

Physics in the Dark

Aman Shrivastava

Imagine Flying to the City of New York when its completely
"Dark"

All you can see is the lights all around

But, we also know that there is a structure and buildings
holding the lights that we observe

But,
What if there wasn't
any structure?

**Because they don't
fall, we know there
something out there.**

So, by the light of the day, we begin to see the physical reality which as we know is the architectural landscape



RIP Ironman
We miss you!



“You can’t be a friendly neighbourhood spiderman if there is no neighbourhood”

But, what if we only have access to the lights?

**which is what we have access to when we
look out to the Universe**

we have to infer the existence of the "**dark stuff**"

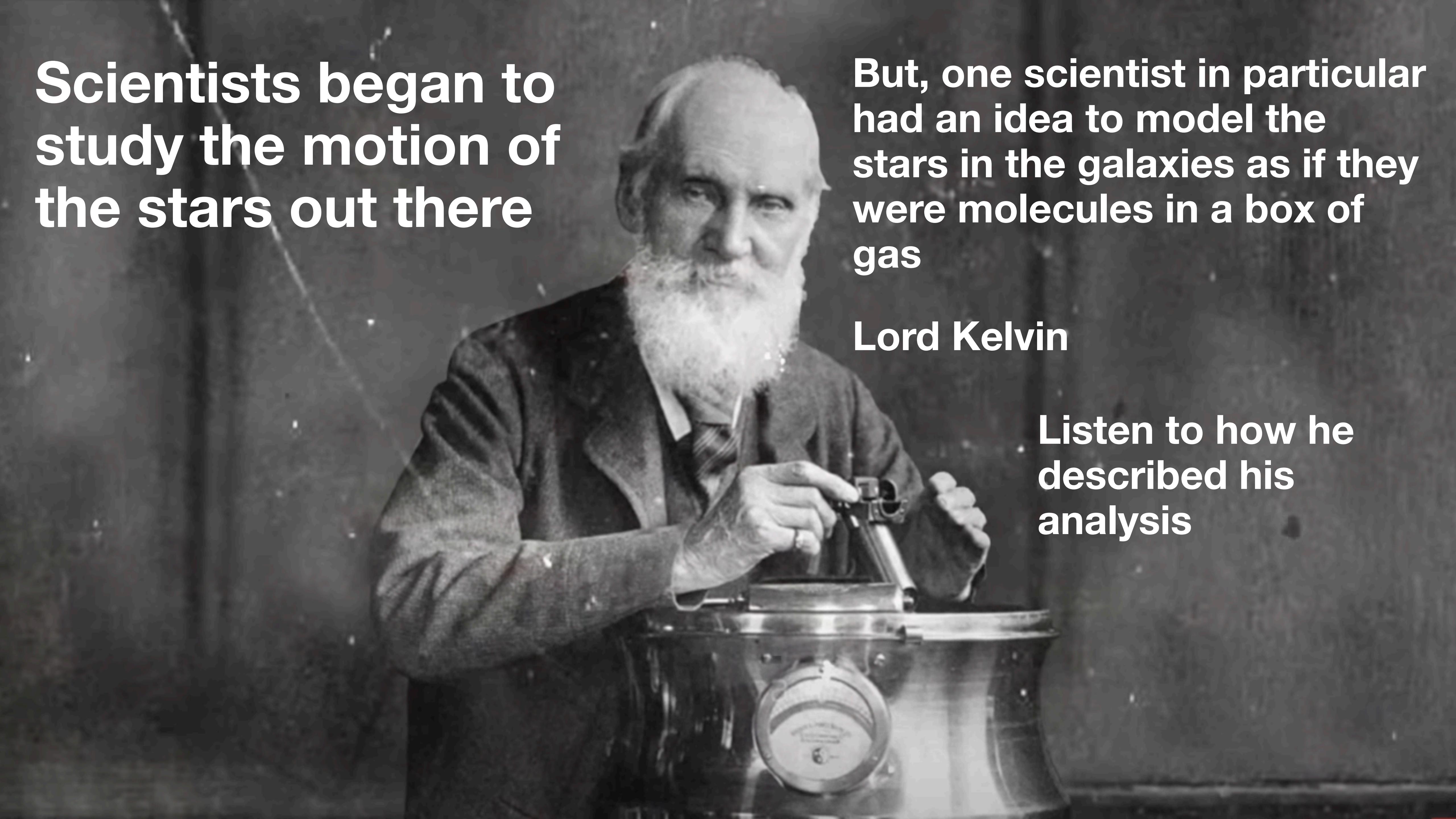


really, really dark!



**Towards the end of 1800s,
we had greater ability to
observe the Night Sky**



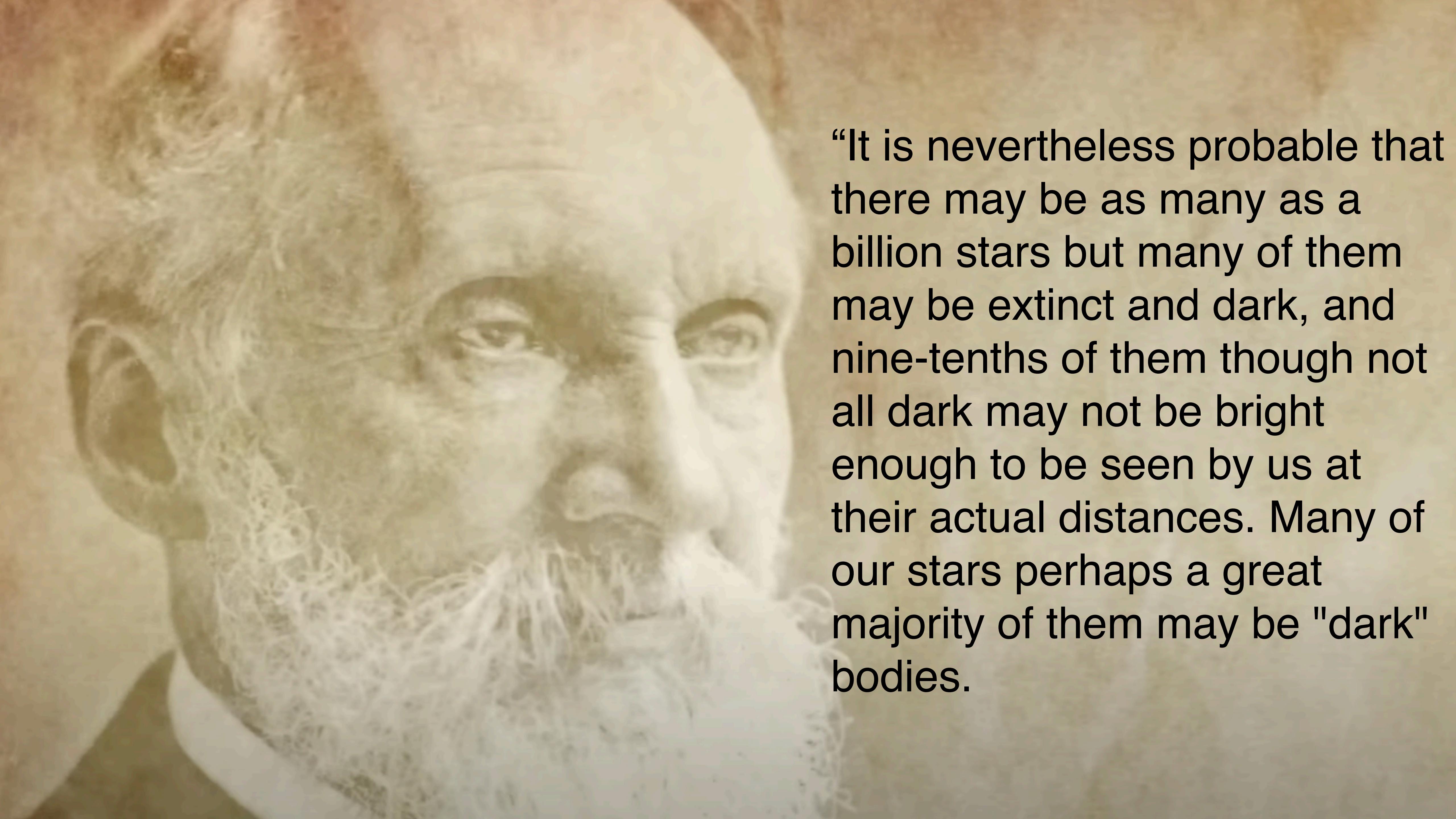


Scientists began to study the motion of the stars out there

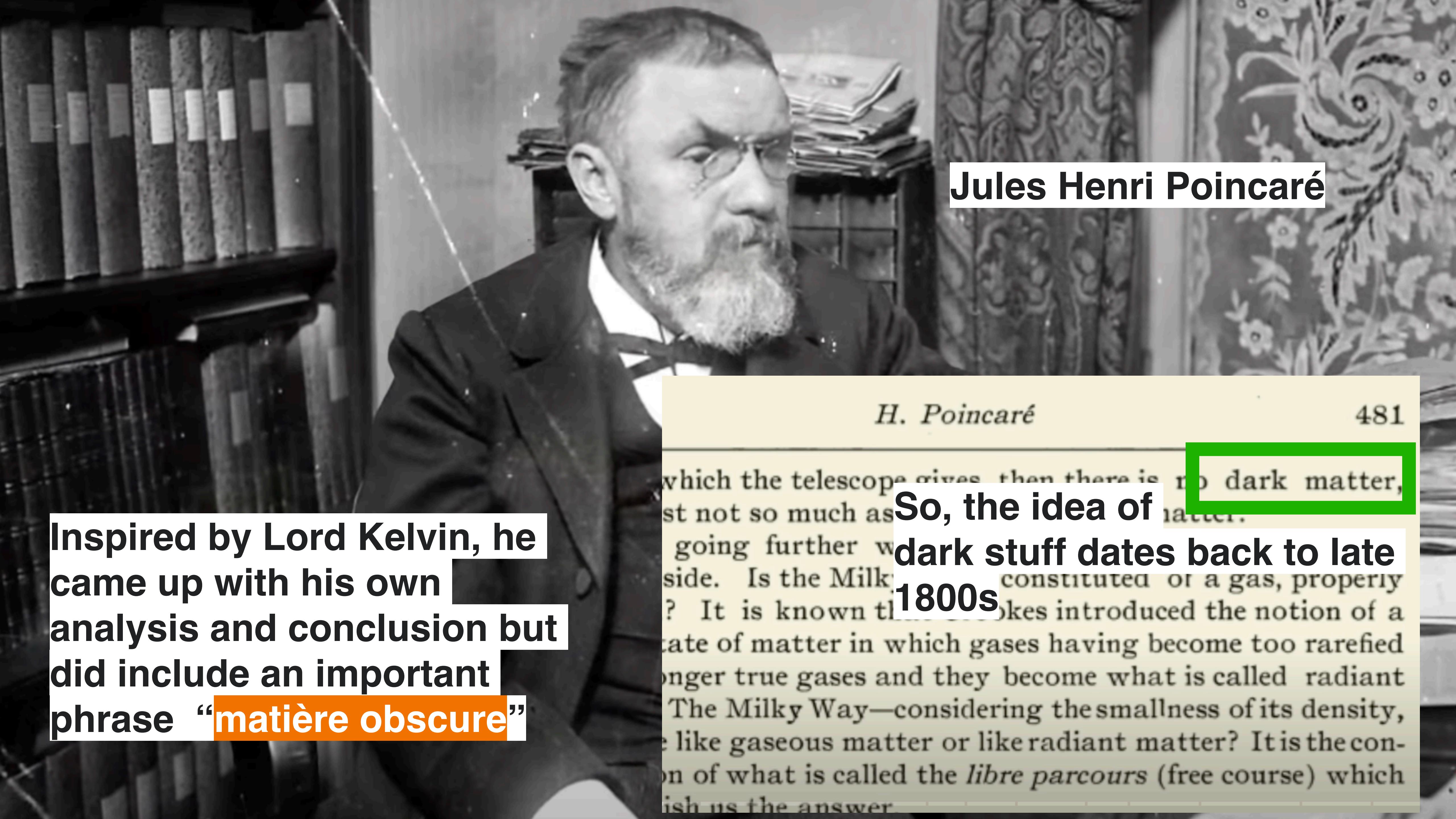
But, one scientist in particular had an idea to model the stars in the galaxies as if they were molecules in a box of gas

Lord Kelvin

Listen to how he described his analysis



"It is nevertheless probable that there may be as many as a billion stars but many of them may be extinct and dark, and nine-tenths of them though not all dark may not be bright enough to be seen by us at their actual distances. Many of our stars perhaps a great majority of them may be "dark" bodies.



Jules Henri Poincaré

Inspired by Lord Kelvin, he came up with his own analysis and conclusion but did include an important phrase “**matière obscure**”

H. Poincaré

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which the telescope gives, then there is no dark matter, but not so much as going further on the side. Is the Milky Way constituted or a gas, properly speaking? It is known that it makes introduced the notion of a state of matter in which gases having become too rarefied longer true gases and they become what is called radiant matter. The Milky Way—considering the smallness of its density, is it like gaseous matter or like radiant matter? It is the question of what is called the *libre parcours* (free course) which will give us the answer.

So, the idea of dark stuff dates back to late 1800s

In the coming decades

Fritz Zwicky also concluded that there had to be additional dark stuff that was out there that would be responsible for the gravity that was pushing and pulling these galaxies around.



Fritz Zwicky, a Swiss astronomer at Caltech studied the motion of the galaxies in coma cluster which is a few hundred light years away.

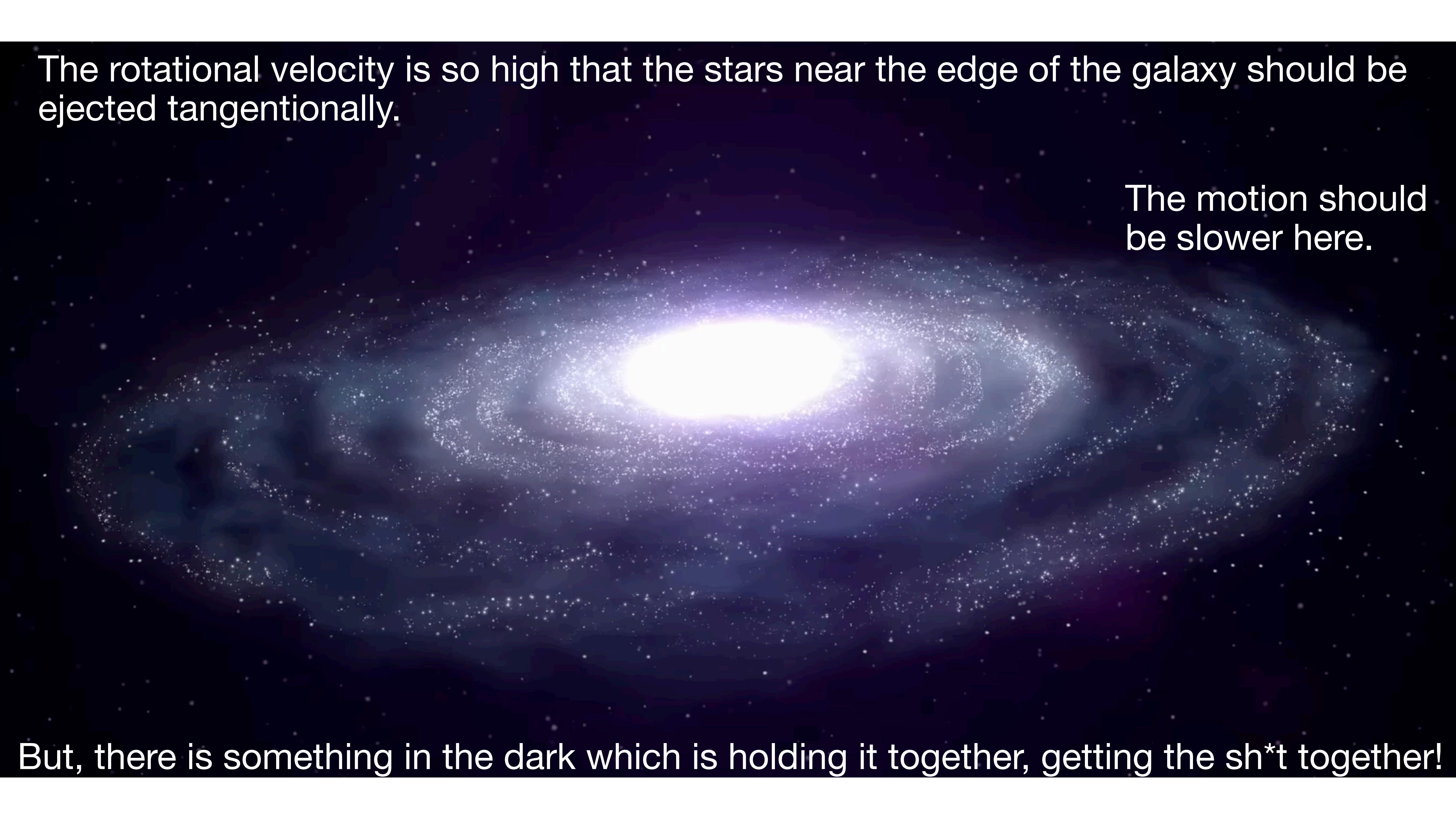


**LSST is now known as
Vera R. Rubin Observatory**

Vera Rubin

It was actually her efforts to study the motion of stars in swirling galaxies that she found that the galaxies are swirling too quickly and that the stars should be sort of ejected out

Where there is a Will, there is a Way!

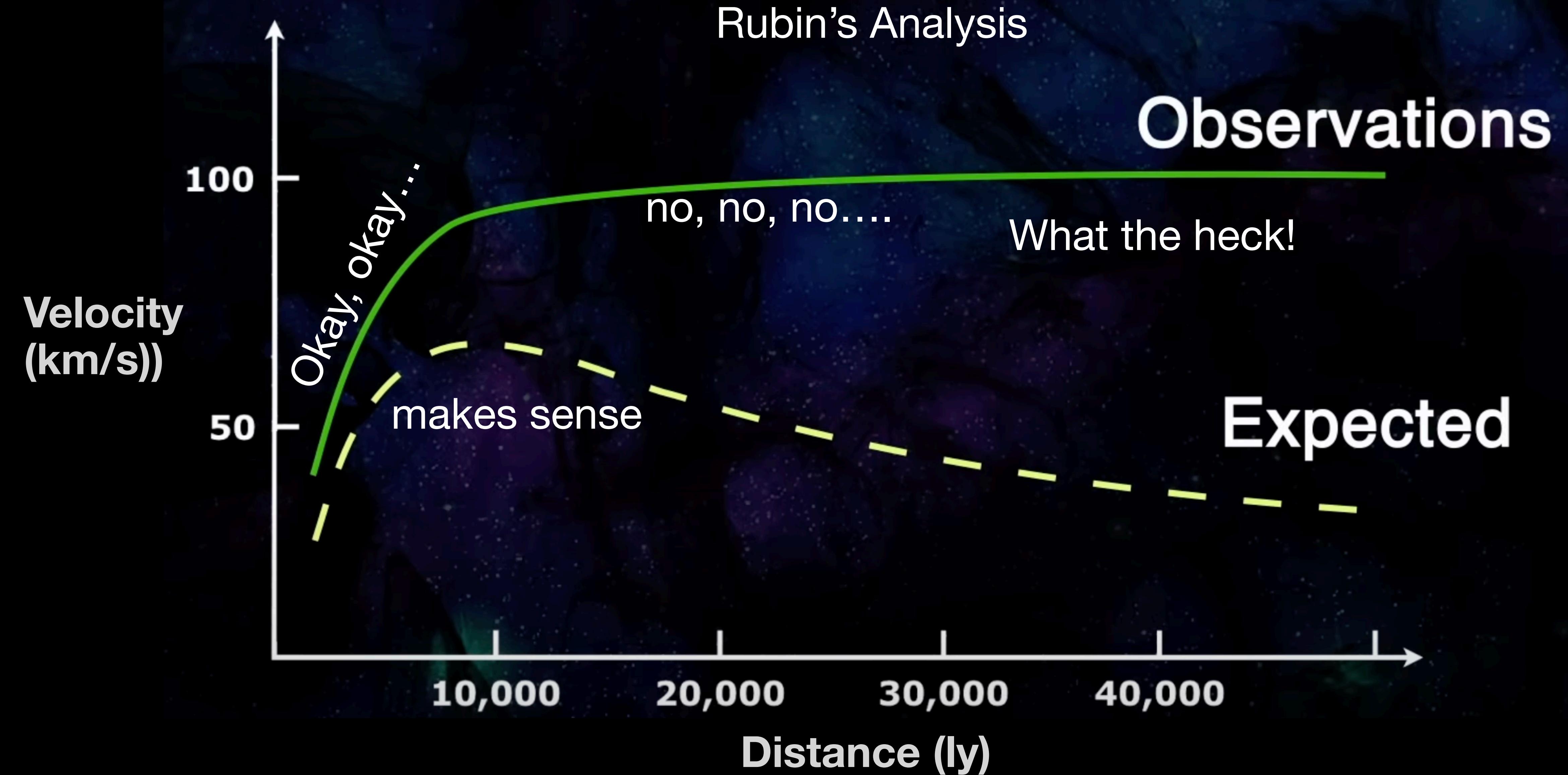


The rotational velocity is so high that the stars near the edge of the galaxy should be ejected tangentially.

The motion should be slower here.

But, there is something in the dark which is holding it together, getting the sh*t together!

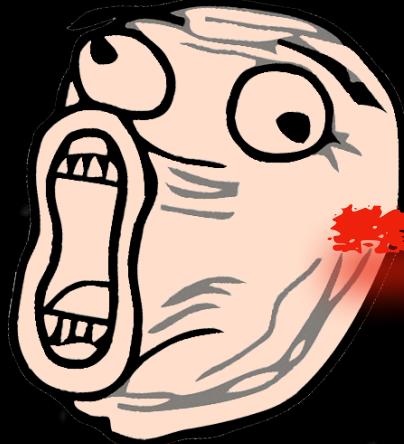
Mathmatically, velocity of stars at the outskirts of galaxy should be lower relative to the ones at the centre.



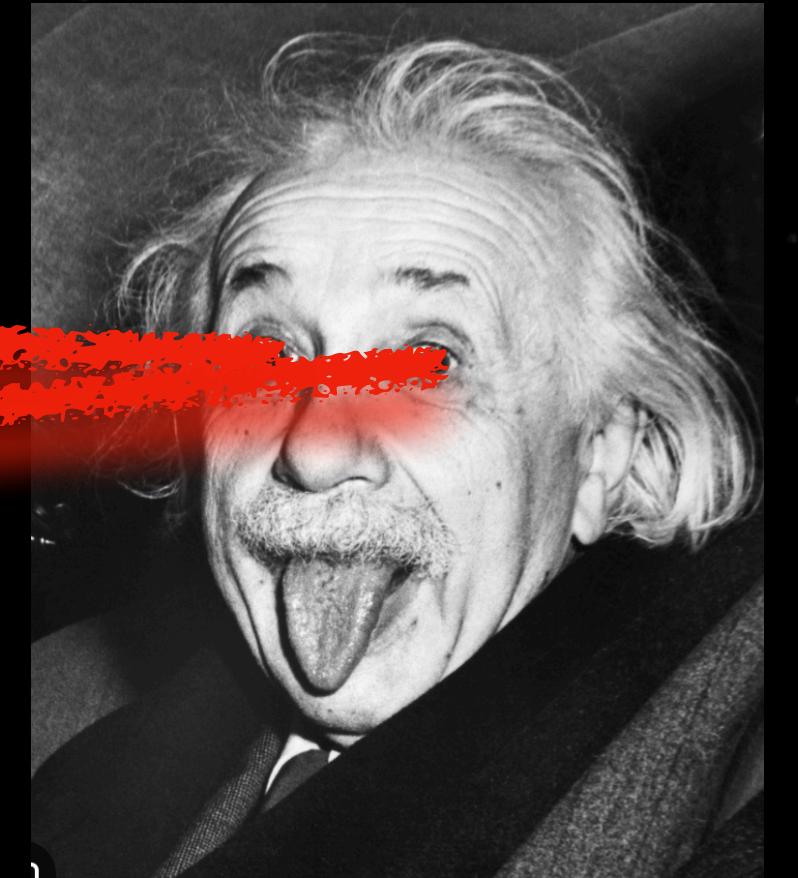


In November 1915, when Einstein was working on relativity, there was this one planet which was of particular interest due to its pesky orbit which was shifting each year.

Flat Earther's

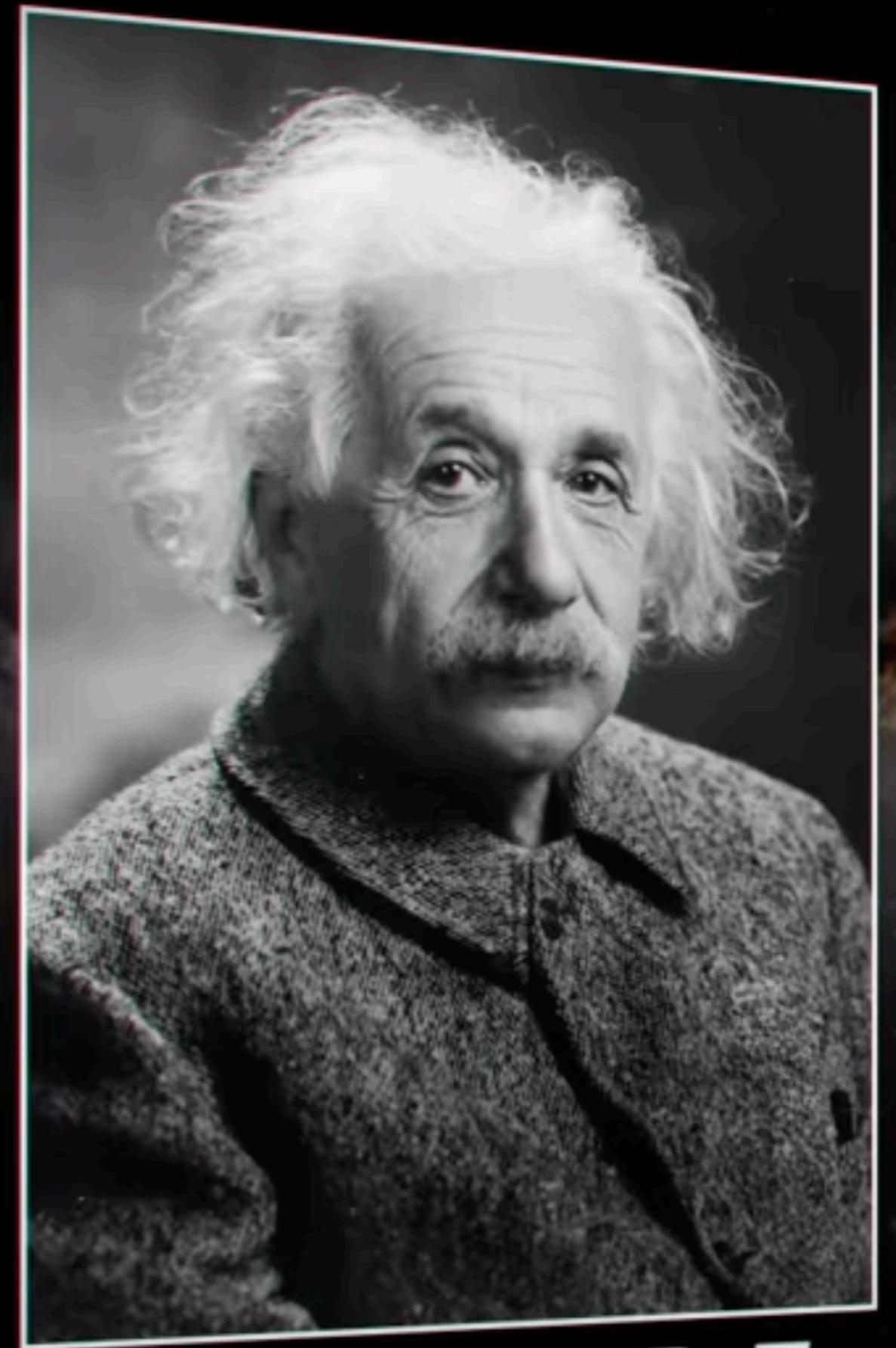


There, there.. there it is...
VULCAN

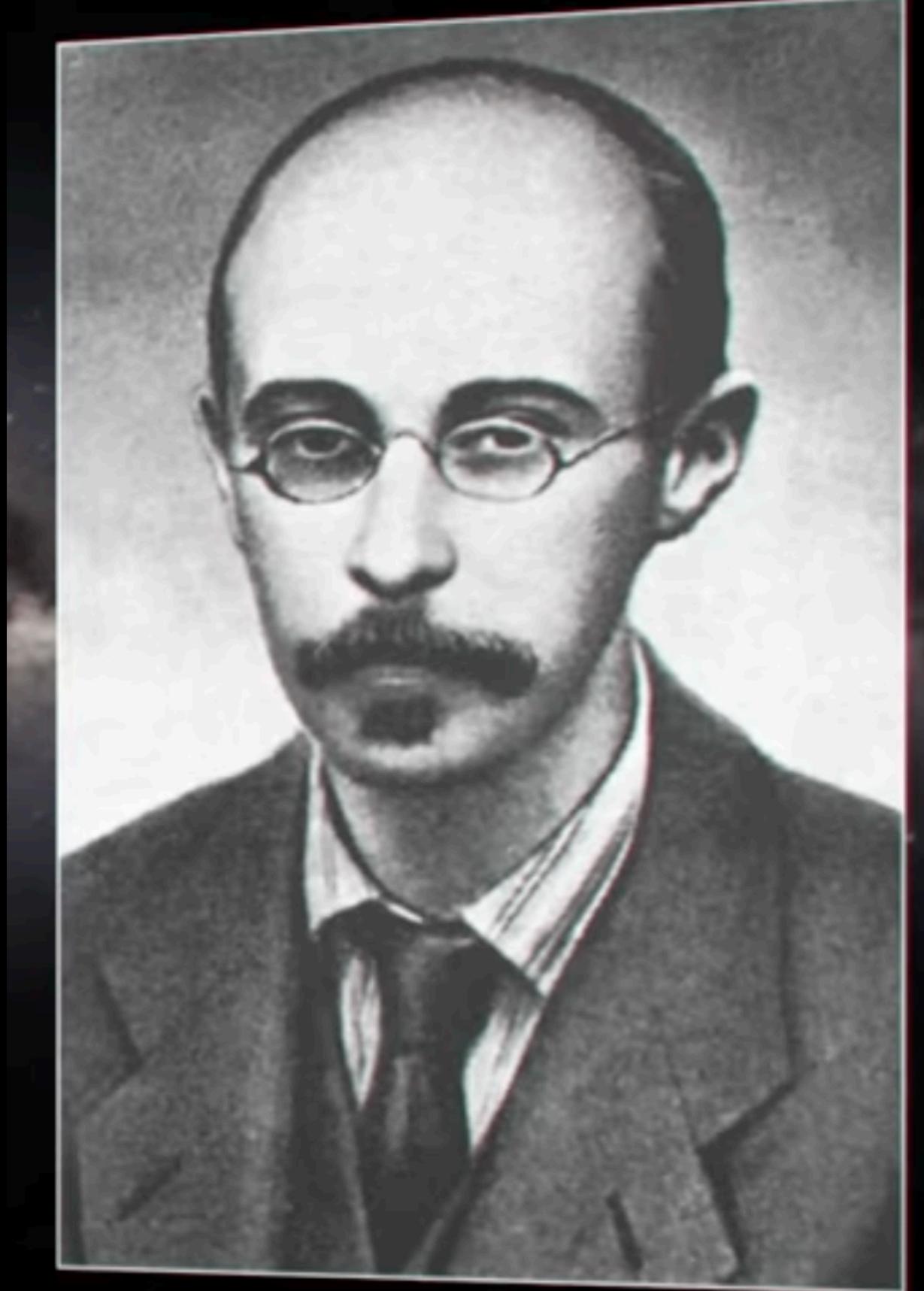


see you in hell...

Previously, some thought there was a hidden “dark” planet out there, undetected, (called VULCAN) which was causing the orbit of Mercury to shift.



**ALBERT
EINSTEIN**



**ALEXANDER
FRIEDMANN**

In 1916, Einstein proposed the theory of general relativity and Alexander Friedmann applied the theory to the entire universe to explain the expansion of Universe.

At the heart of General Relativity are the

EINSTEIN FIELD EQUATIONS

Plural

Einstein Tensor

Defines:

Shape, Curvature of Spacetime

$$G_{\mu\nu} = -\frac{8\pi G}{c^4} T^{\mu\nu}$$

Stress -Energy Tensor

Defines:
The energy
The pressure
The momentum

More

Tensors: Multicomponent Multidimensional quantities

With both having 10 independent components, giving 10 independent field equations

In simple terms, to sum up in few lines



John Wheeler
American Physicist
1911-2008

***"Space-time tells matter how to move.
Matter tells space-time how to curve."***

So, Einsteins Field Equations relates the **geometry of spacetime** to the **distribution of matter in it**.

Let's think about gravity from a Newtonian Perspective – as a force
Rather than an Einsteinian spacetime curvature

When you throw something in air, it falls down due to gravity

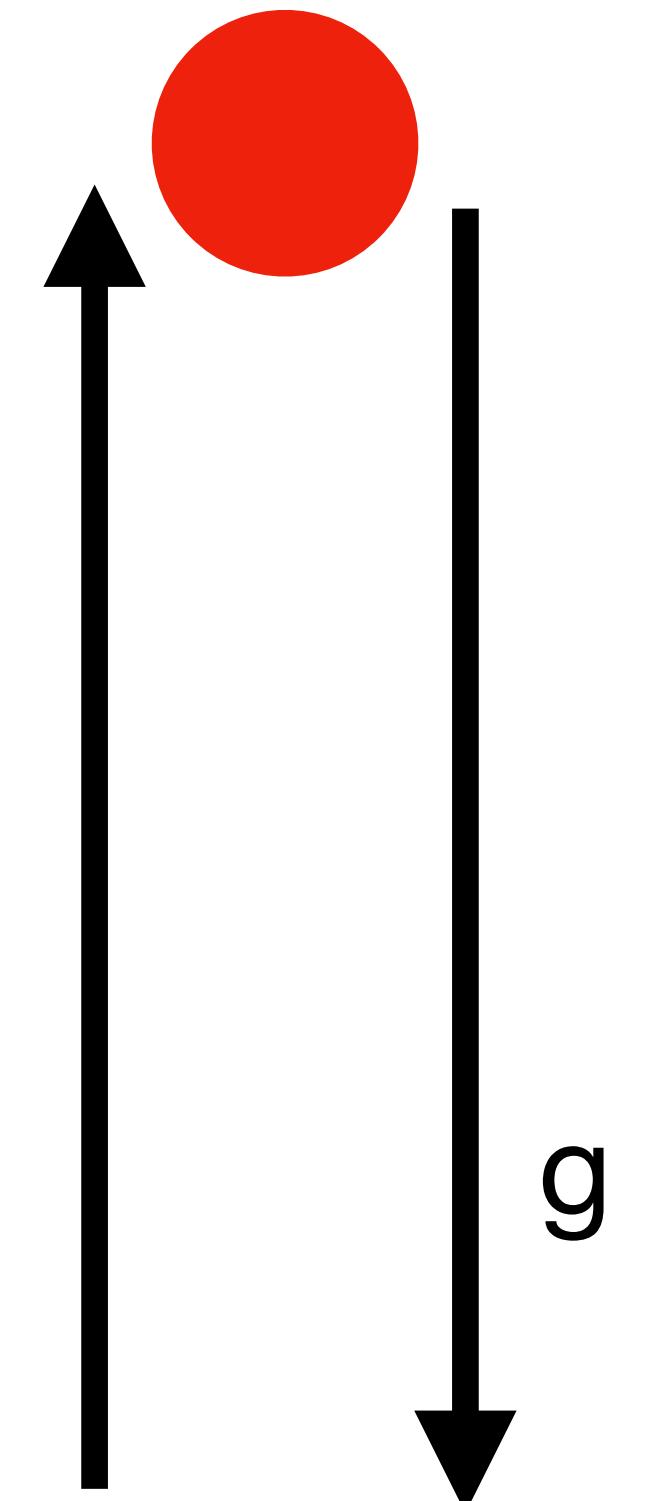
The faster you throw it, the further it travels before falling down

$$F = \frac{GM_1M_2}{r^2}$$

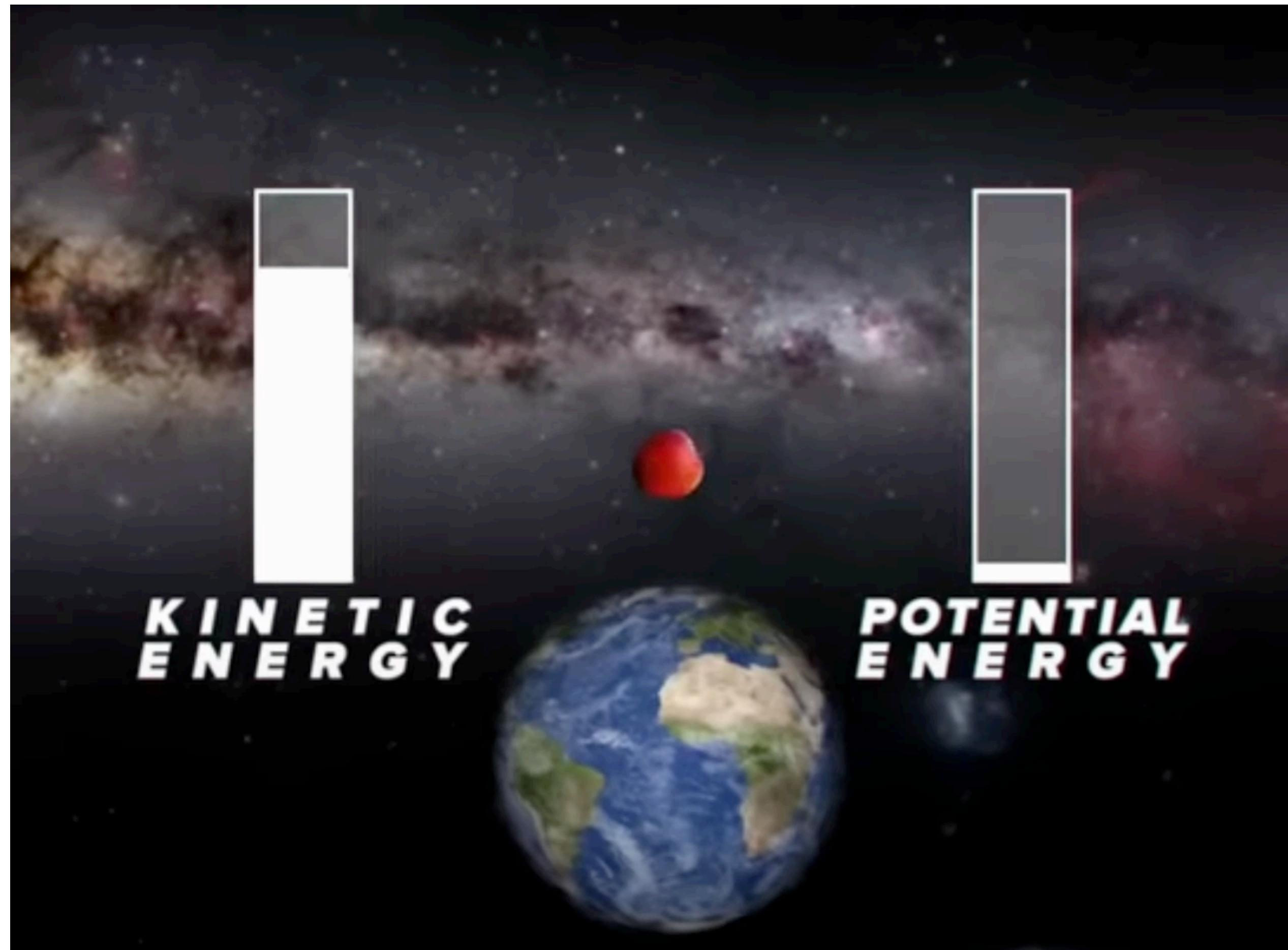
This escape velocity comes out of the Newton's Law of Gravitation which itself can be derived from Einstein's Field Equations.

What happens if you launch it at 11 km/s, the escape velocity of Earth

By the time it stops moving, it will far enough for the gravitational pull to be close to 0.



If you have ever derived the equation for escape velocity, you know it comes from thinking about energy - kinetic and potential energy.



$$v_{esc} = \sqrt{\frac{GM}{r}}$$

As the object rises, the K.E.
is converted to P.E.

There is a minimum kinetic energy you need to escape the earth's gravitational pull which gives you the escape velocity.

Consider the Newtonian Analogy and infer that the universe also has an escape velocity that lets galaxy's escape each other's gravitation pull.

Based on the stuff (density) in the Universe, there is a current expansion speed (kinetic energy) which would cause the future expansion rate to come to a hault (conversion to potential energy).

How do you calculate the espace velocity of the entire Universe?

By solving the Einstein's Field Equations

Lets reduce the 10 EFE's to only 2,
the Friedman's Equations:

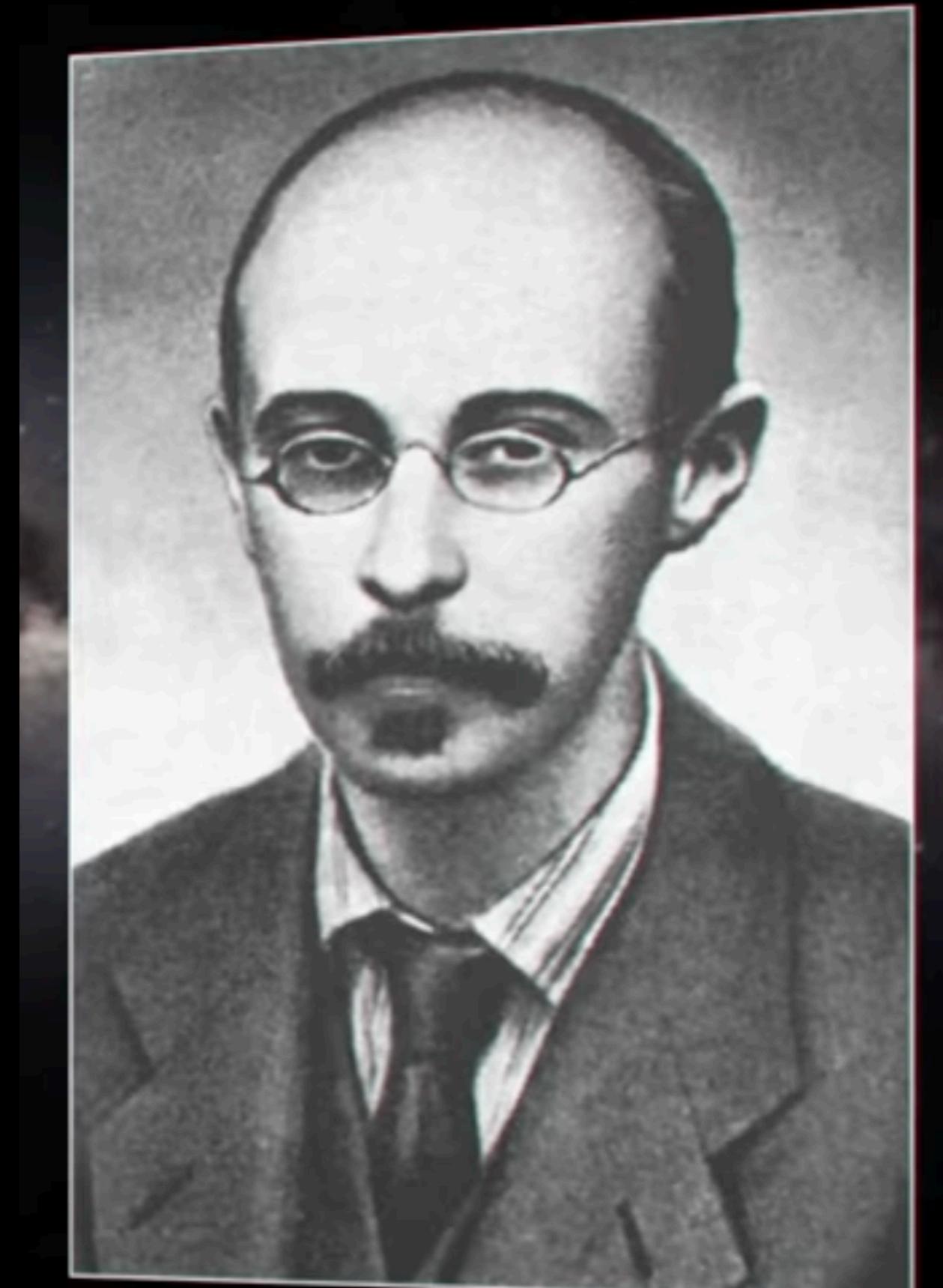
a(dot) is speed of expansion of the universe

$$\left(\frac{\dot{a}}{a}\right)^2 - \frac{8\pi G}{3}\rho = -\frac{kc^2}{a^2}$$

a is the scale factor which
represents size of the Universe

Like average distance between
galaxy's

The Eq tells how a (size) evolves over time



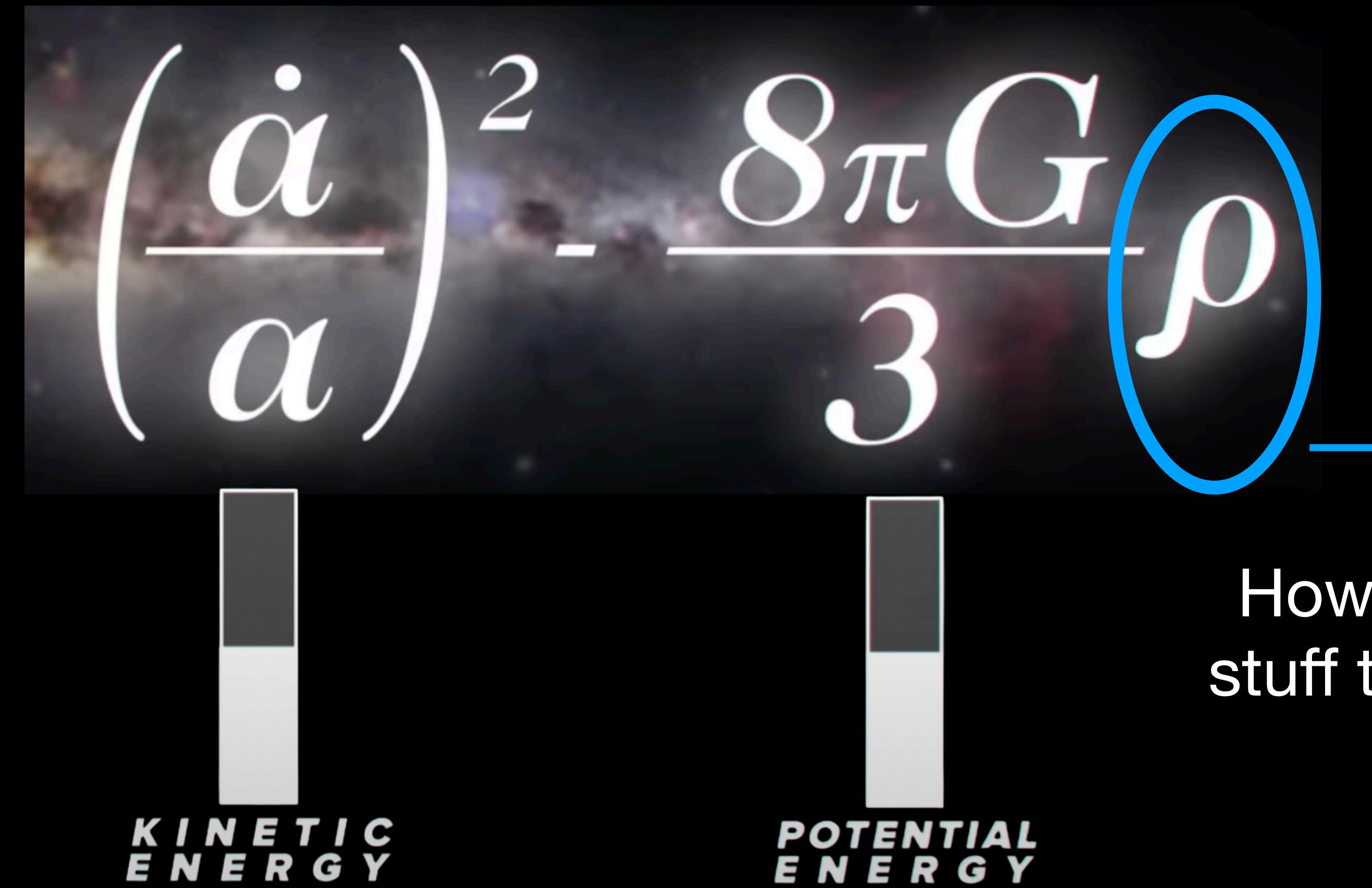
ALEXANDER
FRIEDMANN

Let's stick to the left hand side of the Equation:

Remember the Newtonian Analogy we talked, this equation is analogous to the idea

The equation is an energy equations

(\dot{a}/a)^2
Analgous to the kinetic energy of the expansion



But, the kinetic energy is resisted by the gravitational pull of matter and energy (density) of the universe

How packed with stuff the universe is

The balance between these two tells us “**FATE OF THE UNIVERSE**”

So, what are the possibilities?

Possibility 1:

If the Kinetic Energy of Expansion = Potential Energy of Collapse

The Universe will come to an
halt just like an object
whose K.E. = P.E.

$$\left(\frac{\dot{a}}{a}\right)^2 \cdot \frac{8\pi G}{3} \rho$$

 -  LHS = 0

KINETIC ENERGY POTENTIAL ENERGY



So, what are the possibilities?

Possibility 2:

If the Kinetic Energy of Expansion > Potential Energy of Collapse

$$\left(\frac{\dot{a}}{a}\right)^2 - \frac{8\pi G}{3} \rho > 0$$

KINETIC ENERGY - POTENTIAL ENERGY > 0

The Universe will continue to expand just like an object with higher velocity with K.E. > P.E.



So, what are the possibilities?

Possibility 3:

If the Kinetic Energy of Expansion < Potential Energy of Collapse

The Universe will collapse
just like ball falling to the
ground with K.E. < P.E.

$$\left(\frac{\dot{a}}{a}\right)^2 \cdot \frac{8\pi G}{3} \rho$$

 -  LHS < 0

KINETIC ENERGY POTENTIAL ENERGY



So, what will happen? What do you think?

We know the expansion speed (kinetic energy analogy) through redshfitting of the galaxy's

$$\left(\frac{\dot{a}}{a}\right)^2$$

Astronomers have also calculated the density of matter within our universe but it turns out to be **TOO LOW**

$$\left(\frac{\dot{a}}{a}\right)^2 \cdot \frac{8\pi G}{3} \rho$$

$$\frac{8\pi G}{3} \rho$$

The Left hand side is positive, there is no way around, the
UNIVERSE WILL CONTINUE TO EXPAND FOREVER



A diagram illustrating the energy balance of the universe. It shows two vertical rectangles side-by-side. The left rectangle is divided into two horizontal sections: a smaller black top section and a larger white bottom section. The right rectangle is also divided into two horizontal sections: a larger black top section and a smaller white bottom section. A minus sign (-) is placed between the two rectangles. To the right of the minus sign is a greater than sign (>). To the right of the greater than sign is a large white zero.

$$\text{KINETIC ENERGY} - \text{POTENTIAL ENERGY} > 0$$

Recolapsing is **TOO LOW**

THE HUBBLE CONSTANT

$$H_0 \approx 70 \text{ km/s/Mpc}$$

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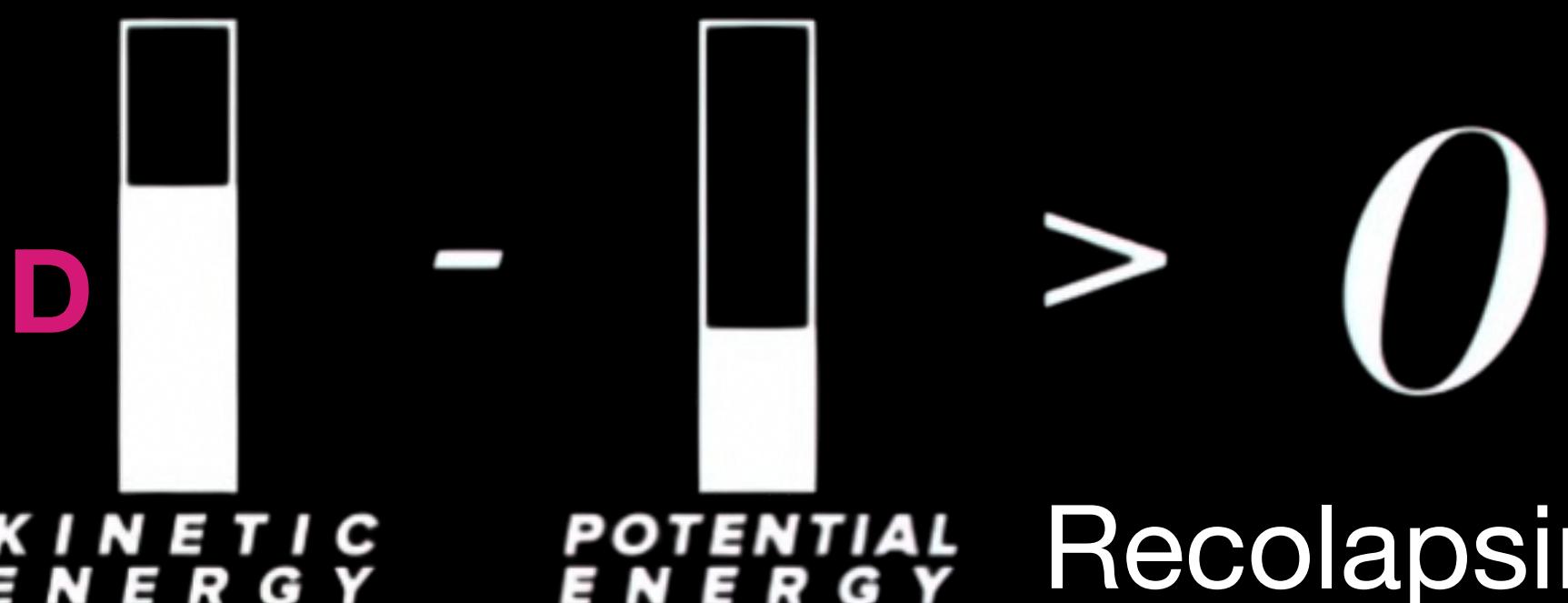
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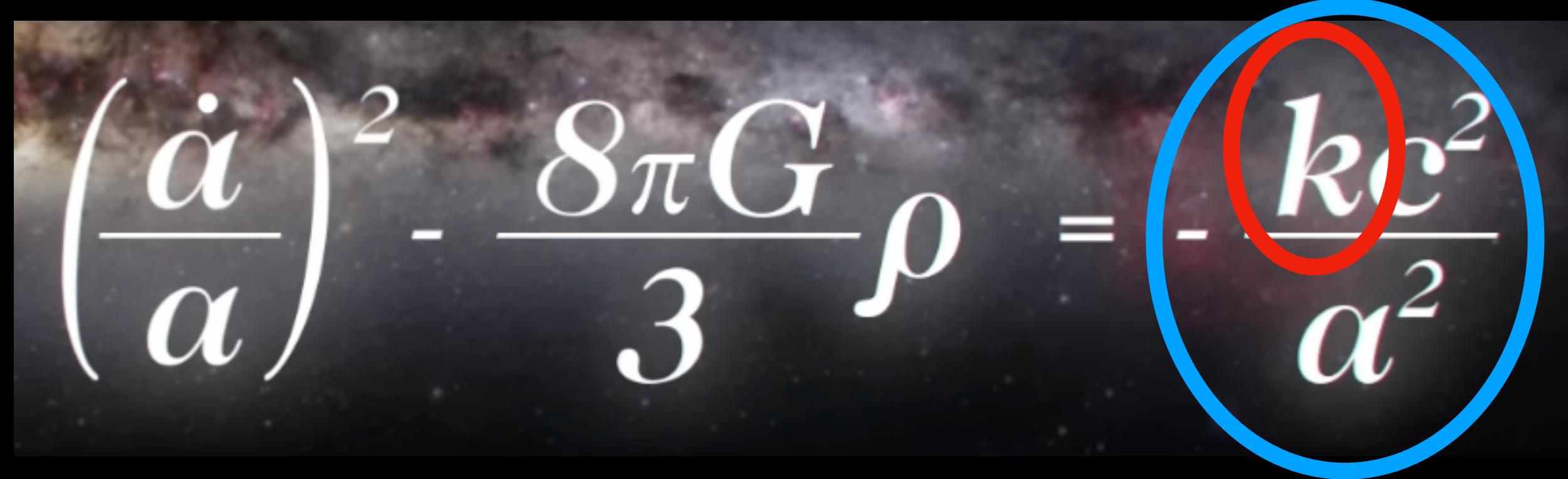
THE HUBBLE CONSTANT

$$H_0 \approx 70 \text{ km/s/Mpc}$$

BUT, wait a minute! What about the right hand side of the equation?

Well, mathematically speaking,
since LHS is positive, RHS should be positive since LHS = RHS

Spatial curvature and spatial extent: finite or infinite



The image shows the first Friedmann equation for a homogeneous and isotropic universe:

$$\left(\frac{\dot{a}}{a}\right)^2 - \frac{8\pi G}{3}\rho = -\frac{k c^2}{a^2}$$

A red circle highlights the term $\frac{k c^2}{a^2}$, which represents the spatial curvature of spacetime.

Describes the
geometry/shape/
curvature of
spacetime fabric.

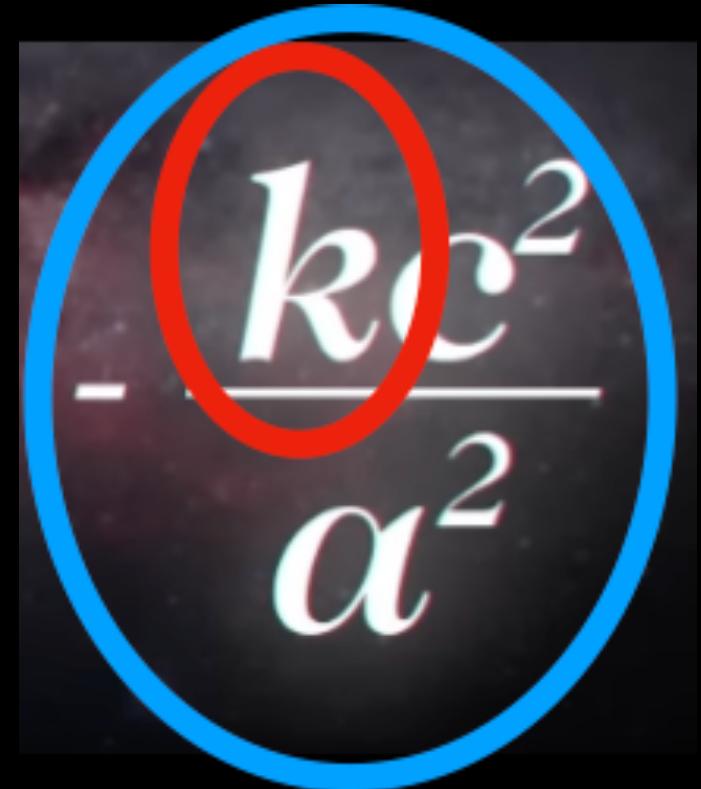
According to the 1st Friedman Equation, the **FATE OF THE UNIVERSE** is tied to its
spatial geometry.

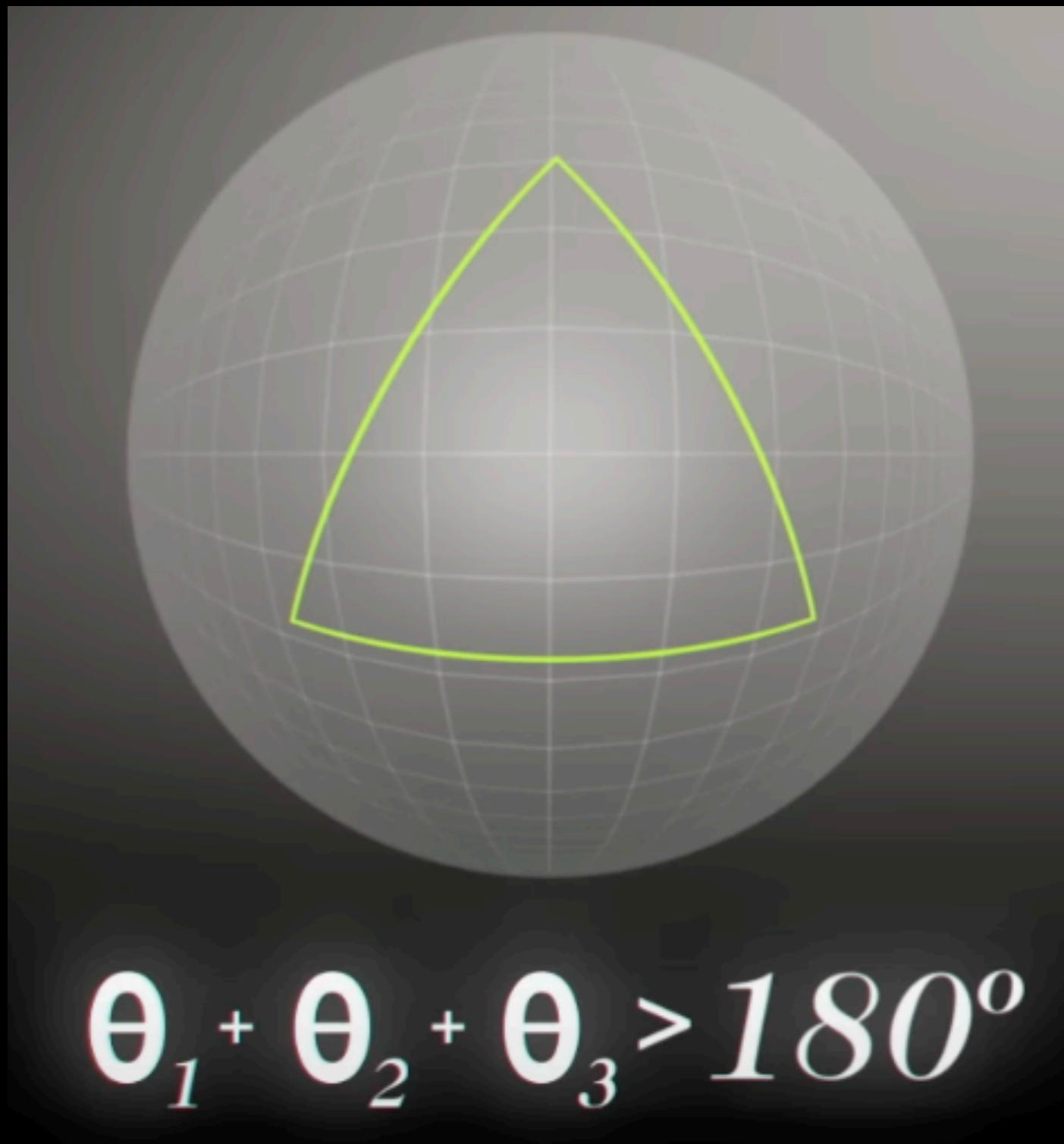
Oh why not! **Matter tells spacetime how to curve**, right!?

There are 3 possibilities:

At any given instant in time, the spatial geometry can be **flat or curved**.

$k = +1$ (meaning **positive curvature, spatial geometry**)


$$-\frac{k c^2}{a^2}$$



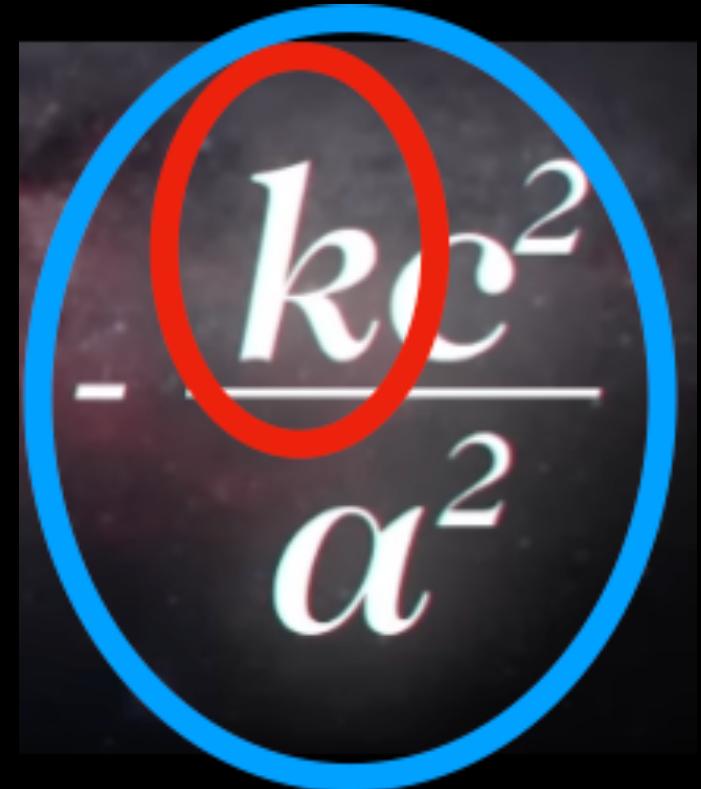
The spatial geometry at a given instant in time will be cured like a sphere but in a Universe like this the geometry is complicated such that

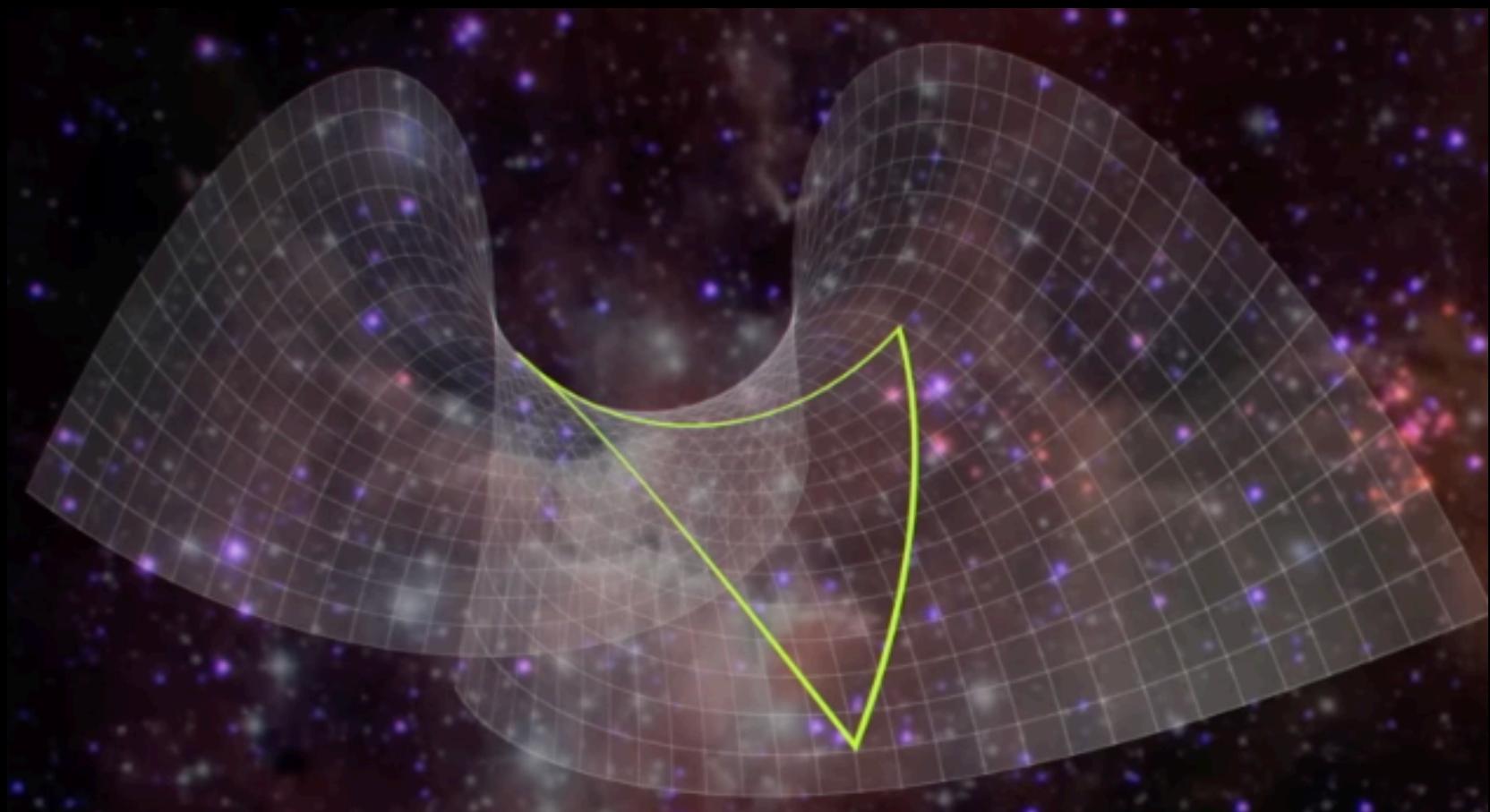
The Angles of Triangle add upto **more than 180 degrees**

There are 3 possibilities:

At any given instant in time, the spatial geometry can be **flat or curved**.

$k = -1$ (**meaning negative curvature**)


$$-\frac{kc^2}{a^2}$$



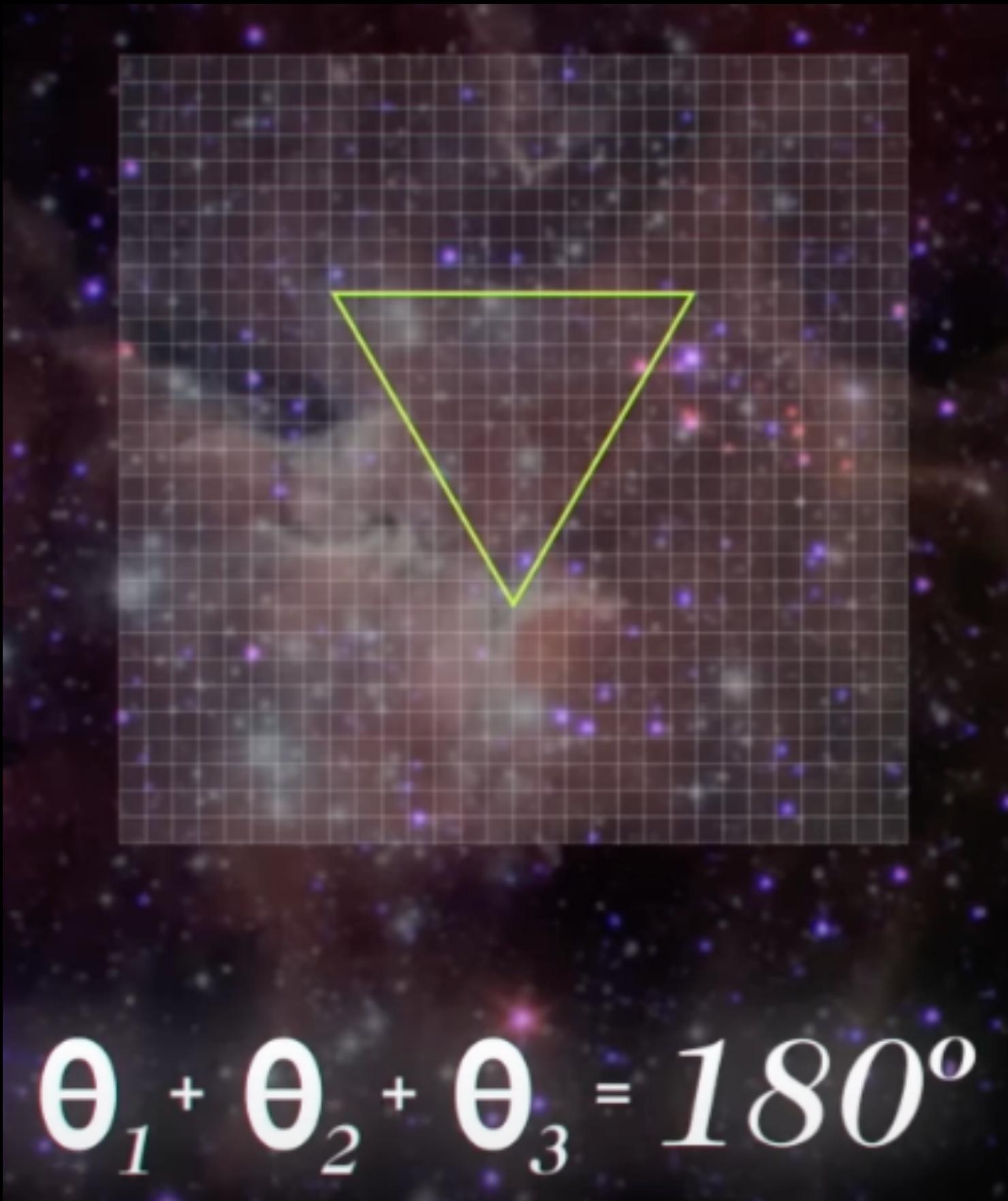
The Universe in this case will be a 3D version of negatively curved hyperbolic plane.

In this geometry, the angles of triangles add upto **less than 180 degrees**

There are 3 possibilities:

At any given instant in time, the spatial geometry can be **flat or curved**.

$K = 0$ (**meaning flat curvature**)



The spatial geometry in such a universe in this case will be flat at any given instant in time.

In this geometry, the angles of triangles add up to perfectly **180 degrees**

$$\theta_1 + \theta_2 + \theta_3 = 180^\circ$$

A circular graphic containing the equation $\frac{kc^2}{a^2}$. The term kc^2 is highlighted with a red circle, and the entire circle is outlined in blue.

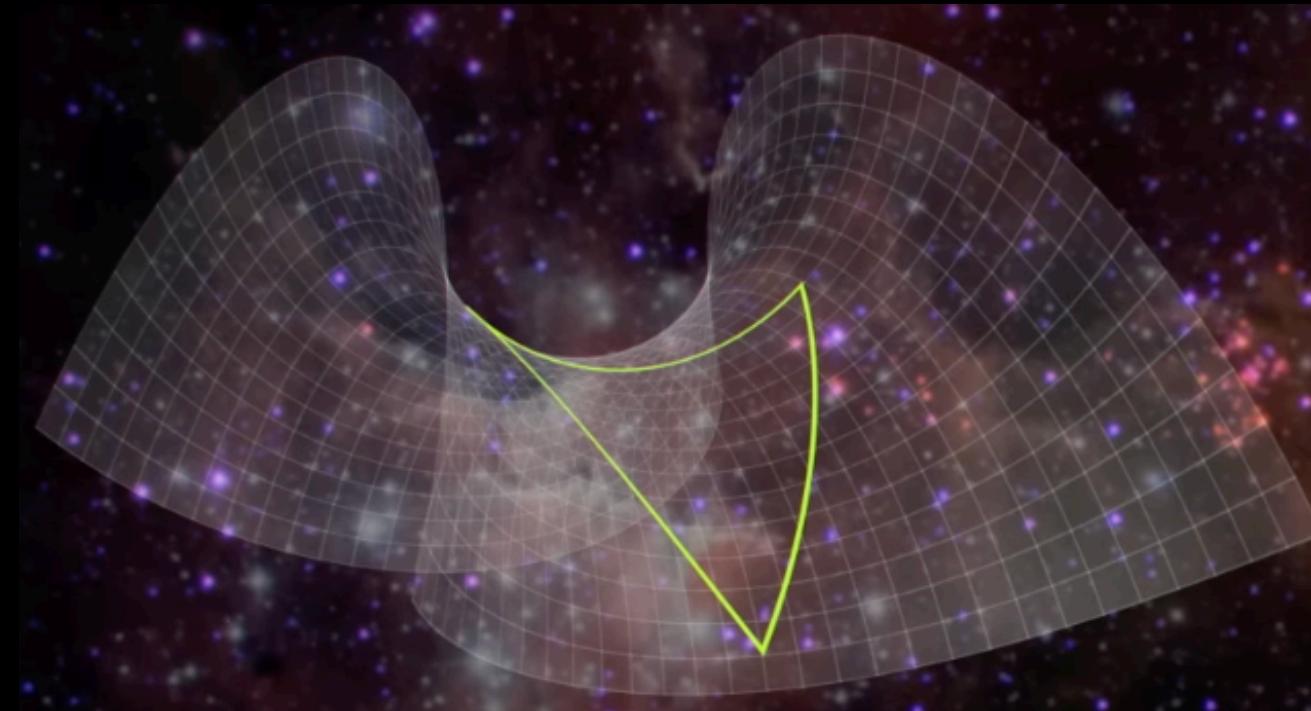
$$\frac{kc^2}{a^2}$$

Given the possibilities of the values of K which is **+1**, **-1** and **0**, gives us a way to **verify** the math we have done so far.

Because LHS = RHS, the RHS has to be positive

$$\left(\frac{\dot{a}}{a}\right)^2 - \frac{8\pi G}{3}\rho = -\frac{kc^2}{a^2}$$

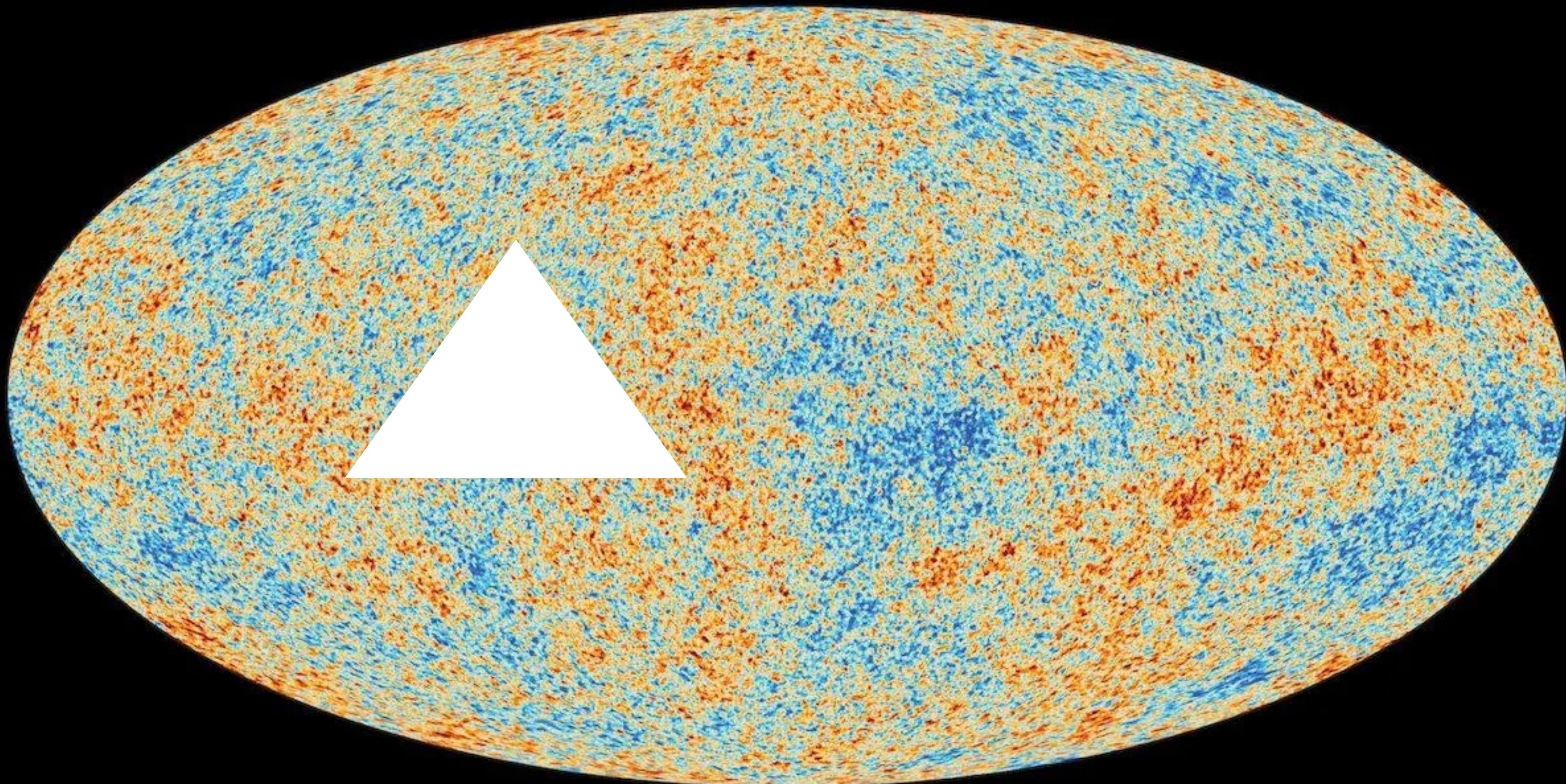
$$\begin{aligned} k &= -1 \\ -(-1) &= +1 \end{aligned}$$



Which means **K = -1**, meaning a **hyperbolic negatively curved geometry**.

We found that our universe should be continuously expanding given that the LHS is positive due to the expansion rate of the universe being more than density.

Here is the climax, astronomer have studied the geometry of spacetime by looking at the **Cosmic Microwave Background** and have found that **the longest triangles in the Universe add upto 180**

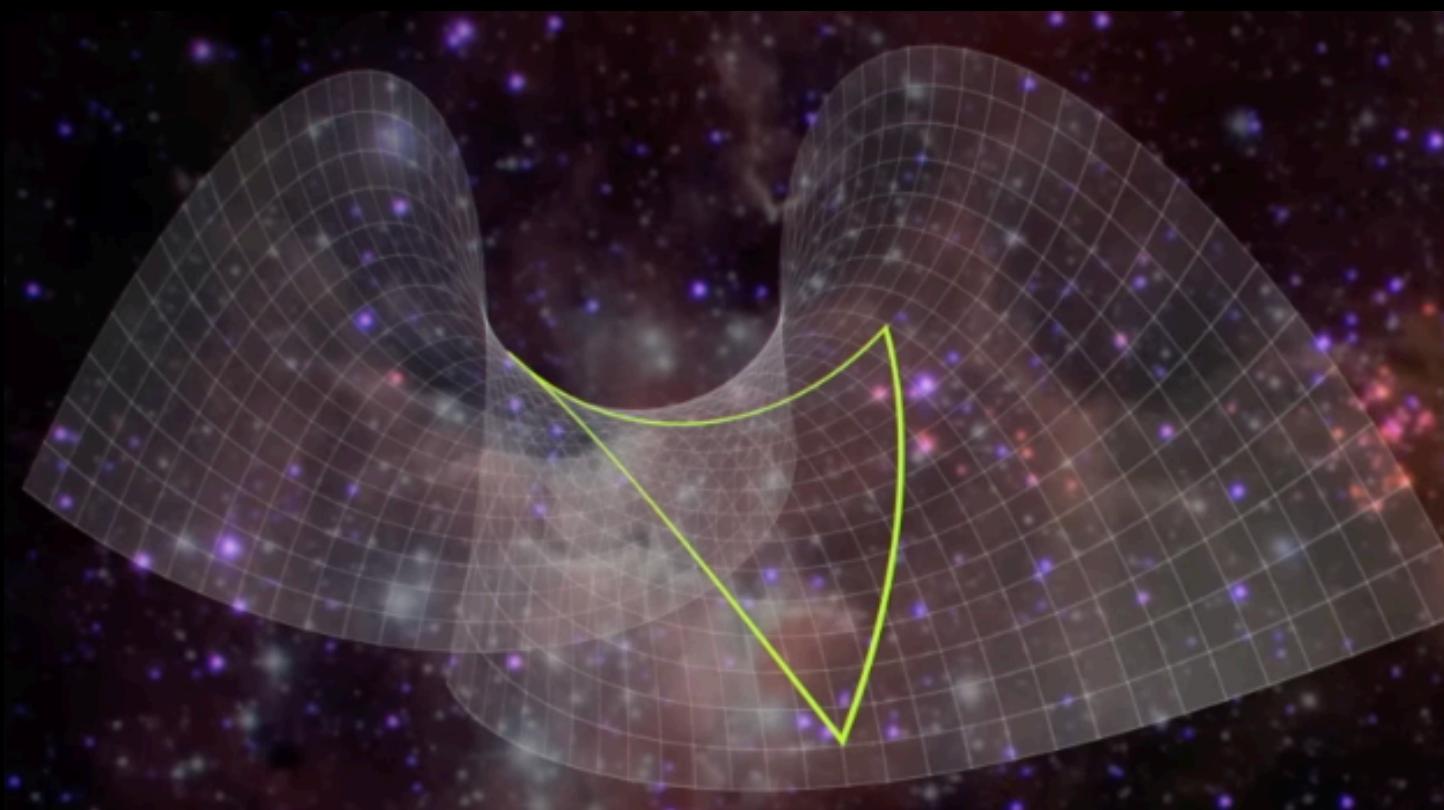


But doesnt that mean the geometry **has to be flat meaning $k=0$**

Did we miss something?

$$\underbrace{\left(\frac{\dot{a}}{a}\right)^2 - \frac{8\pi G}{3}\rho}_{> 0 ???} = \underbrace{-\frac{kc^2}{a^2}}_{= 0}$$

So, if the angles of the triangles in our Universe add upto 180, it means that the **RHS = 0**



Rather than
hyperbolic geometry
as LHS > 0



Representing flat
geometry

$$\Theta_1 + \Theta_2 + \Theta_3 = 180^\circ$$

When we derived the Friedman Equation, we miss the
Cosmological Constant

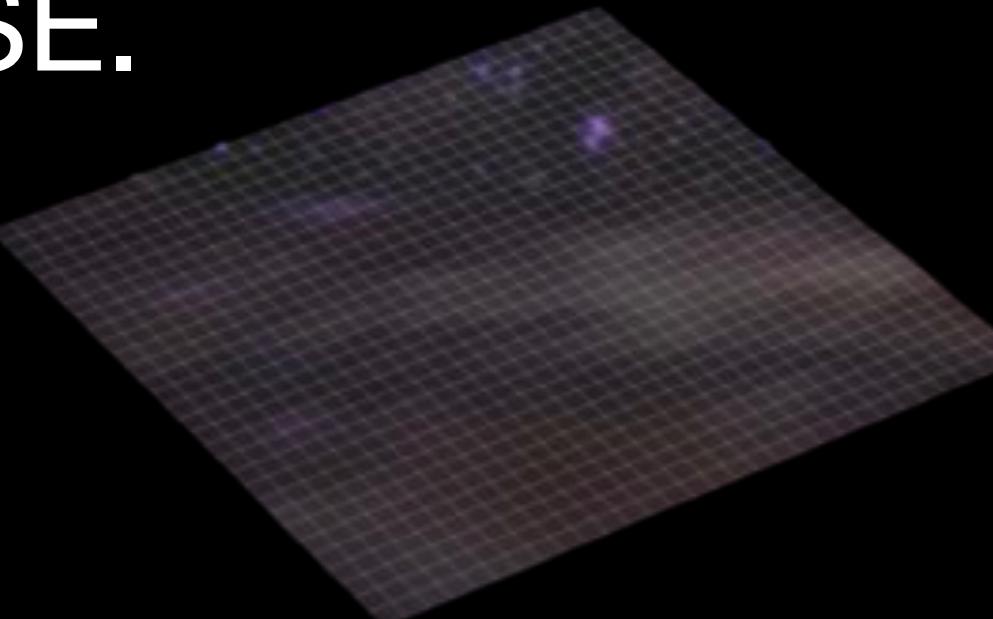
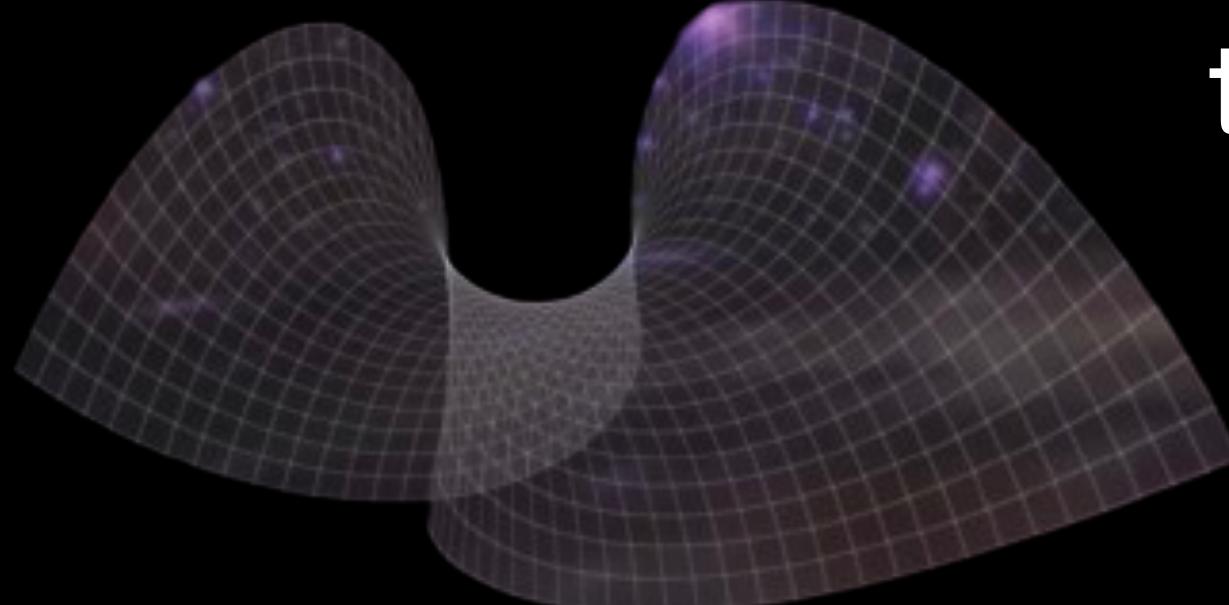
EINSTEIN FIELD EQUATIONS

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = -\frac{8\pi G}{c^4} T_{\mu\nu}$$

$$\underbrace{\left(\frac{\dot{a}}{a}\right)^2 + \frac{8\pi G}{3}\rho + \frac{\Lambda c^2}{3}}_{> 0} = -\frac{kc^2}{a^2}$$

$$\underbrace{\left(\frac{\dot{a}}{a}\right)^2 + \frac{8\pi G}{3}\rho + \frac{\Lambda c^2}{3}}_{= 0} = -\frac{kc^2}{a^2}$$

Geometry is **no longer tied** to
the FATE OF OUR UNIVERSE.





What does the cosmological constant do?

Its a **Clue**, Its a **Constant**

As the universe expands, the regular matter and energy dilutes away but the “**DARK STUFF**” described by the cosmological constant **doesn't do that.**

We Call this “**DARK STUFF**”,
DARK ENERGY

As the Universe expands, the density gets diluted, but the dark energy stays constant and **increase with expansion of space.**

We infer that its the density possessed by “**empty space**”, by **vacuum** itself.

The explanation of Friedmann Equation is one way to realise Dark Energy but what about **observation**?

In **1998**, two separate teams of astronomers studied distant **Type I Supernovae**



What they found was
mind boggling -
the Universe was
accelerating its expansion

Which is also
mathematically
Possible





Both teams won the Nobel Prize in Physics in 2011.

Anti-Gravity Effect: True Nature of Dark Energy

The First Friedmann Equation explains the expansion of the geometry of our Universe

$$\left(\frac{\dot{a}}{a}\right)^2 - \frac{8\pi G}{3}\rho = -\frac{k c^2}{a^2}$$

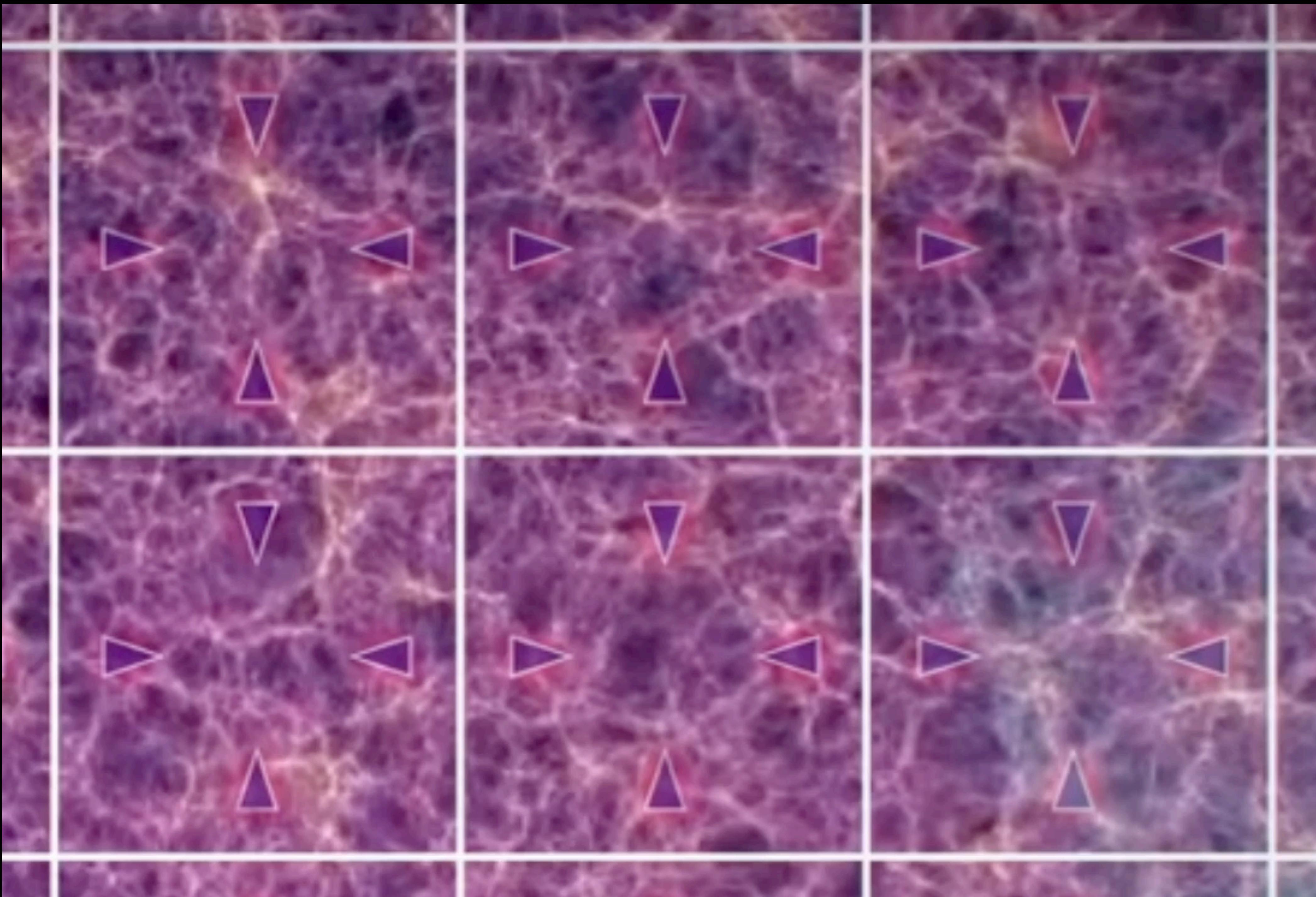
But, it is the Second Equation Friedmann Equation which explains the acceleration and deceleration of the Universe - the pushing and pulling on expansion What is this p?

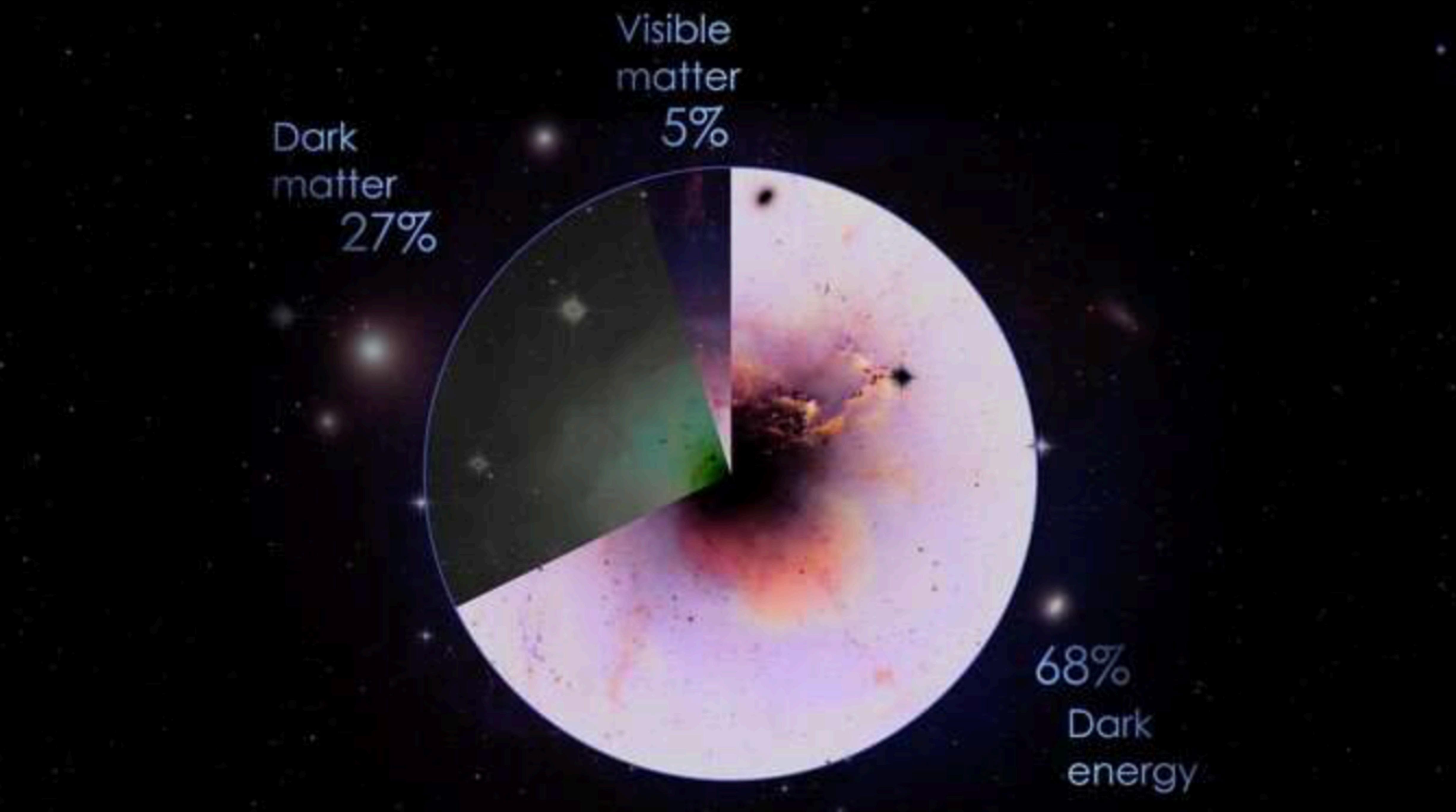
Expansion of our Universe

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$

Pressure

Density of Matter





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**A unifying theory of dark energy and dark matter:
Negative masses and matter creation within a modified Λ CDM framework**

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ABSTRACT

Dark energy and dark matter constitute 95% of the observable Universe. Yet the physical nature of these two phenomena remains a mystery. Einstein suggested a long-forgotten solution: gravitationally repulsive negative masses, which drive cosmic expansion and cannot coexist into light-emitting structures. However, contemporary cosmological results are derived upon the reasonable assumption that the Universe only contains positive masses. By reconsidering this assumption, I have constructed a toy model which suggests that both dark phenomena can be unified into a single negative mass fluid. The model is a modified Λ CDM cosmology, and indicates that continuously-created negative masses can resemble the cosmological constant and can flatten the rotation curves of galaxies. The model leads to a cyclic universe with a time-variable Hubble parameter, potentially providing compatibility with the current tension that is emerging in cosmological measurements. In the first three-dimensional N-body simulations of negative mass matter in the scientific literature, this exotic material naturally forms haloes around galaxies that extend to several galactic radii. These haloes are not cuspy. The proposed cosmological model is therefore able to predict the observed distribution of dark matter in galaxies from first principles. The model makes several testable predictions and seems to have the potential to be consistent with observational evidence from distant supernovae, the cosmic microwave background, and galaxy clusters. These findings may imply that negative masses are a real and physical aspect of our Universe, or alternatively may imply the existence of a superseded theory that in some limit can be modified by effective negative masses. Both cases lead to the surprising conclusion that the compelling puzzle of the dark Universe may have been due to a simple sign error.

Key words. Cosmology: theory – dark energy – dark matter – Galaxies: kinematics and dynamics – large-scale structure of Universe

1. Introduction

One of the most fascinating aspects of scientific history is that regarding Einstein's efforts with the cosmological constant, it is well known that Einstein added a cosmological constant to his equations in order to provide a static Universe. Due to this bias, he failed to predict the expansion of the Universe that was soon observed by Hubble (Hubble 1929). Famously, upon learning of the Universe's expansion, Einstein set the cosmological constant equal to zero and reportedly called its introduction his "biggest blunder".

Most contemporary physicists are familiar with the fact that prior to Hubble's discovery, Einstein associated the cosmological constant term with a constant of integration. However, Einstein did not always believe this to be the case, and important details are currently absent from the historical narrative. In 1918, before famously discarding the cosmological constant, Einstein made the first physical interpretation of the new Λ term that he had discovered:

"a modification of the theory is required such that 'empty space' takes the role of gravitating negative masses which are distributed all over the interstellar space". (Einstein 1918)

Despite this insight, within a year Einstein reformulated his interpretation:

"the new formulation has this great advantage, that the quantity Λ appears in the fundamental equations as a constant of integration, and no longer as a universal constant peculiar to the fundamental law" (Einstein 1919)

What led Einstein to believe that negative masses could provide a solution to the cosmological constant is therefore of interest. To understand the physics of negative masses further, we need to 'polarise' the Universe so that mass consists of both positive and negative counterparts. Polarisation appears to be a fundamental property of the Universe. Indeed, all well-understood physical forces can be described through division into two opposing polarised states. For example, electric charges (+ and -), magnetic charges (N and S), and even quantum information (0 and 1) all appear to be fundamentally polarised phenomena. It could therefore be perceived as odd that gravitational charges – conventionally called masses – appear to only consist of positive monopoles.

* The codes used for the N-body simulations can be downloaded at: <https://github.com/janiefarnes/negative-mass-simulator>

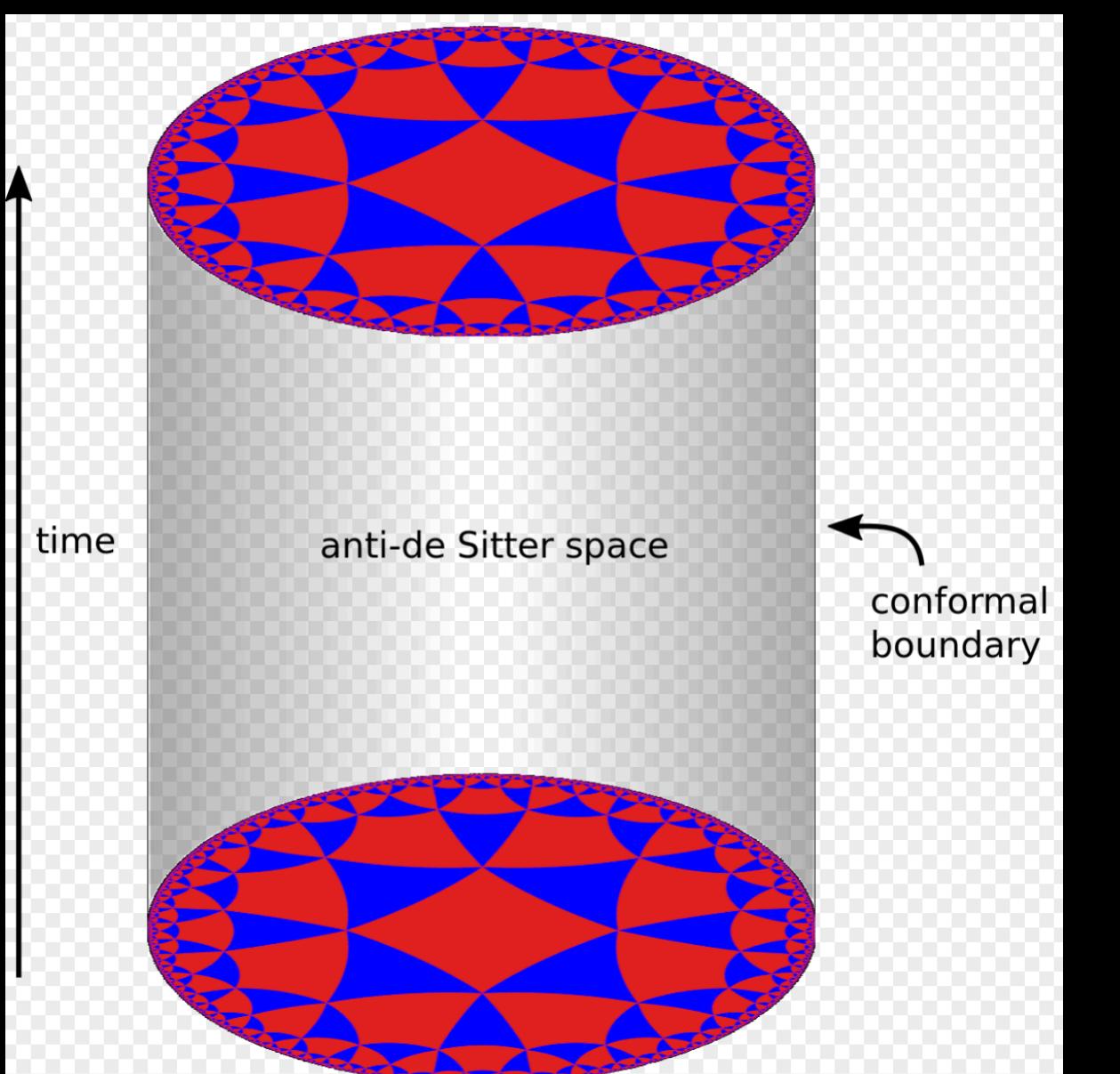
[†] The chosen notation used by Einstein was not Λ , but rather λ .

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Are Dark Matter and Dark Energy the same?

Note that the paper consider particles with negative mass popping into existence in between galaxy's

The consideration of negative mass gives rise to another form of spacetime geometry called anti de sitter (AdS) which we know is not the case as our universe is flat



Good for String theorist
but doesn't align with observations



TRAILER



HD

We are merely explorers of infinity in the pursuit of absolute perfection.

