Understanding the Unknown: The Mystery of Dark Energy

Anthony Kremin

Lawrence Berkeley National Laboratory

Quarknet 2022

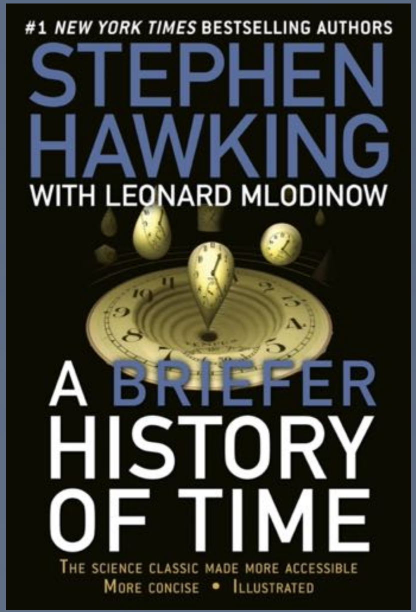
Overview

- Part 1: My academic path
- Part 2: Dark Energy / Cosmology Introduction
- Part 3: The Dark Energy Spectroscopic Instrument

Ideally with lots of your questions mixed in!

Part 1: How I Got Here

High School



credit: Bantam Publishing

- Grew up in Minnesota
- Had a love for math and *concepts* from science
- Watched and read a lot of books on astronomy/physics.
- Didn't have the best physics education in high school (unfortunately)
- Didn't really know what physicists did all day, so thought I wanted to become an engineer.
- Took lots of AP classes which helped me be able to pick classes I liked once in college.

Undergrad (UMN)

- First generation college student, so didn't really know the ropes.
  - Attended lots of seminars/workshops.
  - Talked to professors and guidance counselors.
  - Universities have lots of resources *if* you seek them out!
- Entered college considering physics or aeronautical engineering.
- Decided on physics so I could do research on things I liked:
  - Neutrinos -- NOVA,MINOS (freshman project)
  - Particle Physics -- ATLAS
    - Summer internship at CERN in Switzerland/France in 2012.
    - Honors Senior Thesis on supersymmetric stop squarks.
  - Gravitational Waves -- LIGO
    - Researched for a summer, and part time for two years.
    - Astrophysics Senior Thesis on detecting binary black hole mergers.

While at CERN: 2012 Higgs Announcement

That's me!

Source: CERN

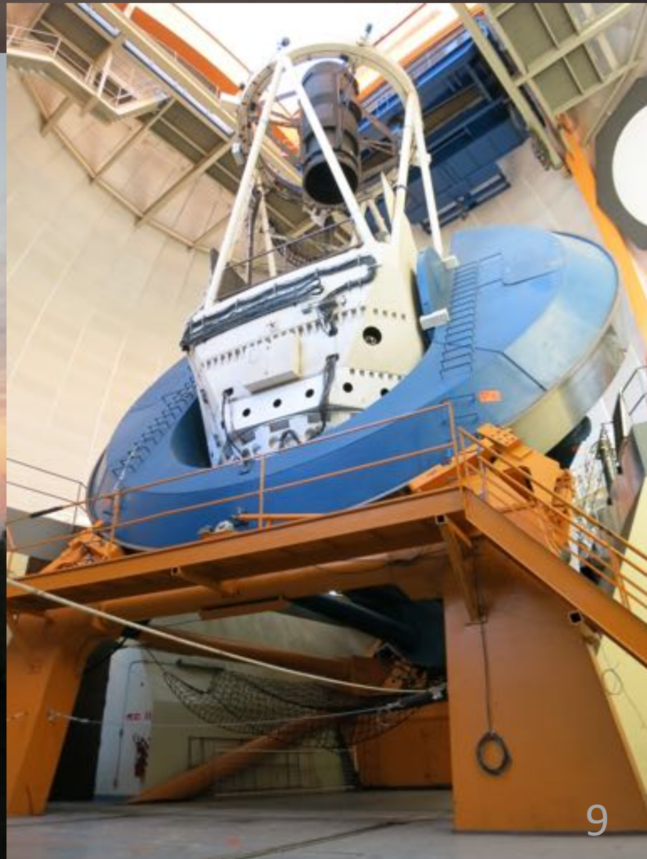
Grad School (UMich)

- I wanted to move in another direction research-wise.
  - Wasn’t sure where particle physics would go after the Higgs.
  - Wasn’t sure if gravitational waves would be discovered anytime soon.
  - Spent my first year deciding what I wanted to work on.
- Eventually landed on studying galaxy clusters.
  - Purpose of my research was to measure the velocities of galaxies in galaxy clusters to estimate the masses of the clusters.
    - The galaxies all orbit one another, so you can measure the total gravitational mass in a similar way to how we can estimate the mass of the sun from the planets.
  - Worked on Dark Energy Survey (DES) and Dark Energy Spectroscopic Instrument (DESI).
  - As an “observationalist” I got to travel to mountain tops in Chile, Australia, and Arizona to use massive (and sophisticated!) telescopes.







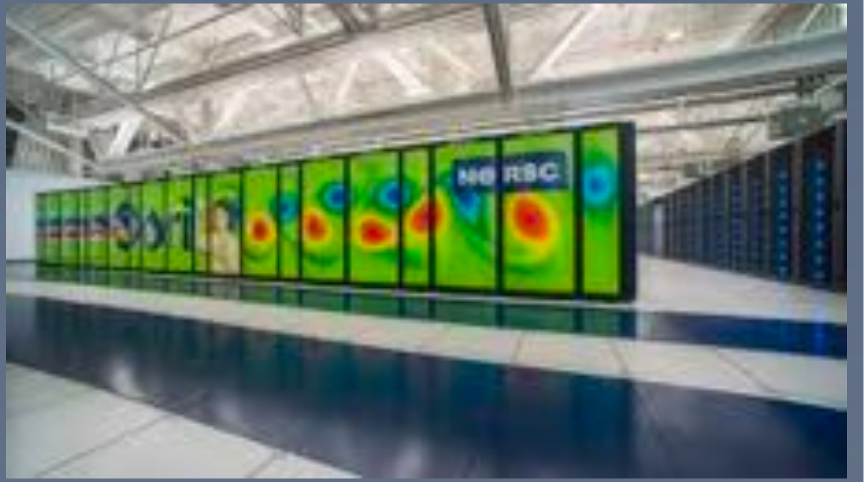



One of thousands of known Galaxy Cluster

NASA, ESA, and G. Bacon (STScI);
Acknowledgment: NASA, ESA, A. Fujii, Digitized Sky Survey (DSS), STScI/AURA, Palomar/Caltech, and UKSTU/AAO, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI)

Postdoc

- DESI Postdoctoral Researcher, Lawrence Berkeley National Laboratory
  - Spend half my time doing research similar to what I did in graduate school.
  - Also study the velocities of nearby galaxies to understand how the local Universe is evolving.
  - Spend the other half helping to develop software for the Dark Energy Spectroscopic Instrument.
  - I’m in charge of processing all the raw data into scientifically useful things for the other 500+ people in the collaboration and the wider community of scientists.
- I’ve been here for almost 2.5 years

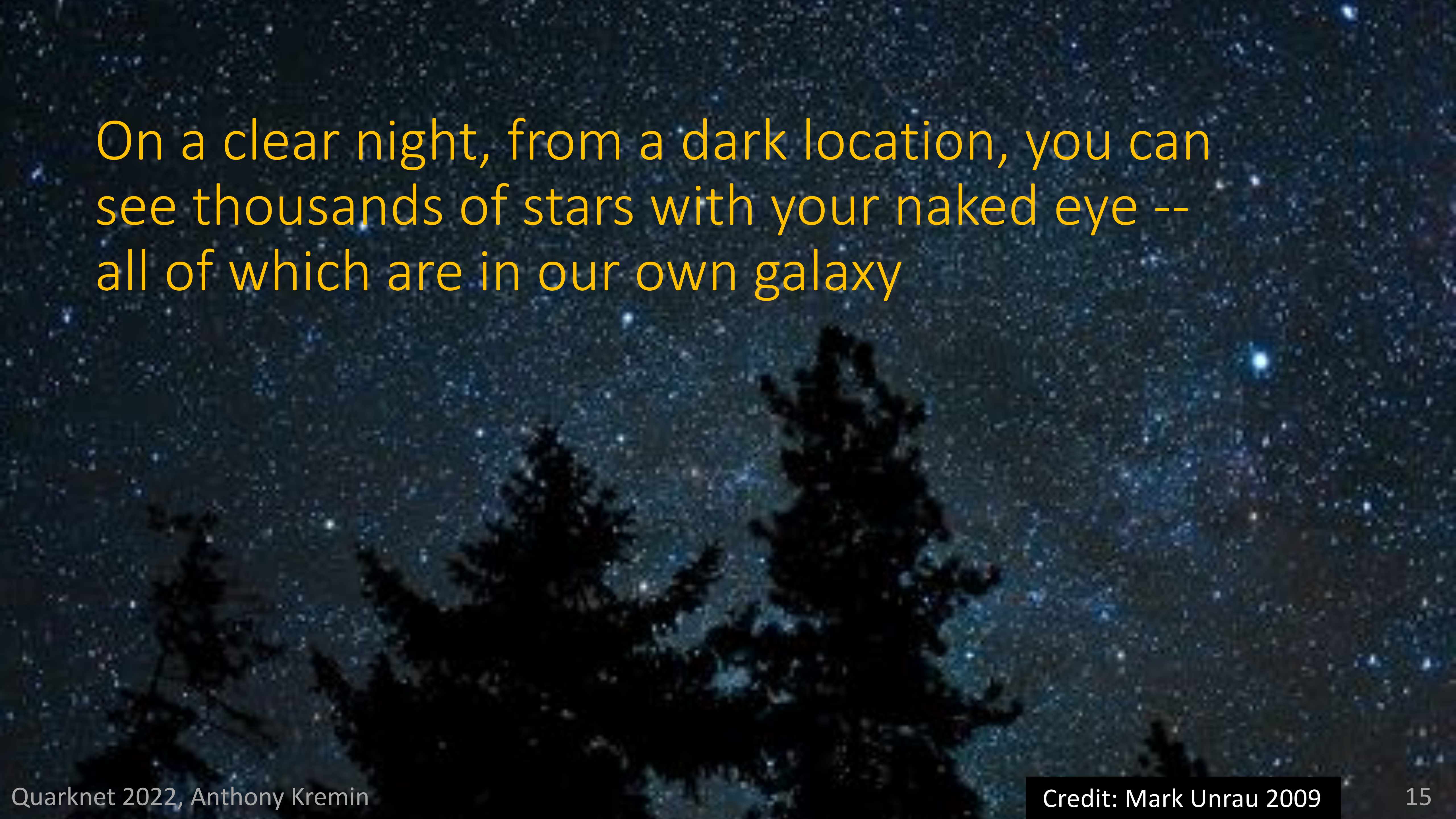


Questions?

Part 2: Dark Energy/Cosmology

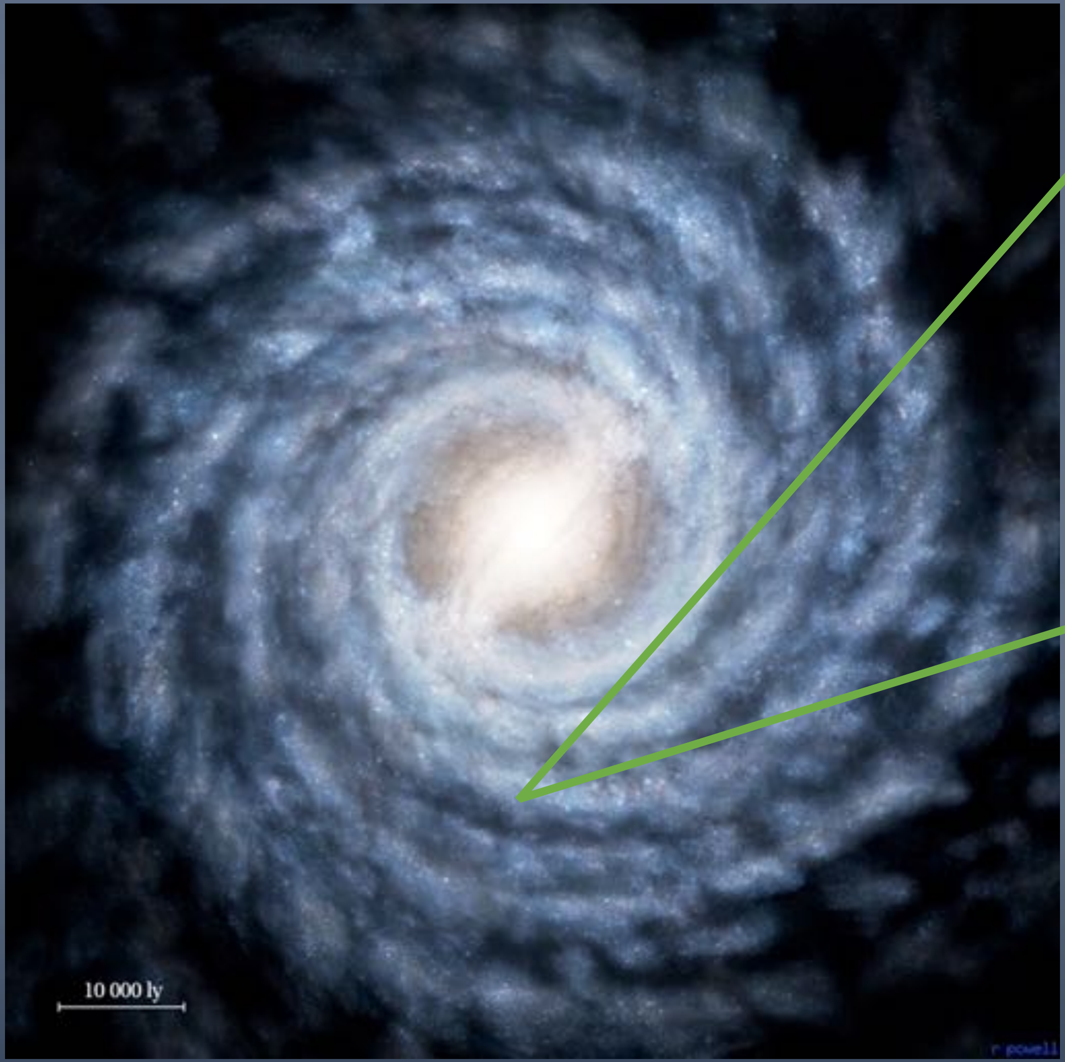
Our place in the Cosmos

On a clear night, from a dark location, you can see thousands of stars with your naked eye -- all of which are in our own galaxy



Credit: Mark Unrau 2009

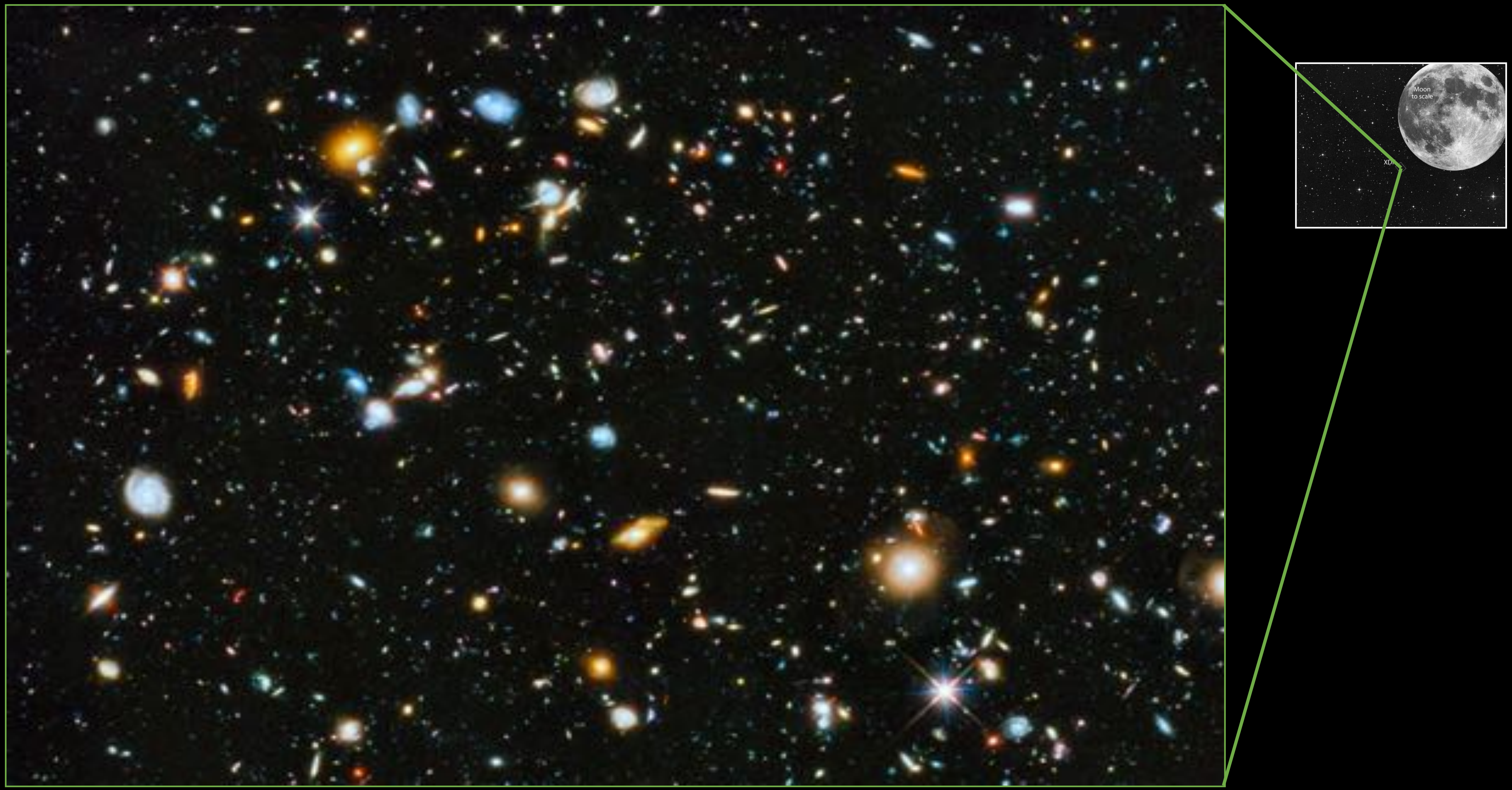
The Sun is just one of roughly 100 billion stars in our Milky Way Galaxy.



Credit: Atlas of the Universe

The night sky is filled with *billions* of galaxies.

Credit: NASA



Credit: NASA

The night sky is filled with *billions* of galaxies.

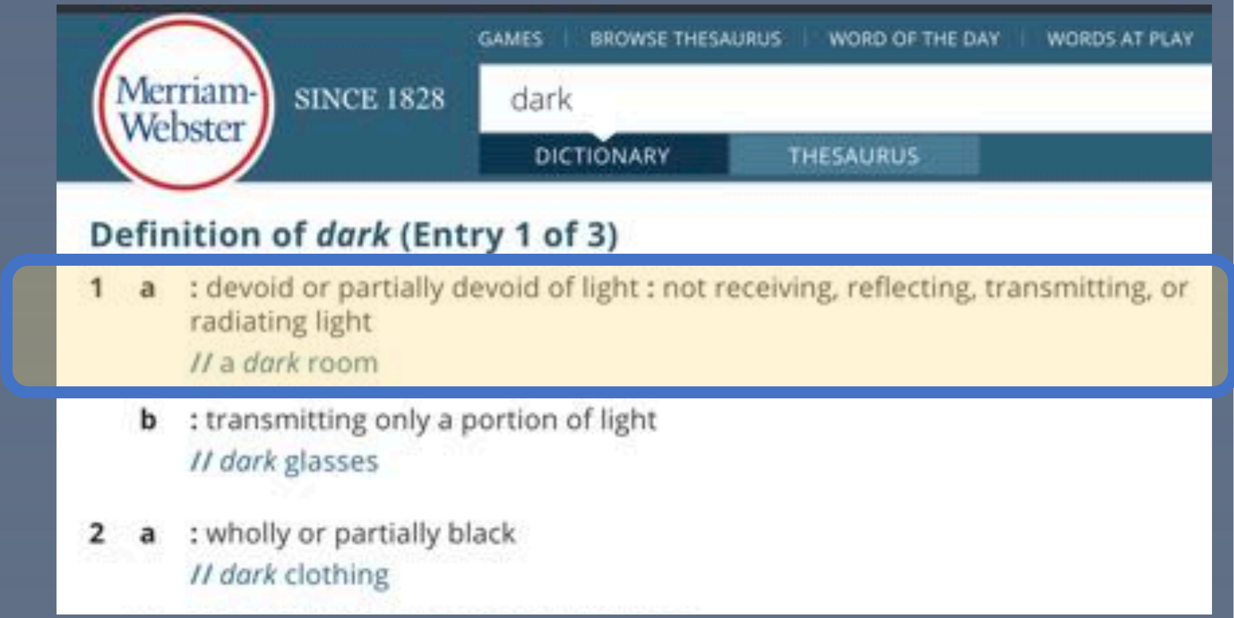
Our knowledge of the Cosmos

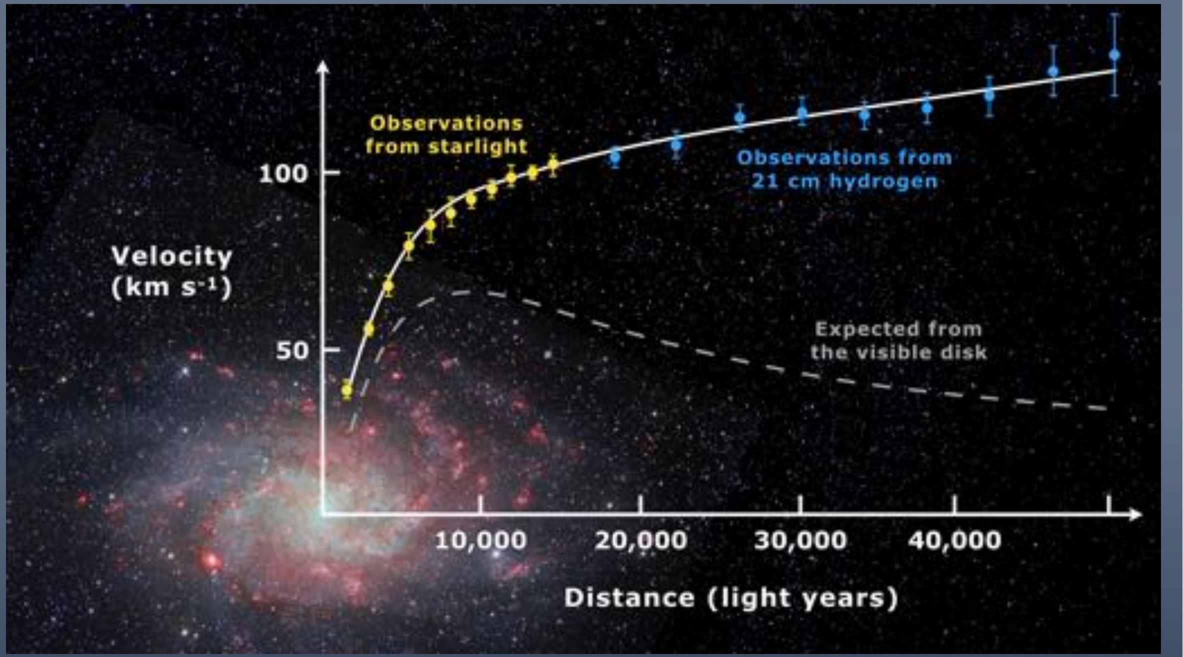
A Brief History of Cosmological Understanding

~500 years ago	
~100 years ago	
~90 years ago	
~60-80 years ago	
~20 years ago	
Today	

Dark Matter

- Dark matter pulls with gravity like normal matter.
- It doesn't absorb or emit light, so it is invisible to us.
- First postulated in the 30/40's by looking at galaxy clusters.
- Shown strikingly by Vera Rubin in the 70's using galactic rotation curves.

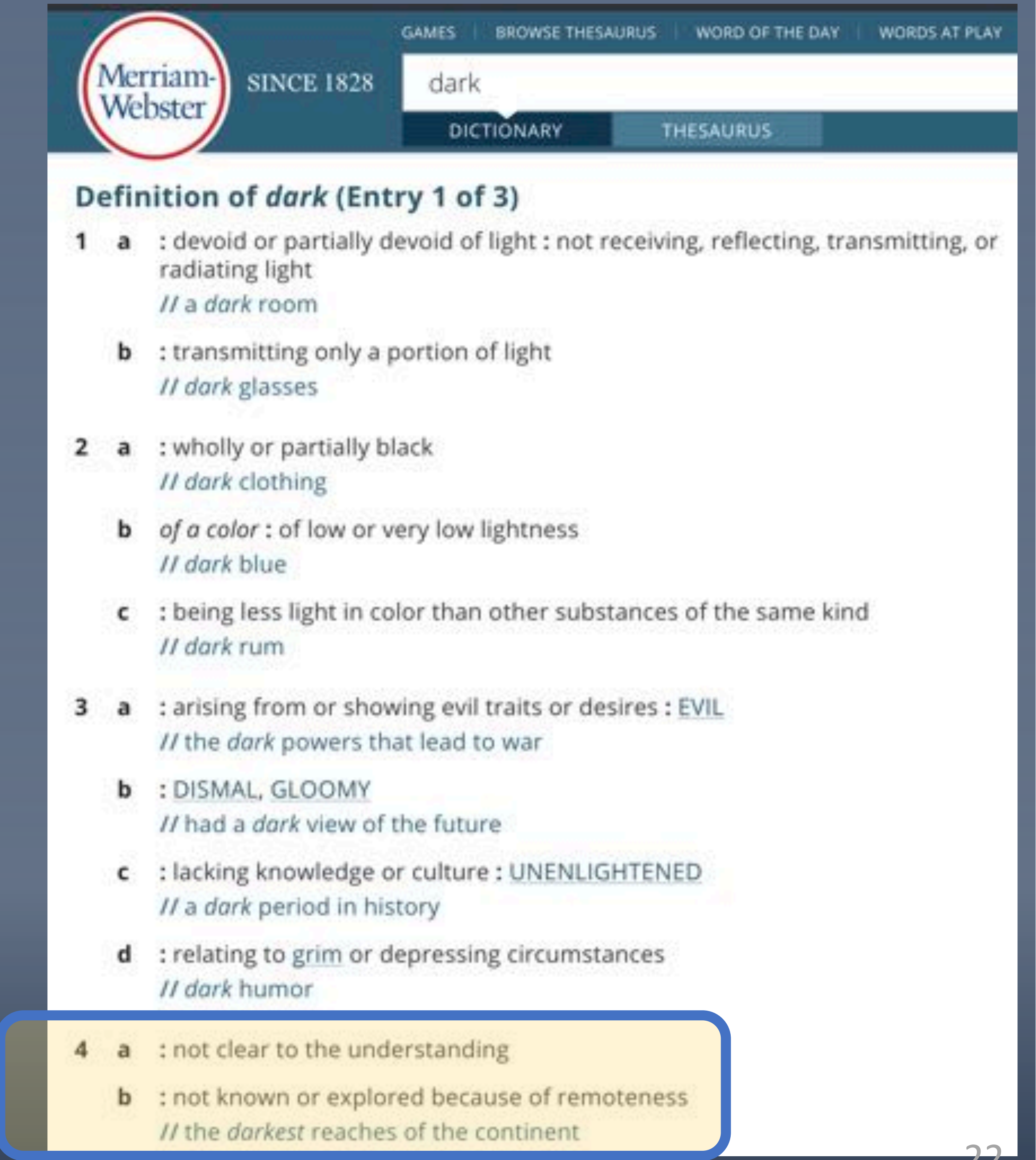




Credit: wikipedia

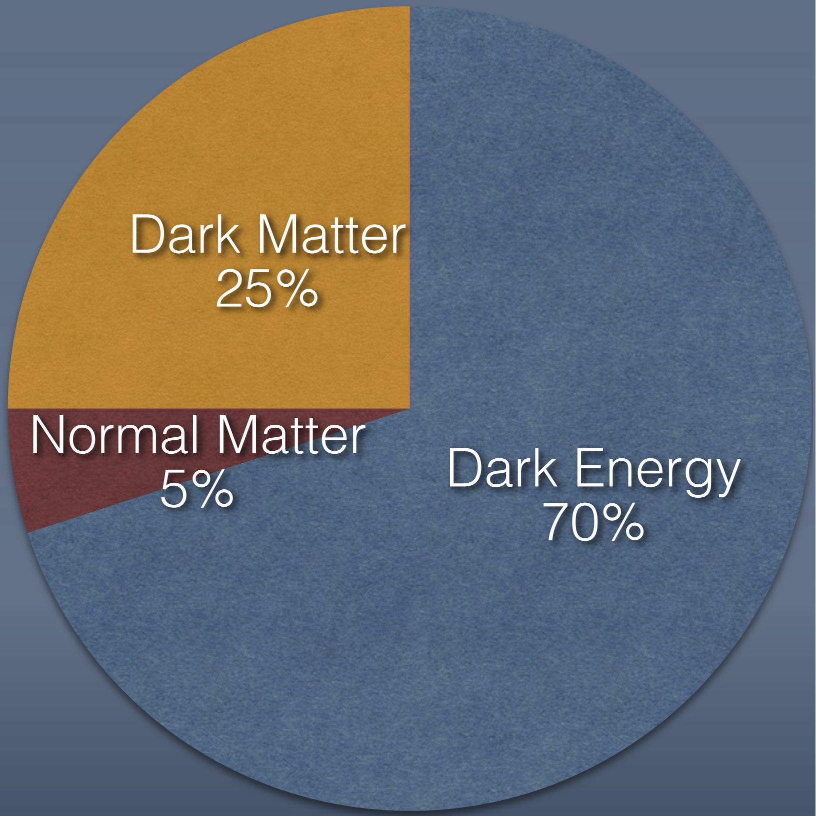
Dark Energy

- Dark energy doesn't *pull* using gravity
  - It *expands* using gravity (negative pressure).
  - Doesn't operate like anything we know.
- However, it does work in our framework of general relativity, and it fits all observations.
- A "cosmological constant"
  - It appears to act the same throughout cosmic time
  - Appears to be uniform in space.

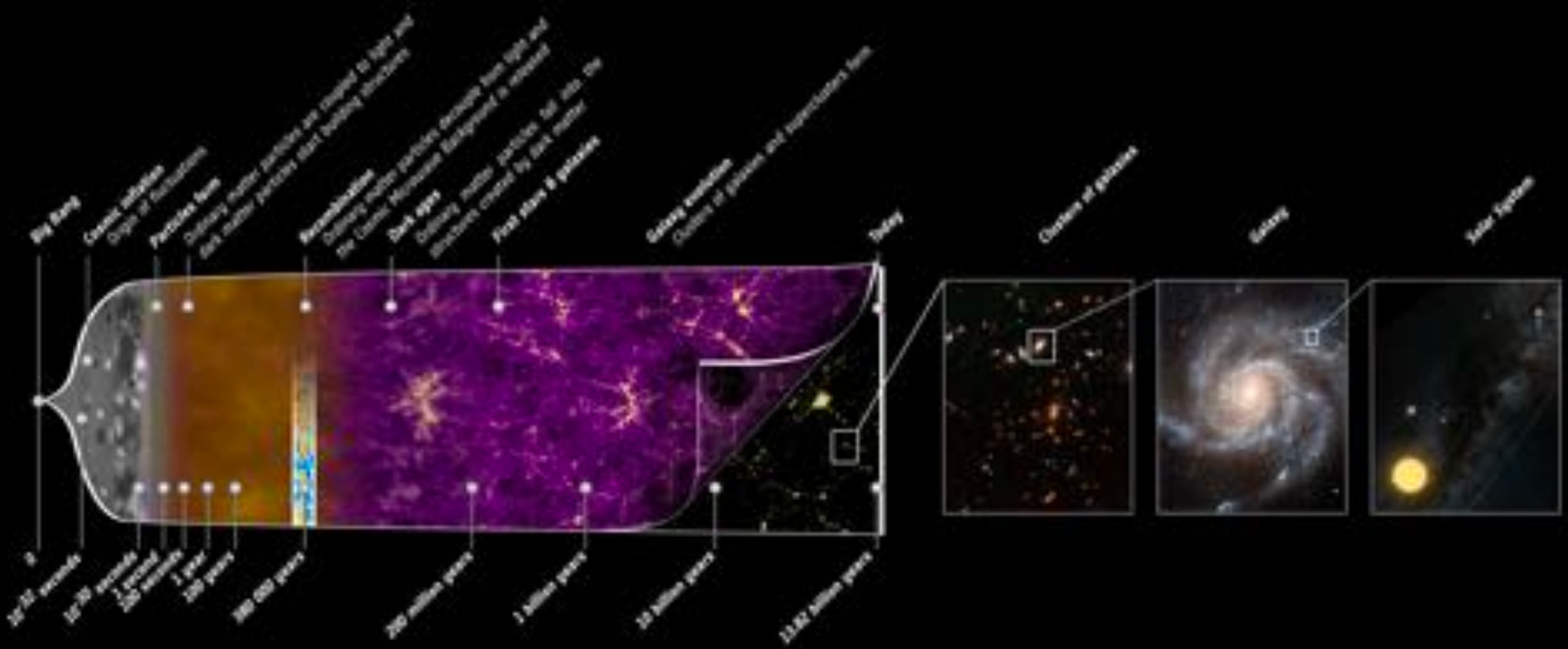


Our Current Knowledge

- The Universe is currently expanding, and accelerating in its expansion. → **dark energy**
- Only about 20% of the gravitational pull we 'observe' can be explained by the galaxies and objects we can see. → **dark matter**
- Many different studies using different techniques all agree to an increasing level of precision.



Evolution of the Universe



Source: Planck, ESA, NASA

Questions?

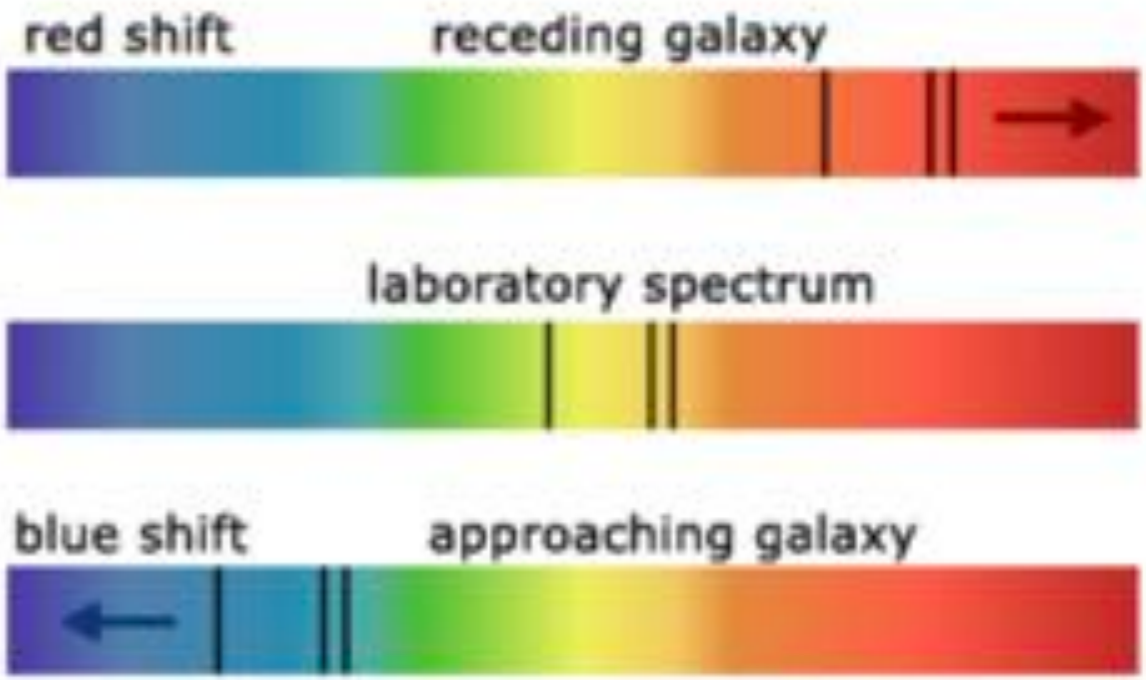
How do we know these things?

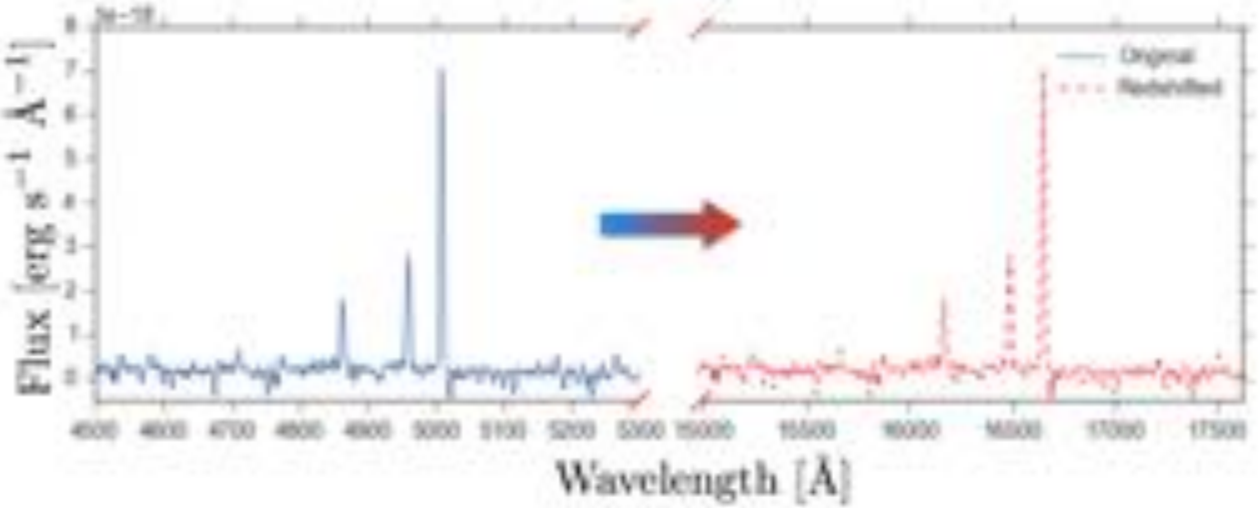
Experiments proving and disproving theories.

Theories explaining experimental findings.

Measuring Redshift

$$1 + z = \frac{\lambda_{obsv}}{\lambda_{emit}}$$





Credit P. Fagrelius

Challenges for Testing Cosmology

- Light travels at finite speed (c)
  - Means looking far away is the same as looking back in time.
  - So we can't look at lots of things at the present day, or any other time.
  - Always looking at "snapshots" of the Universe at many different times
  - Trick is to use this to our advantage!
- Can't know the distance to something
  - No way to lay out rulers 1000's of light years long
  - Need special tricks to get distance to objects.
- Universe is expanding
  - This means the stretching of space is related to the age of the Universe.
  - Can use this "stretch factor," a, as a proxy for time or distance.
  - Or use the related value z, which is the redshift.

Takeaways

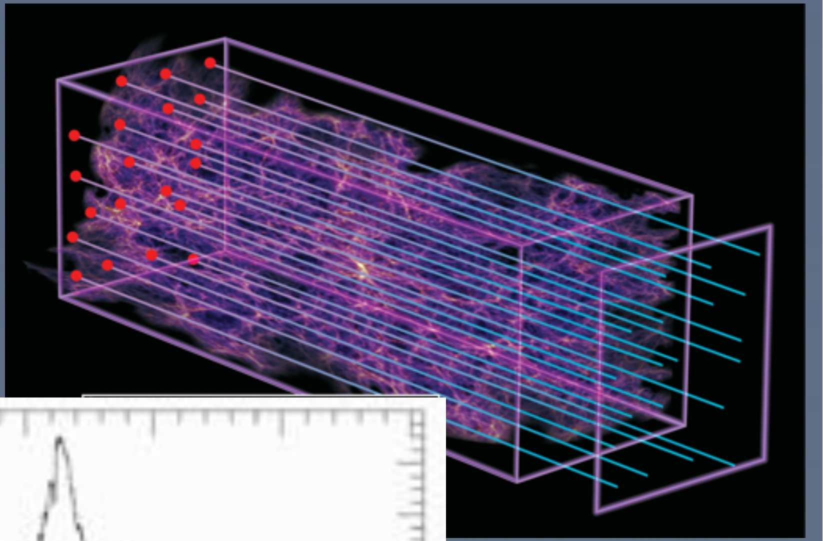
Time often plays a role, whether we like it or not.

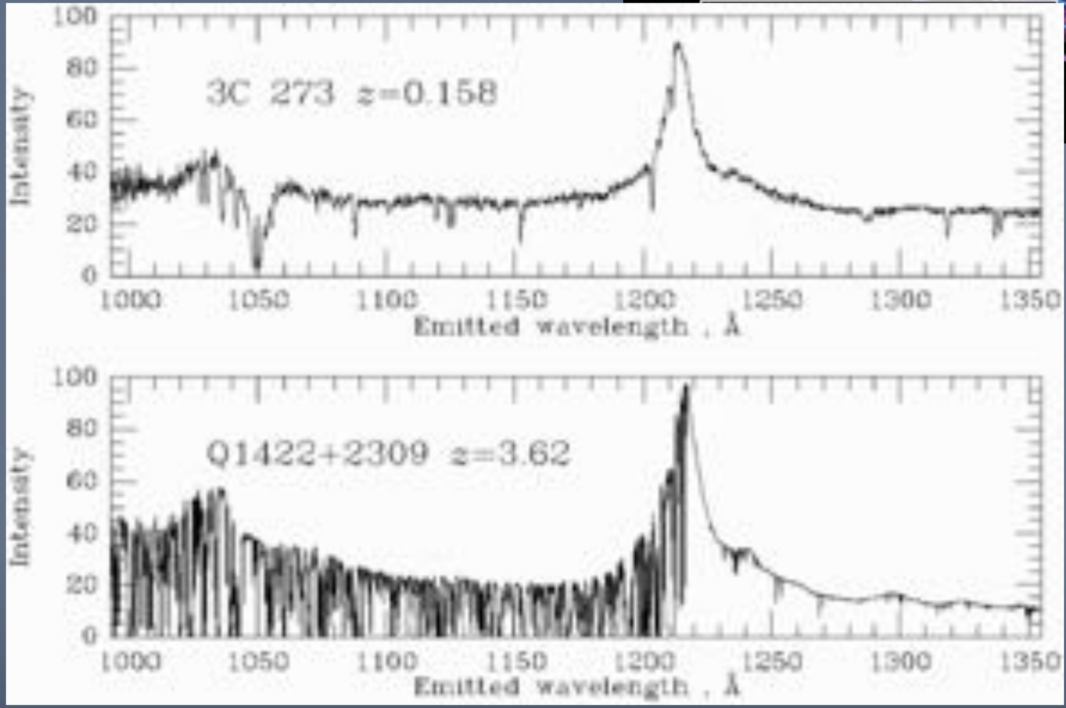
Need to be clever to get distances to things

z = redshift
= look back time
= distance

Measurements

- Cosmic Microwave Background (CMB)
- Supernova
- Baryon Acoustic Oscillations
- Things I won't have a chance to talk about:
  - Galaxy Clusters
  - Redshift Space Distortions
  - Quasars
  - Lyman Alpha Forest
  - Peculiar velocities,
  - Big bang nucleosynthesis,
  - …

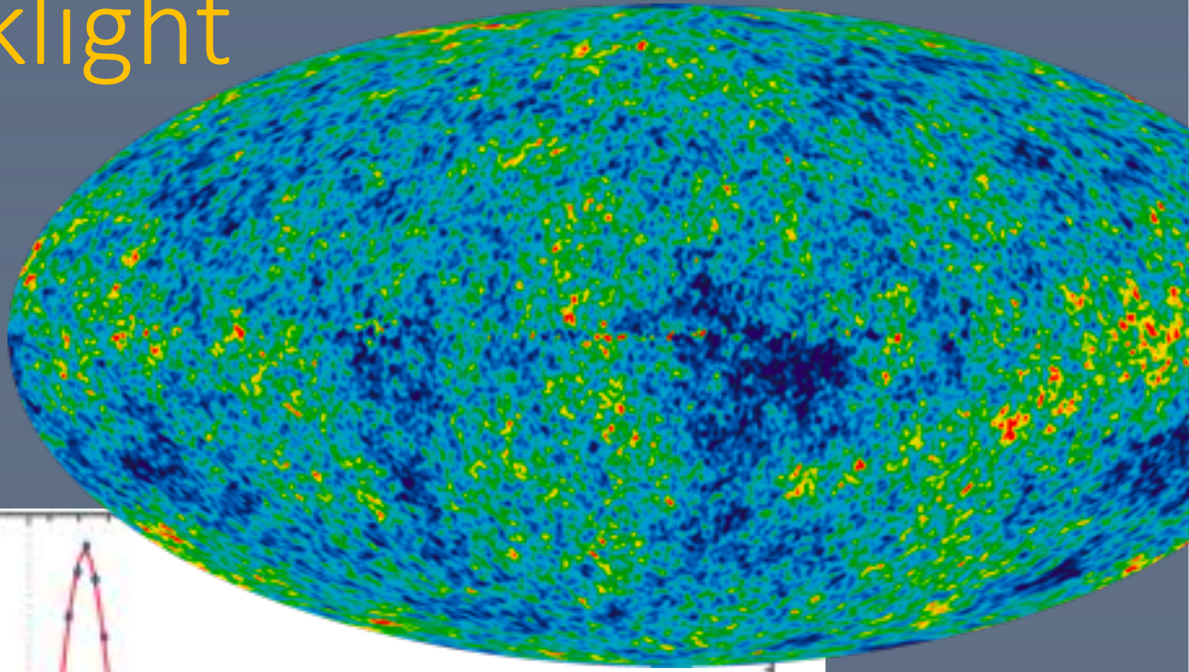


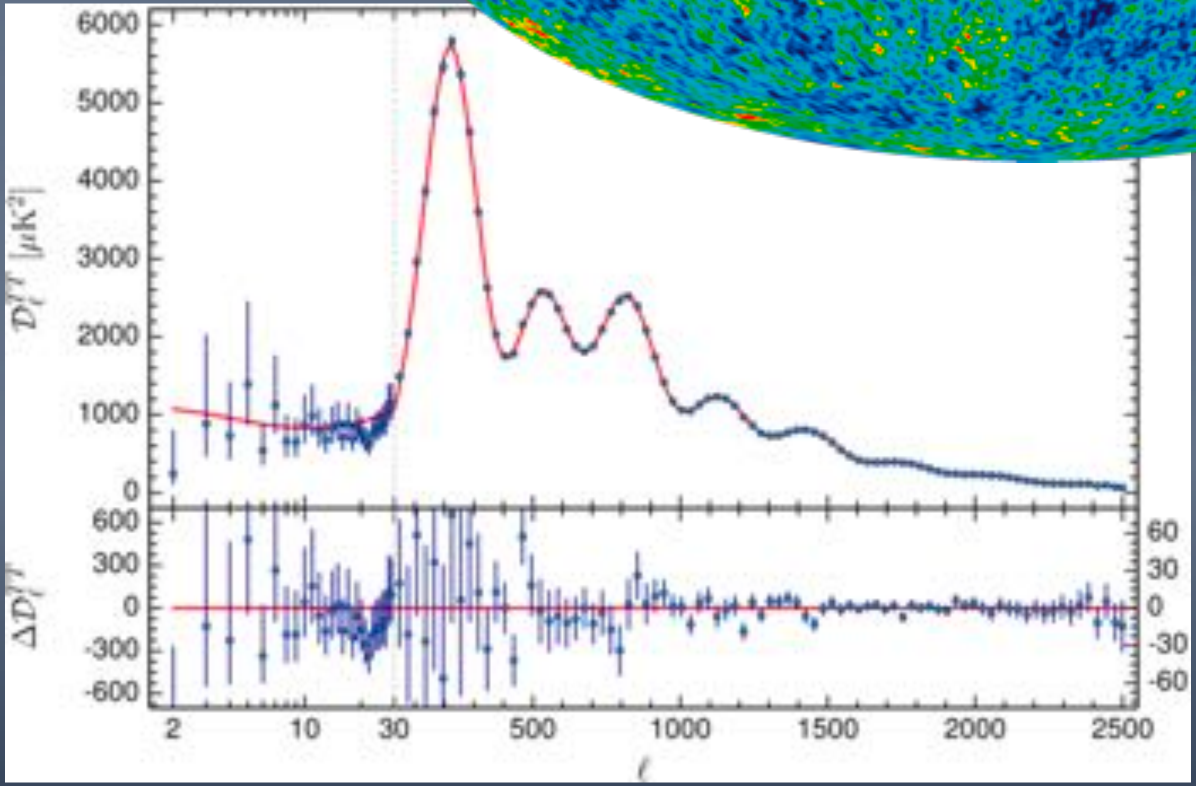


Credit: Bill Keel

Method 1: Universal Backlight

- CMB = Cosmic Microwave Background
- Positions of the peaks give information on total energy in the Universe (curvature)
- Relative heights of larger "l" peaks give information on matter, baryons, and sound speed.
- Can infer dark energy from total budget and the measured amount of matter





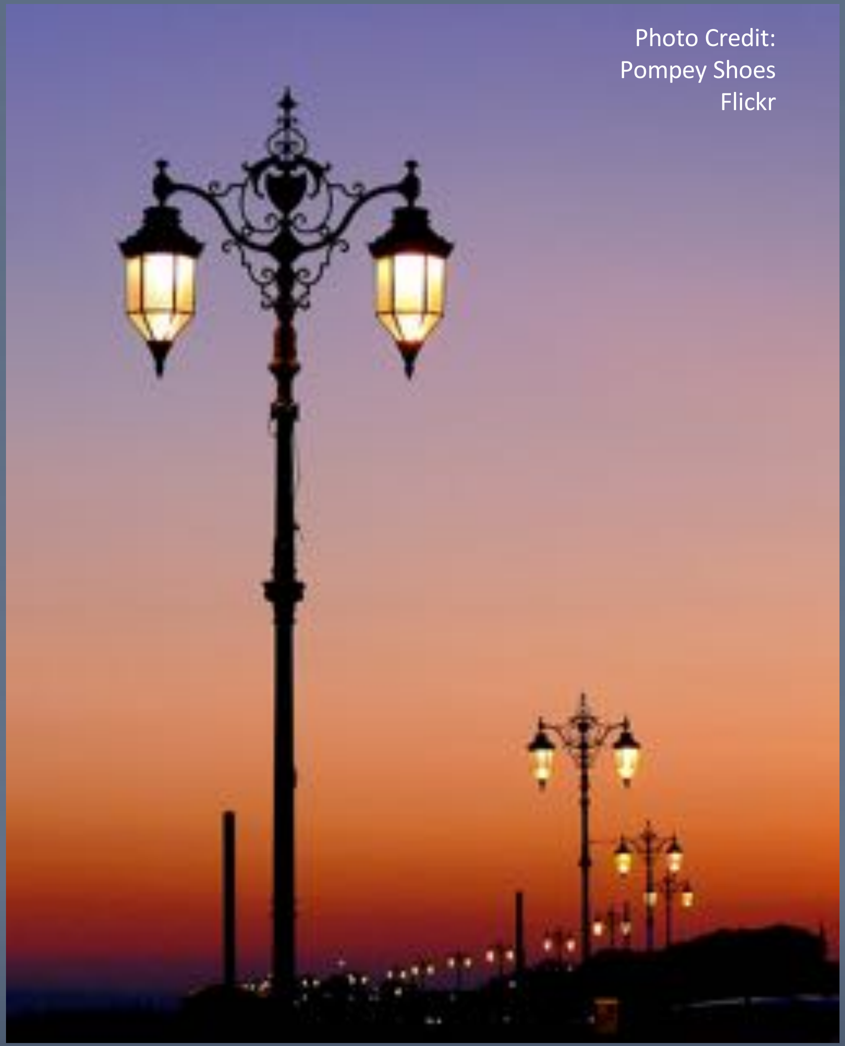
Questions?

Method 2: Supernovae

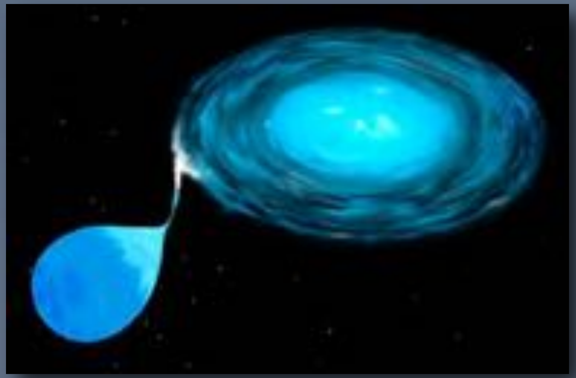
Standard Candles

- Brighter things are closer
  - Luminosity distance
  - Observed brightness = $1/d_L^2$
- The challenge
  - Are some just intrinsically brighter?
  - Need a “standard candle” of uniform brightness

→ Supernova 1a



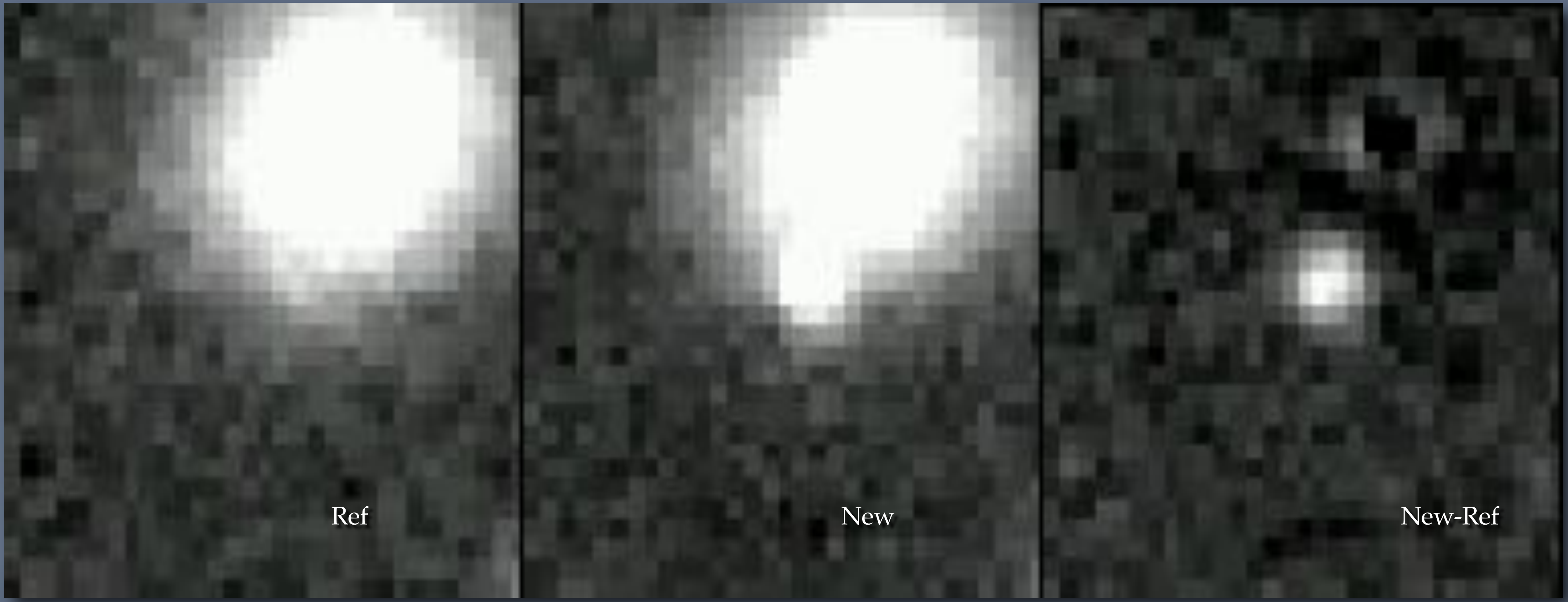
Supernovae (Type Ia, to be exact)



- Carbon-Oxygen White Dwarf
  - Accretes mass from a companion star
  - Collapses under its own weight — boom!
- Standard candle
  - Nuclear physics vs. gravity determines the mass at which it collapses
  - Same mass every time = same energy = same brightness
- Properties
  - **Bright**: ~billion times brighter than the sun
  - **Rare**: ~1 per 100 years per galaxy
  - **Hard to find**: Two weeks from explosion to maximum brightness; then another 6 weeks to fade away


SN 2011fe
Byrne Observatory at Sedgwick Reserve and the Palomar Transient Factory | LCOGT | BJ FULTON

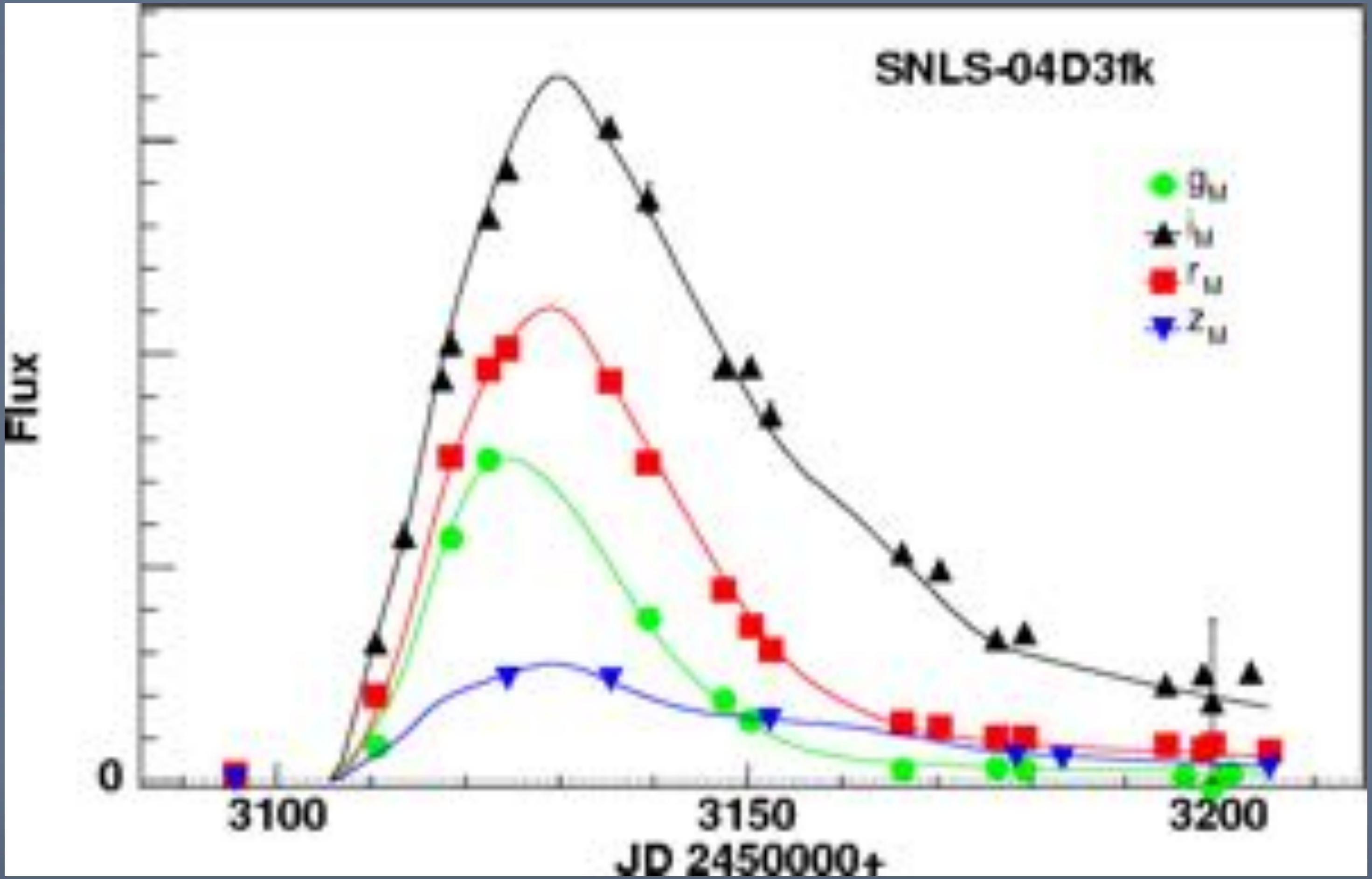
A more typical case



10^{-7} of the area observed per night by the Nearby Supernova Factory

SN Ia light curve

(an unusually well measured example)



Peak brightness –> luminosity distance

Supernovae: The Math

$$d_L(z) = (1+z)\frac{c}{H_0}\int dz' \left(\Omega_M(1+z')^3 + \Omega_k(1+z)^2 + \Omega_\Lambda \exp\left(\int_0^z 3\frac{1+w(z')}{1+z'}dz'\right)\right)^{-1/2}$$

Distance

Redshift

Cosmology parameters

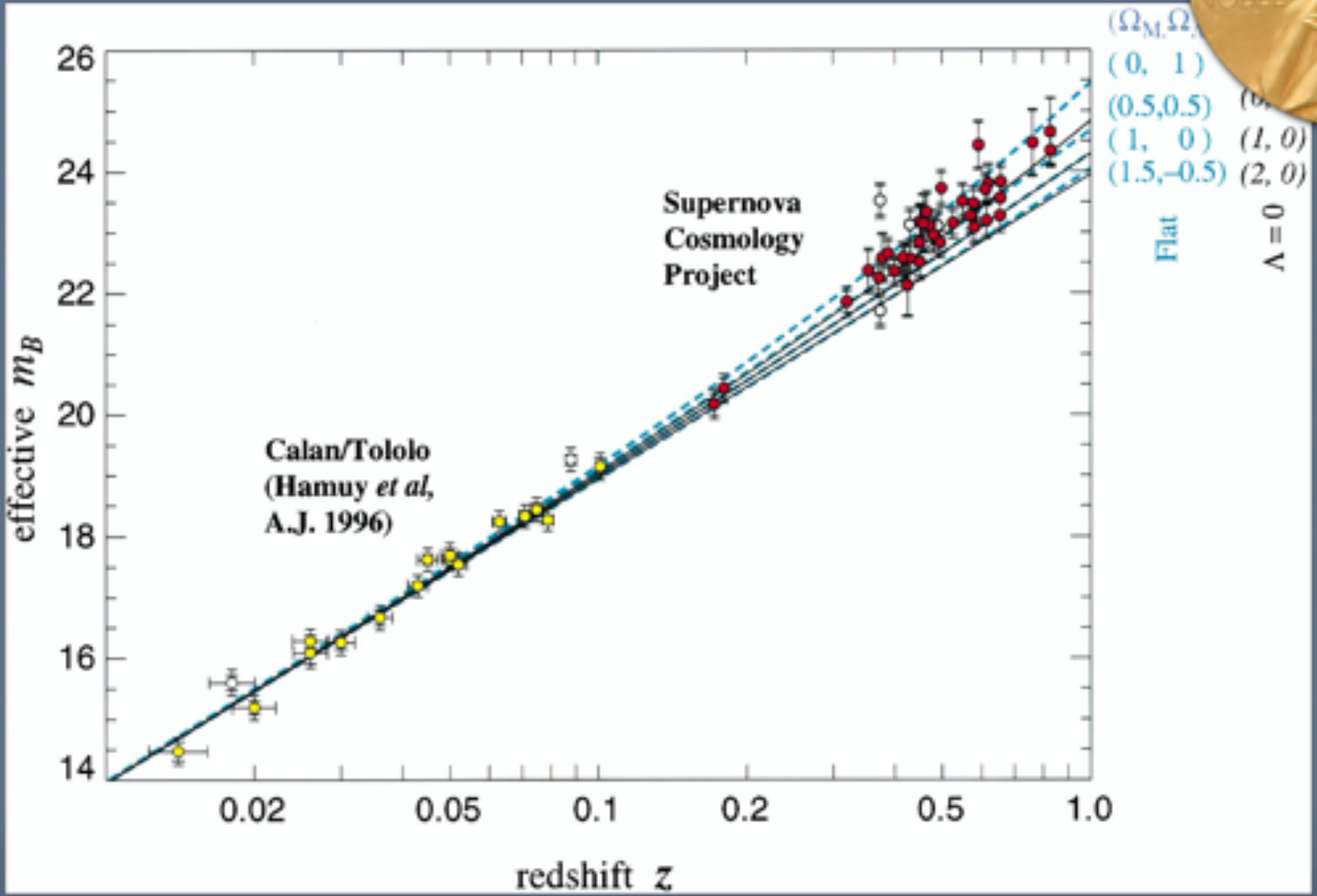
z = redshift: Another proxy for distance (or time)

Ω_x: The energy fraction of that component of the Universe (1 is all).

Λ: Cosmological constant, a simple form for dark energy.

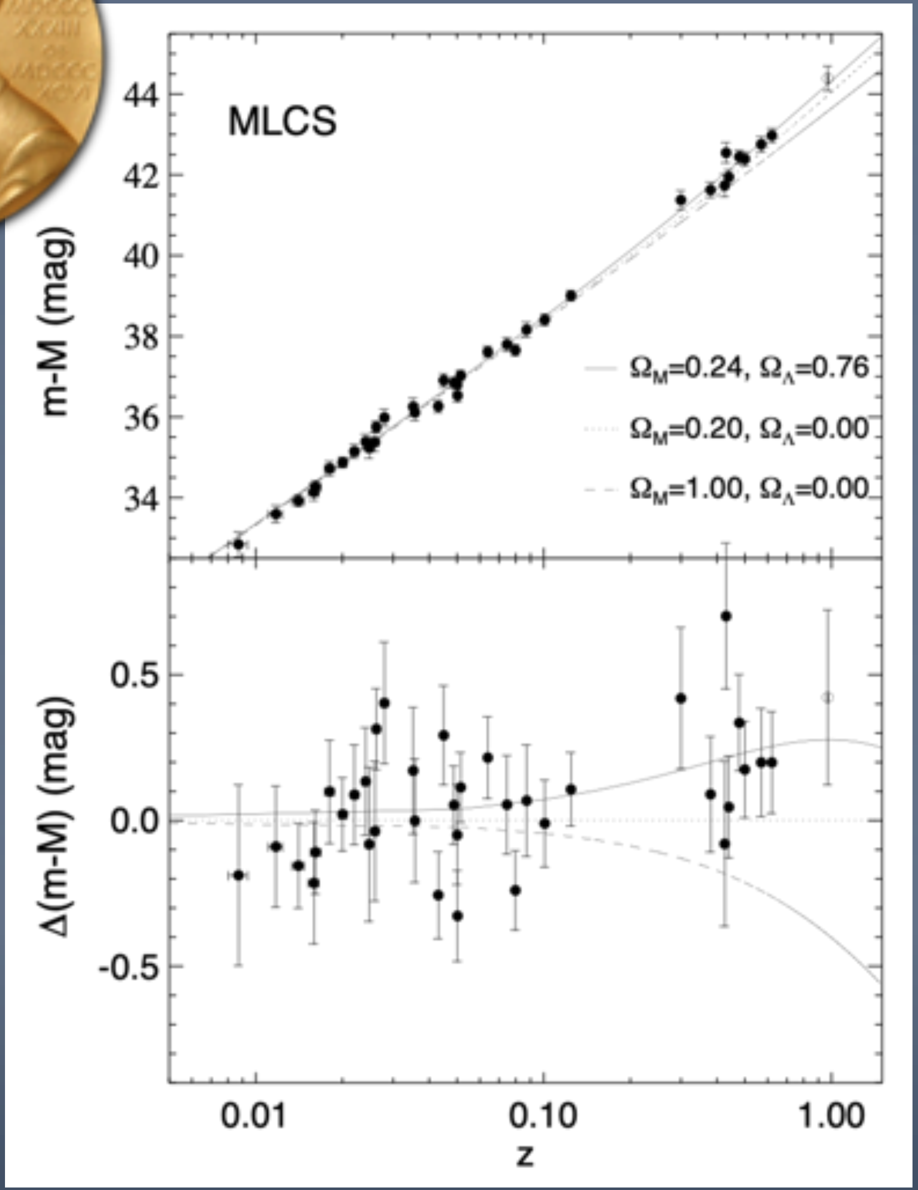
w: A variable that describes how dark energy acts. w=1 is a cosmological constant

Hubble Diagram



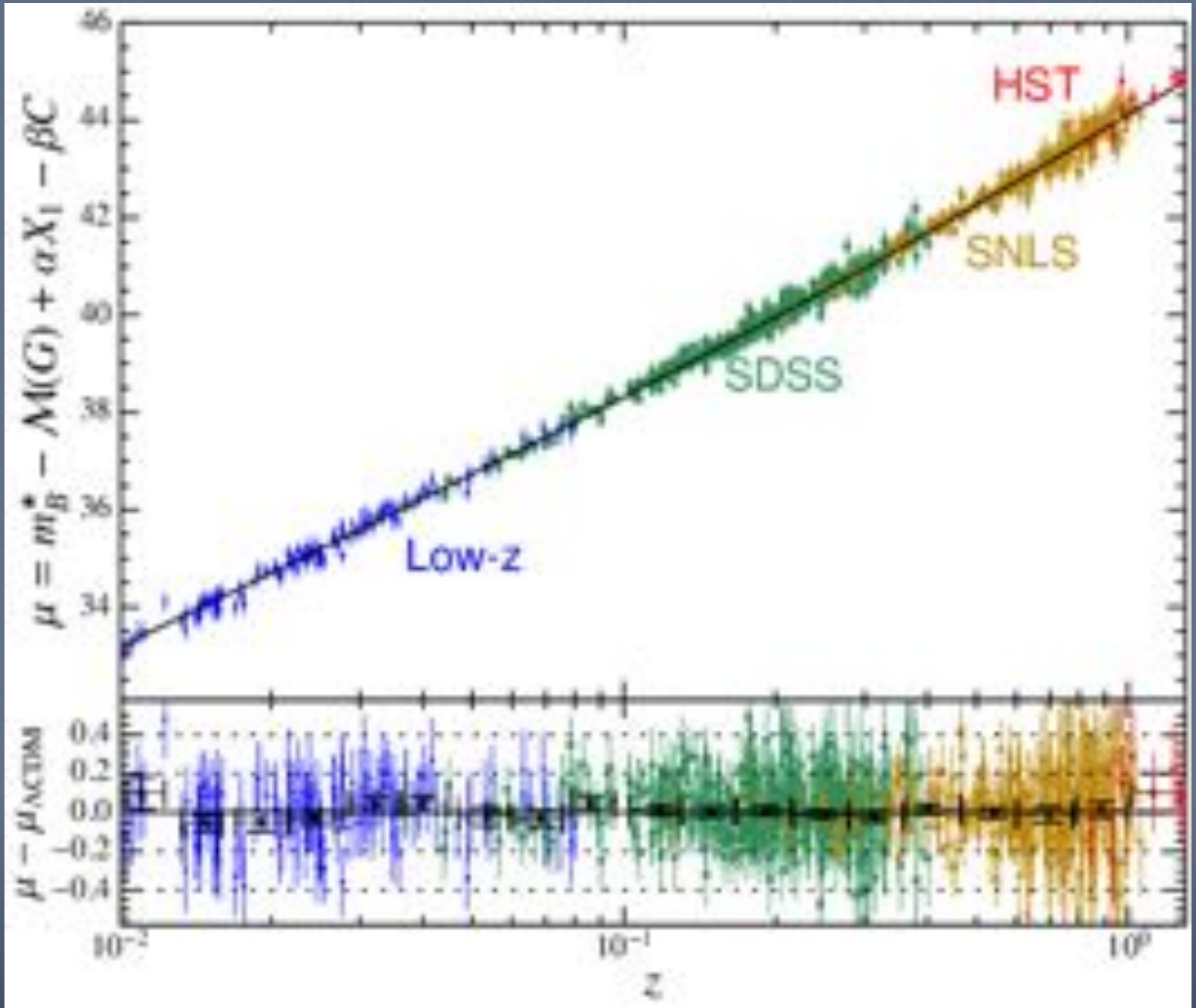
Perlmutter+ 1999

Riess+ 1998



The big surprise –> expansion is accelerating instead of decelerating

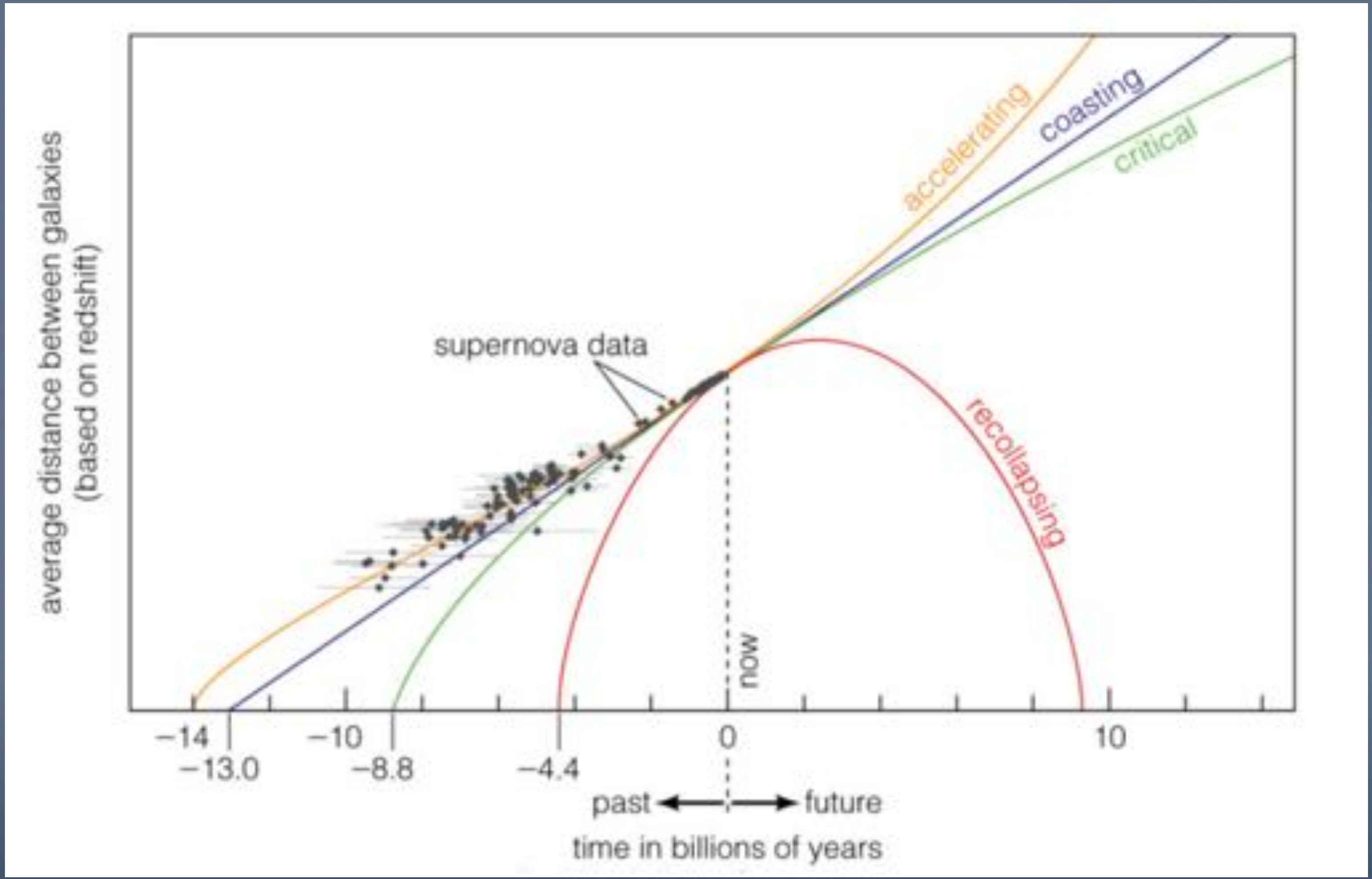
Modern Hubble Diagram

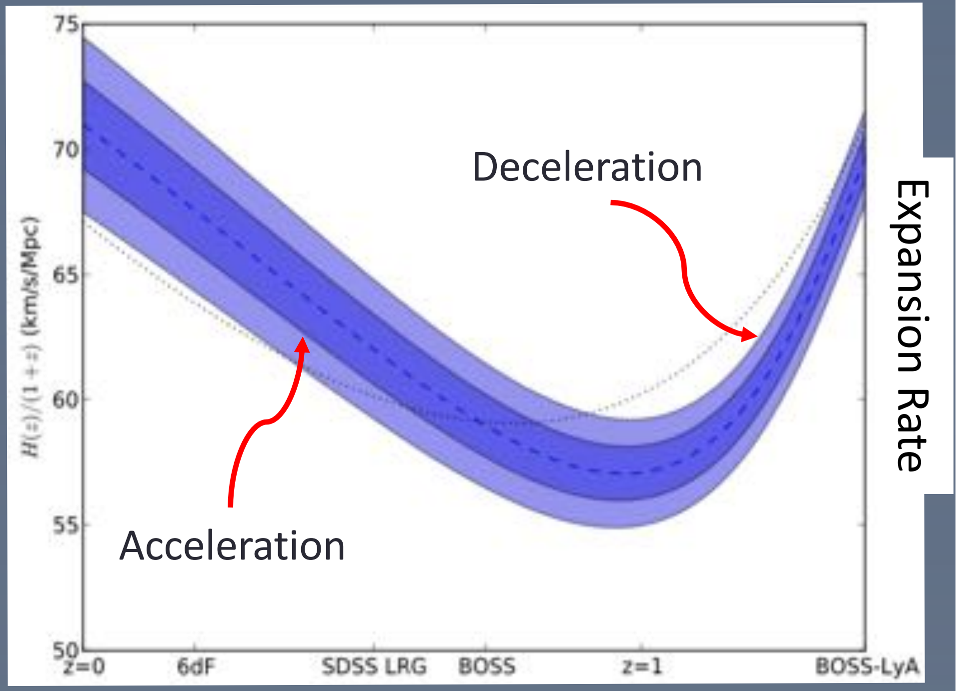


Betoule+ 2014
"Joint Light-curve Analysis"

Observations of supernovae indicate the universe today is expanding at an *accelerating* rate.

Credit: T. Davis, N. Padmanabhan



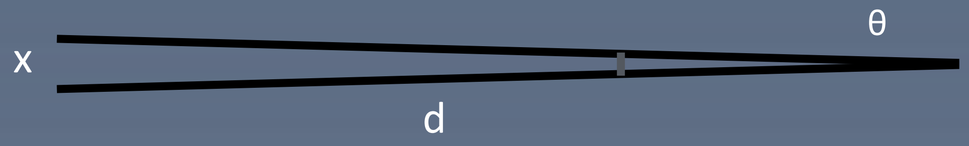


Time

Credit: P. Fagrelius

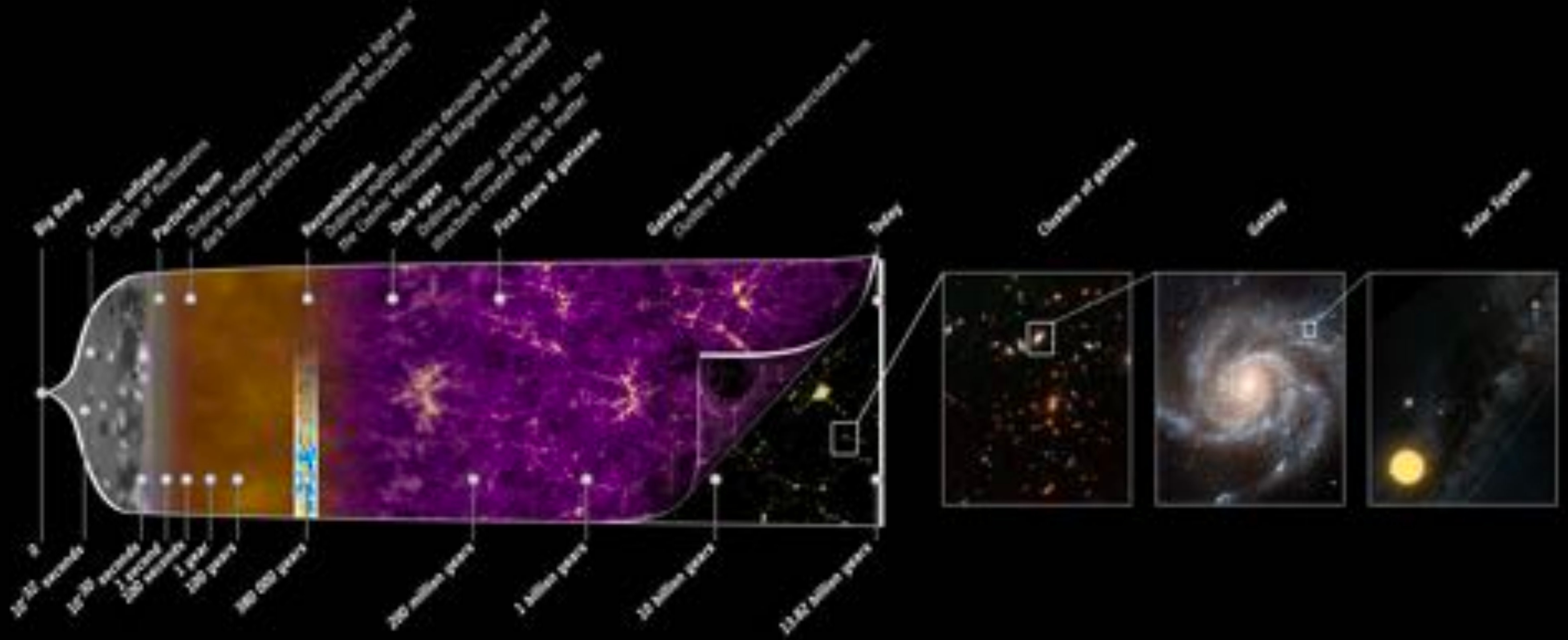
Method 3:
Baryon Acoustic Oscillations (BAO)

Standard Ruler



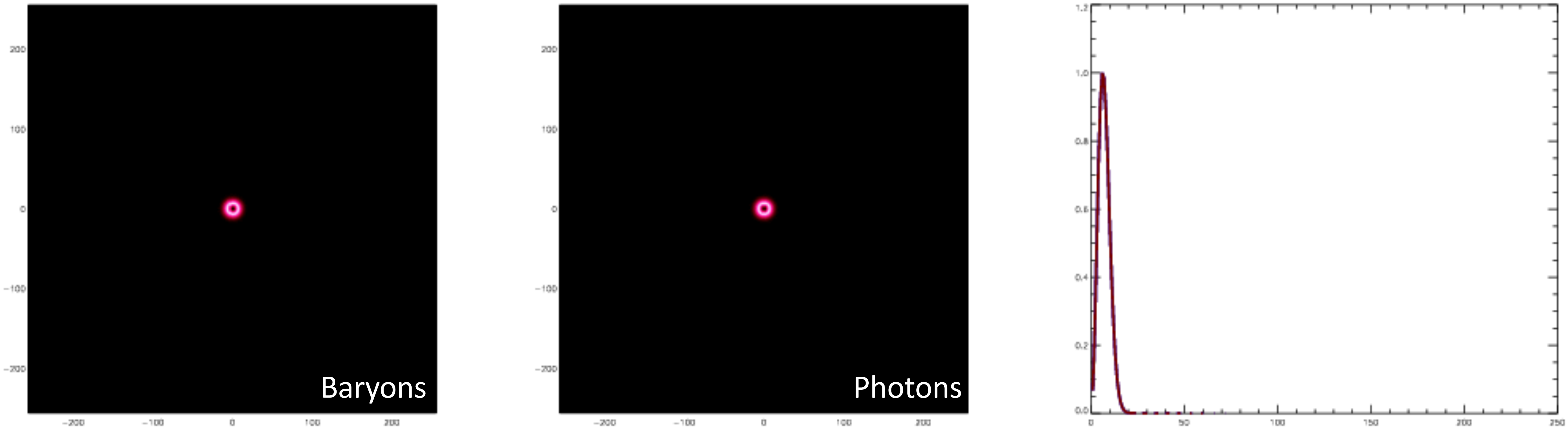
- Bigger things are closer
  - Angular diameter distance
  - Observed size = $1/d_A^2$
- But how do we know if objects are the same size?
- Need to find objects that are a uniform size

→ Baryon Acoustic Oscillations



Source: Planck, ESA, NASA

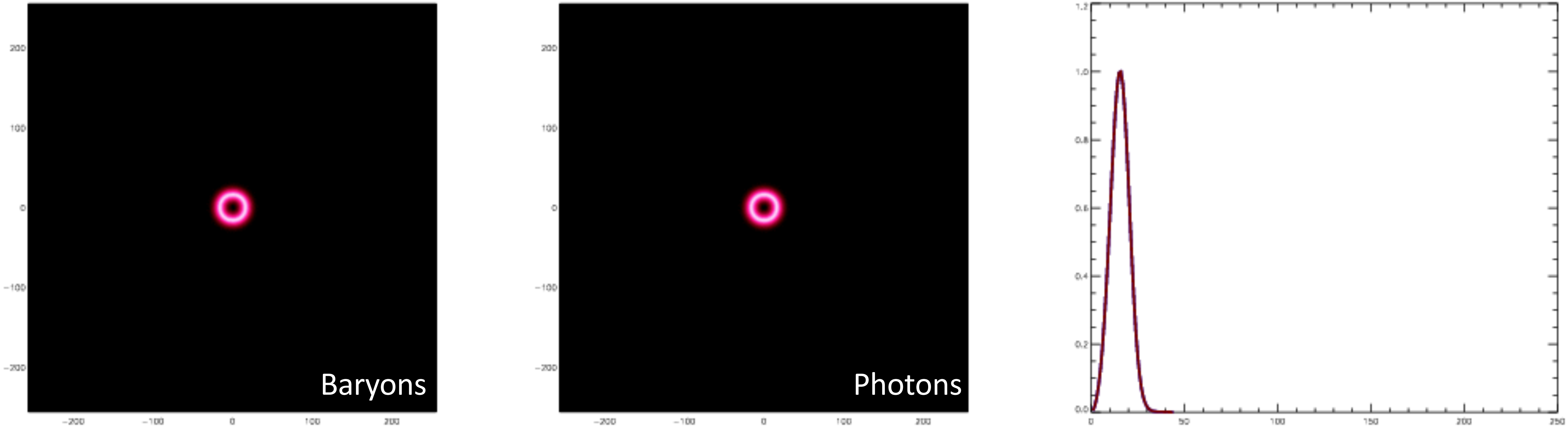
Baryon Acoustic Oscillations (BAO)



Credit: Martin White

- Early universe
  - Dense, ionized (no neutral hydrogen yet)
  - Baryons (protons, neutrons) and photons in equilibrium
- Random density fluctuations expand
  - Let’s consider what happens to a single over-dense region

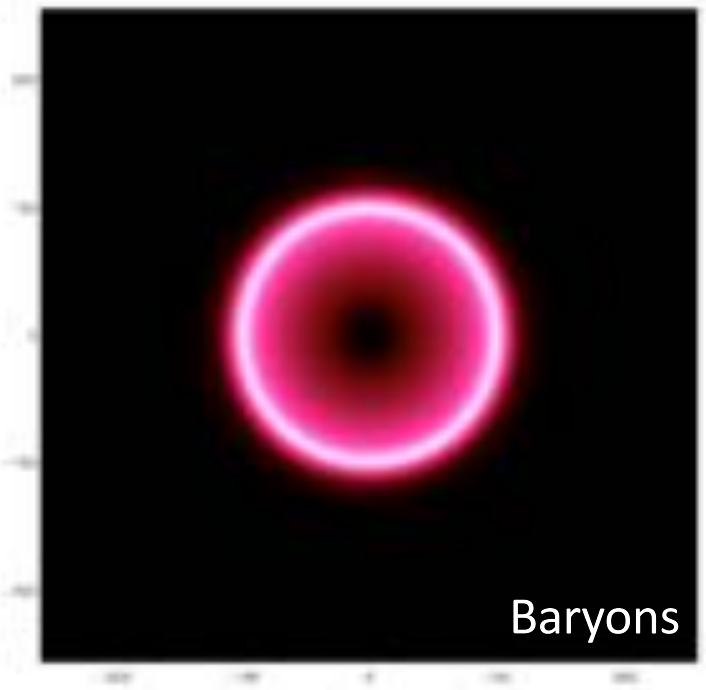
Baryon Acoustic Oscillations (BAO)

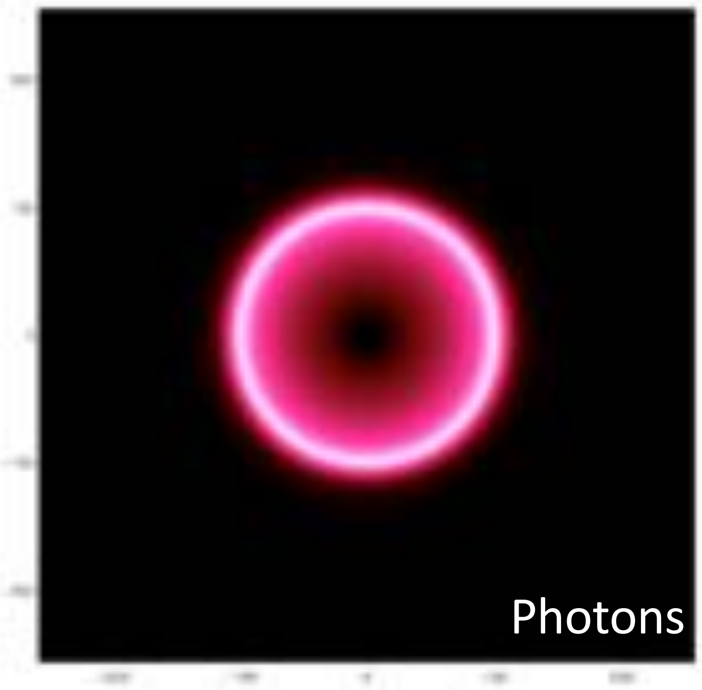


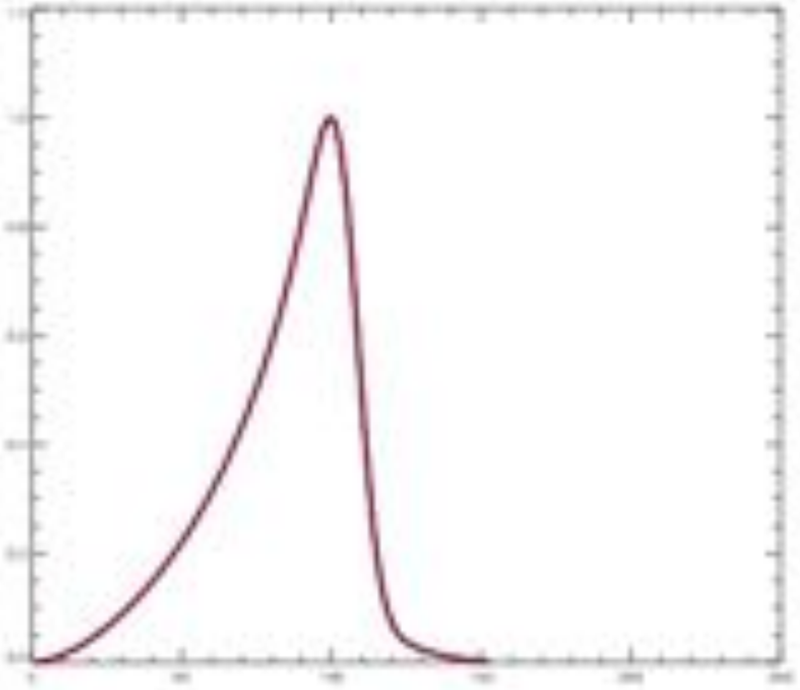
Credit: Martin White

- Perturbations expand at ~c / √3
  - Baryons and photons in equilibrium
  - Density sound waves expand together

Baryon Acoustic Oscillations (BAO)



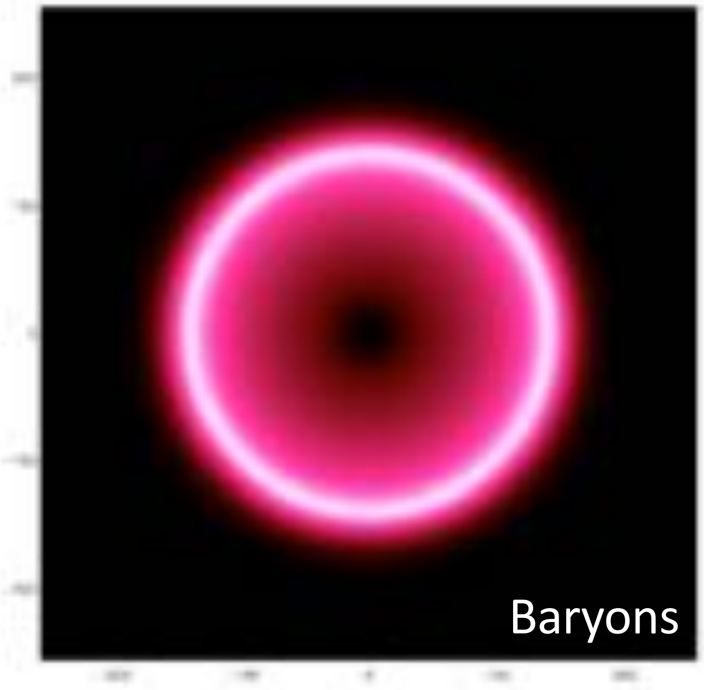


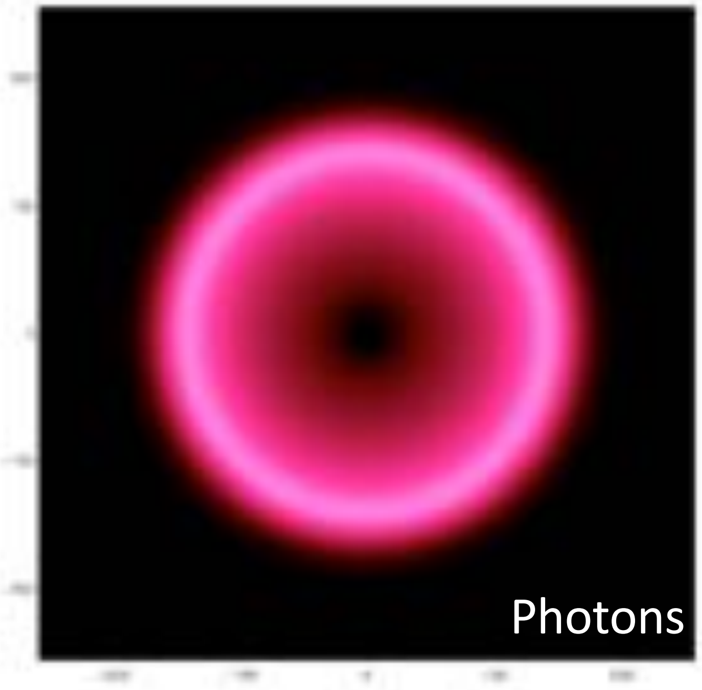


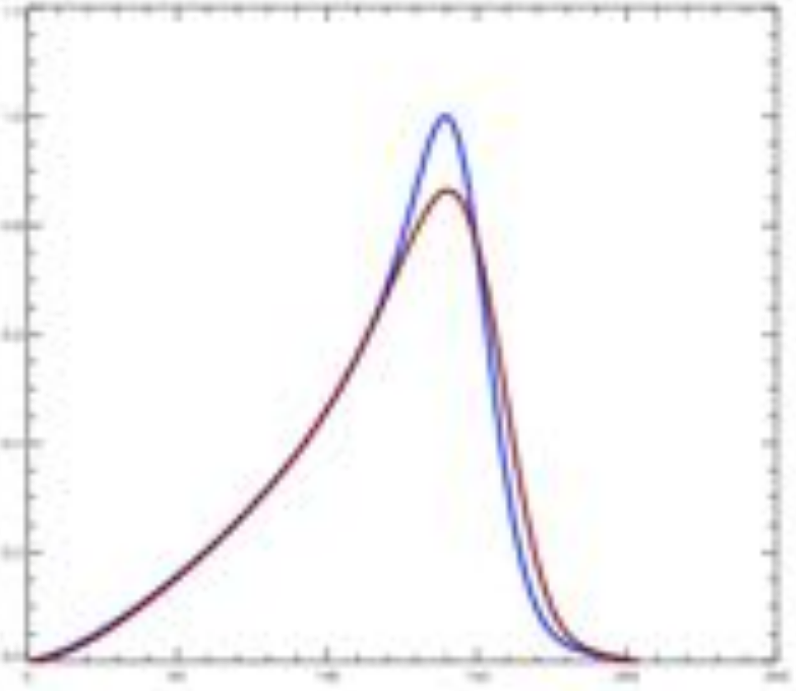
Credit: Martin White

- Continues for ~400,000 years

Baryon Acoustic Oscillations (BAO)



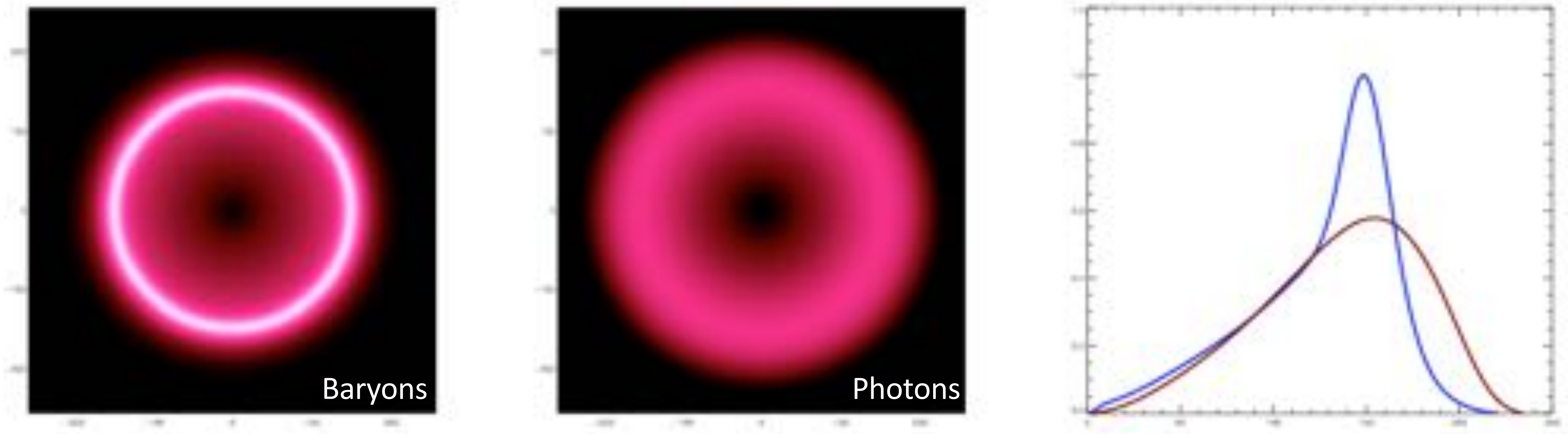




Credit: Martin White

- Universe cools enough to form neutral hydrogen
  - Photons and baryons stop interacting as much
- Photons can fly away without being absorbed by matter
  - This is the “Cosmic Microwave Background” (another 2 Nobel prizes)
- Lower pressure at its ‘back’ -- baryon density peak stalls

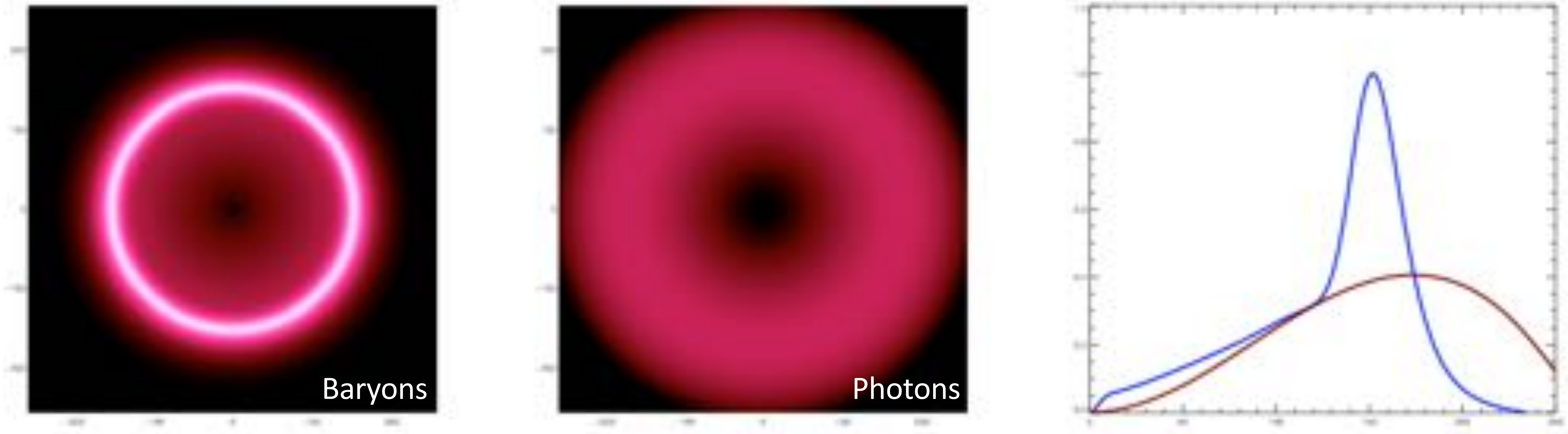
Baryon Acoustic Oscillations (BAO)



Credit: Martin White

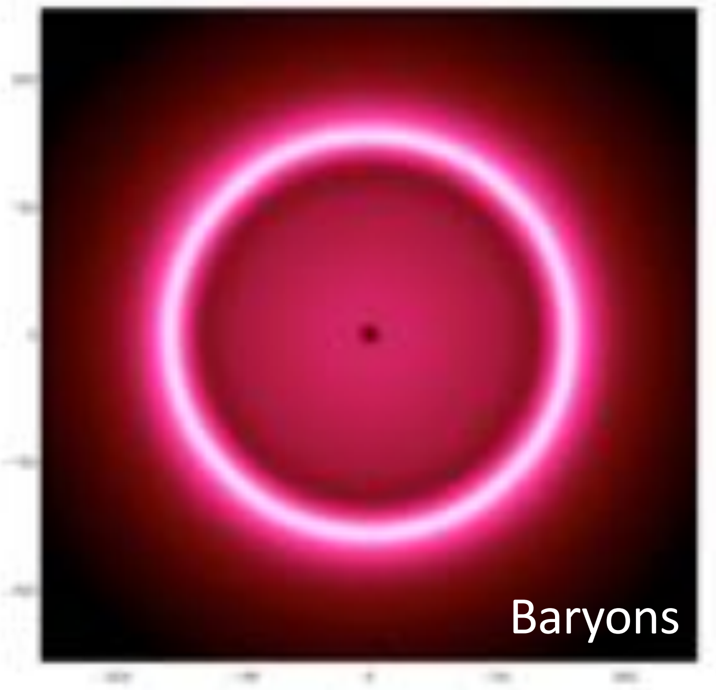
Without the matter stopping them, the photons continue to “free stream” out into space

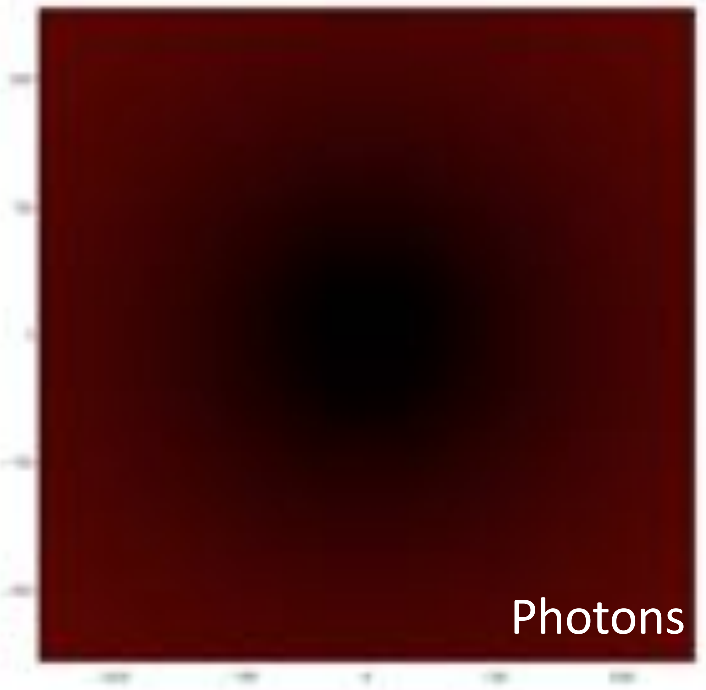
Baryon Acoustic Oscillations (BAO)

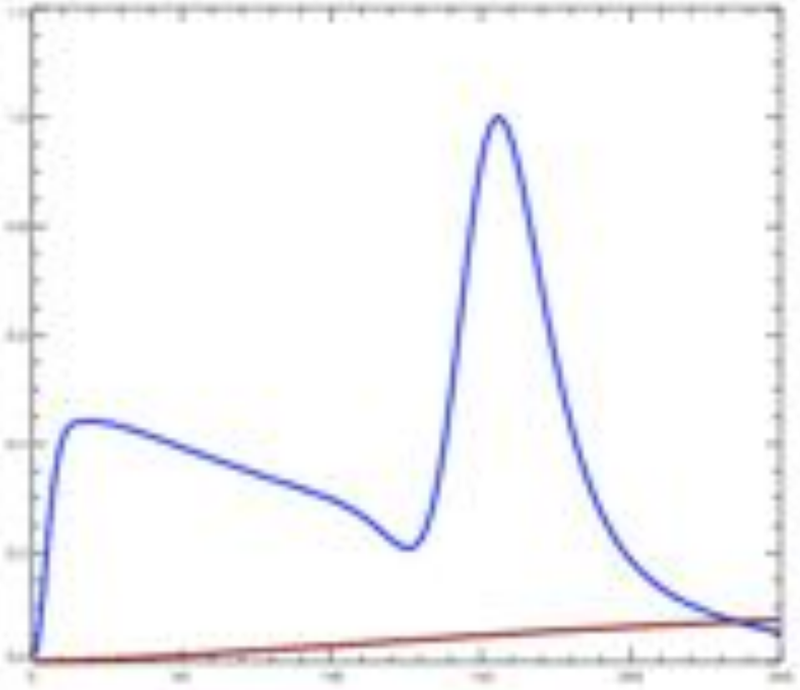


Credit: Martin White

Baryon Acoustic Oscillations (BAO)



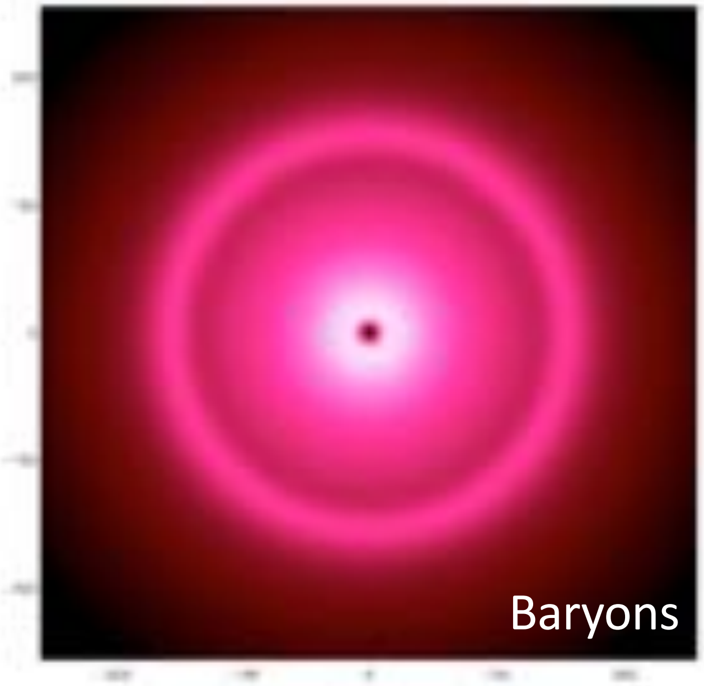


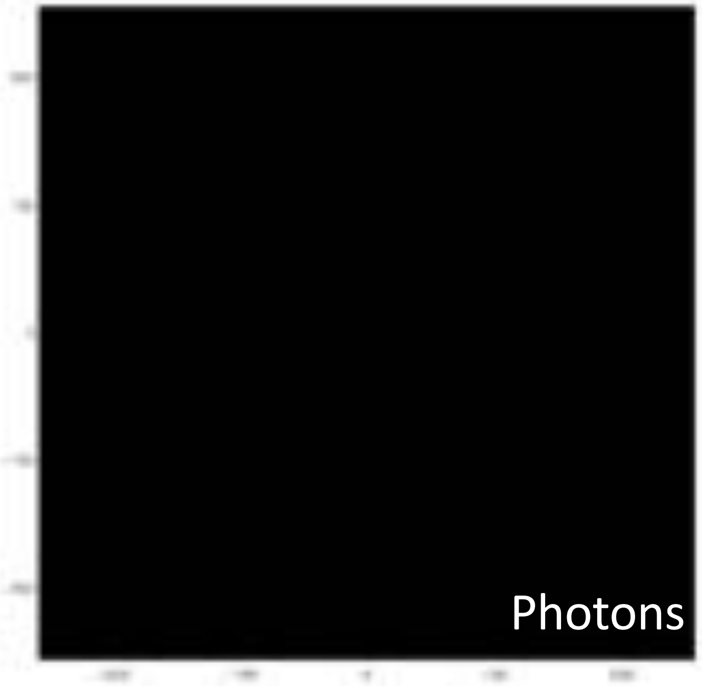


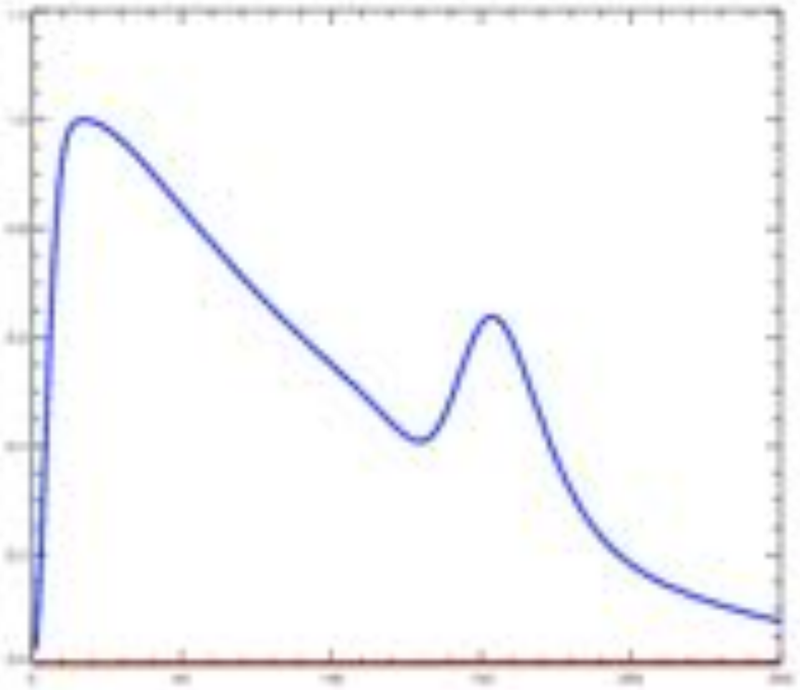
Credit: Martin White

- Photons have almost completely streamed away
- Baryons left in shell with radius ~150 Mpc
- Central over-density starts to pull baryons back in

Baryon Acoustic Oscillations (BAO)





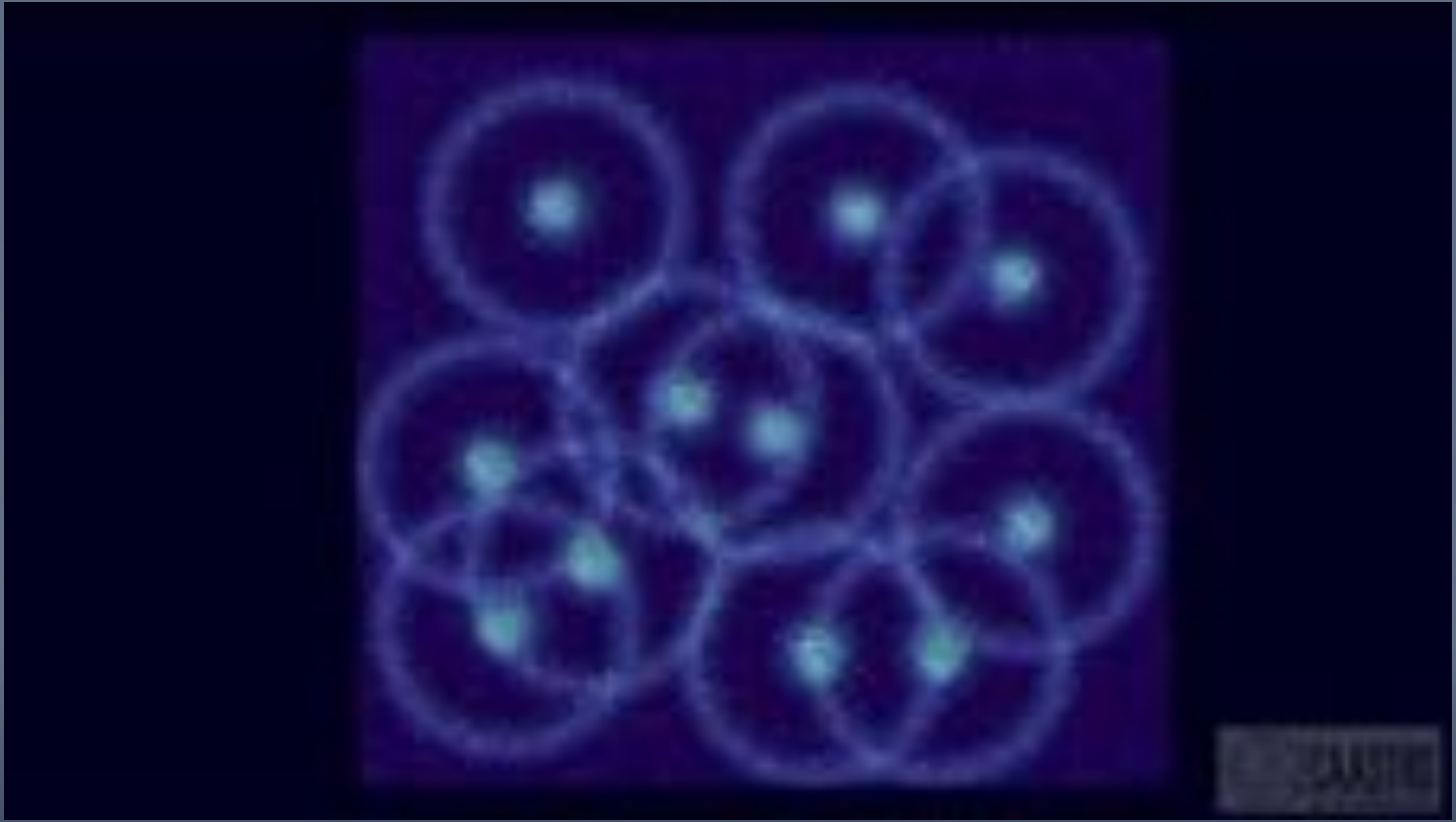


Credit: Martin White

- Final state is original over-density & echo at ~150 Mpc
- Observable: excess probability of galaxies (or hydrogen) separated by ~100 Mpc/h

→ Standard ruler for measuring cosmological distances

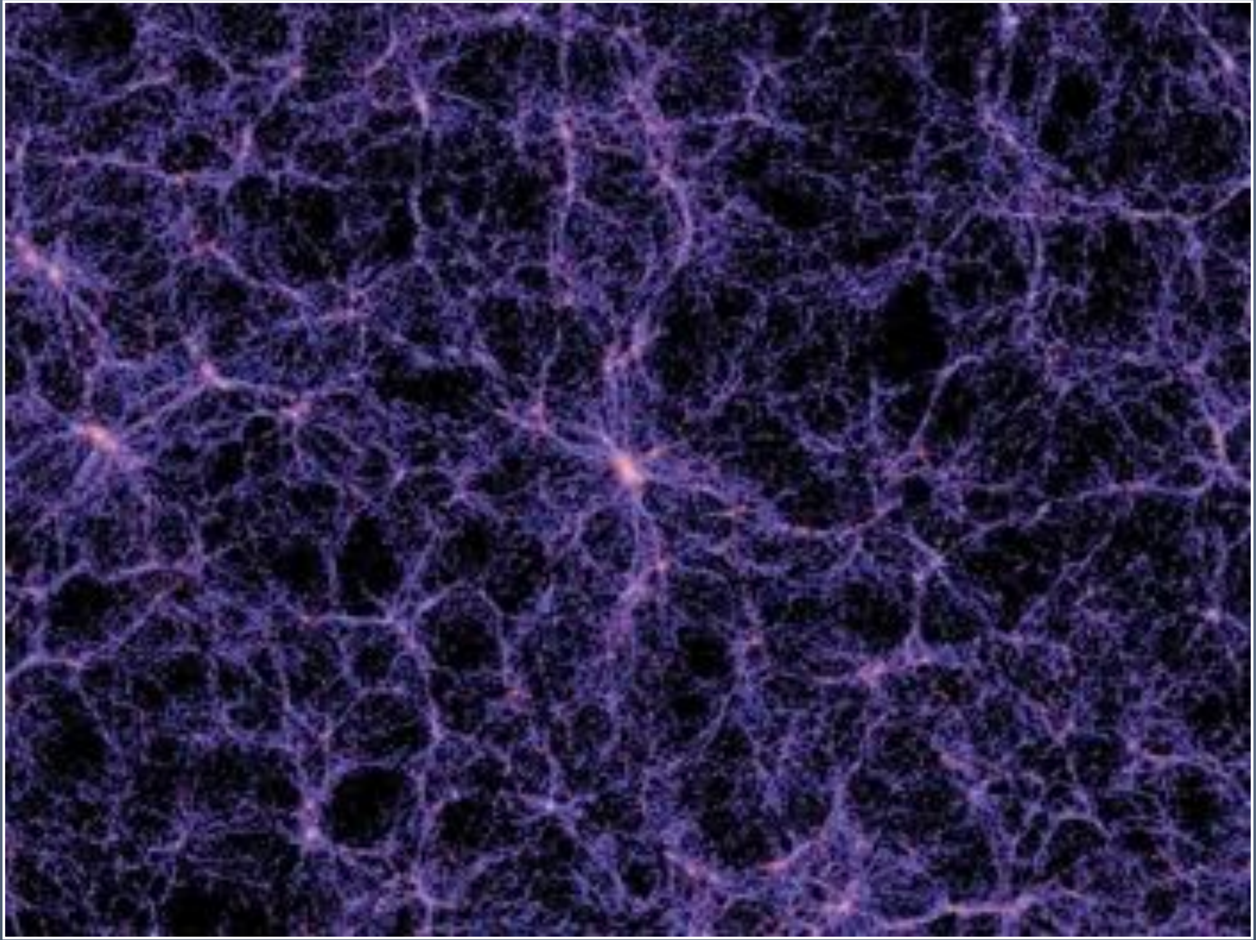
Baryon Acoustic Oscillations Video



credit:
CAASTRO

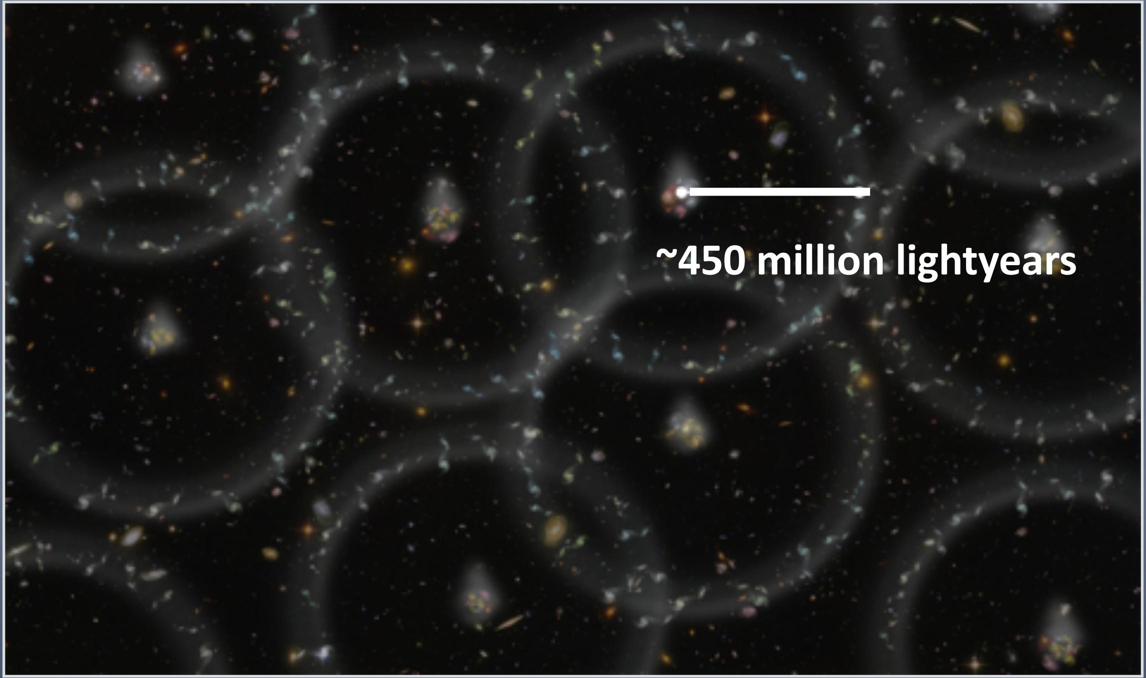
https://www.youtube.com/watch?v=jpXuYc-wzk4

The BAO peak is a *statistical excess* of galaxies at a characteristic physical scale.



Credit: Millenium Simulation

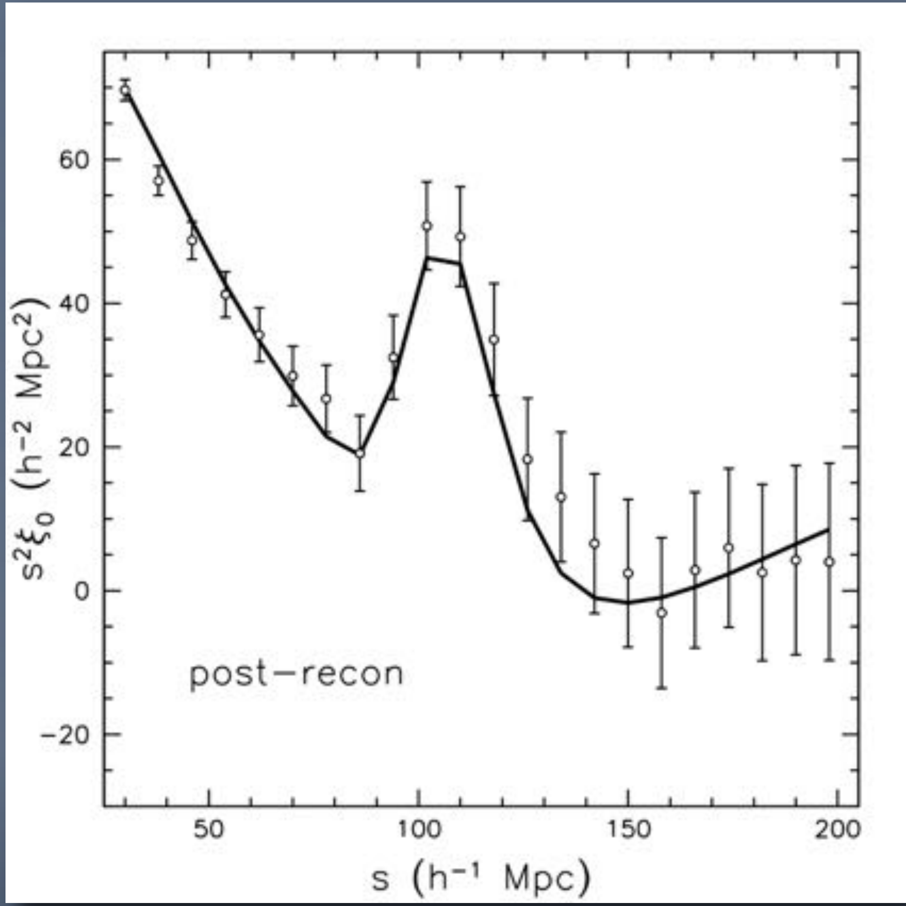
Imagine this takes places all over in spaces, like ripples in a pond



Credit: Z. Rostomian (LBNL)

What do we need to measure this?

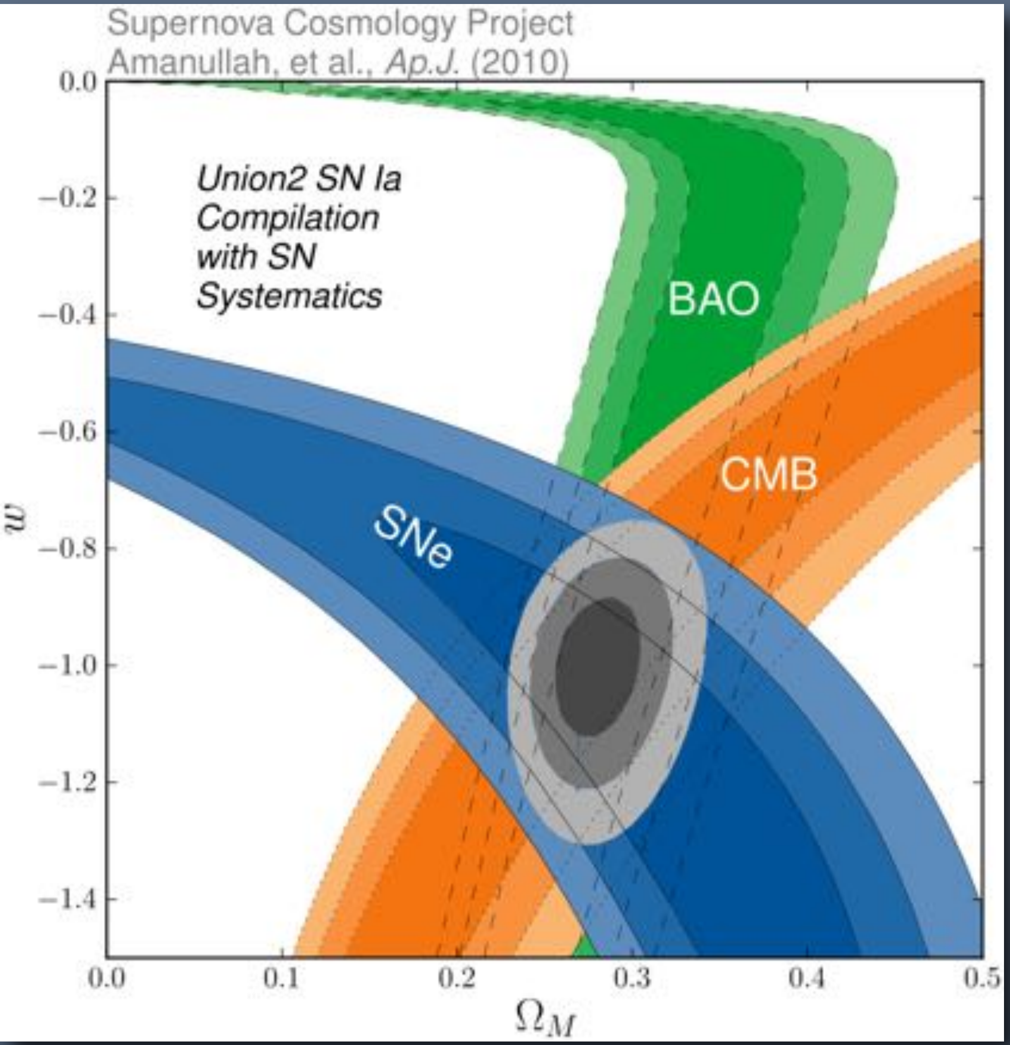
- Observe
  - Locations (x,y,z) of many thousands of galaxies
- Measure
  - Probability that pairs of galaxies are separated by distance s
  - Divide by random probability
  - Look for bump
    - Known size = standard ruler
    - Angular diameter distance
- Infer
  - The same bump will have a different angular size at different distances from us.
  - Figuring out how we have to scale each observed distance to have it equal the nearby one gives us information on the Universe at those distant times and how angles change with distance



Anderson+ 2013b

Supernovae + BAO

Two different kinds of radial distance give nicely complimentary cosmology constraints

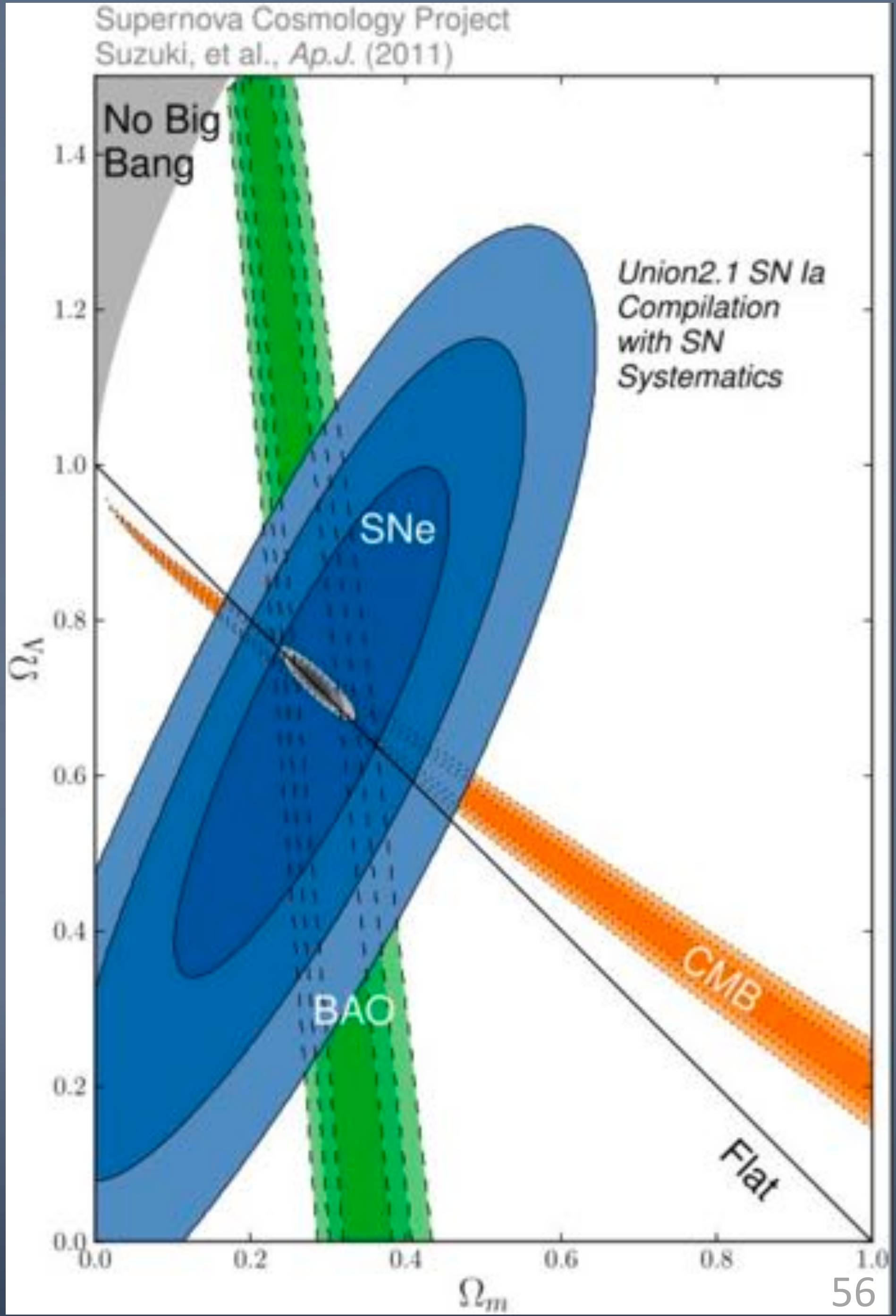


z / redshift: Another proxy for distance

Ω_x: The energy fraction of that component of the Universe (1 is all).

Λ: Cosmological constant, a simple form for dark energy.

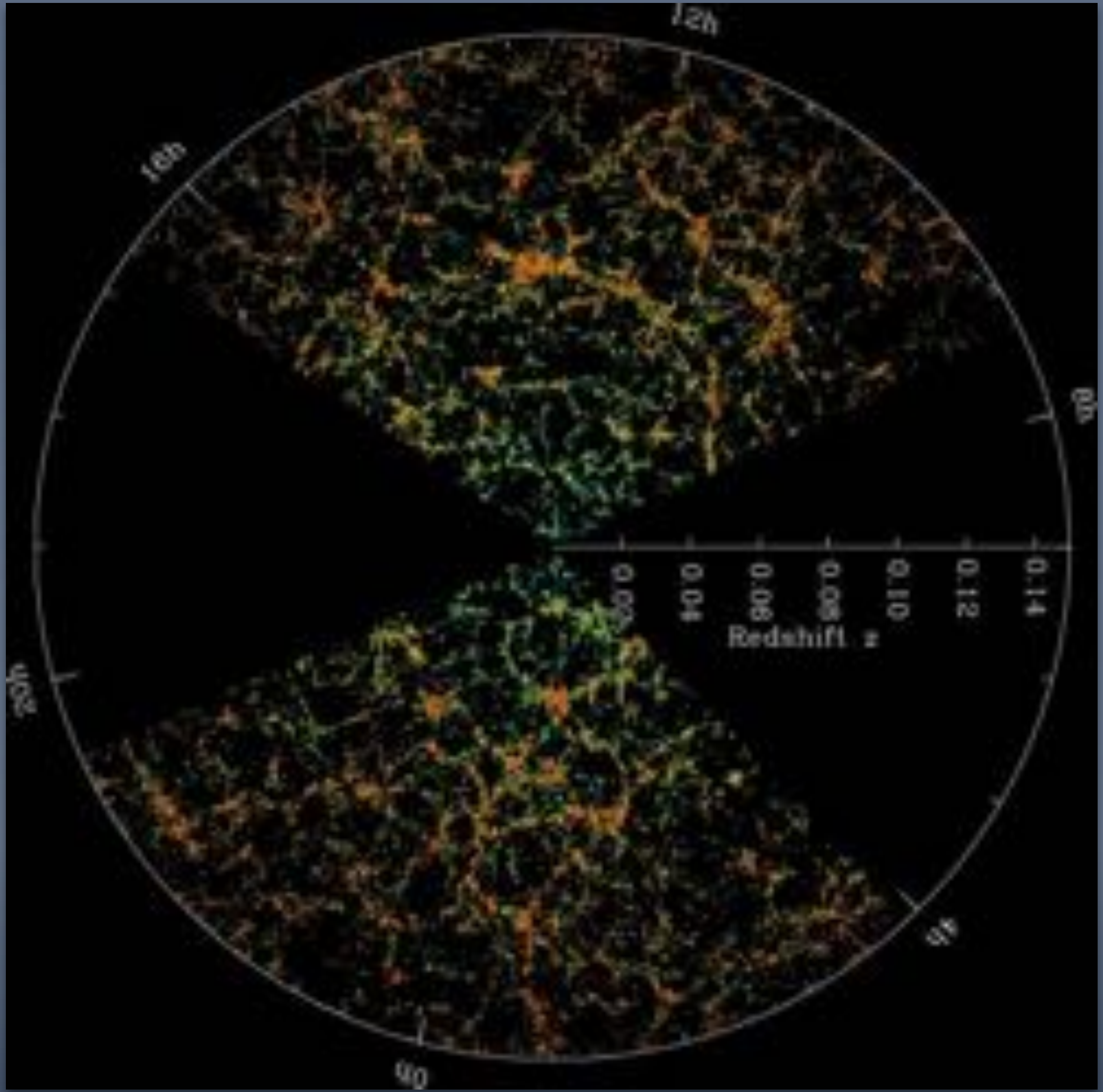
w: A parameter that describes how dark energy acts. w=-1 is a cosmological constant



Questions?

Stretch Break

How do you measure millions of redshifts?



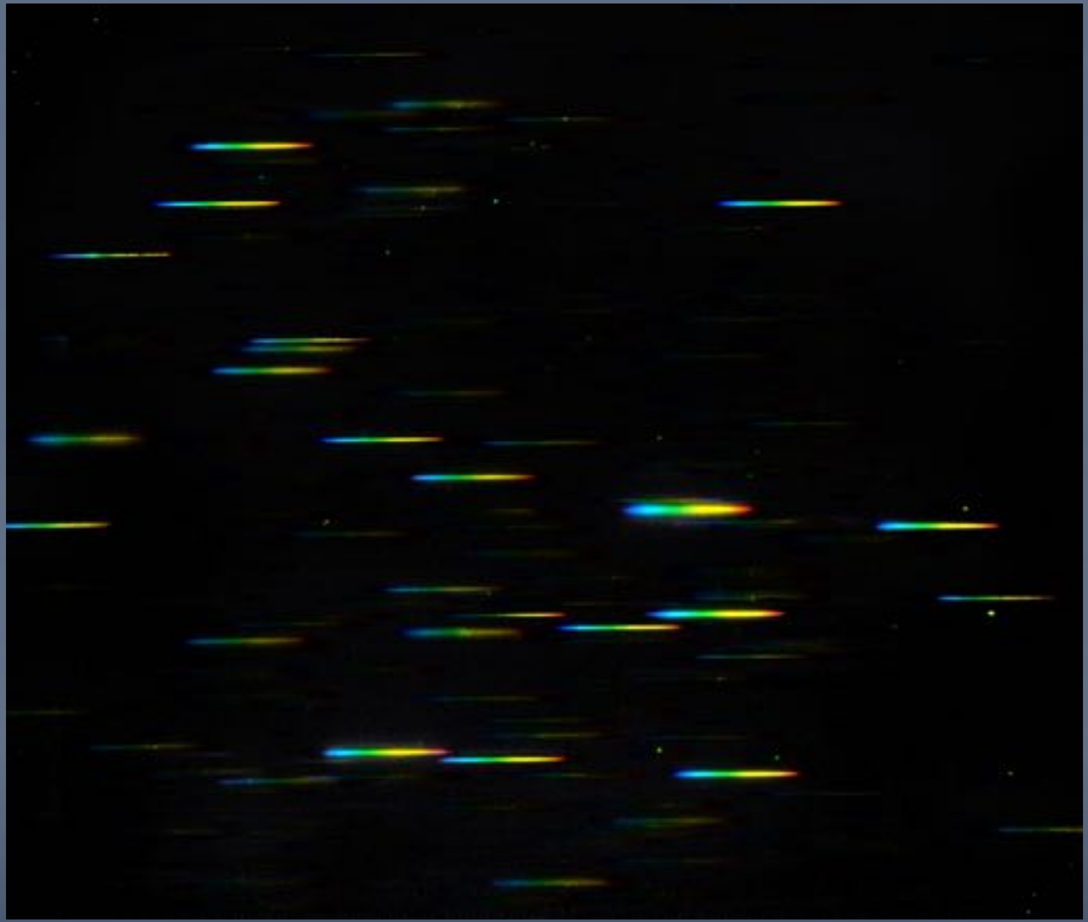
Part 3: DESI

To Get Redshifts

- Measure using a *spectrograph*
  1. Point your telescope at the galaxies you want to observe.
  2. Collect the light from the telescope and shine it onto a metal plate with either:
     a) Slits cut out of it to let light through
     b) Optical fibers plugged into it to catch the light

     Each slit/fiber has the light of one target
  1. Shine that light through a grating+prism to spread out the different colors
  2. Take a picture of the resulting rainbows.

Credit: NASA & ESA



Doesn’t sound so hard?

- How do you know where the galaxies are?
- As the Earth rotates, how do you continue pointing at them?
- How do you know it’s a galaxy?
- How do you know that the light through all the optics will land in the slits you pre-cut on a sheet of metal?
- How do you turn those pictures into redshifts? brightnesses?

Doesn’t sound so hard?

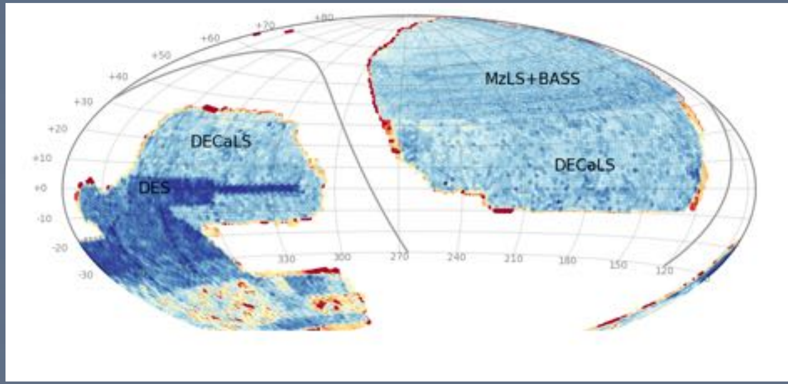
- How do you know where the galaxies are?
- As the Earth rotates, how do you continue pointing at them?
- How do you know it’s a galaxy?
- How do you know that the light through all the optics will land in the slits you pre-cut on a sheet of metal?

Answer is lots of hard work by lots of different people!

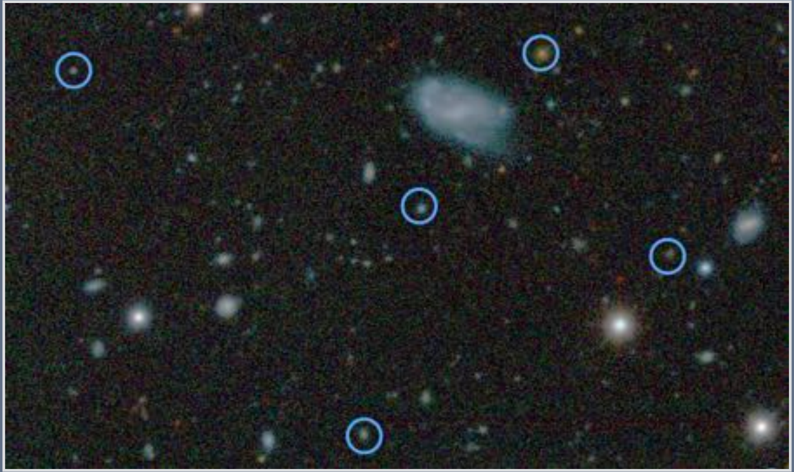
Science is *collaborative*

Constructing a BAO survey

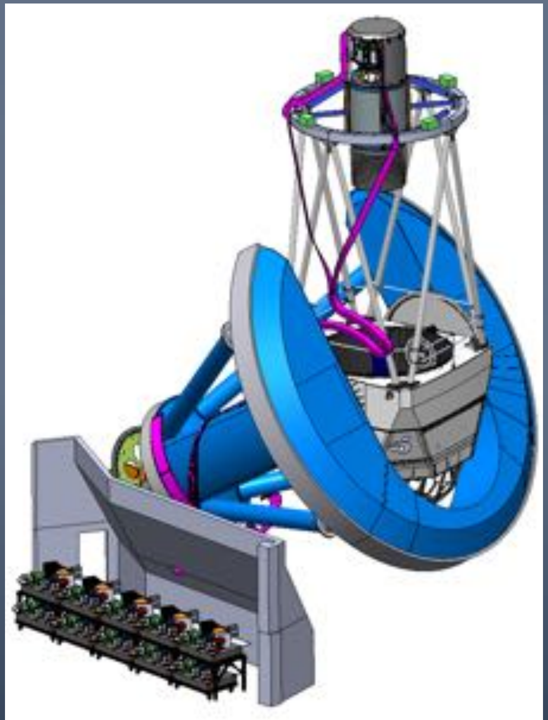
1. Image the sky



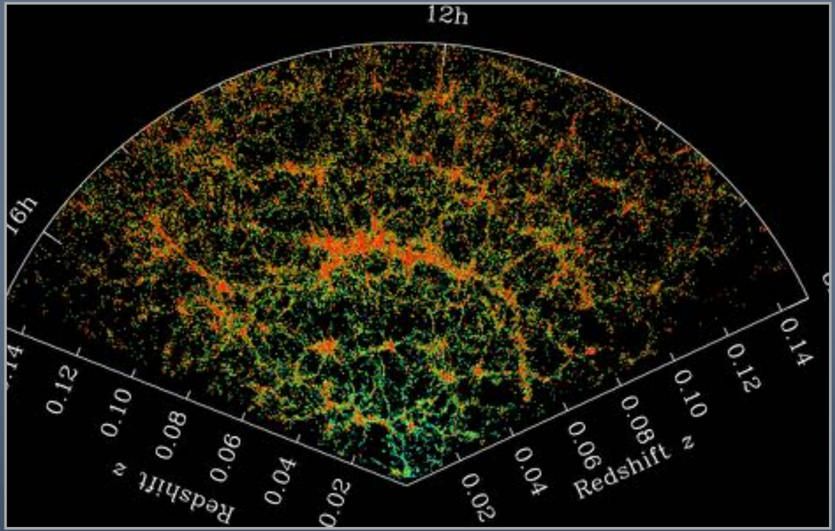
2. Select targets



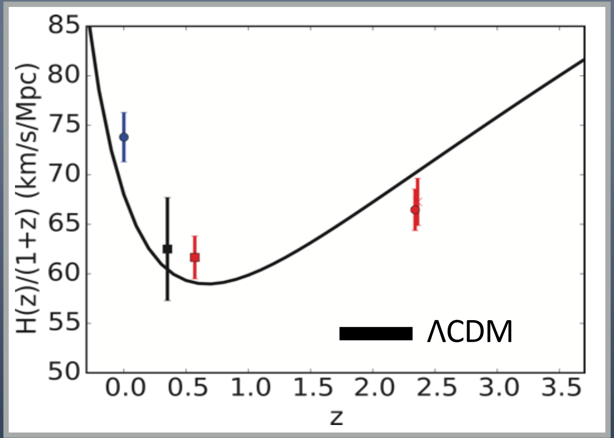
3. Gather spectra



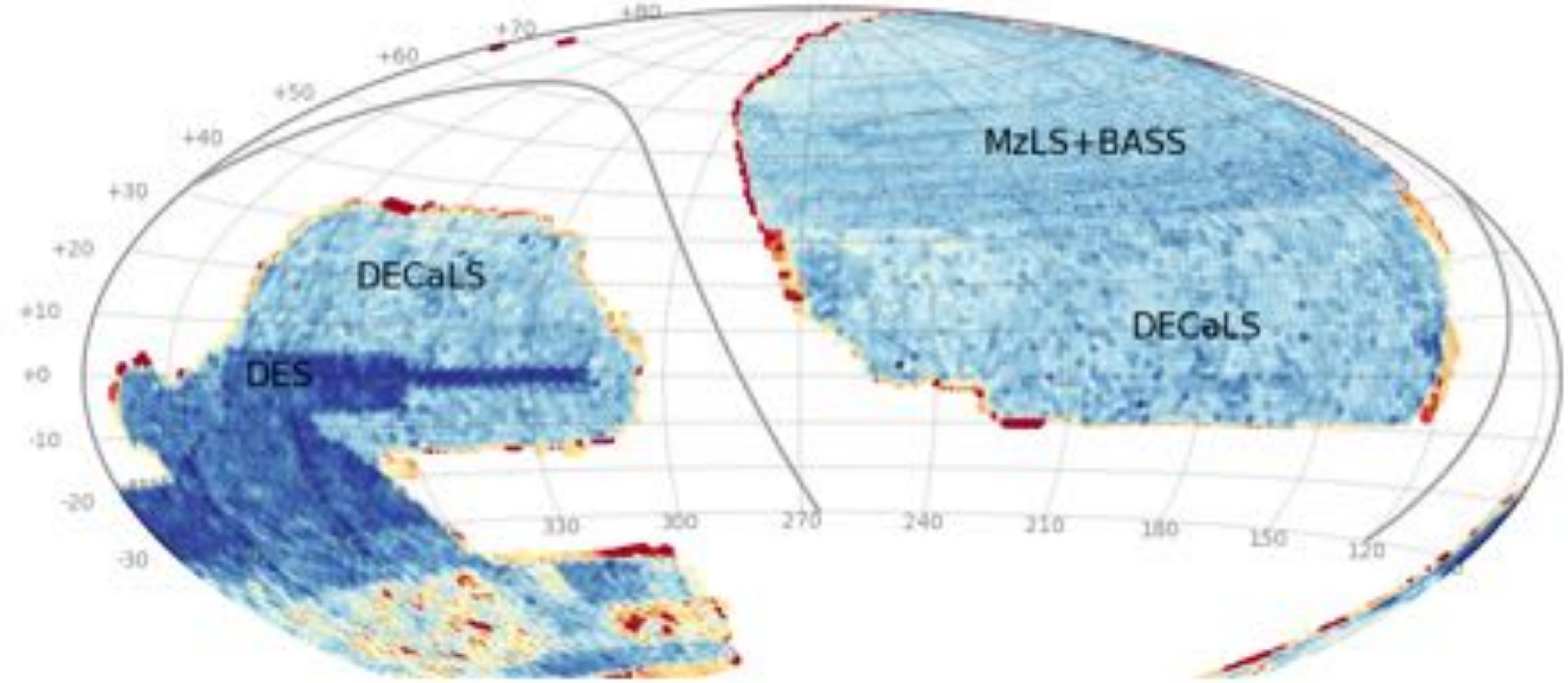
4. Build a 3D map



5. Infer Cosmology



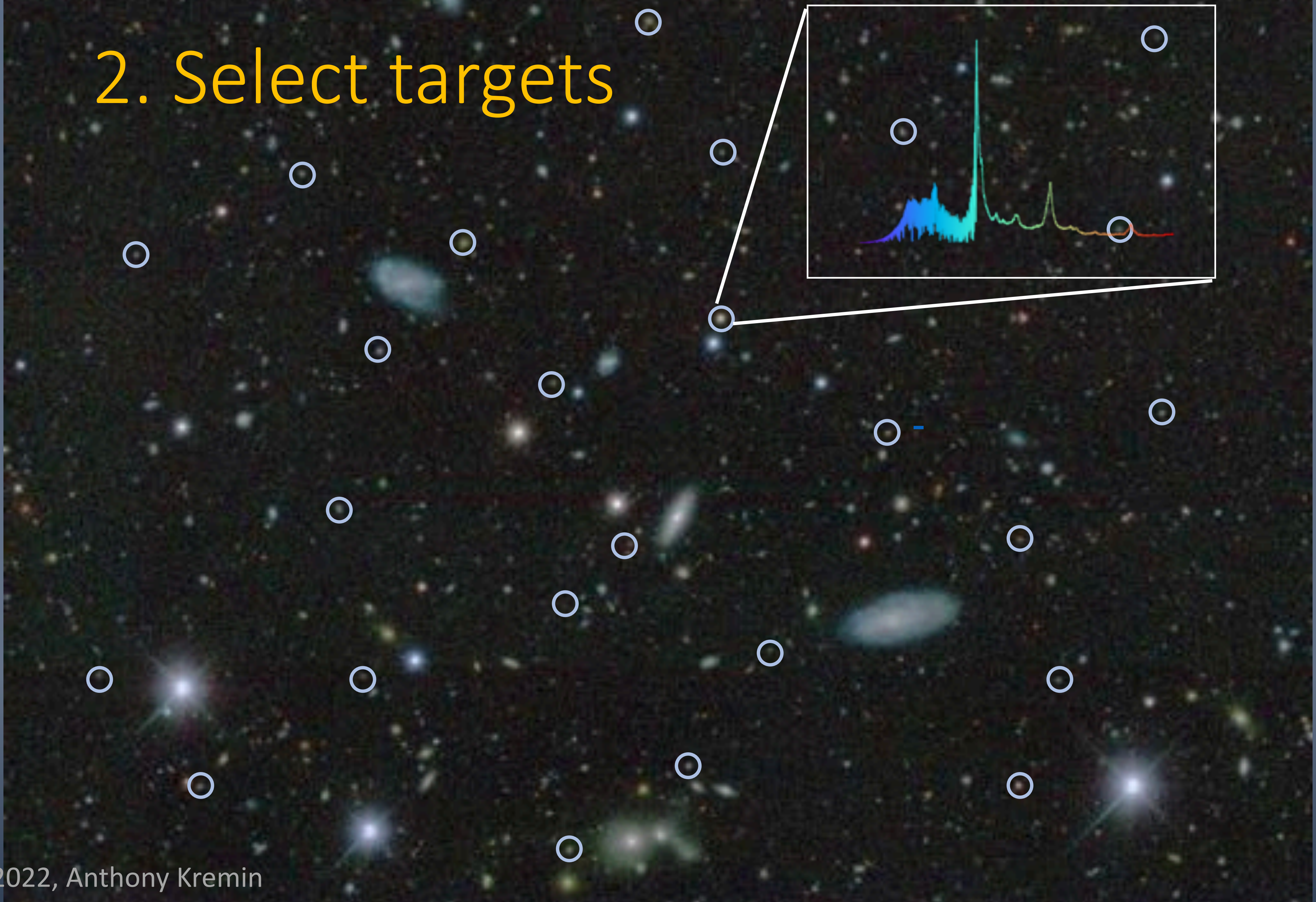
1. Image the sky



legacysurvey.org/viewer

These data are fully public!

2. Select targets



3. Gather spectra

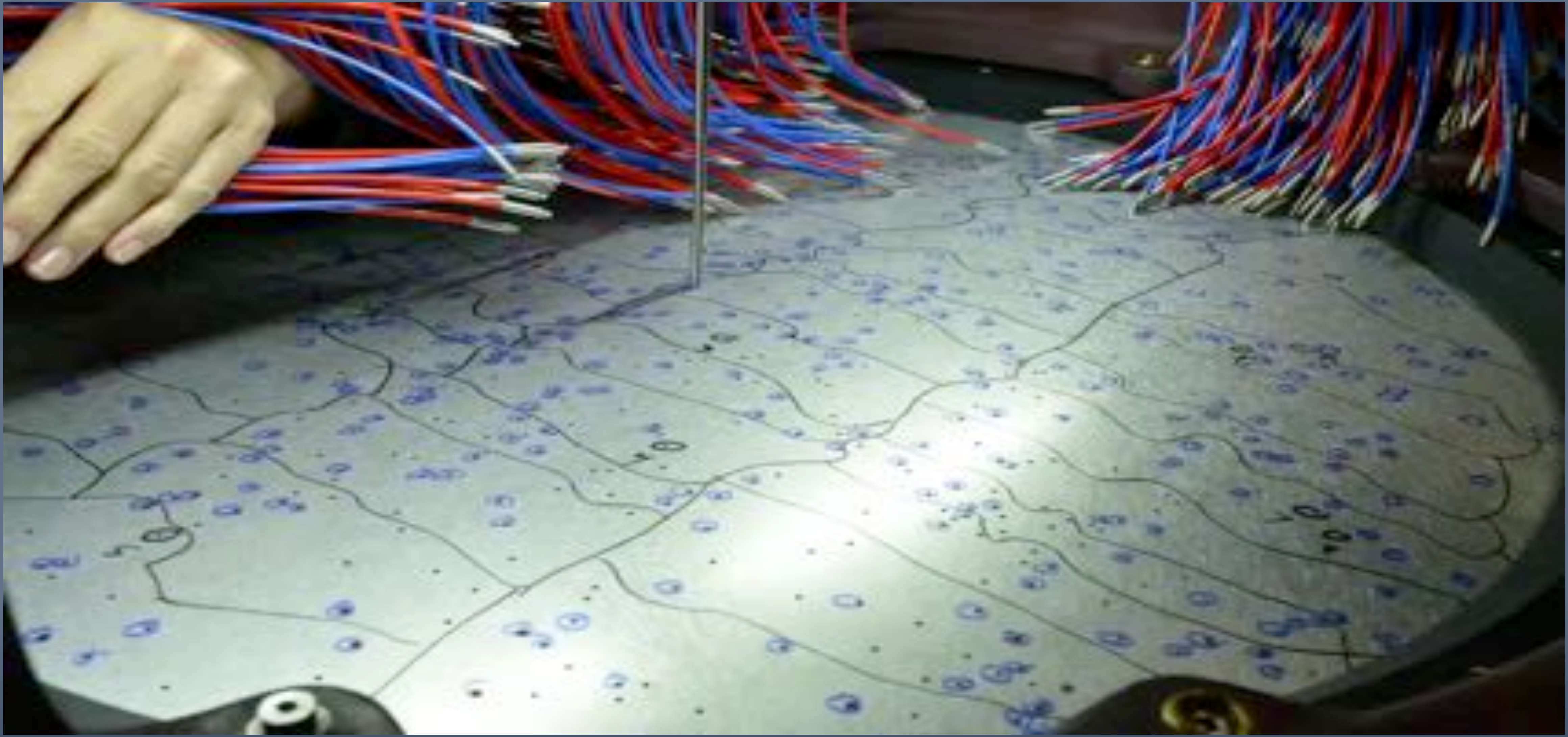
- Previous Generation: Baryon Oscillation Spectroscopic Survey (BOSS)
  - 3rd Generation of Sloan Digital Sky Survey
  - Spectra of:
    - 1.5M galaxies
    - 160k quasars
  - 2.5m telescope at Apache Point Observatory
    - BOSS led by D. Schlegel, LBL

Plate Plugging

- Each field is unique plate drilled with target positions
- 1000 fibers per plate plugged by hand
- Up to 9 plates per night

- Plates are mounted on carts and changed for each field
- Simple, effective, but hard to scale beyond BOSS

BOSS Plugging Video



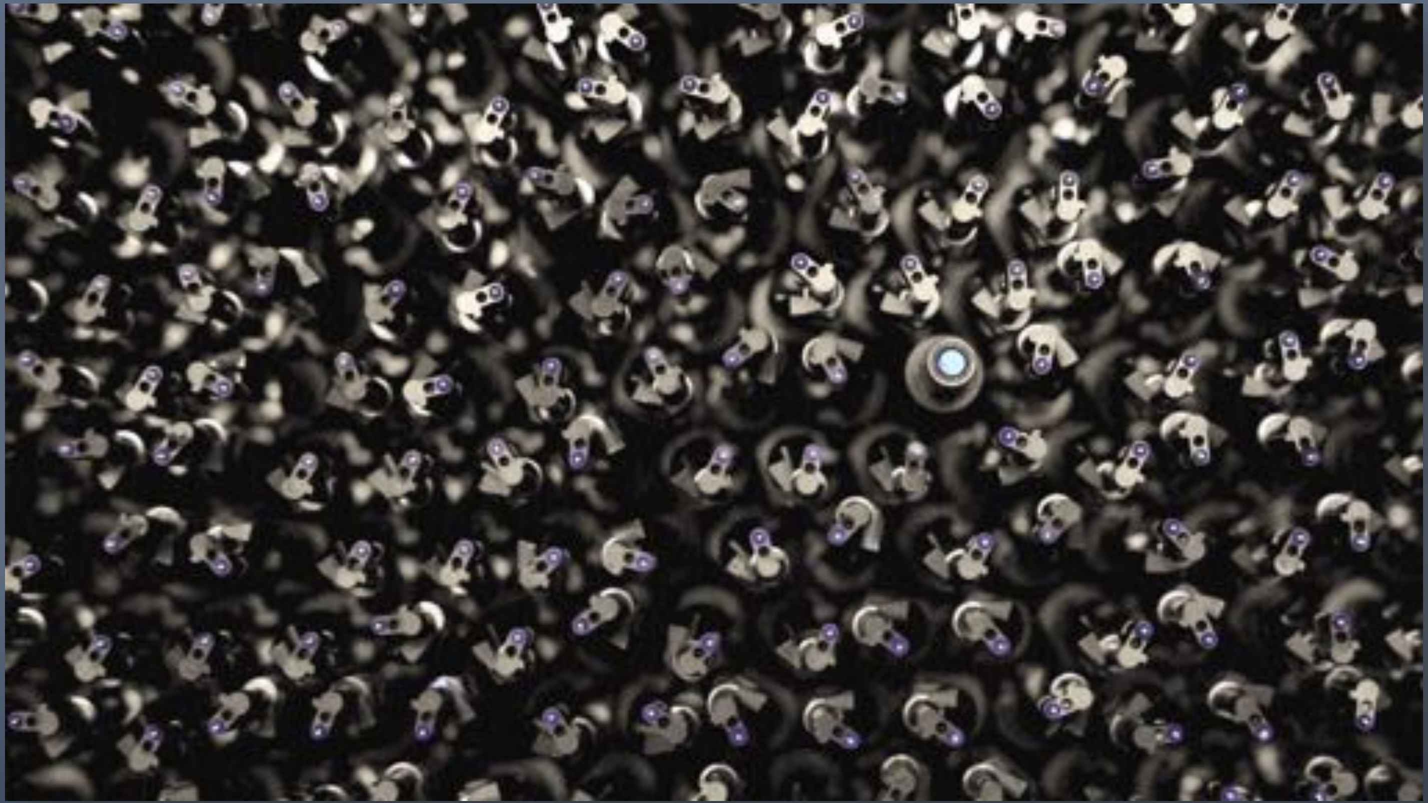
Next Generation: DESI

- Mayall 4m Telescope at Kitt Peak National Observatory
- 6 lens optical corrector with Hexapod
  - ~8 deg^2 FOV
- 5,000 robotic positioners and optical fibers
  - 40m+ fibers run from focal plane to spectrographs
  - Positioners accuracy ~2-5um
- 10 Spectrographs with 3 arms each
  - Wavelength Range: 3600-9800Å
  - Resolution: 2000-5500

One-of-a-Kind Focal Plane Instrument

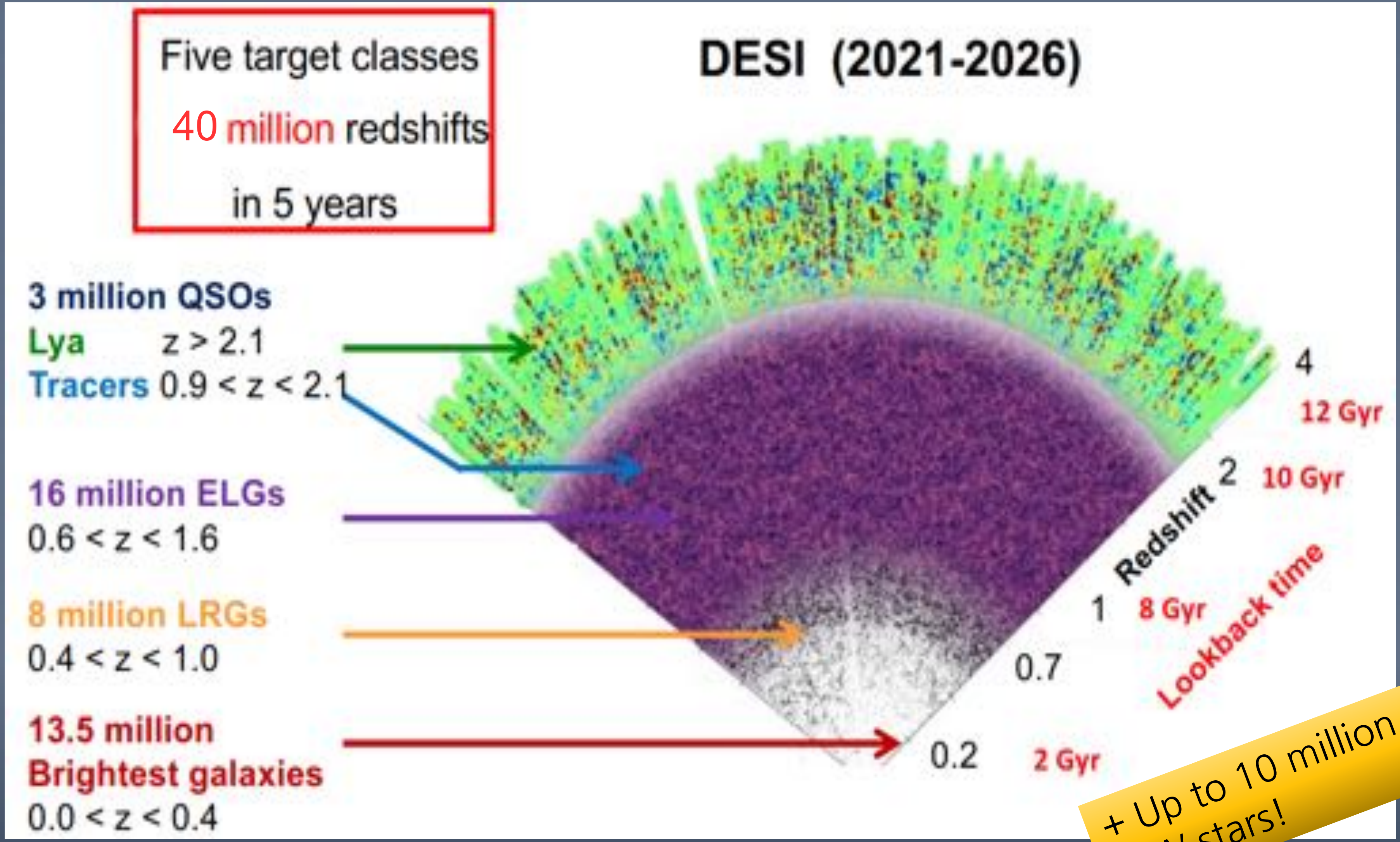
DESI Focal Plane and Fiber Positioning

5,020 phi-theta fiber positioners, 10.4 mm, 12 mm patrol region



- Overlapping ranges
- Carefully planned moves avoid collisions
- Move time 8-12 s
- Positioners accuracy ~2-5um

DESI is creating the largest 3D Map of the Universe

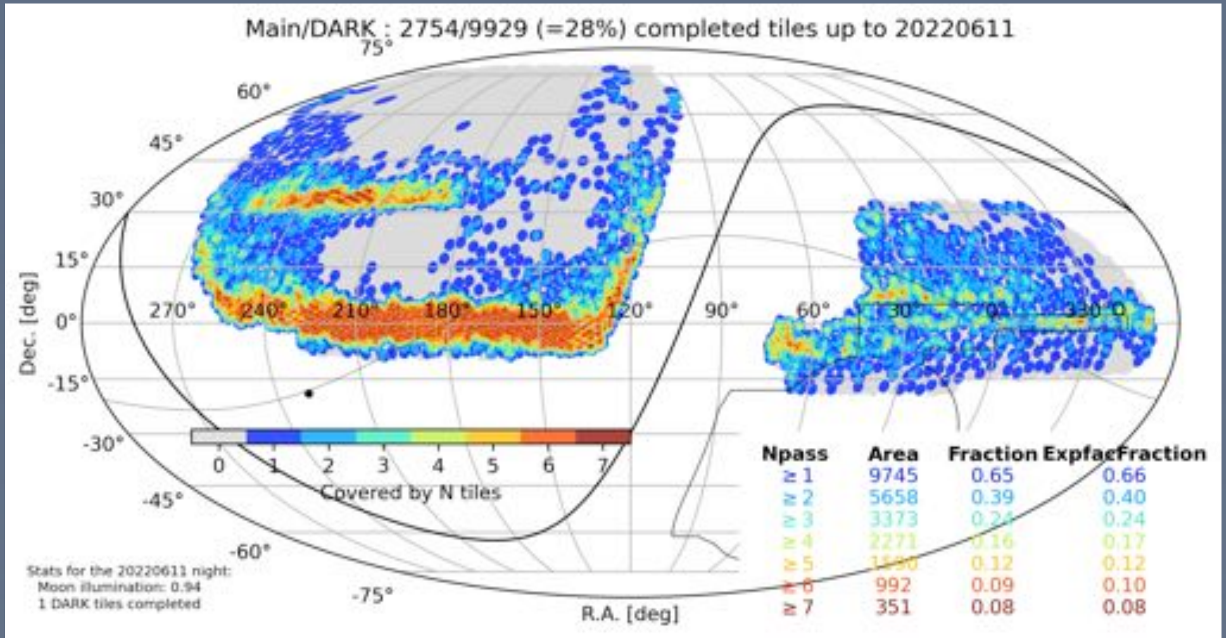


From 2020-2026 DESI will cover 35% of the ENTIRE sky measuring redshifts to ~40 million galaxies spanning ~90% of the age of the universe.

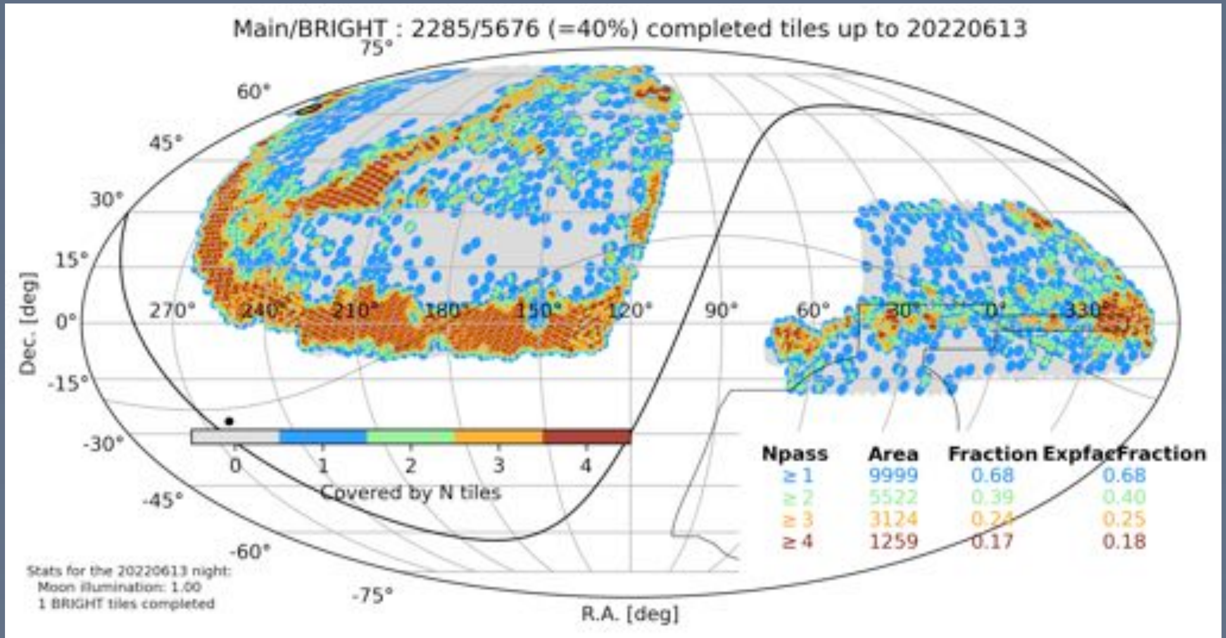
+ Up to 10 million MW stars!

Main Survey

Five-year Main Survey began May 2021



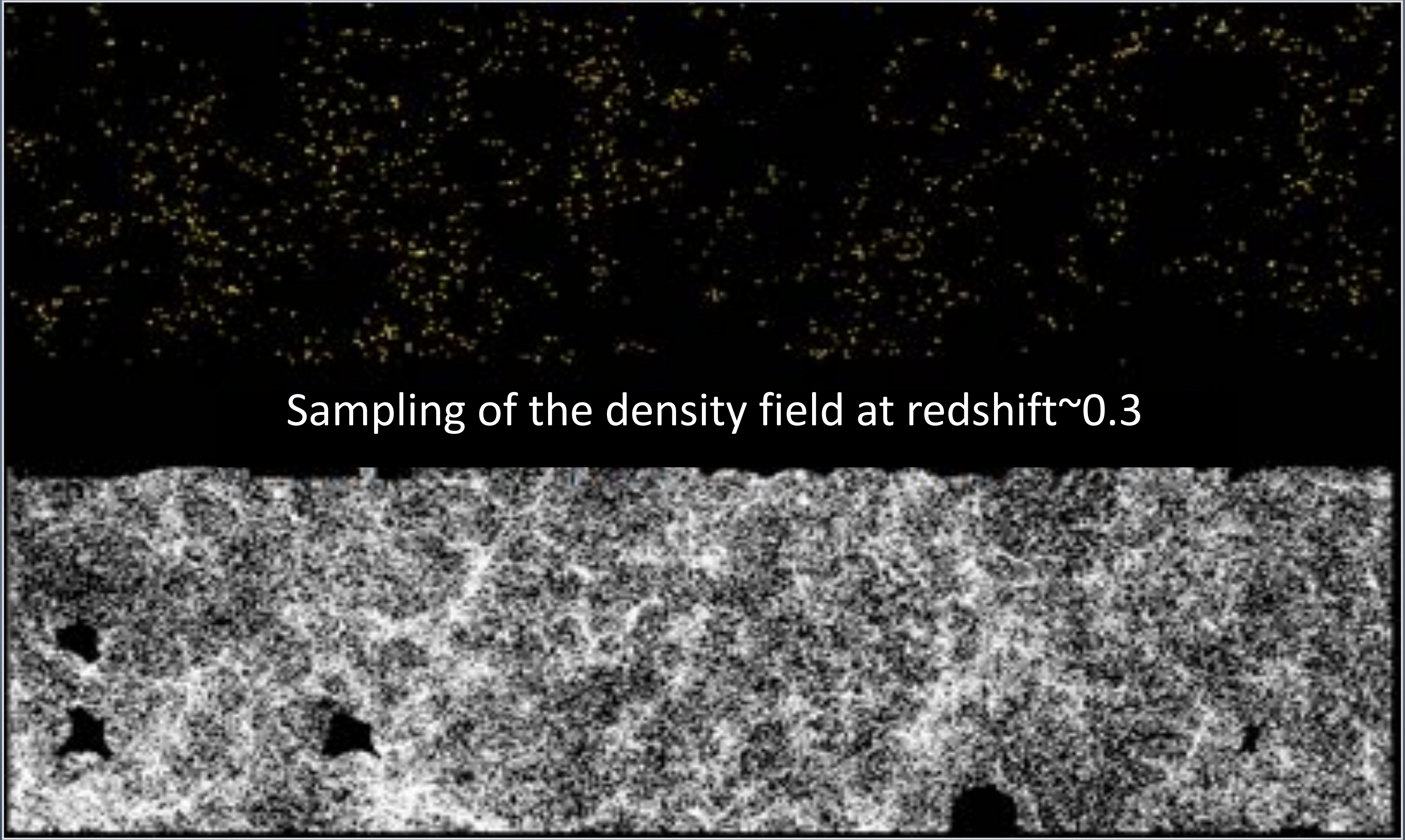
Dark Survey



Bright Survey

animations/figures by: Anand Raichoor

4. Build a 3D map of the universe—

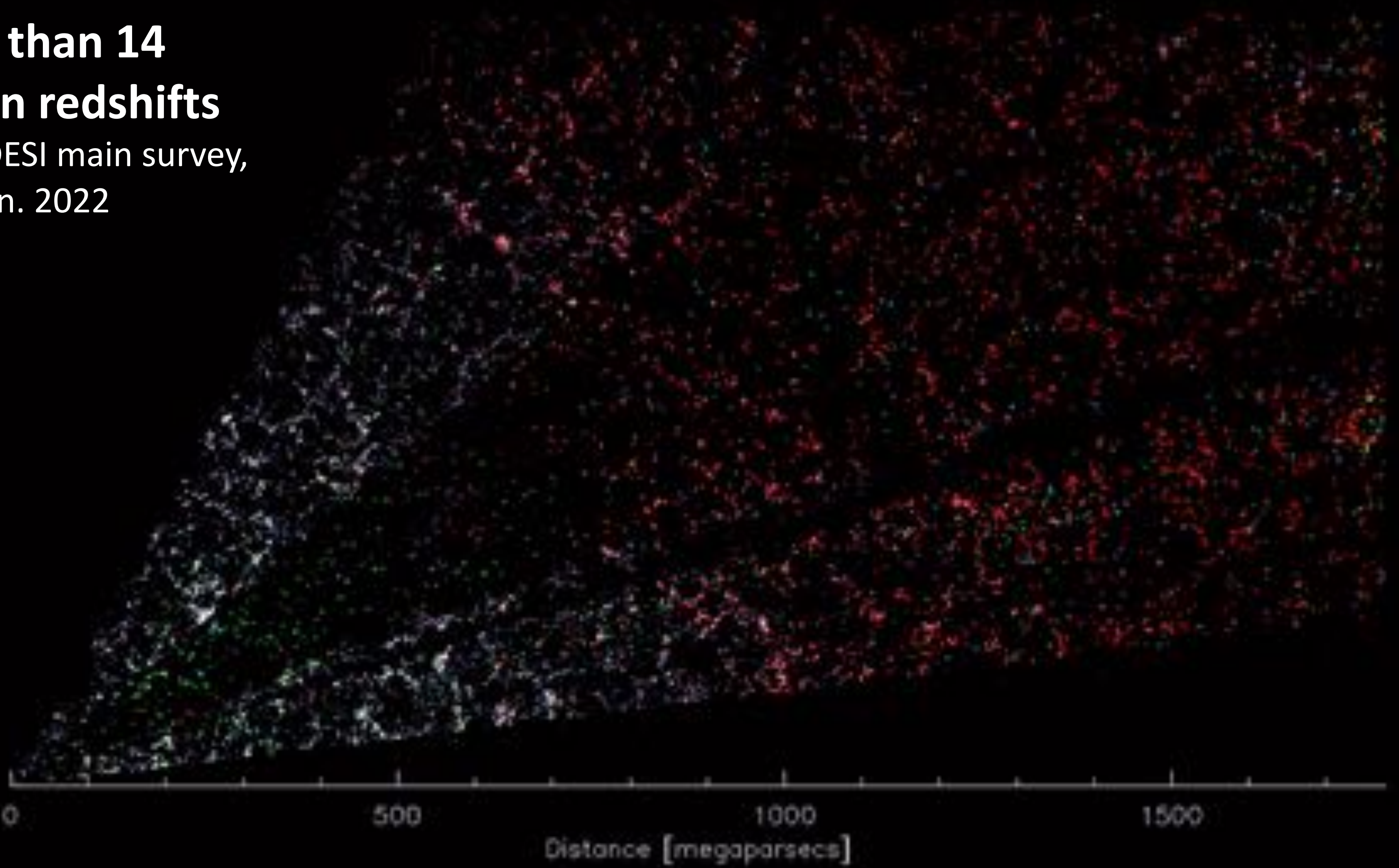


State-of-the-art today (SDSS)

DESI projections

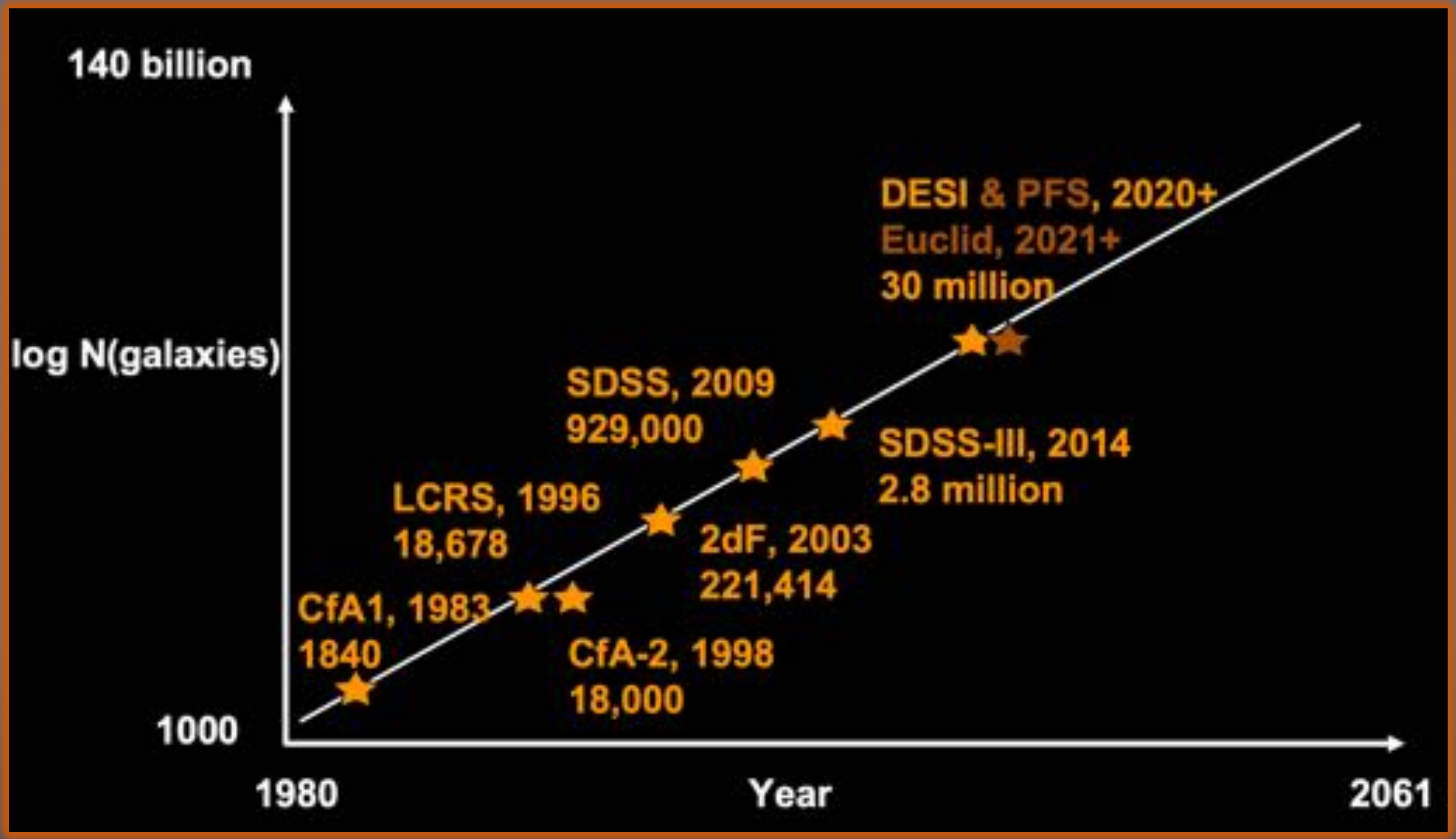
DESI is creating the largest 3D Map of the Universe

More than 14 million redshifts
in the DESI main survey, as of Jun. 2022



20° sweep using early DESI data
Credit: D. Schlegel

DESI is creating a 3D Map of the Universe 10x bigger than anything seen before

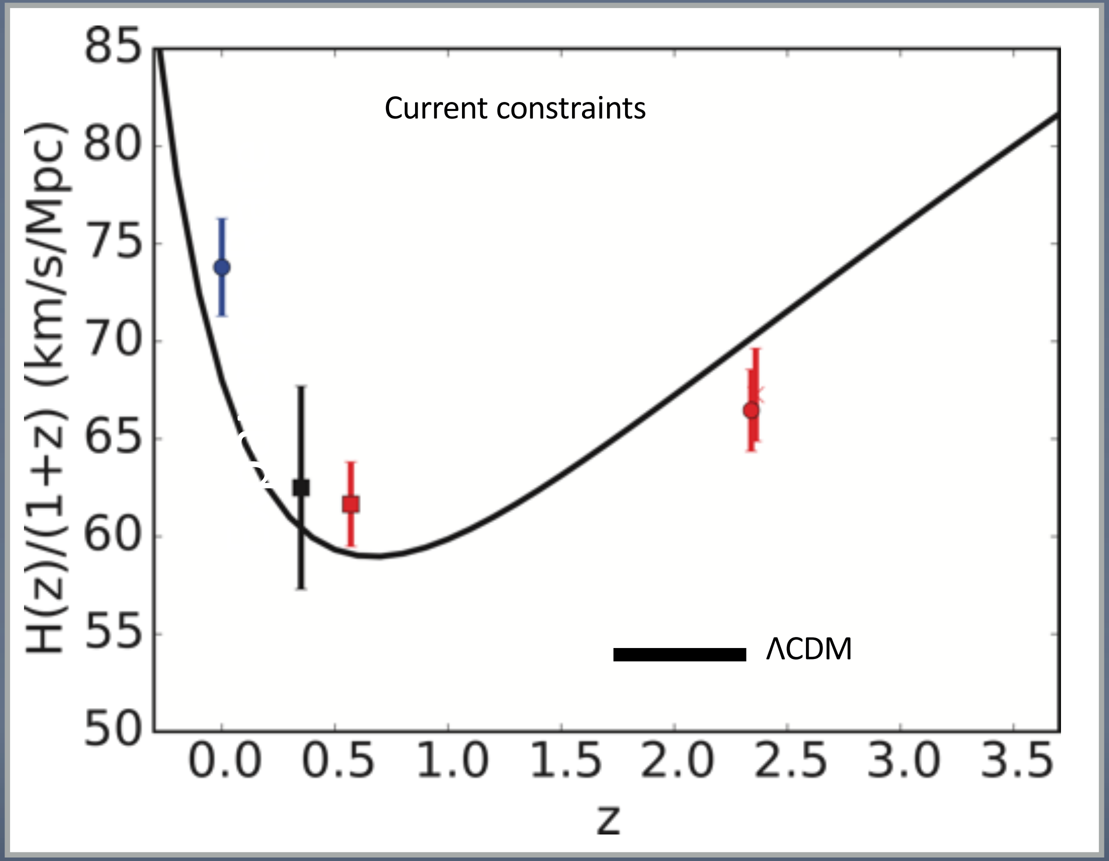


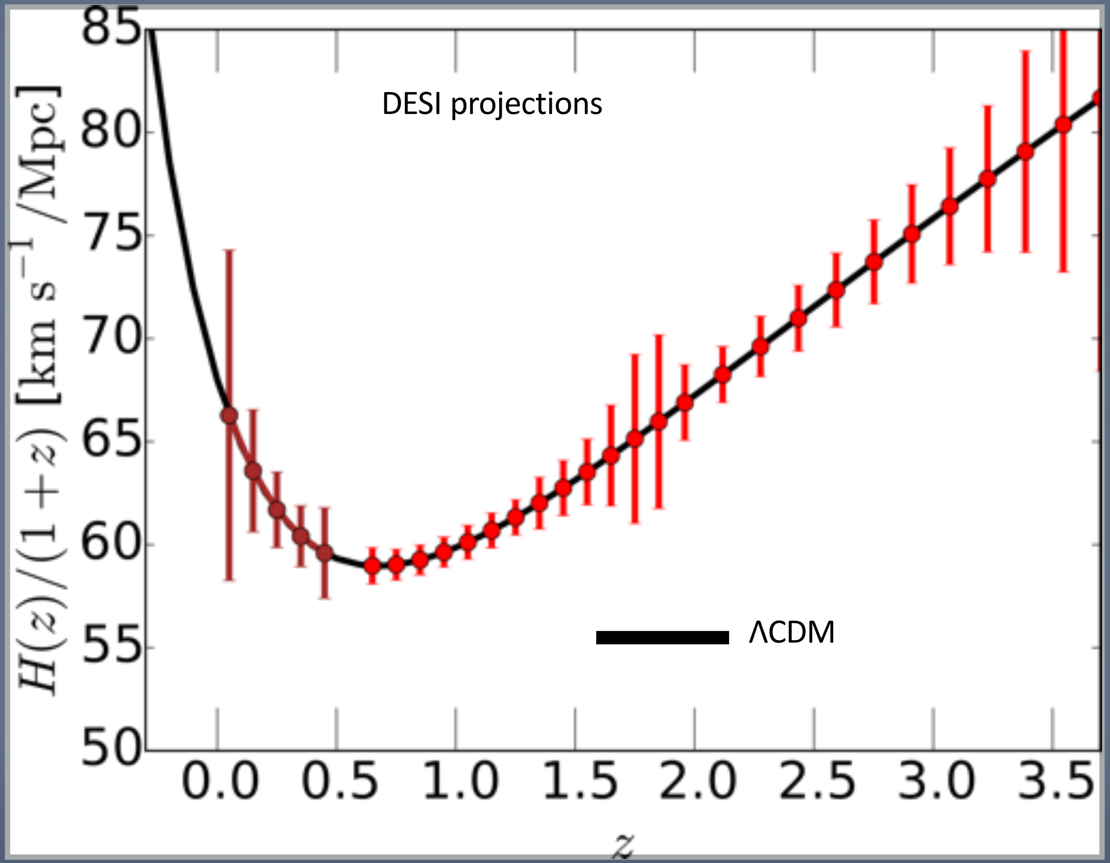
Credit: P. Fagrelius

5. Infer Cosmology

DESI will precisely measure the expansion history of the universe and place tight constraints on dark energy.

Expansion Rate

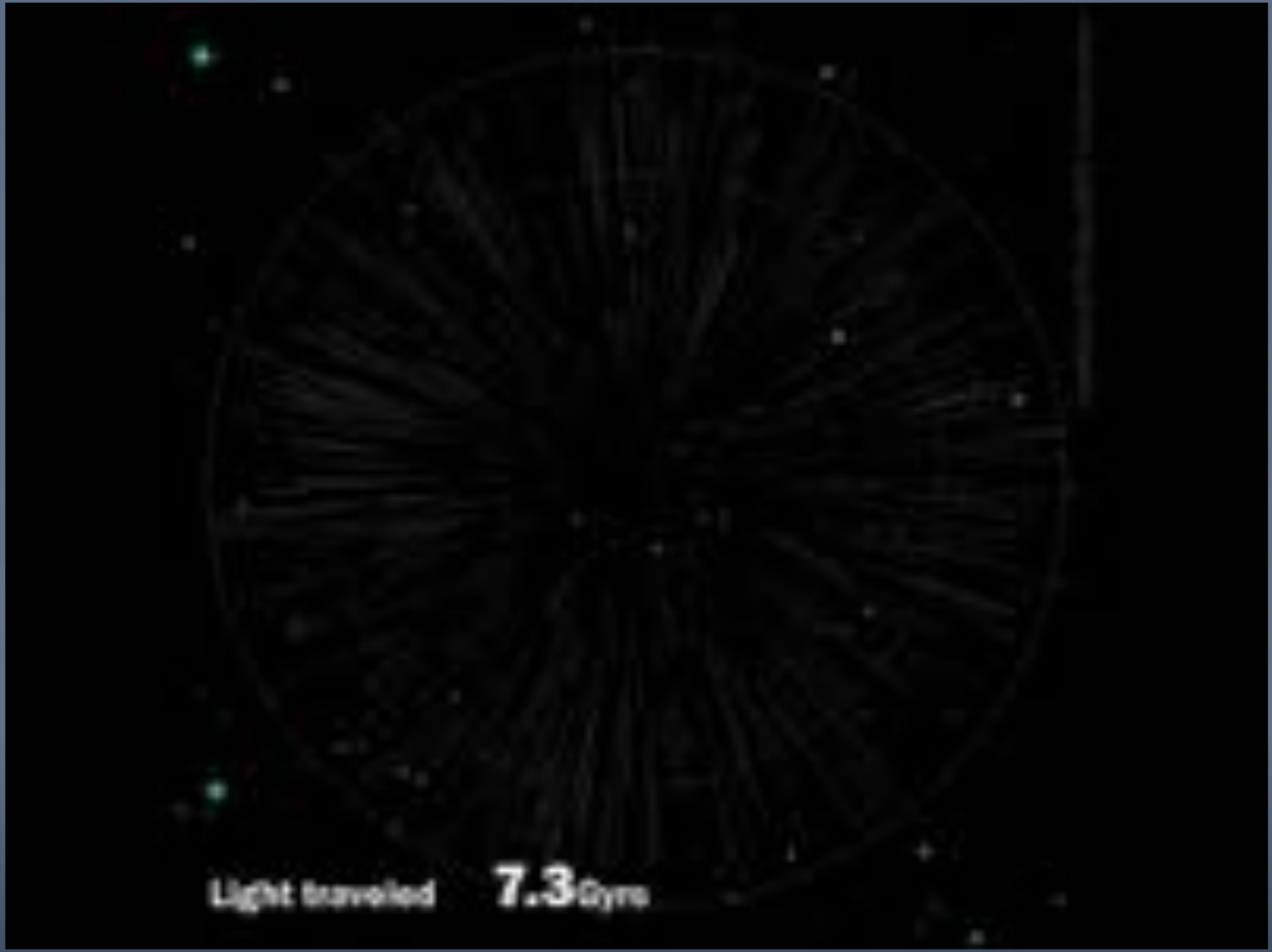




← Age of the Universe

DESI Collaboration et al. 2016

Just for Fun: A DESI Flythrough Video



Credit: David Kirkby

https://data.desi.lbl.gov/public/epo/desi3d/

Thank you!
Questions?