Large-scale Structure

Lecture 4:
Cosmological constraints from
Dark Energy Spectroscopic Instrument (DESI)

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Bucharest 2025 PhD School
July 1-6, 2025

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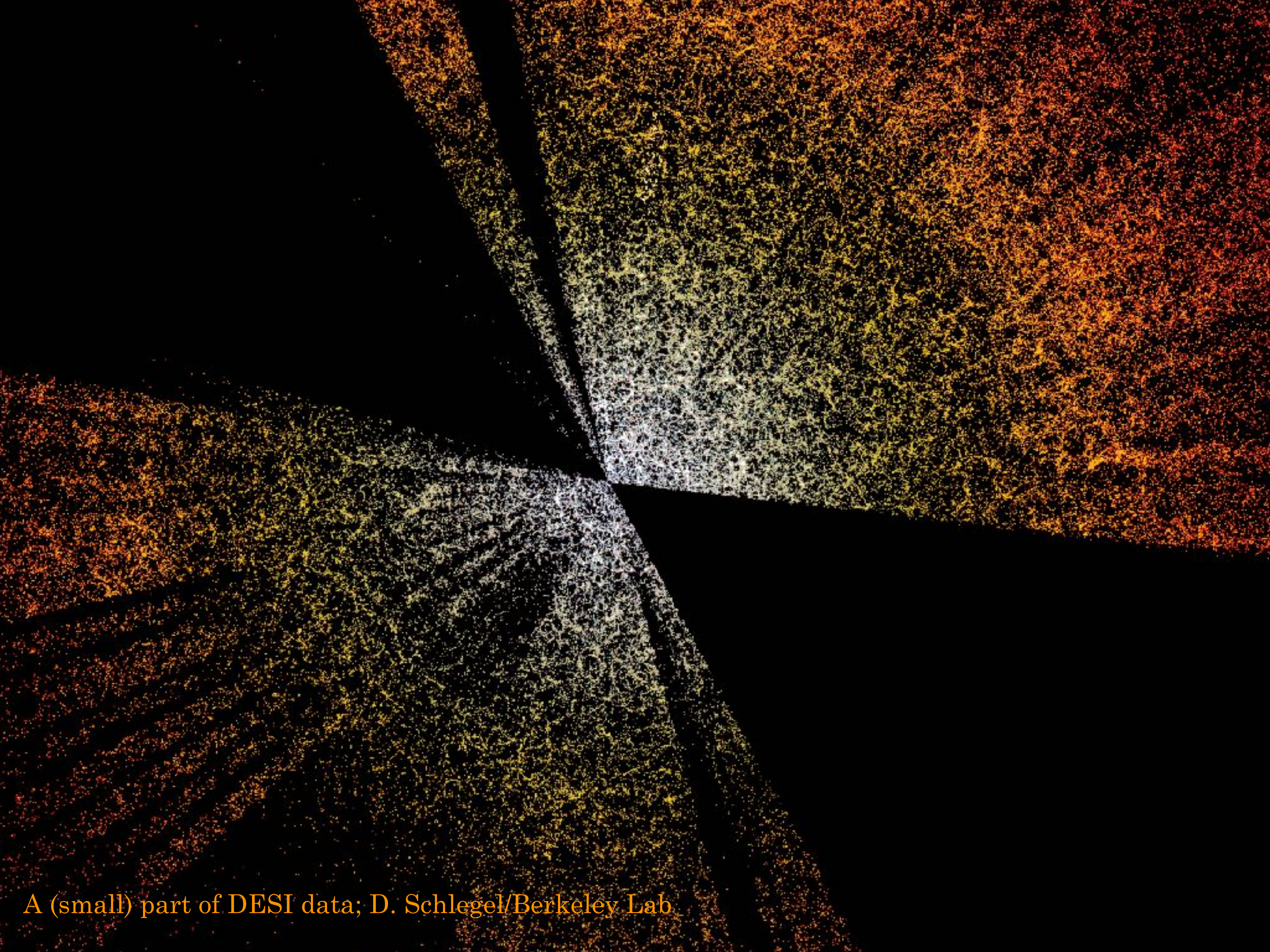
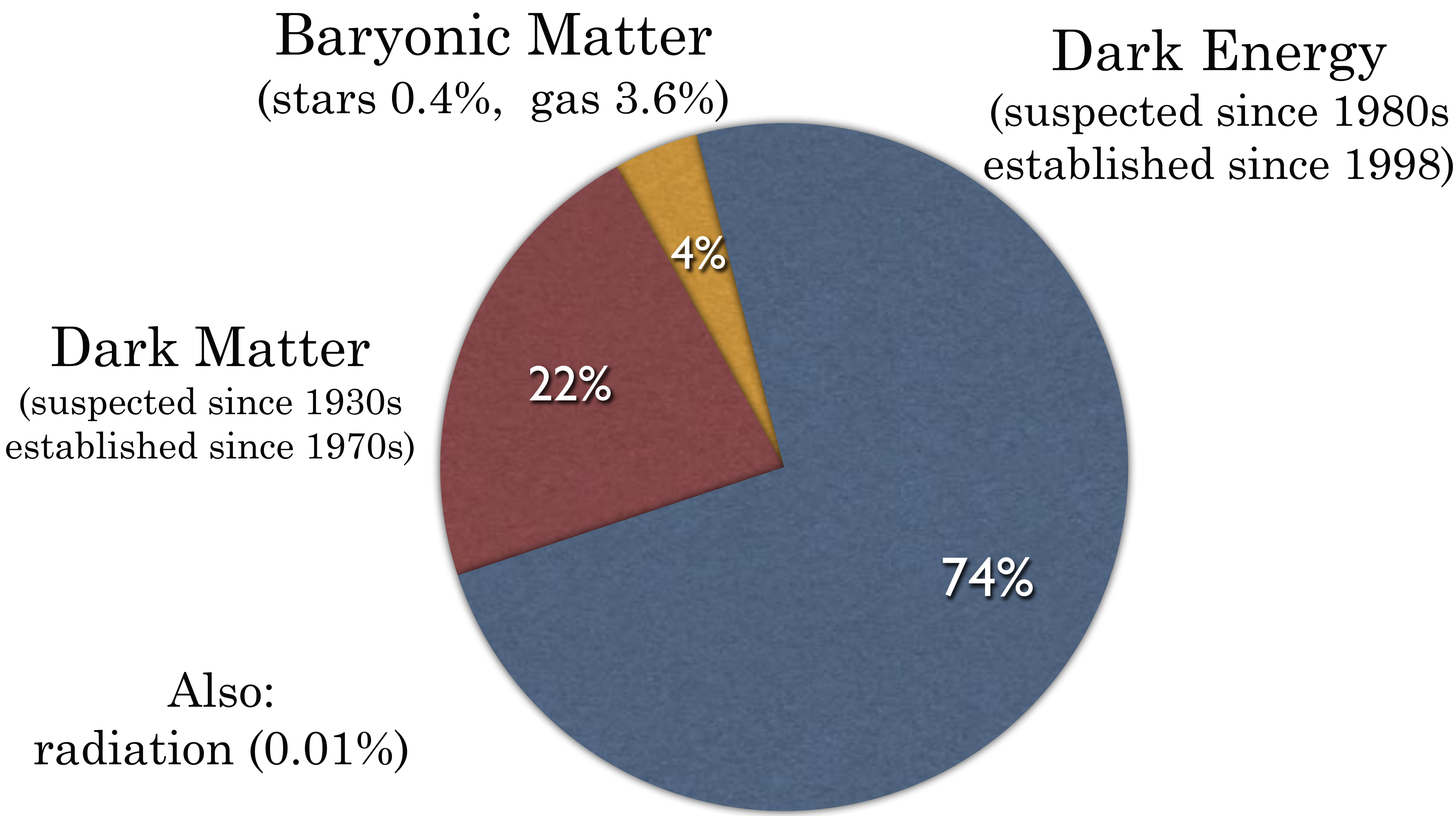
UNIVERSITY OF MICHIGAN

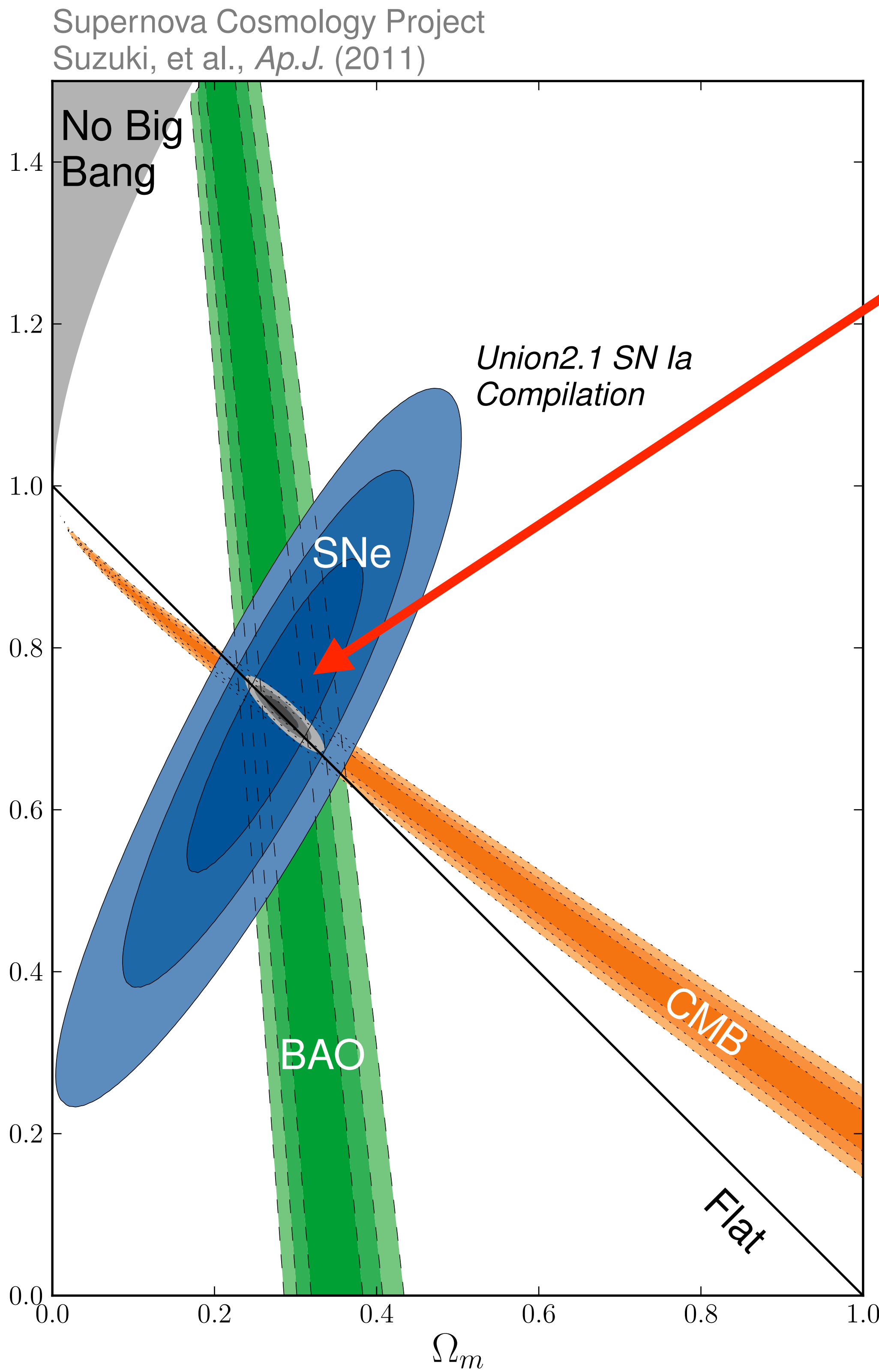


A (small) part of DESI data; D. Schlegel/Berkeley Lab

Makeup of universe today



(Recent) constraints on dark energy



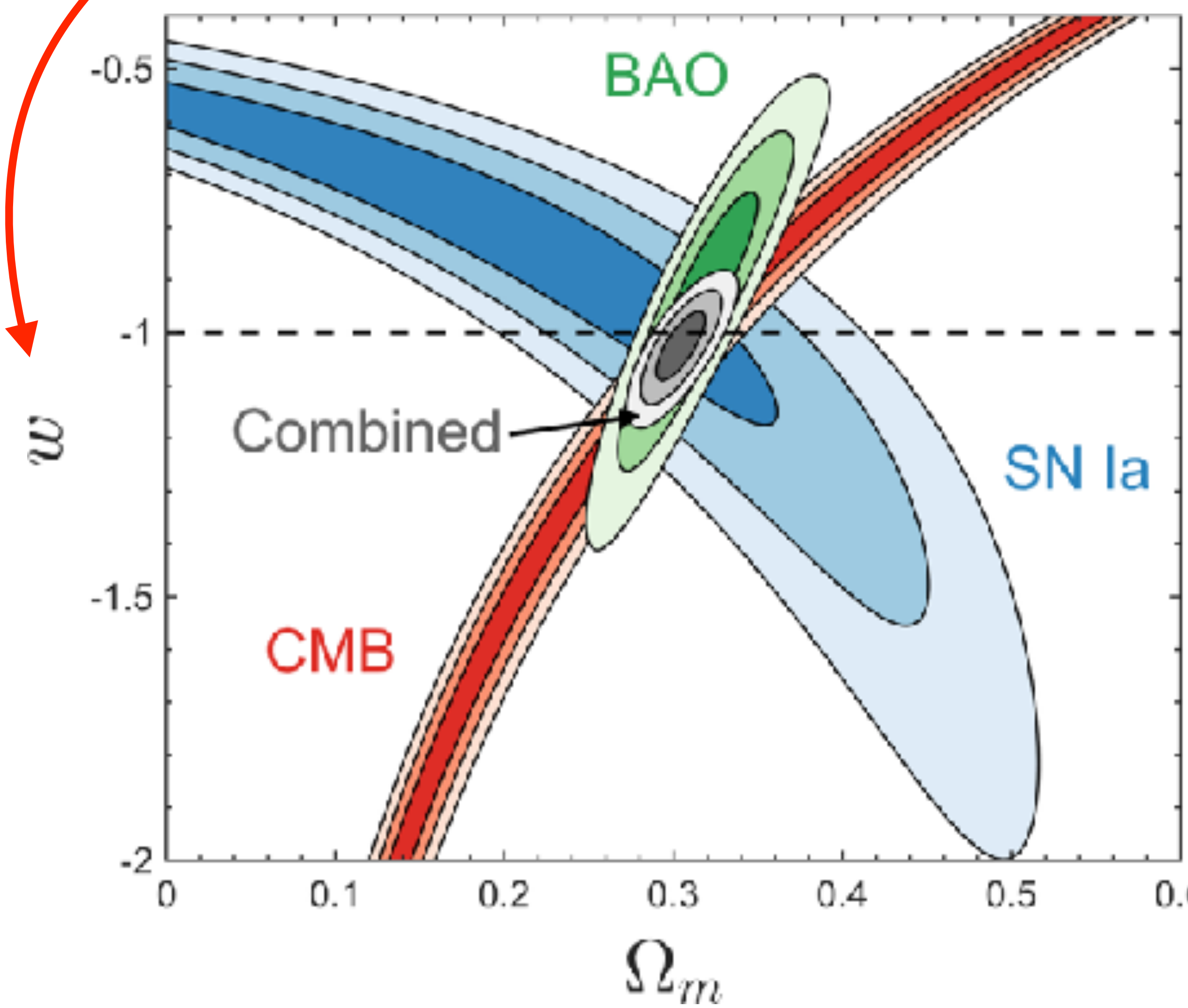
DE density (relative to critical)

Matter density (relative to critical)

70% of energy density is in DE (~30% is in matter)

…and DE equation of state is

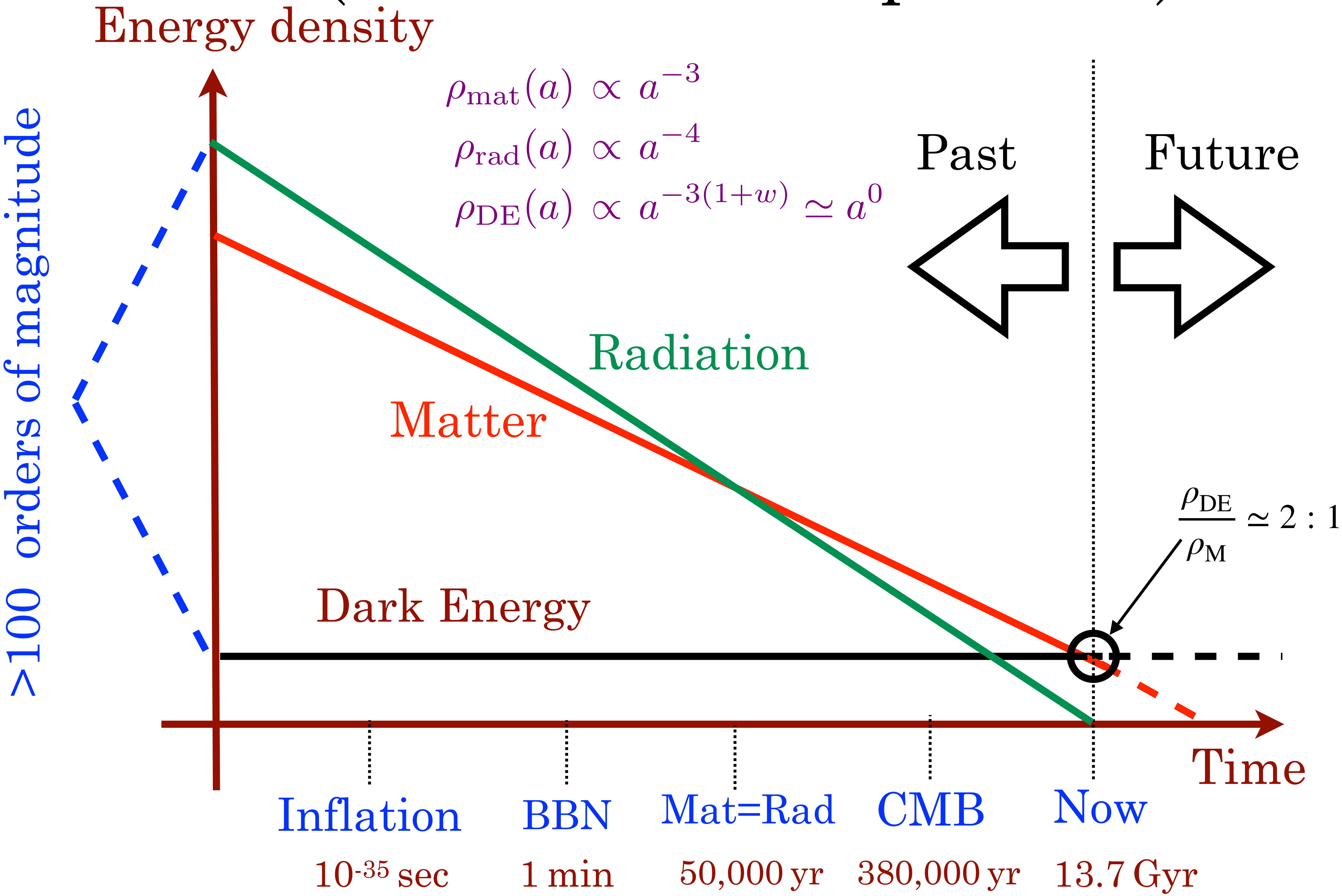
$$w \equiv \frac{p_{\rm DE}}{\rho_{\rm DE}} \simeq -1$$



Huterer & Shafer, Rep. Prog. Phys (2018)

Dark Energy:
Two Grand Mysteries

Fine-tuning problem I: “Why now?” (the coincidence problem)



Fine Tuning Problem II: "Why so small?" (cosmological constant problem)

Vacuum Energy: Quantum Field Theory predicts it to be cutoff scale

$$\rho_{\mathrm{VAC}} = \frac{1}{2} \sum_{\mathrm{fields}} g_i \int_0^\infty \sqrt{k^2 + m^2} \frac{d^3 k}{(2\pi)^3} \simeq \sum_{\mathrm{fields}} \frac{g_i k_{\mathrm{max}}^4}{16\pi^2}$$

$$\left.\begin{array}{ll} \text{Measured:} & (10^{-3}\mathrm{eV})^4 \\ \text{SUSY scale:} & (1\,\mathrm{TeV})^4 \\ \text{Planck scale:} & (10^{19}\,\mathrm{GeV})^4 \end{array}\right\}$$

60-120 orders of magnitude smaller than expected!!

Current status of dark energy is therefore:

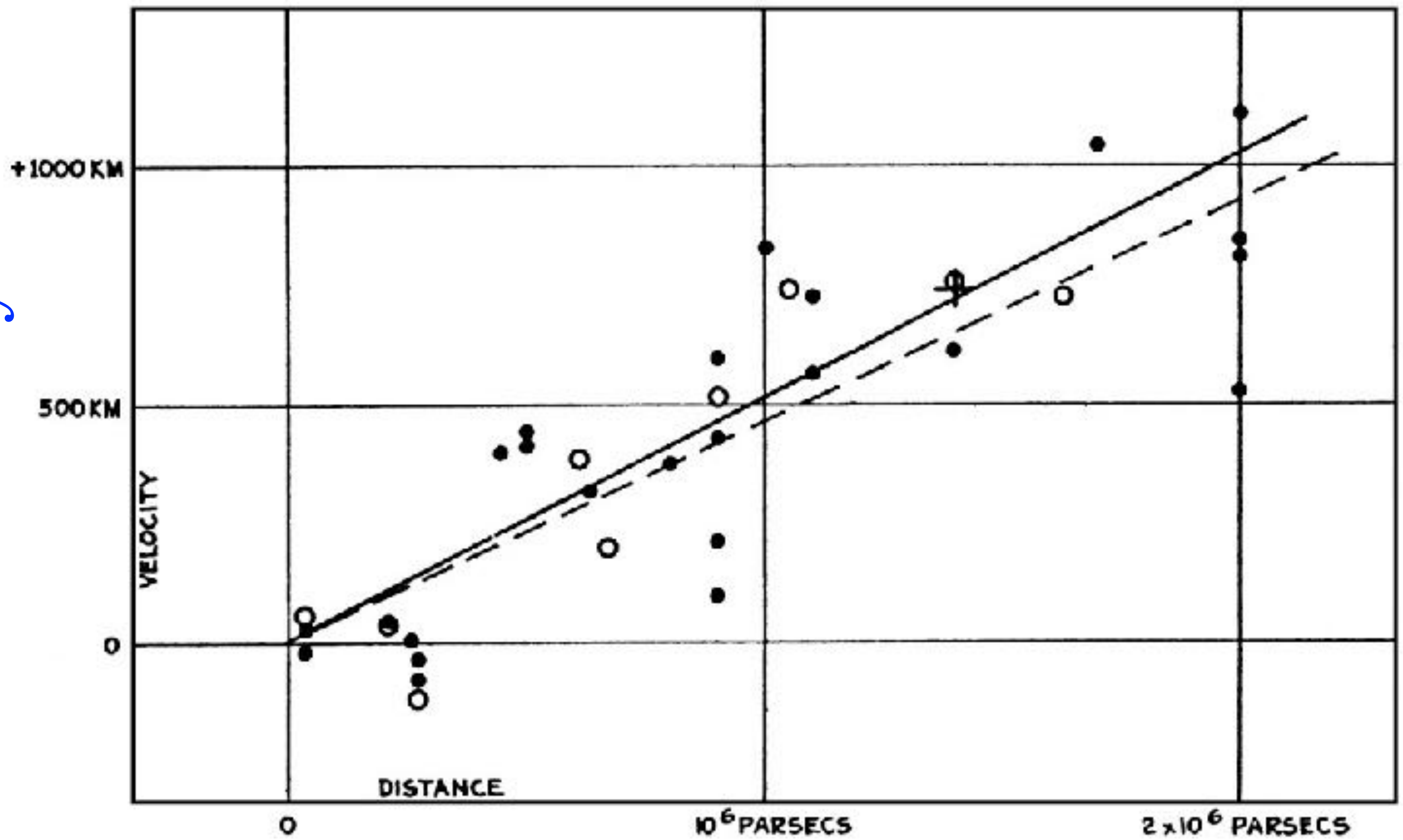
1. Existence of dark energy has been established to a *very* high statistical significance (>100-sigma)

2. The measurements are quite precise (and getting better). They are currently consistent with the cosmological constant (i.e. $w = -1$)

3. Theory (i.e. a compelling theoretical explanation) is lagging *far* behind

Hubble constant

velocity



Edwin Hubble

Hubble (1928)

distance

Slope of this relation (velocity vs. distance) the Hubble constant H_0. Hubble got 500 km/s/Mpc - off by a factor of seven! Modern value:

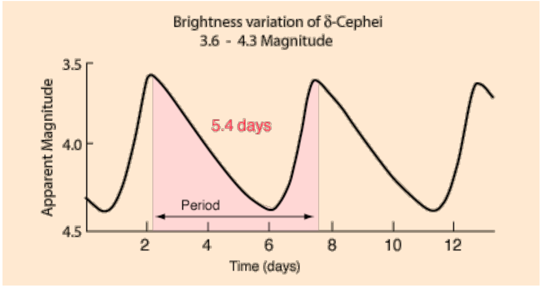
$$H_0 \approx 70 \text{ km/sec/megaparsec}$$

Recent development

Hubble Tension:

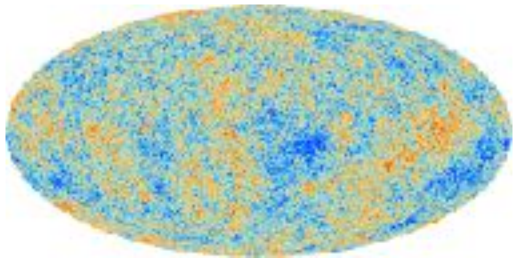
SH0ES (Riess et al 2022)

$$H_0 = 73.04 \pm 1.04 \text{ (km/s/Mpc)}$$



CMB: (ACT 2025 + Planck 2018)

$$H_0 = 67.62 \pm 0.50 \text{ (km/s/Mpc)}$$



Currently the premier challenge for the standard cosmological model, and the most exciting development in cosmology (imo).

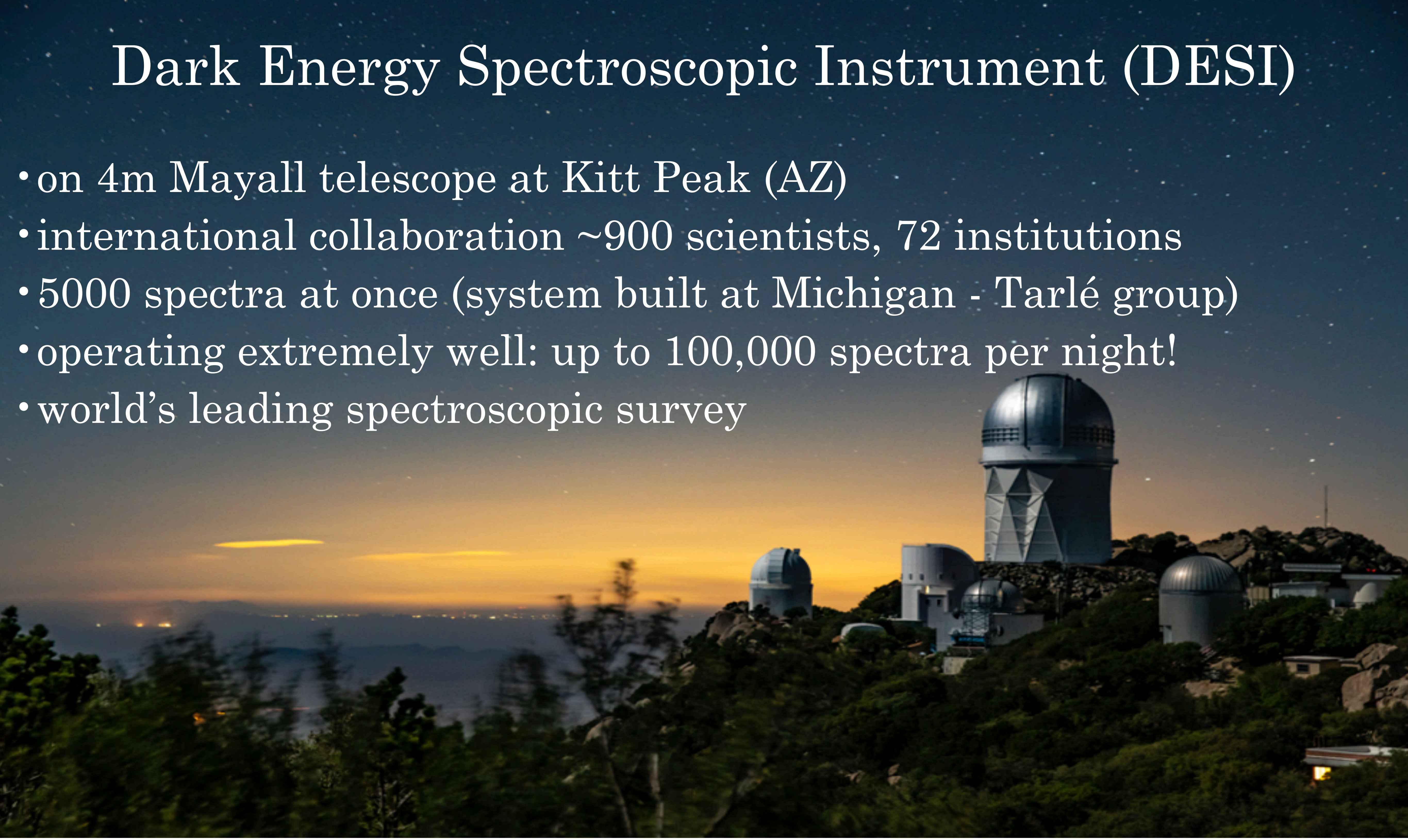
The tension recently crossed the 5-sigma threshold; this is an important step!

Ongoing or upcoming DE experiments:

- **Ground photometric:**
  - Kilo-Degree Survey (KiDS)
  - Dark Energy Survey (DES)
  - Hyper Supreme Cam (HSC)
  - LSST on Vera Rubin Telescope
- **Ground spectroscopic:**
  - Prime Focus Spectrograph (PFS)
  - Dark Energy Spectroscopic Instrument (DESI)
- **Space:**
  - Euclid
  - Roman Space Telescope

Dark Energy Spectroscopic Instrument (DESI)

- on 4m Mayall telescope at Kitt Peak (AZ)
- international collaboration ~900 scientists, 72 institutions
- 5000 spectra at once (system built at Michigan - Tarlé group)
- operating extremely well: up to 100,000 spectra per night!
- world's leading spectroscopic survey



DESI science:

1. dark energy
2. neutrino mass

this talk

3. primordial non-Gaussianity

For cosmologists, galaxies are test particles!

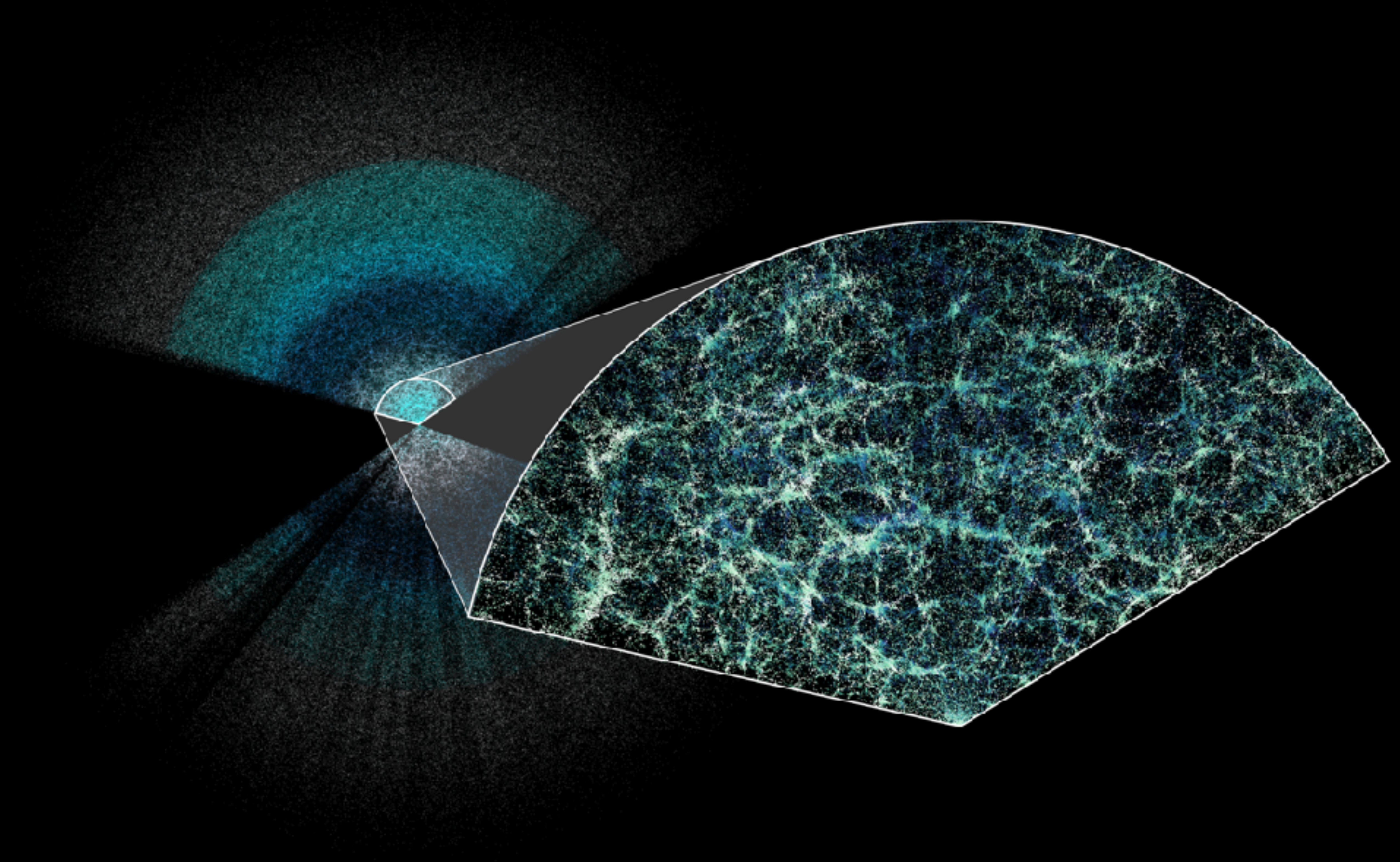
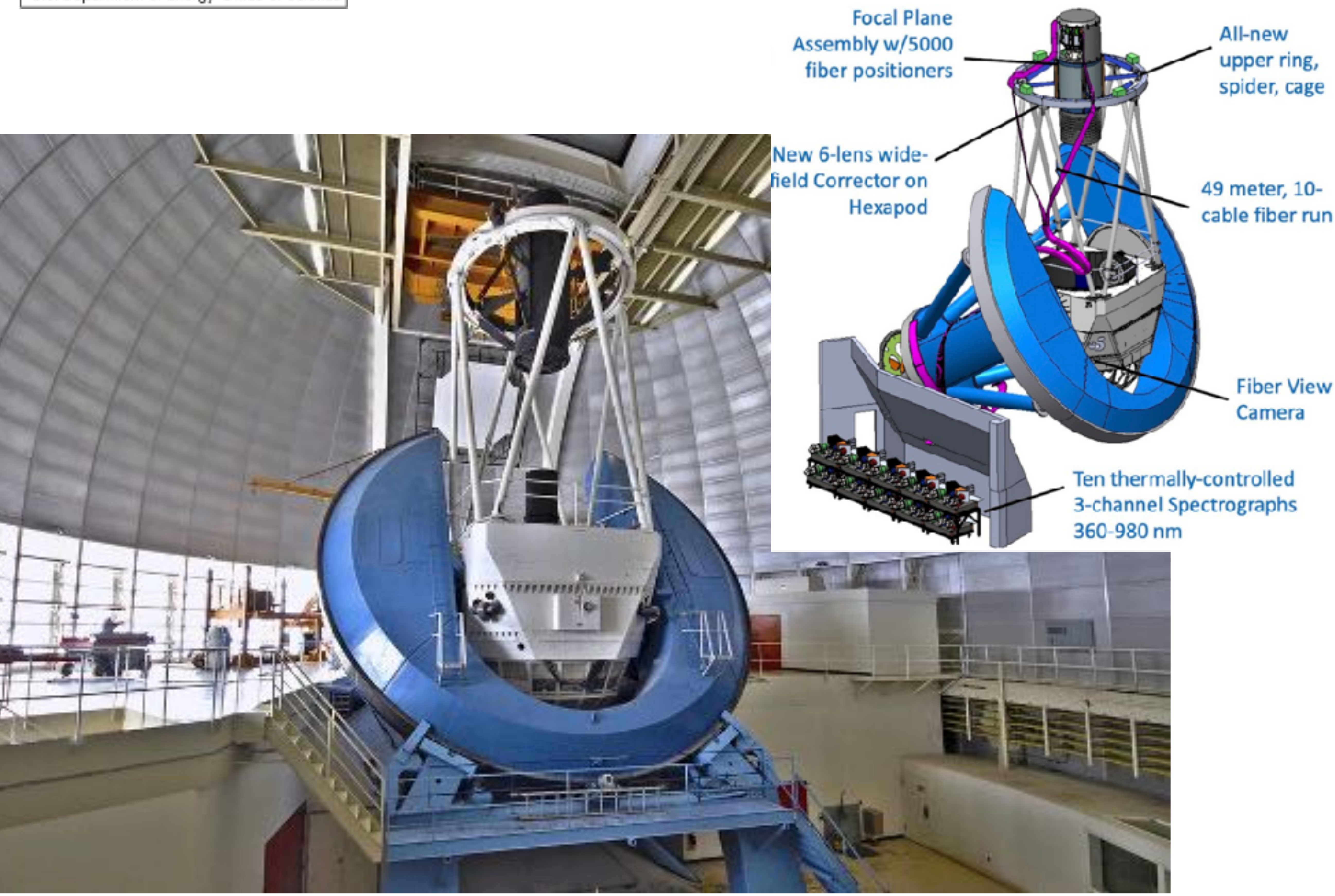


Figure credit: Claire Lamman

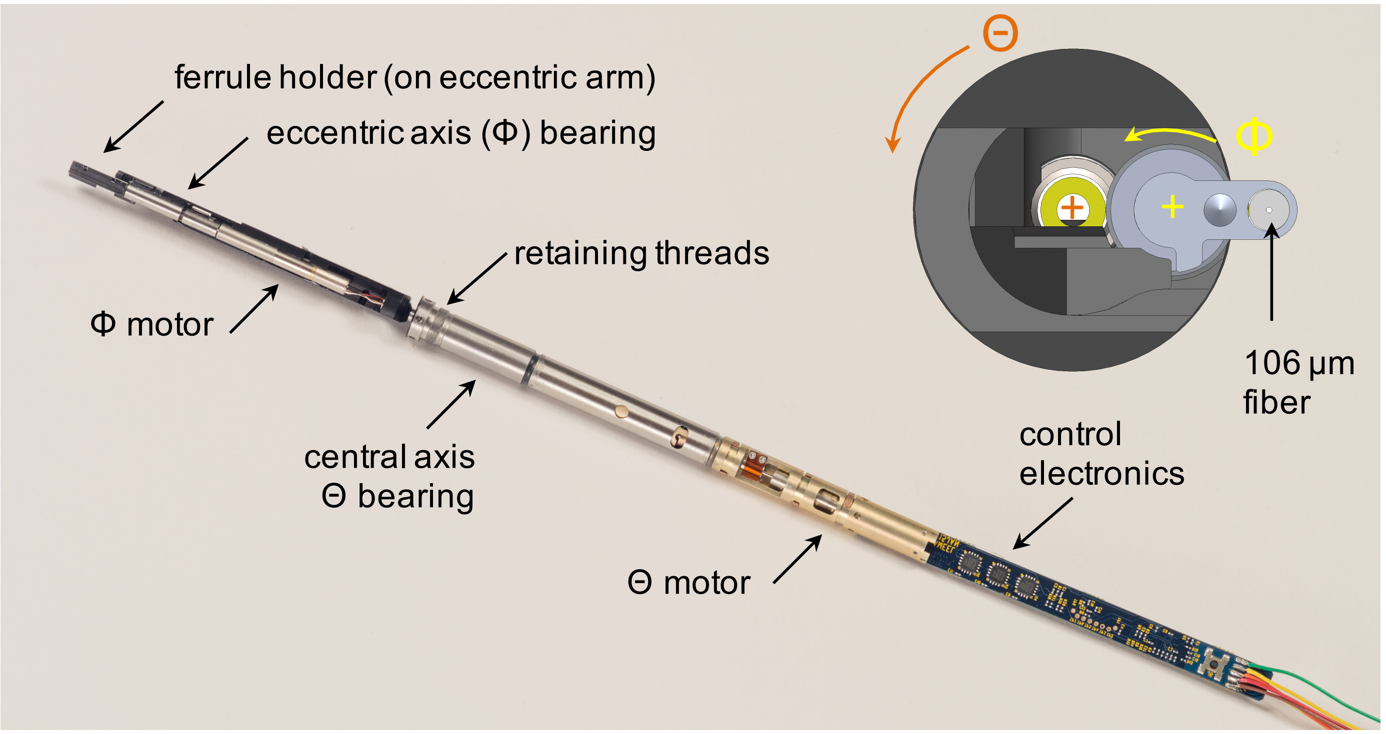
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Mayall telescope at Kitt Peak, AZ



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

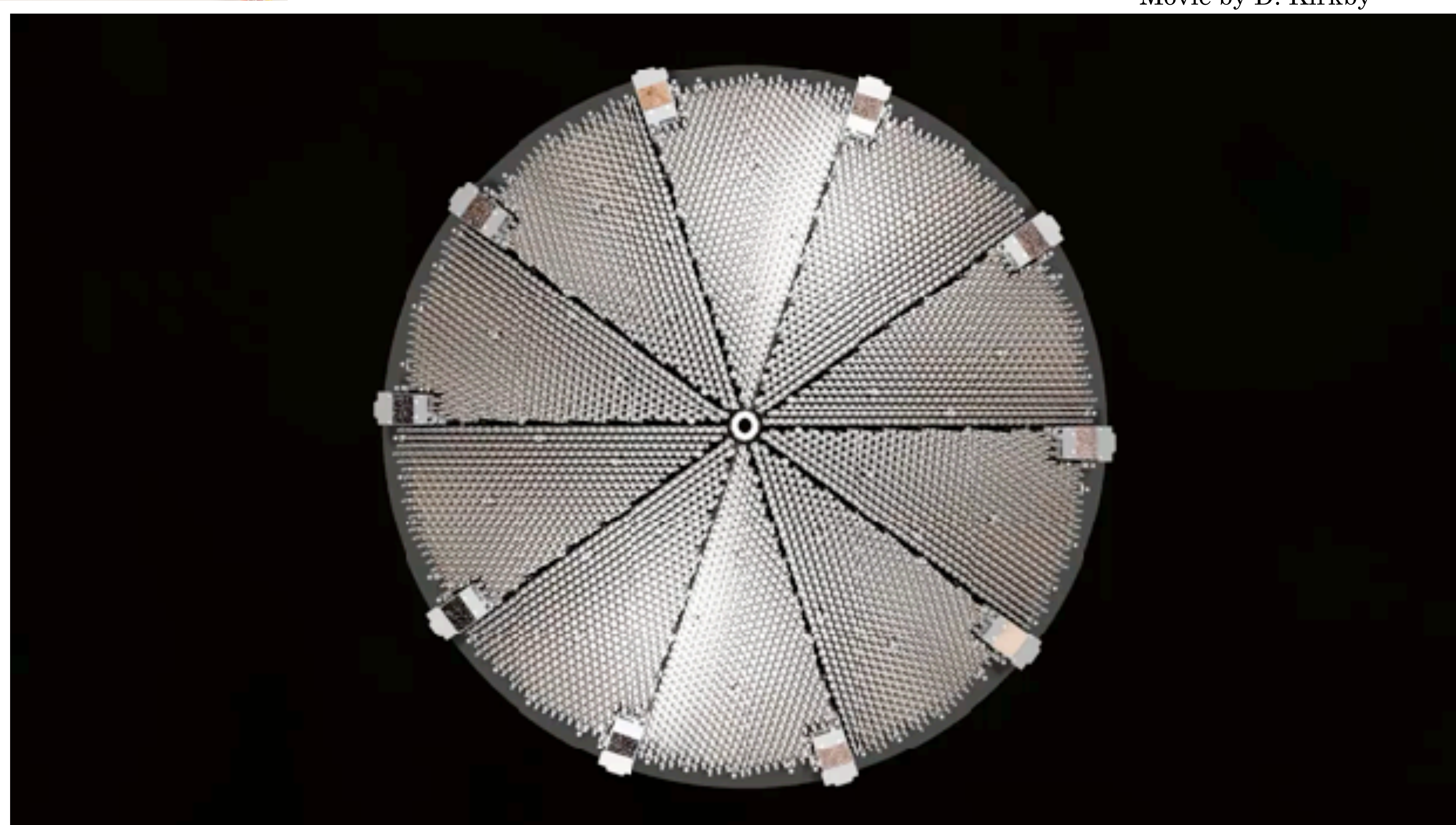
Robotic fiber positioners



Designed and built at
University of Michigan
(Tarlé group)

"5,000 eyes on the sky"

Movie by D. Kirkby



Greg
Tarlé

Michael
Schubnell

DESI tracers

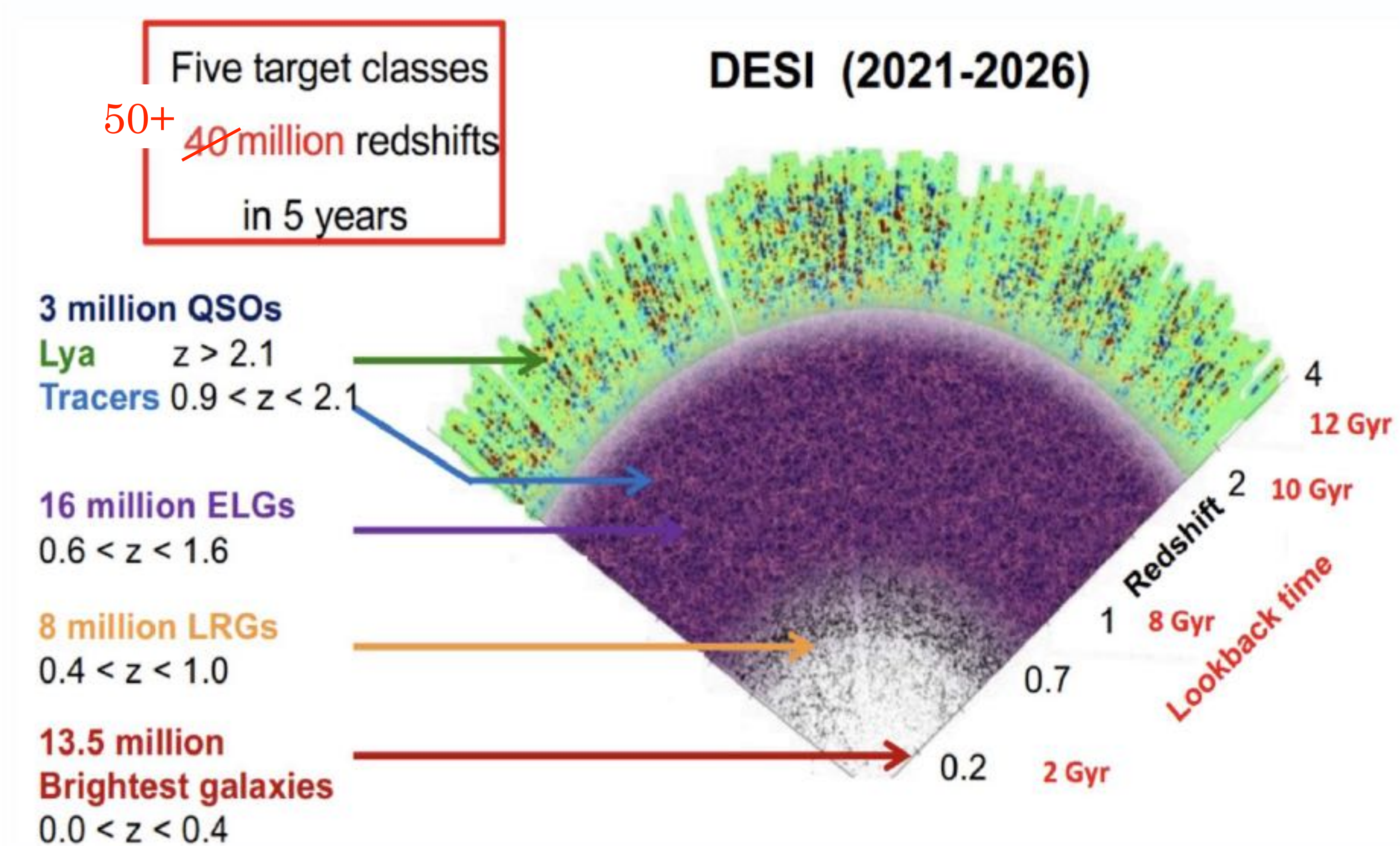
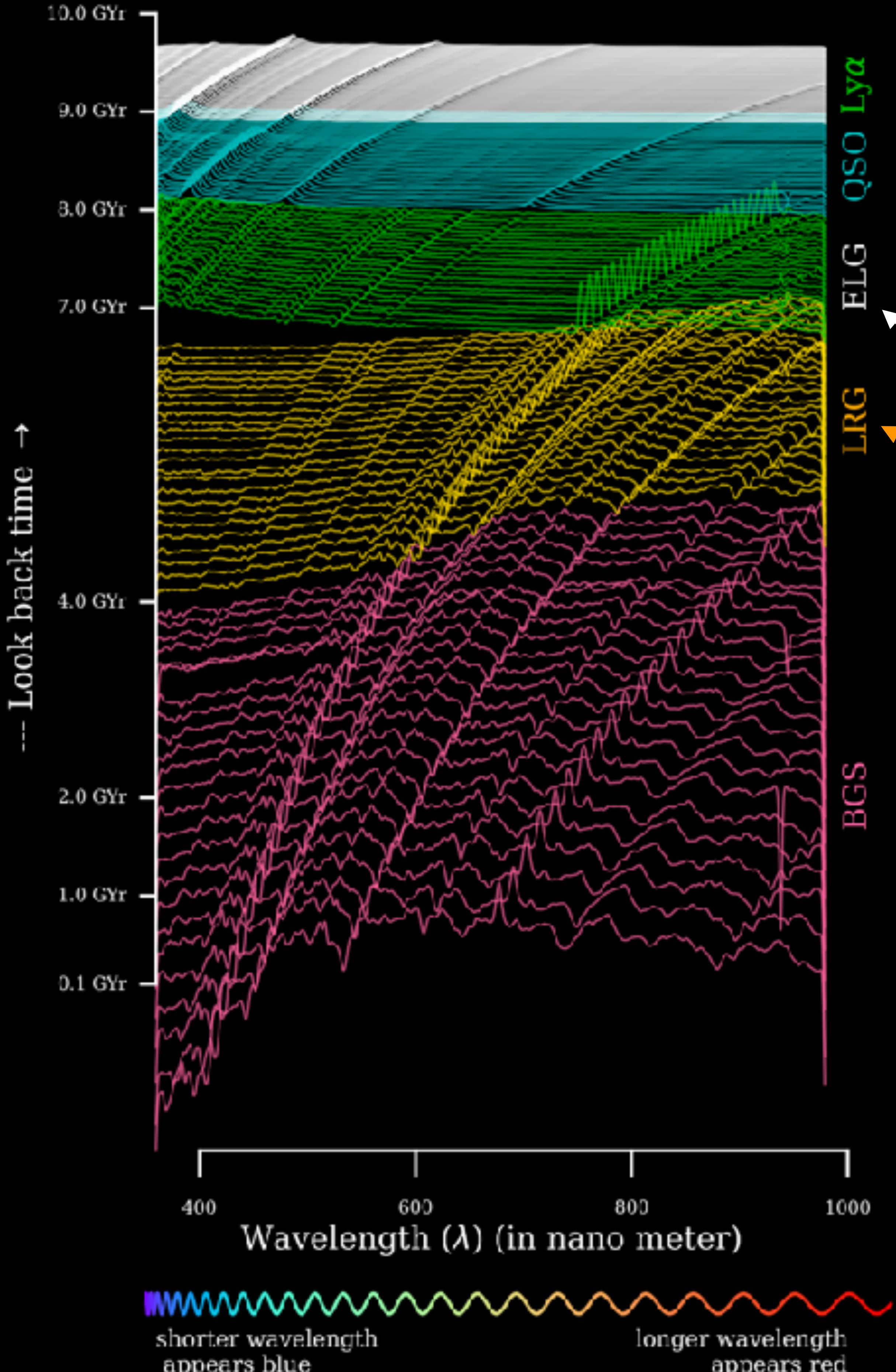


Illustration of how a spectrum evolves in redshift/time



DESI tracers

Figure credit: Shadab Alam

DESI DR2 sample

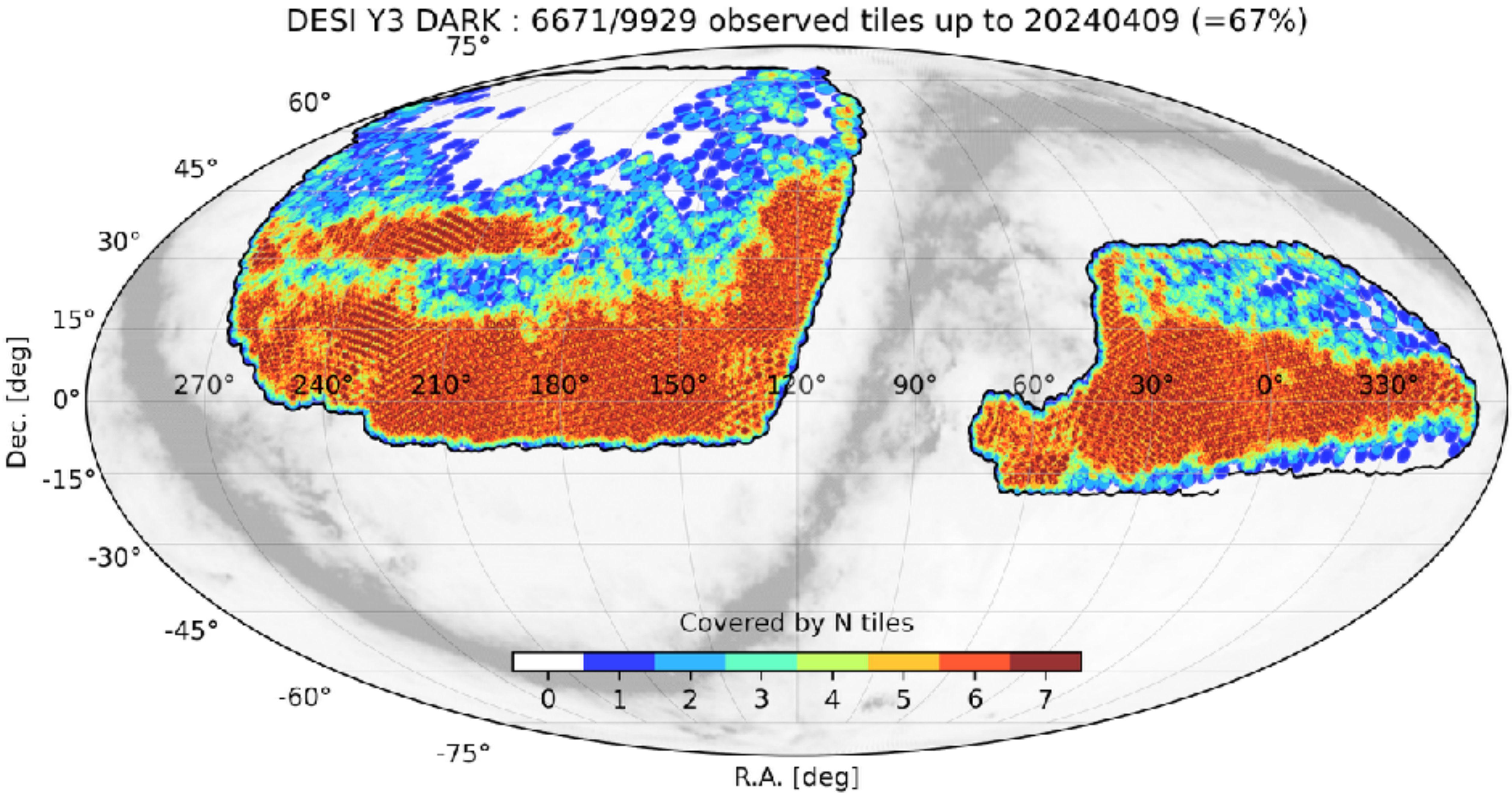
- Over 30M galaxy and quasar redshifts in 3 years of operation, ~14M of which are used in this analysis.
- Compared to DR1 (~6M redshifts), DR2 represents a factor of ~2.4 improvement in data volume.

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**

borrowed from E. Paillas (DESI)

The DESI DR2 sample

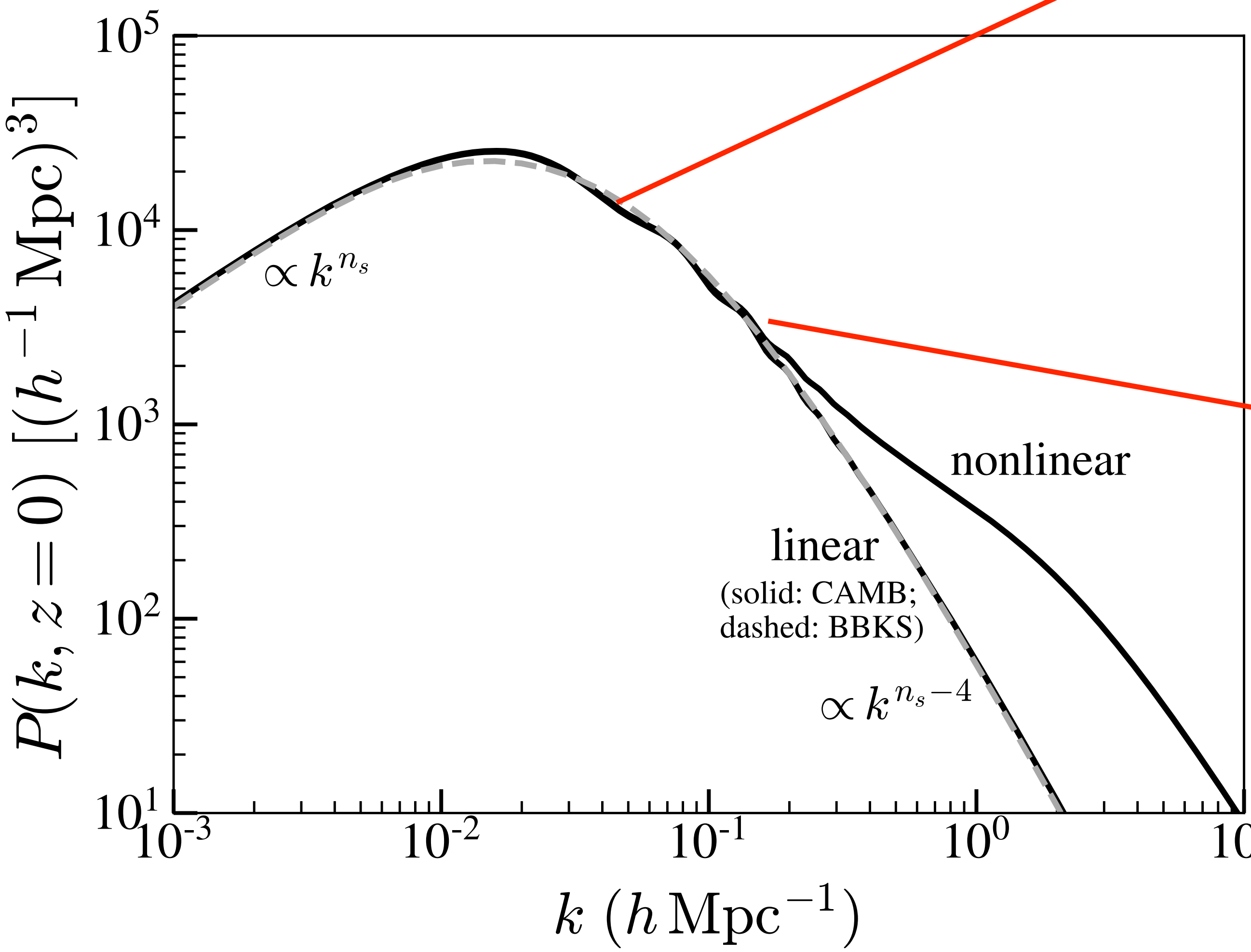


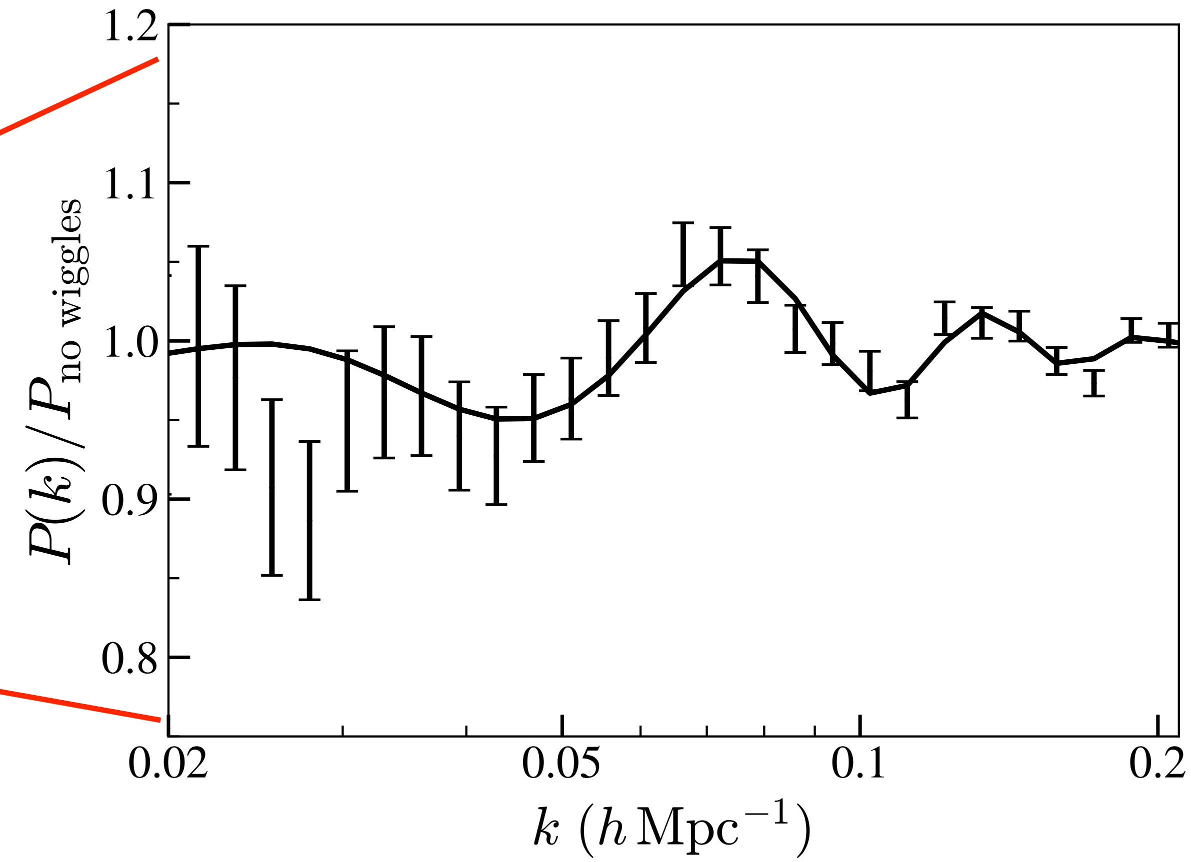
How Baryon Acoustic Oscillations observed by DESI constrain cosmological parameters

[This is the “most essential” application of DESI data]

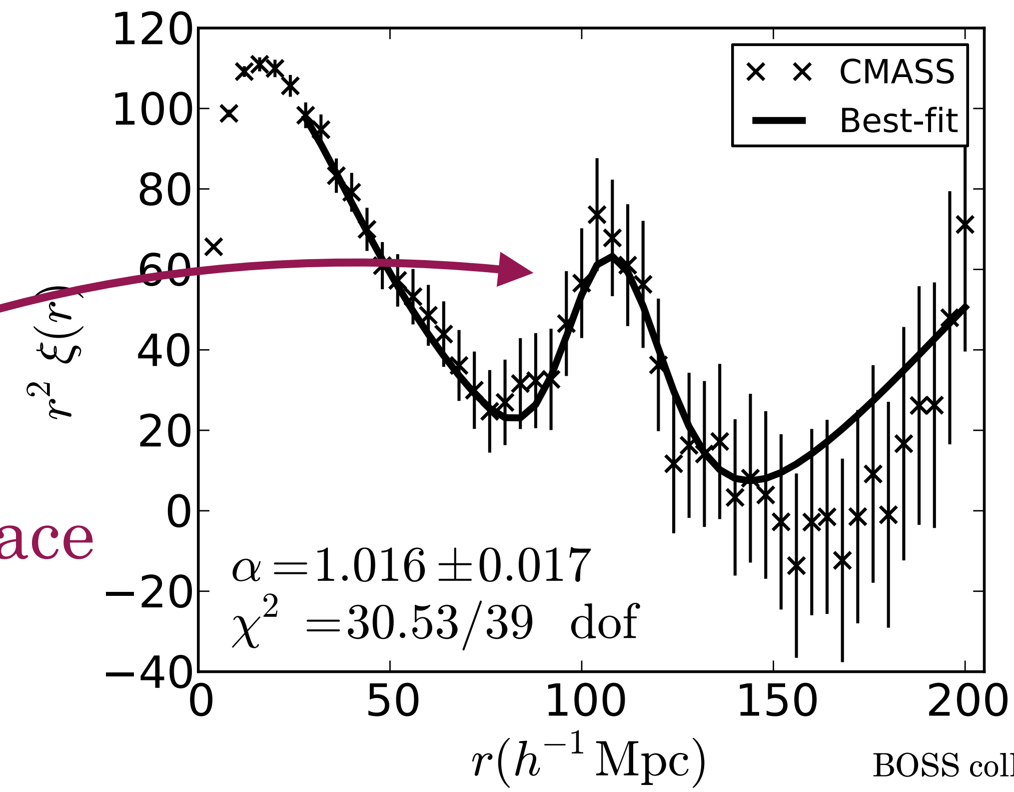
Baryon Acoustic Oscillations (BAO)

Multiple wiggles in Fourier space
(power spectrum)





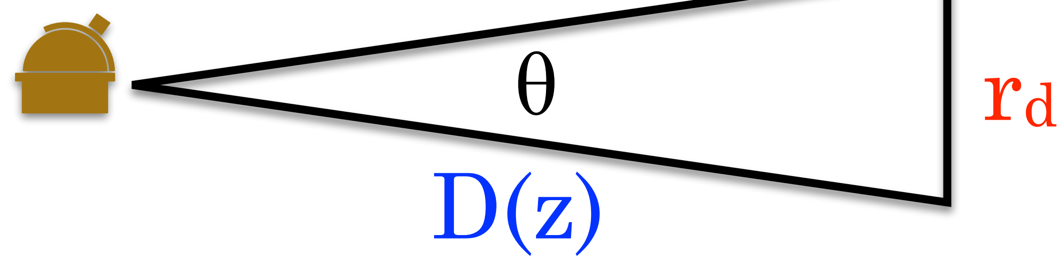
…or one wiggle in configuration space
(2-point correlation function)



BOSS collaboration

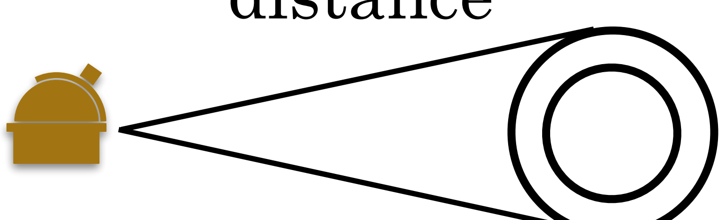
First discussed in: Sunyaev & Zeldovich, 1972

Baryon Acoustic Oscillations

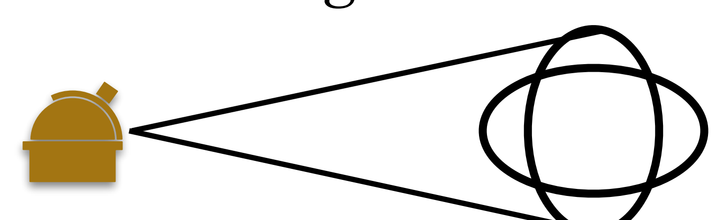


- Therefore, there is excess probability for galaxies having a neighbor at distance r_d — excess probability for clustering
- This imprints a preferred scale in clustering - the “standard ruler"
- The angle to the standard ruler gives $D(z)/r_d$
- Actually measure *two* kinds of distances: transverse or parallel to the line-of-sight; can be expressed as

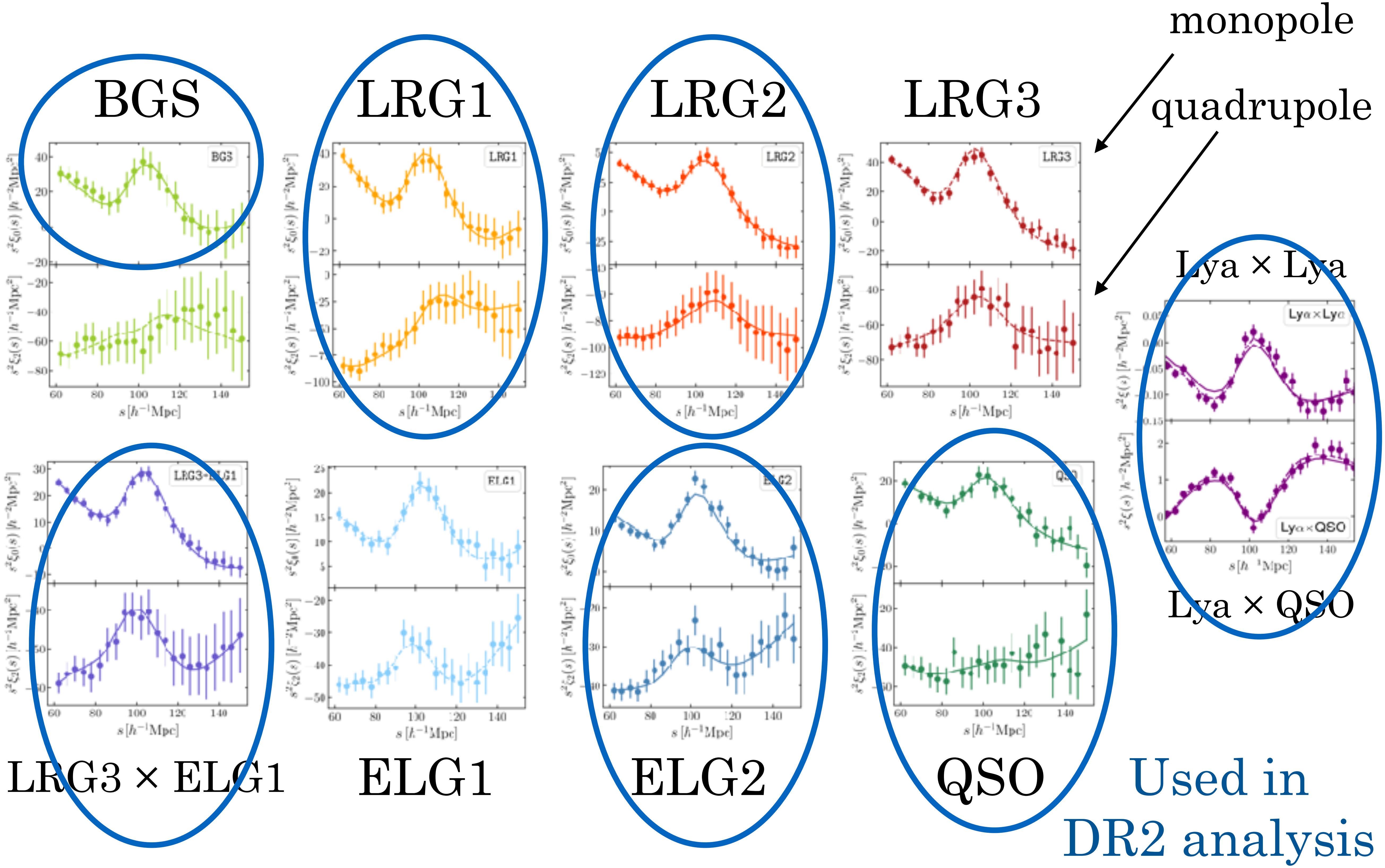
Isotropic (“average”) distance

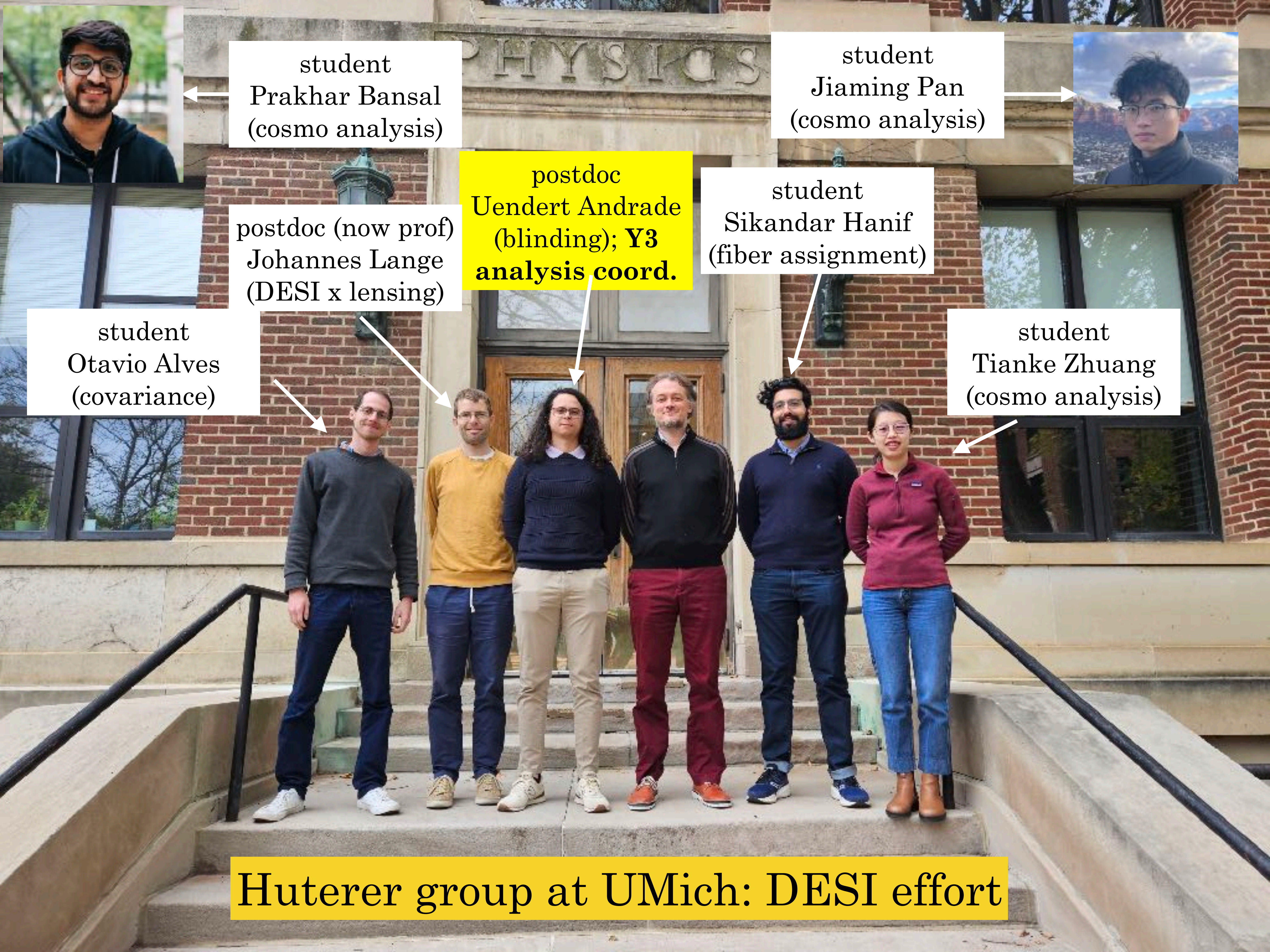


Ratio of transverse and line-of-sight distances



DESI DR2 Clustering Measurements



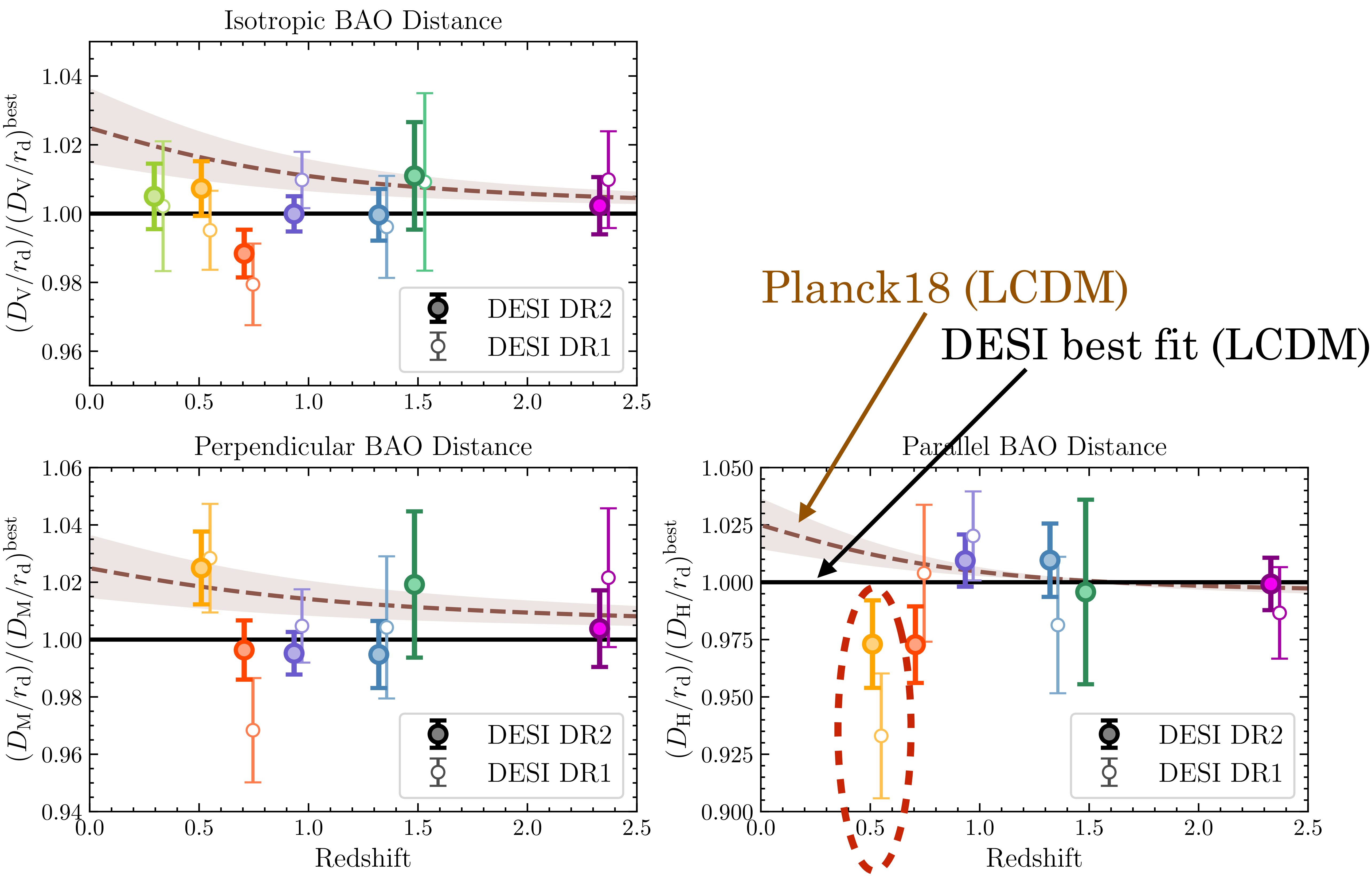

PHYSICS
student
Prakhar Bansal
(cosmo analysis)
student
Jiaming Pan
(cosmo analysis)
postdoc
Uendert Andrade
(blinding); **Y3 analysis coord.**
student
Sikandar Hanif
(fiber assignment)
postdoc (now prof)
Johannes Lange
(DESI x lensing)
student
Otavio Alves
(covariance)
student
Tianke Zhuang
(cosmo analysis)
Huterer group at UMich: DESI effort

DESI Y1/Y3 cosmological analysis

- BAO year-1 results were unblinded in December 2023
- **Two key Y1 papers:** (I was analysis co-coordinator)
  - cosmological constraints from BAO (April 2024)
  - "full-shape" analysis constraints (Nov 2024)
- **Year-3 papers posted in March 2025**
  - **BAO measurements and cosmo constraints** (arXiv:2503.14738)
  - Validation of pipeline (Andrade et al, arXiv:2503.14742)
  - Lya measurements (arXiv:2503.14739)
  - Neutrino physics constraints (Elbers et al, arXiv:2503.14744)
  - Dark energy constraints (Lodha et al, arXiv:2503.14743)

DESI DR2 (that is, Year 3) Cosmological Results

DR2 Distance Measurements

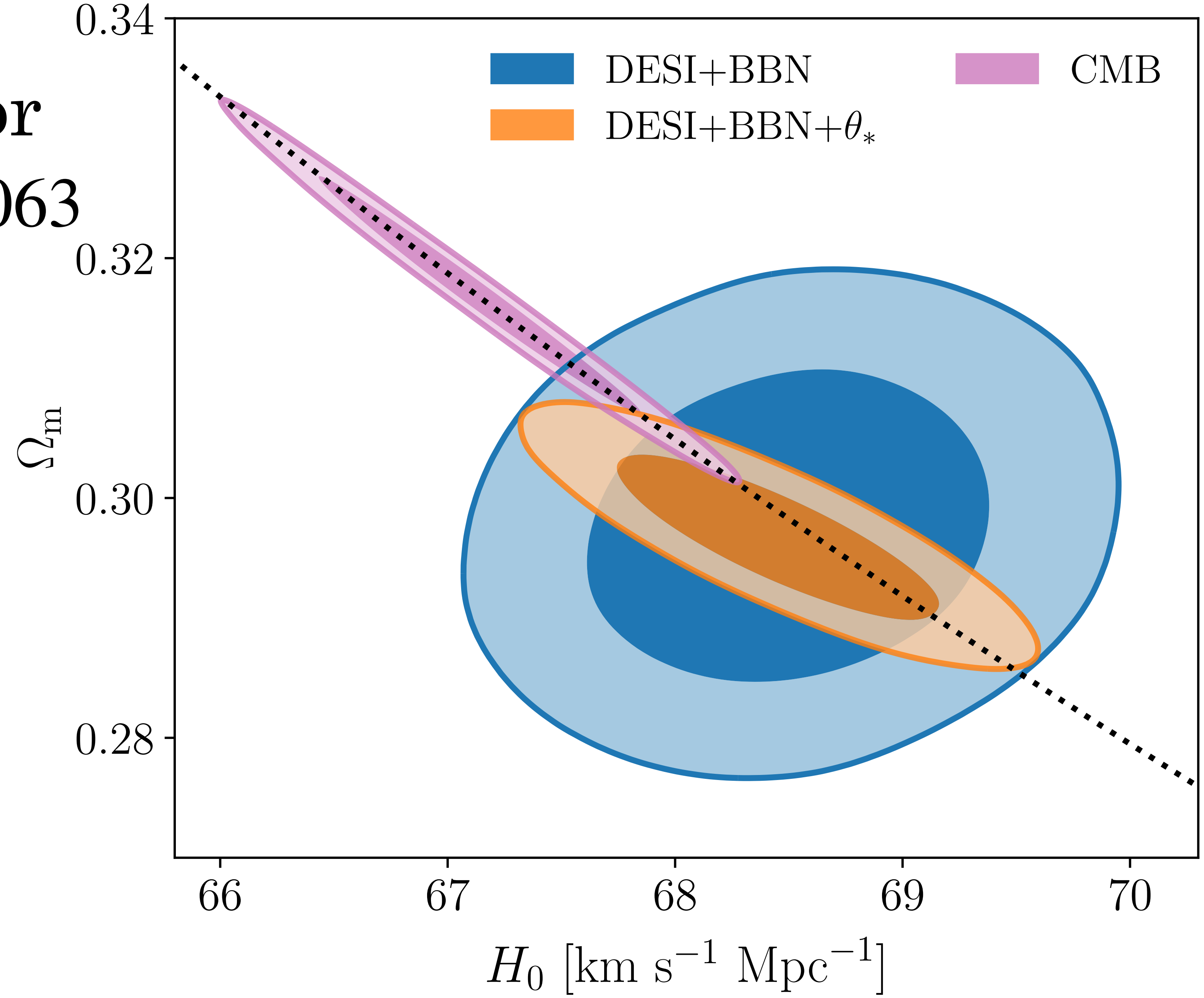


Hubble constant (in LCDM)

Requires BBN prior

$$\Omega_b h^2 = 0.02196 \pm 0.00063$$

(Schöneberg 2024)



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

28% more precise than in DR1;

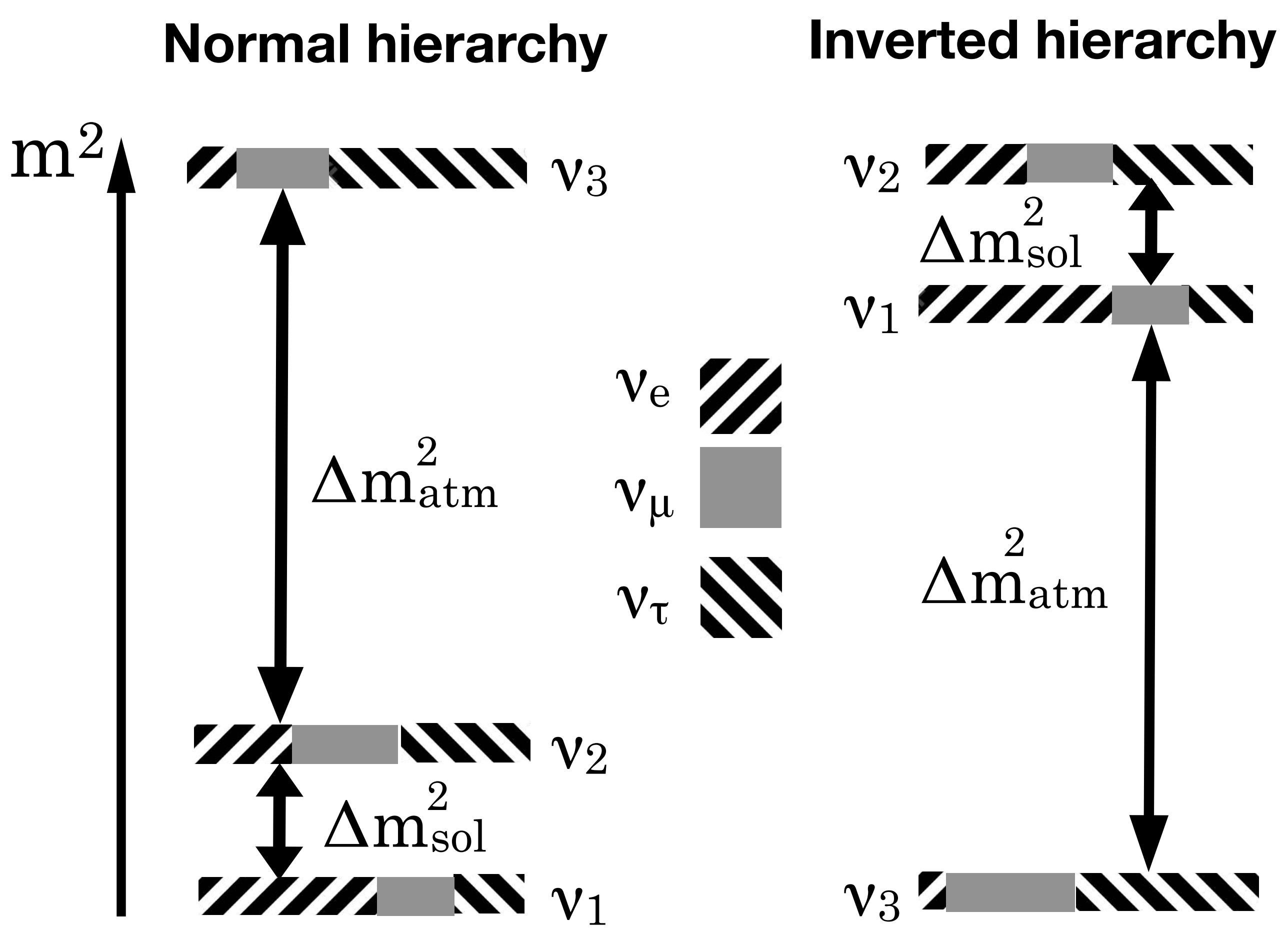
4.5σ away from SH0ES (without CMB!)

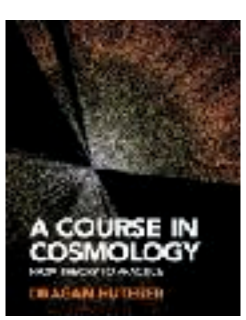
Sum of neutrino masses

From neutrino oscillation experiments

$$\left.\begin{aligned}(\Delta m^2)_{\rm sol} &\simeq 8\times10^{-5}\ {\rm eV}^2\\ (\Delta m^2)_{\rm atm} &\simeq 3\times10^{-3}\ {\rm eV}^2\end{aligned}\right\}\quad \begin{aligned}&\sum m_i = 0.06\ {\rm eV}^*\ \text{(normal)}\\ &\qquad\text{vs.}\\ &\sum m_i = 0.10\ {\rm eV}^*\ \text{(inverted)}\end{aligned}$$

*(assuming m_1=0)





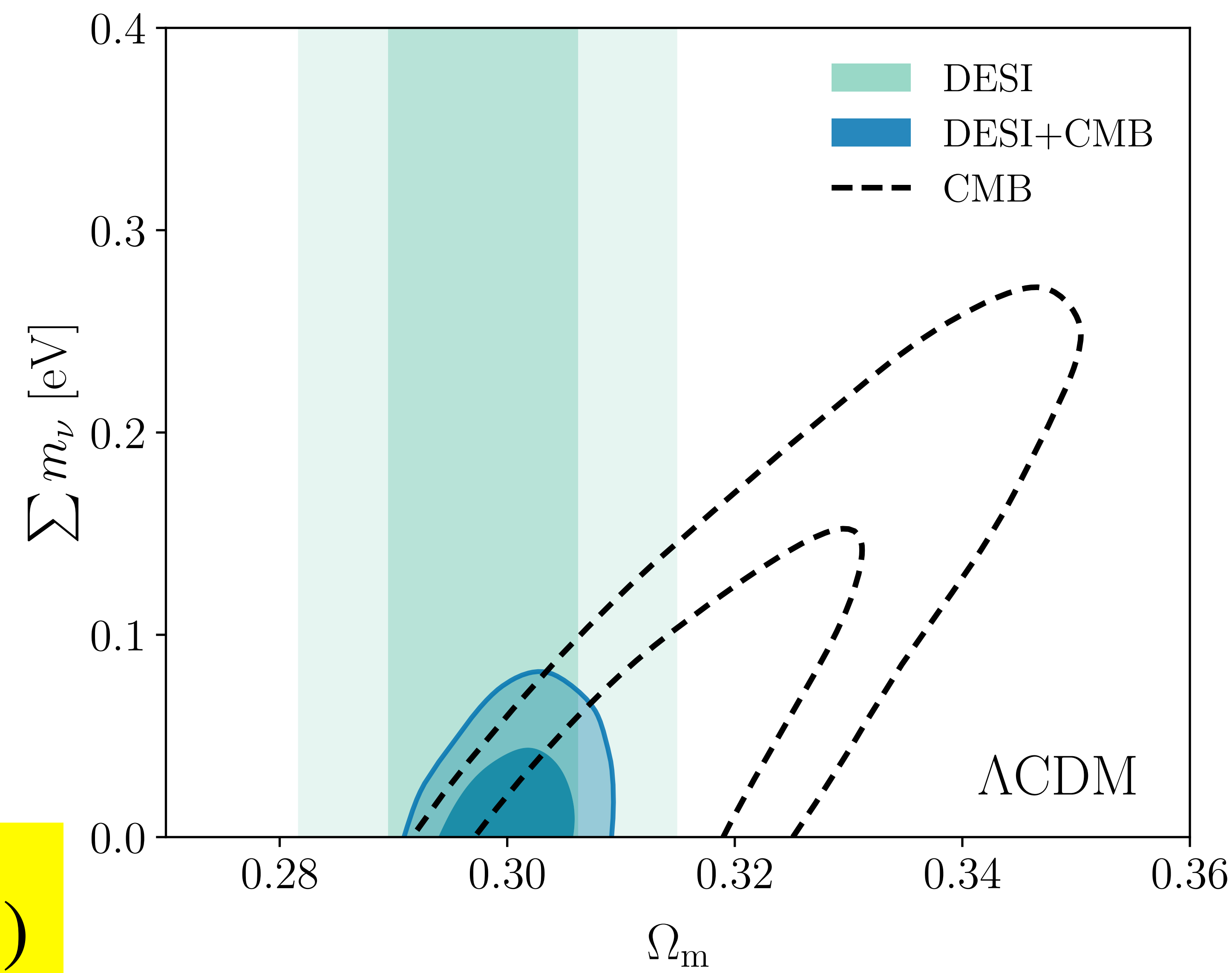
Sum of neutrino masses

Neutrinos are non-relativistic today

$$\sum m_\nu \simeq 0.1\,\mathrm{eV} \gg T_0 \simeq 10^{-4}\,\mathrm{eV}$$

so they contribute to (recent) expansion history just like matter

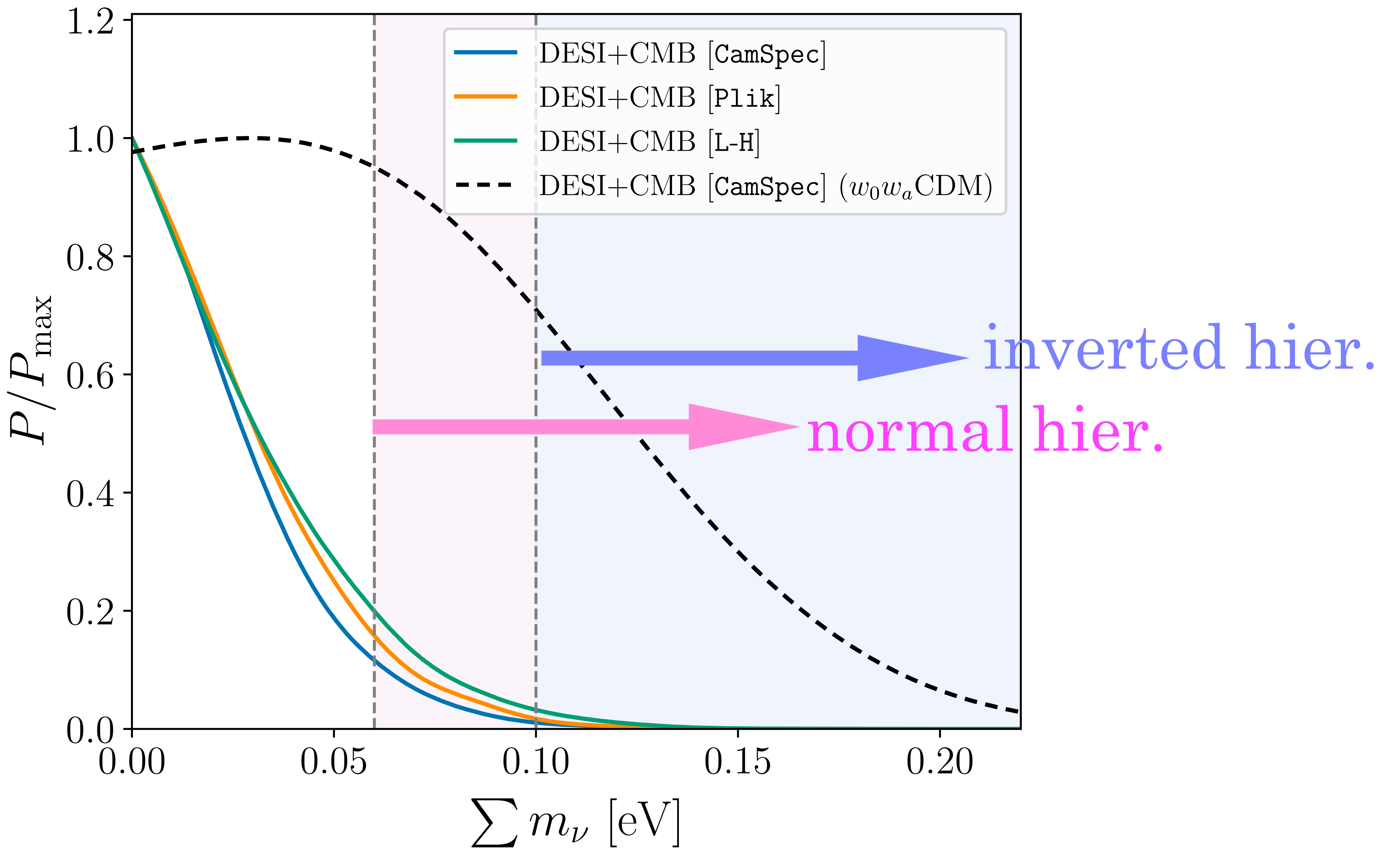
CMB constrains Σm_ν,
but its precision is limited by
degeneracies
⇒ DESI helps here



$$\sum m_\nu < 0.064\,\mathrm{eV} \ \ \text{(at 95\%)}$$

[But significantly weakens in models beyond ΛCDM, e.g. $\sum m_\nu < 0.163\,\mathrm{eV}$ in w_0w_aCDM]

Sum of neutrino masses



$$\sum m_\nu < 0.064\,\text{eV} \quad \text{(LCDM, at 95\%)}$$

Much more detail in DESI neutrino supporting paper (Elbers et al, arXiv:2503.14744)

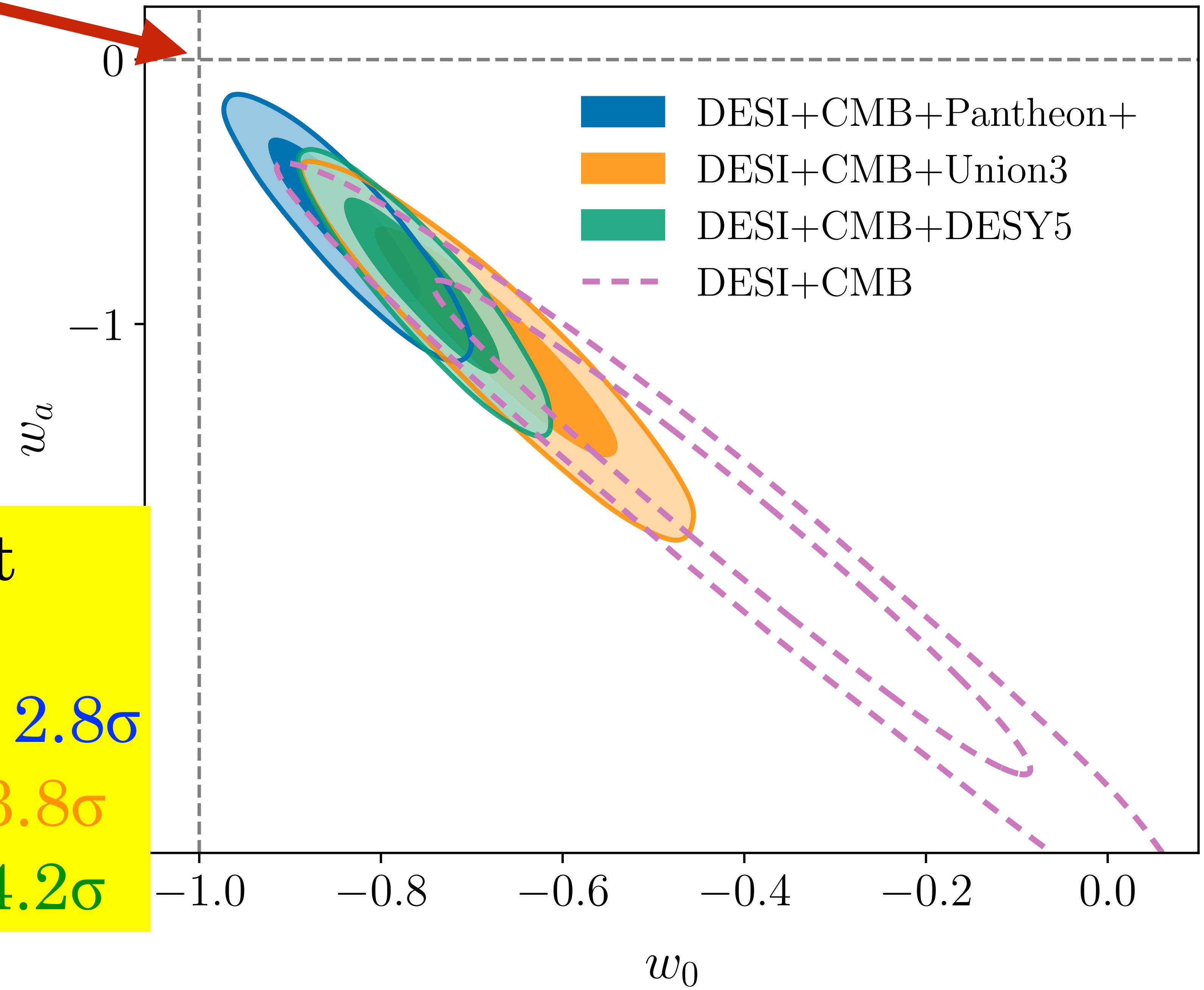
Dark energy - (w_0, w_a)

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

a is scale factor
a=0: Big Bang
a=1: today

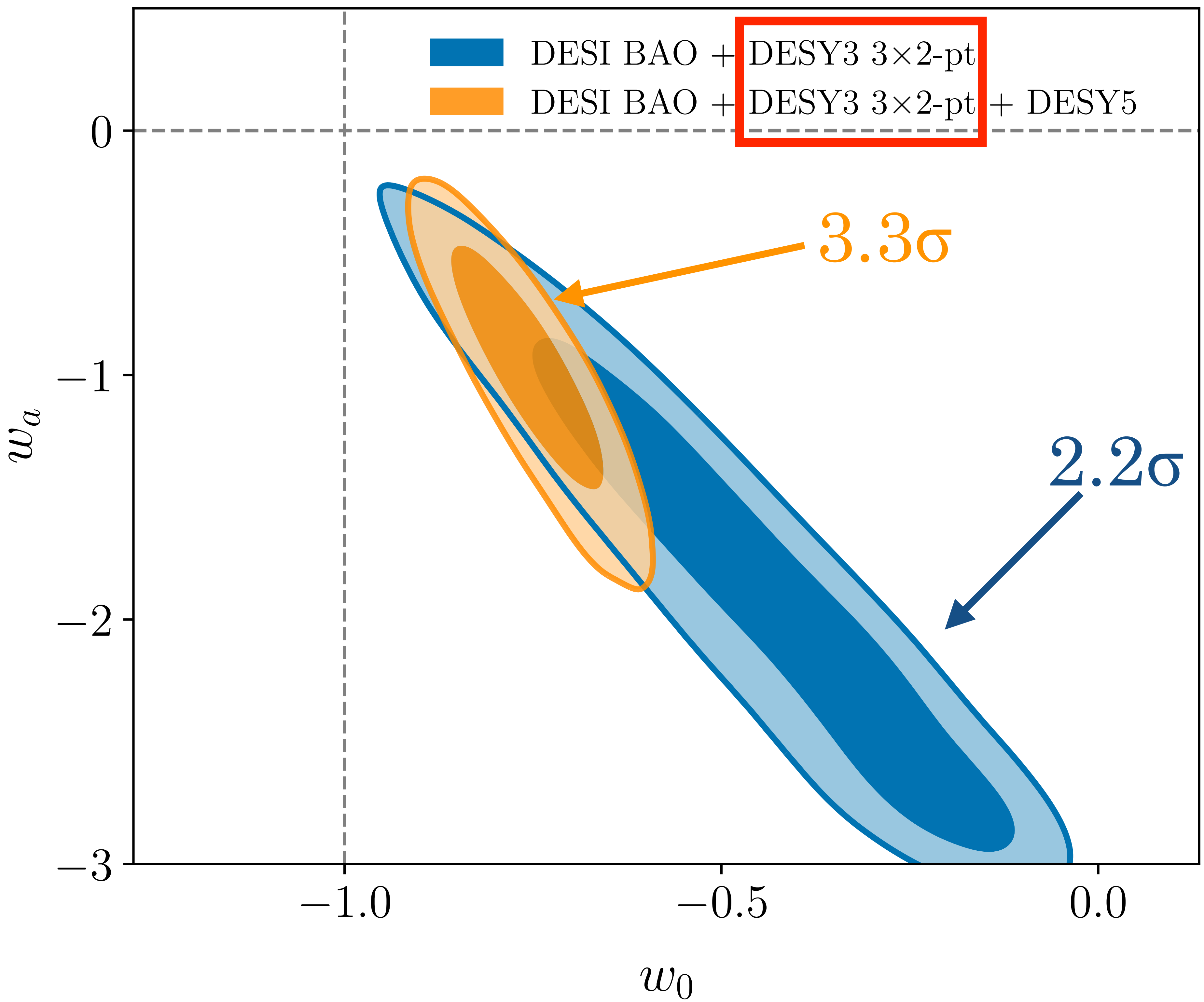
ΛCDM
(standard model)

DESI shows preference for $w_0 > -1$, $w_a < 0$



Significance against LCDM:
DESI+CMB+Pantheon: 2.8σ
DESI+CMB+Union3: 3.8σ
DESI+CMB+DESY5: 4.2σ

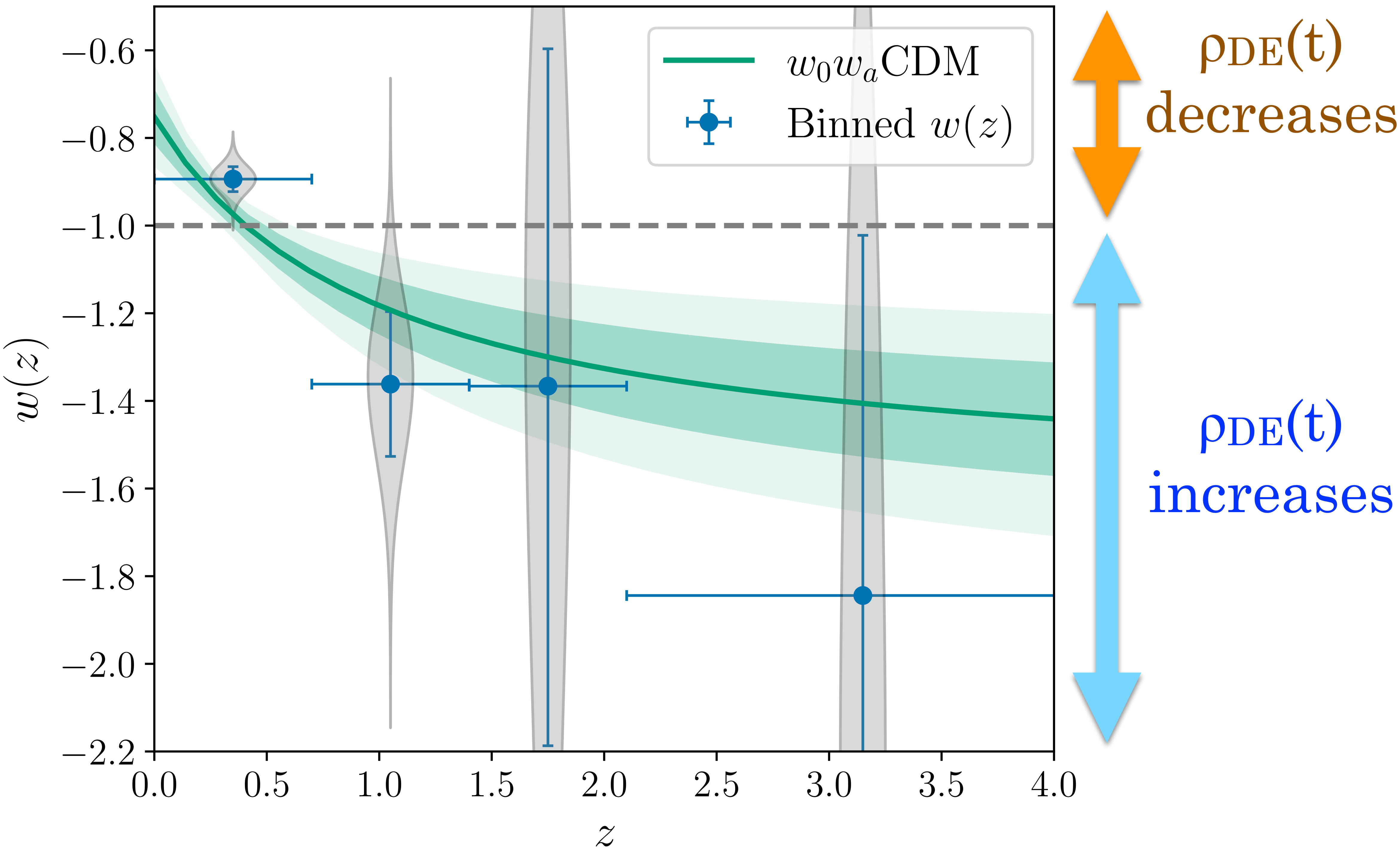
Low-z probes alone hint for ~~LCDM~~



(no CMB here)

Therefore: tantalizing hints of departure from LCDM

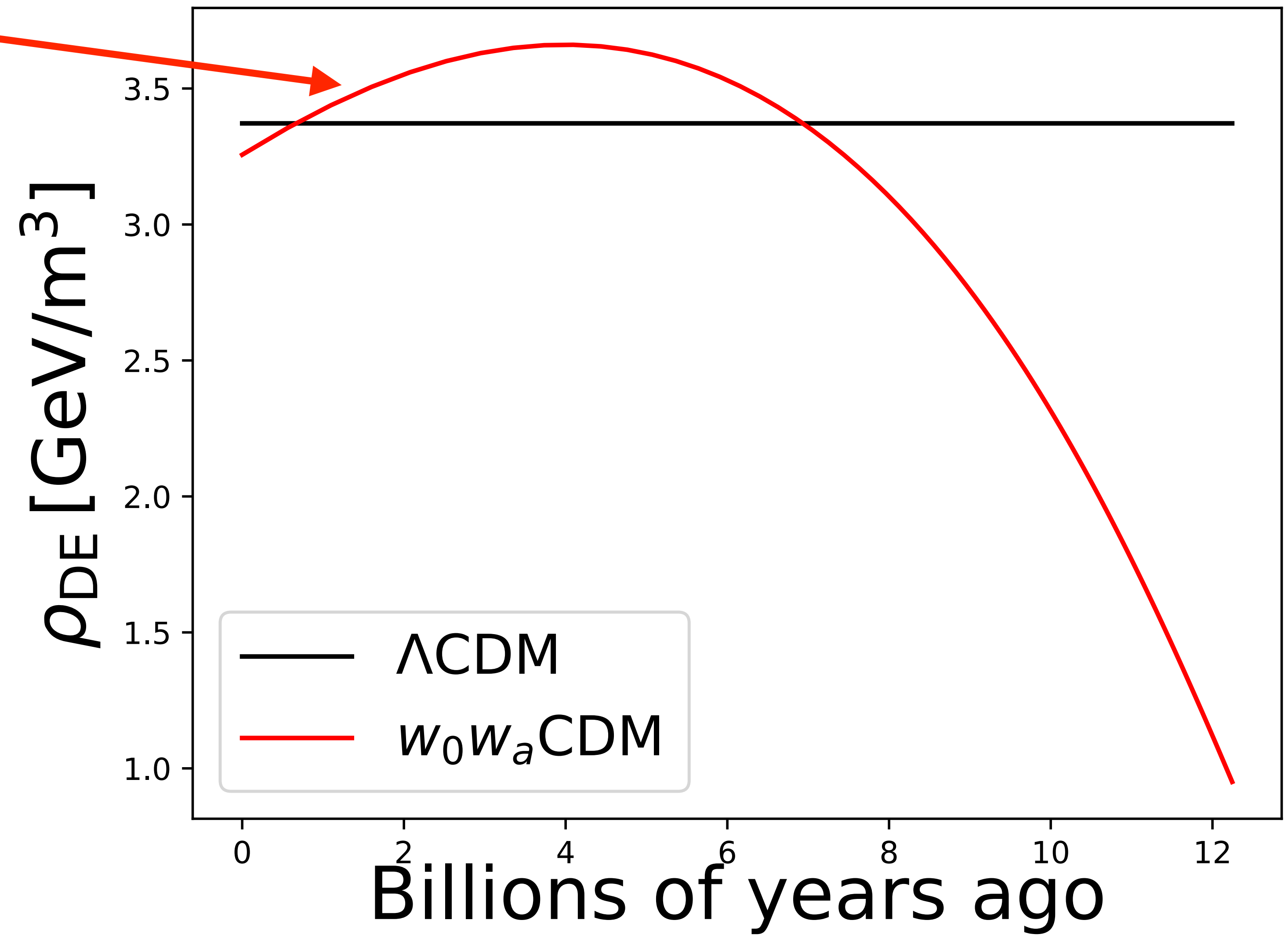
Confirmed by alternative analyses

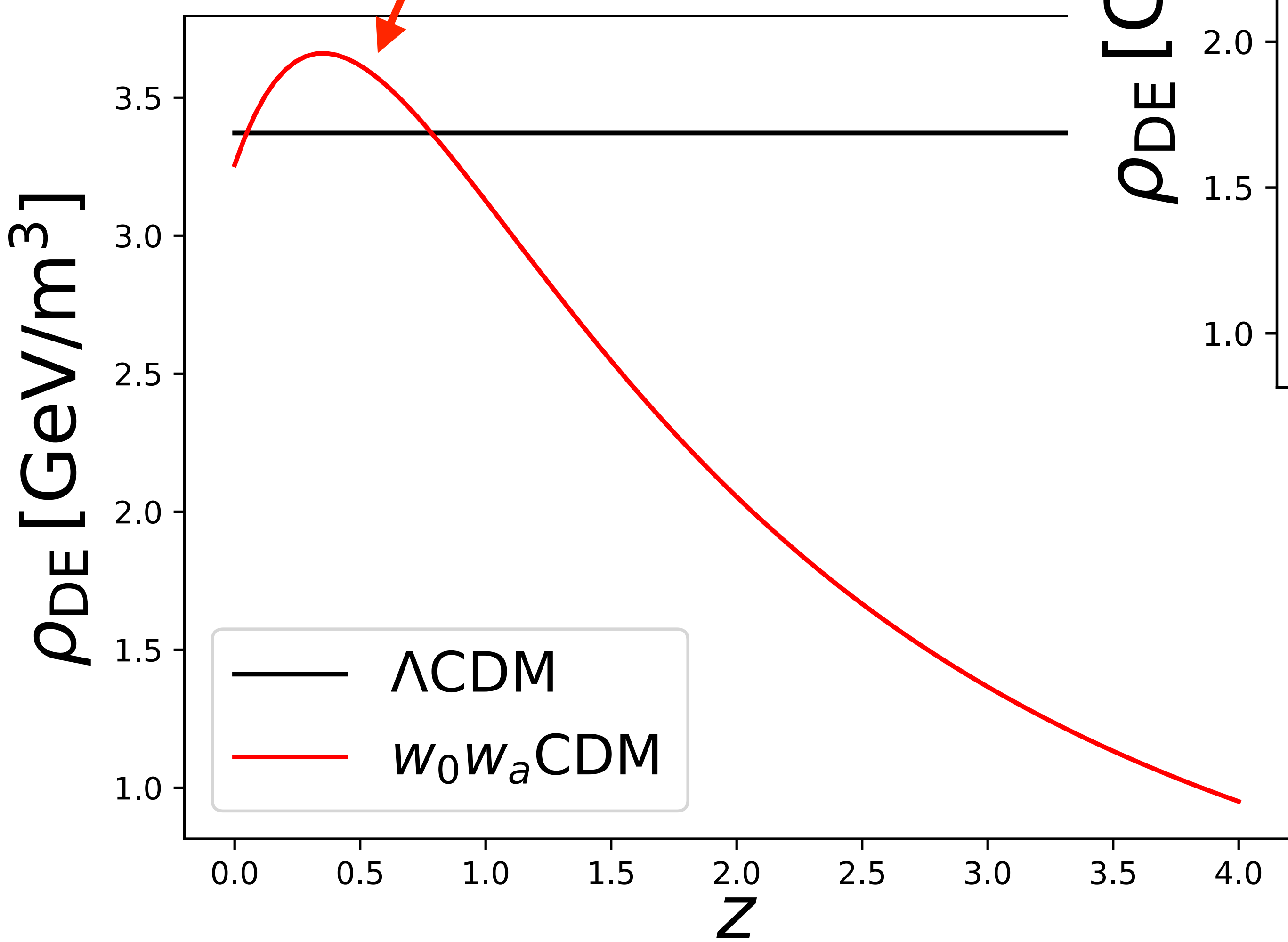


DESI supporting paper on dark energy; Lodha et al, arXiv:2503.147143

in other words

Best-fit w0wa model
from DESI+CMB+SNIa





What's next

- The results presented here were just the BAO; **DESI Y1 full-shape analysis of galaxy clustering is forthcoming** (~summer 2024)
- 5 years of DESI will have information from ~40 million galaxies over 14,000+ square degrees
- DESI-2 (late 2020s) will significantly increase number of galaxies
- Stage-V spectroscopic survey (supported by P5 report; ~2035)

Conclusions

- Dark Energy is a premier mystery in physics/cosmology; physical reason for accelerating universe still an open question

- Impressive variety of new data; forthcoming: DES Y6, HSC, DESI, LSST, Euclid, Roman, ZTF…

- Like particle physicists, we would really like to see some "bumps" in the data (e.g. Hubble tension!).

- DESI Y3 BAO results highlights:
  - $H_0 = (68.51 \pm 0.58)$ km/s/Mpc
  - $\sum m_\nu < 0.064\,\mathrm{eV}$ (DESI + CMB, at 95%)
  - dark energy: 2.8σ–4.2σ preference for model with w(t) varying

- More soon:
  - **DESI Y3 full-shape P(k) analysis; higher-order statistics**
  - DESI Y5, DESI-2, Spec-V (next-gen survey) eventually