What I did on my summer vacation
and
the Cosmic Microwave Background

Donna Kubik NIU 3Oct2014

I went to Holmdel, NJ

?

I went to see the telescope that was used to discover the *Cosmic Microwave Background (CMB)*!

The Holmdel Horn has an alt-az mount

Altitude and azimuth tracks

What is the Cosmic Microwave Background?

Rainbows

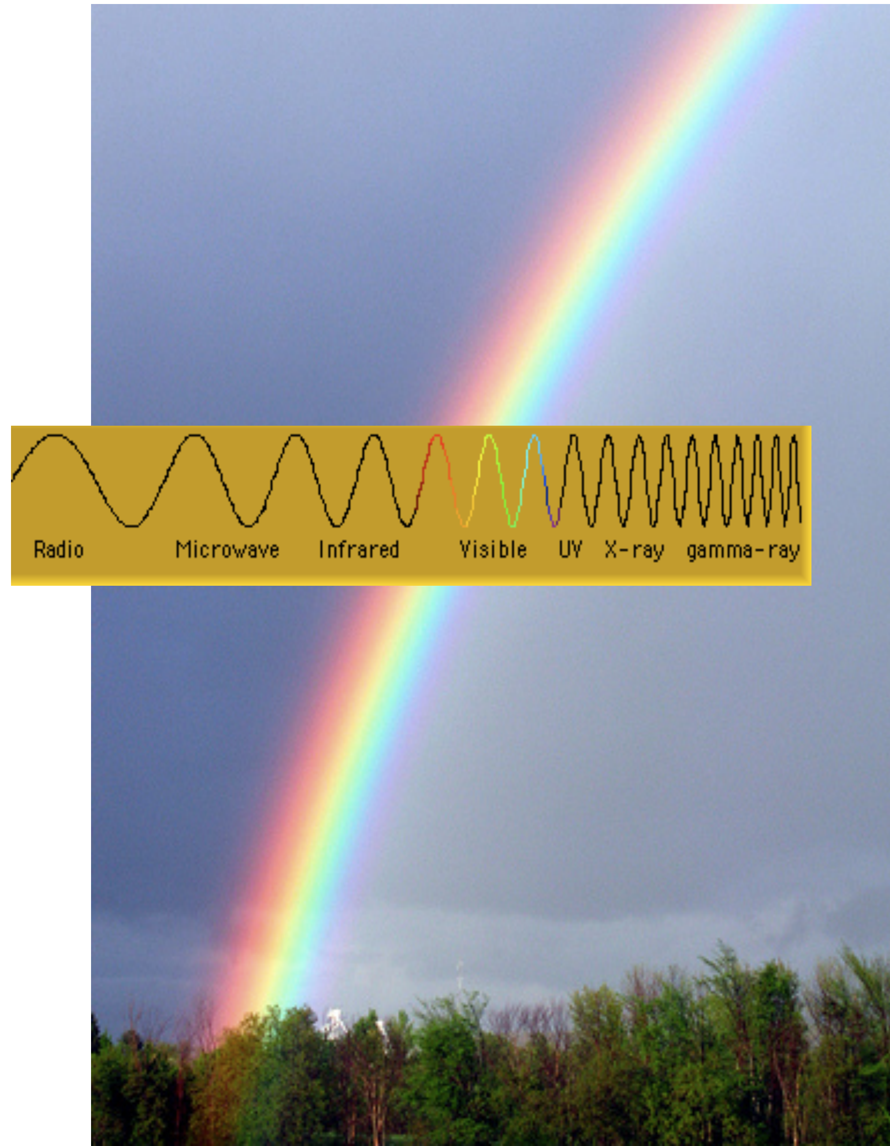
- Consider a rainbow…
- Each color transitions to the next, but when you get to either the red or the violet end, the rainbow seems to stop, or fade into nothing.
- Or does it just actually transition to colors that are invisible to our eyes?

Rainbows

- If we put other detectors on either side of the rainbow, could we detect more ‘colors’?
- Yes.

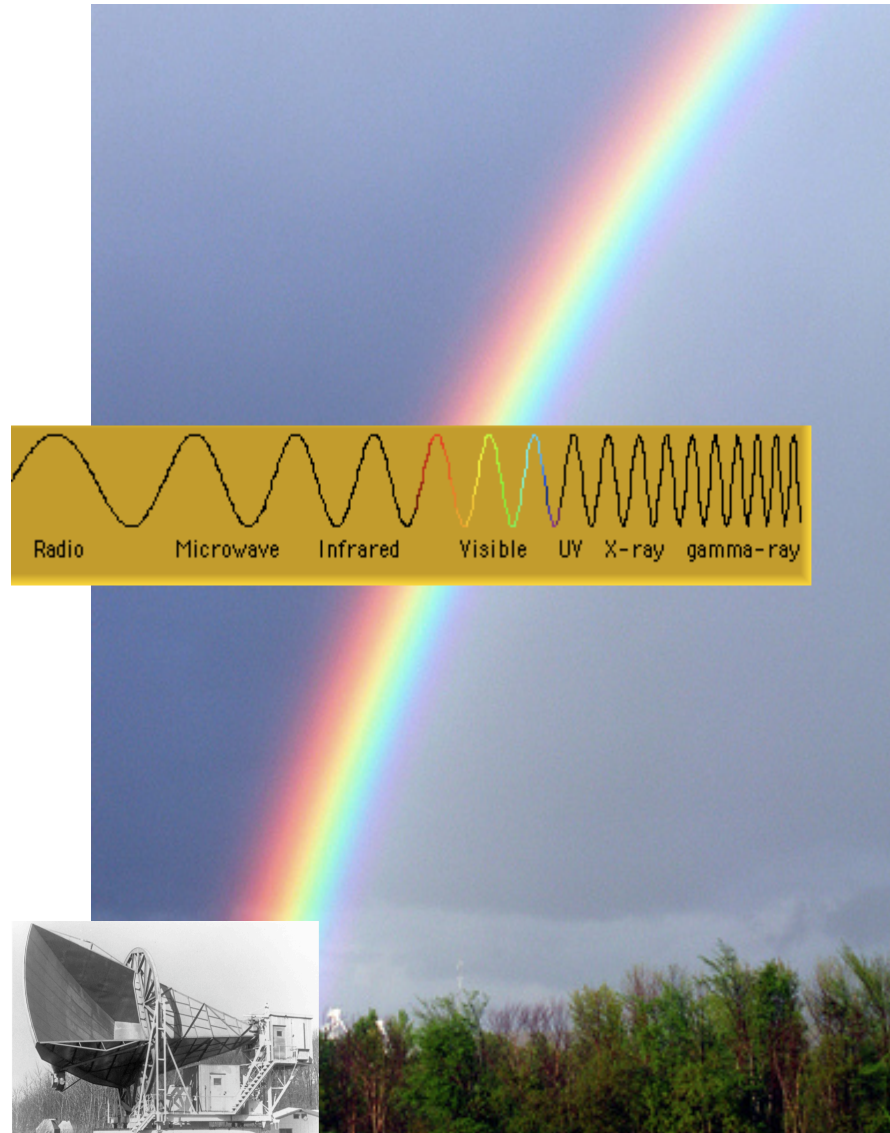
Wavelength

- The different ‘colors’ have different wavelengths.

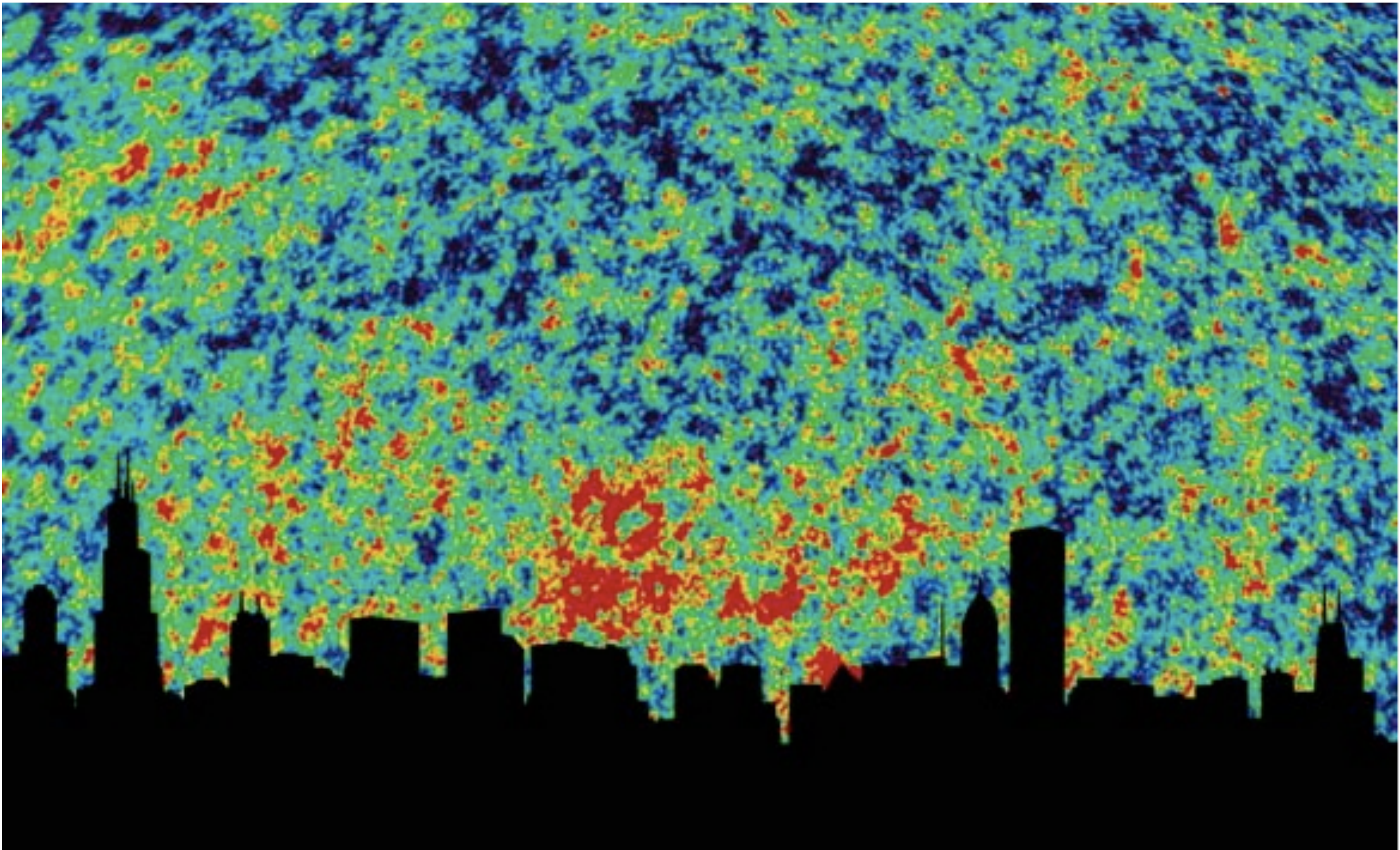


Rainbows

- The Holmdel Horn can detect long wavelengths.



This is how the sky would look if our eyes could detect microwaves.



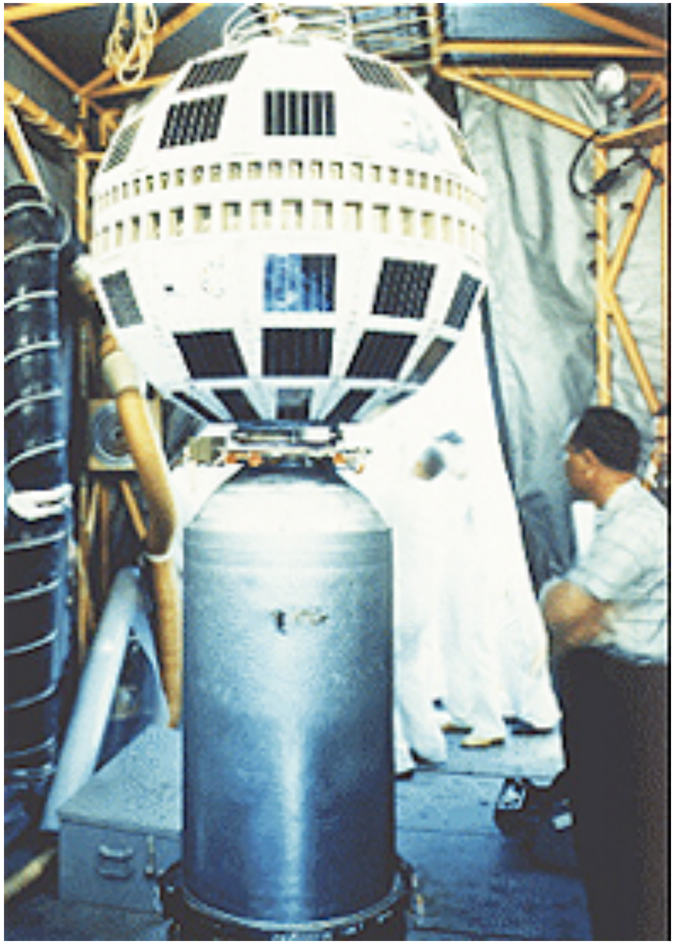
How was the microwave background discovered?

Telstar

- "Telstar" was a 1962 instrumental record performed by the British band, The Tornados.
- It was the first single by a British band to reach number one on the U.S. Billboard 100 and was also a number one hit in the UK.
- Perhaps the cover by the Ventures is better-known to Americans.

Telstar

- The record was named after the AT&T communications satellite, Telstar, which went into orbit in July, 1962.



Telstar

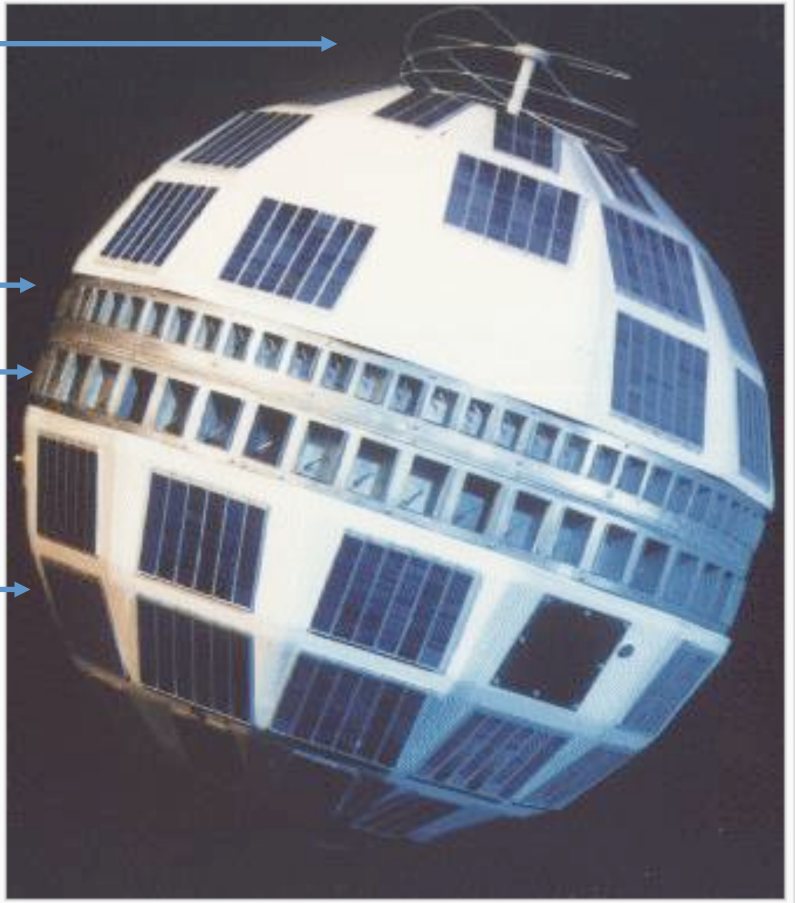
Anatomy of Telstar

Helical antenna
for telecommands from a ground station

6 GHz (5 cm) receivers

4 GHz (7 cm) transmitters

Solar panels

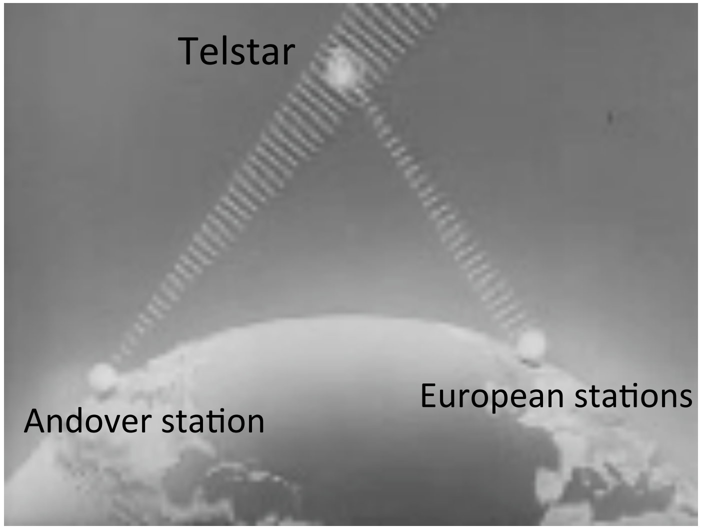


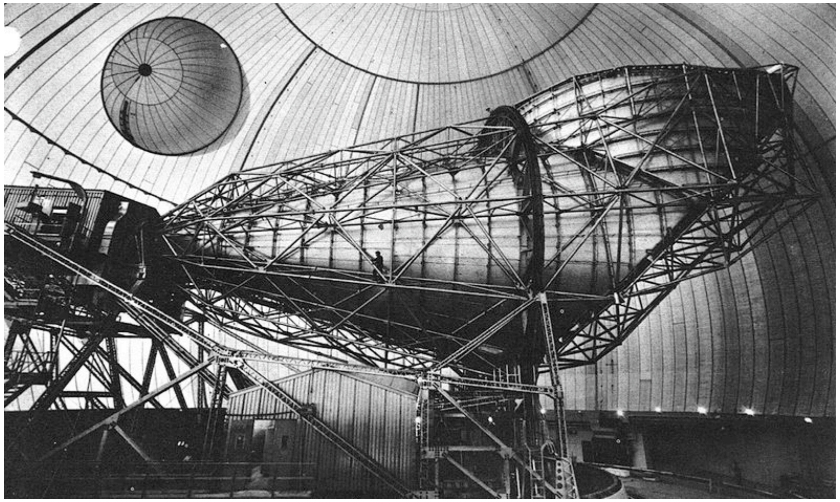
Telstar communications satellite

Holmdel horn antenna

- The primary earth station for Telstar at Andover, Maine was built by Bell Labs.

- It was on schedule, but it was feared that the European partners in the project would not be ready at launch time, leaving Andover with no one to talk to.

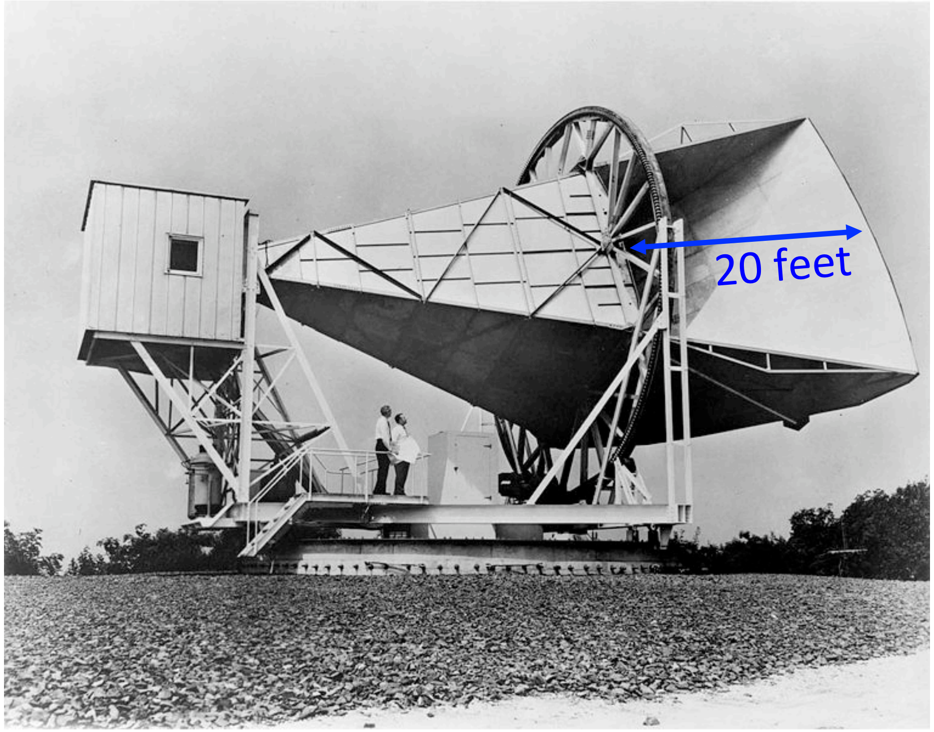




Primary earth station antenna in Andover, Maine

Holmdel horn antenna

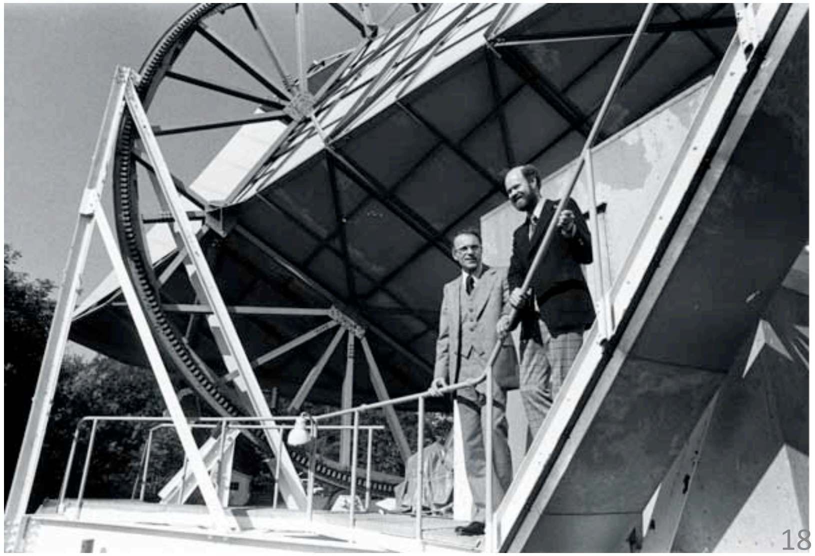
- So Bell Labs outfitted their existing 20-foot horn antenna with a 7 cm (4 GHz) receiver.



20-foot Holmdel horn antenna, Holmdel, NJ

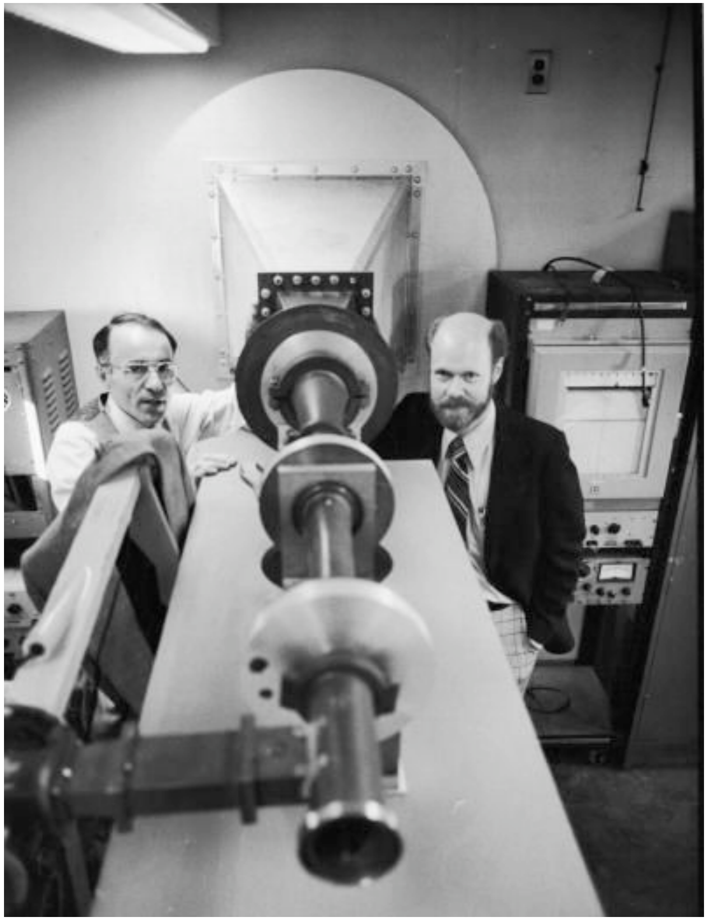
Penzias and Wilson

- As it turned out, fitting the Holmdel horn with the 7 cm (4 GHz) receiver for Telstar proved unnecessary.
- The Europeans were ready at launch time.
- This left the Holmdel Horn and its beautiful new, ultra low-noise 7 cm receiver available for radio astronomy
- Bell Lab astronomers, Arno Penzias and Robert Wilson, started preparing it for use in radio astronomy.



Penzias and Wilson

- Penzias and Wilson detected a faint background noise in all directions.
- The noise was evenly spread over the sky and was present day and night.



Low noise switching and calibration system

Temperature

- Radio astronomers like to use temperature to measure the signal from celestial sources

- And they prefer units of Kelvin!

  0 K = −273.15 °C = −459.67 °F

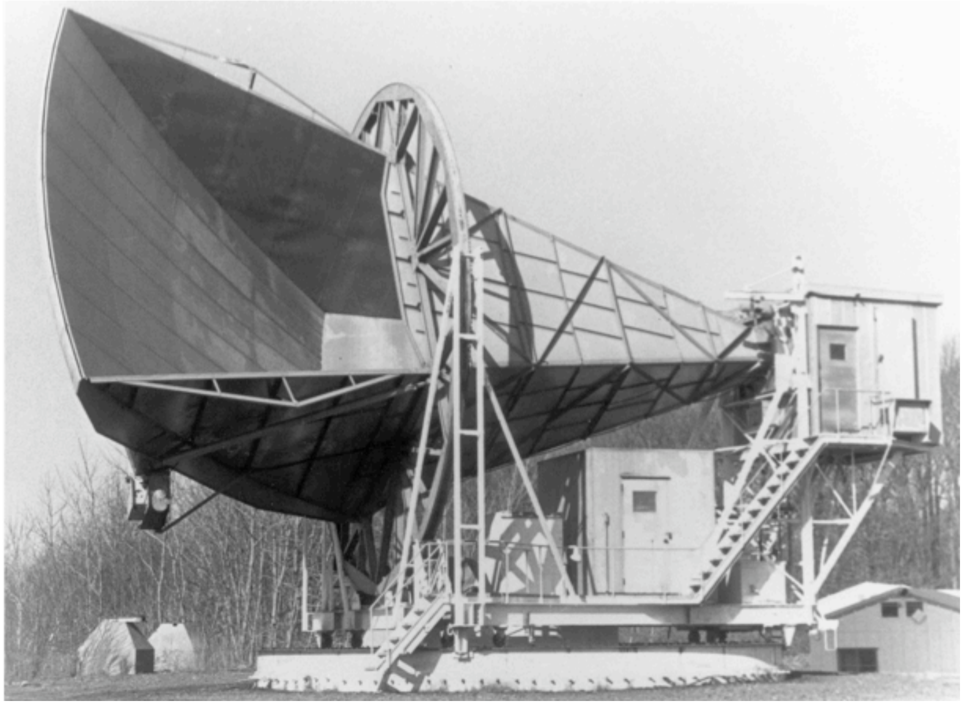
  1 K = 1 °C = 1.8 °F

Excess temperature

$$T_{atmospheric\ absorption} + T_{ohmic\ loss} + T_{back-lobe\ response} = T_{total}$$

$$2.3\ K + 0.8\ K + 0.1\ \mathrm{K} \neq 6.7\ K$$

- The total antenna temperature measured at zenith was 6.7 K
- 2.3 K is due to atmospheric noise
- 0.8 K is due to ohmic losses in the antenna
- 0.1 K is due to back-lobe response.

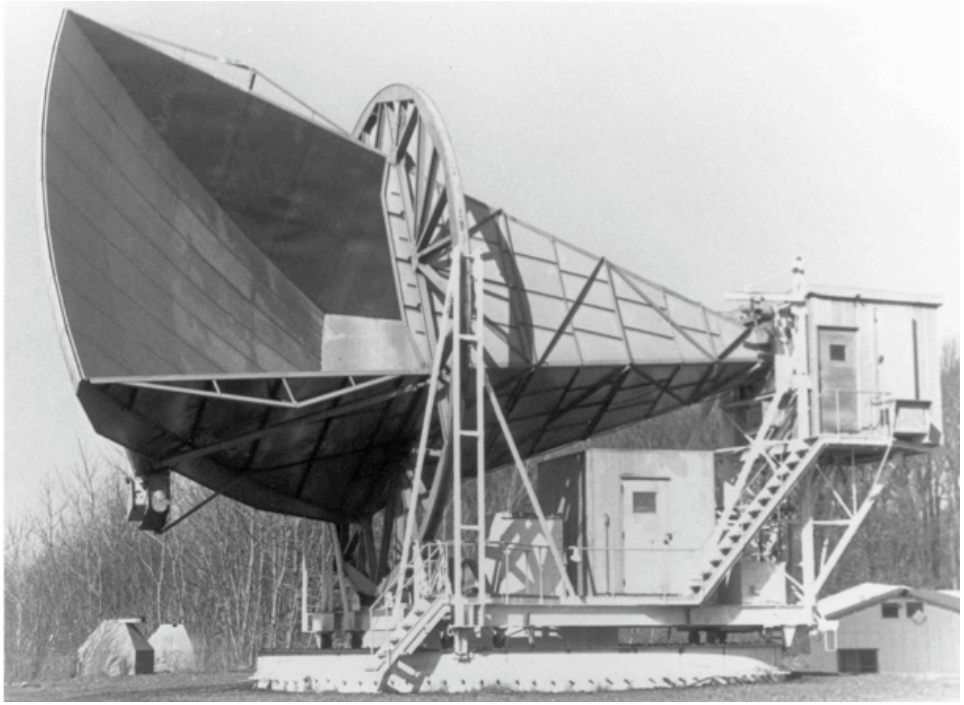


Excess temperature

$$T_{atmospheric\ absorption} + T_{ohmic\ loss} + T_{back-lobe\ response} = T_{total}$$

$$2.3\ K + 0.8\ K + 0.1\ \mathrm{K} \neq 6.7\ K$$

- The contribution from atmospheric absorption was obtained by recording the variation in antenna temperature with elevation angle and employing the secant law.
- The agreement, 2.3 +/- 0.3 K, is in good agreement with published values.

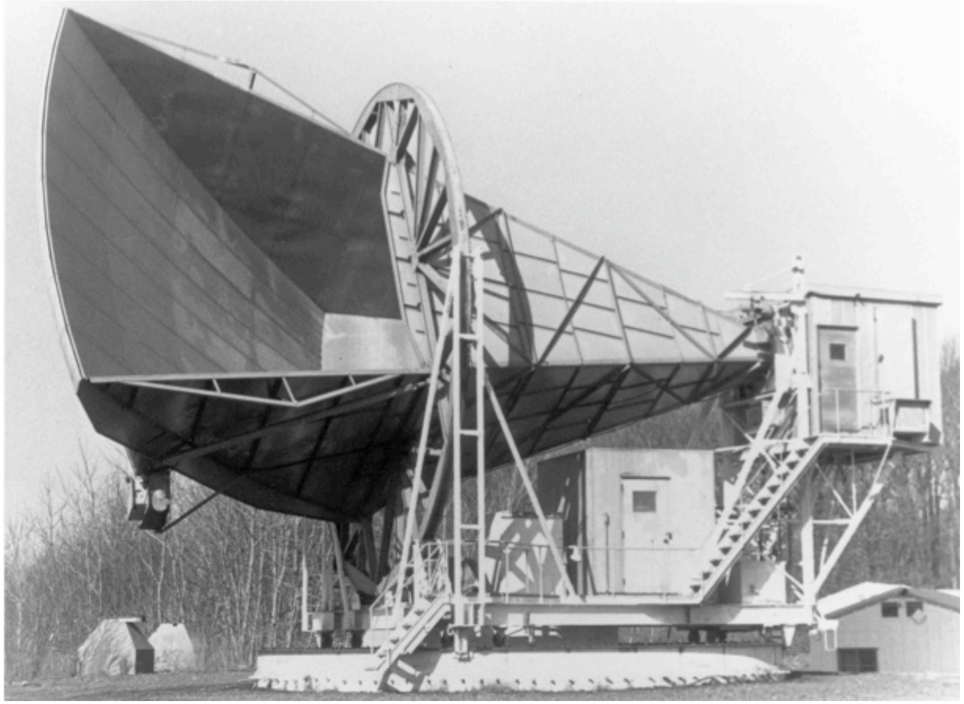


Excess temperature

$$T_{atmospheric\ absorption} + T_{ohmic\ loss} + T_{back-lobe\ response} = T_{total}$$

$$2.3\ K + 0.8\ K + 0.1\ \mathrm{K} \neq 6.7\ K$$

- The contribution for ohmic losses was computed to be 0.8 +/- 0.4 K
  - Tapers,
  - Rotary joint
  - Antenna itself
    - Taped seams with Al tape caused no change



Excess temperature

$$T_{atmospheric\ absorption} + T_{ohmic\ loss} + T_{back-lobe\ response} = T_{total}$$

$$2.3\ K + 0.8\ K + 0.1\ \mathrm{K} \neq 6.7\ K$$

- The back-lobe response to ground radiation was less than 0.1 K.

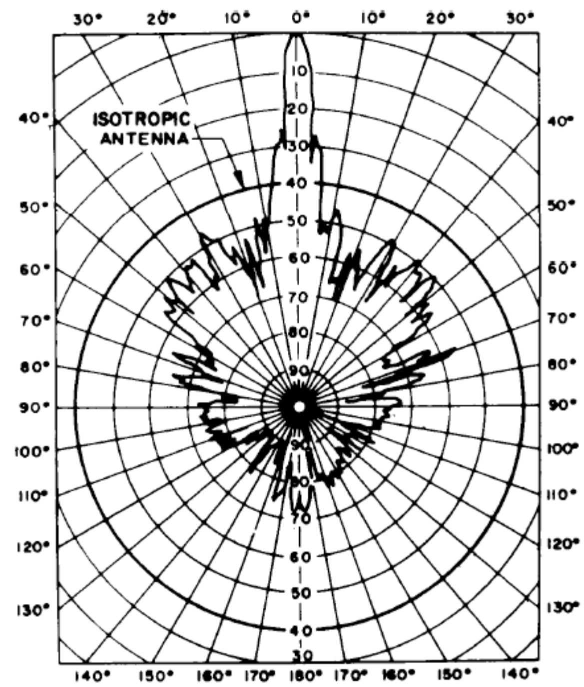


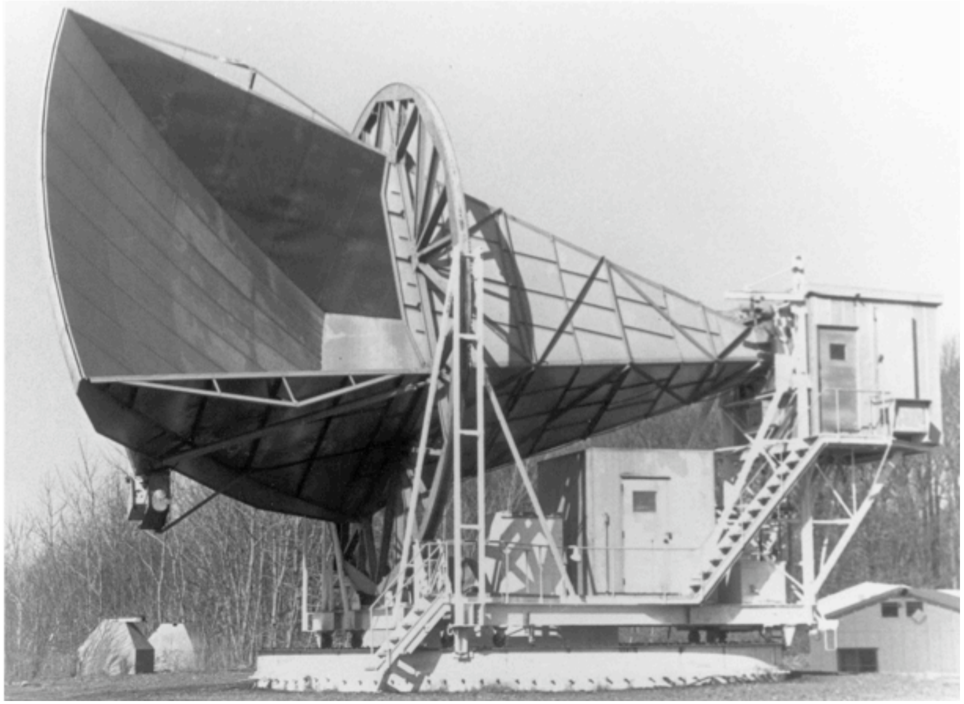
Fig. 2 Sensitivity pattern of a small horn-reflector antenna. This is a logarithmic plot of the collecting area of the antenna as a function of angle from the center of the main beam. Each circle below the level of the main beam represent a factor of ten reduction in sensitivity. In the back direction around 180 the sensitivity is consistently within the circle marked 70, corresponding to a factor of 10^7 below the sensitivity at 0.

3.5 K excess temperature

$$T_{atmospheric\ absorption} + T_{ohmic\ loss} + T_{back-lobe\ response} = T_{total}$$

$$2.3\ K + 0.8\ K + 0.1\ \mathrm{K} \neq 6.7\ K$$

- From a combination of the above, Penzias and Wilson computed the remaining unaccounted-for antenna temperature to be 3.5 +/- 1.0 K.

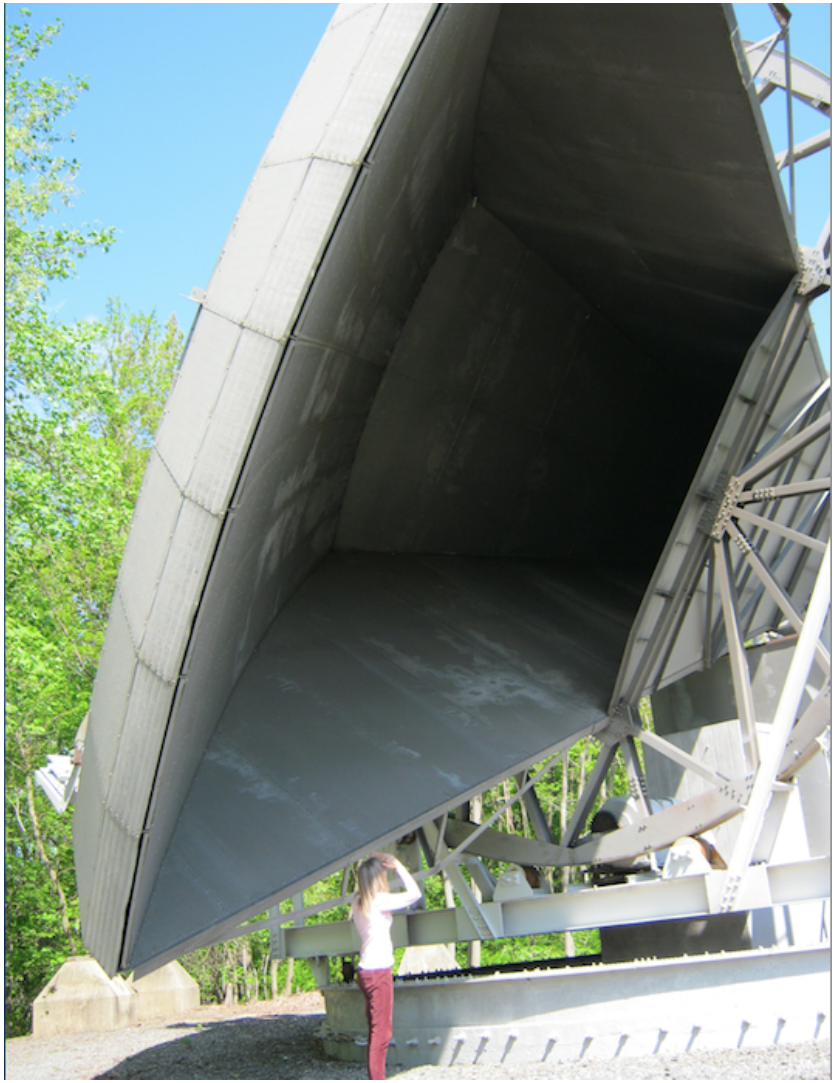


Penzias and Wilson

- They checked and eliminated all the sources of noise they could think of, including cleaning the pigeon droppings inside the horn from birds that had roosted in the antenna.

View from inside the 20-foot Holmdel horn
Cleaning the antenna

I checked, too.



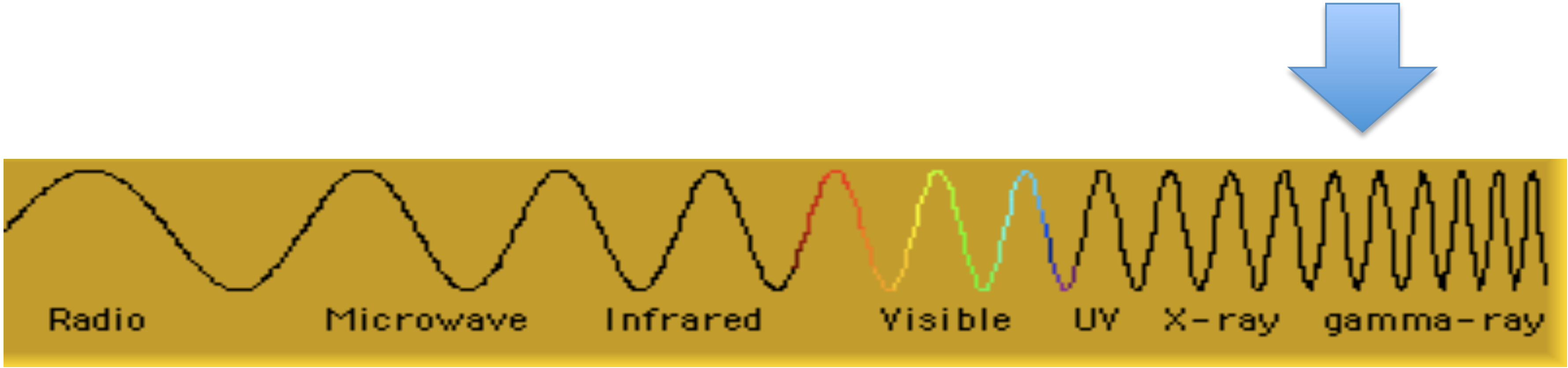
Penzias and Wilson

- They considered man-made noise being picked up by the antenna but when they pointed it at New York City, or to any other direction on the horizon, the antenna temperature did not increase above the thermal temperature of the earth.
- They ruled out galactic and extra galactic radio sources.
- A year passed (July, 1964 – April, 1965) and the extra noise had not changed. Therefore they could rule out seasonal variations.

Evidence for the Big Bang

- They then learned that a group at Princeton was investigating the implications of an oscillating universe with an extremely hot condensed phase which could explain the origin of the extra 3.5 K they detected.

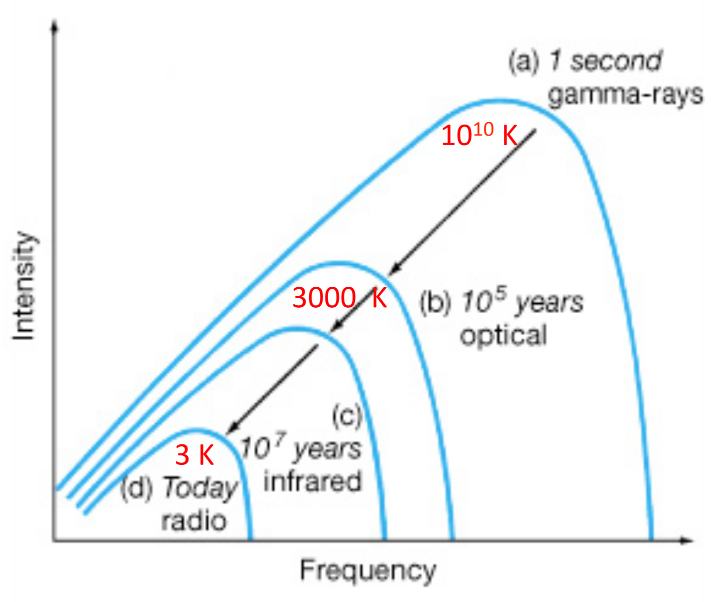
- If there was a Big Bang, the universe immediately following would have been very hot, $>10^{32}$ K, corresponding to short, gamma ray wavelengths.



Black body spectrum

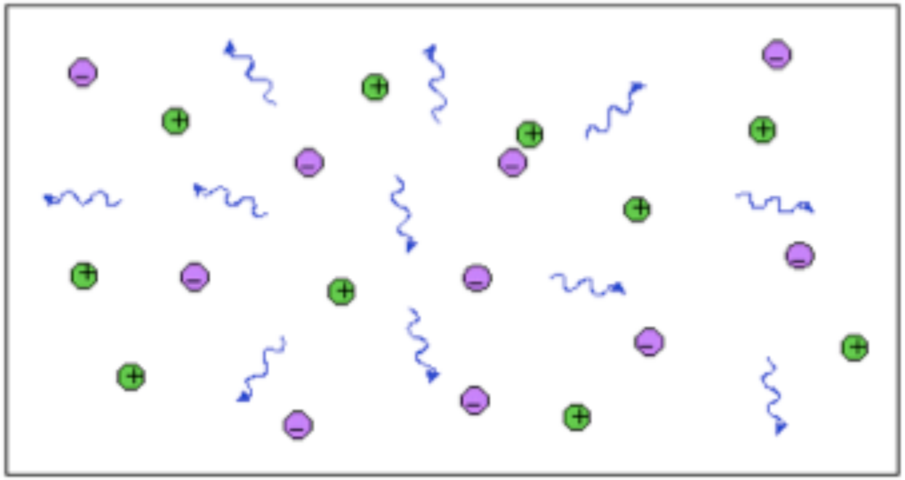
- The photons (radiation) and electrons and protons (matter) were in thermodynamic equilibrium
- A blackbody spectrum emerges from a system thermodynamic equilibrium.

$$\text{Intensity} = \frac{2hf^3}{c^2}\frac{1}{e^{hf/kT}-1}$$



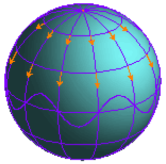
Decoupling and recombination

- Temperatures were so high, photons had enough energy to prevent electrons and protons forming hydrogen.
- The photons scattered off the charged particles in all directions, making the universe opaque.



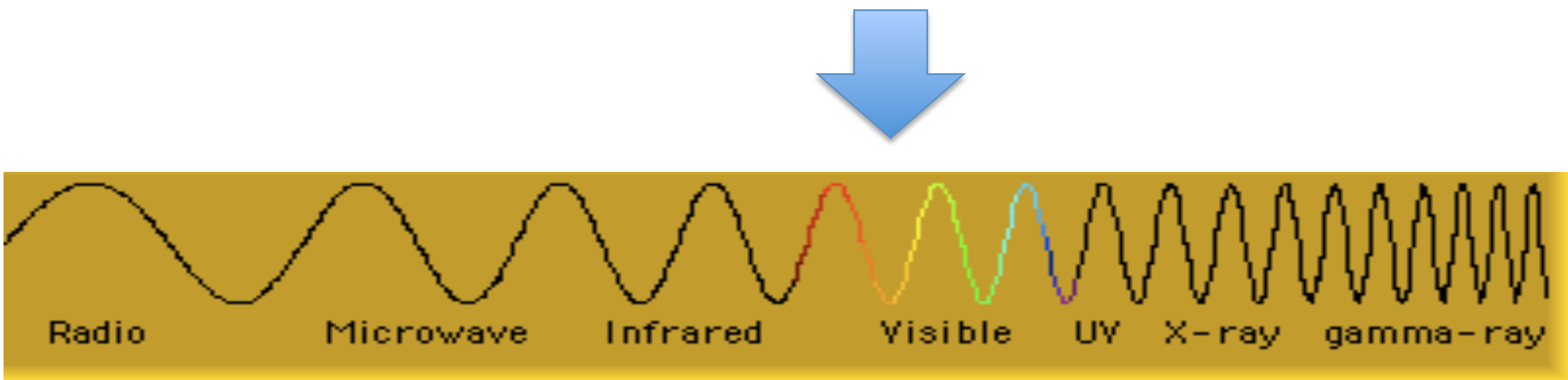
Cosmological redshift

- As the universe expanded, it cooled:
- The Cosmological Redshift is a redshift caused by the expansion of space.
- The wavelength of light increases as it traverses the expanding universe between its point of emission and its point of detection by the same amount that space has expanded during its travel.
- As the wavelength, λ, increases, the energy, E, decreases: $E = \frac{hc}{\lambda}$



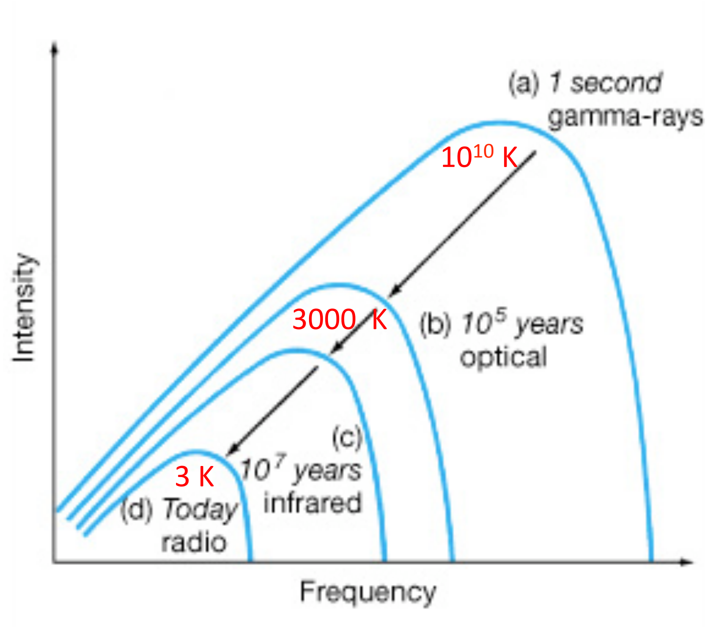
Decoupling and recombination

- As the universe expanded, it cooled.
- When it reached about 3000 K, the average energy of the photons was decreased to the point where they could no longer ionize hydrogen. This is called decoupling.
- 3000 K corresponds to optical wavelengths.



Decoupling and recombination

- The collisions with electrons before last scattering ensured that the photons were still in equilibrium.
- That is, they should still have a blackbody spectrum.

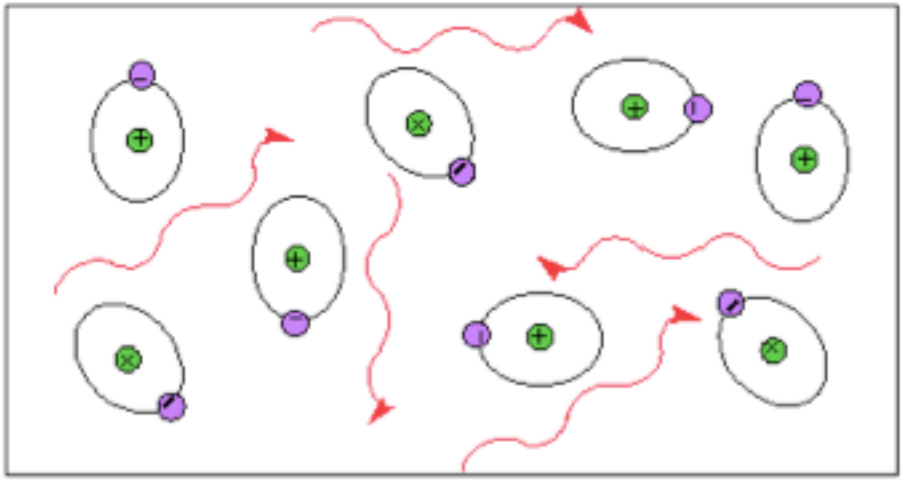


Decoupling and recombination

- Protons and electrons could now combine to form hydrogen and the light was no longer scattered. This is called recombination.

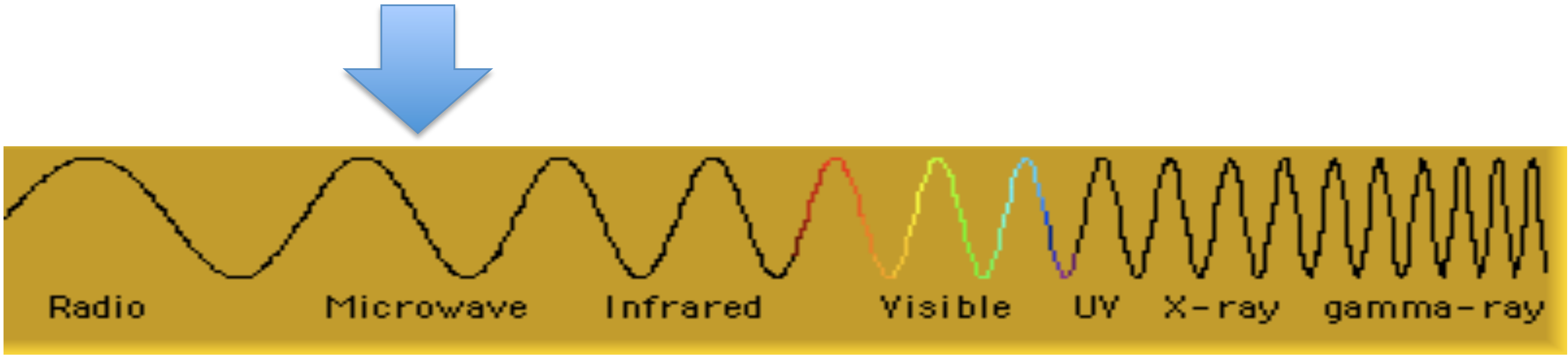
- Now photons could travel long distances without colliding with and ionizing hydrogen atoms.

- These are the photons we see as the CMB!



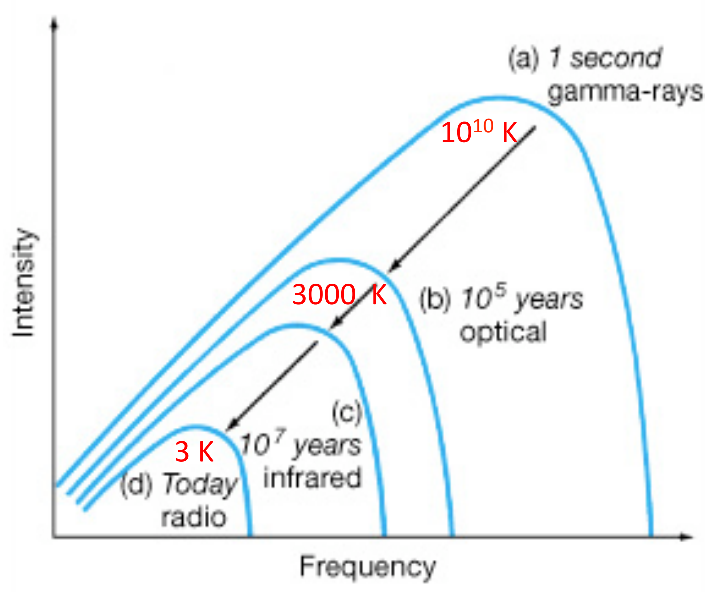
Penzias and Wilson

- The Universe was only about 350,000 years old at the time.
- As the photons travelled, the Universe continued to expand and cool (via the cosmological redshift) until they are detected on Earth today at a temperature a little below 3K.
- This corresponds to microwave wavelengths.



Cosmic Microwave Background

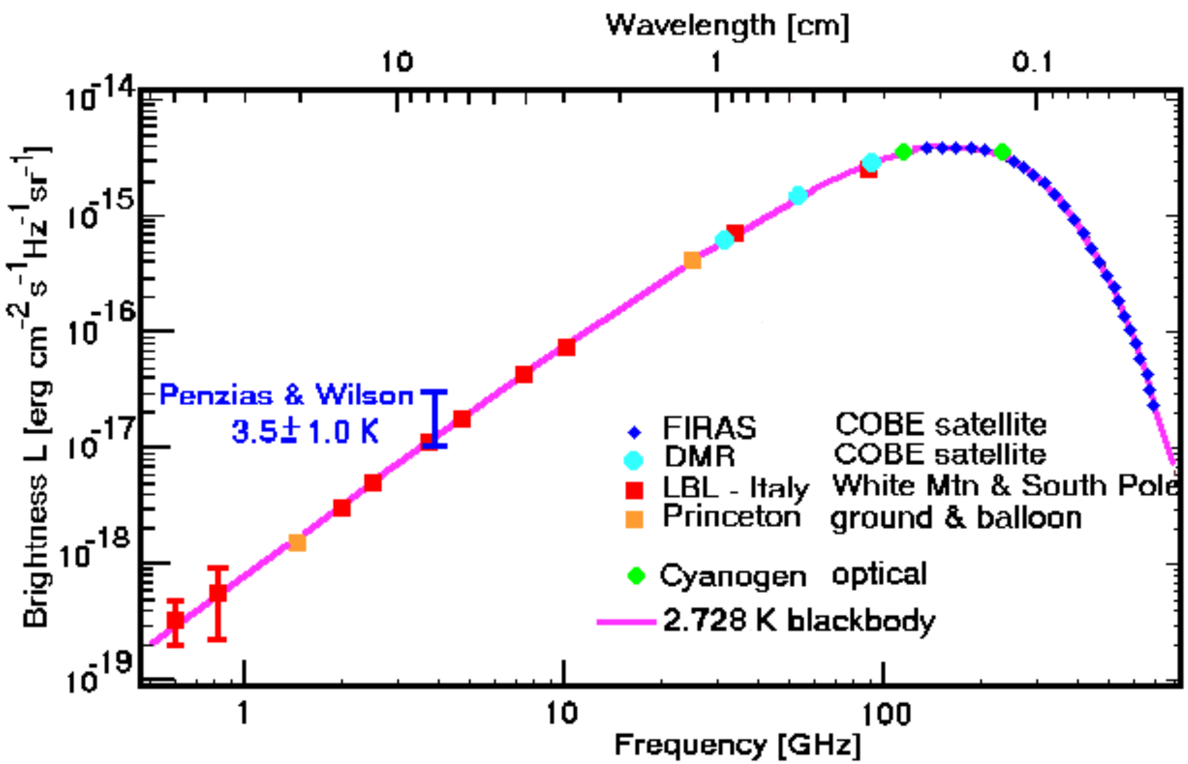
- The 3000 K temperature at decoupling corresponds to the peak microwave wavelength of ~0.001 mm.
- The universe is about 1000 times larger now, so the wavelength is about 1000 times longer (1.86 mm).
- The black body curve corresponding to Penzias and Wilson's detection peaks at 1.86 mm!



Discovery of the CMB

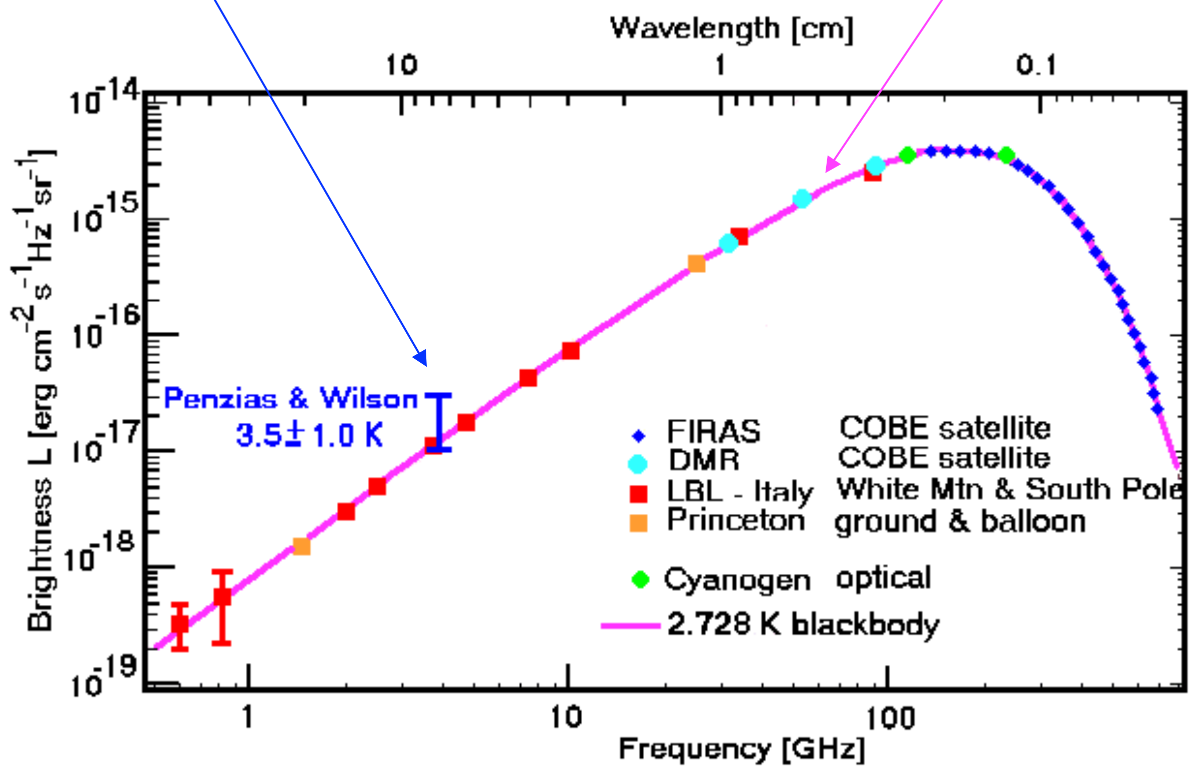
- Penzias and Wilson's measurement was at 4 GHz, since that was Telstar's transmitting frequency!

- Their data point was not at the peak of the black body curve, but *only one point is needed to determine the temperature of a black body curve.*



Discovery of the CMB

- The Princeton scientists visited Penzias and Wilson and were quickly convinced of the accuracy of their measurements.
- Their data point (and many others since then) fit the theoretical curve for a 2.728 K black body!



Penzias and Wilson

- They all agreed to a side-by-side publication of two letters in the *Astrophysical Journal* – a letter on the theory from Princeton and one on Penzias and Wilson's measurements.

- Penzias and Wilson received the Nobel Prize in 1978 for their work.

Why is it called
“Cosmic Microwave Background?

Cosmic

- Cosmic indicates that it comes from outer space, from the cosmos.

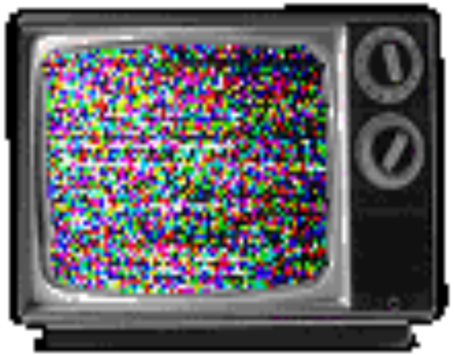
Microwave

- Because of the expansion of the universe, the CMB which was at 3000 K at decoupling is very cold now: ~3 degrees above absolute zero.

- Its wavelength has been stretched out of the visible into the range of microwaves.

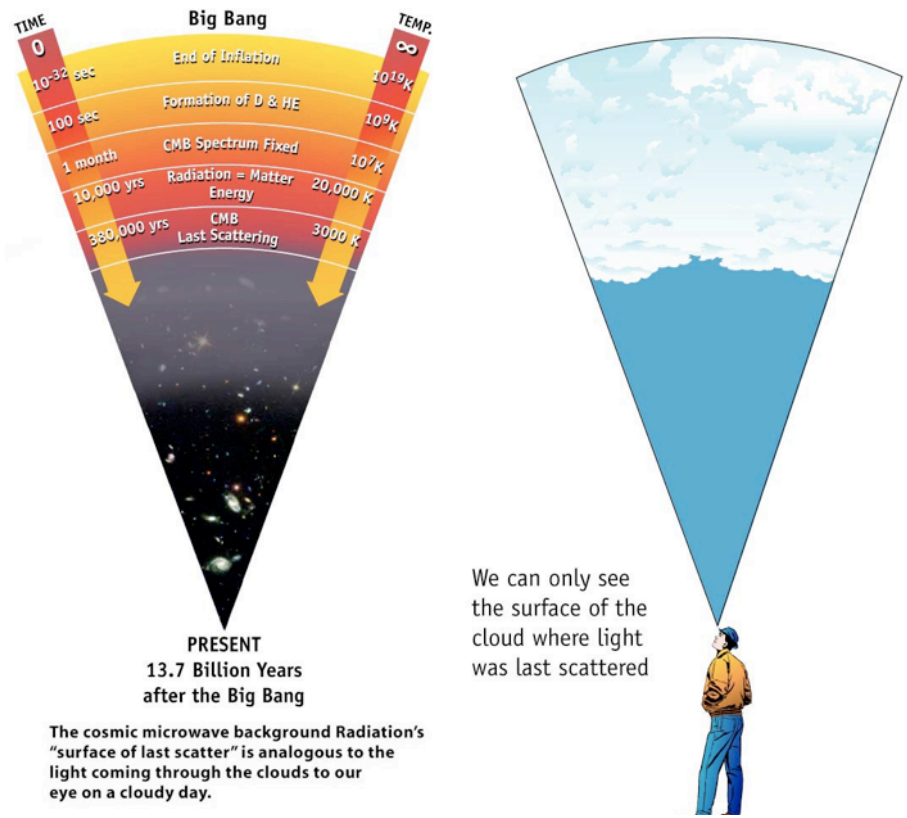
Microwave

- There are quite a few photons in the microwave background: about 400 per cubic centimeter.
- TV waves are in the same frequency range as the CMB.
- A few percent of the TV "snow" you see between channels comes from the microwave background.



Background

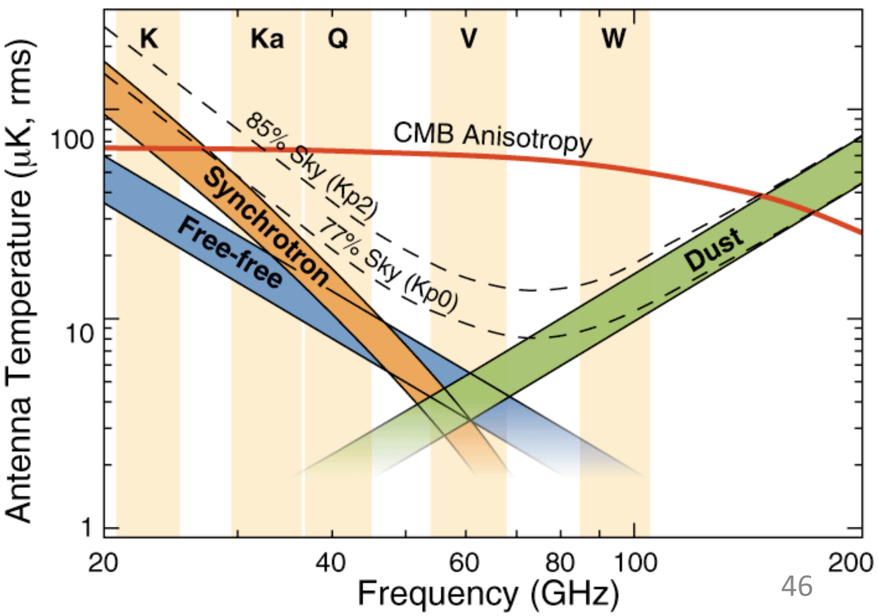
- Background means that the light comes from all parts of the sky and is not produced by any source in the "foreground" (for example, stars, galaxies, or Earth's atmosphere).



The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

Foreground

- Galactic foreground signals are distinguishable from CMB anisotropy by their differing spectra and spatial distributions.
- Multiple frequency coverage is needed to reliably separate Galactic foreground signals from CMB anisotropy.
- For example, WMAP observes with five frequency bands between 22 GHz and 90 GHz.
- Planck observes with nine bands from 9 GHz to 857 GHz.
- Some say even more bands are needed.
- Note it's not necessarily best to observe where signal is maximum!

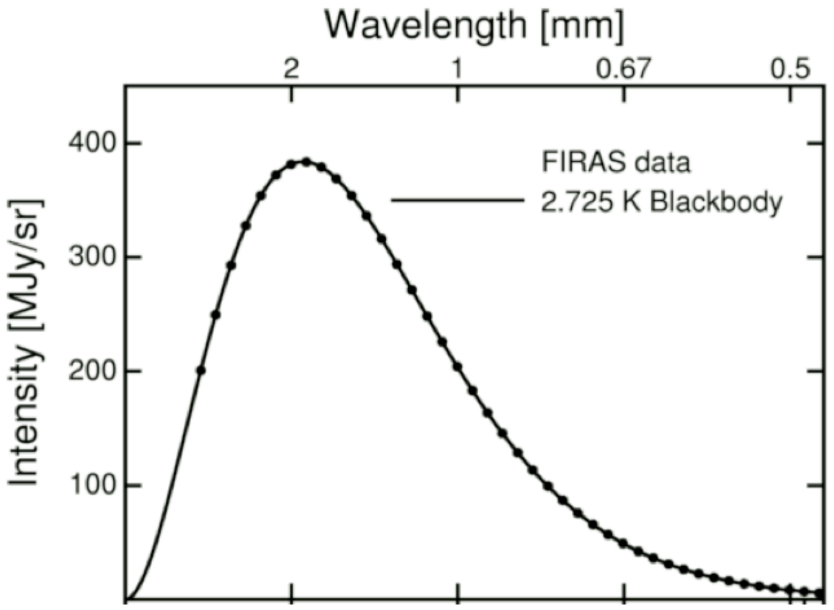


What can we learn from the CMB?

What can we learn from the frequency spectrum?

- That the CMB has *such a precise blackbody spectrum*, is evidence that it came from time when it was much hotter and denser than it is now.

- Hence the CMB spectrum is strong evidence that the Universe experienced a "hot Big Bang" stage.

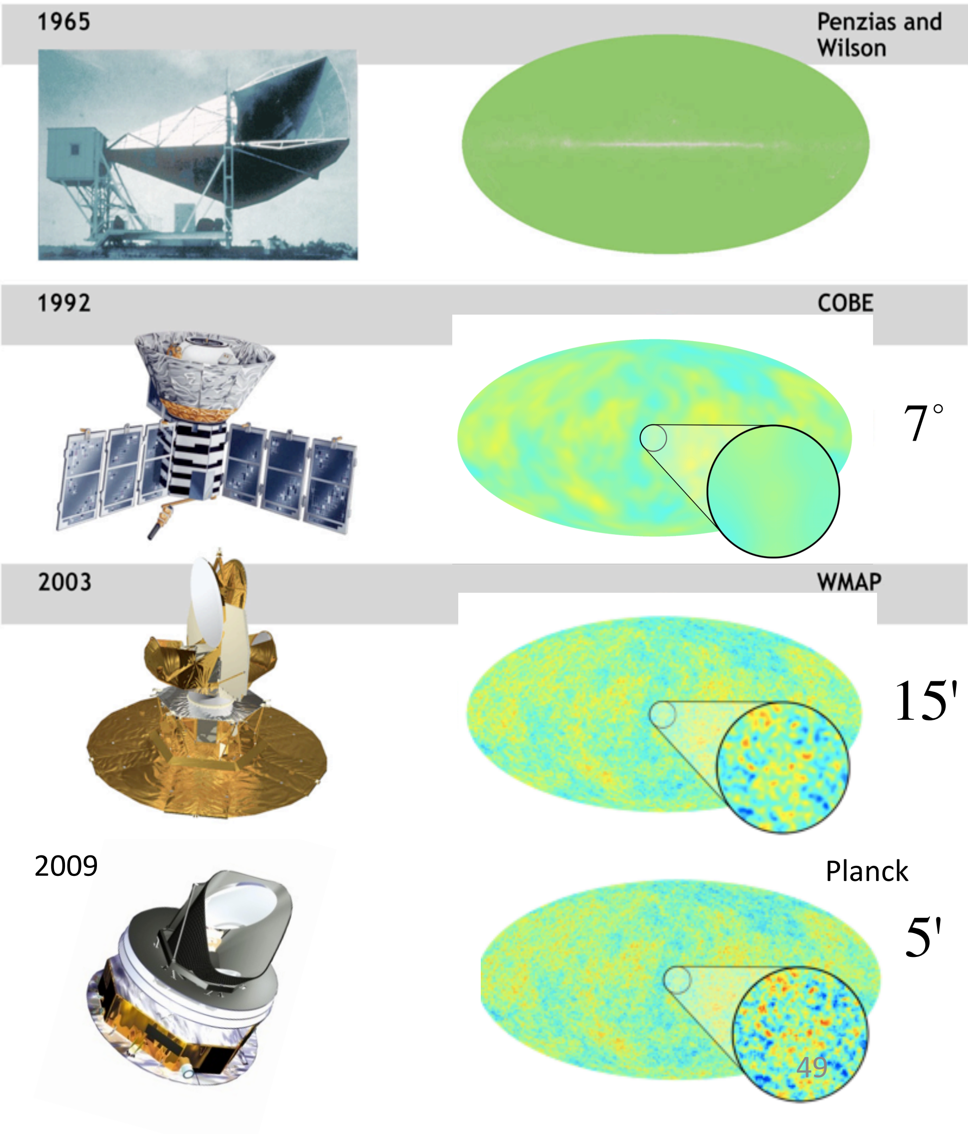


CMB spectrum

Temperature anisotropies

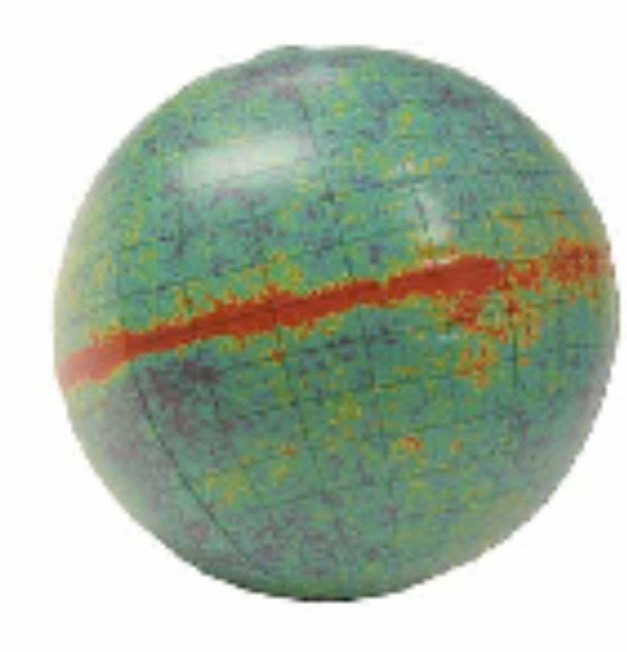
- As the resolution of telescopes looking at the CMB got higher, it was seen that the CMB was not completely smooth.

- The colors indicate temperature variations: red for hotter, blue for cooler.



Temperature anisotropies

- The 12 inch ball represents the distance light has been able to travel in the nearly 13.7 billion years since the matter of the universe cooled to less than 3000 K
- We are at the center of this bubble of light, but many more times this volume of space exists outside this bubble, we just can not yet see its light.
- Every year the bubble of the observable universe grows a little larger as new light reaches our eyes

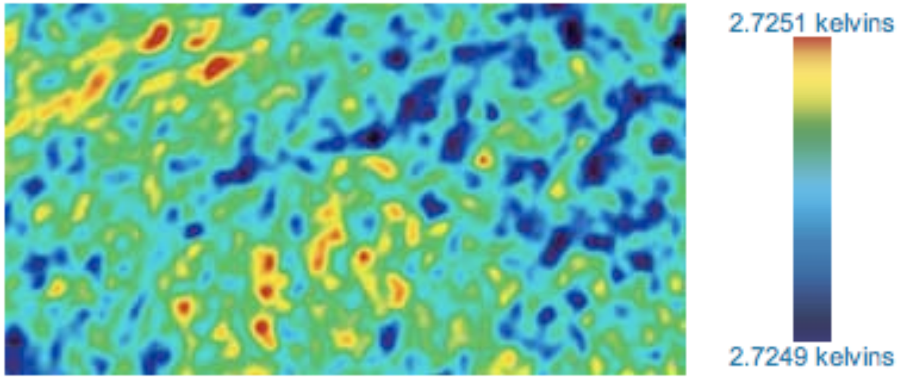


Temperature anisotropy

- These slight variations of temperature were caused by slight variations in the density of the matter from which the light was last scattered.

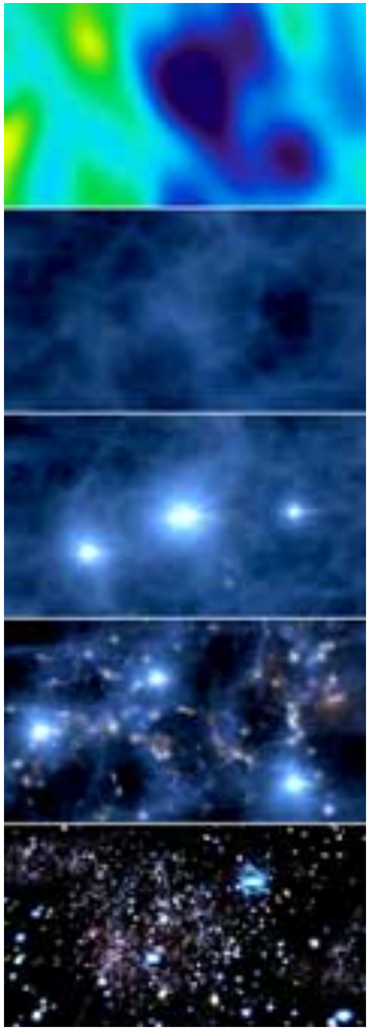
- Photons, electrons, and protons behave like a single fluid before the epoch of last scatter.

- Regions where the density of protons and electrons are higher than average will also be a region where the photon density is higher, and vice-versa.



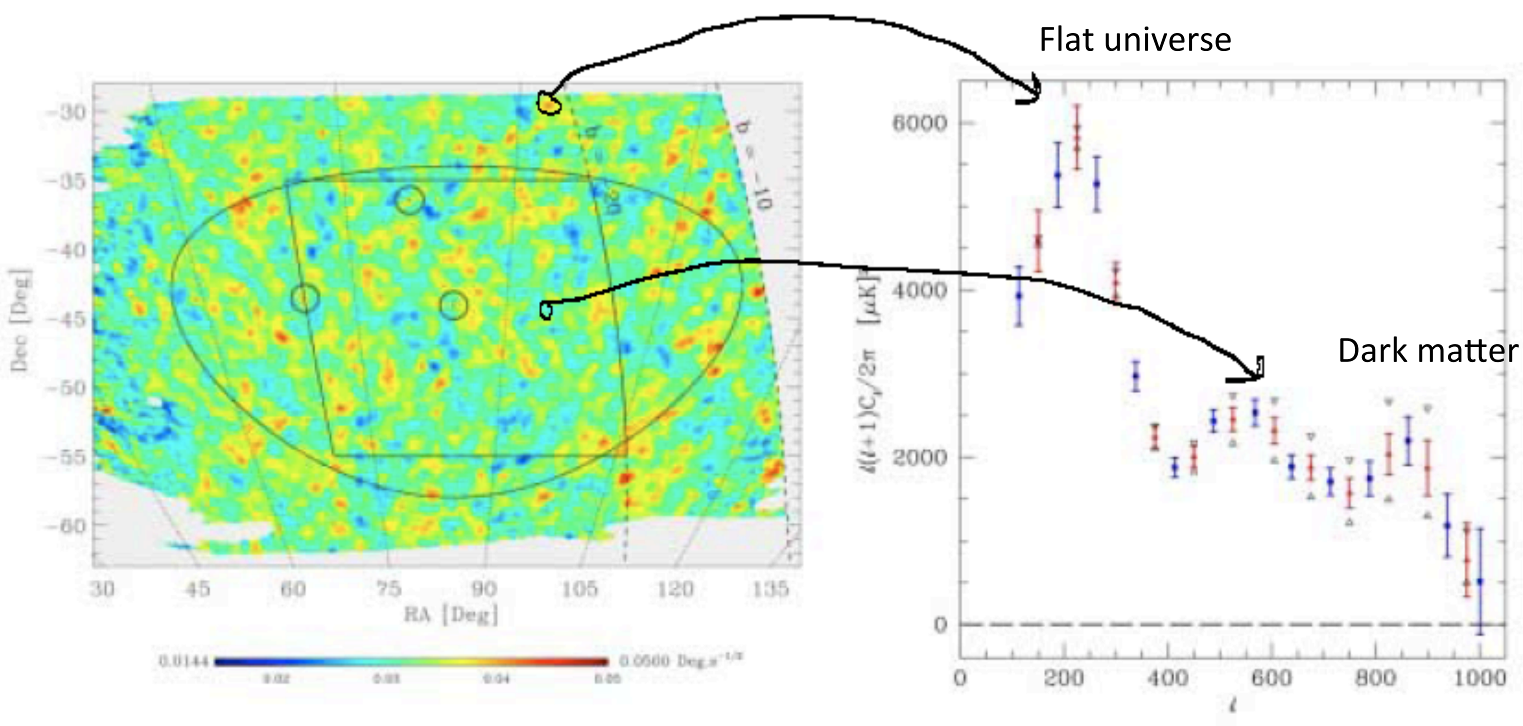
Temperature anisotropy

- It's believed that the 13 billion+ year old temperature fluctuations correspond to the seeds that grew to become the galaxies and clusters we see today.



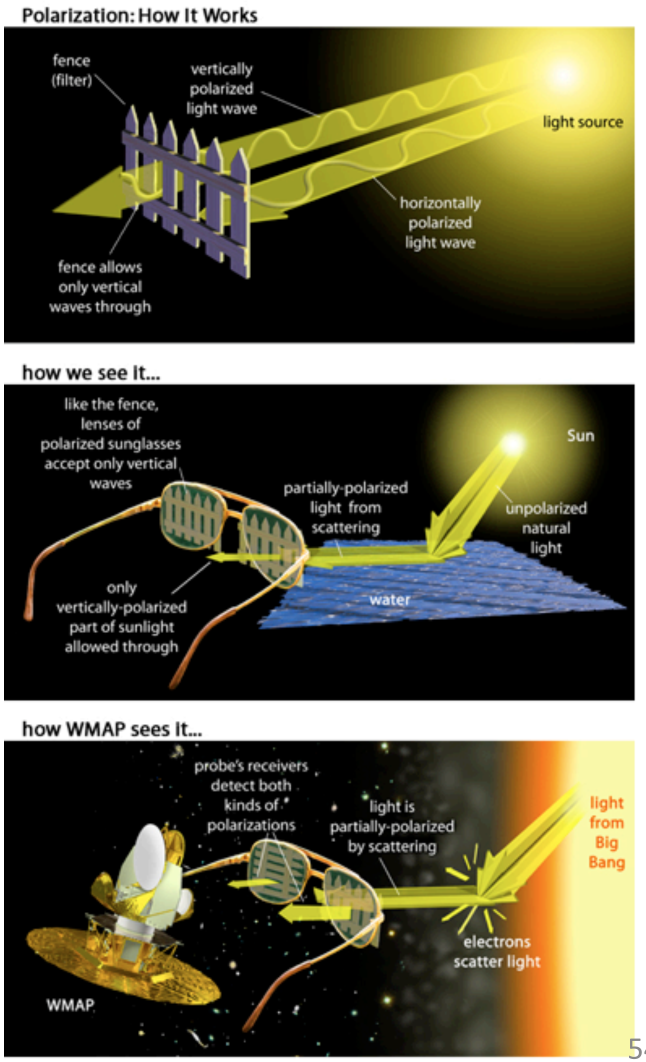
What can we learn from the temperature anisotropy

- From the sizes of the hot and cold spots, scientists can calculate fundamental values for the shape, size, age, content, rate of expansion (and more) of our universe.



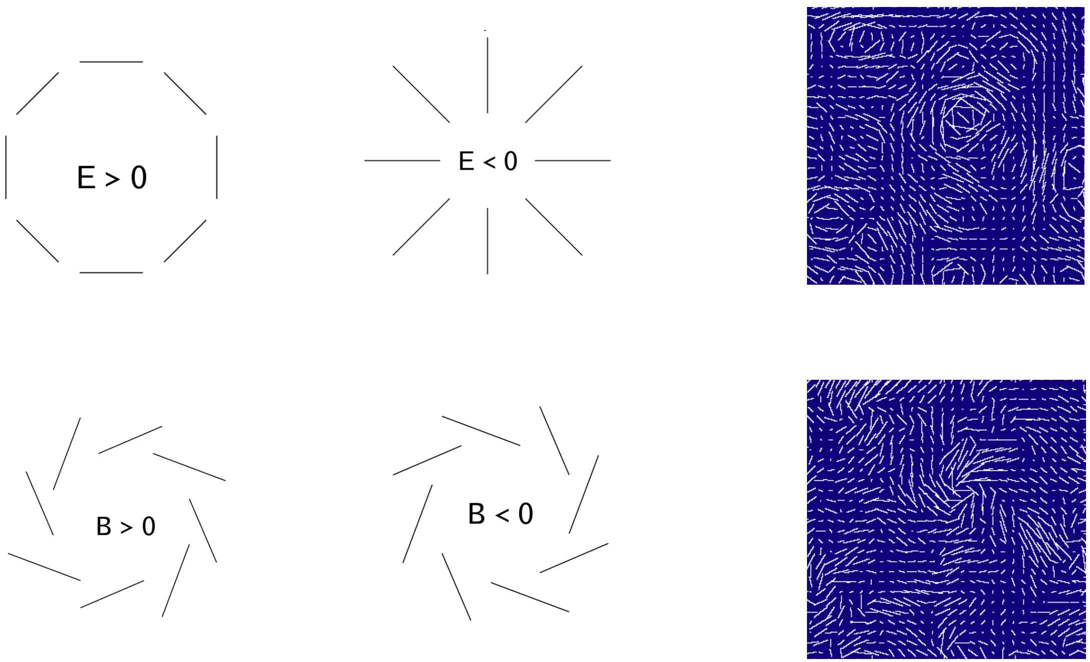
Polarization

- The CMB fluctuations are partially polarized.
- We can detect the polarization of the CMB in a way analogous to the way we detect polarization of optical light.



E modes and B modes

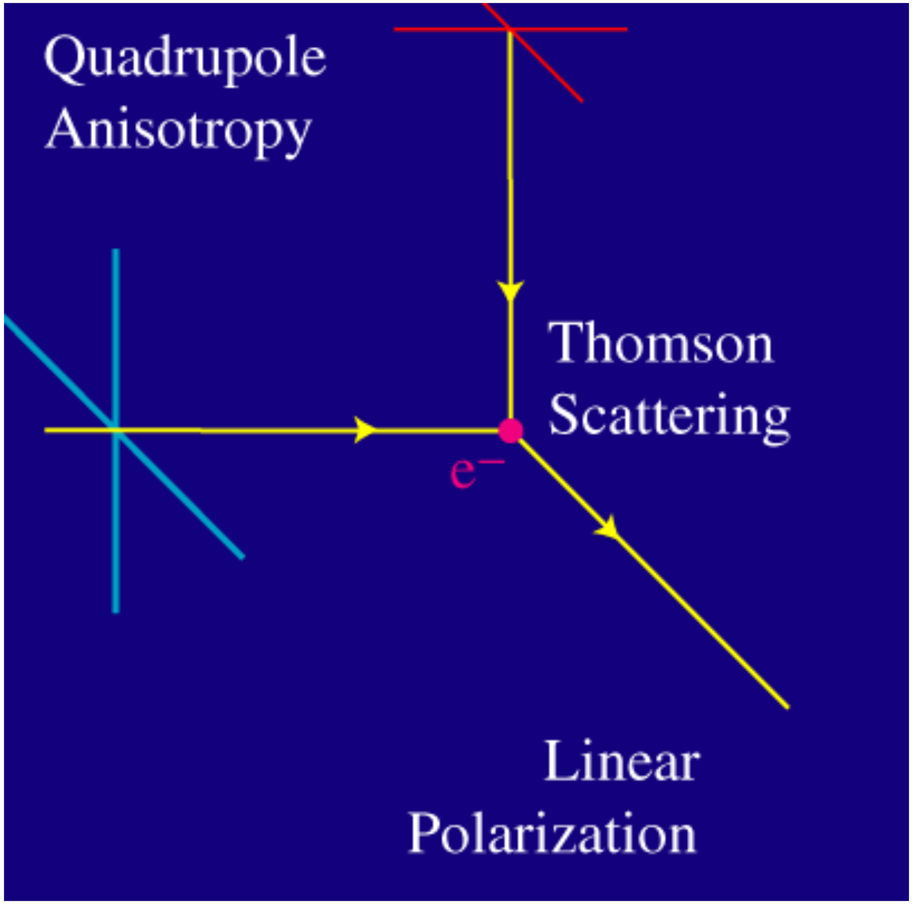
- There are 2 types of polarization patterns: E modes and B modes
- Dynamics due to density inhomogeneities in the early universe -> E modes
- Gravity waves -> B modes
- E modes can be gravitationally lensed into B modes
  - (Just to make things even more interesting!)



How do E modes get generated?

Cooler, less dense
Fewer photons

Hotter, denser
More photons



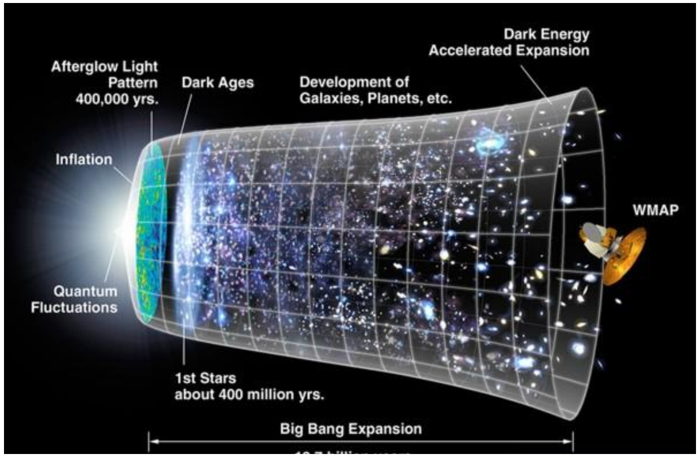
Results in net
vertical polarization

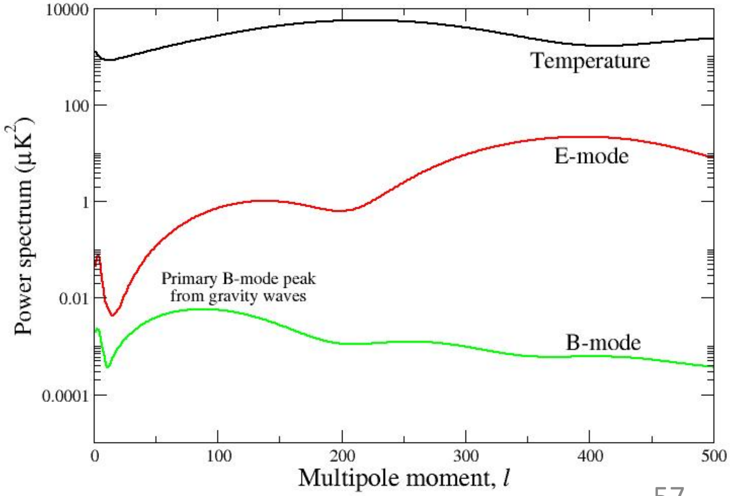
What can we learn from polarization of the CMB?

- Predictions from inflation:
  - Flat universe
  - Gaussian fluctuations
  - Gravity waves

- The first appear to be true by WMAP

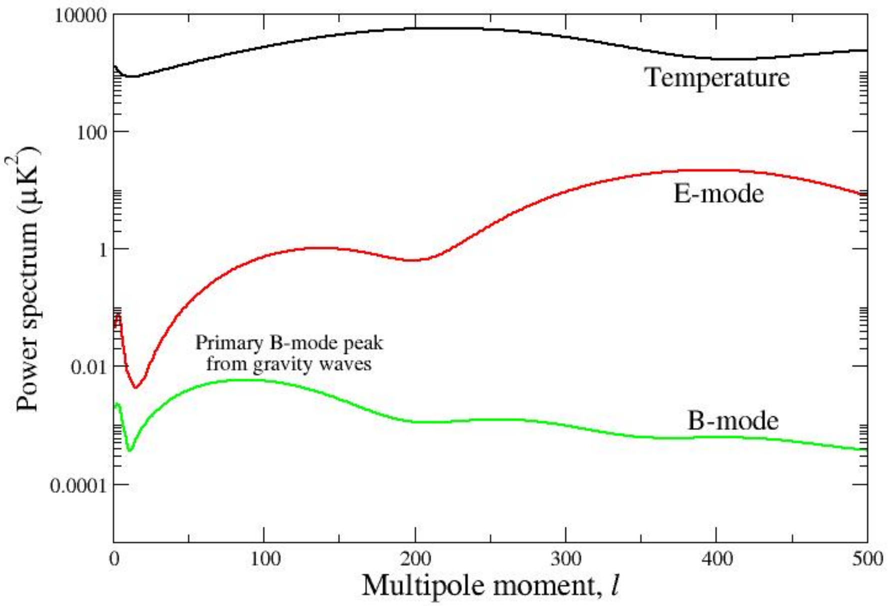
- Detection of B-modes would be a strong confirmation of inflation!





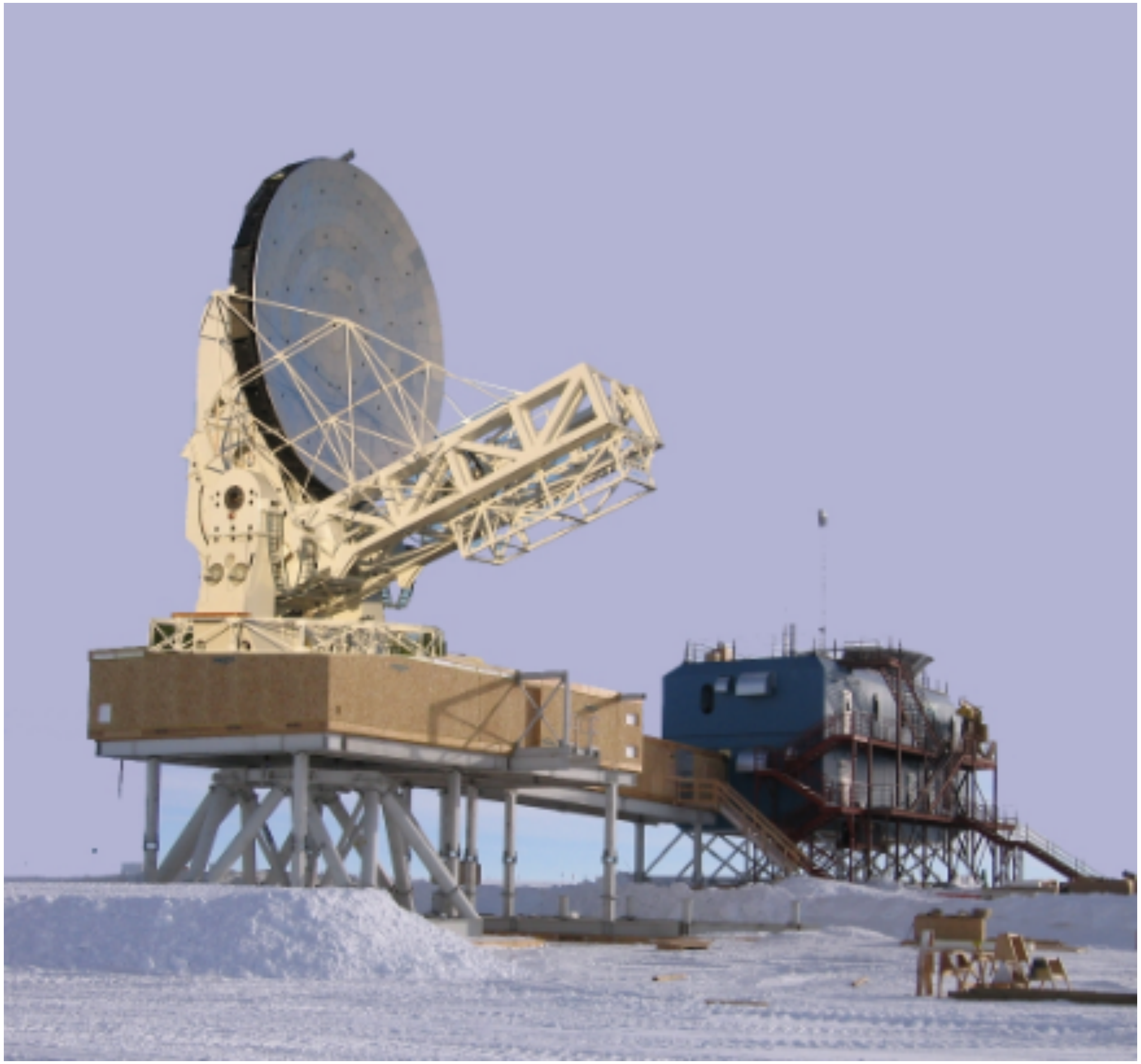
Polarization of the CMB is a field rich for study in the 21st century!

- Anisotropies in the temperature of the CMB were discovered back in the 20th century but E modes weren't detected until 2002.
- The E mode polarized component is orders of magnitude smaller than the CMB temperature and the B modes are smaller still.
- Polarization of the CMB is a field rich for study in 21st century!



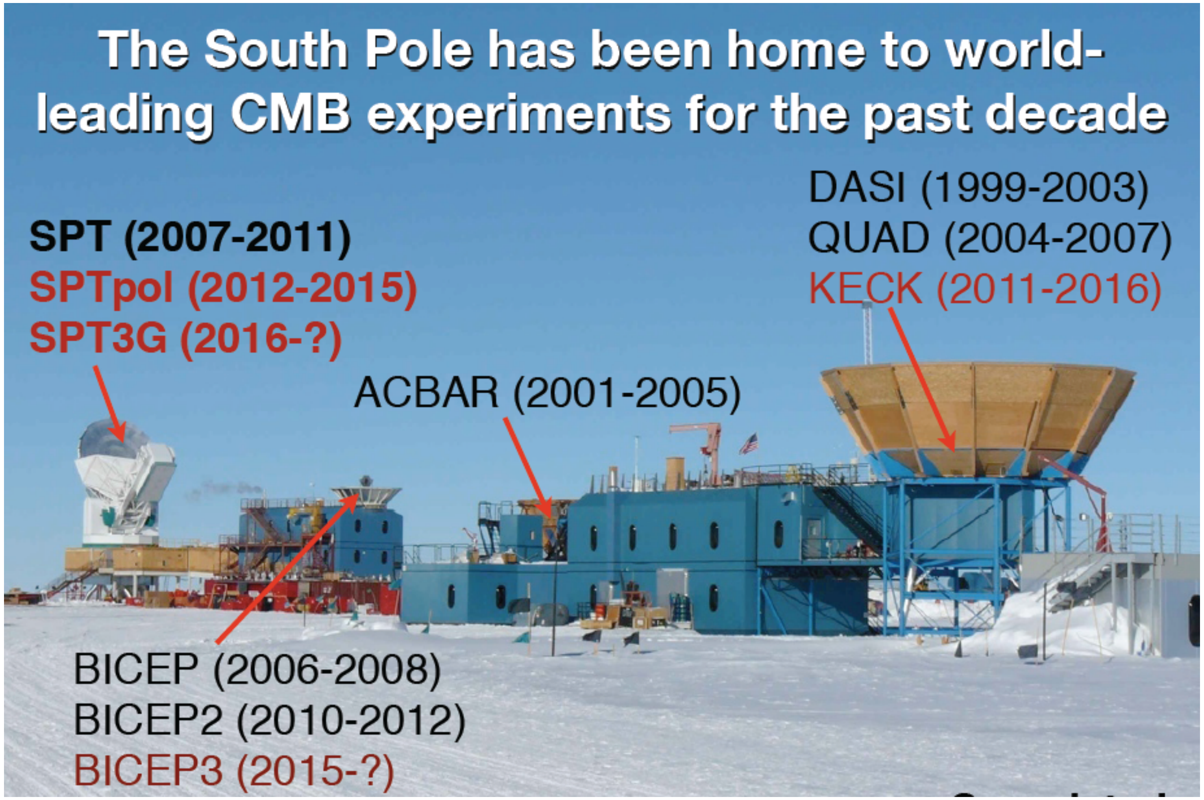
What do I work on at Fermilab that has to do with the CMB?

The South Pole Telescope



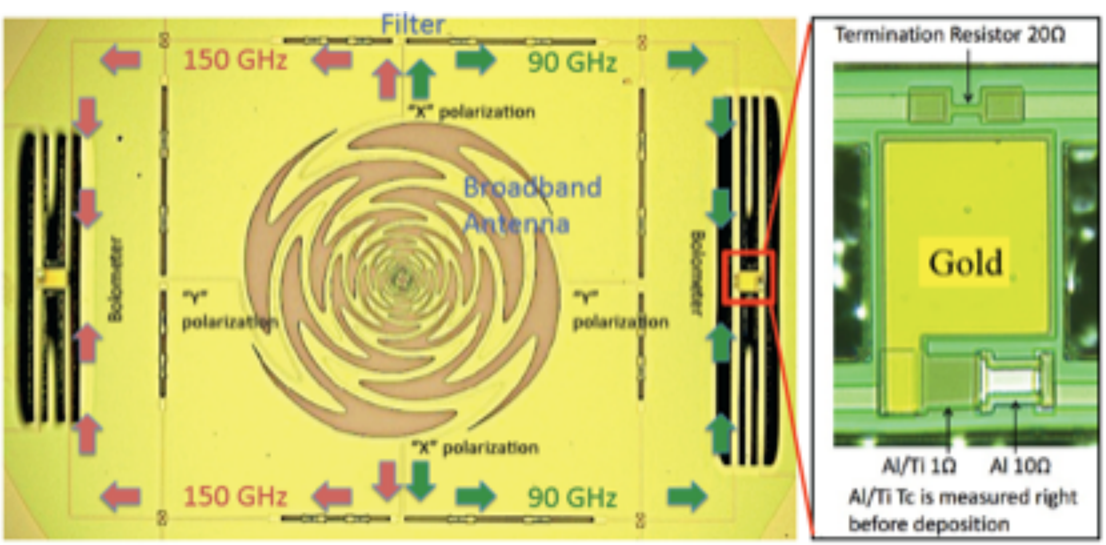
Why the South Pole?

- Water vapor absorbs an attenuates millimeter and submillimeter radiation and thus a dry site is required for short-wavelength radio astronomy.

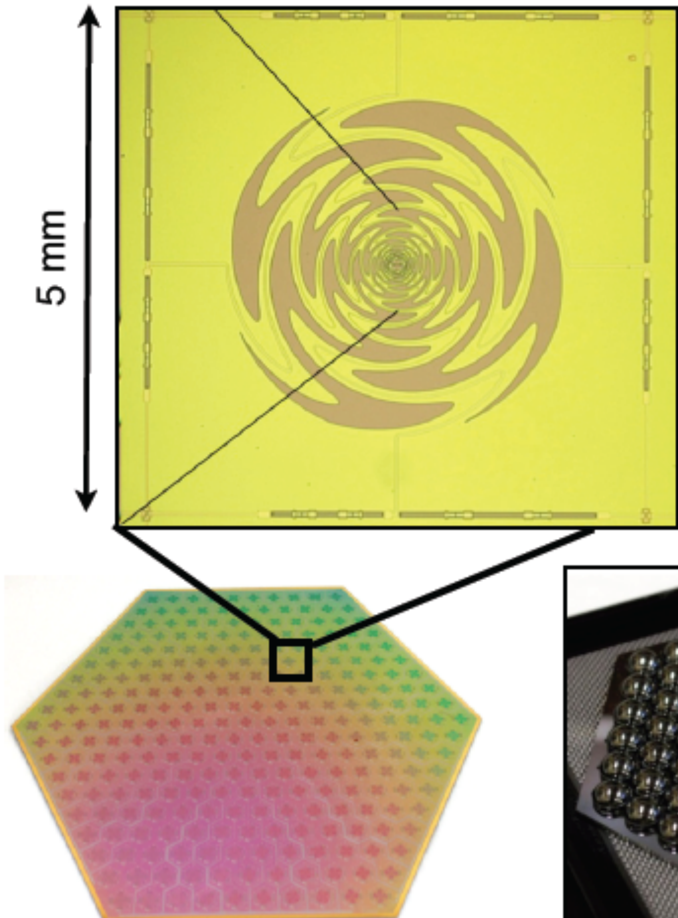


I work on the third generation detector array to deploy on the South Pole Telescope (SPT-3G)

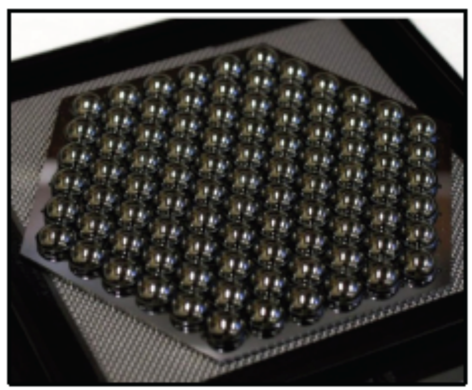
- Each pixel can detect 3 frequency bands and polarization.
- Note only 2 bands (2 polarizations/band) are shown below.
  - We are expanding this design to include 3 bands (2 polarizations/band)
- The detectors must be operated at ~250 mK, so the array is housed in a He-3 refrigerator.
  - Antenna and transmission lines are superconducting niobium
  - The detectors are bolometers called Transition Edge Sensors, with transition temperatures ~250 mK.

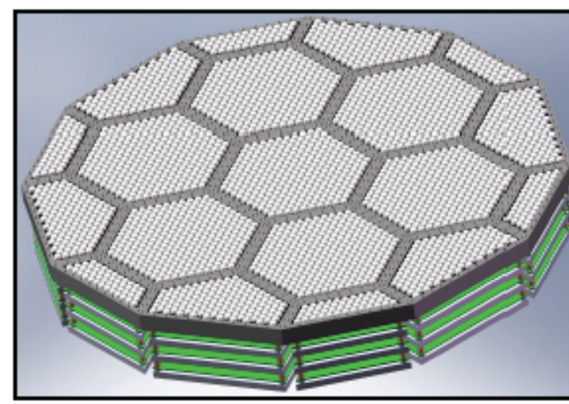


SPT-3G Detector Module Assembly



- ***FNAL will contribute detector module assembly, testing***
- ANL, U. Chicago, UC-Berkeley working in collaboration on 3-band, dual polarization pixel for SPT-3G
- Each SPT-3G detector module consists of 544 pixels, assembly will include:
  - >3,000 wire bonds per module
  - Packaging with silicon lenslet array





SPT-3G Prototype Array (6" wafer) + Silicon Lenslet Array = SPT-3G Focal Plane

Fermilab's Role on SPT-3G and CMB Detectors

1) SPT-3G Receiver Assembly and Testing

- *Summer 2014 expect SPT-3G cryostat parts to start arriving, and assembly and testing to begin*

2) SPT-3G Detector Module Assembly

- *Detector arrays from Argonne wire-bonded and mounted with silicon lenslet arrays (begin Fall 2014)*

3) SPT-3G Detector Module Characterization

- *Commissioning of a new 250 mK cryostat detector module test cryostat, to provide feedback for fabrication of SPT-3G detectors by Argonne (Summer 2014)*

My next vacation destination?