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.

H. Poincaré 481

which the telescope gives, then there is no dark matter,
st not so much as
going further w
side. Is the Milk constituted of a gas, properly
? It is known th okes introduced the notion of a
tate of matter in which gases having become too rarefied
onger true gases and they become what is called radiant
The Milky Way—considering the smallness of its density,
like gaseous matter or like radiant matter? It is the con-
on of what is called the *libre parcours* (free course) which
ish us the answer.

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

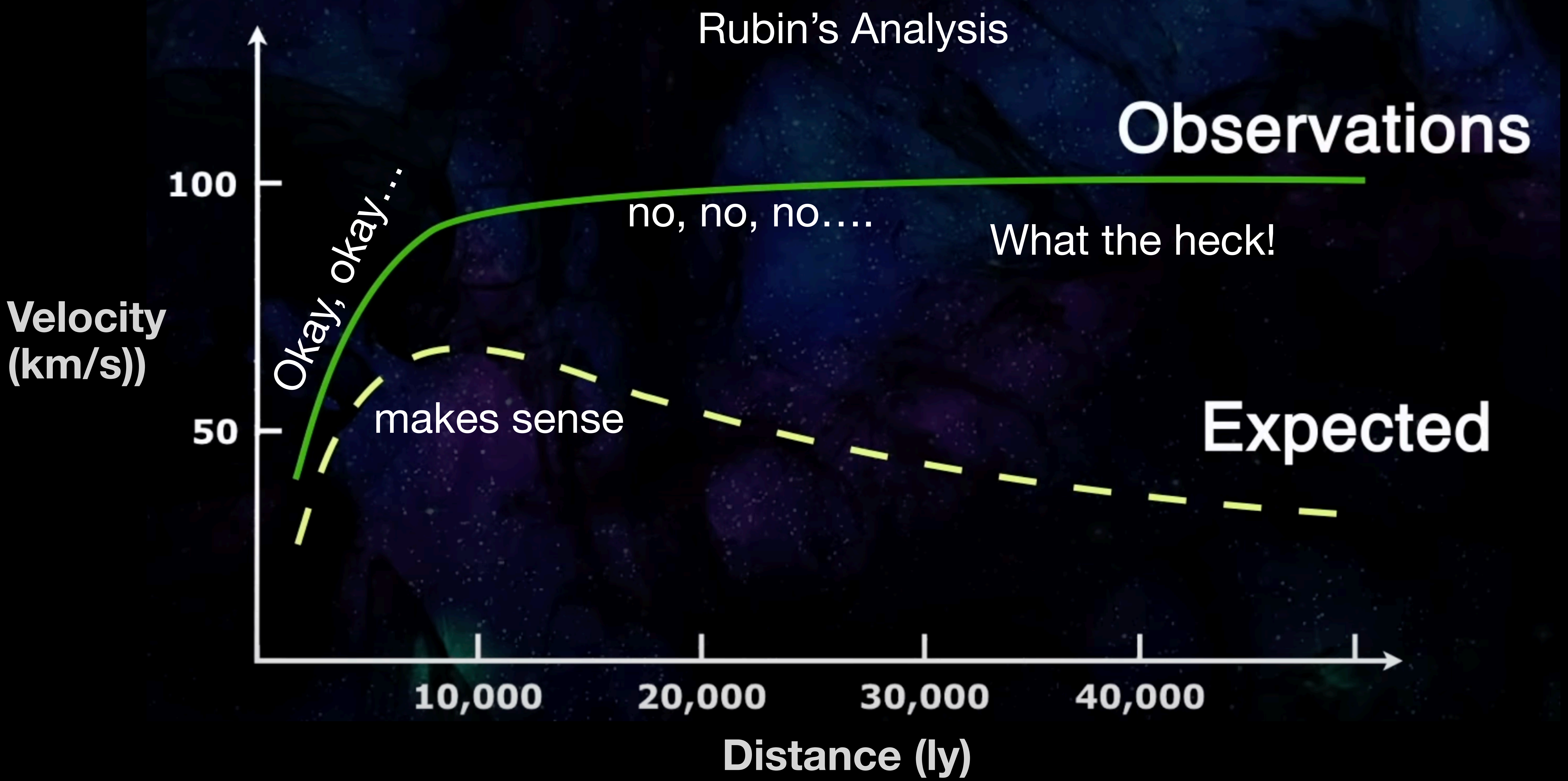
Vera Rubin

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 tangentionally.
The motion should be slower here.
But, there is something in the dark which is holding it together, getting the sh*t together!

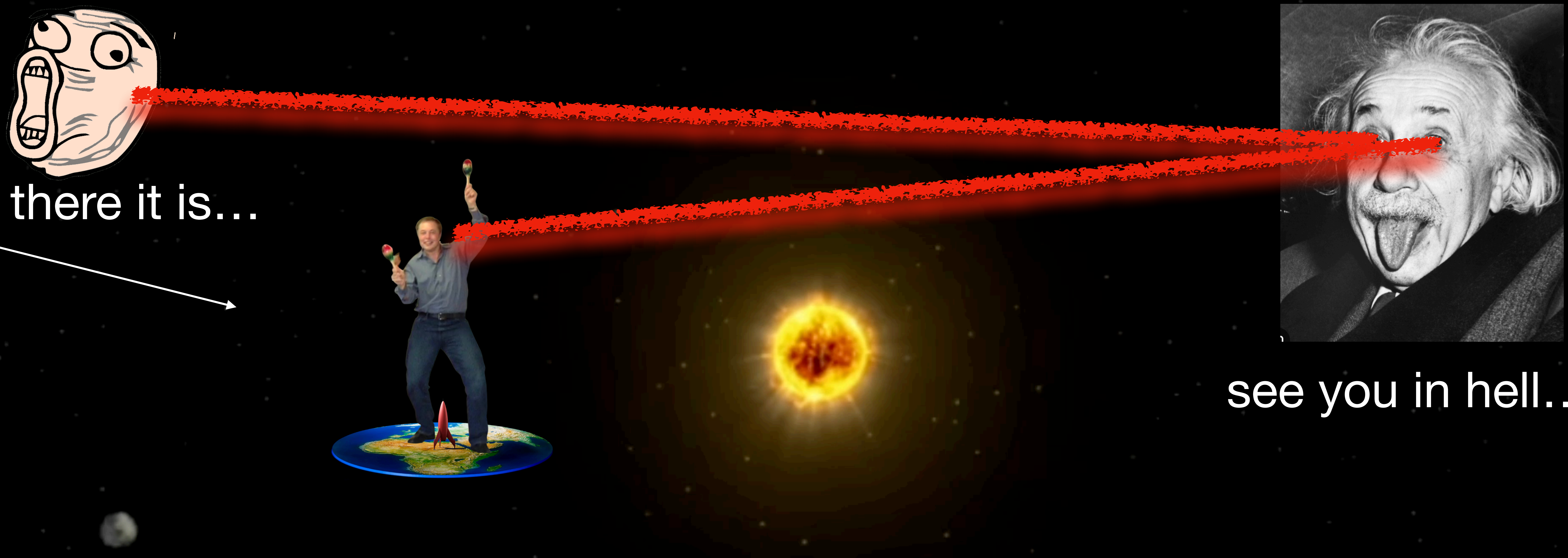
Mathmatically, velocity of stars at the outskirts of galaxy should be lower relative to the ones at the centre.



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.

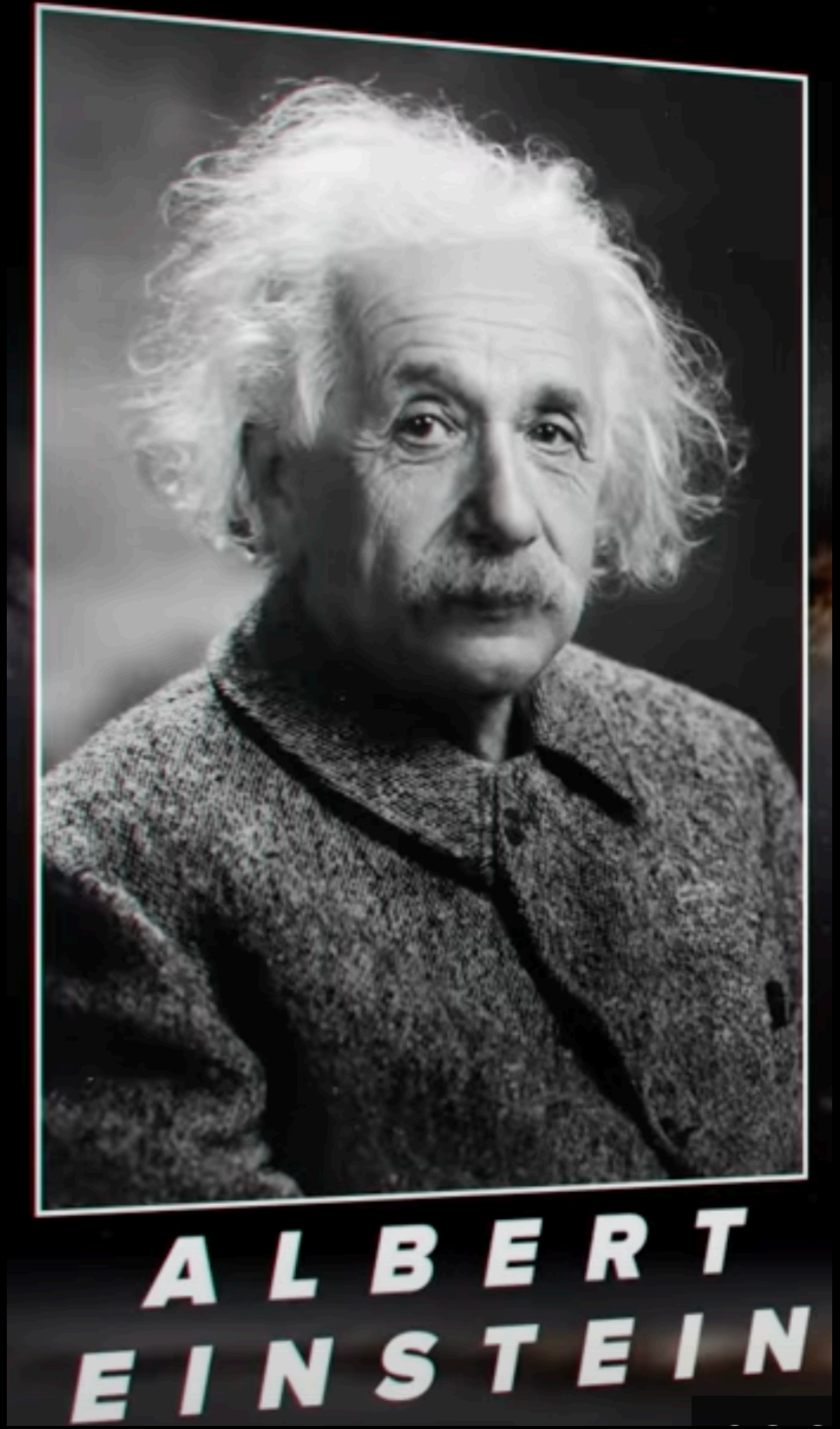
Flat Earther's

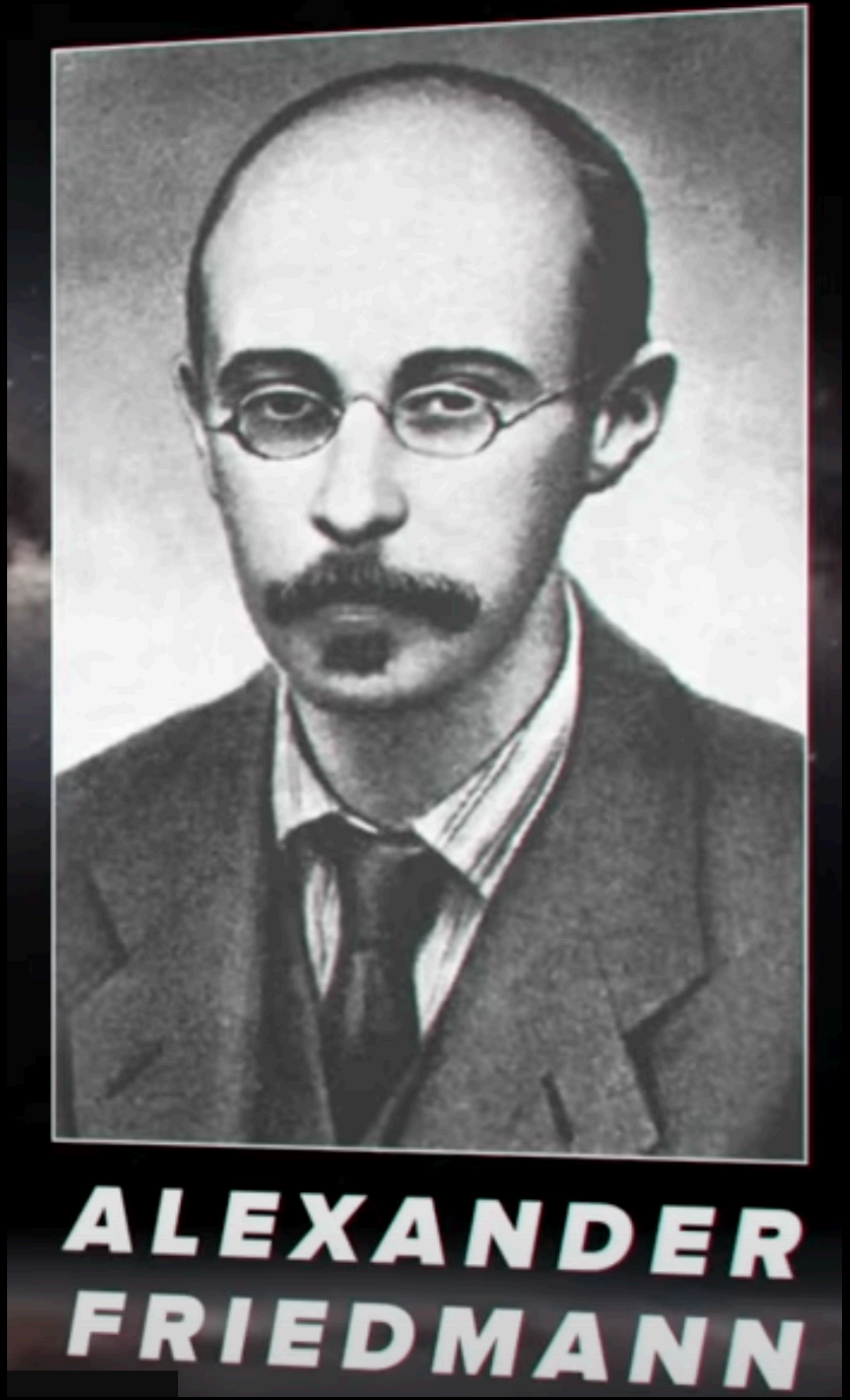
There, there.. there it is…
VULCAN



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.





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

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

Einstein Tensor

Defines:

Shape, Curvature of Spacetime

Defines:

The energy

The pressure

The momentum

More

Stress -Energy Tensor

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

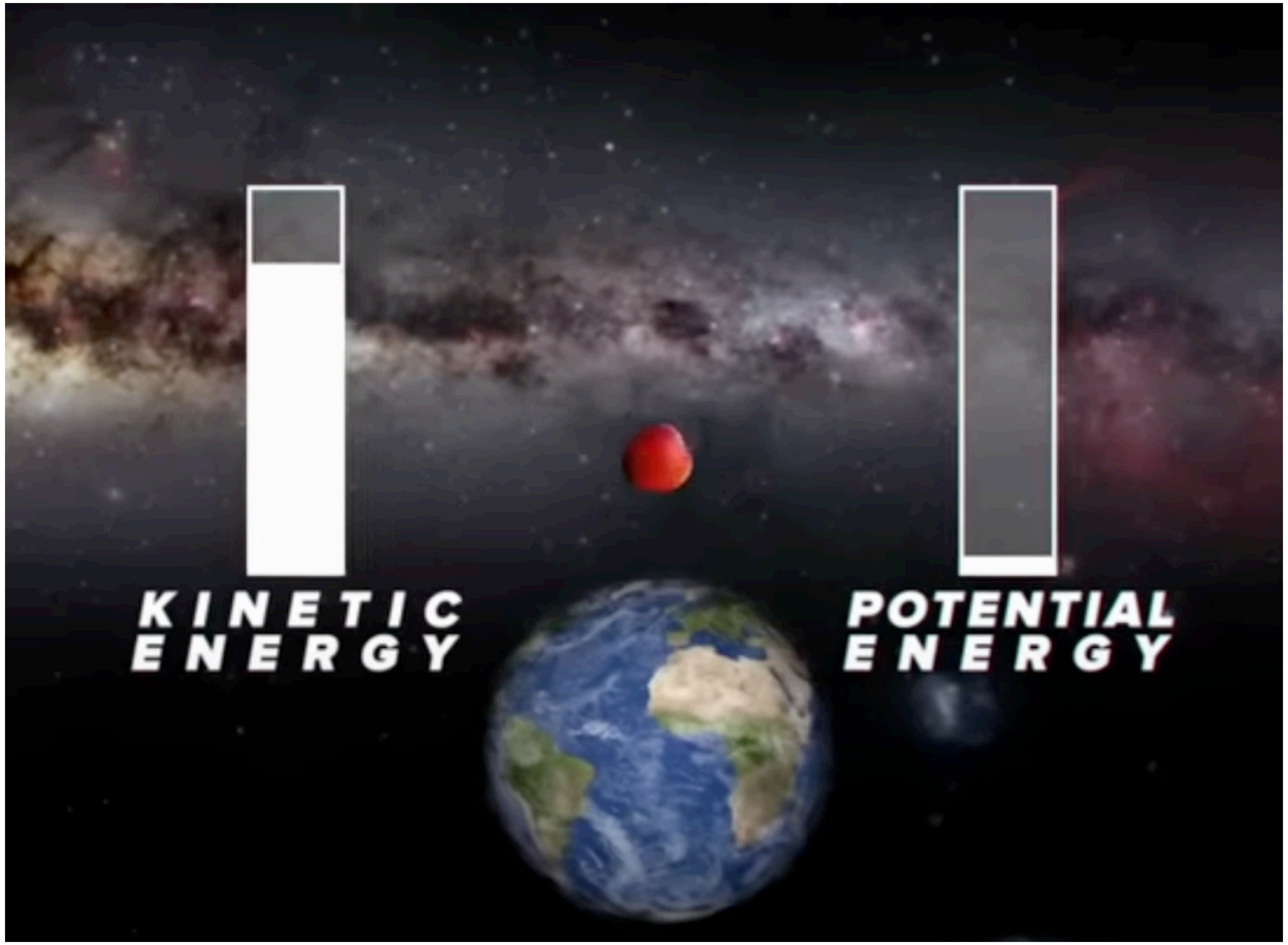
$$F = \frac{GM_1M_2}{r^2}$$

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

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

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 earths’s Gravitational pull which gives you the espace 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.

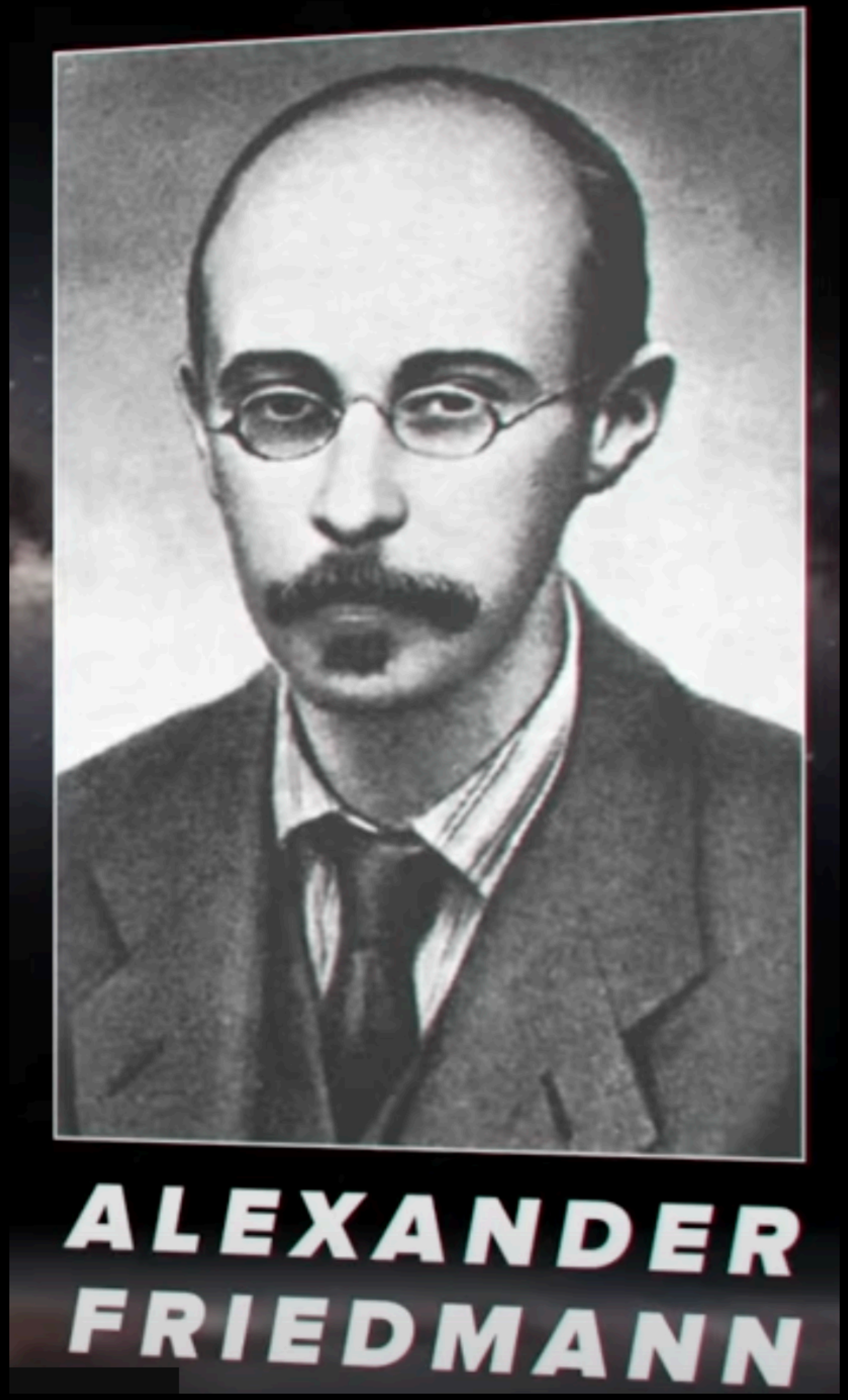
Based on the stuff (density) in the Universe, there is a current expansion speed (kinetic energy) which would cause the future expansion rate to come to a hault (conversion to potential energy).

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

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

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

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

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**”

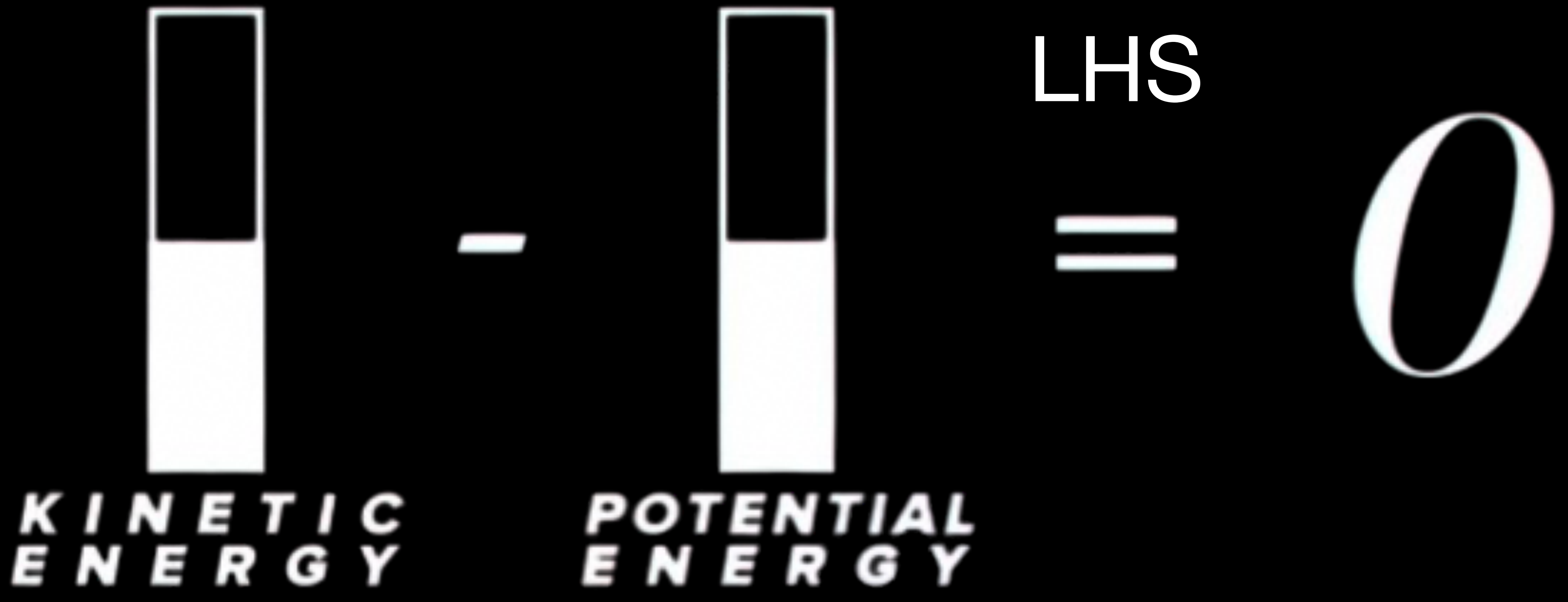
So, what are the possibilities?

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.

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



So, what are the possibilities?

Possibility 2:

If the Kinetic Energy of Expansion > Potential Energy of Collapse

The Universe will continue to expand just like an object with higher velocity with

K.E. > P.E.

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

LHS

$$> 0$$

So, what are the possibilities?

Possibility 3:

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

If the Kinetic Energy of Expansion < Potential Energy of Collapse

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

LHS

< 0

So, what will happen? What do you think?

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

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

THE HUBBLE CONSTANT

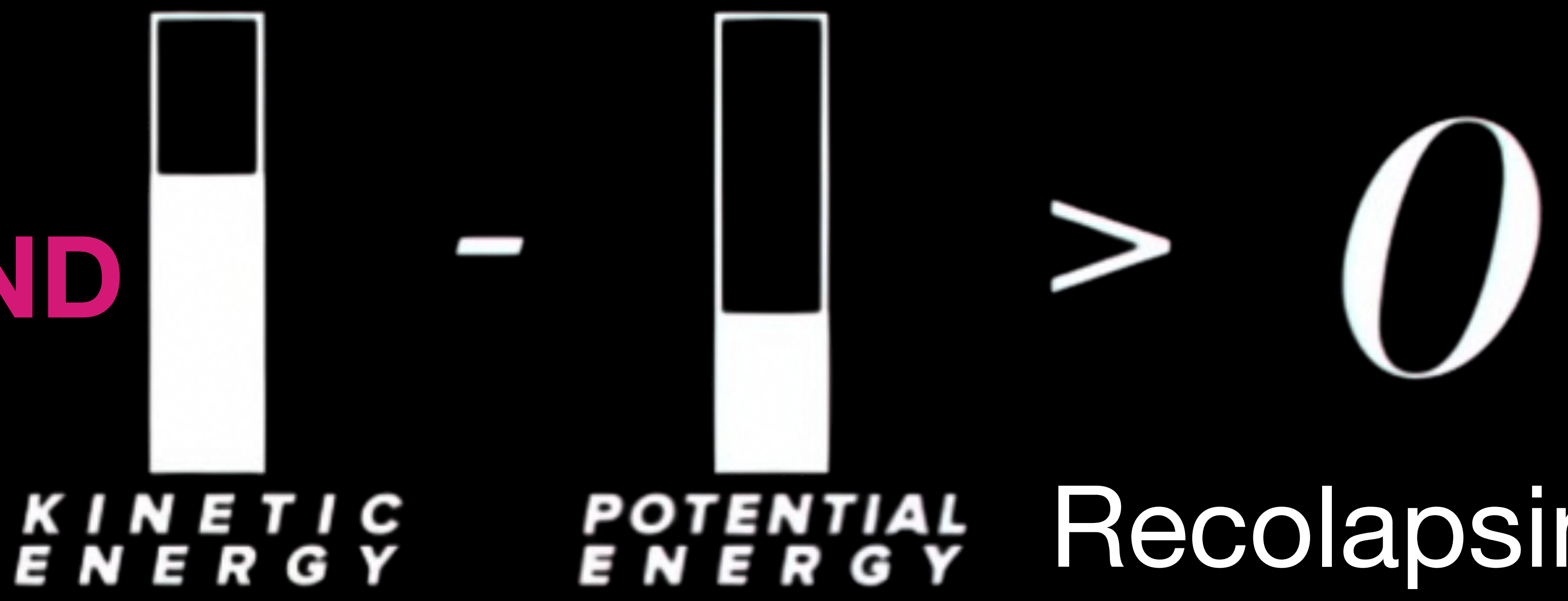
$H_0 \approx 70$ km/s/Mpc

Astronomers have also calculated the density of matter within our universe but it turns out to be **TOO LOW** $\longrightarrow \dfrac{8\pi G}{3}\rho$

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

The Left hand side is positive, there is no way around, the

UNIVERSE WILL CONTINUE TO EXPAND FOREVER



Recolapsing is **TOO LOW**

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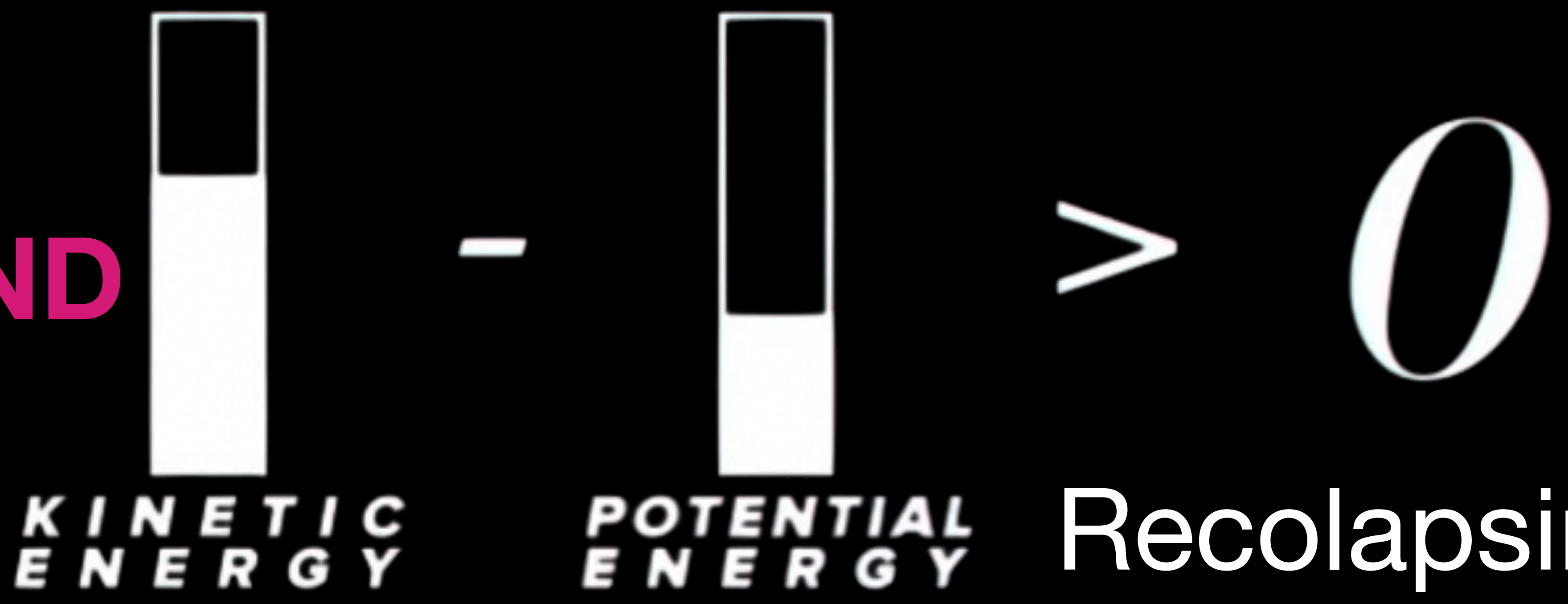


Recolapsing is **TOO LOW**

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

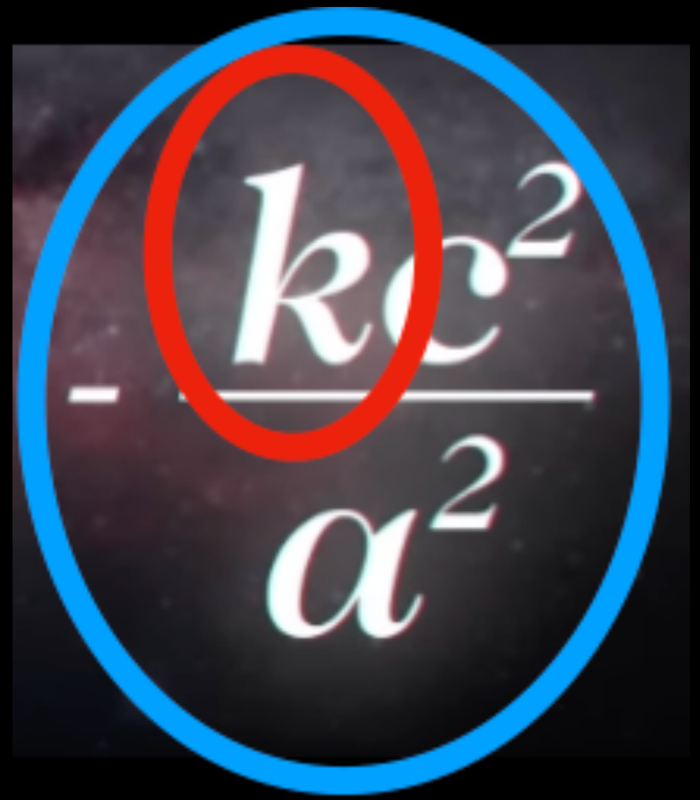
$$\left(\frac{\dot{a}}{a}\right)^2 - \frac{8\pi G}{3}\rho = -\frac{kc^2}{a^2}$$

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.

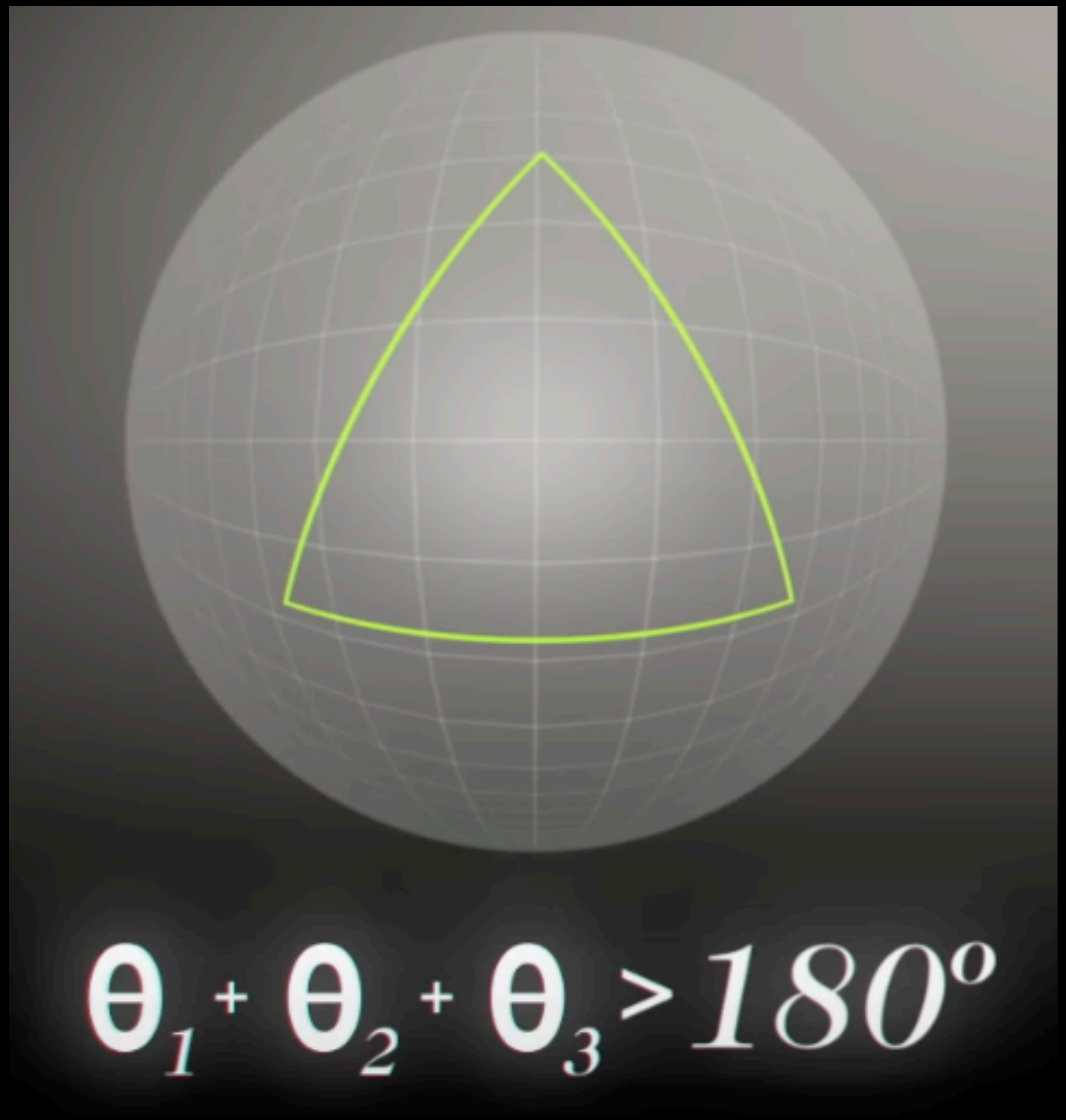
Oh why not! **Matter tells spacetime how to curve**, right!?

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)**



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

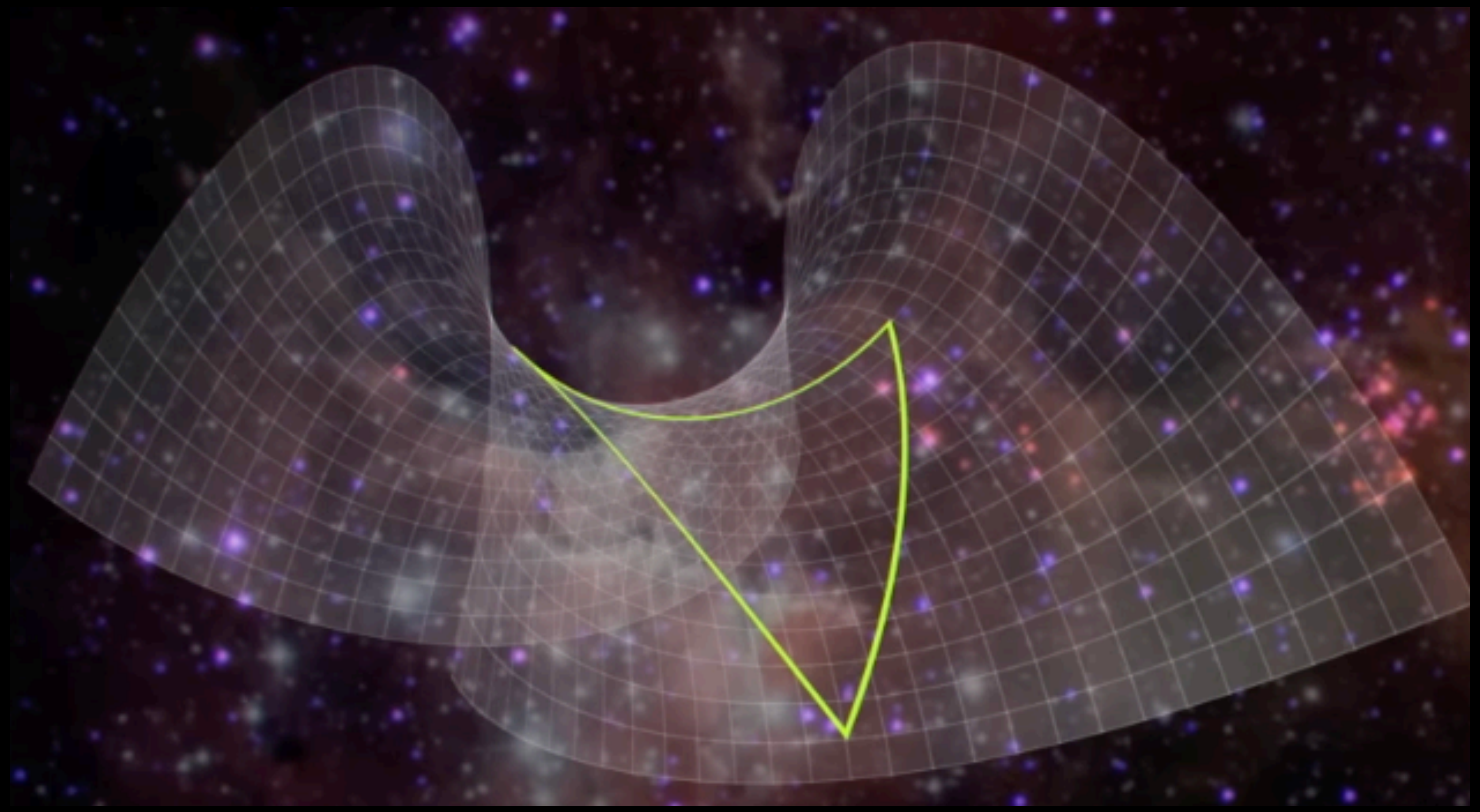
The Angles of Triangle add upto **more** than **180 degrees**

There are 3 possibilities:

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

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

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

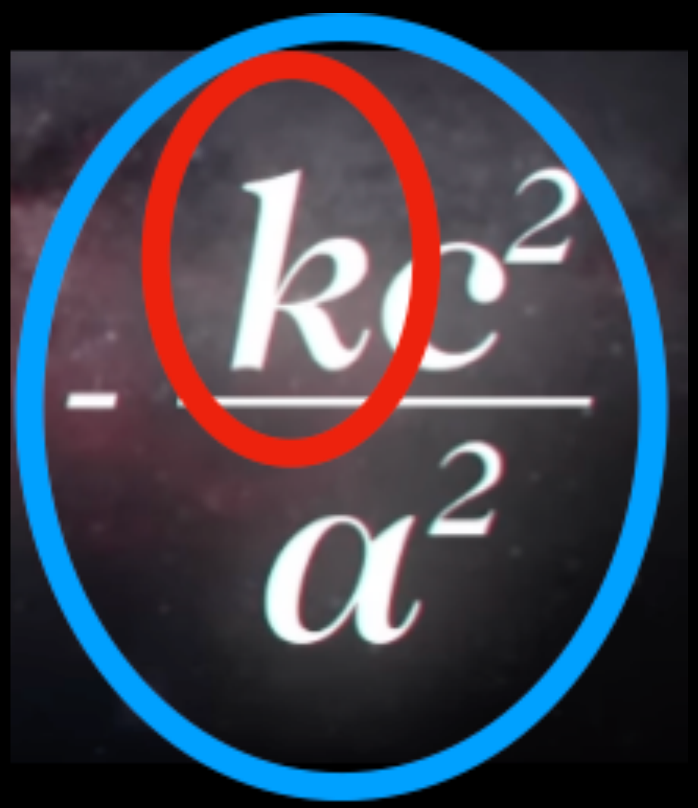


The Universe in this case will be a 3D version of negatively curved hyperbolic plane.

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 in given instant in time.

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

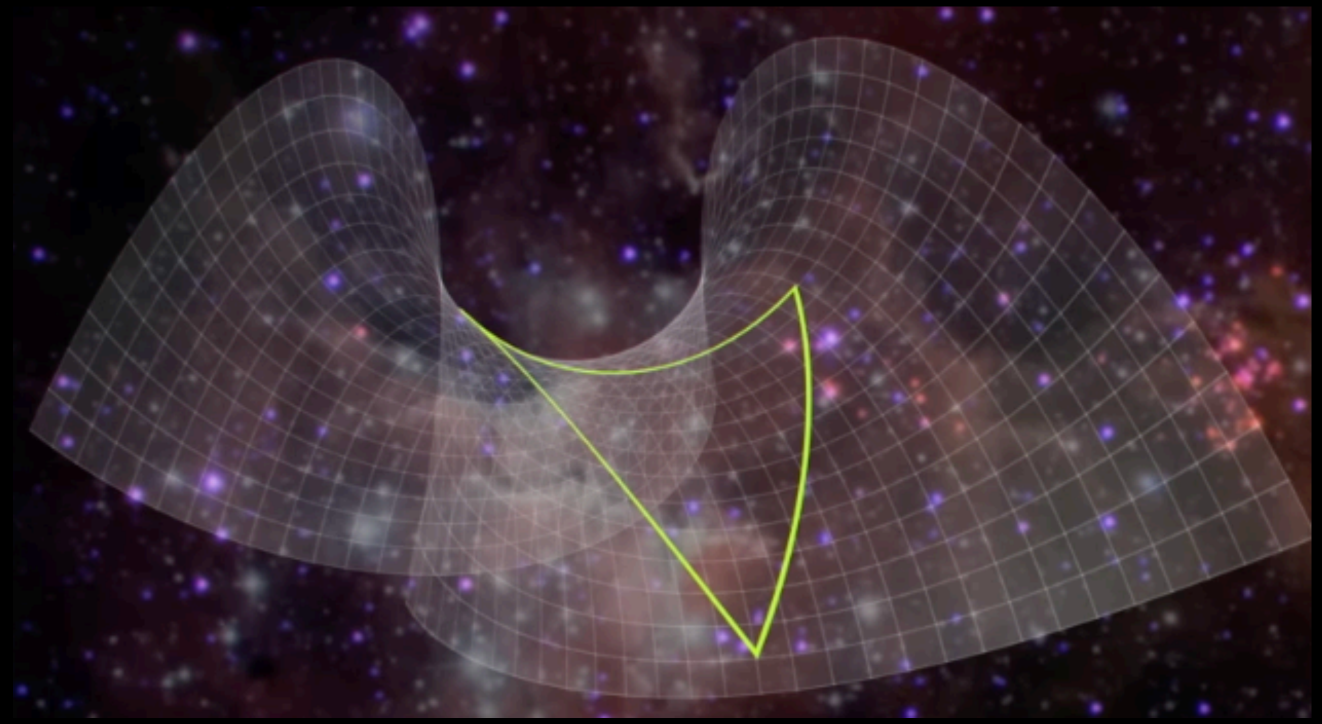
Given the possibilities of the values of K which is +1, -1 and 0, gives us a way to verify the math we have done so far.

Because LHS = RHS, the RHS has to be positive

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

k = -1

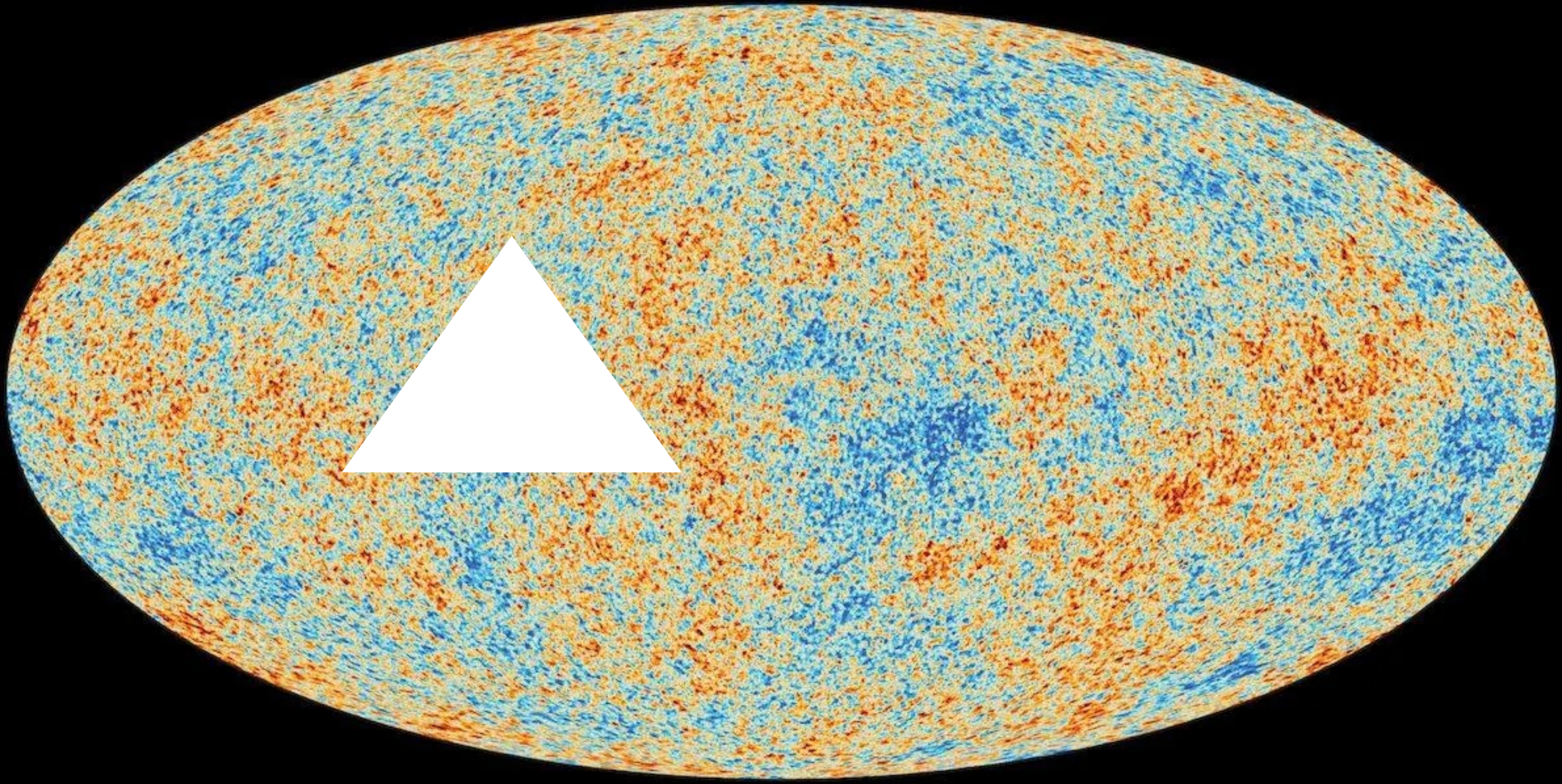
- (-1) = +1



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**

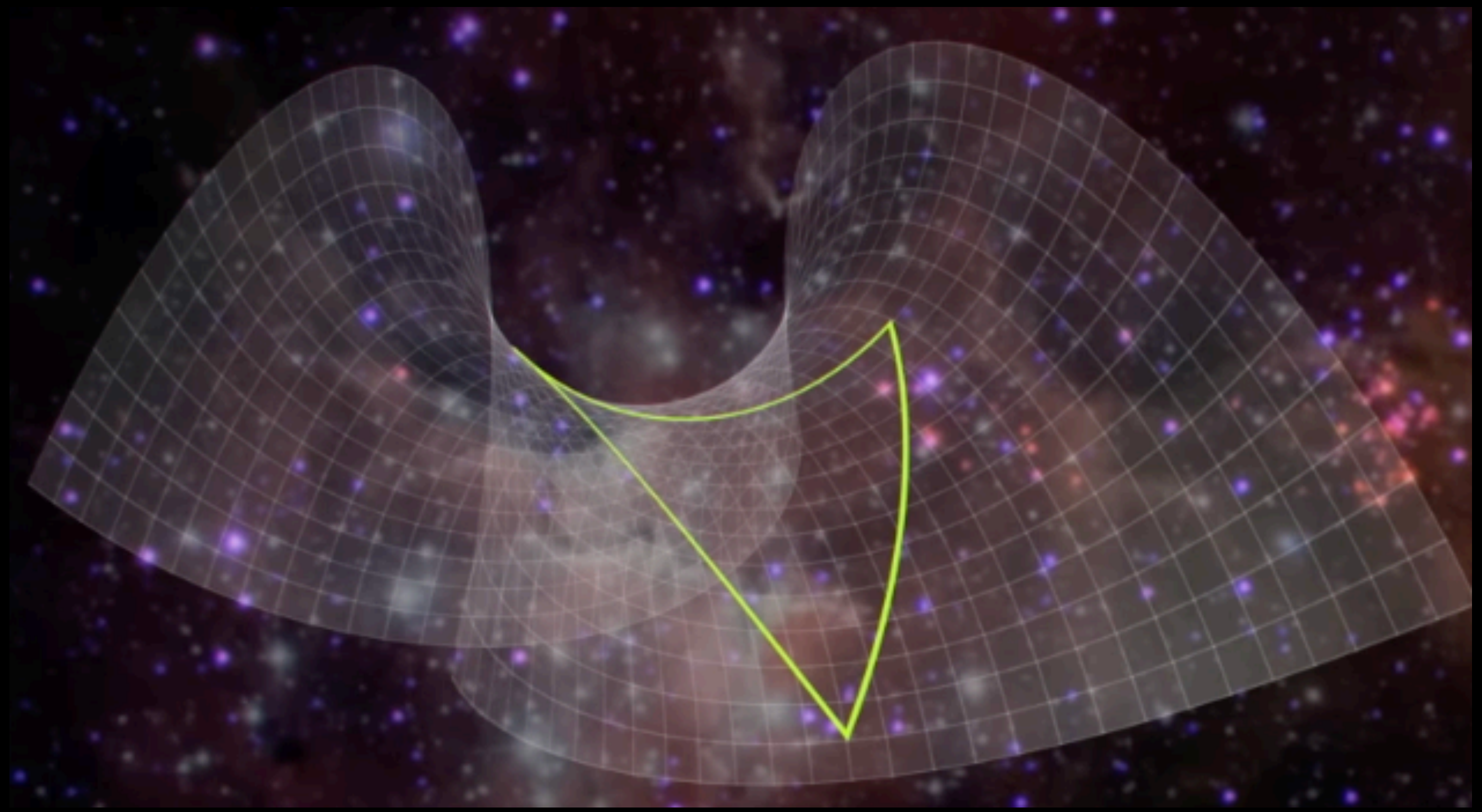


But doesnt that mean the geometry **has to be flat meaning k=0**

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

When we derived the Friedman Equation, we miss the

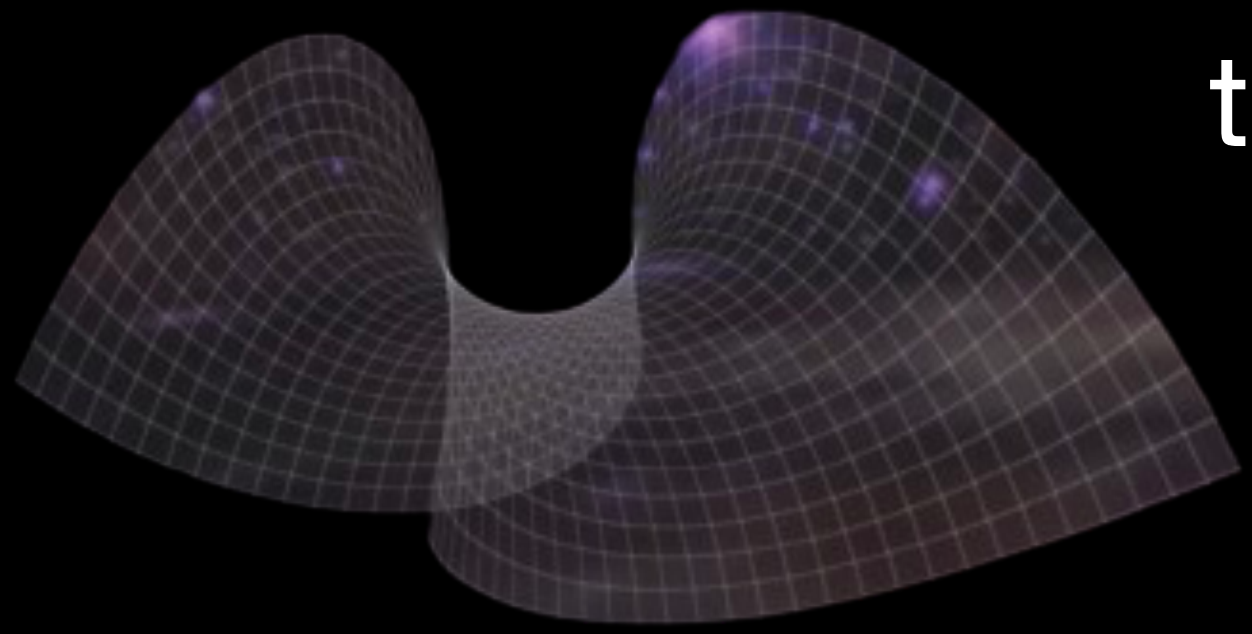
Cosmological Constant

EINSTEIN FIELD EQUATIONS

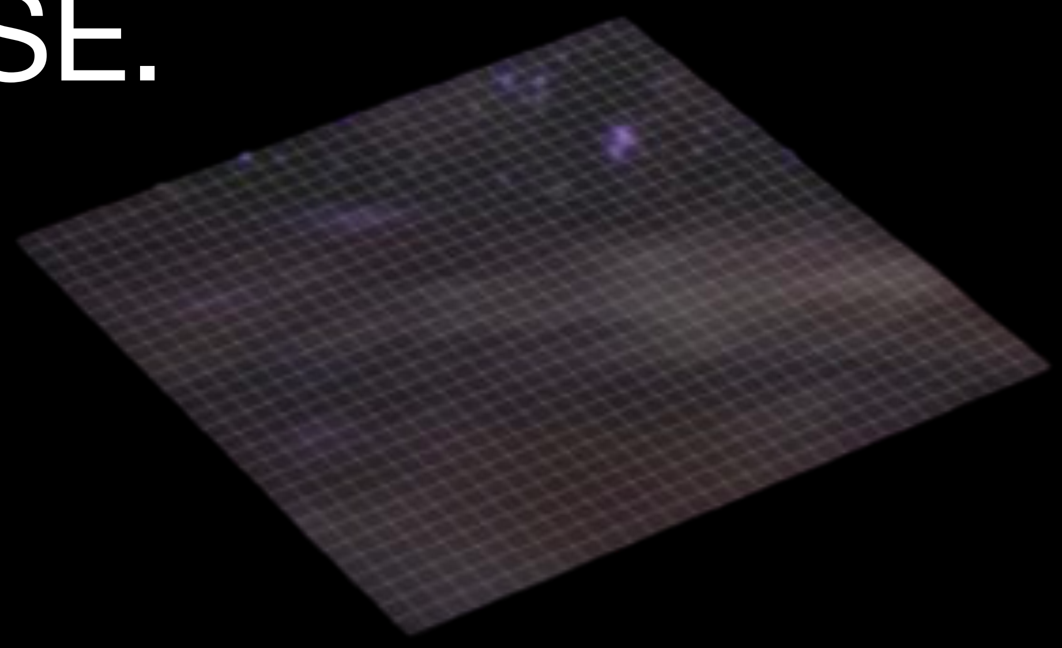
$$G_{\mu\upsilon} + \Lambda g_{\mu\upsilon} = \frac{8\pi G}{c^4} T_{\mu\upsilon}$$

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

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



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



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COSMOLOGICAL CONSTANT

What does the cosmological constant do?

Its a Clue, Its a Constant

As the universe expands, the regular matter and engery dilutes away but the "DARK STUFF" described by the cosmological constant doesnt do that.

We Call this "DARK STUFF",

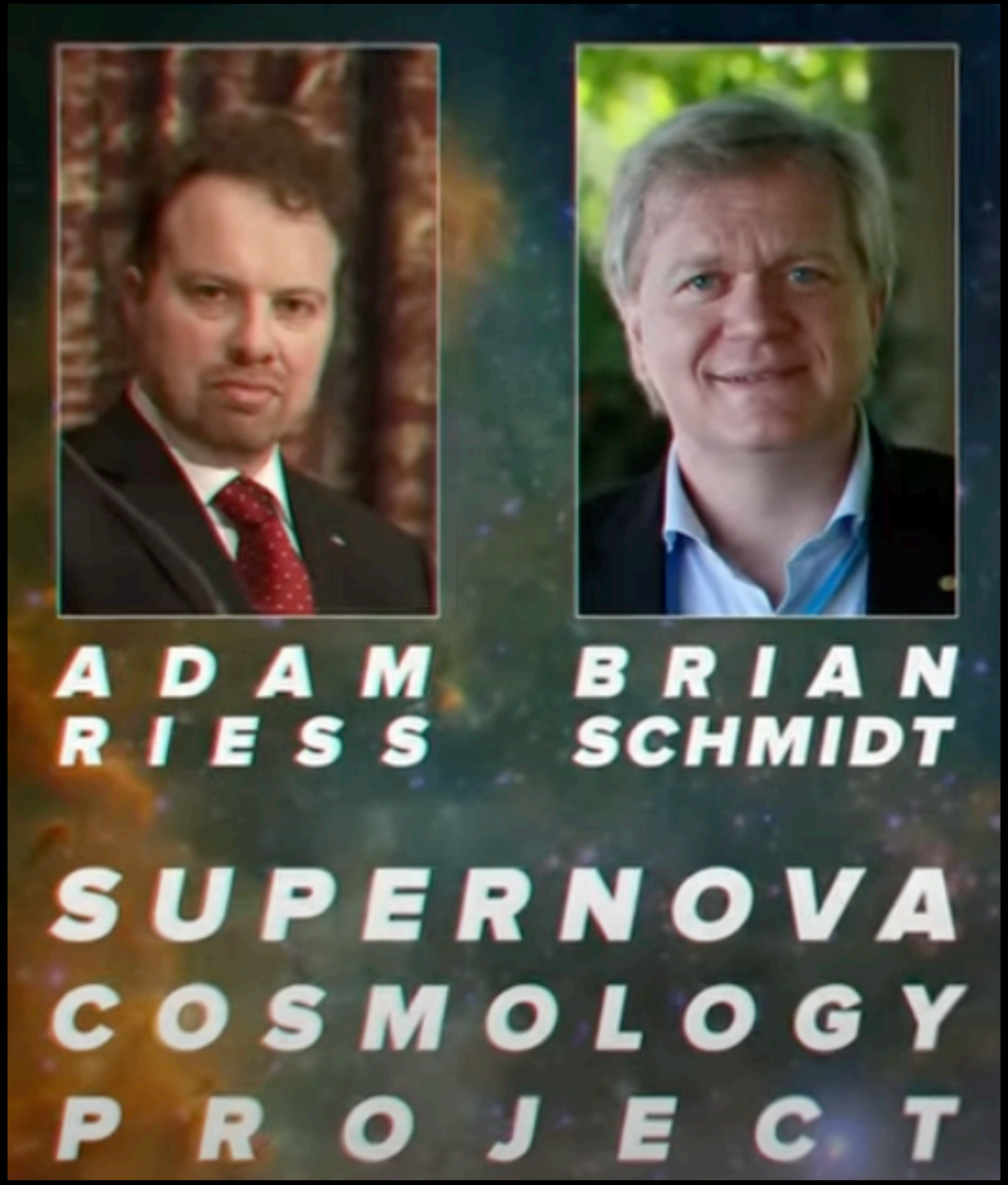
DARK ENEGRY

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 Enegry 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

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

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

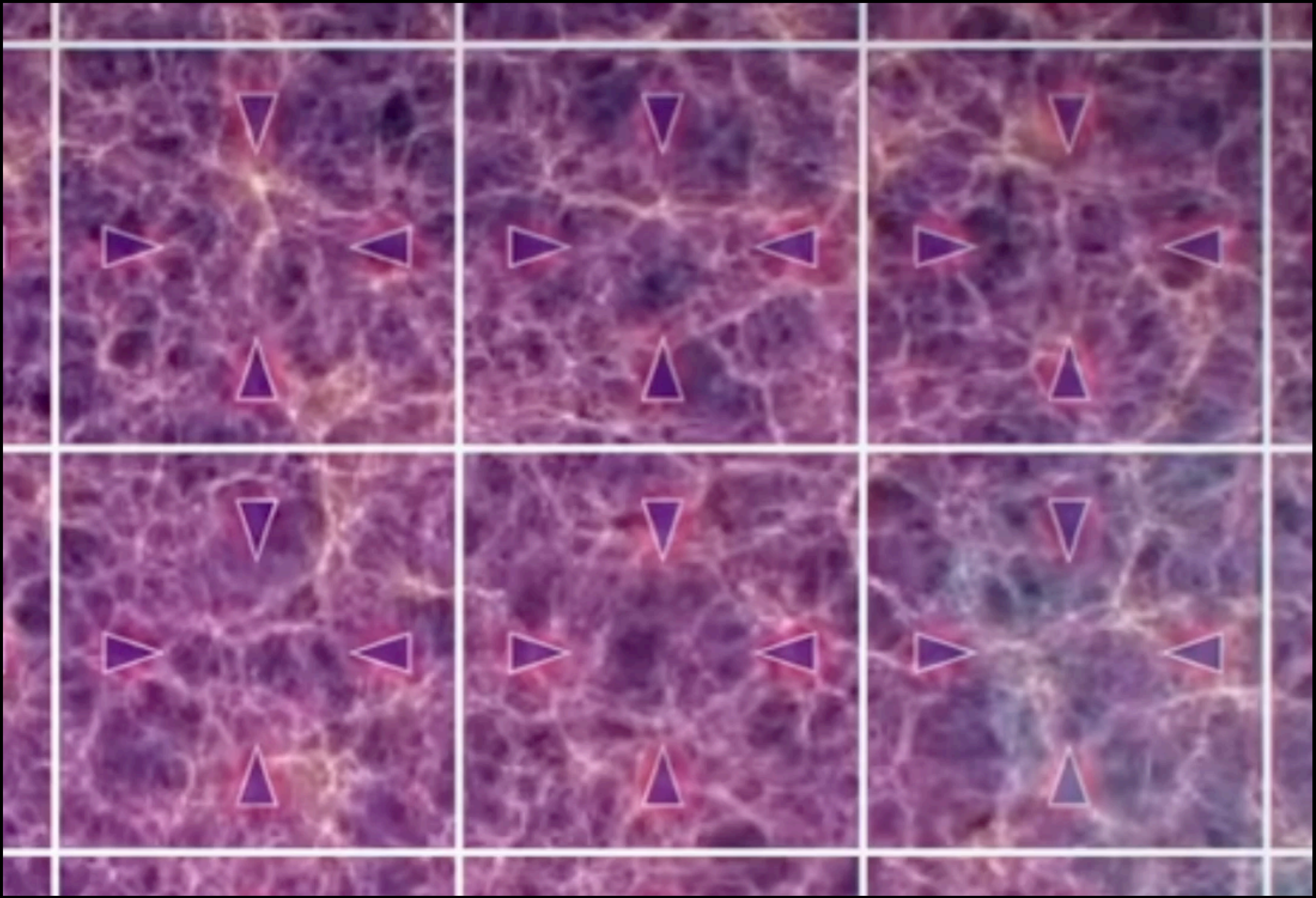
What is this p?

Pressure

Expansion of our Universe

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

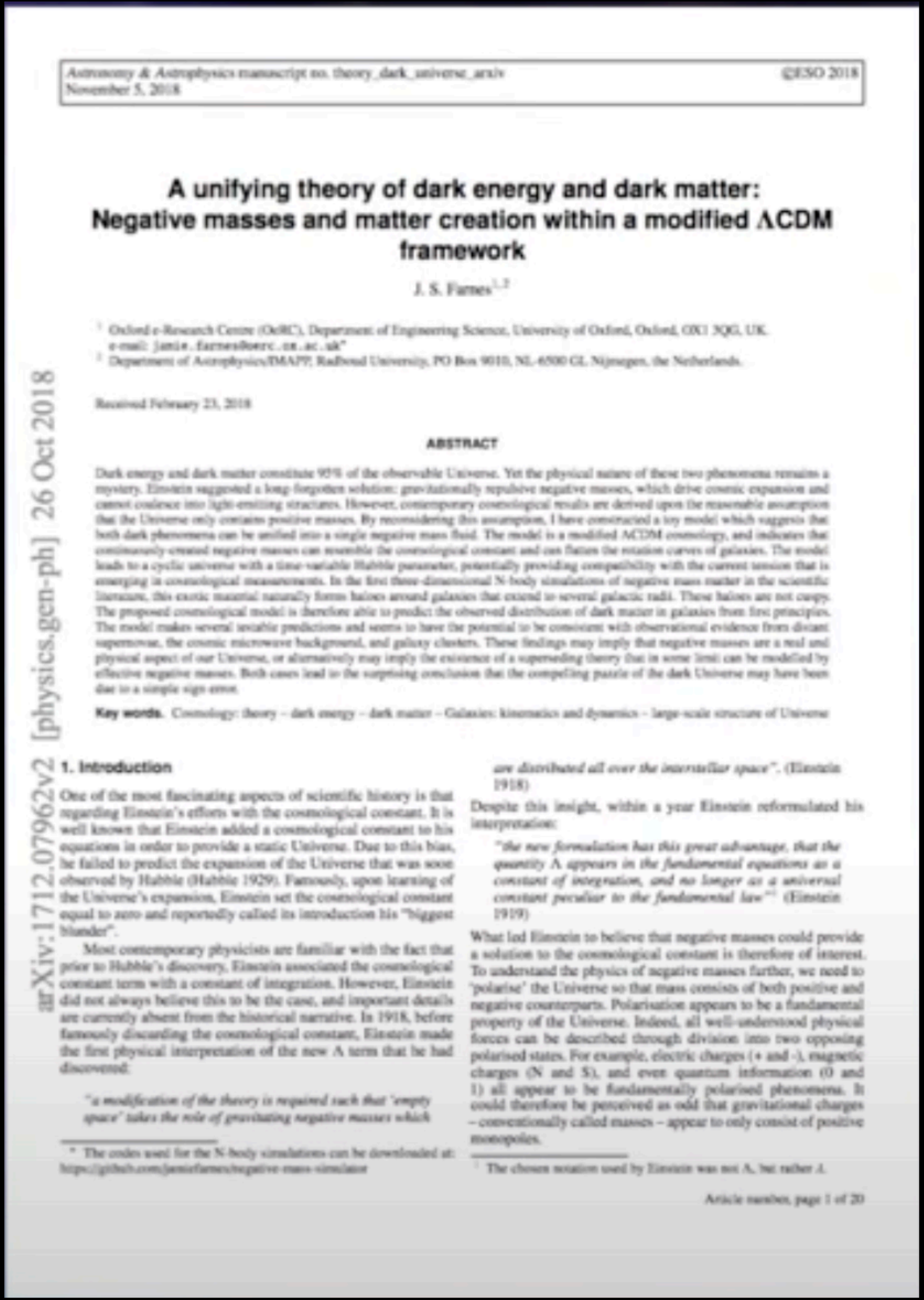
Density of Matter



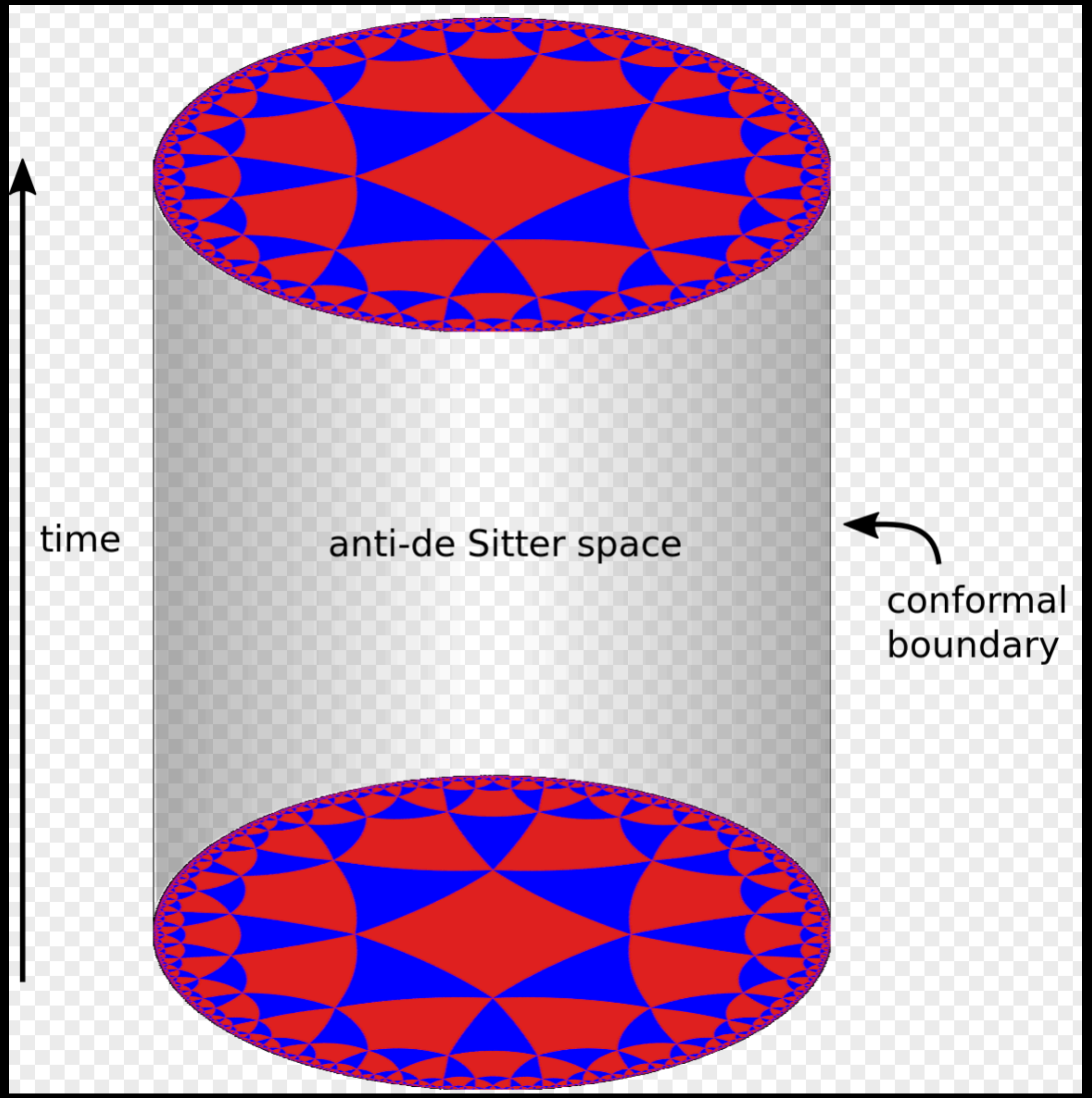

Visible matter 5%
Dark matter 27%
68% Dark energy

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.