



Breaking Paradigms

The Cosmological Constant is Not Constant

Dr. Axel de la Macorra
Physics Institute
National University Mexico (UNAM)

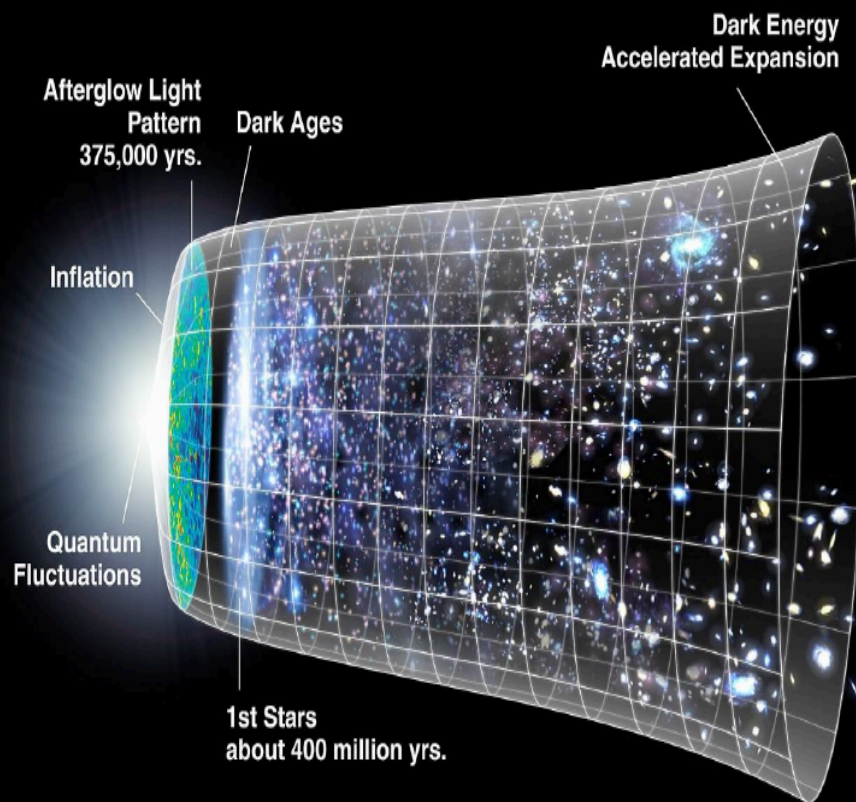




DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

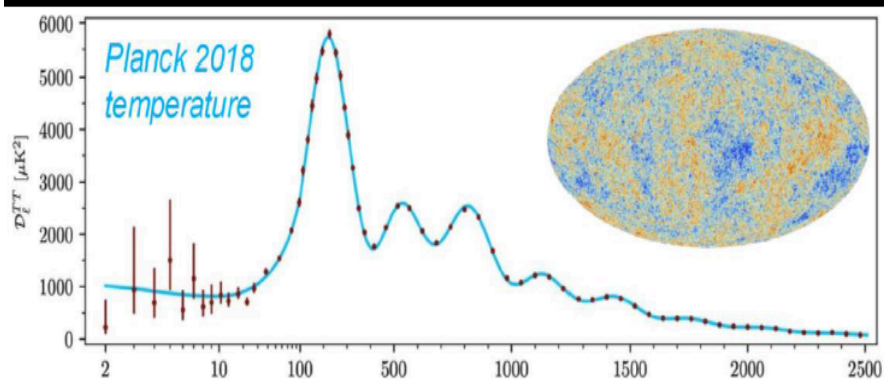
Standard model of cosmology



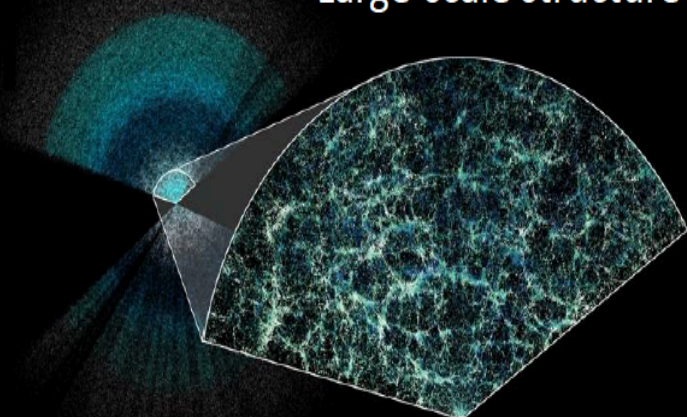
Supernovae

SNIa

Cosmic Microwave Background (CMB)



Large-scale structure



Solving the Friedmann Equation

$H \equiv \frac{\dot{a}}{a}$

Expansion
rate

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{Kc^2}{a^2} + \frac{\Lambda}{3}$$

Density
measures

In order to solve it, we also need to define the behavior of the mass/energy density $\rho(a)$ of any given mass/energy component. Recall the basic GR paradigm:



Each component will lead to a different evolution in redshift

We already saw that:

$$\rho_m(t) = \rho_{m,0} a^{-3}(t)$$

$$\rho_r(t) = \rho_{r,0} a^{-4}(t)$$

$$\rho_v(t) = \rho_v = \text{const.}$$

What is Dominant When?

Matter dominated ($w = 0$): $\rho \sim a^{-3}$

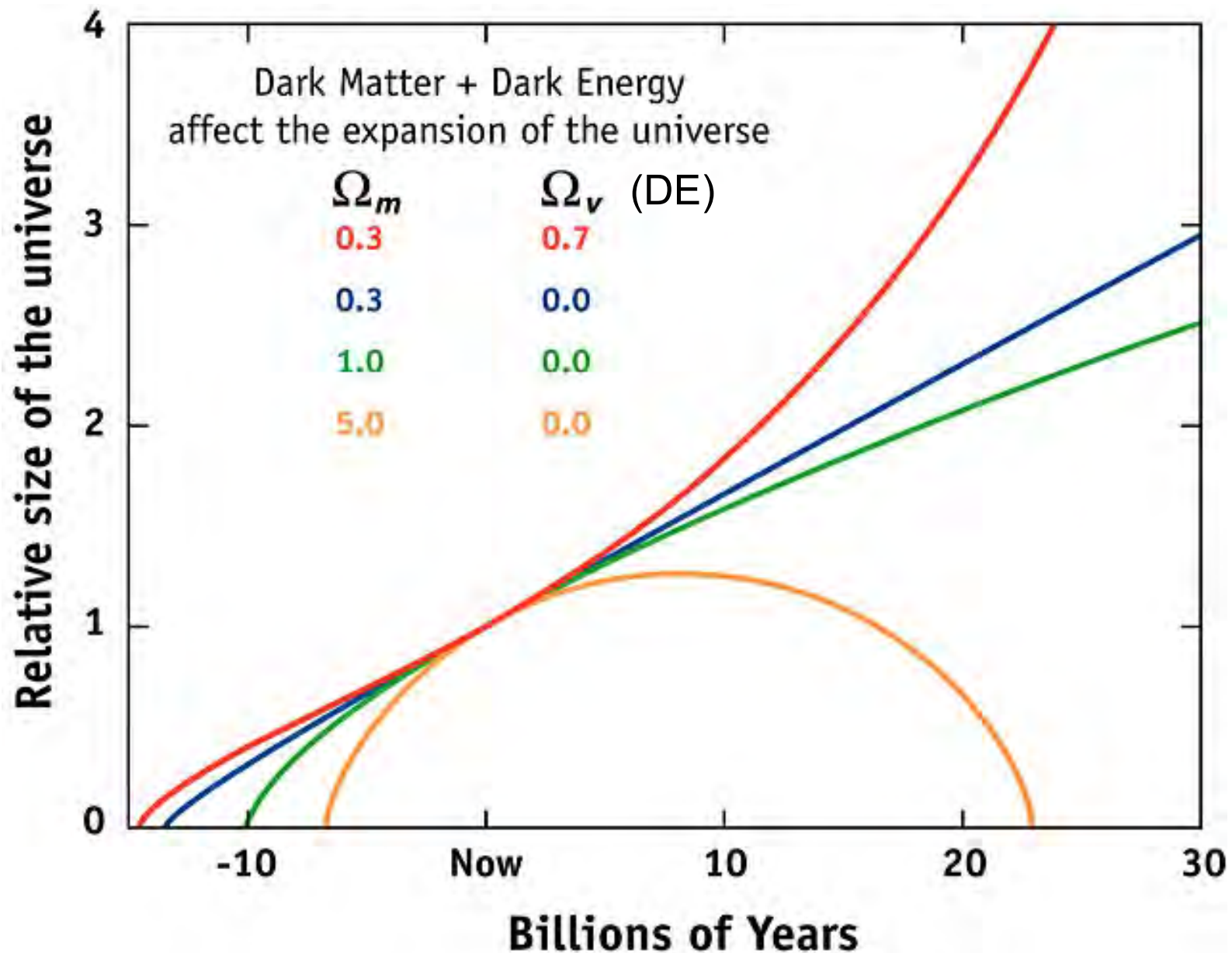
Radiation dominated ($w = 1/3$): $\rho \sim a^{-4}$

Dark energy ($w \sim -1$): $\rho \sim \text{constant}$

- Radiation density decreases the fastest with time
 - Must increase fastest on going back in time
 - Radiation must dominate early in the Universe
- Dark energy with $w \sim -1$ dominates last; it is the dominant component now, and in the (infinite?) future



Examples of Models





DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

DESI Survey: Making the Largest 3D Map of the Universe with over 47 million Galaxies and Quasars

3 million
Quasars ($0.9 < z < 2.1$)
+ Ly- α forest ($2.1 < z$)

16 million Emission Line
Galaxies
($0.6 < z < 1.6$)

8 million Luminous Red
Galaxies
($0.4 < z < 1$)

13.5 million Bright Galaxies
($0.0 < z < 0.4$)

From 2021-2026 DESI will measure precise redshifts to
~40 million galaxies over 14,000 deg²



Credit: DESI Collaboration/KPNO/NOIRLab/NSF/AURA/P. Horálek/R. Proctor



How can we measure cosmological distances?

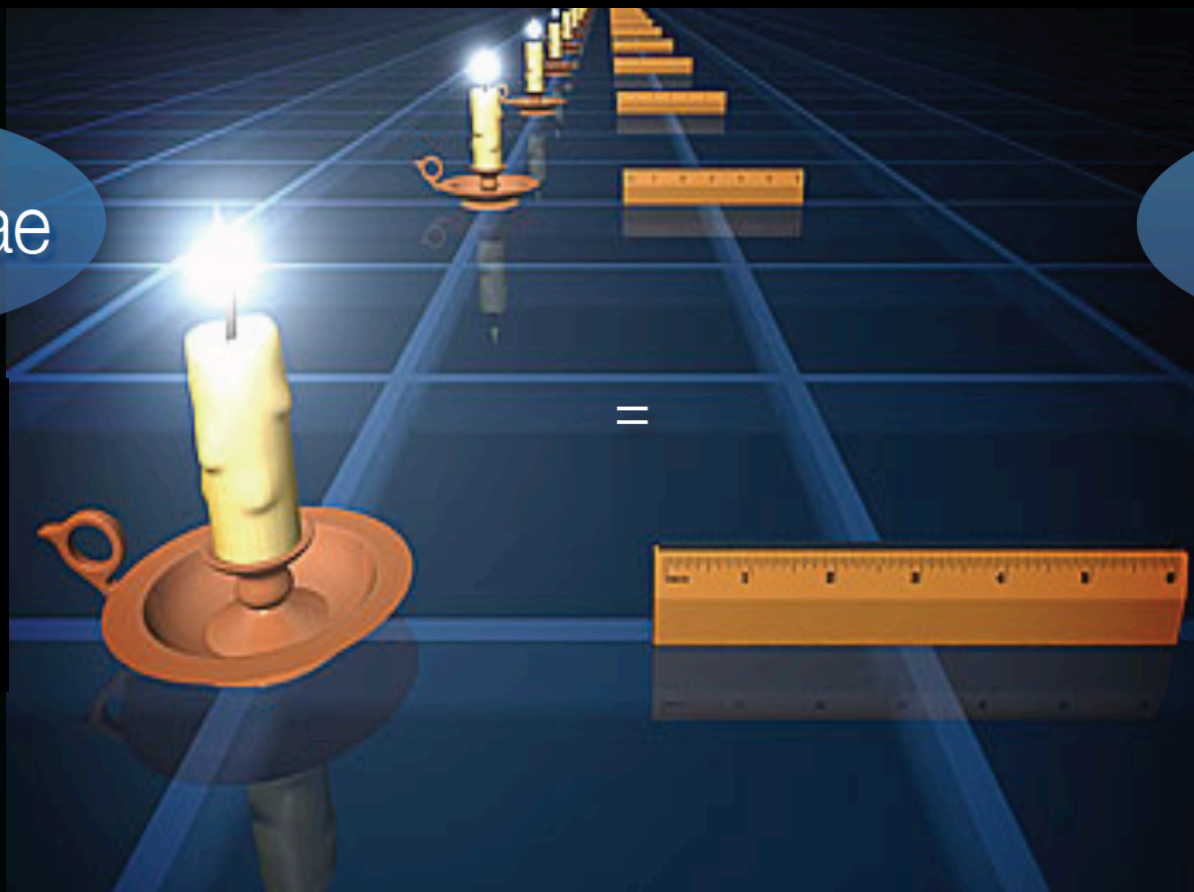
Supernovae

Standard candle

Same luminosity

BAO

Standard Ruler

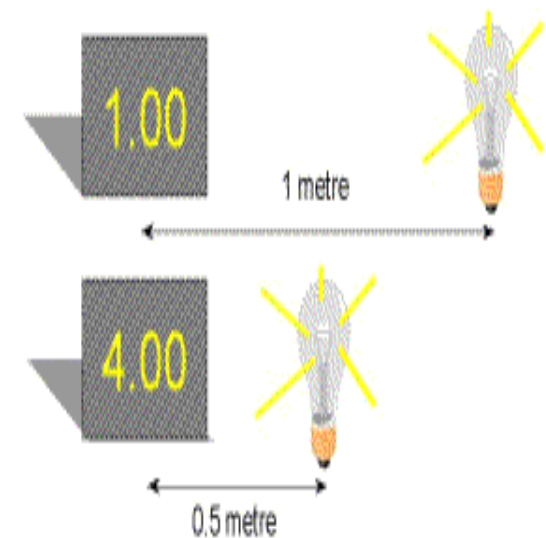


Supernovas

SN Ia as Standard Candles



Measuring Distances with Standard Light Bulbs

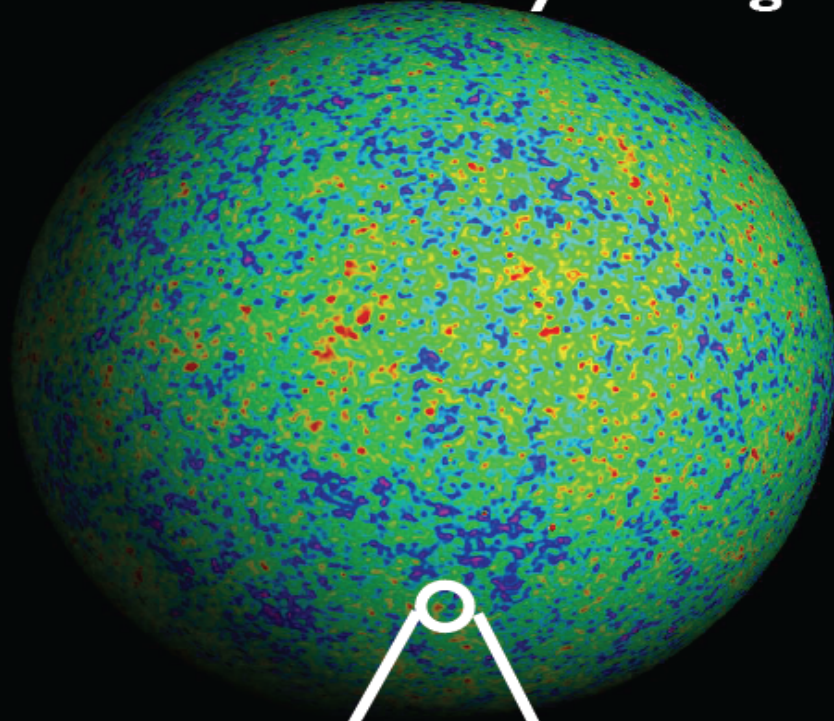


An Object becomes fainter by the square of its distance

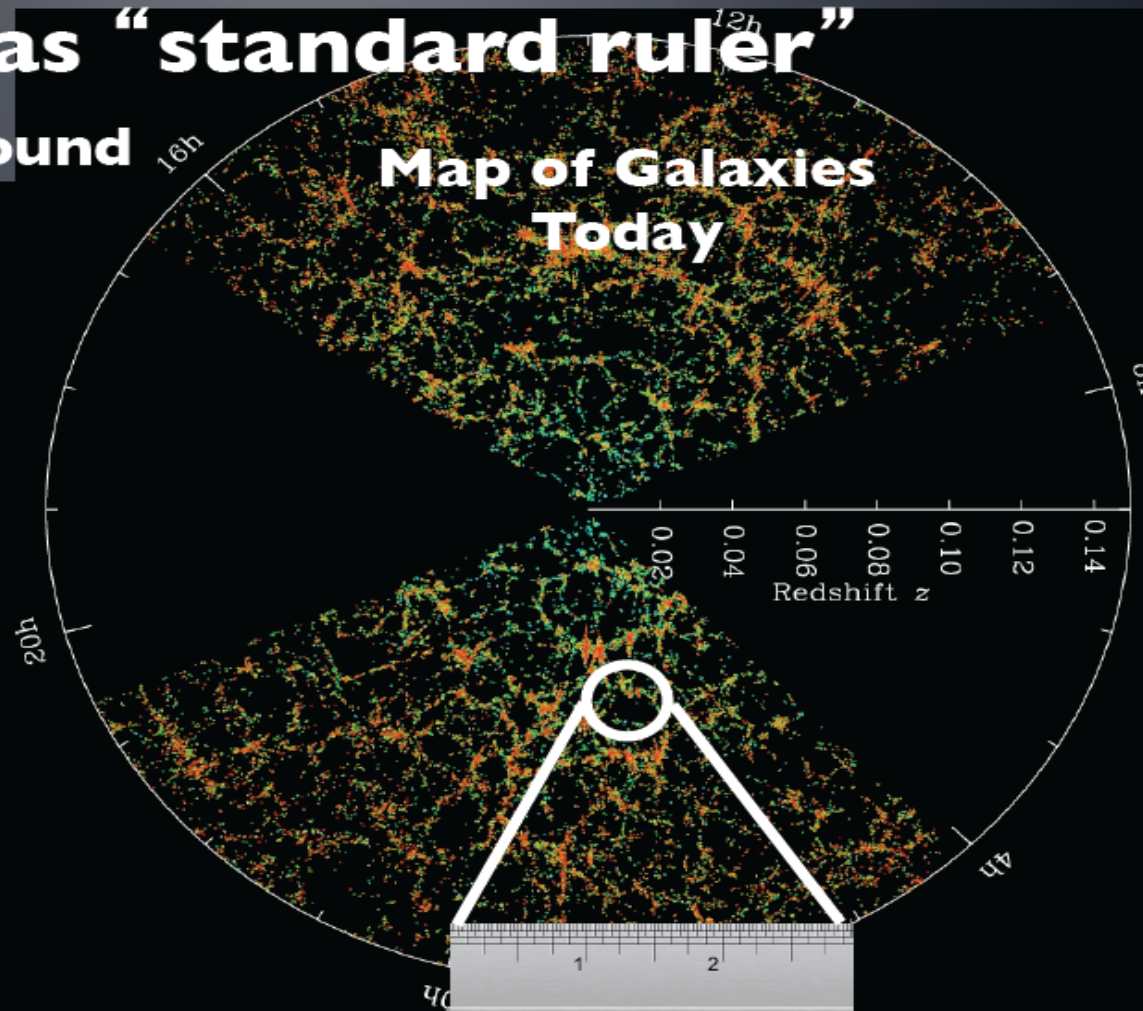
Baryon Acoustic Oscillations

Sound waves as “standard ruler”

Cosmic Microwave Background
14 billion years ago



Map of Galaxies
Today



Same origin but different size (due to the universe expansion)

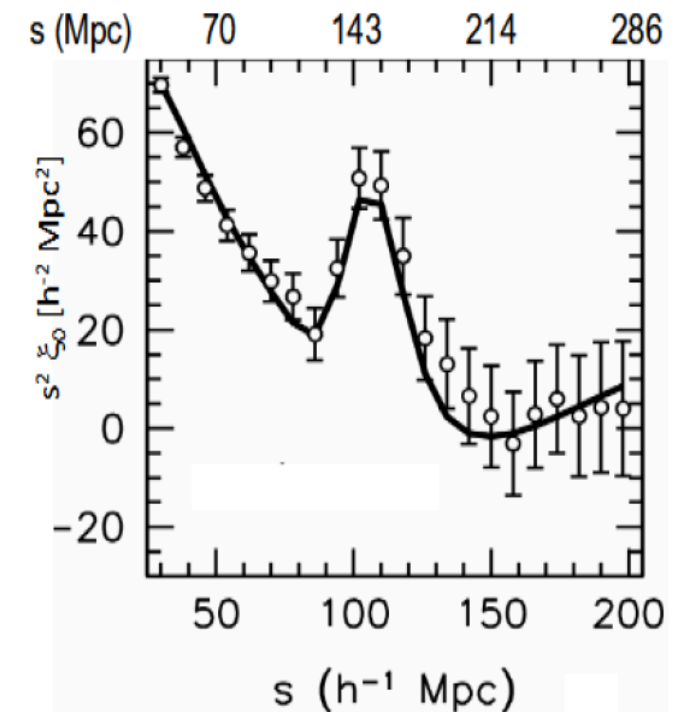
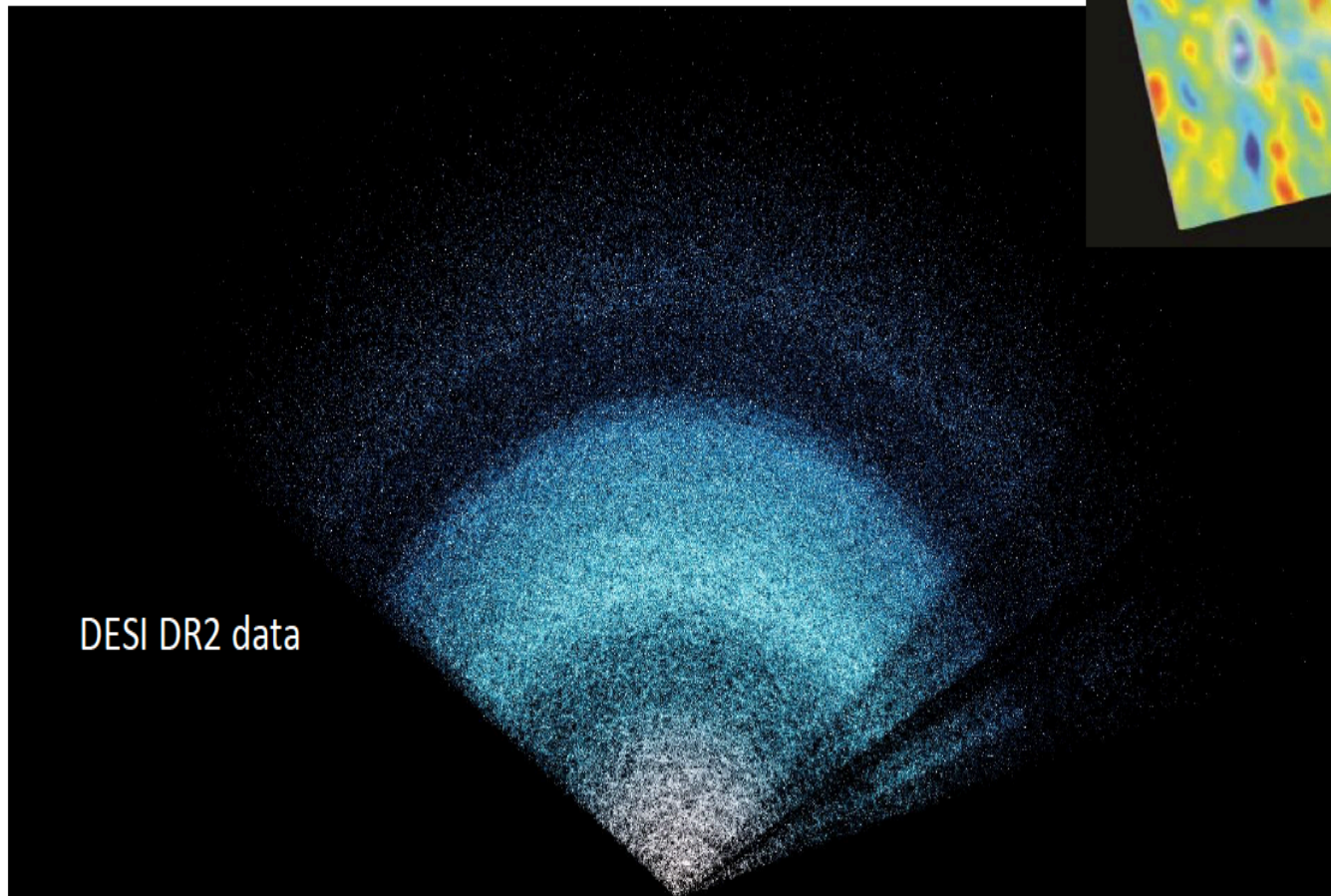
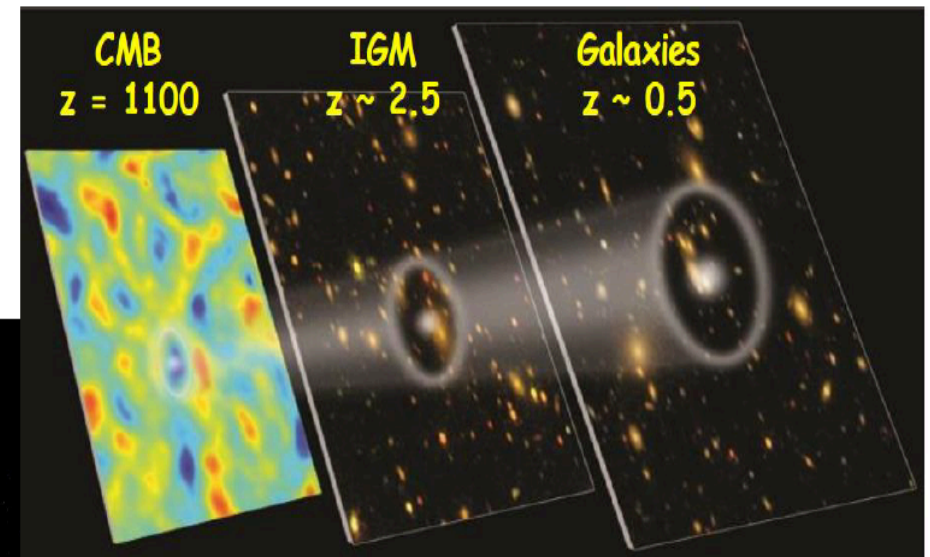


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

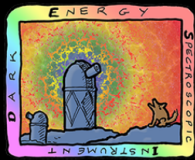
U.S. Department of Energy Office of Science

Baryon Acoustic Oscillations (BAO)

Imprint of fluctuations in primordial plasma
→ Standard Ruler to measure distances



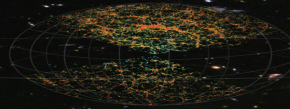
Credit: DESI collaboration



**DARK ENERGY
SPECTROSCOPIC
INSTRUMENT**

U.S. Department of Energy Office of Science

DESI



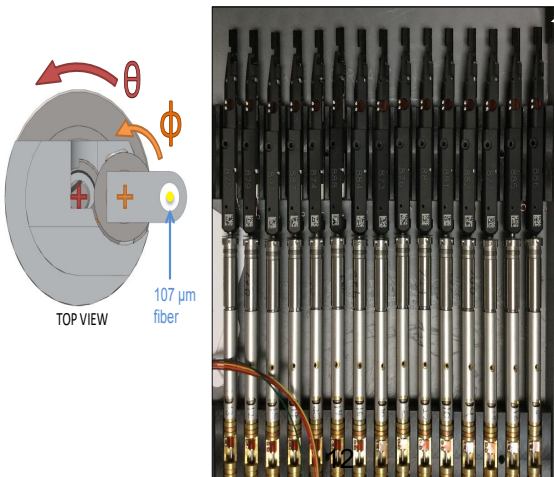
Mayall Telescope, Kit Peak, Arizona (4 mts diameter)



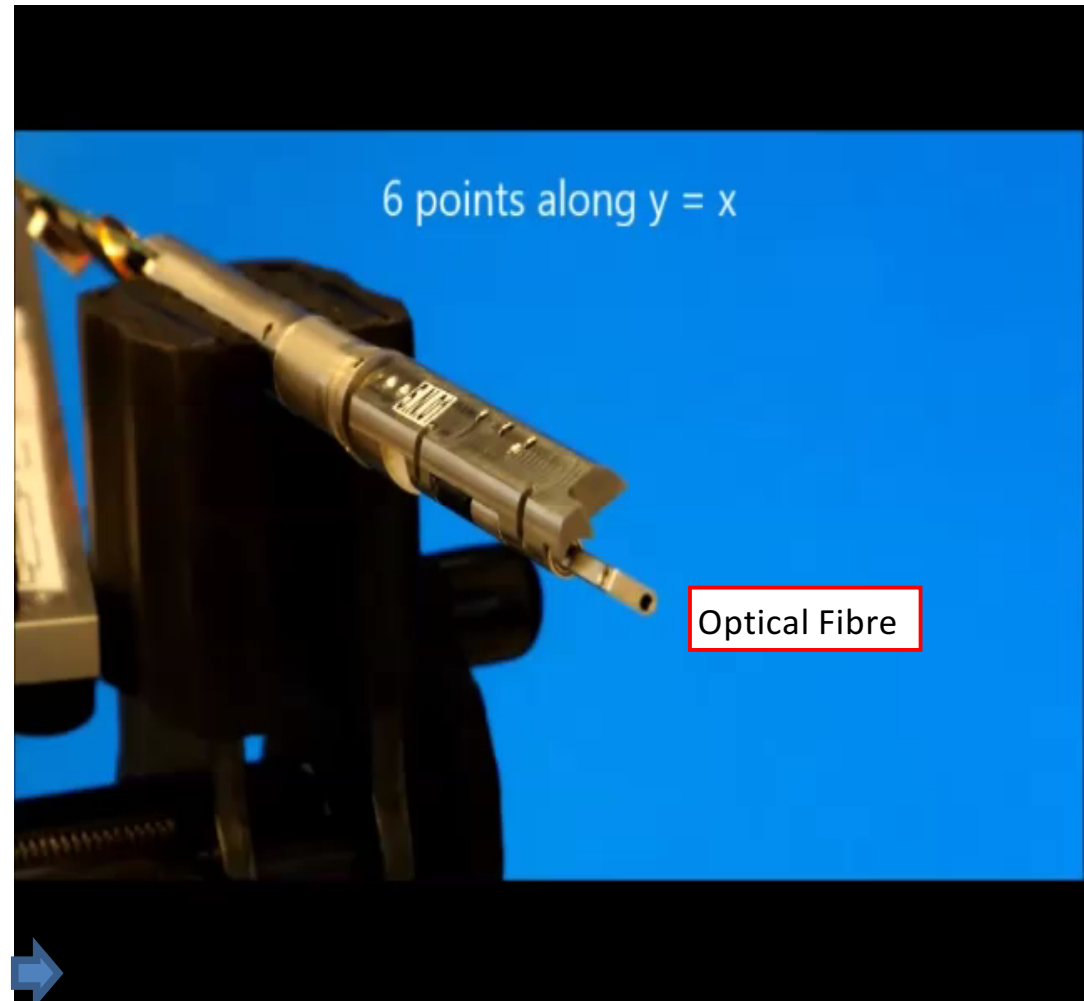
- **DESI has 5000 optical fibers directed by 5000 minirobots**
- **They measure the light (spectra) of 5000 galaxies at the same time**
- **Our 3-dimensional Map consists of two angles and the relative velocity**

Technical progress:

Fiber positioner mass production is proceeding well

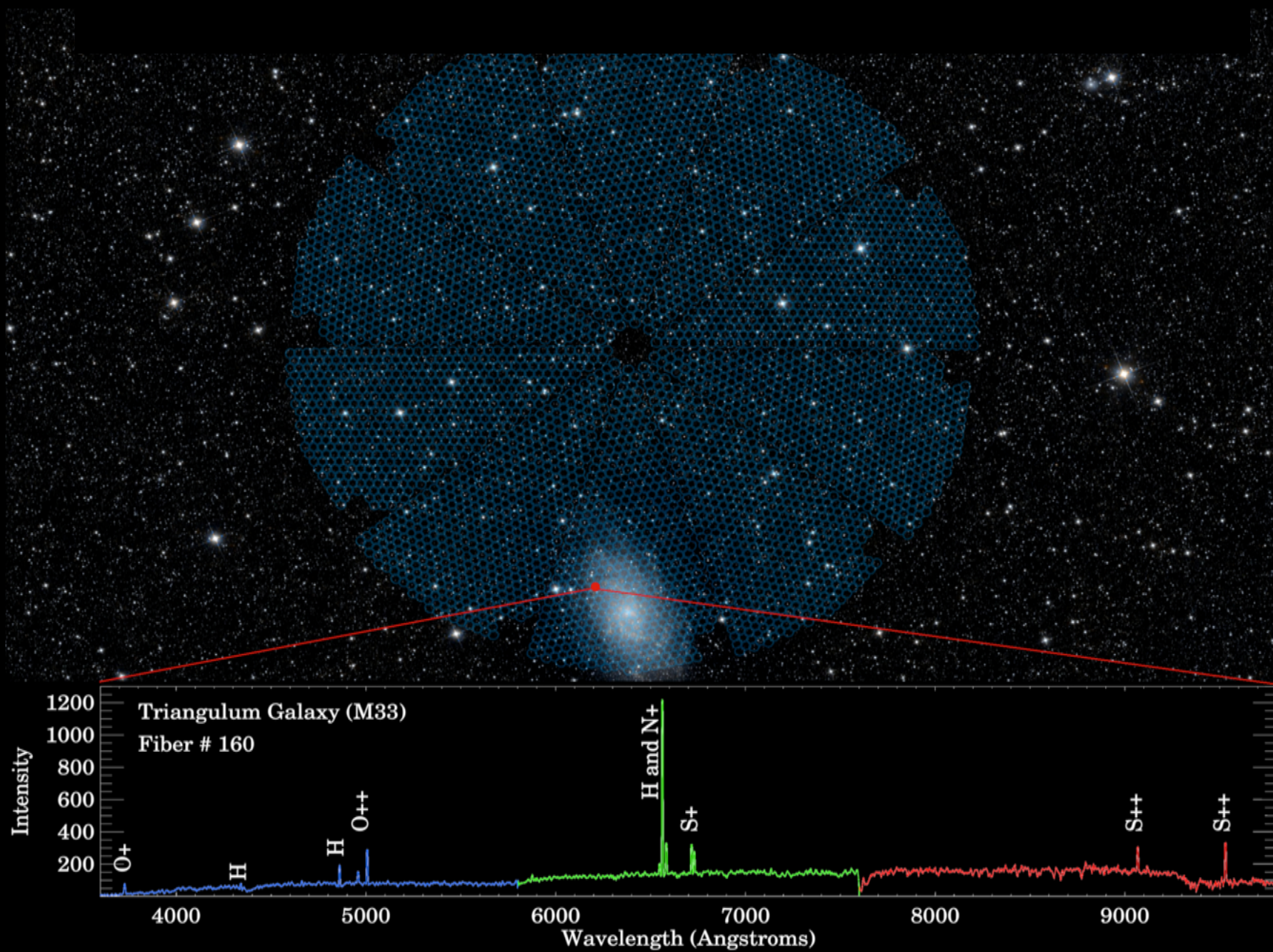


- Over 2500 built
- 98% pass precision accuracy test and infant mortality
- 98% pass inspection of physical envelope, angular alignment, and all other QC
- Our production total is within one week of baseline
- The main challenge at this point is just keeping the part kits flowing from our suppliers to UM

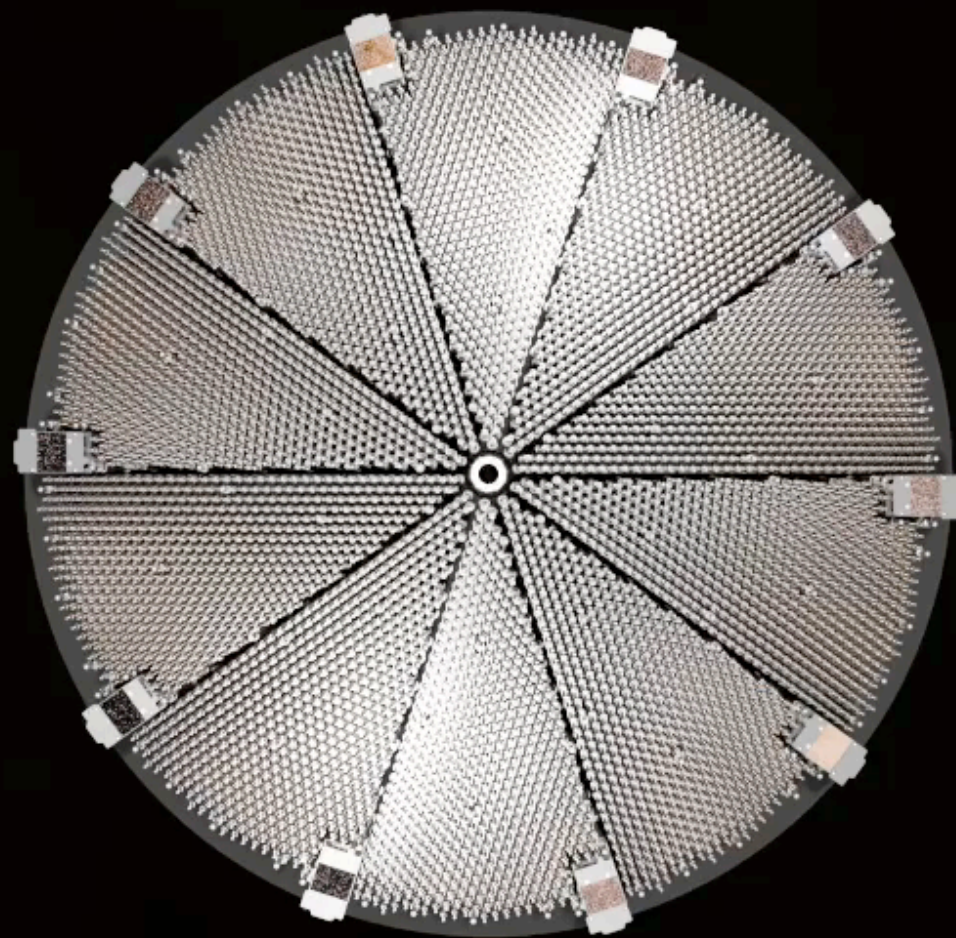


DESI First Light (22 October 2019)

Galaxy Triangulum M33



5000 DESI EYES

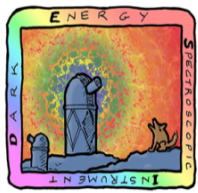




DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

5000 optical fibers
10 hours observation per night
20 minutes in each position
Observe per night $\sim 120,000$
galaxies/quasars





DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

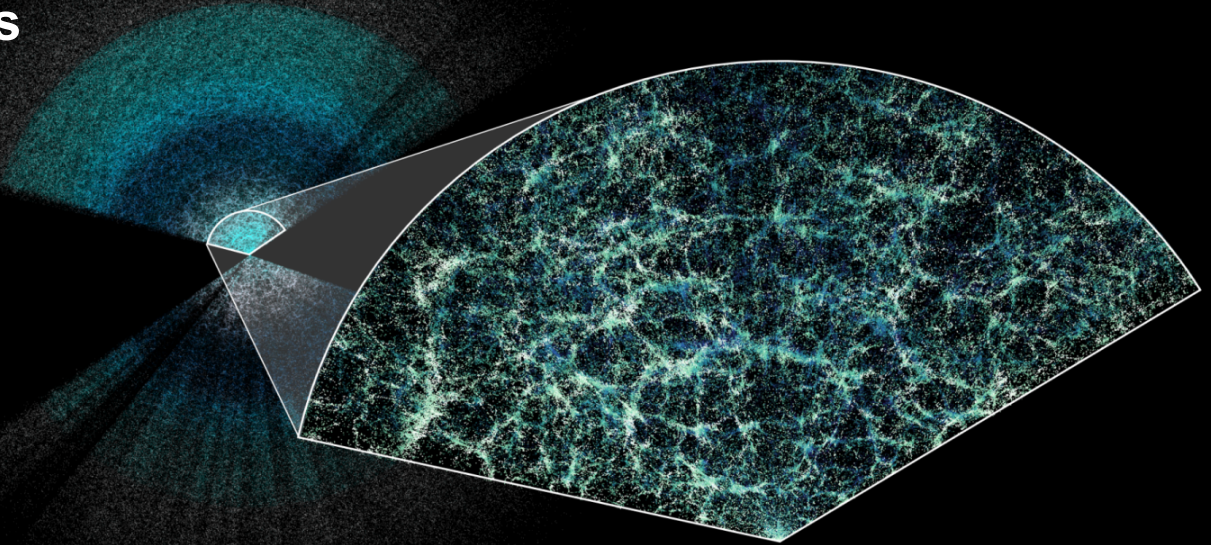
- Largest 3D map
- We have measured over 47 millions galaxies and quasars
- Plus more than 20 millions stars

LRG - Luminous Red Galaxies

ELG - Emission Line Galaxies

QSO - Quasars

QSO - Lyman-alpha forest

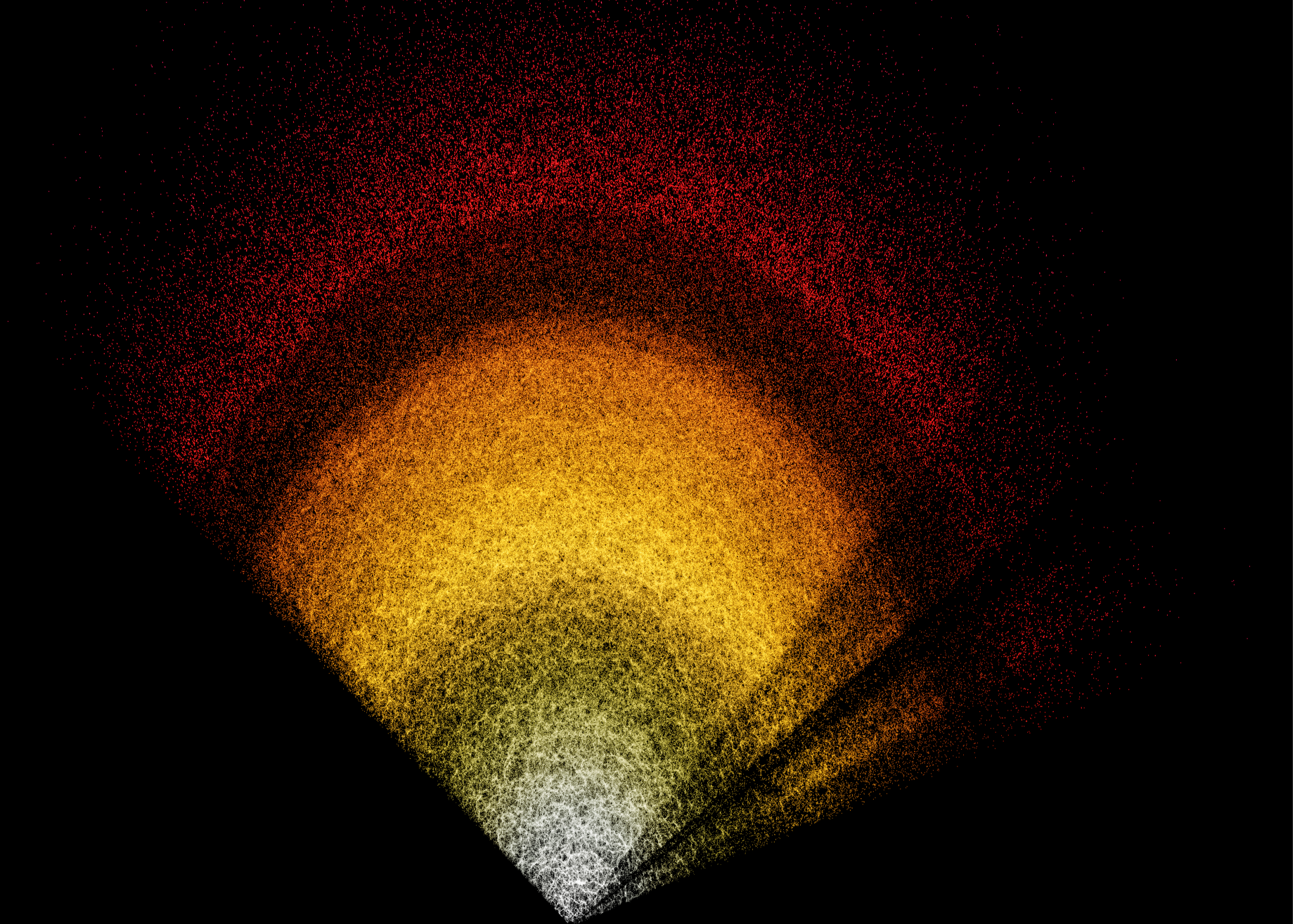


Galaxy type	Redshift range	Bands used	Targets per deg ²	Exposures per deg ²	Good z 's per deg ²	Baseline sample
LRG	0.4–1.0	$r, z, W1$	350	580	285	4.0 M
ELG	0.6–1.6	g, r, z	2400	1870	1220	17.1 M
QSO (tracers)	< 2.1	$g, r, z, W1, W2$	170	170	120	1.7 M
QSO (Ly- α)	> 2.1	$g, r, z, W1, W2$	90	250	50	0.7 M
Total in dark time			3010	2870	1675	23.6 M
BGS	0.05–0.4	r	700	700	700	9.8 M
Total in bright time			700	700	700	9.8 M

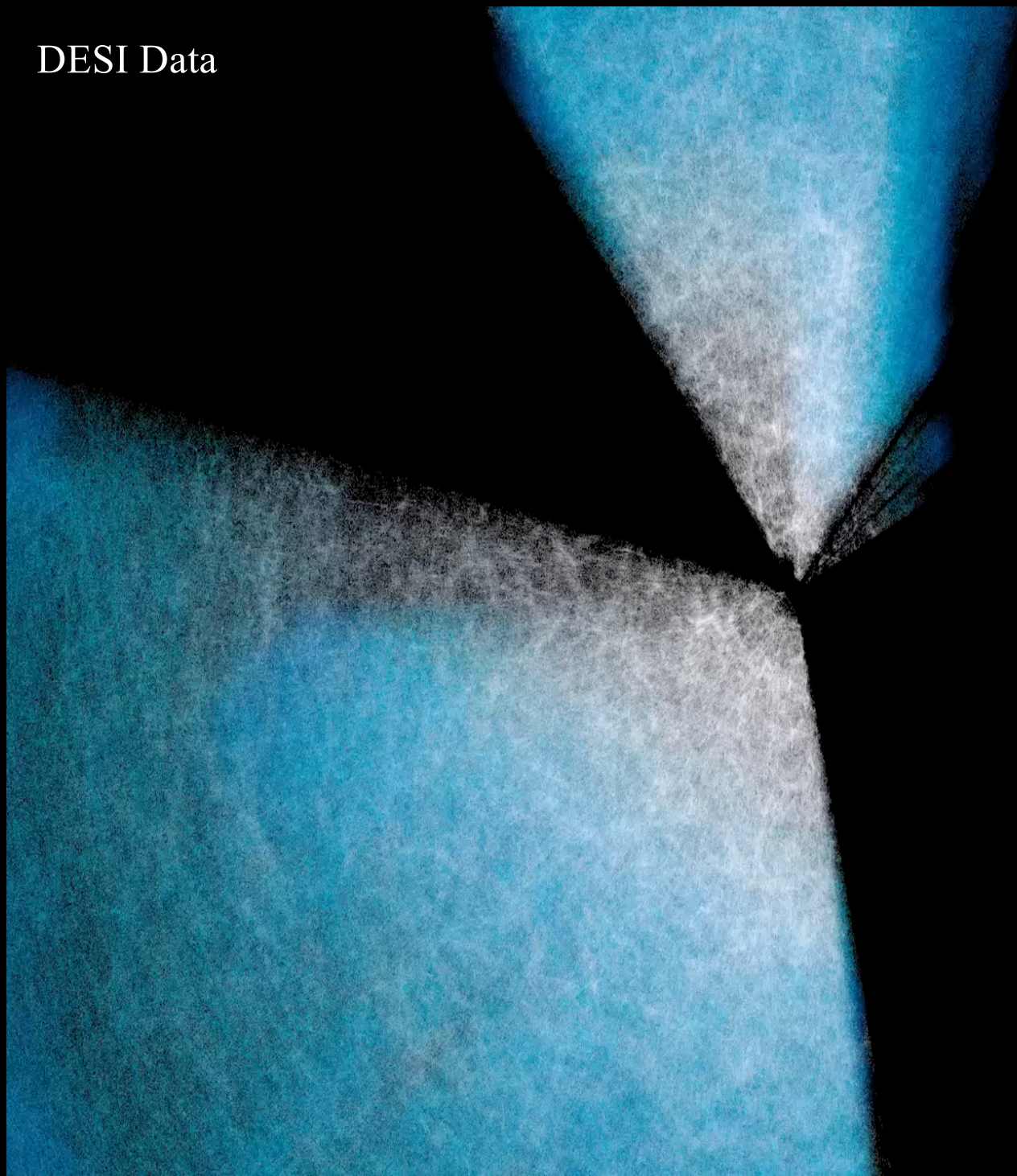
DESI Data

Slice of DESI observation

DESI created a 3-D map with over 47 million Galaxies and Quasars



DESI Data



DESI DR2

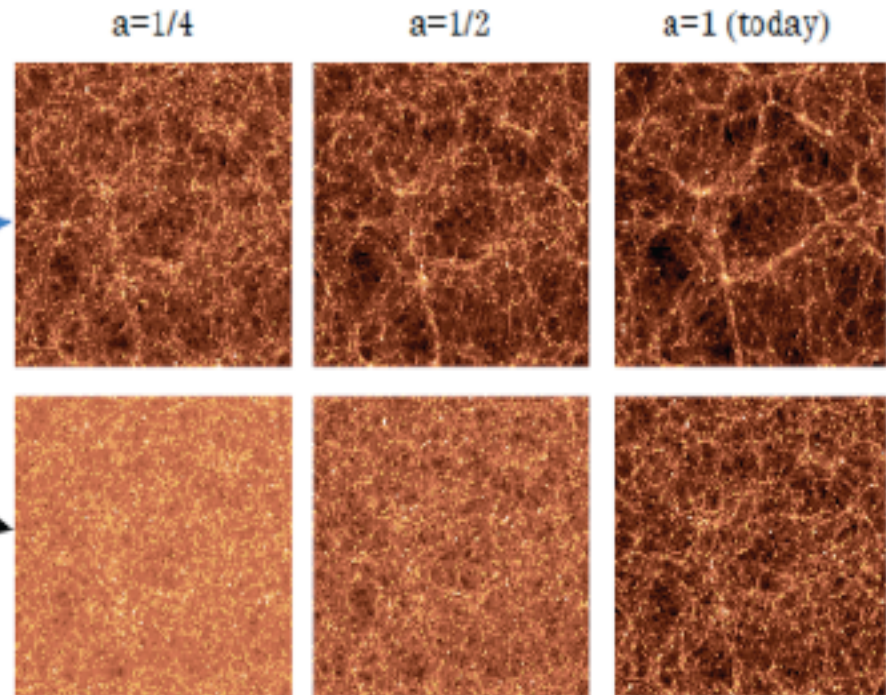
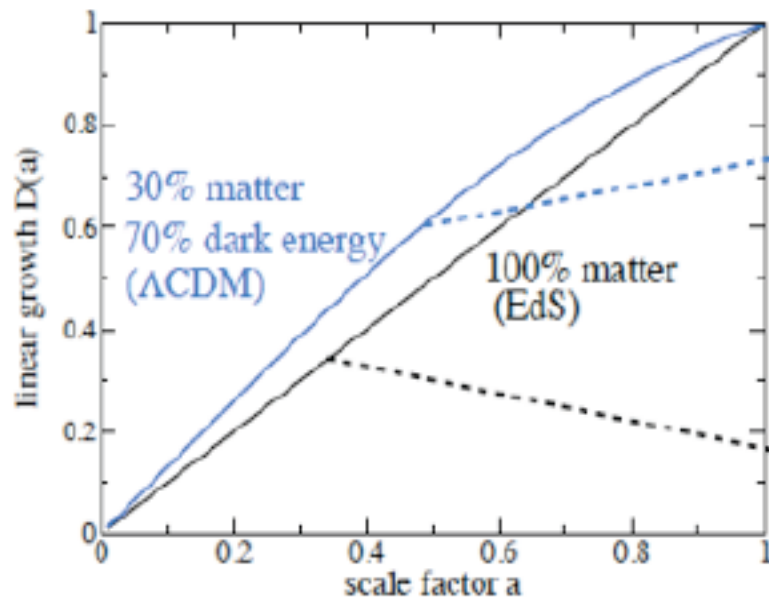
DESI Data

DESI Data



Structure growth as cosmological proves

Structure formation for different scales and models



Community Planning Study: [Snowmass 2013 ARXIV:1309.5385](#)

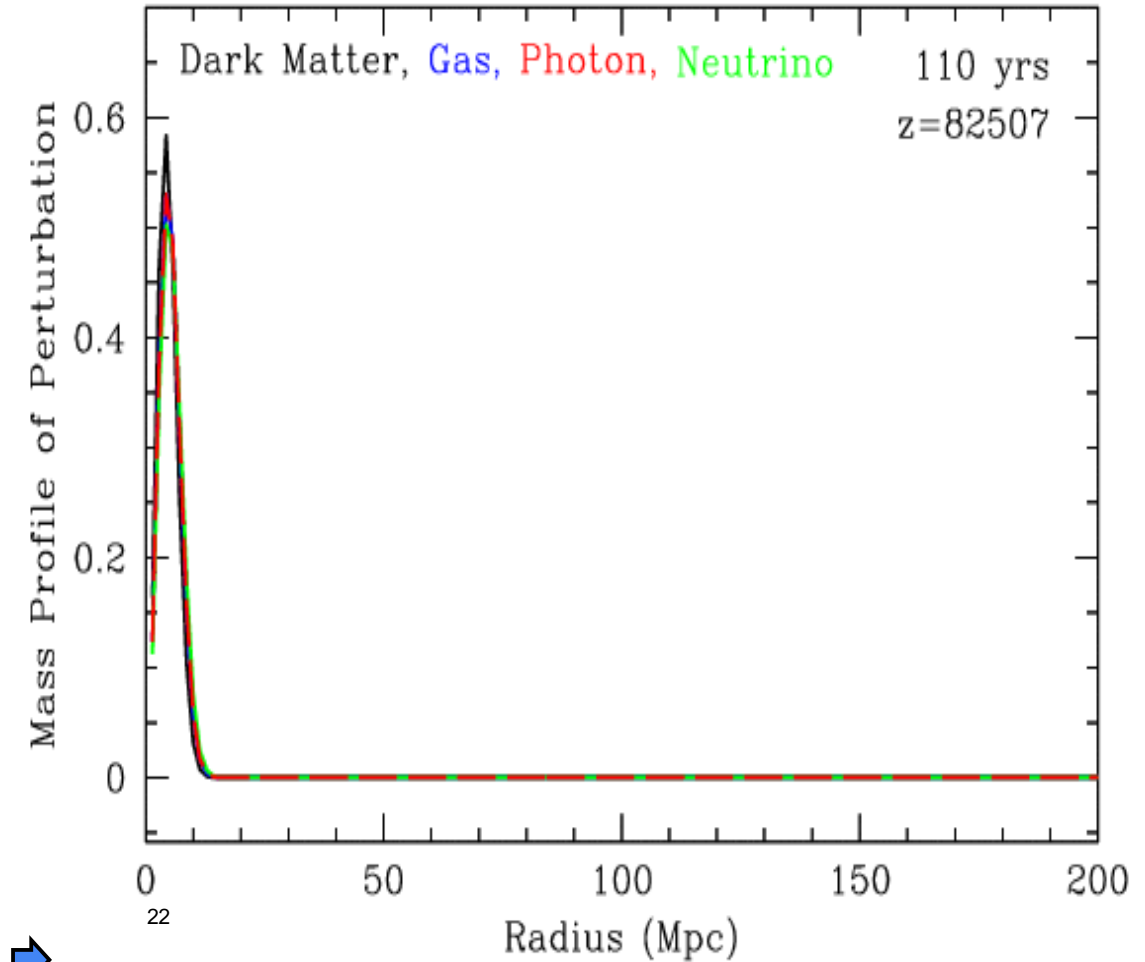
Linear Growth $D(a)$, $D(a=1)=1$

Snashots de 2 N-body simulaciones a diferentes tiempos, muestra fluctuaciones de densidad mayores en un modelo LCDM comparado con un universo dominado por materia (EdS).

Physics behind the Baryon Acoustic Oscillations “BAO”

BAO

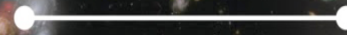
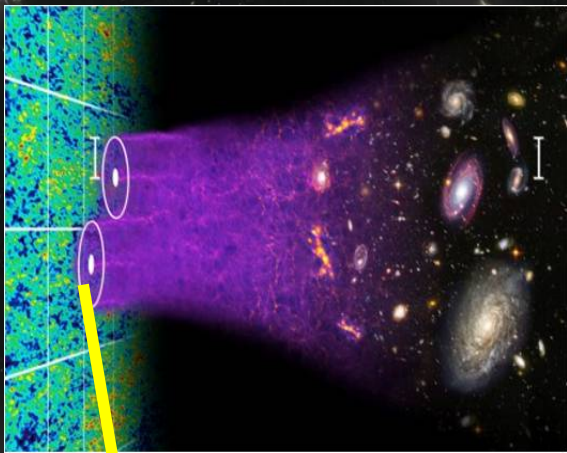
- Initial Fluctuations
- The universe expands and cools down, eventually forming atoms (mainly hydrogen)
- Once the energy of the photons do not longer ionize hydrogen atoms, photons decouple and stream away
- At this stage gravity prevails and forms spheres of matter with a radius given by the acoustic scale
- Matter is mainly distributed at the center of the spheres and at the acoustic scale radius
- The radius is 150Mpc/h



Spheres of Galaxies

- CMB anisotropies produce overdensities
- They will form structure (galaxies, clusters)

- Spheres grow due to the universe expansion
- We measure the size of these spheres at different distances (redshifts)
- We determine the universe expansion rate and infer the dynamics of Dark Energy

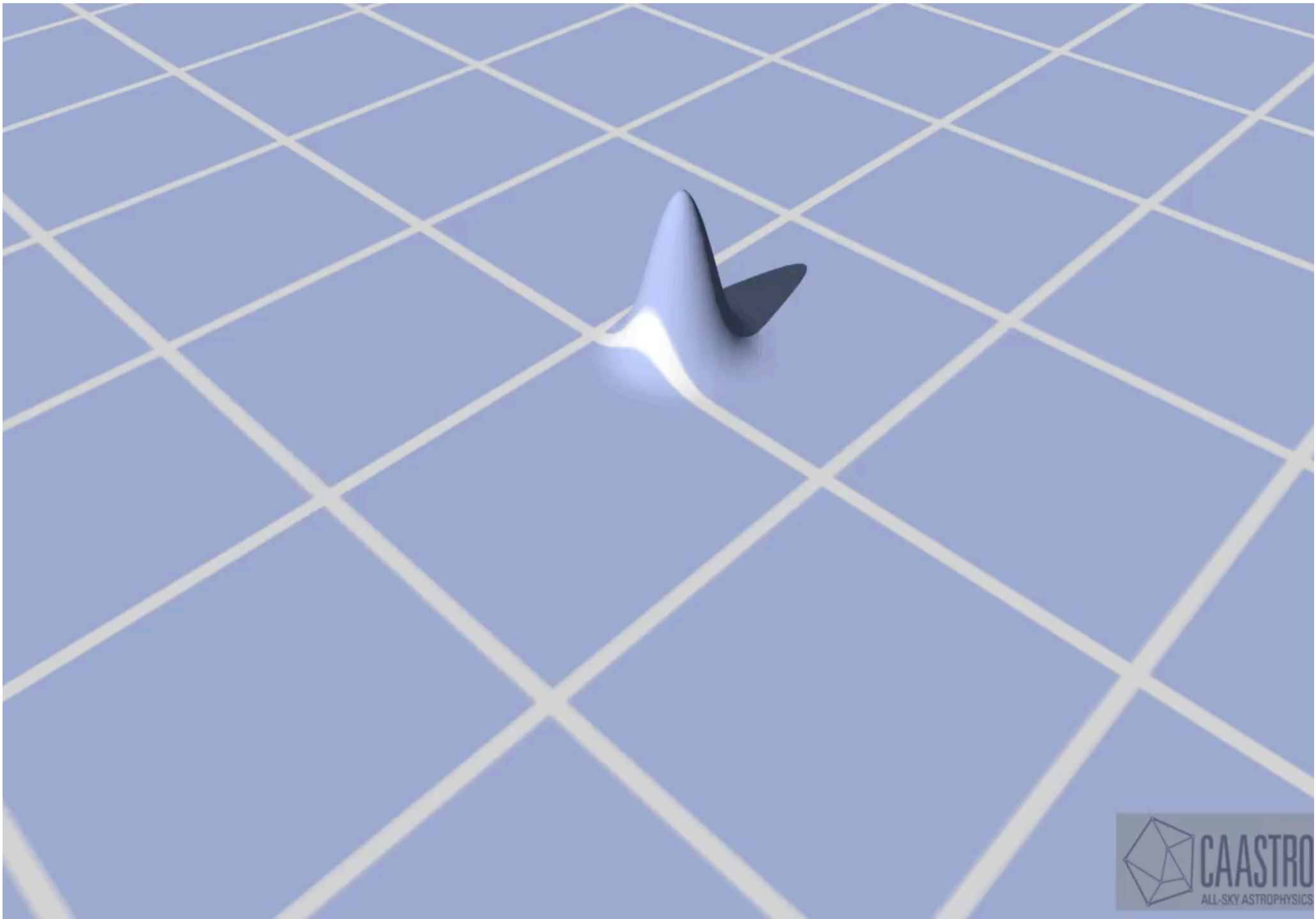




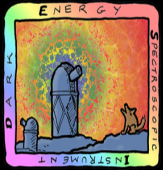
DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

“BAO” (oscillations in a lake)





Animation: Baryon Acoustic Oscillations (BAO) and 2 point de correlation function

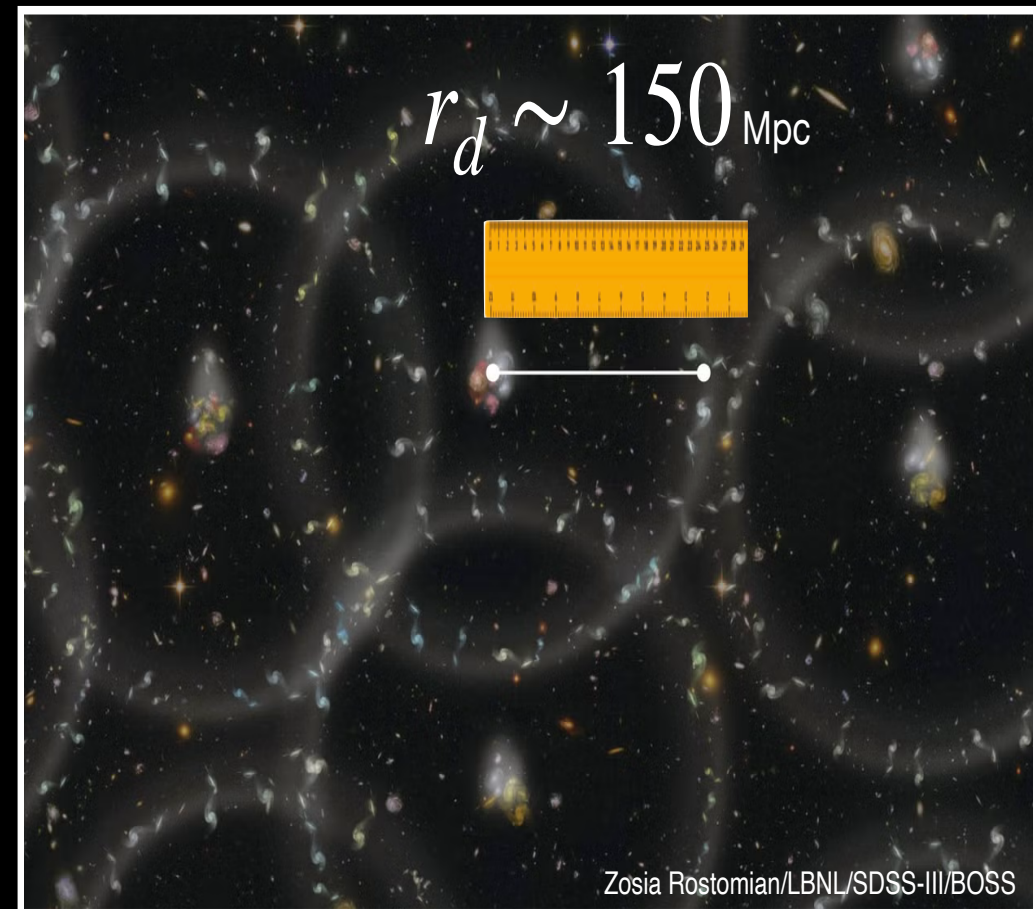
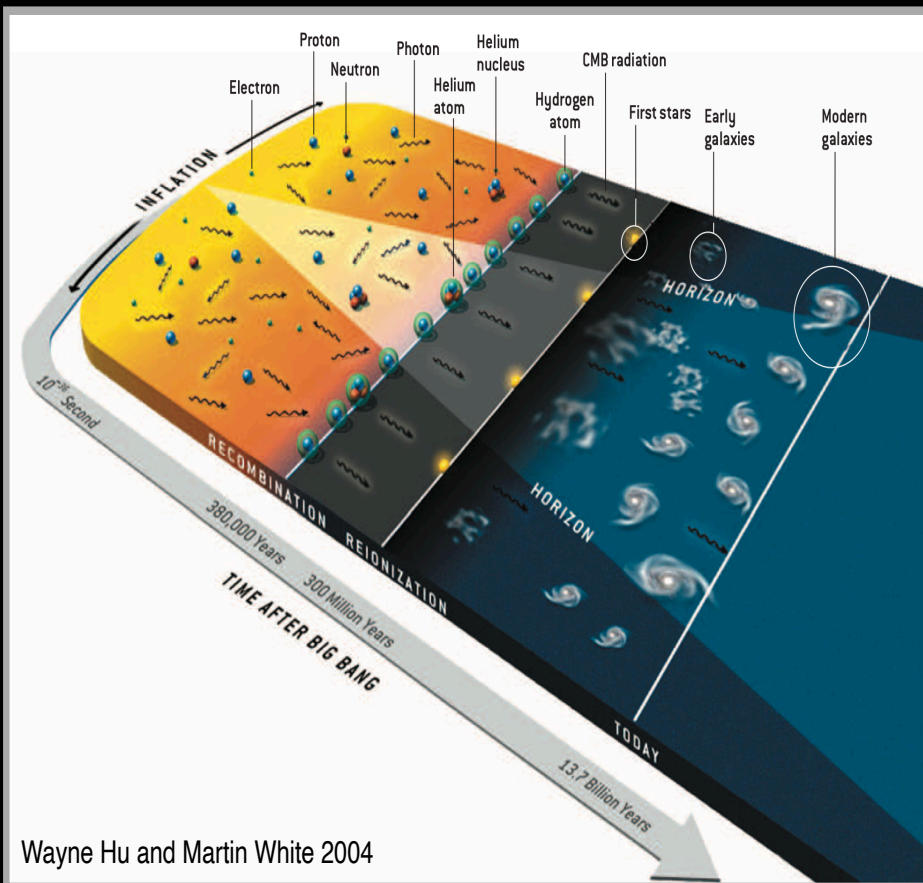


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

Baryon Acoustic Oscillations (BAO)

- Gravity and pressure generated sound waves in the primordial plasma
- When baryons and photons decoupled, the sound waves stopped

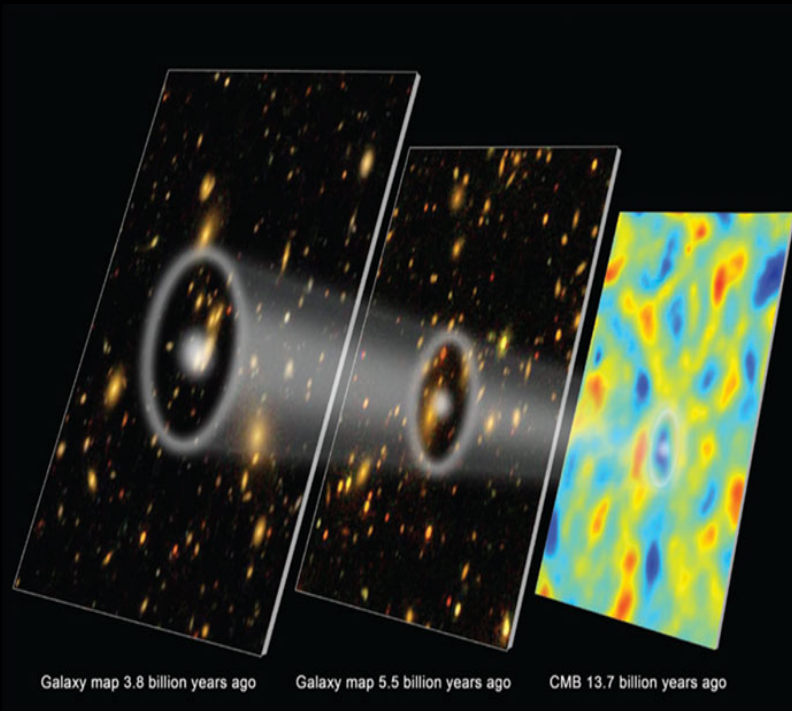




DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

Baryon Accoustic Oscillations

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



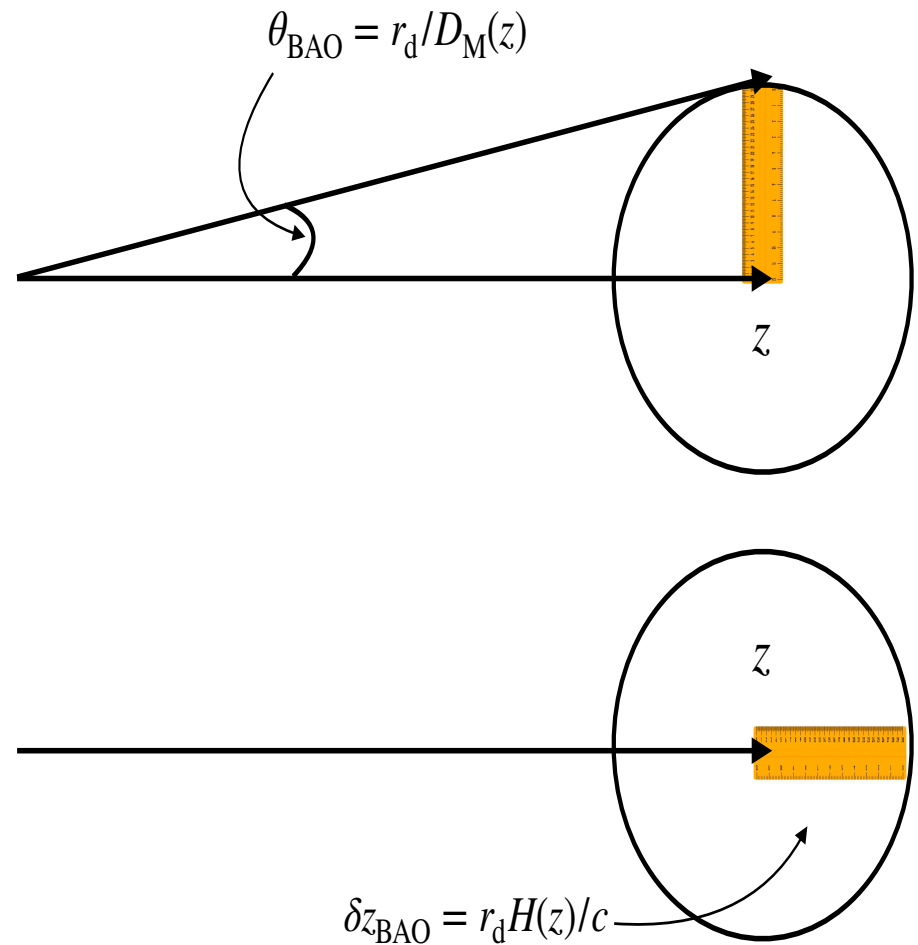
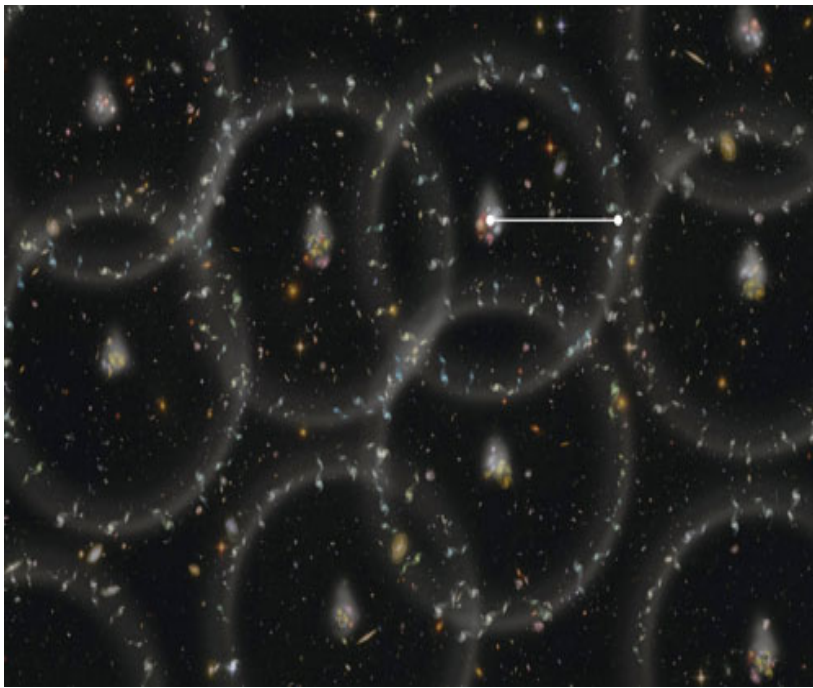
- Galaxies form in the overdense
- There is a 1% enhancement in spheres at 150 Mpc away from the initial overdensities.
- There should be a small excess of galaxies 150 Mpc away from other galaxies
- DESI measures these spheres ~ 150 Mpc
- This corresponds to a single *acoustic peak* in the correlation function of galaxies.



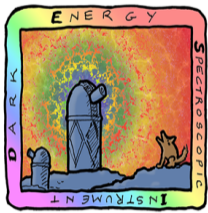
DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

The BAO standard ruler



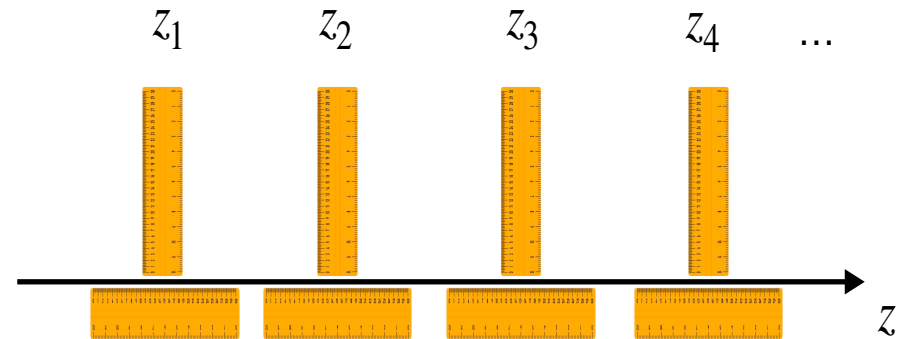
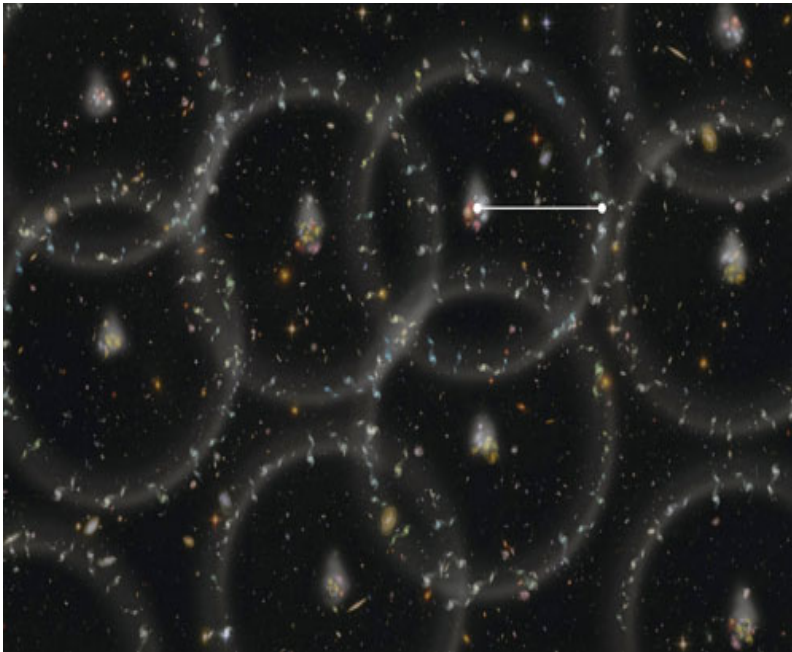
$D_M(z)$ and $H(z)$ encode **expansion history** of the Universe



DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

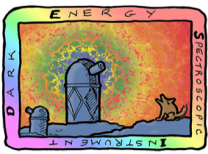
U.S. Department of Energy Office of Science

The BAO standard ruler



DESI measures BAO rulers at many times/redshifts

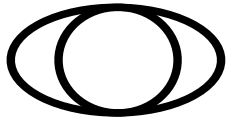
$D_M(z)$ and $H(z)$ encode **expansion history** of the Universe



DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

Scaling parameters



perpendicular ruler size

$$\alpha_{\perp} = \frac{D_M}{r_d} \frac{r_d^{\text{fid}}}{D_M^{\text{fid}}}$$

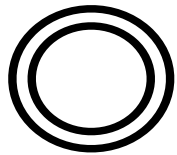
and

$$\alpha_{\parallel} = \frac{D_H}{r_d} \frac{r_d^{\text{fid}}}{D_H^{\text{fid}}}$$



line-of-sight ruler size

OR

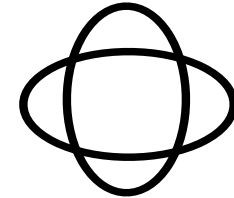


overall scale of BAO

$$\alpha_{\text{iso}} = \left(\alpha_{\perp}^2 \alpha_{\parallel} \right)^{1/3}$$

and

$$\alpha_{\text{AP}} = \frac{D_H}{D_M} \frac{D_M^{\text{fid}}}{D_H^{\text{fid}}}$$



anisotropy of BAO

$$D_M(z) = \frac{c}{H_0 \sqrt{\Omega_K}} \sinh \left[\sqrt{\Omega_K} \int_0^z \frac{dz'}{H(z')/H_0} \right]$$

$$D_H = c / H(z)$$

Λ CDM is

$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_R (1+z)^4 + \Omega_K (1+z)^2 + \Omega_{\Lambda}}.$$

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

$$r_d = \frac{147.05}{\text{Mpc}} \left(\frac{\omega_m}{0.1432} \right)^{-0.23} \left(\frac{N_{\text{eff}}}{3.04} \right)^{-0.1} \left(\frac{\omega_b}{0.02236} \right)^{-0.13}$$

A long-exposure photograph of a night sky filled with star trails, creating a dense pattern of concentric arcs. In the foreground, the silhouettes of several astronomical observatory domes are visible, some illuminated with red light. The background shows a distant cityscape and a body of water under a dark sky.

Main Results

I. Λ CDM constraints

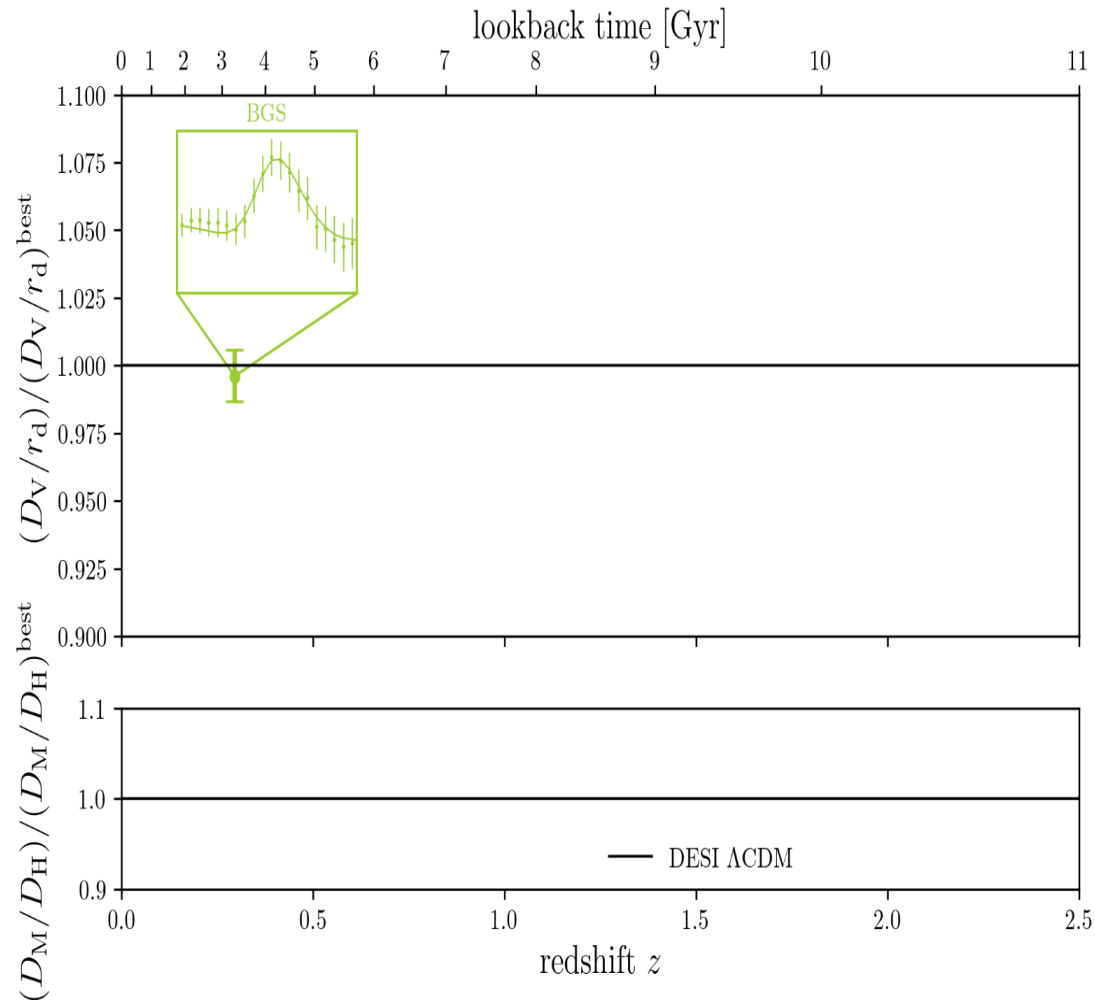


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

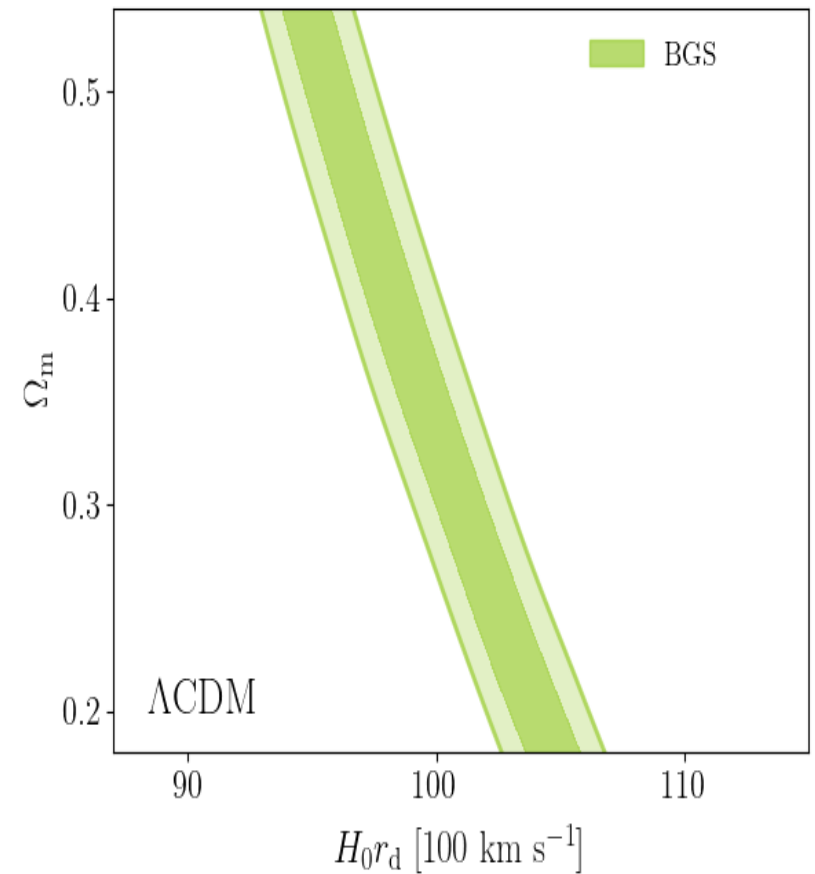
U.S. Department of Energy Office of Science

DESI DR2 BAO

DESI BAO measurements



Flat Λ CDM results



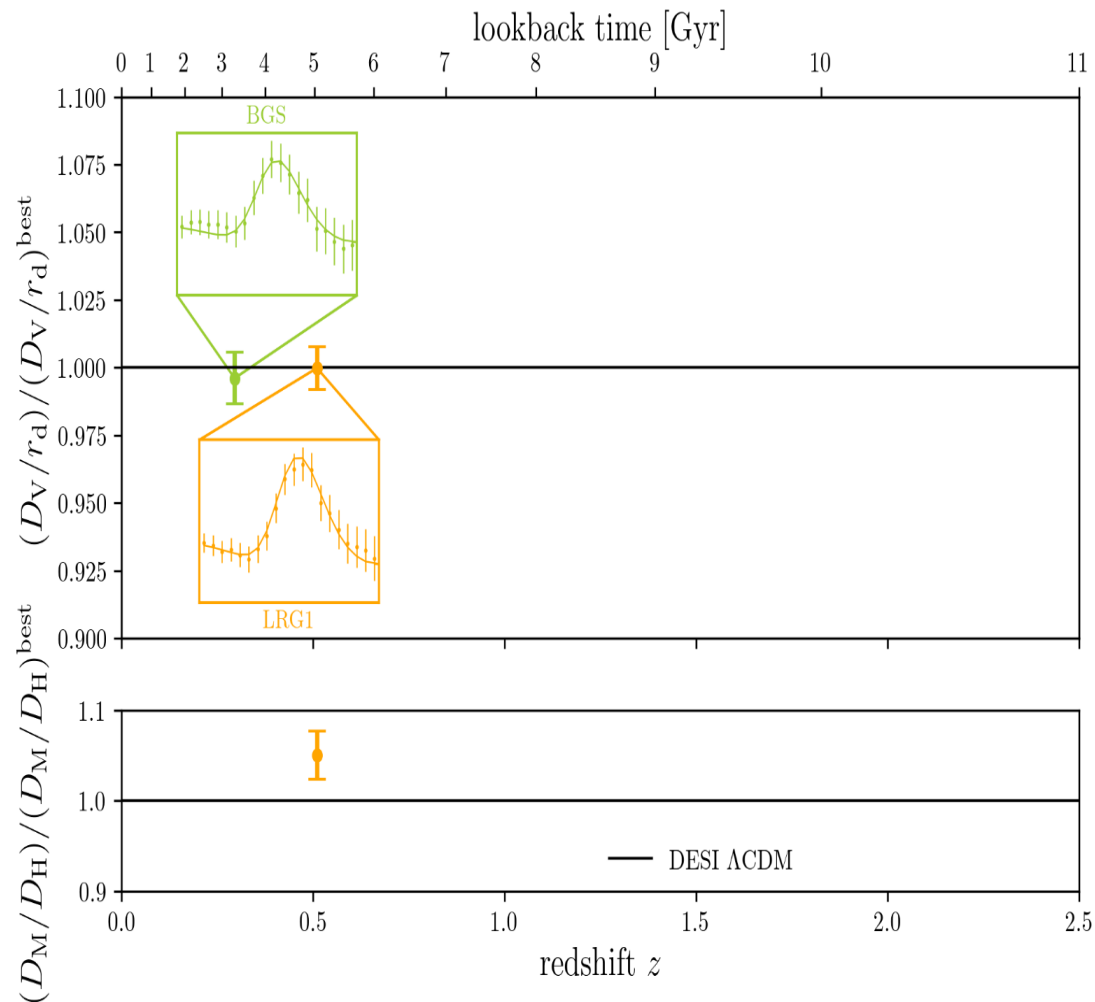


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

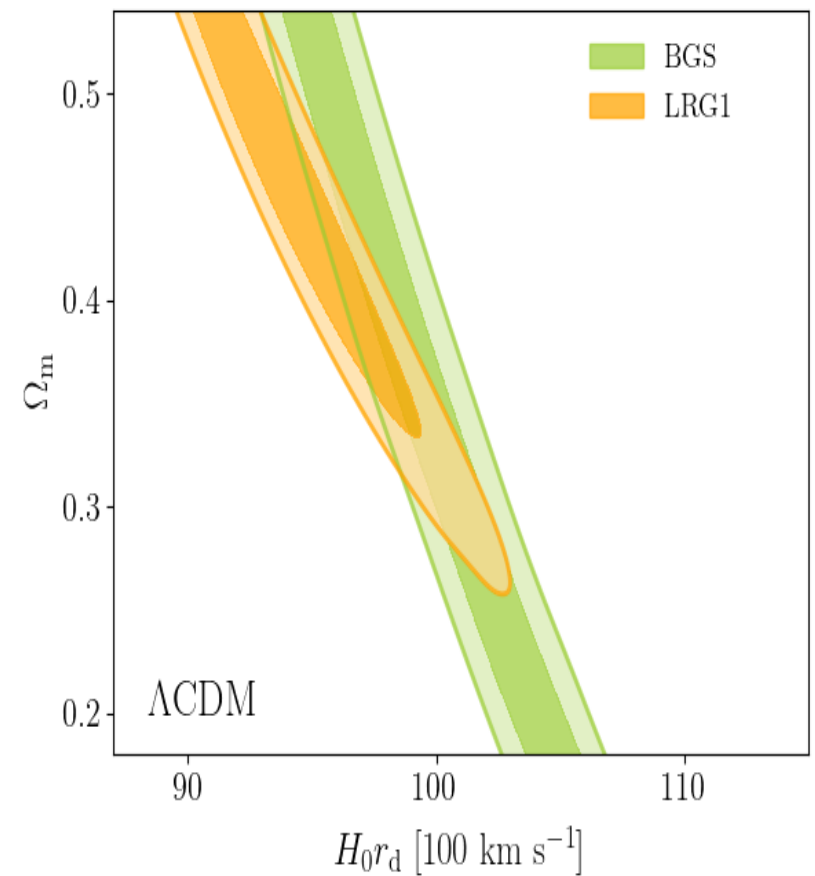
U.S. Department of Energy Office of Science

DESI DR2 BAO

DESI BAO measurements



Flat Λ CDM results



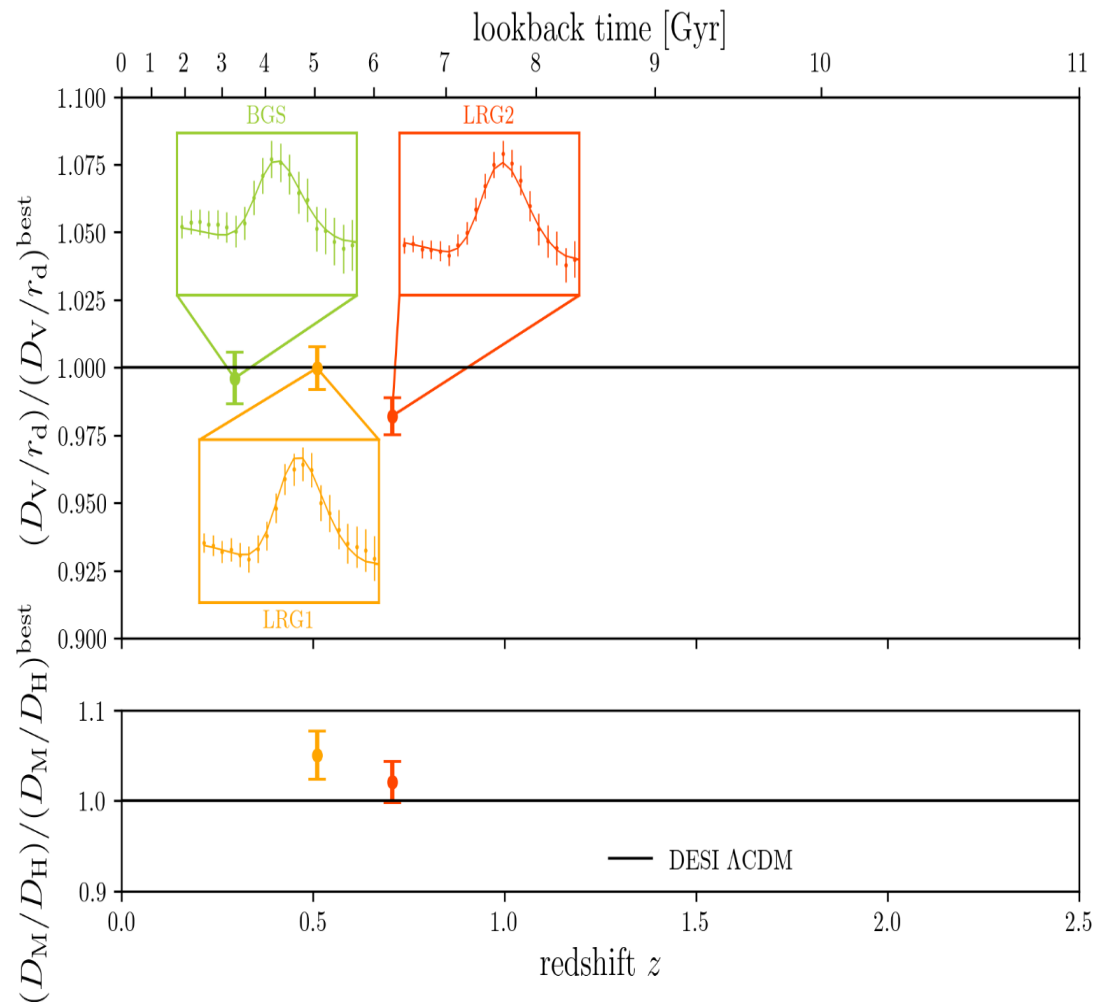


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

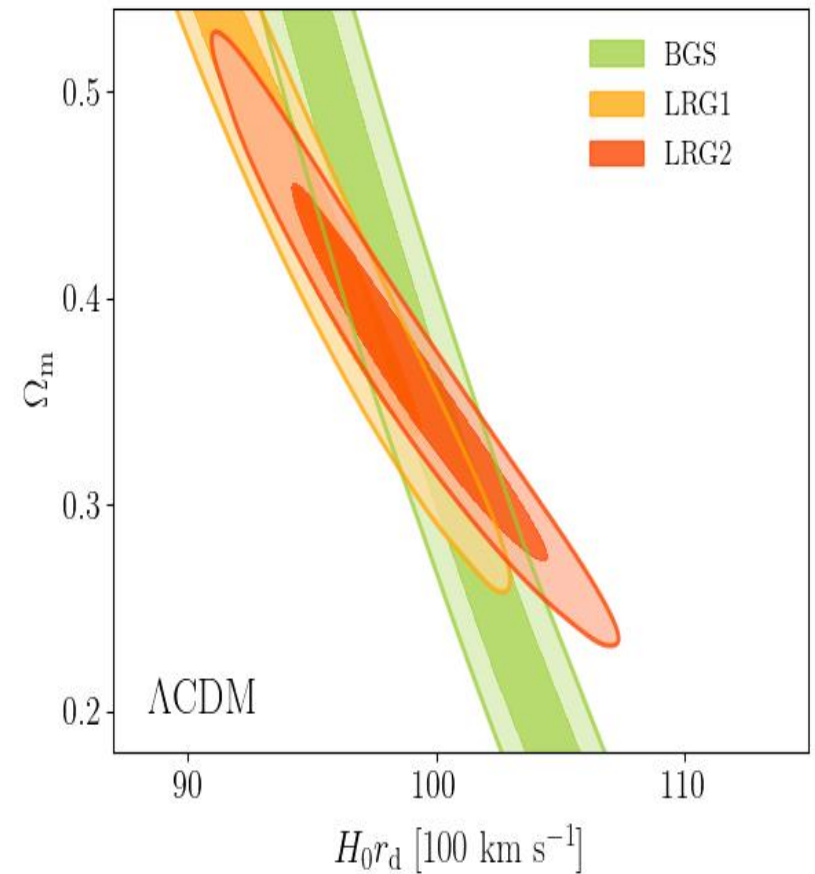
U.S. Department of Energy Office of Science

DESI DR2 BAO

DESI BAO measurements



Flat Λ CDM results



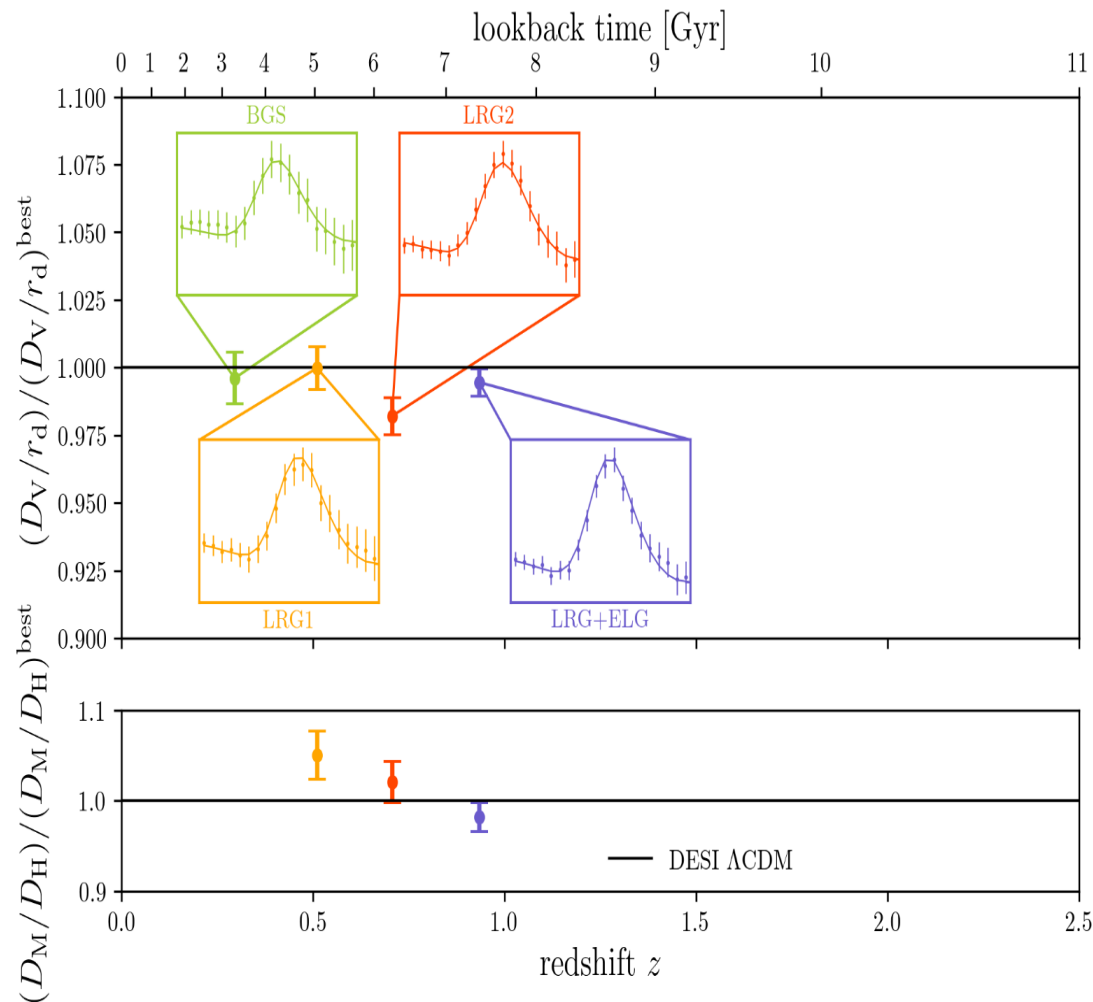


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

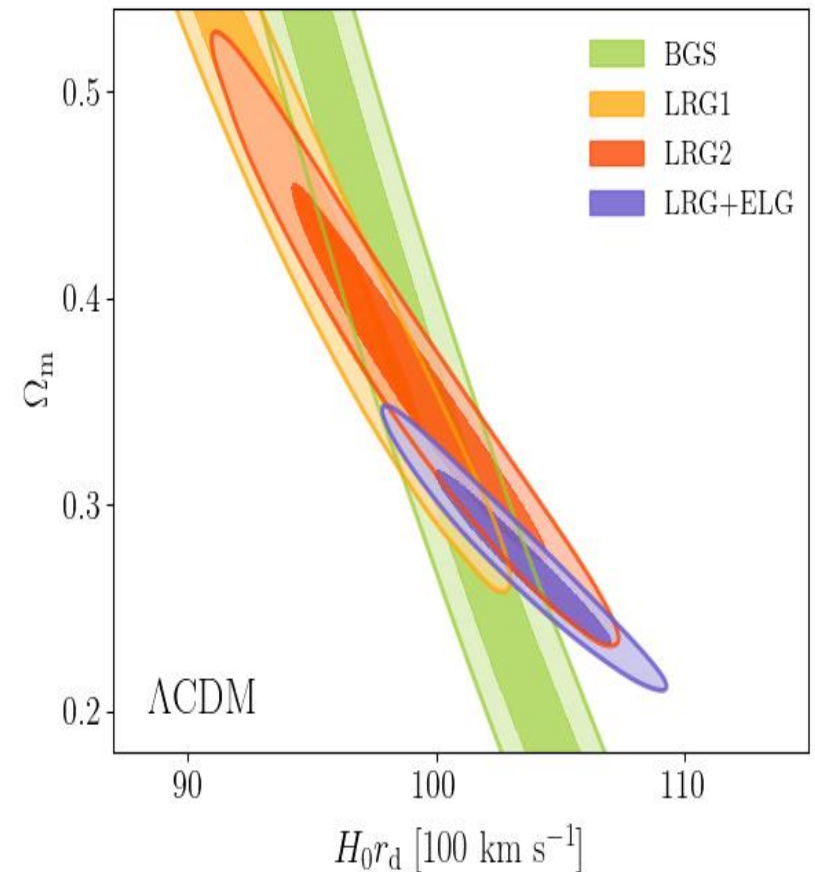
DESI DR2 BAO

U.S. Department of Energy Office of Science

DESI BAO measurements



Flat Λ CDM results



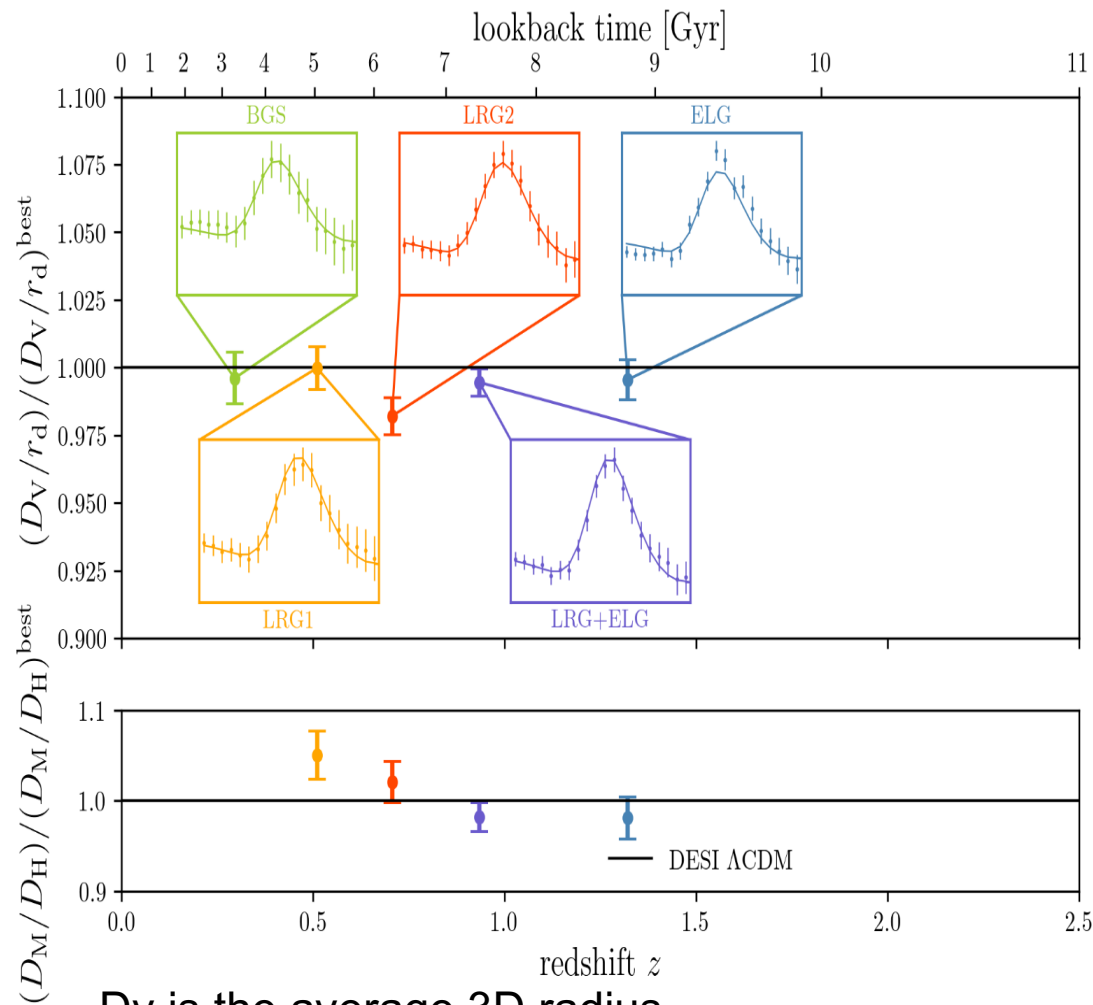


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

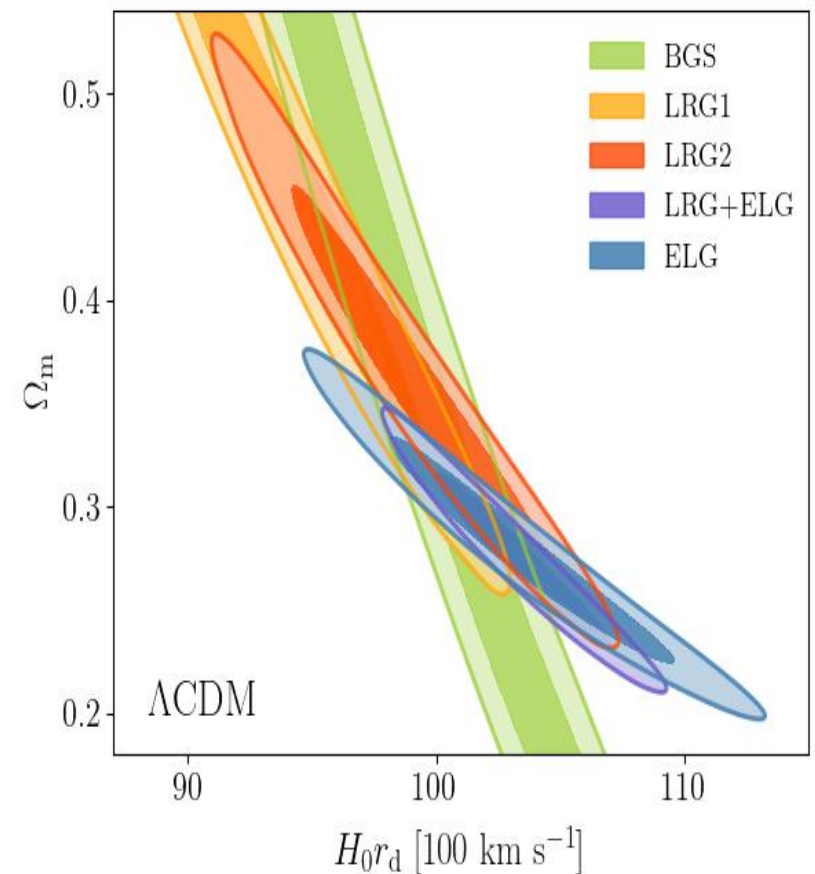
DESI DR2 BAO

DESI BAO measurements



D_V is the average 3D radius

Flat Λ CDM results





DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

DESI DR2 BAO

DESI BAO measurements

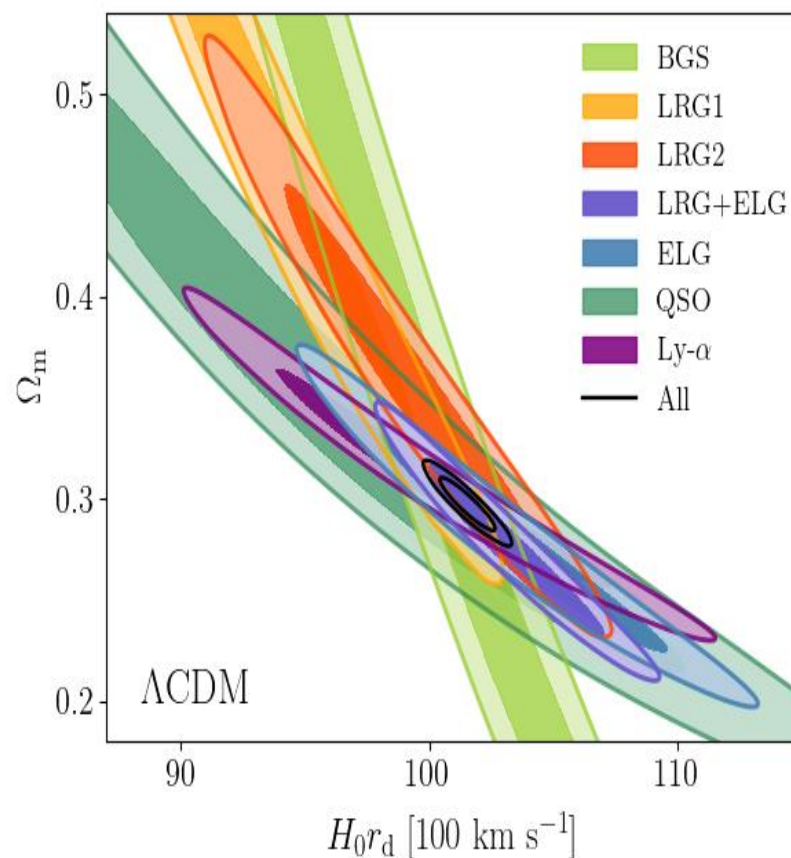
Consistent with each other,
and complementary

$$\Omega_m = 0.2975 \pm 0.0086 \quad (2.9\%)$$

$$H_0 r_d = (101.54 \pm 0.73) [100 \text{ km/s}] \quad (0.7\%)$$

DESI

Flat Λ CDM results



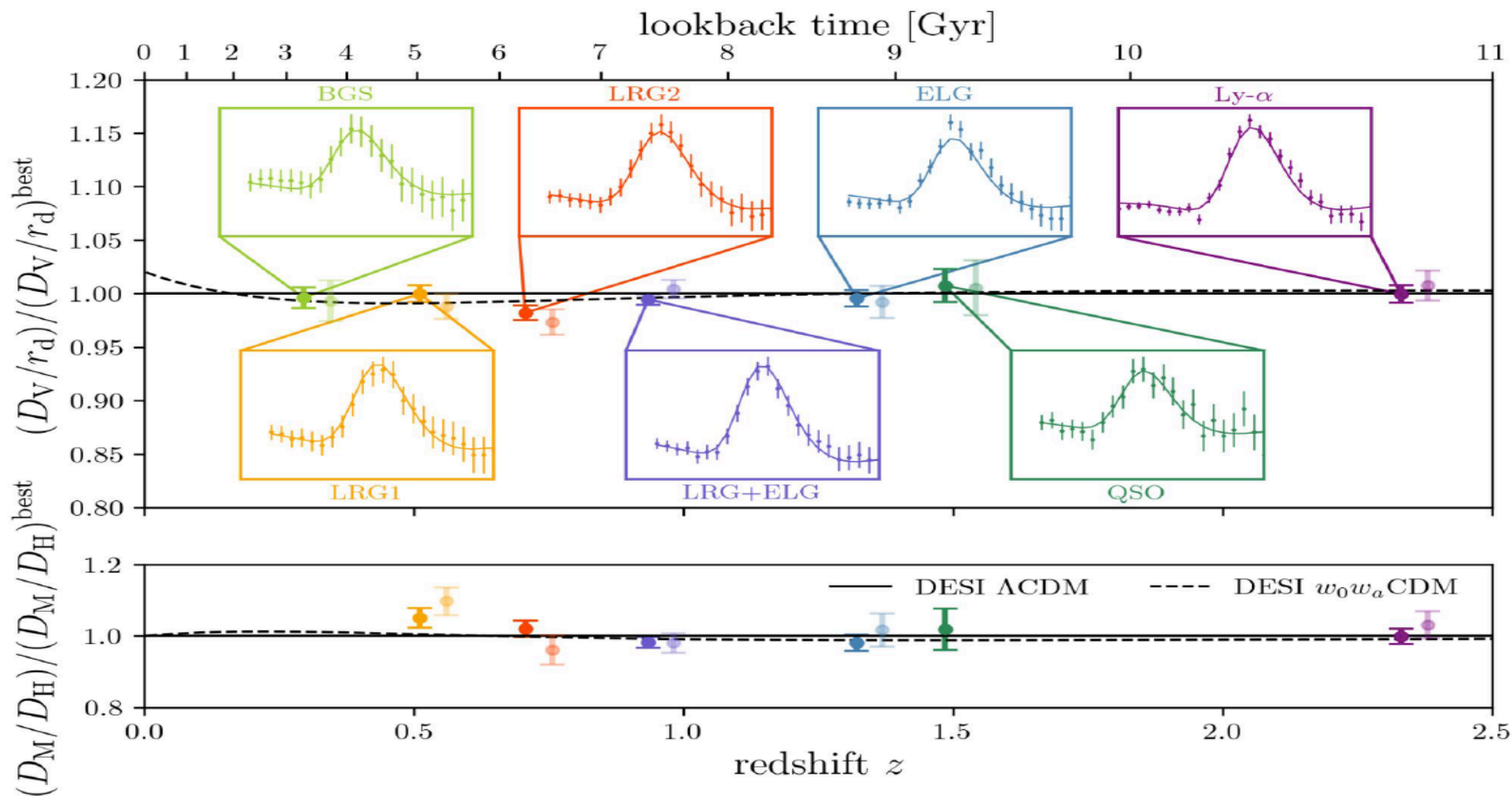


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

BAO measurements from DESI DR2

Baryon Acoustic Oscillations for different tracers



BGS= Bright Galaxy Survey,
LRG = Luminous Red Galaxies,

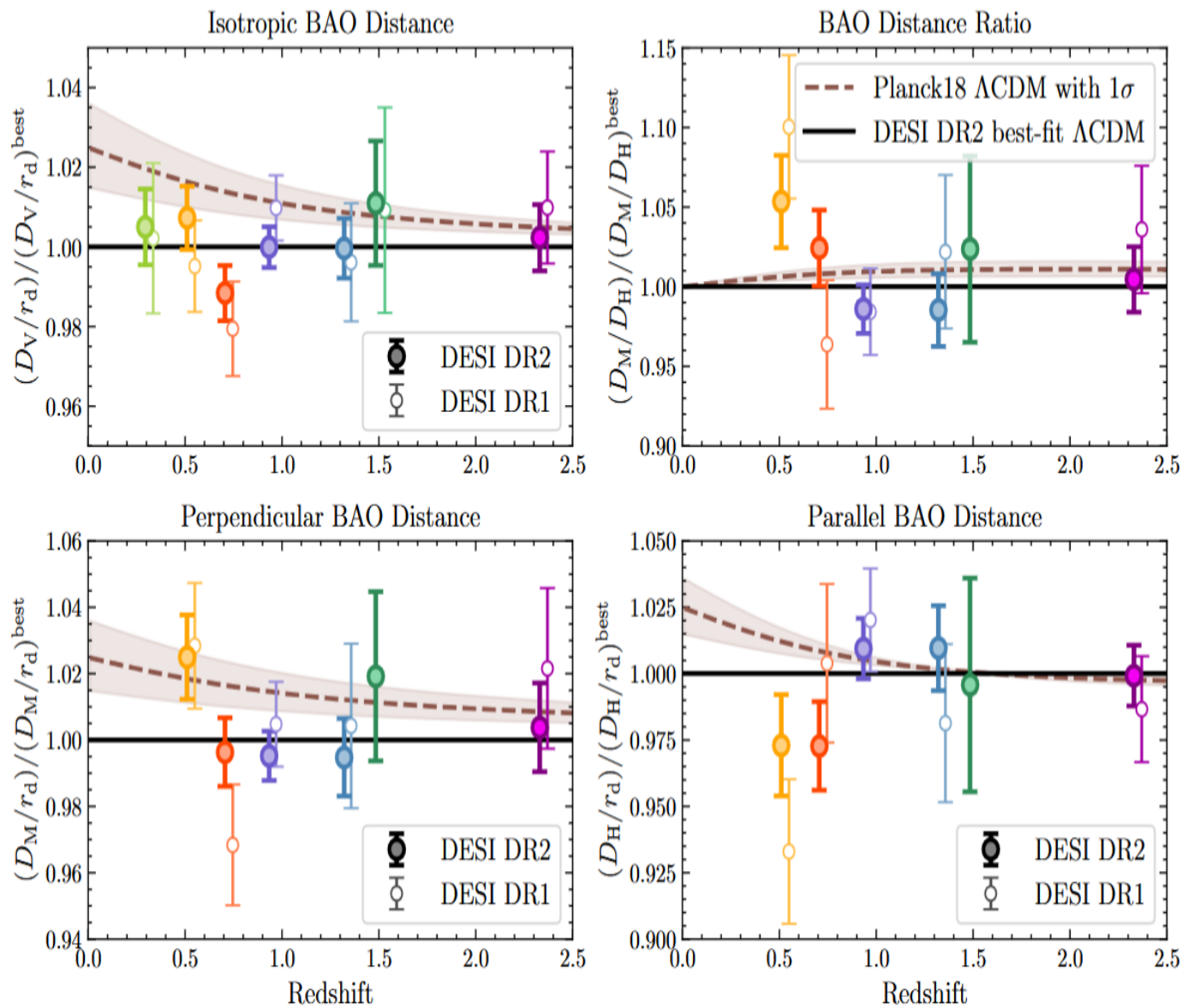
ELG = Emission Line Galaxy,
QSO = Quasars

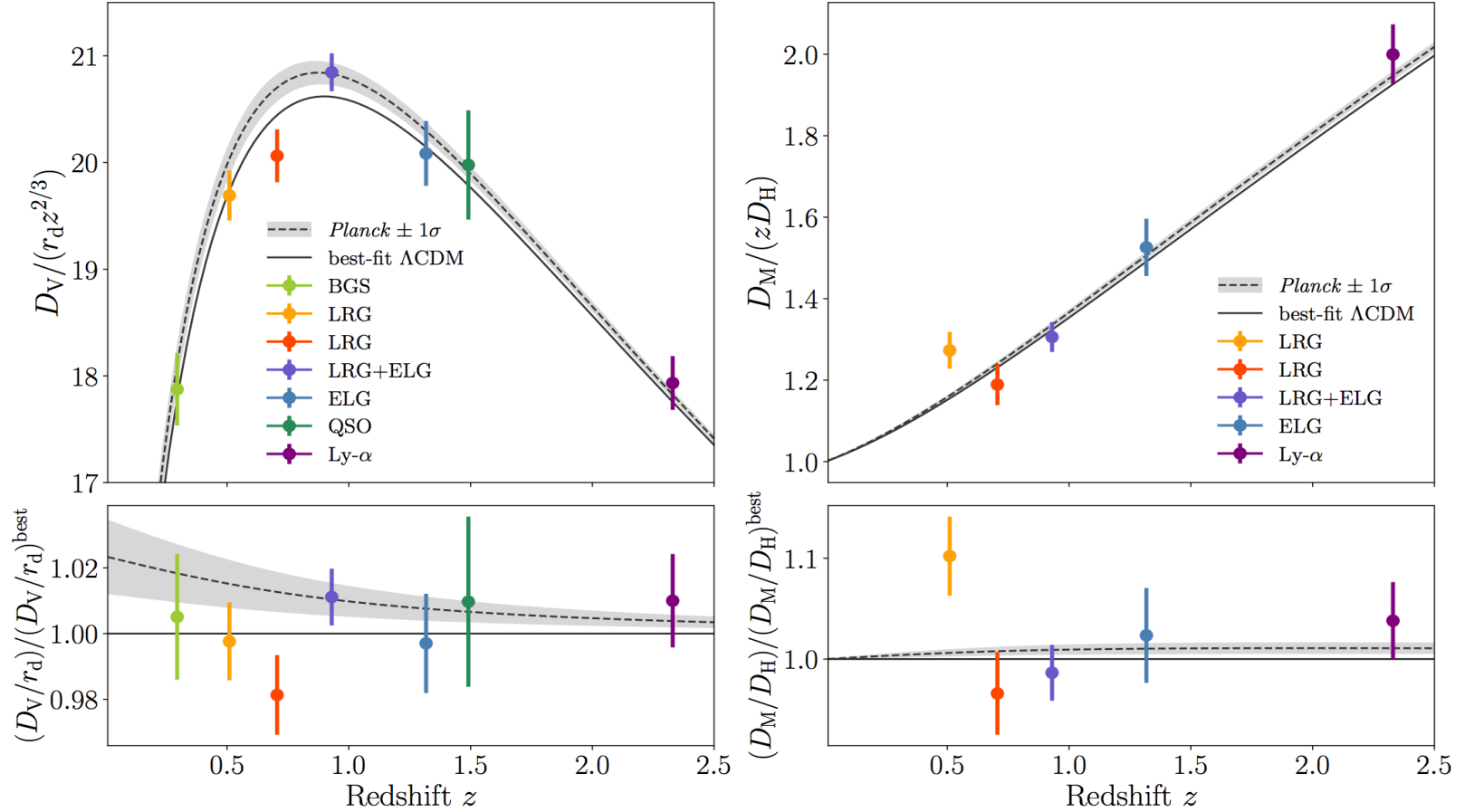


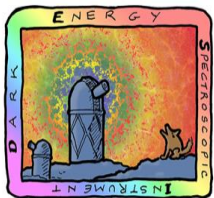
DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

BAO Distance measurements







DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

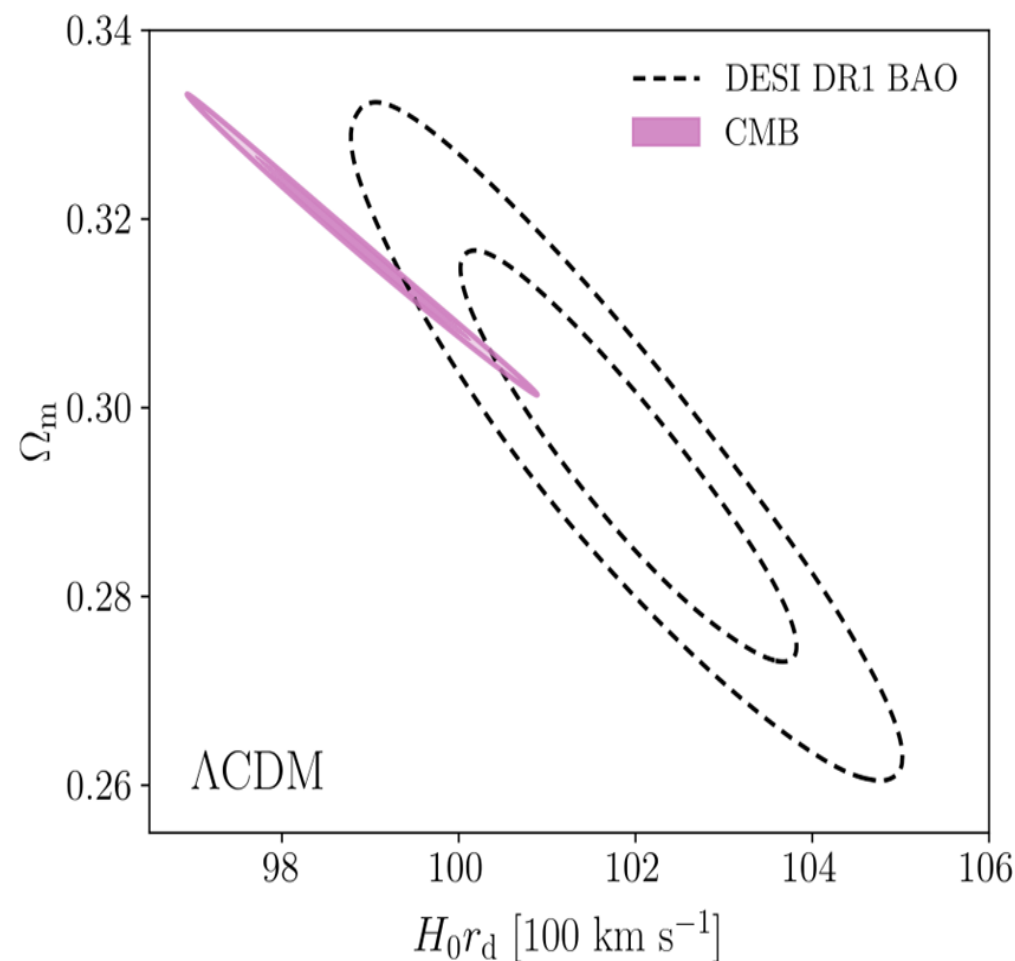
U.S. Department of Energy Office of Science

Λ CDM: Consistency with the CMB

DESI DR1 BAO was 1.9σ from the **CMB**

CMB includes:

- primary CMB from Planck PR4 (CamSpec)
- CMB lensing from Planck PR4 + ACT





DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

Λ CDM: Consistency with the CMB

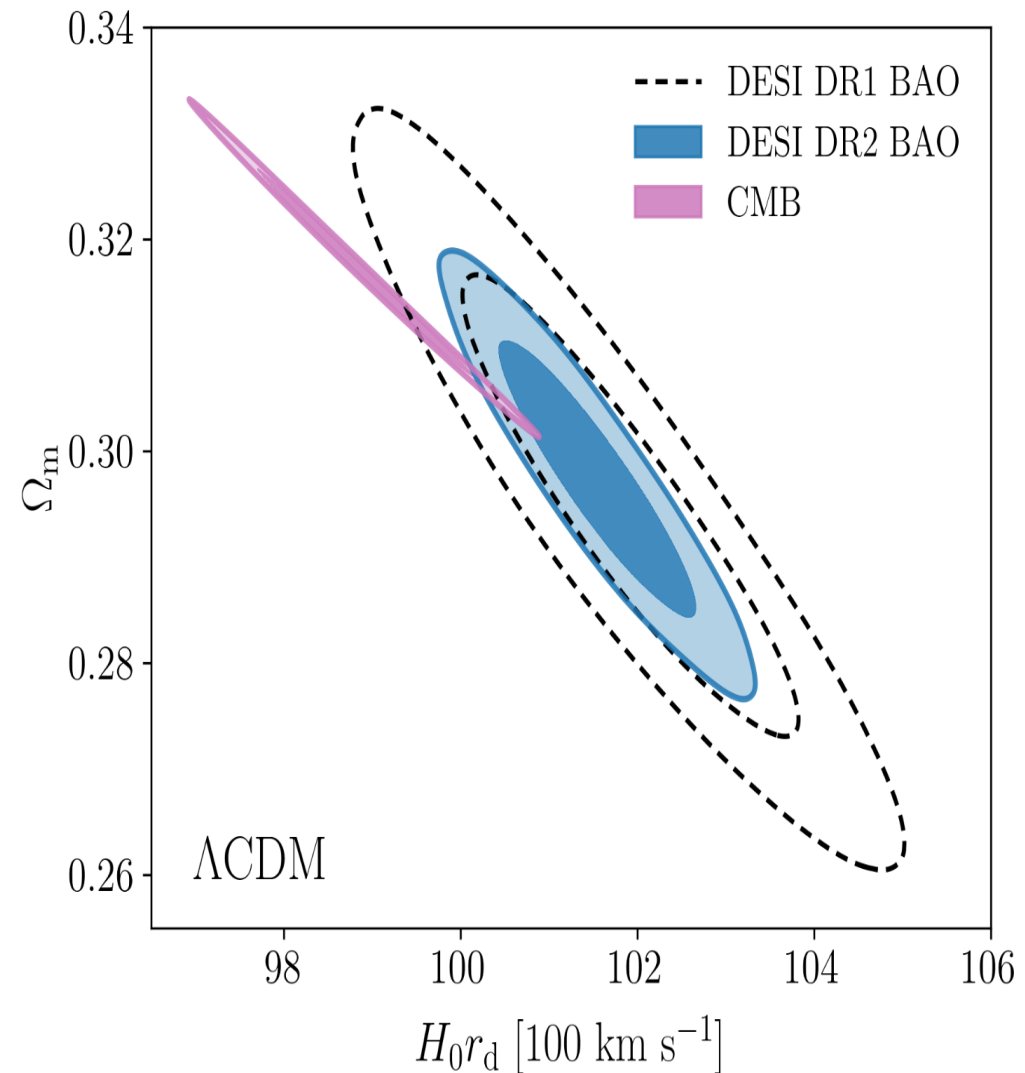
DESI DR1 BAO was 1.9σ from the **CMB**

CMB includes:

- primary CMB from Planck PR4 (CamSpec)
- CMB lensing from Planck PR4 + ACT DR6

DESI DR2 BAO is:

- Consistent with **DESI DR1**
- 2.3σ from the **CMB**



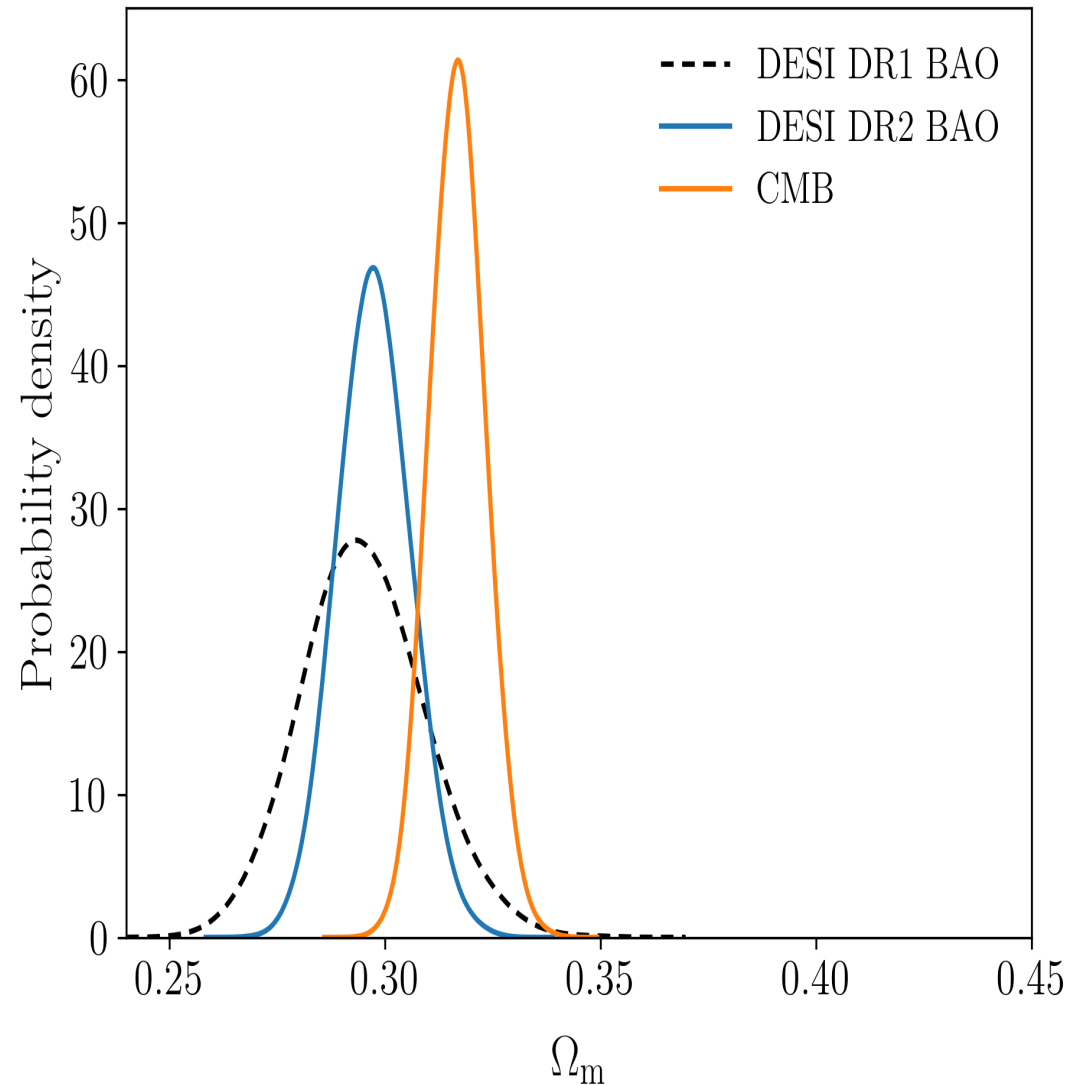


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

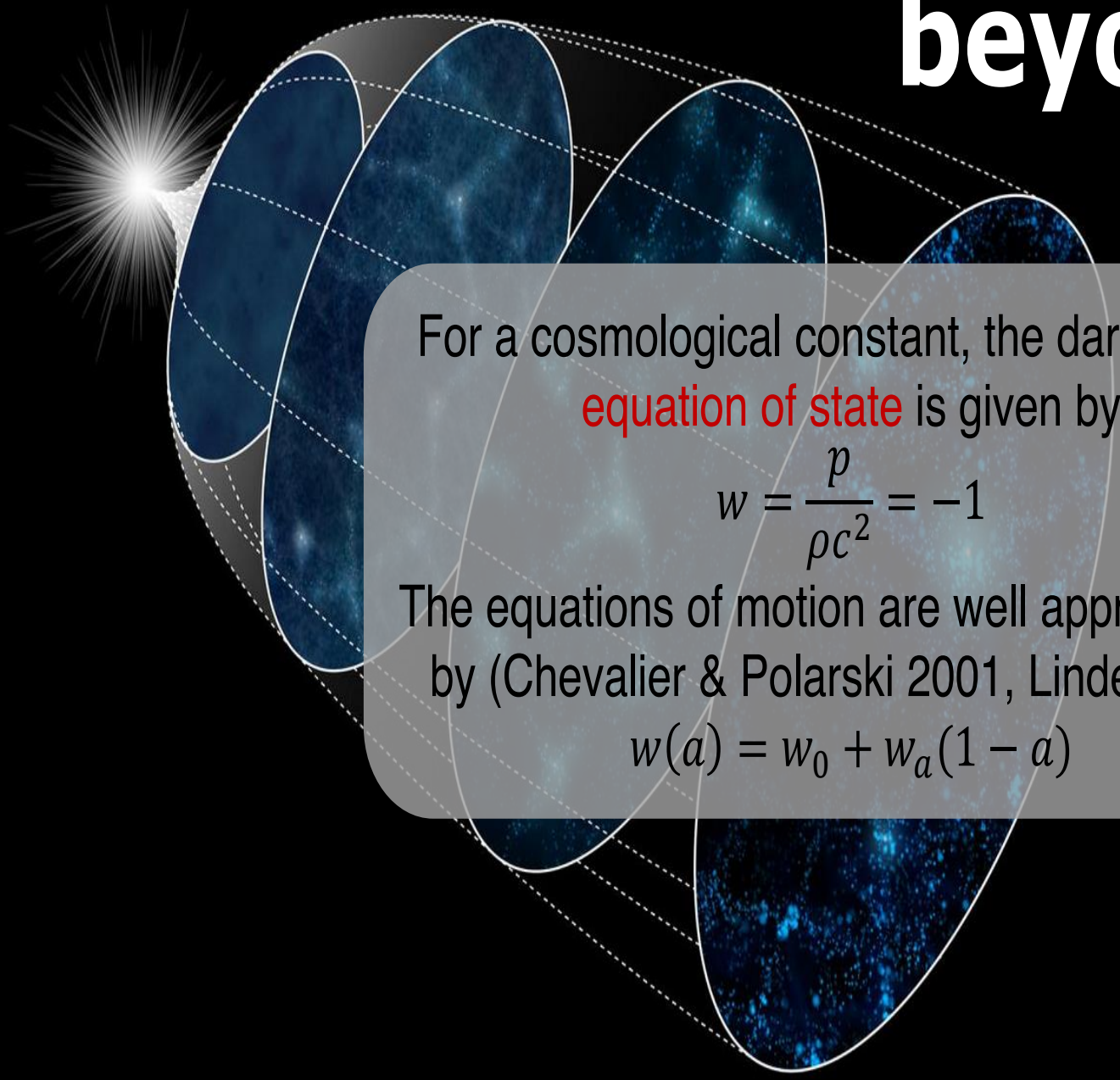
U.S. Department of Energy Office of Science

Λ CDM: Consistency with Supernovae

- **DESI DR2** consistent with DESI DR1
- **DESI DR2** is lower than the **CMB**



II. Dark Energy beyond Λ CDM



For a cosmological constant, the dark energy
equation of state is given by

$$w = \frac{p}{\rho c^2} = -1$$

The equations of motion are well approximated
by (Chevalier & Polarski 2001, Linder 2003)

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



DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

Evolving Dark Energy

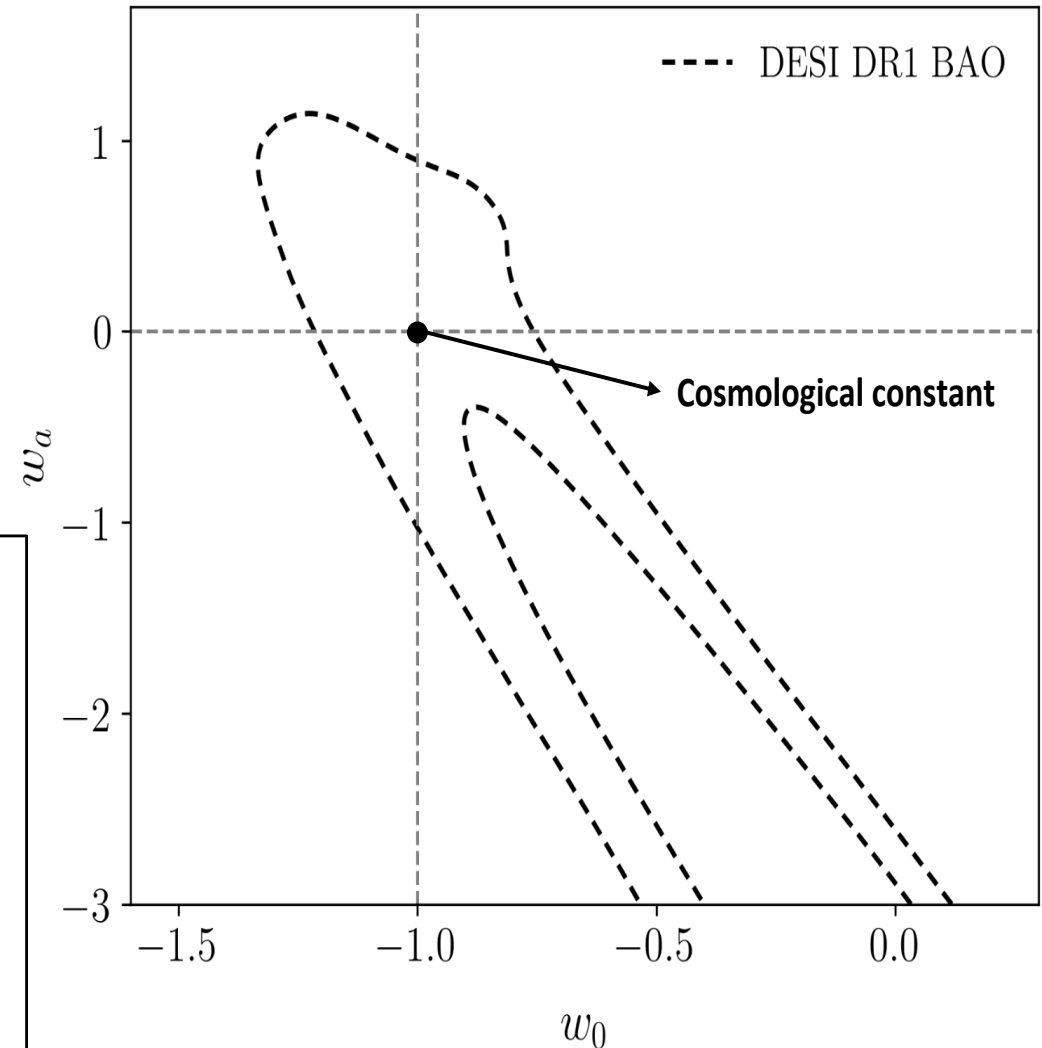
- BAO data define a degeneracy direction in the $w_0 - w_a$ plane

where the equation of state w is parametrized by:

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

w_0 present day value

w_a 1st derivative present day



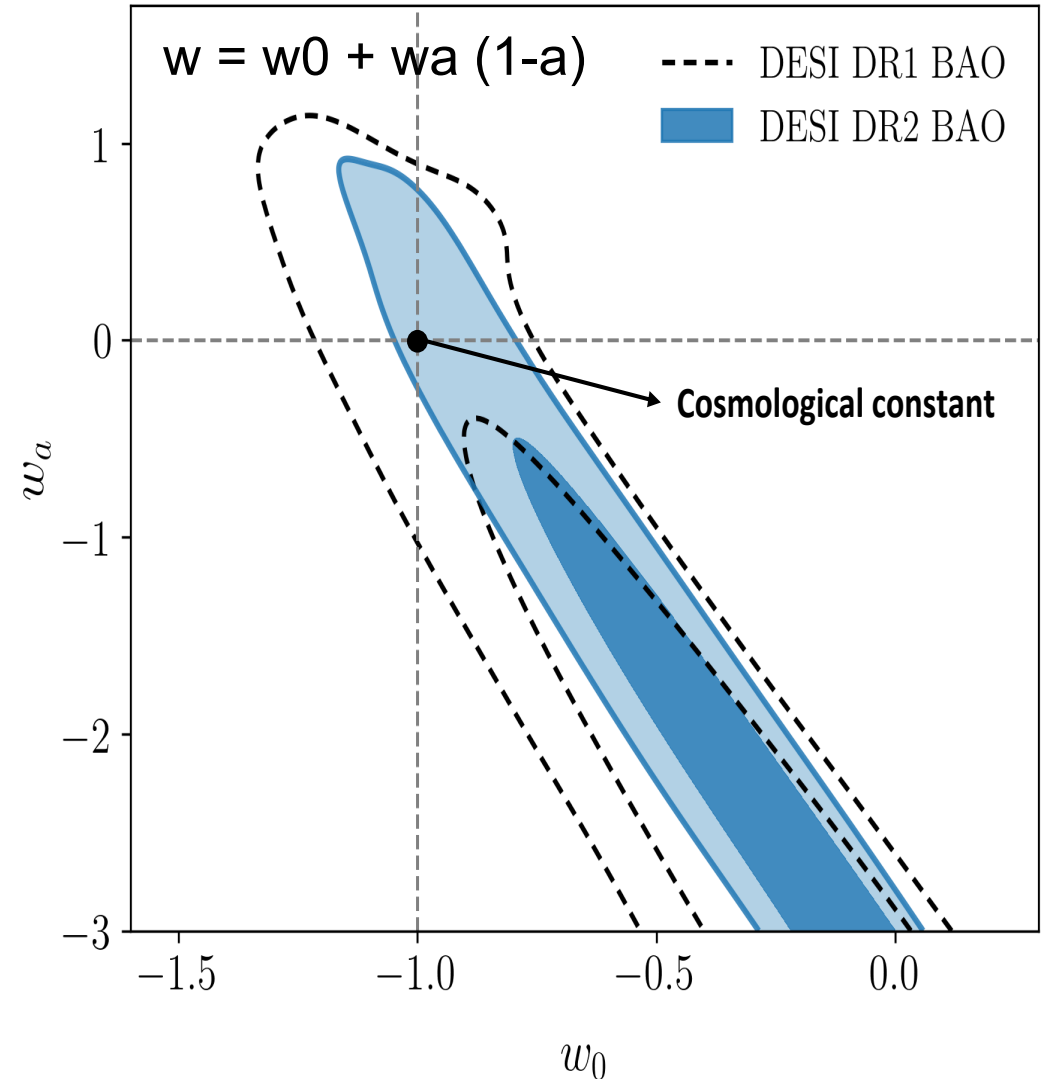


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

Evolving Dark Energy

- BAO data define a degeneracy direction in the $w_0 - w_a$ plane
- DESI DR2 still within 2σ of Λ CDM
- Need to combine with other probes to break this degeneracy



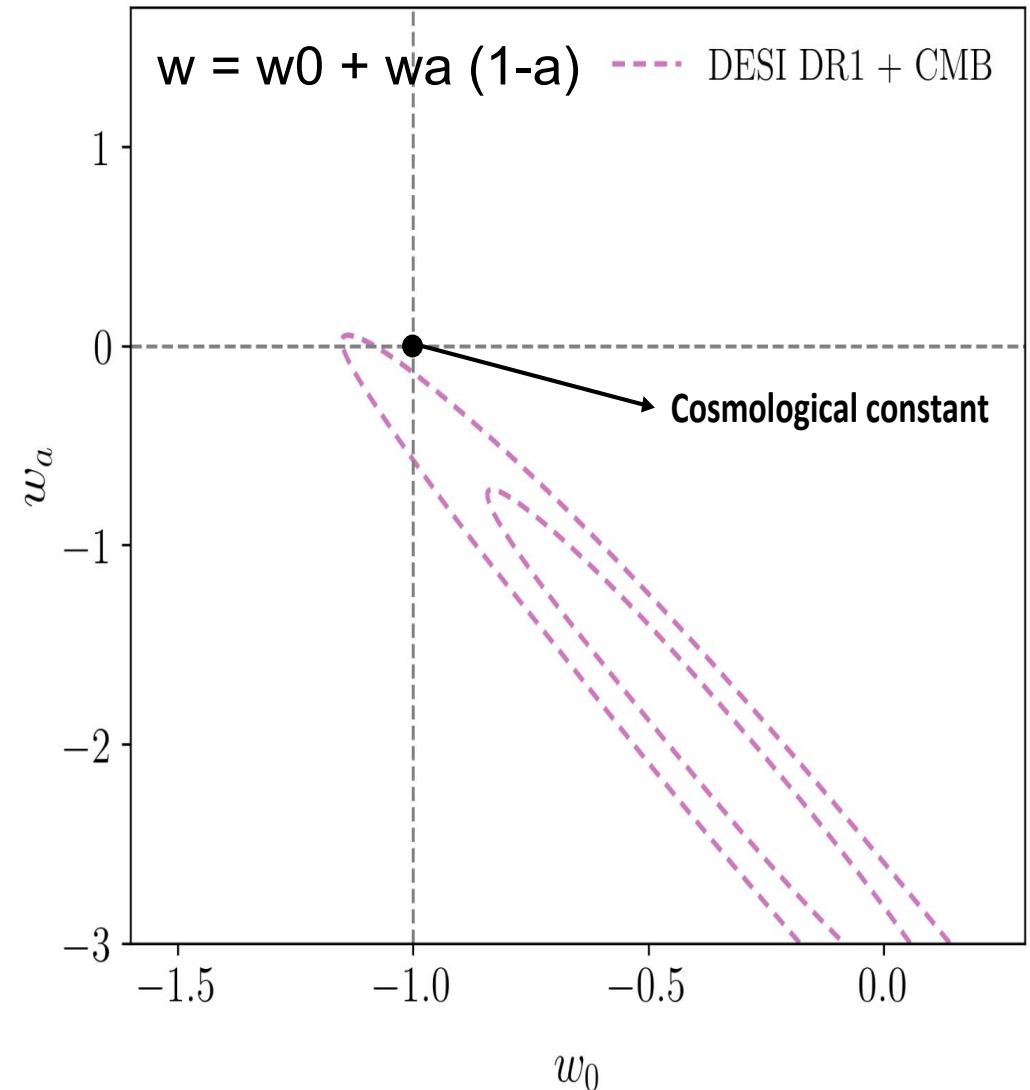


DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

Evolving Dark Energy

- DESI DR1 + CMB: 2.6σ from Λ CDM





DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

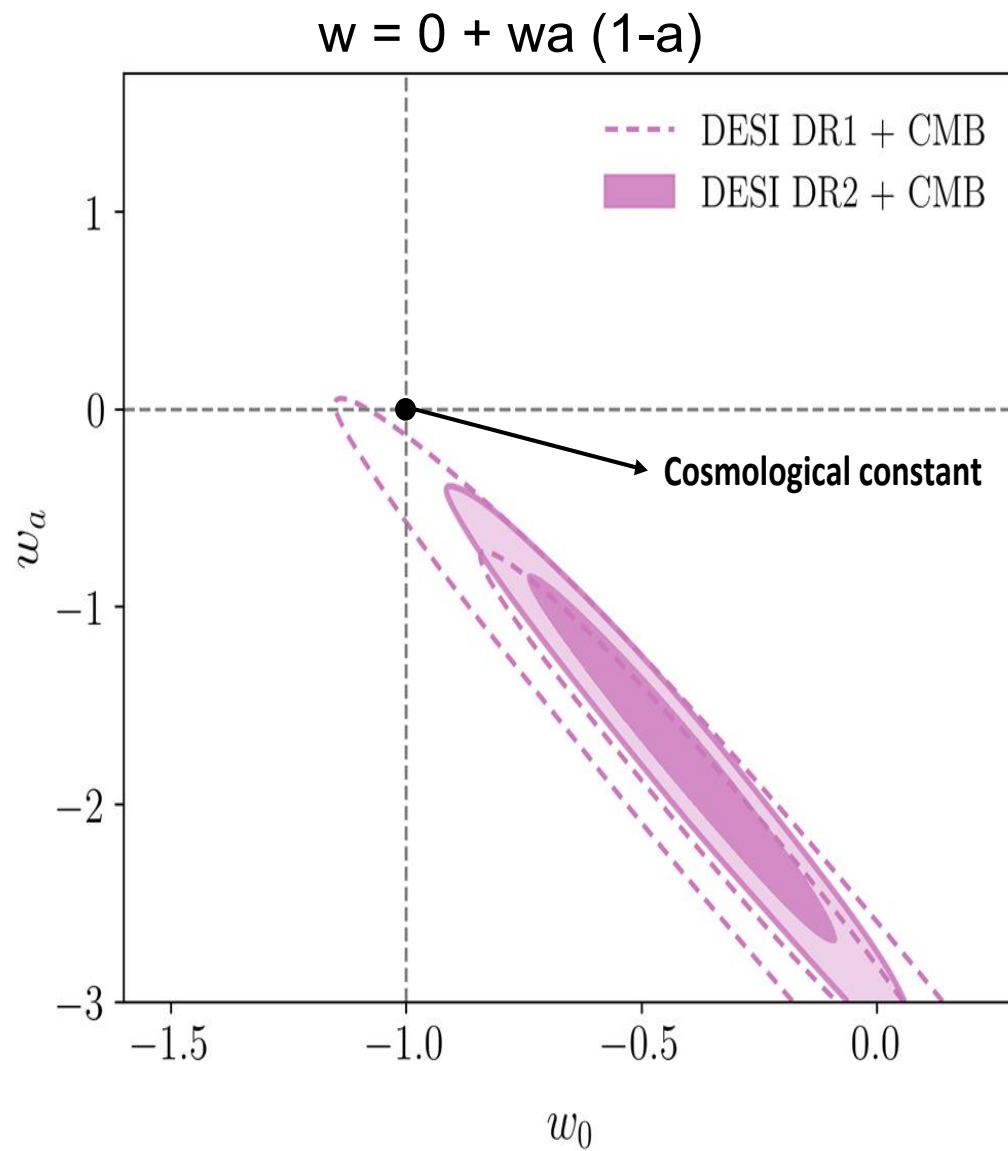
U.S. Department of Energy Office of Science

Evolving Dark Energy

- DESI DR1 + CMB: 2.6σ from Λ CDM

- 3.1σ preference for evolving dark energy with DESI DR2 + CMB

$$\left. \begin{aligned} w_0 &= -0.42 \pm 0.21 \\ w_a &= -1.75 \pm 0.58 \end{aligned} \right\} \text{DESI + CMB}$$





DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

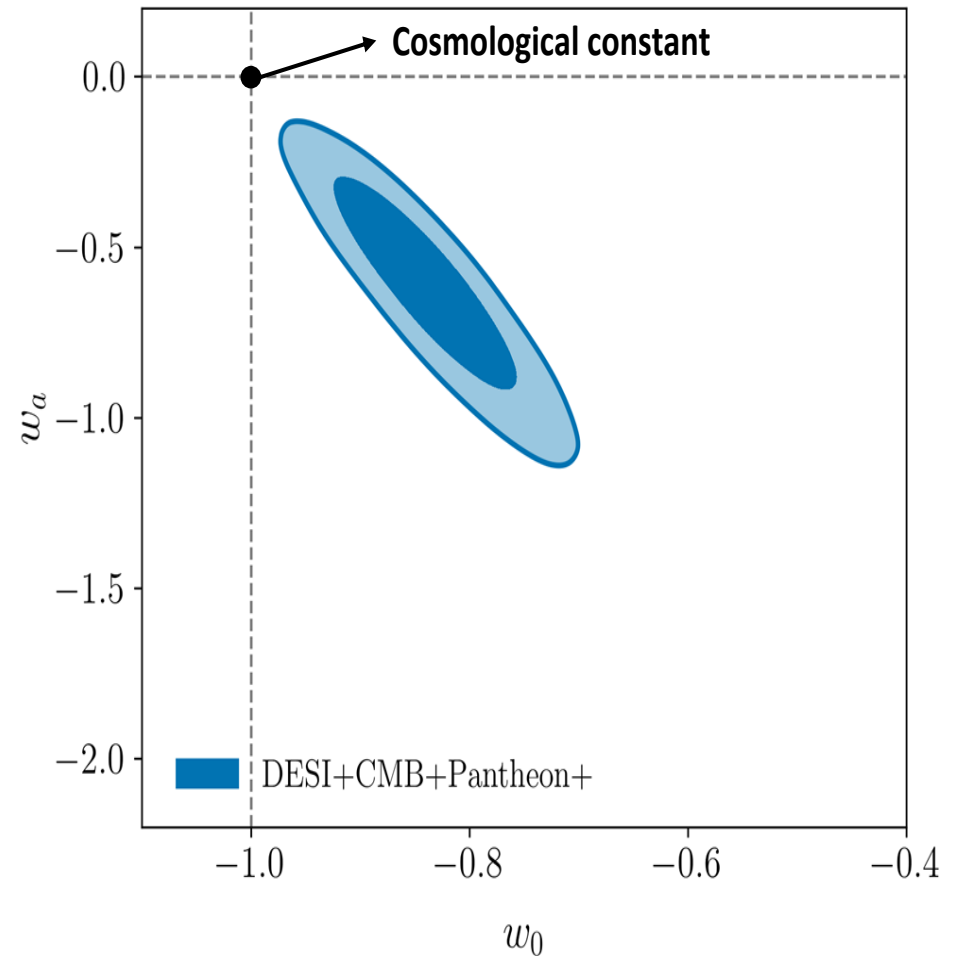
Evolving Dark Energy

Combining all DESI + CMB + SN

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

DESI + CMB + Pantheon+ $\Rightarrow 2.8\sigma$

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





DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

Evolving Dark Energy

Combining all DESI + CMB + SN

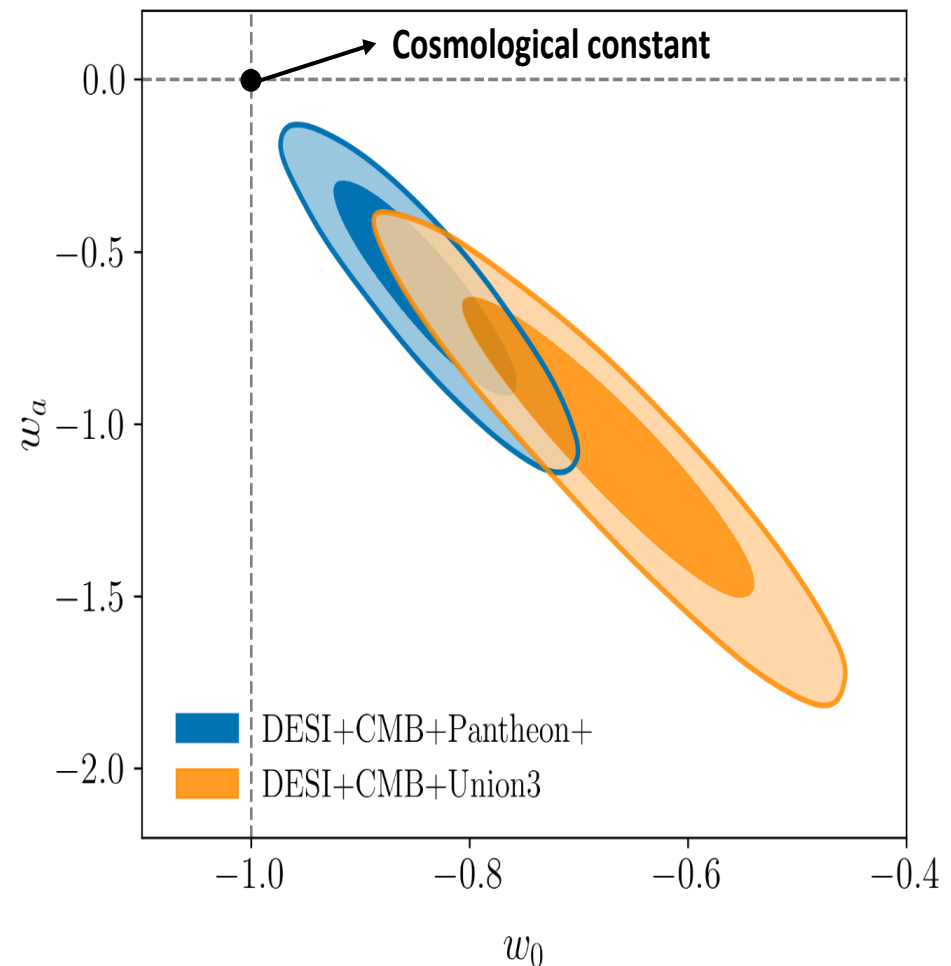
$$w_0 = -0.838 \pm 0.055 \quad w_a = -0.62^{+0.22}_{-0.19}$$

DESI + CMB + Pantheon+ $\Rightarrow 2.8\sigma$

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

DESI + CMB + Union3 $\Rightarrow 3.8\sigma$

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





DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

Evolving Dark Energy

Equation of State
 $w = w_0 + w_a (1-a)$
 $p = w \rho$

Combining all DESI + CMB + SN

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

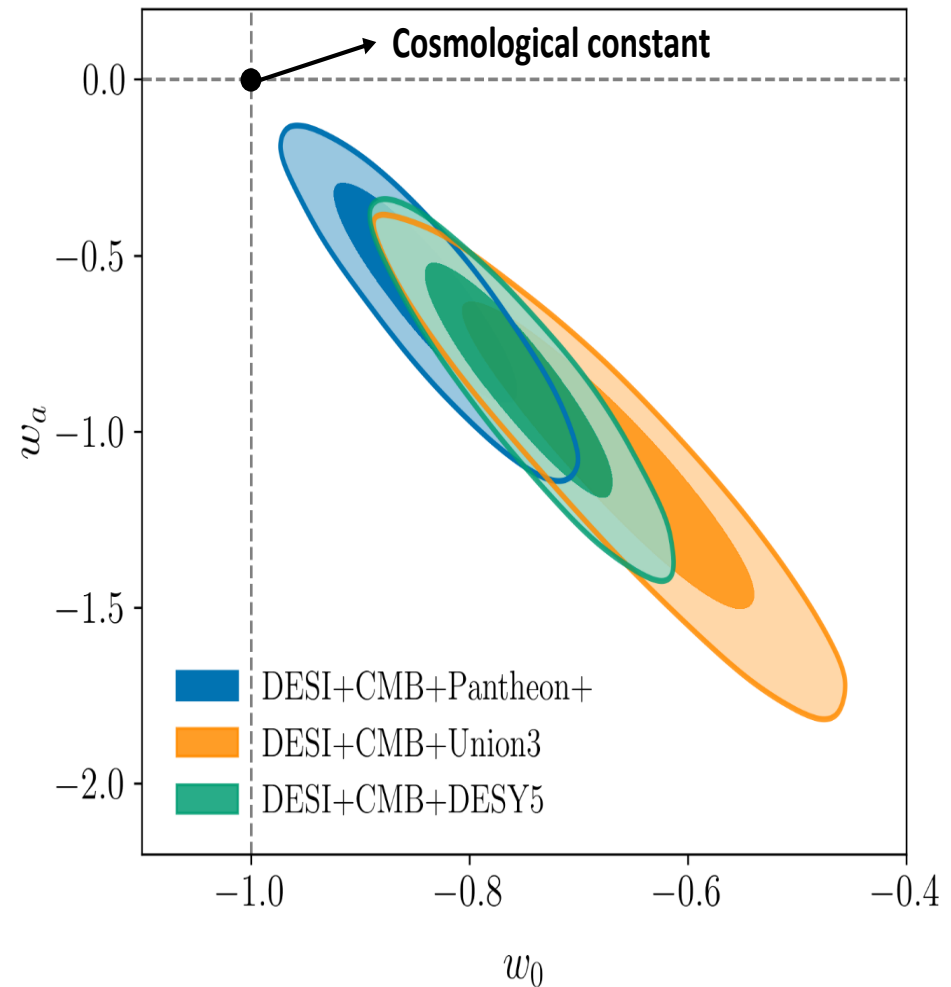
DESI + CMB + Pantheon+ $\Rightarrow 2.8\sigma$

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

DESI + CMB + Union3 $\Rightarrow 3.8\sigma$

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

DESI + CMB + DESY5 $\Rightarrow 4.2\sigma$





DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

Sum of neutrino Mass

Internal CMB degeneracies limiting precision on the sum of neutrino masses

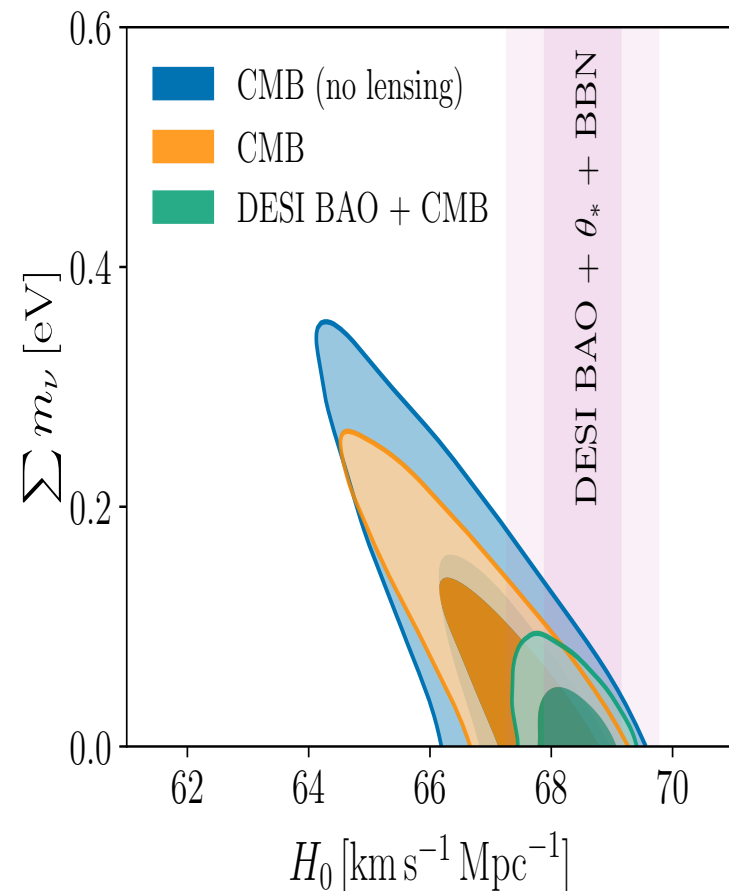
Broken by BAO, especially through H_0 constraint

Low preferred value of H_0 yields

$$\sum m_\nu < 0.072 \text{ eV (95\%, DESI+CMB)}$$

Limit relaxed for extensions to Λ CDM

$$\sum m_\nu < 0.195 \text{ eV for } w_0 w_a \text{CDM}$$

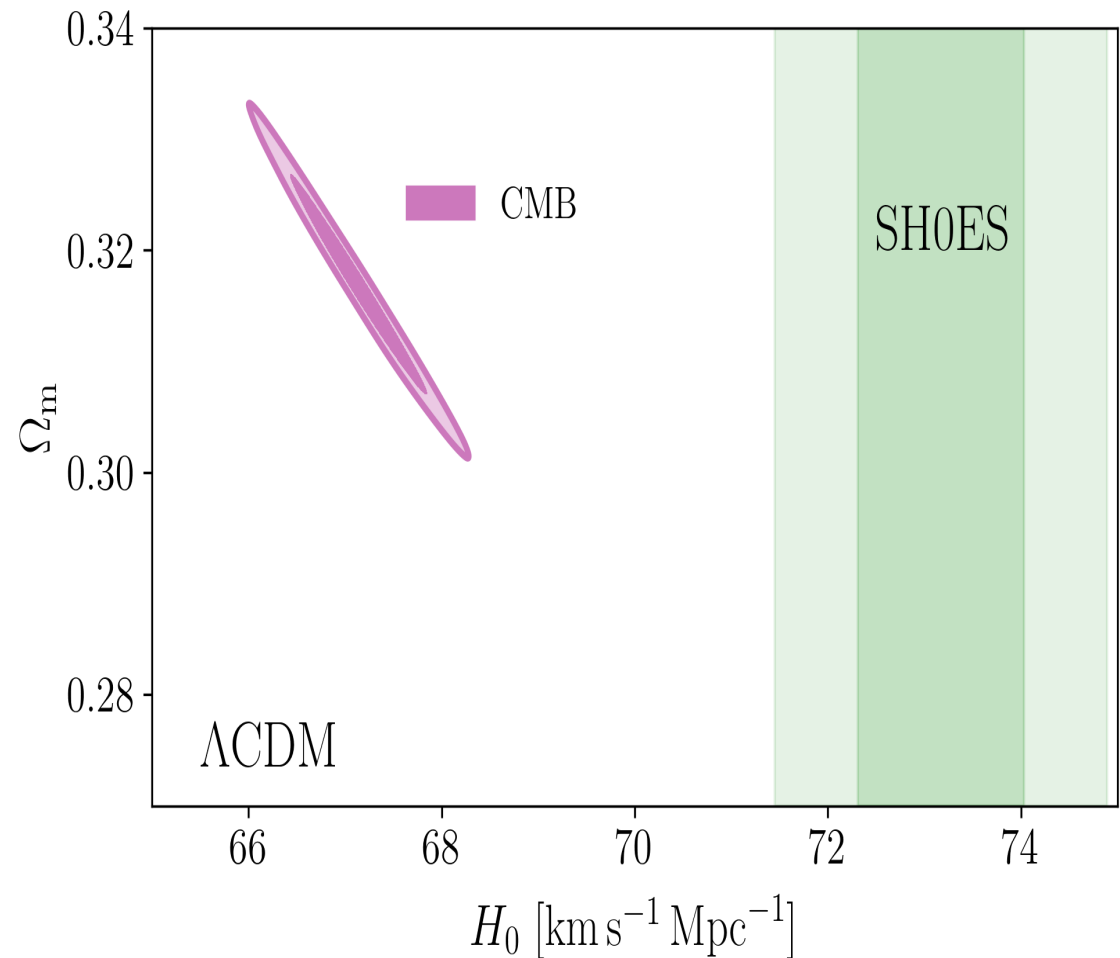




DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

Hubble constant





DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

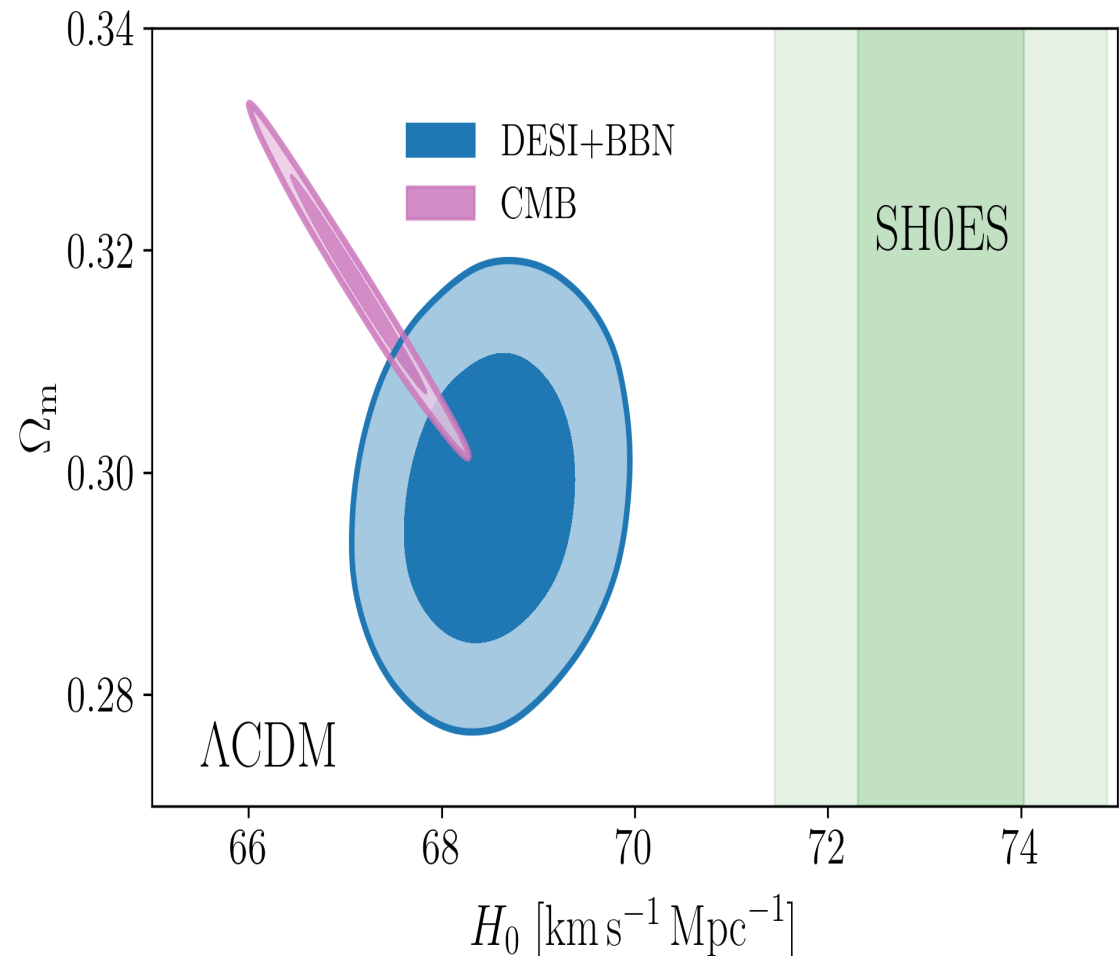
U.S. Department of Energy Office of Science

Hubble constant

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

DESI + BBN

- In 4.5σ tension with SH0ES





DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

Hubble constant

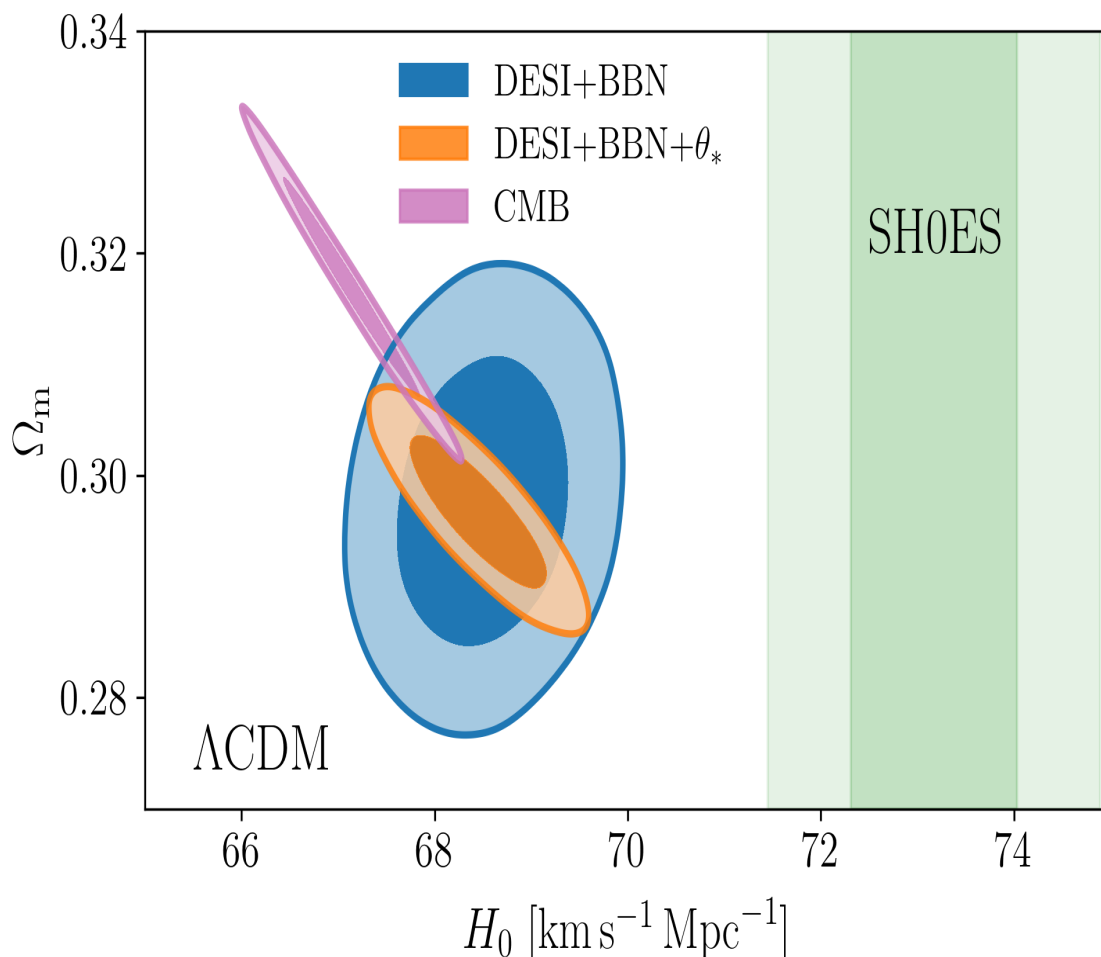
$$H_0 = (68.51 \pm 0.58) \text{ km/s/Mpc}$$

DESI + BBN

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

DESI + θ_* + BBN

- In 4.5σ tension with SH0ES
- θ_* - CMB angular acoustic scale





DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

Hubble constant

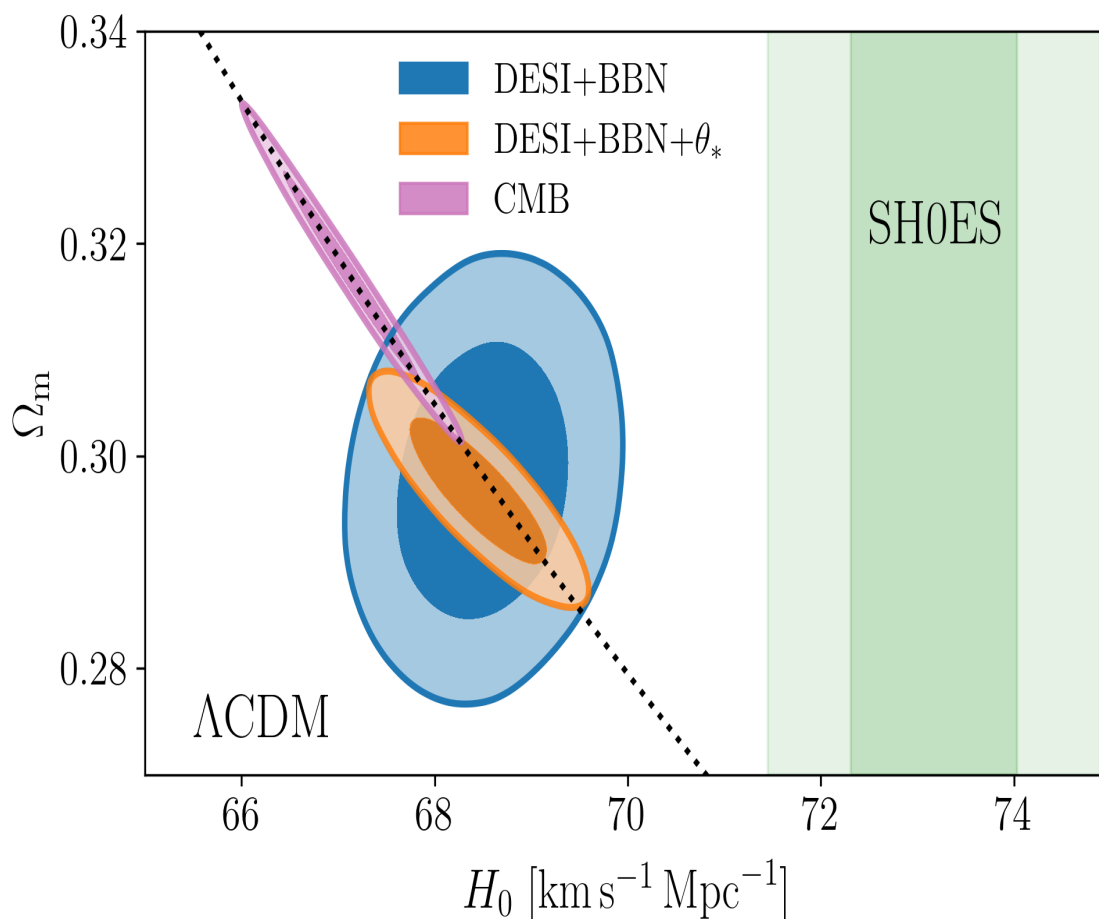
$$H_0 = (68.51 \pm 0.58) \text{ km/s/Mpc}$$

DESI + BBN

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

DESI + θ_* + BBN

- In 4.5σ tension with SH0ES
- θ_* - CMB angular acoustic scale
- Close to CMB, but still higher
- CMB degeneracy direction points to our result (dotted line)



Conclusions

- DESI has measured with great precision the expansion history of the universe, by measuring the “Baryon Acoustic Oscillations” (BAO) scale at different times (redshifts).
- DESI rules out a “Cosmological Constant” at more than 95% c.l.
- Breaking a long time paradigm (over a century).
- Opening the door for new physics !

