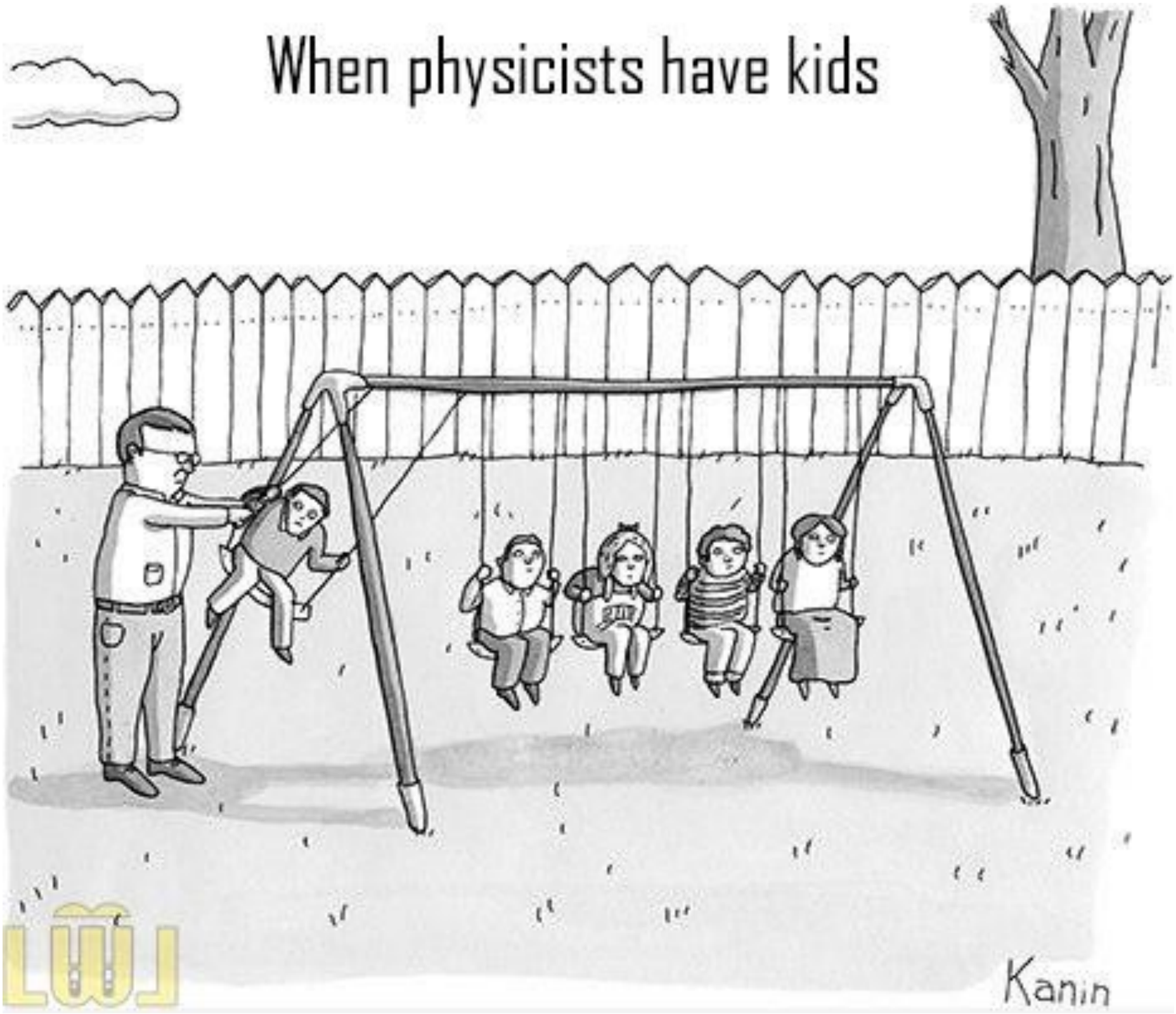
Making sense of making the universe

Enrico Pajer

About me

- I was born and raised in Venice, Italy
- The academic career brought me around the world for many years, from Munich Germany through the US to the Netherland until I landed in Cambridge UK
- I am a Theoretical physicist, namely the type of physicist that, for his own sake, is not allowed in a lab :(



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Outline

- An invitation to Cosmology
- The history of our universe
- The content of our universe
- Two amazing facts about our universe you probably didn’t know

Invitation to Cosmology

Fundamental constants

Speed of gravity (or light)

Special relativity

$\frac{v}{c}$

Quantum Mechanics

Planck's constant $\hbar$

action $\frac{\hbar}{S}$

$\frac{G_N \rho}{c^2}, \frac{G_N \rho L^2}{c^2}$

General relativity

Newton's constant

Strength of gravity

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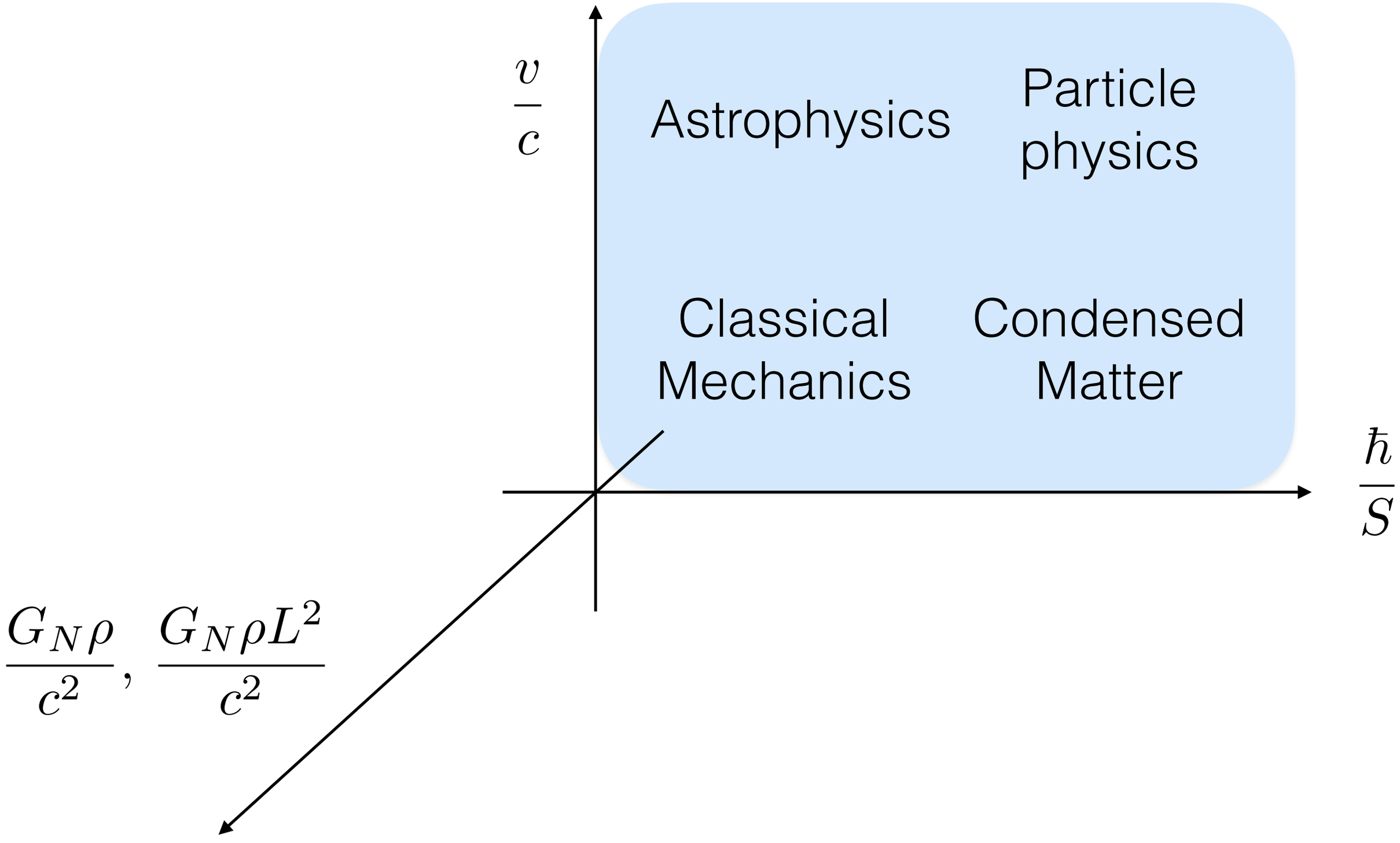
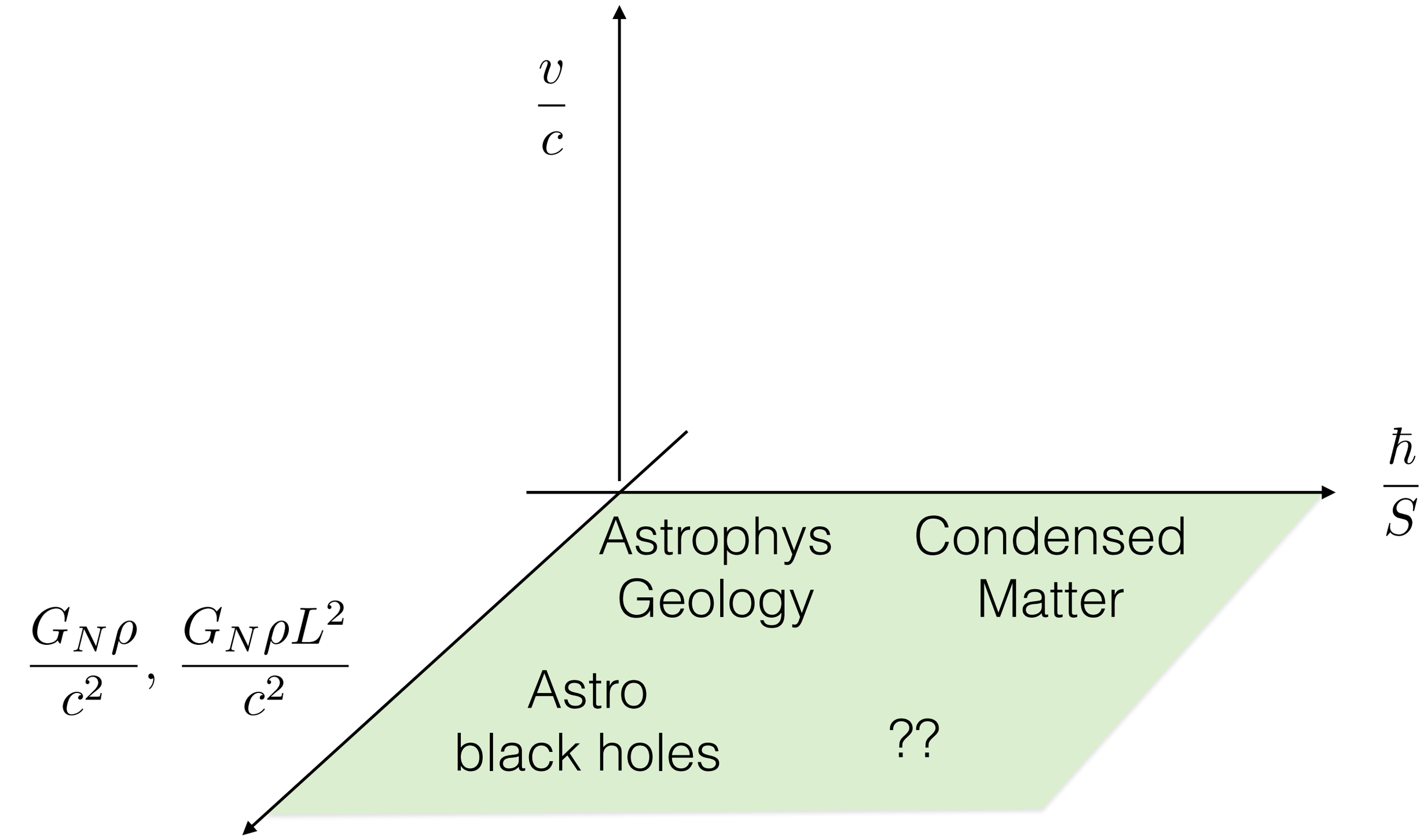
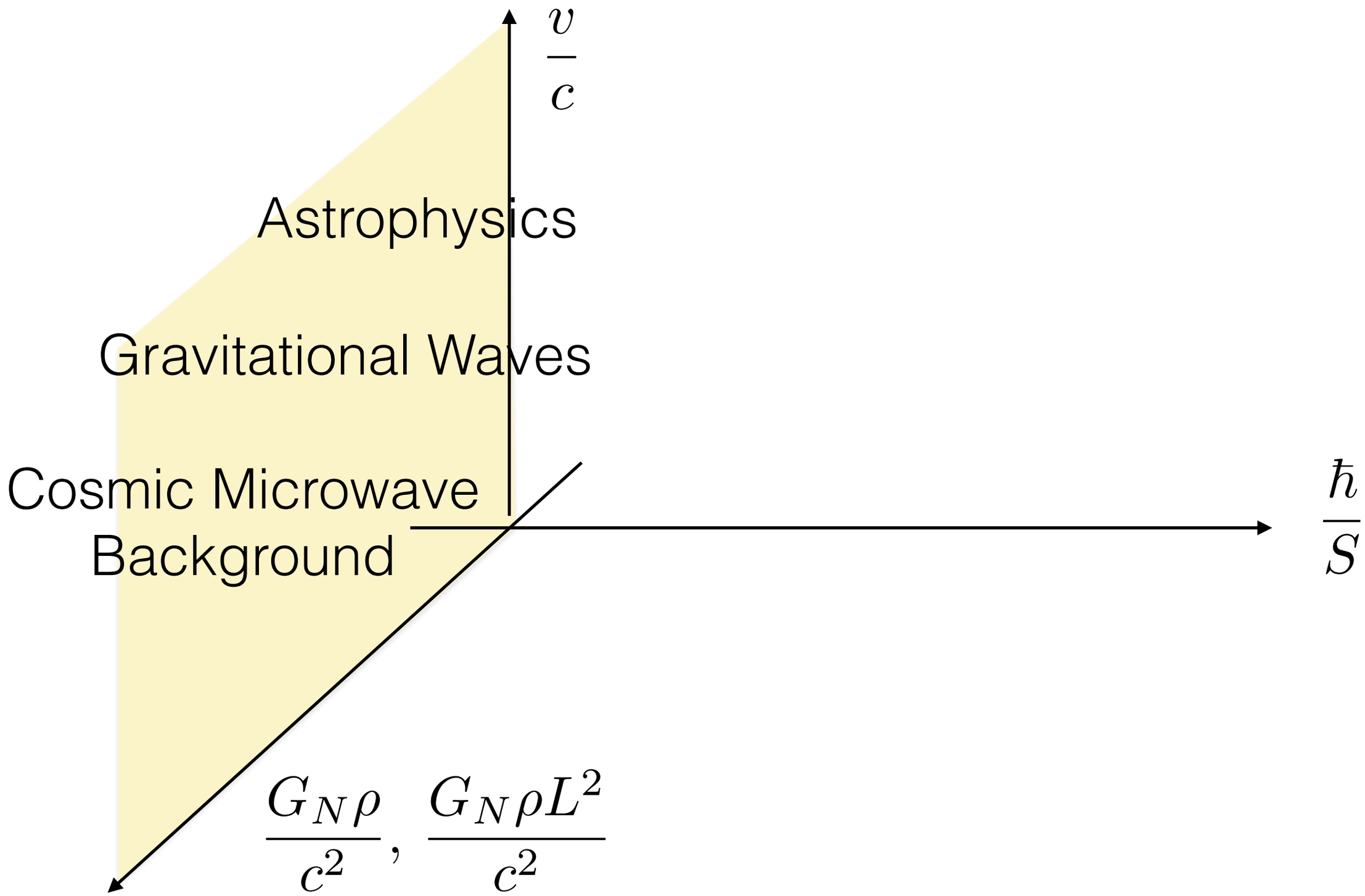
Fundamental constants



Fundamental constants

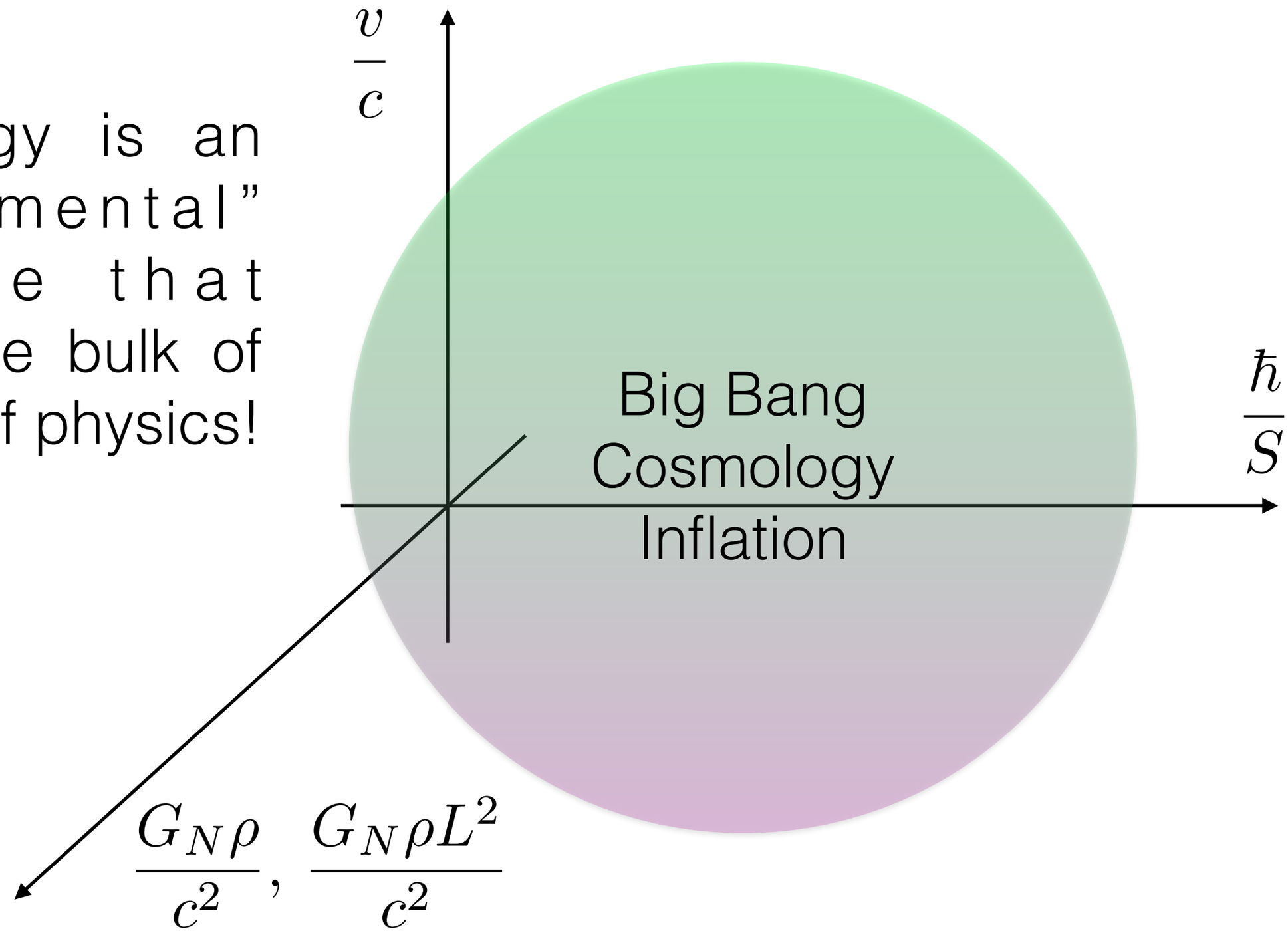


Fundamental constants



Fundamental constants

Cosmology is an "experimental" science that probes the bulk of the laws of physics!



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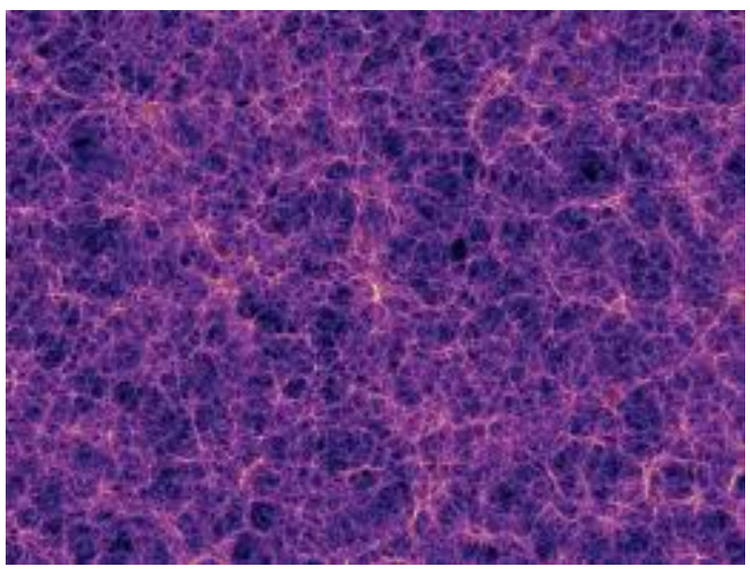
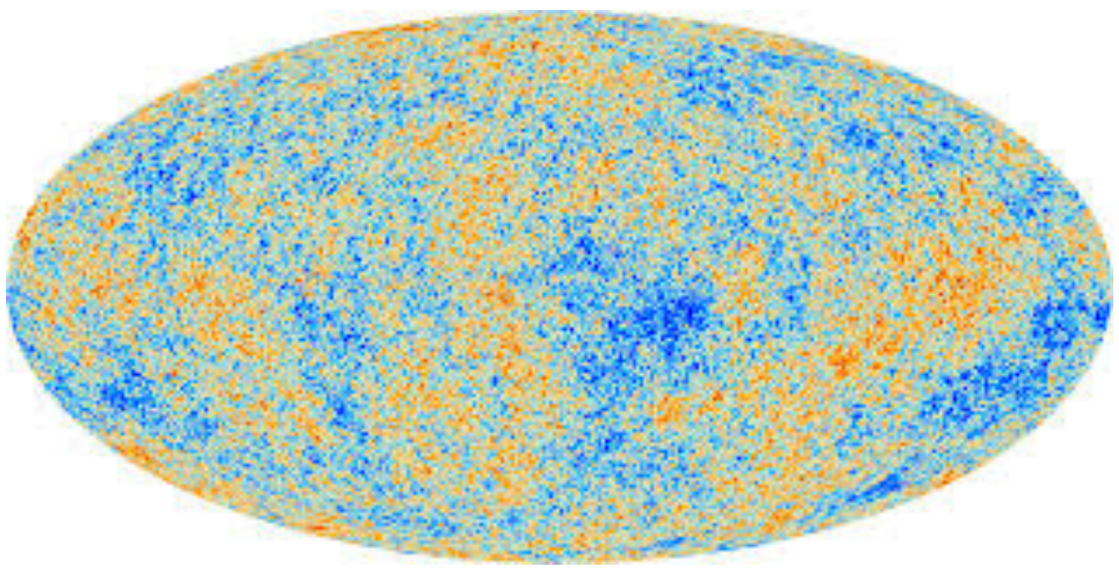
The first dataset on *perturbative* quantum gravity

- According to our leading paradigm, cosmological observations of galaxies and the Cosmic Microwave Background (CMB) are our first dataset on *perturbative* properties of quantum gravity!





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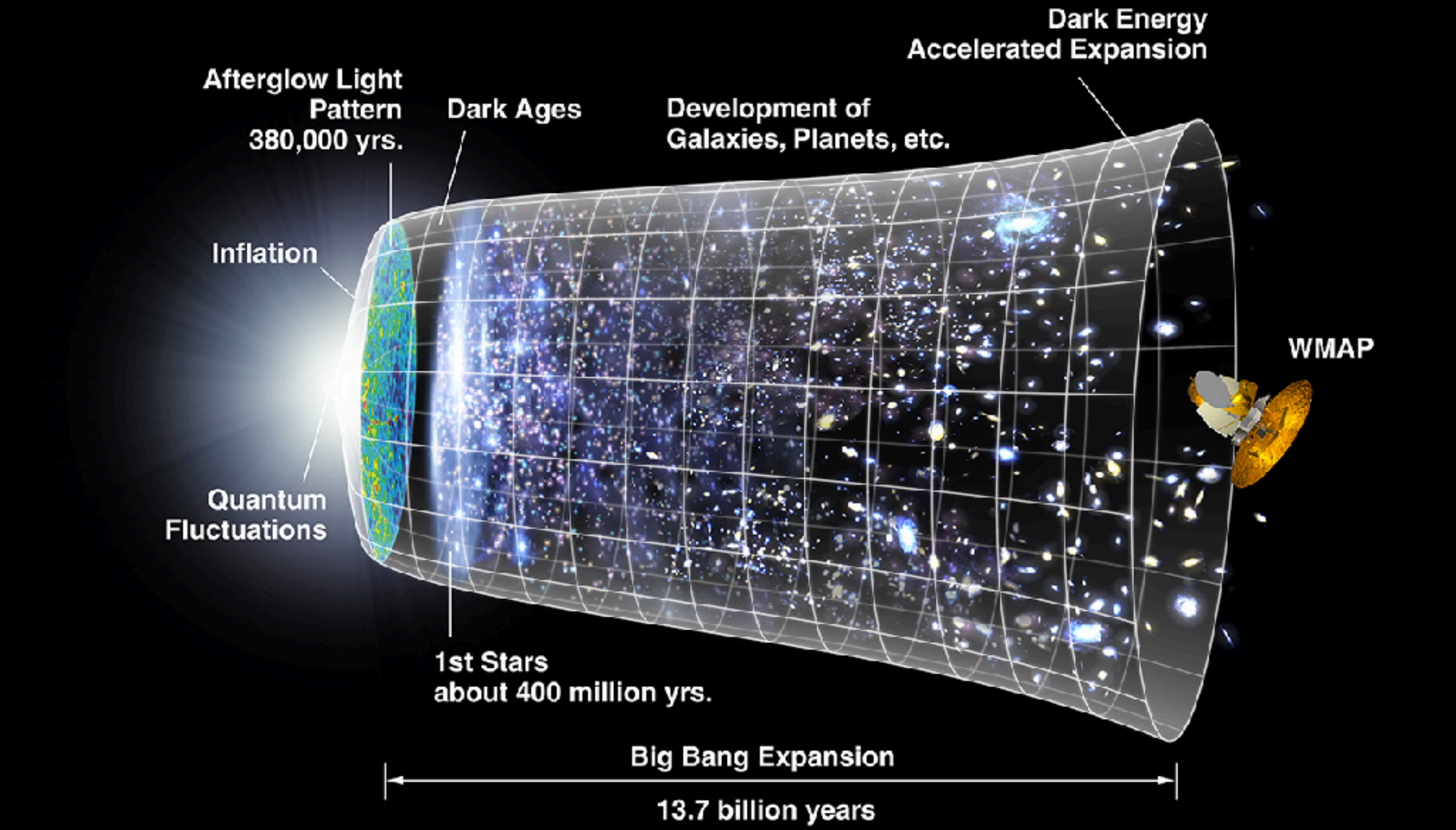
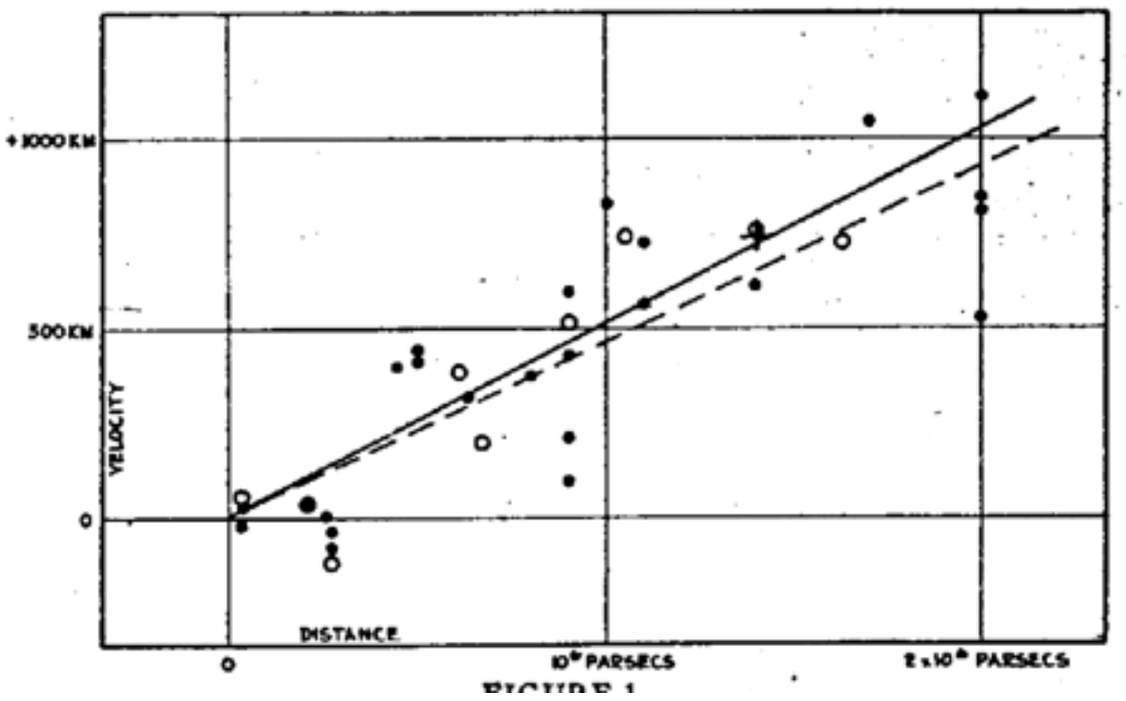
The history of our universe



The Hubble-Lemaitre law

- In the 1929 Edwin Hubble (1889-1953) published his findings that the velocity and distance of galaxies we see are correlated

- His breakthrough was realising he could measure the distance using the properties of special oscillating starts called Cepheids



A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

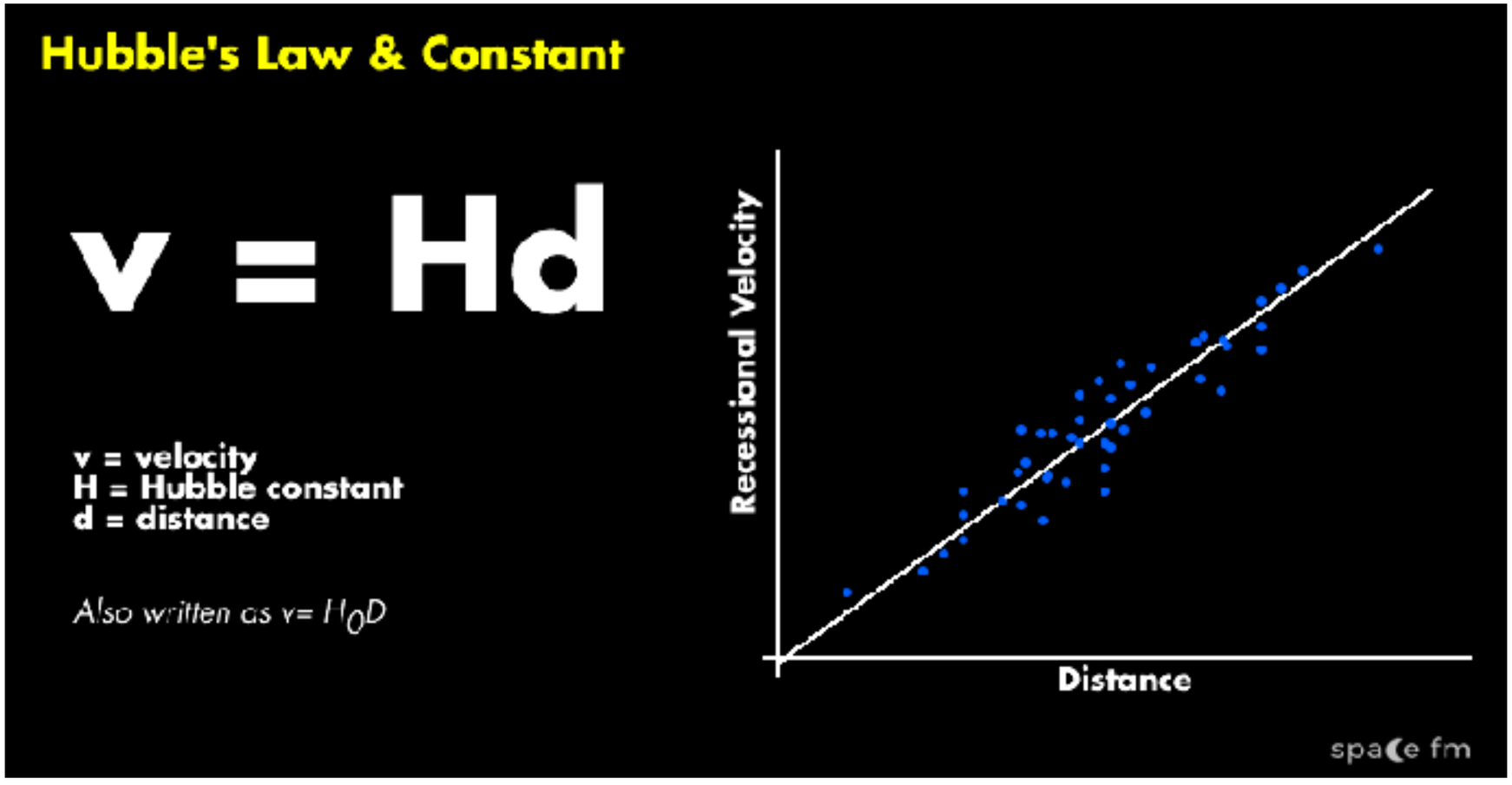
By Edwin Hubble

Mount Wilson Observatory, Carnegie Institution of Washington

Communicated January 17, 1929

Determinations of the motion of the sun with respect to the extra-galactic nebulae have involved a K term of several hundred kilometers which appears to be variable. Explanations of this paradox have been sought in a correlation between apparent radial velocities and distances, but so far the results have not been convincing. The present paper is a re-examination of the question, based on only those nebular distances which are believed to be fairly reliable.

An expanding universe



- The rate of expansion H is known today as the Hubble parameter.
- Hubble had been scooped two years before, but he didn’t know…

Linear relation

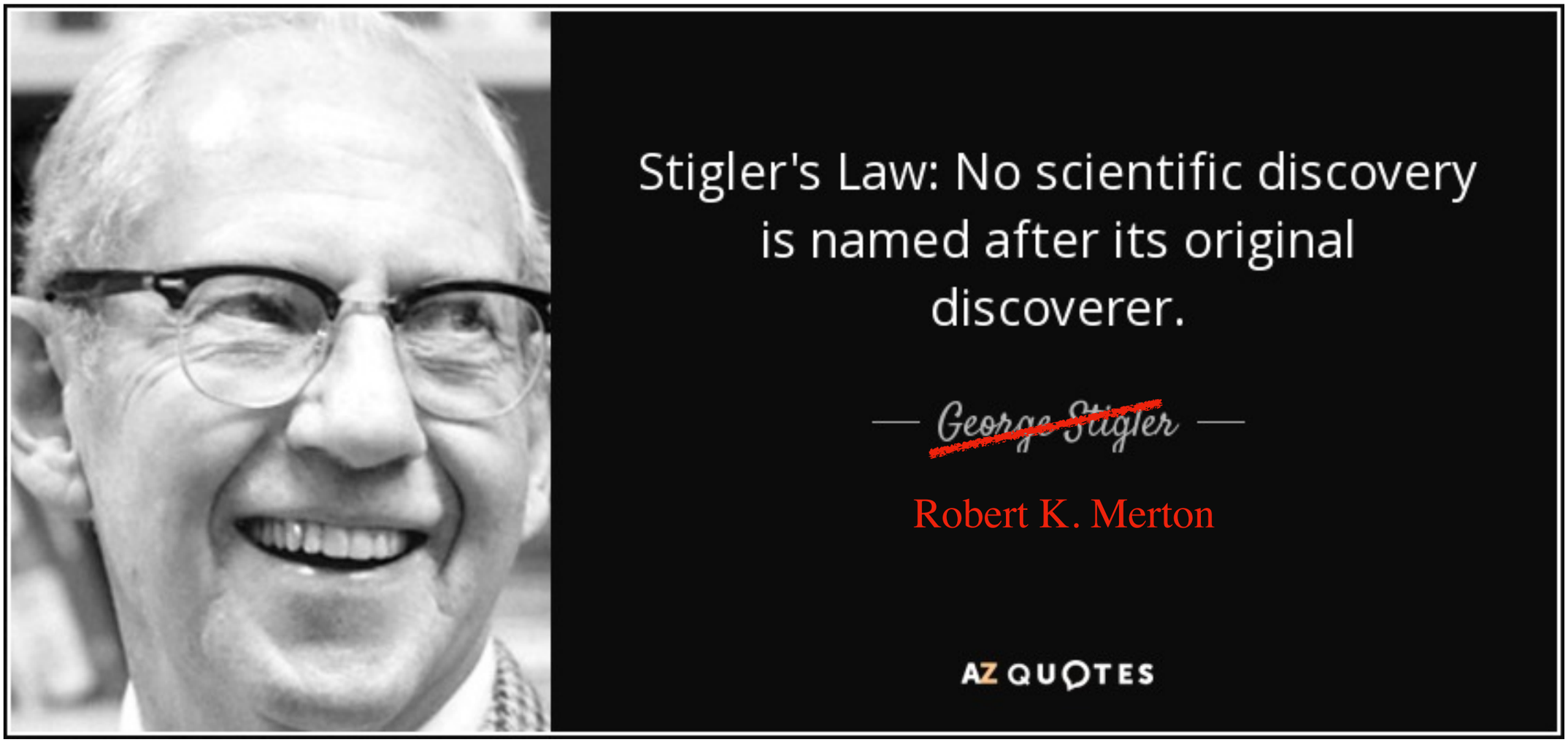
- The correlation is summarised in the compact linear relation

$$v = H_0 r$$

- where v is the velocity away from earth, r is the distance from earth and H_0 is called the Hubble constant.

- Hubble largely overestimated the value of H_0 because of miscalibration of distance. The modern value is (there is an ongoing controversy about the precise value…)

$$H_0 = 70\,\mathrm{km\ sec\ /\ Mpc}$$


Stigler's Law: No scientific discovery is named after its original discoverer.
— George Stigler —
Robert K. Merton
AZ QUOTES

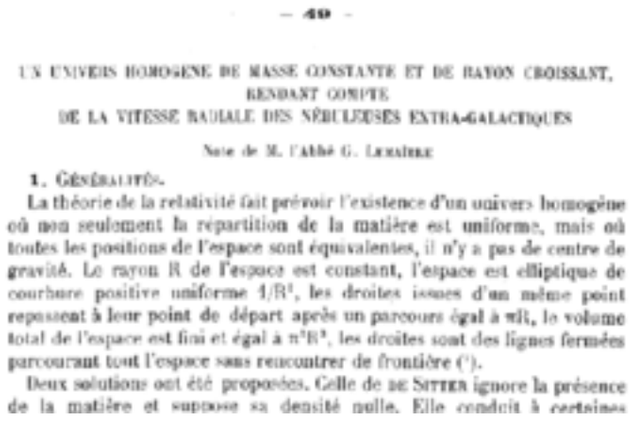
George Lemaitre

- Hubble didn’t know that the Belgian priest Georges Lemaitre had discovered the same thing 2 years before!

- Lemaitre had published a paper in French in which he showed that Einstein’s theory of general relativity admitted a solution in which the universe is expanding.

- Eddington, by than the world’s most famous astronomers, saw Lemaitre paper in French and asked him to translate it into English. In the translation *Lemaitre removed his finding of the Hubble parameter!*

1927



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UN UNIVERS HOMOGÈNE DE MASSE CONSTANTE ET DE RAYON CROISSANT, RENDANT COMPTE DE LA VITESSE RADIALE DES NÉBULEUSES EXTRA-GALACTIQUES

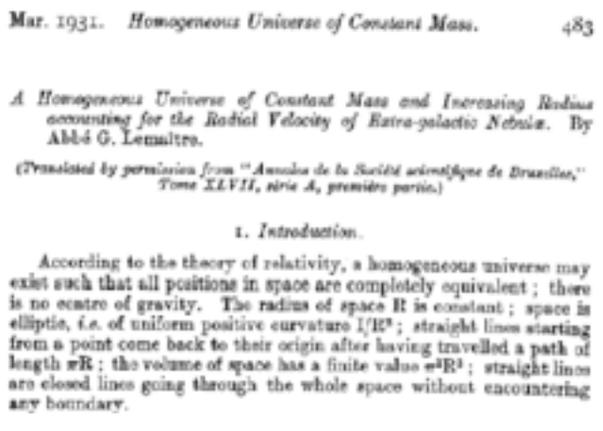
Note de M. l'Abbé G. LEMAÎTRE

1. GÉNÉRALITÉS.

La théorie de la relativité fait prévoir l'existence d'un univers homogène où non seulement la répartition de la matière est uniforme, mais où toutes les positions de l'espace sont équivalentes, il n'y a pas de centre de gravité. Le rayon R de l'espace est constant, l'espace est elliptique de courbure positive uniforme $1/R^2$, les droites issues d'un même point repassent à leur point de départ après un parcours égal à πR, le volume total de l'espace est fini et égal à $\pi^2 R^3$, les droites sont des lignes fermées parcourant tout l'espace sans rencontrer de frontière (1).

Deux solutions ont été proposées. Celle de DE SITTER ignore la présence de la matière et suppose sa densité nulle. Elle conduit à certaines

1931



MAR. 1931. *Homogeneous Universe of Constant Mass.* 483

A Homogeneous Universe of Constant Mass and Increasing Radius accounting for the Radial Velocity of Extra-galactic Nebulæ. By Abbé G. Lemaître.

(Translated by permission from "Annales de la Société scientifique de Bruxelles," Tome XLVII, série A, première partie.)

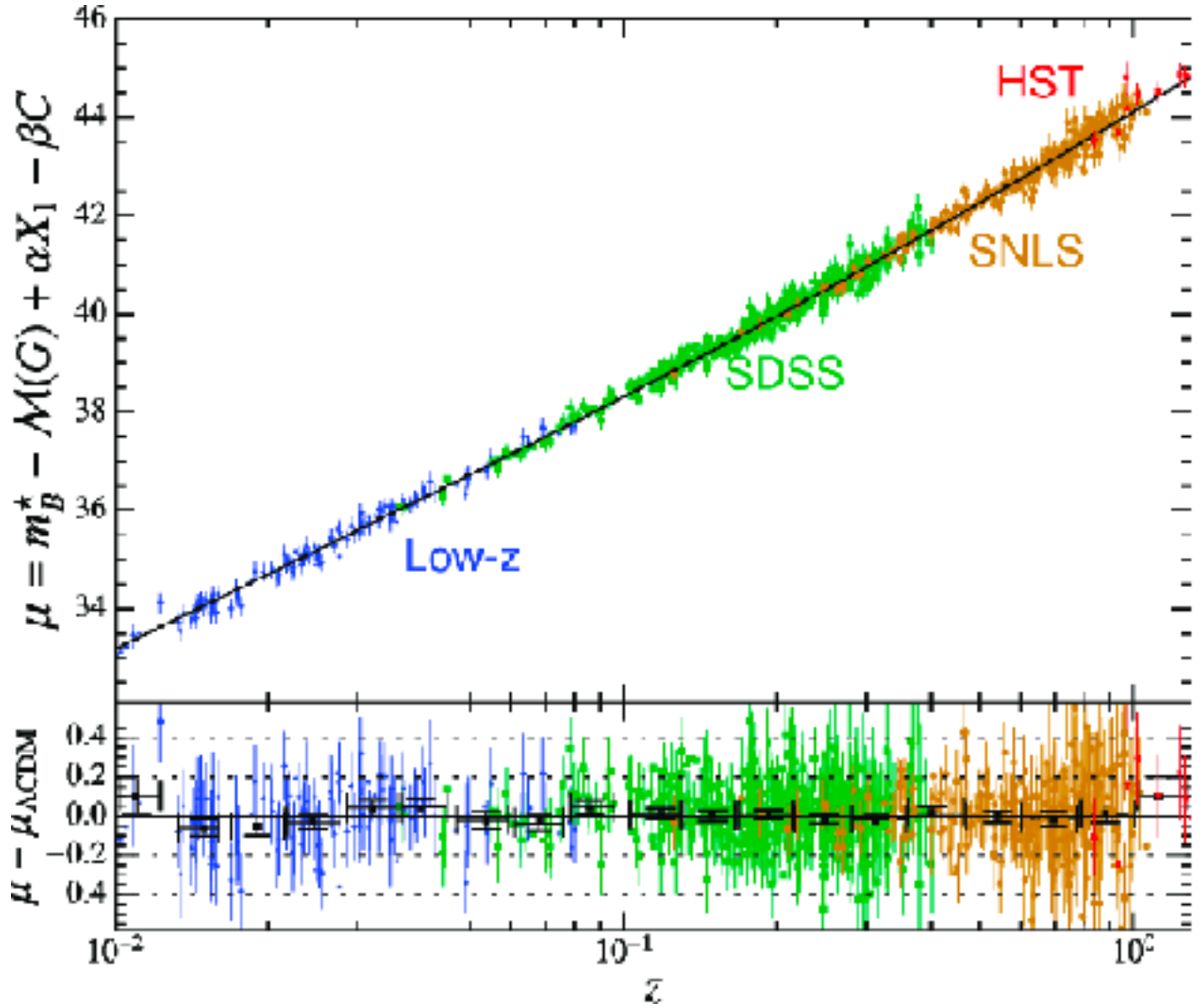
1. *Introduction.*

According to the theory of relativity, a homogeneous universe may exist such that all positions in space are completely equivalent; there is no centre of gravity. The radius of space R is constant; space is elliptic, *i.e.* of uniform positive curvature $1/R^2$; straight lines starting from a point come back to their origin after having travelled a path of length πR; the volume of space has a finite value $\pi^2 R^3$; straight lines are closed lines going through the whole space without encountering any boundary.

The modern Hubble diagram

- In the past 100 years we have measured the distance and velocity of many more objects, not just Cepheid stars but also exploding stars called Supernovae.

- Now the Hubble diagram, i.e. a diagram of velocity over distance is much more precise and we will see later led to a second revolution in cosmology in 1998



A mathematical model

- To make precise predictions we need a mathematical model of the universe that obeys the Hubble-Lemaitre law

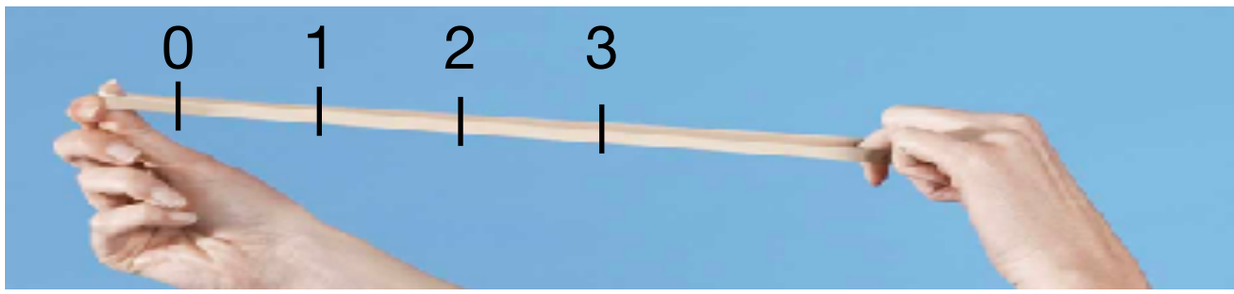
- Lemaitre built such model in his 1927 paper, but it turned out he had been scooped too!

- In 1922 the Russian mathematician Alexander Friedmann had already found that model solving Einstein's equations

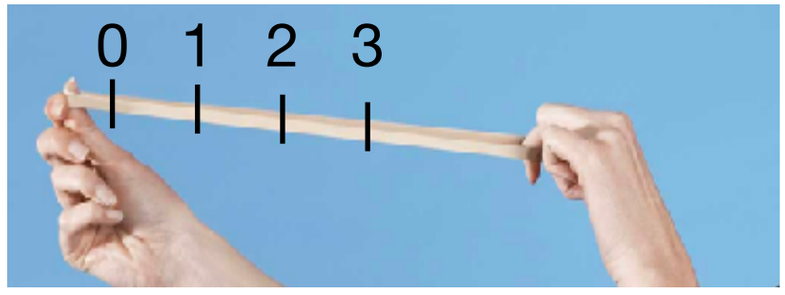
- In the 1930 Robertson and Walker generalized Friedman's and Lemaitre's solution. The resulting F.L.R.W. model is still today a good description of the broad properties of our universe

The rubber band model

- This model is like a rubber band, and the scale factor tells us how much the rubber band has been stretched from it rest position at t_0.



- New “space” is created by the expansion and the distance between any two points increases with *a(t)*



- Mathematically the expanding universe requires to multiply all cosmological distance by a “rubber band” factor $a(t)$ that tells us how much the universe had expanded

$$r(t) = a(t)r$$

The Big Bang

- This very simple model already makes some non-trivial predictions

- If there was ever a time t_{BB} when the scale factor vanished, $a(t_{BB})=0$.

- At that time all distances were zero, no matter how far two points might have been at a different time.

- *The Big Bang is a moment in time, not a point in space*

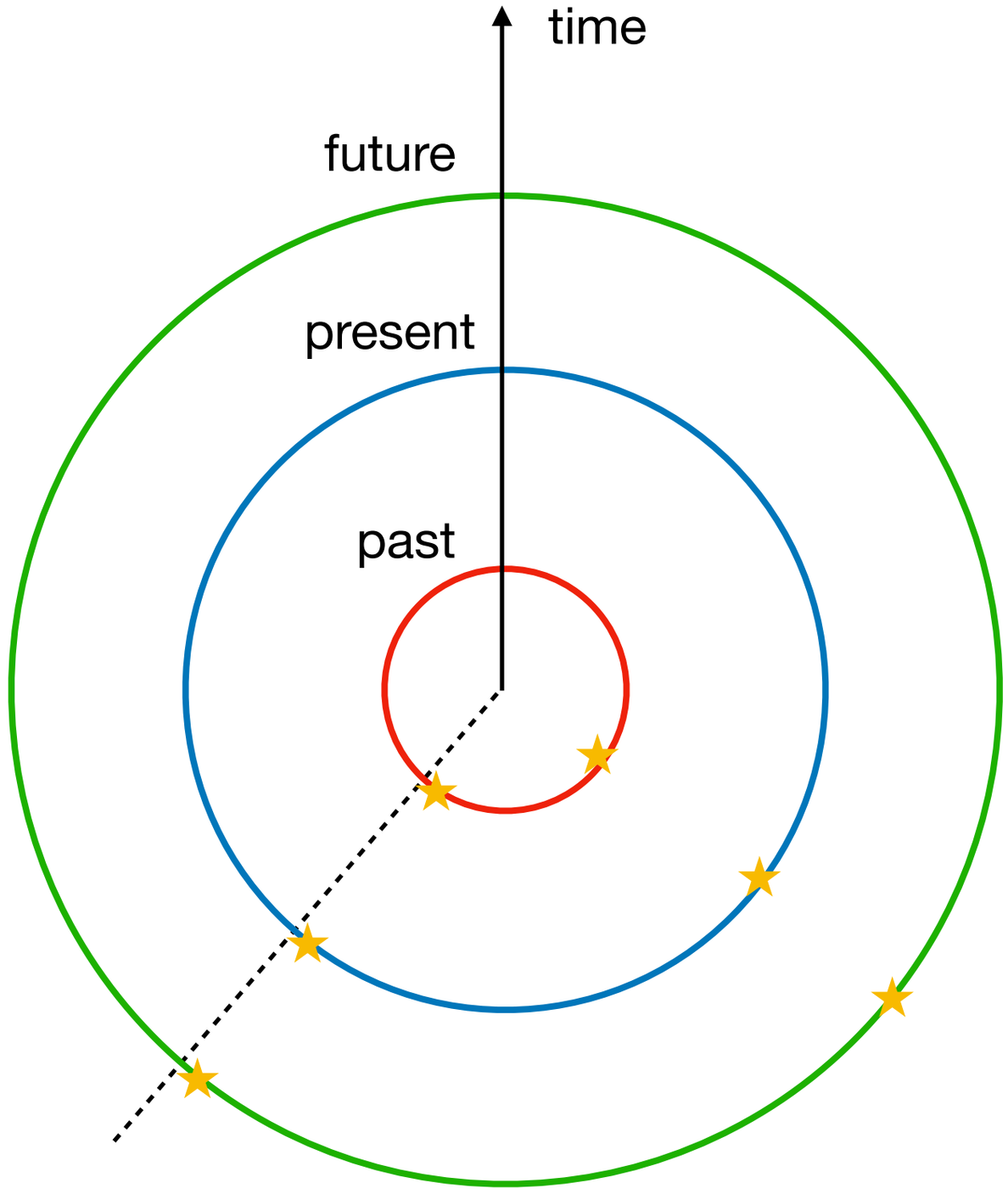
Expanding into the future

- Imagine the radial direction as time and every circle as the whole universe at that time

- Larger circles are the universe in the future

- Smaller circles are the universe in the past

- The origin is the Big Bang when all distance are zero



Distances change

- Notice that distance can change faster than the speed of light.

- Let c=300,000 km/sec be the speed of light

- Then for $r>c/H_0$ we find $v>c$

- Is this a problem? No. This is consistent with special and general relativity because nothing is actually travelling from one point to the other. It's just that a lot of space is created in between

- this has another important consequence

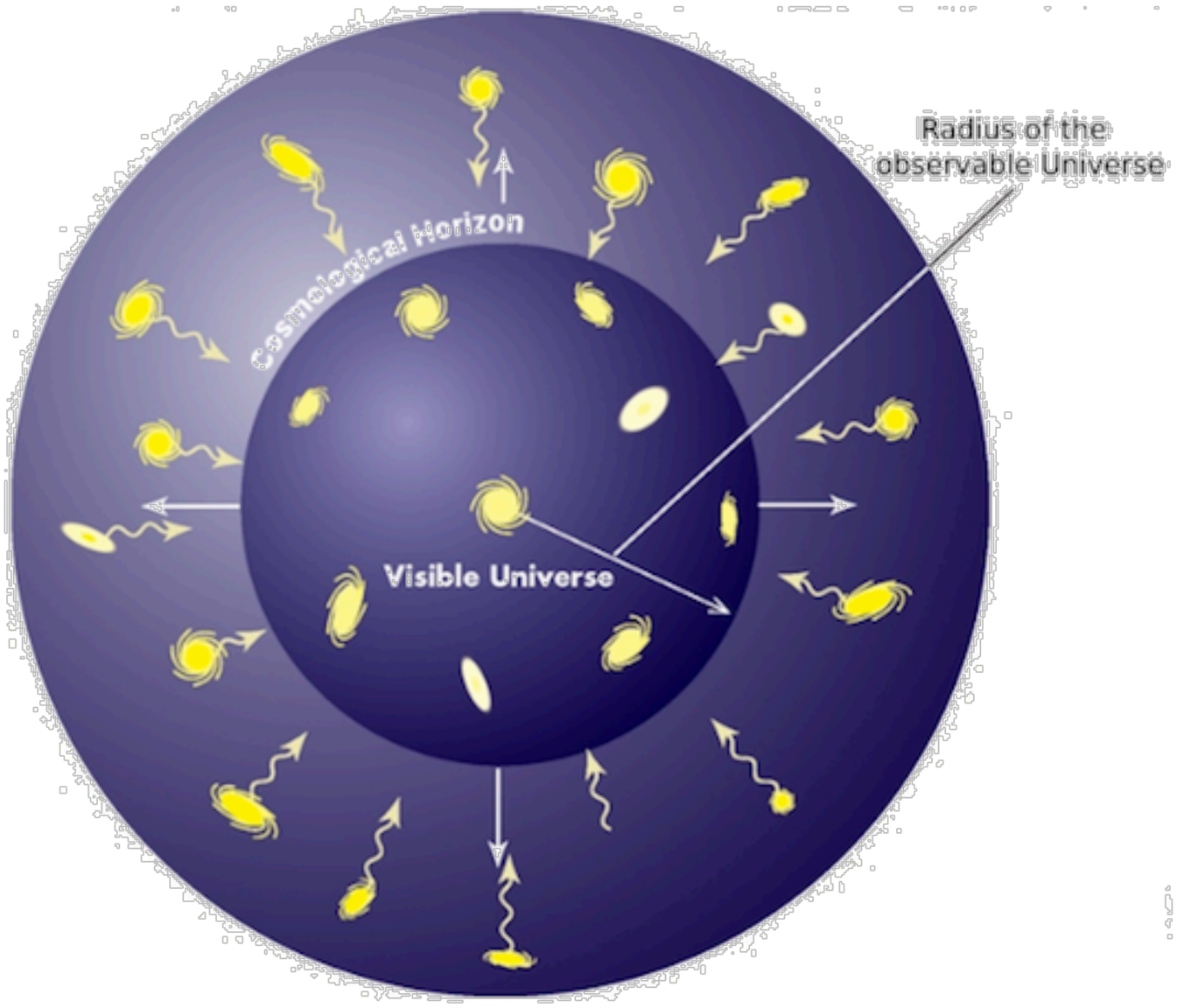
Cosmological horizon

- If the distance to points further than $r>H_0/c$ is increasing faster than the speed of light, we can never see any signal coming from these points

- Hence there is a sphere around us beyond which we cannot see: this is the cosmological horizon

- Just like a horizon is the furthest you can see because the earth is flat

Cosmological horizon



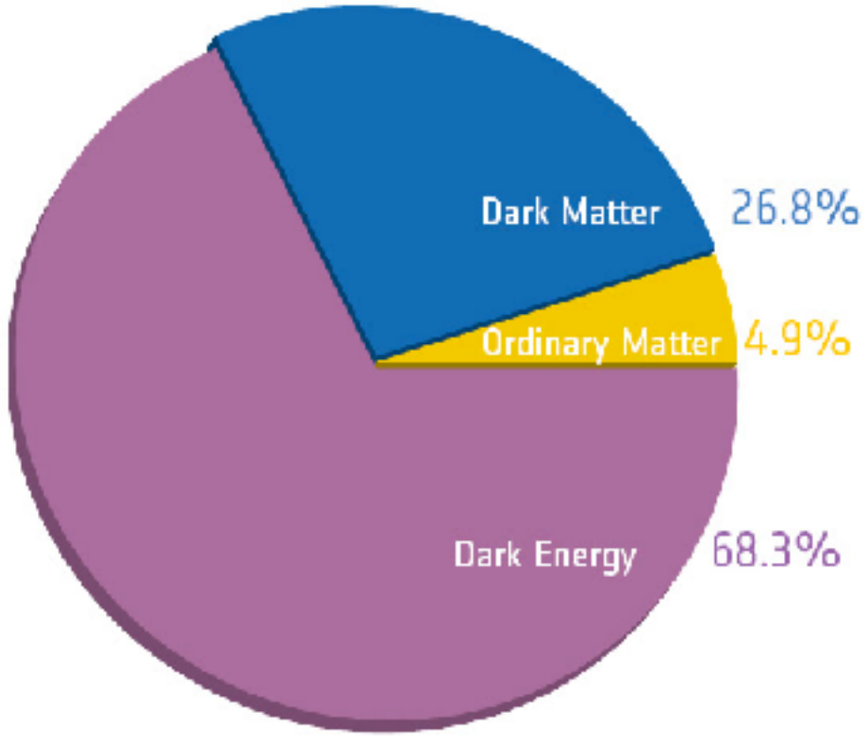
- The horizon is at an approximate distance of c/H_0 = 14 Giga parsec

- the universe might be finite or infinite, but the observable universe is finite and is the only one we can measure and test

The content of our universe

Content of the universe

- The FLRW models tells us that the universe expands. What what's inside it and how does it expand?

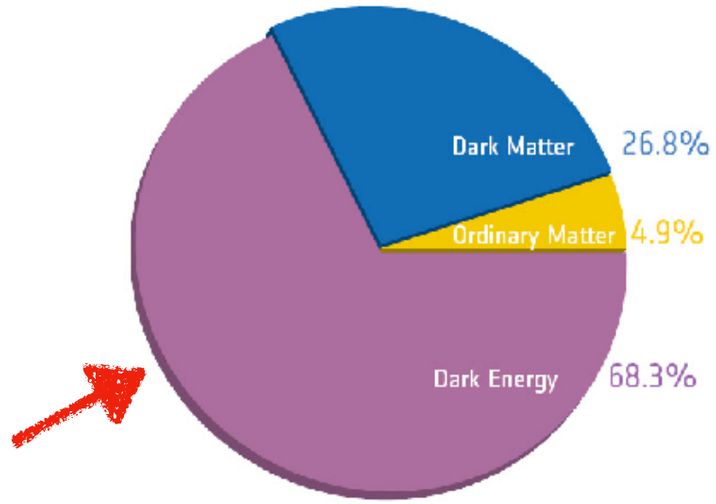


- Let's draw the (energy) density for stuff *today* on a pie chart

- *Density* means how much of something there is a given volume

$$\epsilon = \text{energy density} = \frac{\text{energy in volume}}{\text{volume}}$$

Dark Energy



- The most abundant constituent of the universe is dark energy, 70% of today's total!

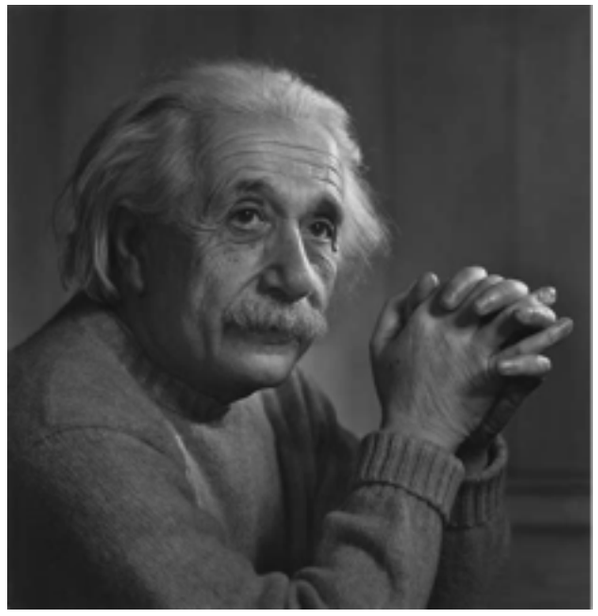
- In 1998, by looking at the distance and velocity of supernovae, astronomer realise that the universe not only expands, but it expands faster and faster every day: it accelerates!

- It is called "dark" because we can't see it using light (it doesn't emit, absorb or interact with light in any way)

- as far as we know everywhere there is space there is dark energy

- Dark energy is an incredible substance: if you put it in a closed box and make the box twice as big you find inside twice as much dark energy

Cosmological constant



- Our best current candidate is a cosmological constant, indicated by Λ.

- Λ was originally proposed by Einstein to create an eternal universe, without a Big Bang. When Hubble and Lemaitre discovered the expansion, Einstein called the cosmological constant “the biggest blunder” of his life. But perhaps, he was right…

Dark Matter

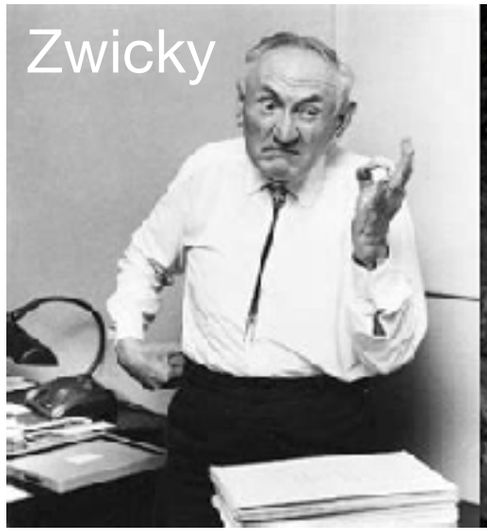
- The second most abundant thing in the universe is a mysterious form of matter called *dark matter*

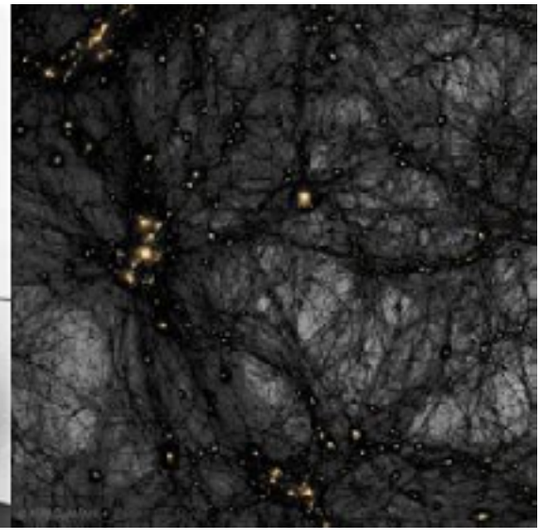
- It is called “dark” because it does not emit, absorb or interact with light

- We can only see dark matter through its gravitational effect on visible matter, such as stars, galaxies and light

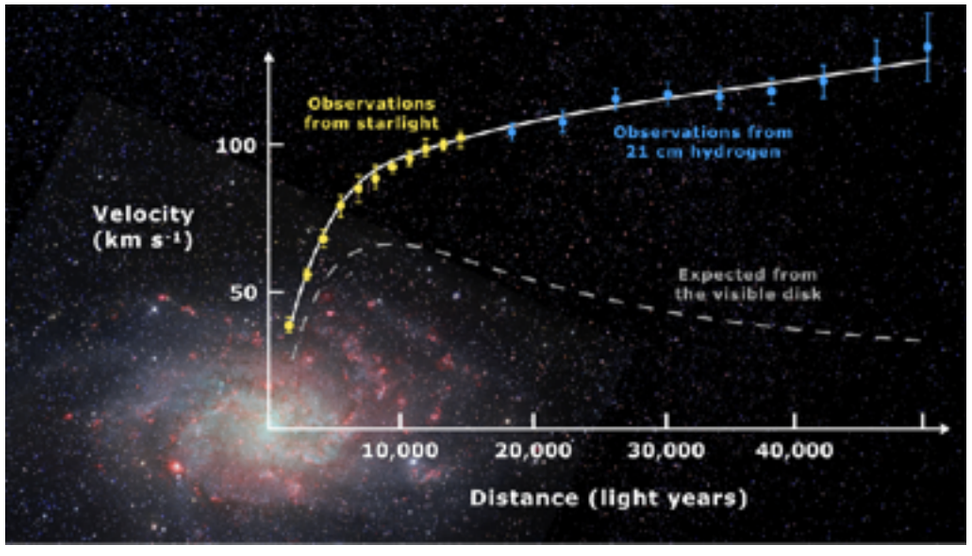
- Dark matter was conjectured back in the 1930s by Zwicky but convincing evidence arrived only in the 70s from *galaxy rotation curves* measured by Vera Rubin and Kent Ford

- Today we detected dark matter in many different ways and we have detailed maps of where it is distributed.

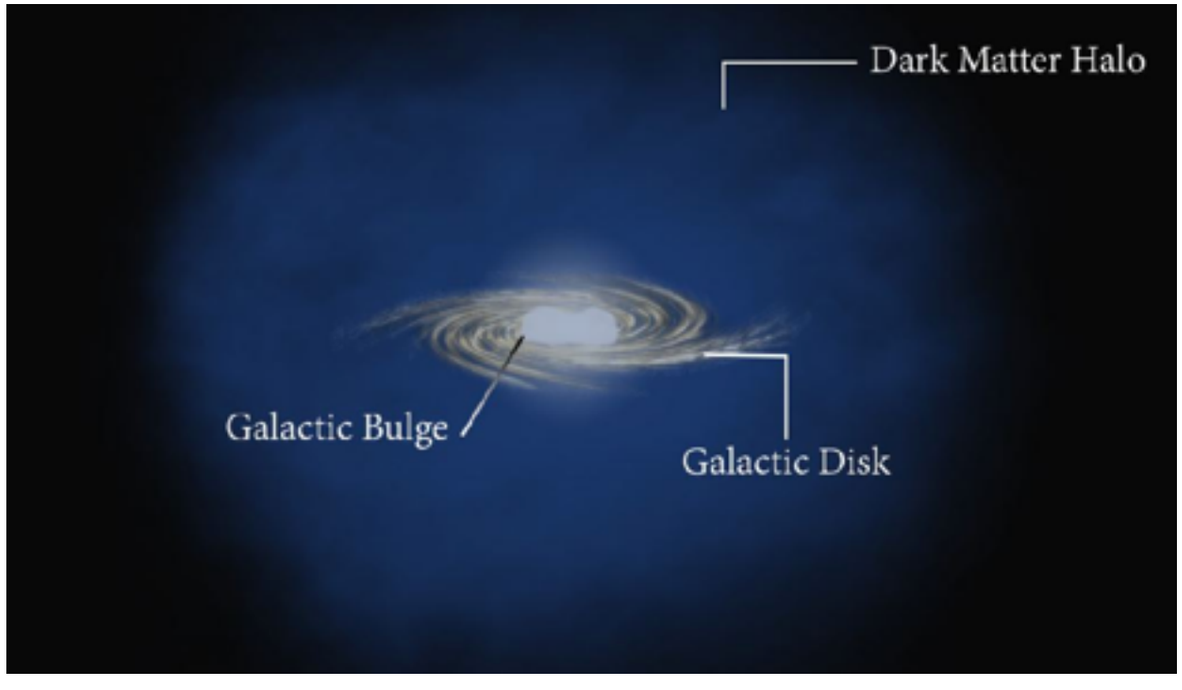




Rubin
&
Ford



Dark matter

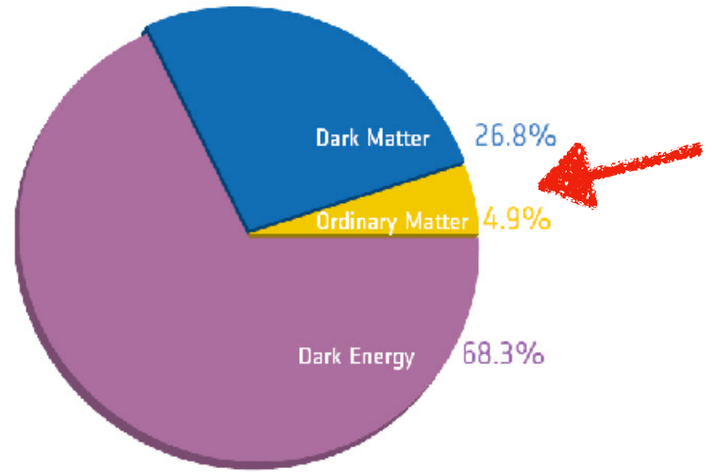


- Dark matter is 6 times more abundant than ordinary matter, i.e. atoms.

- dark matter forms much less dense regions called dark matter *halos.* All galaxies are surrounded by dark matter halos

- The mass of dark matter particles is the most uncertain quantities in the history of science. It can be a

Atoms, a.k.a. us!

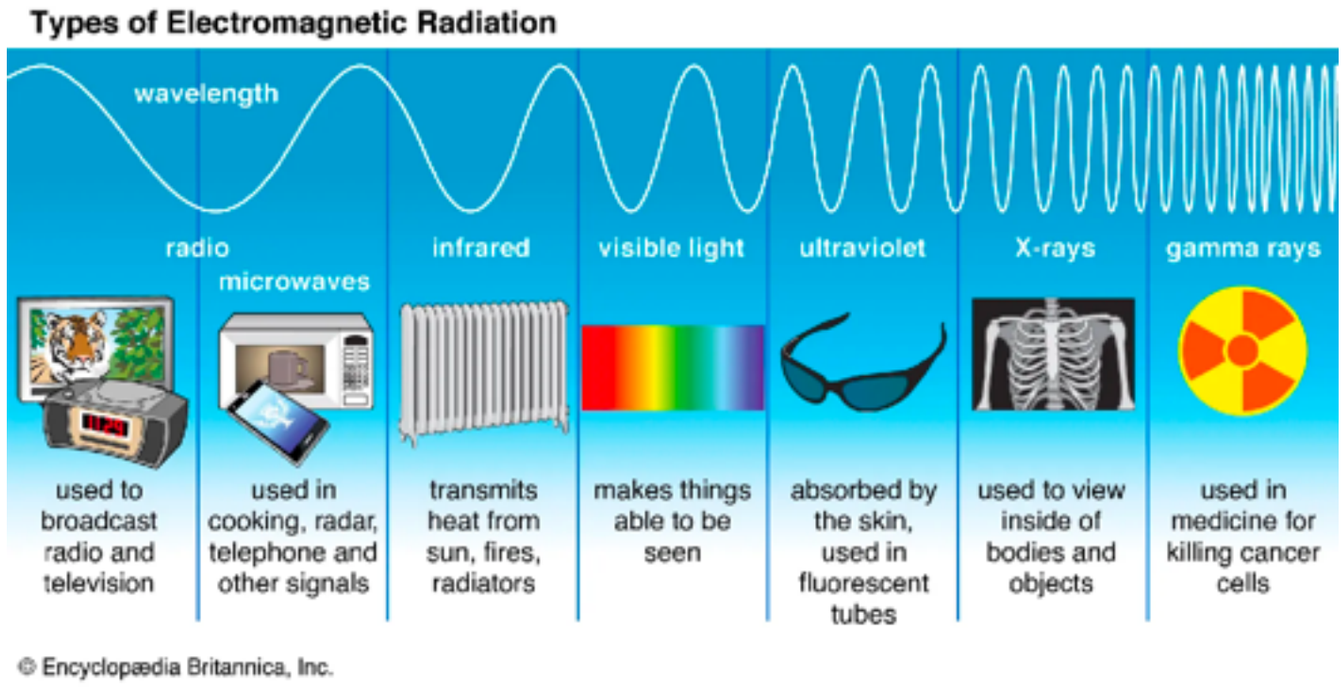


- The next component of the universe is finally something familiar: atoms, about 4% of the total today

- This is the stuff that you and I and the earth are made of (you and I are actually made of sturdust, but that's another story…)

- Stars and galaxies are also made of atoms, but it turns out that most atoms are actually in the dilute gas in between galaxies, called the Inter Galactic Medium (IGM).

Light



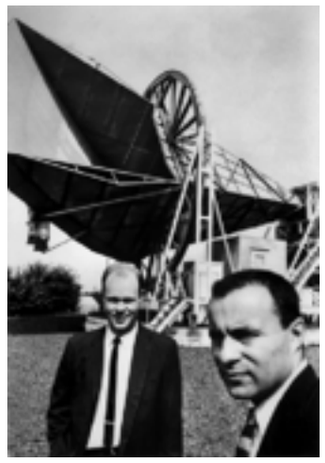
- Our eyes can only see light in the visible spectrum, i.e. with wavelengths in the range 400-800 nanometers. But radio, microwaves, X-rays and gamma rays all made of the same thing (courtesy of J.C. Maxwell 1831-1979), electromagnetic waves, or simply “light”, for short.

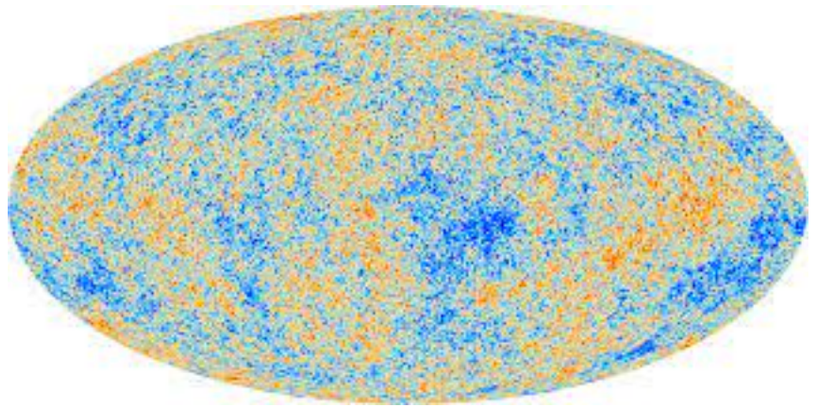
- Light is made of particles called *photons*. A photon is a quantum of light. Our eyes are not sensible enough to see individual photons and so we see a “continuum” of light

- Photons don’t have a mass but are “pure energy”. Their energy is given by the inverse of their wavelength, as first propose by Max Planck in 1900.

- Today the energy density of light is only 0.001% of the total, but light was much more abundant in the past.

The CMB





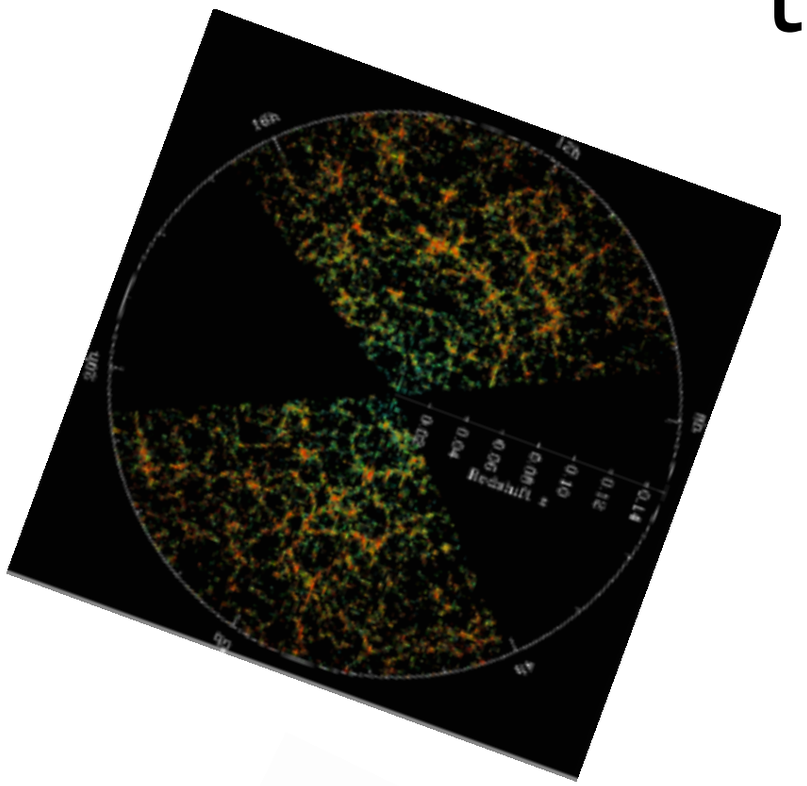
- There is light from all the stars in the universe, but most of the light are photons coming from the afterglow of the big bang, in the *Cosmic Microwave Background* (CMB)

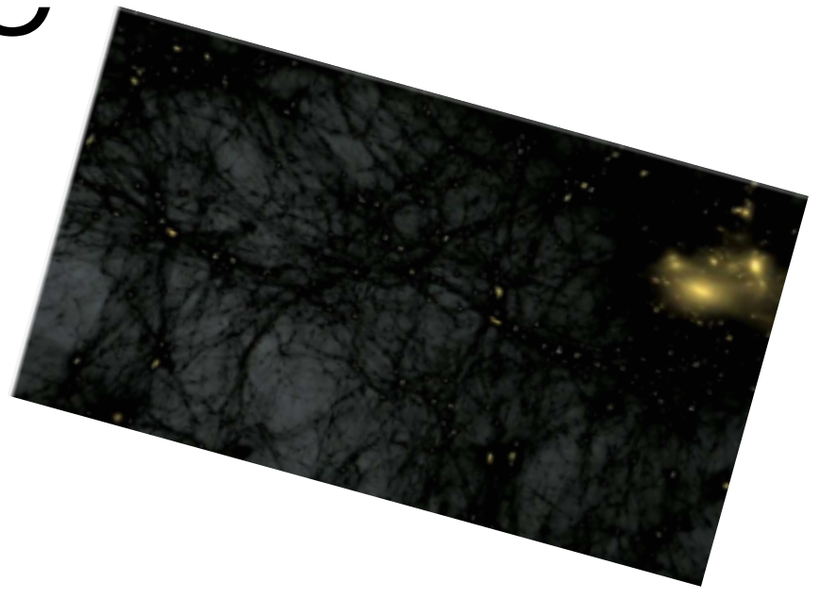
- The CMB has a black body spectrum at a temperature today of T = 2.7 K (Kelvin)

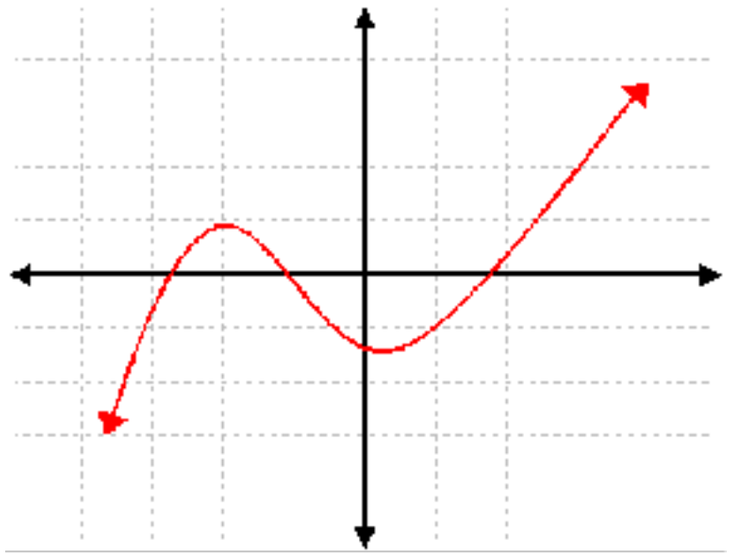
- The CMB was discovered by Penzias and Wilson in 1967, almost by mistake (they were trying to measure something else)

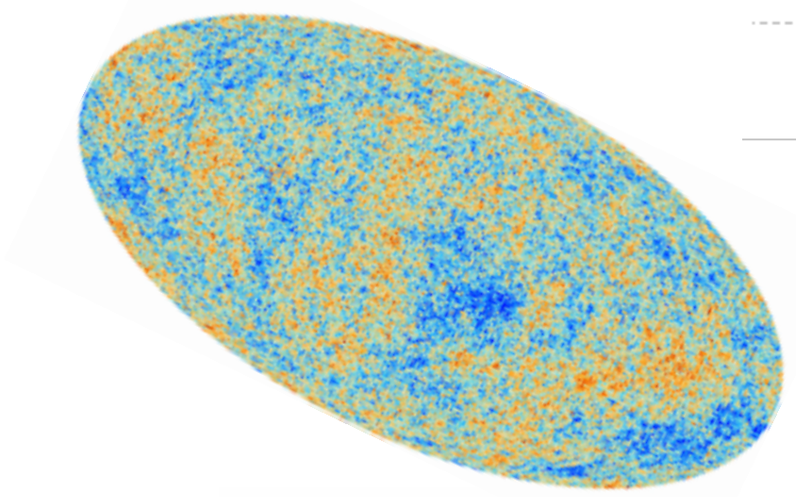
- The CMB was the strongest pieces of evidence to confirm the expansion of the universe and the big bang theory, since it tells us the universe was once hot and dense and glowed like a piece of coal

The function that originated the universe









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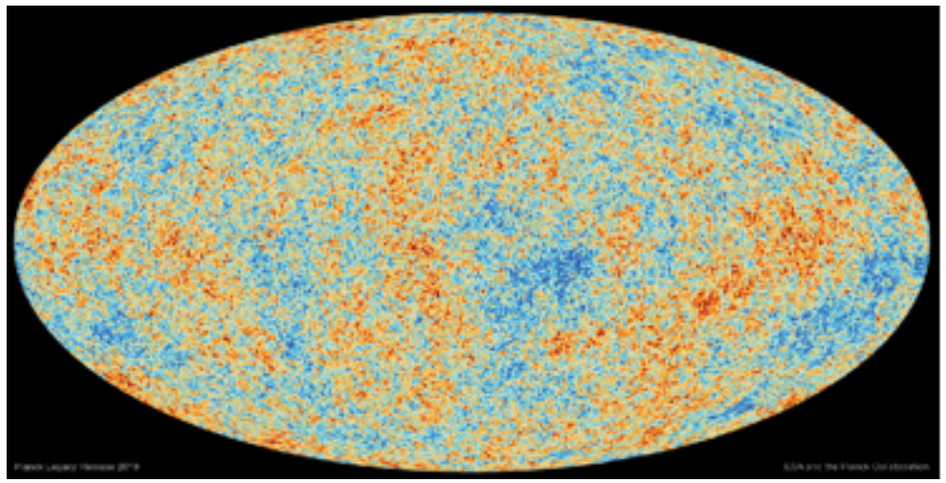
Perturbations
(aka you and I)

- So far we talked about the average expansion of the universe. But what about the distribution of matter and galaxies and light across space?

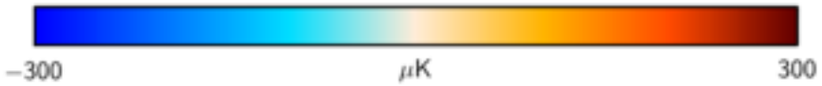
- Why are we here rather than elsewhere? Where does stuff in the universe come from?

- Surprisingly have evidence that it all comes from a fraction of a second after the Big Bang…

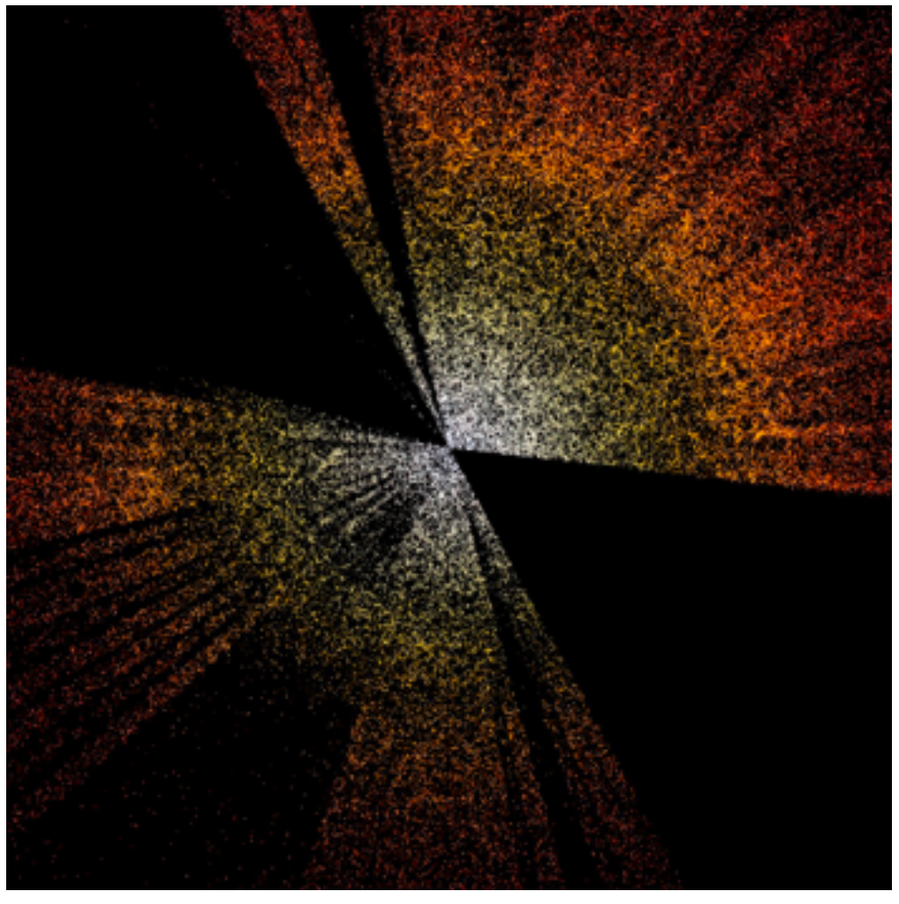
Where are things in the universe?



Distribution of light from the Planck satellite imaging the Cosmic Microwave Background. Different colors represent different temperature and hence different density

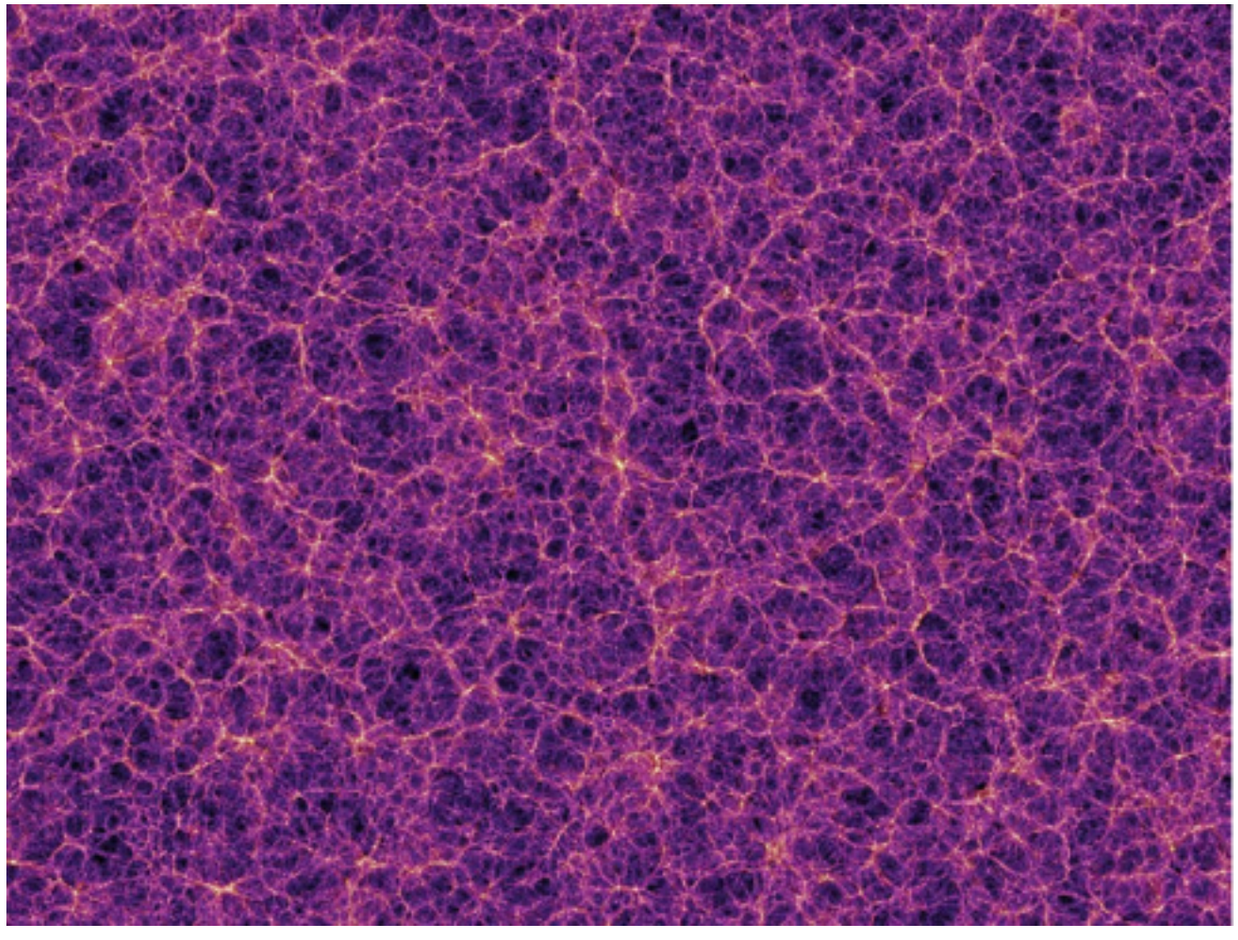


Distribution of galaxies from the Dark Energy Spectroscopic Instrument, a.k.a. DESI (these are “only” 40k of the 35 million galaxies in their catalogue!).
The black fans are because our own galaxies obscures our vie of extragalactic objects.

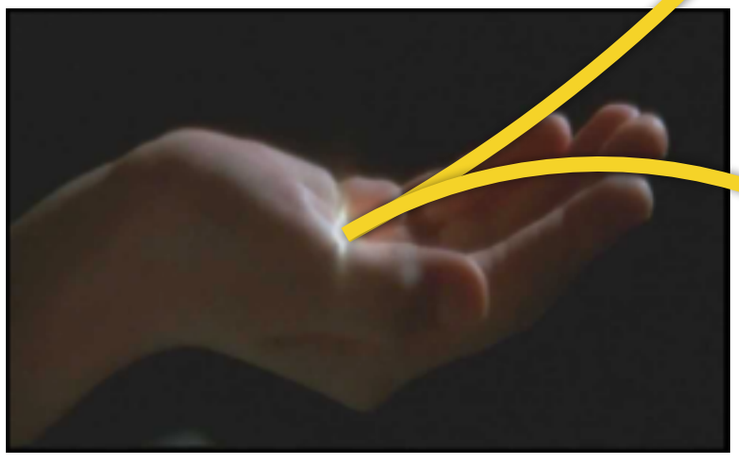


Where are things in the universe?

- We even have (3d) pictures of the distribution of dark matter. This one is derived by a computer simulation (Millennium) that used the observed properties of dark matter



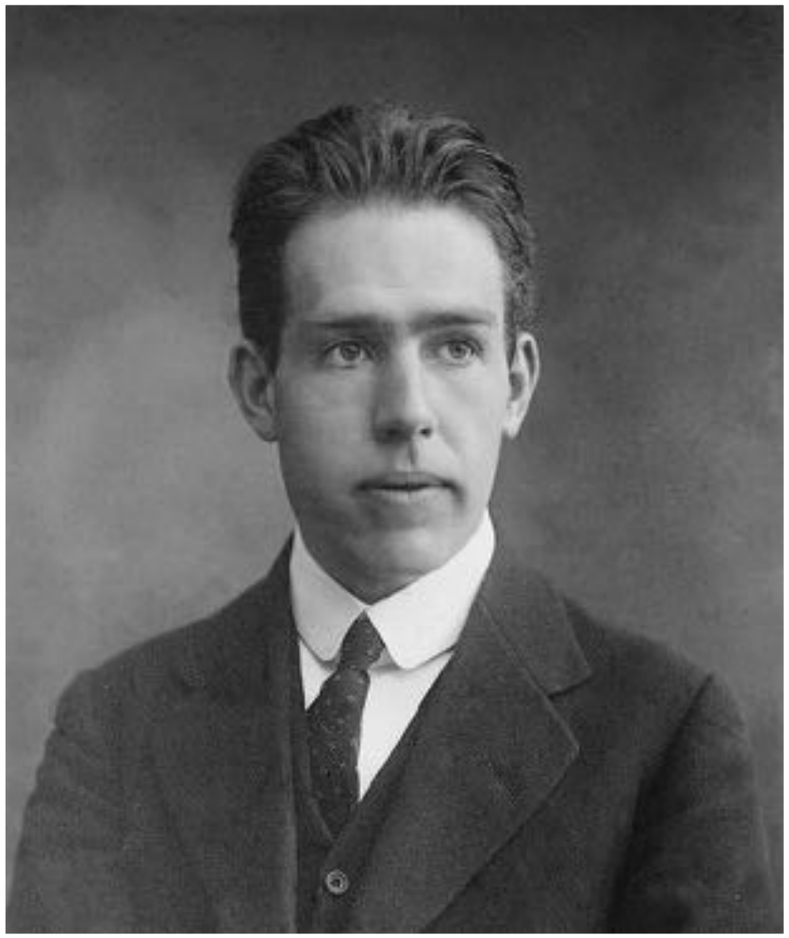
Inflation



- All of the space we see in our universe was once contained in a volume much smaller than a grain of sand

- We believe that in a tiny fraction of a second, a process called *Cosmological Inflation* expanded it to cosmic size: the universe was born

- This idea was pioneered by Alan Guth in 1980 and developed by many others (Linde, Starobinski, Steinhardt, Albrecht, …)



“Your theory is crazy. But it’s not crazy enough to be true.”

Niels Bohr

here are two of the craziest things I have ever learned in my life…

Tutti Frutti

Imagine for a moment how fruit is distributed in each house of the world

Our universe is simple

Our universe is much simpler! It started our with the same ratio of stuff everywhere. This is as if every house in the world had the same pile of fruit, just a bit bigger or a bit small, but with the same ratio of bananas, oranges, kiwis etc

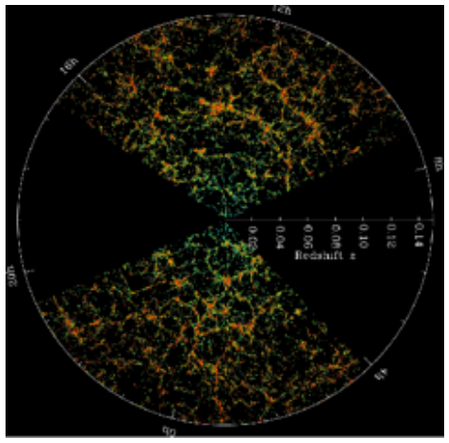









Tutti Frutti goes Cosmic



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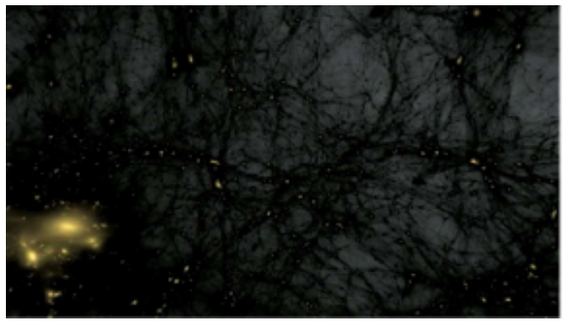

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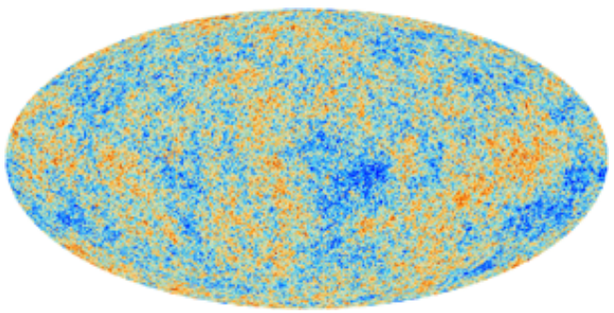

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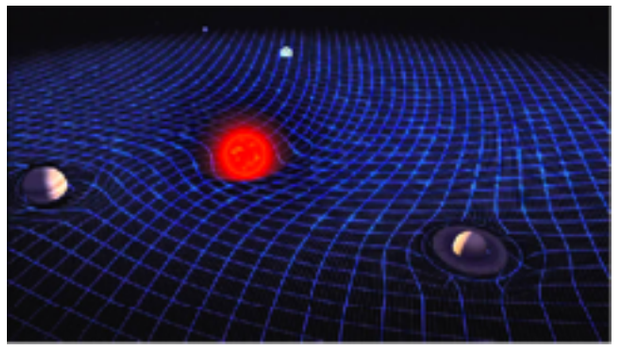

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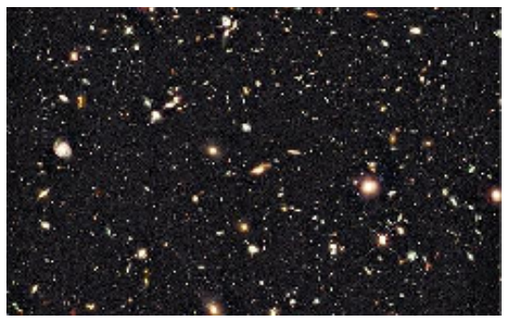

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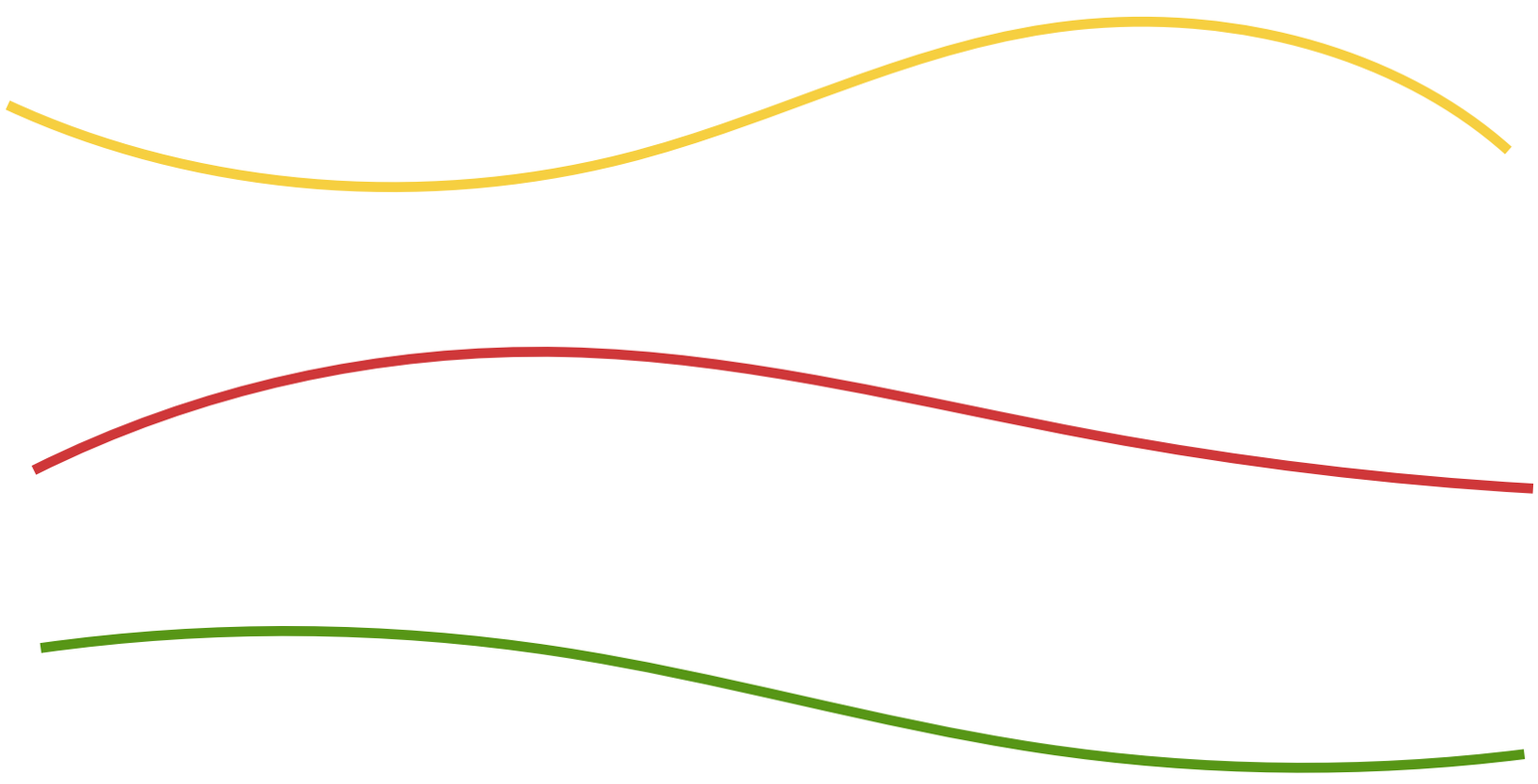
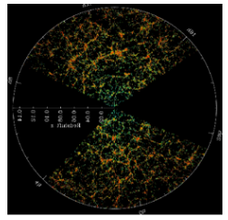
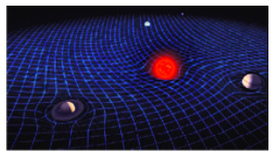
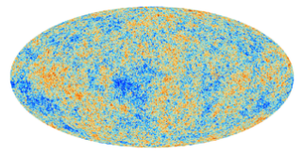
Many functions







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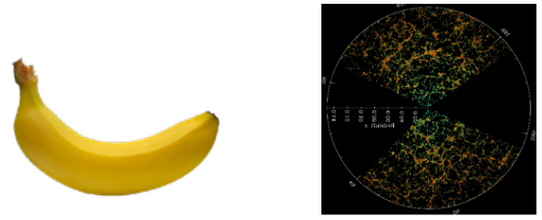
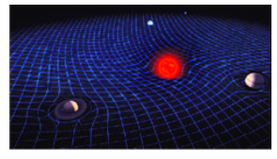
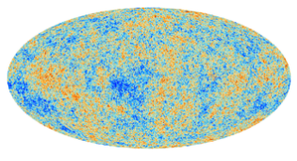
Only one function







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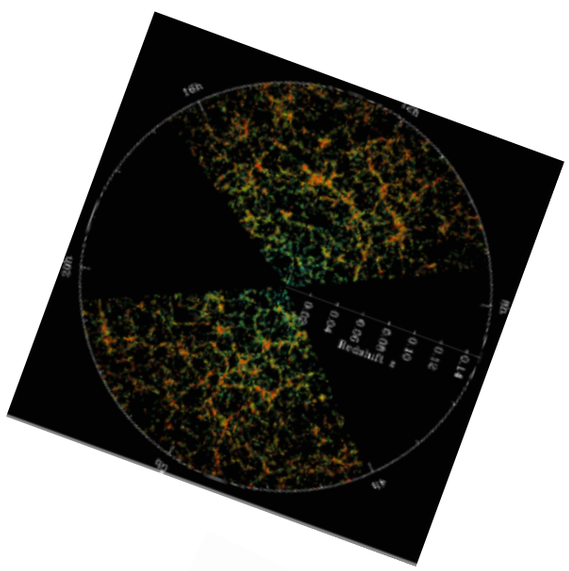
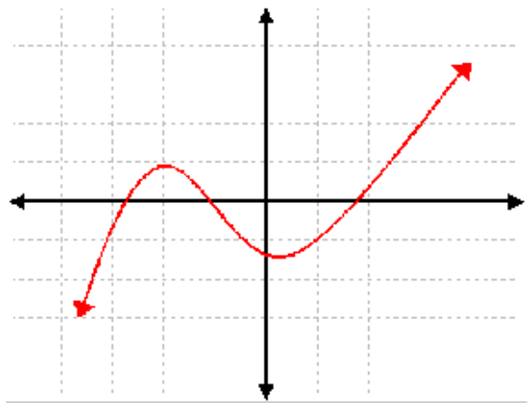
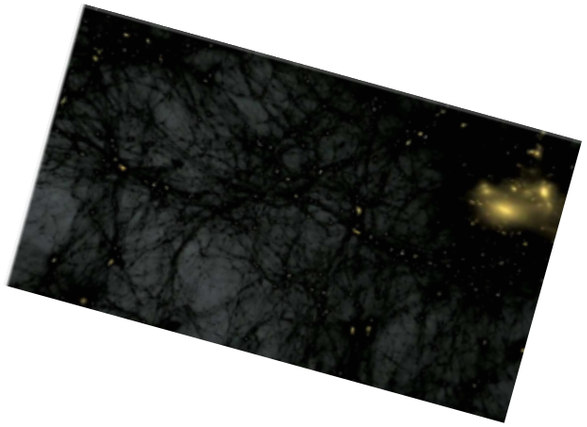
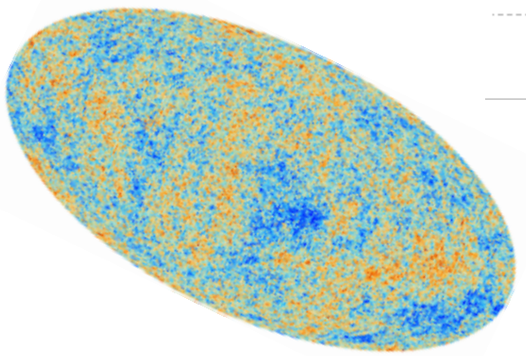
The function that originate the universe









Only one function, called the “adiabatic mode”

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Current paradigm

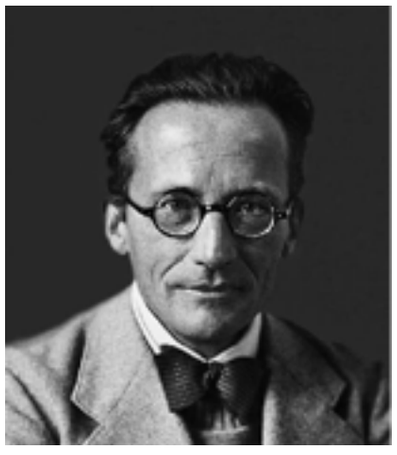
- What is the origin of this astonishing simplicity?

- Current paradigm: cosmological inflation was so simple that the whole universe was described by one single function (“single field inflation”)

- *Simplicity come from simplicity*

- We still don’t know if this is the ultimate explanation or if simplicity actually came from a very complicated primordial universe, but future data will clarify this. Stay tuned

Our quantum origins



Schrödinger

Quantum mechanics

Heisenberg

- By the early 1900 physicists felt pretty good about themselves. They had conquered mechanics and gravity thanks to Newton, they conquered statistical physics thanks to Boltzmann and Gibbs, which fuelled the industrial revolution and now also electromagnetism thanks to Maxwell, Faraday and Ampere. What else could there be to discover?!

- After pioneering work by Max Planck, Albert Einstein and Neils Bohr in the 1920's a new generation of physicists discovered that when we go down to the size of an atom, the laws of physics drastically change. Through the work of Schrödinger, Heisenberg, Dirac, von Neumann and others *quantum mechanics* was developed

Quantum mechanics

- What is important for our cosmic story is that according to quantum mechanics things can never stay put. They are always jittering a bit. These are called quantum fluctuations and are measured routinely in the lab
- To understand quantum fluctuations, consider a pendulum making small “harmonic” oscillations (”the career of a theoretical physicist is about studying harmonic oscillators in increasing levels of abstraction” S. Coleman)

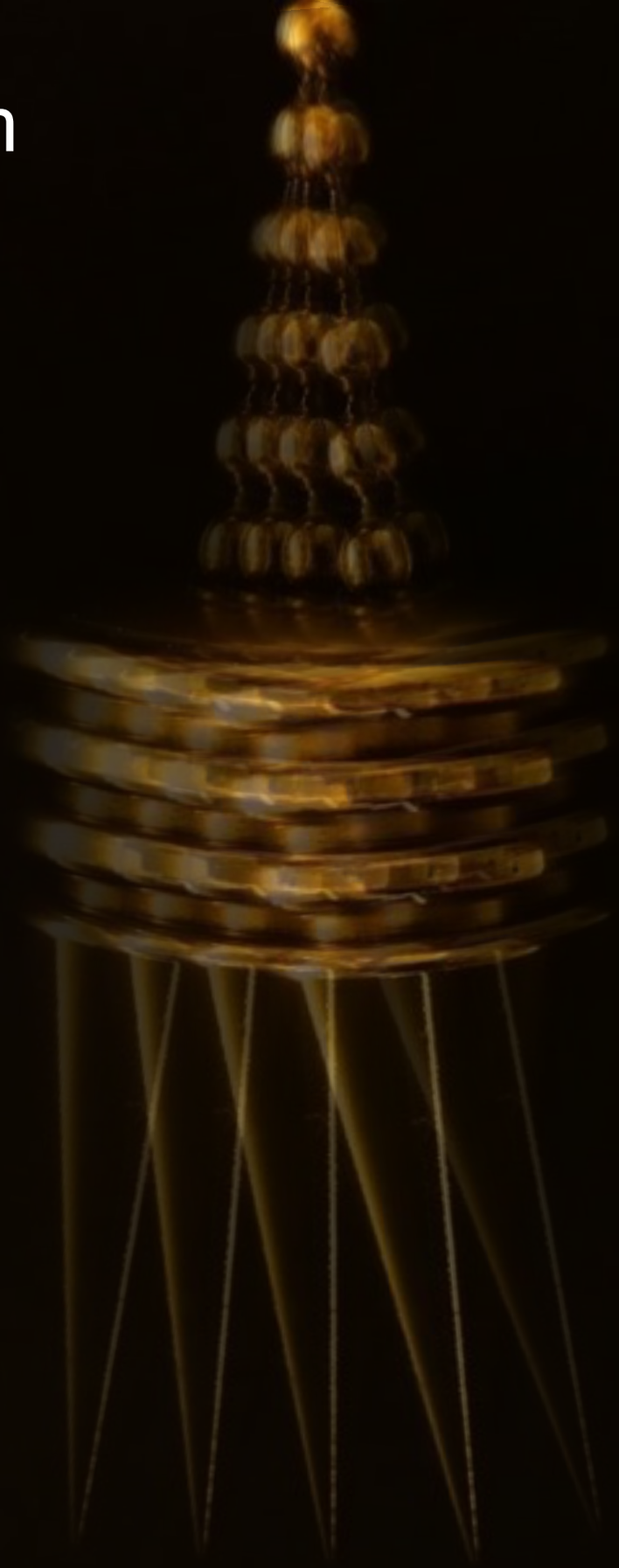
Classically you can always stop a pendulum

But what happens when the pendulum is very, very small?

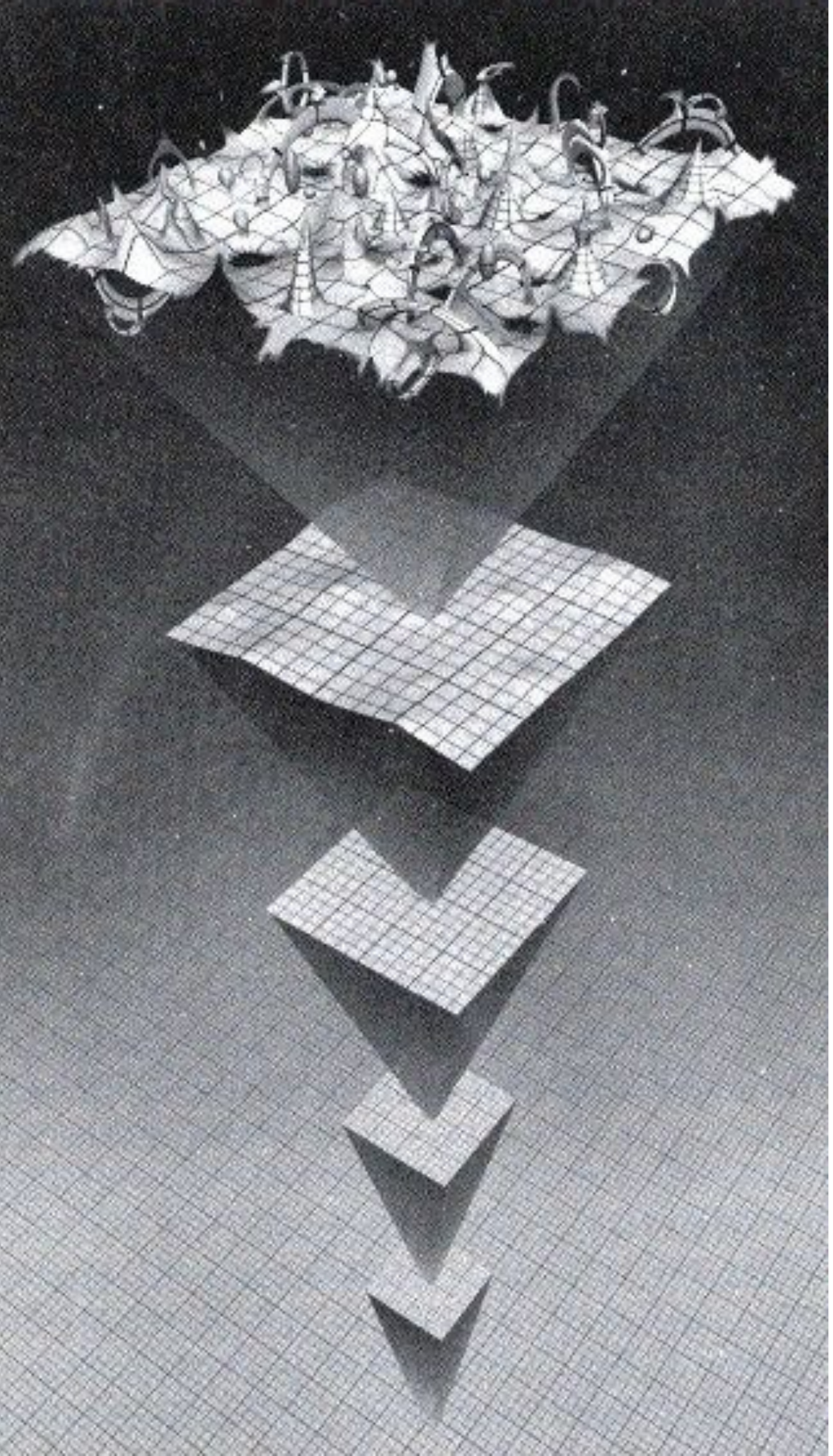
Heisenberg postulated that we cannot know both the position and the velocity of the pendulum with arbitrary precision: the *indetermination* principle

This was the birth of Quantum Mechanics

Imagine a pendulum
so small that it
exhibits a quantum
behaviour



A quantum pendulum
is always in motion!



All things we know obey the principles of quantum mechanics

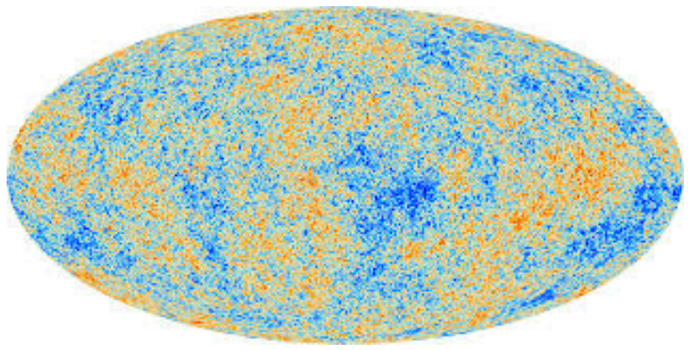
We expect that spacetime obeys quantum mechanics

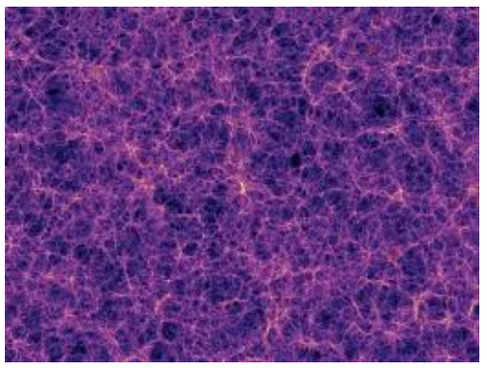
At tiny distances, spacetime must be continuously moving!

We believe that the distribution of everything originated from these tiny quantum fluctuations during inflation!

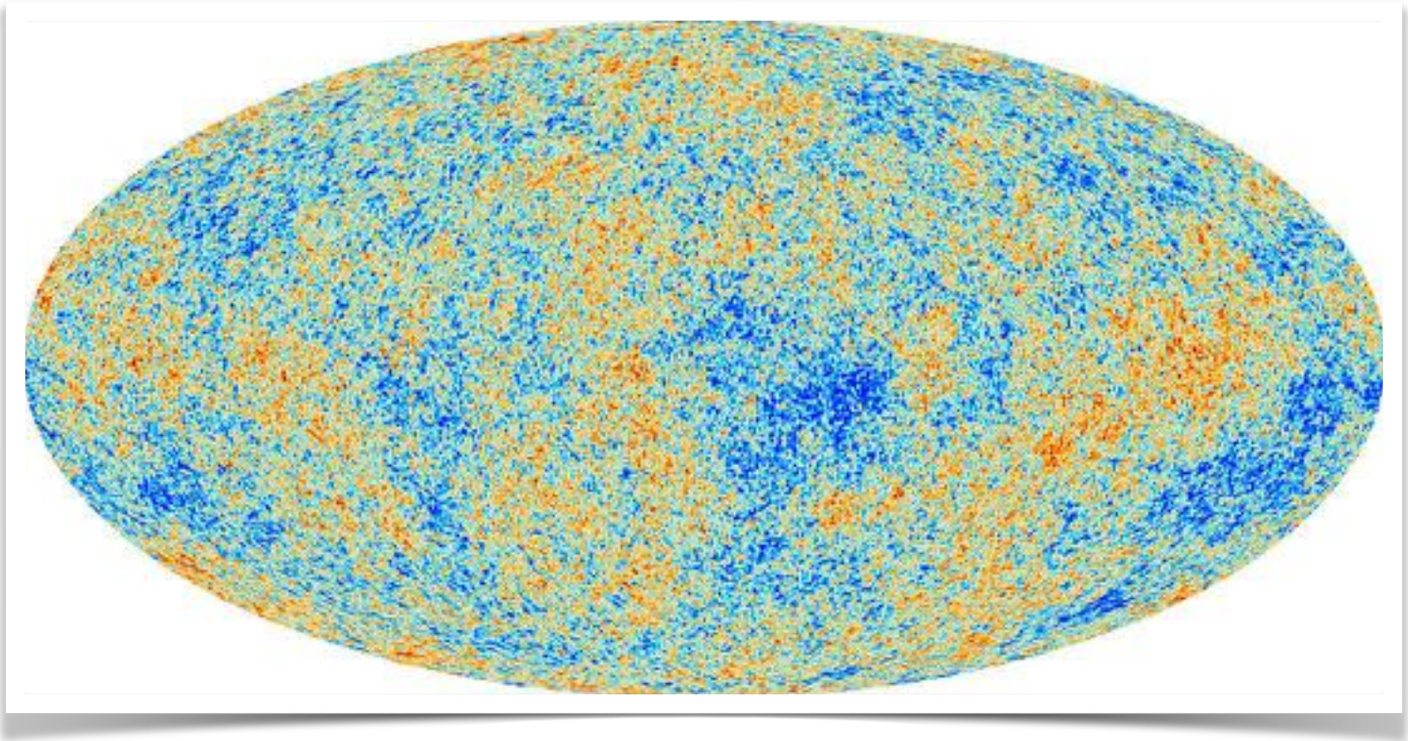
Conveniently conserved

- Remarkably, these power spectra are conserved throughout most of the history of the universe and we can measure them in the amplitude of perturbations in the CMB and galaxy distribution





- To know more about the laws of physics during inflation, physicists want to compute and observe more complicated statistical properties of these perturbations known as primordial non-Gaussianities. Despite 20 years of looking no one has discovered them yet, but the largest ever cosmological datasets are about to come online, stay tuned.



Quantum oscillations of spacetime from the big bang create also *Gravitational Waves*

The search for these Waves is the current frontier to understand the nature of spacetime

Summary

- Cosmology has revealed many amazing and astounding things about our universe

- Our universe appears to have been expanding throughout its history and the expansion is even accelerating now due to the dark energy

- We and the stuff we are made of, namely atoms, are only a small fraction of what's around and we are grappling to understand dark matter and dark energy

- Everything started out being distributed in the universe in an amazingly simple way and we how to understand why

- We all come from tiny subatomic fluctuations that have been stretched and amplified by inflation.

"Think deeply of simple things"

C. F. Gauss