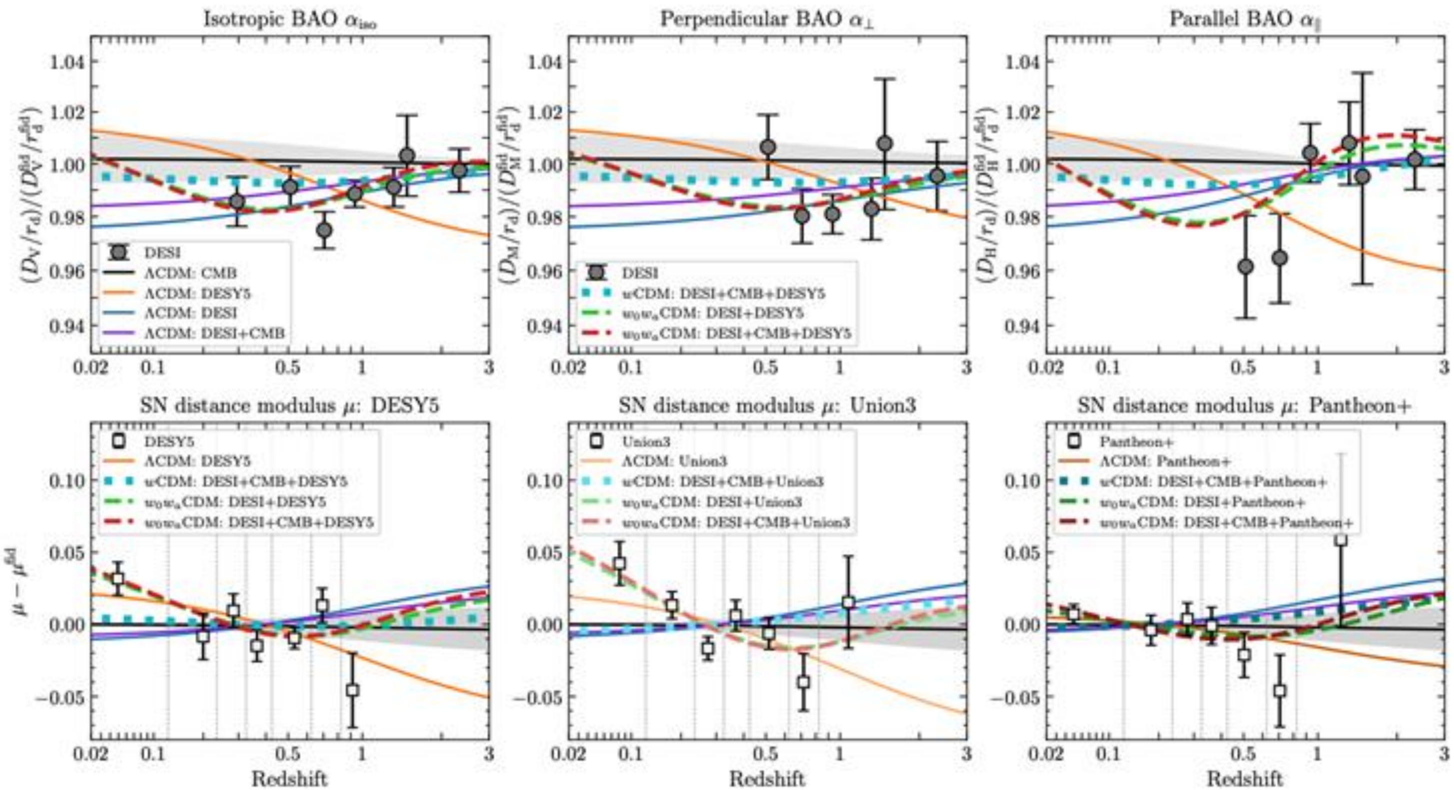
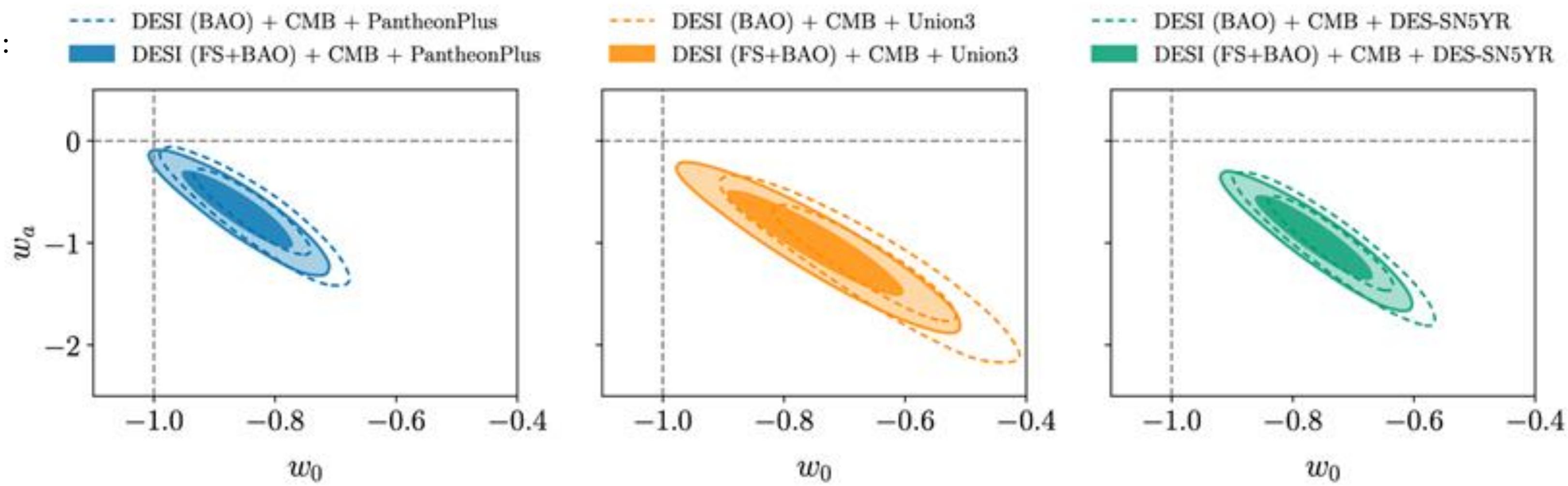
Robustness of the Dark Energy results

For supernovae at z > 0.1, which partially overlap the redshift range of DESI, the ΛCDM model that best fits the DESI data is also a good fit to the SNe data (blue line)



Evolving DE: Adding Full-shape to the mix

For DR1:



2.5σ ⇒ 2.5σ

3.5σ ⇒ 3.4σ

3.9σ ⇒ 3.8σ

Full-shape DR1: Modified Gravity

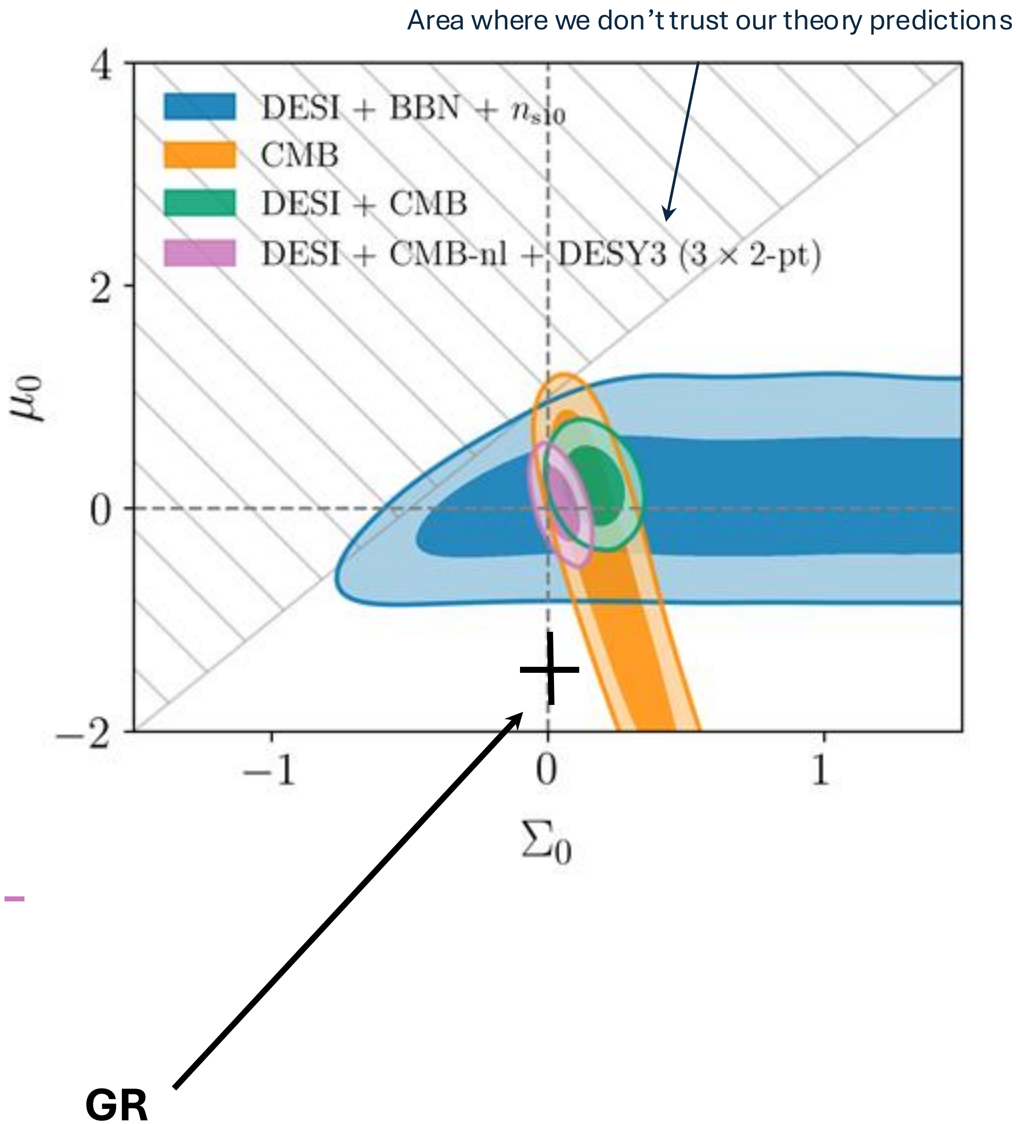
Combination of clustering and lensing:

$$\mu_0 = 0.21 \pm 0.24$$
$$\Sigma_0 = 0.166 \pm 0.074$$

DESI +CMB

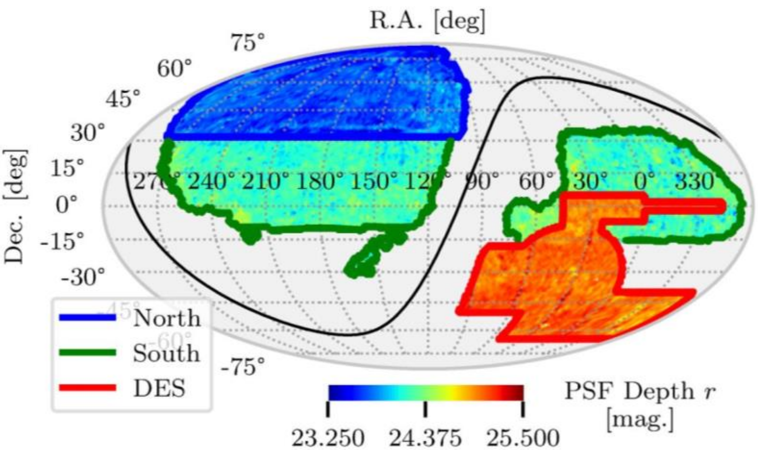
$$\mu_0 = 0.04 \pm 0.22$$
$$\Sigma_0 = 0.044 \pm 0.047$$

DESI +CMB-nl+ DESY3



DESI Imaging systematics: QSO case

TS use Legacy survey DR9:

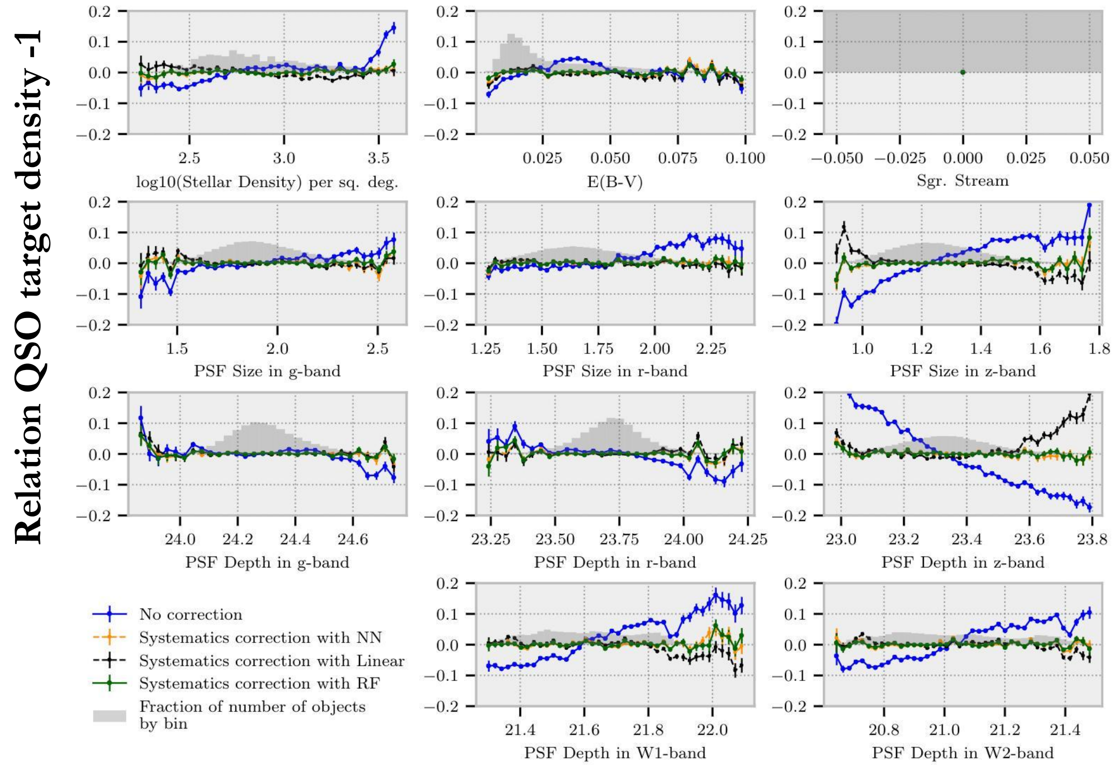


Systematics need to be estimated for each photometric regions

Trends are corrected using different regression techniques:

- **Linear**
- **Neural network (NN)**
- **Random forets**

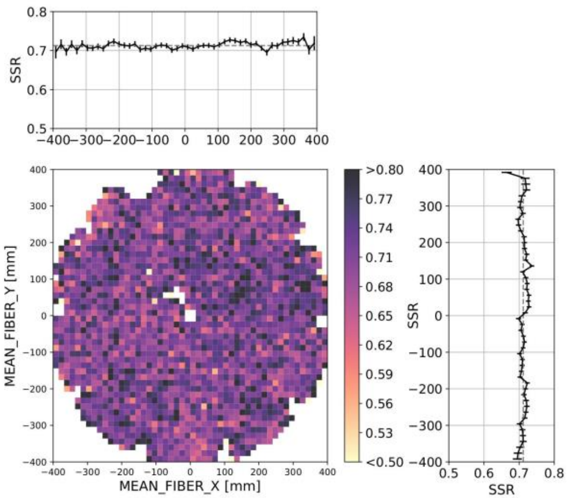
Trends in the number density of QSO vs imaging features (north region)



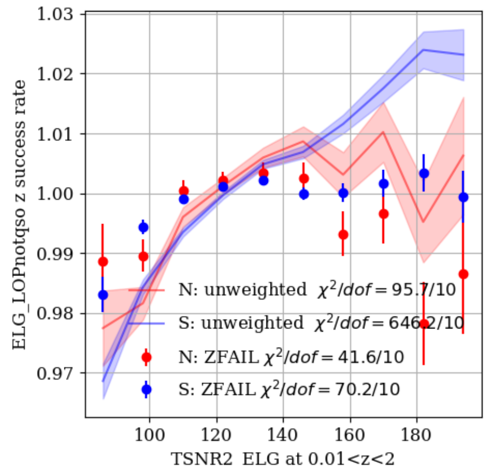
Chaussidon et al. 2022

Spectroscopic systematics: ELG case

Trends in the spectroscopic sucess rate vs spectroscopic features



Across the focal plane



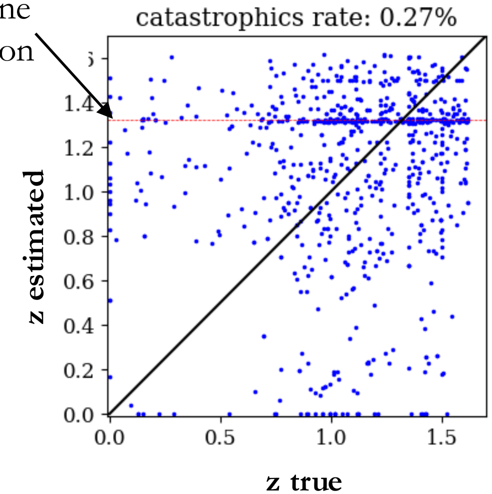
Vs the SNR

+ lots of other features…

=> We observed only **small trends according to spectroscopic features**

Redshift **catastrophics failure** with sky-residual lines confusion

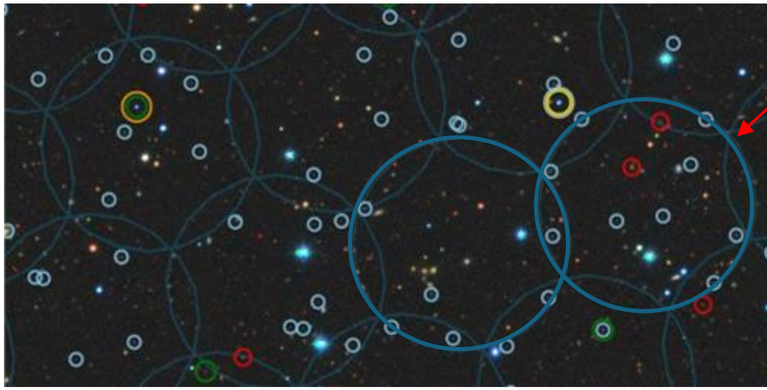
[OII] line confusion



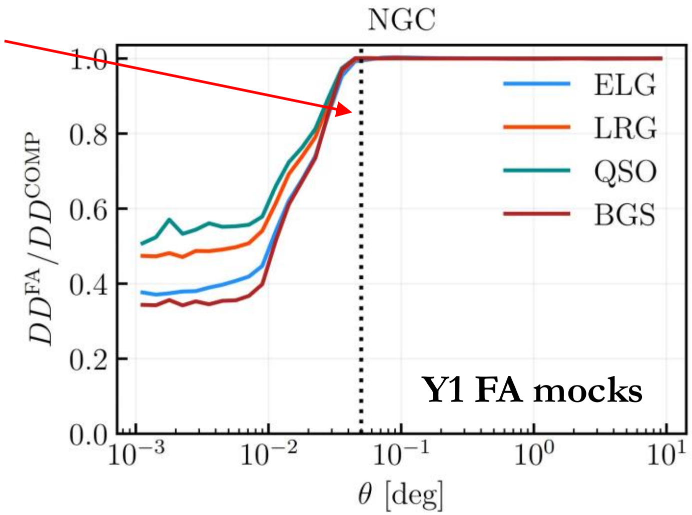
Yu et al. 2024
Krolewski et al. 2024

Trends with spectroscopy are minors and have < 0.2σ impact on clustering measurements

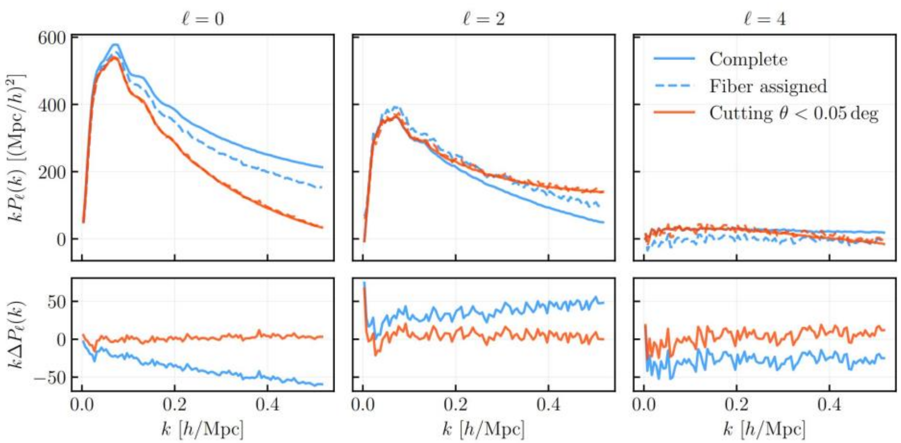
Fiber assignment (FA)



Fiber patrol radius



Tests on ELG Y1 DESI mocks

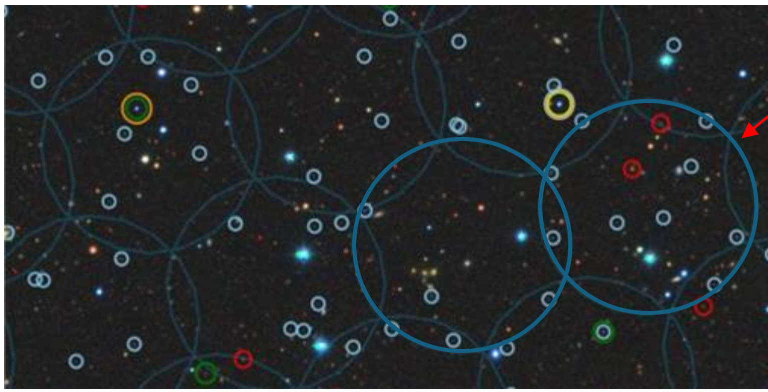


Missing pairs at small separations!

Cut pair separation < 0.05 deg (~ size of the patrol radius) leads to **unbiased measurement with FA**

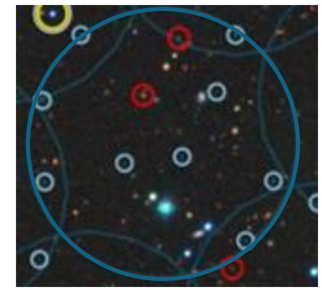
Pinon et al. in 2024

Fiber assignment:
Pairwise-Inverse-Probability (PIP) weighting scheme

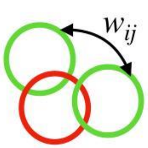


Fiber patrol radius

Bianchi & Percival 2017
Mohammad et al. 2020



Statistical estimation to observe a **galaxy pair**:



$$w_{ij} = \frac{\text{Number of FA runs}}{\text{Number of time the galaxy pair has been observed}}$$

= 0 for galaxy inside the same patrol radius

Angular up-weight (ANG)

$$w_{\text{ang}}^{DD}(\theta) = \frac{DD^{\text{par}}(\theta)}{DD^{\text{fib}}_{\text{PIP}}(\theta)},$$

$$w_{\text{ang}}^{DR}(\theta) = \frac{DR^{\text{par}}(\theta)}{DR^{\text{fib}}_{\text{IIP}}(\theta)}.$$

The pairs DD and DR at a given separation angle θ are up-weighted