Dark Energy

Dr Priya Hasan

Asst Professor

Department of Physics

Maulana Azad National Urdu University

priya.hasan@gmail.com

Accelerating expansion of the universe

1998, by two independent projects, the Supernova Cosmology Project and the High-Z Supernova Search Team, which both used distant type Ia supernovae to measure the acceleration of the expansion

The Nobel Prize in Physics 2011

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Saul Perlmutter

Prize share: 1/2

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Brian P. Schmidt

Prize share: 1/4

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Adam G. Riess

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Supernova

A supernova is a powerful and luminous stellar explosion. This transient astronomical event occurs during the last evolutionary stages of a massive star or when a white dwarf is triggered into runaway nuclear fusion.

Supernova Type 1 a

The typical visual absolute magnitude of Type Ia supernovae is Mv = −19.3 (about 5 billion times brighter than the Sun)!

G299 Type Ia supernova remnant.

Standard Candles!

Measured distances with Standard Candles & velocities with spectra....Hubble's Law V=Hd

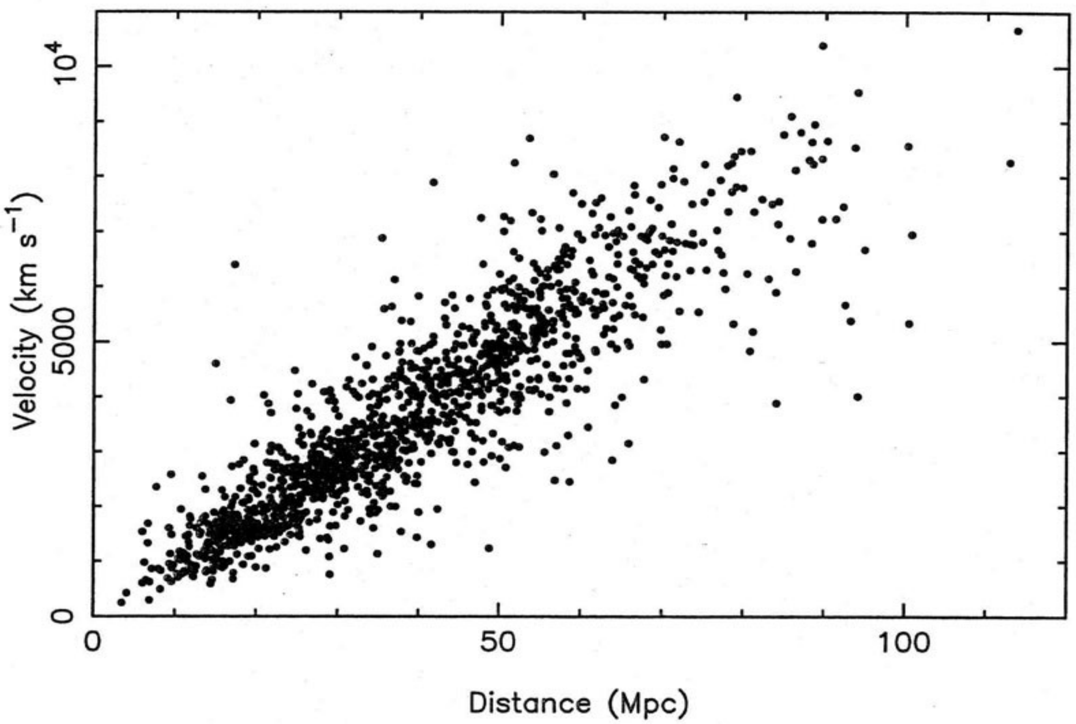
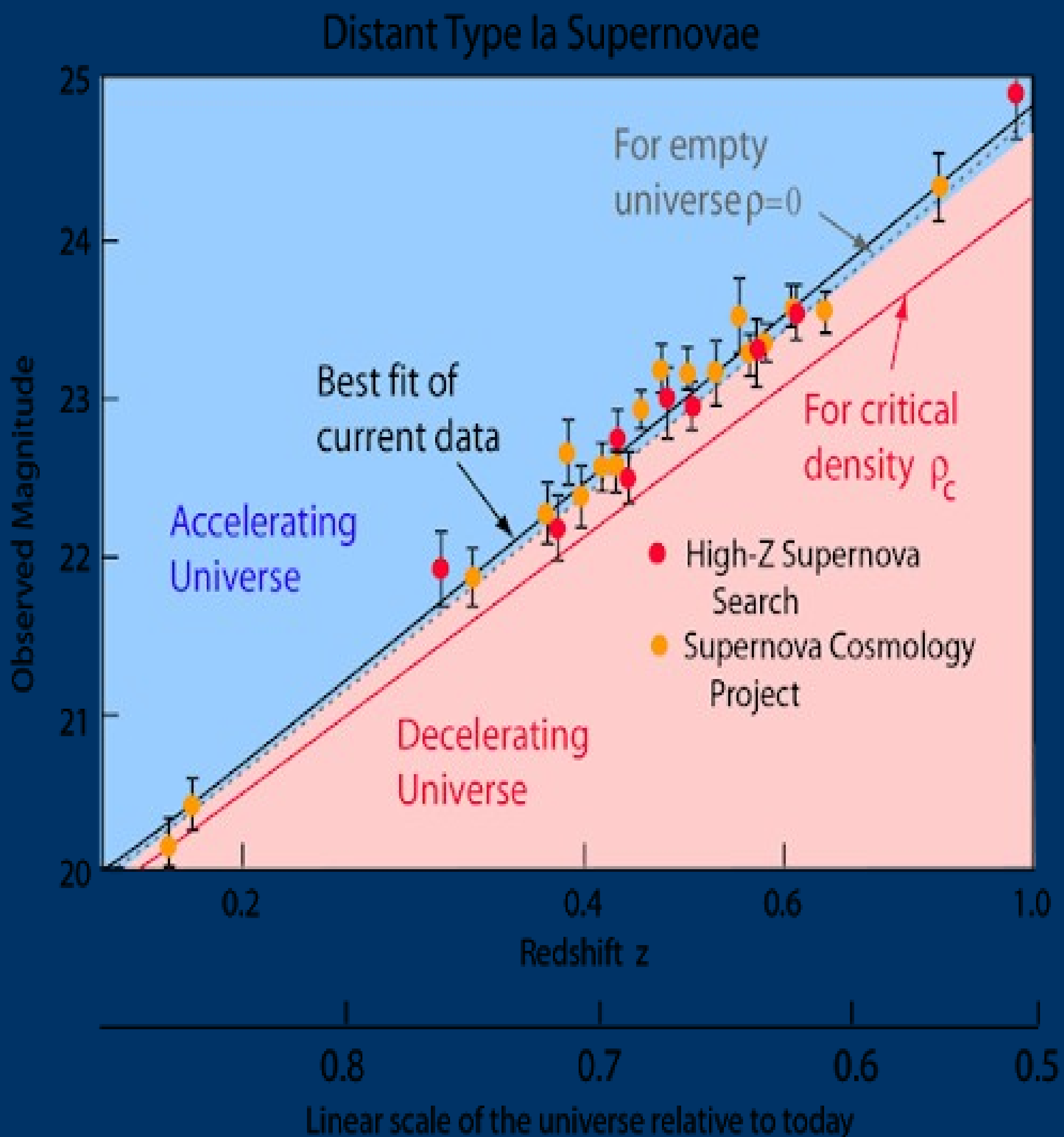


Figure 2.5 A plot of velocity versus estimated distance for a set of 1355 galaxies. A straight-line relation implies Hubble's law. The considerable scatter is due to observational uncertainties and random galaxy motions, but the best-fit line accurately gives Hubble's law. [The x-axis scale assumes a particular value of H_0.]

Objects in the universe are moving away from one another at an accelerated rate.

Accelerated expansion began 4 billion years ago!

Acceleration implies an energy density that acts in opposition to gravity to cause the expansion to accelerate... "dark energy".



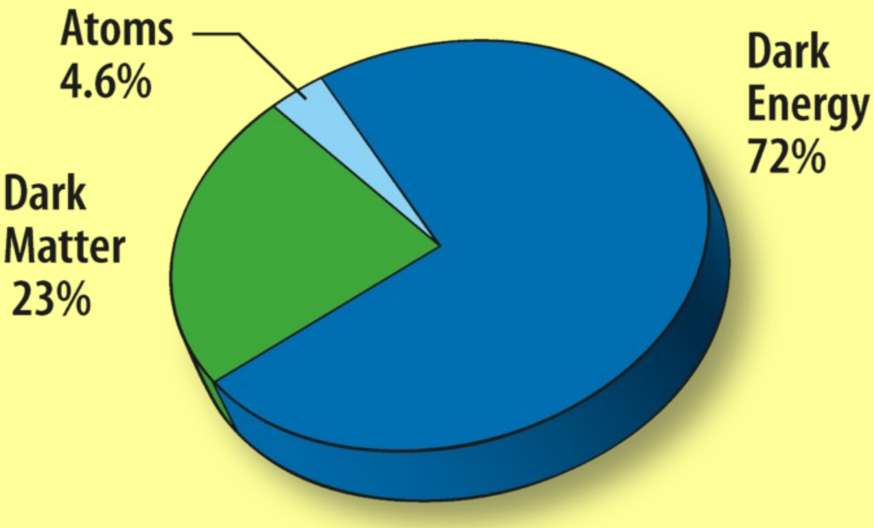
Dark Energy

Within the framework of general relativity, an accelerated expansion can be accounted for by a positive value of the cosmological constant Λ, equivalent to the presence of a positive vacuum energy "dark energy".

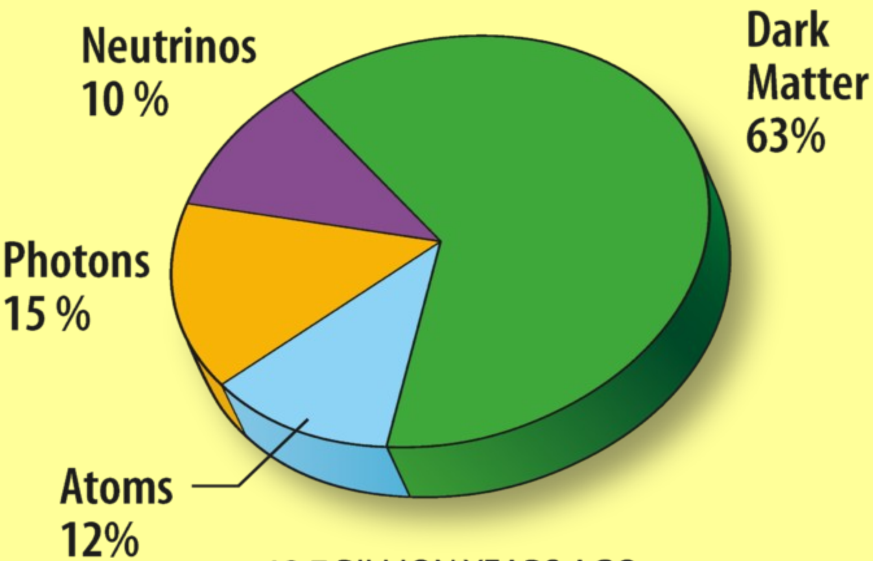
Energy and not Matter

- Negative Pressure!
- Can't be done by matter
- Not dark.....just transparent! Light passes through it!

Wilkinson Microwave Anisotropy Probe (WMAP) spacecraft seven-year analysis estimated a universe made up of 72.8% dark energy, 22.7% dark matter, and 4.5% ordinary matter. Planck spacecraft observations of 2014 of the CMB gave a more accurate estimate of 68.3% dark energy, 26.8% dark matter, and 4.9% ordinary matter.

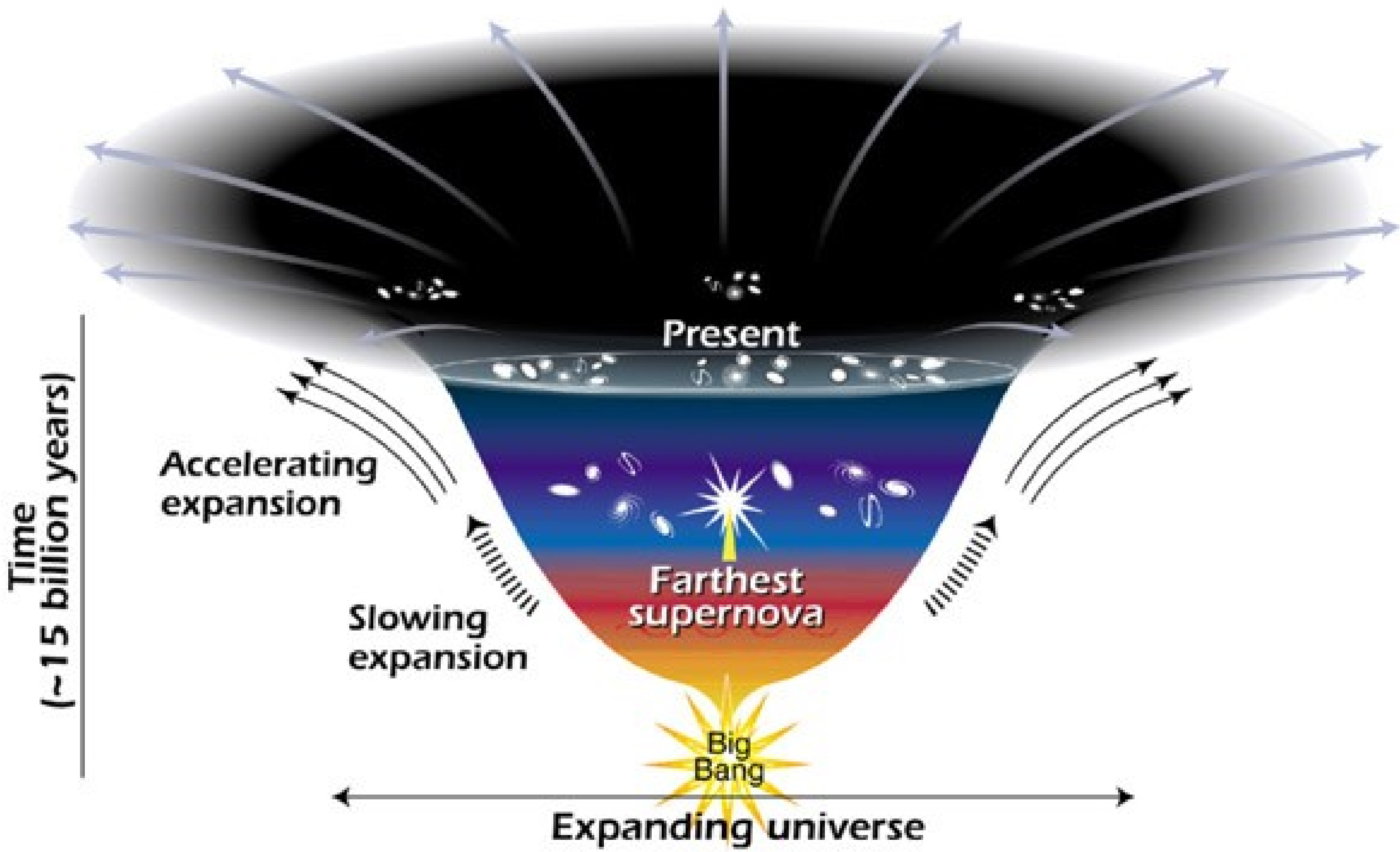


TODAY



13.7 BILLION YEARS AGO

(Universe 380,000 years old)



This diagram reveals changes in the rate of expansion since the universe's birth 15 billion years ago. The more shallow the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart at a faster rate. Astronomers theorize that the faster expansion rate is due to a mysterious, dark force that is pushing galaxies apart.

Cosmological principle

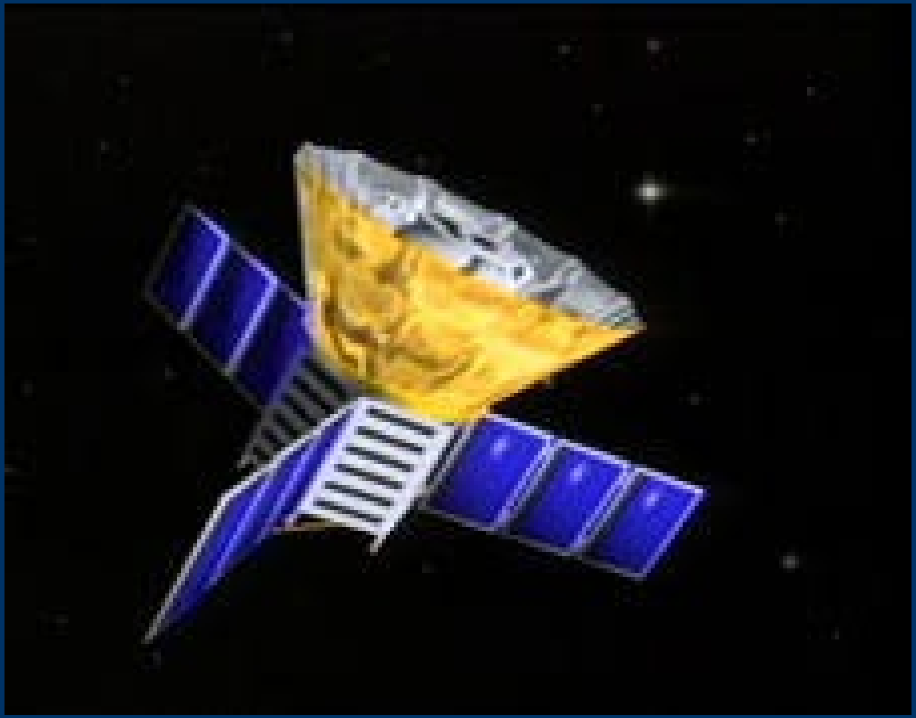
The spatial distribution of matter in the universe is homogeneous and isotropic when viewed on a large enough scale, since the forces are expected to act uniformly throughout the universe, and should, therefore, produce no observable irregularities in the large-scale structuring over the course of evolution of the matter field that was initially laid down by the Big Bang.

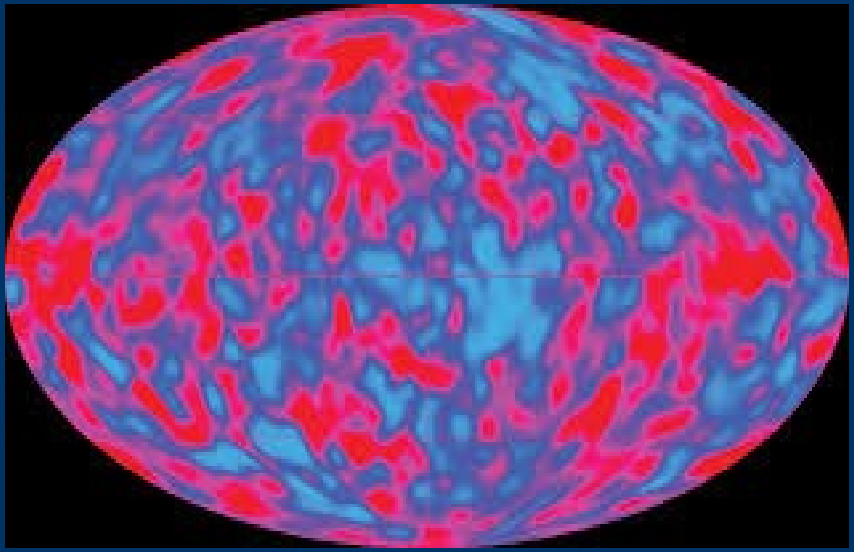
Cosmic microwave background (CMB, CMBR)

In Big Bang cosmology, it is electromagnetic radiation as a remnant from an early stage of the universe, also known as "relic radiation".

The Holmdel Horn Antenna on which Penzias and Wilson discovered the cosmic microwave background. Penzias and Wilson received the 1978 Nobel Prize in Physics

NASA Cosmic Background Explorer (COBE) satellite that orbited in 1989–1996

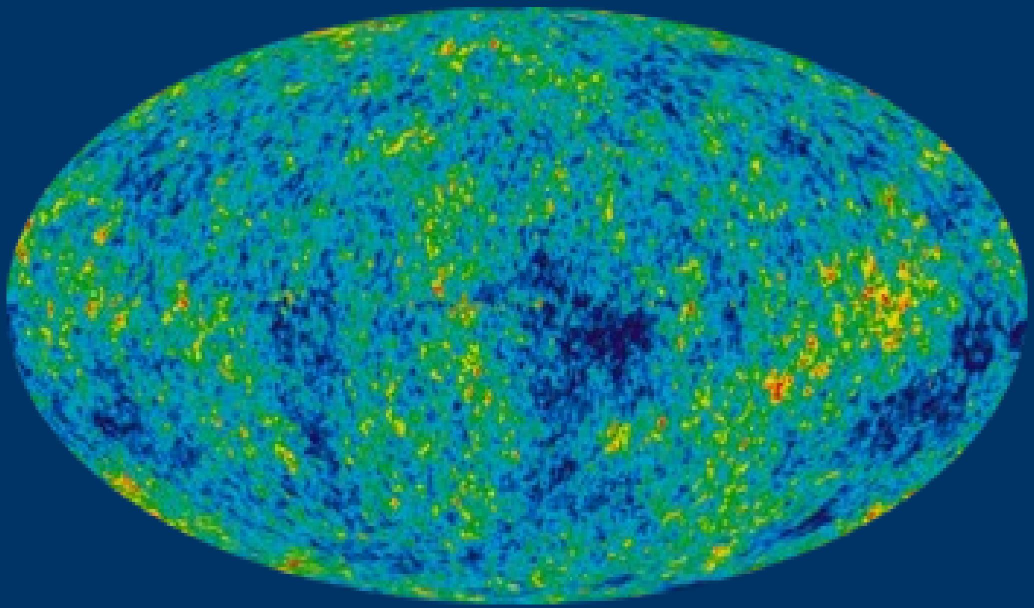




COBE's principal investigators, George Smoot and John Mather, received the Nobel Prize in Physics in 2006 for their work on the project.

June 2001, NASA launched a second CMB space mission, WMAP

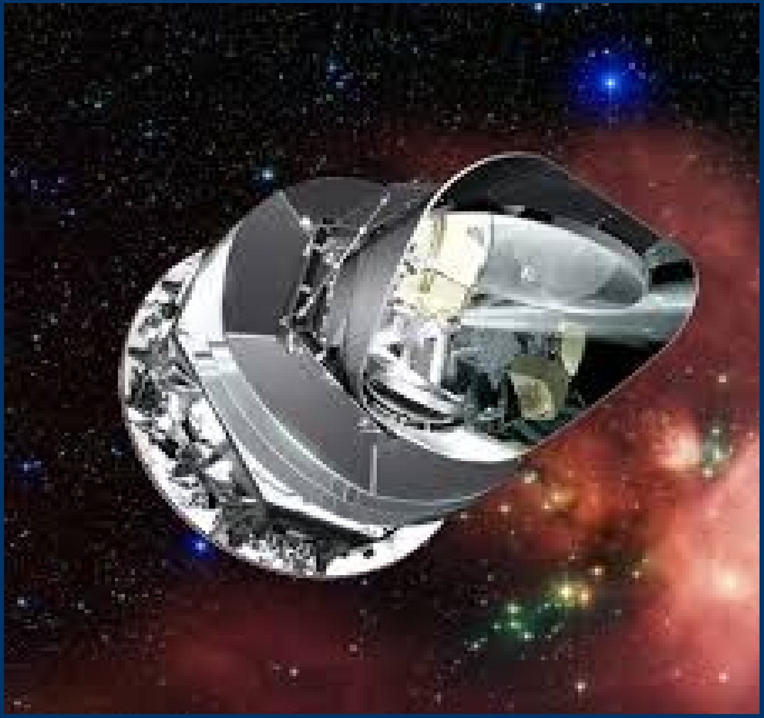
Wilkinson Microwave Anisotropy Probe

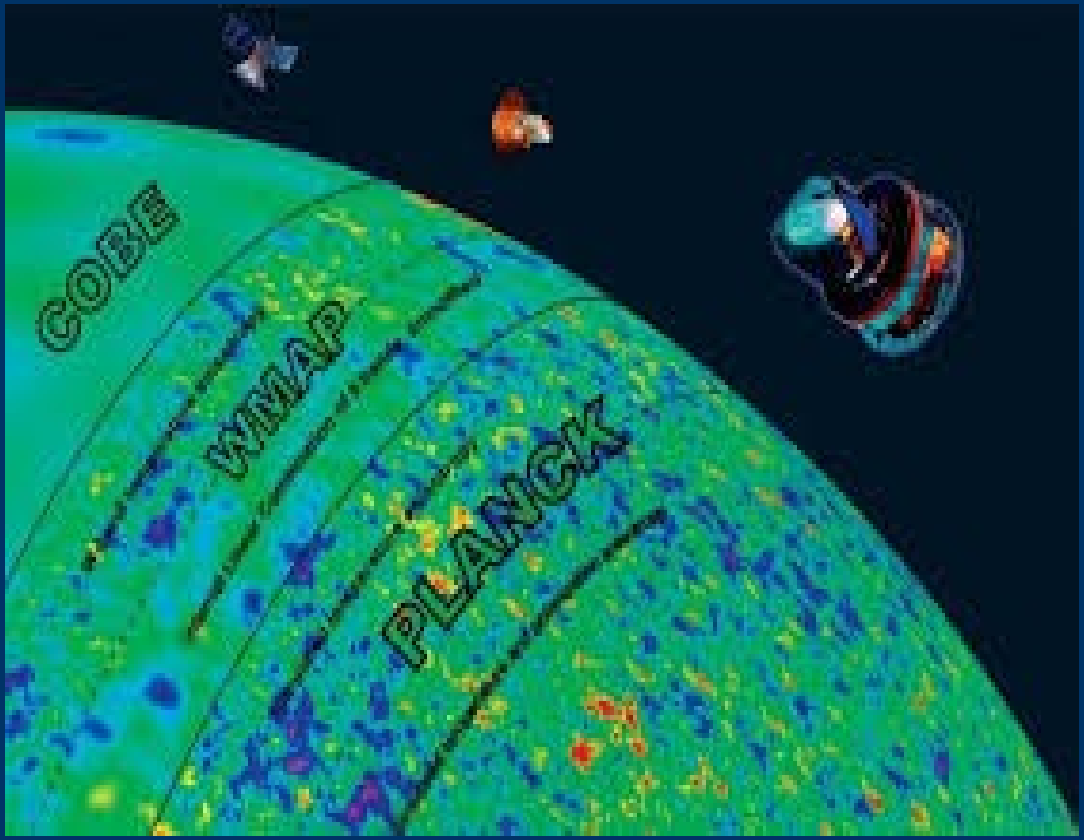


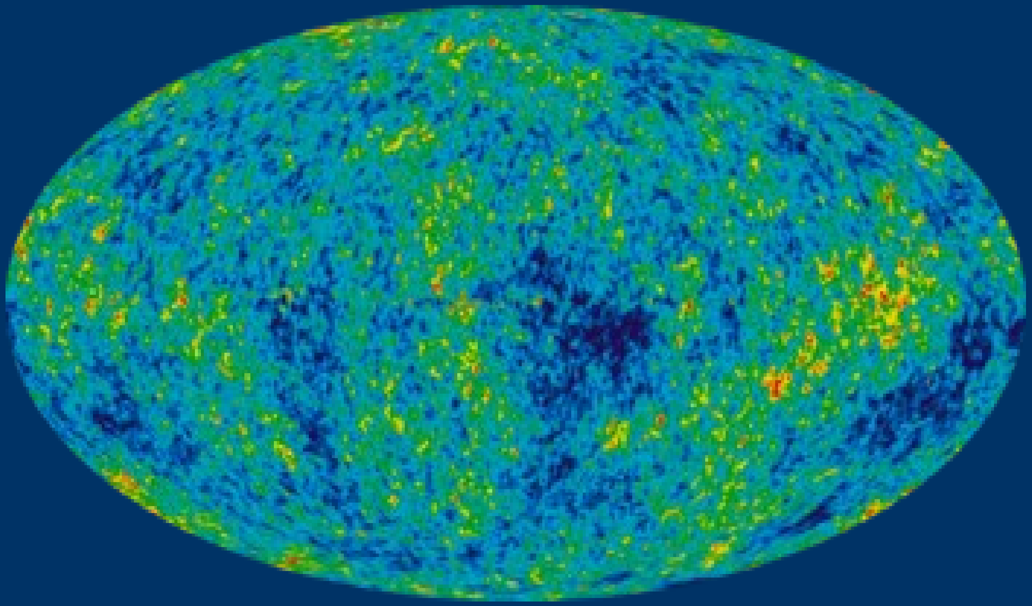
Temperature anisotropies of the CMB based on the nine year WMAP data (2012). Smooth, homogeneous universe with density anisotropies of 10 parts per million.

ESA (European Space Agency) Planck (2009 - 2013.

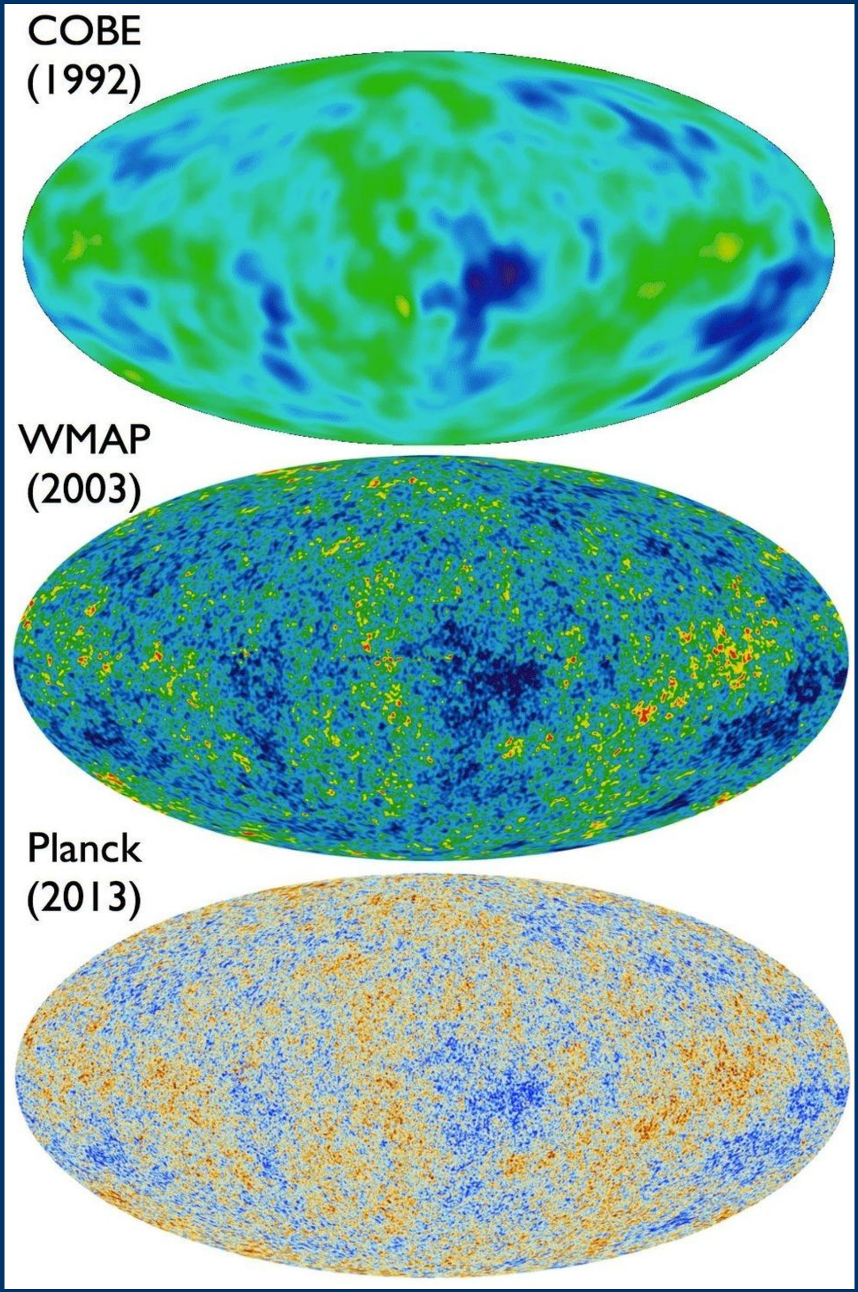
Mapped the anisotropies of the cosmic microwave background at microwave and infra-red frequencies, with high sensitivity and small angular resolution



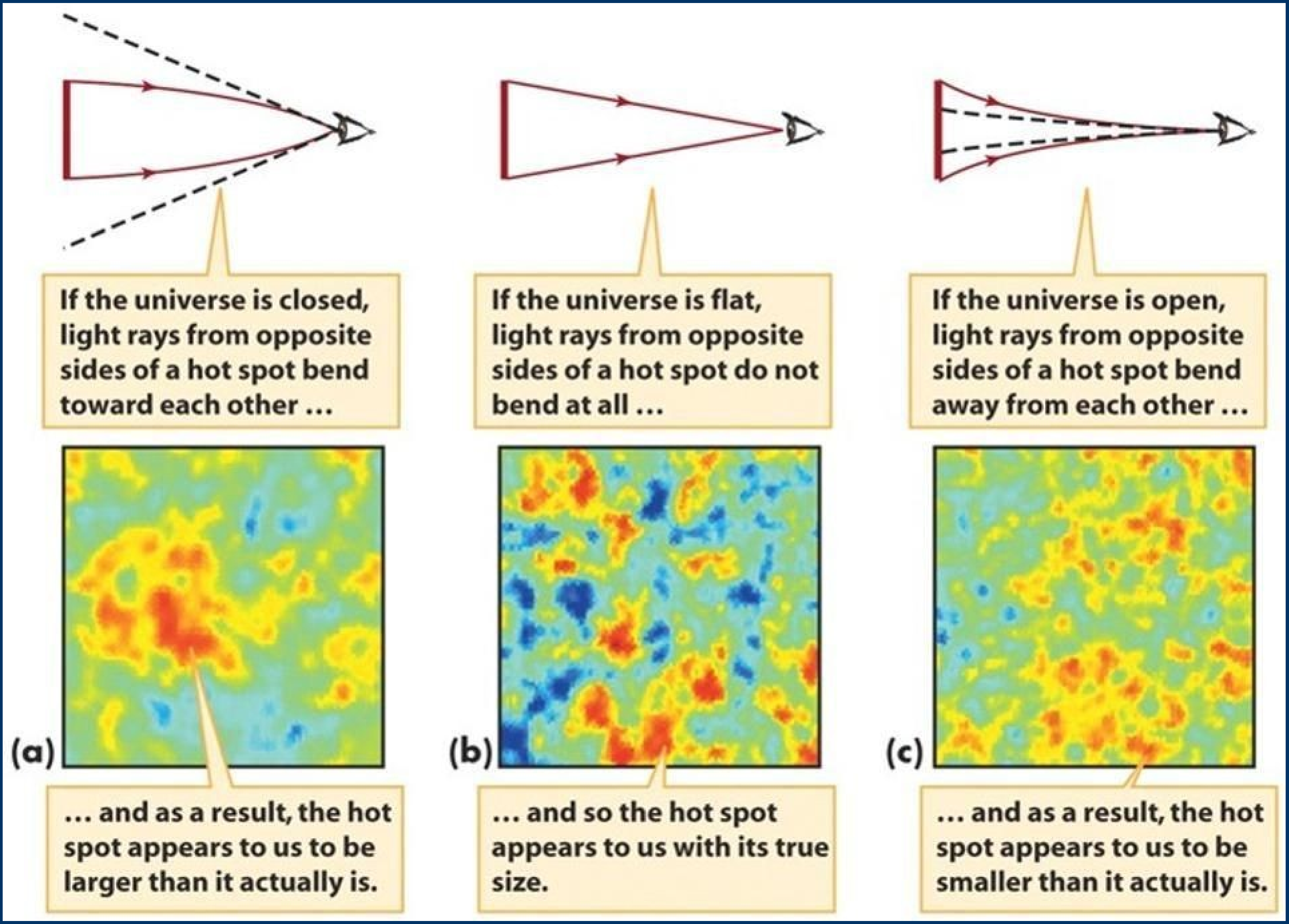


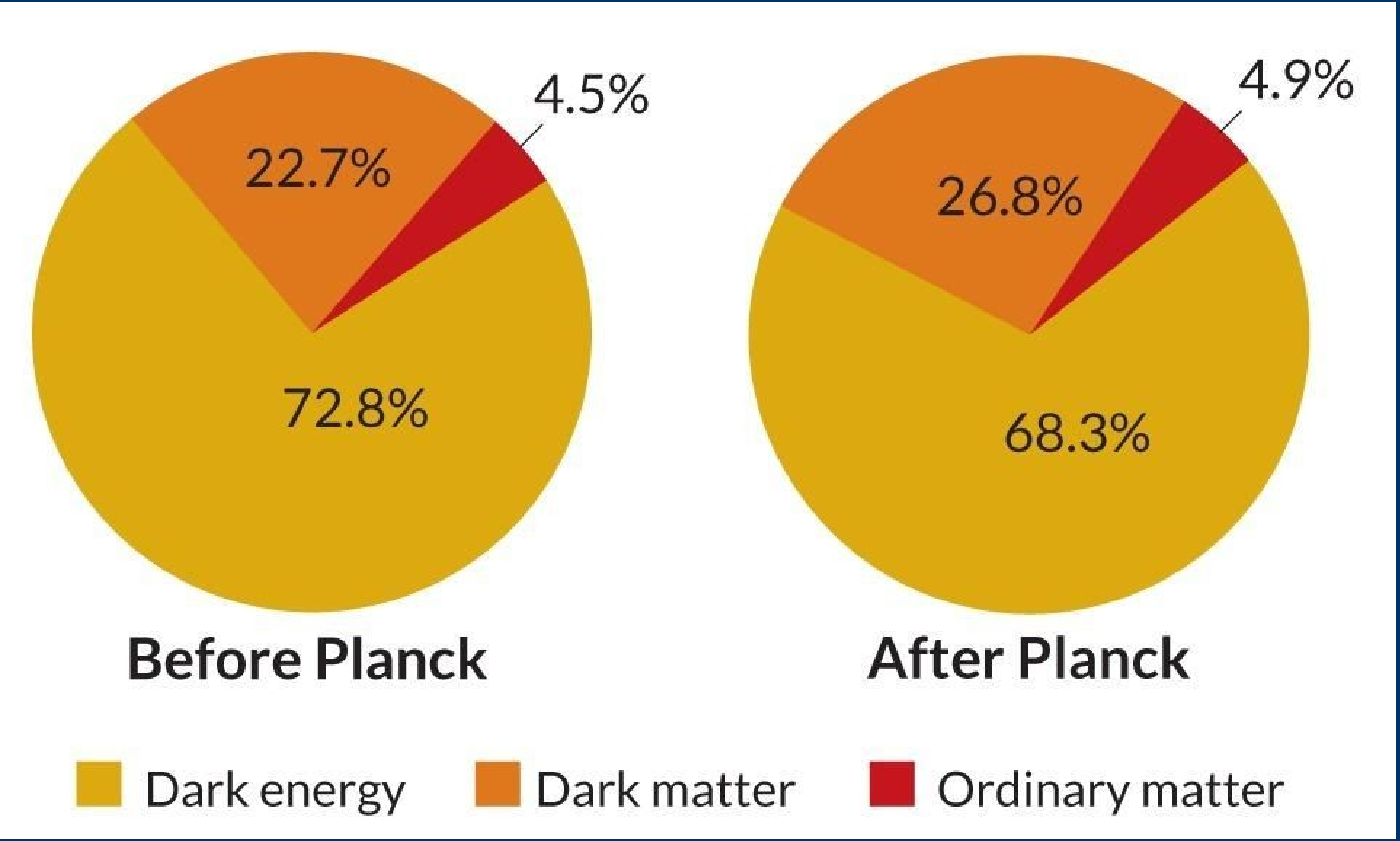


Universe was built bottom-up, the small anisotropies of the early universe acted as gravitational seeds for the structure observed today. Overdense regions attract more matter, whereas underdense regions attract less, and thus these small anisotropies, seen in the CMB, became the large scale structures in the universe today.

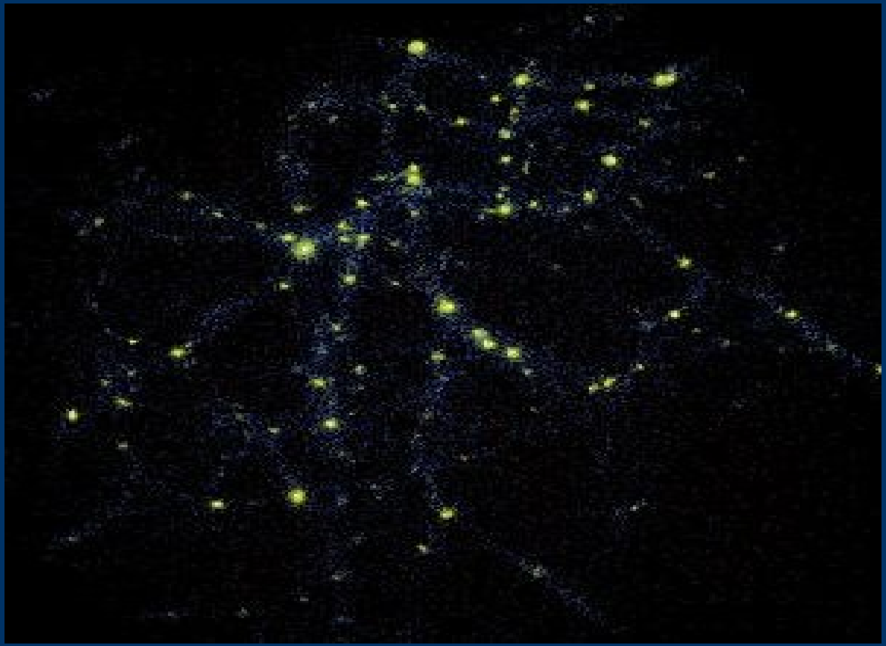


CMB when the Universe was only 380,000 years old. COBE satellite gave us the first precision, all-sky map of the cosmic microwave background, down to a resolution of about 7 degrees. About a decade ago, WMAP managed to get that down to about half-a-degree resolution. Planck is so sensitive that we can measure down to 0.07°


If the universe is closed, light rays from opposite sides of a hot spot bend toward each other …
If the universe is flat, light rays from opposite sides of a hot spot do not bend at all …
If the universe is open, light rays from opposite sides of a hot spot bend away from each other …
(a)
(b)
(c)
… and as a result, the hot spot appears to us to be larger than it actually is.
… and so the hot spot appears to us with its true size.
… and as a result, the hot spot appears to us to be smaller than it actually is.

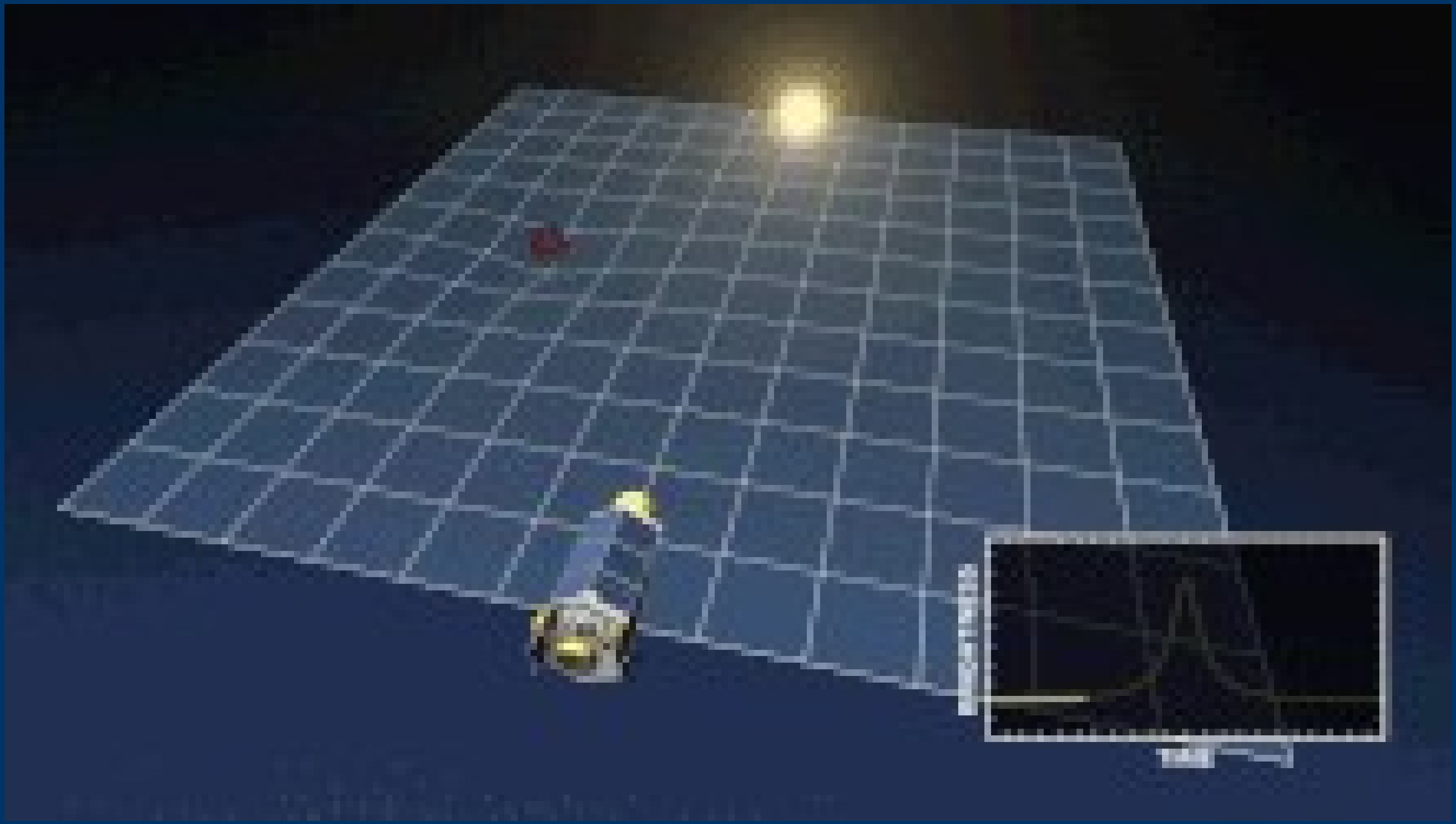

4.5%
22.7%
72.8%
Before Planck
4.9%
26.8%
68.3%
After Planck
Dark energy
Dark matter
Ordinary matter

Structure formation



Computer simulation of large scale structure formation in a Lambda-CDM universe

Gravitational microlensing



Accelerating Universe

- 2000 CMBR balloon expts
- Baryon acoustic oscillations (BAO) by looking at the large scale structure of matter using astronomical surveys
- Micro-lensing Expt
- BICEP
- look at the growth of large-scale structure, and find that the observed values of the cosmological parameters are best described by models which include an accelerating expansion.

Exiting Times Ahead!