



Cosmological Constraints from the
DESI Y1
Baryon Acoustic Oscillation Measurements

Dragan Huterer
University of Michigan

Timeline of the universe

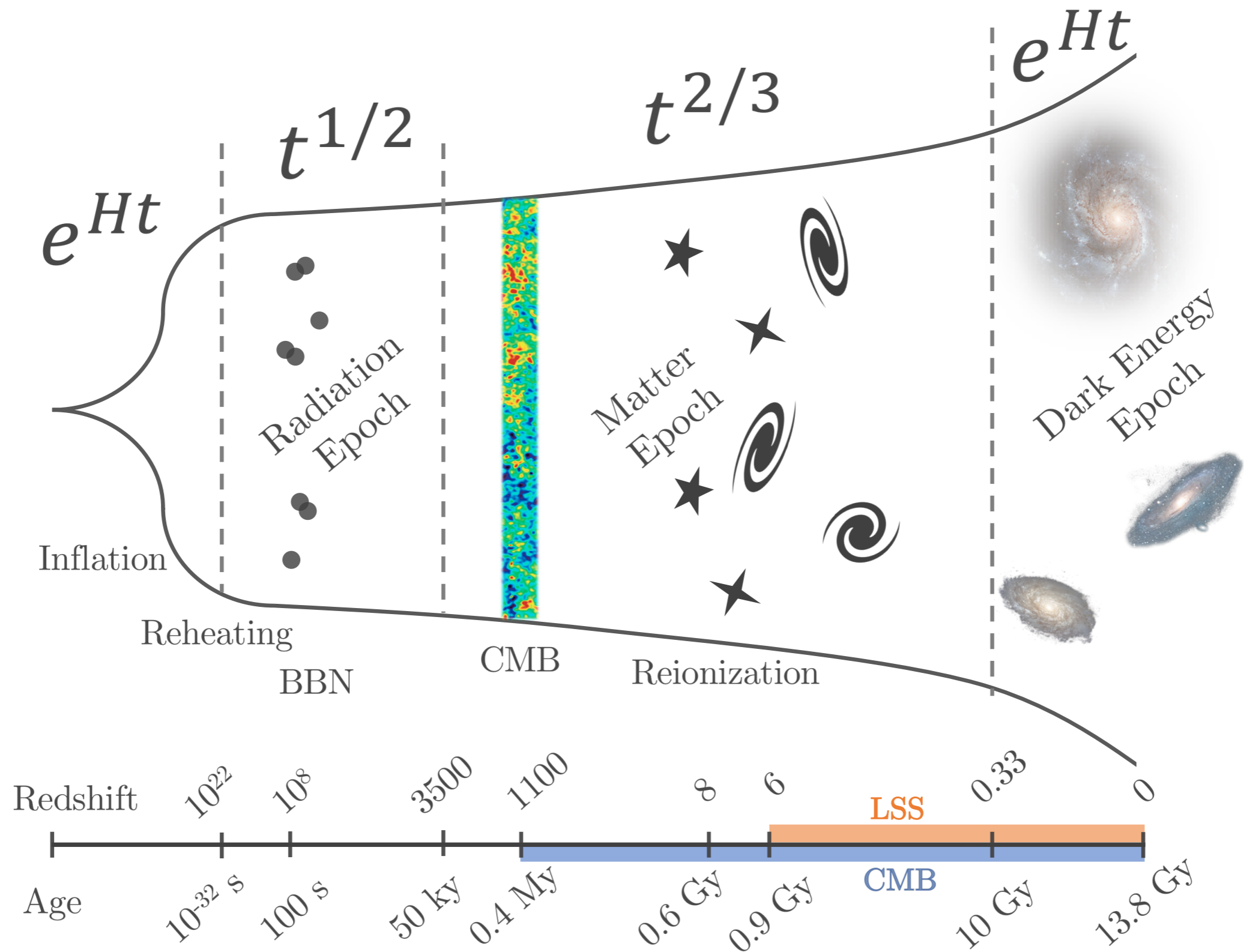
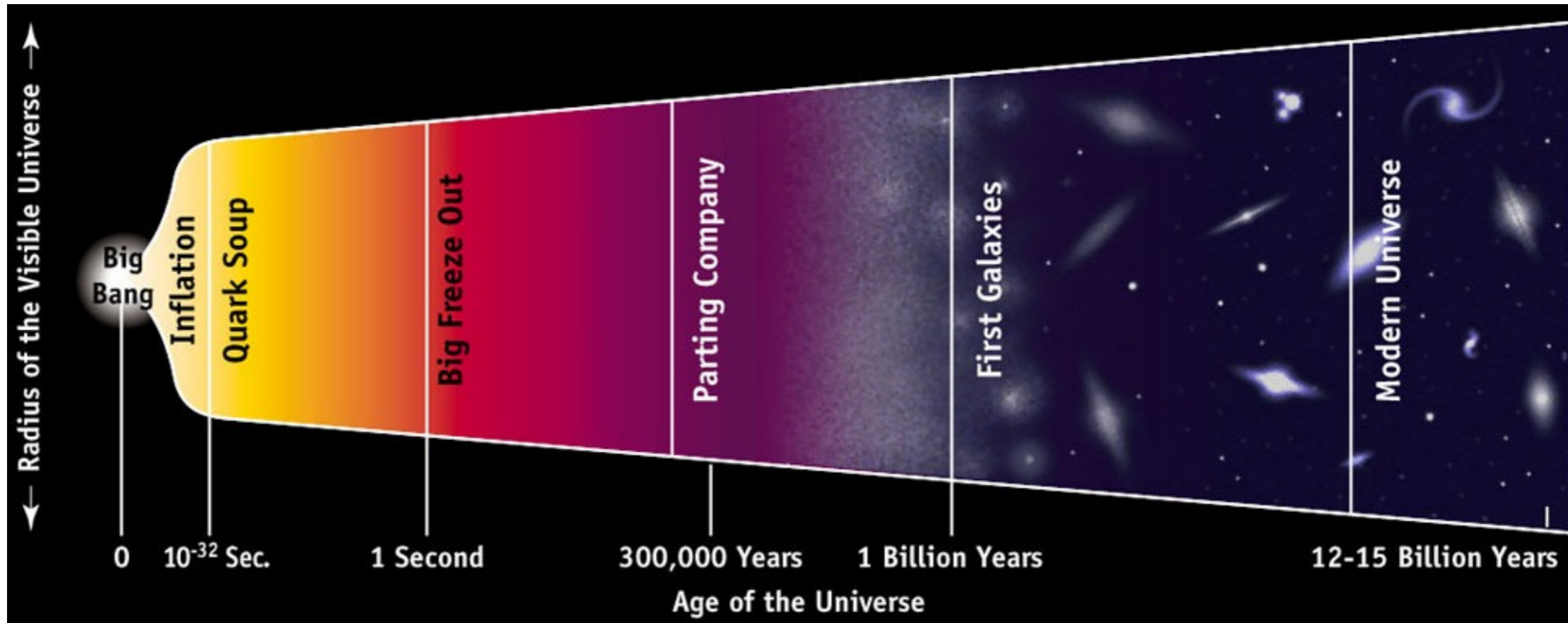


Figure credit: Noah Weaverdyck

Three key questions in cosmology



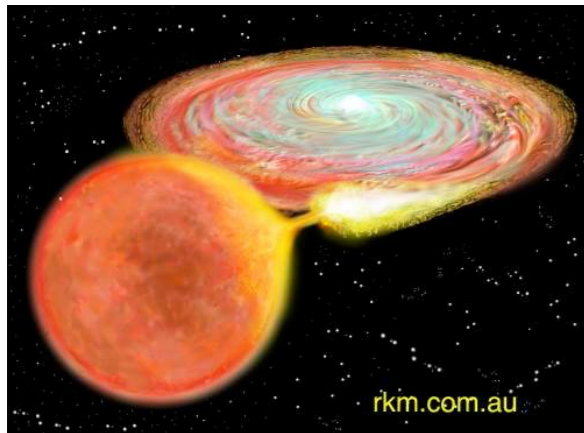
Inflation

Dark
Matter

Dark
Energy

Discovery of dark energy

(late 1990s; Physics Nobel Prize in 2011)

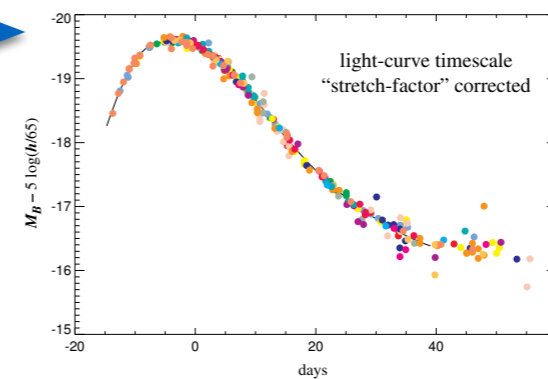
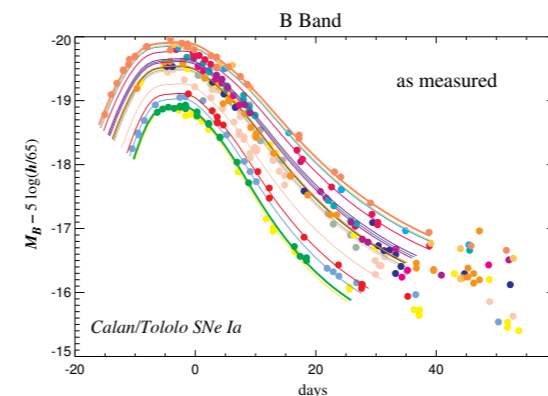
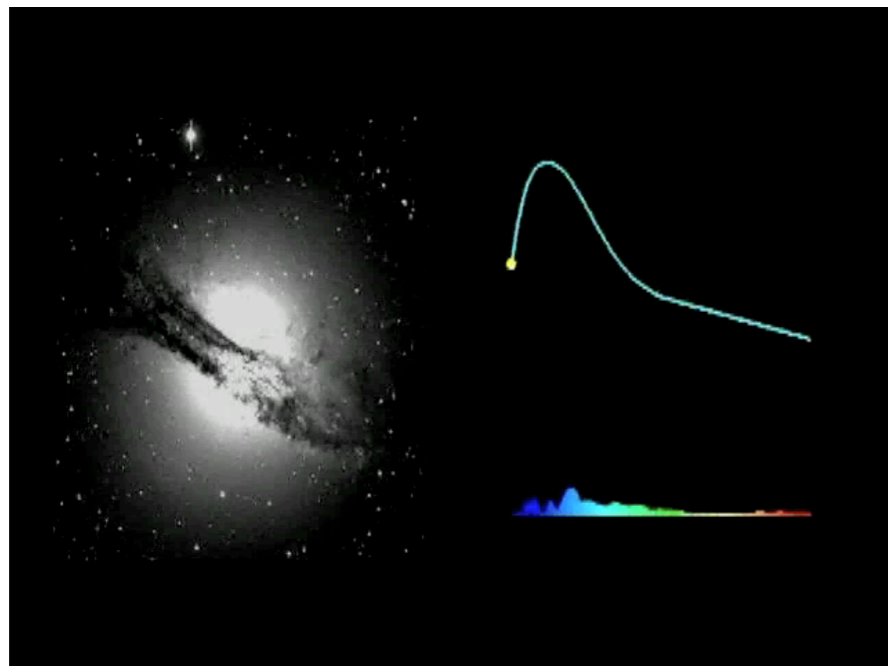


type Ia
supernova
explodes...

...to use it as a
standard candle
(i.e. $L = \text{const}$)

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

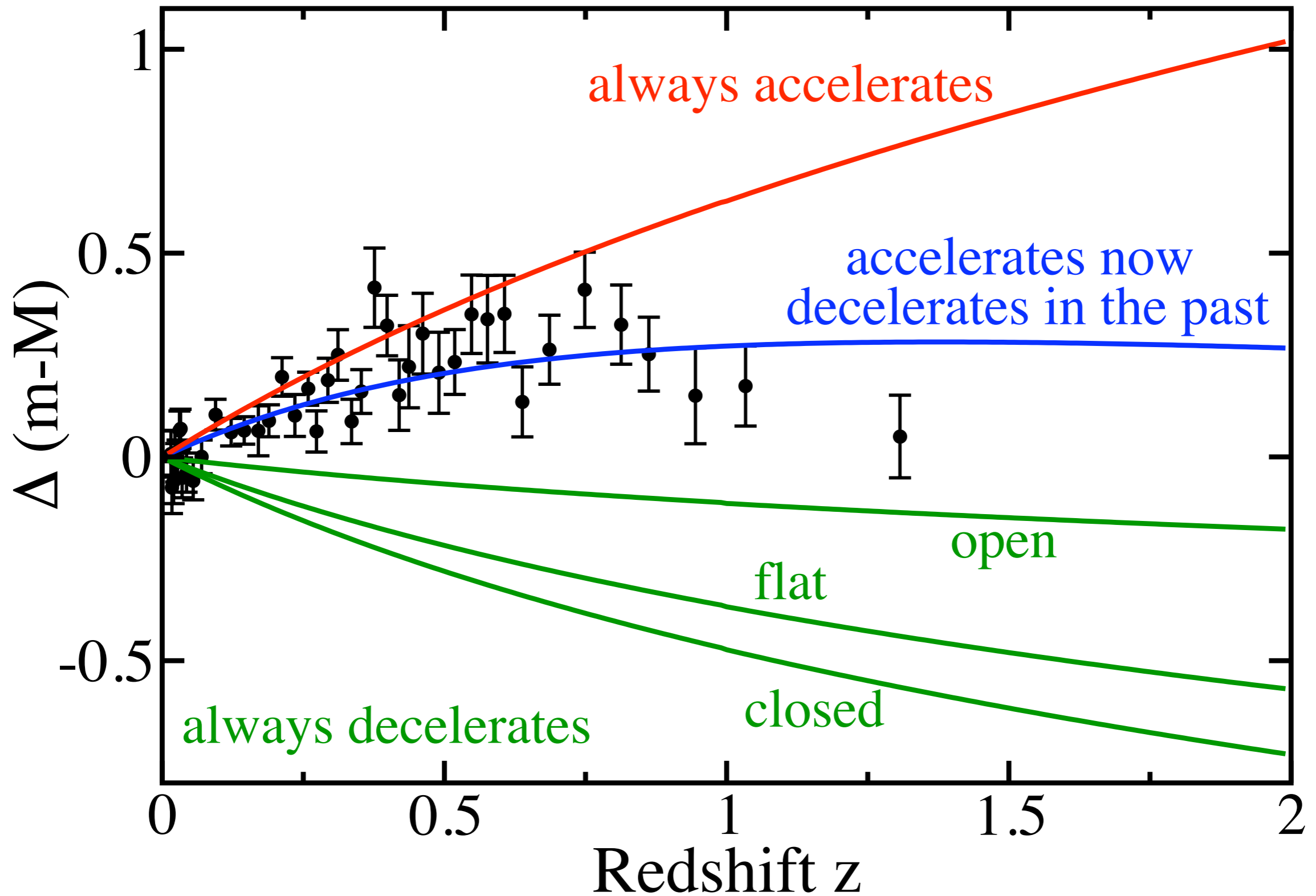
...astronomers detect it and follow it up;
they measure the light-curve...



...and make a
correction
for its width...

Supernova Hubble diagram

(binned; each error bar denotes ~ 20 SN)

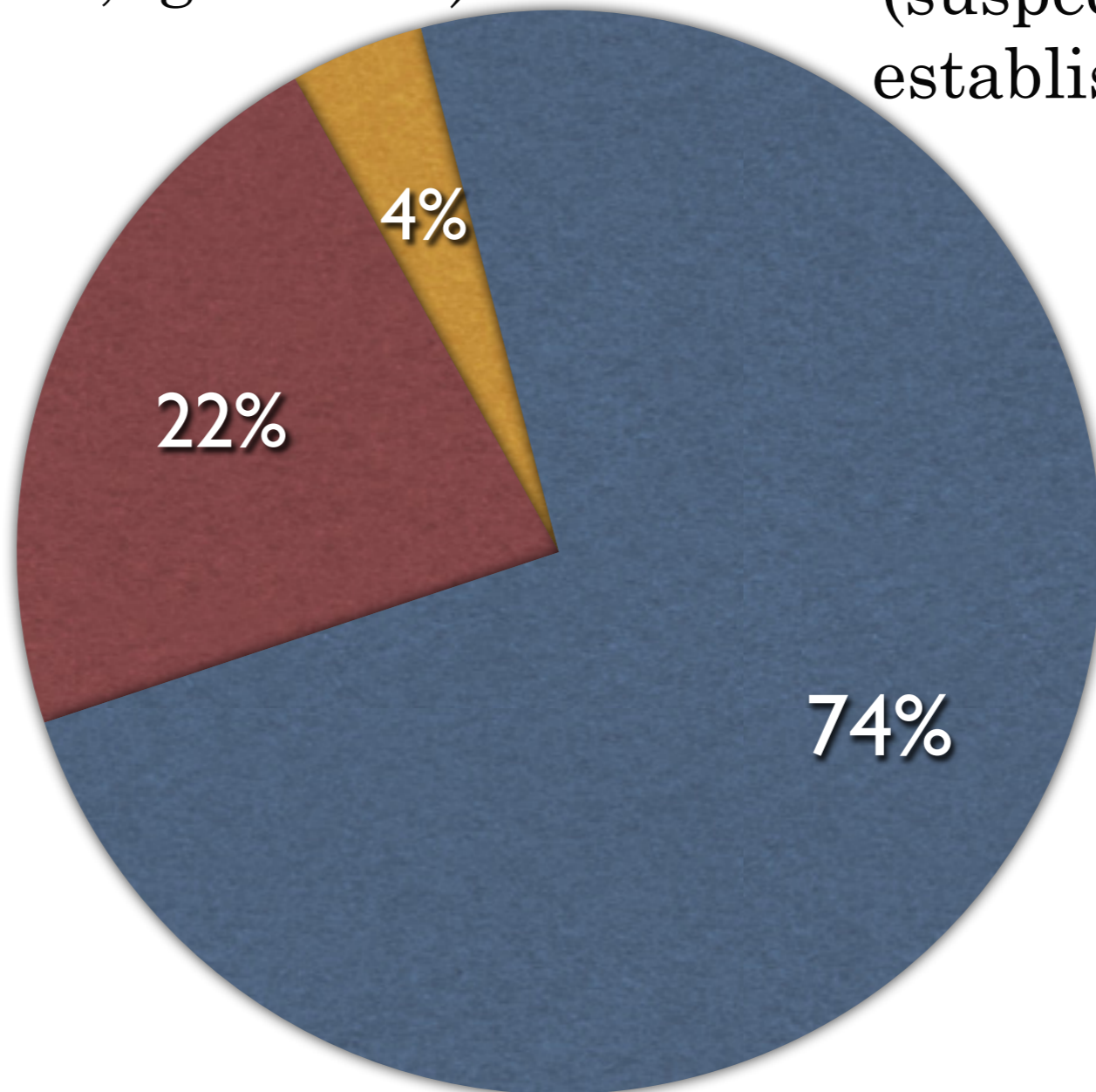


Makeup of universe **today**

Baryonic Matter
(stars 0.4%, gas 3.6%)

Dark Energy
(suspected since 1980s
established since 1998)

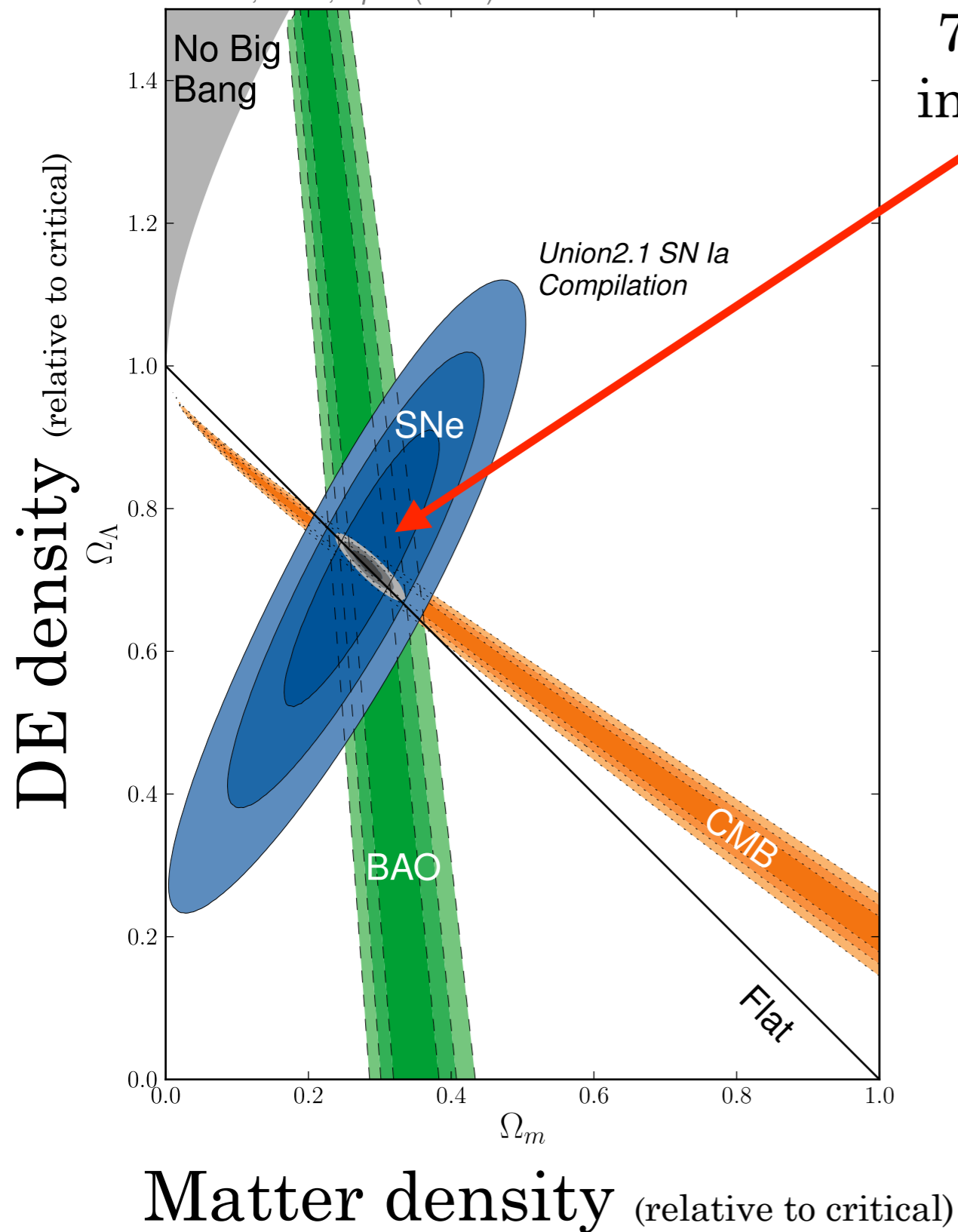
Dark Matter
(suspected since 1930s
established since 1970s)



Also:
radiation (0.01%)

(Recent) constraints on dark energy

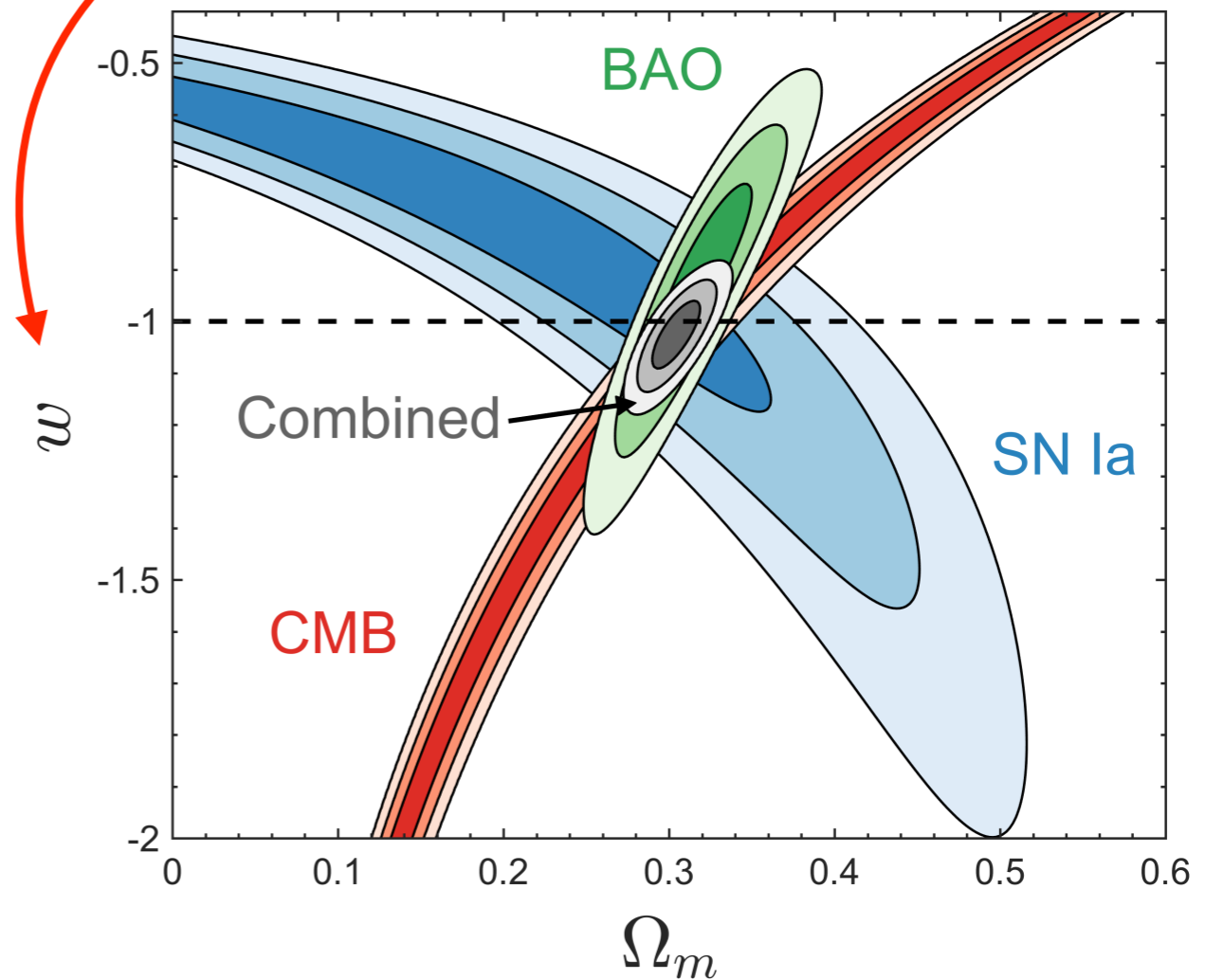
Supernova Cosmology Project
Suzuki, et al., *Ap.J.* (2011)



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

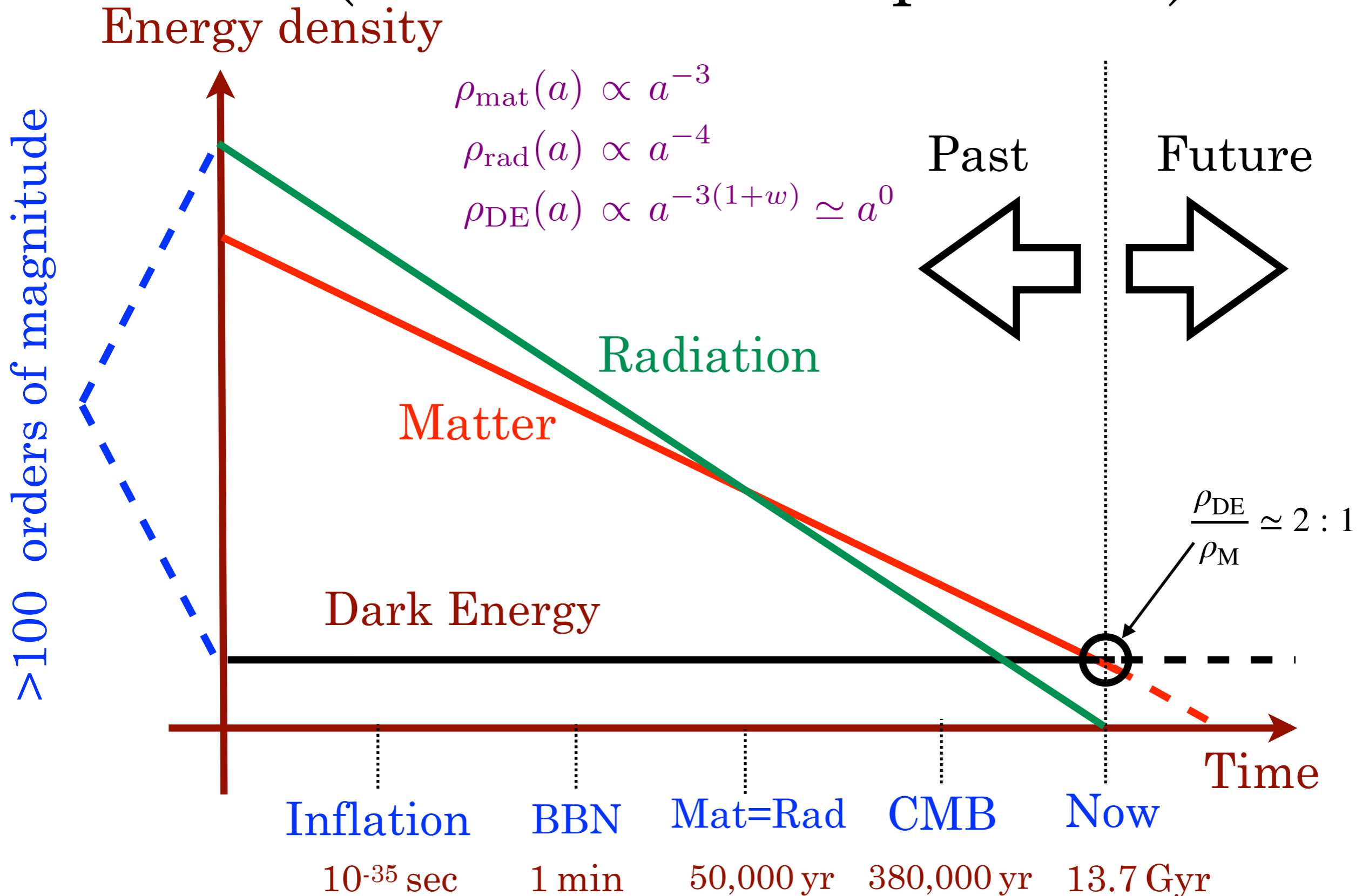
...and DE equation of state is

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



Dark Energy: Two Grand Mysteries

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



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

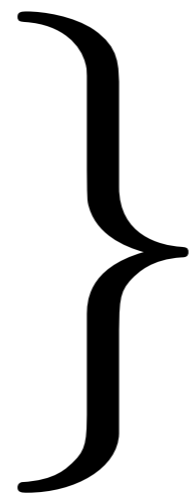
Vacuum Energy: Quantum Field Theory
predicts it to be cutoff scale

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

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

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

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

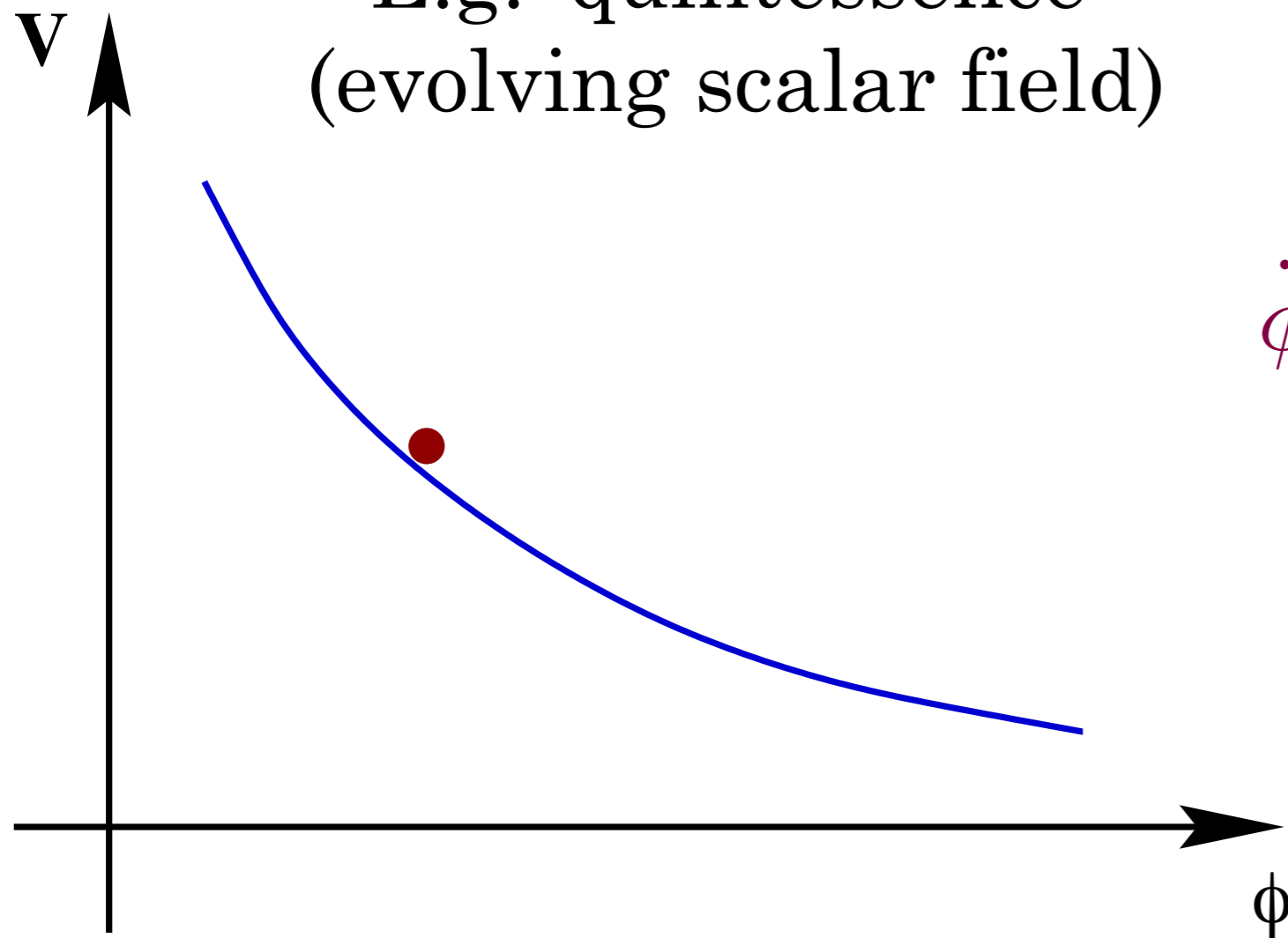


60-120 orders of magnitude
smaller than expected!!

Lots of theoretical ideas, few compelling ones:

Very difficult to motivate DE naturally

E.g. 'quintessence'
(evolving scalar field)



$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

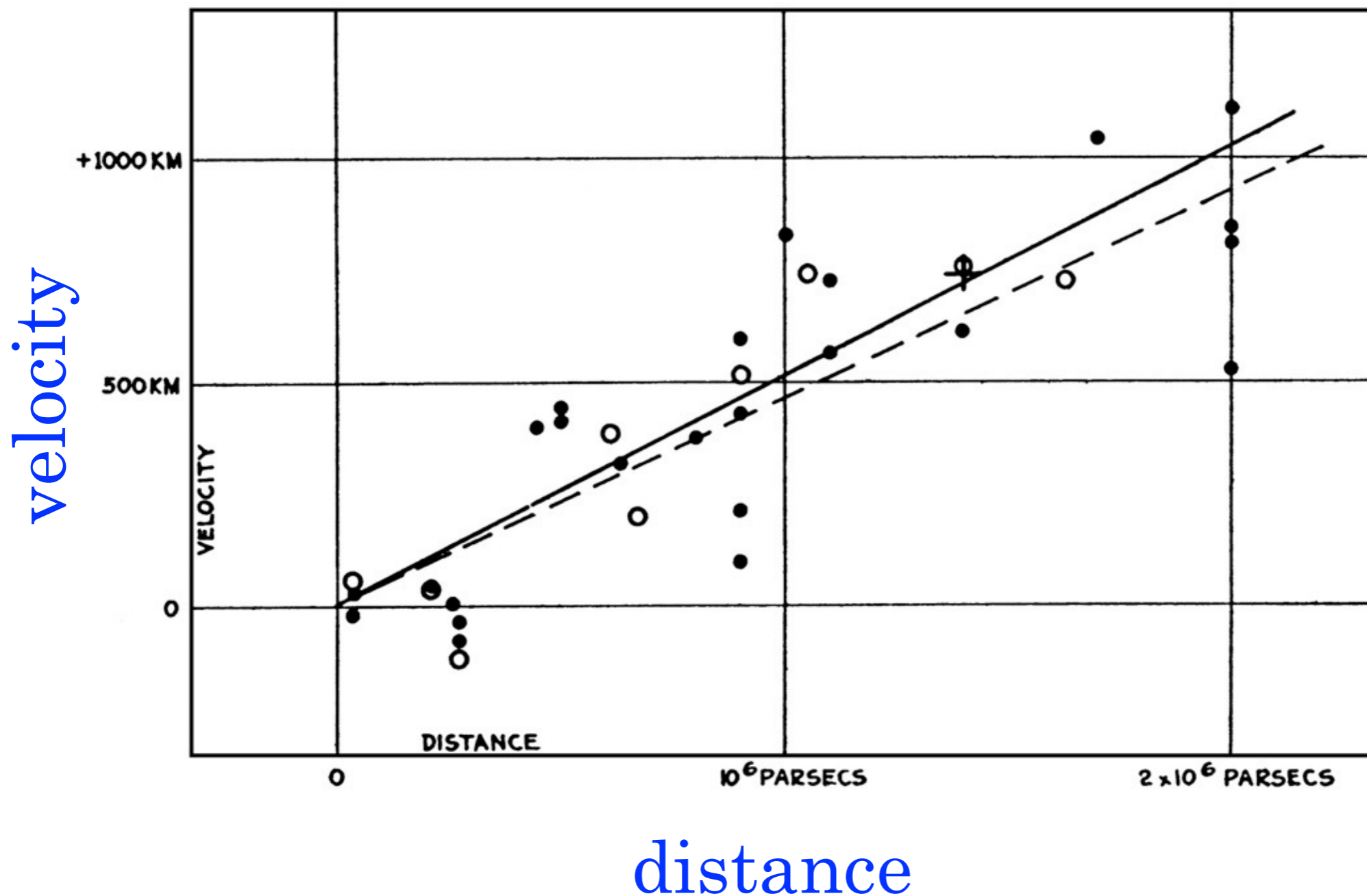
but would have to have a *teeny* mass:

$$m_{\phi} \simeq H_0 \simeq 10^{-33} \text{ eV}$$

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



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

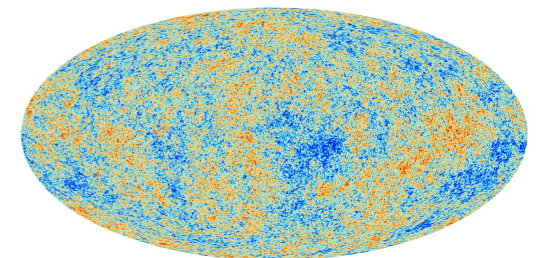
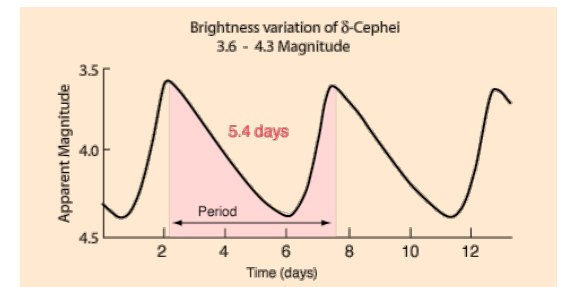
Hubble Tension:

SH₀ES (Riess et al 2022)

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

CMB: (Planck 2018)

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



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

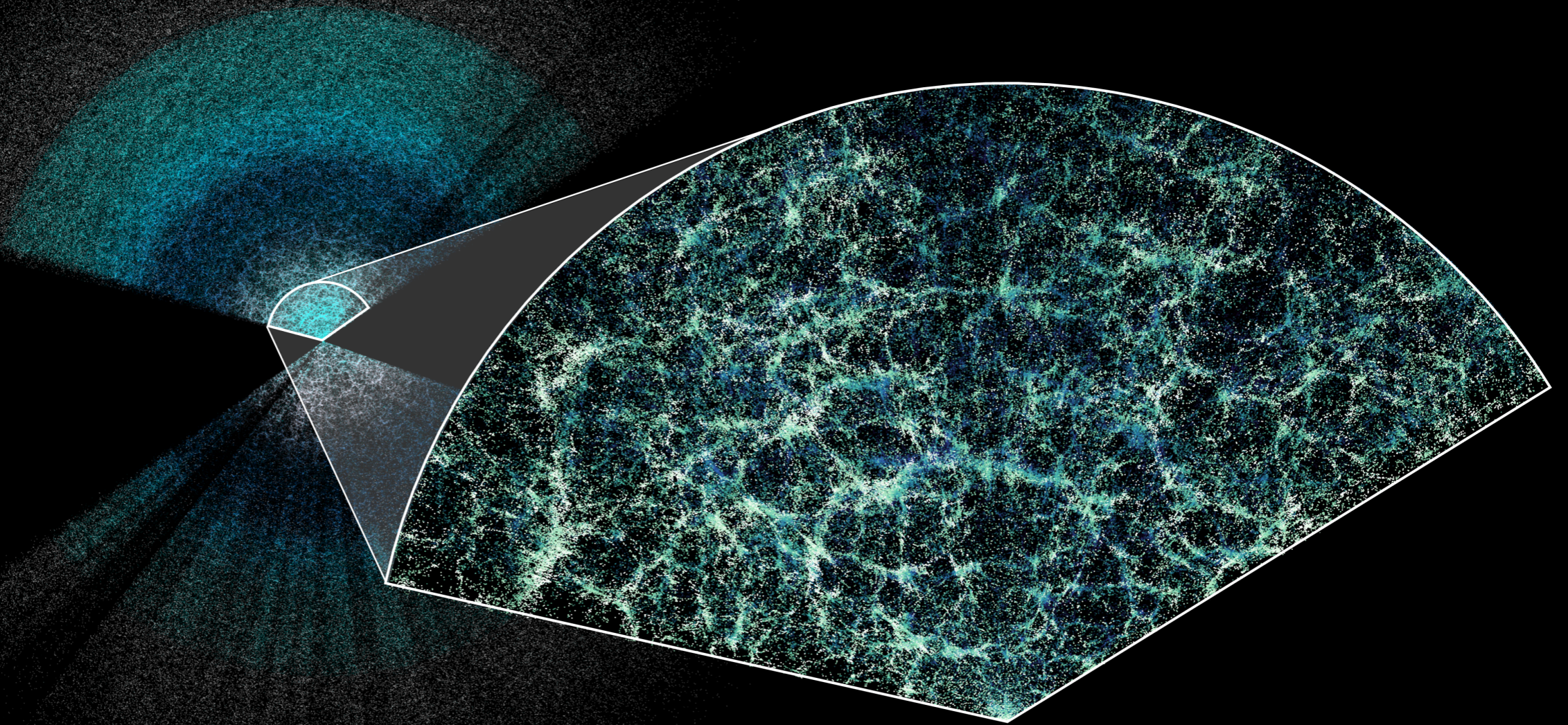
Dark Energy Spectroscopic Instrument (DESI)

- 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:

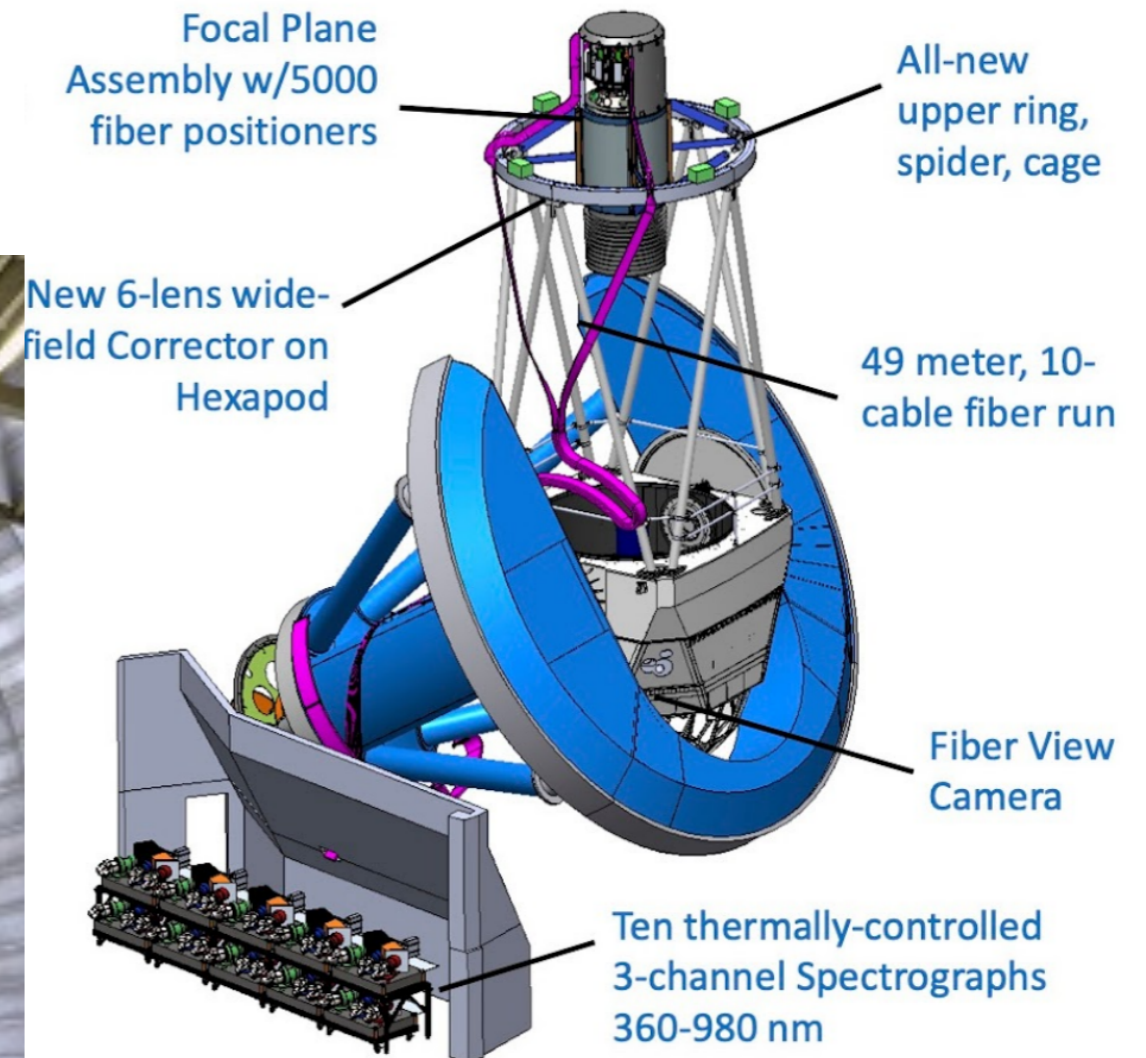
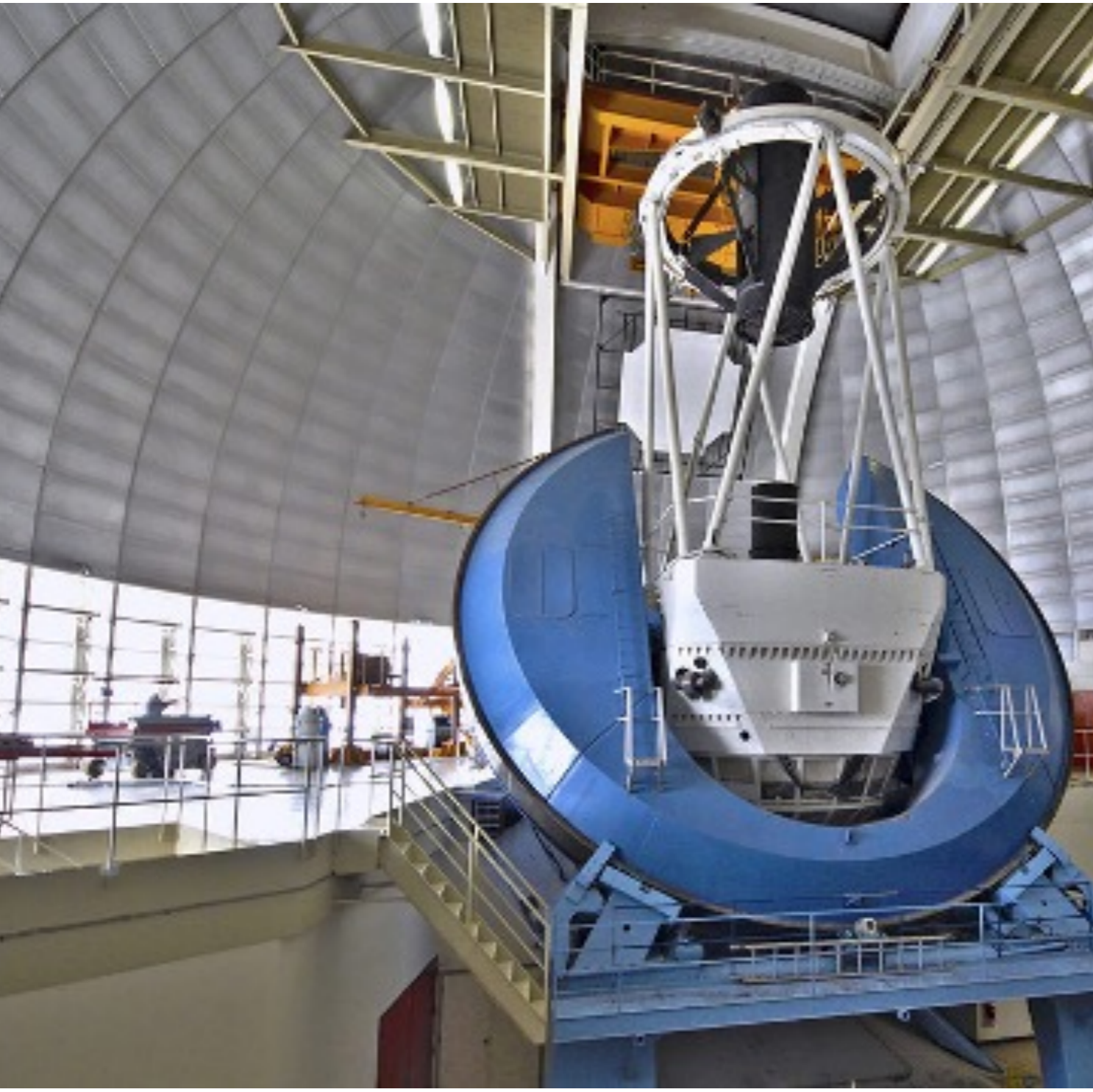
1. dark energy
 2. neutrino mass
 3. primordial non-Gaussianity
- } this talk

For cosmologists, galaxies are test particles!





Mayall telescope at Kitt Peak, AZ



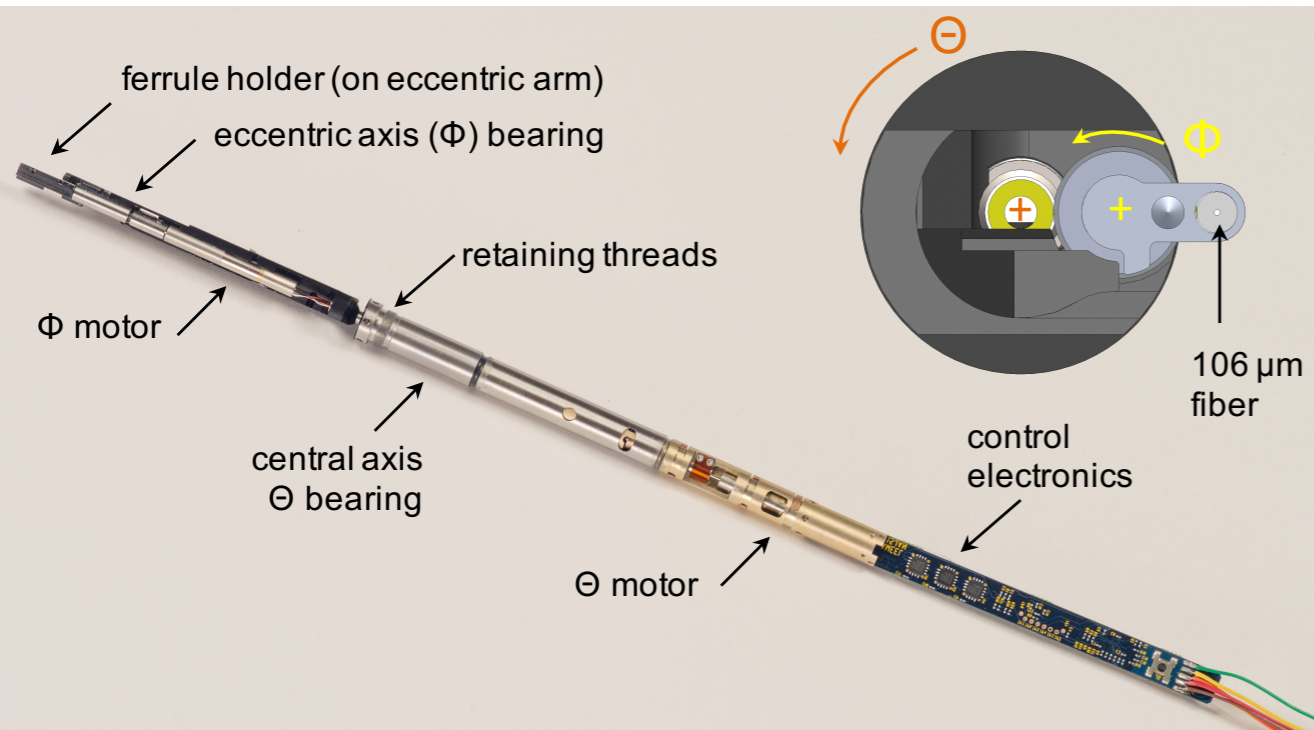


Robotic fiber positioners

Designed and built at
University of Michigan
(Tarlé group)

“5,000 eyes on the sky”

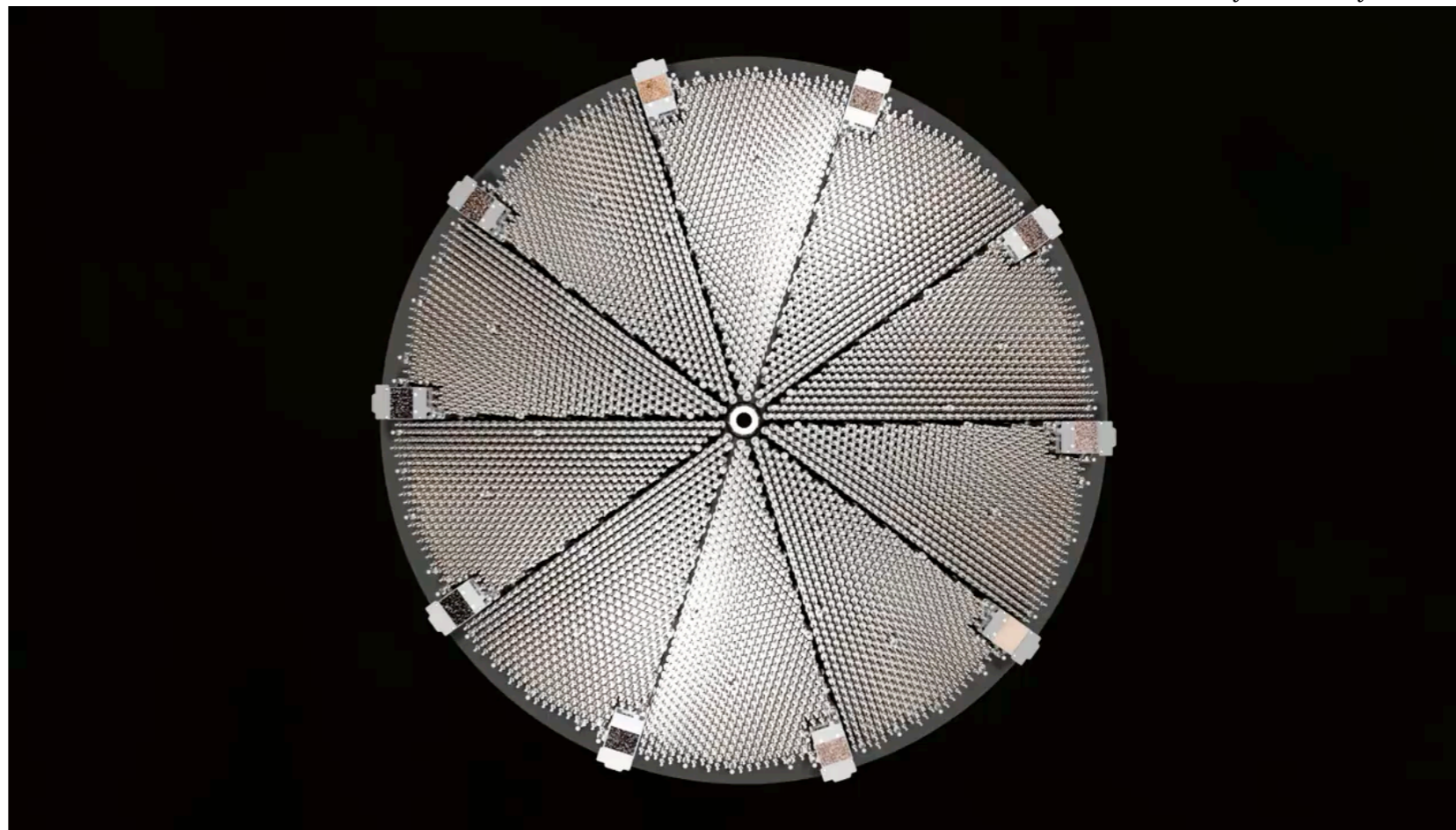
Movie by D. Kirkby



Greg
Tarlé



Michael
Schubnell





DESI tracers

Five target classes

40 million redshifts

in 5 years

DESI (2021-2026)

3 million QSOs

Lya $z > 2.1$

Tracers $0.9 < z < 2.1$

16 million ELGs

$0.6 < z < 1.6$

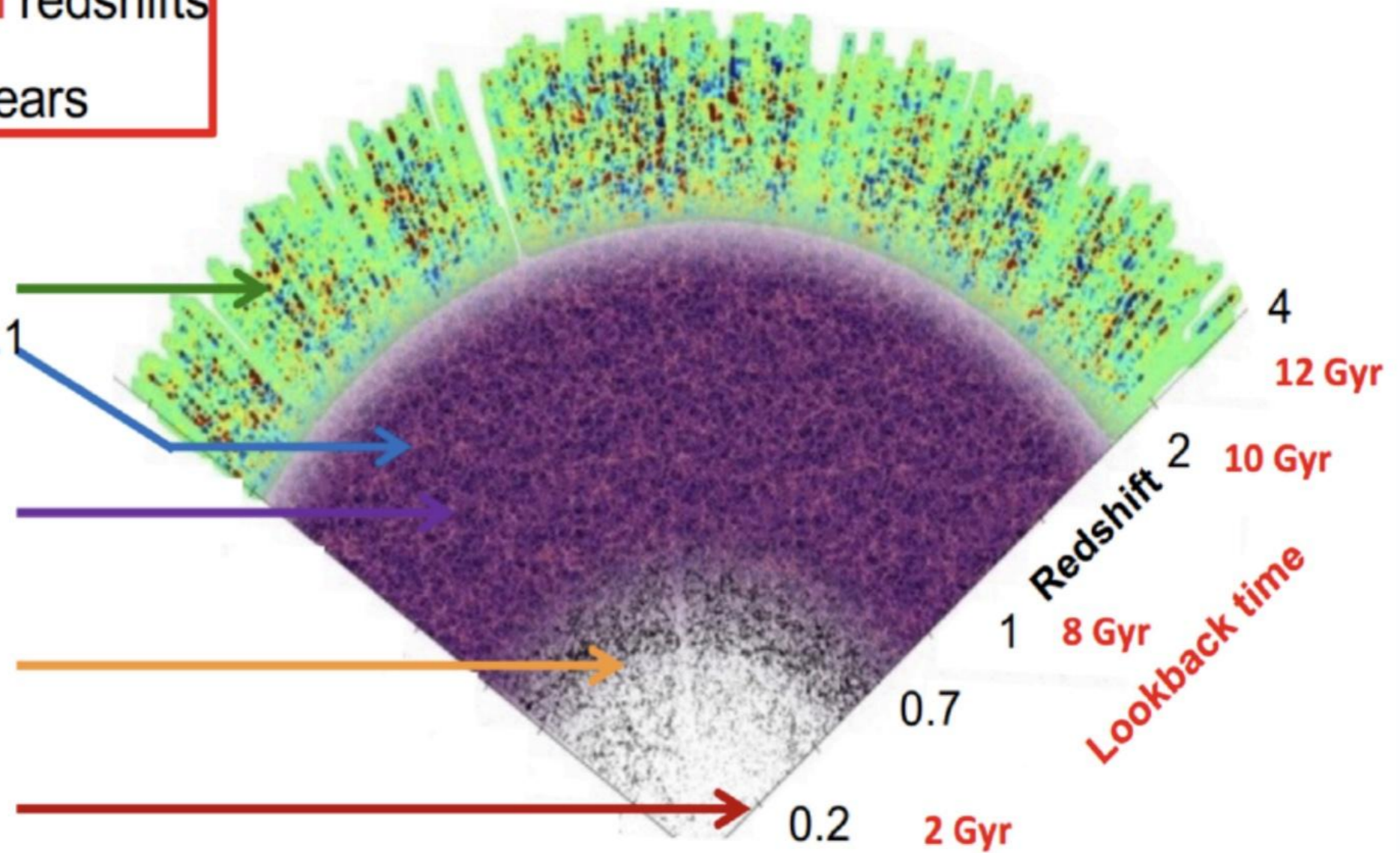
8 million LRGs

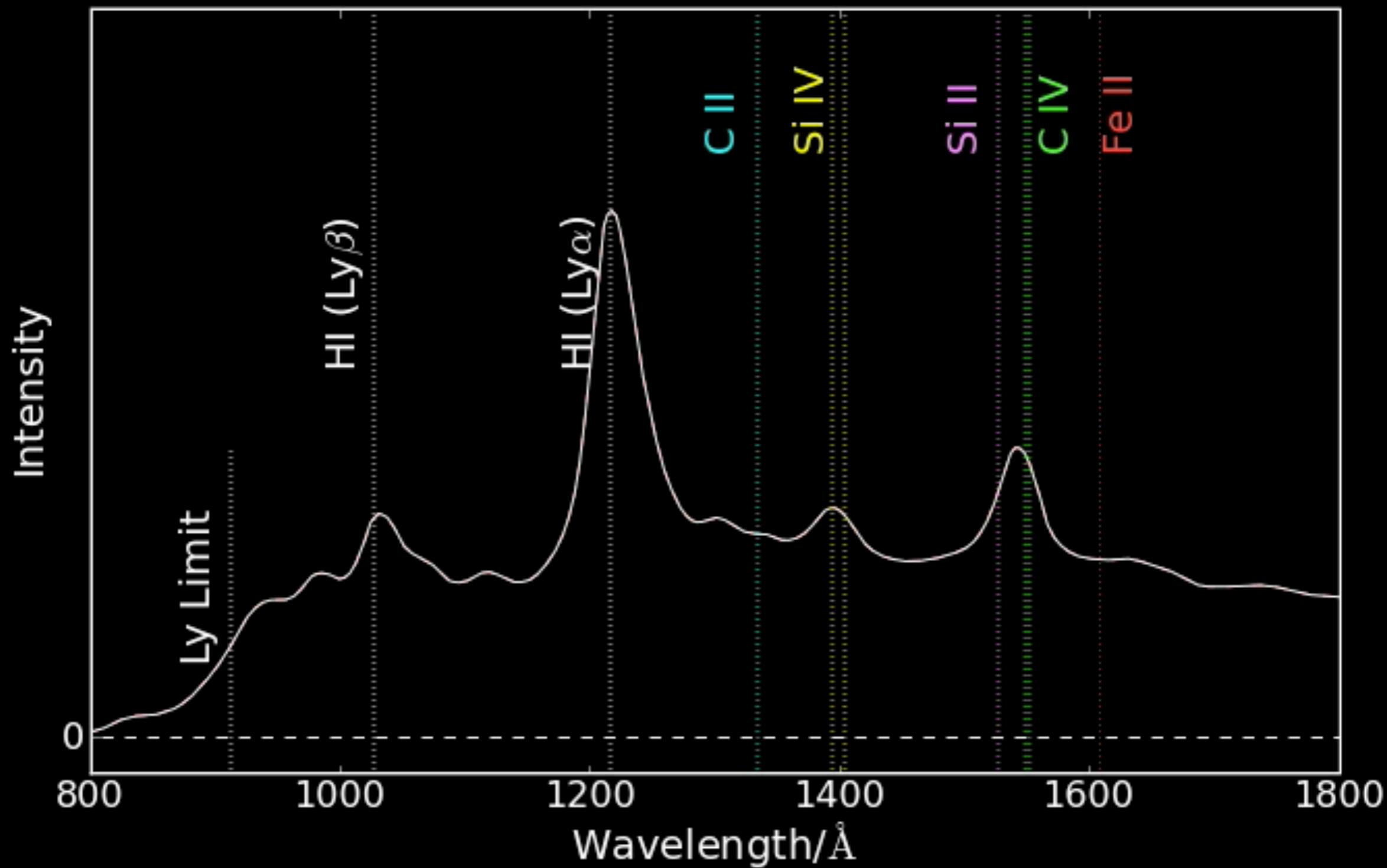
$0.4 < z < 1.0$

13.5 million

Brightest galaxies

$0.0 < z < 0.4$





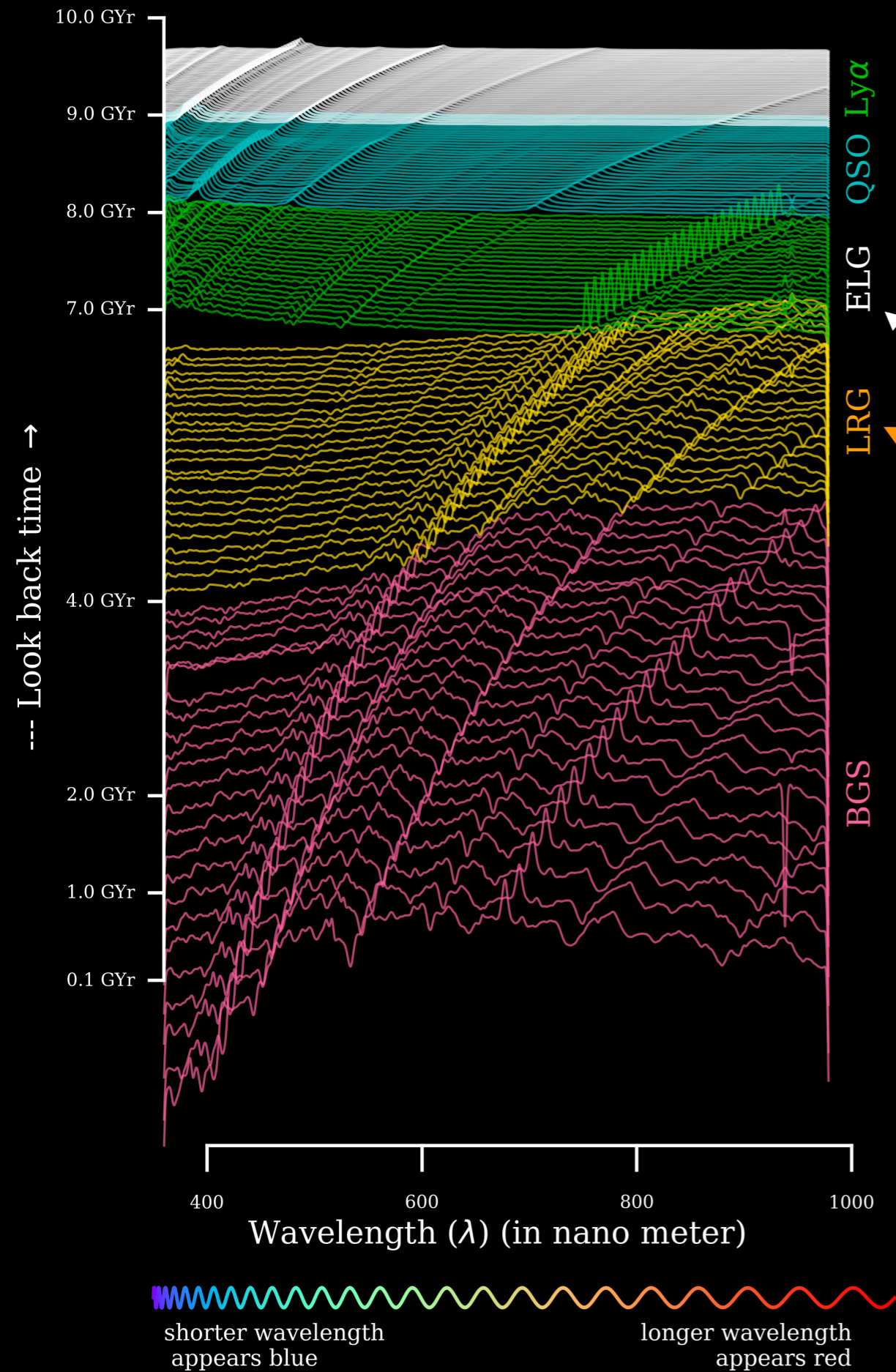
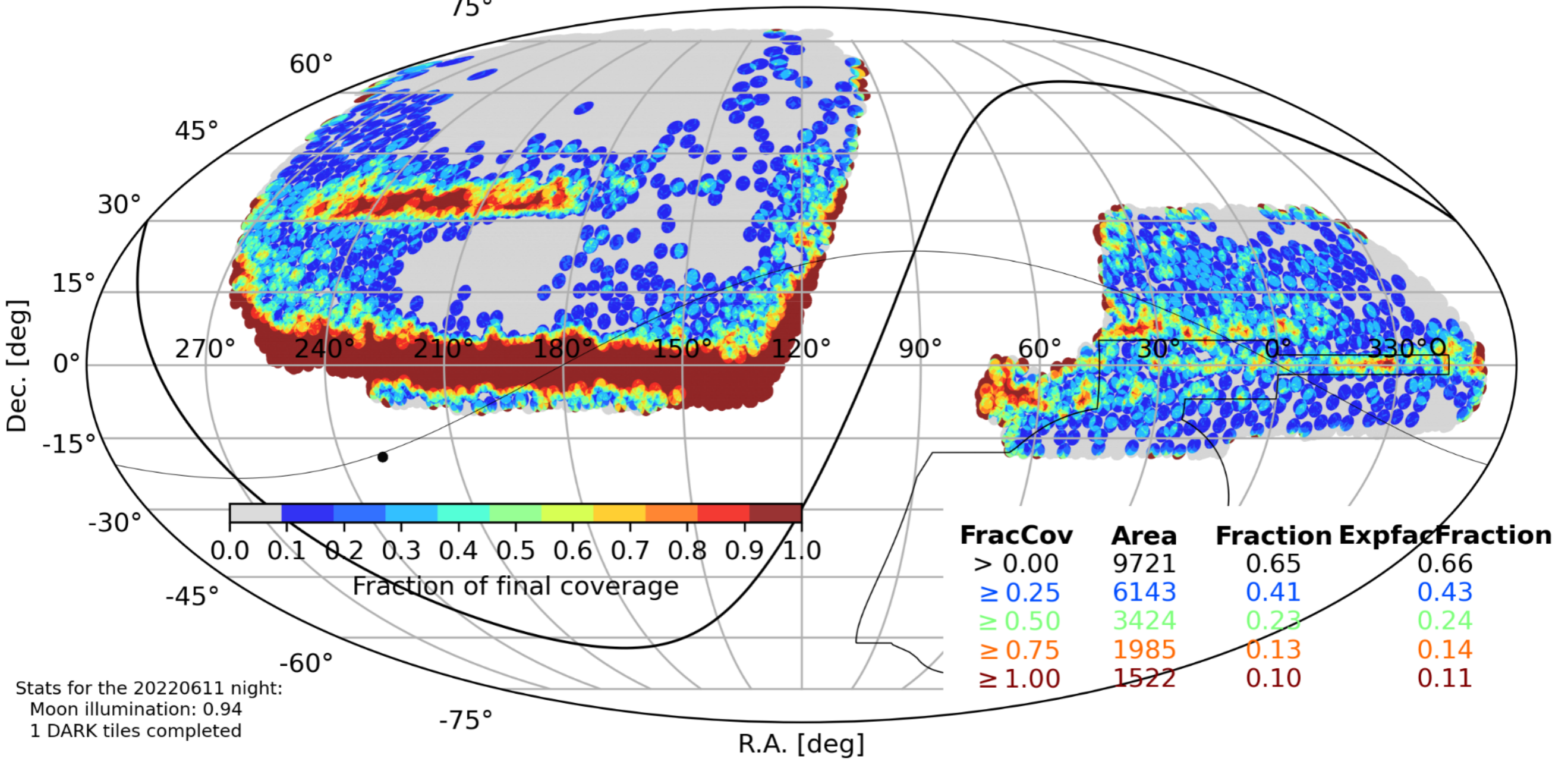


Illustration of how
a spectrum evolves
in redshift/time

DESI tracers



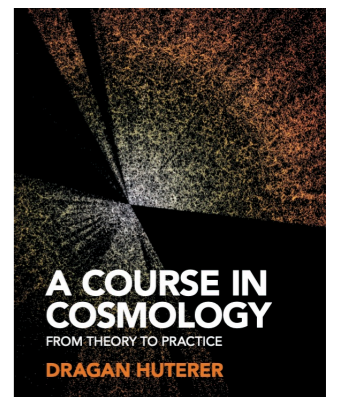
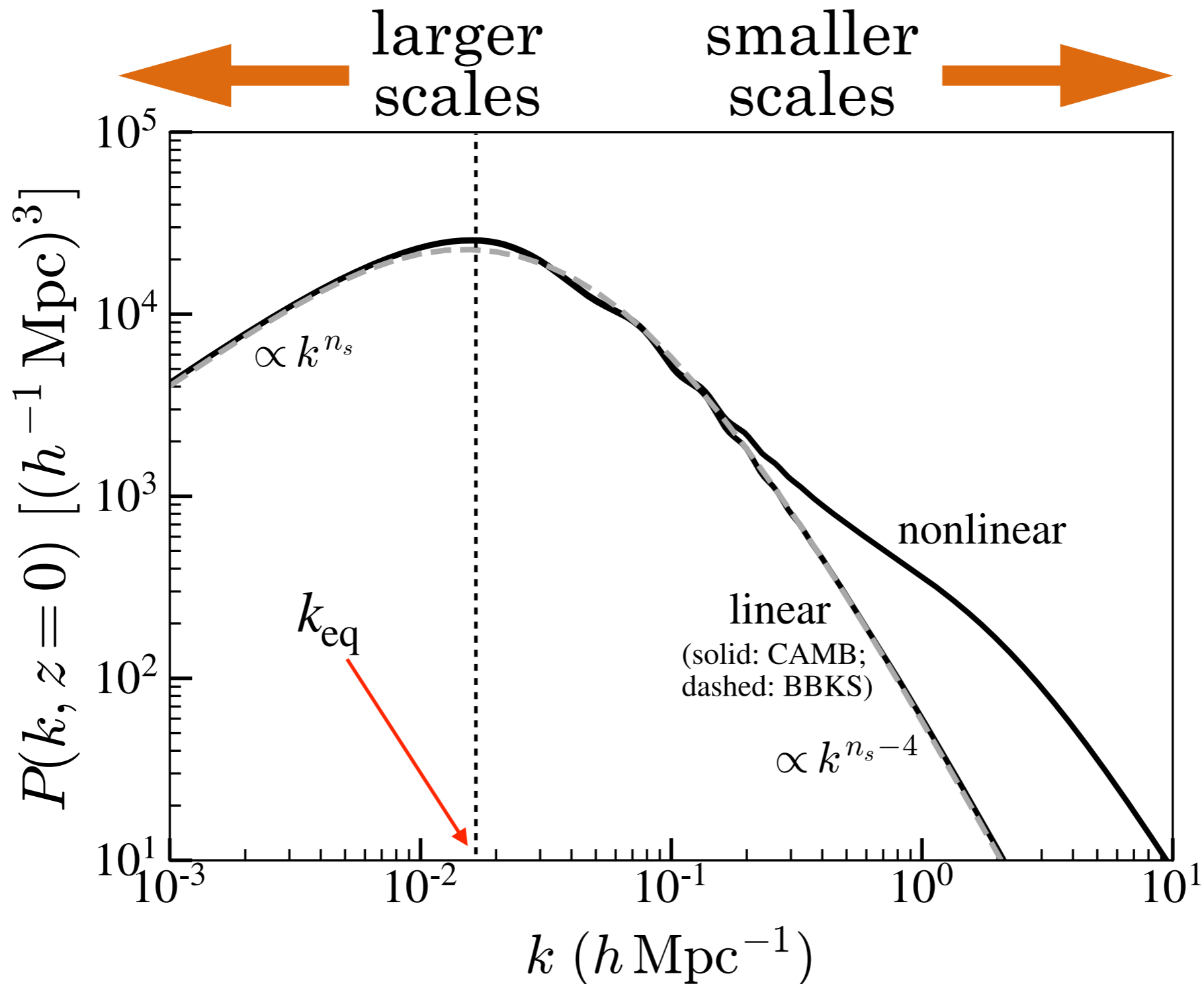
Main/DARK : 2744/9929 completed tiles up to 20220611 (=28%, weighted=29%)



How Baryon Acoustic Oscillations observed by DESI constrain cosmological parameters

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

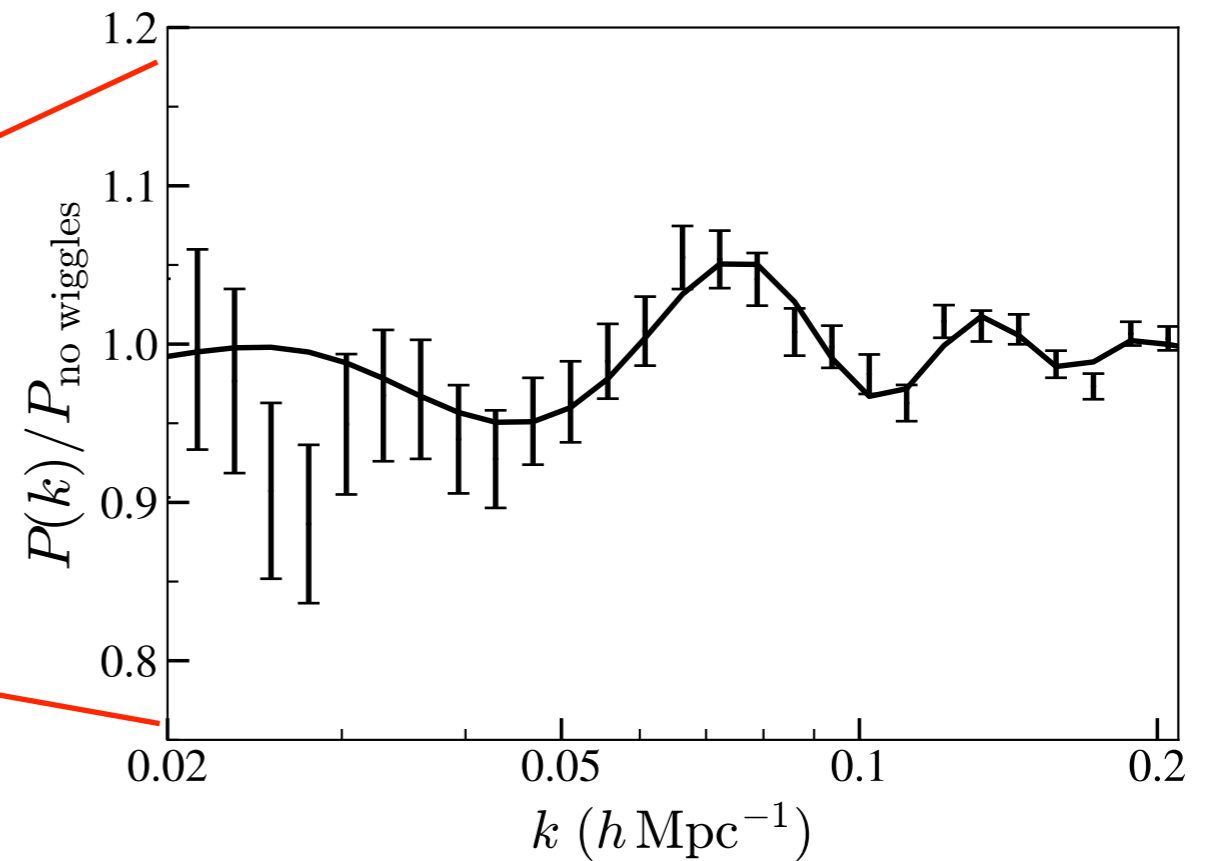
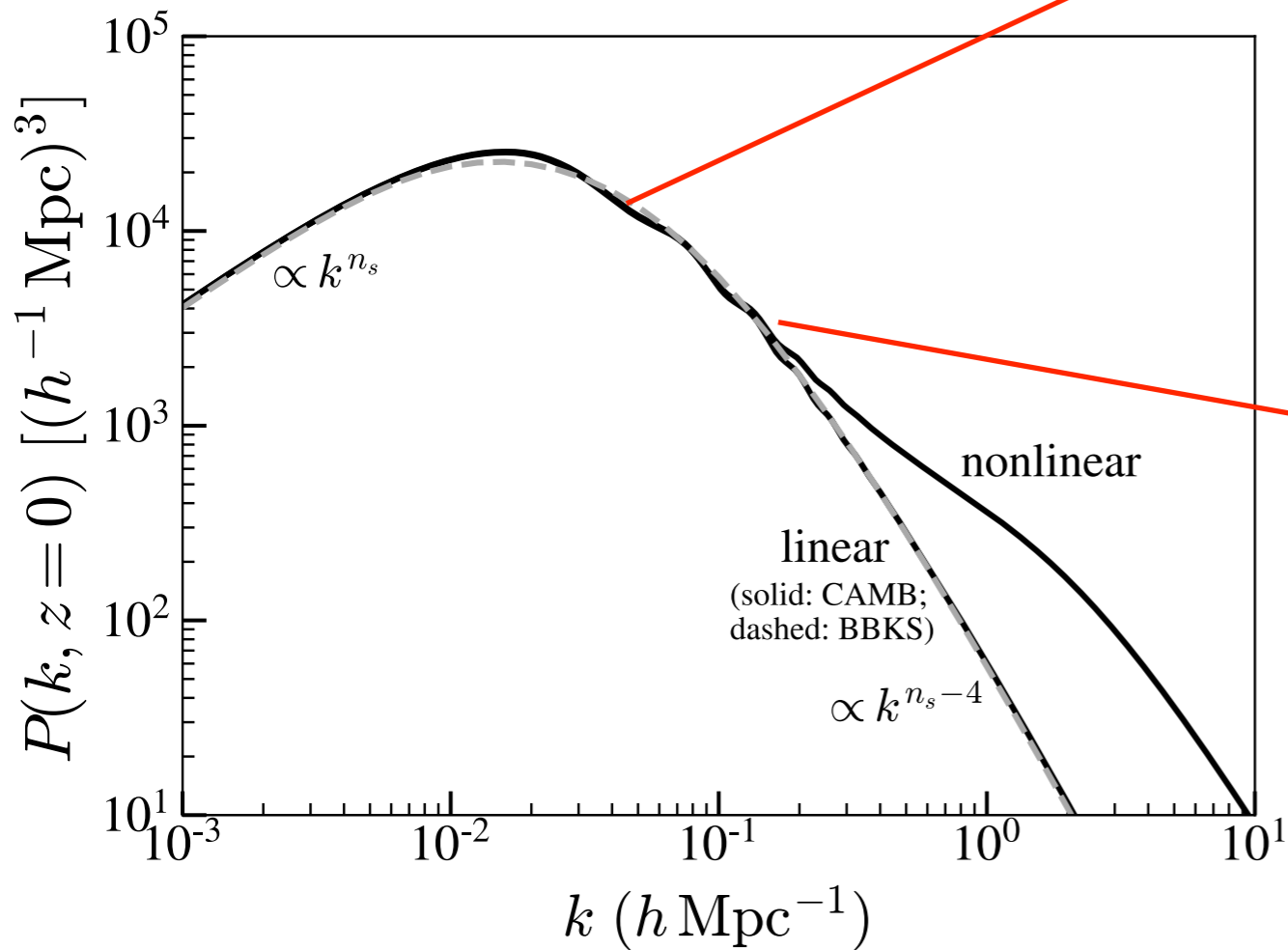
Galaxy power spectrum



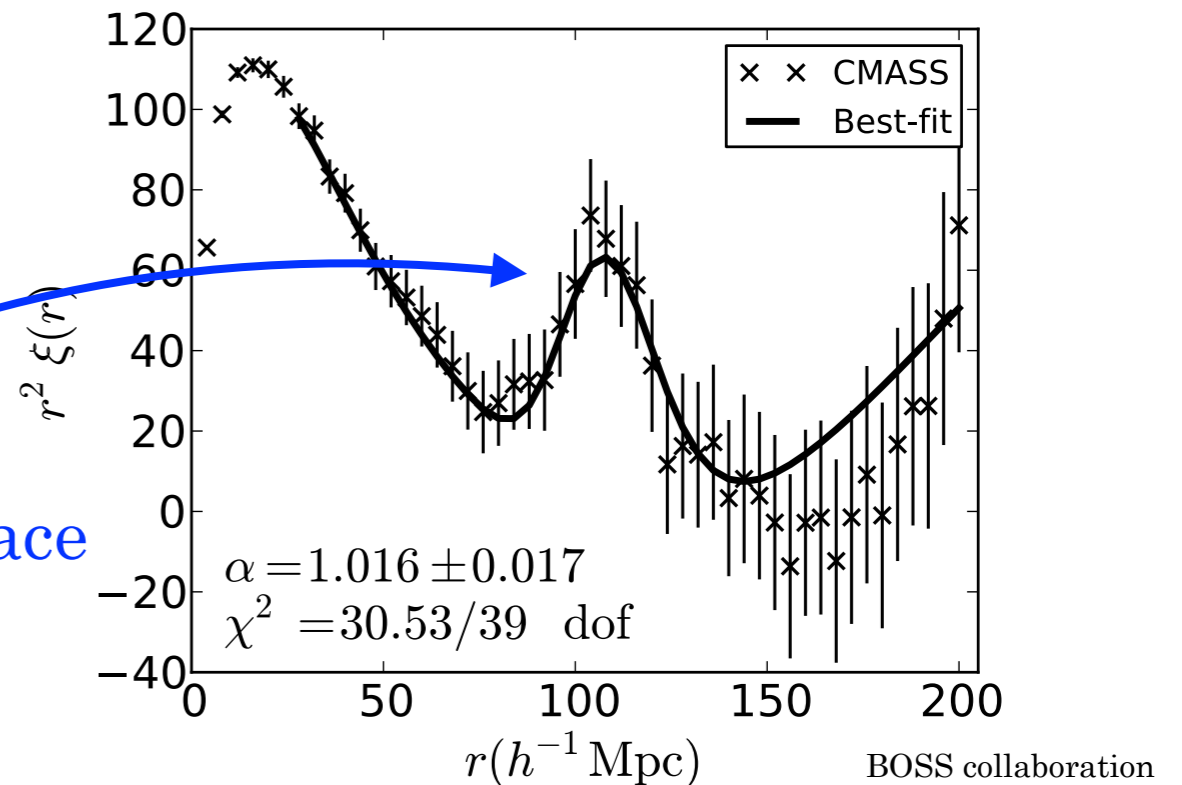
Matter power spectrum contains (almost!) all information
at large scales in cosmology

Baryon Acoustic Oscillations (BAO)

Multiple wiggles in Fourier space
(power spectrum)

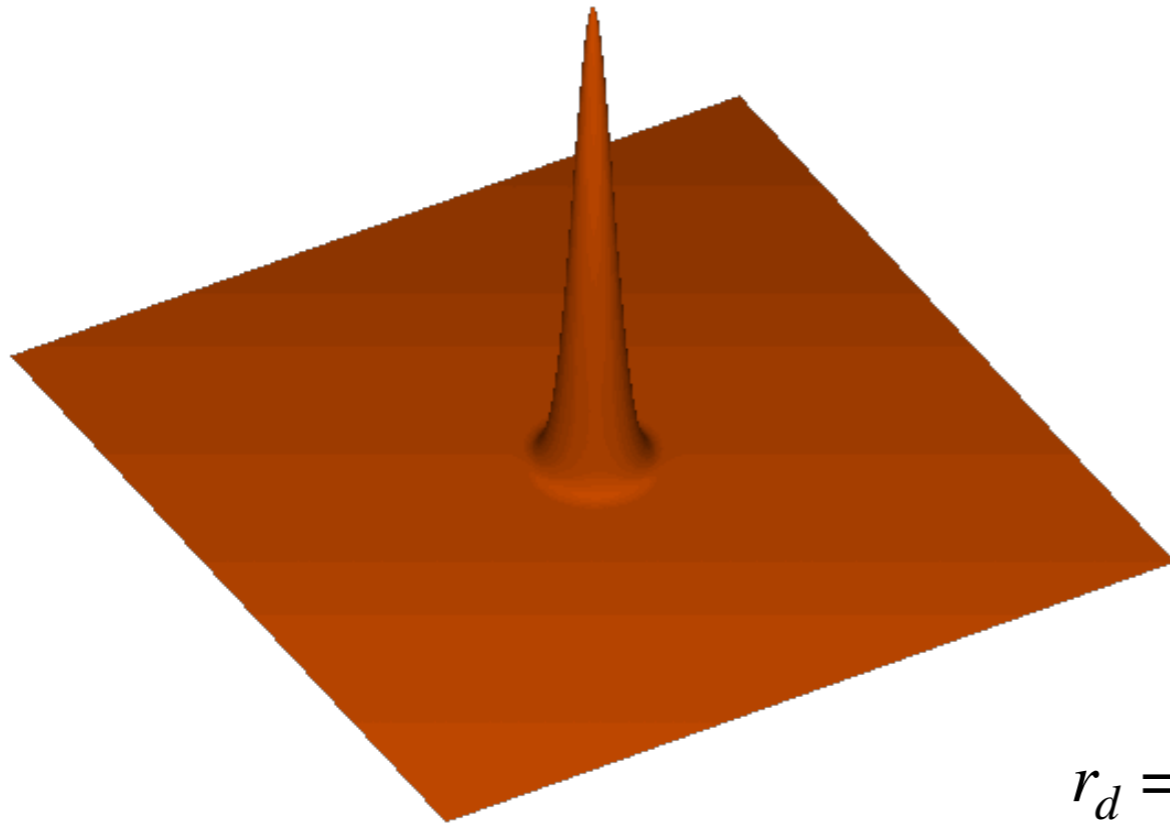


...or one wiggle in configuration space
(2-point correlation function)



How do the BAO wiggles come about?

At recombination ($z \sim 1000$, $t \sim 300,000$ yrs)



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

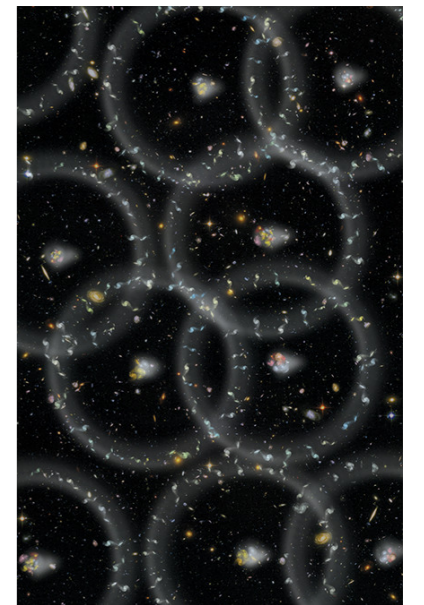
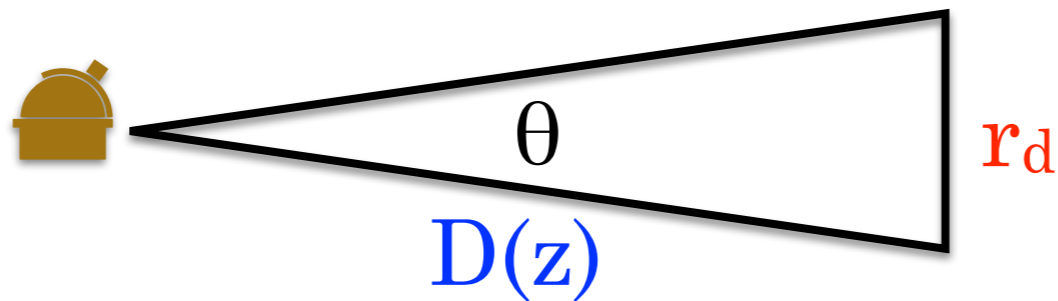
$$r_d = \frac{c}{\sqrt{3}} \int_0^{a_*} \frac{da}{a^2 H(a) \sqrt{1 + \frac{3\Omega_B}{4\Omega_\gamma} a}} \simeq 150 \text{ Mpc}$$

Eisenstein, Seo et al (2007)

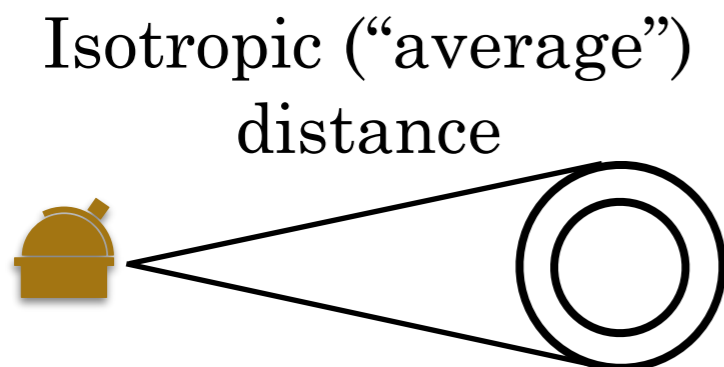
A feature is imprinted the distance that the wave has traveled between the Big Bang and recombination

\Rightarrow the sound horizon distance at recombination ($r_d \simeq 150$ Mpc)

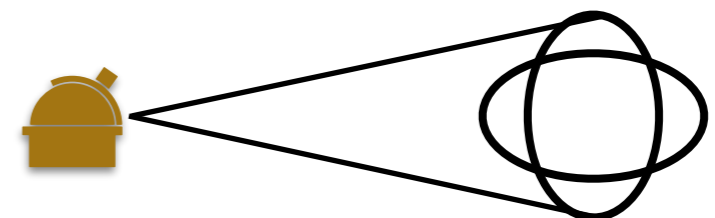
Baryon Acoustic Oscillations



- 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



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**
- We have been writing 2 key papers (I am analysis co-coordinator)
- 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 \sim summer 2024. Expect constraints on cosmic growth; highly complementary to BAO.



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)



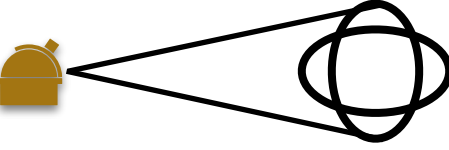
DESI Y1 analysis at UMich

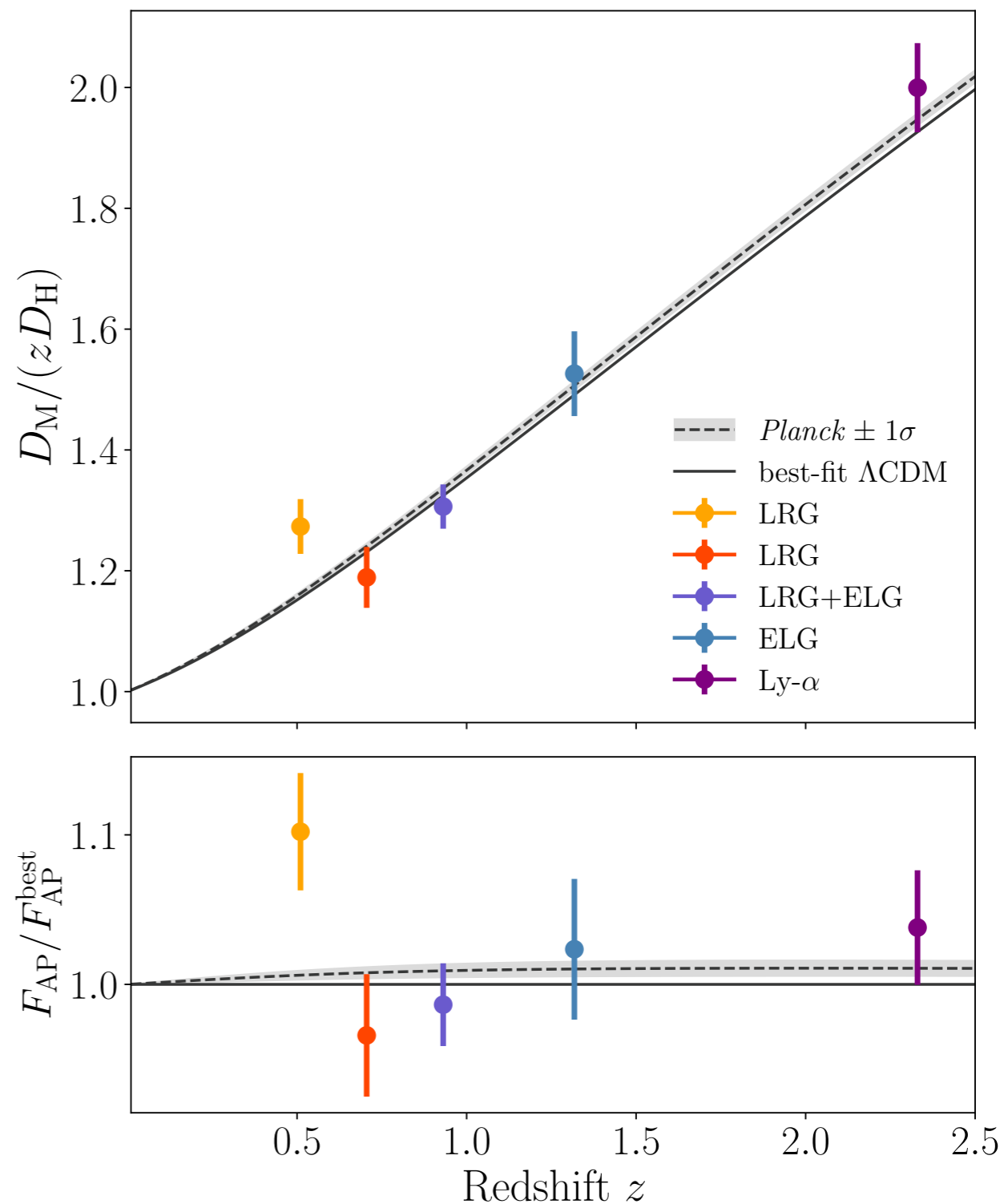
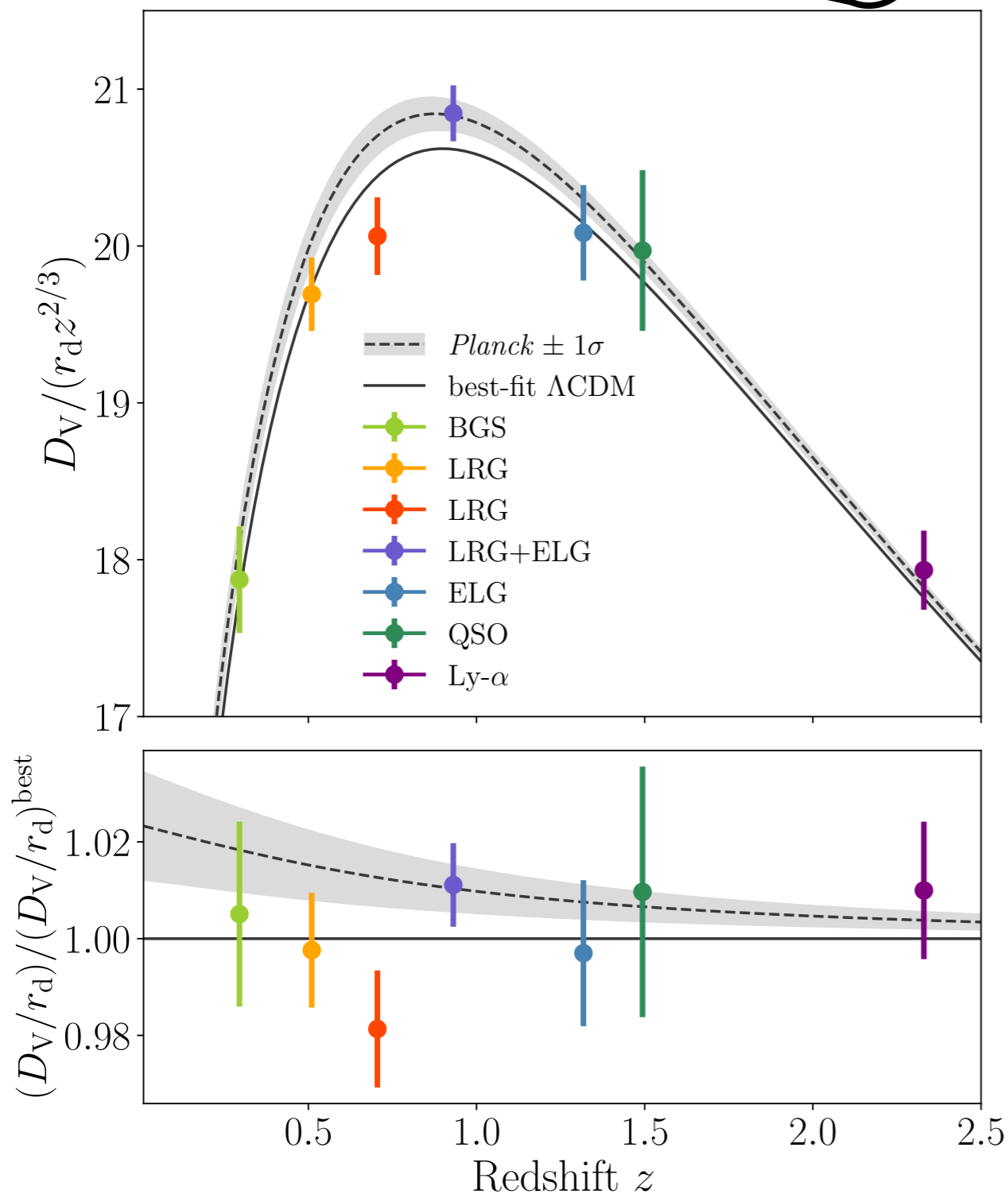
DESI Y1

Cosmological Results

DESI Y1 measurements: compression to distances

$D_{\text{isotropic}} / r_d$ 

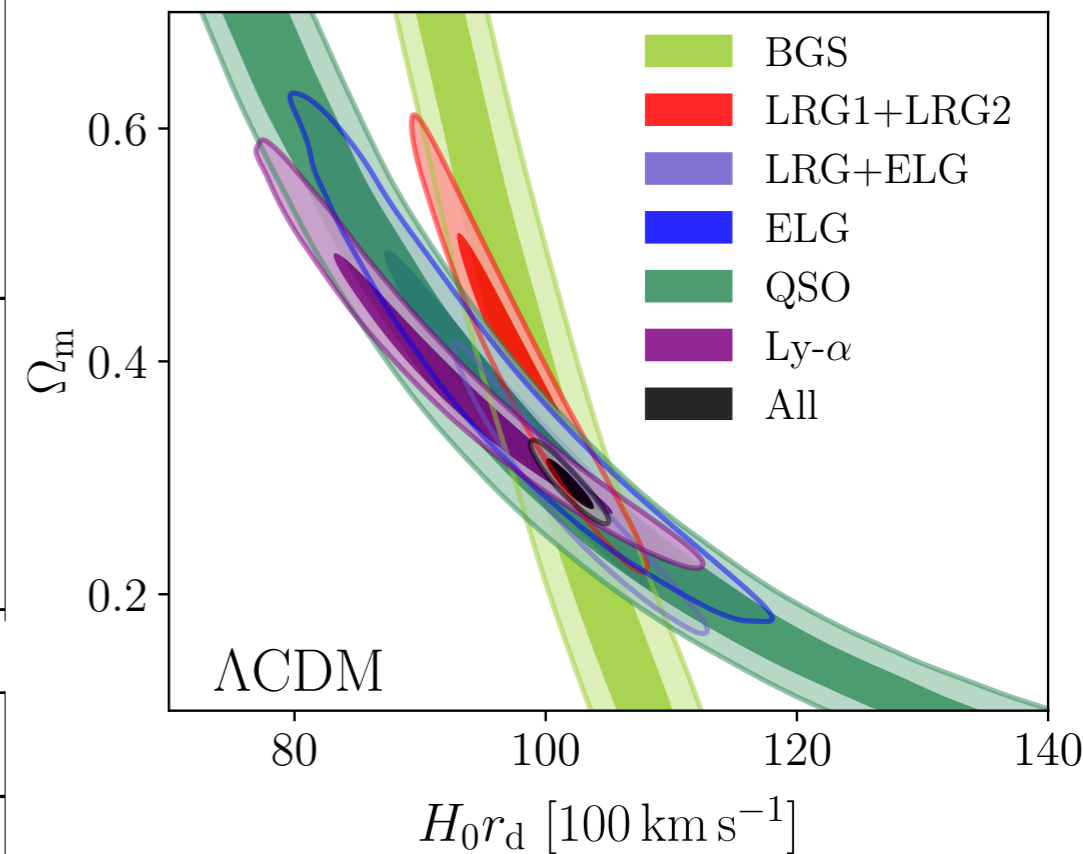
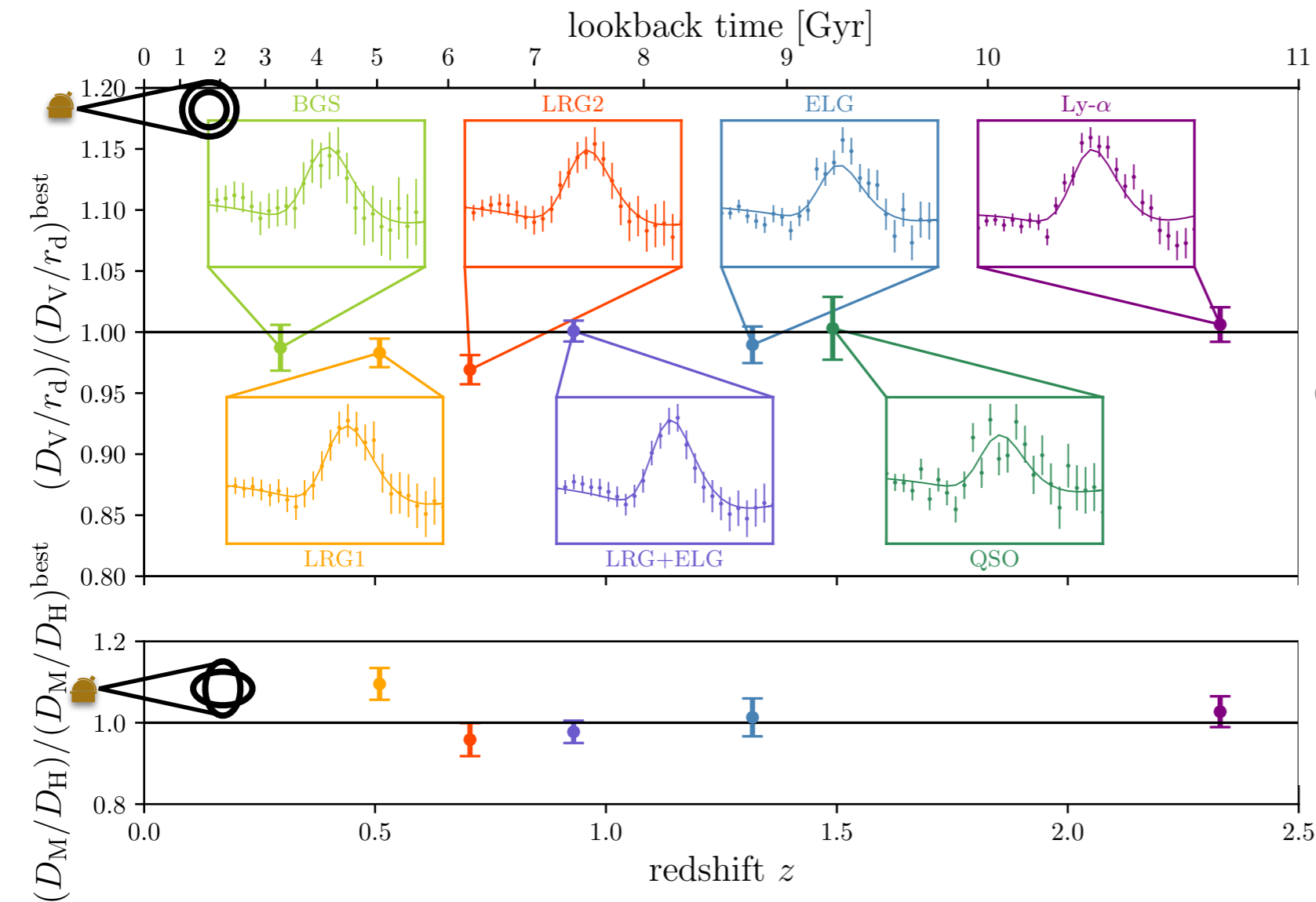
$D_{\text{transverse}} / D_{\text{line-of-sight}}$ 



Unblinded on December 12, 2023

Constraints from DESI Y1 BAO

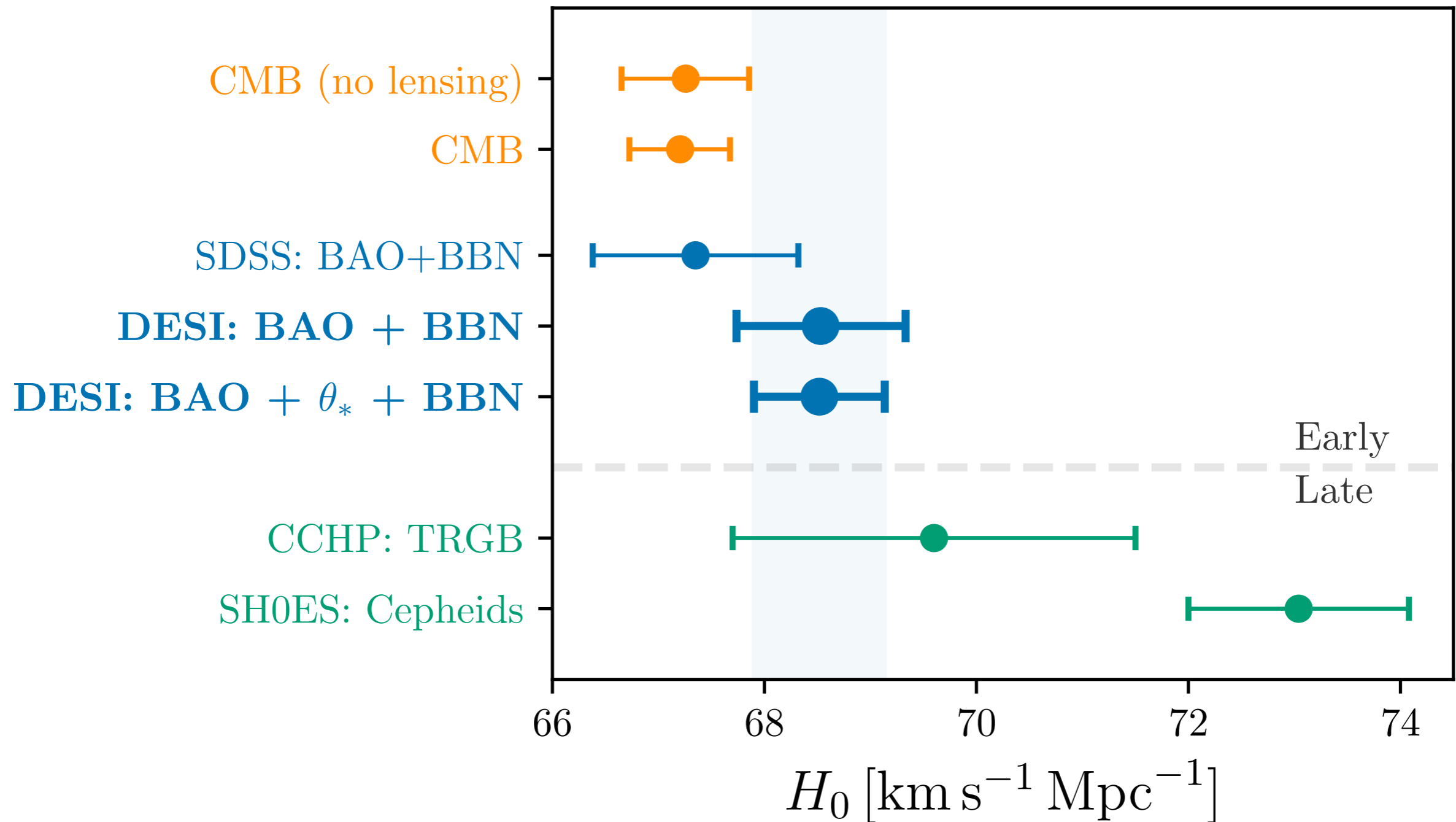
Basic constraints in Λ CDM model



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

$$r_d H_0 = (101.8 \pm 1.3) [100 \text{ km/s}] \quad (1.3\%)$$

Hubble constant



$$H_0 = (68.52 \pm 0.62) \text{ km/s/Mpc} \quad (\text{DESI} + \theta_* + \text{BBN})$$

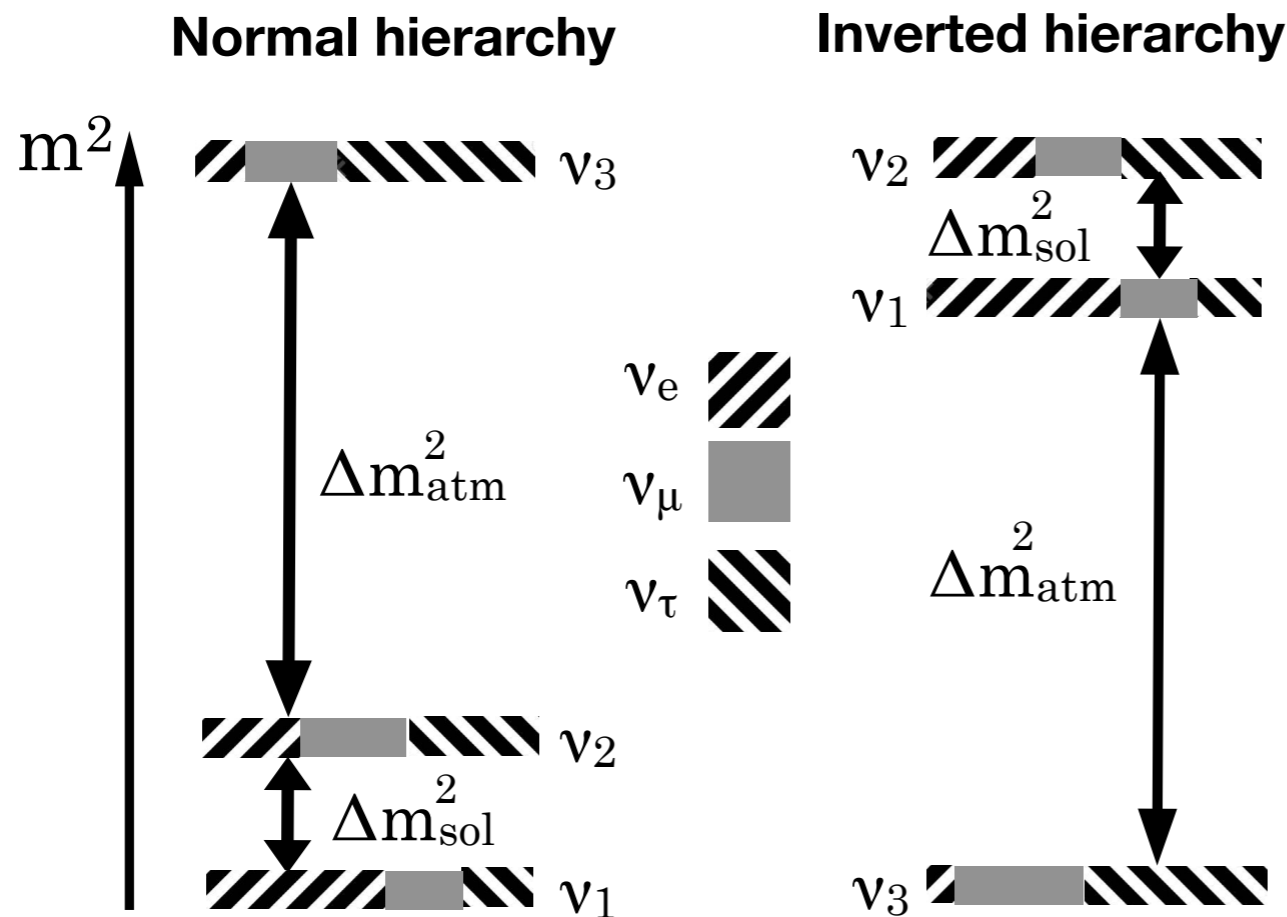
Consistent with CMB measurements

Sum of neutrino masses

From neutrino oscillation experiments

$$\left. \begin{aligned}
 (\Delta m^2)_{\text{sol}} &\approx 8 \times 10^{-5} \text{ eV}^2 \\
 (\Delta m^2)_{\text{atm}} &\approx 3 \times 10^{-3} \text{ eV}^2
 \end{aligned} \right\} \begin{aligned}
 \sum m_i &= 0.06 \text{ eV}^* \quad (\text{normal}) \\
 &\text{vs.} \\
 \sum m_i &= 0.10 \text{ eV}^* \quad (\text{inverted})
 \end{aligned}$$

*(assuming $m_1=0$)



Sum of neutrino masses

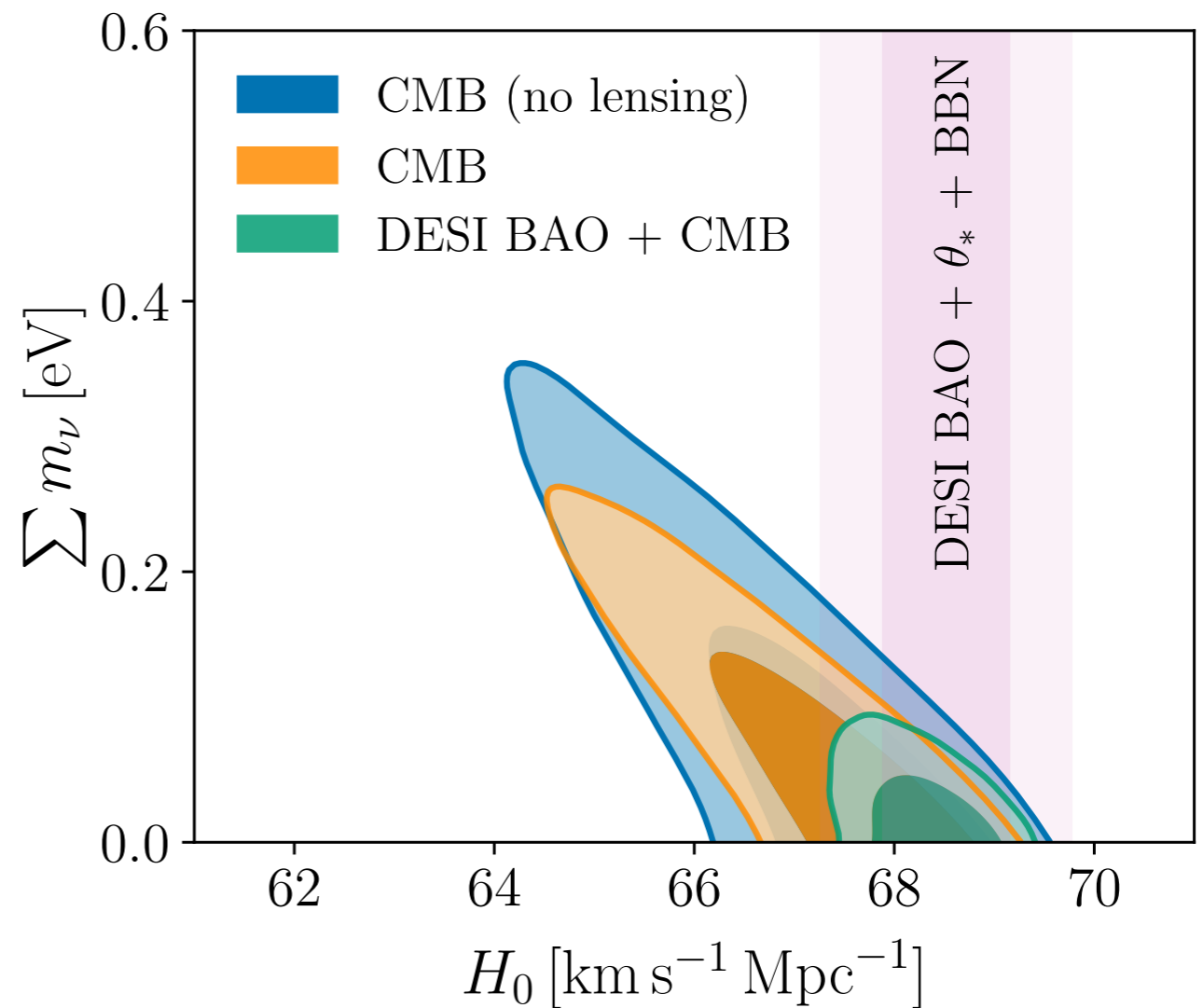
Neutrinos are non-relativistic today

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

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

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

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



[But significantly weakens in models beyond Λ CDM, e.g. $\sum m_\nu < 0.195 \text{ eV}$ in w_0w_a CDM]

Dark energy - constant w

Distances measured by BAO are very sensitive to dark energy

DESI alone:

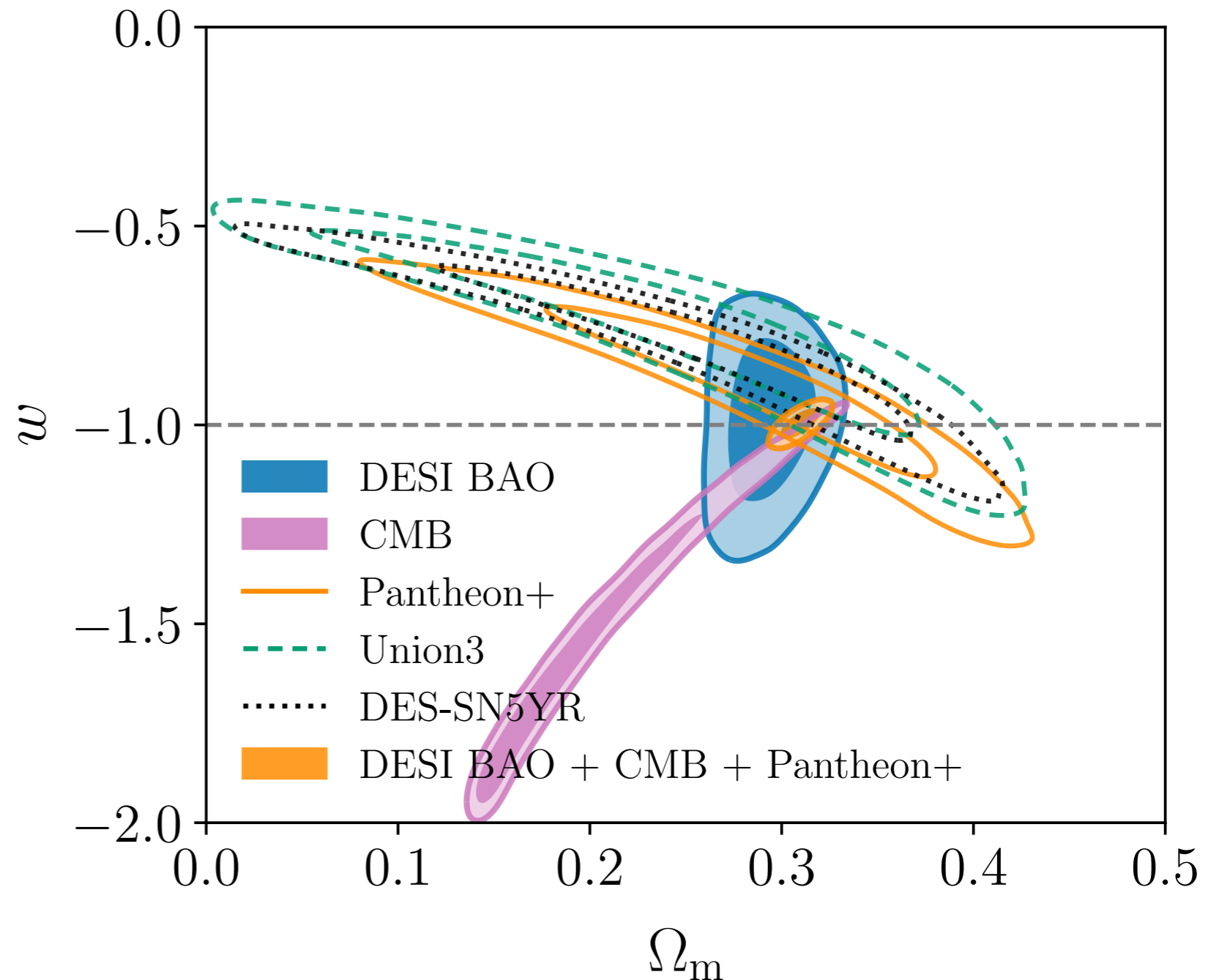
$$\Omega_m = 0.293 \pm 0.015$$

$$w = -0.99^{+0.15}_{-0.13}$$

DESI + CMB + Panth:

$$\Omega_m = 0.3095 \pm 0.0065$$

$$w = -0.997 \pm 0.025$$



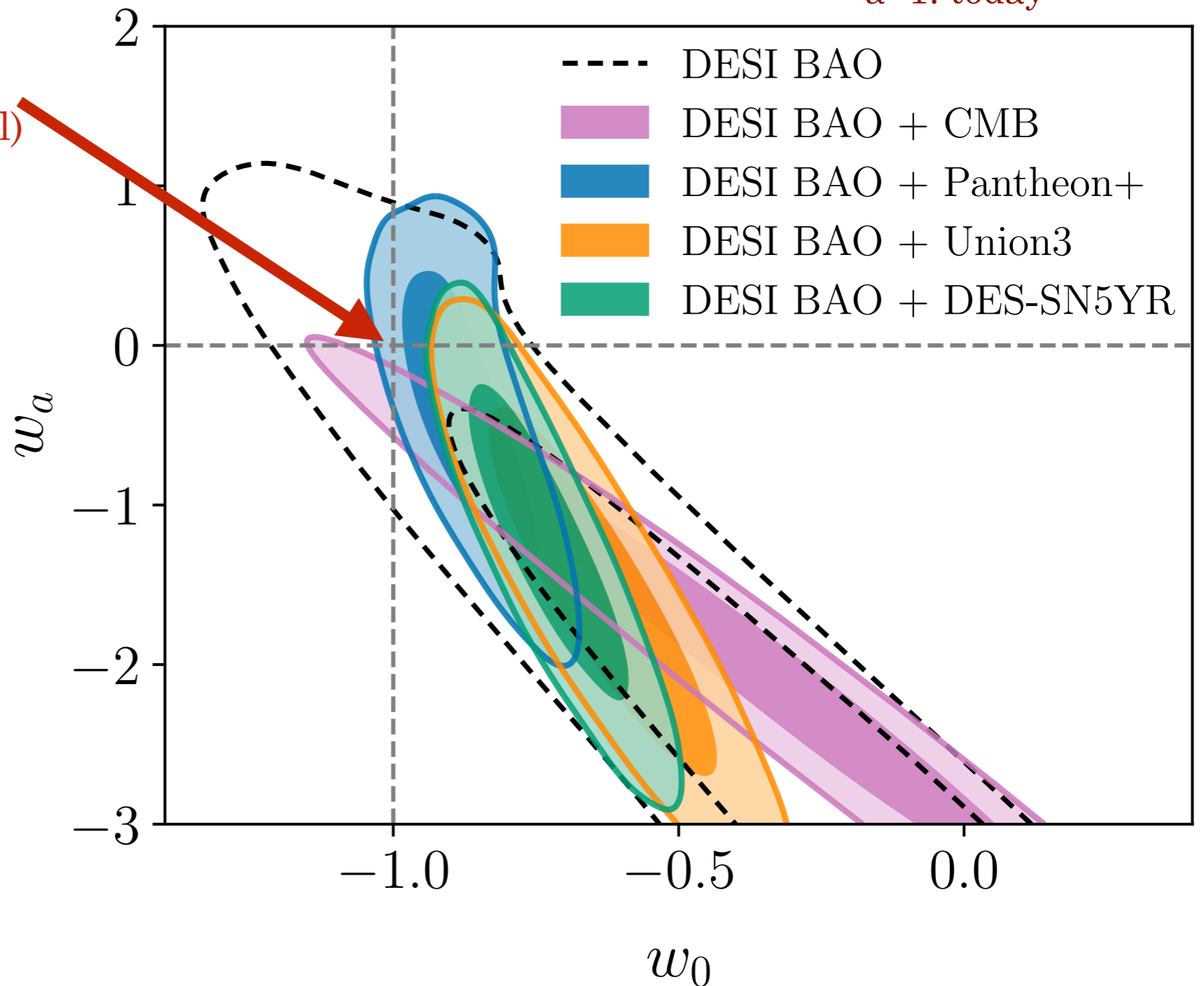
Dark energy - (w_0, w_a)

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

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

Λ CDM
(standard model)

DES I 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 Λ CDM)

DESI+CMB+Union3

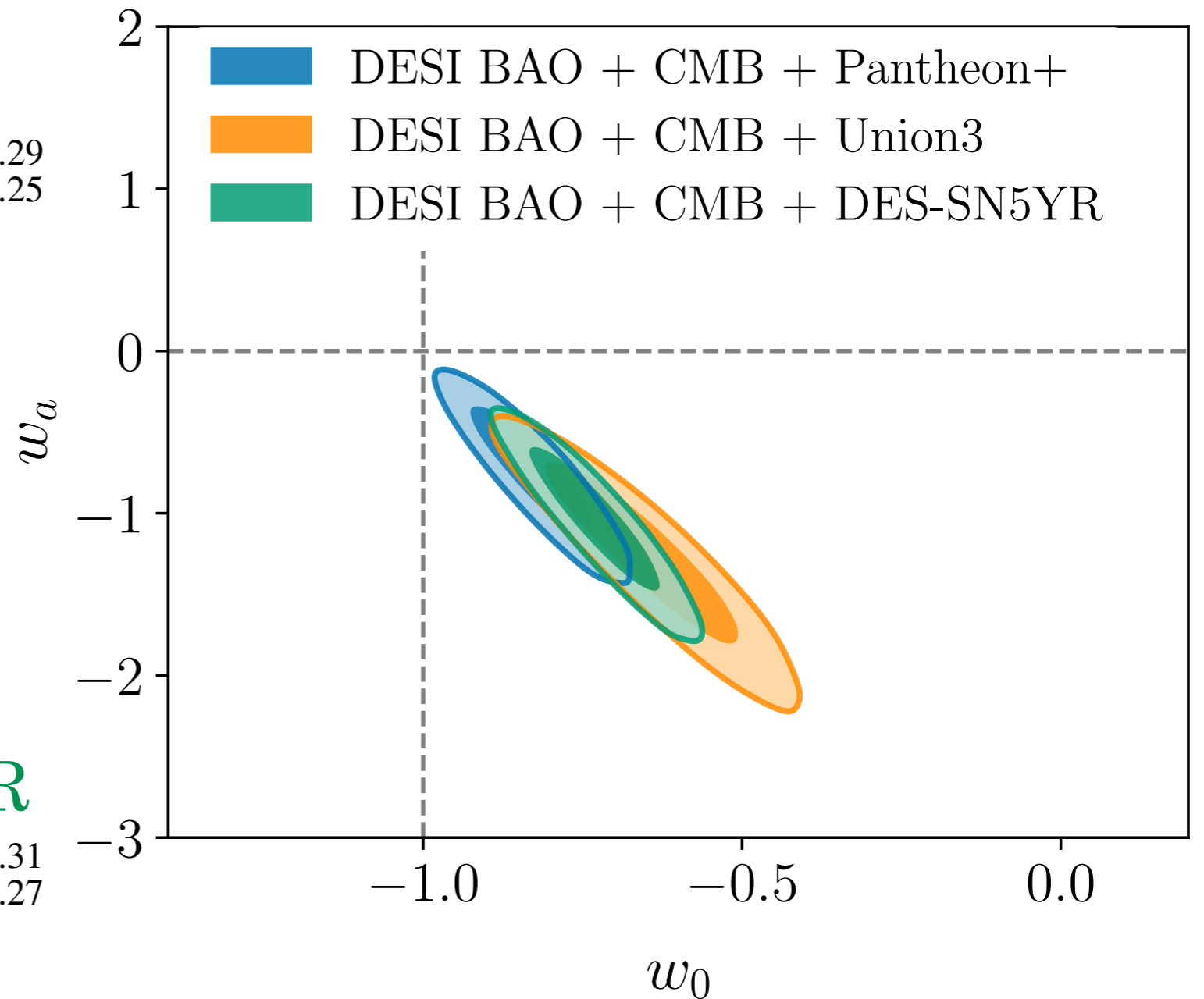
$$w_0 = -0.64 \pm 0.11 \quad w_a = -1.27^{+0.40}_{-0.34}$$

(3.5σ away from Λ CDM)

DESI+CMB+DES-SN5YR

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

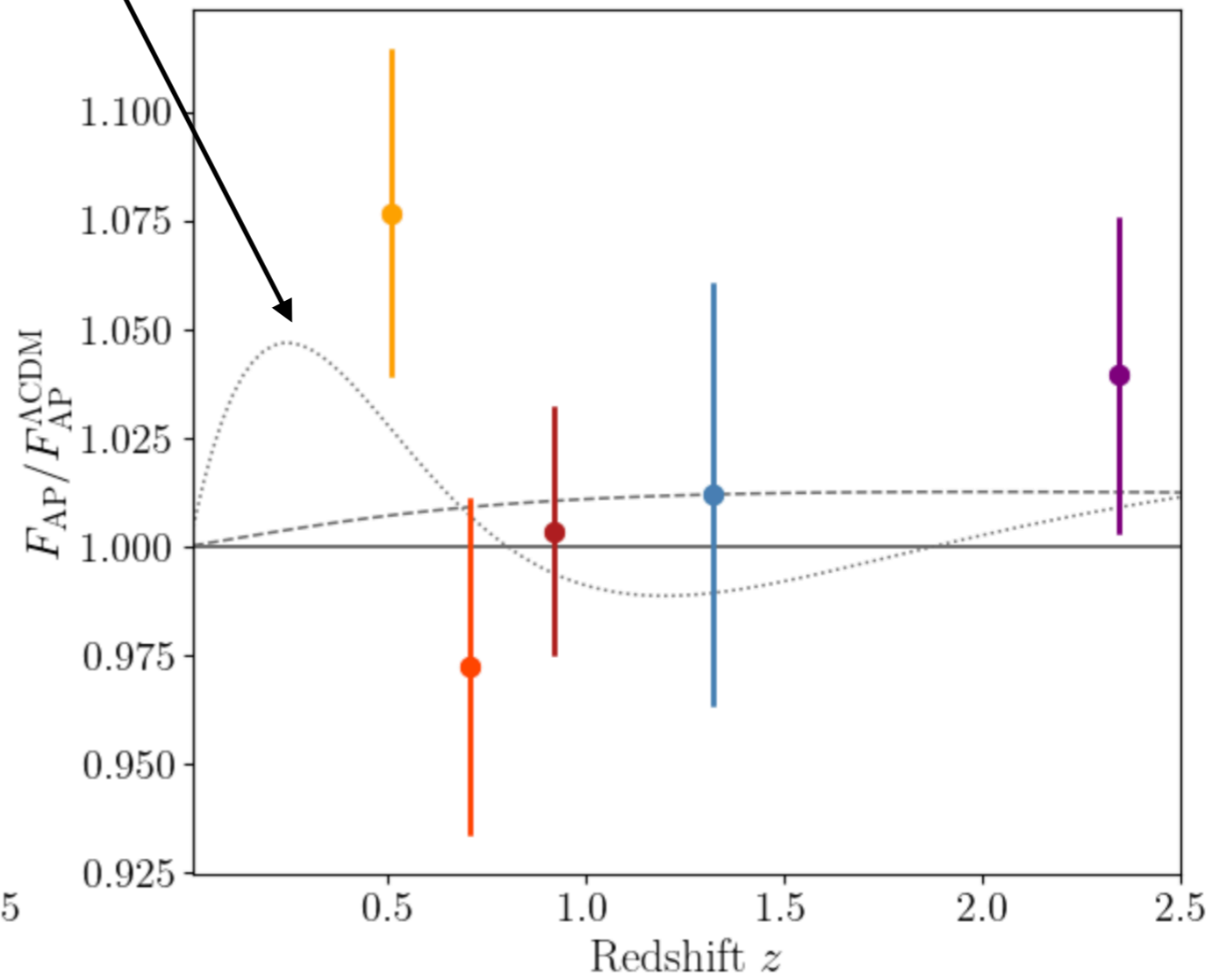
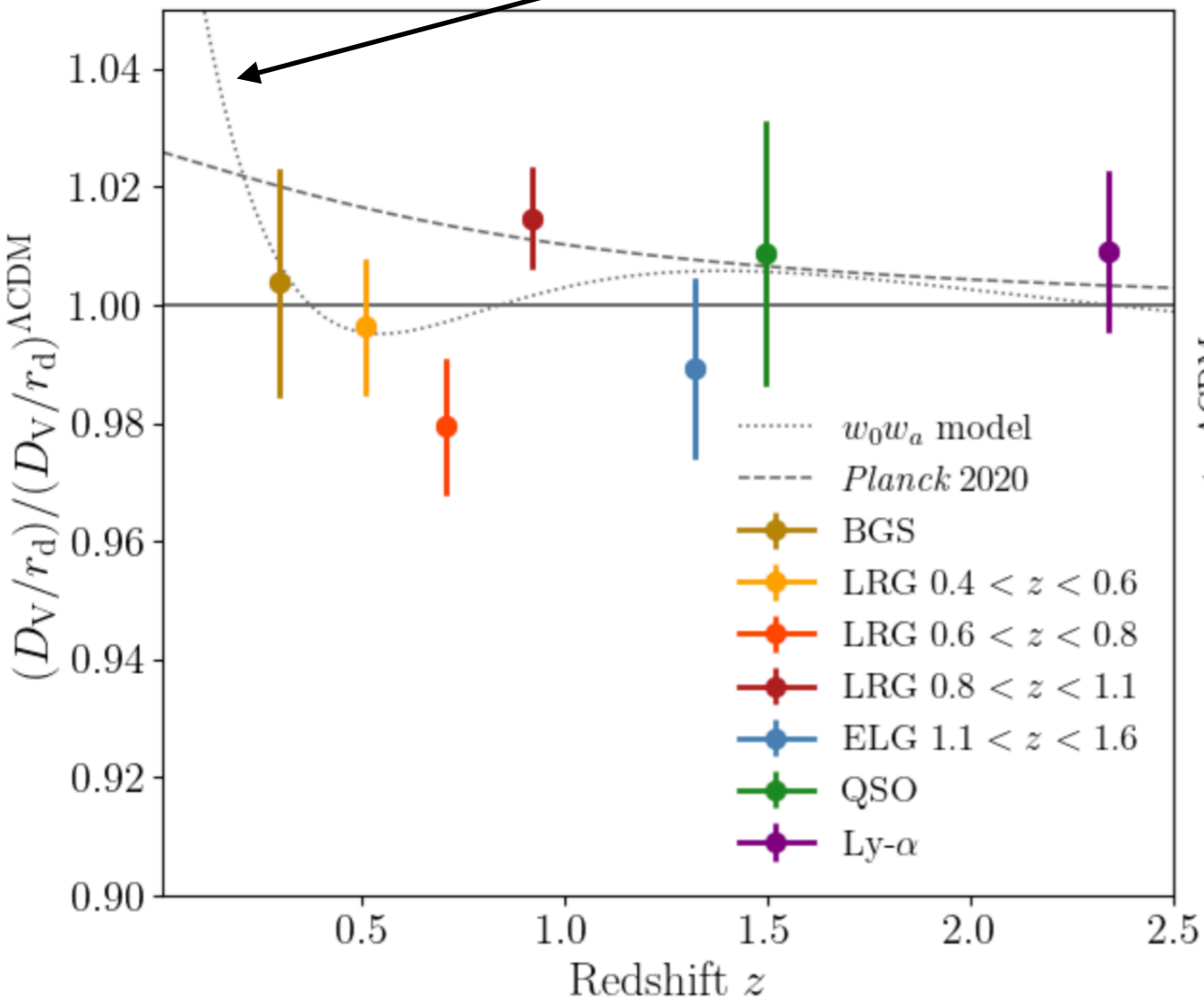
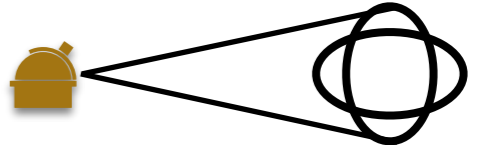
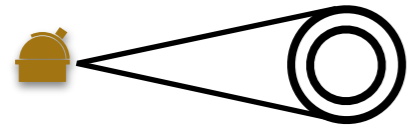
(3.9σ away from Λ CDM)



Therefore: tantalizing hints of departure from Λ CDM

Dark energy: what the data prefer

best-fit w_0w_a model



What's next

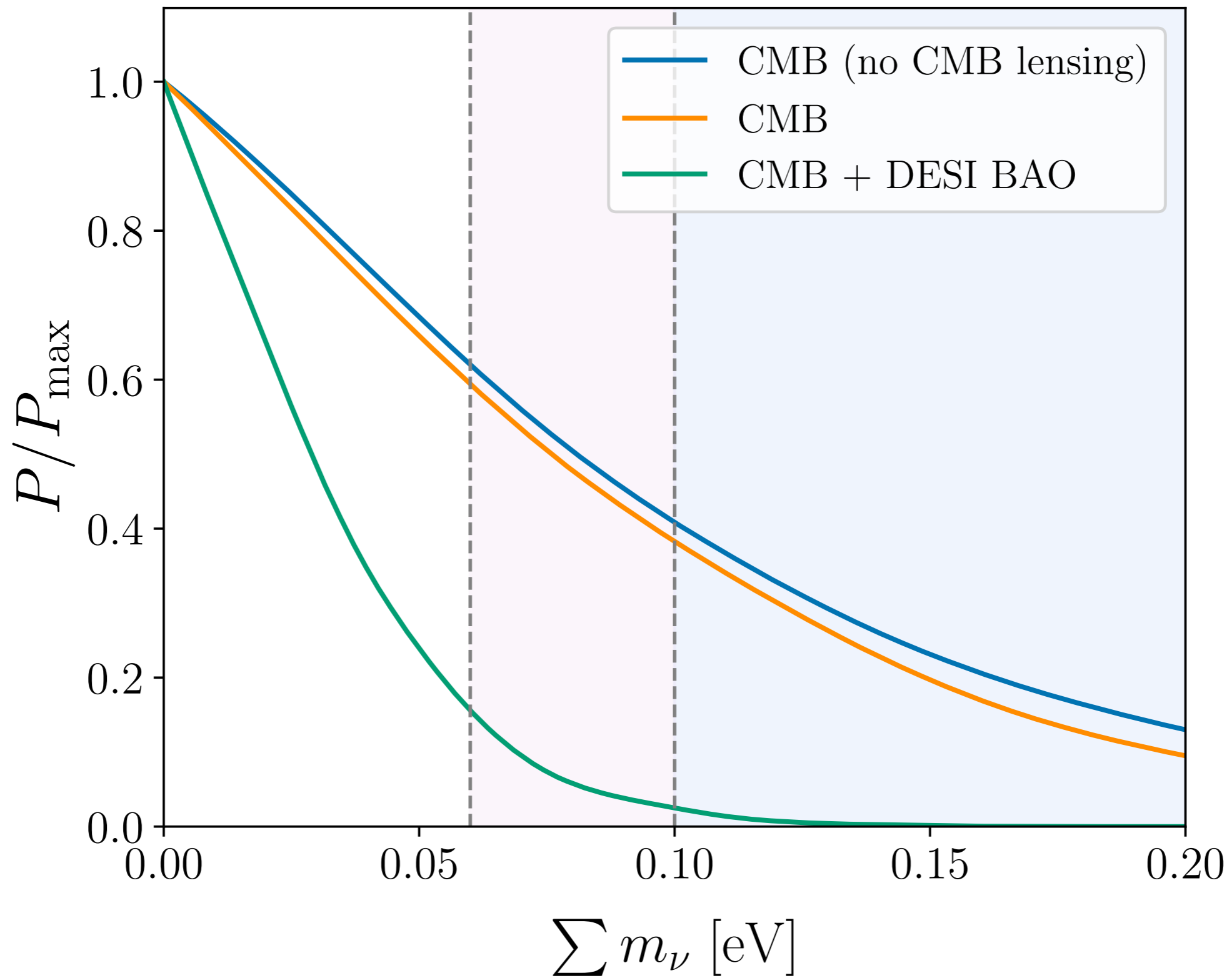
- The results presented here were just the BAO; **DESI Y1 full-shape analysis of galaxy clustering is forthcoming** (~summer 2024)
- There will be a number of significant new analyses from DESI Y1:
 - correlation of DESI with photometric surveys (coordinated by UM postdoc \Rightarrow American Univ. professor Johannes Lange)
 - 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)

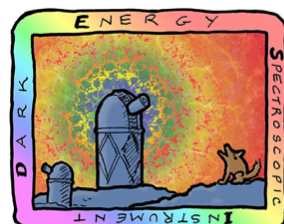
Conclusions

- Dark Energy is a premier mystery in physics/cosmology; physical reason for accelerating universe still an open question
- Impressive variety of new data; forthcoming: DES Y6, HSC, Hetdex; DESI, LSST, Euclid, Roman.
- 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
 - $\sum m_\nu < 0.072$ 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
 - DESI Y3, Y5

Extra slides

Sum of neutrino masses

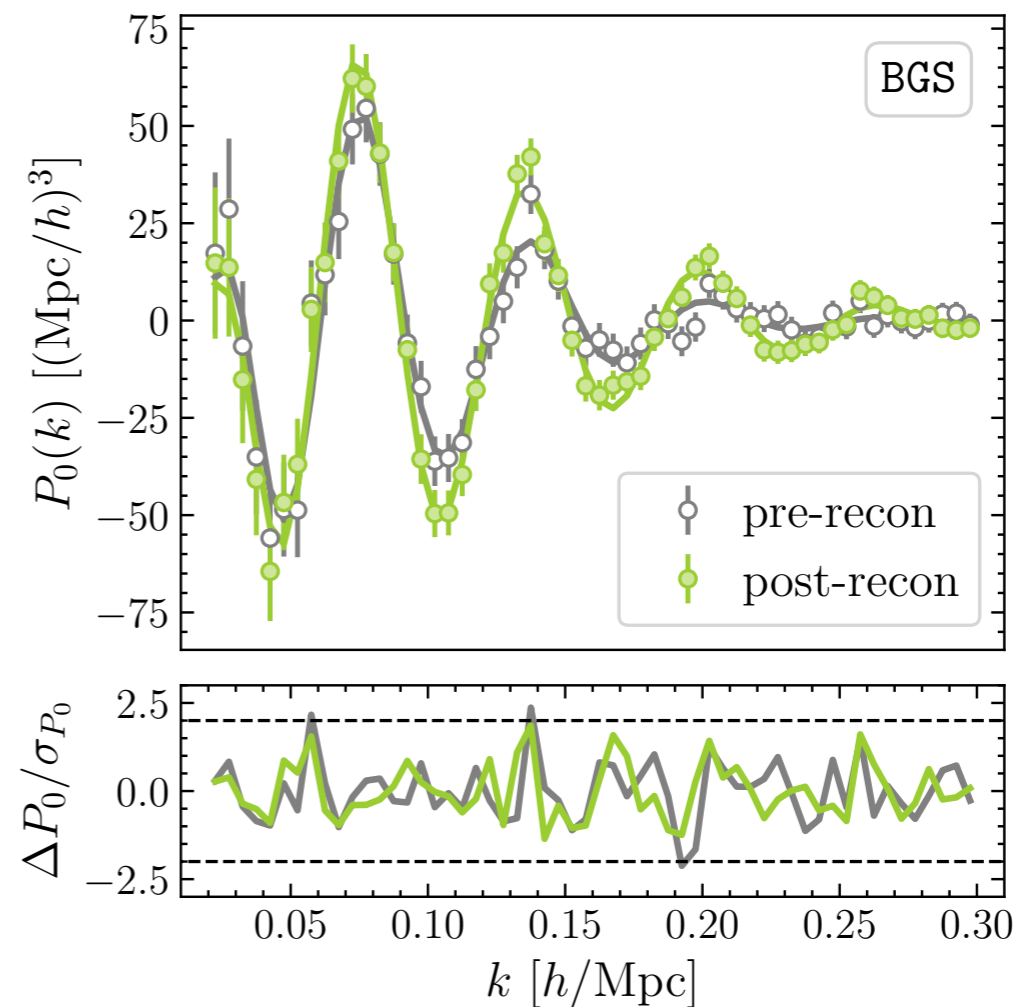
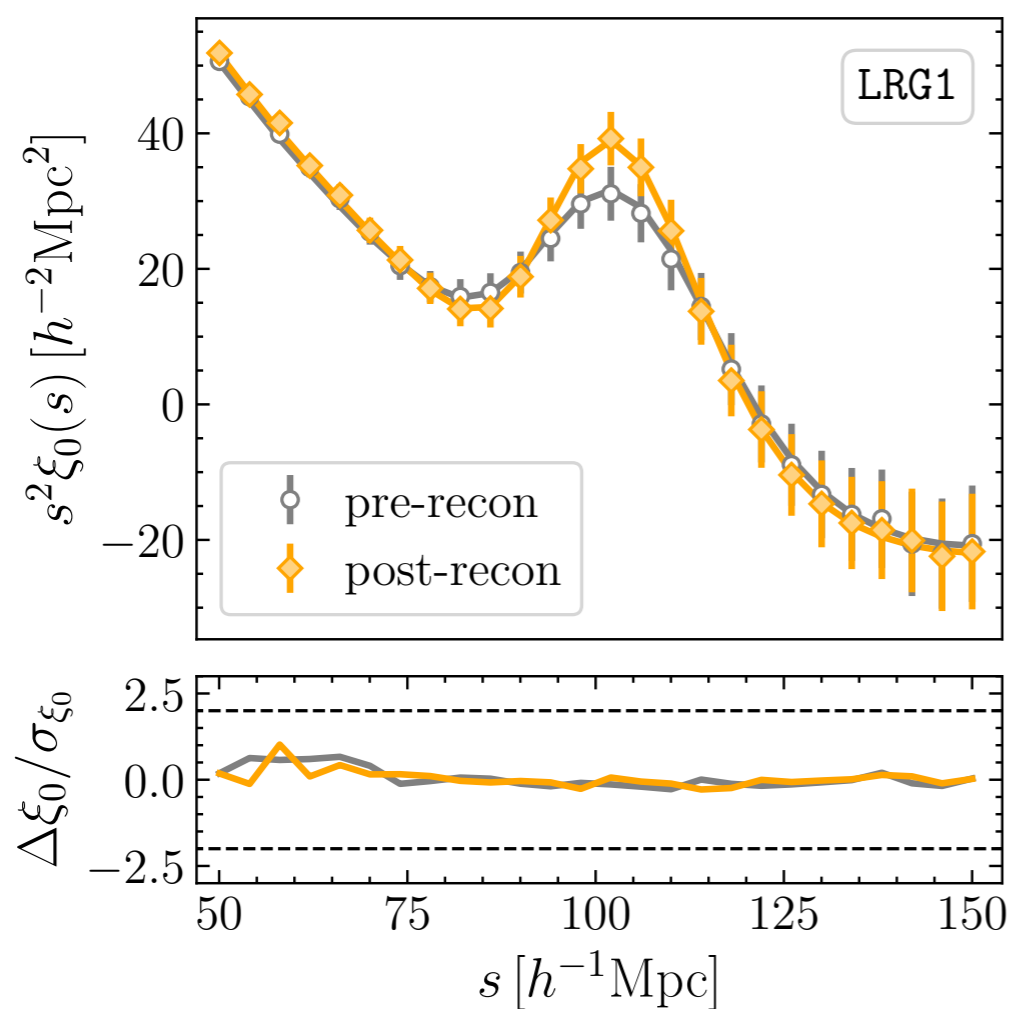




DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

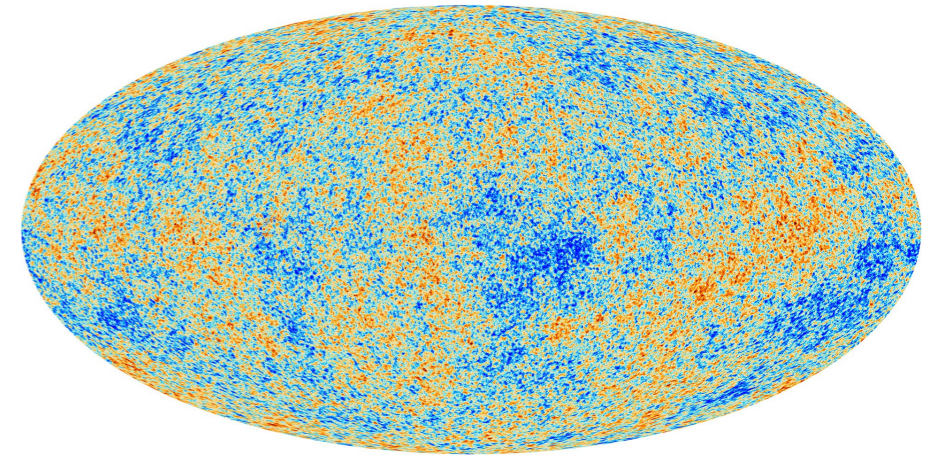
Density field reconstruction



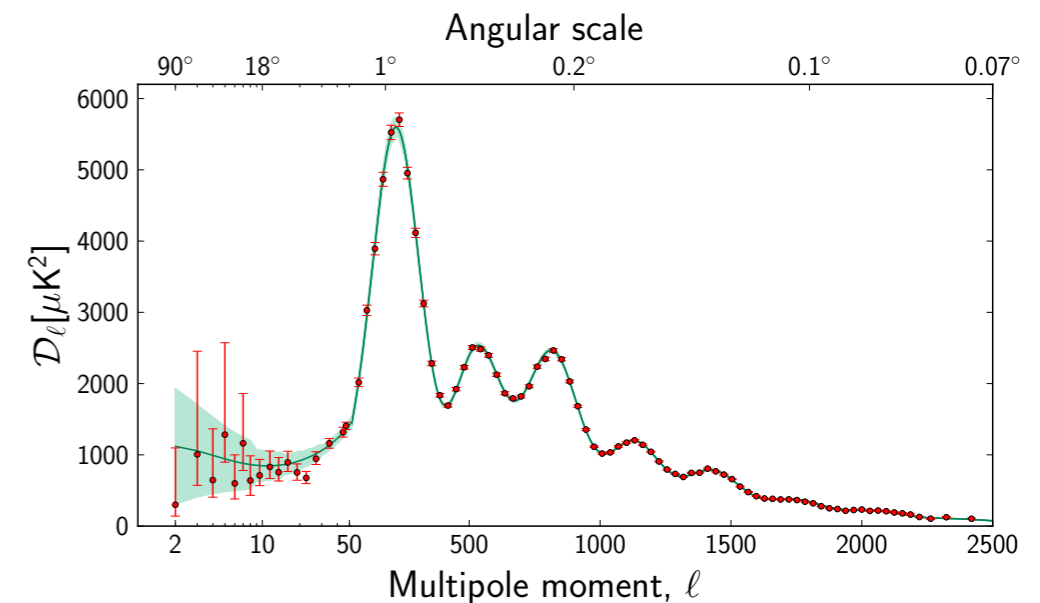
Refurbishes the ruler – **improves both precision and accuracy**

CMB measurement of H_0

H_0 is a “derived parameter” in the CMB - no special signature, but constrained very well.



Planck (2018) finds:



$$H_0 = (67.36 \pm 0.54) \text{ km/s/Mpc} \quad [\text{flat } \Lambda\text{CDM}]$$

$$H_0 = (63.6 \pm 2.2) \text{ km/s/Mpc} \quad [\text{curved } \Lambda\text{CDM}]$$

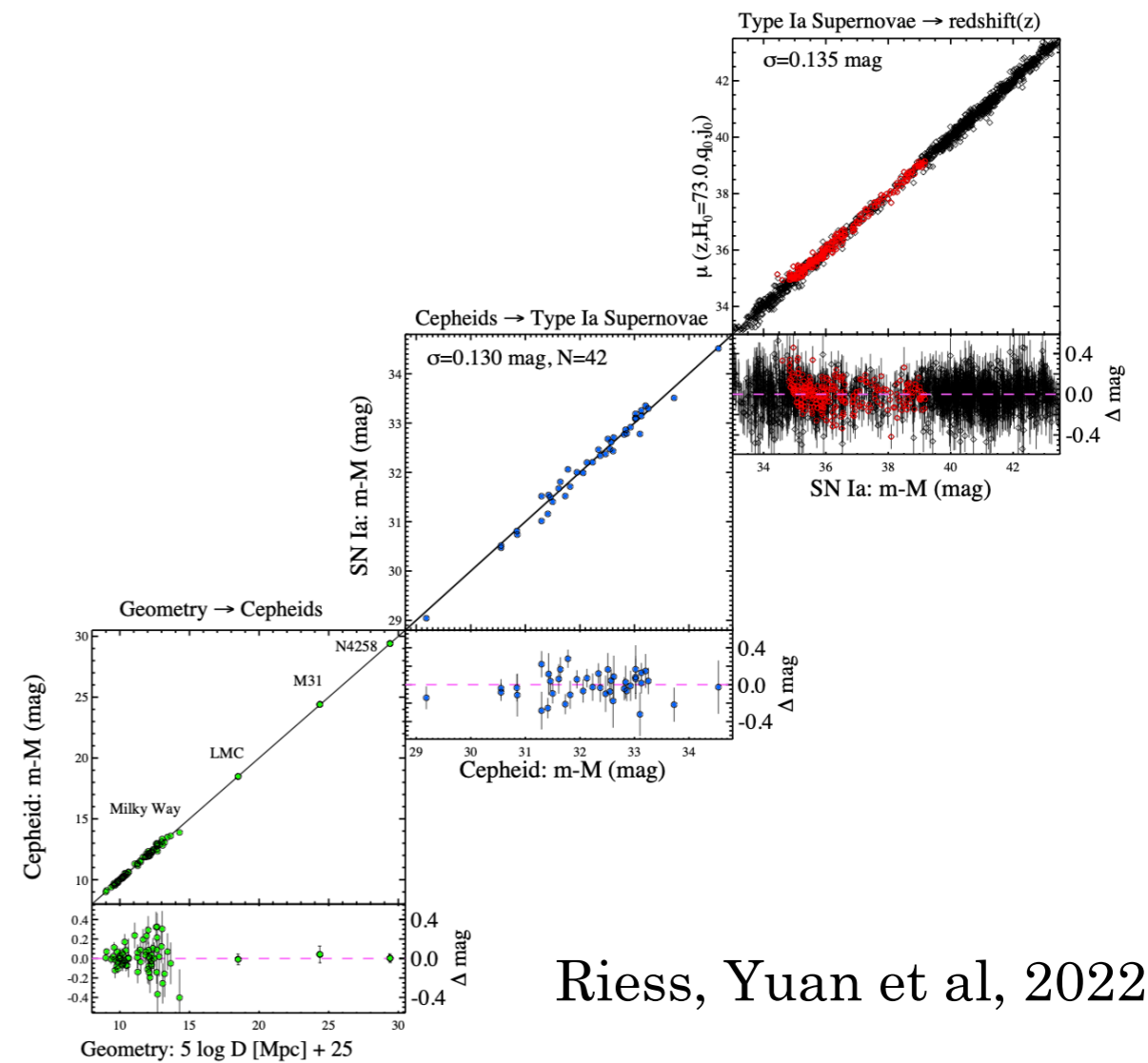
Distance-ladder measurements of H_0

starting with

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

we get

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



Riess, Yuan et al, 2022

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

- Therefore, the simplest “model” for Hubble tension - sample variance - is firmly ruled out
- This leaves many (~1000!) other models, most/all of which are fine-tuned



Clashing Cosmic Numbers Challenge Our Best Theory of the Universe

By [Liz Kruesi](#)

January 19, 2024

That kind of fine-tuned model, where an additional type of dark energy surges for a moment and then fades out, is too complicated to explain what’s happening, said [Dragan Huterer](#), a theoretical cosmologist at the University of Michigan. And other proposed solutions to the Hubble tension tend to match observations even more poorly. They’re “hopelessly tuned,” he said, like just-so stories that are too specific to be in step with the long-held idea that simpler theories tend to win out against complex ones.

H_0 tension - theory

- There are literally hundreds of models out there
- **However, there is only ONE simple model.**

Sample/cosmic variance?

⇒ Global H_0 is ~ 67 , but H_0 in our local volume is ~ 73
(equivalent to: “we live in a void”)

However that model is completely ruled out.

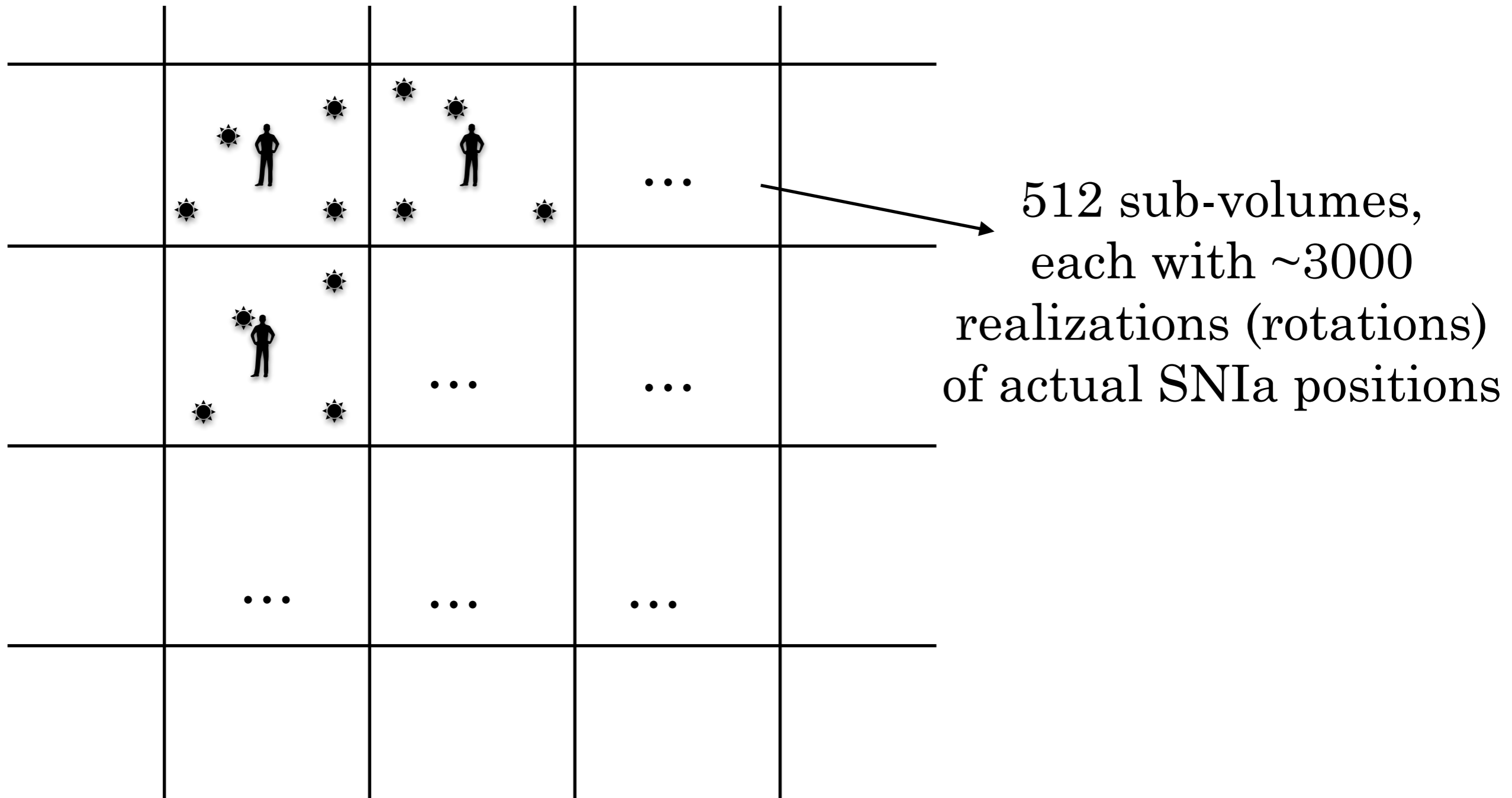
Wu & Huterer (2017), Kenworthy, Scolnic & Riess (2019)

essentially because local measurements map out a pretty
big local volume (so cosmic variance is small)

as explained on next slide...

We determined the **sample variance** of H_0 from the distance-ladder measurement by repeating the analysis **~ 1.5 million times** on numerical (Nbody) LCDM simulations

Wu & Huterer (2017)

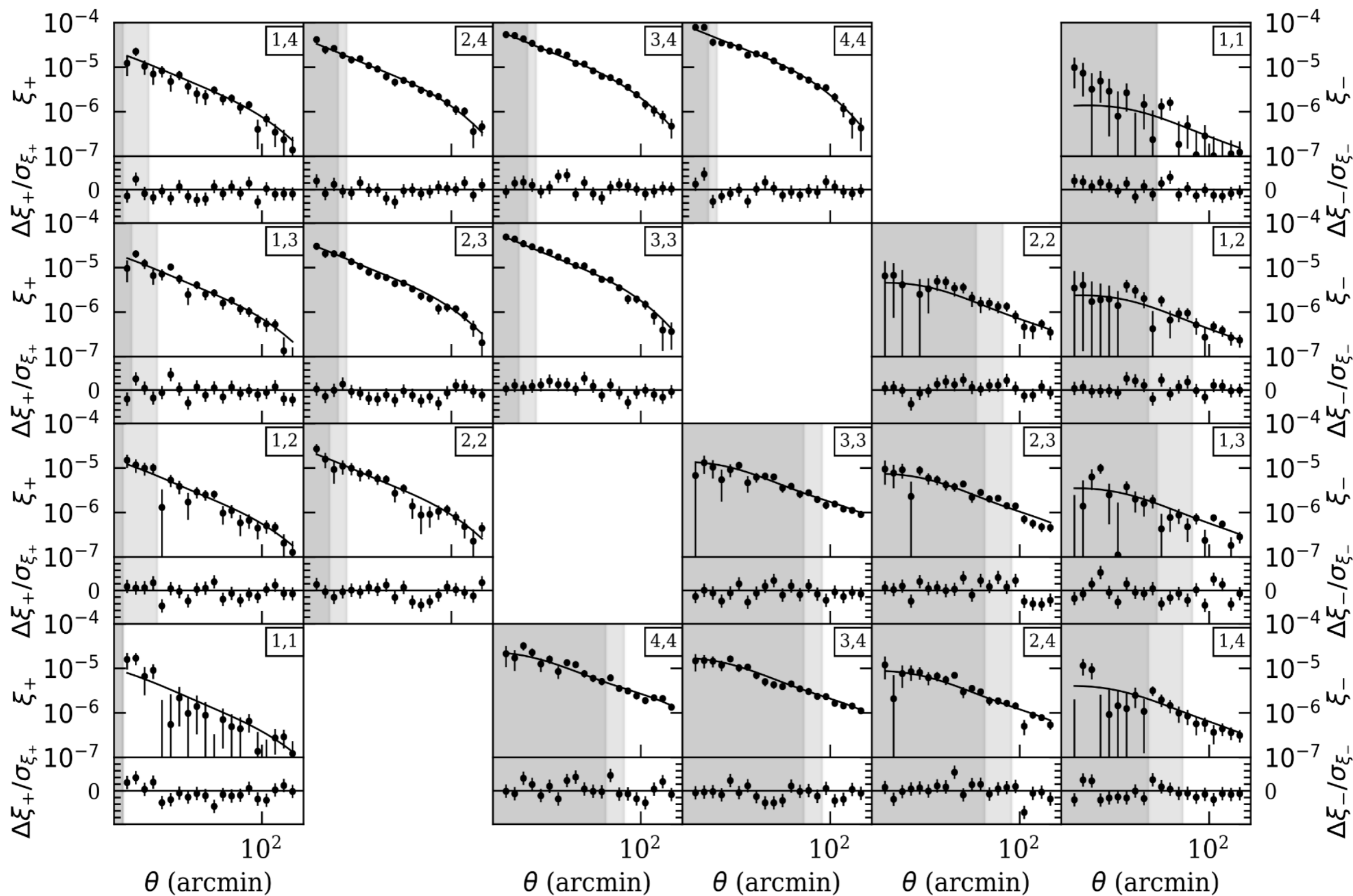


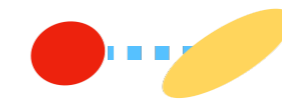
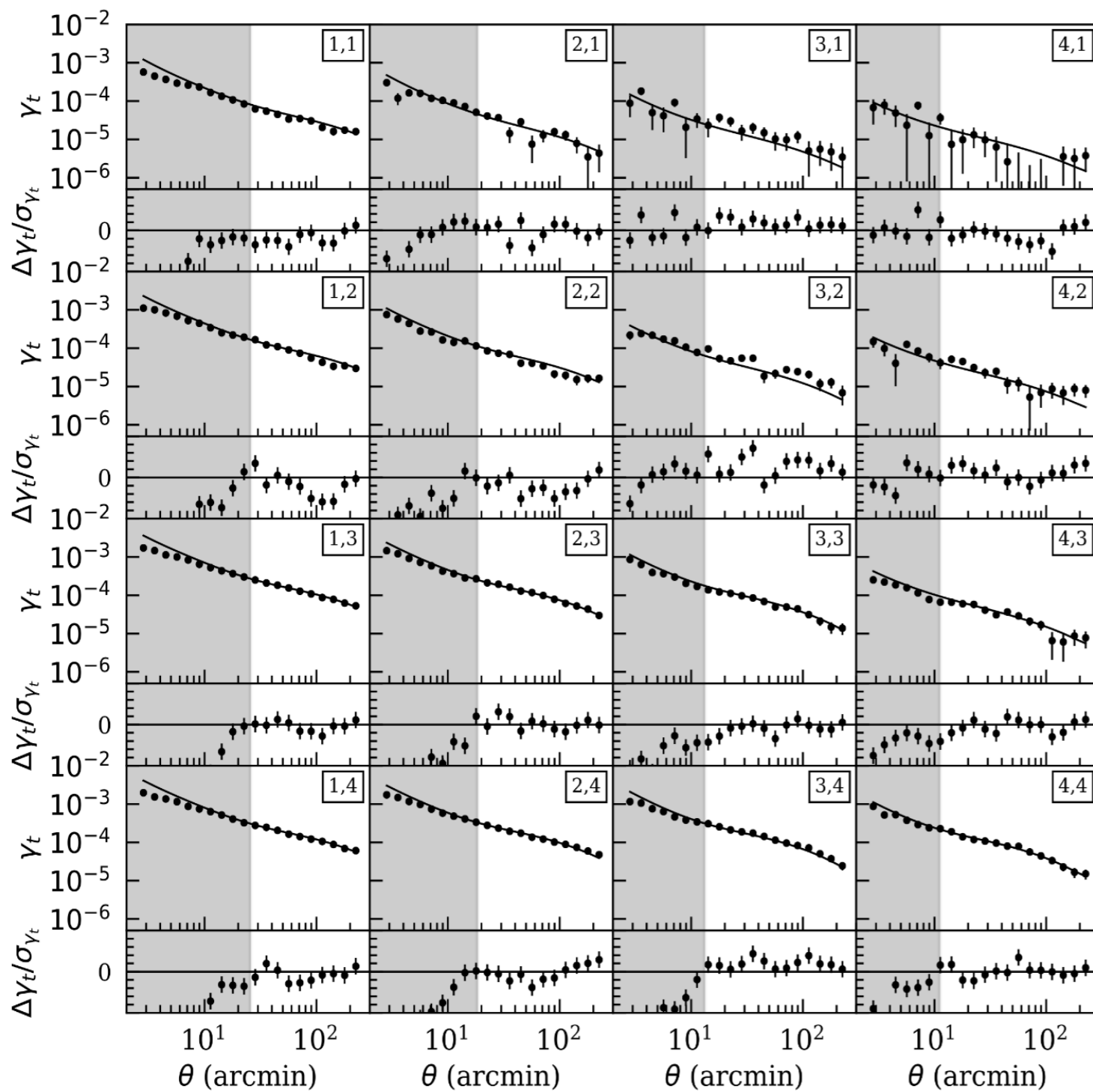
$$\sigma^{\text{CV}}(H_0) \simeq 0.3 \text{ km/s/Mpc} \simeq \frac{1}{20} (H_0^{\text{SHOES}} - H_0^{\text{CMB}})$$

DES Y1 Measurements:

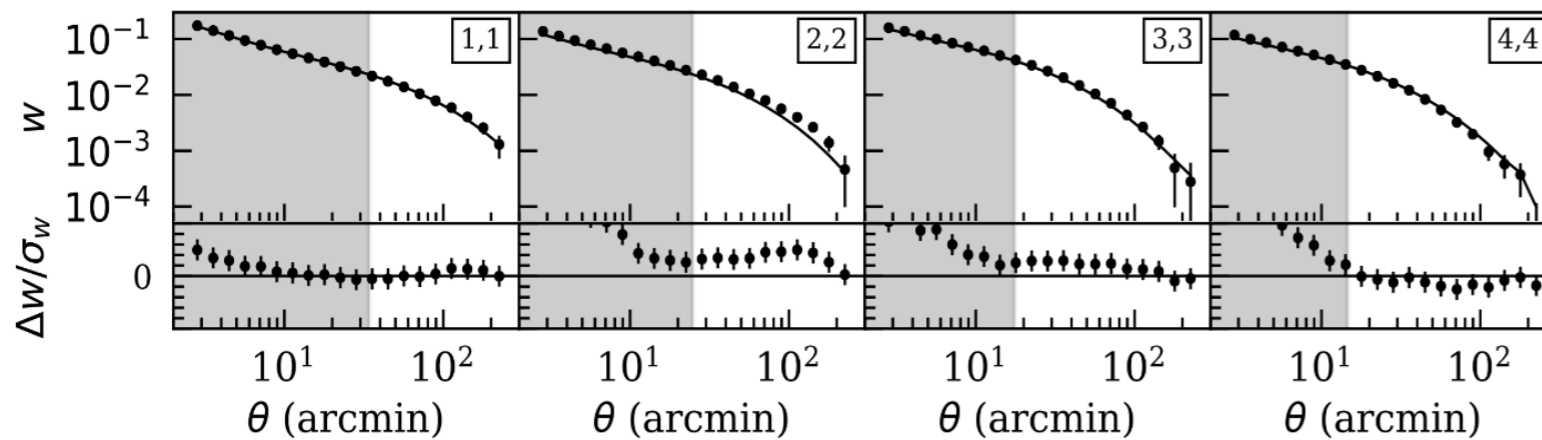
shear clustering, galaxy-galaxy lensing, gal clustering

 **cosmic shear** Amon+, Secco, Samuroff+





galaxy-galaxy lensing
Prat+



galaxy clustering
Rodriguez-Monroy+

(Bizarre) Consequences of DE

- Geometry is not destiny any more! Fate of the universe (accelerates forever vs. recollapses etc) depends on the **future behavior** of DE
- In the accelerating universe, **galaxies are leaving our observable patch** -> the sky will be empty in 100 billion years
- **Under certain conditions** we will have a **Big Rip** - galaxies, stars, planets, our houses, atoms, and then the fabric of space itself will rip apart!