BAO results from DESI DR2

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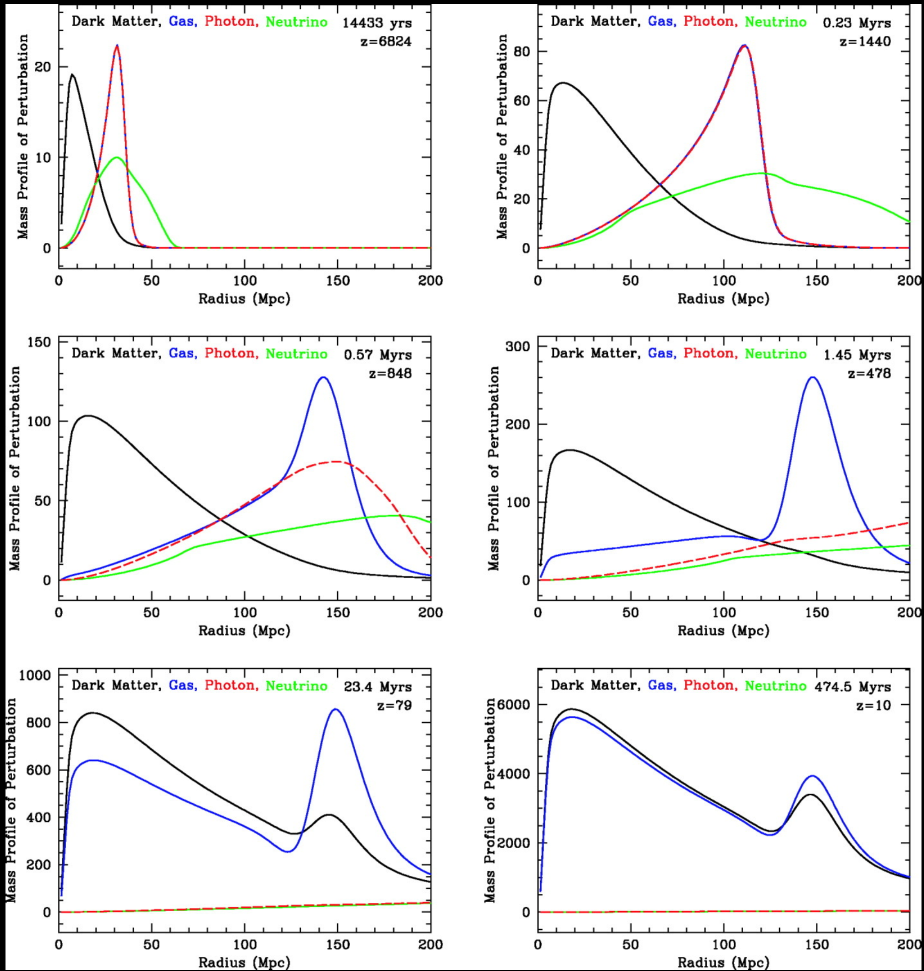
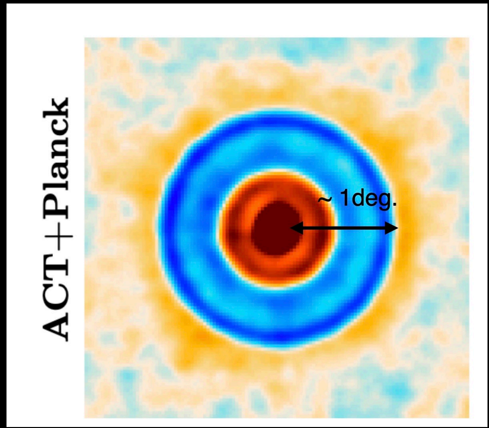
CMB France – Oct 13, 2025

- Cosmological model and BAO
- The DESI project
- Results on Dark Energy and neutrinos masses
- Prospects

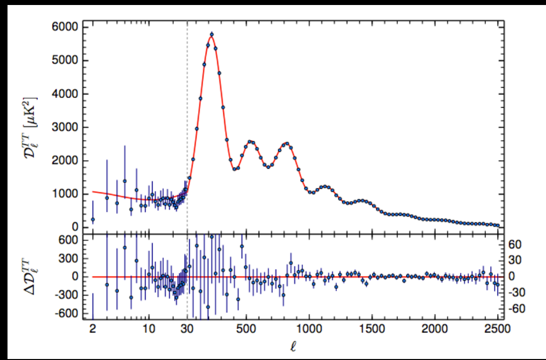
BAO : Propagation of density waves



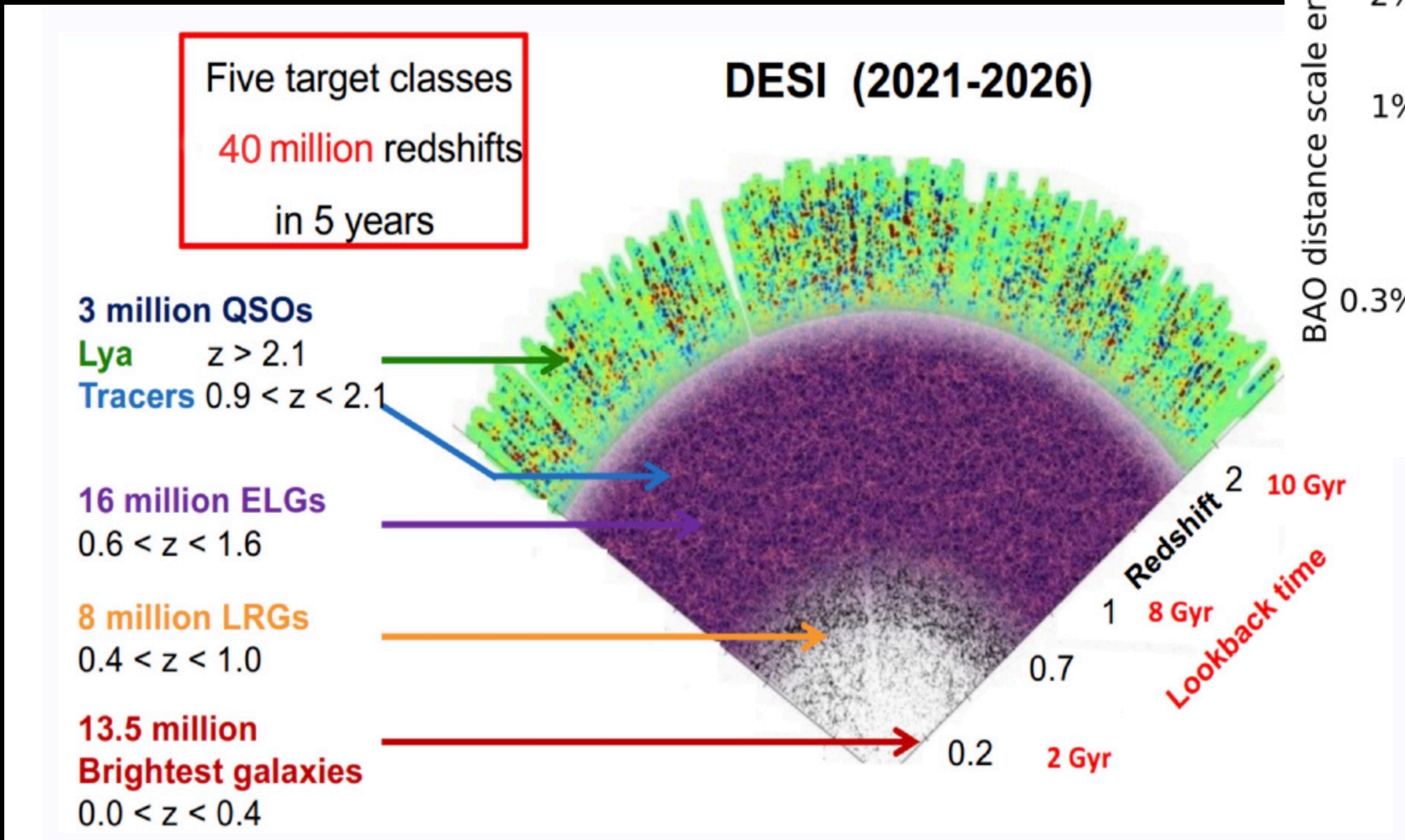
Einsentein, Seo, White (2007)

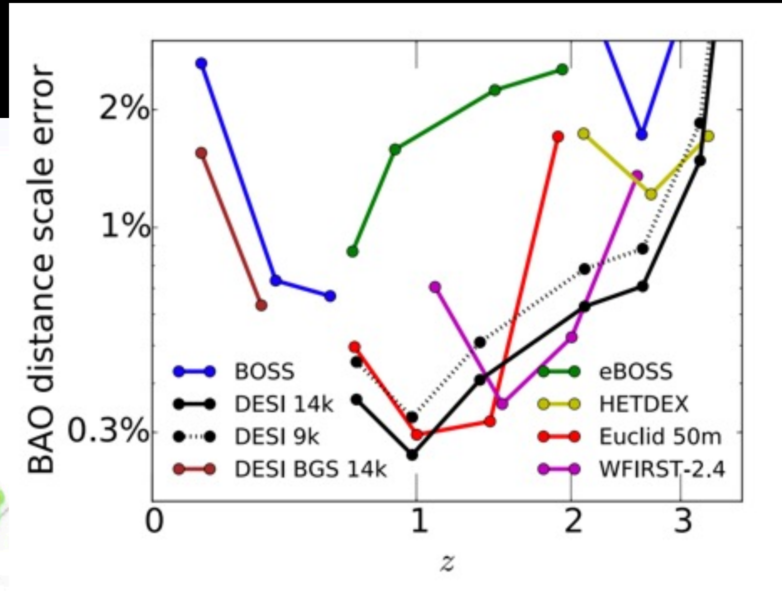


Stack of CMB maps
on temperature hotspots



DESI – tracers of the matter distribution

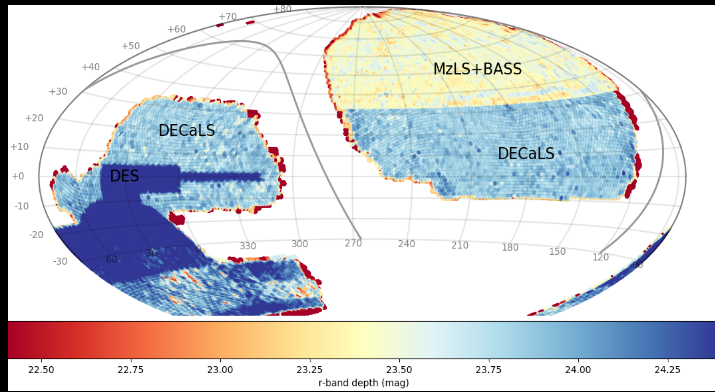




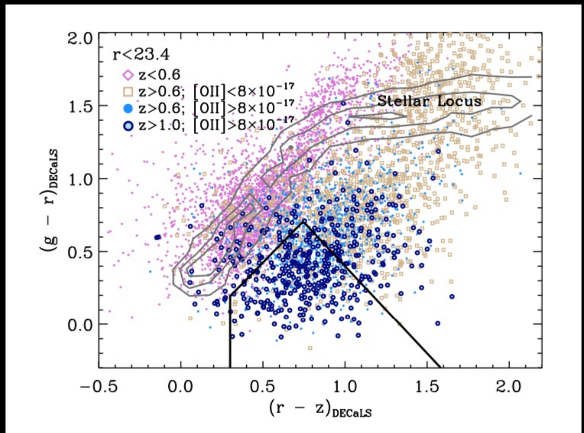
Measuring the “BAO” scale with Large scale surveys

Multi-objects Spectrocopic Survey

2D photometric surveys

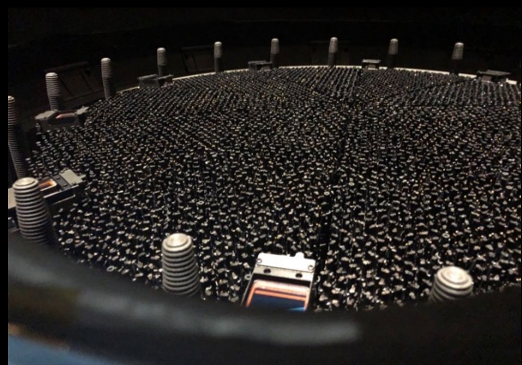


Target selection

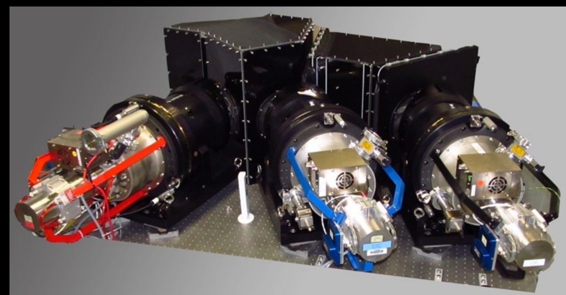


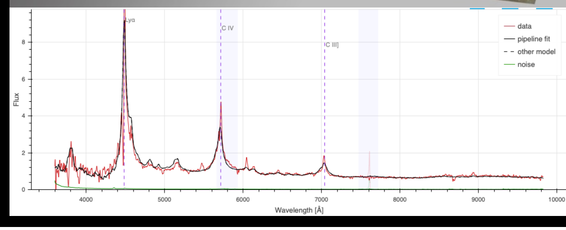
Observation…

… of 5000 targets
every ~ 20 mins…

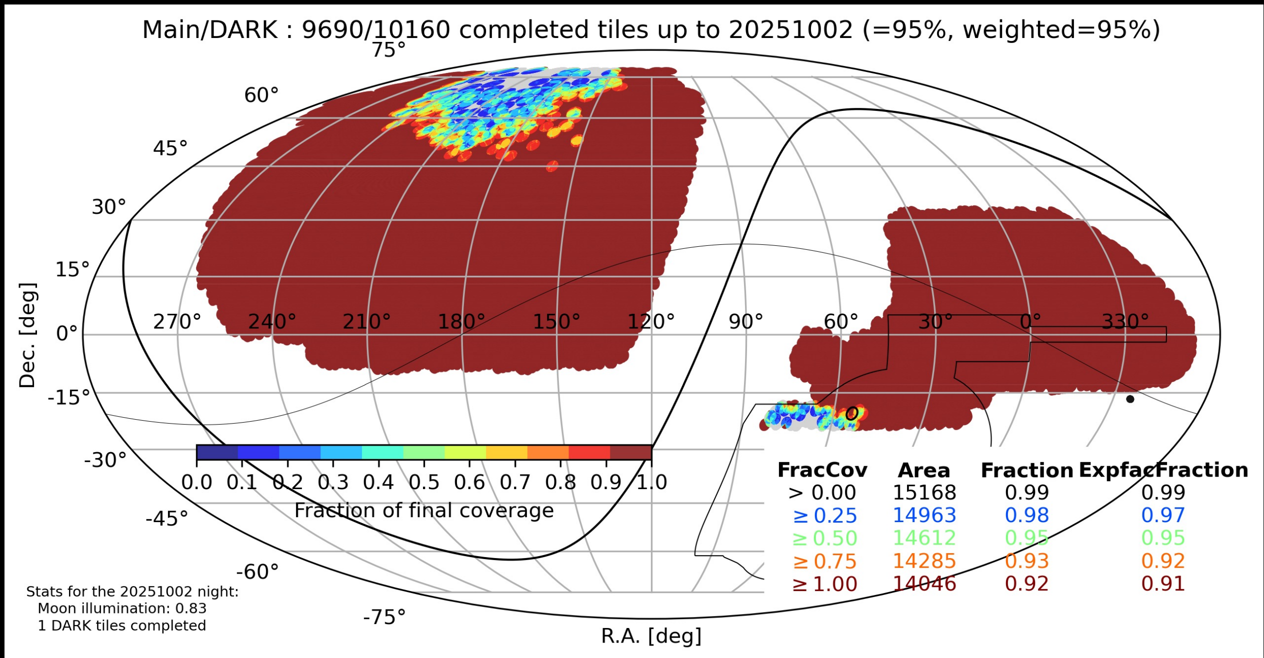


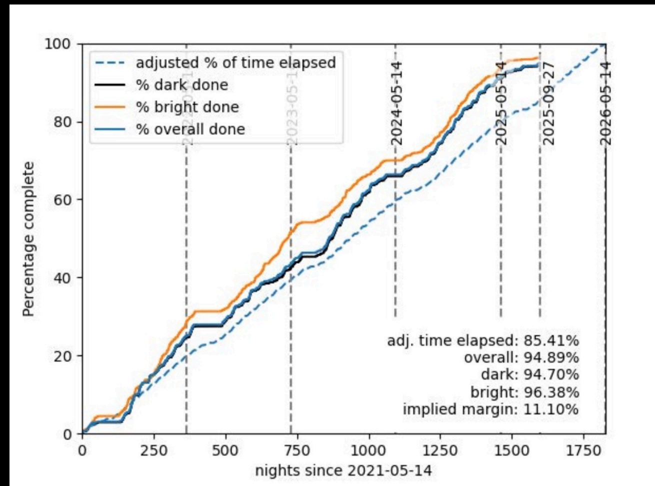
… and measure their redshift





Progress of observations

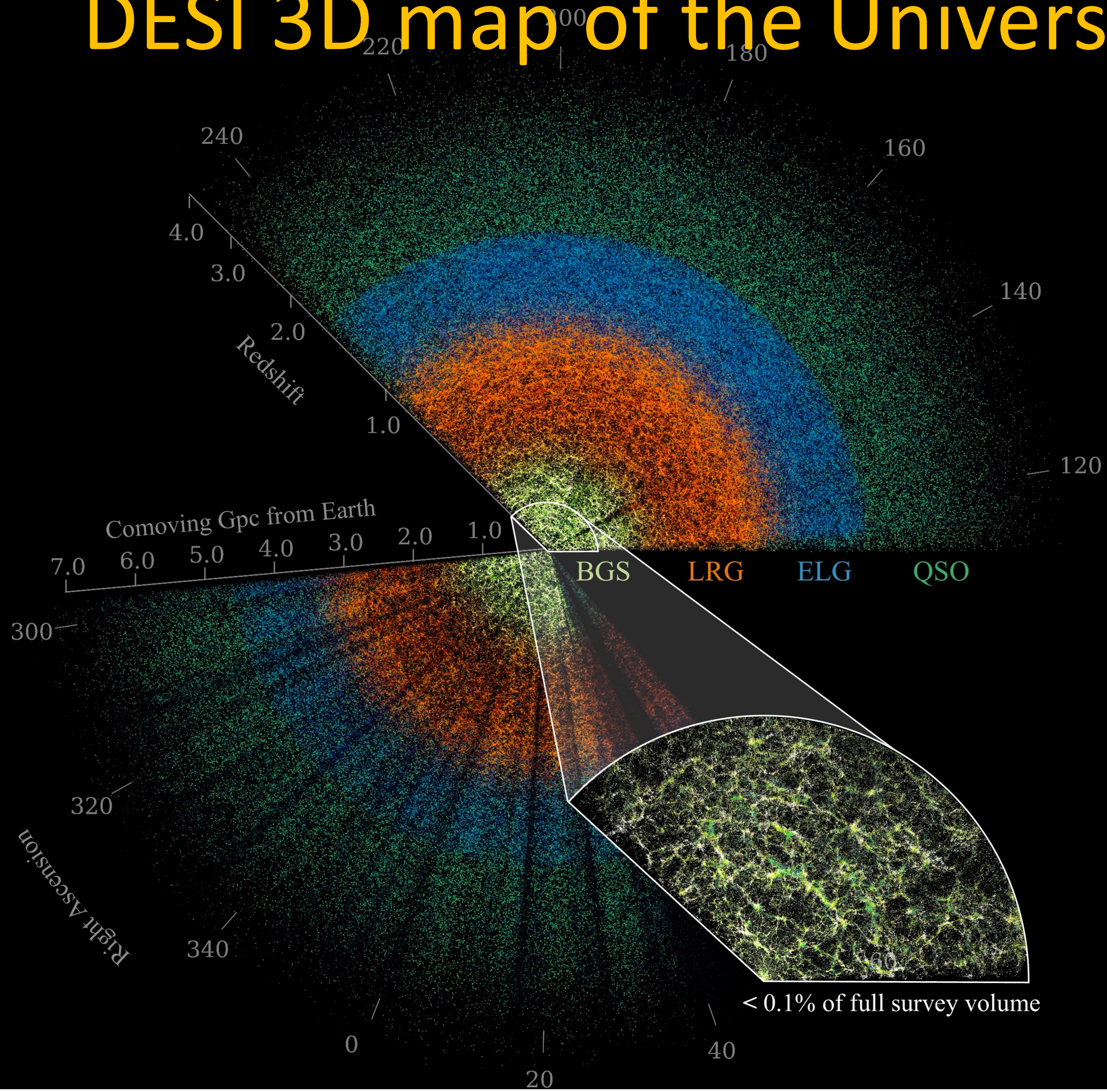


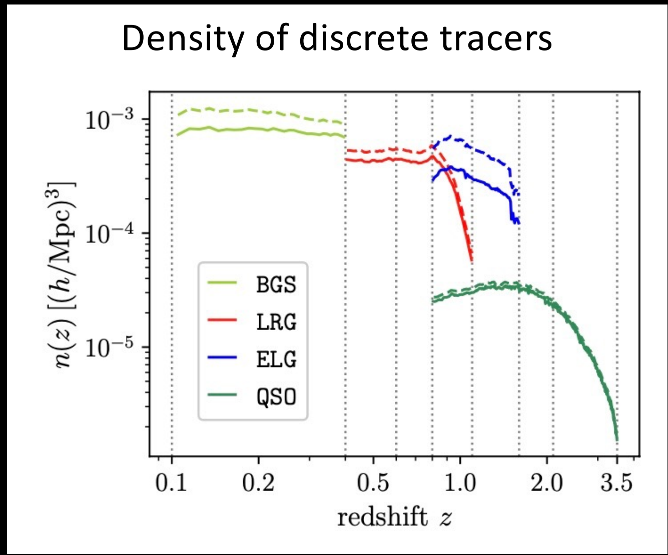


Downtime:
- Weather (as expected)
- COVID
- Contreras fire
- Hacking
- Dome motion

DR1 : 1 year of data – release in March 25
DR2 : 3 years of data – BAO results in March 25 – Data release in 2026
Already taking additional passes over the footprint

DESI 3D map of the Universe





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**

Data analysis

Publications :

- Cosmological constraints : Abdul-Karim++ 2025
- Ly-alpha BAO : Abdul-Karim++ 2025
- BAO Systematics : Andrade++ 2025
- Dark energy : Lodha++ 2025
- Neutrino masses : Elbers++ 2025

Imaging

Spectroscopy

Catalogs:
R.A, Dec, redshfit

Blinding !

Catalogs:
x_{com}, y_{com}, z_{com}

$$d(z) = c\int_0^z \frac{dz'}{H(z')}$$

Universe expansion in reference cosmology

$$\frac{H^2(z)}{H_0^2} = \Omega_m(1+z)^3 + \Omega_\Lambda$$

Take Planck flat-ΛCDM

2-point statistics :
- Correlation function
- Power spectrum

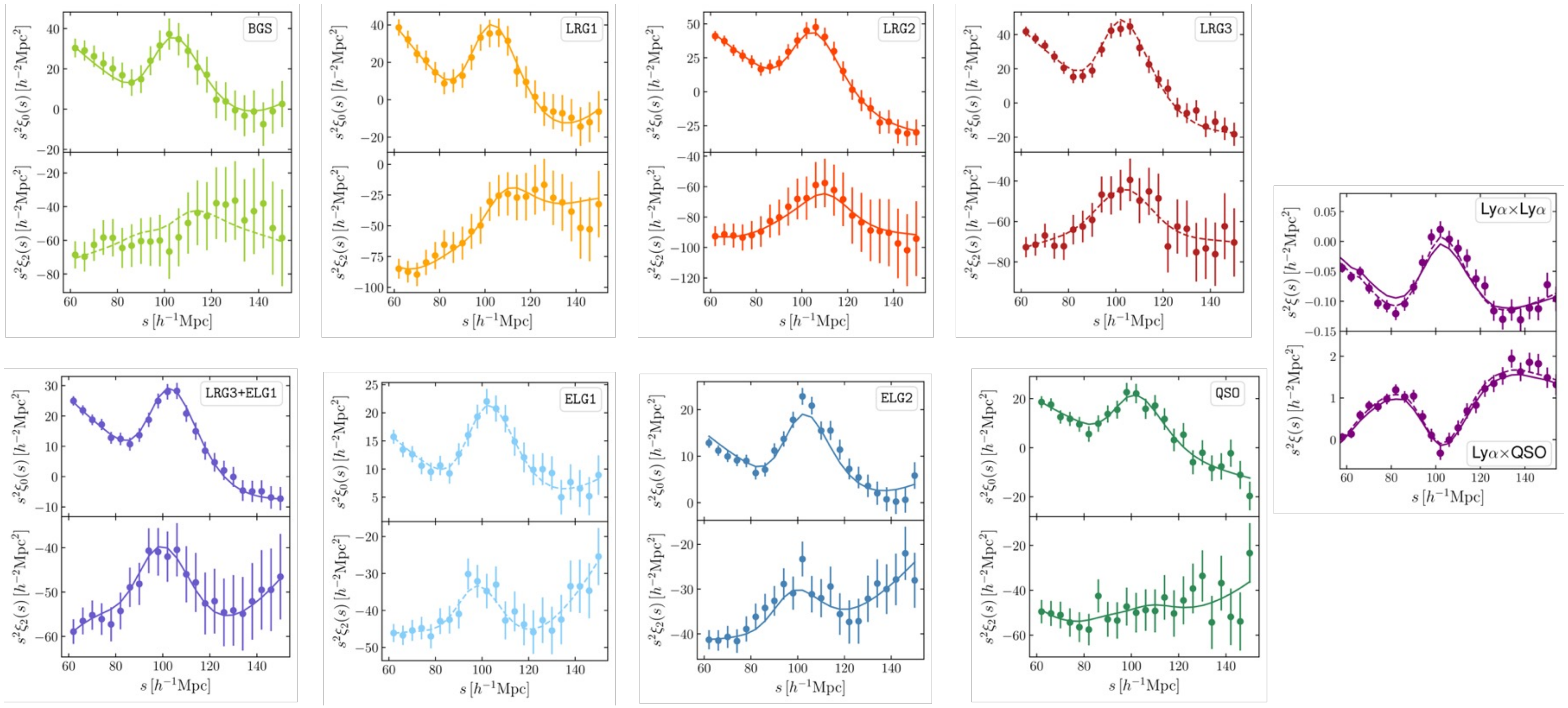
" BAO scale(s)"

$$\alpha = \frac{D_{bao}}{D_{bao\_ref}}$$

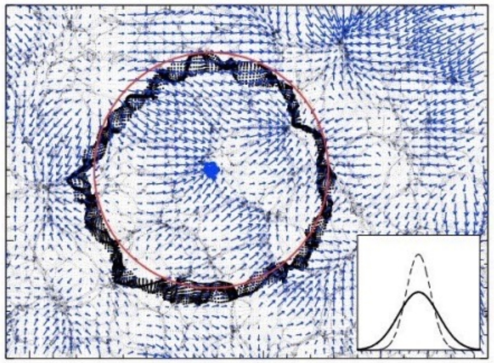
Cosmological constraints

DESI DR2 2-pt statistics

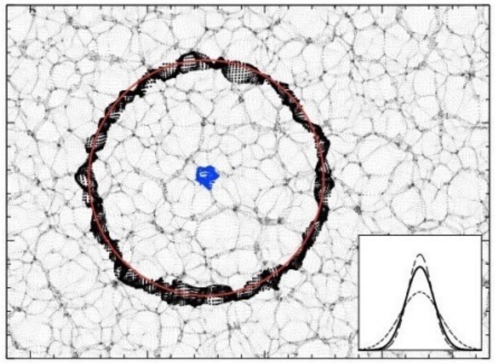
2-point correlation function : excess probability to find galaxies separated by distance *s*



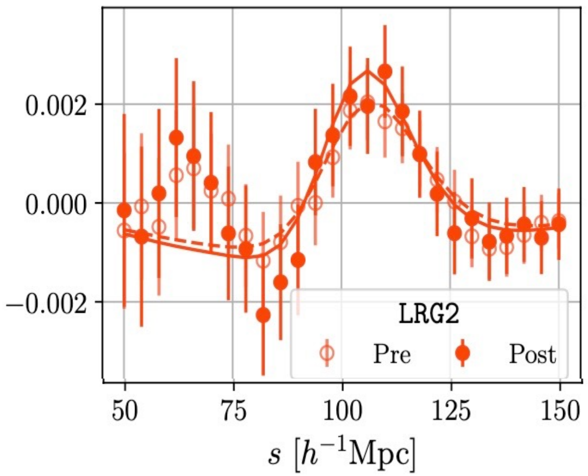
Density field reconstruction

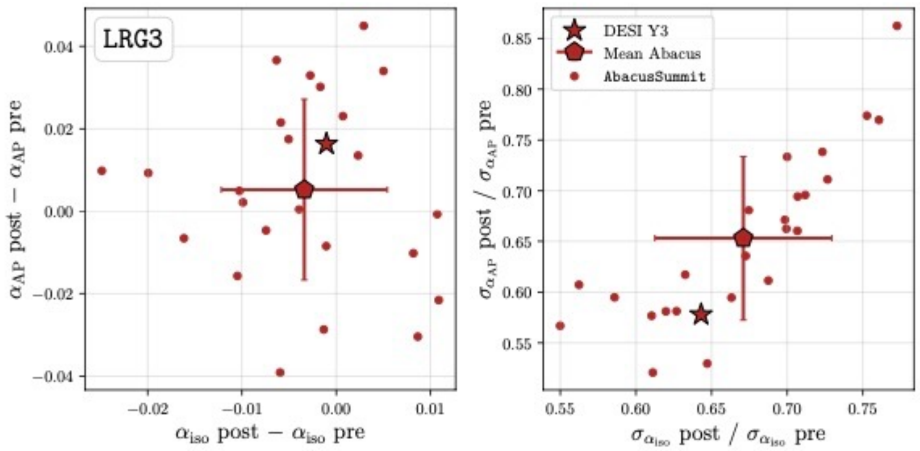


Reconstruction



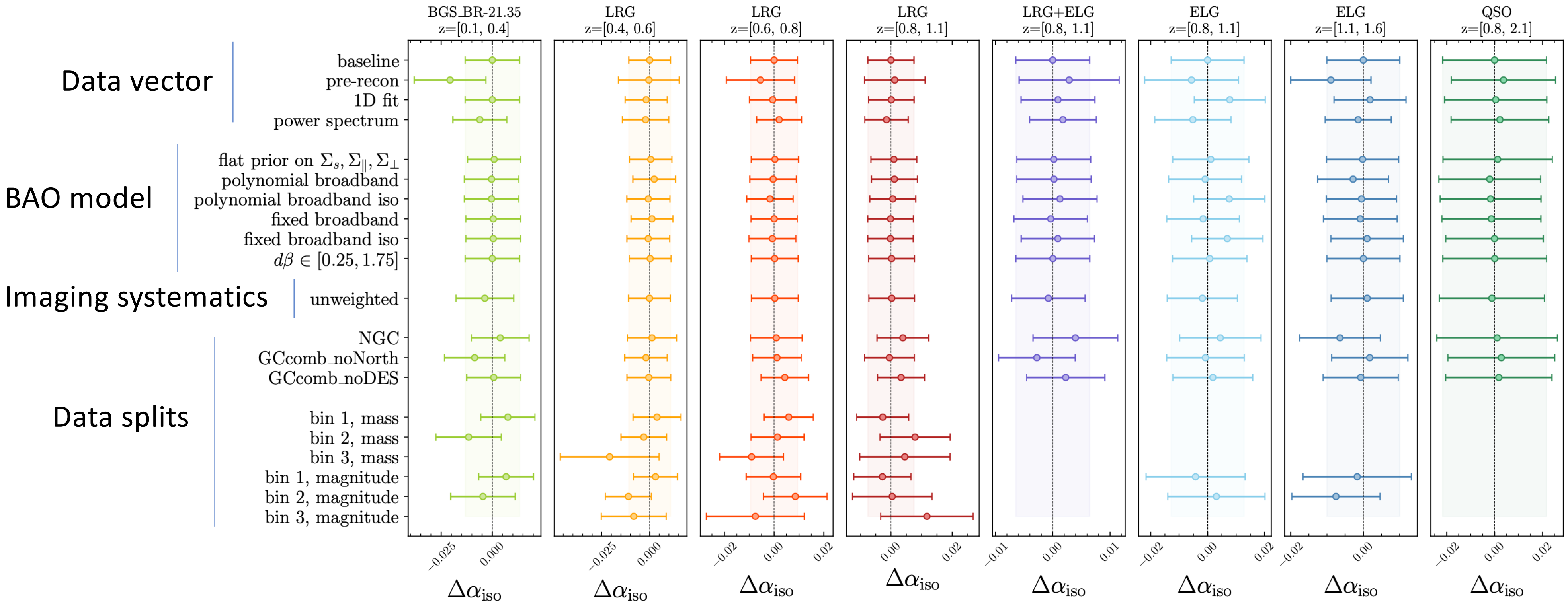
- Galaxies move in the density field
- Displacement field determined from the tracer field in Zel'dovich approximation (1st order)





Improvement in precison :
10% to 40%
depending on tracer

Systematics checks in BAO measurements



Simulation (mocks) based systematics estimate :

- BAO model
- Galaxy-halo connection
- Choice of fiducial cosmology

Total systematic errors :

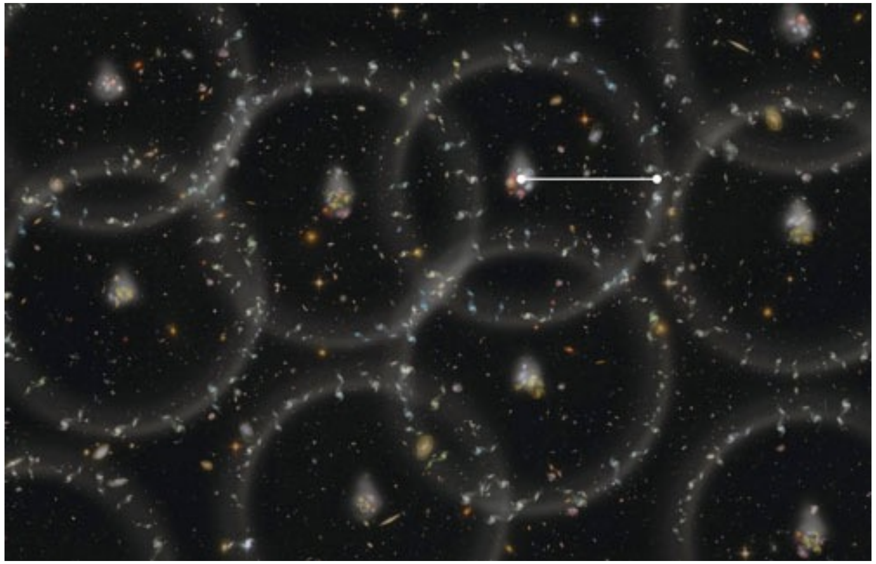
0.2 % on α_{iso}, 0.3 % on α_{AP}

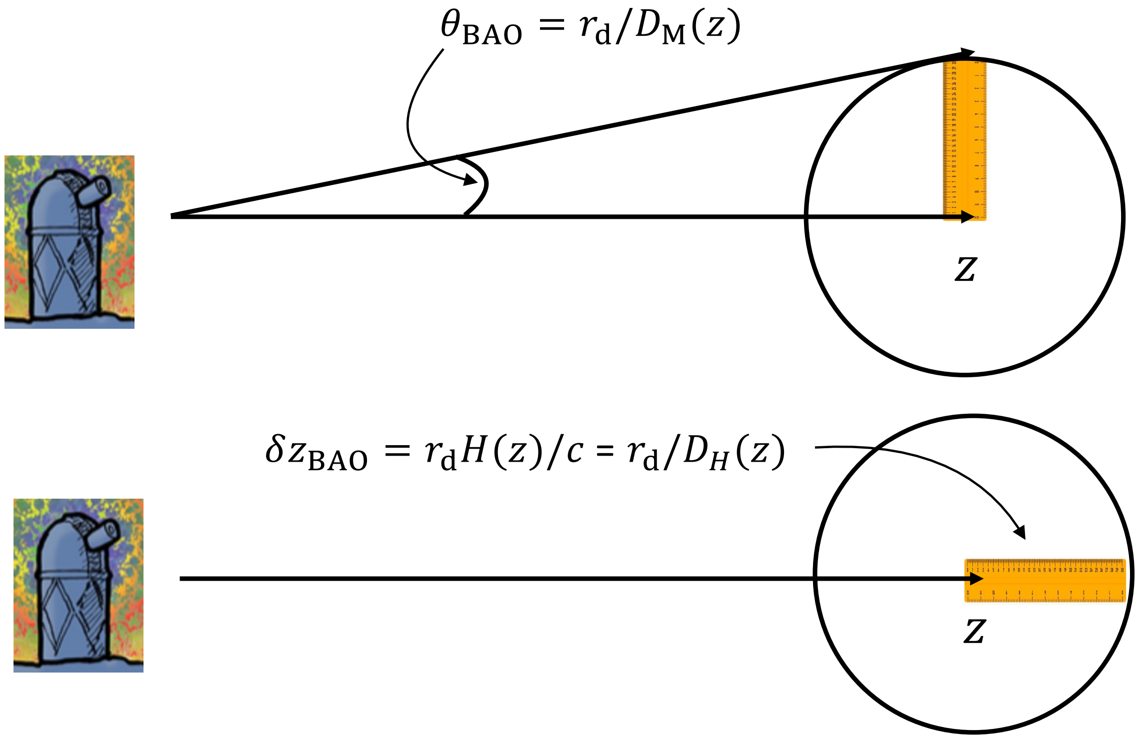
Limited by mock precison

Ly-alpha systematic errors : 0.3 % on α_{par}, 0.3 % on α_{perp} (non-linear evolution of the peak)

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

The BAO standard ruler

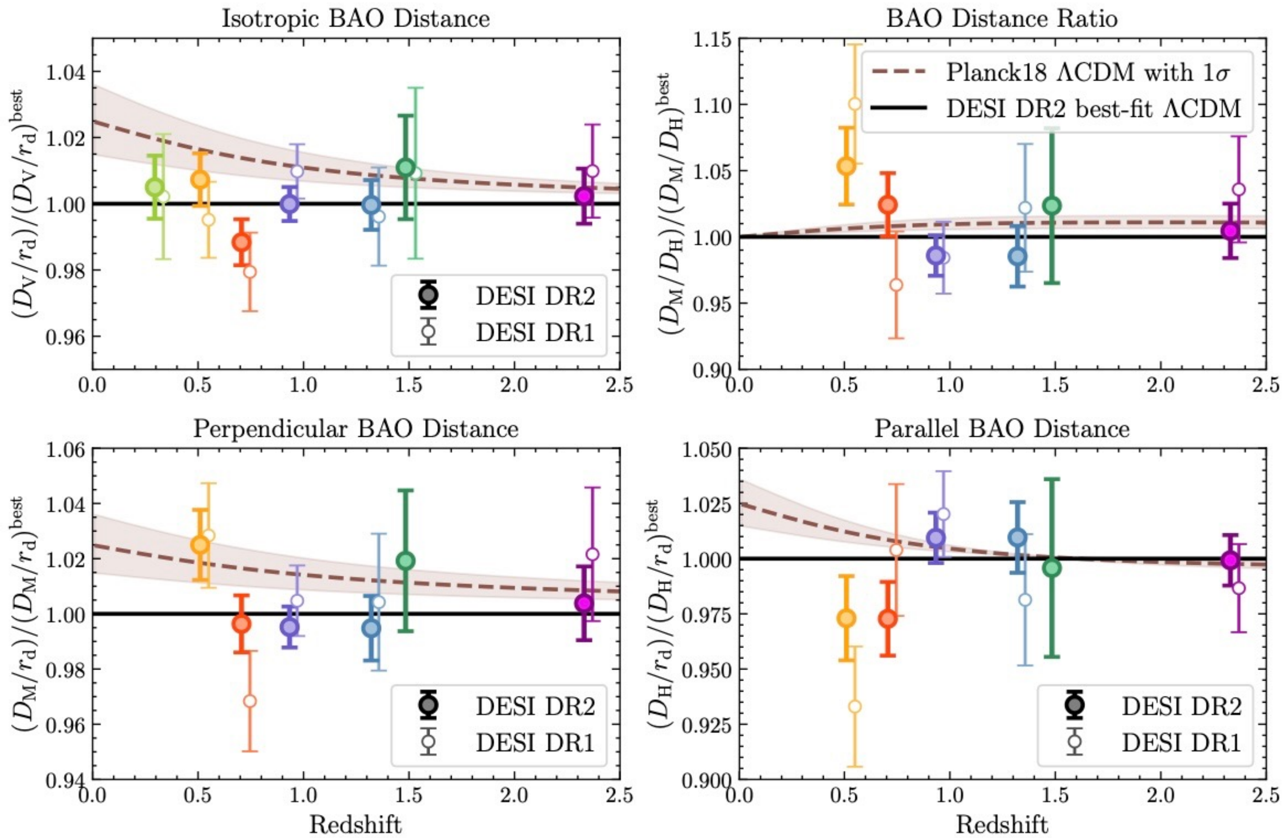




Also define an isotropic distance $D_V(z) = [zD_{\rm M}(z)^2 D_H(z)]^{1/3}$

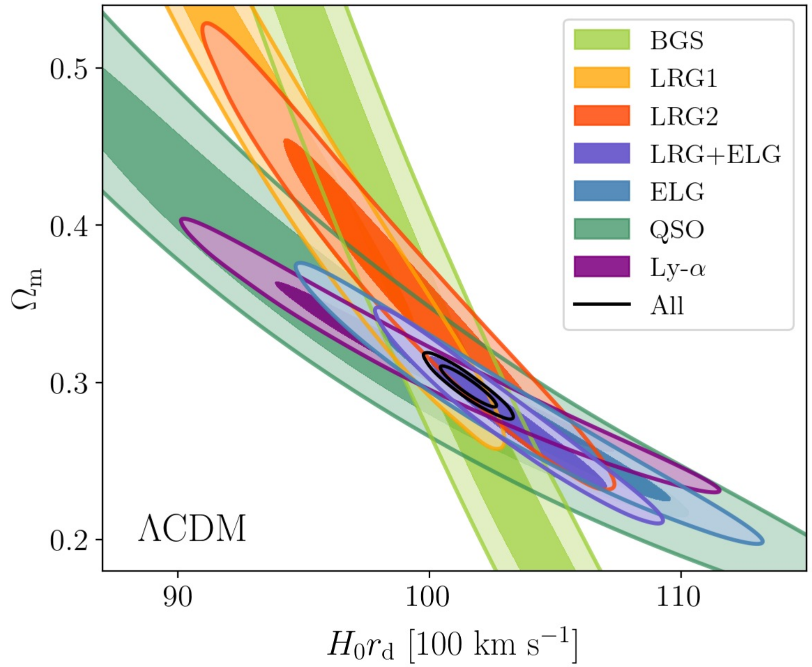
$D_{\rm M}(z), D_V(z), H(z)$ encode **expansion history** of the Universe

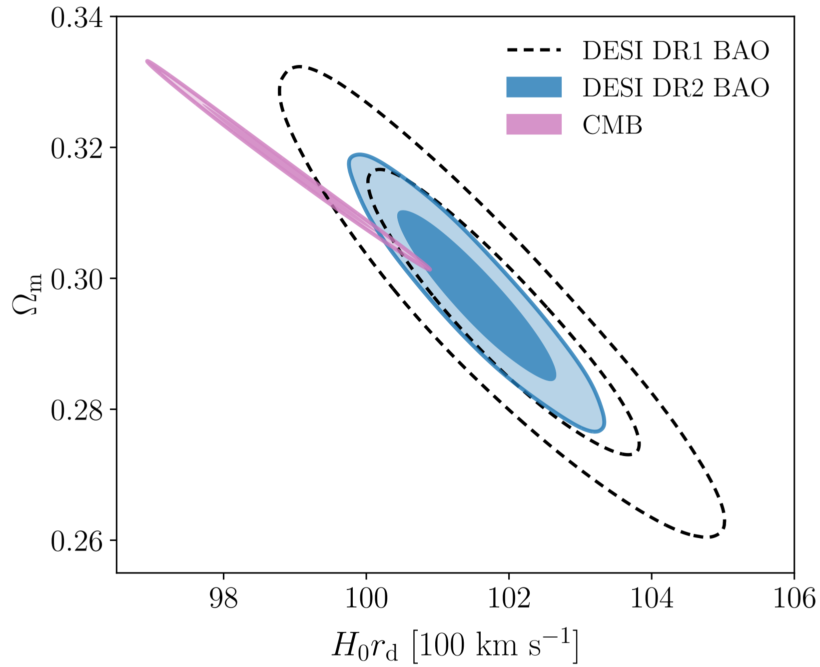
BAO inferred dilation parameters



- DESI is consistent with ΛCDM
- ~2% / 2.3 σ discrepancy with Planck ΛCDM best fit

Cosmological constraints

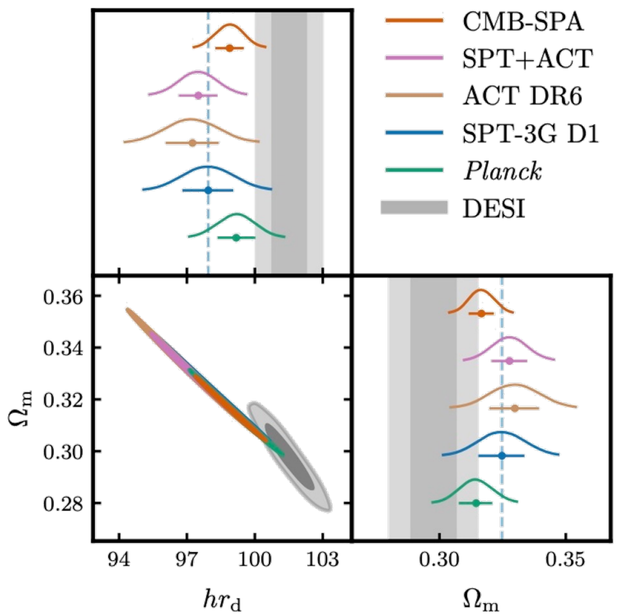




- DESI tracers are consistent
- Different degeneracy directions

- Factor 2 improvement in the Ω_m/H_0r_d plane with DR2
- 2% / **2.3 σ** discrepancy with Planck ΛCDM best fit
- CMB includes :
  - Primary CMB from Planck PR4 (camspec)
  - CMB lensing from Planck PR4 and ACT DR6

Cosmological constraints including ACT & SPT results



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

There is now a BAO-CMB tension

arXiv:2507.12459

The BAO-CMB Tension and Implications for Inflation

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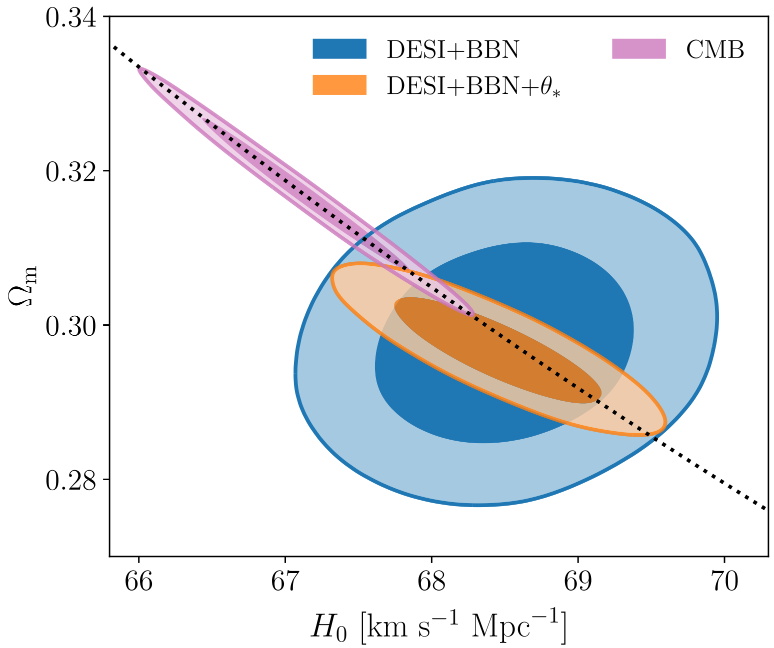
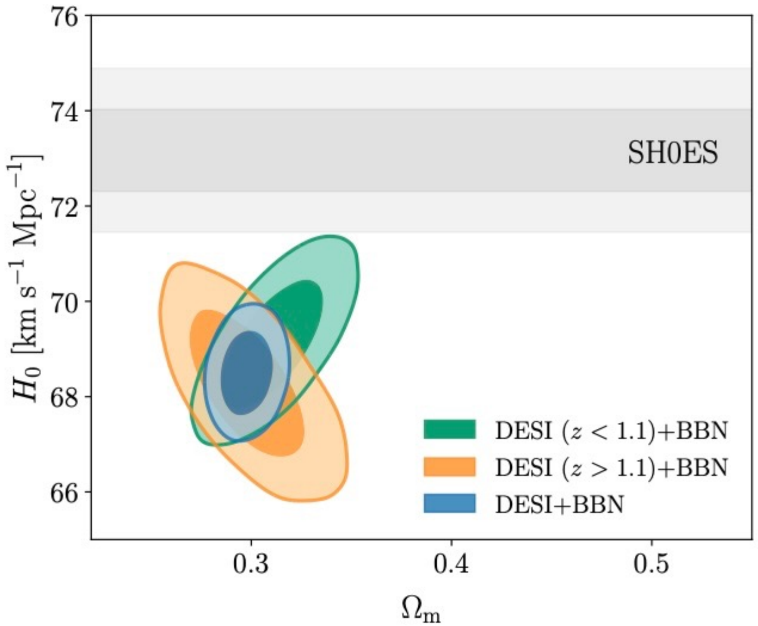
[5] *Stanford Institute for Theoretical Physics, Stanford, CA 94305, USA*
[6] *Department of Physics and Astronomy, University of California, Davis, CA, 95616 USA*

The scalar spectral index n_s is a powerful test of inflationary models. The tightest constraint on n_s to date derives from the combination of cosmic microwave background (CMB) data with baryon acoustic oscillation (BAO) data. The resulting n_s constraint is shifted significantly upward relative to the constraint from CMB alone, with the consequence that previously preferred inflationary models are seemingly disfavored by $\gtrsim 2\sigma$. Here we show that this shift in n_s is the combined effect of a degeneracy between n_s and BAO parameters exhibited by CMB data and the tension between CMB datasets and DESI BAO data under the assumption of the standard cosmological model. Given the crucial role of n_s in discriminating between inflationary models, we urge caution in interpreting CMB+BAO constraints on n_s until the BAO-CMB tension is resolved.

Constraints on the Hubble constant





- r_d calibrated using ω_b from BBN
- Complementarity of DESI tracers
- **4.5 σ** tension between DESI+BBN and SH0ES

Model/Dataset	Ω_m	H_0 [km s^{-1} Mpc^{-1}]
ΛCDM		
CMB	0.3169 ± 0.0065	67.14 ± 0.47
DESI	0.2975 ± 0.0086	—
DESI+BBN	0.2977 ± 0.0086	68.51 ± 0.58
DESI+BBN+θ_*	0.2967 ± 0.0045	68.45 ± 0.47
DESI+CMB	0.3027 ± 0.0036	68.17 ± 0.28

Constraints on Dark Energy

The nature of Dark Energy is encoded in the equation of state parameter

$$w = \frac{p}{\rho}$$

Cosmological constant: $w = -1$

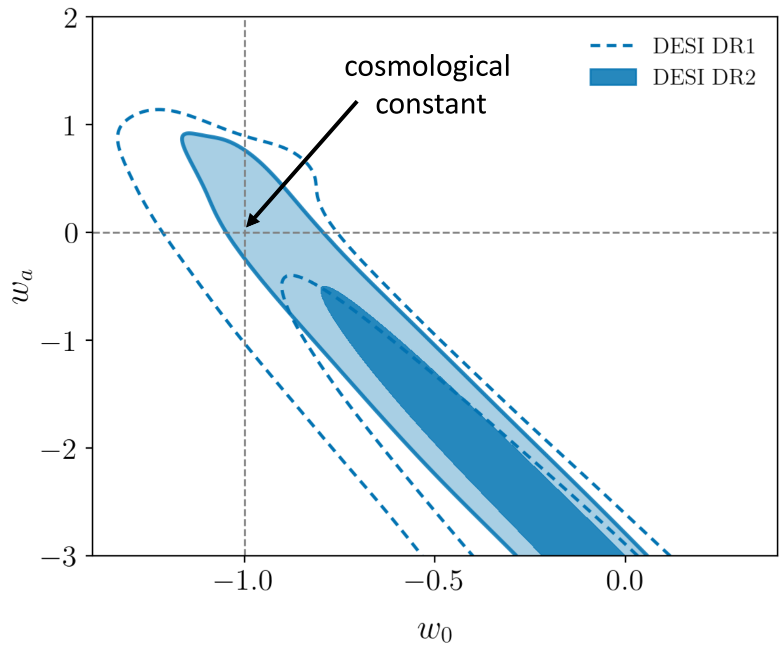
Dynamical Dark Energy (Chevalier & Polarski 2001, Linder 2003)

General parametrization:

$$w = w_0 + (1-a)w_a \qquad a = \frac{1}{1+Z} \text{ is the scale factor}$$

Contribution to *H(z)* :

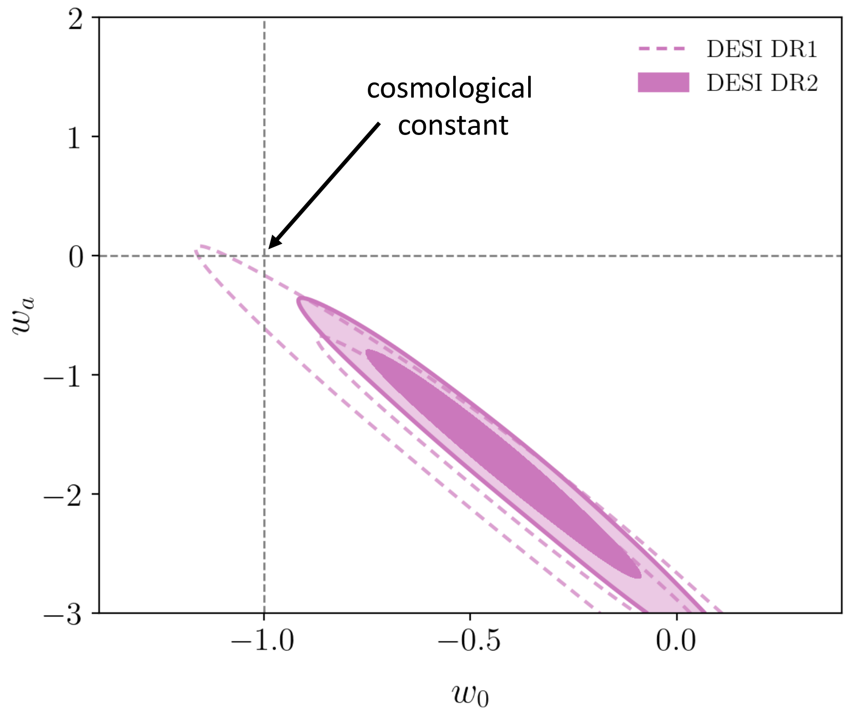
$$\frac{\rho_{\mathrm{DE}}(a)}{\rho_{\mathrm{DE},0}} = a^{-3(1+w_0+w_a)}e^{-3w_a(1-a)}$$



Adding CMB data

DESI + CMB :

3.1 σ preference for w_0w_aCDM over ΛCDM



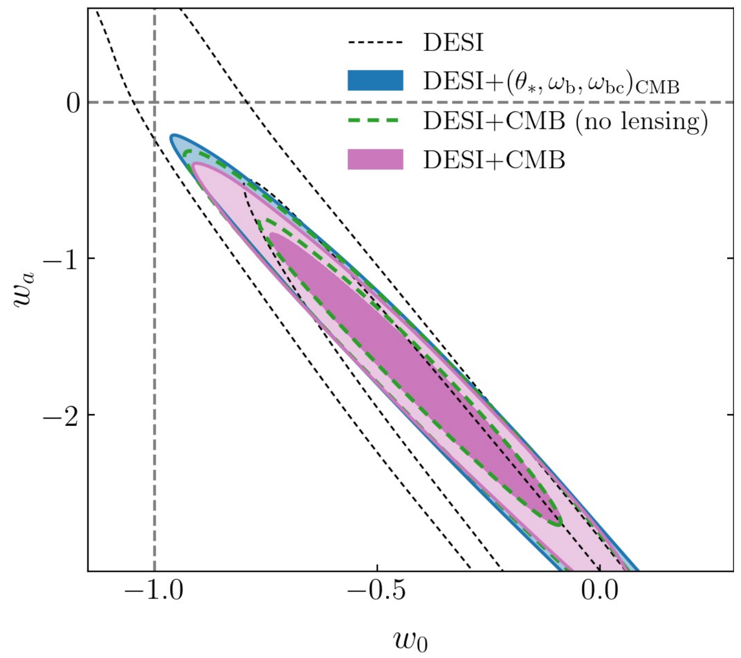
Adding “less” CMB data

DESI + CMB :

3.1 σ preference for w_0w_aCDM over ΛCDM

DESI + CMB :

- « early » time priors **: 2.4 σ**
- No lensing : **2.7 σ**



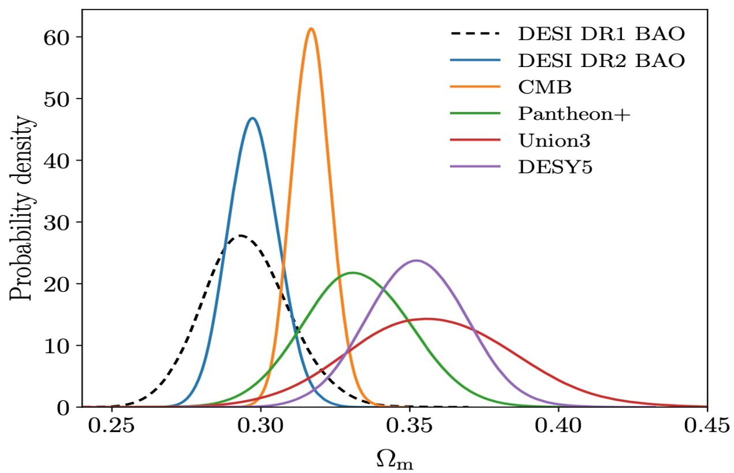
Adding CMB and SN1a data

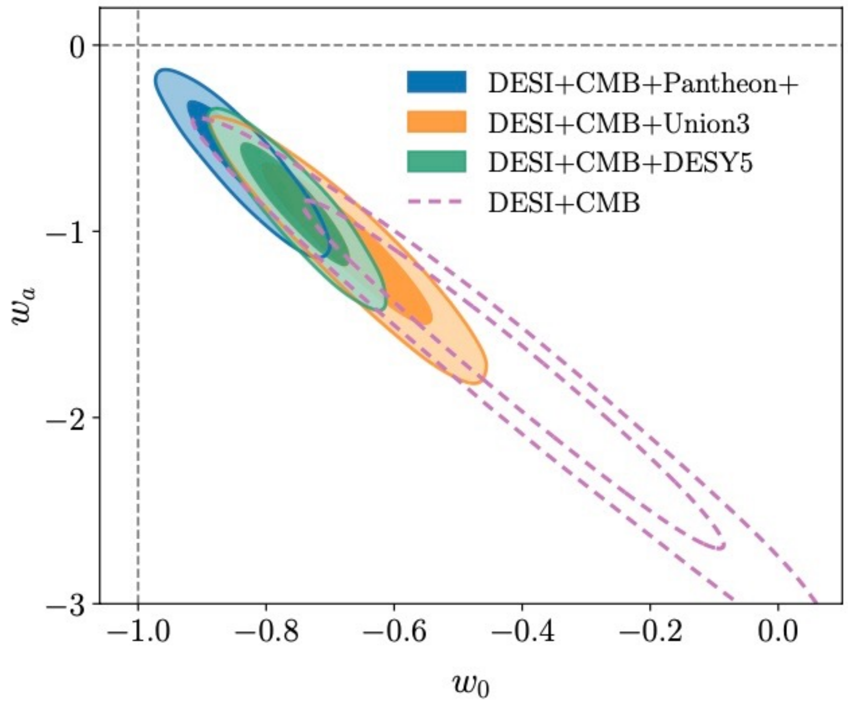
DESI + CMB :

3.1 σ preference for w_0w_aCDM over ΛCDM

DESI + CMB + Type 1a Supernovae :

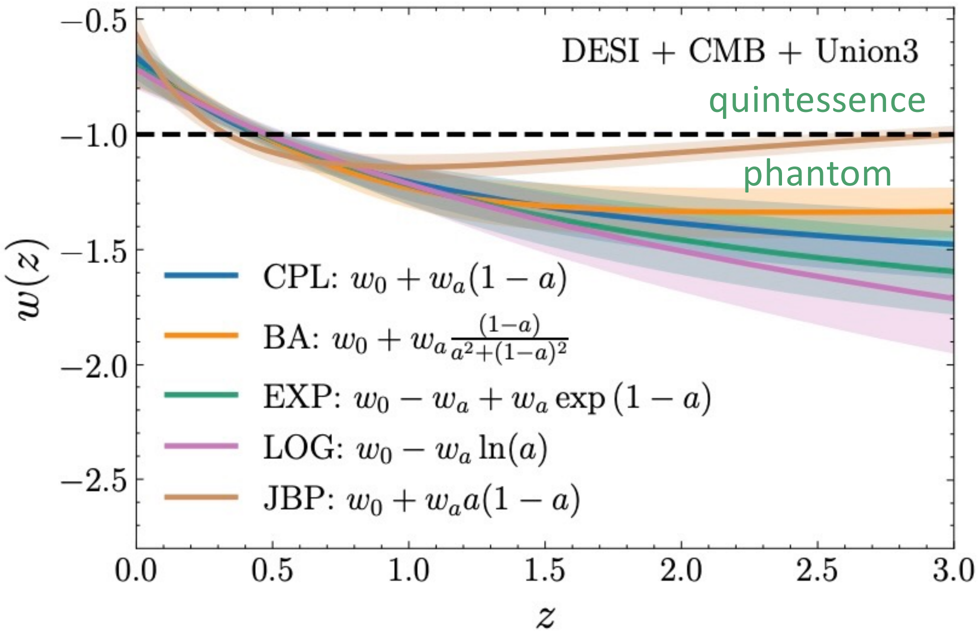
- DESI + CMB + **Pantheon+ : 2.8 σ**
- DESI + CMB + **Union3 : 3.8 σ**
- DESI + CMB + **DES Y5 : 4.2 σ**





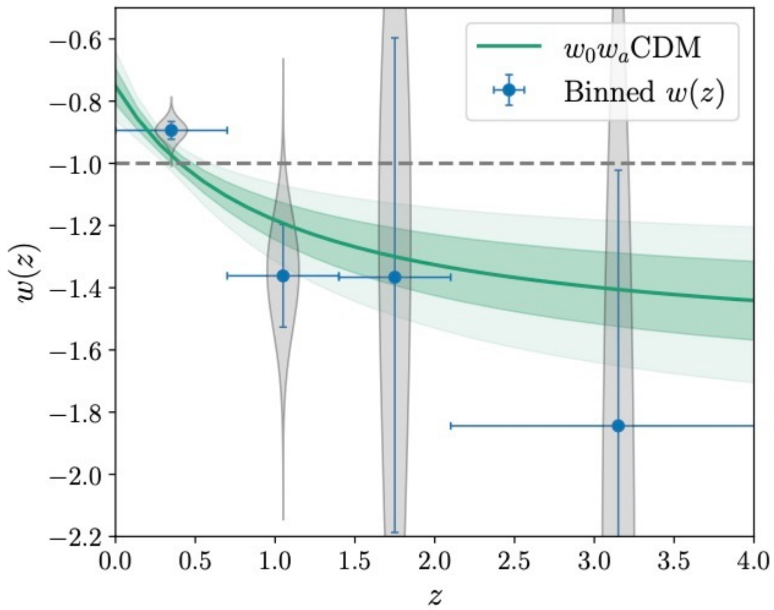
Further studies on dynamical dark energy

Changing w(a) parametrization :



- Similar results with gaussian process
- Data agrees with “mirage” DE model with <w> = -1

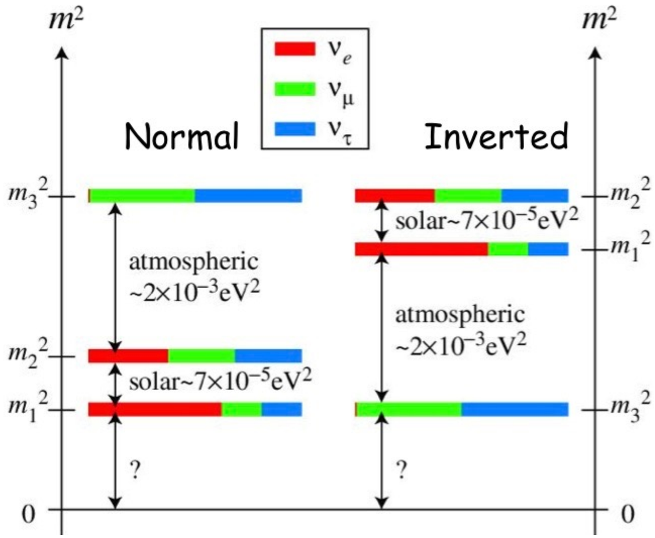
Binned w(z) :



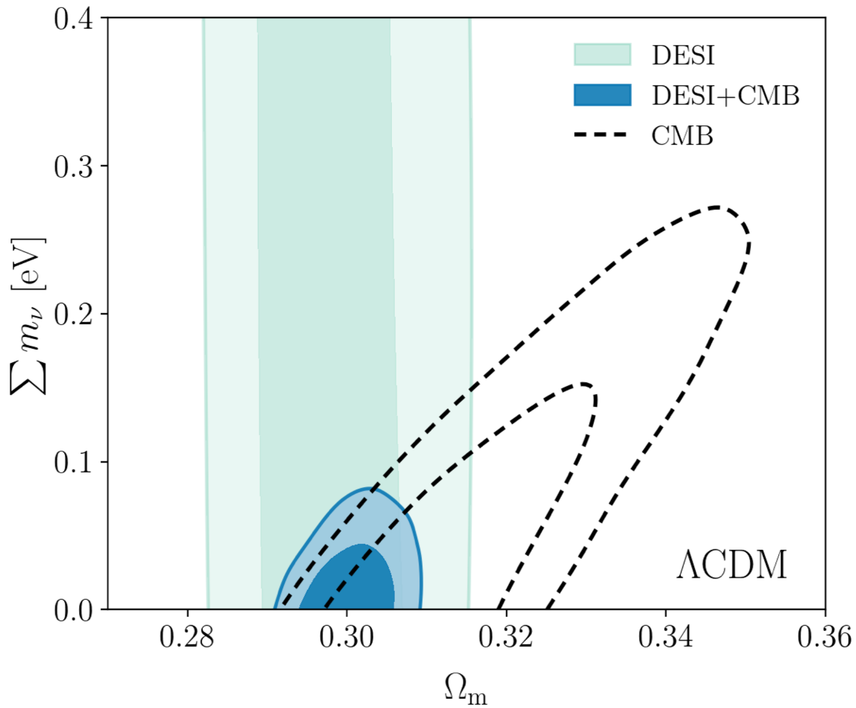
- Signal is robust w.r.t. analysis choices
  - “Phantom” crossing at z ~ 0.4
  - Challenging for single scalar field DE models
- Sensitive to ~2 additional d.o.f.

Constraints on the sum of neutrino masses in ΛCDM

In particle physics:
3 mass eigenstates and 3 flavor eigenstates
Solar neutrinos $m_2^2 - m_1^2$ ~ 7.5 10^{-5} eV^2
Atmospheric neutrinos $|m_3^2 - (m_1^2 + m_2^2)/2|$ ~ 2.4 10^{-3} eV^2



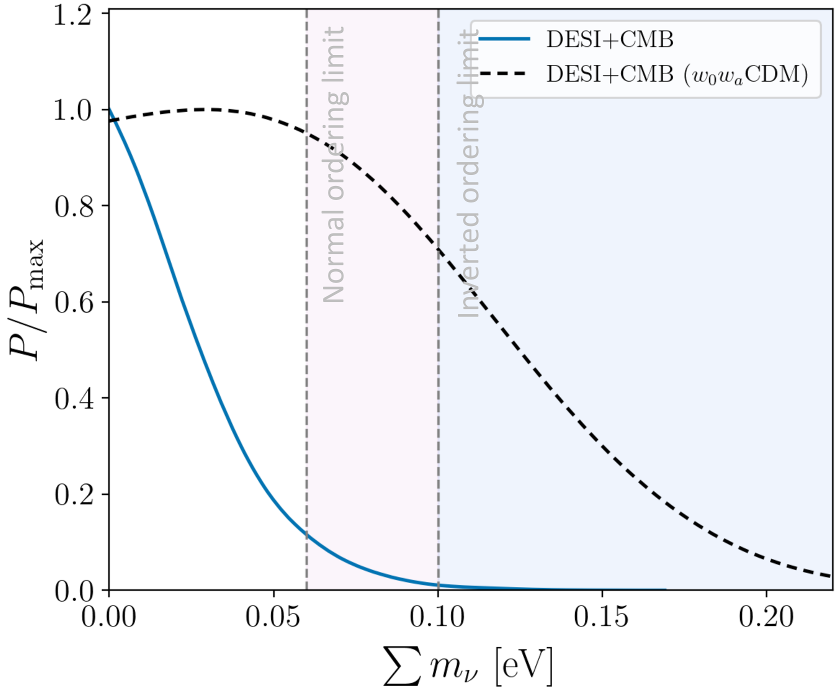
$\sum m_\nu$ > 0.06 eV $\sum m_\nu$ > 0.10 eV



- CMB data contraints are degenerate in the $\sum m_\nu$ vs Ω_m plane
- BAO data helps to break this degeneracy
- Lower Ω_m for BAO drives the constraint
- Quoted limits midly depend on ordering (DESI+CMB)

Constraints on neutrino mass

Measured sum of the neutrino masses depends on the assumed cosmological model



For DESI + CMB, the limit is :

$$\sum m_\nu < 0.064\ eV\ (95\%, \mathbf{\Lambda CDM})$$

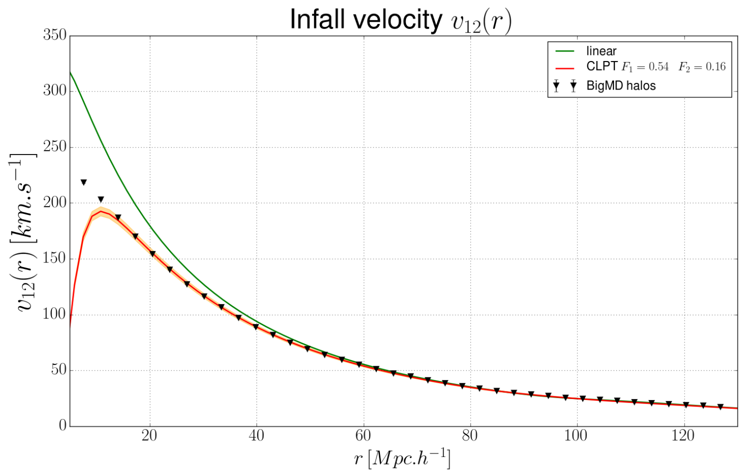
For DESI + CMB, the limit is :

$$\sum m_\nu < 0.163\ eV\ (95\%, \mathbf{w_0 w_a CDM})$$

For DESI + CMB + SN1a , the limits are :

$$\sum m_\nu < 0.117 - 0.139\ eV\ (95\%, \mathbf{w_0 w_a CDM})$$

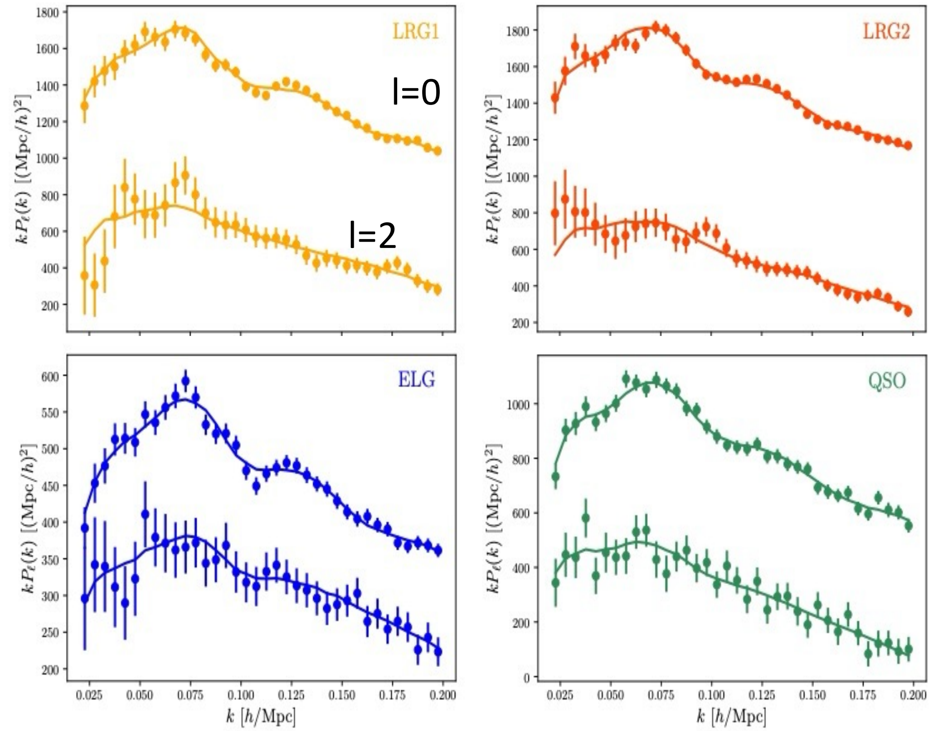
Beyond BAO : Full-Shape analysis



Infall velocity depends on:

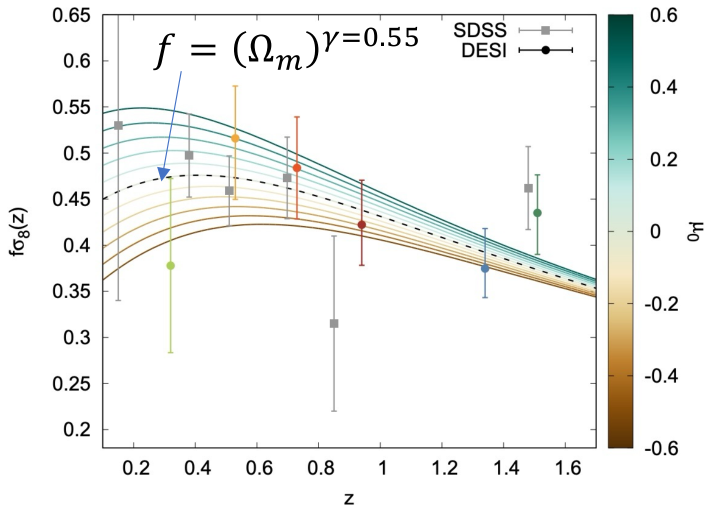
- Matter content of the Universe
- Theory of gravity

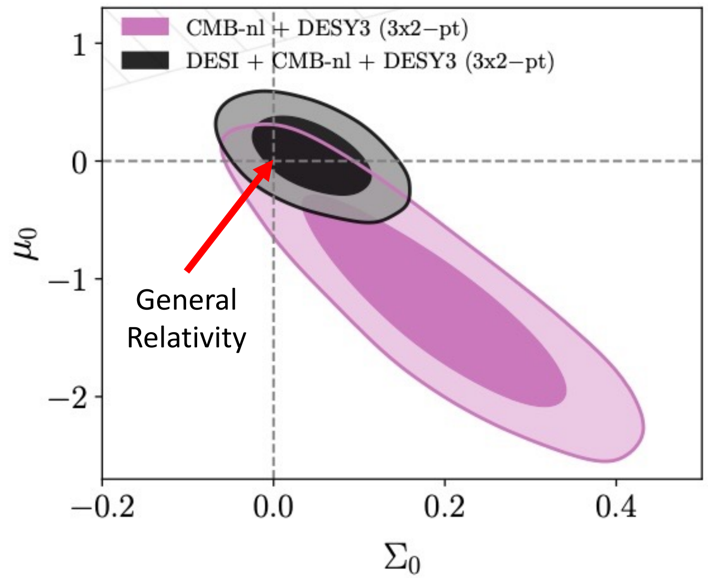
Power spectrum measurements



DESI DR1 Full-Shape analysis – Test of GR

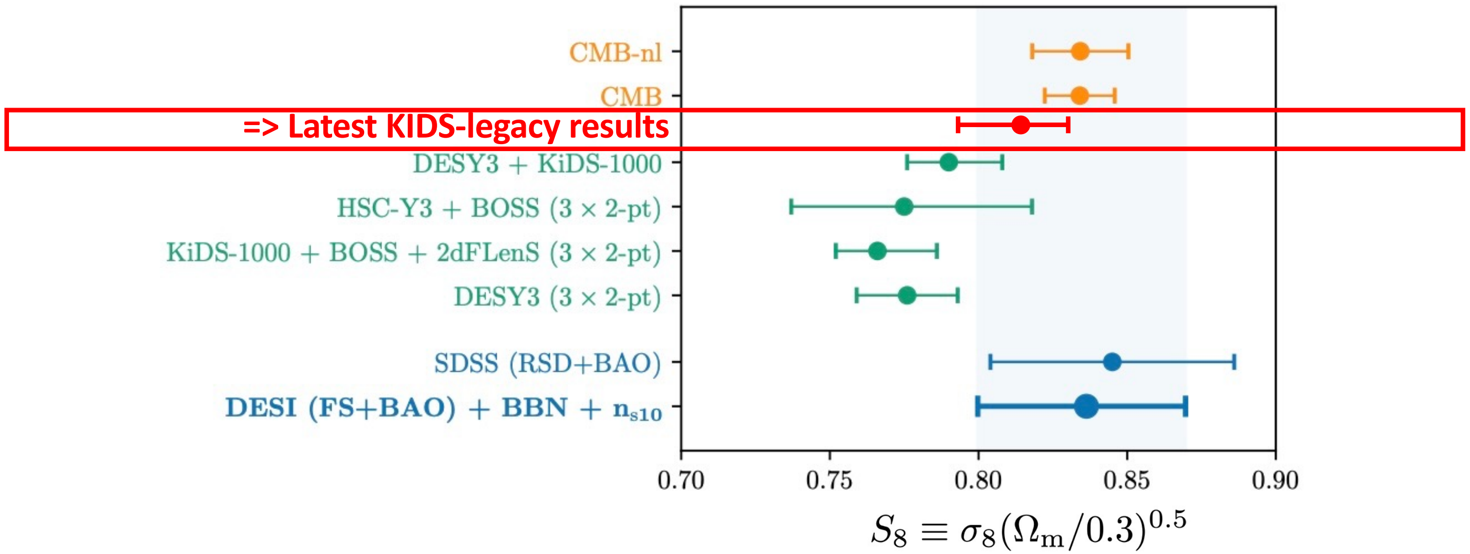
https://arxiv.org/pdf/2411.12022

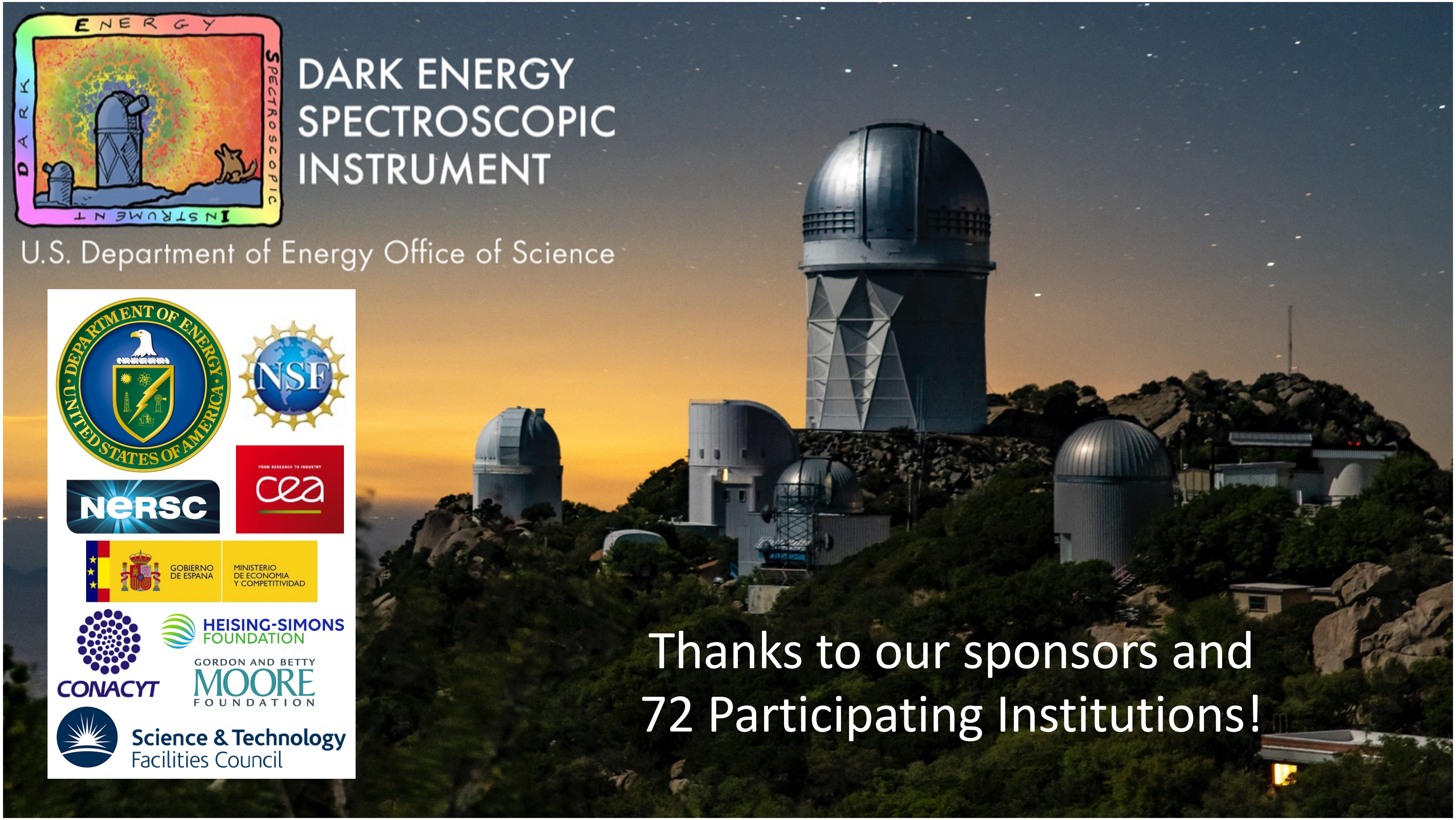




DESI DR2 Full-Shape results : Spring 2026

Tension on growth is vanishing…

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INSTRUMENT
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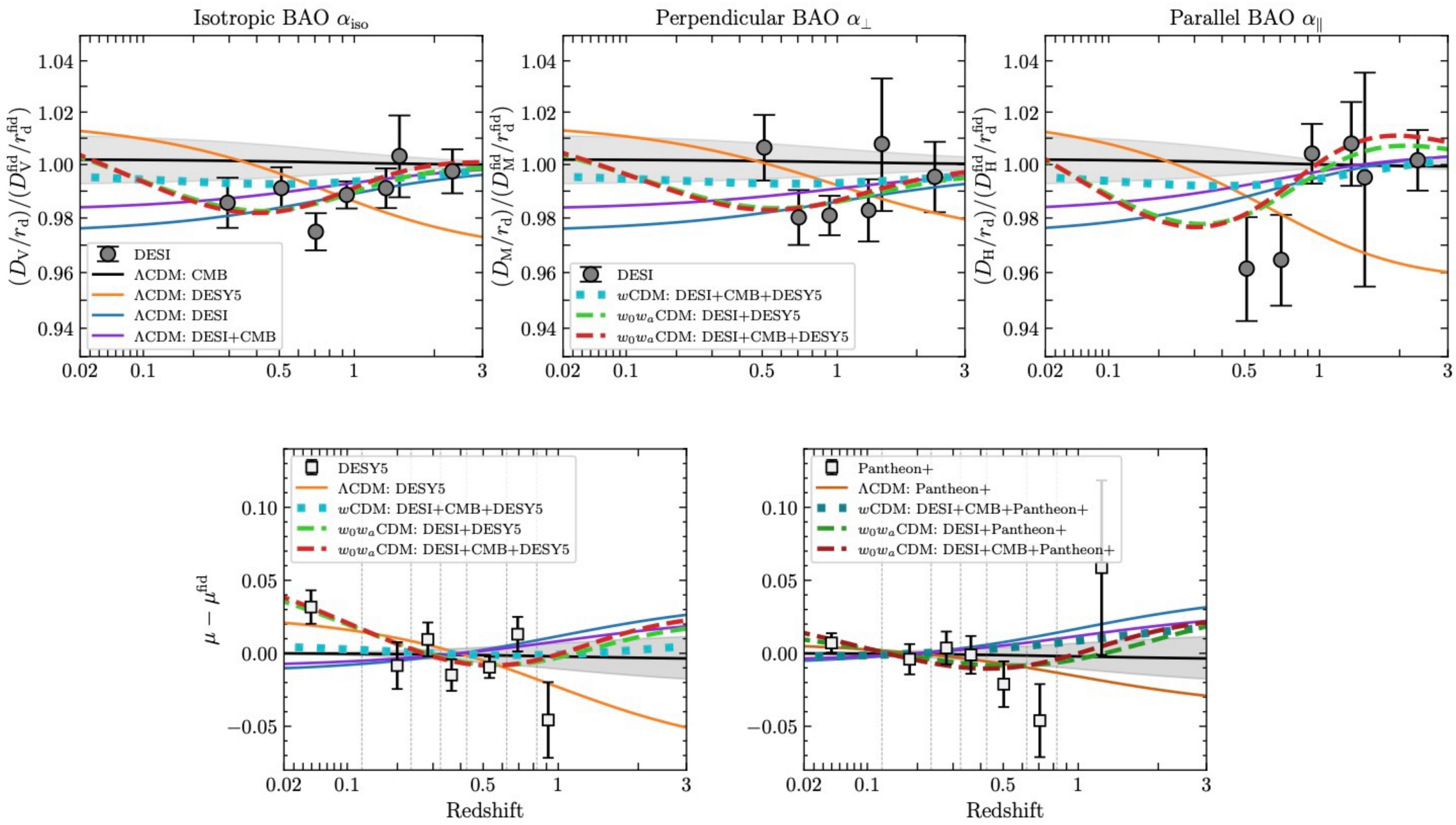
Conclusions

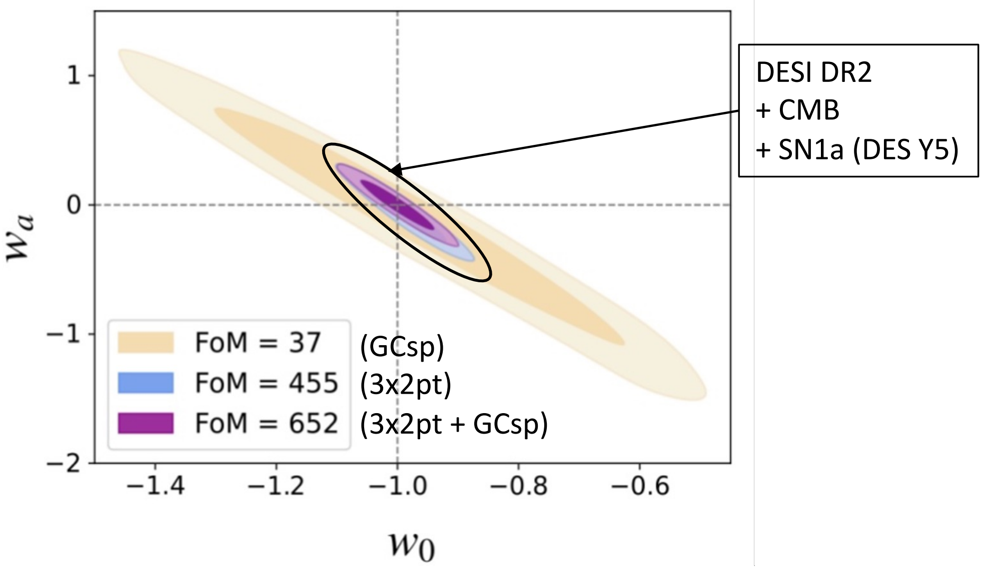
- DESI is taking data at a high pace
  - Data Release 1 (1st year) is public !
  - DR2 BAO data published, DR2 Full shape analyse in 2026
  - Main survey (->mid ’26) 6 month ahead, taking data until the end of 2028
- DESI measures BAO at sub-percent precision over $0.2 < z < 2.3$
- ΛCDM results
  - DESI alone in agreement with ΛCDM
  - But there is now a 2.8σ BAO-CMB tension
- Dynamical Dark Energy
  - DESI + CMB has a 3σ preference for Dynamical DE over ΛCDM
  - Preference remains when adding SN1a data, but significant dispersion
  - Favored DE models (a.k.a. Phantom) are surprising and challenging

Fits of available data



Upcoming results from other probes

Weak Lensing:
constraints on Dark Energy
from the complete Euclid (Forecast, 2030+)



Euclid DR1 (2027) : similar as DESI DR2

Cosmic Microwave Background :

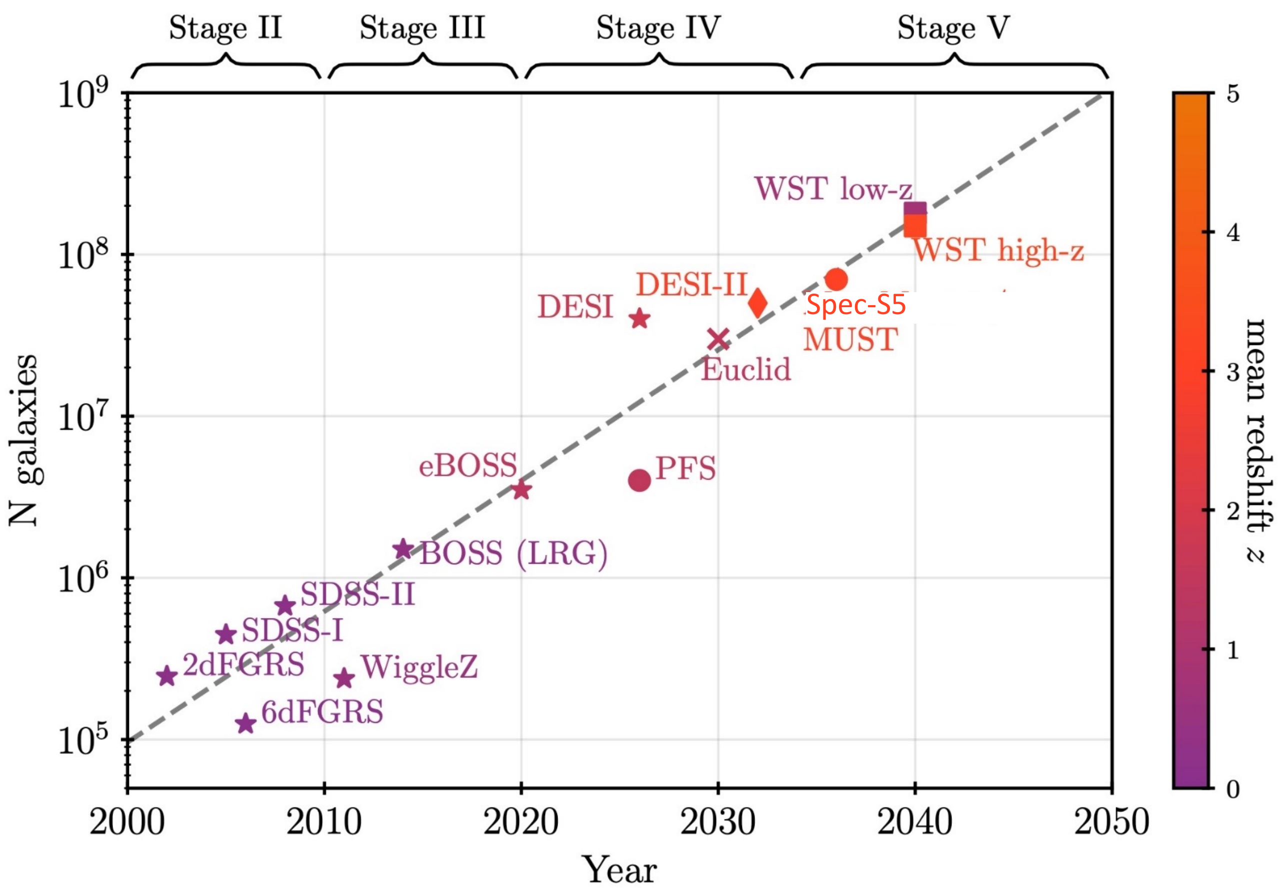
- Atacama Cosmology telescope:
  - Combination DESI+Planck+ACT in press
- South Pole telescope

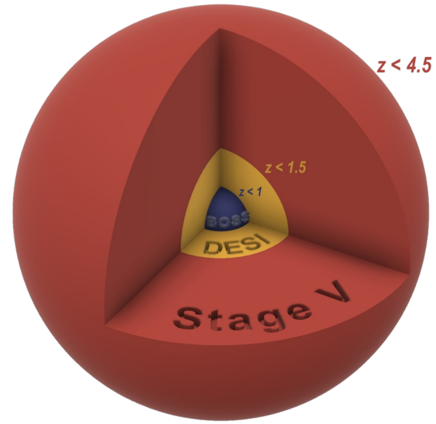
Longterm: Simons Observatory, LiteBird, CMB-S4

Type 1a Supernovae :

- Zwicky Transient Factory (4x more SN1a)
- Vera Rubin – LSST

Future of Large Scale Spectroscopic Surveys



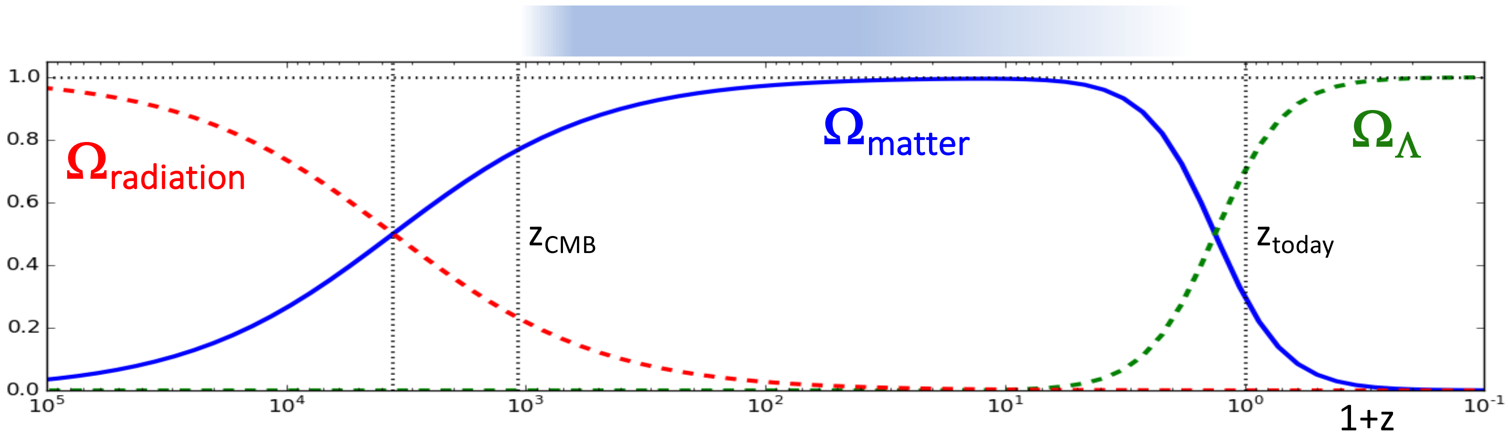


- **10-fold increase every decade**
- **Goals of future programs**
  - High-density low-redshift
  - High redshift
    - ➔ Largest Universe volume

Neutrinos and cosmology

- At early times, neutrinos act as additional relativistic species $\frac{\rho_\nu}{\rho_\gamma} = \frac{7}{8} N_{\rm eff} \left(\frac{4}{11}\right)^{4/3}$
- At late times, neutrinos behave as matter
- Non-relativistic transition: $z_{nr} \sim 1900 \, \frac{m_\nu}{1\,{\rm eV}}$

Latest KATRIN results m_{eff}<0.45 eV => z_{nr} < 800
N.O. lower valuer (degenerate mass) => z_{nr} > 40



$$\frac{H^2(z)}{H_0^2} = \Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\nu \frac{\rho_\nu(z)}{\rho_{\nu,0}} + \Omega_{DE}\frac{\rho_{DE}(z)}{\rho_{DE,0}}$$

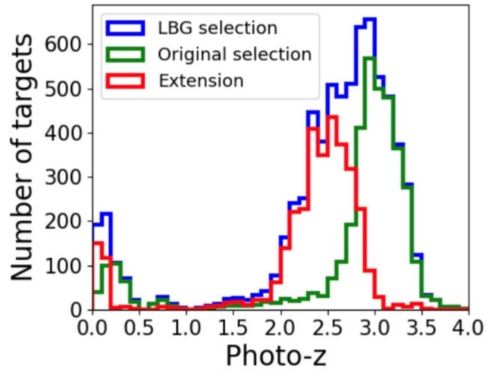
"Early" expansion history depends on the sum of neutrino masses

LSS – 2029-2035 DESI-II

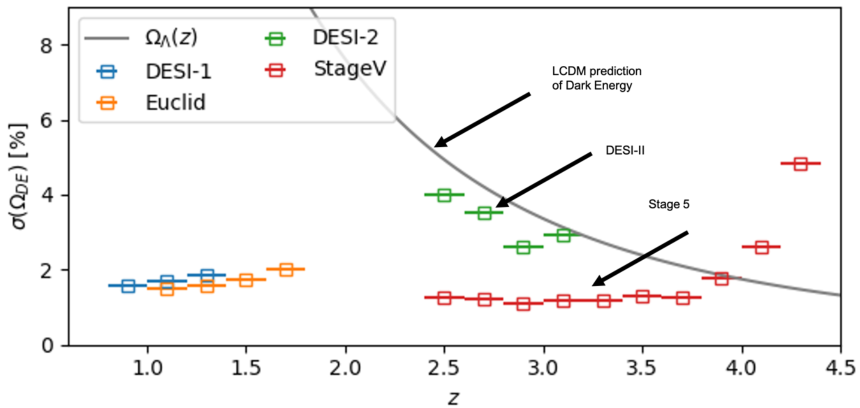
DESI-II (after a 2.5 extension of DESI)

- **a pathfinder for Stage-5 spectroscopic surveys**
- Modest hardware upgrades
- **Low-z program:**
  - ~20x density of DESI
  - Growth of structures
  - Modified gravity
  - Challenge for theoretical models
- **High-z program 2 < z < 3.5:**
  - New tracers : star forming galaxies (LAE, LBG)
  - Onset of Dark Energy
  - Non-gaussianities

DESI-2 high-z target selection



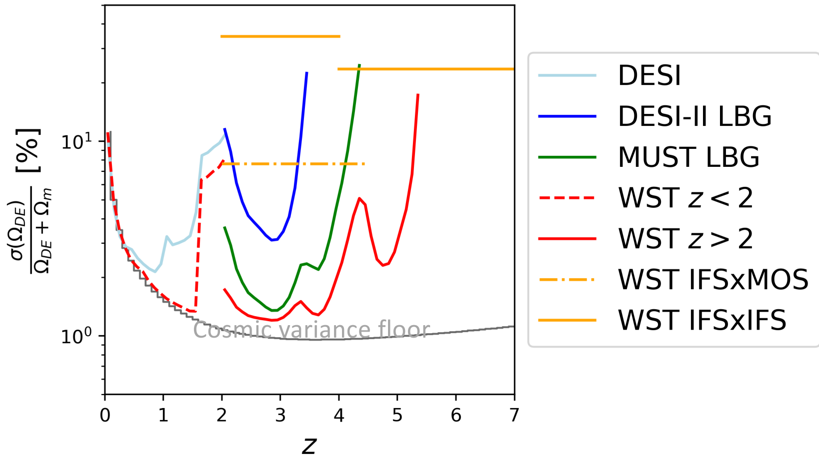
Onset of Dark Energy

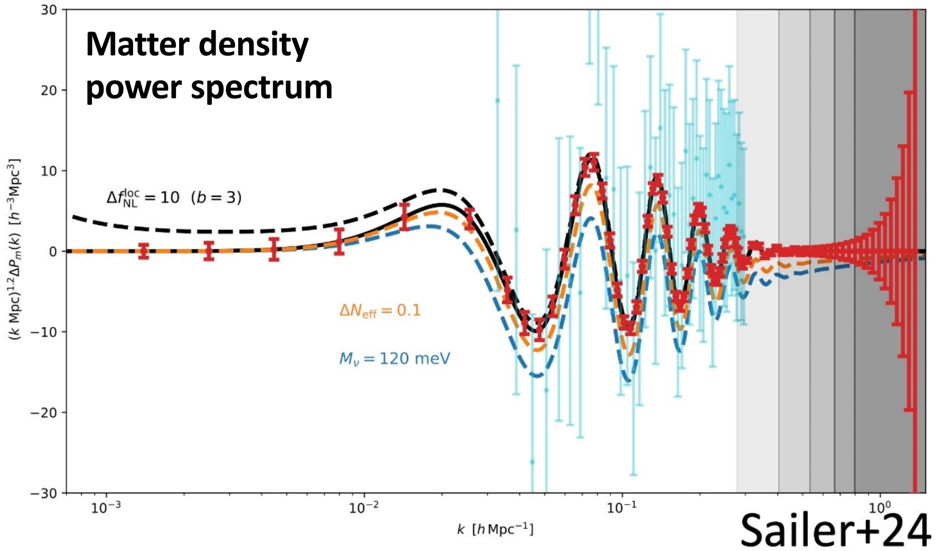


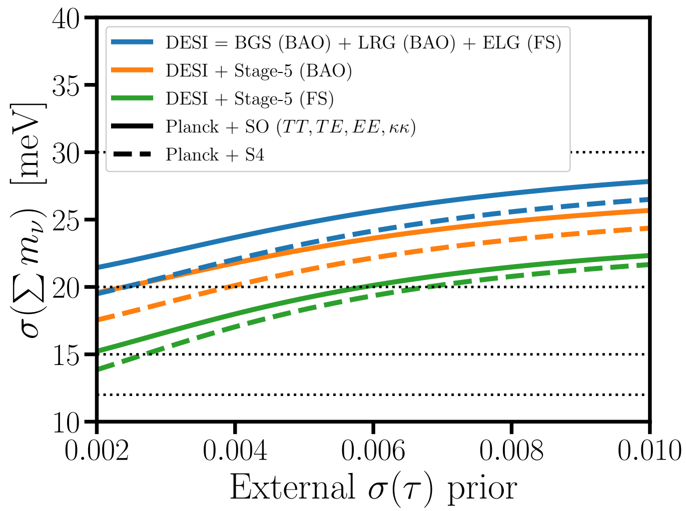
LSS – “Stage 5” surveys (>2035)

Key science goals

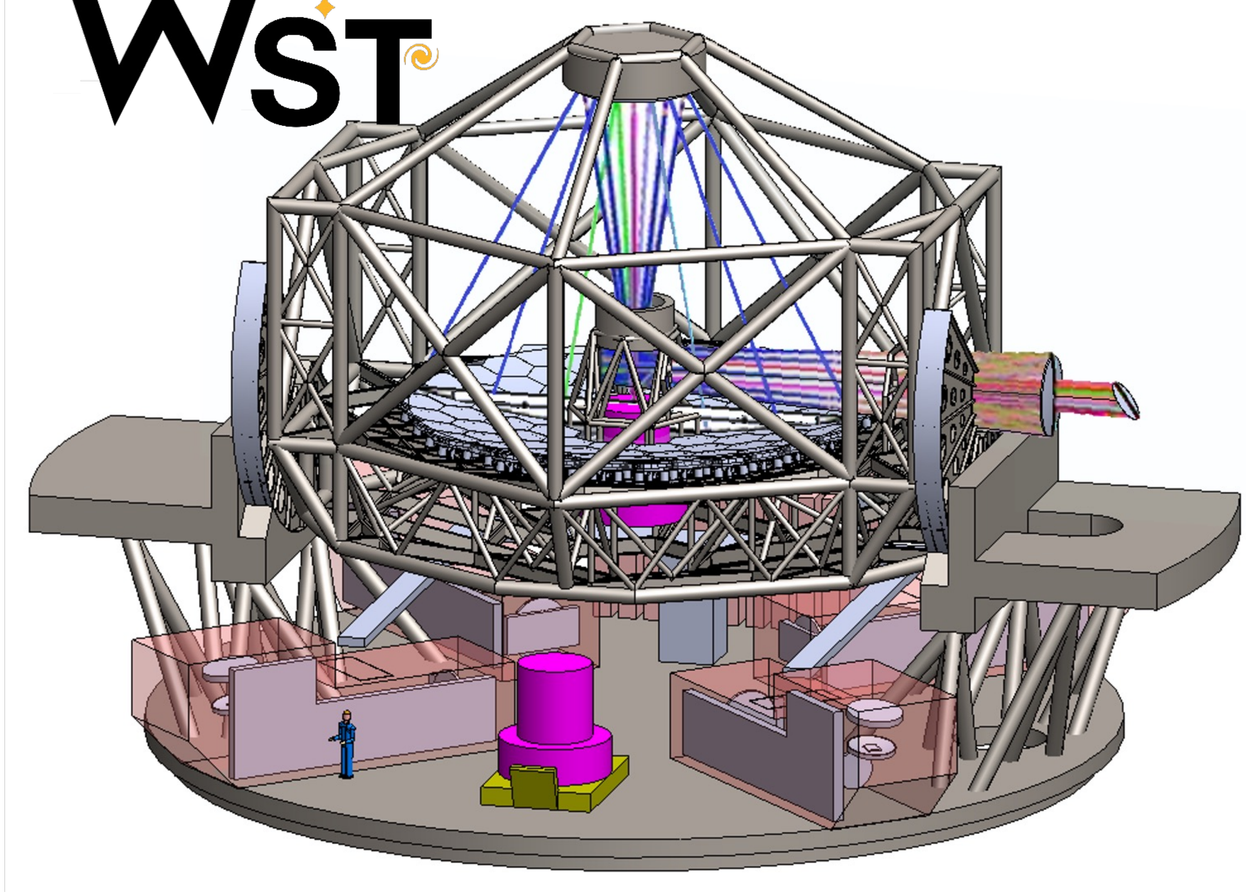
- “Saturate” cosmic variance up to z = 4
- σ(**DE**) < 2% → Rule out EDE models
- σ(Σm_ν) < 15 meV → 4σ detection,
- non-gaussianities :
  - Distinguish single and multi-field **inflationary models**







The Wide-field Spectroscopic Telescope



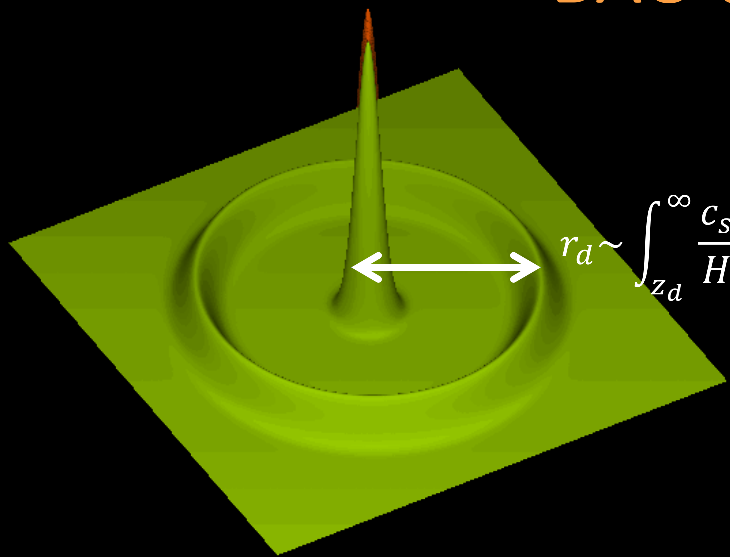
The ultimate spectroscopic telescope :

- 12m segmented Telescope – 3 deg^2 field of view
- Spectroscopic capability:
  - 20000-fiber Multi-Object Spectrograph
  - 9 $arcmin^2$ Integrated Field Spectrograph
- In Chile
- **Supported by ESO community**

Timeline :

- Received EU funds for a 3-year concept study phase (”Horizon”, -> Jan ’28)
- ESO selection Q3 ‘28
- **ESO approval Q4 ‘28**
- First light 2040

BAO distance scale



$$r_d \sim \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)}\, dz$$

Sound speed in primordial plasma

$$c_s(z) = \frac{c}{\sqrt{3}} \frac{1}{\sqrt{1 + \frac{3\omega_b(z)}{4\omega_\gamma(z)}}}$$

Baryons

photons

Expansion of the universe $H(z)$

r_d = 150 Mpc today (distance to Virgo cluster ~20Mpc)

Big Bang Nucleosynthesis

Abundance of light elements

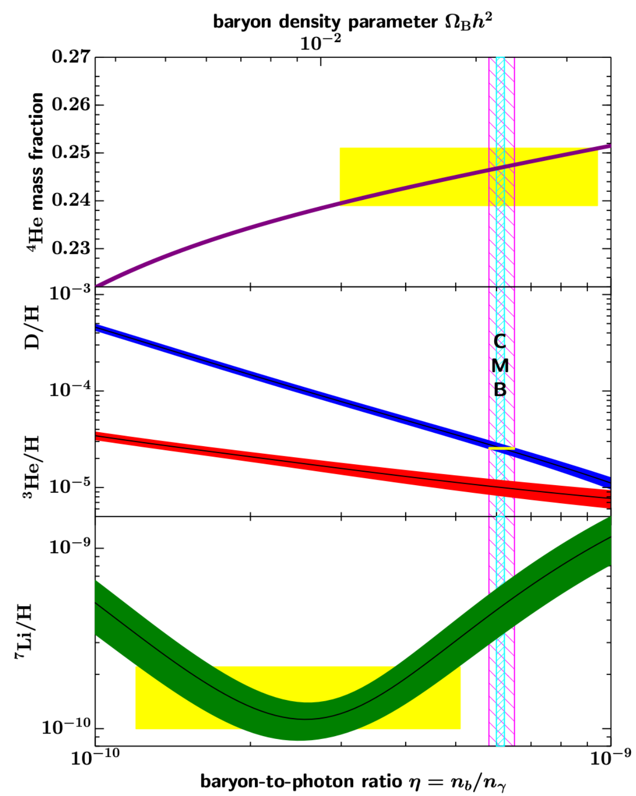
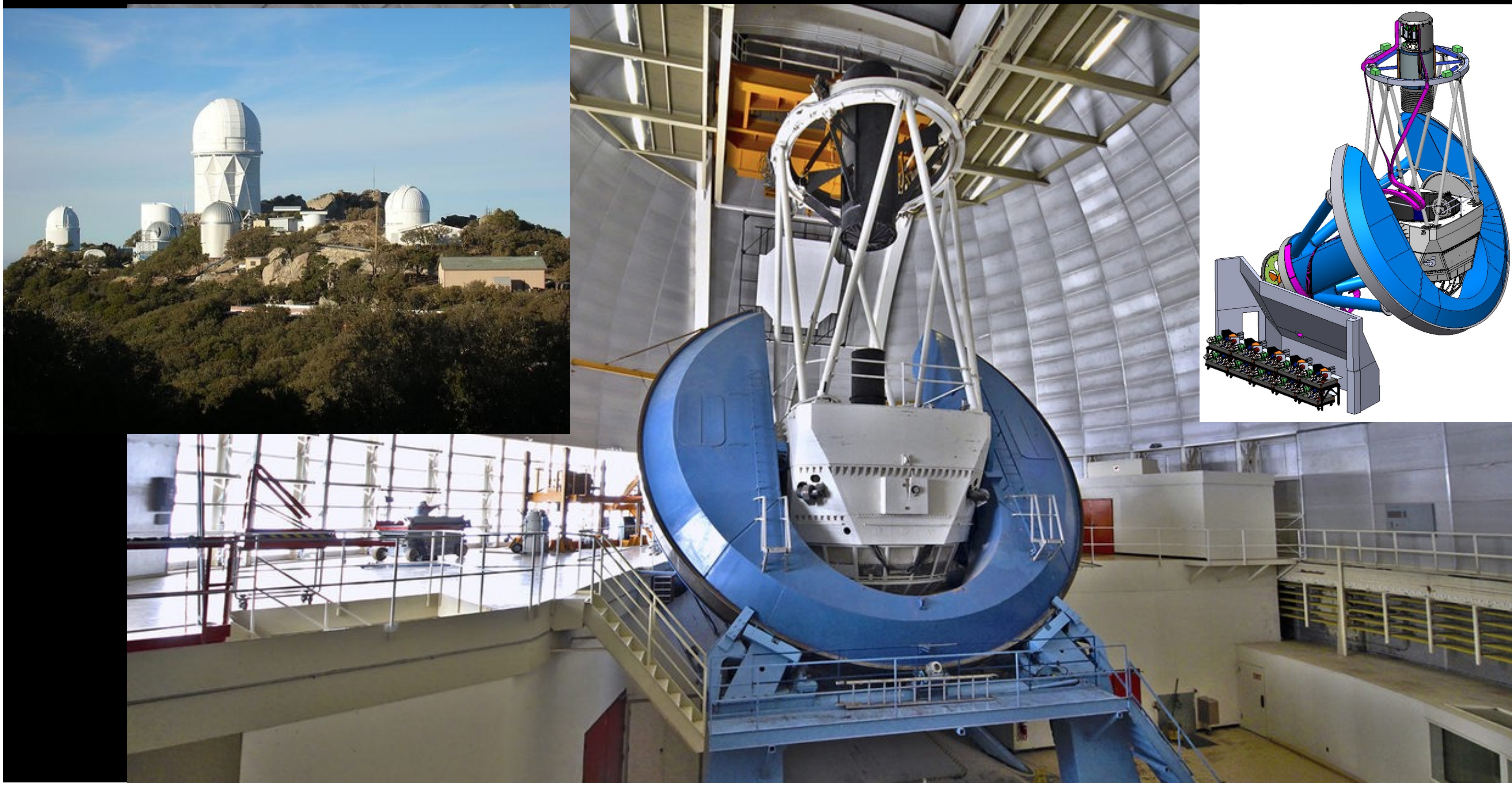
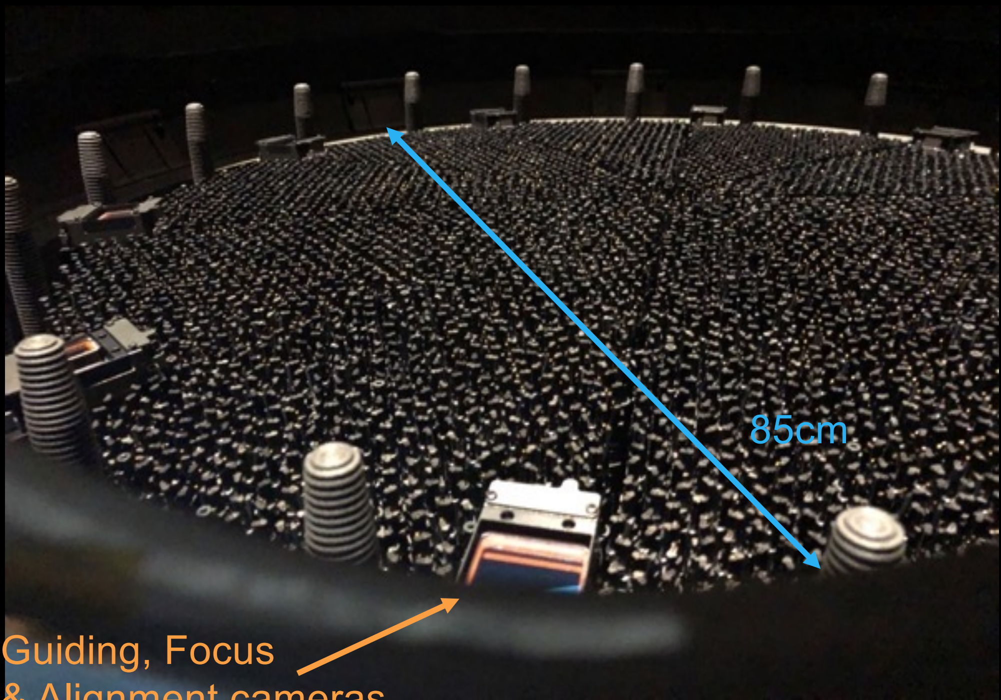


Figure 24.1: The primordial abundances of ^{4}He, D, ^{3}He, and ^{7}Li as predicted by the standard model of Big-Bang nucleosynthesis — the bands show the 95% CL range [47]. Boxes indicate the observed light element abundances. The narrow vertical band indicates the CMB measure of the cosmic baryon density, while the wider band indicates the BBN D+^{4}He concordance range (both at 95% CL).

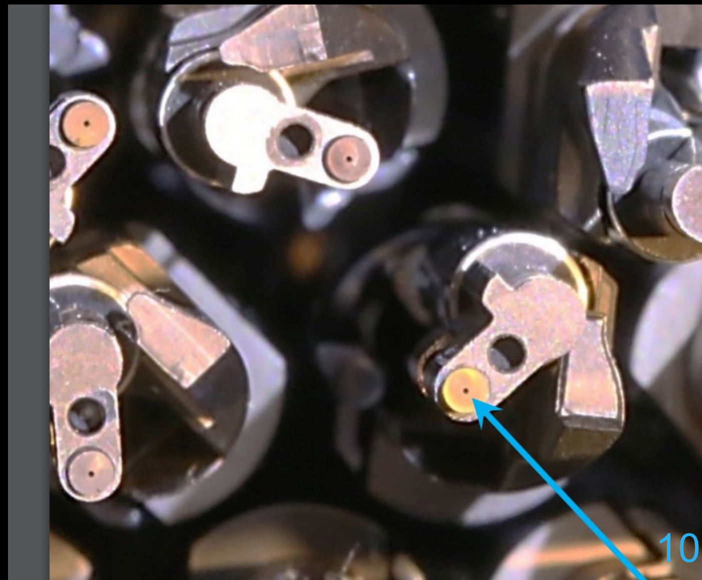
Telescope – Mayall 4m @ Kitt Peak (Arizona)



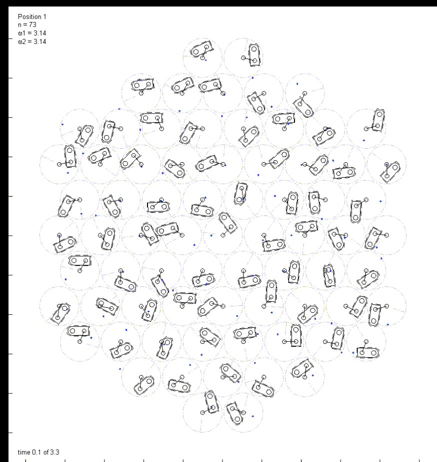
Fiber positioners



Guiding, Focus
& Alignment cameras



100 microns



DESI spectrographs

- 10 spectrographs 500 fibres each
- Red, Blue, Red and near IR
- CCD readout

- French Contribution to DESI
  CEA/Saclay, CNRS, AMU
- Industrial partner :

Winlight