Cosmology – Historical Overview

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Physics 8803

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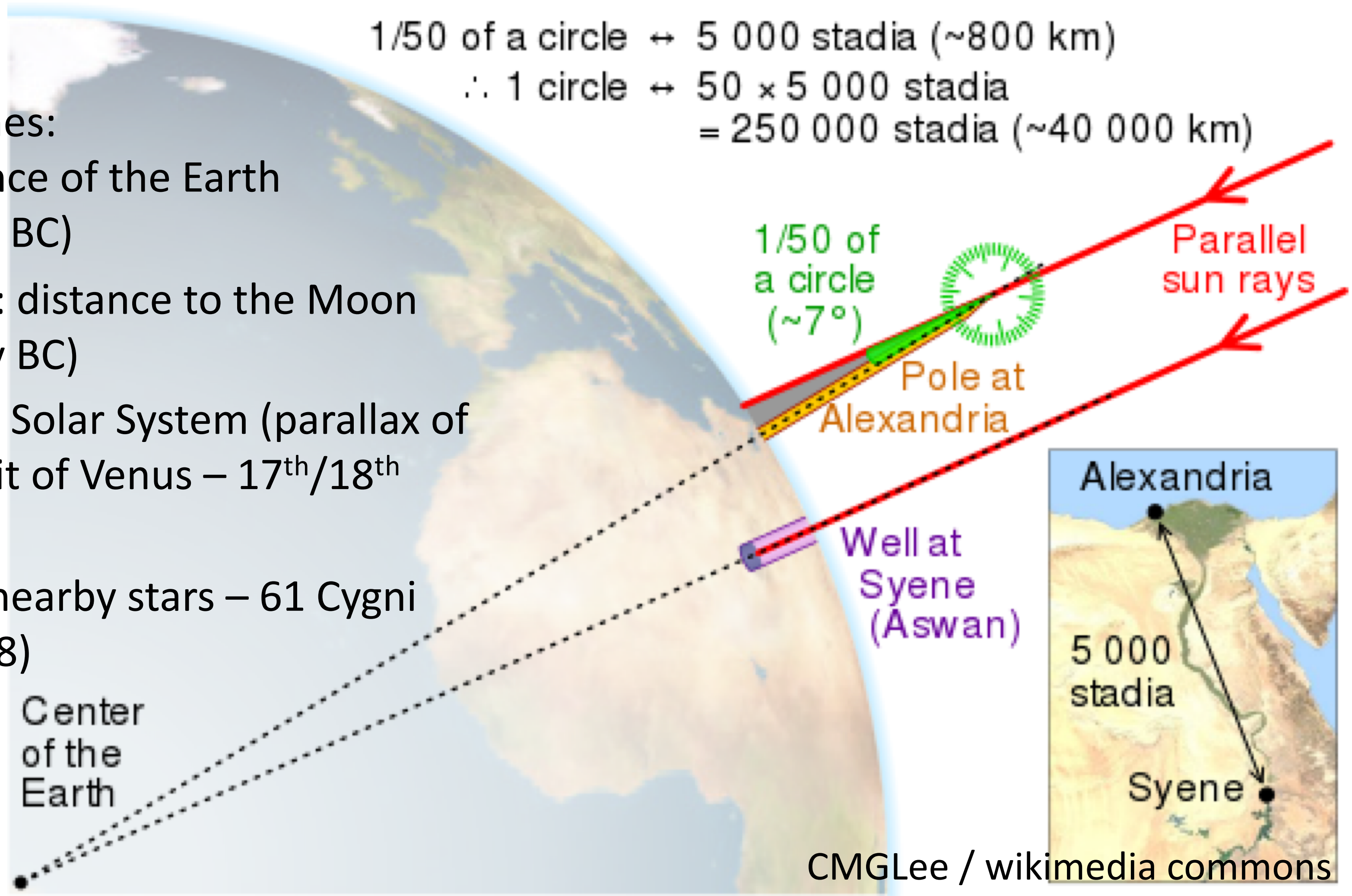
Title image: SDSS

Cosmology aims to infer the scale, structure, composition, and evolution of the Universe, based on the observations that we can make from our location in space and time.

Geometry and the Scale of the Universe

- Erastosthenes: circumference of the Earth (3rd century BC)
- Hipparchus: distance to the Moon (2nd century BC)
- Scale of the Solar System (parallax of Mars, transit of Venus – 17th/18th cenuries)
- Parallax of nearby stars – 61 Cygni (Bessel 1838)



CMGLee / wikimedia commons

At the beginning of the 20th century …

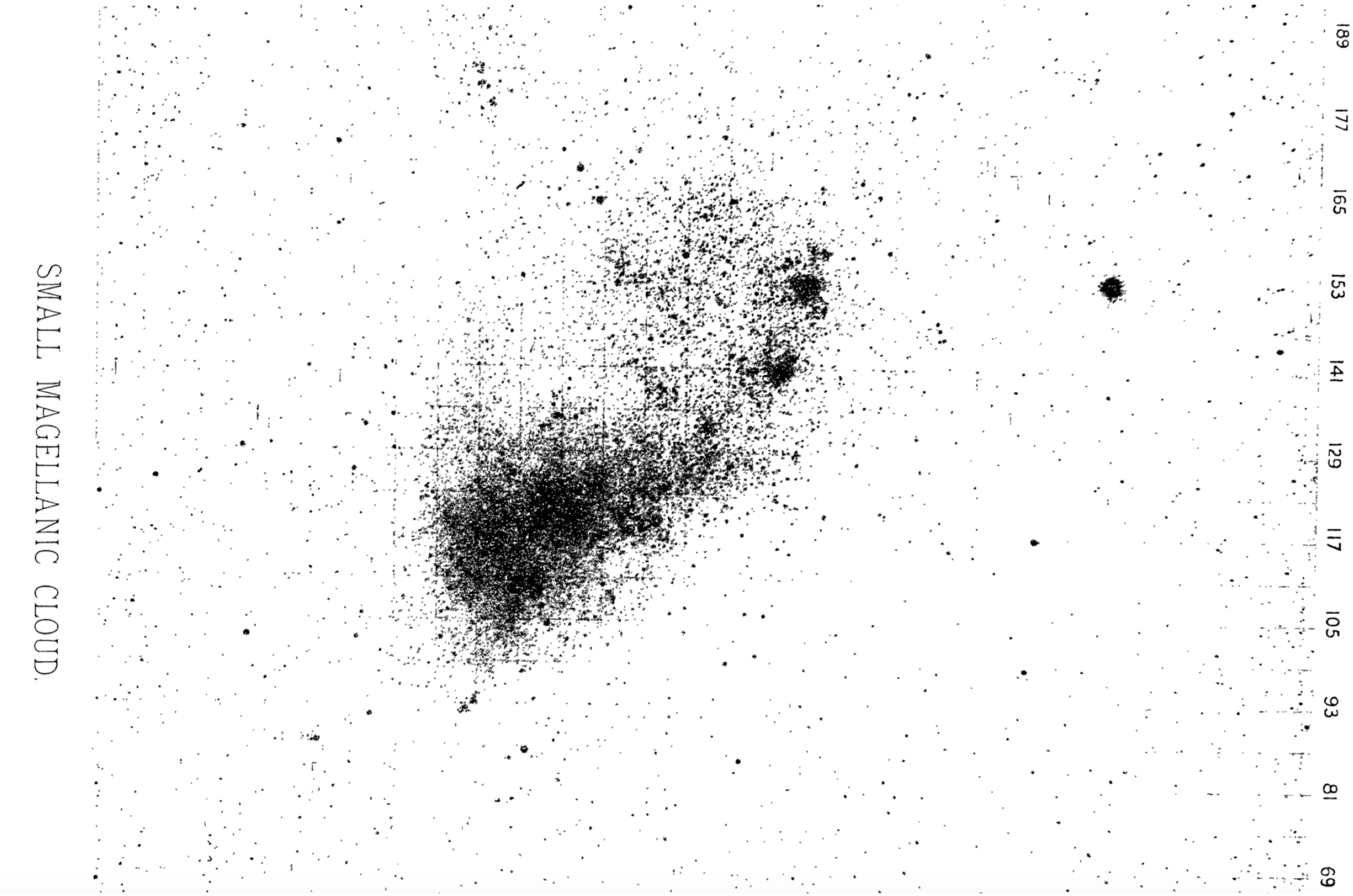
- We had observed other galaxies, but did not recognize them as such. (e.g.: the “Andromeda Nebula”)

- The only astronomy was optical astronomy; the most advanced detector was the photographic plate

- Planck’s constant was known (blackbody radiation) but there was no understanding of quantum theory or atomic structure

- The ingredients of special relativity were being built, but the theory was not fully formulated and there was no general relativity

Cepheids as Standard Candles



Leavitt 1908 (5 hr exposure on a 0.6 m telescope with a photographic plate)

Cepheids as Standard Candles

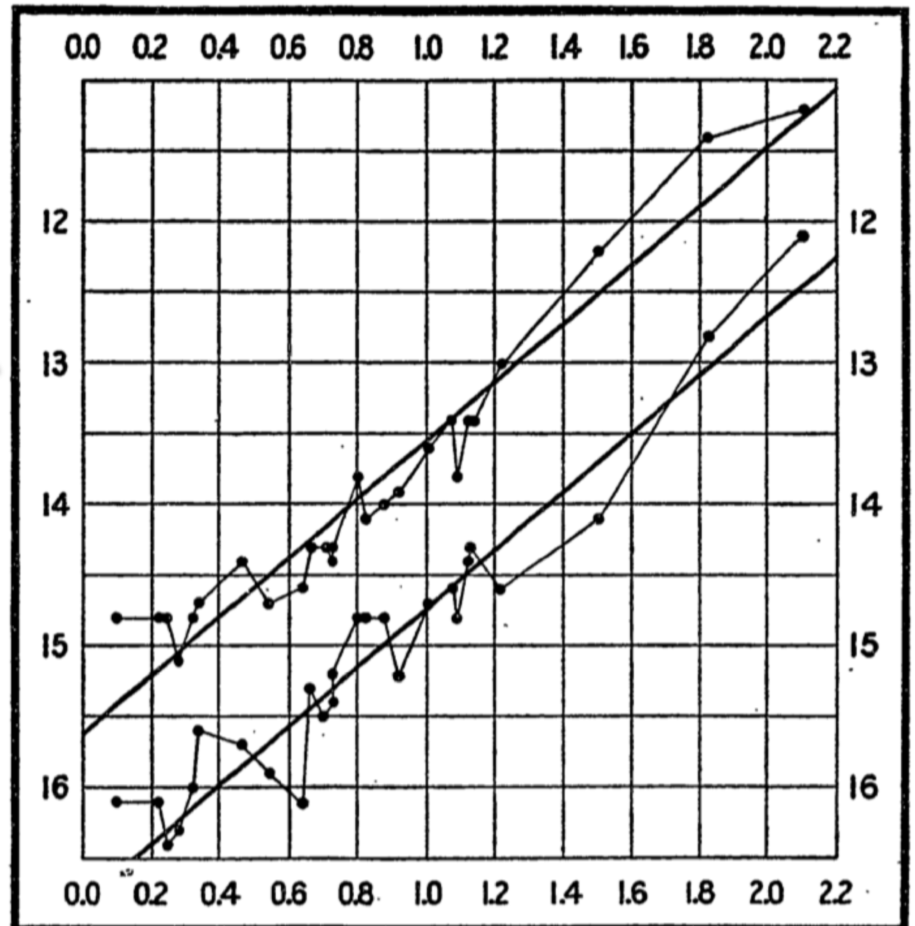
Period-Luminosity Relation for Cepheid Variables in the Small Magellanic Cloud

Henrietta Leavitt:

Harvard College Observatory circular, 1912

"Since the variables are probably at nearly the same distance from the Earth, their periods are apparently associated with their actual emission of light, as determined by their mass, density, and surface brightness."

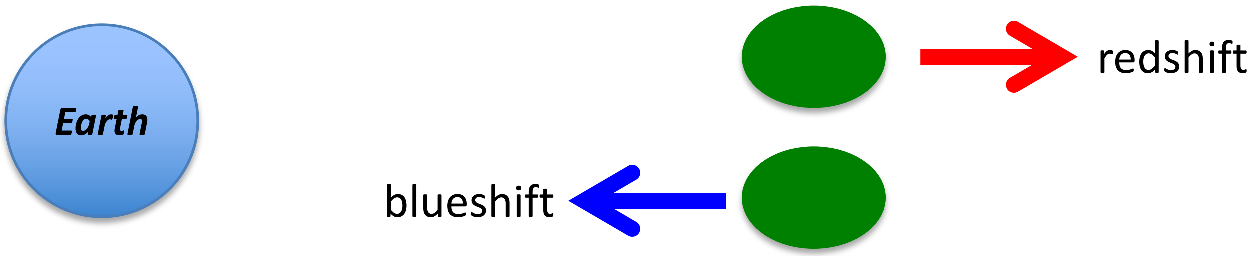
Brightness
(magnitudes – log scale)



Period
(logarithm, in days)

Doppler Shifts of Galaxies

(before they were recognized as other galaxies!)



IPAC

$$z = \frac{\lambda_{\text{observed}}}{\lambda_{\text{original}}} - 1$$

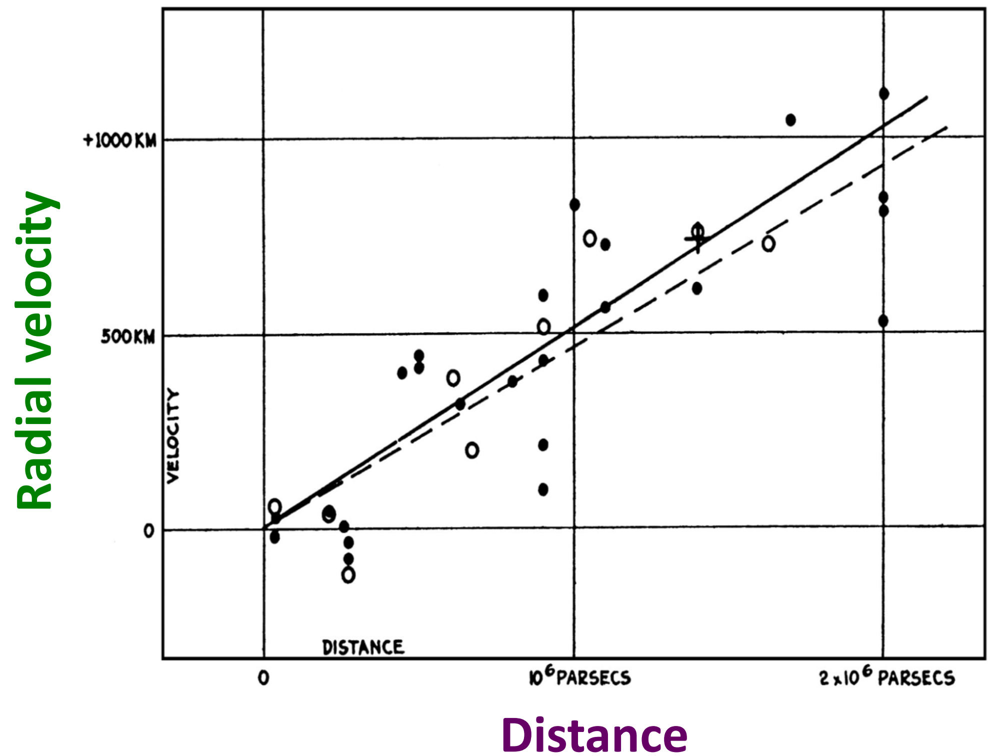
"The Velocity of the Andromeda Nebula"
Vesto Slipher, Lowell Obs. Bulletin, **2**:56

These spectrograms were measured with the Hartmann spectrocomparator, using a magnification of fifteen diameters. A similar plate of Saturn was employed as a standard. The observations were as follows:

1912,	September	17,	Velocity,	—284 km.
	November	15–16,	"	296
	December	3–4,	"	308
	December	29–30–31,	"	—301
			Mean velocity,	—300 km.

The expanding Universe

- Hubble's law on radial velocities of galaxies: **$v = H_0 D$**
  (velocity proportional to distance)
- H_0 = Hubble constant
- Modern measurement:
  $H_0 \approx 70$ km/s/Mpc
  $1/H_0 \approx 14$ Gyr
- Hubble's measurement of H_0 was way too high …



Hubble (1929)

The expanding Universe

- Friedmann-Lemaître-Robertson-Walker metric:

$$ds^2 = -c^2\,dt^2 + [a(t)]^2\left[\frac{dr^2}{1-Kr^2} + r^2(d\theta^2 + \sin^2\theta\,d\phi^2)\right]$$

(mathematical development in the 1920s and 1930s)

- Describes a homogeneous, isotropic Universe in the context of curved spacetime.
  - Homogeneity and isotropy were initially philosophically based assumptions – today they are observationally established.
  - Spacetime coordinates (t,r,θ,ϕ)
  - Model has one constant (curvature K) and scale factor a(t) describing expansion history.
- Dynamics in GR from the Friedmann equations:

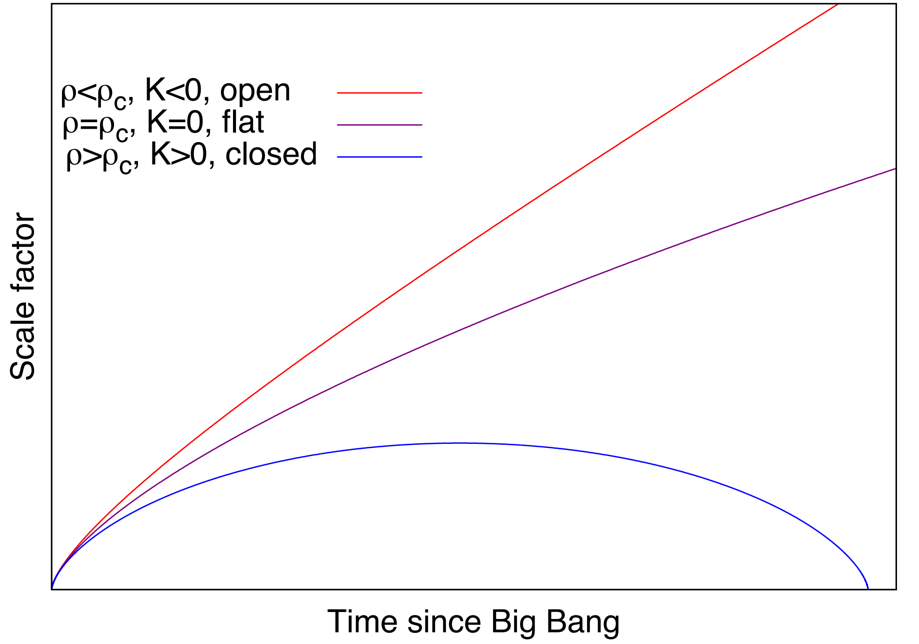
$$\frac{\ddot{a}}{a} = -\frac{4}{3}\pi G\left(\rho + \frac{3p}{c^2}\right) \qquad \left(\frac{\dot{a}}{a}\right)^2 = \frac{8}{3}\pi G\rho - \frac{Kc^2}{a^2}$$

The theory of a matter-filled Universe

- In a matter-filled Universe, we should have: $\rho \propto 1/a^3$
- Thus the Friedmann equations are equations of motion for a(t).
- Solution depends on how the density of the Universe compares to the critical density ρ_c:

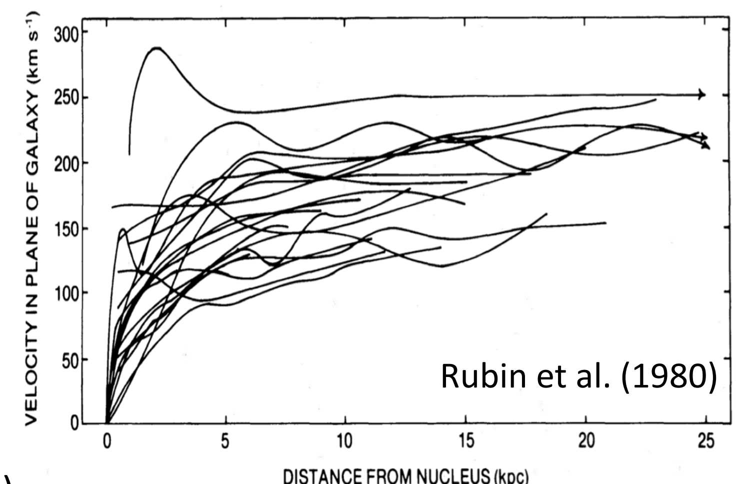
$$\rho_c = \frac{3H_0^2}{8\pi G}, \quad H = \frac{\dot{a}}{a} \quad (H_0 = \text{value today})$$

- For decades, the big question in observational cosmology was to measure $\Omega=\rho/\rho_c$.
  - Shape and fate of the Universe!
  - This is very difficult, either by measuring ρ or a(t). As we now know, the question had to be reformulated …



Most of the Universe is Dark!

- We normally "weigh" the Universe with gravity: $v^2 = GM/r$
  - Planets via their moons or artificial satellites; stars (often) with binaries
  - Natural to try galaxies and clusters by the same method
- But gravitational mass exceeds visible mass:
  - Coma cluster (Zwicky 1933)
  - Explored much more systematically via rotation of spiral galaxies (Rubin et al.)



Rubin et al. (1980)

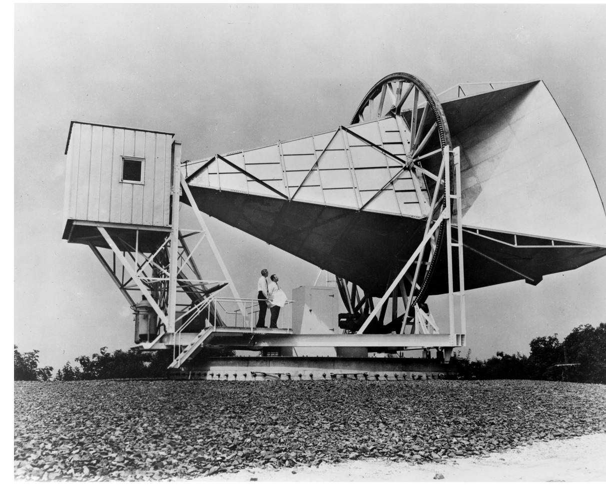
- Now known that most dark matter is:
  - Non-baryonic in nature (Big Bang Nucleosynthesis)
  - Not in large compact objects (microlensing – 1990s)
- Can still try to measure a(t) by other means – distance vs. redshift. This was successfully done in the 1990s with surprising results, but I want to consider another thread of history first.

The Cosmic Microwave Background

Radiation at a temperature of 2.7 K seen in all directions

Discovery – Penzias & Wilson (1965), Nobel Prize!

Matches a blackbody spectrum (i.e. the spectrum when all frequencies are in equilibrium at the same temperature)



A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.

…

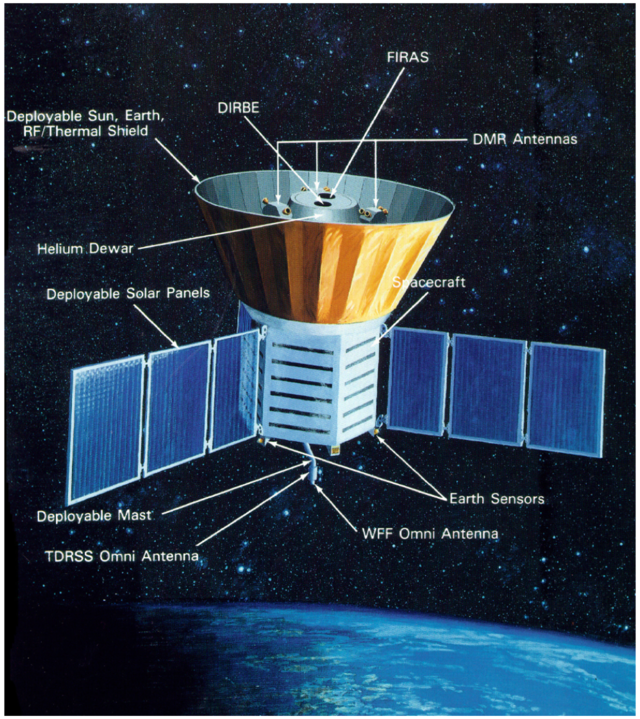
From a combination of the above, we compute the remaining unaccounted-for antenna temperature to be 3.5° ± 1.0° K at 4080 Mc/s.

…

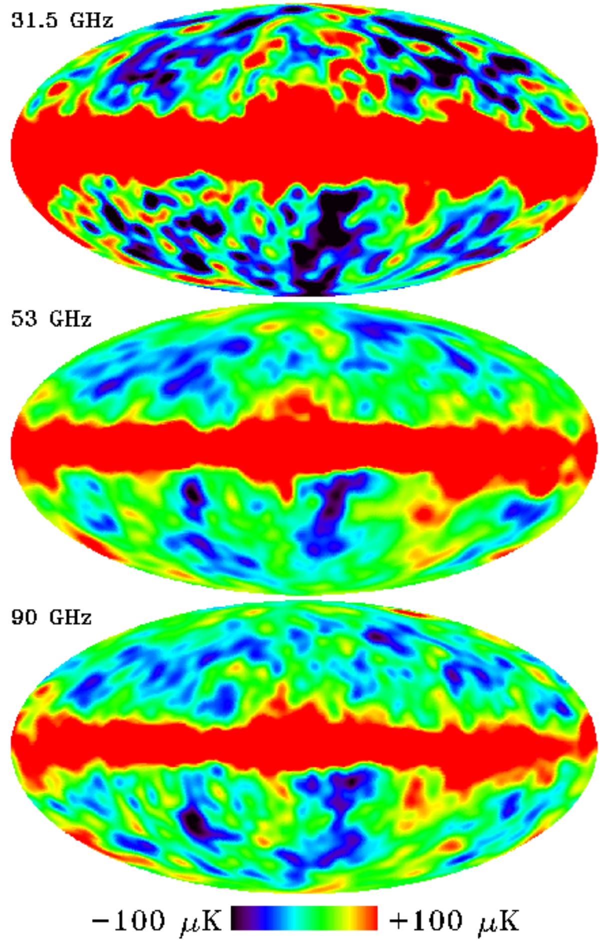
A. A. Penzias
R. W. Wilson

May 13, 1965
Bell Telephone Laboratories, Inc
Crawford Hill, Holmdel, New Jersey

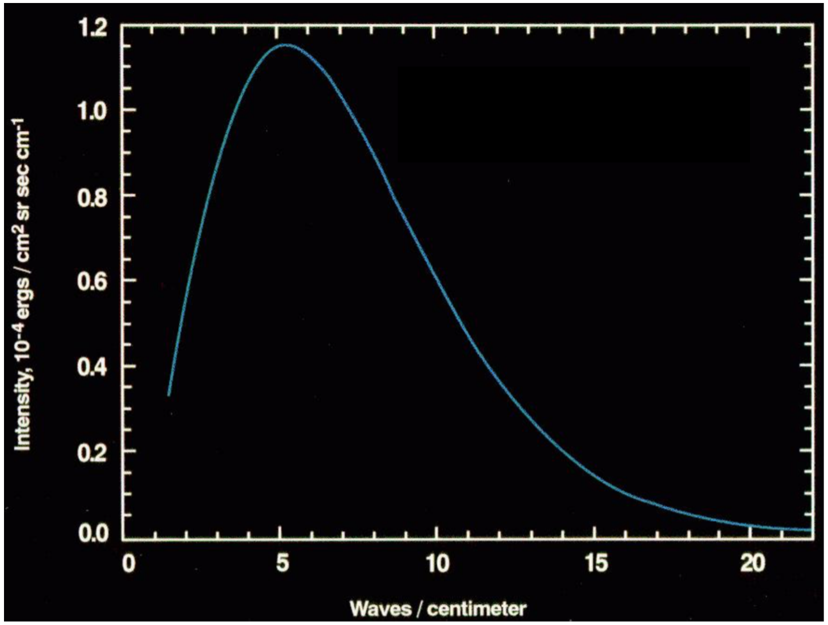
COBE – 1989



Anisotropy measured by DMR: structure in the early Universe

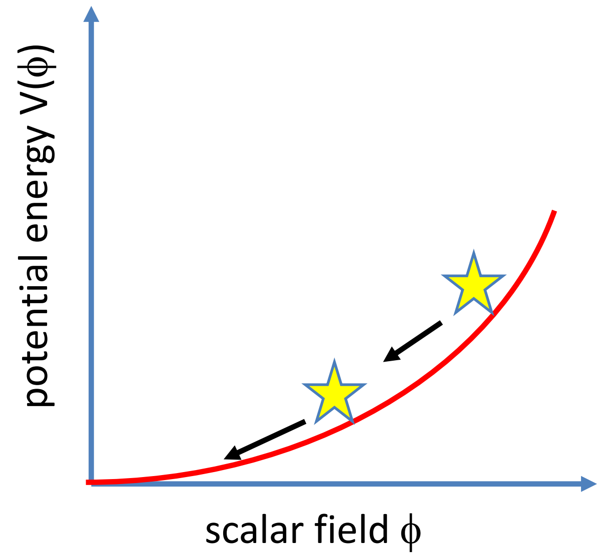


Spectrum Measured by the COBE satellite, 1992



Origin of the fluctuations?

- Observable features in the CMB were imprinted when the Universe became transparent (T ~ 3000 K for hydrogen plasma, or z=1000)
- But the Universe was too young for information to travel between these regions – so:
  - Why is the Universe so uniform?
  - and how did the perturbations develop?

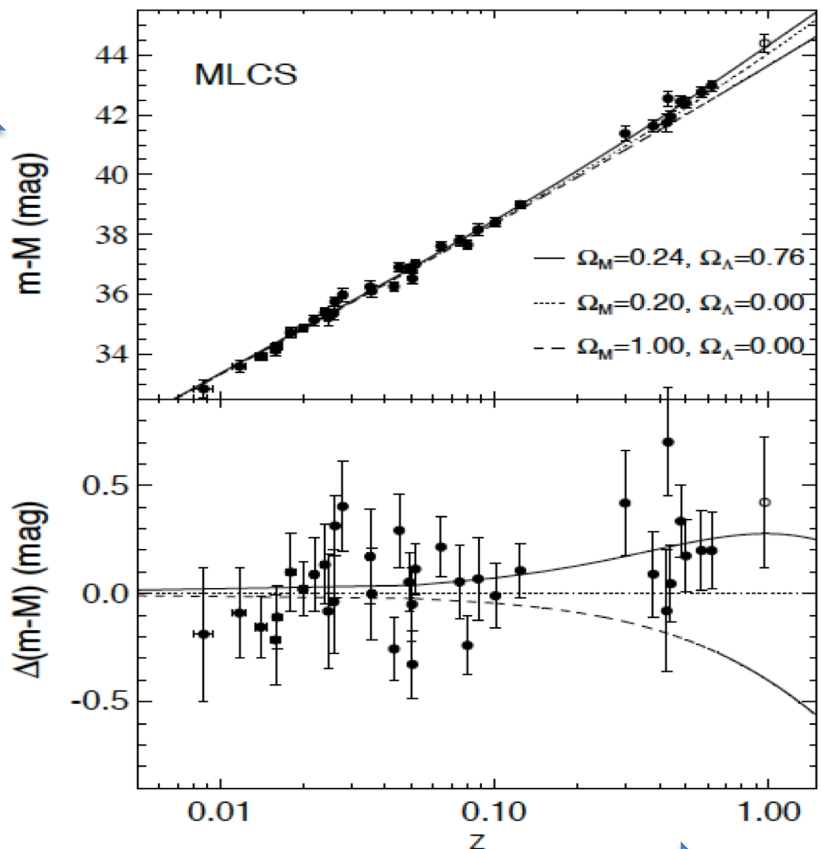


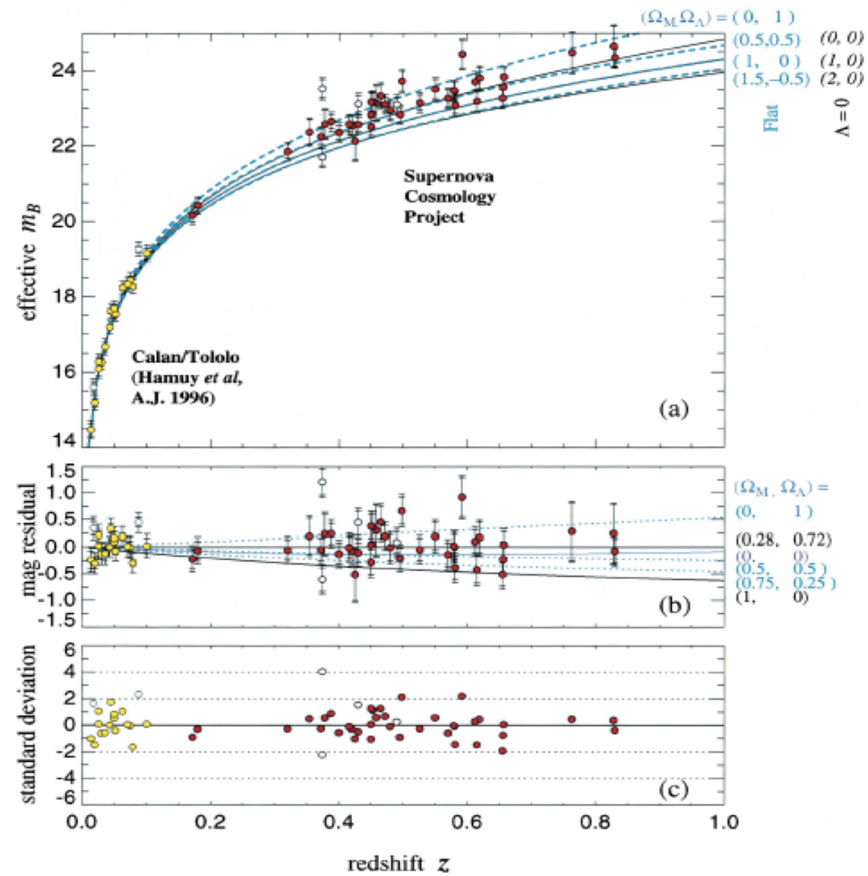
- Leading explanation is **inflation**, developed in early 1980s
  - Period of exponential expansion solves communication problem
  - Perturbations are quantum fluctuations stretched to cosmic scale
  - Many successes in CMB statistics (Gaussianity, adiabaticity, near-scale-invariance …) but inflation remains a theory

Cosmic acceleration ("dark energy")

1998-9: *Discovery of accelerating Universe from Type Ia supernovae. There is some new field or force that causes all of space to be repulsive.*

fainter

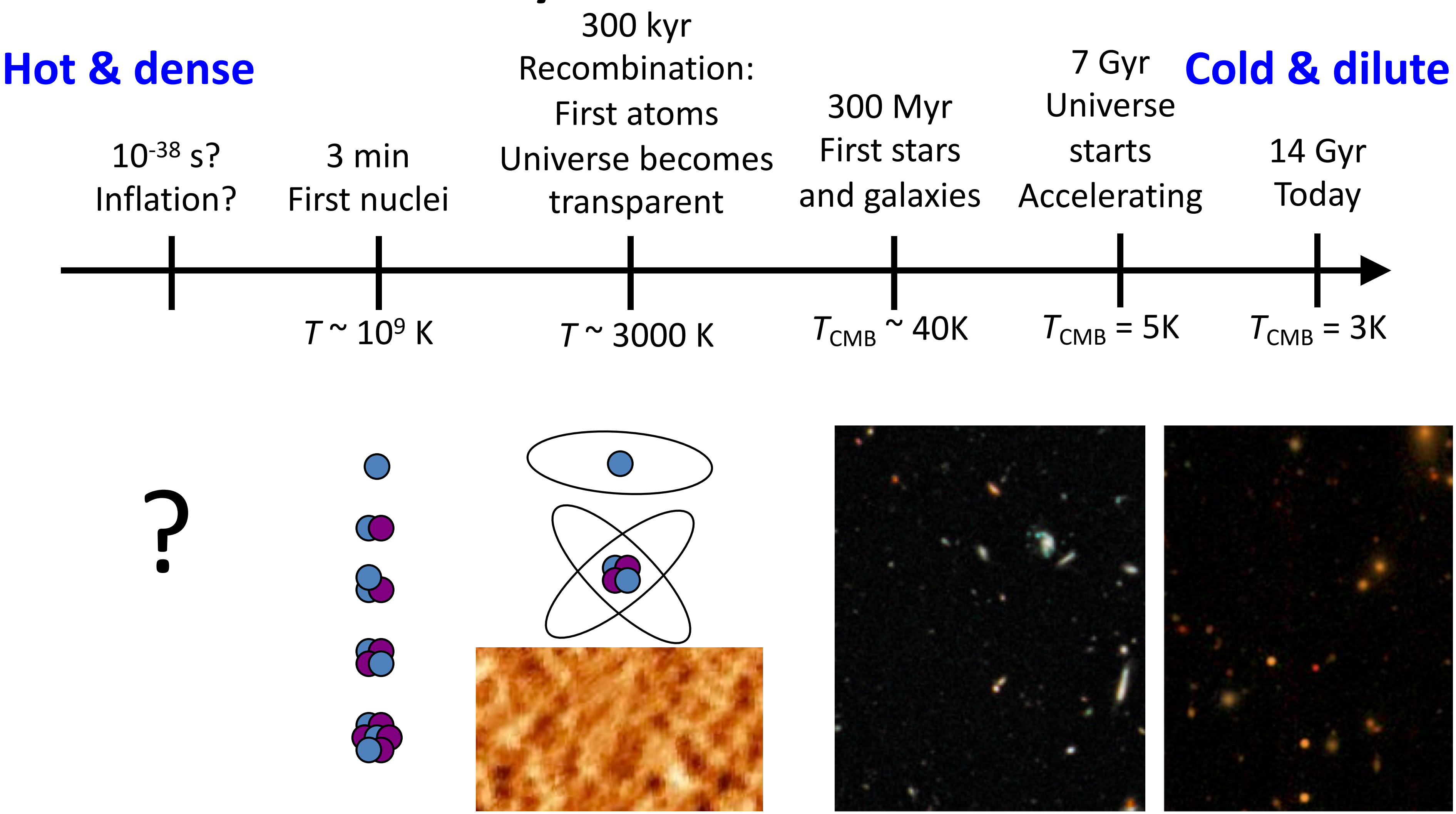




moving away from us faster

Riess et al, Perlmutter et al

History of the Universe

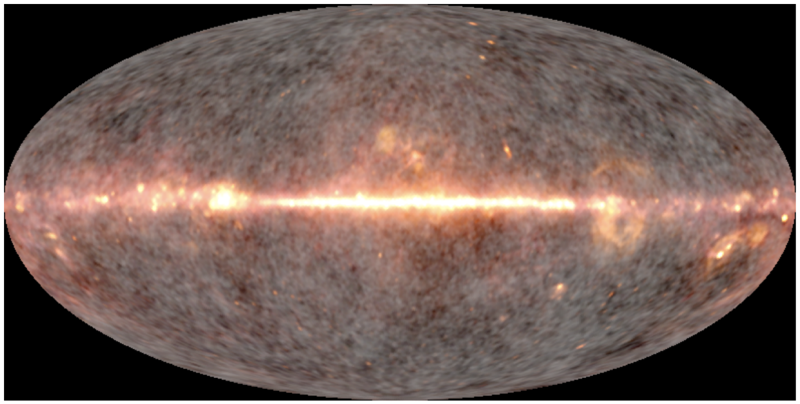


ACBAR

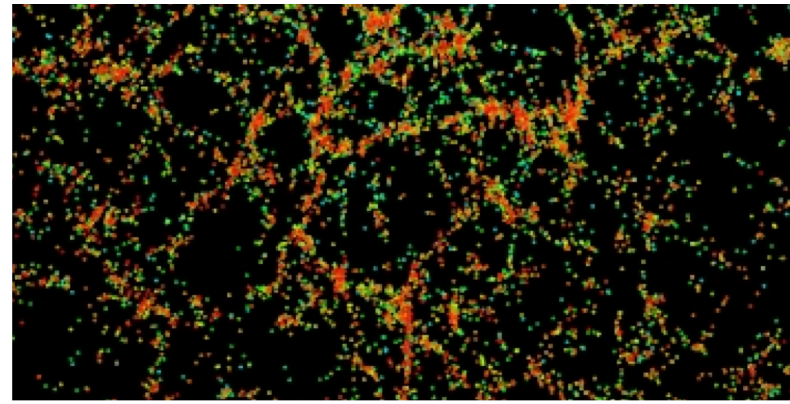
NASA/ESA/Z. Levay

SDSS

Modern Statistical Cosmology



The Cosmic Microwave Background (WMAP)



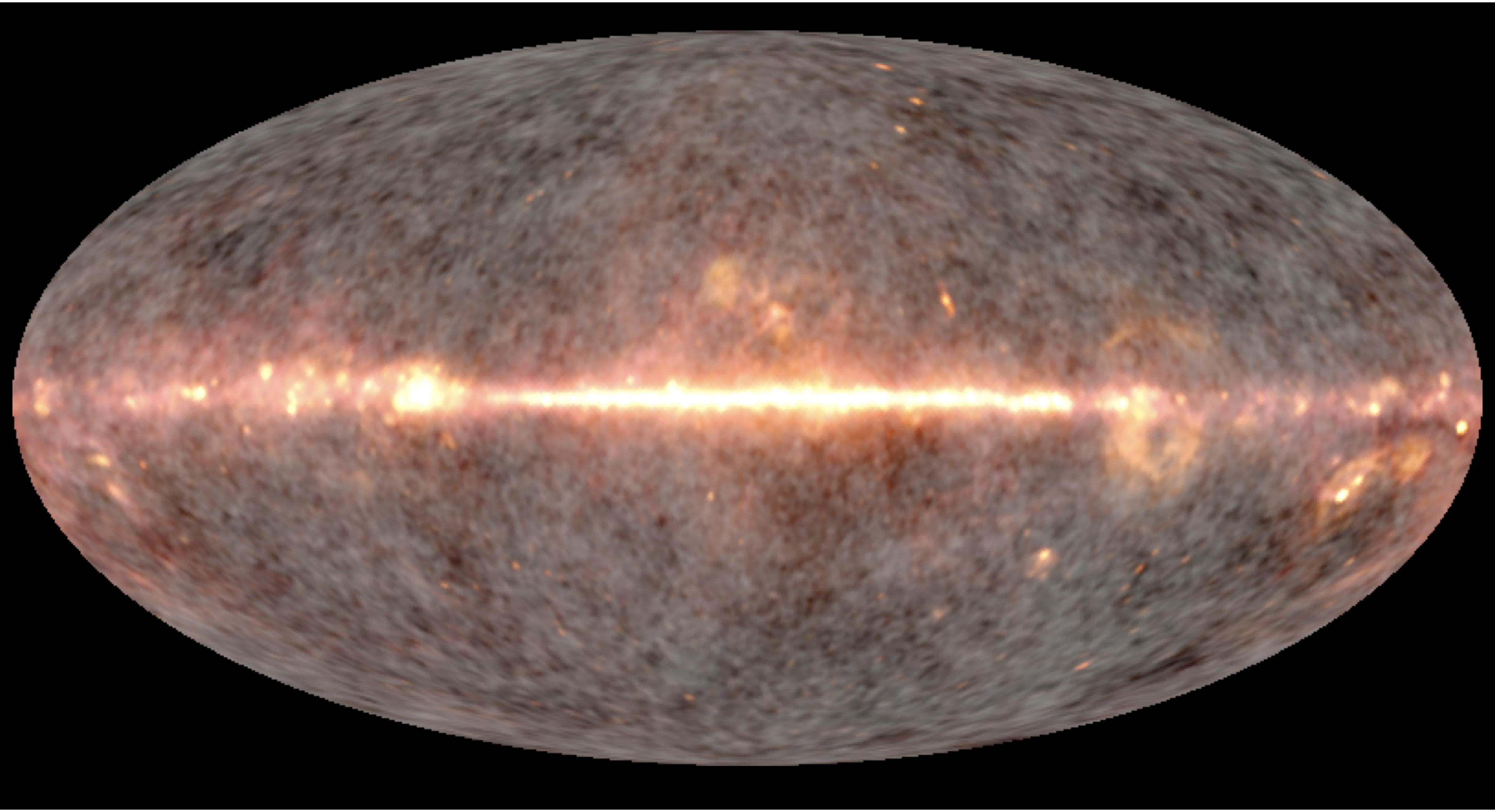
The Galaxy Distribution (SDSS)

Goal: To learn about the composition of the Universe, and the laws governing the largest scales, by comparing the statistical properties of the Universe across cosmic time …
and to use the perturbations to learn about the earliest moments of the Universe.

Only in a **statistical** sense are the structures that we see at different epochs the same.

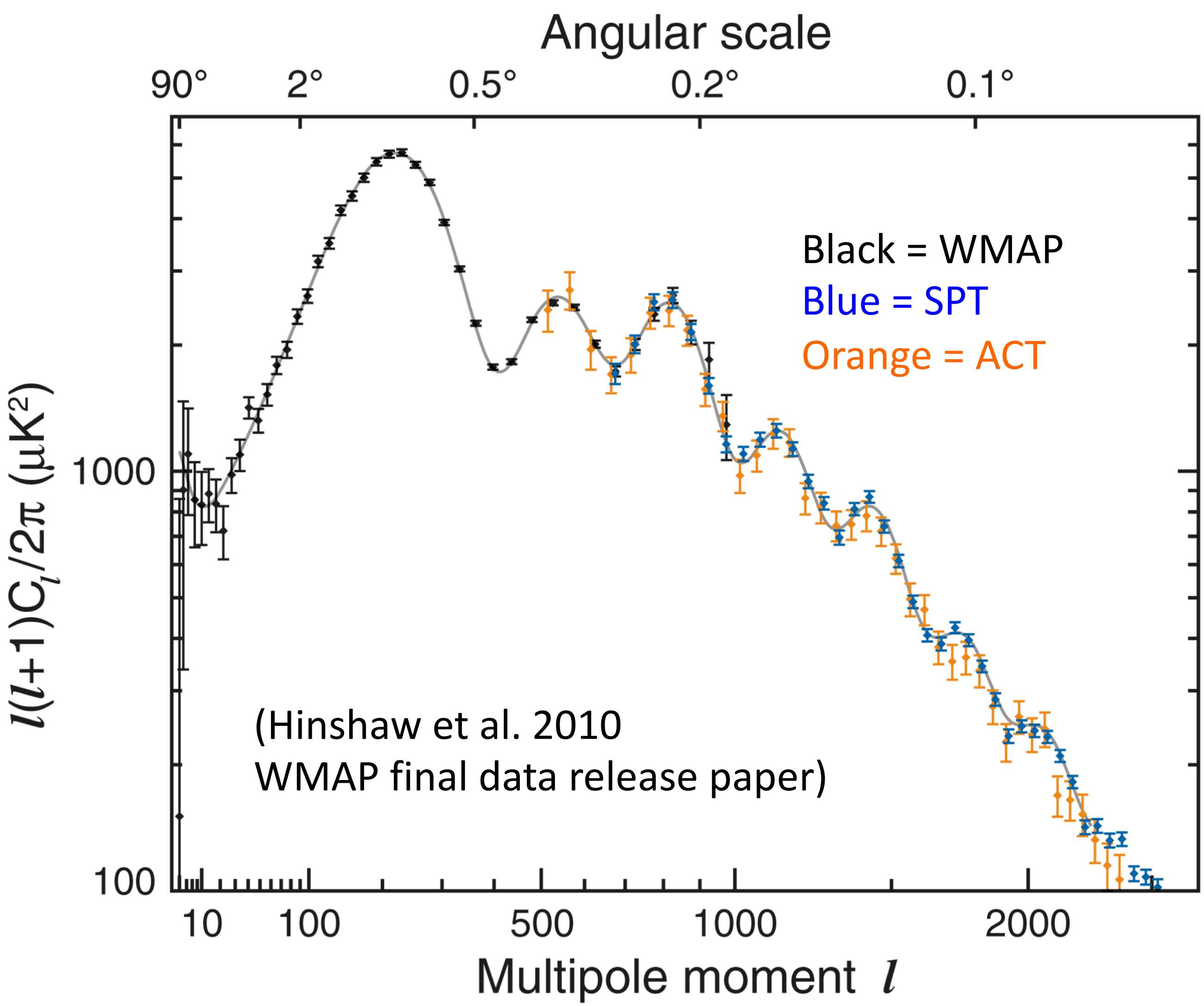
The microwave sky as seen by WMAP

[launched 2001]



Composite of 22, 41, and 94 GHz sky maps from WMAP

CMB Anisotropies: Seismology of the early Universe

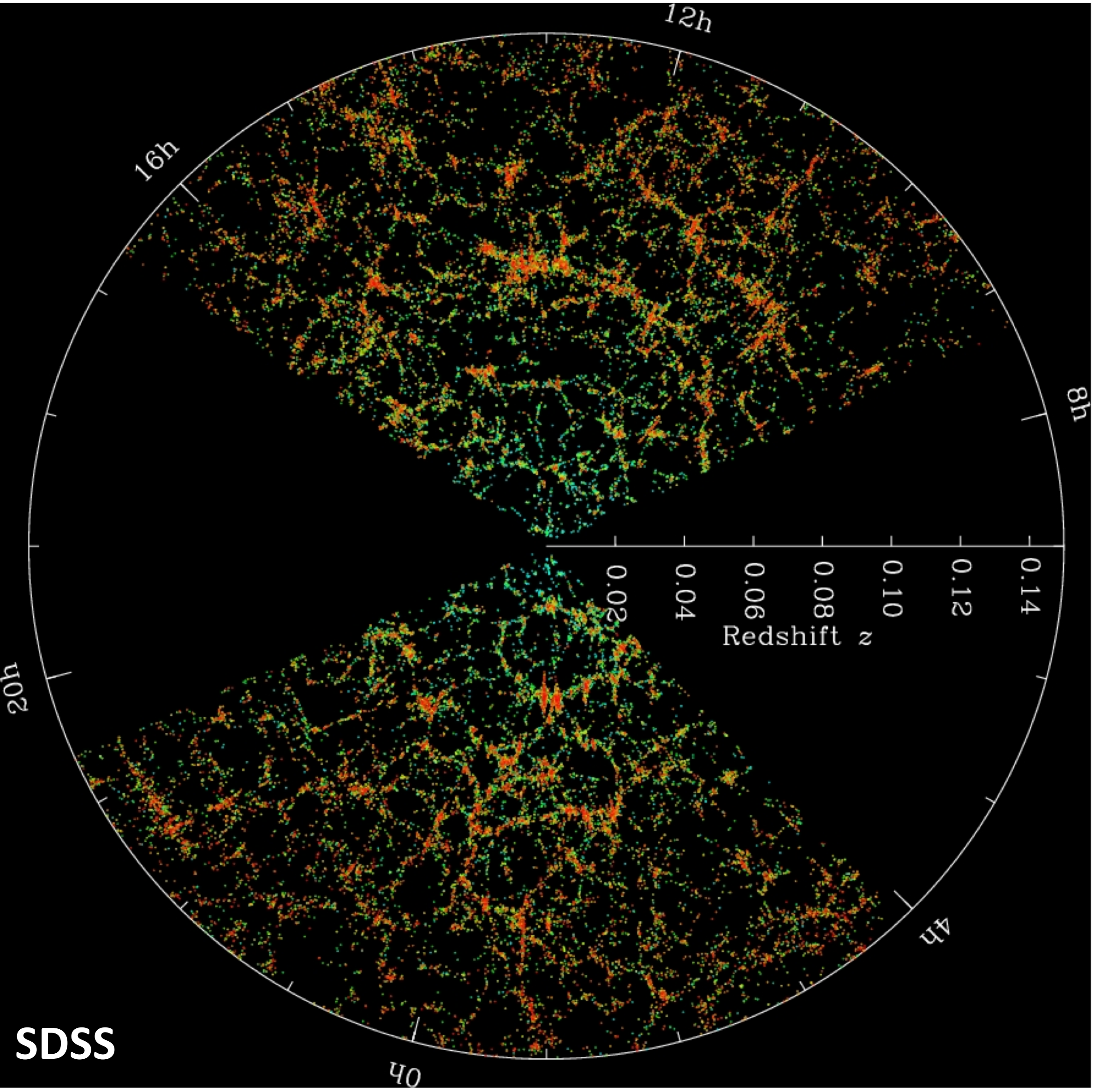


Baryon:photon ratio
$(6.10 \pm 0.10) \times 10^{-10}$
by number

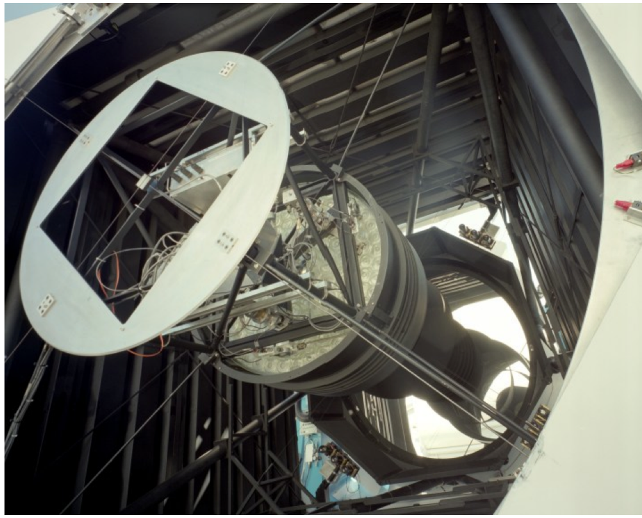
Dark matter:baryon ratio
5.05 ± 0.16
by mass

Initial density perturbations
$(4.93 \pm 0.09) \times 10^{-5}$
standard deviation per logarithmic range in scale

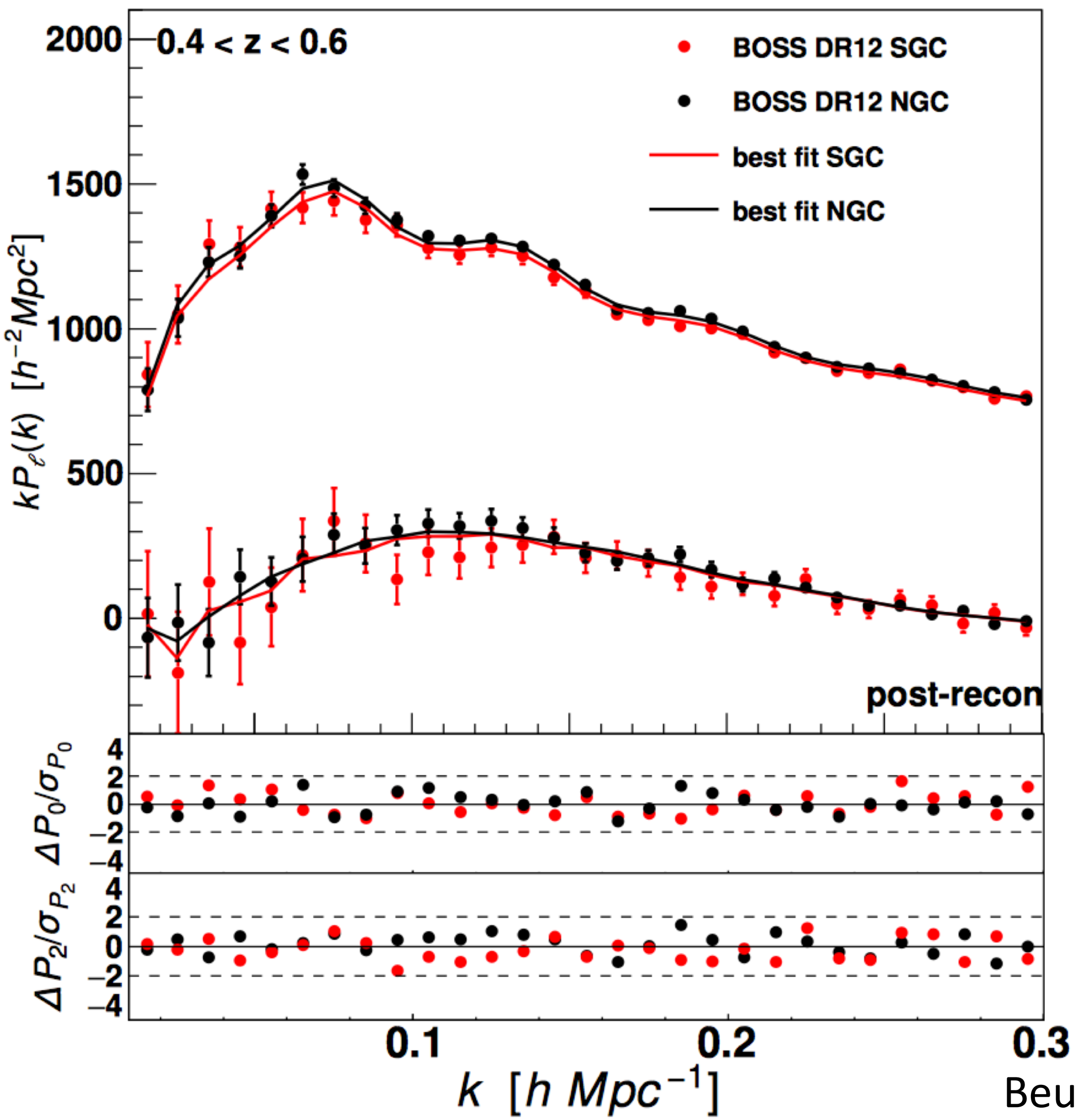
The Sloan Digital Sky Survey



Uniform digital images of ¼ of the sky, >1 million spectra



Statistics of the Distribution of Galaxies



Beutler et al. 2016

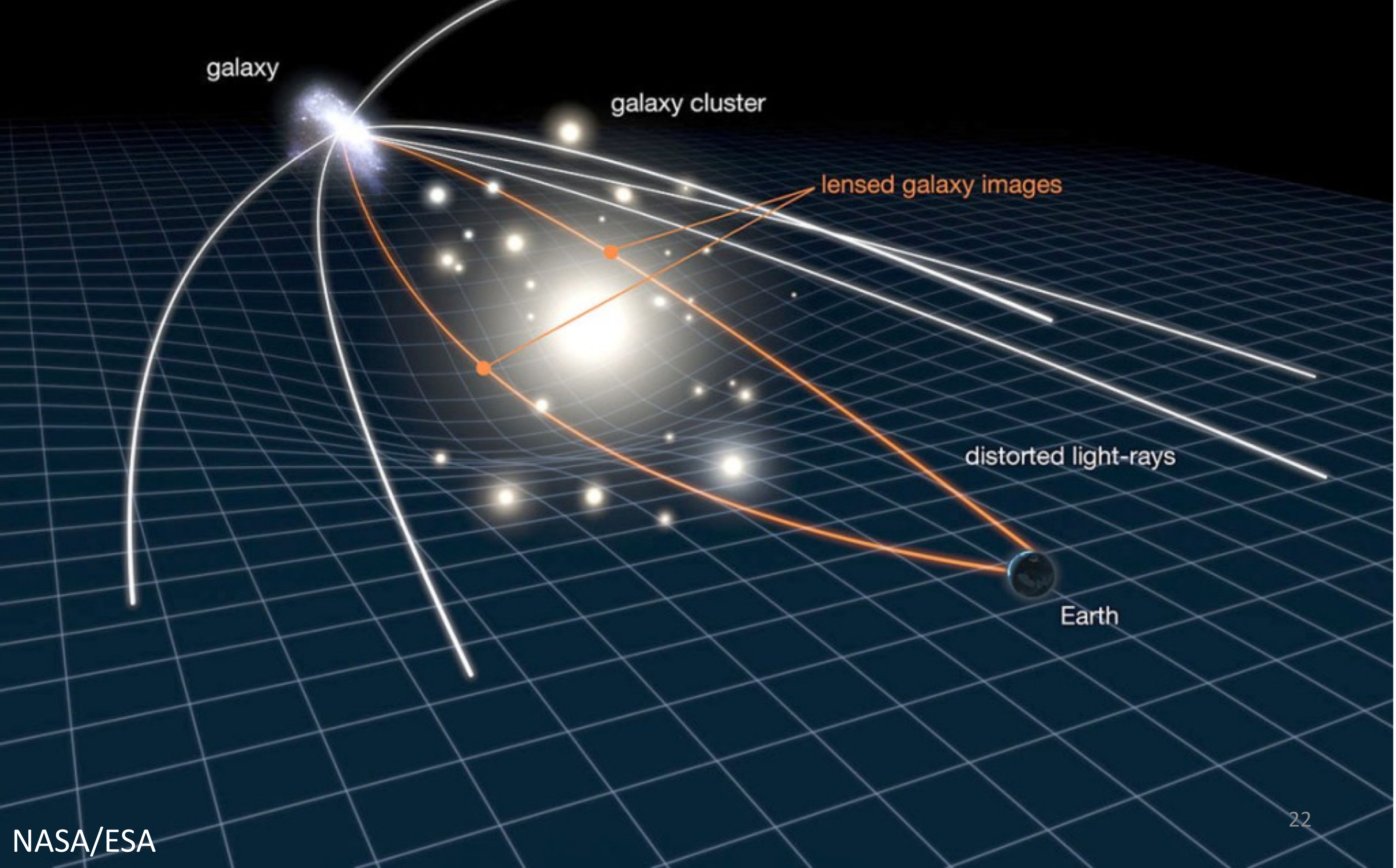
The same oscillations as seen in the CMB!

Can find best-fit models to both the CMB and the local Universe.

Planck + SDSS-BOSS:
Total matter fraction of the Universe = 30.1±1.4%

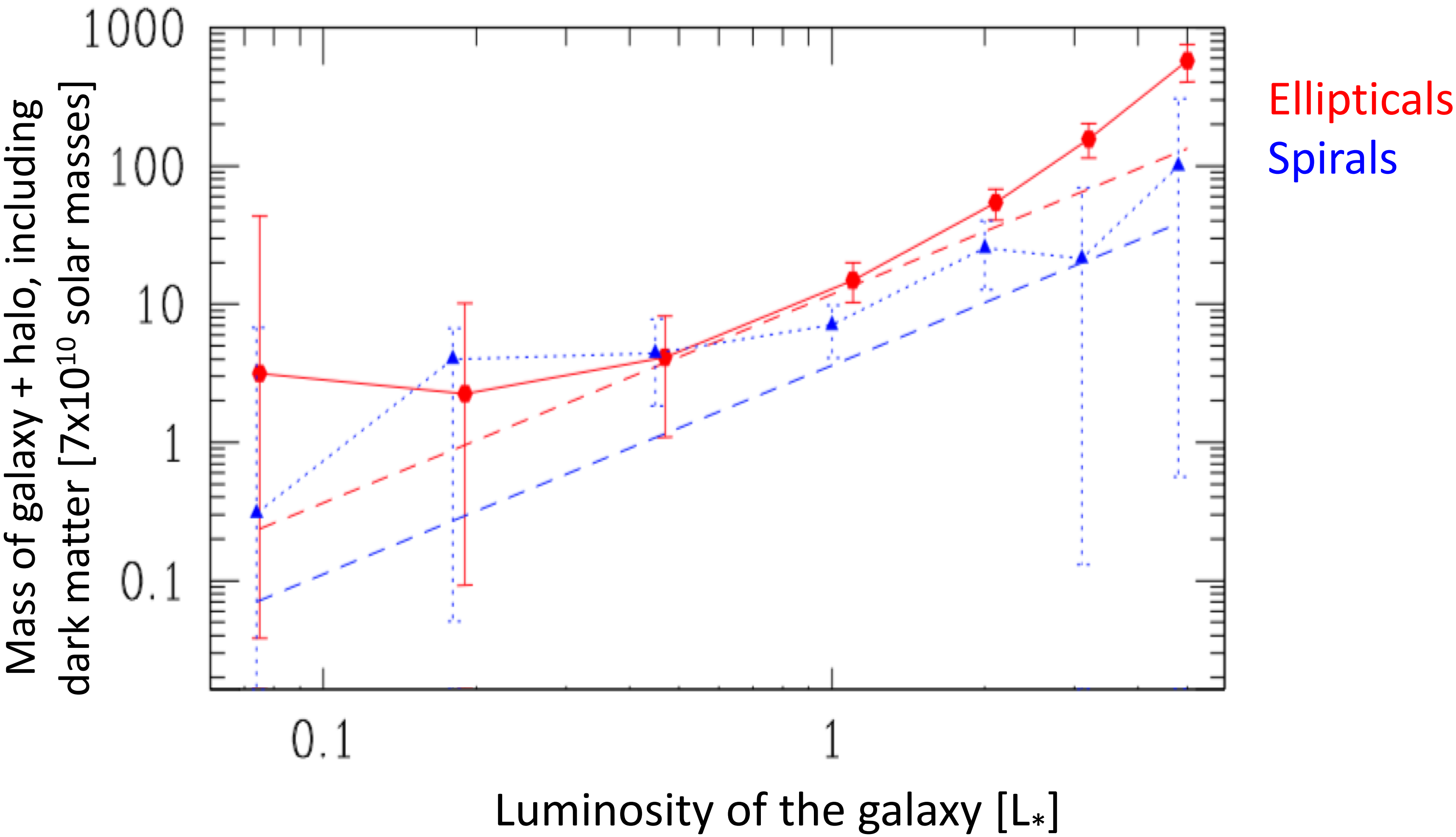
(Alam et al. 2016)

Gravitational lensing



NASA/ESA

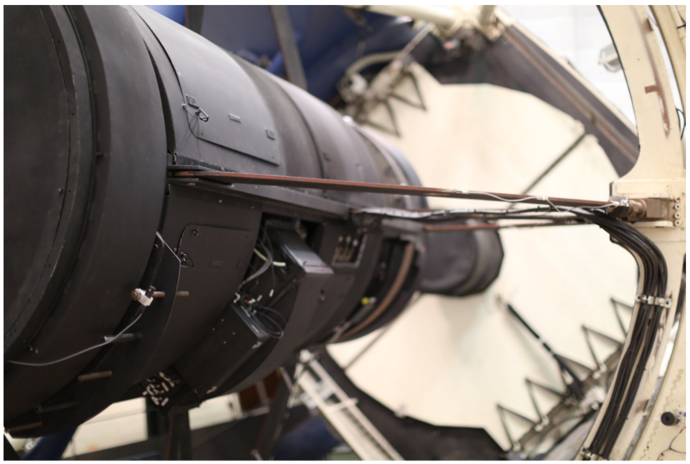
Weak lensing by galaxies



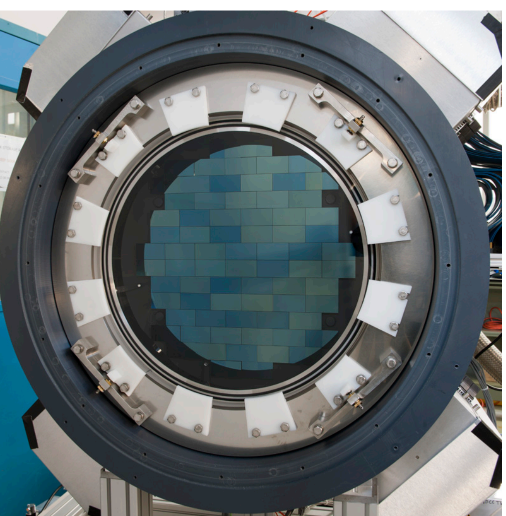
Mandelbaum et al. 2006

Weak lensing by large scale structure

CFHTLens (2000s)
KiDS, DES, HSC (2010s)

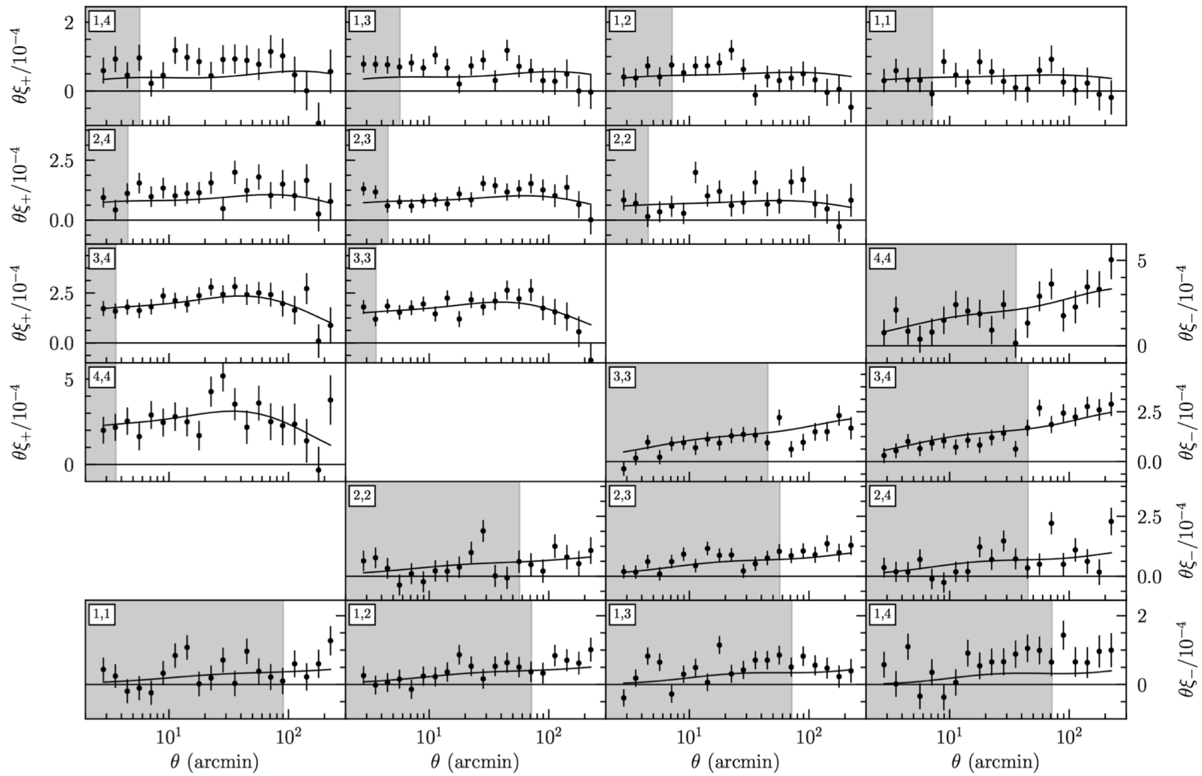


DECam on the Blanco telescope in 2015



DECam in 2011 -- 520 Mpix CCD camera
(DES Fermilab gallery)

Lensing as a function of redshift bin and scale in DES
(Troxel et al. 2017)



A Cosmological Constant?

- Simplest explanation for cosmic acceleration:
  a **cosmological constant**, Λ
- New addition to Einstein's equation:

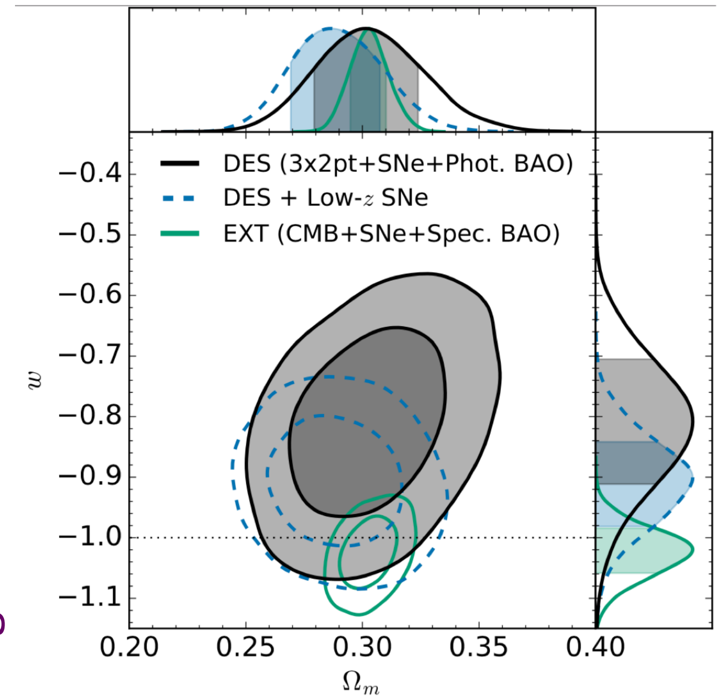
$$R_{\mu\nu} - \tfrac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

- Current recent results consistent with a constant (w = −1)

$$\rho_{\text{dark energy}} \propto a^{-3(1+w)}$$

Source of acceleration getting weaker →

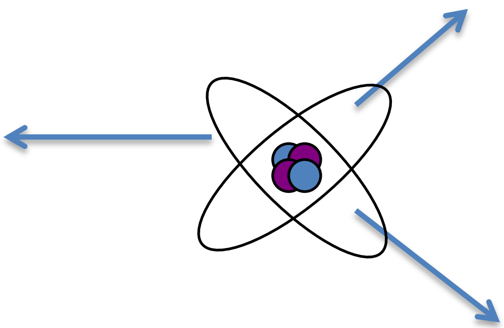
← stronger



Dark Energy Survey, 2018

The Fate of the Universe?

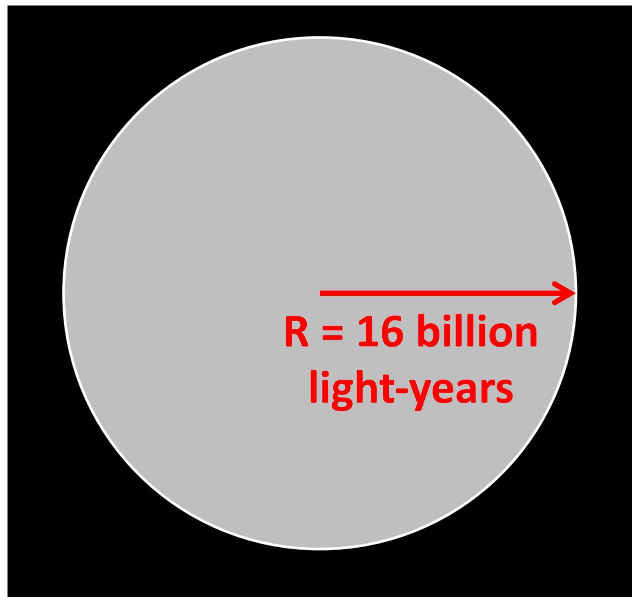
$w < -1$



In a finite amount of time, the Universe ends as even atoms and nuclei are torn apart!

The “Big Rip”

$w = -1$



Observable Universe becomes an inside-out black hole.

The de Sitter spacetime

$w > -1$

In the far future, the expanding Universe empties out. Density and temperature approach zero.

The “Big Freeze”

What is coming next?

- Galaxy surveys to push to higher redshift and explore more of the Universe’s history (DESI, Euclid, LSST, WFIRST)
- Cosmic microwave background as a back-light for lensing and scattering studies
- New ways of observing the Universe – gravitational waves, diffuse 21 cm radiation
- Maybe something we haven’t thought of yet?

- You may get to be a part of this!