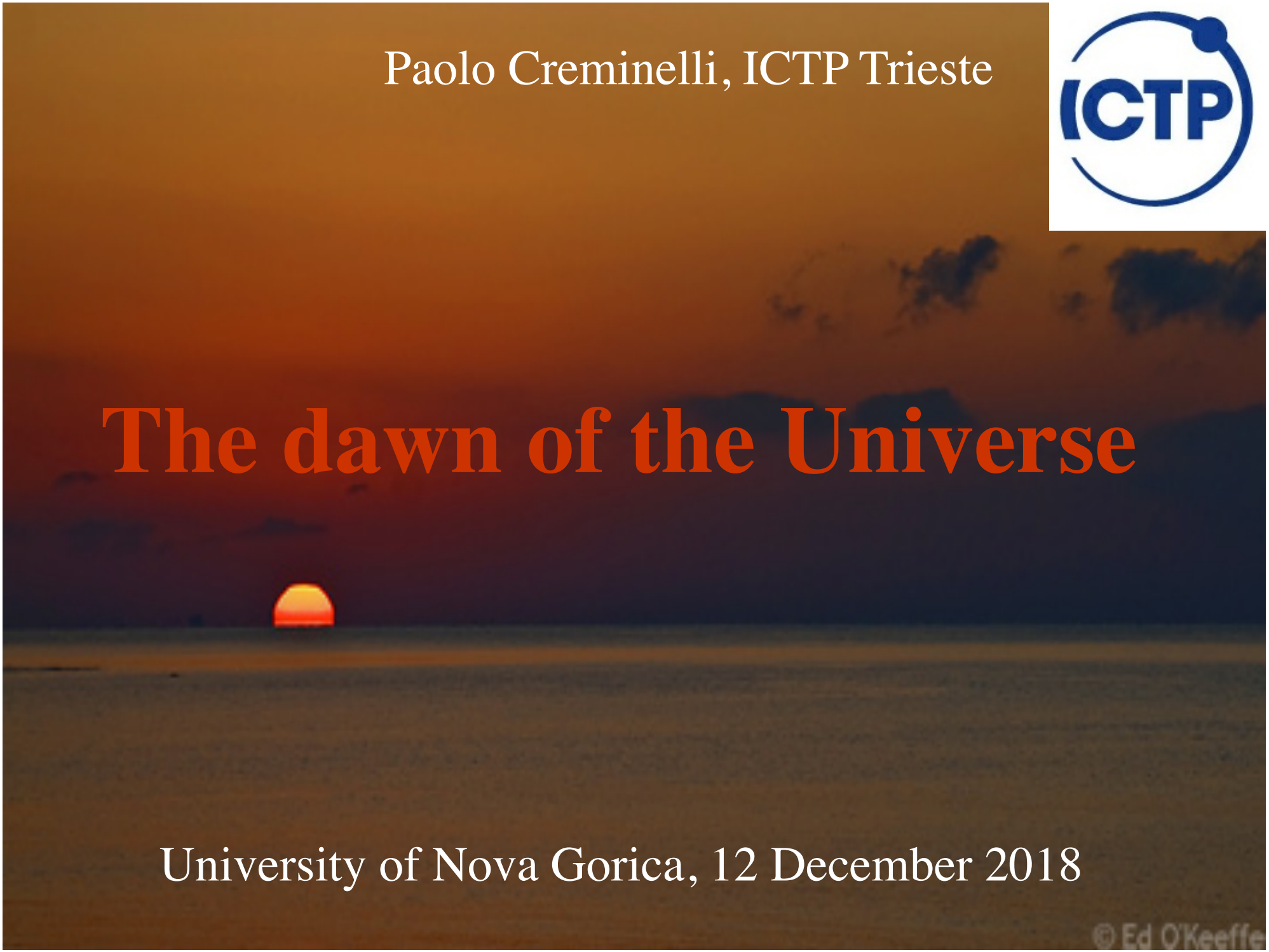
Paolo Creminelli, ICTP Trieste



The dawn of the Universe

University of Nova Gorica, 12 December 2018

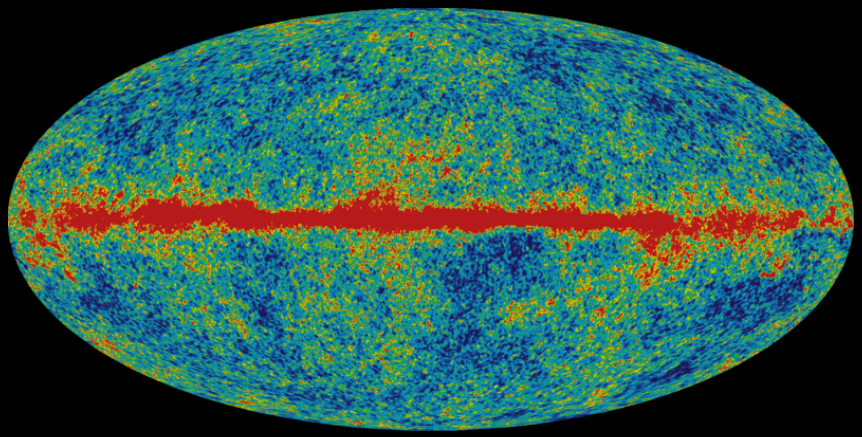
What is a cosmologist?

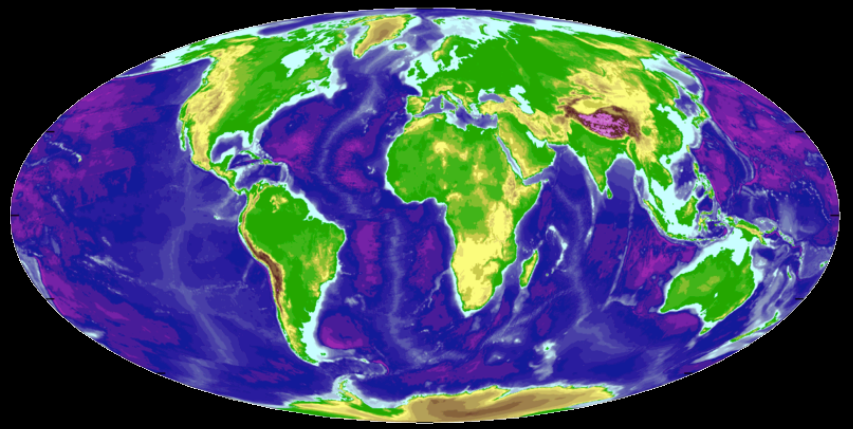
She/He studies the Universe as a whole (not caring about details!)

On much larger distances and time scales she is

- **A geographer**

3d maps of the cosmo until the most remote regions

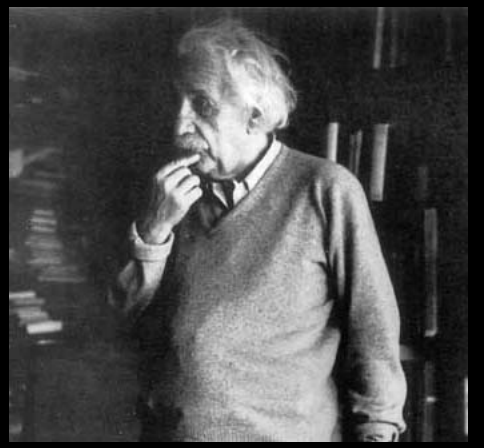




- **An archaeologist**

The history of the Universe: various phases, as geological eras

Geographer or archaeologist ?!



The speed of light is finite: ~ 300.000 km/s.
Far away objects appear to us as they were
millions or billions years ago.

Earth

1.2 seconds

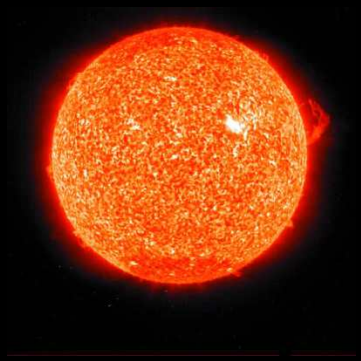
Moon

Looking at far away objects is a travel
backwards in time

Distances and velocities

We want to know the distance and the velocity of each Galaxy

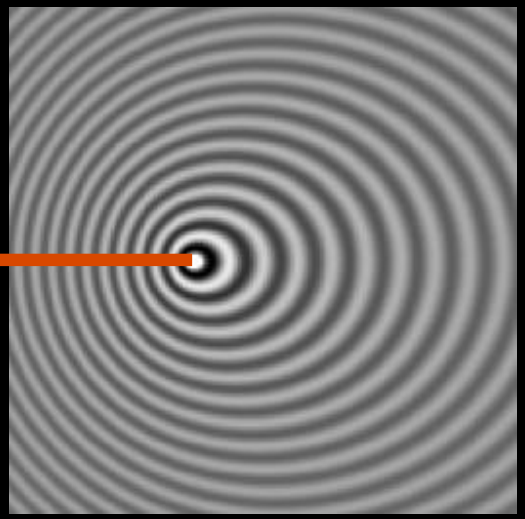
- **Distance**. The farther an object is, the fainter it is



Standard candles

- **Velocity**. The motion changes the frequency of light

Doppler effect

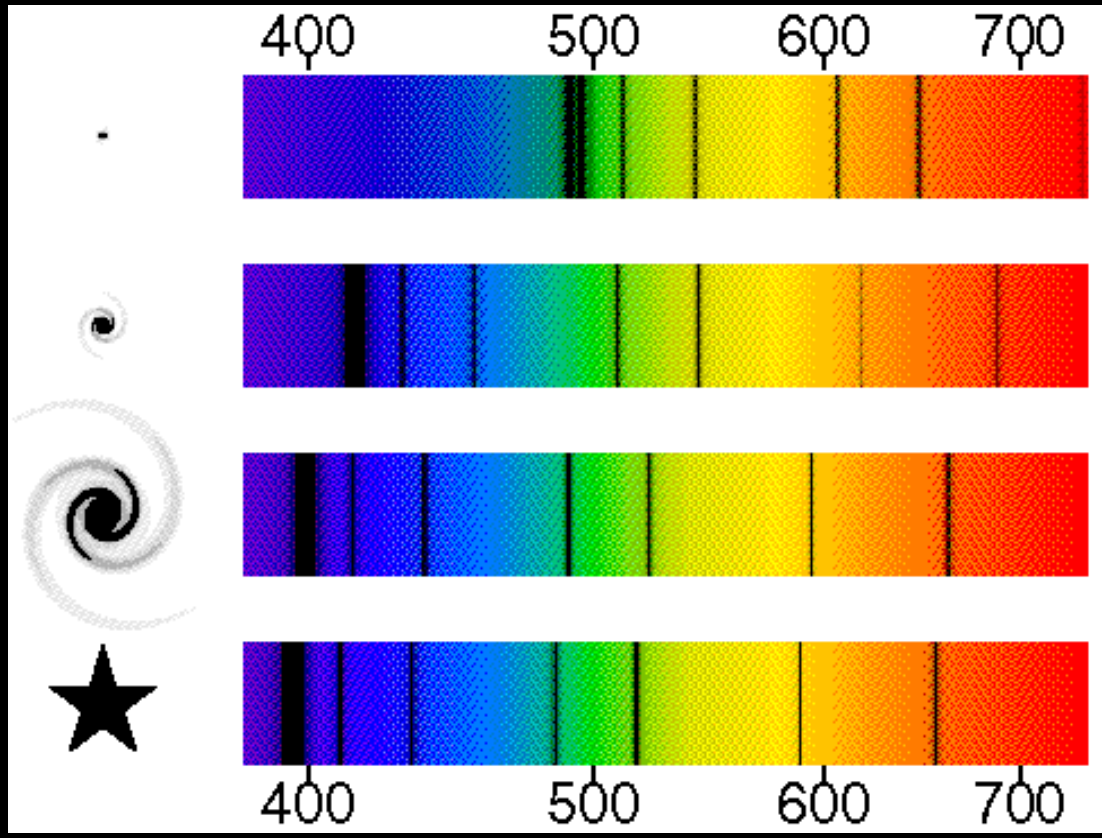


The light has a higher frequency if the source comes towards us

Spectra and redshift

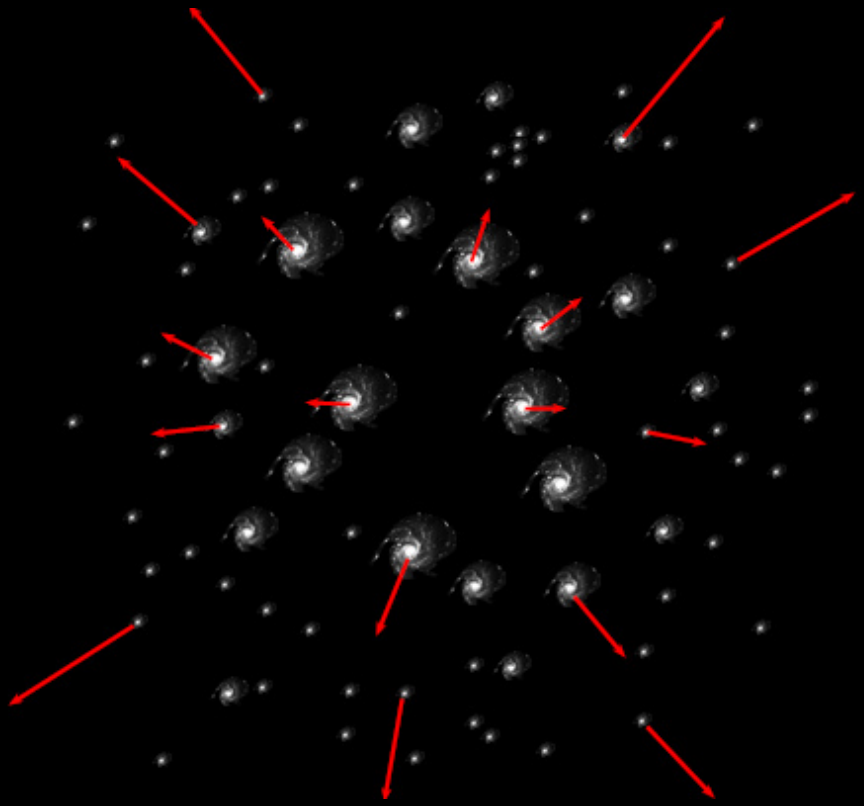
Every atom is characterized by its own frequencies of emission

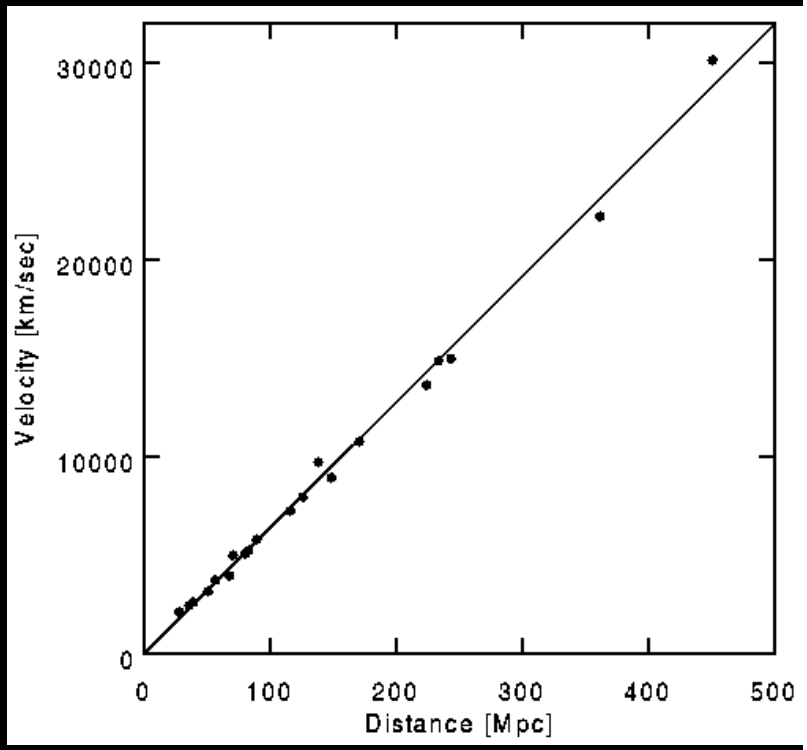
In far away Galaxies these frequencies are moved towards the red (redshift).



Galaxies are moving away from us!!

Hubble law (1929)



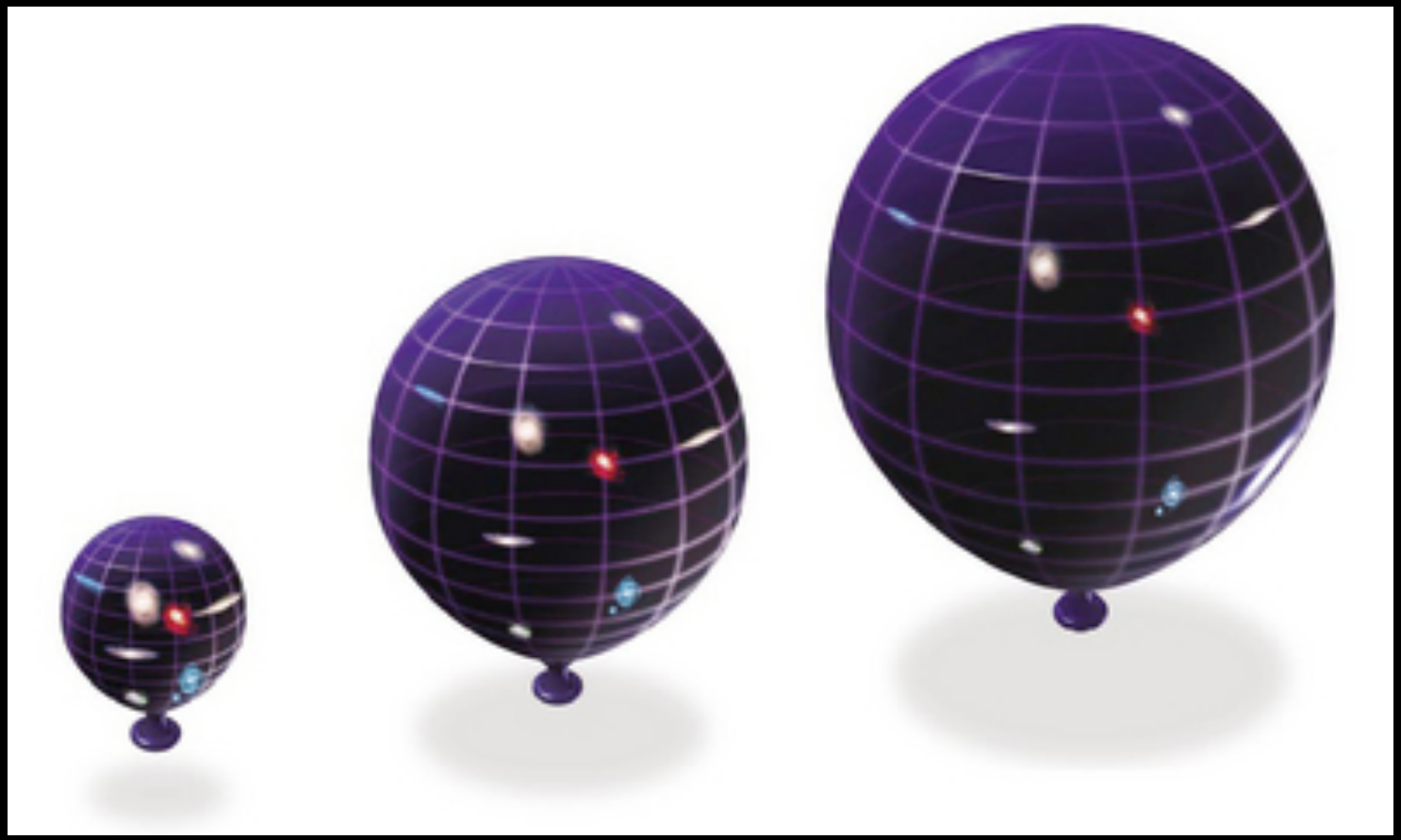


The farthest Galaxies are the quickest to fly away from us

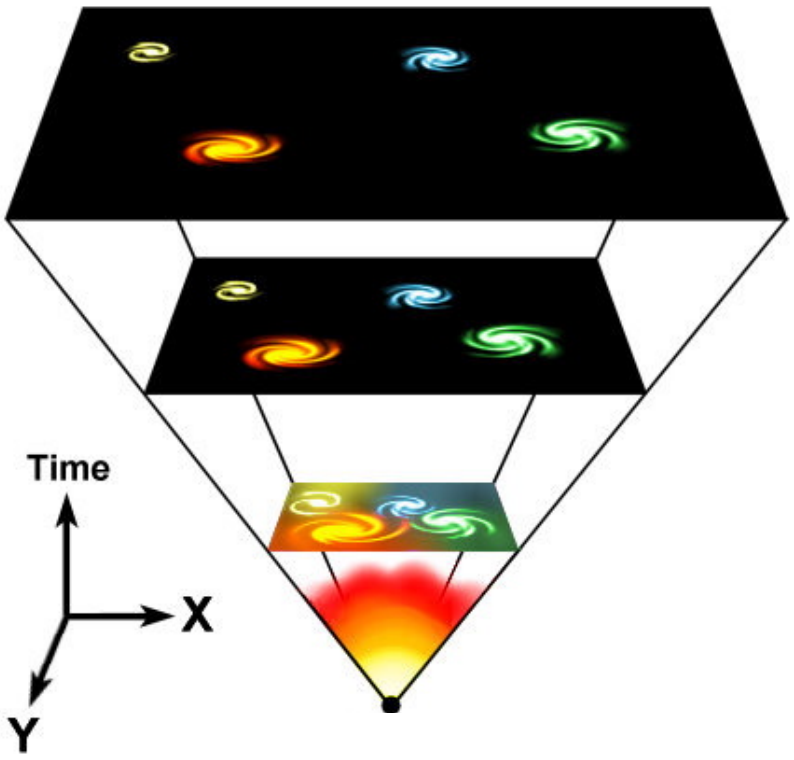
Hubble law: $v = H_0 d$

Velocity is proportional to distance!

The Universe is expanding!



Backwards in time...



Matter is denser and denser

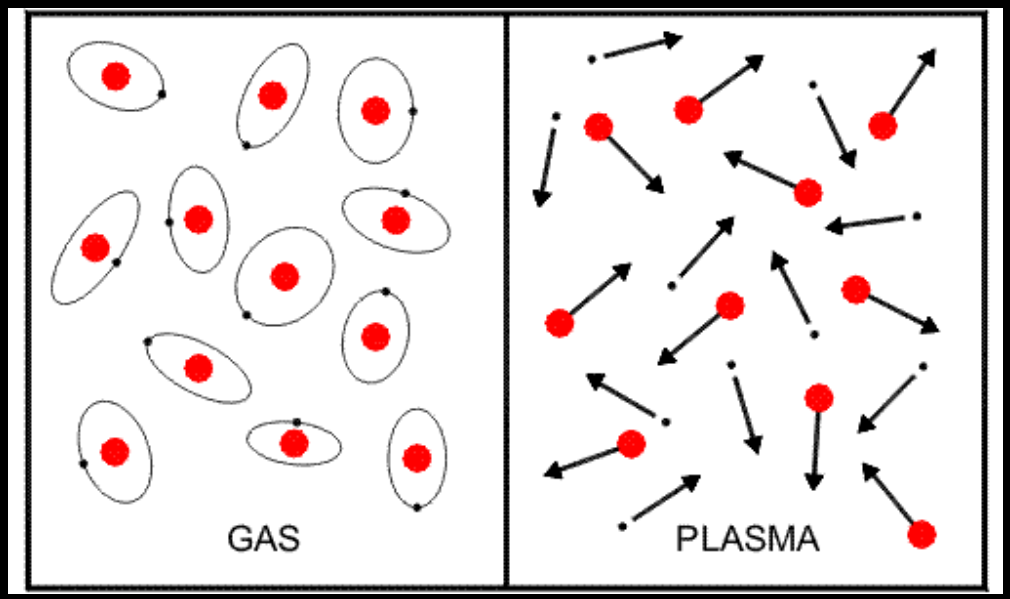
As in a compressed gas, energy grows more and more!

$$T \propto \frac{1}{a}$$


Big Bang
Our Universe was in a
very energetic and hot state

Primordial soup

At high energy matter gets simpler:
atoms and even nuclei “melt”



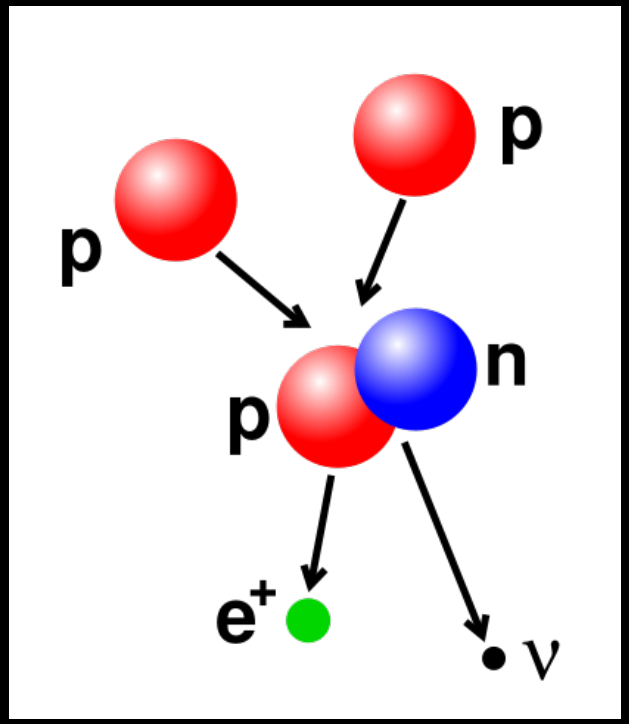
We arrive to an enormous cosmic soup, composed by few **fundamental constituents** (electrons, protons, neutrinos...)

Nucleosynthesis

Are we sure? How much can we go back in time?

From the primordial expanding soup,
light elements (hydrogen and helium) form.

We can calculate this abundance and compare
it with experiments



We understand the evolution of the Universe since
when the soup had a temperature of 10 billion degrees,
13.7 billion years ago!

The Universe as an accelerator

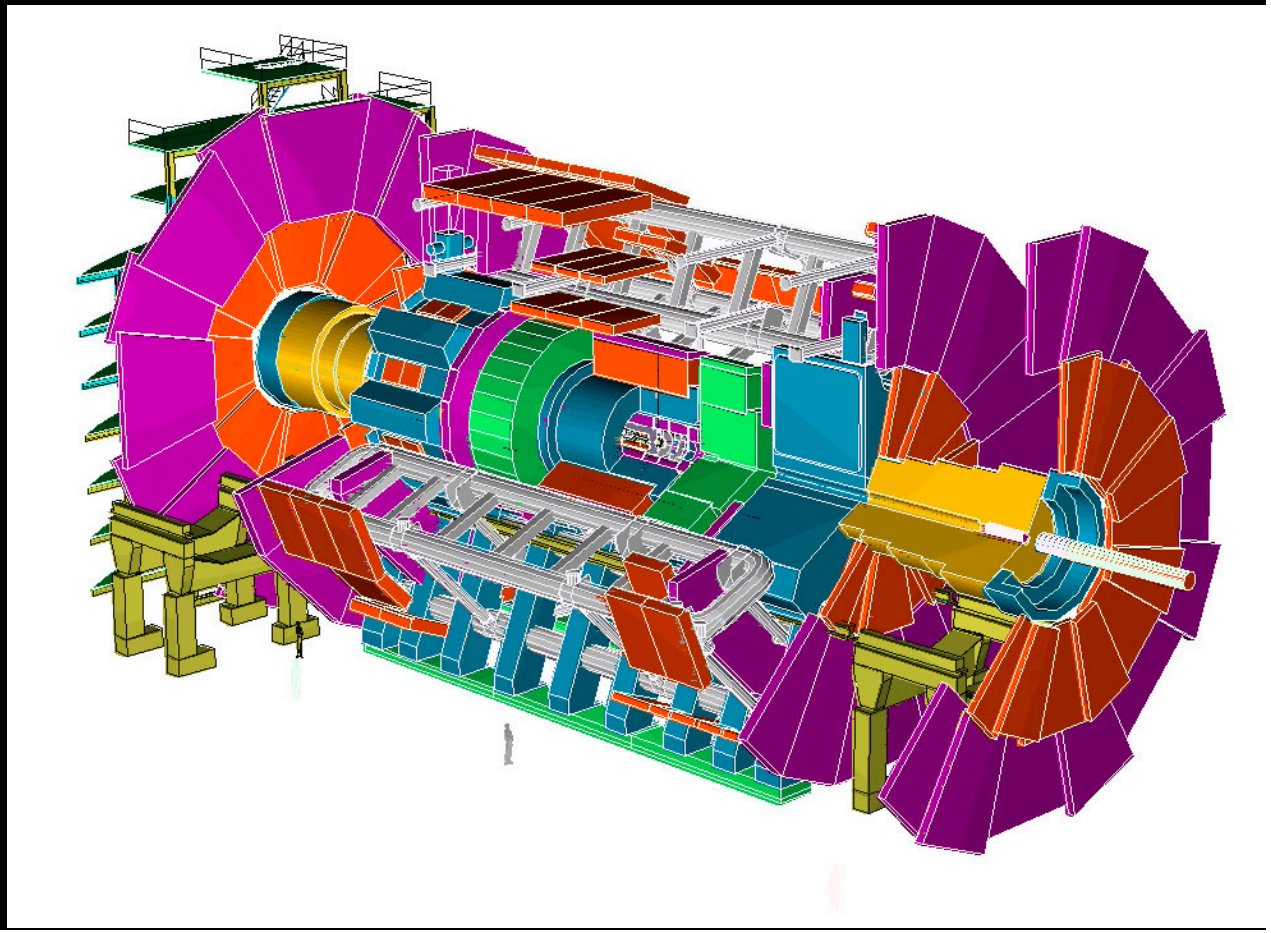
Going backwards in time the energy of the particles is so high that .... we do not really understand what is going on.
It depends on the microscopic structure of matter and on the behaviour of forces at unexplored distances.

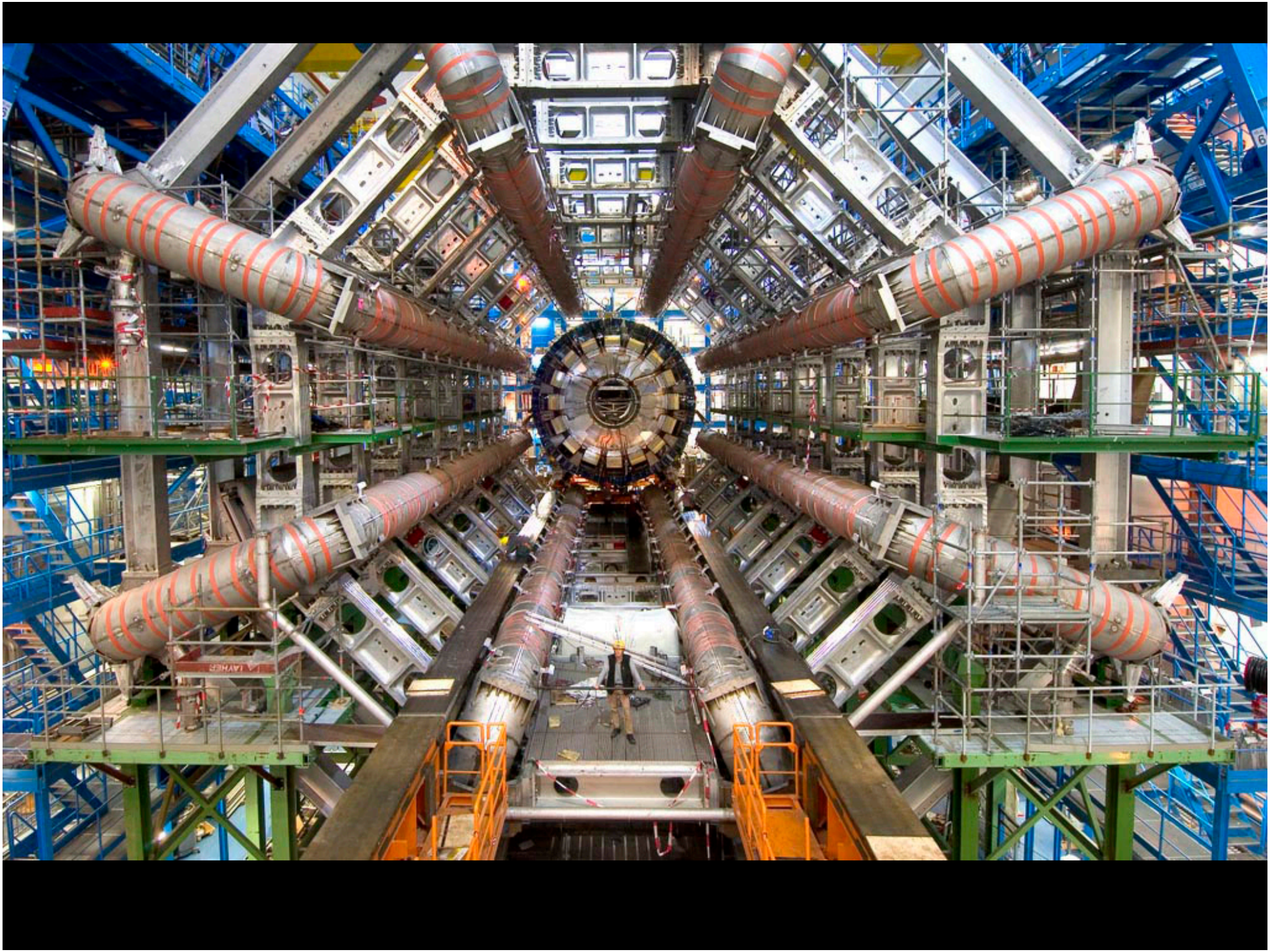
Similar conditions can be recreated in particle accelerators

CERN- Geneva

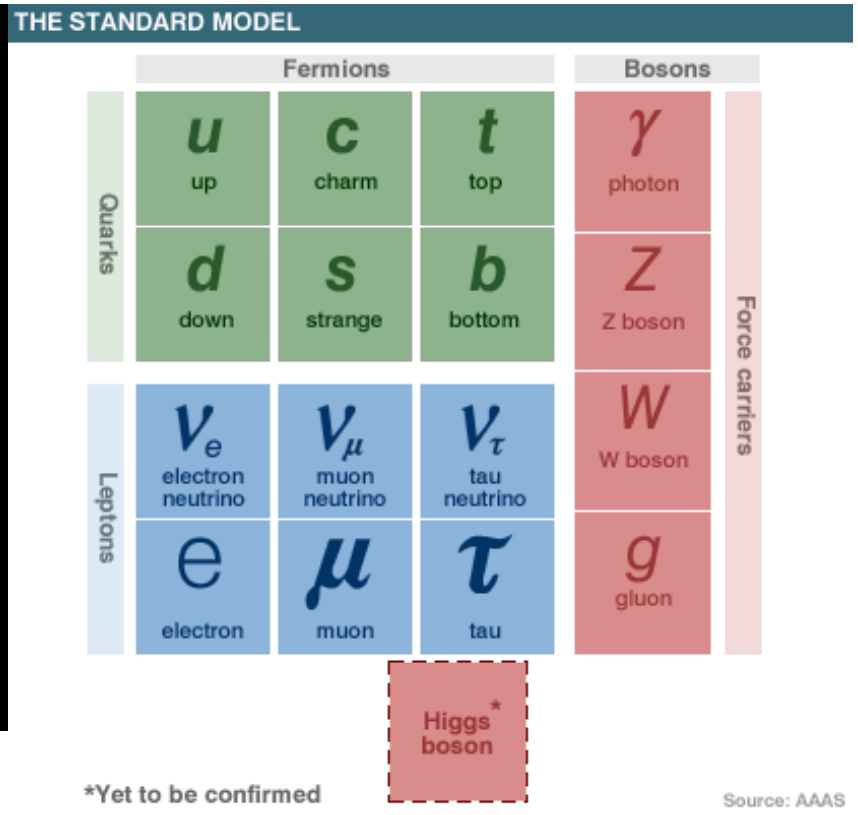
Infinitely large - infinitely small: the same frontier

Looking at the farthest away objects in the cosmo is a way to study the fundamental laws of particles!





The Standard Model



$$\mathcal{L}_{GWS} = \sum_f (\bar{\Psi}_f (i\gamma^\mu \partial\mu - m_f)\Psi_f - eQ_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu) +$$

$$+\frac{g}{\sqrt{2}} \sum_i (\bar{a}_L^i \gamma^\mu b_L^i W_\mu^+ + \bar{b}_L^i \gamma^\mu a_L^i W_\mu^-) + \frac{g}{2c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I_f^3 - 2s_w^2 Q_f - I_f^3 \gamma_5) \Psi_f Z_\mu +$$

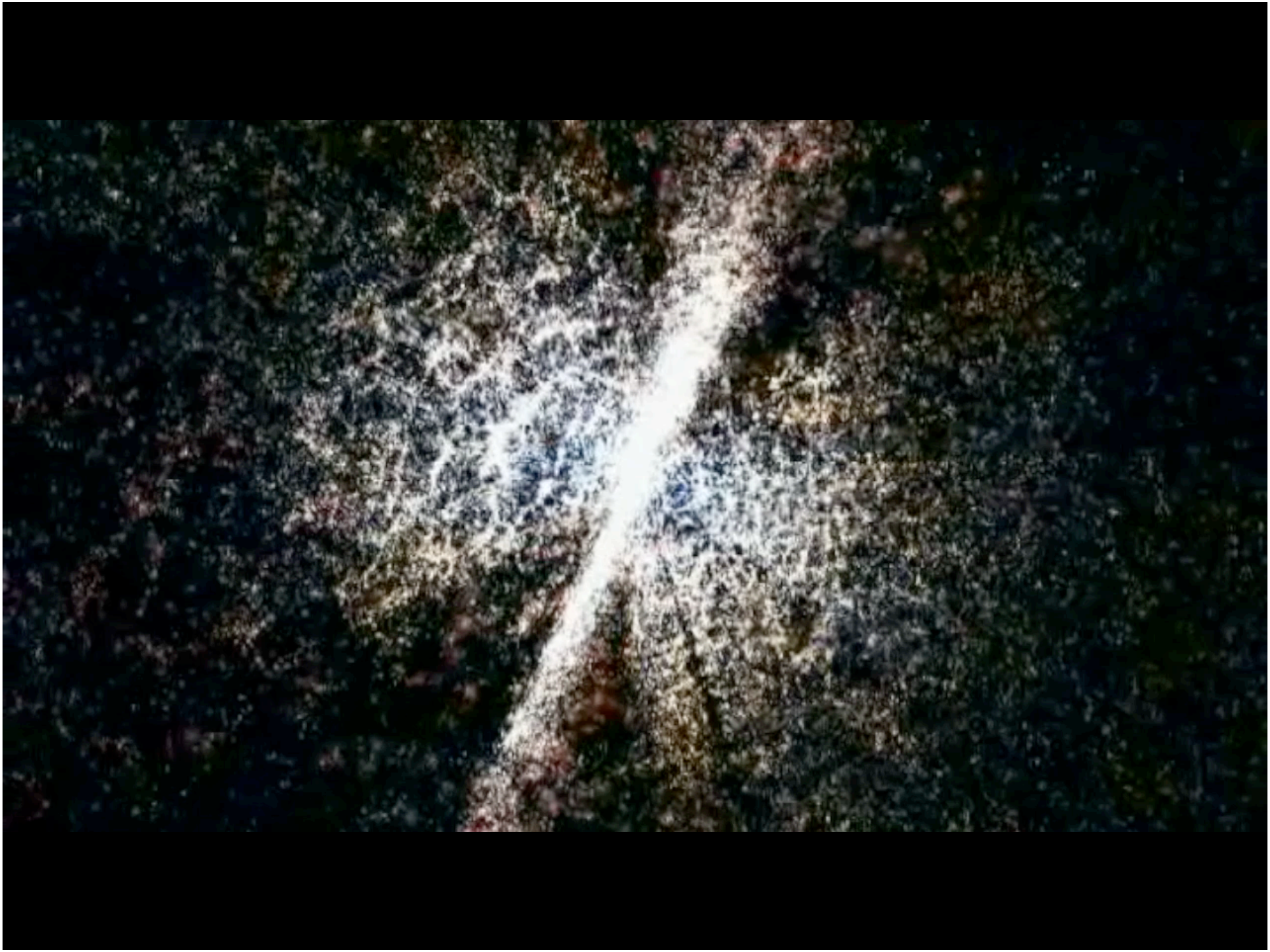
$$-\frac{1}{4}|\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 - \frac{1}{2}|\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+ +$$

$$-ie(W_\mu^+ A_\nu - W_\nu^+ A_\mu) + ig' c_w (W_\mu^+ Z_\nu - W_\nu^+ Z_\mu|^2 +$$

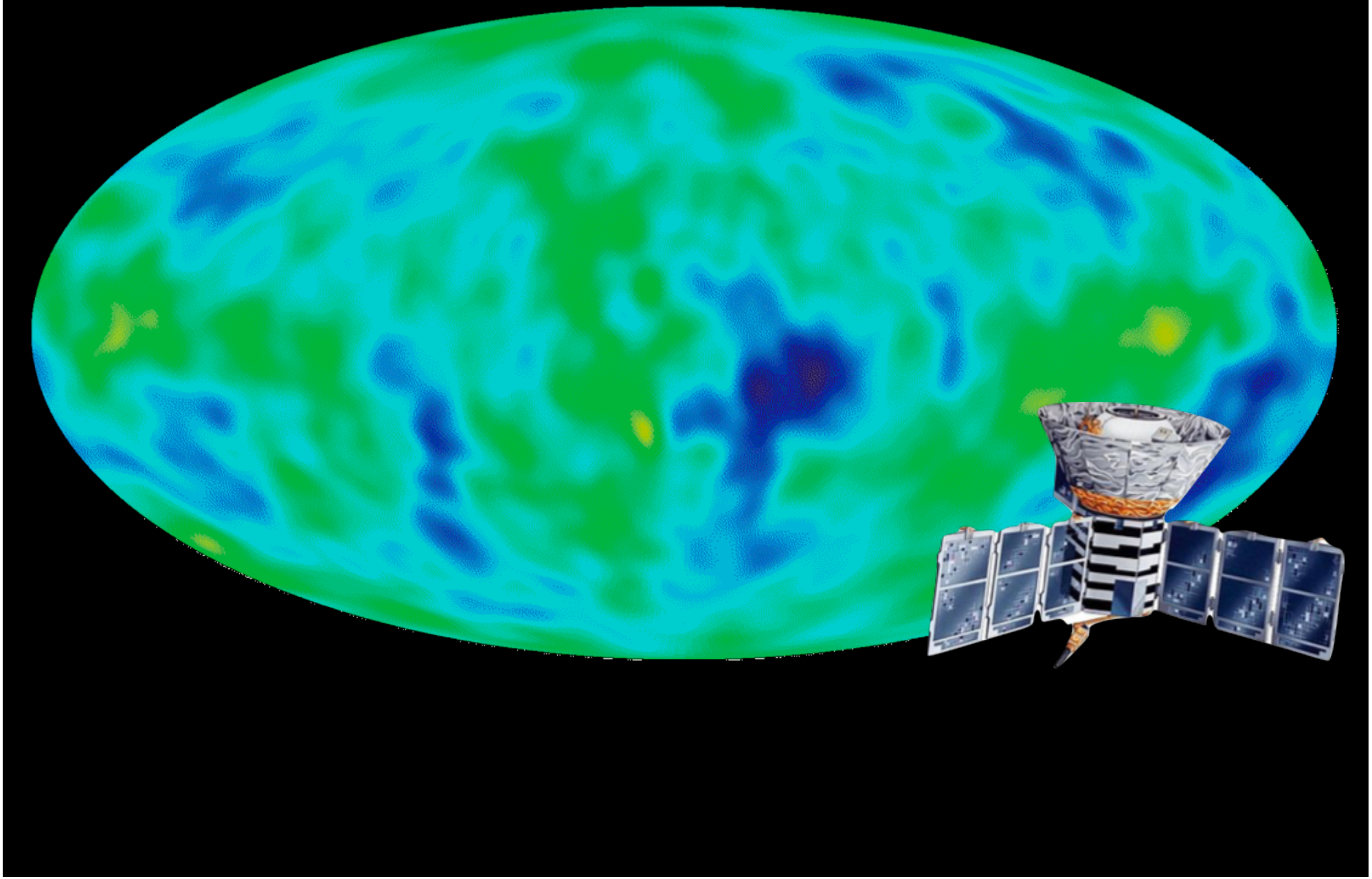
$$-\frac{1}{4}|\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 +$$

$$-\frac{1}{2} M_\eta^2 \eta^2 - \frac{g M_\eta^2}{8 M_W} \eta^3 - \frac{g'^2 M_\eta^2}{32 M_W} \eta^4 + |M_W W_\mu^+ + \frac{g}{2} \eta W_\mu^+|^2 +$$

$$+\frac{1}{2}|\partial_\mu \eta + i M_Z Z_\mu + \frac{ig}{2c_w} \eta Z_\mu|^2 - \sum_f \frac{g}{2} \frac{m_f}{M_W} \bar{\Psi}_f \Psi_f \eta$$

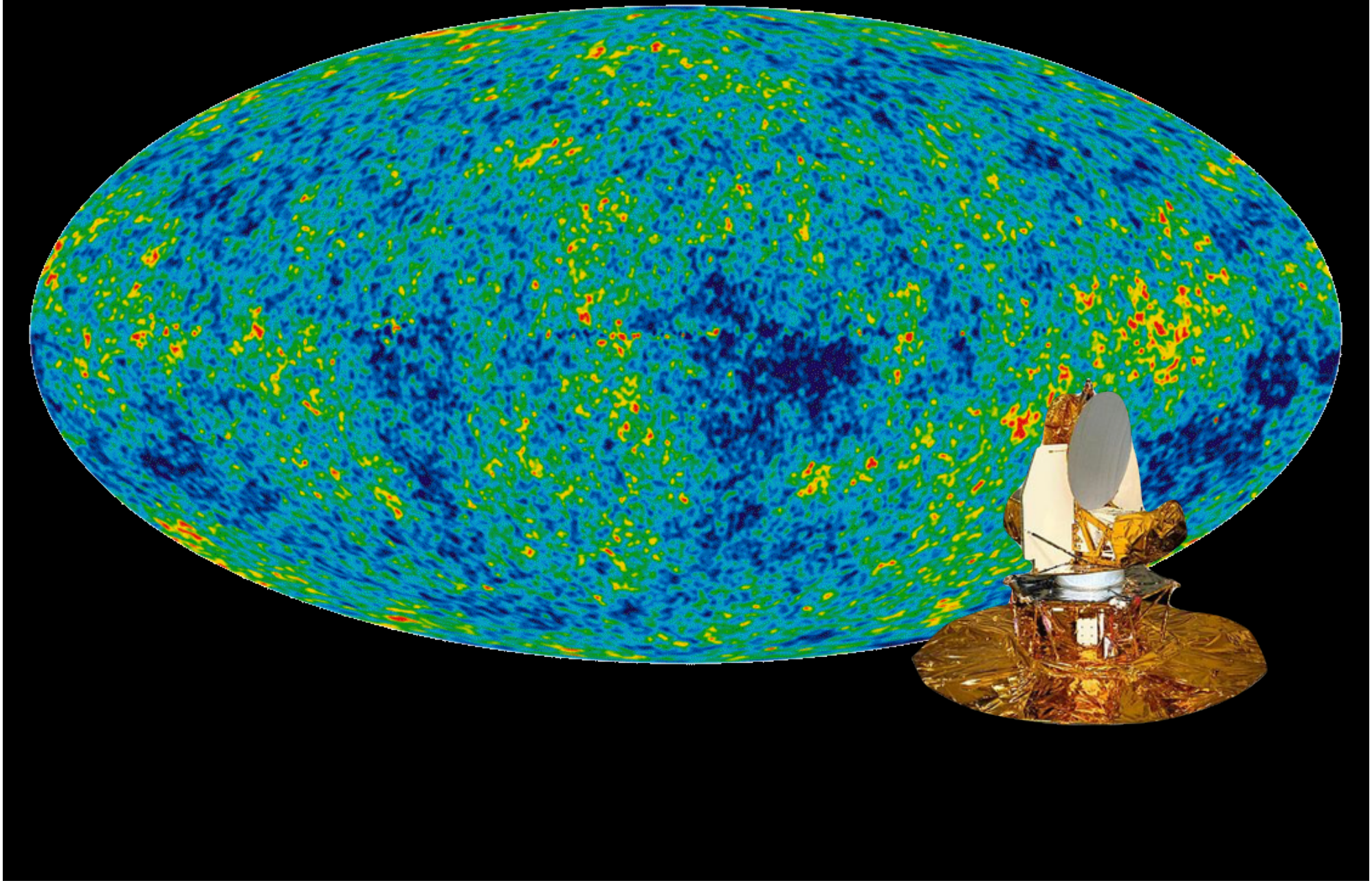


COBE (1992)



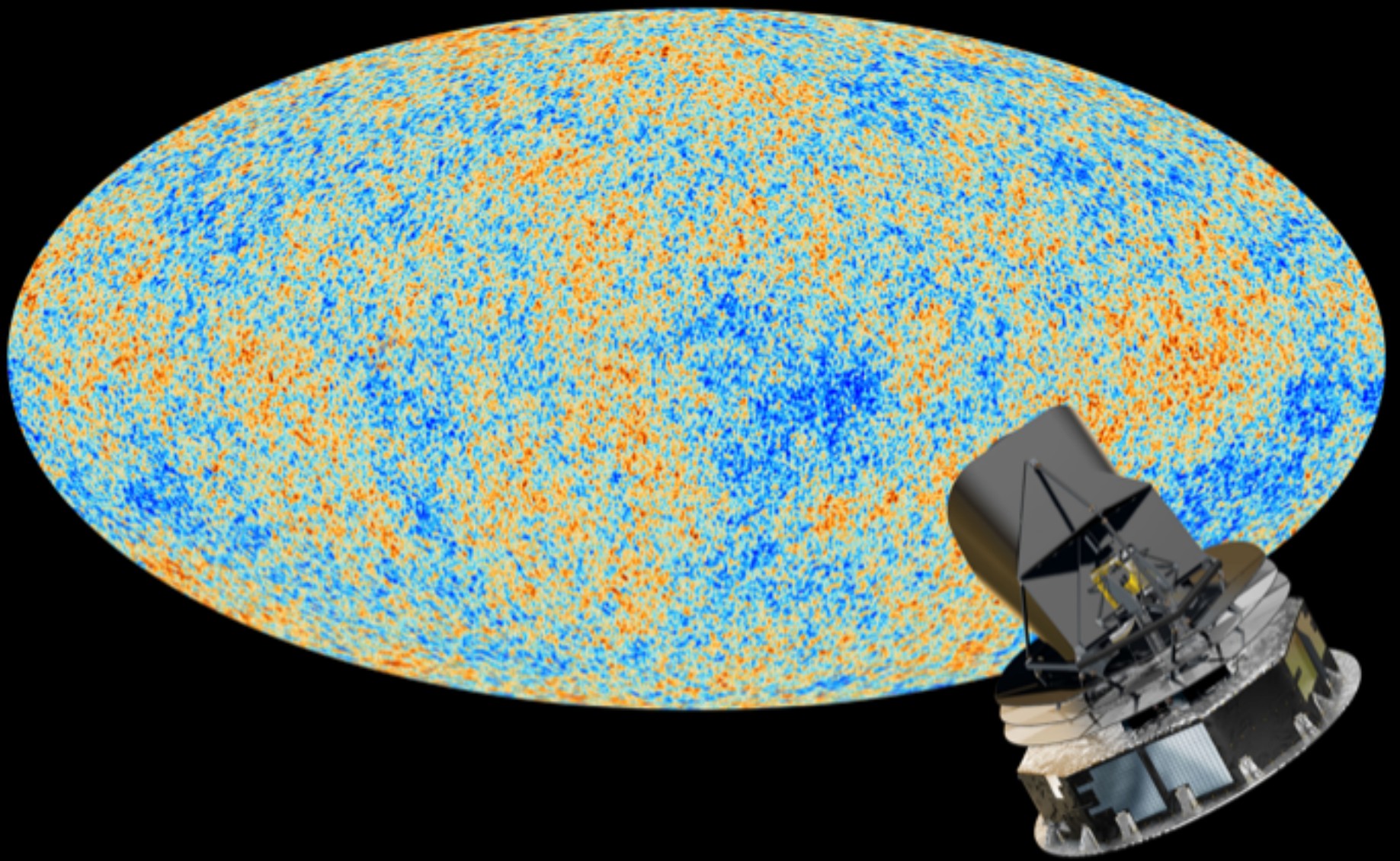
Occhiali da 150 milioni di $

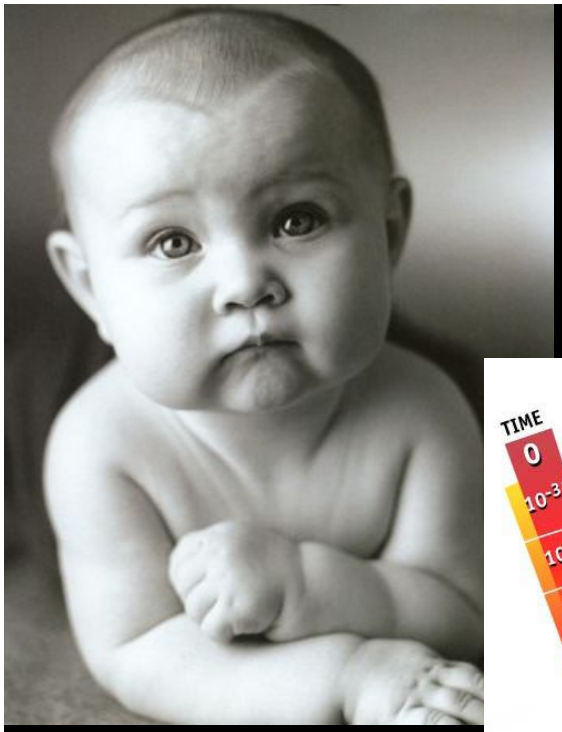
WMAP (2009)



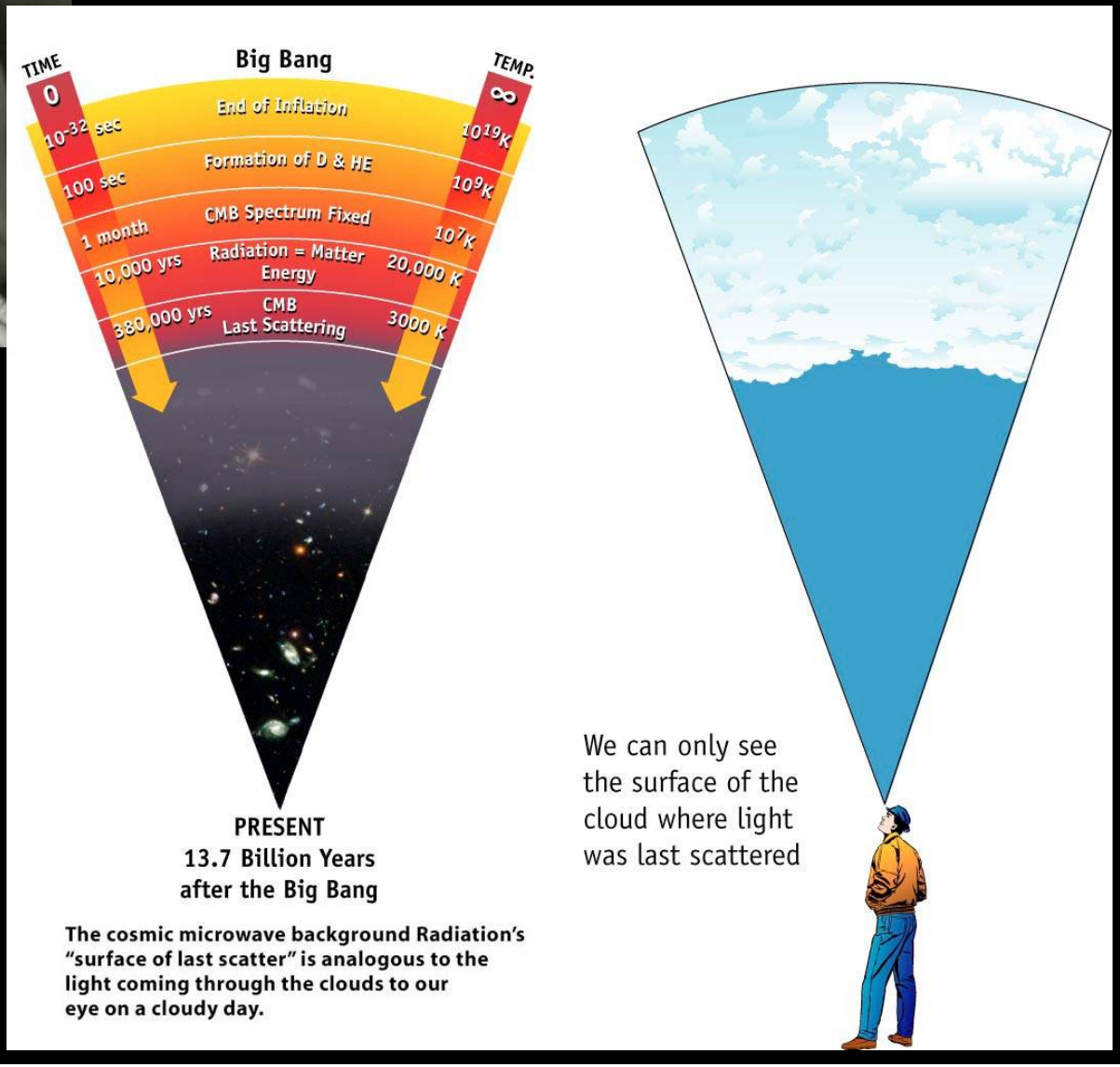
Occhiali da 700 milioni di $

Planck (2013)

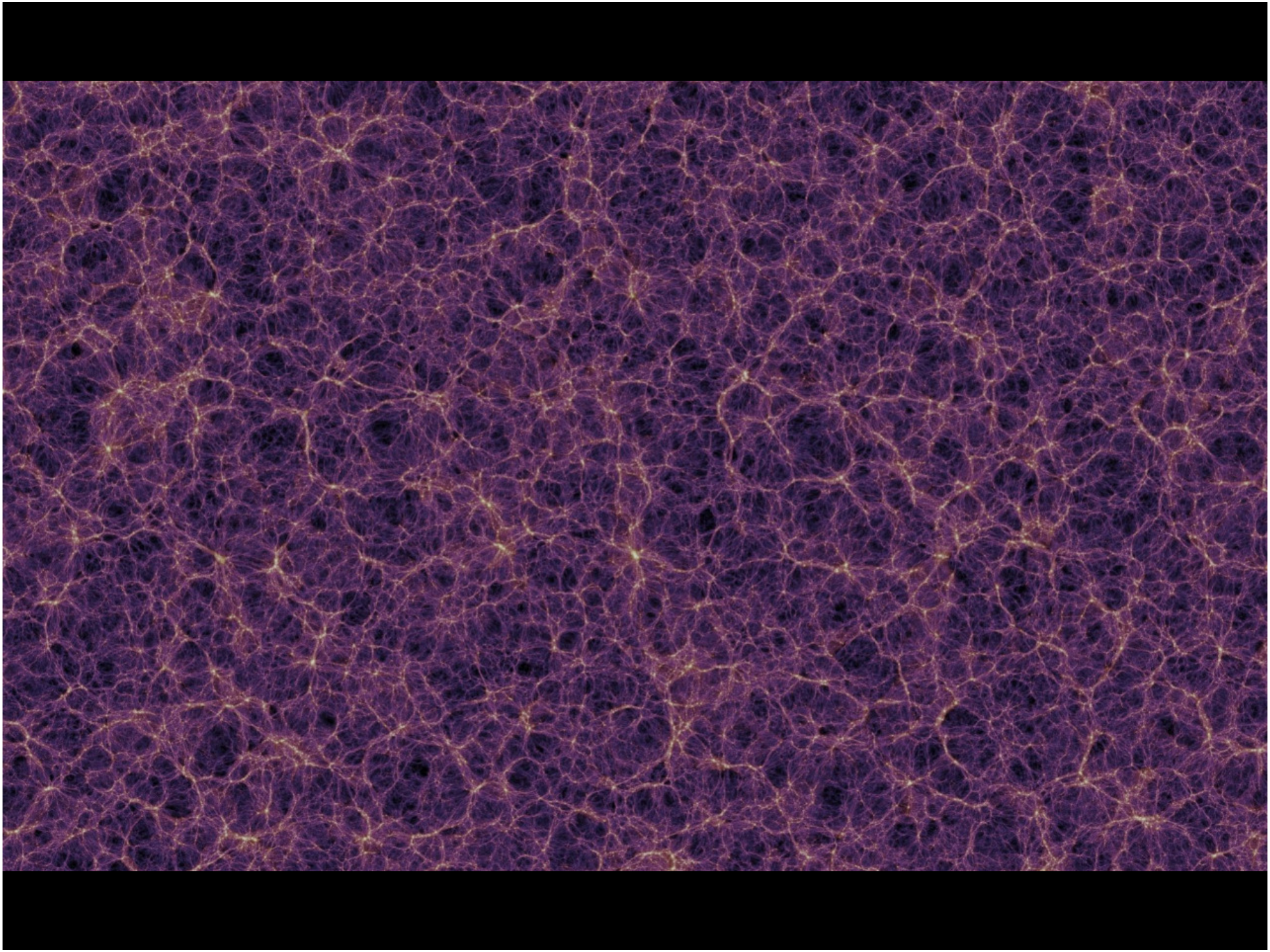




Baby Universe



The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

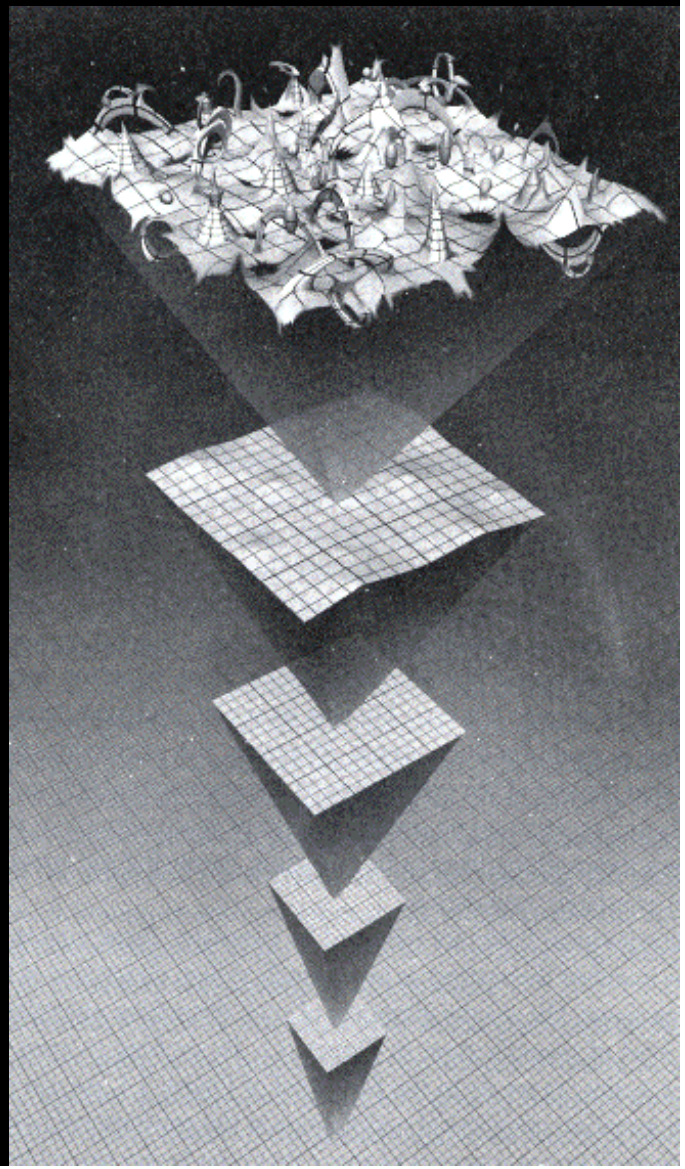


Quantum mechanics

... but we forgot about quantum mechanics!

Indetermination principle

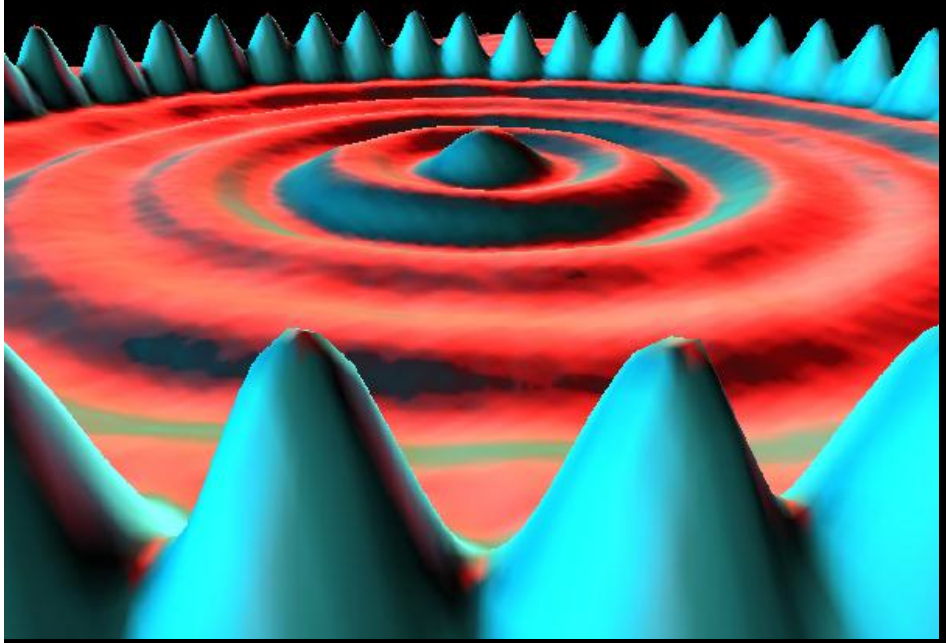
$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

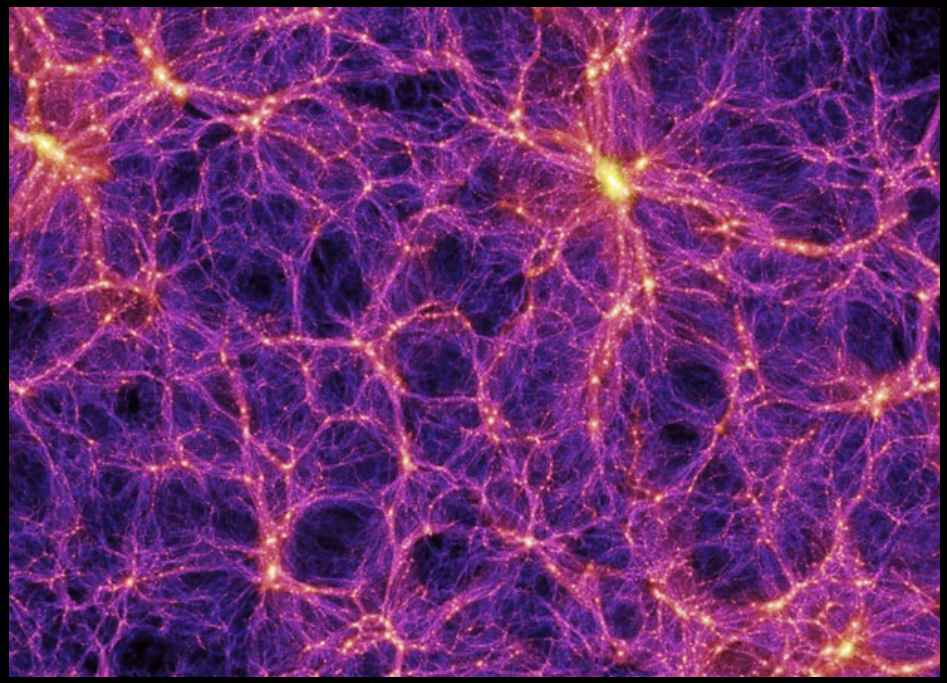


Everything from nothing

The very fast expansion makes fluctuations macroscopic.

Everything comes from quantum fluctuations and gravity!





The eternal mystery of the world is its comprehensibility

Albert Einstein

Other Universes?

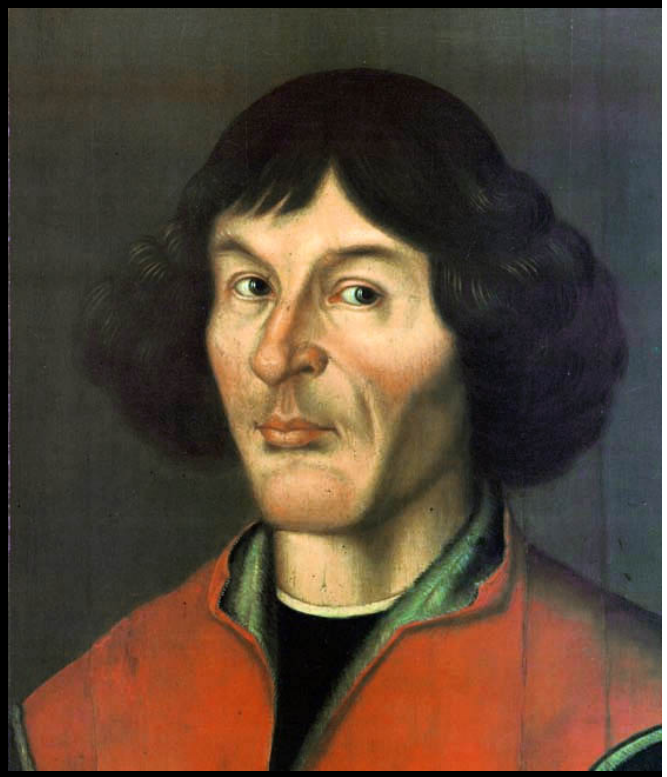
Going backwards fluctuations gets larger and larger...

Far away regions trapped in different “valleys”

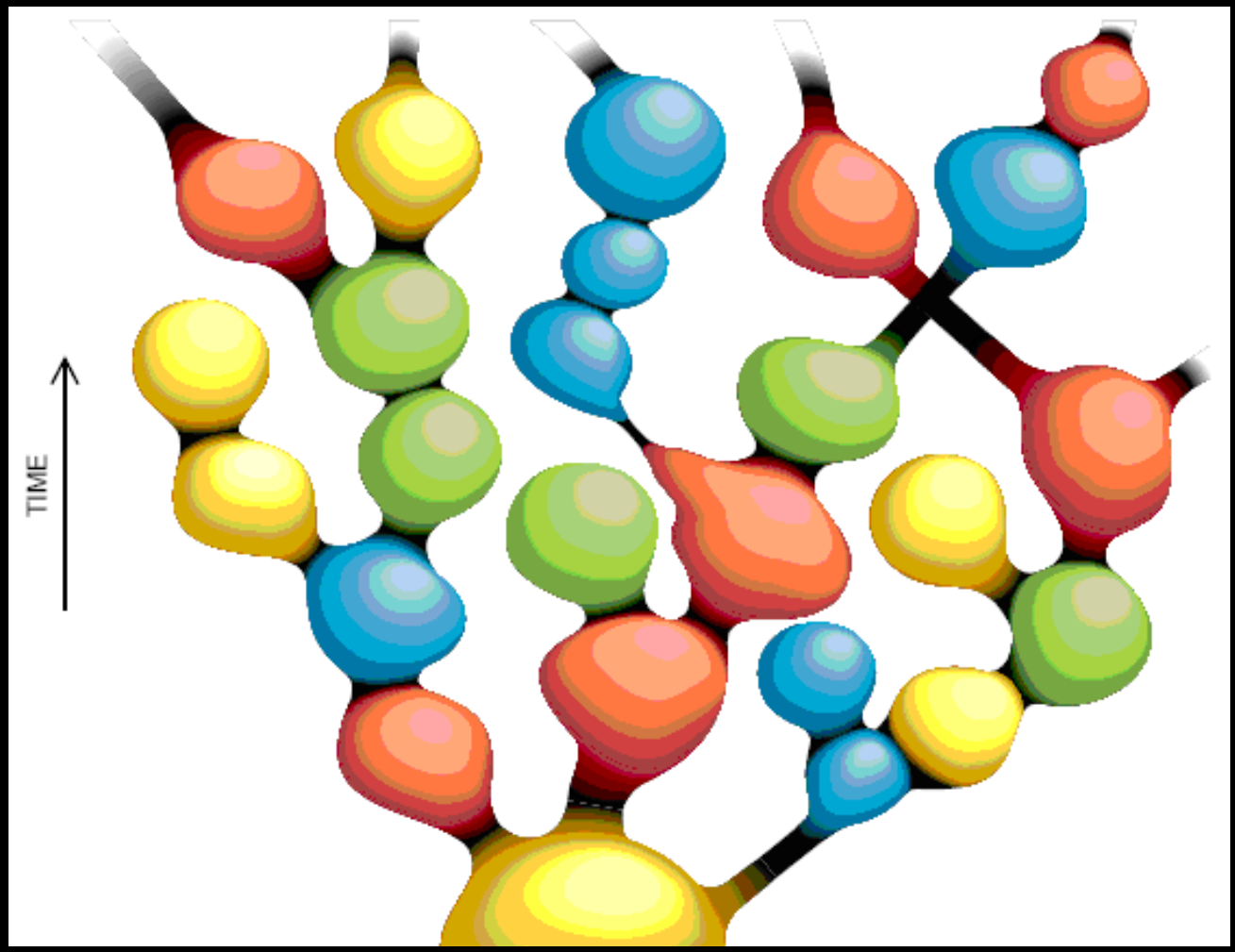
Different physical laws in different places

The last Copernican revolution?

As our position in the cosmo,
maybe even the laws of Nature
that we observe are not particular
but they change from place to place



Multi-Universe?

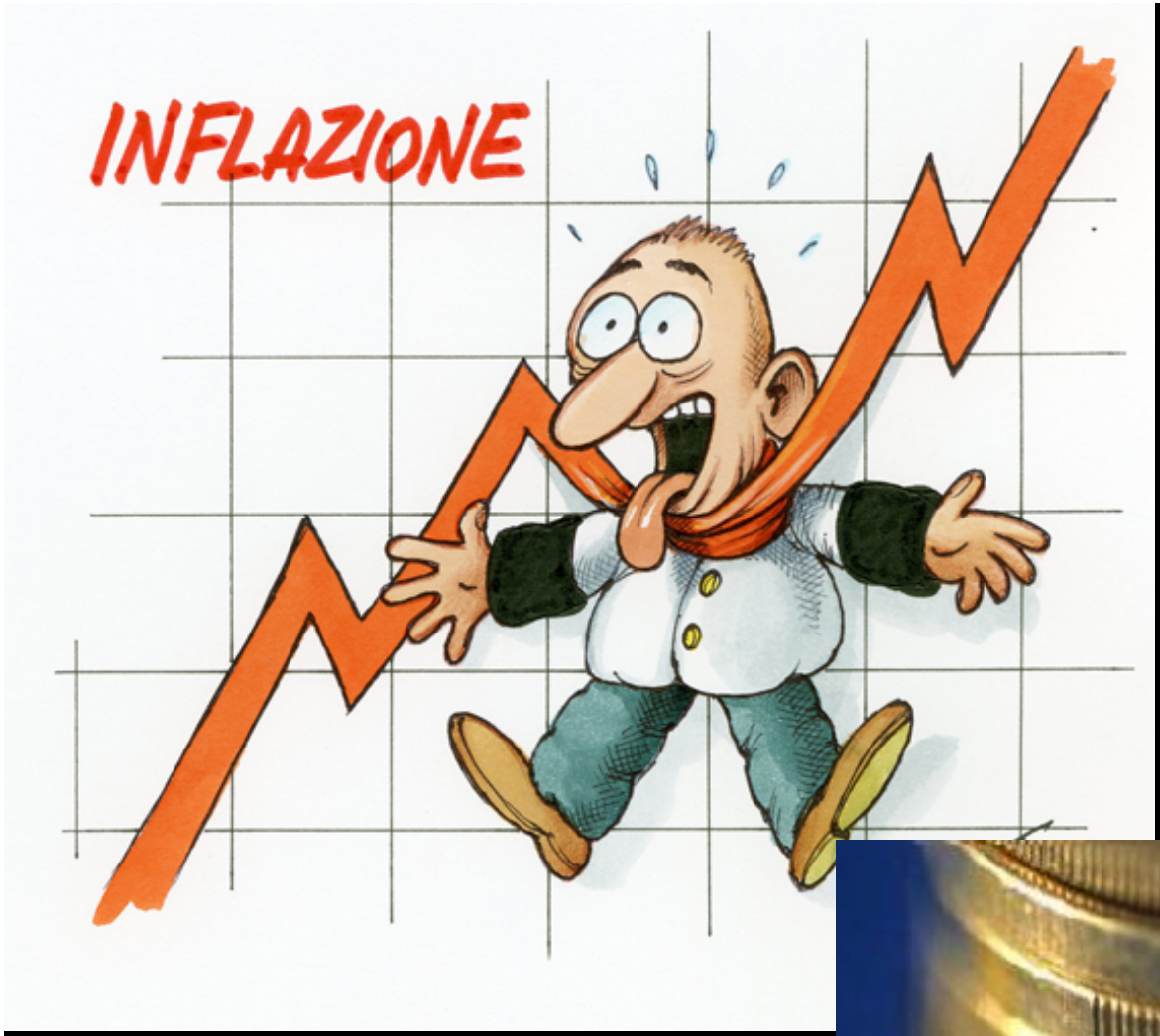


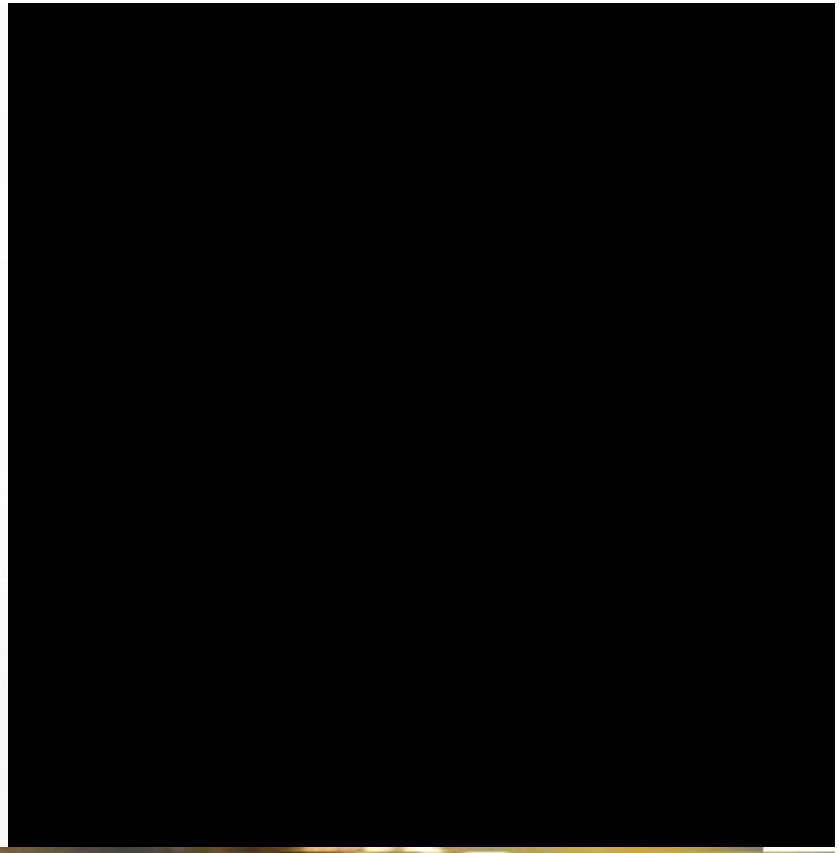
Initial conditions

The Universe appears very homogeneous on large distances

The primordial soup must have a very similar temperature in different regions
But how is it possible? Different regions could not talk to each other...

???


INFLAZIONE



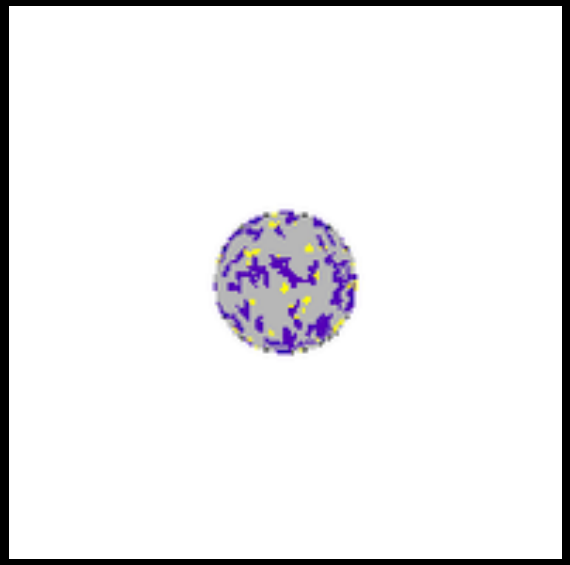
Inflation

Alan Guth in 1981 finds a solution...

... inspired by the desperate situation of his office

Inflation

A phase of very fast expansion, before the Big Bang



The whole energy stored in a single field: the inflaton

Our initial conditions

Cosmology is now able to study the initial conditions, usually outside what one can "predict"

The initial state of the Universe is the vacuum, but in QM the vacuum is pretty reach