The Origin of our Universe

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Our whole universe came from (absolutely) Nothing

13.8 billions years ago

Nothing = 無

NOT
Vacuum = 真空

The Universe　宇宙

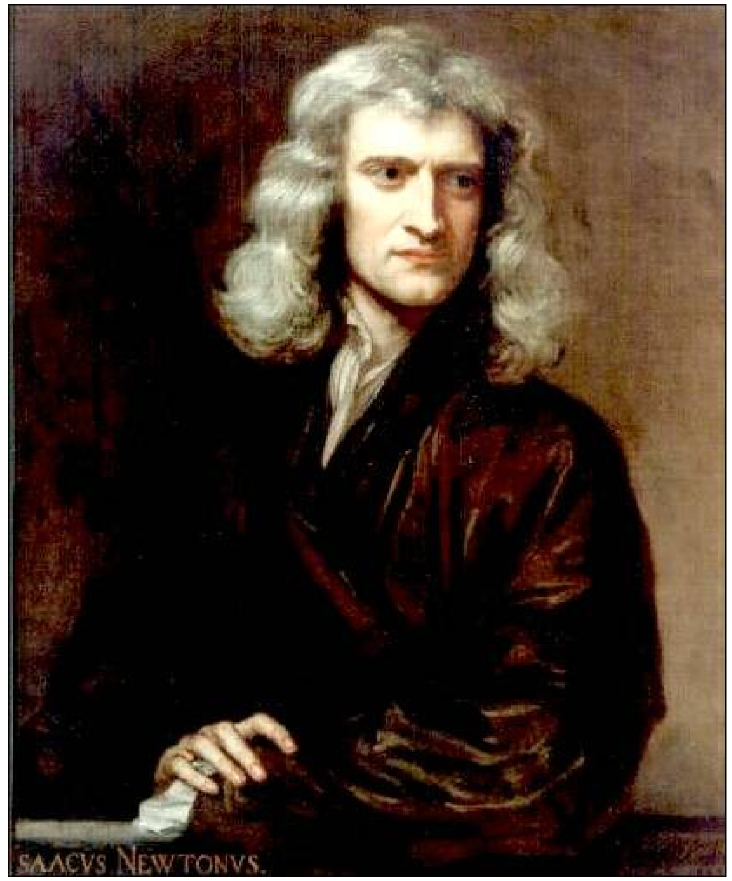
四方上下曰宇,古往今来曰宙。－　《庄子》

"The Universe" means "all of space-time".

Gravity

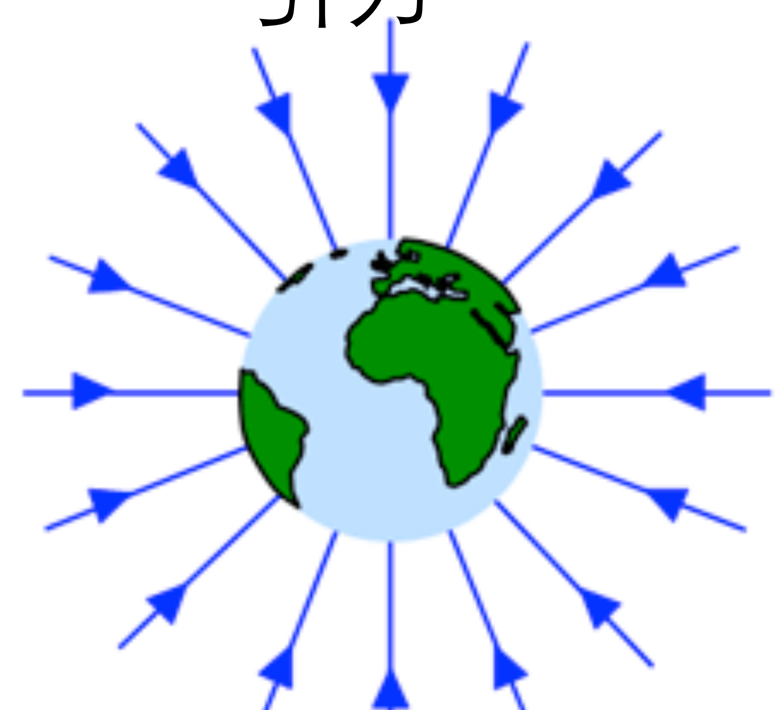
重力

1687



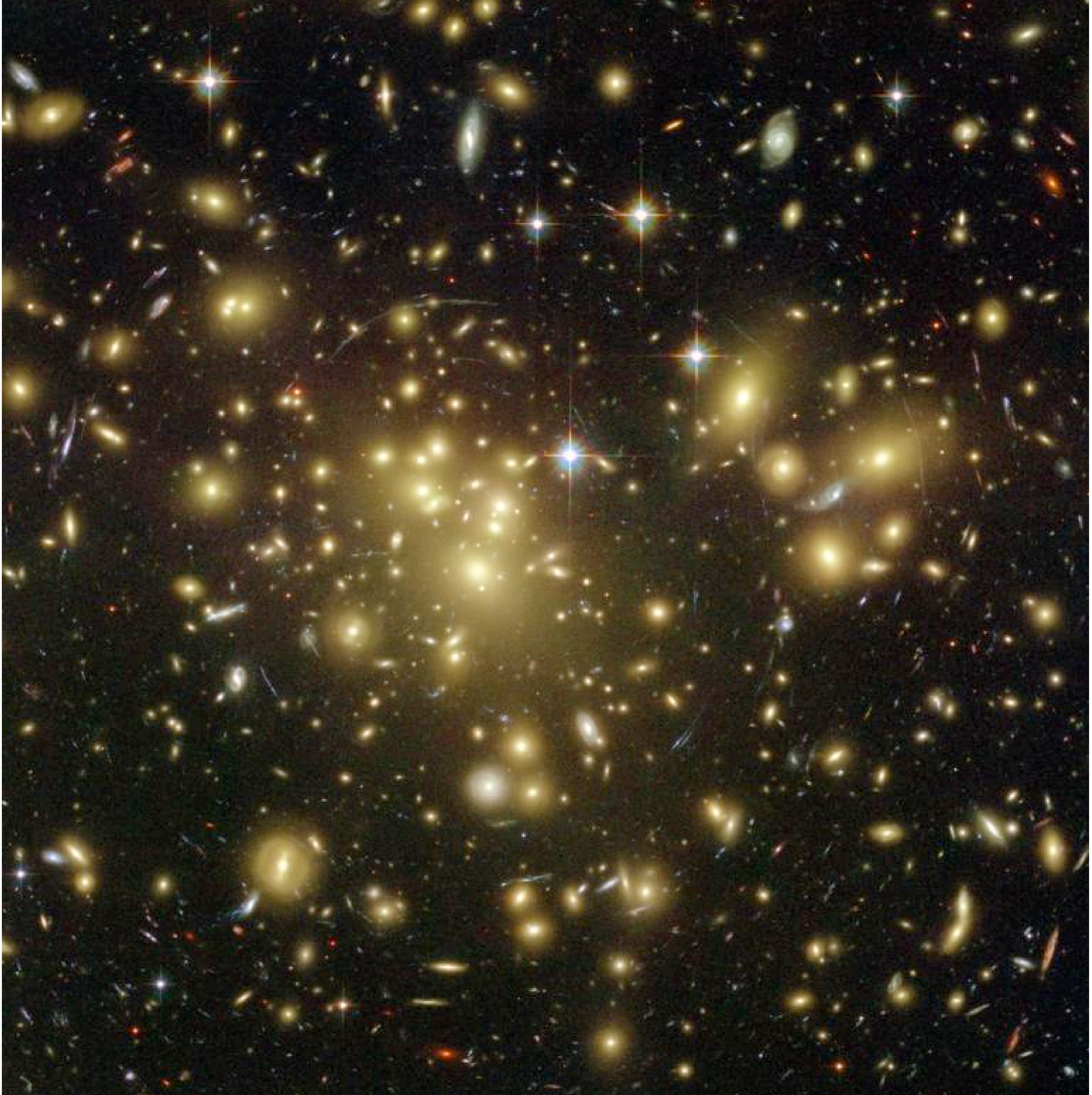
Newton's apple tree

Gravitational force
引力



There are about 400 billion stars in our galaxy.
Our sun is a star close to the edge.

Hubble Space Telescope



There are
many billions
of galaxies
in
our universe.

A convenient way to write very big and very small numbers

- Speed of light c = 299,792,458 meters per second
- $c \sim 300{,}000{,}000$ m/s = 3×10^8 m/s
- $10^{-3} = 0.001$
- 10^{-34} second

Einstein's Theory of Special Relativity (1905)

$E=Mc^2$

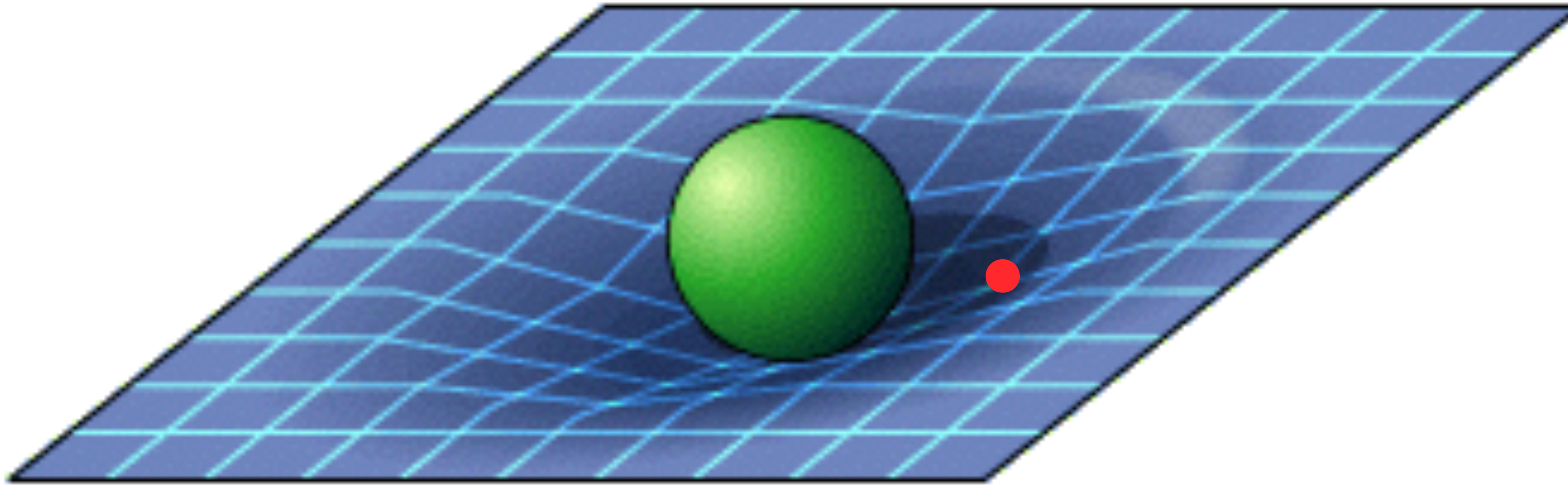
Planets move according to
Newton's gravitational force law

Einstein asked :

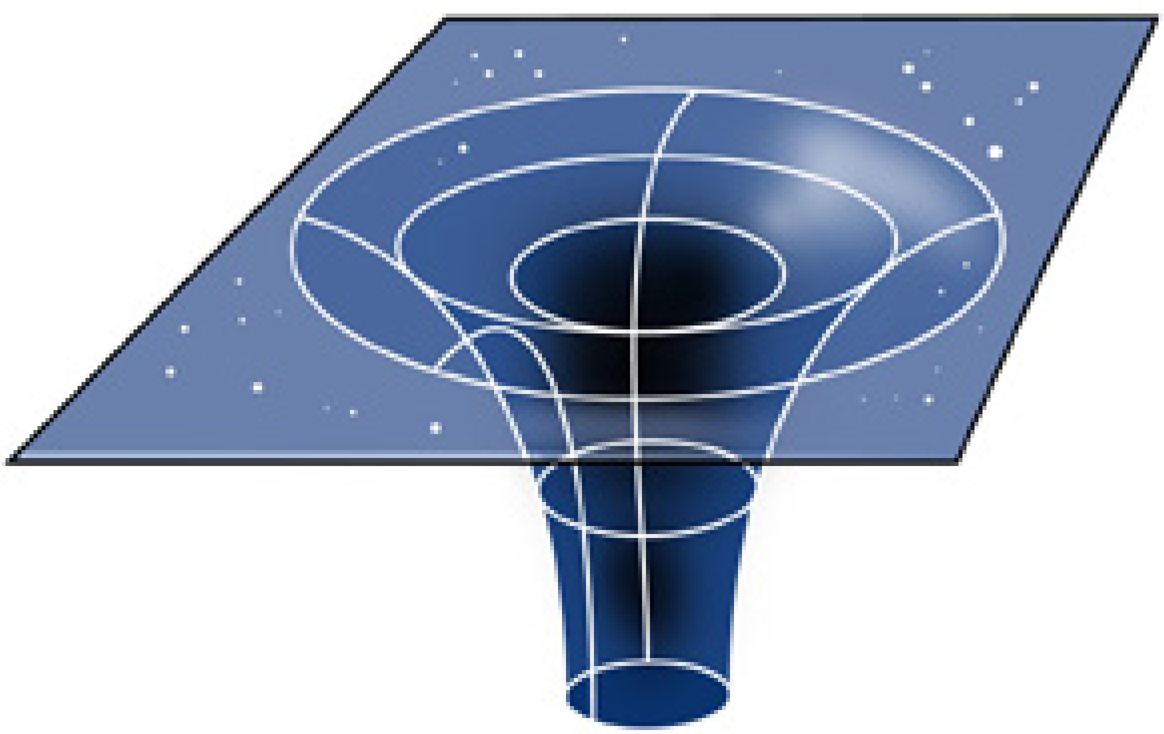
Since there is nothing in between the earth and the sun except empty space, how does the earth know about the gravitational pull of the sun ?

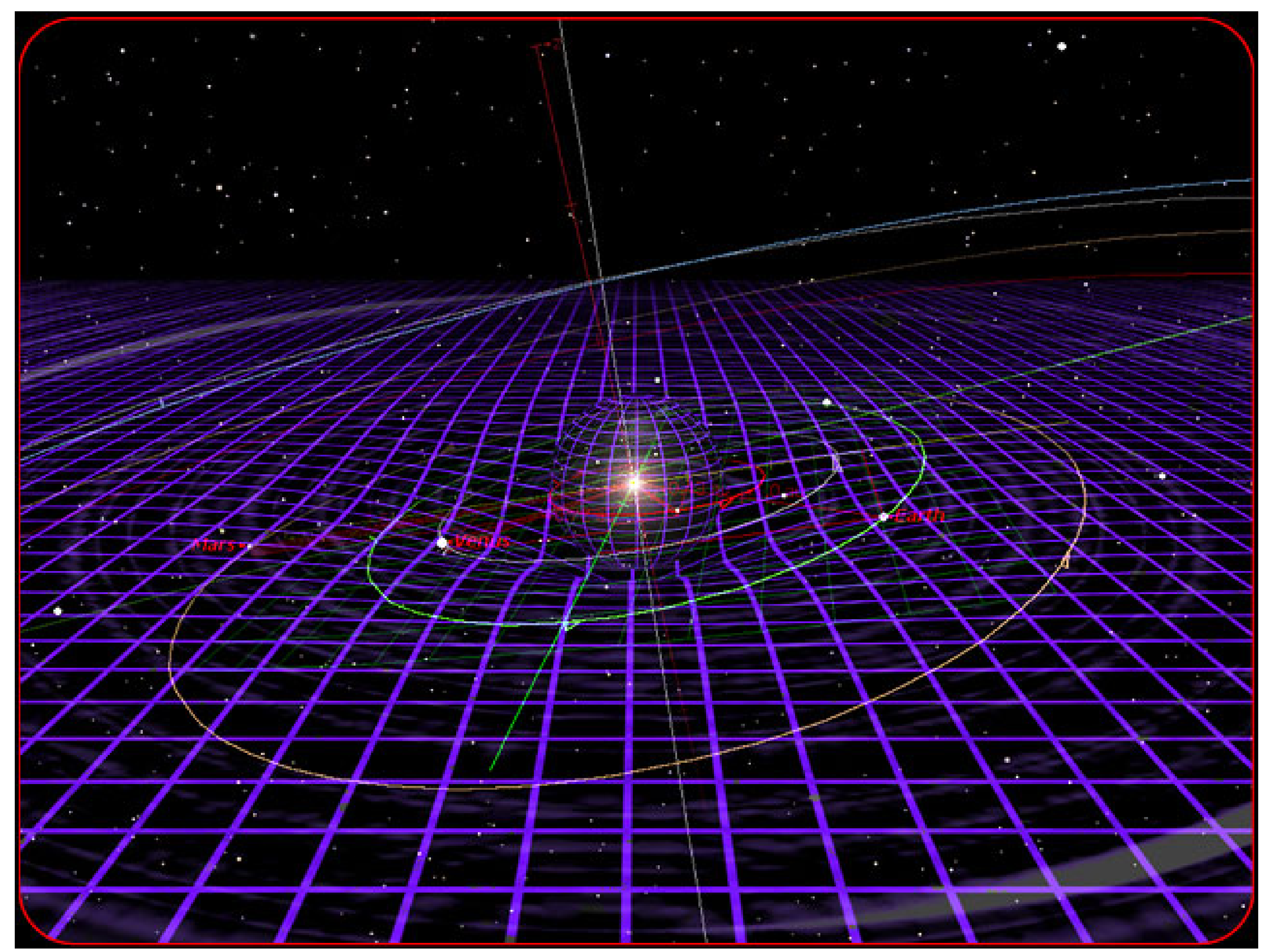
There is space !

Theory of General Relativity
(1915)



Space-time is an active player:
warps, curves, expands, shrinks, …



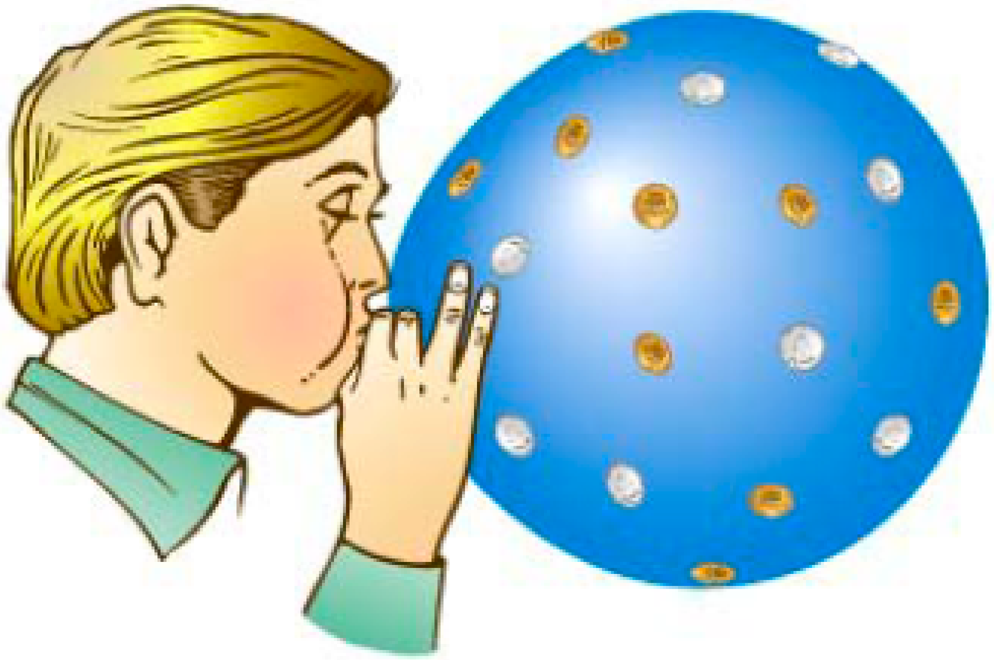


Hubble(1929):

The Universe is Expanding

The further away a galaxy is, the faster it moves away from us.

The expansion of the Universe is similar to the expansion of a balloon: while objects are fixed at their comoving locations, their relative distances are increasing in all directions.



http://www.astro.ucla.edu/~wright

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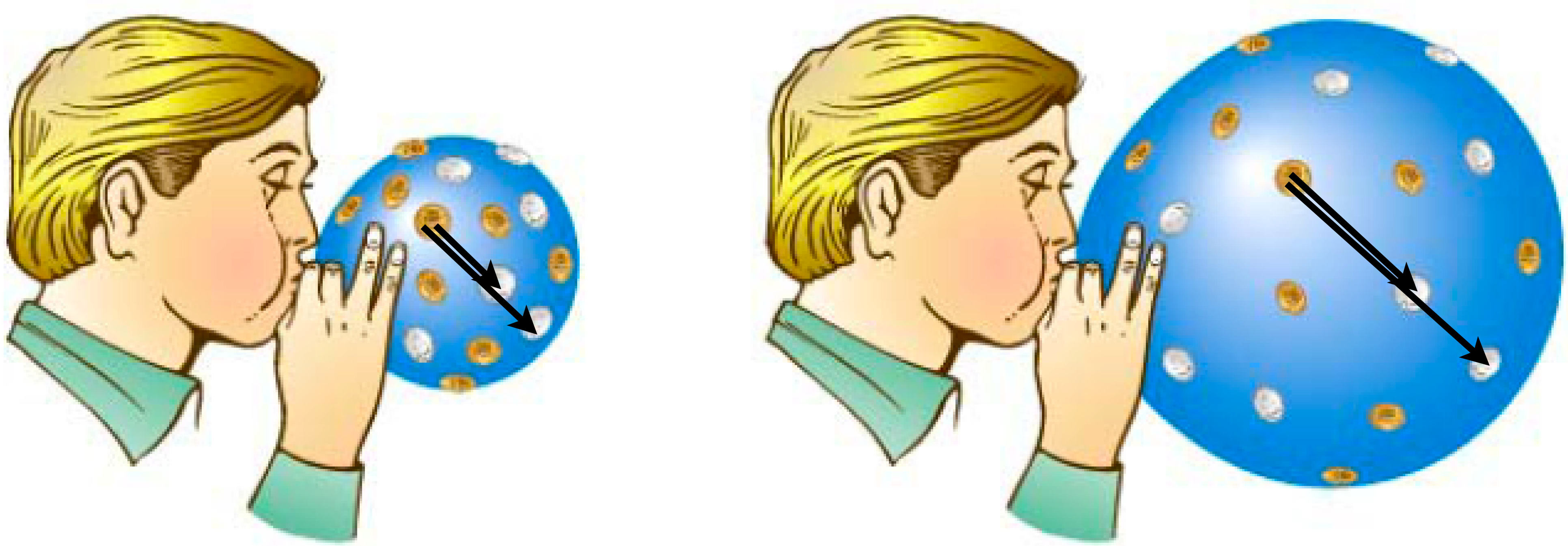


http://www.astro.ucla.edu/~wright

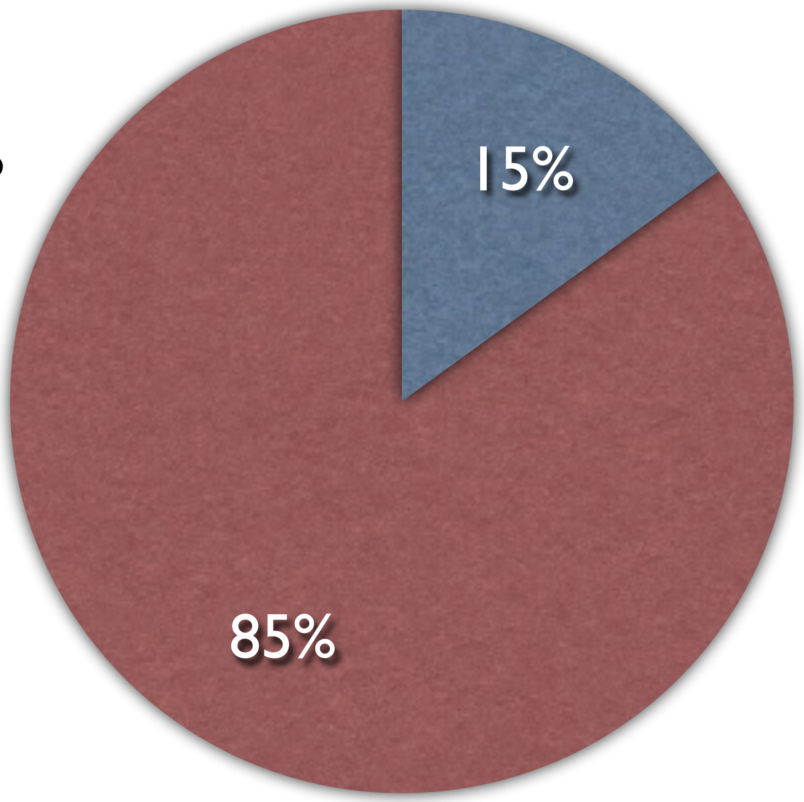
What is in Our Universe today ?

Are all we see in the sky all there are ?

Atoms, molecules, electrons, photons, ...

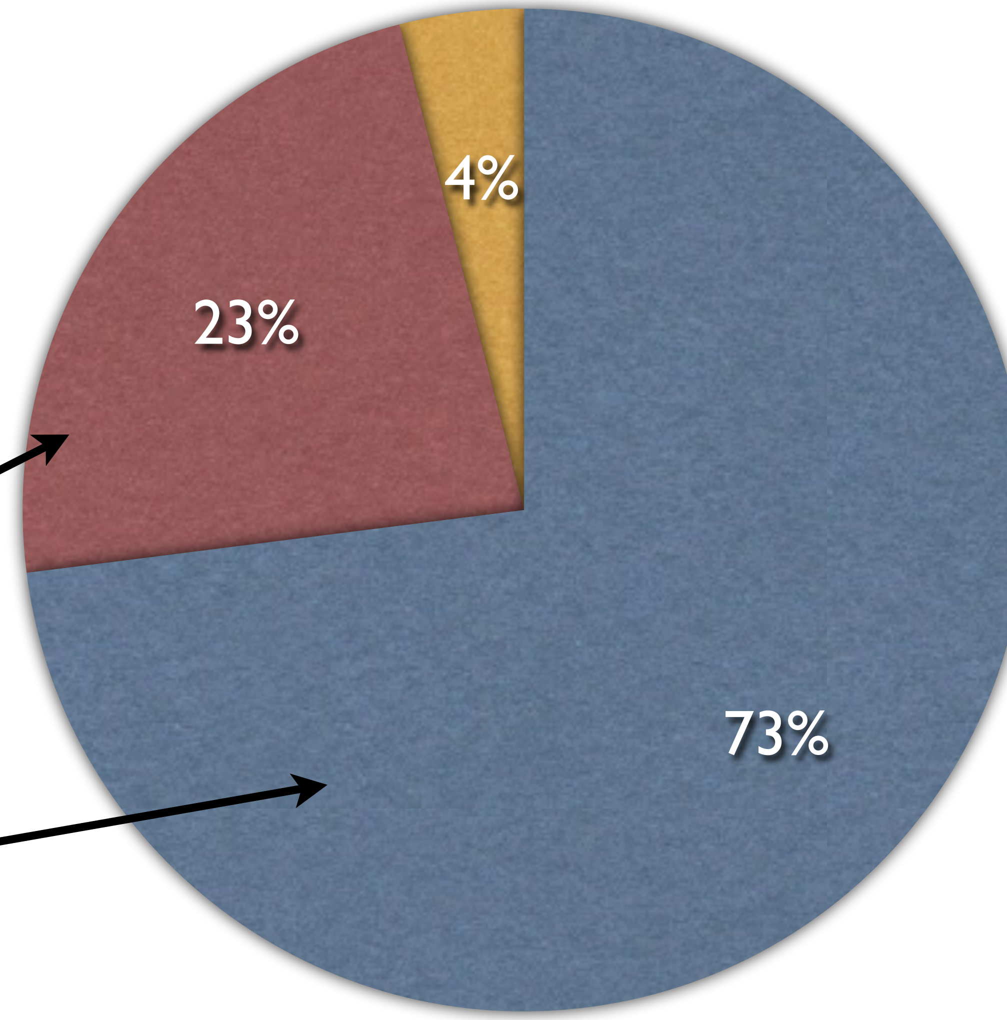
Matter in Our Universe

- Ordinary matter = atoms and molecules
- Other matter ?



Contents in Our Universe

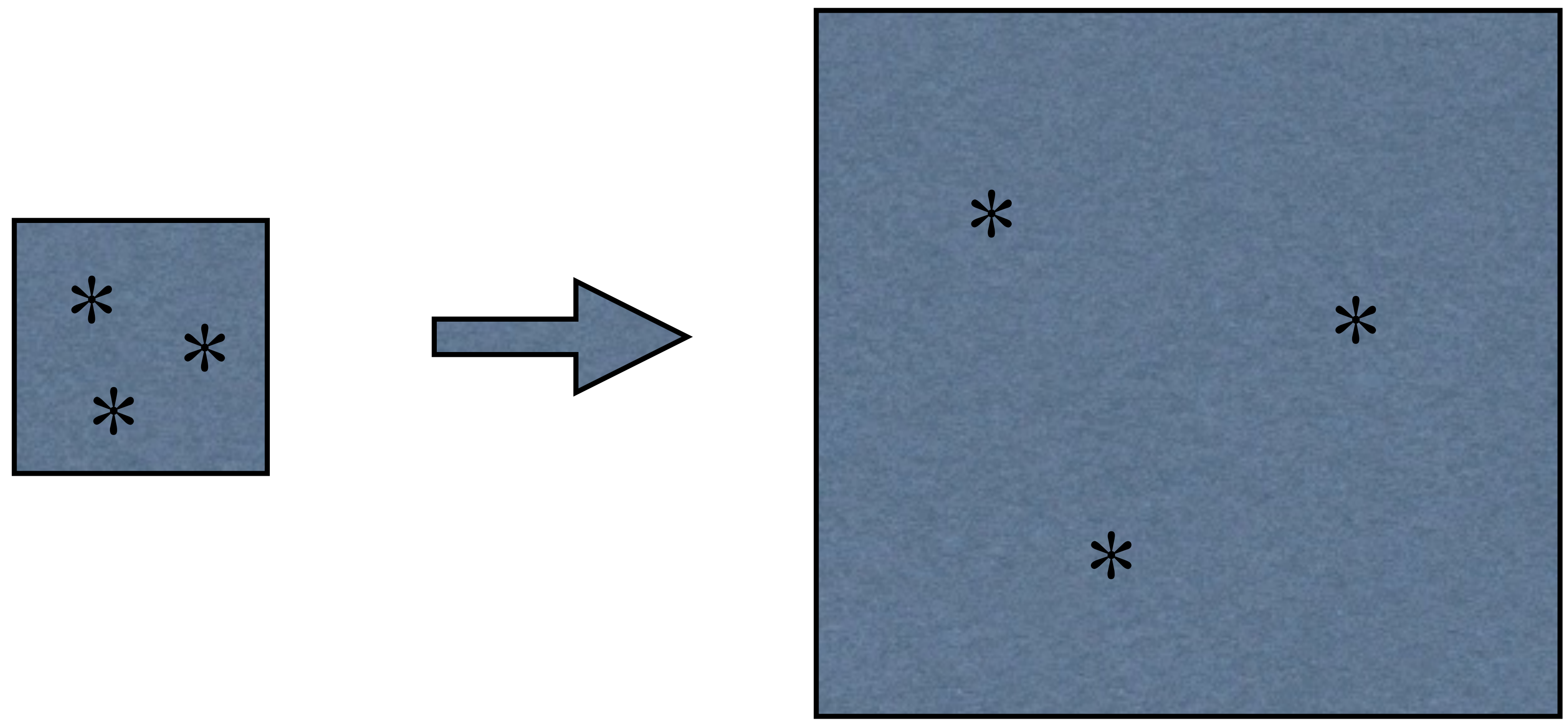
- Dark energy
- Dark matter
- Ordinary matter



mysterious

very mysterious

What is the difference between dark matter and dark energy ?



While the objects move away from each other,

matter * density goes down, but not
the dark energy (blueness) density.

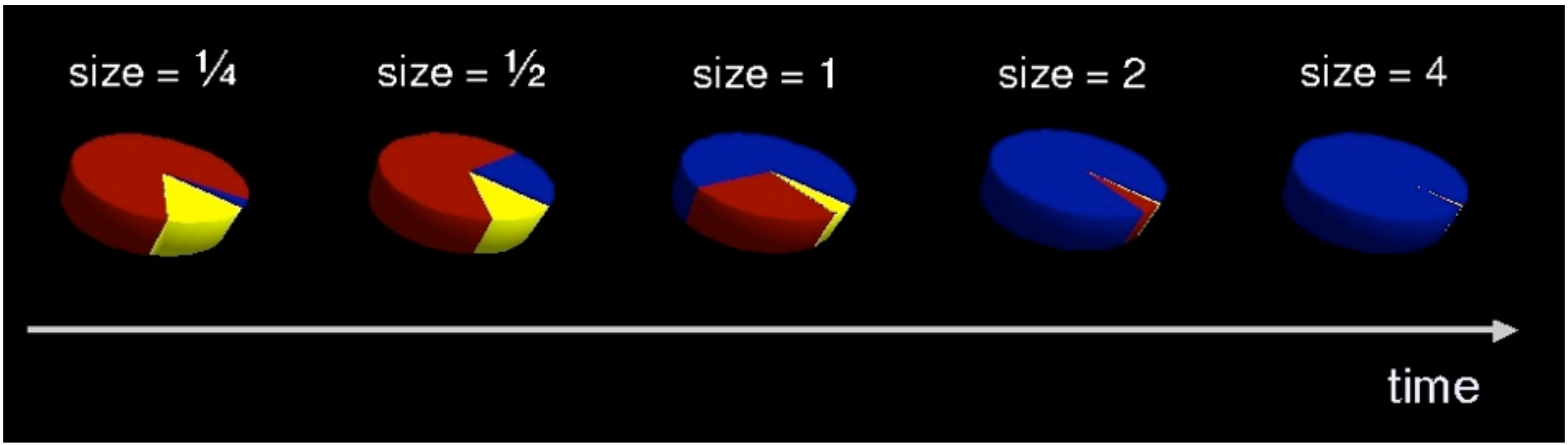
How is it possible that the volume grows while the energy density stays constant ?

[Lesson 5]

It is possible because General Relativity tells us that dark energy has negative pressure.

It also tells us that the expansion becomes “exponential”.

As universe expands :



Past Today Future

Blue : dark energy

Red : dark matter

Yellow : ordinary matter

Our future universe will be space filled with only dark energy.

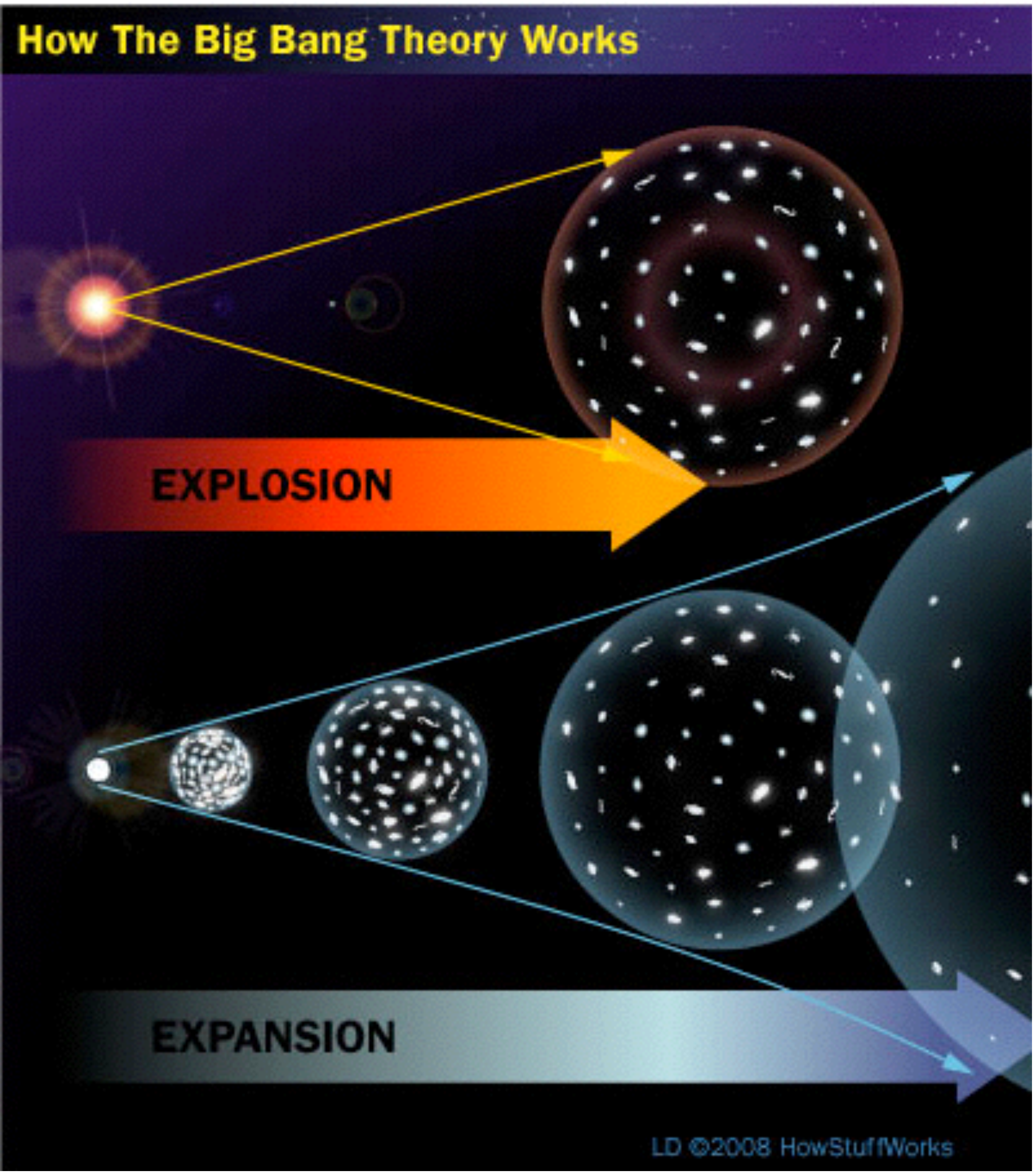
So the expansion of the universe is accelerating.

This is what Perlmutter, Schmidt and Riess and their teams observed in 1998.
They shared the Nobel prize in 2011.

The dark energy is the vacuum energy, most likely the cosmological constant that Einstein introduced and abandoned almost a century ago.

大爆炸理论

Big Bang Theory



Our universe is expanding and cooling today

Going back in time, the universe was smaller and hotter.

Prediction :

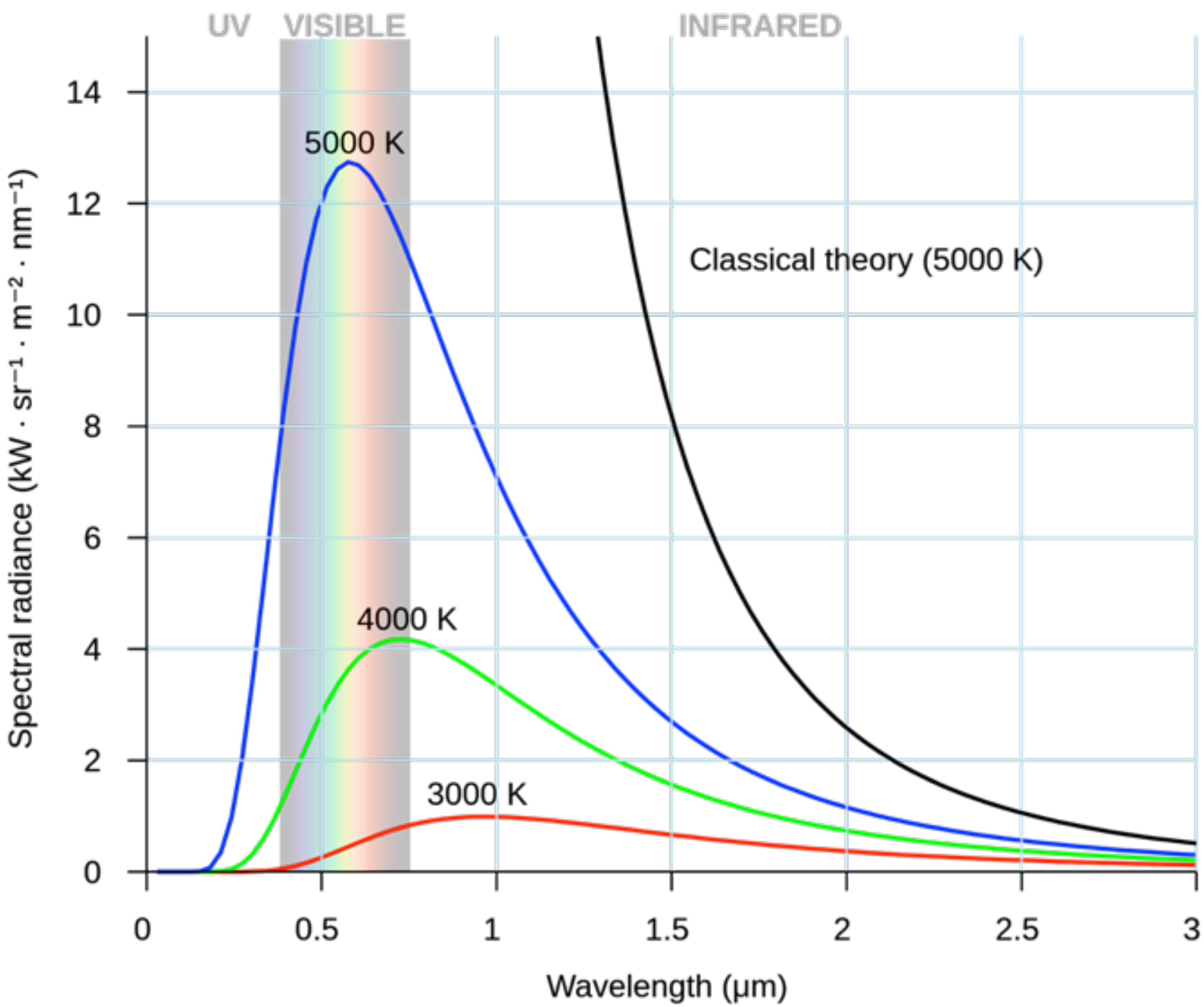
Today, it should have a temperature of about $3K = -270^0C$.

Note : $0K = -273^0C$ is absolute zero.

A little quantum physics

- Wave-particle duality : waves behave like particles and particles behaves like waves.
- Example : Light or microwaves are collections of photons.
- An electron behaves like a wave, so it fluctuates, say, over a barrier, or around a proton to form a hydrogen atom.

Planck's Black Body Radiation Spectrum

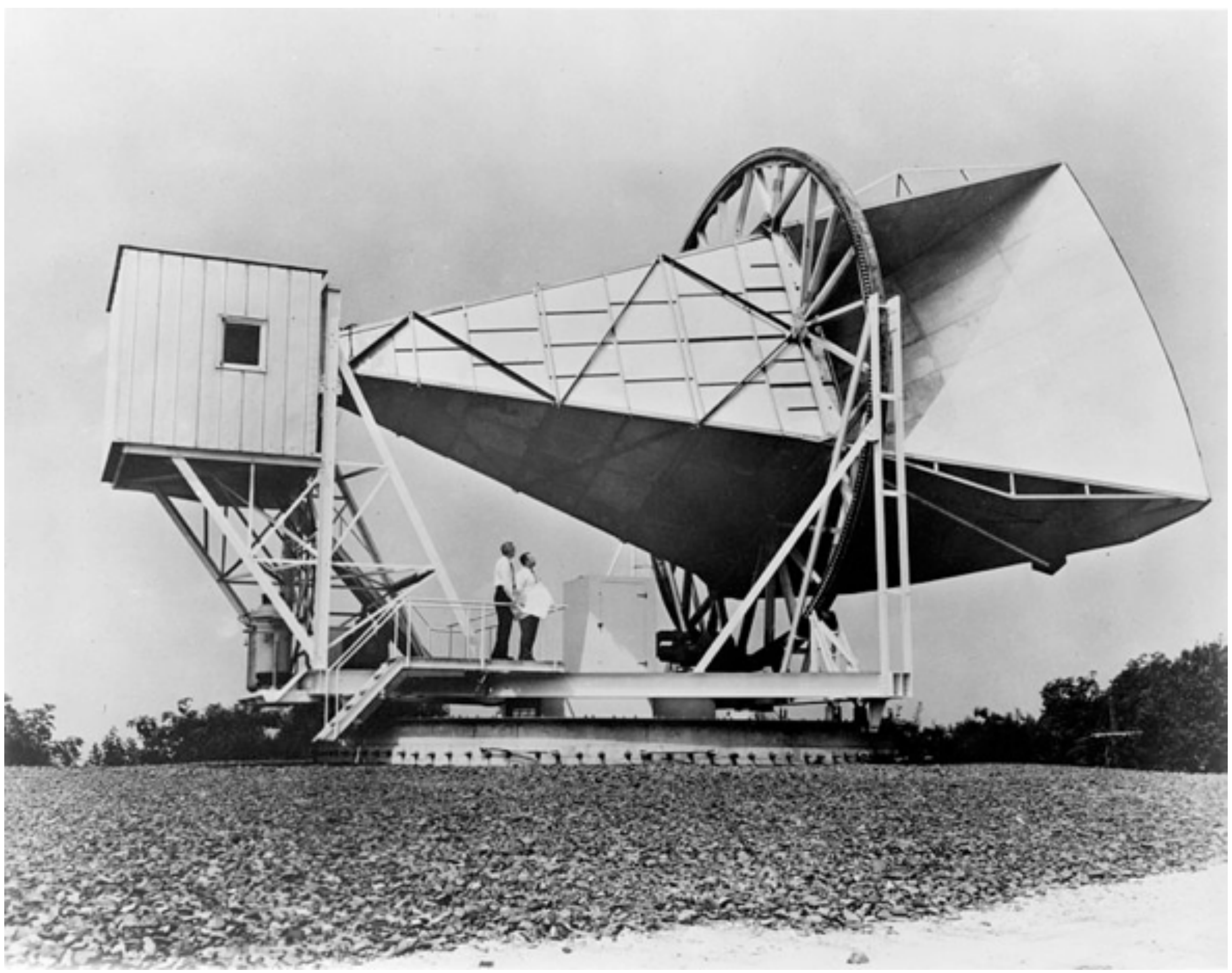


microwave →

Today, the universe should have a temperature of about
3K = -270^0C.

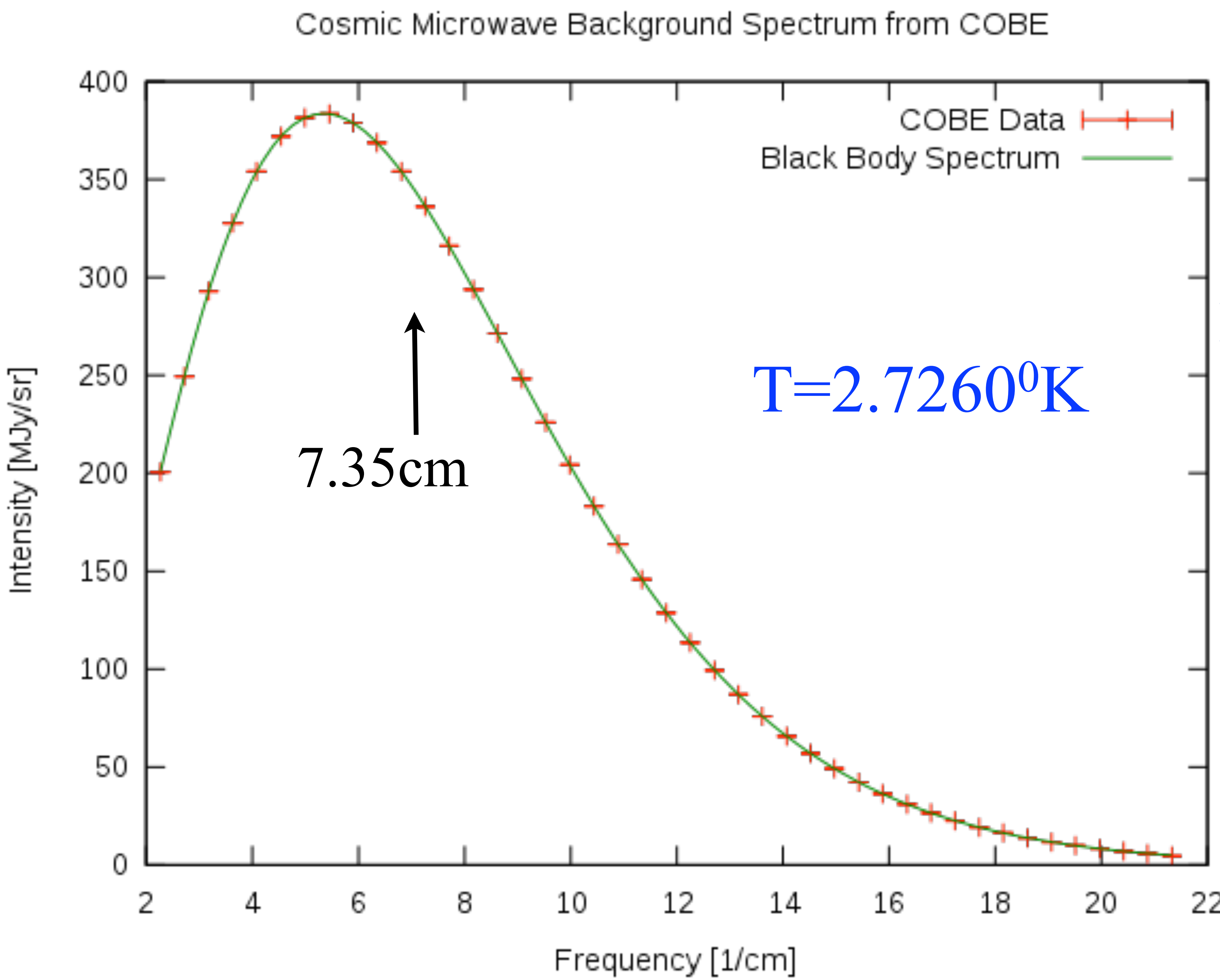
This means we are living in a "thermal" bath of cosmic microwave radiation.

In 1964, Penzias and Wilson measured the intensity of microwave at 7.35cm.



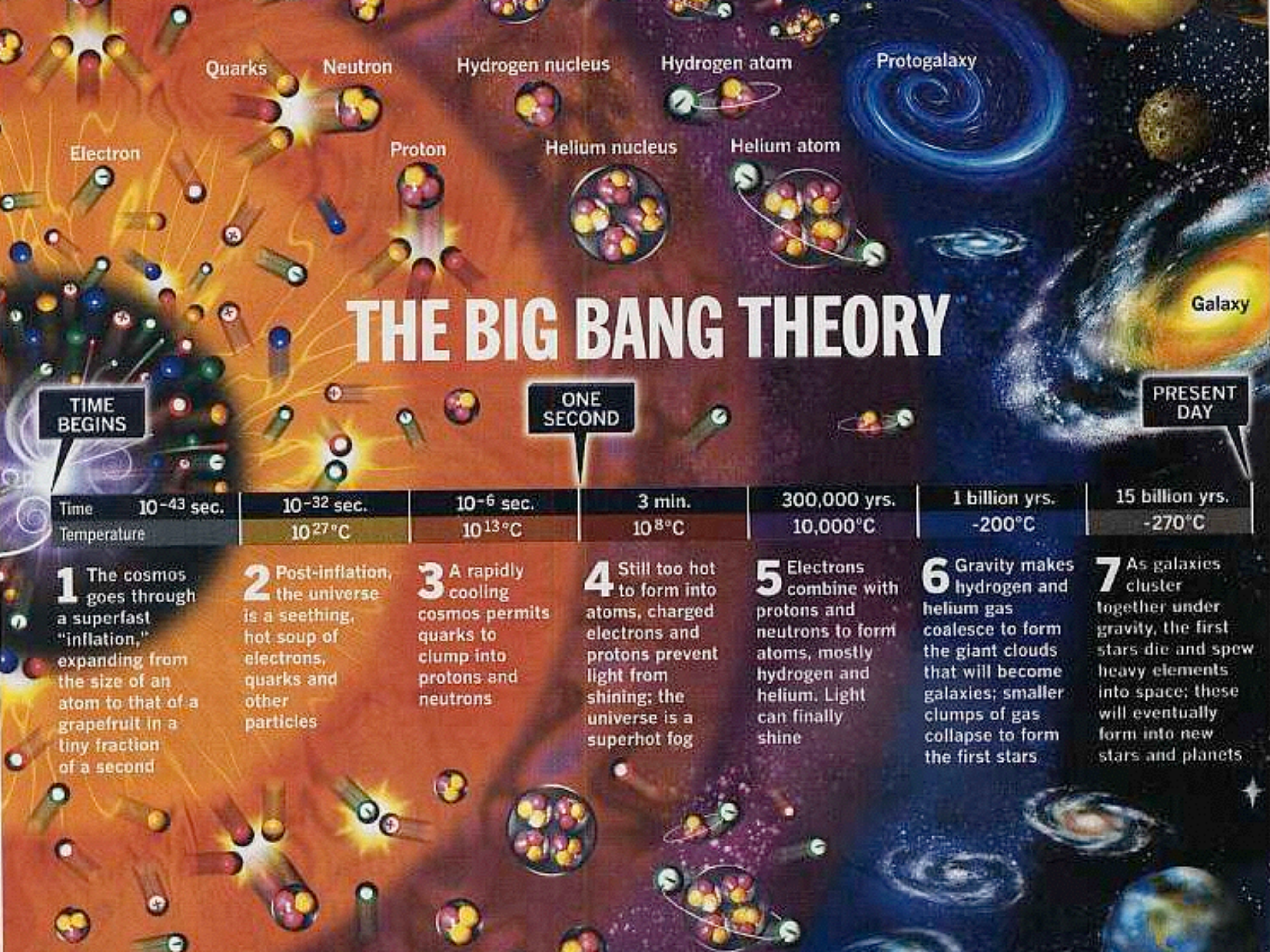
They received the Nobel prize in 1978.

The age of our universe is 13.798 billion years.



COBE

Mather etc. 1992
Nobel prize in 2006.



Quarks
Neutron
Hydrogen nucleus
Hydrogen atom
Protogalaxy
Electron
Proton
Helium nucleus
Helium atom
Galaxy
THE BIG BANG THEORY
TIME BEGINS
ONE SECOND
PRESENT DAY
Time 10^{-43} sec. | 10^{-32} sec. | 10^{-6} sec. | 3 min. | 300,000 yrs. | 1 billion yrs. | 15 billion yrs.
Temperature | 10^{27}°C | 10^{13}°C | 10^{8}°C | 10,000°C | -200°C | -270°C
1 The cosmos goes through a superfast "inflation," expanding from the size of an atom to that of a grapefruit in a tiny fraction of a second
2 Post-inflation, the universe is a seething, hot soup of electrons, quarks and other particles
3 A rapidly cooling cosmos permits quarks to clump into protons and neutrons
4 Still too hot to form into atoms, charged electrons and protons prevent light from shining; the universe is a superhot fog
5 Electrons combine with protons and neutrons to form atoms, mostly hydrogen and helium. Light can finally shine
6 Gravity makes hydrogen and helium gas coalesce to form the giant clouds that will become galaxies; smaller clumps of gas collapse to form the first stars
7 As galaxies cluster together under gravity, the first stars die and spew heavy elements into space; these will eventually form into new stars and planets

$$H^2 = \Lambda + \frac{k}{a^2} + \frac{\rho_m}{a^3} + \frac{\rho_r}{a^4}$$

$$\rightarrow H^2 = (\frac{\dot{a}}{a})^2 \simeq \Lambda$$

$$\rightarrow a(t) \simeq e^{Ht}$$

After a while,

$$\Lambda \rightarrow \rho$$

Going back in time, the size of our universe becomes smaller and smaller, eventually becomes a point.

We learned that the universe would have been a point about 13.8 billions years ago.

Squeezing everything into a point is not possible, but a very small region is possible.

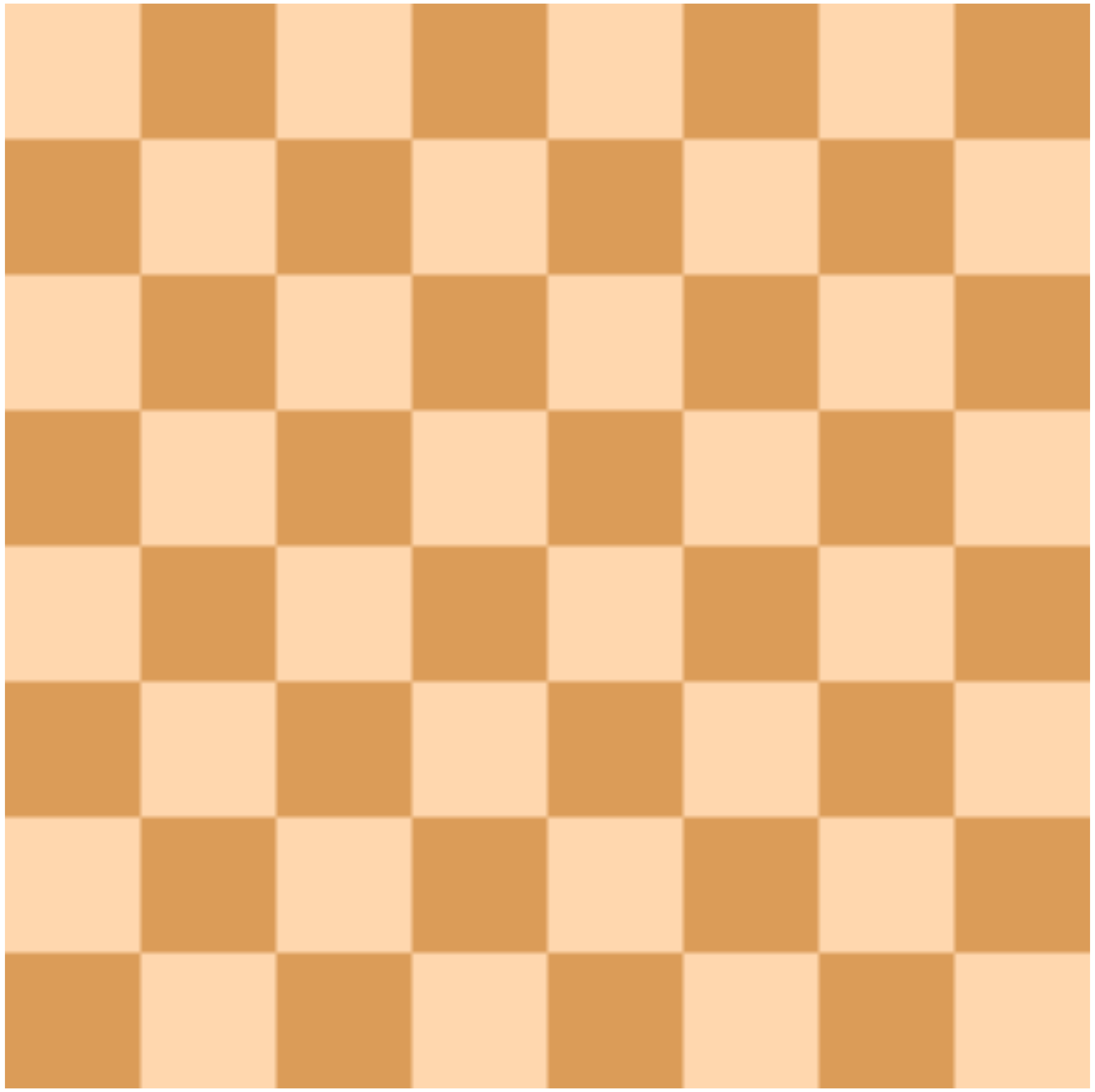
When squeezed to a very small region, the universe was very hot, and the description becomes very simple.

The history of our universe can be traced all the way back to 10^{-37} second old.

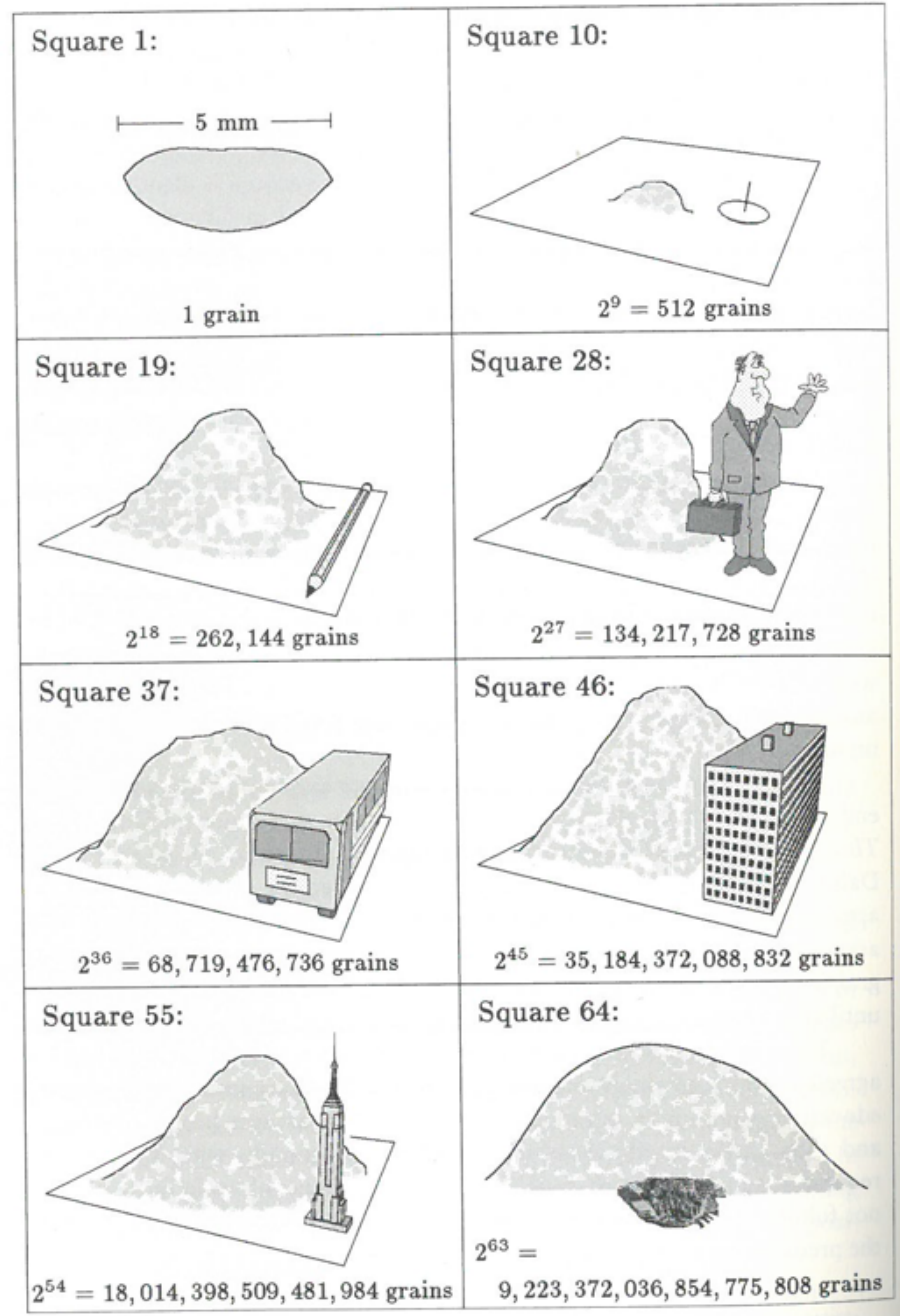
How did the hot big bang start ?

The inflationary universe 暴涨宇宙论

- Start with a single point of size 10^{-30} m, with total energy much less than that of a single electron.
- This point is filled with a much much larger dark energy density than today's.
- This point grows "exponentially" in the inflationary phase, with the dark energy density staying more or less constant.
- At the end of inflation, at about 10^{-35} second, almost all of the dark energy converts to radiation and particles. This leads to the hot big bang.



- 1, 2, 3, 4, 5, 6, ...
- 1, 2, 4, 8, 16, 32, 64, ...



The Inflationary Universe Scenario says :

- All matter comes from inflation (converted from dark energy).
- Space is created by inflation.

Ultimate free lunch

無極生太極

Everything comes from nothing

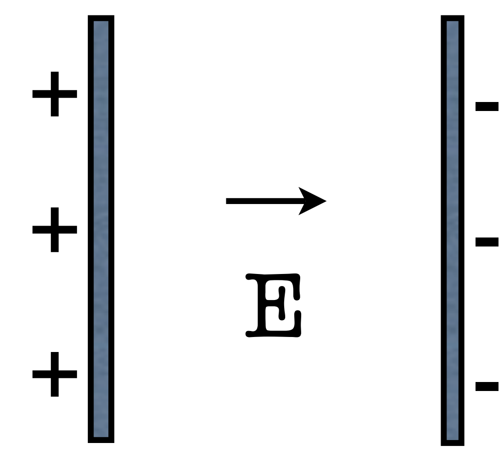
無中生有

Everything (all matter as well as space) comes from nothing !

What About Energy Conservation ?

Energy is conserved only if the total energy of our whole universe is exactly zero today.

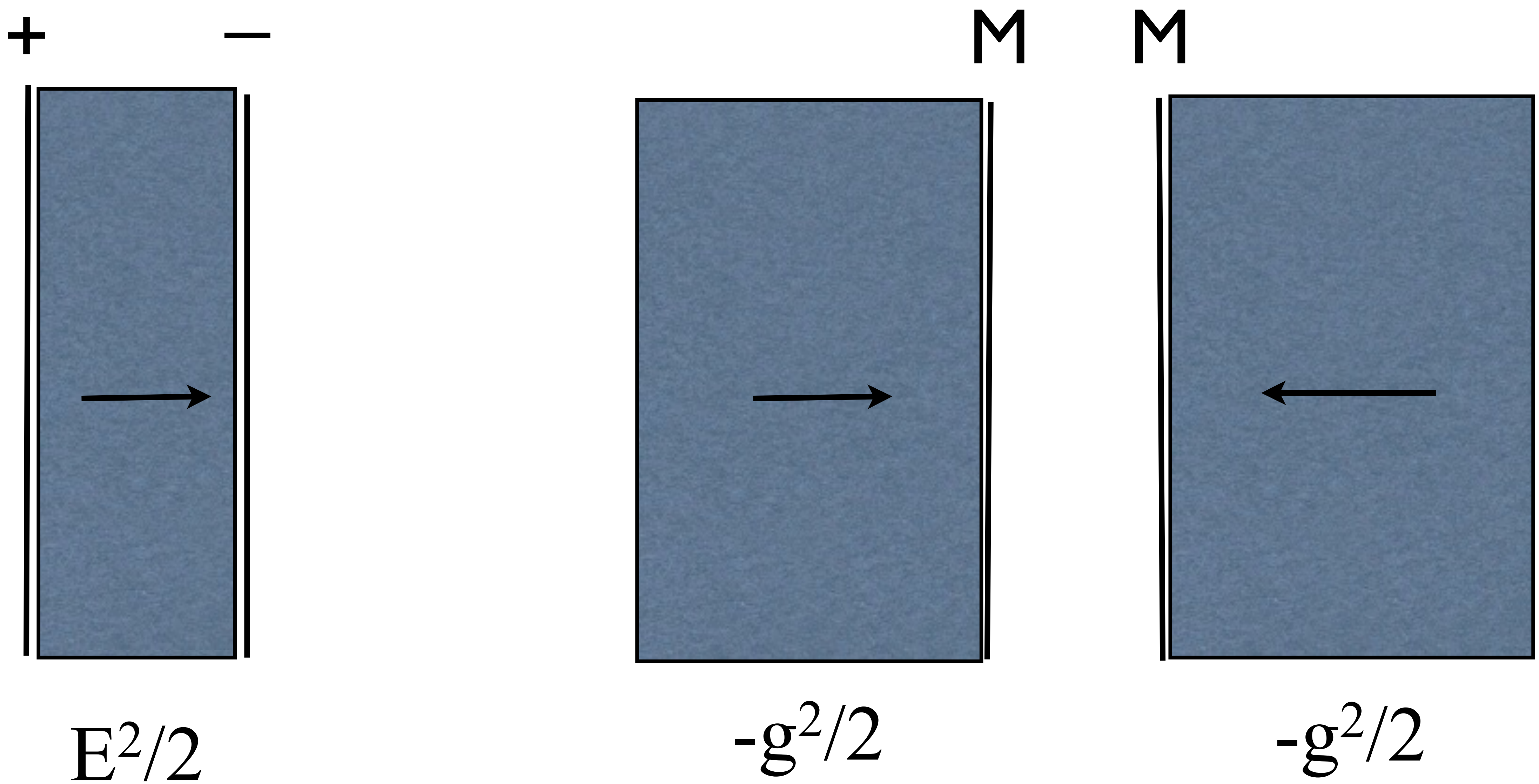
Capacitor



Energy can be conserved !

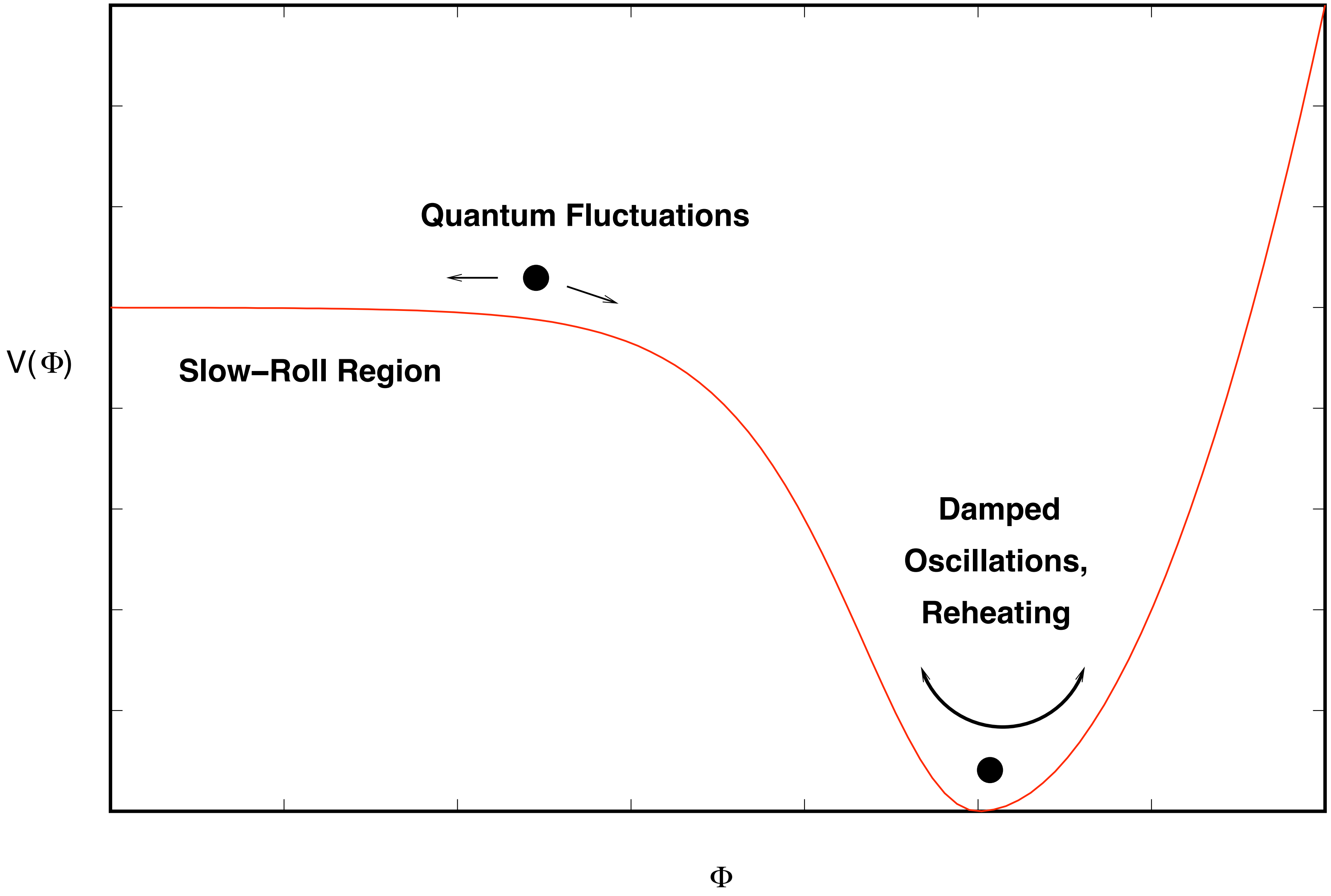
- Recall the electric field E. Energy is stored in the electric field : energy ~ $+E^2/2$. The 2 (oppositely charged) plates are attracted towards each other.
- For gravitational field g, the 2 (same) massive plates are attracted toward each other, so energy is taken away from g: energy ~ - $g^2/2$.
- So gravitational field g yields negative energy.
- Matter + gravitational field energy = matter - $g^2/2$ = 0

Negative energy stored in the gravitational field.



So the total energy of our universe is exactly ZERO.

Dark energy comes from the inflaton potential



The quantum fluctuation resulted in density and temperature fluctuations.

What started the hot big bang ?

The Inflationary Universe Scenario says :

- All matter comes from inflation (converted from dark energy).
- Space was created by inflation.

Alan Guth

Ultimate free lunch 無極生太極？

It solves

- The magnetic monopole problem
- The flatness problem
- The horizon (or homogeneity) problem

The inflationary universe 暴涨宇宙论

- Start with a single point of size 10^{-30} m, with total energy much less than that of a single electron.
- This point could have been a single quantum fluctuation out of absolute Nothing.
- This point grows exponentially in the inflationary phase, to 10^{-35} second.
- At the end of inflation, almost all of the dark energy converts to radiation and matter, starting the hot big bang.
- The size of an apple then expanded to our observable universe today.
- Our observable universe is only a tiny fraction (of size 10^{-20}) of the whole universe from the original point.

The general theoretical picture of the inflationary universe was completed by 1983.

- Many cosmologists embrace it. Many hate it. Overtime, more and more accept it.
- E.g., Steve Hawking considers the evidence for inflation to be overwhelming.
- Some very vocal objections to it, e.g., Roger Penrose believes inflation is totally unlikely.
- One of the founding leaders of inflation, Paul Steinhardt, became its sharpest critic in recent years.

走火入魔

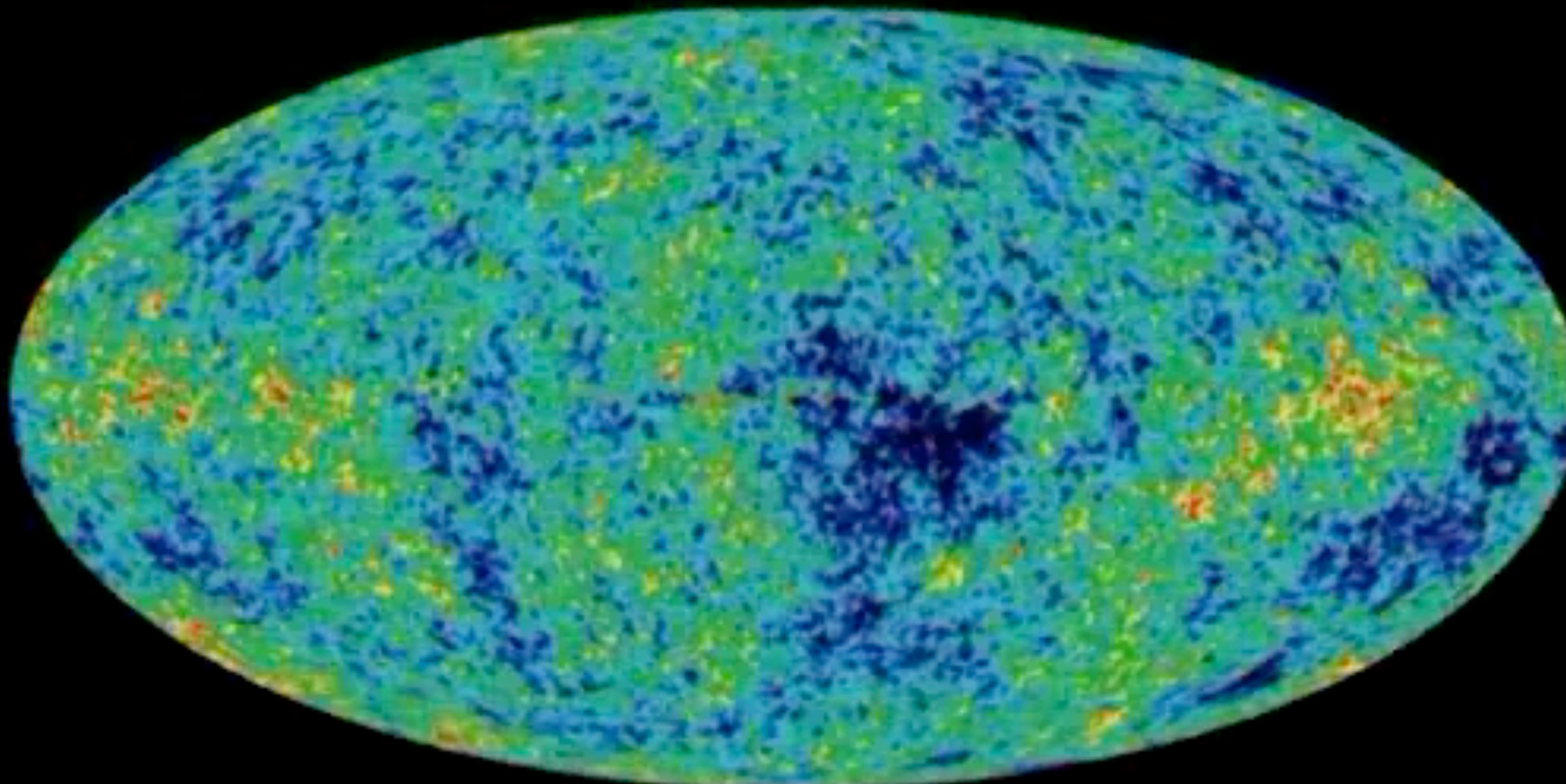
The general theoretical picture was essentially completed by 1983.

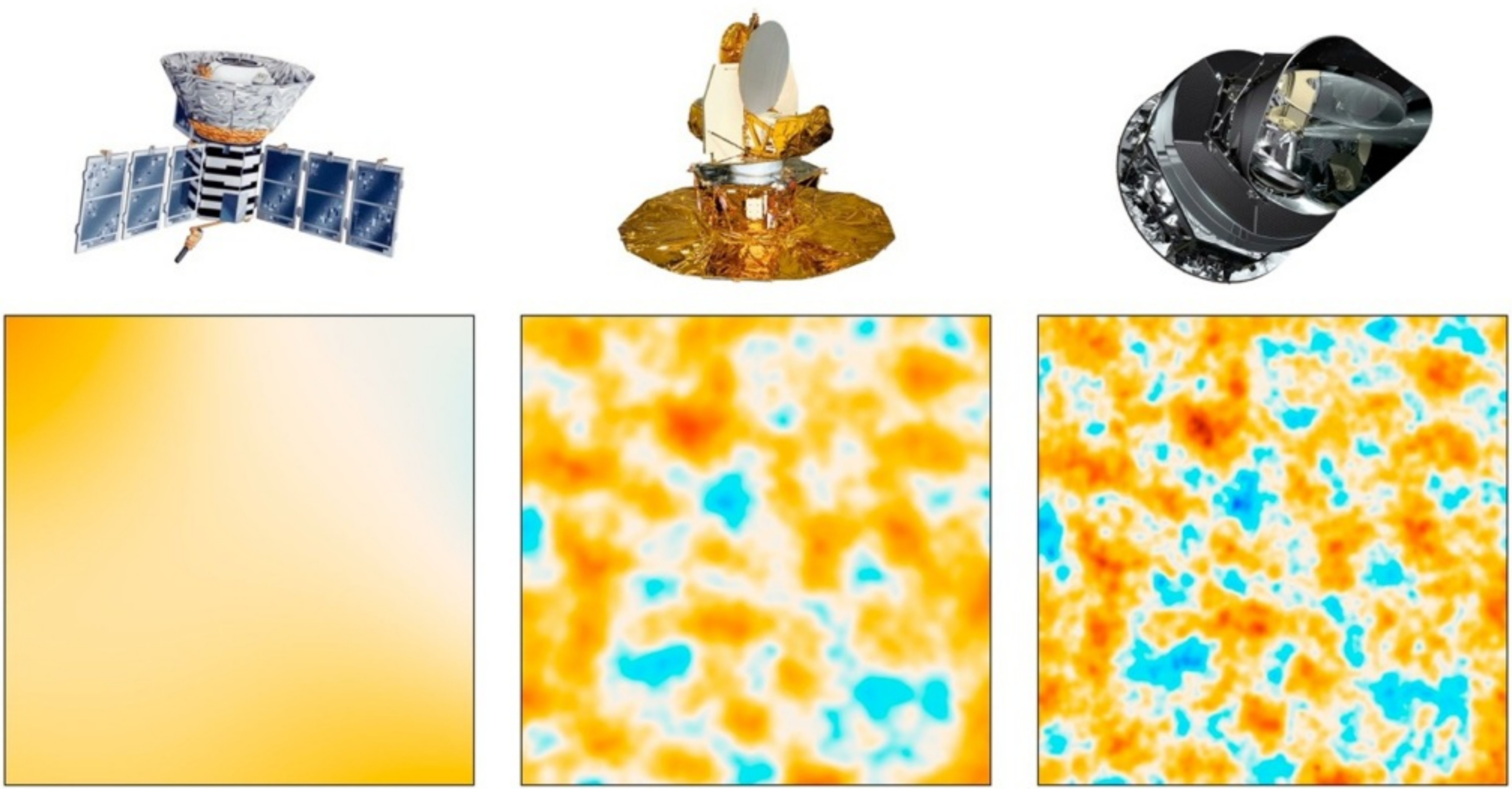
Quantum fluctuations during inflation led to fluctuations in density and temperature.

This fluctuation will eventually lead to star and galaxy formation.

The temperature fluctuations was first observed by the COBE satellite in 1992.

2.7260^0K to 2.7261^0K

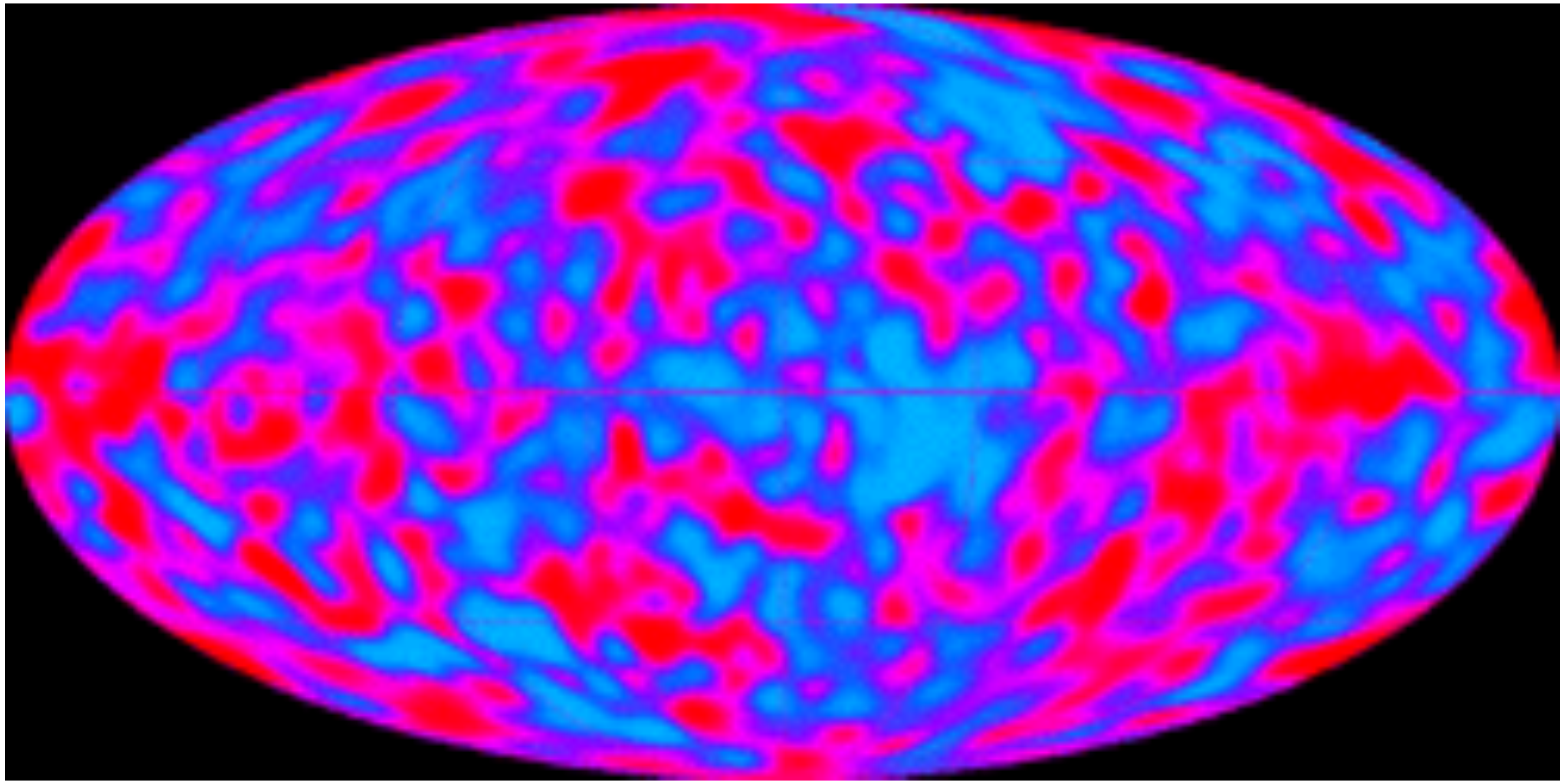




COBE 1993

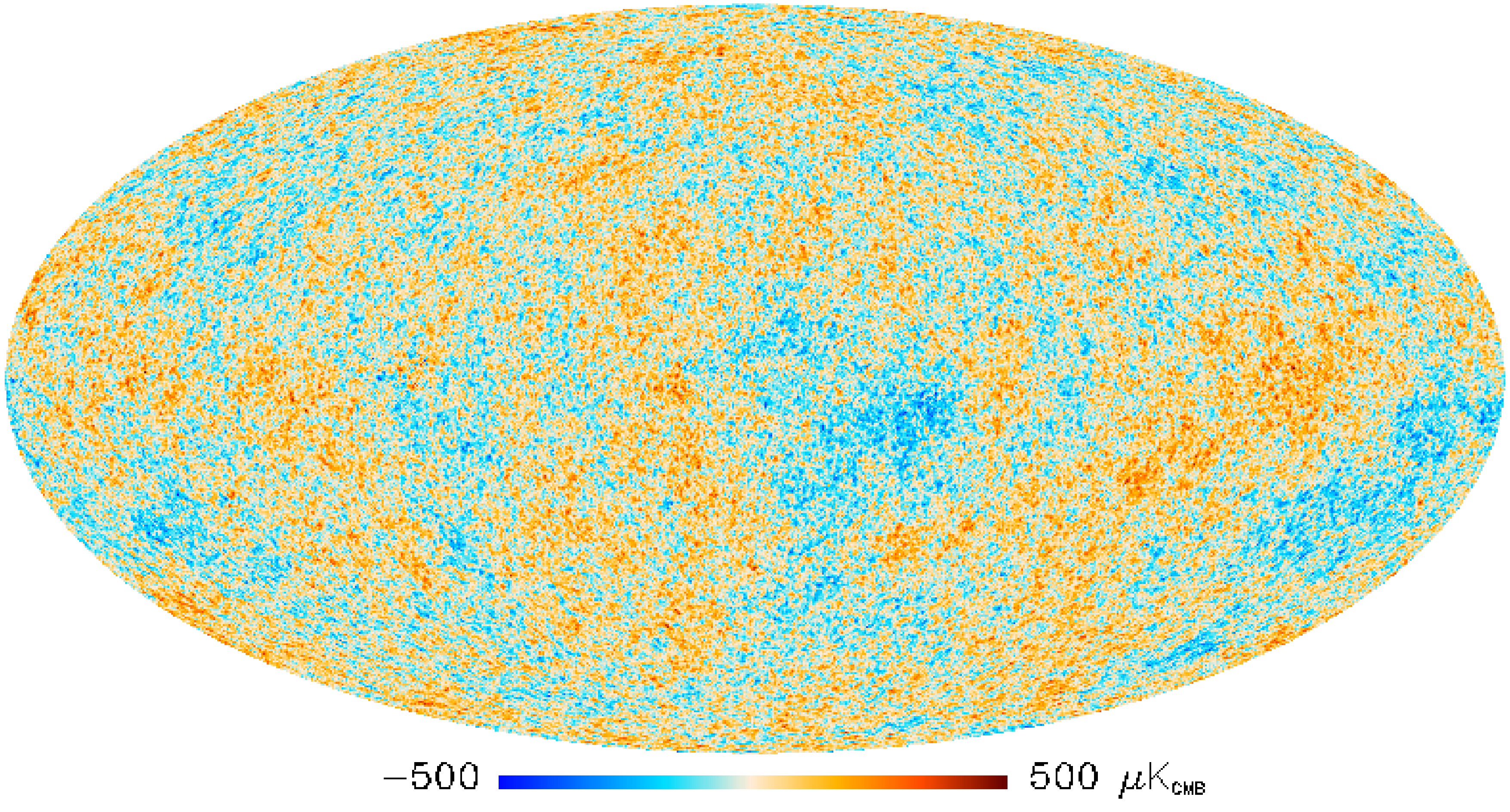
WMAP 2005

Planck 2013



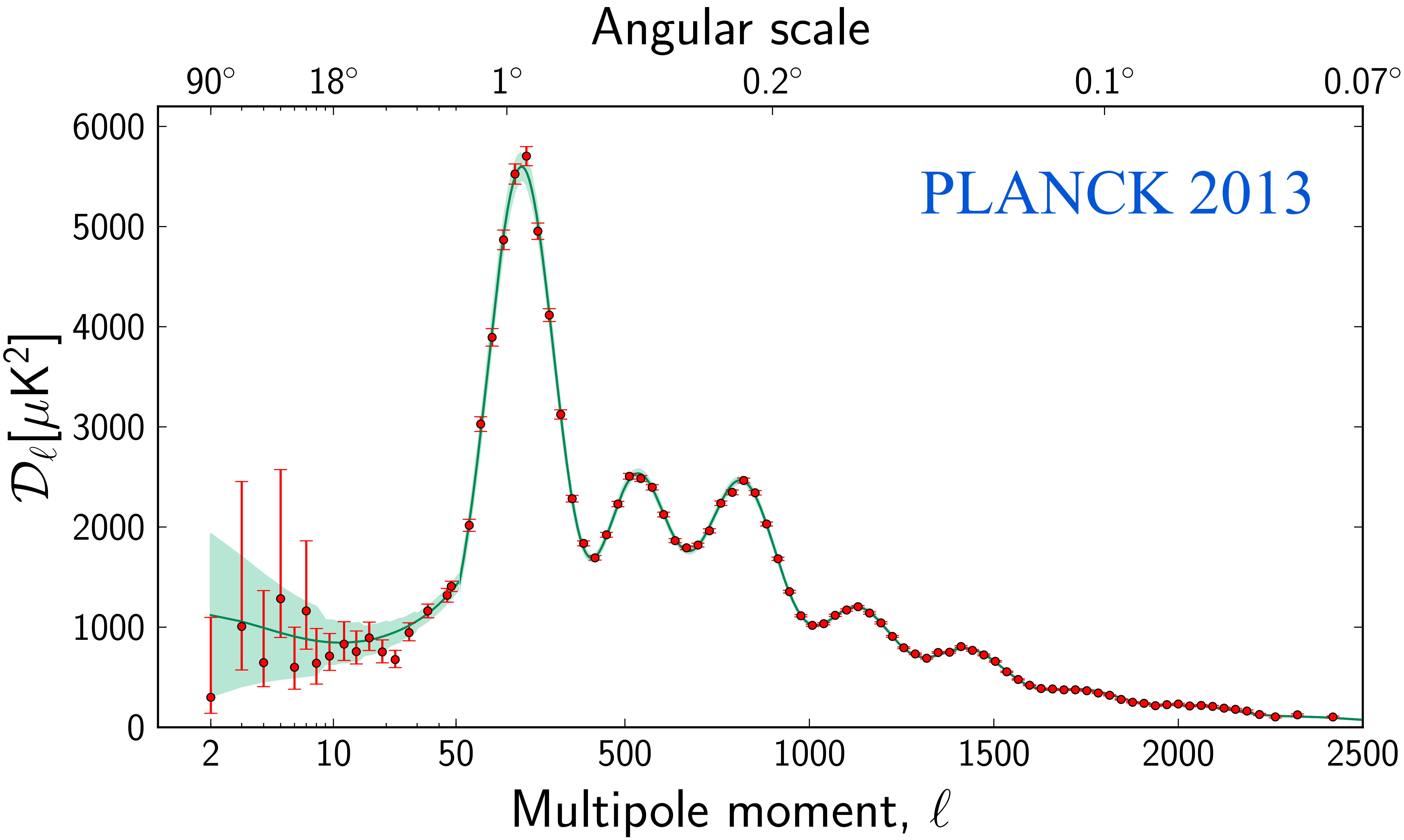
COBE 1992

George Smoot,
Nobel 2006

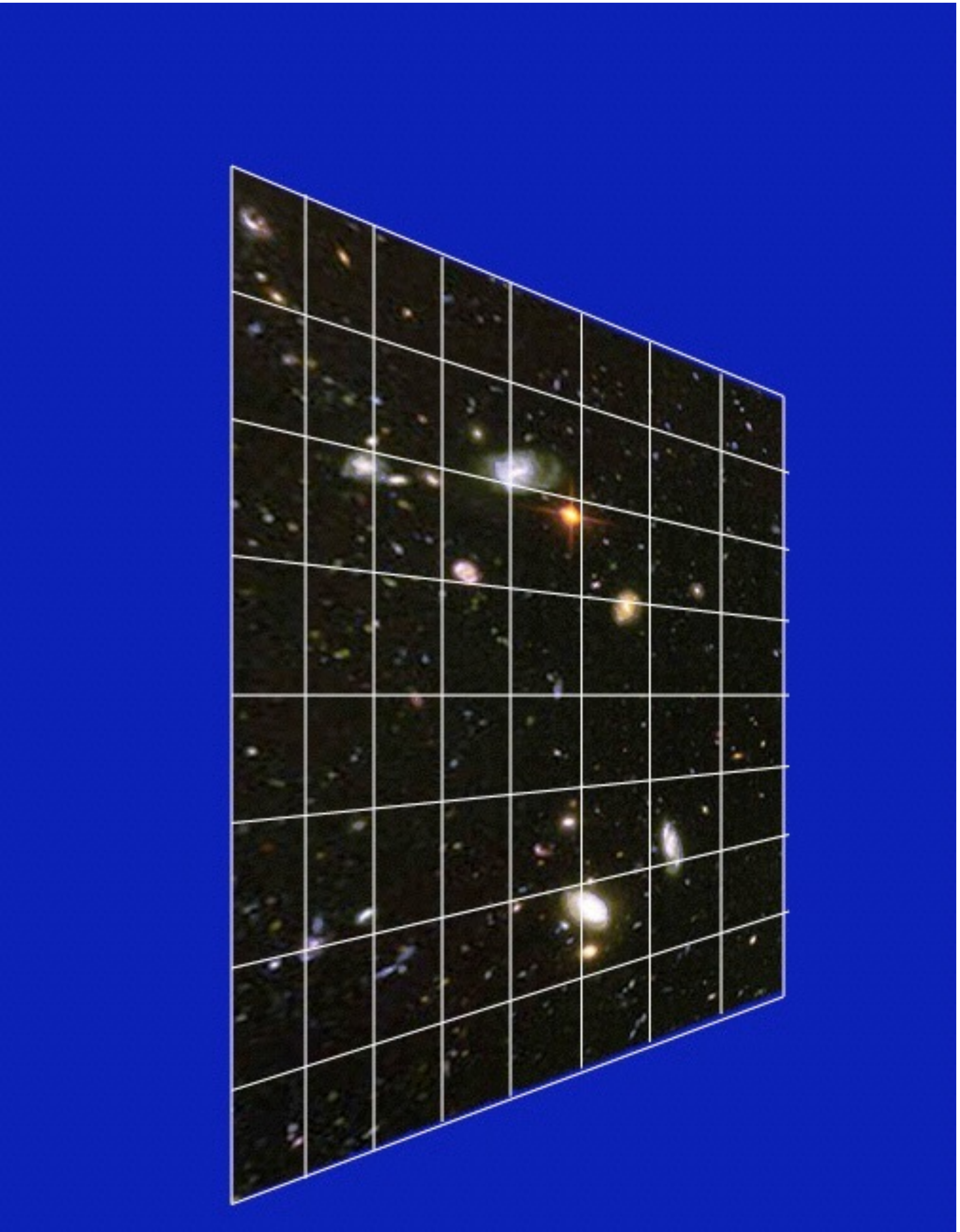


Planck 2013

Inflation predicts quantum fluctuation that creates a density fluctuation which seeds the galaxy formation. This leads to a temperature fluctuation that can be measured and tested.



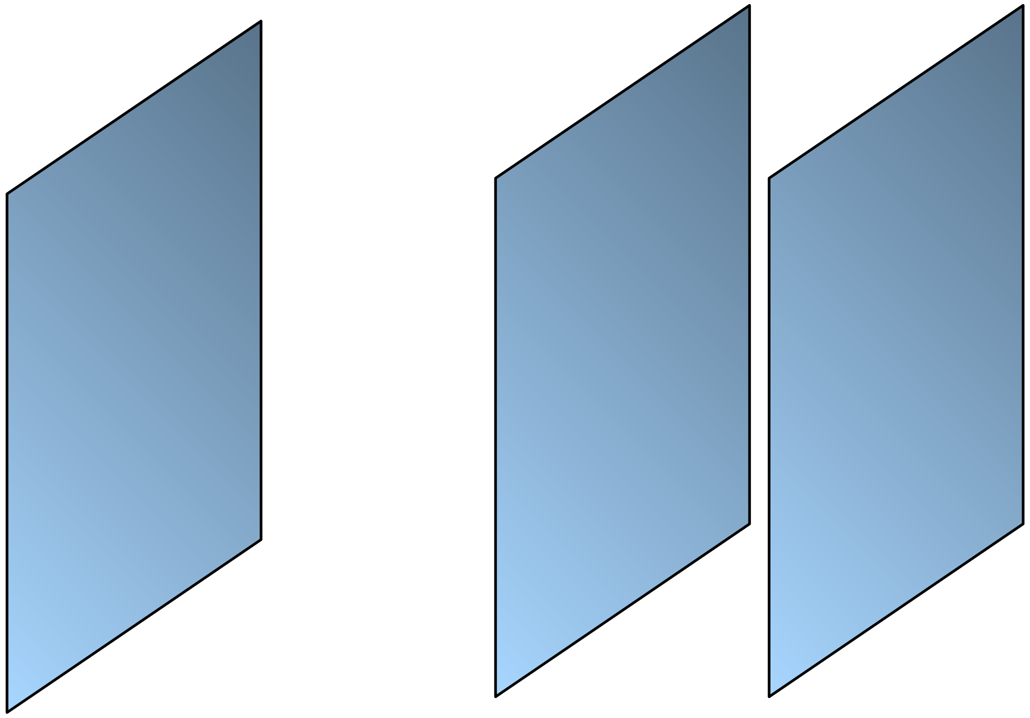
String Theory → Brane World



Extra dimensions

We live in a 3-brane,
with 3 spatial dimensions

Brane Inflation



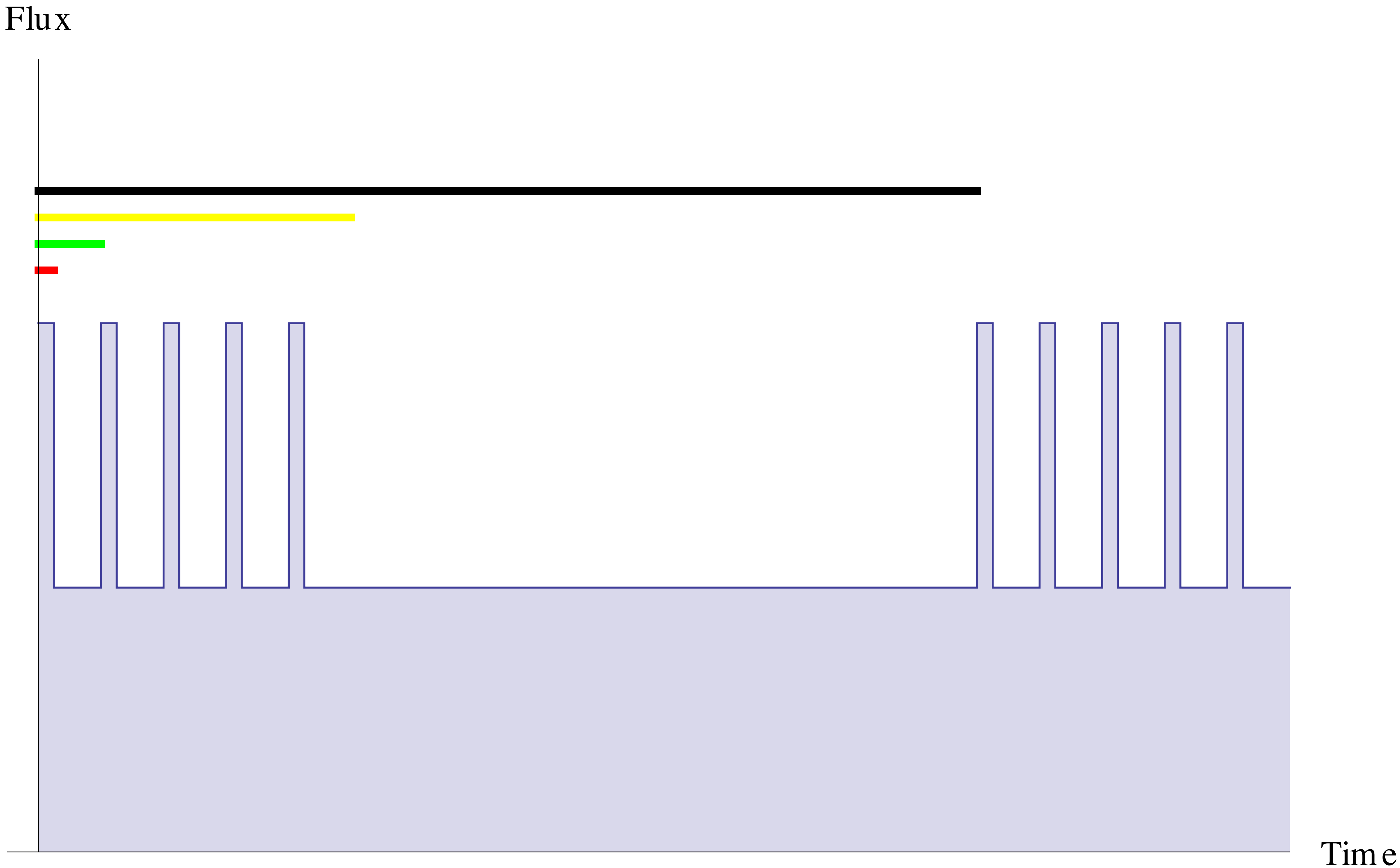
Multiverse ~
multiple universes

In string theory:

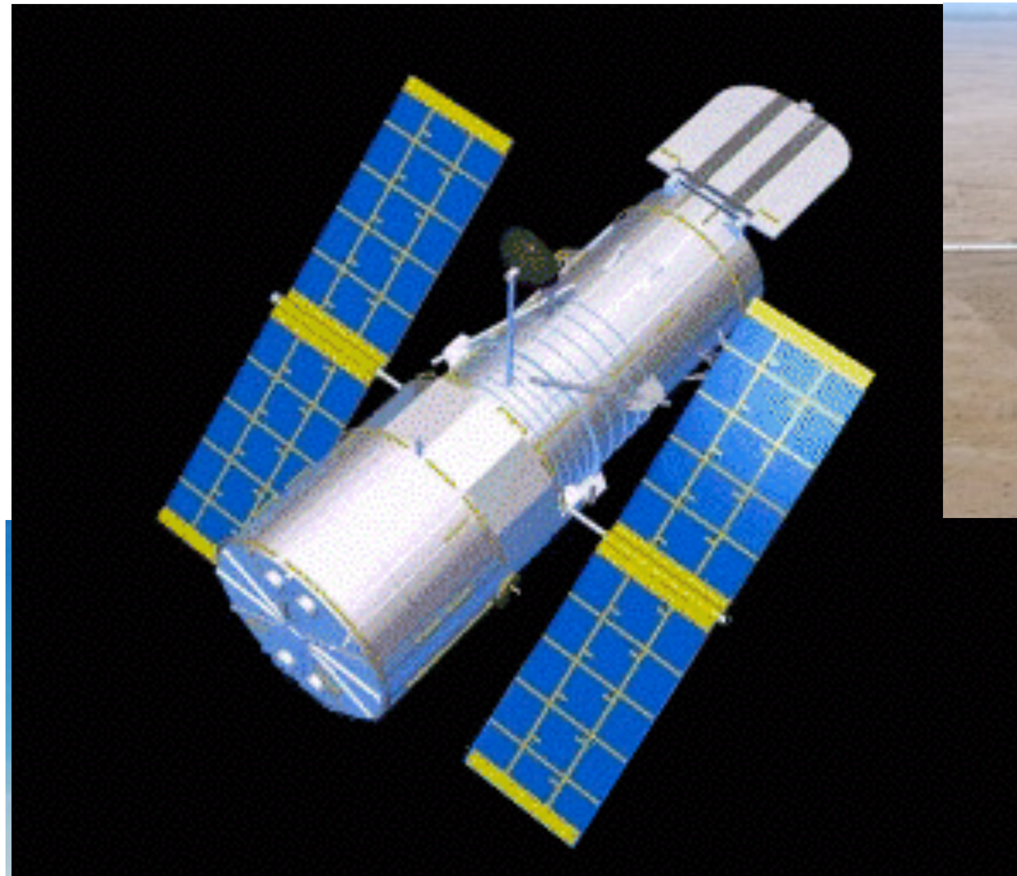
Strings $\Rightarrow$ Cosmic strings

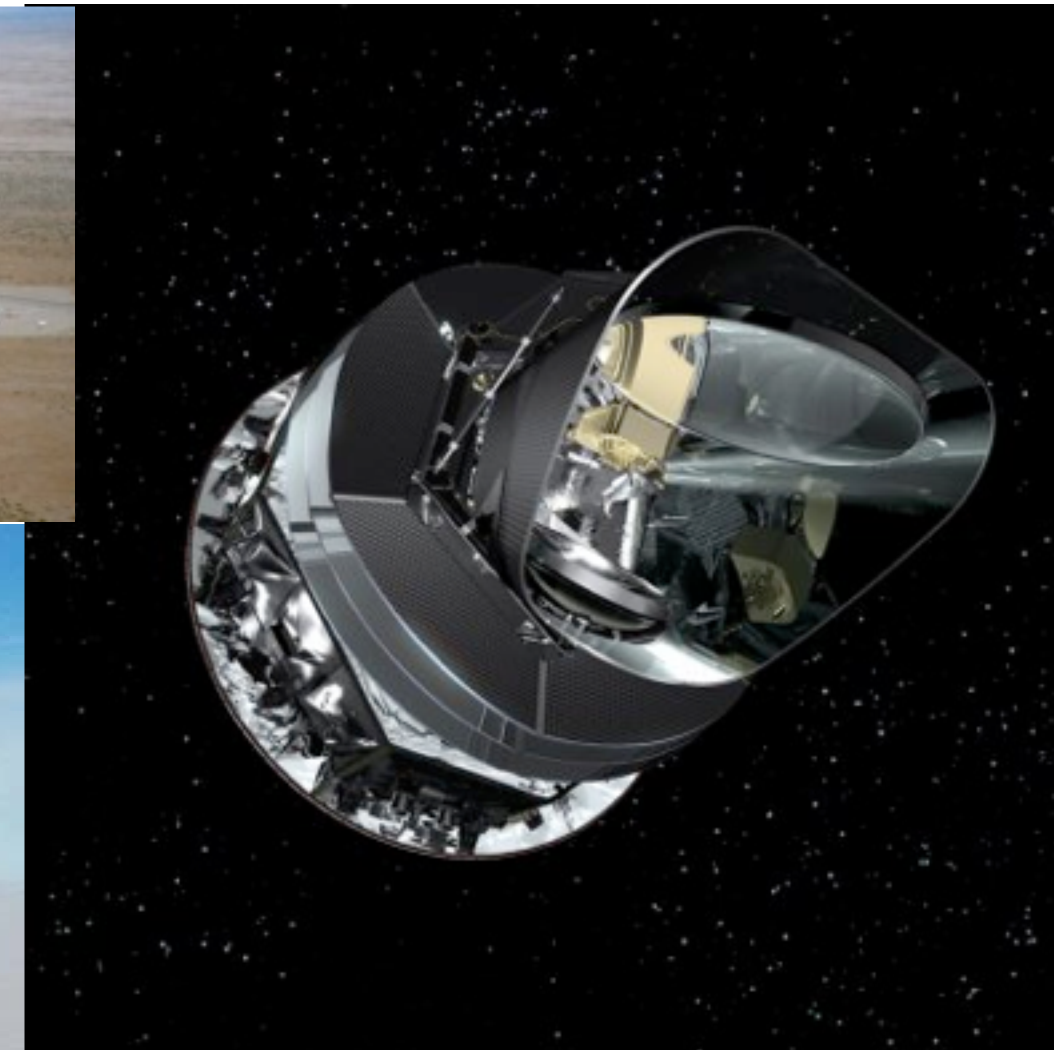
- Due to warped geometry, cosmic strings can have different tensions and spectra.
- Small tension cosmic strings decay slowly, so they can cluster, just like dark matter.
- They can micro-lens stars, which may be detected in the coming years.

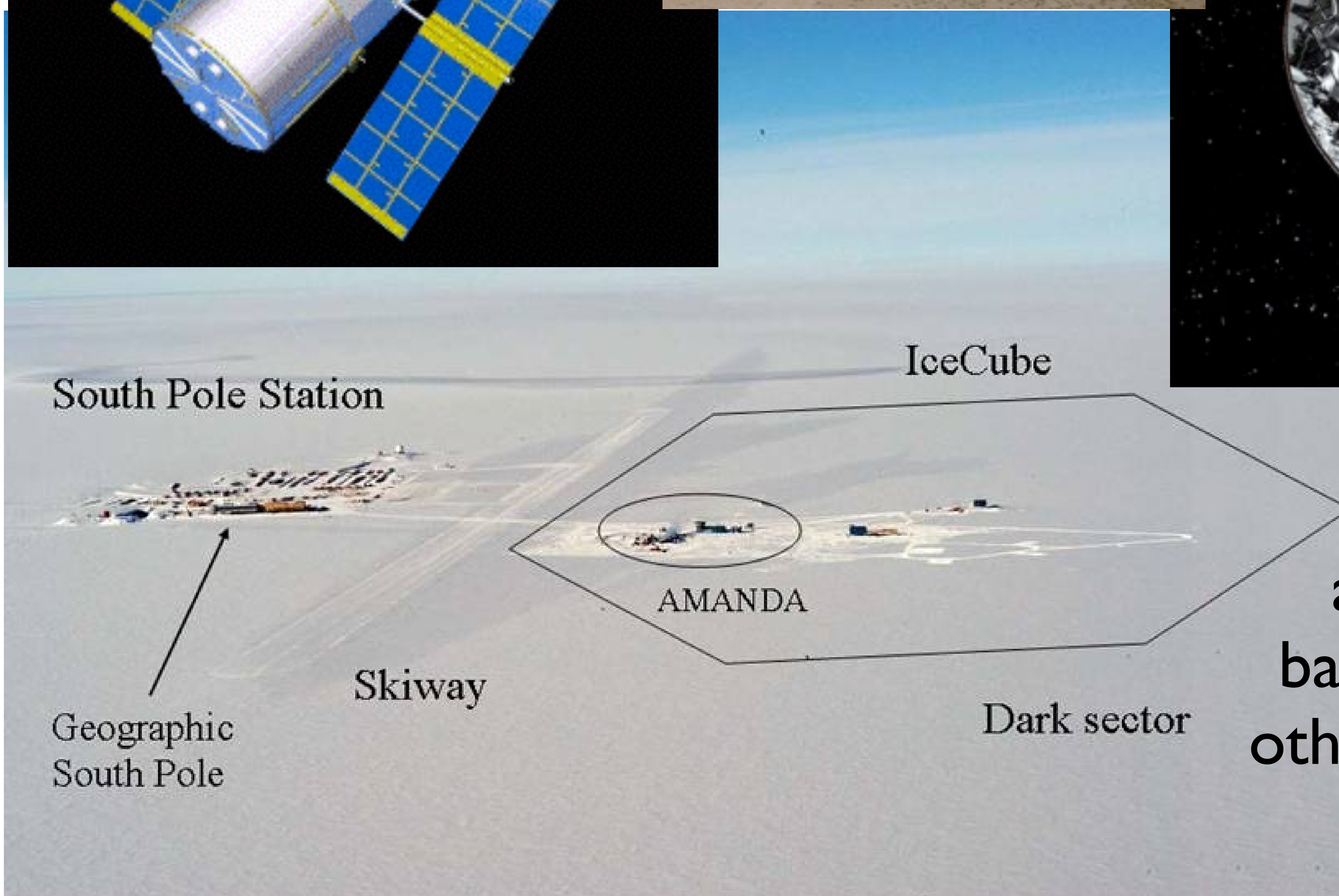
A typical microlensing signal of a star by a moving cosmic string



Many ways to study the universe

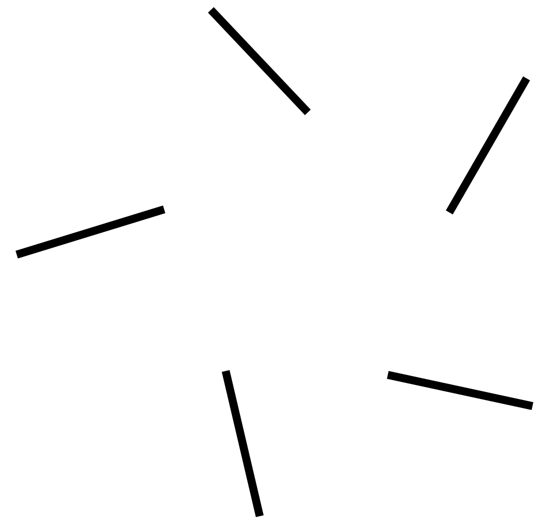




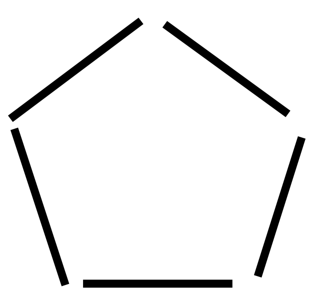


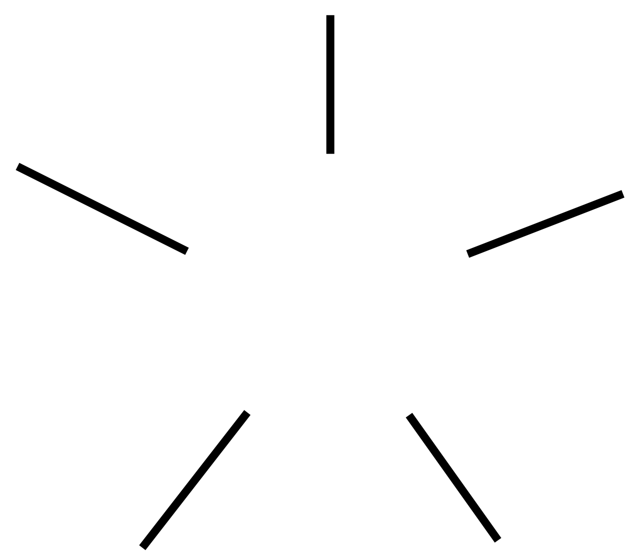
and many ground based telescopes and other detectors as well as satellites

Fluctuation of space-time

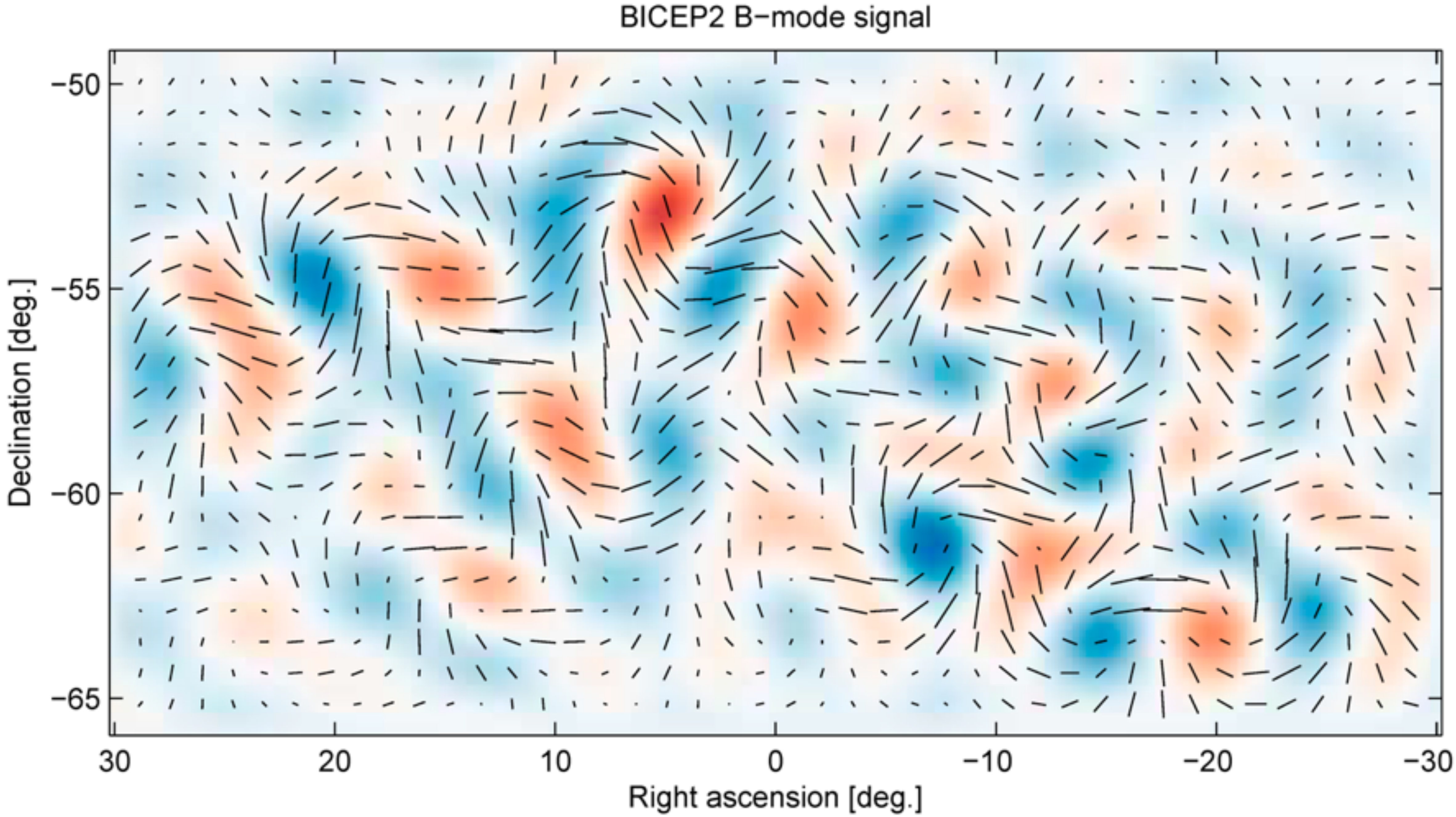


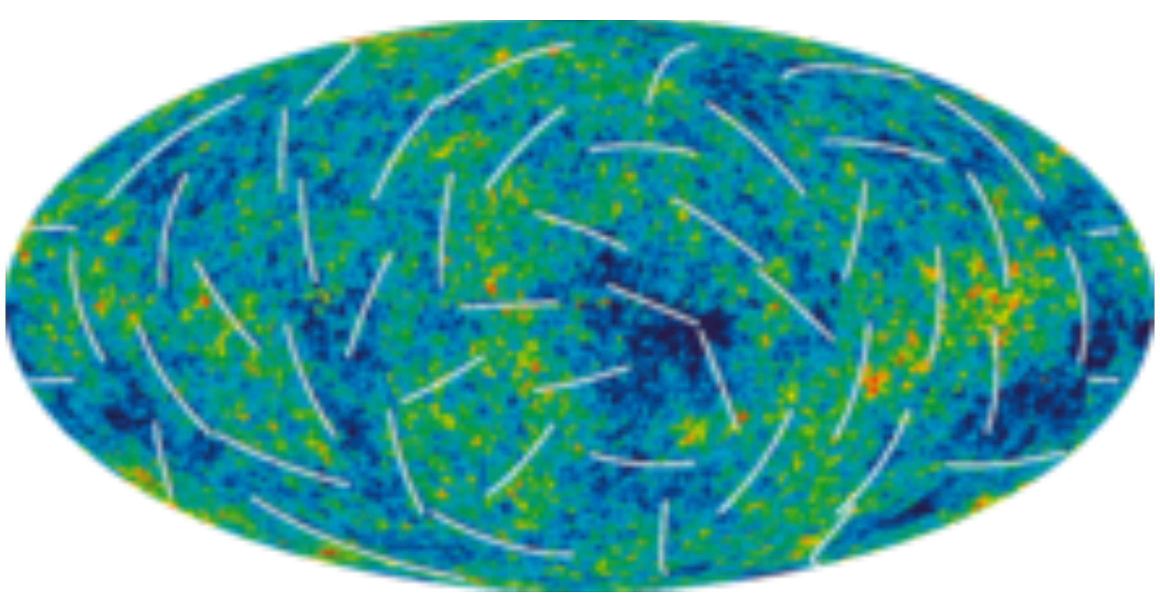
B-mode



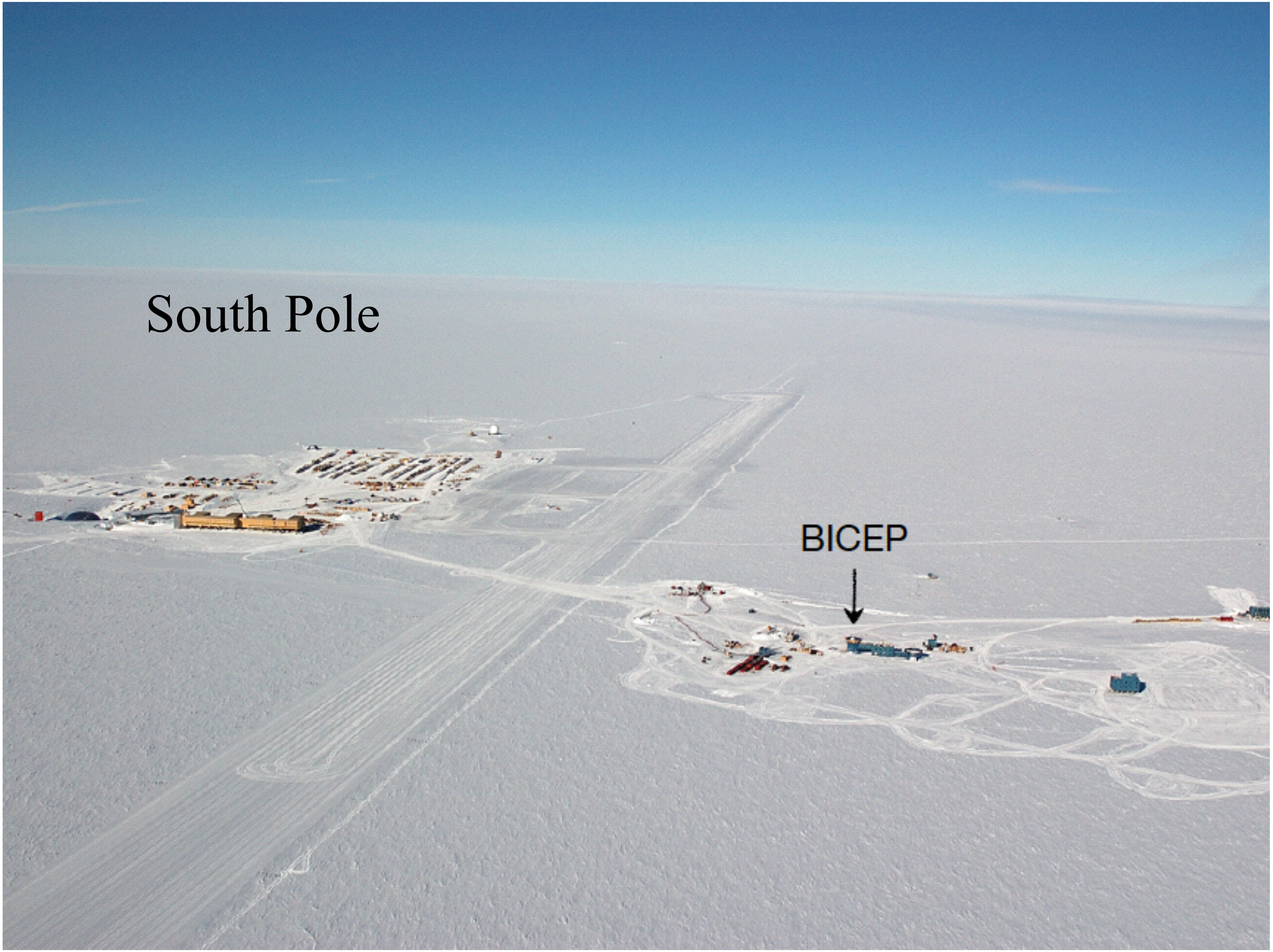


E-mode





The red and blue shading shows the degree of clockwise and anti-clockwise twisting of this B-mode pattern.


South Pole
BICEP

Why the B-mode polarization is important ?

- Inflation predicts the existence B-mode polarization with a well determined spectrum.
- "Alternative to inflation" models predict none.
- It comes from the quantum fluctuation of space-time. So this will confirm that space-time is also quantized.

Other experiments, PLANCK, ACT, PolarBeaR, SPT, SPIDER, QUEIT, Clover, EBEX, QUaD..., will have a lot of data coming soon, so we should wait for confirmation and more detail.

It has been very exciting in cosmology in the past century. More exciting discoveries are expected in the coming years.

THANKS