Cosmology - Part III
Dark Energy Spectroscopic Instrument
DESI

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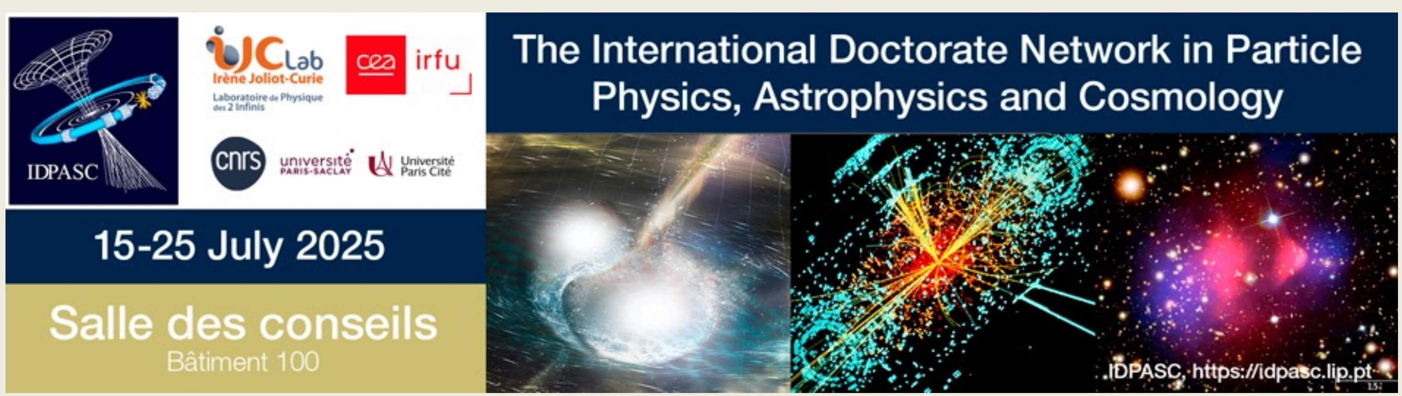
14th IDPASC school, July 23, Orsay



Reminder
of the first two
cosmology lectures
(Josquin Errard)

Context in Cosmology
Friedmann Equation

Cosmological principal ⟹ FRLW metric

- Universe isotropic + homogeneous on large scales
- Universe looks the same whoever and wherever you are

⟹ Friedmann, Lemaitre, Robertson, Walker (FRLW) metric

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

- Dimensionless scale factor: $a(t)=R(t) / R(t_0)$
- Curvature of Universe: k

Einstein Equation ⟹ Friedmann Equation

$$\left(\frac{\dot{R}}{R}\right)^2 + \frac{k}{R^2} = \frac{8\pi\rho}{3}$$

Other form with density parameters Ω_m, Ω_r, Ω_Λ

$$H^2(a) = \left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda + \overbrace{(1-\Omega_T)}^{\Omega_k} a^{-2}\right]$$

Context in Cosmology
ΛCDM

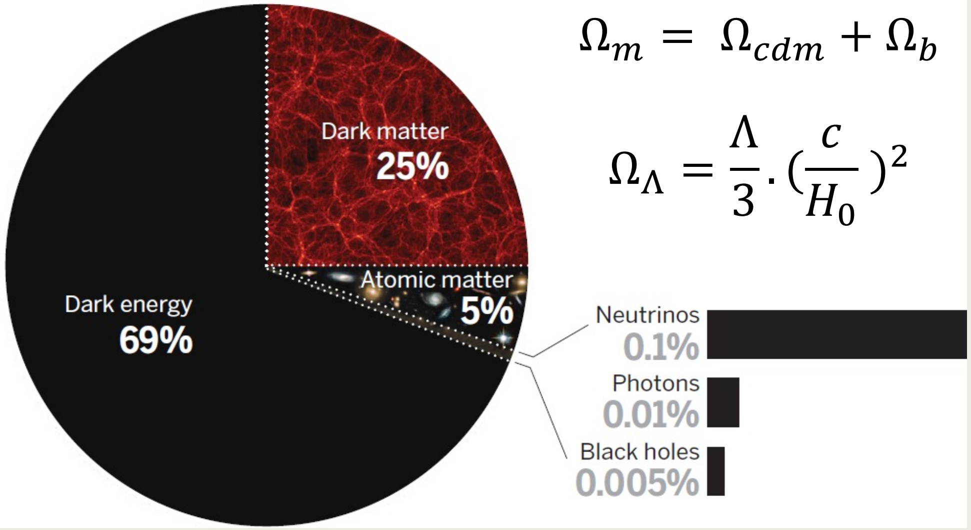
ΛCDM

- "Standard Model" of cosmology
- General Relativity (GR)
- Cosmological constant (Λ)
- Flat Universe

$$\Omega_m + \Omega_\Lambda + \Omega_r = \Omega_T = 1$$

$$\Omega_m = \Omega_{cdm} + \Omega_b$$

$$\Omega_\Lambda = \frac{\Lambda}{3} . (\frac{c}{H_0})^2$$



Extensions of ΛCDM

- Equation of state of Dark Energy

$$w(z) = \frac{p(z)}{\rho(z)}$$

$$a = \frac{1}{1+z}$$

- Time evolving Dark Energy

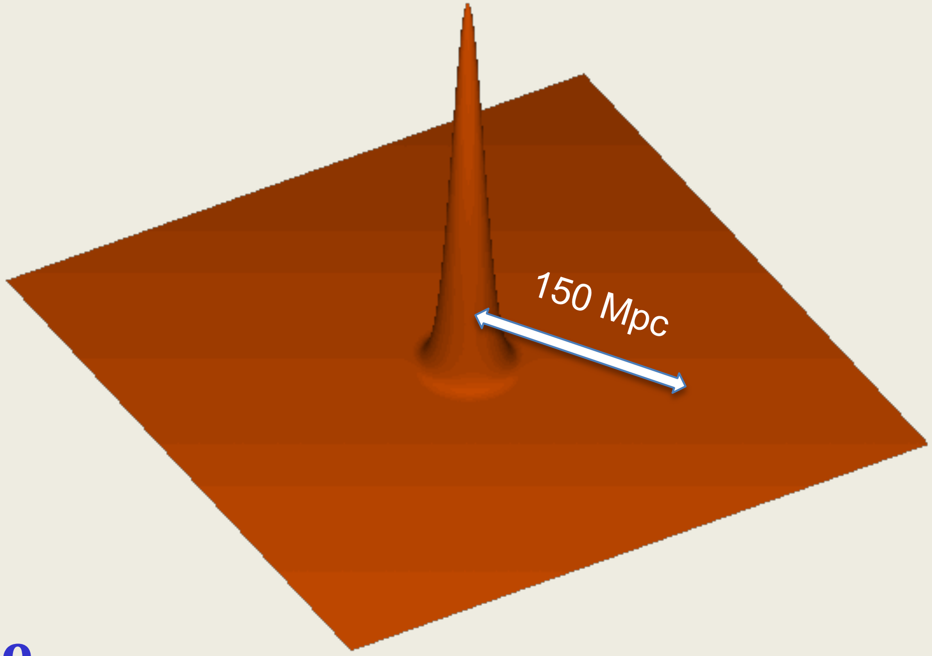
$$w(z) = w_0 + \frac{z}{1+z} w_a$$

Open questions

- H_0 tensions
- Time evolving DE ($w_0 w_a$CDM)

Discovery and first measurements of the Baryonic Acoustic Oscillations (BAO)

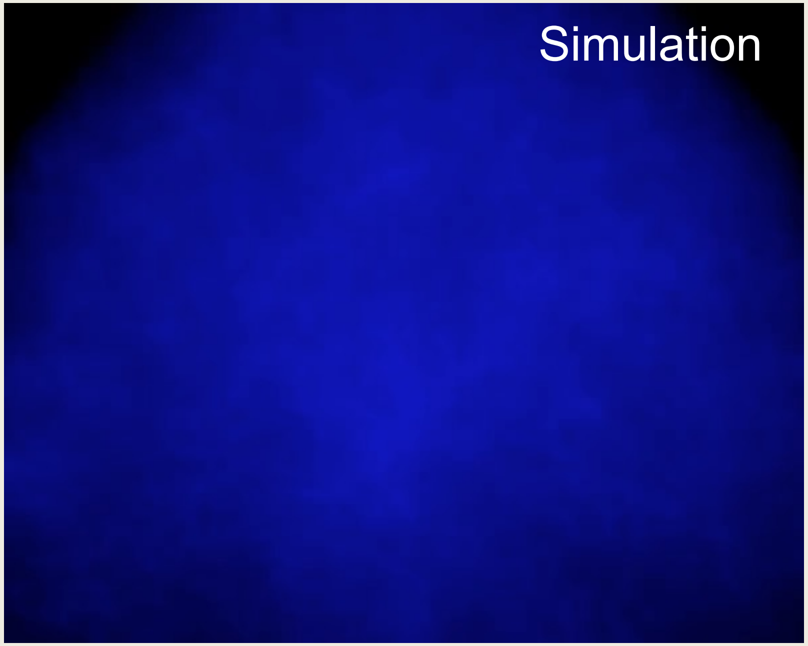
A probe for Dark Energy: Baryonic Acoustic Oscillations

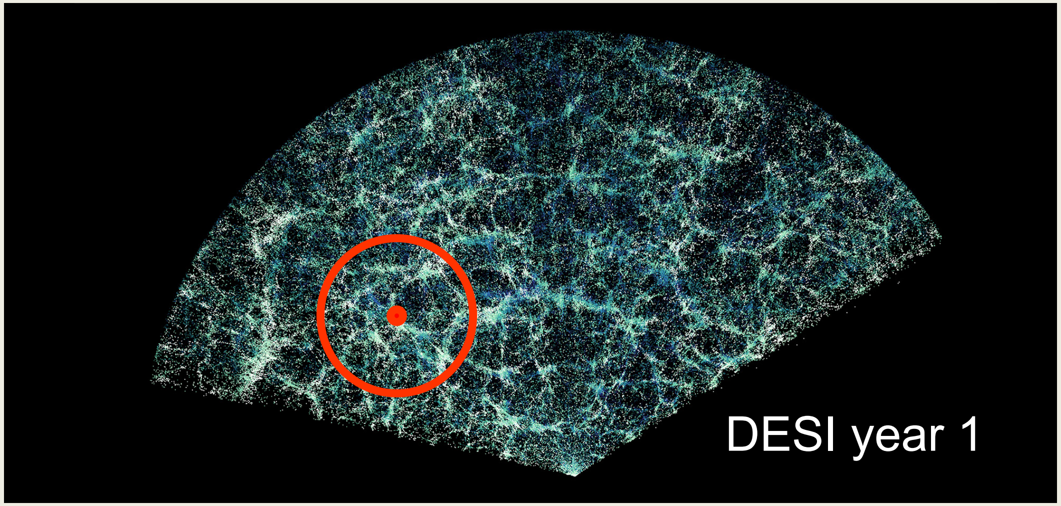


A special distance

- Sound waves propagate through relativistic plasma (baryons, electrons, photons) with a speed $\sim c/\sqrt{3}$
- They freeze at recombination (z~1100 i.e 380,000 years)
- Galaxies form in the overdense shells about $r_d \sim 150$ Mpc in radius from initial overdensities.

Baryonic Acoustic Oscillations





A special distance:

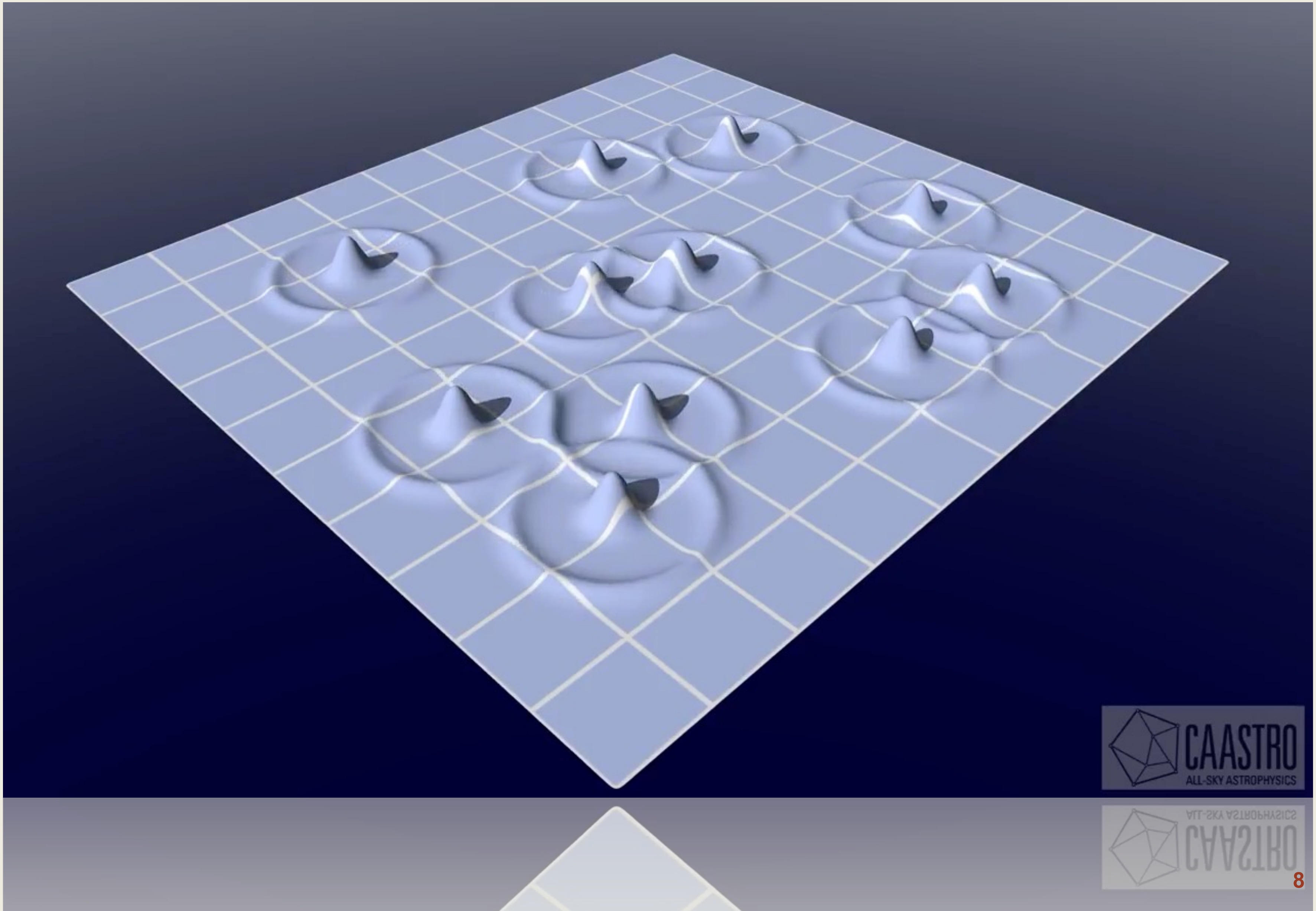
➢ Galaxies form in the overdense shells about 150 Mpc in radius.

➢ For all z, small excess of galaxies 150 Mpc (in comoving coordinates) away from other galaxies.

$\Rightarrow$ **Standard Ruler**

BAO method: we just assume that it is the same distance for all redshifts, **we don't need to know its value**!

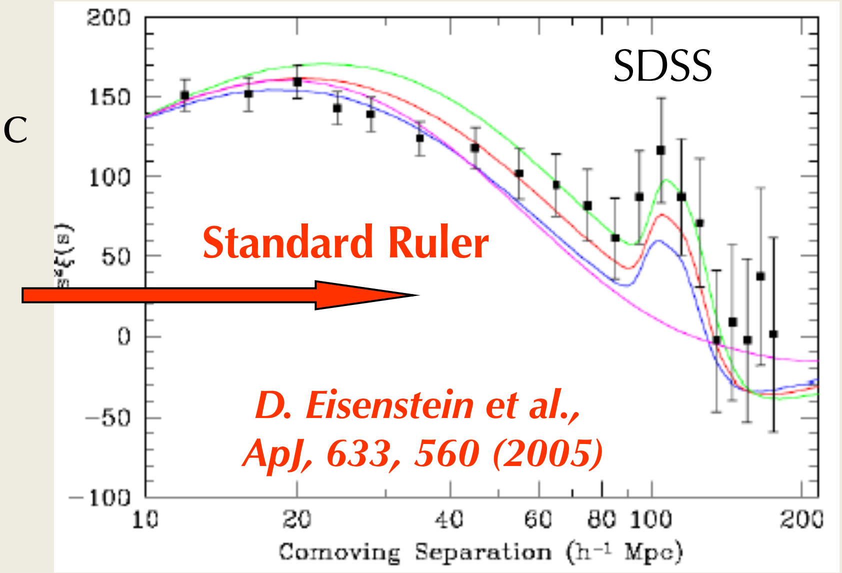
Baryonic Acoustic Oscillations

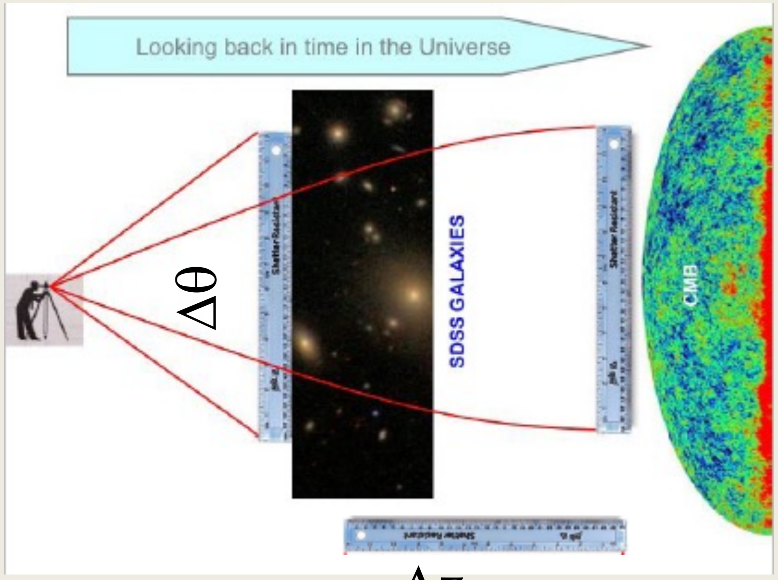


Observation of baryonic acoustic peak

First observation:

- In 2005: First observations of baryonic oscillations by 2 teams (2dFGRS and SDSS)
- SDSS observe a peak at ~150 Mpc
- SDSS: ~50 000 LRGs
  "Luminous Red Galaxies"
  <z> ~ 0.35





$$H(z) \equiv H_0\sqrt{\Omega_m\,(1+z)^3 + (1-\Omega_m\,)}$$

A 3D measurements

- **Radial direction** (along the line of sight):

$\Delta z = r_d \cdot H(z)/c$

$\Rightarrow$ Sensitive to Hubble parameter H(z).

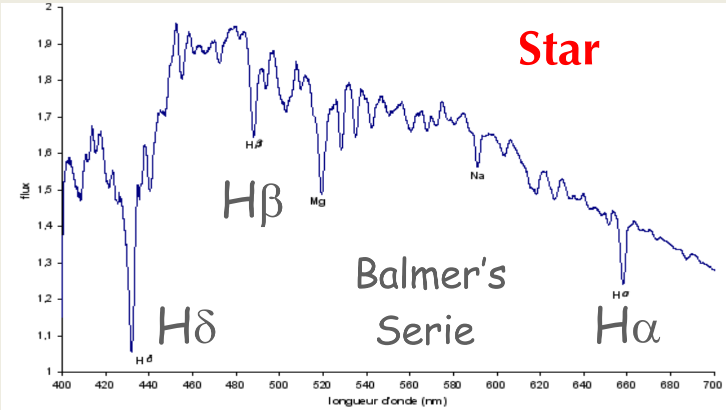
- **Transverse direction:**

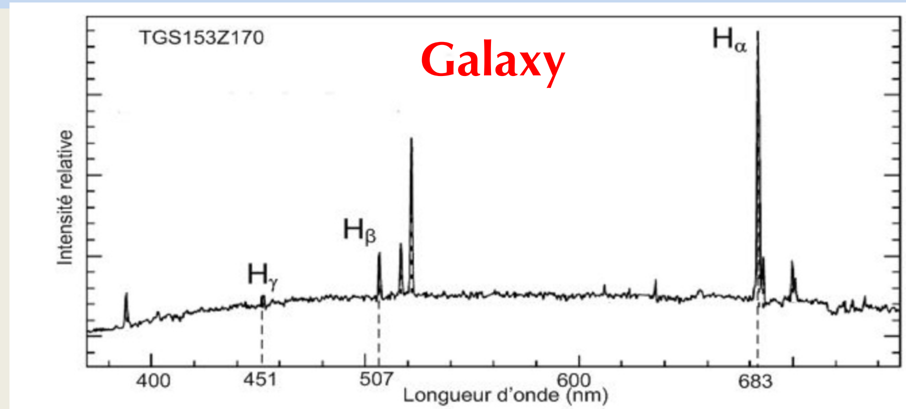
$\Delta\theta = r_d/(1+z)/D_A(z) = r_d/D_M(z)$

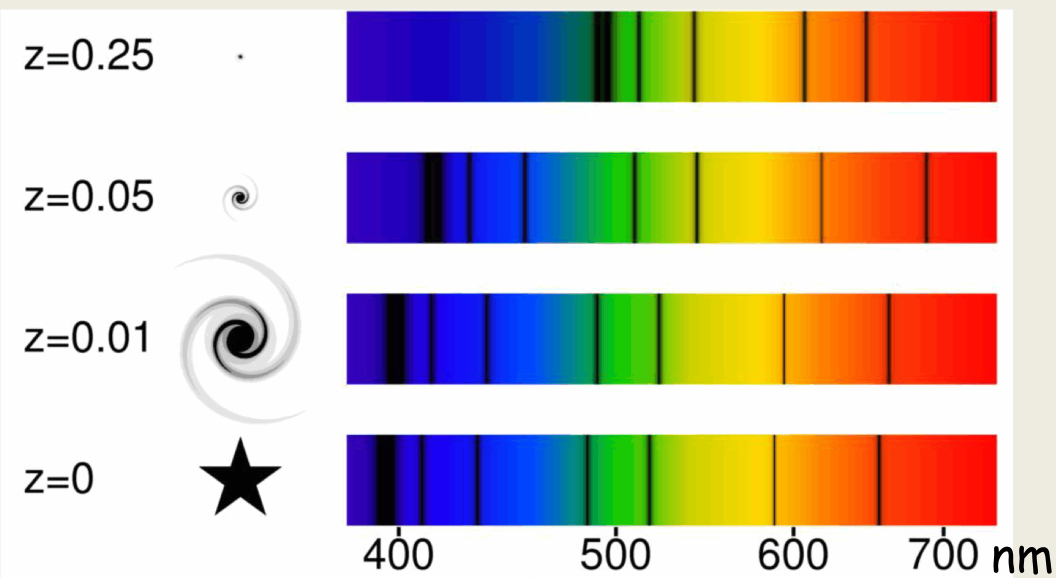
$\Rightarrow$ Sensitive to angular distance $D_A(z)$

$\Rightarrow \sim \int 1/H(z)$

How do we measure redshift?







Stars spectra

- Absorption lines

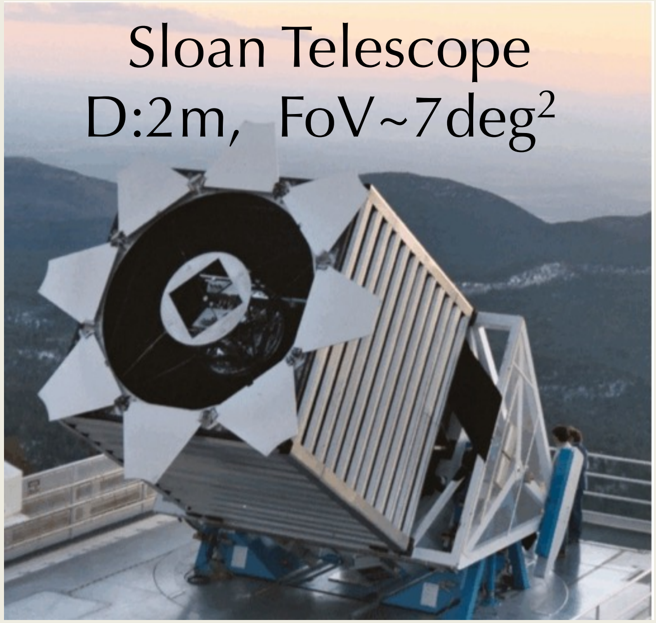
Galaxies

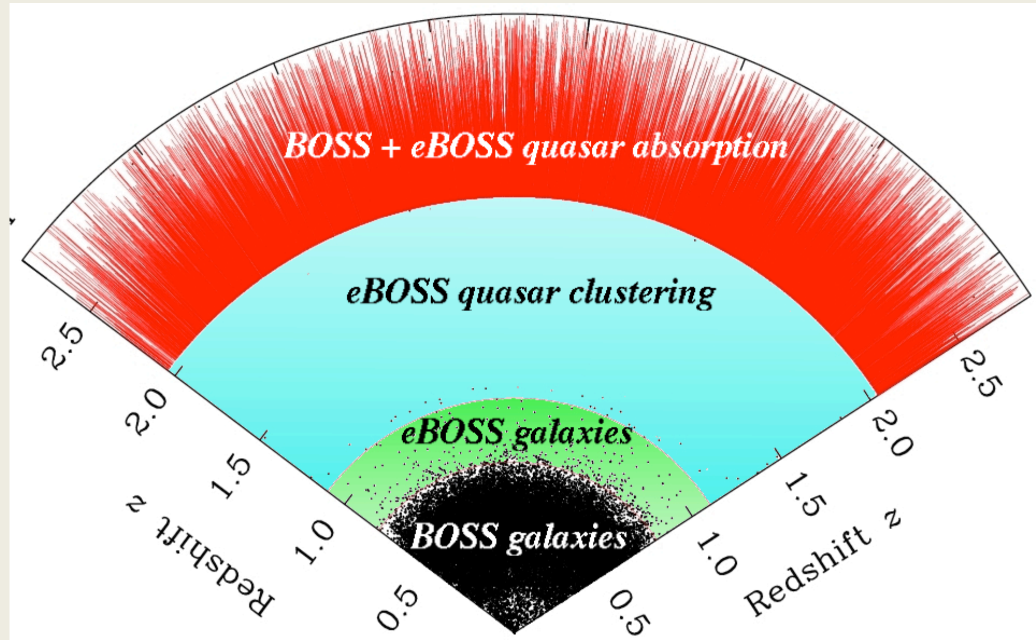
- Emission lines
- Balmer/Lyman breaks

Redshift

- Doppler effect
- $V/c=(\lambda-\lambda_0)/\lambda_0=z$

SDSS: 2009-2019





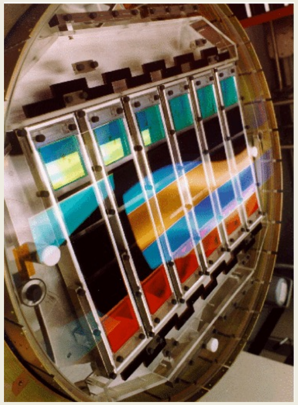
BOSS (2009→2014)

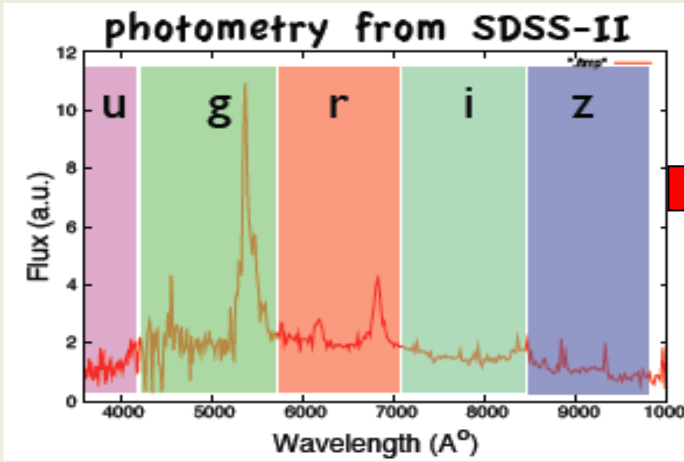
- ➢ 1.2 millions of Luminous Red Galaxies (LRG)
  - $0.15<z<0.7$
- ➢ 170 000 quasars
  - $z>2.1$, HI absorption)

eBOSS (2014→2019)

- ➢ Redshift of LRG extended to 0.8
- ➢ Emission Line Galaxies (ELG): star forming galaxies, $z\sim0.85$
- ➢ Quasars direct tracers
  - $0.9<z<2.2$

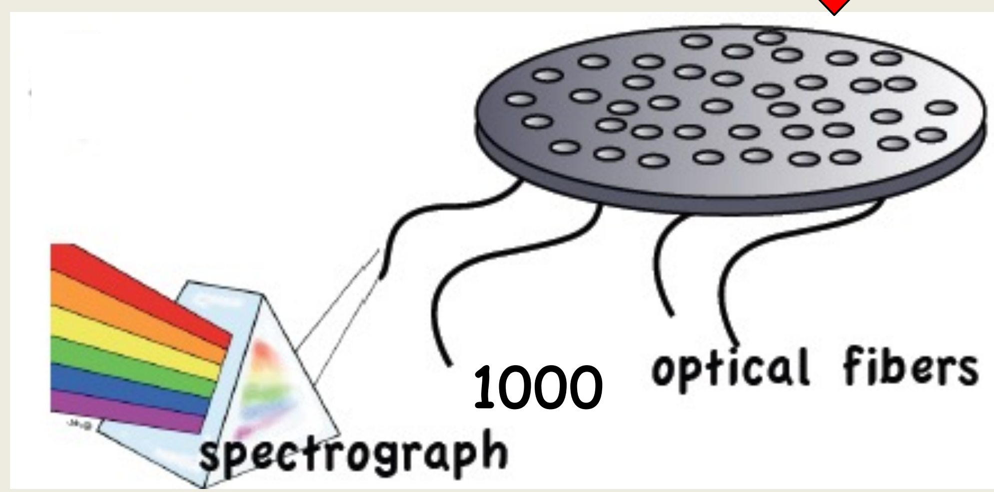
SDSS Observation Strategy



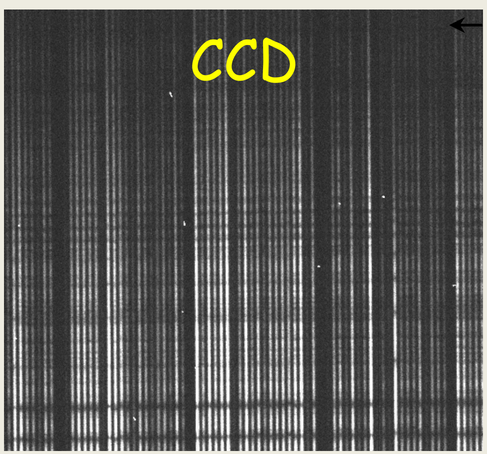


List of targets

SDSS J112253.51+005329.8
SDSSp J120441.73-002149.6
SDSSp J130348.94+002010.4
SDSSp J141205.78-010152.6
SDSSp J141315.36+000032.1
....

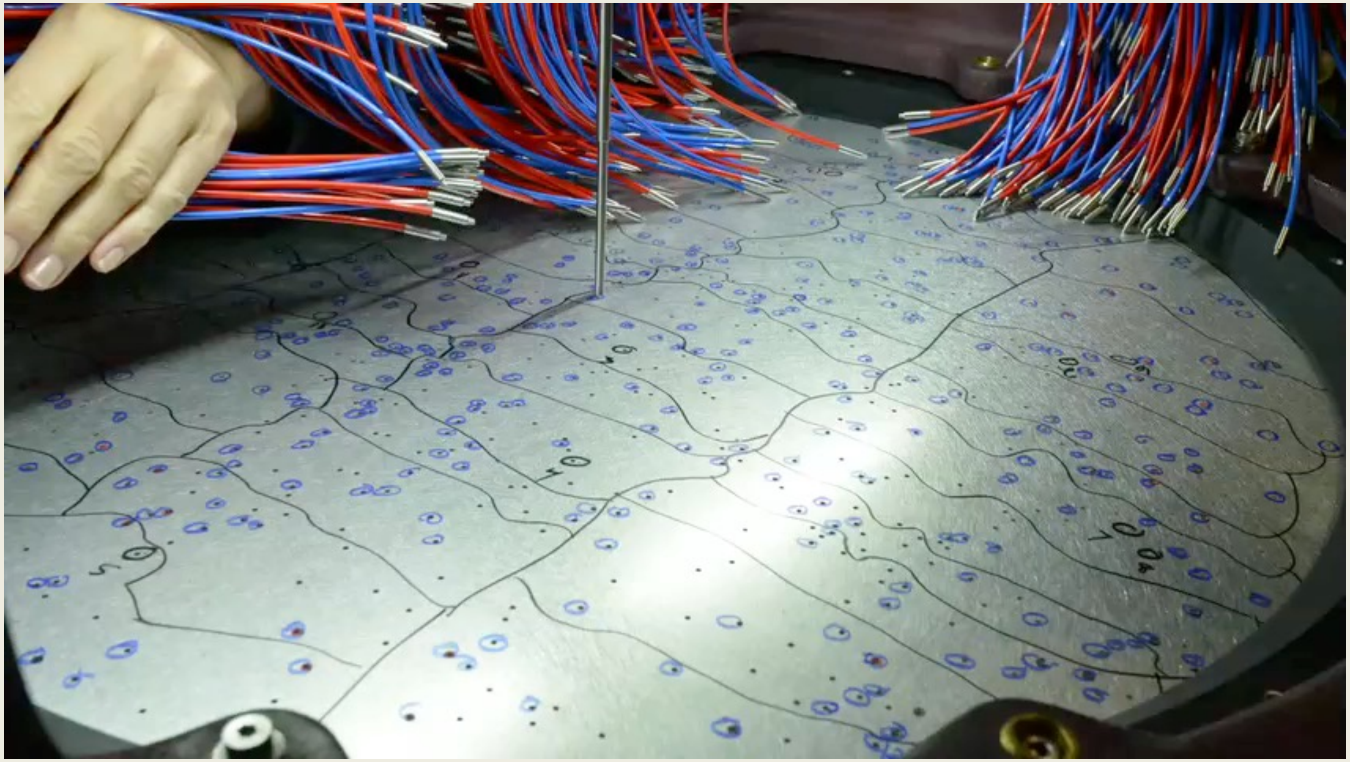


λ



Fiber number

Plug and Observe



Several steps (~3 months)

- Target selection
- Drill plates (1000 holes per plate)
- Plug plates on cartridges during day
- Observation of 5-9 cartridges per night.

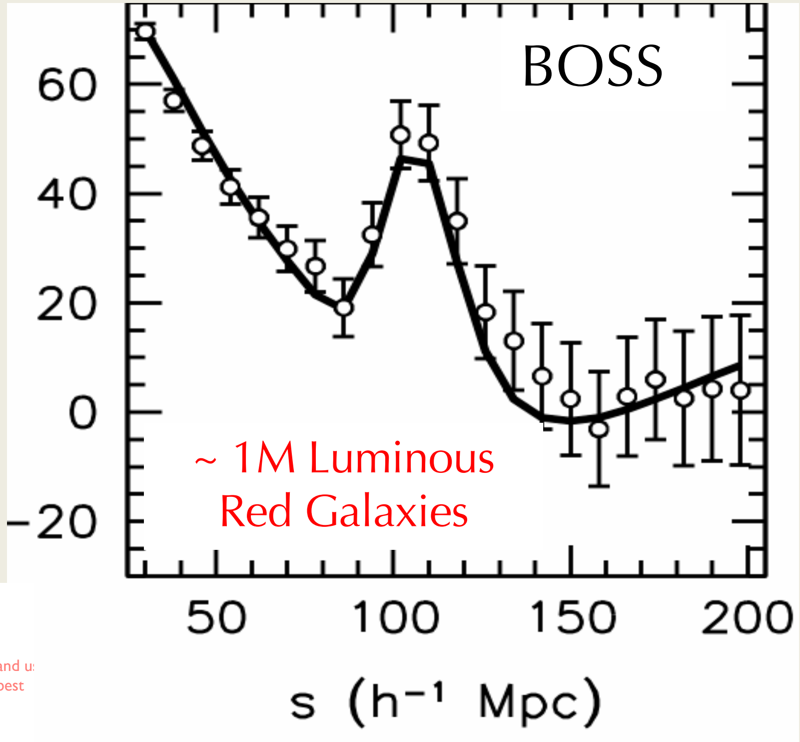
BAO with galaxies and quasars

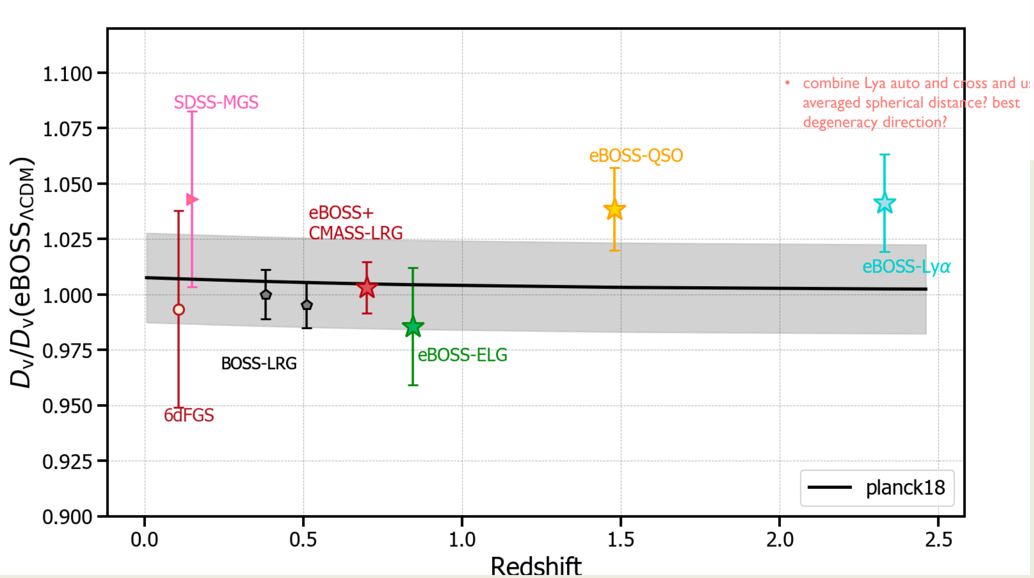
Confirmation with BOSS in 2012

- ➢ Redshift range 0.15<z<0.7
- ➢ BOSS-only 8-σ observation of BAO

Even better with eBOSS in 2O20

- ➢ Redshift range 0.15<z<2.5





Agreement with Planck

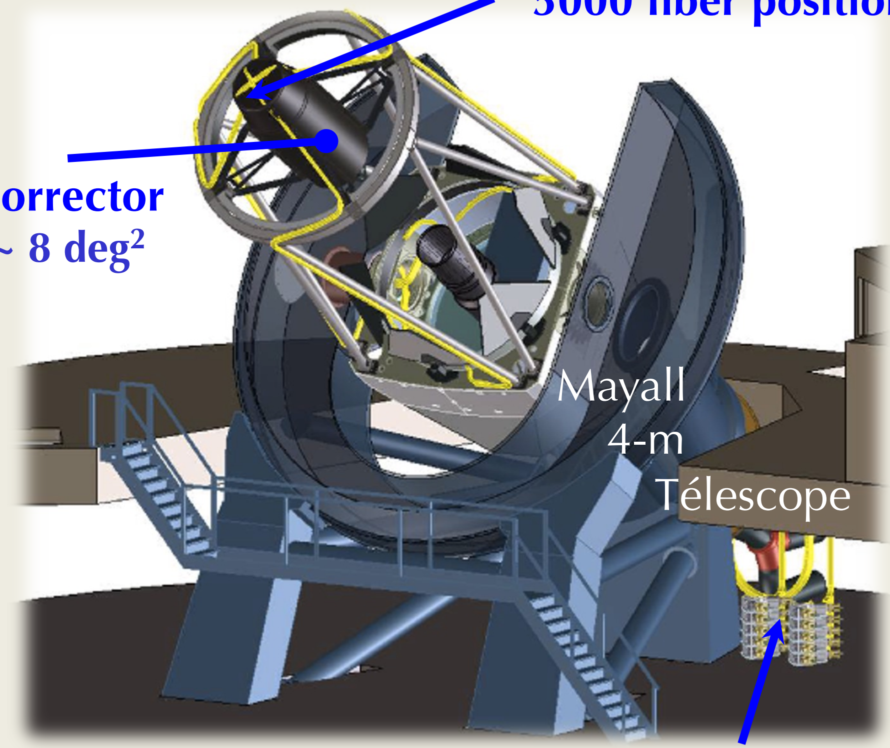
- ➢BAO scales consistent with Planck
- ➢Consistency of cosmological measurements

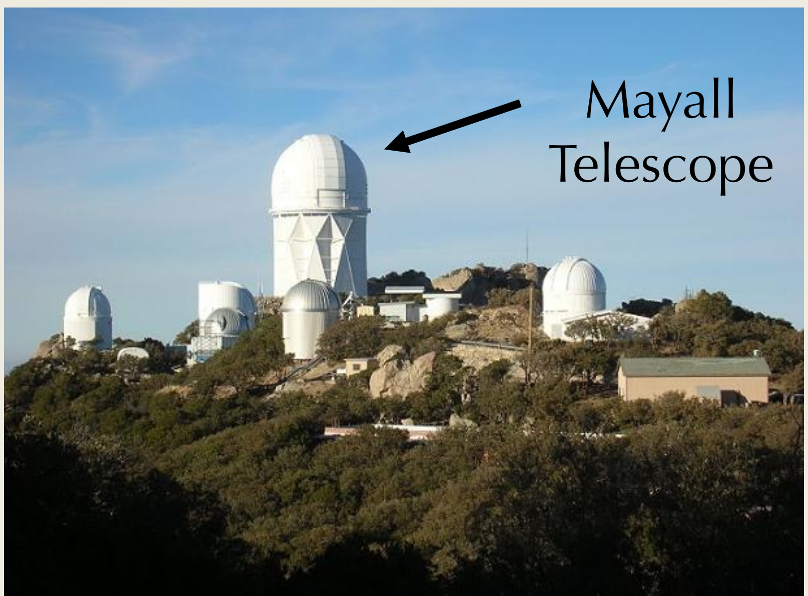
Dark Energy Spectroscopic Instrument

DESI

DESI Project

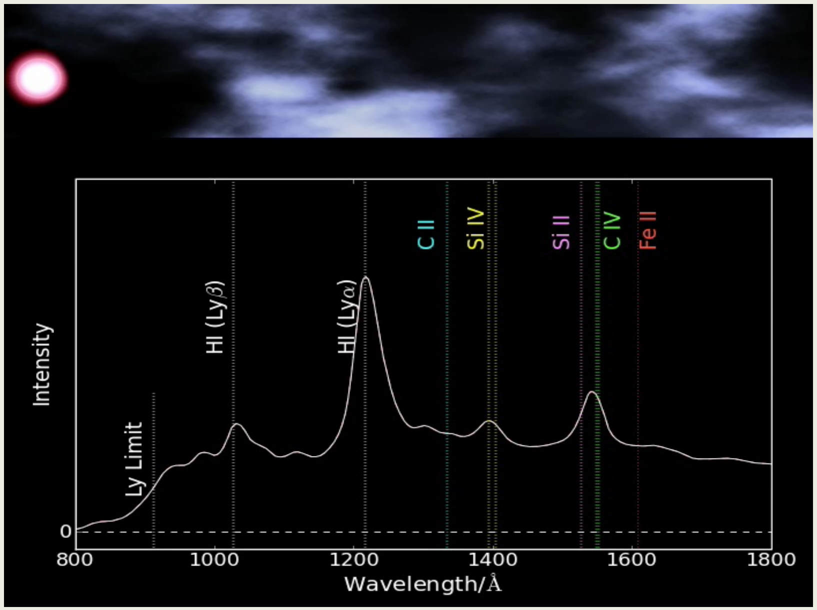
- **Scientific project**
  - 14000 deg^2 3D survey for $0<z<4$
  - International collaboration
  - 72 institutions (46 non-US)
  - 900 members





- **Instrument**
  - 4-m telescope at Kitt Peak (Arizona)
  - Wide FoV (~ 8 deg^2)
  - Robotic positioner with 5000 fibers
  - 10 spectrographs x 3 bands (blue, visible, red-NIR) → 360-1020 nm

BAO with Ly-α forests

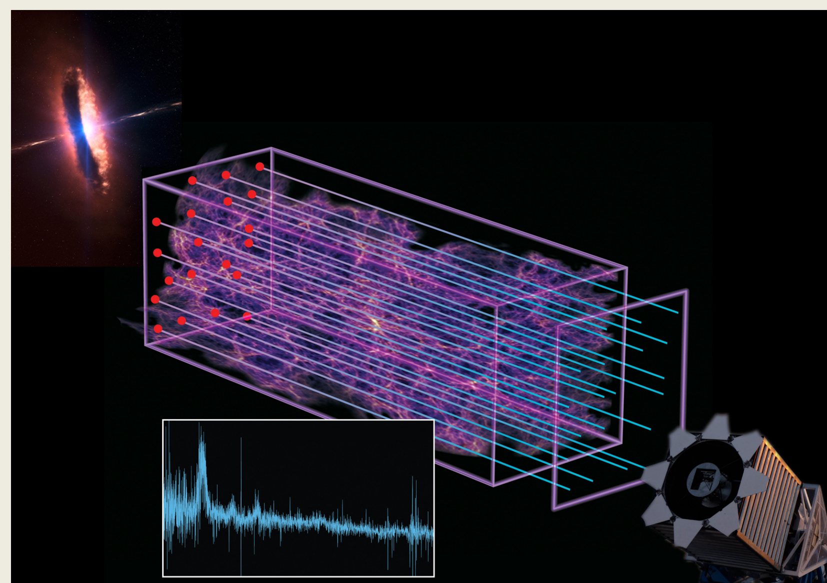


Principles

- Use Ly-α forests of quasars (2.2<z<4)
- HI absorption in IGM along the line of sight of QSOs
- We expect low density gas (IGM) to follow the dark matter density

Tomography with Ly-α

- 3D map of HI absorption
- Detect overdensity and voids



DESI tracers of the Matter

Five target classes

~40 million redshifts

in 5 years

3 million QSOs

Ly-a $z > 2.1$

Tracers $0.9 < z < 2.1$

16 million ELGs

$0.6 < z < 1.6$

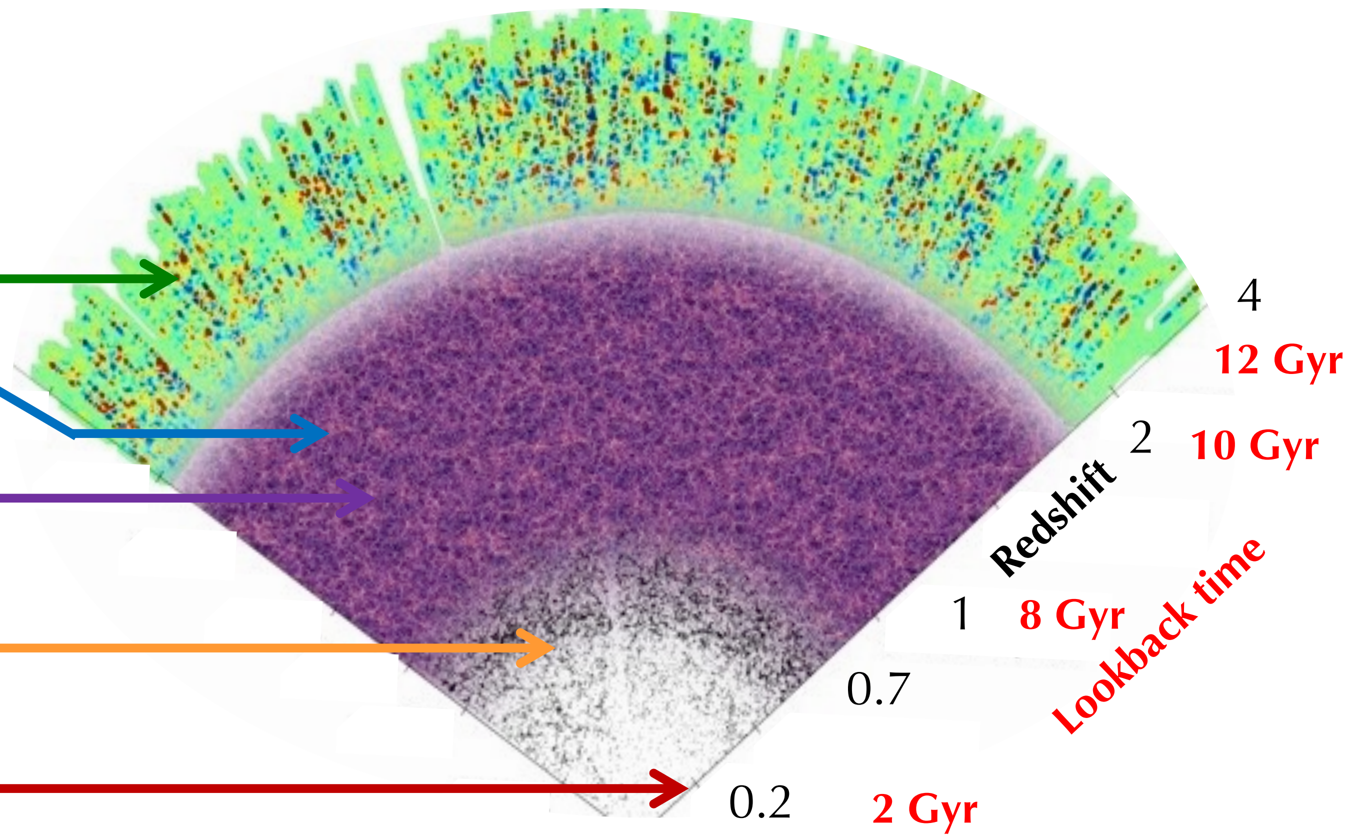
8 million LRGs

$0.4 < z < 1.0$

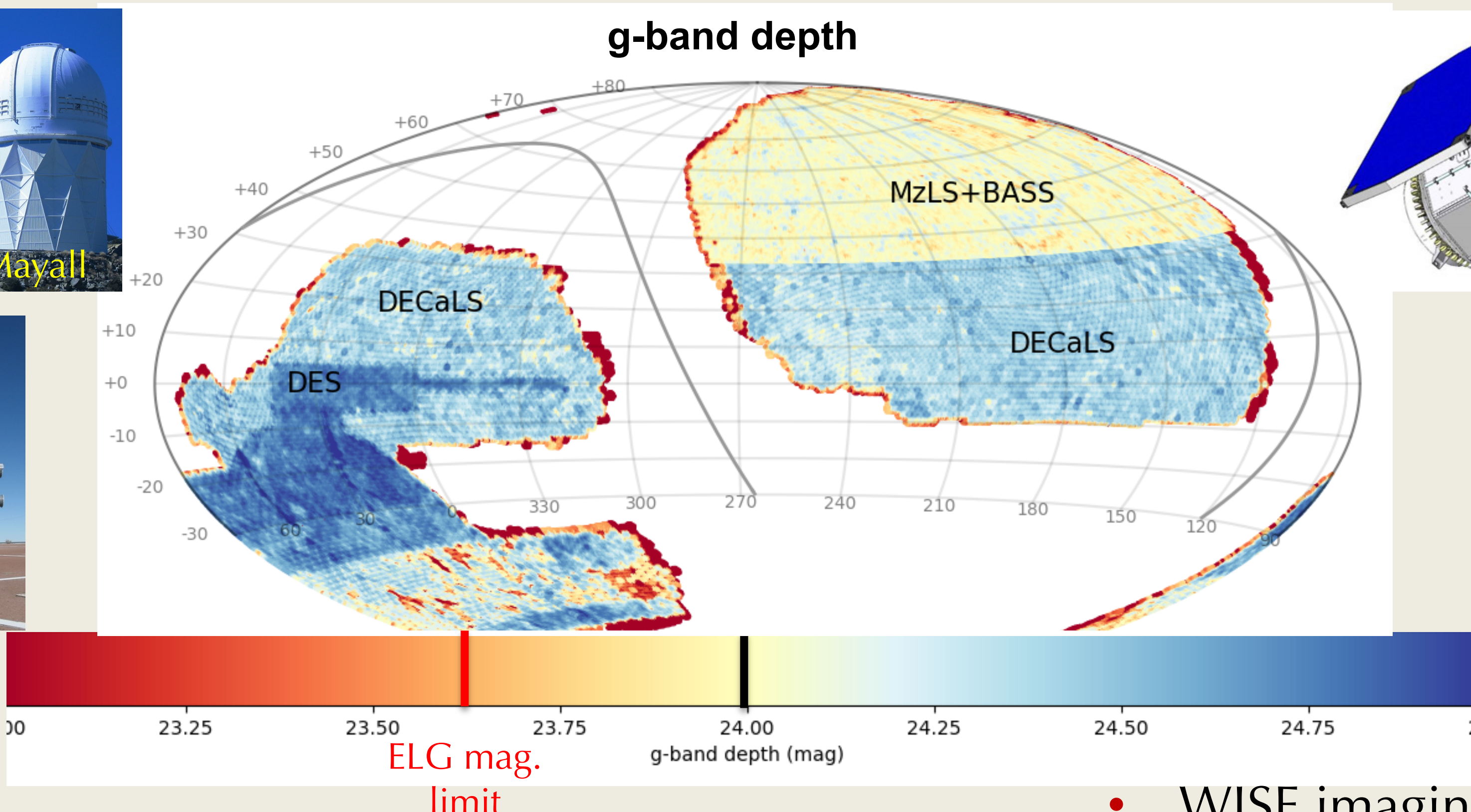
13.5 million

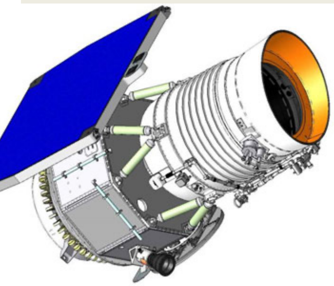
Brightest galaxies

$0.0 < z < 0.4$



Imaging for Target Selection

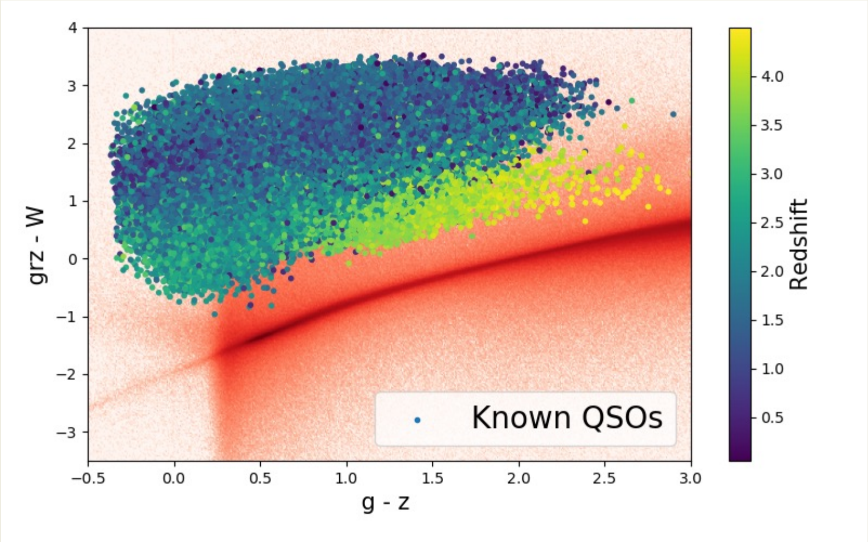


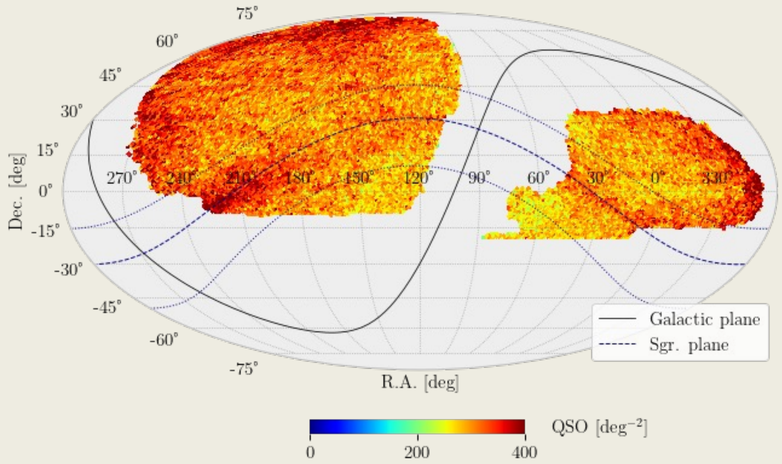


WISE

- Optical bands with
  - g=24.0, r=23.4, z=22.5
  - DECAM deeper in g,r,z
- Footprint
  - 14,000 deg^2 required
  - 16,000 deg^2 available for d>-30^0
- WISE imaging
  - Two bands W1,W2
  - 6 years with all-sky coverage
  - Used for LRG/QSO

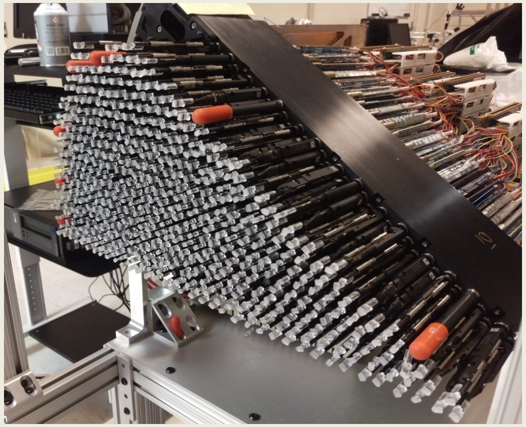
Target Selection of QSOs





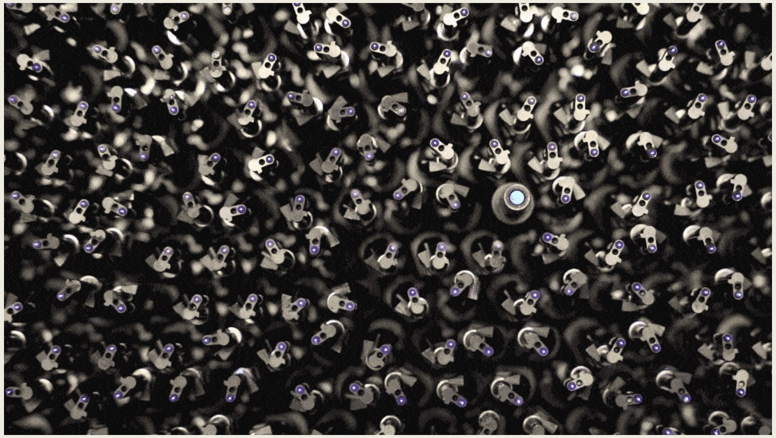
- **Principles**
  - Point source morphology (PSF)
  - grz optical bands and W_1W_2 NIR bands
  - Use NIR excess for quasars
  - Initial Mag. Limit: r<22.7
- **Selection based on Machine learning**
  - Two approaches:
    - Color cut selection
    - Machine learning with Random Forest

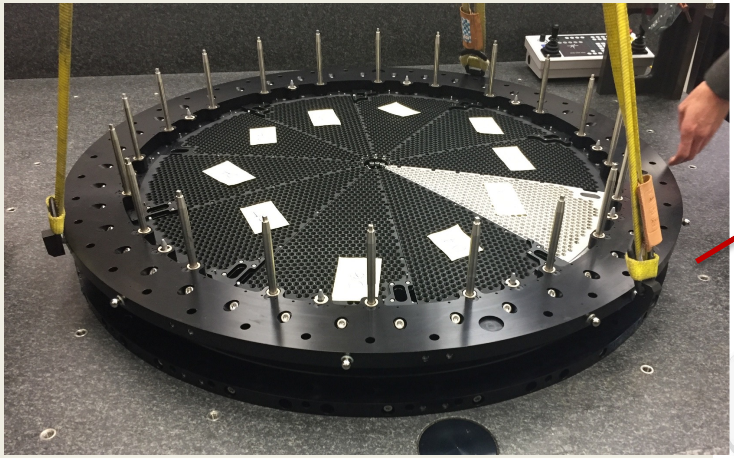
5000 robotic fiber positioners

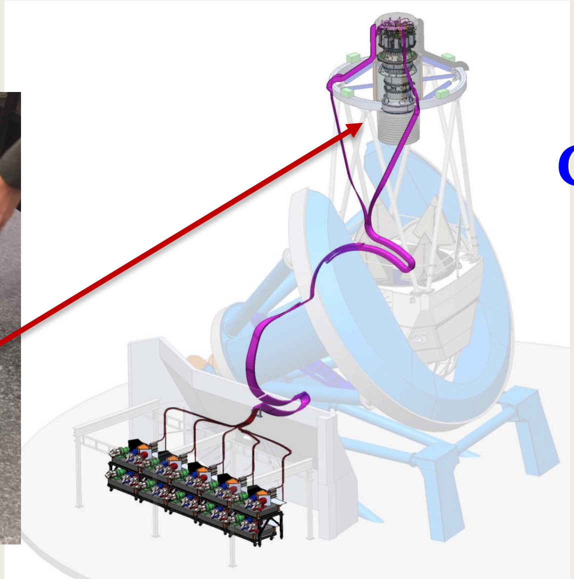


Configuration

- 10 petals in focal plane
- 500 fibers each petal
- 5000 total
- 10.4 mm pitch
- 2 motors per positioner







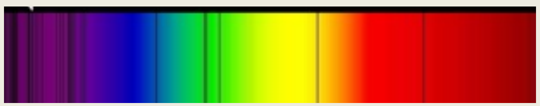
Challenge

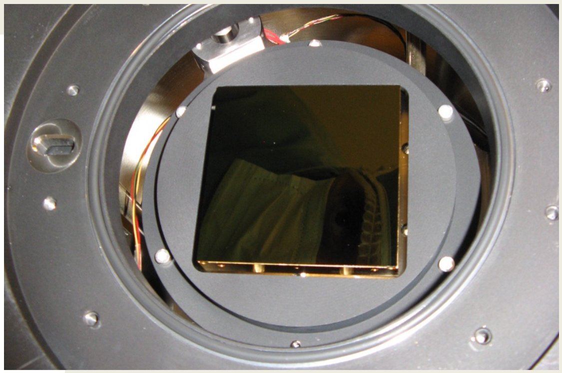
– Reposition the 5000 fibers in less than 2mns
– Position of each fiber better than 15 mm

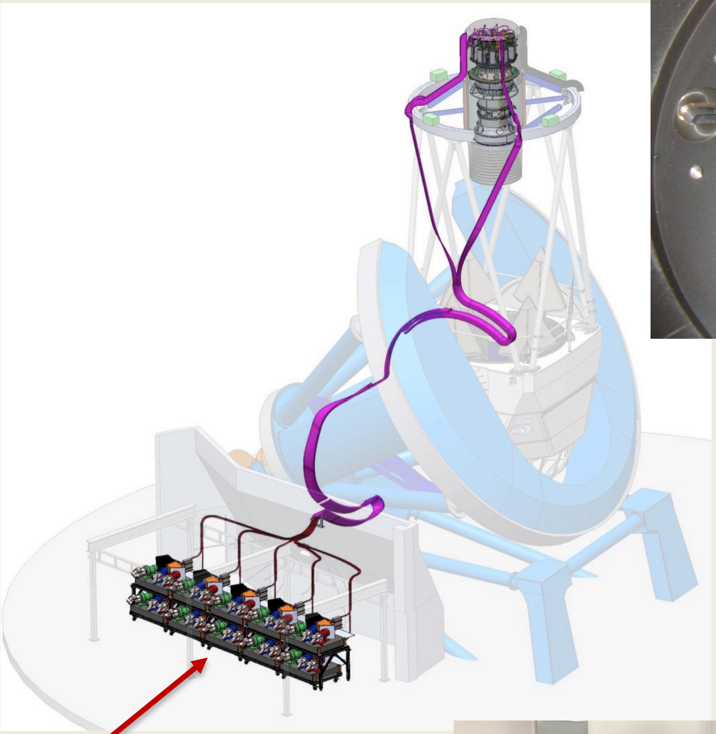
Ten spectrographs

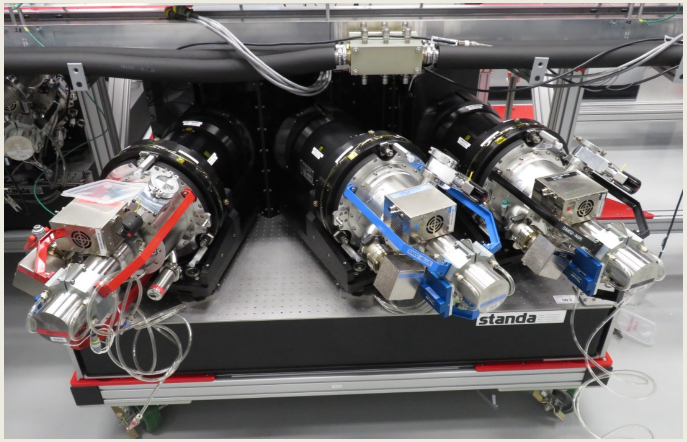
Ten 3-channel spectrographs

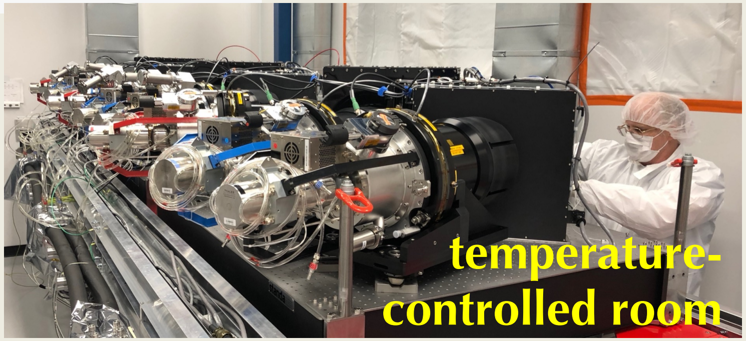
l = 360 nm to 980 nm





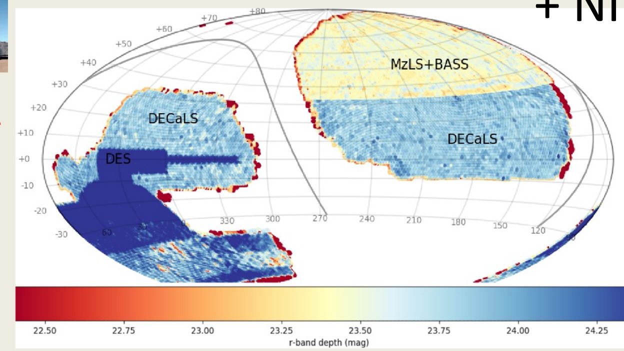


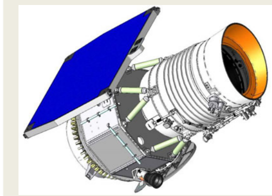




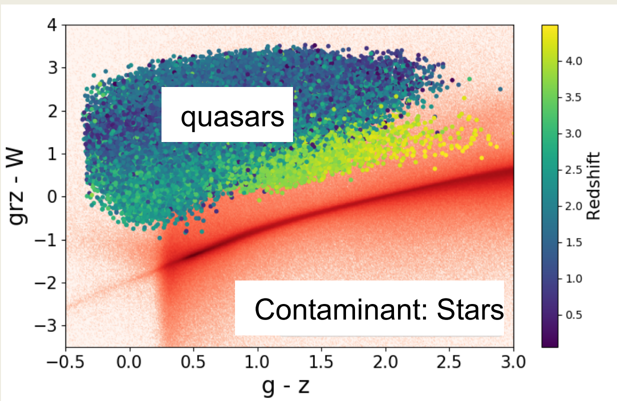
Rolling observations- Redshift factory

Imaging Surveys: optical grz bands
+ NIR with WISE

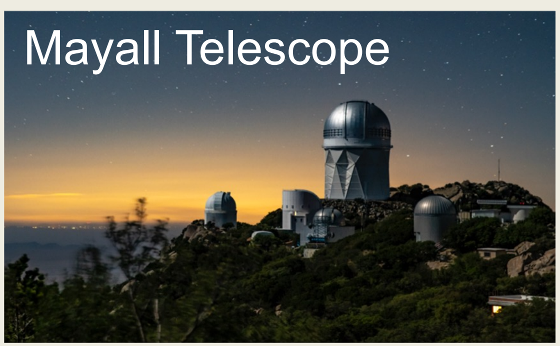




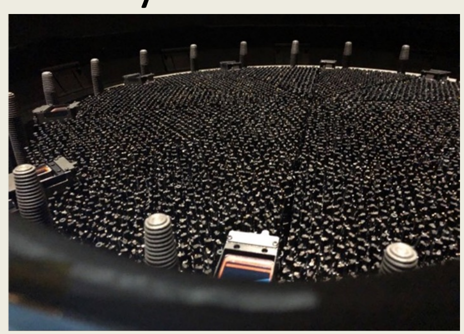
Target Selection



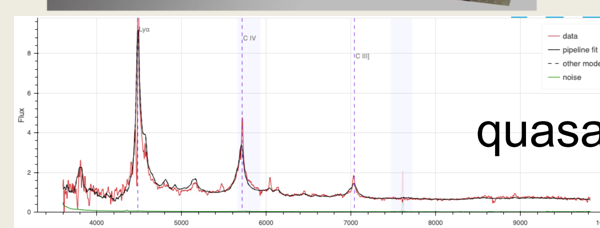
Observation...



...of 5000 objects
every ~20mins...



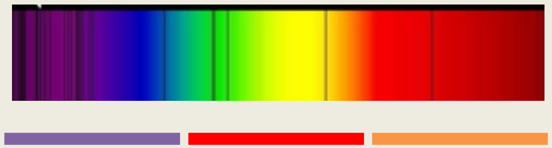
...and measure their redshift



Ten spectrographs

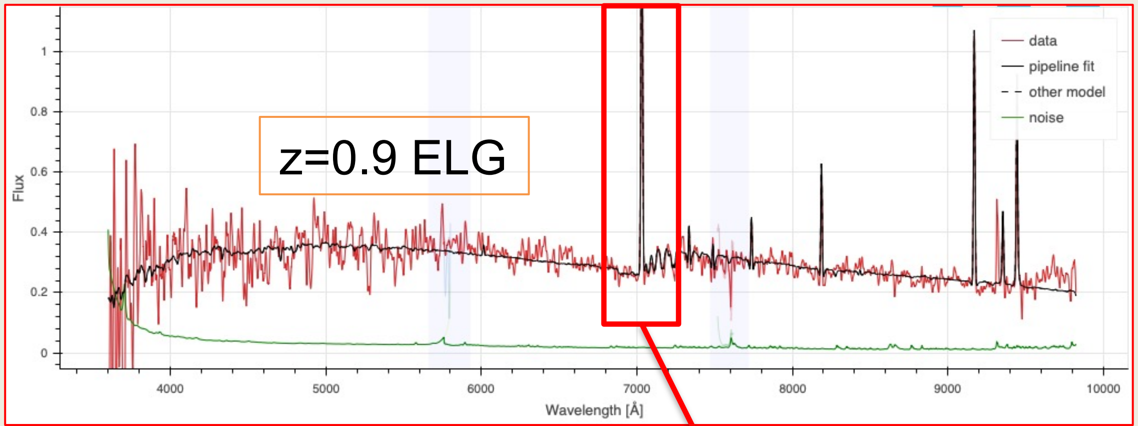
Ten 3-channel spectrographs

λ = 360 nm to 980 nm

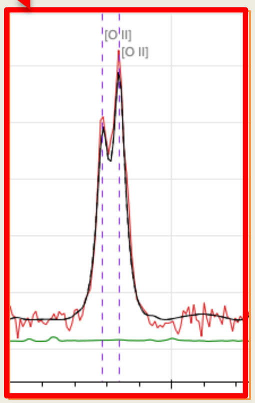


$$z = \frac{\lambda - \lambda_0}{\lambda_0}$$

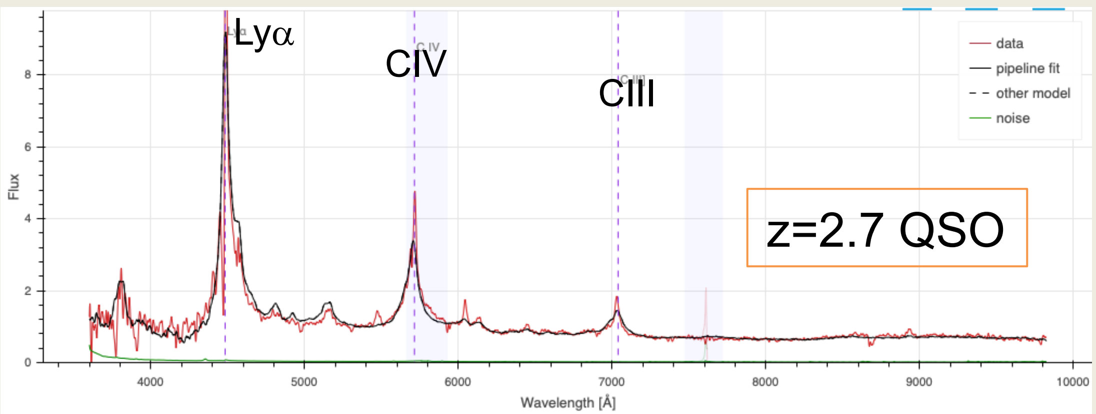
[OII] 373 nm
up to z = 1.6



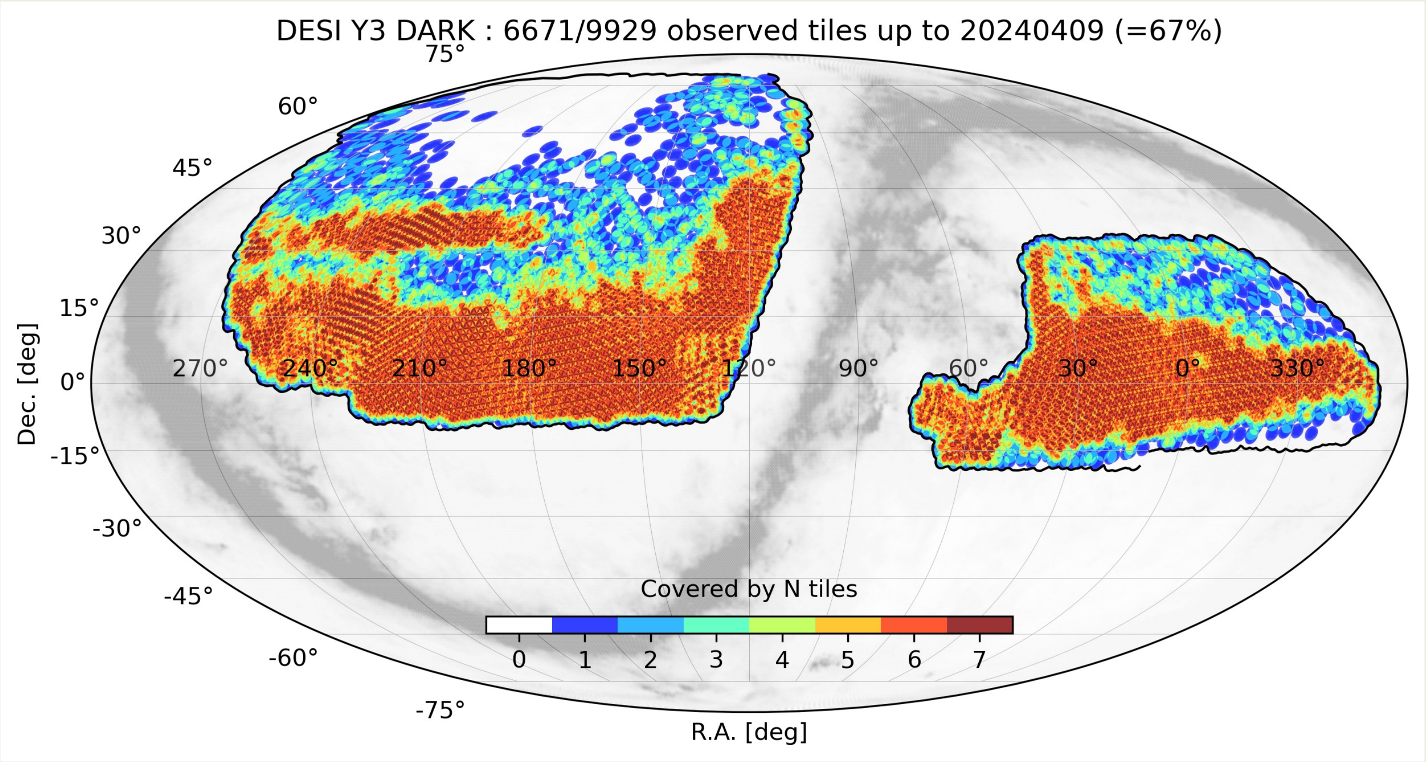
[OII] doublet



Ly-α 121.6 nm
down to z = 2.0

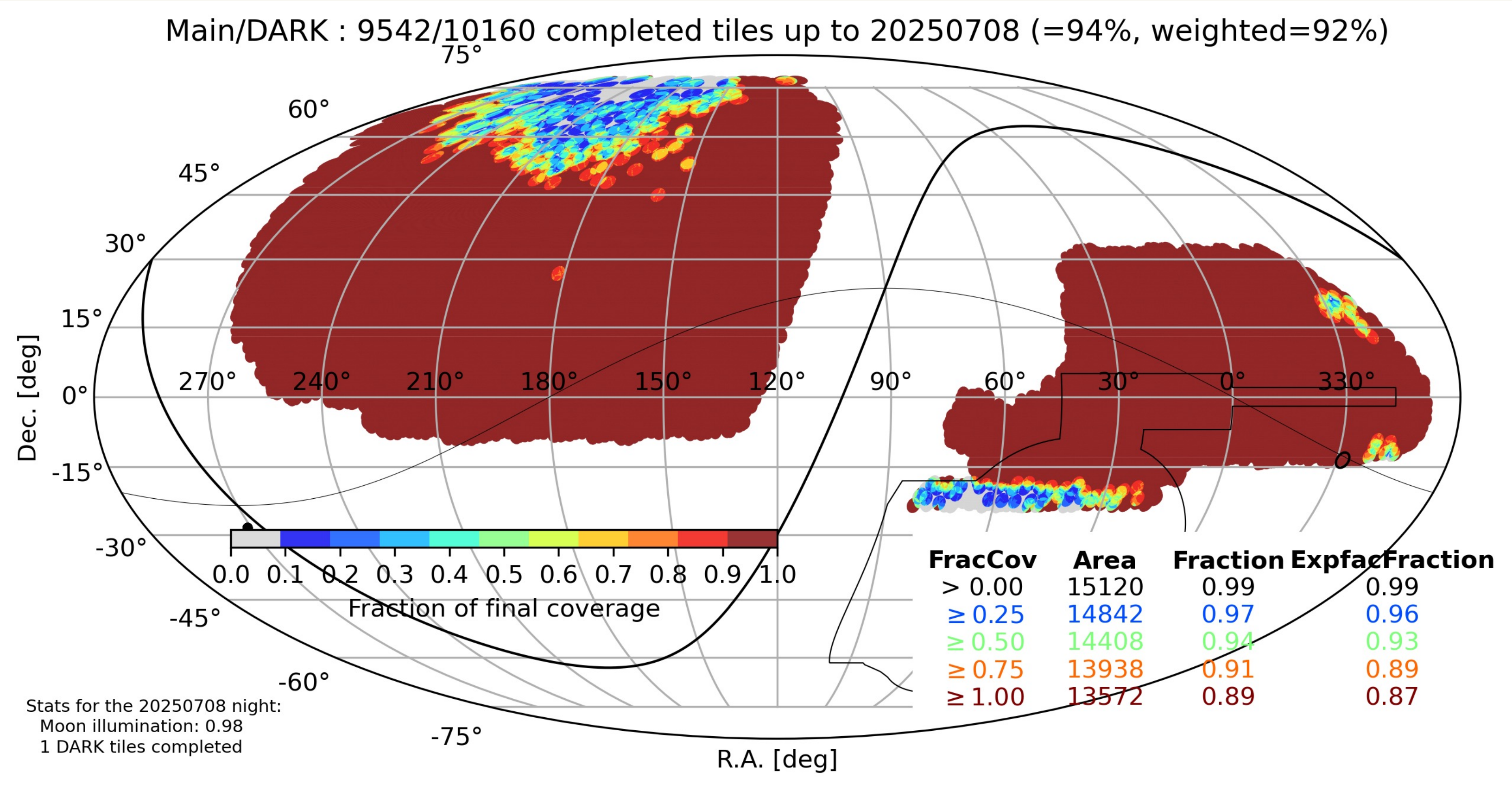


DESI DR2 footprint



- DESI footprint over 5 years ~14000 deg^2 (1/3 of sky)
- DR2 ~70% of final footprint
- Increase of V_{eff} by a 2.3 factor from DR1 (2024) to DR2 (2025)
- 14.3M discrete tracers (galaxies and quasars), 800k Ly-α QSOs

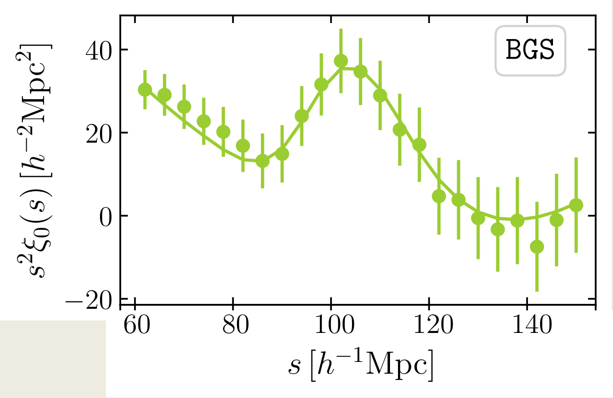
Observations: current status



- Now, ~95% of the final dataset (much more ELGs)
- New results (DR3) expected by the end of 2026
- Extension of the footprint till end of 2028

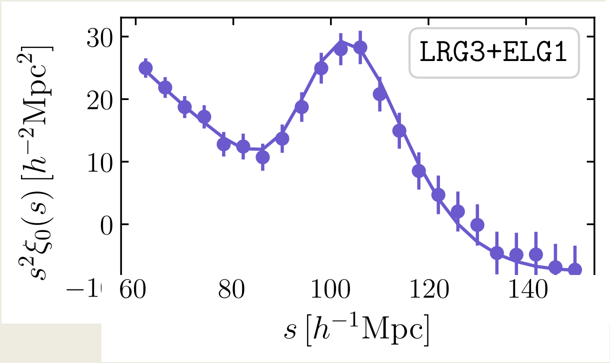
First results

BGS z=0.30



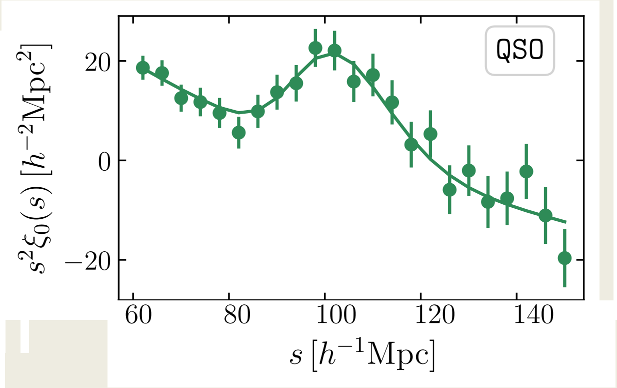
Precision: 0.93%

LRG3+ELG1 z=0.93



Significance: 14.7σ
Precision: 0.45%

QSO z=1.48

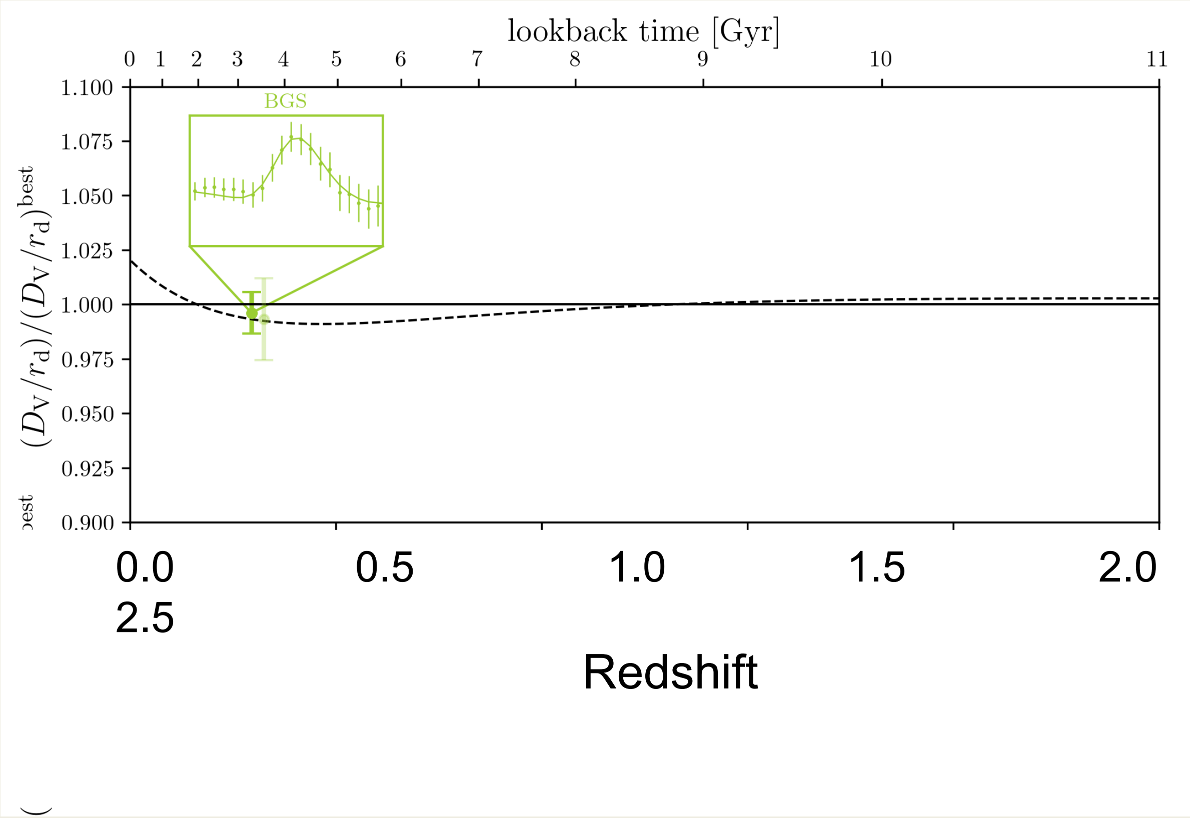


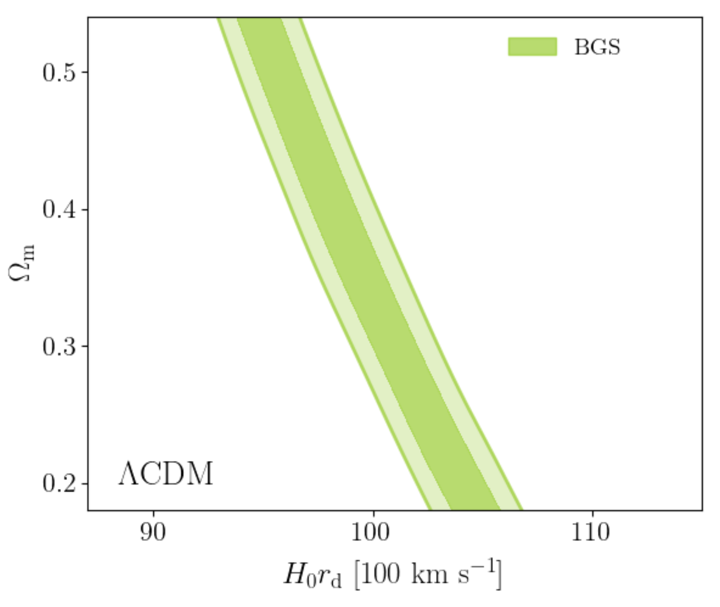
Significance: 5.6σ
Precision: 1.5%

- **Dilation compared to a fiducial cosmology**
  - Perpendicular or parallel to the line of sight, $\alpha_\perp$ and $\alpha_{||}$
  - Combined through $\alpha_{\mathrm{iso}} = (\alpha_\perp^2 \alpha_{||})^{1/3}$
- 6 bins in redshifts covering the redshift range, 0.1<z<2.1
- Bin with lowest significance 5.6σ

DR2: BGS

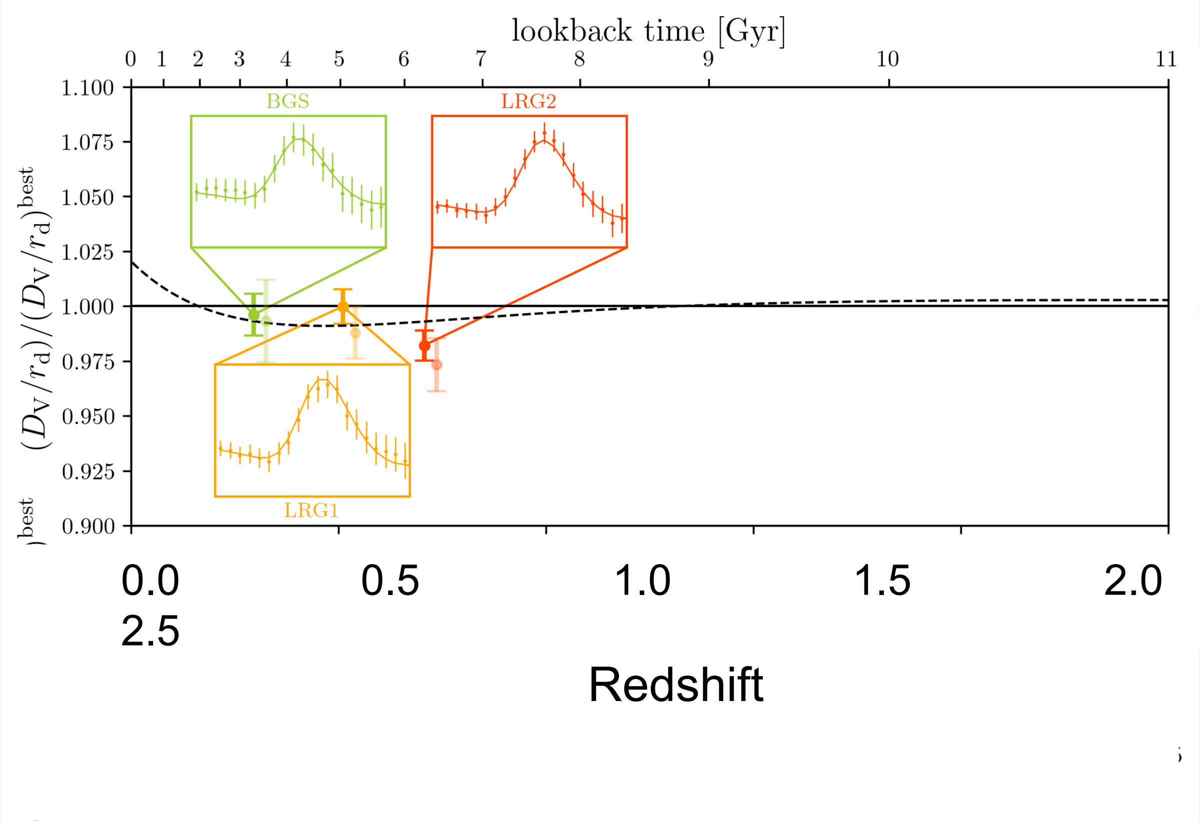
$\alpha_\perp = \frac{D_M}{r_d}\frac{r_d^{fid}}{D_M^{fid}}$ $\alpha_{||} = \frac{H^{fid} r_d^{fid}}{H r_d}$ $\alpha_{iso} = (\alpha_\perp^2 \alpha_{||})^{1/3}$ In ΛCDM, the α parameters depend on $H_0 r_d$ and Ω_m

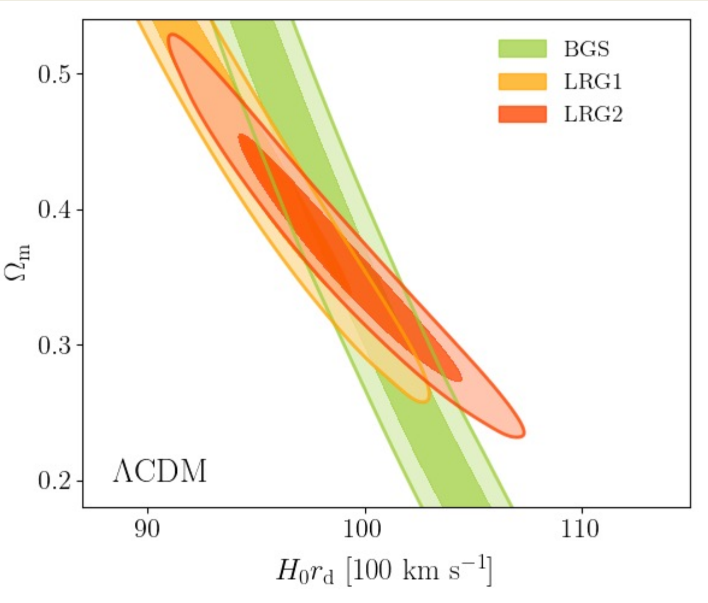




- Friedman equation for ΛCDM $H(z) \equiv H_0\sqrt{\Omega_m (1+z)^3 + (1-\Omega_m)}$
- Limitation due the cosmic variance (small part of the visible Universe)

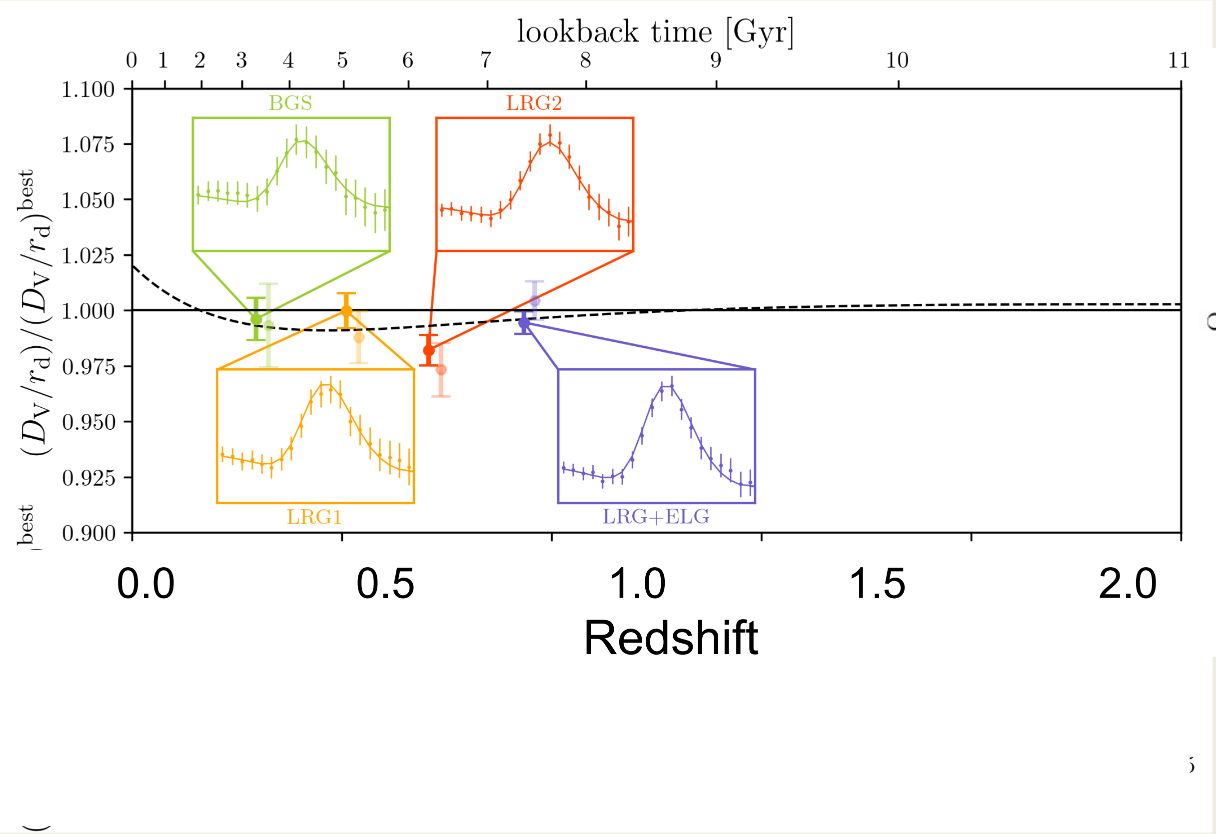
DR2: BGS +LRG

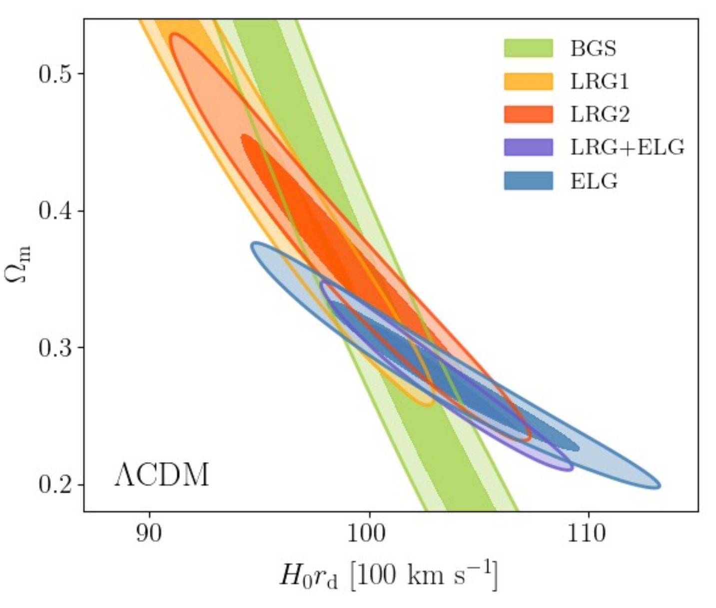




– LRG: Main tracer in SDSS, precise measurement in DESI

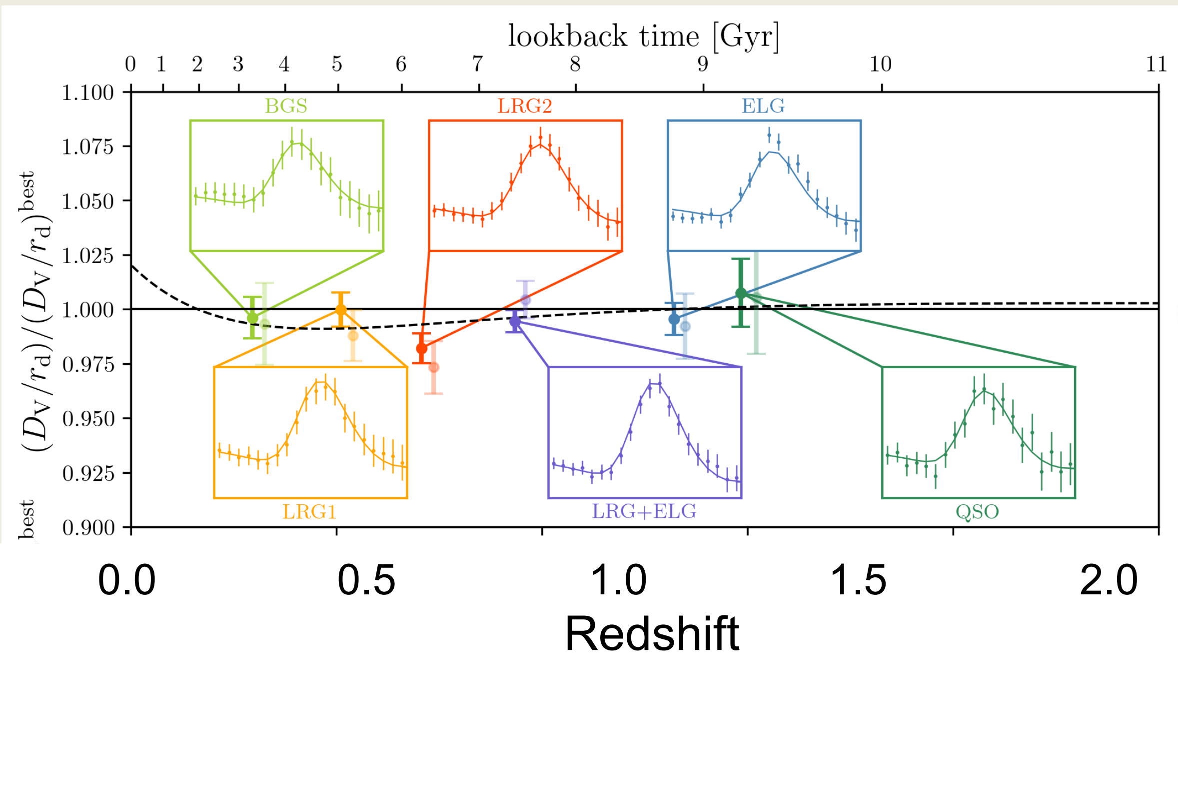
DR2: BGS +LRG+ELG

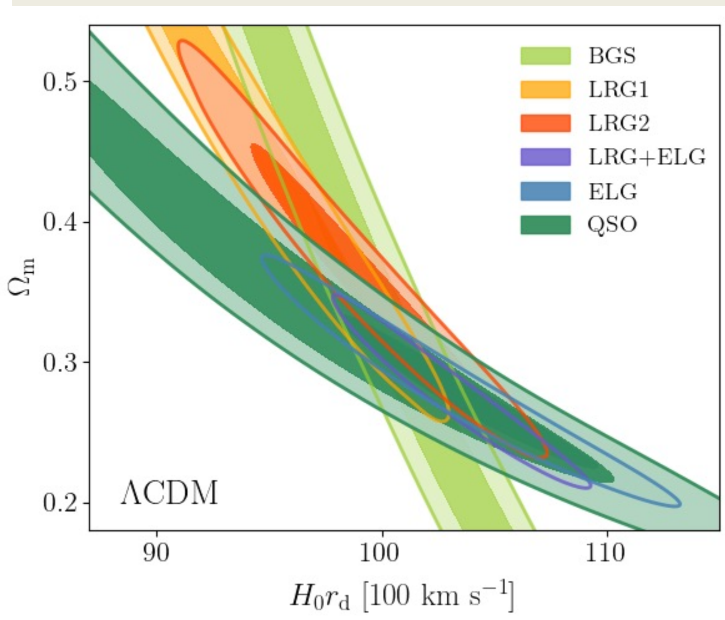




– ELG: Main tracer in DESI, precise measurement
– x 2.7 with DR2 compared to DR1

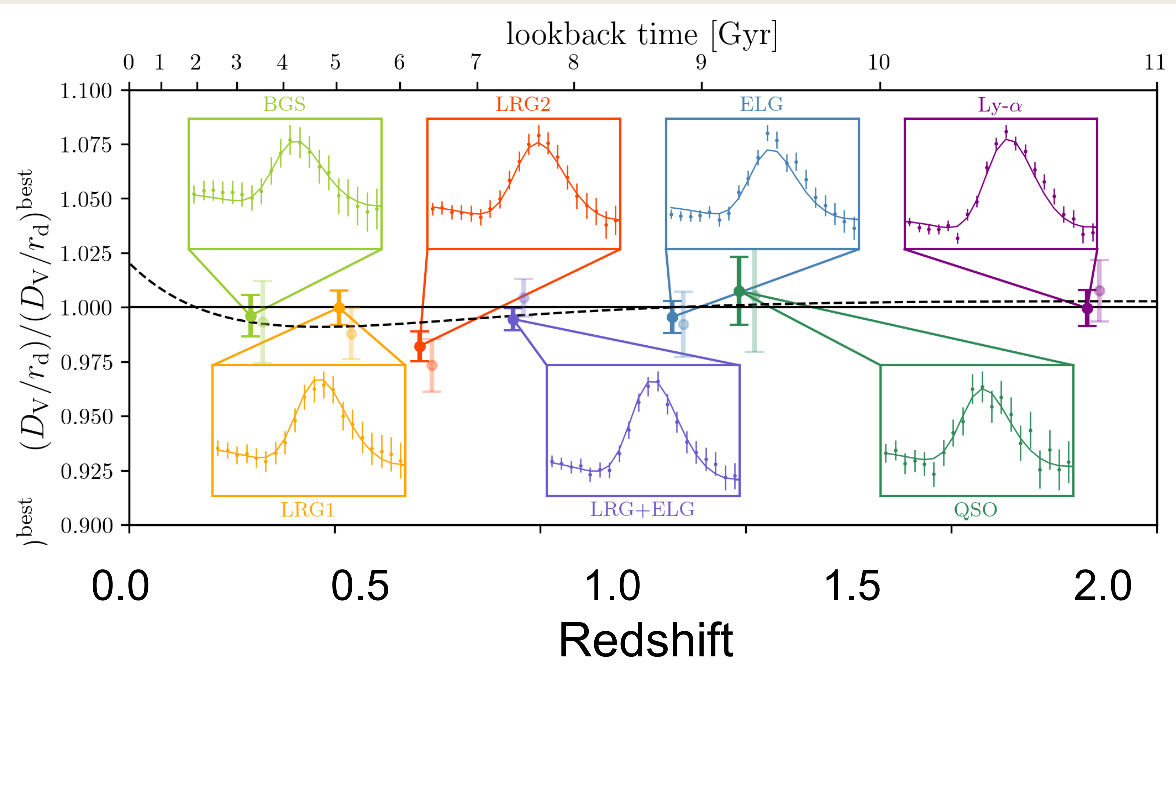
DR2: BGS +LRG+ELG+QSO

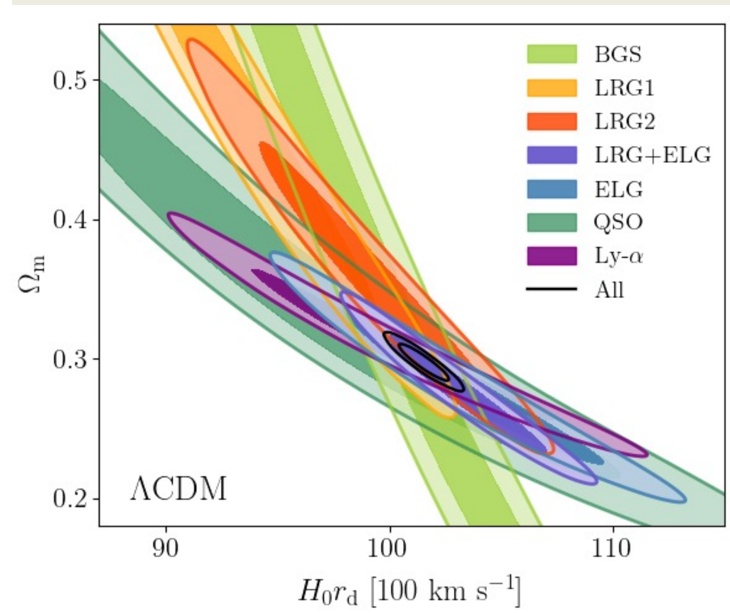




– QSO: huge volume but small density (shot noise limitation)

DR2: BGS +LRG+ELG+QSO+Lyα





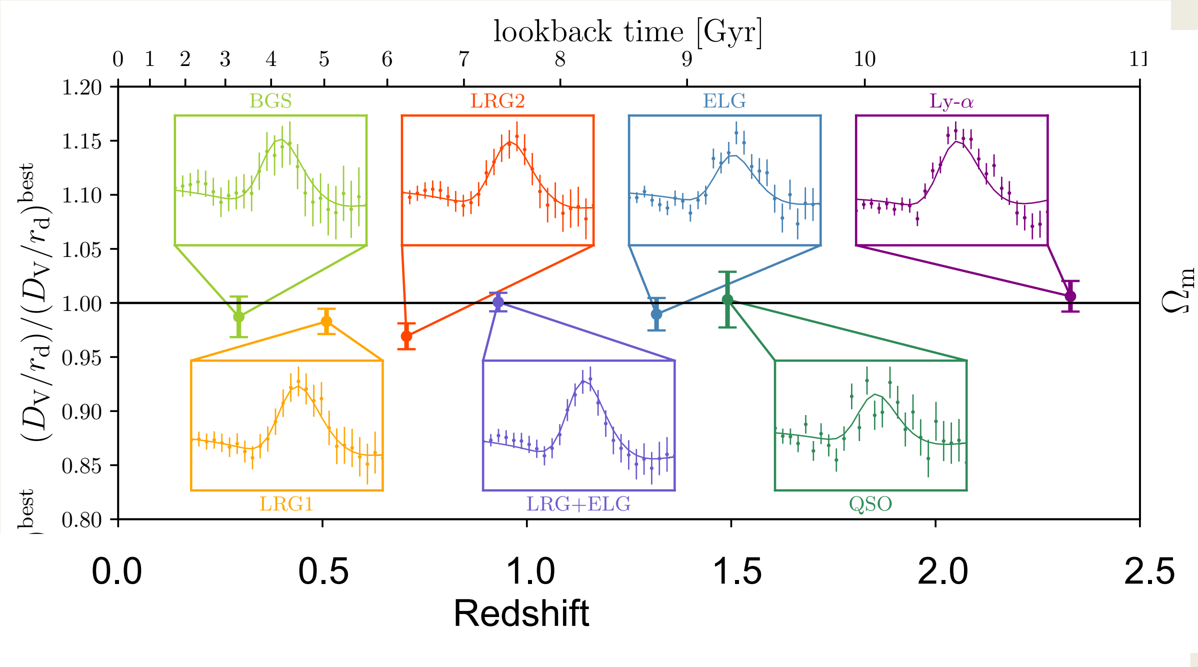
– Different dependence as a function of redshift (Ω_m,r_d)

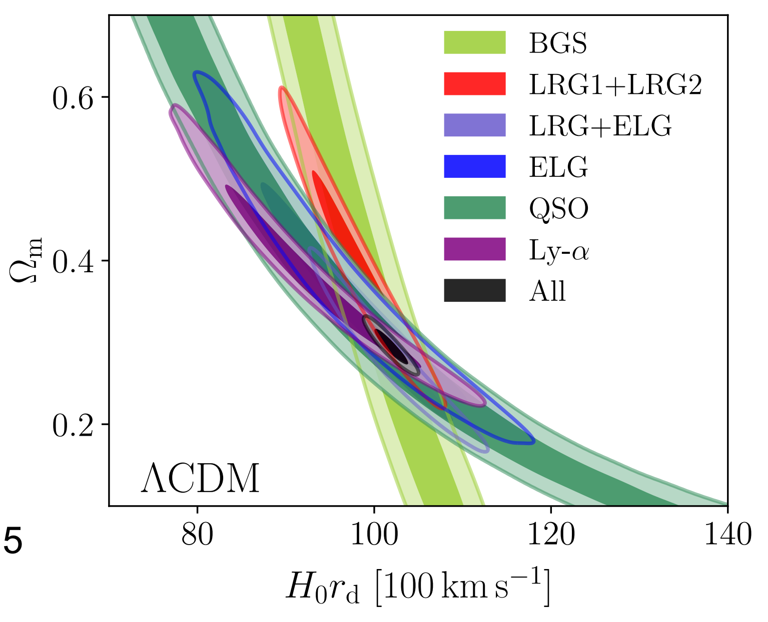
Dynamical (Time Evolving) Dark Energy

Measurement of Ω_m

$$\alpha_\perp = \frac{D_M}{r_d}\frac{r_d^{fid}}{D_M^{fid}} \qquad \alpha_{||} = \frac{H^{fid} r_d^{fid}}{H r_d} \qquad \alpha_{iso} = (\alpha_\perp^2 \alpha_{||})^{1/3}$$

In ΛCDM, the α parameters depend on $\mathbf{H_0 r_d}$ and $\mathbf{\Omega_m}$

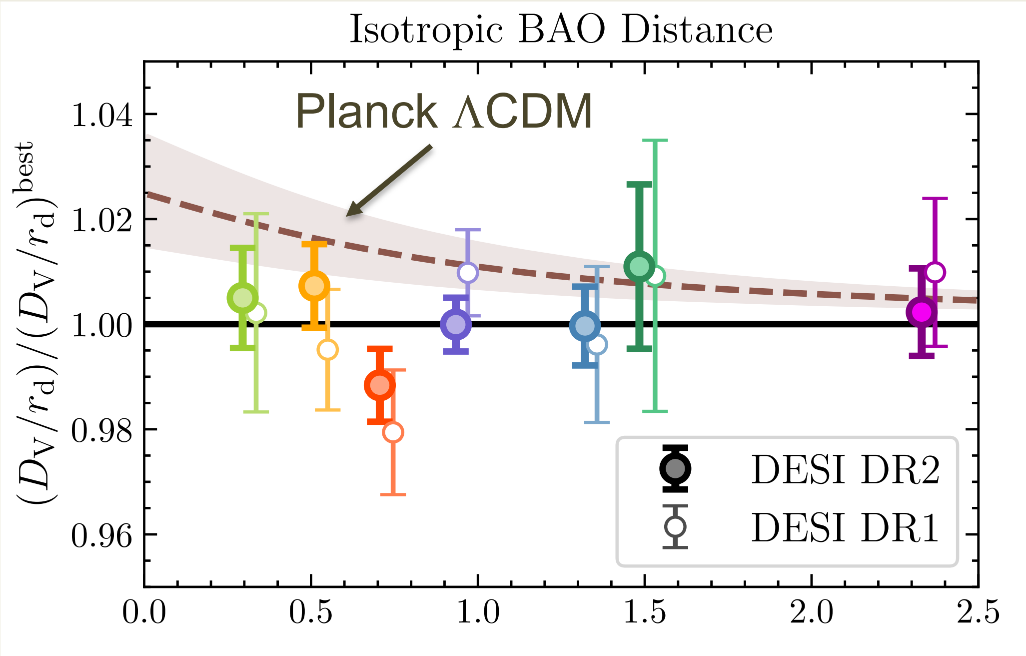




- Friedman equation for ΛCDM $H(z) \equiv H_0\sqrt{\Omega_m (1+z)^3 + (1-\Omega_m)}$
- Break the degeneracy without knowing r_d

$$\Omega_m = 0.2975 \pm 0.0086$$

Hubble diagram

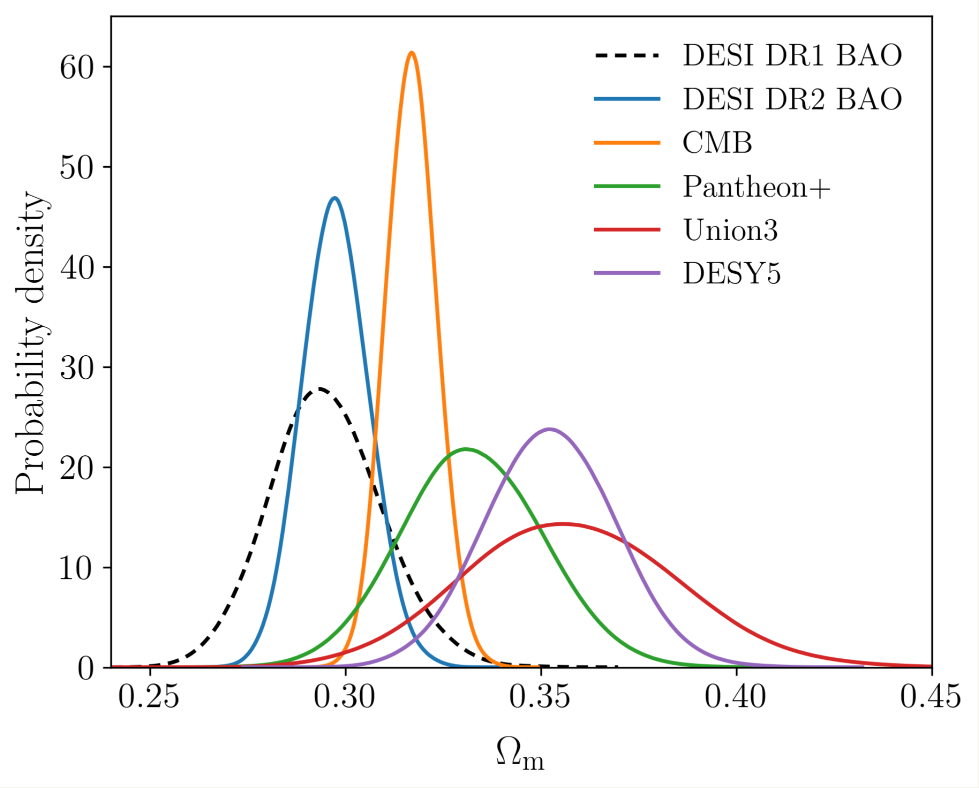


DESI: 1 year
DR1: April 2024

DESI: 3 years
DR2: April 2025

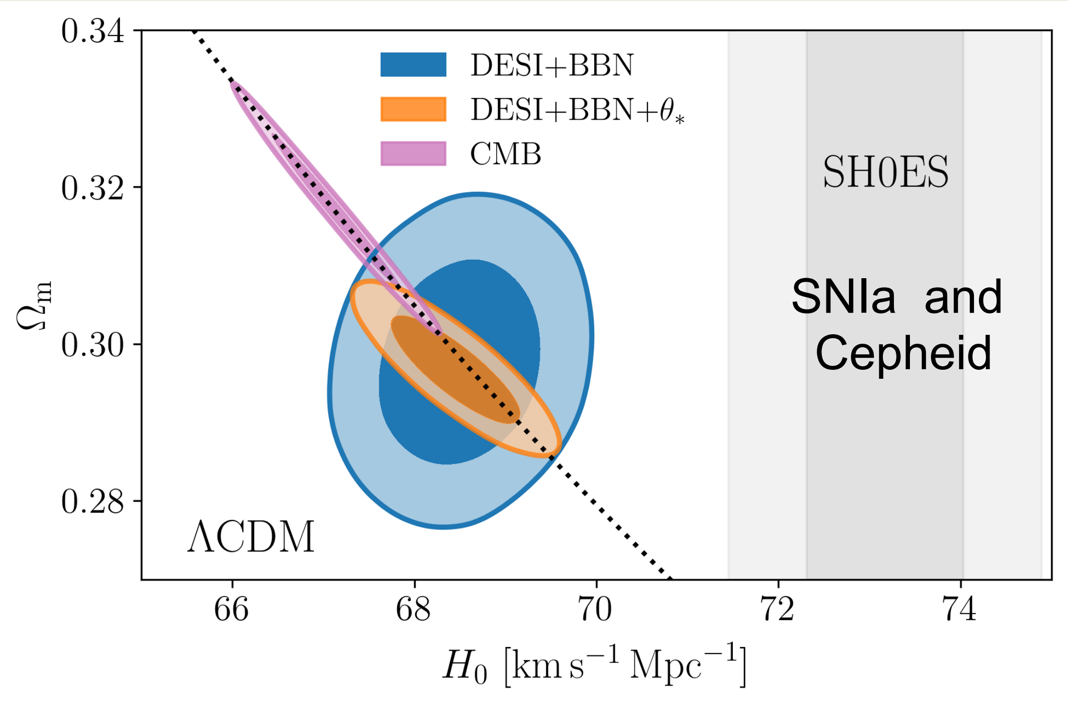
- ~14M discrete tracers with 0.1<z<2.1 in 6 redshift bins
- Precision on BAO: from 1.5% (QSO) to 0.45% (LRG3+ELG1)
- With Ly-a forest of QSOs at z~2.3 : precision on BAO 0.7%
- **Excellent agreement** between DESI DR1 and DR2
- Consistent with LCDM but **small tension with Planck LCDM : 2.3σ**

Ω_m - Tension in ΛCDM



- Consistent results DR1/DR2
- Comparable precision on Ω_m for DESI and CMB
- 2.3σ discrepancy between CMB and DESI
- Discrepancies with SNIa samples
  - Pantheon+: 1.7σ
  - Union3: 2.1σ
  - DESY5: 2.9σ

Measurement of H_0



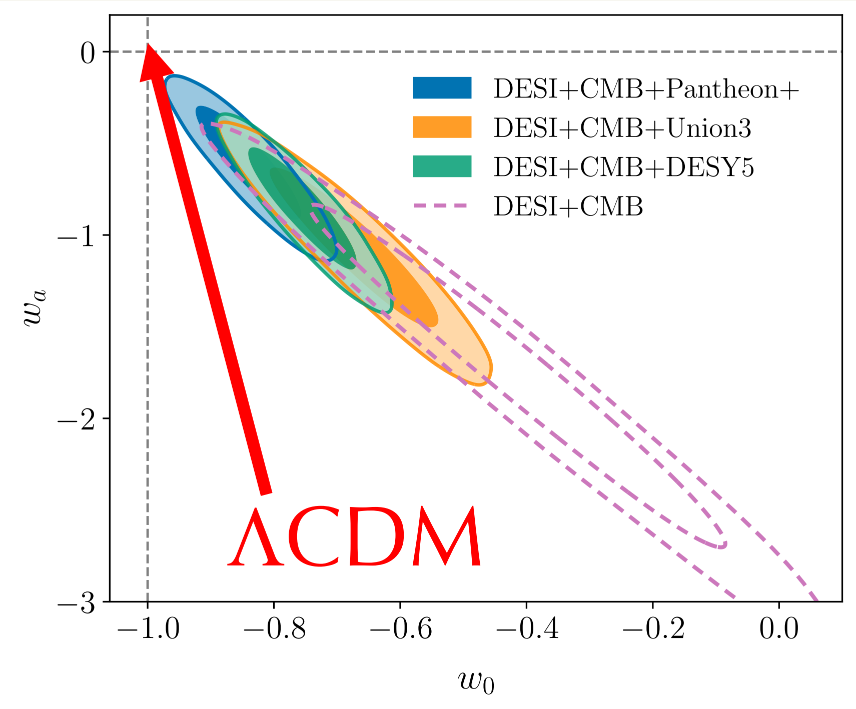
$$\underbrace{H_0 = (68.51 \pm 0.58)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}}_{\text{DESI + BBN}}$$

$$\underbrace{H_0 = (68.45 \pm 0.47)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}}_{\text{DESI} + \theta_* + \text{BBN}}$$

θ_* : CMB angular scale

- **Main tension in cosmology**: 5σ discrepancy between CMB and late measurements (SNIa)
- Big Bang Nucleosynthesis (BBN) can be used to measure r_d
- DESI + BBN (without CMB), **tension with SNIa** (SH0ES): 4.5σ

Beyond ΛCDM



Extensions of LCDM

- Equation of state of Dark Energy

$$w(z) = \frac{p(z)}{\rho(z)}$$

- Time evolving Dark Energy

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

– For ΛCDM, we expect w=-1, i.e. w_0=-1 and w_a=0

– Combining DESI+CMB: **3.1s effect**

– Combining DESI+CMB+SN: **2.8s to 4.2s** effect depending on the SN sample

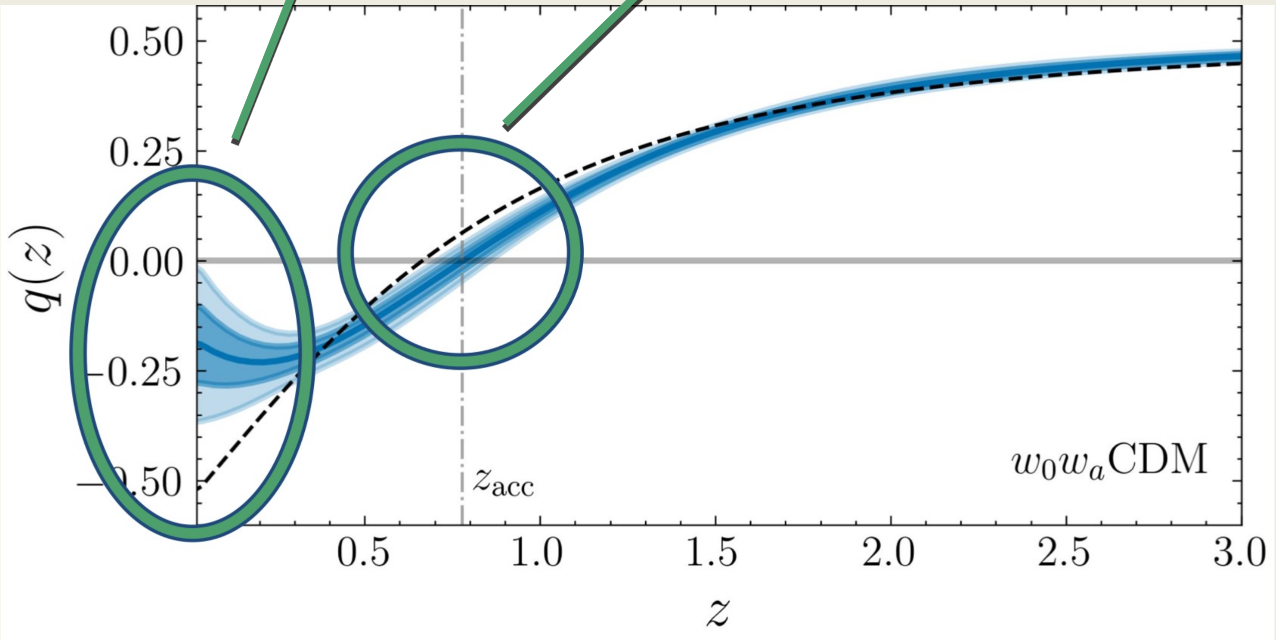
– **Stronger Indications of dynamical dark energy with DR2**

Dynamical Dark Energy

Acceleration is lower than ΛCDM at present.

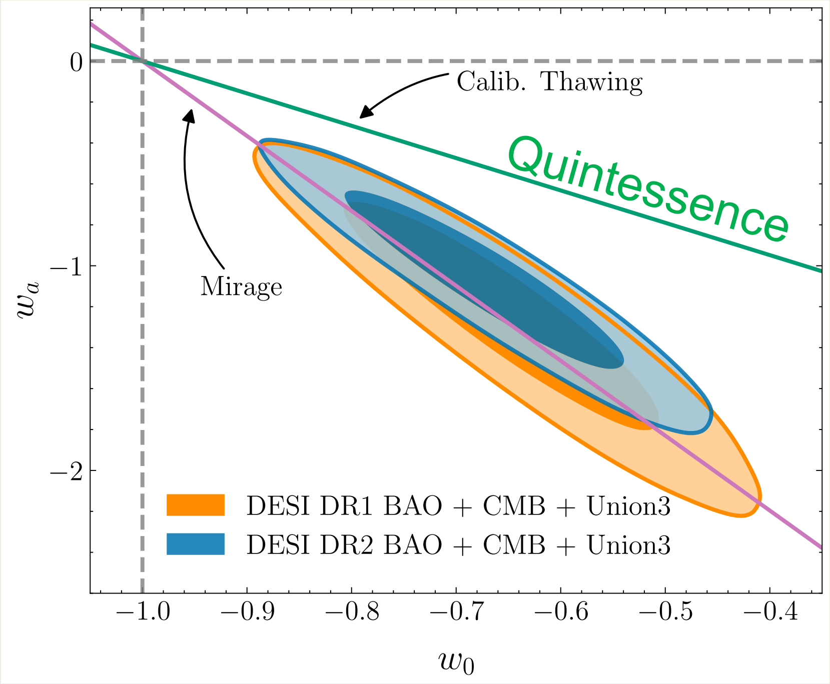
Acceleration started earlier than in ΛCDM.

Deceleration parameter



Redshift

Dynamical Dark Energy - Models



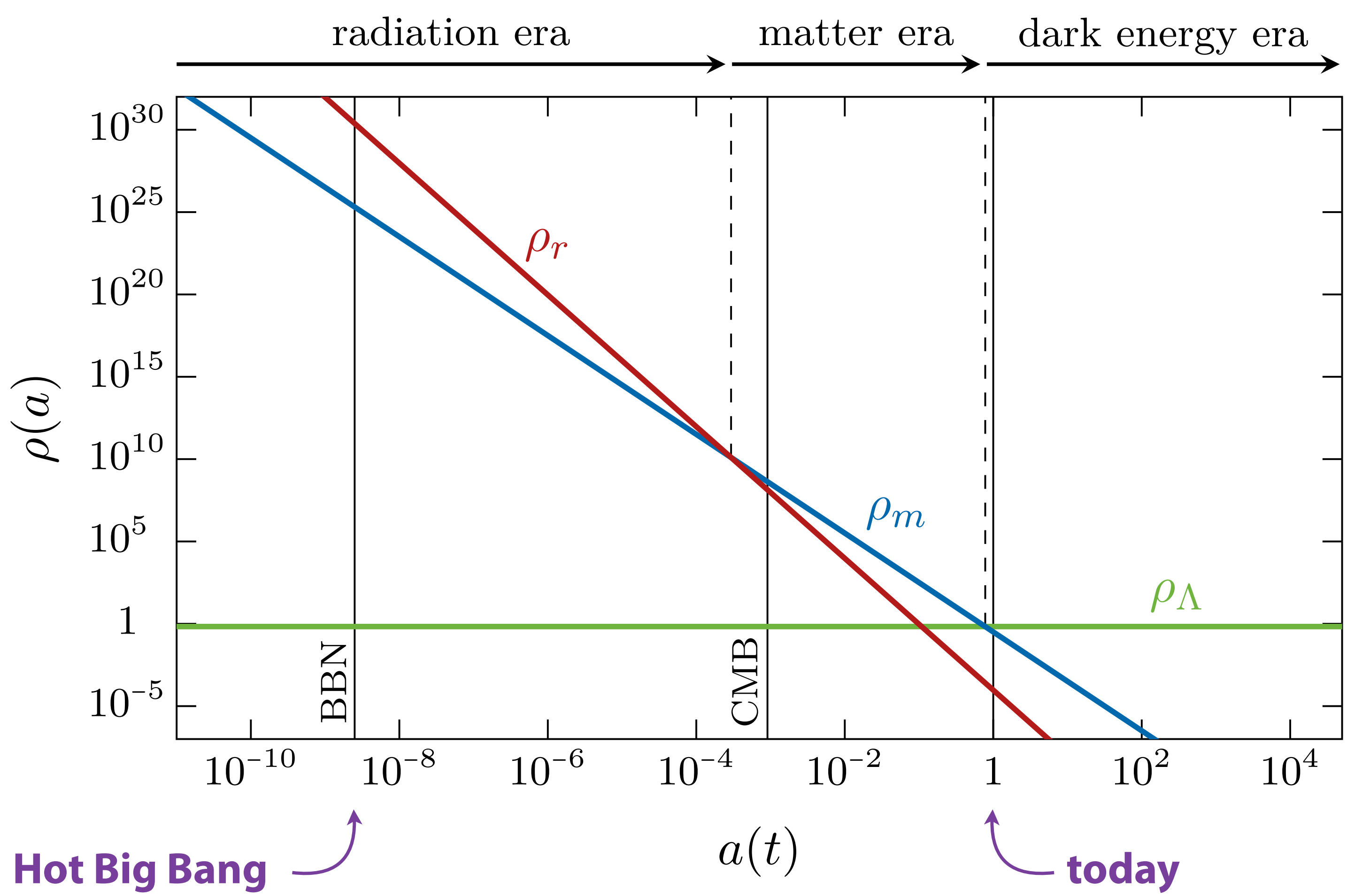
DESI+CMB:	+PantheonPlus		+Union3		+DESY5	
DE classes		ΔDIC ($\Delta\chi^2$)				
Thaw. (Cal.)	+0.4	(−1.6)	−0.6	(−2.5)	−5.8	(−7.1)
Thaw. (Alg.)	−1.0	(−2.9)	−4.6	(−6.9)	−10.1	(−13.2)
Emergent	+2.1	(−0.05)	+1.8	(−0.1)	+0.2	(−1.5)
Mirage	−9.1	(−10.5)	−13.8	(−16.2)	−18.7	(−20.7)
$w_0 w_a$	−6.8	(−10.7)	−13.5	(−17.4)	−17.2	(−21.0)

- Mirage Dark Energy is preferred to Thawing (Quintessence) models
- “Mirage” models mimic ΛCDM and <w> ~ -1 whereas there is a real time evolving Dark Energy

Mass of the neutrinos

Expanding Universe

- The Universe started hot and dense, but then cooled and diluted:



From Josquin's lectures

Neutrinos with Cosmology

At early times ($T_n \gg m_n$), **neutrinos contribute as radiation** $\rho_\nu \propto T_\nu^4$

At late times ($T_n \ll m_n$), **neutrinos contribute as matter** $\rho_\nu = m_\nu n_\nu$

Non-relativistic transition

$$\Omega_\nu = \frac{\Sigma m_\nu}{93.1 eV}$$

$$m_\nu \sim \langle p \rangle = \frac{\int p f(p) d^3p}{\int f(p) d^3p} = 3.15\, T_\nu \quad \text{with} \quad f(p) = \frac{1}{e^{p/T_\nu} + 1}$$

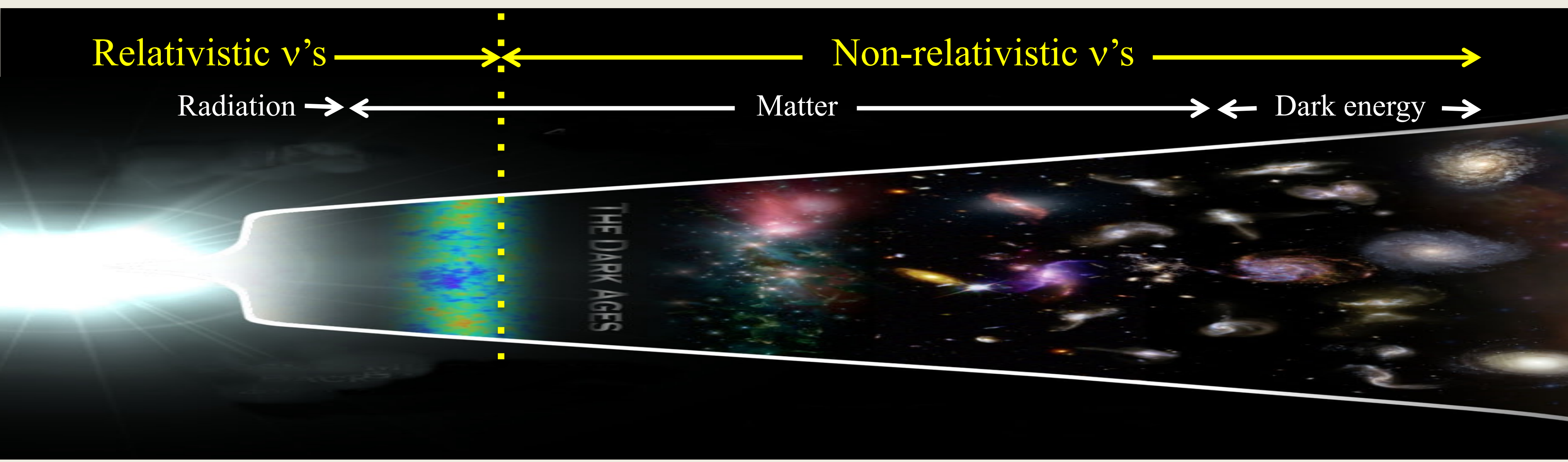
$$z_{nr} \sim 1900 \, \frac{m_\nu}{1\,\mathrm{eV}}$$

→

At recombination

$m_\nu < 0.6$ eV ($\Sigma m_\nu < 1.7$) : relativistic

$m_\nu > 0.6$ eV ($\Sigma m_\nu > 1.7$) : matter-like



Two effects due to neutrino masses

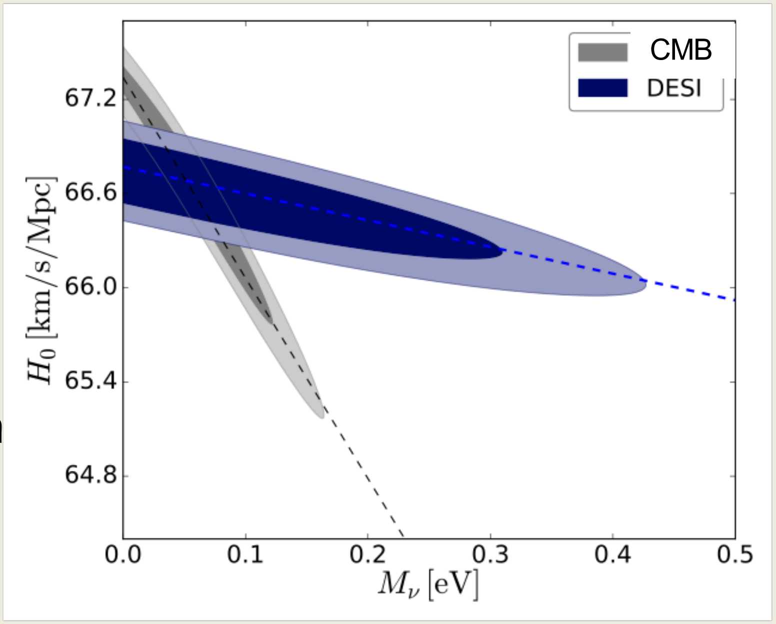
- As Σm_ν <1 eV, we can neglect ISW effect and we have only two effects

1) **Geometrical:** size of horizon (integral of 1/H(z))
2) **Free streaming:** suppression of small scales

- When z decreases, $\Omega_m(1+z)^3$ decreases slower than $\Omega_r(1+z)^4$

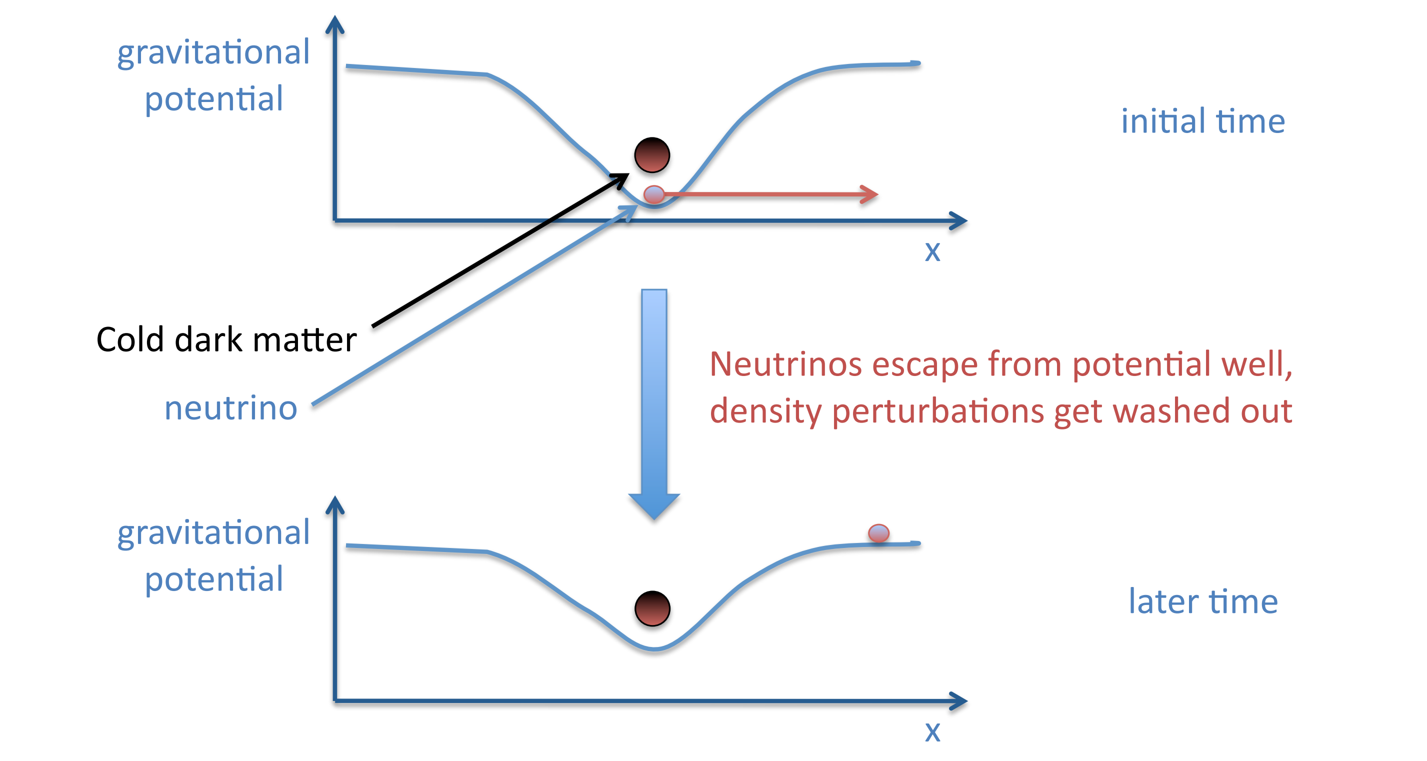
$$H(z) = H_0\sqrt{\Omega_m(1+z)^3+\Omega_r(1+z)^4+\Omega_\Lambda}$$

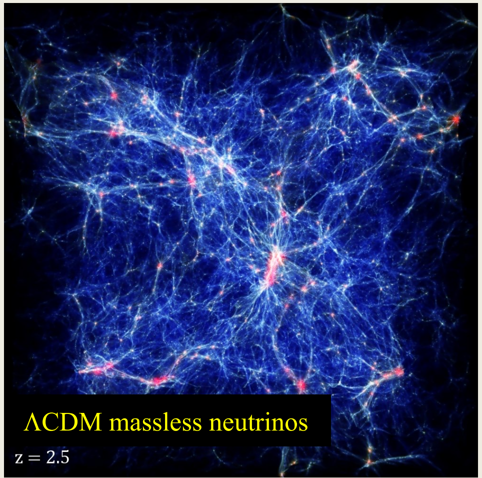
- Massive neutrinos increases of H(z)
- To keep the same size of sound horizon (same H(z)), we need a lower H_0
- **Anti-correlation (H_0,Σm_ν)**
- **Correlation (Ω_m,Σm_ν) because CMB measures $\Omega_m.H_0^3$**



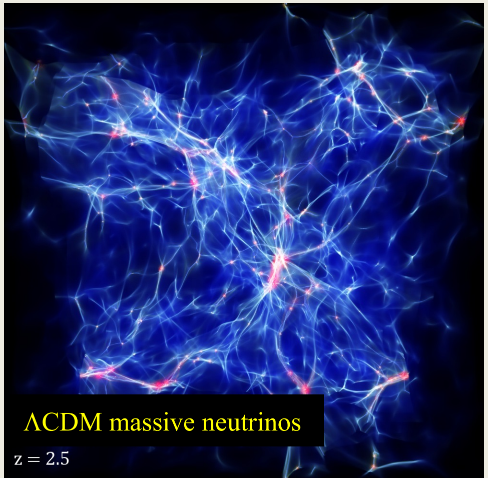
- BAO breaks the (H_0,Σm_ν) degeneracy by adding another measurement of the acoustic scale at a different redshift

Impacts of neutrinos through free-streaming



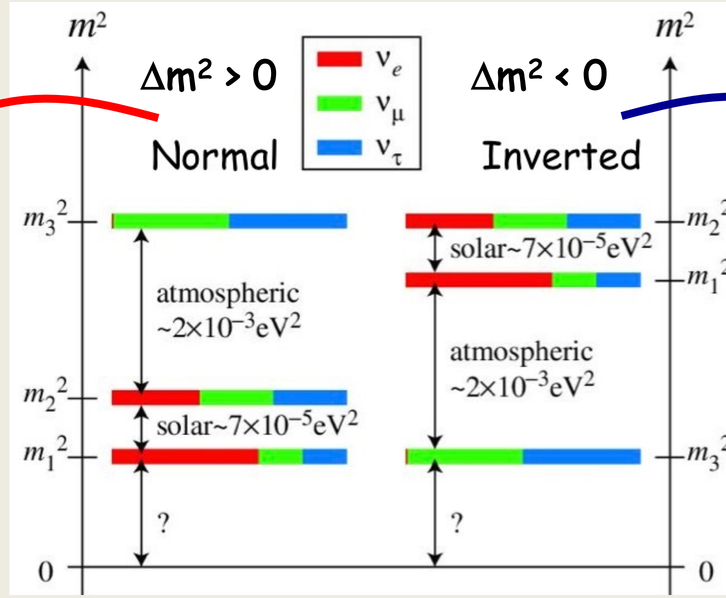


Suppression of the small scales



Neutrinos masses and Hierarchy

$\Sigma m > 60$ meV

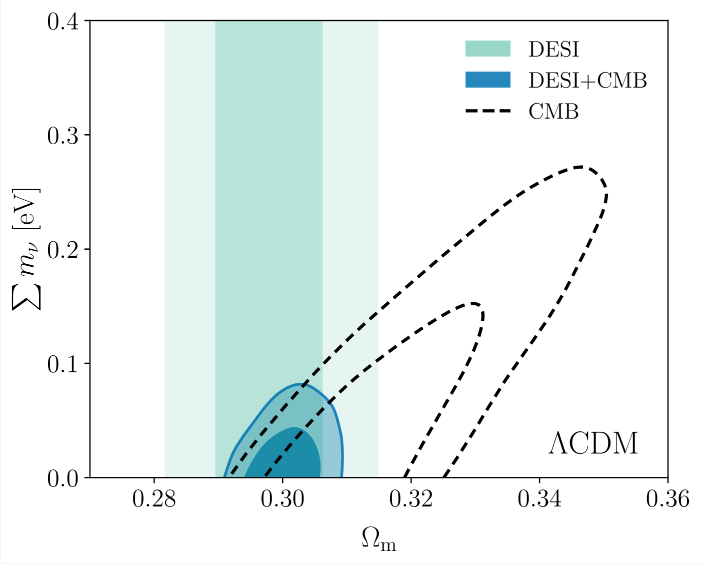


$\Sigma m > 100$ meV

An answer to mass hierarchy with cosmological neutrinos

- Particles Physics: atmospheric and solar oscillations
- No constraint on absolute masses
- 2 possible schemes: normal vs inverted hierarchy
- The lowest possible mass is **~60 meV**
- With **$\sigma(\Sigma m_\nu)$~20 meV**, we measure the mass of the neutrinos with a precision better than **3σ**

Sum of neutrino masses - Bayesian



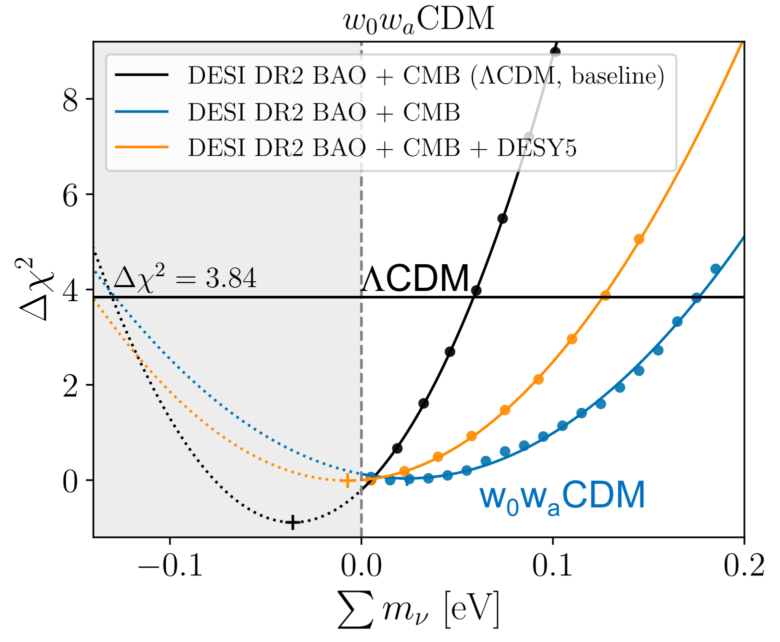
- CMB is sensitive to $\sum m_\mu$
- BAO measures Ω_m and breaks the degeneracies

Limits at 95% CL:

- For ΛCDM with CMB alone: $\Sigma m_\nu < 210\ meV$
- For ΛCDM with CMB + DESI: $\Sigma m_\nu < 64\ meV$
- For w_0w_aCDM with CMB + DESI + SN $\Sigma m_\nu < 130\ meV$

Sum of neutrino masses - Frequentist

Model/Dataset	μ_0 [eV]	σ [eV]	95% CL [eV]
ΛCDM+$\sum m_\nu$			
DESI DR2 BAO+CMB (CamSpec)	−0.036	0.043	< 0.053
DESI DR1 BAO+CMB (CamSpec)	−0.048	0.054	< 0.063
DESI DR1 BAO+CMB-nl (CamSpec)	−0.068	0.067	< 0.074
w_0w_aCDM+$\sum m_\nu$			
DESI DR2 BAO+CMB	0.024	0.078	< 0.177
DESI DR2 BAO+CMB+DESY5	−0.007	0.068	< 0.126



– Our “real” sensitivity on $\sum m_\nu$ is σ ~ 40 meV with ΛCDM
– Because of the tension on Ω_m the limits artificially are too stringent

Limits at 95% CL with Feldman-Cousins:

– For ΛCDM with CMB + DESI: $\Sigma m_\nu < 53\ meV$
– For w_0w_aCDM with CMB + DESI + SN $\Sigma m_\nu < 126\ meV$

Conclusions

Summary: Results from DESI BAO

– **BAO results with DR2**

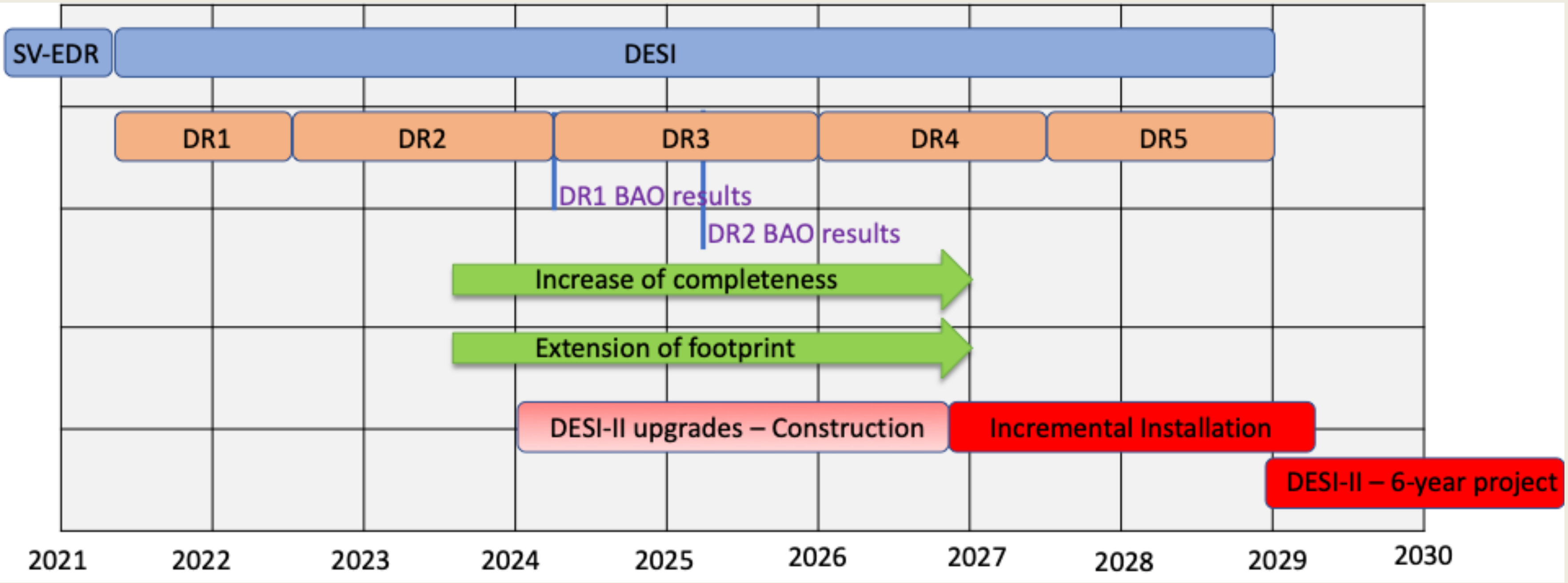
- With three years (DR2), DESI provides the most precise measurement of BAO over 0<z<3.5
- DR2 (April 2024) results confirm DR1 (April 2025) results
- In ΛCDM, DESI is in slight tension with CMB (~2σ) and DESI prefers lower Ω_m The tension still present with ACT and SPT
- Indications of time-varying Dark Energy equation of state, especially when SNIa are added

  $\Longrightarrow$ **a 2.8σ to 4.2σ effect, not 5σ yet!**

– **What next?**

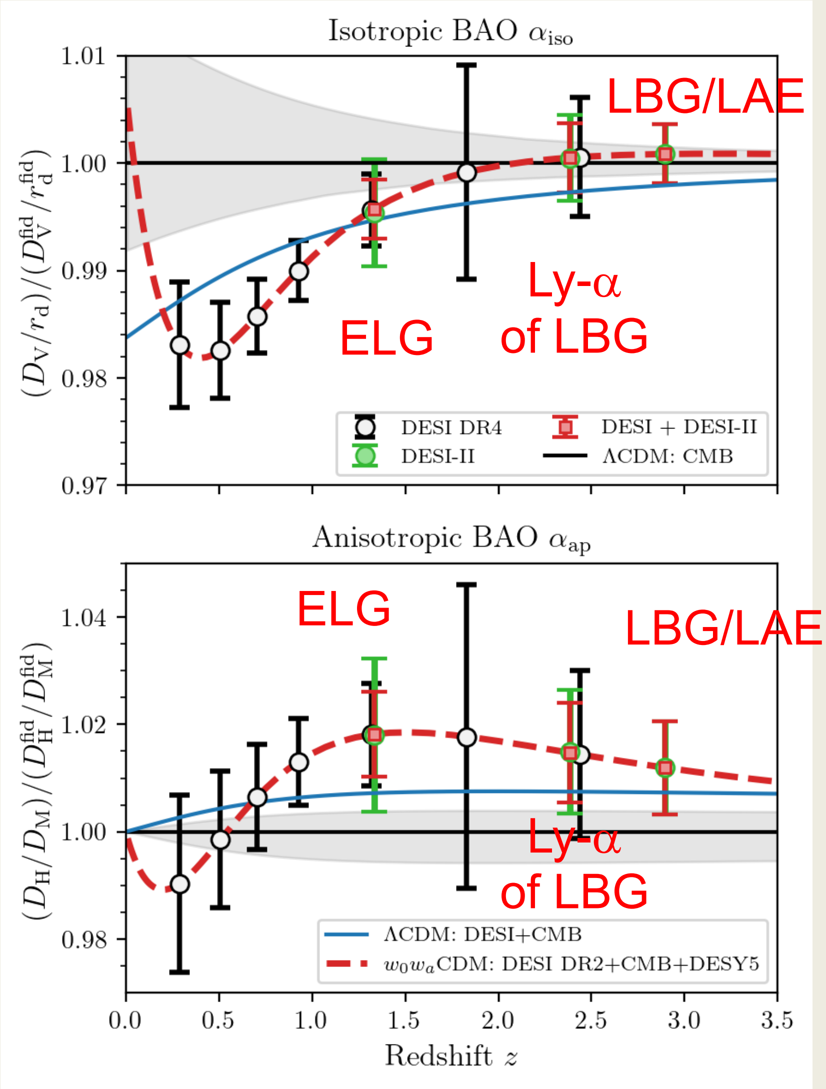
- BAO: Full dataset for DESI in 2026 (+ Full shape analysis)
- SNIa: ZTF and LSST homogeneous sample at z<0.1
- CMB: SPT and in the long term SO and CMB-S4

DESI and DESI-II timeline



- **DESI** (DR1-DR3) should finish in Nov. 2025
- Continuation of DESI (DR4-DR5) to end of 2028 with an extension of the footprint and an increase of the completeness
- **DESI-II (2029):** Dark Matter, high-density and high-z programs

DESI and DESI-II BAO program



– **DESI (DR1-DR3)** is focused on the studies of DE

– **DESI (DR4-DR5) :**

- Extension of footprint
- Denser in DE region

– **DESI-II:**

- higher-density at low-z
- high-z programs