Cosmological Constraints from DESI Year-1 Baryon Acoustic Oscillation Measurements

Dragan Huterer
University of Michigan

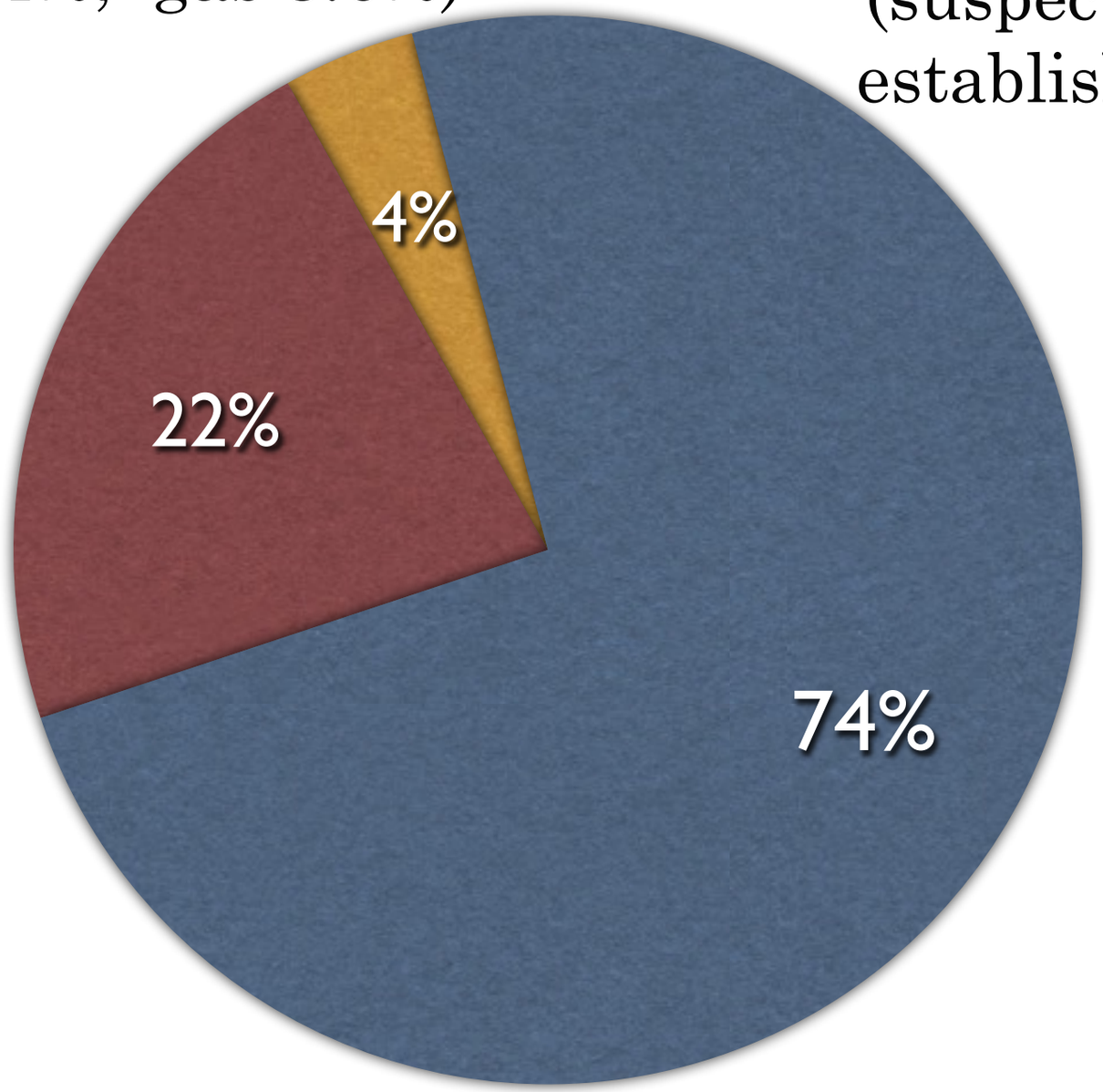
[co-coordinator of DESI Year-1 cosmology analysis]

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

Makeup of universe today

Baryonic Matter
(stars 0.4%, gas 3.6%)

Dark Energy
(suspected since 1980s
established since 1998)

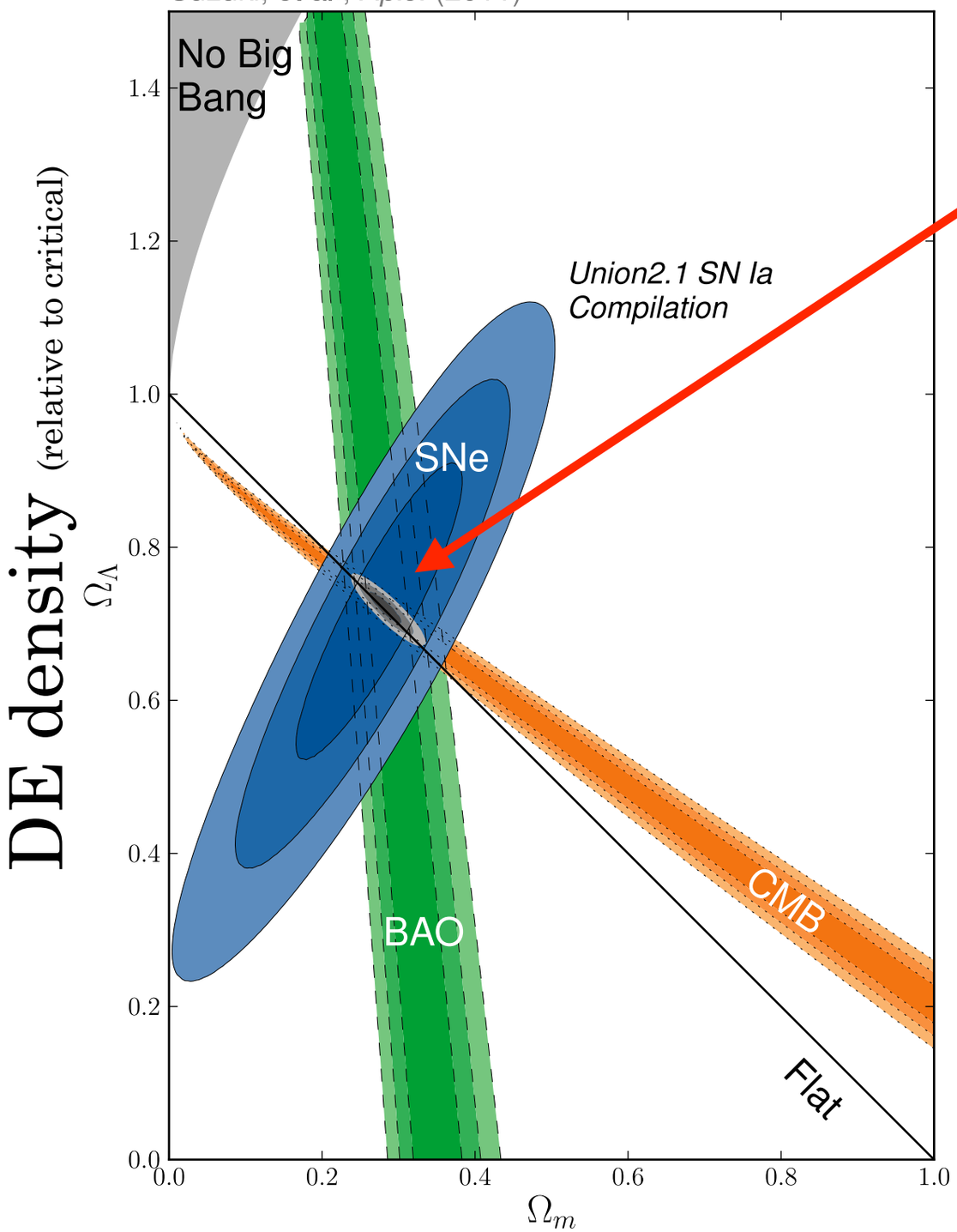


Dark Matter
(suspected since 1930s
established since 1970s)

Also:
radiation (0.01%)

(Recent) constraints on dark energy

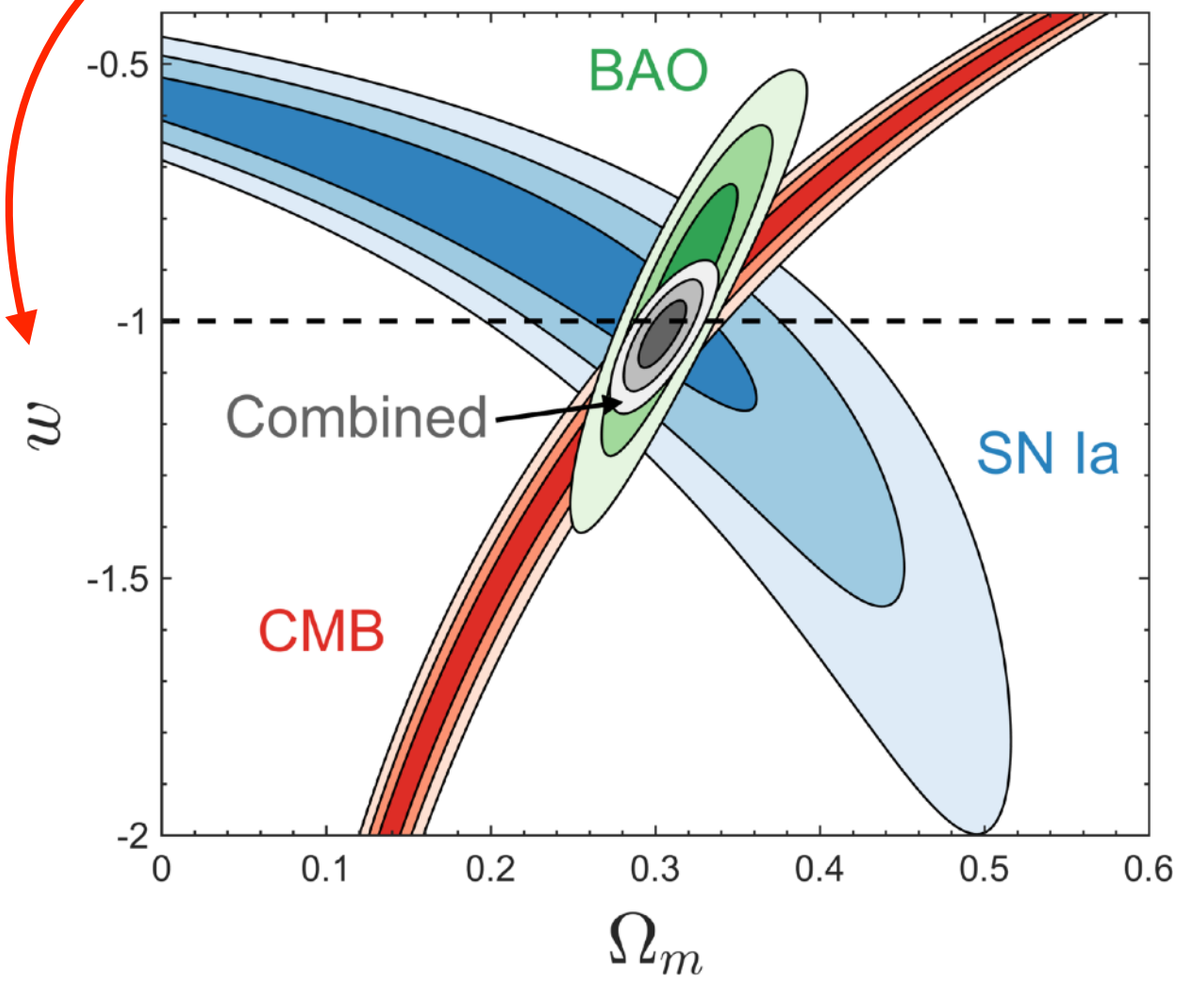
Supernova Cosmology Project
Suzuki, et al., *Ap.J.* (2011)



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)

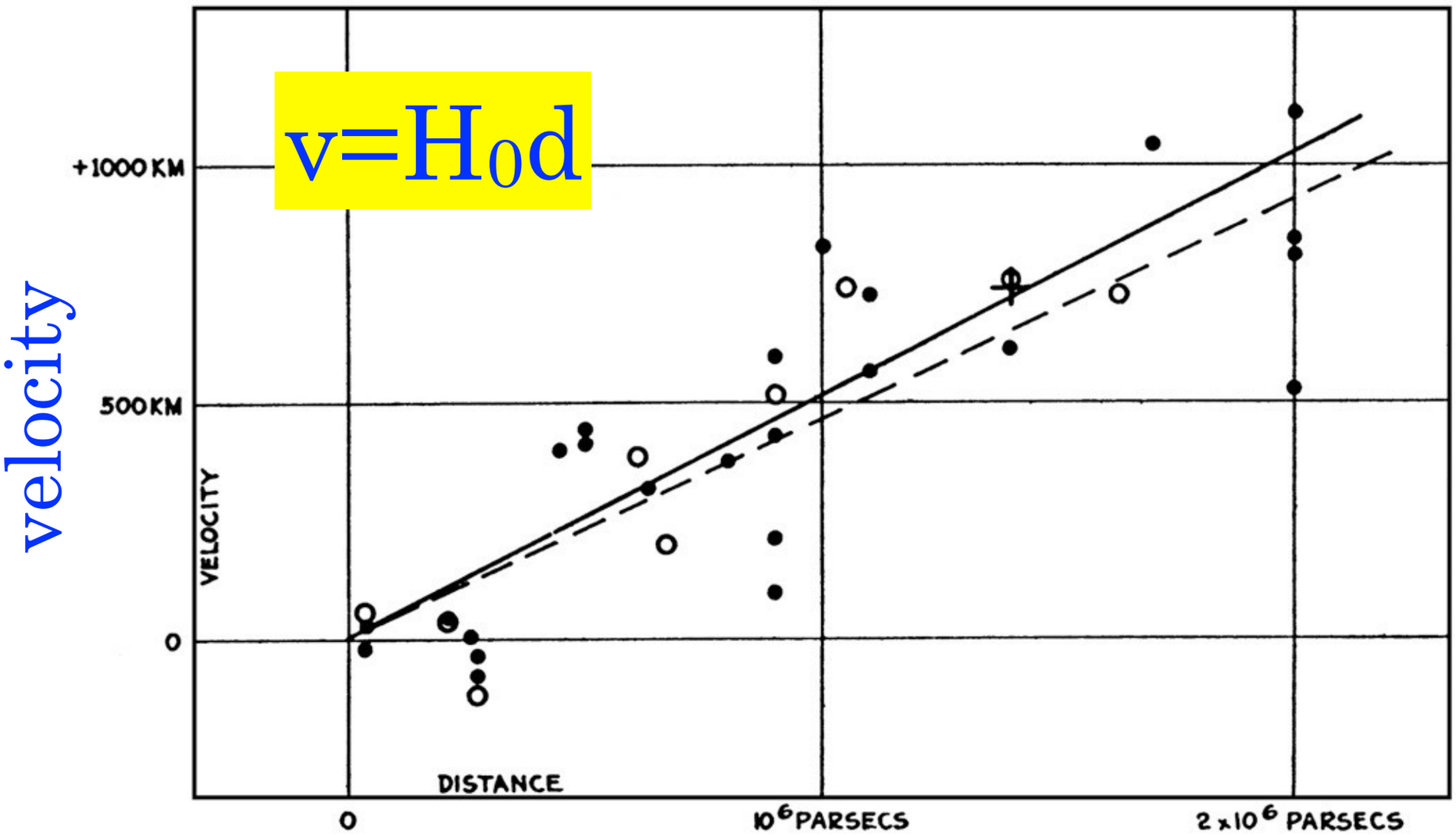
Current status of dark energy is:

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. $w(t) = -1$)

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

Hubble constant



$v = H_0 d$

velocity

distance

Edwin Hubble

Hubble (1928)

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:

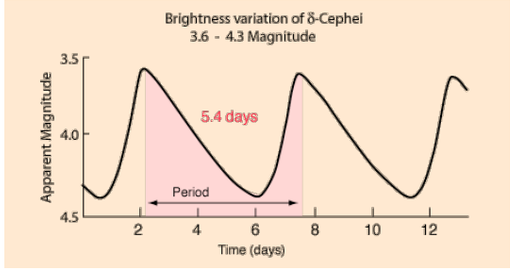
$$H_0 \approx 70 \text{ km/sec/megaparsec}$$

Recent development

Hubble Tension:

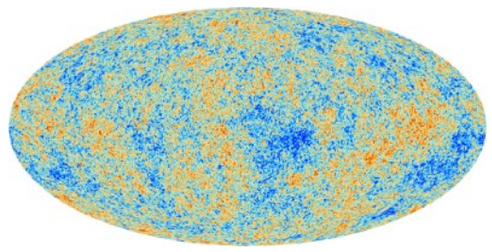
SH$_0$ES (Riess et al 2022)

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



CMB: (Planck 2018)

$H_0 = 67.36 \pm 0.54$ (km/s/Mpc)



5-sigma discrepancy: a major challenge for the standard cosmological model, and the most exciting recent development in cosmology (imo).

It would be great to shed light on the Hubble tension with new data.

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

} this talk

3. primordial non-Gaussianity

For cosmologists, galaxies are test particles!

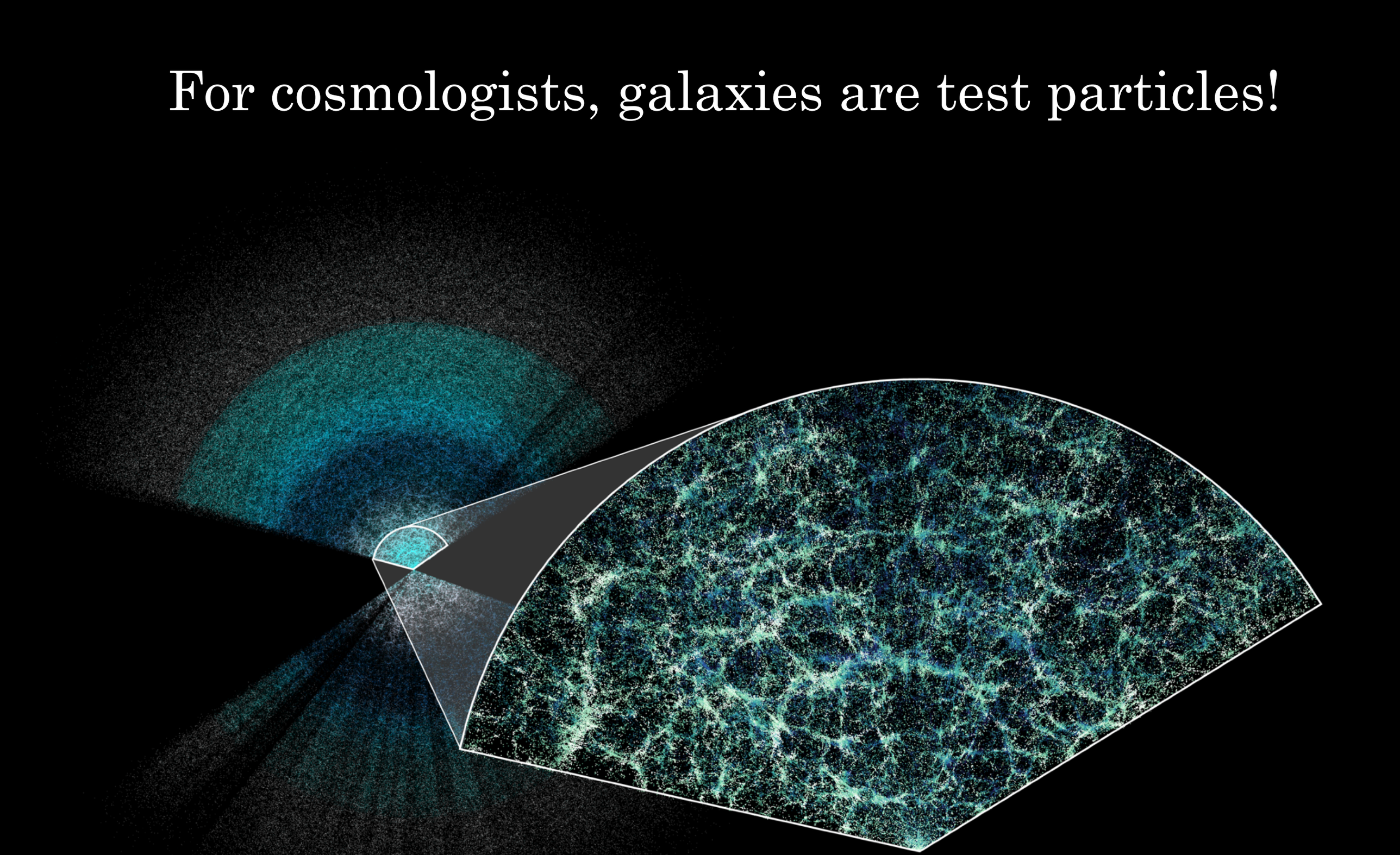
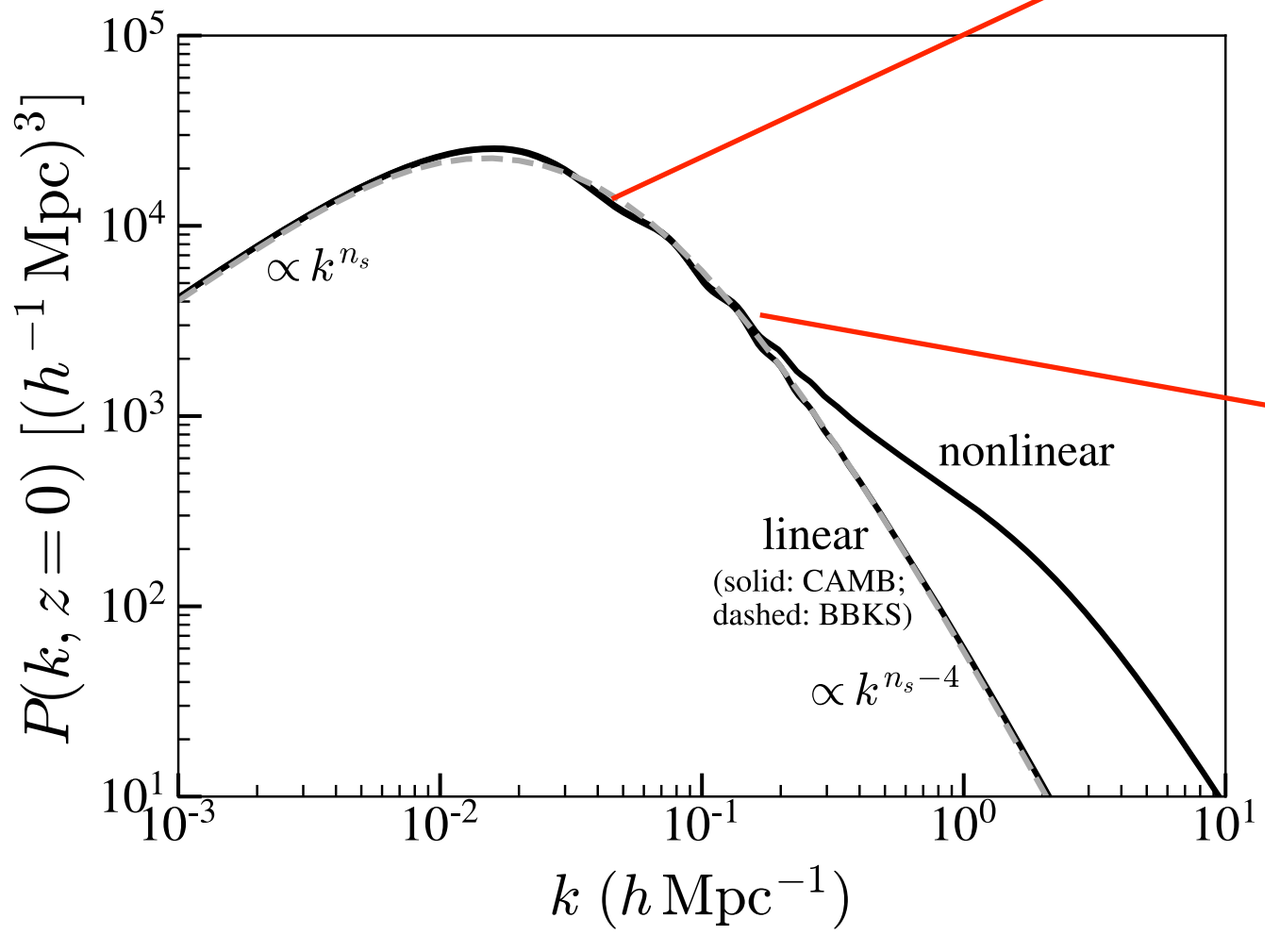
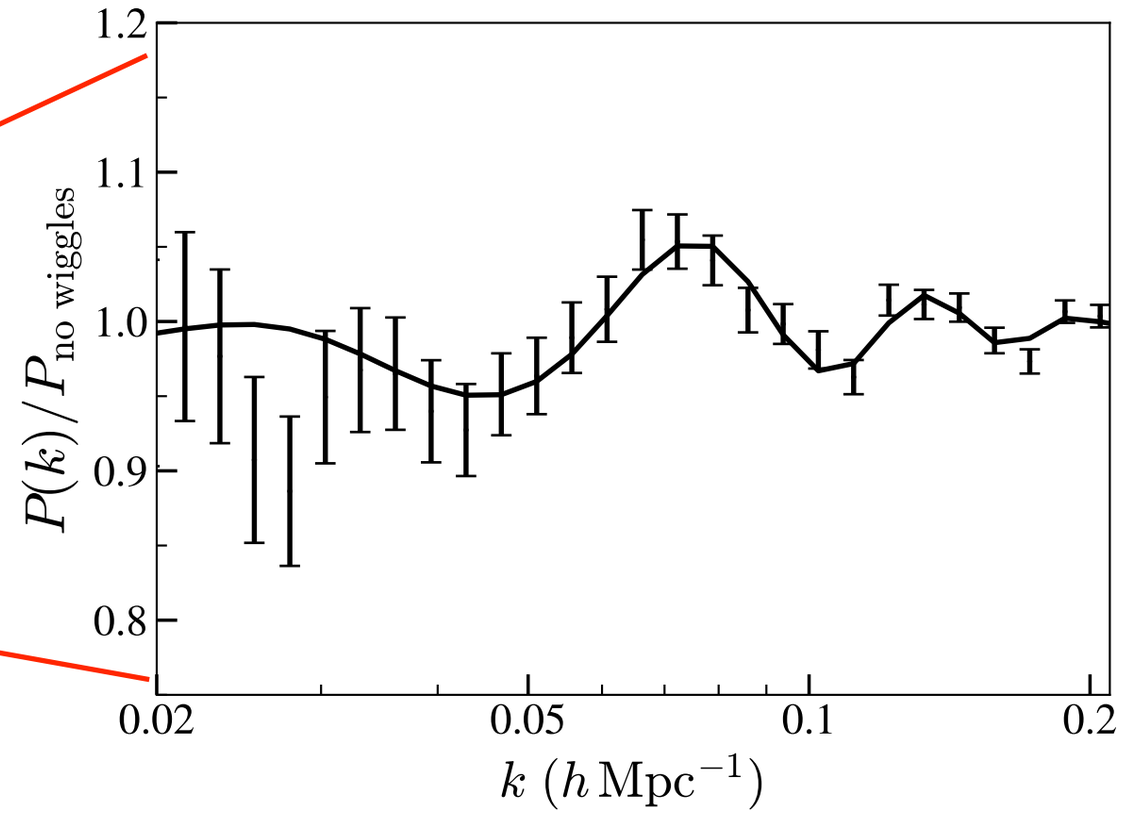


Figure credit: Claire Lamman and DESI collaboration

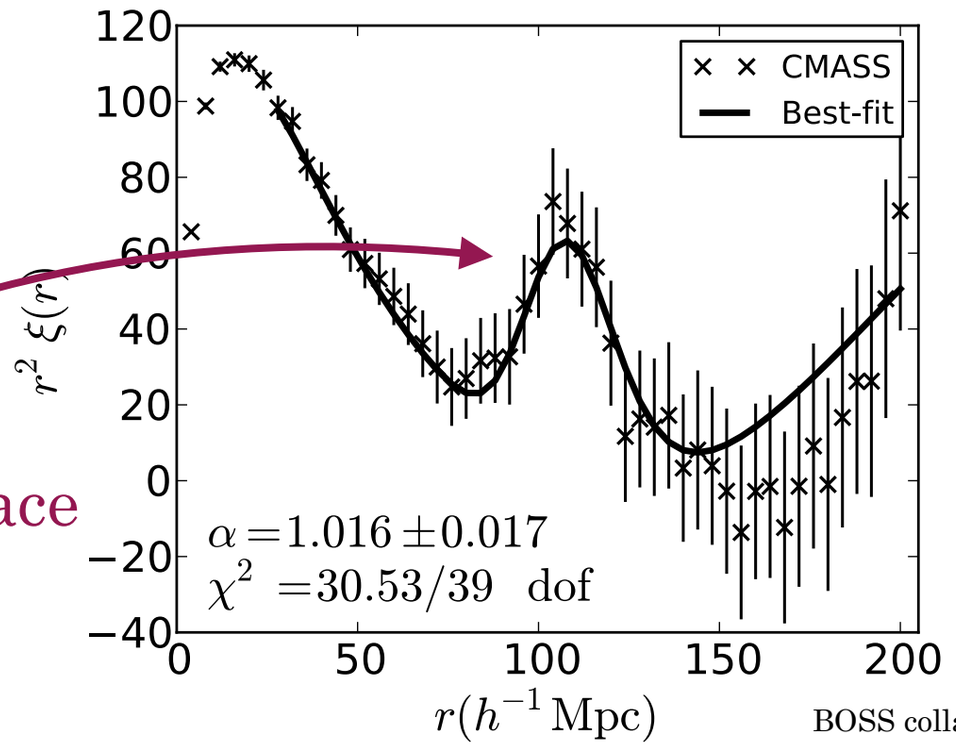
Baryon Acoustic Oscillations (BAO)

Multiple wiggles in Fourier space
(power spectrum)





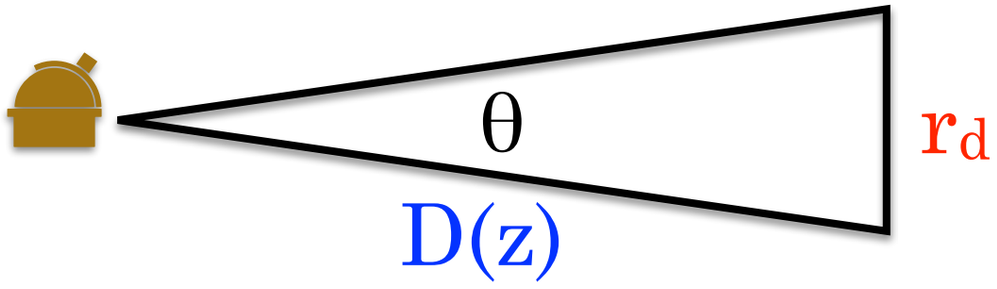
…or one wiggle in configuration space
(2-point correlation function)

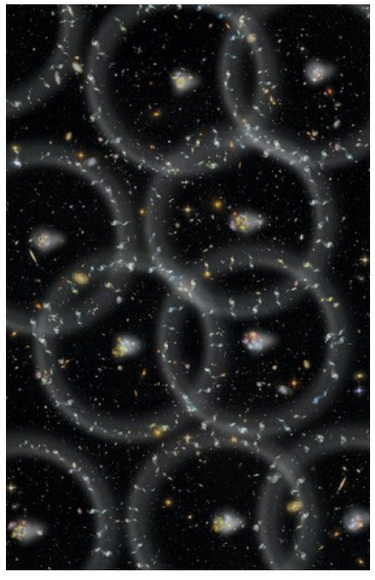


BOSS collaboration

First discussed in: Sunyaev & Zeldovich, 1972

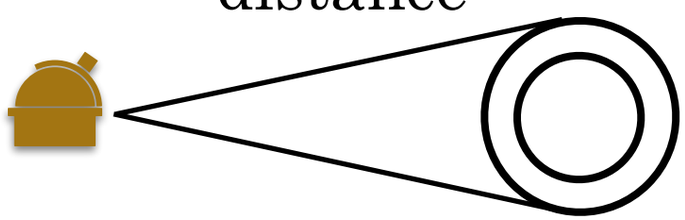
Baryon Acoustic Oscillations



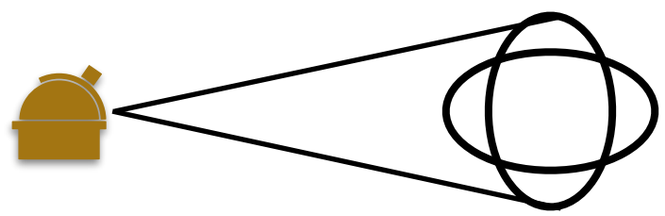


- Therefore, there is excess probability for galaxies having a neighbor at distance r_d — <u>excess probability for clustering</u>
- This imprints a preferred scale in clustering - the “standard ruler"
- The angle to the standard ruler gives $D(z)/r_d$
- Actually measure *two* kinds of distances: transverse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

Isotropic (“average”) distance



Ratio of transverse and line-of-sight distances



DESI Y1 cosmological analysis

- Fully **blinded** analysis ~7 million galaxies (with spectra!)
- Fully validated pipeline on how to extract the BAO signal
- **BAO results were unblinded in December 2023**
- BAO results announced at APS and in Moriond on April 4, 2024
- Full-shape analysis (the second key paper) still ongoing - quite a bit more complex than BAO. Results expected ~end of 2025. Expect constraints on cosmic growth (i.e. σ_8).

postdoc
Minh Nguyen
(cosmo analysis)

student
Jiaming Pan
(cosmo analysis)

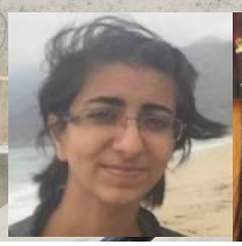
postdoc
Johannes Lange
(DESI x lensing)

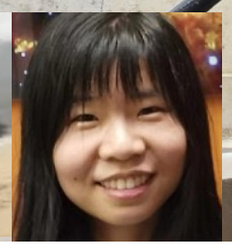
postdoc
Uendert Andrade
(blinding)

student
Sikandar Hanif
(fiber assignment)

student
Otavio Alves
(covariance)

student
Tianke Zhuang
(cosmo analysis)





postdocs
Humna Awan
and Kuan Wang
(Lyman-alpha)

professor
Camille Avestruz

professor
Greg Tarlé

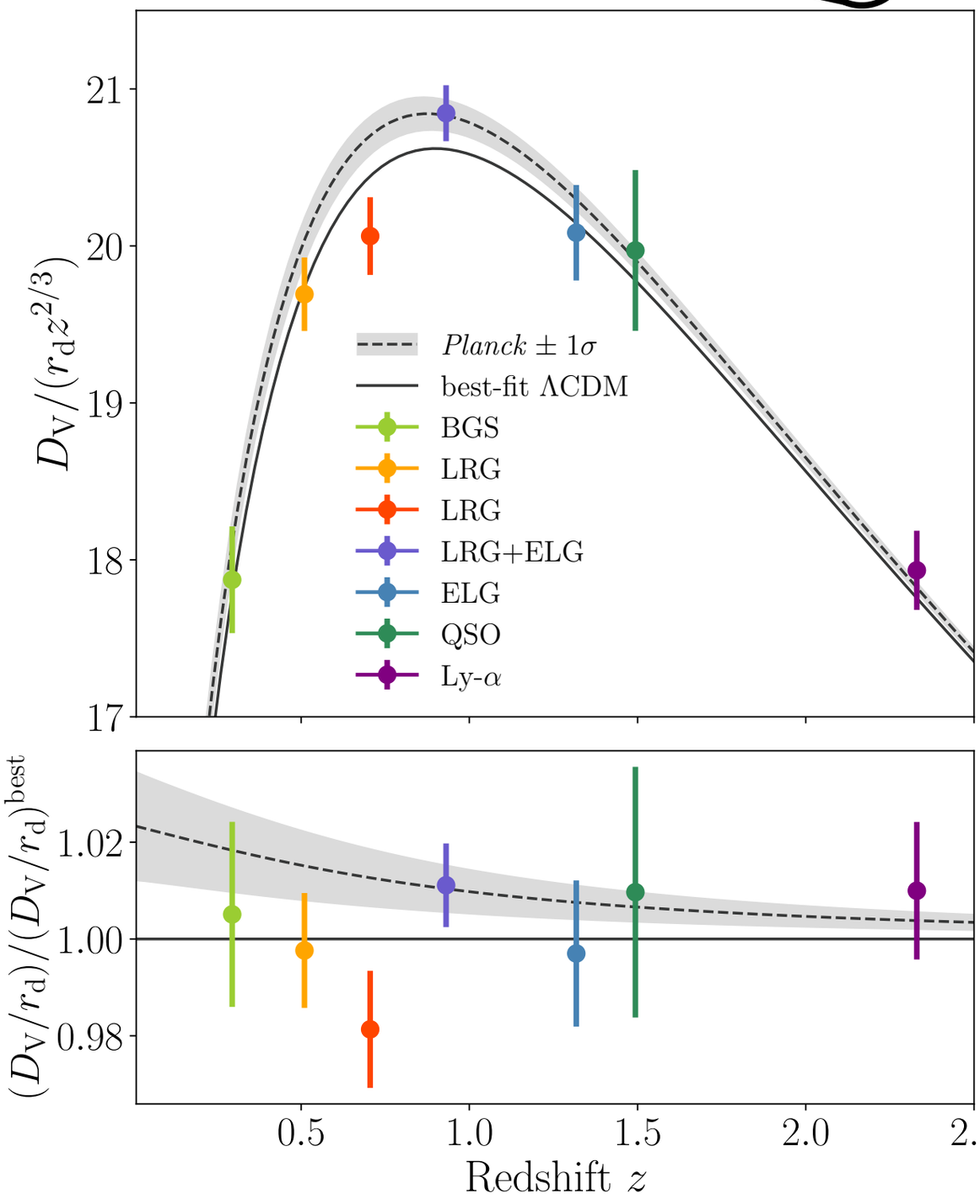
Dr.
Michael Schubnell

DESI Y1 analysis at UMich

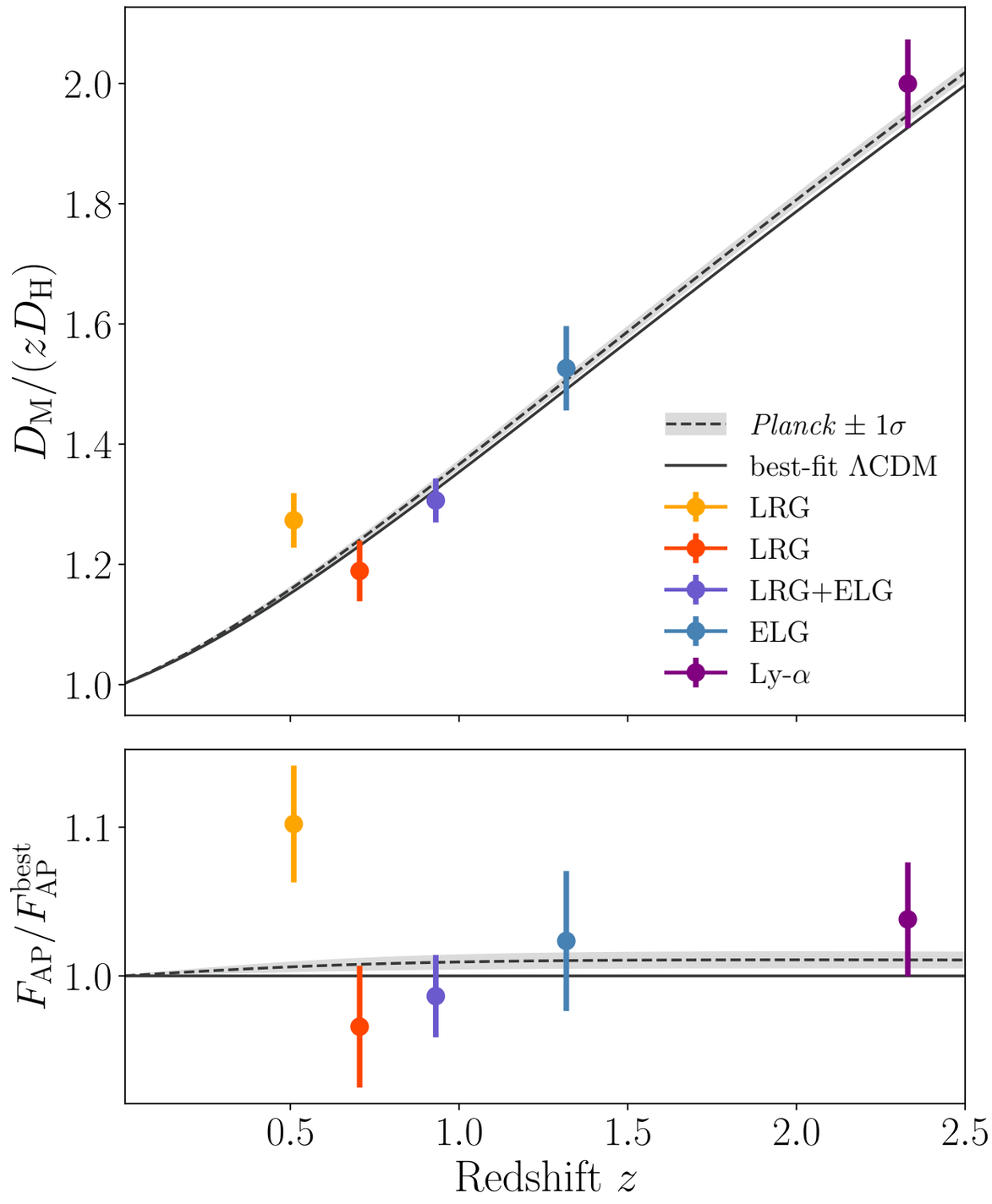
DESI Y1 Cosmological Results

DESI Y1 measurements: compression to distances

$D_{isotropic} / r_d$



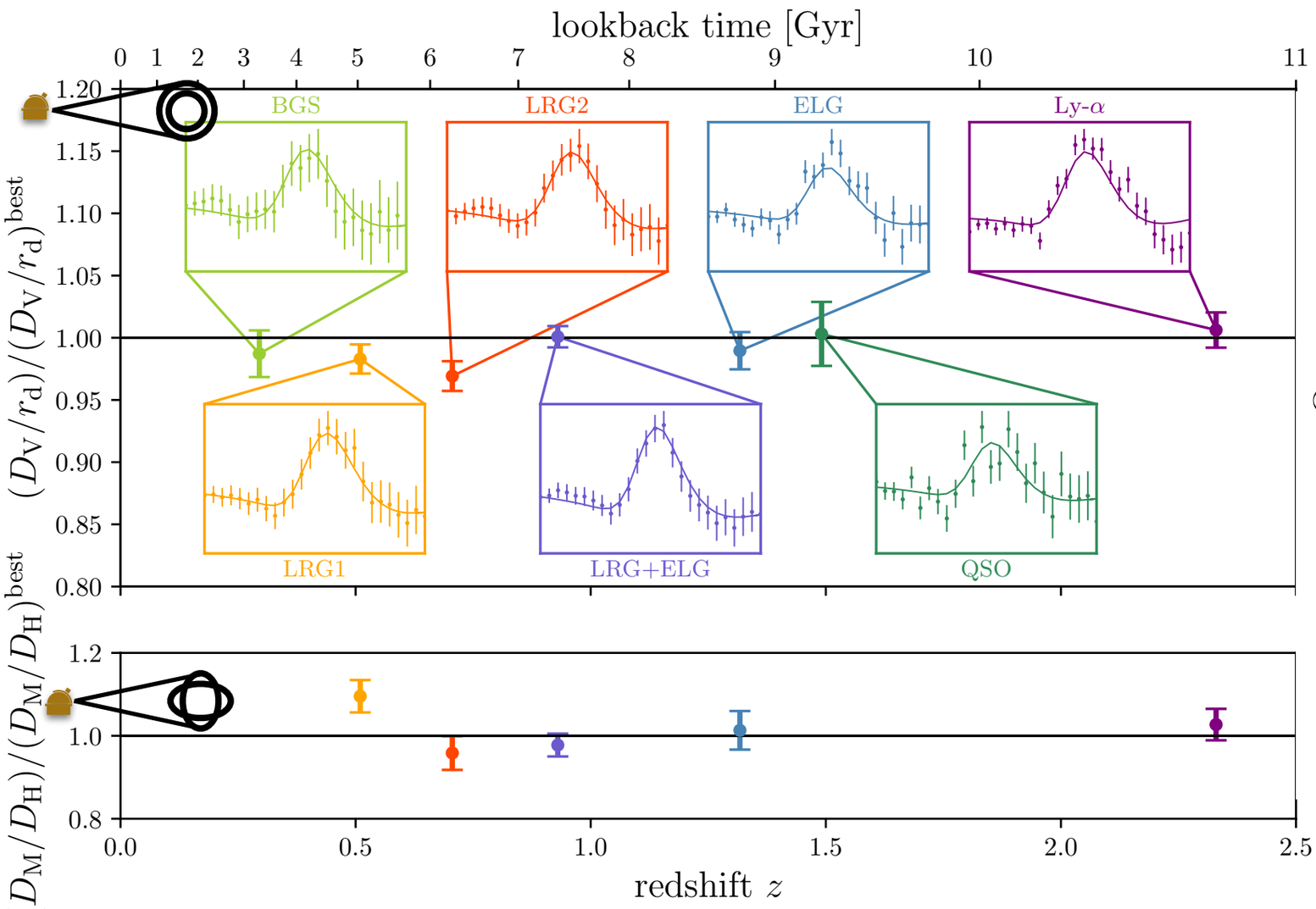
$D_{transverse} / D_{line-of-sight}$

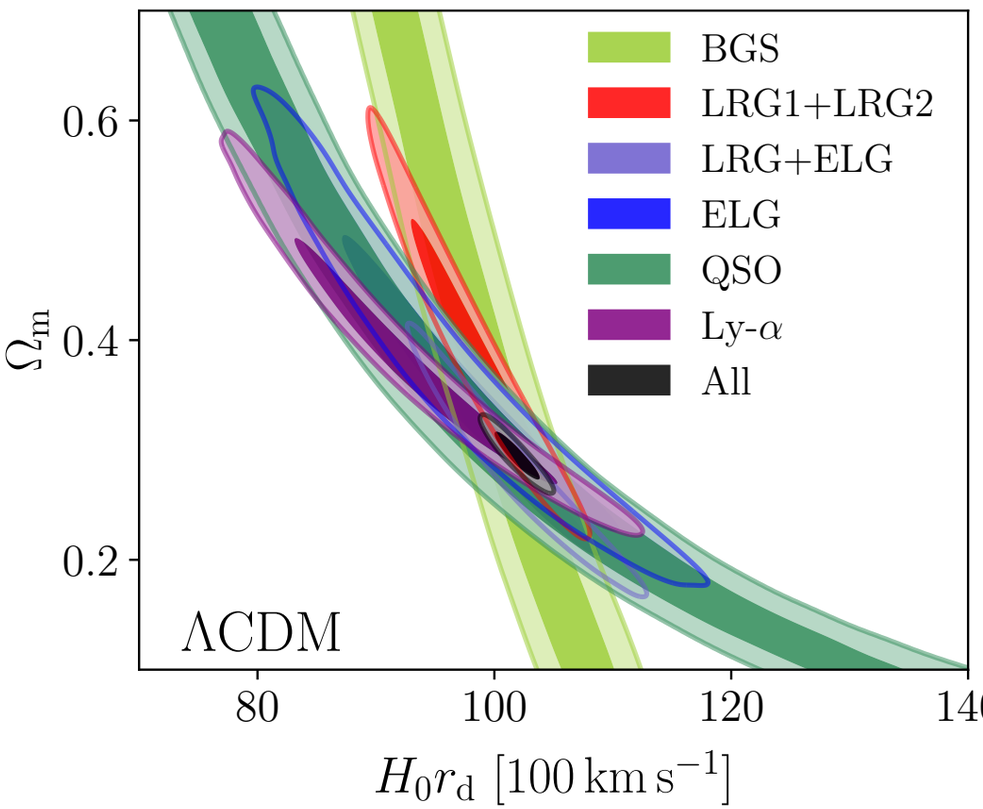


Unblinded on December 12, 2023

Constraints from DESI Y1 BAO

Basic constraints in ΛCDM model

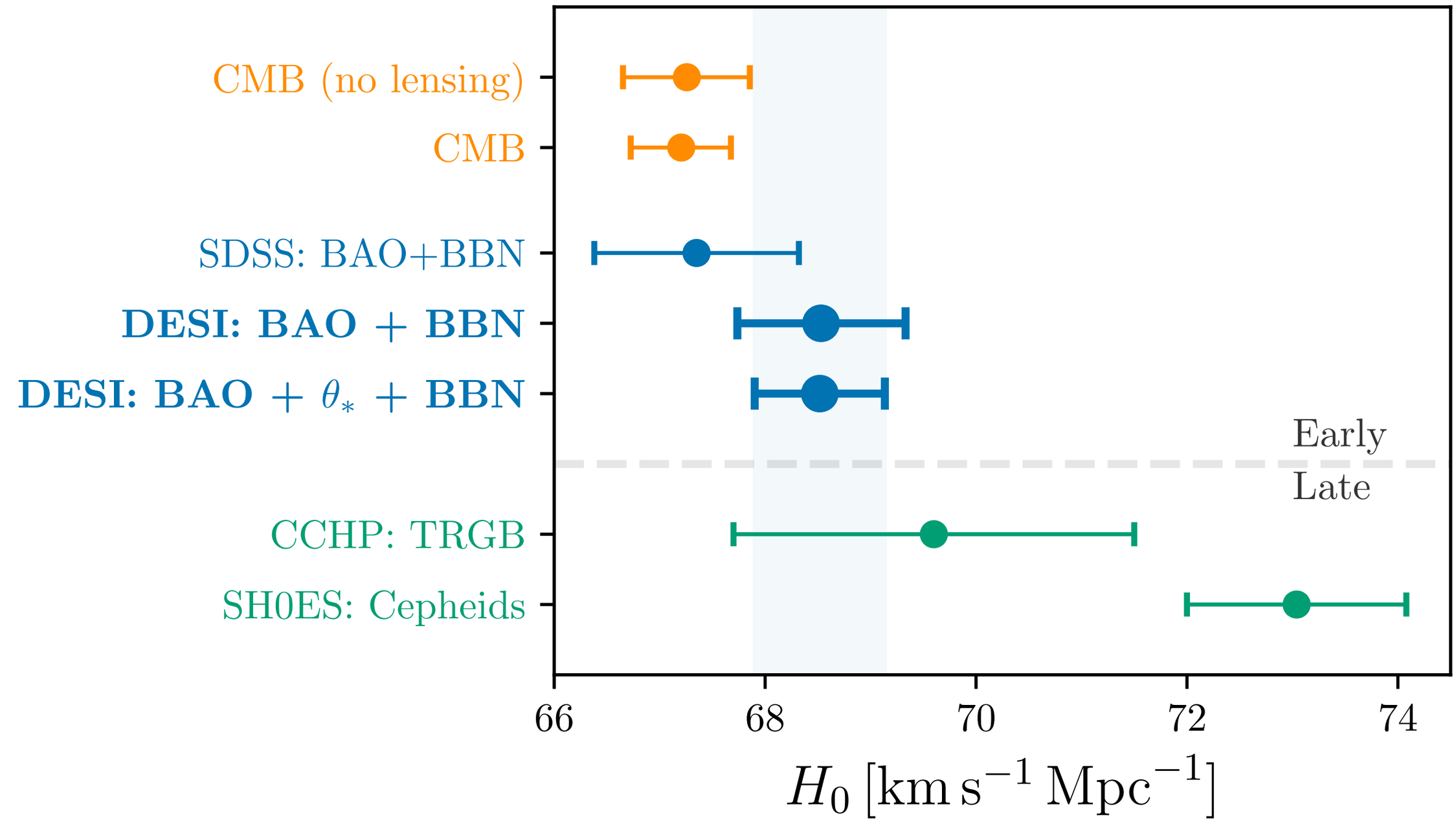




$$\Omega_m = 0.295 \pm 0.015 \qquad (5.1\%)$$

$$r_d H_0 = (101.8 \pm 1.3)\,[100\,\mathrm{km/s}] \qquad (1.3\%)$$

Hubble constant



$H_0 = (68.52 \pm 0.62)$ km/s/Mpc (DESI + θ_* + BBN)

Consistent with CMB measurements

Sum of neutrino masses

From neutrino oscillation experiments

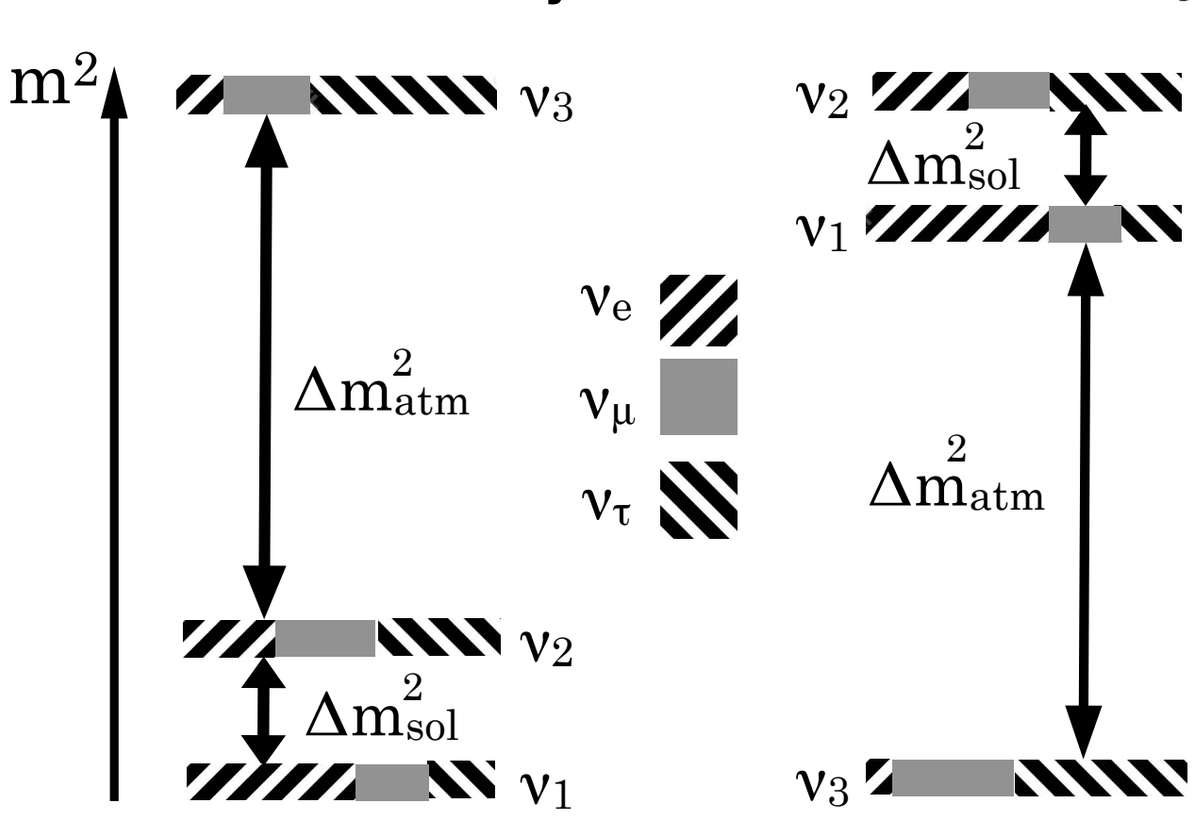
$$(\Delta m^2)_{sol} \simeq 8\times10^{-5}\ eV^2$$
$$(\Delta m^2)_{atm} \simeq 3\times10^{-3}\ eV^2$$

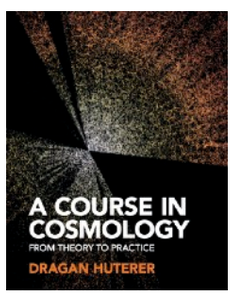
$$\Big\} \quad \sum m_i = 0.06\ eV^* \quad \text{(normal)}$$

vs.

$$\sum m_i = 0.10\ eV^* \quad \text{(inverted)}$$

*(assuming $m_1=0$)





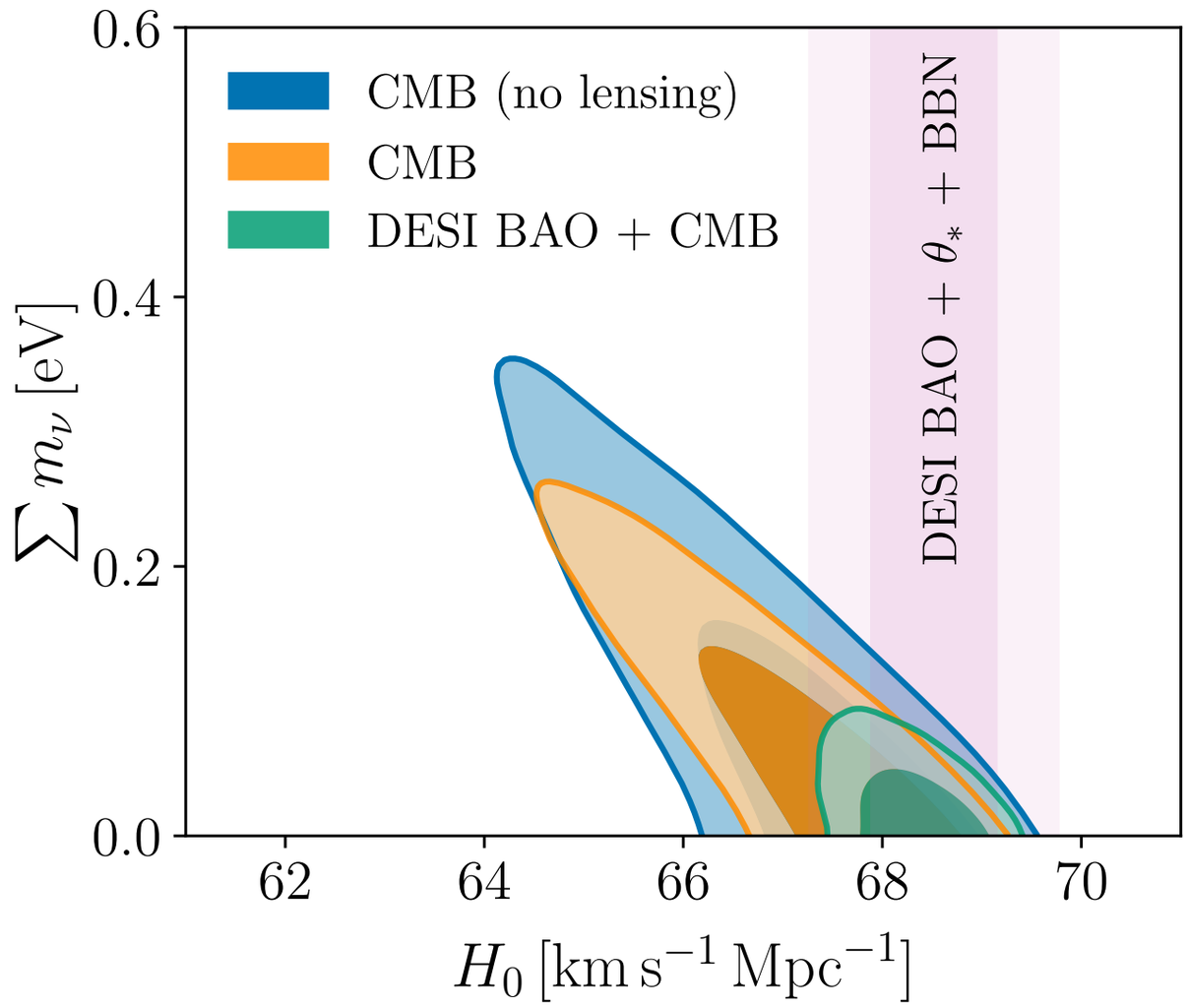
Sum of neutrino masses

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



$$\sum m_\nu < 0.072\,\mathrm{eV} \quad (\text{at } 95\%)$$

[But significantly weakens in models beyond ΛCDM, e.g. $\sum m_\nu < 0.195\,\mathrm{eV}$ in w_0w_aCDM]

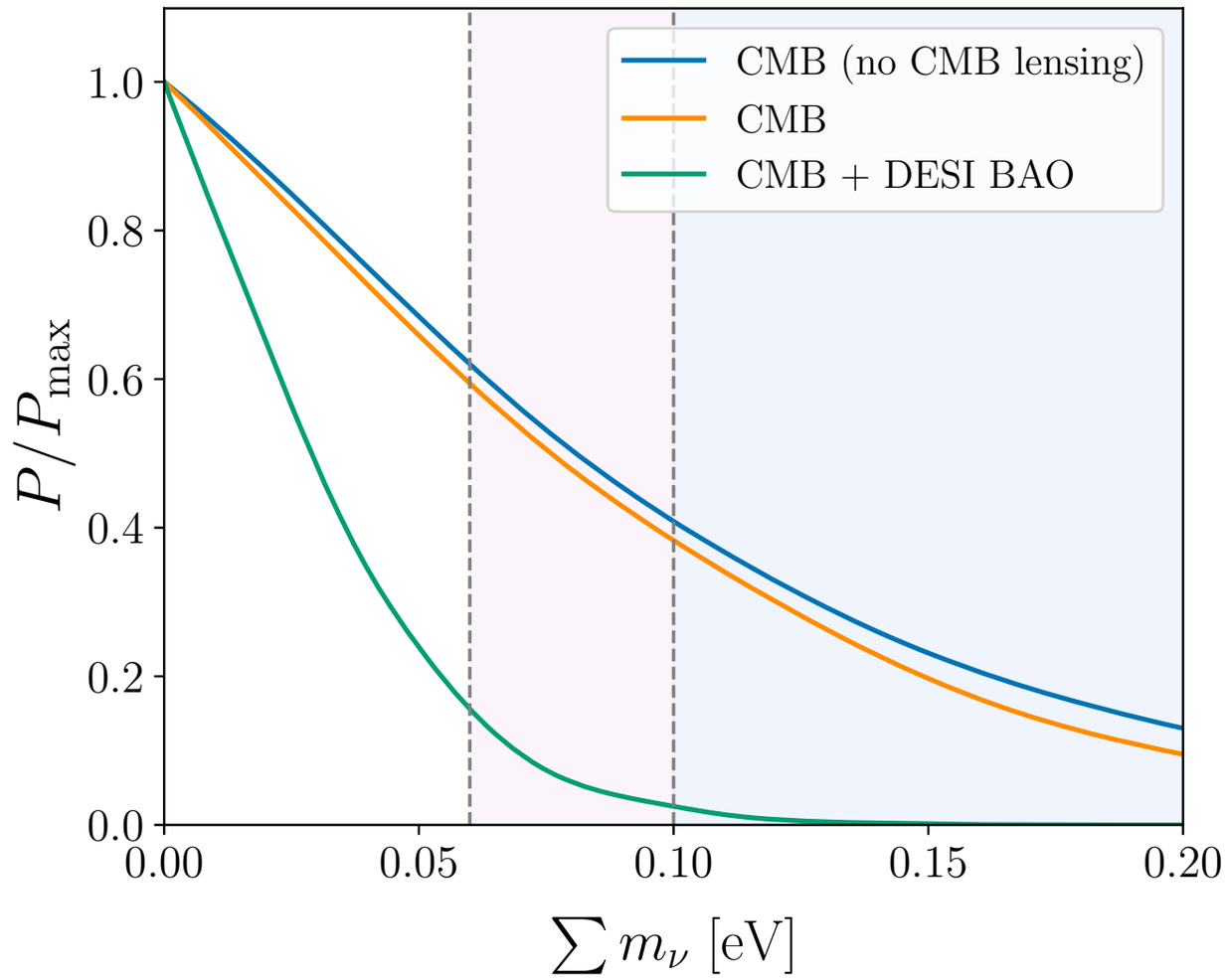
Sum of neutrino masses

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



$$\sum m_\nu < 0.072\,\mathrm{eV} \quad \text{(at 95\%)}$$

[But significantly weakens in models beyond ΛCDM, e.g. $\sum m_\nu < 0.195\,\mathrm{eV}$ in w_0w_aCDM]

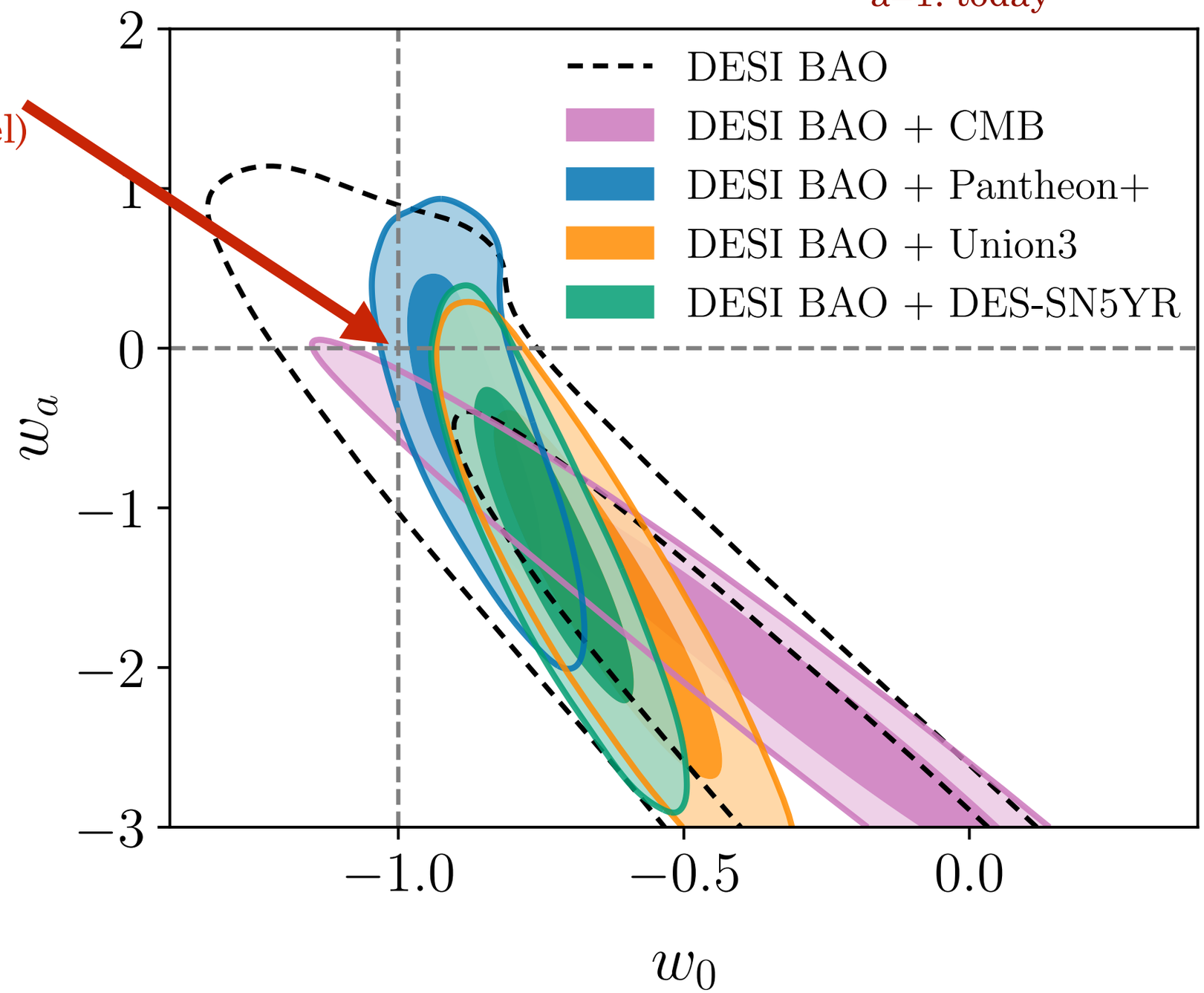
Dark energy - (w_0, w_a)

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

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

ΛCDM
(standard model)

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



Dark energy - (w_0, w_a)

DESI+CMB+Pantheon+

$w_0 = -0.827 \pm 0.063 \quad w_a = -0.75^{+0.29}_{-0.25}$

(2.5σ away from ΛCDM)

DESI+CMB+Union3

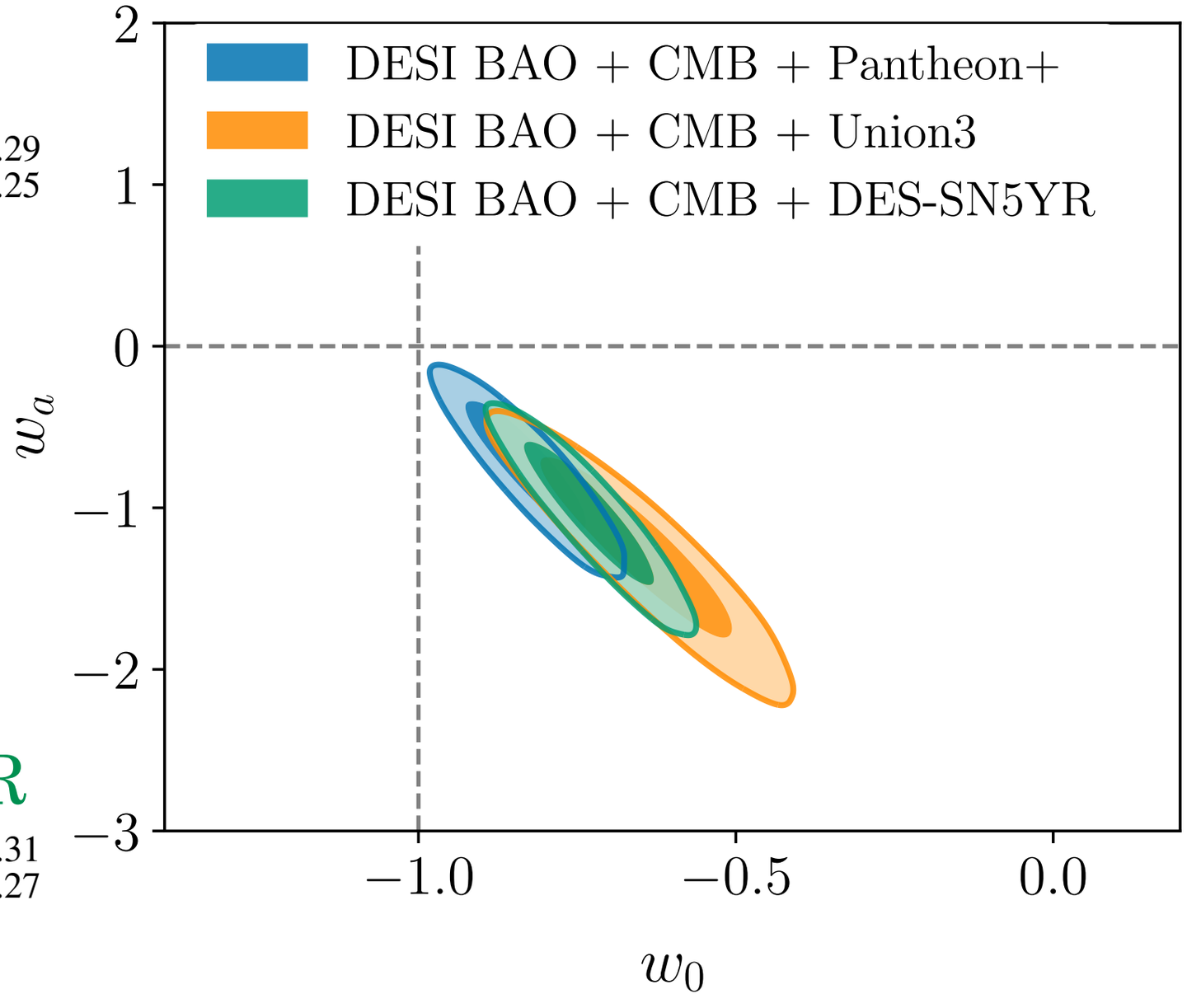
$w_0 = -0.64 \pm 0.11 \quad w_a = -1.27^{+0.40}_{-0.34}$

(3.5σ away from ΛCDM)

DESI+CMB+DES-SN5YR

$w_0 = -0.727 \pm 0.067 \quad w_a = -1.05^{+0.31}_{-0.27}$

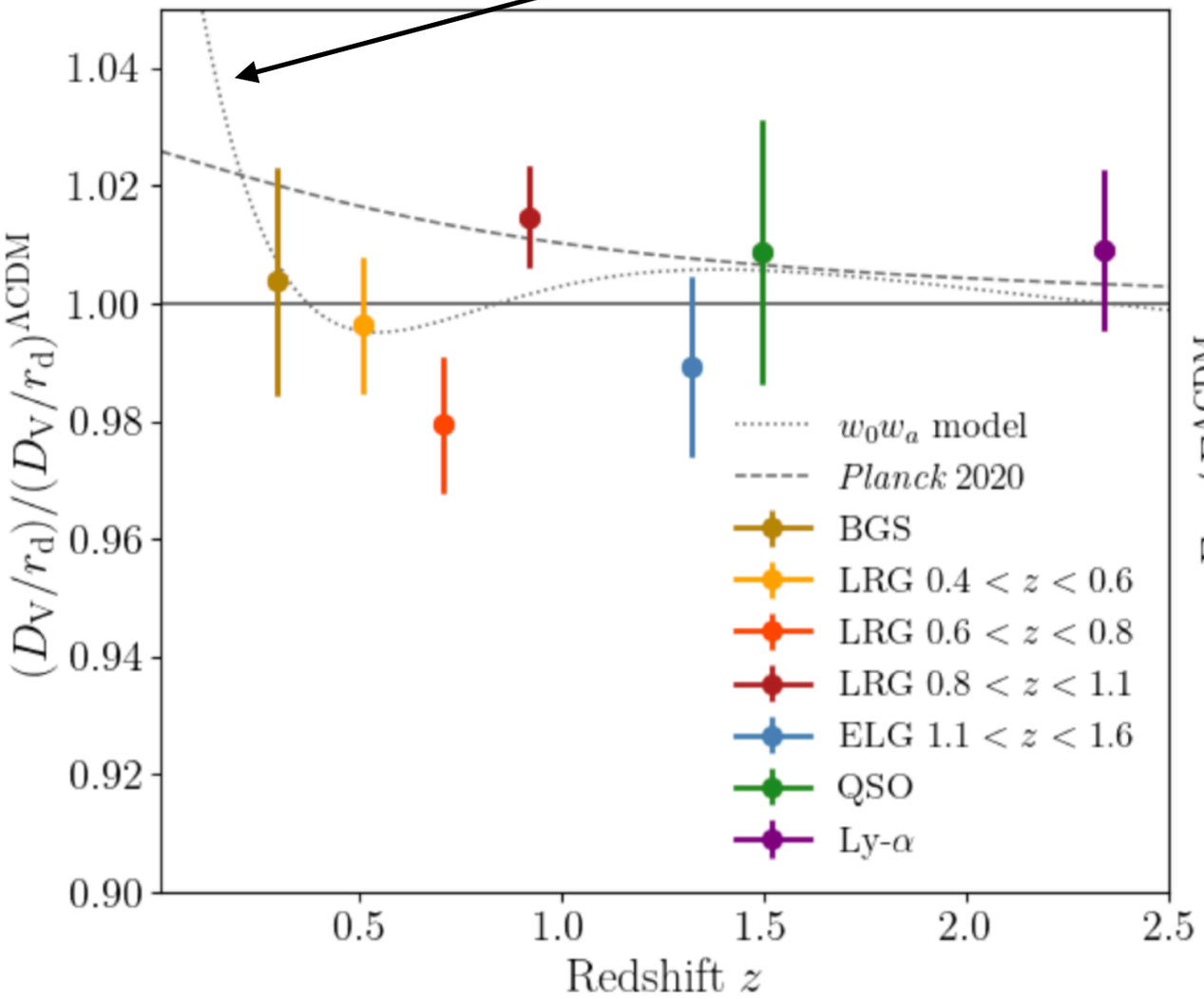
(3.9σ away from ΛCDM)

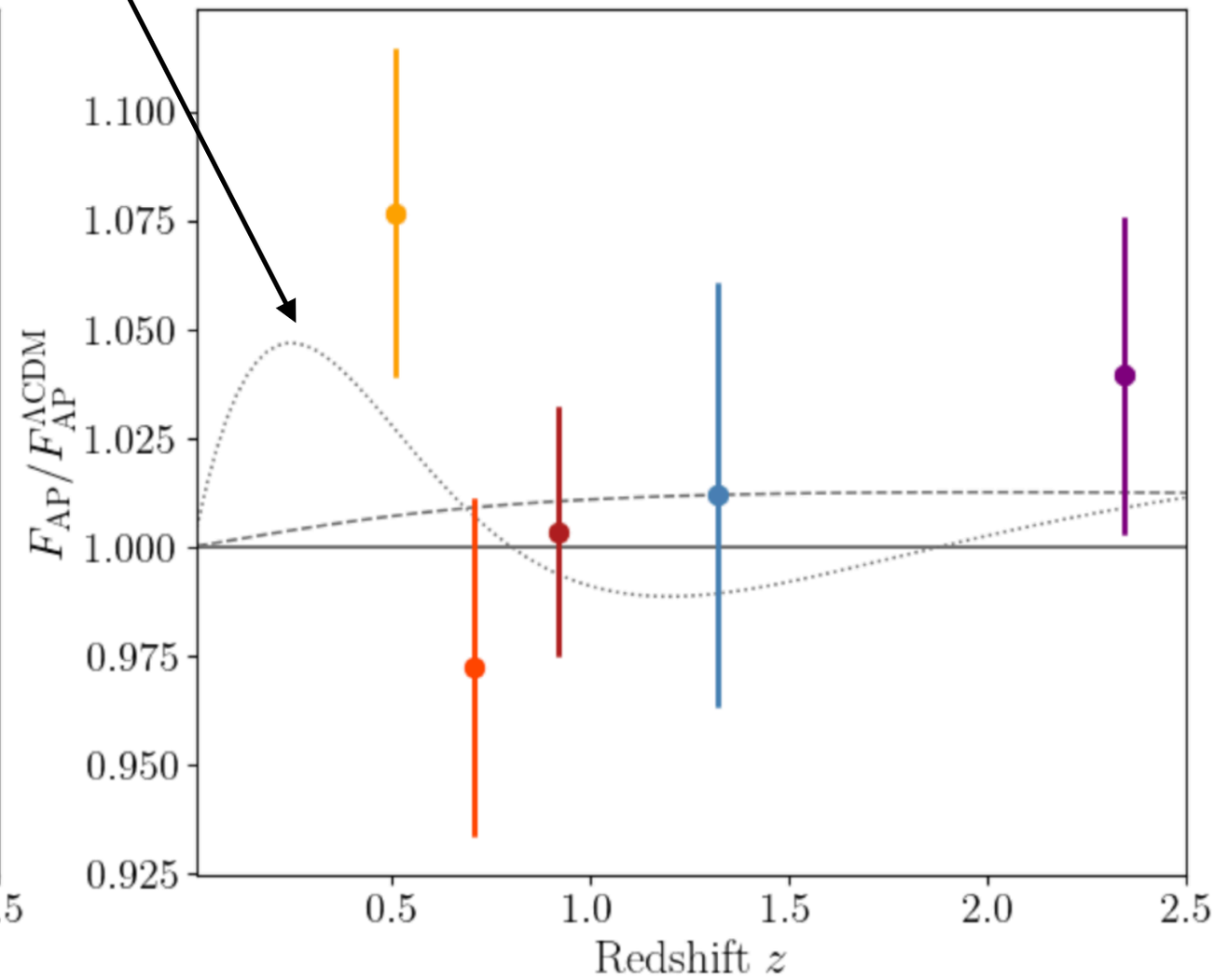


Therefore: tantalizing hints of departure from LCDM

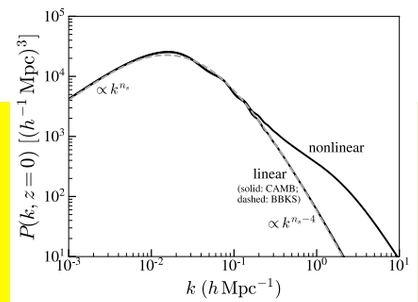
Dark energy: what the data prefer

best-fit w_0w_a model





What's next



- **DESI Y1 "full-shape" analysis of galaxy clustering is forthcoming** (before the end of this year)
  - analysis is much more complex (galaxy bias, RSD; nuisance parameters…)
  - expect constraints on structure growth (σ_8), DE and mnu; first constraints on modified gravity from DESI
- There will be a number of significant new analyses from DESI:
  - correlation of DESI with photometric surveys
  - peculiar velocities (probe of gravity and dark energy)
  - higher-order correlation functions (3-pt, 4-pt…)
  - ……
- 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

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

- DESI Y1 BAO results highlights:
  - $H_0 = (68.52 \pm 0.62)$ km/s/Mpc
  - $\sum m_\nu < 0.072\,\mathrm{eV}$ (DESI + CMB, at 95%)
  - dark energy: 2.5σ-3.9σ preference for model with w(t) varying

- More soon:
  - **DESI Y1 full-shape P(k) analysis (results out soon!)**
  - DESI Y3, Y5