Understanding DESI results

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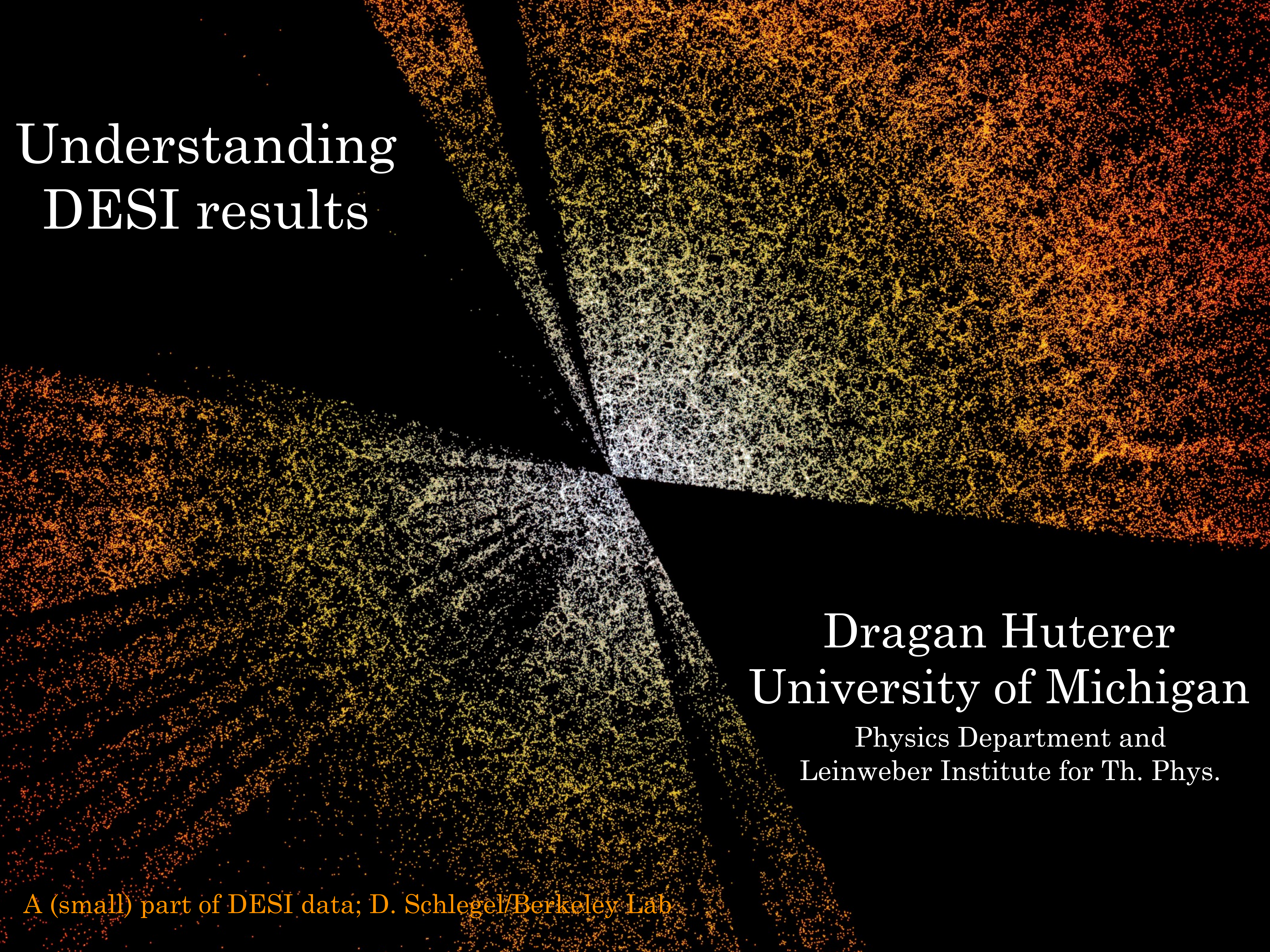
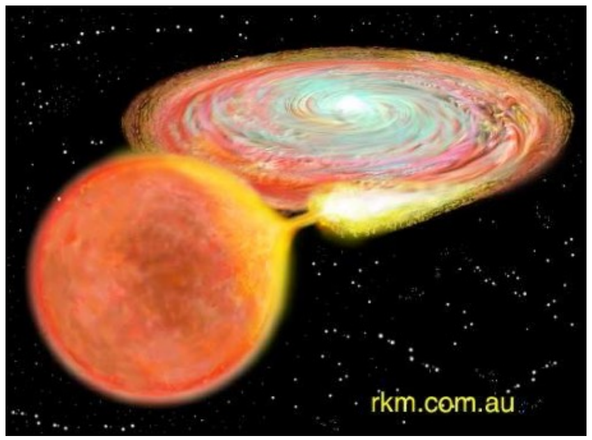


A (small) part of DESI data; D. Schlegel/Berkeley Lab

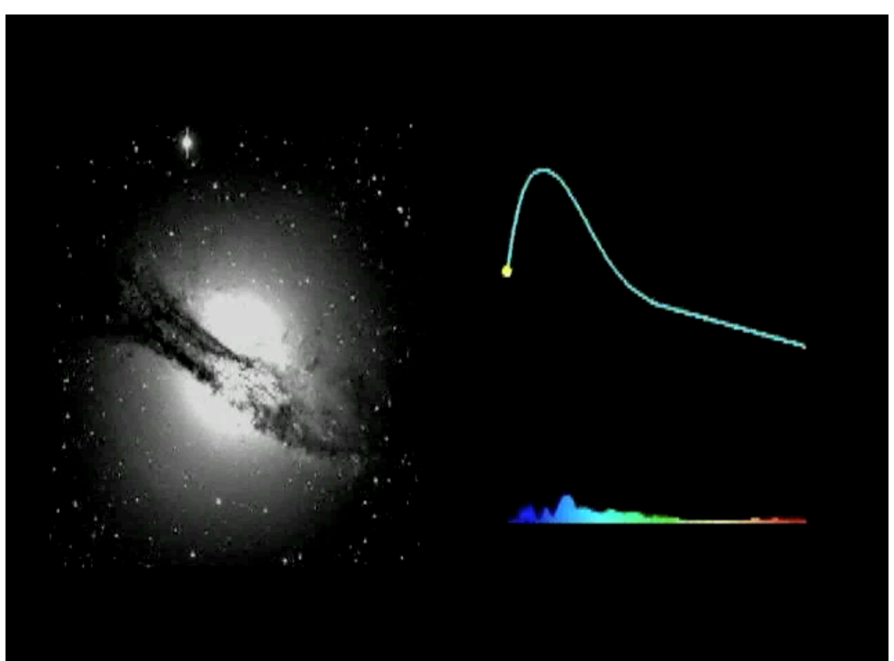
Discovery of dark energy

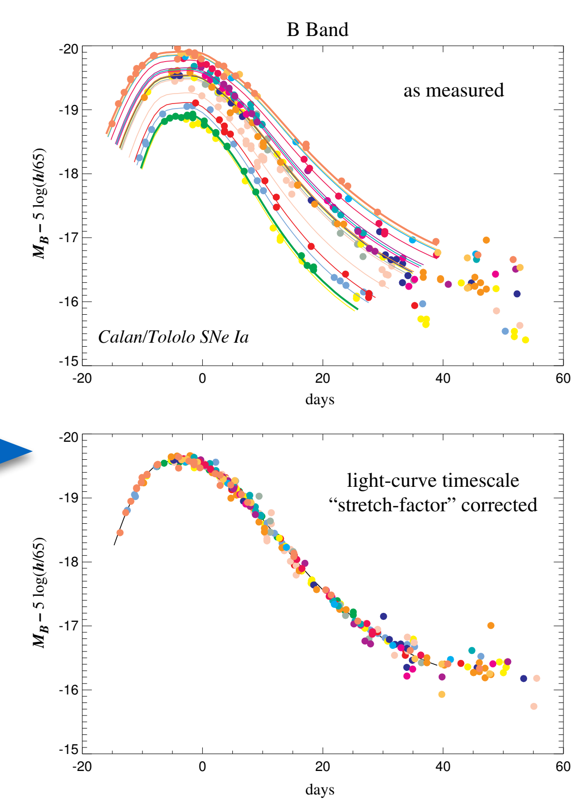
(late 1990s; Physics Nobel Prize in 2011)



type Ia
supernova
explodes…

…astronomers detect it and follow it up;
they measure the light-curve…





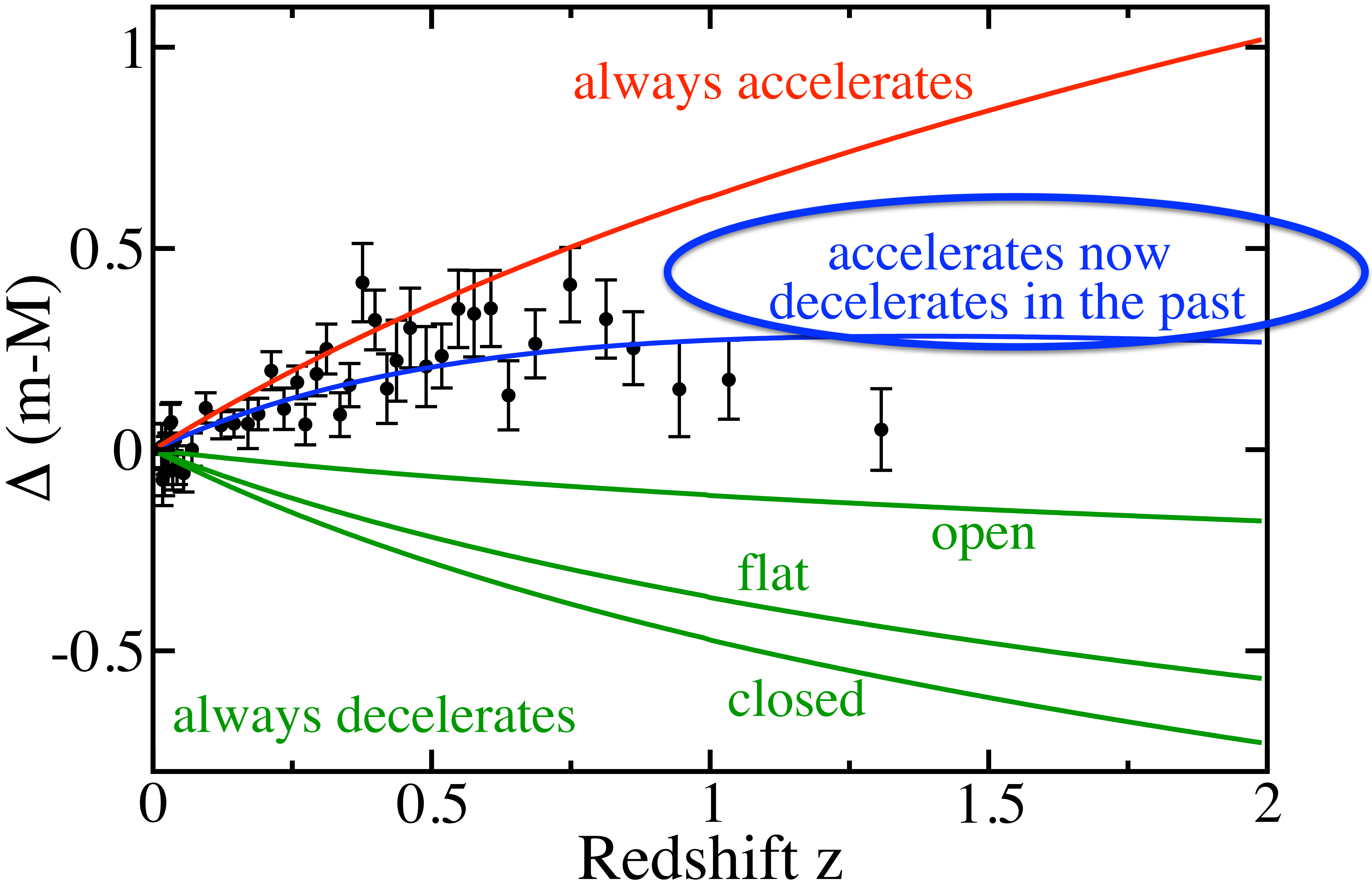
…and make a
correction
for its width…

…to use it as a
standard candle
(i.e. L = const)

$$f = \frac{L}{4\pi d_L^2}$$

Supernova Hubble diagram

(binned; each error bar denotes ~20 SN)

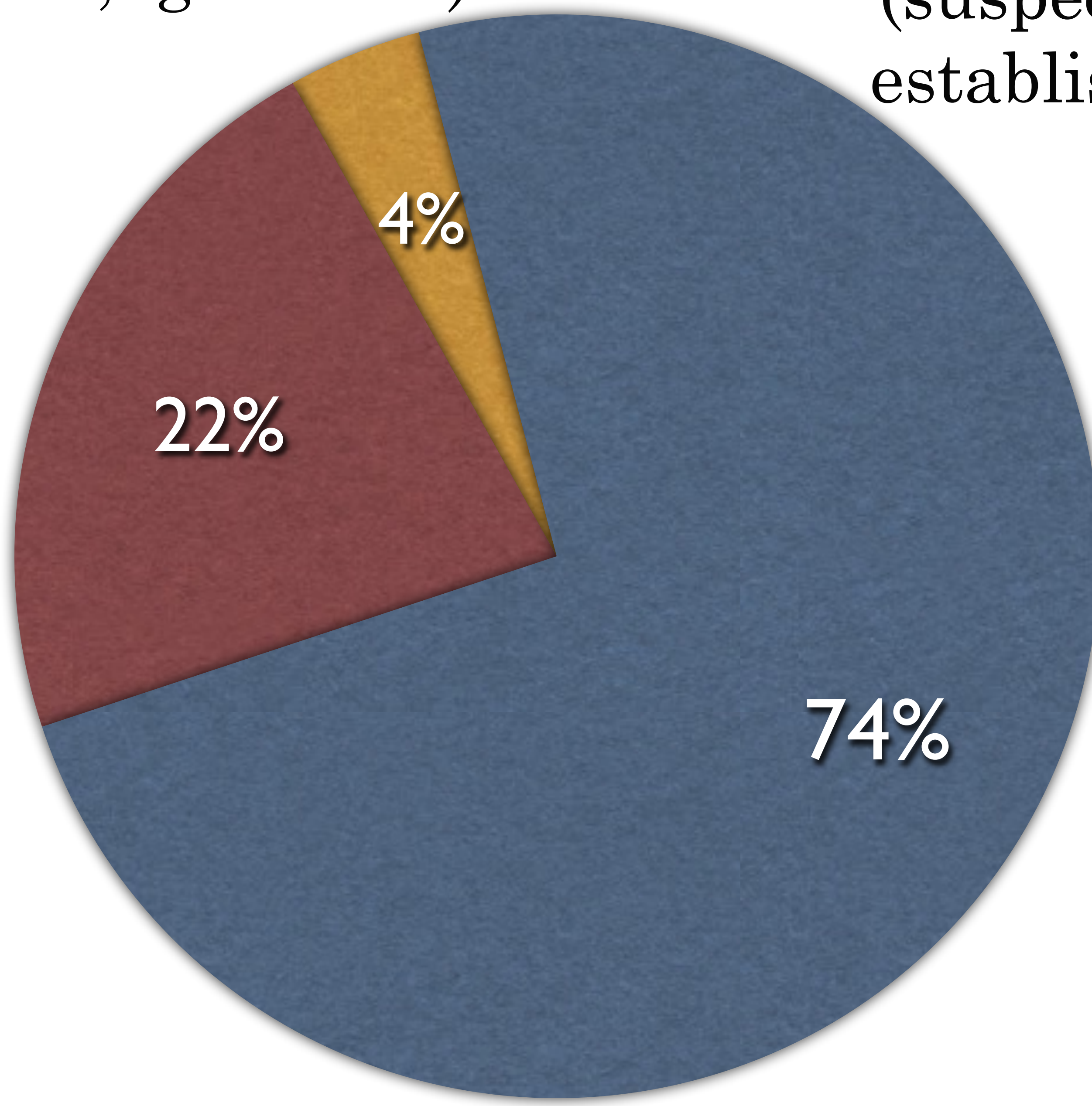


Makeup of universe today

Baryonic Matter
(stars 0.4%, gas 3.6%)

Dark Energy
(suspected since 1980s
established since 1998)

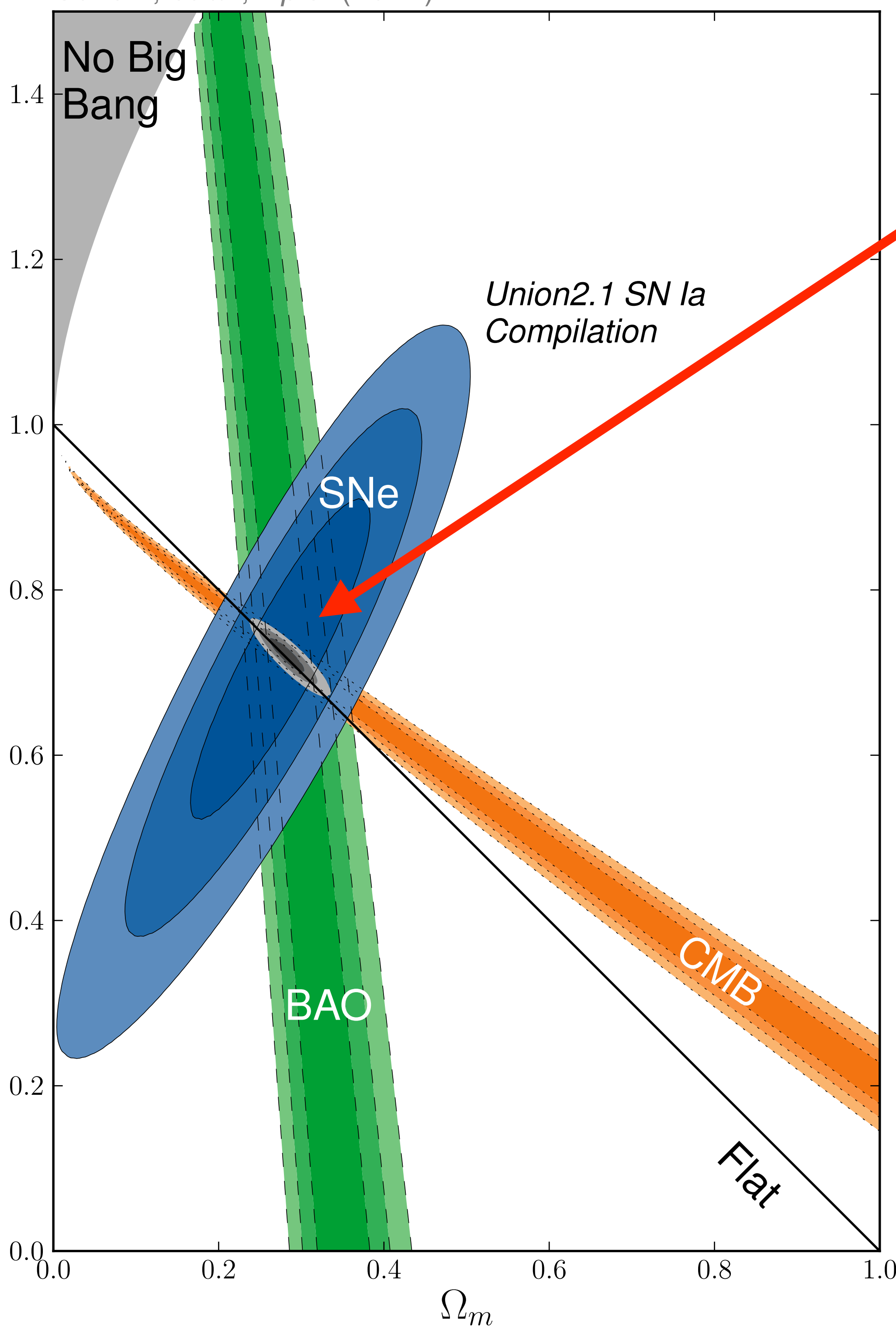
Dark Matter
(suspected since 1930s
established since 1970s)



Also:
radiation (0.01%)

(Recent) constraints on dark energy

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



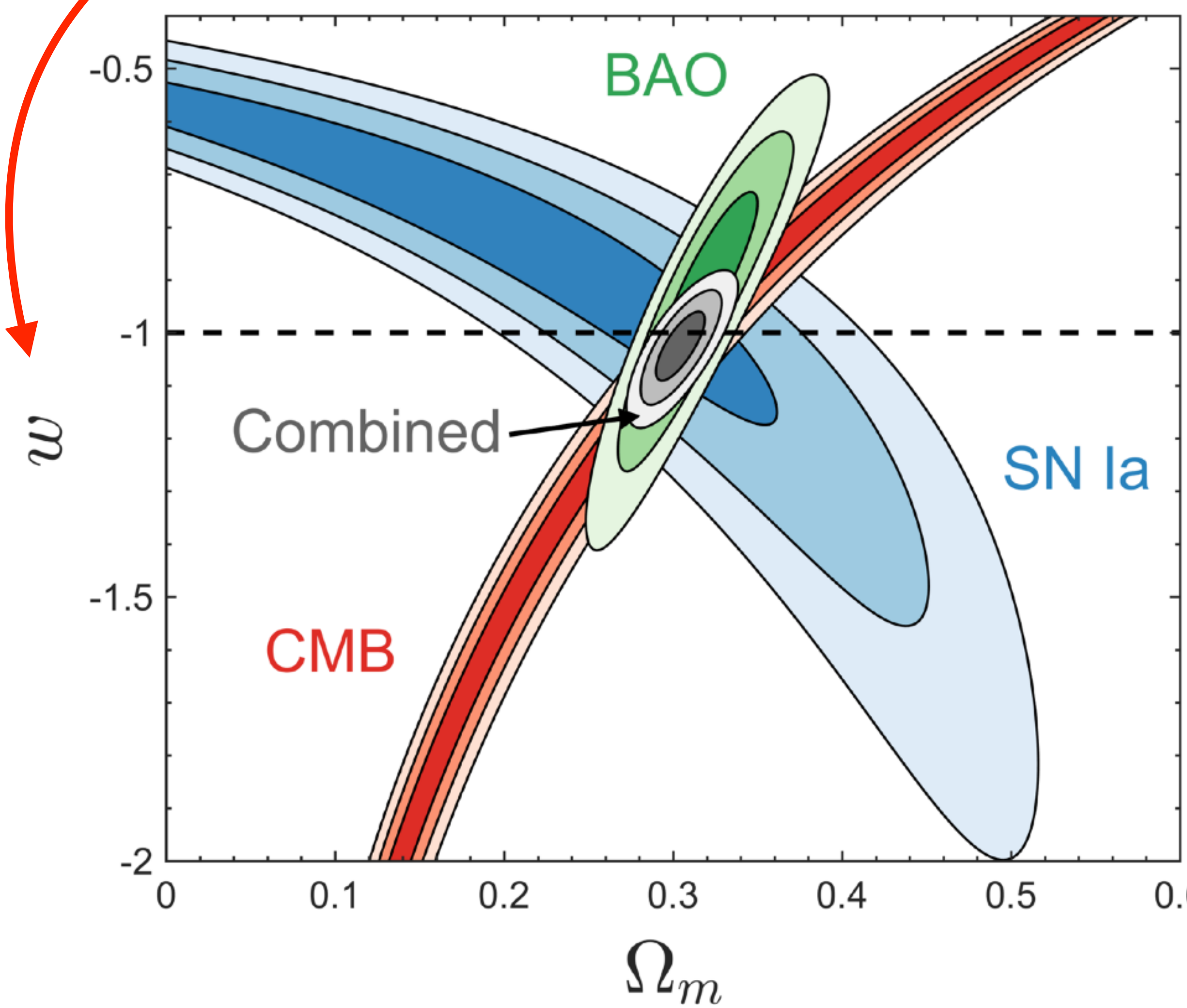
DE density (relative to critical)

Matter density (relative to critical)

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

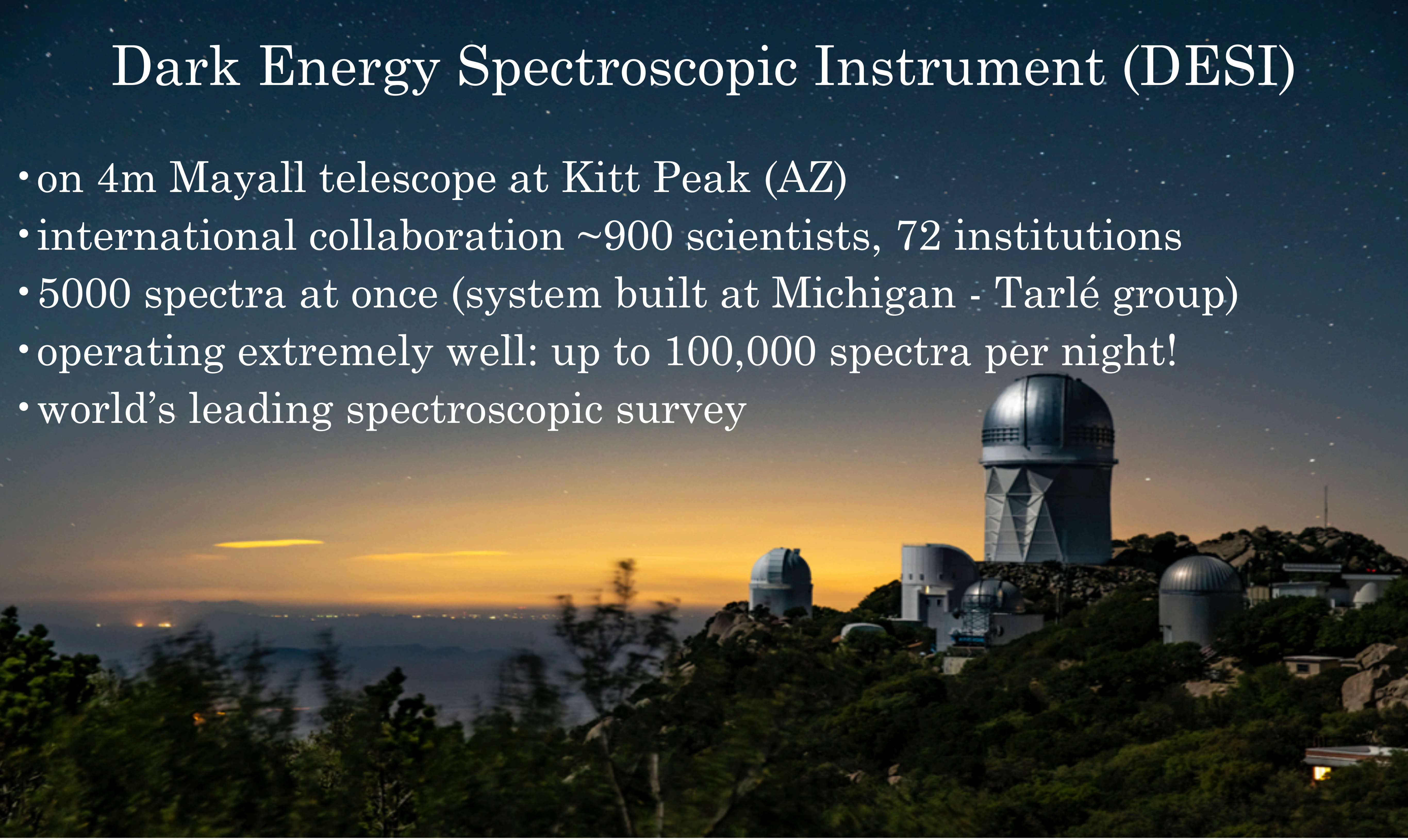
…and DE equation of state is

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



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

Dark Energy Spectroscopic Instrument (DESI)

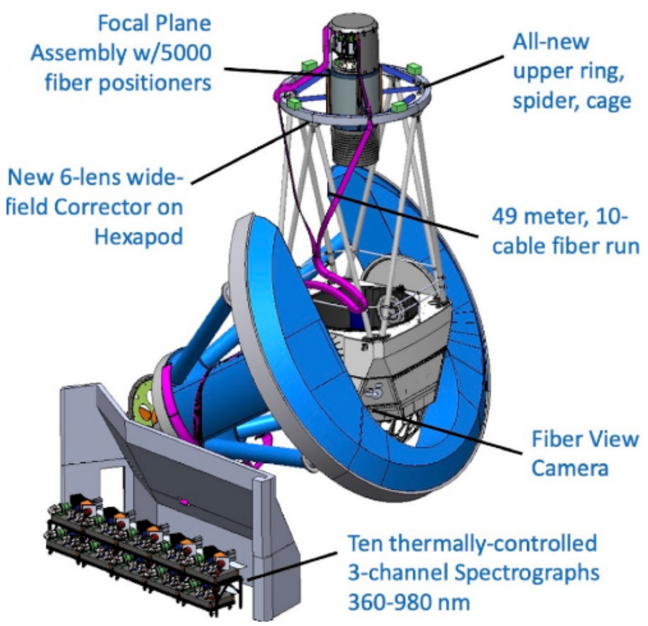


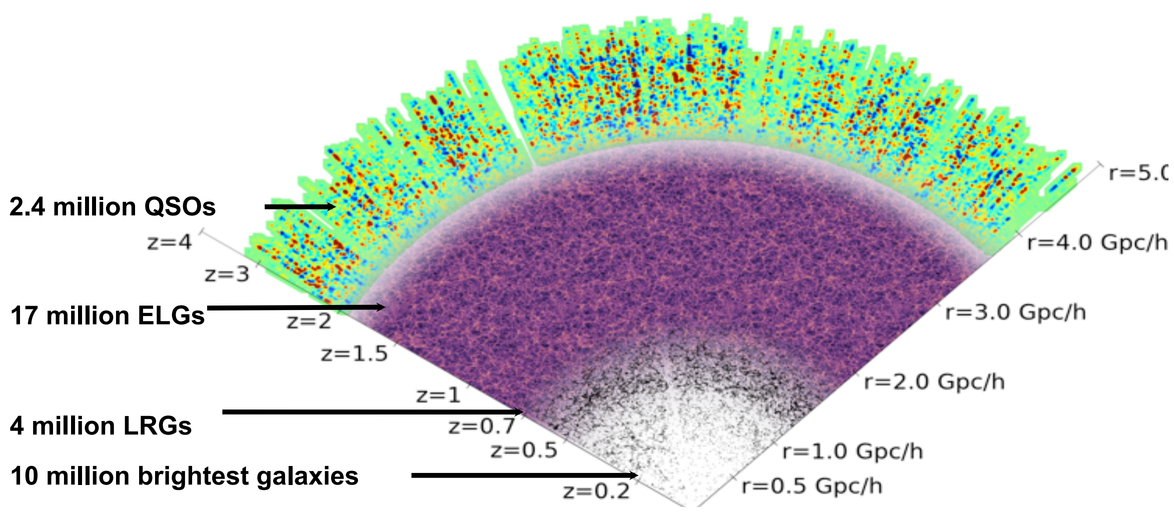
- on 4m Mayall telescope at Kitt Peak (AZ)
- international collaboration ~900 scientists, 72 institutions
- 5000 spectra at once (system built at Michigan - Tarlé group)
- operating extremely well: up to 100,000 spectra per night!
- world's leading spectroscopic survey

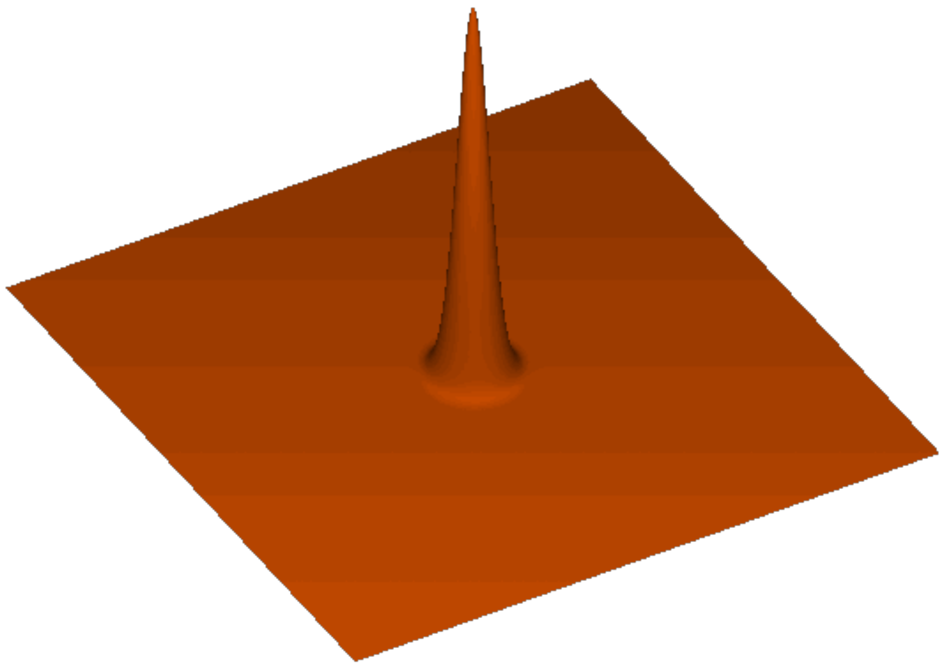
key DESI science:

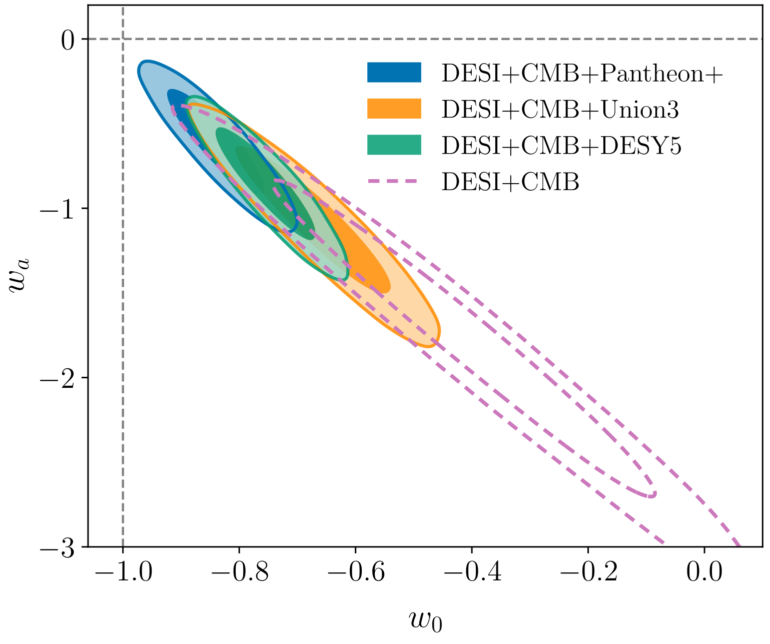
1. dark energy
2. neutrino mass
3. primordial non-Gaussianity

DESI and DR2 results were nicely reviewed in Satya's talk at GGI 2 weeks ago





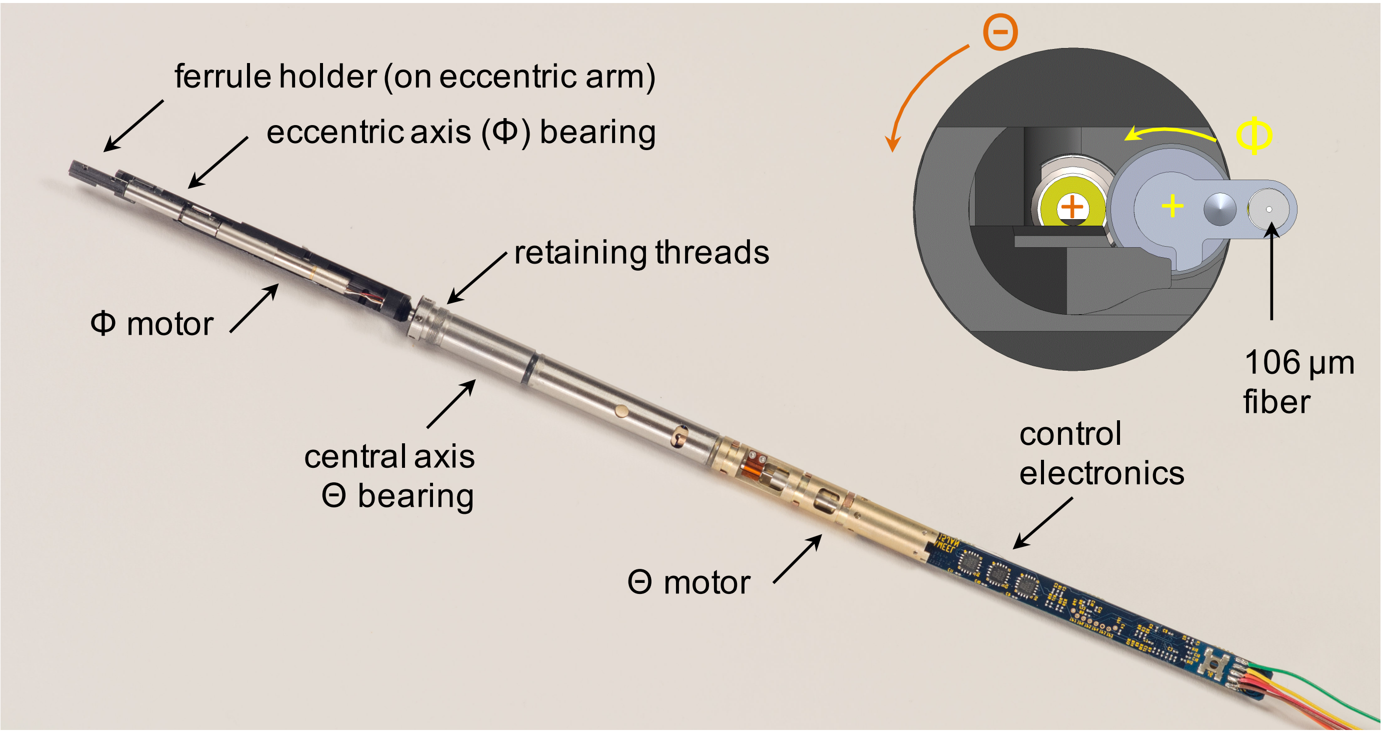




I will mostly focus on the <u>discussion</u> of cosmology results

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

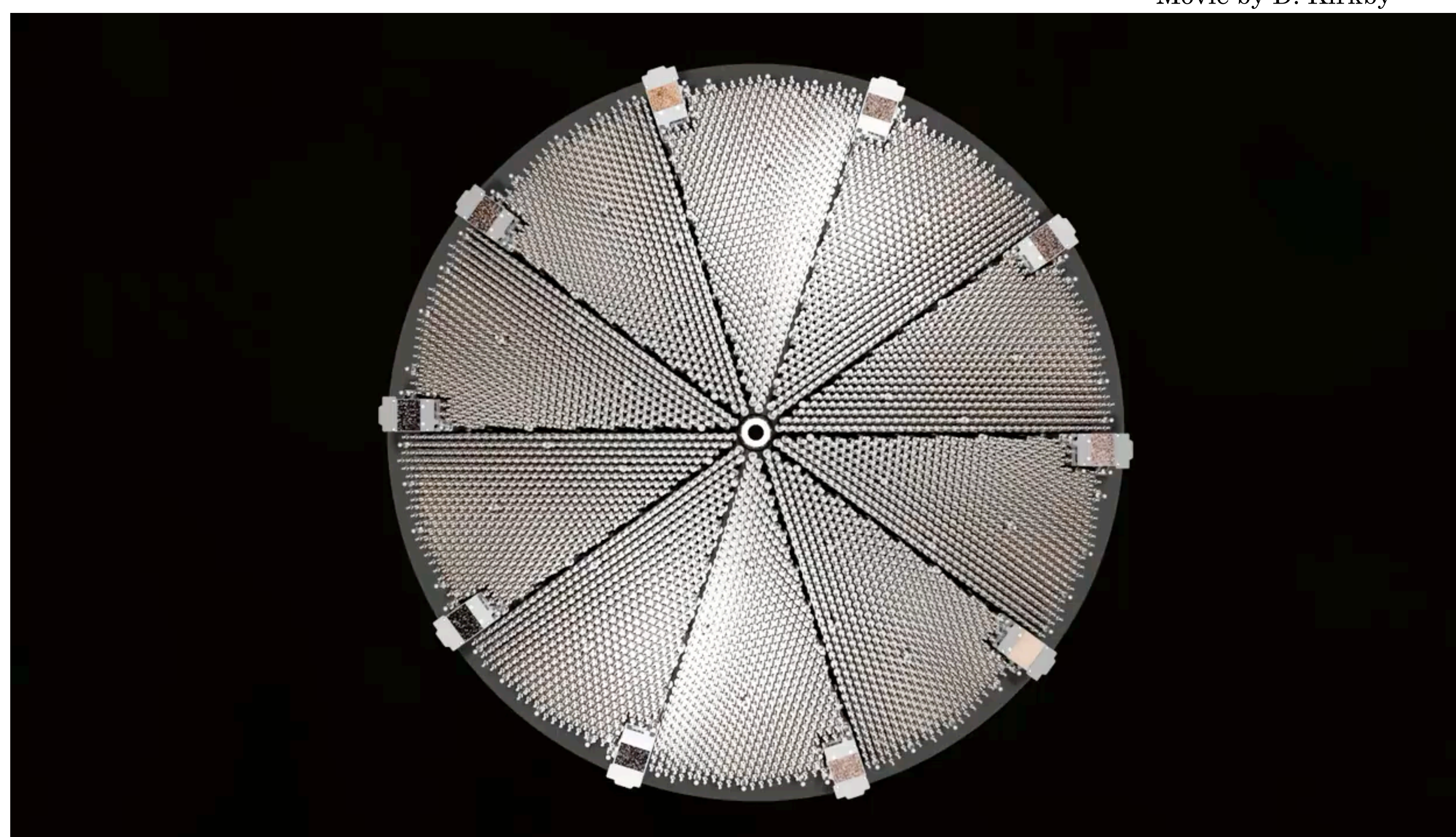
Robotic fiber positioners



Designed and built at
University of Michigan
(Tarlé group)

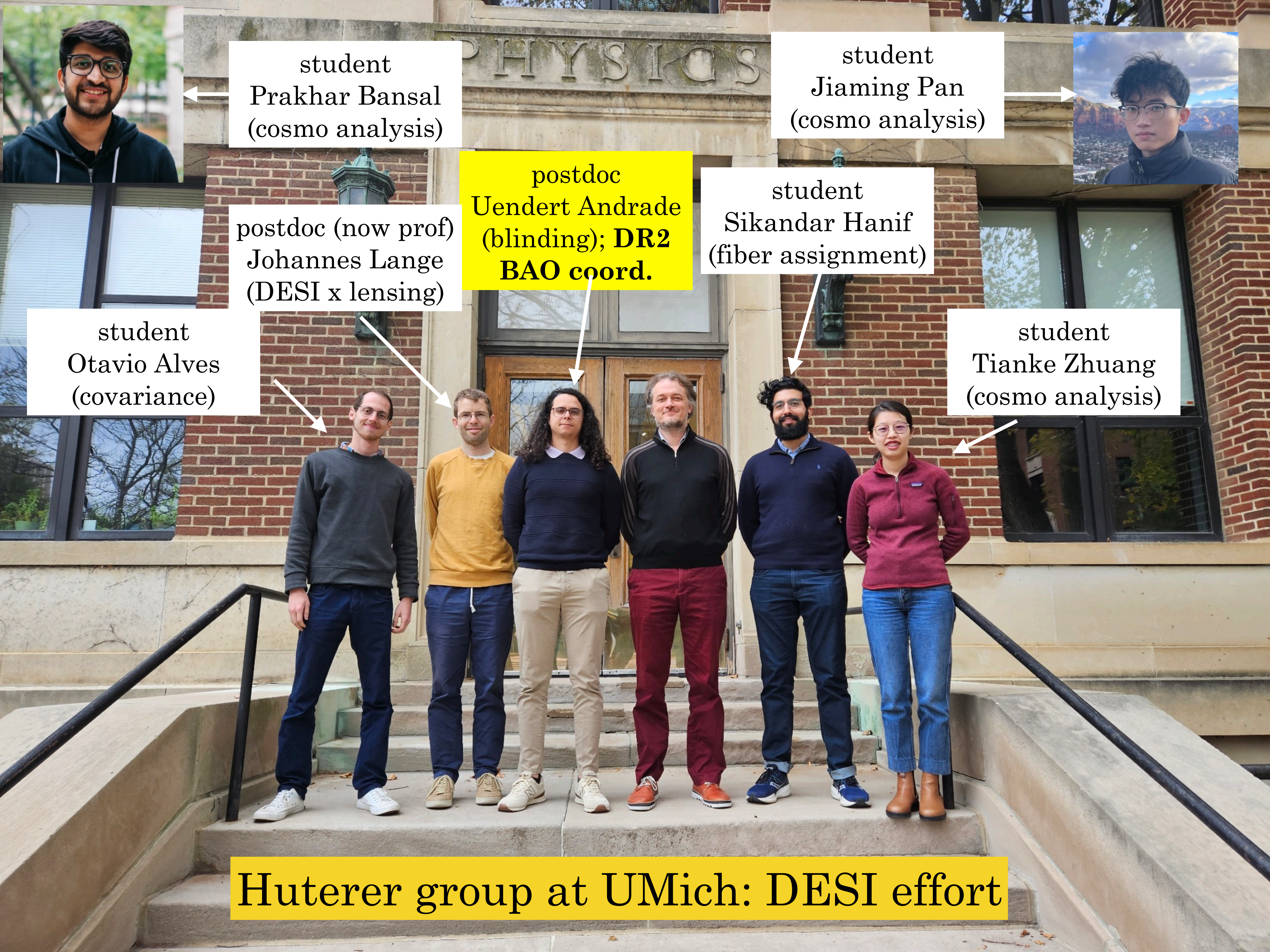
"5,000 eyes on the sky"

Movie by D. Kirkby



Greg
Tarlé

Michael
Schubnell


Huterer group at UMich: DESI effort
student
Prakhar Bansal
(cosmo analysis)
student
Jiaming Pan
(cosmo analysis)
postdoc
Uendert Andrade
(blinding); **DR2 BAO coord.**
student
Sikandar Hanif
(fiber assignment)
postdoc (now prof)
Johannes Lange
(DESI x lensing)
student
Otavio Alves
(covariance)
student
Tianke Zhuang
(cosmo analysis)

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

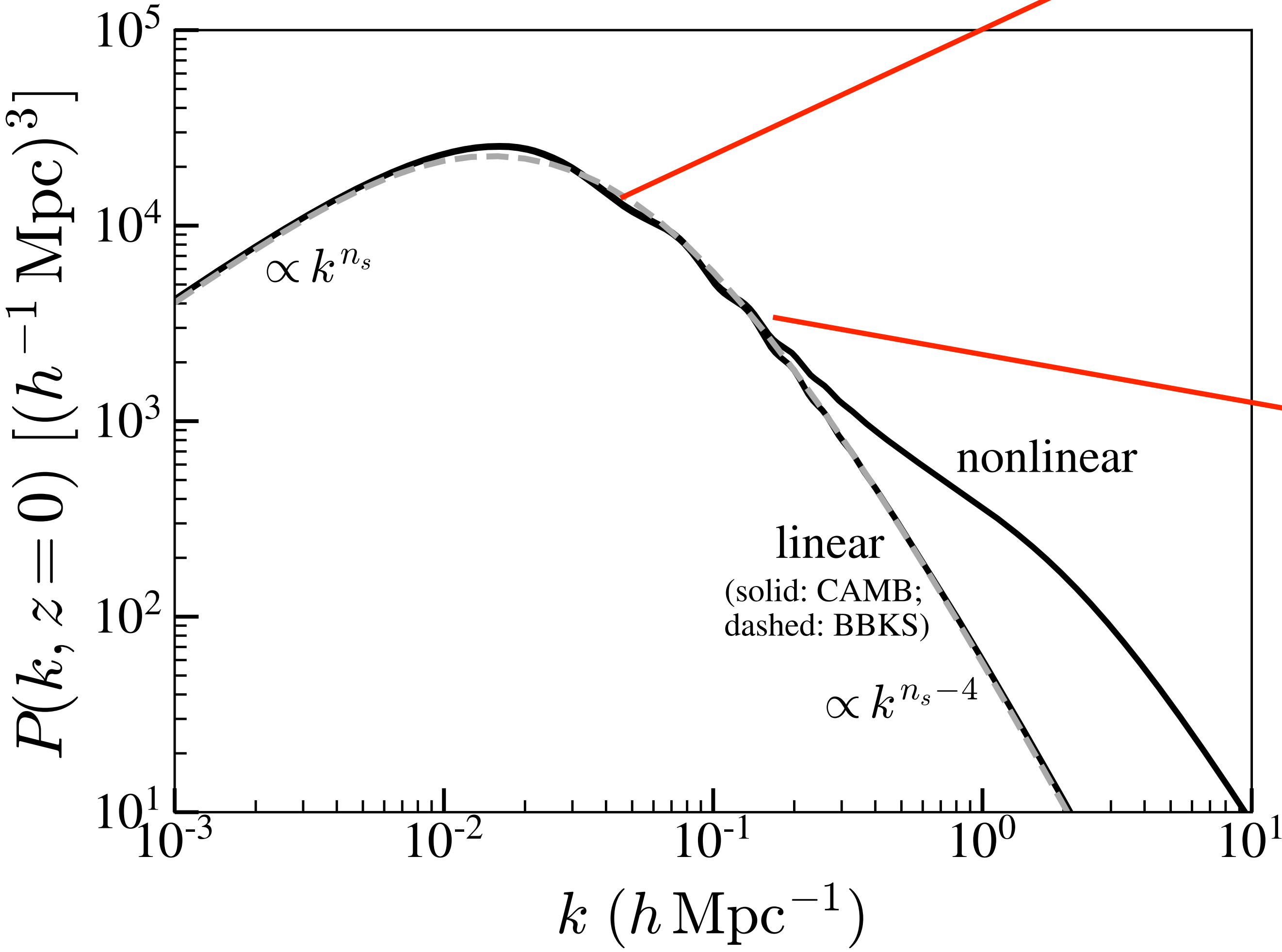
Tracer	DR1	**DR2**
BGS	300,043	**1,188,526**
LRG	2,138,627	**4,468,483**
ELG	2,432,072	**6,534,844**
QSO	1,223,391	**2,062,839**
Total	6,094,133	**14,254,692**

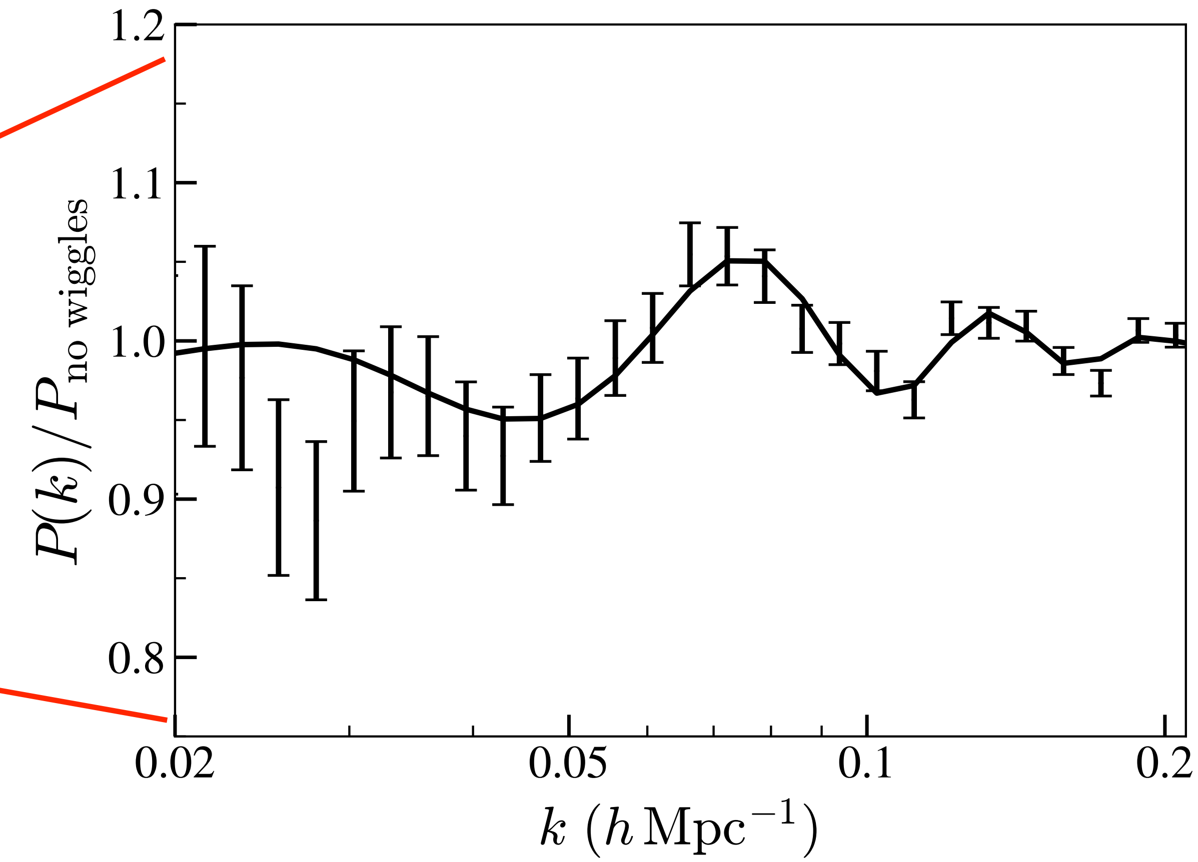
borrowed from E. Paillas (DESI)

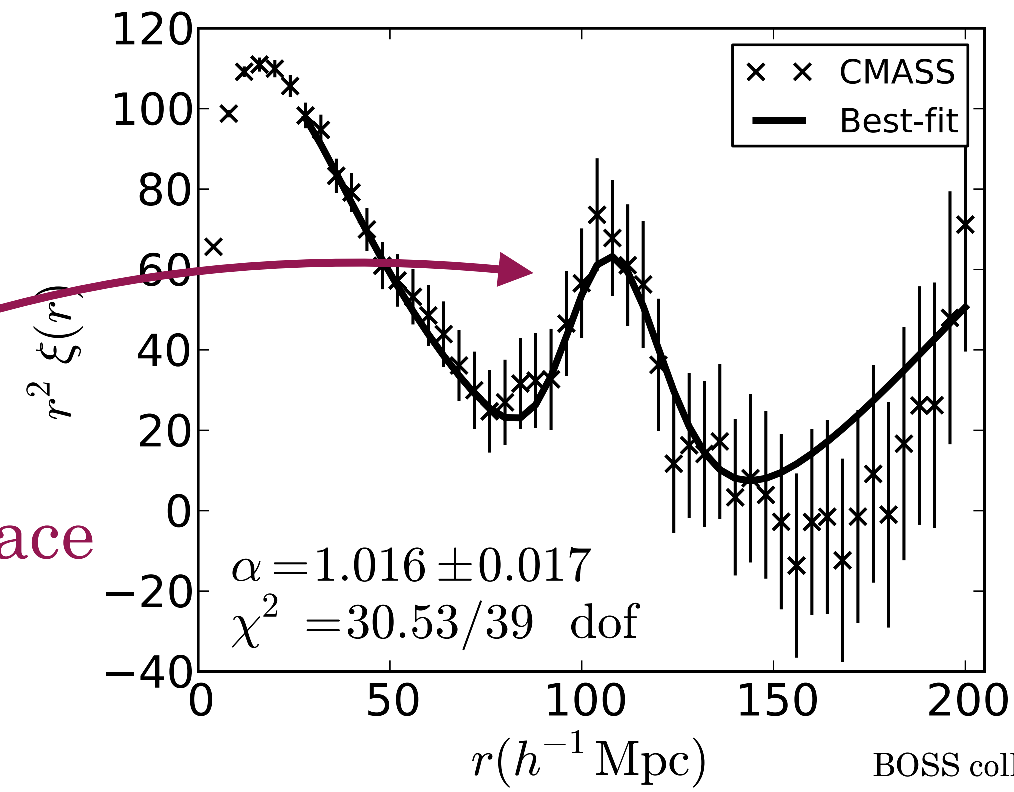
Baryon Acoustic Oscillations (BAO)

First discussed in: Sunyaev & Zeldovich, 1972

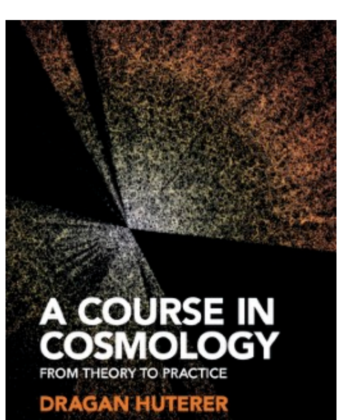
Multiple wiggles in Fourier space
(power spectrum)





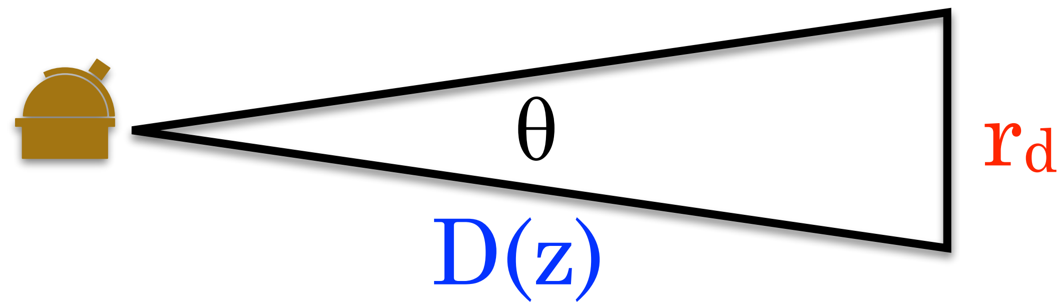


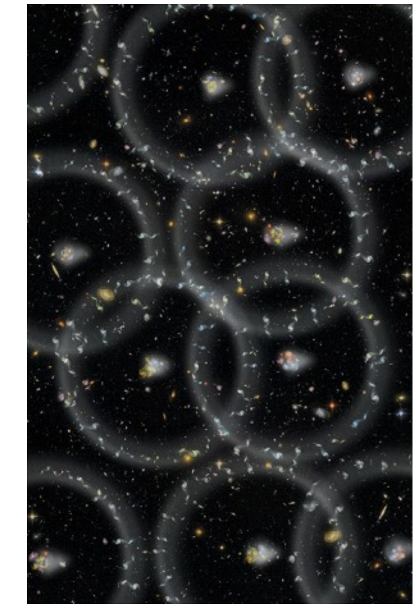
BOSS collaboration



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

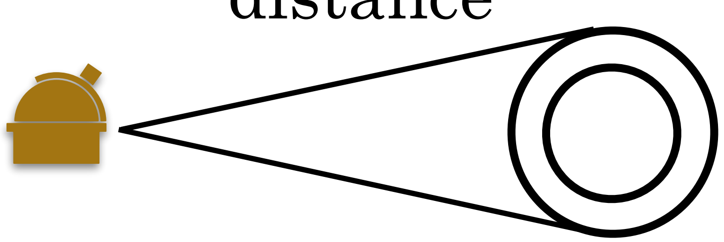
Baryon Acoustic Oscillations



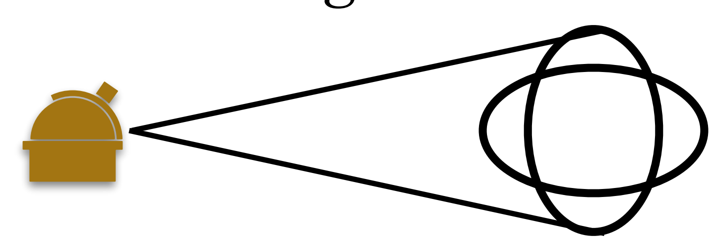


- Therefore, there is excess probability for galaxies having a neighbor at distance r_d — <u>excess probability for clustering</u>
- This imprints a preferred scale in clustering - the "standard ruler"
- The angle to the standard ruler gives $D(z)/r_d$
- Actually measure *two* kinds of distances: transverse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

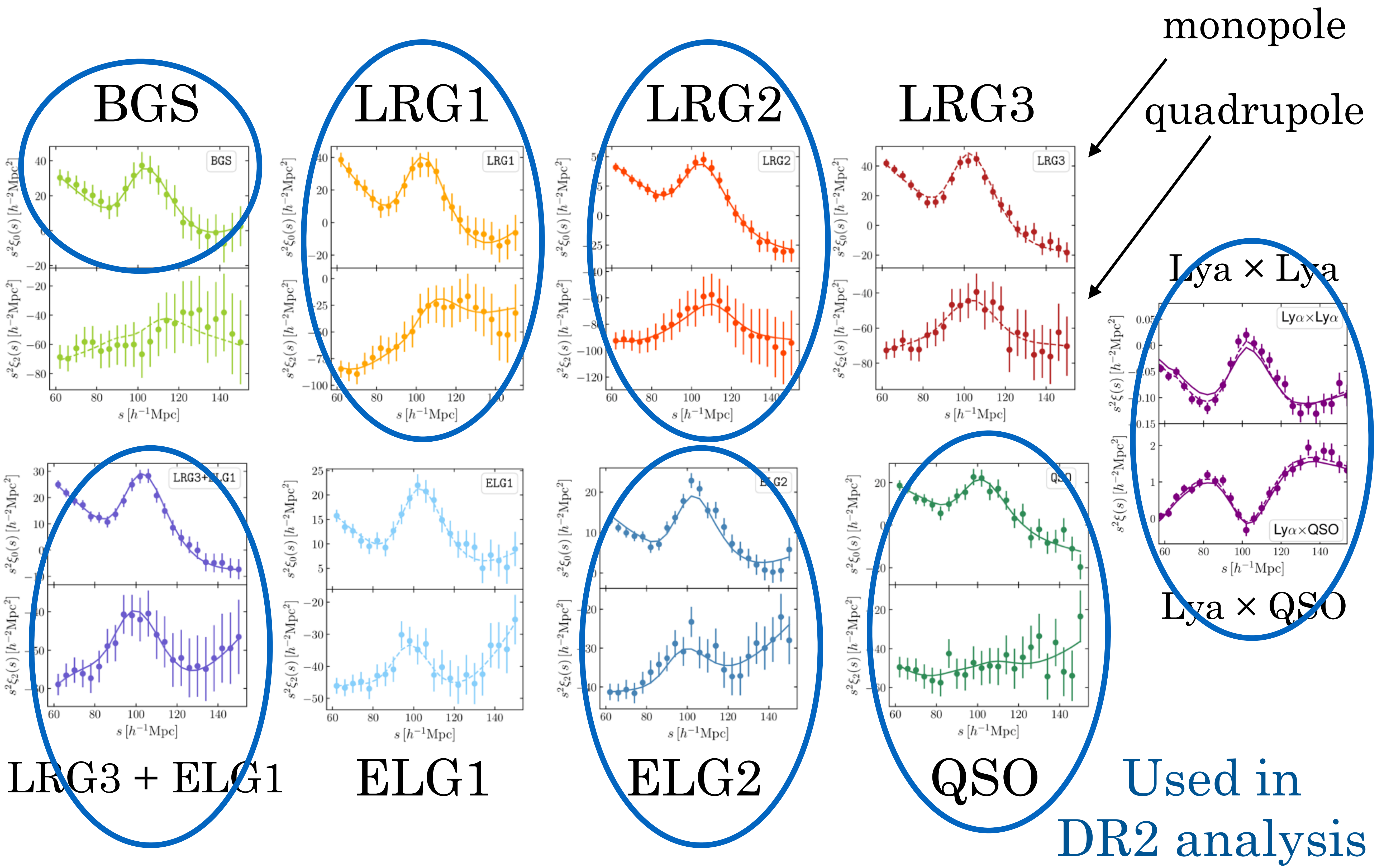
Isotropic ("average") distance



Ratio of transverse and line-of-sight distances



DESI DR2 Clustering Measurements

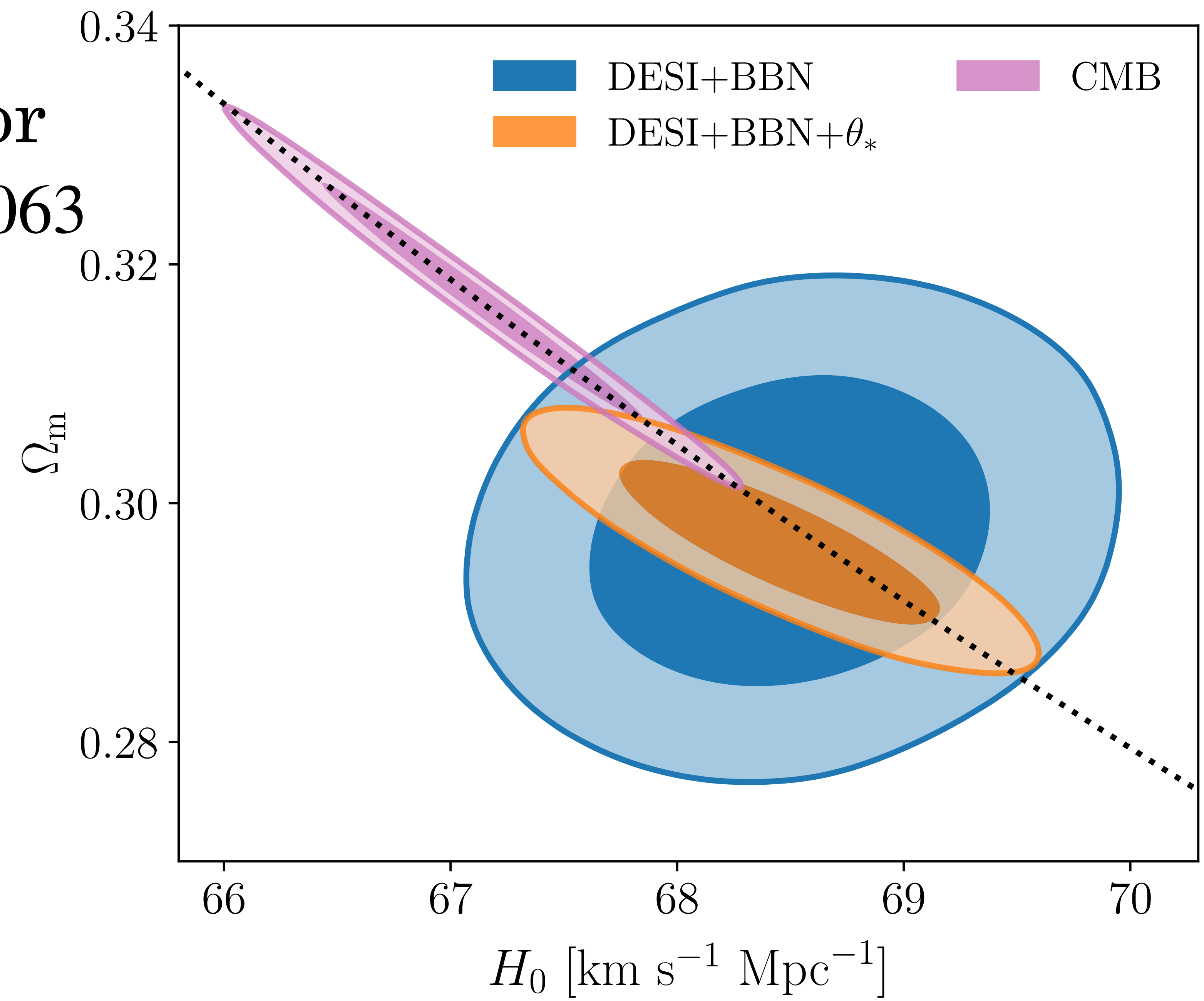


Hubble constant (in LCDM)

Requires BBN prior

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

(Schöneberg 2024)



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

28% more precise than in DR1;
4.5σ away from SH0ES (without CMB!)

Abdul Karim et al (2025)

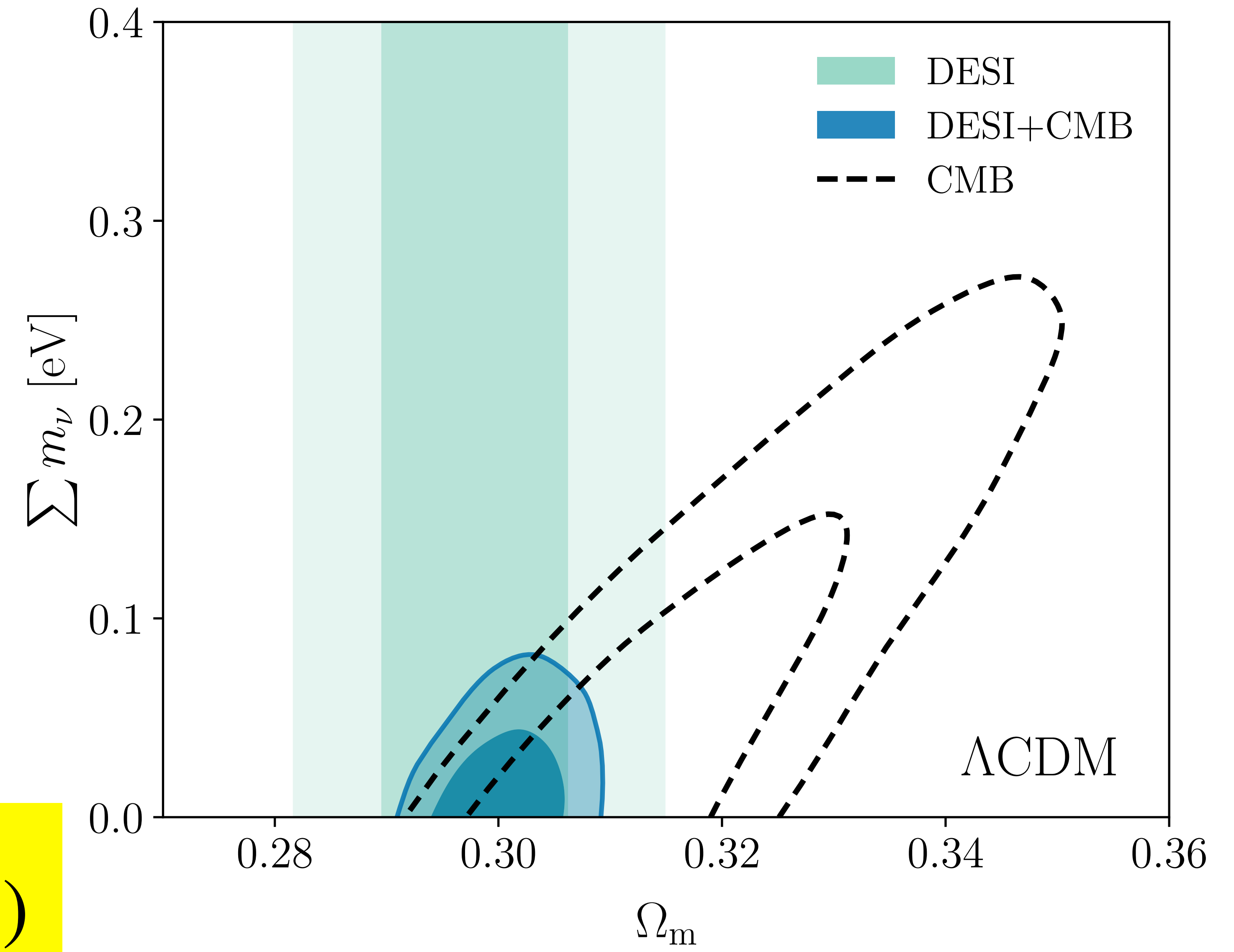
Sum of neutrino masses

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

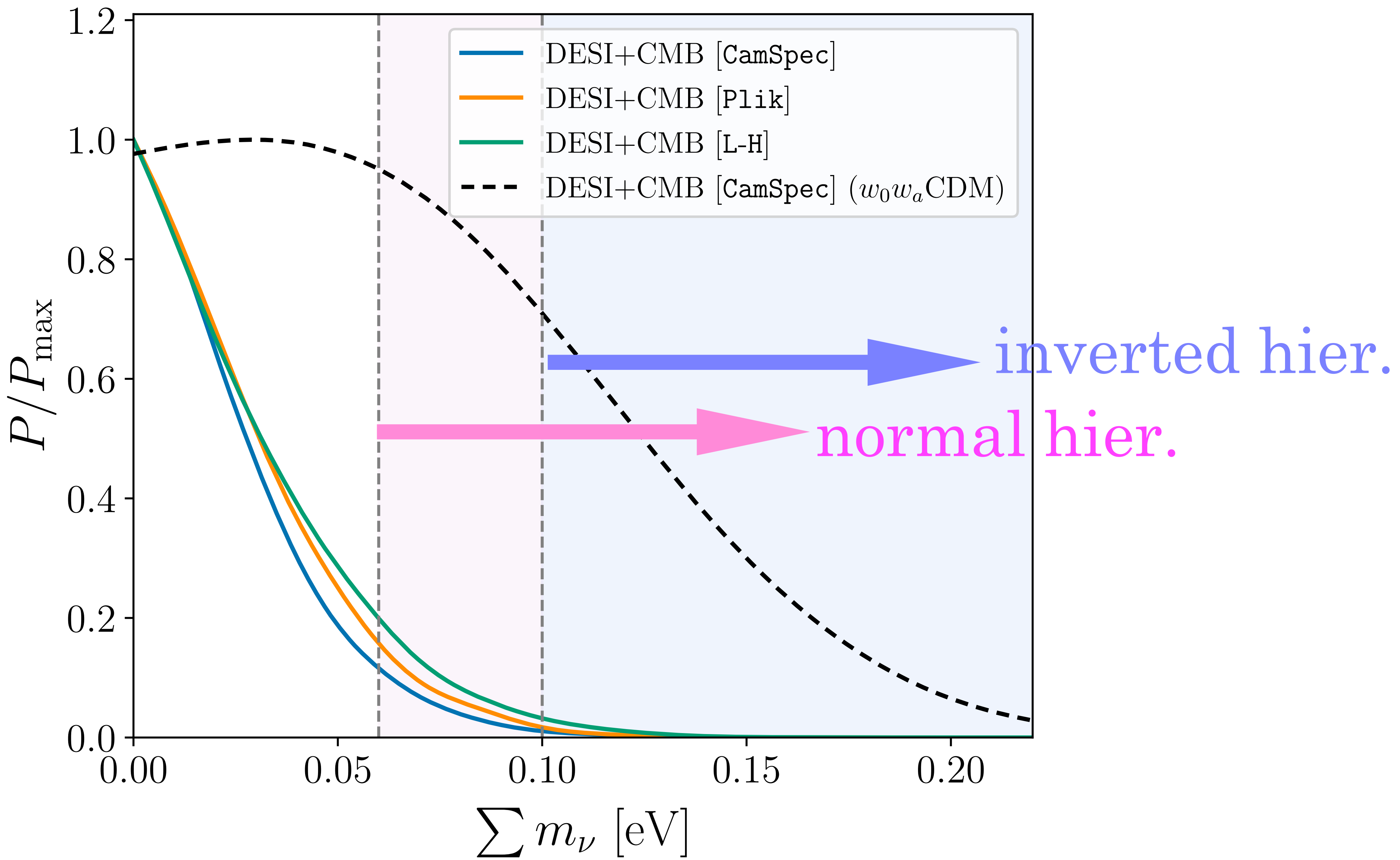
CMB constraints ,
but its precision is limited by
degeneracies
$\Rightarrow$ DESI helps here



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

[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)

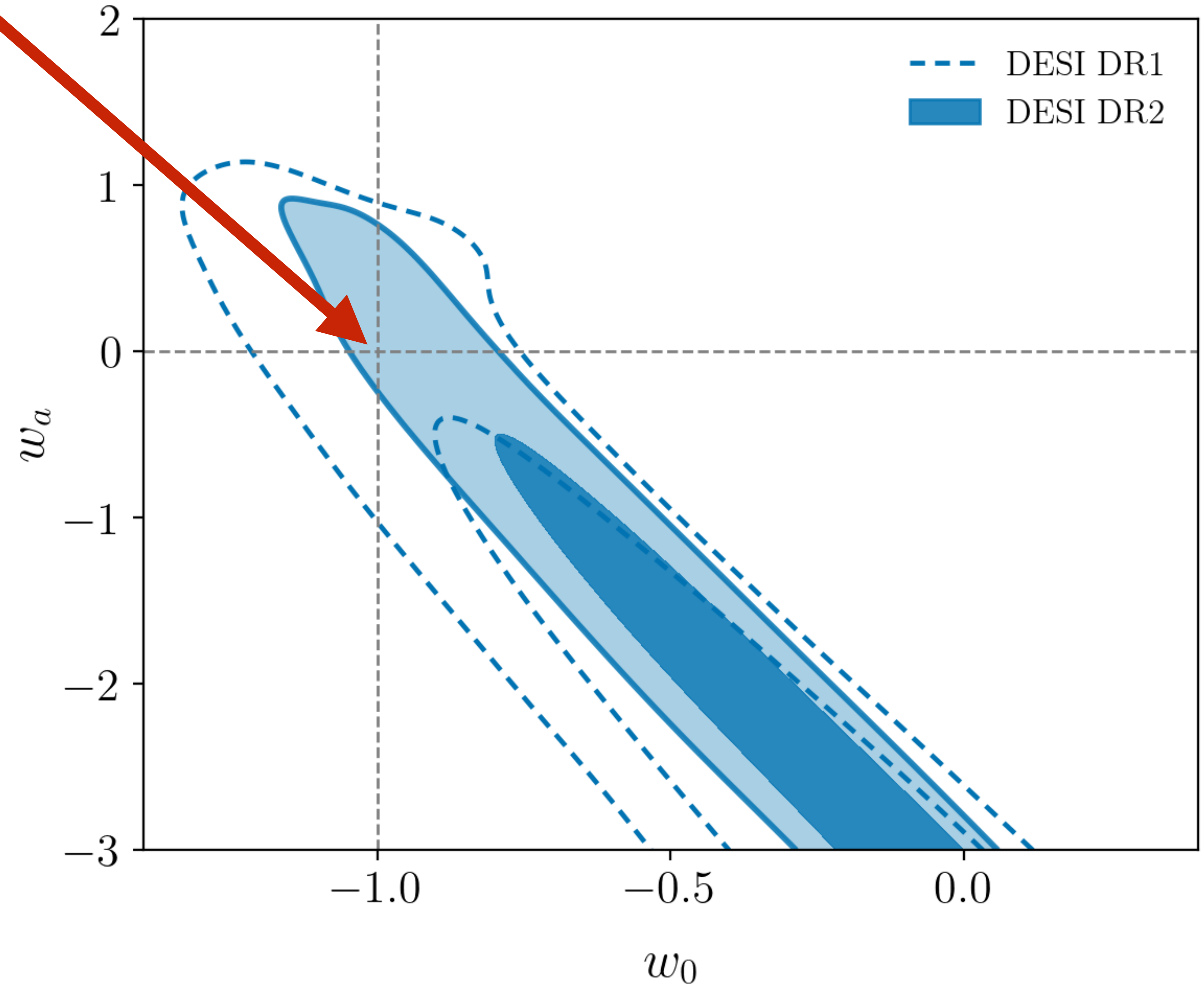
Dark energy - (w_0, w_a)

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

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

ΛCDM
(standard model)

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



Abdul Karim et al (2025)

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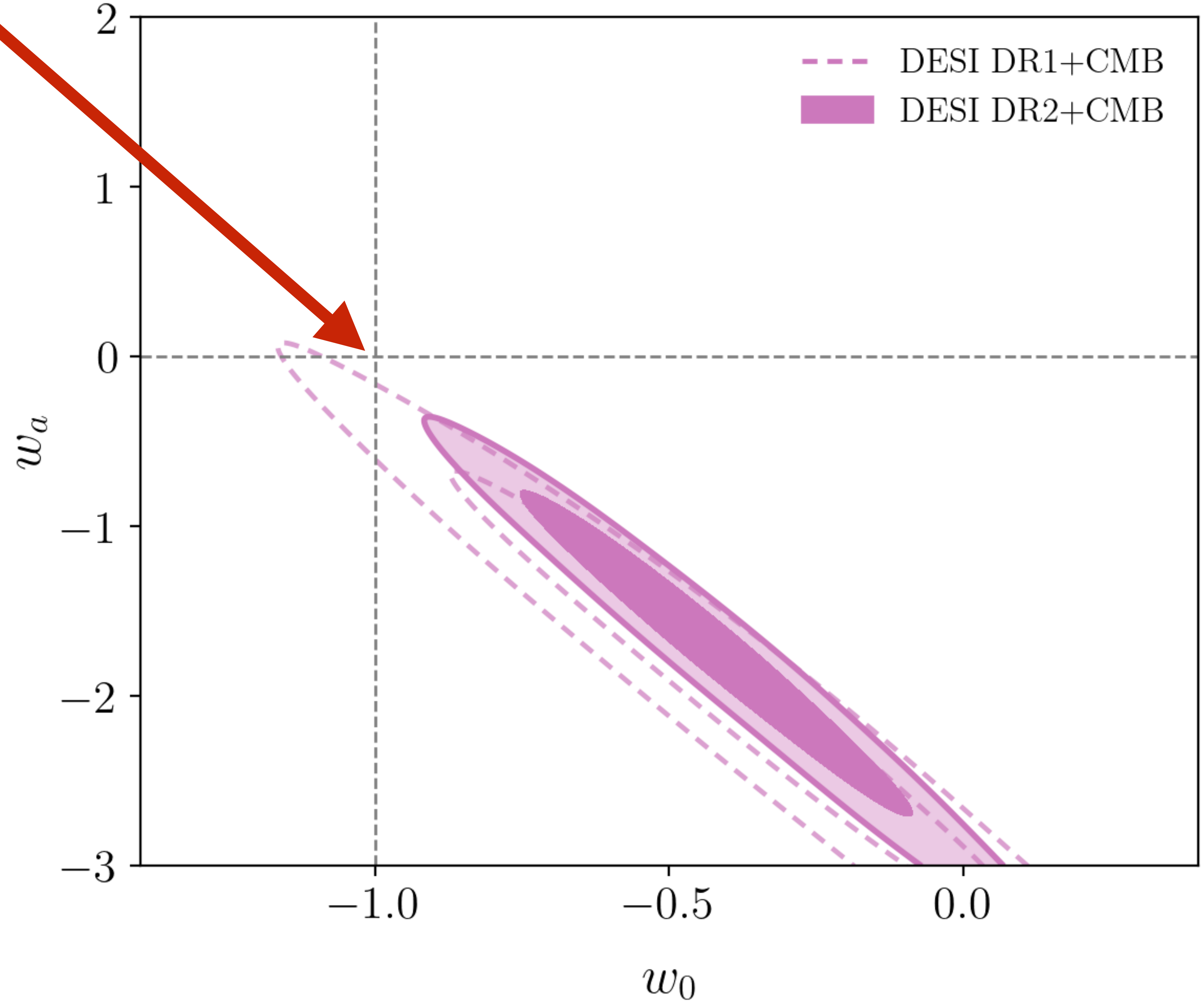

Abdul Karim et al (2025)

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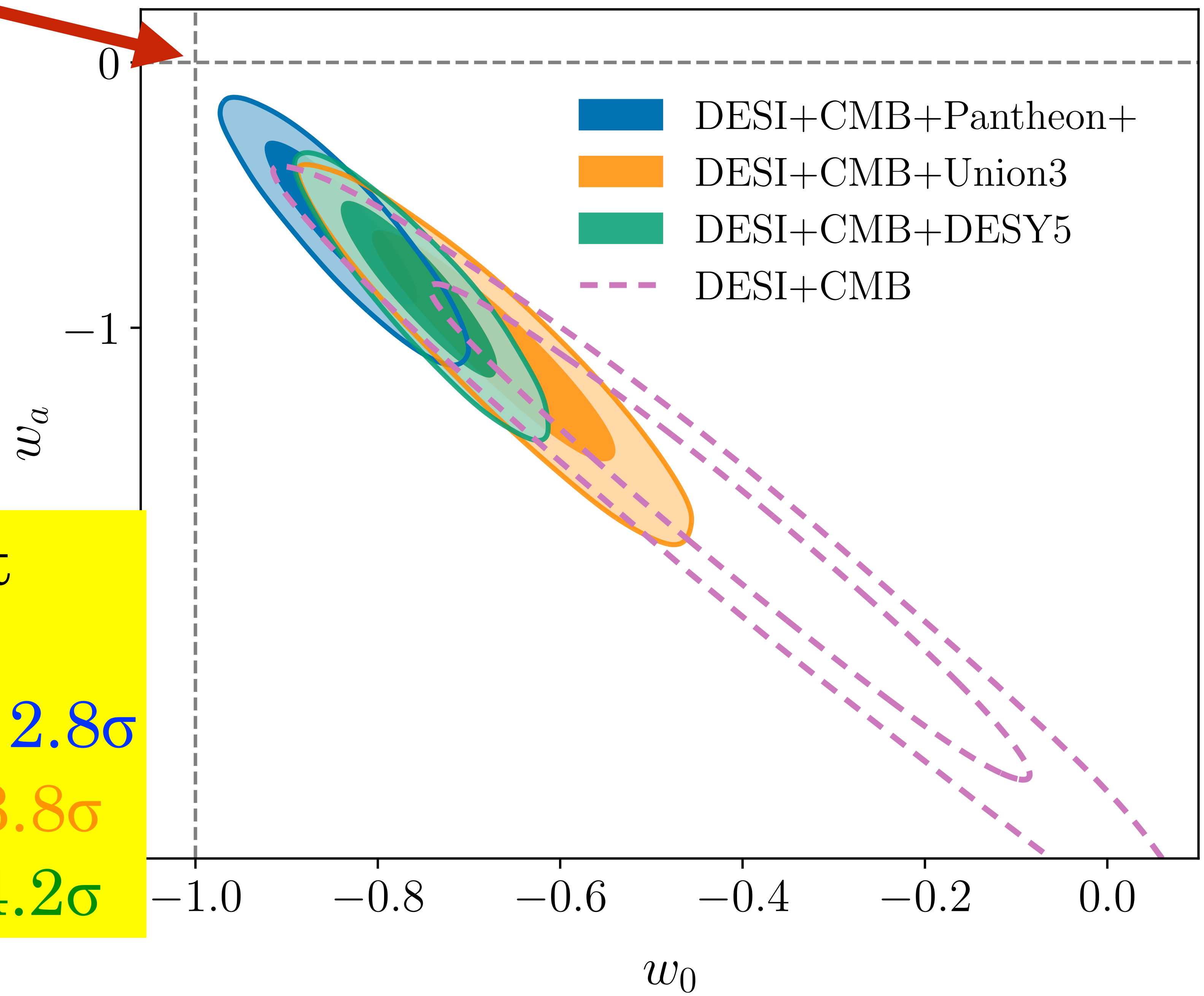
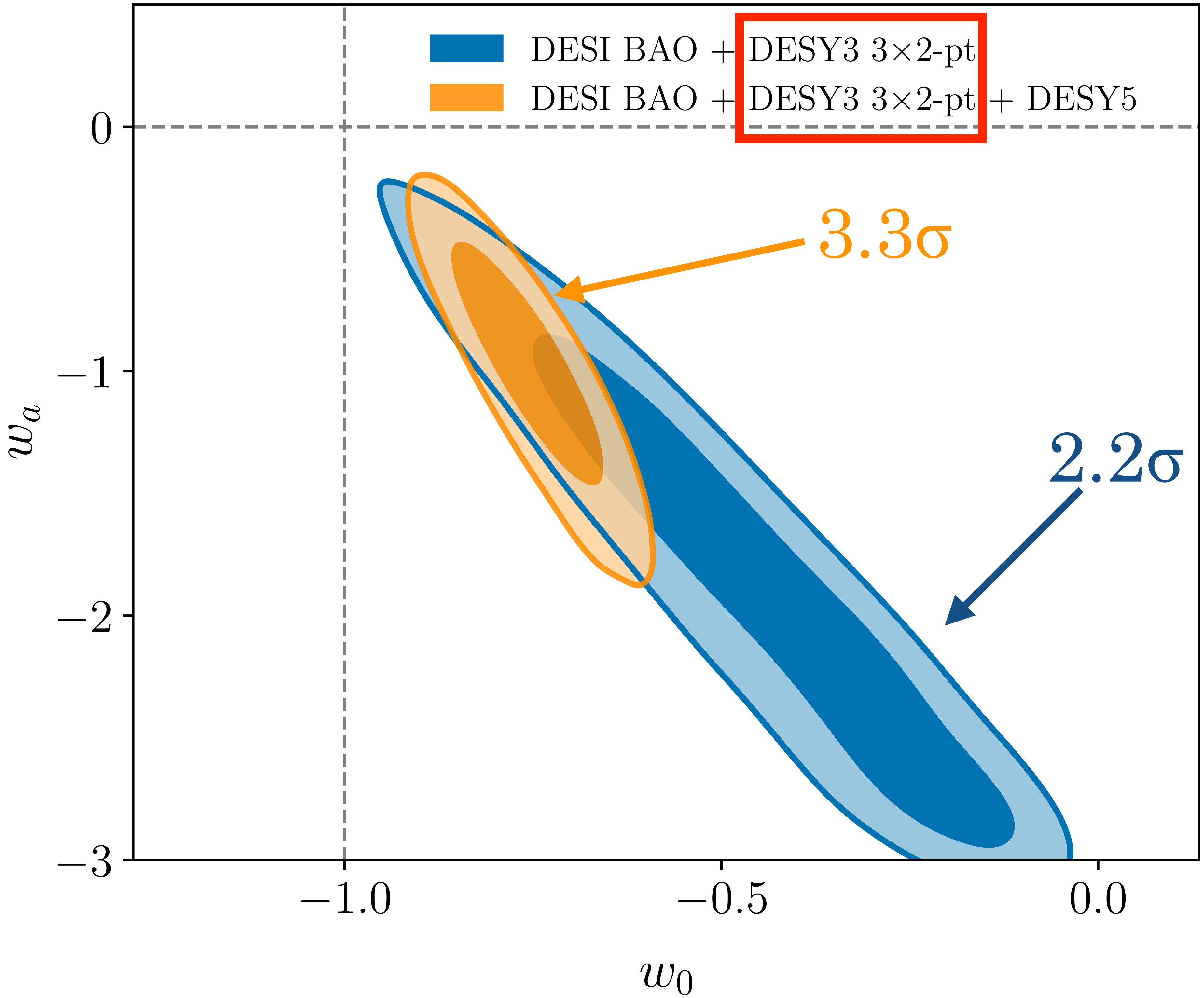
ΛCDM
(standard model)



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

Abdul Karim et al (2025)

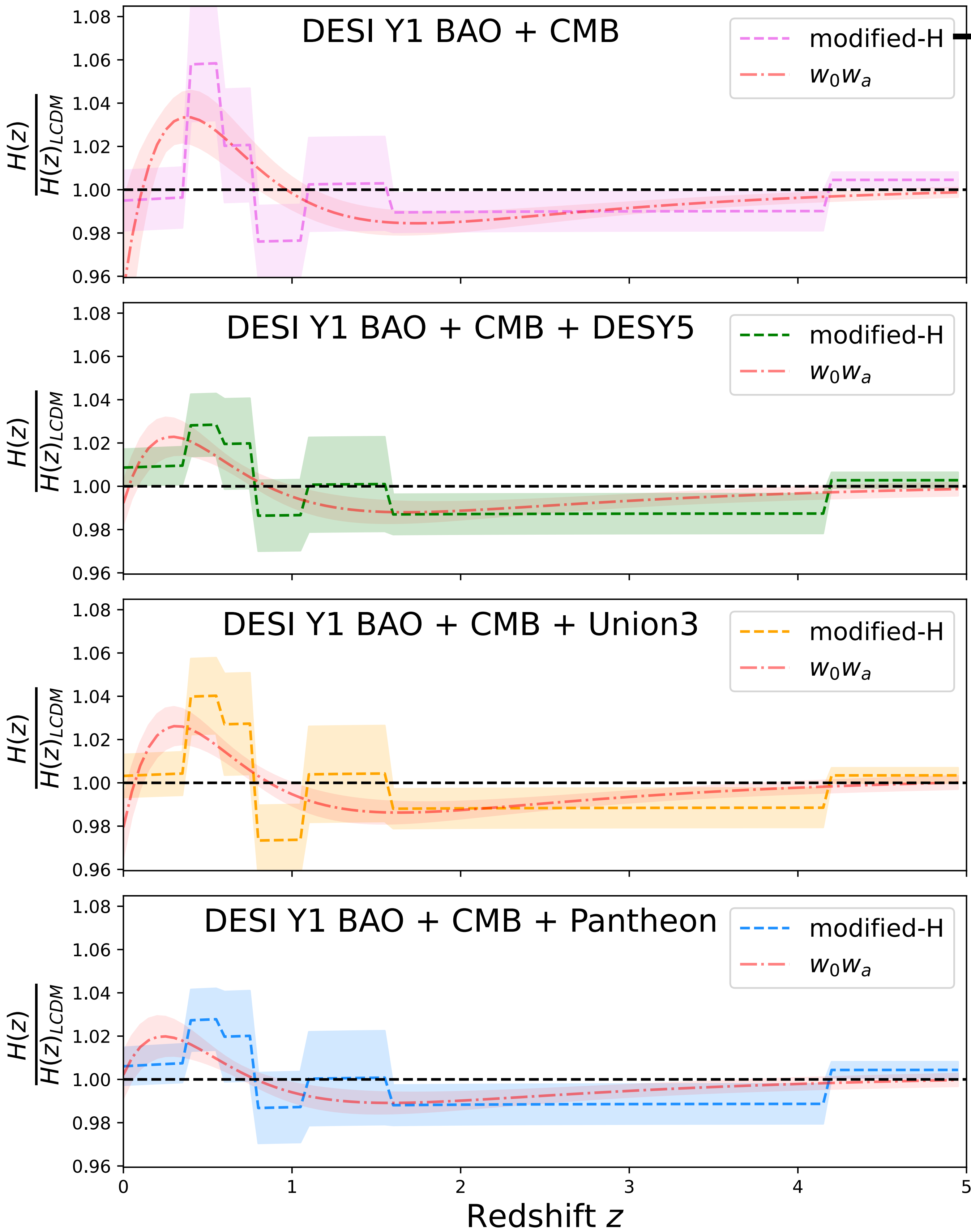
Low-z probes alone hint for ~~LCDM~~



(no CMB here)

Therefore: tantalizing hints of departure from LCDM

Attempt to understand this DE tension



new model with lots of H(z) freedom

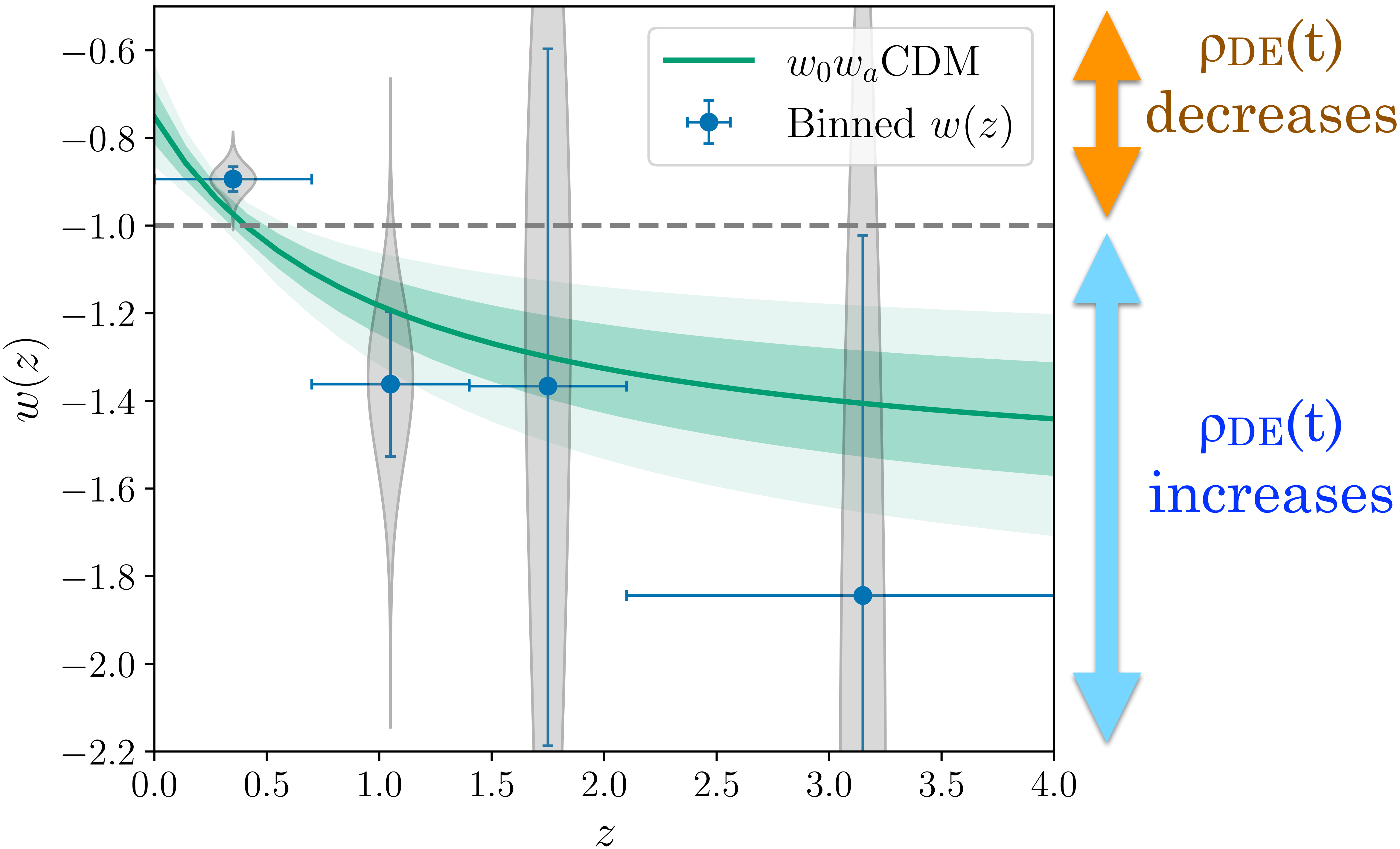
We find: a more general expansion history <u>agrees very well</u> with best-fit w_0w_a

(so e.g. goodness of fit only marginally better with several more parameters)

⇒ "unreasonable effectiveness" with which w_0w_a fits the data?!

Bansal & Huterer, arXiv:2502.07185

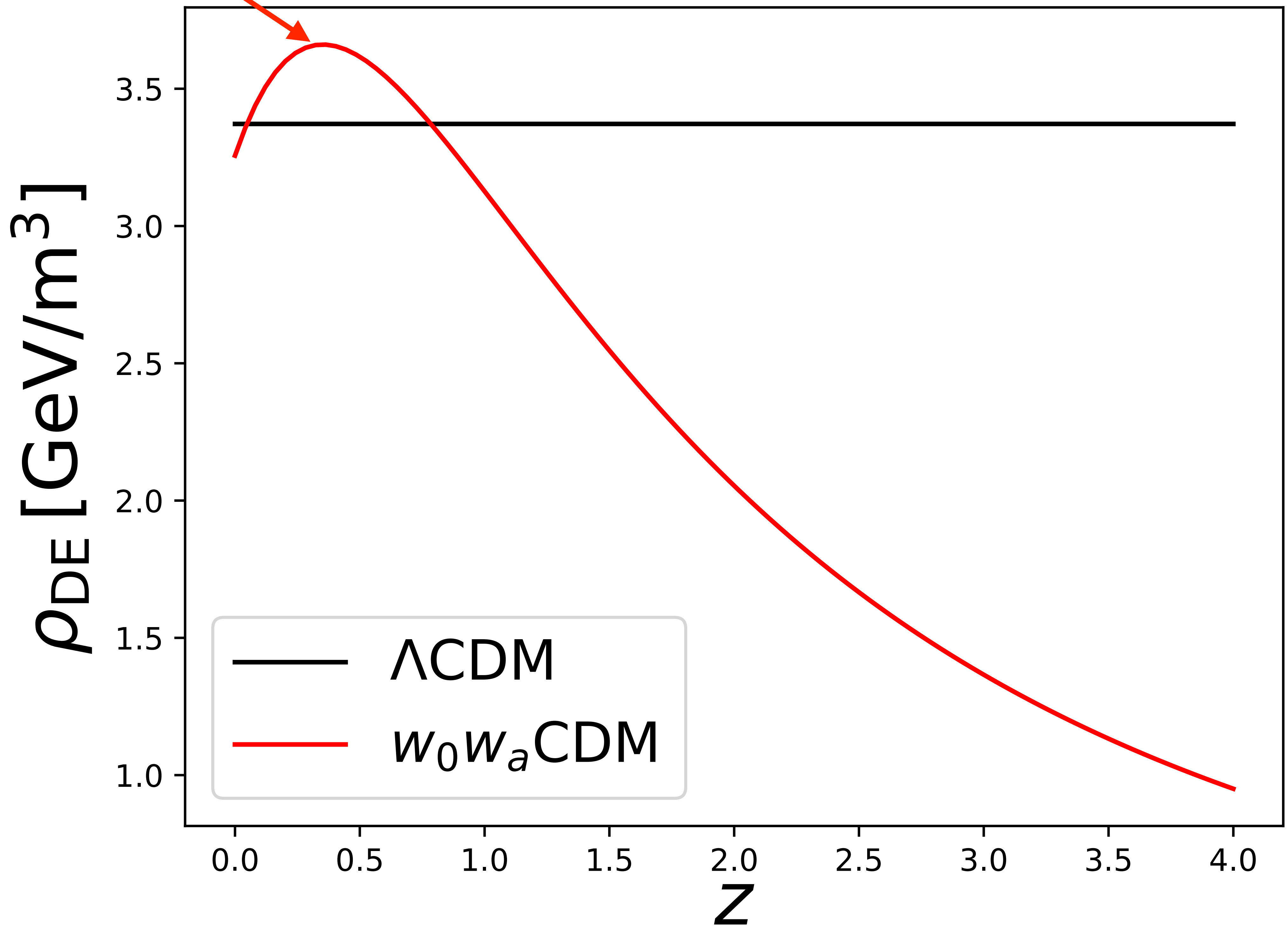
Robustness (to DE parameterization) confirmed by alternative analyses



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

in other words

Best-fit w0wa model
from DESI+CMB+SNIa



My opinion:

To declare ruling out of LCDM, we should require a very high statistical confidence (e.g. 8σ or 10σ)

But also:

These hints for evolving DE are very interesting, and, at the very minimum, point to potential inconsistencies among datasets

DESI DR2 Frequently Asked Questions!

★Are the datasets that you are combining in conflict/tension?

➡ No. For example, DESI BAO and DESY5 SNIa are consistent in w_0w_aCDM.

★Is DESI DR2 BAO data in tension with SDSS BAO?

➡ No, even at level of individual data pts

(e.g. z=0.71 data pt that showed a 3-sigma difference is now <2 sigma)

★Is conflict w LCDM due to specific data point XYZ (e.g. z=0.51 BAO)?

➡ No - we checked!

★Isn't it an "unsettling" coincidence that we find $w(z) \simeq -1$ at $z_{\rm pivot}$?

➡ No:

1) it's a coincidence, nothing unsettling;
2) in fact $w(z_p)$ is away from -1 (DESI BAO + SNIa + CMB gives -0.954 ± 0.024);
3) it also is likely to happen (in w_0w_a) when the CMB distance agrees with LCDM, as explained in E. Linder's "mirage of $w = -1$" 2007 paper

Sesh Nadathur, Kushal Lodha, and DESI collaboration

Five facts about hints for dynamical dark energy (and Hubble tension)

Fact #1:

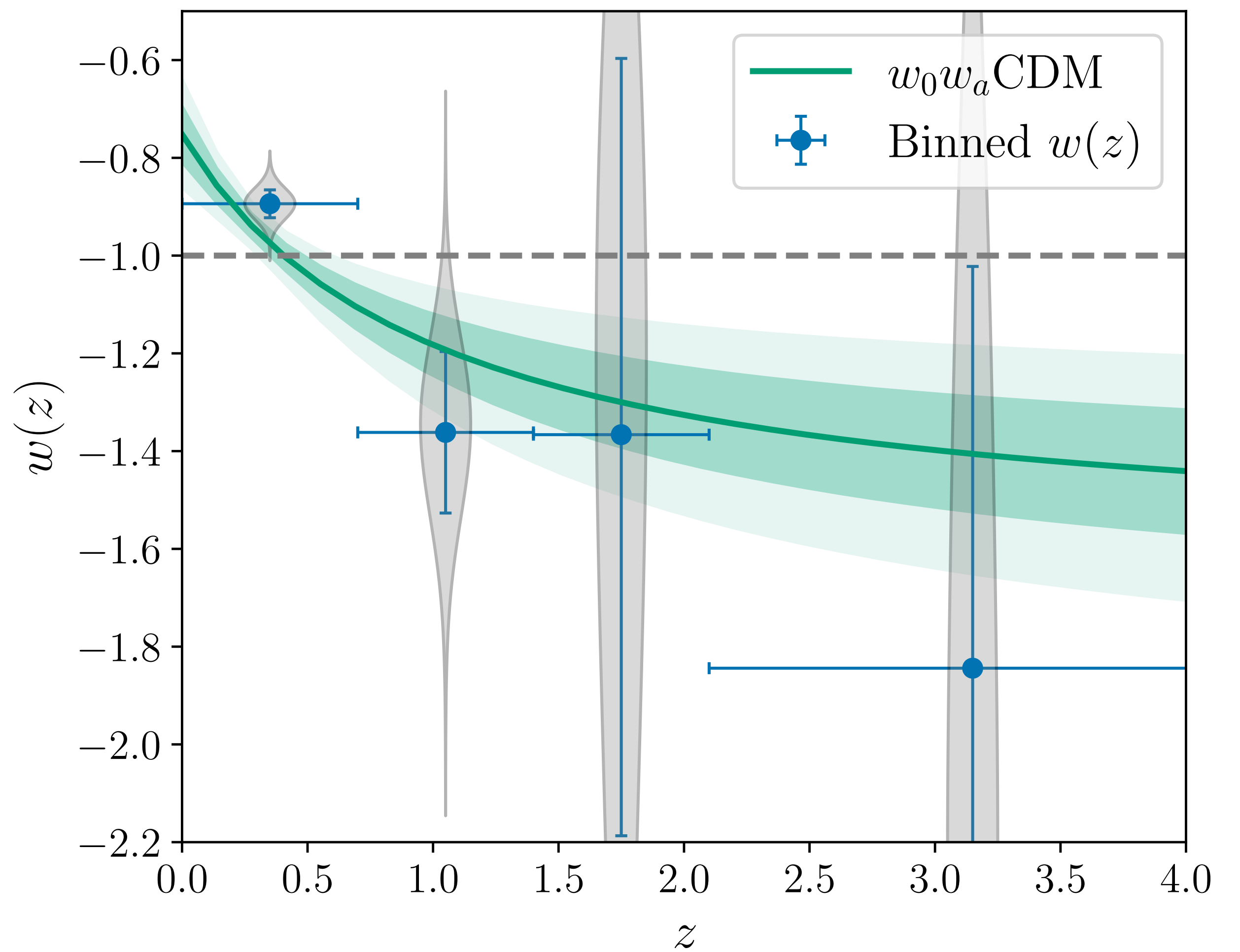
- The preference for w0waCDM model does not come from a single cosmological probe

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

Fact #2:

Question: is there convincing evidence in the data for

- phantom dark energy, or
- phantom crossing, or
- "slowdown" of DE (w > −1)?



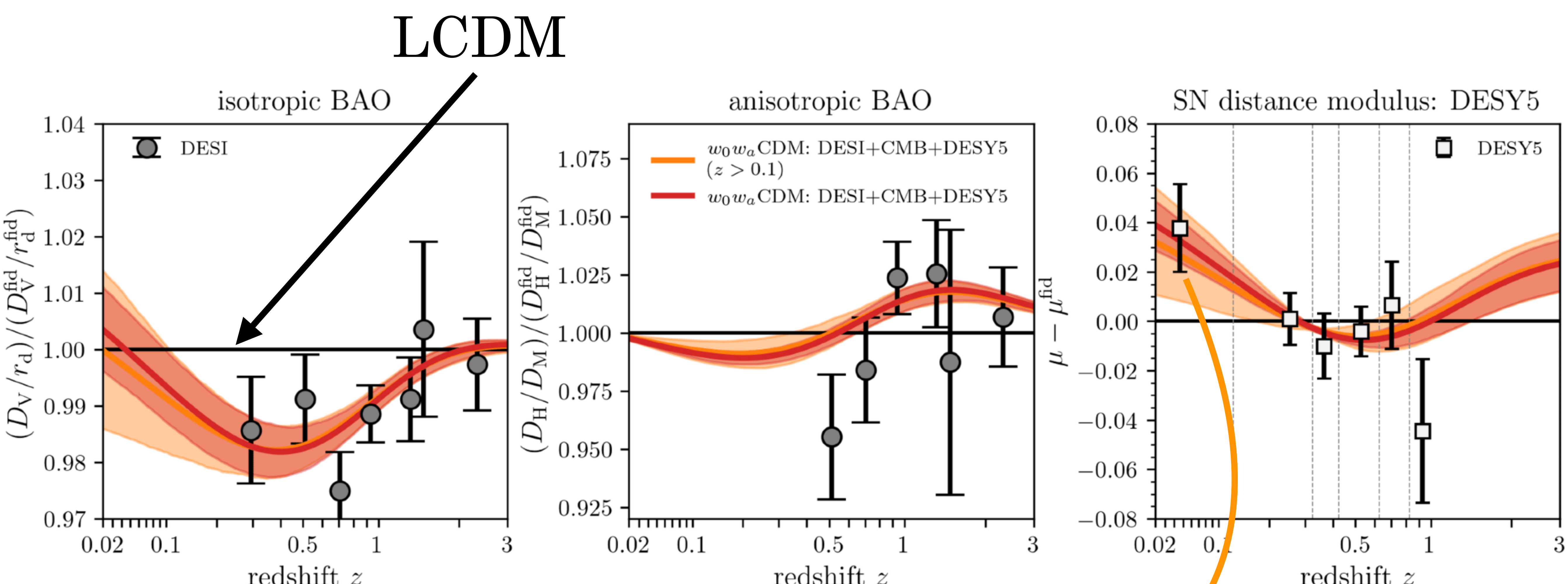
No (for either).

- The strongest statistical hints are for departure from LCDM, in particular in w0waCDM model.
- We have not tested the above aspects alone, but <u>statistical evidence for them will be necessarily weaker</u>.

Fact #3:

Preference for dynamical dark energy comes about because data prefer "curvature" in distance(z)

(but why *that* is, I don't know)



Arnaud de Mattia

orange contours:
same result even when
dropping z<0.1 SNIa data

Fact #4:

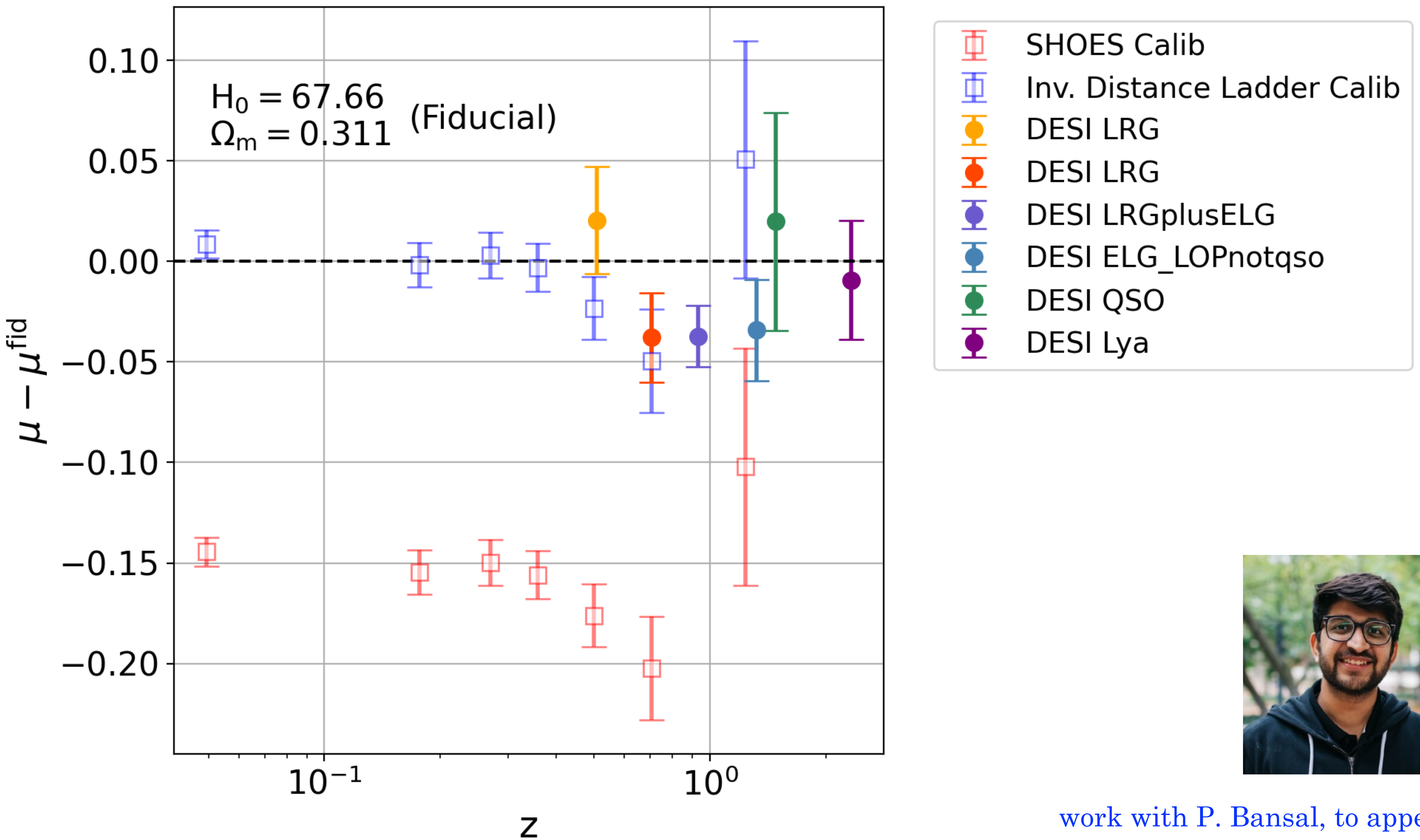
LCDM tension and Hubble tension are different!

- No apparent relationship (afaik)
- Also Hubble tension gets worse in $w_0 w_a$CDM:

$$H_0^{\mathrm{w_a w_a CDM}} \simeq (63 - 67)\ \mathrm{km/s/Mpc}$$

Fact #5:

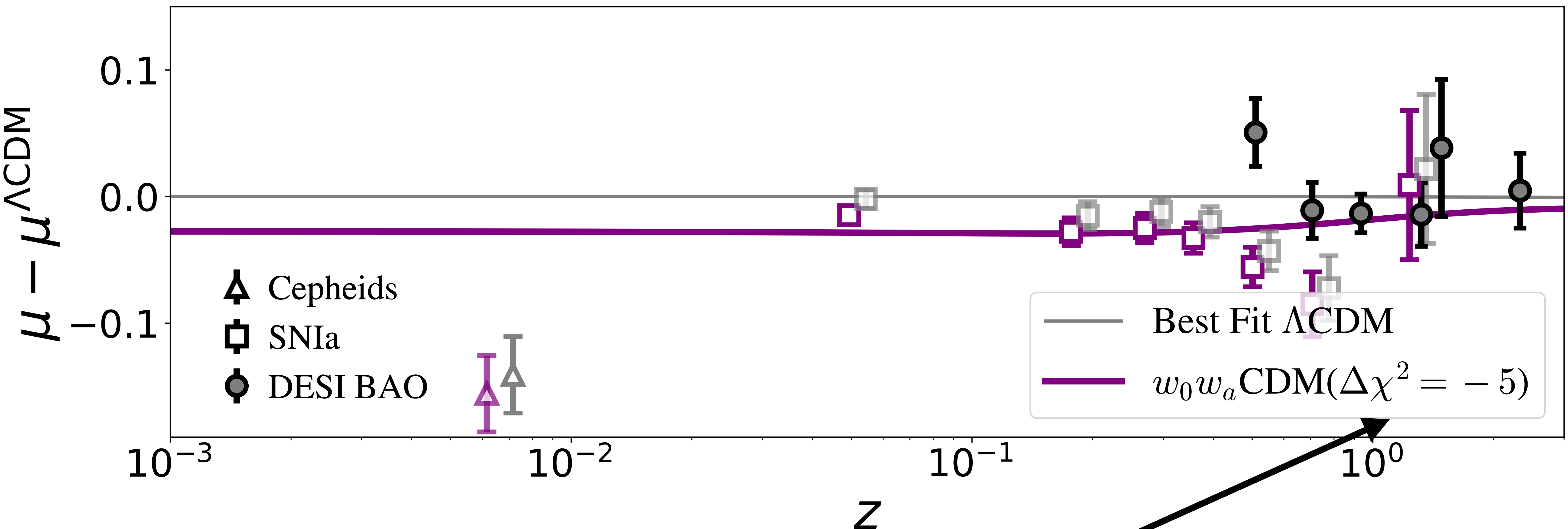
It is near impossible to relax both Hubble tension and evidence for dynamical DE with a low-z model - even w/ model with a sharp jump in H(z)



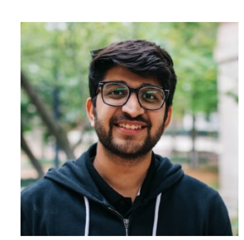
work with P. Bansal, to appear

More on Fact #5:

Low-z solutions (for data <u>including SH0ES</u>) don't work -
except for a very bizarre scenario of a step in M 150 myr ago (z_t=0.01)



very small improvement with w_0w_aCDM alone



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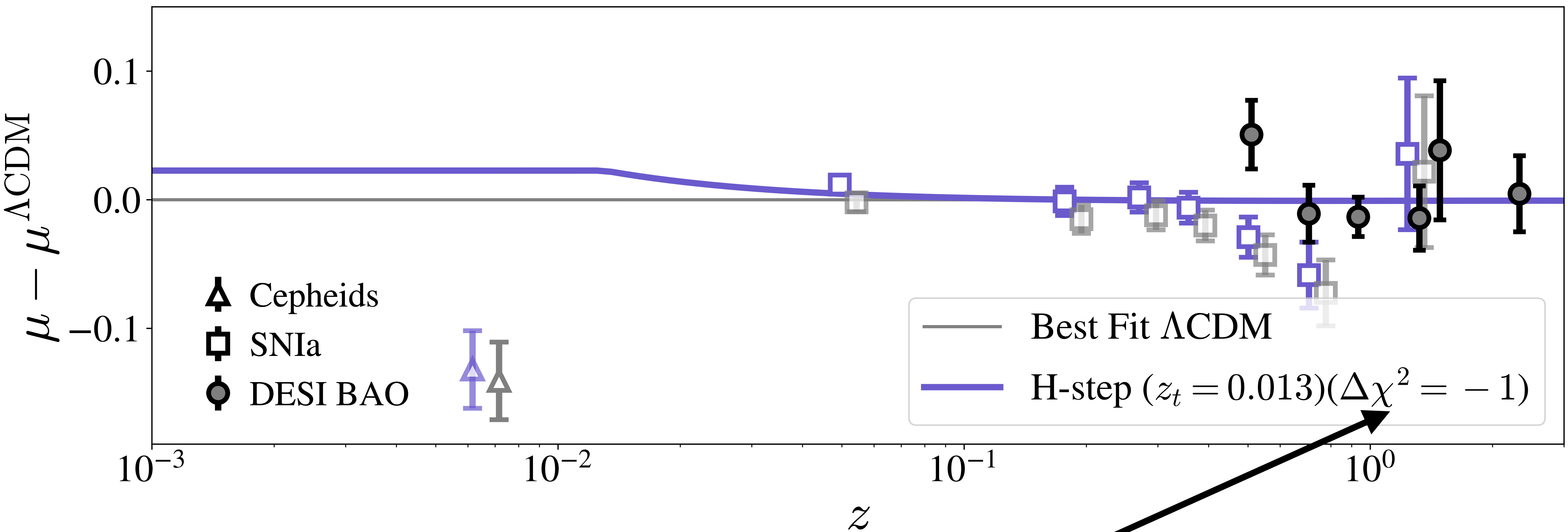

similarly small improvement for e.g. sharp step in H(z)

work with P. Bansal, to appear

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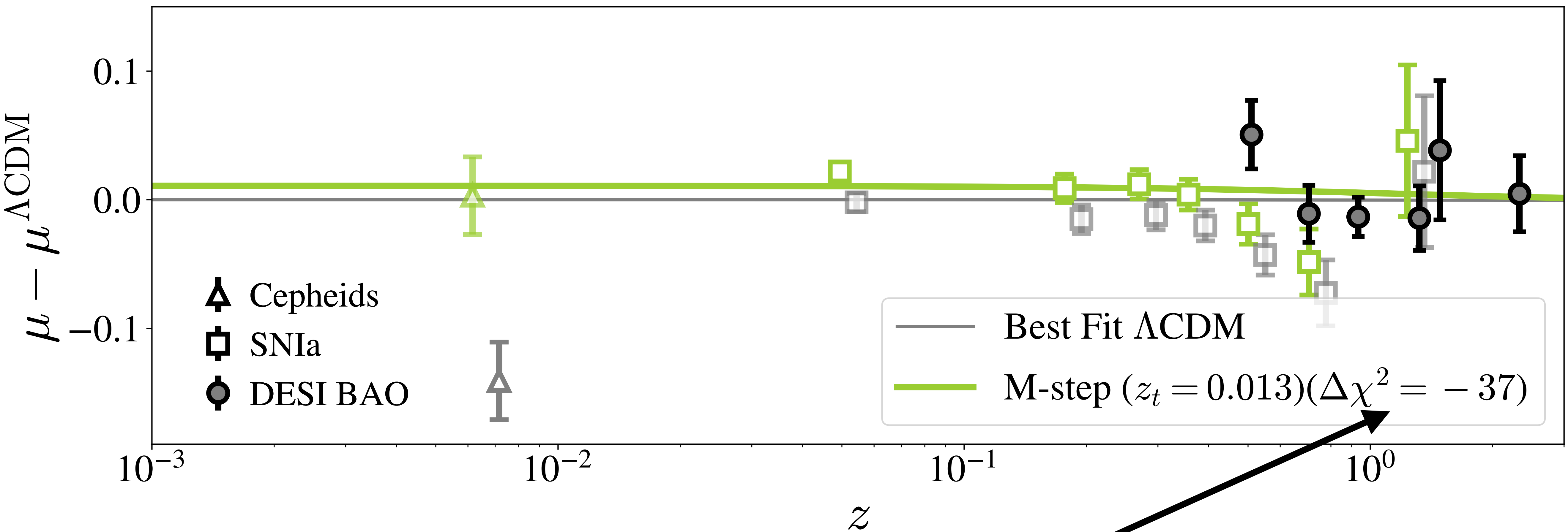

big improvement with step in M (abs mag of SNIa) at zt=0.01,
[but this essentially takes out SH0ES data out of the mix]

work with P. Bansal, to appear

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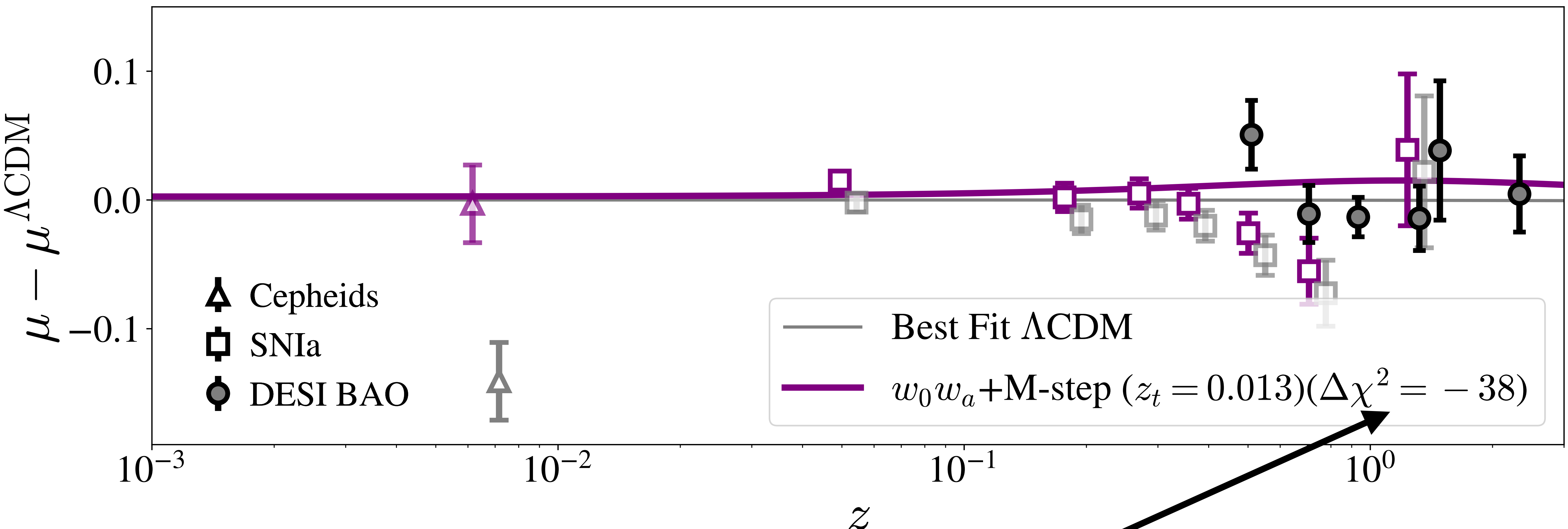
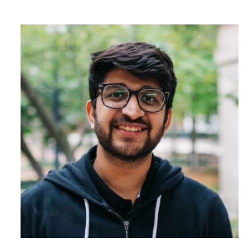


$w_0 w_a$ doesn't change the "success" of M-step model



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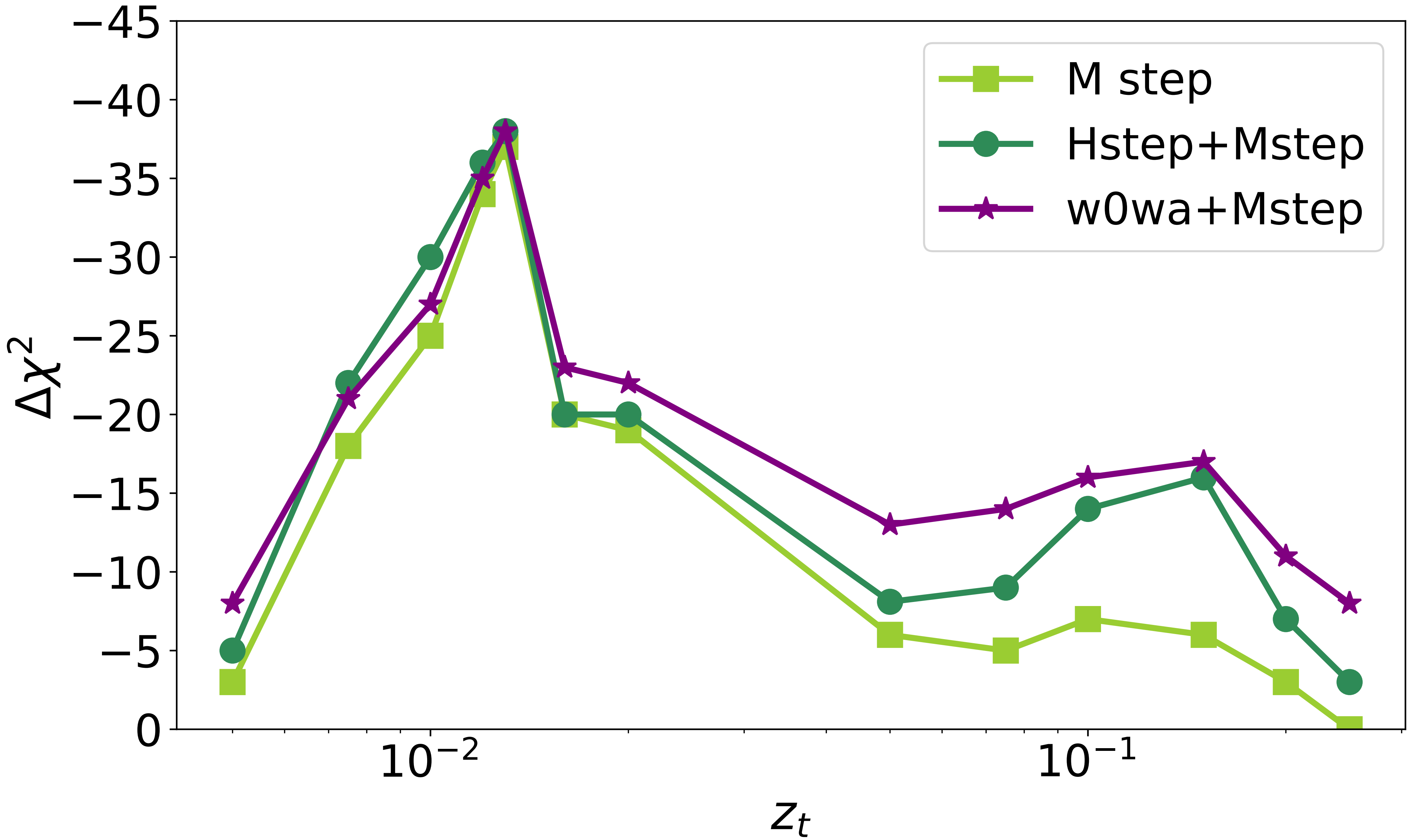
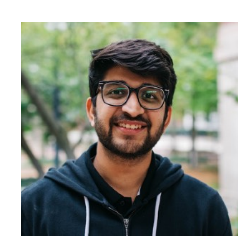
More on Fact #5:

Low-z solutions (for data including SH0ES) don't work - except for a very bizarre scenario of a step in M 150 myr ago (z_t=0.01)





work with P. Bansal, to appear

Conclusions

- Preference for w_0w_aCDM over LCDM is driven by "curvature" in distance(z) measurements.
- This preference is not due to any one single measurement, or a single cosmological probe. It appears to be very robust w.r.t. DE parameterization.
- Hints for departure from LCDM model are independent from (albeit statistically weaker than) the Hubble tension.
- These hints are exciting, but to claim evidence for departure from the standard LCDM model should require a **very high bar**
- It will be exciting to see what forthcoming data show:
  - DESI DR2 full shape (later this year)
  - DESI Pk + Bk (2026)
  - DESI 5-year data (soon-ish)
  - ZTF, SO, cross-correlations, Euclid? Spherex?