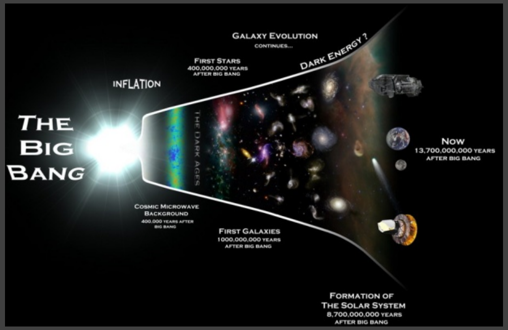
Early Universe Cosmology: A Primer

Mairi Sakellariadou

KING'S College LONDON



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  Sun: 5 billion years
  Oldest stars: ~ 13 billion years

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- The Universe is very big; the most distant objects we can see are at about 100,000,000,000,000,000,000,000 miles away, which is about 30 billion light-years

  Light travels at 186,000 miles per second -> in a year light travels 6 trillion miles
  The Sun is 8 light-minutes away from the Earth

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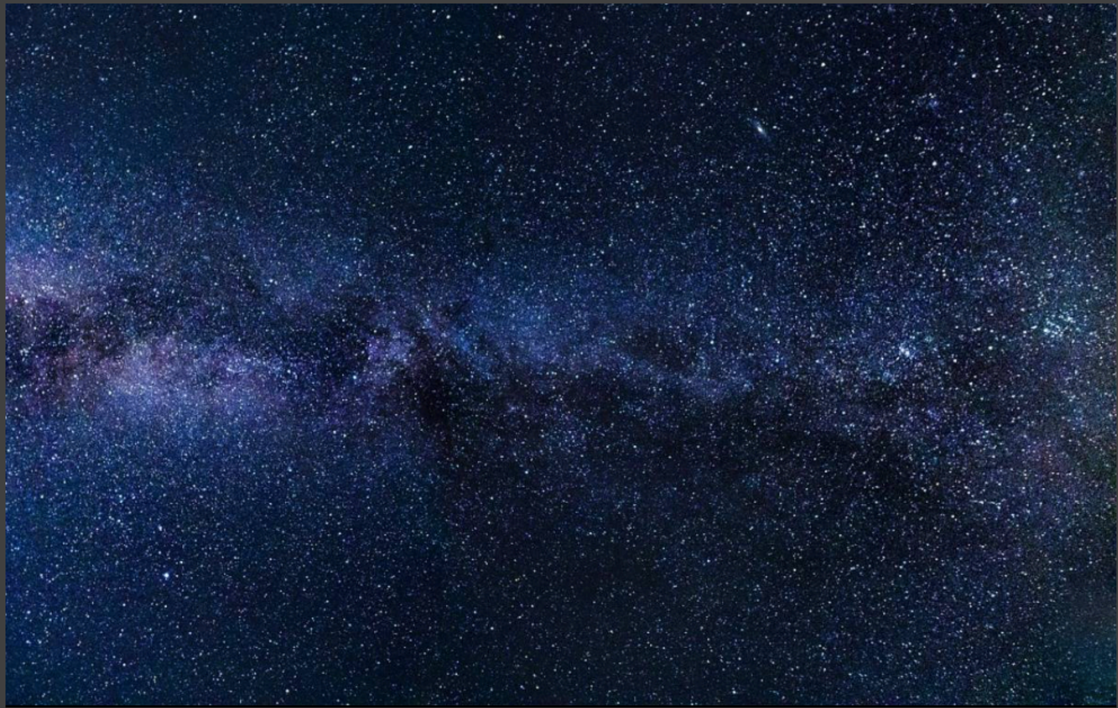
To answer these questions, we use Einstein's theory of General Relativity and the precise experimental and observational tools of the 21st century

From the Milky Way (our plane of observation), all galaxies seem to move away from each other with a speed that is proportional to their distance



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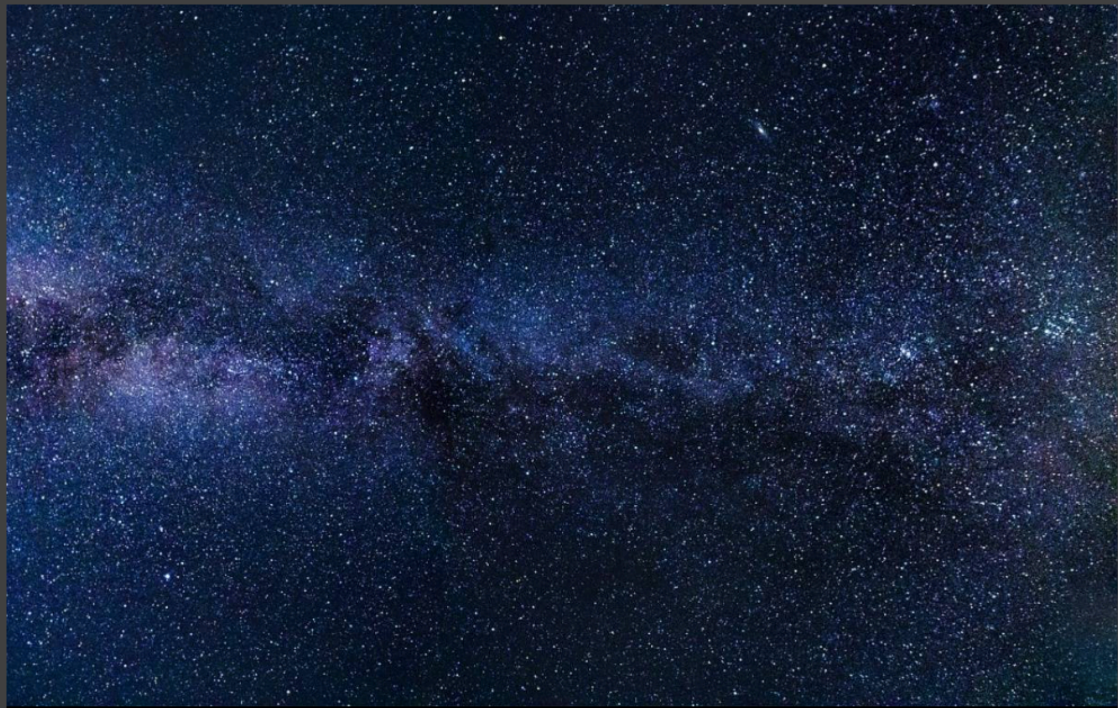

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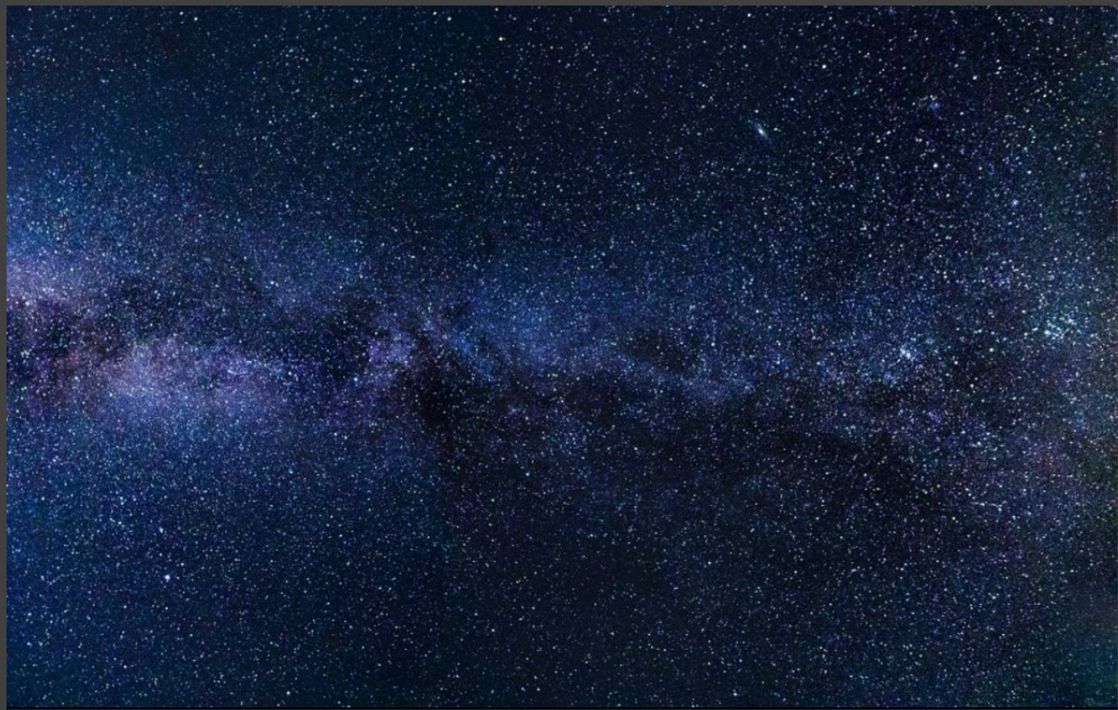

Every particle attracts every other particle in the universe with a force that is proportional to the product of their masses and inversely proportional to the square of the distance between their centres

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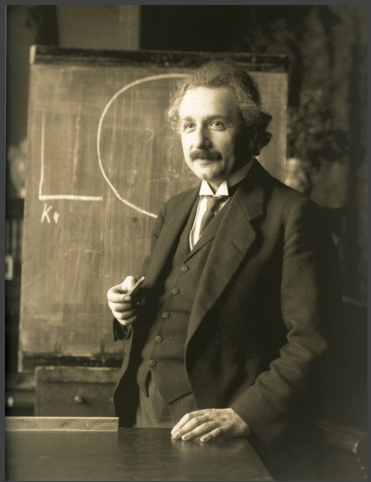
The Universe according to Einstein's theory of General Relativity



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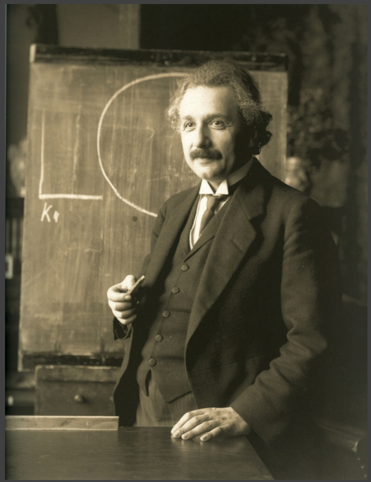
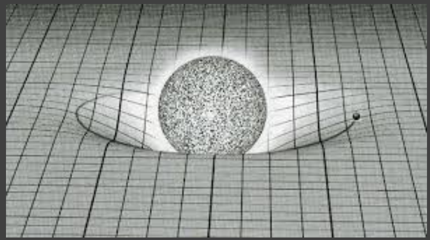


A larger mass or energy density of the Universe leads to a higher spatial curvature and vice versa



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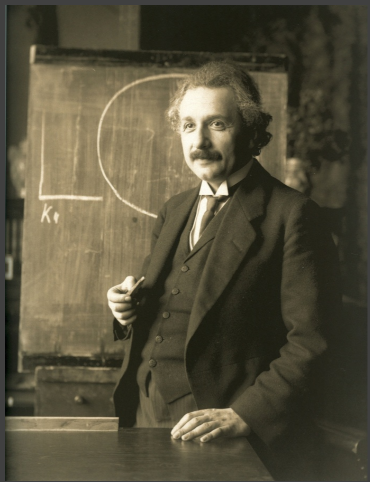

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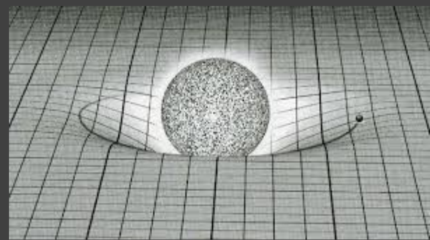

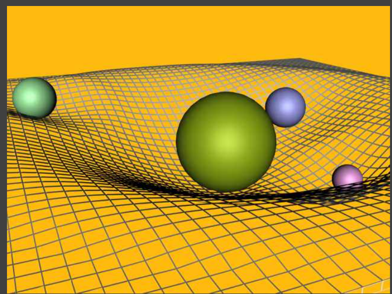

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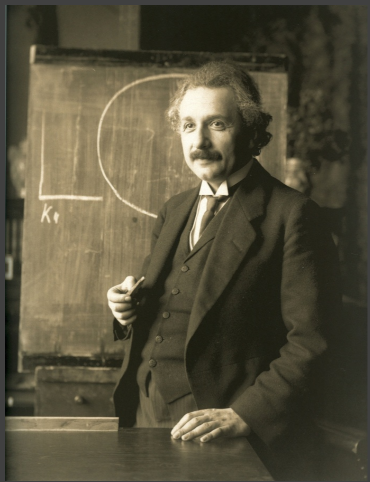

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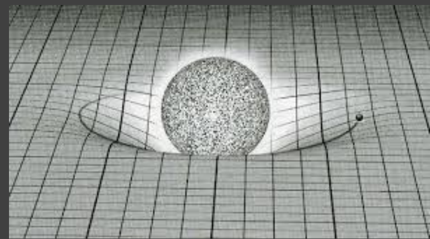

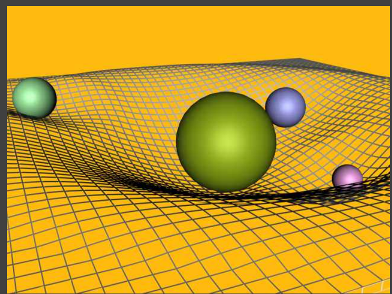

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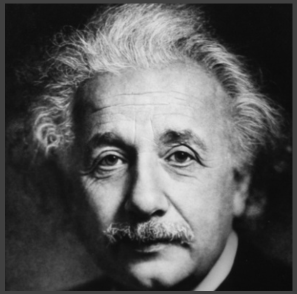
Space- time has an invisible structure that determines how we move

We perceive this structure as the force of gravity

General Relativity (GR) - 1915

is the description of warps in space-time



NASA's GPB mission, launched in April 2004,
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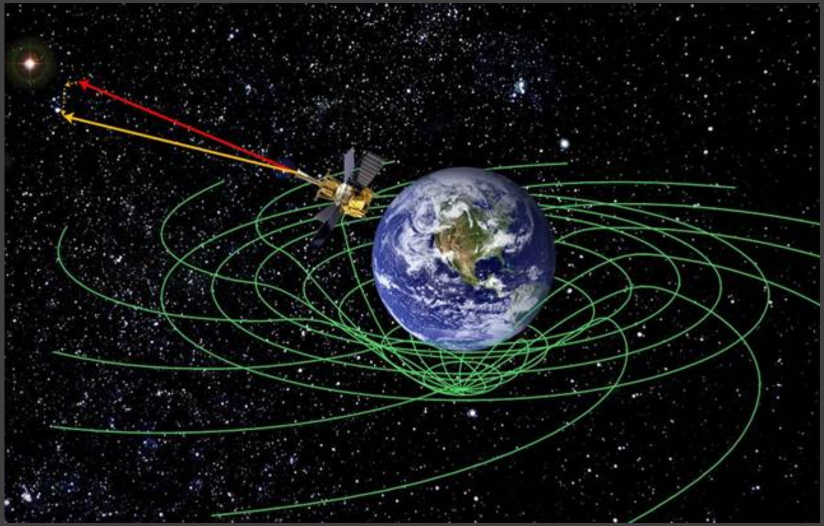

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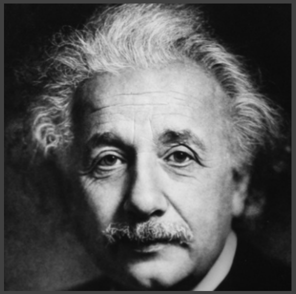

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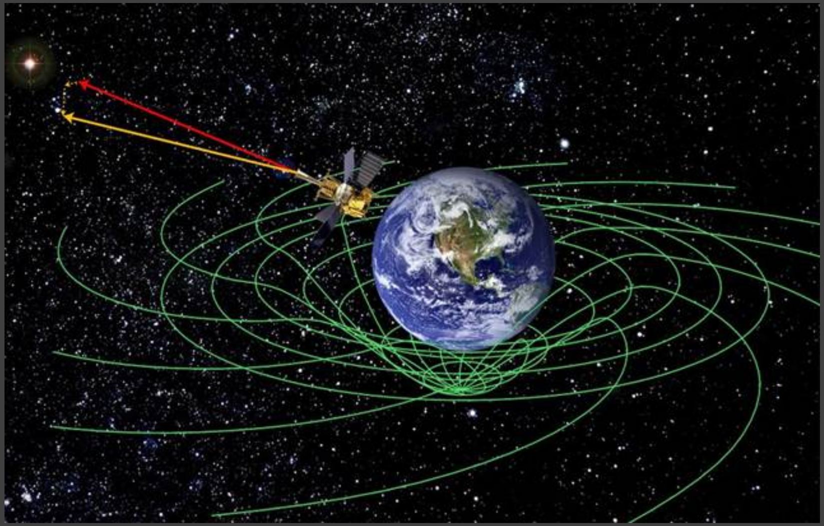

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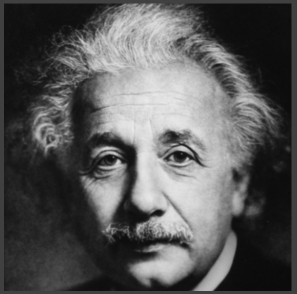

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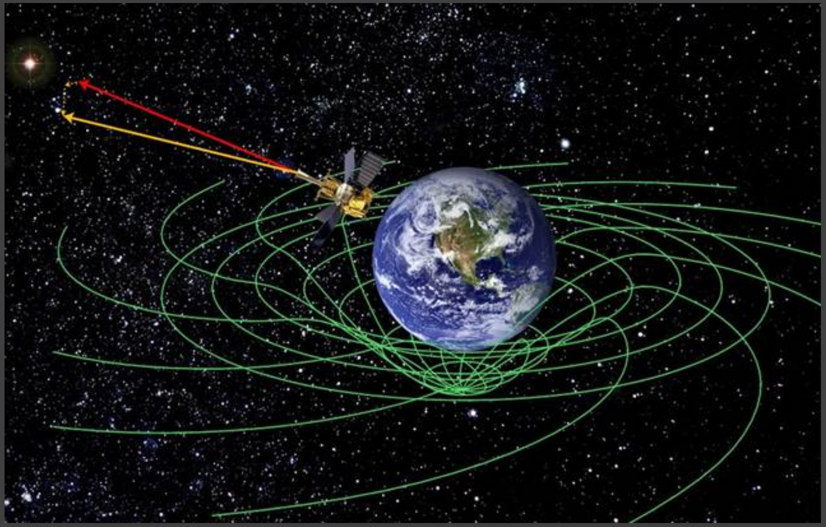
- The amount of space-time the Earth (a spinning body) pulls with it as it rotates



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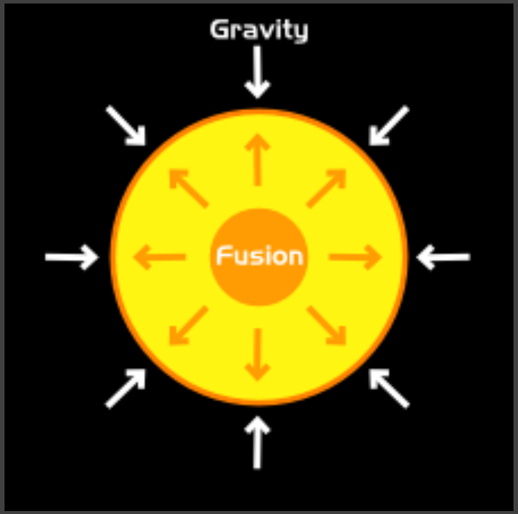

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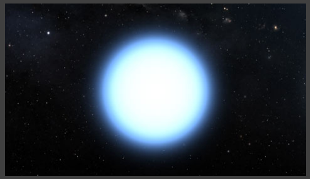
- mass comparable to the Sun
- radius about 0.01 radius of the Sun



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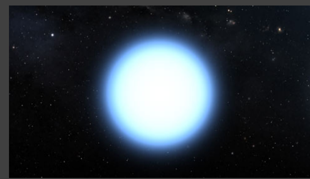
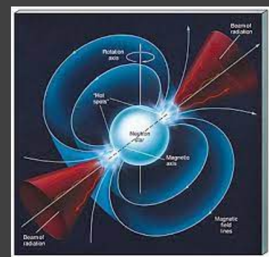


between 10 and 20 solar masses: neutron star
- mass 1.4 solar masses and radius about 10-20 km
- *a teaspoon of neutron star material would weigh around a billion tonnes*
- *magnetic field about trillion times Earth's*
- surface gravity > 100 billion times Earth's
- *spins up to 700 times a second*, so 60 million times faster than Earth



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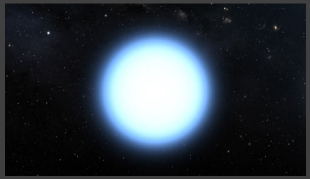

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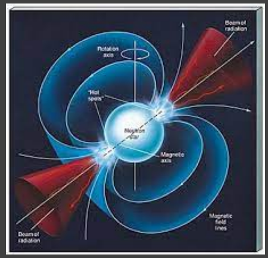

greater that 20 solar masses: black hole

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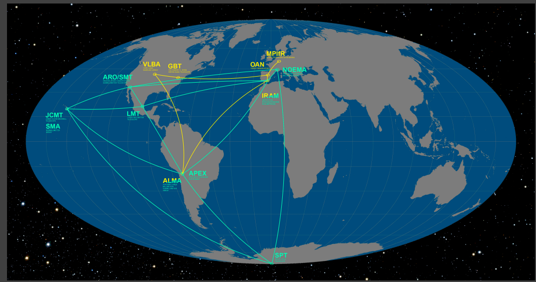

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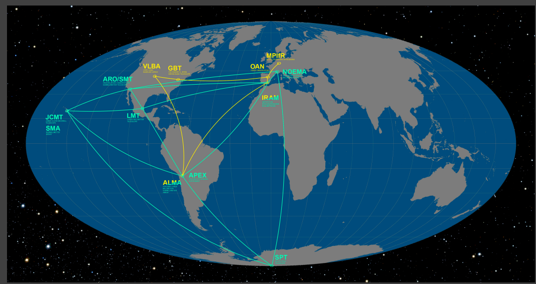

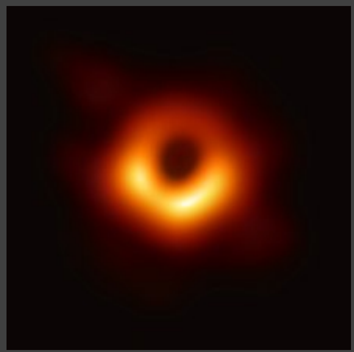

10 April 2019: first images of a supermassive black hole M87*(6 billion solar masses, at 54 million light years away from the Earth) at the centre of the galaxy M87

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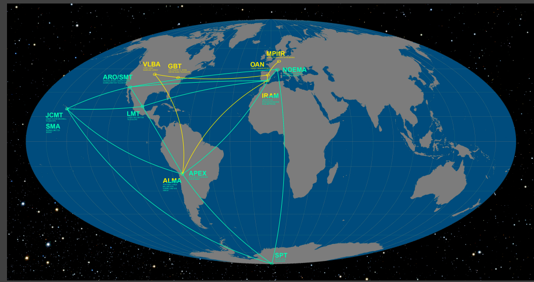

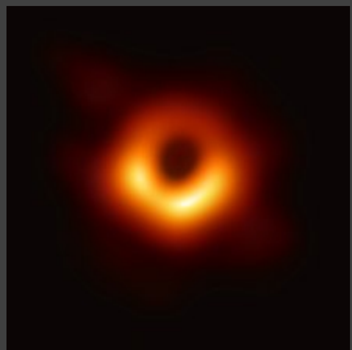

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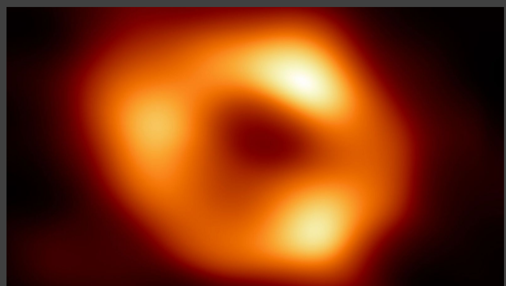
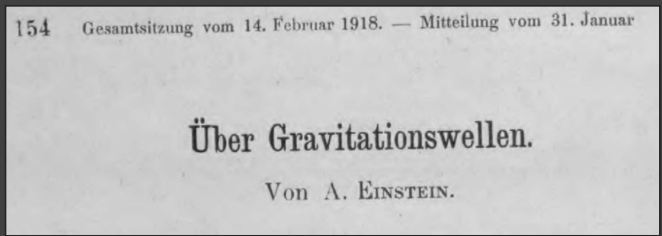


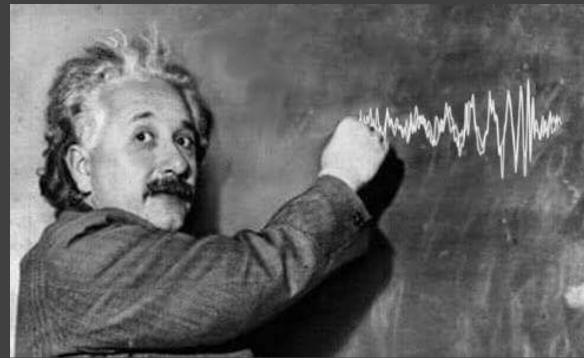
12 May 2022: images of a supermassive black hole Sagittarius A* (4 million solar masses, at 26000 light years away from the Earth) at the centre of our galaxy

1916: Einstein's paper on linear approximation to GR predicting gravitational waves


154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

Über Gravitationswellen.

Von A. Einstein.



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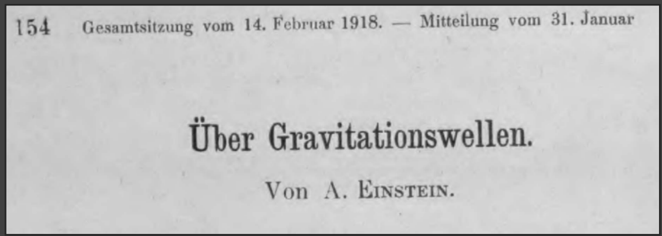
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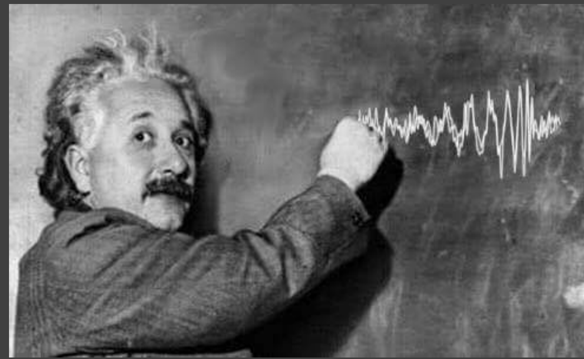

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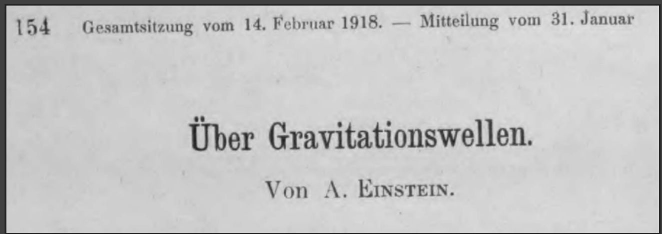
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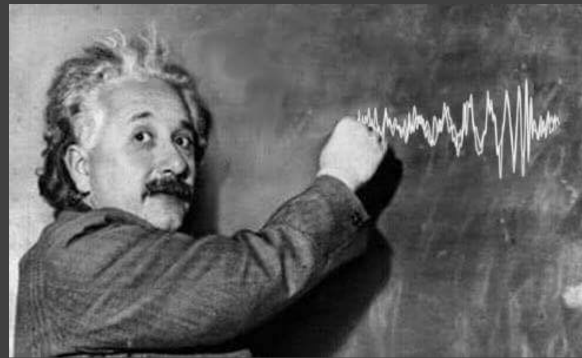

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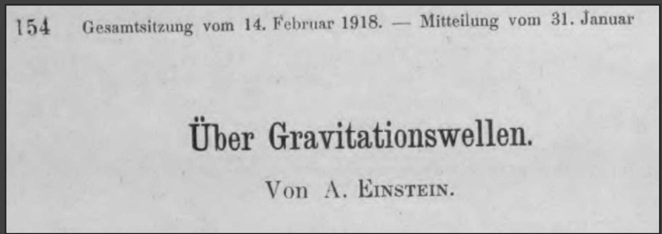
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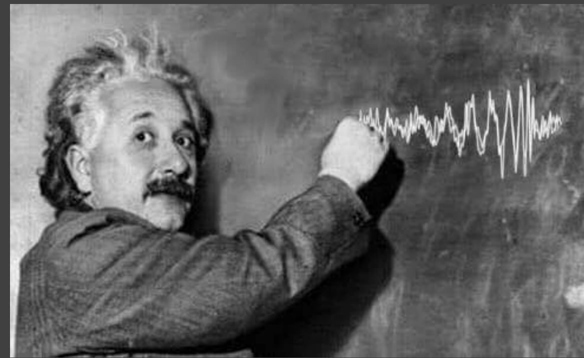

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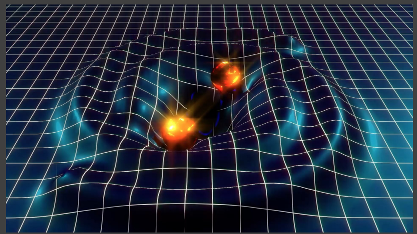
- These cosmic ripples would travel at the speed of light, carrying with them information about their origins

Ultimate test of Einstein's theory of General Relativity



On September 14, 2015, the twin LIGO interferometers physically sensed the undulations in spacetime caused by gravitational waves (GWs) generated by two colliding black holes 1.3 billion light-years away

GW150914

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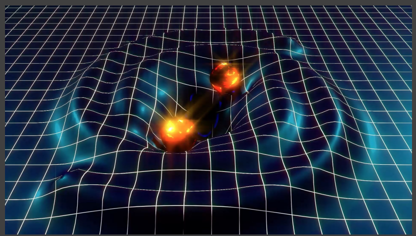

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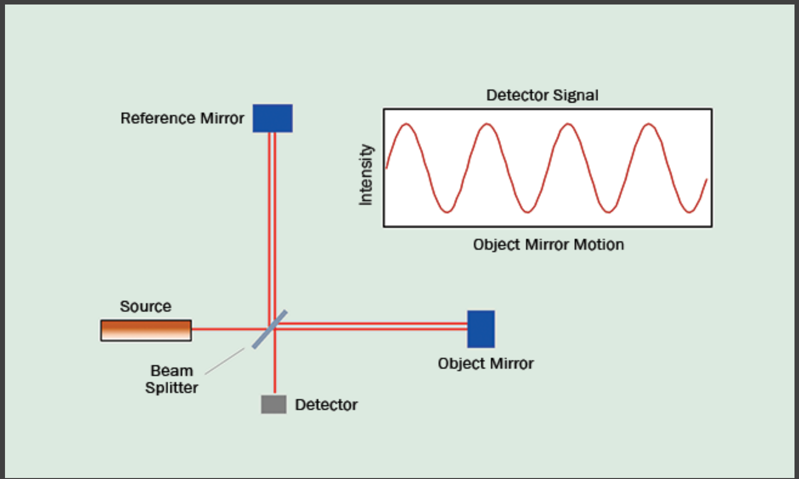

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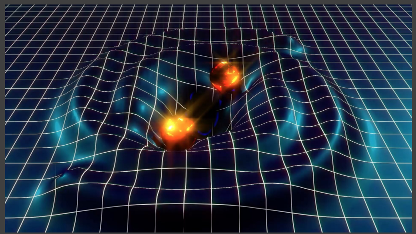

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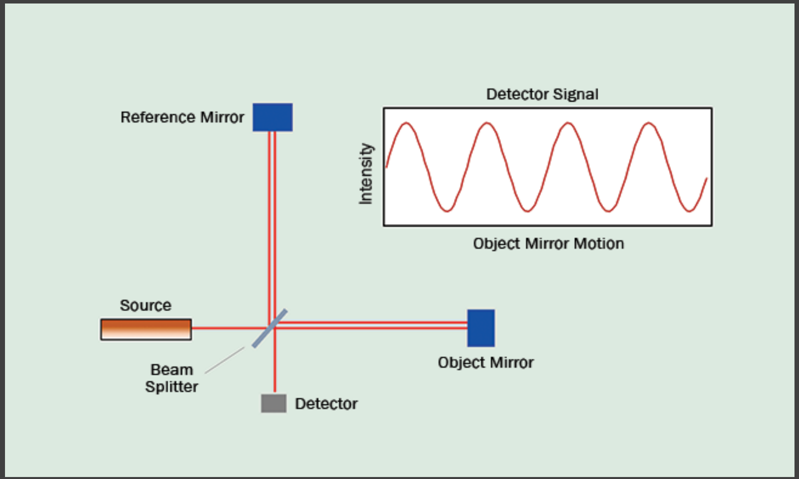
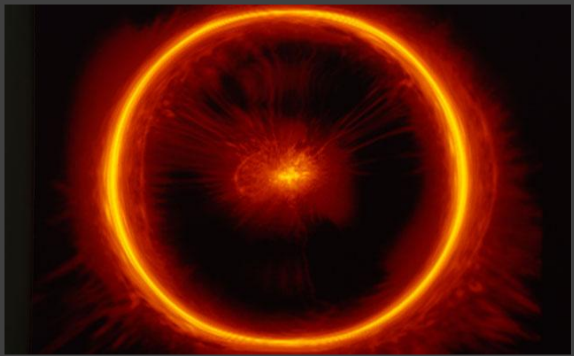


The GW power radiated by GW150914 was more than ten times greater than the combined luminosity of every star and galaxy in the Universe

The GWs travelled about 1.3 billion years to arrive to the Earth where it produced a tiny (1/1000 of the diameter of a proton) vibration of spacetime

How was created the Universe?

According to General Relativity at a finite time in the past the Universe must have been in a state of ultra-high curvature and density



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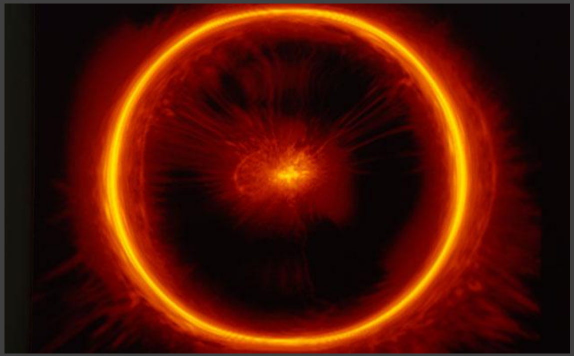

Big Bang theory:
13.8 billion years ago, matter and energy of today's Universe were confined to a space of a subatomic speck

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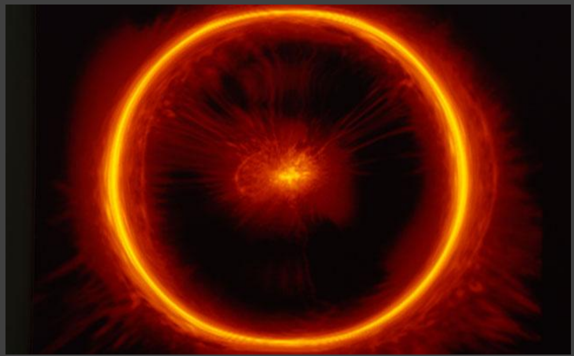

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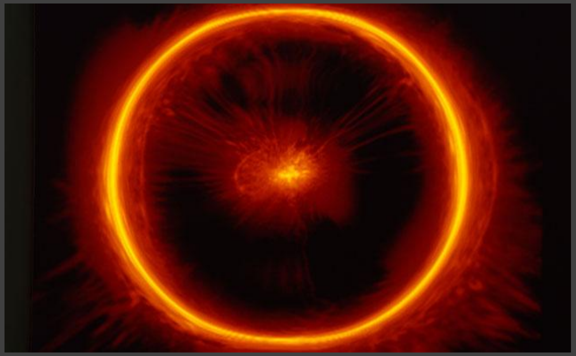

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The cosmological singularity is unavoidable in General Relativity:

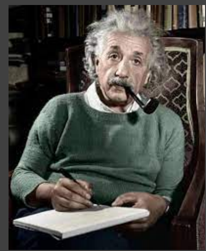
- How did the Universe come into being?
- What was there before the Big Bang?
- Is the singularity real or our theory is incomplete?

There are two fundamental theories in physics:

Quantum Mechanics

behaviour and position of atoms and sub-atomic particles becomes uncertain; certainties become probabilities

and General Relativity



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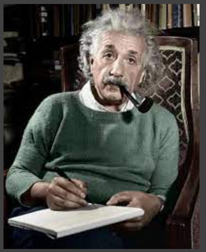

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They seem to be incompatible with each other

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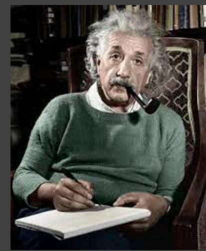
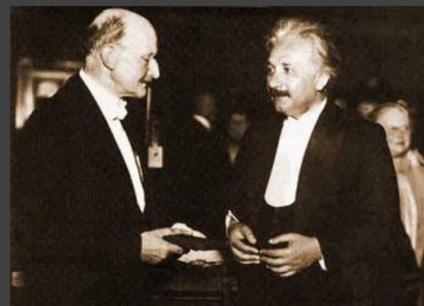
behaviour and position of atoms and sub-atomic particles becomes uncertain; certainties become probabilities

and General Relativity



They seem to be incompatible with each other

However, there are some situations where we have to use both theories simultaneously: we need a theory of Quantum Gravity



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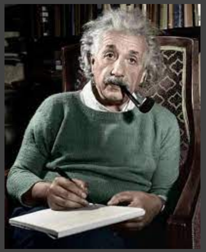

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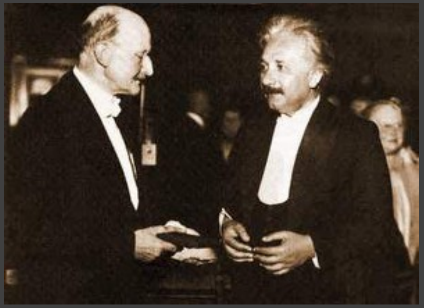


To study the centre of black holes and the early cosmological ear near the Big Bang, we need a theory that is both relativistic and quantum

How does the Universe evolve?

Cosmological principle:

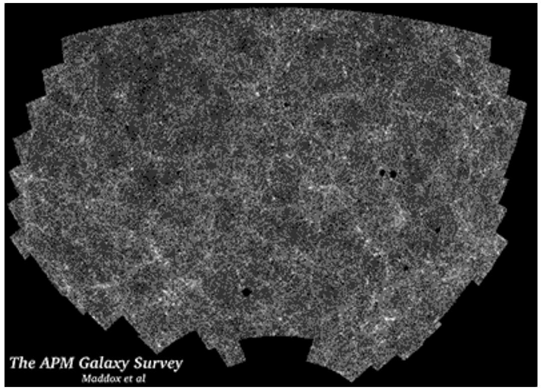
The Universe is homogeneous and isotropic on large scales.

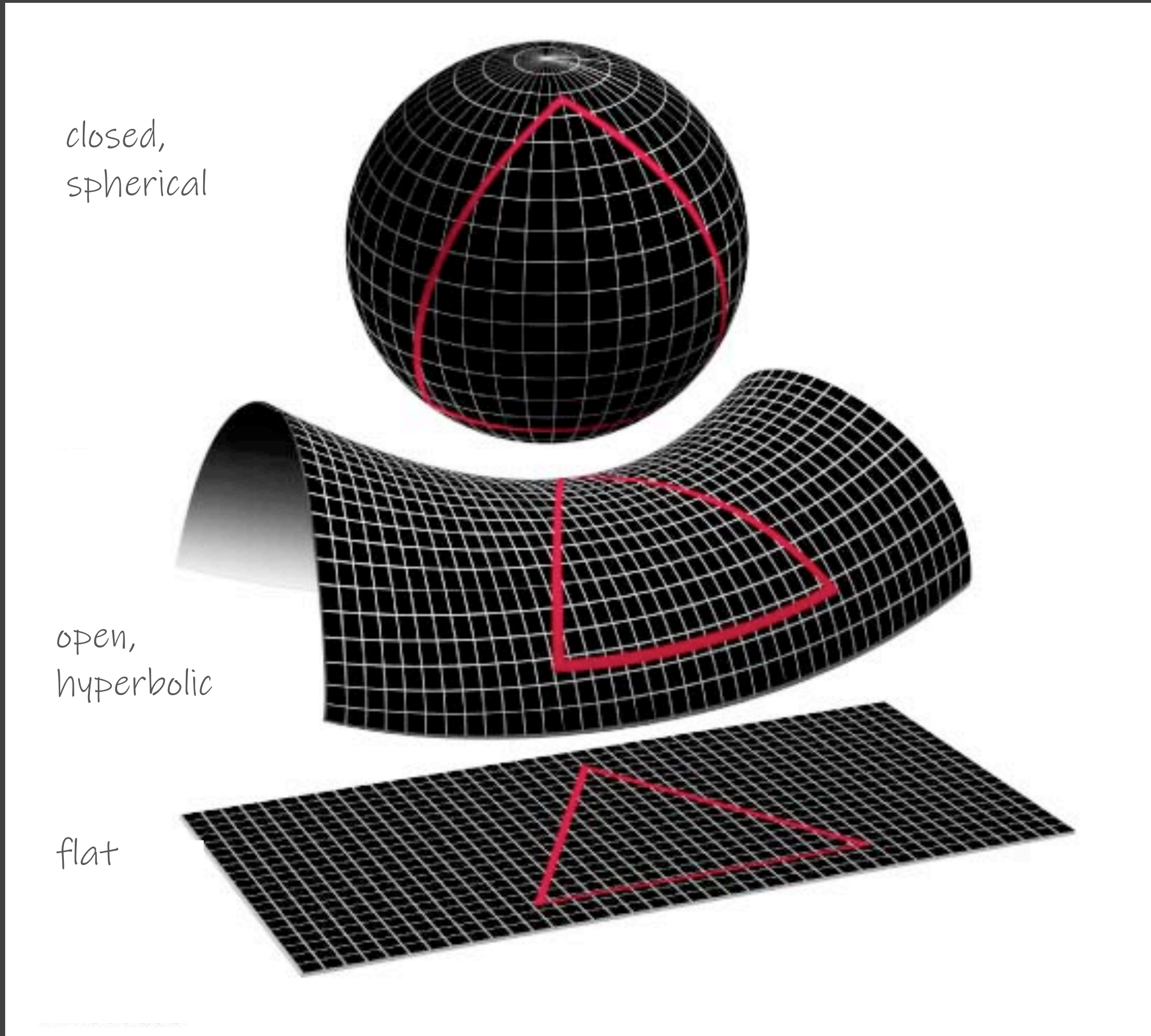
Homogeneity:The physical conditions are the same at every point of any given hypersurface.

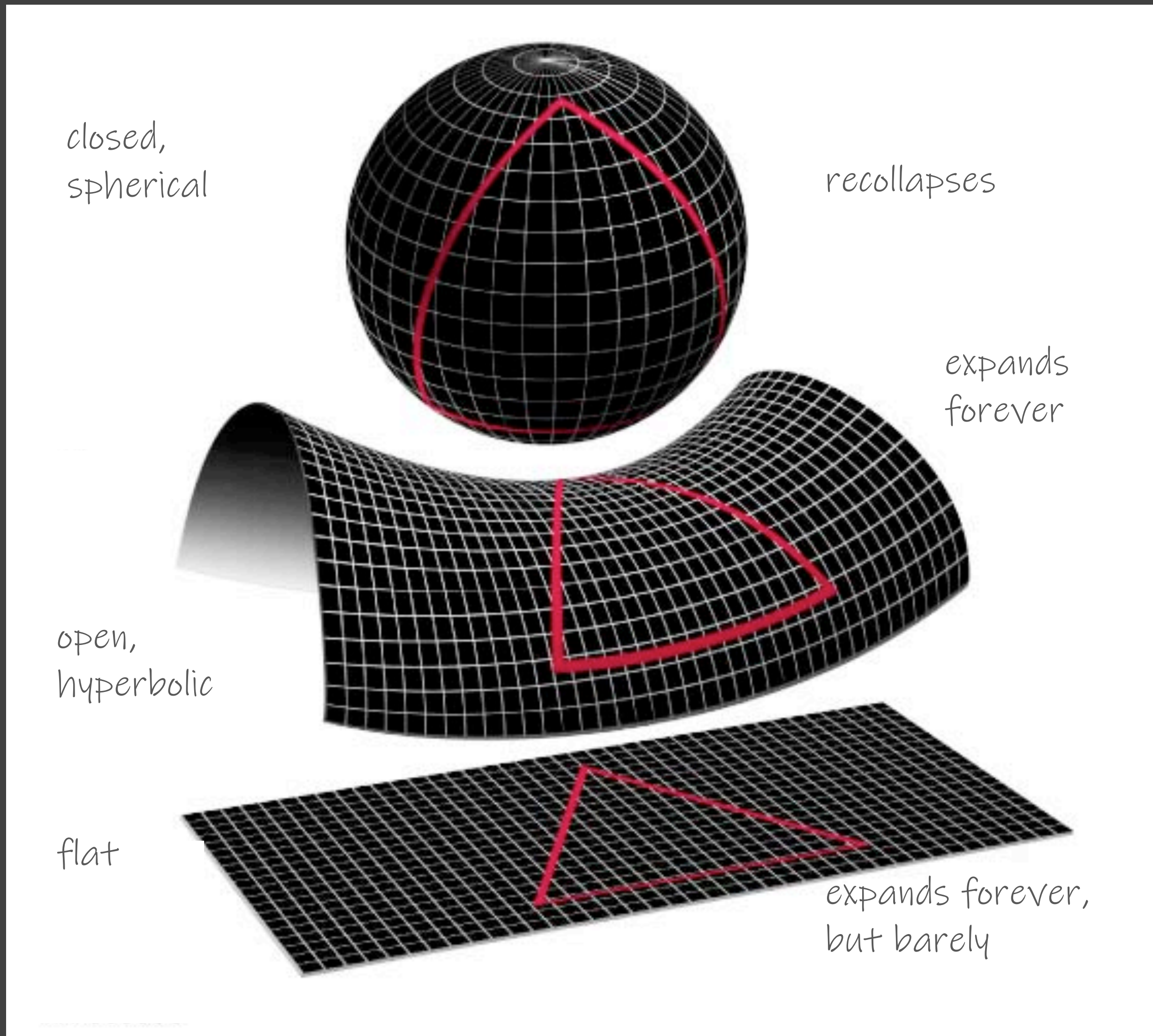
Isotropy: The physical conditions are identical in all directions when viewed from a given point on the hypersurface.

Isotropy at every point automatically enforces homogeneity.

Homogeneity does not necessarily imply isotropy.



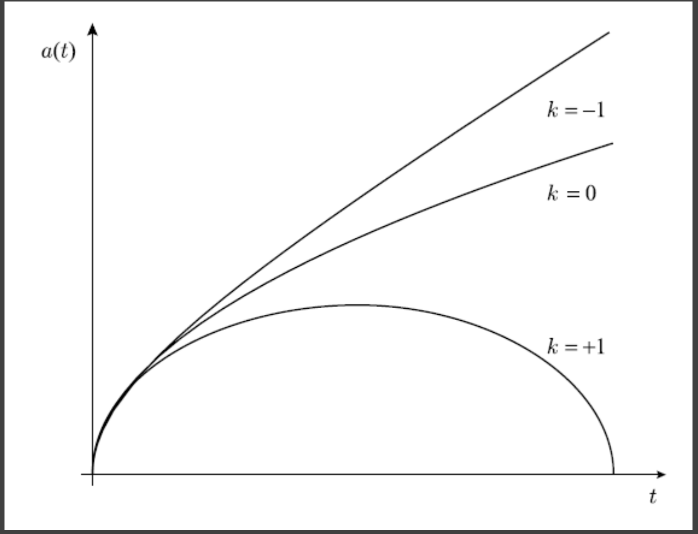

closed,
spherical
open,
hyperbolic
flat


closed,
spherical
recollapses
expands
forever
open,
hyperbolic
flat
expands forever,
but barely

The Friedmann-Lemaître-Robertson-Walker (FLRW) metric

The only way to preserve the homogeneity and isotropy of space and incorporate time evolution is to allow the curvature scale, characterised by the scale factor a, to be time dependent,

The scale factor $a(t)$ completely describes the time evolution of a homogeneous and isotropic universe.



$$a(t) = \frac{1}{1+z}.$$

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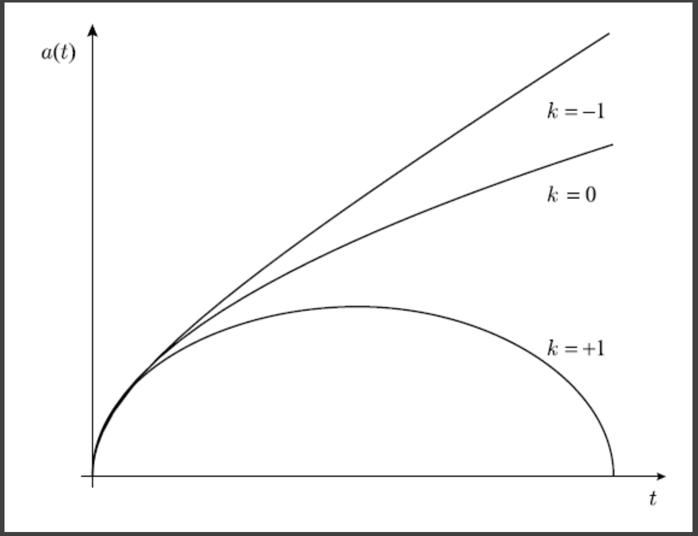
$$a(t) \propto t^{1/2}$$

$$a(t) \propto t^{2/3}$$



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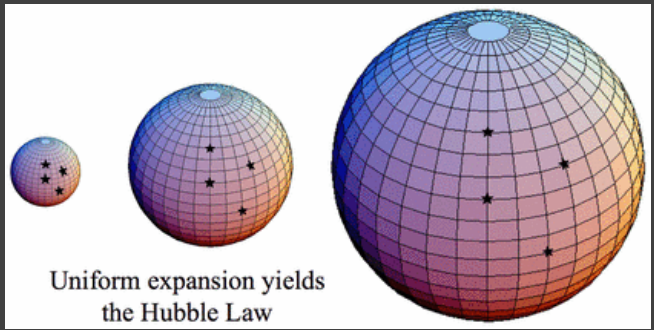
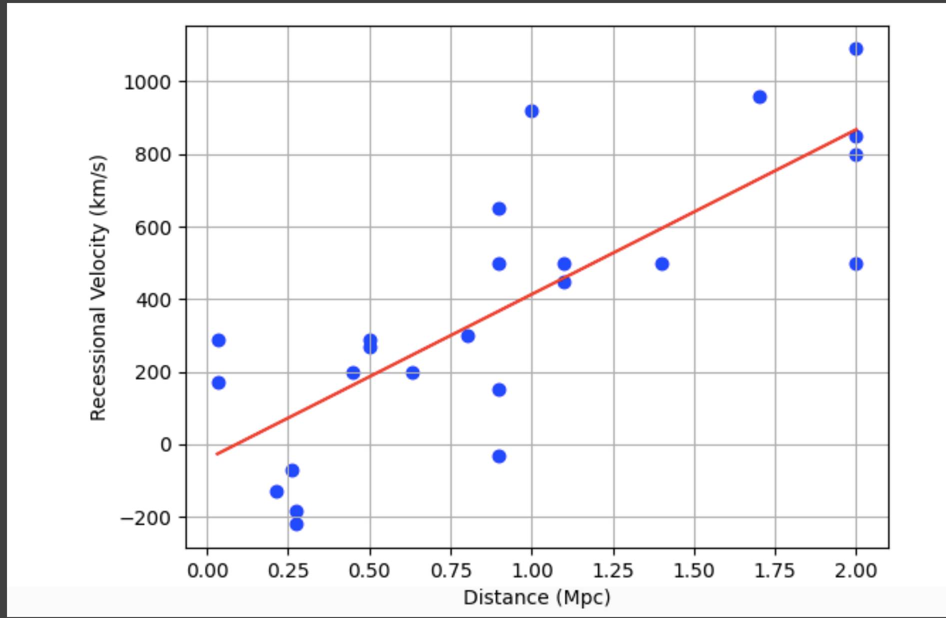
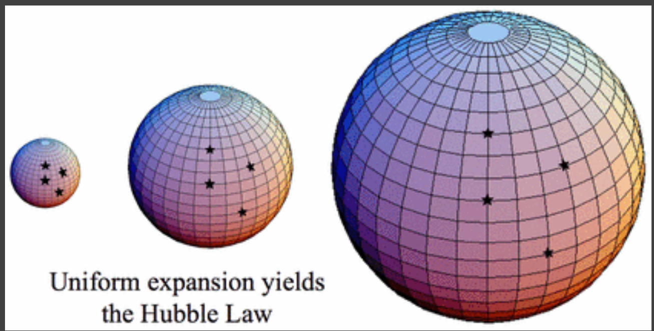
Hubble's law

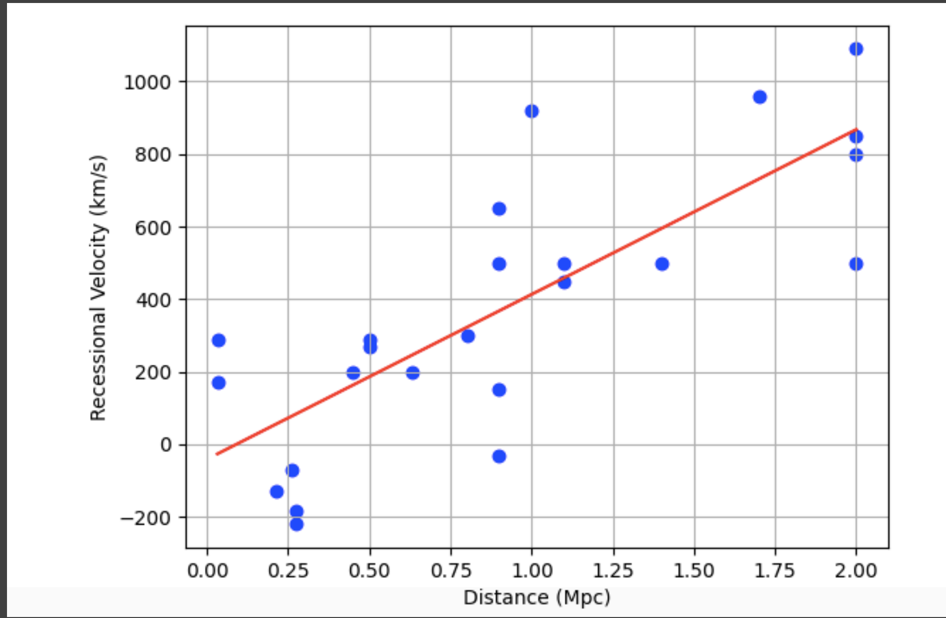

Uniform expansion yields
the Hubble Law


Recessional Velocity (km/s)
Distance (Mpc)
1000
800
600
400
200
0
−200
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00

Hubble's law

$$v \simeq Hd.$$





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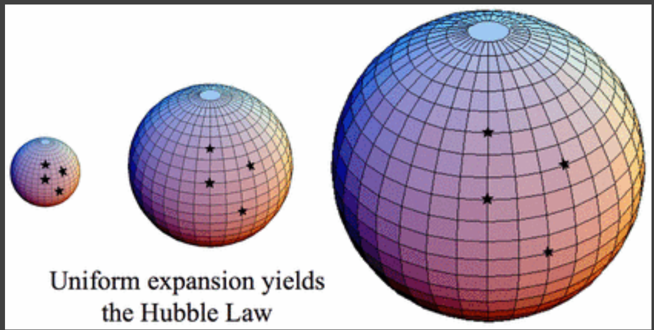
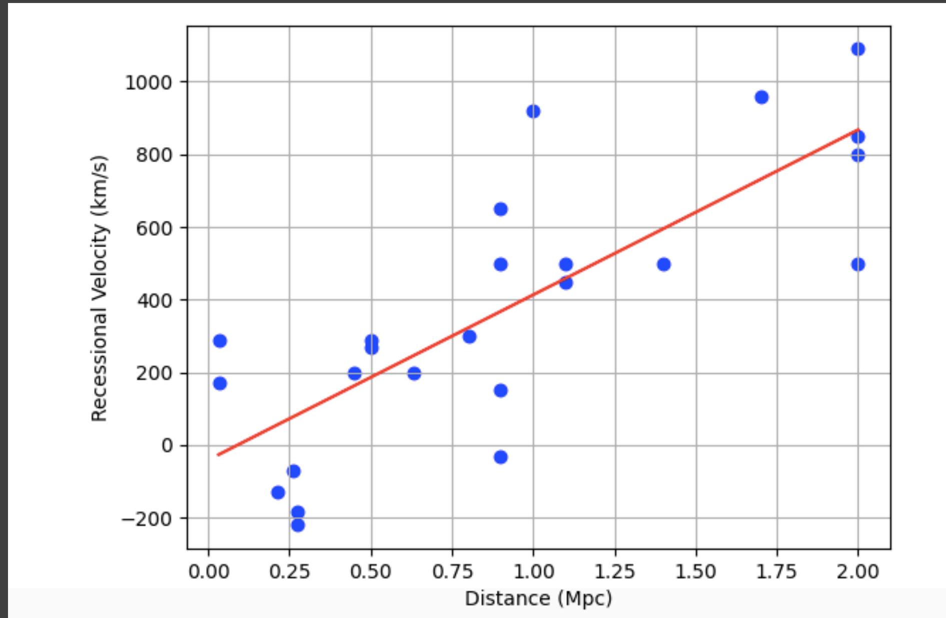




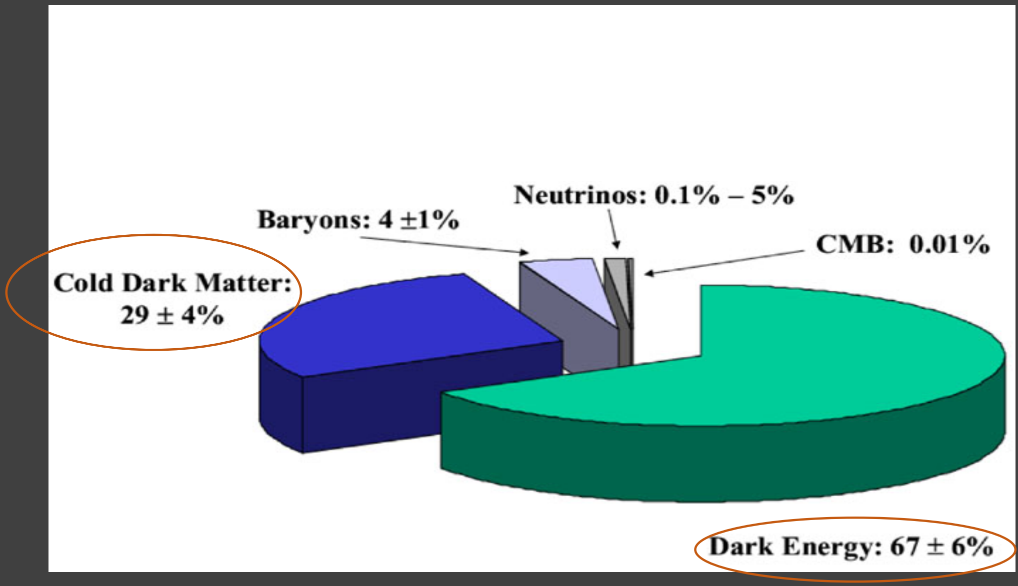
On large scales, galaxies are moving apart, with velocity proportional to their distance

It is not galaxies moving through space

Space is expanding, carrying the galaxies along

What is the Universe made of?

The Universe is made out of stars, hot or cold gaz, but mainly from dark matter (it does not emit any electromagnetic radiation, so we can detect it only through its gravitational effects), and mainly of dark energy which is even more mysterious



96% of the mass-energy of our Universe is unknown

Galaxies: about 60,000 light-years across; they contain about 10 billion stars

Cluster of galaxies: consists of anywhere from hundreds to thousands of galaxies that are are bound together by gravity with typical masses ranging from 10^{14} to 10^{15} solar masses

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- We know dark matter exists because it exerts gravitational pull on the galaxies we can see in clusters

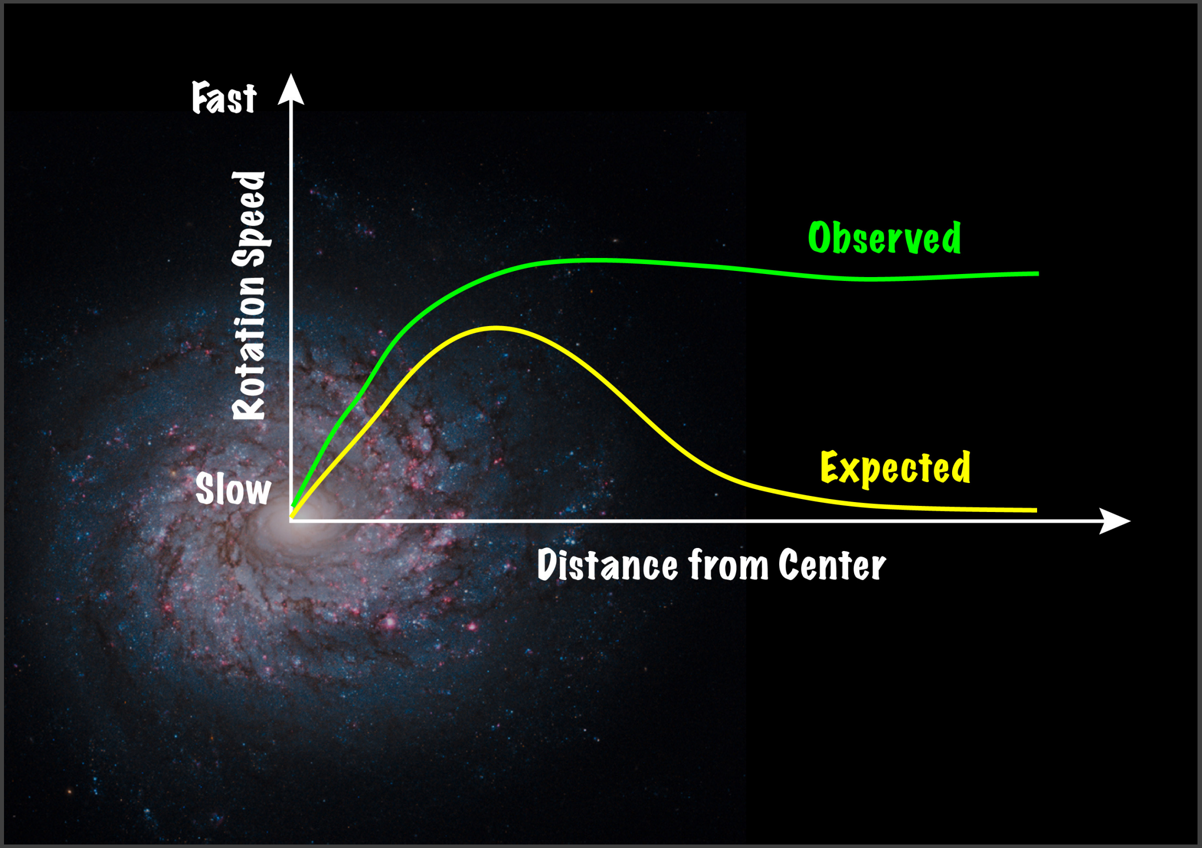
Fitz Zwicky (1898-1974)

Rotation of stars around galaxies

Vera Rubin (1970's)

- Flat rotation curves

- The galaxies are mostly made of dark matter



Dark Energy

The universe is expanding, and it expands a little faster all the time

Cosmic acceleration: the speeding up of the expansion of the Universe

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Type Ia supernova: almost the same intrinsic brightness, and since objects that are further away appear dimmer, we use the observed brightness of these supernovae to measure the distance to them

The distance can then be compared to the supernovae's cosmological redshift, which measures how much the universe has expanded since the supernova occurred; the Hubble law established that the further an object is from us, the faster it is receding

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The unexpected result was that **objects in the universe are moving away from one another at an accelerated rate**

The accelerated expansion of the universe is thought to have begun since the universe entered its dark-energy dominated roughly **5 billion years ago**

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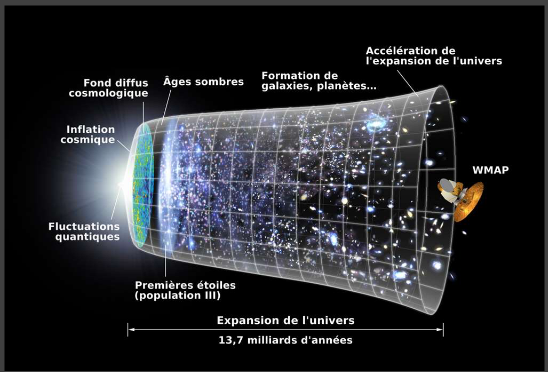

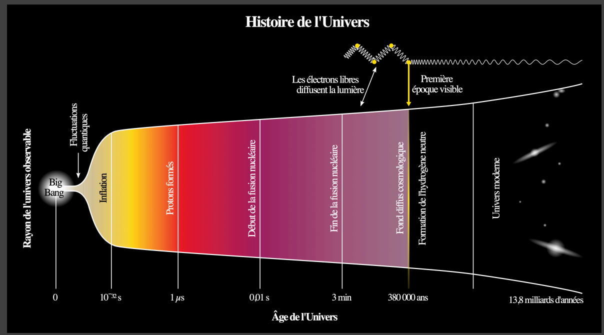

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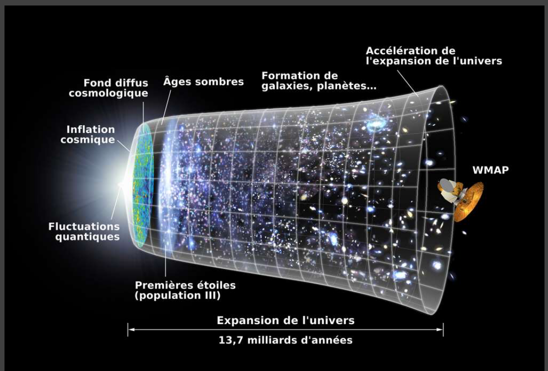

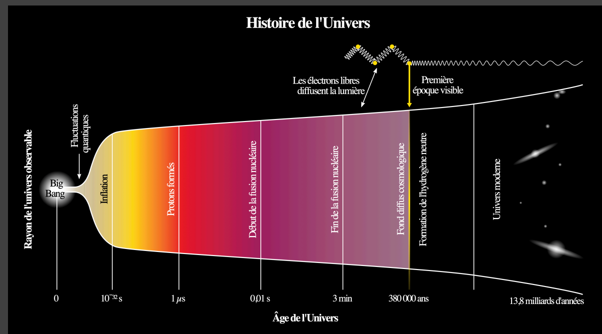

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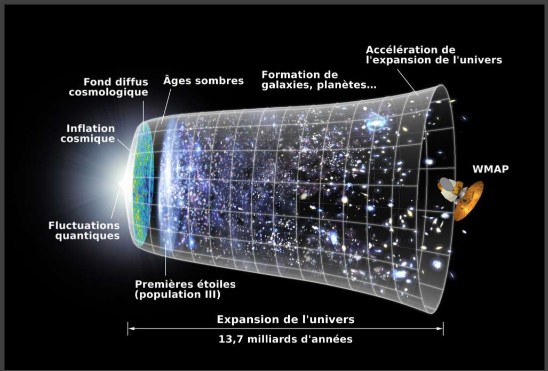
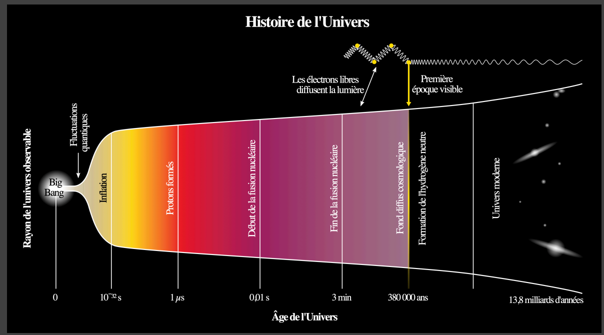
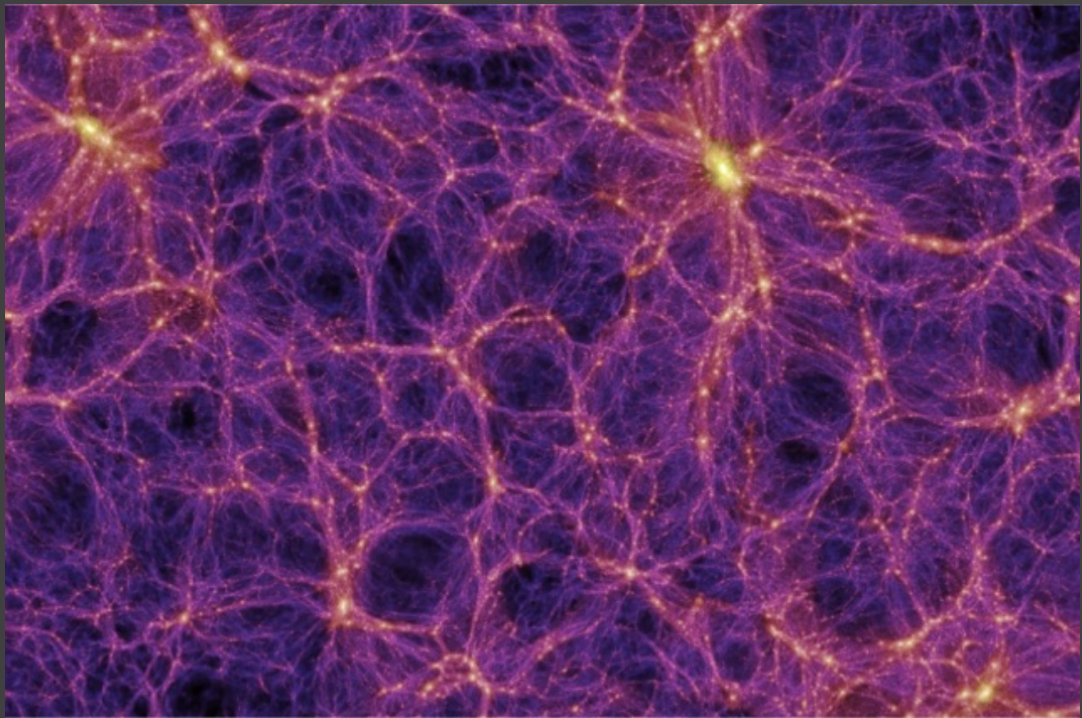




- Hundreds of million of years later, the Universes entered the reionisation phase

- In the last era (during more than 13 billion years) stars and galaxies were formed and evolved

The Universe has evolved from a quasi-homogeneous state of gas to an inhomogeneous distribution of matter characterised by filaments or matter filled up with galaxies which intersect forming clusters surrounded by void



The Cosmic Microwave Background (CMB)

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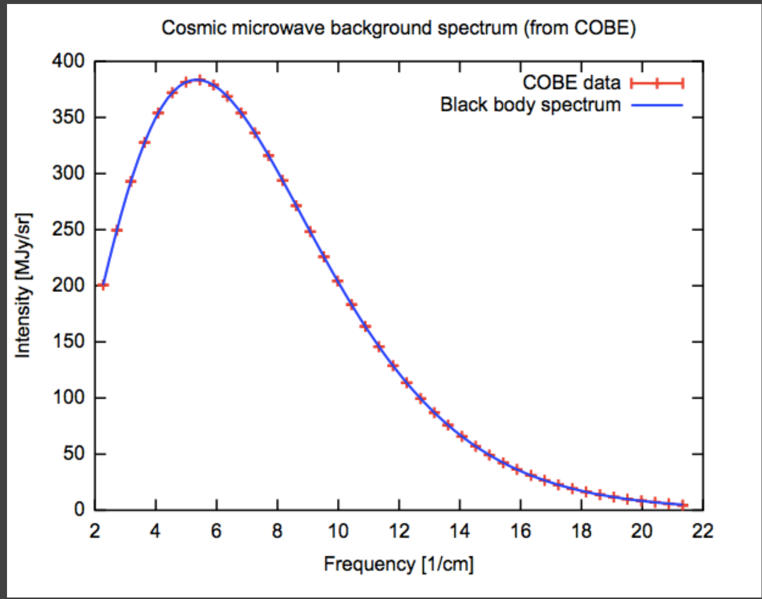


- The CMB radiation was discovered by chance in 1965

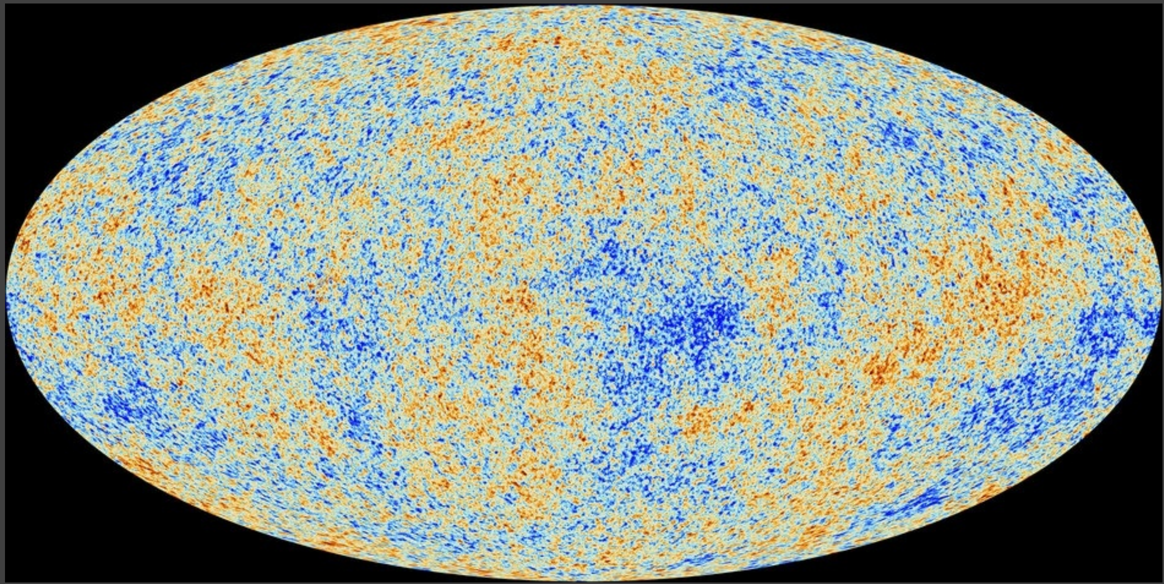
Penzias and Wilson, two radio astronomers, registered a **signal in their radio telescope** that could not be attributed to any precise source in the sky

- It **apparently came from everywhere with the same intensity**
- This discovery is a solid evidence for the Big Bang theory

The CMB has the spectrum of a blackbody

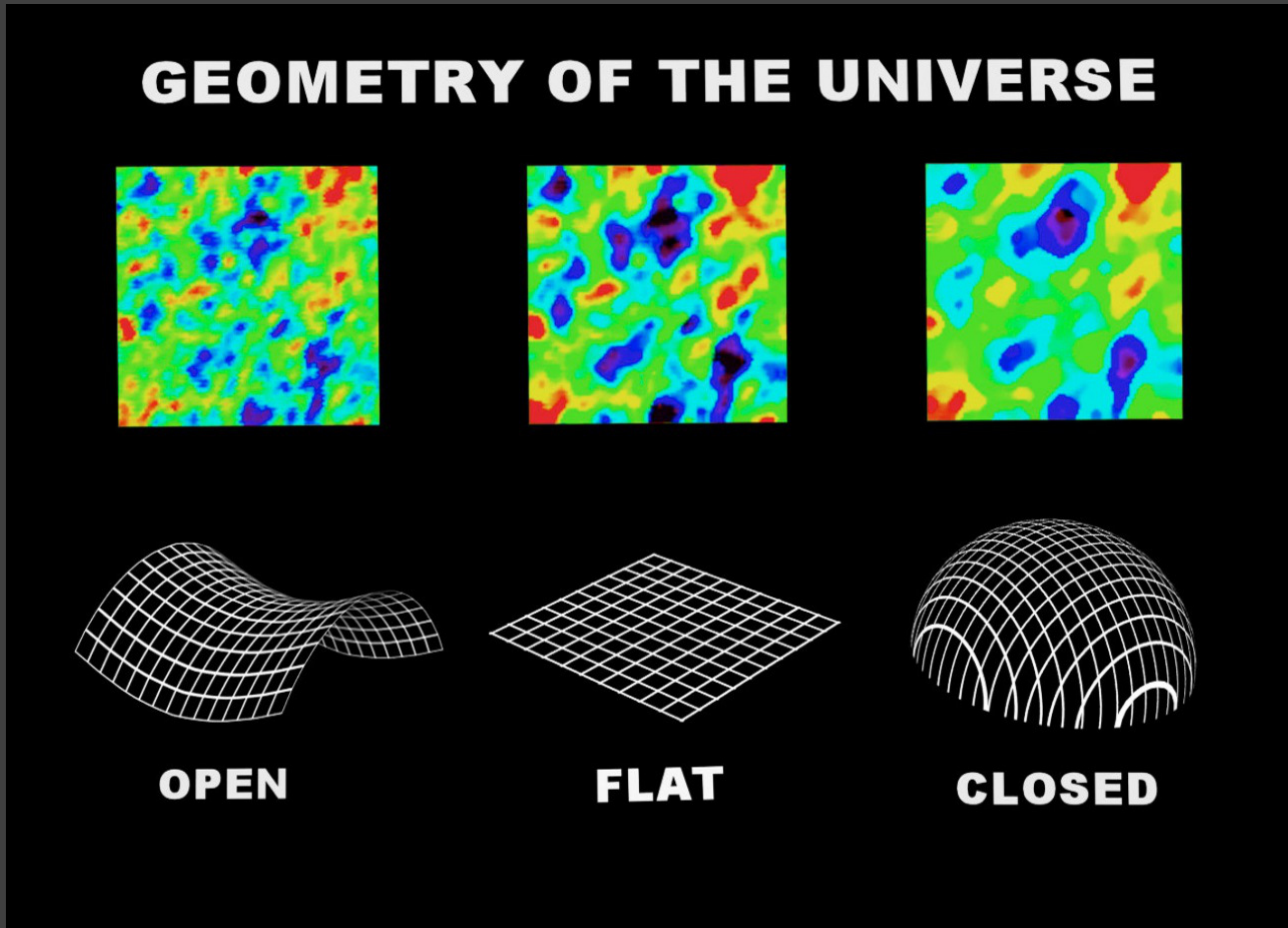
A blackbody spectrum is produced by an isothermal, opaque and non-reflecting object

The Cosmic Microwave Background (CMB)



The temperature of the CMB is today 2,728 K

CMB is isotropic to a very high degree (tiny fluctuations of one part in 100000)



We live in a flat universe

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While the Big Bang theory successfully explains the blackbody spectrum of the CMB and the origin of light elements, it has some important shortcomings

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- **Horizon problem**

Distant regions of space in opposite directions of the sky are so far apart that, assuming standard Big Bang expansion, they could never have been in causal contact with each other

➡ **The uniformity of the CMB imply that these regions must have been in contact with each other in the past**

Cosmological Inflation

Early period of extremely rapid (exponential) expansion of the universe, during which time the energy density of the universe was dominated by an exotic matter with constant energy density, that later decayed to produce the matter and radiation that fill the universe today

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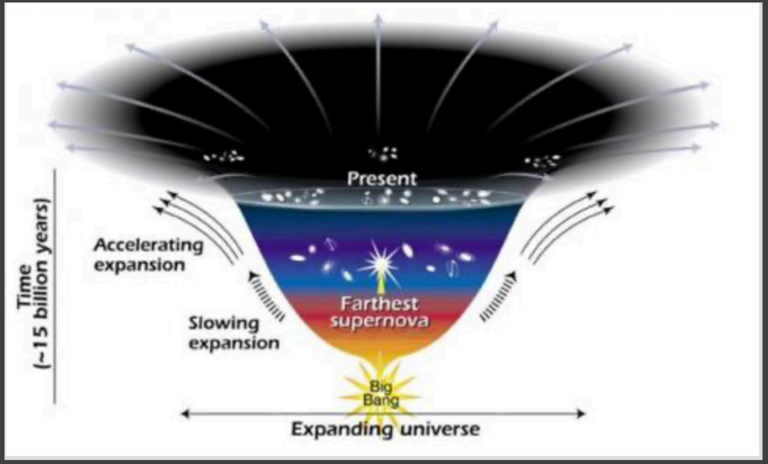
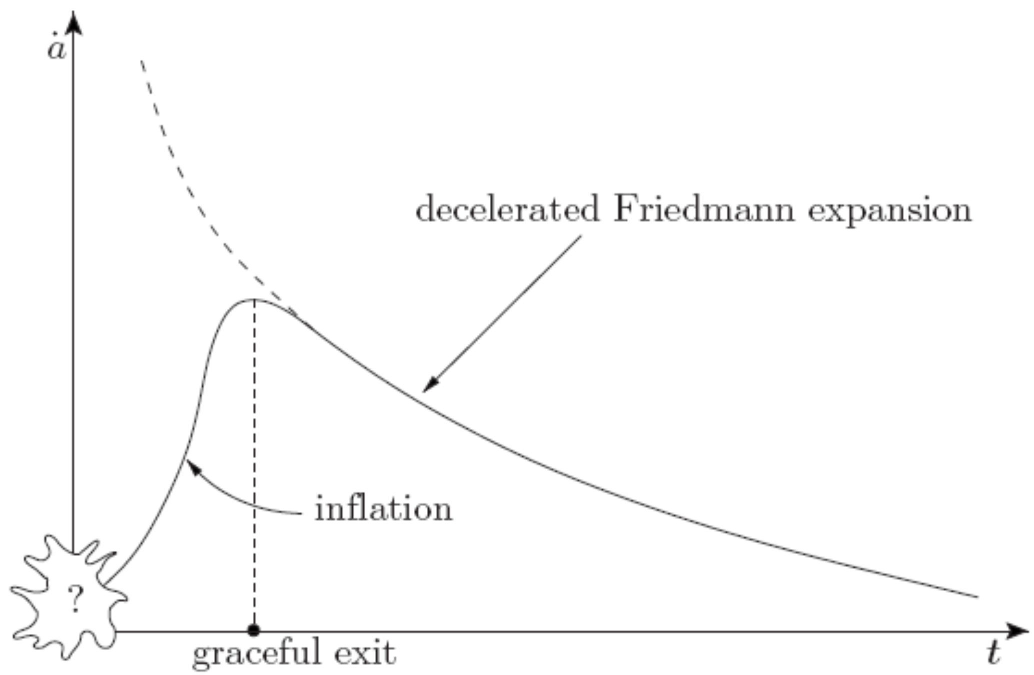
Inflation increased the linear size of the universe by a factor of at least **10^{26} between 10^{-36} et 10^{-33} seconds after the Big Bang**



Cosmological Inflation

Inflation is a stage of accelerated expansion of the universe when gravity acts as a repulsive force.



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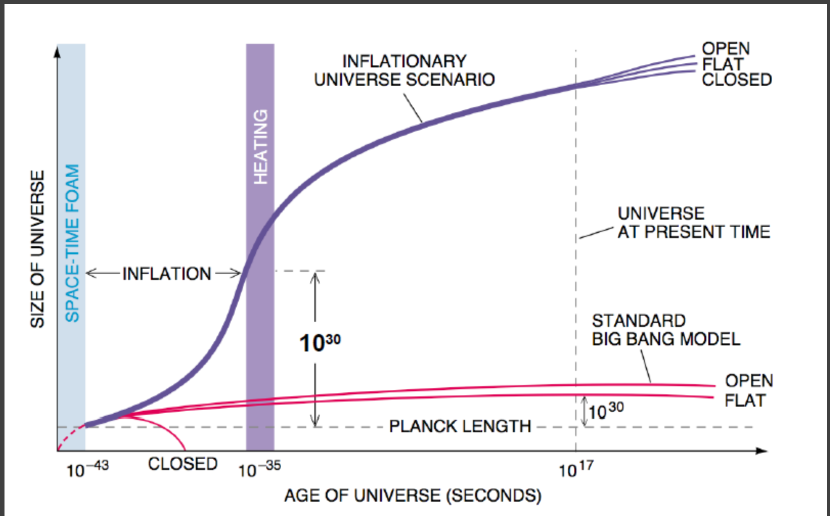


during inflation the universe was dominated by *a fluid with negative pressure*

⟹ accelerated expansion

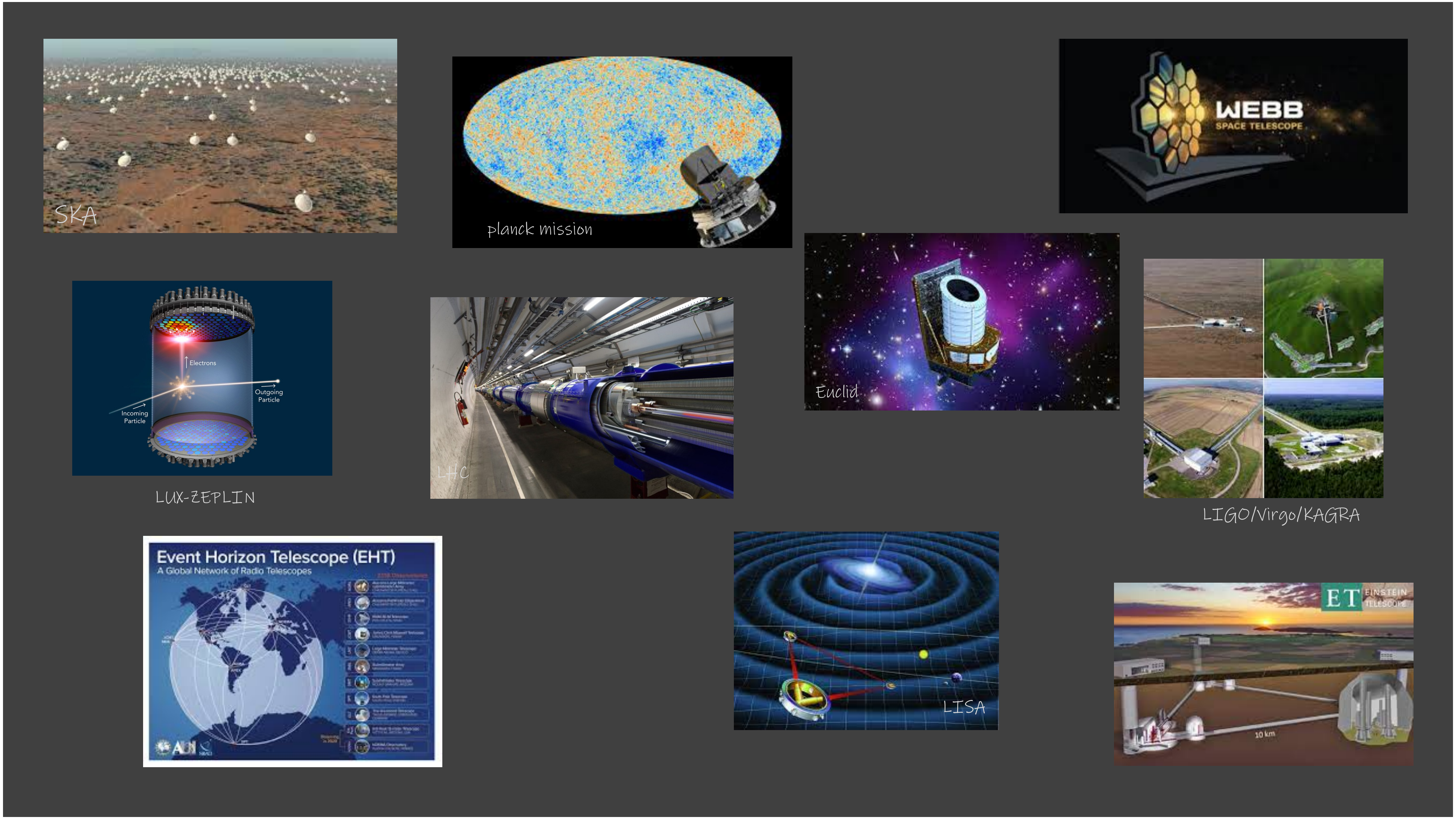
$$\rho_{\rm now} \simeq 10^{-47}{\rm GeV}^4$$

$$\rho_{\rm LHC} \simeq (100{\rm GeV})^4$$

inflation

$$\rho_{\rm inf} \simeq \left(10^{16}{\rm GeV}\right)^4$$

1 giga-electron volt = 4.45049045931e-17 kilowatt hours


SKA
planck mission
WEBB
SPACE TELESCOPE
Electrons
Outgoing Particle
Incoming Particle
LUX-ZEPLIN
LHC
Euclid
LIGO/Virgo/KAGRA
Event Horizon Telescope (EHT)
A Global Network of Radio Telescopes
LISA
ET EINSTEIN TELESCOPE
10 km

Interplay of General Relativity, Astrophysics and Particle Physics, with the use of very precise measurements and observations help us to understand our Universe, its laws and its evolution

We live a golden era for Cosmology

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In particular, we have to understand the origin of the early and late acceleration expansion; at present we now only the mechanism

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We need a theory that combines General Relativity and Quantum Mechanics, the two pillars of physics