Expansion of the universe

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Goals

- Understand the expansion of the universe
- Understand that there is no centre of the universe
- Understand the Hubble-Lemaître Law
- Understand how to detect dark matter

Presentation

This workshop is about:

- The origin of the universe: the Big Bang
- The galaxies: they do not “move” through space, the space is that expands
- The Hubble’s Constant : $v = H \times d$
- There is no centre of the universe
- The cosmic microwave background (CMB)
- Gravitational lenses.

Models, predictions, verification: Experiment with a tablecloth

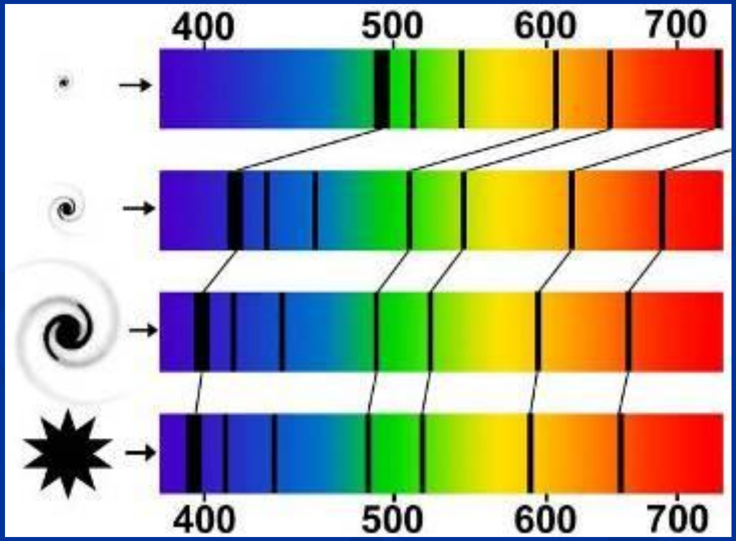
Prediction: if you pull a tablecloth very quickly nothing on the table will fall down. If we are able to verify this, our prediction is fulfilled.

If one pulls the tablecloth quickly, frictional forces do not have time to act on the objects on the table, which explains why they do not fall. The experiment is successful because physics is a science which predicts what will happen.

The Physics that we developed on the Earth is the same one that we apply to the rest of the Universe.

Movement towards the red

- Light absorption is different for each chemical element. The light absorption spectrum presents characteristic lines for each chemical element.
- When we observe the light from galaxies, we can see that the lines are shifted toward the red end of spectrum. The further away the galaxy, the greater the redshift.
- This is interpreted as a result of the galaxy's movement away from us.



Movement towards the red

- Nearby galaxies have relatively small and irregular movements: the Large Magellanic Cloud +13 km/s, the Small Magellanic Cloud -30 km/s, Andromeda Galaxy -60 km/s, M32 +21 km/s.
- In the Virgo cluster, (50 million lyr away), all galaxies are moving away from us at speeds of between 1 000 and 2 000 km/s.
- In the Coma Berenice supercluster (300 million lyr away) the speeds are between 7 000 and 8 500 km/s.

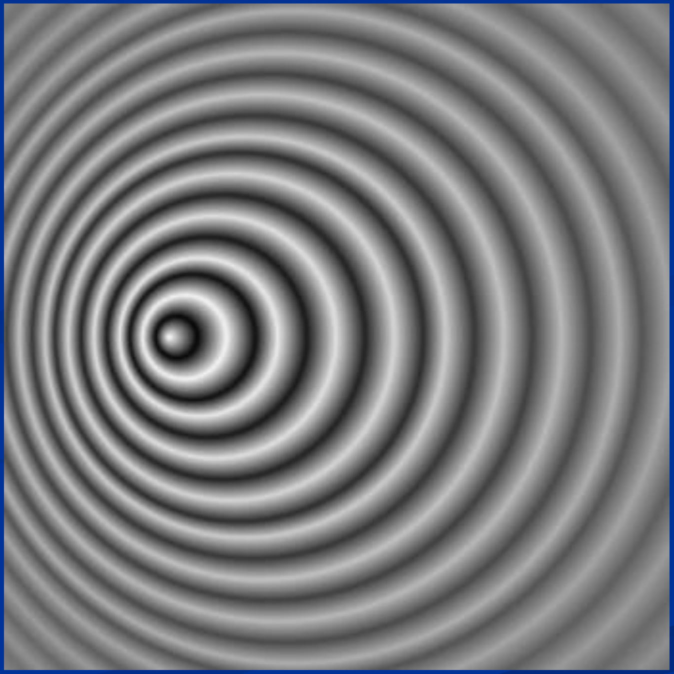
Movement towards the red

- In the opposite direction, M 74 moves away at 800 km/s and M 77 at 1 130 km/s.
- If we observe distant and faint galaxies, the recession velocity is even greater: the galaxy NGC 375 moves away at 6 200 km/s, NGC 562 at 10 500 km/s and NGC 326 at 14 500 km/s.
- Independent of the direction in which we observe, all except the very close galaxies are moving away from us.

Doppler Effect

In the same way as in the tablecloth example, we can apply other physical principles to the study of the universe.

- If an ambulance, a motorcycle or a train is approaching, we will hear a higher pitched sound. When they move away we hear a lower pitched sound.



- Higher pitch → the wavelength is shortened
- Lower pitch → the wavelength is lengthened

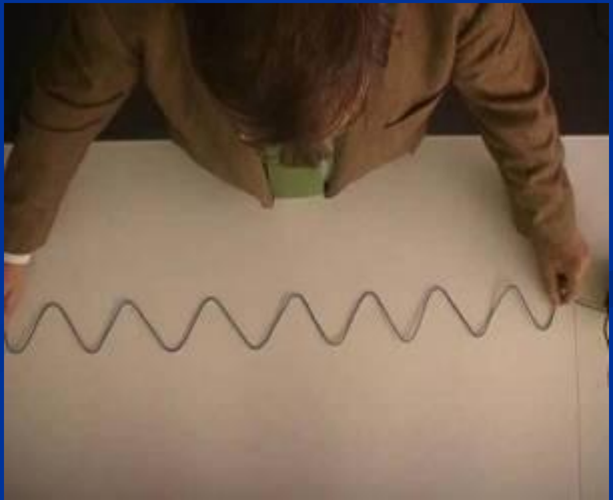
Activity 1: Doppler Effect

- The Doppler effect can be heard by rotating an alarm clock or buzzer in a horizontal plane.
- When it approaches the listener, λ is shortened and the pitch of the sound is higher.
- When it moves away, λ is stretched and the pitch of the sound is lower.
- This happens with the sounds of motorcycles, ambulances, trains...

In the experiment, the Doppler effect is due to relative source-receiver displacement and is highlighted with sounds. In the case of the expansion of the Universe, the effect occurs with electromagnetic waves

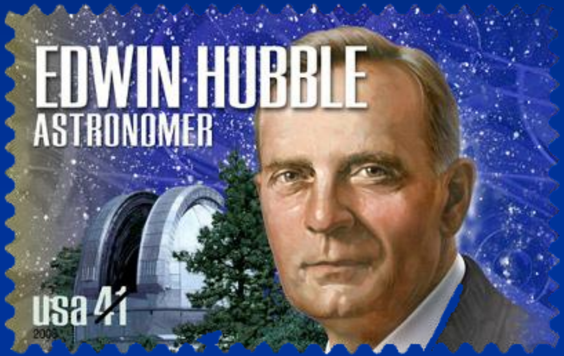
Activity 2: "Stretching" of photons

- The universe, when it expands, "stretches" the photons in it.
- You can make a model of that stretching using a semi-rigid cable of the type used in domestic wiring.
- The longer the photon's path, the more they are stretched.



Hubble-Lemaître Law

Between 1920 and 1930, George Lemaître and Edwin Hubble realized that the most distant galaxies are moving away faster than nearby ones.

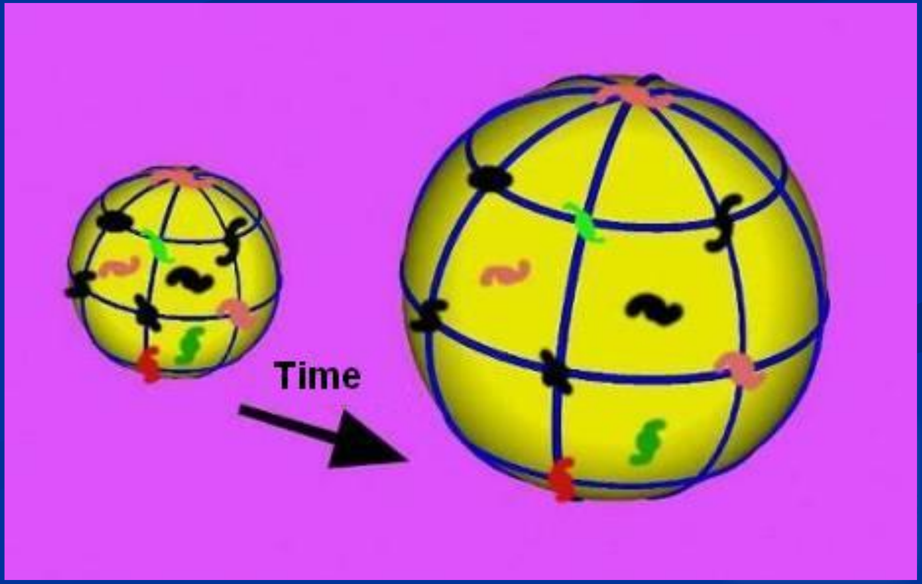


George Lamaître

Hubble-Lemaître Law:

$$v = H \times d$$

The galaxies don't move through the space: it is the space which expands, dragging the galaxies.



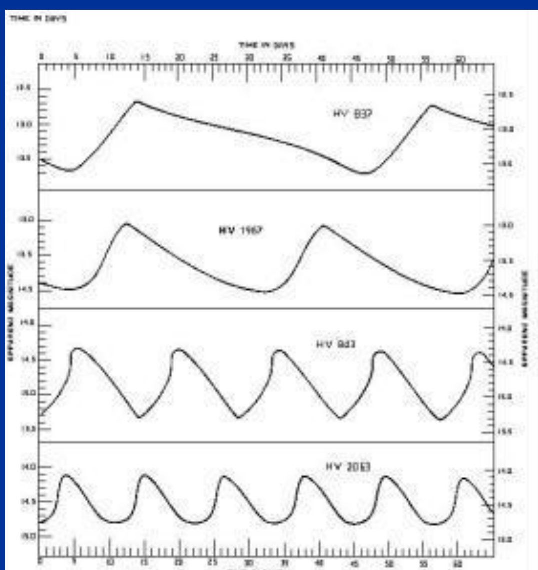
Activity 3: The universe in an elastic band

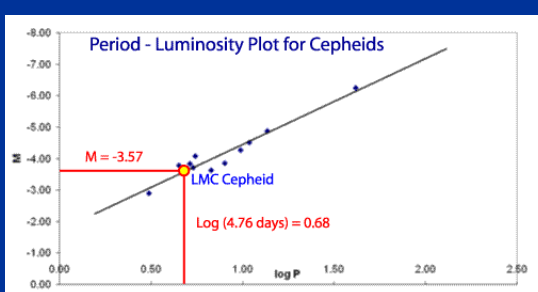
Activity 4: The universe in a balloon

- The distance between the galaxies increases with the expansion.
- The galaxies are not moving through the balloon
- Locating ourselves in any "galaxy" on the balloon we see that the others move away from us.

Expansion of the universe

1) The distance to the nearest galaxies can be obtained from the period-luminosity relation of the Cepheid variable stars (discovered by Henrietta Leavitt, at Harvard, early in 20th century)



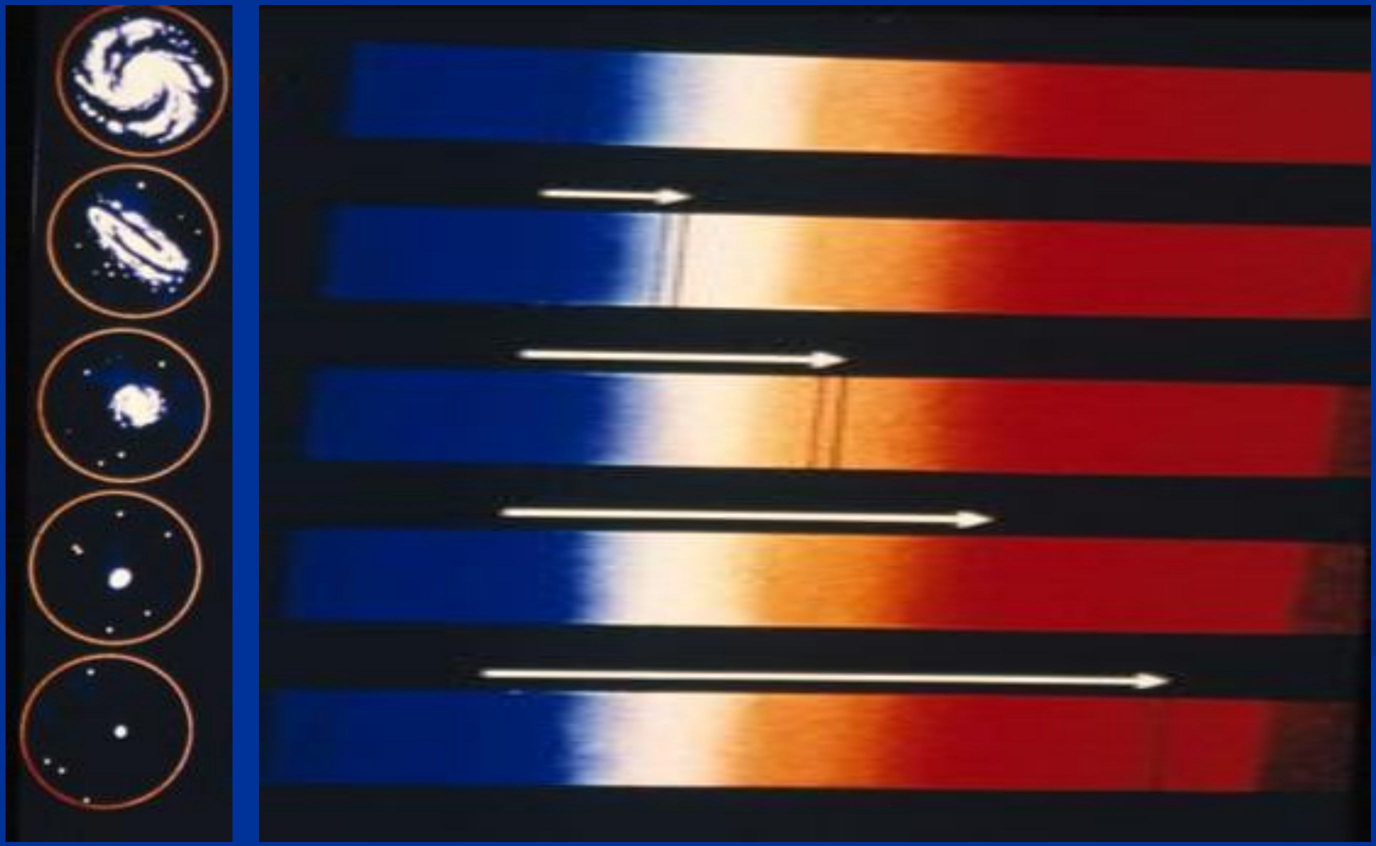


- From the light curve it is possible to obtain the period P
- From the relation period-luminosity we can get the absolute magnitude M
- With M and m, it is possible to measure the distance to the galaxy $d=10^{(m-M+5)/5}$ parsec
- To determine distances of the most distant galaxies the astronomers can use a particular type of supernova (type Ia) which have similar peak luminosities.

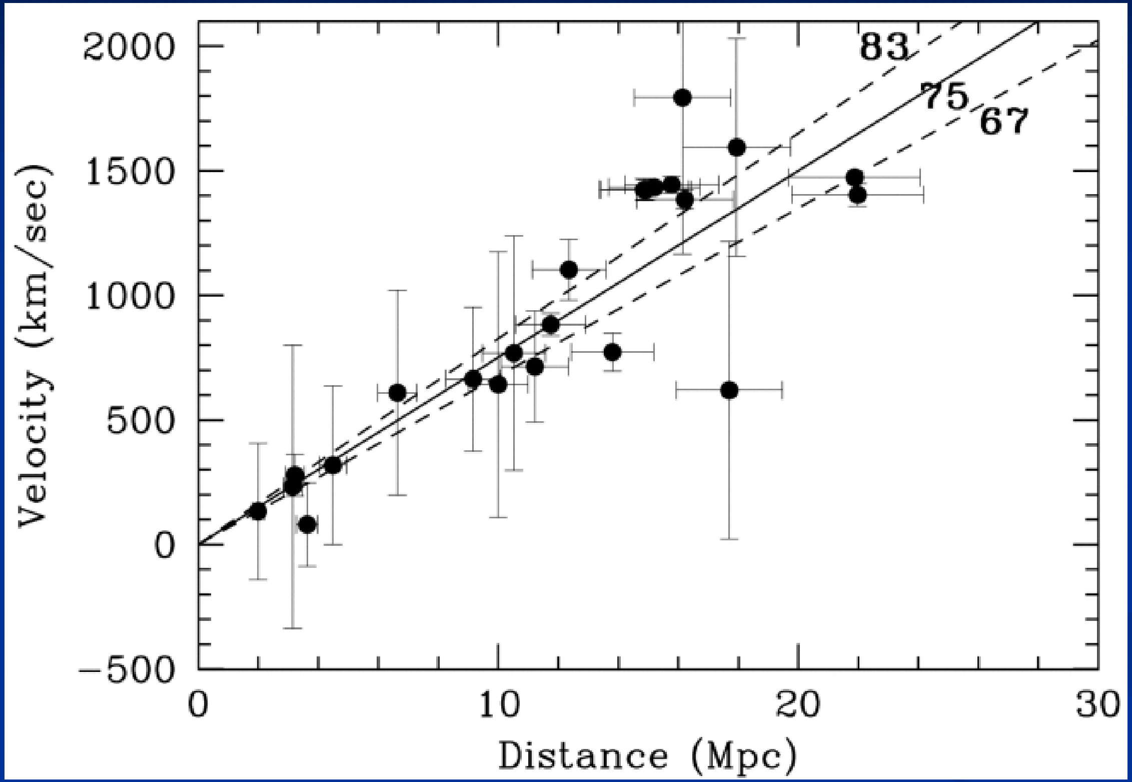
Expansion of the universe

2) The recession velocity is measured from the shift of the absorption lines in the spectrum, using the equation:

$$v = (\Delta \lambda / \lambda) \times c$$



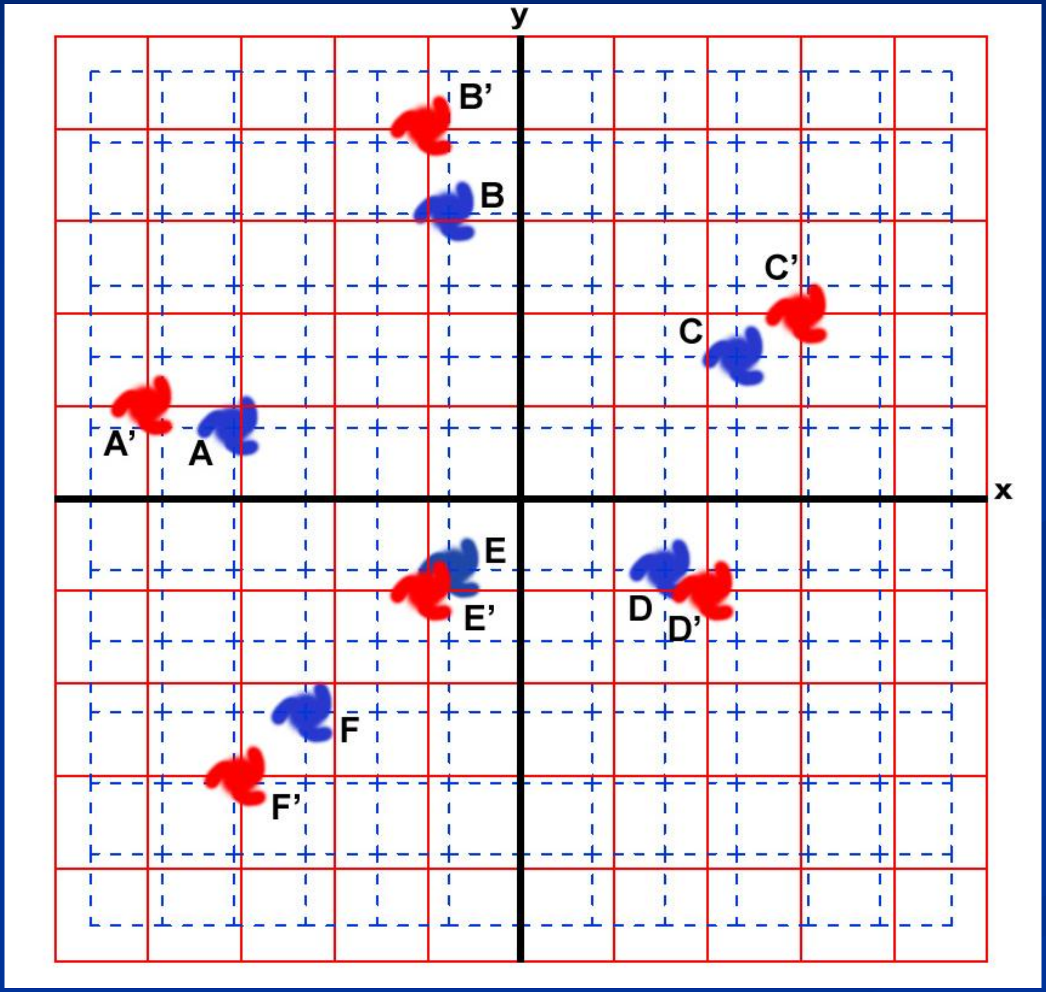
Expansion of the universe



(from Freedman et al, 2001, ApJ, vol 553, p47)

3. The Hubble constant is the slope of the function graph: $v = H_0 \times d$, where H_0 is the rate of expansion of the universe: $H_0 = 72$ km/s.Mpc

Activity 5: Calculation of the Hubble-Lemaître constant

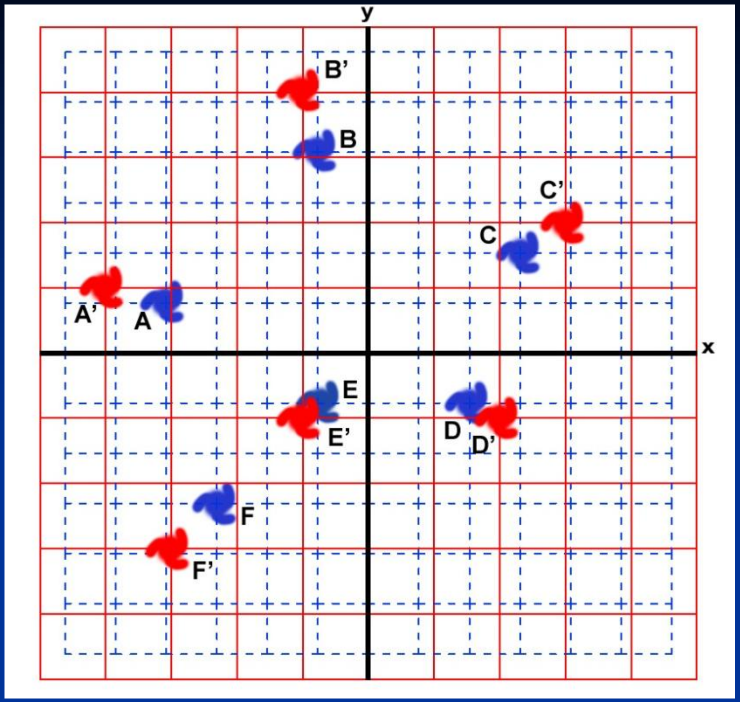


Blue = Universe before expanding

Red = Universe after expanding

Activity 5: Calculation of the Hubble-Lemaître constant

Galaxy	*Coordinates x,y*	*d=distance to origin*	Δd	$v=\frac{\Delta d}{\Delta t}$	$H=\frac{v}{d}$
A					
A'					
B					
B'					
C					
C'					
D					
D'					
E					
E'					
F					
F'					

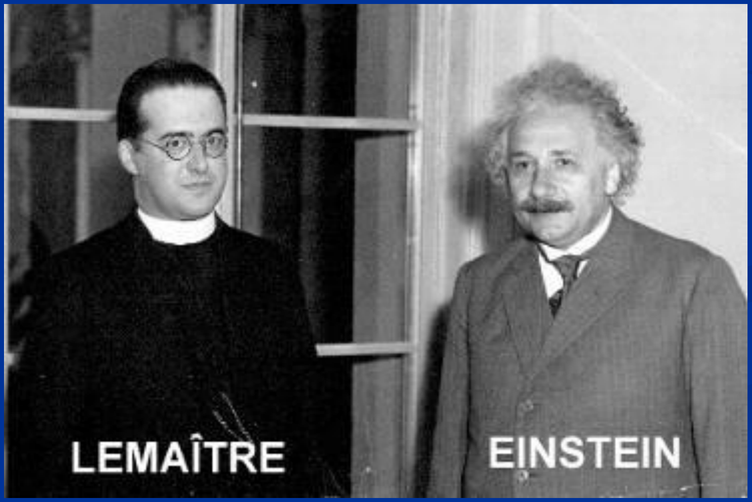


Galaxy	Coordinates x,y	d=distance to origin	Δd	$v = \frac{\Delta d}{\Delta t}$	$H = \frac{v}{d}$
A	(-4, 1)				
A'	(-4, 1)				
B	(-1, 4)				
B'	(-1, 4)				
C	(3, 2)				
C'	(3, 2)				
D	(2, -1)				
D'	(2, -1)				
E	(-1, -1)				
E'	(-1, -1)				
F	(-3, -3)				
F'	(-3, -3)				

The Big Bang

- If we go back, there was a time when everything was united: universe in expansion.

- Georges Lemaître, solving the equations of relativity, came to the idea of an expanding universe that began as a "cosmic egg".



The Big Bang

- Name of the Big Bang: big explosion.
- Fred Hoyle, with certain anti-religious prejudices, thought it seemed too consistent with the idea of a Creator.
- S & T made a competition to rename it. There were 12 000 proposals. None was better!

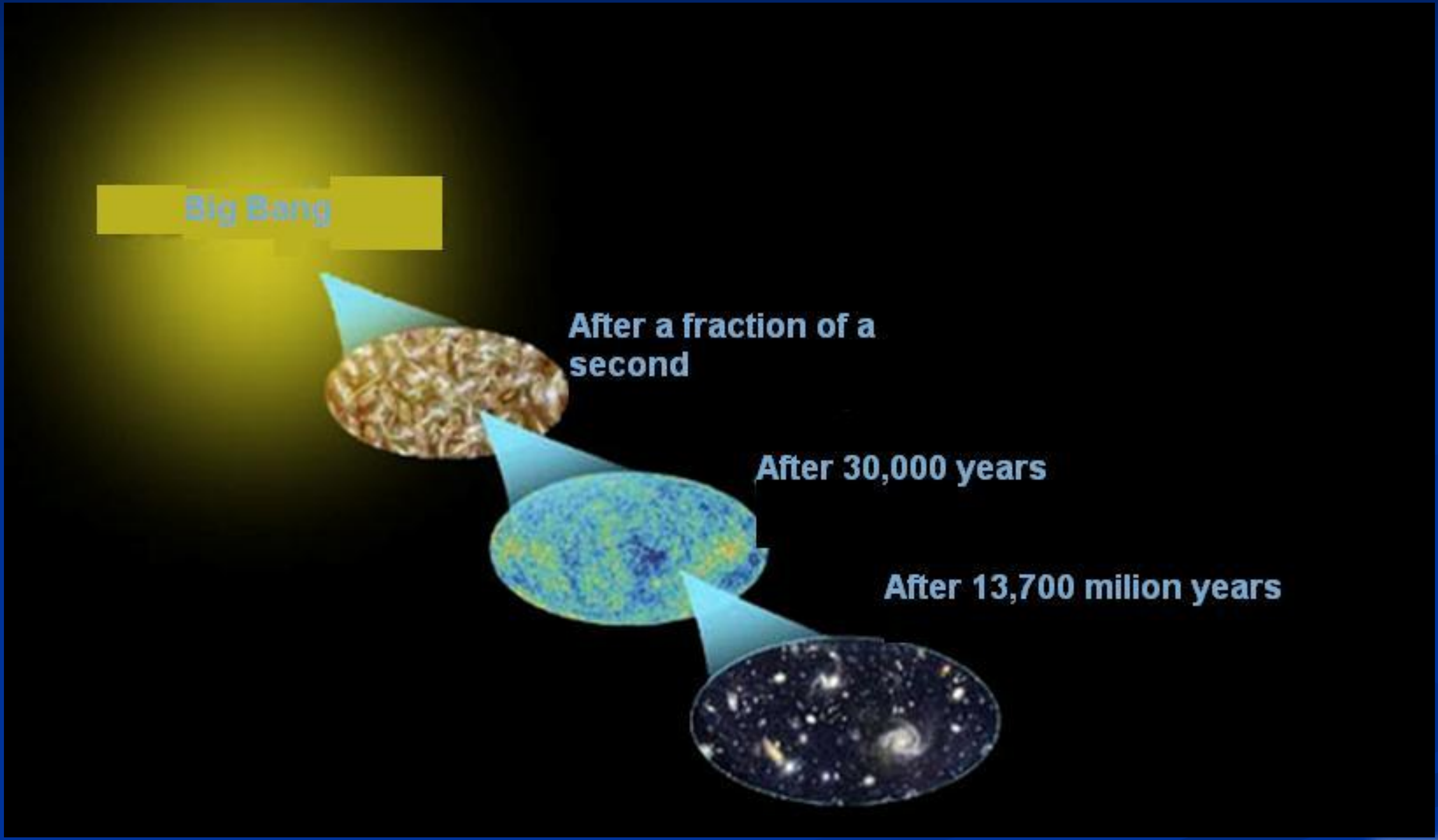
The Big Bang

- Before the Big Bang? We do not know anything.
- What was the cause? Why did it happen? Why does it observe the same physical laws everywhere?
- Physics is about how the existing things work, not about why do they exist.
- Physics studies the matter from its origin (since the Big Bang), not before, nor does it study the reason or purpose of why it exists. These are philosophical and religious questions but not scientific questions.

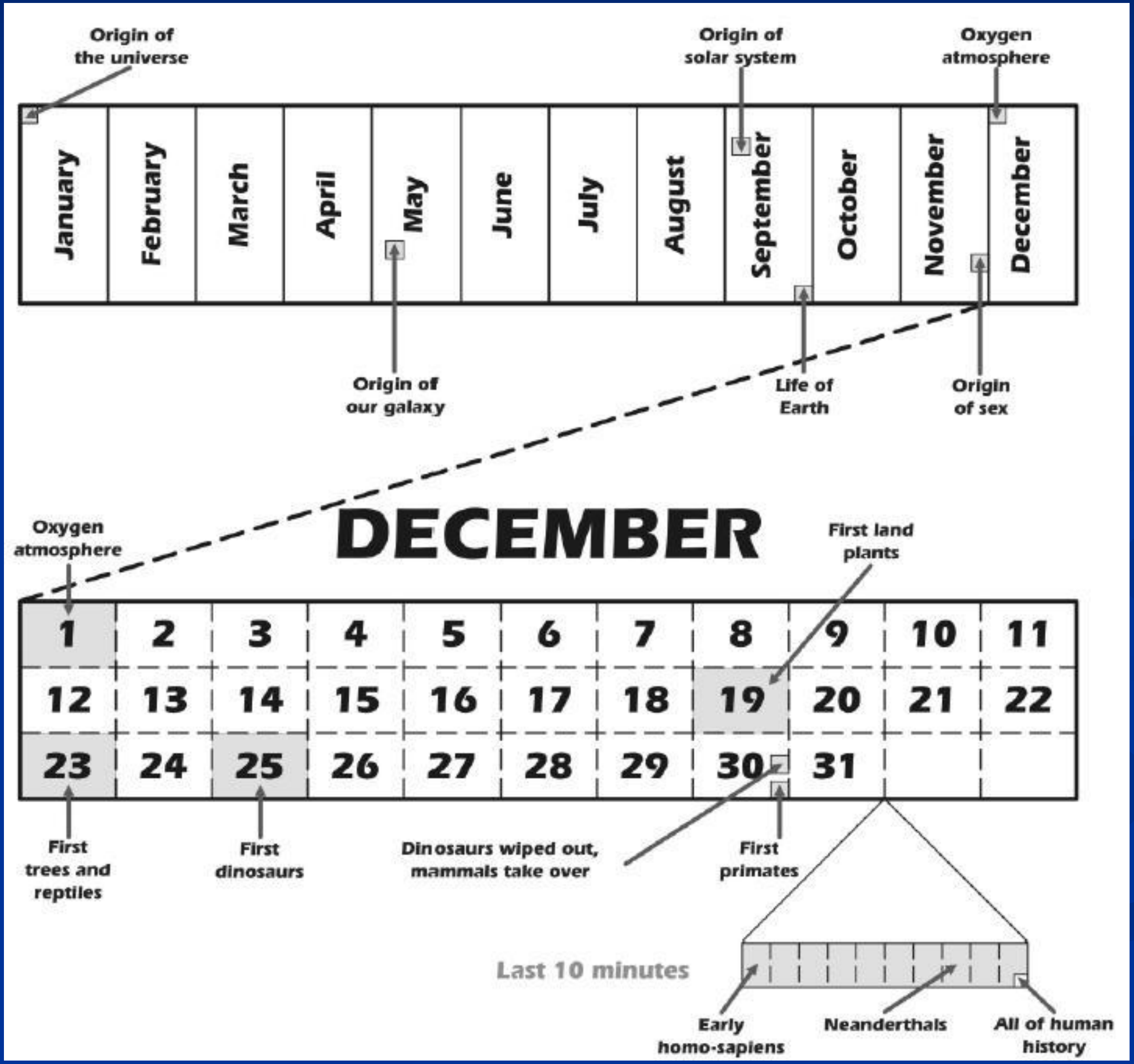
The Big Bang

- Fluctuation of the quantum vacuum?
- Emptiness is not nothing, it exists.
- Multiple universes? Indemonstrable by definition.

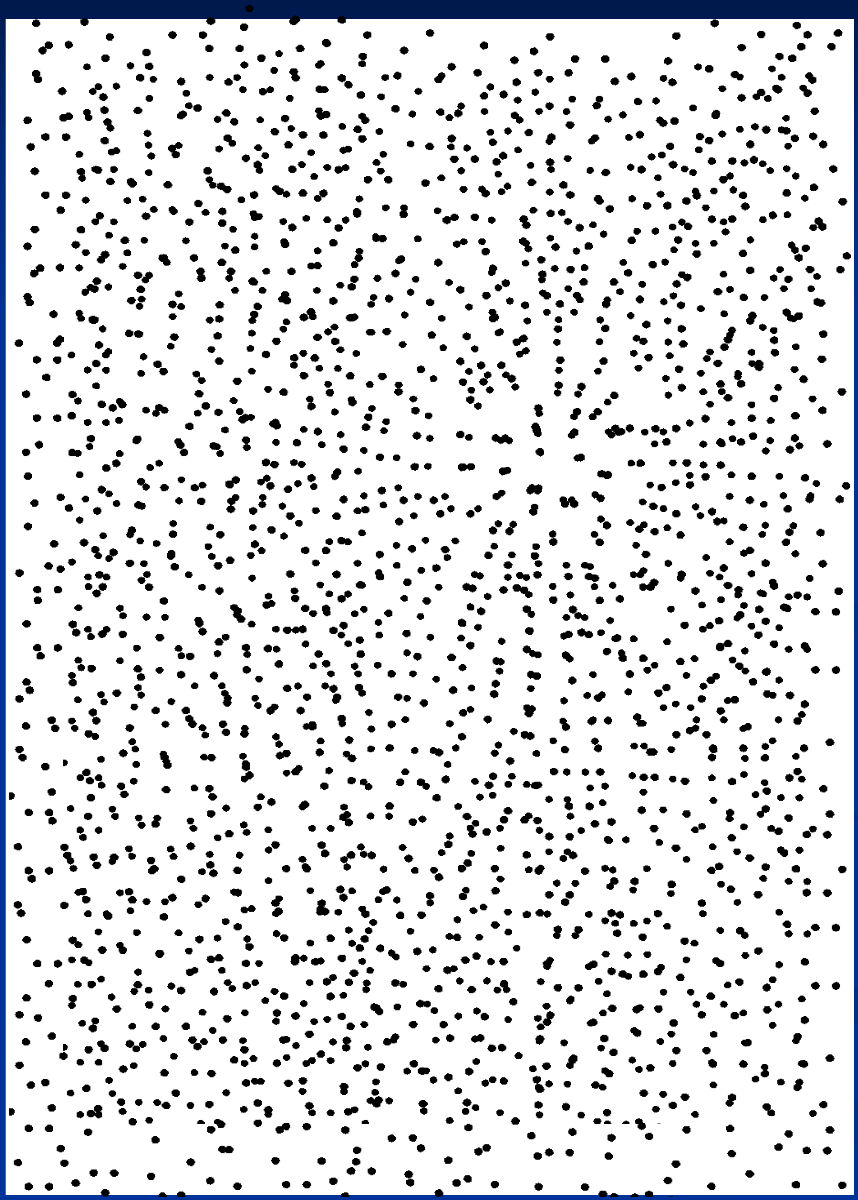
Evolution of the universe



Development of the universe in a year



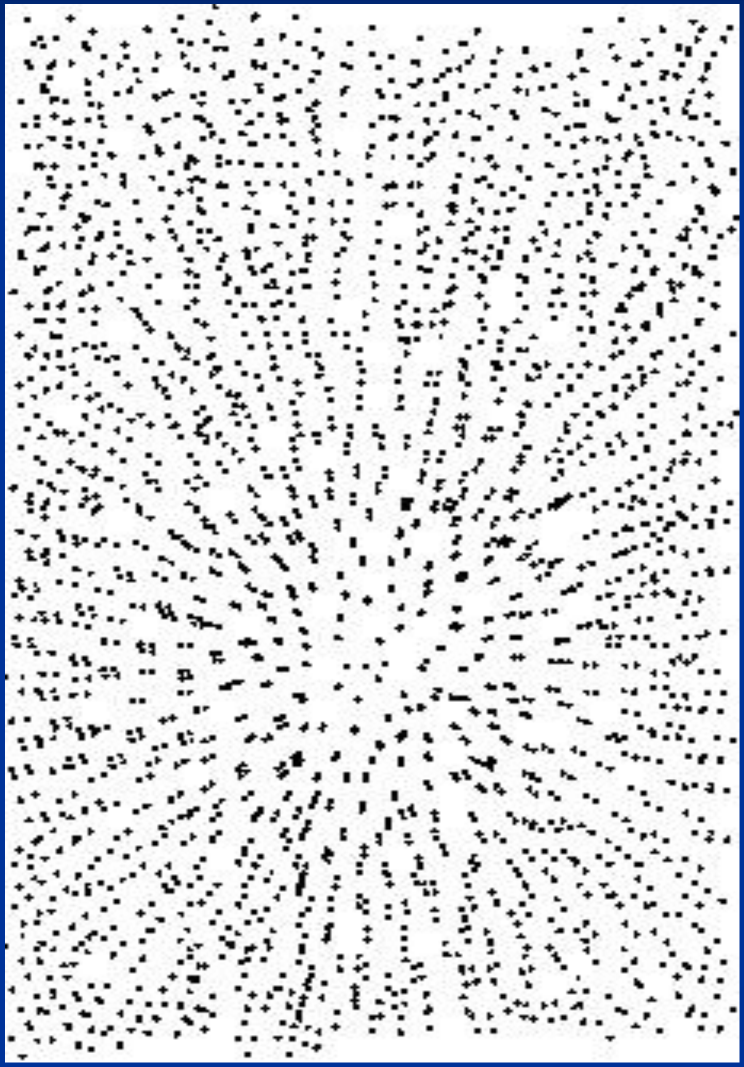
Activity 6: There is no center of expansion

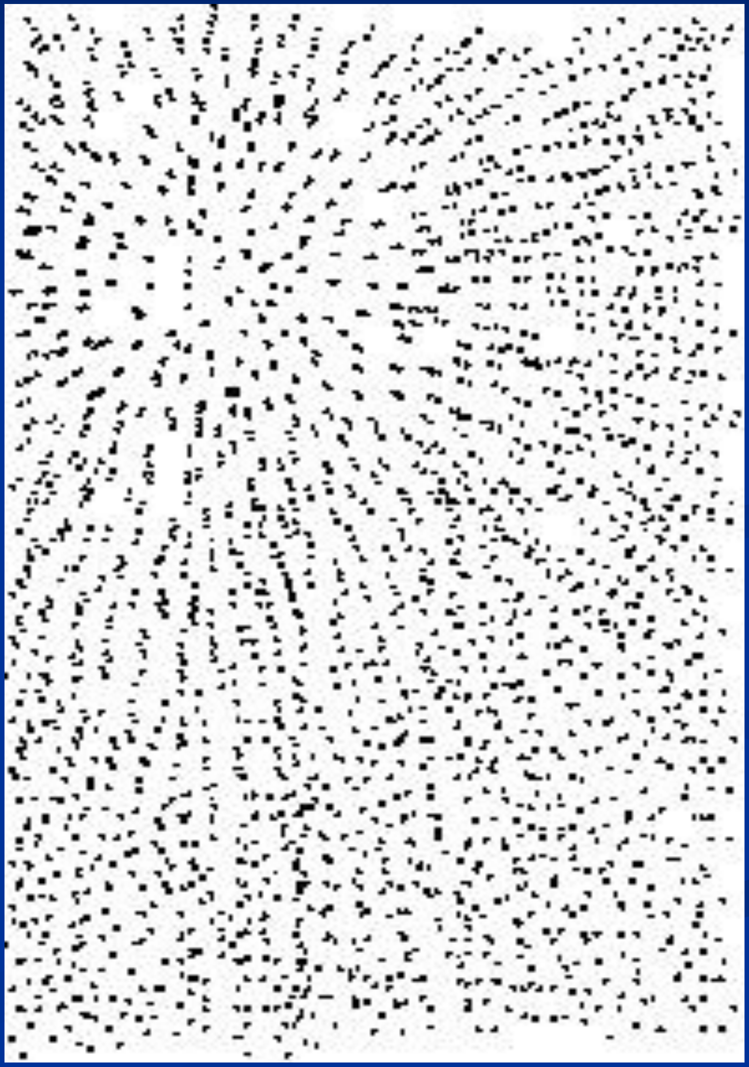


100%

105%

Activity 6: There is no center of expansion



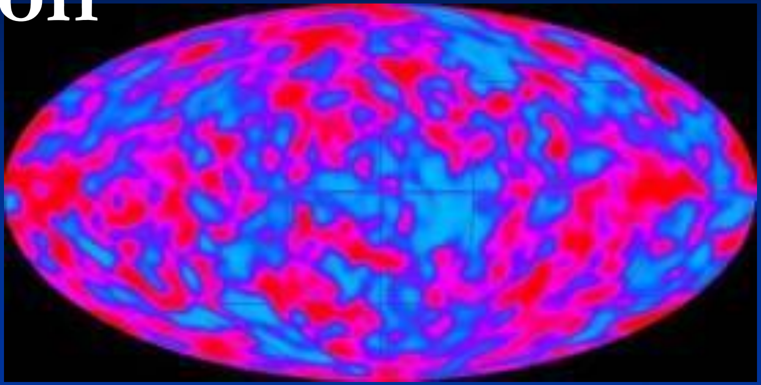


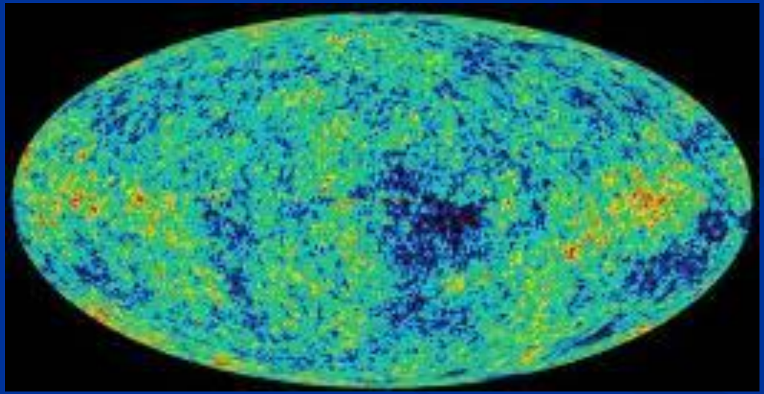
Cosmic Microwave Background (CMB) Radiation

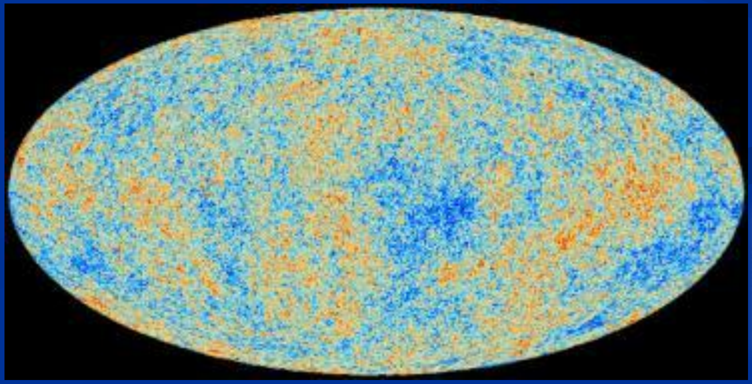
- Radiation which became free at 380 000 years after the Big Bang.
- Over time, as space expands, the CMB photons expanded in their wavelength.
- They are now in the microwave region.

Cosmic Microwave Background (CMB) Radiation

- **The COBE, WMAP and PLANCK** missions made a map of the sky of CMB radiation, every time with more detail. They detected small fluctuations: imprints of lumps of matter from which galaxies began to form.







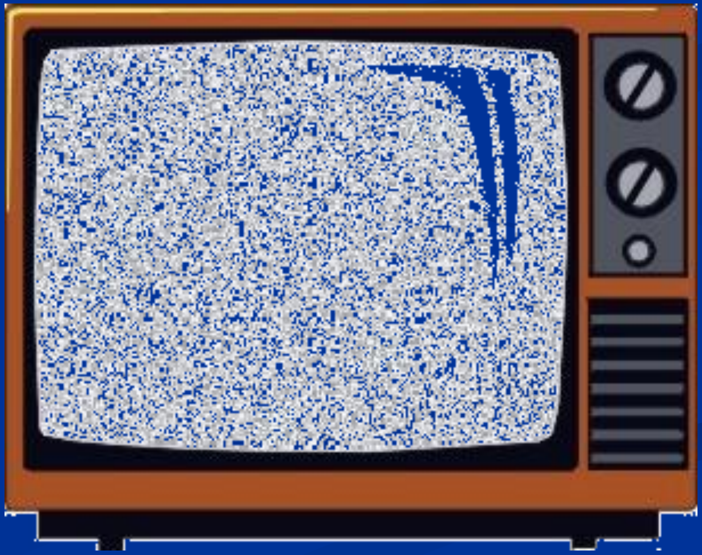
Activity 7: Cosmic background radiation

- More than 300 000 years after the Big Bang, the photons separated from matter and began to travel freely through the universe.

- By expanding the space, photons extended their wavelength, currently $\lambda = 2$ mm, equivalent to $T = 2.7$ K = -270 °C.

Activity 7: Cosmic background radiation (CMB)

We can detect CMB with an analogue TV. In an empty channel, one out of ten points comes from microwave background radiation. A similar effect can be heard on a VHF radio which is tuned off-station.



Dark Mater: Spin table which compensates for the attraction of terrestrial gravity

Black Holes are invisible, but we know that they exist because their gravitational force makes the stellar systems to move around them.

Although the dark matter is invisible, one way to detect it is by observing and studying the motion of the spiral arms of galaxies.

Another way to detect dark matter: gravitational lensing

The gravitational lens acts like an optical lens, its mass distorts the surrounding space and deflects the light of a distant object.

Gravitational lenses

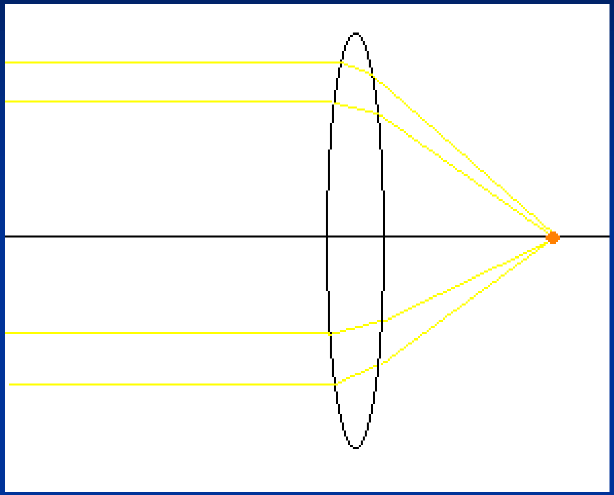
- Light always follows the shortest possible path
- If the surface is curved, the path is curved.

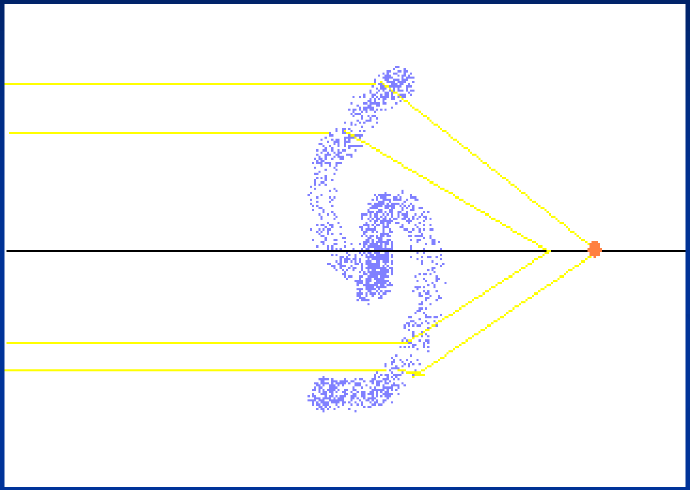
Why light bends when passing near a body?

- If there is a mass, the space is curved and the shortest path between two points is a curve.

- A similar situation can be seen using an Earth globe.

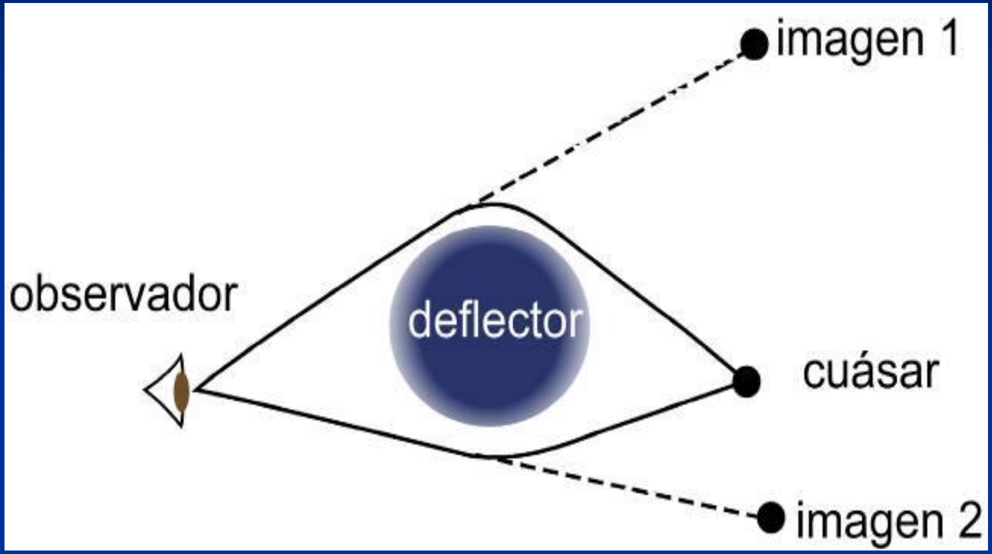
How do gravitational lenses work?

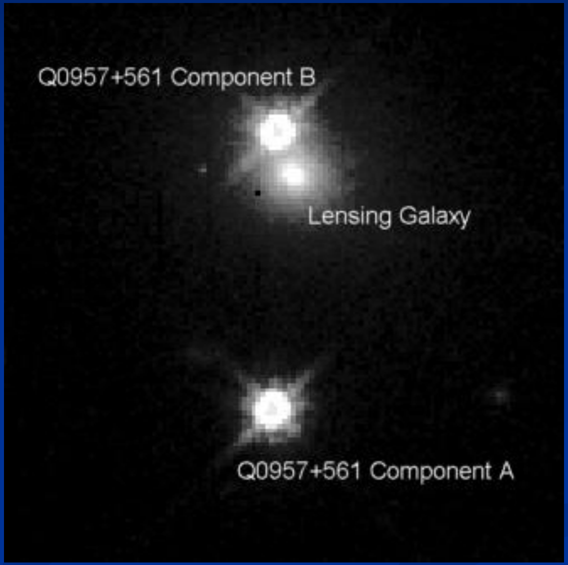




- A convex optical lens focuses parallel rays of light into one point: the focus.
- A gravitational lens (e.g. galaxy or group/cluster of galaxies) focuses the light rays into a line instead of a point; this can introduce several distortions in the image.

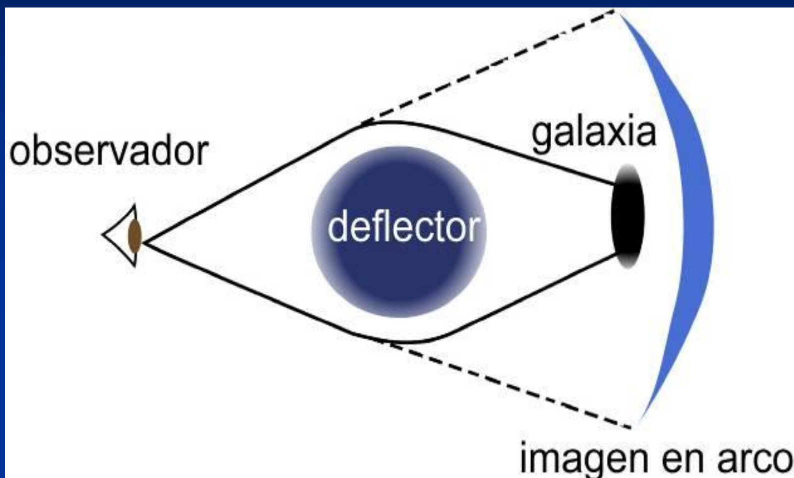
Position changes and multiplication

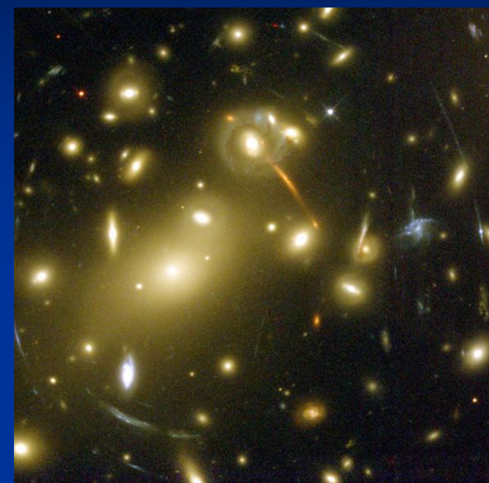




- The deflection produces the apparent position of star, galaxy or quasar.
- Gravitational lenses are not perfect, the largest ones can produce multiple images.

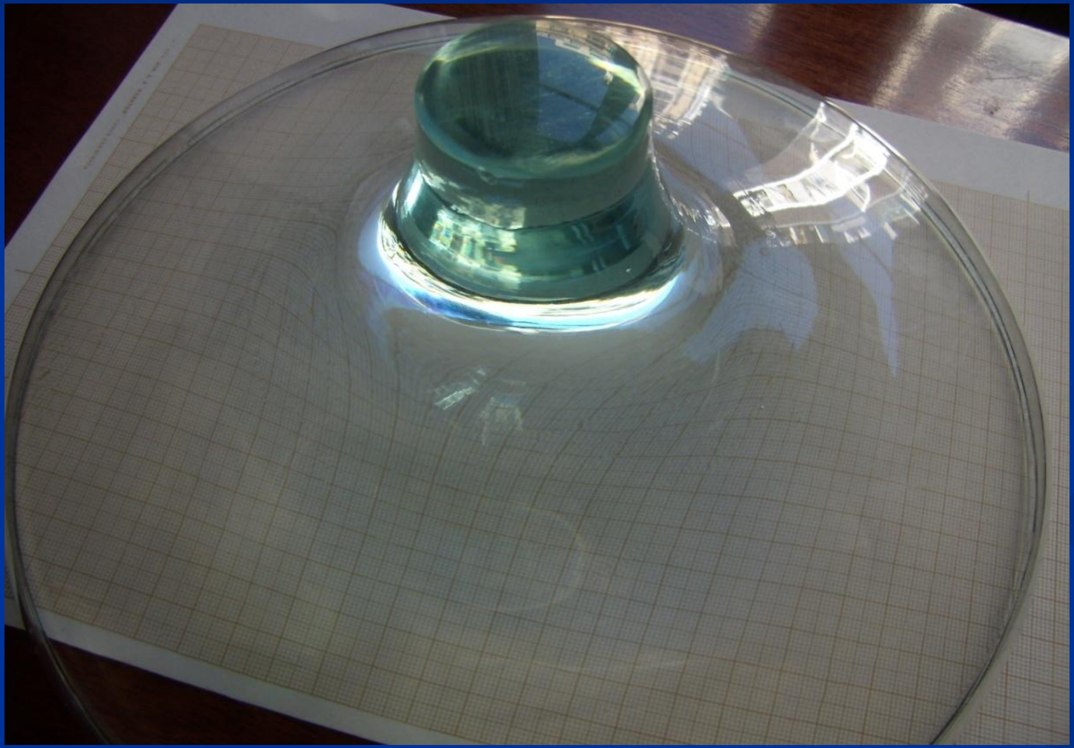
Deflection





- If the deflecting body is an extended astronomical source, the resulting images are a set of bright arcs.
- If the lens system is perfectly symmetrical, the rays converge and the result is a ring - an Einstein Ring.
- If the deflecting body is a star or a quasar, the image is a point.

Activity 8: Simulation of the deformation with the foot of a wine glass



If we place the base of a wine glass on a graph paper we can see the deformation.

Activity 8: Looking through the "bottom of a wine glass"

Just cut the bottom off the glass.

+

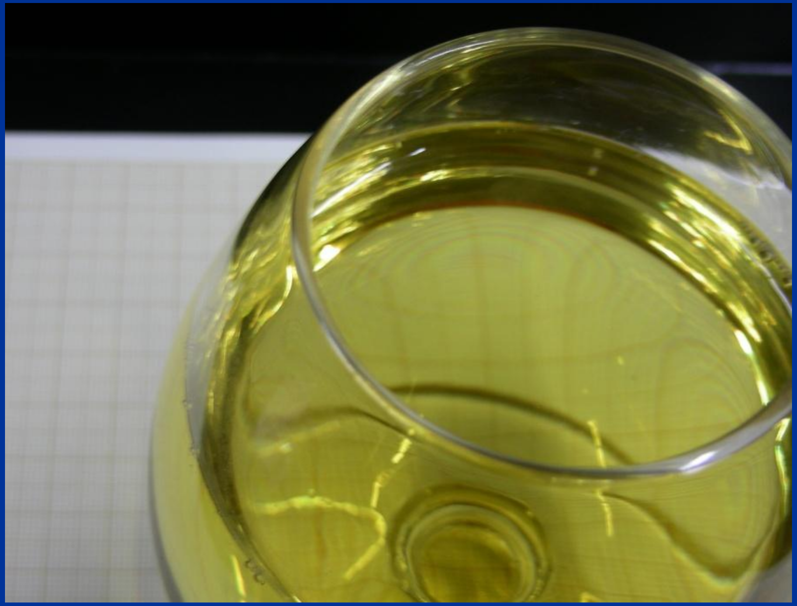
=

Arc fragment

Einstein Cross

Einstein ring

Activity 9: Simulation of the space deformation with a glass of wine



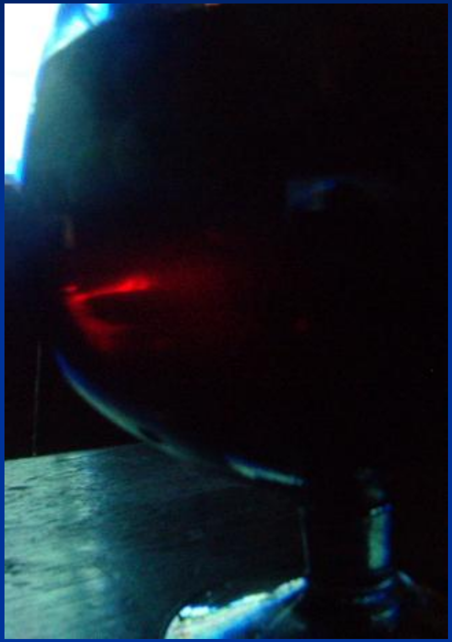
If you put a glass of white wine on graph paper and look through the wine, you can see this deformation.

Activity 9: Fix a flashlight and move slowly while looking through a glass of wine

This simple model shows that "matter" can reproduce distortions in images observed through it.

(The wine can be replaced by another translucent liquid)

Activity 9: Fix a flashlight and move slowly while looking through a glass of wine



Fragment of arc

Amorphous figure

Einstein cross

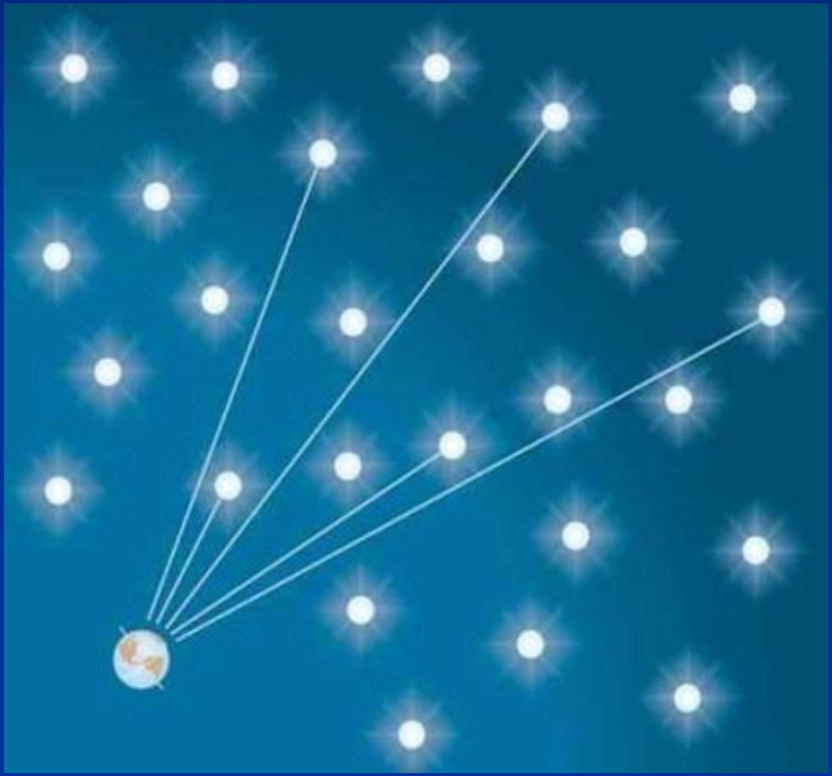
Einstein's Ring

A theme outside the workshop: Why is the sky dark at night?

In 1923 Olbers suggested that if:

- The universe is infinite in extent.
- The stars are uniformly distributed throughout the universe.
- All stars have a similar luminosity throughout the universe, then…

A theme outside the workshop: Why is the sky dark at night?



… an infinite universe will have an infinite number of objects and should be bright during the night.

Why is the sky dark at night?

Then :

- Any point on the sky would be bright, not dark, since there would be always a distant star shining.
- The number of stars in each “onion layer” of the sky is proportional to r^2, and their light is inversely proportional to r^2, where each layer provides the same amount of light at the Earth. If there are an infinite number of layers, the sky should appear bright at night.

Why is the sky dark at night?

But there are errors in this reasoning:

- The stars look redder the further away they are because of the expansion. They are less luminous because their distance.
- But above all, the universe doesn't have an infinite age. There are no infinite layers of stars.

Edgar Allan Poe was the one who correctly explains the phenomena in his essay "Eureka", published in 1848.

The night can be dark!

Thank you very much for your attention!