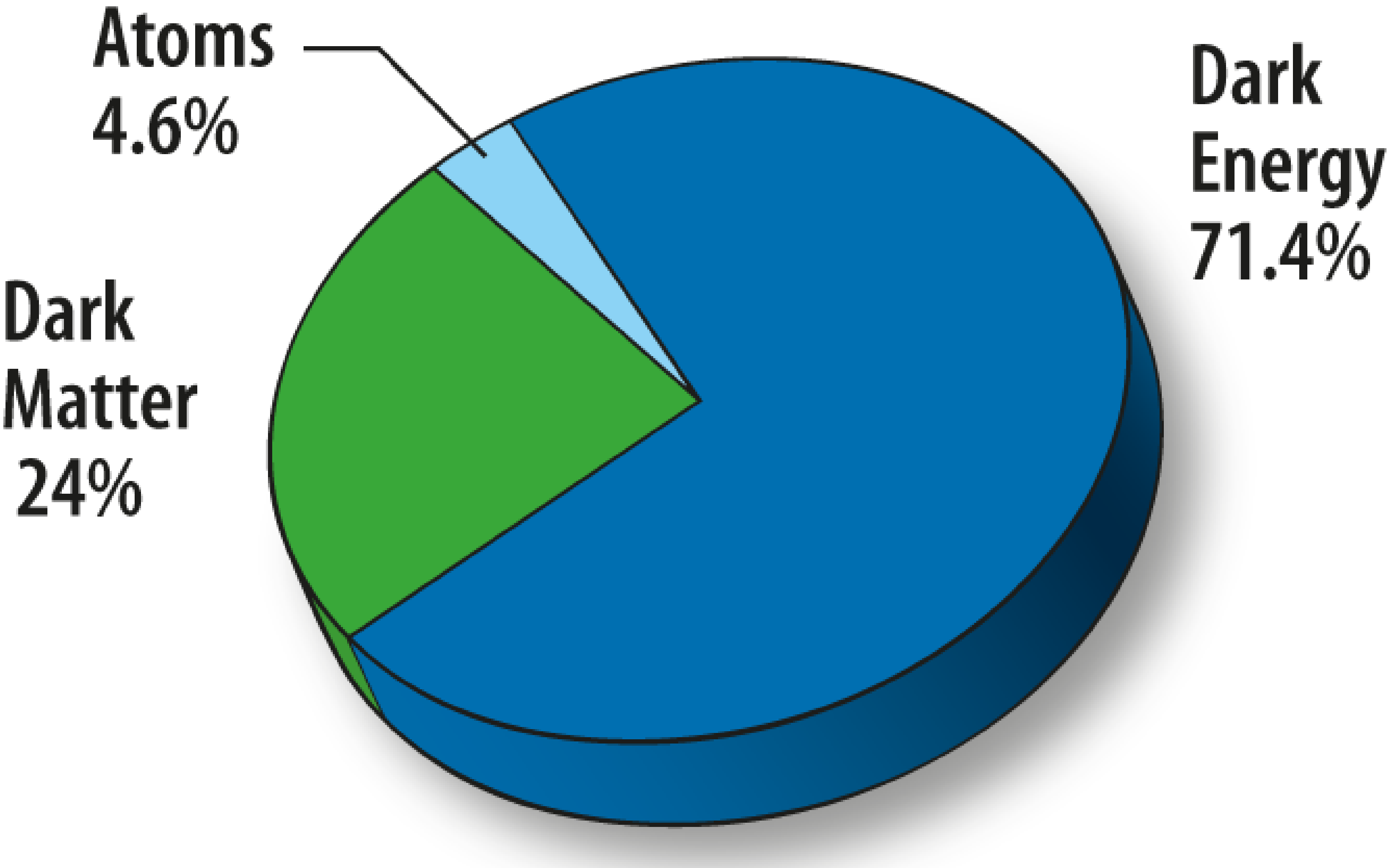
The Dark Energy

Part 2: The observational evidence for the Big Bang



1929: Edwin Hubble

Almost all galaxies are moving AWAY from us!

In 1929, Hubble examined the relation between distance and redshift of galaxies.

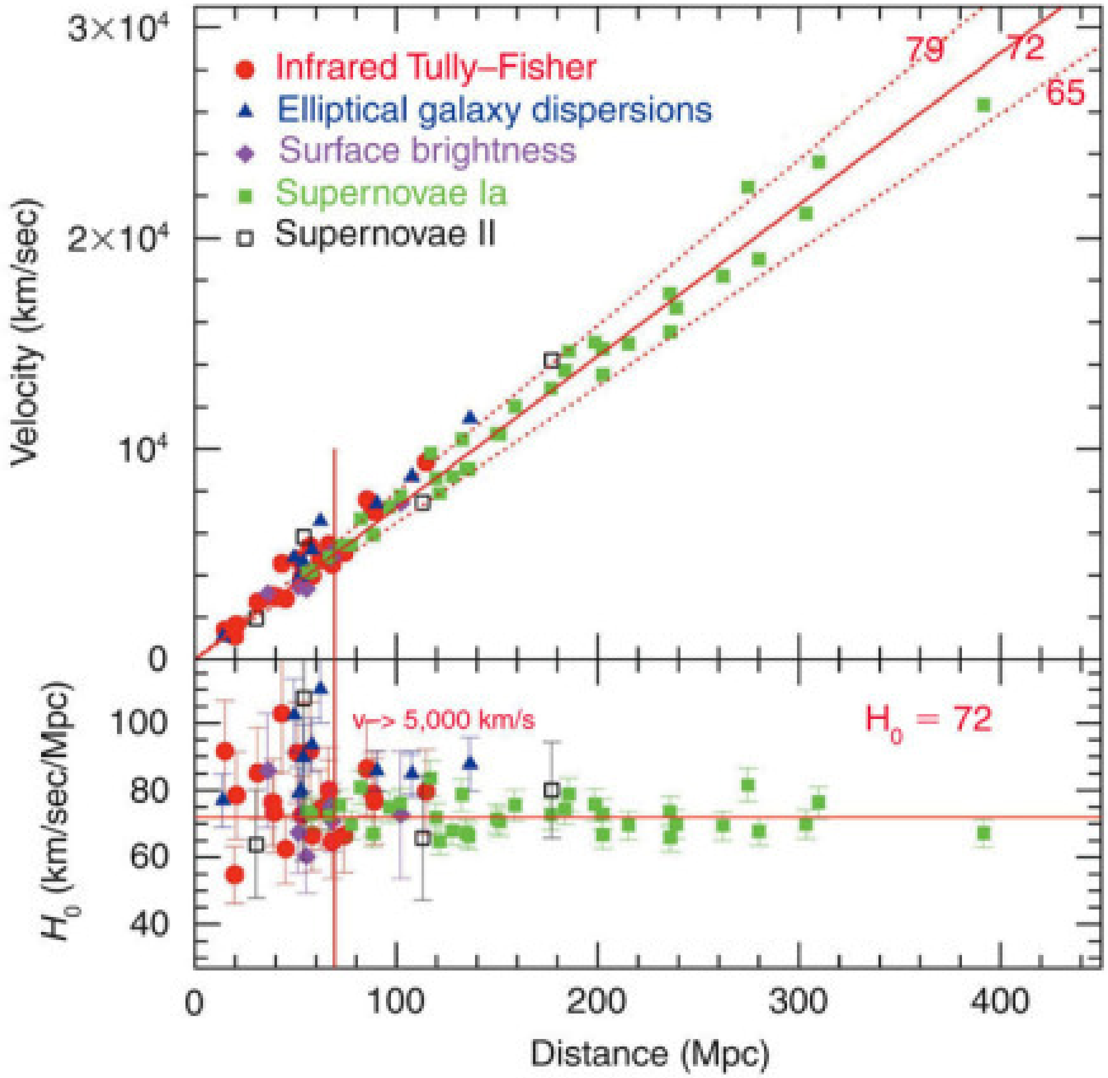
He found a rough proportionality of these objects' distances with their redshifts, nowadays termed Hubble's law.

$$v = H_0 D$$

↓

Hubble constant

$$H_0 \approx 70 \frac{\text{km/s}}{\text{Mpc } (10^6 \text{ parsecs})}$$



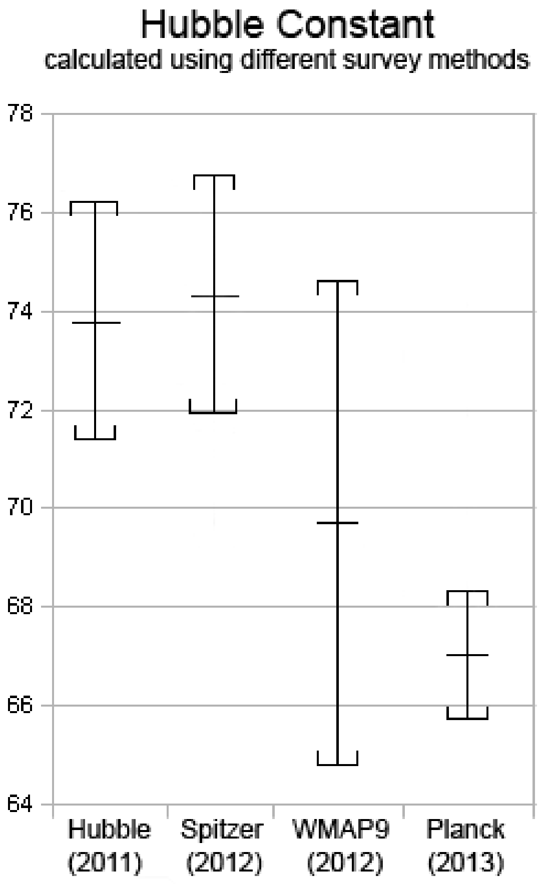
B

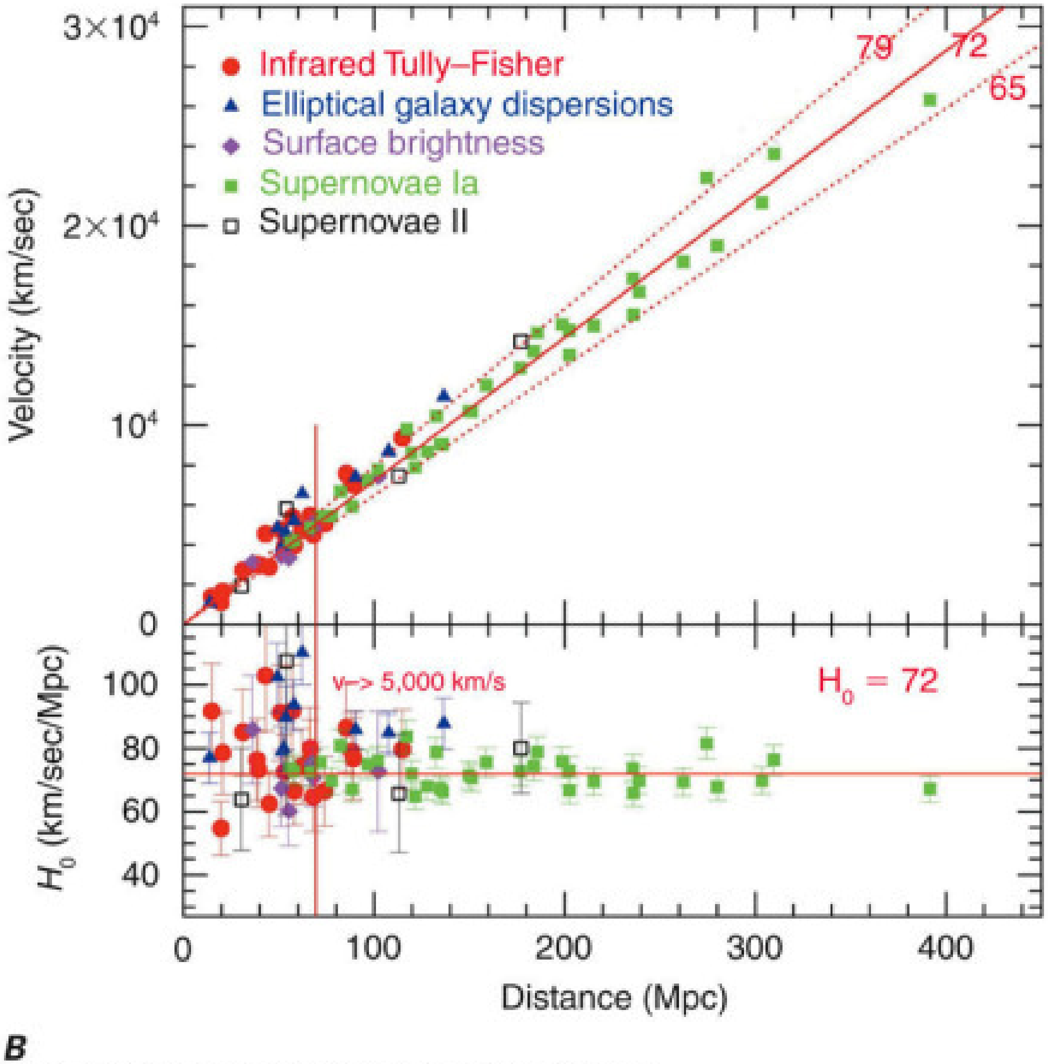
(Wendy L. Freedman, Observatories of the Carnegie Institution of Washington, and NASA)

Hubble's Law

$v = H_0 D$

Hubble's law: the galaxies that are farther away are moving faster.





(Wendy L. Freedman, Observatories of the Carnegie Institution of Washington, and NASA)

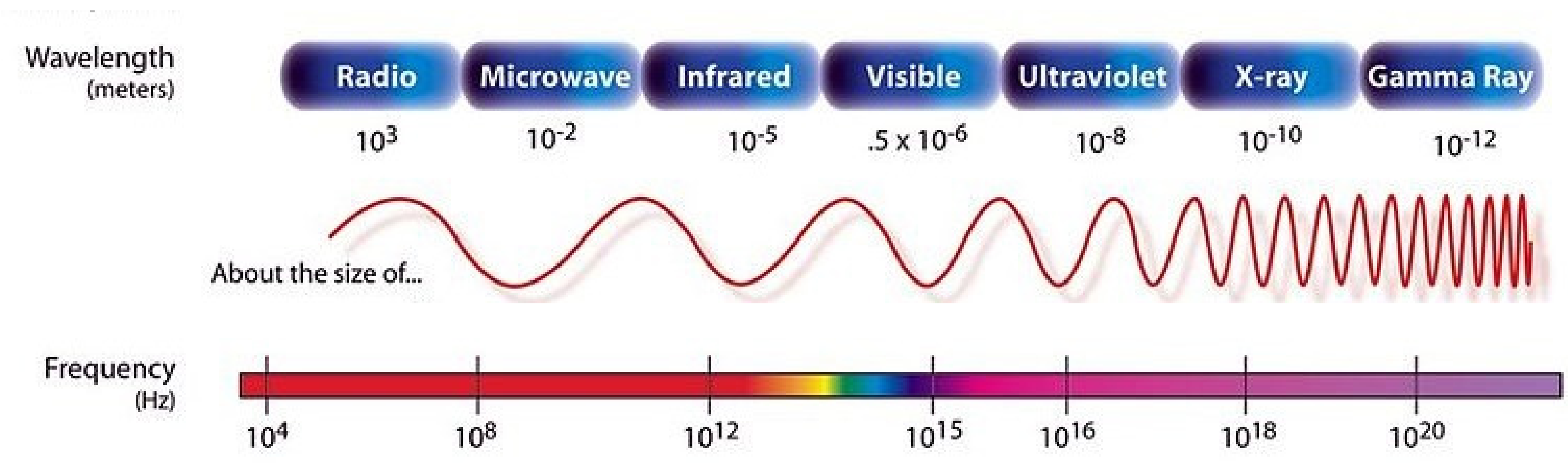
$$H_0 \text{ units: } \frac{\text{km/s}}{\text{Mpc } (10^6 \text{ parsecs})}$$

https://en.wikipedia.org/wiki/Hubble%27s_law#/media/File:Recent_Hubble%27s_Constant_Values.png

General relativity interpretation of the Hubble's Law:

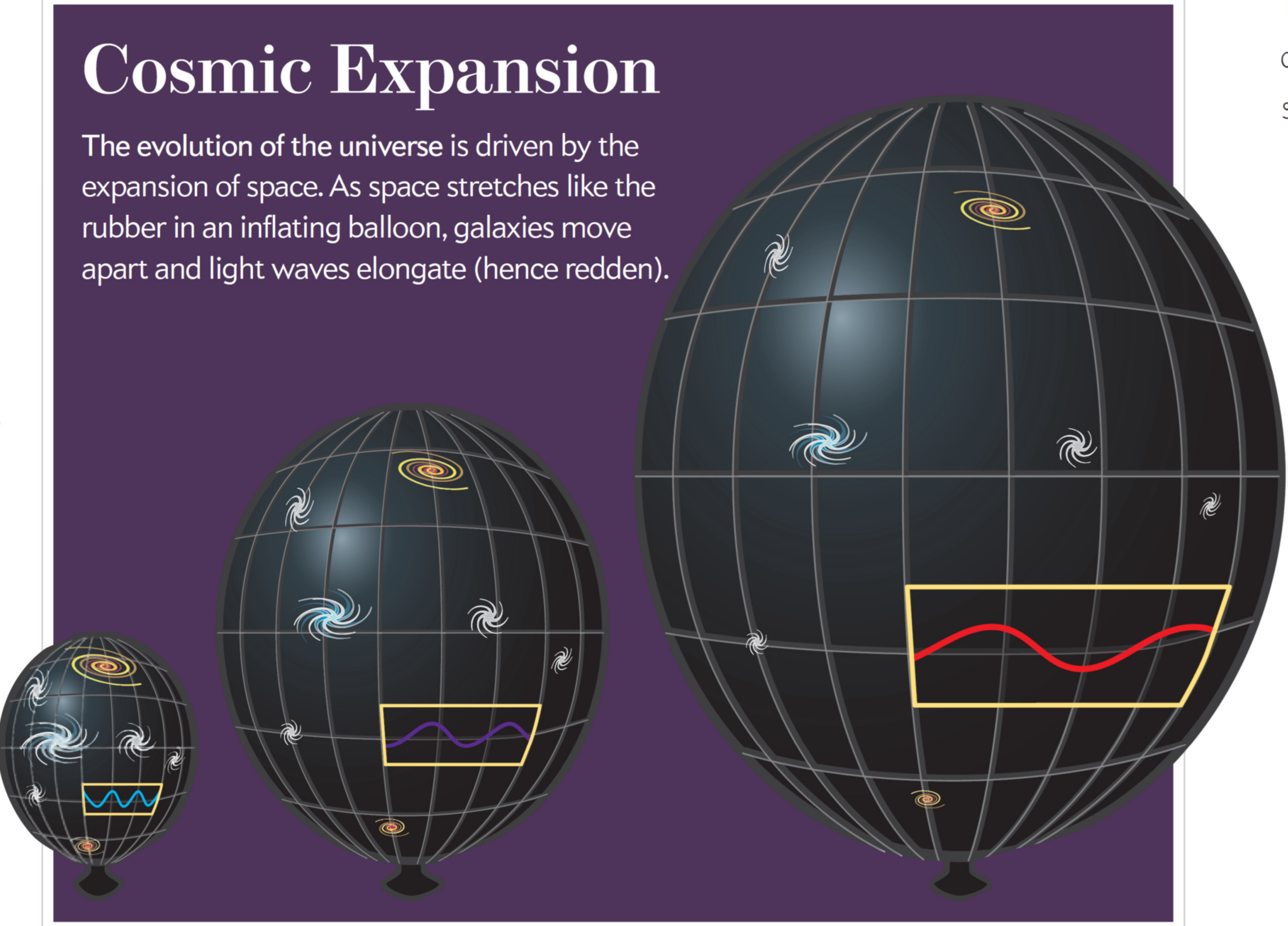
Space itself is expanding, and galaxies are being carried along for the ride.

Light, too, is being stretched, i.e. redshifted



Redshifted

←



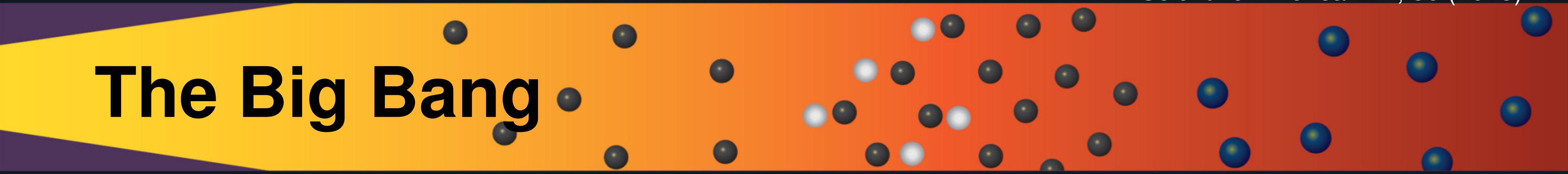
Cosmic Expansion

The evolution of the universe is driven by the expansion of space. As space stretches like the rubber in an inflating balloon, galaxies move apart and light waves elongate (hence redden).

Scientific American **22**, 36 (2013)

Scientific American **22**, 36 (2013)

The Big Bang

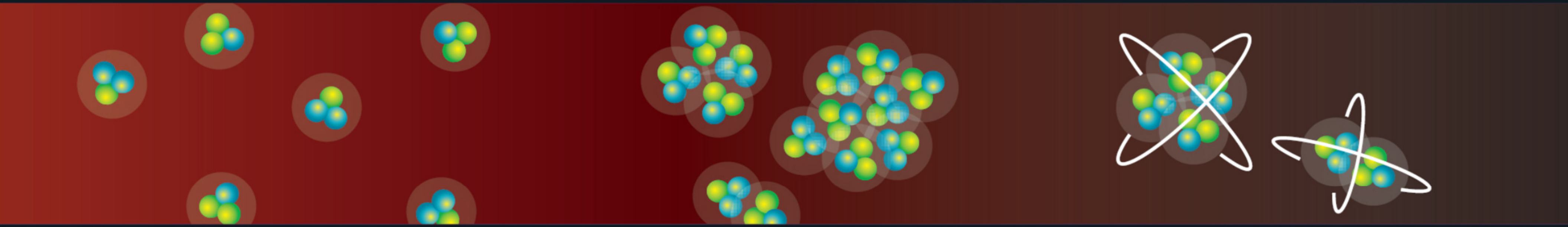


10^{-35} second
Cosmic inflation creates a large, smooth patch of space filled with lumpy quark soup

10^{-30} s
One potential type of dark matter (axions) is synthesized

10^{-11} s
Matter gains the upper hand over antimatter

10^{-10} s
A second potential type of dark matter (neutralinos) is synthesized



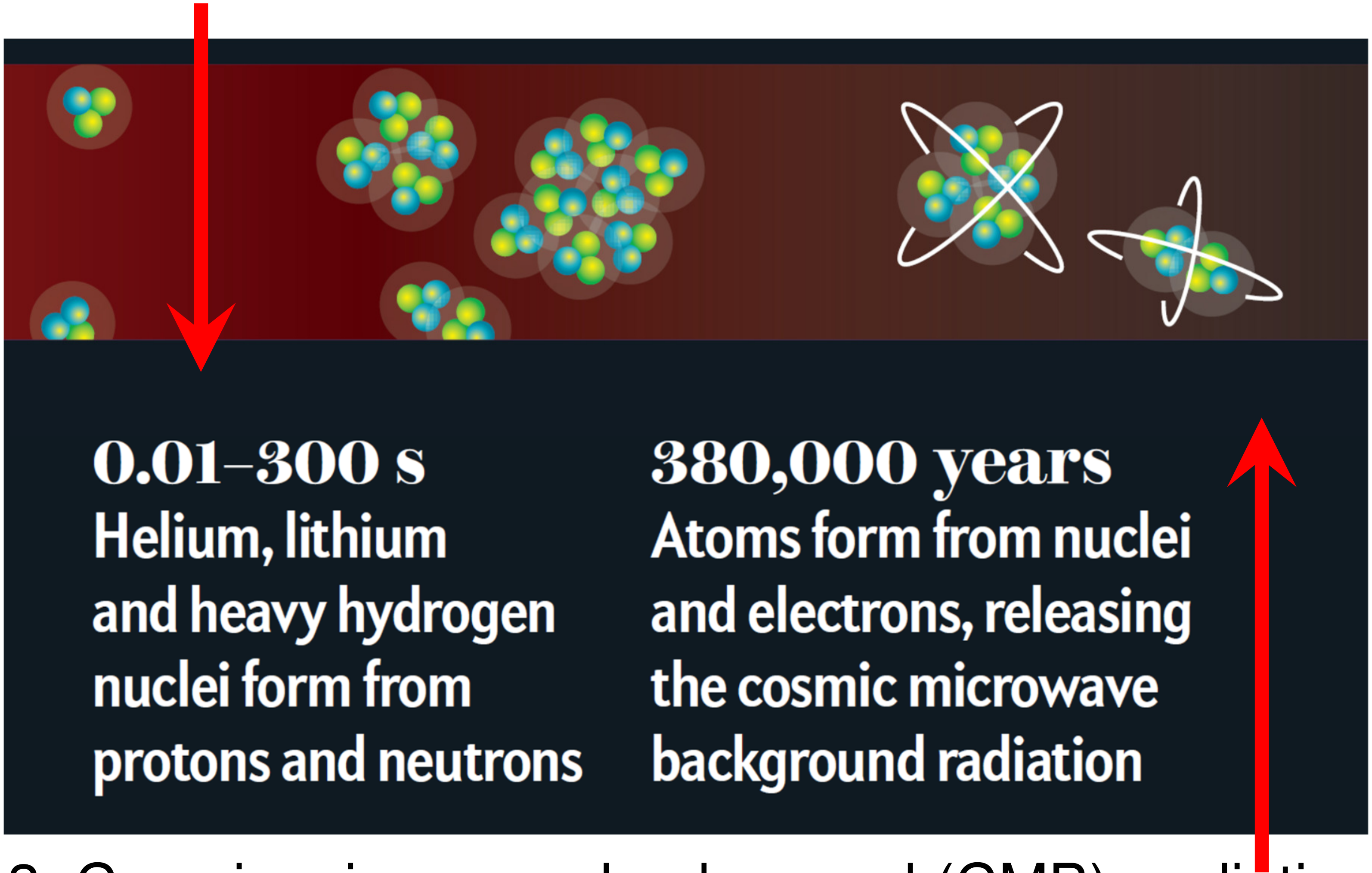
10^{-5} s
Protons and neutrons form from quarks

0.01–300 s
Helium, lithium and heavy hydrogen nuclei form from protons and neutrons

380,000 years
Atoms form from nuclei and electrons, releasing the cosmic microwave background radiation

The observational evidence for the Big Bang

1. Expansion of the Universe
2. Big Bang Nucleosynthesis



0.01–300 s
Helium, lithium and heavy hydrogen nuclei form from protons and neutrons

380,000 years
Atoms form from nuclei and electrons, releasing the cosmic microwave background radiation

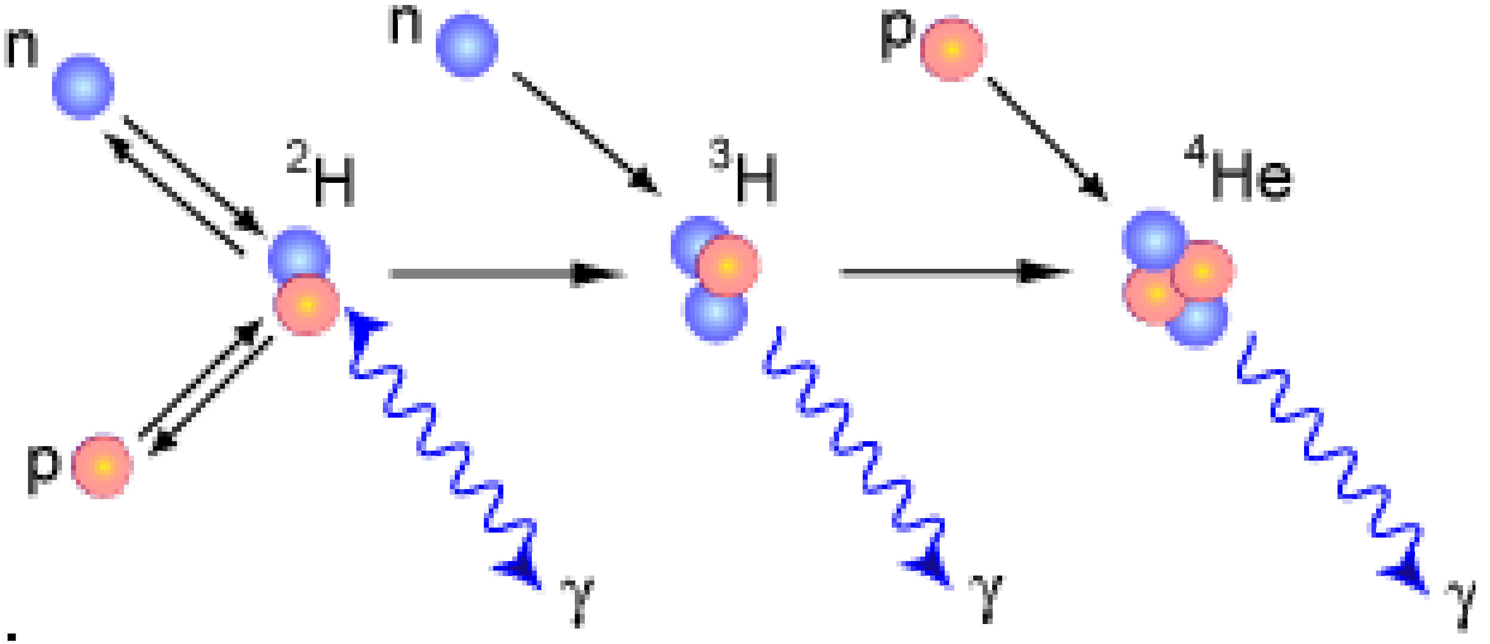
3. Cosmic microwave background (CMB) radiation

Scientific American **22**, 36 (2013)

Big Bang Nucleosynthesis

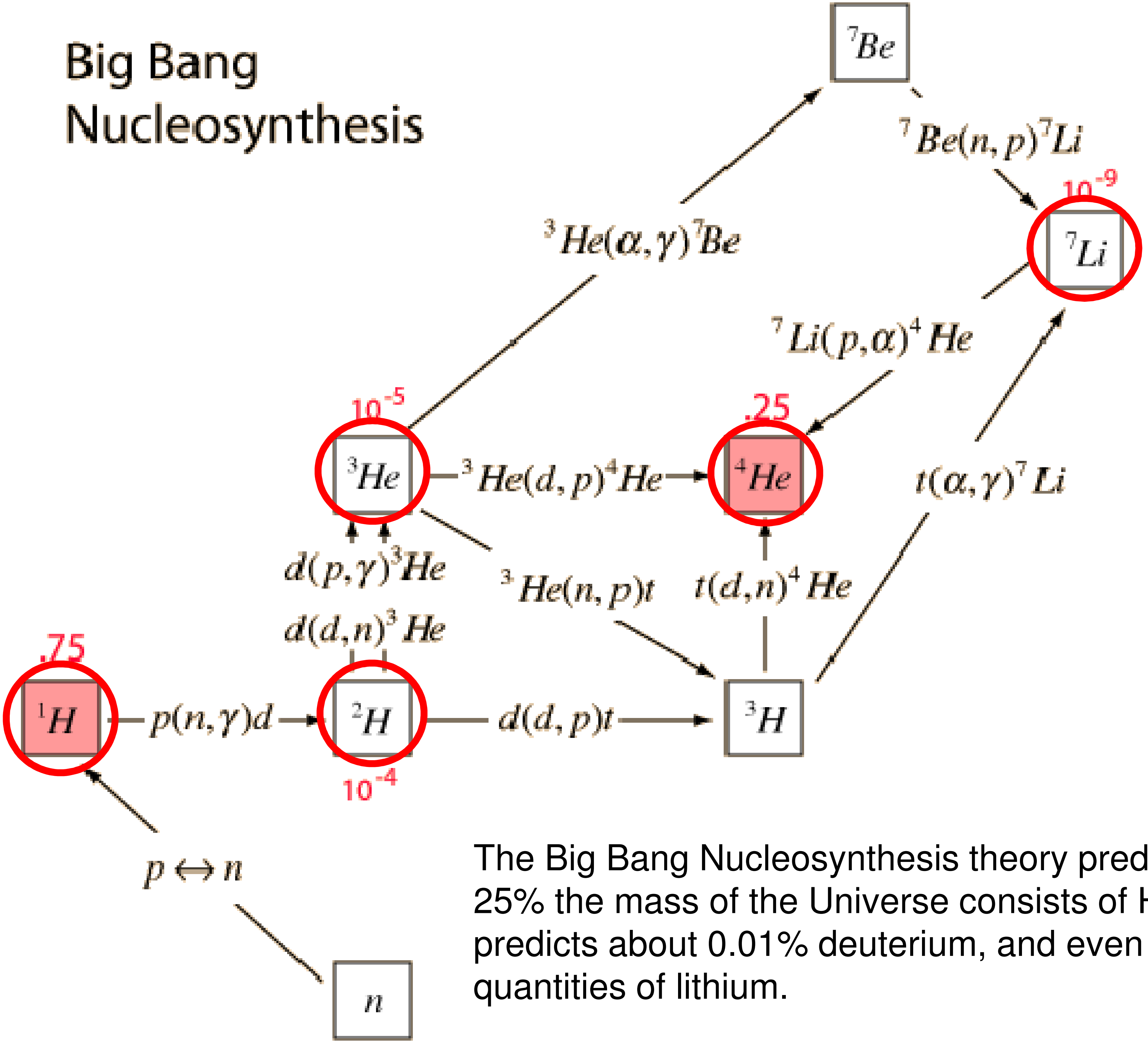
As the Universe cools down, protons and neutrons can undergo fusion to form heavier atomic nuclei.

This process is called nucleosynthesis.

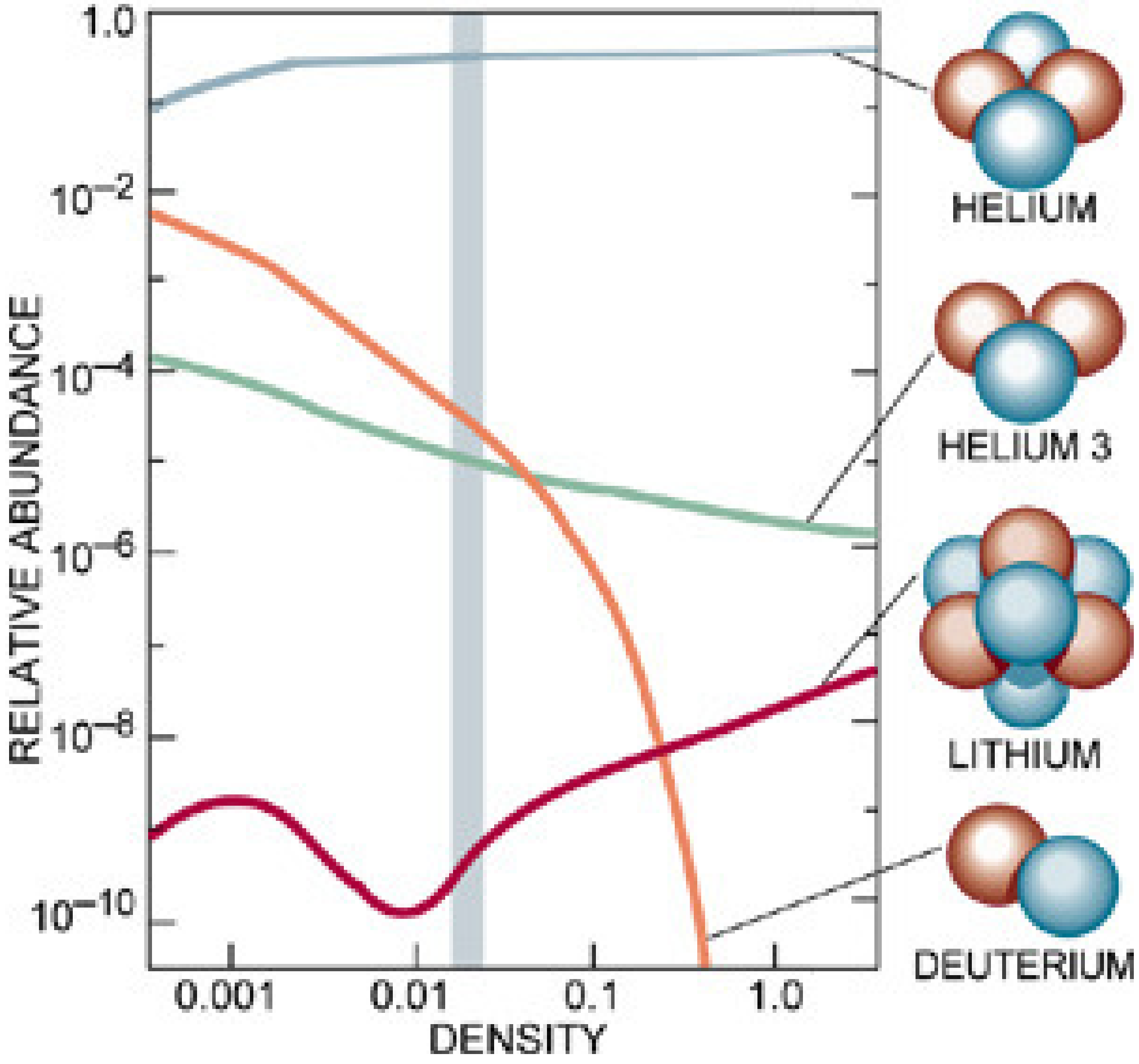


Animations:
http://astro.unl.edu/classaction/animations/sunsolarenergy/fusion01.html
http://ecuip.lib.uchicago.edu/originsoftheelements/

Big Bang Nucleosynthesis



The Big Bang Nucleosynthesis theory predicts that roughly 25% the mass of the Universe consists of Helium. It also predicts about 0.01% deuterium, and even smaller quantities of lithium.



The prediction depends critically on the density of baryons (i.e neutrons and protons) **at the time of nucleosynthesis.**

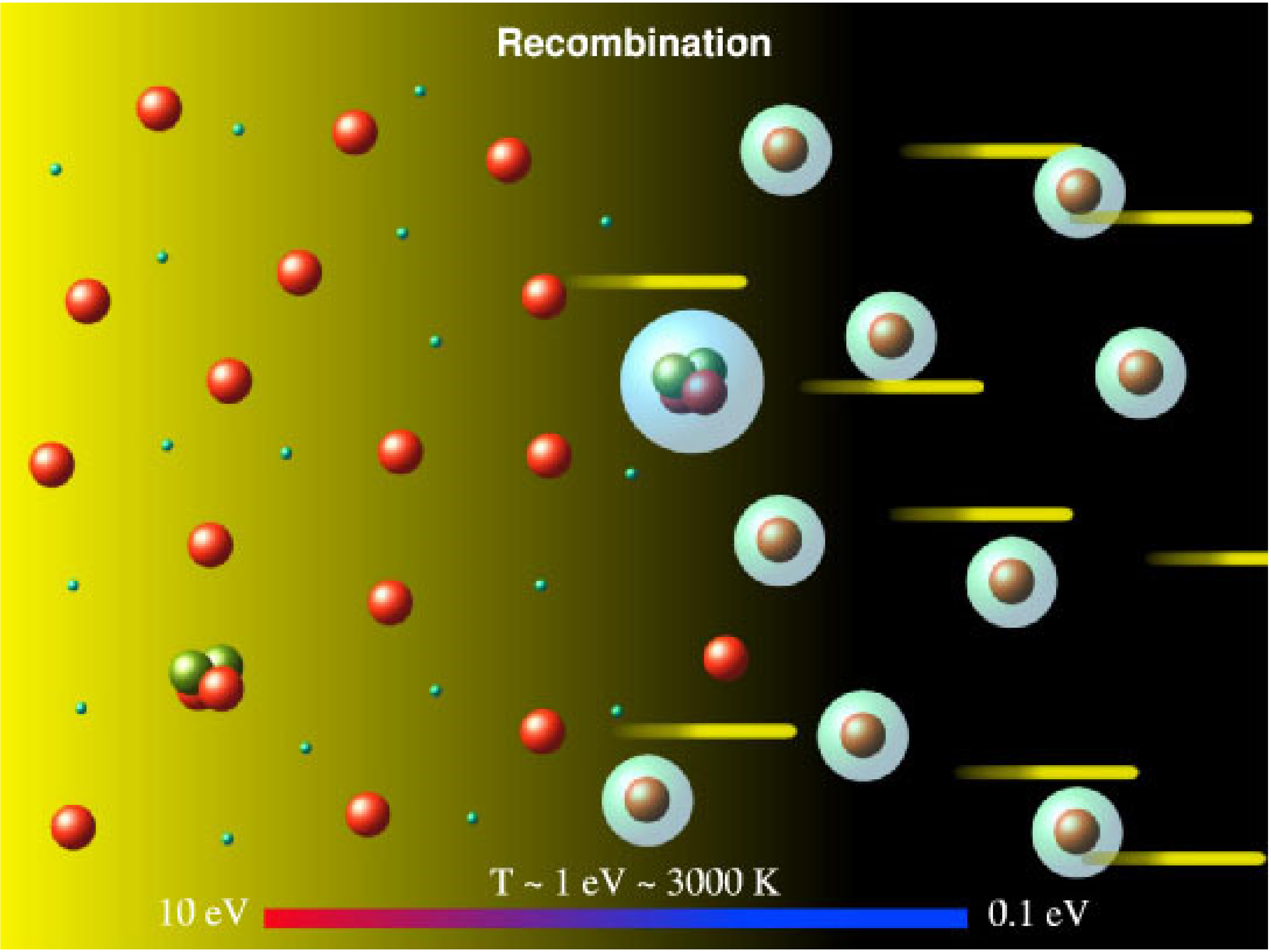
Furthermore, one value of this baryon density can explain all the abundances at once.

In terms of the present day critical density of matter, the required density of baryons is a few percent.

http://w.astro.berkeley.edu/~mwhite/darkmatter/bbn.html

The recombination epoch: 380 000 years after the Big Bang

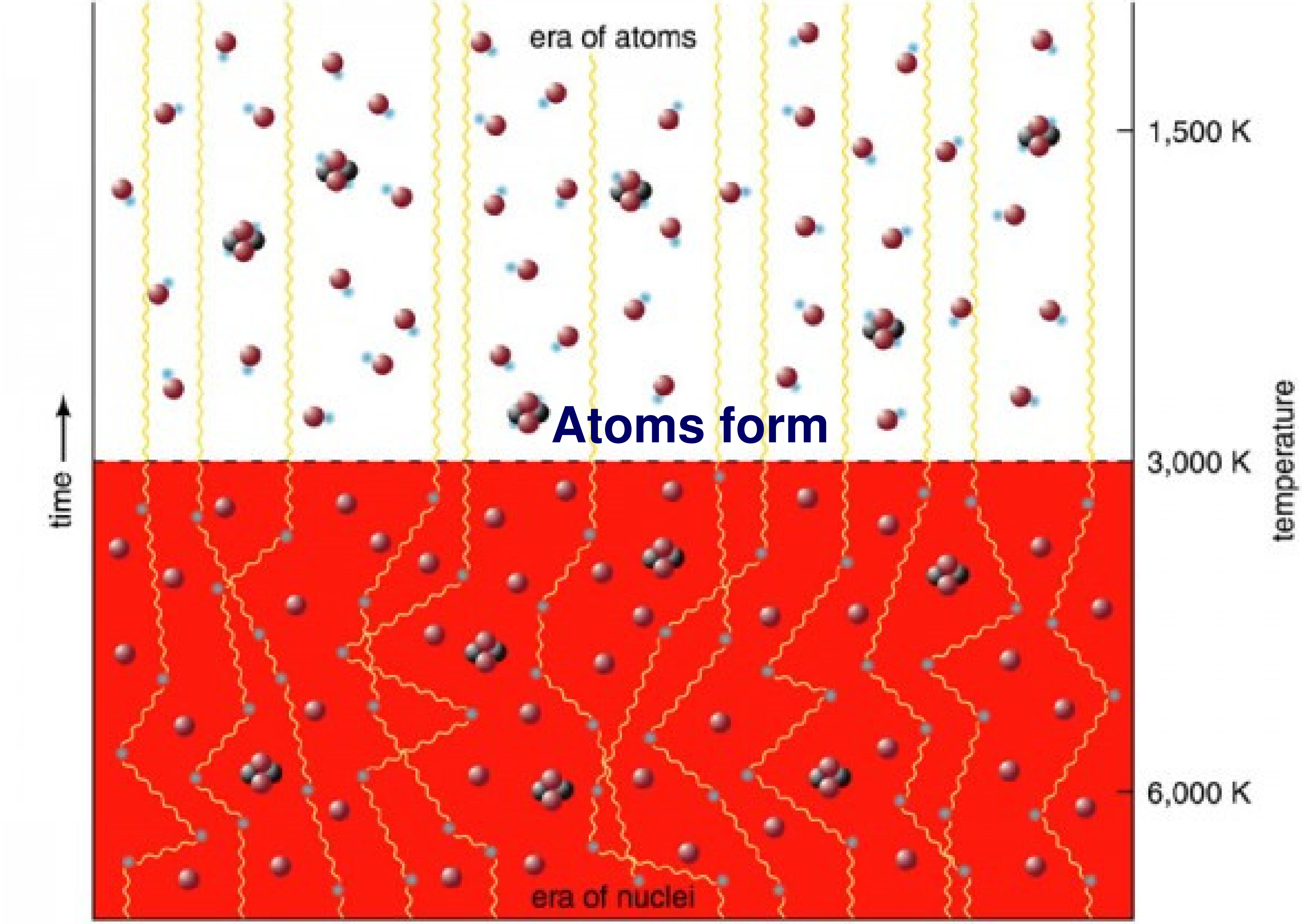
When the universe cooled enough, protons and electrons combined to form neutral hydrogen atoms.



https://ned.ipac.caltech.edu/level5/Sept02/Kinney/Kinney3.html

The photons started to travel freely through space rather than constantly being scattered by electrons and protons.

Universe expands and cools down



Atoms form

Image credit: Pearson / Addison Wesley

Cosmic Microwave Background Radiation

The recombination epoch: when the universe cooled enough, protons and electrons combined to form neutral hydrogen atoms.

These atoms could no longer absorb the thermal radiation, and so the universe became transparent instead of being an opaque fog.

The photons started to travel freely through space rather than constantly being scattered by electrons and protons.

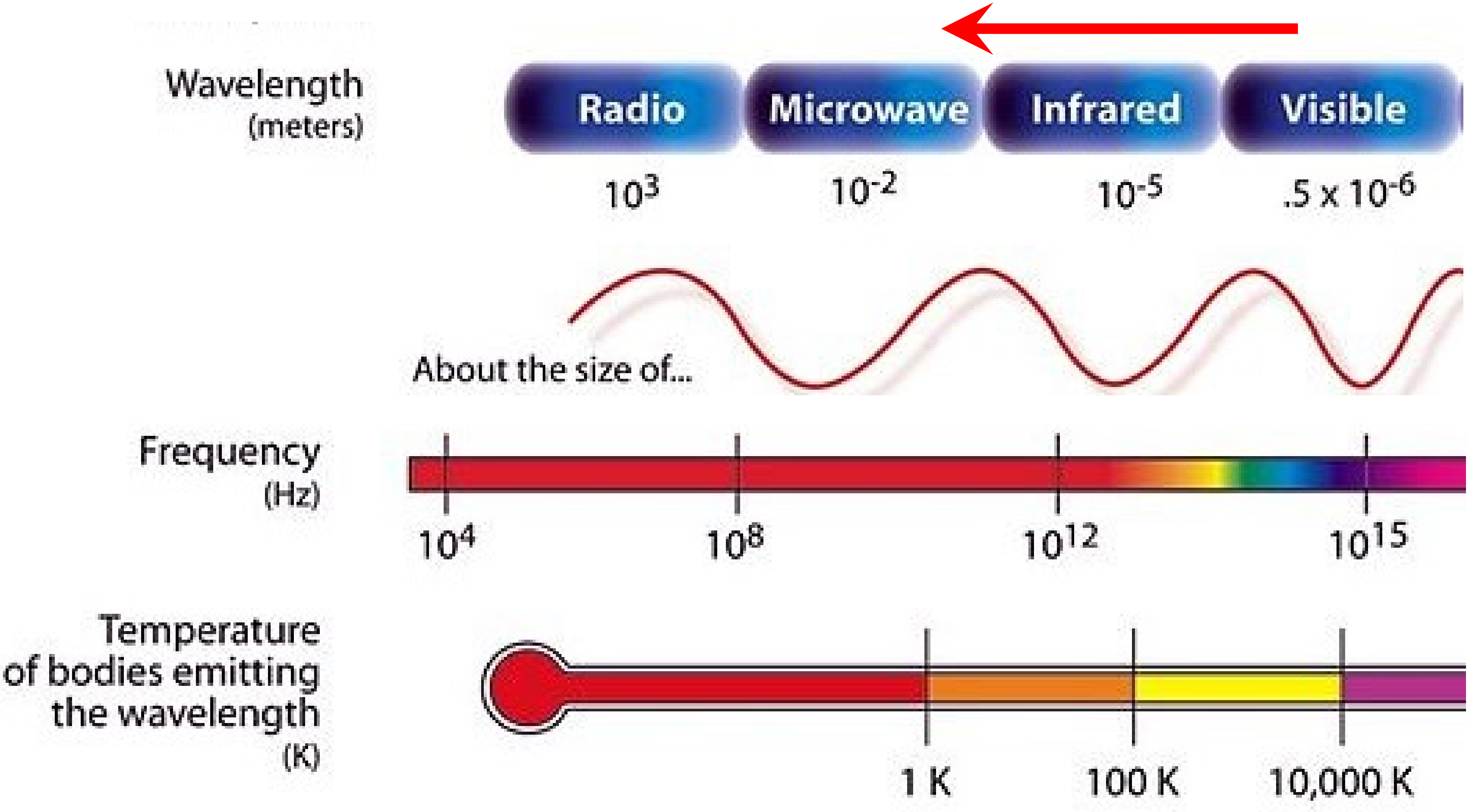
The photons that existed at the time of photon decoupling have been propagating ever since – we observe them now as cosmic microwave background (CMB).

Summary: The cosmic microwave background (CMB) is the thermal radiation left over from the time of recombination in Big Bang cosmology

Cosmic Microwave Background

Over the lifetime of the Universe, these photons grew fainter and less energetic, since the expansion of space causes their wavelength to increase over time.

3000 K to 2.7 K



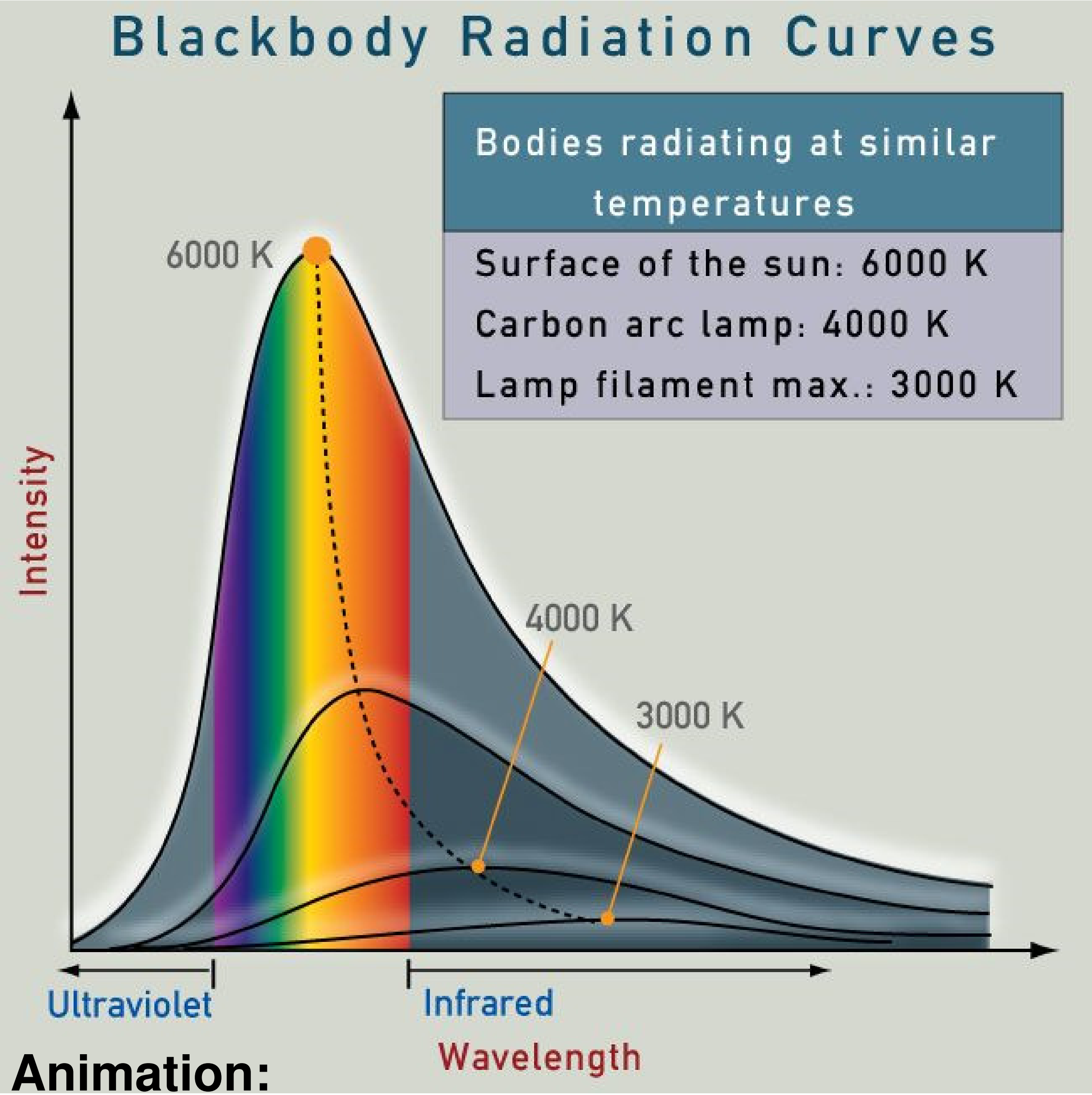
Cosmic Microwave Background: Blackbody radiation

380 000 years after the Big Bang: temperature is 3000 K.

Radiation emitted by such a glowing “body” is distributed between different wavelengths in a specific manner, where the shape of the spectrum depends only on the temperature.

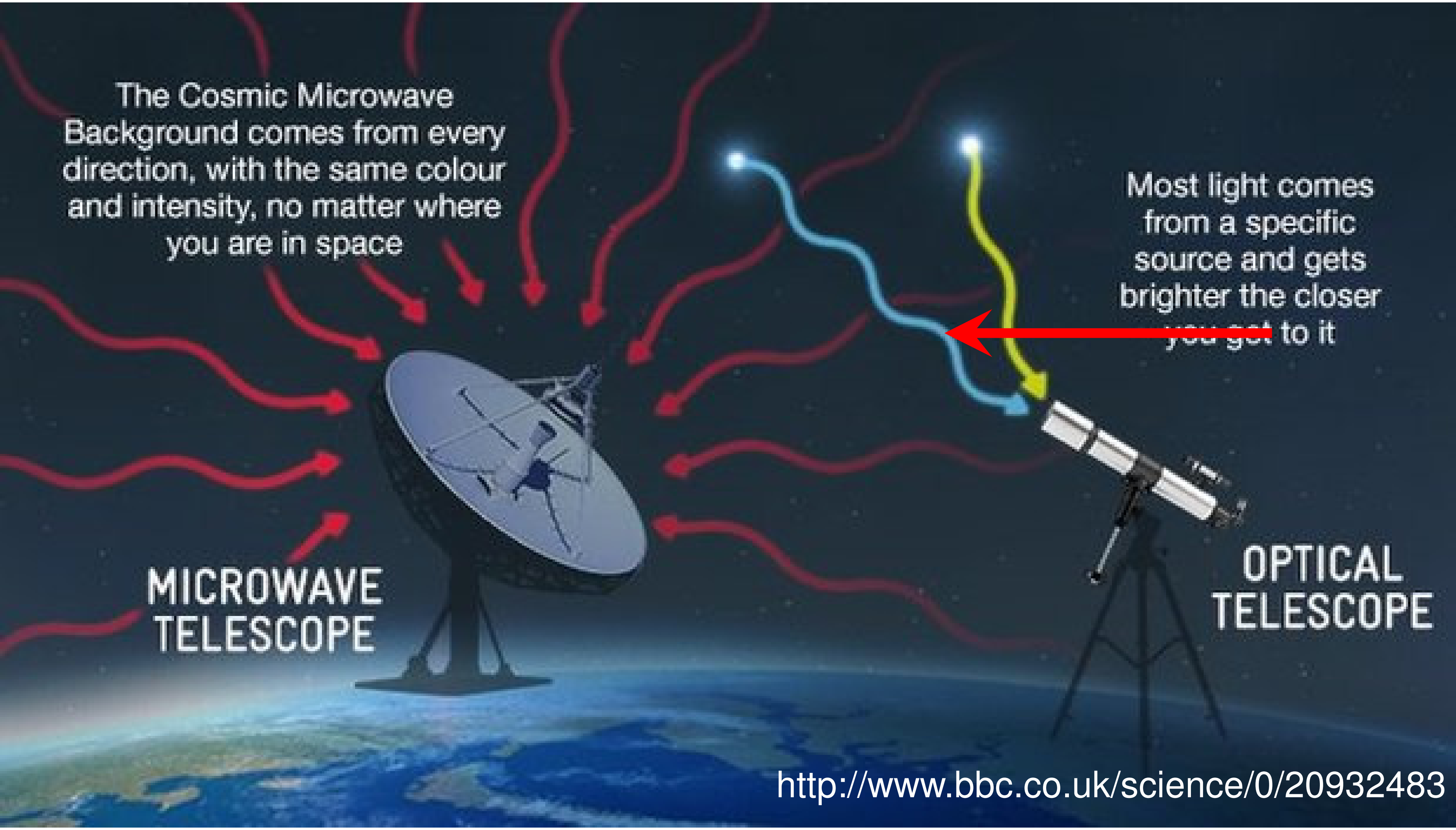
This kind of radiation is blackbody radiation.

One only needs to know the temperature to predict exactly what spectrum is going to look like.



Animation: http://astro.unl.edu/classaction/animations/light/bbexplorer.html

http://www.webexhibits.org/causesofcolor/3.html



The Cosmic Microwave Background comes from every direction, with the same colour and intensity, no matter where you are in space

Most light comes from a specific source and gets brighter the closer you get to it

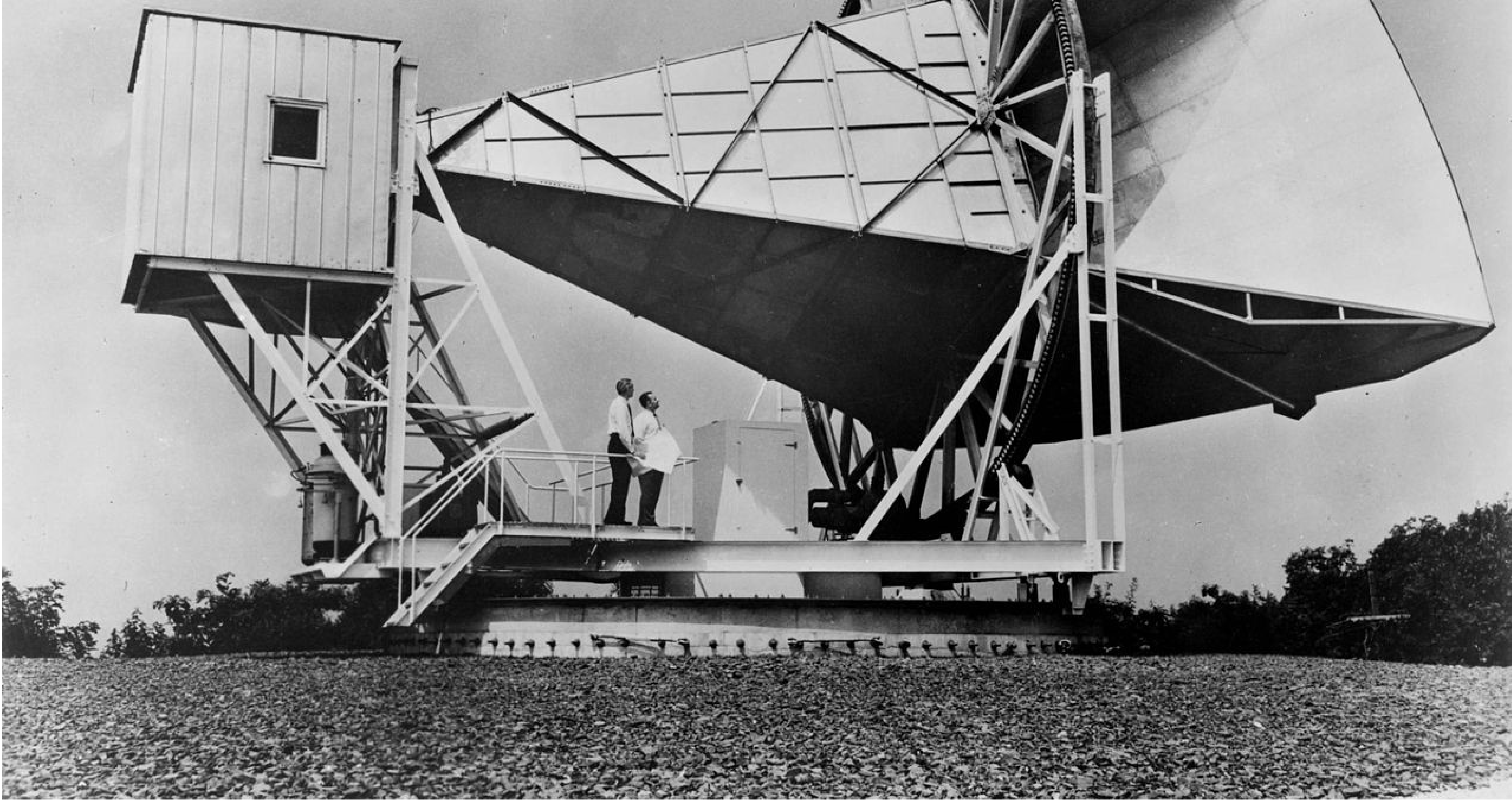
http://www.bbc.co.uk/science/0/20932483

Radio astronomy studies celestial objects at radio frequencies.

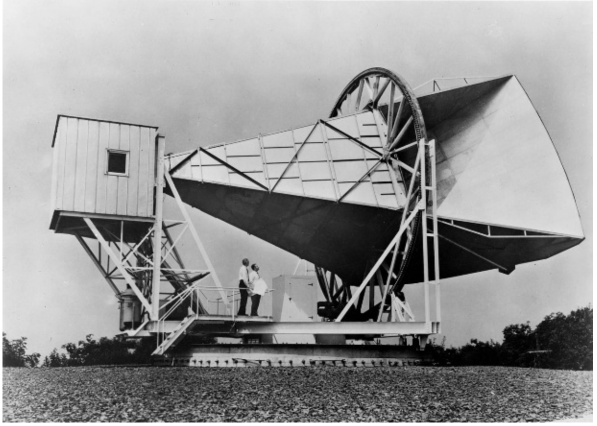
Holmdel Horn Antenna

Holmdel, NJ

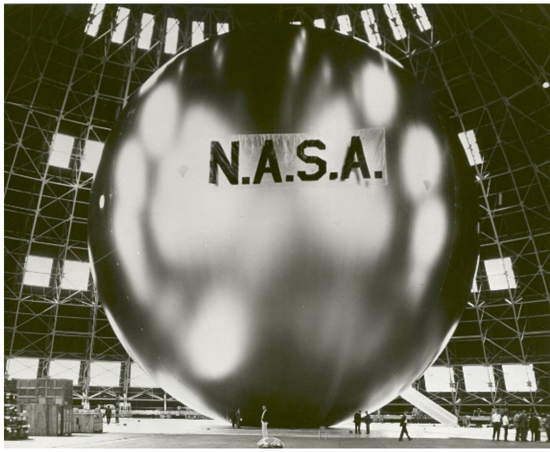
The horn antenna at Bell Telephone Laboratories in Holmdel, New Jersey, was constructed in 1959 to support **Project Echo**—the National Aeronautics and Space Administration's passive communications satellites.



https://en.wikipedia.org/wiki/Holmdel_Horn_Antenna#/media/File:Horn_Antenna-in_Holmdel,_New_Jersey.jpeg



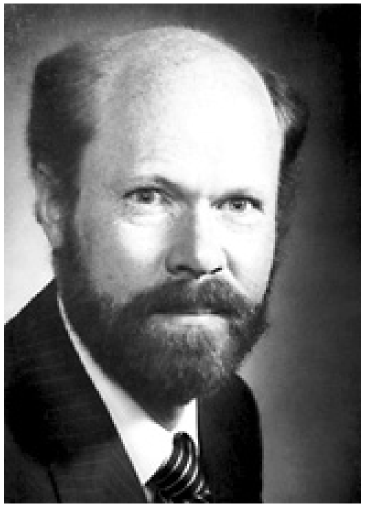
Project Echo was the first passive communications satellite experiment. Each of the two American spacecraft, launched in 1960 and 1964, was a metalized balloon satellite acting as a passive reflector of microwave signals.



Communication signals were bounced off them from one point on Earth to another.

Another use for Holmdel Horn Antenna: Radio Astronomy

Arno Penzias

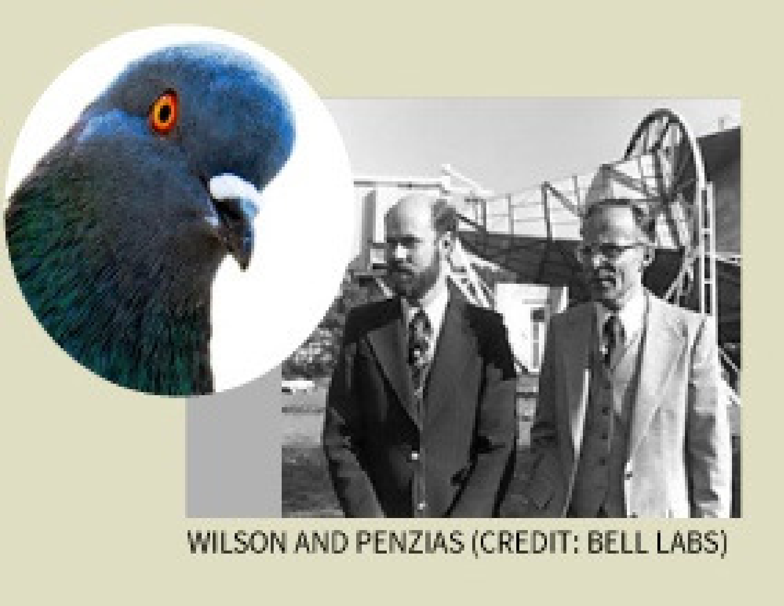


Robert Wilson

To measure these faint radio waves, they had to eliminate all recognizable interference from their receiver. They removed the effects of radar and radio broadcasting, suppressed interference from the heat in the receiver itself by cooling it with liquid helium to –269 °C, only 4 K above absolute zero and removed some pigeons nesting in the antenna.

Despite their effort, they were constantly being hampered by the presence of an annoying background hiss.

https://en.wikipedia.org/wiki/Project_Echo#/media/File:Echo_II.jpg



WILSON AND PENZIAS (CREDIT: BELL LABS)

1964: Accidental discovery of cosmic microwave background radiation

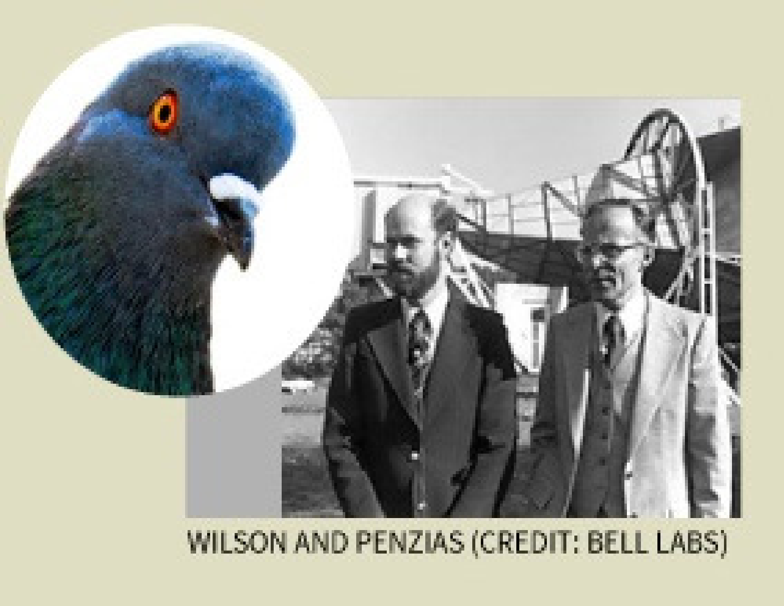
This residual noise was 100 times more intense than they had expected, was evenly spread over the sky, and was present day and night.

After a year spent persistently and painstakingly trying to identify and remove all possible causes for the unwanted noise at 7.35 cm - they concluded that this interference was due to microwaves that did not come from the Earth, the Sun, or our galaxy.

They had no idea what this noise actually was.

At that same time, Robert H. Dicke, Jim Peebles, and David Wilkinson, astrophysicists at Princeton University just 60 km (37 mi) away, were preparing to search for microwave radiation in this region of the spectrum.

A friend from MIT told Penzias about this work, leading to the identification of unknown noise as the cosmic **microwave background radiation leftover from the recomibination era of the Big Bang.**


WILSON AND PENZIAS (CREDIT: BELL LABS)

1964: Accidental discovery of cosmic microwave background radiation

> **"Once you eliminate the impossible, whatever is left, no matter how improbable, it must be the truth.“**
> ***-Sir Arthur Conan Doyle,***
> ***Sherlock Holmes***

At that same time, Robert H. Dicke, Jim Peebles, and David Wilkinson, astrophysicists at Princeton University just 60 km (37 mi) away, were preparing to search for microwave radiation in this region of the spectrum.

A friend from MIT told Penzias about this work, leading to the identification of unknown noise as the cosmic **microwave background radiation leftover from the recomibination era of the Big Bang.**

1964: Accidental discovery of cosmic microwave background radiation
1978 Nobel Prize: Penzias and Wilson

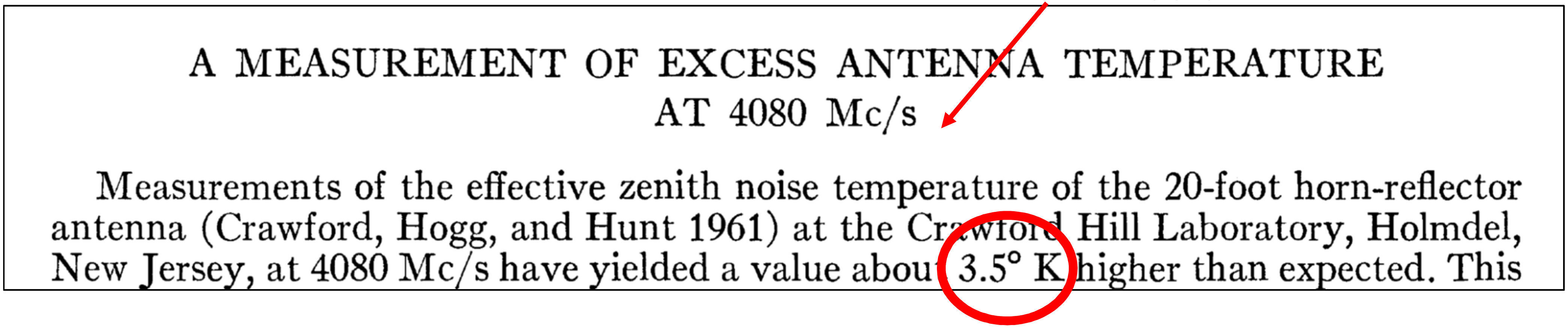
Astrophysical Journal Letters published the sequence of two papers:

Dicke, R. H.; Peebles, P. J. E.; Roll, P. J.; Wilkinson, D. T. (July 1965).
"Cosmic Black-Body Radiation".
Astrophysical Journal Letters **142**: 414–419.

Penzias, A.A.; R. W. Wilson (July 1965).
"A Measurement Of Excess Antenna Temperature At 4080 Mc/s".
Astrophysical Journal Letters **142**: 419–421.

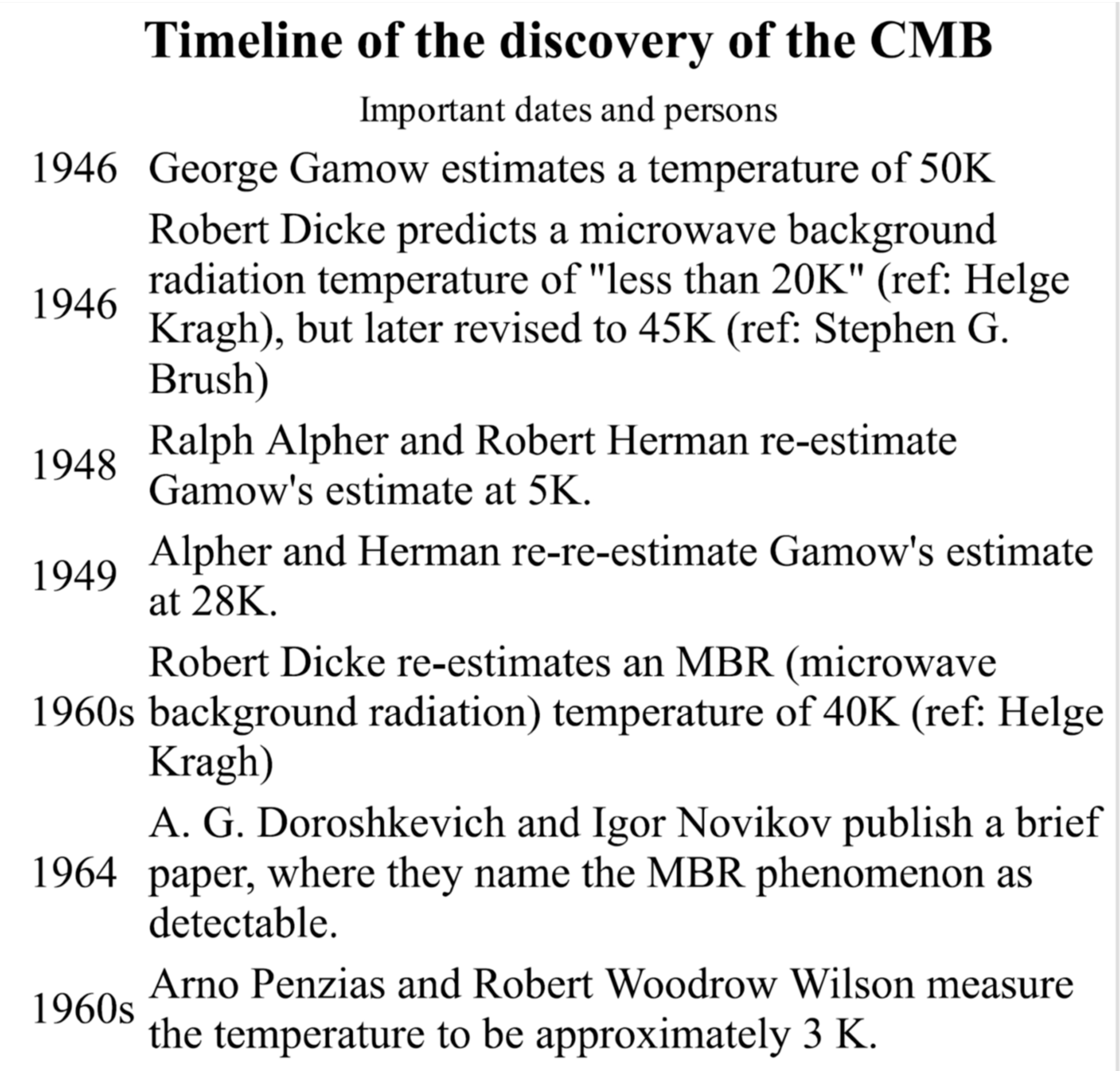
$$\lambda \nu = c$$

4080×10^6 cycles/second
$\lambda = 7.35$ cm



A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This



Timeline of the discovery of the CMB

Important dates and persons

1946	George Gamow estimates a temperature of 50K
1946	Robert Dicke predicts a microwave background radiation temperature of "less than 20K" (ref: Helge Kragh), but later revised to 45K (ref: Stephen G. Brush)
1948	Ralph Alpher and Robert Herman re-estimate Gamow's estimate at 5K.
1949	Alpher and Herman re-re-estimate Gamow's estimate at 28K.
1960s	Robert Dicke re-estimates an MBR (microwave background radiation) temperature of 40K (ref: Helge Kragh)
1964	A. G. Doroshkevich and Igor Novikov publish a brief paper, where they name the MBR phenomenon as detectable.
1960s	Arno Penzias and Robert Woodrow Wilson measure the temperature to be approximately 3 K.

Problem: one point at 7.35 cm does not prove that the spectrum is blackbody.

https://en.wikipedia.org/wiki/Discovery_of_cosmic_microwave_background_radiation

Problems with further measurements

The Earth’s atmosphere absorbs much of the radiation.

Even at high altitudes only a small part of the spectrum belonging to the background radiation can actually be measured.

A large proportion of the wavelengths included in the spectrum are so efficiently absorbed by air that it is necessary to conduct the measurements outside the Earth’s atmosphere.

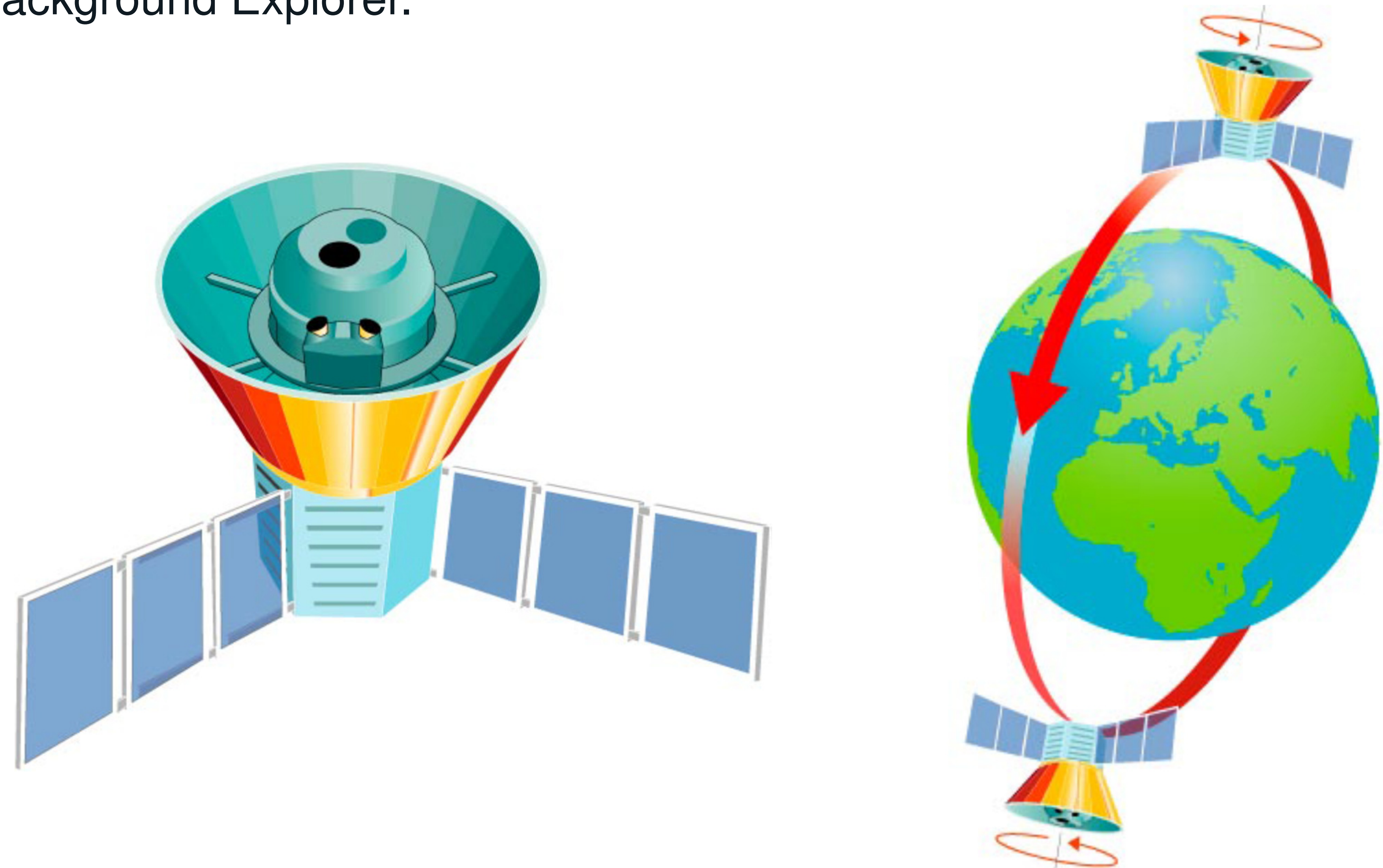
This made it difficult to know if the background radiation was really of the type predicted by the Big Bang scenario.

In addition, earthbound instruments cannot easily investigate all directions of the Universe, which made it difficult to prove that the radiation was indeed a true background, similar in all directions.

Measuring from a satellite solves both these problems – the instruments can be lifted above the atmosphere and measurements can easily be made in all directions.

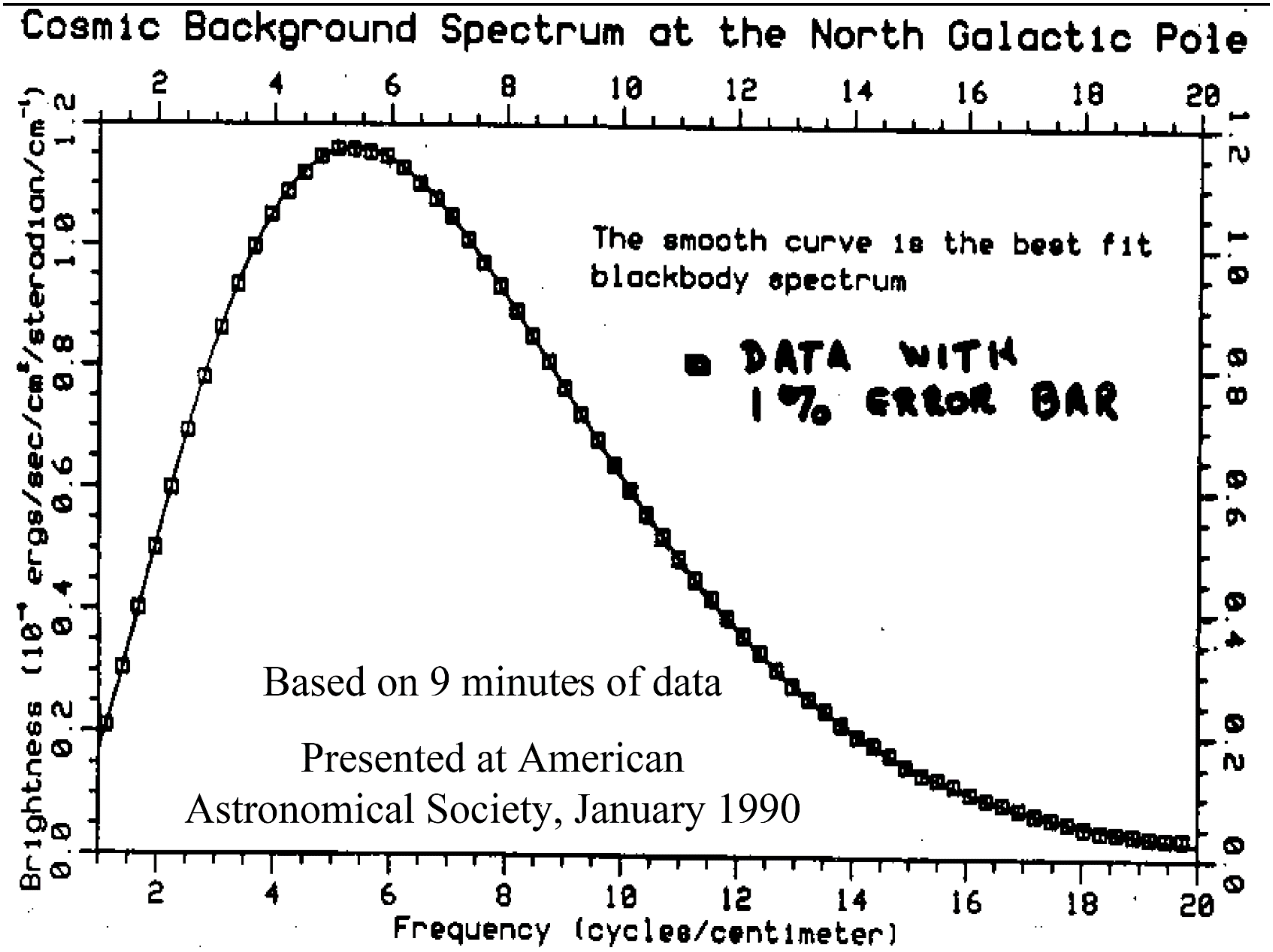
The COsmic Background Explorer (COBE)

In 1974 the US Space Administration, NASA, issued an invitation to astronomers and cosmologists to submit proposals for new space-based experiments. This led to the initiation of the COBE-project, the COsmic Background Explorer.



http://www.nobelprize.org/nobel_prizes/physics/laureates/2006/popular.html

COBE, and the satellite was finally launched on November 18, 1989.
The first results arrived after only nine minutes of observations: COBE had registered a perfect blackbody spectrum!

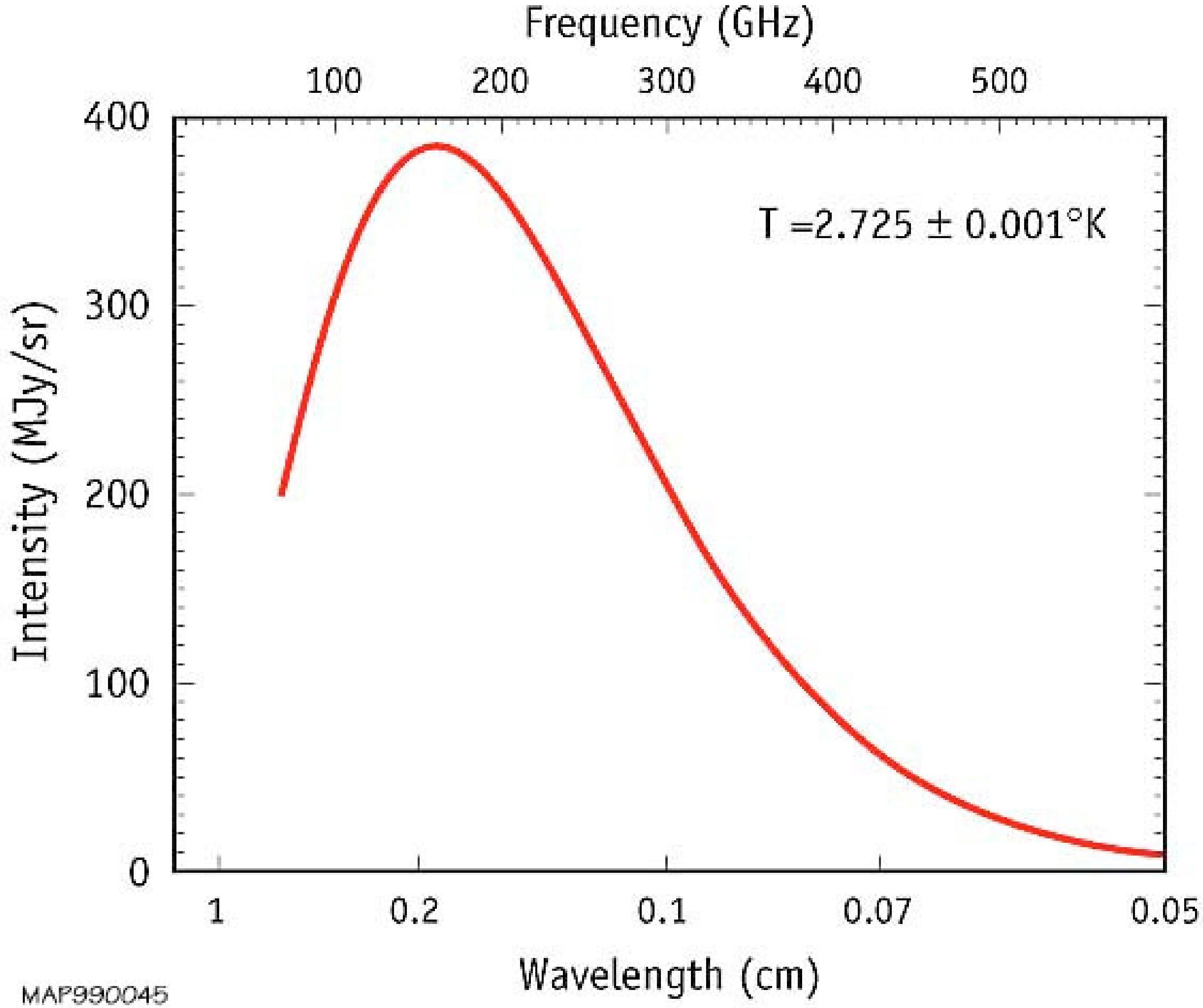


Based on 9 minutes of data

Presented at American Astronomical Society, January 1990

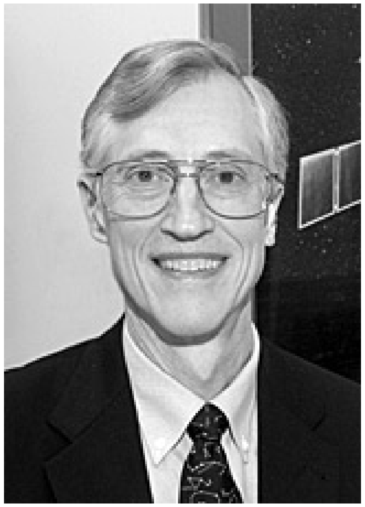
http://www.nobelprize.org/nobel_prizes/physics/laureates/2006/mather-lecture.html

SPECTRUM OF THE COSMIC MICROWAVE BACKGROUND



http://map.gsfc.nasa.gov/universe/bb_tests_cmb.html

The Nobel Prize in Physics 2006



John C. Mather

George F. Smoot

The Nobel Prize in Physics 2006 was awarded jointly to John C. Mather and George F. Smoot ***"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation".***

John Mather was the true driving force behind this gigantic collaboration in which over 1 000 individuals (scientists, engineers and others) were involved.

John Mather was also in charge of one of the instruments on board, which was used to investigate the blackbody spectrum of the background radiation.

George Smoot was in charge of the other determinative instrument, which was to look for small variations of the background radiation in different directions.

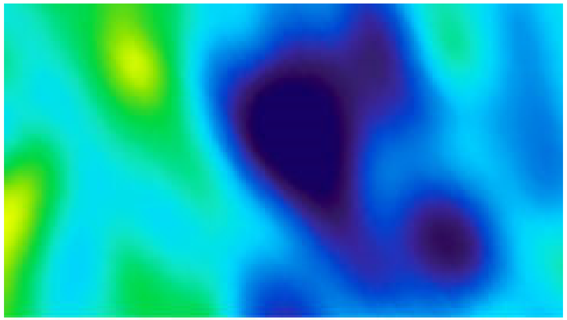
http://www.nobelprize.org/nobel_prizes/physics/laureates/2006/

CMB carries an imprint of the Universe when it was 380 000 old
It is the only tool that we have to look that far back in time

The experiment for which George Smoot was responsible was designed to look for small variations of the microwave background in different directions.

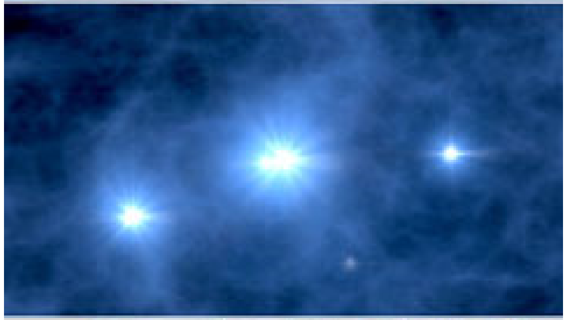
Minuscule variations in the temperature of the microwave background in different parts of the universe could provide new clues about how galaxies and stars once appeared; why matter in this way had been concentrated to specific localities in the Universe rather than spreading out as a uniform sludge.

Tiny variations in temperature could show where matter had started aggregating. Once this process had started, gravitation would take care of the rest: Matter attracts matter, which leads to stars and galaxies forming.

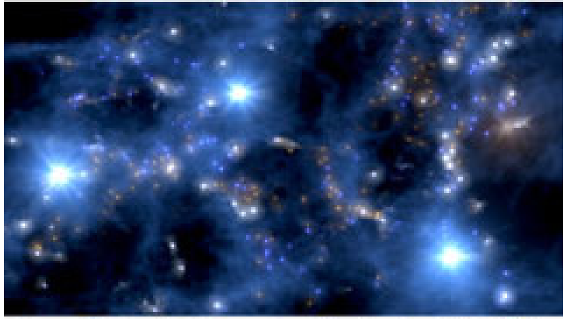


380,000 years old: First light escapes; Universe already has structure (light still arriving today)

Early fluctuations become denser condensations of matter



First stars form after ~150 million years ("reionization")



Galaxies and galaxy clusters form, according to the floorplan laid out at 380,000 years

The Universe today: lots of stars and galaxies!

The anisotropies are very small!
Very difficult to measure!

Initial prediction: the variation in temperature of the microwave background would be about **1/1000 of a degree Centigrade.**

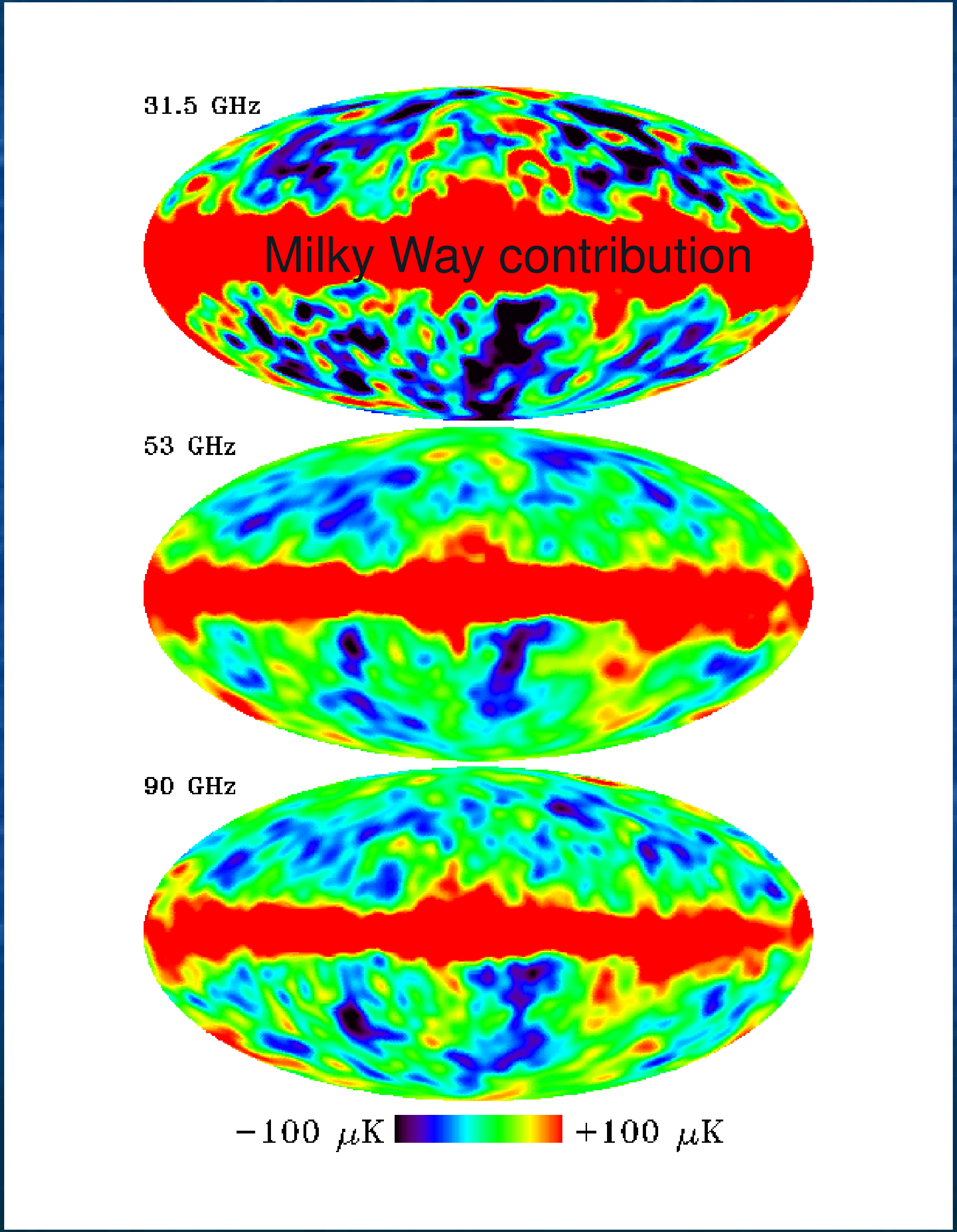
While COBE was still being constructed, other researchers reported that the influence of dark matter will make these **1/100 000 of a degree.**

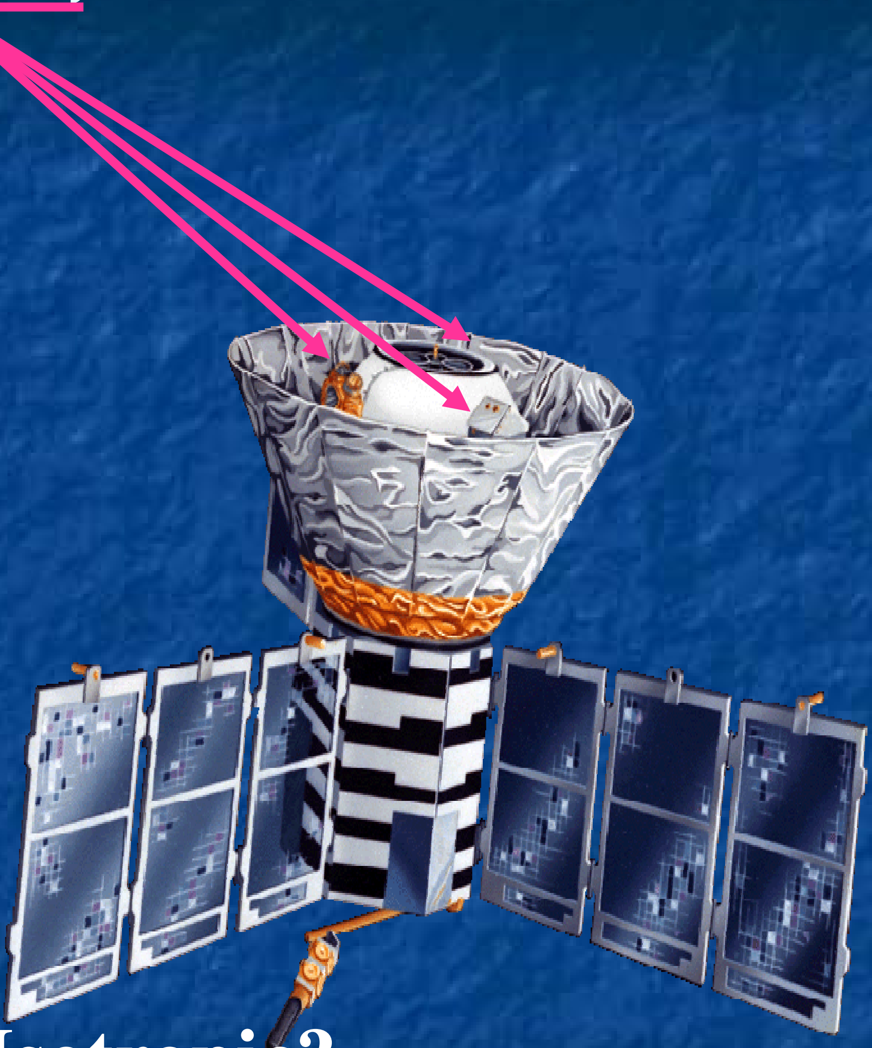
Even though the **instrument was redesigned**, the results from COBE became much more uncertain and difficult to interpret than expected.

1992: correlate COBE with ground-based measurement:
The directions in space in which COBE had registered temperature variations turned out to be exactly the same as those where variations seemed to have been detected from Earth and using balloons.

Differential Microwave Radiometers (DMR)

COBE/DMR, 1992



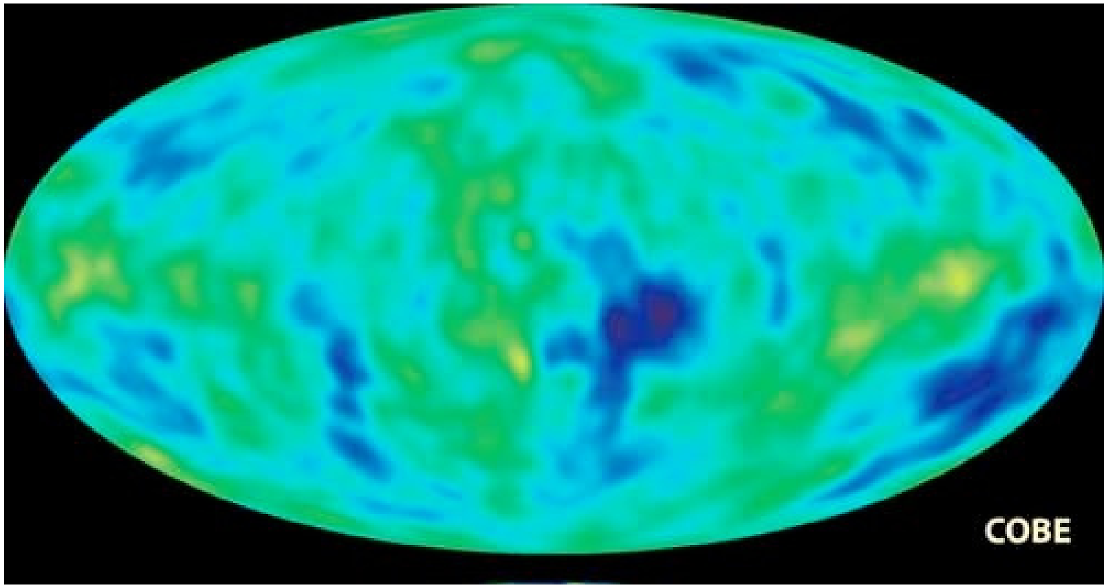


Isotropic?

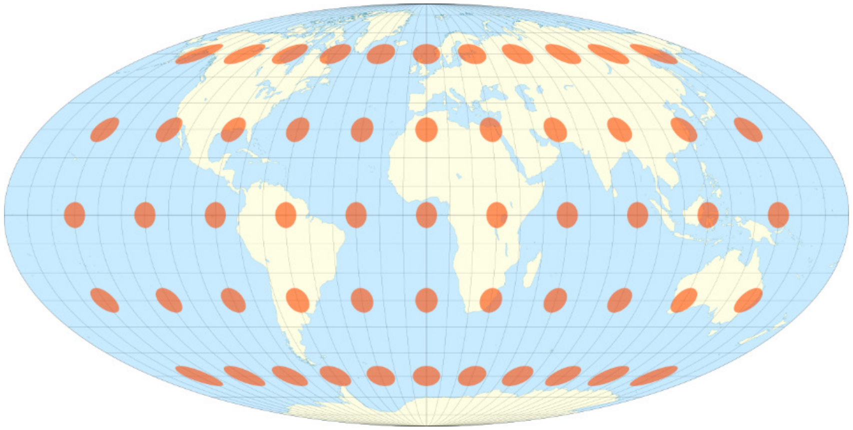
CMB is anisotropic! (at the 1/100,000 level)

http://wwwmpa.mpa-garching.mpg.de/~komatsu/presentation/acoustic_seminar_07.ppt

Milky Way contribution subtracted out

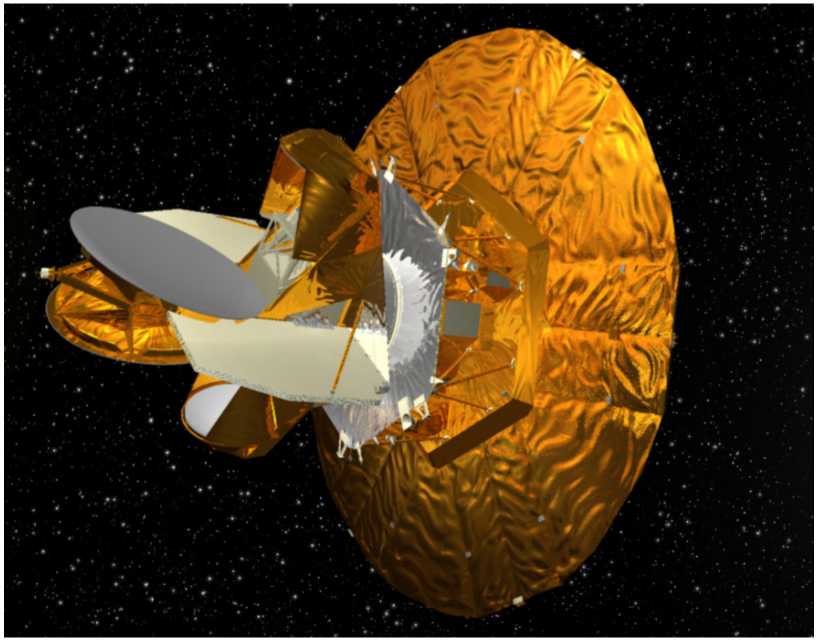


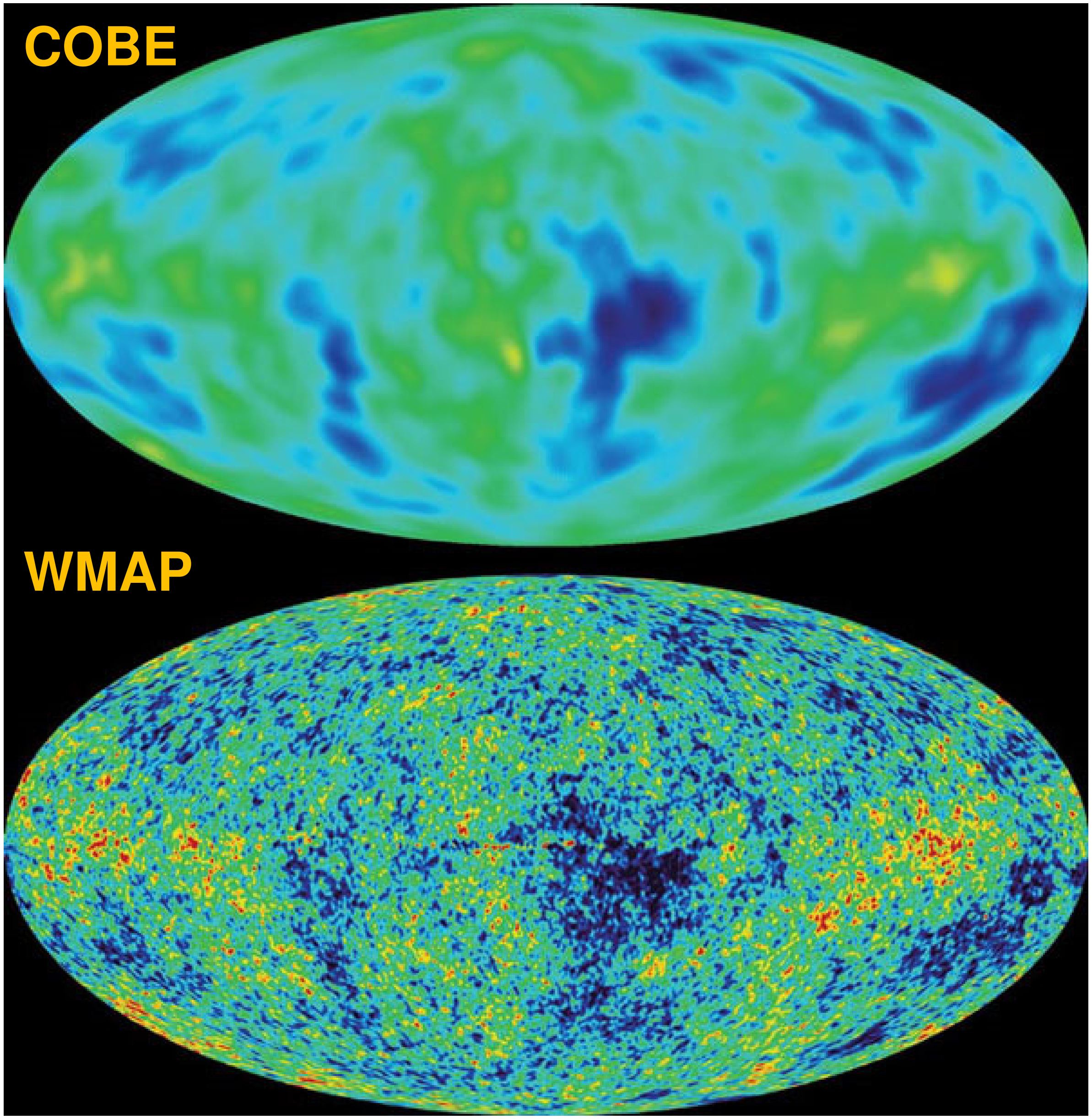
Note on why this looks as an oval:
The Mollweide projection is an equal-area, pseudocylindrical map projection generally used for global maps of the world or night sky.



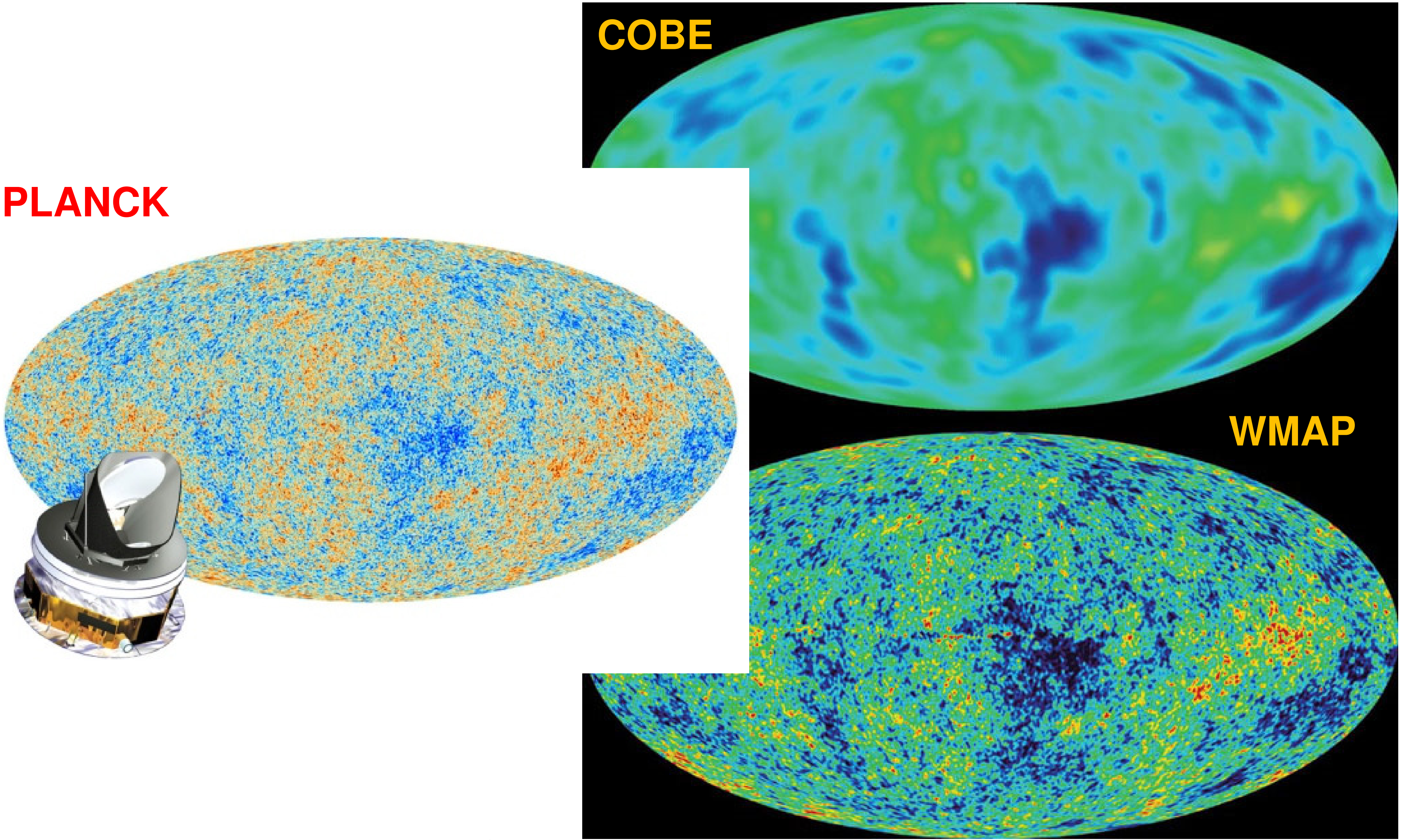
https://en.wikipedia.org/wiki/Mollweide_projection

The Wilkinson Microwave Anisotropy Probe (WMAP) is a NASA Explorer mission that launched June 2001 to make fundamental measurements of cosmology -- the study of the properties of our universe as a whole.

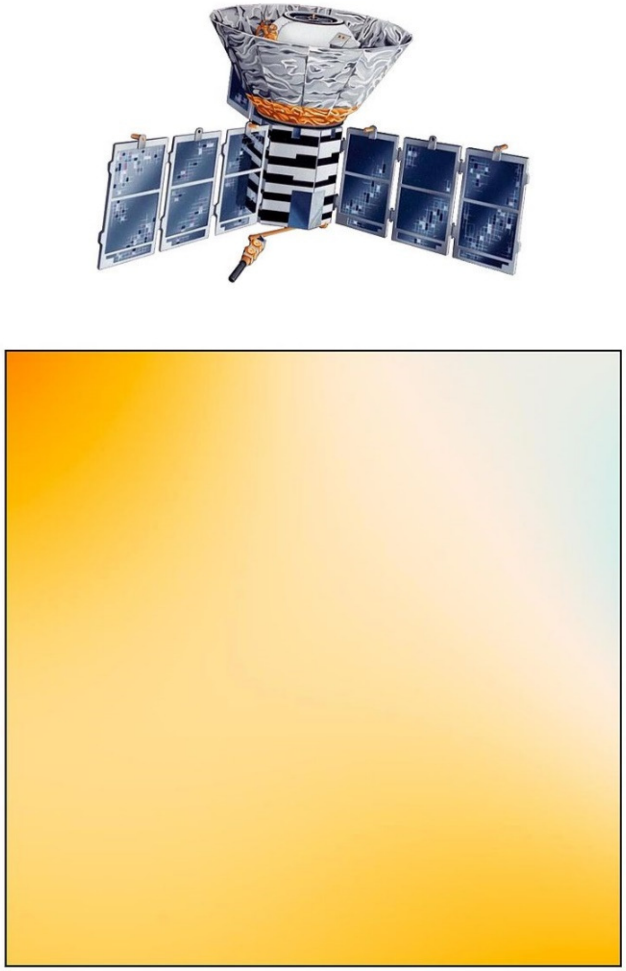




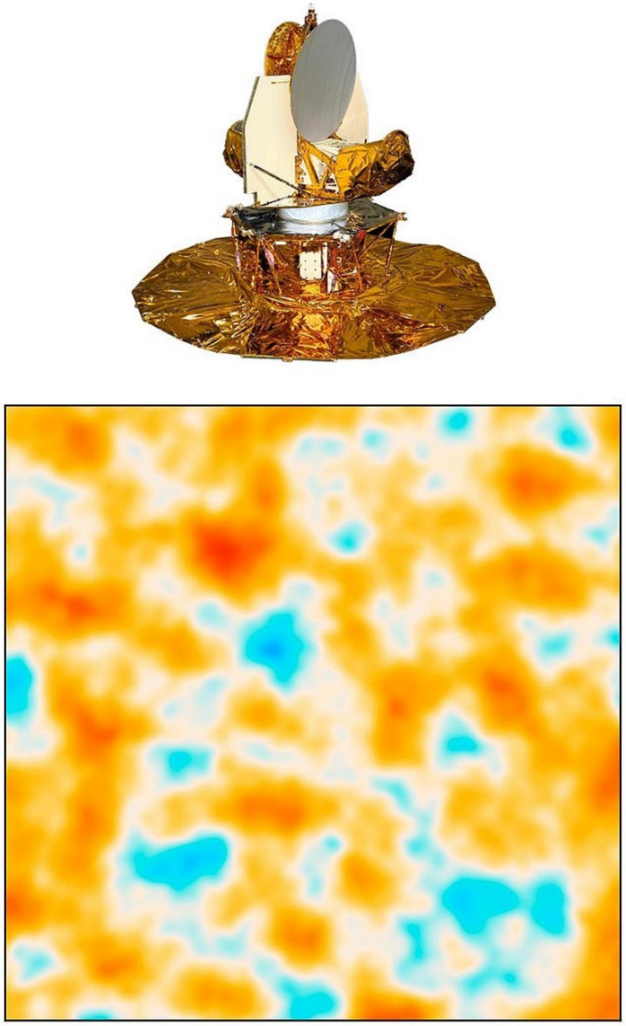
Planck was a space observatory operated by the European Space Agency (ESA) from 2009 to 2013.



http://www.nature.com/news/planck-snaps-infant-universe-1.12671

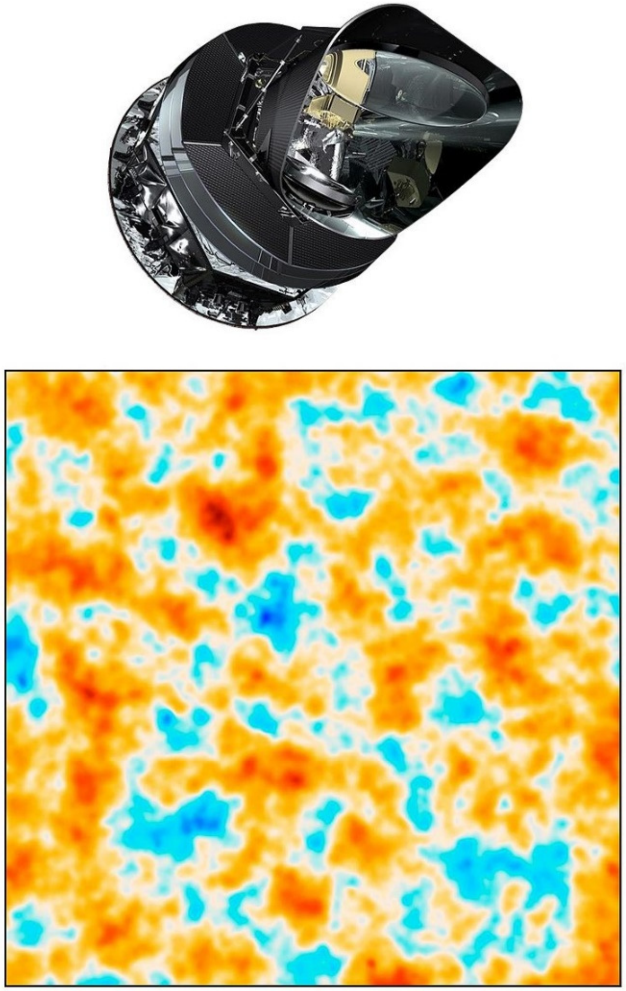


COBE



WMAP

x 30 times better resolution



Planck

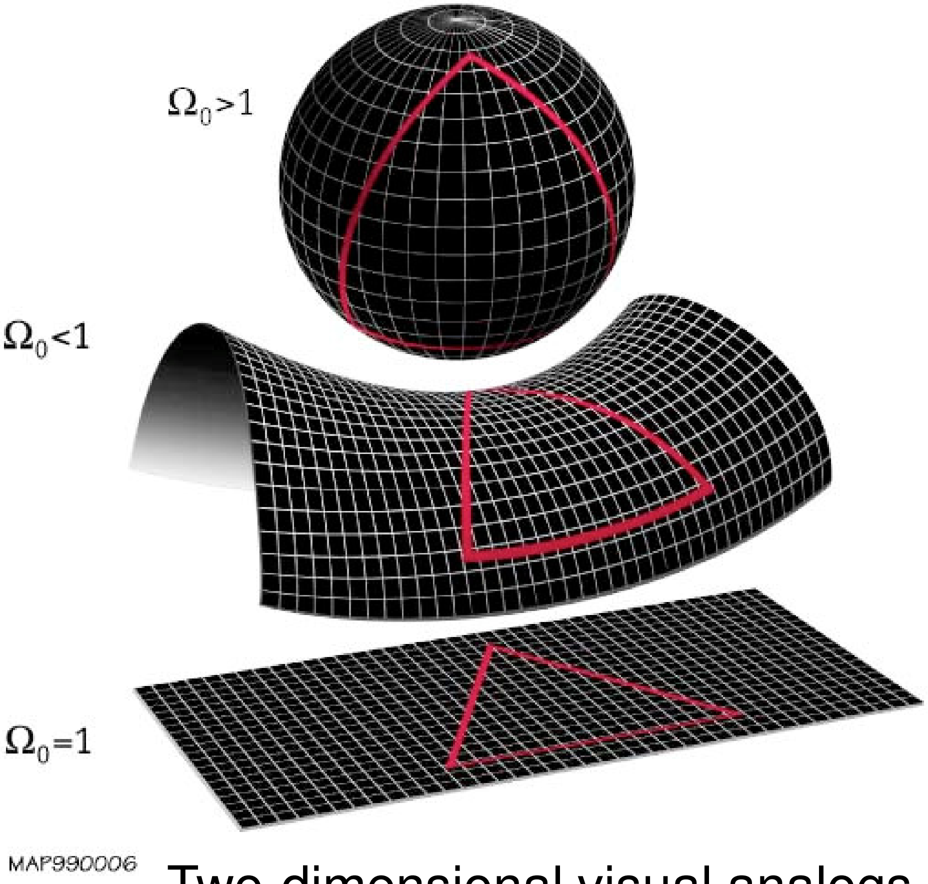
x 2.5 times better resolution

Image credit: NASA / JPL-Caltech / ESA.

Cosmic Microwave Background: study property of the Universe

What is the curvature of the Universe?

The shape of the universe is related to general relativity which describes how spacetime is curved and bent by mass and energy.



Two-dimensional visual analogs

There are three possible curvatures the universe can have.

1. Positively curved (A drawn triangle's angles add up to more than 180°)

2. Negatively curved (A drawn triangle's angles add up to less than 180°)

3. Flat (A drawn triangle's angles add up to 180°)

https://en.wikipedia.org/wiki/Shape_of_the_universe#/media/File:End_of_universe.jpg

The shape of the universe indicates its matter and energy content

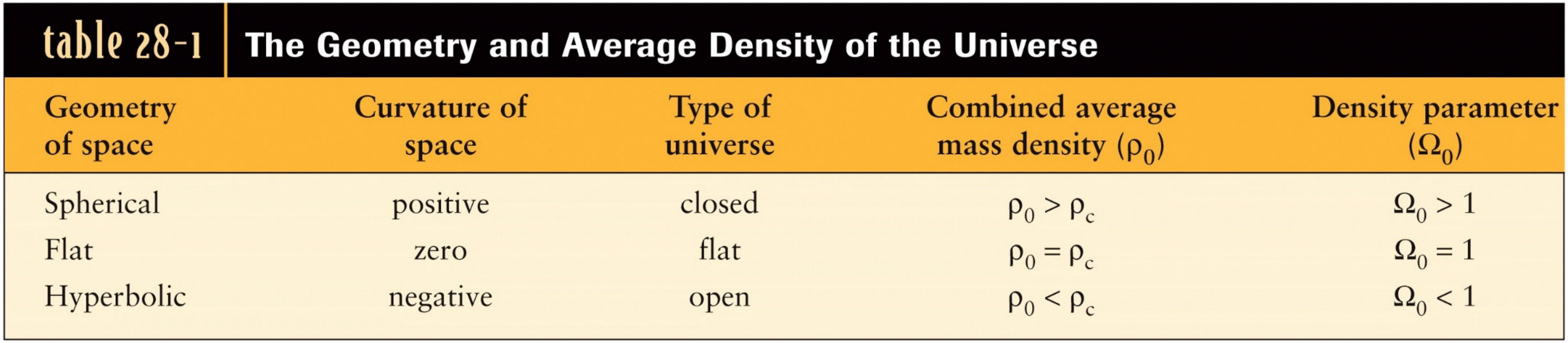


table 28-1 The Geometry and Average Density of the Universe

Geometry of space	Curvature of space	Type of universe	Combined average mass density (ρ_0)	Density parameter (Ω_0)
Spherical	positive	closed	$\rho_0 > \rho_c$	$\Omega_0 > 1$
Flat	zero	flat	$\rho_0 = \rho_c$	$\Omega_0 = 1$
Hyperbolic	negative	open	$\rho_0 < \rho_c$	$\Omega_0 < 1$

$$\rho_c = \frac{3H^2}{8\pi G}$$

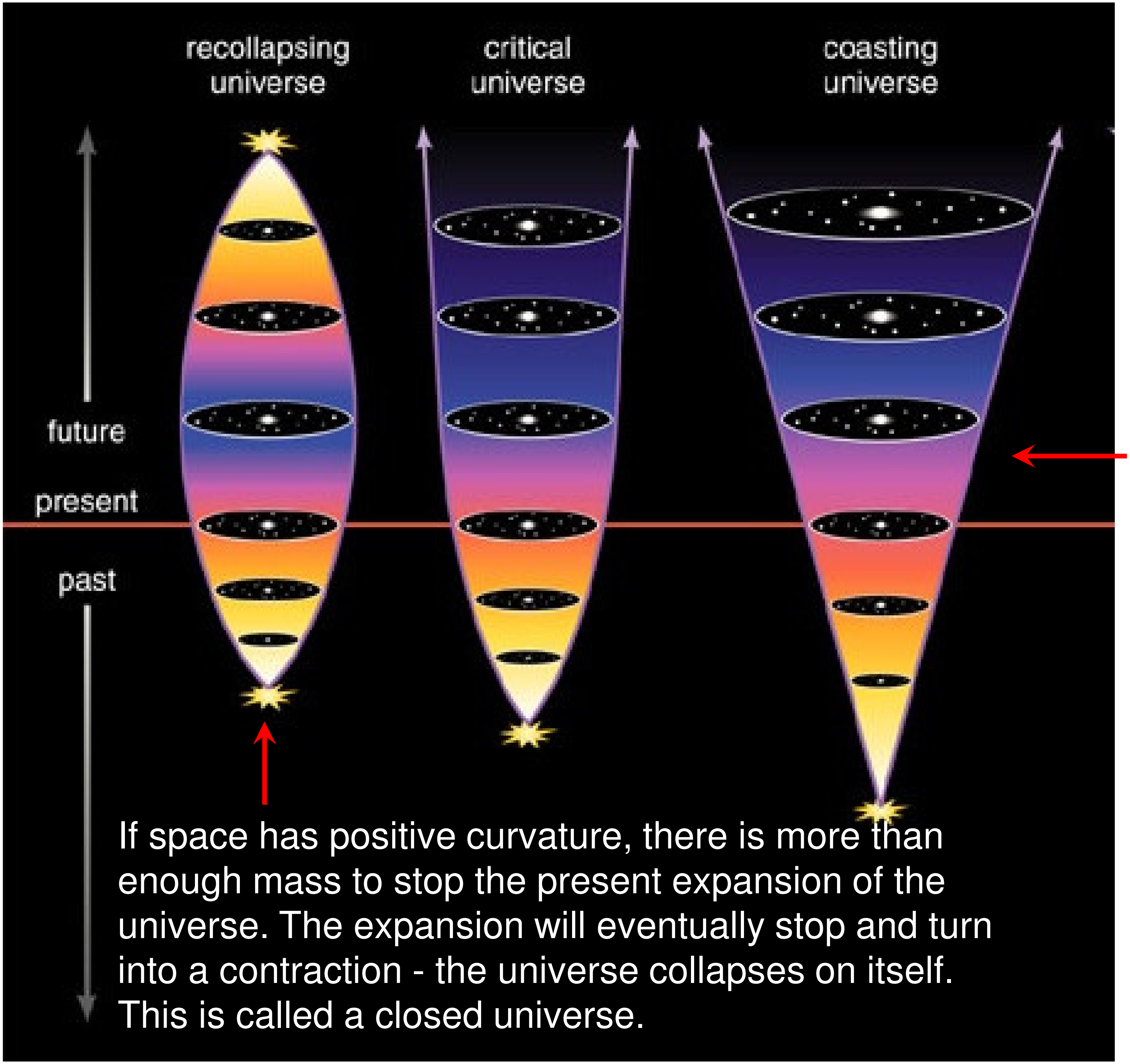
Hubble constant

Gravitational constant

The geometry of the universe is often expressed in terms of the "density parameter“ Ω_0, which is defined as the ratio of the actual density of the universe to the critical density that would be required to cause the expansion of the Universe to stop.

The curvature of the universe as a whole depends on how the combined average mass density ρ_0 compares to a critical density ρ_c.

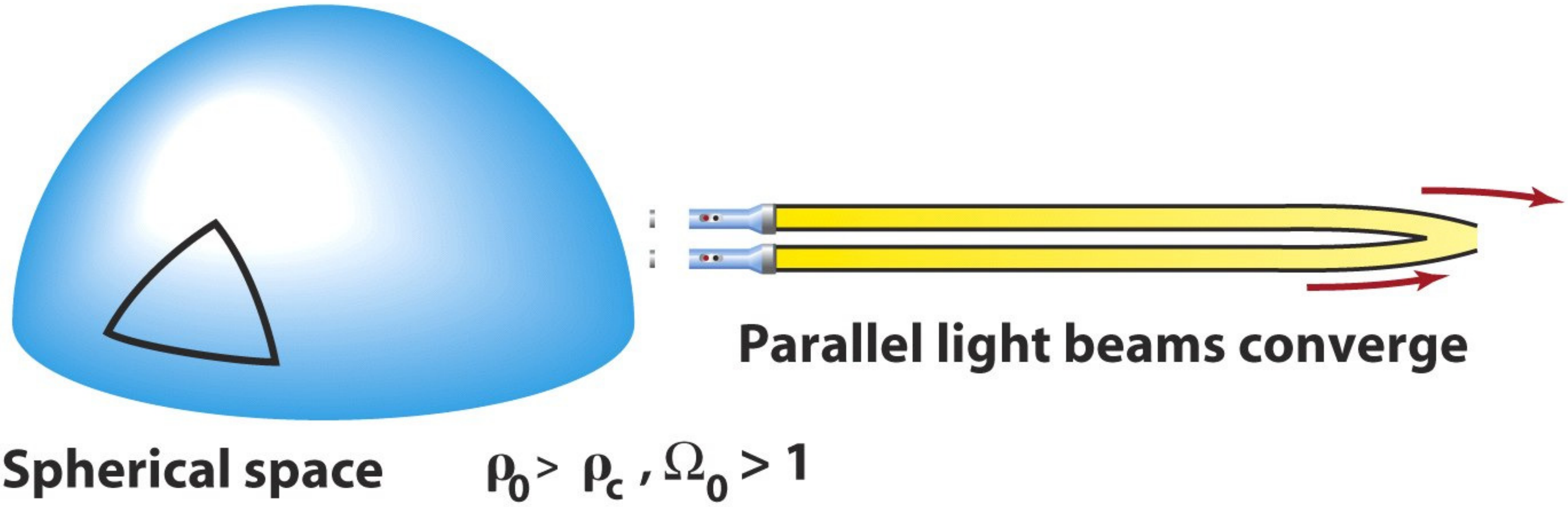
physics.gmu.edu/~hgeller/ch28.ppt



If space has negative curvature, there is insufficient mass to cause the expansion of the universe to stop.
The universe has no bounds, and will expand forever - open universe.

If space has positive curvature, there is more than enough mass to stop the present expansion of the universe. The expansion will eventually stop and turn into a contraction - the universe collapses on itself. This is called a closed universe.

If ρ_0 is greater than ρ_c, the density parameter Ω_0 has a value greater than 1, the universe is closed, and space is spherical (with positive curvature)



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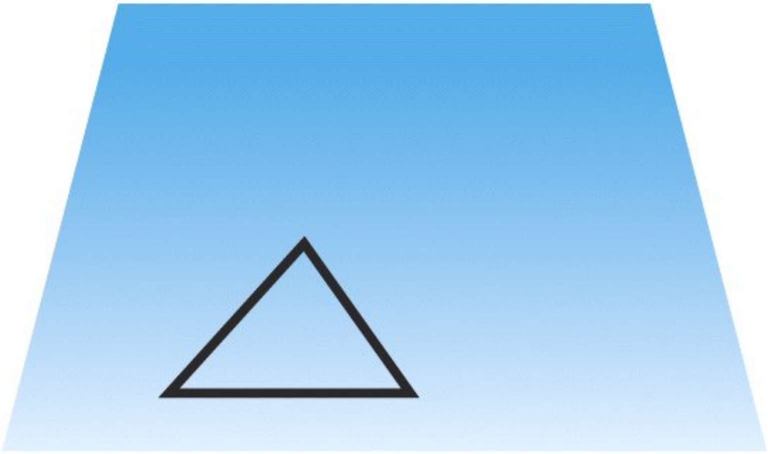
If ρ_0 is equal to ρ_c, the density parameter Ω_0 is equal to 1 and space is flat (with zero curvature)



Parallel light beams remain parallel

Flat space

$\rho_0 = \rho_c$, $\Omega_0 = 1$

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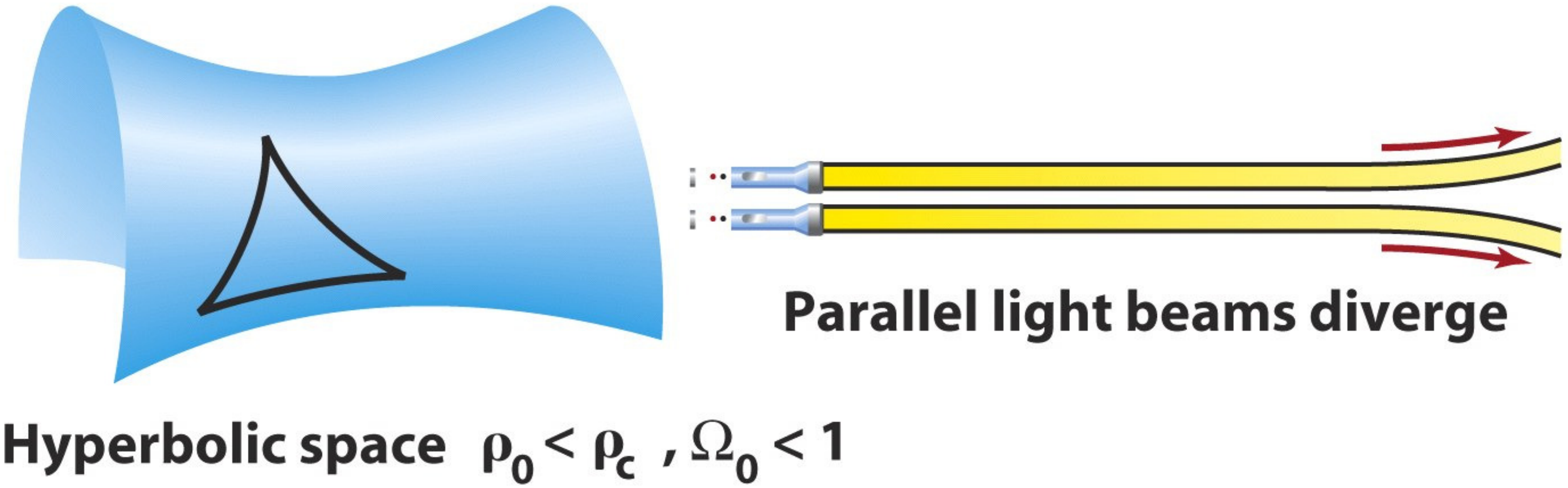
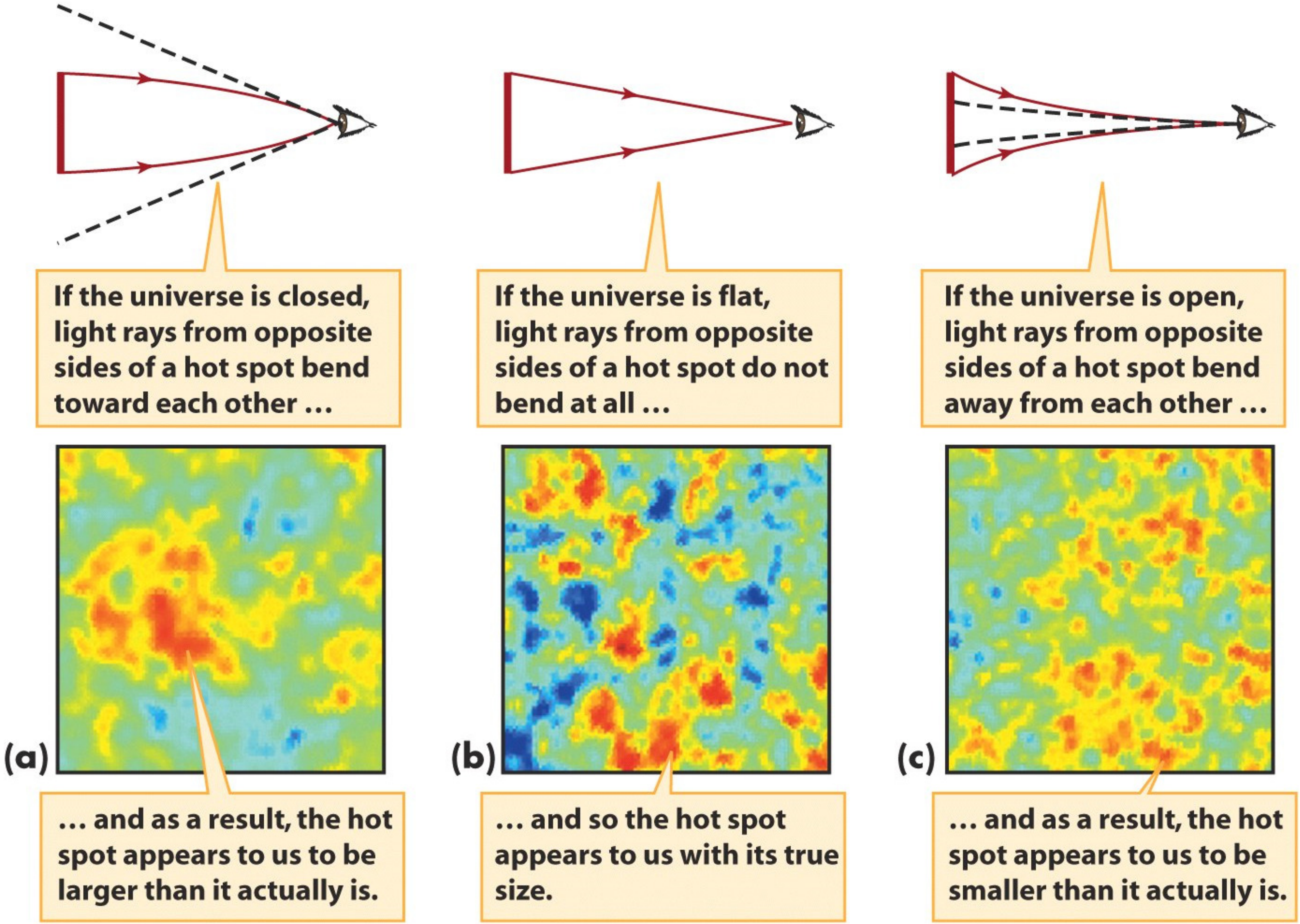
If ρ_0 is less than ρ_c, the density parameter Ω_0 has a value less than 1, the universe is open, and space is hyperbolic (with negative curvature)



physics.gmu.edu/~hgeller/ch28.ppt



If the universe is closed, light rays from opposite sides of a hot spot bend toward each other …

… and as a result, the hot spot appears to us to be larger than it actually is.

If the universe is flat, light rays from opposite sides of a hot spot do not bend at all …

… and so the hot spot appears to us with its true size.

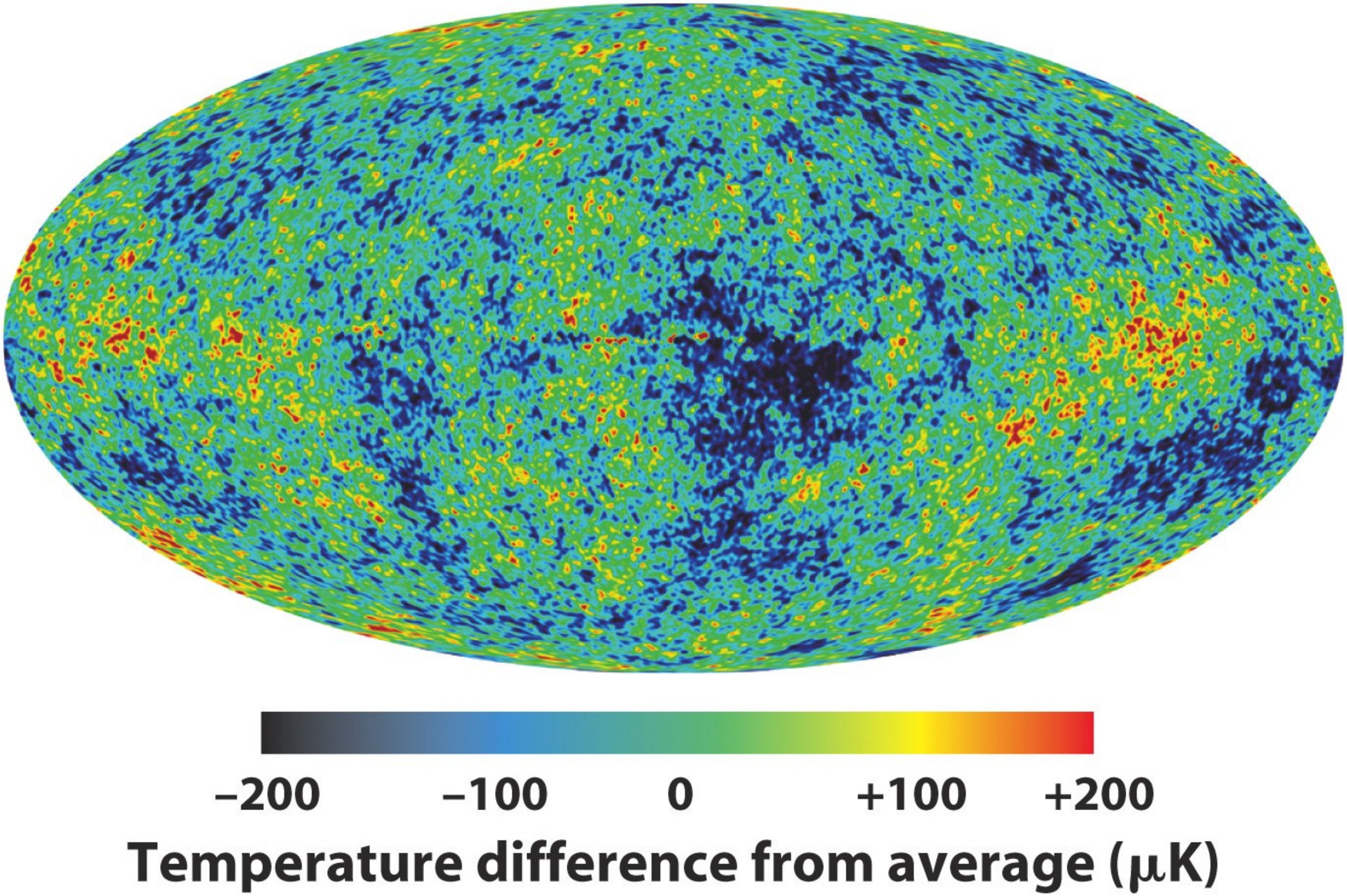
If the universe is open, light rays from opposite sides of a hot spot bend away from each other …

… and as a result, the hot spot appears to us to be smaller than it actually is.

Note: we can measure their apparent size in the sky.

physics.gmu.edu/~hgeller/ch28.ppt

Observations of temperature variations in the cosmic microwave background indicate that the universe is flat or nearly so (to 0.4%), with a combined average mass density equal to the critical density



physics.gmu.edu/~hgeller/ch28.ppt

The Universe is flat

Deep Astronomy video:
https://www.youtube.com/watch?v=zqb1lSdqRZY