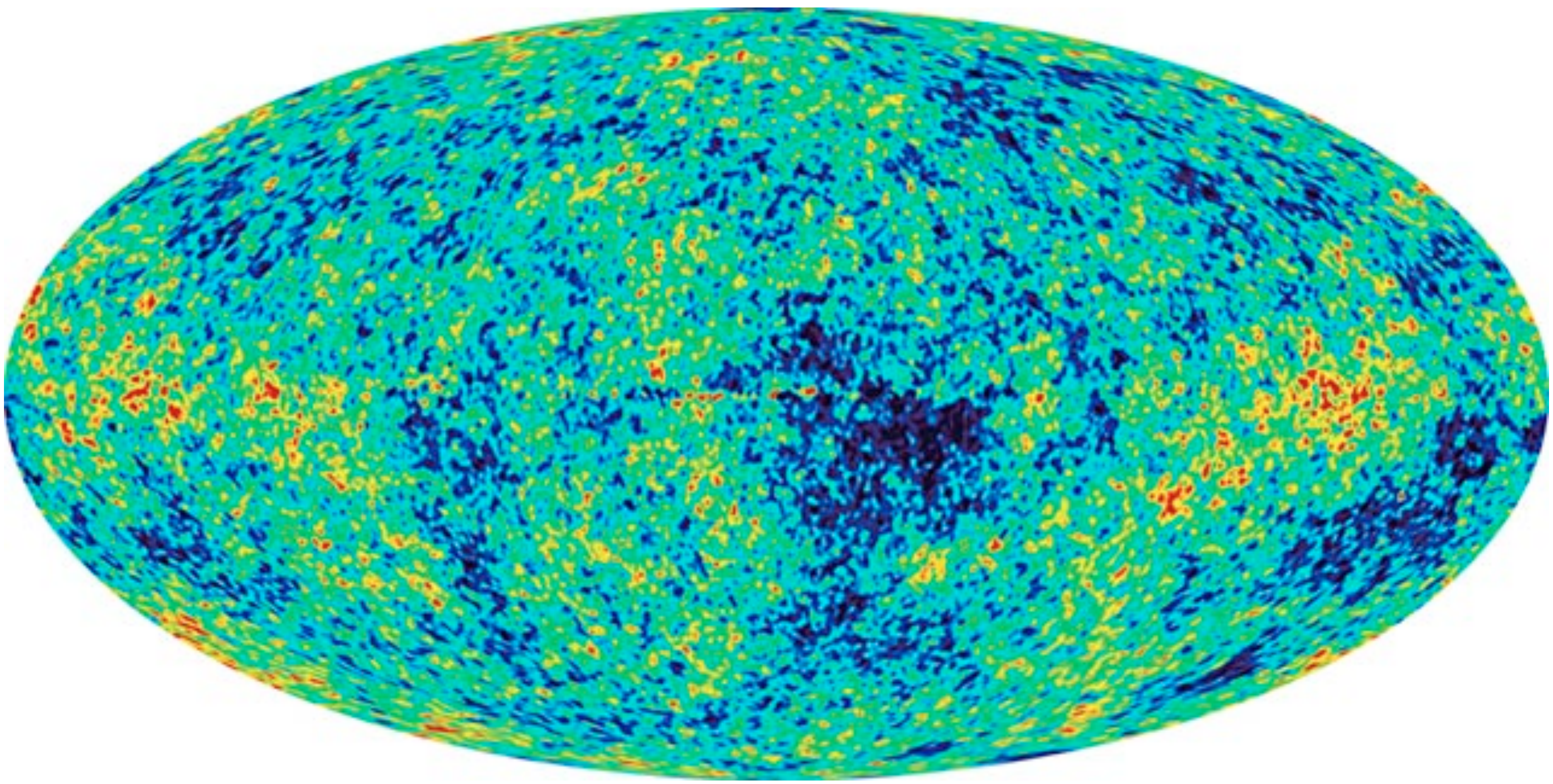
The Exciting Cosmic Microwave Background



Donna Kubik

NAA June 7, 2011

Outline

- Part 1 Discovery of the Cosmic Microwave Background (CMB)
- Part 2 First successful experiment specifically designed for radio astronomy masterminded by local amateur astronomer!
- Part 3 A closer look at the CMB
  - Why is it called Cosmic?
  - Why is it called Microwave?
  - Why is it called Background?
- Part 4 What can we learn from the CMB?
  - Frequency spectrum
  - Temperature anisotropy
  - Polarization
- Part 5 The best is yet to come!

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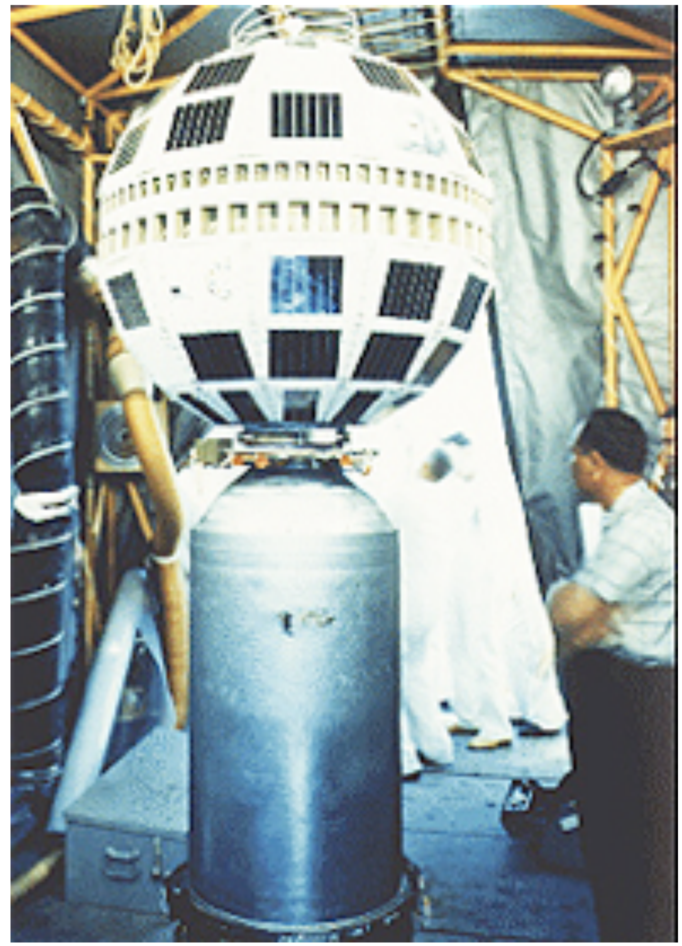
Telstar

- "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

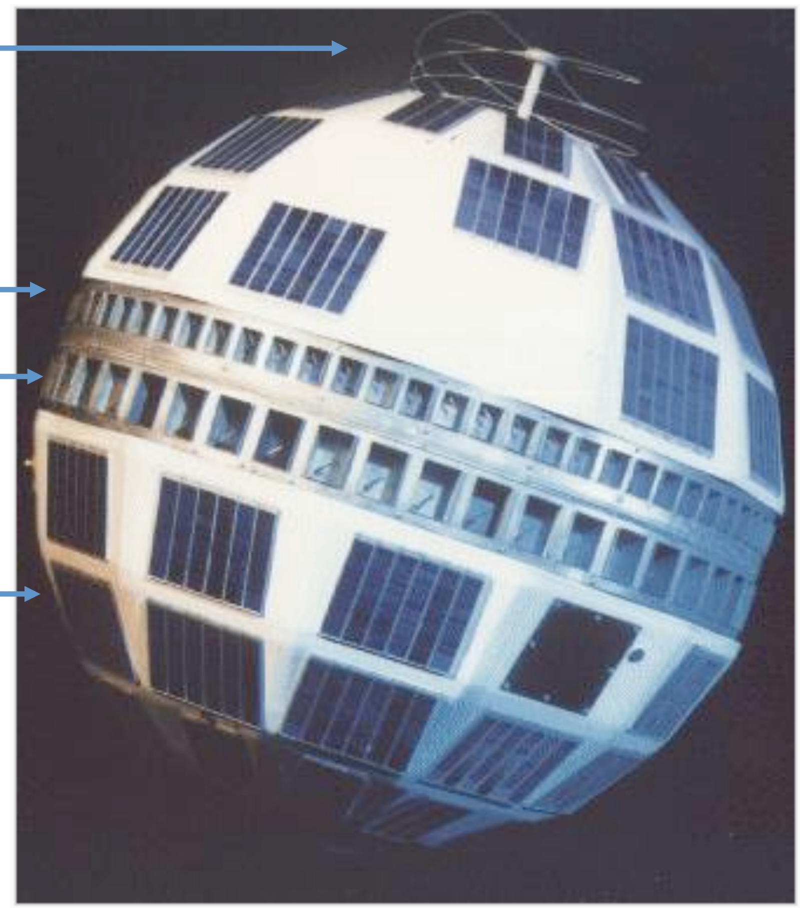
Anatomy of Telstar

Helical antenna
for telecommands from a ground station

6 GHz (5 cm) receivers

4 GHz (7 cm) transmitters

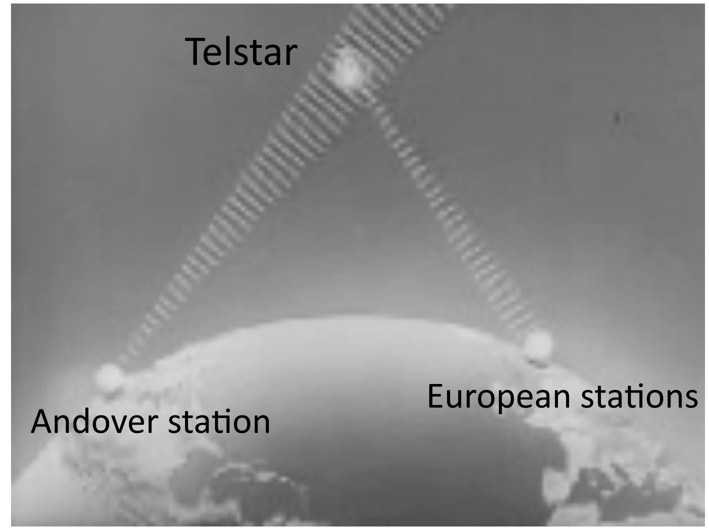
Solar panels

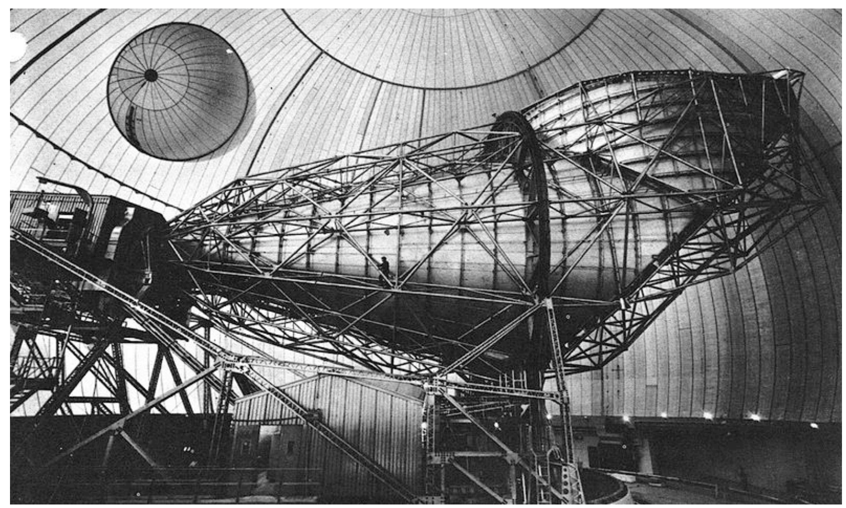


Telstar communications satellite

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.

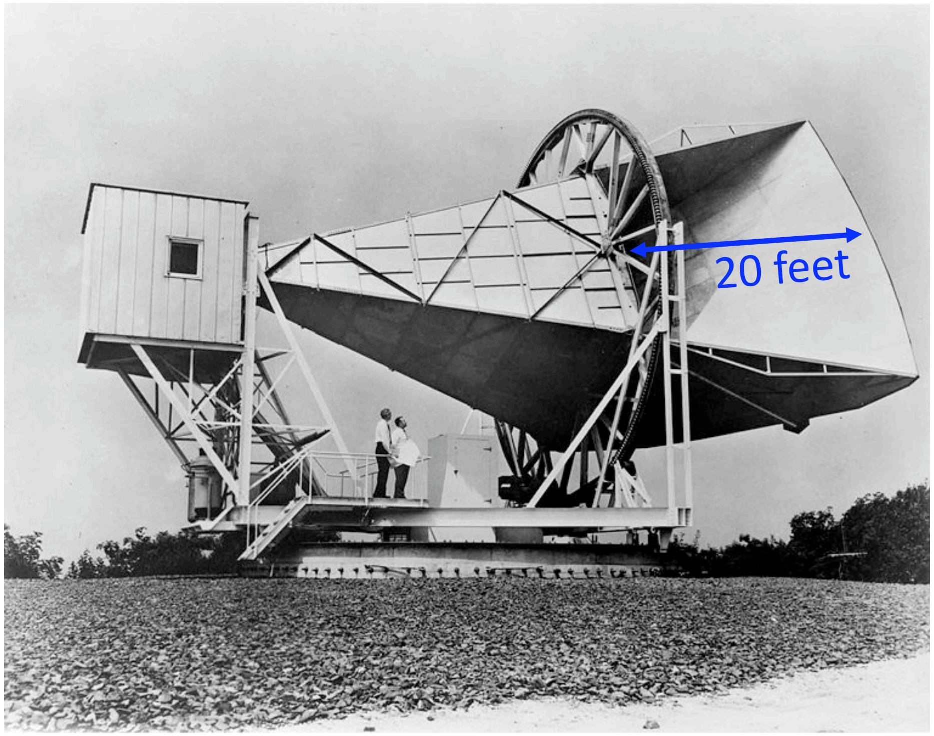




Primary earth station antenna in Andover, Maine

Holmdel horn antenna

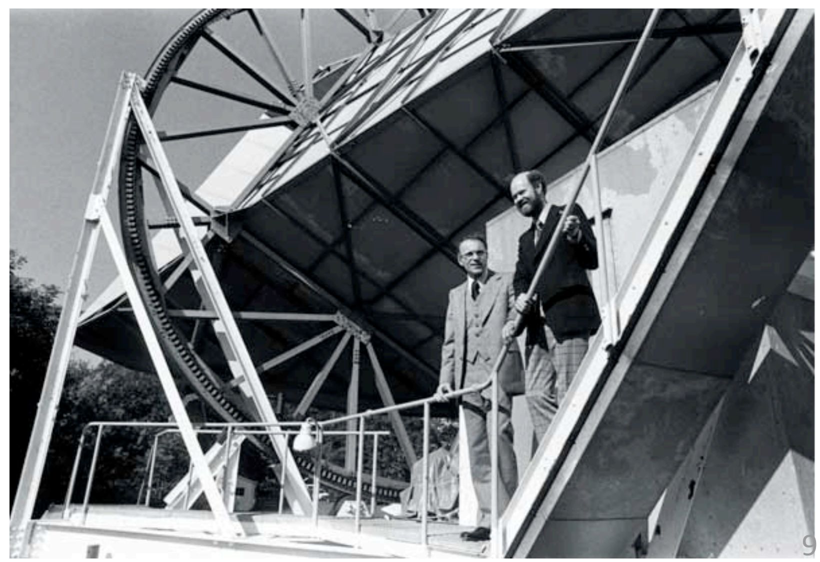
- So Bell Labs outfitted their existing 20-foot horn antenna with a 7 cm (4 GHz) receiver.



20-foot Holmdel horn antenna, Holmdel, NJ

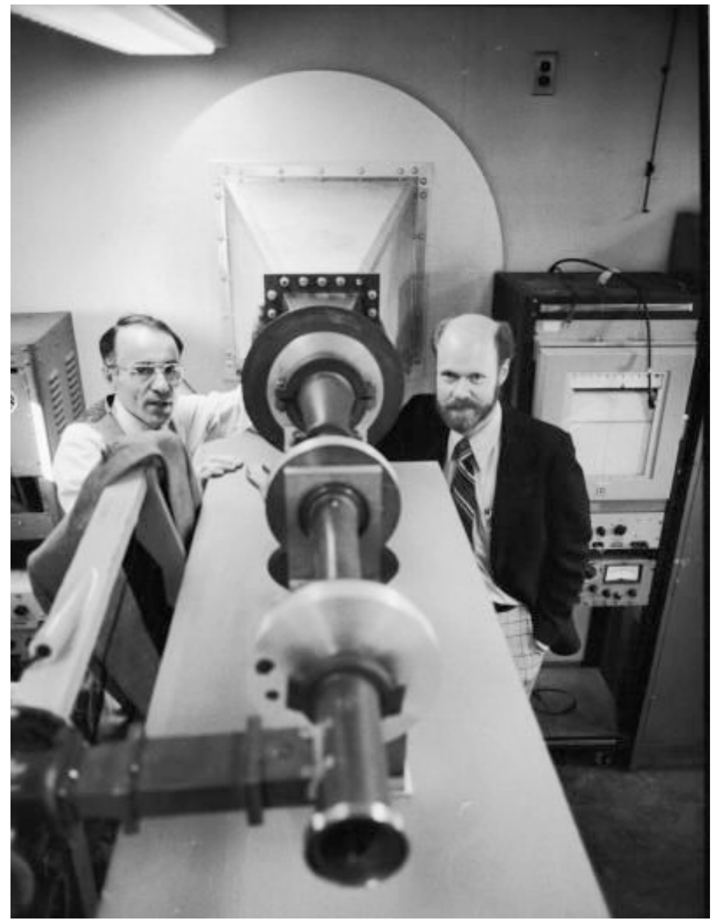
Penzias and Wilson

- 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

- A radiometer is a device for measuring the intensity of radiation.
  - Filter
  - Detector (voltage proportional to input power)
  - Amplifier

- "Astronomical radio sources produce random, thermal noise very much like that from a hot resistor. Therefore the calibration of a radiometer is usually expressed in terms of a thermal system. Instead of giving the noise power that the radiometer receives from the antenna, we quote the temperature of a resistor which would deliver the same power to the radiometer." ~ R. W. Wilson

- And they prefer units of Kelvin!

  0 K = −273.15 °C = −459.67 °F

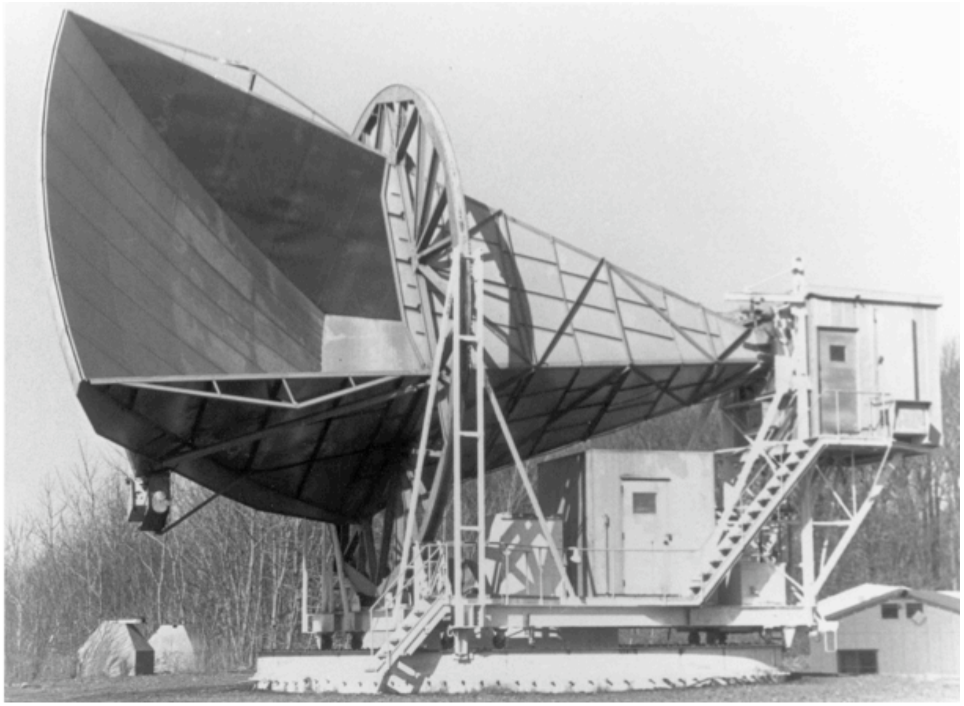
  1 K = 1 °C = 1.8 °F

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.



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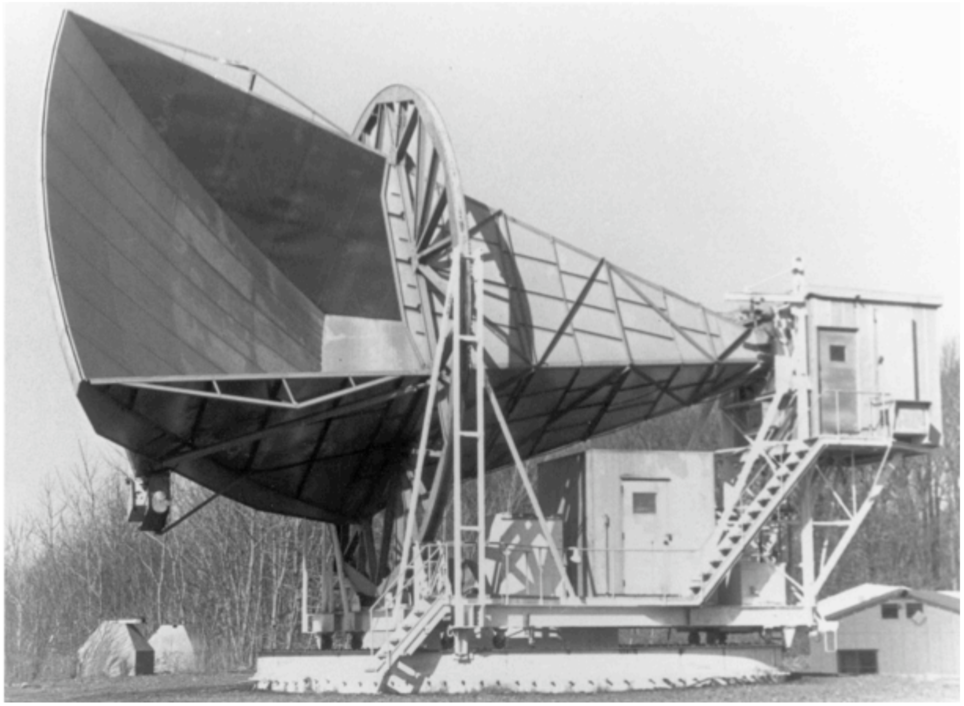
- They measured 6.7 +/- 0.3 K
- The error comes largely from uncertainty in the absolute calibration of the reference termination



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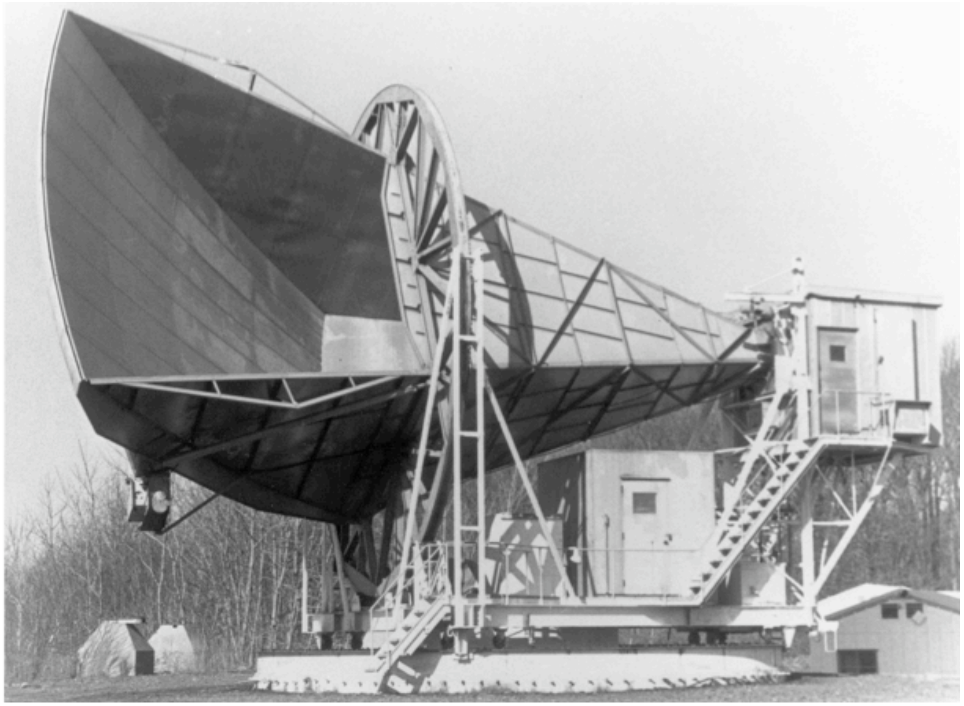
- The contribution from atmospheric absorption was obtained by recording the variation in antenna temperature with elevation angle and employing the secant law.
- The agreement, 2.3 +/- 0.3 K, is in good agreement with published values.



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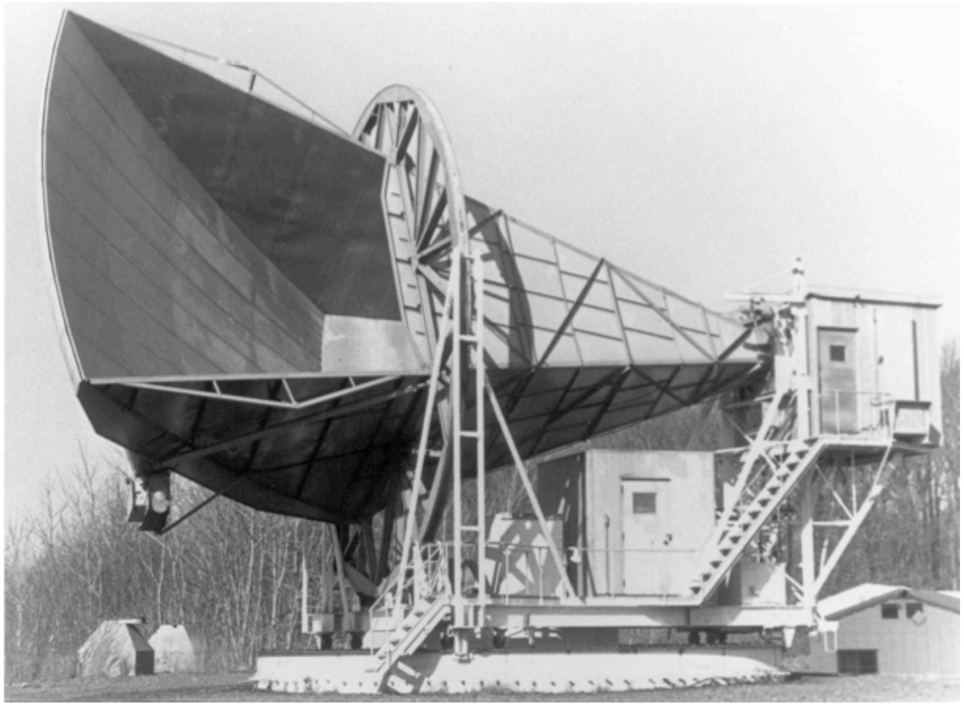
- The contribution for ohmic losses was computed to be 0.8 +/- 0.4 K
  - Tapers,
  - Rotary joint
  - Antenna itself
    - Taped seams with Al tape caused no change



Excess temperature

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- The back-lobe response to ground radiation was taken to be less than 0.1 K for two reasons
  - Measurements of the response of the antenna to a small transmitter located on the ground indicate an average back-lobe level more then 30 dB below isotropic response.
  - Measurements on smaller horn antenna in the lab consistently showed a back-lobe response 30 db below isotropic response. The large Holmdel horn would be expected to have an even lower back-lobe level.

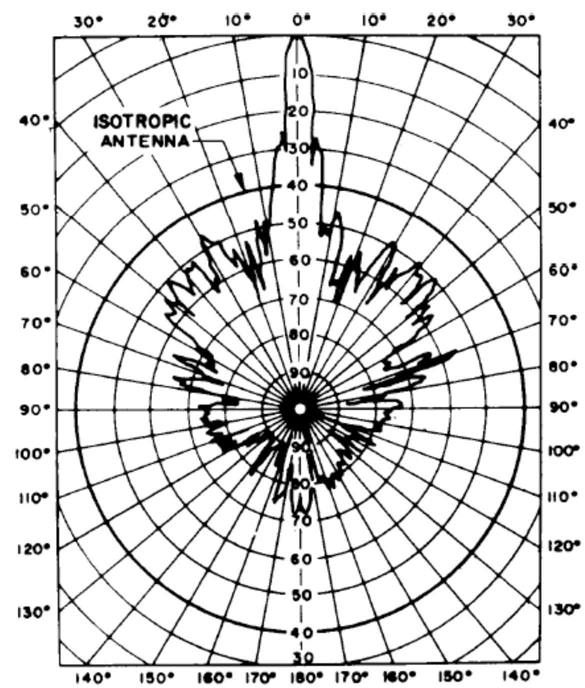


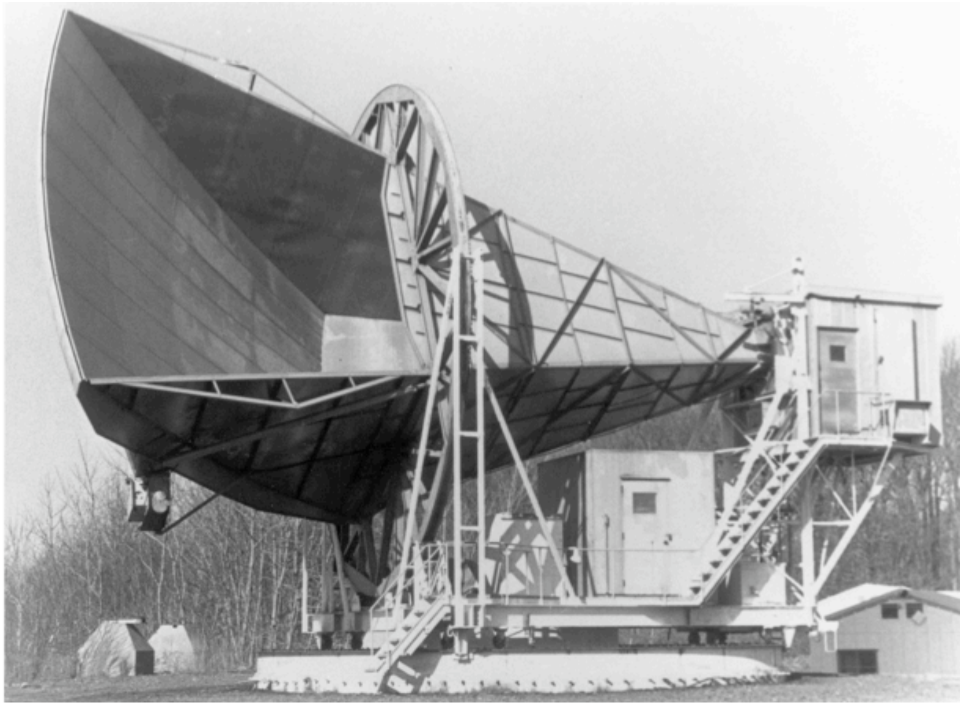
Fig. 2 Sensitivity pattern of a small horn-reflector antenna. This is a logarithmic plot of the collecting area of the antenna as a function of angle from the center of the main beam. Each circle below the level of the main beam represent a factor of ten reduction in sensitivity. In the back direction 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 compute 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

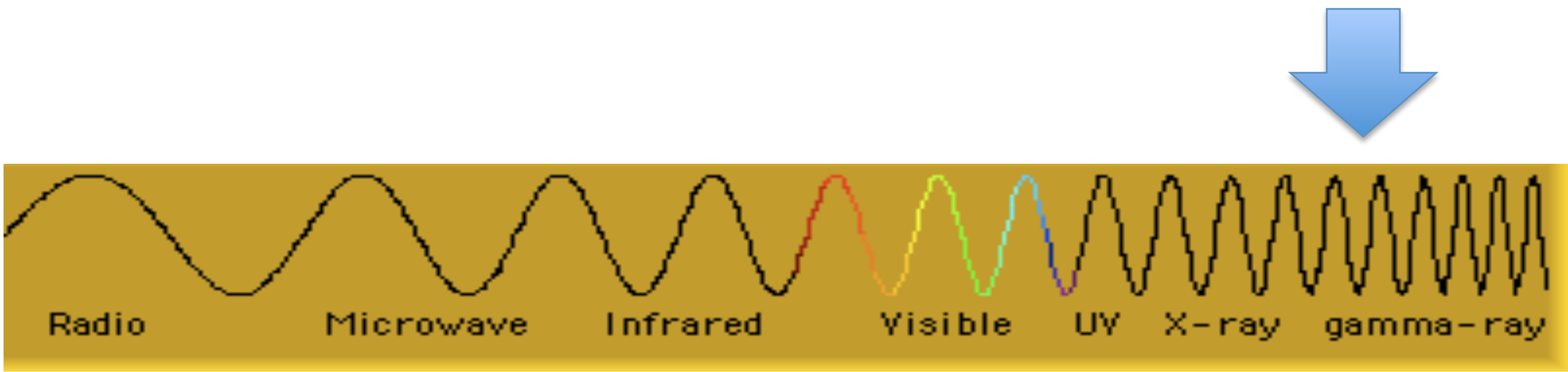
Penzias and Wilson

- 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.

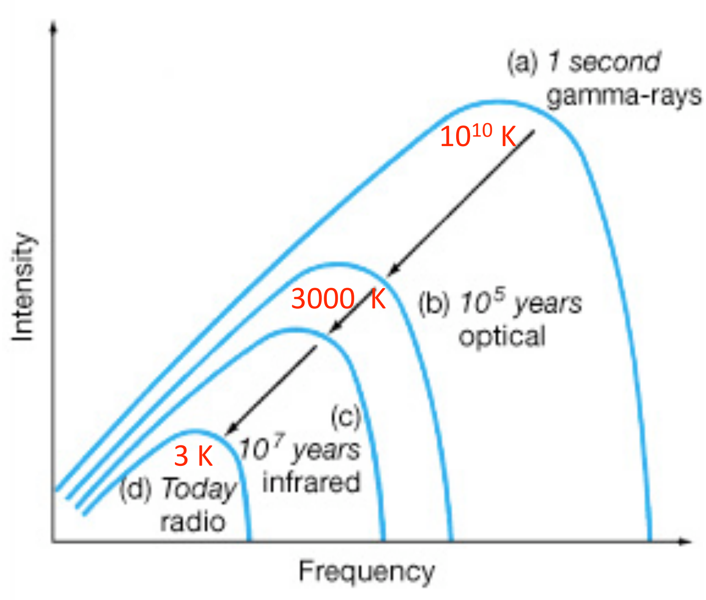
- If there was a Big Bang, the universe immediately following would have been very hot, >10^{32} K, corresponding to short, gamma ray wavelengths.



Black body spectrum

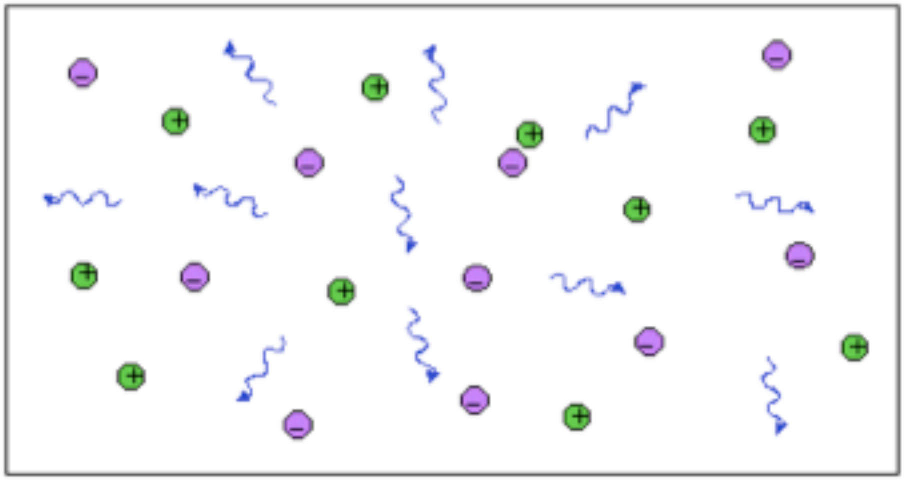
- The photons (radiation) and electrons and protons (matter) were in thermodynamic equilibrium
- A blackbody spectrum emerges from a system thermodynamic equilibrium.

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



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.

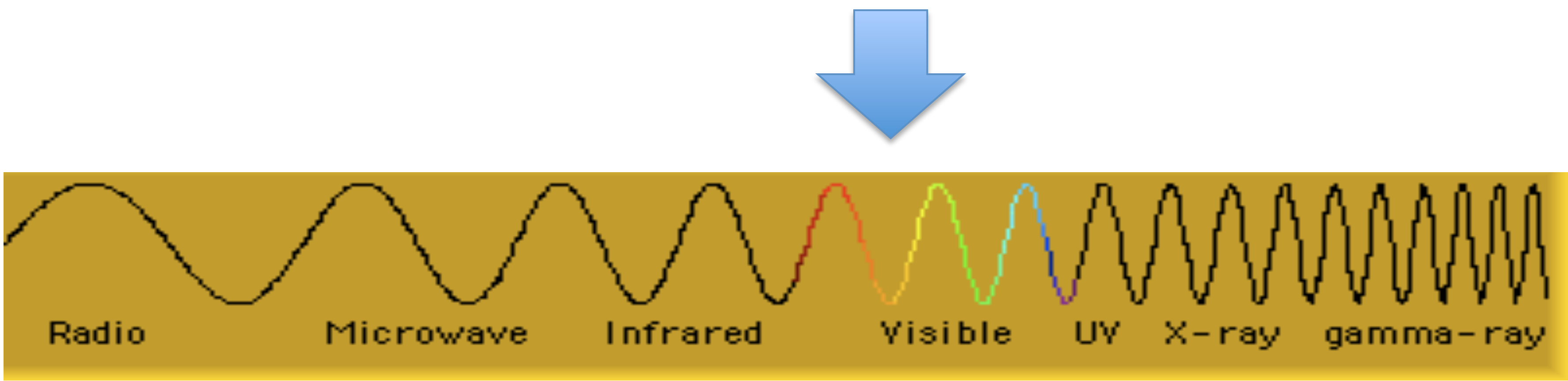


Cosmological redshift

- 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: $E = \dfrac{hc}{\lambda}$

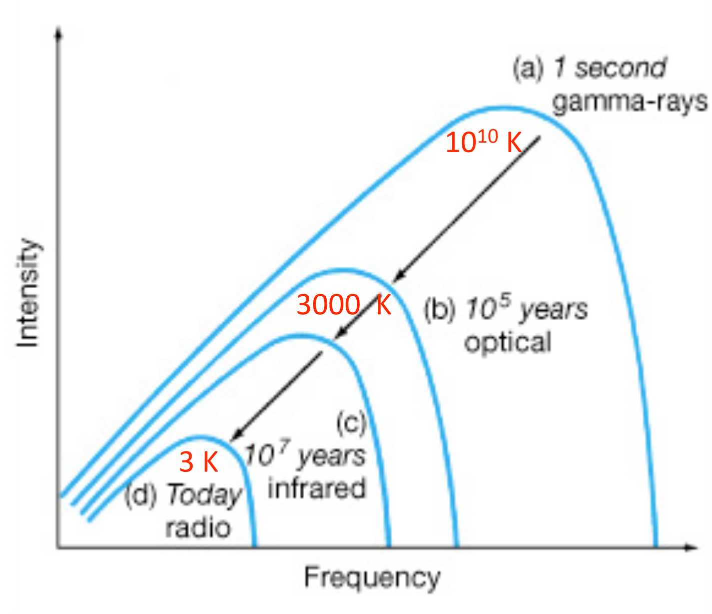
Decoupling and recombination

- 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.

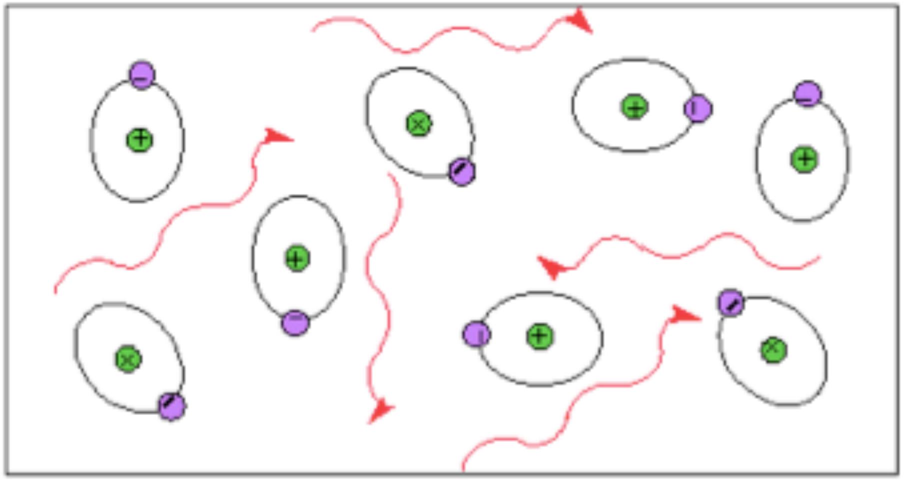


Decoupling and recombination

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

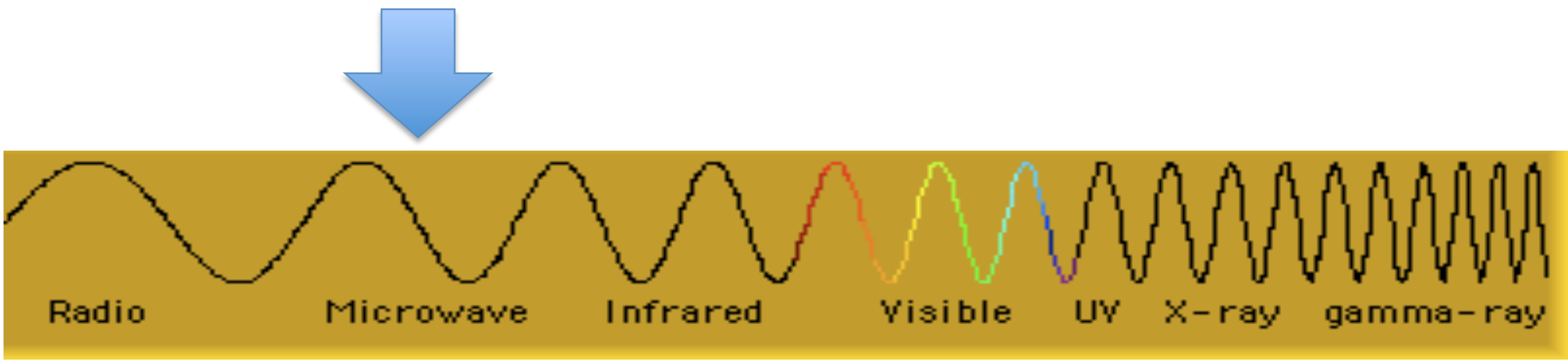
- Now photons could travel long distances without colliding with and ionizing hydrogen atoms.

- These are the photons we see as the CMB!



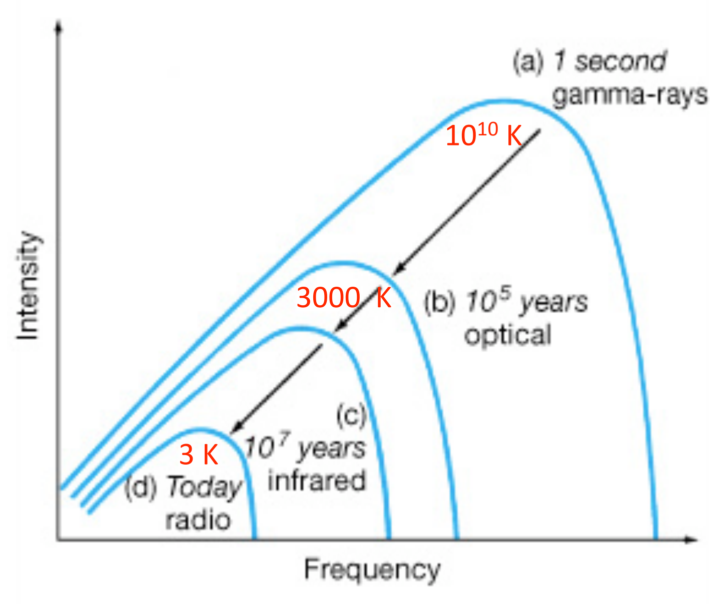
Penzias and Wilson

- 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

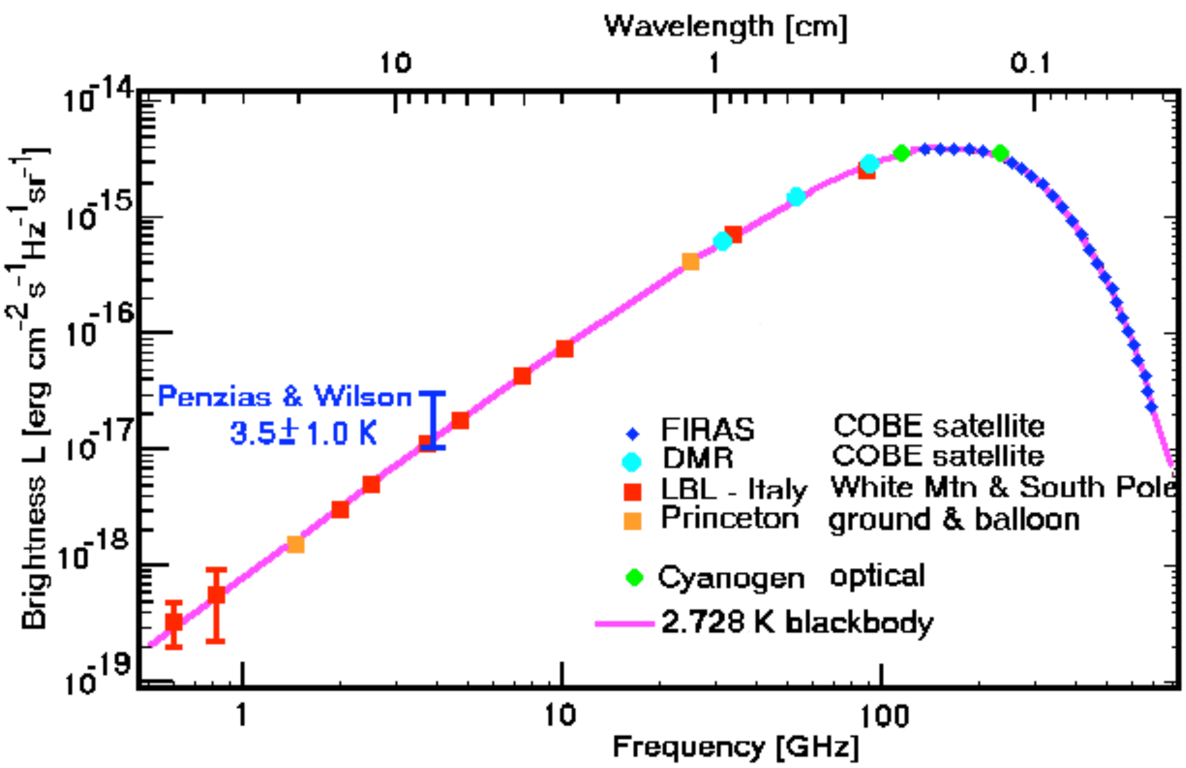
- The 3000 K temperature at decoupling corresponds to the peak microwave wavelength of ~0.001 mm.
- The universe is about 1000 times larger now, so the wavelength is about 1000 times longer (1.86 mm).
- The black body curve corresponding to Penzias and Wilson's detection peaks at 1.86 mm!



Discovery of the CMB

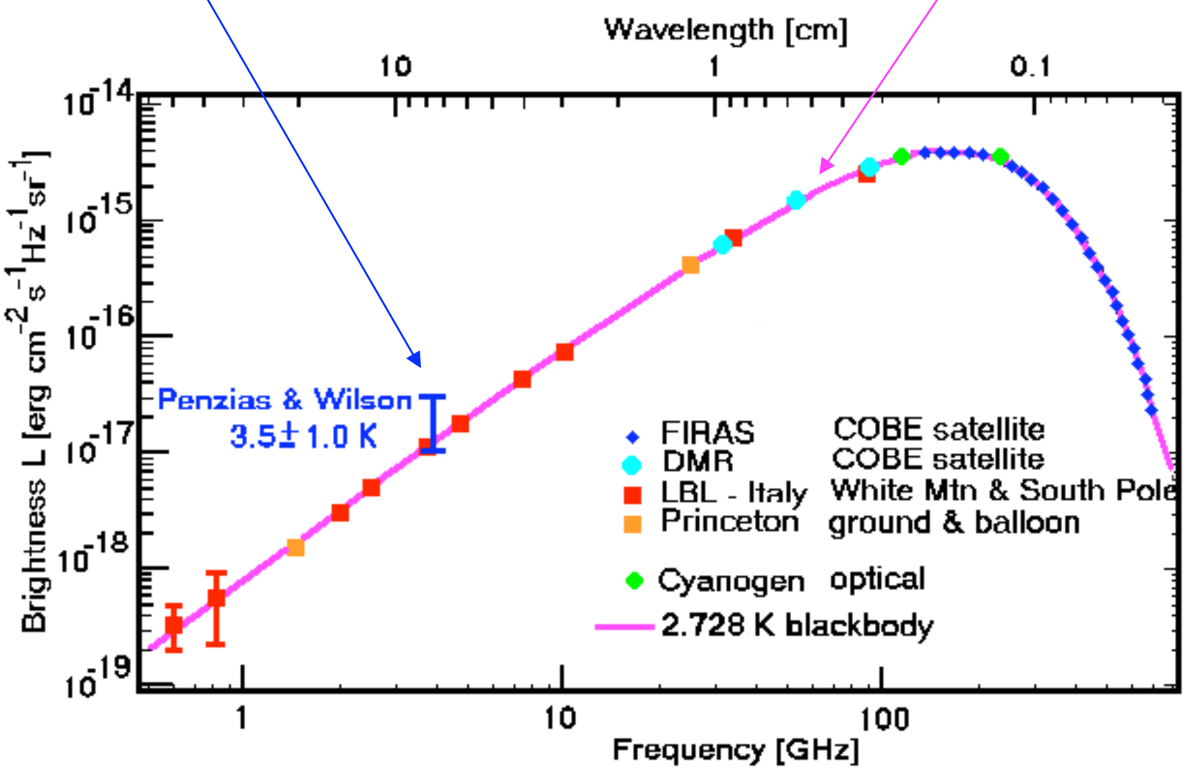
- Penzias and Wilson's measurement was at 4 GHz, since that was Telstar's transmitting frequency!

- 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.

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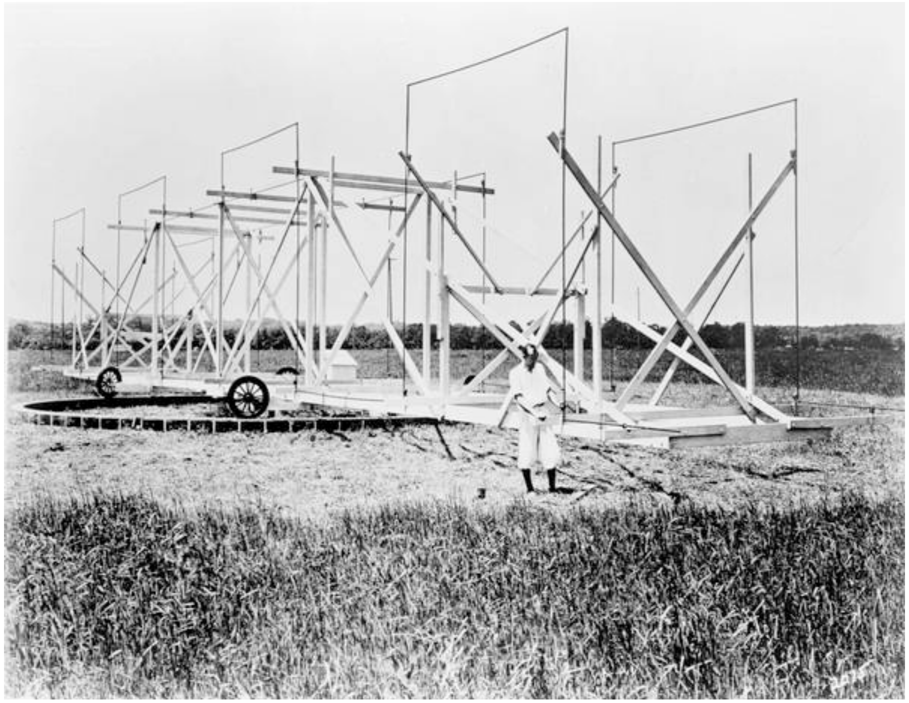
Jansky's telescope

- Karl Jansky's antenna was built in 1931 to study the direction of thunderstorms, which were suspected to cause signal-to-noise problems in Bell Lab's initial transoceanic radio-telephone circuits.
- In addition to detecting lightning, Jansky detected a signal that that appeared 4 minutes earlier each day and was strongest when Sagittarius was high in the sky.
- The center of the Galaxy is in the direction of Sagittarius, so Jansky concluded that he was detecting radio waves from an astronomical source



Wheaton amateur astronomer: Radio astronomy pioneer

- Grote Reber read about Jansky's discovery.
- In 1937, Reber built his own 32-foot-diameter parabolic dish antenna in his backyard in Wheaton, IL
- He experimented with several receivers operating at different frequencies.

Grote Reber’s telescope in Wheaton, IL

Grote Reber's radio survey

- In the spring of 1939, he was able to detect cosmic radio emissions with his equipment. In 1941, he made the first survey of the sky at radio wavelengths (160 MHz and 480 MHz).

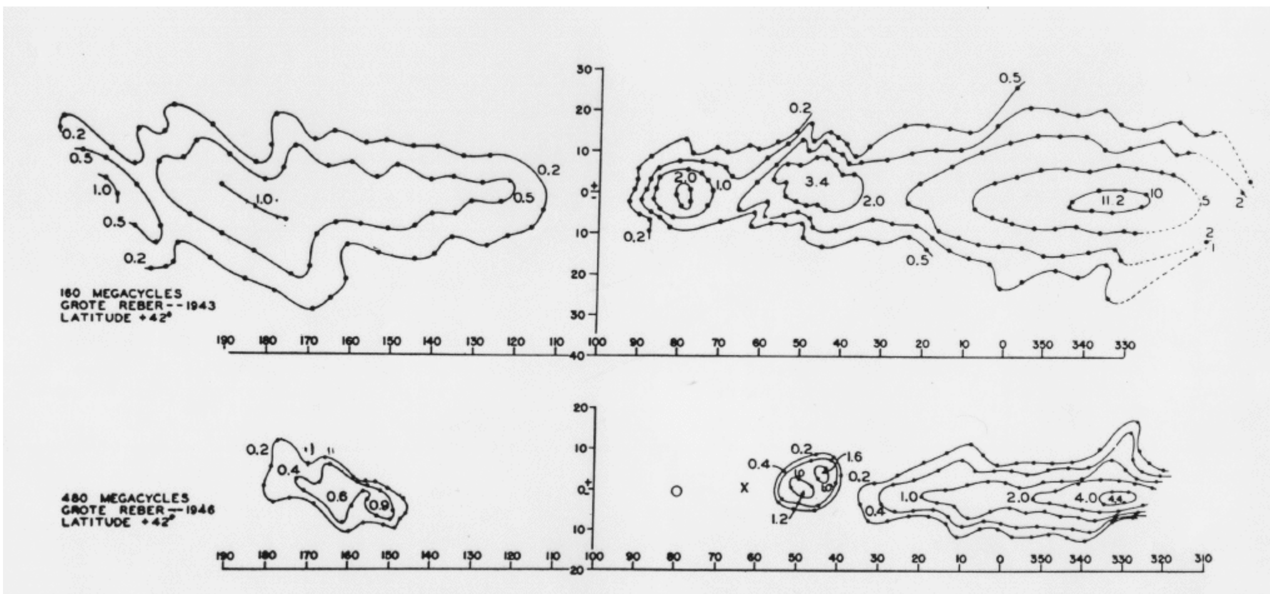
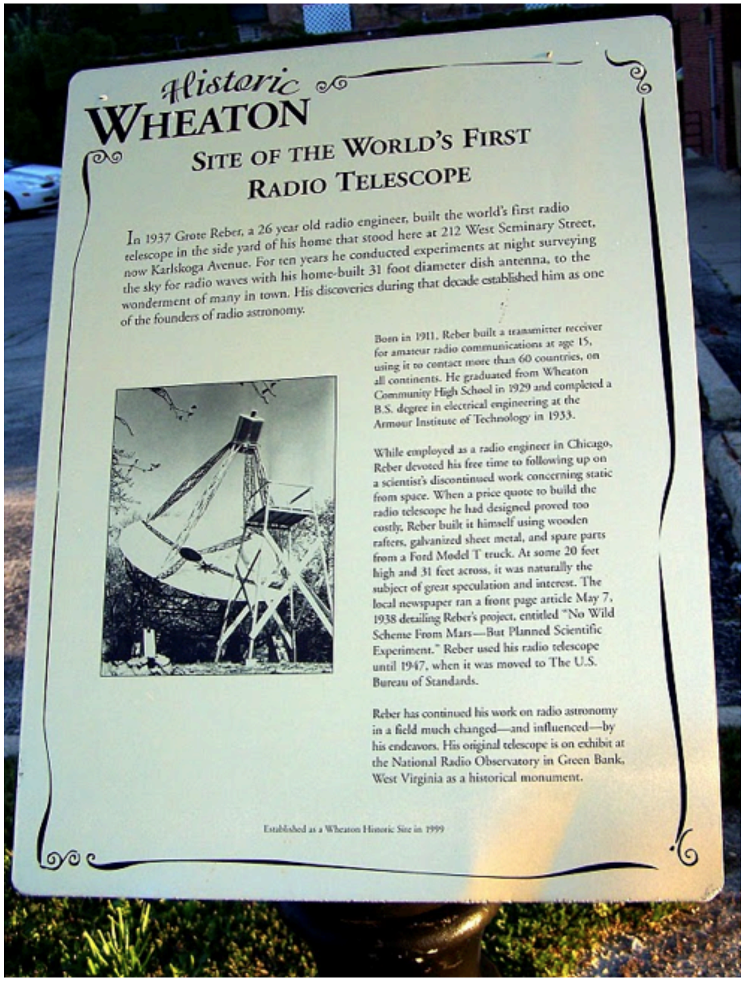


FIG. 7—Contours of constant intensity at 160 MHz and 480 MHz, taken at Wheaton, Illinois.

Grote Reber's radio maps

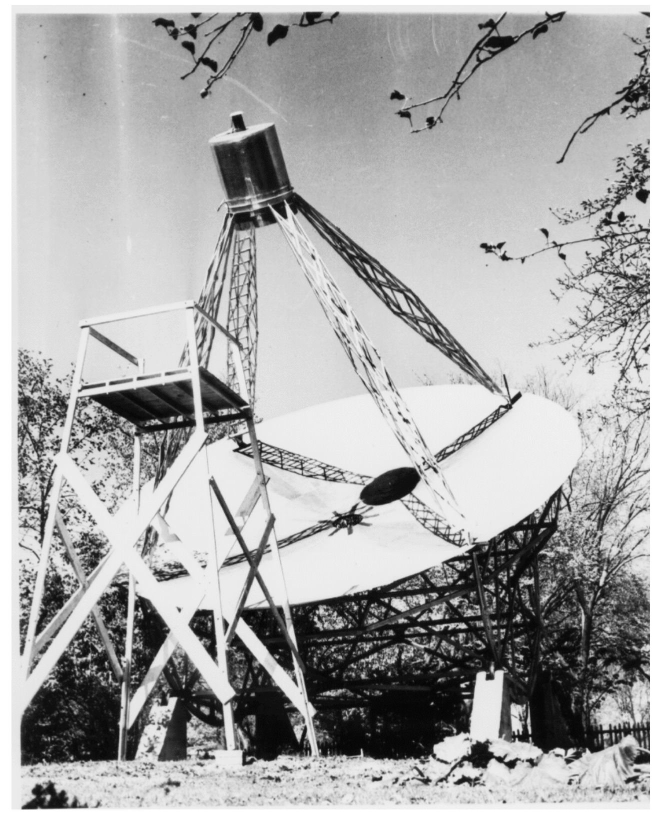
"Site of the World's First Radio Telescope”



NAA’s Bill Higgins at the historic site

"Site of the World's First Radio Telescope"

Grote Reber's radio telescope is visible in a 1939 photo of downtown Wheaton



From NAA's Bill Higgins website

Grote Reber's telescope

- Grote Reber's telescope is now on display at the National Radio Astronomy Observatory in Greenbank, West Virginia

Grote Reber and his telescope at Greenbank Radio Observatory

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Cosmic

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

Microwave

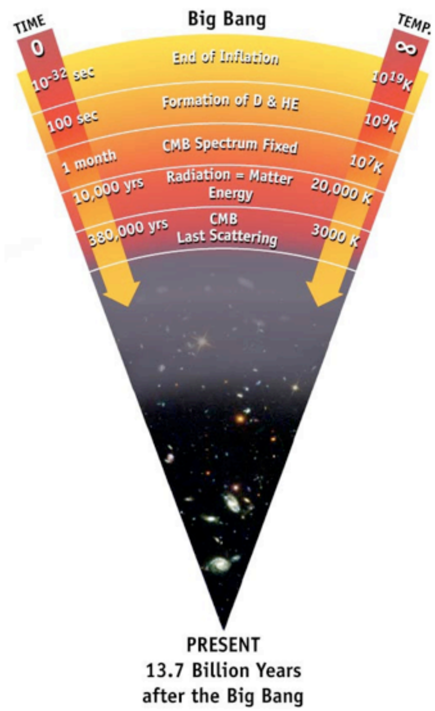
- Because of the expansion of the universe, the CMB which was at 3000 K at decoupling is very cold now: ~3 degrees above absolute zero.
- Its wavelength has been stretched out of the visible into the range of microwaves.

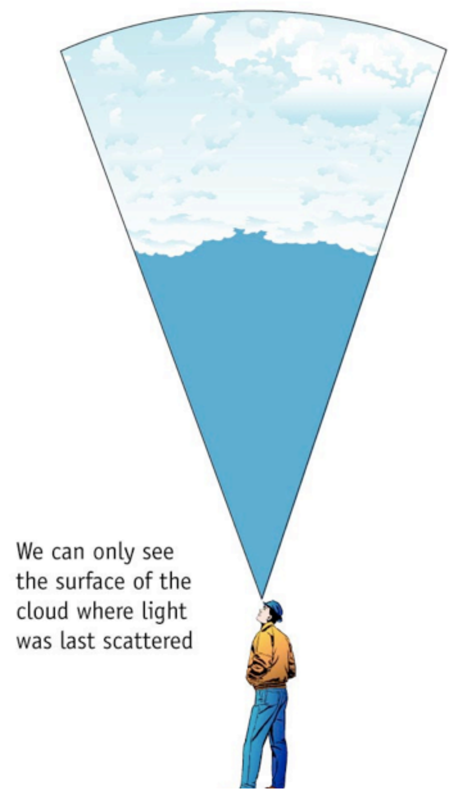
Microwave

- 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.

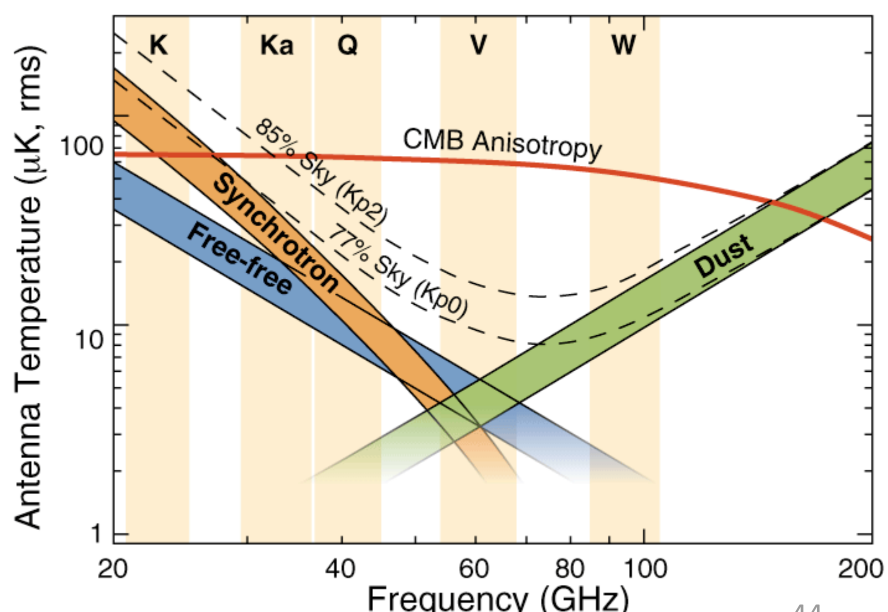
Foreground

- 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!



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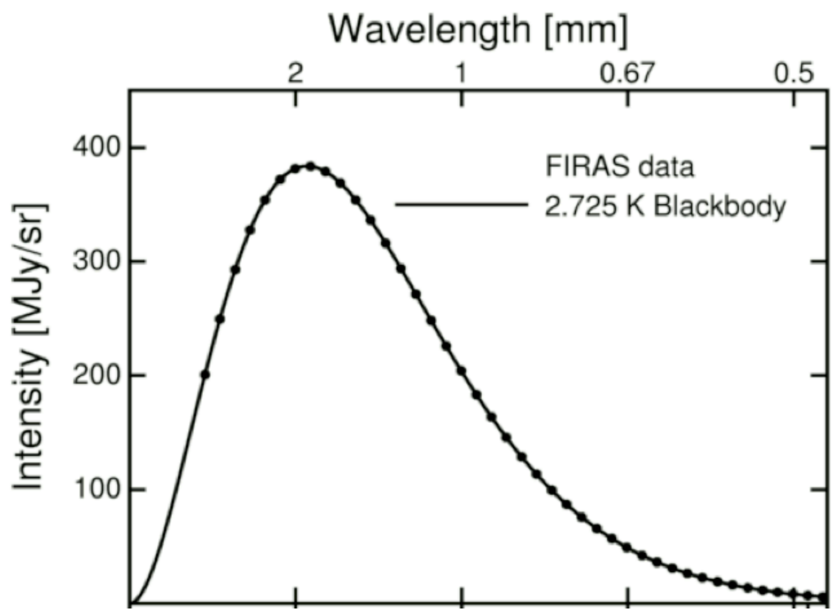
What can we learn from the frequency spectrum?

- 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.

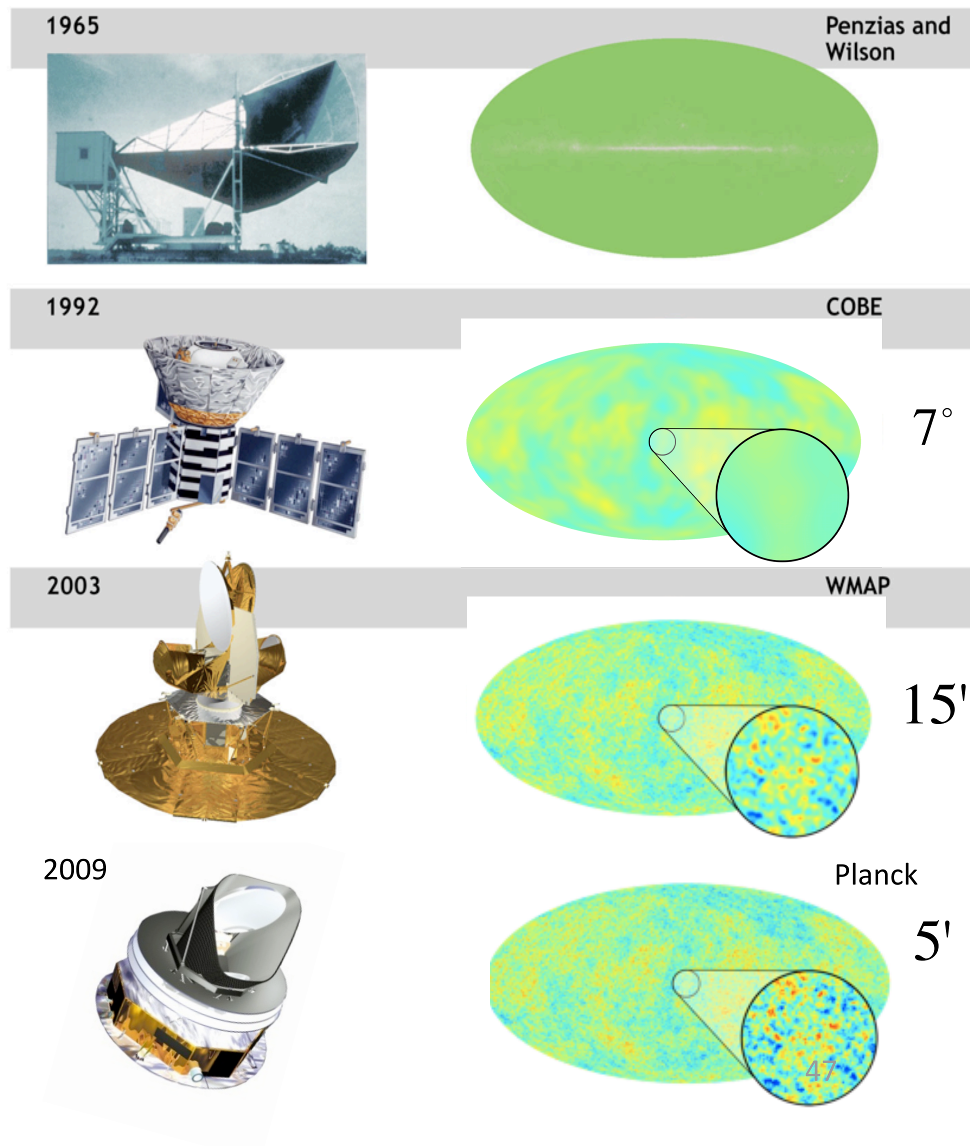


CMB spectrum

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.

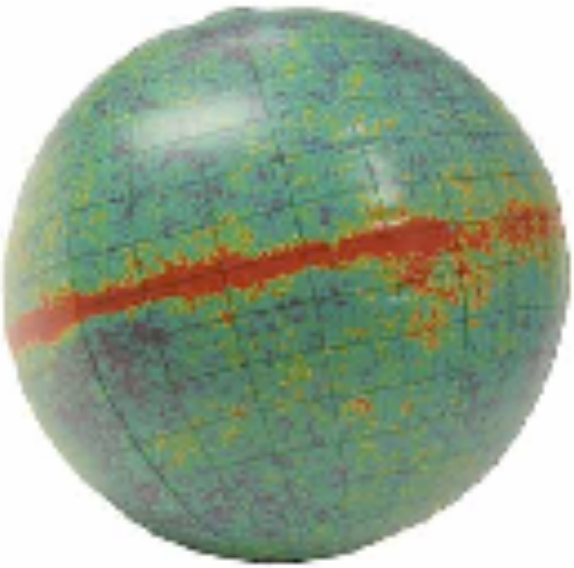


Temperature anisotropies

- 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

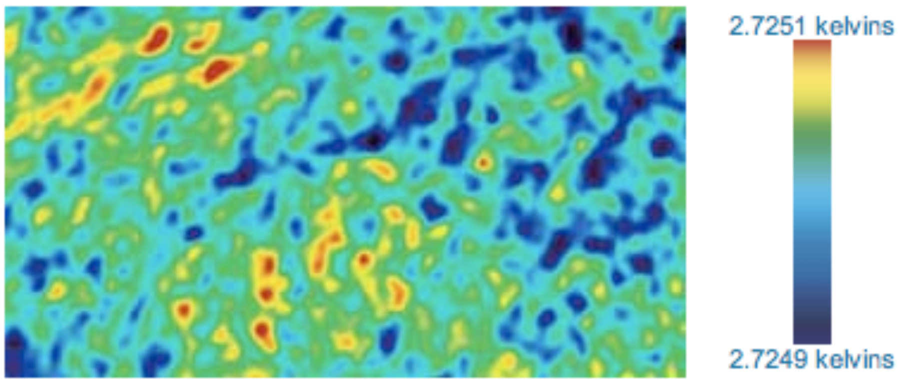
- We are at the center of this bubble of light, but many more times this volume of space exists outside this bubble, we just can not yet see its light.

- Every year the bubble of the observable universe grows a little larger as new light reaches our eyes



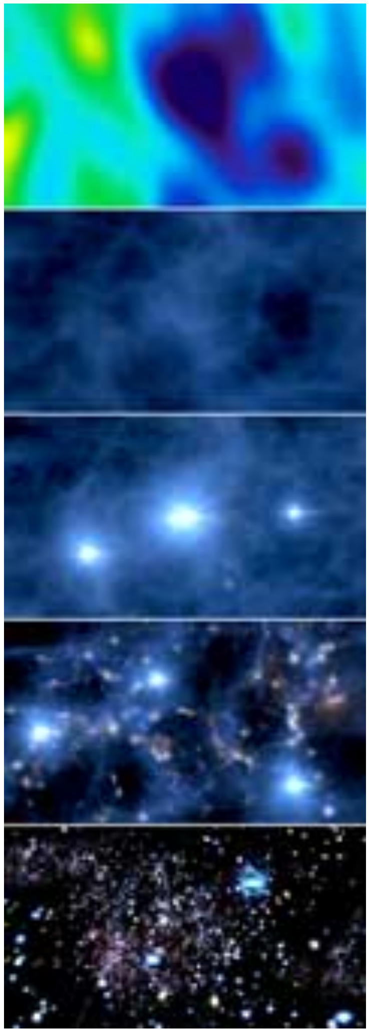
Temperature anisotropy

- 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.



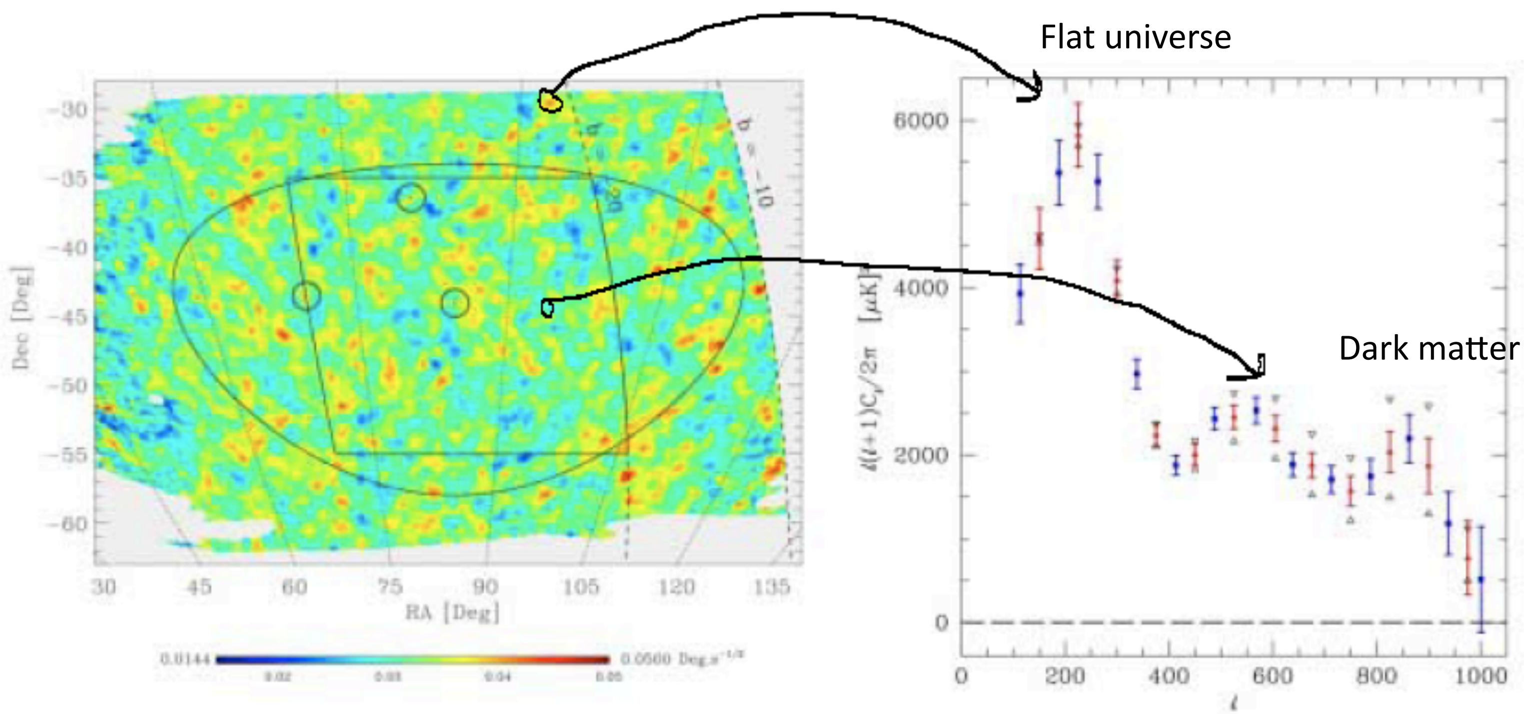
Temperature anisotropy

- 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

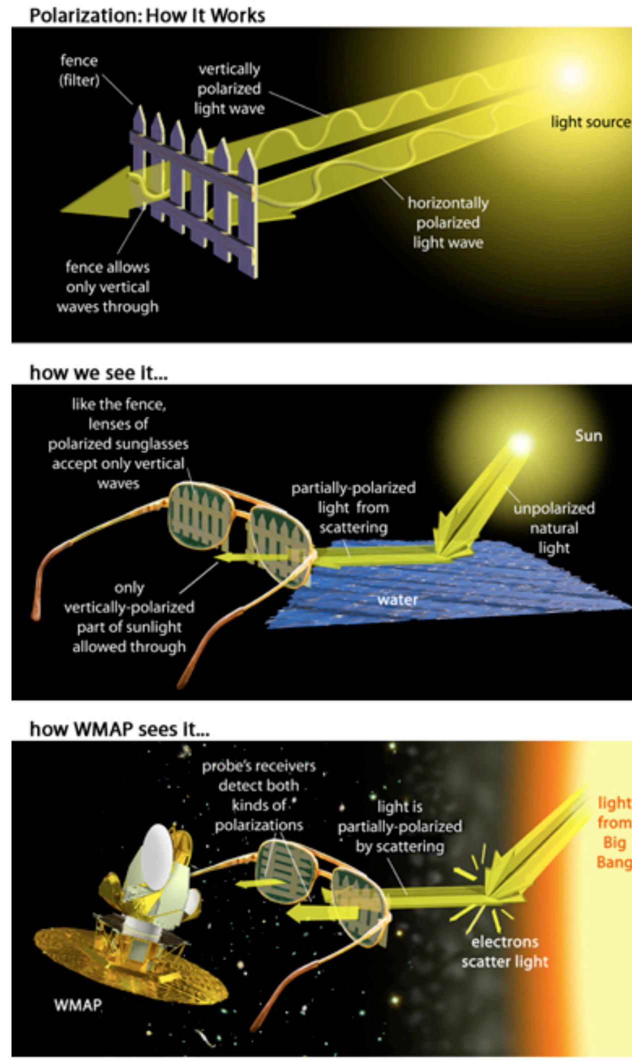
- From the sizes of the hot and cold spots, scientists can calculate fundamental values for the shape, size, age, content, rate of expansion (and more) of our universe.



Polarization

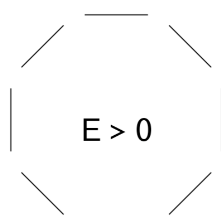
- The CMB fluctuations are partially polarized.

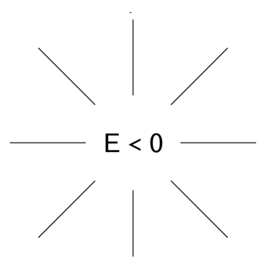
- We can detect the polarization of the CMB in a way analogous to the way we detect polarization of optical light.

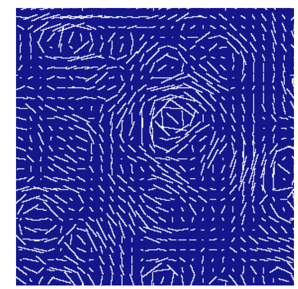


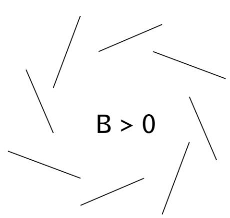
E modes and B modes

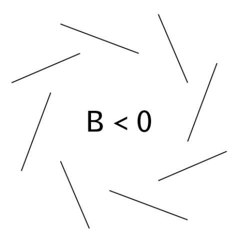
- There are 2 types of polarization patterns: E modes and B modes
- Dynamics due to density inhomogeneities in the early universe -> E modes
- Gravity waves -> B modes
- E modes can be gravitationally lensed into B modes
  - (Just to make things even more interesting!)

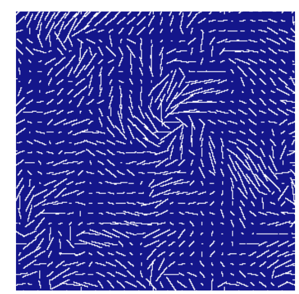








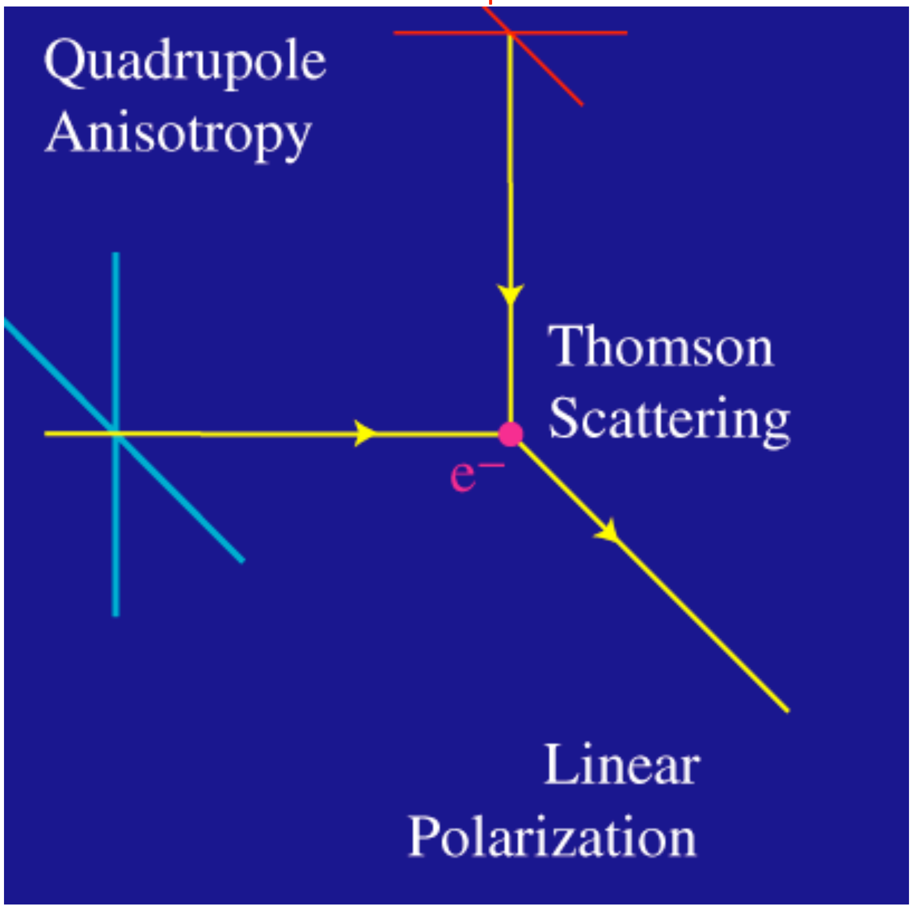




How do E modes get generated?

Cooler, less dense
Fewer photons

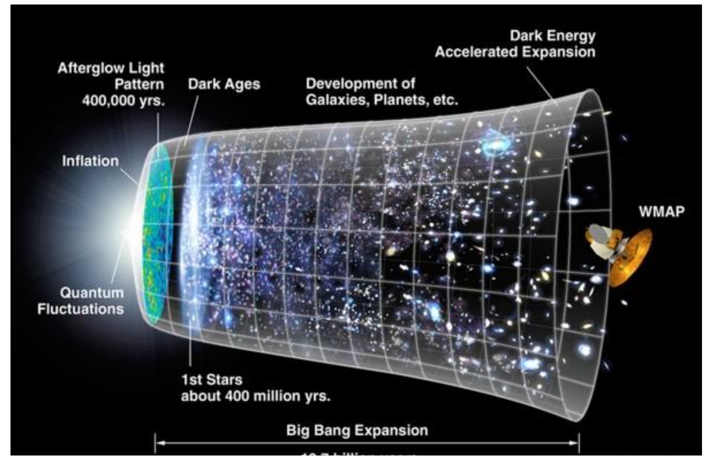
Hotter, denser
More photons



Results in net
vertical polarization

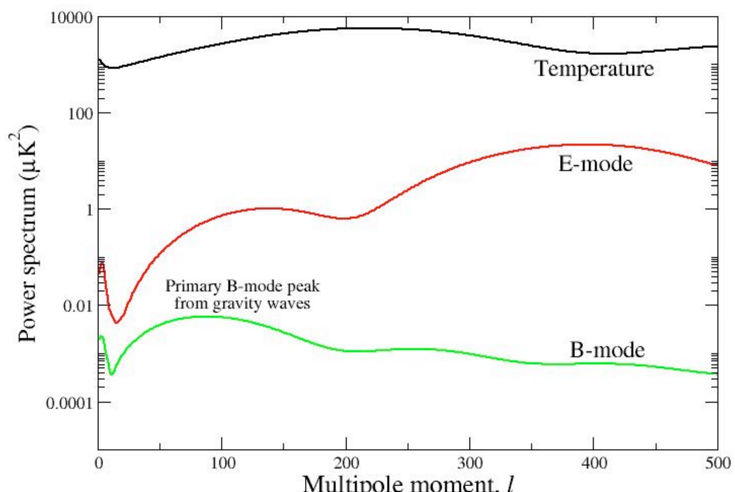
What can we learn from polarization of the CMB?

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



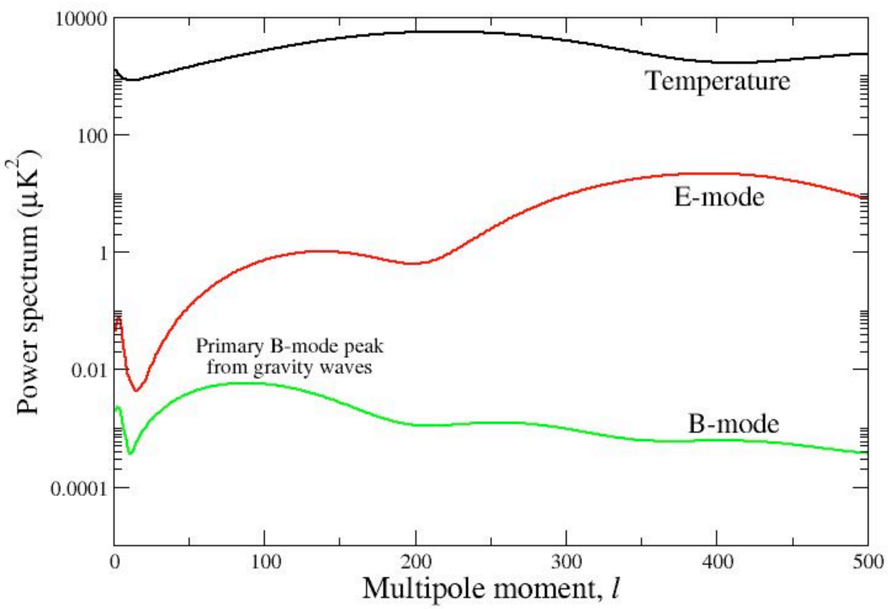
- The first appear to be true by WMAP

- 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!



Outline

- Part 1 Discovery of the Cosmic Microwave Background (CMB)
- Part 2 First successful experiment specifically designed for radio astronomy masterminded by local amateur astronomer!
- Part 3 A closer look at the CMB
  - Why is it called Cosmic?
  - Why is it called Microwave?
  - Why is it called Background?
- Part 4 What can we learn from the CMB?
  - Frequency spectrum
  - Temperature anisotropy
  - Polarization
- Part 5 The best is yet to come!

QUIET (Q/U Imaging ExperimenT)

- QUIET hopes to measure the B mode polarization of the CMB which can reveal information about the early universe.
- Sensitive microwave detectors are needed
- The Q/U of QUIET refer to the Q and U Stokes parameters.

QUIET telescope in Chajnantor Plateau in Chile

Chajnantor Plateau

- QUIET was located on the Chajnantor Plateau, which is the site for many astronomical observatories

- It is located at an altitude of ~5100 meters in the Chilean Atacama desert, 50 kilometers to the east of San Pedro de Atacama

- It is a very dry site, somewhat inhospitable to humans, but an excellent site for millimeter and submillimeter astronomy.

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

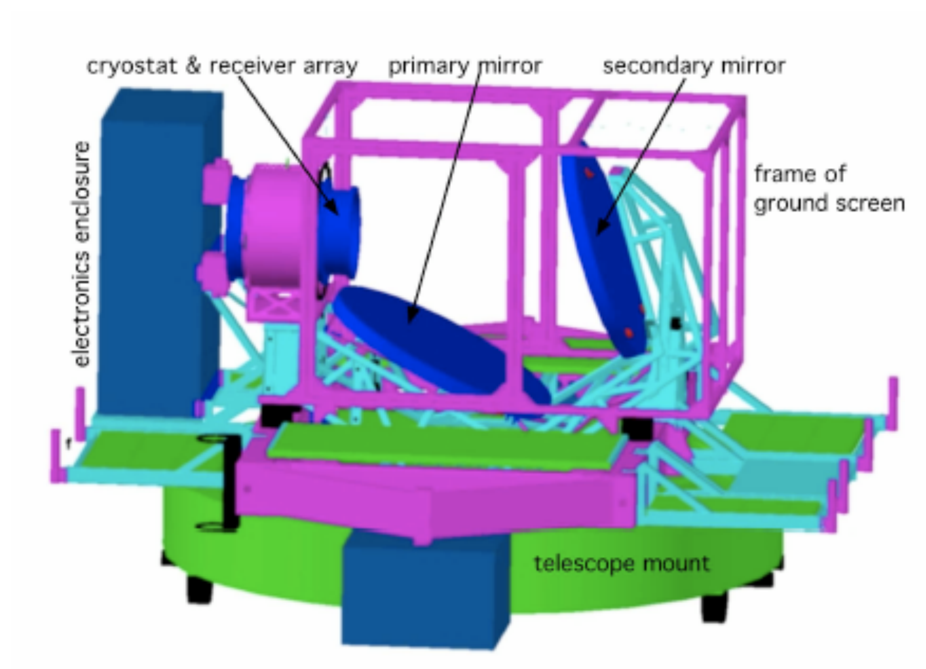
QUIET control room

QUIET site

Inside the QUIET control room

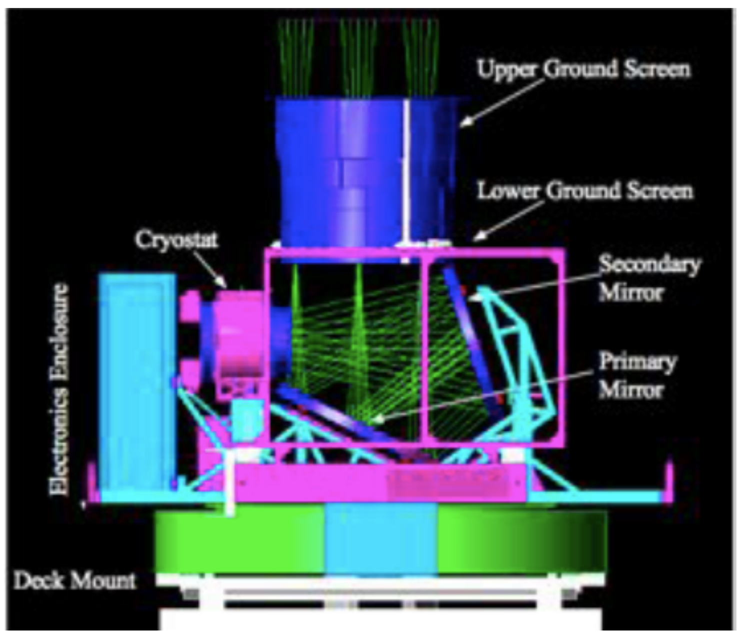
QUIET

- QUIET used a 1.4-meter crossed Mizuguchi-Dragone (MD) dual reflective telescope
- A co-moving ground screen prevents radiation from the ground from entering the receivers

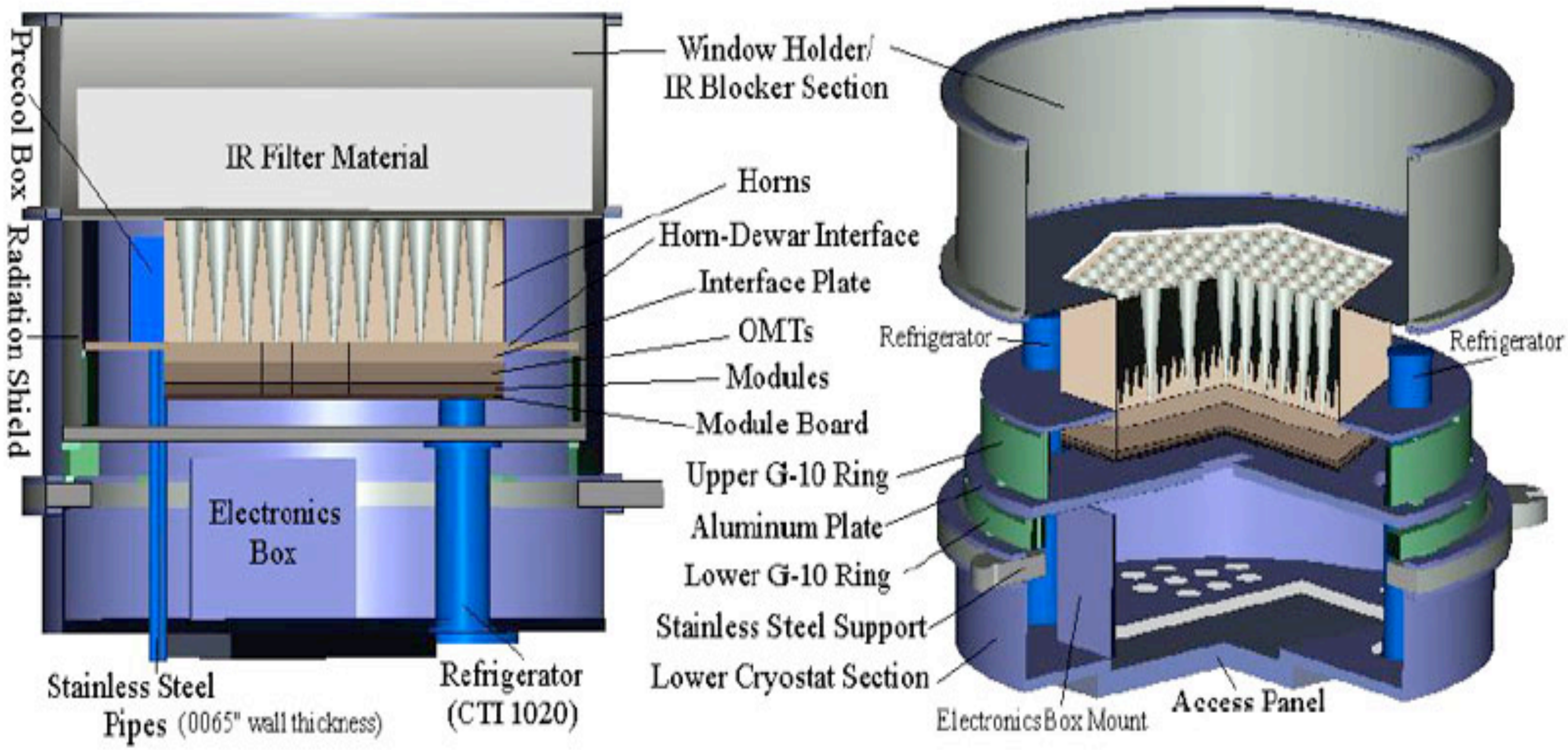


Mitsuguchi-Dragone optics

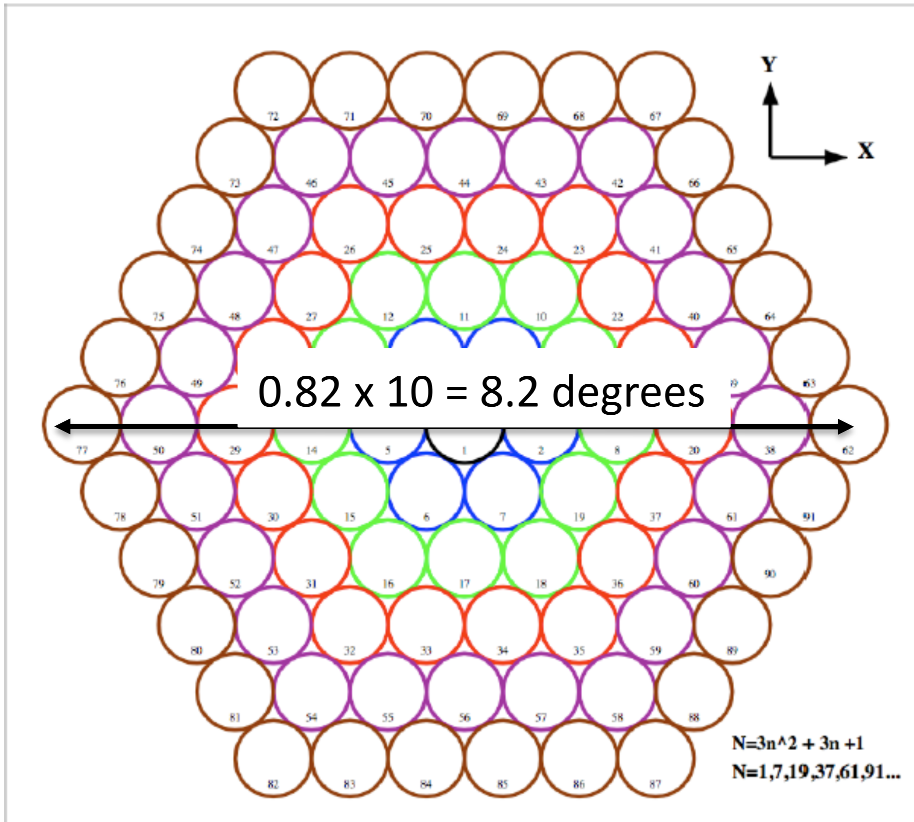
- MD optics
  - Are compact
  - Provide low cross polarization
  - Provide large diffraction-limited field of view



The QUIET cryostat operated at a low temperature (26 K) to minimize noise

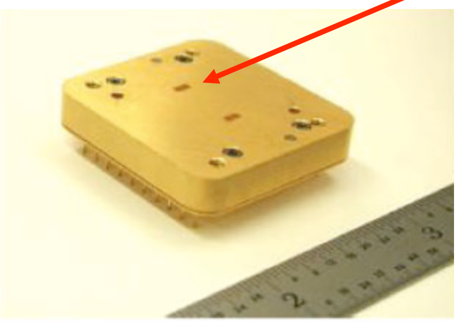


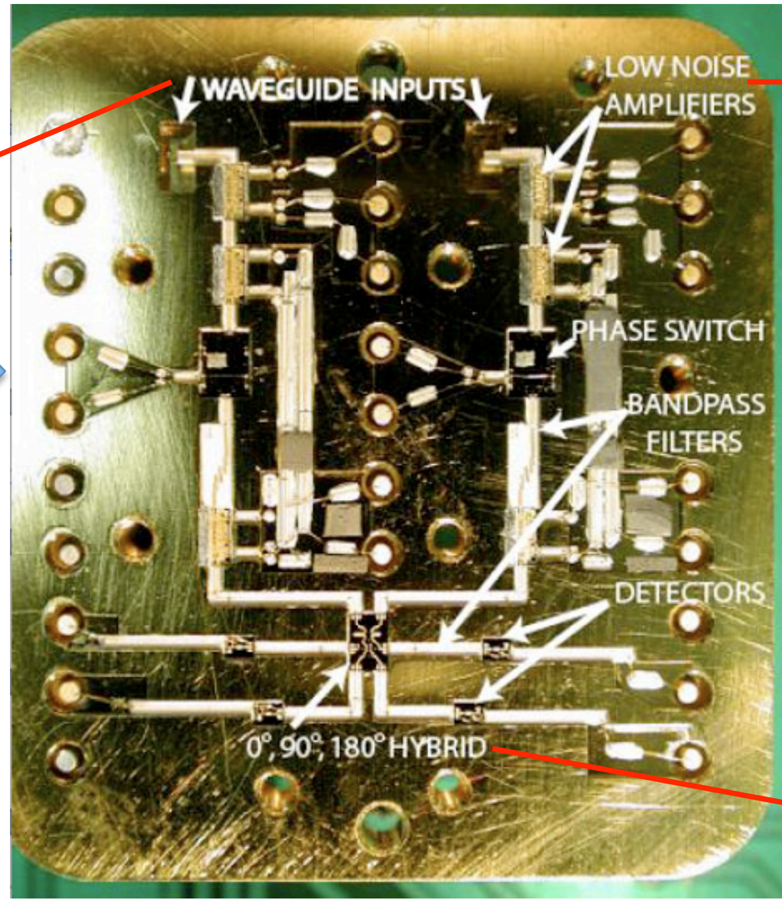
QUIET beam sizes

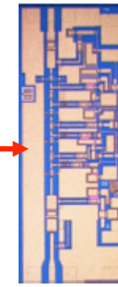


- The horn beam size is
  - 27.3 arcmin for Q-band
  - 12.6 arcmin for W-band
- The distance between the horn beams
  - 1.74 deg. for Q-band
  - 0.82 deg. for W-band
- Field of view of array
  - (1.74 deg between horns)*4 = 7 deg for Q-band
  - (0.82 deg between horns)*10=8.2 deg for W-band.

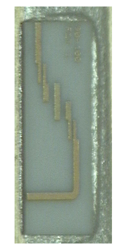
QUIET's miniaturized polarimeter makes large arrays feasible



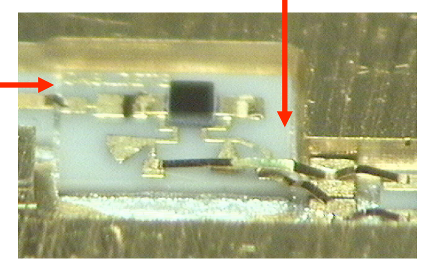


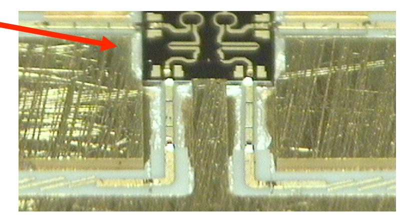


MMIC LNA
InP-based HEMTs
(JPL,
Northrup Grumman)

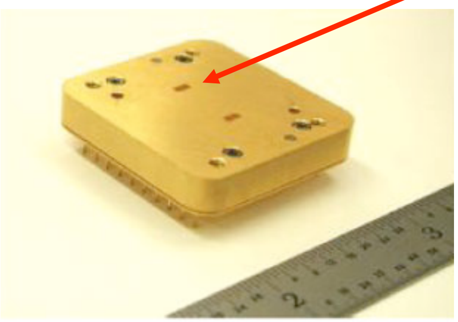


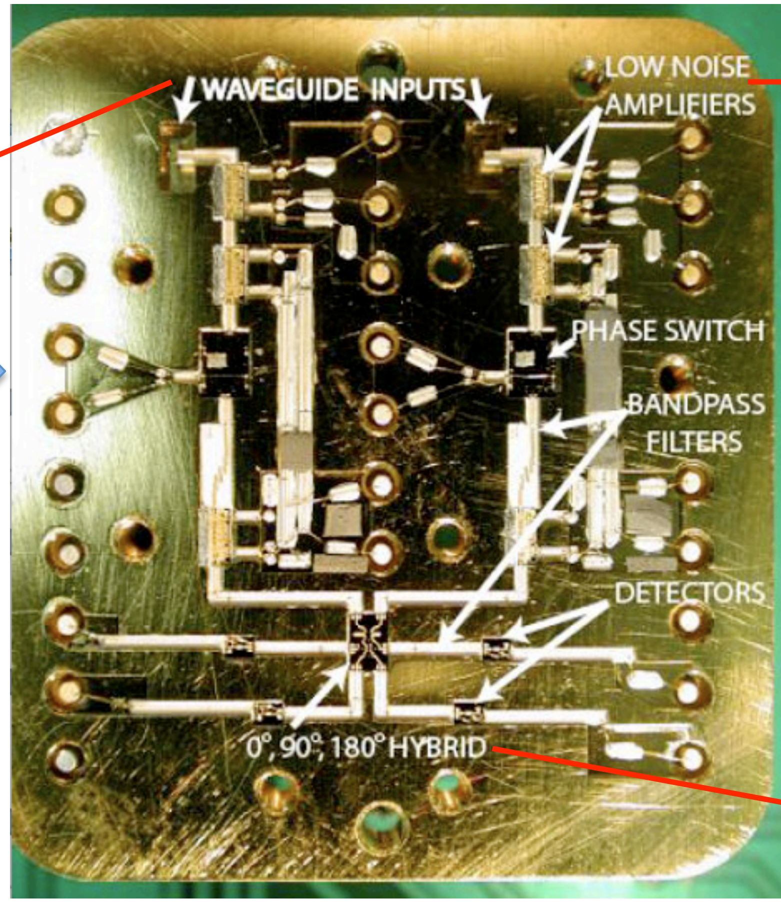
Ribbon bonding capability at Sidet

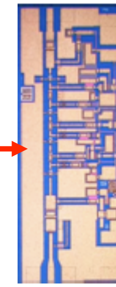




QUIET uses low noise HEMT amplifiers







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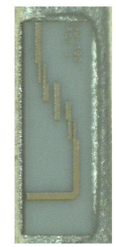

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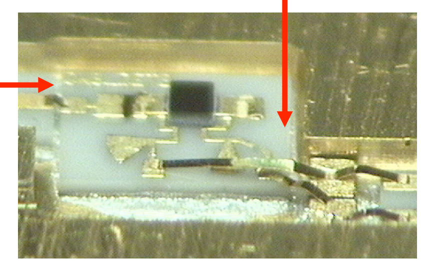
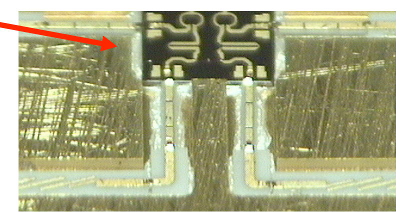
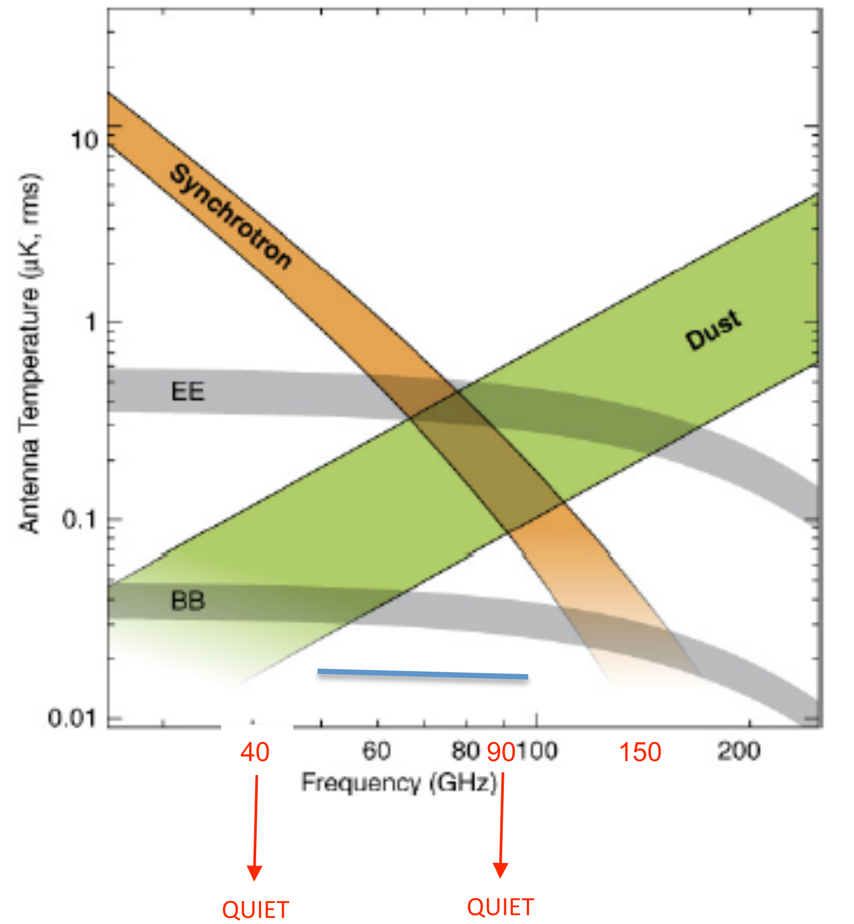


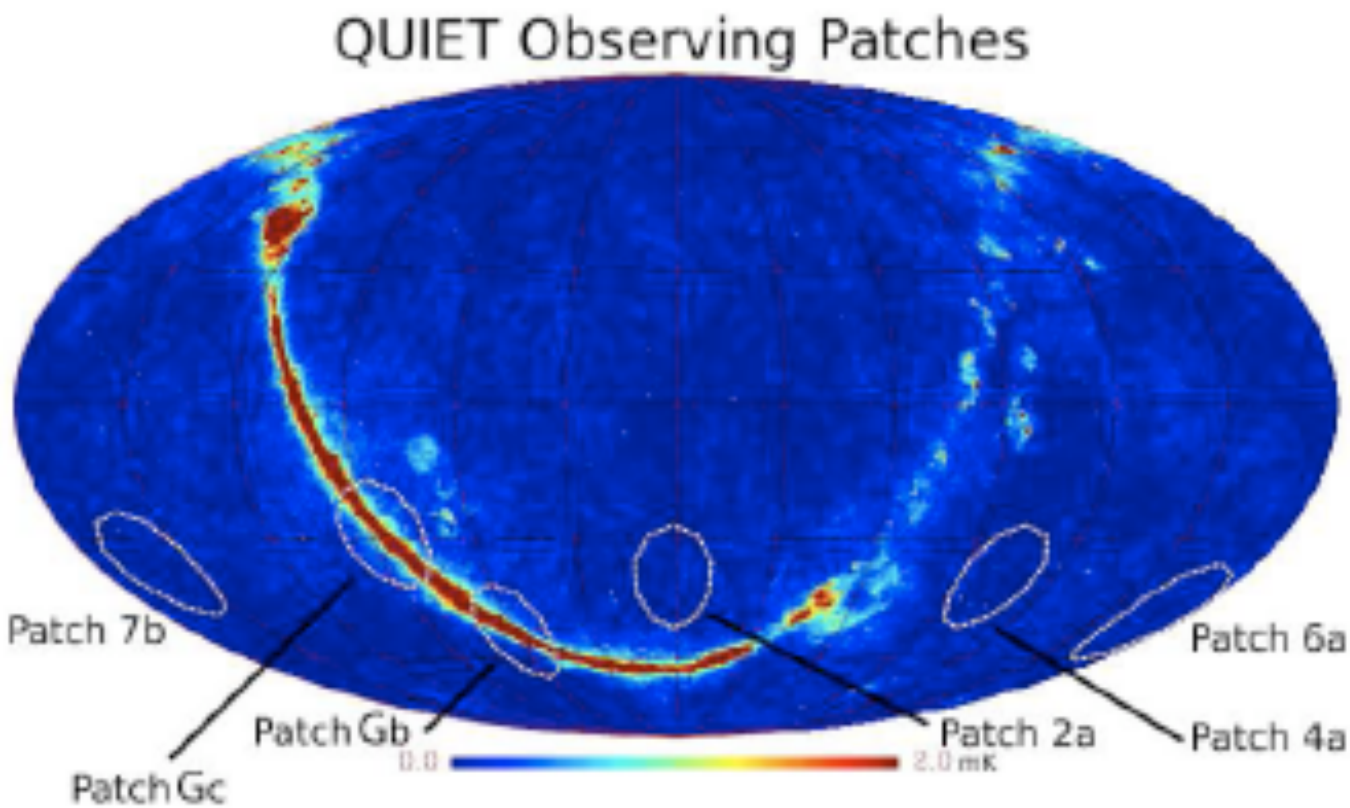


What frequency does QUIET observe at?

- QUIET observed at 40 GHz and 90 GHz
- The polarized foregrounds are a bit different from the unpolarized foregrounds.
- The foregrounds are still poorly understood.
- In addition to actual detection of the E and B modes, CMB polarization experiments strive to better quantify the foregrounds via multifrequency observations.



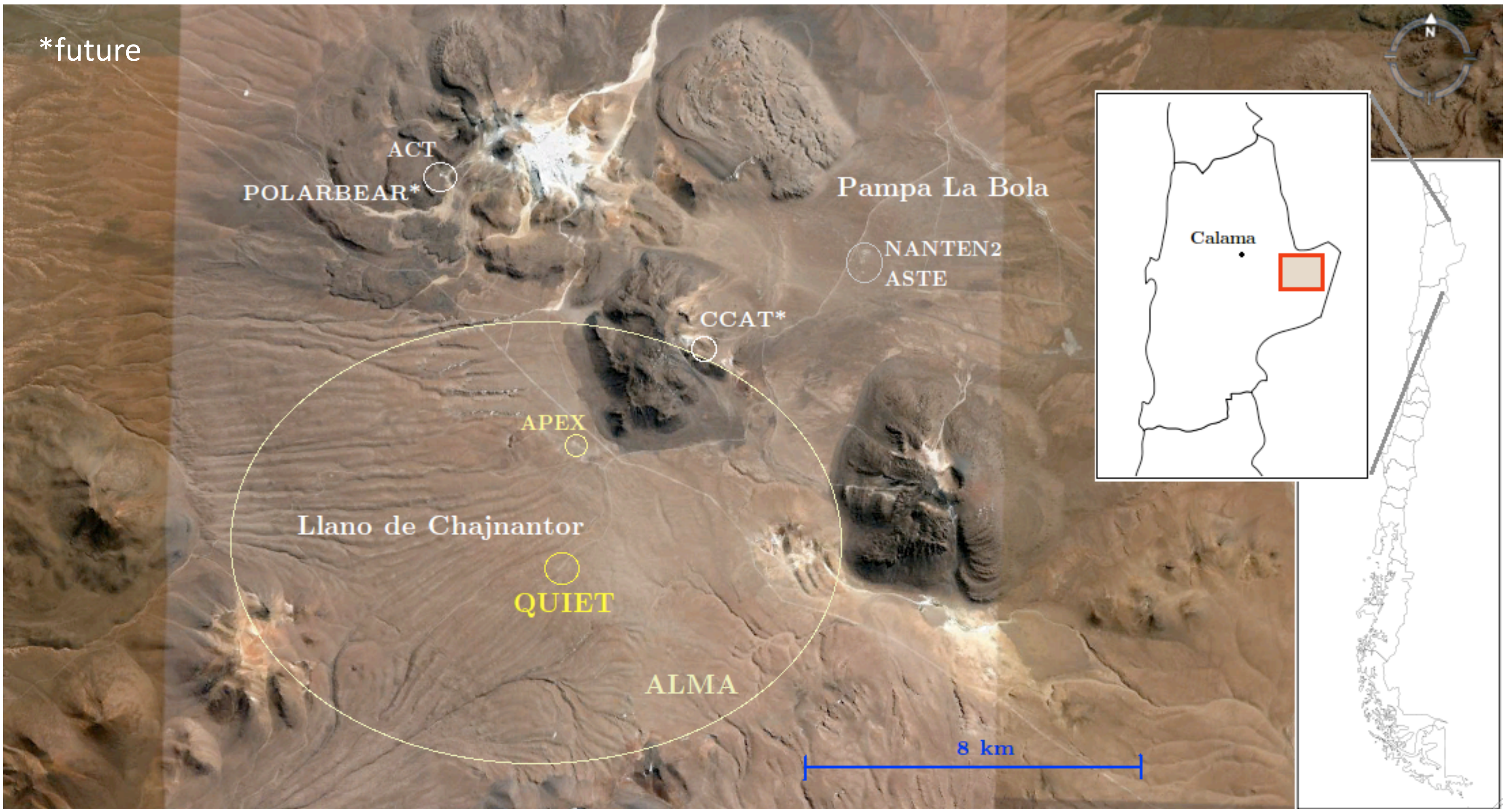
What parts of the sky does QUIET observe?

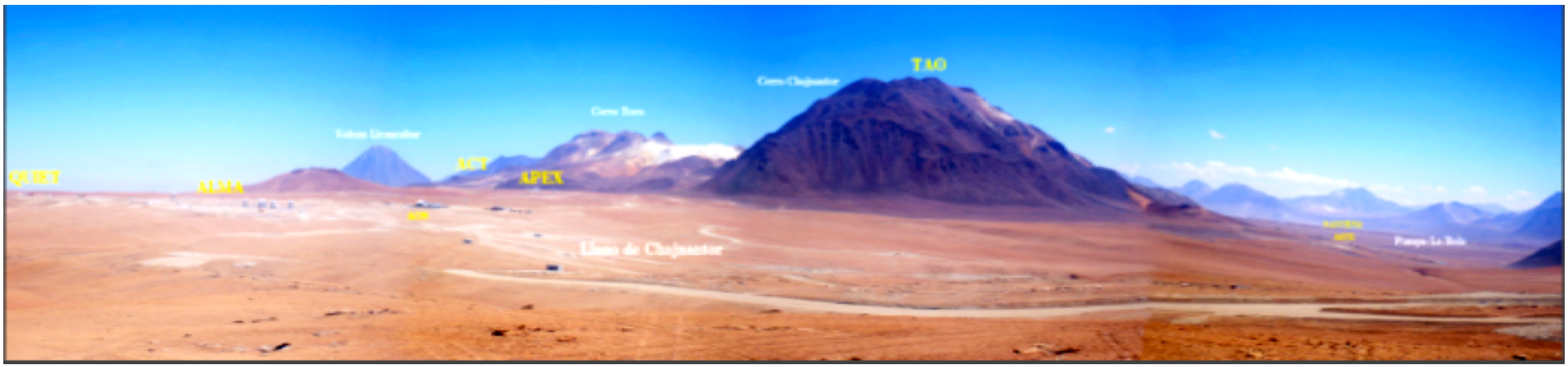


Chronology of telescopes on the Chajnantor Plateau

- 1999, Cosmic Background Imager (CBI)
  - The first radio telescope to start observations at Chajnantor
- 2002, Atacama Submillimeter Telescope Experiment (ASTE) installed at Pampa La Bola
- 2003, Atacama Pathfinder Experiment (APEX)
- 2004, NANTEN2 Observatory (NANTEN2)
- 2007, Atacama Cosmology Telescope (ACT)
- 2008, Q/U Imaging ExperimenT, (QUIET)
- 2009, University of Tokyo Atacama Observatory (TAO)
- Under construction: Atacama Large Millimeter Array (ALMA)
  - The first antennas installed in 2009
- 2011, POLARBEAR
- 2017, Cornell Caltech Atacama Telescope (CCAT)

Telescopes on the Chajnantor plateau





QUIET
ALMA
ACT
APEX
Cerro Chajnantor
TAO
Llano de Chajnantor
Pampa La Bola

Telescopes on the Chajnantor Plateau

- Telescopes on the Llano de Chajnantor site
  - Cosmic Background Imager (CBI)
  - Atacama Pathfinder Experiment (APEX) 12-meter at 5105 meters
  - Atacama Large Millimeter Array (ALMA) 54 12-meter & 12 7-meter at ~5000 meters
  - Q/U Imaging ExperimenT (QUIET) 1.4 meter at 5080 meters

- Telescopes on the adjacent Pampa La Bola site
  - Atacama Submillimeter Telescope Experiment (ASTE) 10-meter at 4865 meters
  - NANTEN2 Observatory (NANTEN2) 4-meter at 4865 meters

- Telescopes on Cerro Toco
  - Atacama Cosmology Telescope (ACT), 6-meter at 5190 meters
  - POLARBEAR, 3.5-meter at 5280 meters

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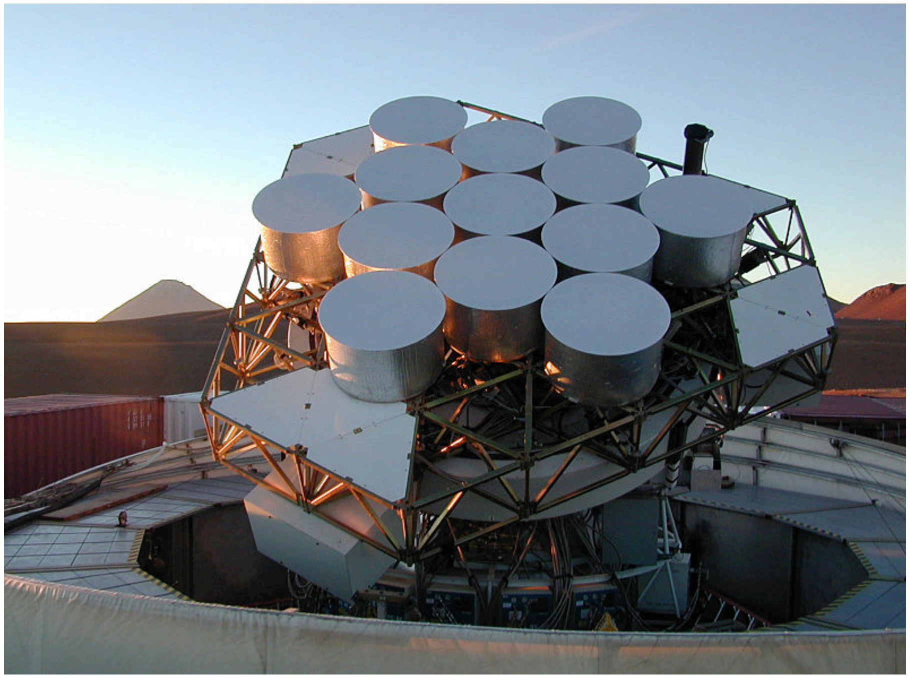
CBI

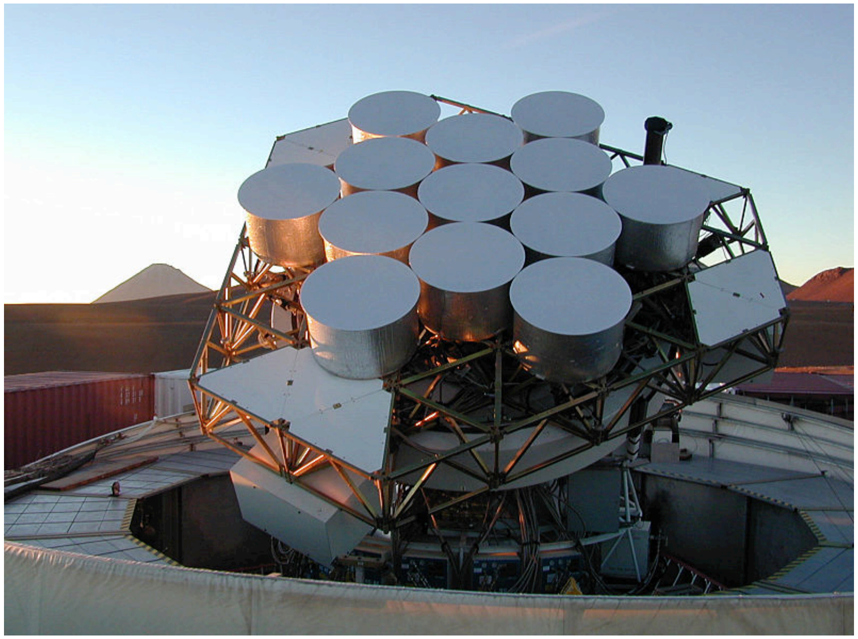
- The Cosmic Background Imager was the first telescope on the Chajnantor plateau
- Operated 1999-2008
  – QUIET moved to the CBI site in 2008 and uses CBI mount
- 13-element interferometer
- Conducted measurements at frequencies between 26 and 36 GHz in ten bands of 1 GHz bandwidth.
- It had a resolution of better than 1/10 of a degree.
- CBI was the first experiment to detect intrinsic anisotropy in the microwave background on mass scales of galaxy clusters
- Detailed E-mode spectrum



CBI

QUIET

- QUIET is at the site CBI was at and uses CBI's mount



CBI

QUIET uses CBI's mount

APEX

- The Atacama Pathfinder Experiment is a modified ALMA prototype antenna and is located at the future site of the ALMA observatory.
- It is designed to work at sub-millimetre wavelengths, in the 0.2 to 1.5 mm range.
- The main dish has a diameter of 12 meters (like the ALMA dishes)
- Uses both bolometer-based and heterodyne instrumentation

APEX

APEX and QUIET

ALMA

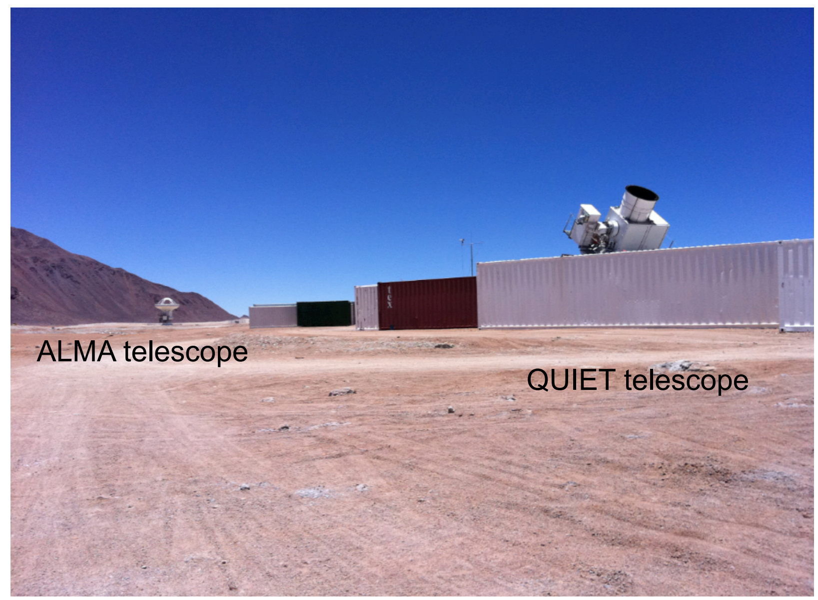
- At least fifty 12-meter antennas for sensitive, high resolution imaging
- Twelve 7-meter antennas comprising the ALMA Compact Array (ACA)
- Array configurations with maximum baselines from approximately 150 meters to 15 km

ALMA today (plus one more – see next slide)

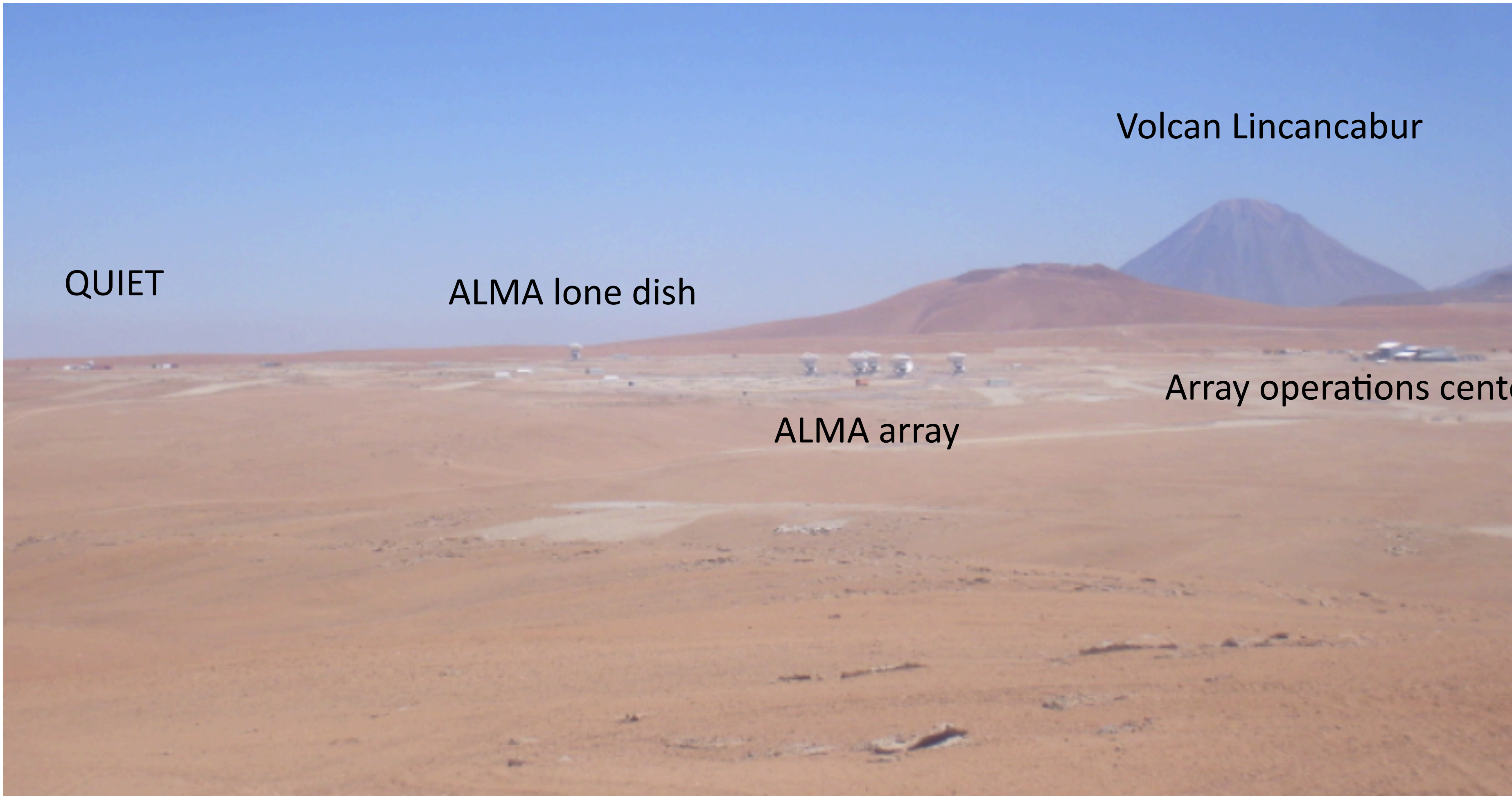
ALMA antenna being moved to location near QUIET

- We saw an ALMA antenna being driven up to the site on the transporter.
- It was located away from the array, quite near to QUIET.

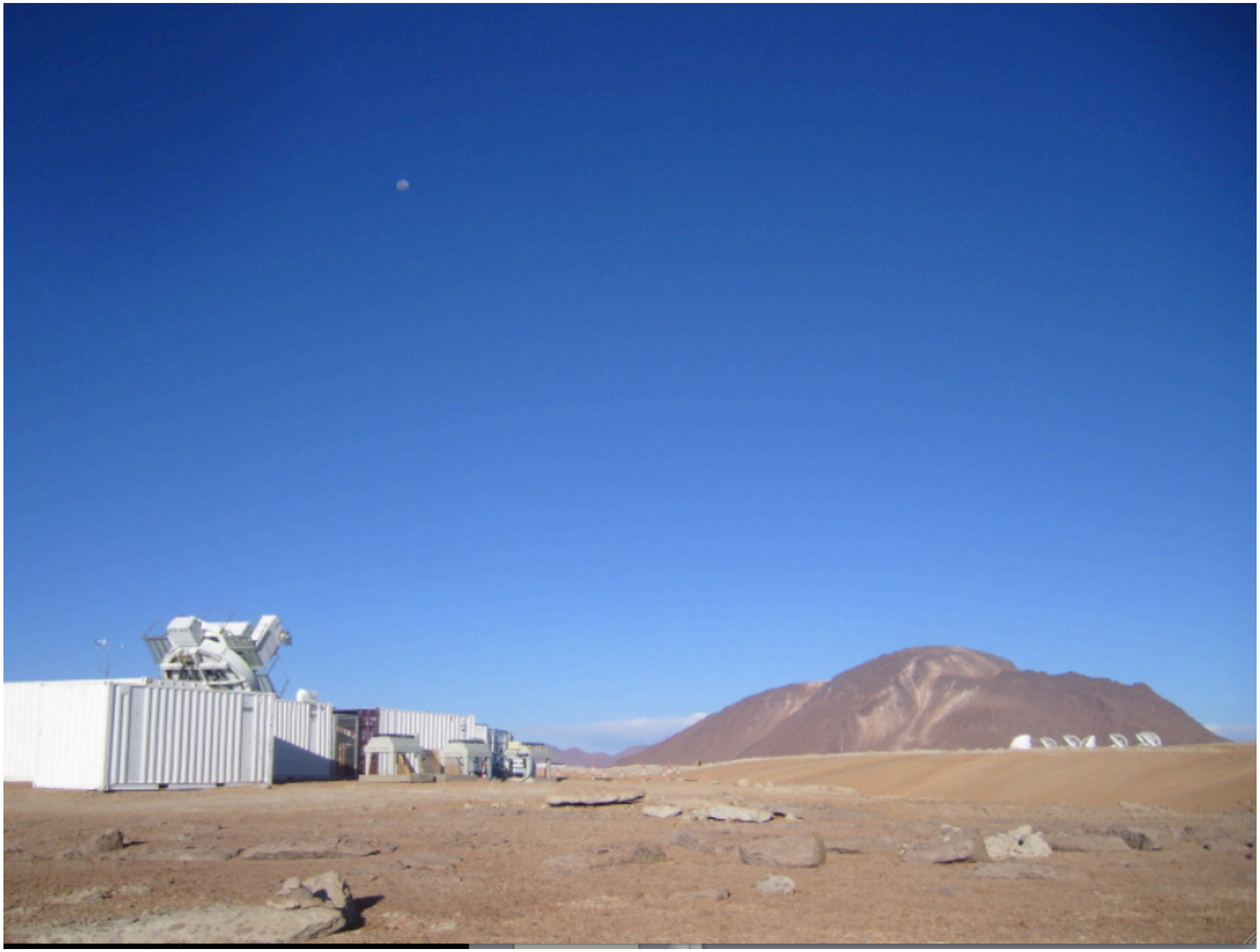
ALMA telescope on transporter



ALMA is close to QUIET



ALMA is close to QUIET



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ASTE

- The Atacama Submillimeter Telescope Experiment is a 10 m submillimeter telescope
- The purposes of the project are to explore the southern sky with submillimeter waves up to 900 GHz, as well as development and on-site evaluation of observation techniques and methods for submillimeter observations.
- Led by NAOJ

ASTE

NANTEN2

- NANTEN is Japanese for “southern sky”
- NANTEN was first at Las Campanas
- In 2004 moved to Pampa La Bola
- The telescope is a 4 m Cassegrain
- NANTEN2 is equipped with coherent receivers covering frequencies from 110 to 345 GHz, 460-490 GHz, and 809-880 GHz.

NANTEN2 (left) ASTE (right)

NANTEN2 (left) ASTE (right)

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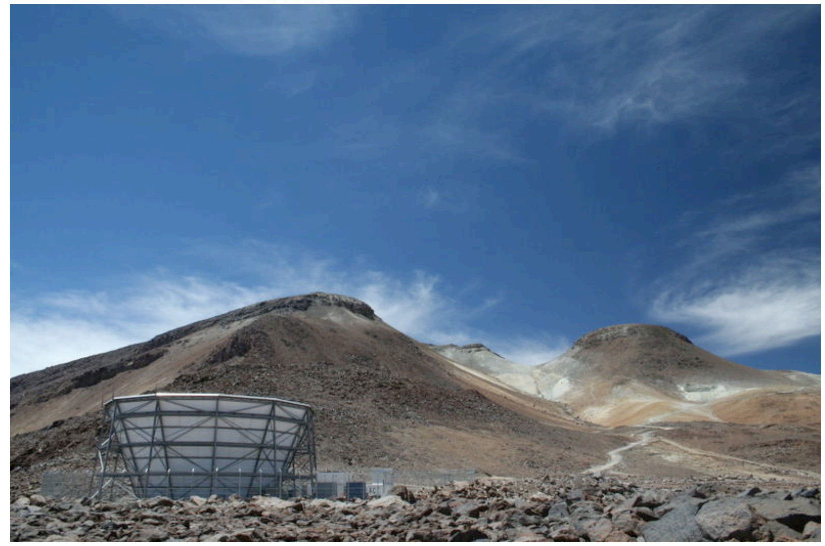
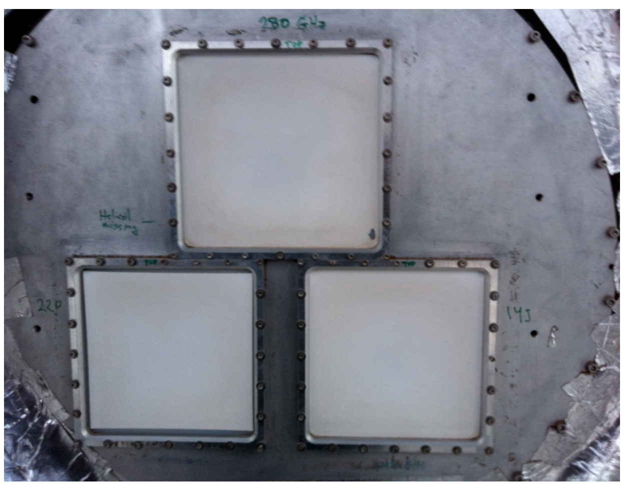
ACT

- The Atacama Cosmology Telescope (ACT) is a six-meter telescope on Cerro Toco.
- ACT is looking for SZ clusters at 145 GHz, 215 GHz, and 280 GHz
- Uses TES bolometers

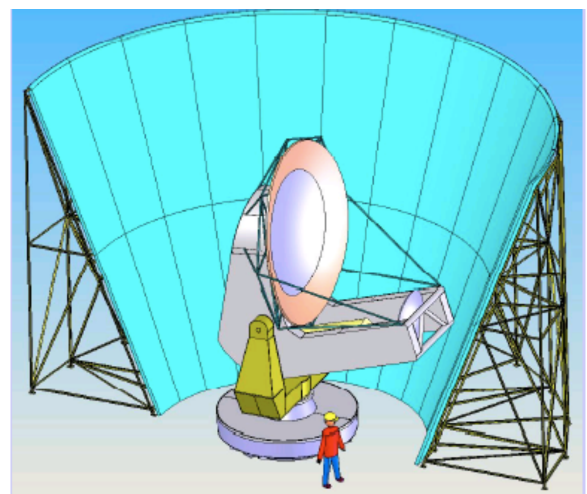




POLARBEAR

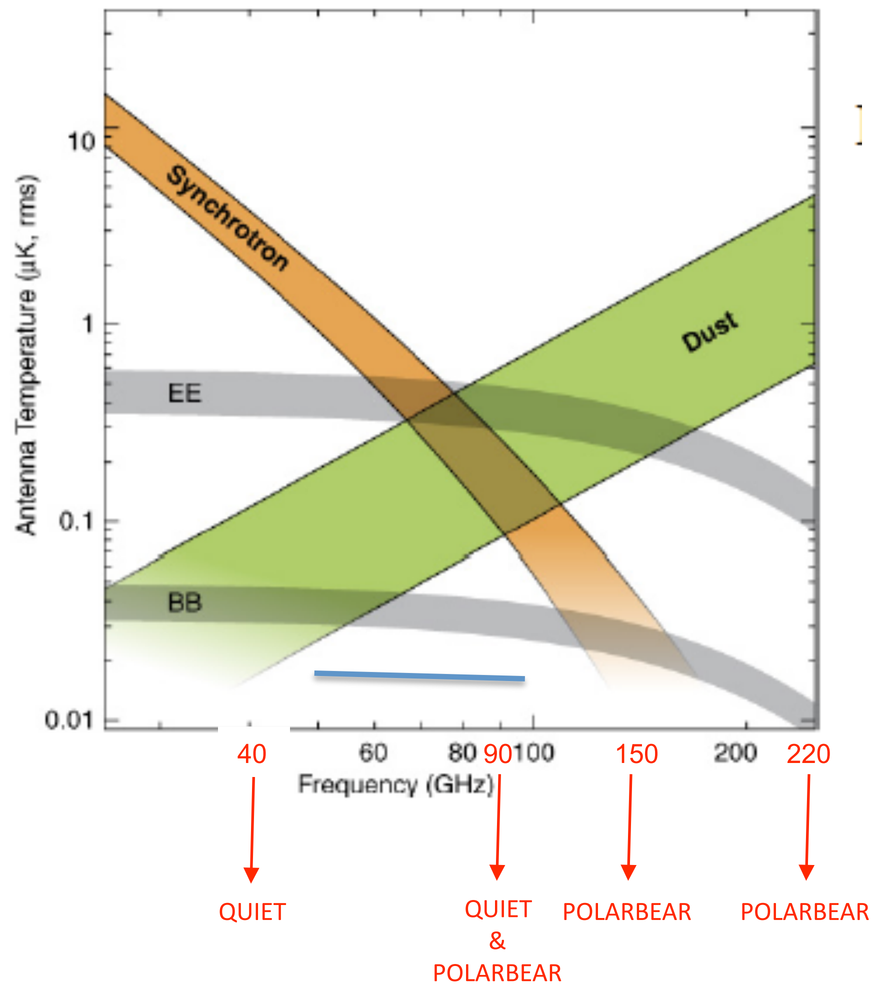
- POLARBEAR is a 3.5-meter off-axis Gregorian telescope that will be sited on Cerro Toco near ACT.
- POLARBEAR has been designed specifically to search for the B mode signal from both gravitational waves and from gravitational lensing.
- The focal plane houses ~1000 polarization sensitive antenna-coupled TES detectors read out with the Digital Frequency Domain Multiplexer.

POLARBEAR at Cedar Flat, CA. CARMA in background.
Now waiting in Antofagasta, Chile to be installed on Cerro Toco



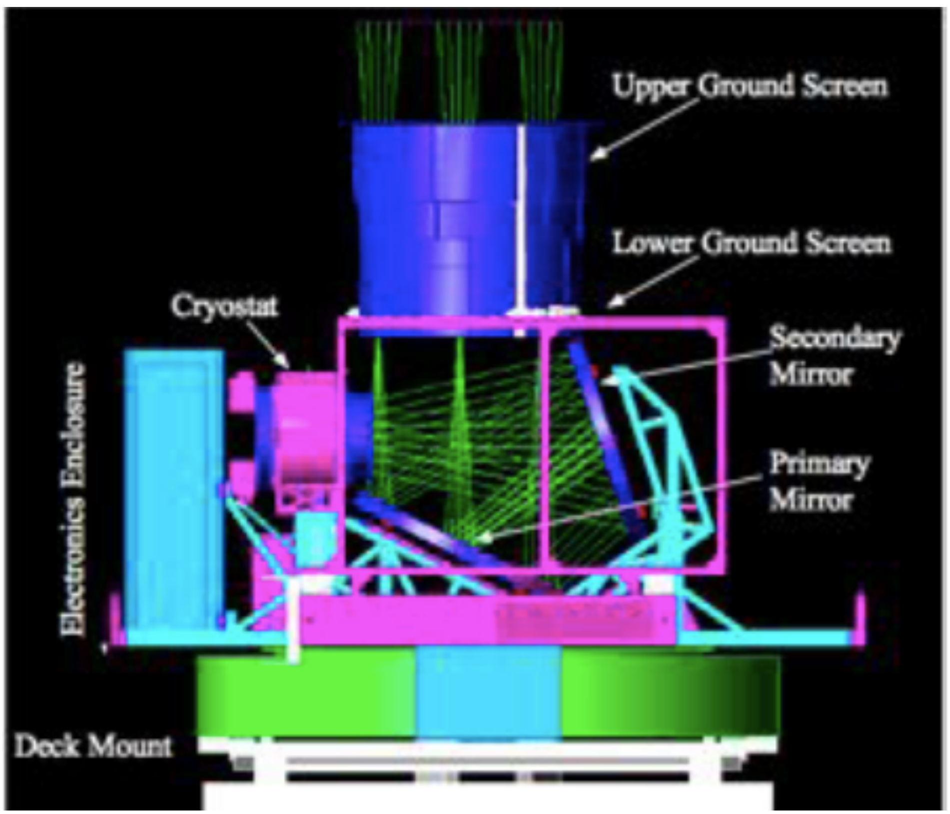
POLARBEAR

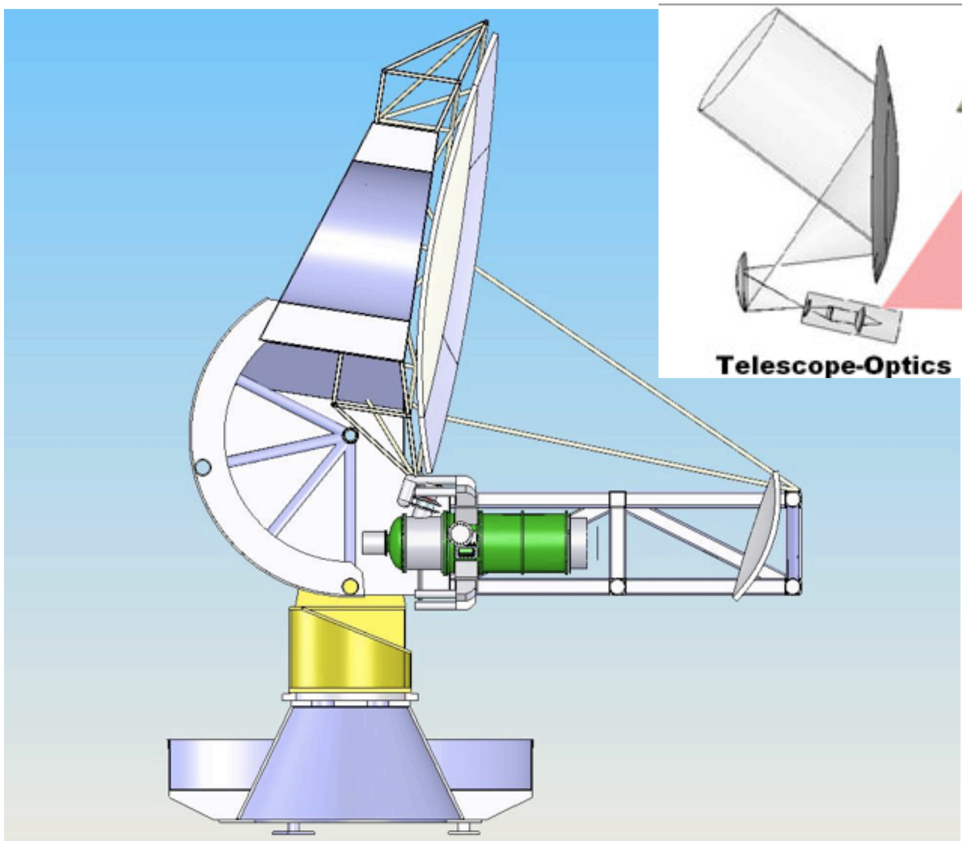
- POLARBEAR and QUIET will observe the same sky patches.
- Together they will have frequency bands at 40, 90, 150, and 220 GHz giving broad coverage of galactic foregrounds and a valuable cross-check by comparison of polarization maps.
- QUIET (40 and 90 GHz)
- POLARBEAR (90, 150 and 220 GHz)



Compare POLARBEAR and QUIET optics

Both are offset dual-reflector antennas





QUIET
Crossed Mizuguchi-Dragone

POLAREAR
Gregorian Mizuguchi-Dragone

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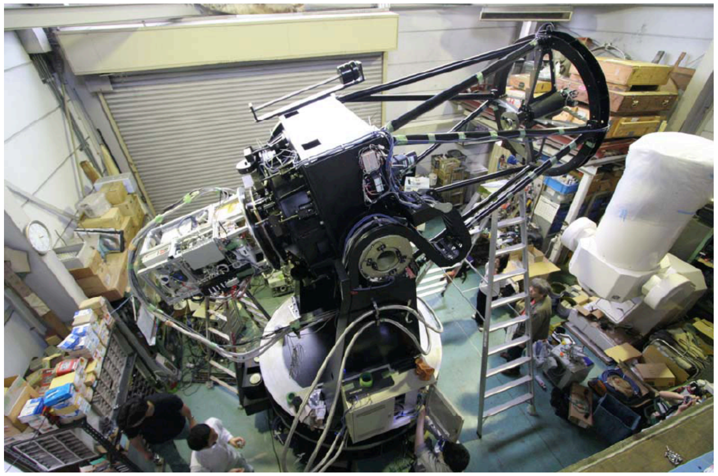
- Telescopes on Cerro Chajnantor
  - University of Tokyo Atacama Observatory (TAO) *Infrared*, 1.0-meter for miniTAO, 6.5-meter for TAO (planned 2014) at 5640 meters
  - Cornell Caltech Atacama Telescope (CCAT), 25-meter at 5600 meters.

TAO

- MiniTAO, at 5640 meters at the summit of Cerro Chajnantor, is the highest telescope in the world.
- MiniTAO is a 1-meter telescope.
- The mid-IR camera on miniTao can access the 30-micron wavelength region from the ground for the first time.
- TAO, a 6.5-meter telescope, is planned for the future
- At summit, it's cold and windy (note we all have our O_2 on our backs).



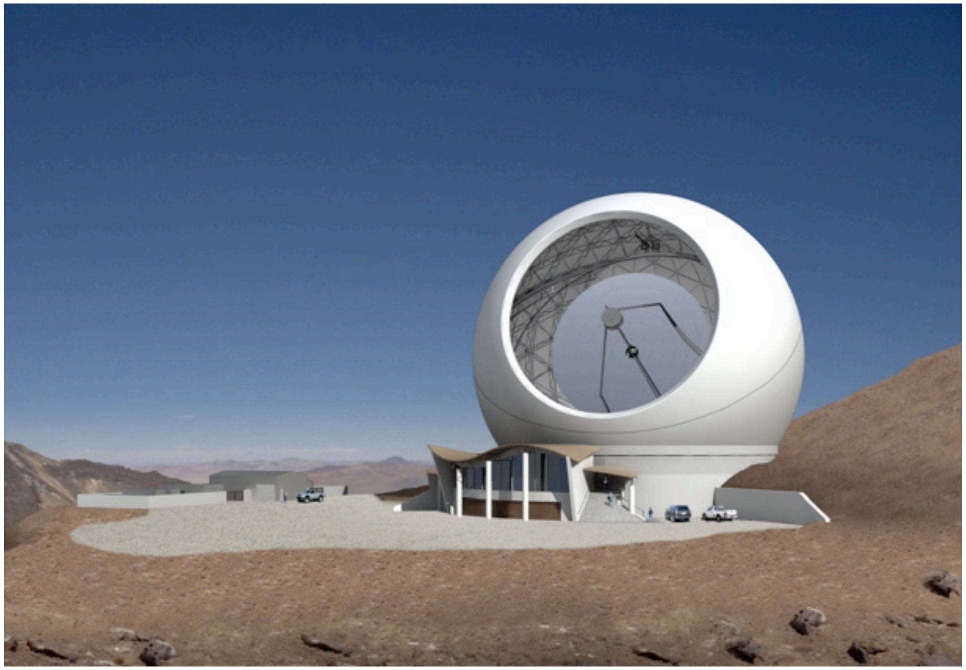
miniTAO

TAO

Chile issued a postage stamp commemorating the inauguration of mini TAO

CCAT

- CCAT will be a 25 meter telescope for submillimeter astronomy located at 5600 m altitude on Cerro Chajnantor in northern Chile.
- CCAT was ranked the highest priority among medium scale, ground based projects by the Astro2010 survey.

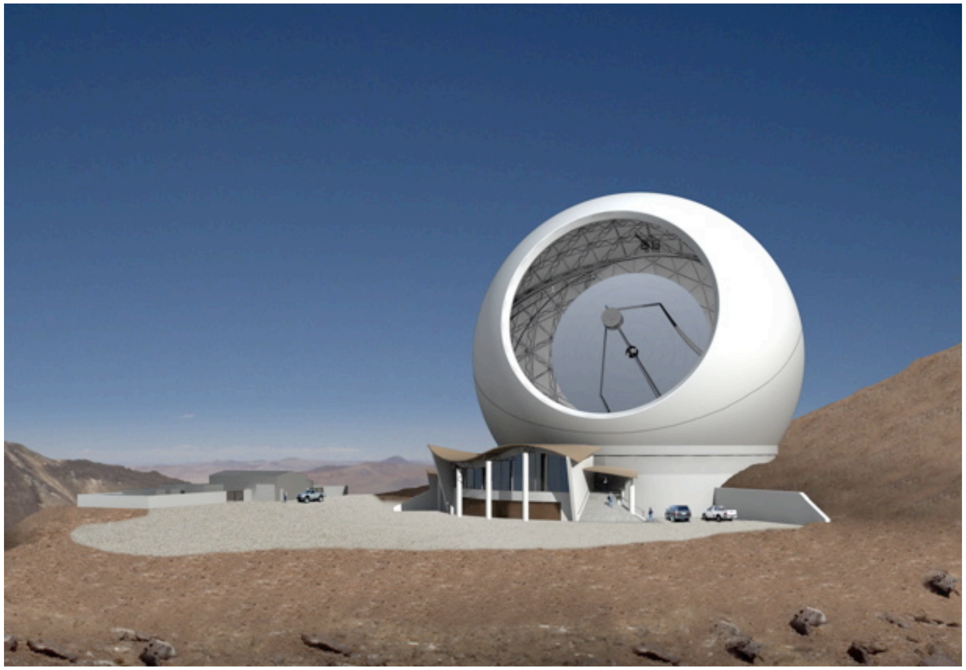


Artist's conception of CCAT

CCAT

- Science objectives include galaxy formation and evolution throughout the history of the Universe; the hot gas pervading clusters of galaxies; star formation, protoplanetary disks, and debris disks in the Milky Way galaxy; and Kuiper belt objects in the outer reaches of the Solar system.

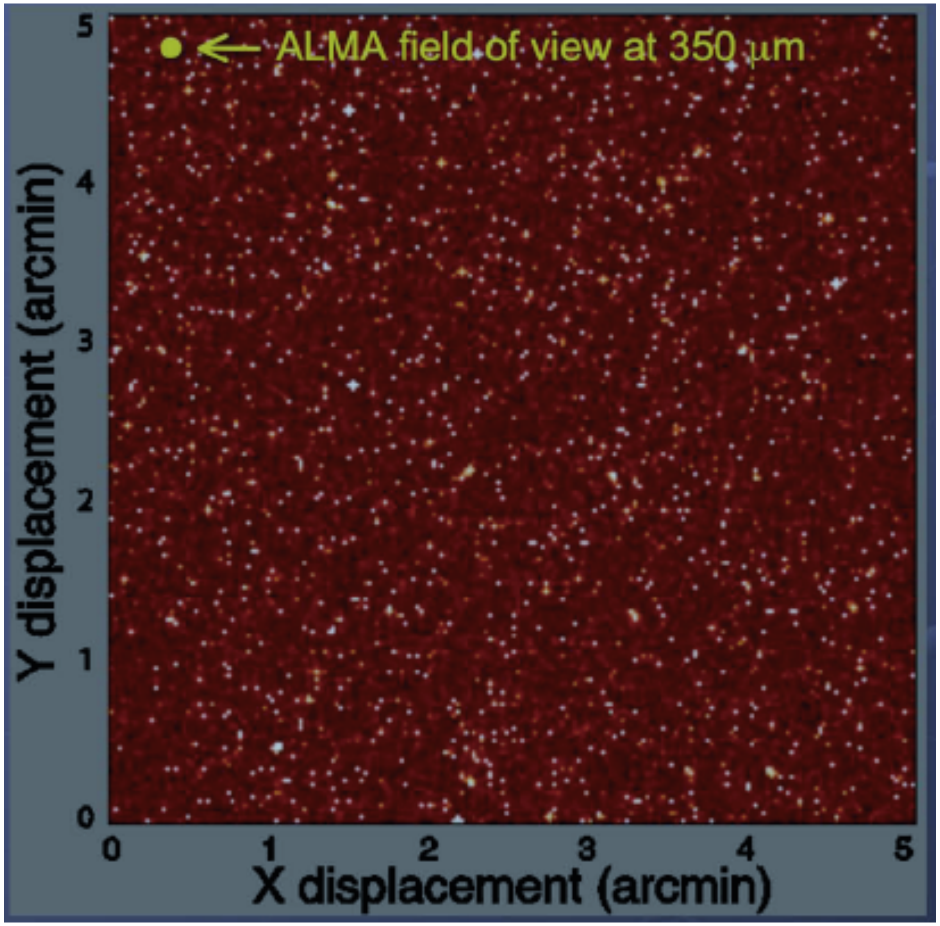
- Instrumentation will include bolometer cameras, direct detection spectrometers, and heterodyne receiver arrays.



Artist's conception of CCAT

CCAT

- Complementary to ALMA
- Detectors designs include MKIDs (Microwave Kinetic Inductance Detectors)



CCAT SITE

- To evaluate environmental and observing conditions at the CCAT site, a submillimeter tipper, a weather station, and other instruments were deployed there in 2006 May.

- We added another solar panel when I was there.

- The tipping radiometer measures the atmospheric transparency in the continuum at 350 um and 200 um.

- Estimating the transparency at other wavelengths requires a model, such as ATM.

Beautiful, but scary, drive up to CCAT site & TAO

Camaraderie

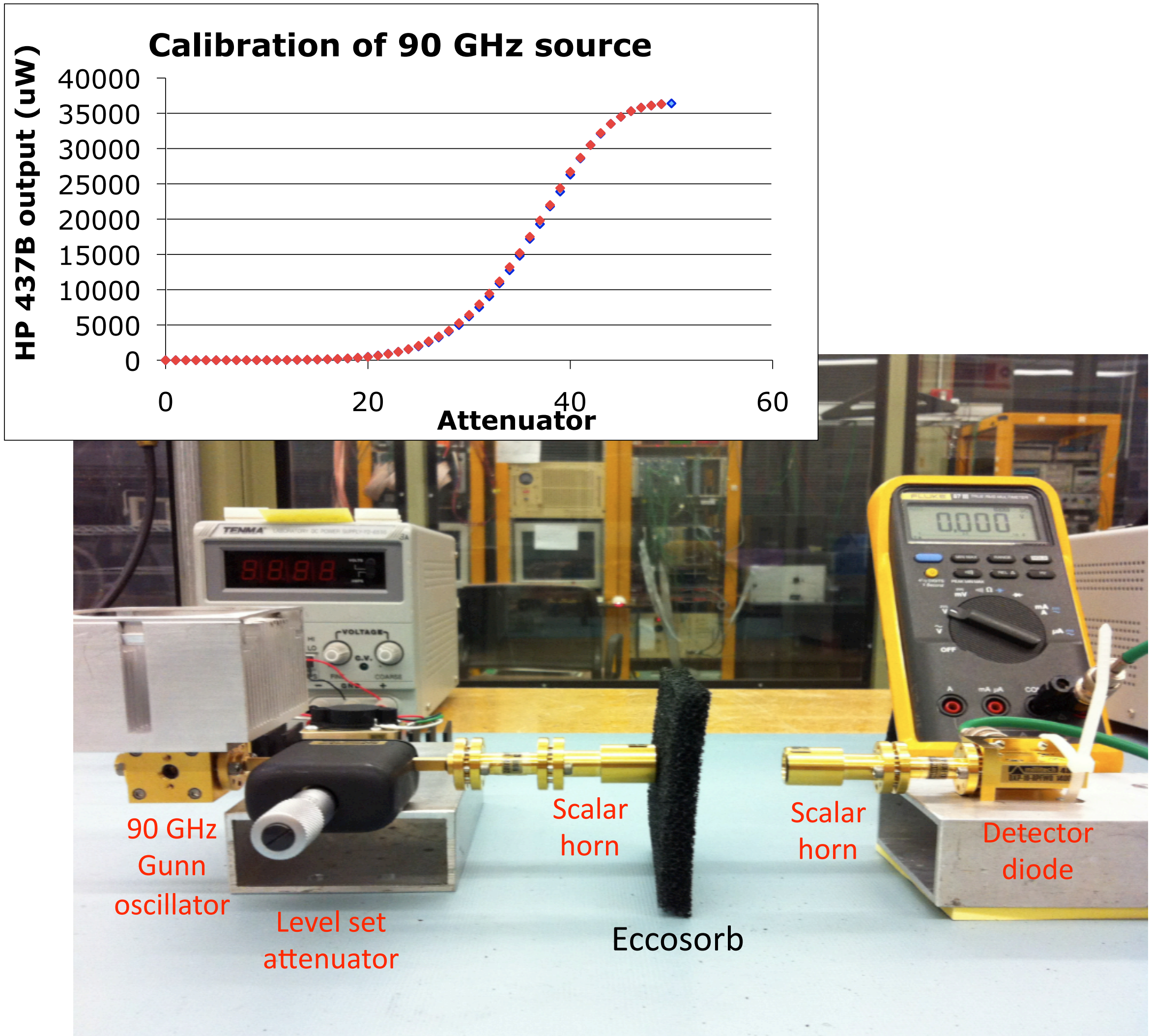
- Not only is it simply interesting to know that there are more and more telescopes at Chajnantor, it is also nice to know there is a strong camaraderie among projects.
- Just in the 2 weeks I was there, I saw at least 4 examples
    - QUIET used one of ALMA's truck cranes to remove the upper ground screen,
    - QUIET helped both ACT and APEX move a radiometer to their sites
    - QUIET routinely accesses APEX weather information

Removing QUIET's upper ground screen with an ALMA crane

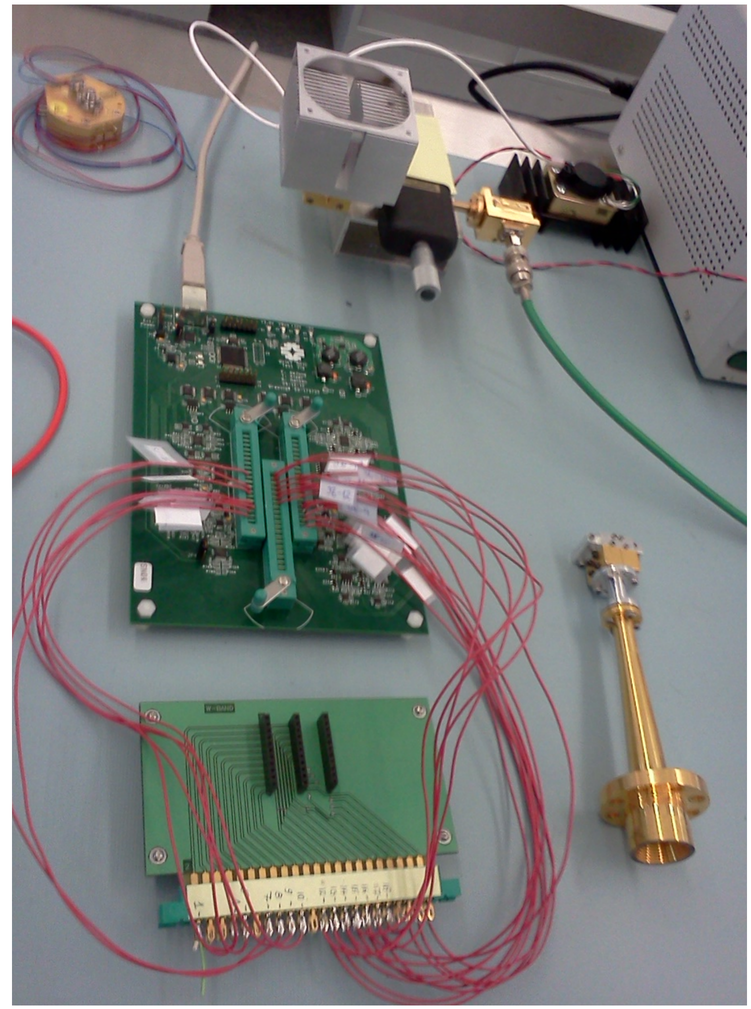
The best is yet to come!

QUIET@ Fermilab

QUIET@Fermilab: Warm Microwave Test Stand



FNAL Bias Board

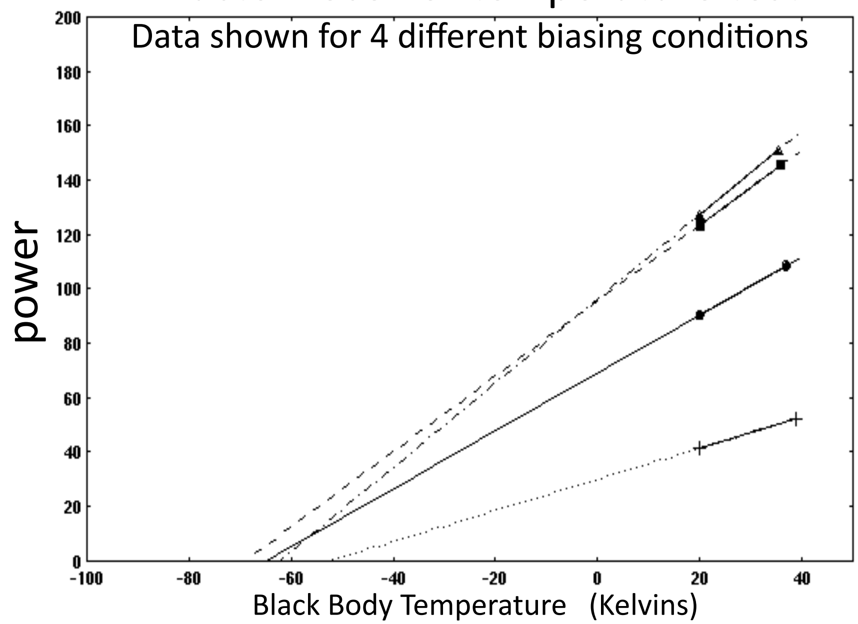


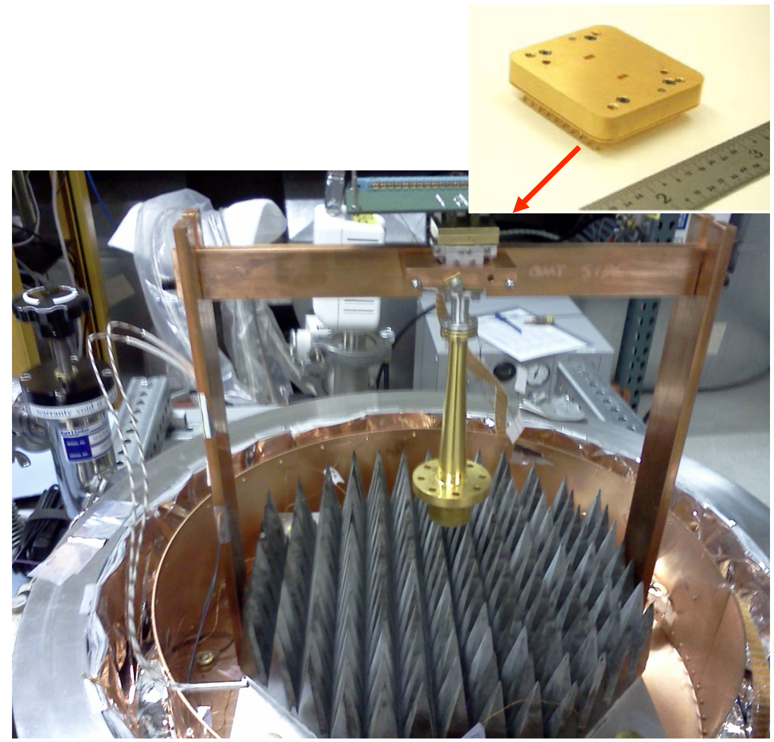
Used to measure transmission, reflection, and absorption of materials and receiver noise

QUIET@Fermilab: Cold Microwave Test Stand

- Our receiver *noise* goal is ~ 40K or better per module.
- Our *sensitivity* goal is 200 uK*sqrt(seconds) per module ->400 modules, -> 1600 detector diodes
- Sensitivity = (Noise Temp)/(sqrt(N*Band Width*B))
  where N = 4, since we have 4 diodes per module, B = 90%, is a blanking factor, since we avoid samples that are near where the phase switches.
- So we need the bandwidth to be about 10 GHz.

Y factor receiver temperature test

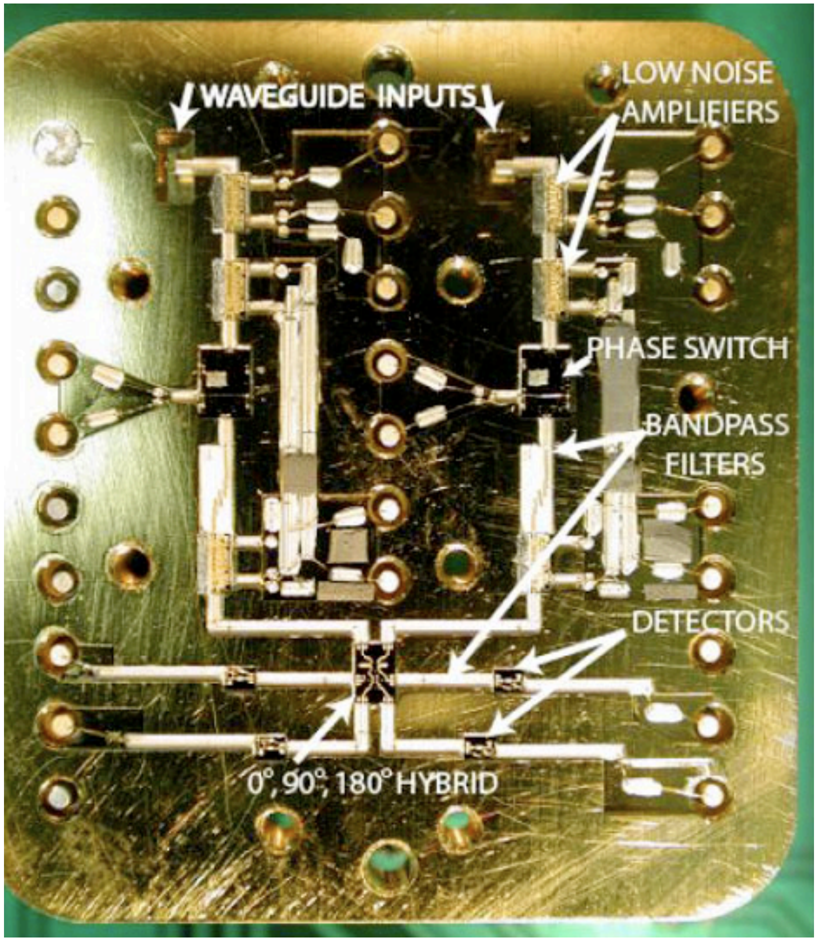




The Fermilab Large Cold Black Body Teststand for CMB R&D.

Overall Plan for QUIET (Q/U Imaging ExperimenT) receiver module redesign

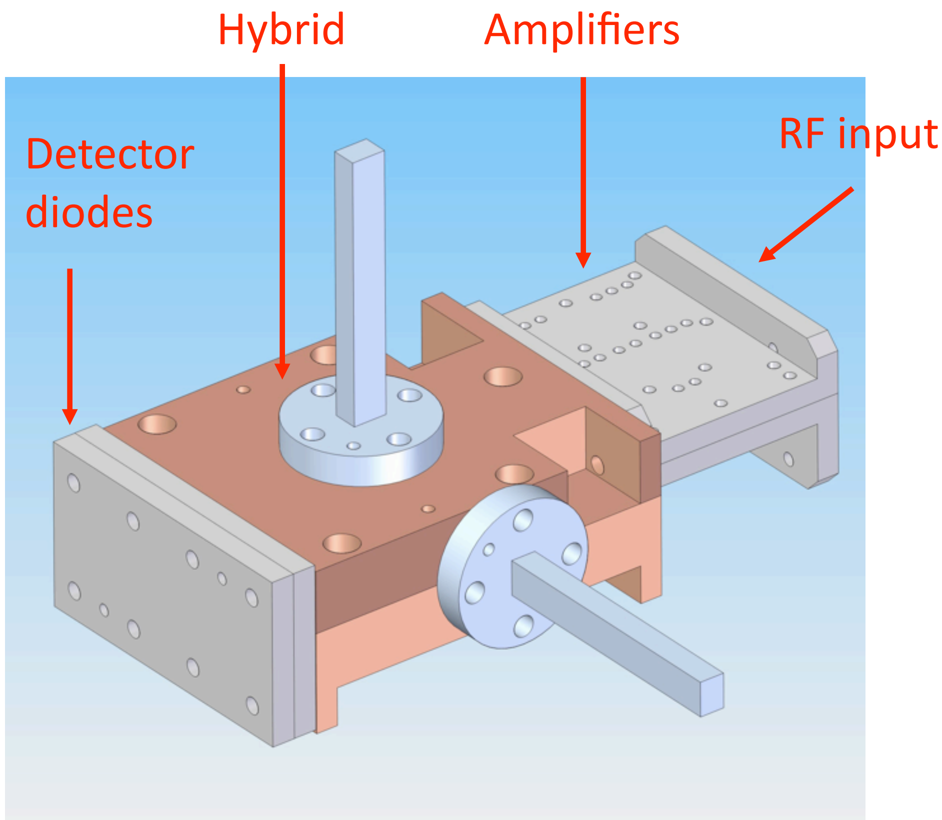
- We plan to redesign the original W-band receiver module shown here.
- Here, traditional waveguide block components and connections have been replaced with strip-line coupled devices.
- Here, the receiver is a "black box". One only has access to the two RF inputs and the four detector diode outputs.



Dimensions = 3.2 x 2.9 cm

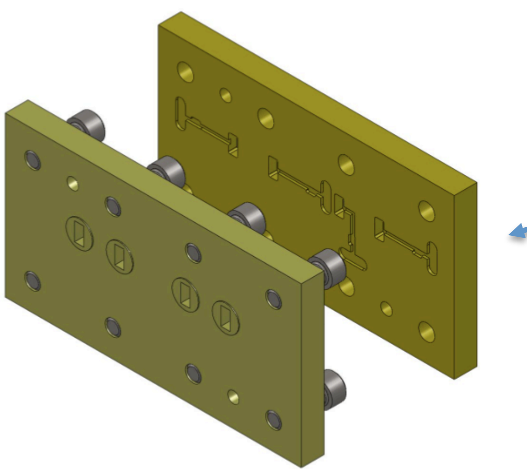
Overall Plan for QUIET module redesign

- However, the receivers didn't perform as well as expected.
- In order to determine where the unexpected noise originates, a split block is being built.
- With a split block, the 3 functions (amplifiers, hybrid, and detector diodes) are split into 3 modules that can be bolted together.
- This design makes it possible to probe the inputs and outputs of each stage.

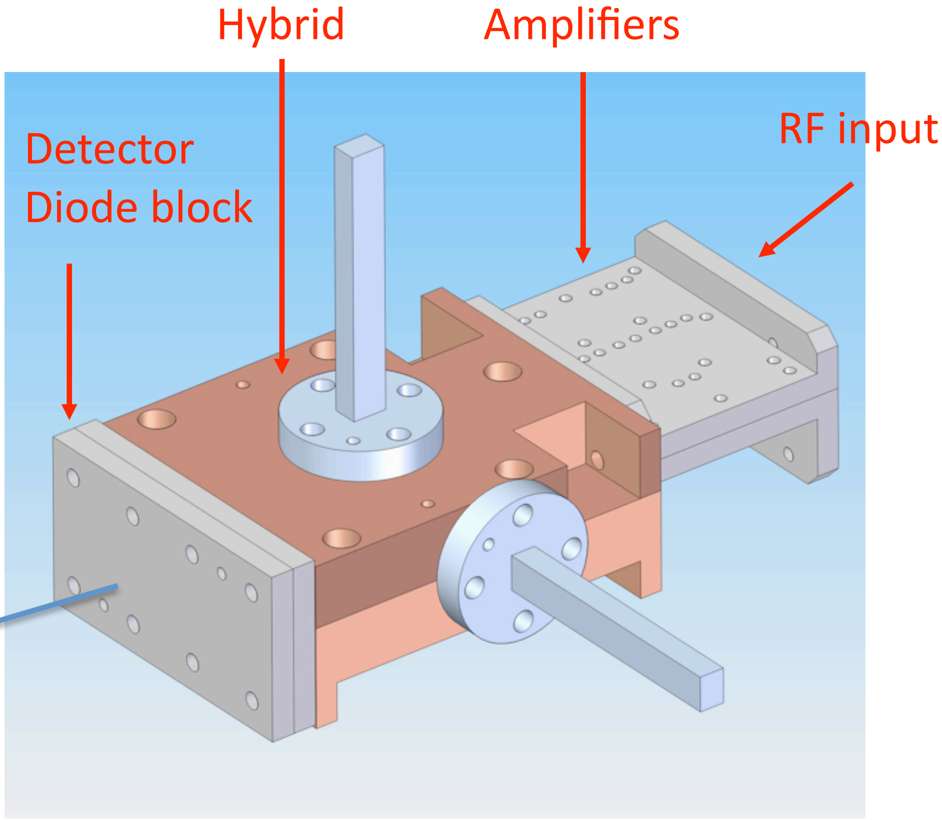


Overall Plan for QUIET module redesign

- We (FNAL) are working on the Detector Diode Block.
- The following slide gives a bit more information about what's inside the Detector Diode Block.

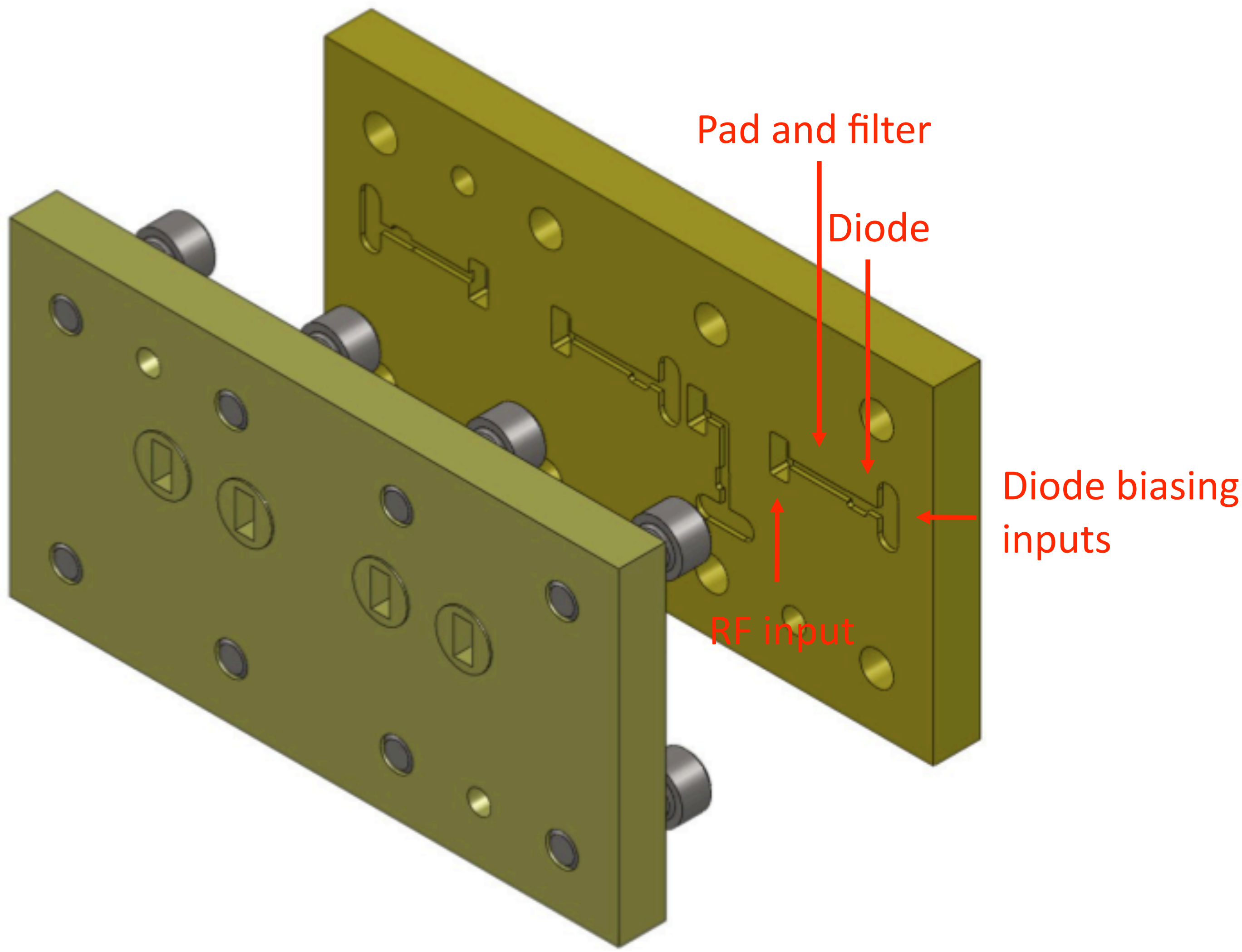


Detector diode block



Split block

Detector diode block
Solid model



QUIET-II Module New Design

Improved Noise Reduces Channel Count and Cost

QUIET-II aiming for ~ 10 $\mu K \cdot \sqrt{s}$ sensitivity with a ~500 module array

Prototype Modules Have Been Fabricated and currently under testing.