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NASA/NSTA Web Seminar Series

How Telescopes Have Changed Our View of the Universe

Webinar III: **From Sound Waves to Microwaves: "Listening" to the Oldest Light of the Universe with the Planck Mission**

Presenter: **Dr. Jatila van der Veen**

Wednesday, December 16, 2009

Resources from this seminar can be found at: http://planck.caltech.edu

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International Year of Astronomy 2009 (IYA)

World-wide celebration of astronomy, its contribution to society and culture

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How Telescopes Have Changed Our View of the Universe

What this series offers you:

• Use science from cutting edge NASA telescopes to illustrate to your students the process of discovery and scientific investigation;

• Learn about telescopes across the electromagnetic spectrum and how advances in technology enable leaps in science;

• Trace how our understanding of the physical universe has progressed over history.

How Telescopes Have Changed Our View of the Universe

Web seminar series:

I. Anti-matter Eyes on the Gamma-Ray Skies — Nov 12

II. A Century of Cosmic Surprises — Dec 08

III. From Sound Waves to Microwaves: "Listening" to the Oldest Light of the Universe with the Planck Mission — Dec 16

PLANCK Education and Public Outreach

From Sound Waves to Microwaves: "Listening" to the Oldest Light of the Universe with the Planck Mission

Have you ever looked up on a clear night and wondered, *"Where did it all come from?"* Wondering about the origin of the universe has been central to humankind since time immemorial! Today scientists are peering almost back to the Big Bang itself, with the amazingly sensitive detectors aboard the Planck Mission, measuring the Cosmic Microwave Background (CMB) radiation. - the oldest light we can observe. The variations in this ancient light, which are measured today as millionths of a degree above and below the background temperature of space (2.73 Kelvin), tell us about the acoustic oscillations in the early universe, which seeded the formation of the largest structures we observe in the universe today.

Presented by:

Dr. Jatila van der Veen

Education and Public Outreach Coordinator for the Planck Mission, JPL/NASA,
Visiting Project Scientist, Experimental Cosmology Lab and Lecturer, College of Creative Studies,
University of California, Santa Barbara

NSTA WEB SEMINARS
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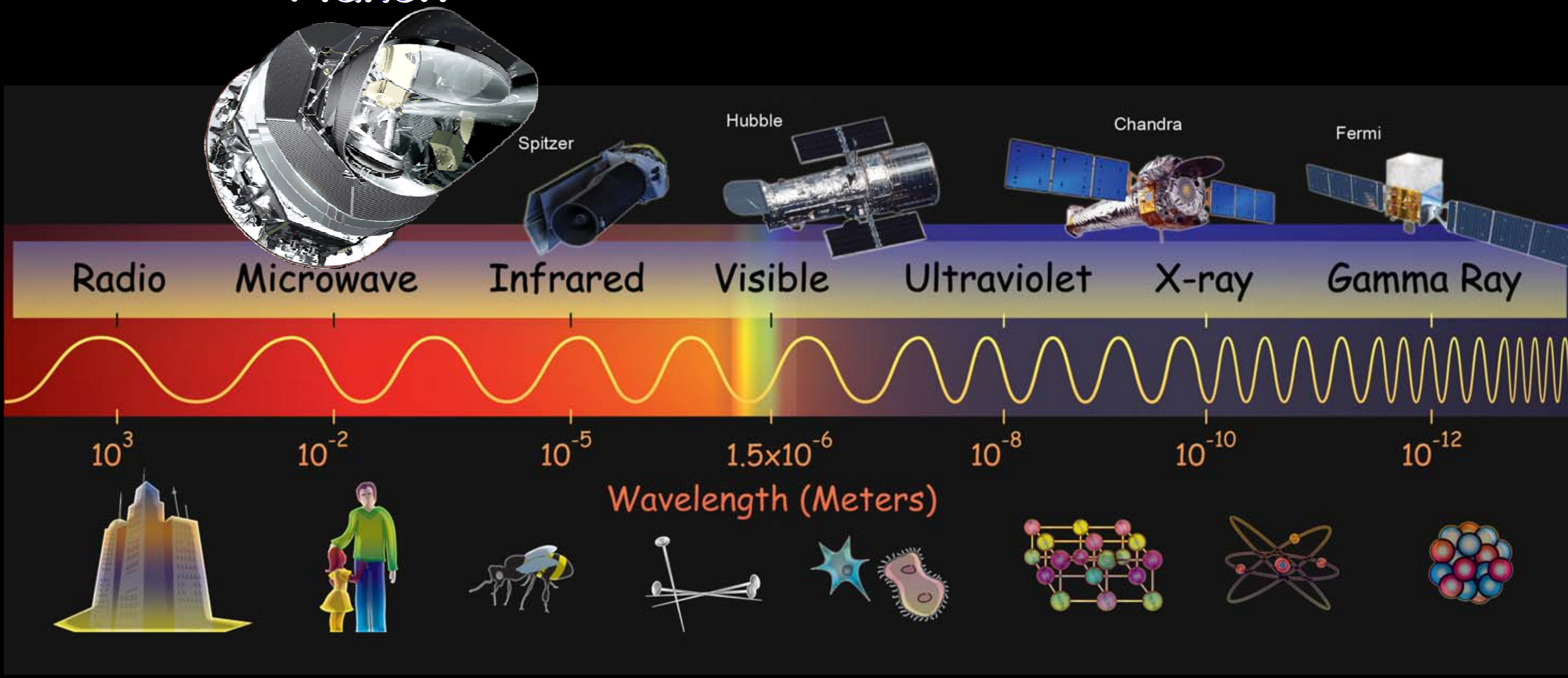
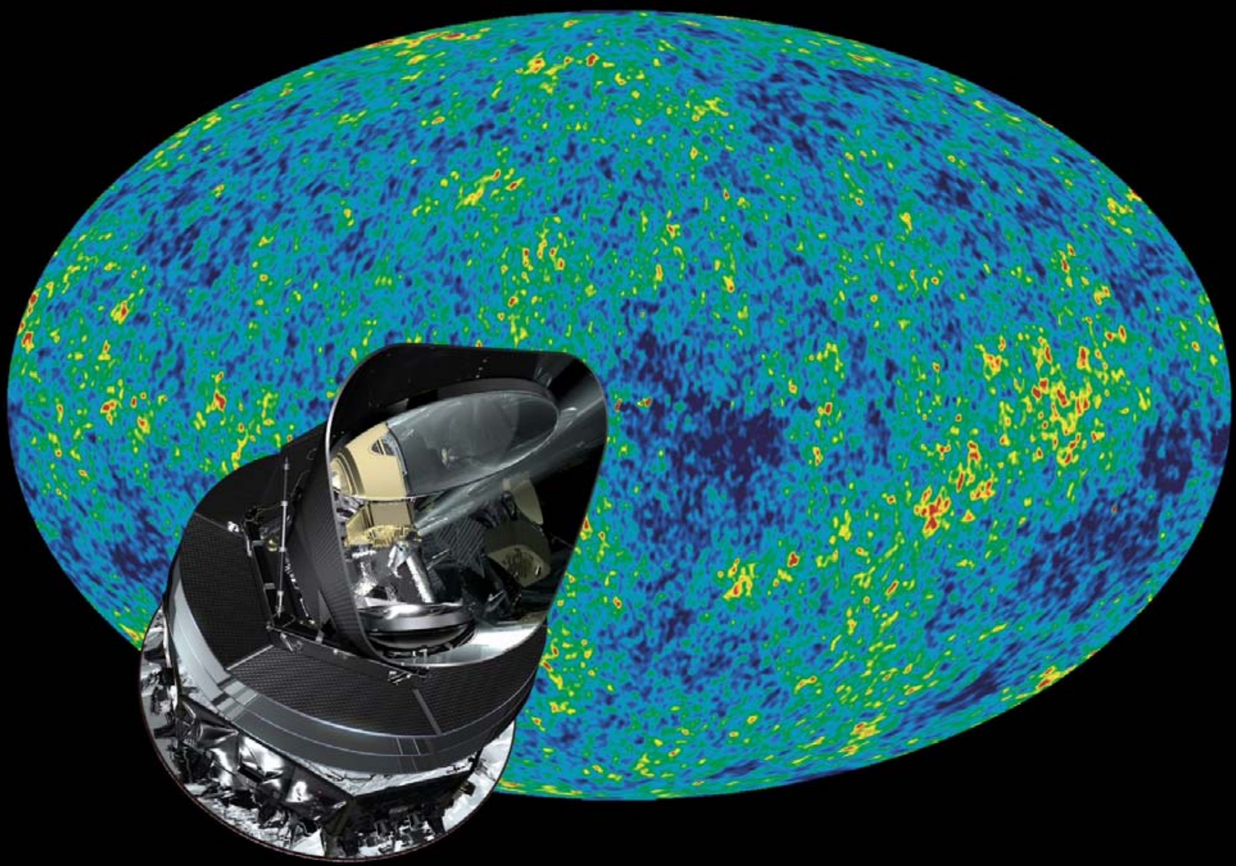
Telescopes Across the Electromagnetic Spectrum



Before we get started with my presentation about the Planck Mission, let's first have a look at how the sky appears to us in all the different wavelengths listed in this slide. Go to http://www.chromoscope.net/ to access the Chromoscope, created by Dr. Chris North at the University of Cardiff, Wales, and Dr. Stuart Lowe at the University of Manchester, England.

Planck is a Mission led by the European Space Agency, with significant participation by NASA.

Planck's purpose is to map the Cosmic Microwave Background radiation (or CMB) - the oldest light we can detect - with a sensitivity of a few millionths of a degree Kelvin, and an angular resolution as fine as 5 arc minutes on the sky.



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‘Listening’ to the Oldest Light of the Universe with Planck

Outline of this talk:

Part 1: What is the CMB?

Part 2: About the Planck Mission

- **The Mission, Science Objectives, Orbit; Brief overview of the instruments**

Part 3: Acoustic Oscillations in the Early Universe

- **How we understand acoustic oscillations in the early universe from the power spectrum of the CMB today; Understanding what is a power spectrum by using the analogy of music**

Summary, Q & A, and references for more information

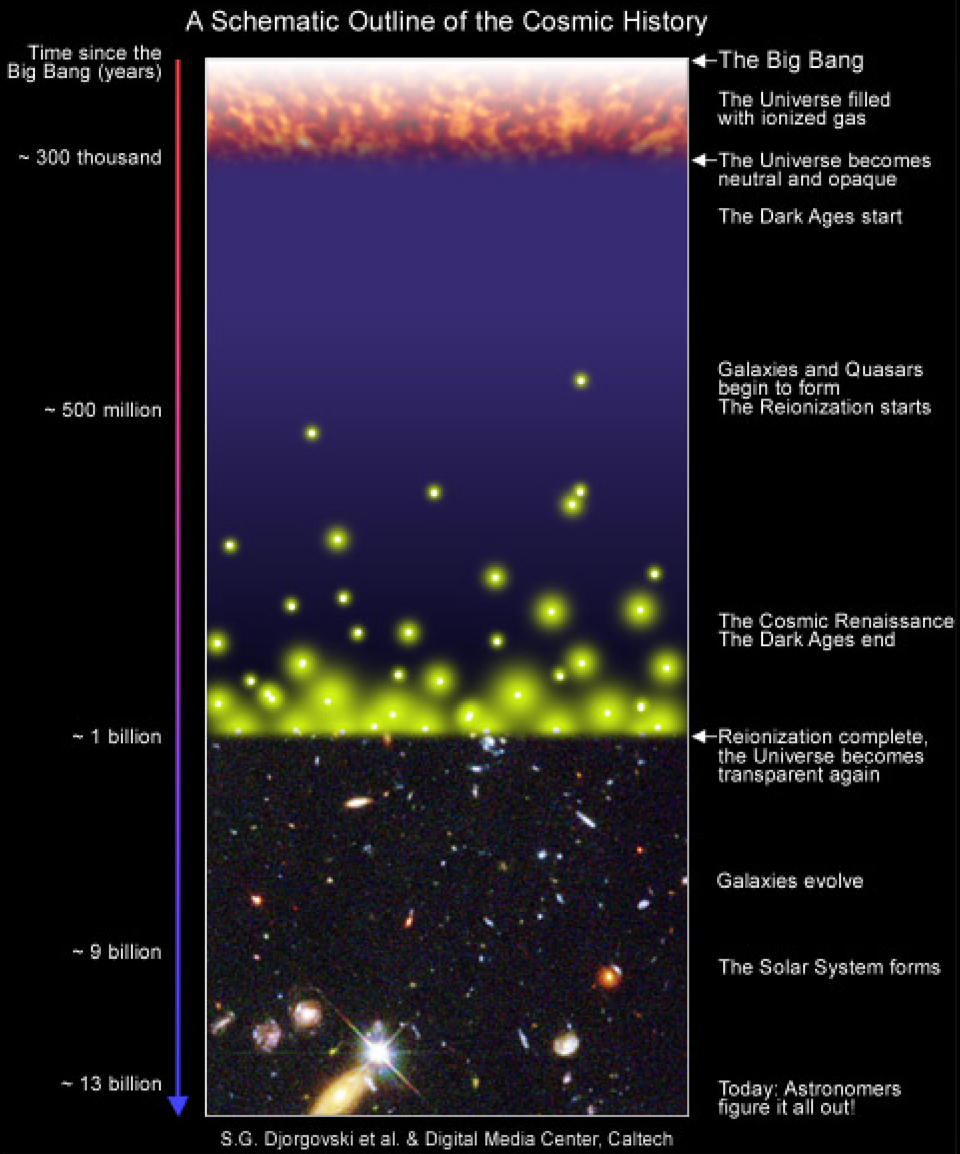
1. What is the Cosmic Microwave Background, or CMB?

The CMB is the thermal radiation left over from the hot Big Bang, 13.7 billion years ago, now observed at a temperature of 2.75 Kelvin.

It is the oldest light we can observe, coming to us from the time when the universe first became cool enough so as to be transparent to electromagnetic radiation, approximately 380,000 years after the Big Bang.

Before this time the universe was too hot and bright to see through, and photons could not travel very far before being scattered by charged particles.

A ‘geologic column’ of the universe



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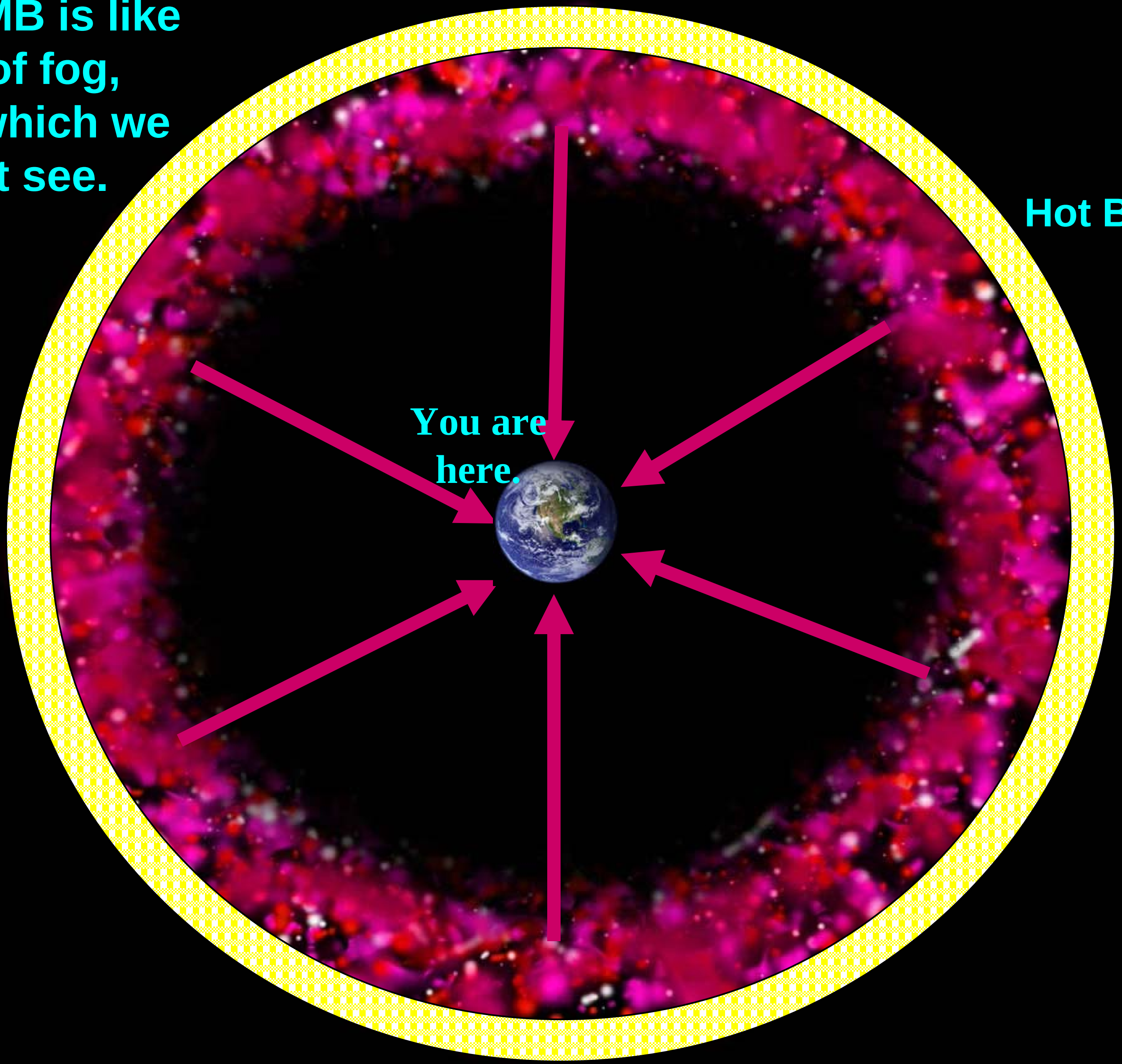
The CMB is like a wall of fog, beyond which we cannot see.



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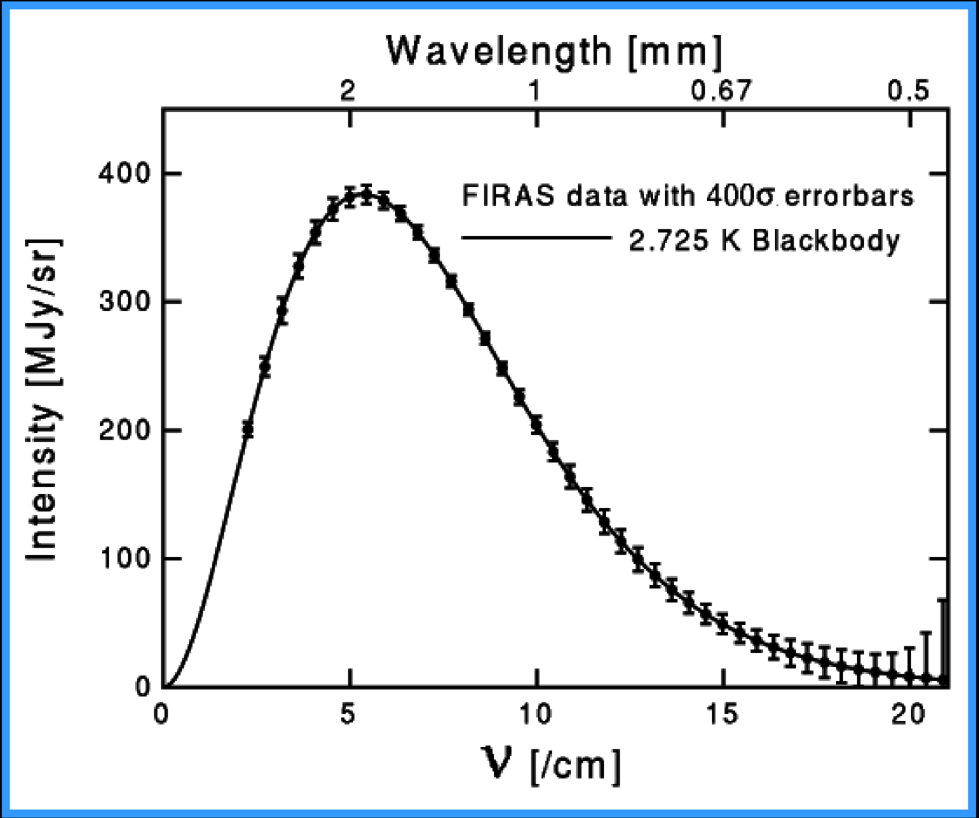
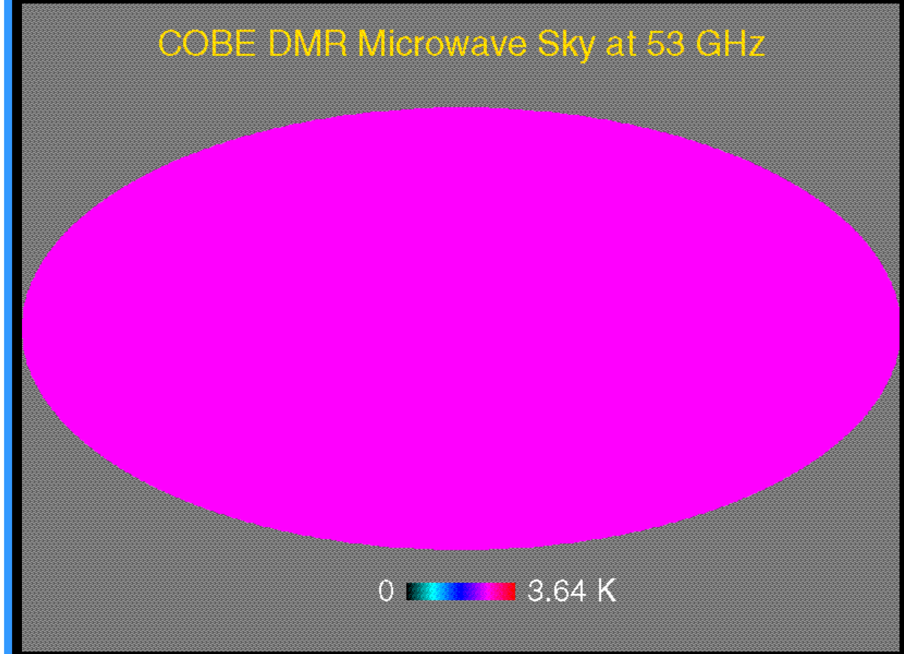
Discovered by Arno Penzias and Robert Wilson in 1964, to a first order, the CMB follows a perfect black body thermal radiation curve which peaks at 2.75 Kelvin, however…

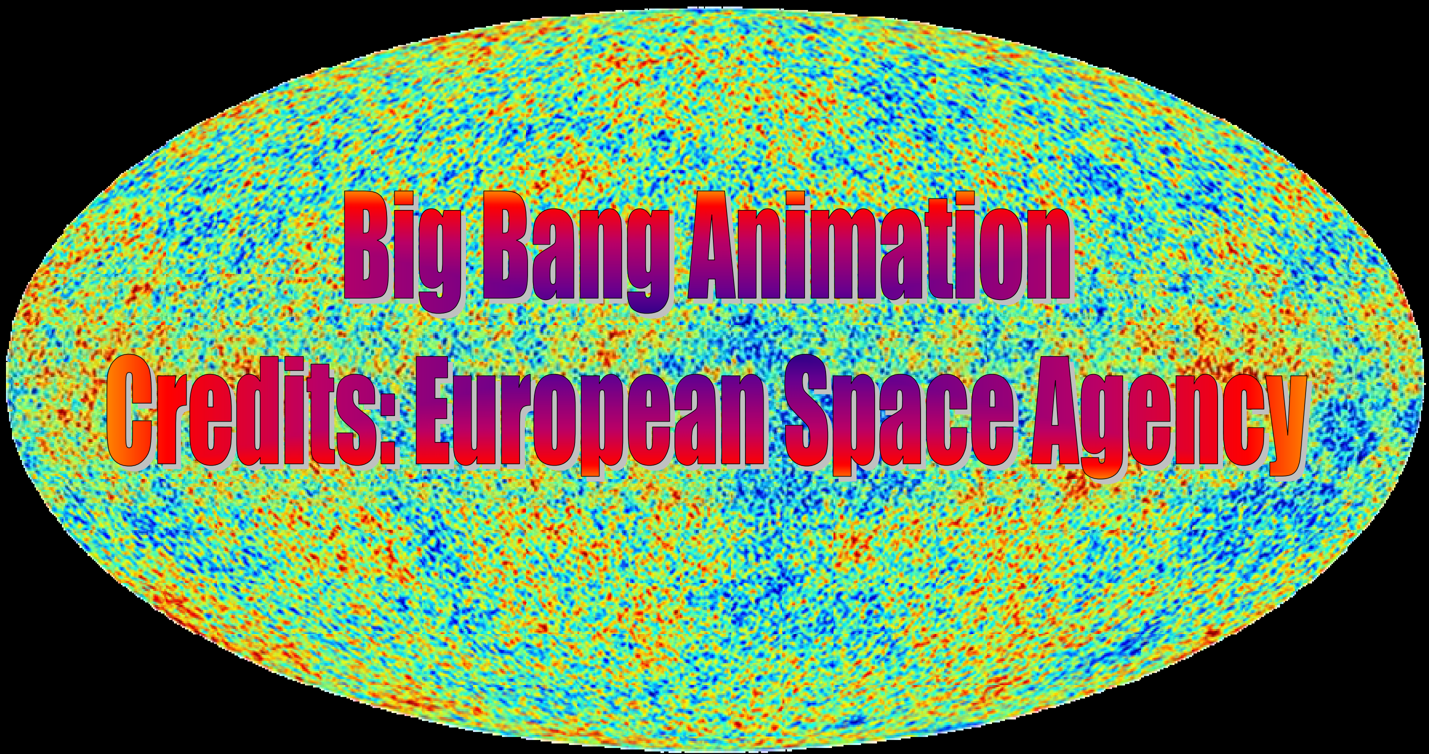




…if the CMB were totally uniform, galaxies, stars, and life would not have evolved! Thus, as soon as it was discovered, people began looking for variations in the CMB, which would indicate some inhomogeneities in the earliest moments of the universe, and which eventually led to the growth of structure in the universe.

Animation: Big Bang – Inflation – formation of the CMB
go to www.physics.ucsb.edu/~jatila/planck and click on the first animation.

Produced by the Education Office at the European Space Agency Technology Center, Noordwijk, Netherlands



Looking Back to the Dawn of Time

Planck, like the other missions that came before it, is looking back through spacetime to this oldest observable light of the infant universe, the cosmic microwave background radiation, or CMB.

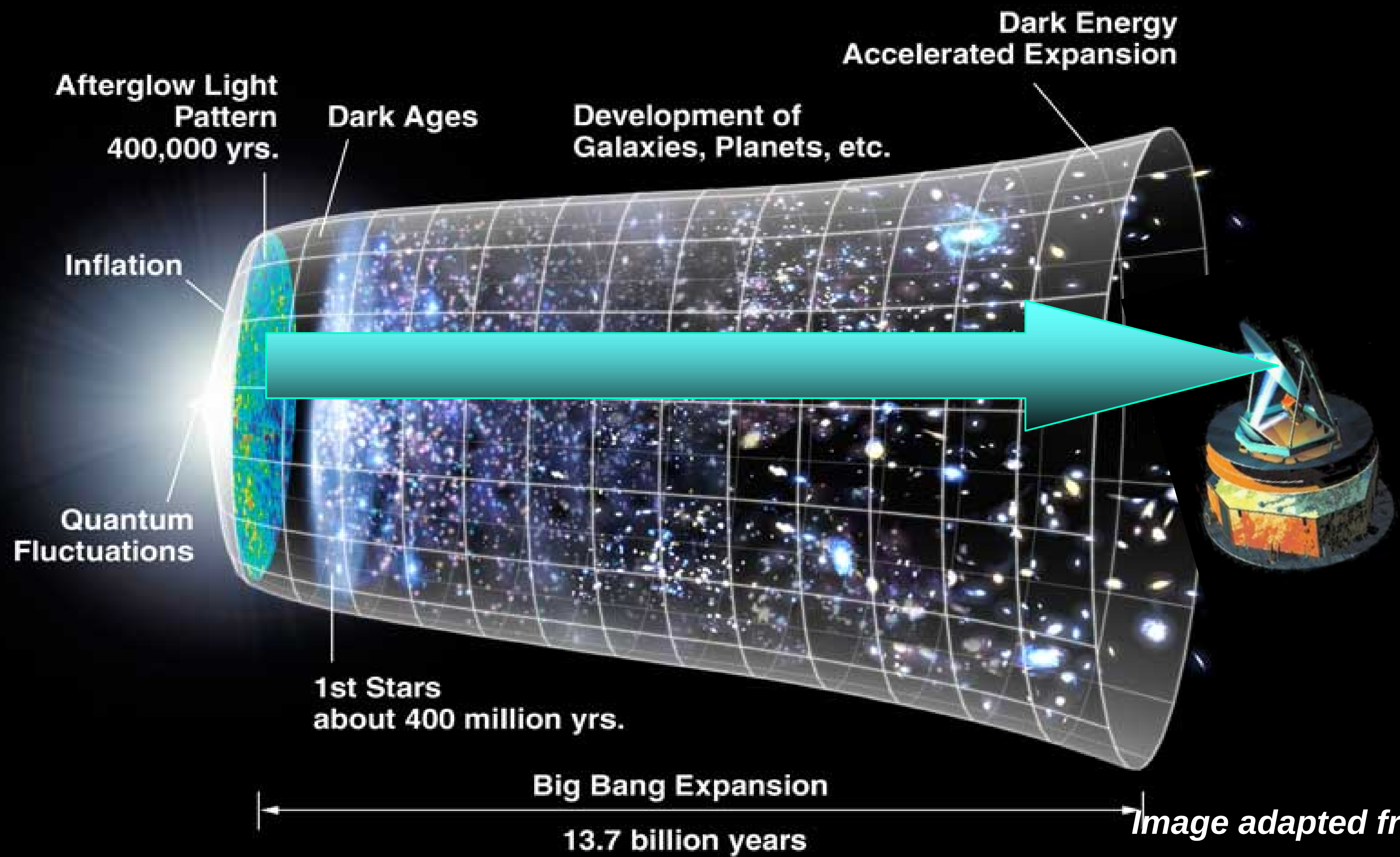


Image adapted from WMAP.

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Check for understanding:

What is the CMB?

Check for understanding:

What is the CMB?

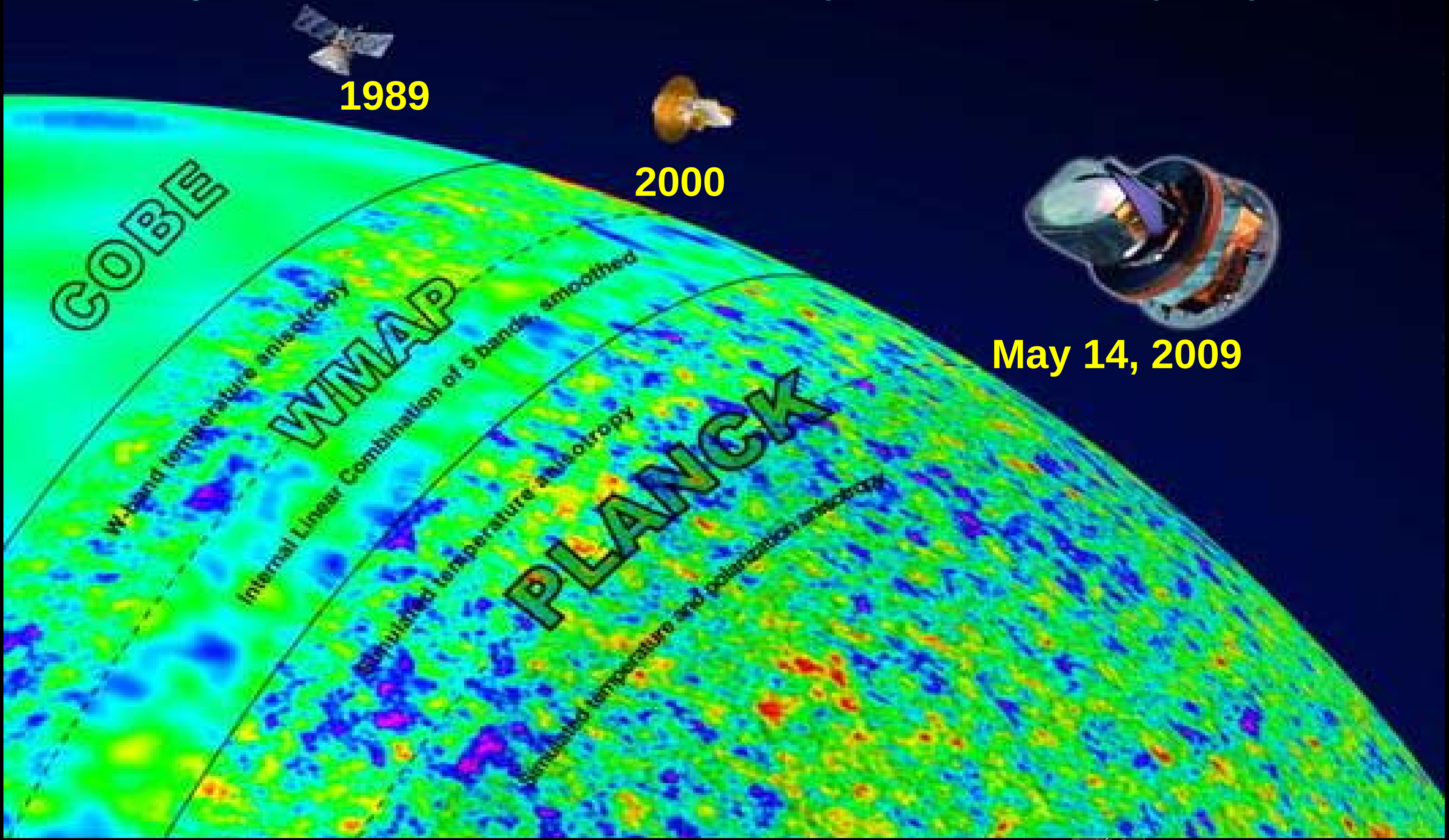
CMB = Cosmic Microwave Background

The CMB is the oldest light we can observe, as close to the "Big Bang" as we can get, around 380,000 after the Big Bang.

The CMB represents the last time that light scattered off matter, when the universe became cool enough so that protons and electrons could combine to form neutral hydrogen, and light decoupled from matter.

2. About the Planck Mission

Planck is the third generation of satellite to map the entire sky in microwave and infrared wavelengths, after COBE and WMAP, but with unprecedented accuracy and precision.



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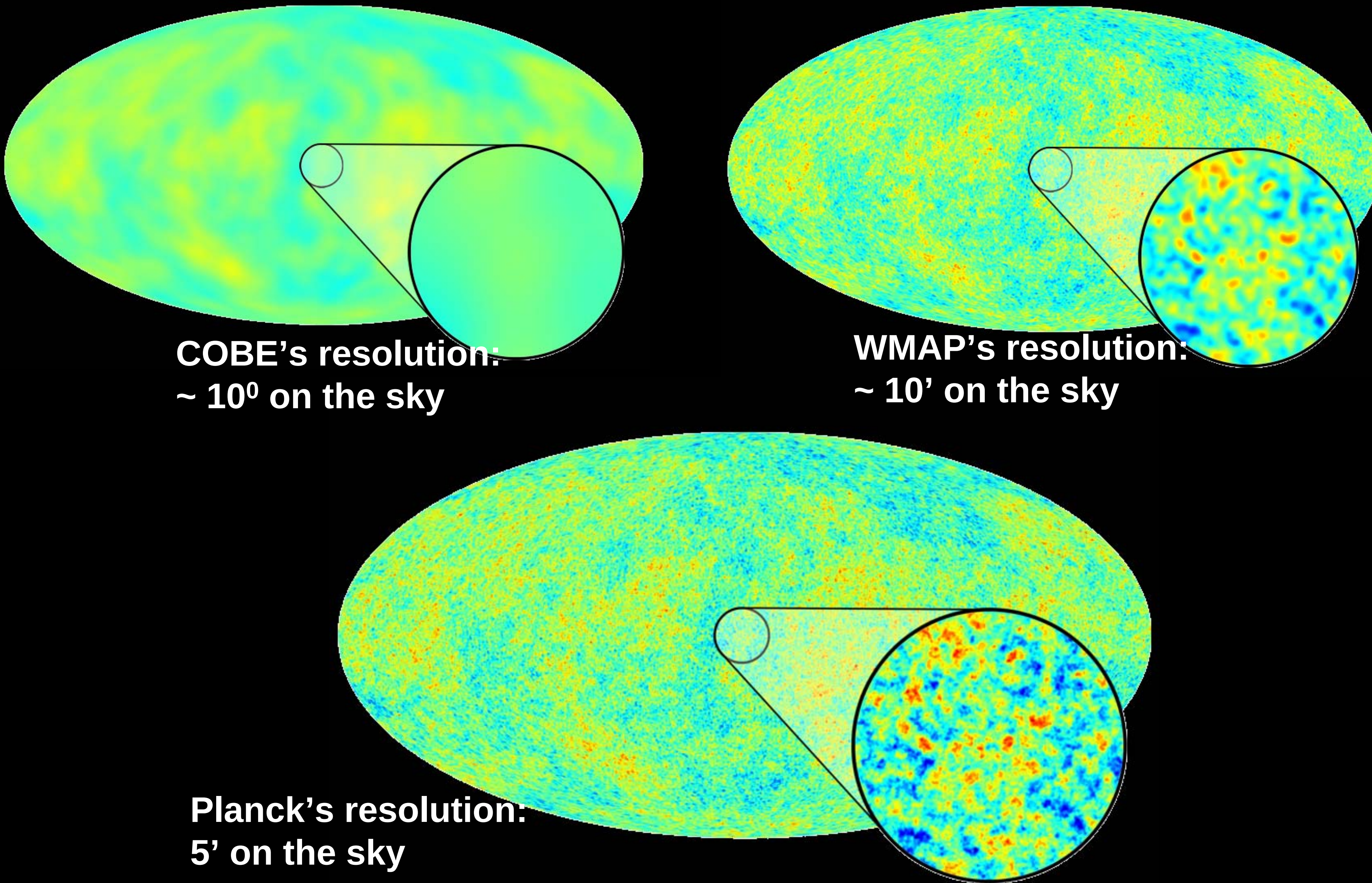

Image credit: Chris North, Cardiff University
http://planck.cf.ac.uk/cmb

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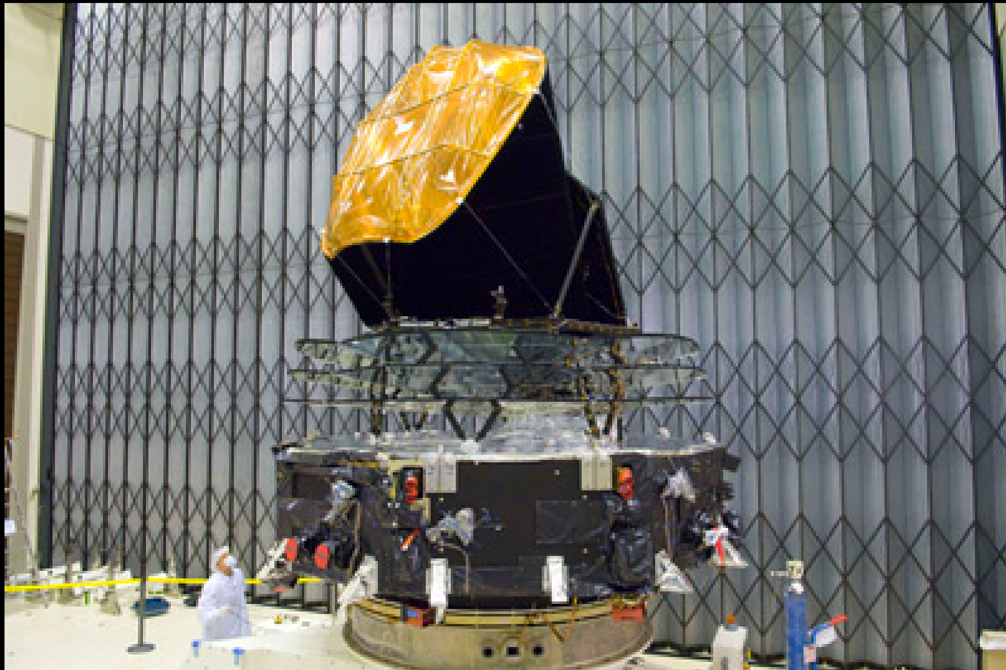

Planck was built by an international industrial team. Different components, including the mirrors, instruments, payload package, and cooling systems were built in France, Austria, Germany, Denmark, Finland, Belgium, Italy, Ireland, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, the United Kingdom, and the United States. The Planck spacecraft is 4.2 m high and has a maximum diameter of 4.2 m, with a launch mass of around 1.8 tons

Primary mirror, 1.9 x 1.5 meters

Secondary mirror 1.1 x 1.0 meter

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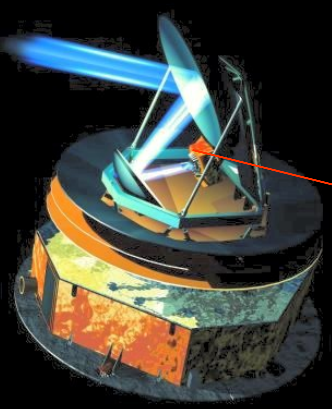
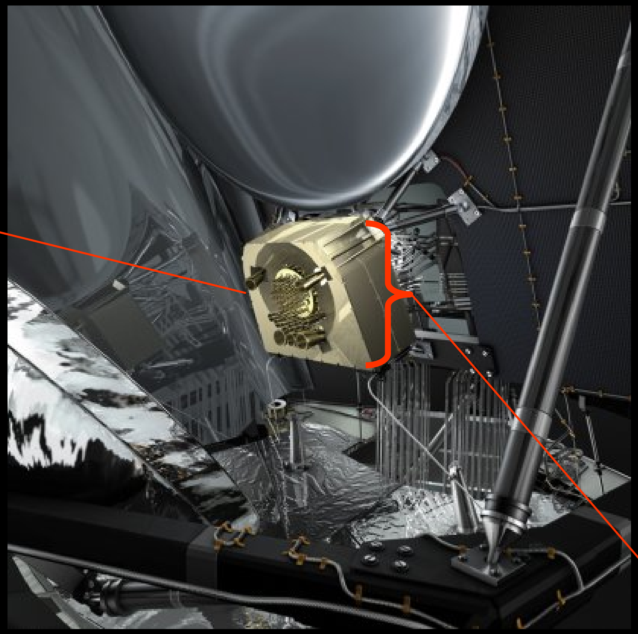




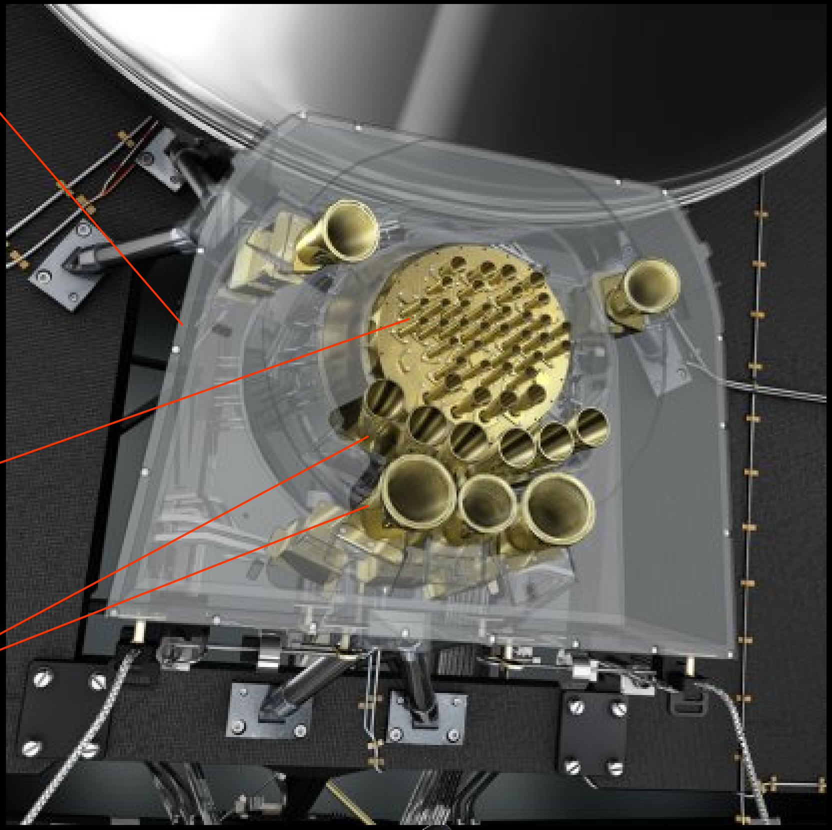
Planck has two sets of detectors which are mapping the CMB across 9 frequency bands, from 30 to 900 GHz, or wavelengths from 1 cm to .3 mm

HFI (High frequency Instrument): an array of microwave detectors using spider web bolometers, cooled to 0.1 K

LFI (Low frequency Instrument): an array of radio receivers using high electron mobility transistors, cooled to 20 K.

HFI feed horn array

LFI feed horn array



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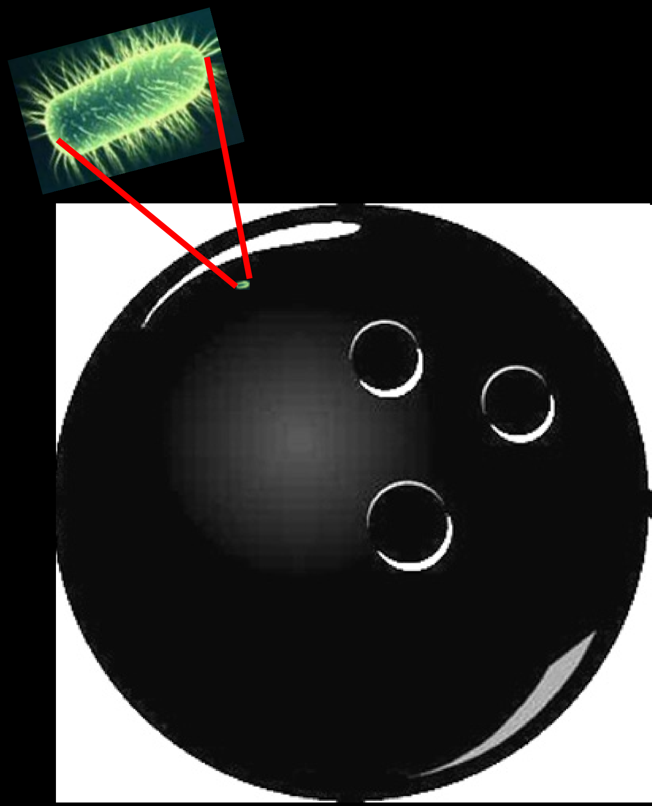
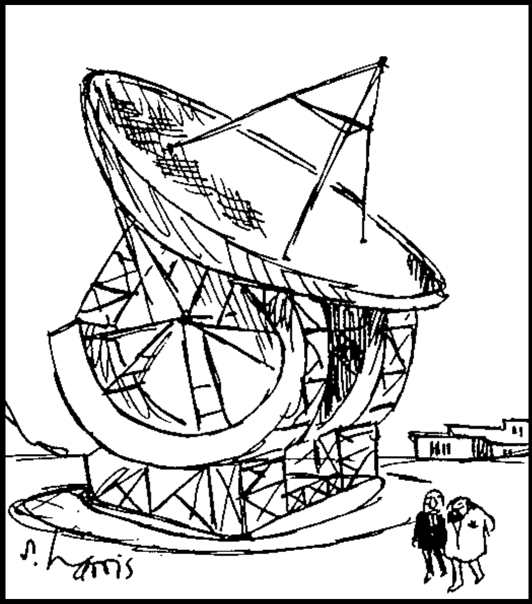
Planck's resolution is said to be equivalent to being able to resolve a bacterium on top of a bowling ball, and its sensitivity has been compared with detecting the heat output of a rabbit in space, at the distance of the Moon, by a person standing next to the detector on Earth (neglecting atmospheric attenuations).

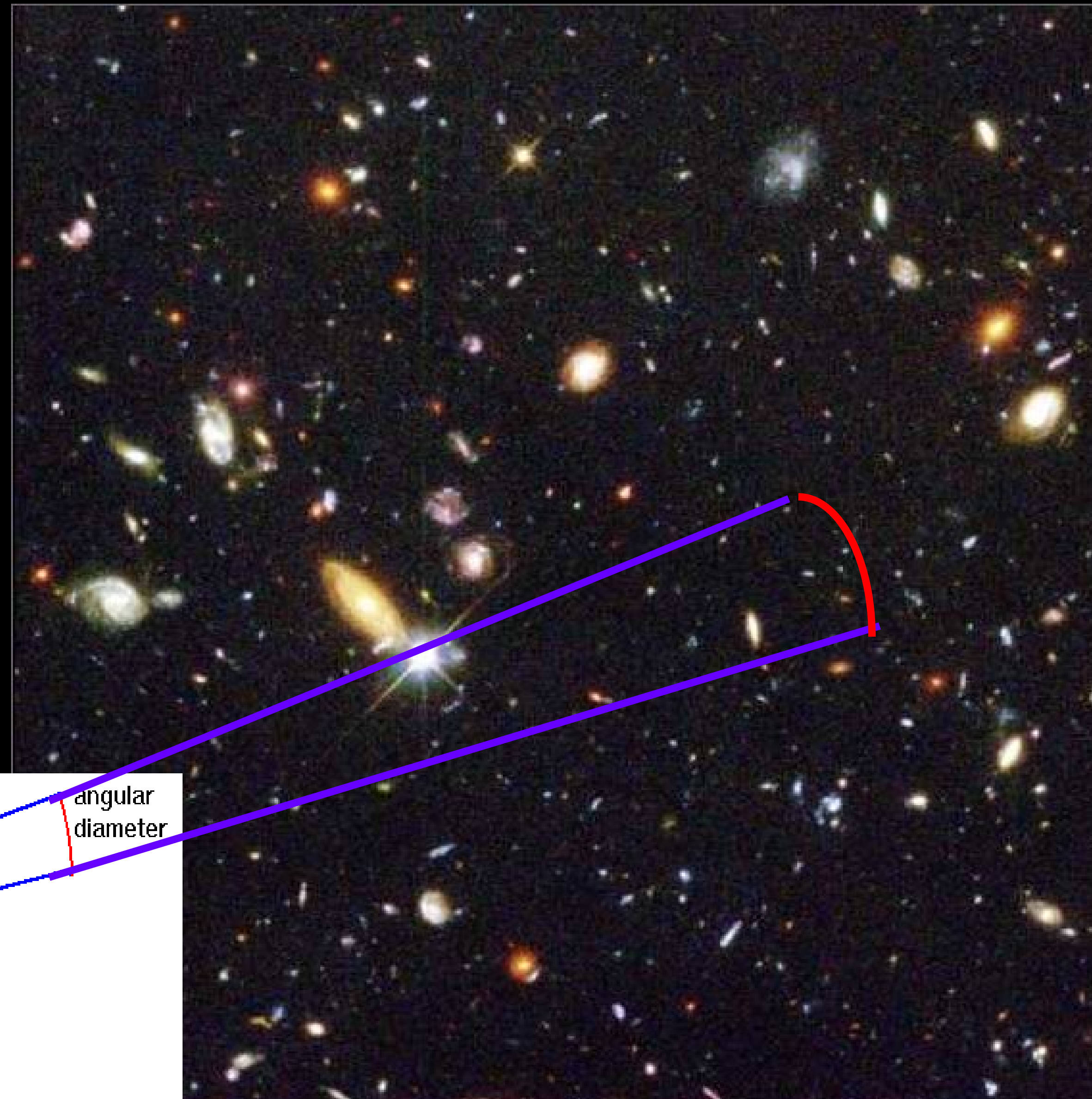


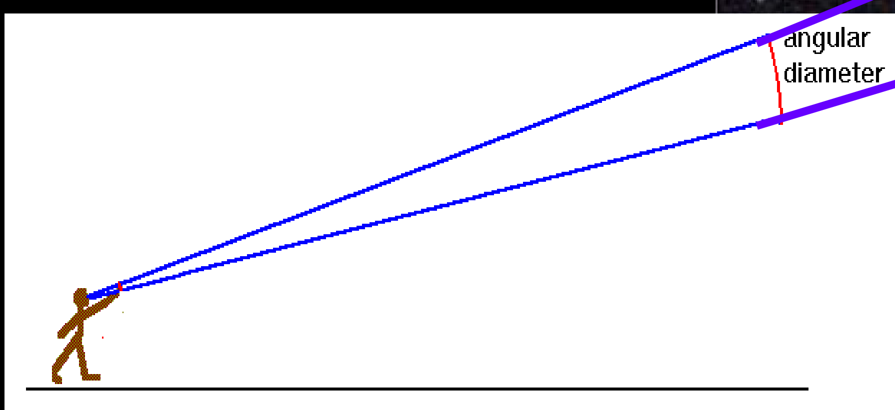


To achieve this level of sensitivity, Planck's detectors are cooled to within 0.1 degree above absolute zero by an elaborate cooling system.

For reference, 1^0 of arc on the sky is approximately equal to the width of your pinky, held at arm's length.

A patch of 5 arc minutes on a side is approximately 6 billionths of the total area of the sky.





Go to www.physics.ucsb.edu/~jatila/planck
and click on the second animation to view Planck's cooling system.

Planck's passive cooling system cools the telescope to about 50 K. Then liquid hydrogen is used to reduce the temperatures to 20 K. Next a mechanical pump uses liquid helium (4He) to bring the temperature down to 4 K. Finally the bolometers are cooled by the mixing of Helium 3 and Helium 4 (3He and 4He), which produces an endothermic reaction that takes the temperature down to an amazingly low temperature of just 0.1 K.

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Launched on 14 May, 2009, Planck is now mapping the sky, in a sun-synchronous orbit around "L2" – the second Lagrange point in the Earth-Sun system. Planck rotates on an axis pointed in the anti-Sun direction at 1 rpm, and takes around 7 months to scan the entire sky once. It will make two complete sky scans in its projected life time.

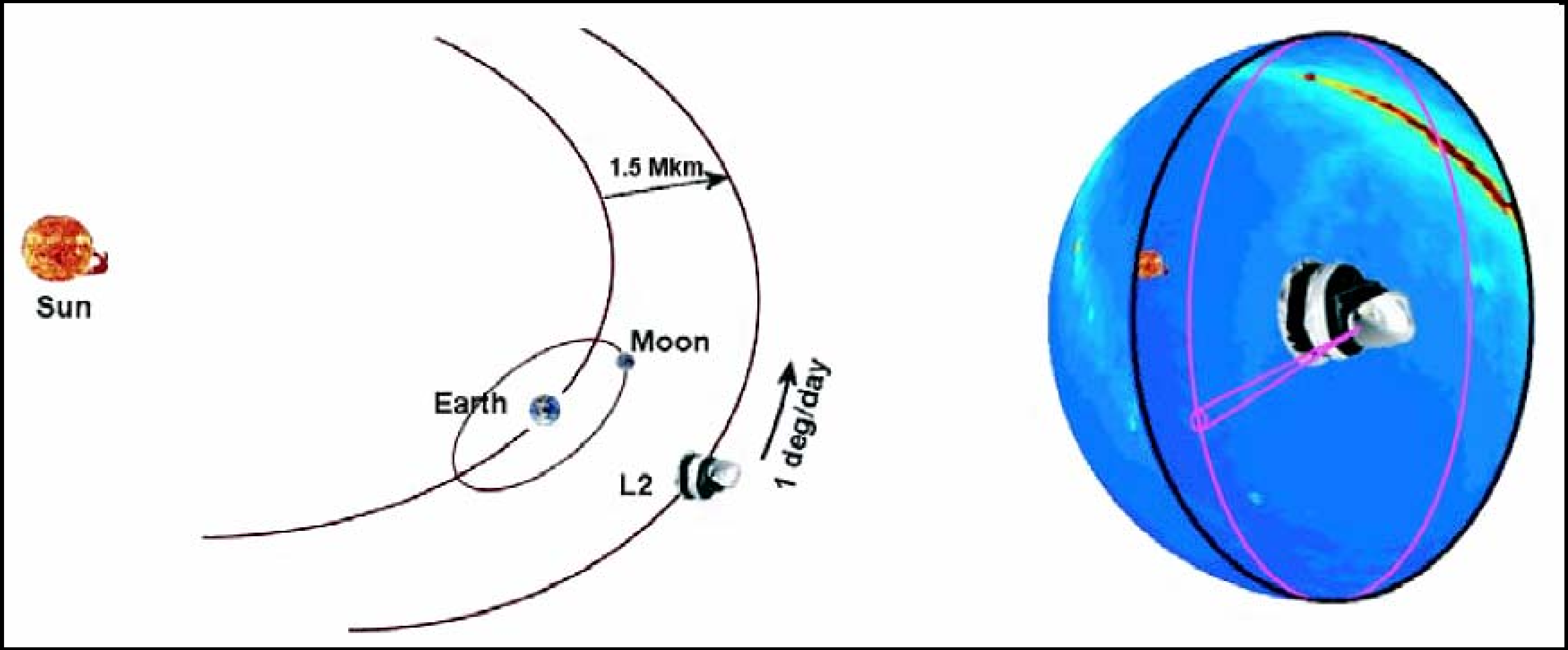
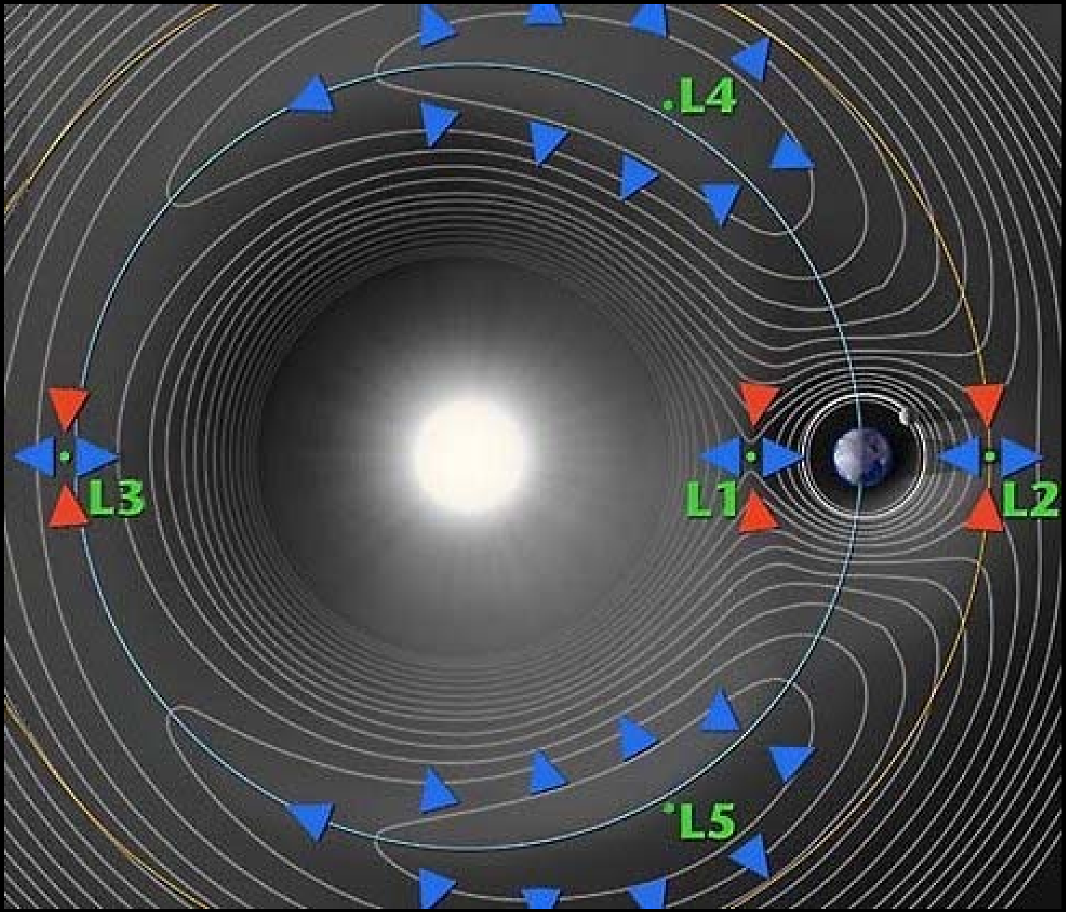


Image: http://smsc.cnes.fr/PLANCK/Fr/GP_mission.htm

The Lagrange points



There are 5 locations in the Earth-Sun system where the gravitational and Coriolis forces are balanced. These are named “L1” through “L5” after Joseph Luis Lagrange who first predicted their existence in 1772.

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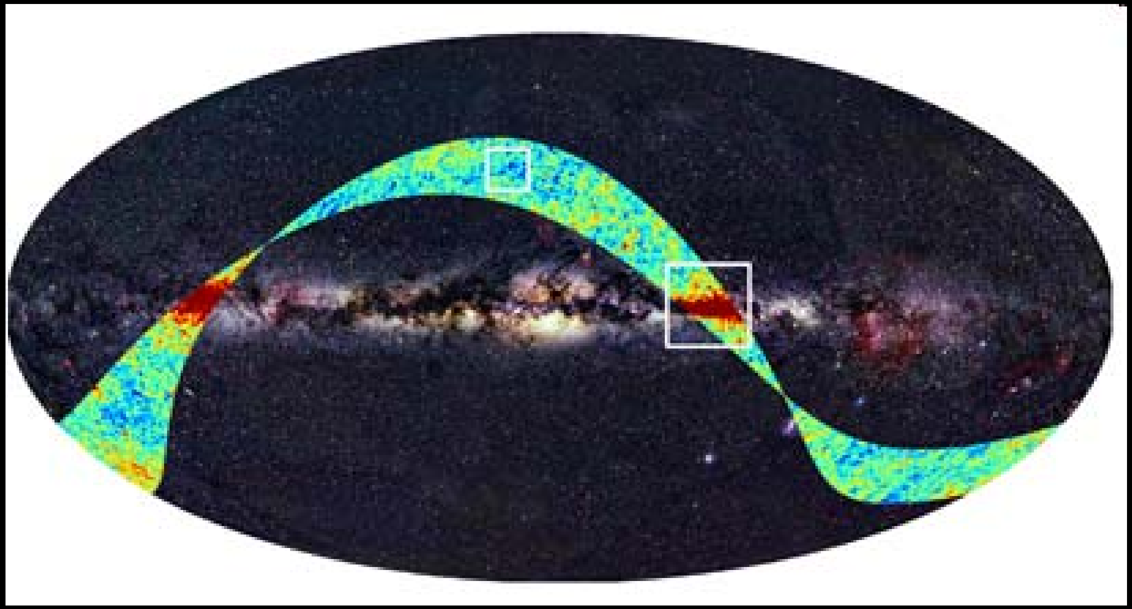
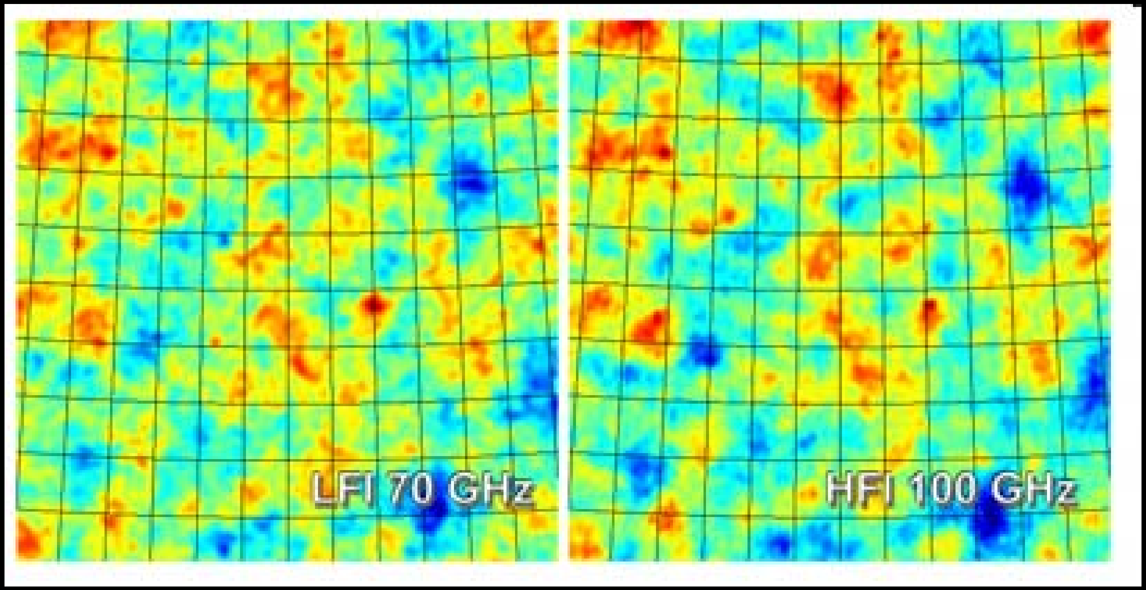
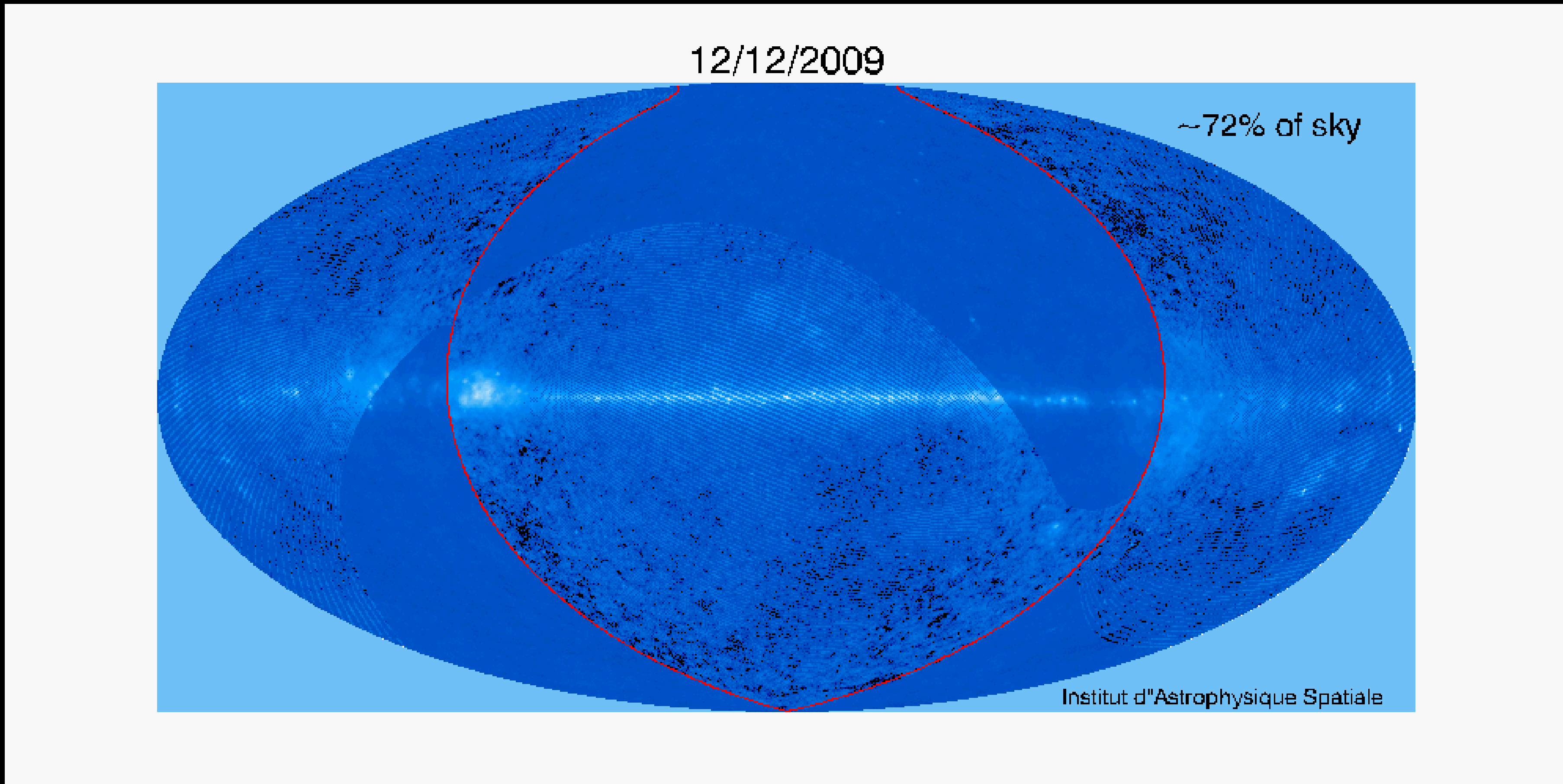
Press Release, September 17, 2009: Preliminary results from ESA's Planck mission to study the early Universe indicate that the data quality is excellent.





Detail at high galactic latitude of 10^0 x 10^0 patch of sky from the 70 GHz and 100 GHz channels, from Planck's First Light Survey

Source:
http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=45531



This map shows the sky already observed by Planck from the start of the First Light survey (only one ring per day is shown). The red circle shows one day's worth of sky coverage.

Watch video on YouTube: http://www.youtube.com/watch?v=WwFXuZ0B3B8 made by Dr. Chris North of Cardiff University, U.K.

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Check your understanding:

What's the coolest spacecraft ever to be flown?

Check your understanding:
What's the coolest spacecraft ever to be flown?

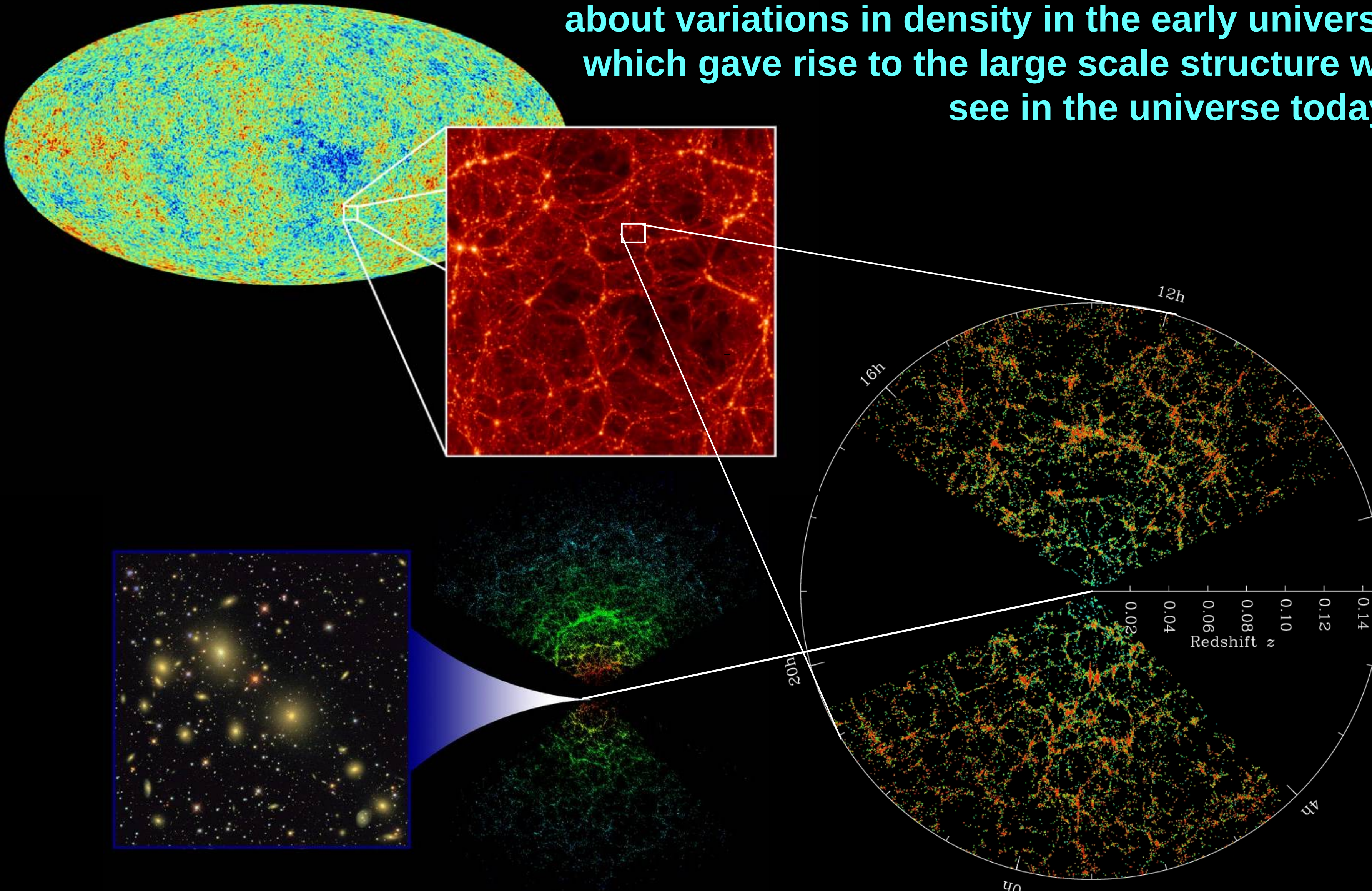
Planck! Planck's high frequency instrument is chilled to within a tenth of a degree above absolute zero - colder than the background temperature of space, which is 2.725 Kelvin.

So, not only is Planck the most sophisticated microwave telescope ever built, it is literally the coldest object in space!

So…

Why all the fuss about detailed measurements of the CMB?

Understanding the minute temperature fluctuations in the CMB tells us about variations in density in the early universe which gave rise to the large scale structure we see in the universe today.



Images courtesy of Professor Max Tegmark, MIT

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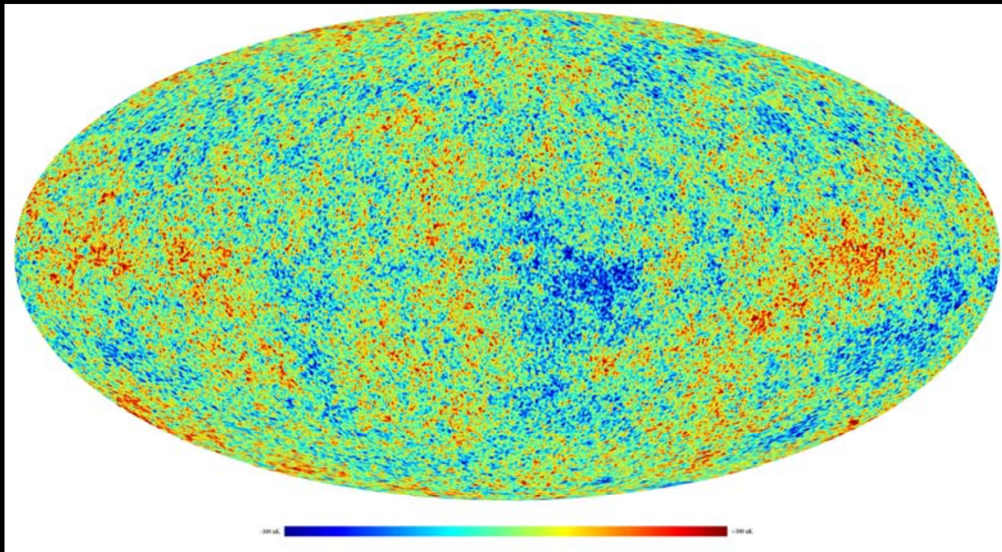
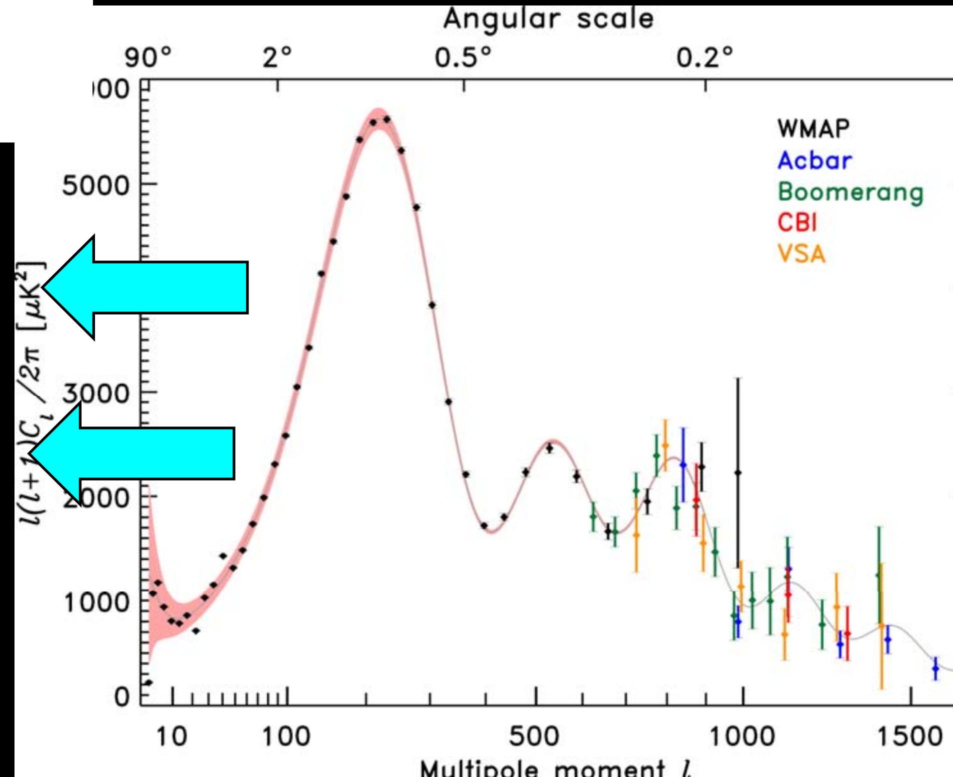


From the detailed, temperature map we derive the angular power spectrum of CMB anomalies, from which we can fer not only how structure formed, but



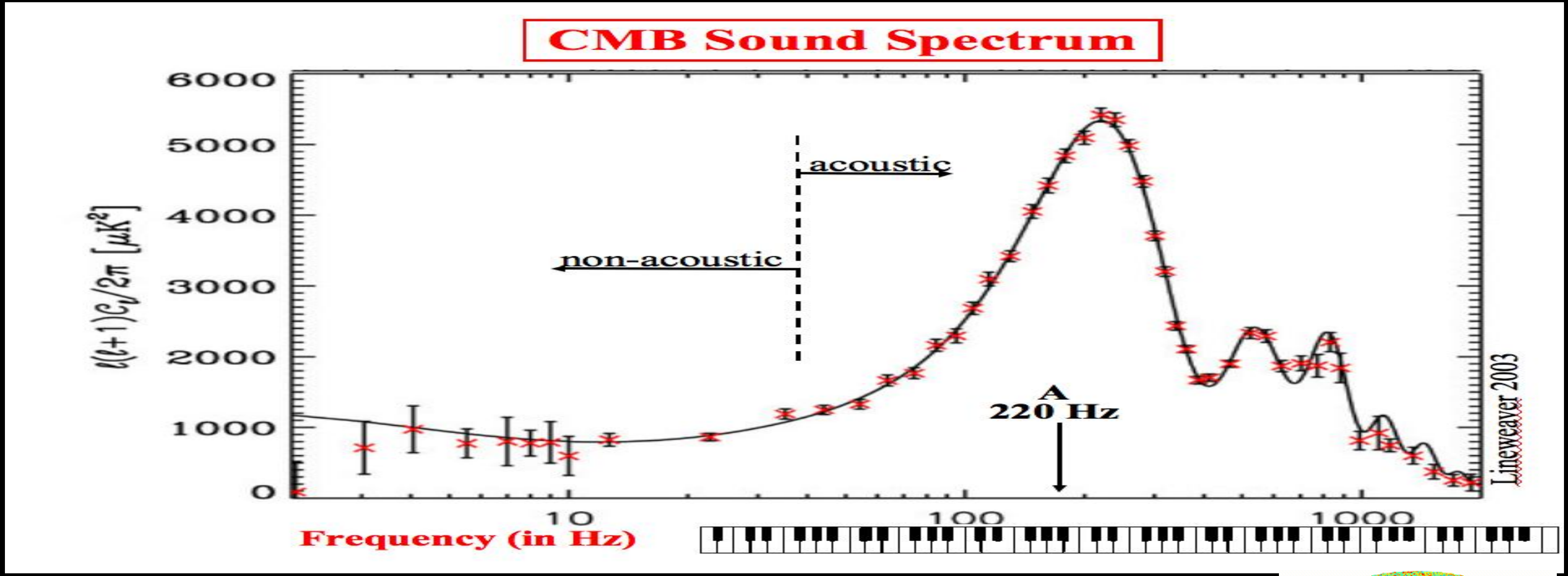
composition of the universe!

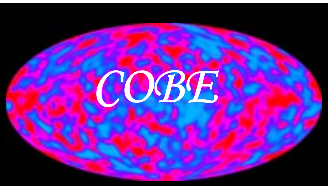
fundamental physics!

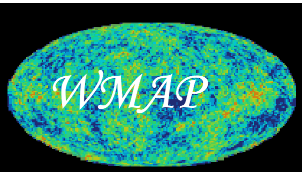
Which brings us to Part 3: The Music of the Cosmos

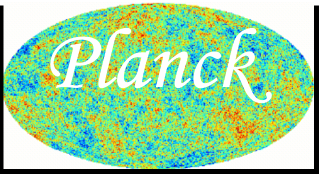
"Listening" to the Oldest Light of the Universe

Understanding how we extract information about the Universe from the Power Spectrum of the CMB









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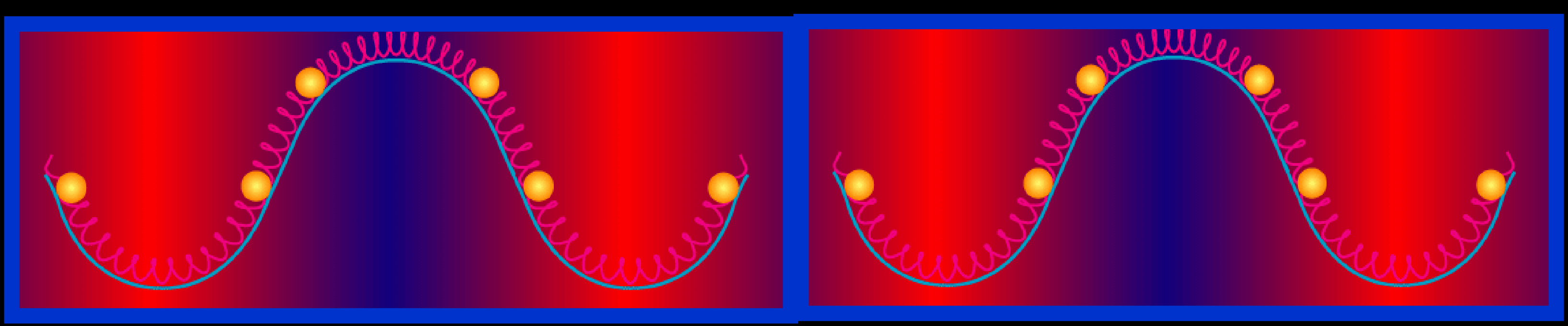
The variations in temperature that we observe in the CMB ...

$$\boxed{\frac{\Delta T}{T} = \frac{\phi}{3c^2} \Rightarrow \frac{\Delta \rho}{\rho}}$$

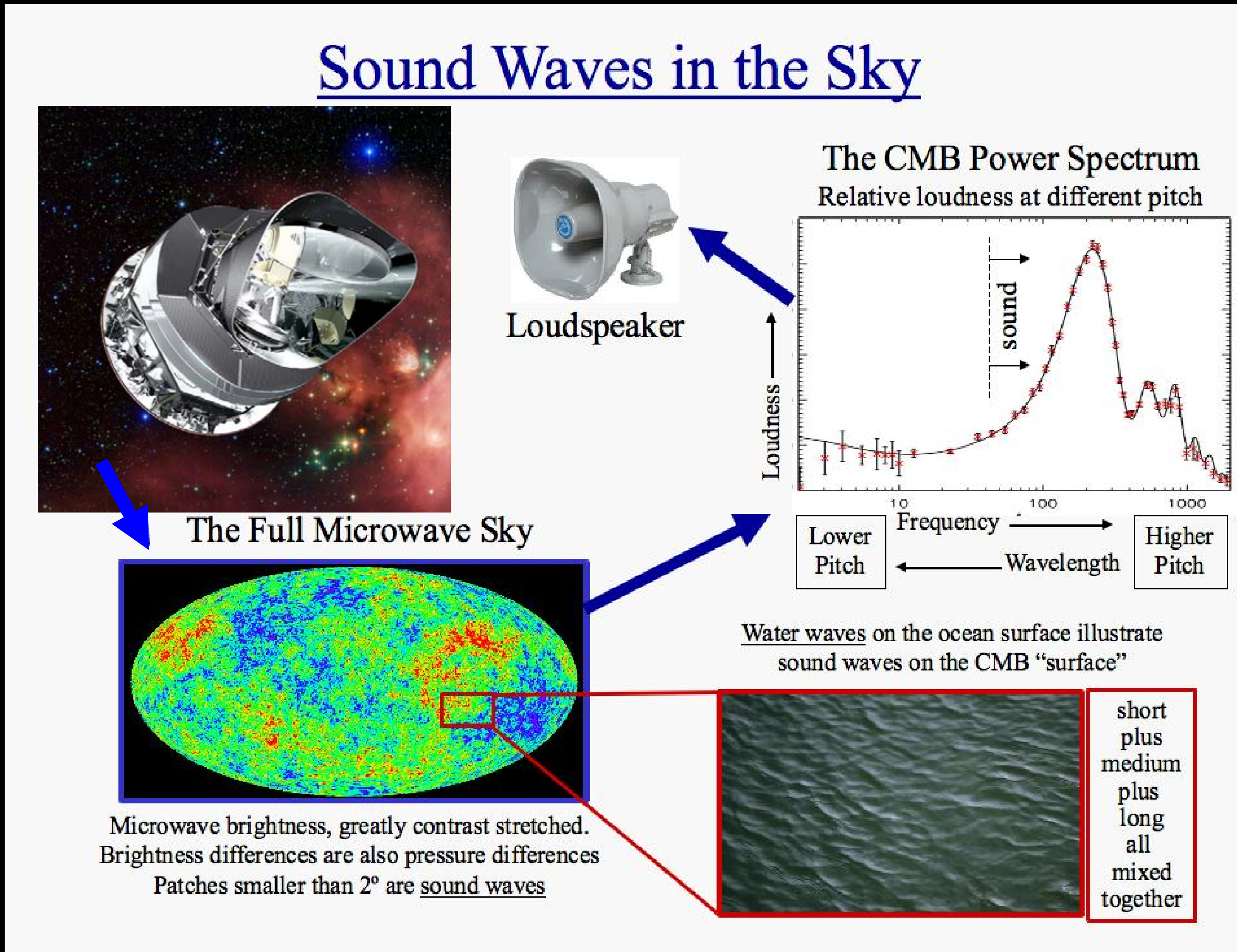
...tell us about variations in density in the early universe...

Variations in density in the early universe led to

ACOUSTIC OSCILLATIONS
in the photon-baryon fluid which were induced by primordial inhomogeneities in the Big Bang



animation by Wayne Hu, University of Chicago



slide adapted with permission from Mark Whittle, University of Virginia

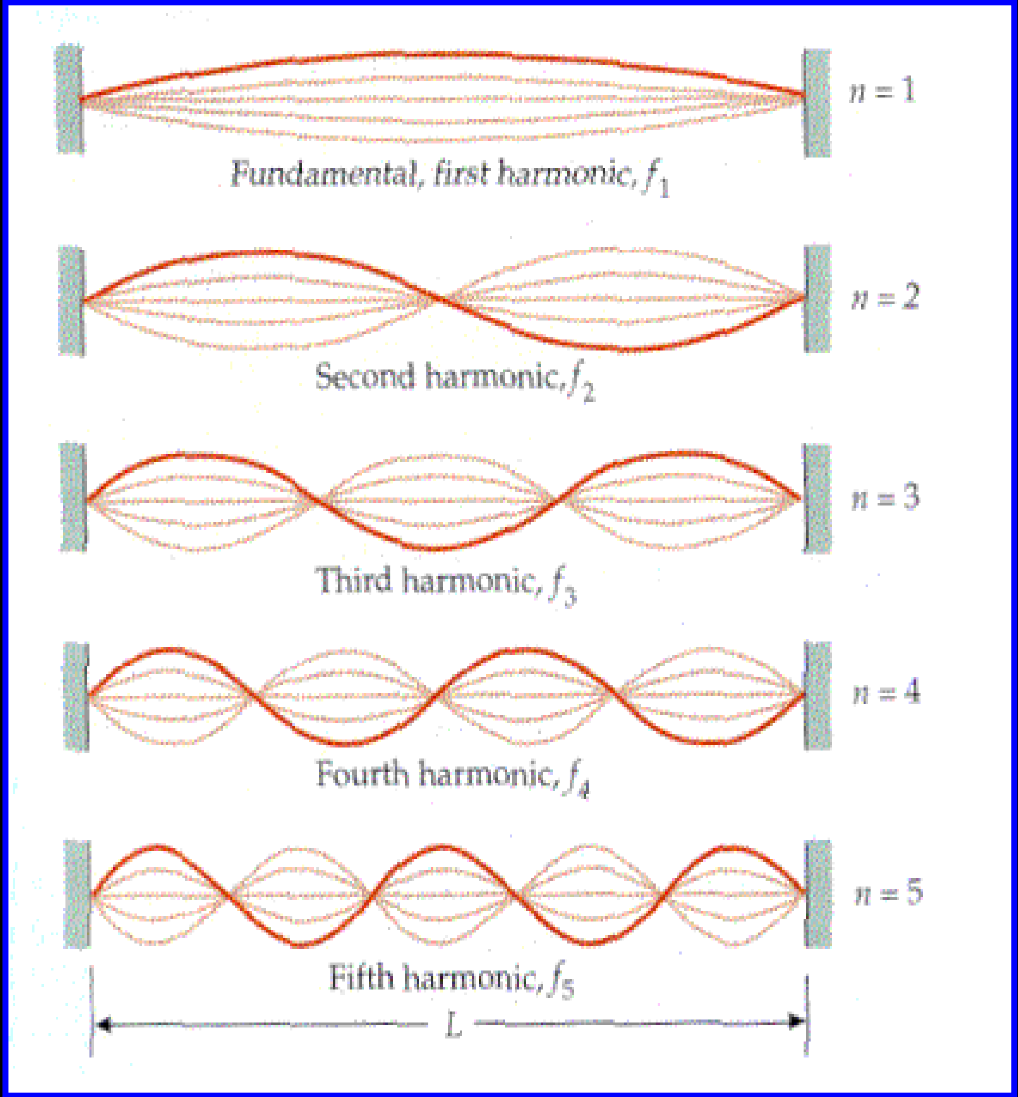
Since the 1960s it has been understood that the early universe contained sound waves.

Thus, we can use techniques of spectral analysis which are familiar to us from MUSIC to analyze the CMB.

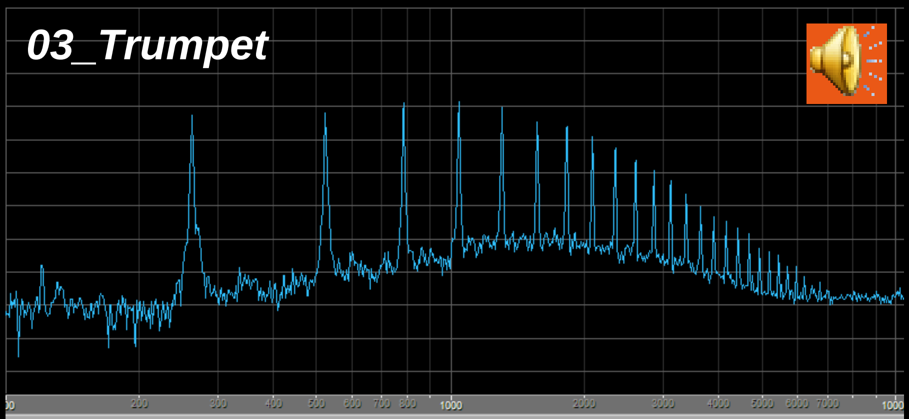
Resonating systems have a fundamental and higher harmonics which are the frequencies at which they naturally vibrate.

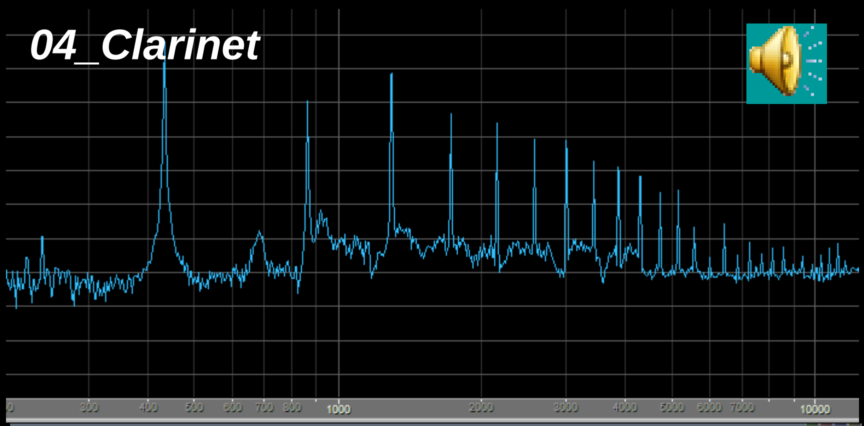
The wavelength of the fundamental is determined by the size of the instrument and the speed of sound waves that travel from one end to the other.

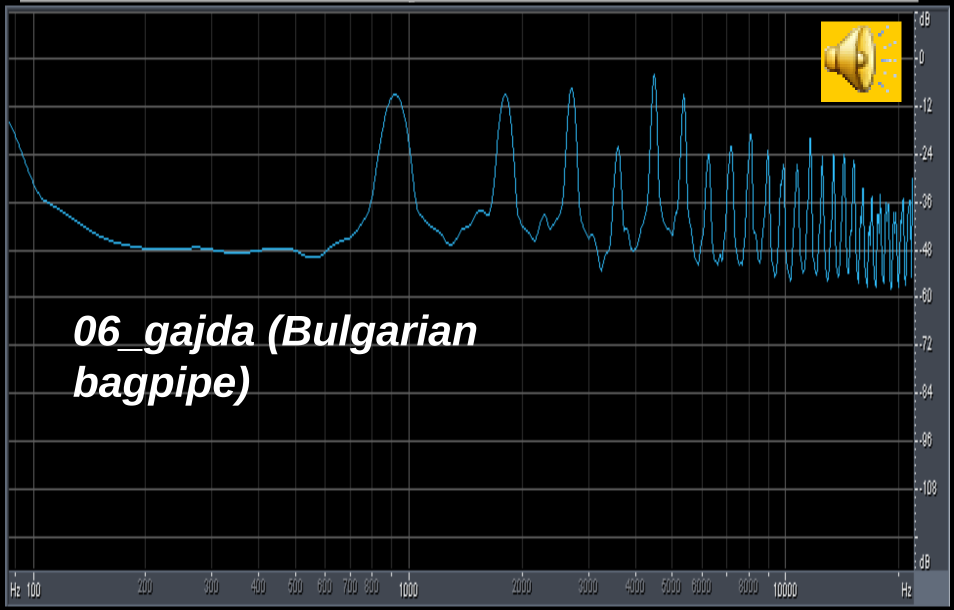
The higher harmonics are multiples of the fundamental, and the highest harmonics, with the smallest wavelengths, contain information about the small variations inside the instrument, which allow us to distinguish one instrument from another, just by listening!

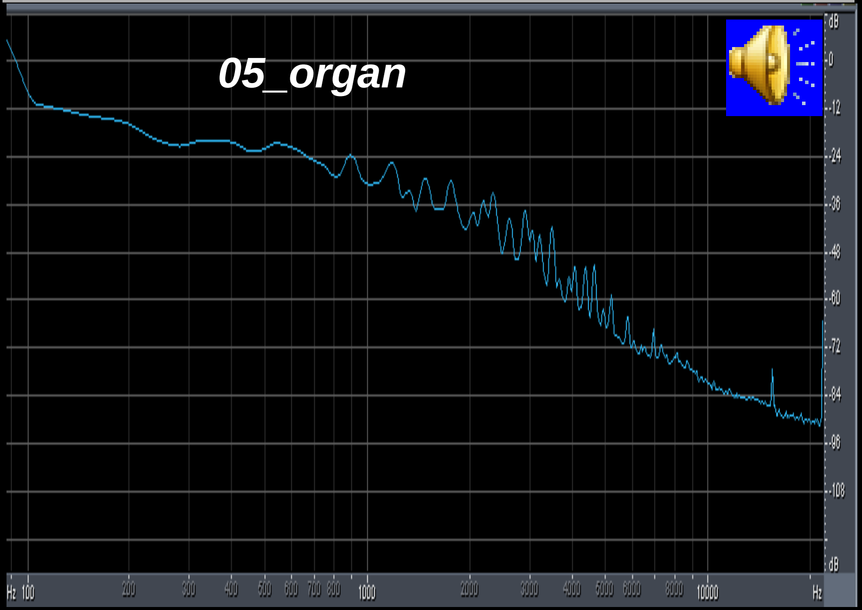


To play all the following sound files, open ww.physics.ucsb.edu/~jatila/planck in your web browser, and click on:









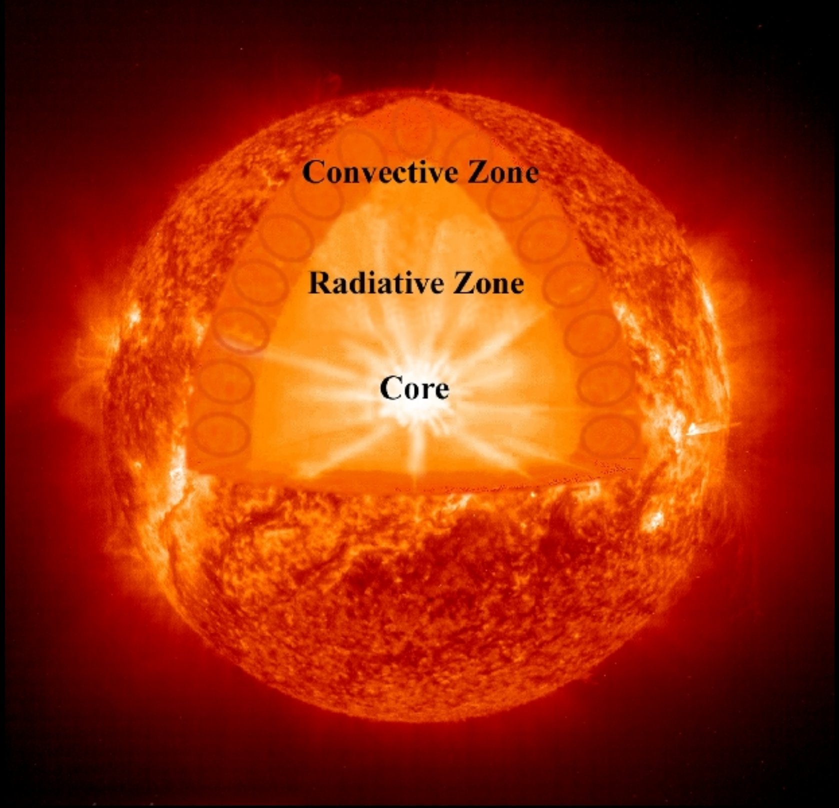
A power spectrum is thus a bit like a finger print.

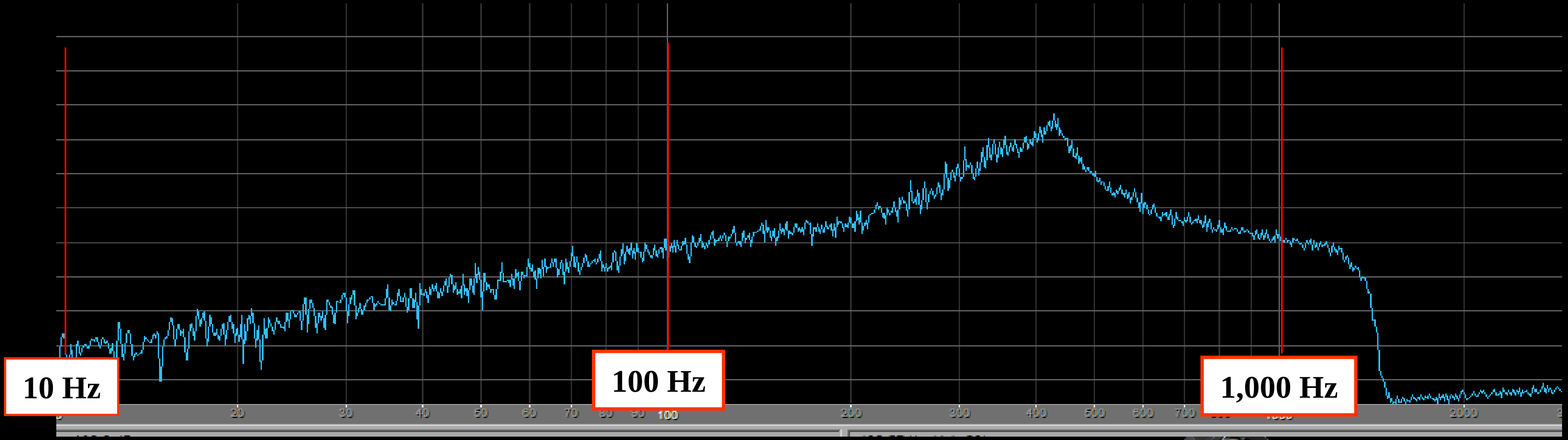
Pressure waves sloshing around inside a big ball of gas, such as the Sun, also generate sound waves!

If you could go inside the Sun without boiling up into gas yourself, here is what it might sound like:

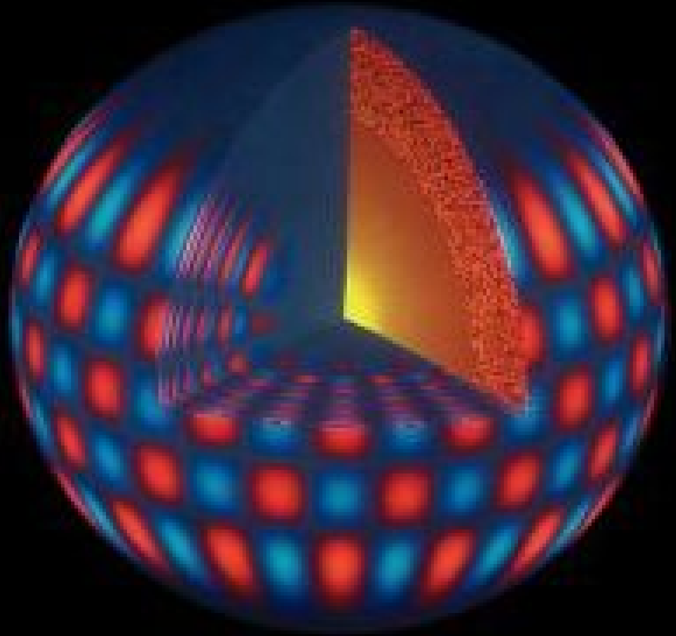
Source: http://bison.ph.bham.ac.uk/ .

07_Sun-wideband





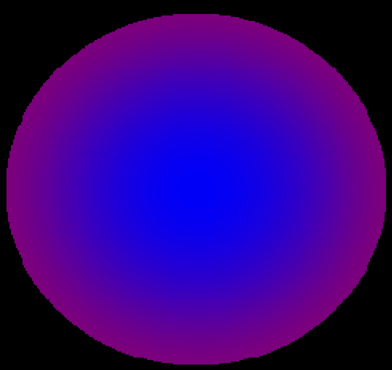
The waves that slosh around inside the Sun create variations in the height of the surface of the Sun. These lumps and bumps on the surface of the Sun can be analyzed using the technique of Spherical Harmonic Analysis.



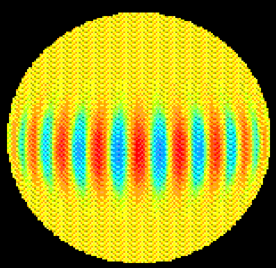
Similarly, the acoustic waves in the early universe left their imprint on the surface of last scattering, which we see today as the CMB!

Thus, looking at the CMB is looking at the surface of the early universe, but from the inside out!

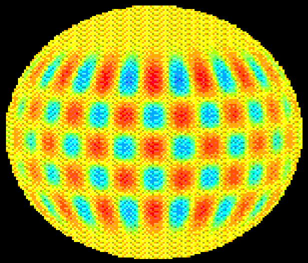
And, we use the same mathematics for both!



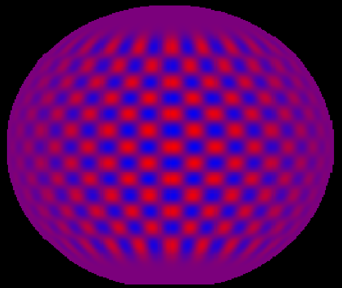
l = 1, m = 1



l = 19, m = 19



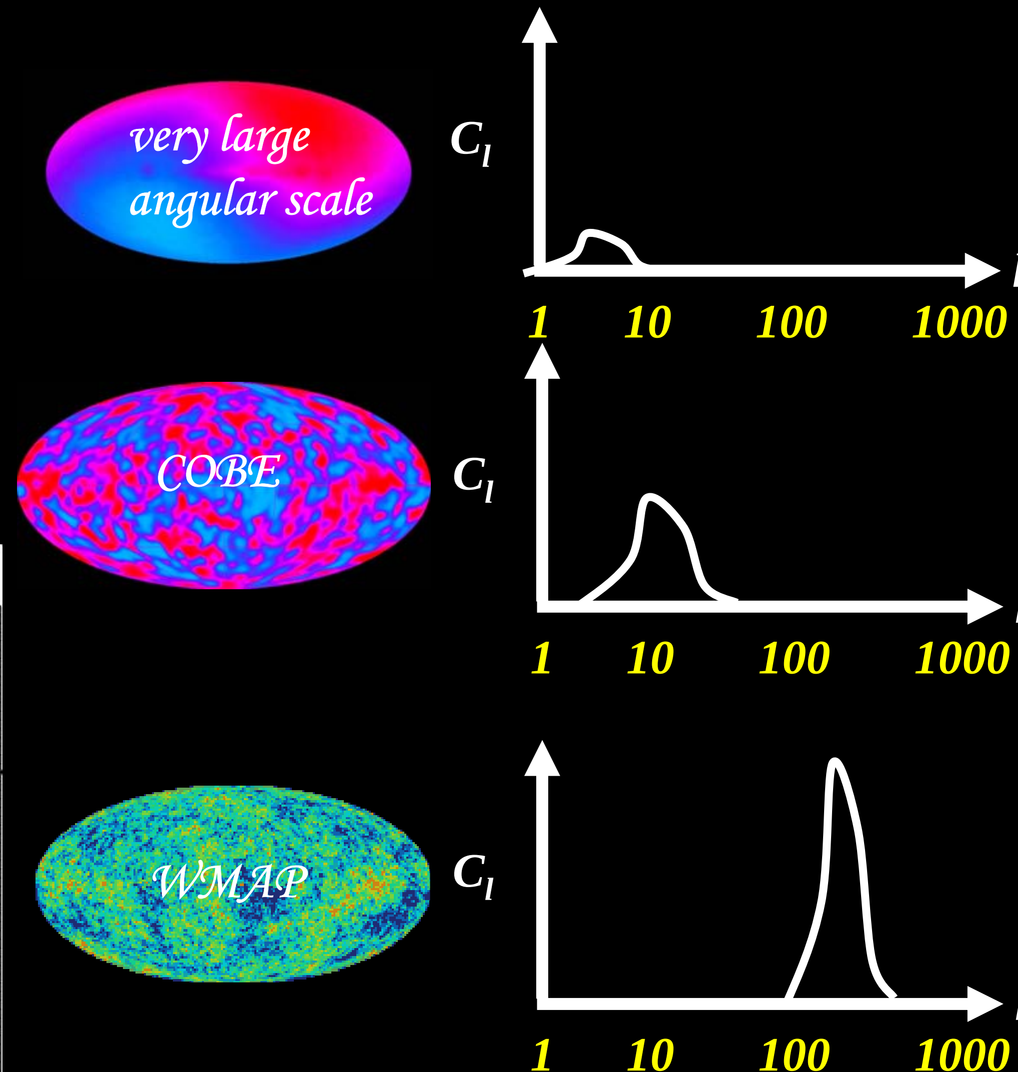
l = 19, m = 15

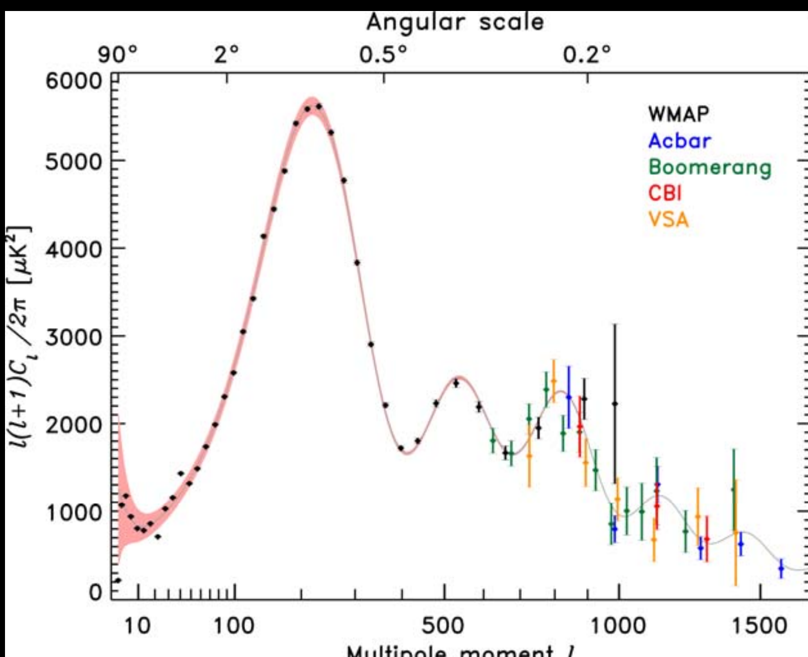


l = 36, m = 24

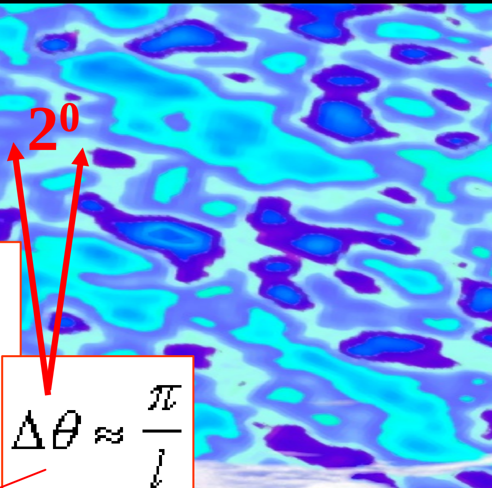
Image credits: gong.nso.edu/ and sohowww.nascom.nasa.gov/gallery/Helioseismology/.

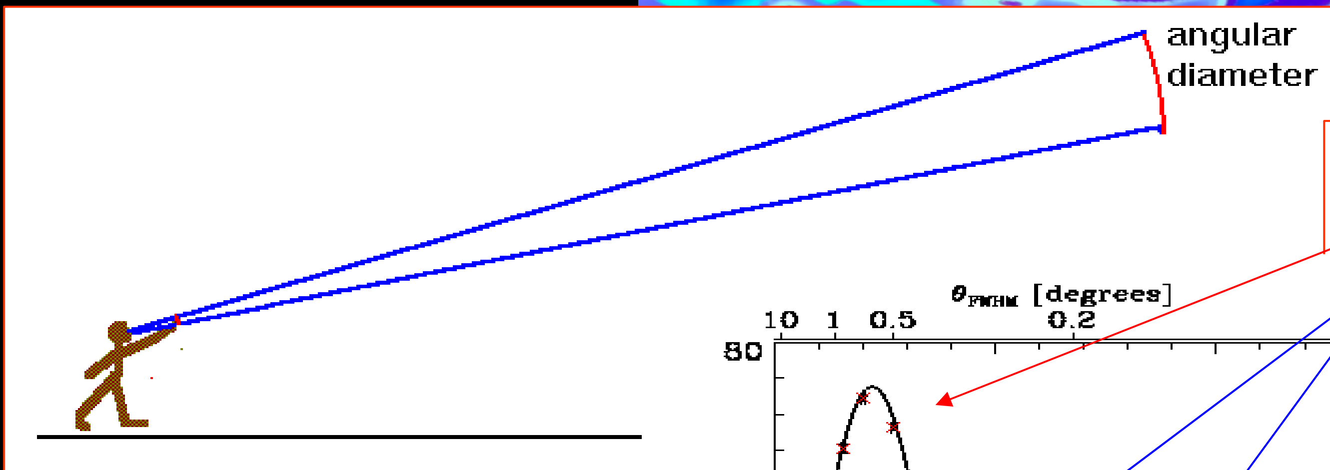
The CMB represents the last time that light scattered off the acoustic waves of the early universe, thus the power spectrum of the CMB contains the information that can tell us about the characteristic properties of the Universe...

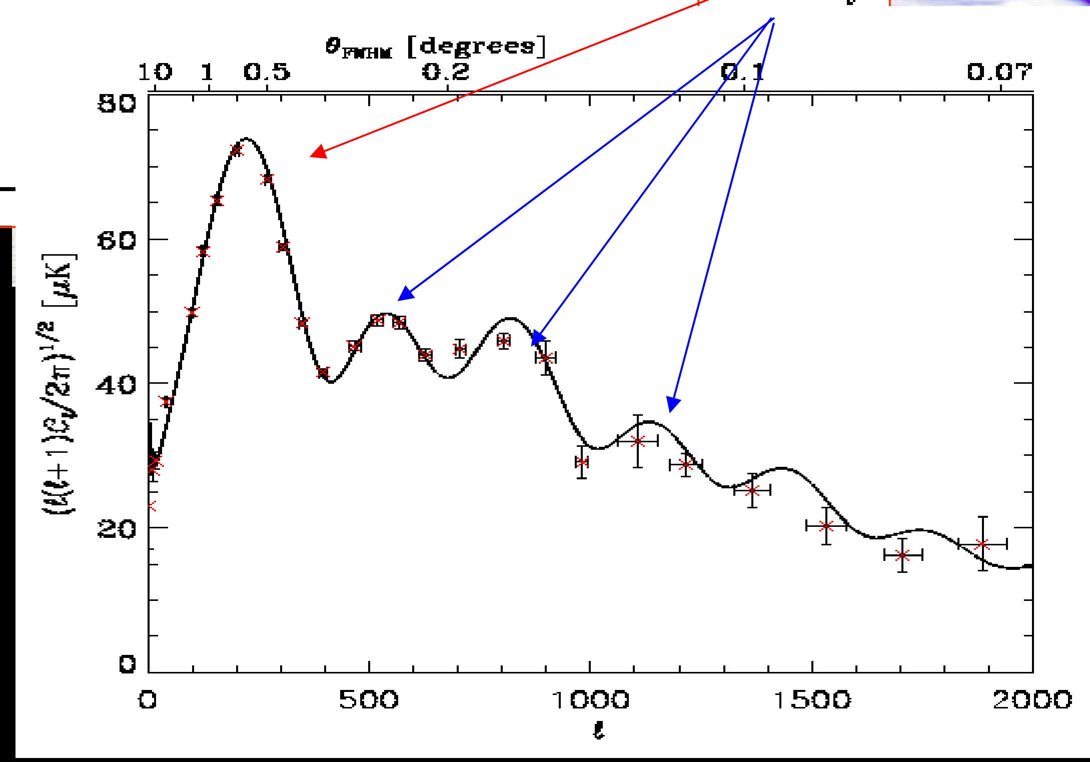




Anisotropies of 2^0 on the sky and smaller in the CMB…







correspond to the fundamental and higher harmonics in the power spectrum of the CMB.

What might the fundamental of the universe sound like?

longest wavelength in CMB = wave speed x age of universe at recombination

$$1.73 \times 10^{8} \ \frac{m}{\sec} \times 1.2 \times 10^{13} \ \sec \ = \ 2.08 \times 10^{21} \ m$$

Converting meters to light years, we get:

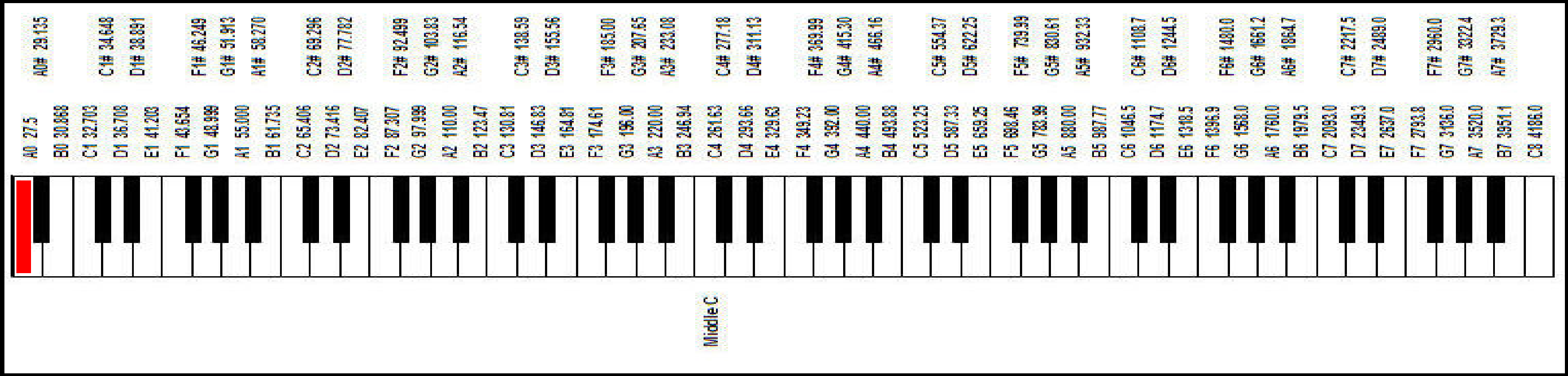
$$2.08 \times 10^{21} m \div 9.46 \div 10^{14} m / ly \cong 220{,}000 ly$$

Could any living creature hear a sound wave with a wavelength of 220,000 light years?

frequency = wave speed / wavelength

$$\frac{1.73\times10^{8}\ {}^{m}\!/\!_{sec}}{2.08\times10^{21}m}=1.44\times10^{-13}\,Hz$$

The lowest frequency that humans can hear is around 20 Hz, slightly lower than the lowest note on a piano (27 Hz).



So the answer is NO. The lowest note of the universe is $20/1.44 \times 10^{-13}$, or 1.88×10^{14} times LOWER than the lowest note humans can hear, or 47 octaves below the lowest note on a grand piano!

Scaled up by around 50 octaves, and using the power spectrum of the 2-dimensional surface variations in the CMB, we can generate a sound to represent the CMB like this:

To play sound:
Click on 08_Whittle-obeserved-CLs

To see animation:
Click on 09_Surfaceof last scattering

Animation by John Arballo, JPL/NASA, Caltech
Sound file courtesy of Mark Whittle, University of Virginia

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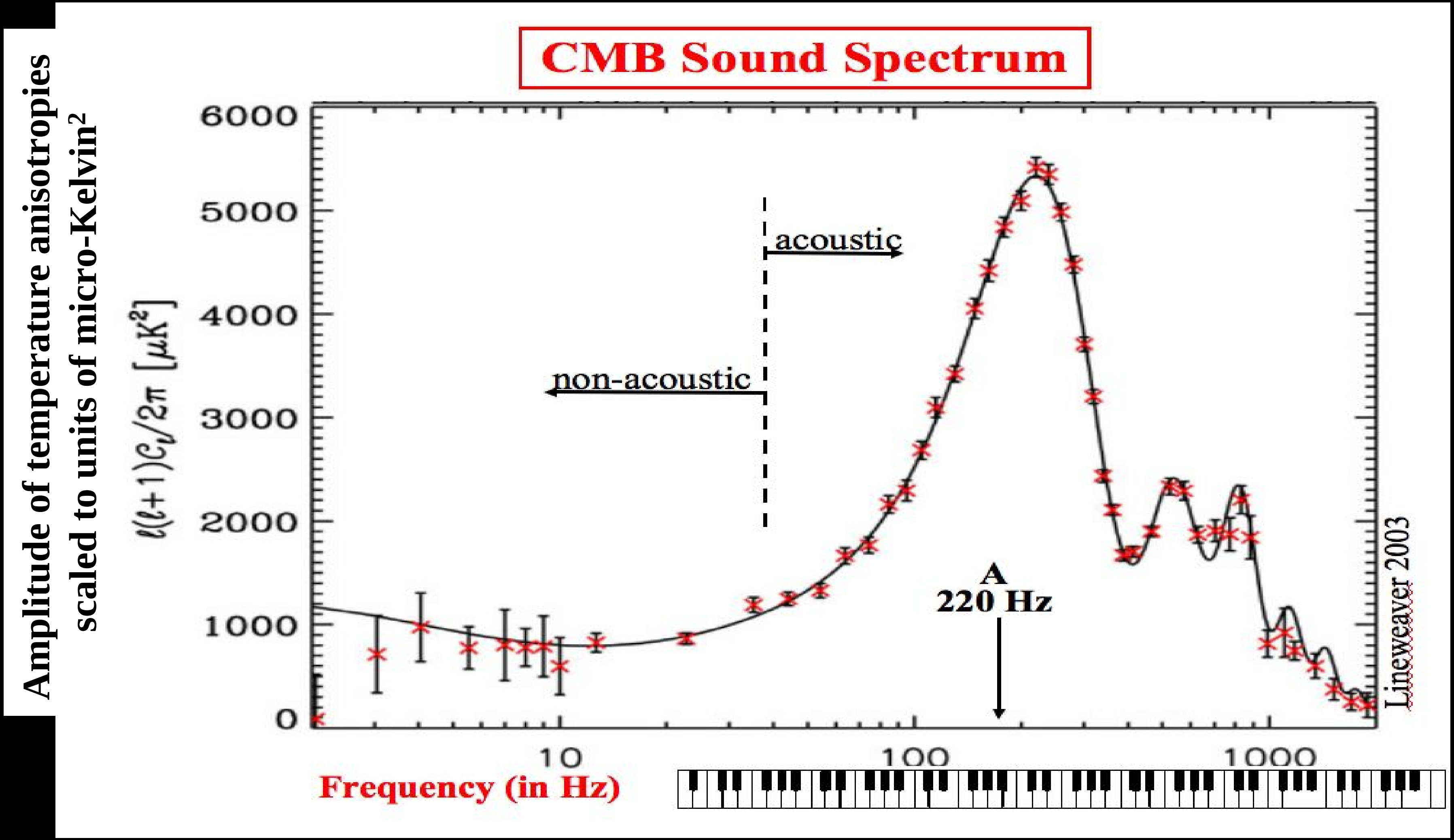
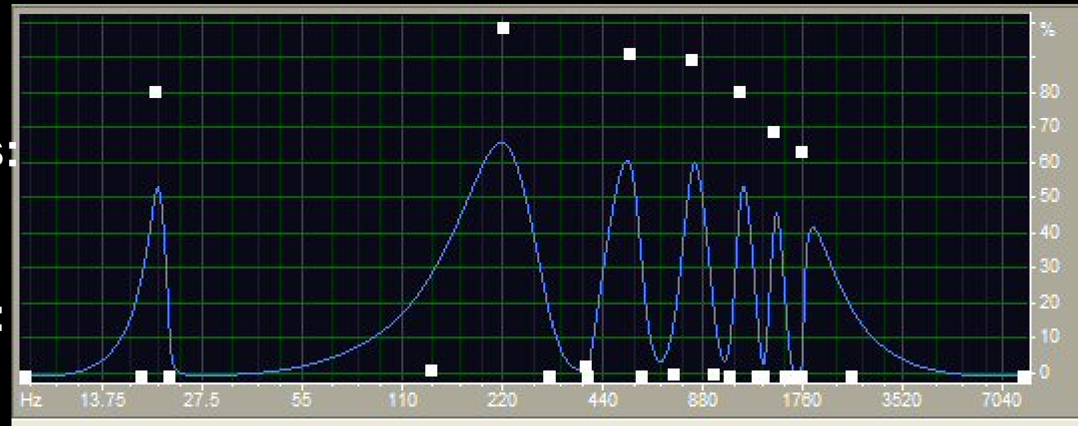


Figure adapted from website of Mark Whittle, University of Virginia

The power spectrum of the CMB tells us the distribution of the surface expression of the acoustic waves in the early universe, AT the time that matter and radiation first separated, 380,000 years after the Big Bang. To get an idea of the sound of the actual acoustic waves *in 3-D* just prior to recombination, we can filter the sound derived from the angular power spectrum to pick out the fundamental and higher harmonics.

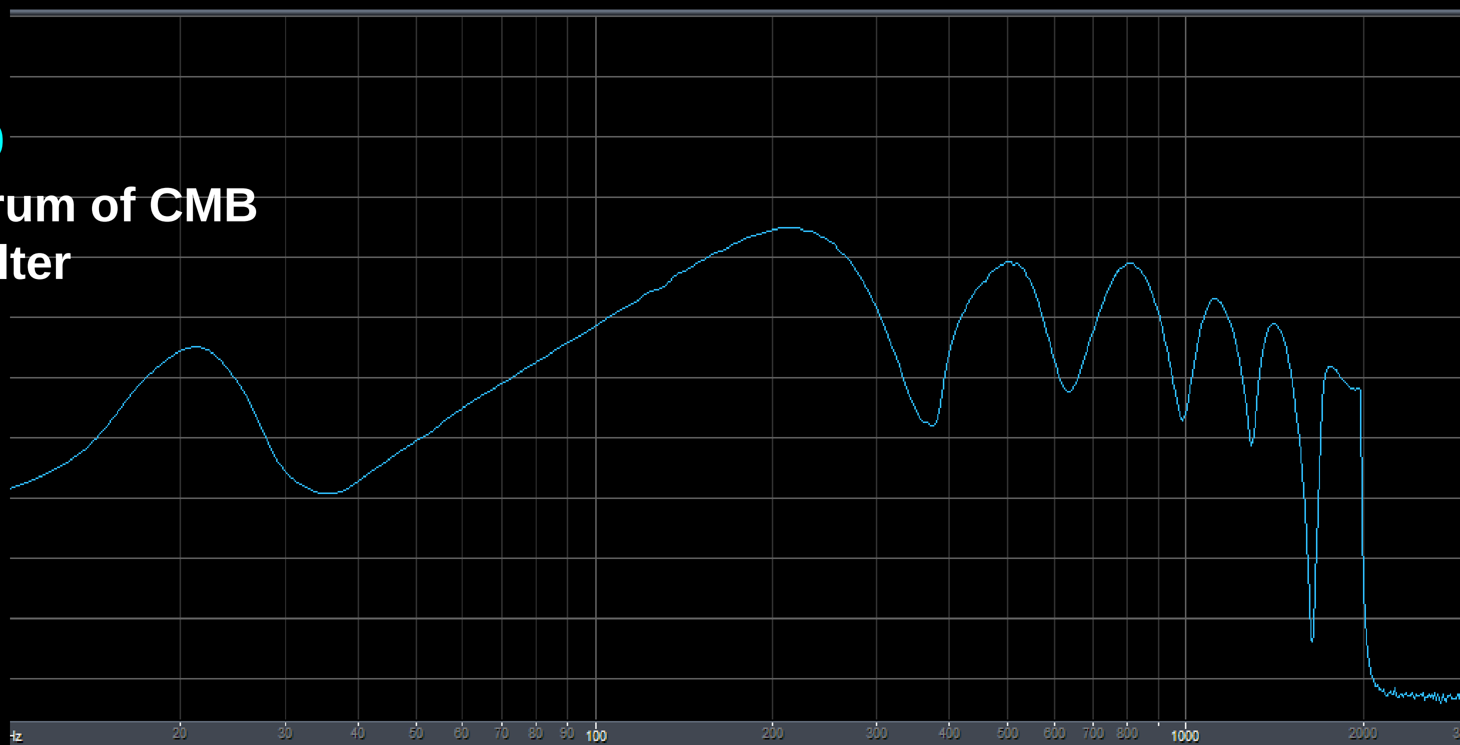
We apply a spline filter
centered on CMB peaks:



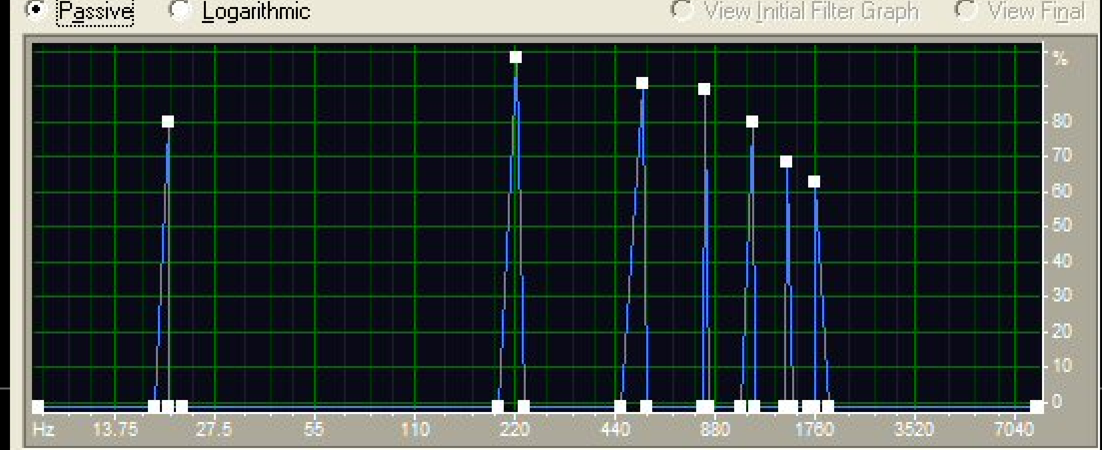
to get a sound like this:

Sound file 10

power spectrum of CMB
with spline filter
applied:

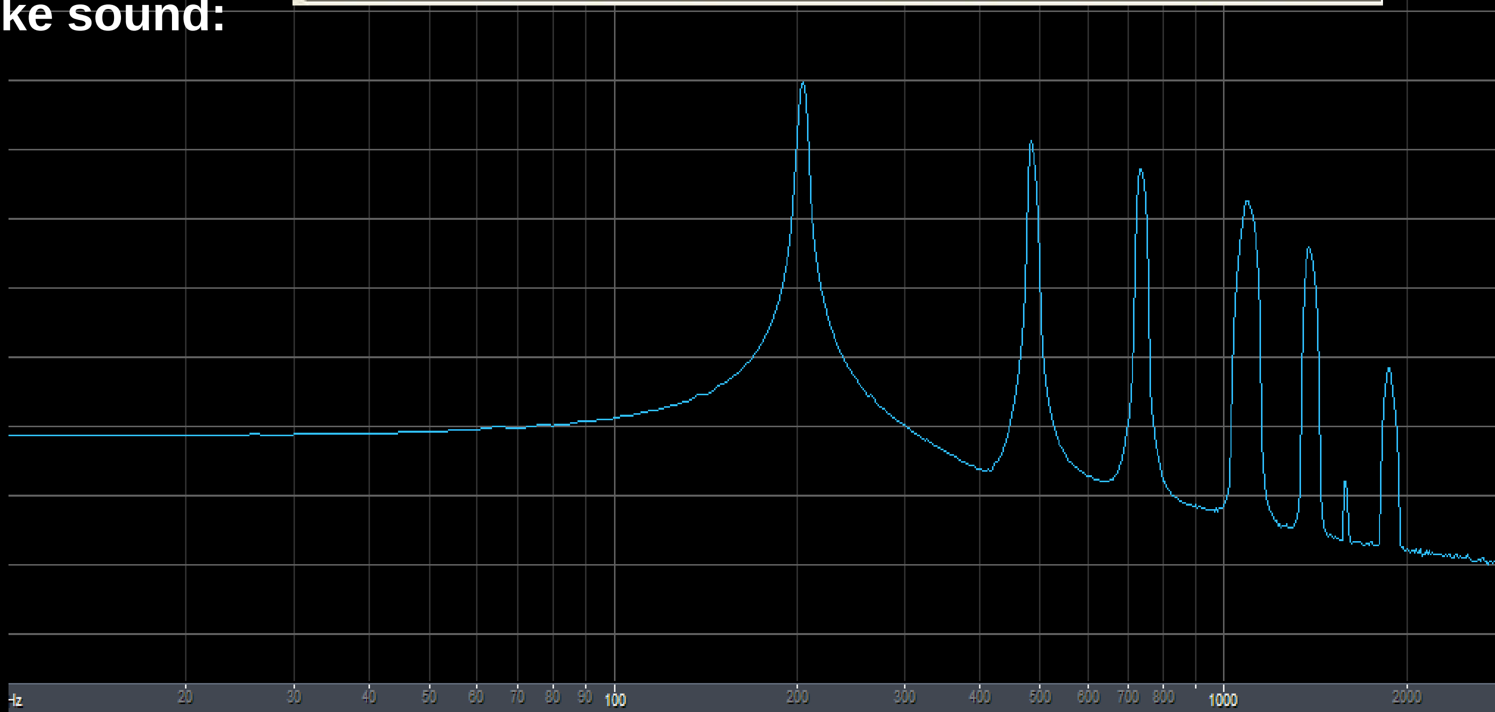


spike filter applied after spline filter:



plus a 12-db boost, yields a bell-like sound:

Sound file 11



Finally, we get the approximate power spectrum of the last chord of the early universe, prior to recombination, scaled up by 50 octaves to human hearing!

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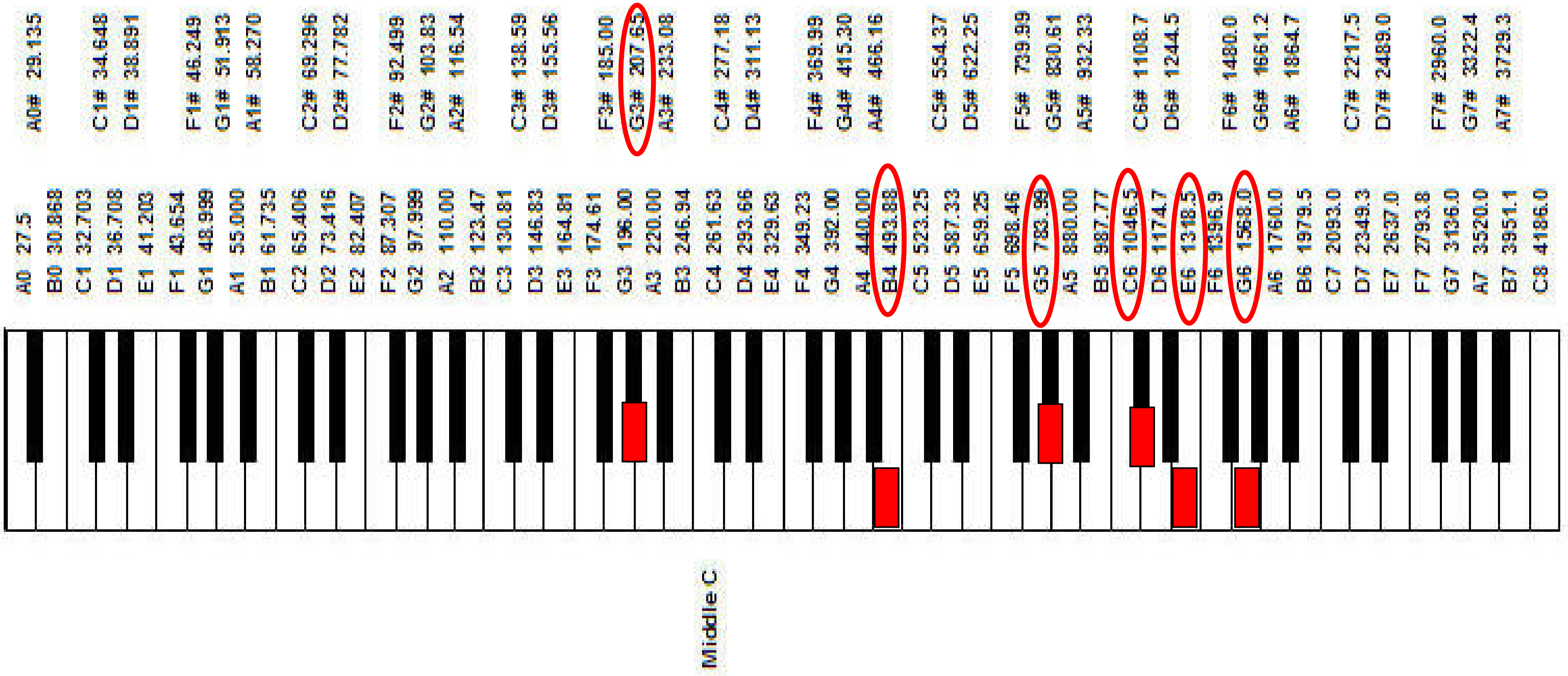
If you try to play the “chord of the CMB” on a piano, the closest you would come on a western piano would be something like this:

G3# - B4 – G5 – C6 - E6 – G6

and synthesized on a computer, would sound something like this:

Sound file 12



To summarize:

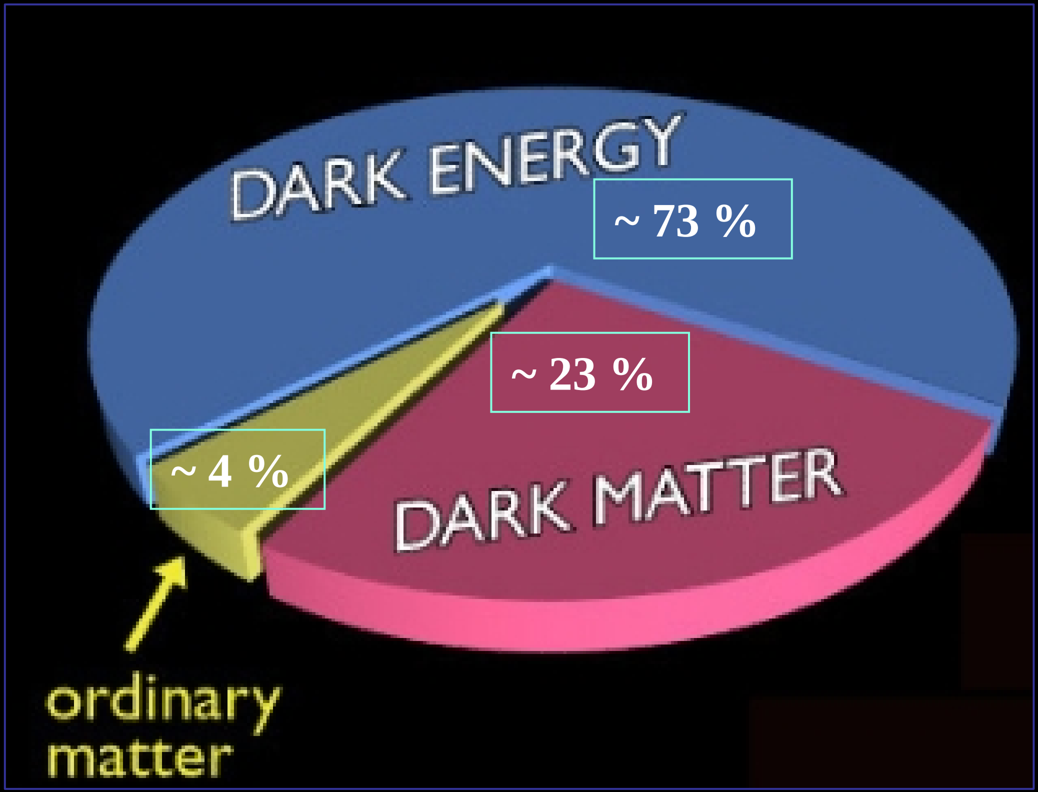
Well cleaned, high resolution map of milliKelvin temperature anisotropies in the CMB allows us to determine the angular power spectrum of the statistical distribution of these temperature anomalies with high precision.

The properties of the universe prior to recombination, during which the acoustic waves which gave rise to the CMB were propagating, can be derived from the precise angular power spectrum of the CMB in much the same way as we derive the properties of a musical instrument from its power spectrum, or the properties of the Sun from its angular power spectrum.

We model the power spectrum using software, and fine tune the parameters, until we get a model that matches the observed power spectrum.

We can't *really* listen to the CMB, but the principles of spectral analysis that we use in music are the same as those we use to understand the properties of the universe from the power spectrum of the CMB, *because* the early universe was full of SOUND WAVES!

As of today, we understand the composition of the universe to be:



From the geometry of the universe we understand that the average energy density is close to the so-called critical density, about 10^{-29} gr/ cubic centimeter.

Current expansion rate: 71 km/sec/Mpc

What more do we expect to learn from Planck?

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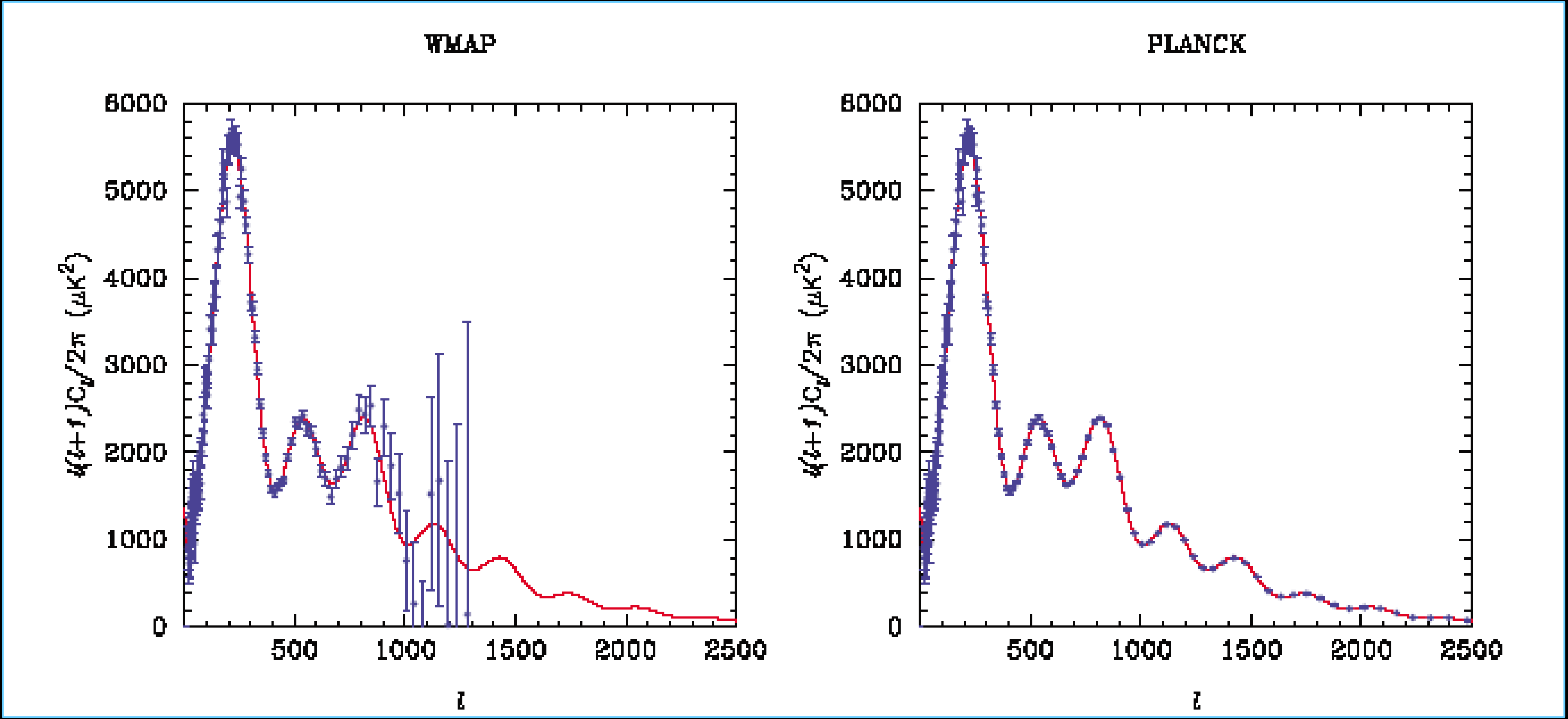
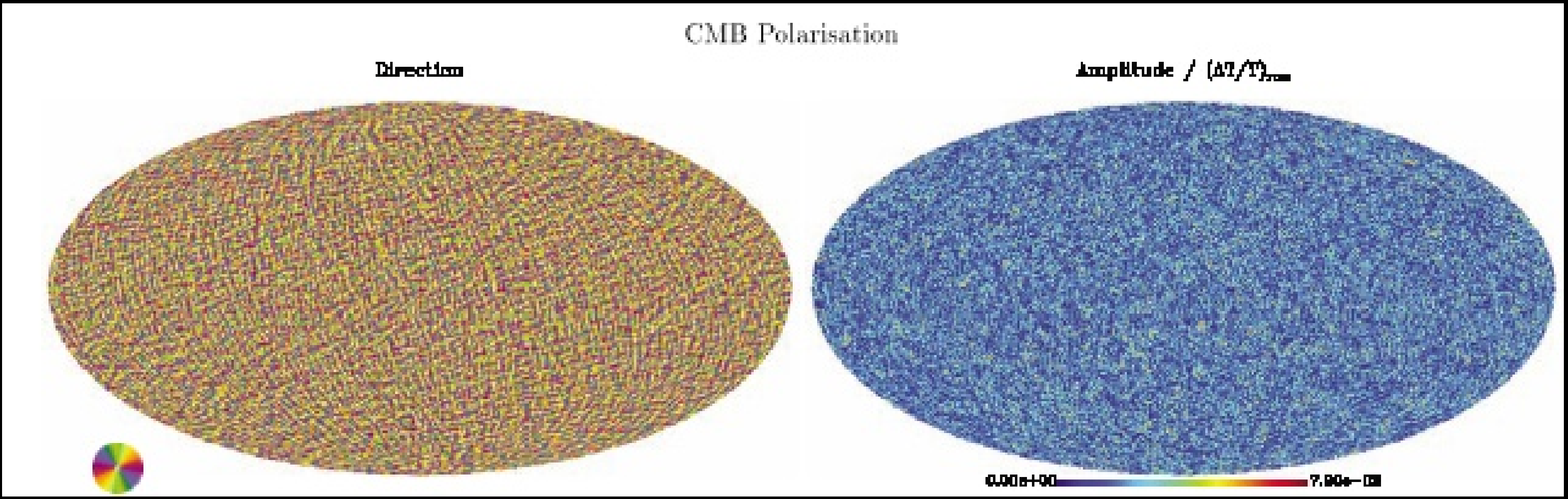


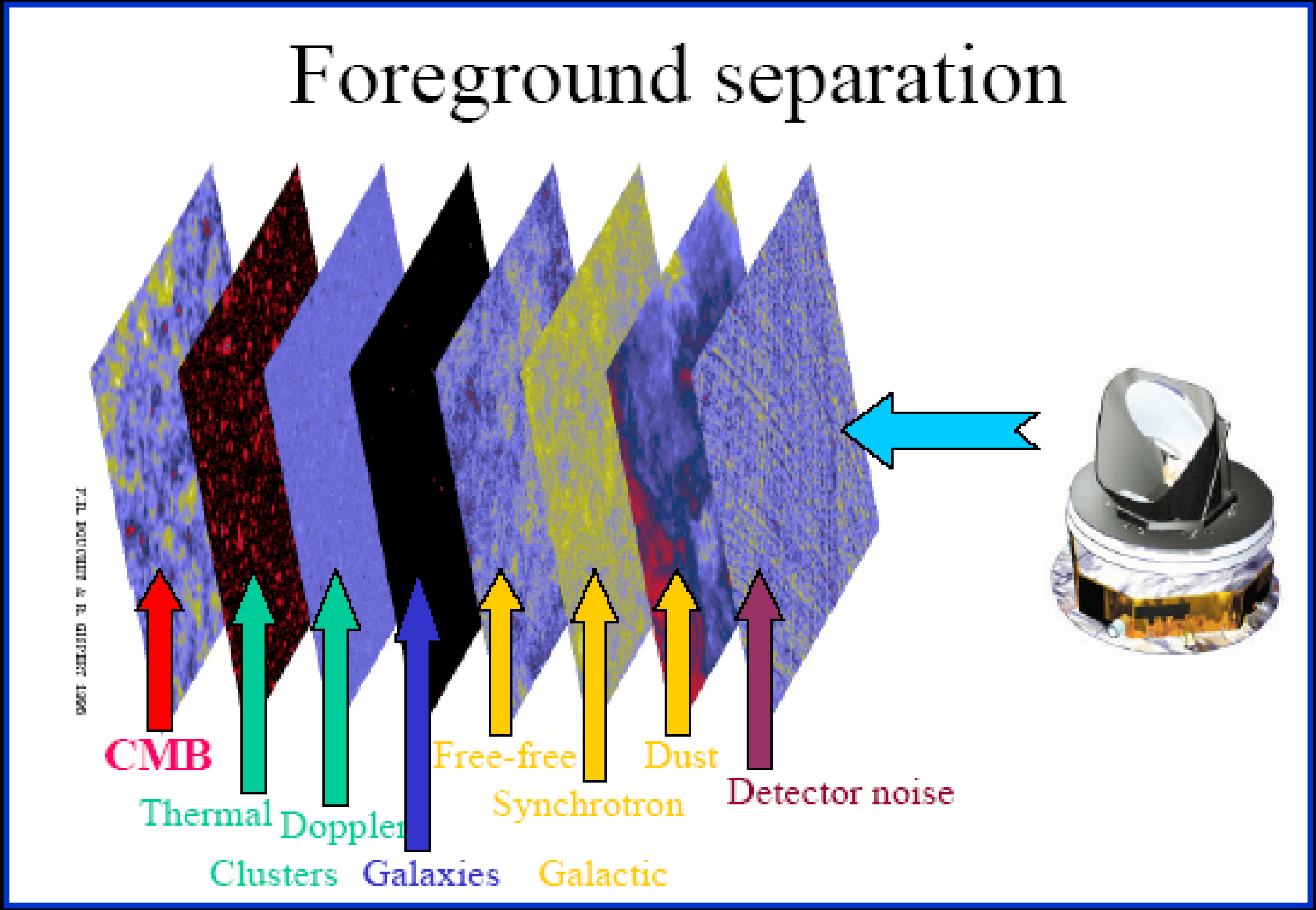
1. More precise determination of the ratios of the heights of the fundamental, second, and third harmonics will permit more precise determination of the relative abundances of dark matter and dark energy relative to baryons (normal matter).

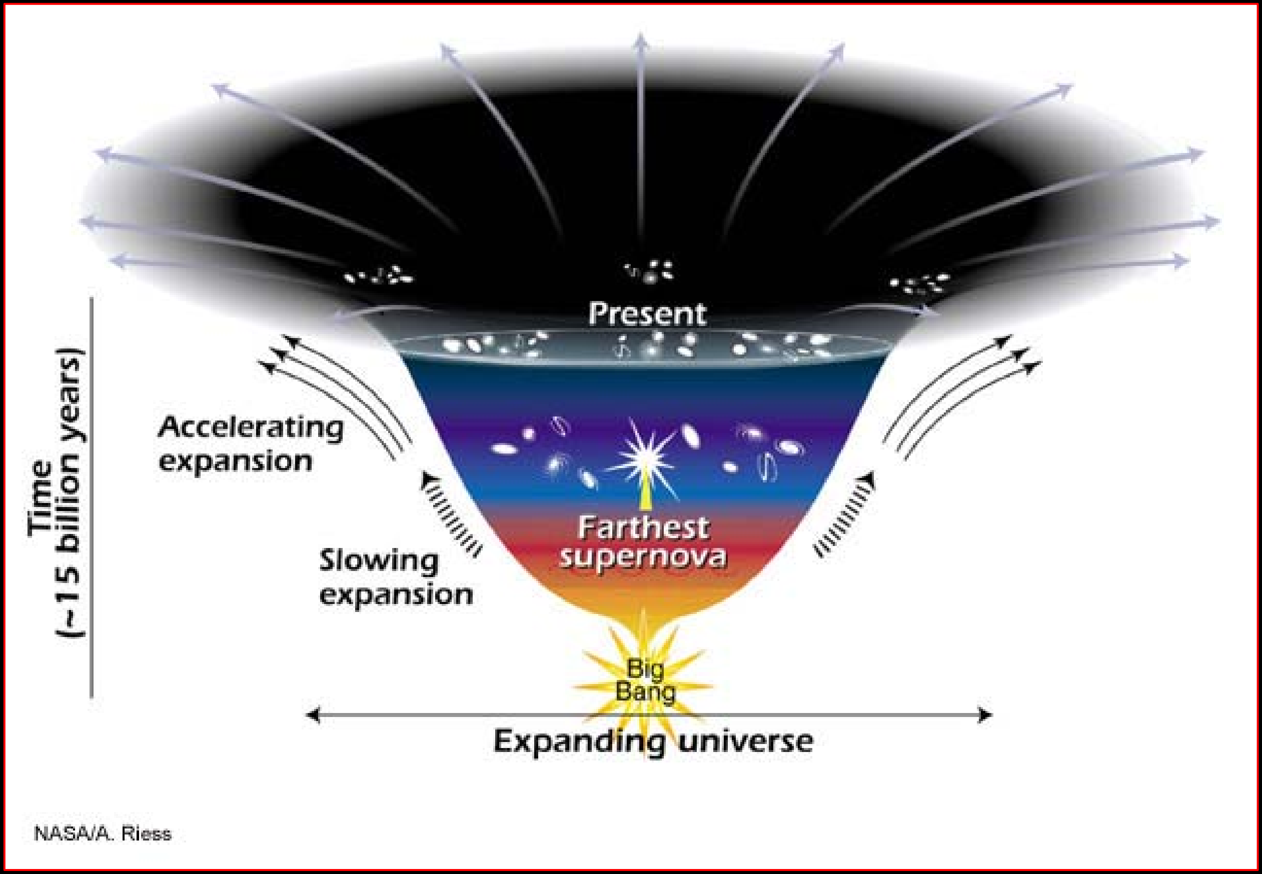
2. Finer angular resolution of Planck will sample essentially all the higher angular wave numbers accurately. These higher order peaks are effected by the distribution of dark energy between the CMB and us, and also by the effect on the CMB photons of ionized gas in galaxy clusters on their way from the CMB to our telescopes.

3. Planck will also measure the polarization of the CMB, which indicates how the light was scattered in the early Universe. The polarization will give us information about when the first stars formed and re-ionized the universe, and also about the velocities of the acoustic waves on the surface of last scattering.

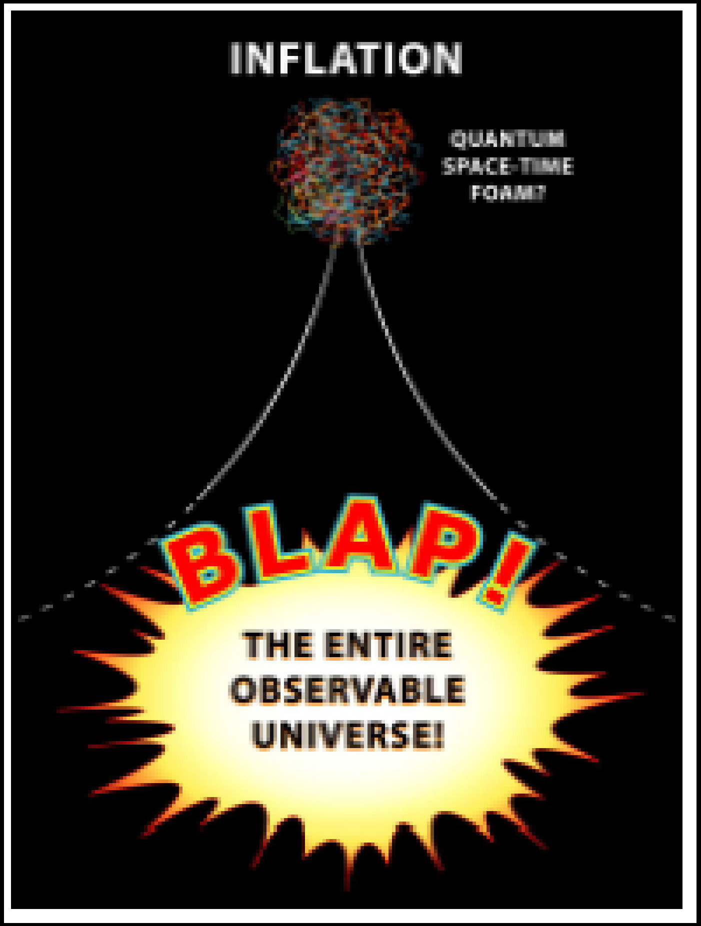


The nine frequency bands will allow Planck to accurately remove foreground sources from the CMB maps, but also to prepare accurate catalogs of foreground sources in microwave and radio frequencies, which will be useful for astronomers.





From WMAP's power spectrum, we have determined that the amount of ordinary matter (baryons) and dark matter has remained constant since recombination, and thus their relative densities have decreased due to the expansion of the universe. HOWEVER, the nature of dark energy is such that its density is CONSTANT over time, thus the total amount of dark energy has INCREASED over time! This has caused an ACCELERATION in the expansion of the universe that began around 5 billion years ago. Planck's accurate power spectrum will help constrain the nature of this mysterious dark energy and shed light on fundamental physics, perhaps giving us information which can support or refute new theories.



Cosmic inflation:

In some miniscule time period, around 10^{-35} seconds after the Big Bang, the universe underwent a sudden expansion by around 50 orders of magnitude.

figure: G. Eftstatiou

Planck's high precision at all angular wave numbers, as well as its ability to measure the polarization power spectrum, will help illuminate the physics behind the model of INFLATION that explains our observations, but for which a physical mechanism has not been found.

So, stay tuned for more news of the Planck Mission, now in progress!

Planck web pages of particular interest:

http://planck.caltech.edu/ : Planck site at the Jet Propulsion Lab

http://sci.esa.int/science-e/www/area/index.cfm?fareaid=17 : Planck science and technology page at the European Space Agency

http://www.planck.fr/heading8.html : The Planck High Frequency Instrument consortium in France

http://planck.cf.ac.uk/home : The Planck Pages in the United Kingdom

http://planckmission.wordpress.com/ : The Planck Blog

http://twitter.com/planck: Follow Planck on Twitter!
and on Facebook at
www.facebook.com/pages/Herschel-and-Planck-Astronomy/30562814194

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Classroom Connections

The Big Idea

We know that we live in an expanding universe, in which ordinary matter comprises only 4% or less of the total matter-energy density of the universe, and in which 96% of the matter-energy density is in some DARK form that we still don't understand. How could stars, galaxies, and life have evolved if the universe were even a tiny bit different? What process caused the universe as we know it to come into being, and how will it end? The Cosmic Microwave Background, the oldest radiation we can observe, holds the clues.

Connection to Standards

Experimental Cosmology connects to all sciences and mathematics: Physics – Astronomy – Earth Science – Chemistry – Computer Science – as well as Sociology – History – and Philosophy.

In addition, Experimental Cosmology is an INTERNATIONAL endeavor, thus you can tie the Planck Mission to your multicultural standards!

Teacher Resources

Connected Resources

The most complete teaching resources on line about Experimental Cosmology to date are those which have been developed by the WMAP team: http://map.gsfc.nasa.gov/resources/edresources1.html. As Planck resources are completed, they will be posted on http://planck.caltech.edu.

Related Resources

• Professor Wayne Hu's Cosmology Tutorials:
http://background.uchicago.edu/~whu/physics/physics.html
• Professor Mark Whittle's Big Bang Acoustics:
http://www.astro.virginia.edu/~dmw8f/

Additional Professional Development

• July 31 – August 4, 2010 – Cosmos in the Classroom, Astronomy Education Seminar which is bursting with resources for teachers, hosted by the Astronomical Society of the Pacific. See http://www.astrosociety.org/events/meeting.html