The Universe Caught Speeding: Dark Energy 2 Decades After

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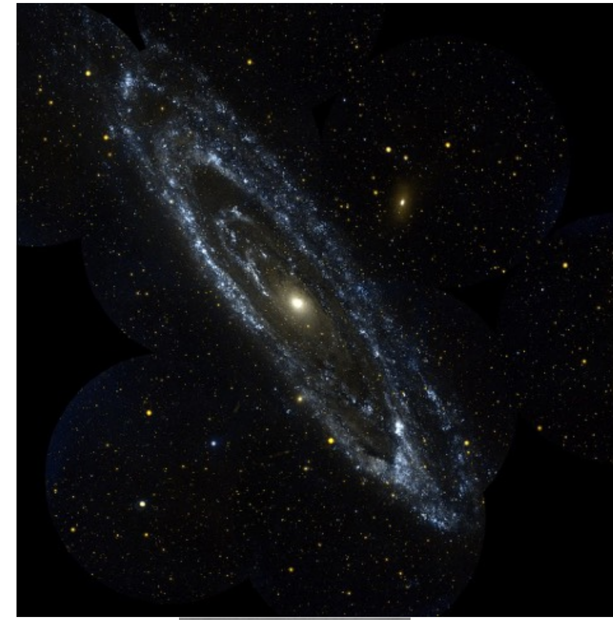
What are these objects?

Hubble Ultra Deep Field

Shapley-Curtis debate

(Washington DC, 1920)

What is the nature of
"spiral nebulae"
(today called galaxies)
such as Andromeda?

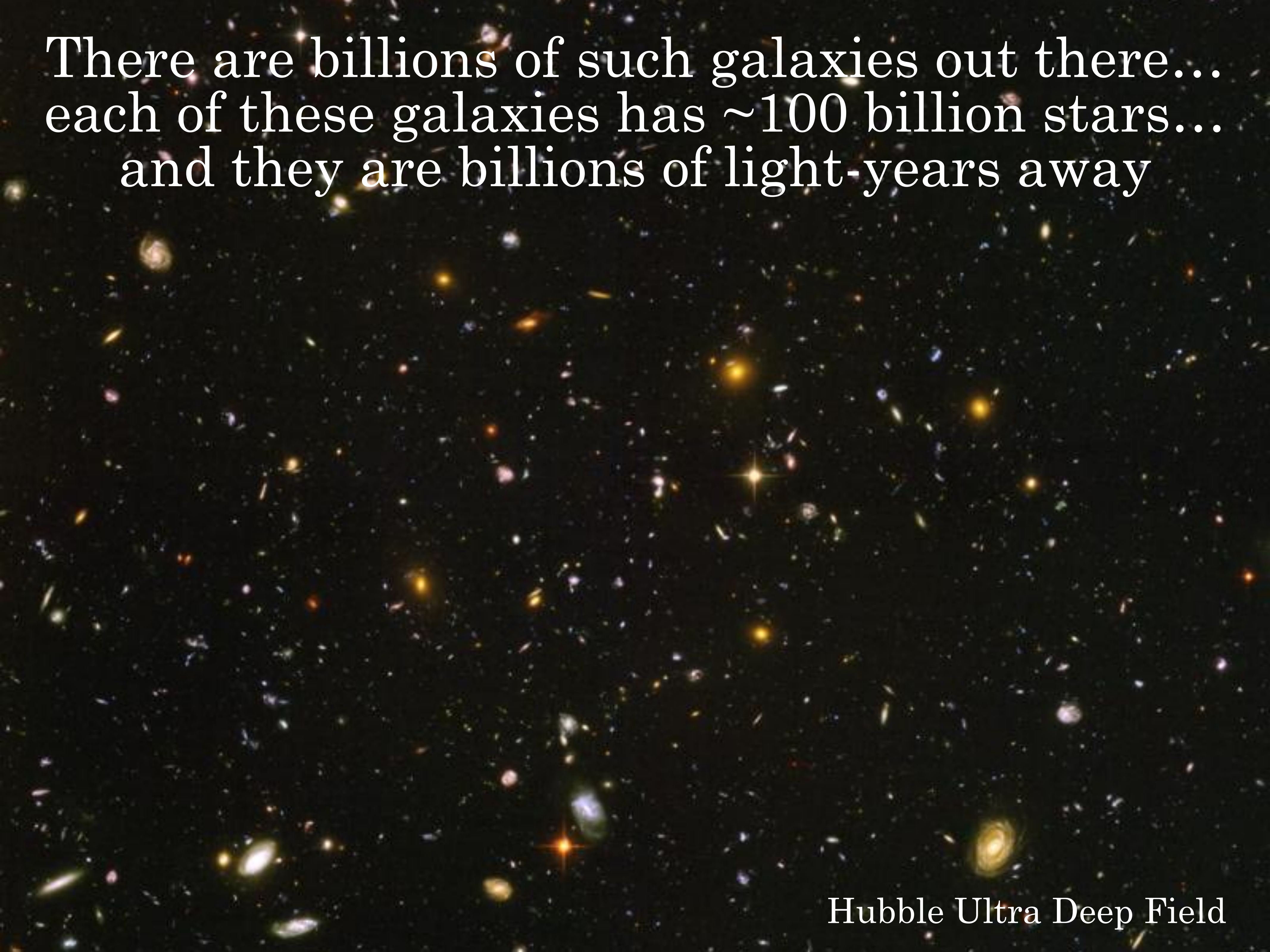


- Shapley: they are all part of **our** Galaxy, the Milky Way

- Curtis: they are **separate** "island universes" (i.e. galaxies)

Curtis was correct!

There are billions of such galaxies out there…
each of these galaxies has ~100 billion stars…
and they are billions of light-years away



Hubble Ultra Deep Field

Edwin Hubble and the Expansion of the Universe (1929)

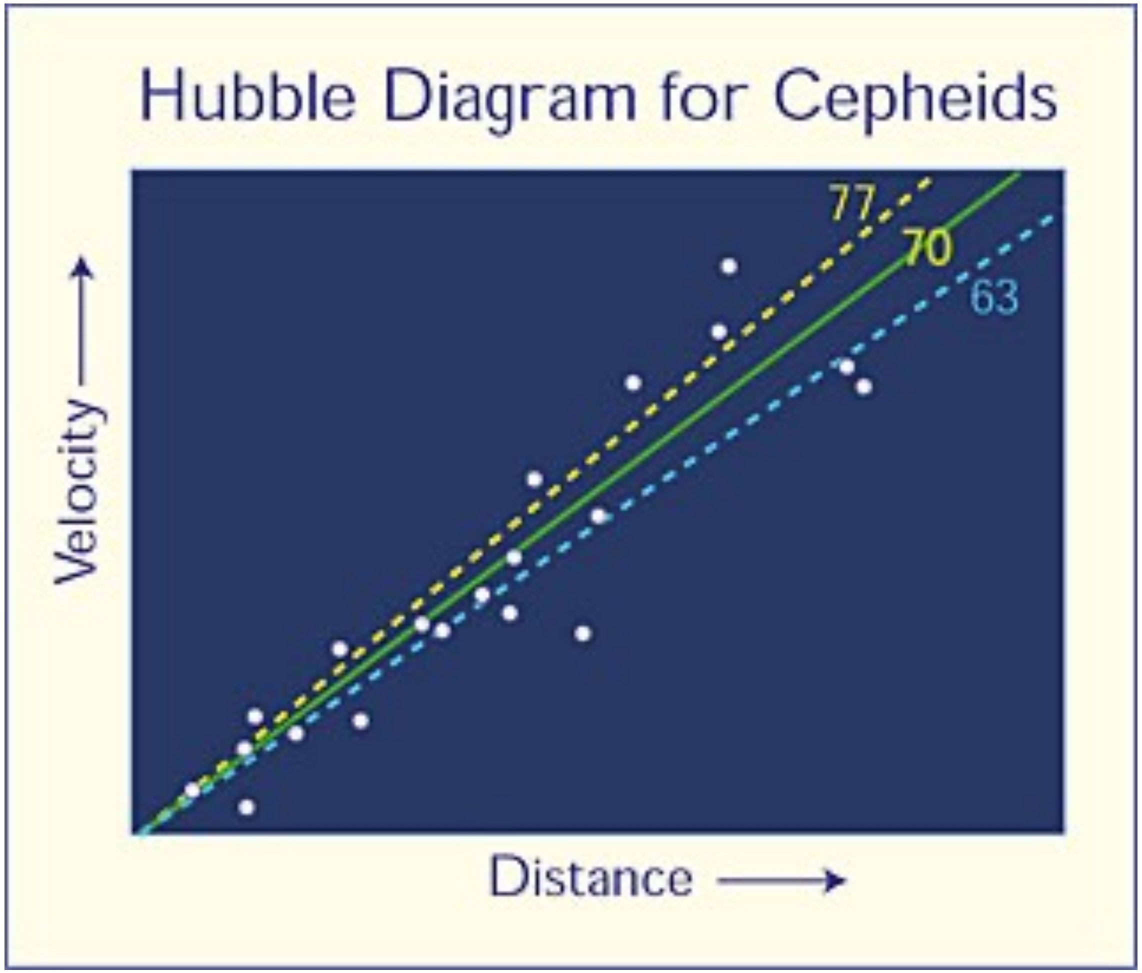
In 1929 Hubble measured the red shift (or, redshift) of nearby galaxies and found that they nearly all move away from us

⇒

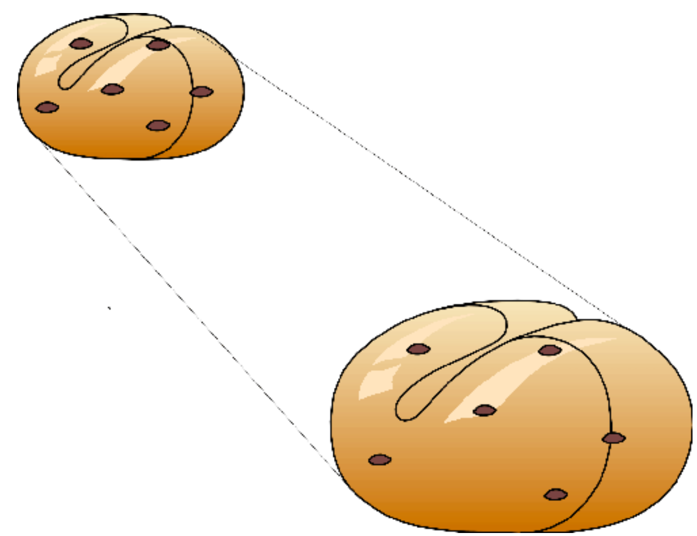
The Universe is Expanding!

100 inch Hooker telescope
(Mt Wilson, CA)

Expanding spaces: bread & universe



Baking the raisin bread: the **farther** two raisins are, the **faster** they are receding



- Velocity is easy: from the Doppler recession of galaxy spectra
  (first done by astronomer Vesto Slipher, whom Hubble never credited)
- Distance is hard: from Cepheid variable stars

Redshift: shift of galaxy light wavelength

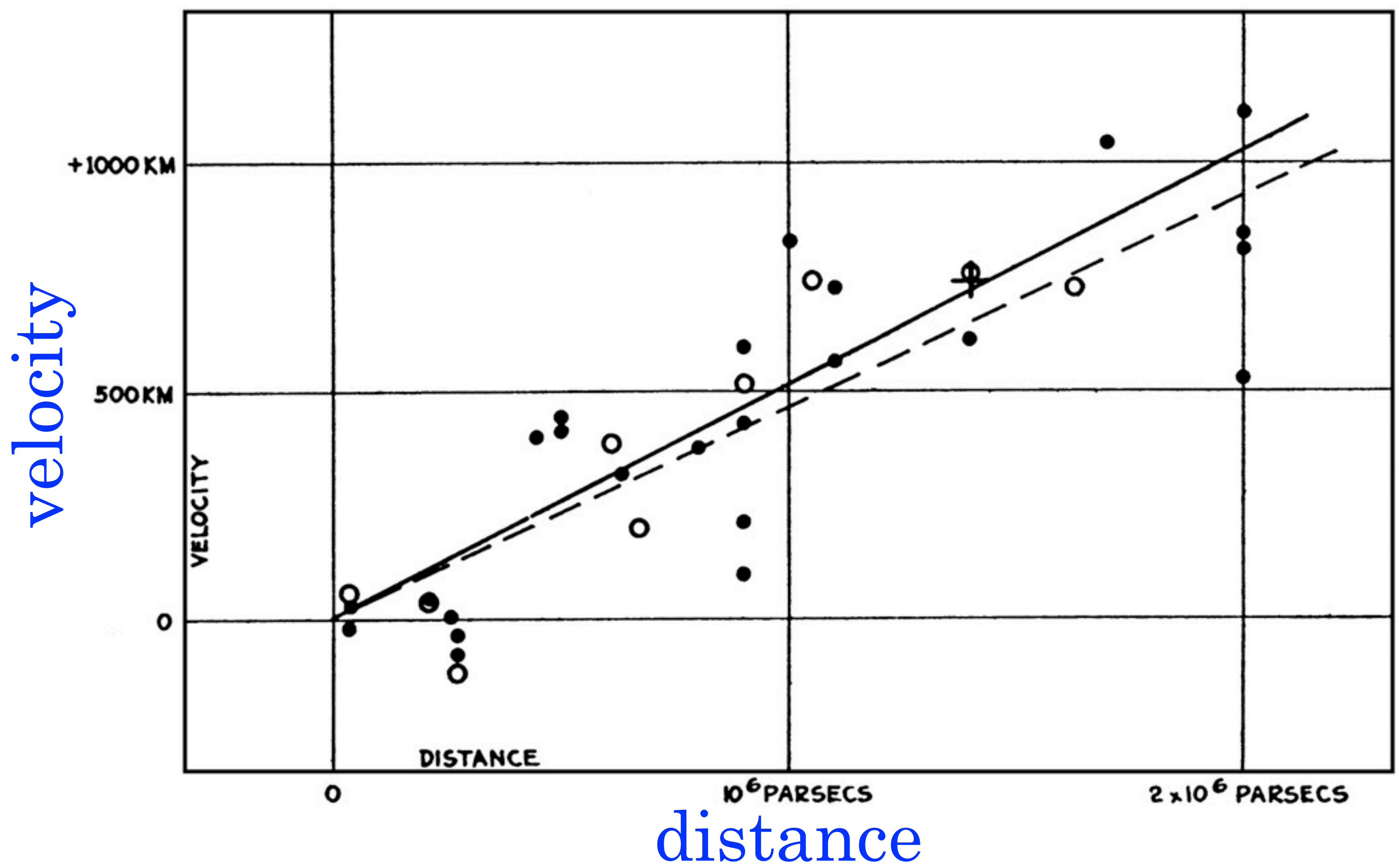
(due to galaxy's motion relative to us)

larger wavelength observed (receding)

smaller wavelength observed (approaching)

Light from almost all galaxies is redshifted (and not blueshifted)
- **the galaxies are receding away from us**!

The original Hubble diagram (1929)

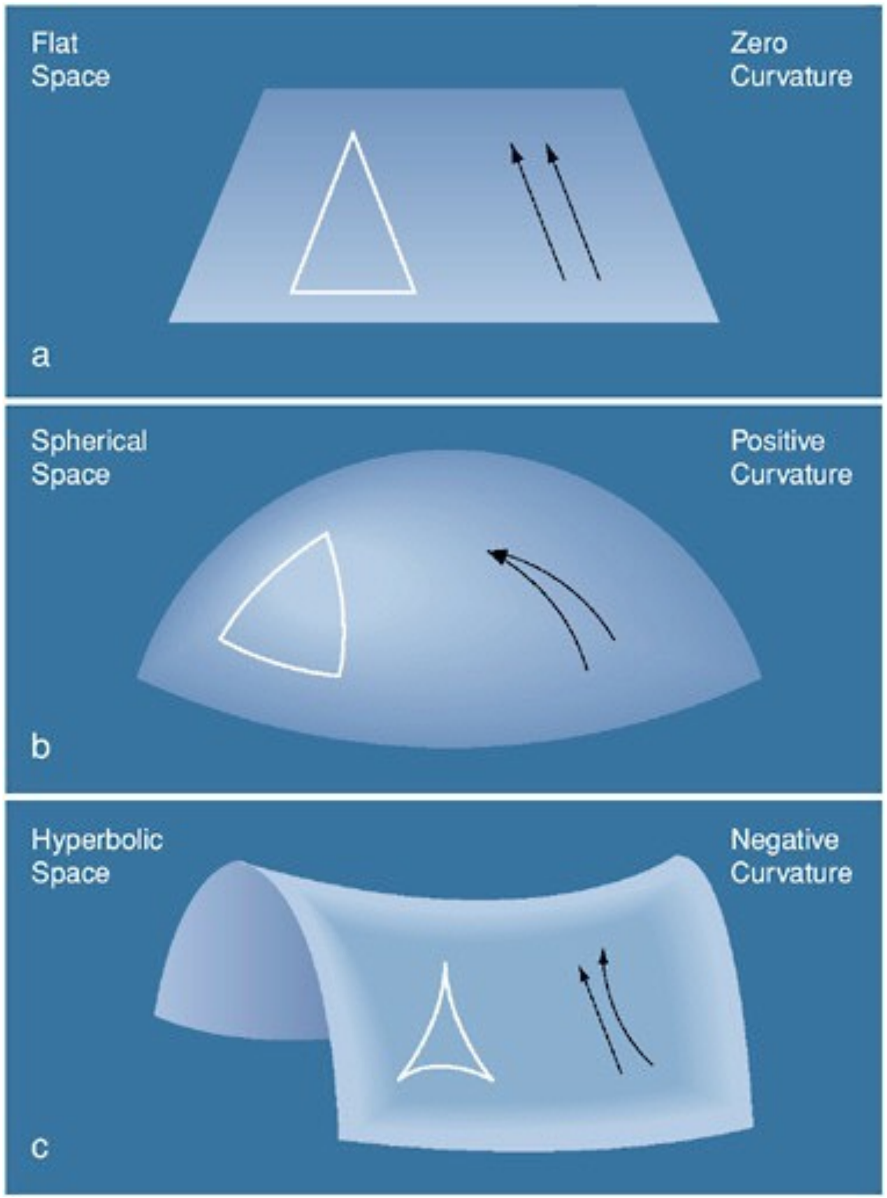


Slope of this relation (velocity vs. distance) is called the Hubble constant H_0.

Modern value:

$H_0 \approx 70$ km/sec/megaparsec (will return to H_0 later!)

What is the geometry of space?

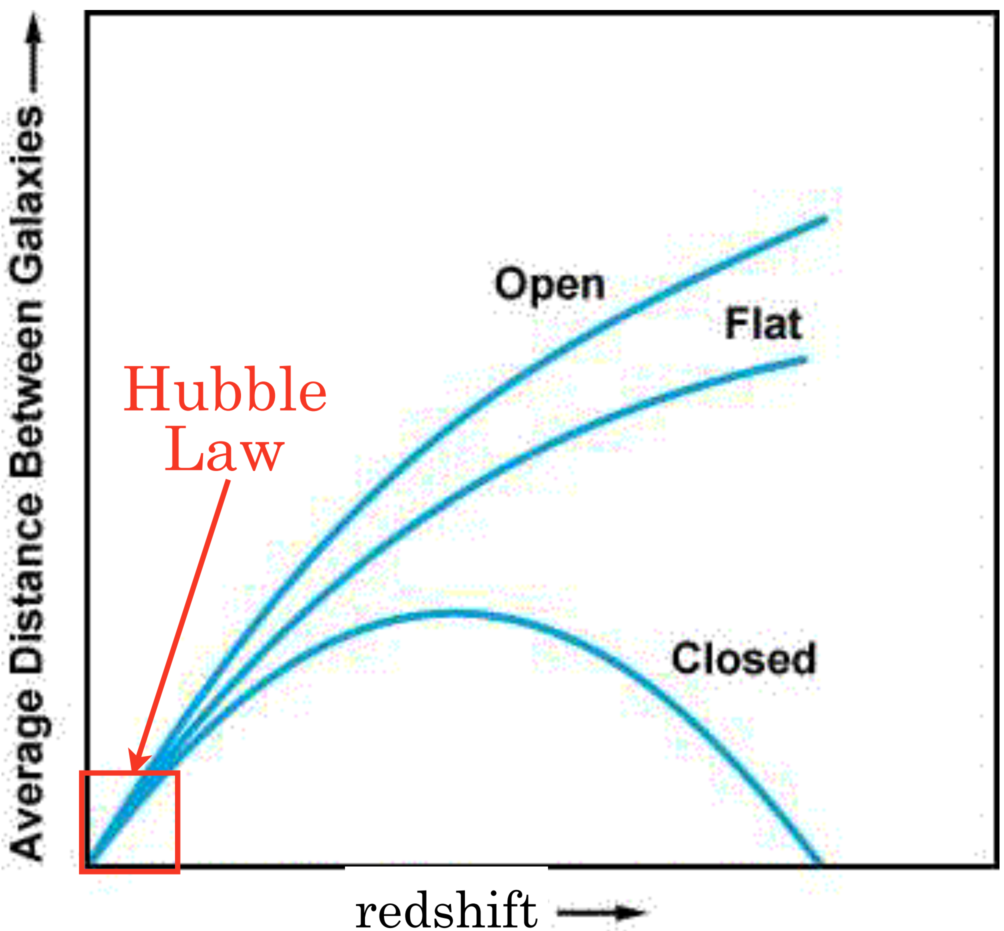


Flat (zero curvature)

Positively curved
("closed")

Negatively curved
("open")

By measuring distances in the universe, you can determine its **geometry**



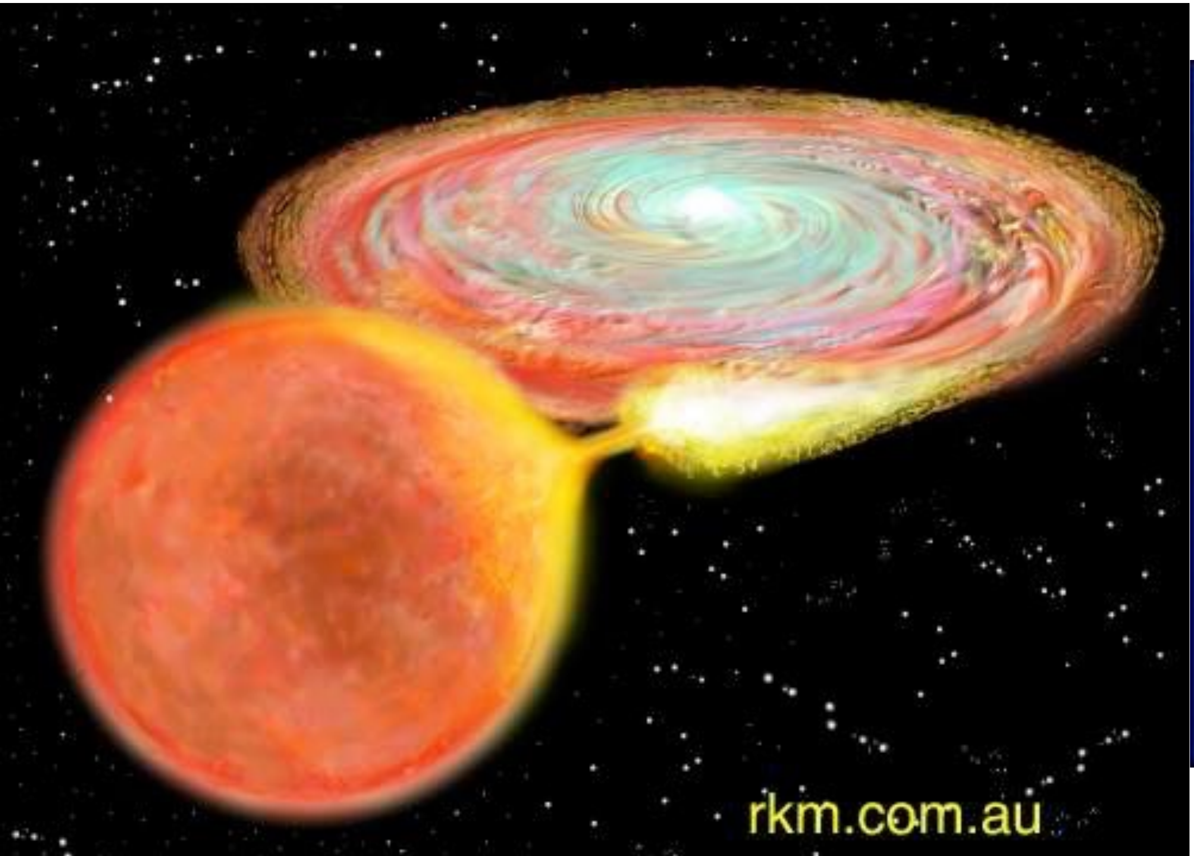
Problem:
distances in astronomy are notoriously hard to measure

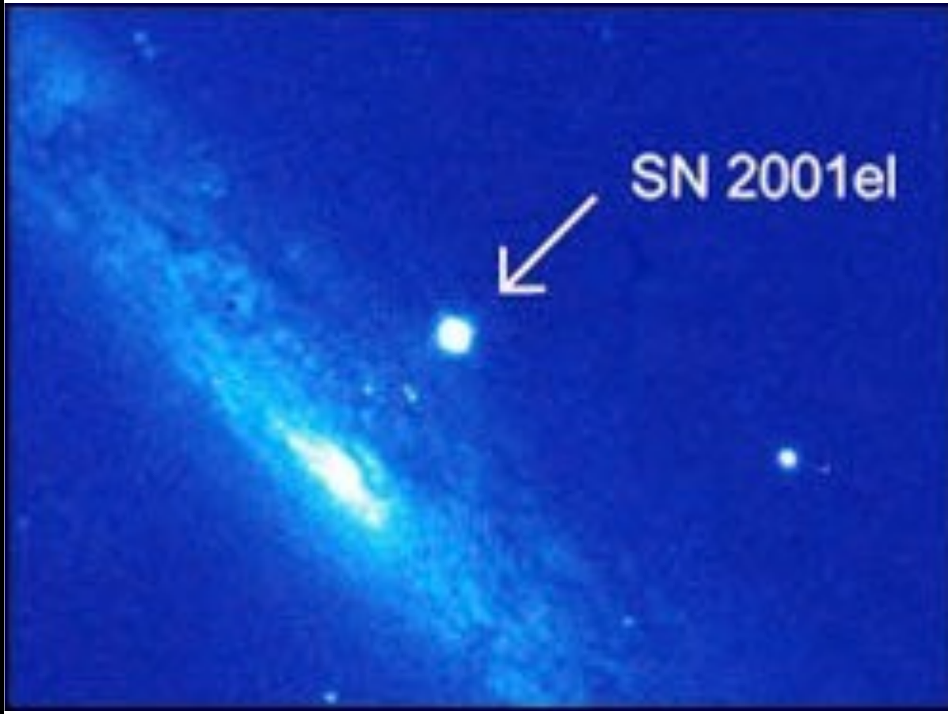
Type Ia Supernovae!

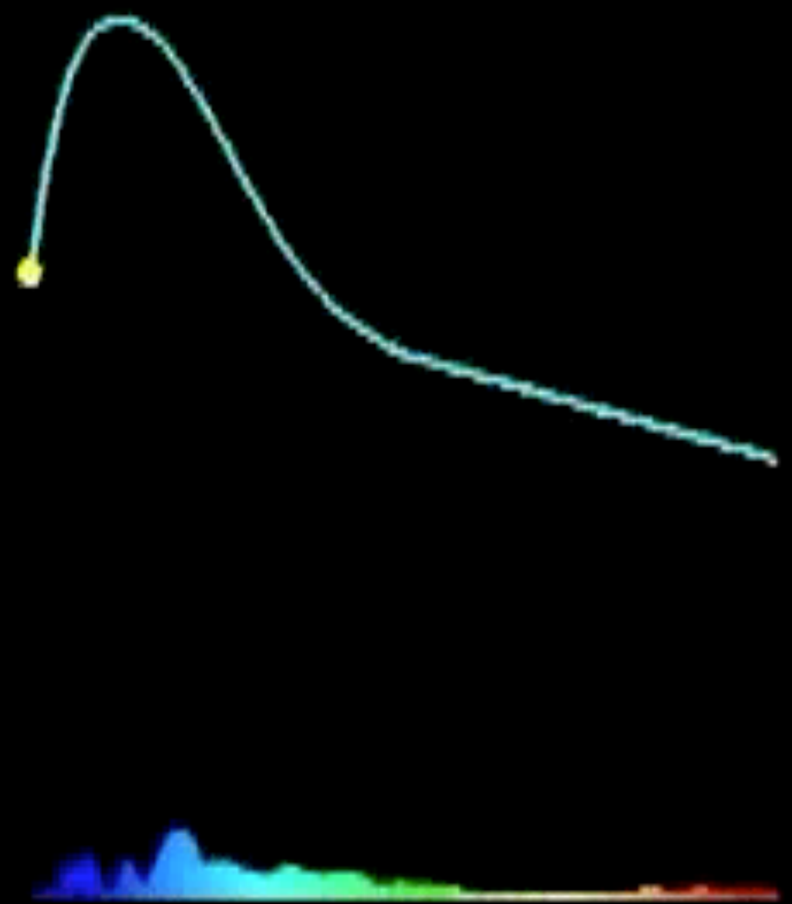
A white dwarf accretes matter from a companion.

Once the WD star's mass reaches a certain limit, the star explodes

Each explosion yields (about) the same amount of energy/light $\Longrightarrow$ **standard candle**







credit: Supernova Cosmology Project

A “Standard Candle” analogy: Headlights of a Car

If you know the intrinsic brightness of the headlights, you can estimate how far away the car is

$$f = L / (4\pi d^2)$$

(f = flux
L = luminosity
d = distance)

But how do you find SNe?

Rate: 1 SN per galaxy per 500 yrs!

Solution:

- use world's large telescopes,
- schedule them to find, then "follow-up" SNe
- heroic hard work by two teams of researchers

Nobel Prize in Physics 2011

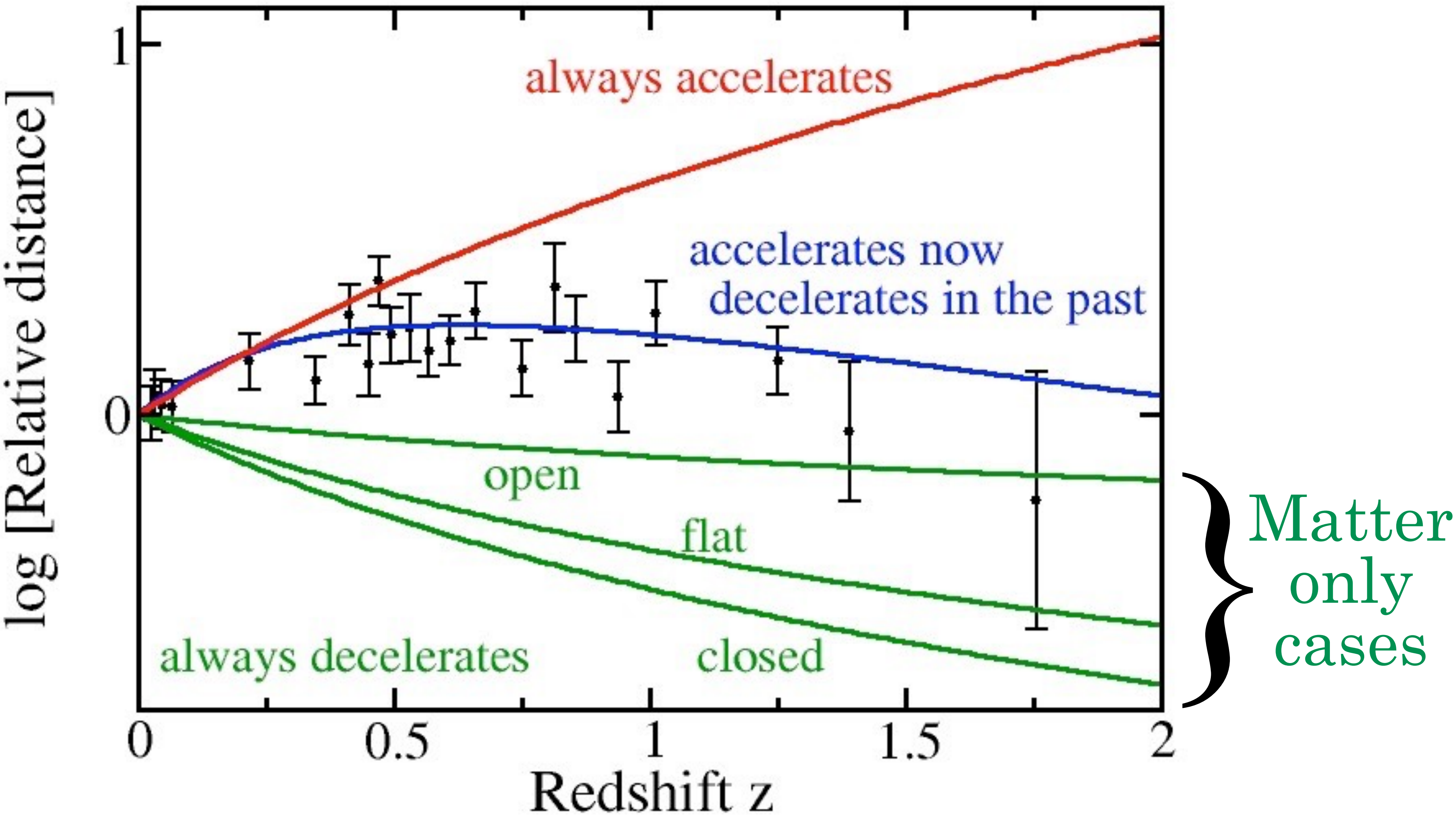
Adam Riess
Johns Hopkins University

Saul Perlmutter,
Lawrence Berkeley Lab

Brian Schmidt,
Australian National Univ.

Supernova Hubble diagram

(actual data; each error bar denotes ~20 SN)

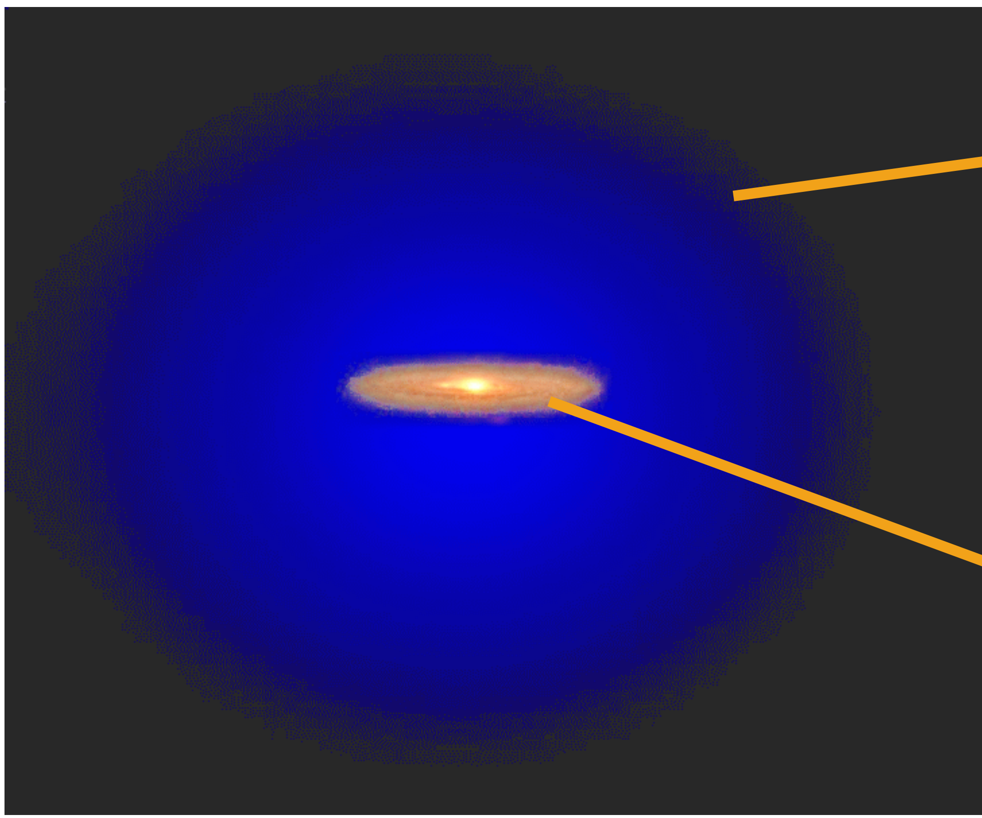


Dr. Michael Turner
University of Chicago

Dark Energy

- Universe is dominated by something other than dark matter
- This new component - “dark energy” - makes the universe expand faster and faster (i.e. slower as we look in the past)
- This new component is smooth
- Other than that, we don’t know much!

Recall: Dark Matter is in "halos" around galaxies



(invisible)
Dark Matter halo

(visible) light
from galaxy

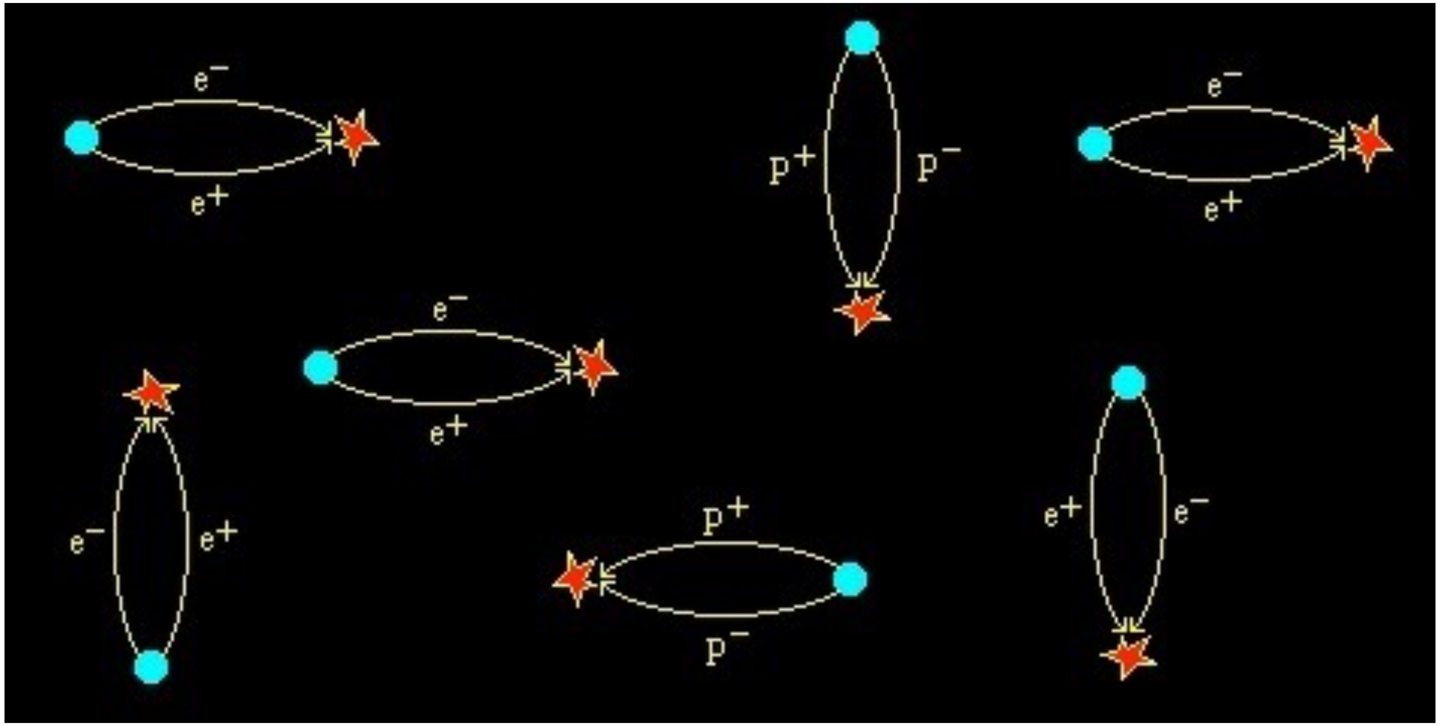
Dark Matter ≠ Dark Energy

Facts about DE

- DE is smooth
- DE pushes things (galaxies) apart
- DE energy *density* approximately constant - double the volume, double the energy (for matter, double the volume, energy stays the same)
- $\Rightarrow$ Verifying whether this is true is at forefront of measurements in cosmology
- DE is only noticeable at recent times (ie. low redshifts), and completely subdominant in early univ.
- DE slows down the growth of structure

A Candidate: Vacuum Energy

Quantum Physics says:
"empty space" is filled with particles and antiparticles getting created and annihilated



Theoretical prediction for vacuum energy

Mystery #1

A straightforward calculation using quantum mechanics gives
100,000,000,000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,000,000,
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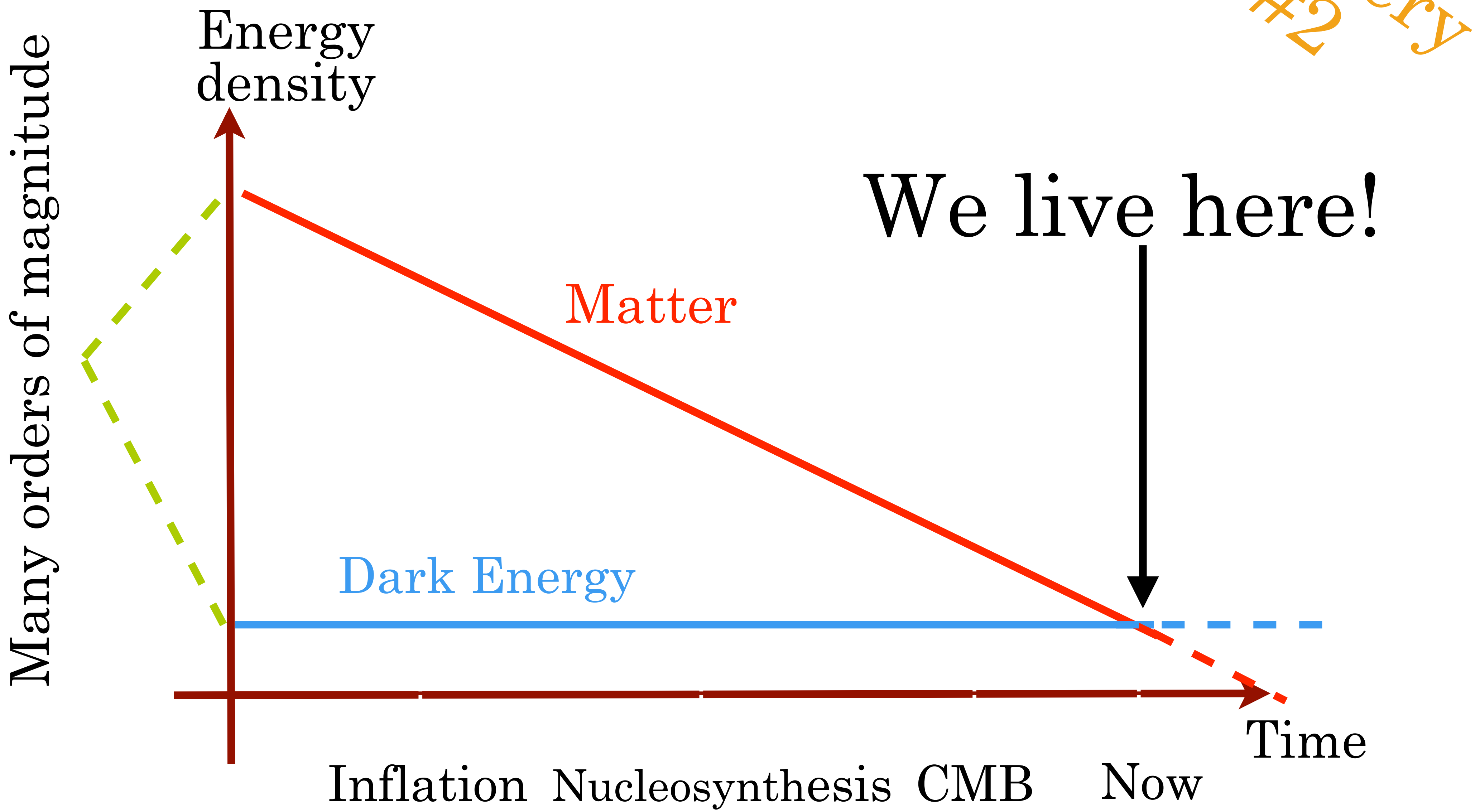
(or 10^{120}) times more than the observed amount

This is known as the
COSMOLOGICAL CONSTANT PROBLEM

"Why Now!?"



This is known as the COINCIDENCE PROBLEM

What is dark energy?

- Is it vacuum energy?
- Is it modification of Einstein's theory of gravity?
- Is it a (funny) fluid that fills up universe?
- Or is it something else - completely, utterly unexpected?

(Bizarre) Consequences of DE

- In the accelerating universe, galaxies are leaving our observable patch $\Longrightarrow$ the sky will be empty in 100 billion years!

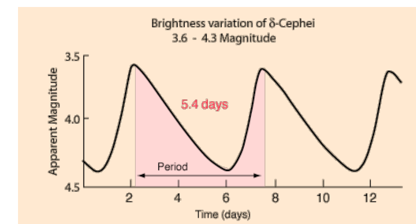
- In particular, under certain circumstances we will have a Big Rip - galaxies, stars, planets, our houses, atoms, and then the fabric of space itself will rip apart!

Breaking news:

Hubble tension!

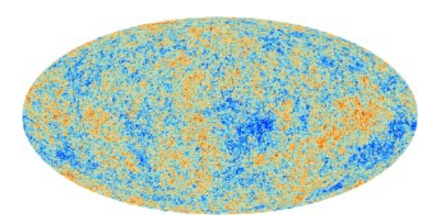
Type Ia supernovae + Cepheid distances give

$$H_0 = 74.0 \quad \text{(km/s/Mpc)}$$



Cosmic Microwave Anisotropies give

$$H_0 = 67.0 \quad \text{(km/s/Mpc)}$$



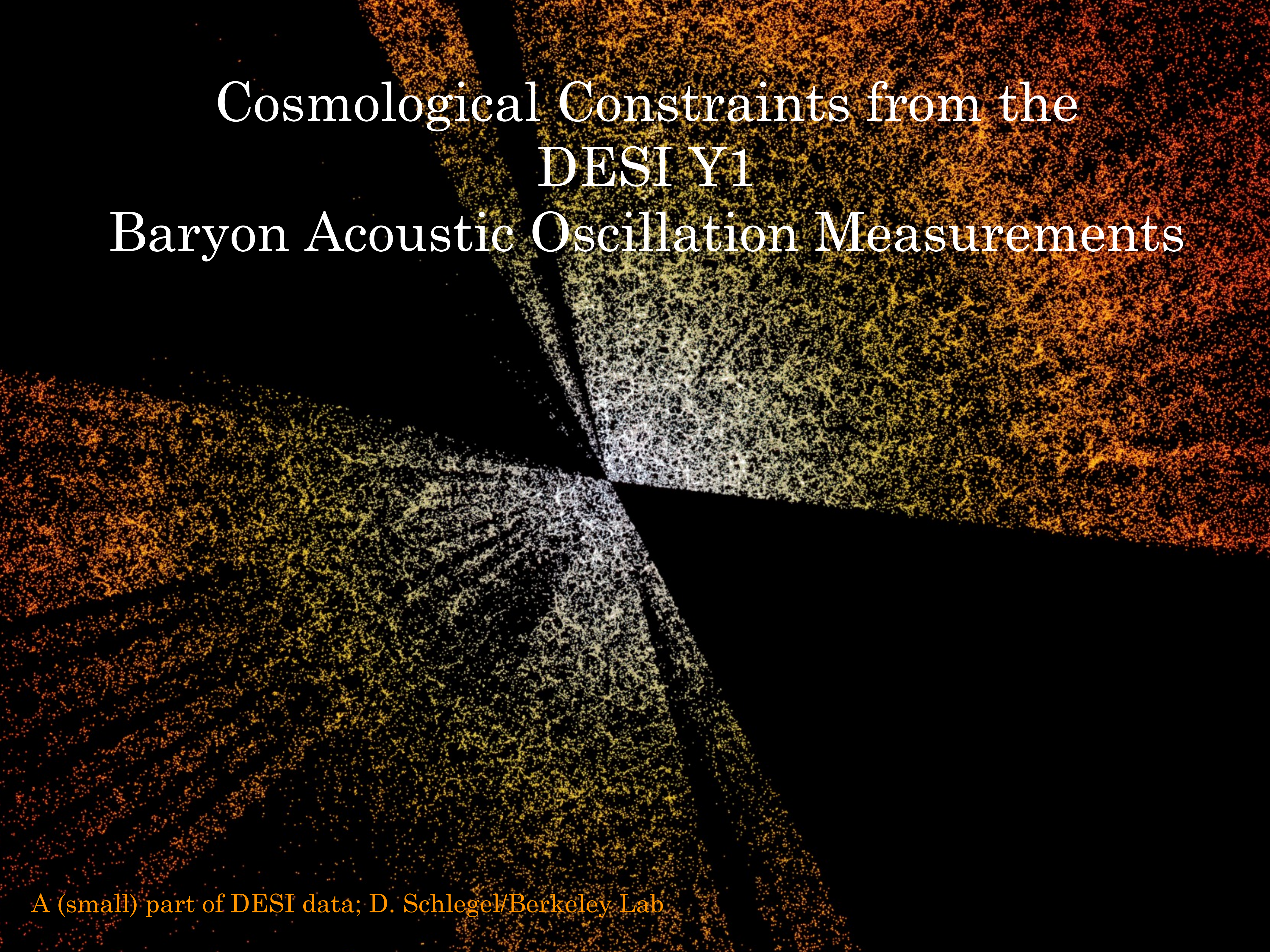
These two measurements are about five standard deviations (quoted errors) apart

$\Longrightarrow$ discrepant at 99.99997% confidence

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

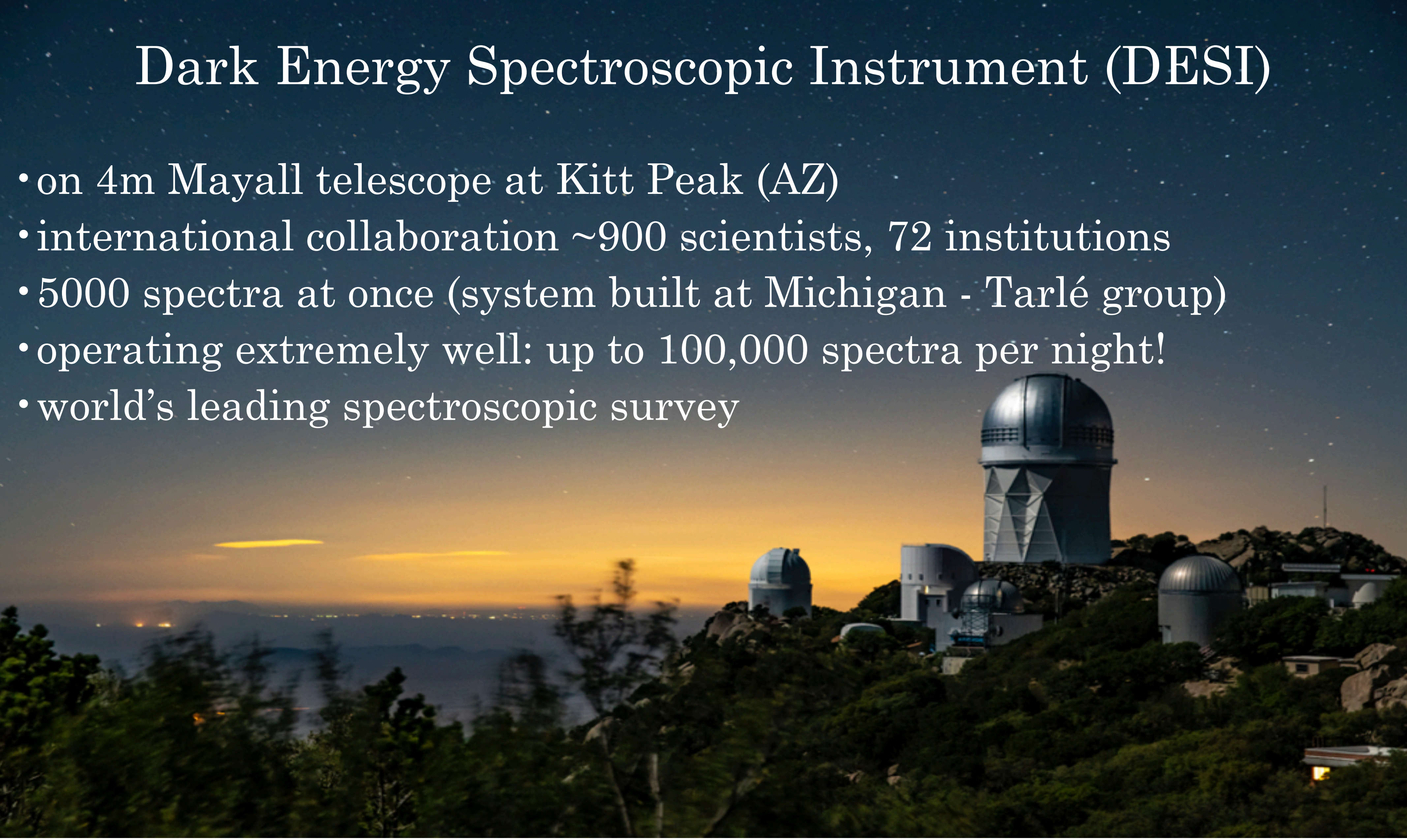
Cosmological Constraints from the DESI Y1 Baryon Acoustic Oscillation Measurements



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

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

For cosmologists, galaxies are test particles!

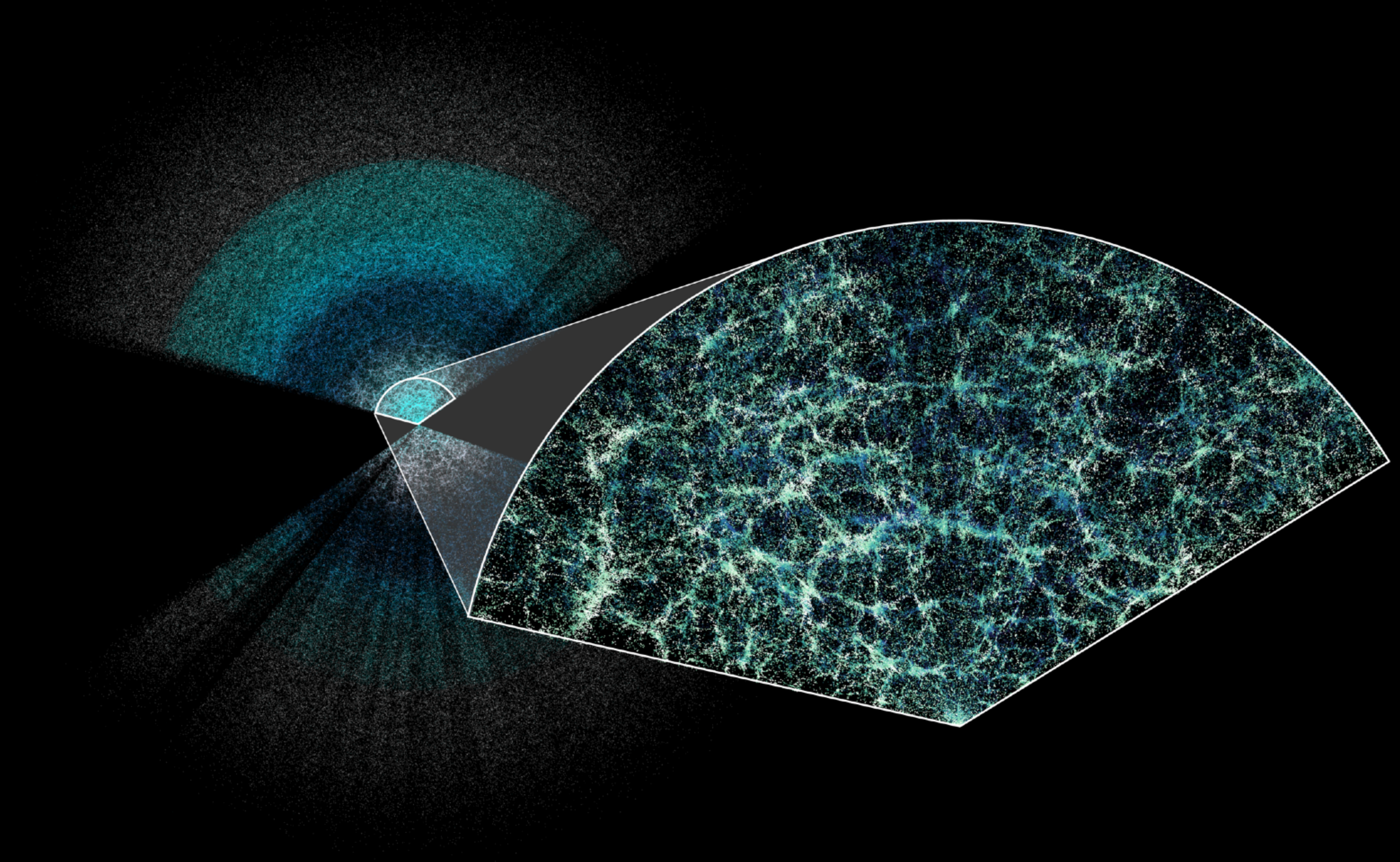
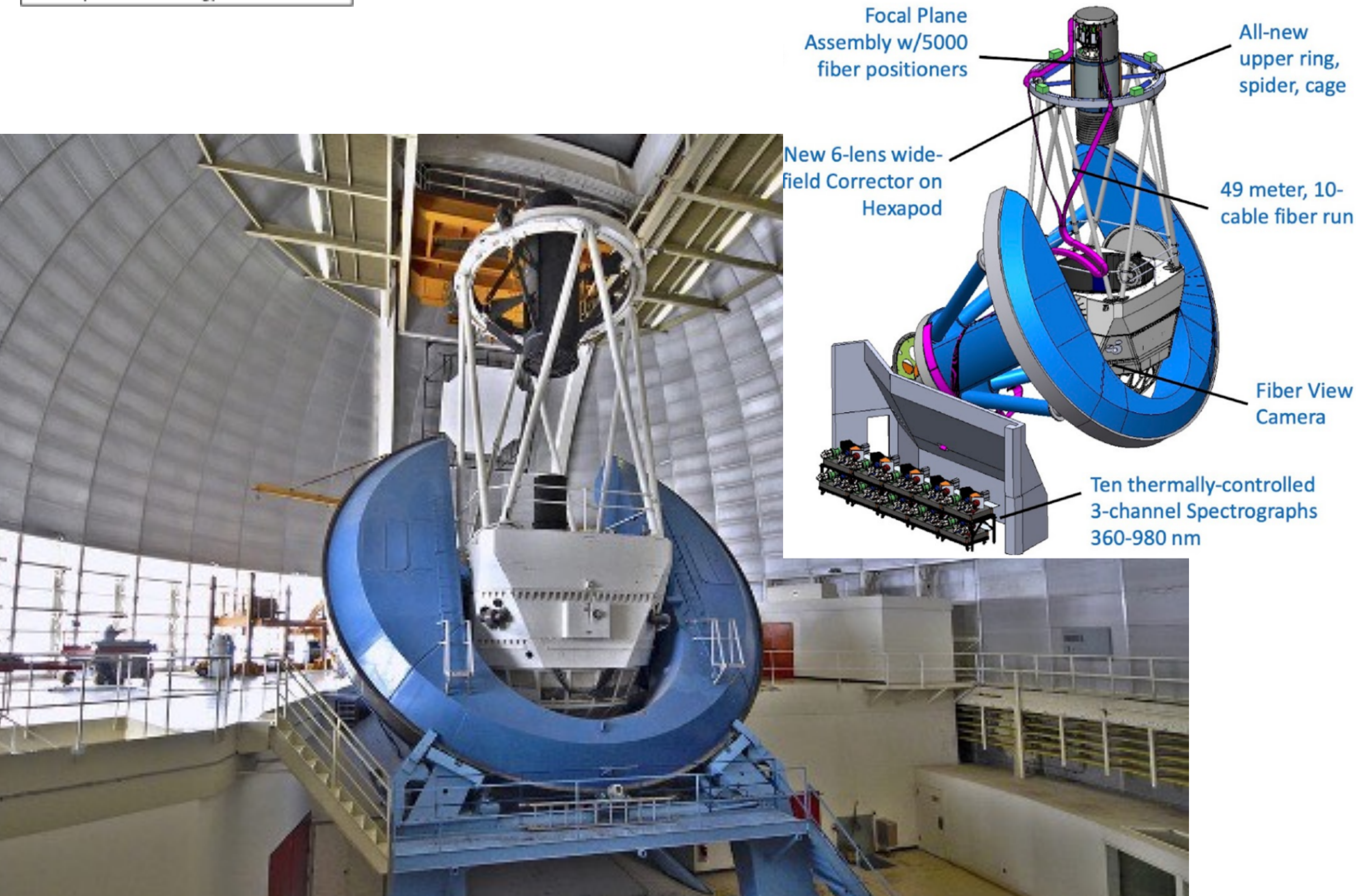


Figure credit: Claire Lamman

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

Mayall telescope at Kitt Peak, AZ



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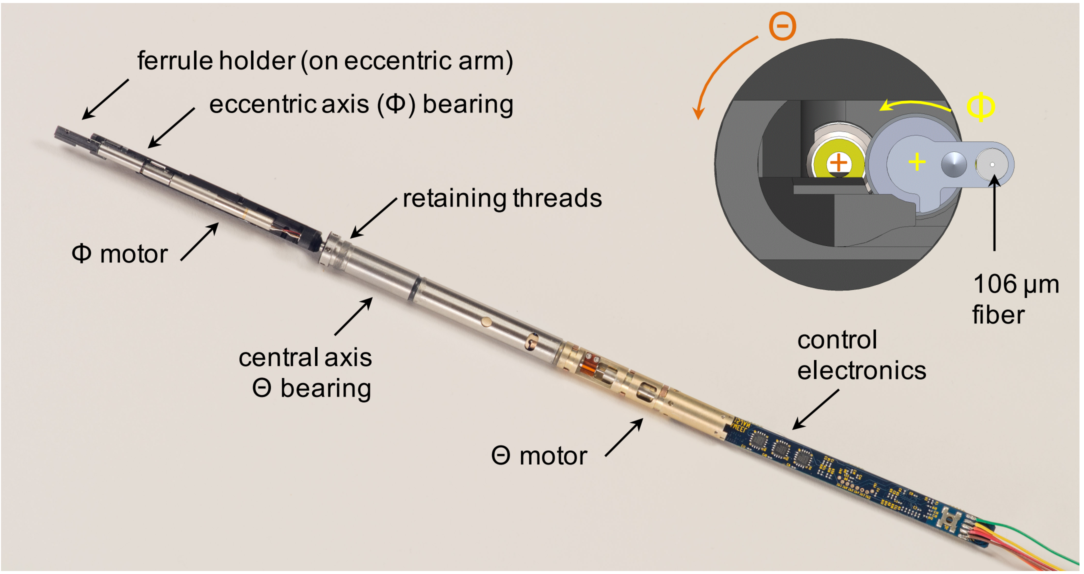
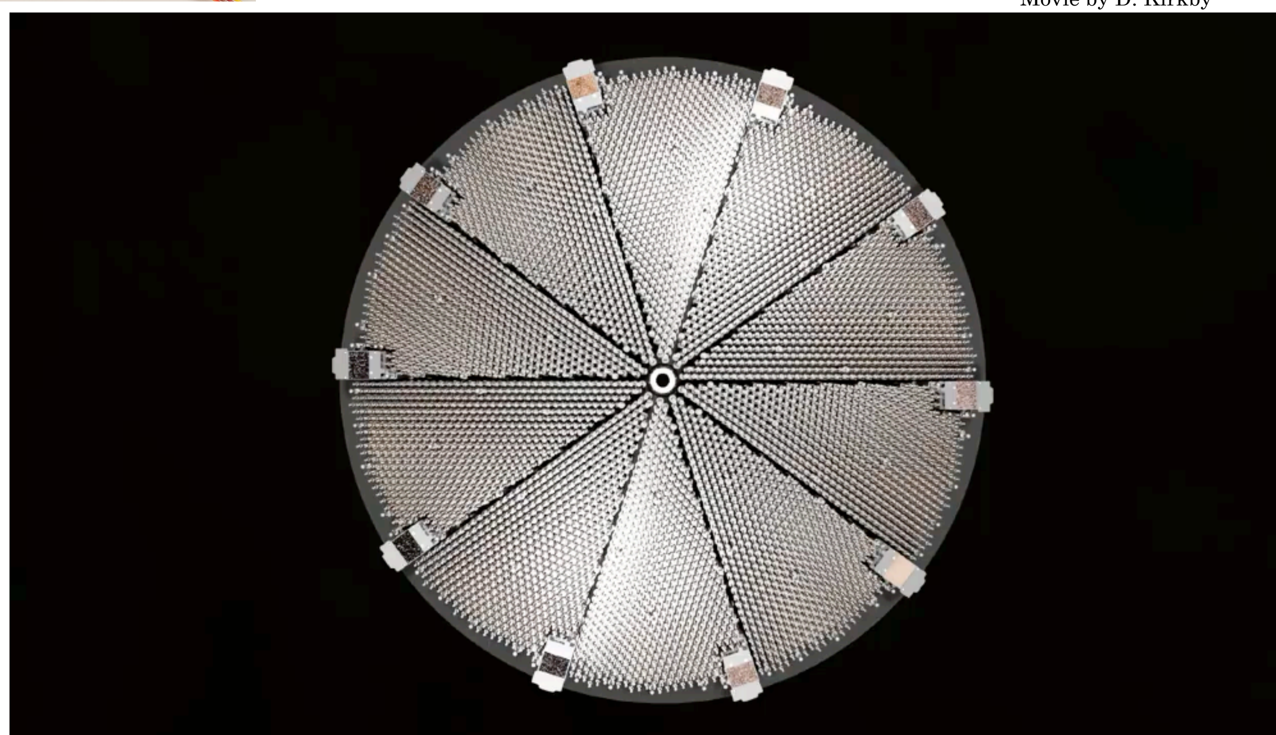
Robotic fiber positioners



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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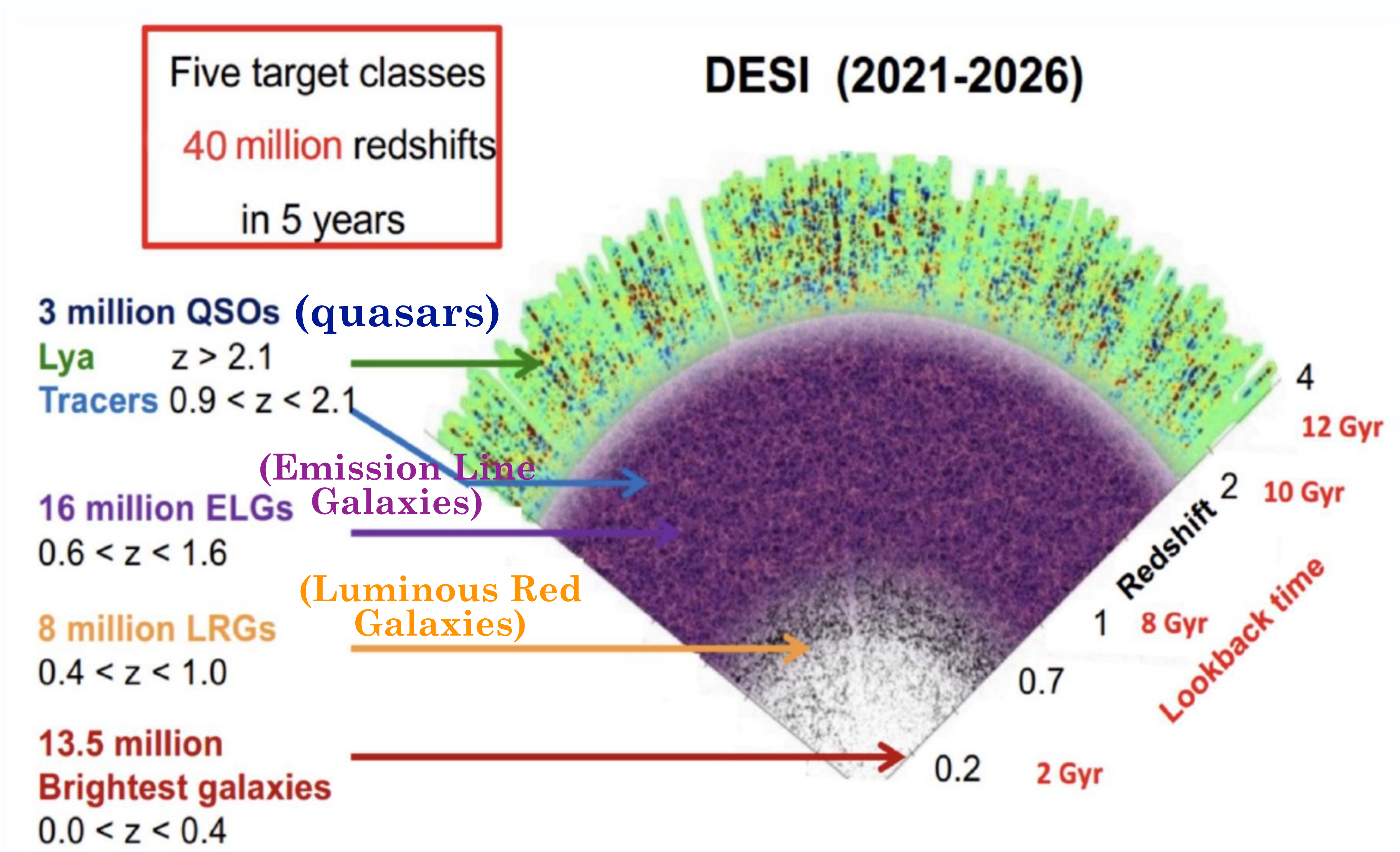
DESI tracers



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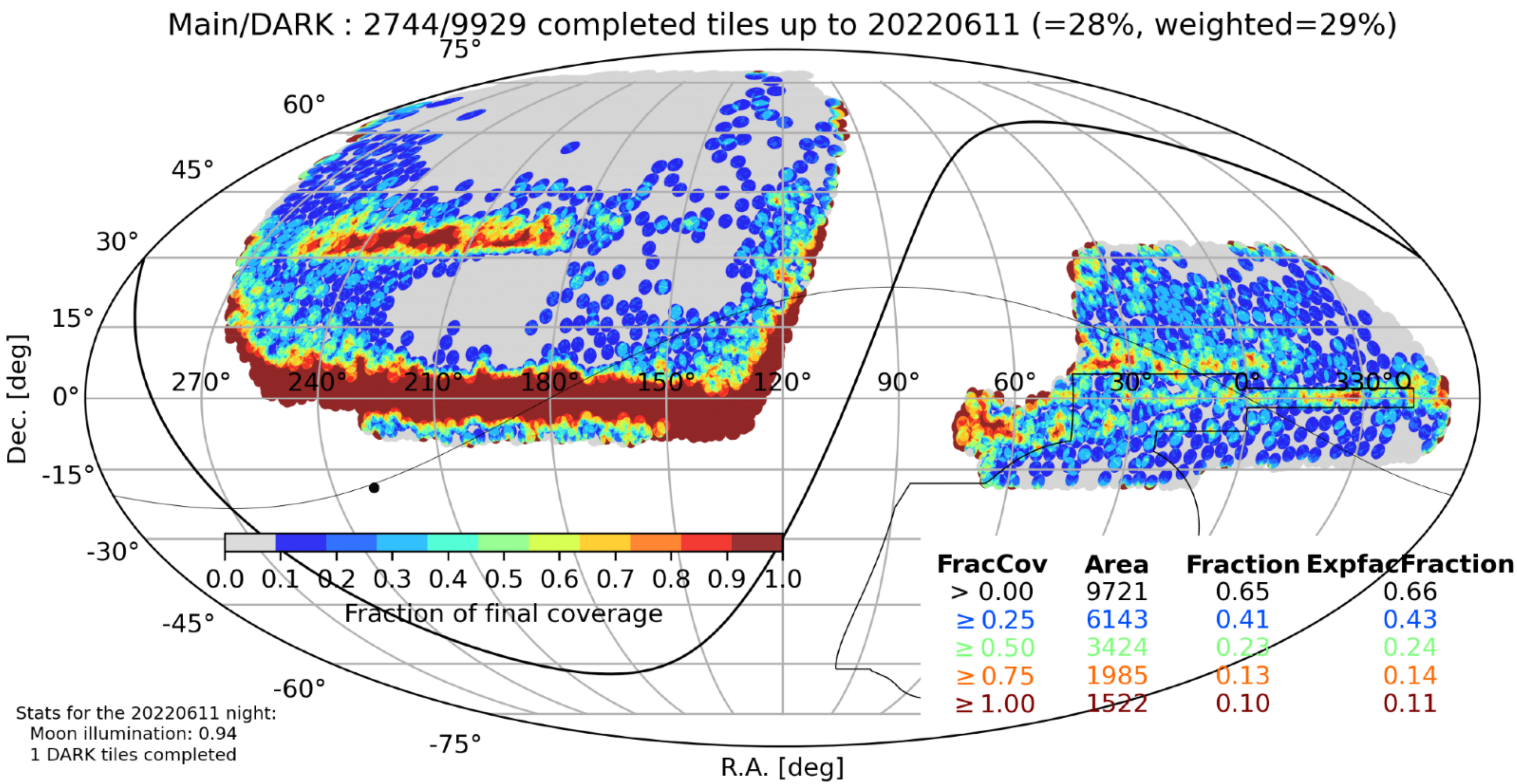
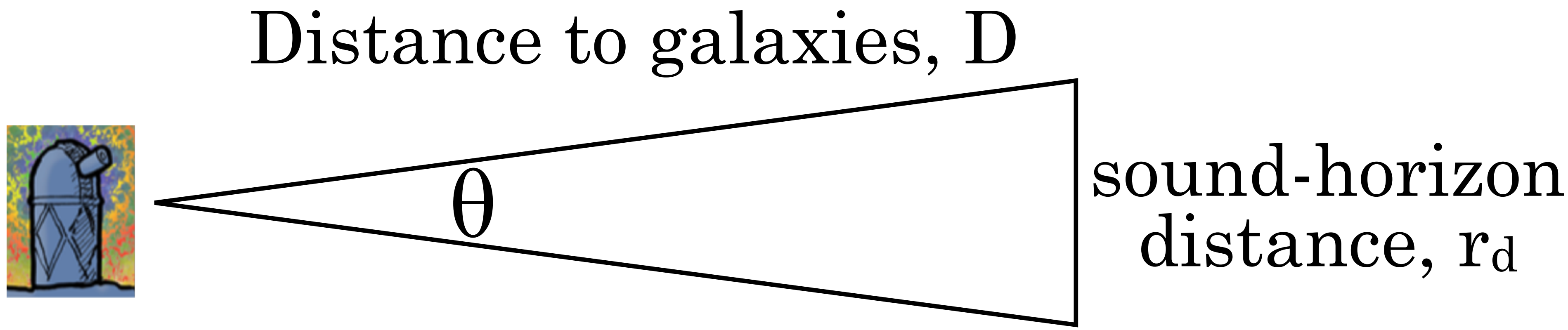


How **Baryon Acoustic Oscillations (BAO)** observed by DESI constrain cosmological parameters

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

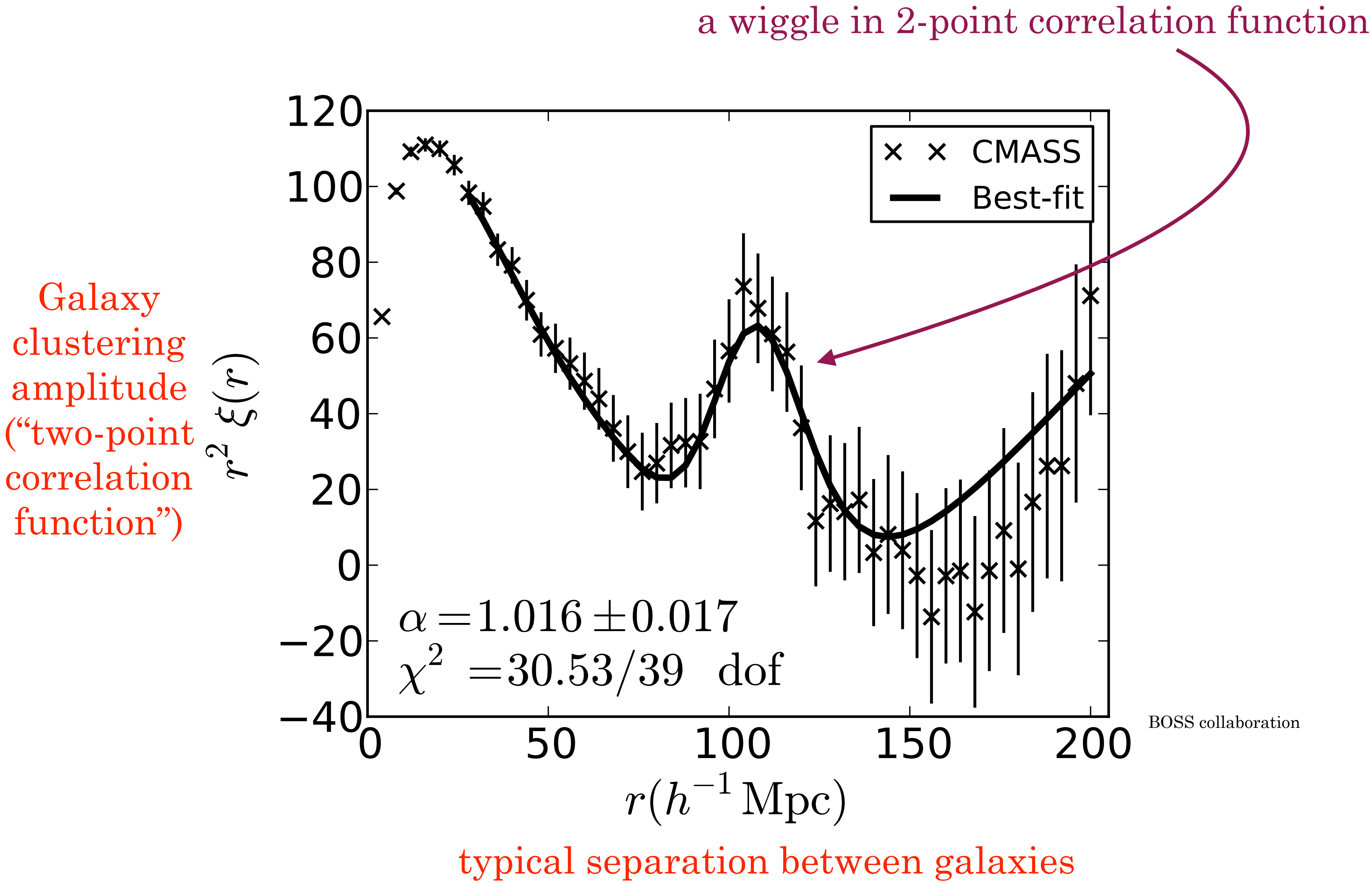
Baryon Acoustic Oscillations (BAO): how it works



We measure angle θ and “know” the sound horizon r_d, hence we can measure distances to galaxies D

Next few slides: what is actually the sound horizon?

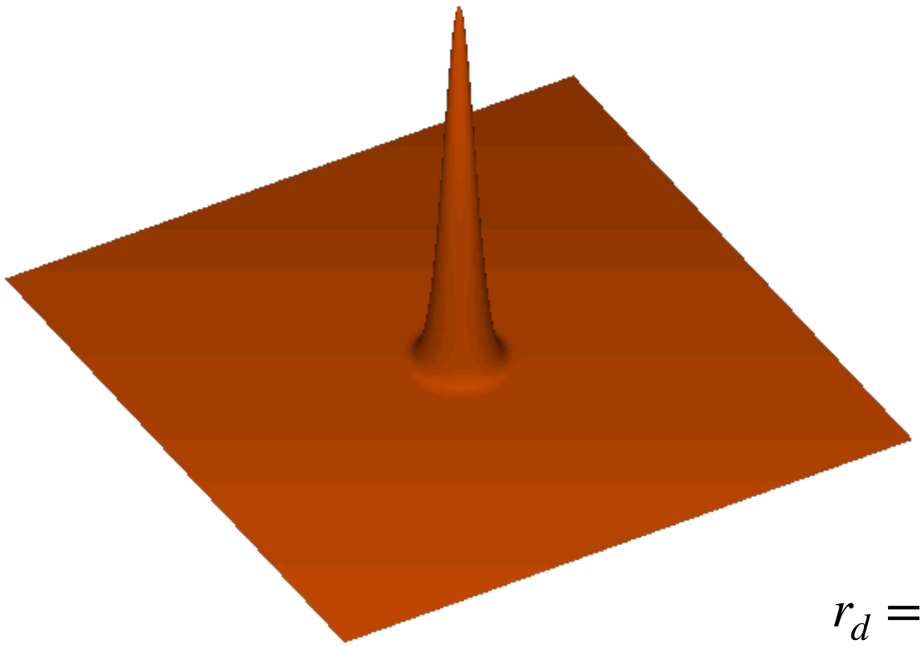
Baryon Acoustic Oscillations (BAO)



First discussed in: Sunyaev & Zeldovich, 1972

How do the BAO wiggles come about?

At recombination (z~1000, t~300,000 yrs)



Eisenstein, Seo et al (2007)

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

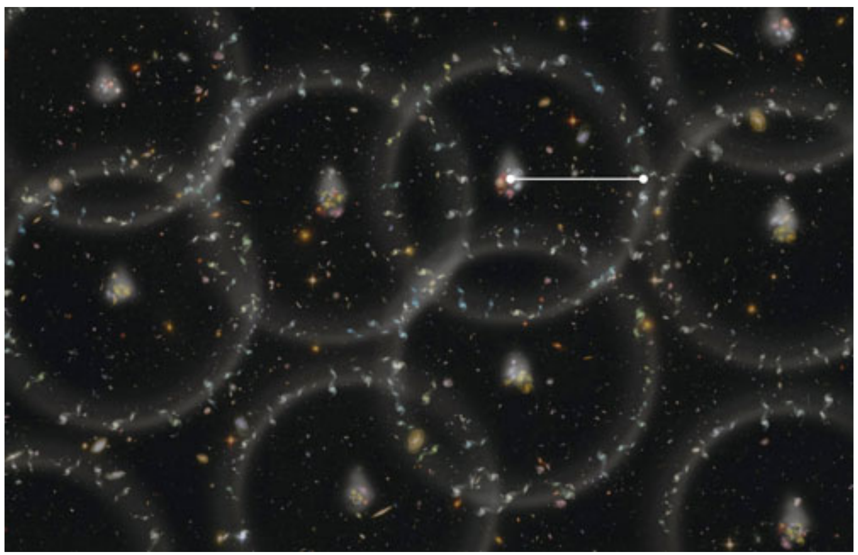
$$r_d = \frac{c}{\sqrt{3}} \int_0^{a_*} \frac{da}{a^2 H(a) \sqrt{1 + \frac{3\Omega_B}{4\Omega_\gamma} a}} \simeq 150\,\mathrm{Mpc}$$

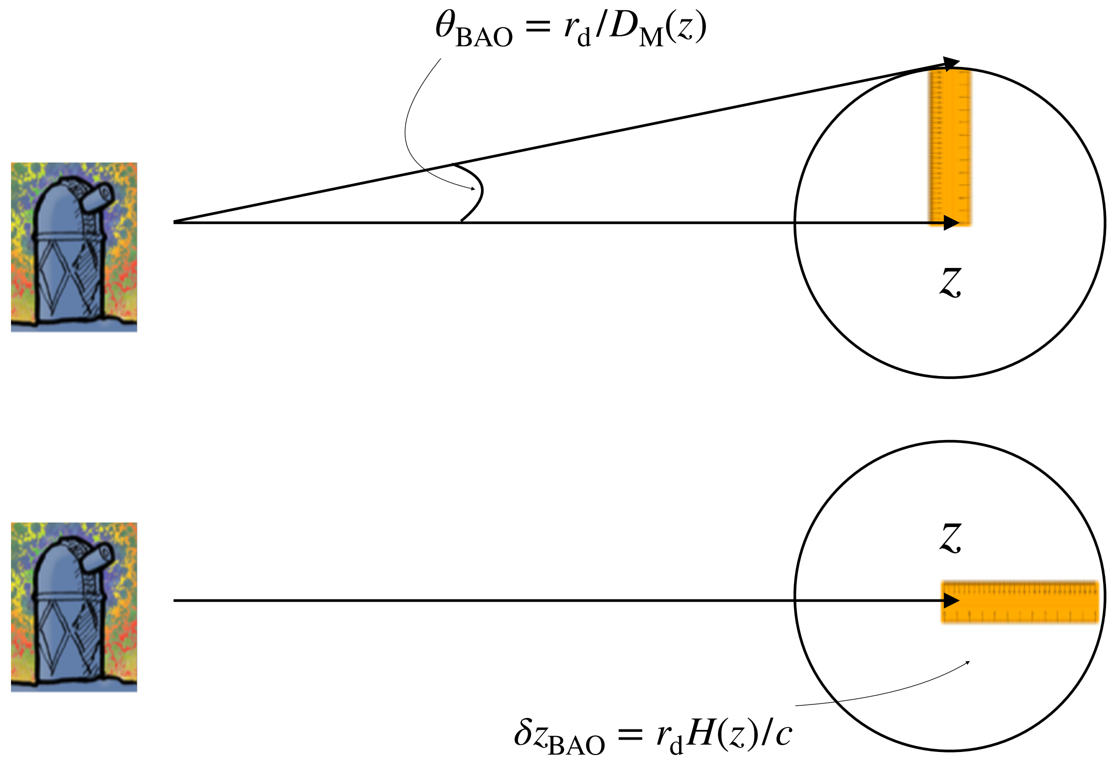
A feature is imprinted the distance that the wave has traveled between the Big Bang and recombination

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

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

The BAO standard ruler

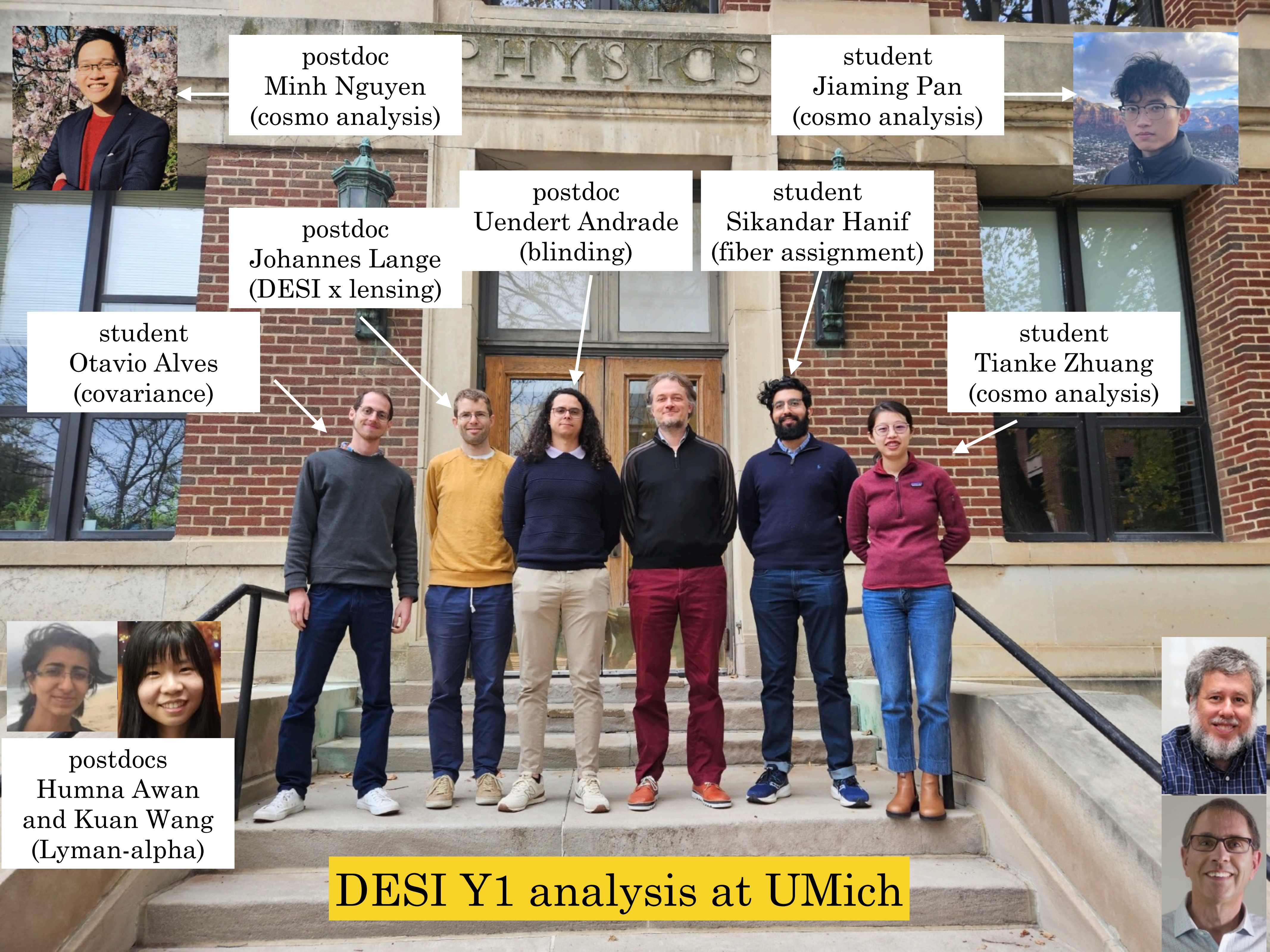




$D_{\rm M}(z)$ and $H(z)$ encode **expansion history** of the Universe

DESI Y1 cosmological analysis

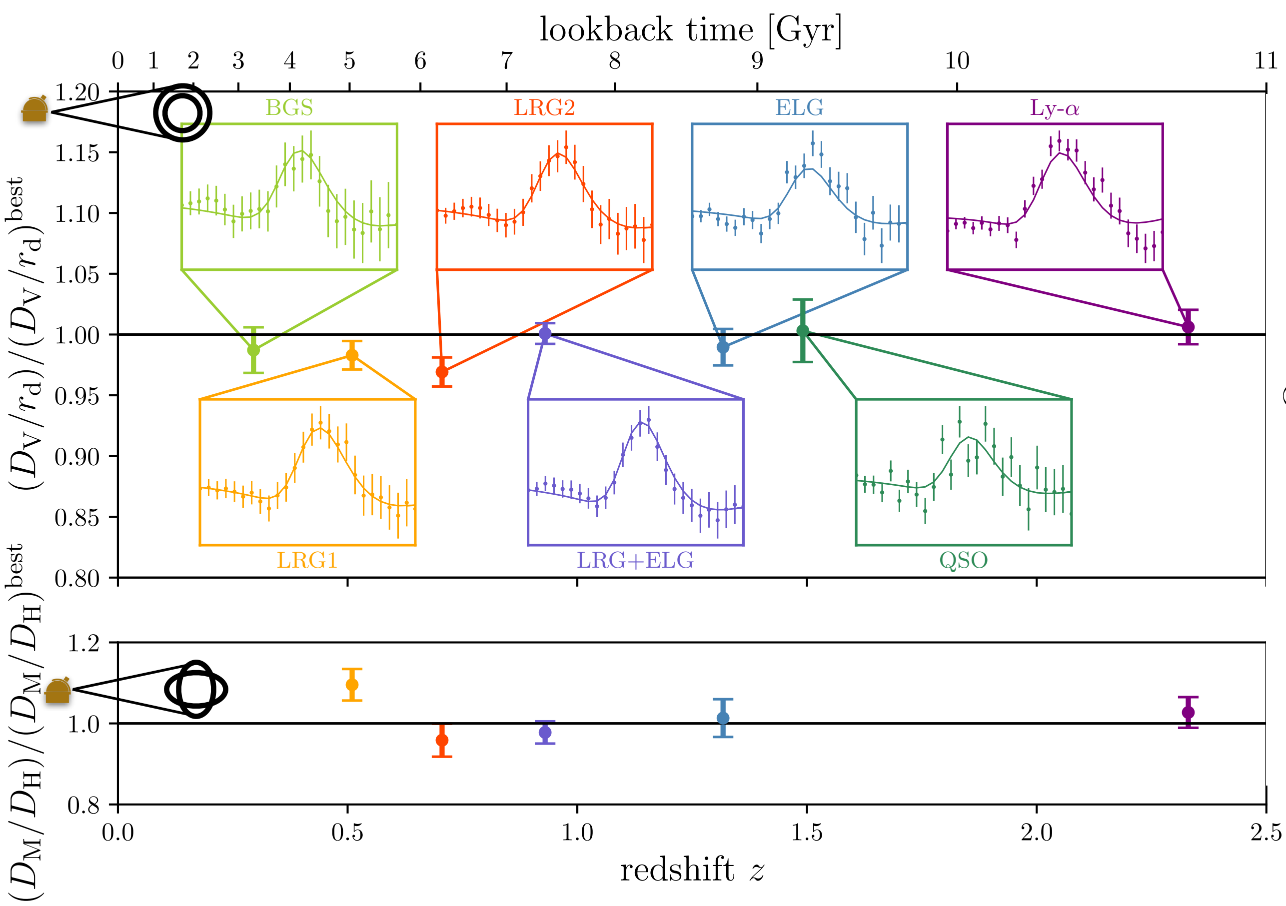
- Fully **blinded** analysis ~7 million galaxies (with spectra!)
- Fully validated pipeline on how to extract the BAO signal
- BAO results were unblinded in December 2023
- We have been writing 2 key papers (I am analysis co-coordinator)
- **BAO results announced at APS and in Moriond on April 4, 2024**
- **Full-shape analysis (the second key paper) will be announced next Tuesday (Nov 19)** - quite a bit more complex than BAO. Expect constraints on cosmic growth; highly complementary to BAO.

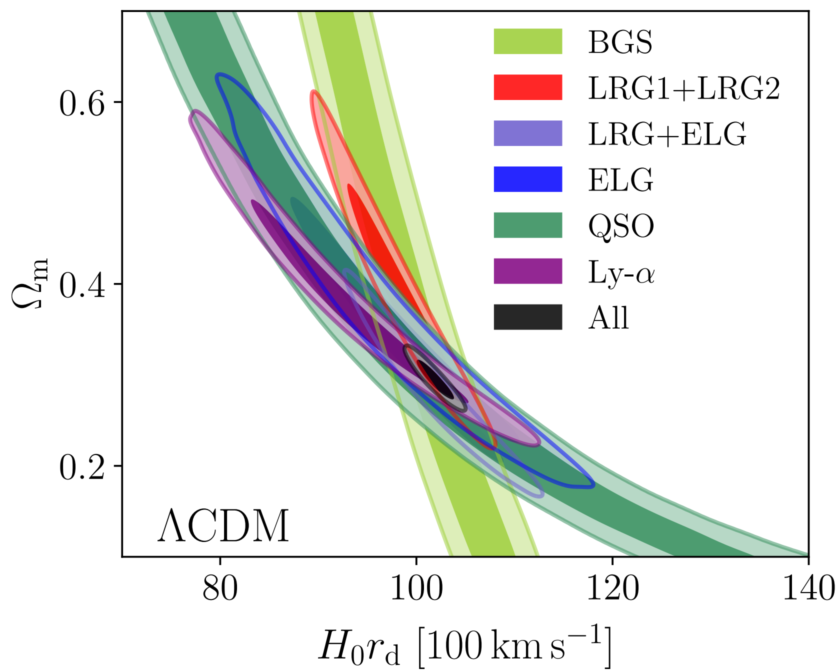

PHYSICS
postdoc
Minh Nguyen
(cosmo analysis)
student
Jiaming Pan
(cosmo analysis)
postdoc
Uendert Andrade
(blinding)
student
Sikandar Hanif
(fiber assignment)
postdoc
Johannes Lange
(DESI x lensing)
student
Otavio Alves
(covariance)
student
Tianke Zhuang
(cosmo analysis)
postdocs
Humna Awan
and Kuan Wang
(Lyman-alpha)
DESI Y1 analysis at UMich

DESI Y1 Cosmological Results

Constraints from DESI Y1 BAO

Basic constraints in ΛCDM model

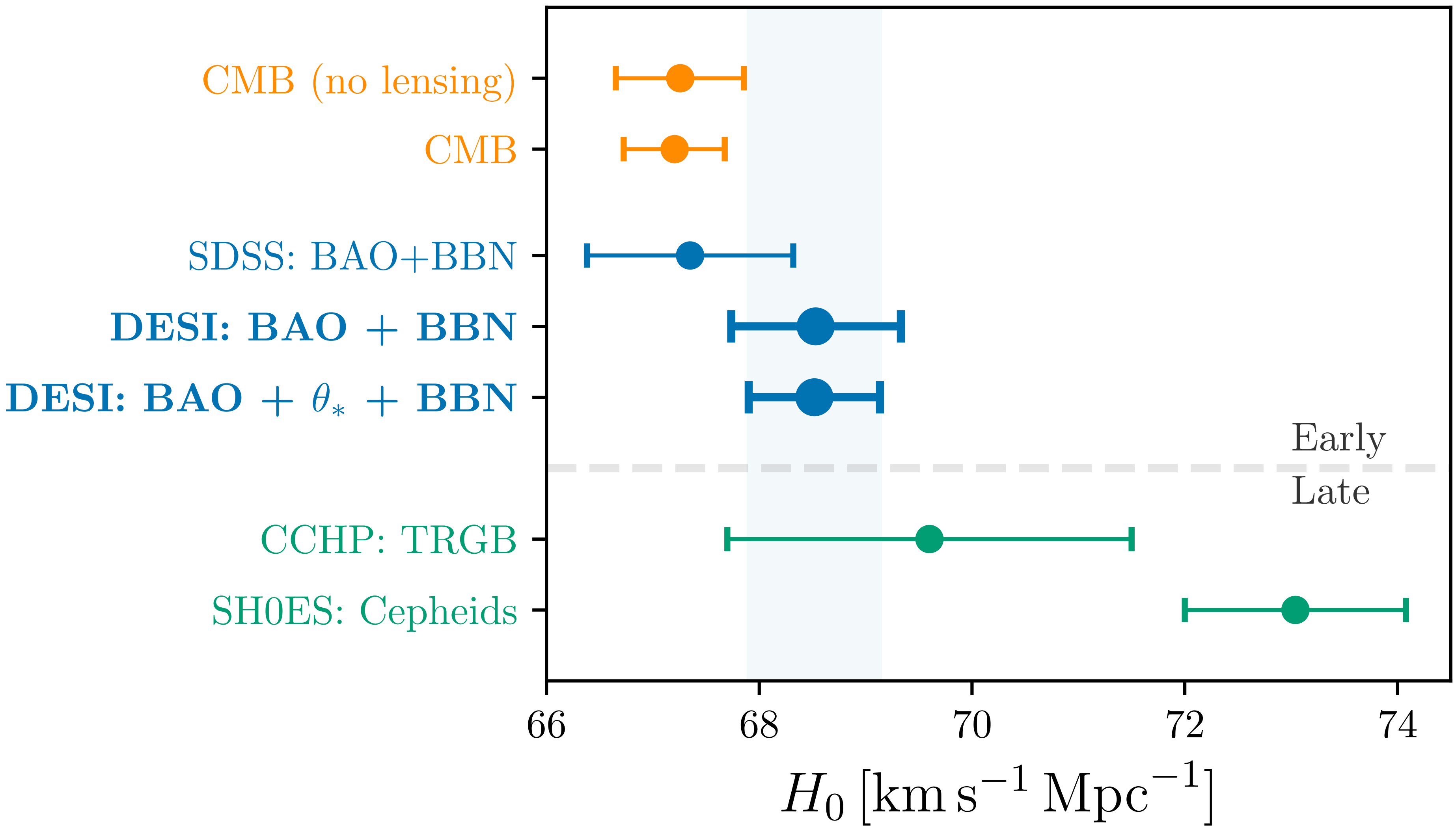




$$\Omega_m = 0.295 \pm 0.015 \qquad (5.1\%)$$

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

Hubble constant



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

Consistent with CMB measurements

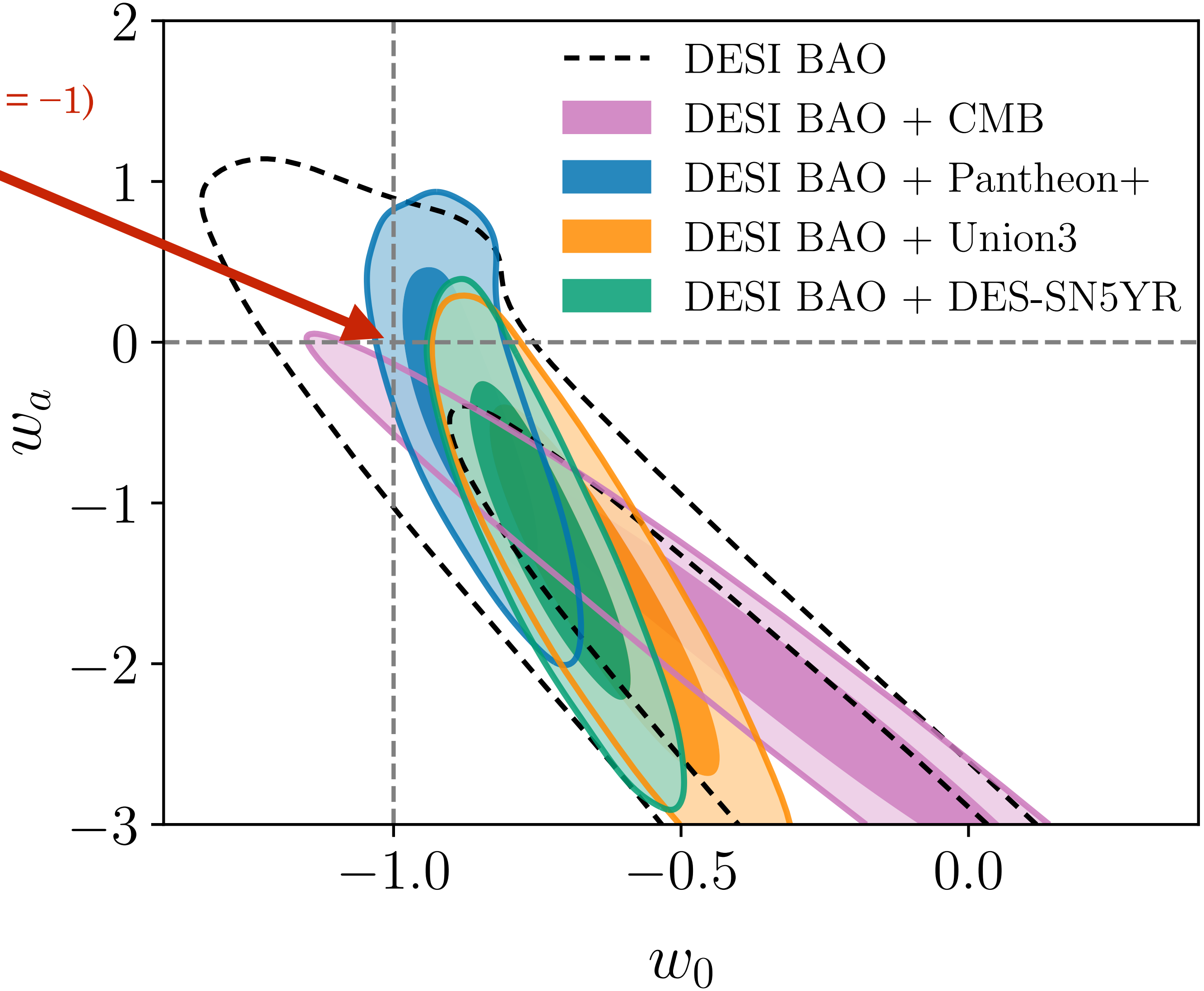
Dark energy - (w_0, w_a)

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

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

ΛCDM
(DE is cosmological constant; $w(a) = -1$)

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



Dark energy - (w_0, w_a)

DESI+CMB+Pantheon+

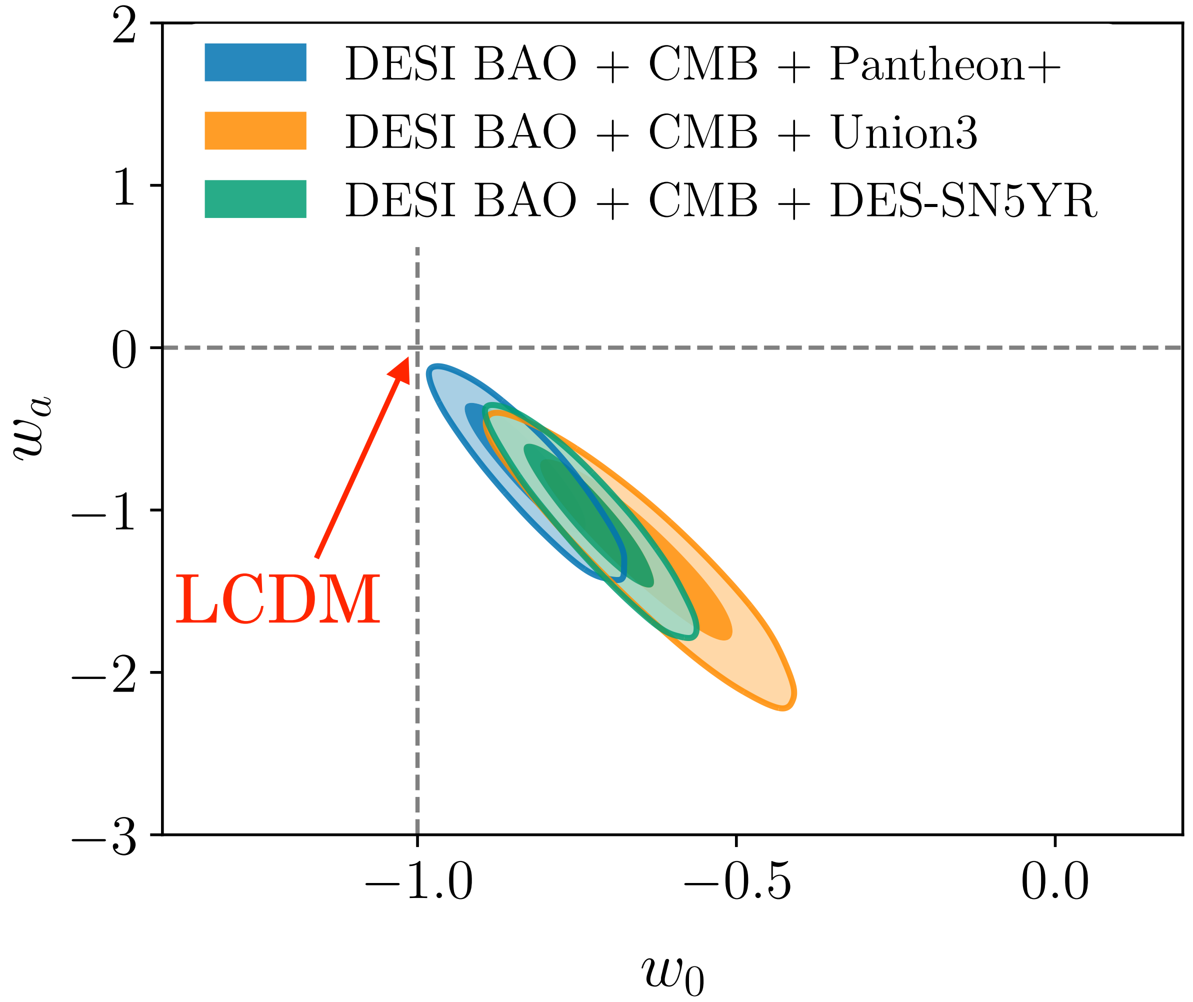
(2.5σ away from ΛCDM)

DESI+CMB+Union3

(3.5σ away from ΛCDM)

DESI+CMB+DES-SN5YR

(3.9σ away from ΛCDM)



Therefore: tantalizing hints of departure from LCDM

What's next for DESI and beyond

- The results presented here were just the BAO;
  DESI Y1 "full-shape" analysis of galaxy clustering is forthcoming (next week!)
- DESI **Year-3** analysis (out in **2025**) will have a major improvement in precision
- 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 (more fibers, maybe on new dedicated telescope?) has been recommended by national agencies to move forward (~2035)

Conclusions

1. Dark Energy $\Longrightarrow$ universe is accelerating, worldwide effort to understand/measure better

2. Hubble tension $\Longrightarrow$ discrepancy in measurements of H_0 by two trusted methods, may indicate a major new discovery!

3. DESI $\Longrightarrow$ world's leading spectroscopic survey with goals to probe dark energy, H_0, and neutrino masses tantalizing hints for departure from standard model

Talk available at
http://www-personal.umich.edu/~huterer/activities.html

New textbook, out May 2023 (Cambridge University Press)
Emphasis: pedagogy, computation
Level: upper undergraduate - lower graduate