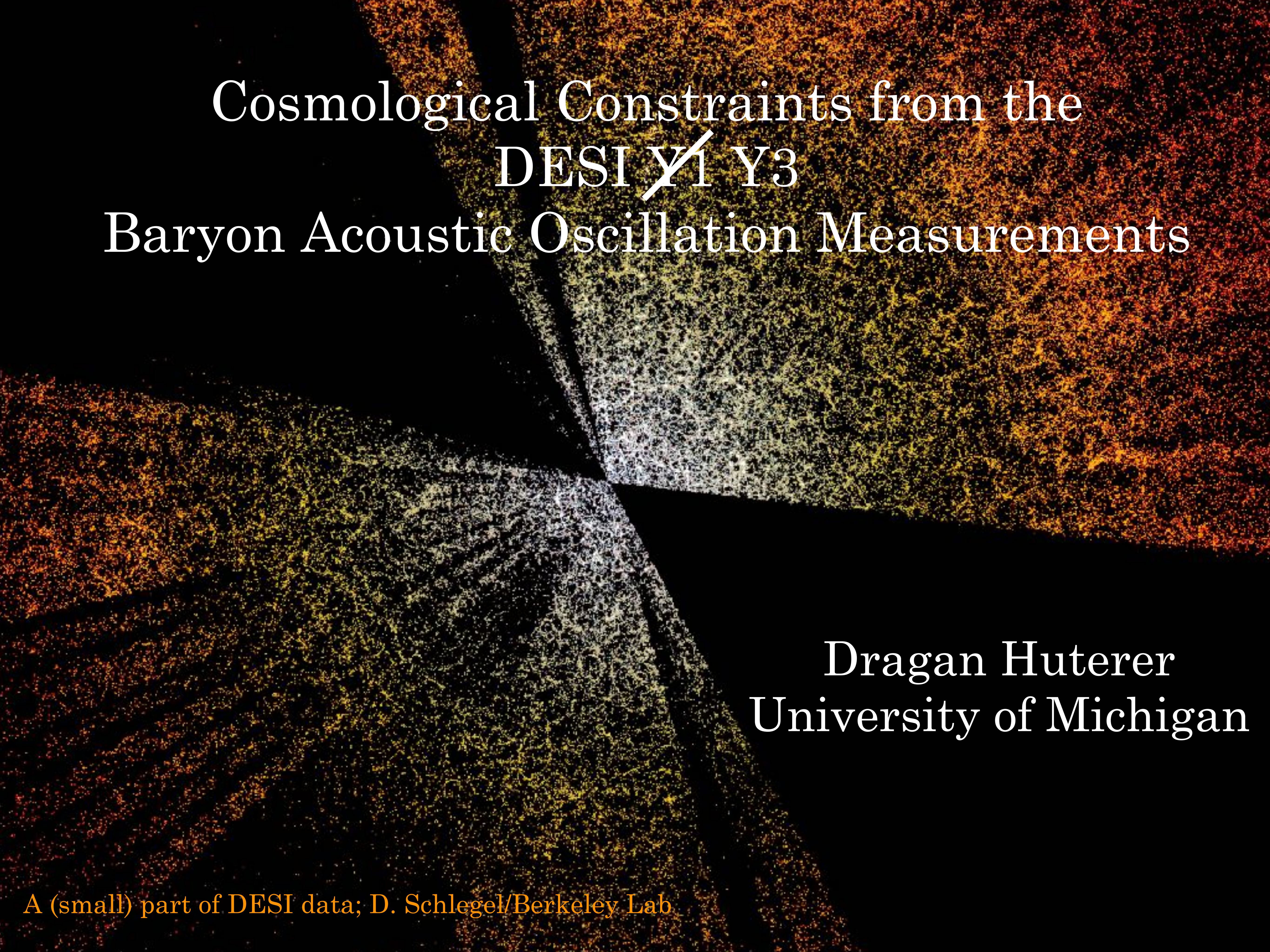
Cosmological Constraints from the DESI ~~Y1~~ Y3 Baryon Acoustic Oscillation Measurements

Dragan Huterer
University of Michigan



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

Timeline of the universe

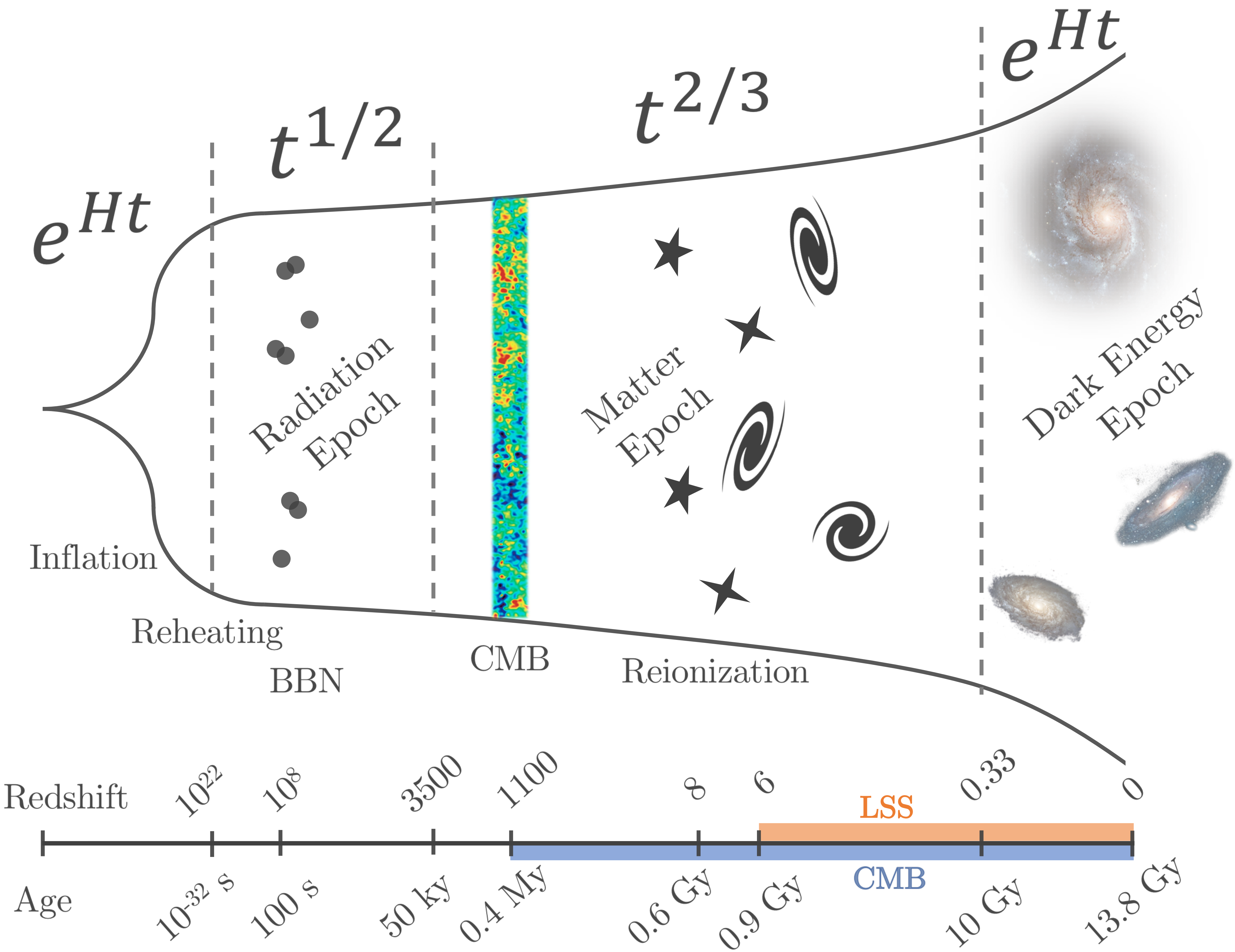
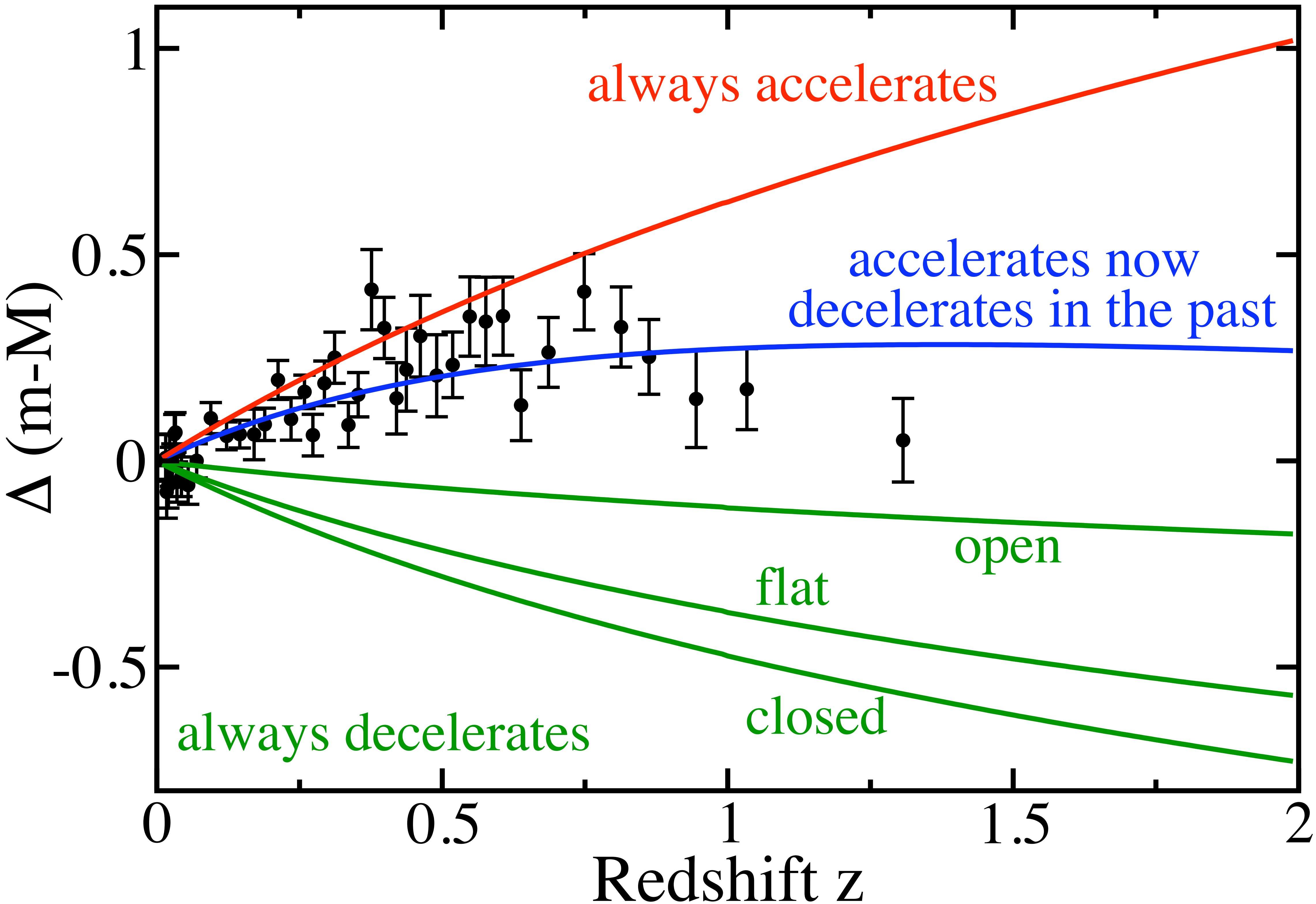


Figure credit: Noah Weaverdyck

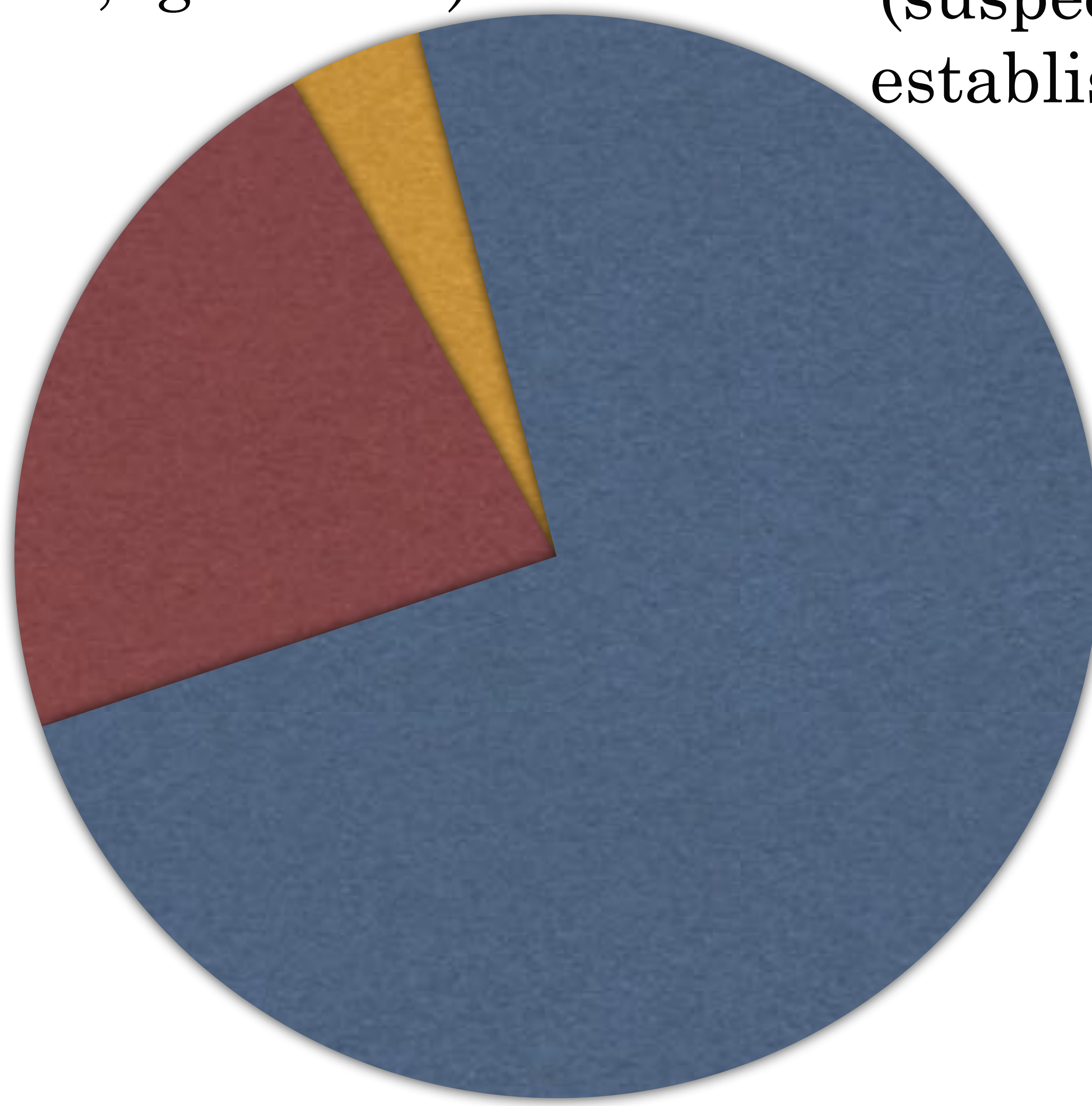
Supernova Hubble diagram
(binned; each error bar denotes ~20 SN)



Makeup of universe today

Baryonic Matter
(stars 0.4%, gas 3.6%)

Dark Energy
(suspected since 1980s
established since 1998)

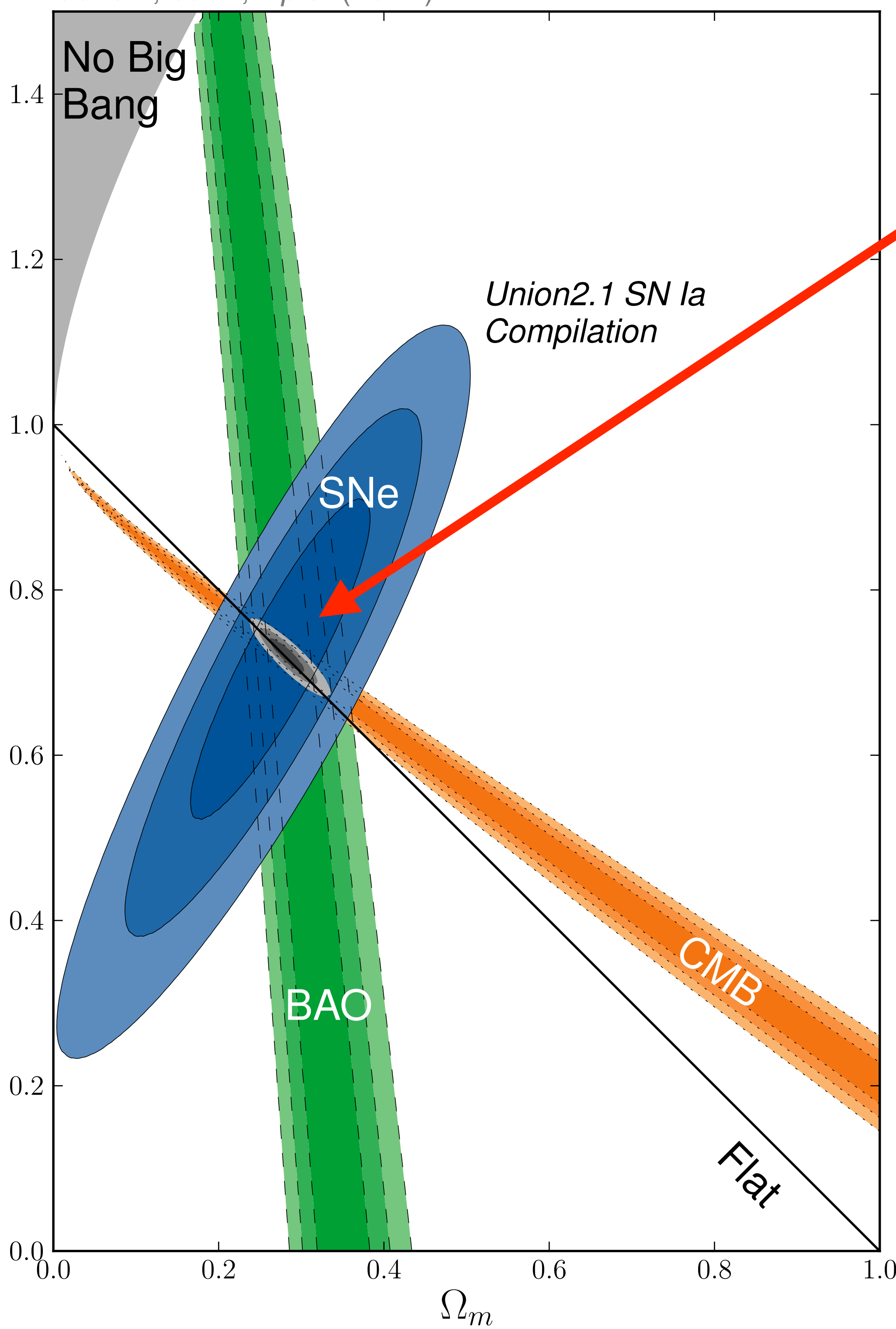


Dark Matter
(suspected since 1930s
established since 1970s)

Also:
radiation (0.01%)

(Recent) constraints on dark energy

Supernova Cosmology Project
Suzuki, et al., *Ap.J.* (2011)



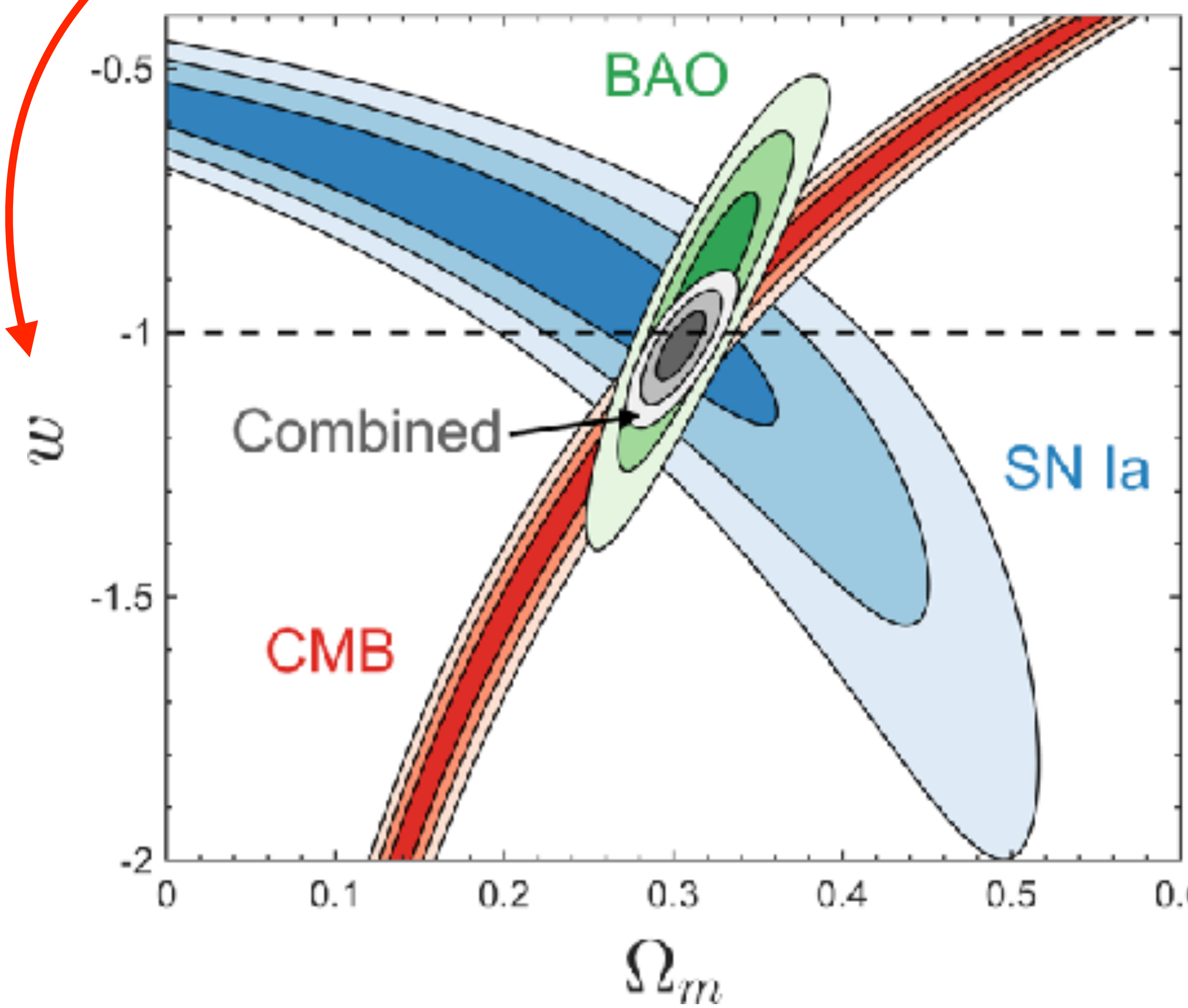
DE density (relative to critical)

Matter density (relative to critical)

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

…and DE equation of state is

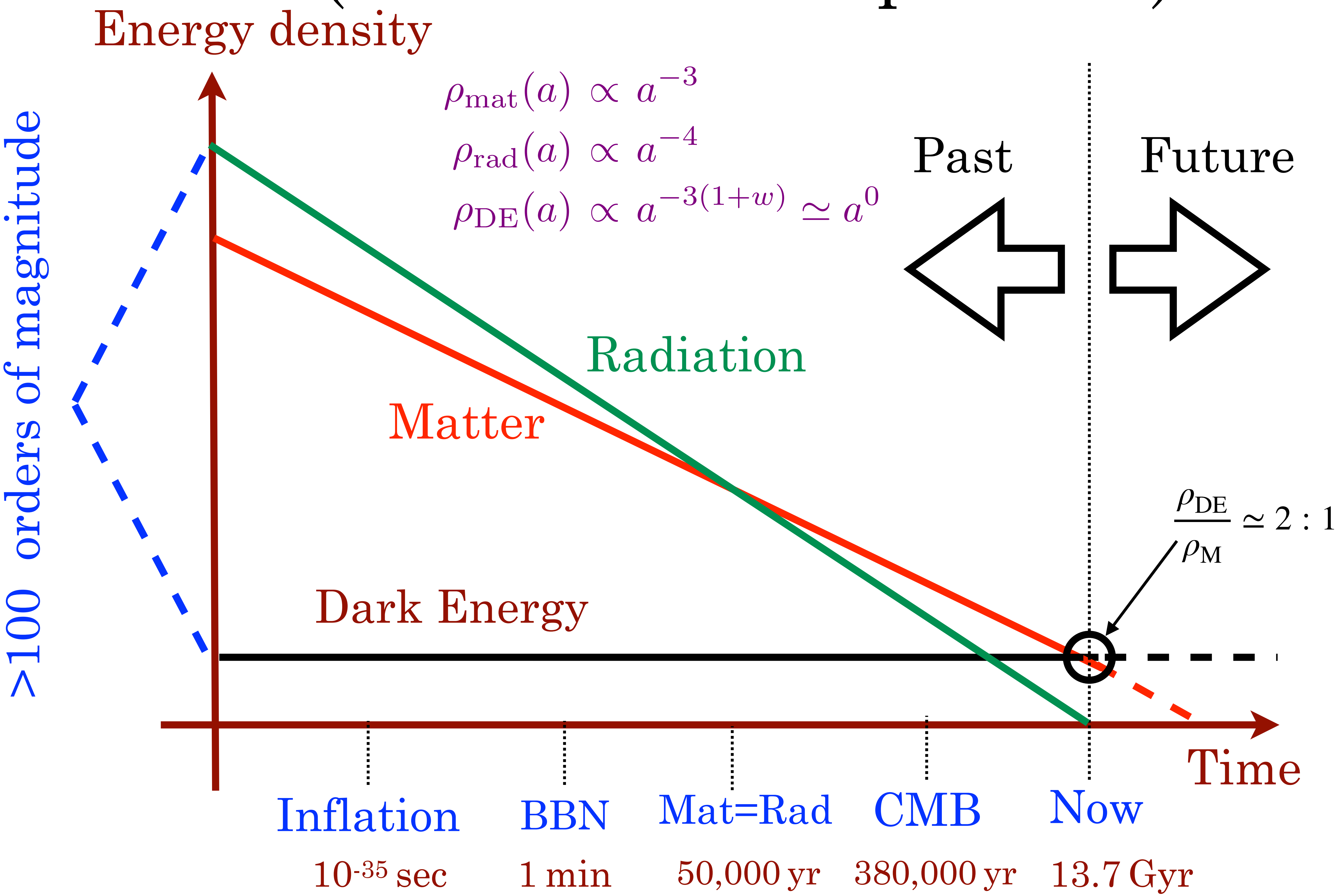
$$w \equiv \frac{p_{\rm DE}}{\rho_{\rm DE}} \simeq -1$$



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

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

Measured: $(10^{-3}\,{\rm eV})^4$

SUSY scale: $(1\,{\rm TeV})^4$

Planck scale: $(10^{19}\,{\rm GeV})^4$

} 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. $w = -1$)

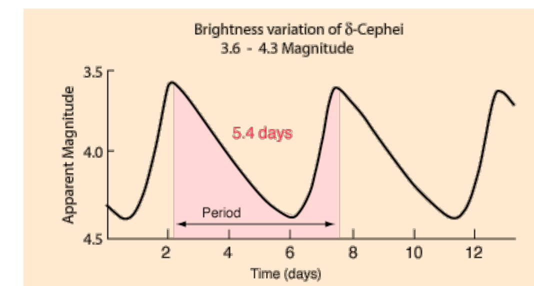
3. Theory (i.e. a compelling theoretical explanation) is lagging *far* behind

Recent development

Hubble Tension:

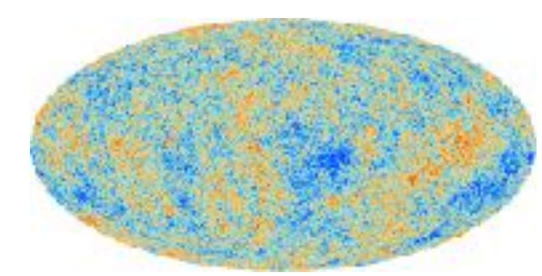
SH0ES (Riess et al 2022)

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



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).

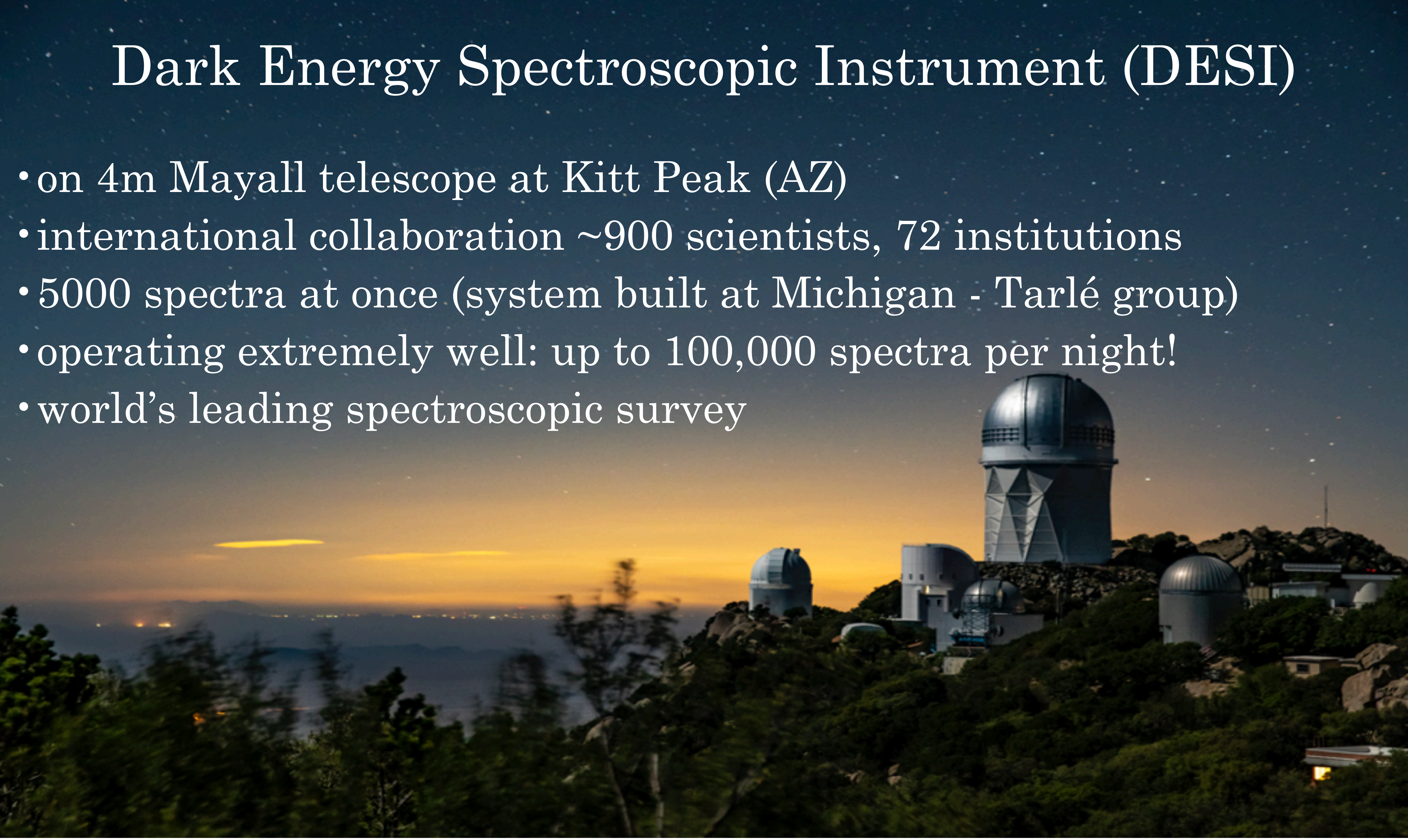
The tension recently crossed the 5-sigma threshold; this is an important step!

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:**
  - Hobby Eberly Telescope DE Experiment (HETDEX)
  - 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
3. primordial non-Gaussianity

(1 and 2: this talk)

For cosmologists, galaxies are test particles!

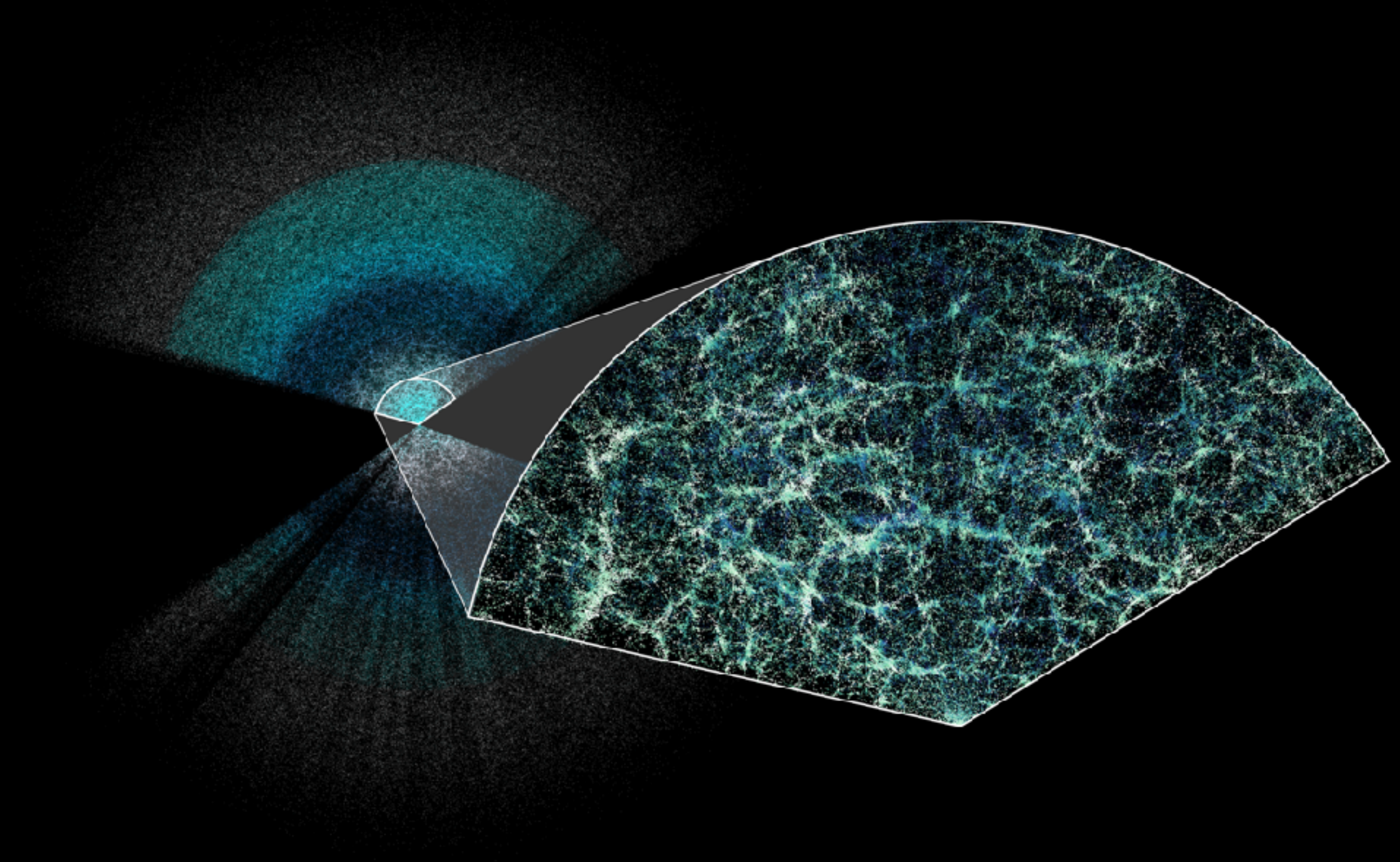
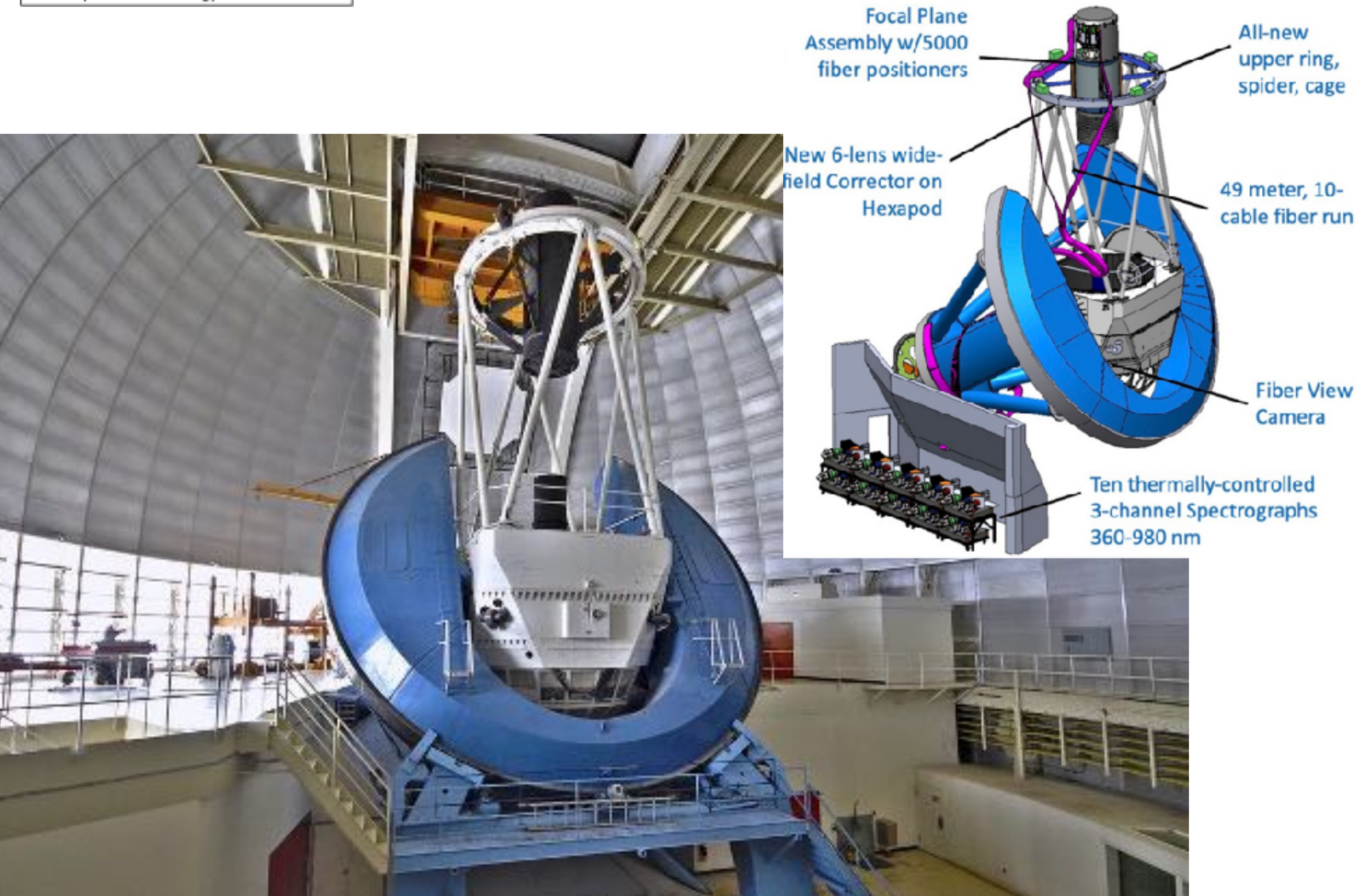


Figure credit: Claire Lamman

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

Mayall telescope at Kitt Peak, AZ



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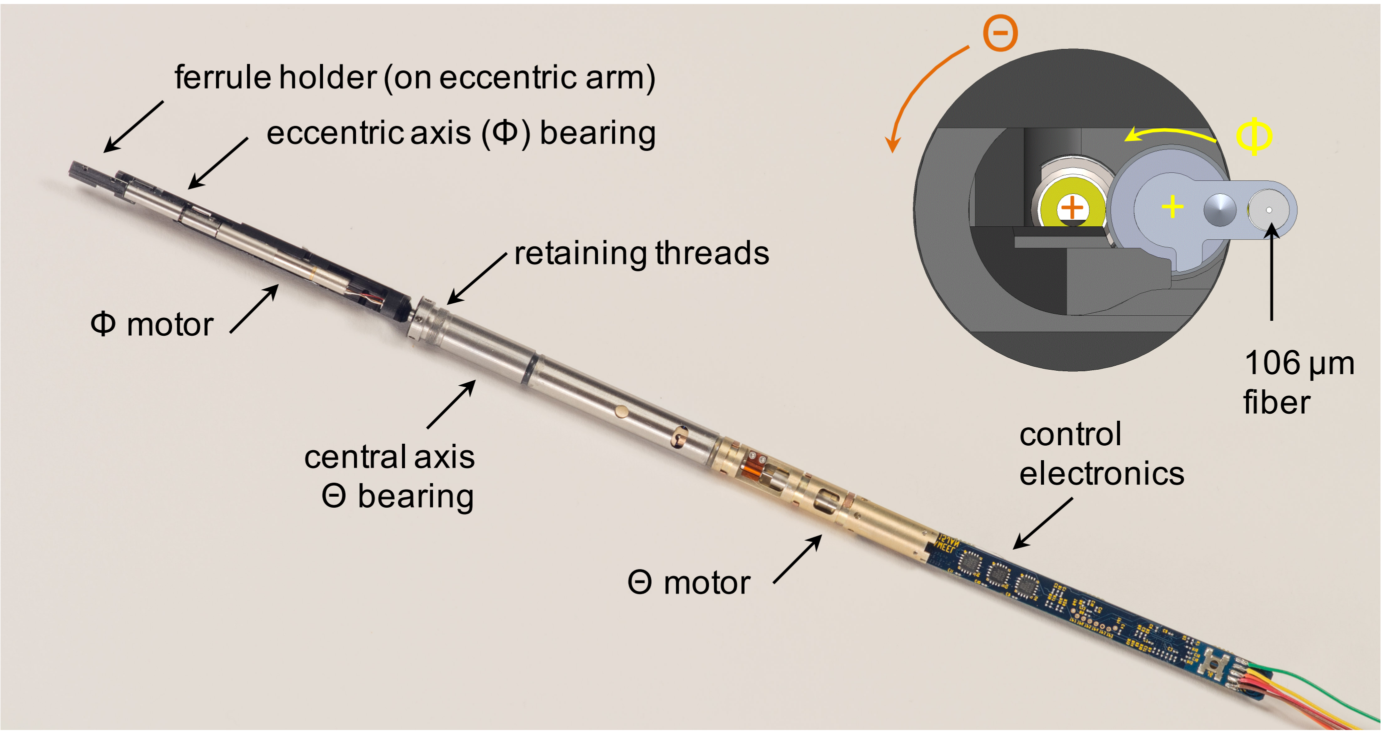
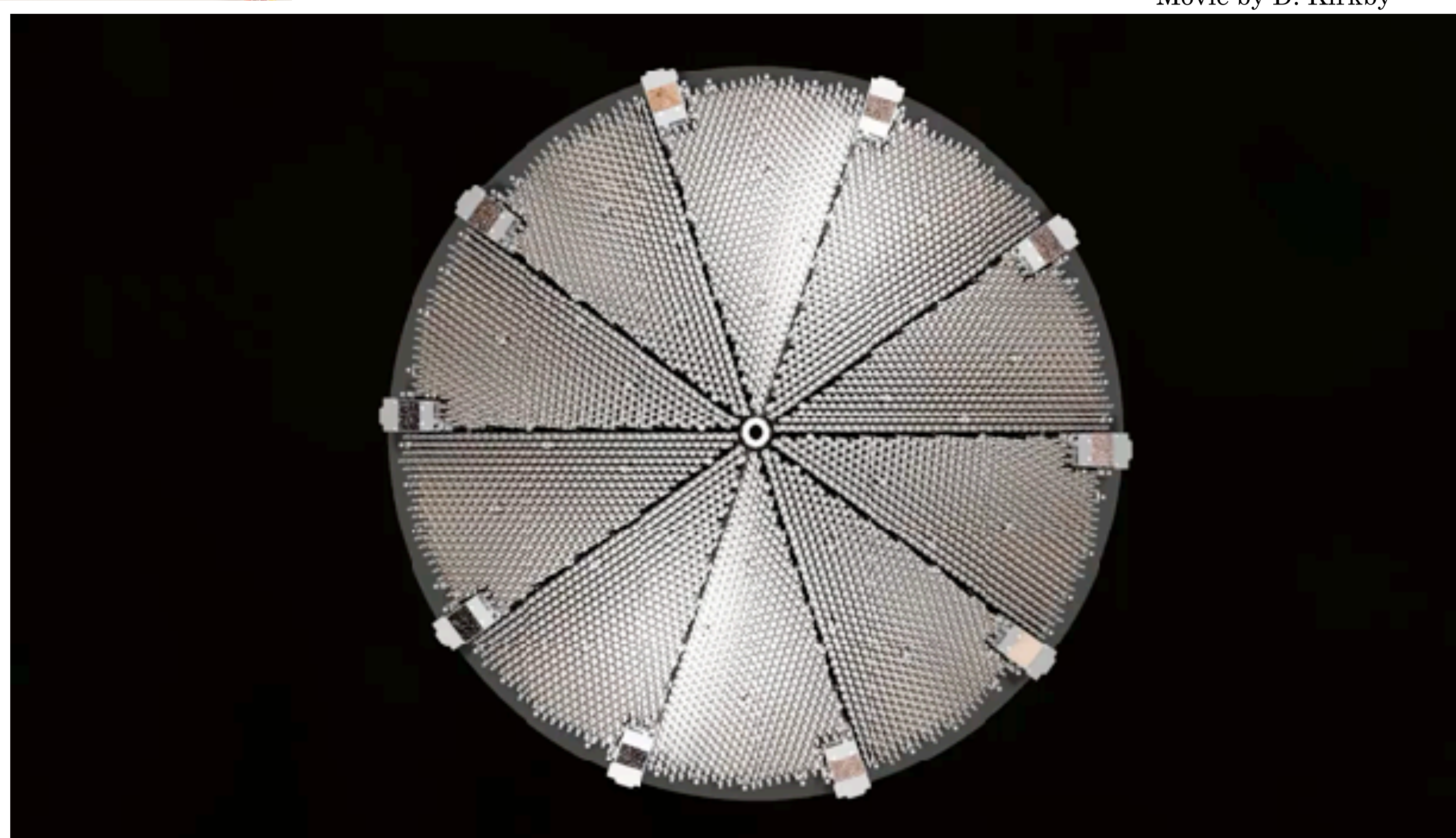
Robotic fiber positioners



Designed and built at
University of Michigan
(Tarlé group)

“5,000 eyes on the sky”

Movie by D. Kirkby



Greg
Tarlé

Michael
Schubnell

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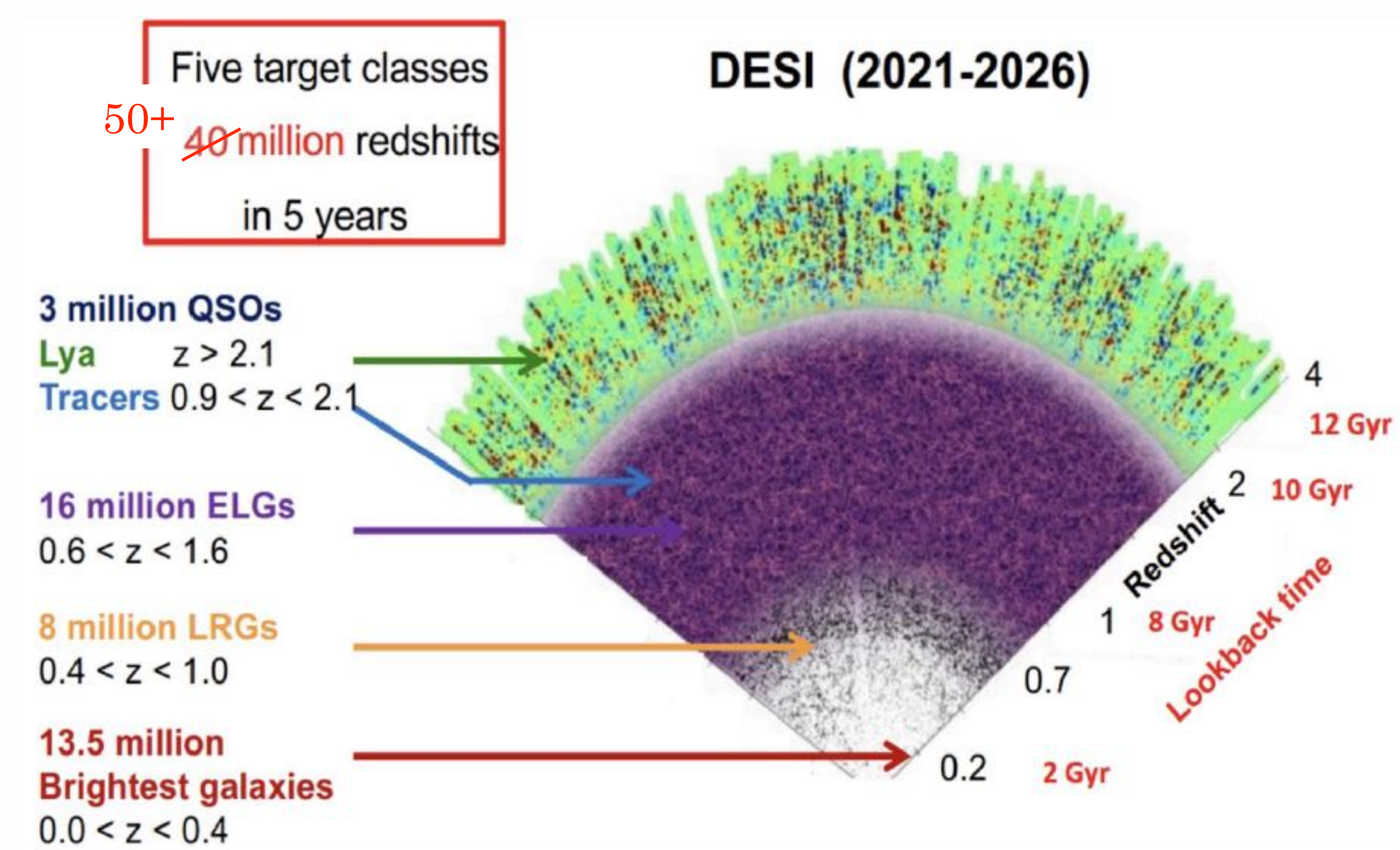
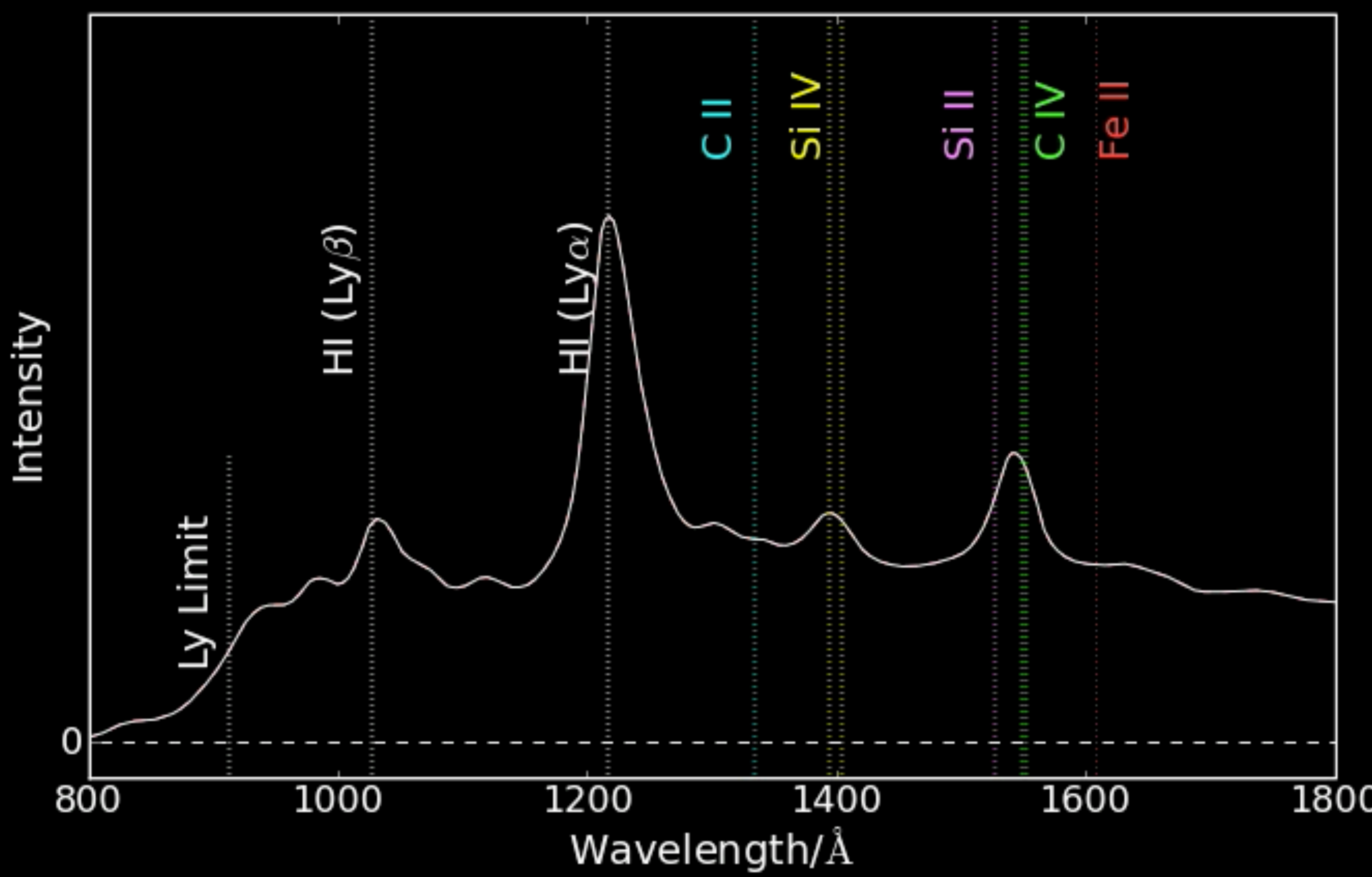
DESI tracers





Intensity
Wavelength/Å
0
800
1000
1200
1400
1600
1800
Ly Limit
HI (Lyβ)
HI (Lyα)
C II
Si IV
Si II
C IV
Fe II

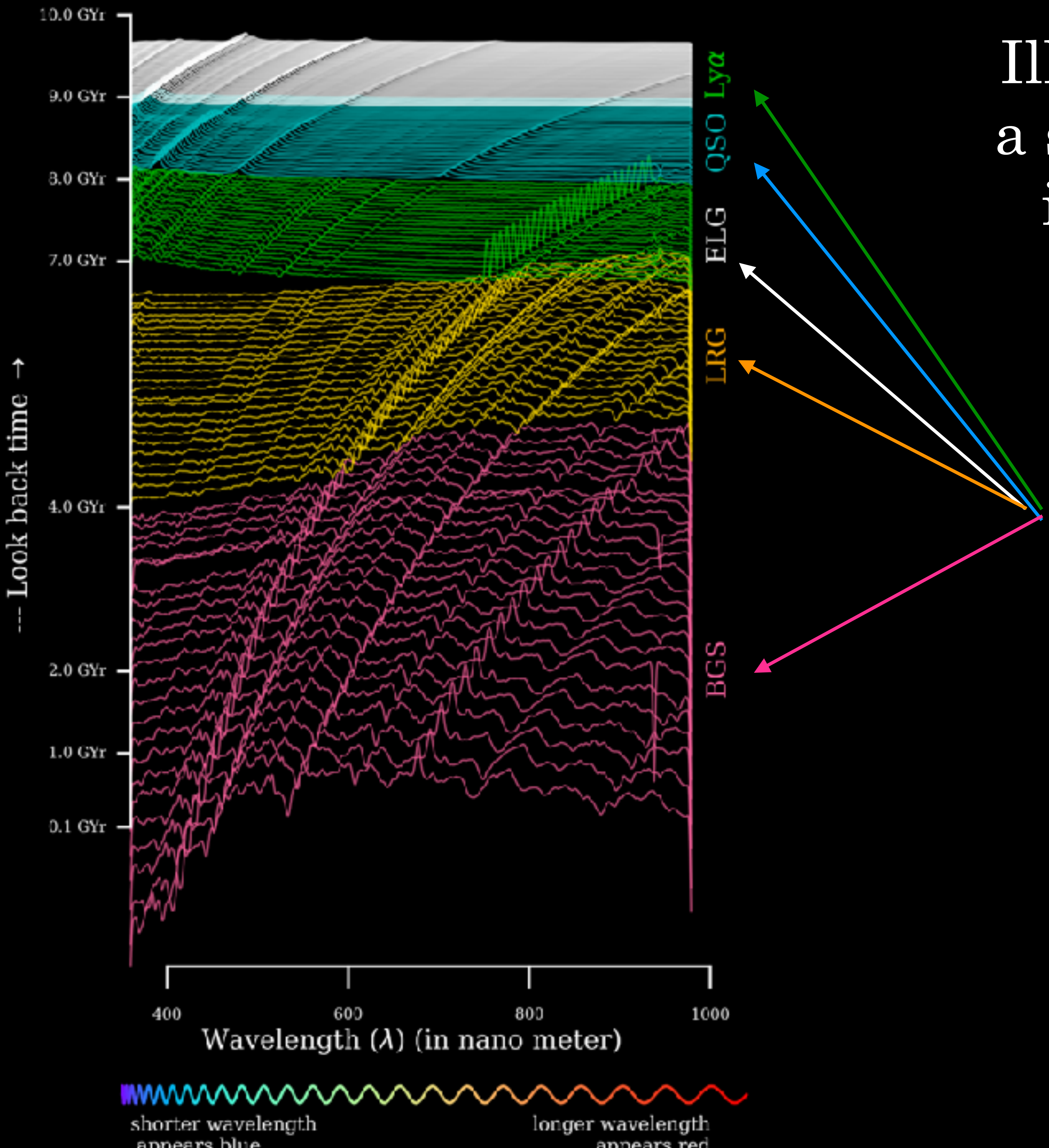


Illustration of how a spectrum evolves in redshift/time

DESI tracers

Figure credit: Shadab Alam

DESI DR2 sample

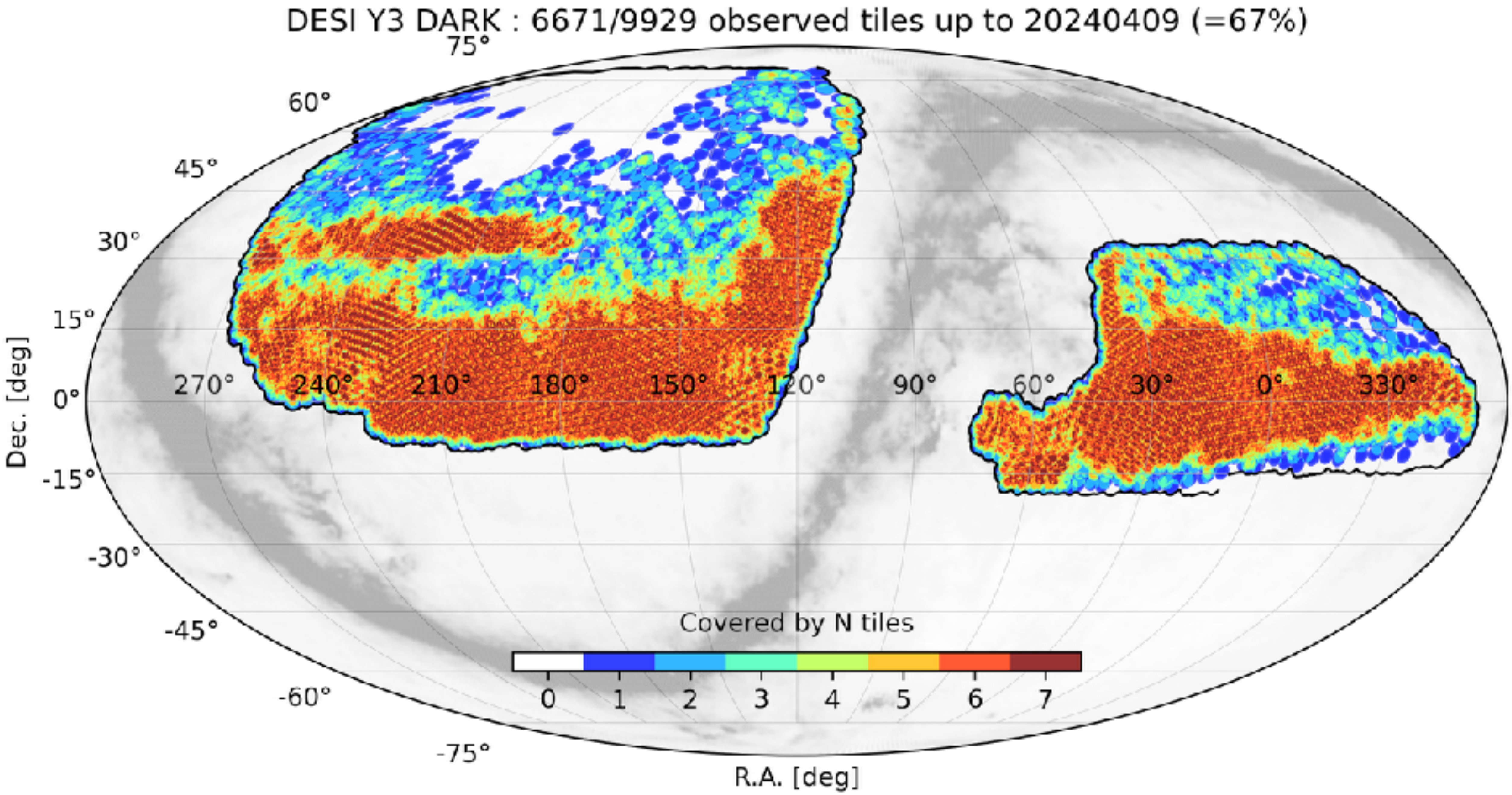
- Over 30M galaxy and quasar redshifts in 3 years of operation, ~14M of which are used in this analysis.
- Compared to DR1 (~6M redshifts), DR2 represents a factor of ~2.4 improvement in data volume.

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)

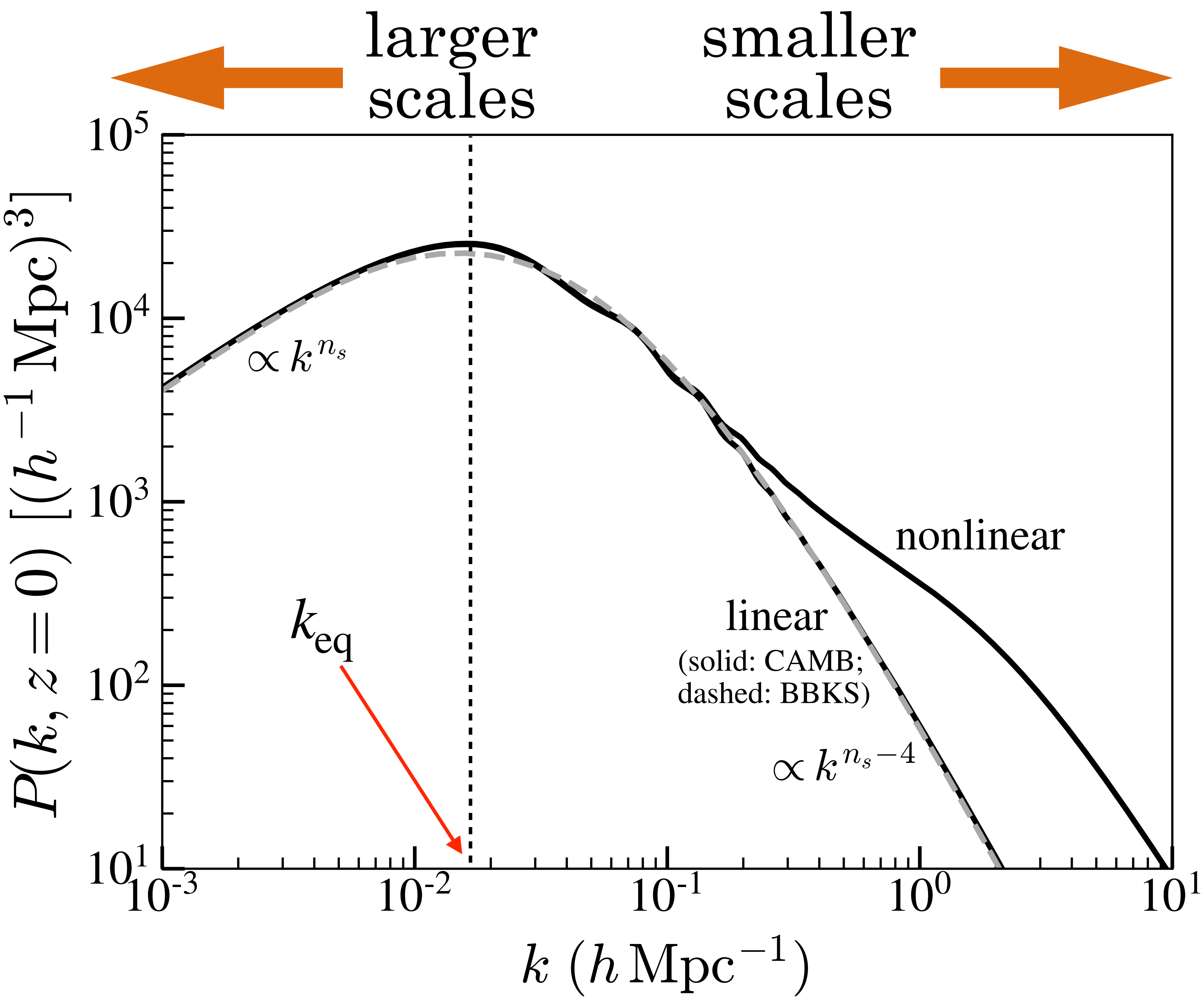
The DESI DR2 sample

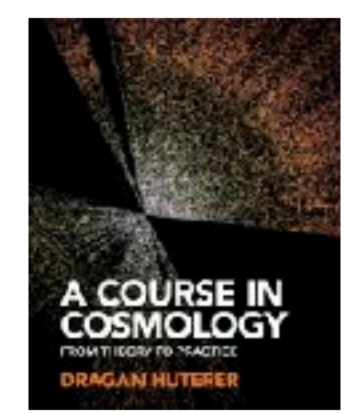


How Baryon Acoustic Oscillations observed by DESI constrain cosmological parameters

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

Galaxy power spectrum

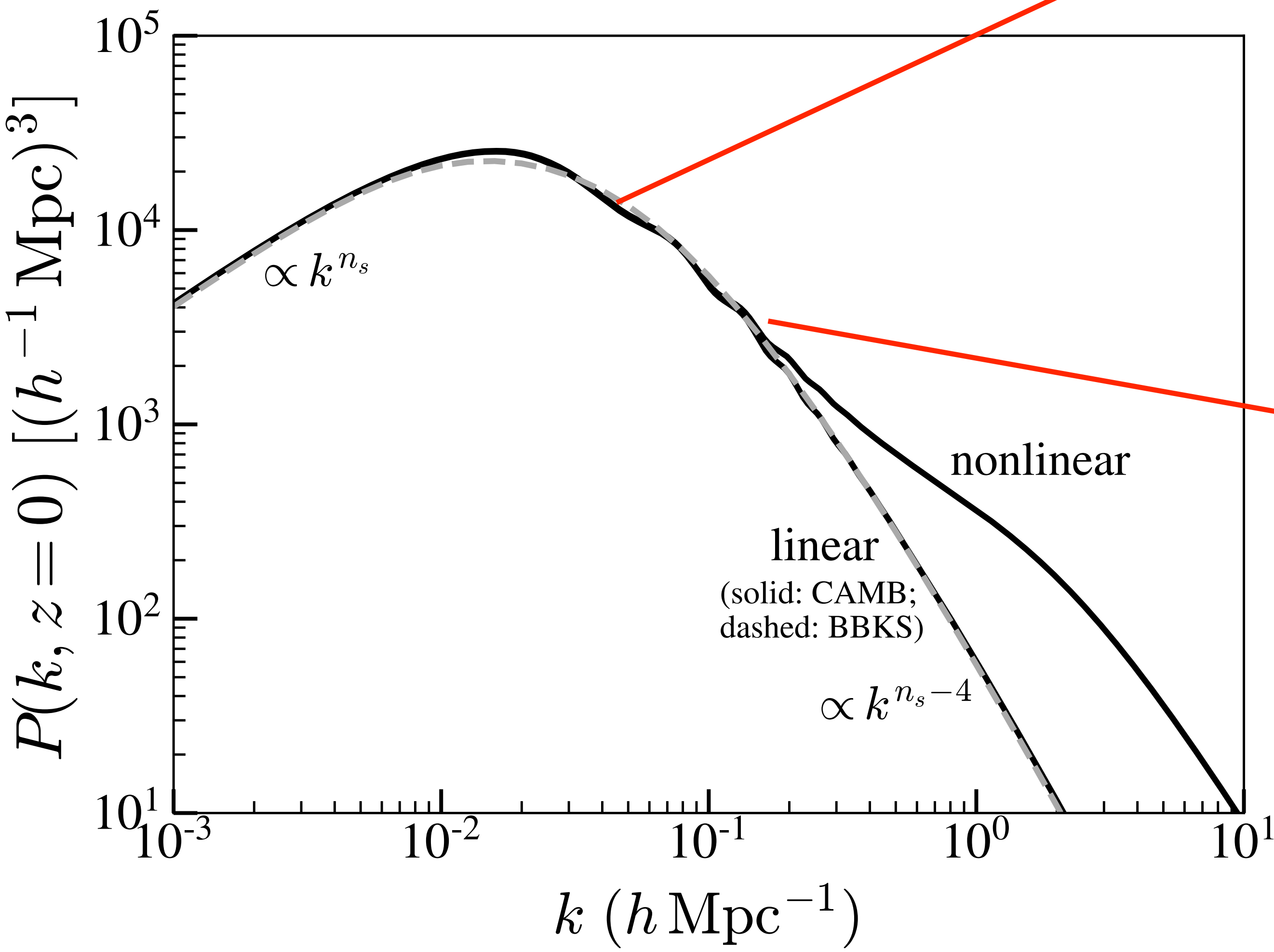


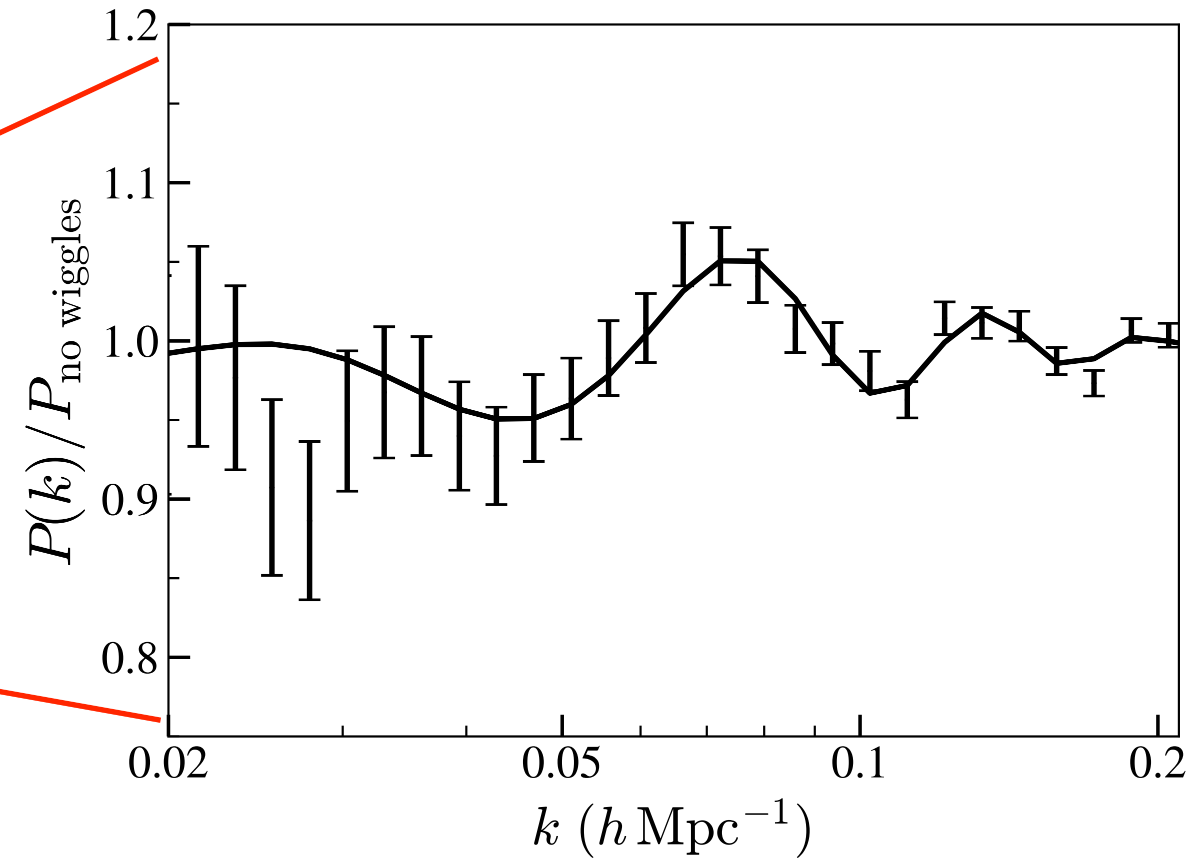


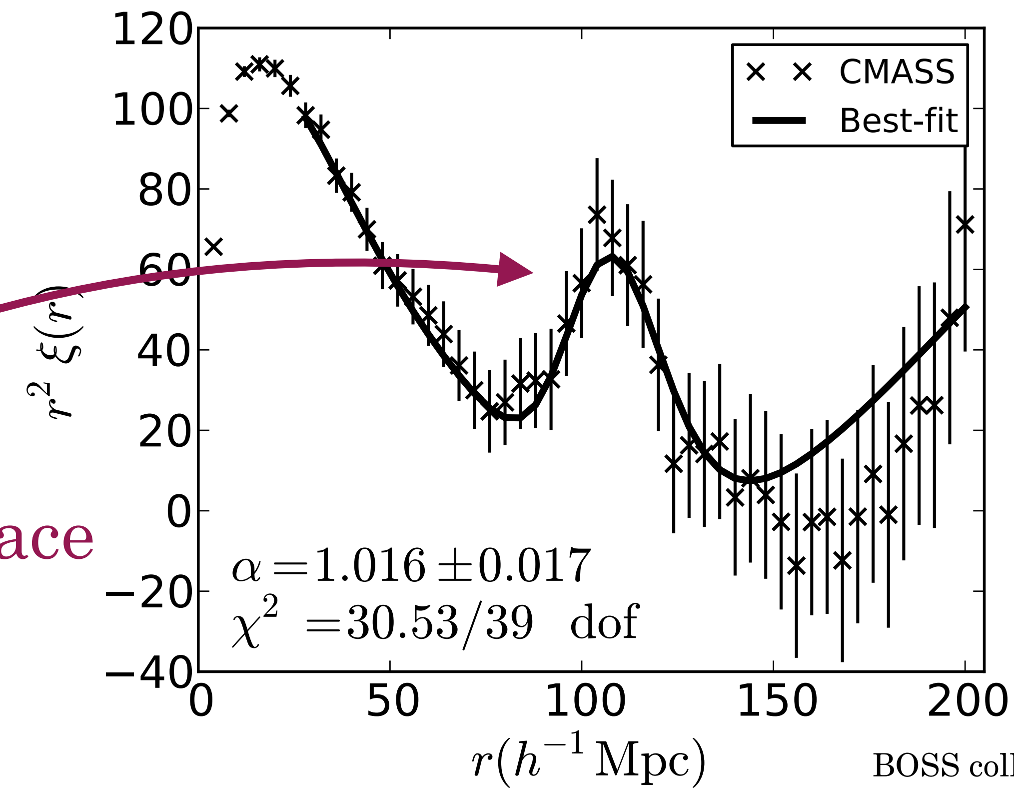
Matter power spectrum contains (almost!) all information at large scales in cosmology

Baryon Acoustic Oscillations (BAO)

Multiple wiggles in Fourier space
(power spectrum)





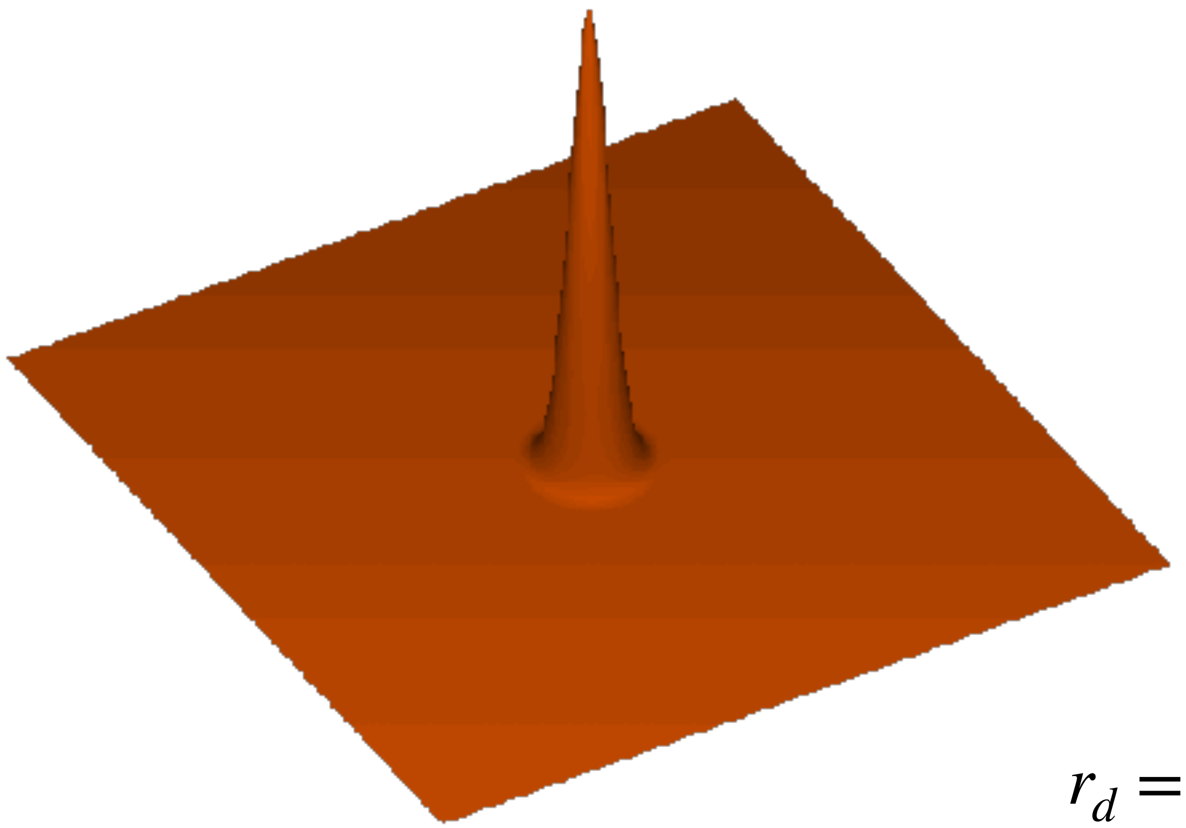


BOSS collaboration

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

First discussed in: Sunyaev & Zeldovich, 1972

How do the BAO wiggles come about?



Eisenstein, Seo et al (2007)

At recombination (z_{drag}~1060, t~300,000 yrs)

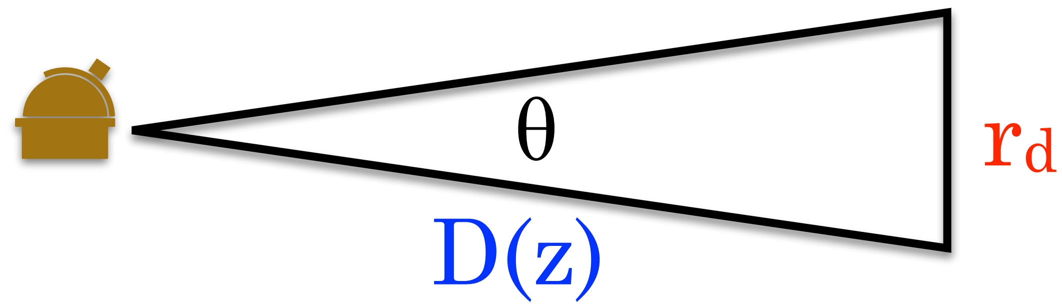
- Plasma becomes optically thin
- Baryons decouple from photons
- Sound wave stalls

$$r_d = \frac{c}{\sqrt{3}} \int_0^{a_*} \frac{da}{a^2 H(a) \sqrt{1 + \frac{3\Omega_B}{4\Omega_\gamma} a}} \simeq 150\,\mathrm{Mpc}$$

A feature is imprinted the distance that the wave has traveled between the Big Bang and recombination

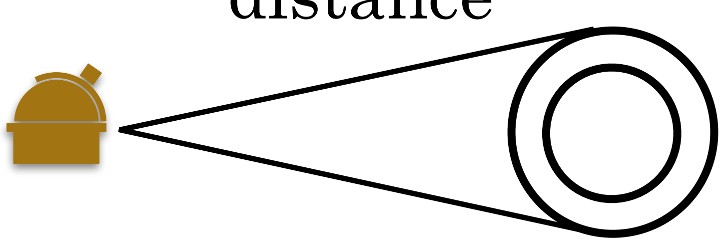
⟹ the sound horizon distance at recombination ($r_d \simeq 150\,\mathrm{Mpc}$)

Baryon Acoustic Oscillations

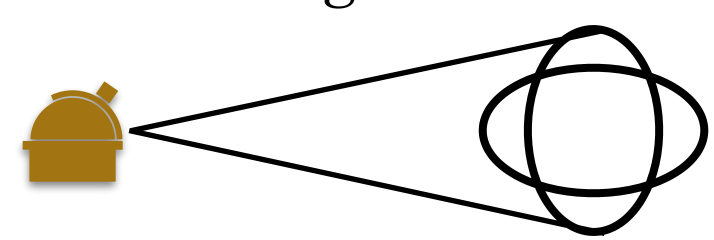


- Therefore, there is excess probability for galaxies having a neighbor at distance r_d — excess probability for clustering
- This imprints a preferred scale in clustering - the “standard ruler"
- The angle to the standard ruler gives $D(z)/r_d$
- Actually measure *two* kinds of distances: transverse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

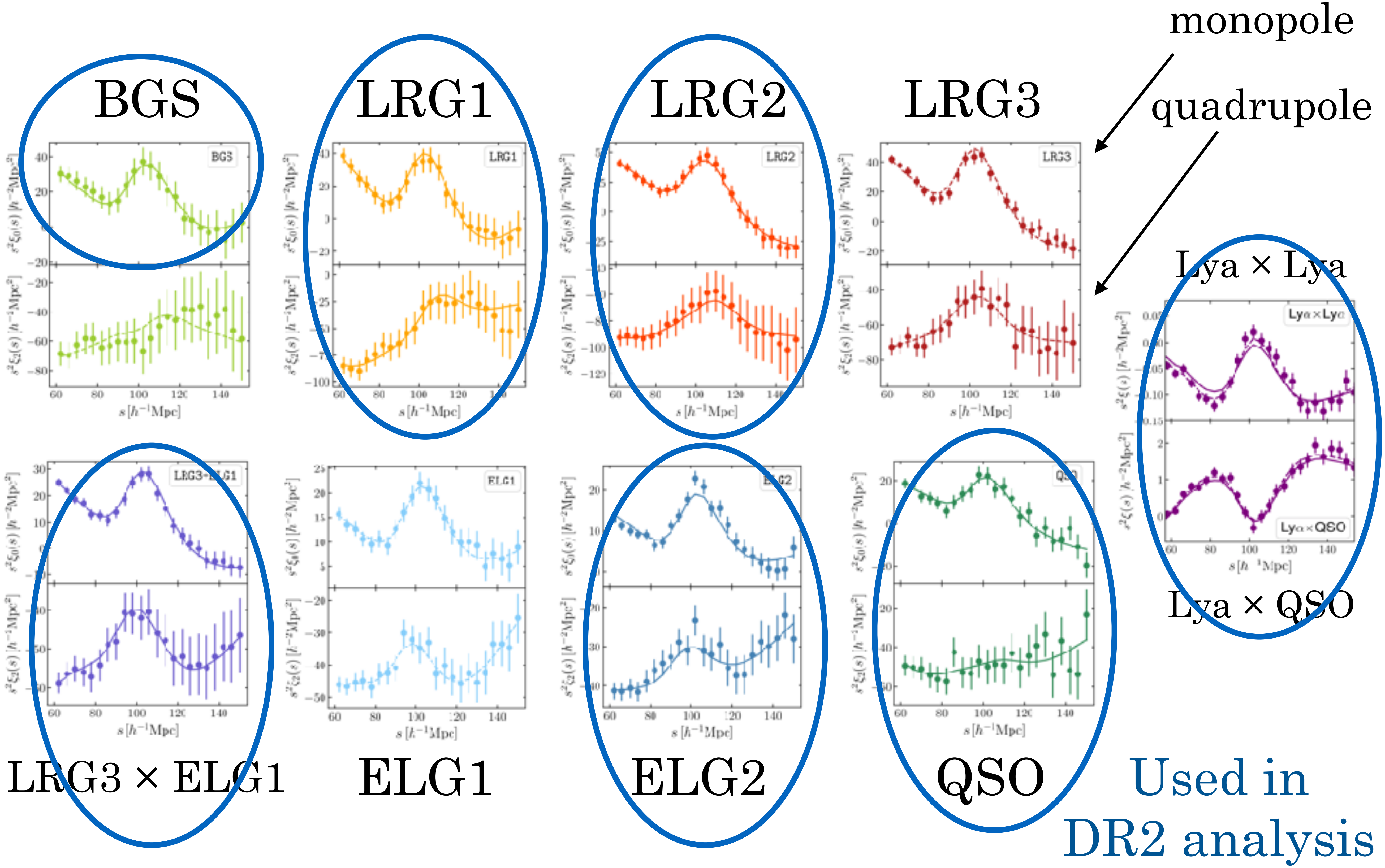
Isotropic (“average”) distance

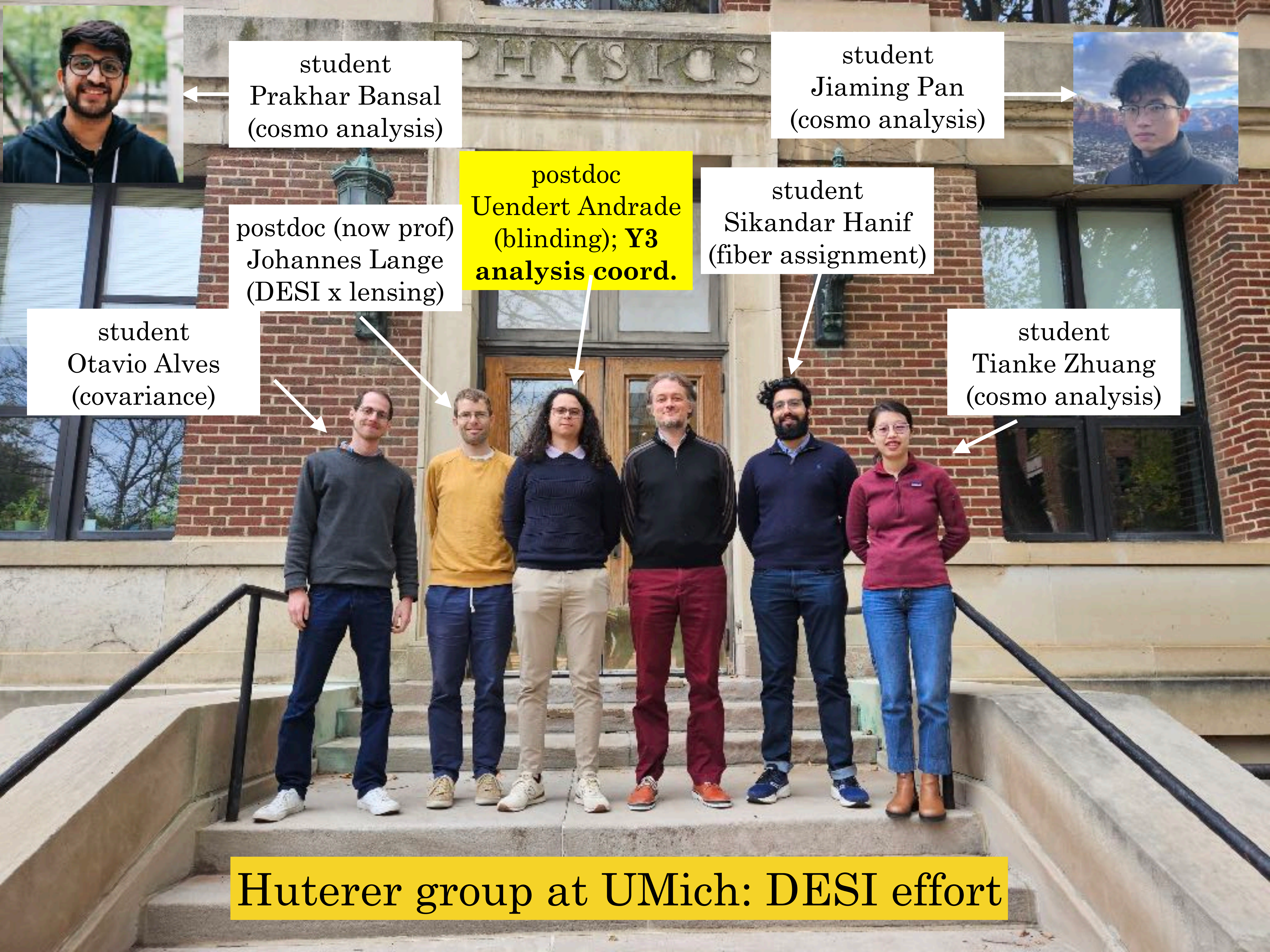


Ratio of transverse and line-of-sight distances



DESI DR2 Clustering Measurements



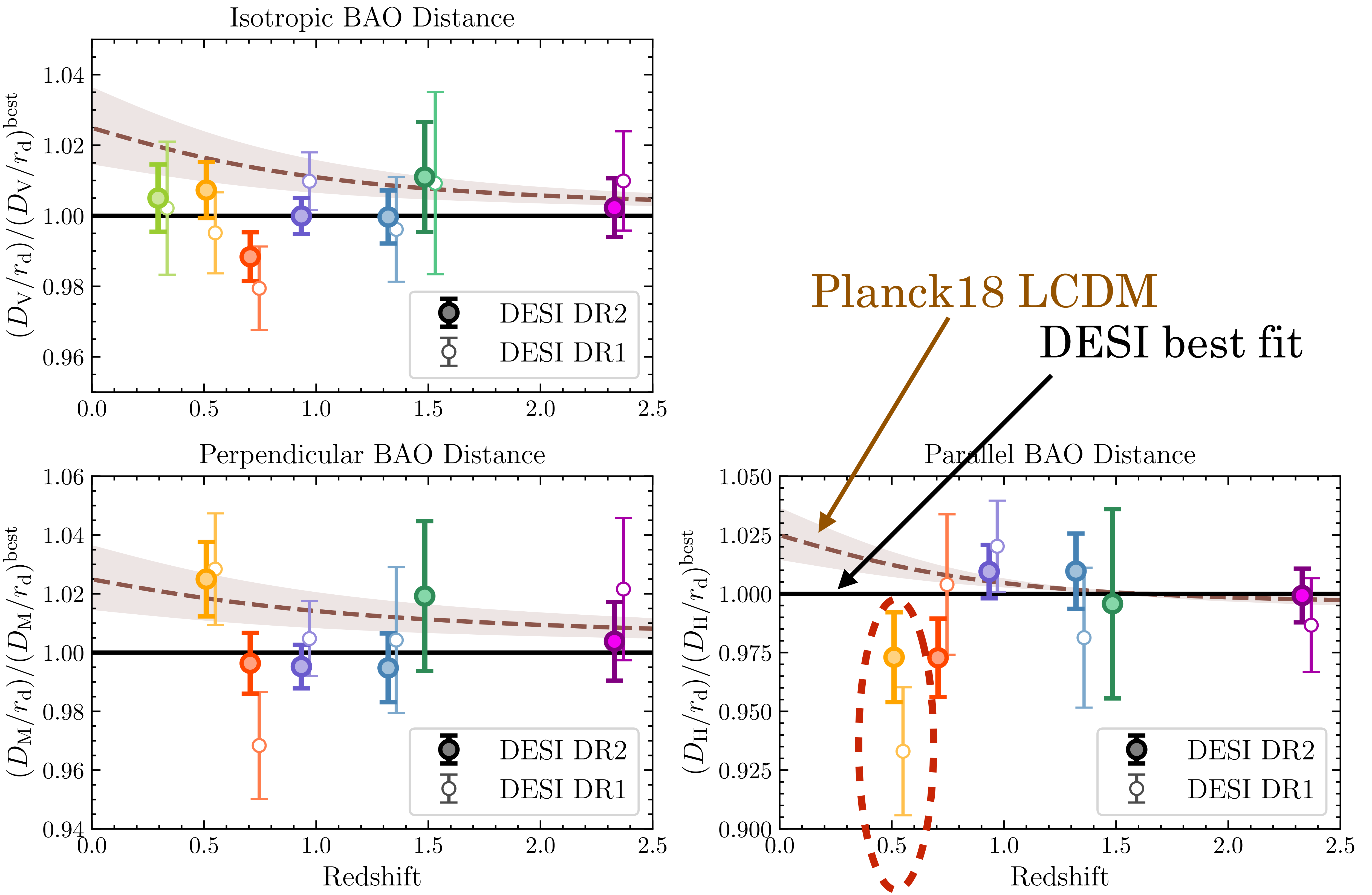

student
Prakhar Bansal
(cosmo analysis)
PHYSICS
student
Jiaming Pan
(cosmo analysis)
postdoc
Uendert Andrade
(blinding); Y3
analysis coord.
student
Sikandar Hanif
(fiber assignment)
postdoc (now prof)
Johannes Lange
(DESI x lensing)
student
Otavio Alves
(covariance)
student
Tianke Zhuang
(cosmo analysis)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

DESI Y1/Y3 cosmological analysis

- Fully **blinded** analysis (U. Andrade et al, arXiv:2404.07282)
- 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)

DESI DR2 (that is, Year 3) Cosmological Results

DR2 Distance Measurements



Basic constraints in LCDM

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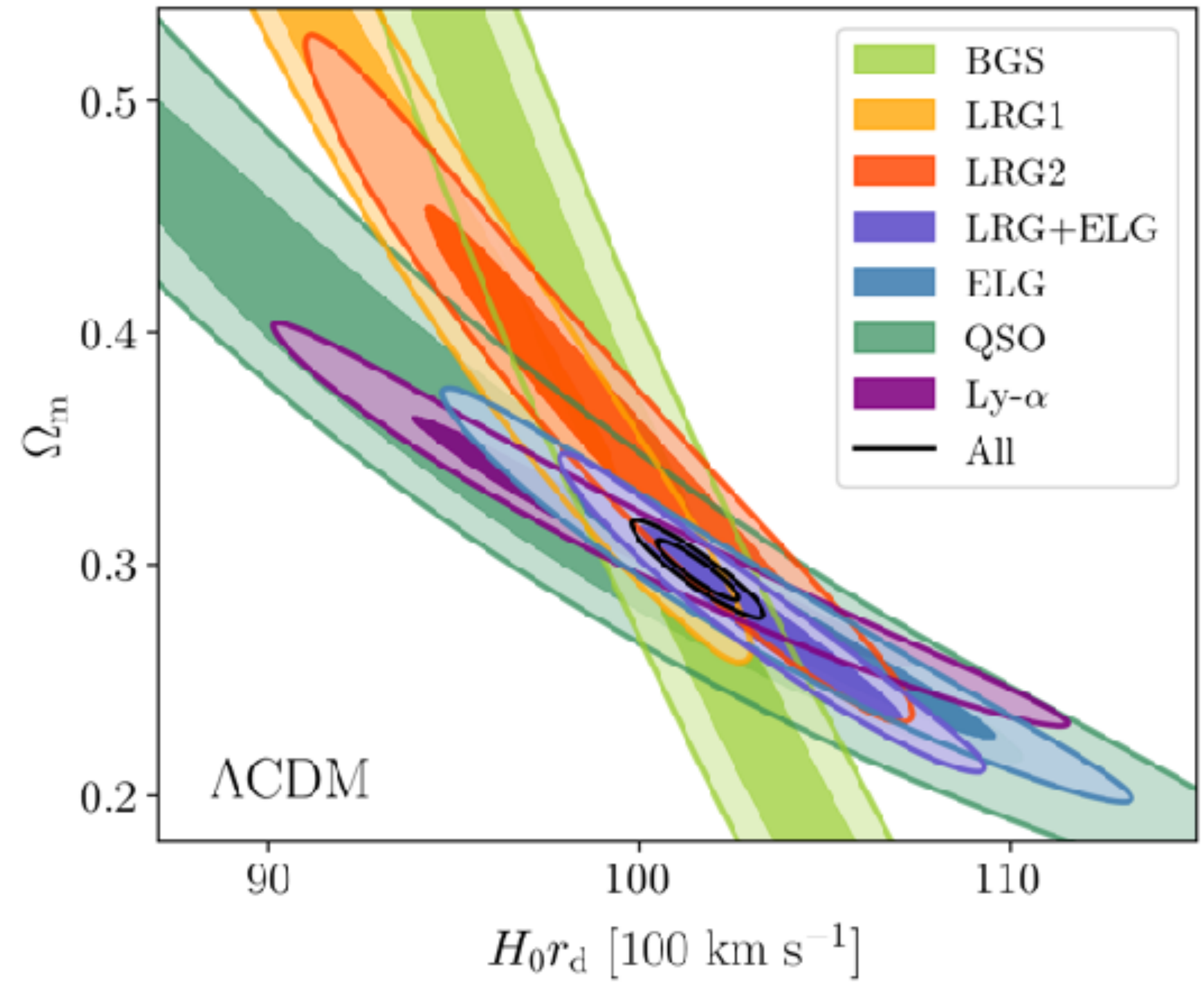
Because the BAO measure $D(z)/r_d$, in LCDM they constrain these two parameters: Ω_m, $H_0 r_d$



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

$$hr_d = (101.54 \pm 0.73)\,\text{Mpc} \qquad (0.7\%)$$

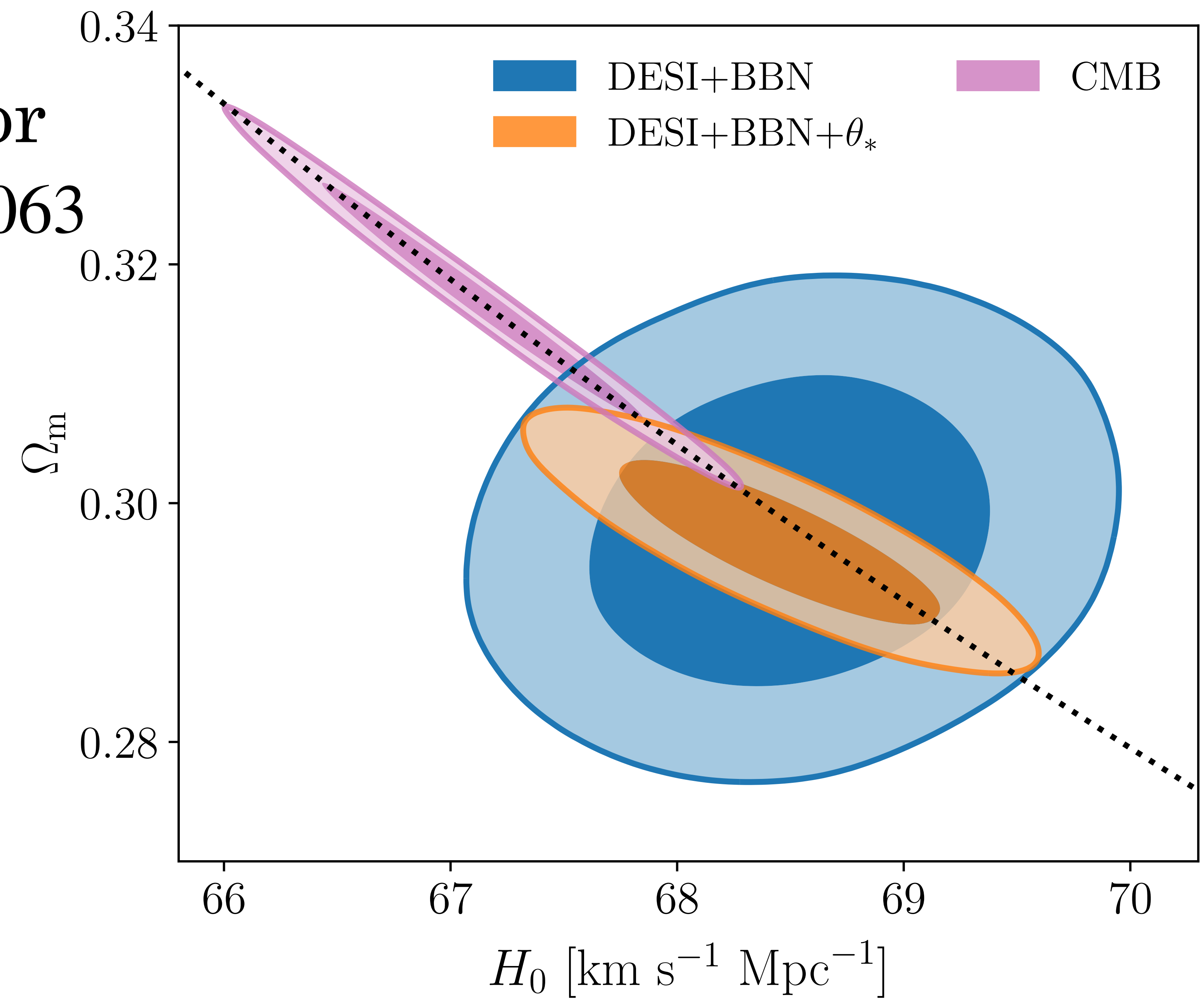
40% improvement in each par. relative to DR1

Hubble constant (in LCDM)

Requires BBN prior

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

(Schöneberg 2024)



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

28% more precise than in DR1;

4.5σ away from SH0ES (without CMB!)

Sum of neutrino masses

From neutrino oscillation experiments

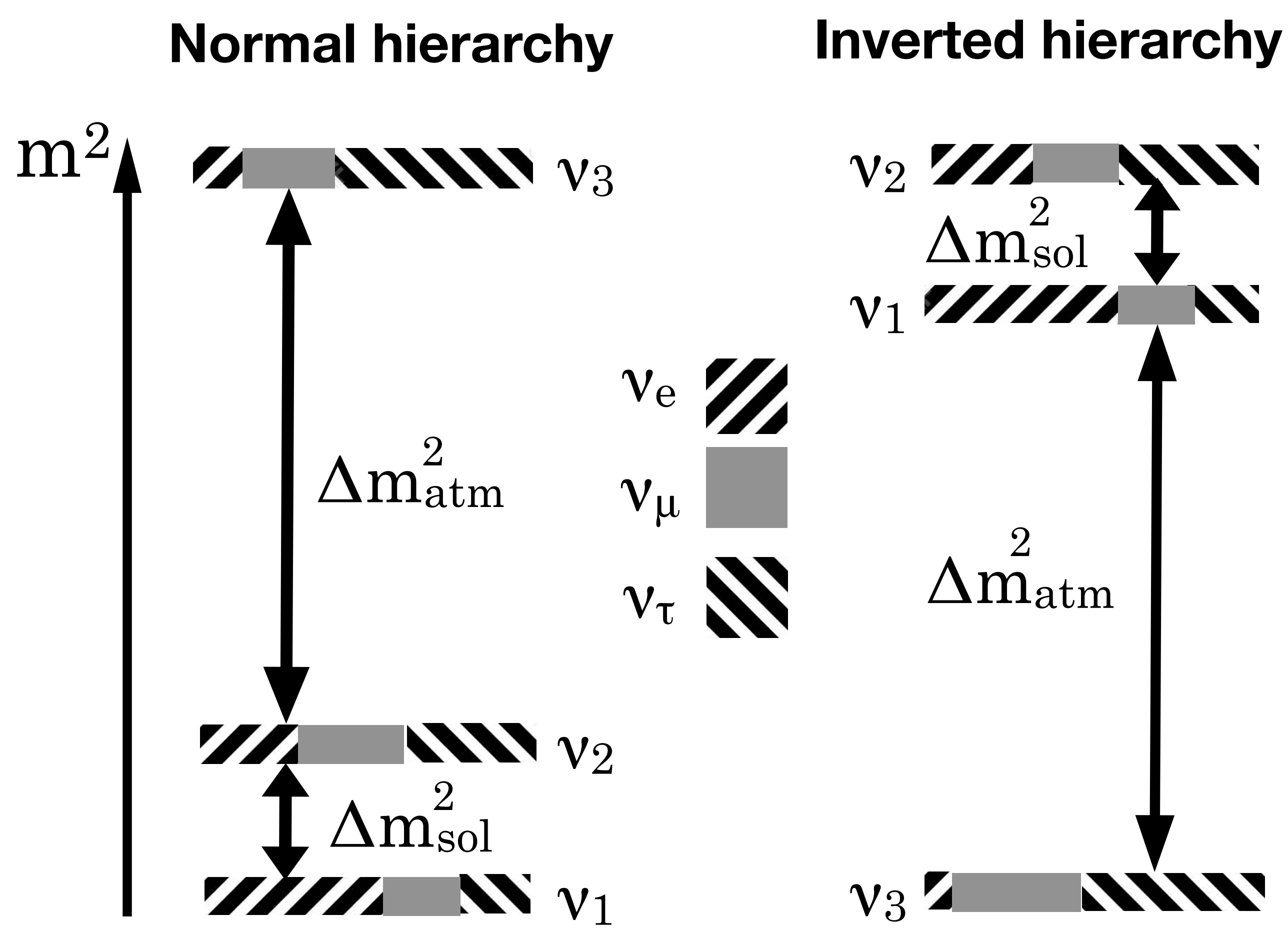
$$\left.\begin{array}{l}(\Delta m^2)_{sol} \simeq 8\times10^{-5}\ eV^2 \\ (\Delta m^2)_{atm} \simeq 3\times10^{-3}\ eV^2\end{array}\right\}$$

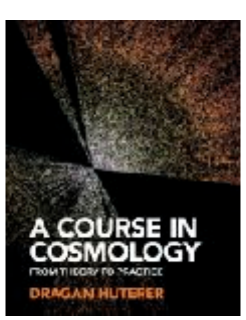
$\sum m_i = 0.06$ eV* (normal)

vs.

$\sum m_i = 0.10$ eV* (inverted)

*(assuming m_1=0)





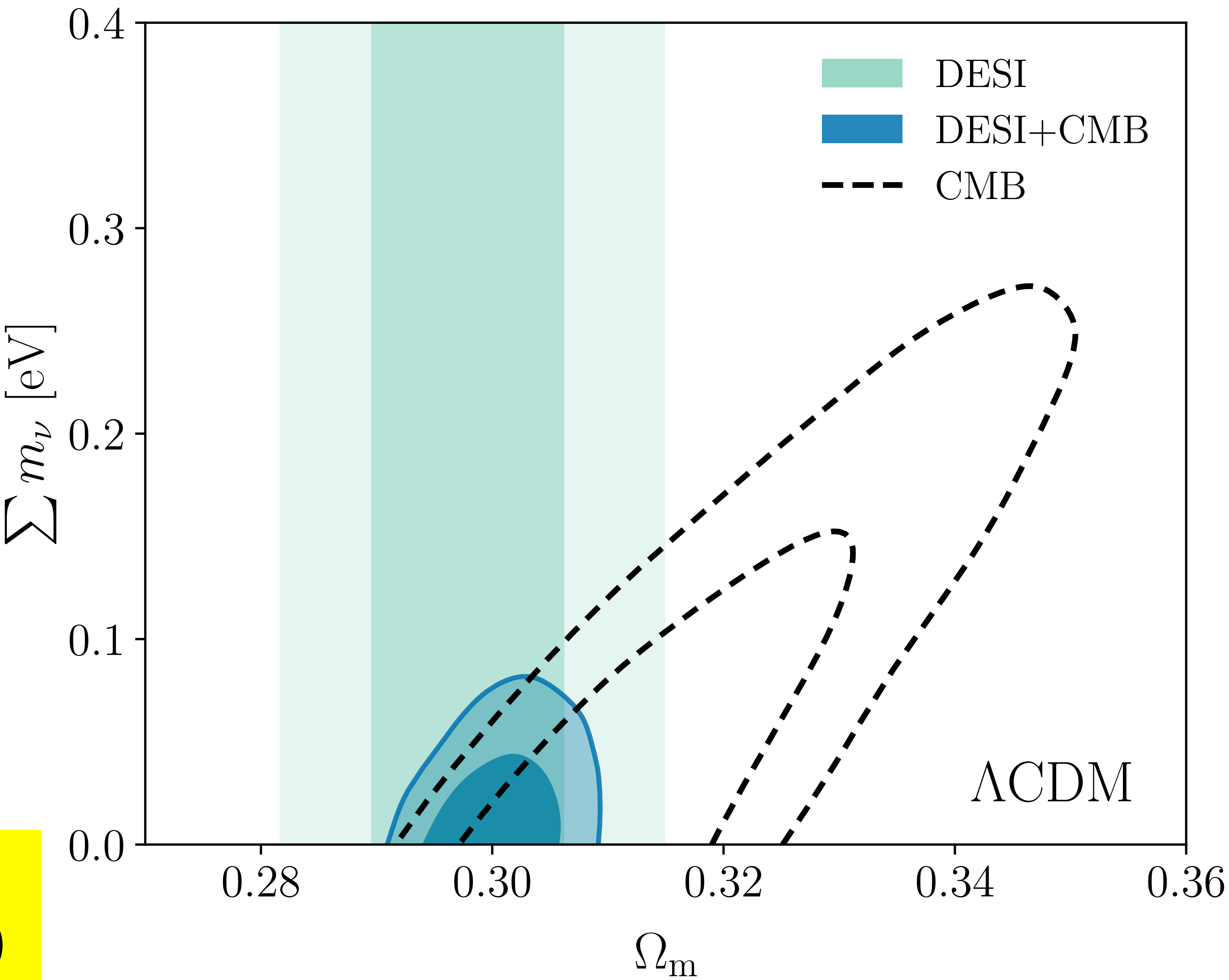
Sum of neutrino masses

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

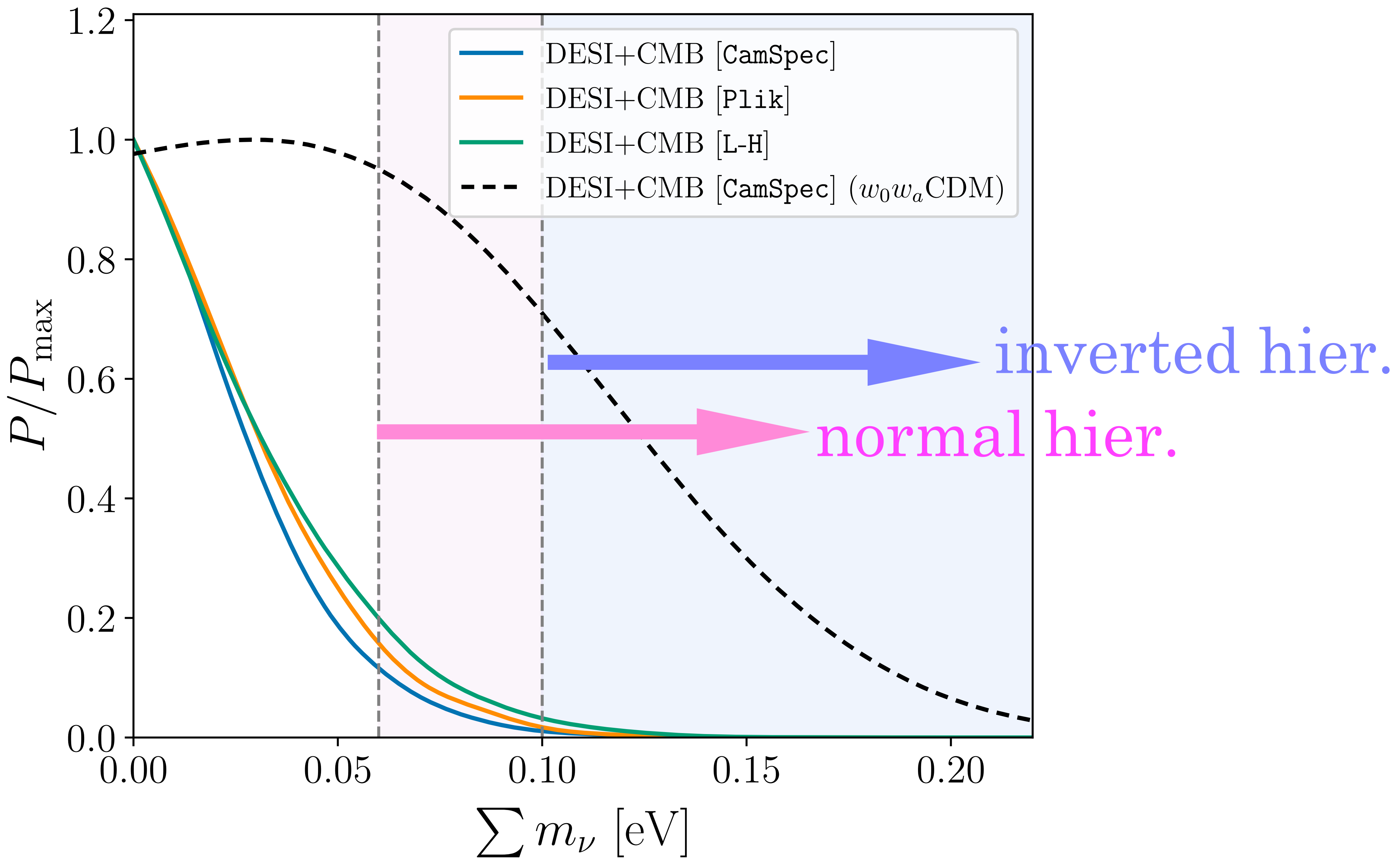
CMB constraints ,
but its precision is limited by
degeneracies
⇒ DESI helps here



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

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

Sum of neutrino masses



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

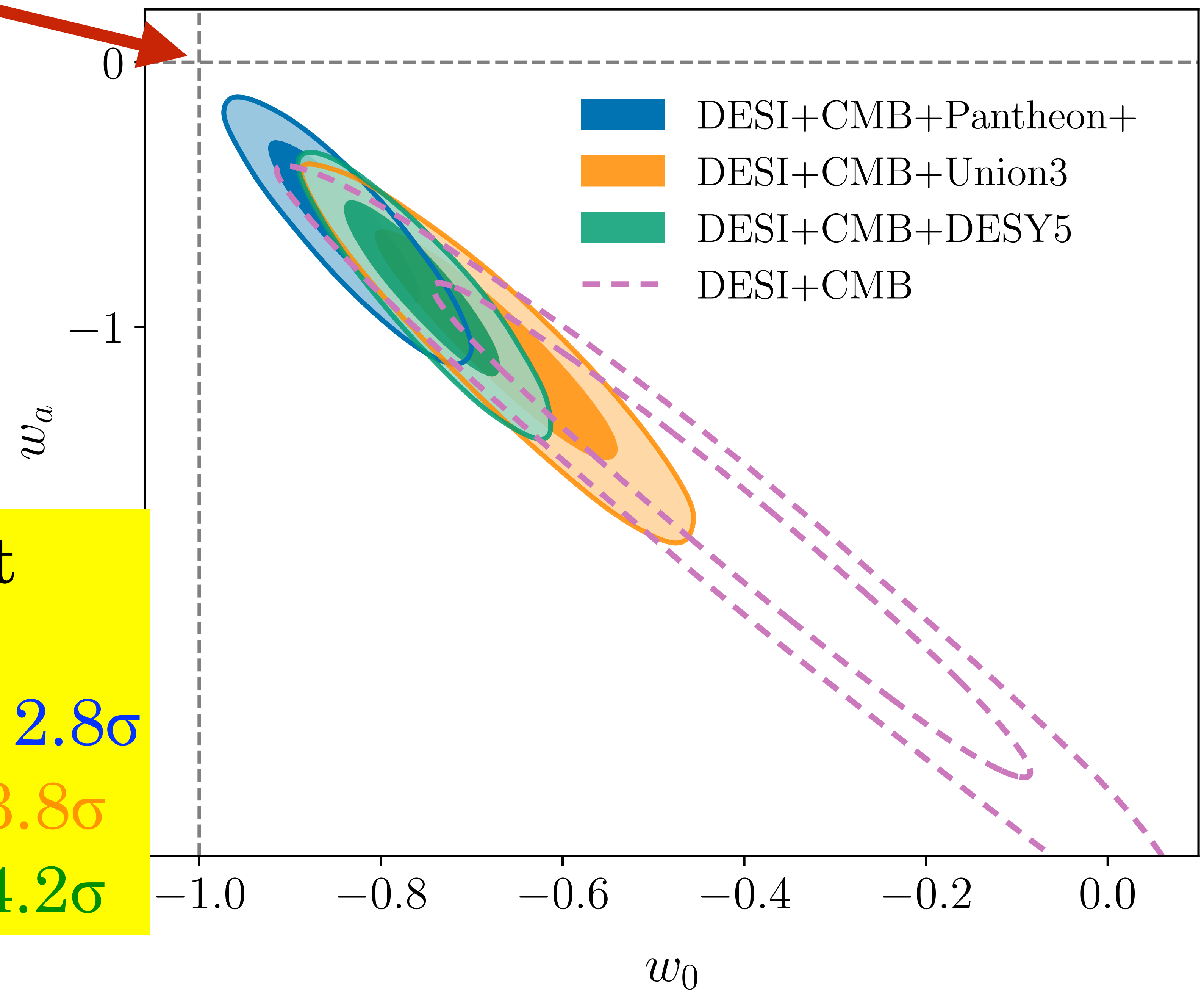
Much more detail in DESI neutrino supporting paper (Elbers et al, arXiv:2503.14744)

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

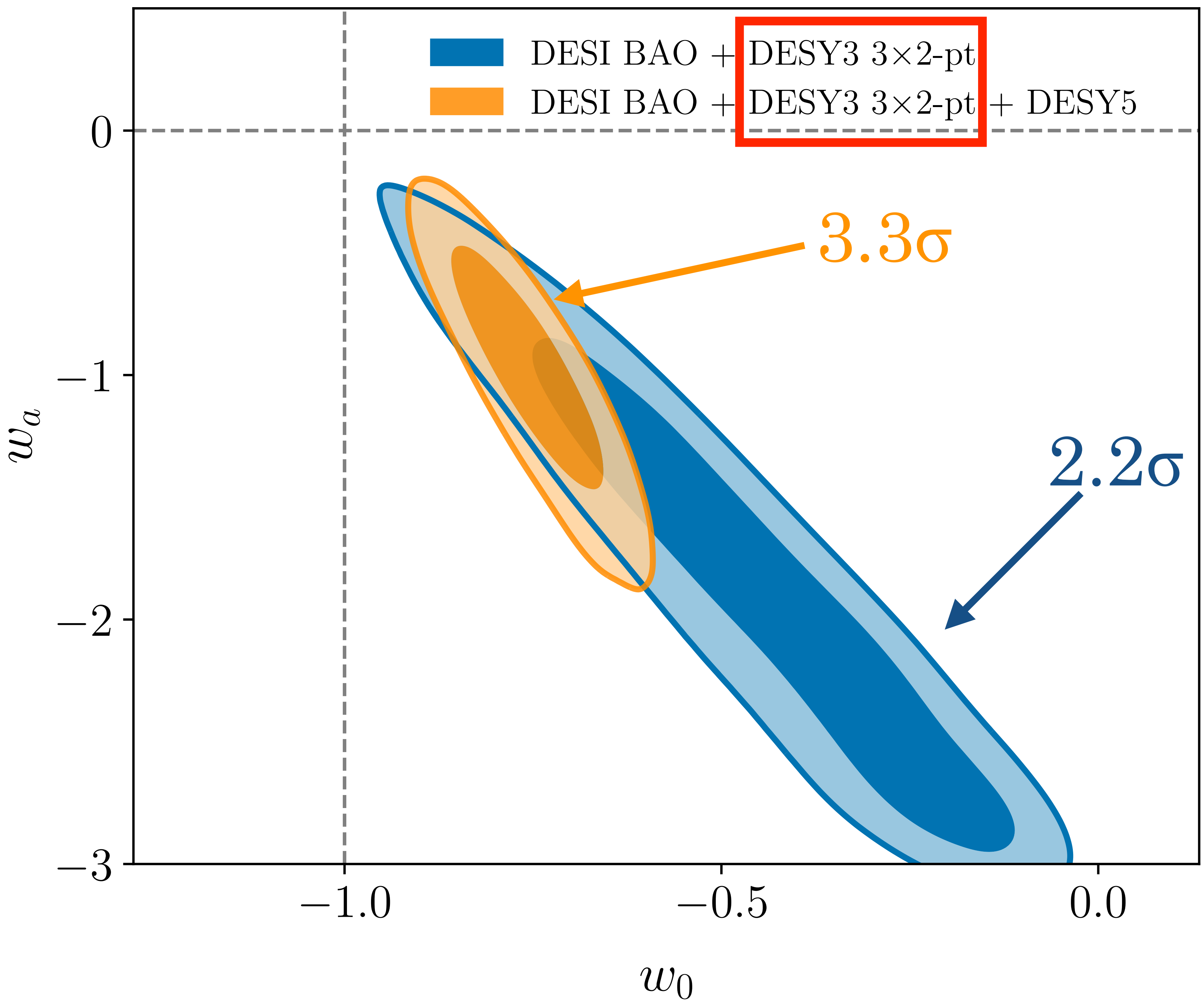
ΛCDM
(standard model)



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~~



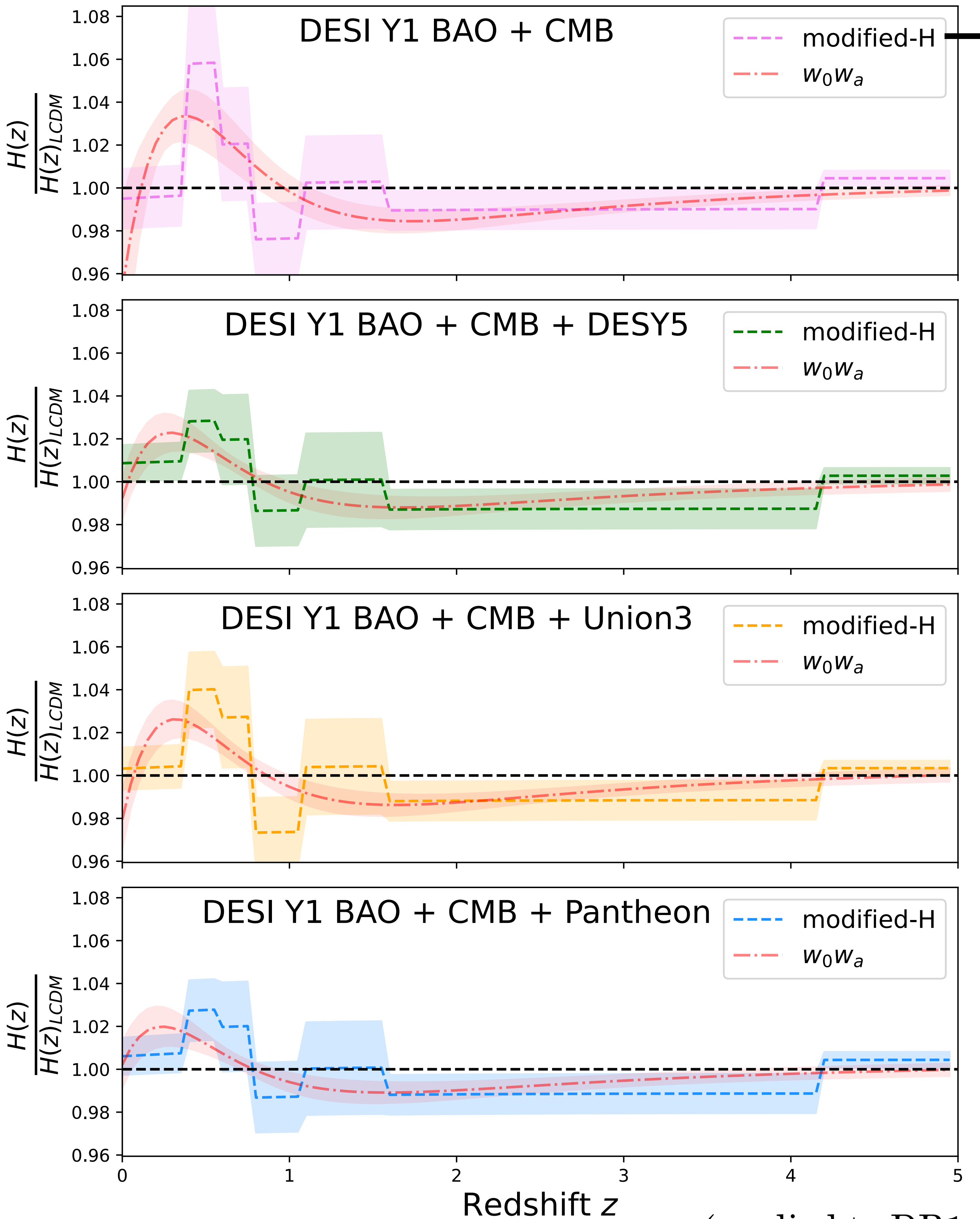
(no CMB here)

Therefore: tantalizing hints of departure from LCDM

Basic question:
what <u>in the data</u> pulls away from LCDM?

(in all data, not just DESI)

Attempt to answer this question



new model with lots of H(z) freedom

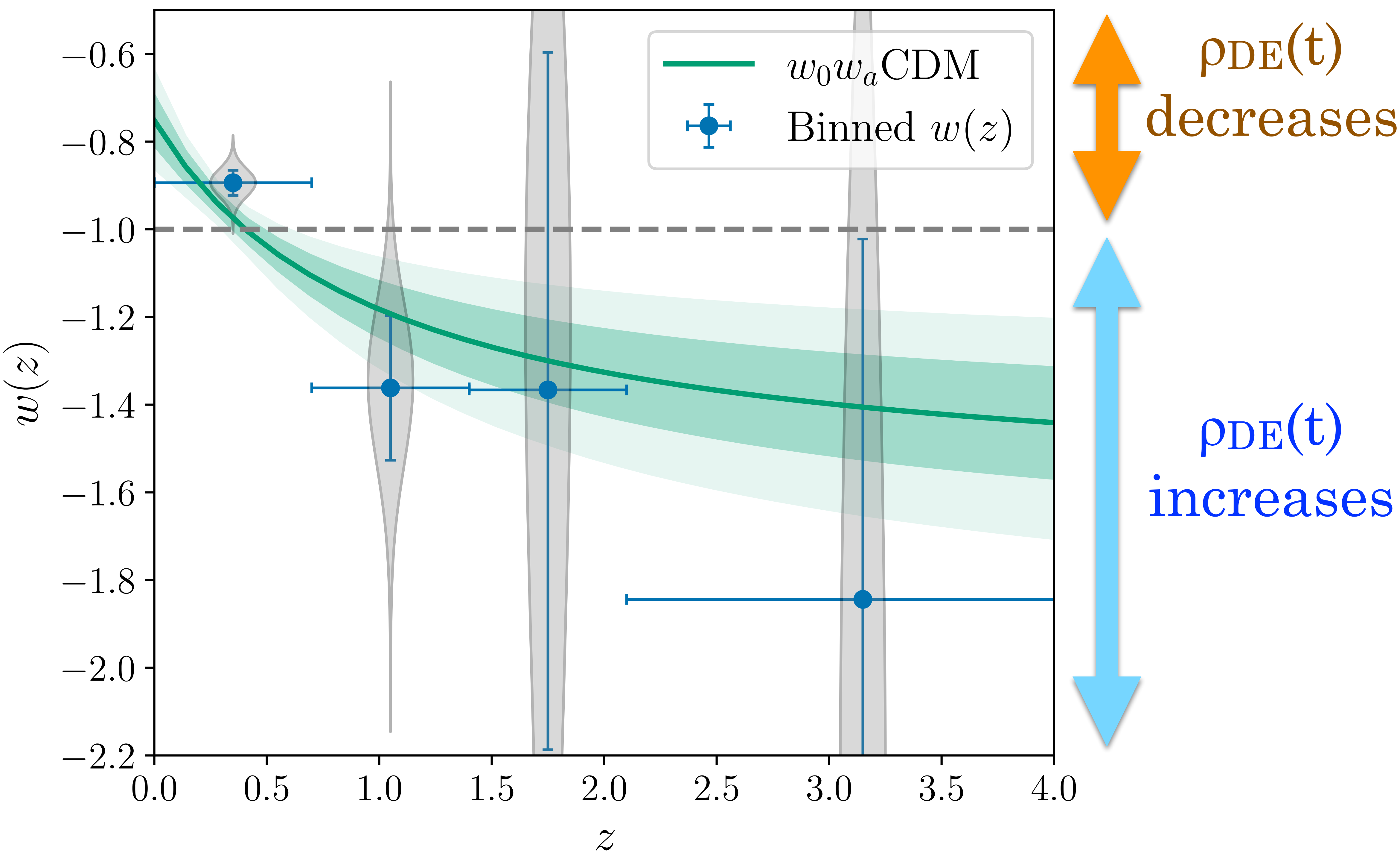
We find: a more general expansion history agrees with best-fit $w_0 w_a$!

...an accident?!

(applied to DR1 data)

Bansal & Huterer, arXiv:2502.07185

Confirmed by alternative analyses



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

Conclusions

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

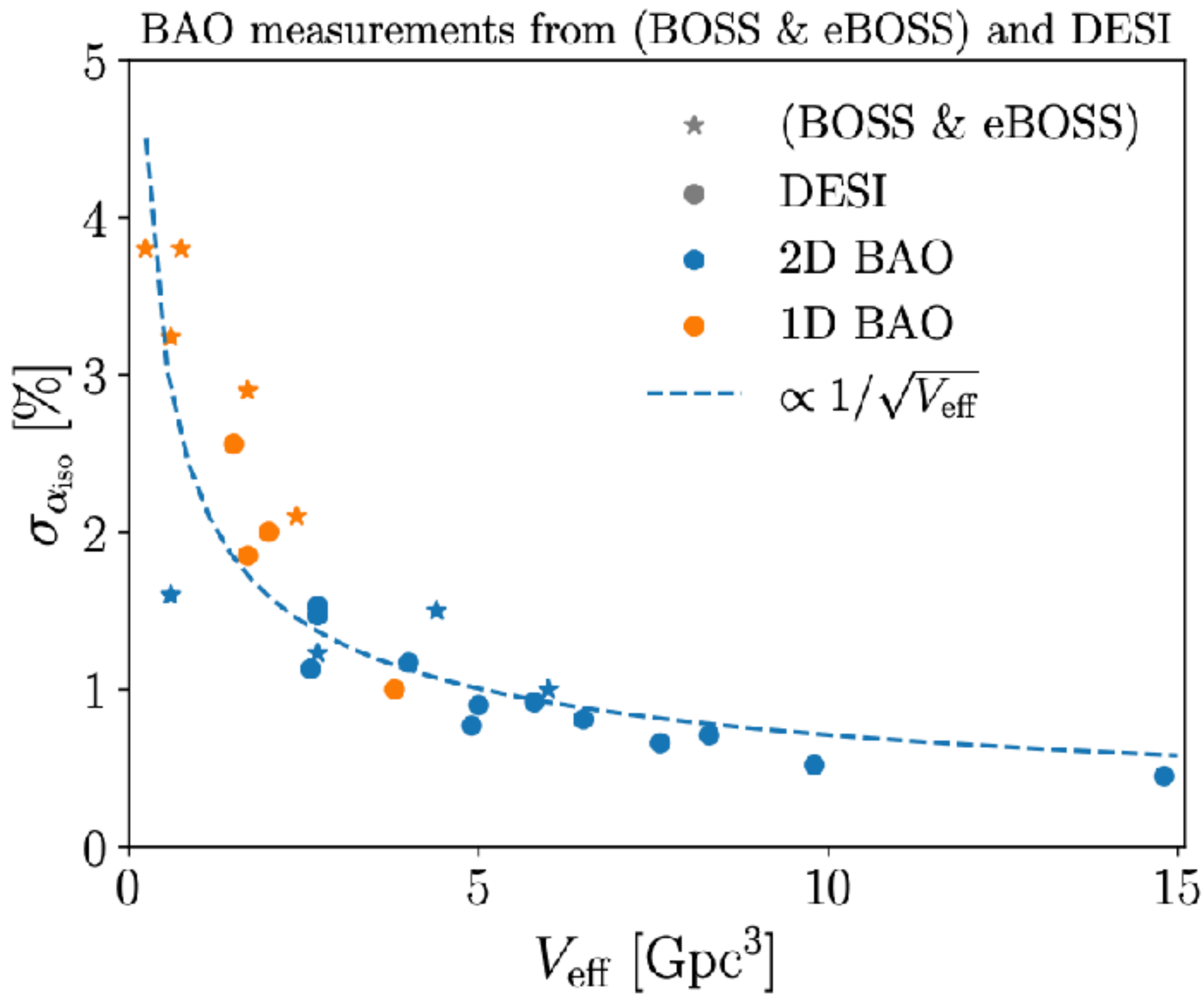
- Impressive variety of new data; forthcoming: DES Y6, HSC, Hetdex; DESI, LSST, Euclid, Roman, ZTF…

- 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

Extra slides



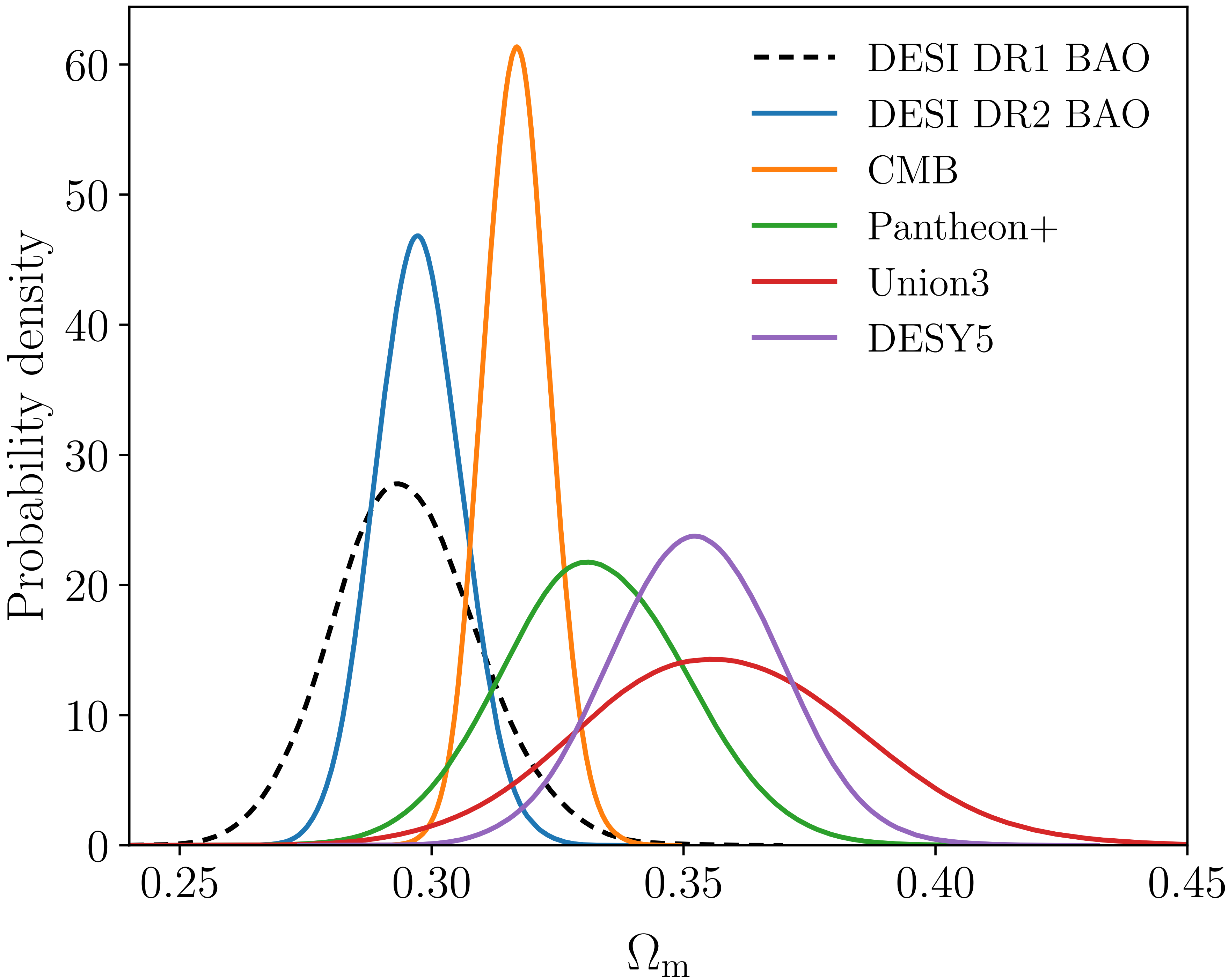
Andrade et a; (DESI collab); arXiv:2503.14742

Significances of w0wa vs LCDM

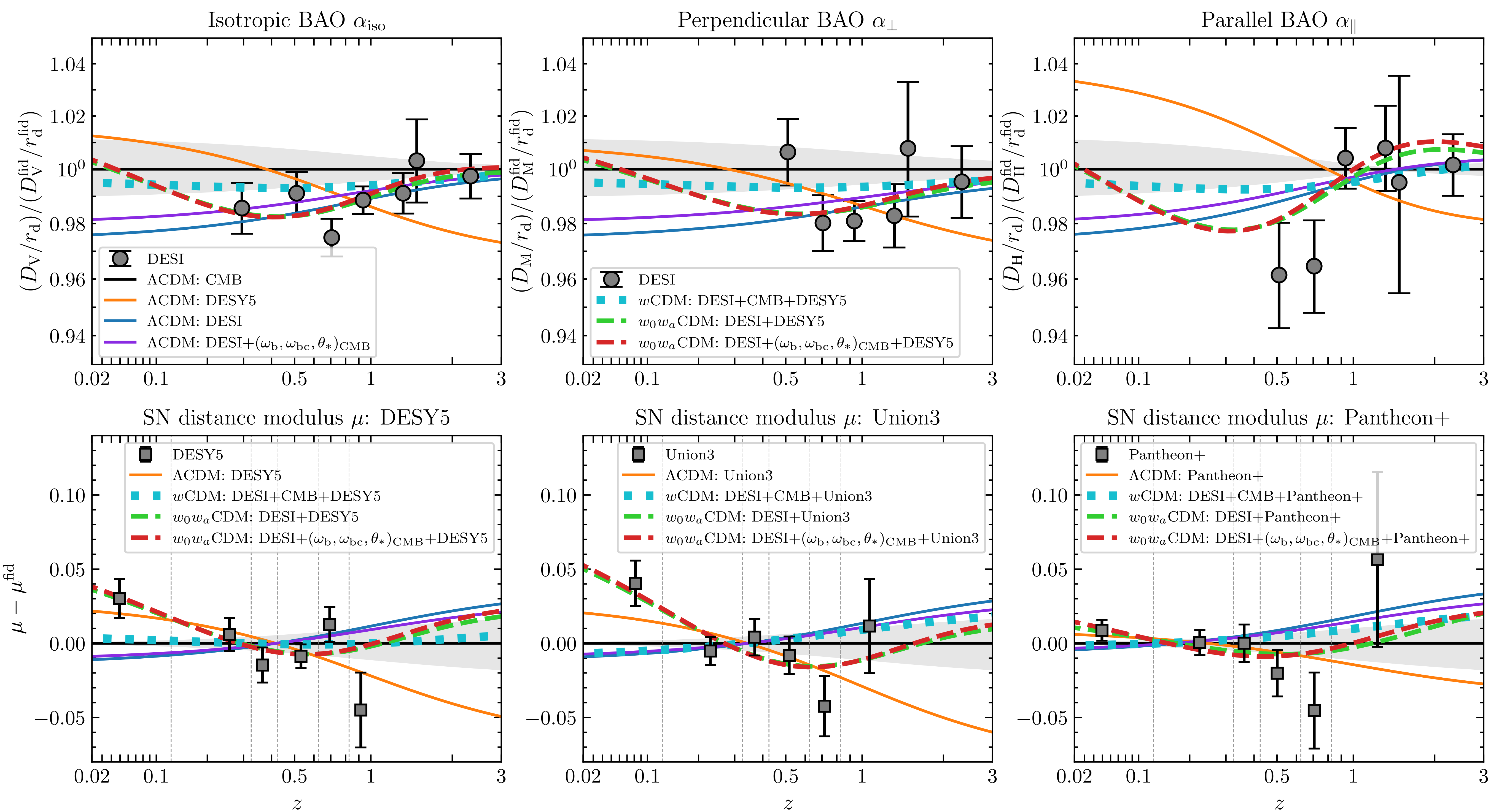
Datasets	$\Delta\chi^2_{\rm MAP}$	Significance	Δ(DIC)
DESI	-4.7	1.7σ	-0.8
DESI+$(\theta_*, \omega_{\rm b}, \omega_{\rm bc})_{\rm CMB}$	-8.0	2.4σ	-4.4
DESI+CMB (no lensing)	-9.7	2.7σ	-5.9
DESI+CMB	-12.5	3.1σ	-8.7
DESI+Pantheon+	-4.9	1.7σ	-0.7
DESI+Union3	-10.1	2.7σ	-6.0
DESI+DESY5	-13.6	3.3σ	-9.3
DESI+DESY3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

DESI collab, arXiv:2503.14738

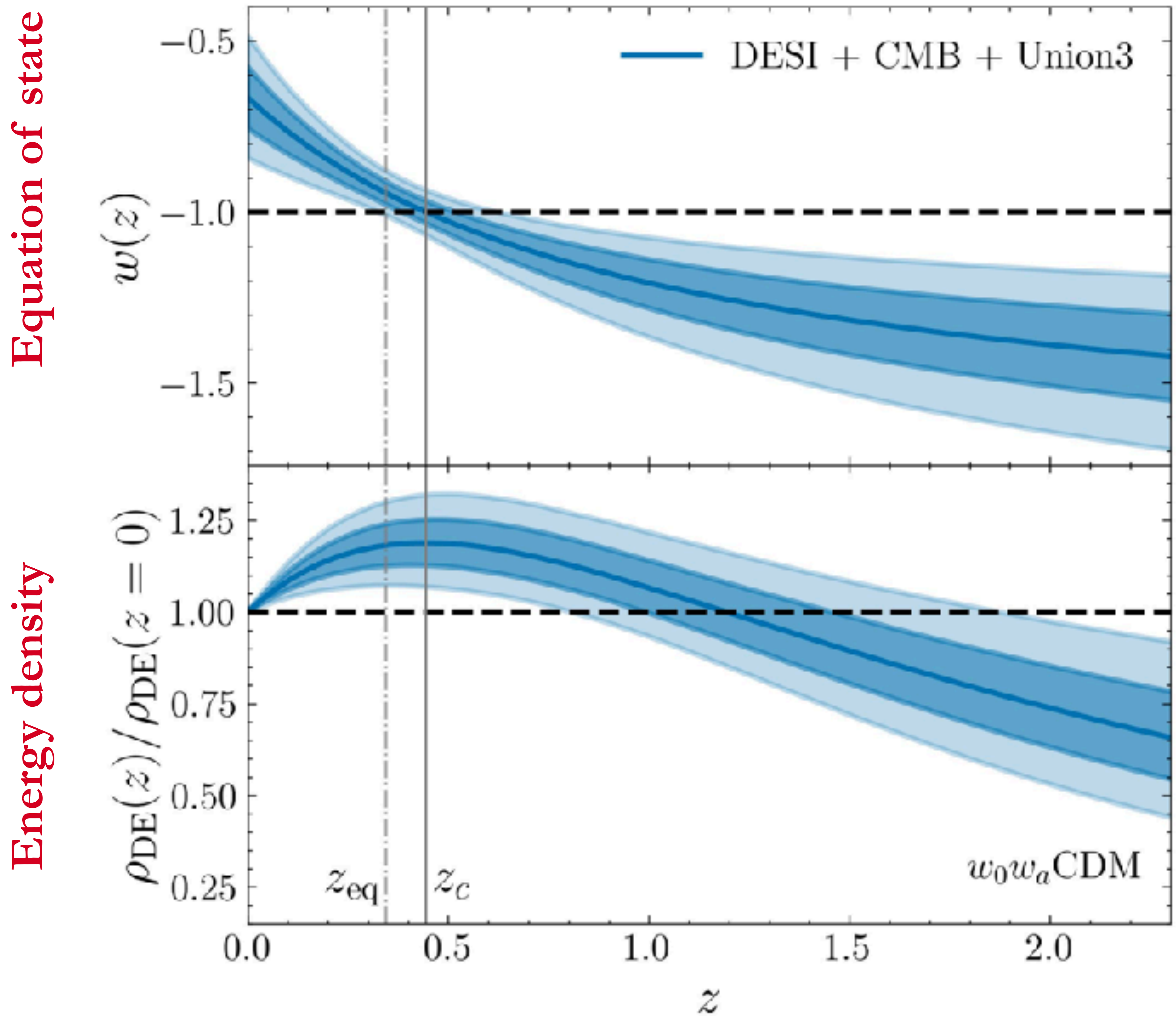
Ω_m constraints in LCDM



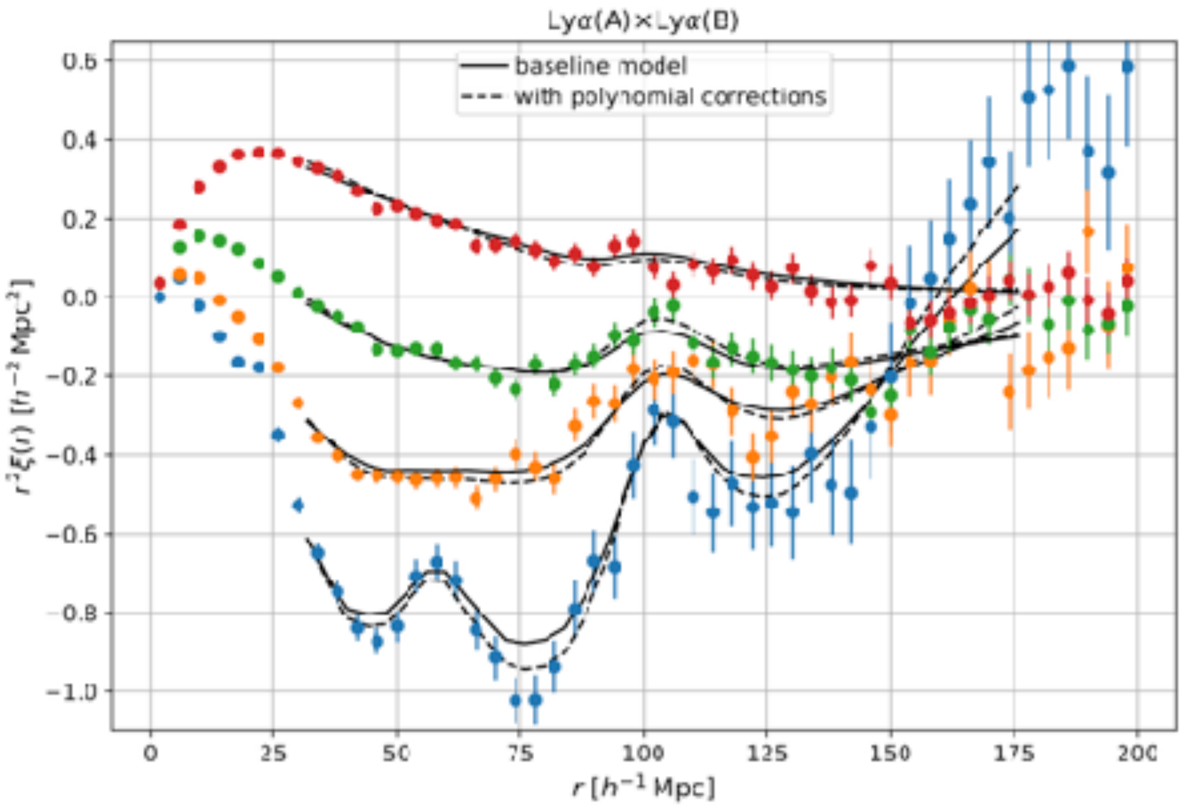
Why preference for w0wa (from DR2 key paper)



What best-fit w_0w_a model predicts

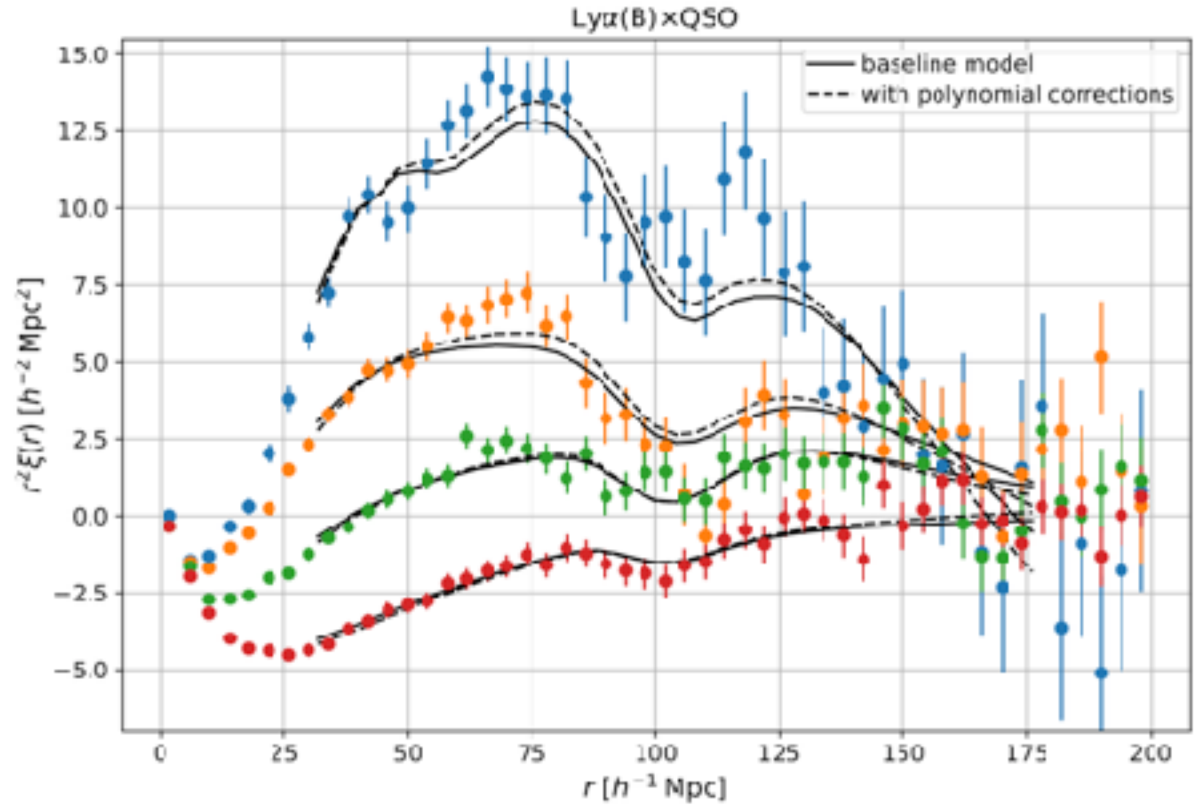


Lyman α Forest Correlations



Lyα forest autocorrelation

$$\xi(r) = \left\langle \delta_F(x)\ \delta_F(x+r) \right\rangle$$



Lyα-QSO cross-correlation

$$\xi(r) = \left\langle \delta_F(x)\ Q(x+r) \right\rangle$$

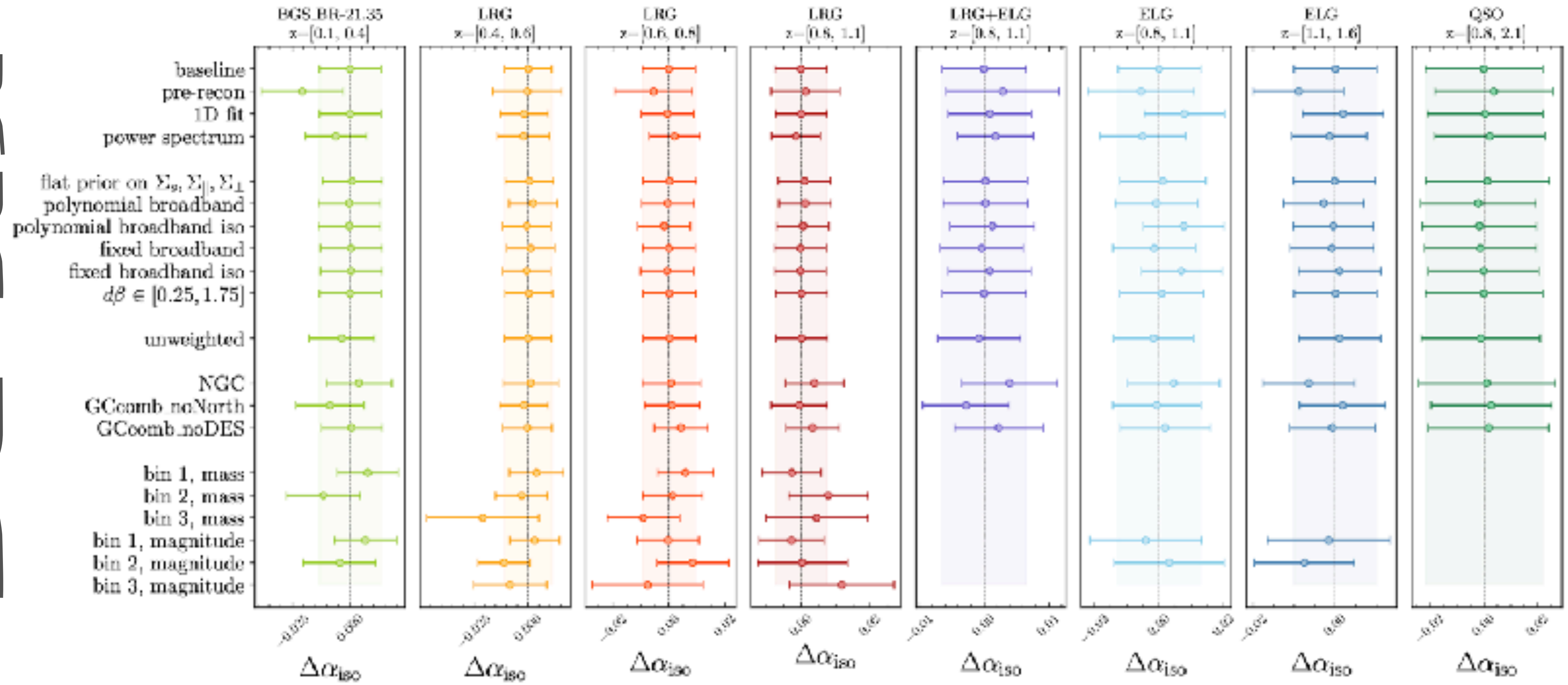
DR2 BAO is robust against different pipeline choices

Data vector choices

BAO modeling

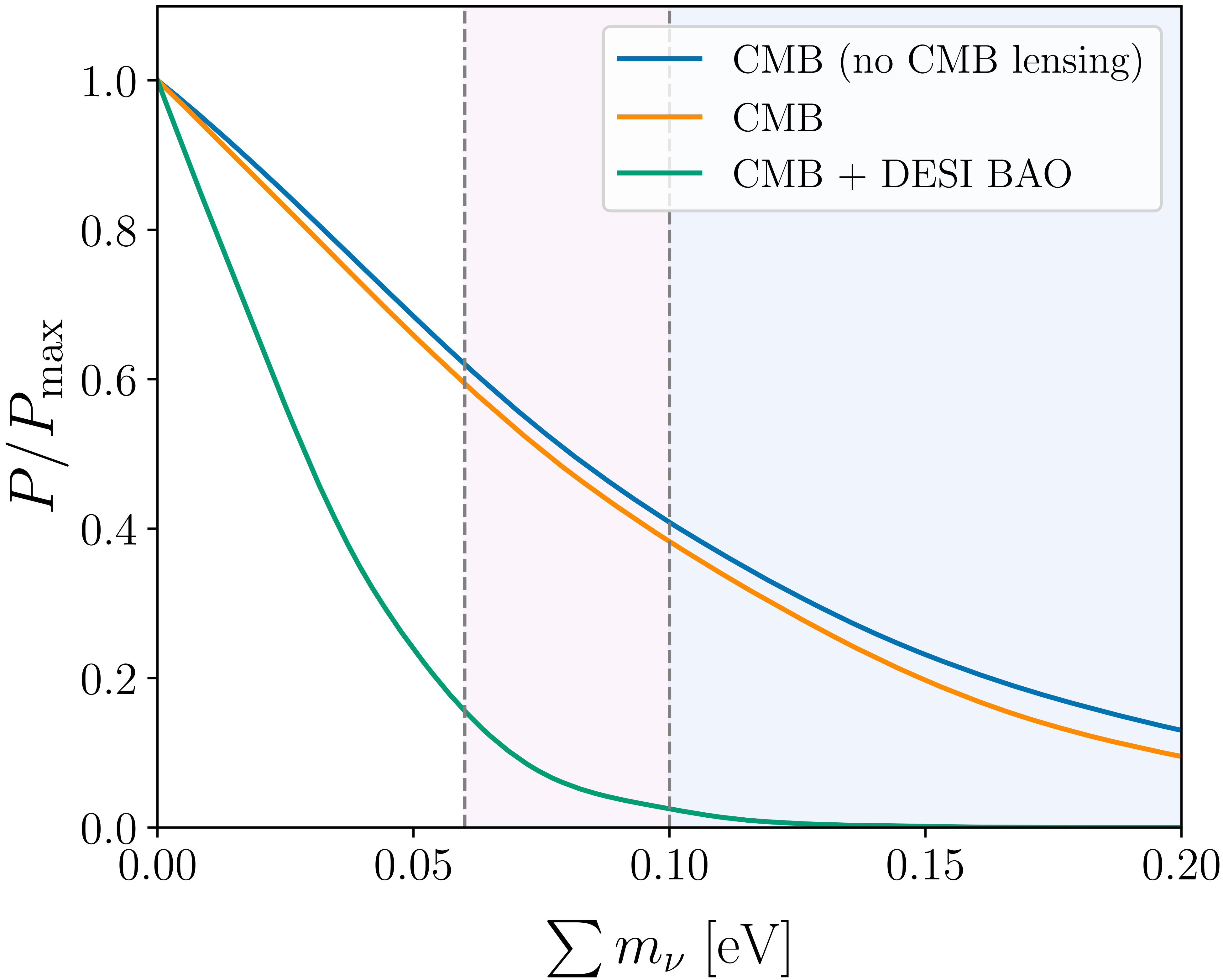
Imaging systematics

Data splits



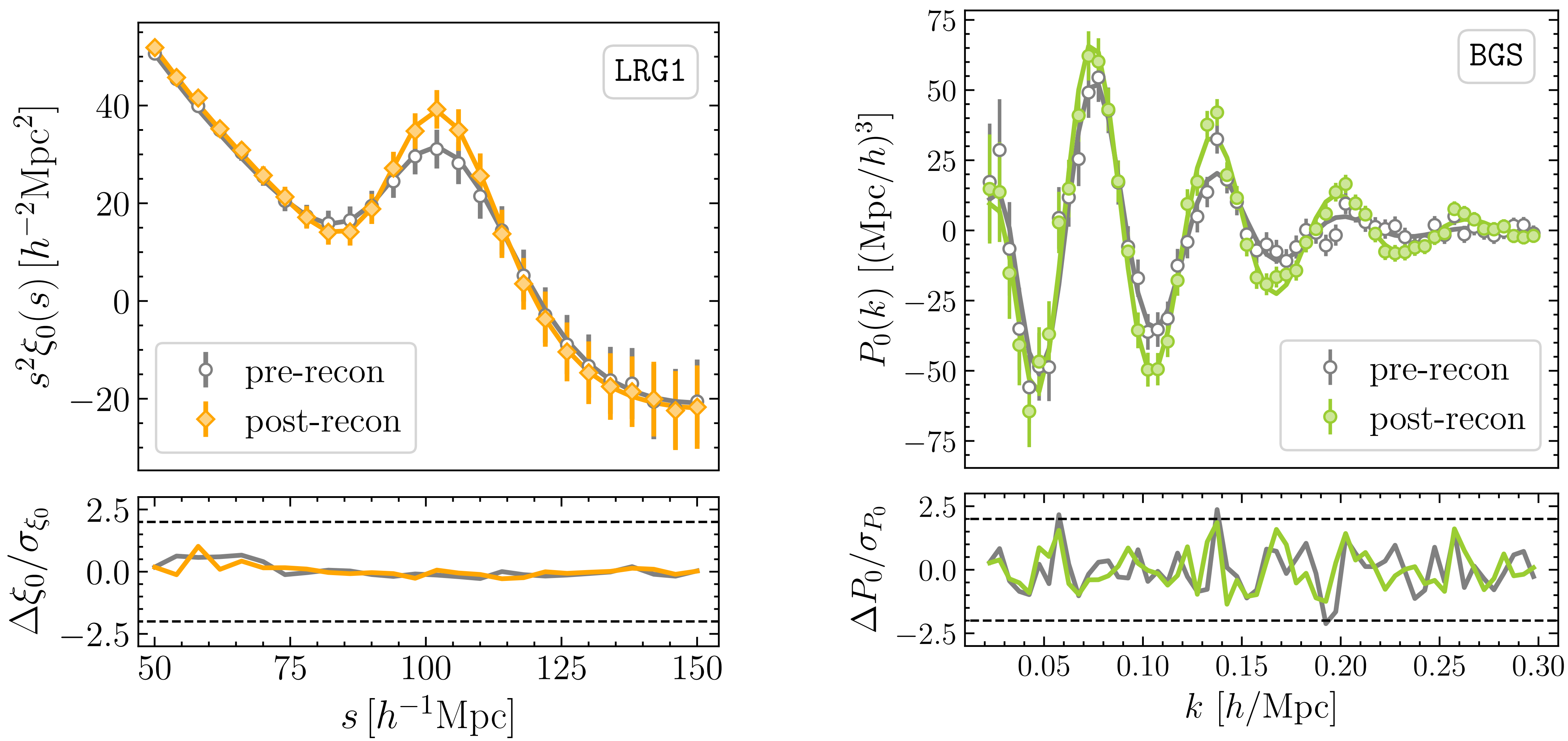
Differences in the isotropic BAO dilation

Sum of neutrino masses



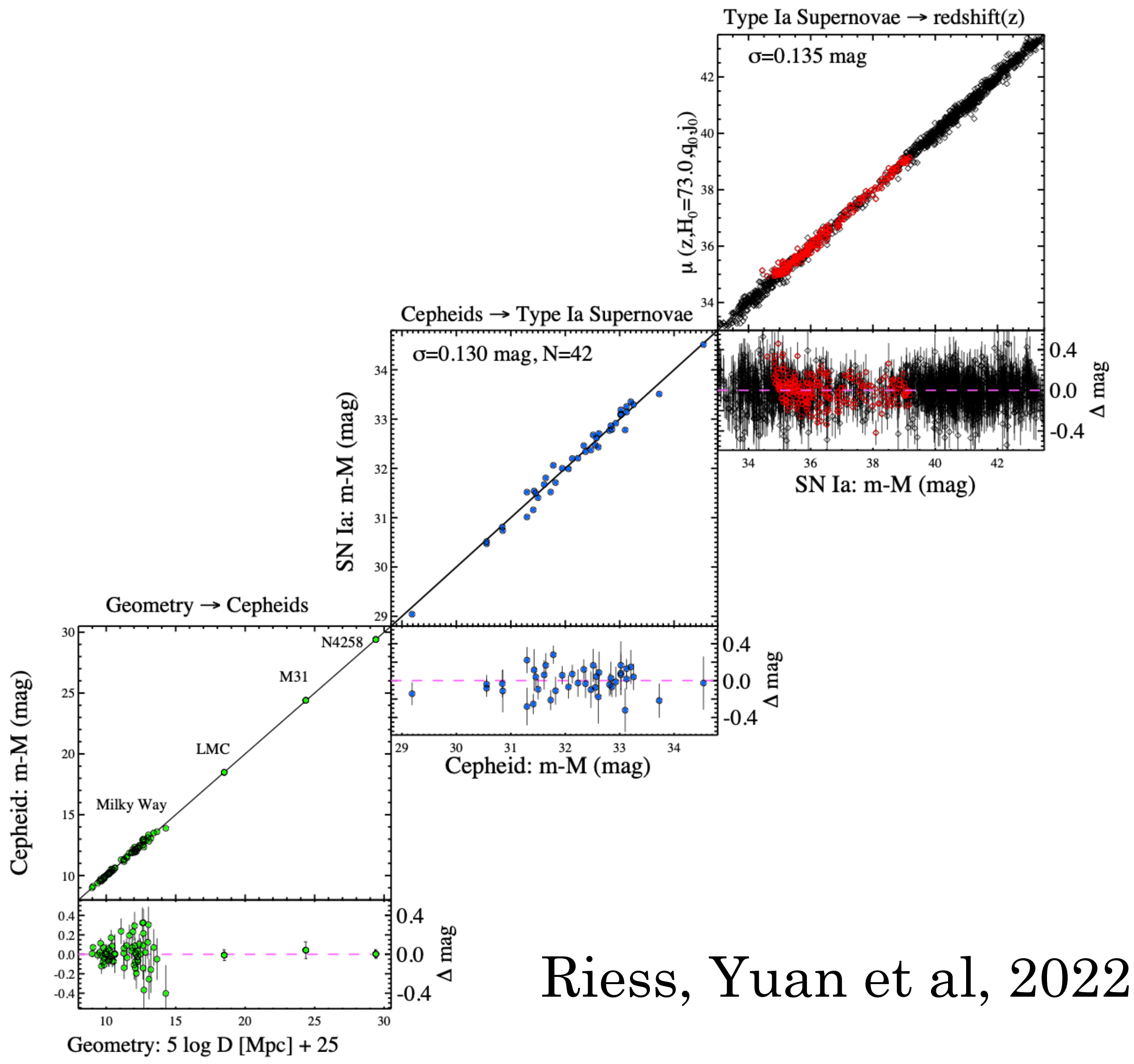
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Density field reconstruction



Refurbishes the ruler – **improves both precision and accuracy**

Distance-ladder measurements of H_0



Riess, Yuan et al, 2022

starting with

$$m - M = 5\log_{10}\left(\frac{d_L}{10\mathrm{pc}}\right)$$

we get

$$m = 5\log_{10}(H_0 d_L) + \mathscr{M}, \quad \text{where} \quad \mathscr{M} \equiv M - 5\log_{10}\left(H_0 \cdot 1\mathrm{Mpc}\right) + 25$$

Because SNIa measure relative distances, to get at H_0 they need to be "anchored" by absolute distances from e.g. Cepheids