Title: Relativity 5

Date: Jul 30, 2008 02:00 PM

URL: http://pirsa.org/08070046

Abstract:


Black Holes

A huge great enormous thing, like — like nothing. A huge big — well, like a — I don't know — like an enormous big nothing ...

Piglet describes the Heffalump,
in *Winnie the Pooh* by A.A. Milne

Dark stars

- **Rev. John Michell (1783)**

  A British born "natural philosopher" dared to combine the corpuscular description of light with Newton's gravitation laws to predict what large compact stars should look like.

- He showed that a star, that has the same density of the sun, but 500 time as big, would have such a gravity, that "All light emitted from such a body would be made to return towards it". He said we wouldn't be able to see such a body, but we sure will feel it's gravitational pull.

- We could fly close to this "Dark star" and look around and describe the features of the object.

- A novelty, world lost interest when light was shown to be waves in 1803 by Thomas Young.

Calculation of Escape Velocity for Earth

$$\frac{1}{2}mv^2 = \frac{GMm}{r}$$

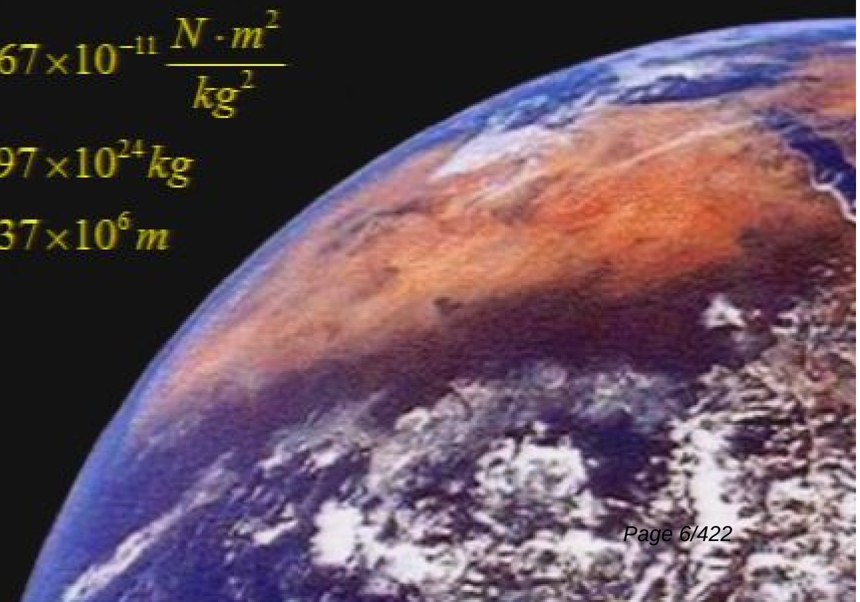
Calculation of Escape Velocity for Earth

$$\frac{1}{2}mv^2 = \frac{GMm}{r}$$

$$G = 6.67\times10^{-11}\frac{N\cdot m^2}{kg^2}$$

$$M = 5.97\times10^{24}kg$$

$$r = 6.37\times10^{6}m$$



Calculate Escape Velocity

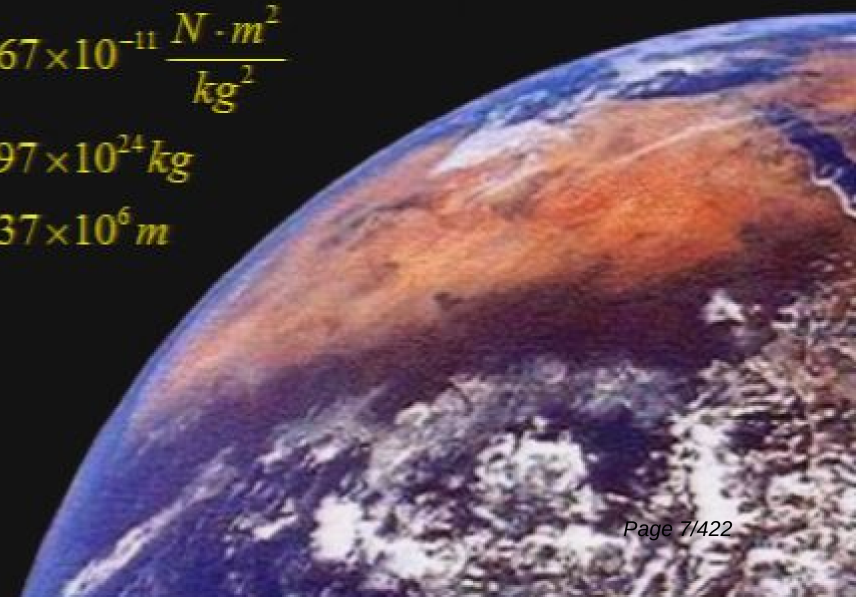
Calculation of Escape Velocity for Earth

$$\frac{1}{2}mv^2 = \frac{GMm}{r}$$

$$G = 6.67 \times 10^{-11} \frac{N \cdot m^2}{kg^2}$$

$$M = 5.97 \times 10^{24} kg$$

$$r = 6.37 \times 10^{6} m$$



Calculation of Escape Velocity for Earth

$$\frac{1}{2}mv^2 = \frac{GMm}{r}$$

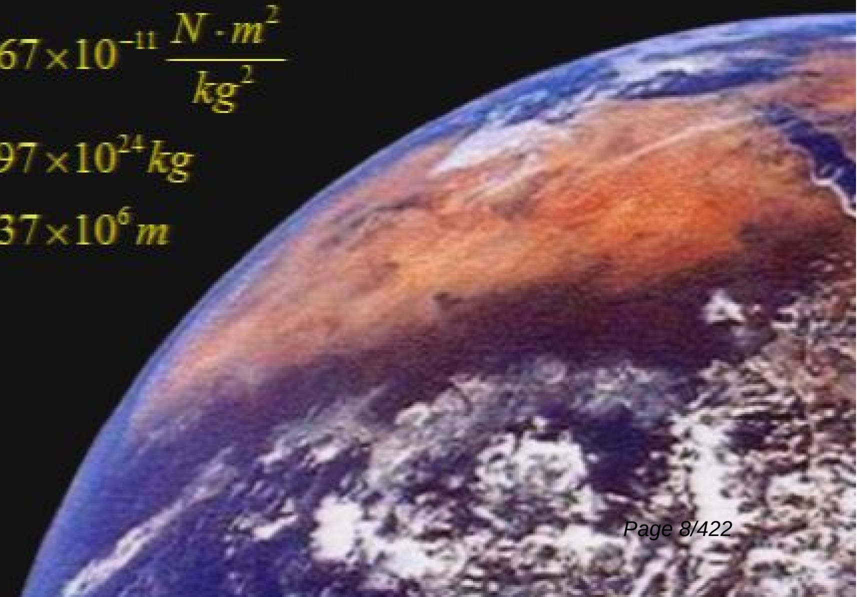
$$\frac{1}{2}v^2 = \frac{GM}{r}$$

$$v = \sqrt{2\frac{\left(6.67\times10^{-11}\right)\left(5.97\times10^{24}\right)}{6.37\times10^{6}}}$$

$$G = 6.67\times10^{-11}\,\frac{N\cdot m^2}{kg^2}$$

$$M = 5.97\times10^{24}\,kg$$

$$r = 6.37\times10^{6}\,m$$



Calculation of Escape Velocity for Earth

$$\frac{1}{2}mv^2 = \frac{GMm}{r}$$

11.2 km/s

$$\frac{1}{2}v^2 = \frac{GM}{r}$$

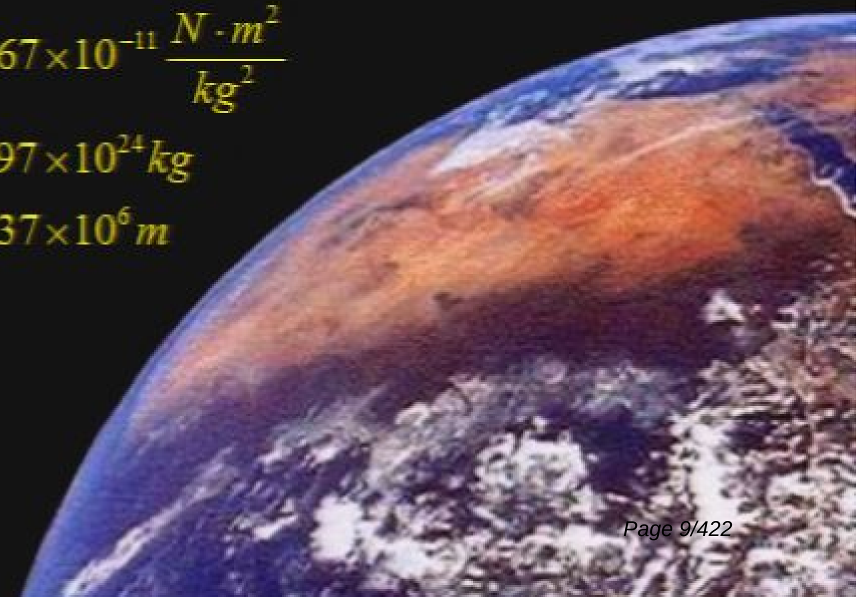
$$v = \sqrt{2\frac{\left(6.67\times10^{-11}\right)\left(5.97\times10^{24}\right)}{6.37\times10^{6}}}$$

$$G = 6.67\times10^{-11}\,\frac{N\cdot m^2}{kg^2}$$

$$M = 5.97\times10^{24}\,kg$$

$$r = 6.37\times10^{6}\,m$$

$$v \approx 11181\,m/s$$

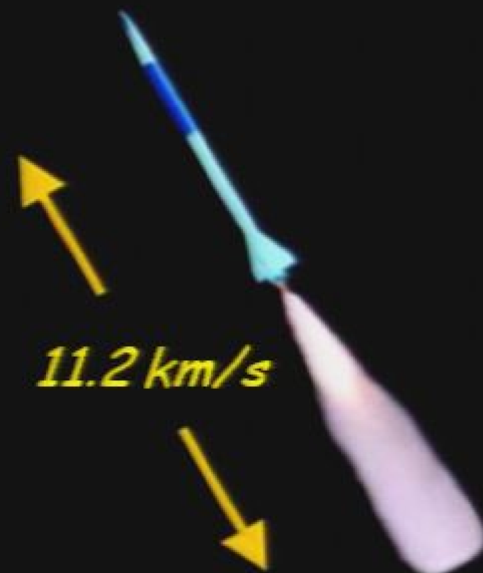


$$\frac{1}{2}mv^2 = \frac{GMm}{r}$$

$$\frac{1}{2}v^2 = \frac{GM}{r}$$

$$v = \sqrt{2\frac{(6.67\times10^{-11})(5.97\times10^{24})}{6.37\times10^{6}}}$$

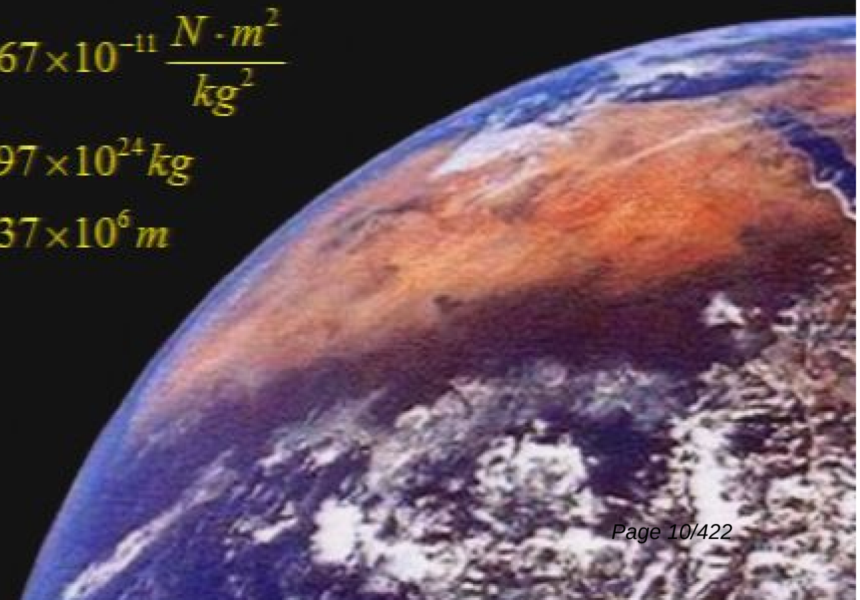
$$v \approx 11181 m/s$$



$$G = 6.67\times10^{-11}\,\frac{N\cdot m^2}{kg^2}$$

$$M = 5.97\times10^{24}\,kg$$

$$r = 6.37\times10^{6}\,m$$



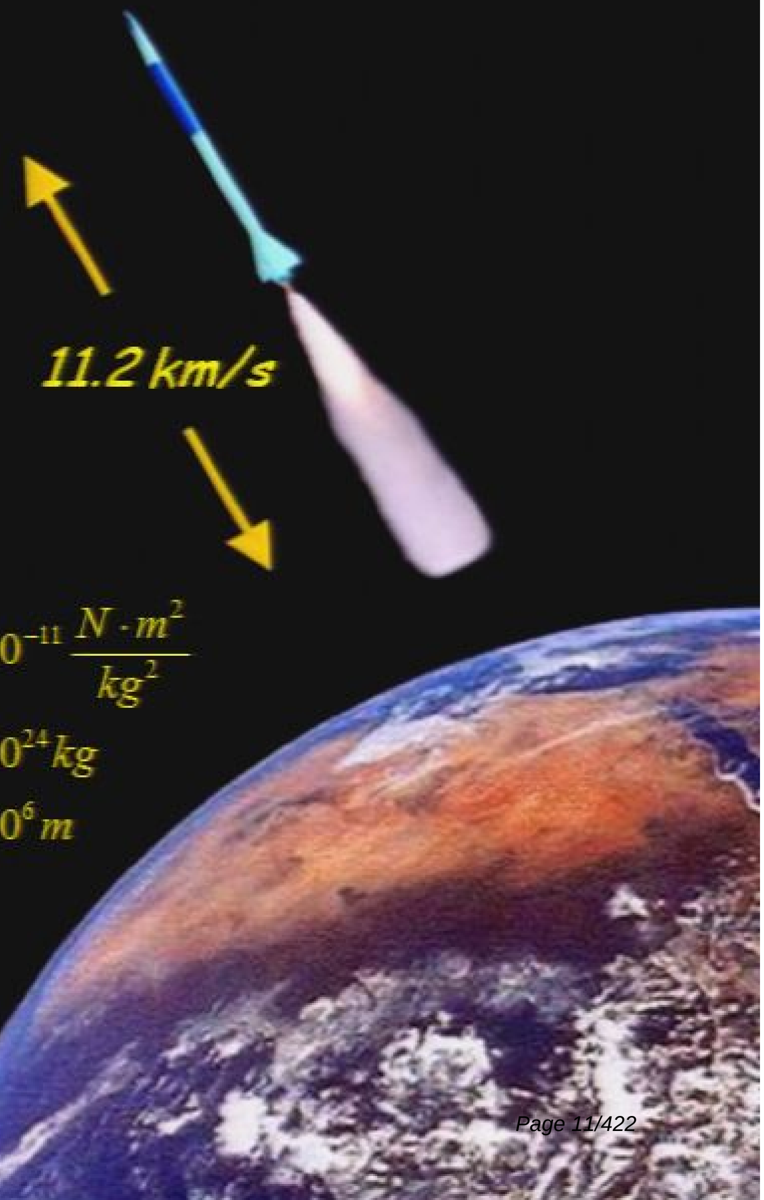
What is Earth's r when escape velocity is 3×10^8 m/s

$$\frac{1}{2}mv^2 = \frac{GMm}{r}$$

$$\frac{1}{2}v^2 = \frac{GM}{r}$$

$$v = \sqrt{2\frac{(6.67\times10^{-11})(5.97\times10^{24})}{6.37\times10^{6}}}$$

$$v \approx 11181 m/s$$



$$G = 6.67\times10^{-11}\frac{N\cdot m^2}{kg^2}$$

$$M = 5.97\times10^{24} kg$$

$$r = 6.37\times10^{6} m$$

What is Earth's r when escape velocity is $3x10^8$ m/s

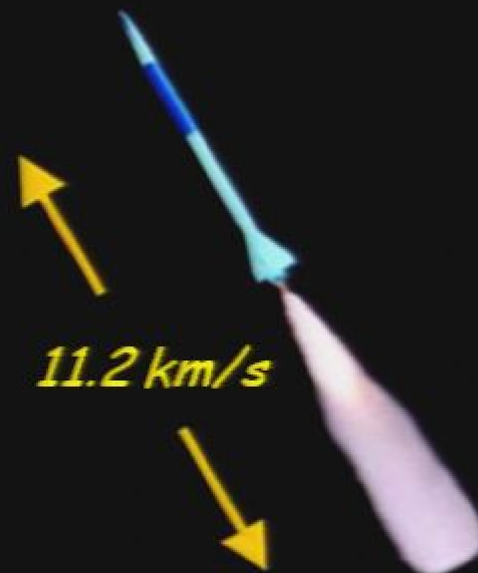
~8.9 mm

$$\frac{1}{2}mv^2 = \frac{GMm}{r}$$

$$\frac{1}{2}v^2 = \frac{GM}{r}$$

$$v = \sqrt{2\frac{(6.67\times10^{-11})(5.97\times10^{24})}{6.37\times10^{6}}}$$

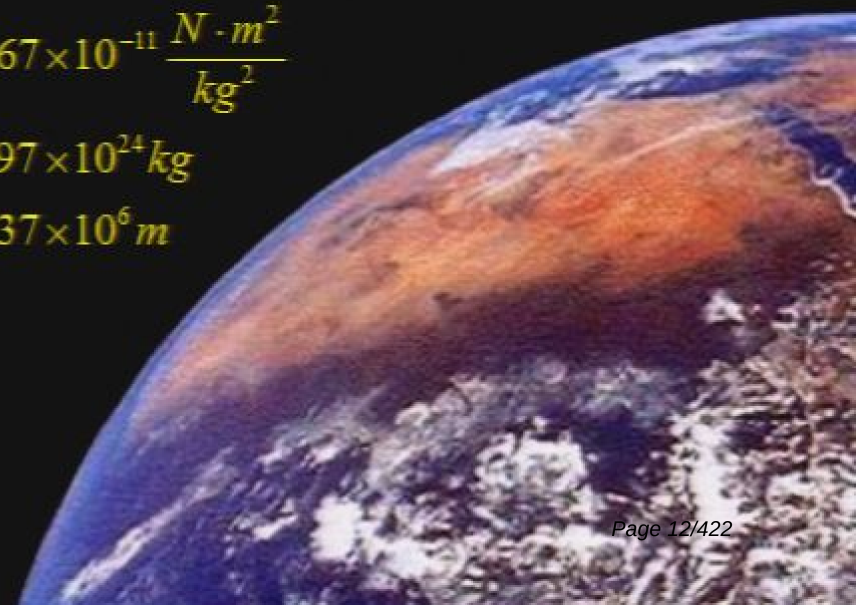
$$v \approx 11181 m/s$$



$$G = 6.67\times10^{-11}\frac{N\cdot m^2}{kg^2}$$

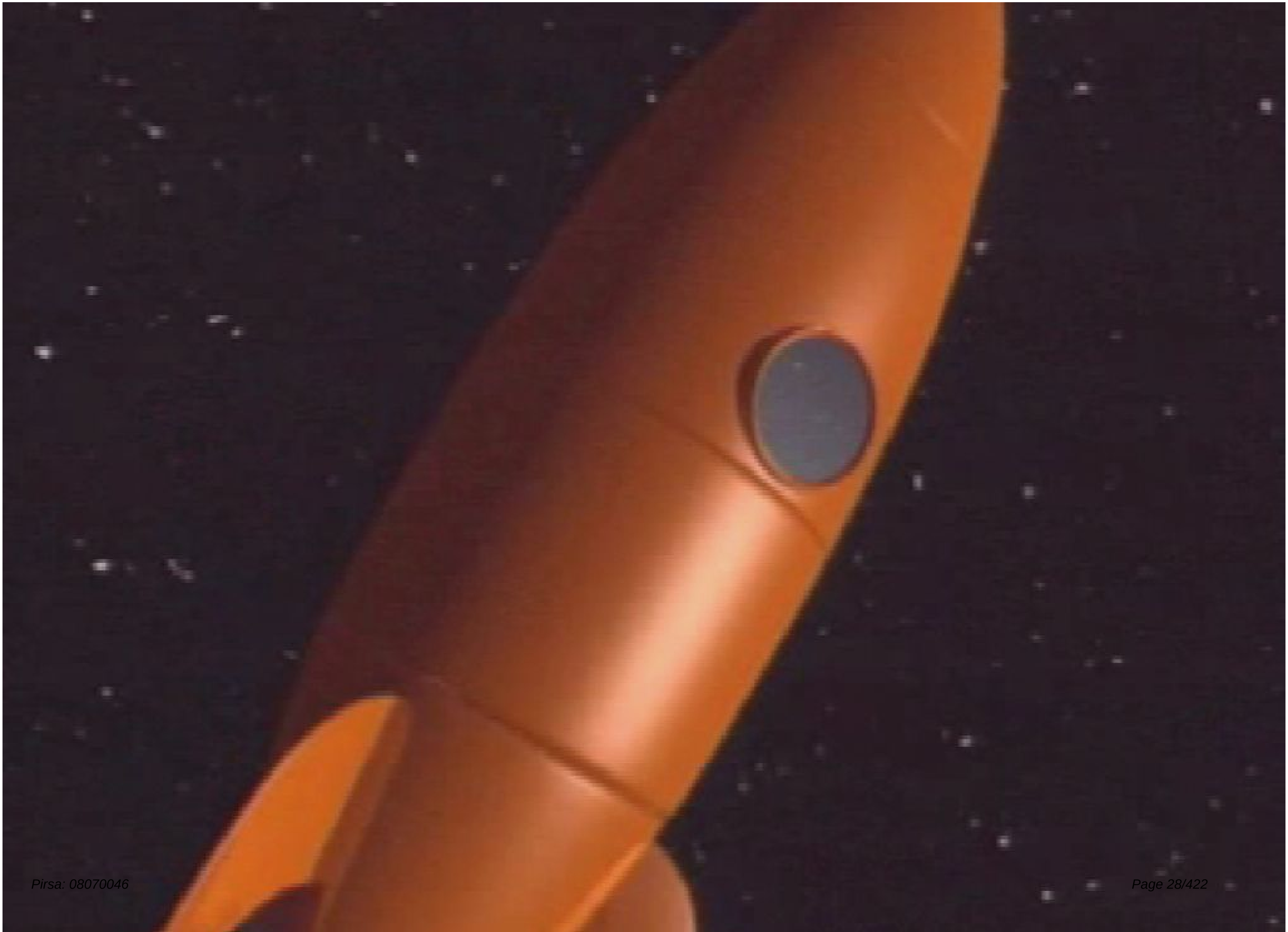
$$M = 5.97\times10^{24} kg$$

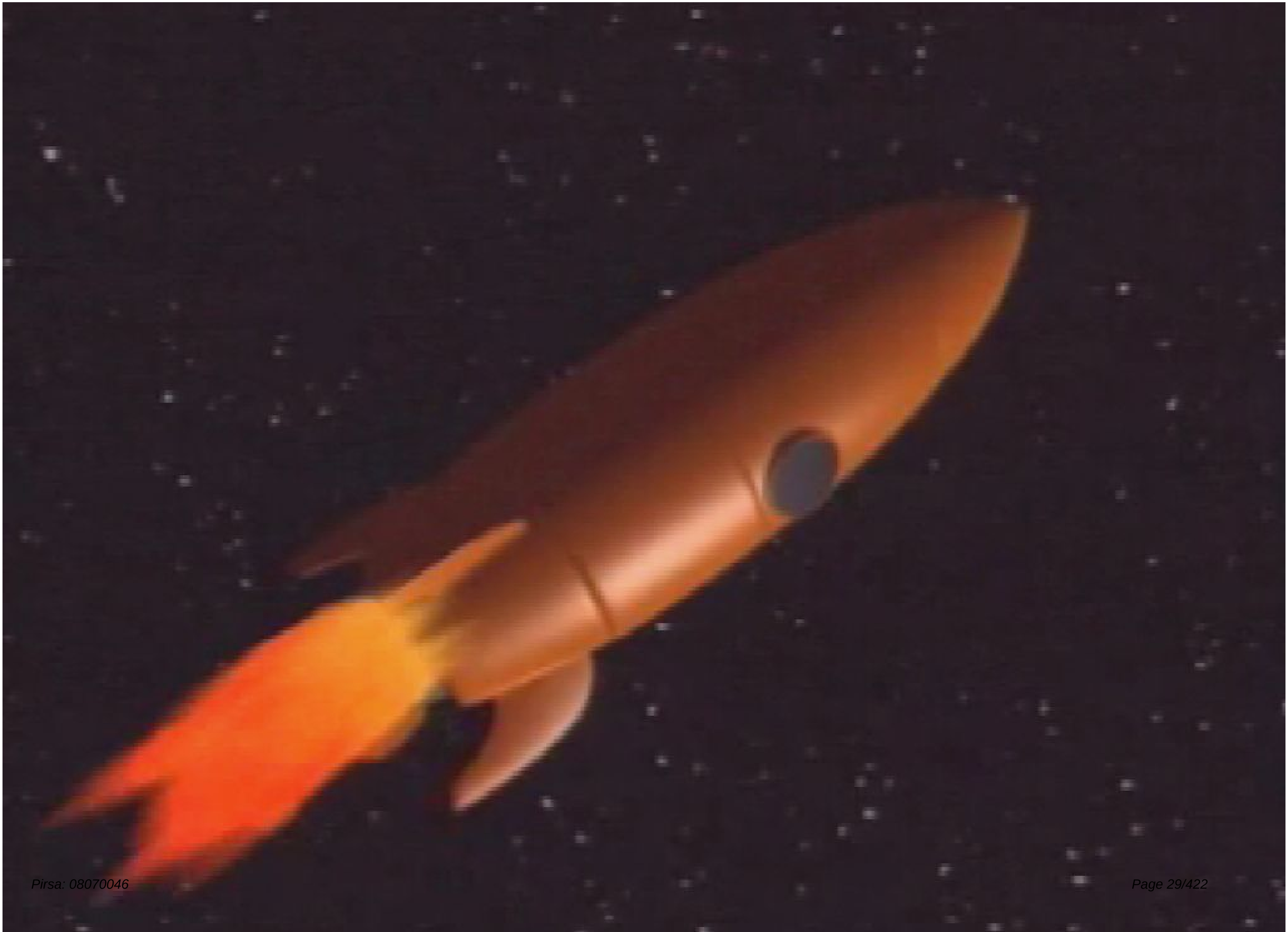
$$r = 6.37\times10^{6} m$$



Einstein's Equivalence Principle

- There is no experiment that you can perform that will distinguish these two diagrams





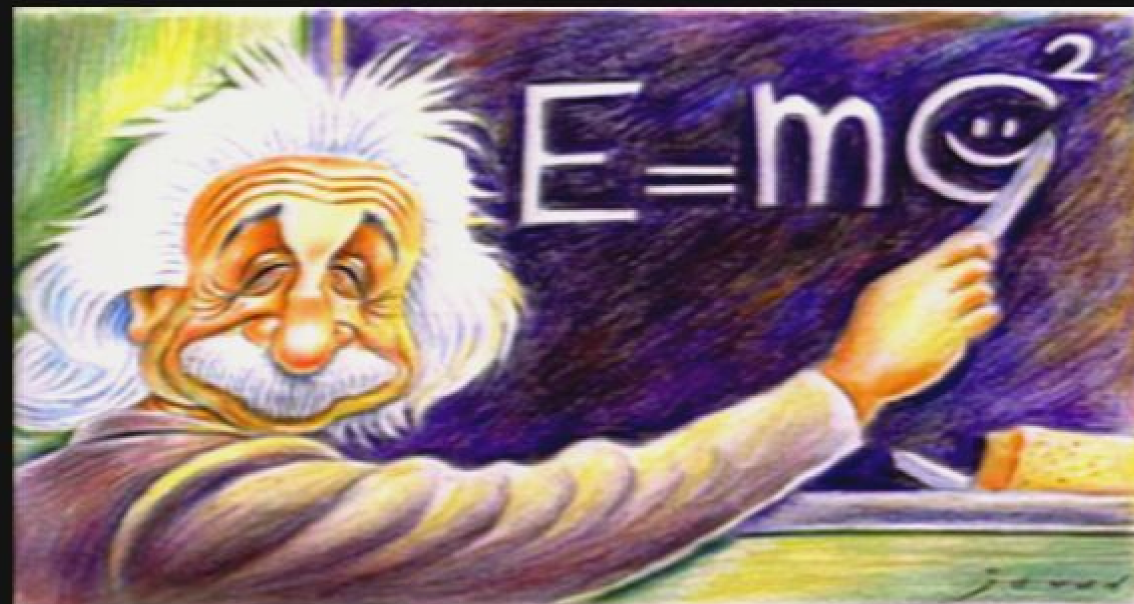
Einstein's Equivalence Principle

- There is no experiment that you can perform that will distinguish these two diagrams

Gravity as a Curvature of Spacetime

The early 1900's changed the way gravity is looked at. Einstein didn't think of gravity as a force between objects, but as a curving of "straight lines" due to mass. Light always follows these straight lines.

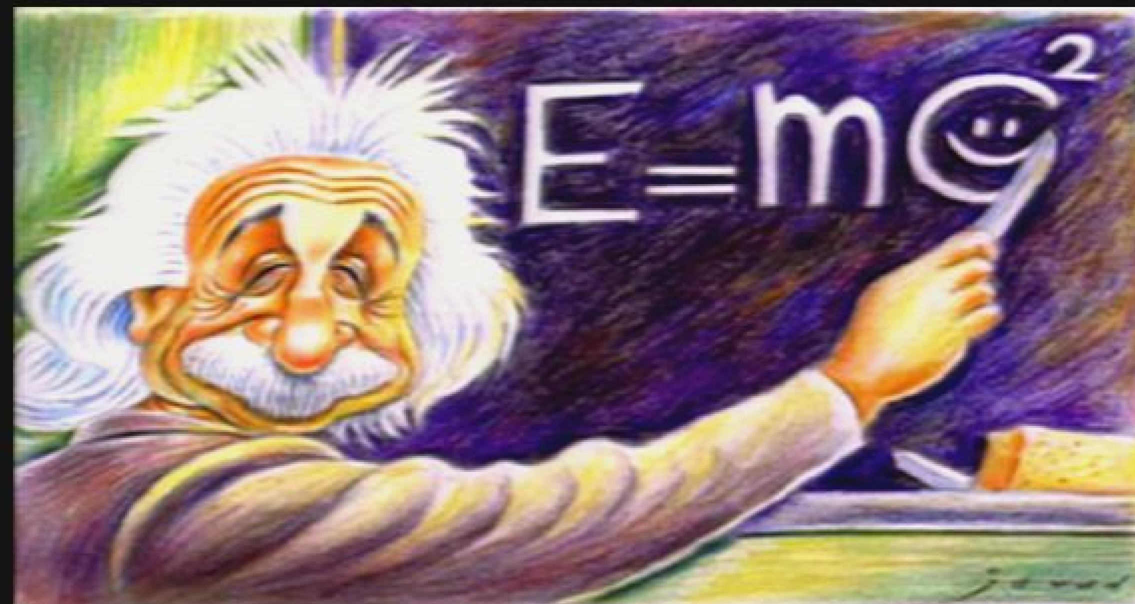
Time also slows down near masses (space and time are different parts of "spacetime", which is what gets bent).



$$G_{uv} + \Lambda g_{uv} = 8\pi T_{uv}$$

Gravity as a Curvature of Spacetime

The early 1900’s changed the way gravity is looked at. Einstein didn’t think of gravity as a force between objects, but as a curving of “straight lines” due to mass. Light always follows these straight lines. Time also slows down near masses (space and time are different parts of “spacetime”, which is what gets bent).



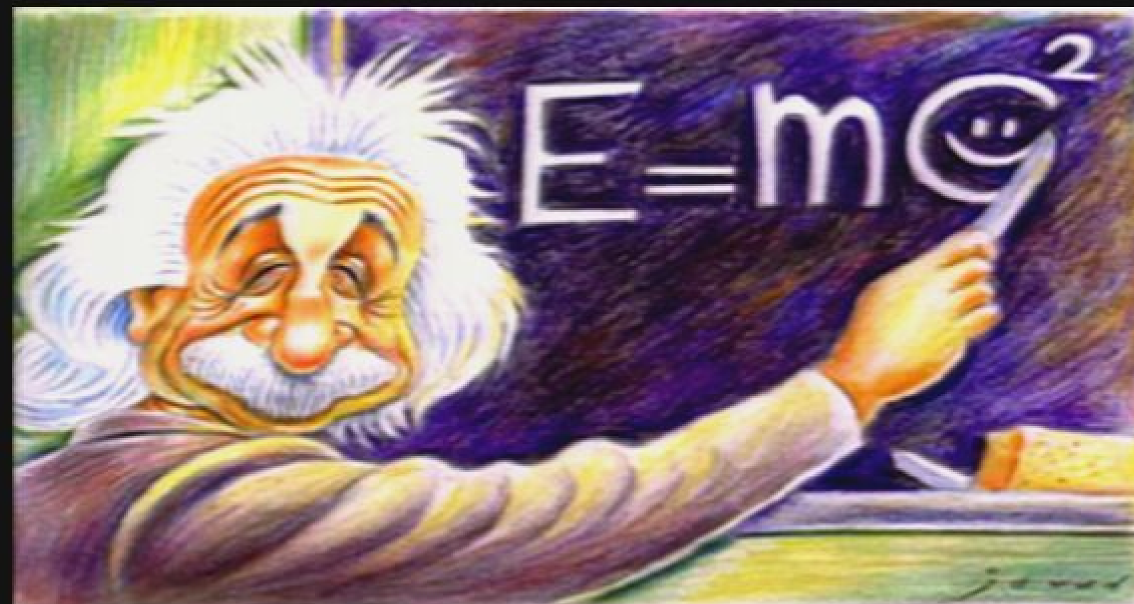
$$G_{uv} + \Lambda g_{uv} = 8\pi T_{uv}$$

Encodes geometry (curving) of Space Time

Gravity as a Curvature of Spacetime

The early 1900's changed he way gravity is looked at. Einstein didn't think of gravity as a force between objects, but as a curving of straight lines" due to mass. Light always follows these traight lines.

Time also slows down near nasses (space and time re different parts of spacetime", which is what ets bent).



$$G_{uv} + \Lambda g_{uv} = 8\pi T_{uv}$$

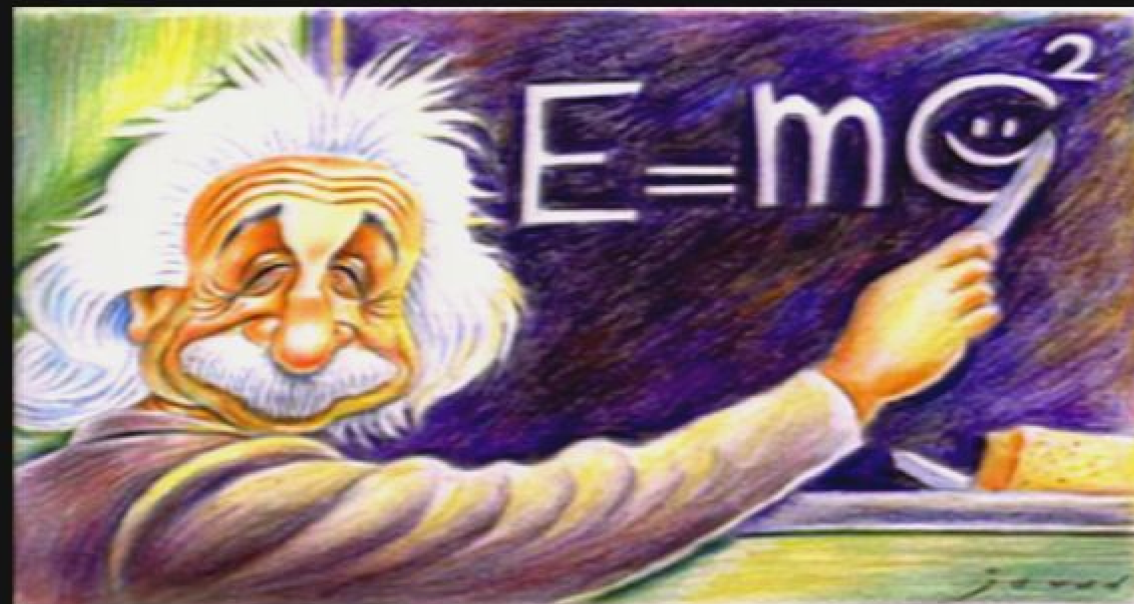
Encodes geometry (curving) of Space Time

Cosmological Constant

Gravity as a Curvature of Spacetime

The early 1900's changed the way gravity is looked at. Einstein didn't think of gravity as a force between objects, but as a curving of "straight lines" due to mass. Light always follows these straight lines.

Time also slows down near masses (space and time are different parts of "spacetime", which is what gets bent).

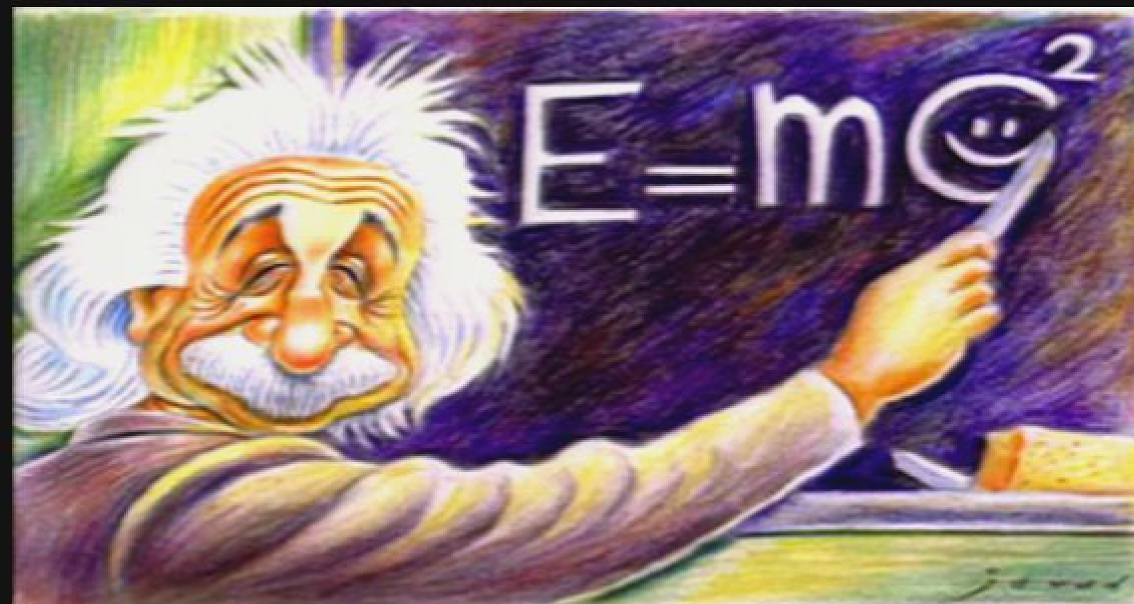


$$G_{uv} + \Lambda g_{uv} = 8\pi T_{uv}$$

- G_{uv}: Encodes geometry (curving) of Space Time
- Λ: Cosmological Constant
- T_{uv}: Encodes the distribution of matter and its motion in Space Time

Gravity as a Curvature of Spacetime

The early 1900's changed
he way gravity is looked at.
Einstein didn't think of
gravity as a force between
objects, but as a curving of
straight lines" due to mass.
Light always follows these
straight lines.
Time also slows down near
nasses (space and time
are different parts of
spacetime", which is what
gets bent).



$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi T_{\mu\nu}$$

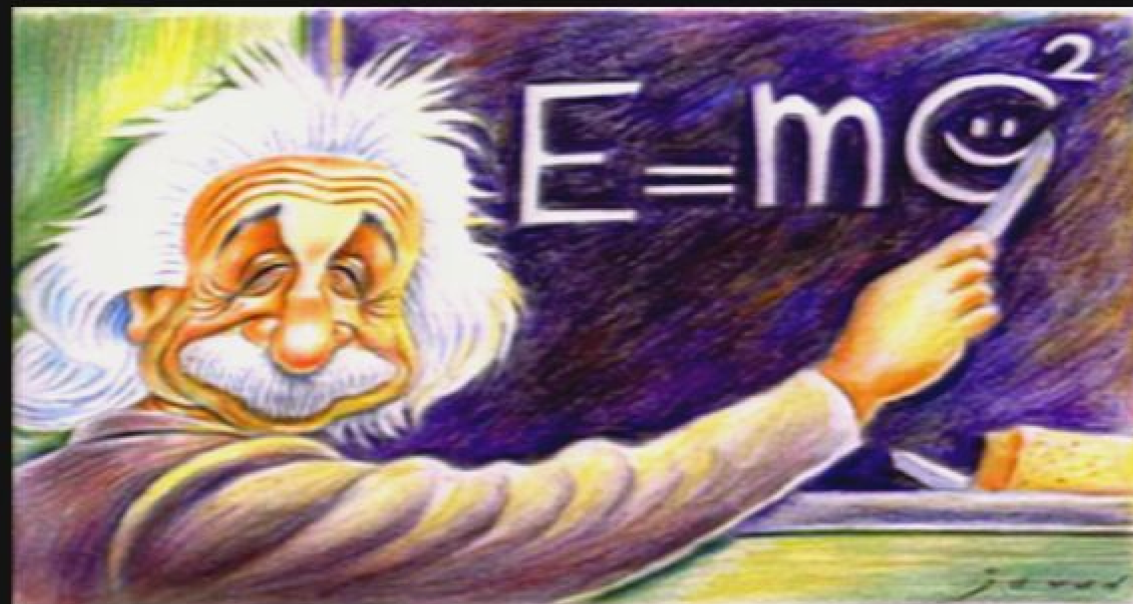
Encodes geometry (curving) of Space Time

Cosmological Constant

Encodes the distribution of matter and its motion in Space Time

Gravity as a Curvature of Spacetime

The early 1900's changed he way gravity is looked at. Einstein didn't think of gravity as a force between objects, but as a curving of "straight lines" due to mass. Light always follows these straight lines.
Time also slows down near masses (space and time are different parts of "spacetime", which is what gets bent).



$$G_{uv} = 8\pi T_{uv}$$

Encodes geometry (curving) of Space Time

Encodes the distribution of matter and its motion in Space Time

Einstein Field Equation: another dissection

- Generally speaking, Einstein field equation: $G_{\mu\nu} = 8\pi T_{\mu\nu}$

is coupled elliptic-hyperbolic nonlinear partial differential equations for the metric components.

- Just so that we are clear on definitions:

Einstein Field Equation: another dissection

• Generally speaking, Einstein field equation: $G_{\mu\nu} = 8\pi T_{\mu\nu}$

is coupled elliptic-hyperbolic nonlinear partial differential equations for the metric components.

• Just so that we are clear on definitions:

"coupled" – each differential equation contains multiple terms; equations cannot be solved individually.

Einstein Field Equation: another dissection

- Generally speaking, Einstein field equation: $G_{\mu\nu} = 8\pi T_{\mu\nu}$

is coupled elliptic-hyperbolic nonlinear partial differential equations for the metric components.

- Just so that we are clear on definitions:

"coupled" – each differential equation contains multiple terms; equations cannot be solved individually.

"elliptic-hyperbolic" – determinants of sub-matrices of the system of equations matrix are either positive or negative; never zero.

Einstein Field Equation: another dissection

- Generally speaking, Einstein field equation: $G_{\mu\nu} = 8\pi T_{\mu\nu}$

is coupled elliptic-hyperbolic nonlinear partial differential equations for the metric components.

- Just so that we are clear on definitions:

"coupled" – each differential equation contains multiple terms; equations cannot be solved individually.

"elliptic-hyperbolic" – determinants of sub-matrices of the system of equations matrix are either positive or negative; never zero.

"nonlinear" – dependent on nonlinear function of metric components

Einstein Field Equation: another dissection

- Generally speaking, Einstein field equation: $G_{\mu\nu} = 8\pi T_{\mu\nu}$

is coupled elliptic-hyperbolic nonlinear partial differential equations for the metric components.

- Just so that we are clear on definitions:

"coupled" – each differential equation contains multiple terms; equations cannot be solved individually.

"elliptic-hyperbolic" – determinants of sub-matrices of the system of equations matrix are either positive or negative; never zero.

"nonlinear" – dependent on nonlinear function of metric components

"partial differential equation" – an equation containing partial derivatives of functions, for example $\partial^2 f(x,y,z)/\partial x \partial y$

Einstein Field Equation: another dissection

- Generally speaking, Einstein field equation: $G_{\mu\nu} = 8\pi T_{\mu\nu}$

is coupled elliptic-hyperbolic nonlinear partial differential equations for the metric components.

- Just so that we are clear on definitions:

"coupled" – each differential equation contains multiple terms; equations cannot be solved individually.

"elliptic-hyperbolic" – determinants of sub-matrices of the system of equations matrix are either positive or negative; never zero.

"nonlinear" – dependent on nonlinear function of metric components

"partial differential equation" – an equation containing partial derivatives of functions, for example $\partial^2 f(x,y,z)/\partial x \partial y$

"metric components" – components of the metric tensor $g_{\mu\nu}$

Let's Review

EMITECAPS

Let's Review

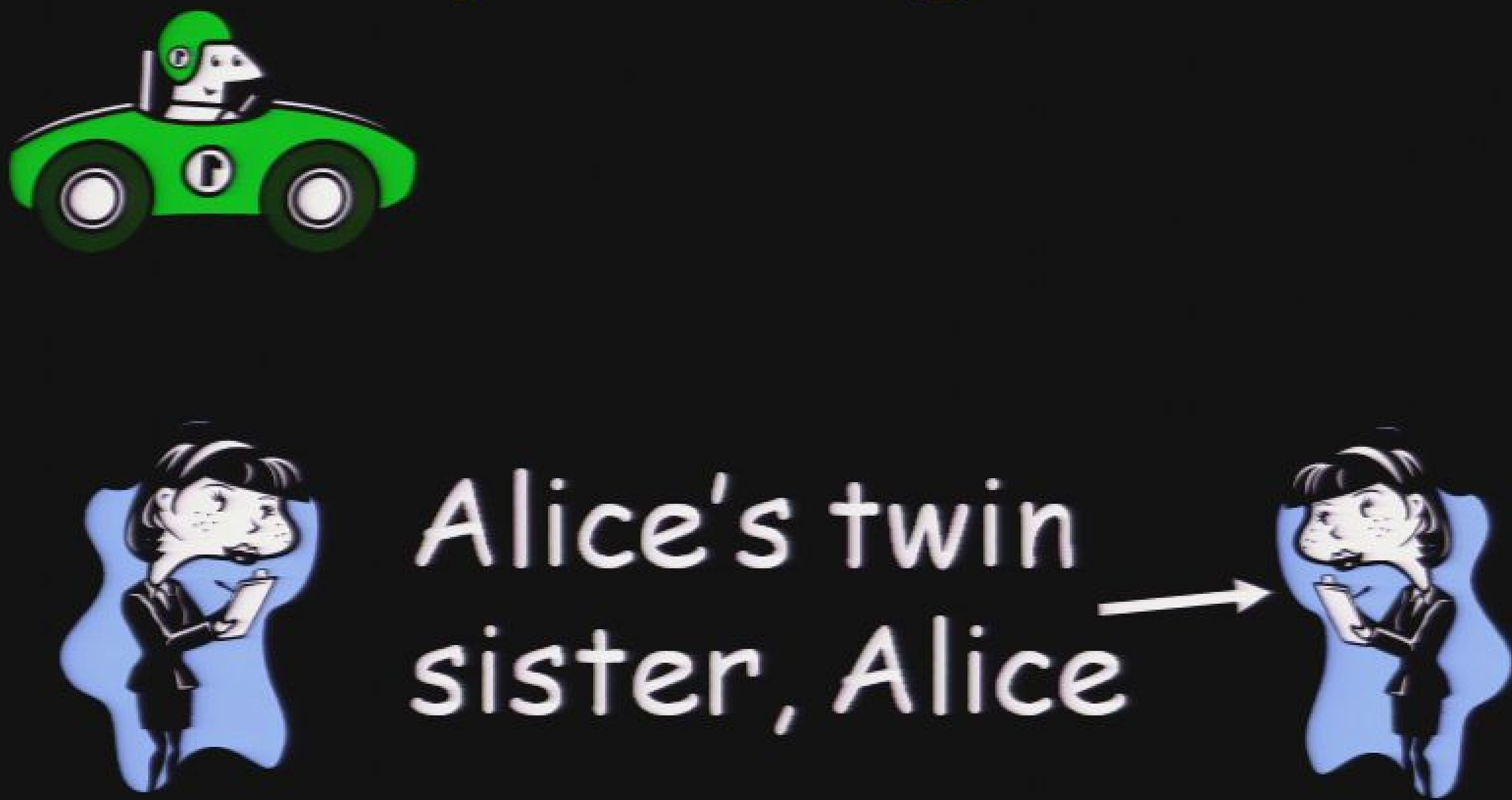
Let's Review

SPACETIME

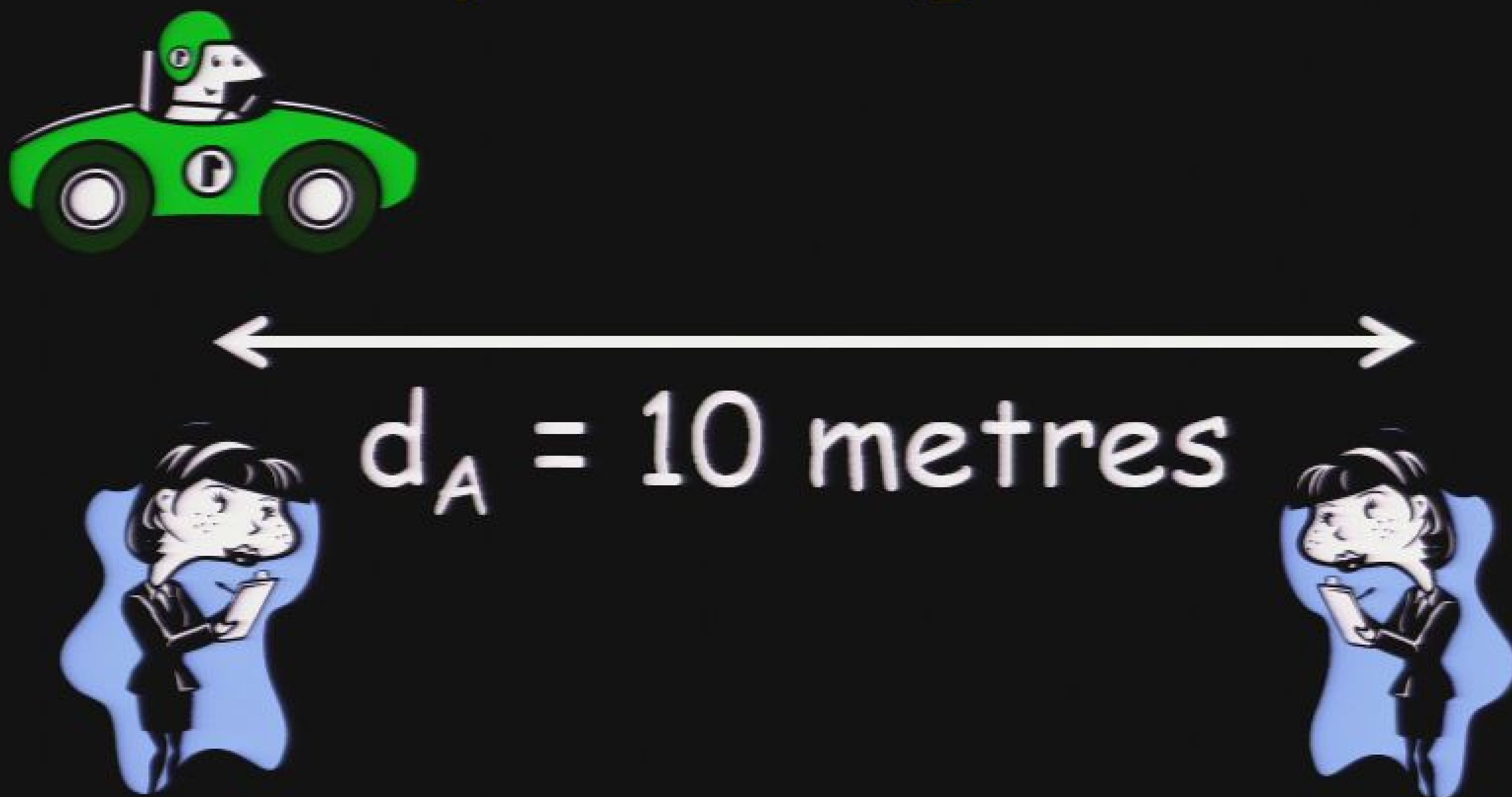
Space Diagram

Space Diagram

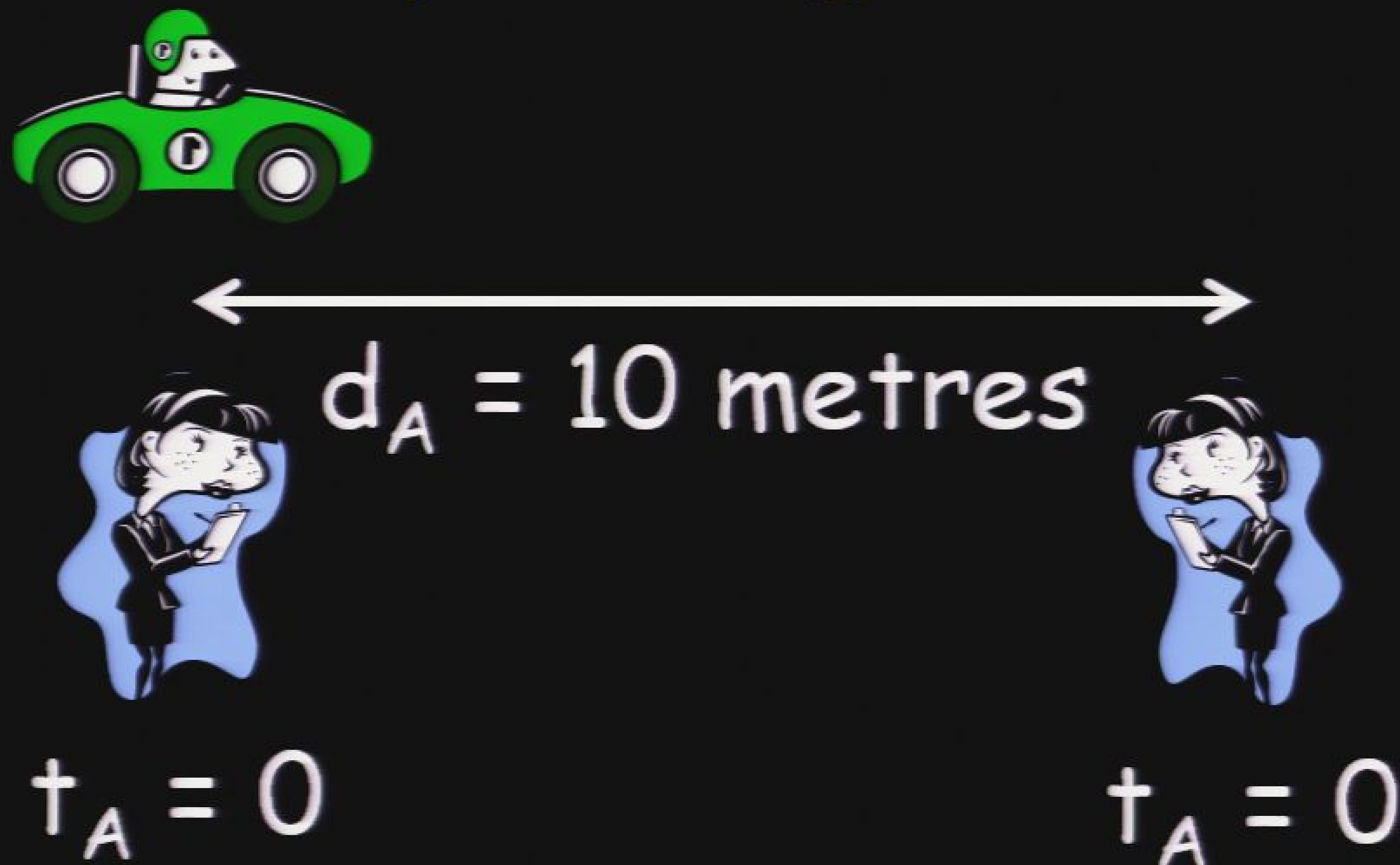
Space Diagram



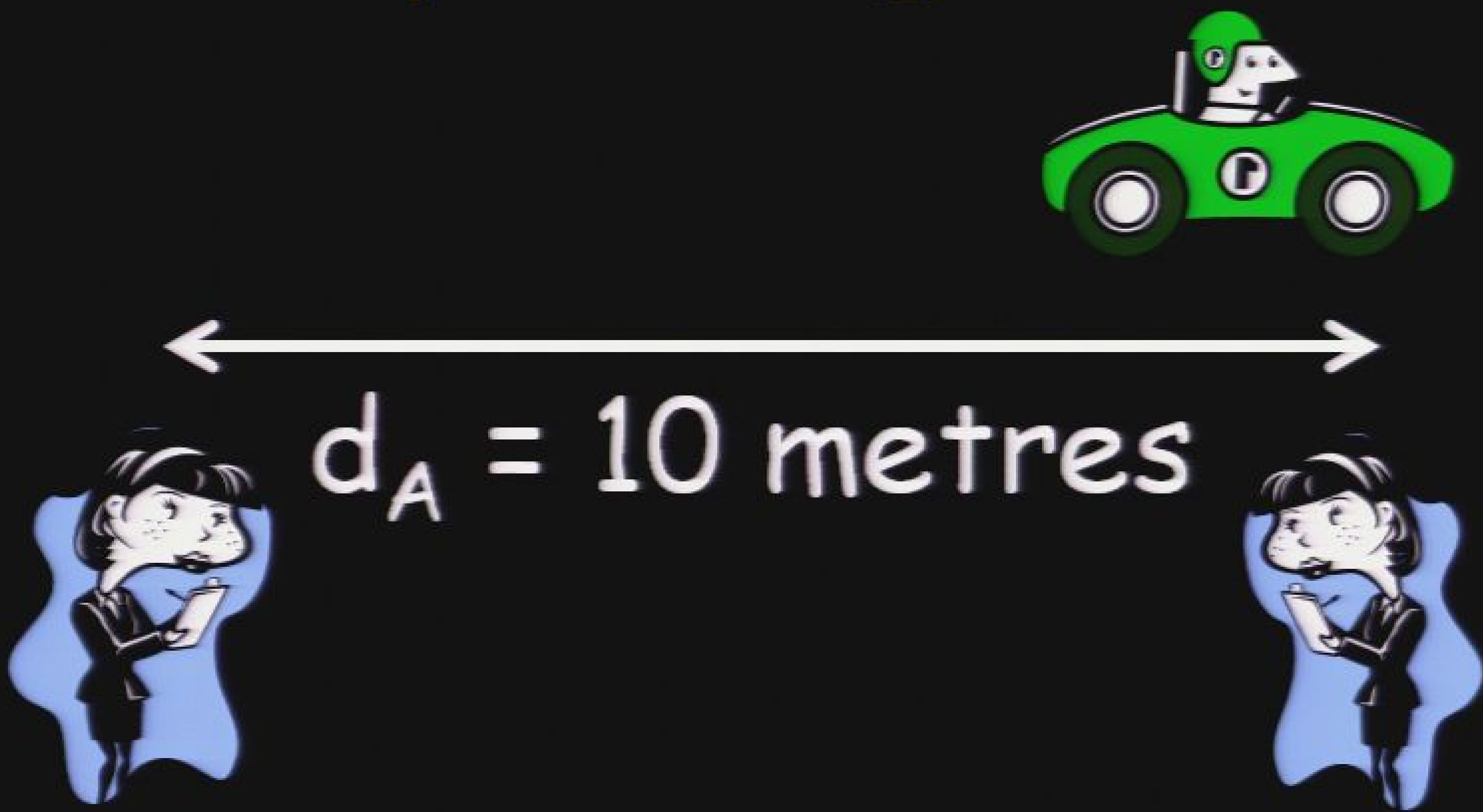
Space Diagram



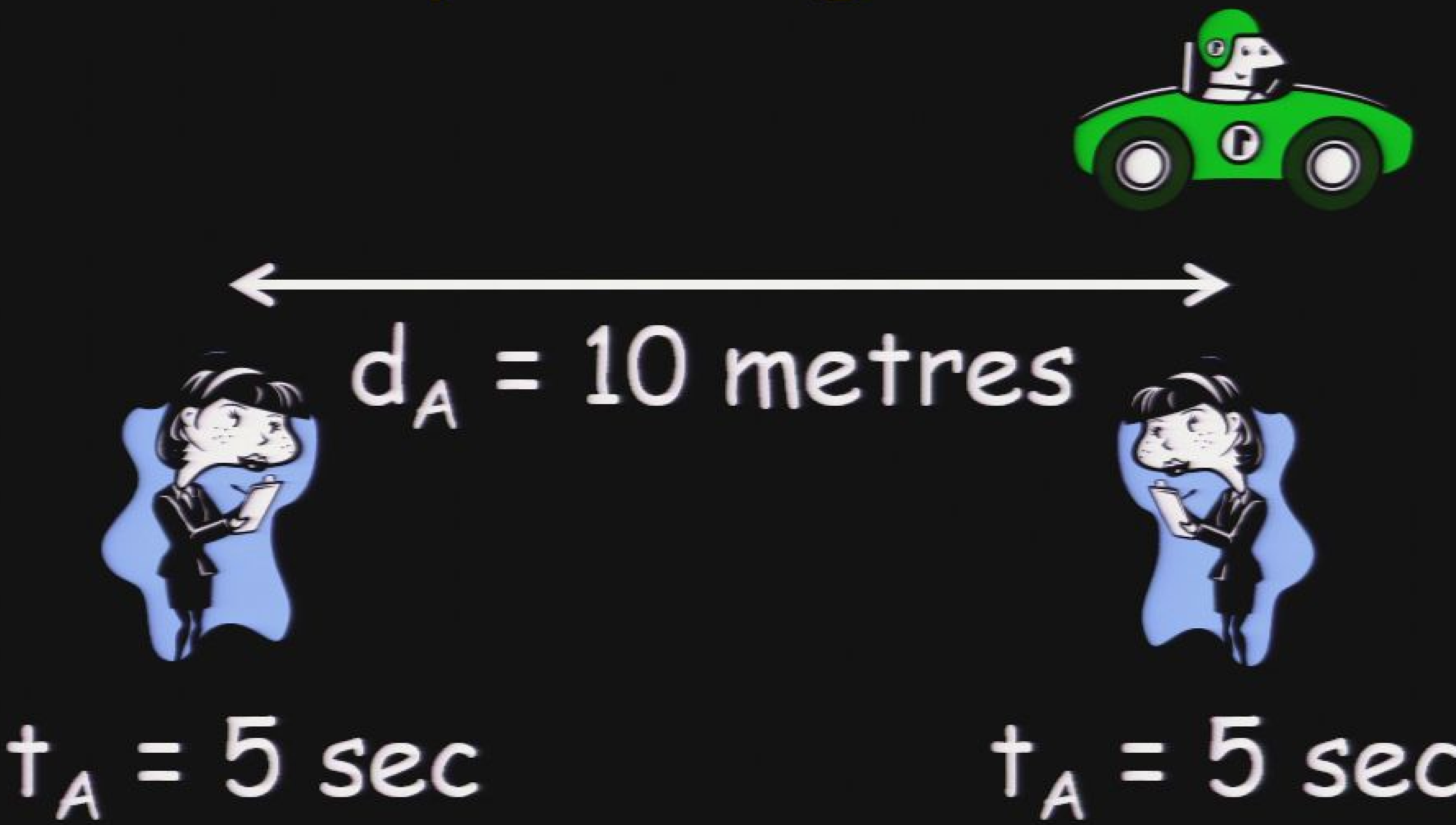
Space Diagram



Space Diagram



Space Diagram



Space Diagram

d_A = 10 metres

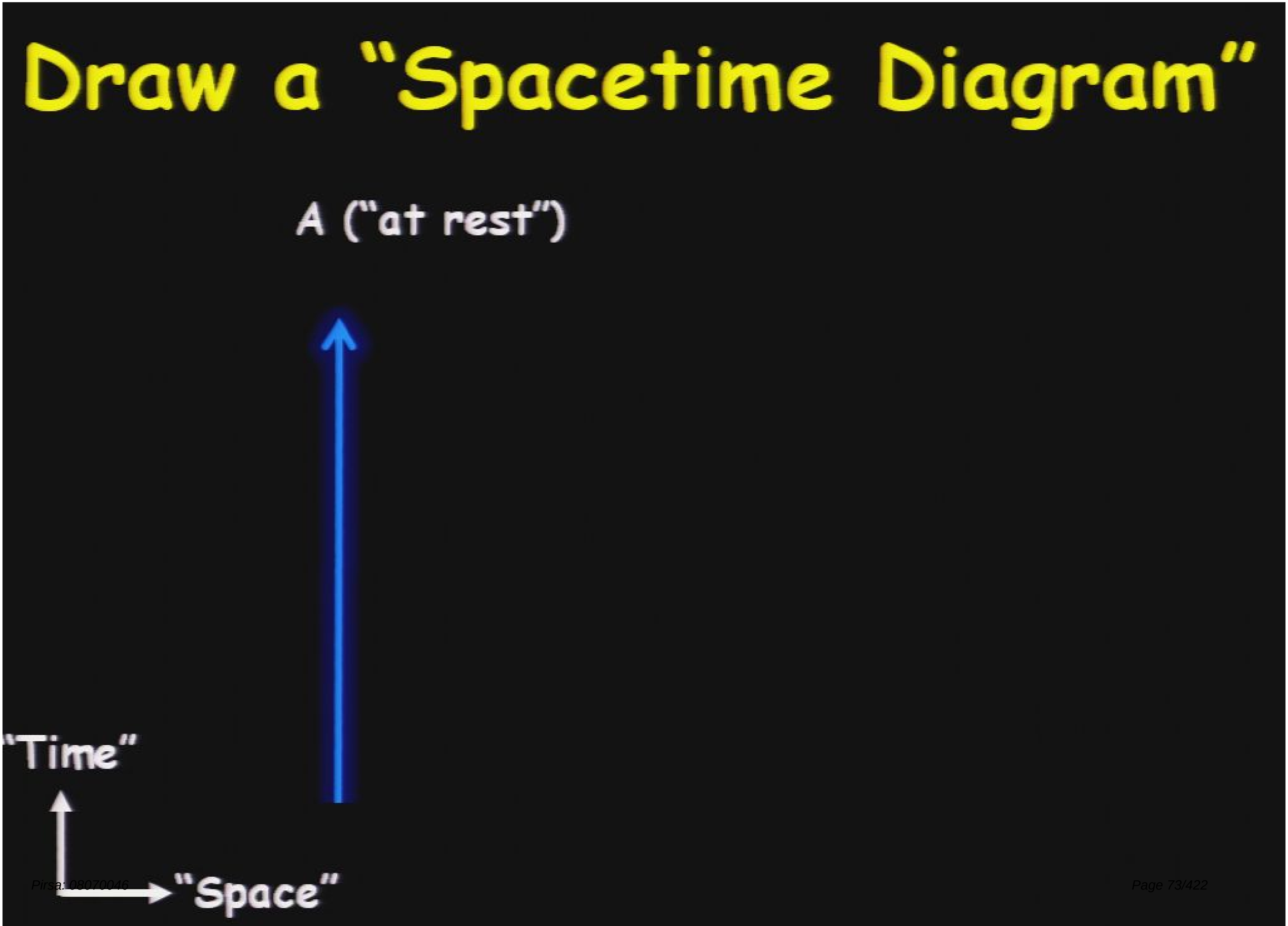
t_A = 5 sec

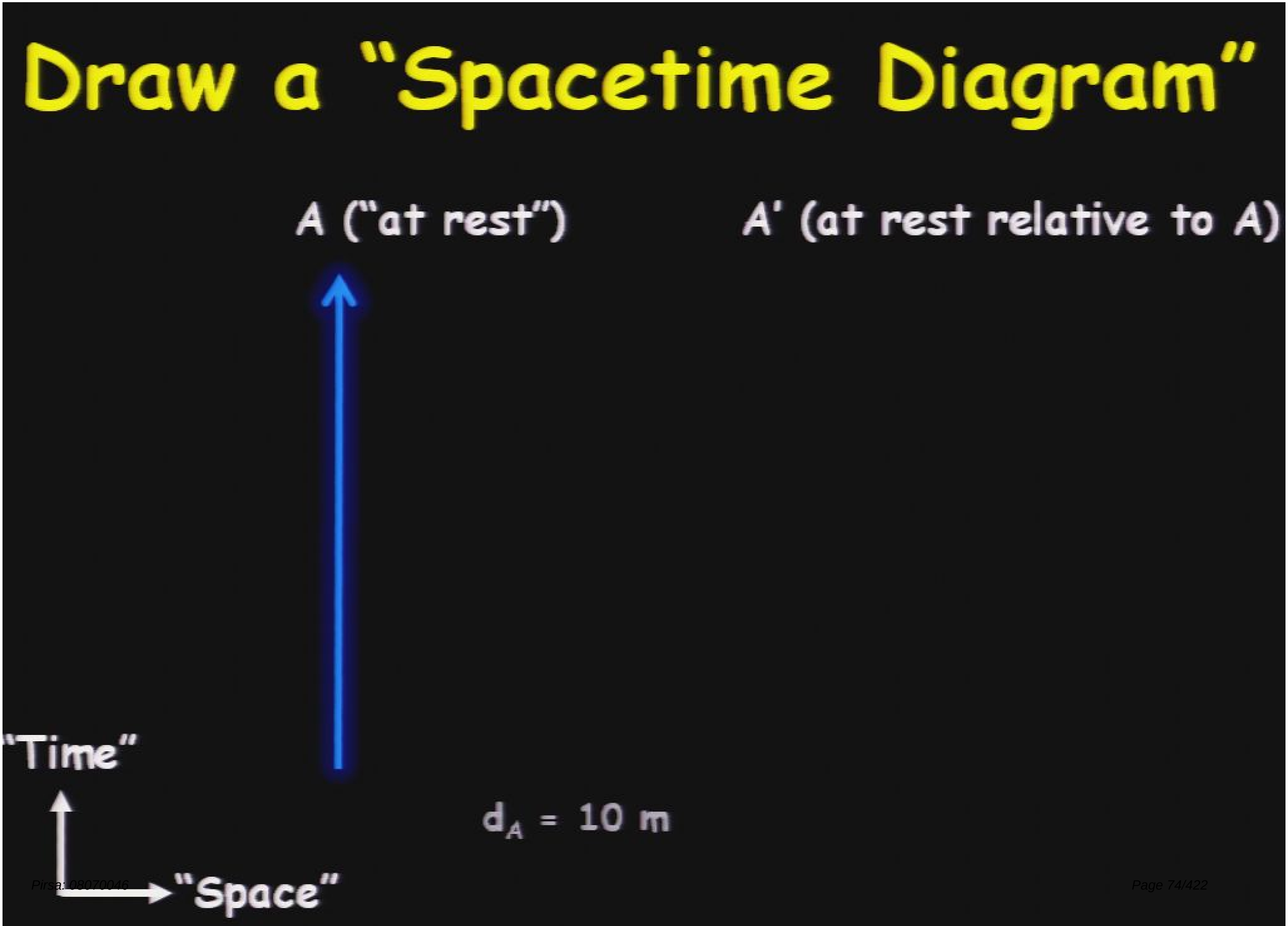
t_A = 5 sec

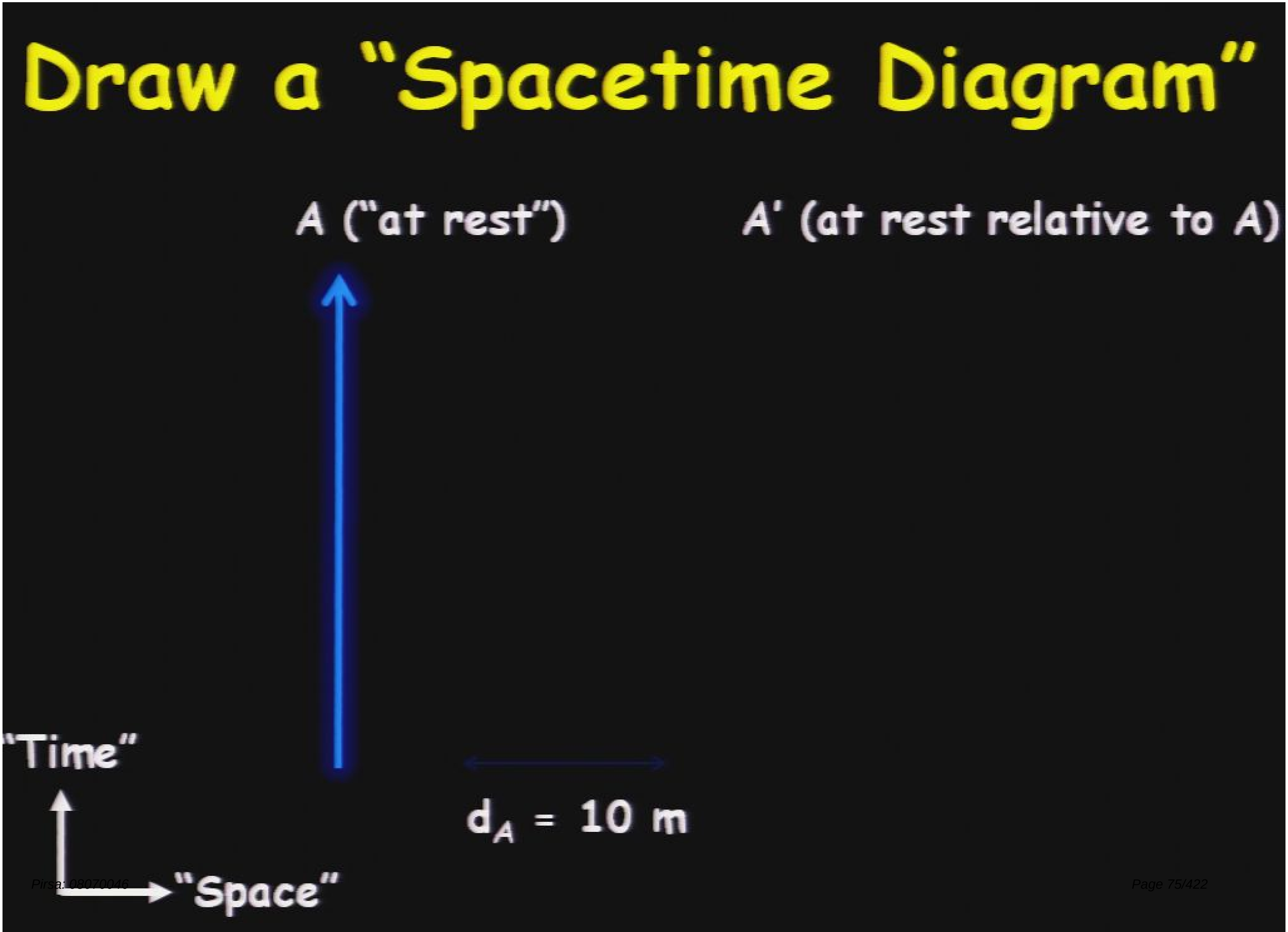
Question: How much time has elapsed for Bob?

Draw a “Spacetime Diagram”

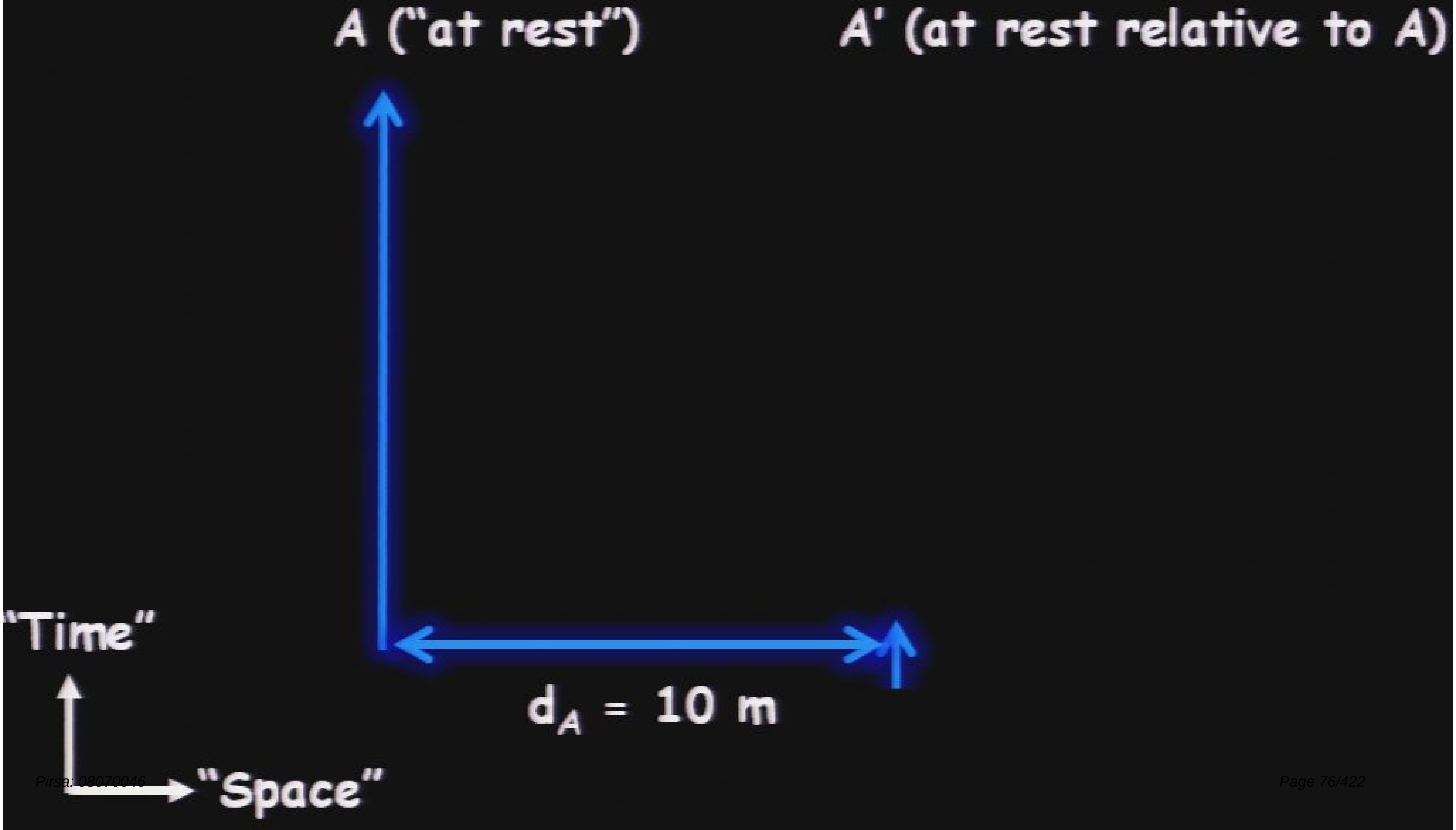
Draw a "Spacetime Diagram"


Draw a "Spacetime Diagram"
A ("at rest")
"Time"
"Space"

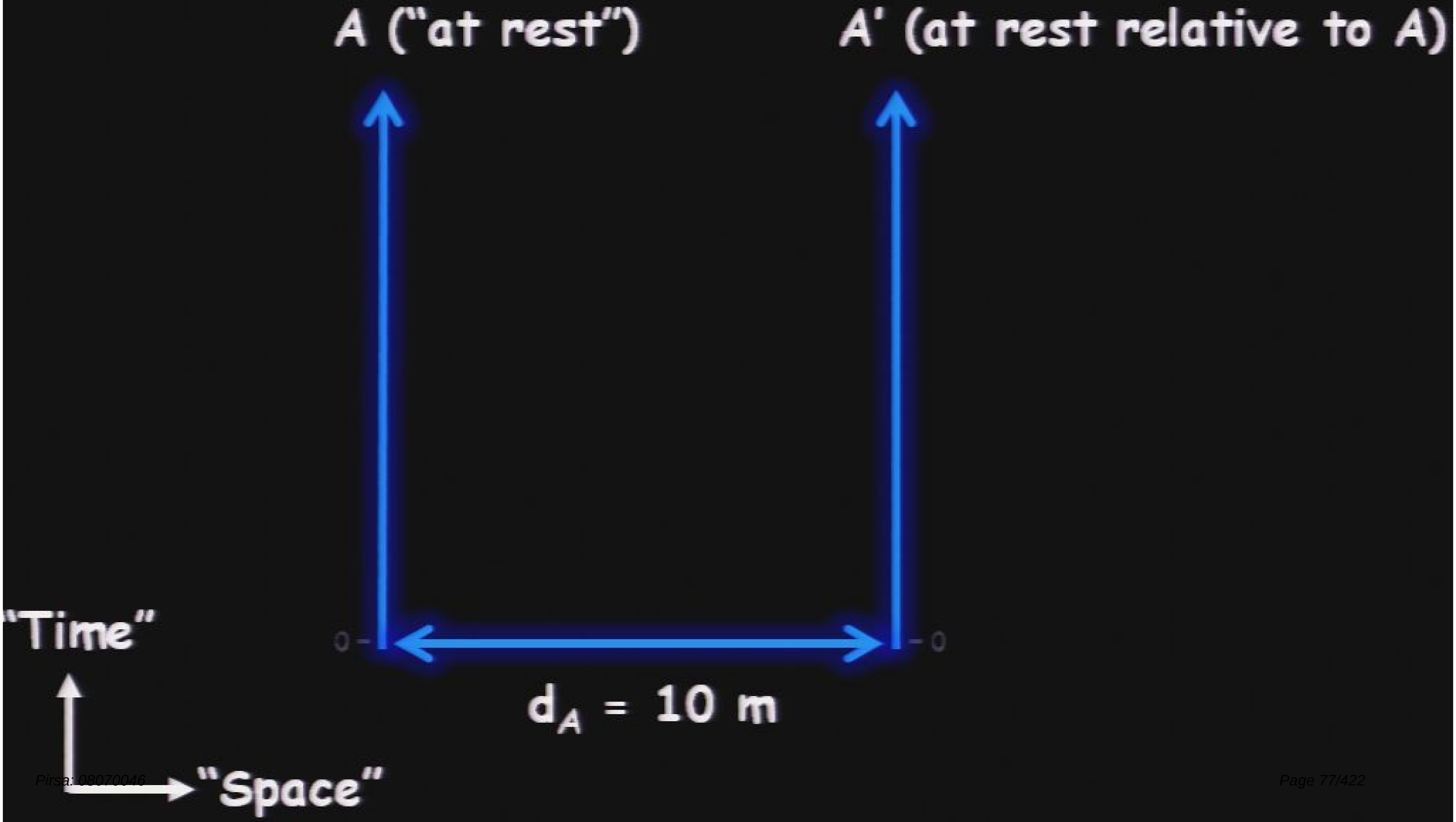

Draw a "Spacetime Diagram"
A ("at rest")
A' (at rest relative to A)
"Time"
"Space"
d_A = 10 m


Draw a "Spacetime Diagram"
A ("at rest")
A' (at rest relative to A)
"Time"
"Space"
d_A = 10 m

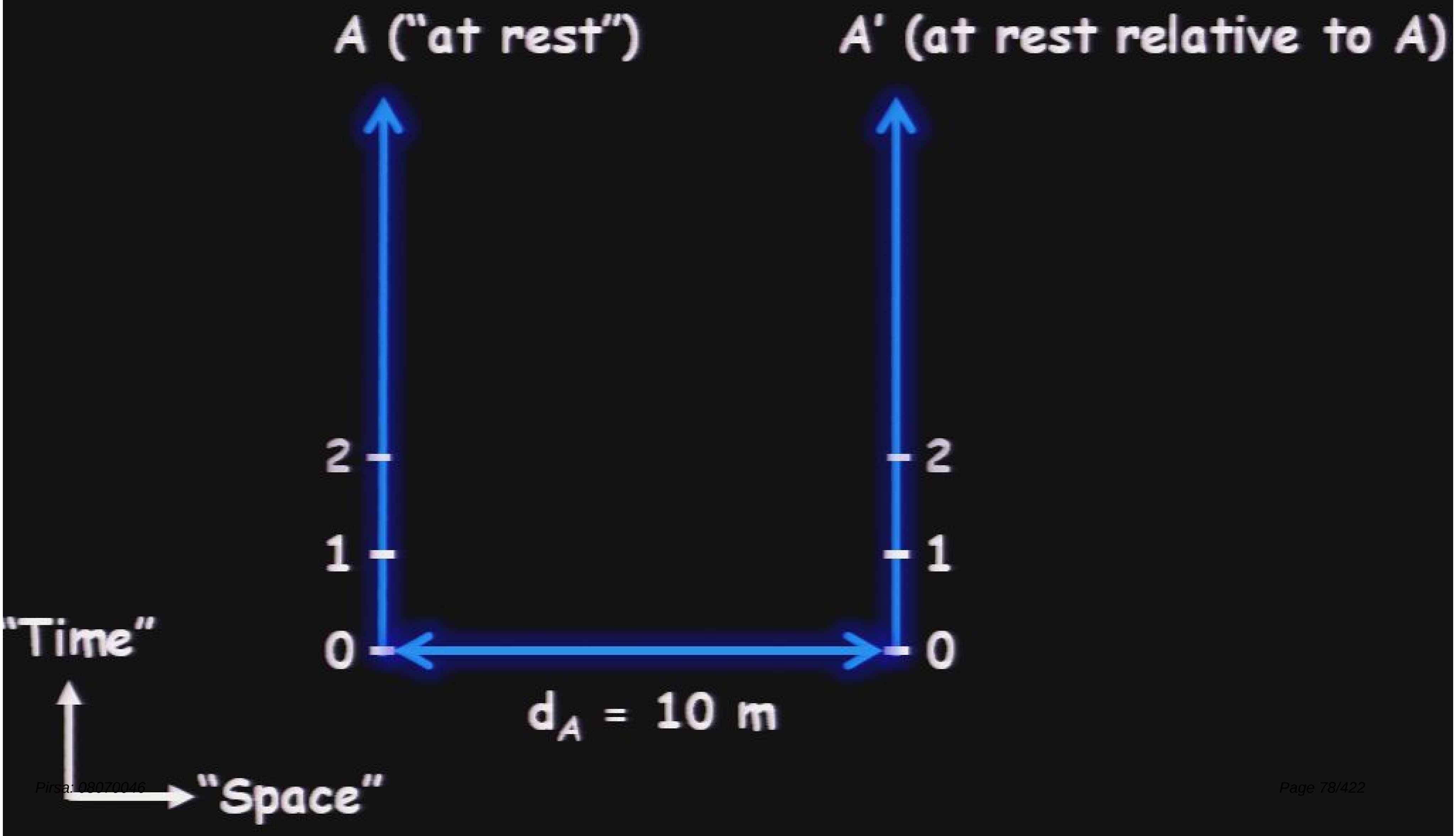
Draw a "Spacetime Diagram"



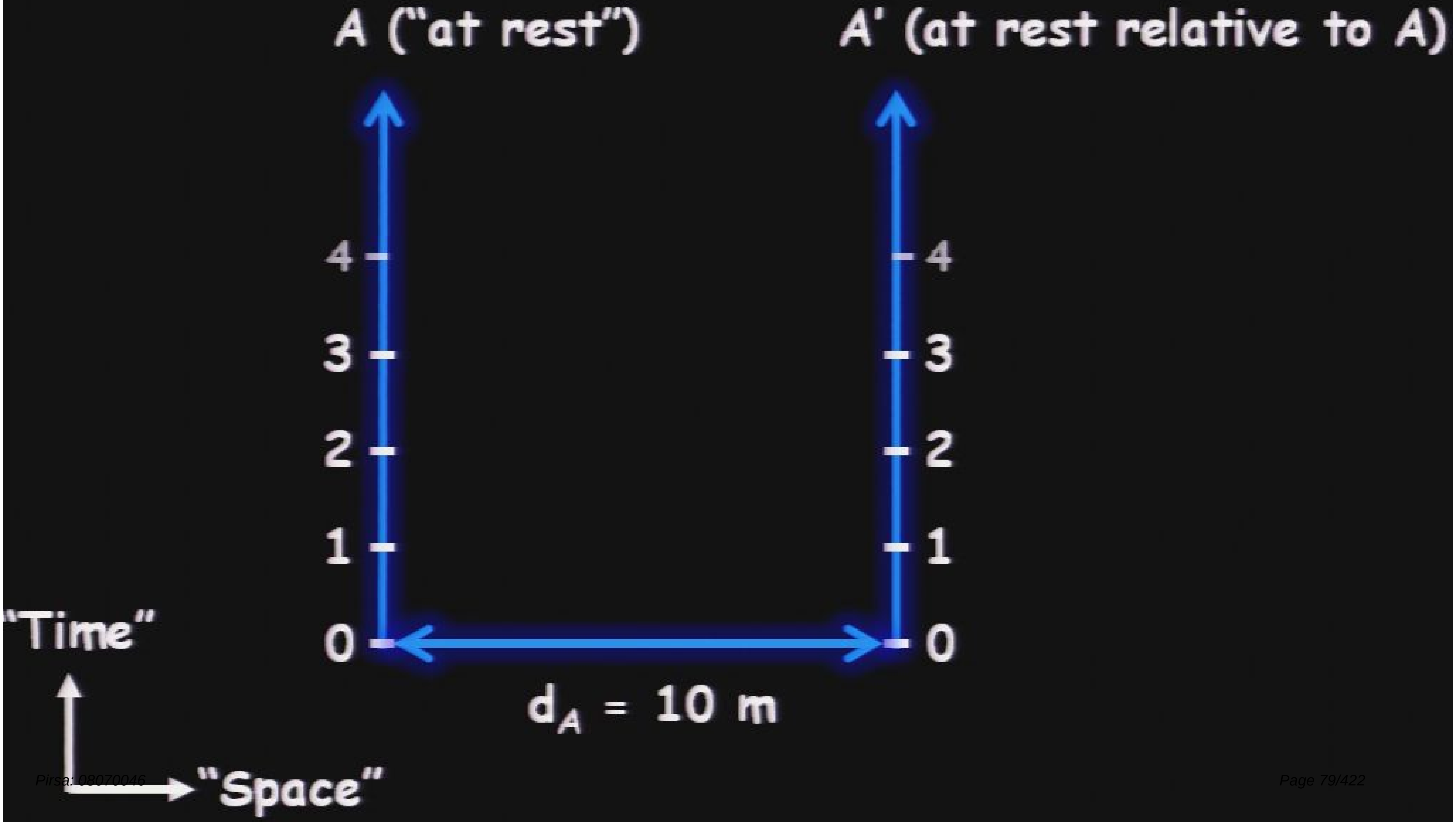
Draw a "Spacetime Diagram"



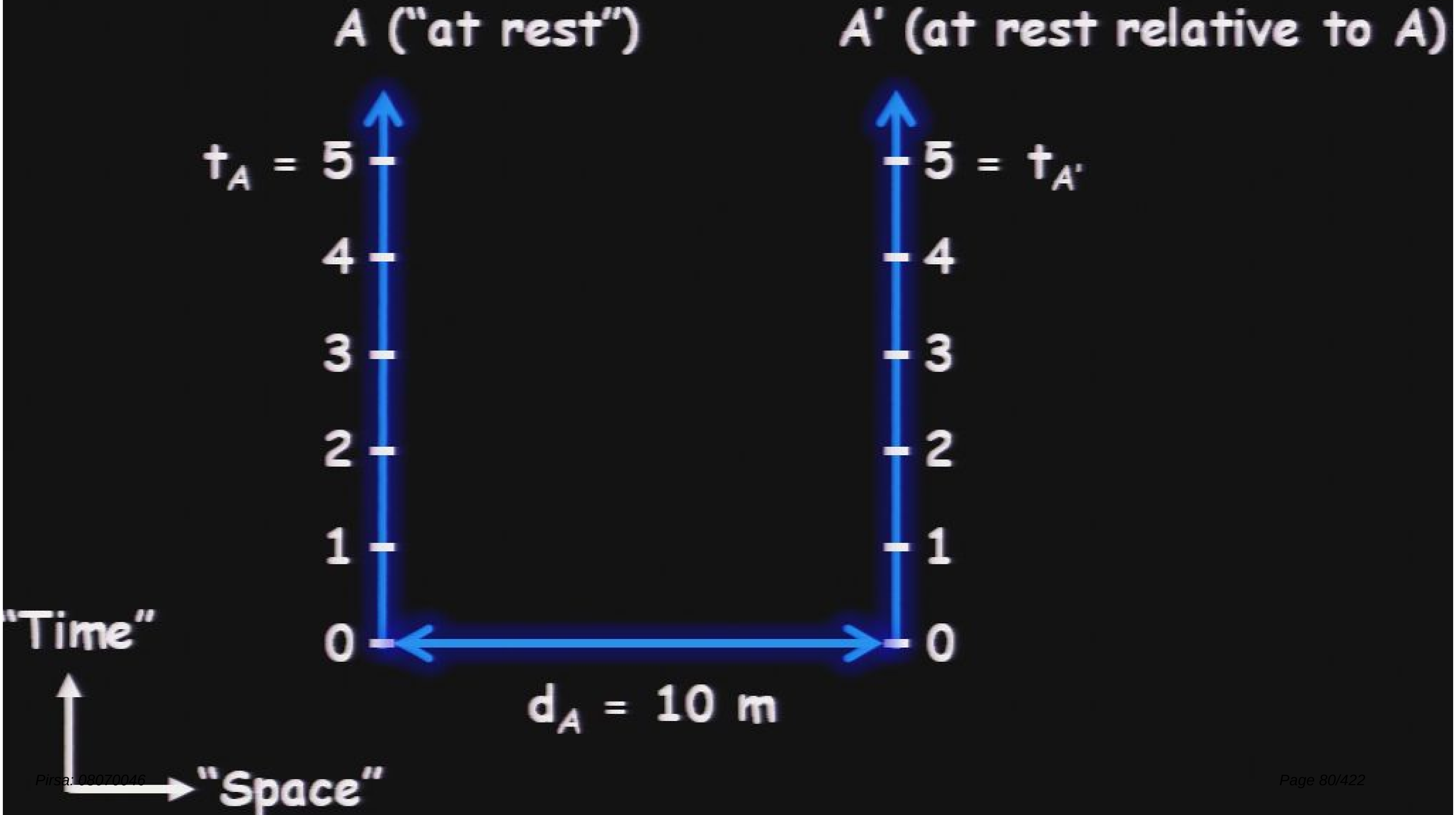
Draw a “Spacetime Diagram”

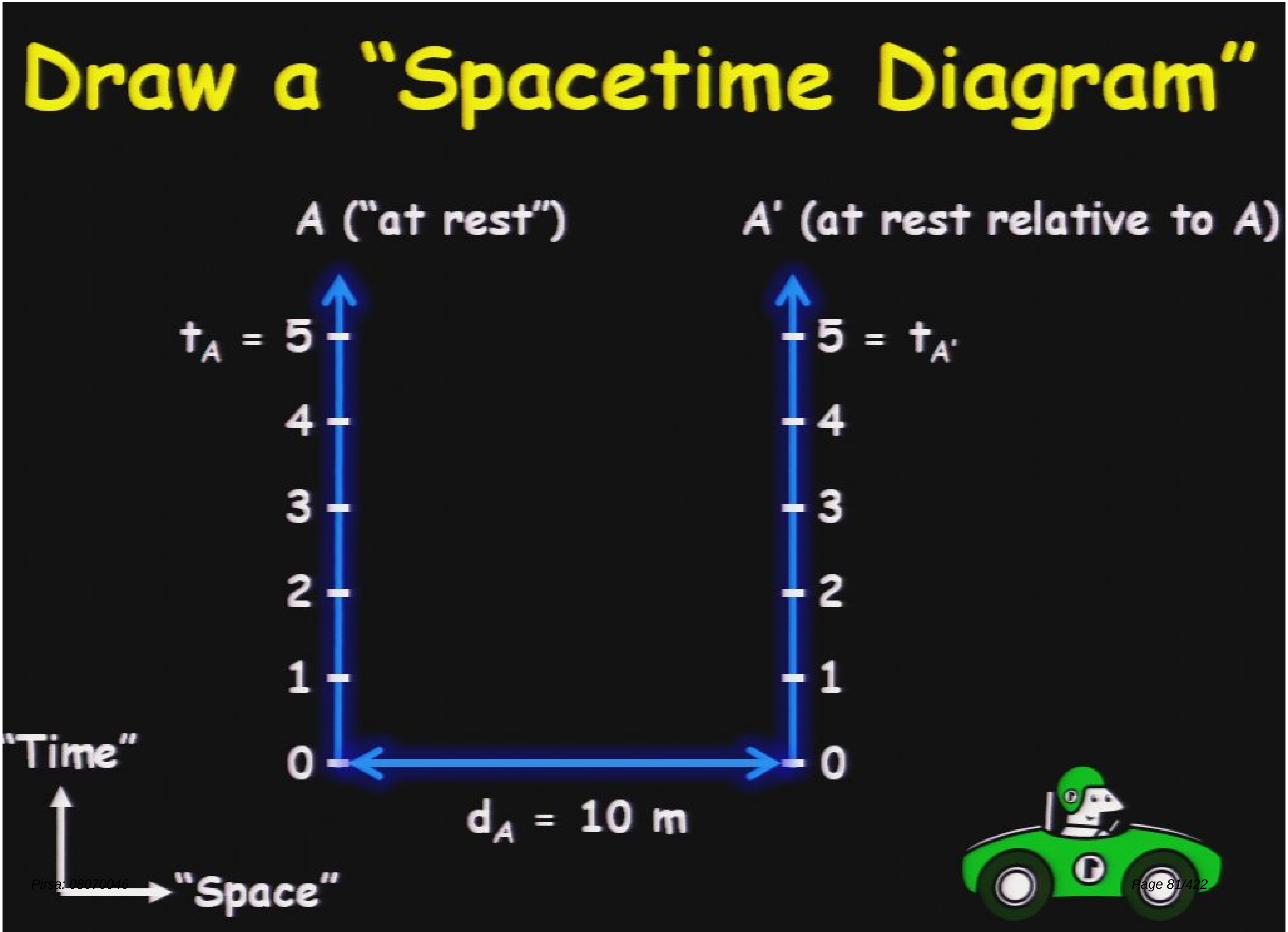


Draw a "Spacetime Diagram"



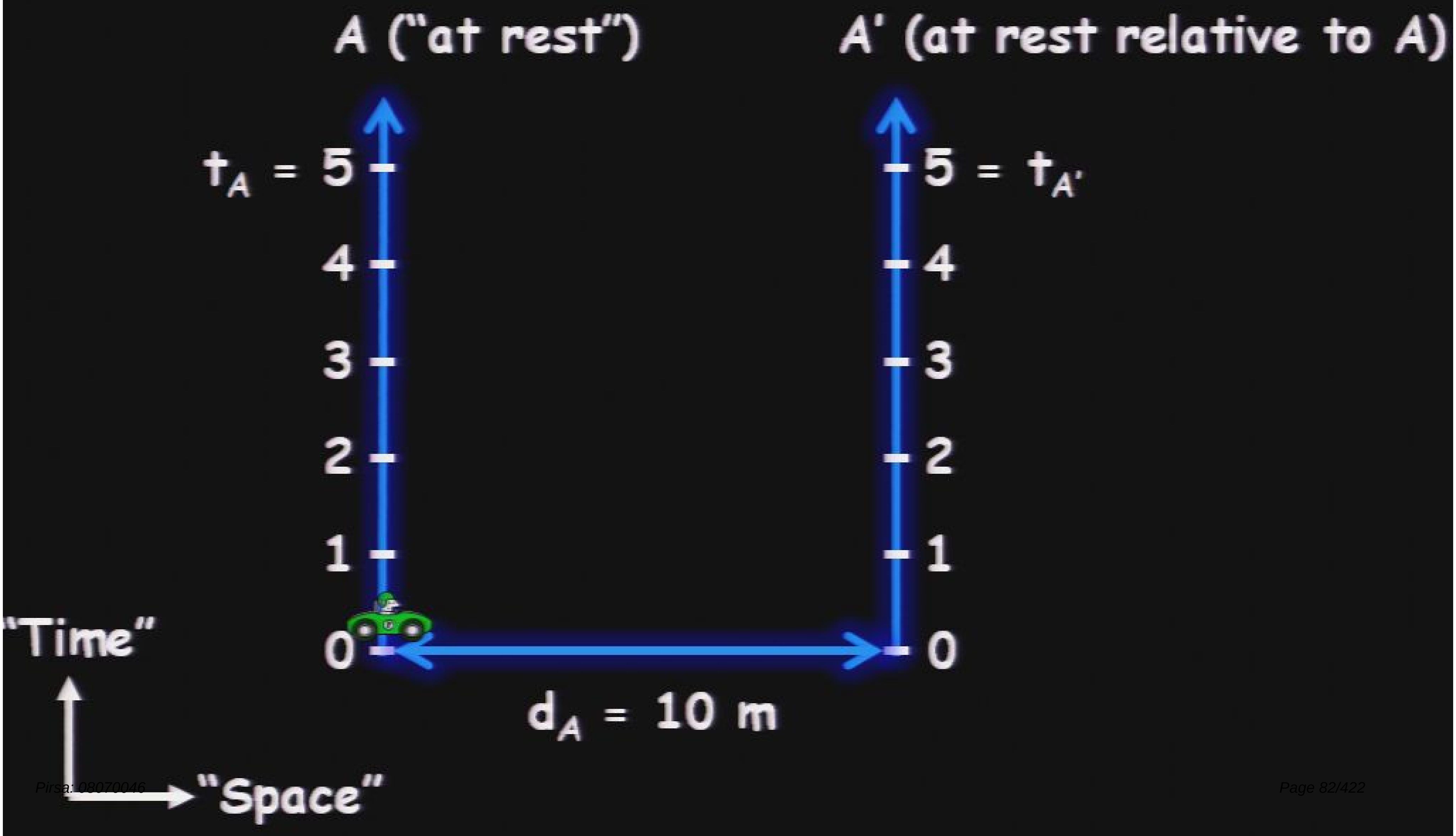
Draw a "Spacetime Diagram"



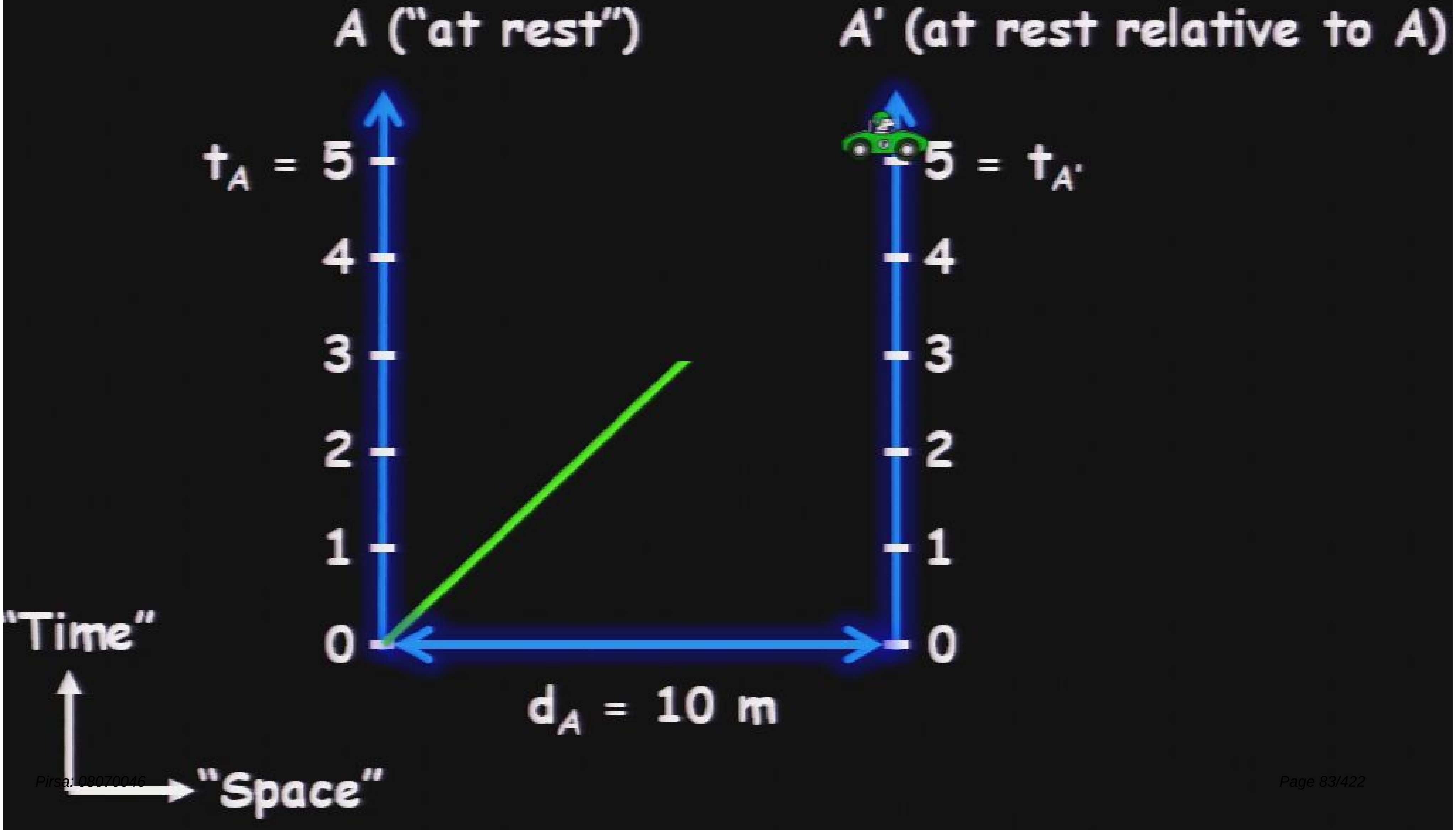


Draw a "Spacetime Diagram"
A ("at rest")
A' (at rest relative to A)
t_A = 5
4
3
2
1
0
5 = $t_{A'}$
4
3
2
1
0
d_A = 10 m
"Time"
"Space"

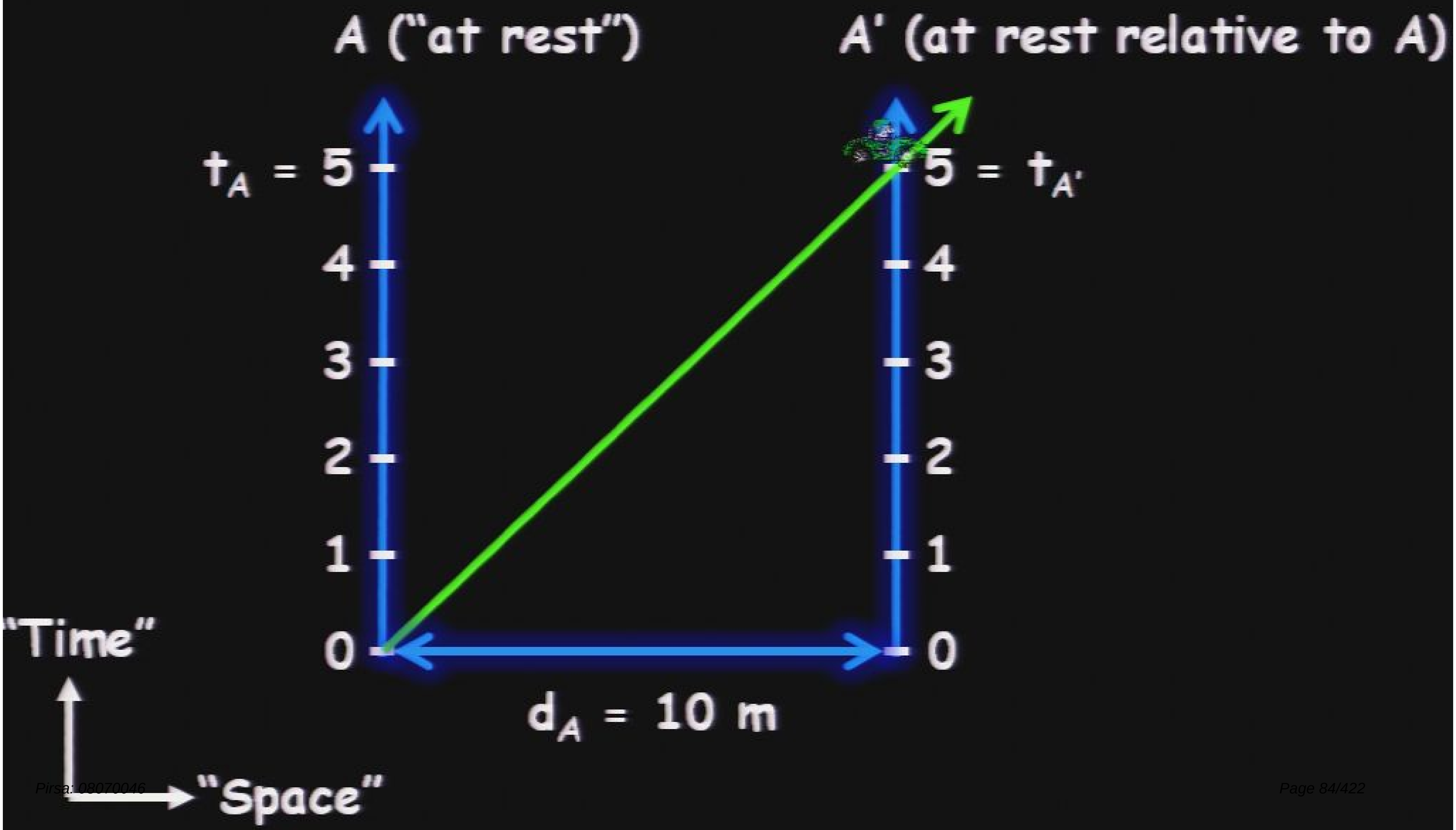
Draw a "Spacetime Diagram"



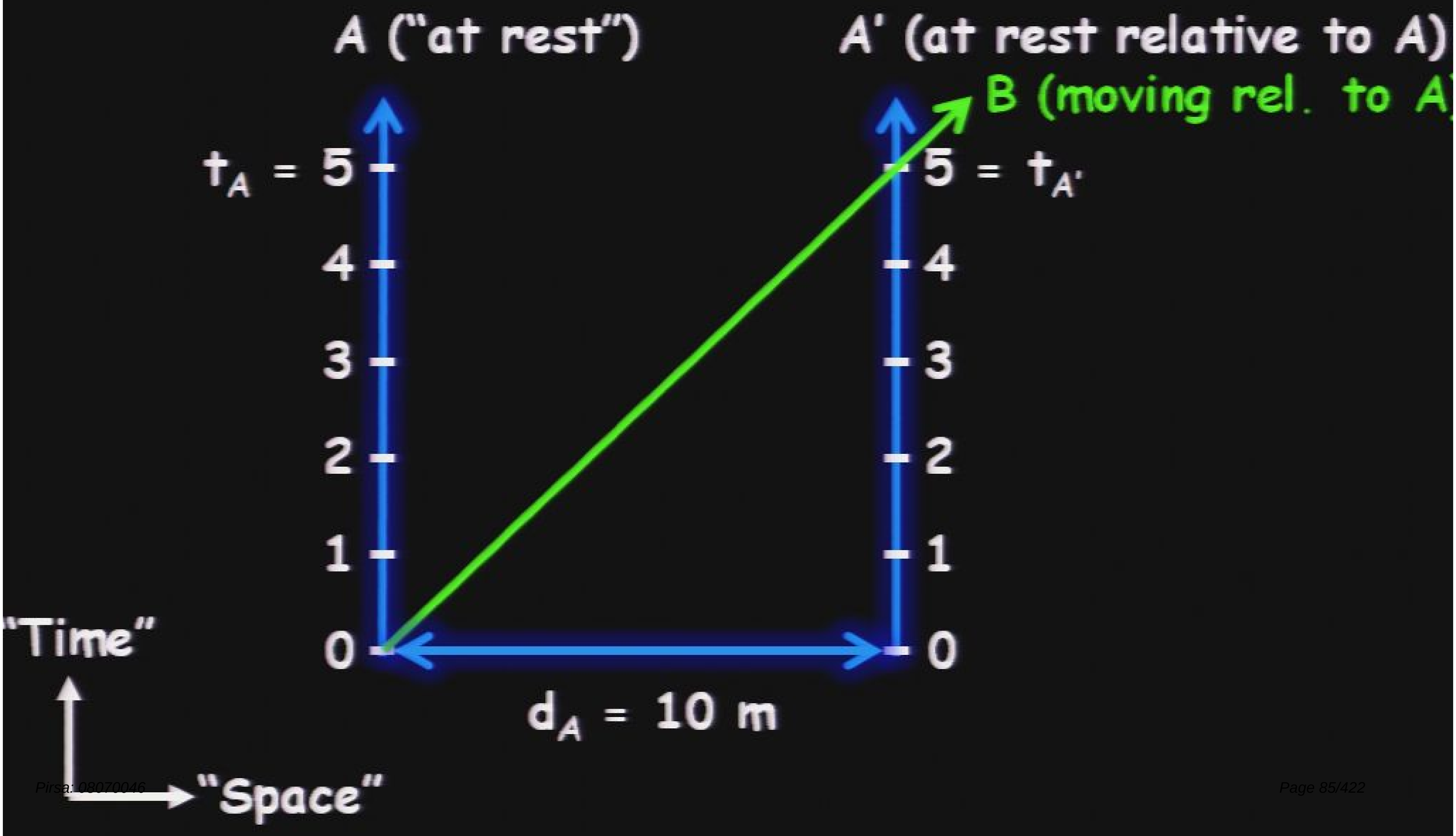
Draw a "Spacetime Diagram"



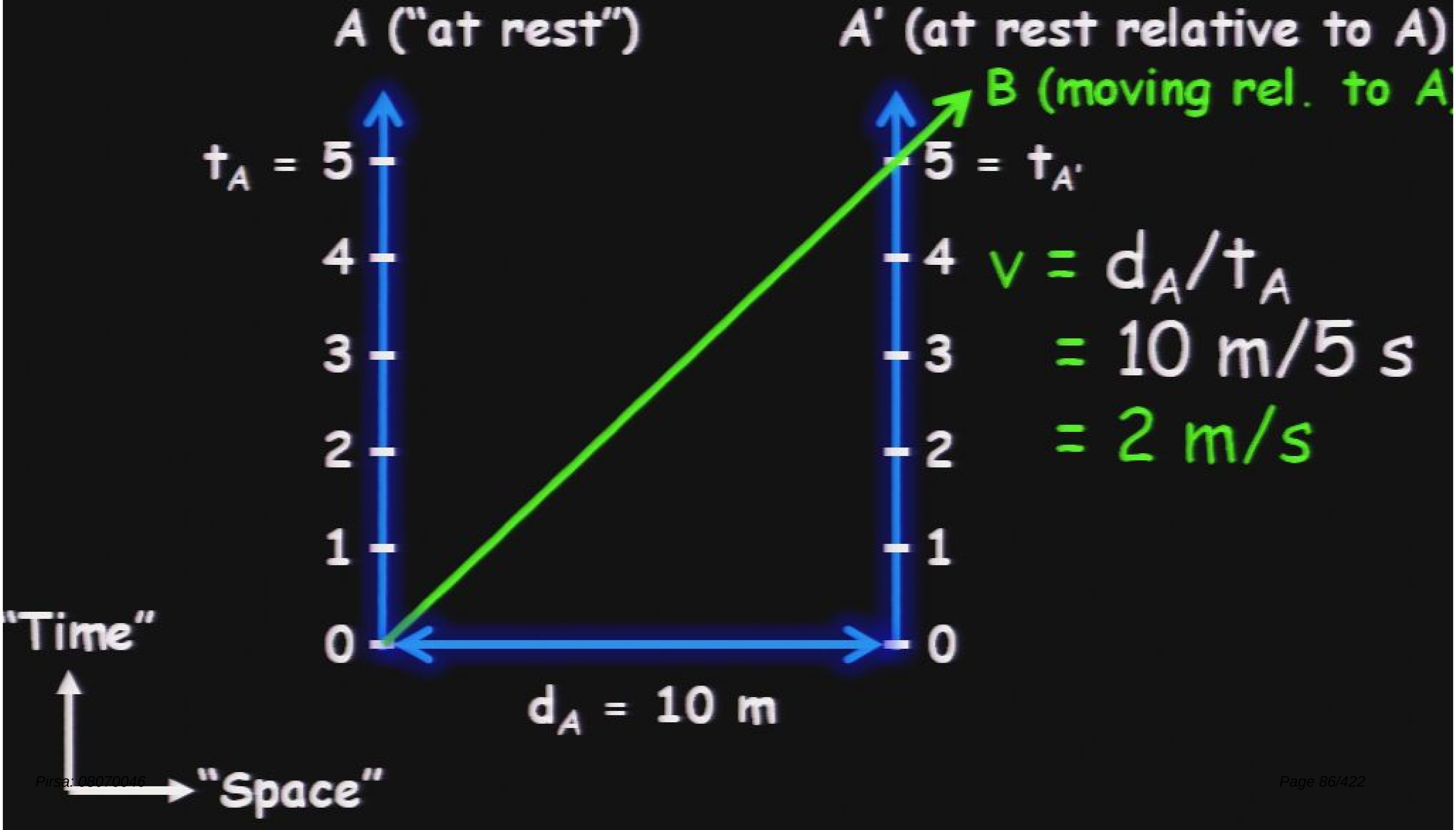
Draw a "Spacetime Diagram"



Draw a "Spacetime Diagram"



Draw a "Spacetime Diagram"



$$v = d_A/t_A$$
$$= 10\ m/5\ s$$
$$= 2\ m/s$$

Let's Have Spacetime Fun!

Sketch spacetime diagrams for each:

1: Bob at rest relative to Alice

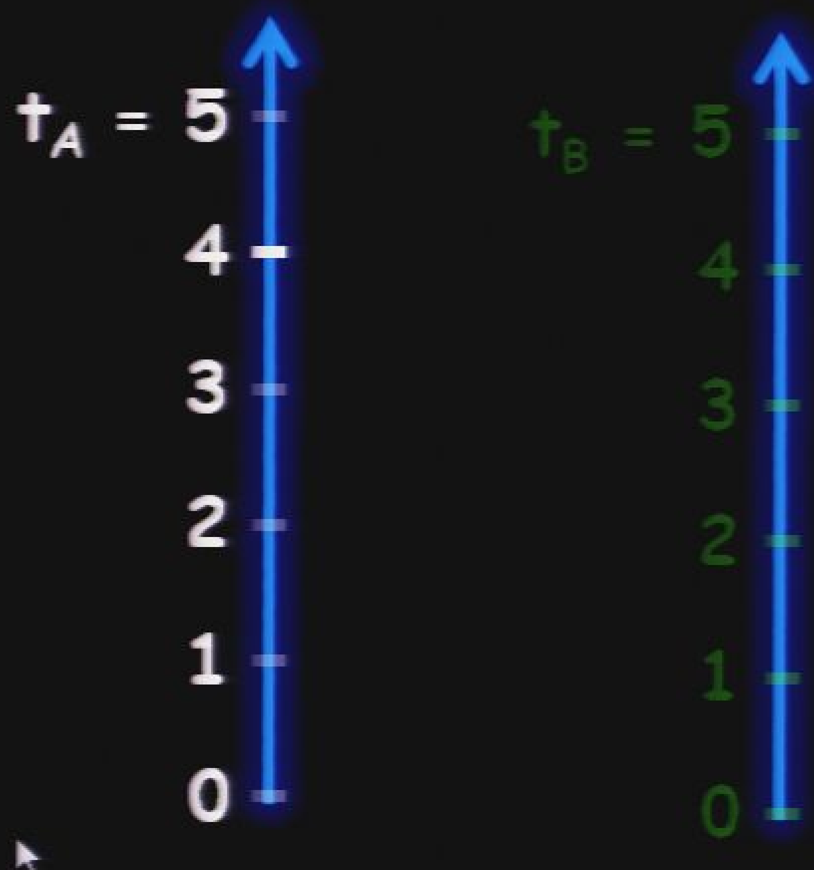
2: Alice tossing a baseball up

3: Bob moving Fast

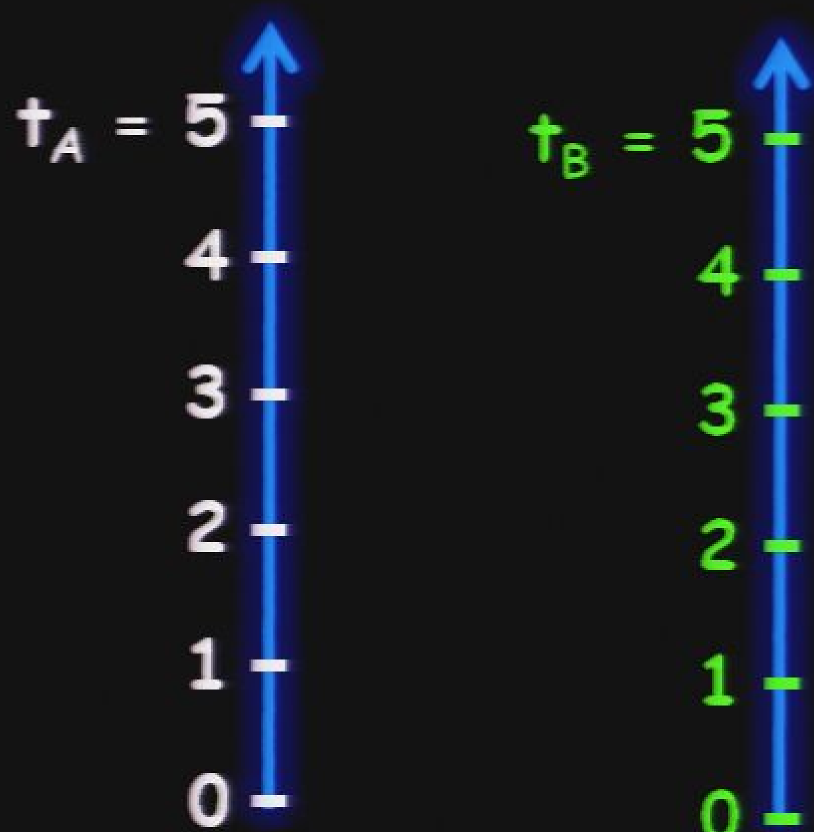
4: Bob moving Slow

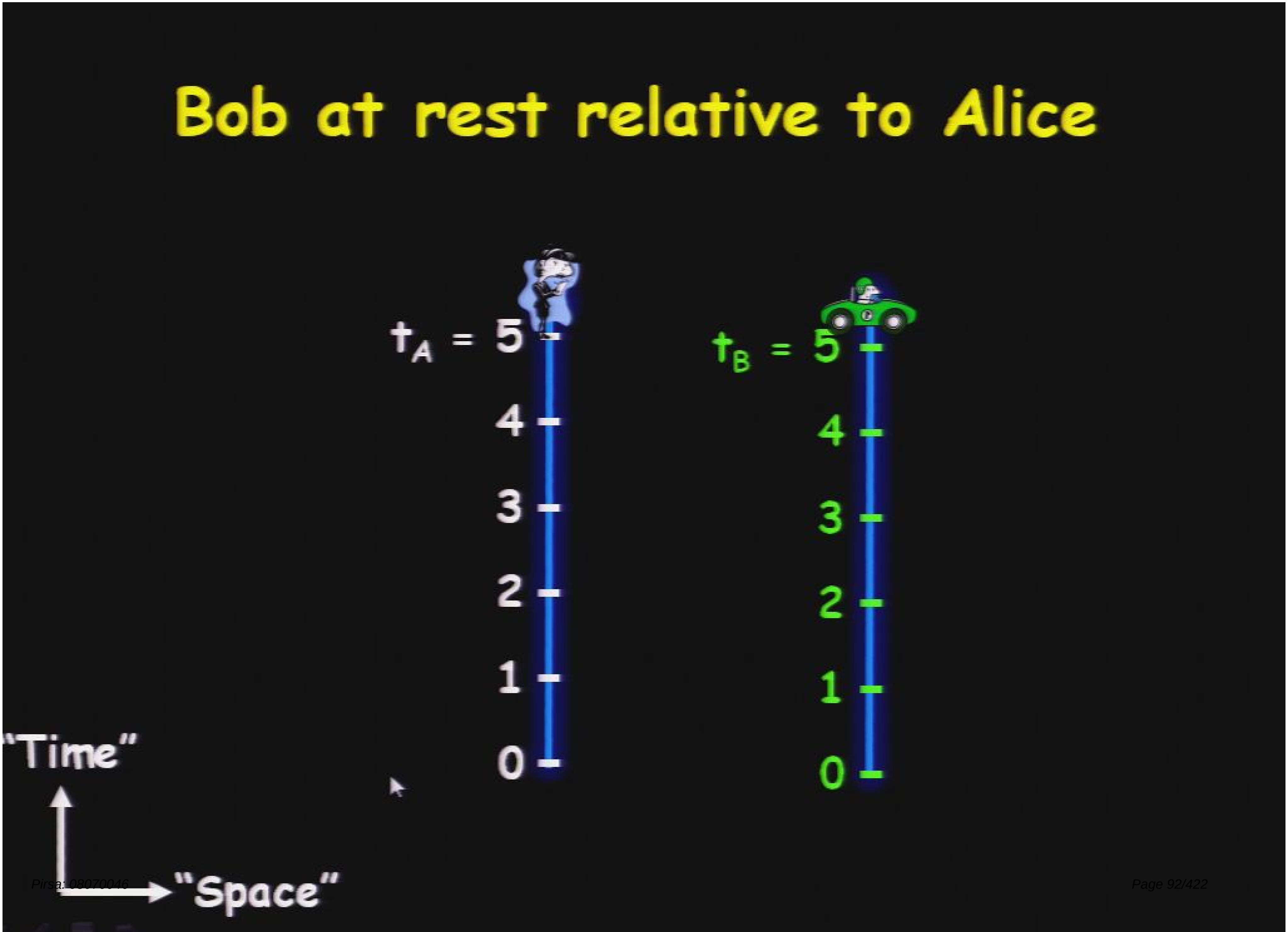
5: The Earth orbiting about the Sun

Bob at rest relative to Alice



Bob at rest relative to Alice




Bob at rest relative to Alice
t_A = 5
4
3
2
1
0
t_B = 5
4
3
2
1
0
"Time"
"Space"

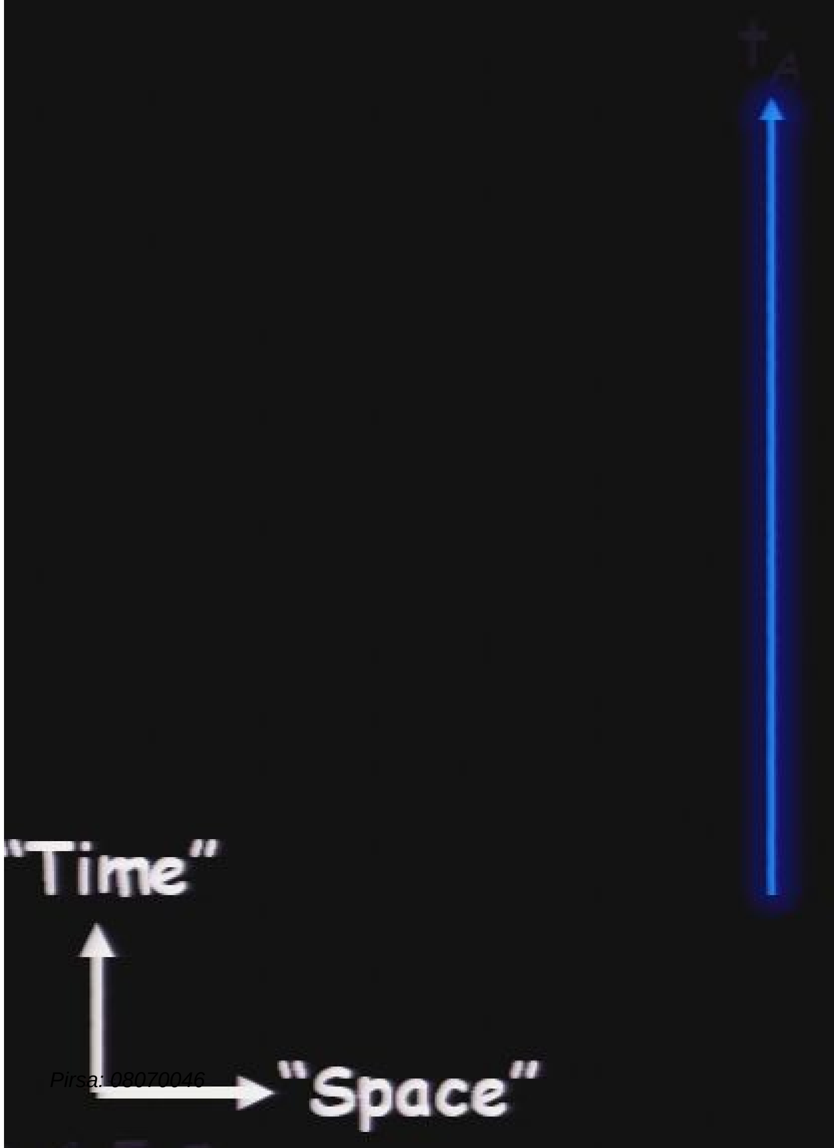
Alice Tossing a Baseball Up

Alice Tossing a Baseball Up

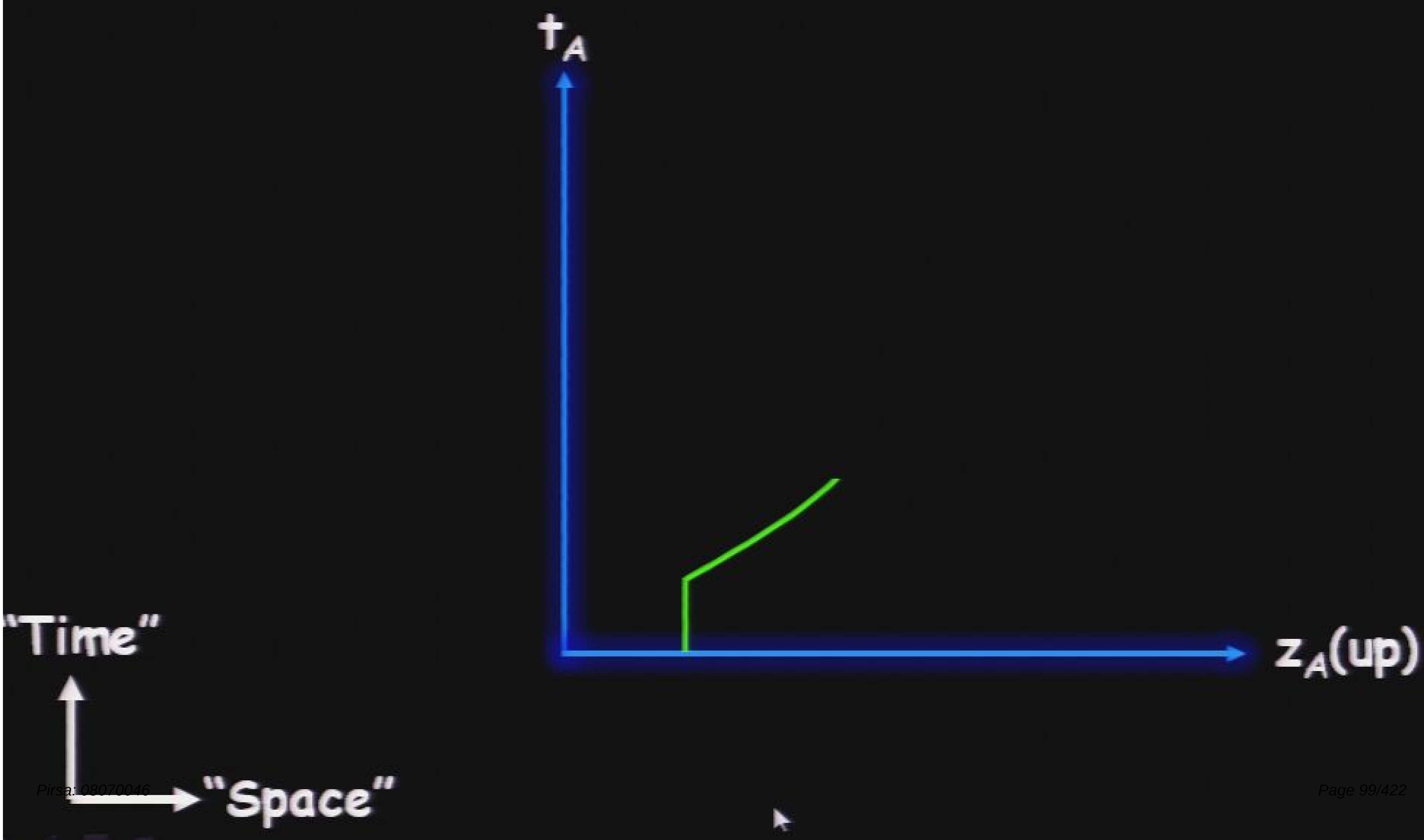
Alice Tossing a Baseball Up

Alice Tossing a Baseball Up

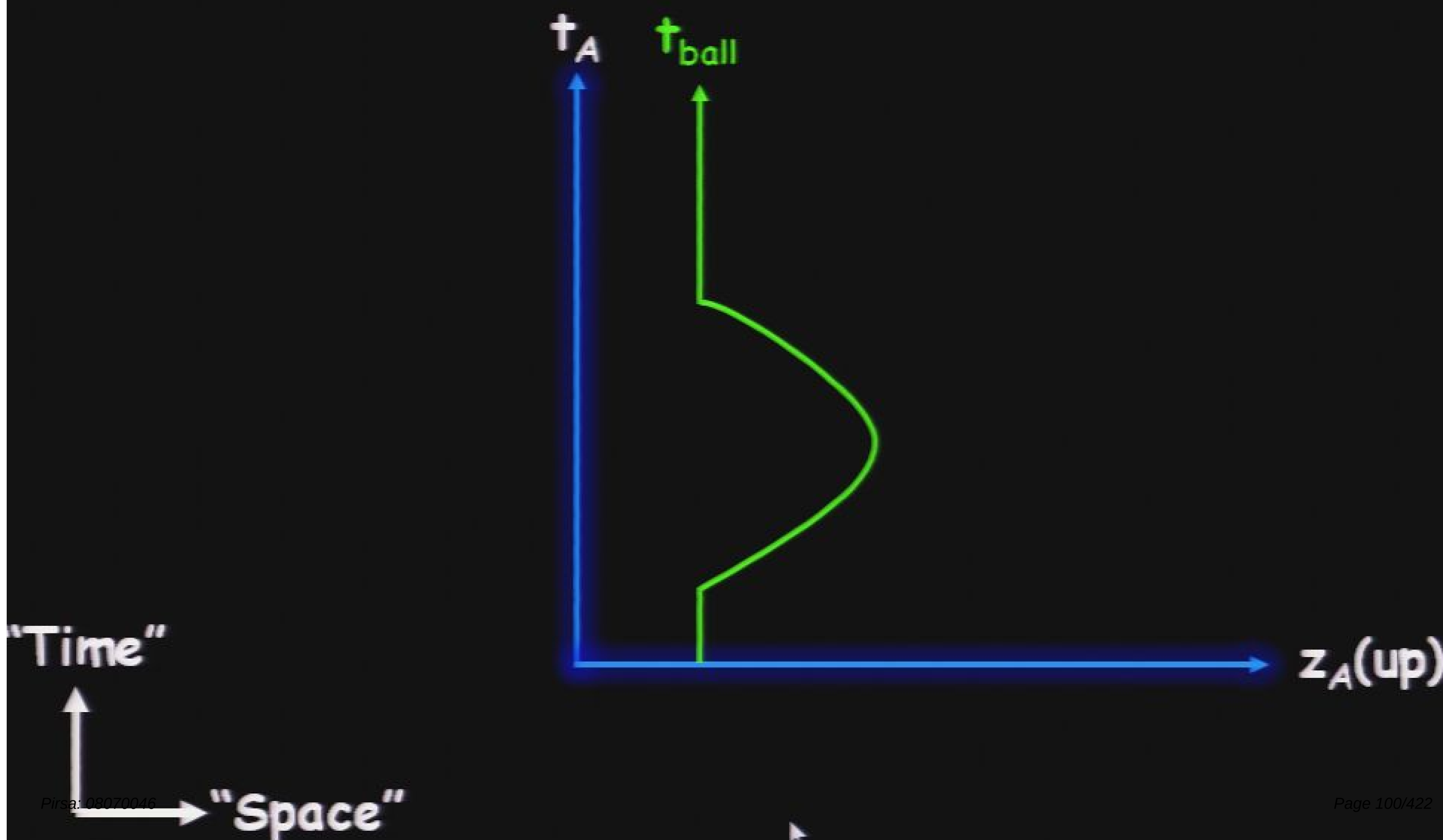
Alice Tossing a Baseball Up



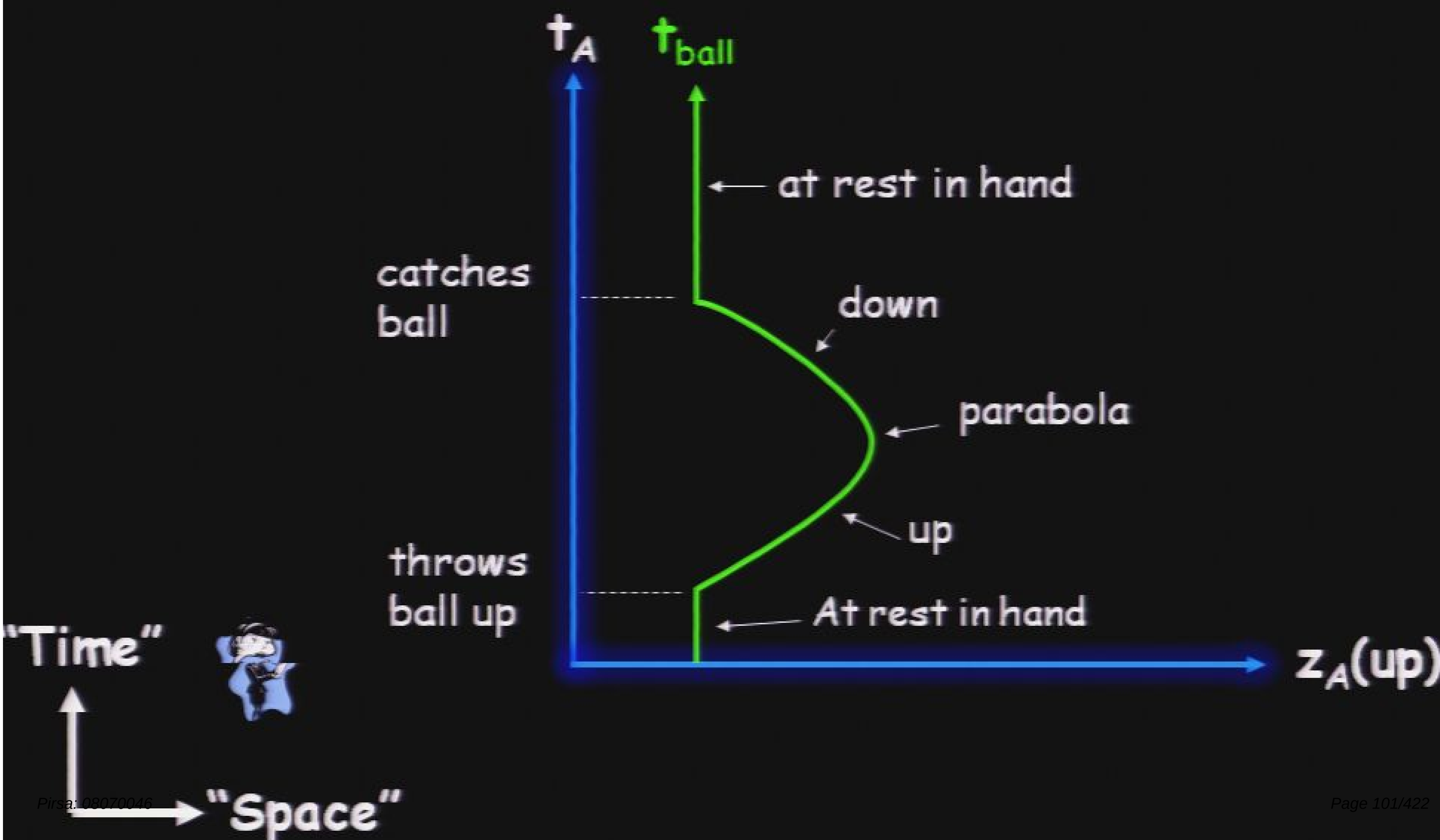
Alice Tossing a Baseball Up



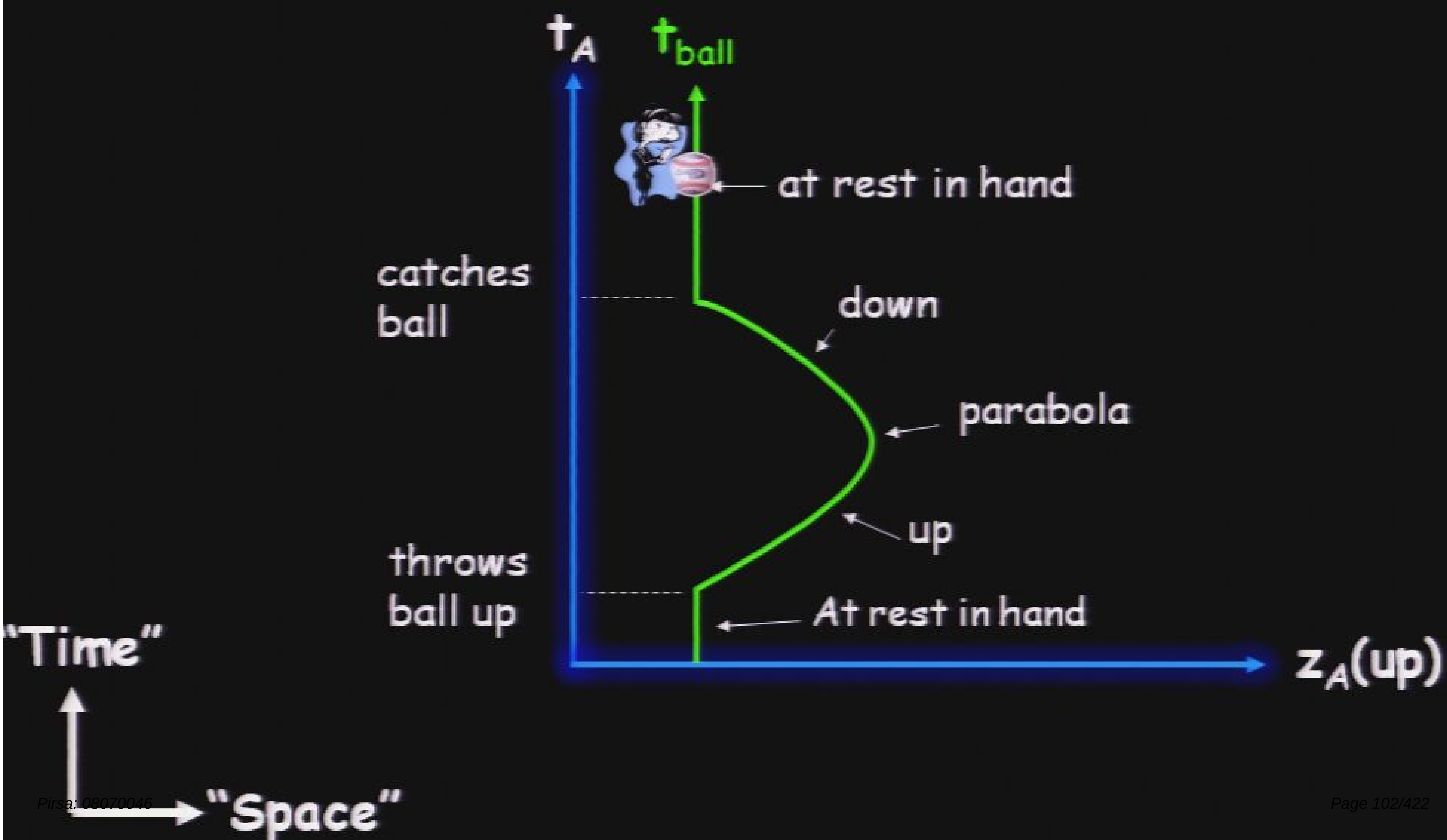
Alice Tossing a Baseball Up



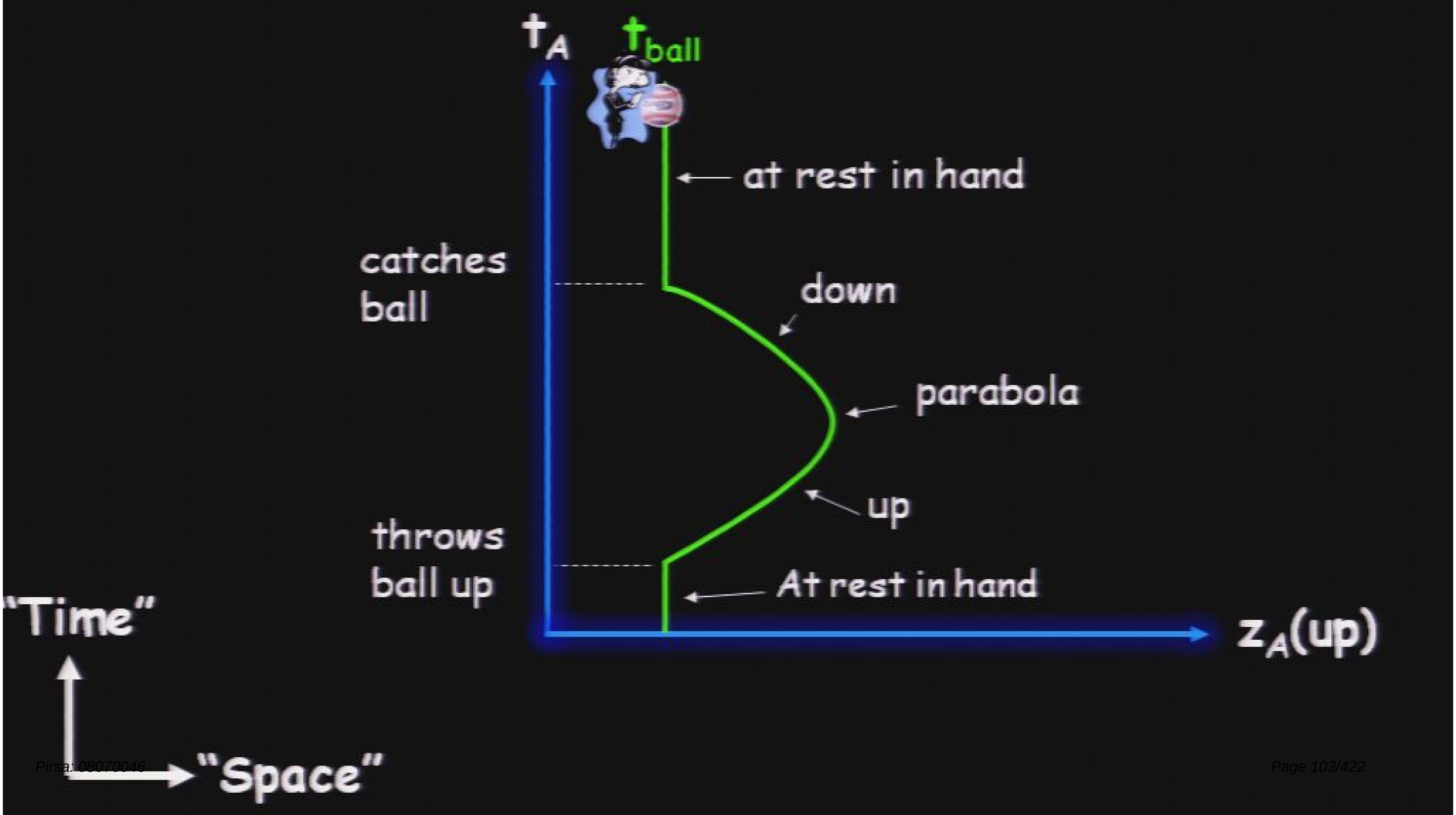
Alice Tossing a Baseball Up



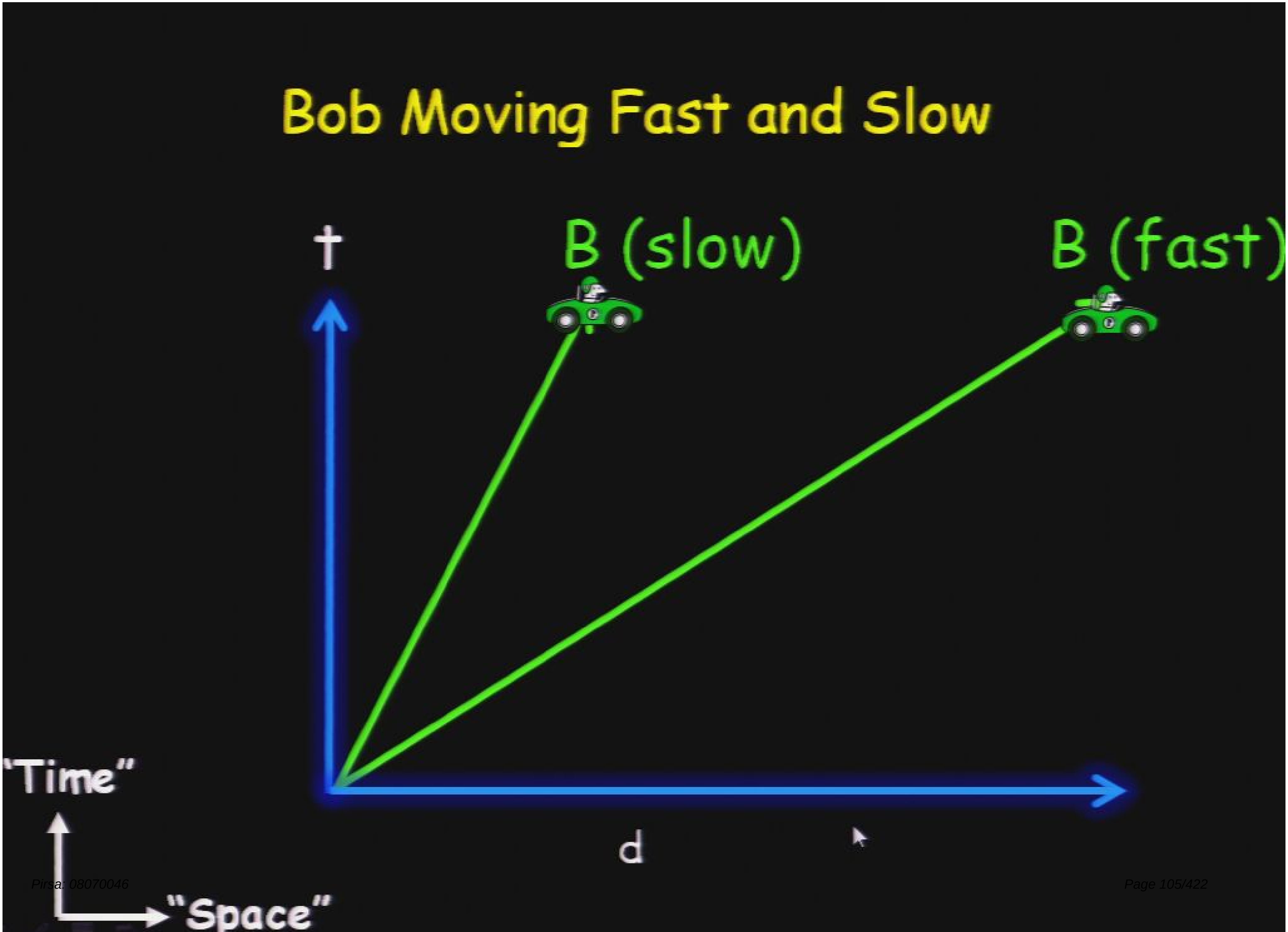
Alice Tossing a Baseball Up



Alice Tossing a Baseball Up

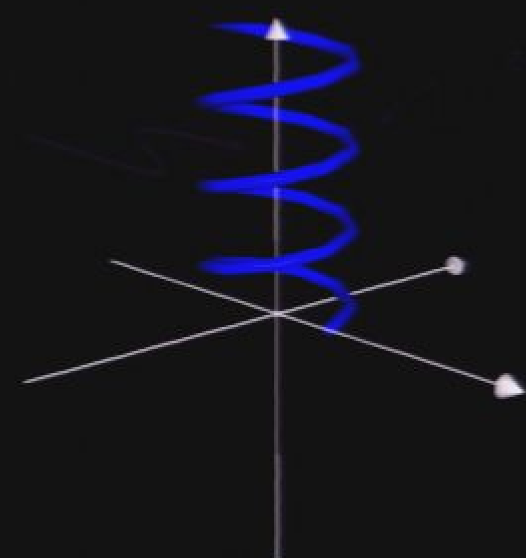


Bob Moving Fast and Slow

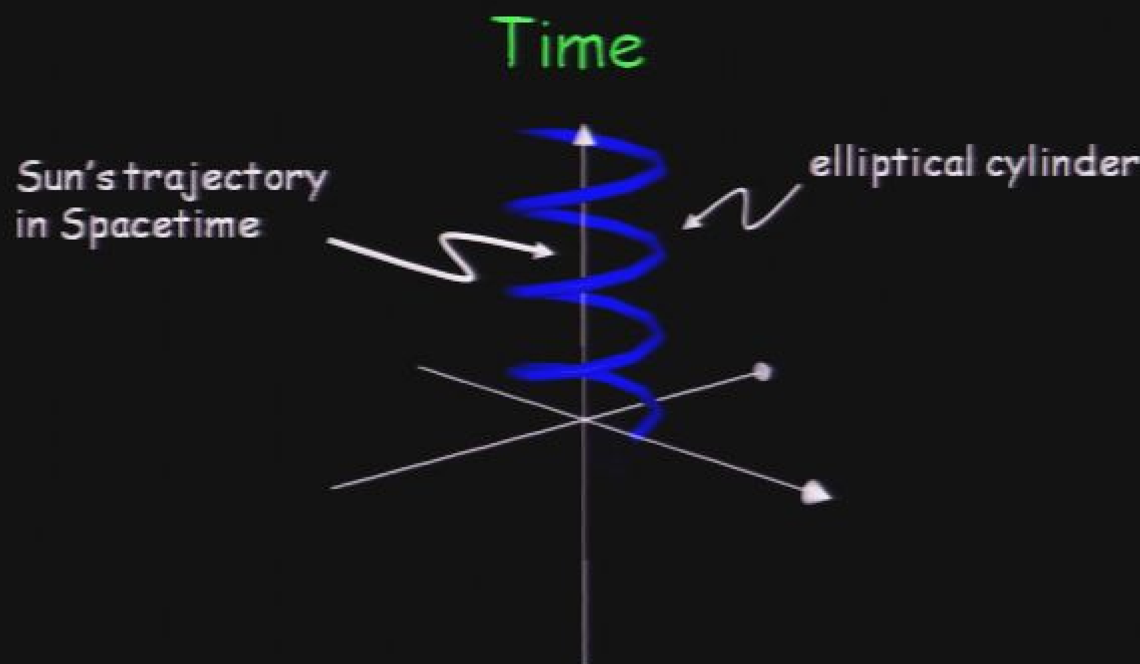

Bob Moving Fast and Slow
t
B (slow)
B (fast)
d
"Time"
"Space"

Earth Orbiting the Sun

Earth Orbiting the Sun



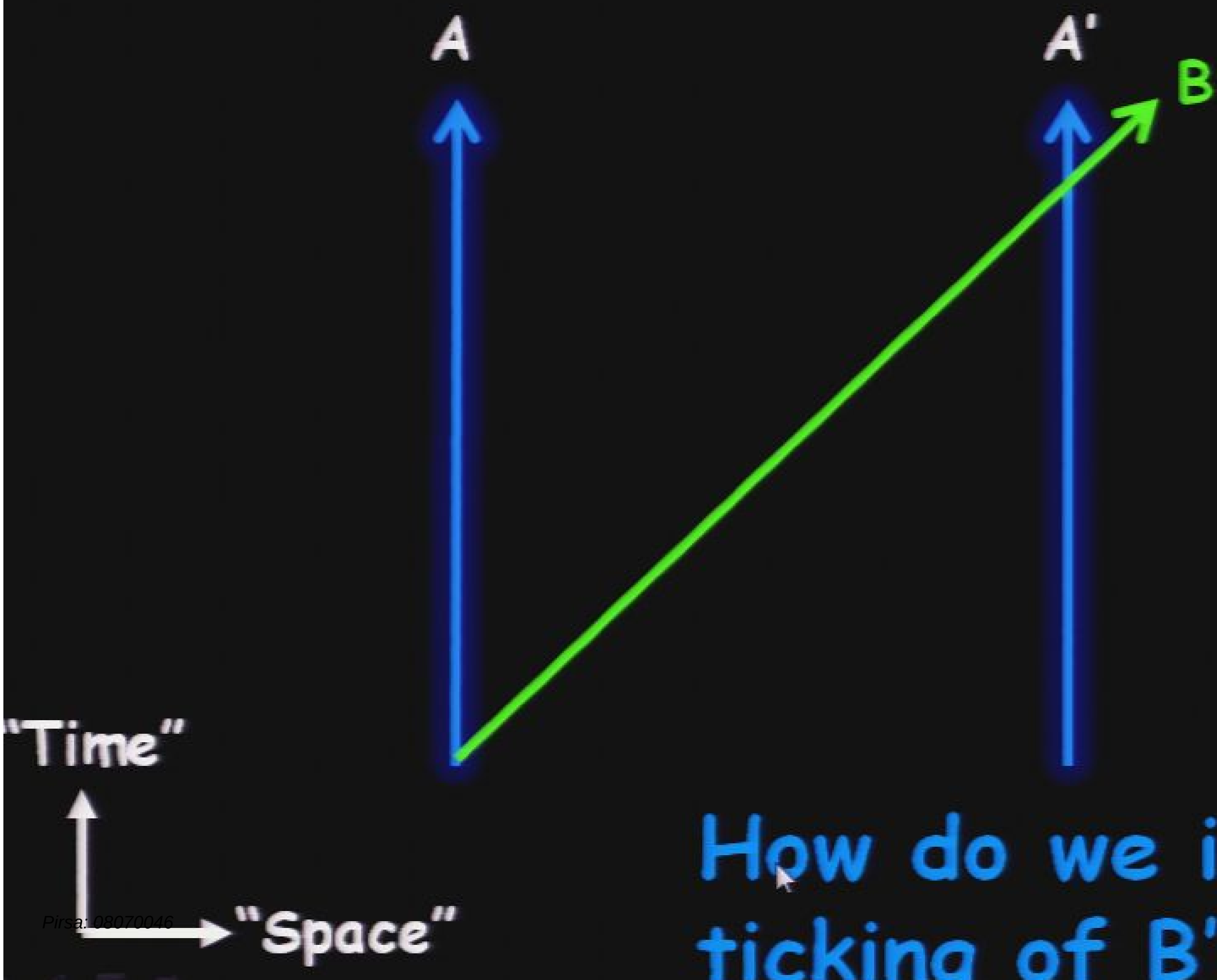
Earth Orbiting the Sun



Earth's Trajectory

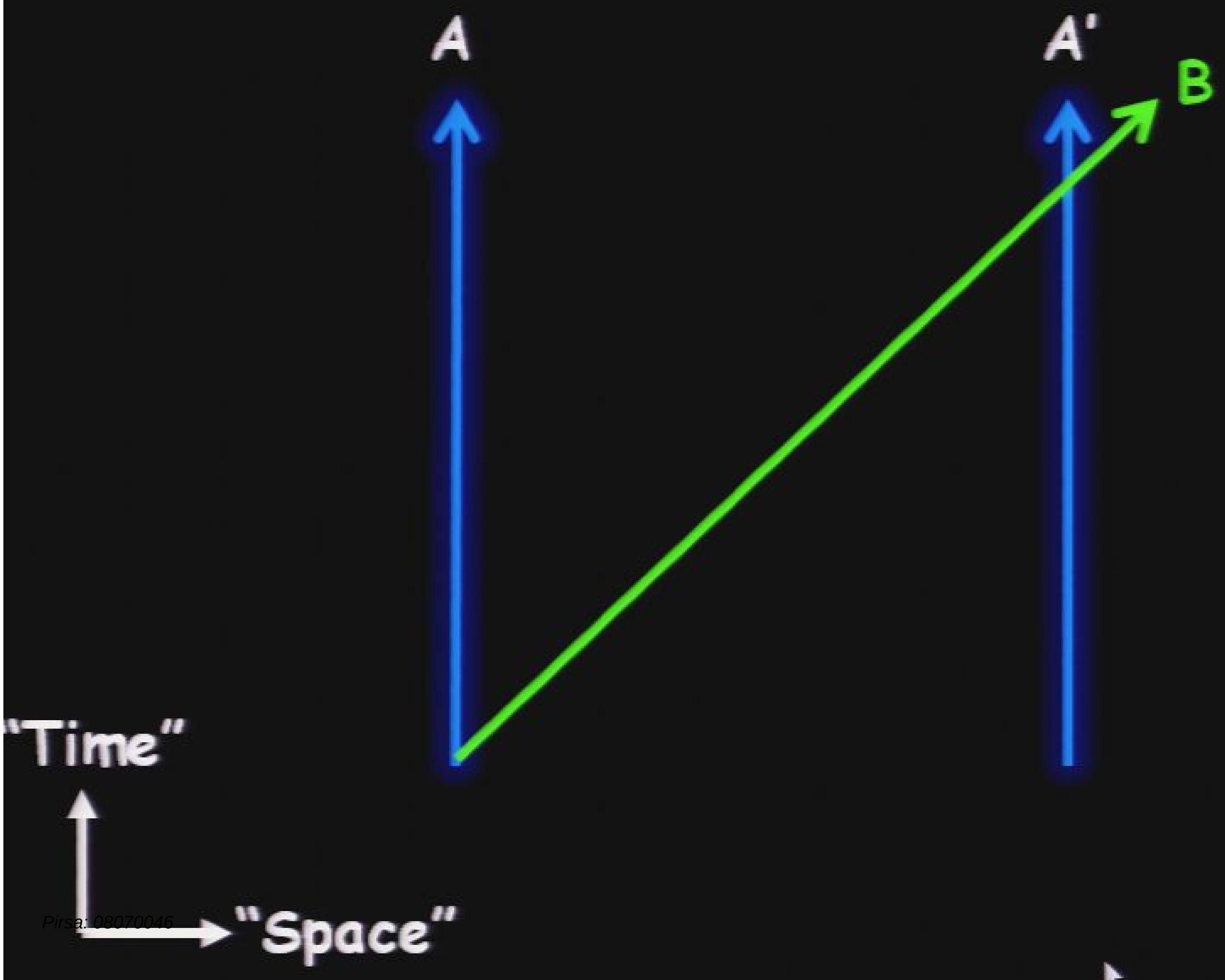
Back to Bob and Alice

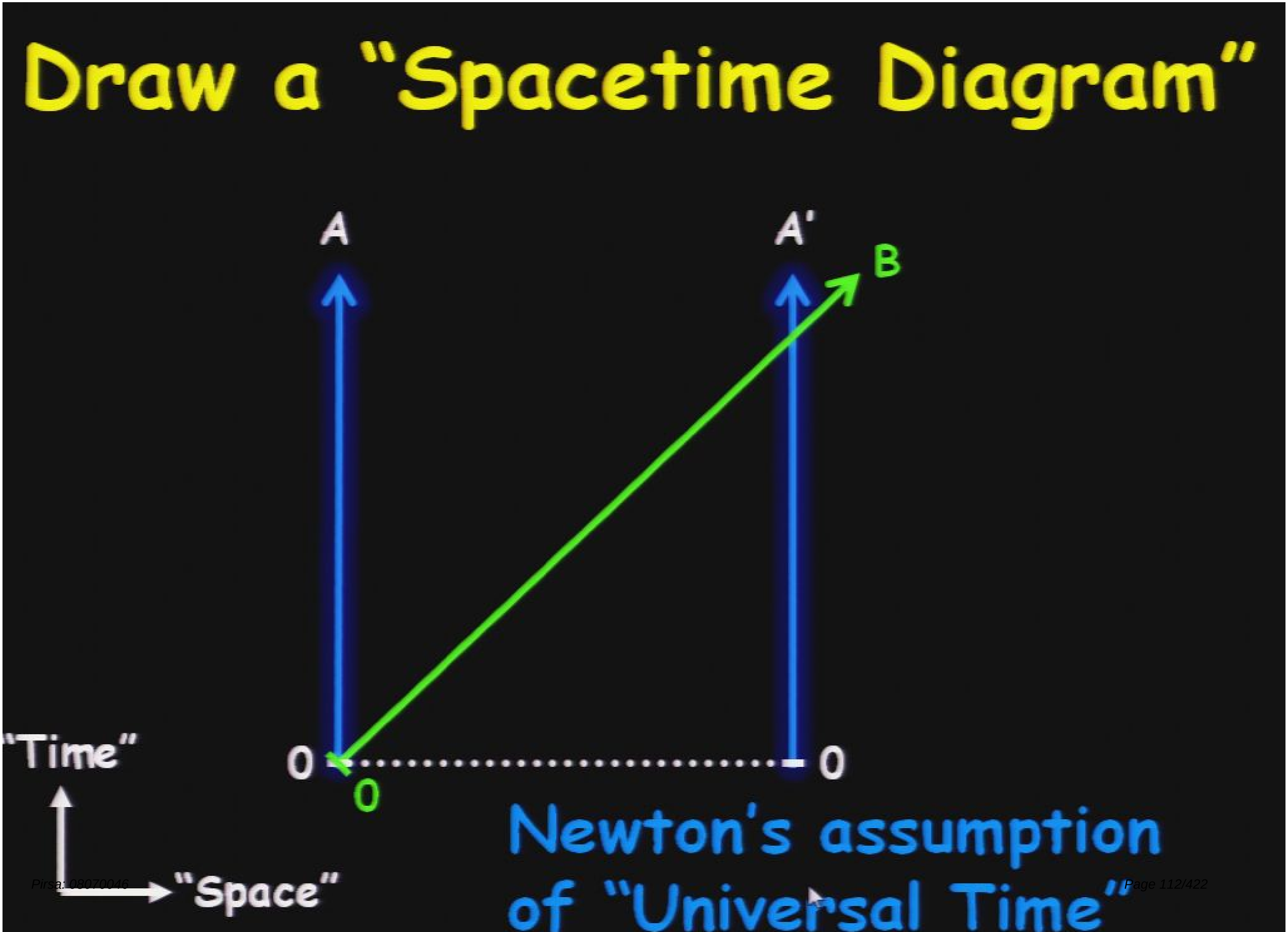
Draw a "Spacetime Diagram"



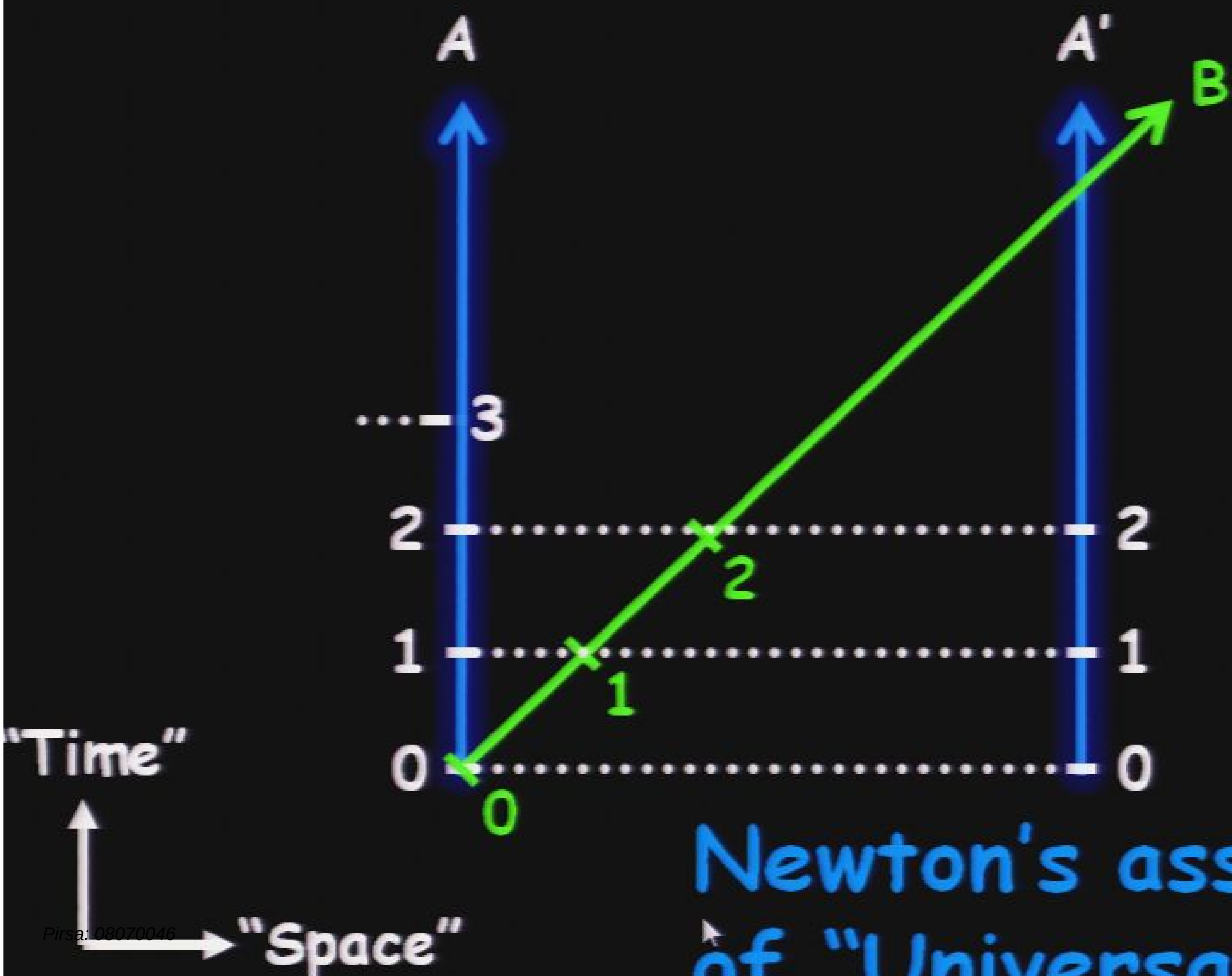
How do we indicate the ticking of B's clock?

Draw a "Spacetime Diagram"



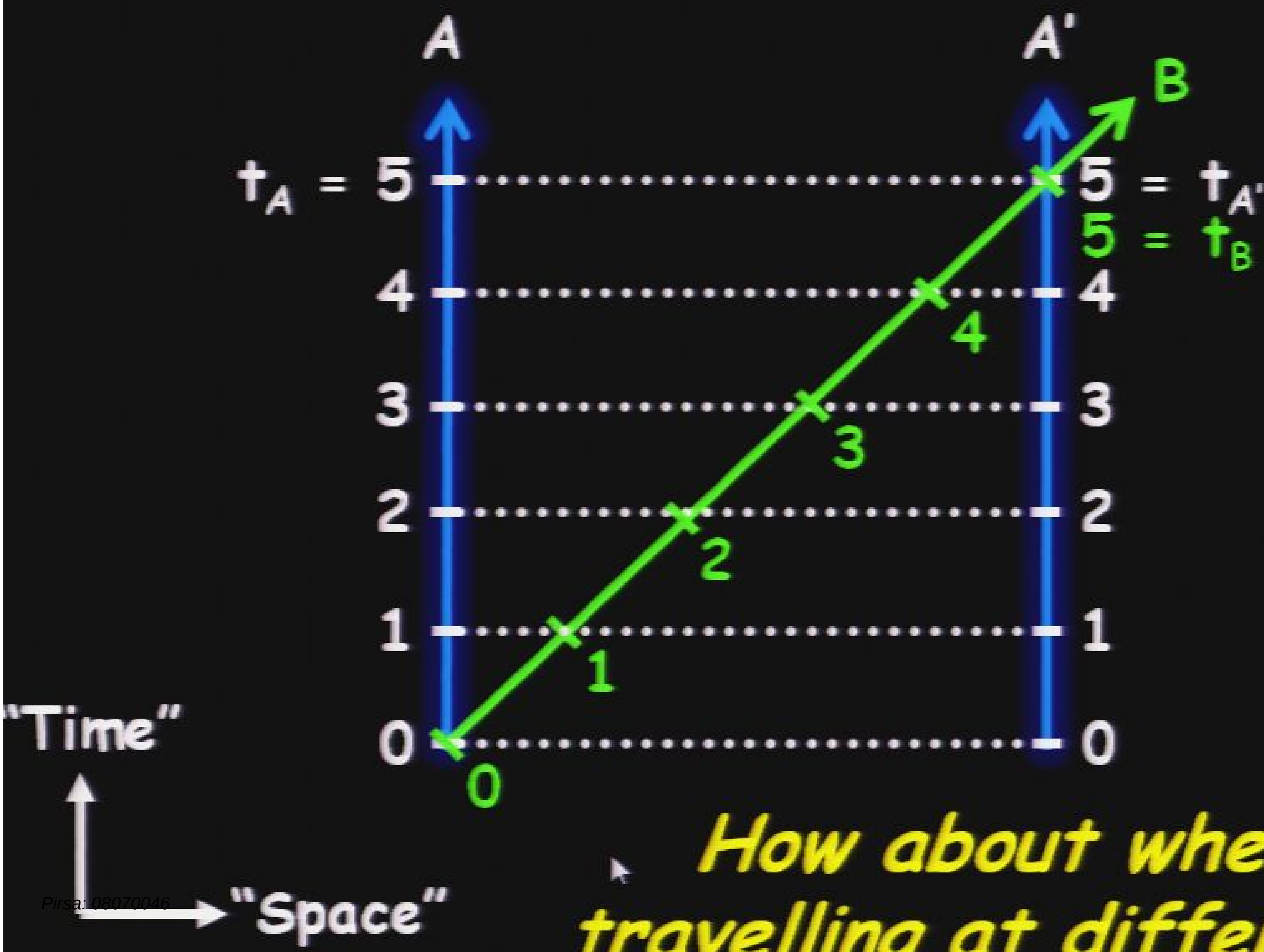

Draw a "Spacetime Diagram"
A
A'
B
"Time"
0
0
0
"Space"
Newton's assumption
of "Universal Time"

Draw a "Spacetime Diagram"

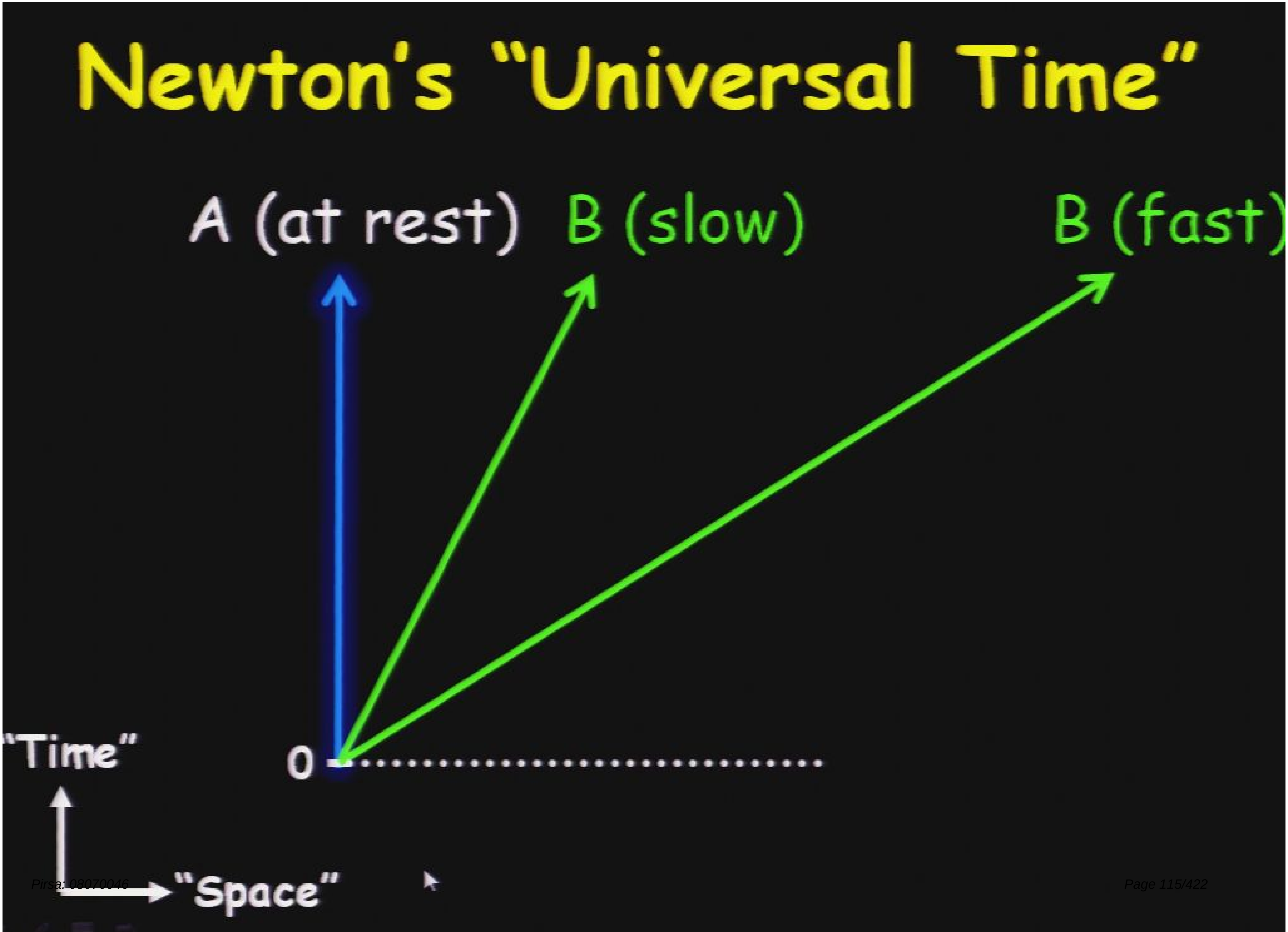


Newton's assumption
of "Universal Time"

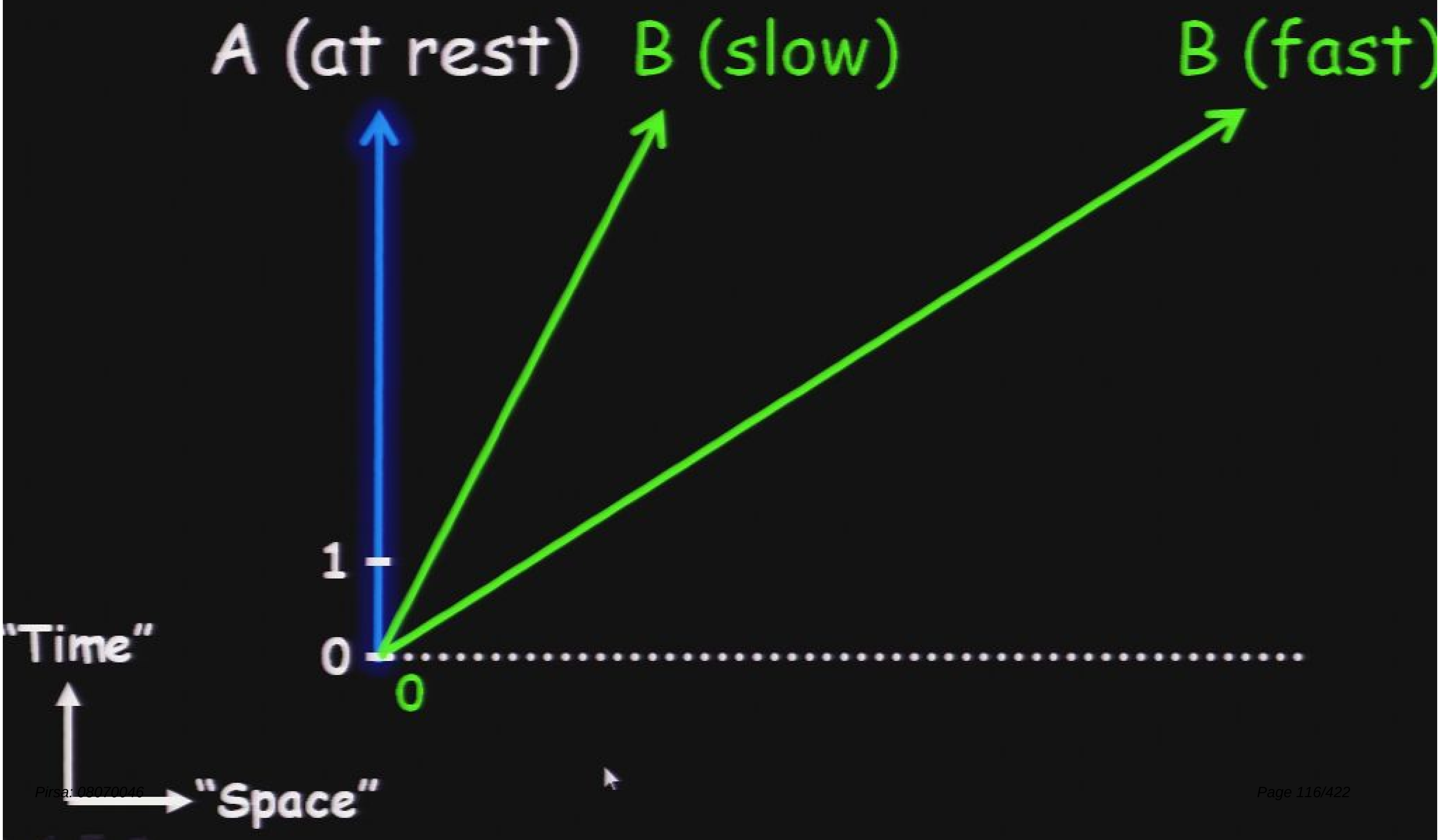
Draw a "Spacetime Diagram"



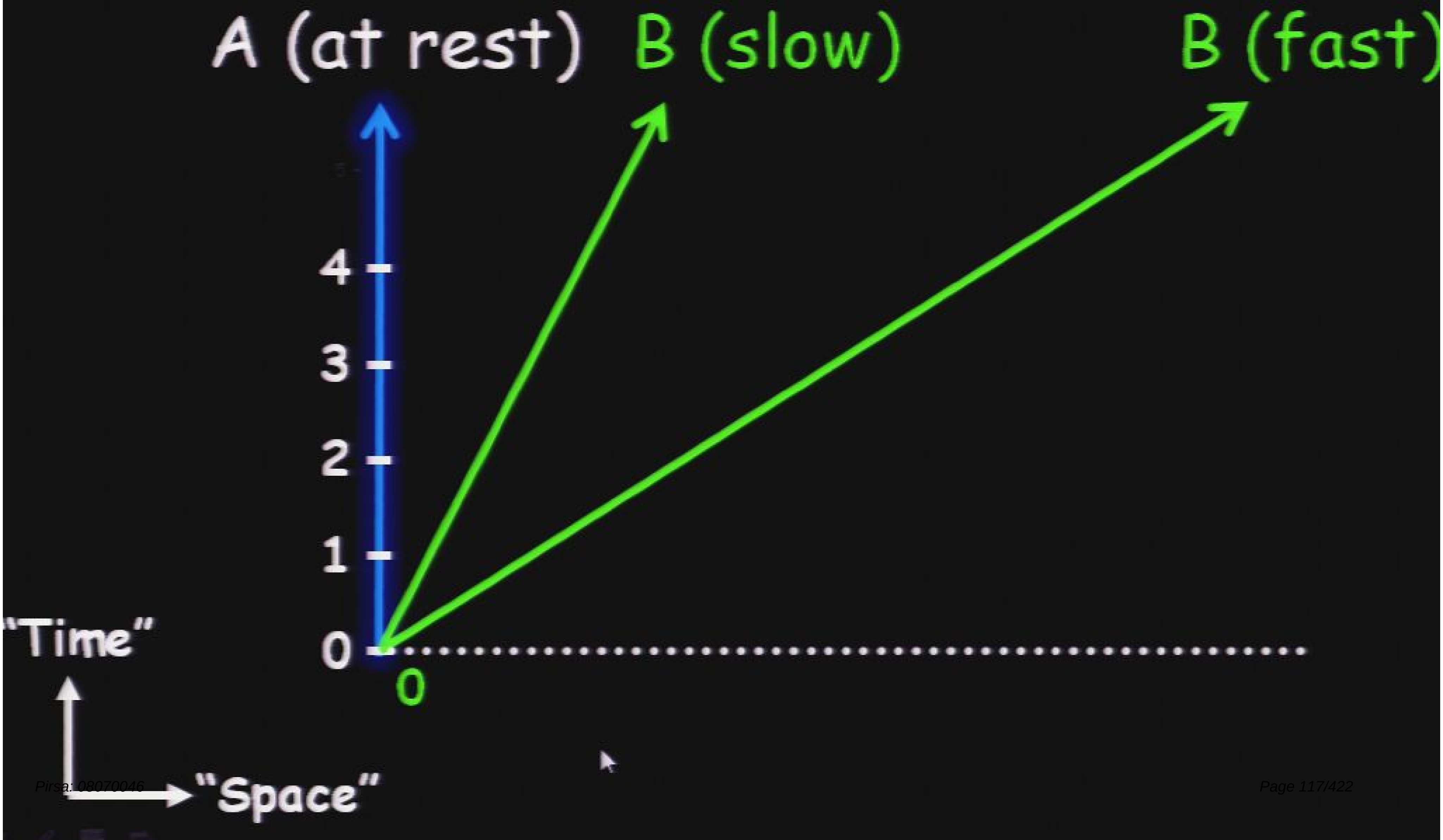
How about when Bob is travelling at different speeds


Newton's "Universal Time"
A (at rest)
B (slow)
B (fast)
"Time"
0
"Space"

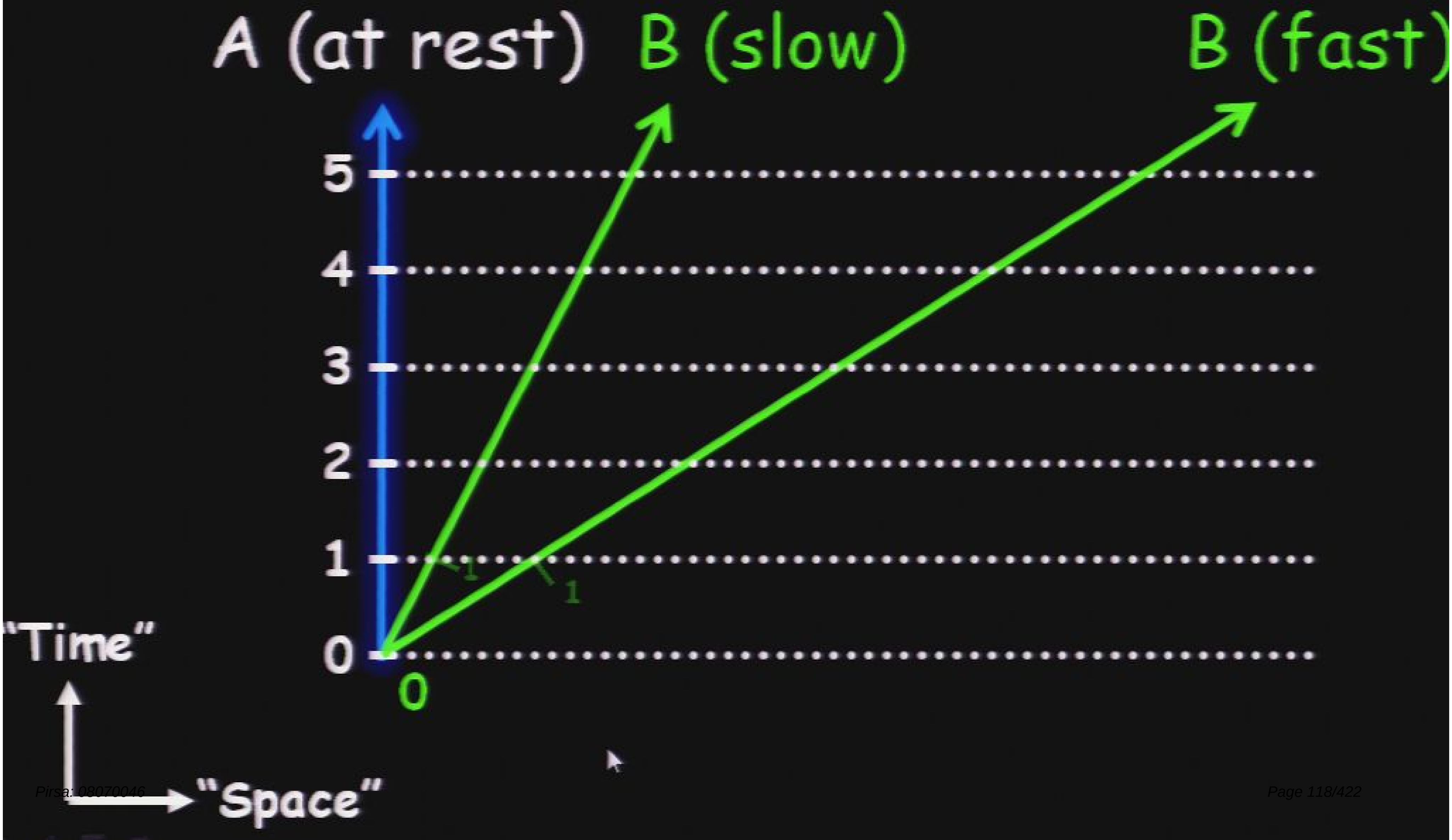
Newton's "Universal Time"

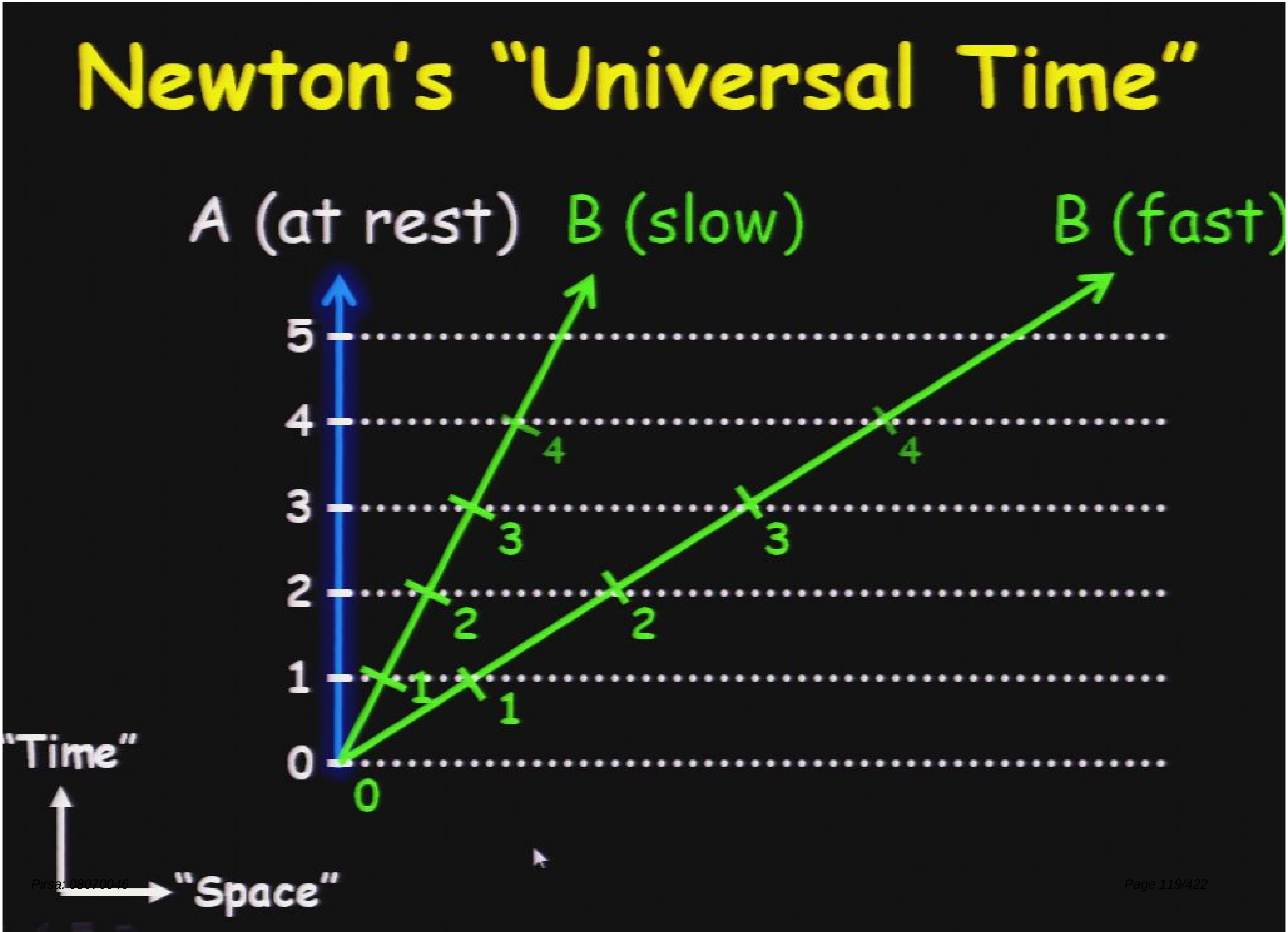


Newton's "Universal Time"

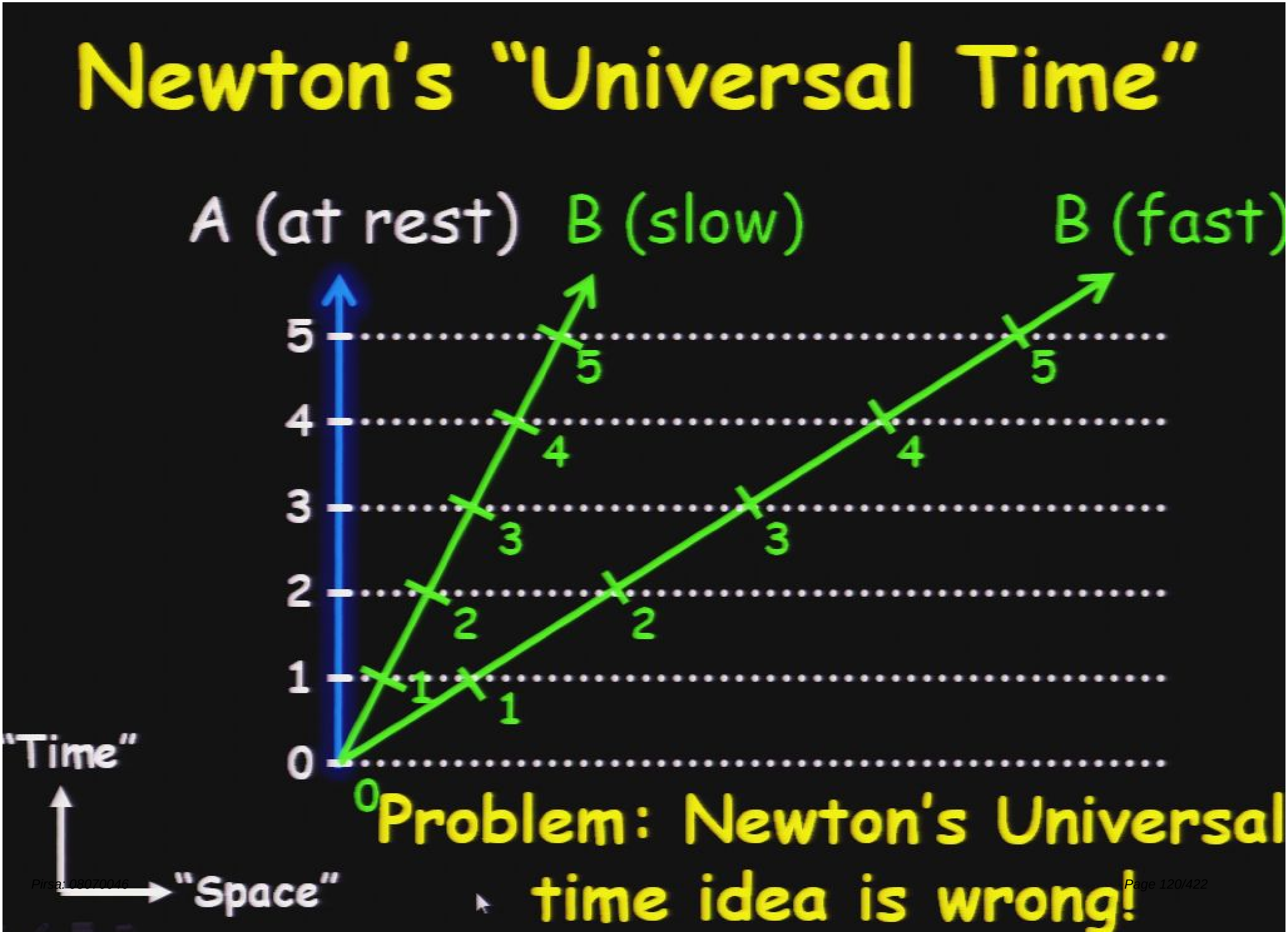


Newton's "Universal Time"

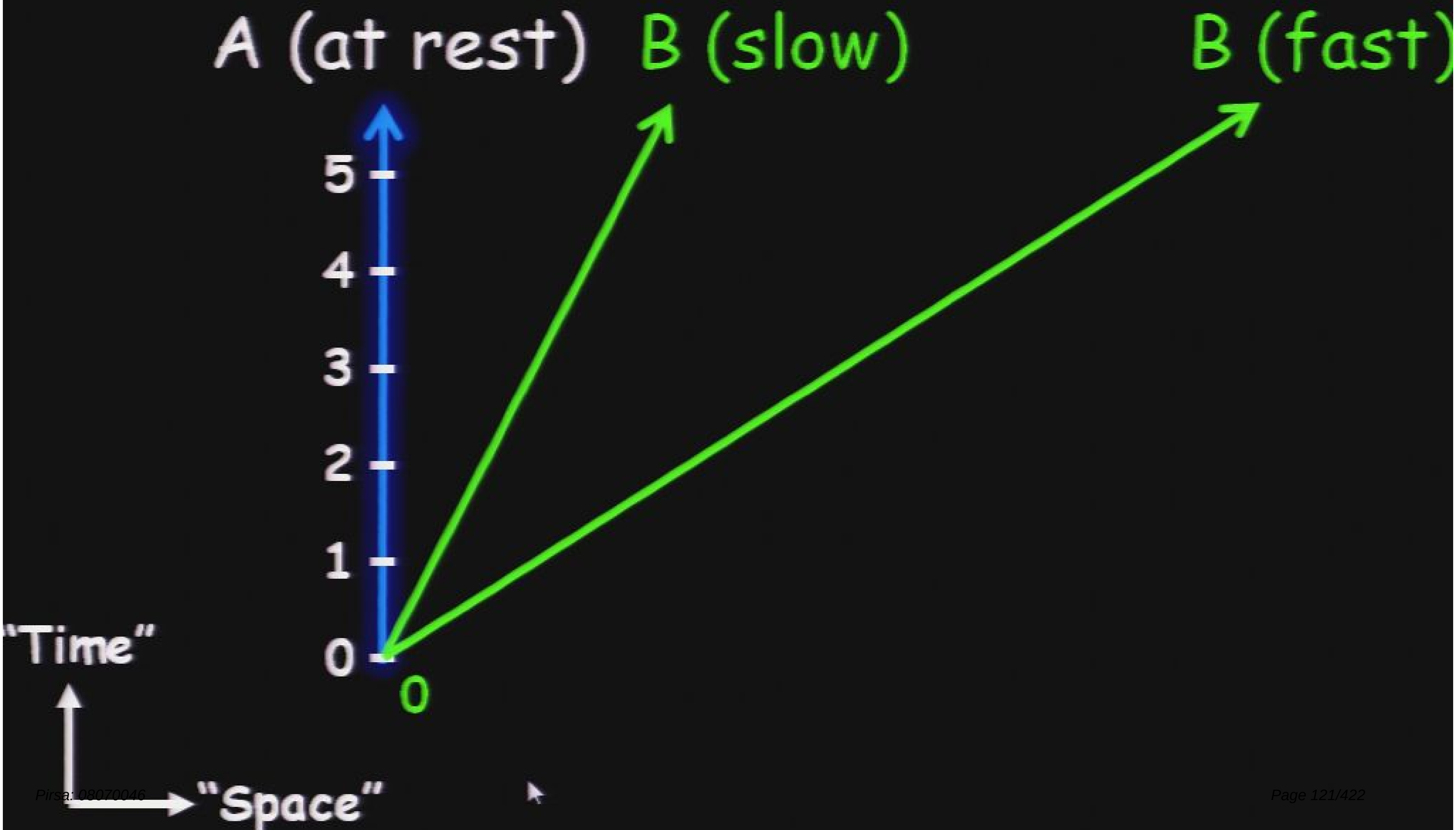


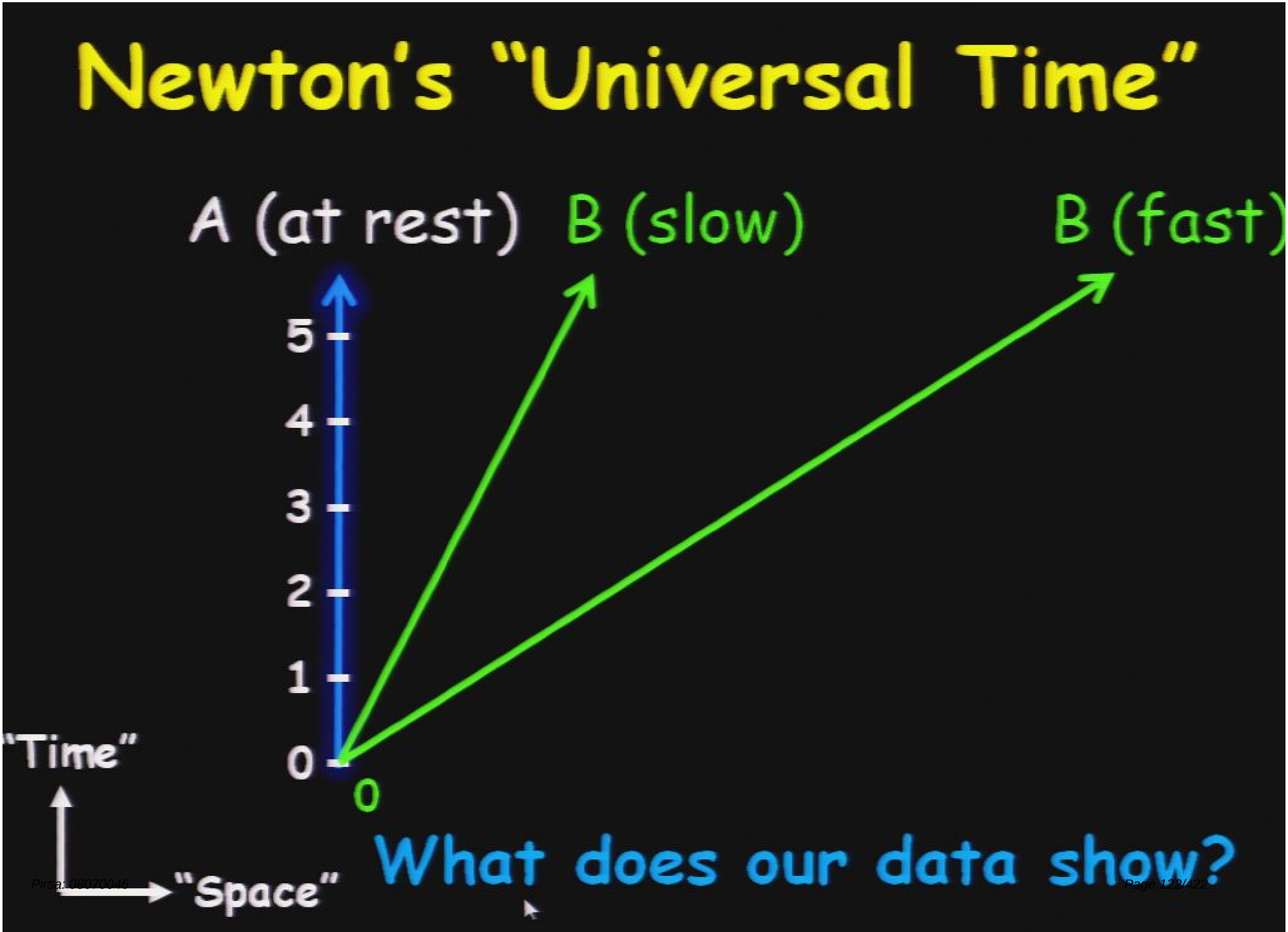


Newton's "Universal Time"
A (at rest)
B (slow)
B (fast)
5
4
3
2
1
0
"Time"
"Space"

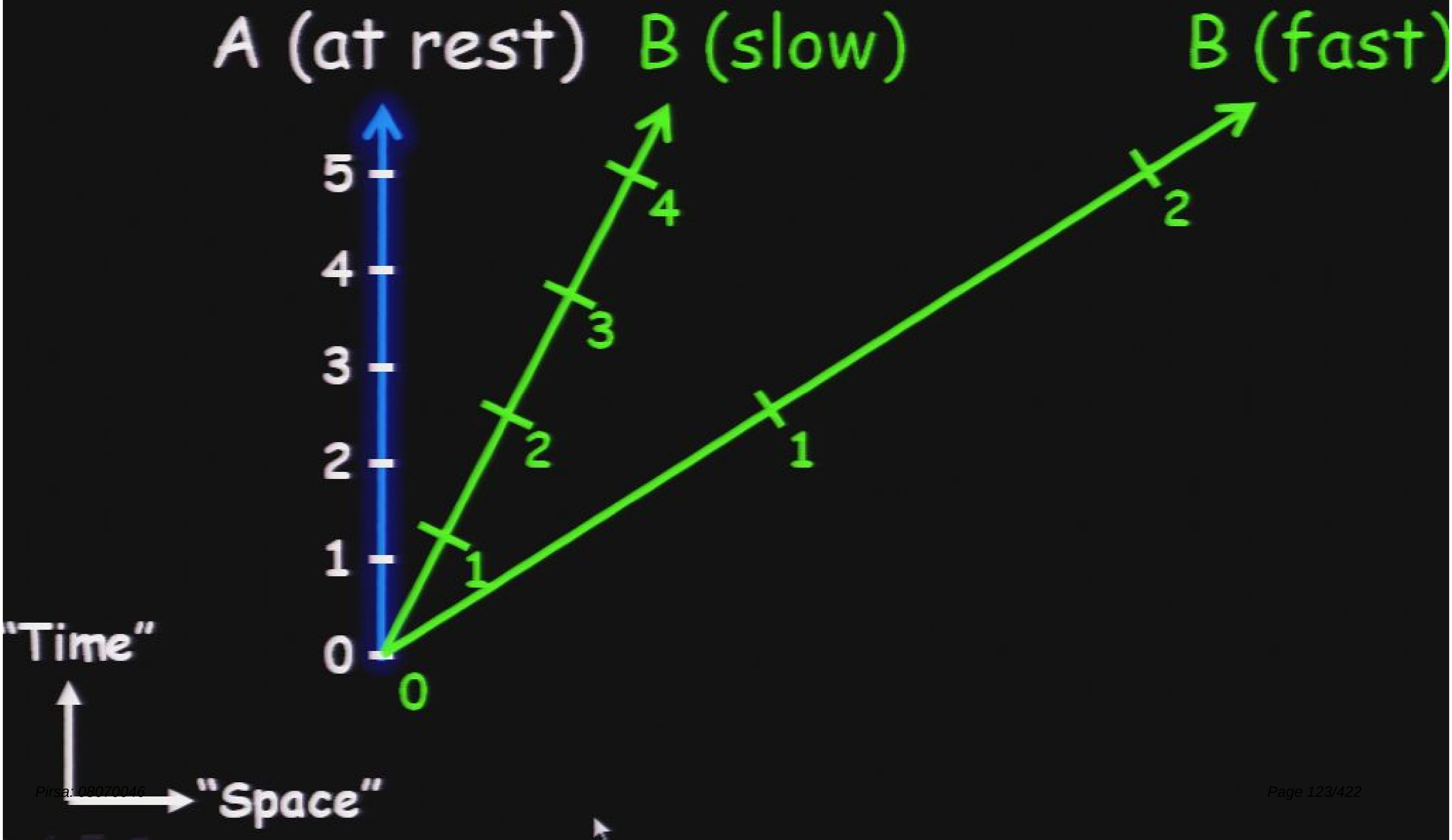

Newton's "Universal Time"
A (at rest)
B (slow)
B (fast)
5
4
3
2
1
0
"Time"
"Space"
Problem: Newton's Universal time idea is wrong!

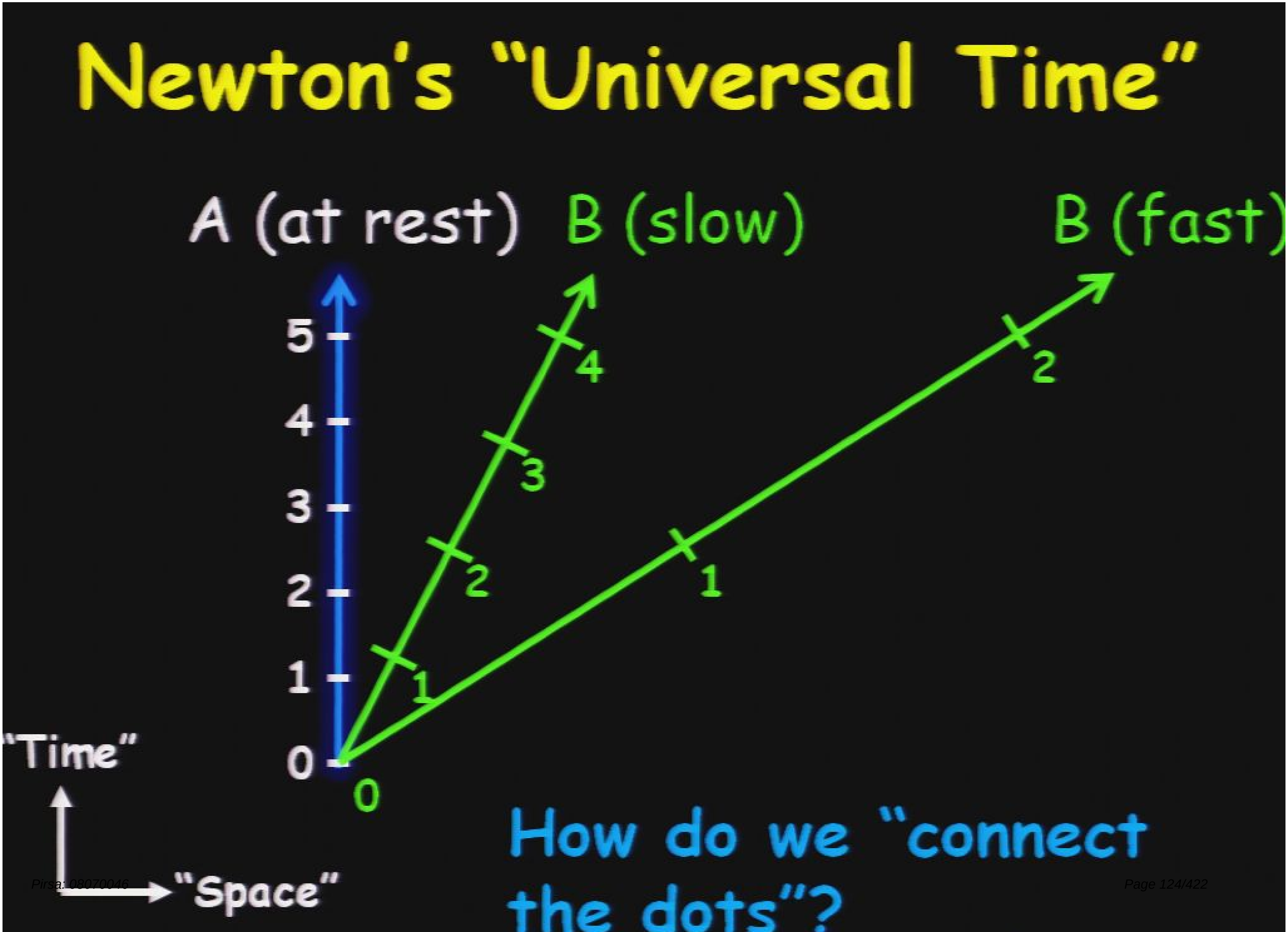
Newton's "Universal Time"

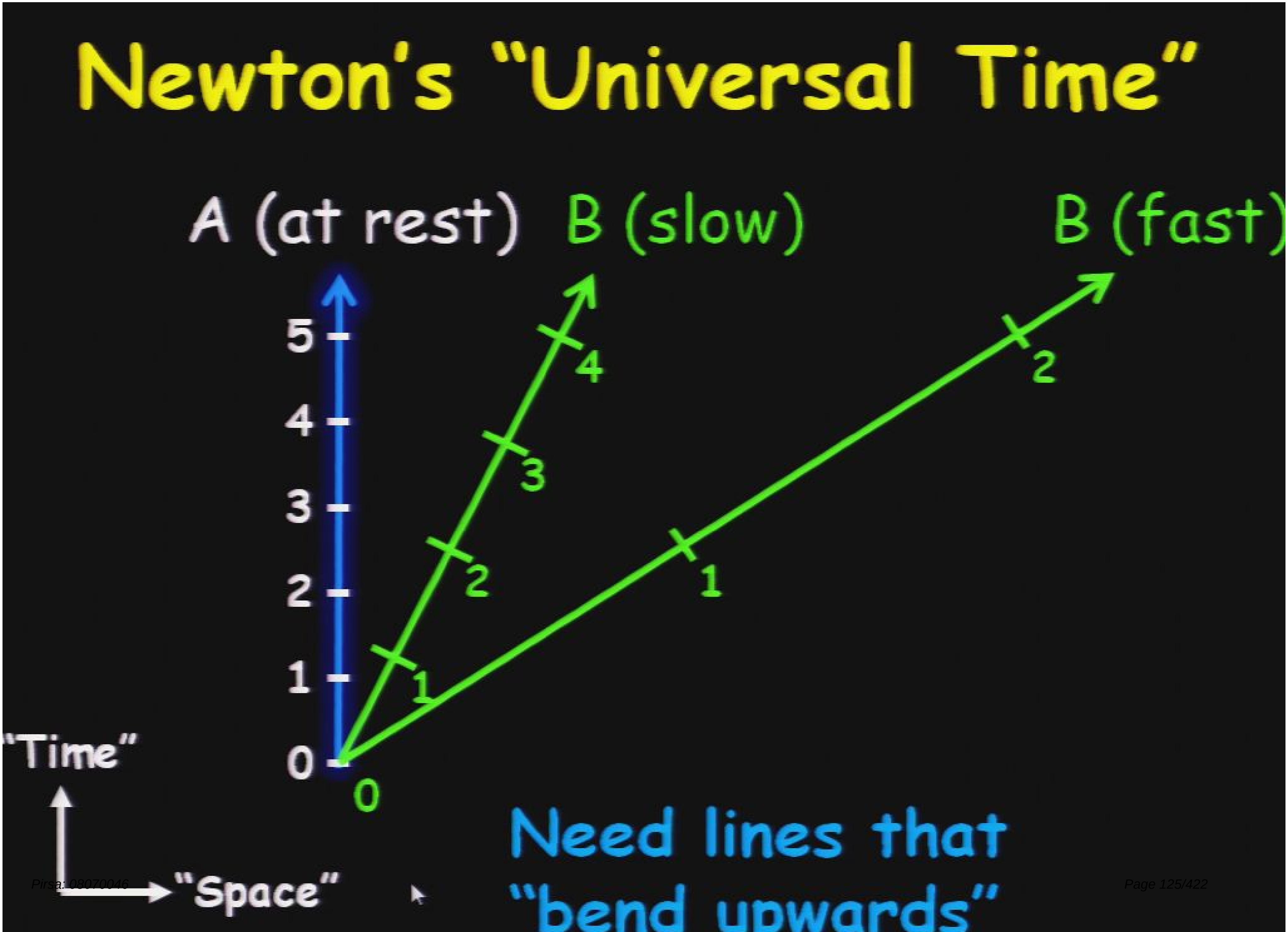


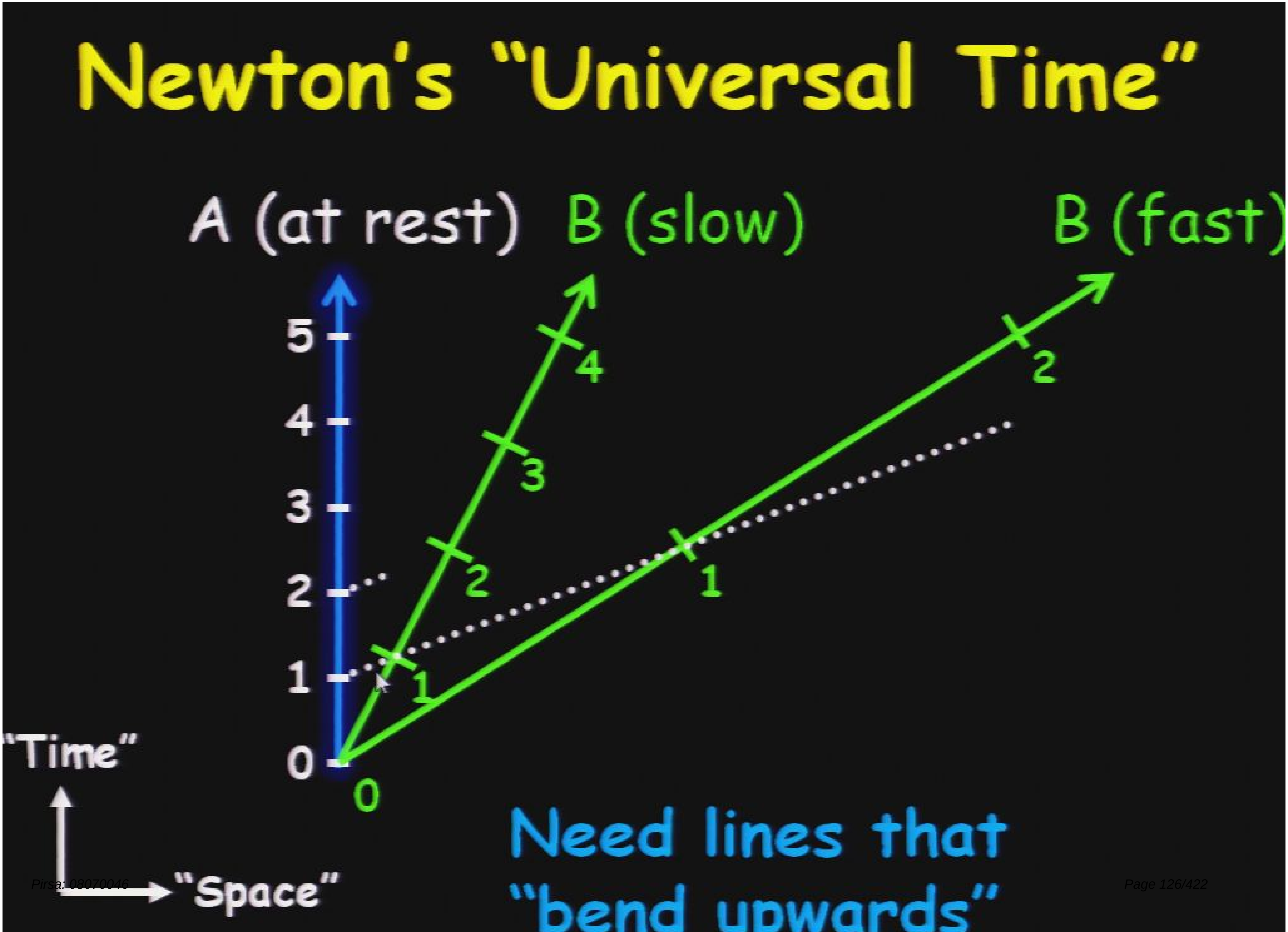

Newton's "Universal Time"
A (at rest)
B (slow)
B (fast)
5
4
3
2
1
0
0
"Time"
"Space"
What does our data show?

Newton's "Universal Time"

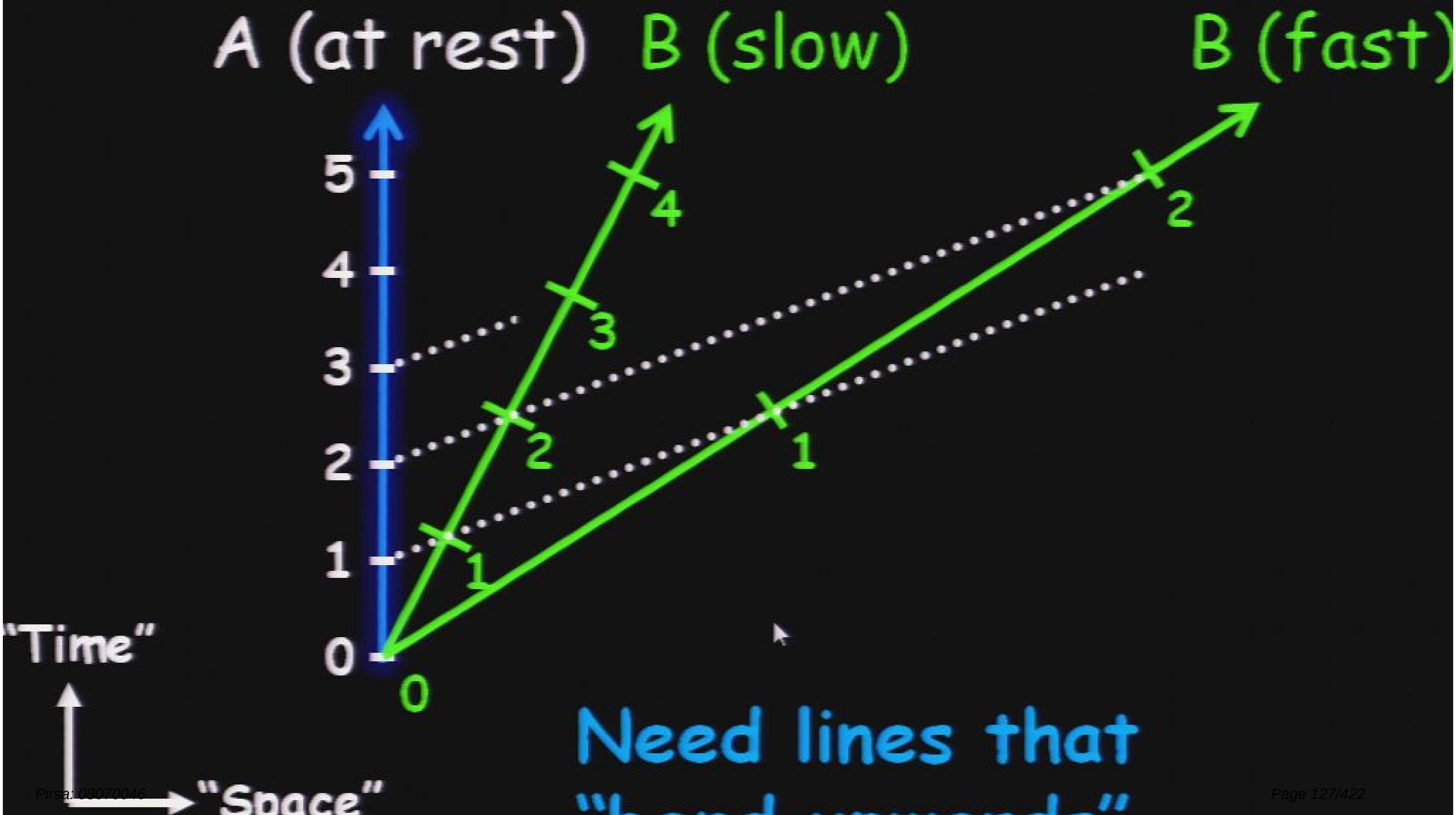



Newton's "Universal Time"
A (at rest)
B (slow)
B (fast)
5
4
3
2
1
0
1
2
3
4
0
1
2
"Time"
"Space"
How do we "connect
the dots"?


Newton's "Universal Time"
A (at rest)
B (slow)
B (fast)
5
4
3
2
1
0
4
3
2
1
0
2
1
"Time"
"Space"
Need lines that
"bend upwards"

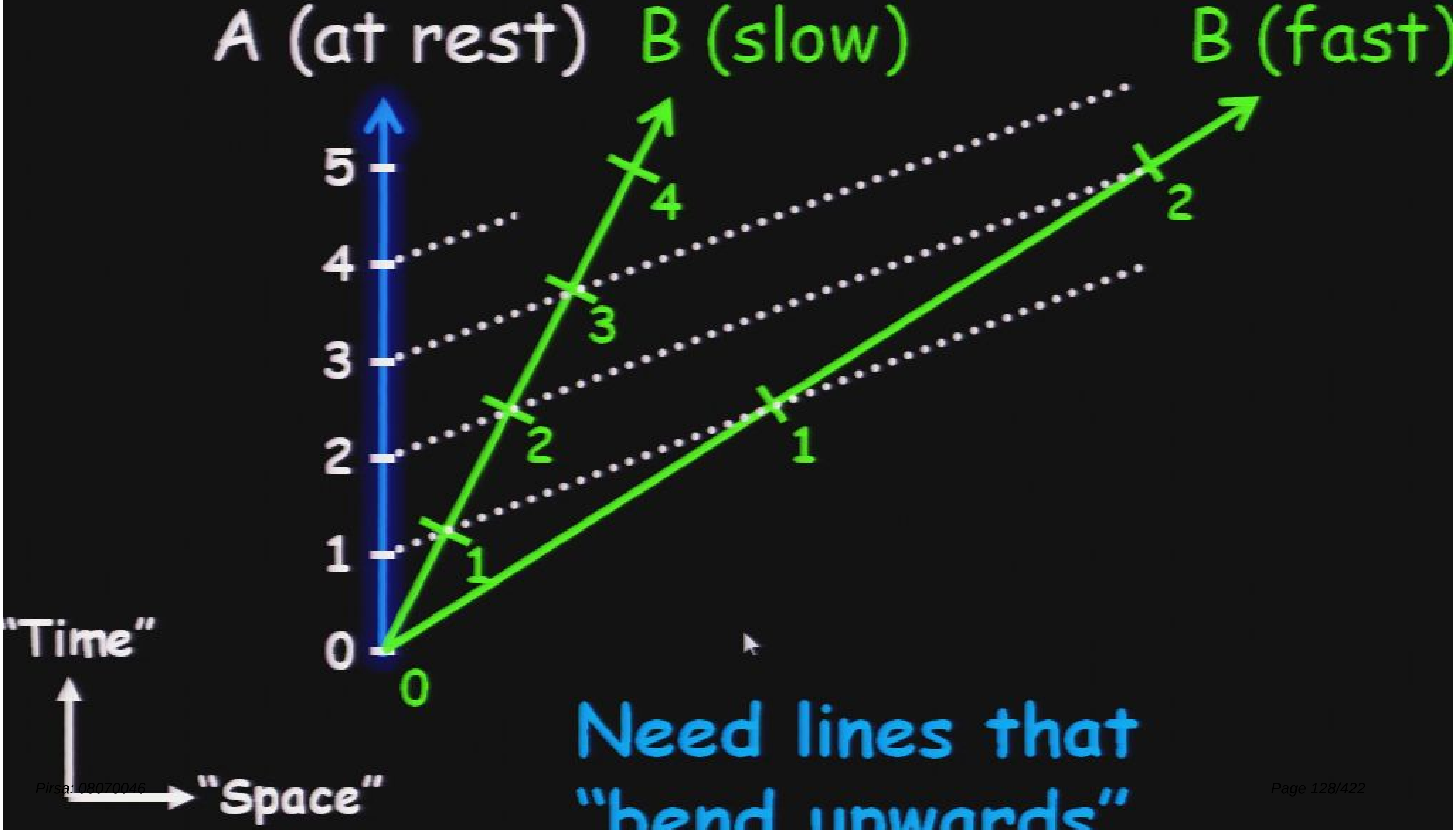

Newton's "Universal Time"
A (at rest)
B (slow)
B (fast)
5
4
3
2
1
0
"Time"
"Space"
Need lines that
"bend upwards"

Newton's "Universal Time"



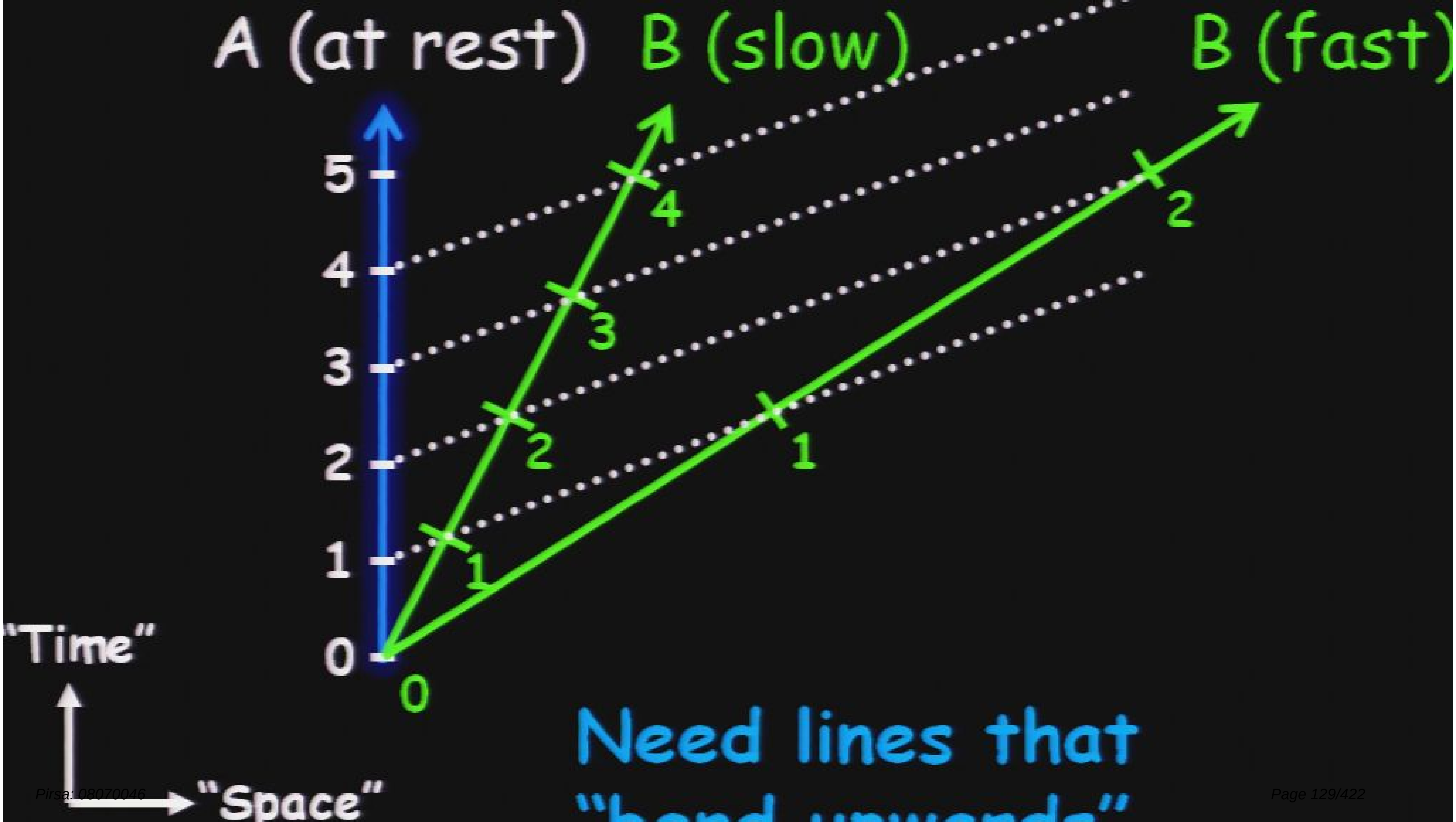
Need lines that
"bend upwards"

Newton's "Universal Time"

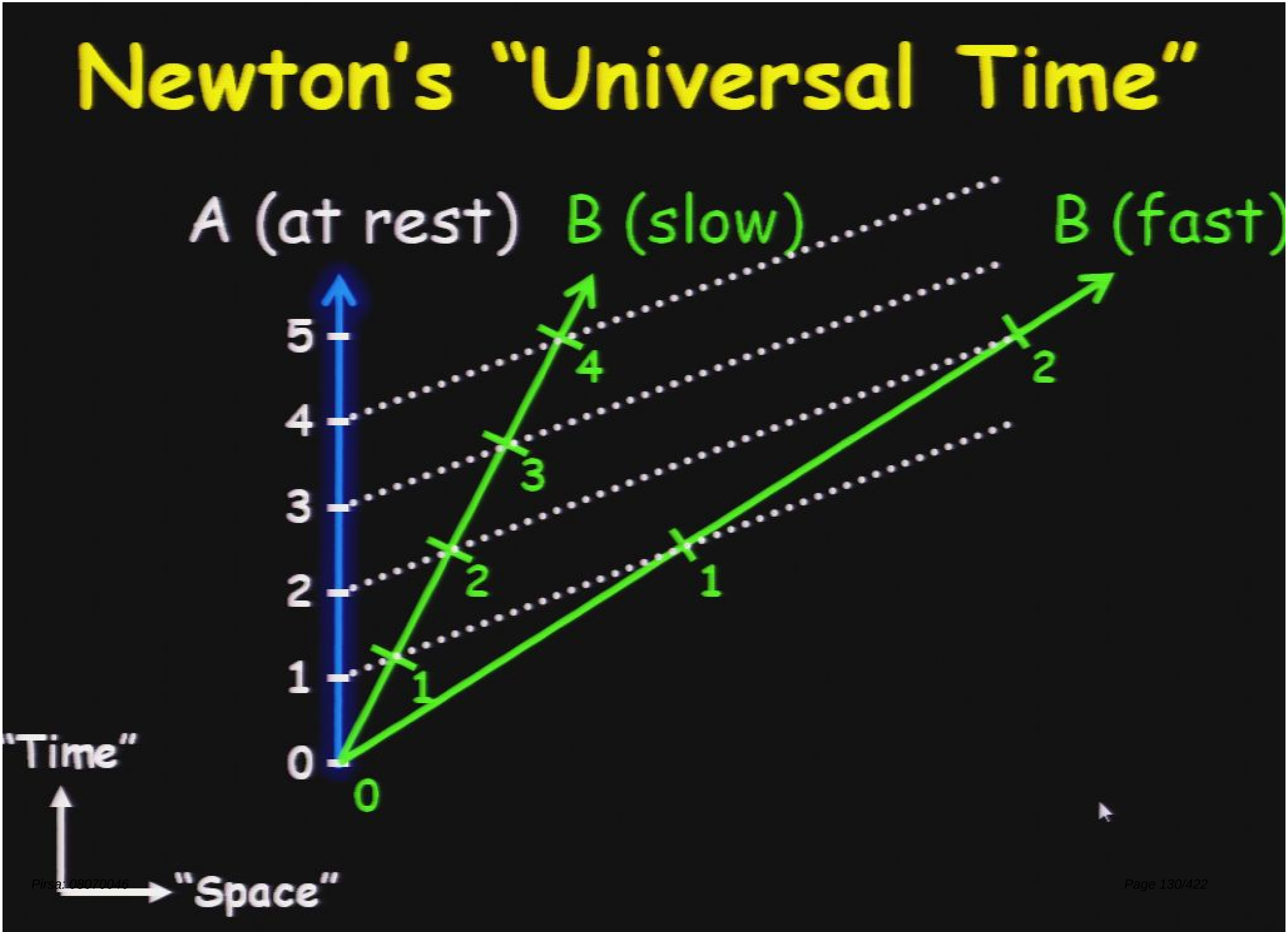


Need lines that "bend upwards"

Newton's "Universal Time"



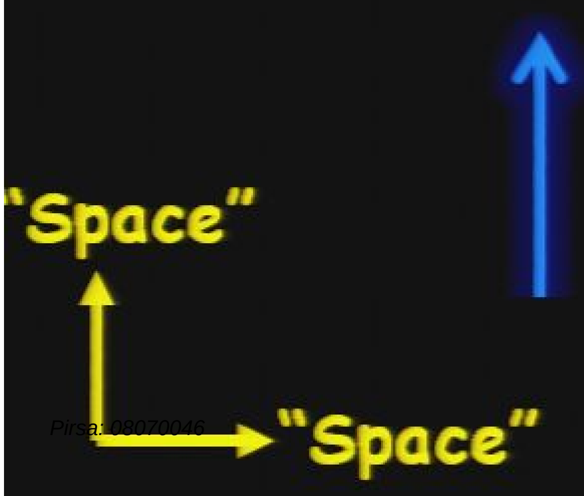
Need lines that "bend upwards"

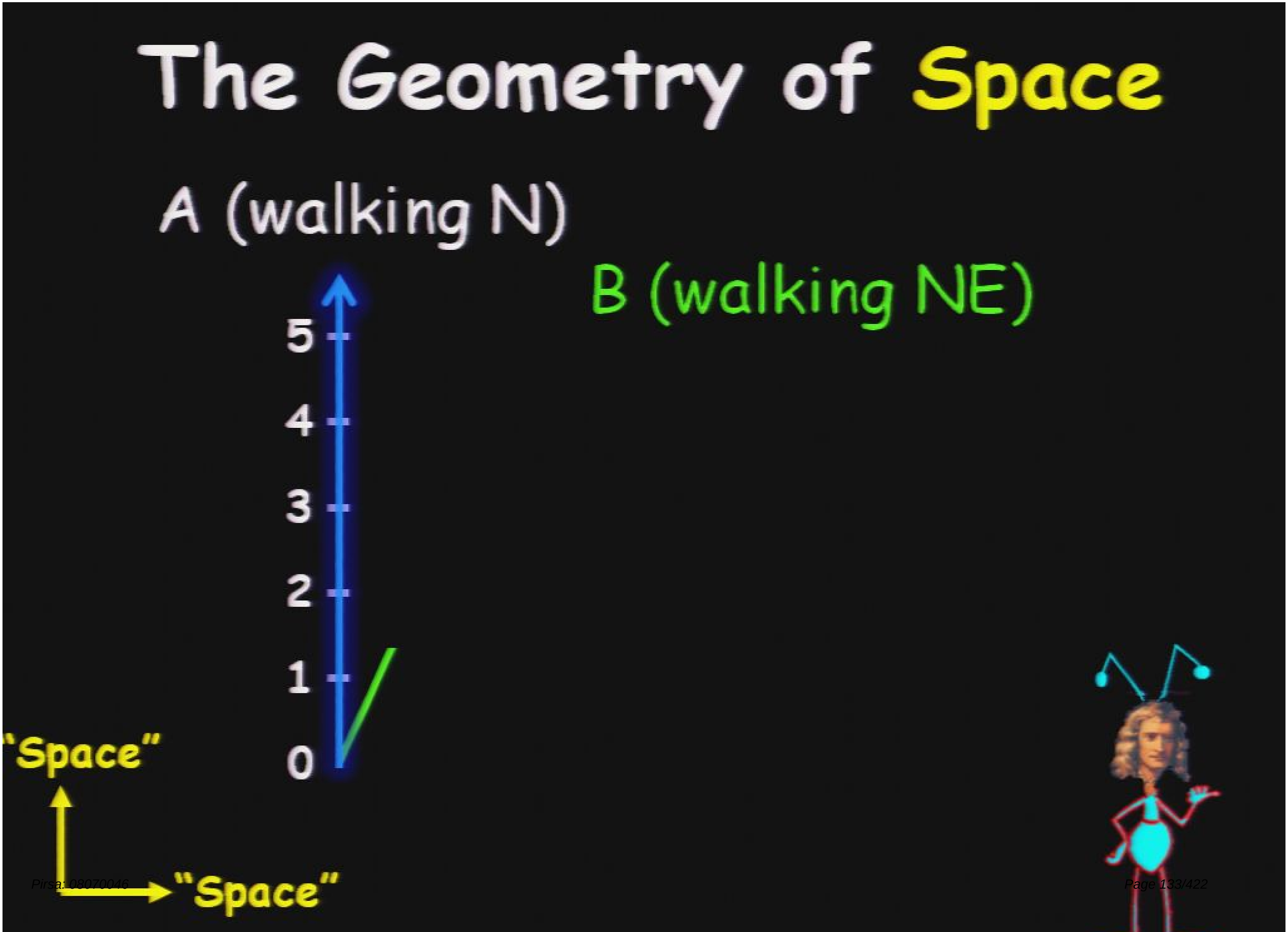

Newton's "Universal Time"
A (at rest)
B (slow)
B (fast)
5
4
3
2
1
0
0
1
2
3
4
1
2
"Time"
"Space"

The Geometry of Space

The Geometry of Space

A (walking N)




The Geometry of Space
A (walking N)
B (walking NE)
5
4
3
2
1
0
"Space"
"Space"

The Geometry of Space

A (walking N)

B (walking NE)

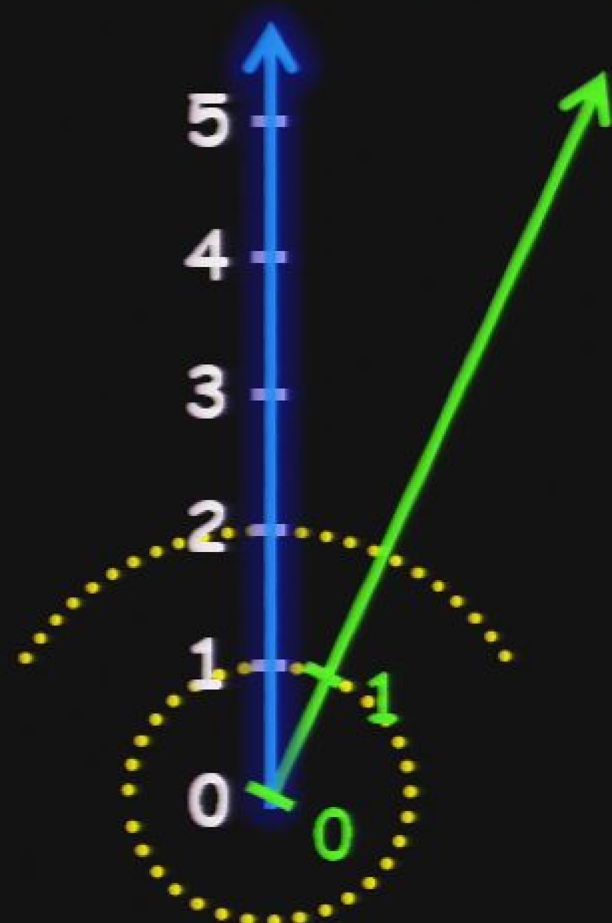
How do we transfer A's tick marks?

Let's Try CIRCLES

The Geometry of Space

A (walking N)

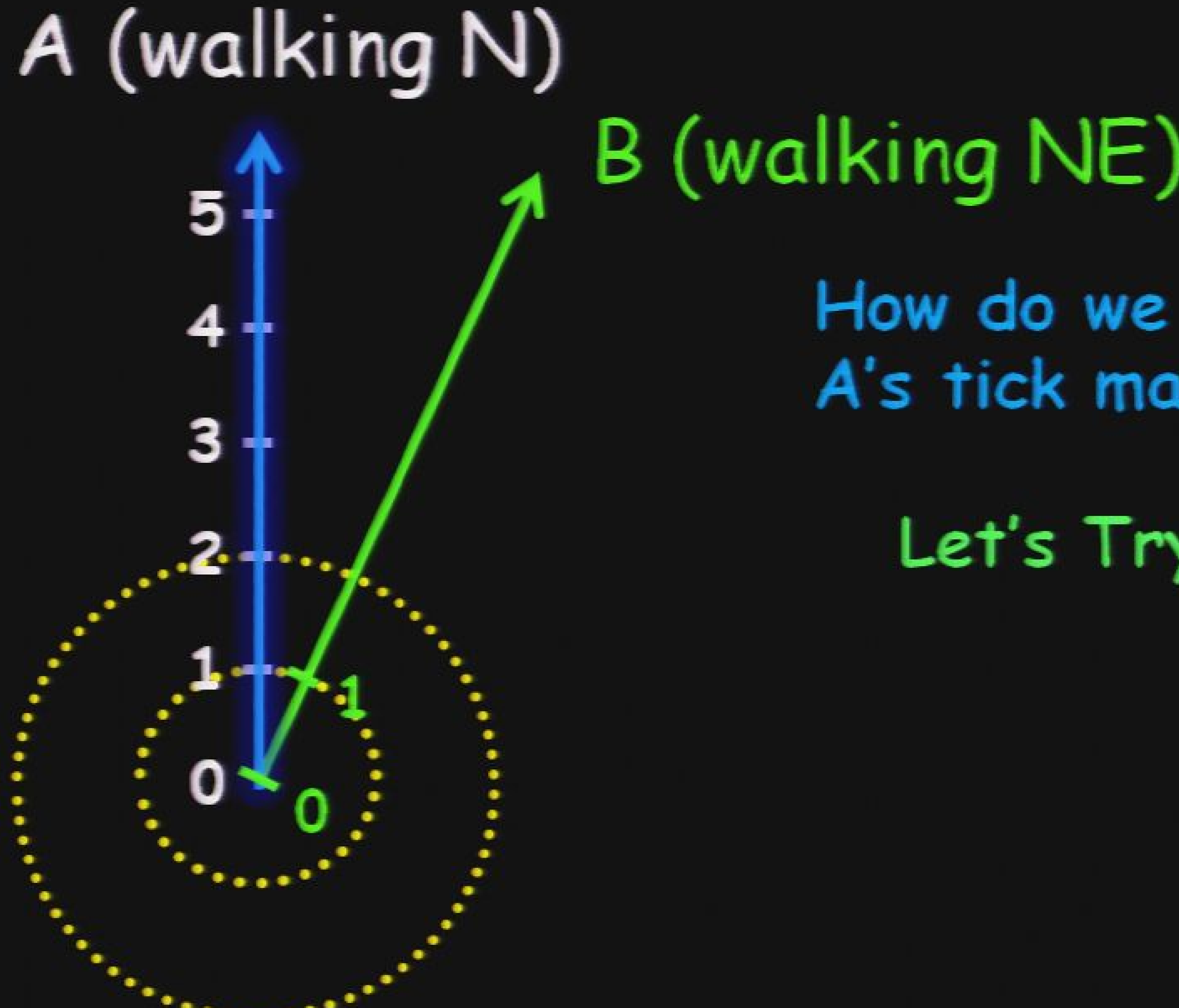
B (walking NE)



How do we transfer A's tick marks?

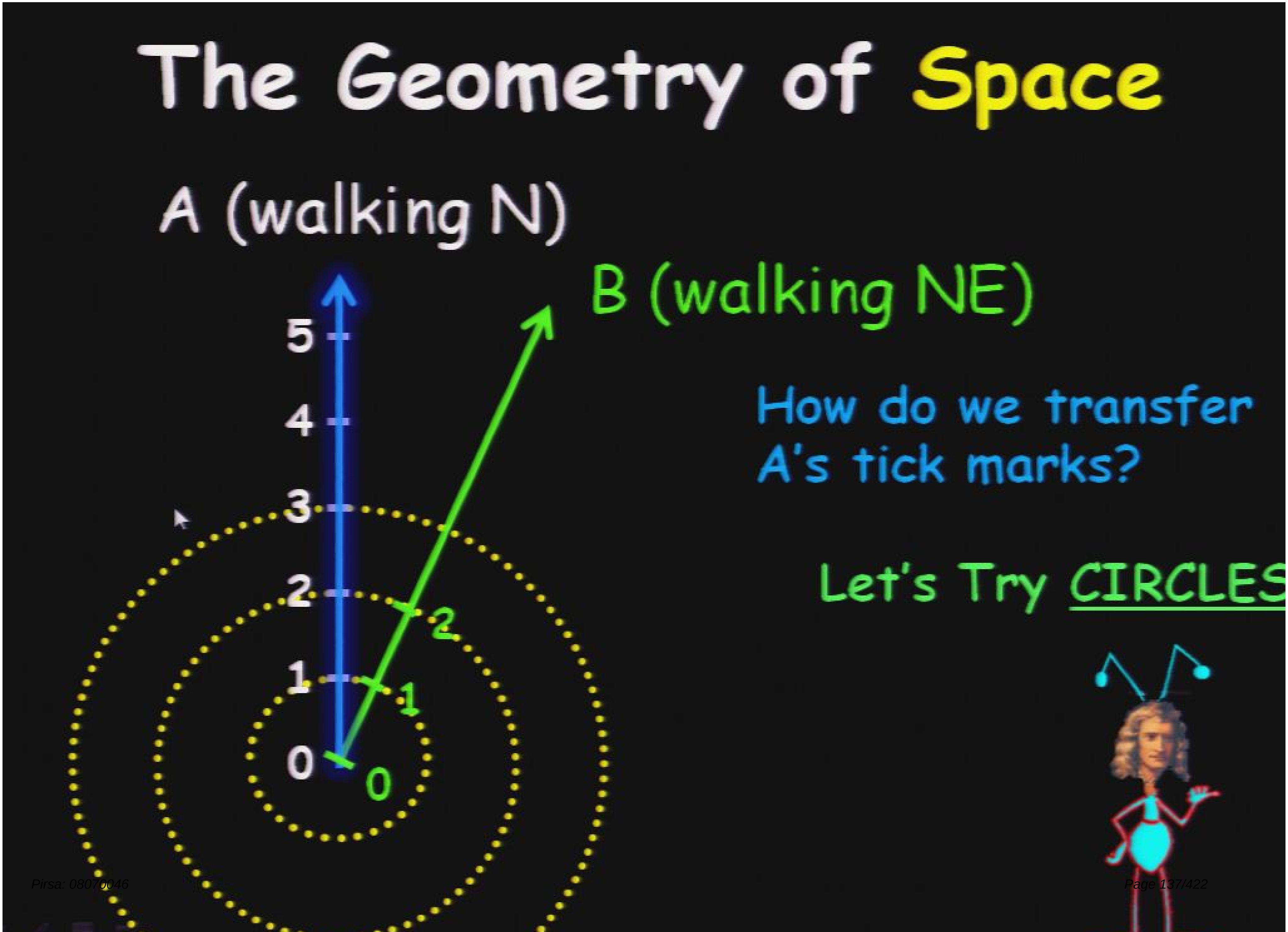
Let's Try CIRCLES

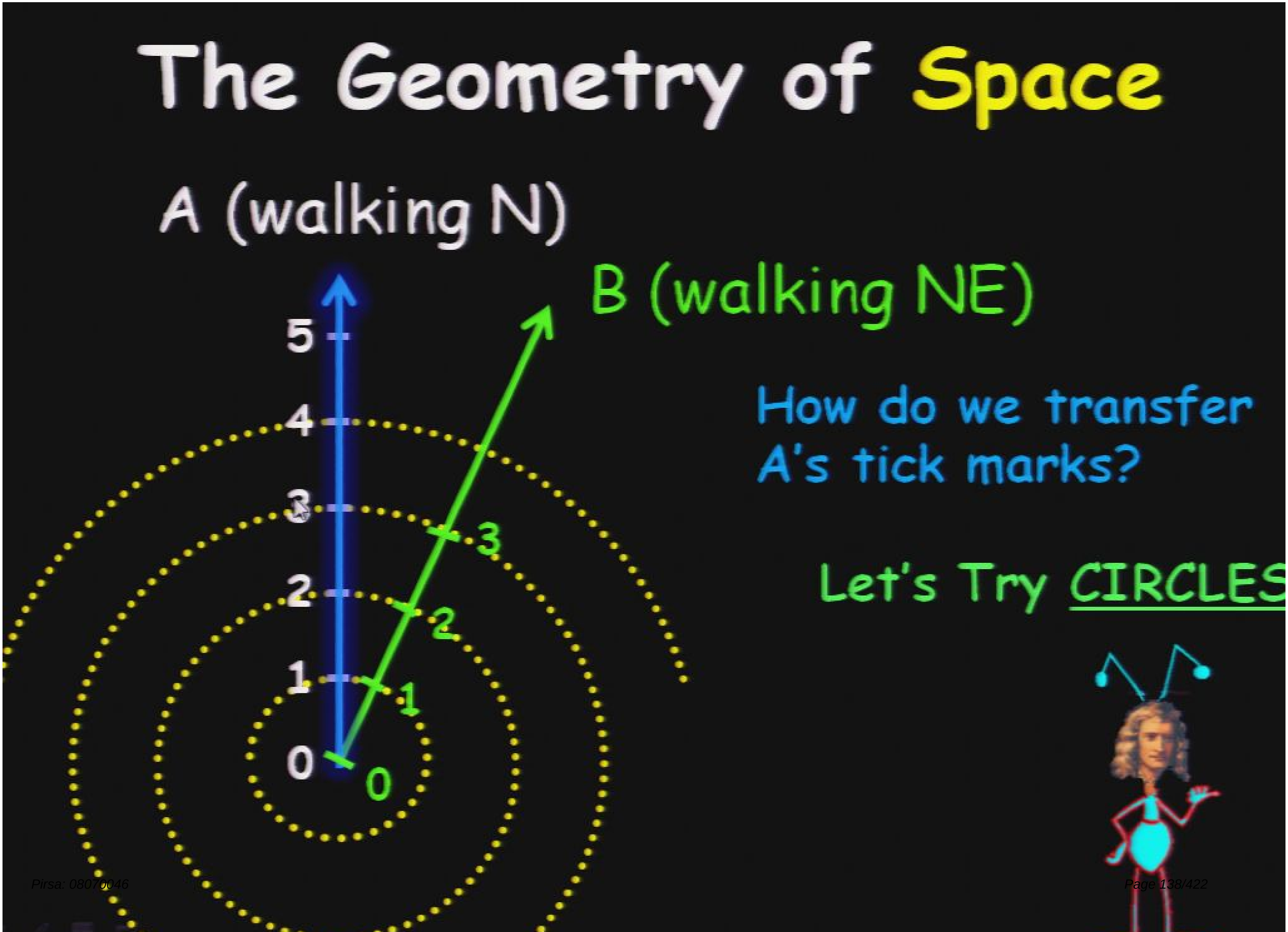
The Geometry of Space

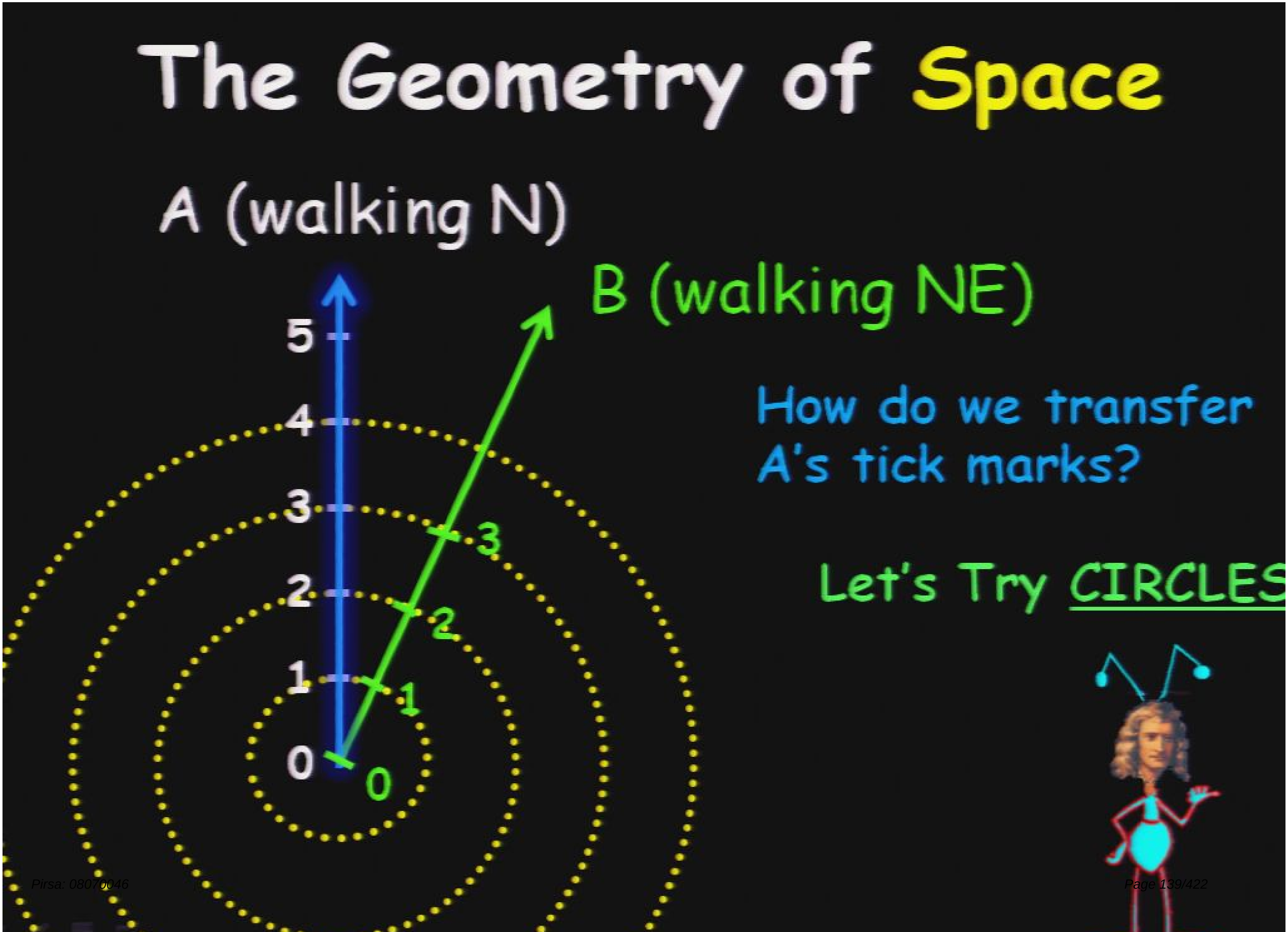


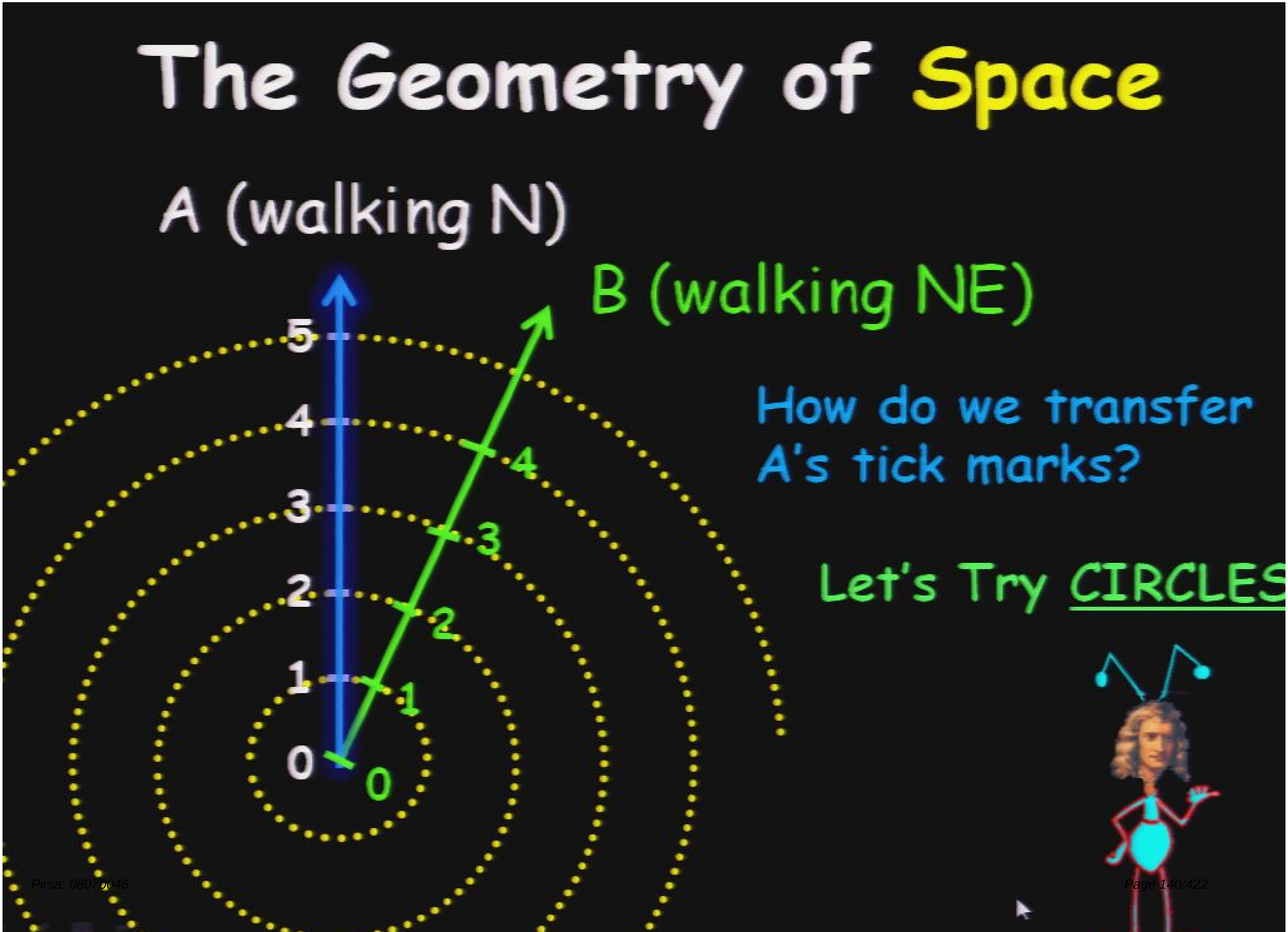
How do we transfer
A's tick marks?

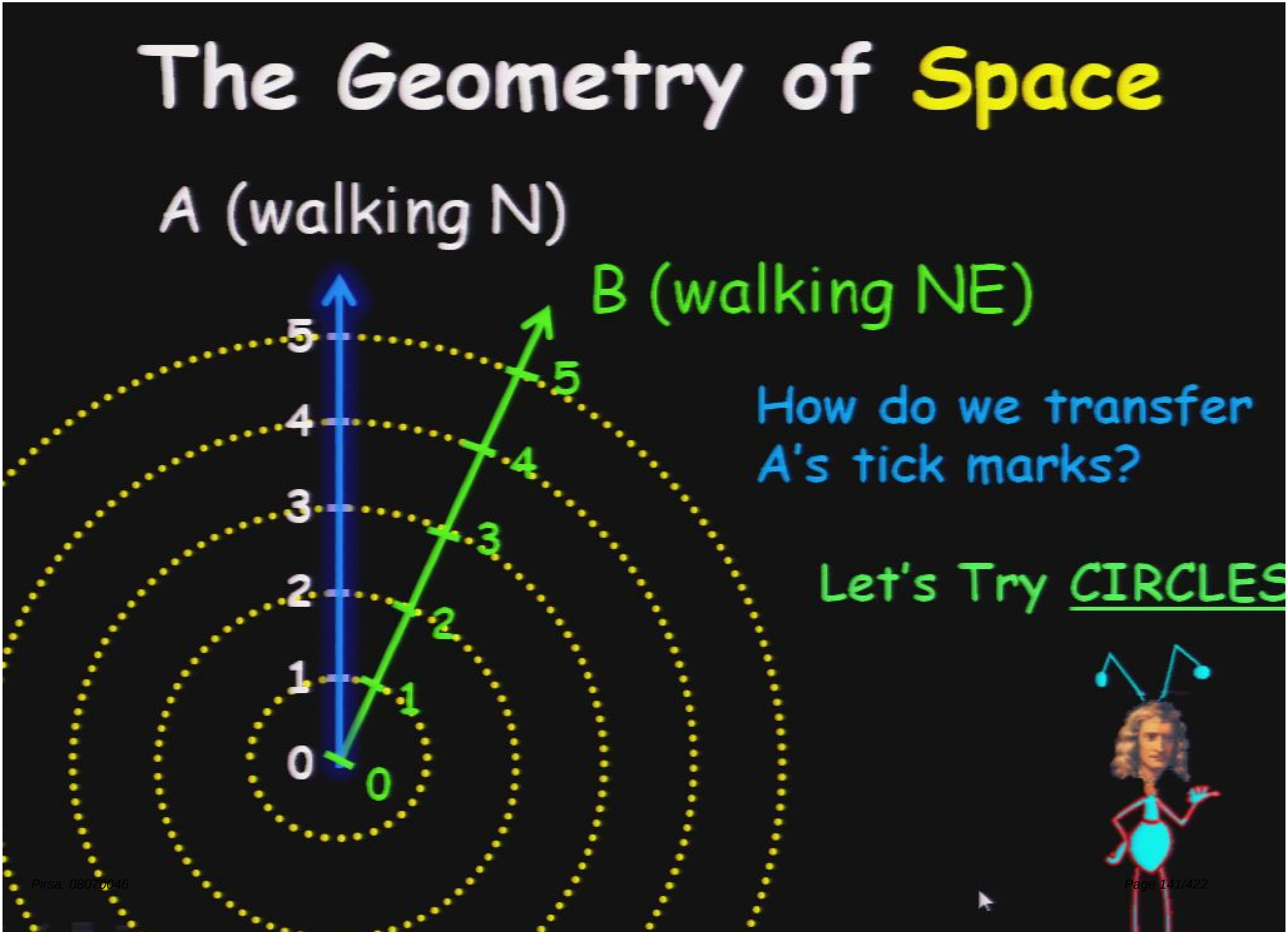
Let's Try CIRCLES


The Geometry of Space
A (walking N)
B (walking NE)
5
4
3
2
1
0
2
1
0
How do we transfer
A's tick marks?
Let's Try CIRCLES

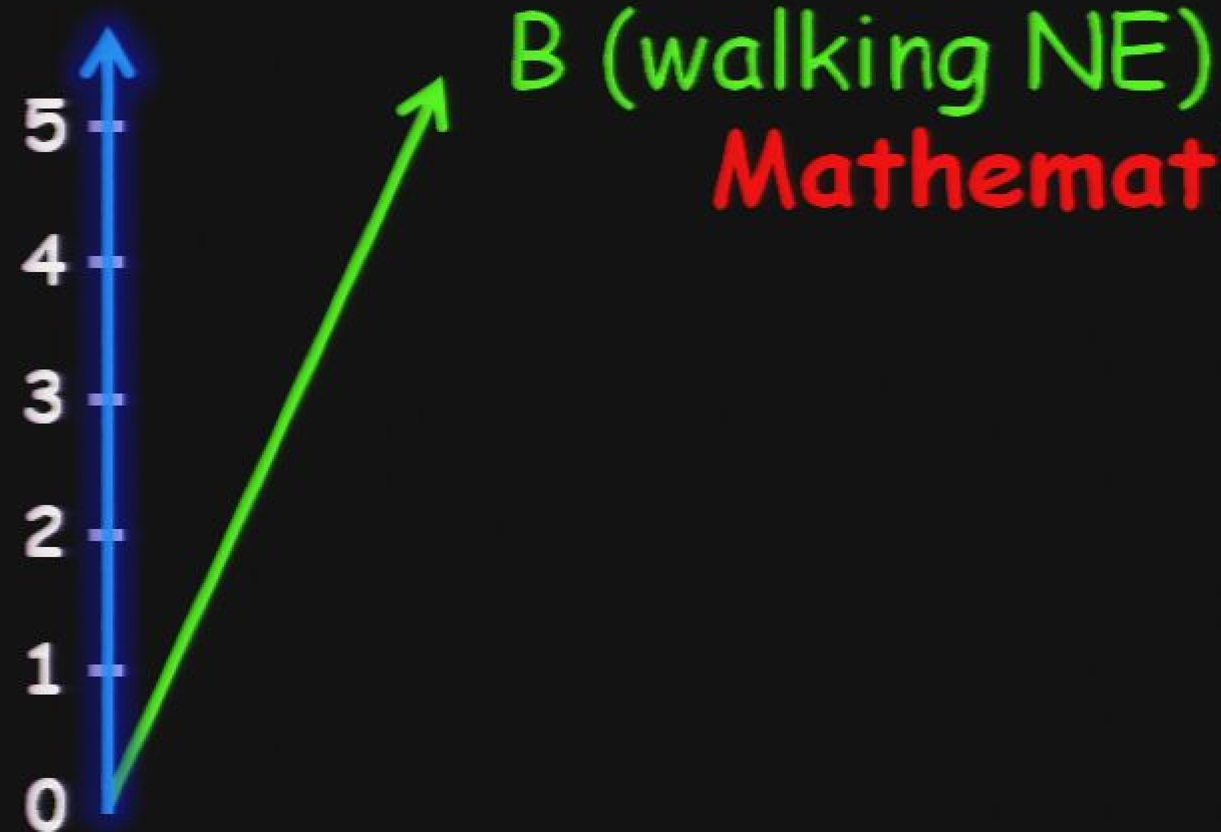

The Geometry of Space
A (walking N)
B (walking NE)
5
4
3
2
1
0
3
2
1
0
How do we transfer
A's tick marks?
Let's Try CIRCLES


The Geometry of Space
A (walking N)
B (walking NE)
5
4
3
2
1
0
3
2
1
0
How do we transfer
A's tick marks?
Let's Try CIRCLES

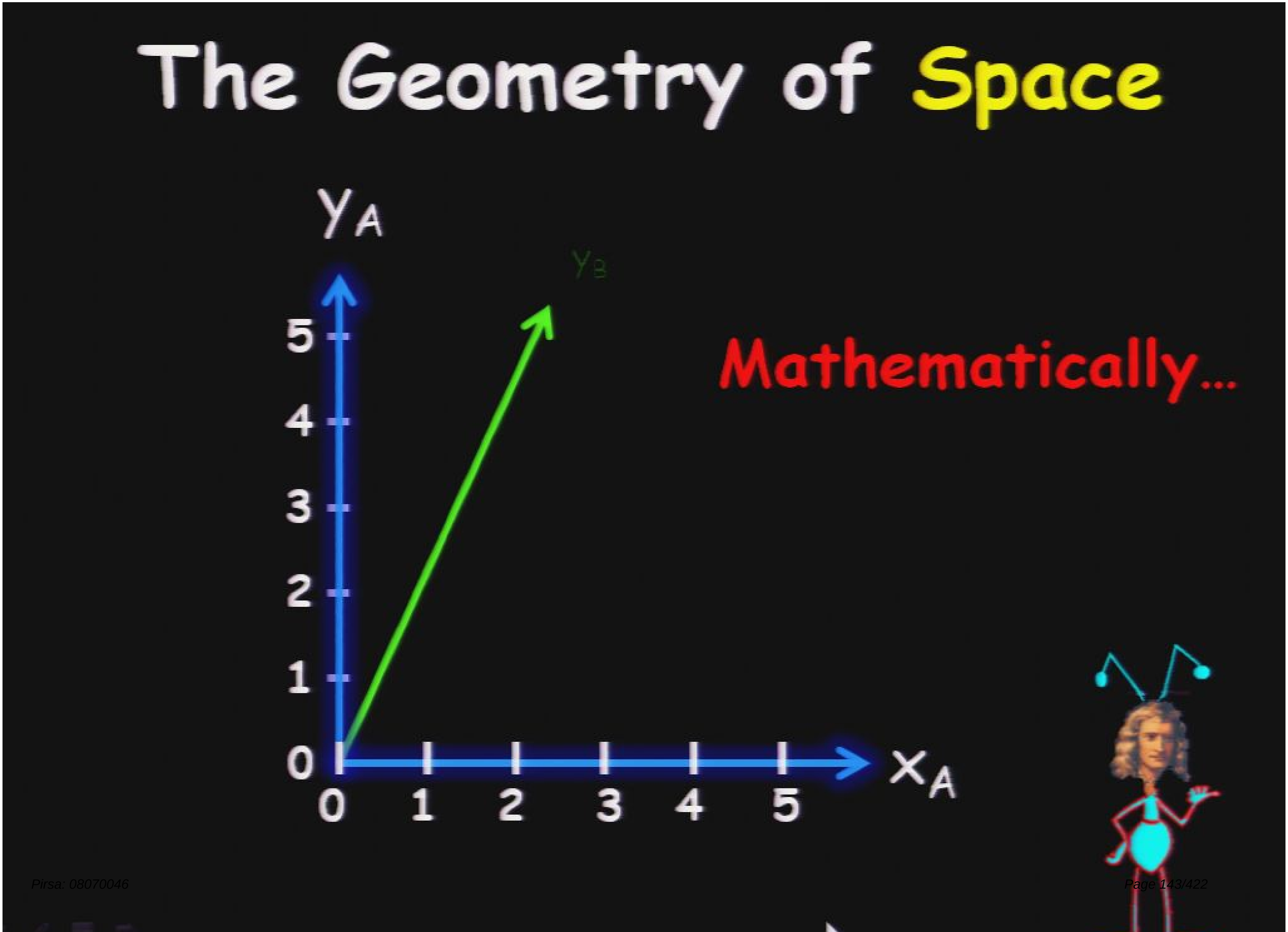

The Geometry of Space
A (walking N)
B (walking NE)
5
4
3
2
1
0
4
3
2
1
0
How do we transfer A's tick marks?
Let's Try CIRCLES


The Geometry of Space
A (walking N)
B (walking NE)
5
4
3
2
1
0
5
4
3
2
1
0
How do we transfer
A's tick marks?
Let's Try CIRCLES

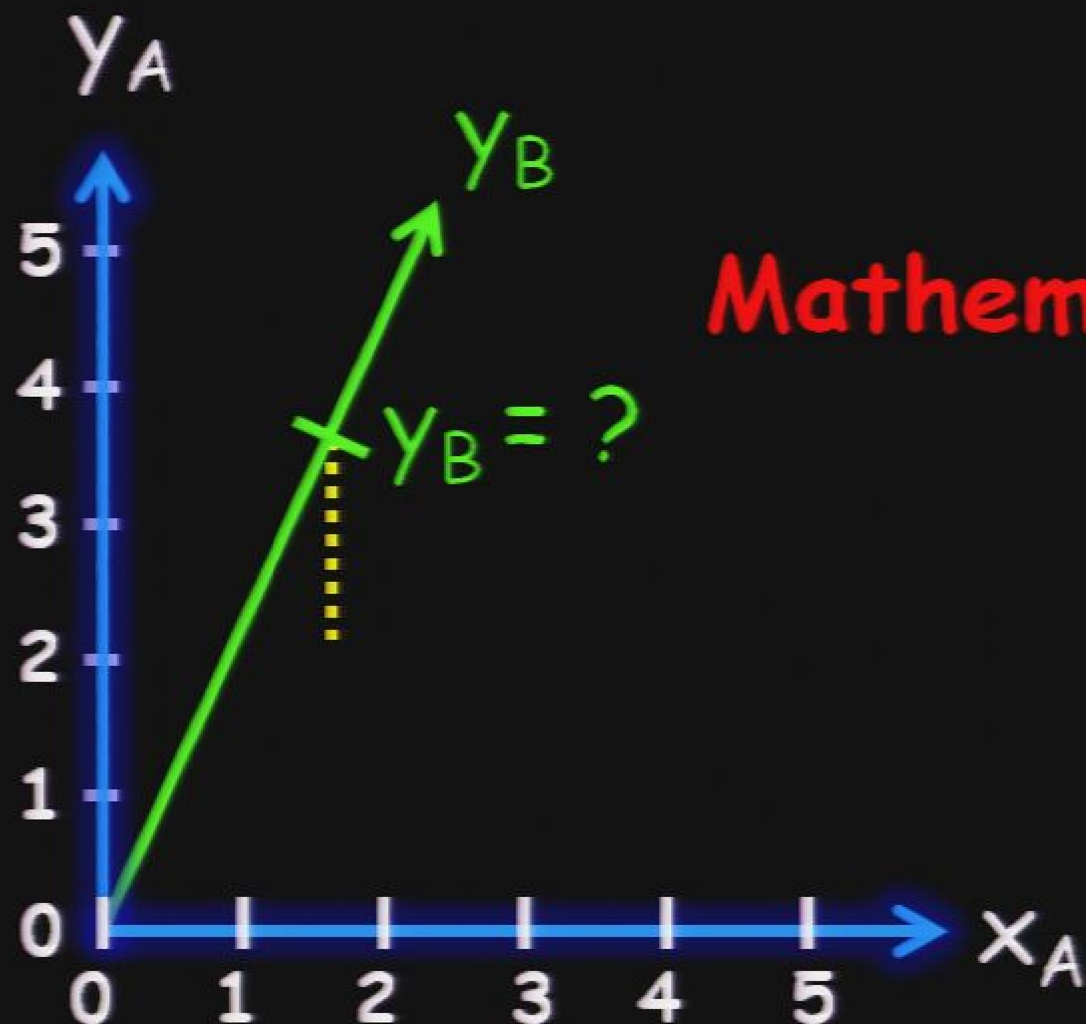
The Geometry of Space



Mathematically...

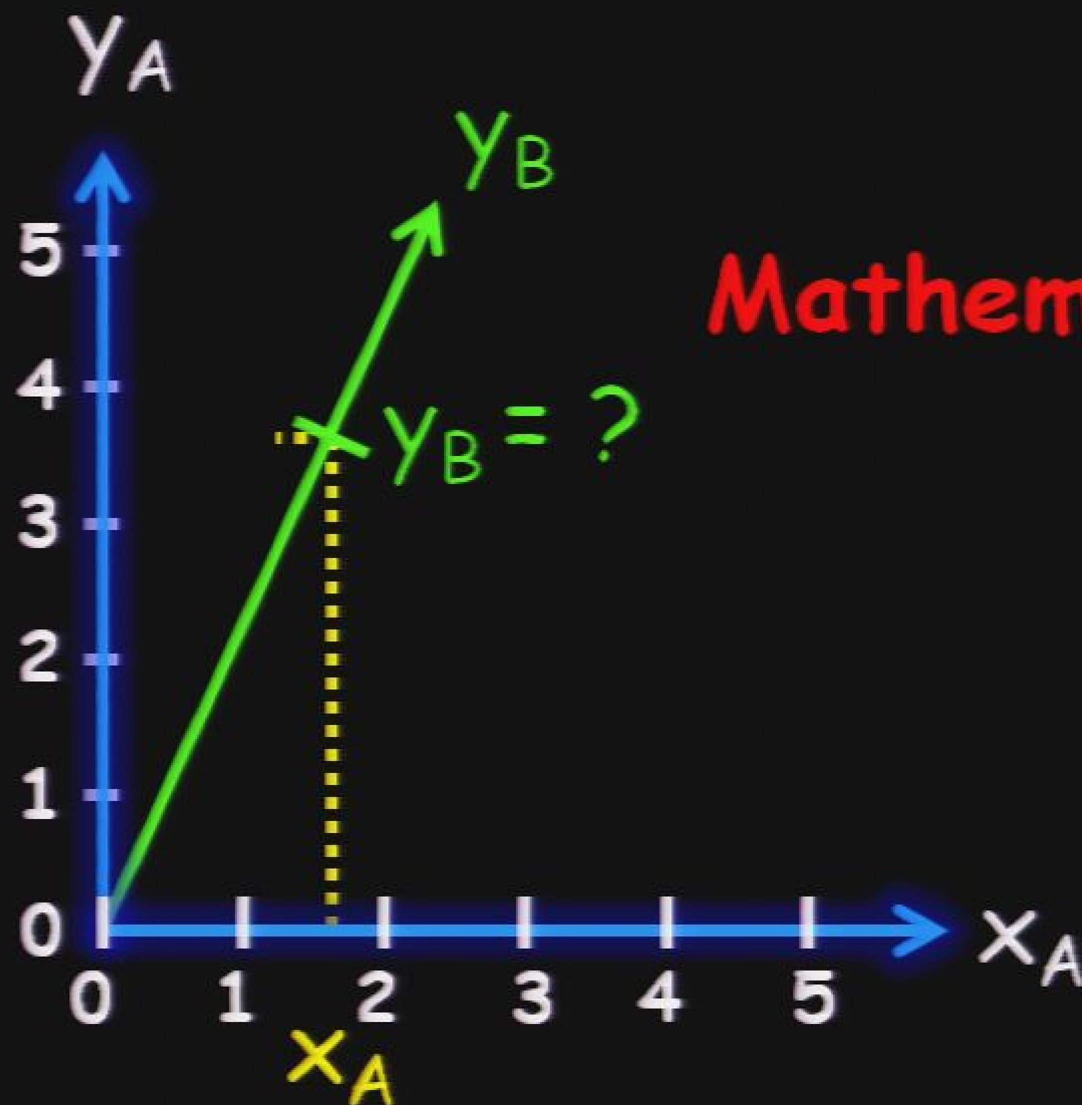

The Geometry of Space
Mathematically...
yA
yB
xA
0 1 2 3 4 5
0 1 2 3 4 5

The Geometry of Space



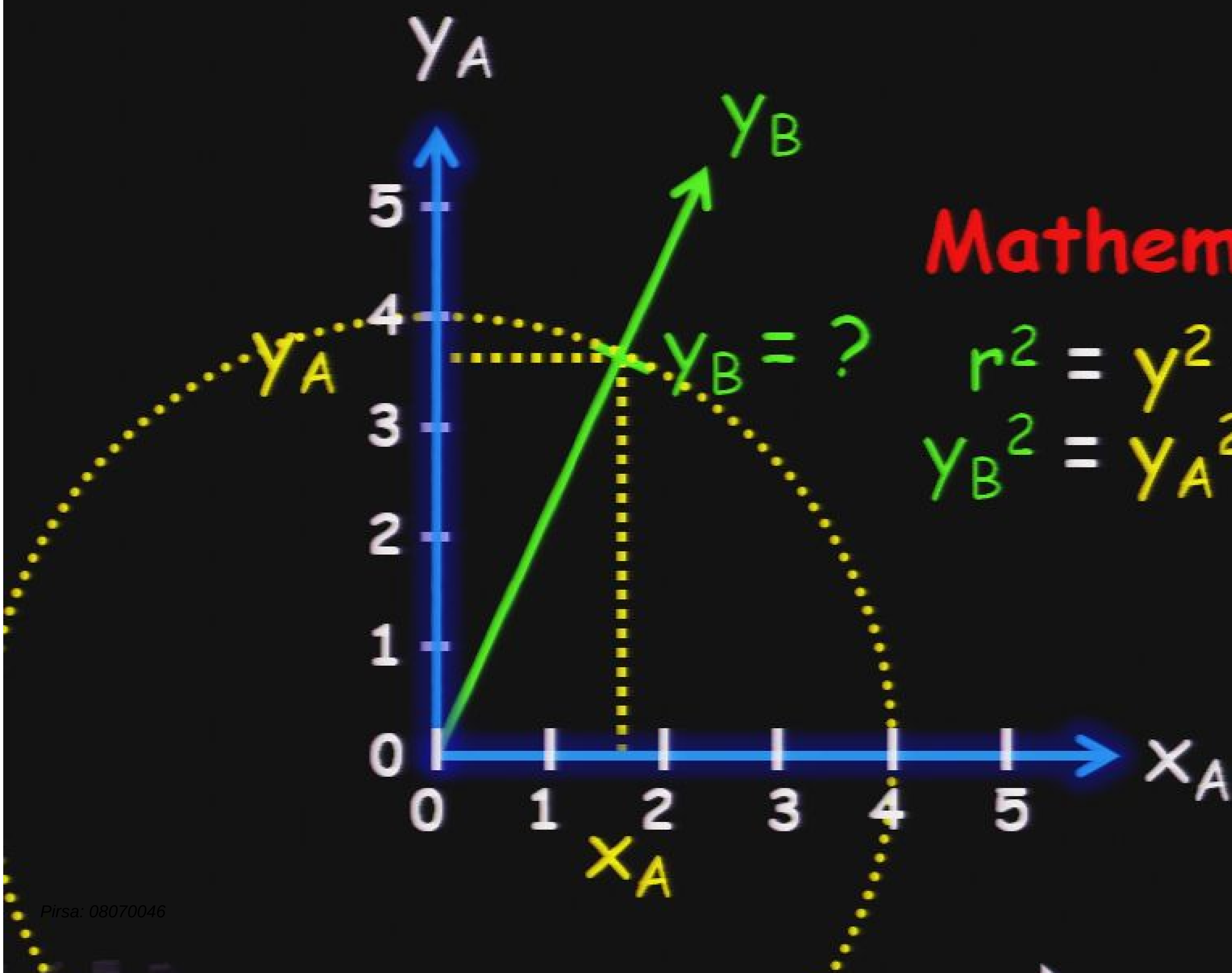
Mathematically...

The Geometry of Space



Mathematically…

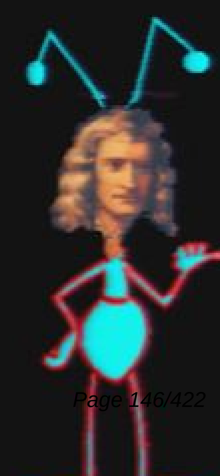
The Geometry of Space



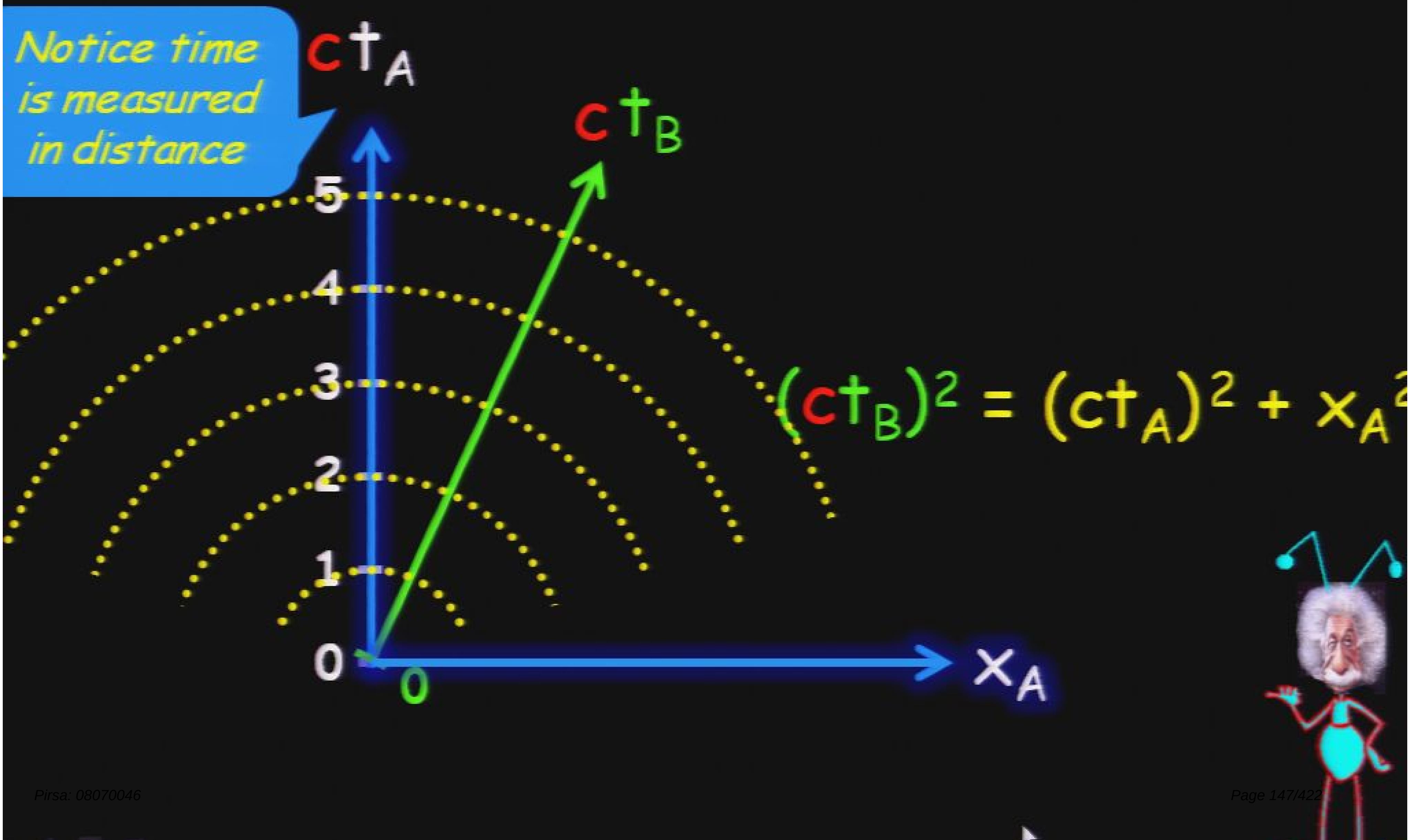
Mathematically...

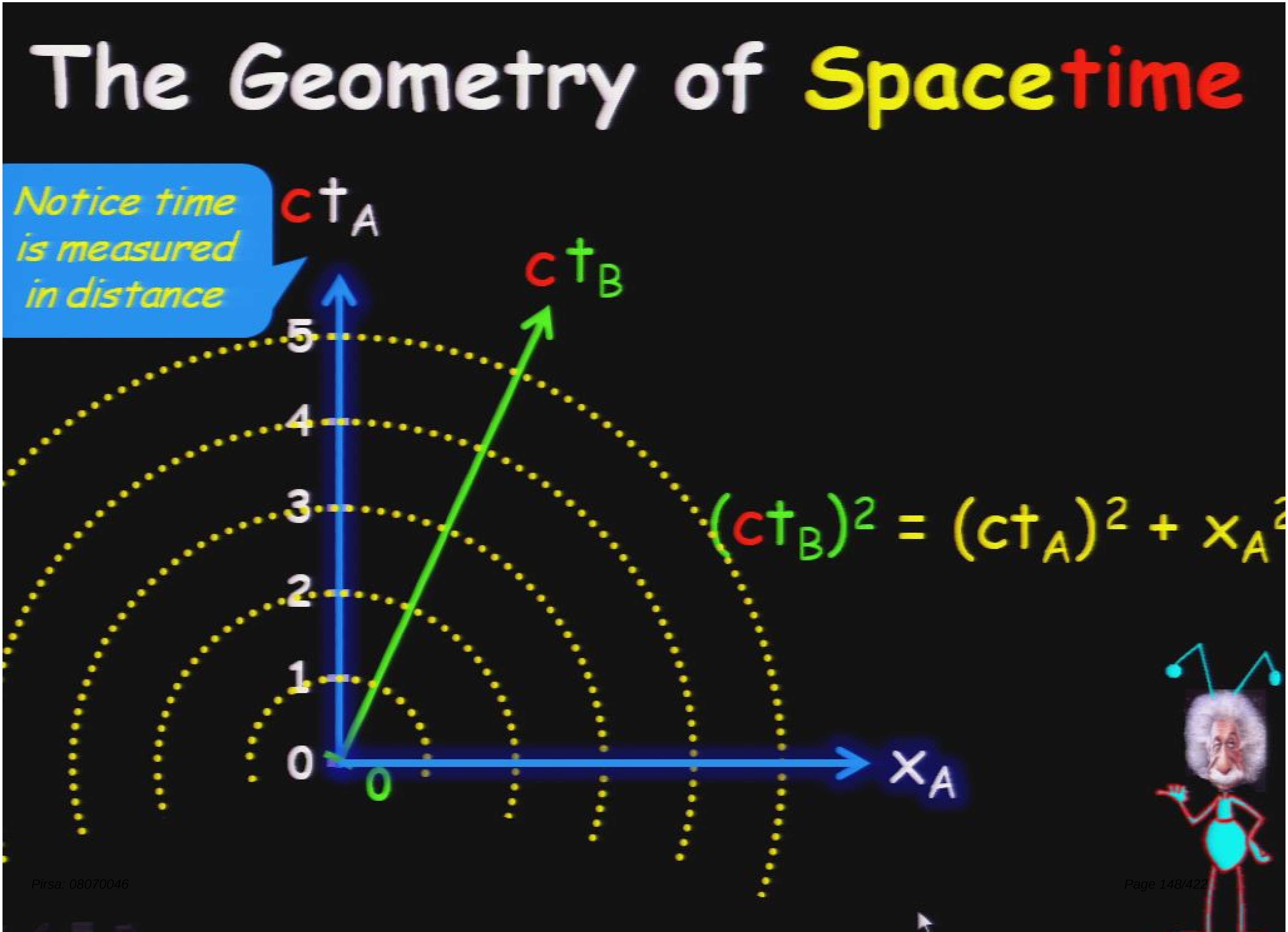
$$r^2 = y^2 + x^2$$

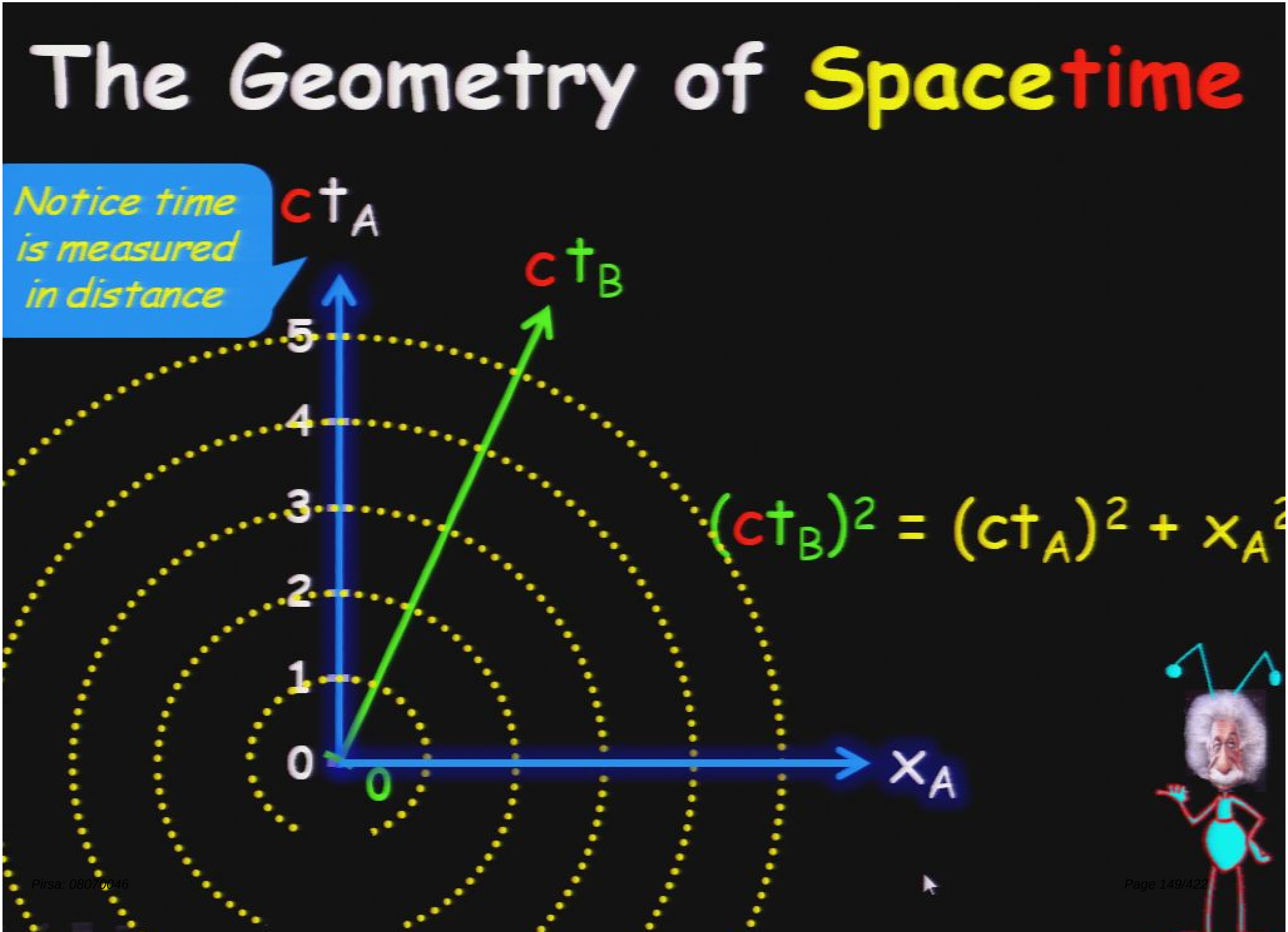
$$y_B{}^2 = y_A{}^2 + x_A{}^2$$



The Geometry of Spacetime

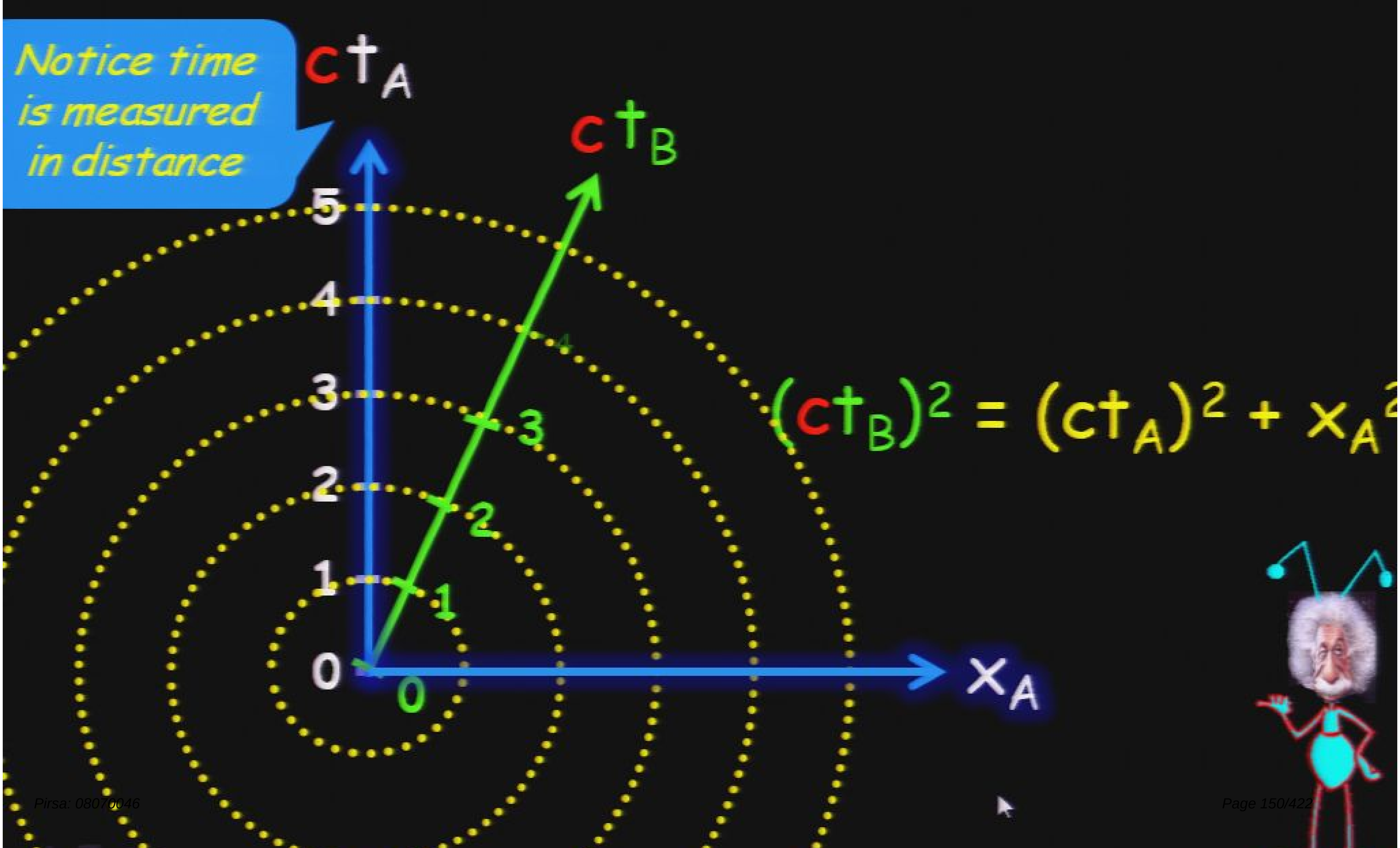



The Geometry of Spacetime
Notice time is measured in distance
ct_A
ct_B
5
4
3
2
1
0
0
x_A
$(ct_B)^2 = (ct_A)^2 + x_A^2$

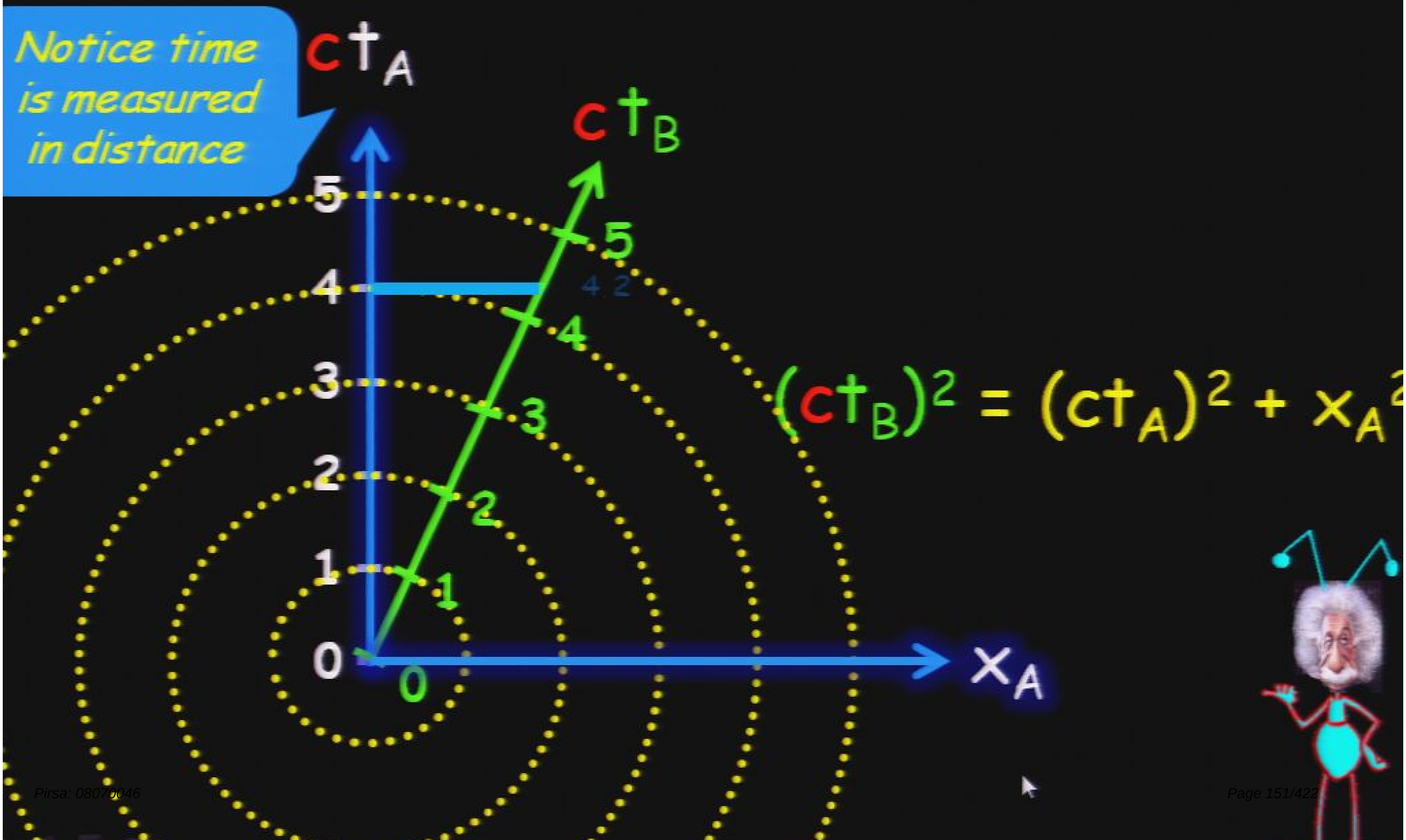


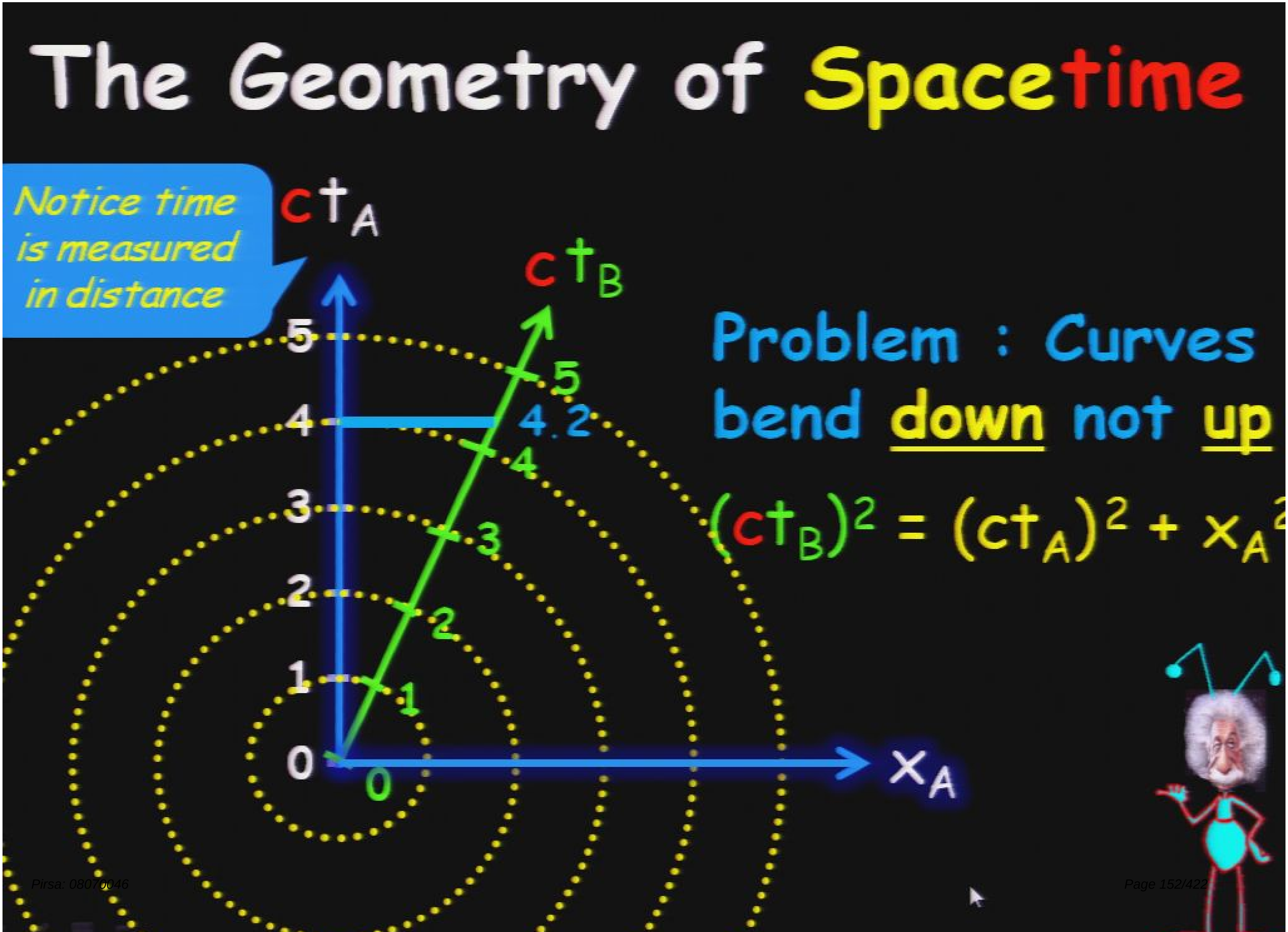
The Geometry of Spacetime
Notice time is measured in distance
ct_A
ct_B
5
4
3
2
1
0
0
x_A
$(ct_B)^2 = (ct_A)^2 + x_A^2$

The Geometry of Spacetime

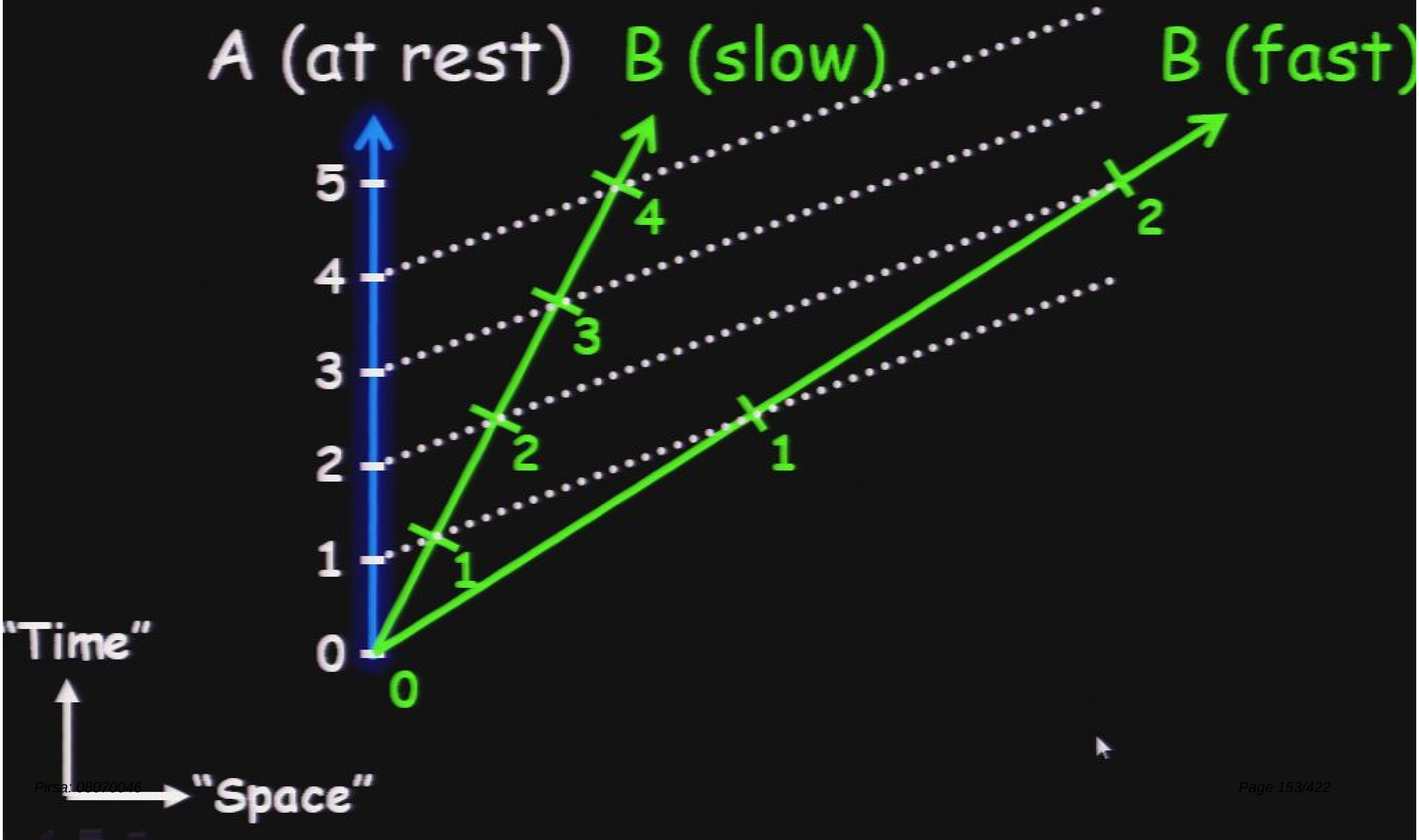


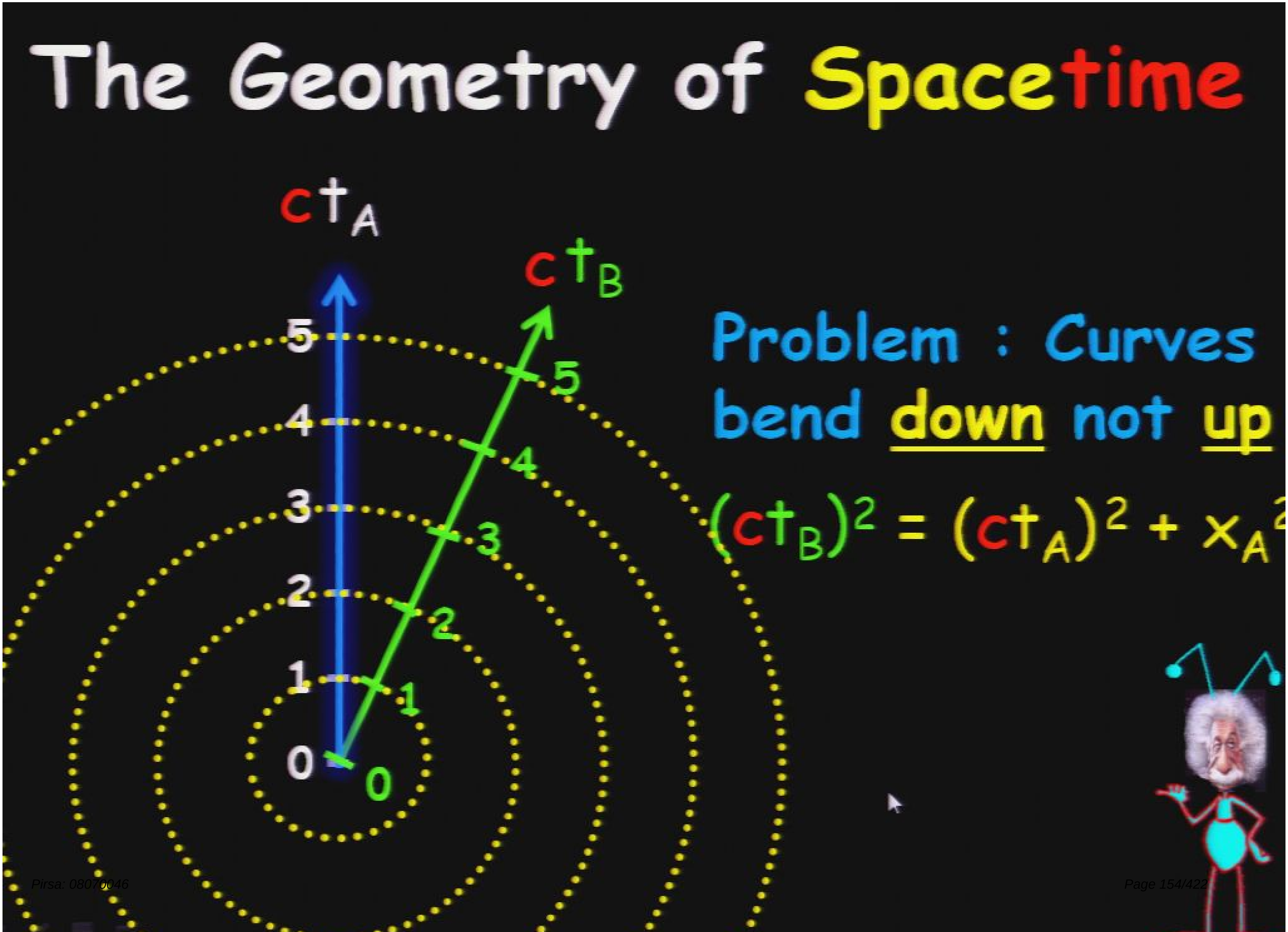
The Geometry of Spacetime




The Geometry of Spacetime
Notice time is measured in distance
ctA
ctB
Problem : Curves bend down not up
(ctB)2 = (ctA)2 + xA2
4.2
xA

Experimental Data:





The Geometry of Spacetime
ctA
ctB
5
4
3
2
1
0
5
4
3
2
1
0
Problem : Curves bend down not up
$(ct_B)^2 = (ct_A)^2 + x_A^2$

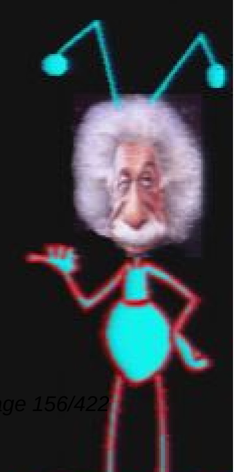
The Geometry of Spacetime

Problem : Curves bend down not up

$$(ct_B)^2 = (ct_A)^2 + x_A^2$$

The Geometry of Spacetime

$$(ct_B)^2 = (ct_A)^2 + x_A^2$$



The Geometry of Spacetime

Try hyperbolas instead of circles:

$$(ct_B)^2 = (ct_A)^2 + x_A^2$$

The Geometry of Spacetime

Try <u>hyperbolas</u> instead of circles:

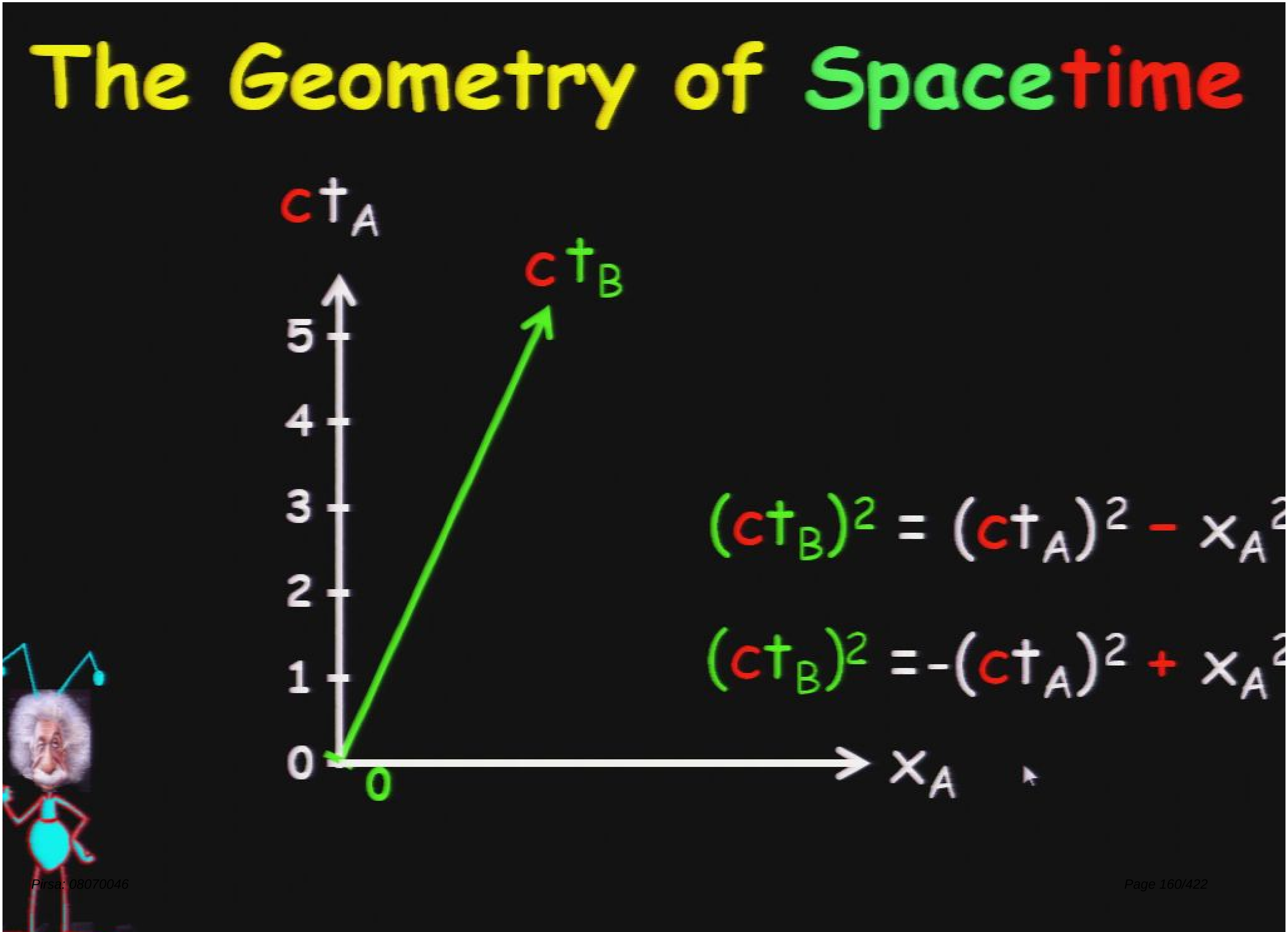
$$(ct_B)^2 = (ct_A)^2 - x_A^2$$

Minus sign

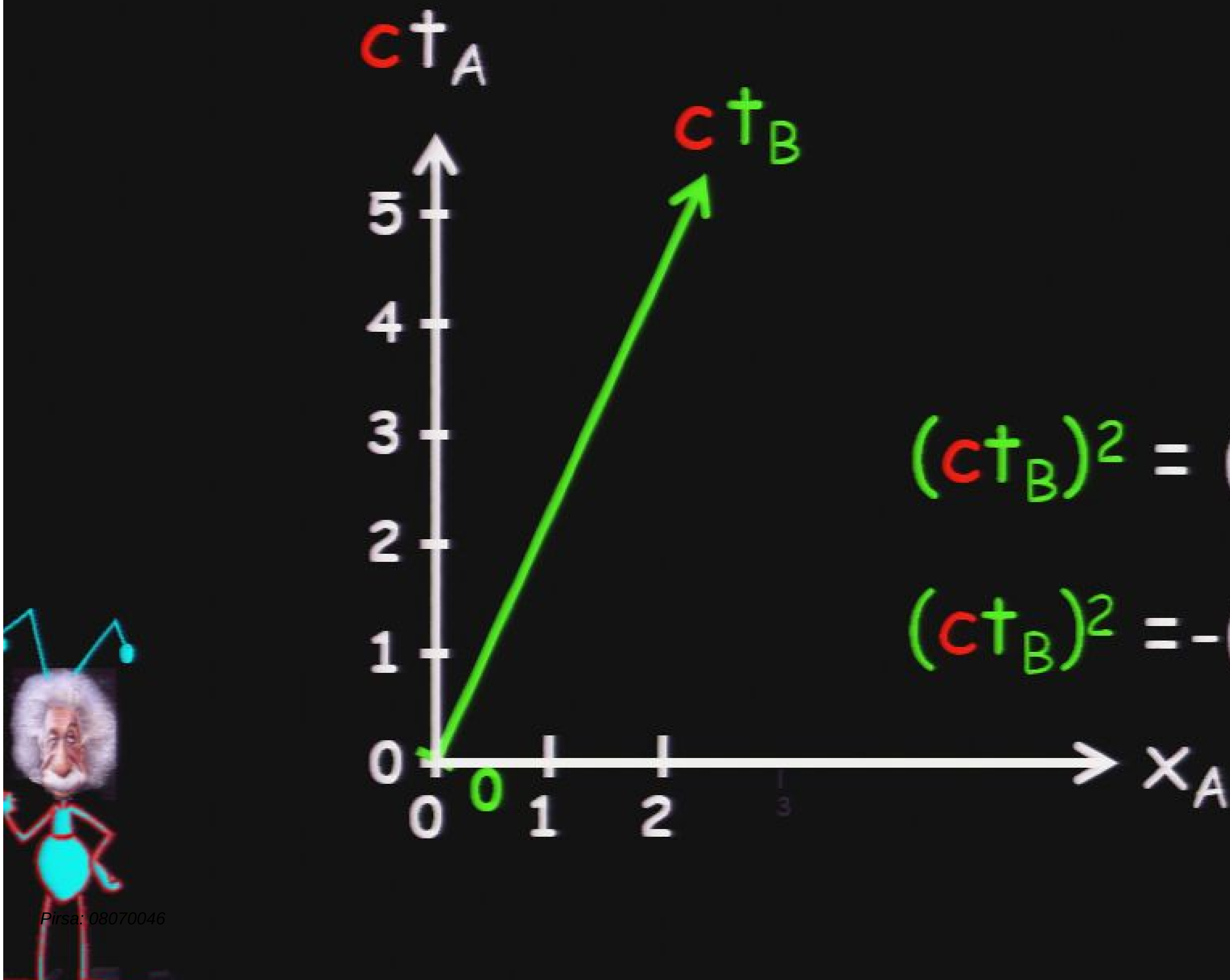
The Geometry of Spacetime

$$(ct_B)^2 = (ct_A)^2 - x_A^2$$

$$(ct_B)^2 = -(ct_A)^2 + x_A^2$$


The Geometry of Spacetime
ct_A
ct_B
5
4
3
2
1
0
0
x_A
$(ct_B)^2 = (ct_A)^2 - x_A^2$
$(ct_B)^2 = -(ct_A)^2 + x_A^2$

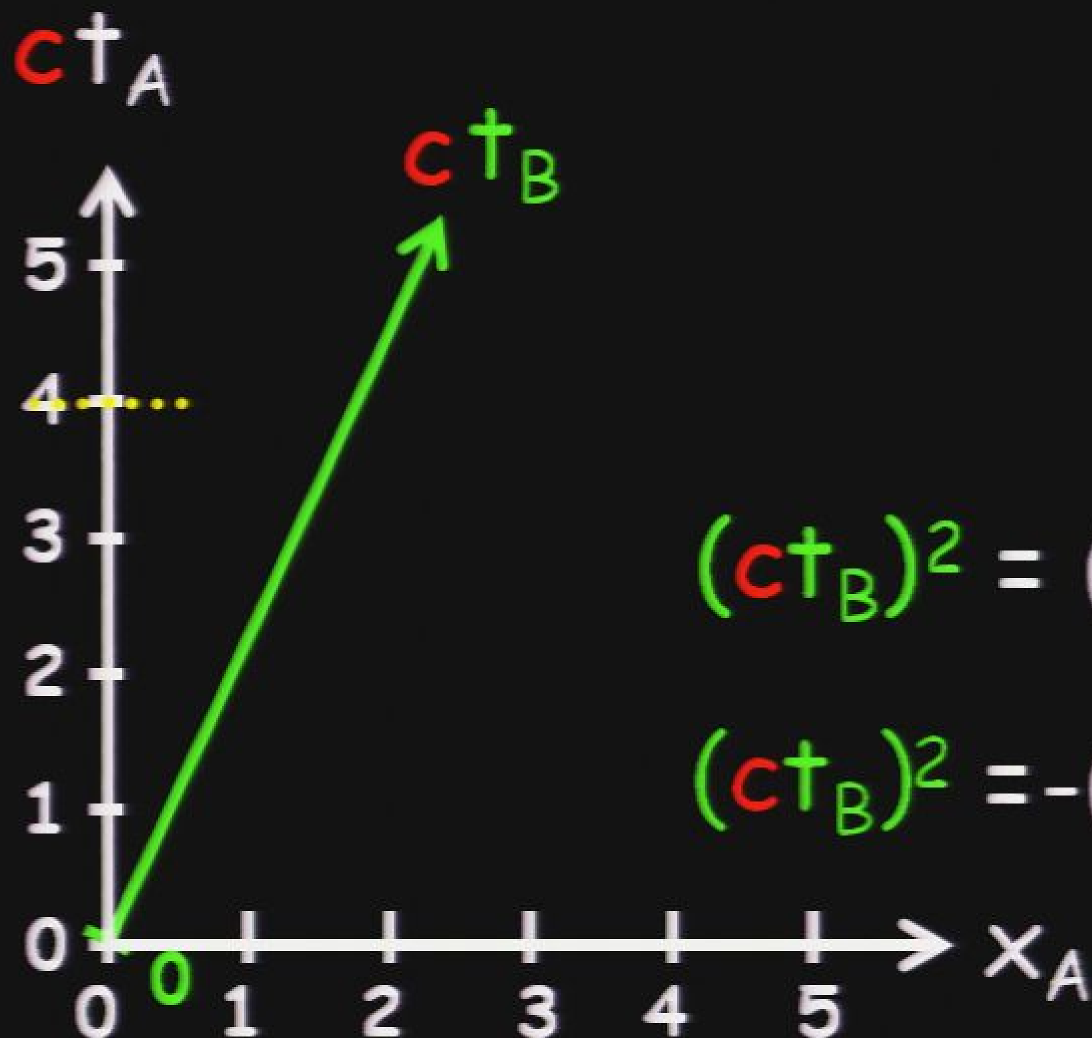
The Geometry of Spacetime



$$(ct_B)^2 = (ct_A)^2 - x_A^2$$

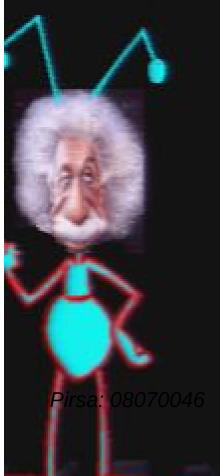
$$(ct_B)^2 = -(ct_A)^2 + x_A^2$$

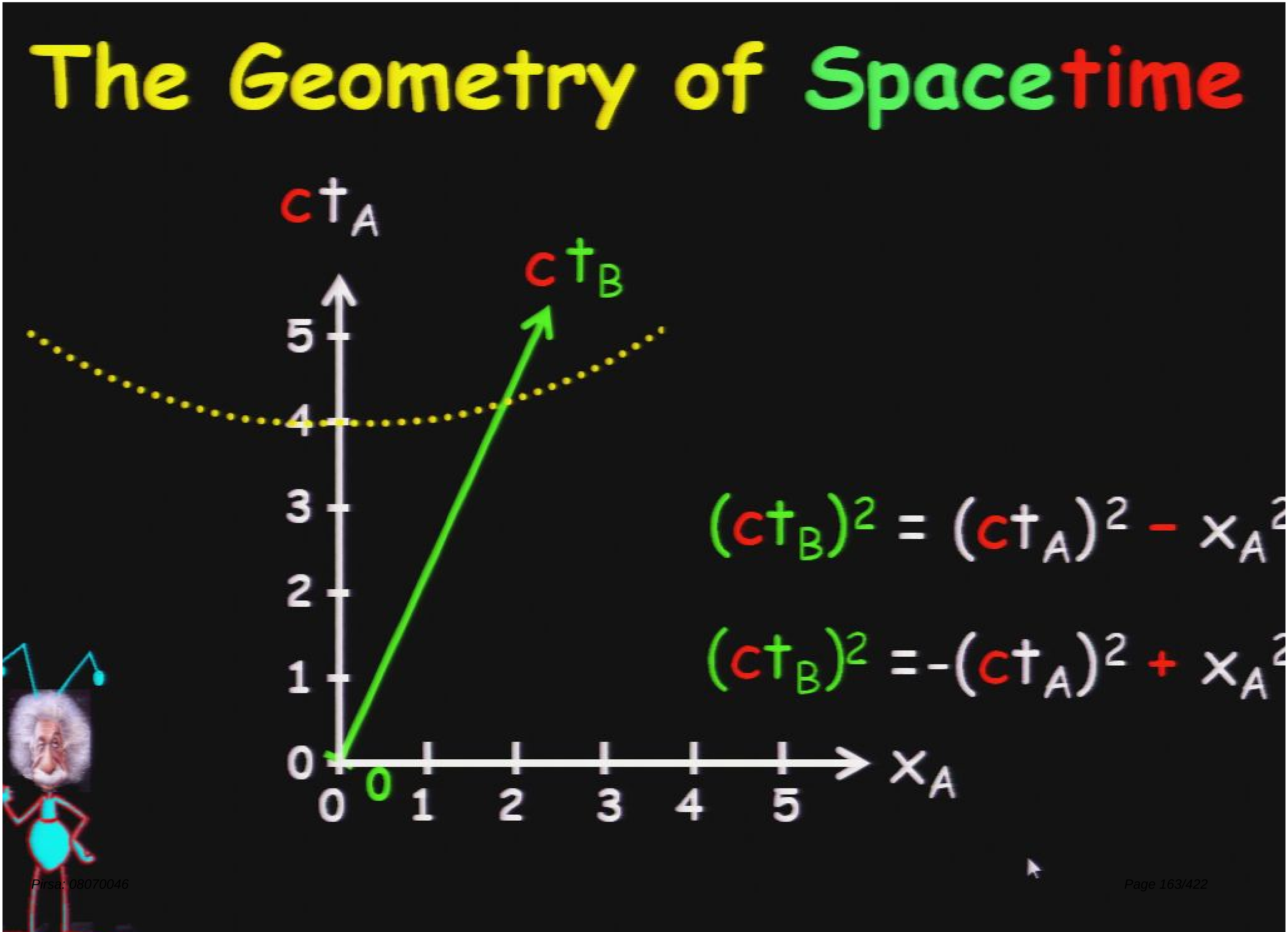
The Geometry of Spacetime



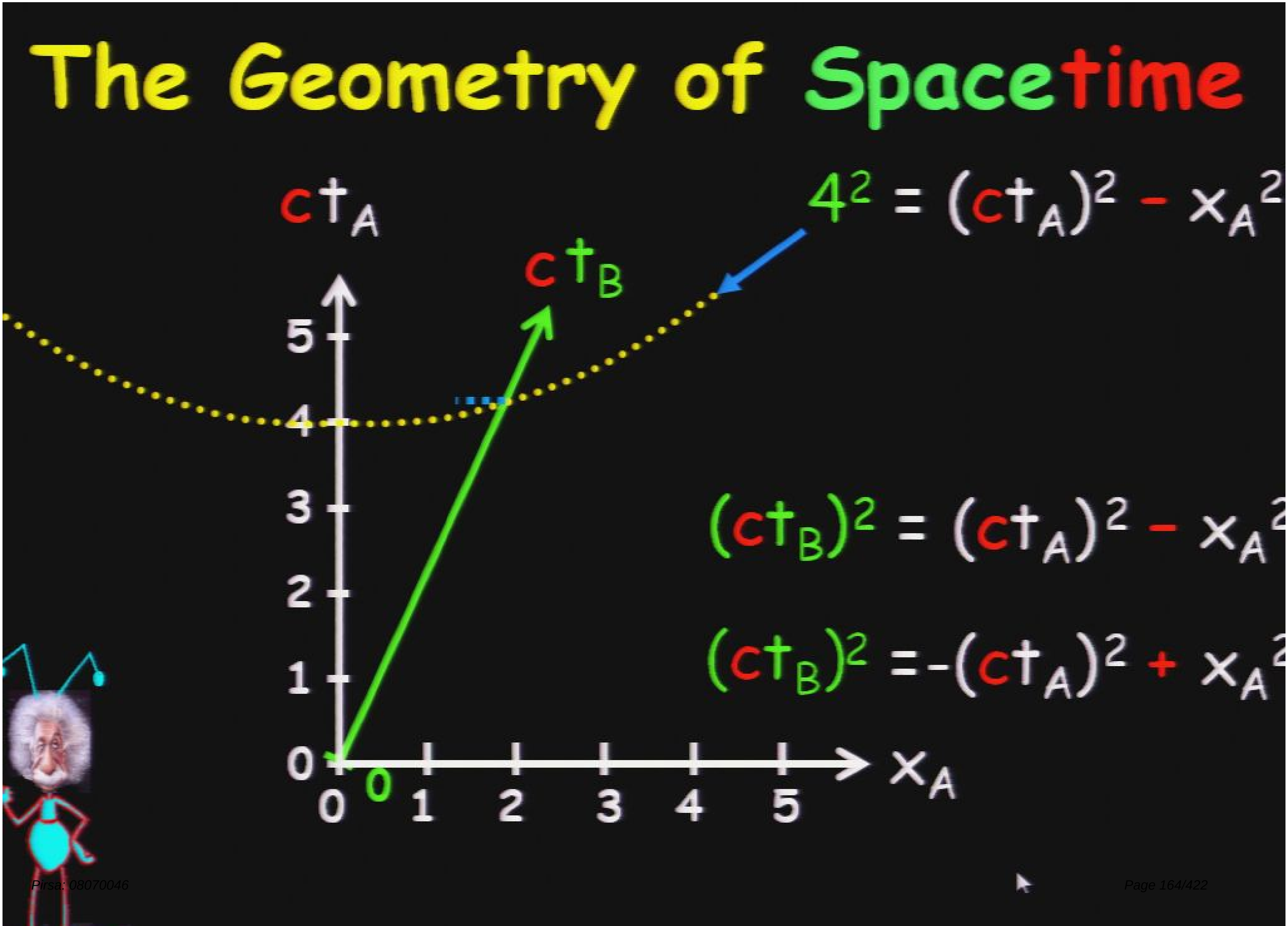
$$(ct_B)^2 = (ct_A)^2 - x_A^2$$

$$(ct_B)^2 = -(ct_A)^2 + x_A^2$$

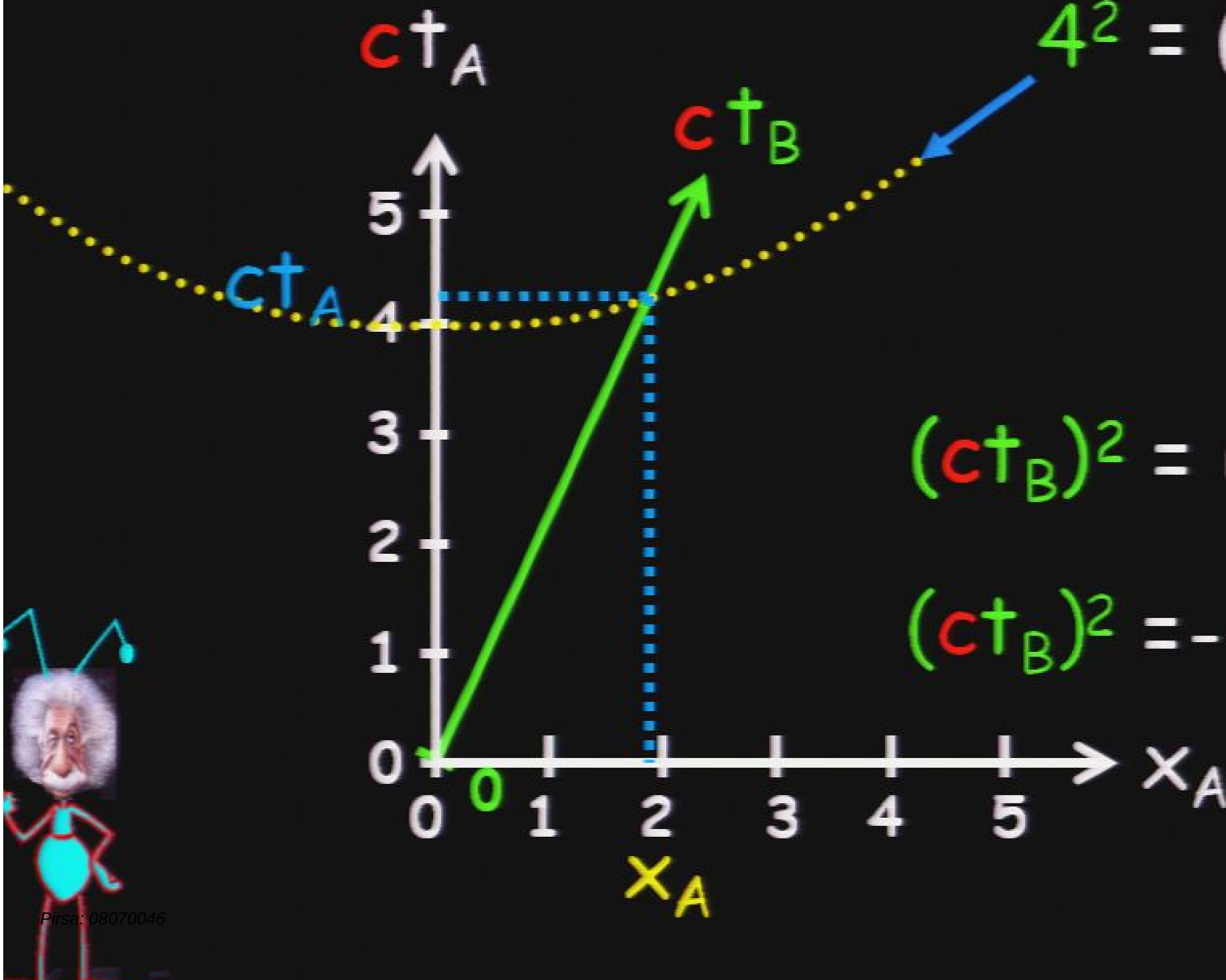




The Geometry of Spacetime
ct_A
ct_B
$(ct_B)^2 = (ct_A)^2 - x_A^2$
$(ct_B)^2 = -(ct_A)^2 + x_A^2$
x_A
0 1 2 3 4 5
0


The Geometry of Spacetime
ct_A
ct_B
$4^2 = (ct_A)^2 - x_A^2$
$(ct_B)^2 = (ct_A)^2 - x_A^2$
$(ct_B)^2 = -(ct_A)^2 + x_A^2$
5
4
3
2
1
0
0
0
1
2
3
4
5
x_A

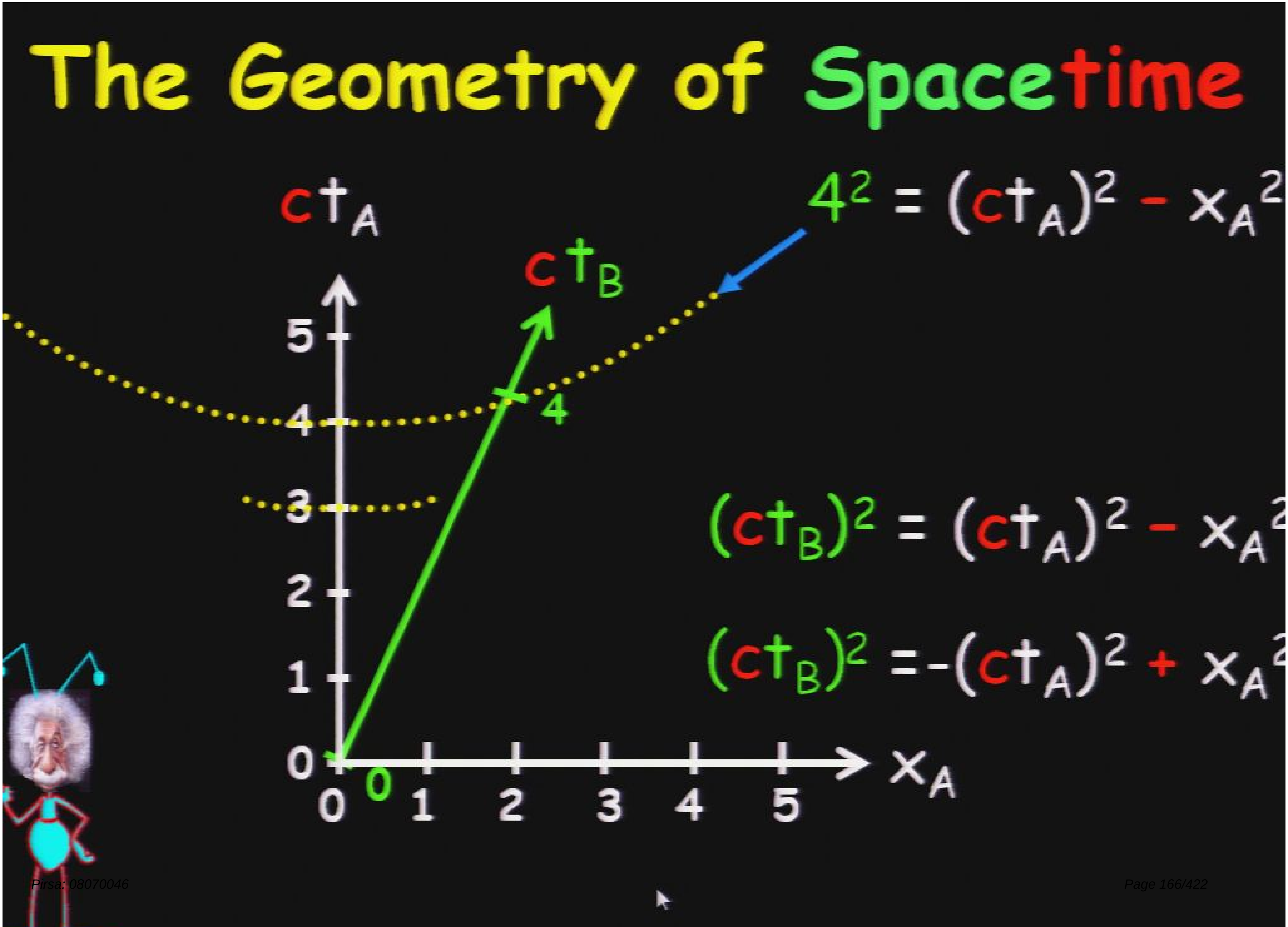
The Geometry of Spacetime

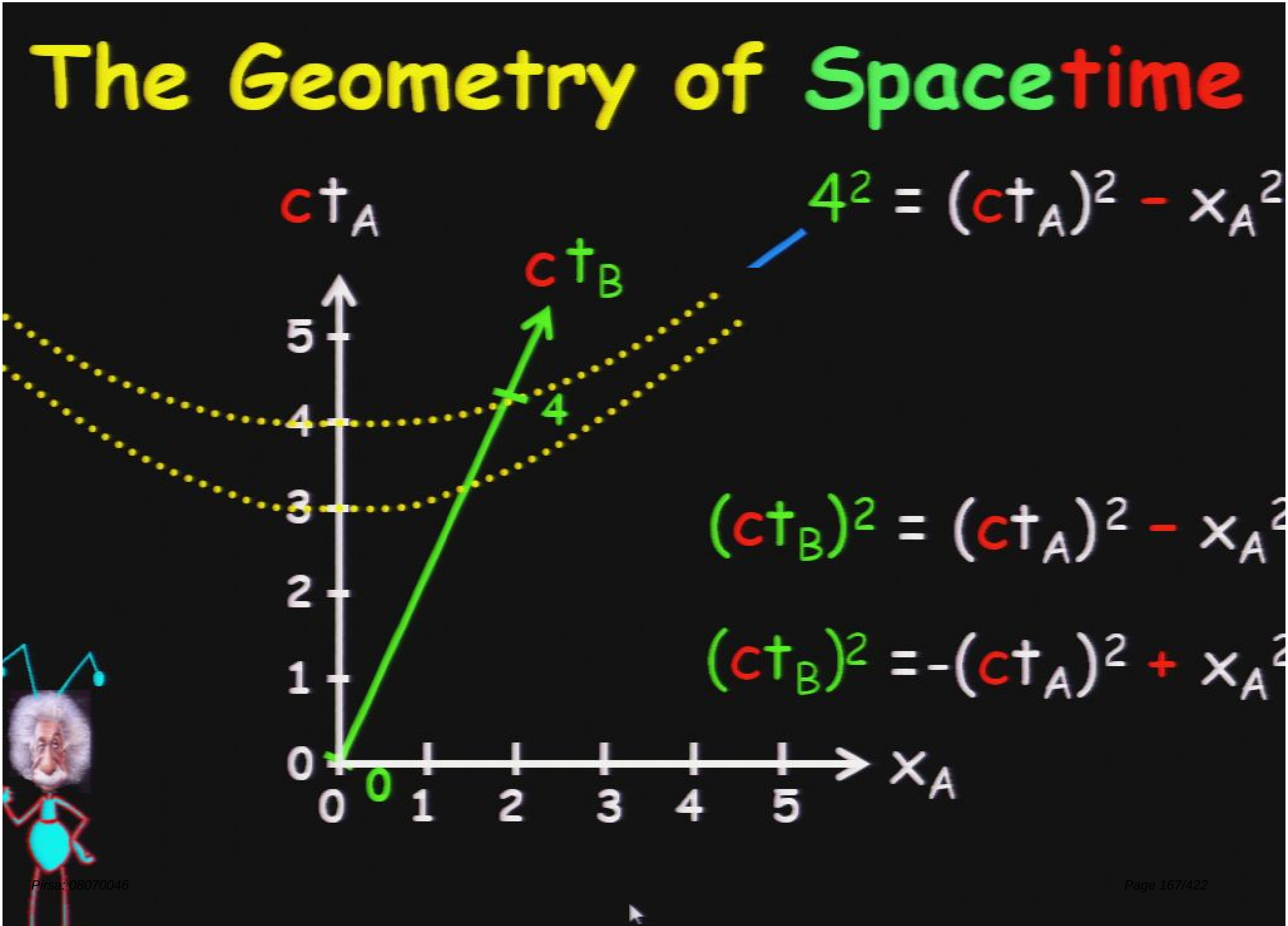


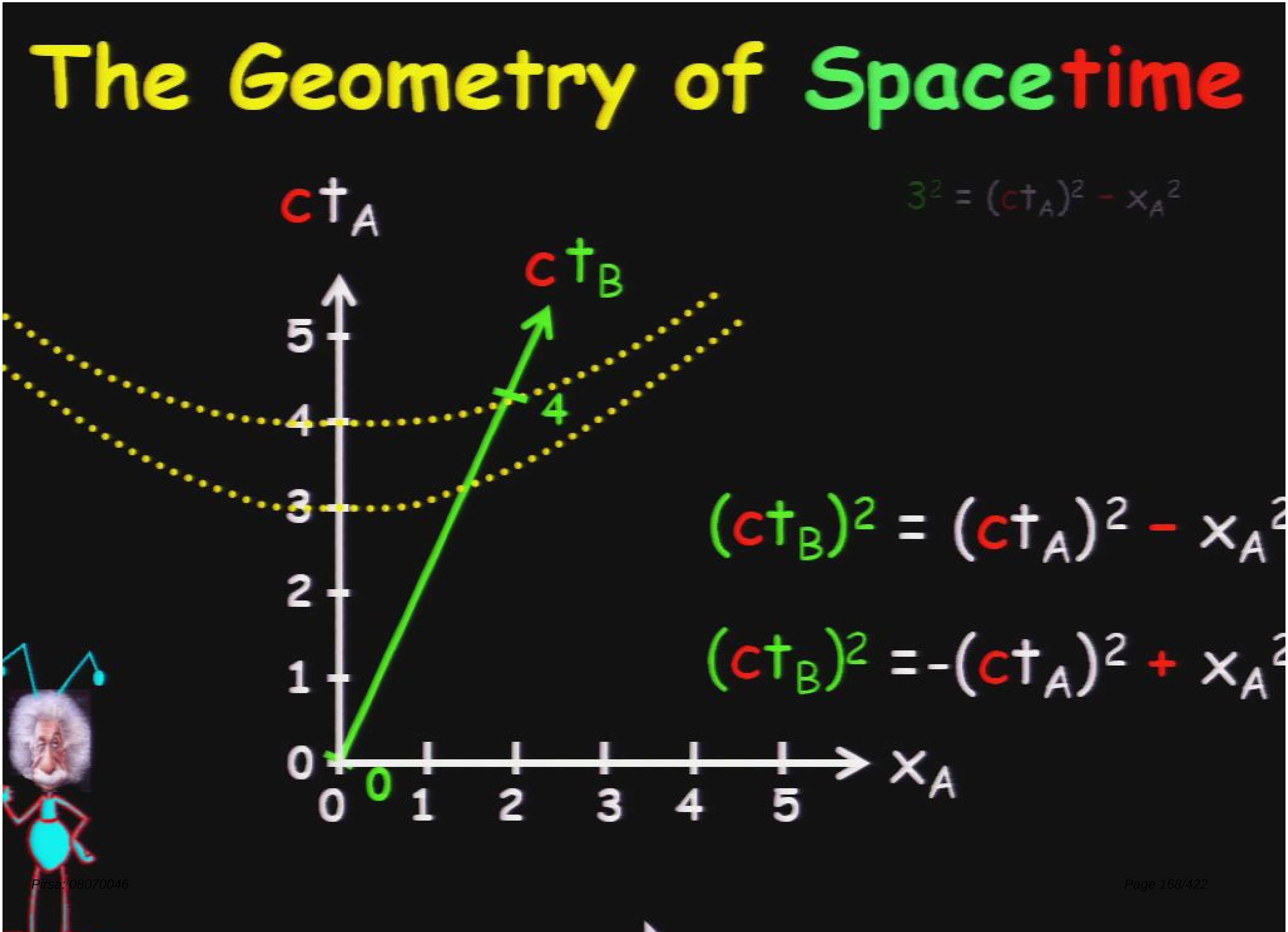
$$4^2 = (ct_A)^2 - x_A^2$$

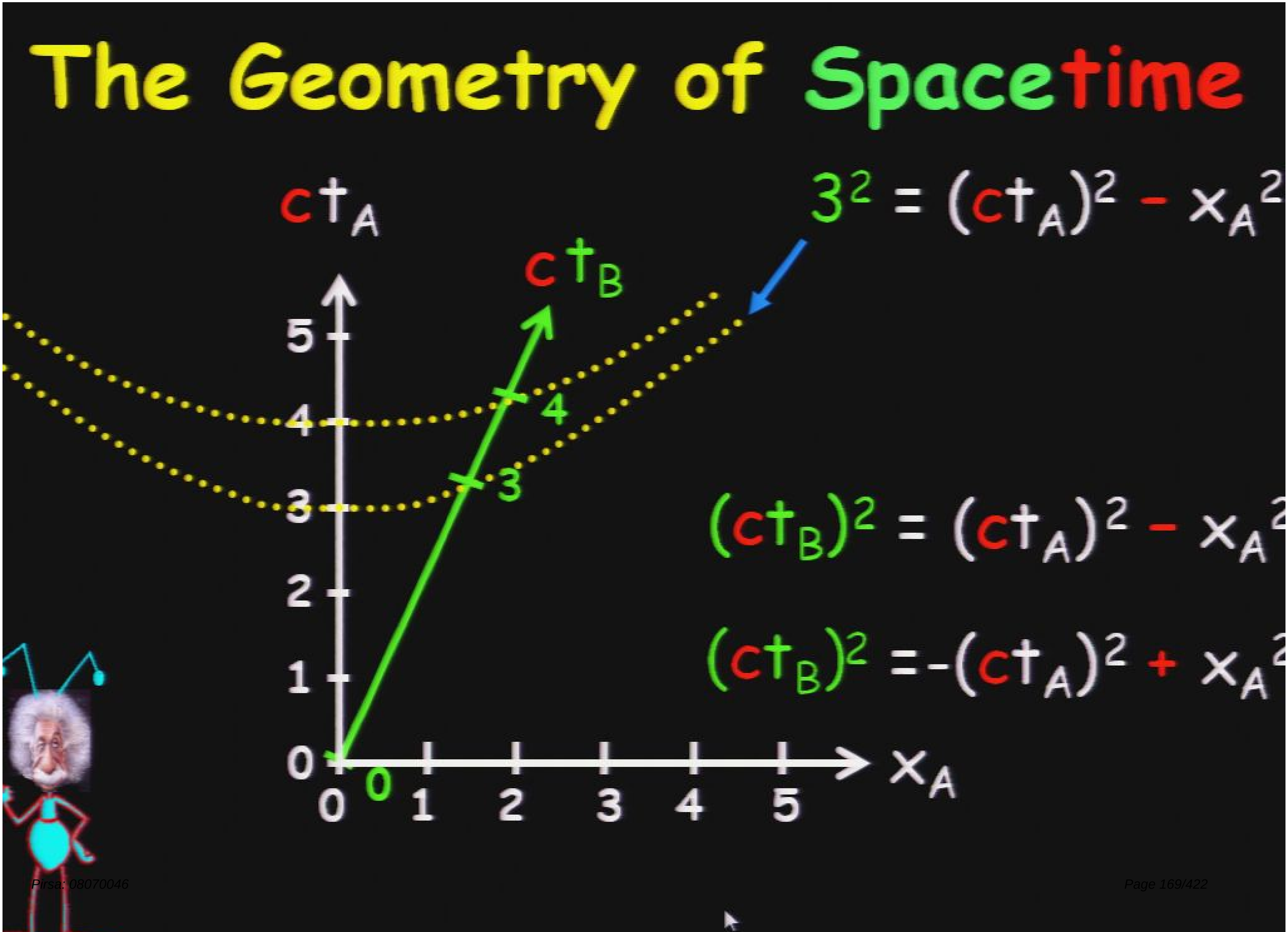
$$(ct_B)^2 = (ct_A)^2 - x_A^2$$

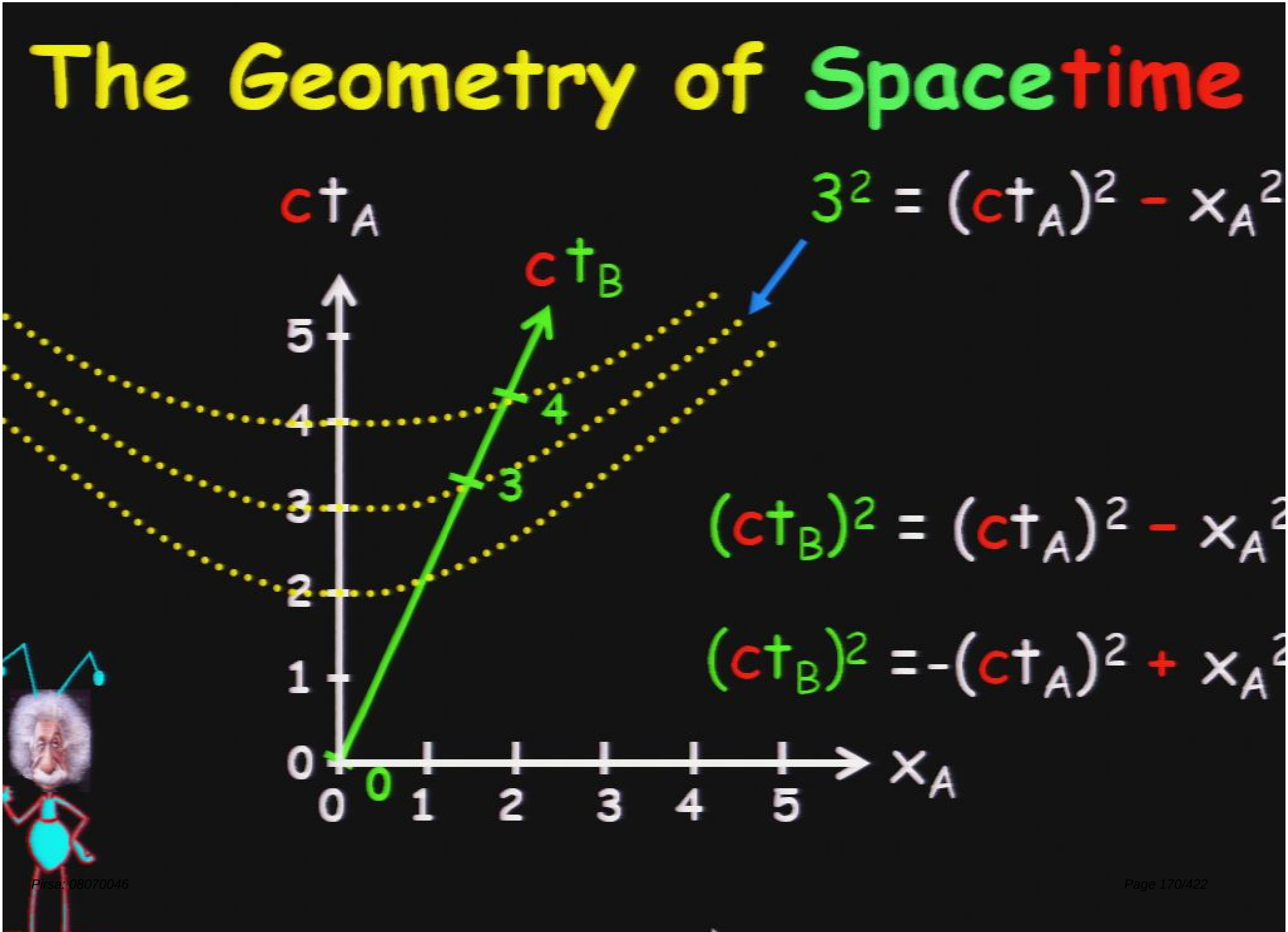
$$(ct_B)^2 = -(ct_A)^2 + x_A^2$$


The Geometry of Spacetime
ct_A
ct_B
$4^2 = (ct_A)^2 - x_A^2$
5
4
3
2
1
0
4
0
0 1 2 3 4 5
x_A
$(ct_B)^2 = (ct_A)^2 - x_A^2$
$(ct_B)^2 = -(ct_A)^2 + x_A^2$

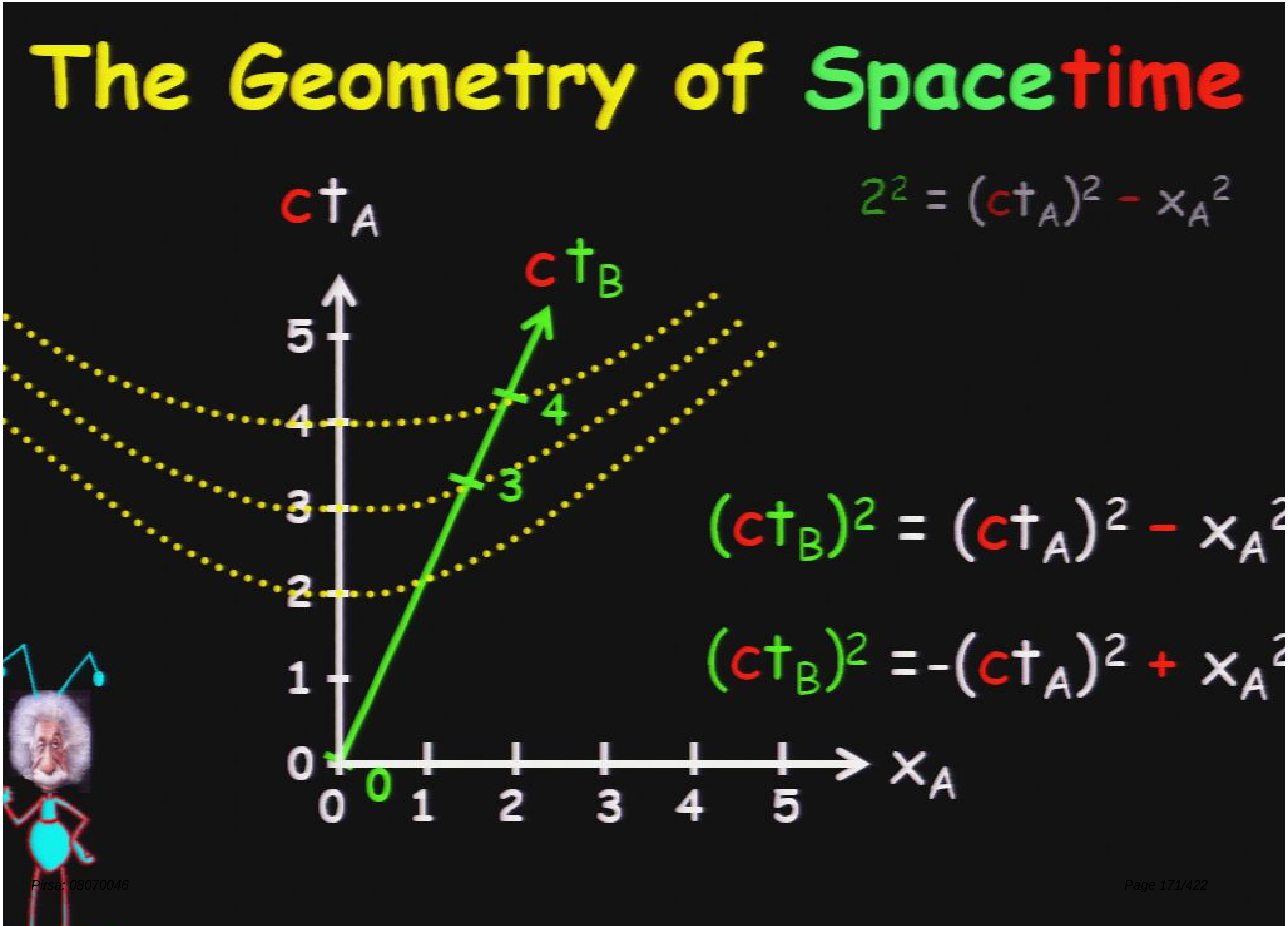

The Geometry of Spacetime
ct_A
ct_B
$4^2 = (ct_A)^2 - x_A^2$
$(ct_B)^2 = (ct_A)^2 - x_A^2$
$(ct_B)^2 = -(ct_A)^2 + x_A^2$
x_A
0 1 2 3 4 5
0 1 2 3 4 5
4
0

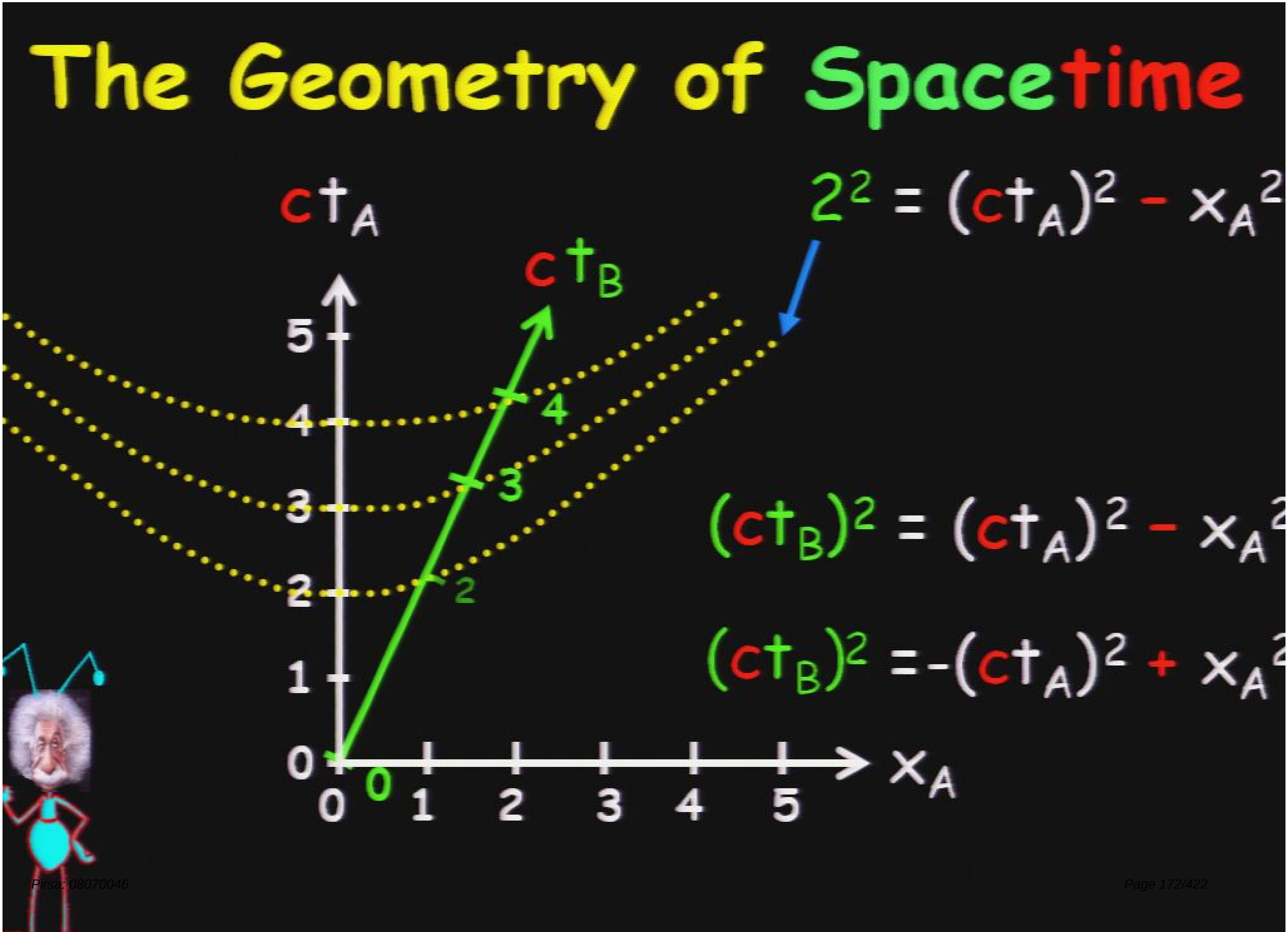

The Geometry of Spacetime
$3^2 = (ct_A)^2 - x_A^2$
ct_A
ct_B
5
4
3
2
1
0
4
0
0 1 2 3 4 5
x_A
$(ct_B)^2 = (ct_A)^2 - x_A^2$
$(ct_B)^2 = -(ct_A)^2 + x_A^2$


The Geometry of Spacetime
ctA
ctB
3² = (ctA)² − xA²
(ctB)² = (ctA)² − xA²
(ctB)² =−(ctA)² + xA²
0 1 2 3 4 5
xA



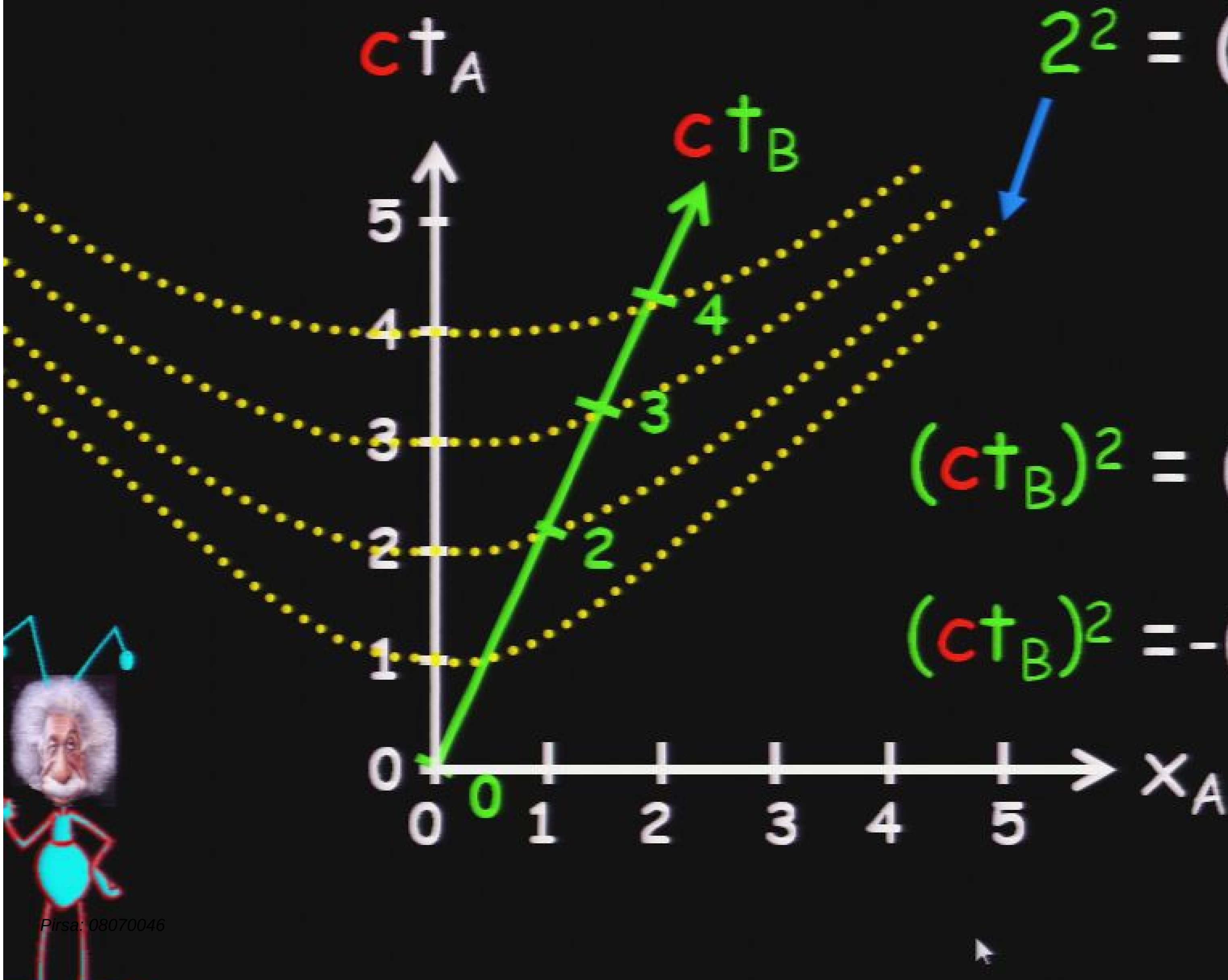
The Geometry of Spacetime
$3^2 = (ct_A)^2 - x_A^2$
ct_A
ct_B
5
4
3
2
1
0
4
3
0
0 1 2 3 4 5
x_A
$(ct_B)^2 = (ct_A)^2 - x_A^2$
$(ct_B)^2 = -(ct_A)^2 + x_A^2$


The Geometry of Spacetime
$2^2 = (ct_A)^2 - x_A^2$
ct_A
ct_B
$(ct_B)^2 = (ct_A)^2 - x_A^2$
$(ct_B)^2 = -(ct_A)^2 + x_A^2$
x_A
0 1 2 3 4 5



The Geometry of Spacetime
ct_A
ct_B
$2^2 = (ct_A)^2 - x_A^2$
$(ct_B)^2 = (ct_A)^2 - x_A^2$
$(ct_B)^2 = -(ct_A)^2 + x_A^2$
x_A
0 1 2 3 4 5

The Geometry of Spacetime



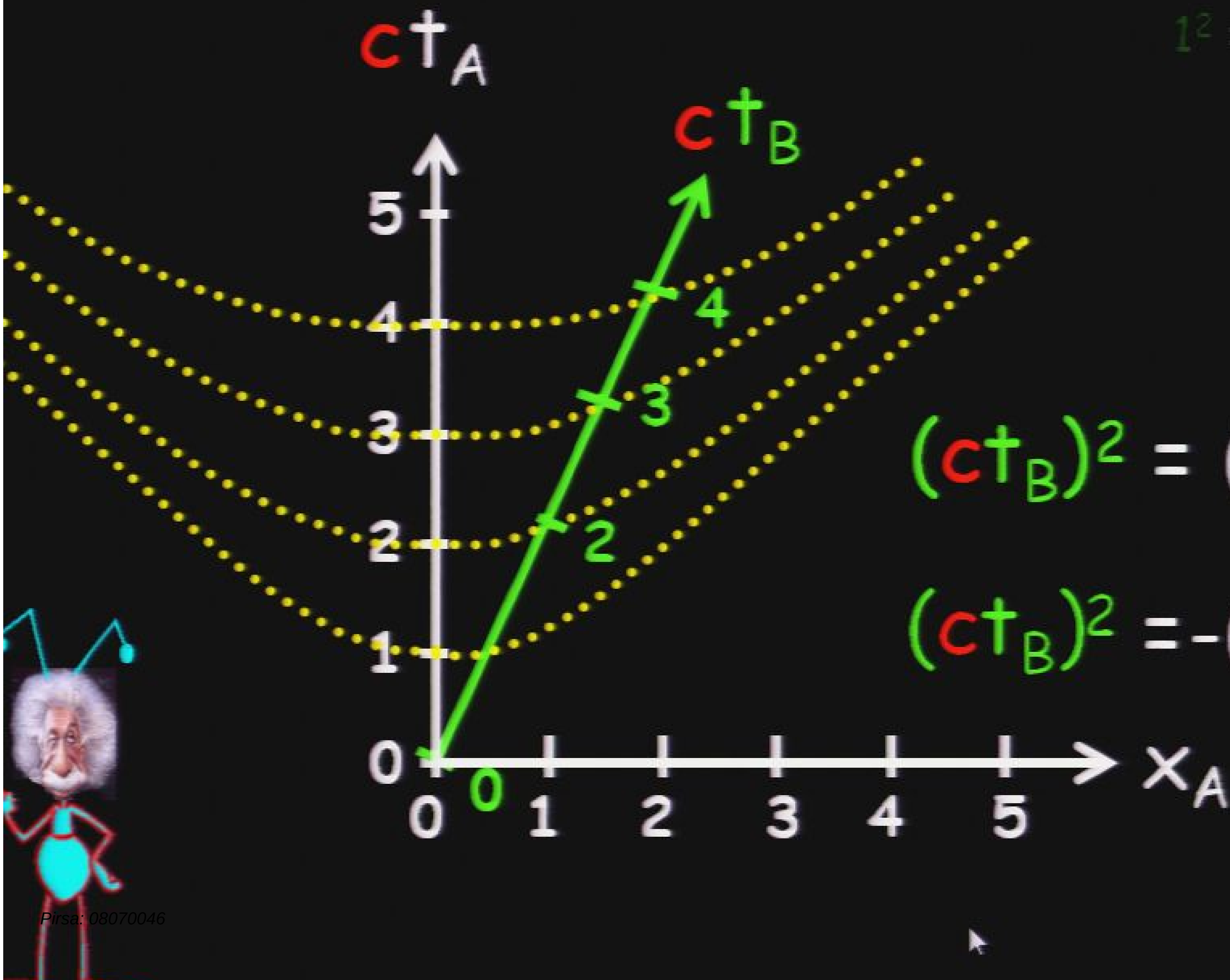
$$2^2 = (ct_A)^2 - x_A^2$$

$$(ct_B)^2 = (ct_A)^2 - x_A^2$$

$$(ct_B)^2 = -(ct_A)^2 + x_A^2$$

The Geometry of Spacetime

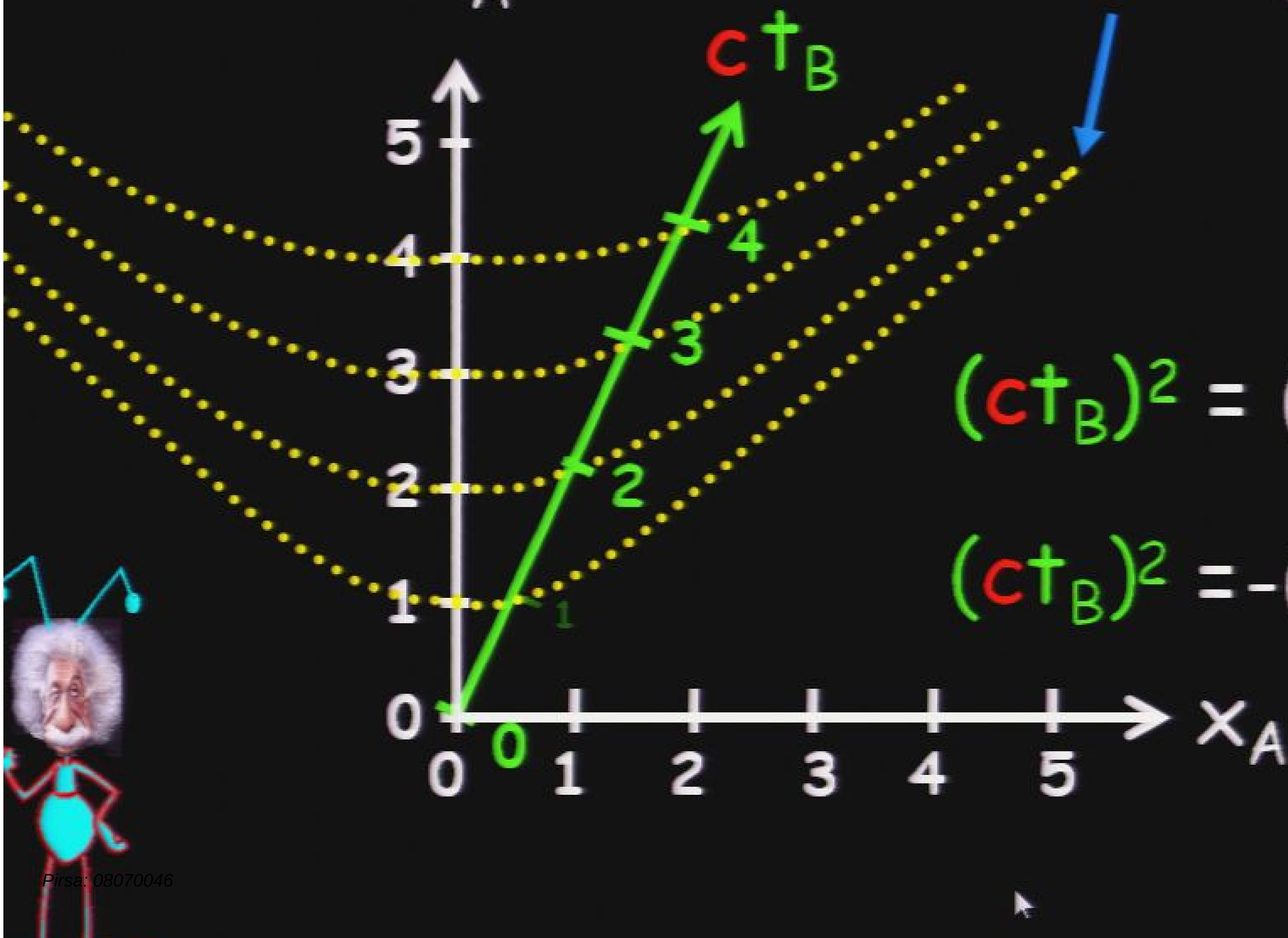
$$1^2 = (ct_A)^2 - x_A^2$$



$$(ct_B)^2 = (ct_A)^2 - x_A^2$$

$$(ct_B)^2 = -(ct_A)^2 + x_A^2$$

The Geometry of Spacetime

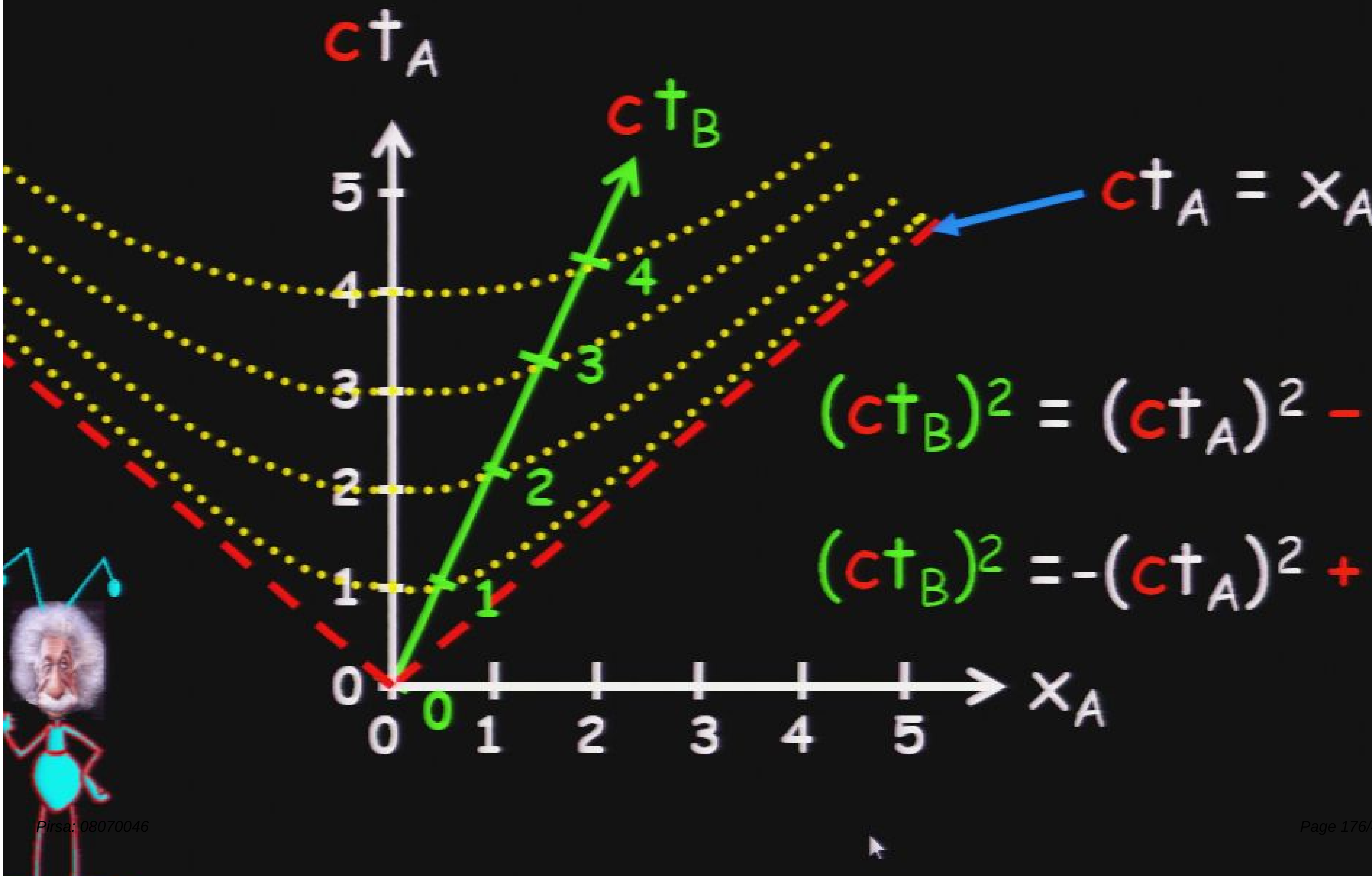


$$1^2 = (ct_A)^2 - x_A^2$$

$$(ct_B)^2 = (ct_A)^2 - x_A^2$$

$$(ct_B)^2 = -(ct_A)^2 + x_A^2$$

The Geometry of Spacetime

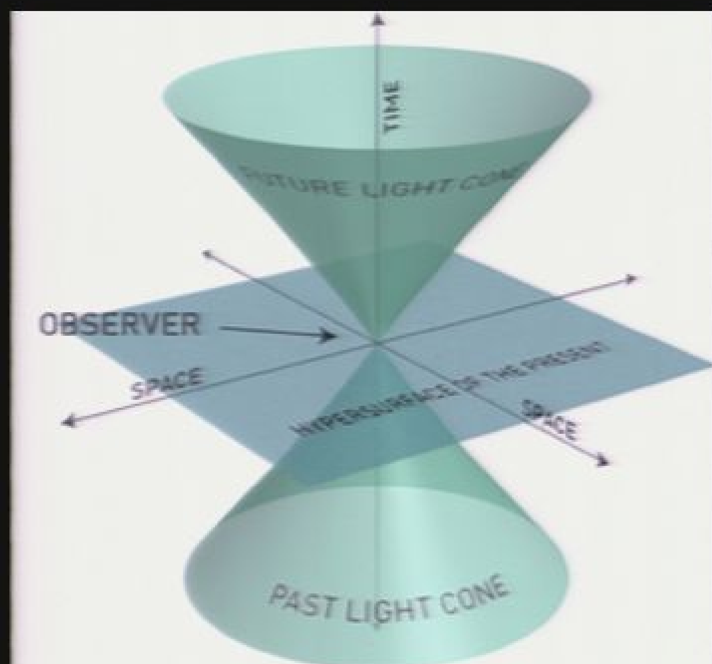


$$(ct_B)^2 = (ct_A)^2 - x_A^2$$

$$(ct_B)^2 = -(ct_A)^2 + x_A^2$$

Spacelike, Null, Timelike

Special relativity implies that all matter must move at less than or equal to the speed of light.



Einstein's Spacetime

- *Define a mathematical tool that handles both Space and Time* $P(t,x,y,z)$

Einstein's Spacetime

- *Define a mathematical tool that handles both Space and Time* $P(t,x,y,z)$
- *Example two dimensional Euclidean Space*

$$(\Delta s)^2 = (\Delta x)^2 + (\Delta y)^2$$ *Cartesian coordinates*

$$(\Delta s)^2 = (\Delta r)^2 + r^2 (\Delta \phi)^2$$ *Polar coordinates*

Einstein's Spacetime

- *Define a mathematical tool that handles both Space and Time* *P(t,x,y,z)*
- *Example two dimensional Euclidean Space*

$$(\Delta s)^2 = (\Delta x)^2 + (\Delta y)^2$$ *Cartesian coordinates*

$$(\Delta s)^2 = (\Delta r)^2 + r^2 (\Delta \phi)^2$$ *Polar coordinates*

Einstein's Spacetime

- *Define a mathematical tool that handles both Space and Time* $P(t,x,y,z)$
- *Example two dimensional Euclidean Space*

$$(\Delta s)^2 = (\Delta x)^2 + (\Delta y)^2$$ *Cartesian coordinates*

$$(\Delta s)^2 = (\Delta r)^2 + r^2 (\Delta \phi)^2$$ *Polar coordinates*

- *Example of two dimensional Minkowski Space*

$$(\Delta s)^2 = -(\Delta t)^2 + (\Delta x)^2$$ *Usual representation*

$$(\Delta s)^2 = -(\Delta t)^2 + t^2 (\Delta \phi)^2$$ *Milne representation*

The Geodesics

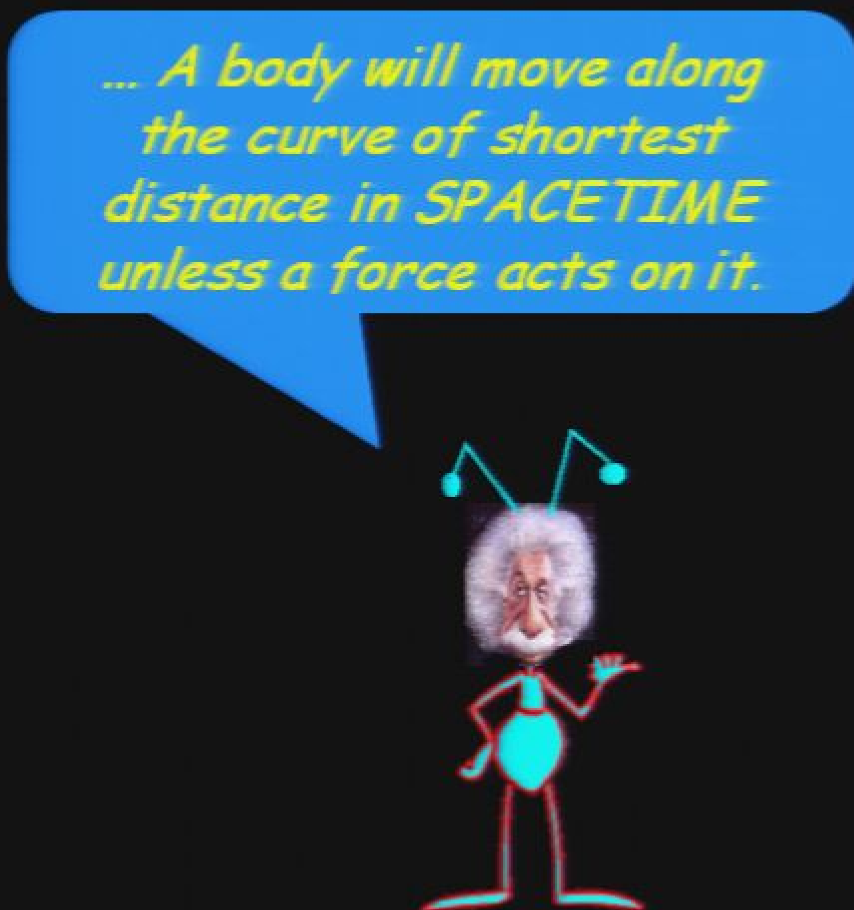
- Einstein needed to modify Newton's First Law and he did it like like this...

The Geodesics

- Einstein needed to modify Newton's First Law and he did it like like this...

The Geodesics

- Einstein needed to modify Newton's First Law and he did it like like this…



The Geodesics

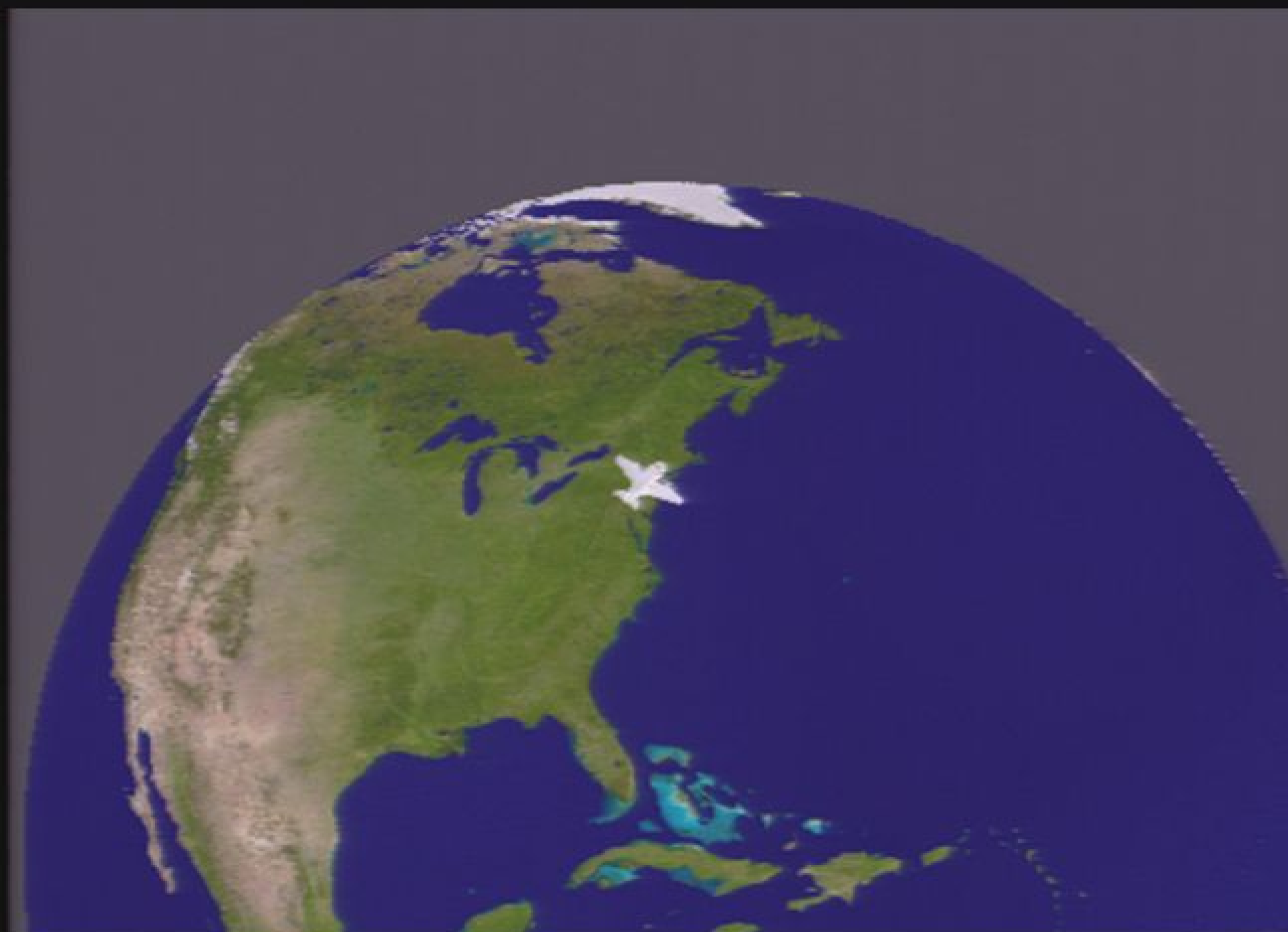
- Einstein needed to modify Newton's First Law and he did it like like this…

… A body will move along the curve of shortest distance in SPACETIME unless a force acts on it.

… The shortest distance between two points in general space isn't generally a straight line.

Curves of shortest distance are known in relativistic jargon as geodesics.

You are familiar with the Geodesic



The pilot does not need to turn the plane to fly from Toronto to Rome

You are familiar with the Geodesic

The pilot does not need to turn the plane to fly from Toronto to Rome

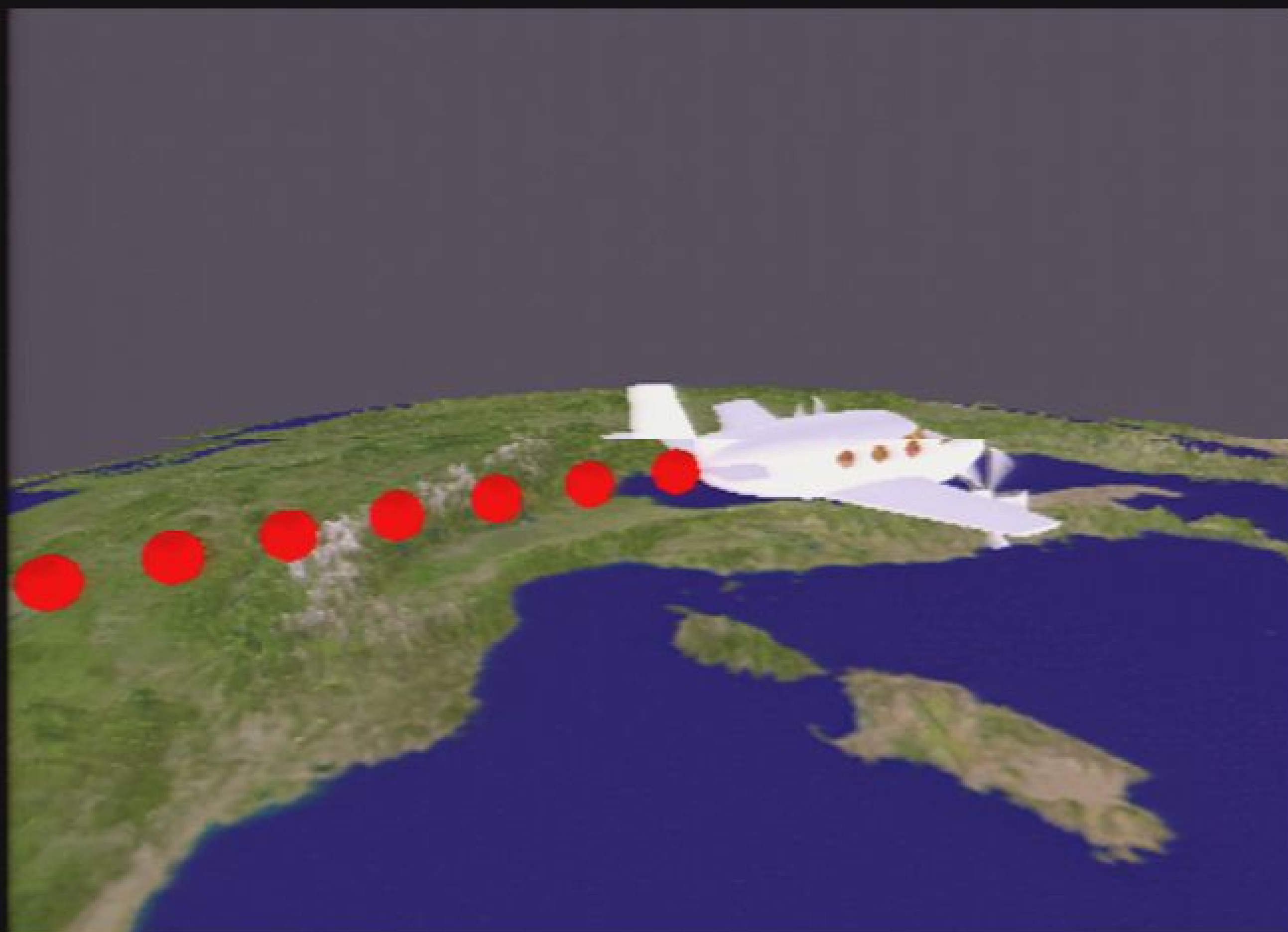
You are familiar with the Geodesic

The pilot does not need to turn the plane to fly from Toronto to Rome

You are familiar with the Geodesic

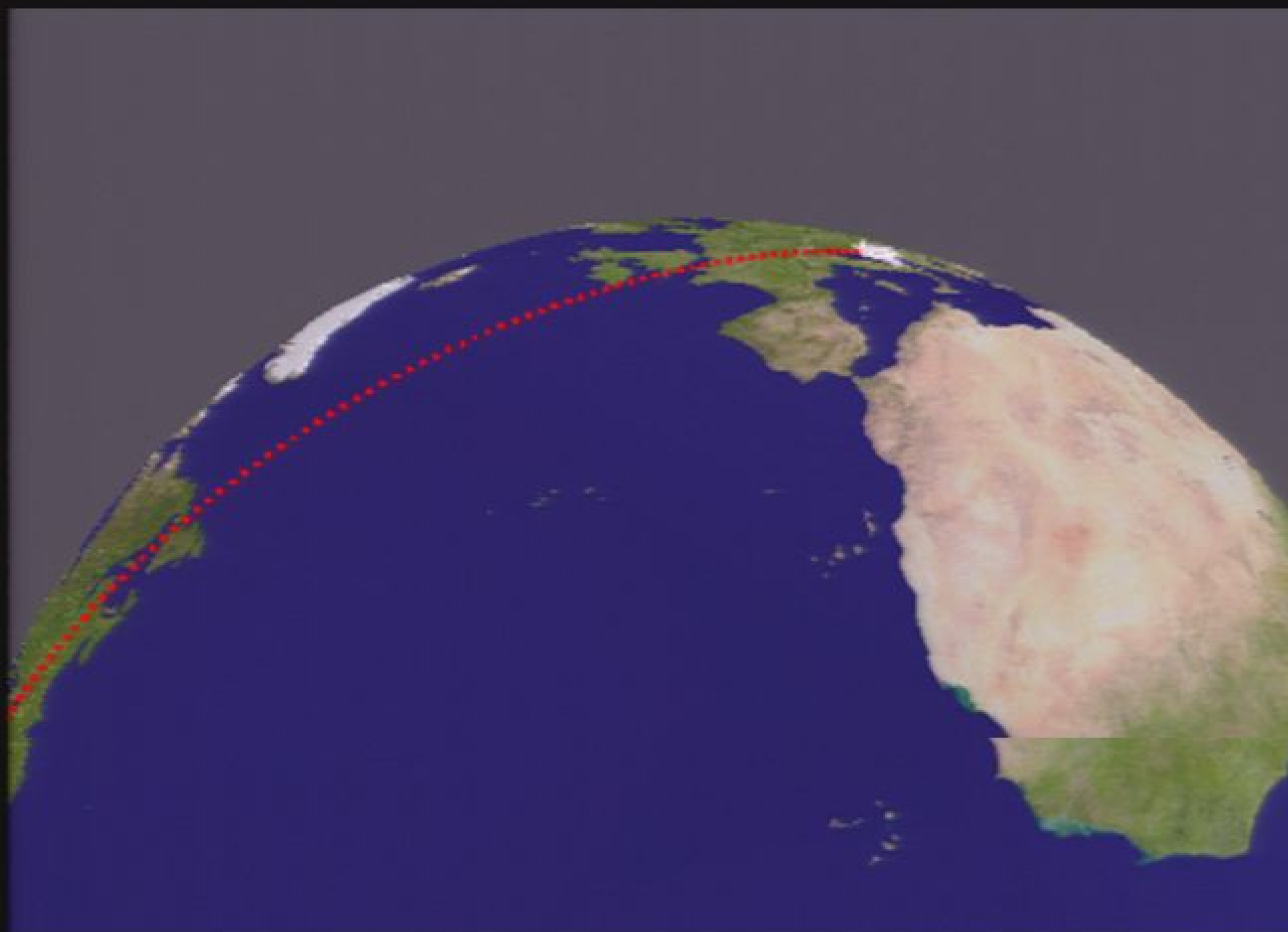
The pilot does not need to turn the plane to fly from Toronto to Rome

You are familiar with the Geodesic



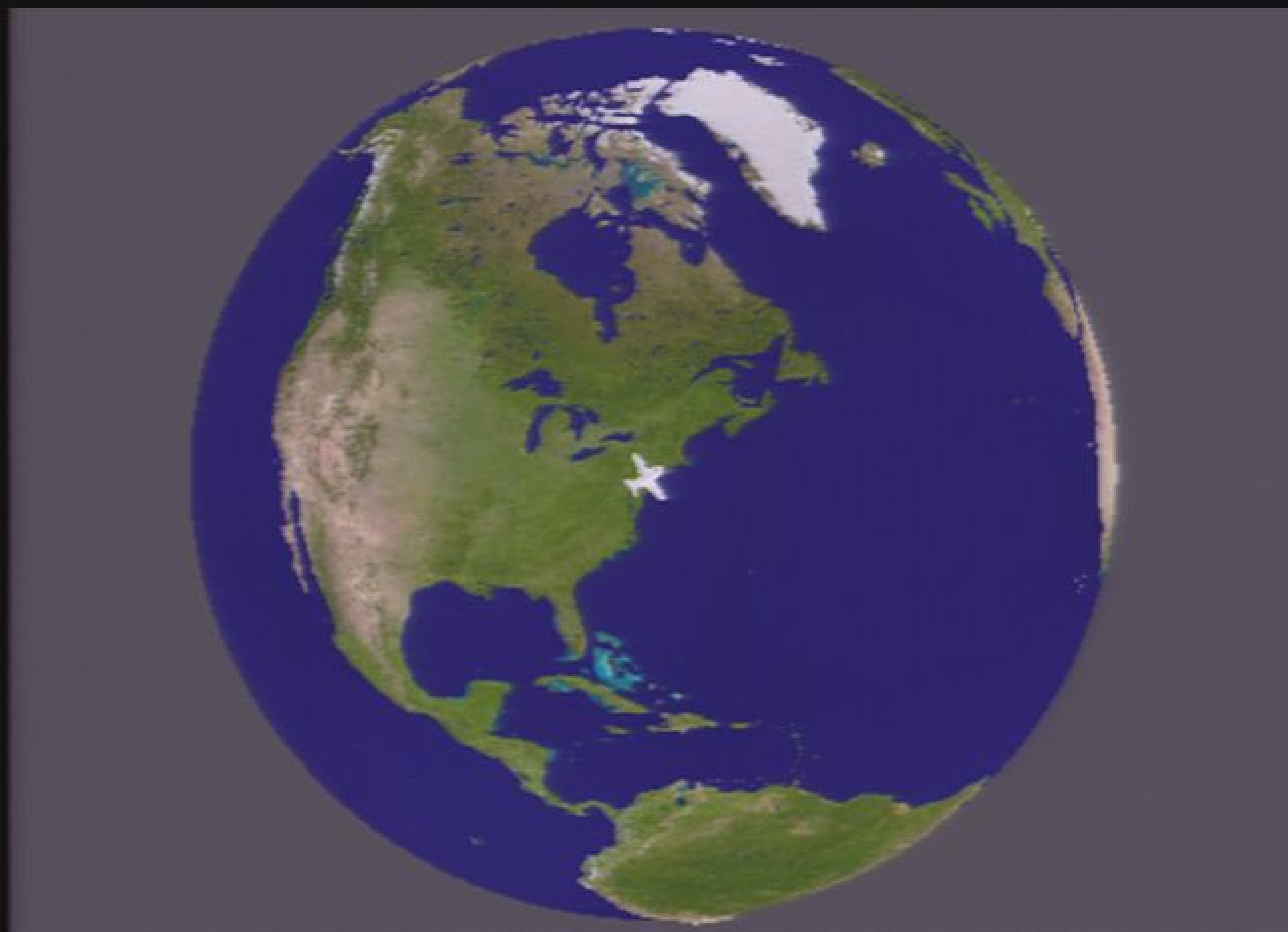
The pilot does not need to turn the plane to fly from Toronto to Rome

You are familiar with the Geodesic



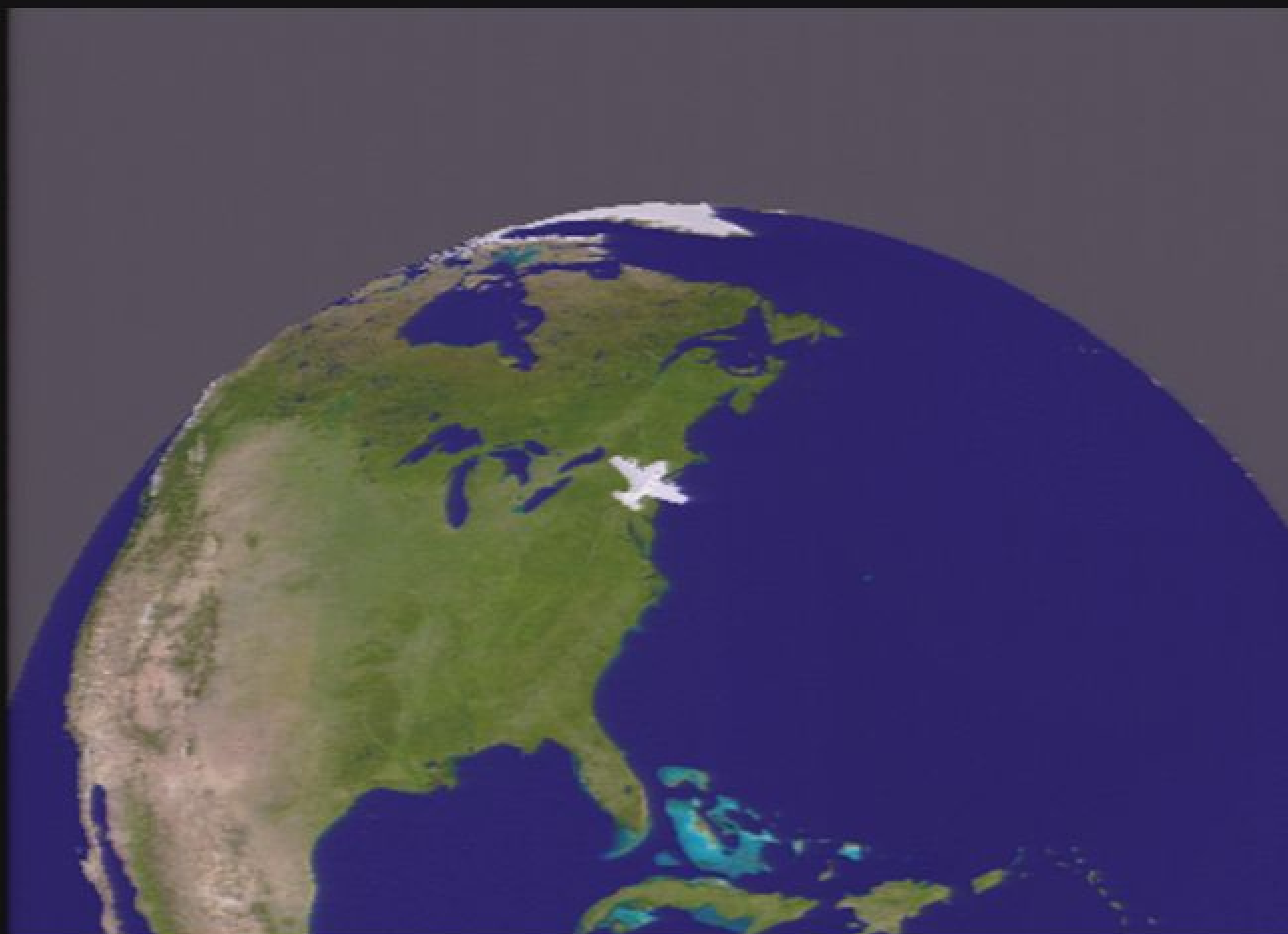
The pilot does not need to turn the plane to fly from Toronto to Rome

You are familiar with the Geodesic



The pilot does not need to turn the plane to fly from Toronto to Rome

You are familiar with the Geodesic



The pilot does not need to turn the plane to fly from Toronto to Rome

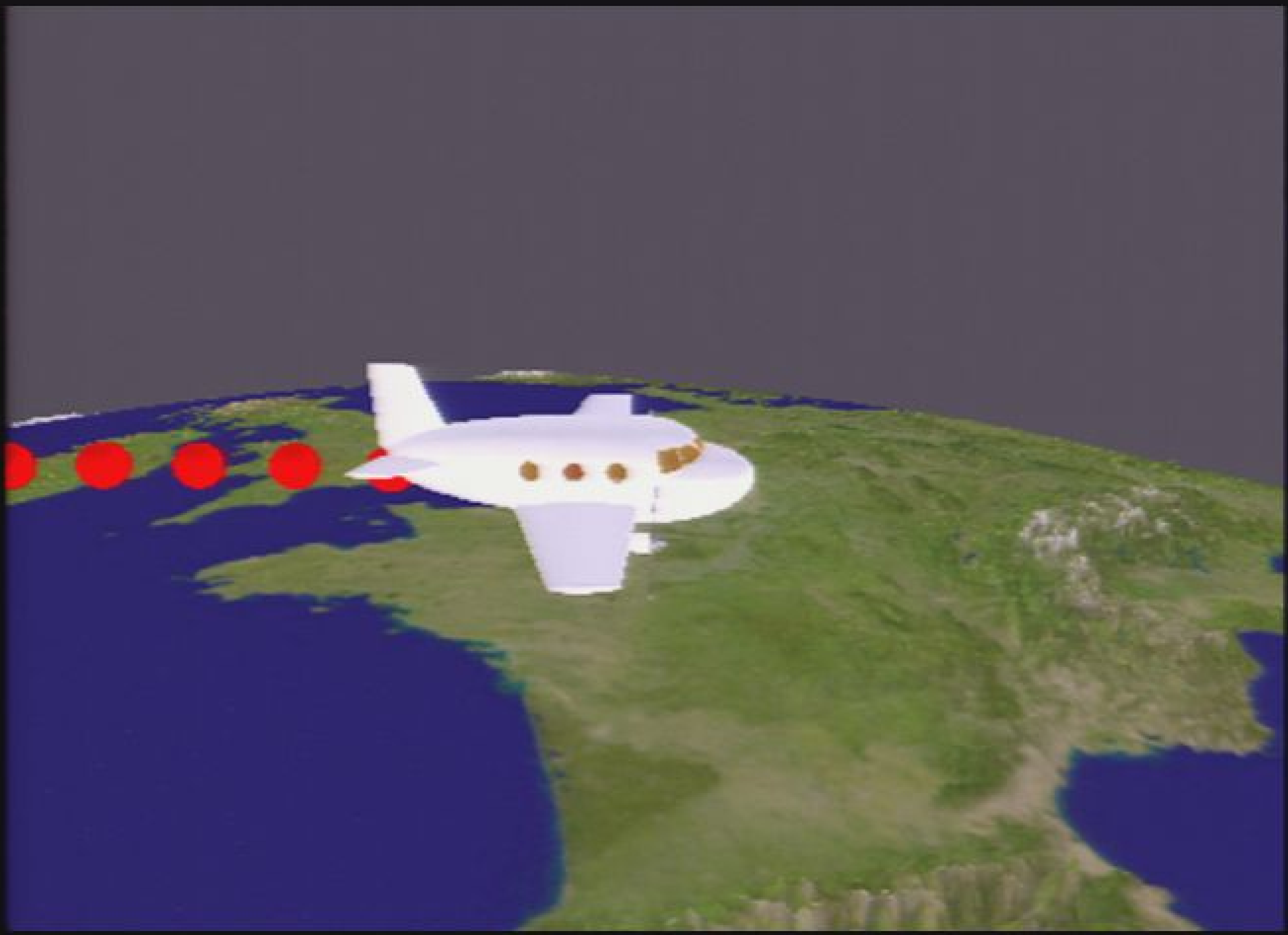
You are familiar with the Geodesic

The pilot does not need to turn the plane to fly from Toronto to Rome

You are familiar with the Geodesic

The pilot does not need to turn the plane to fly from Toronto to Rome

You are familiar with the Geodesic

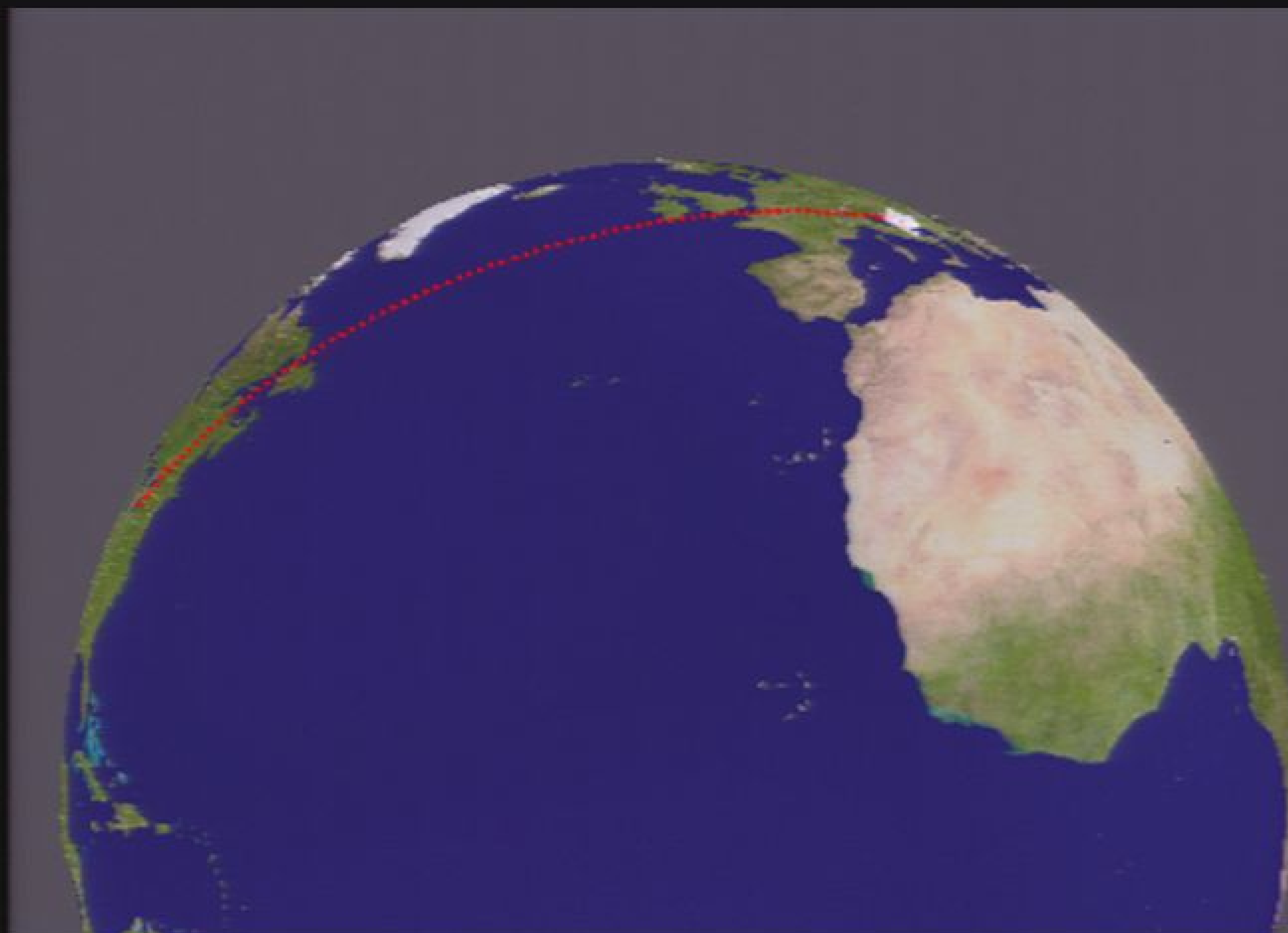


The pilot does not need to turn the plane to fly from Toronto to Rome

You are familiar with the Geodesic

The pilot does not need to turn the plane to fly from Toronto to Rome

You are familiar with the Geodesic

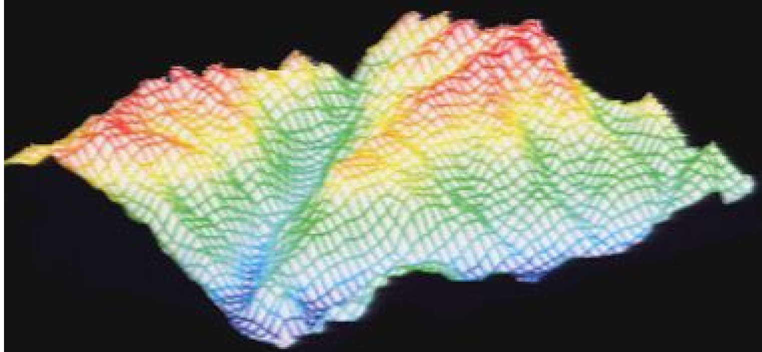


The pilot does not need to turn the plane to fly from Toronto to Rome

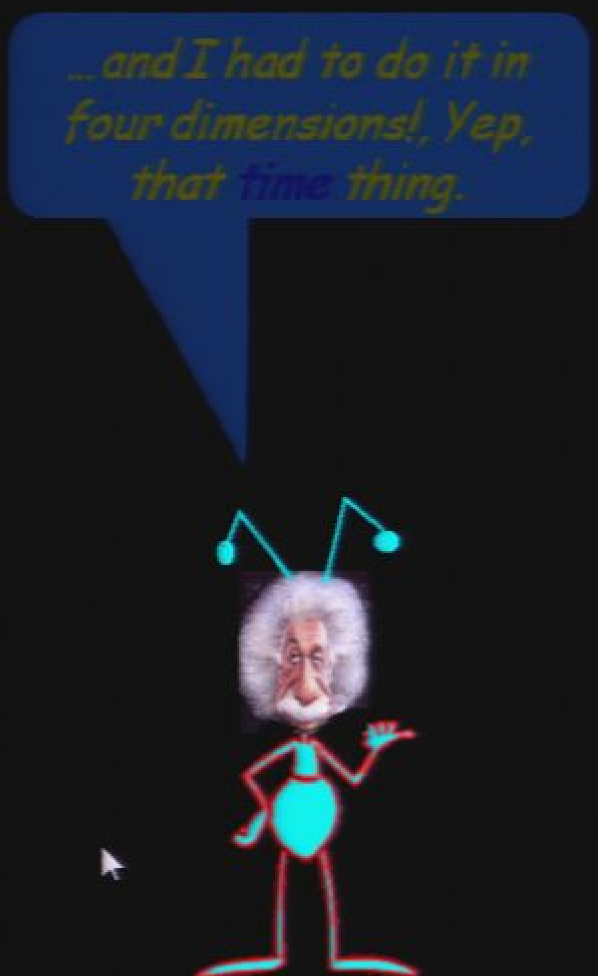
You are familiar with the Geodesic

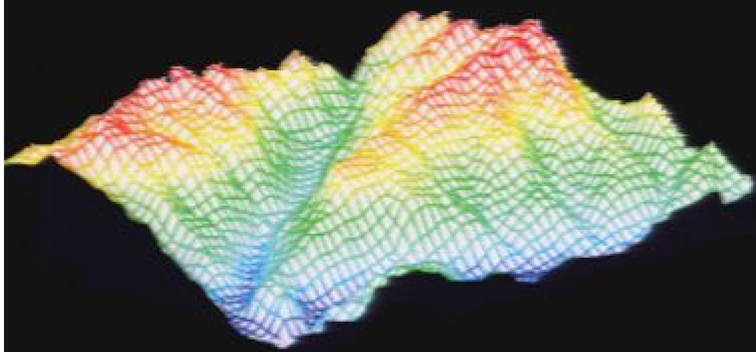
The pilot does not need to turn the plane to fly from Toronto to Rome

Geodesics are very difficult to calculate in general. Imagine surveying a complex landscape with hills and valleys. How is one to calculate the shortest distance over this terrain?



Geodesics are very difficult to calculate in general. Imagine surveying a complex landscape with hills and valleys. *How is one to calculate the shortest distance over this terrain?*





Geodesics are very difficult to calculate in general. Imagine surveying a complex landscape with hills and valleys. How is one to calculate the shortest distance over this terrain?

...and I had to do it in four dimensions!, Yep, that *time* thing.

It would by very easy to do this is we looked at the landscape from above. Then I could use $ds^2=dx^2+dy^2$

...but I needed the distance in SPACETIME, so I used a mathematical quantity which converts the flat map distances into actual distances on our curved space. This is the METRIC of the space. Denoted by "g".

The Metric

The idea of a metric is very common to us. It is a way of converting universal distance (the distance on a flat space) to distances on curved spaces.

The Metric

The idea of a metric is very common to us. It is a way of converting universal distance (the distance on a flat space) to distances on curved spaces.

It's like a taxi meter which converts fixed amounts of time and distance into a cost for the passenger

The Metric

The idea of a metric is very common to us. It is a way of converting universal distance (the distance on a flat space) to distances on curved spaces.

It may cost you more at night than it does in daytime to go the same distance

It's like a taxi meter which converts fixed amounts of time and distance into a cost for the passenger

The Metric

The idea of a metric is very common to us. It is a way of converting universal distance (the distance on a flat space) to distances on curved spaces.

It's like a taxi meter which converts fixed amounts of time and distance into a cost for the passenger

It may cost you more at night than it does in daytime to go the same distance

It may cost you more to take a taxi in New York than it does in Waterloo to travel the same distance.

The Metric

The idea of a metric is very common to us. It is a way of converting universal distance (the distance on a flat space) to distances on curved spaces.

It may cost you more at night than it does in daytime to go the same distance

It's like a taxi meter which converts fixed amounts of time and distance into a cost for the passenger

It may cost you more to take a taxi in New York than it does in Waterloo to travel the same distance.

The "taxi metric" can depend on time, it can depend on location.

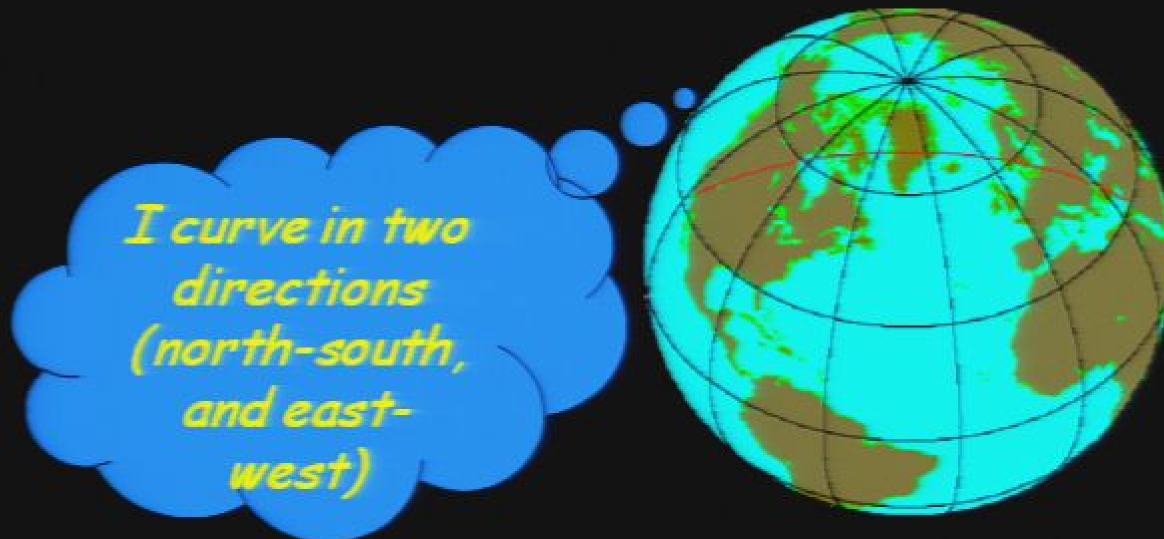
The Metric, g

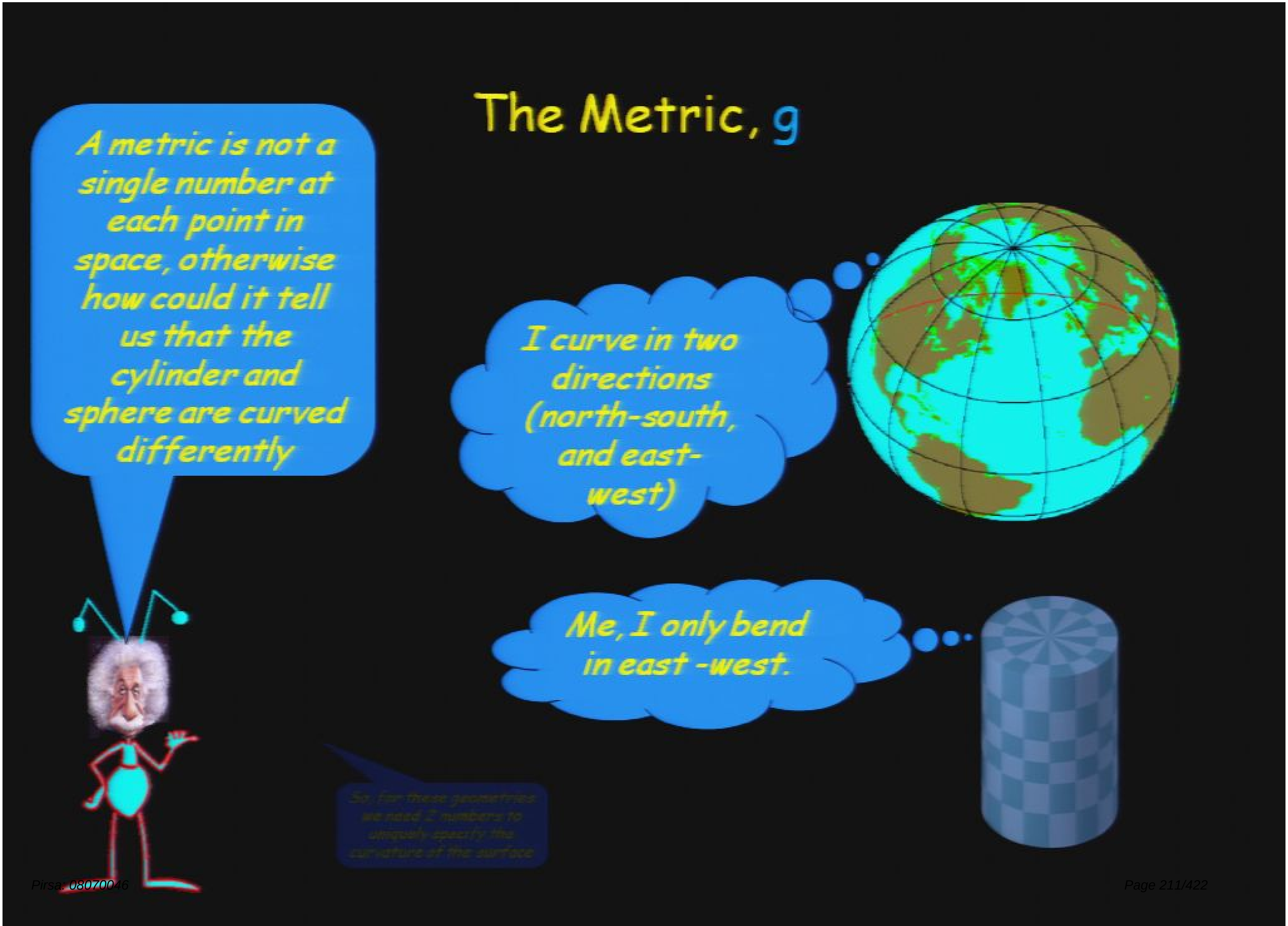
The Metric, g

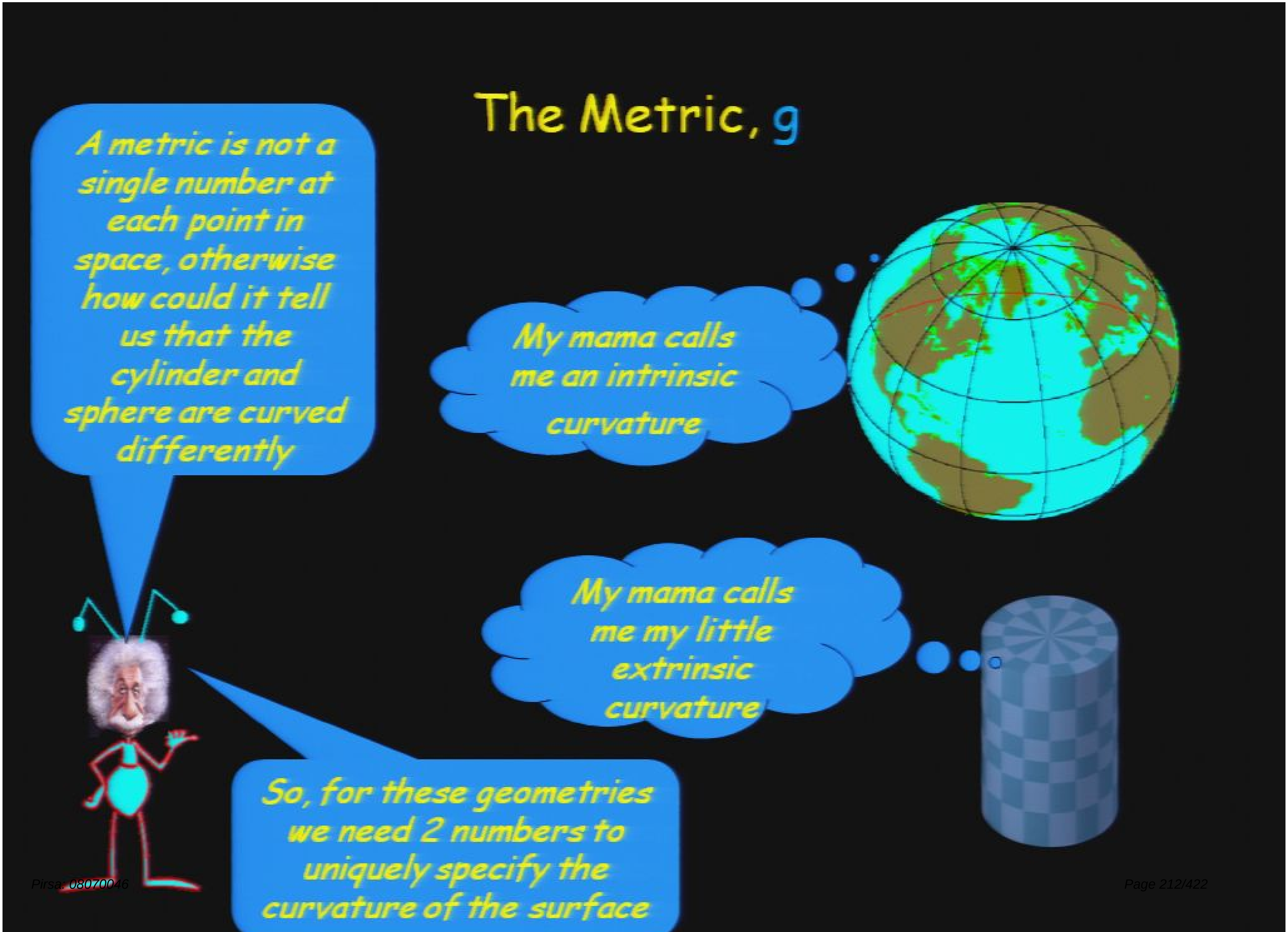

A metric is not a single number at each point in space, otherwise how could it tell us that the cylinder and sphere are curved differently

The Metric, g


A metric is not a single number at each point in space, otherwise how could it tell us that the cylinder and sphere are curved differently


I curve in two directions (north-south, and east-west)


The Metric, g
A metric is not a single number at each point in space, otherwise how could it tell us that the cylinder and sphere are curved differently
I curve in two directions (north-south, and east-west)
Me, I only bend in east -west.
So, for these geometries we need 2 numbers to uniquely specify the curvature of the surface


The Metric, g
A metric is not a single number at each point in space, otherwise how could it tell us that the cylinder and sphere are curved differently
My mama calls me an intrinsic curvature
My mama calls me my little extrinsic curvature
So, for these geometries we need 2 numbers to uniquely specify the curvature of the surface

What about g, in Four Dimensions?

What about g, in Four Dimensions?

We will designate two numbers representing the metric, g_{xx} and g_{yy} ,to show that they are associated with curvature in the x and y direction.

In four dimensions, it works out that we need 10

I needed another mathematical tool to help me keep the numbers straight, and yet allow me to do calculations.

The Tensor (in Spacetime)

The Tensor (in Spacetime)

The Tensor (in Spacetime)

Tensors are mathematical objects that are simply organized groups of numbers. They have an index that indicate there size (how many numbers they hold)

The Tensor (in Spacetime)

Tensors are mathematical objects that are simply organized groups of numbers. They have an index that indicate there size (how many numbers they hold)

0-tensor is a single number: for example "5"

The Tensor (in Spacetime)

Tensors are mathematical objects that are simply organized groups of numbers. They have an index that indicate there size (how many numbers they hold)

0-tensor is a single number: for example "5"

1-tensor is a string of 4 numbers: for example A_j=(1, 0, -3.14, 2)

The Tensor (in Spacetime)

Tensors are mathematical objects that are simply organized groups of numbers. They have an index that indicate there size (how many numbers they hold)

0-tensor is a single number: for example "5"

1-tensor is a string of 4 numbers: for example $A_j=(1, 0, -3.14, 2)$

2- tensor is a matrix of 4x4=16 numbers

$$B_{ij} = \begin{pmatrix} 3 & -1 & 17 & 2 \\ 7 & 99 & 0 & 34 \\ 1000 & 3 & 0 & -1 \\ 4 & -2.5 & 7 & -12.3 \end{pmatrix}$$

The Tensor (in Spacetime)

With these tools, I can finally write down how the Geometry of SpaceTime is affected by mass or is it how mass is affected by the geometry of SpaceTime

0-tensor is a single number: for example "5"

1-tensor is a string of 4 numbers: for example $A_j=(1, 0, -3.14, 2)$

2- tensor is a matrix of 4x4=16 numbers

$$B_{ij} = \begin{pmatrix} 3 & -1 & 17 & 2 \\ 7 & 99 & 0 & 34 \\ 1000 & 3 & 0 & -1 \\ 4 & -2.5 & 7 & -12.3 \end{pmatrix}$$

The Einstein field equation (EFE) is usually written in the form

$$G_{ij} = 8\pi T_{ij} + \Lambda g_{ij}$$

Einstein's Tensor

Stress-Energy Tensor

Metric Tensor

$$\begin{pmatrix} G_{11} & G_{12} & G_{13} & G_{14} \\ G_{21} & G_{22} & G_{23} & G_{24} \\ G_{31} & G_{32} & G_{33} & G_{34} \\ G_{41} & G_{42} & G_{43} & G_{44} \end{pmatrix} = 8\pi \begin{pmatrix} T_{11} & T_{12} & T_{13} & T_{14} \\ T_{21} & T_{22} & T_{23} & T_{24} \\ T_{31} & T_{32} & T_{33} & T_{34} \\ T_{41} & T_{42} & T_{43} & T_{44} \end{pmatrix} + \Lambda \begin{pmatrix} g_{11} & g_{12} & g_{13} & g_{14} \\ g_{21} & g_{22} & g_{23} & g_{24} \\ g_{31} & g_{32} & g_{33} & g_{34} \\ g_{41} & g_{42} & g_{43} & g_{44} \end{pmatrix}$$

$$G_{ij} = R_{ij} - \frac{1}{2} g_{ij} R$$

Curvature of SpaceTime

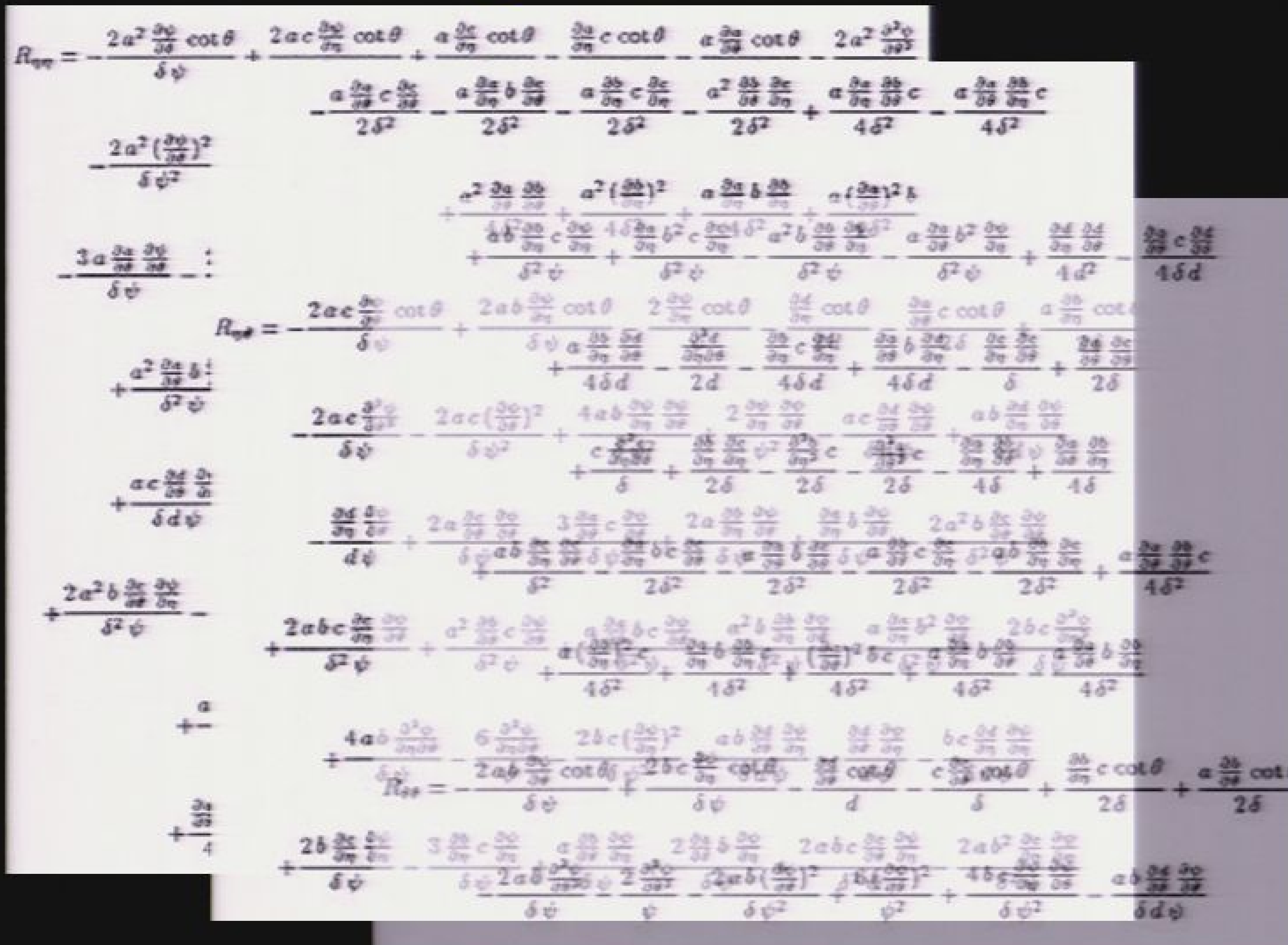
describes the density and flux of energy and momentum in spacetime

The EFE is a tensor equation relating a set of symmetric 4 x 4 tensors. Einstein's equations are actually 16 equations in the form: $G_{11} = 8\pi T_{11} + \Lambda g_{11}$

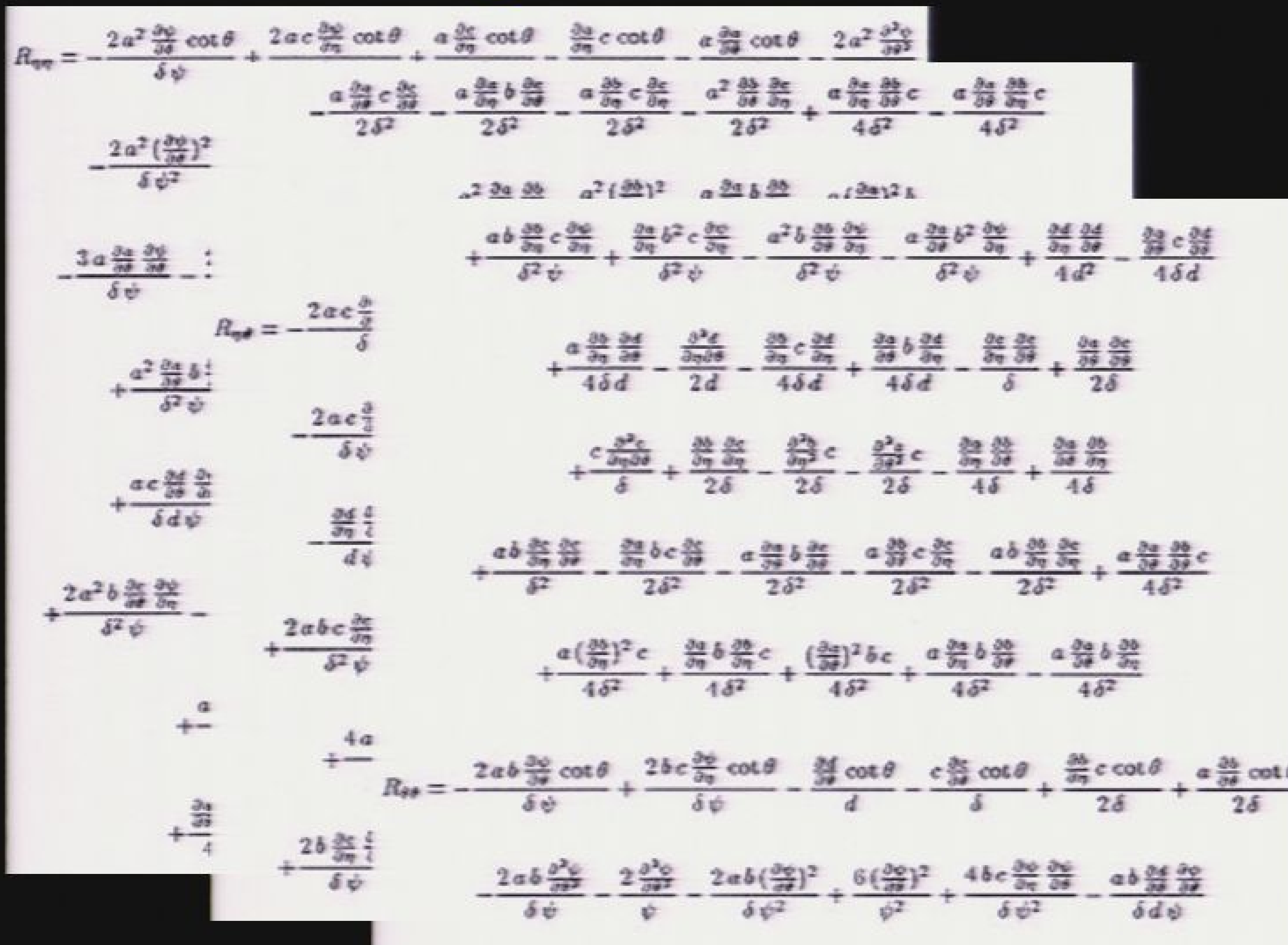
If you sit down and write down the Ricci tensor for a general case of a 2-dimensional space with axial symmetry, you would get something like this:

$$R_{\eta\eta} = -\frac{2a^2 \frac{\partial\psi}{\partial\theta}\cot\theta}{\delta\psi} + \frac{2ac\frac{\partial\psi}{\partial\eta}\cot\theta}{\delta\psi} + \frac{a\frac{\partial c}{\partial\eta}\cot\theta}{\delta} - \frac{\frac{\partial a}{\partial\eta}c\cot\theta}{2\delta} - \frac{a\frac{\partial a}{\partial\theta}\cot\theta}{2\delta} - \frac{2a^2\frac{\partial^2\psi}{\partial\theta^2}}{\delta\psi}$$

... and just a little bit more.



... and just a little bit more.

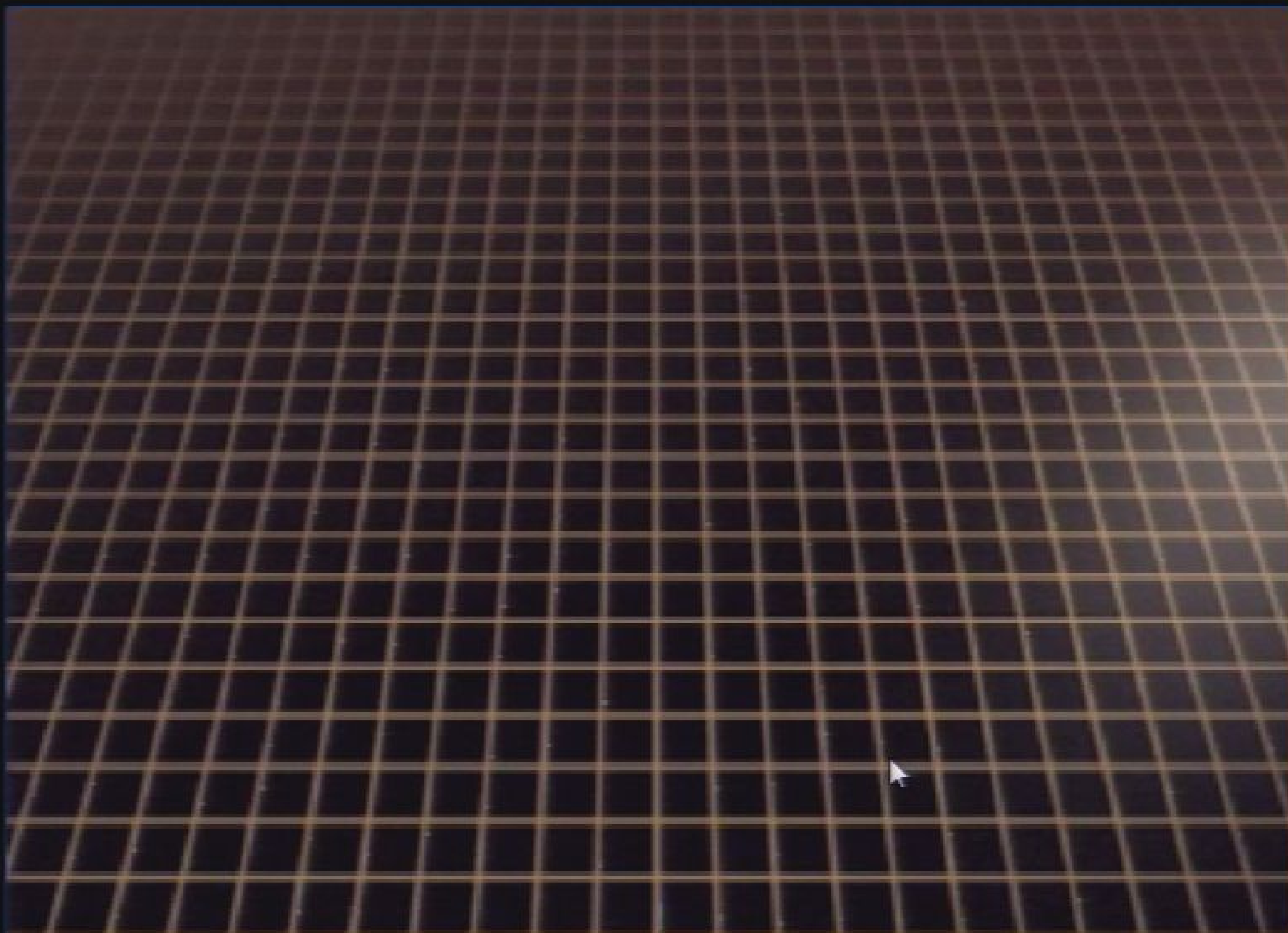


This is a general expression for Ricci tensor R_{mn} in only two dimensions, with axial symmetry.

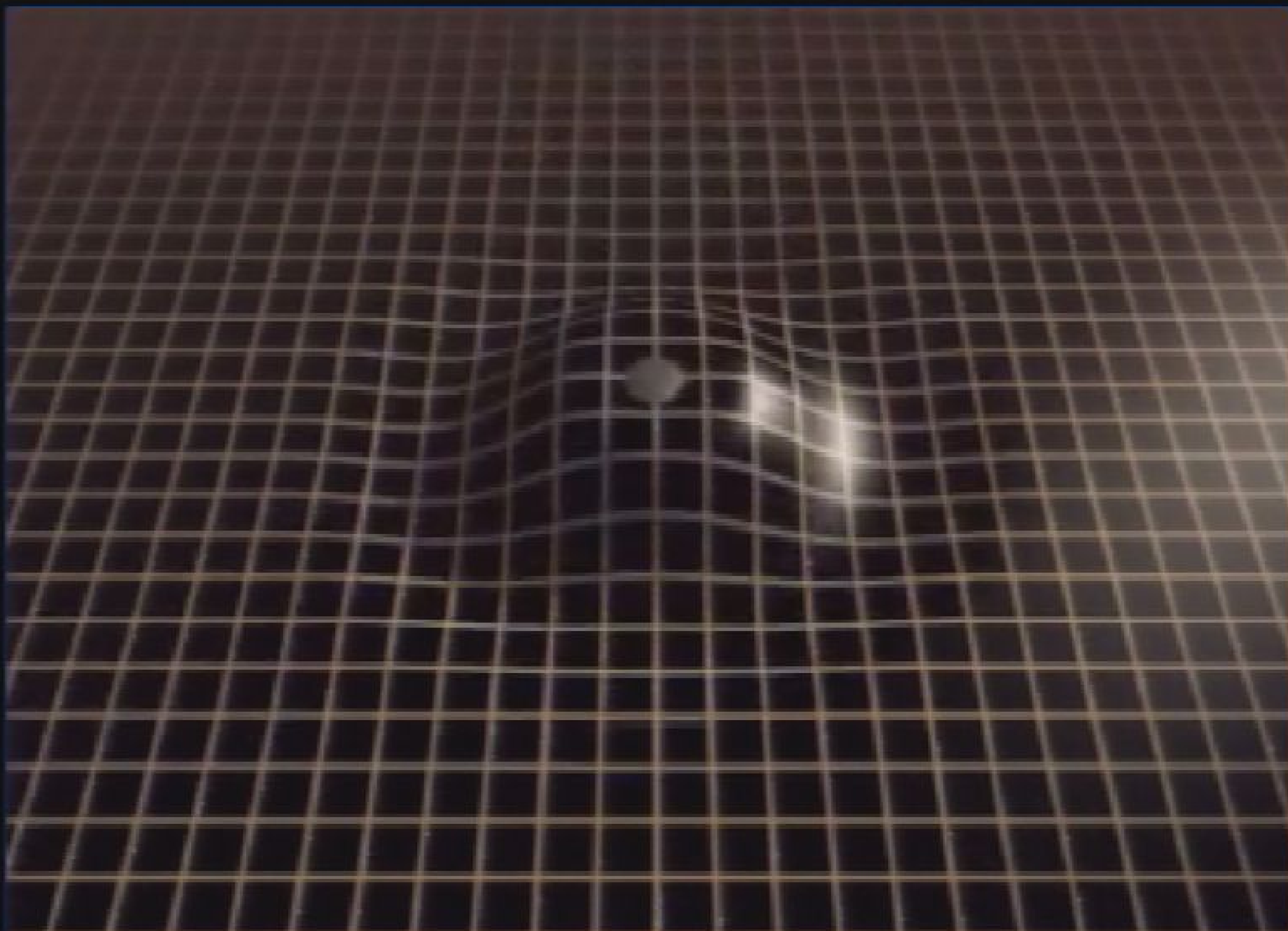
Just try to imagine all of three dimensions of space plus one of time!

What does all this say?

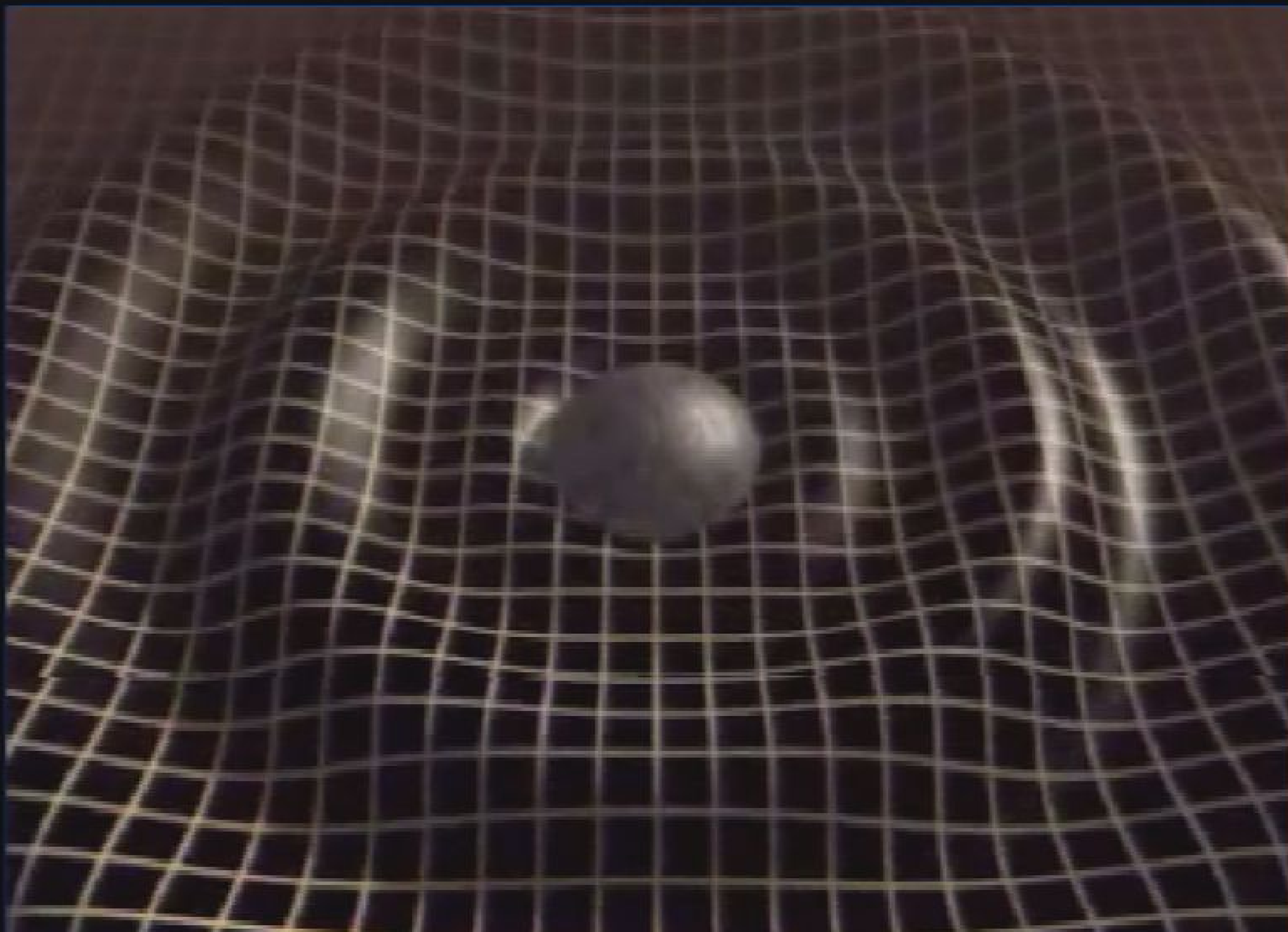
Curvature



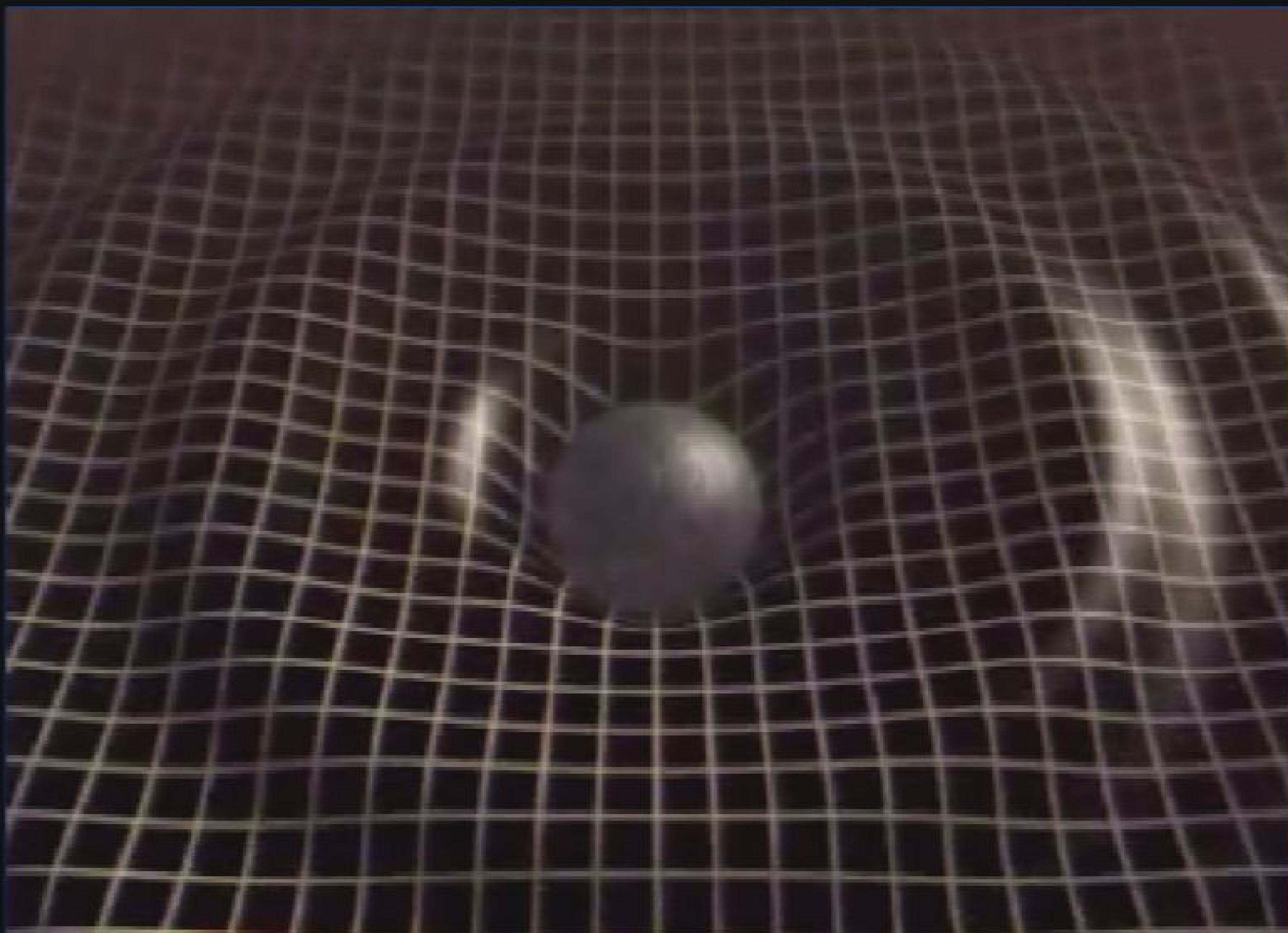
Curvature



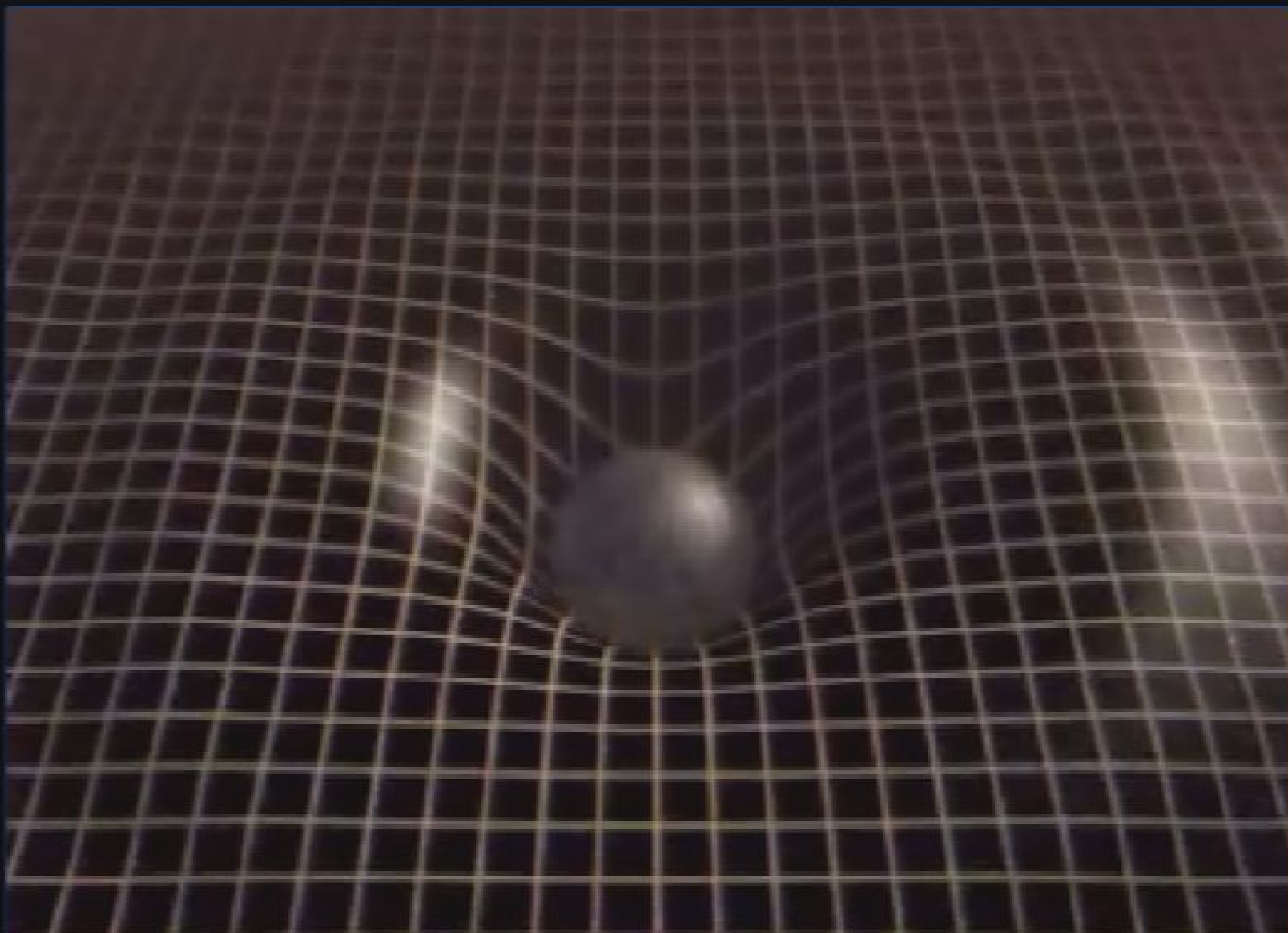
Curvature



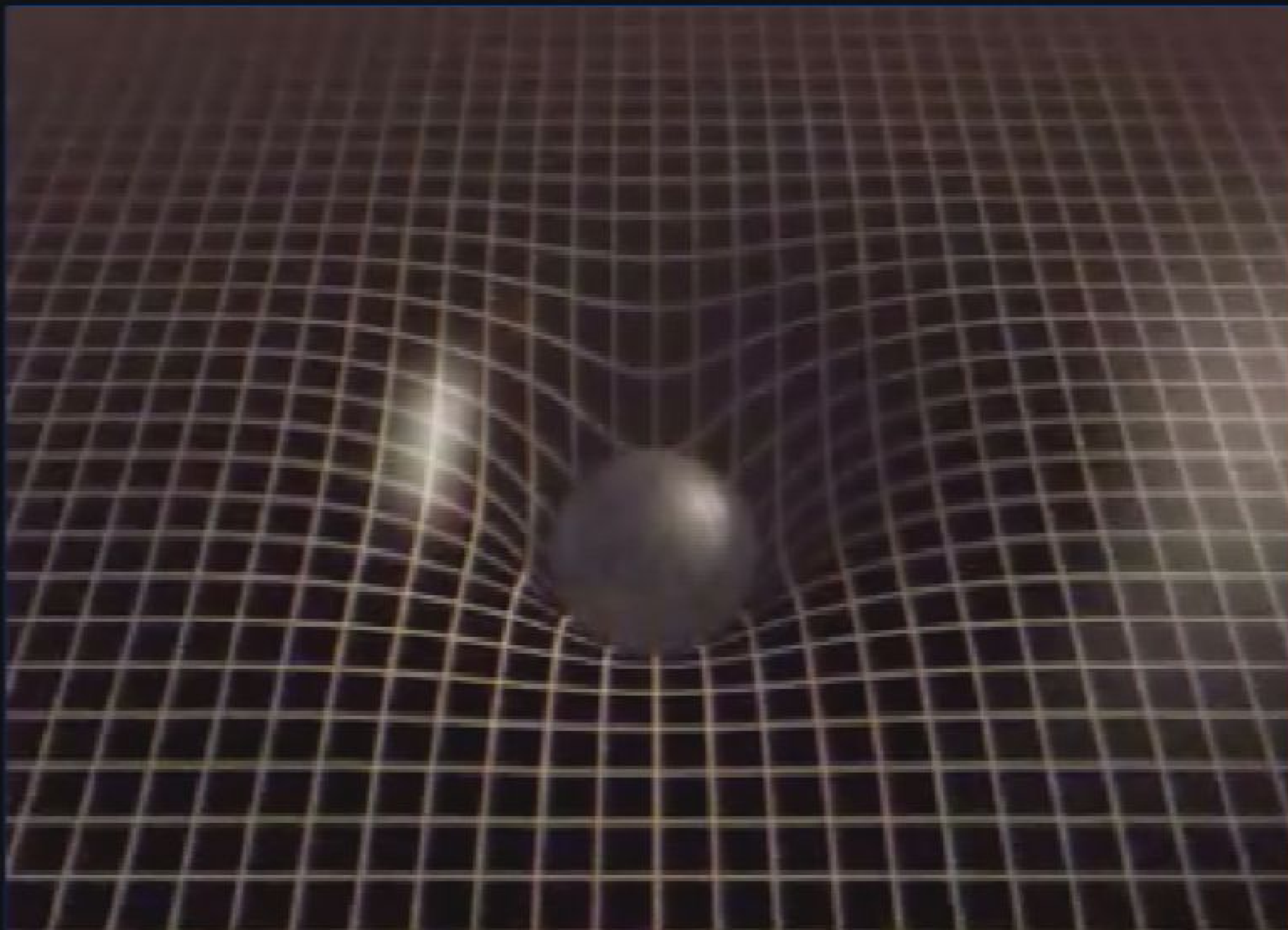
Curvature



Curvature

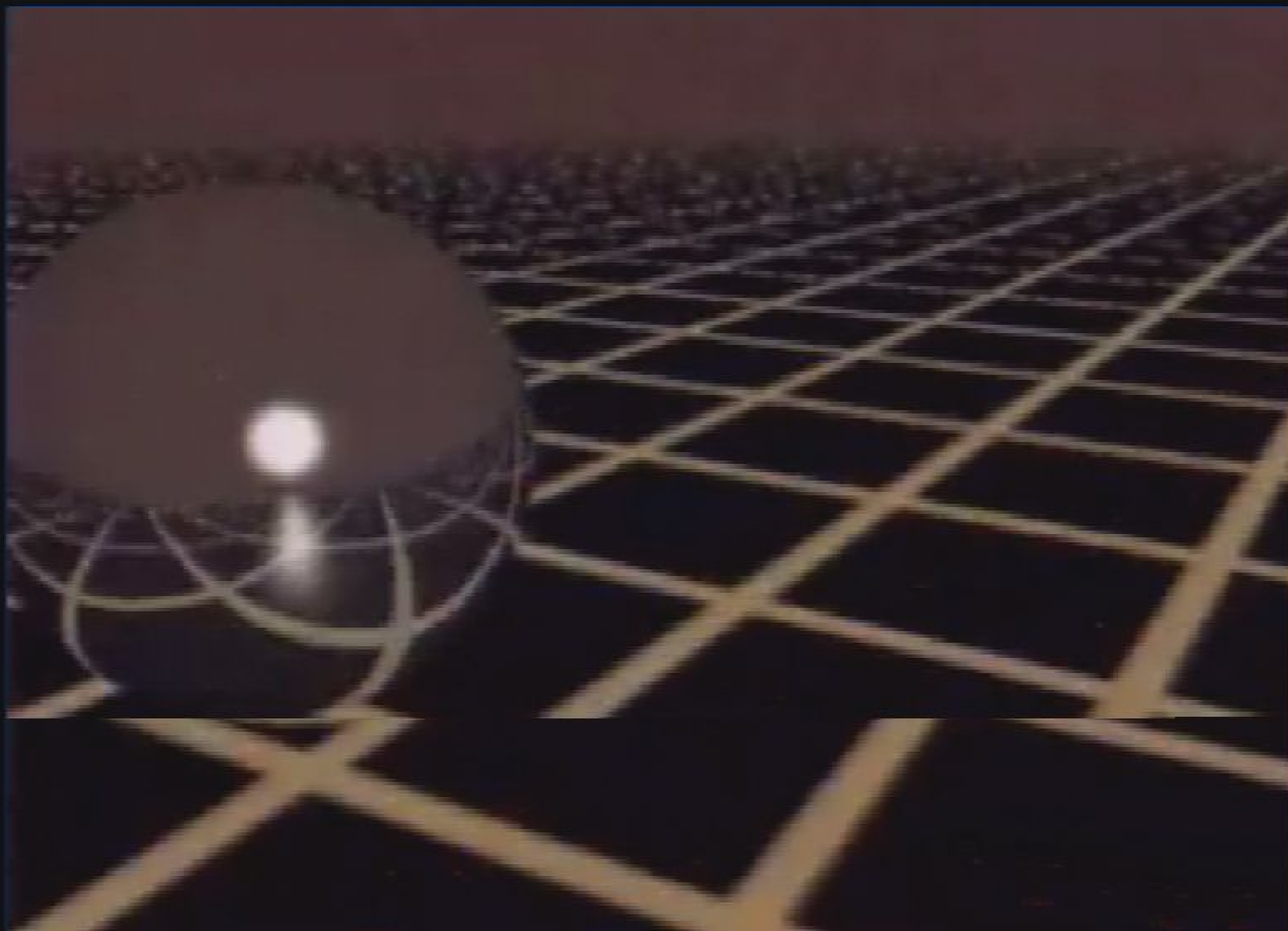


Curvature

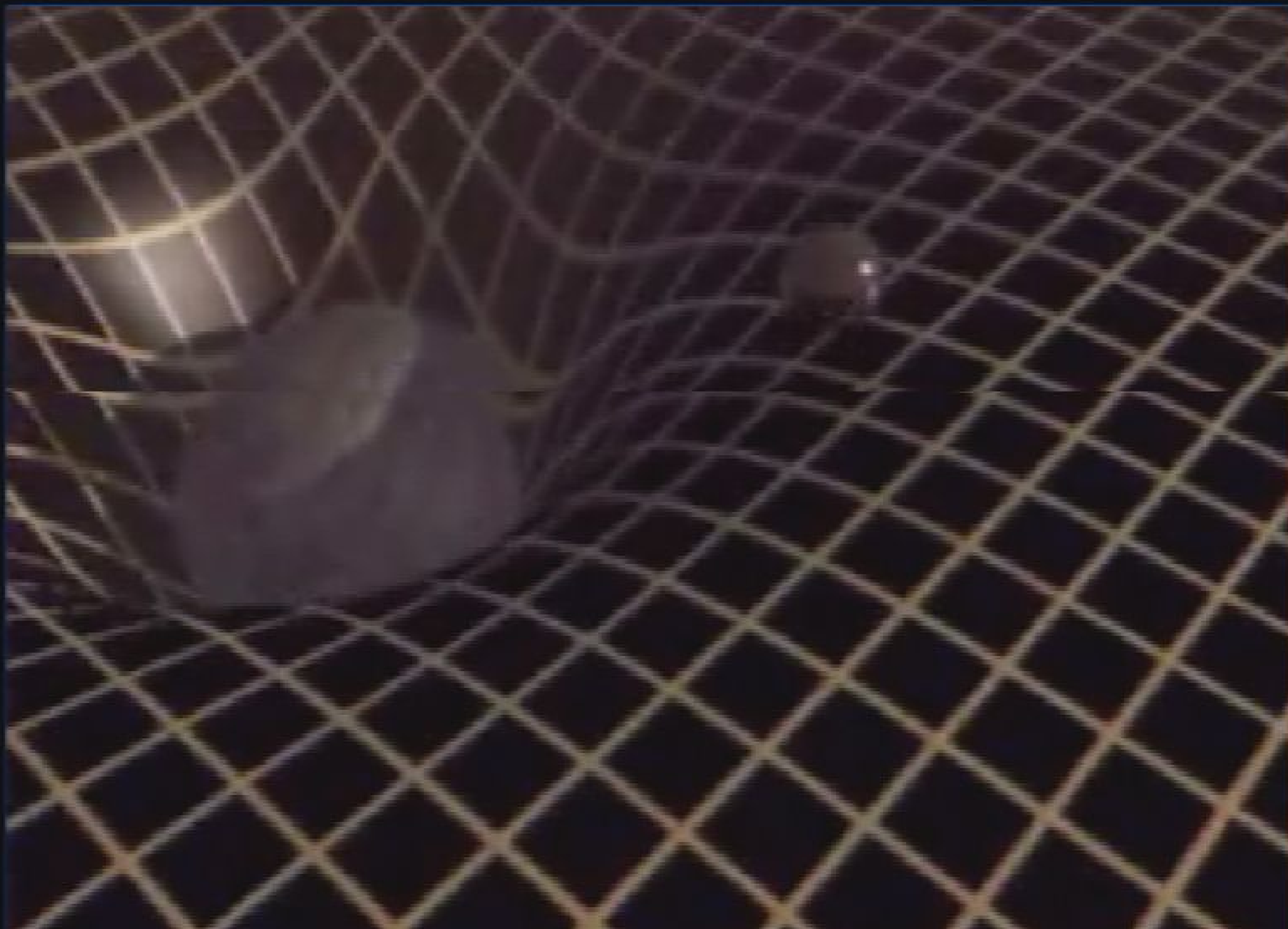


Curvature

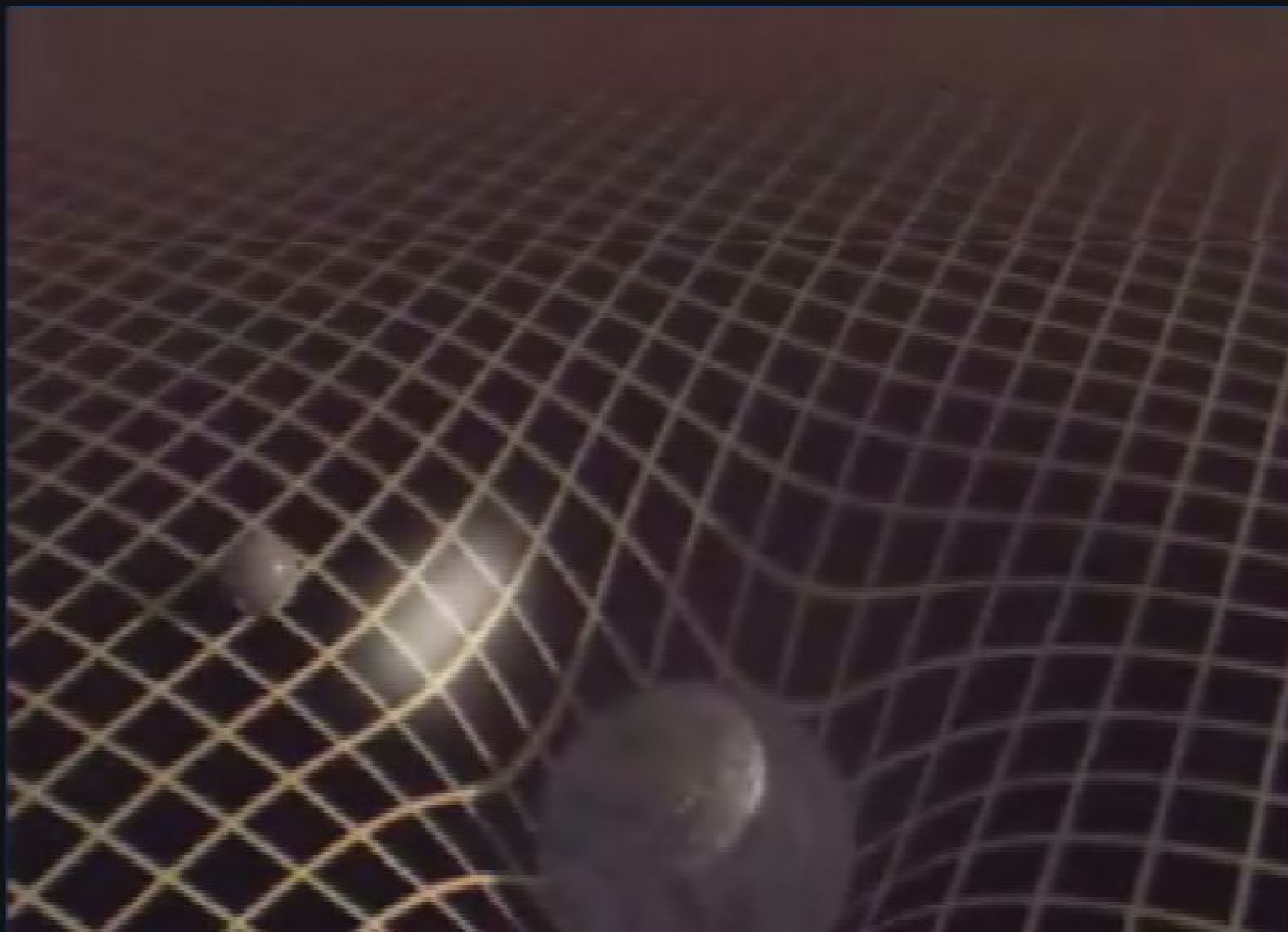
Curvature



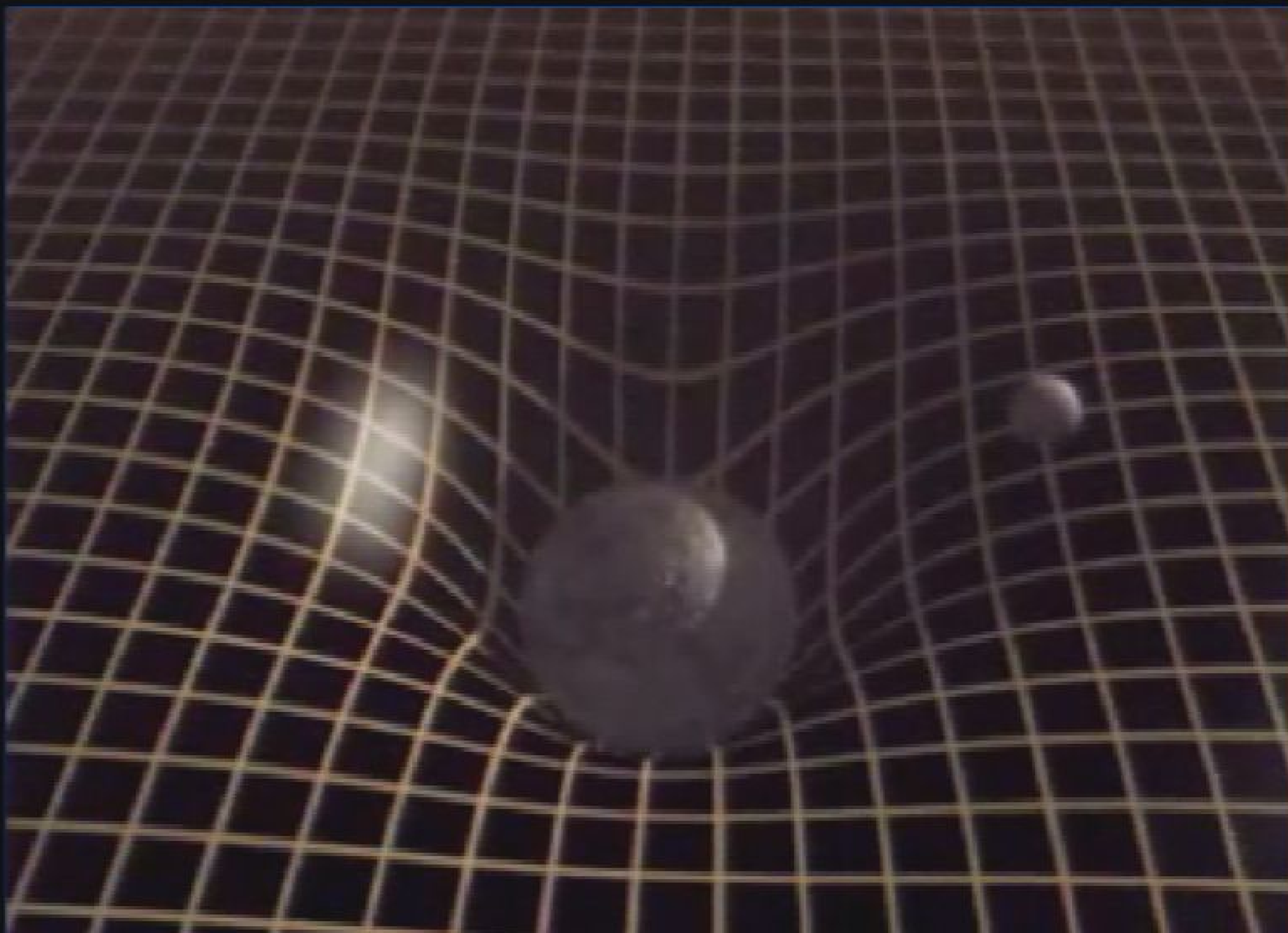
Curvature



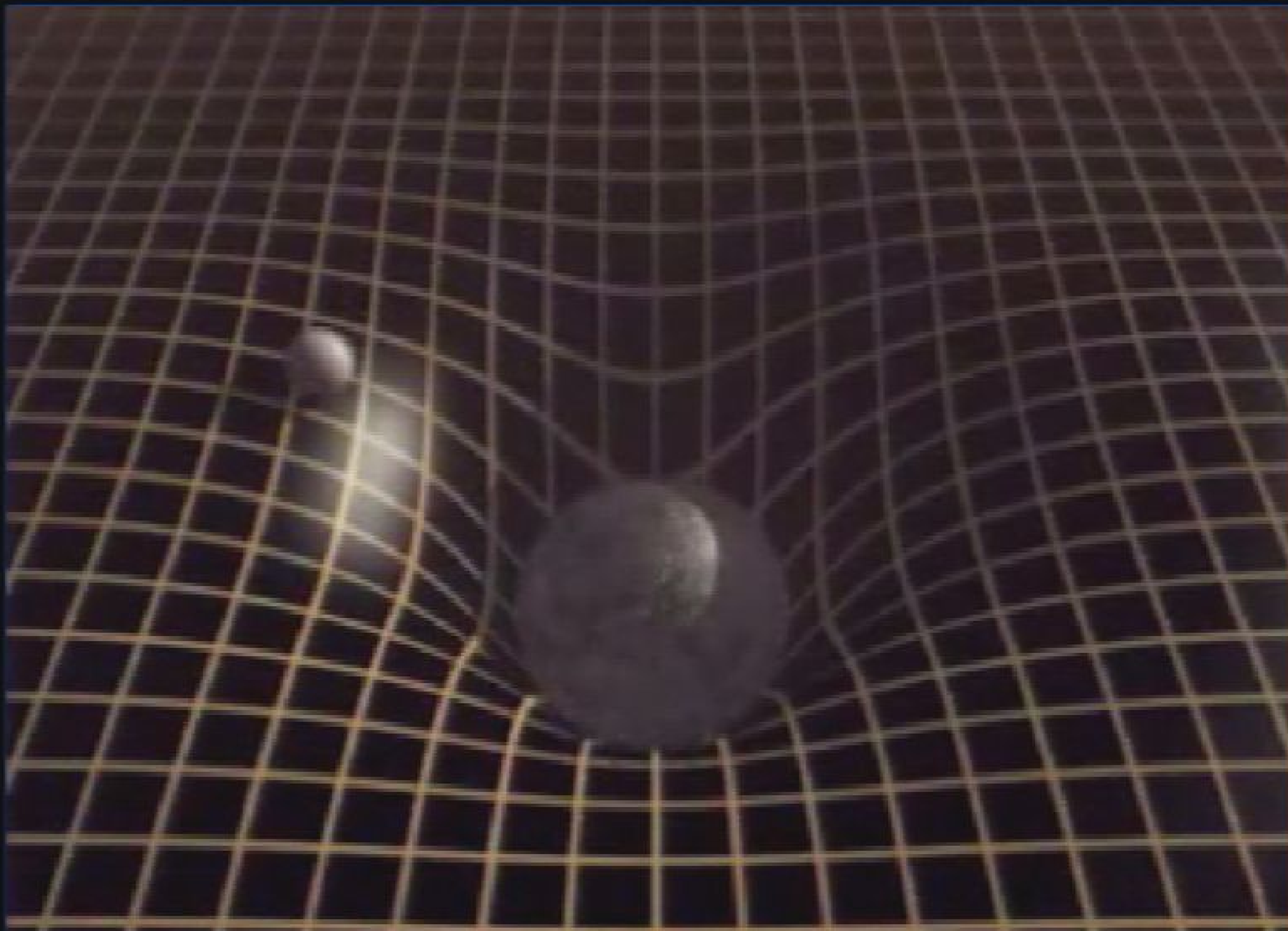
Curvature



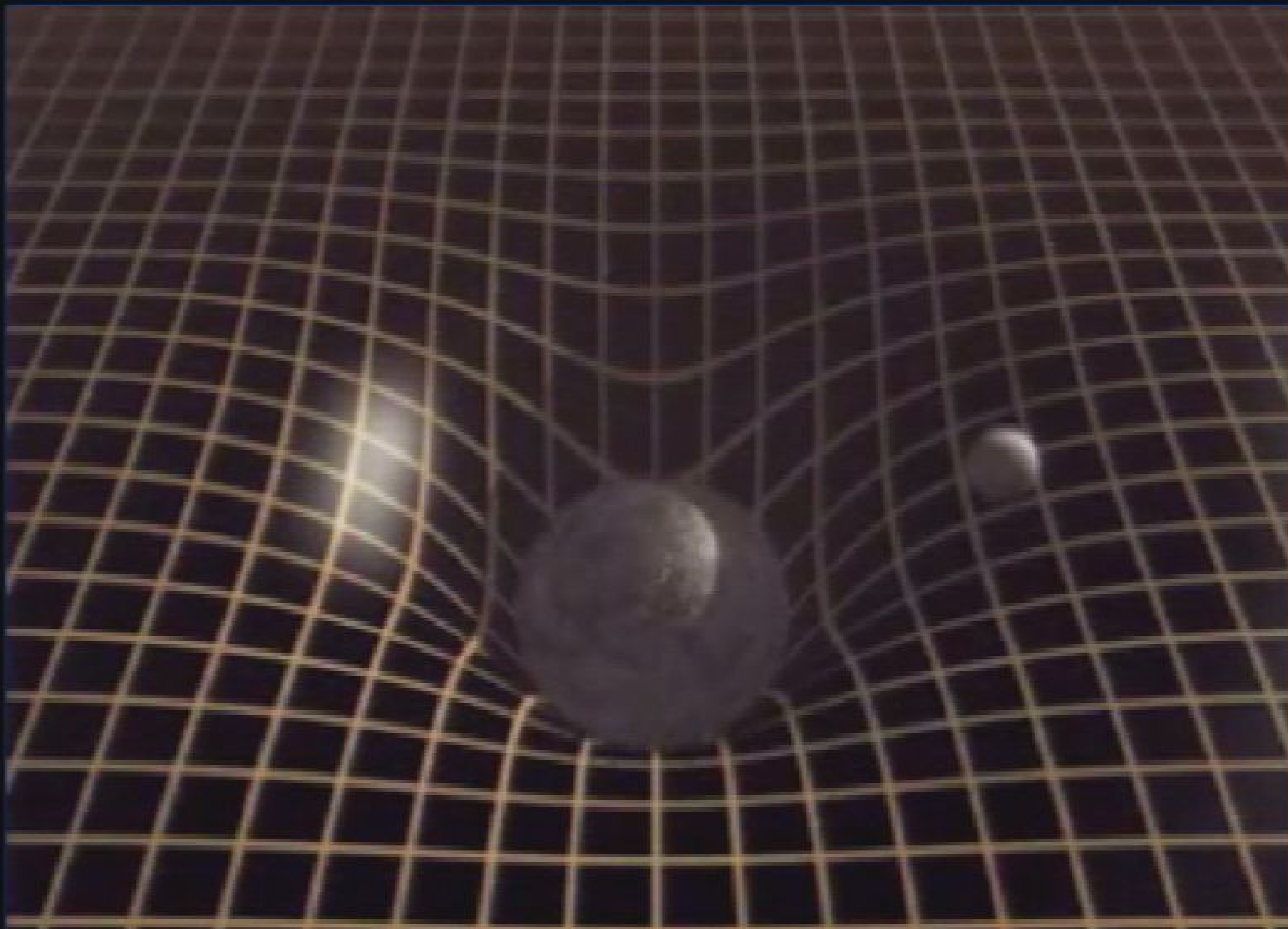
Curvature



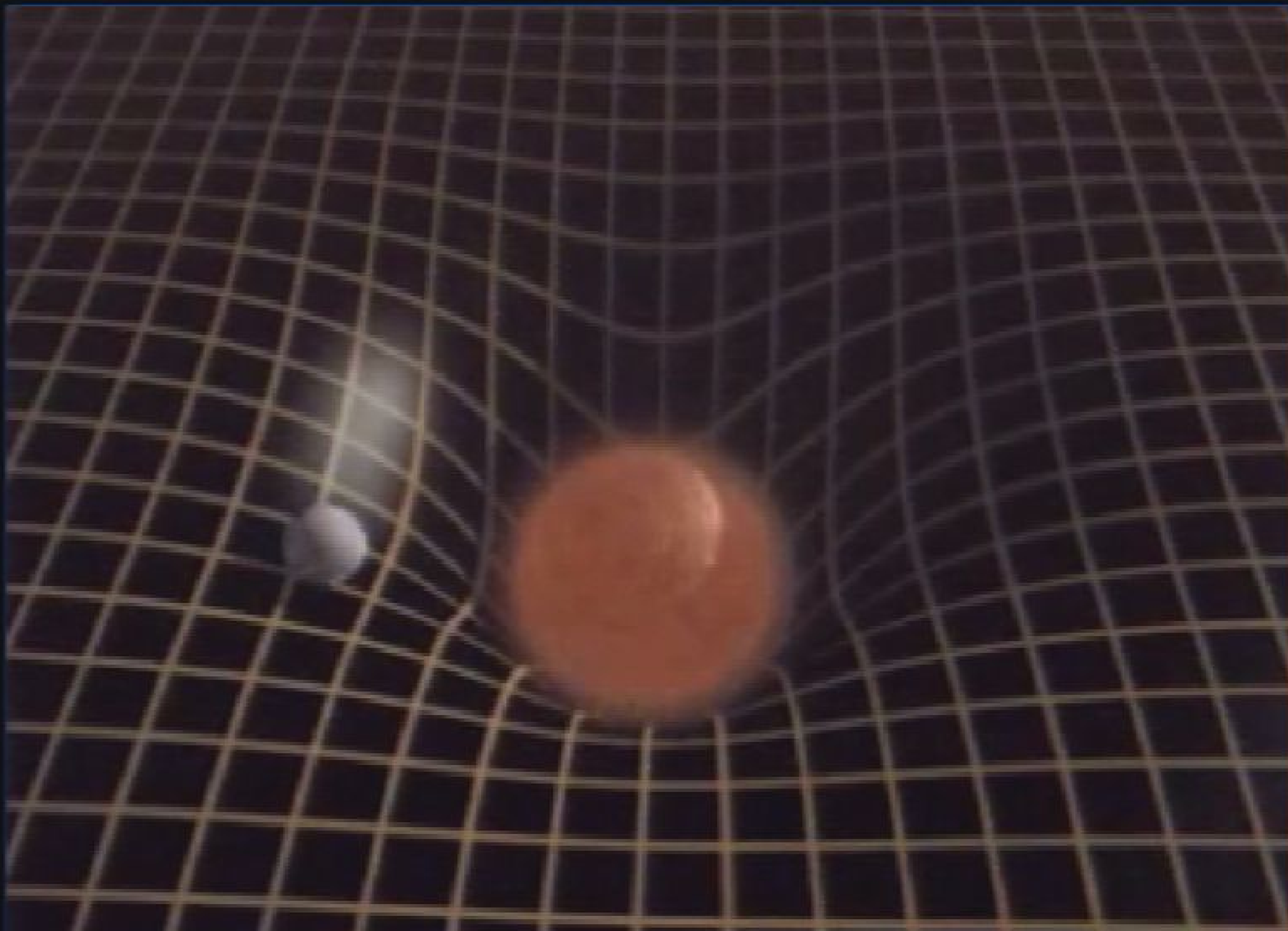
Curvature



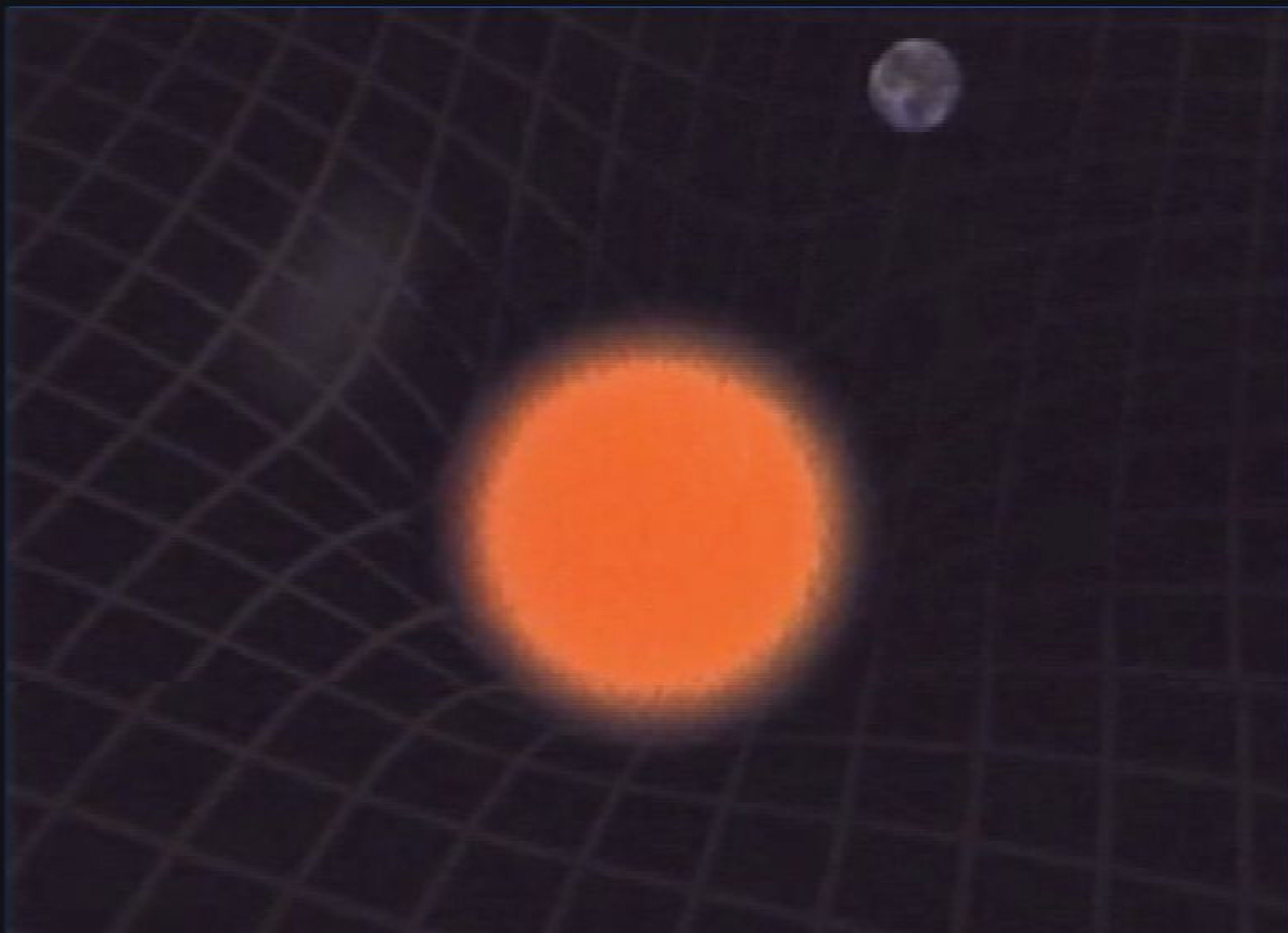
Curvature



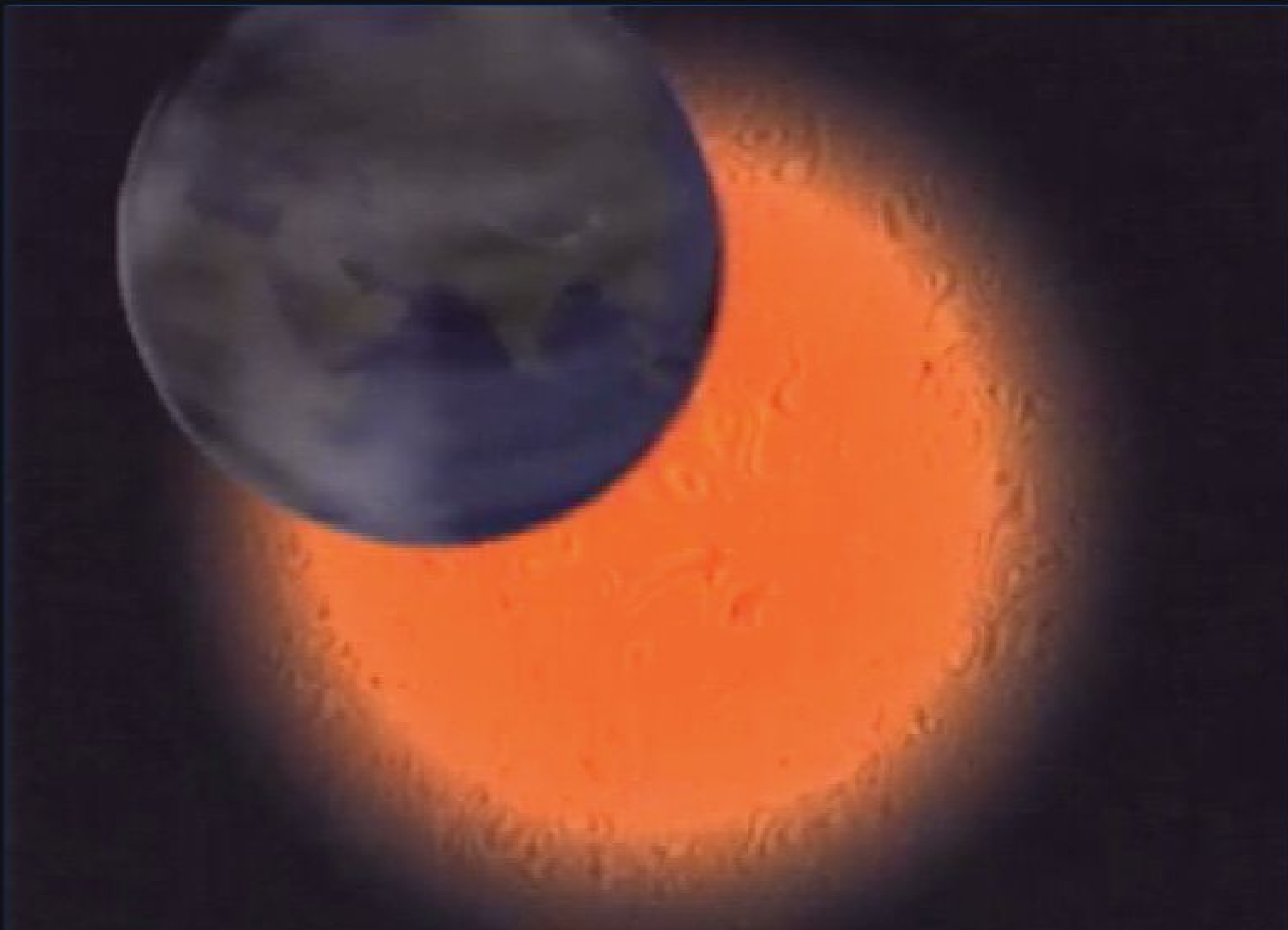
Curvature



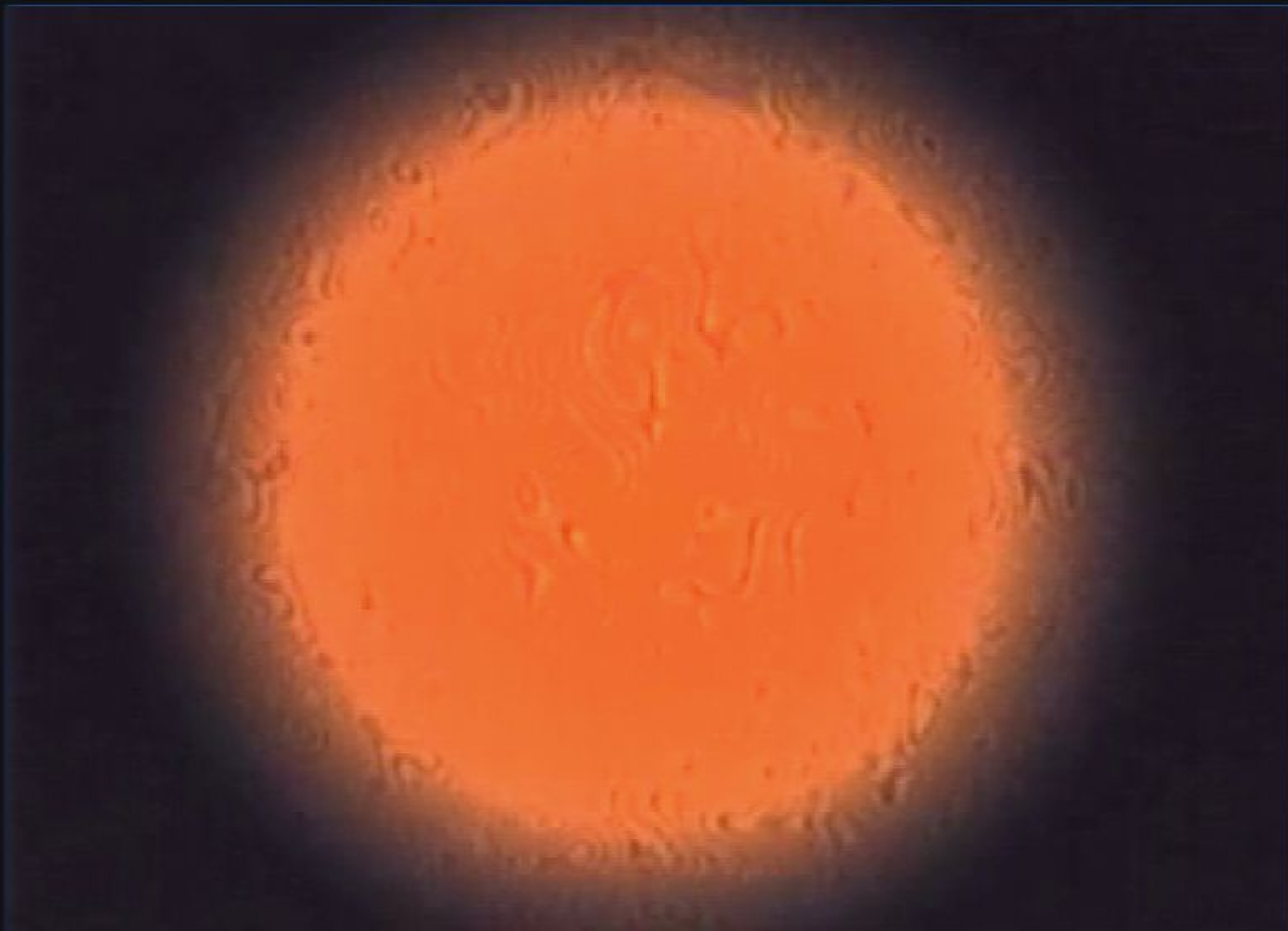
Curvature



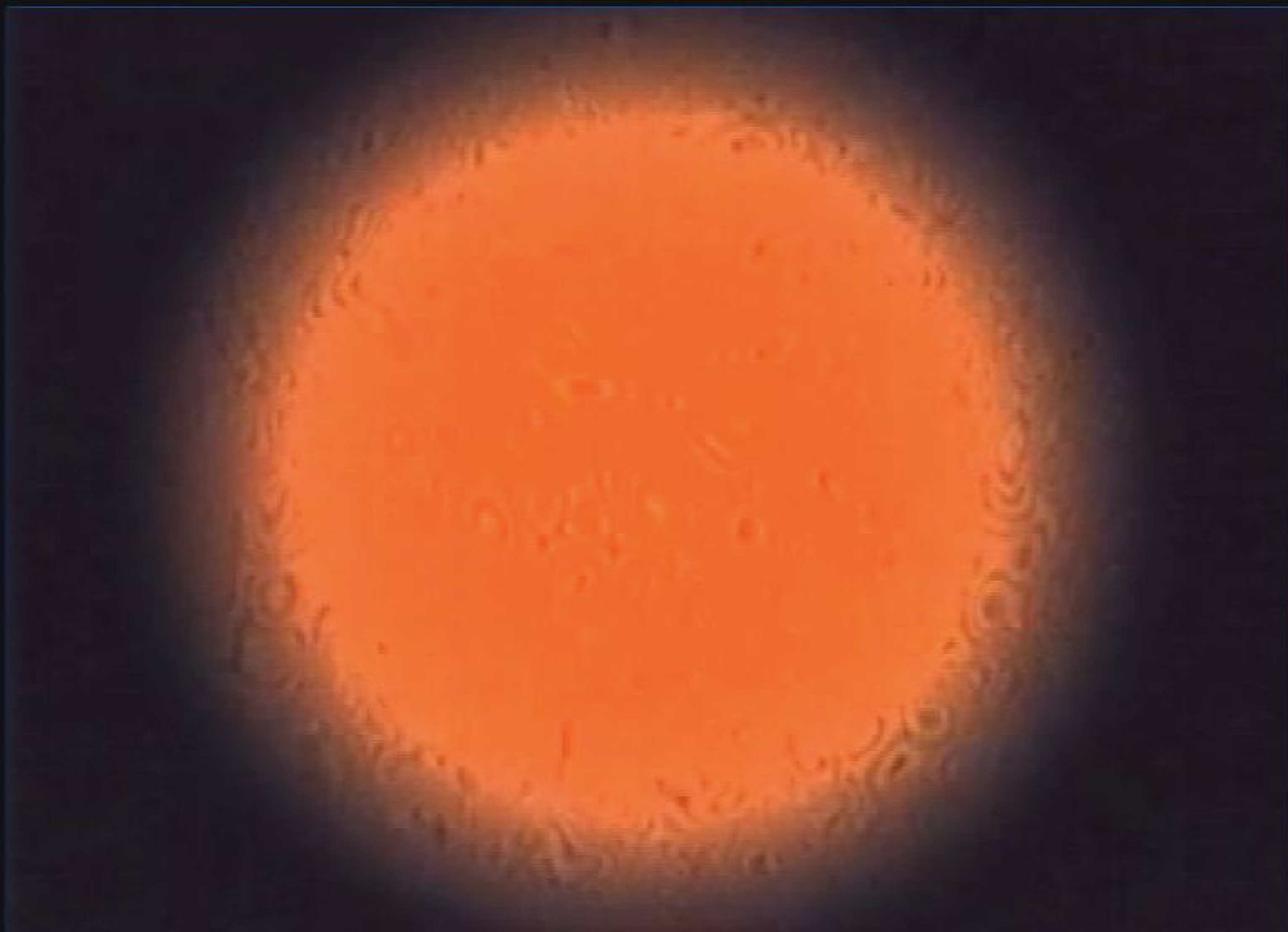
Curvature



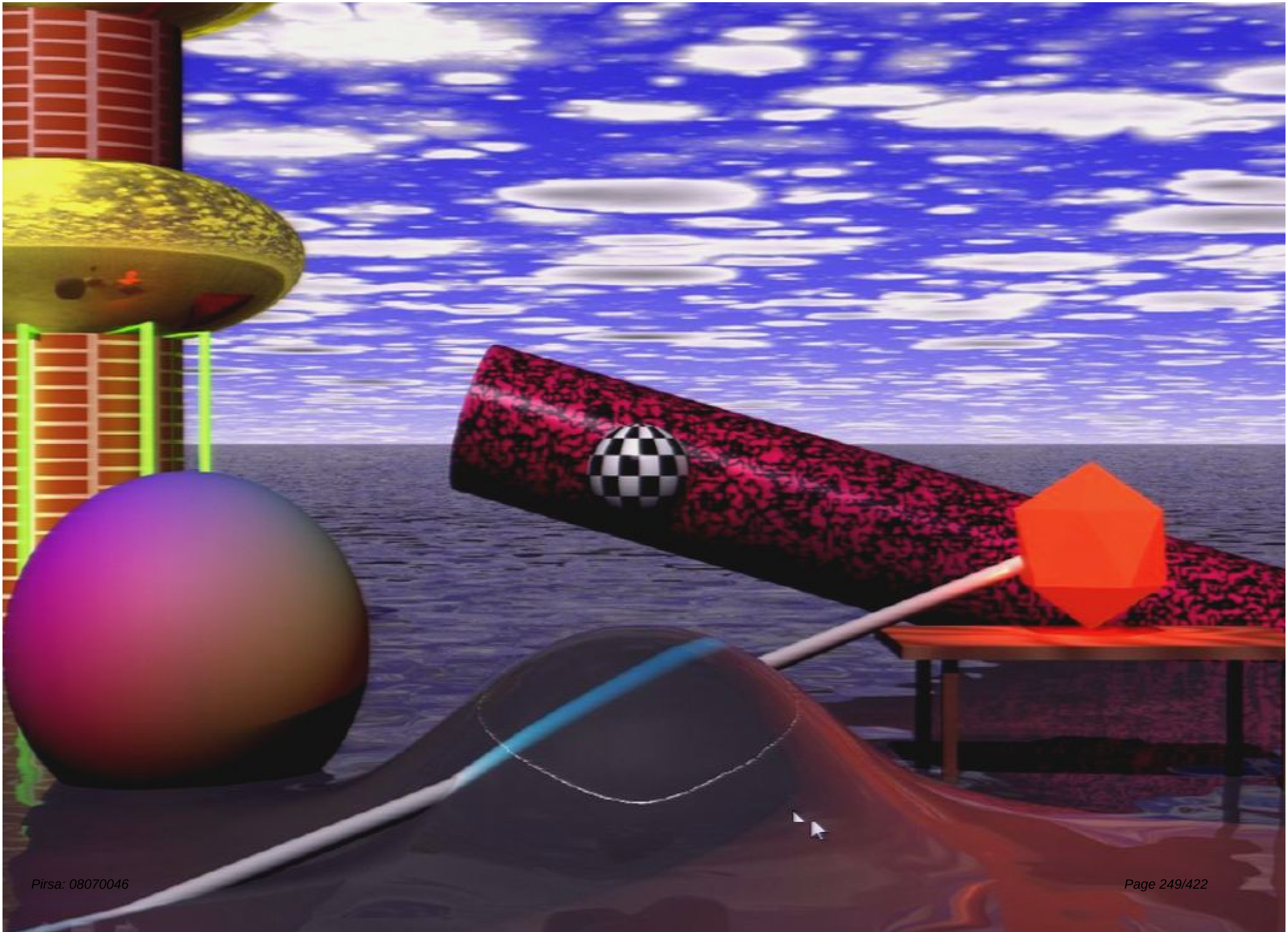
Curvature

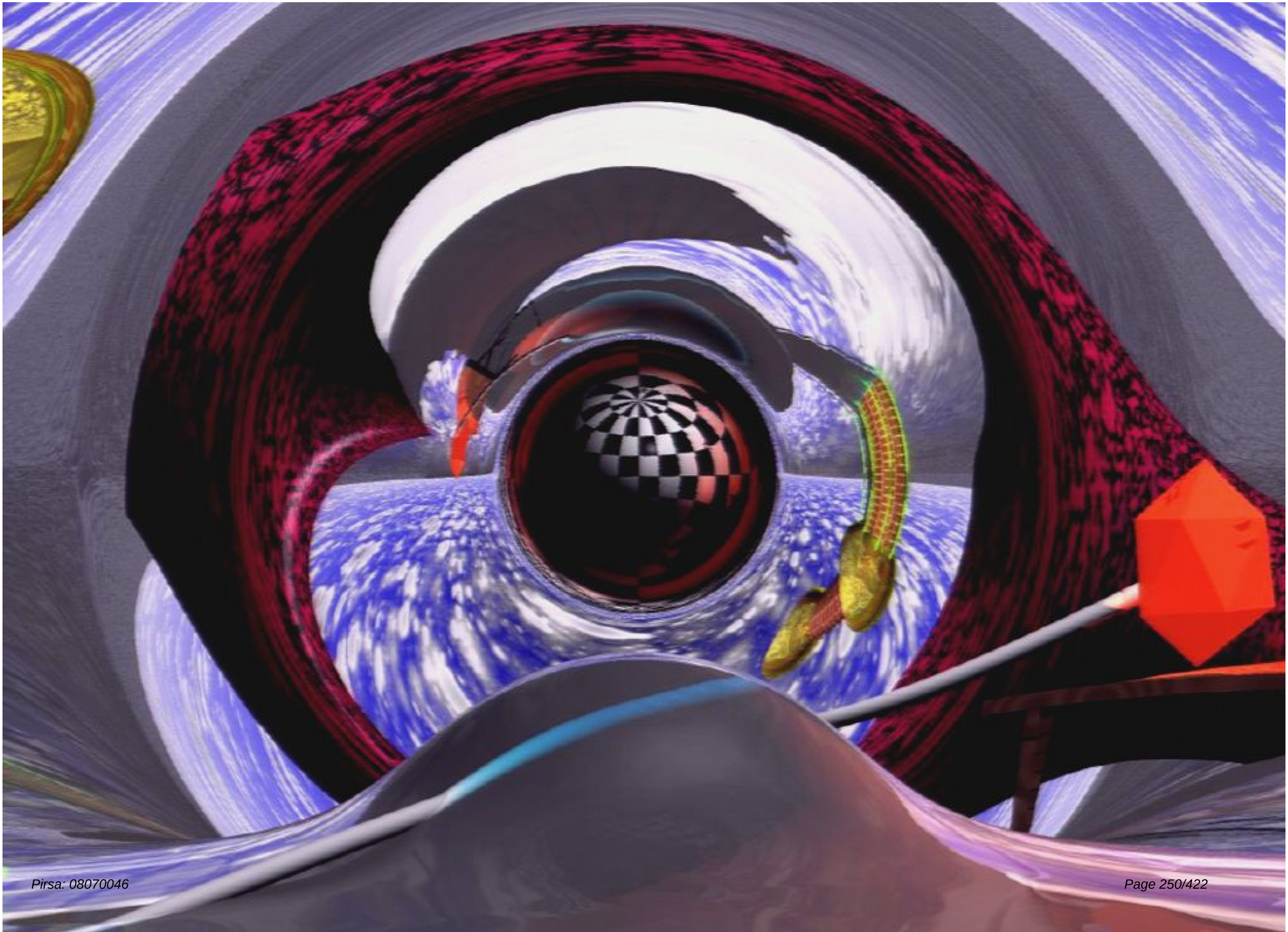


Curvature

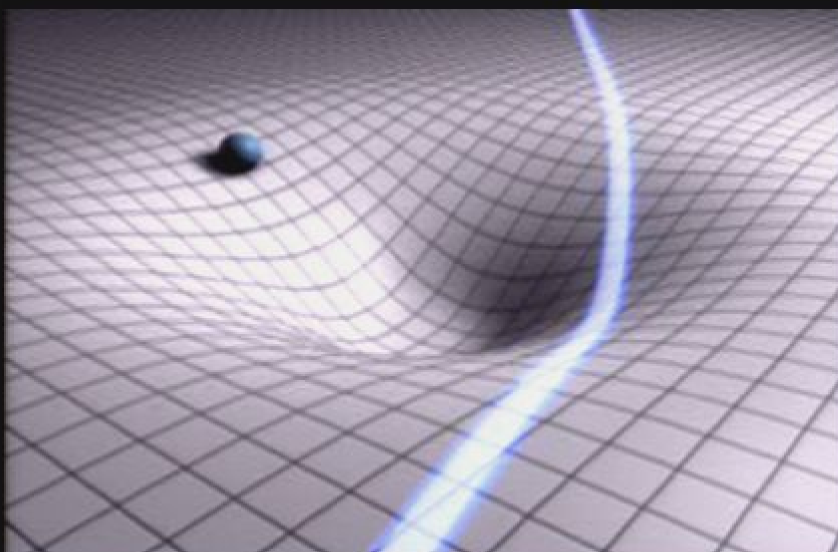


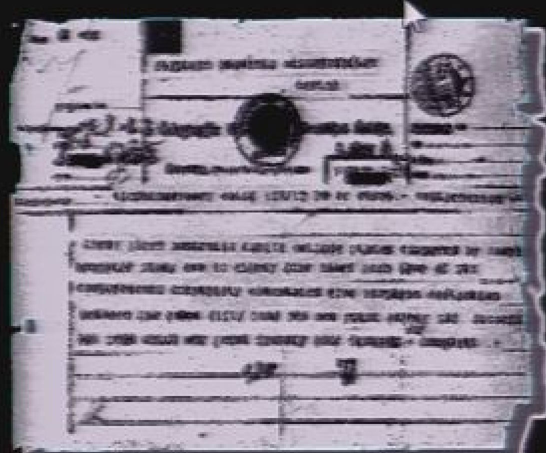
Curvature





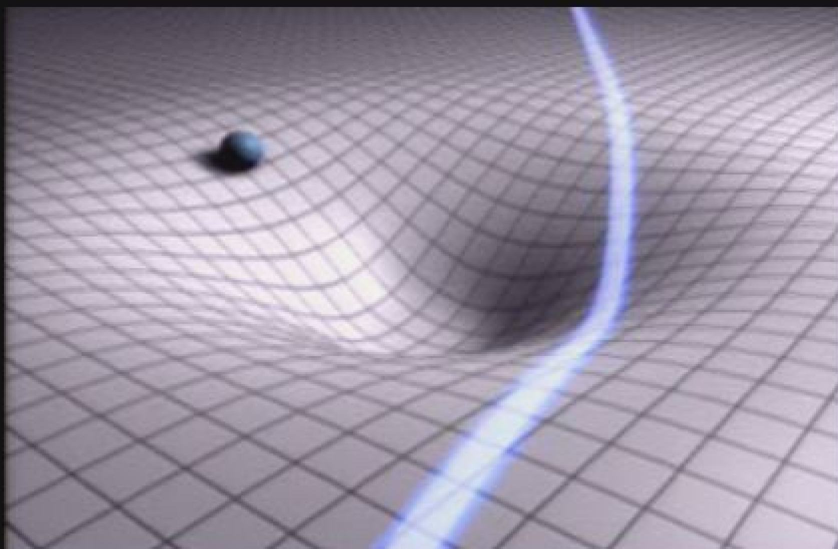
1919 Verification

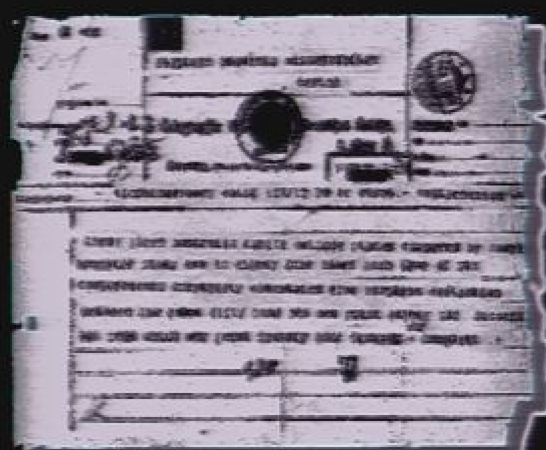




The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.

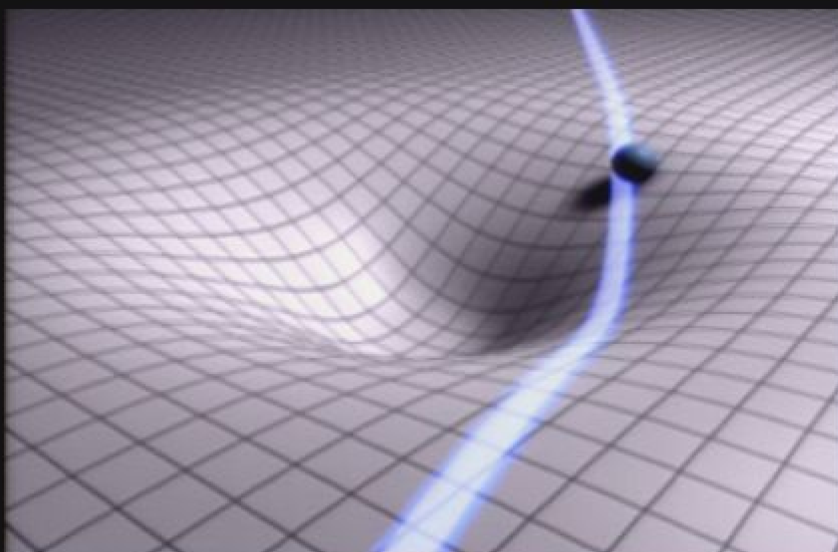
1919 Verification

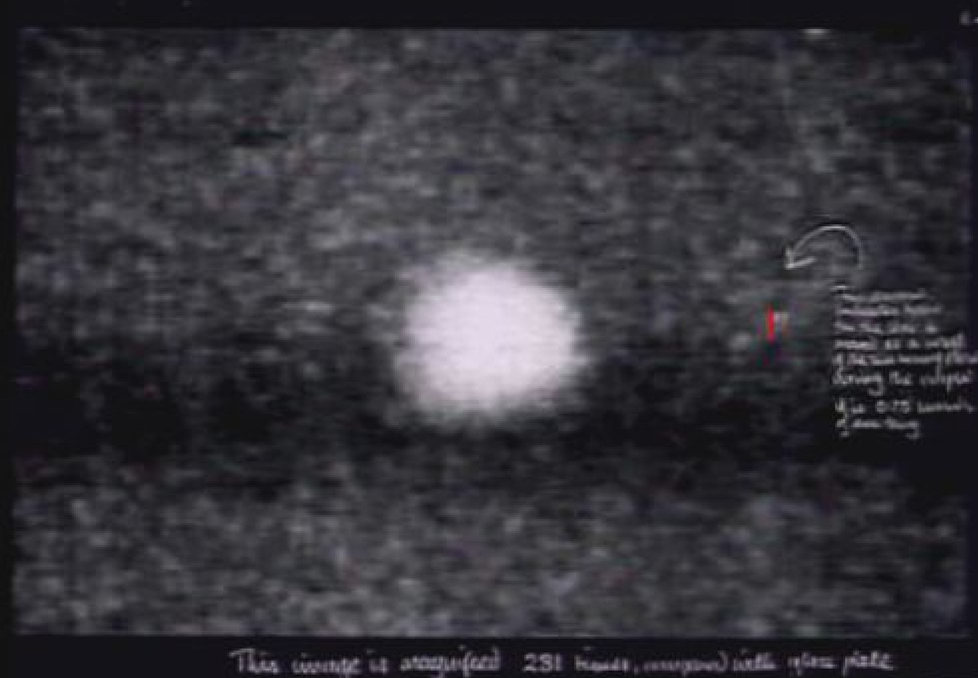




The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.

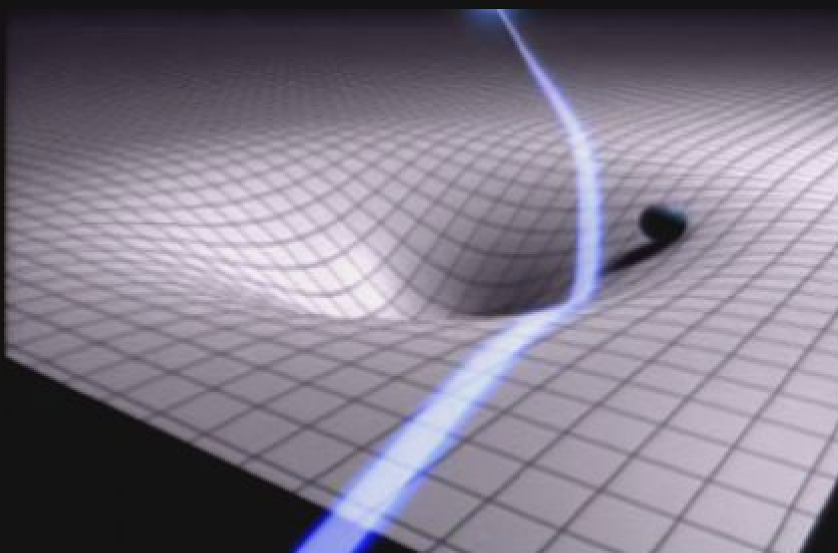
1919 Verification

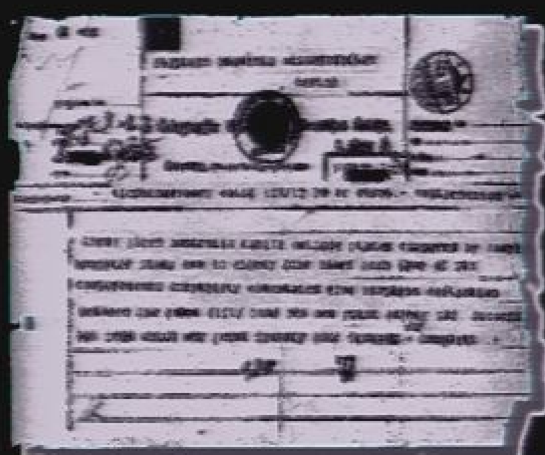




The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.

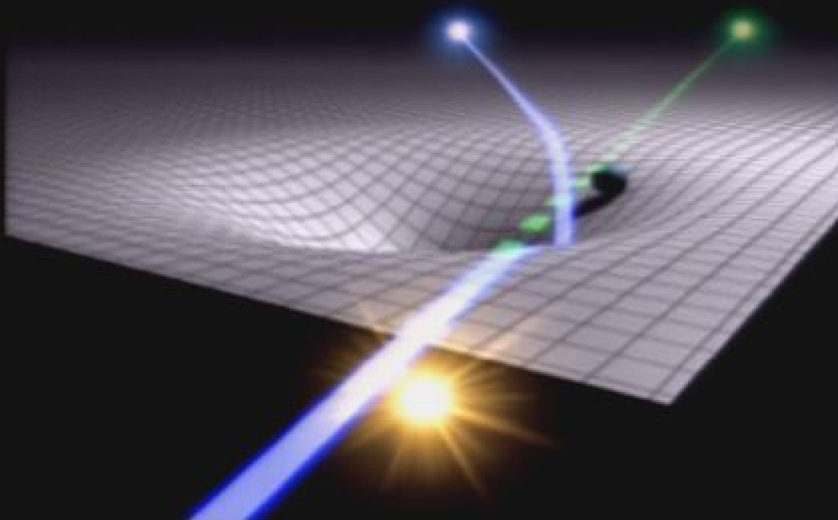
1919 Verification

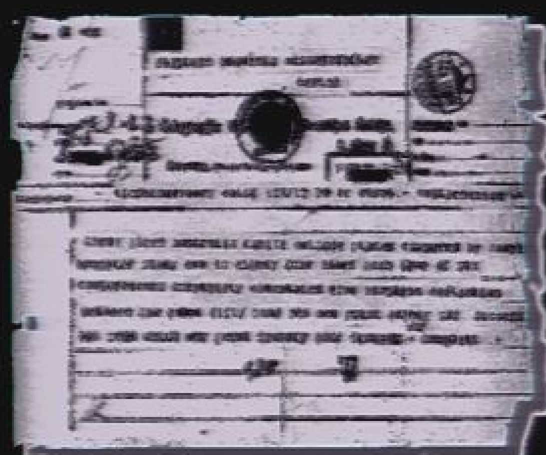




The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.

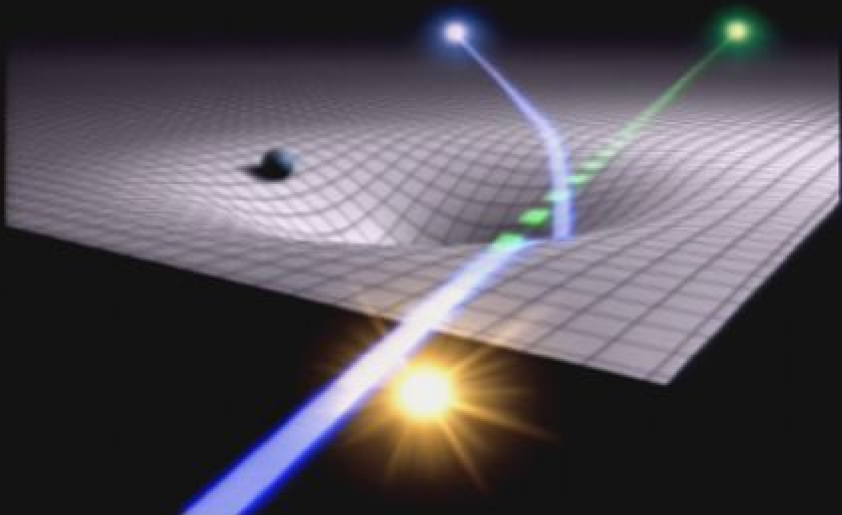
1919 Verification





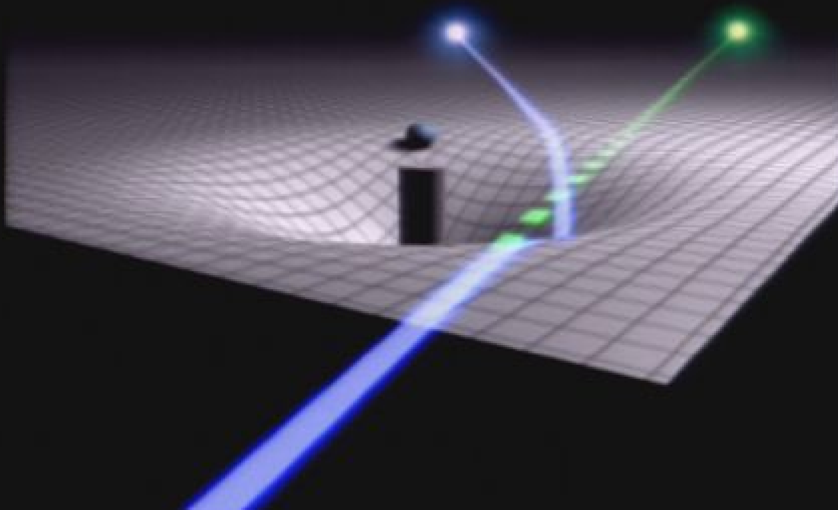
The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.

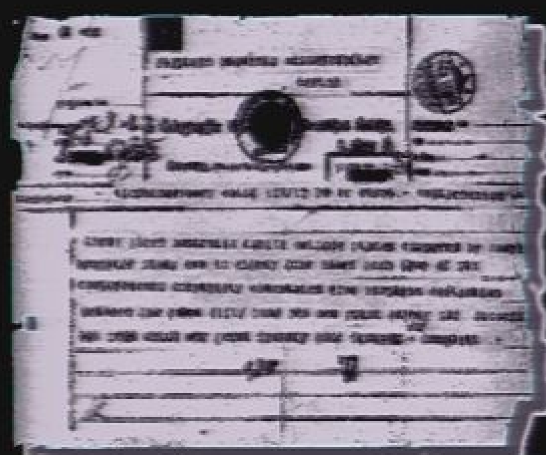
1919 Verification



The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.

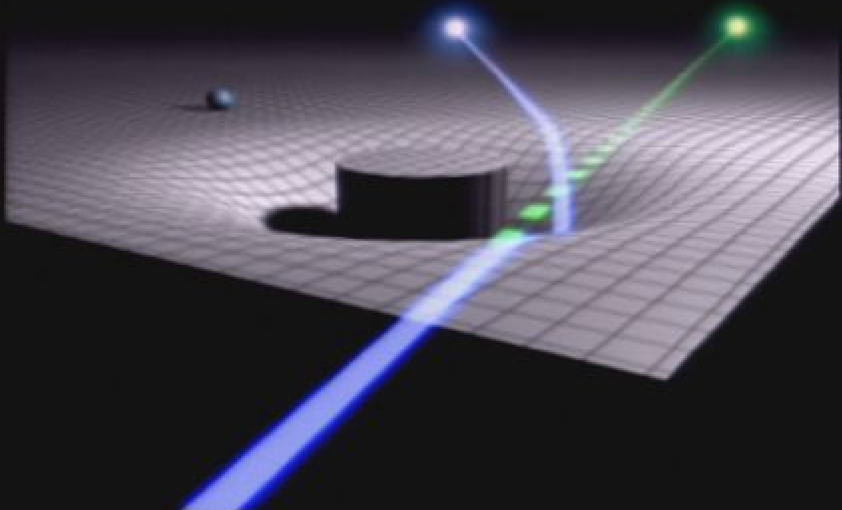
1919 Verification

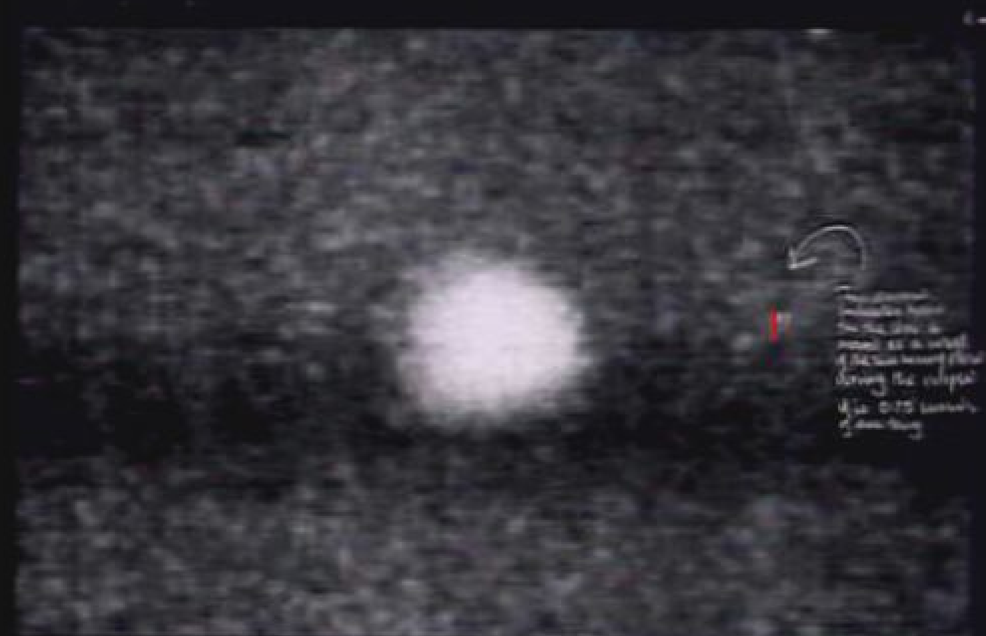




The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.

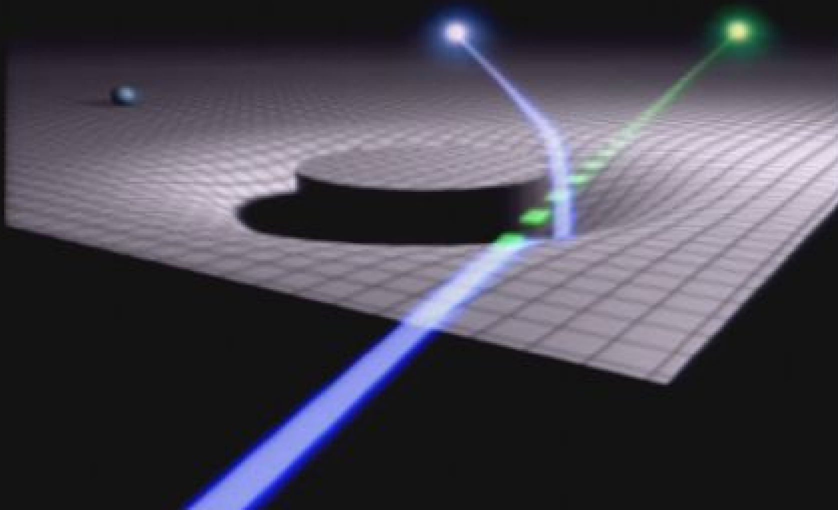
1919 Verification

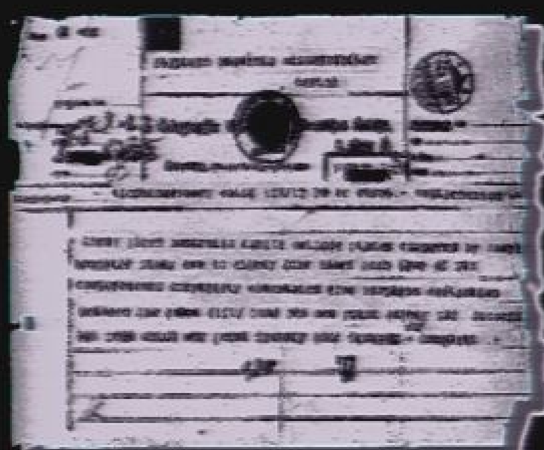




The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.

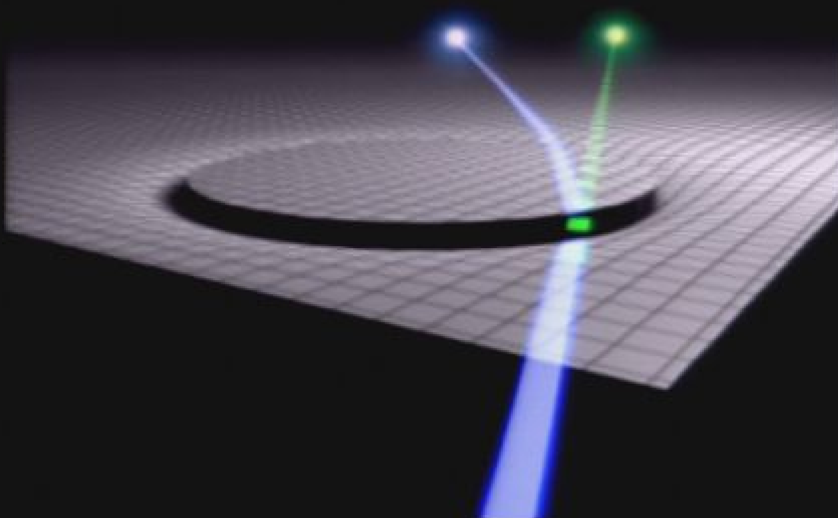
1919 Verification

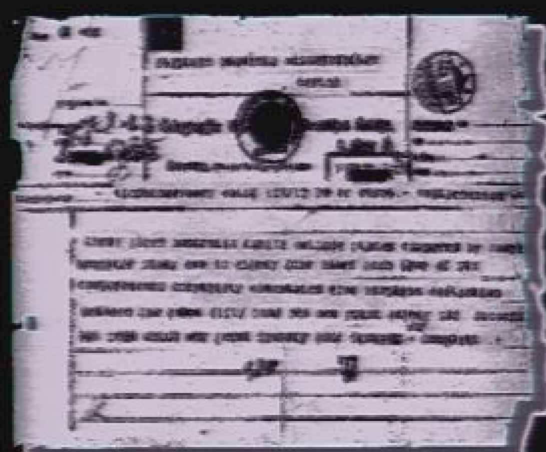




The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.

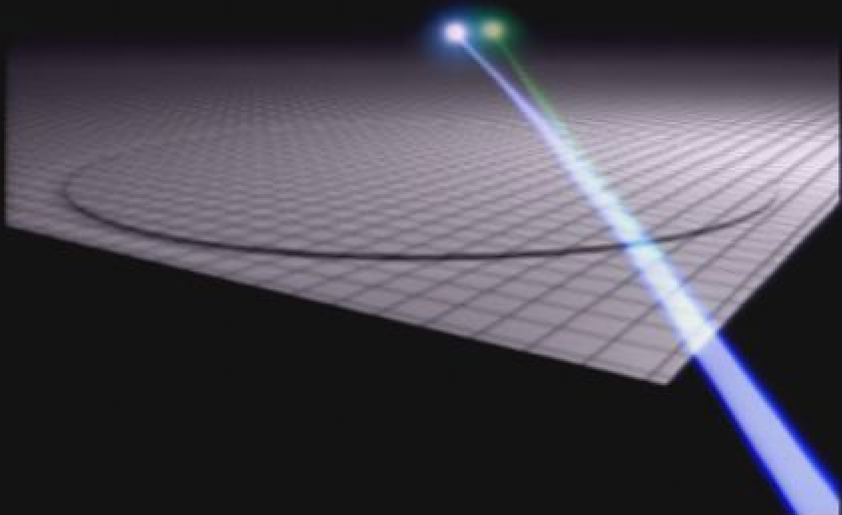
1919 Verification

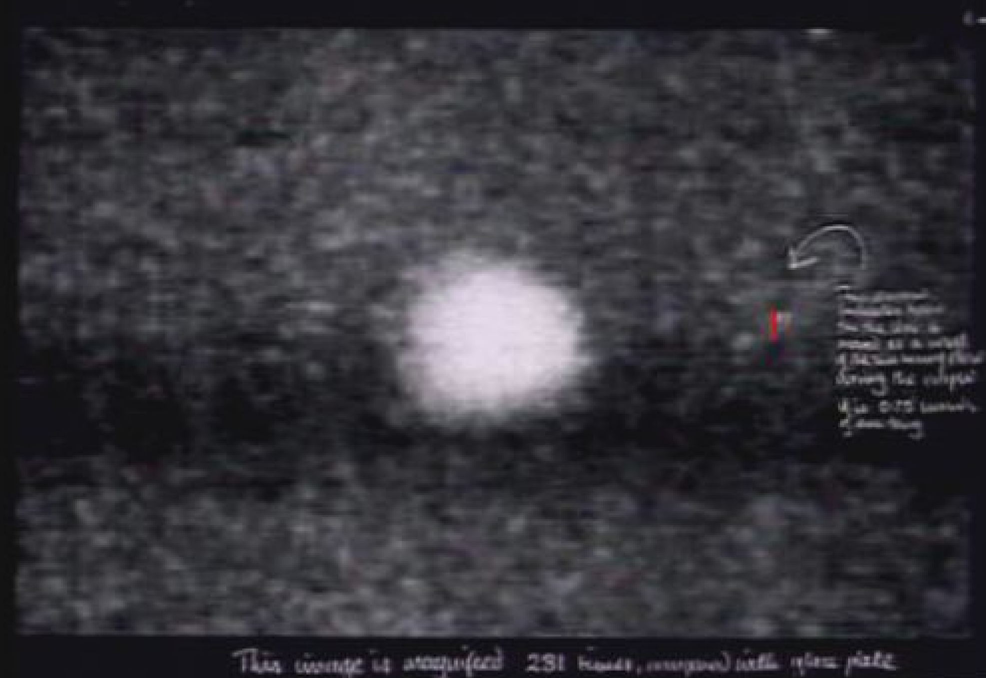


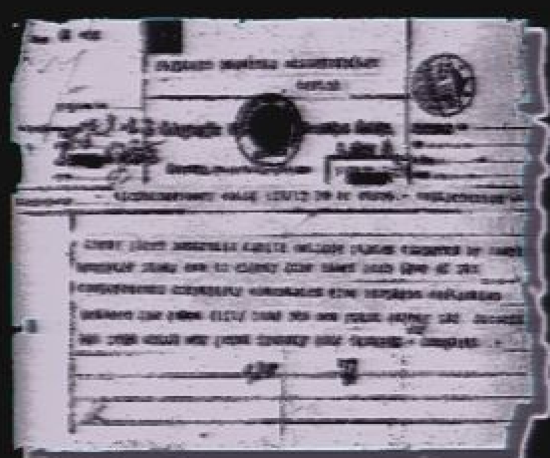


The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.

1919 Verification

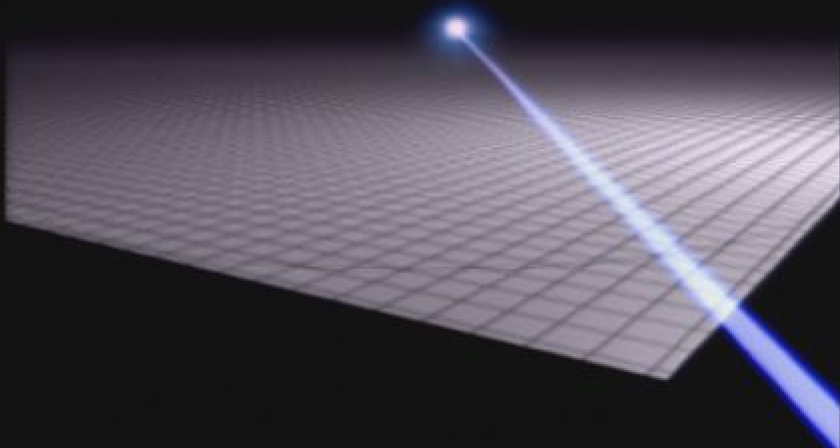


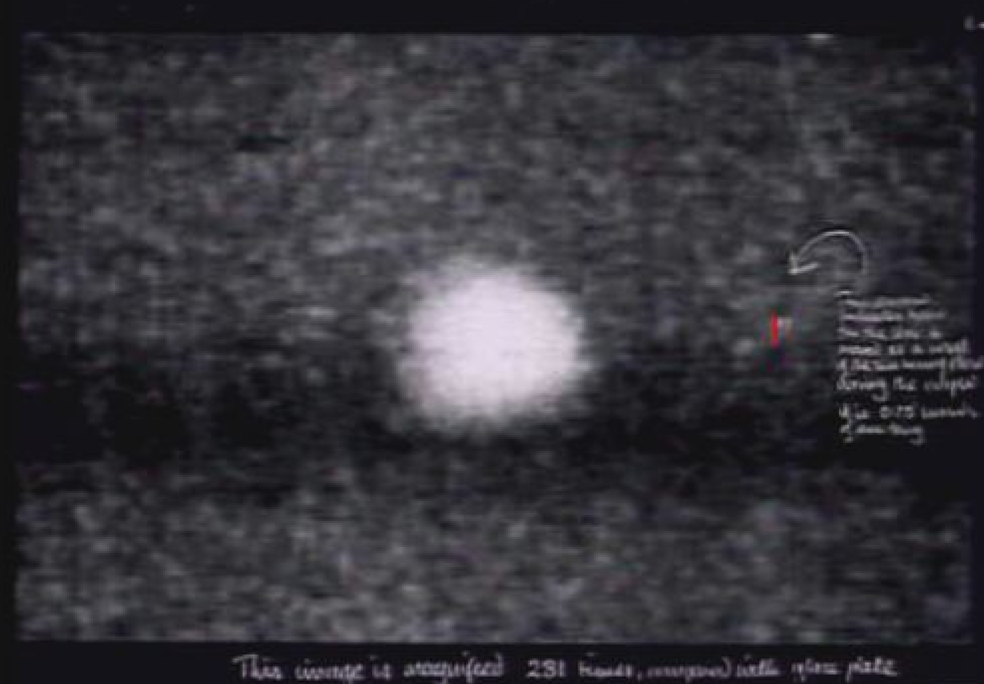


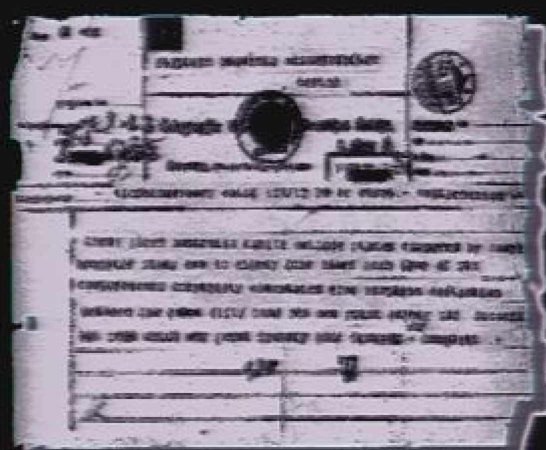


The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.

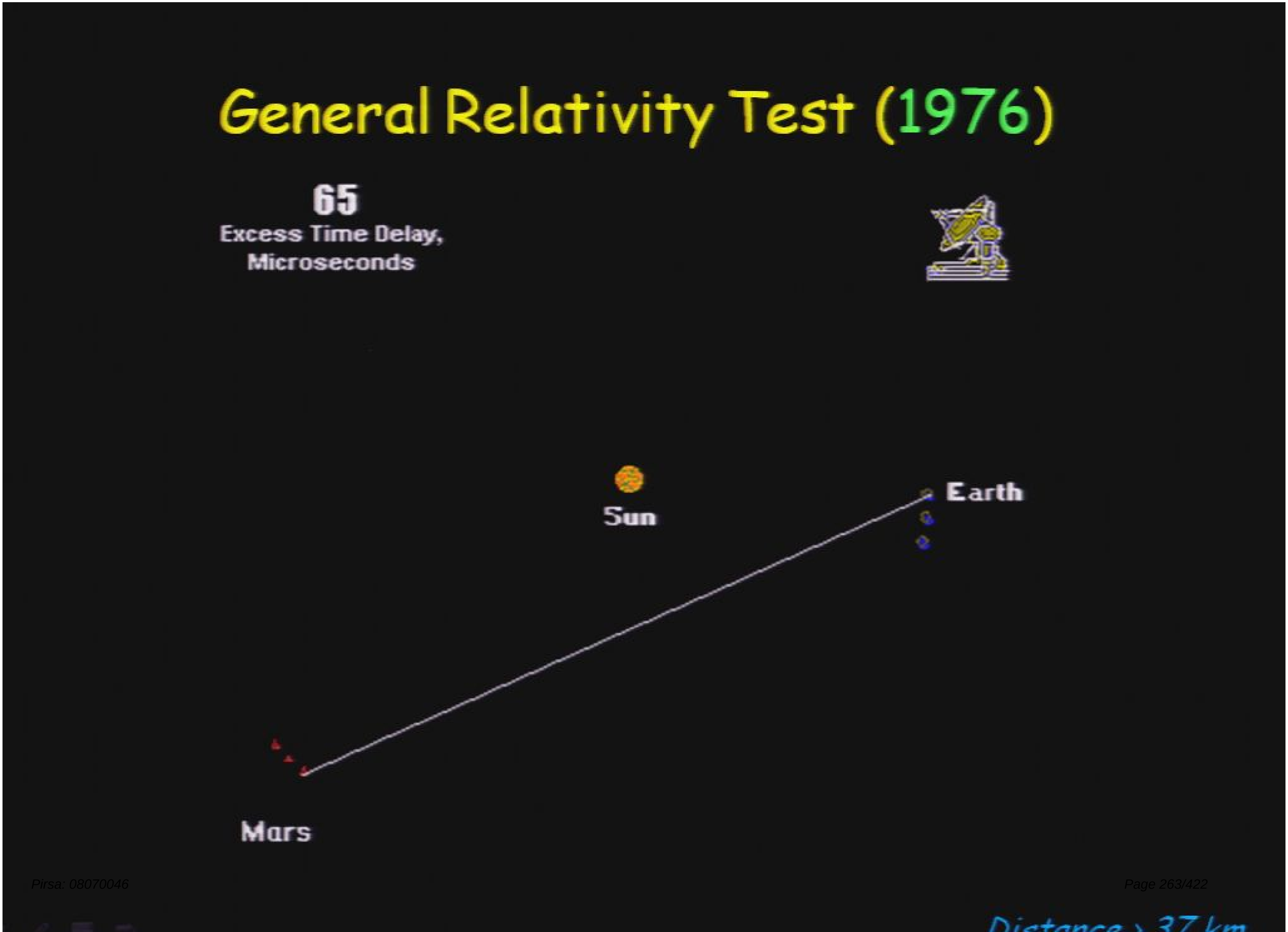
1919 Verification



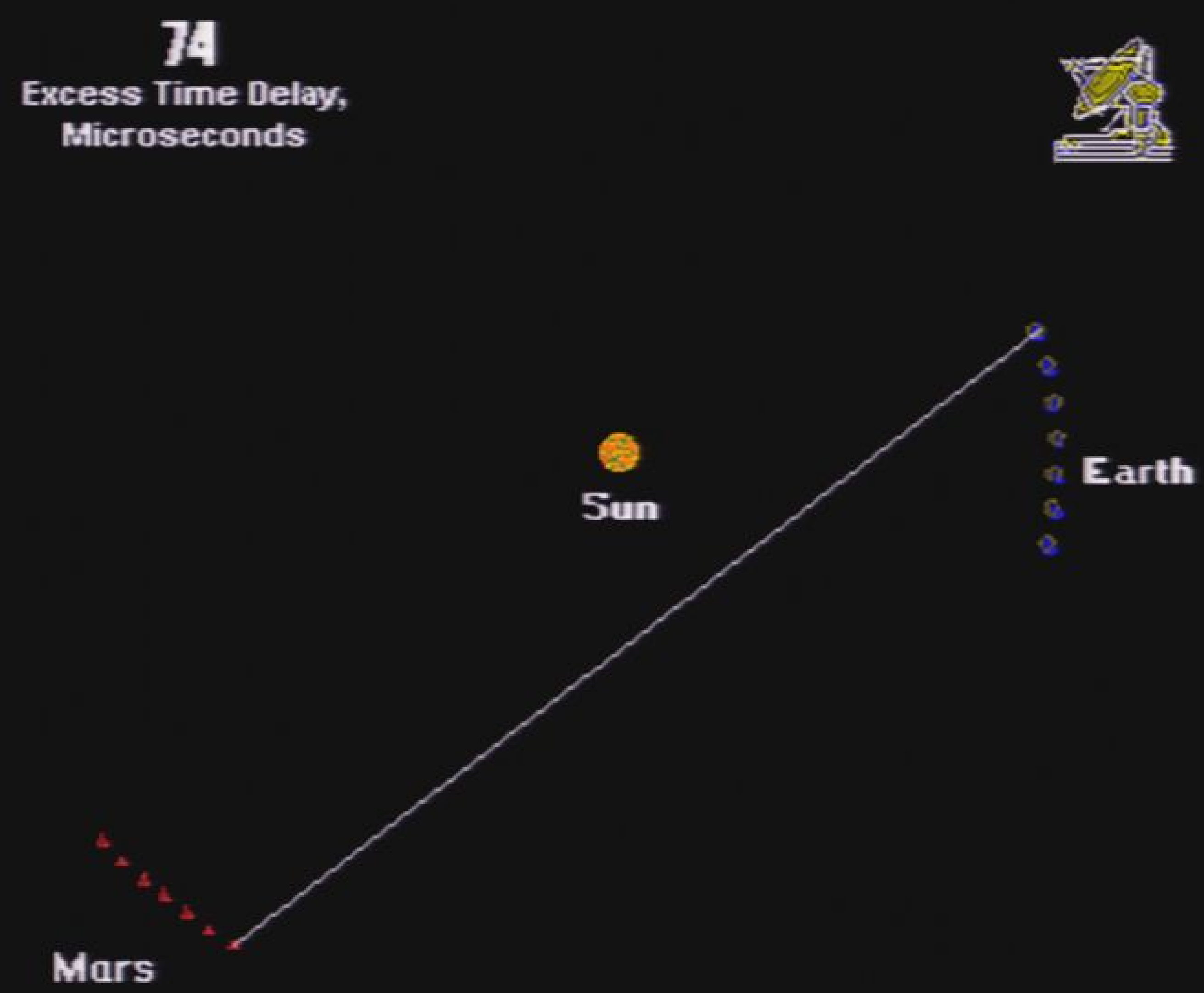


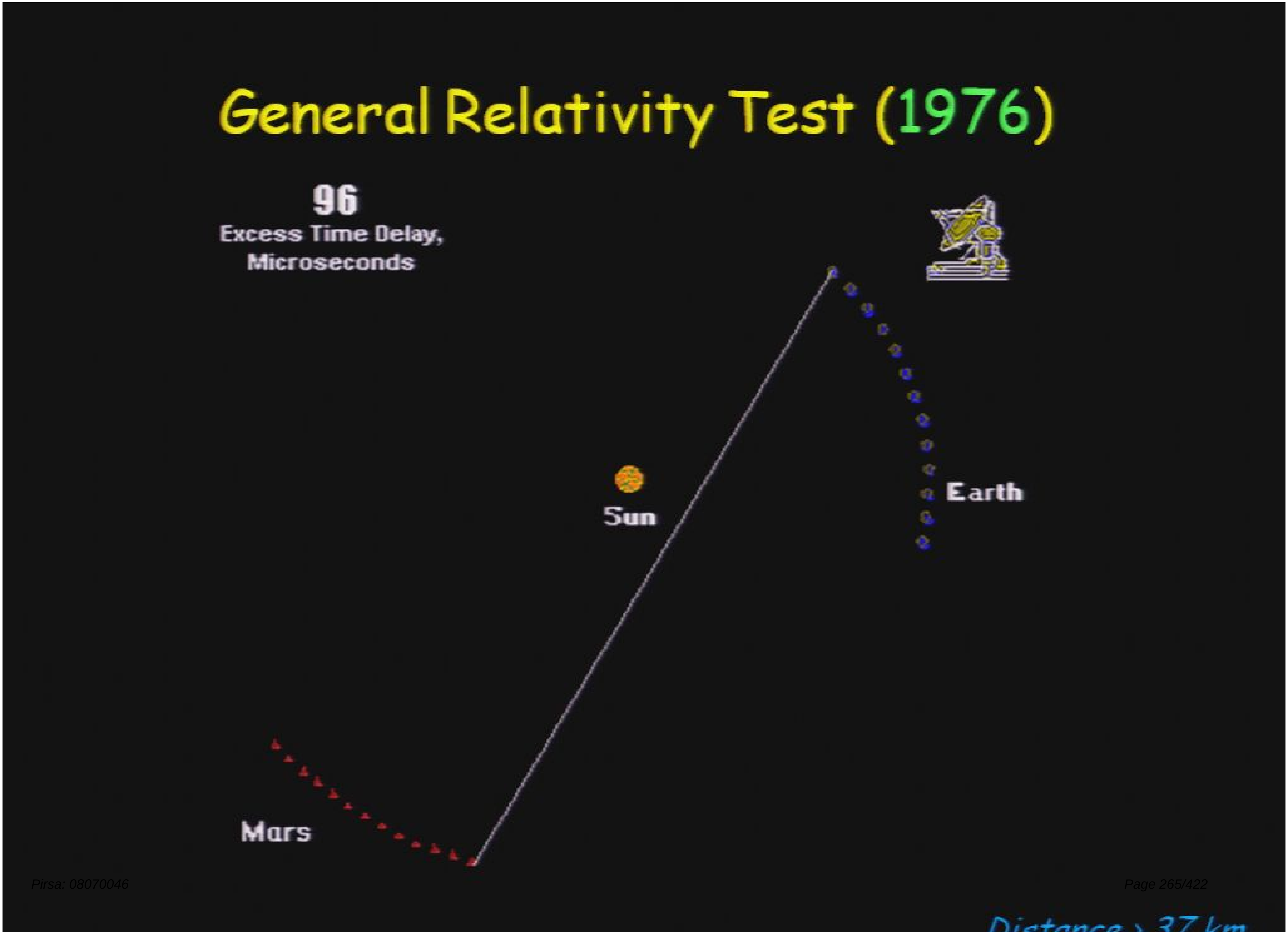


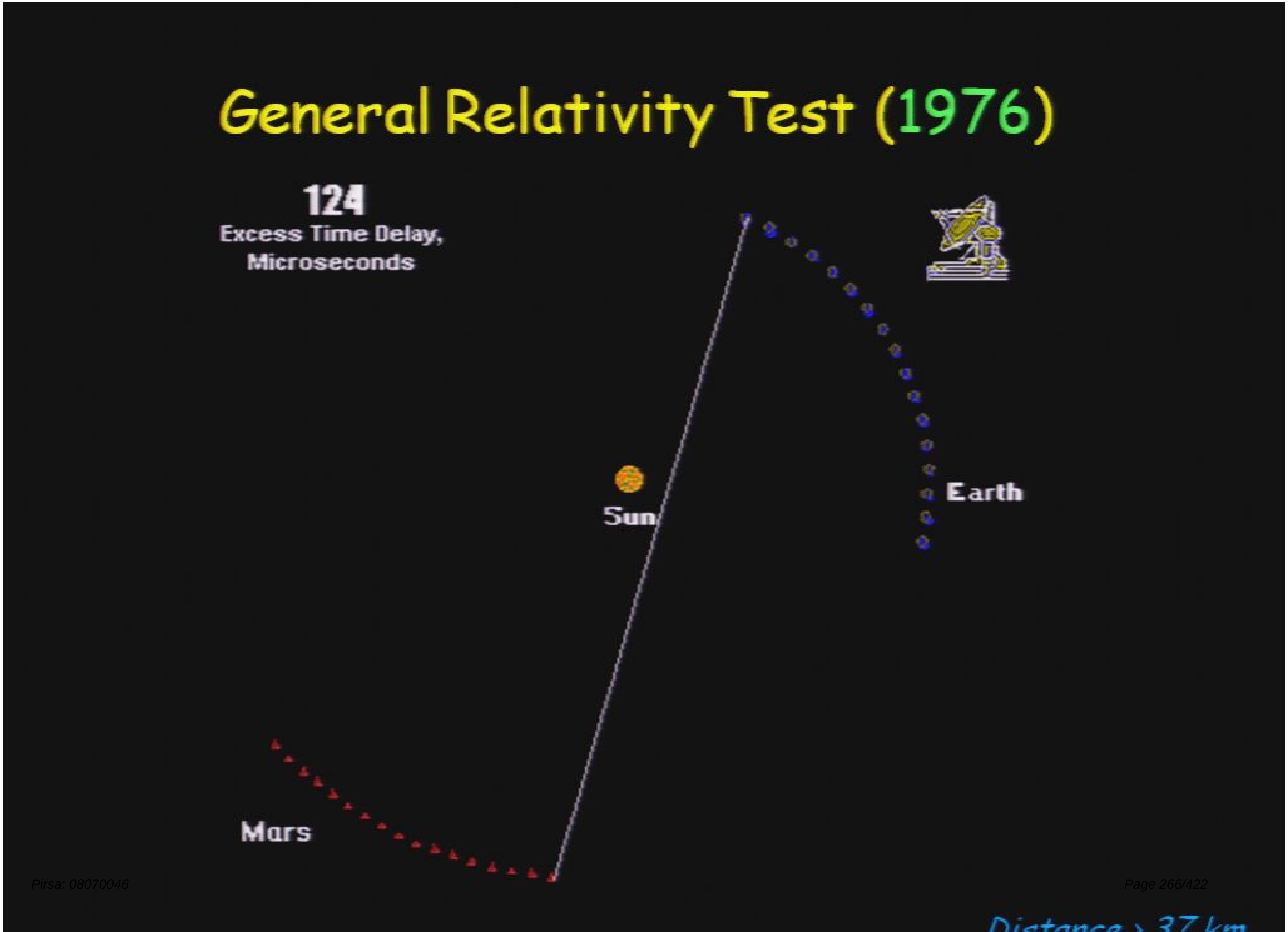
The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.


General Relativity Test (1976)
65
Excess Time Delay,
Microseconds
Sun
Earth
Mars

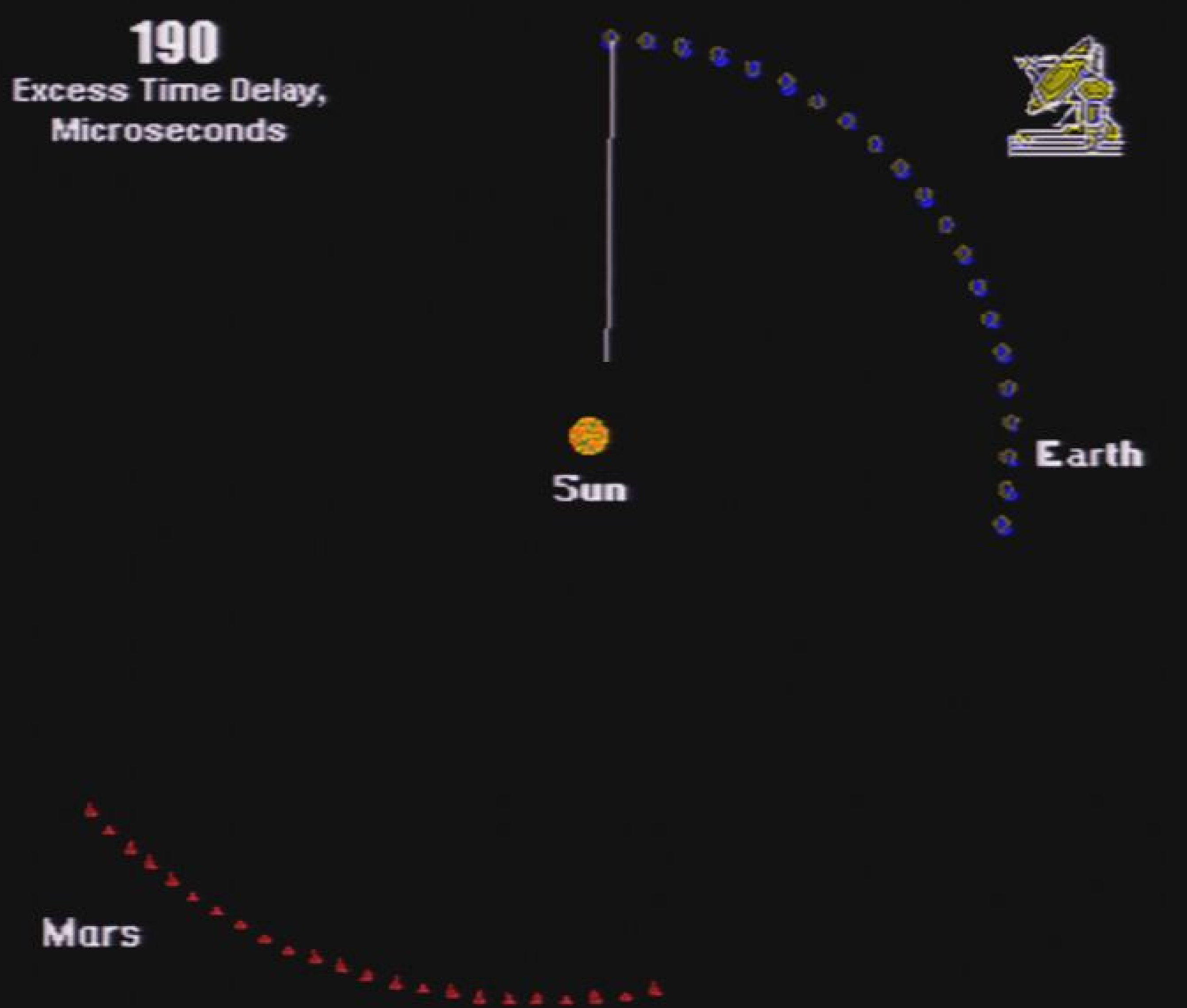
General Relativity Test (1976)




General Relativity Test (1976)
96
Excess Time Delay,
Microseconds
Sun
Earth
Mars

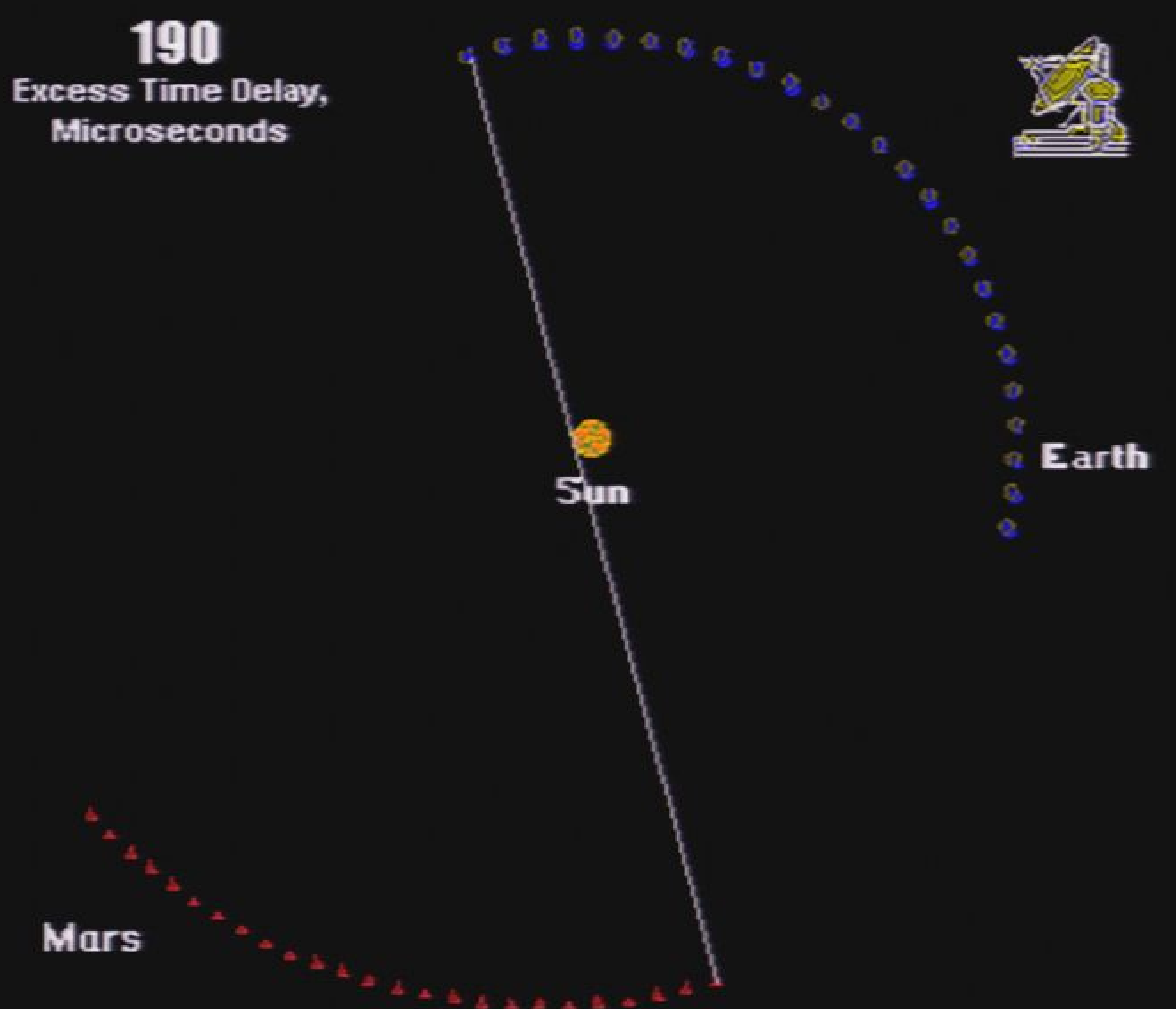

General Relativity Test (1976)
124
Excess Time Delay,
Microseconds
Sun
Earth
Mars

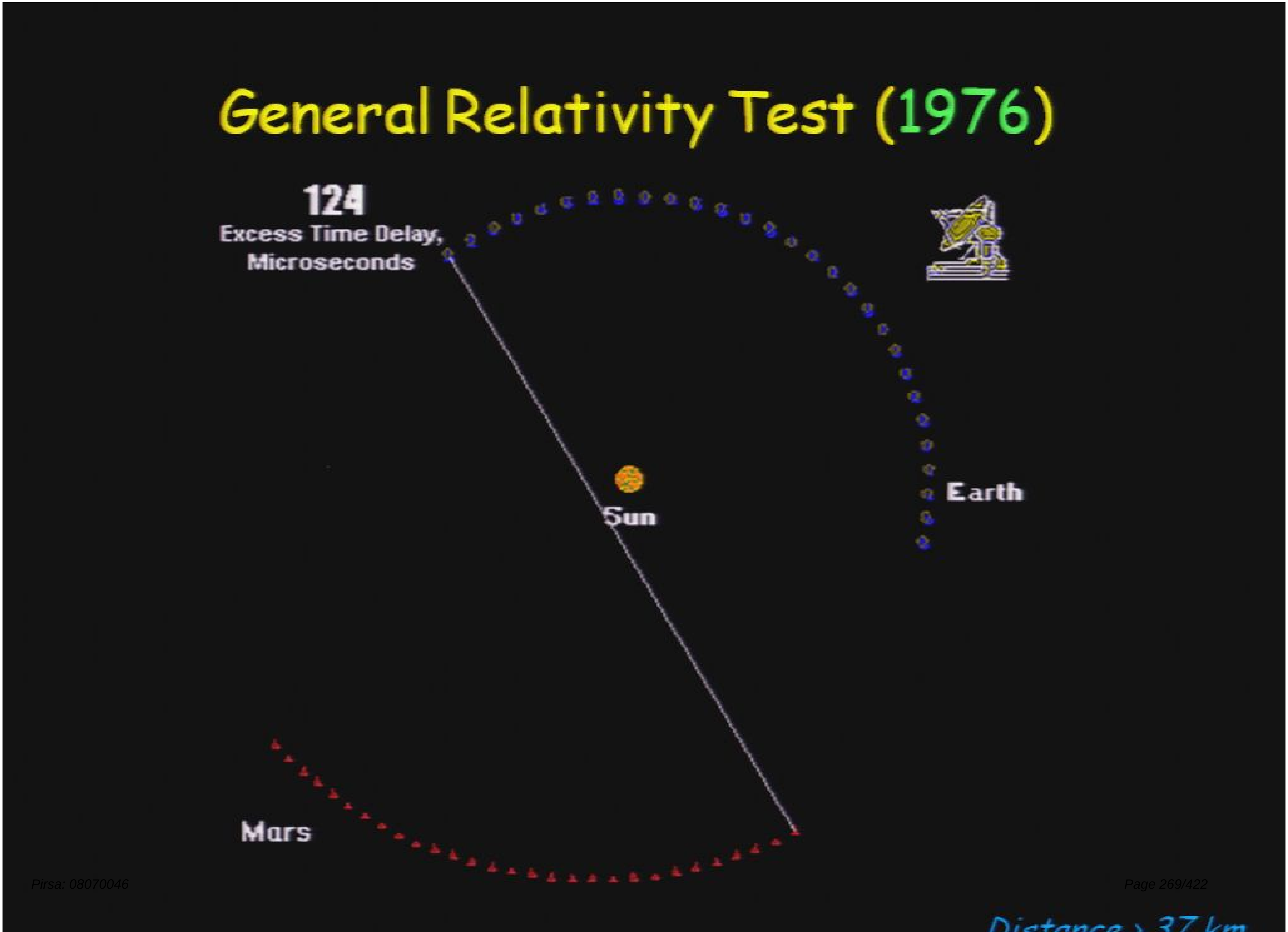
General Relativity Test (1976)

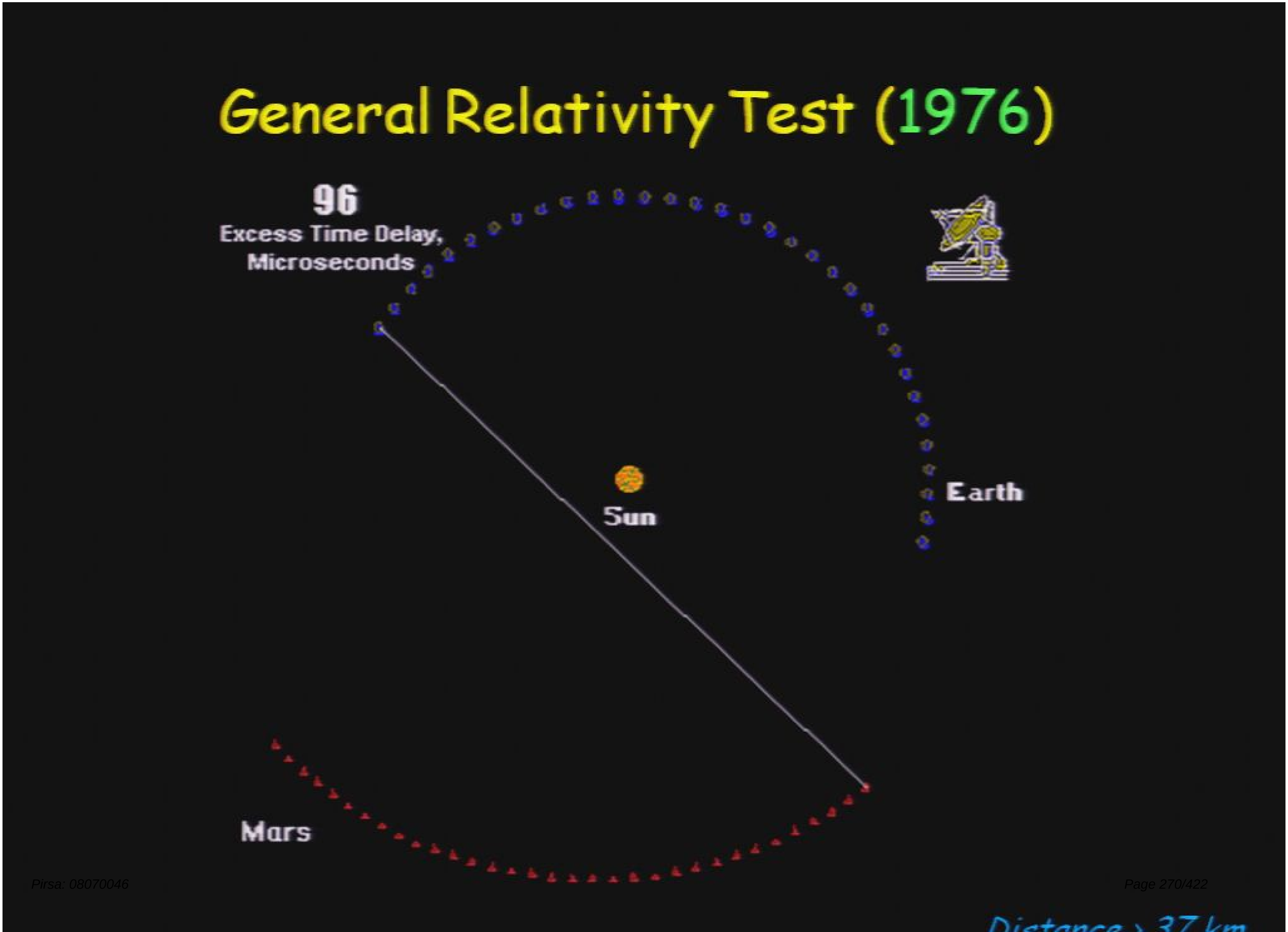


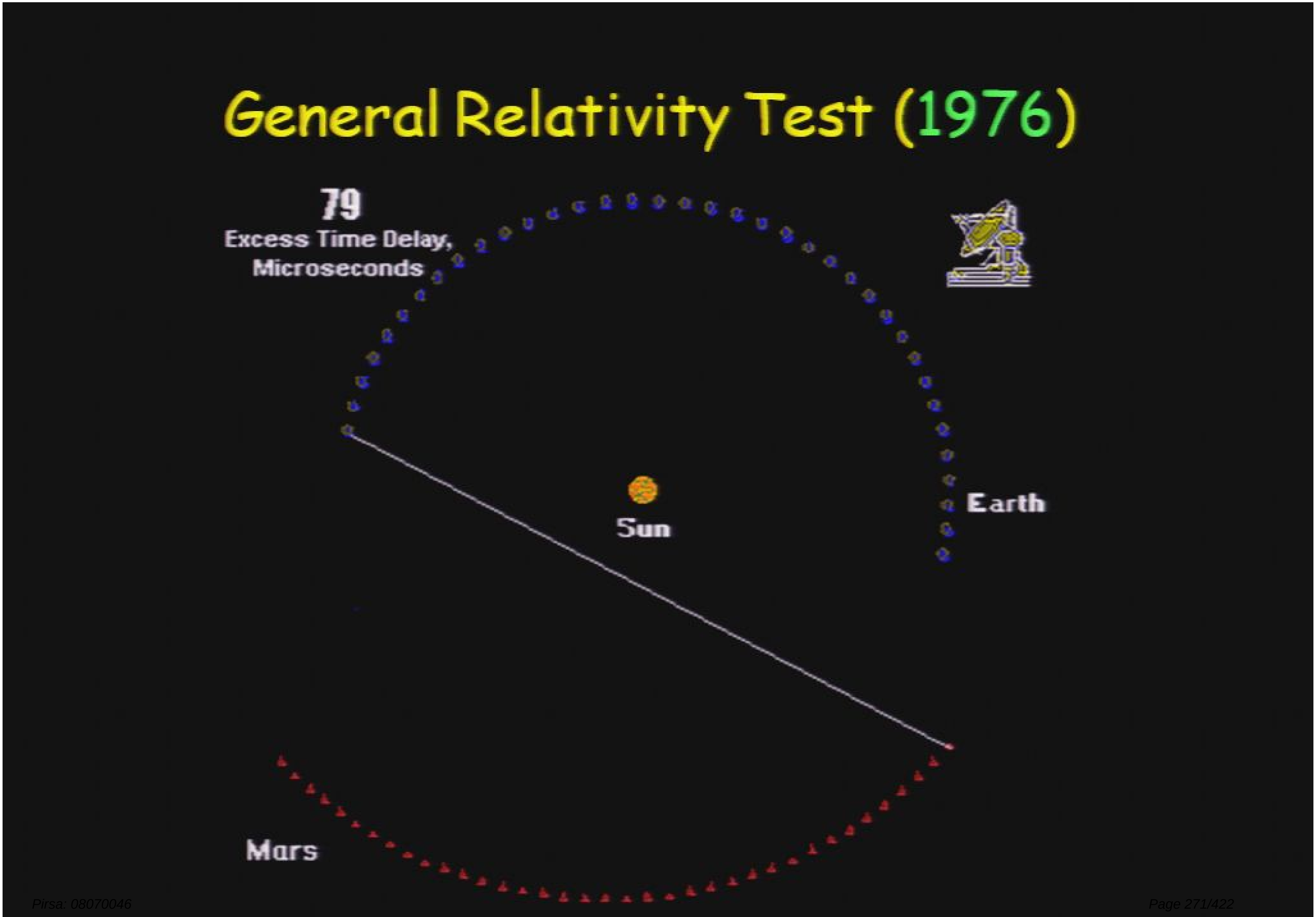
Distance > 37 km

General Relativity Test (1976)

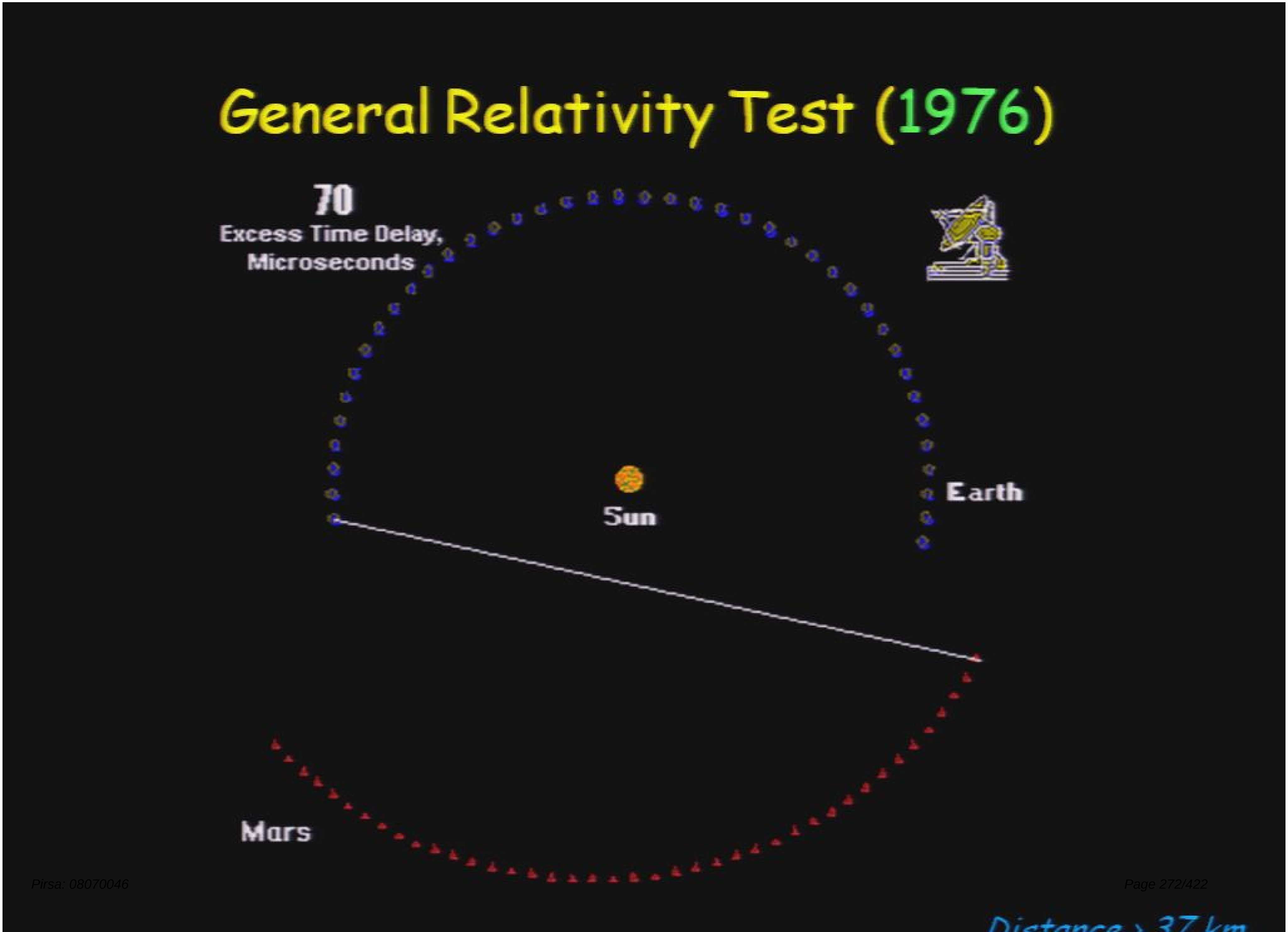


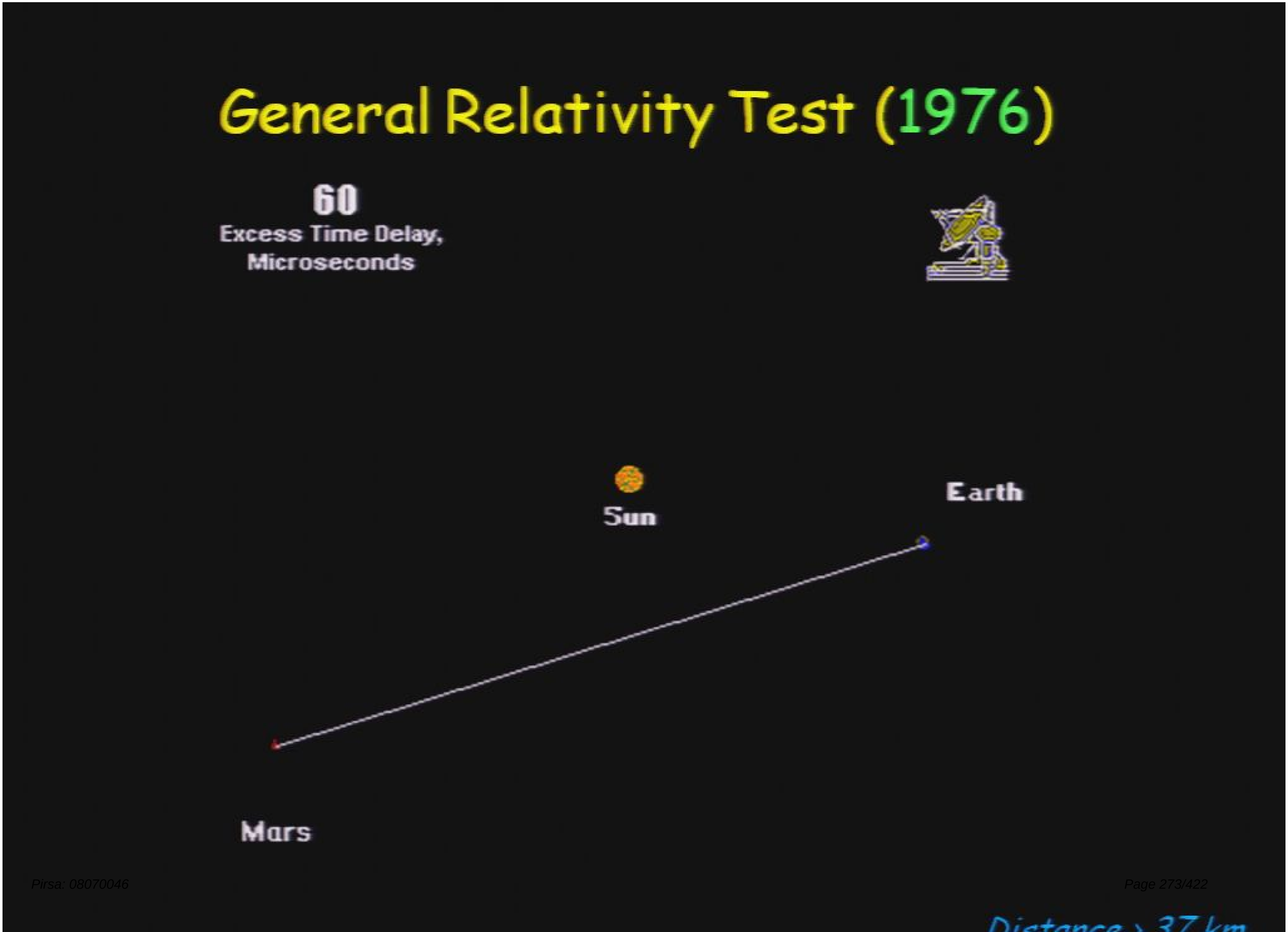

General Relativity Test (1976)
124
Excess Time Delay, Microseconds
Earth
Sun
Mars
Distance > 37 km


General Relativity Test (1976)
96
Excess Time Delay,
Microseconds
Earth
Sun
Mars

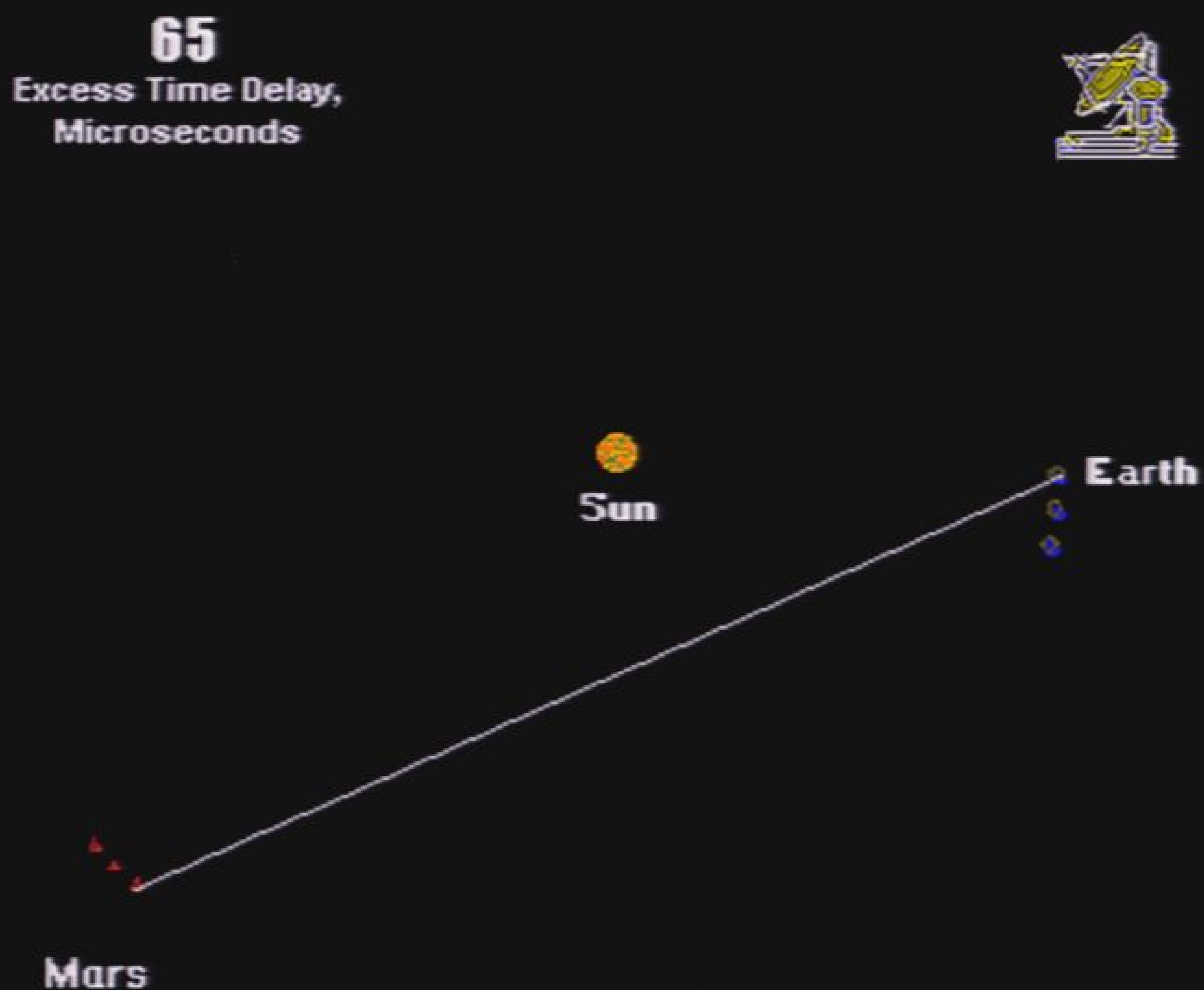


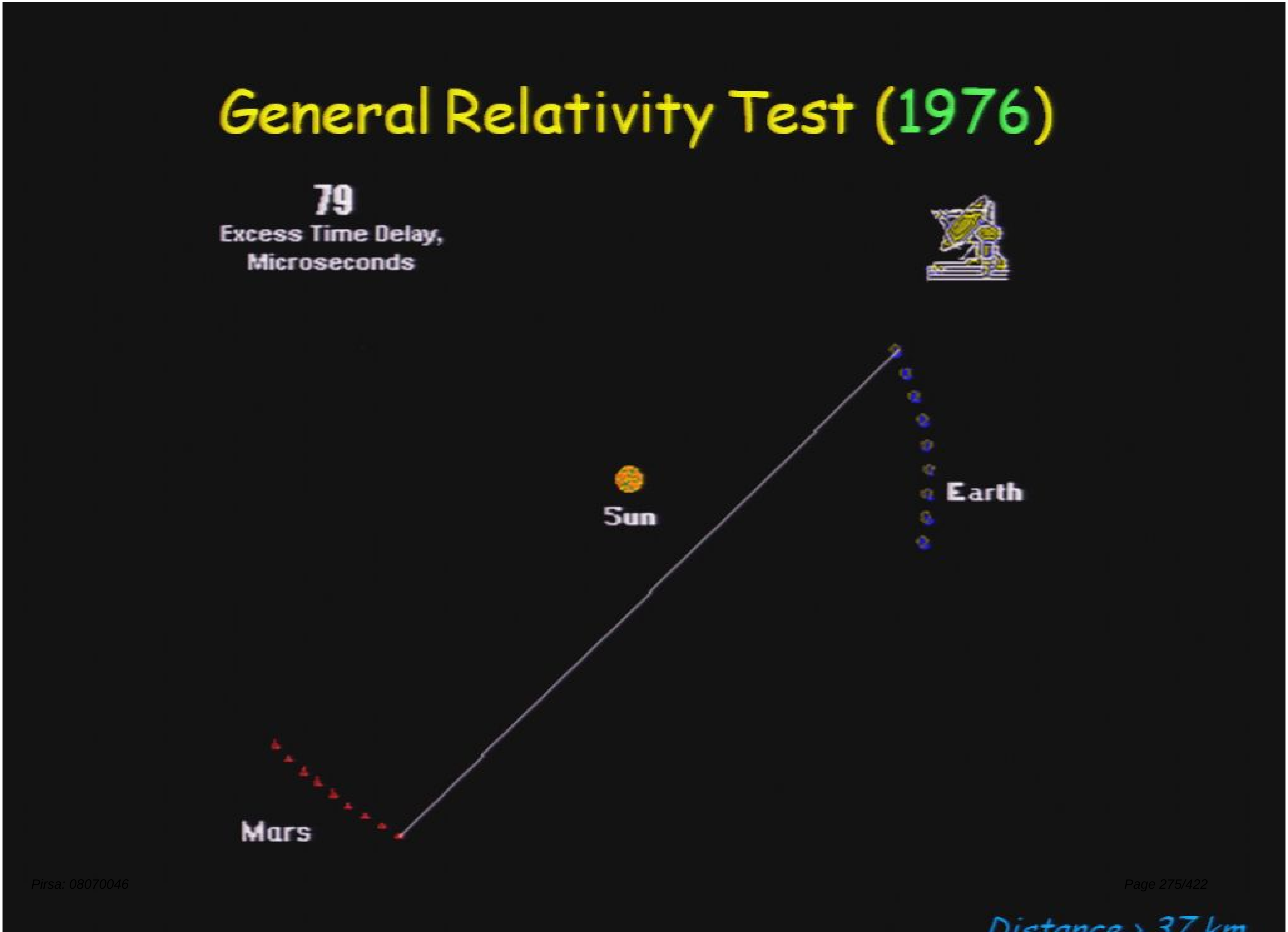
Distance > 37 km


General Relativity Test (1976)
70
Excess Time Delay, Microseconds
Earth
Sun
Mars

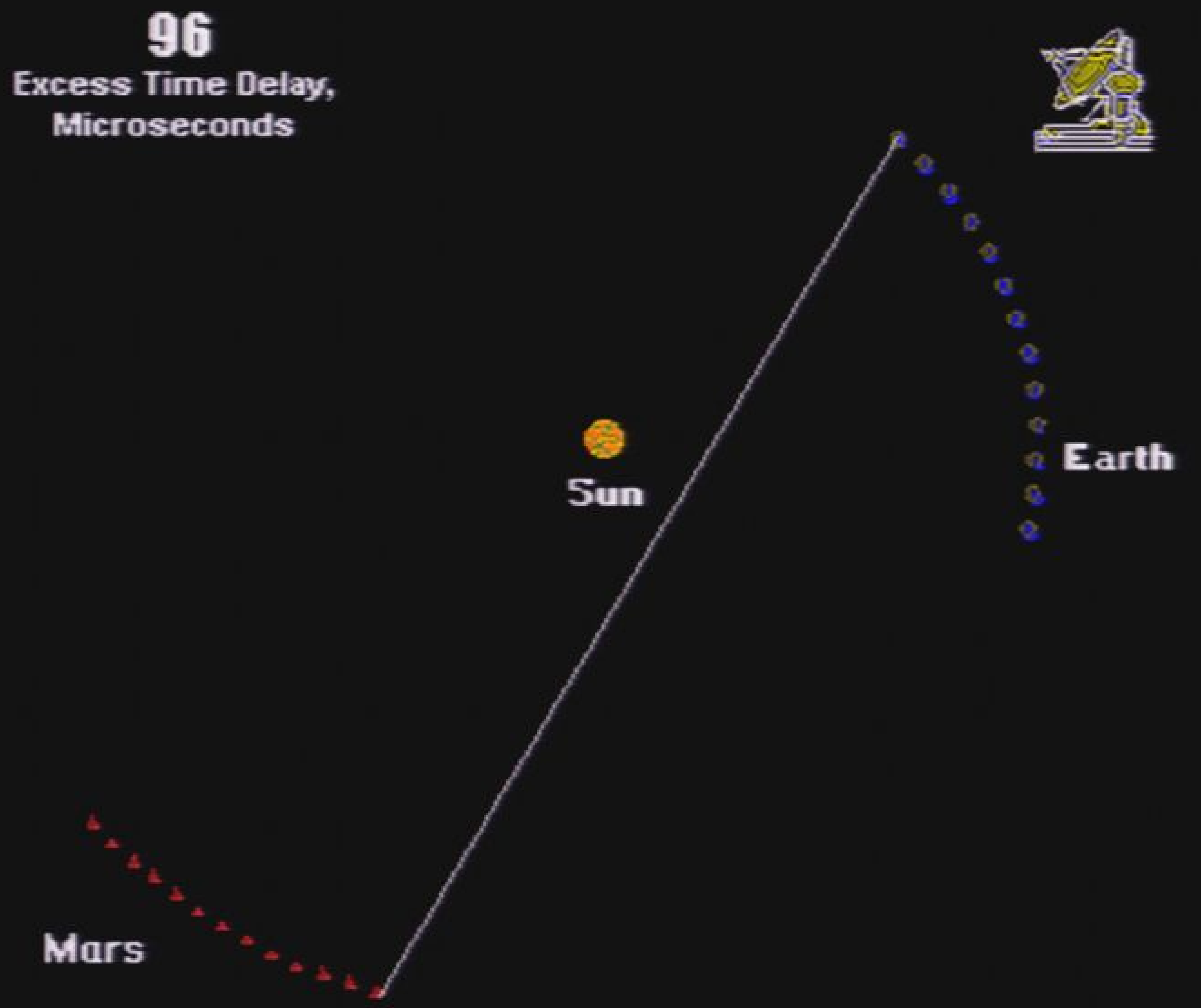

General Relativity Test (1976)
60
Excess Time Delay,
Microseconds
Sun
Earth
Mars

General Relativity Test (1976)



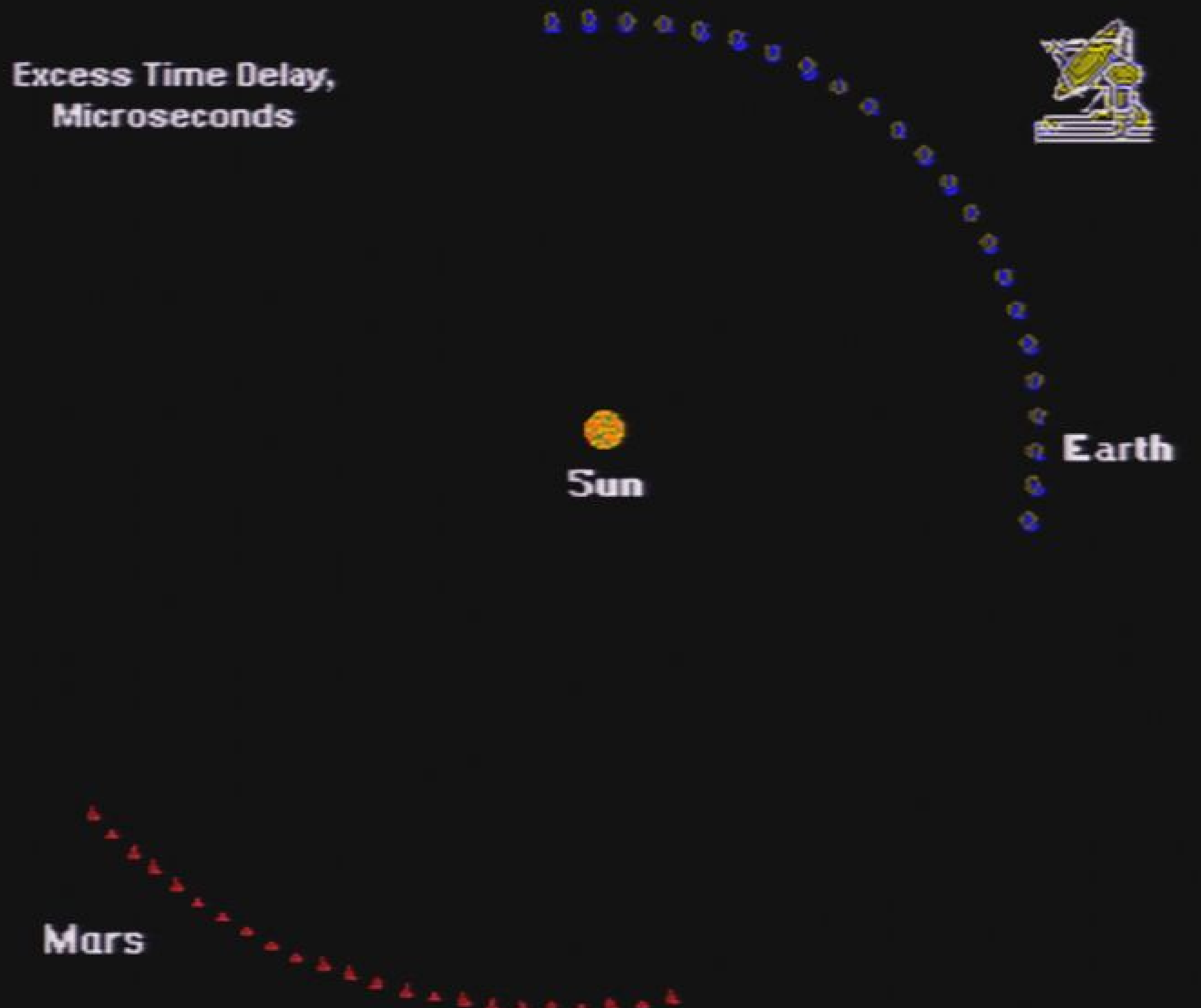

General Relativity Test (1976)
79
Excess Time Delay,
Microseconds
Sun
Earth
Mars

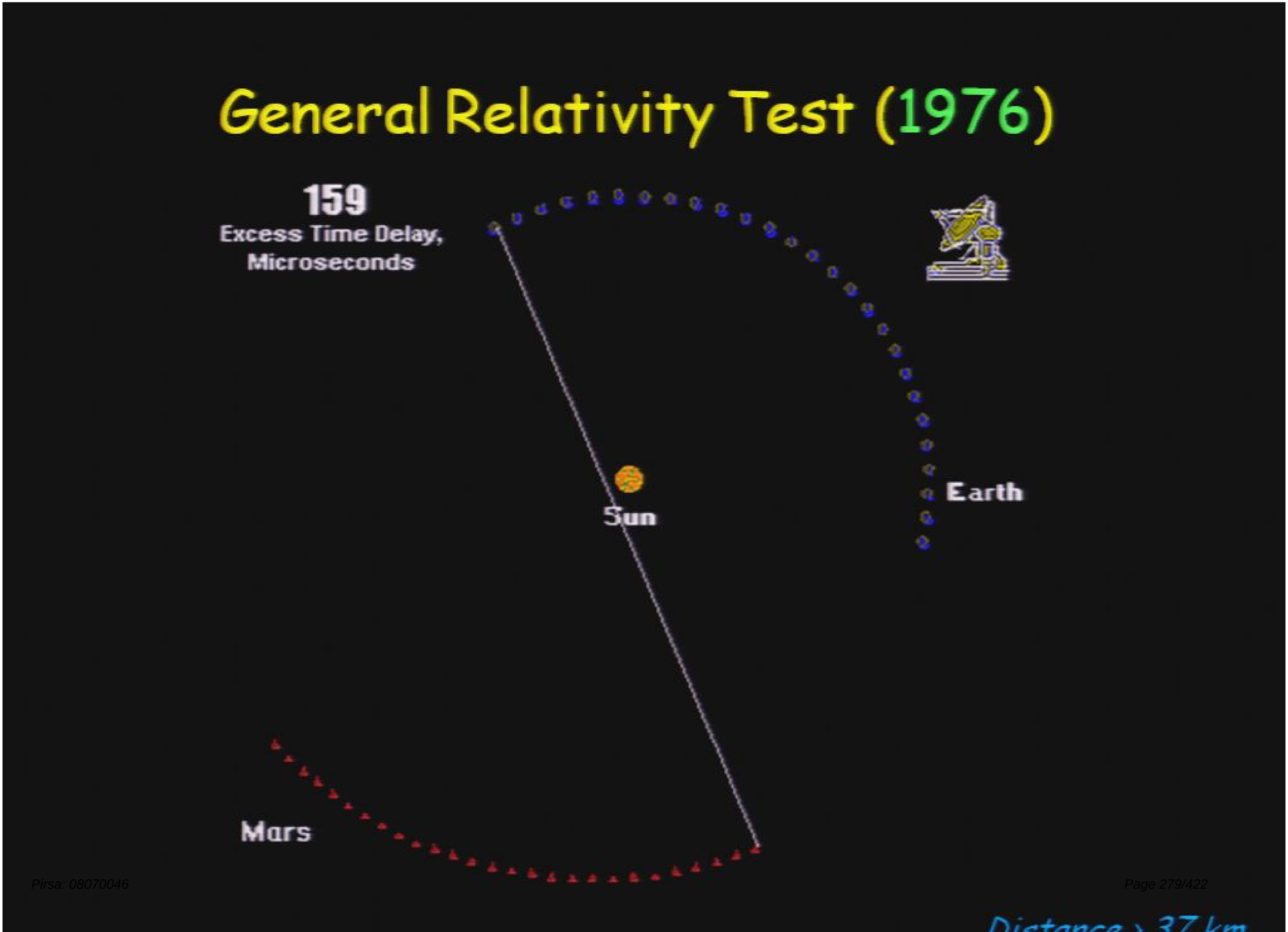
General Relativity Test (1976)

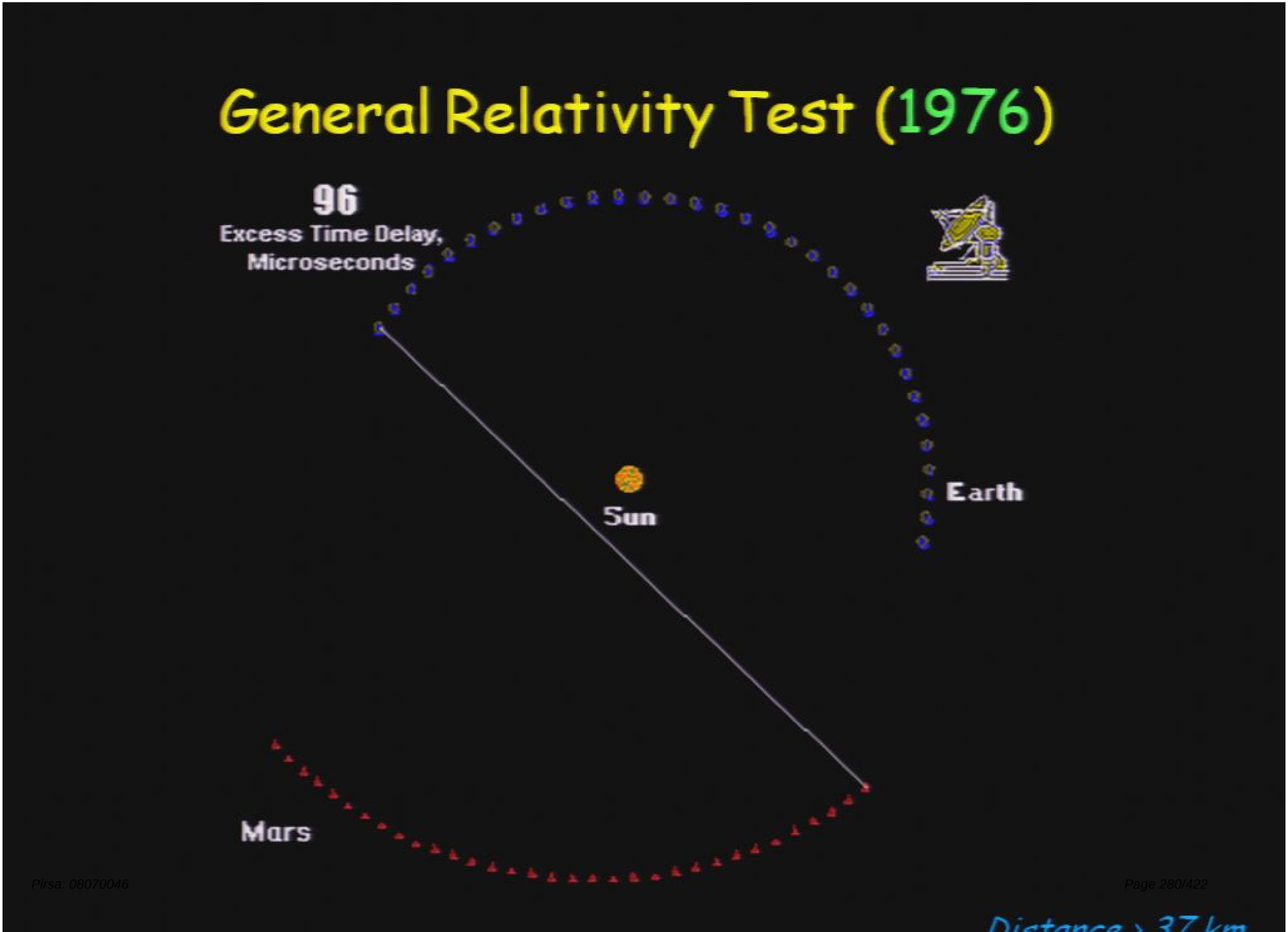


General Relativity Test (1976)

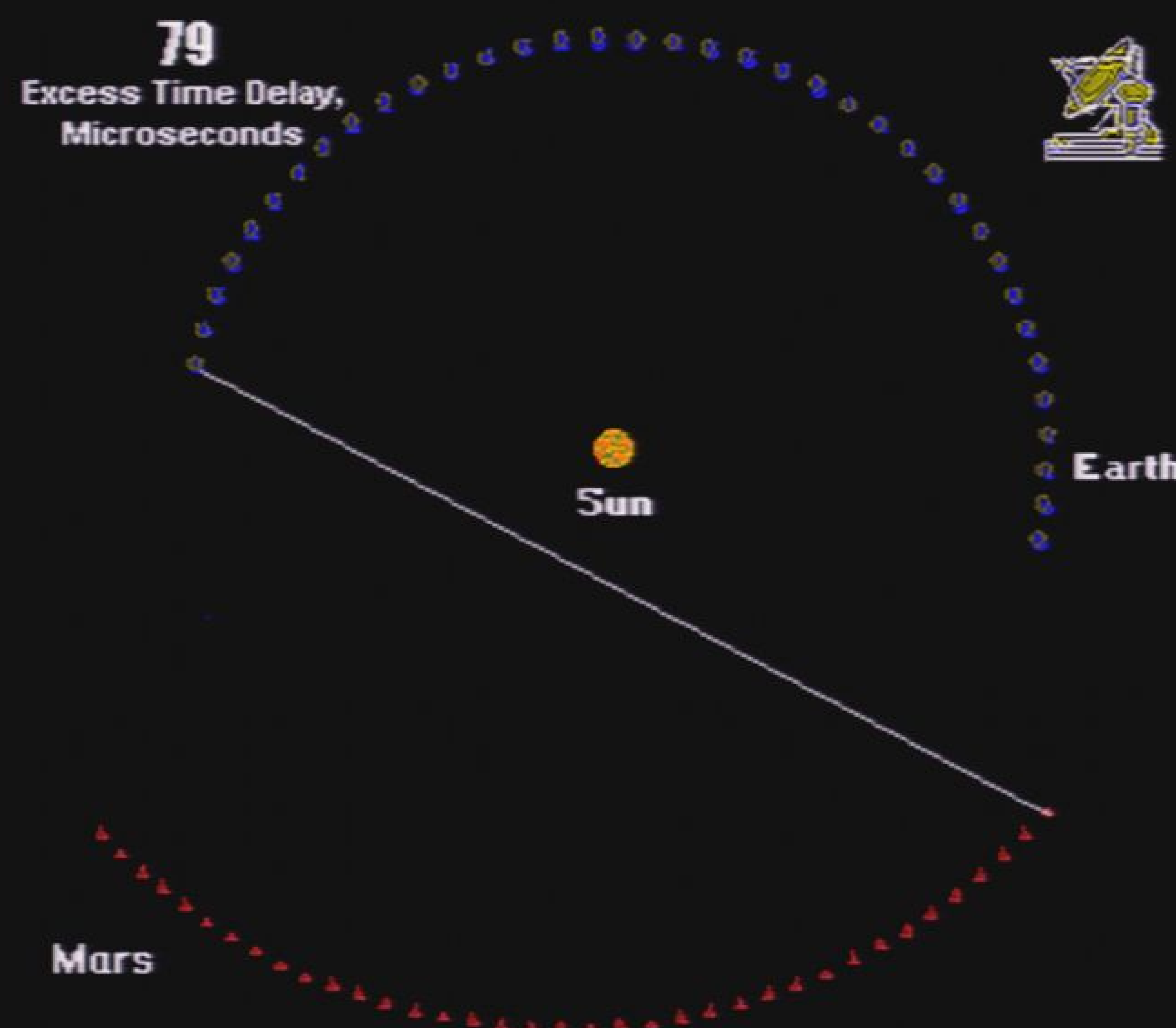
General Relativity Test (1976)

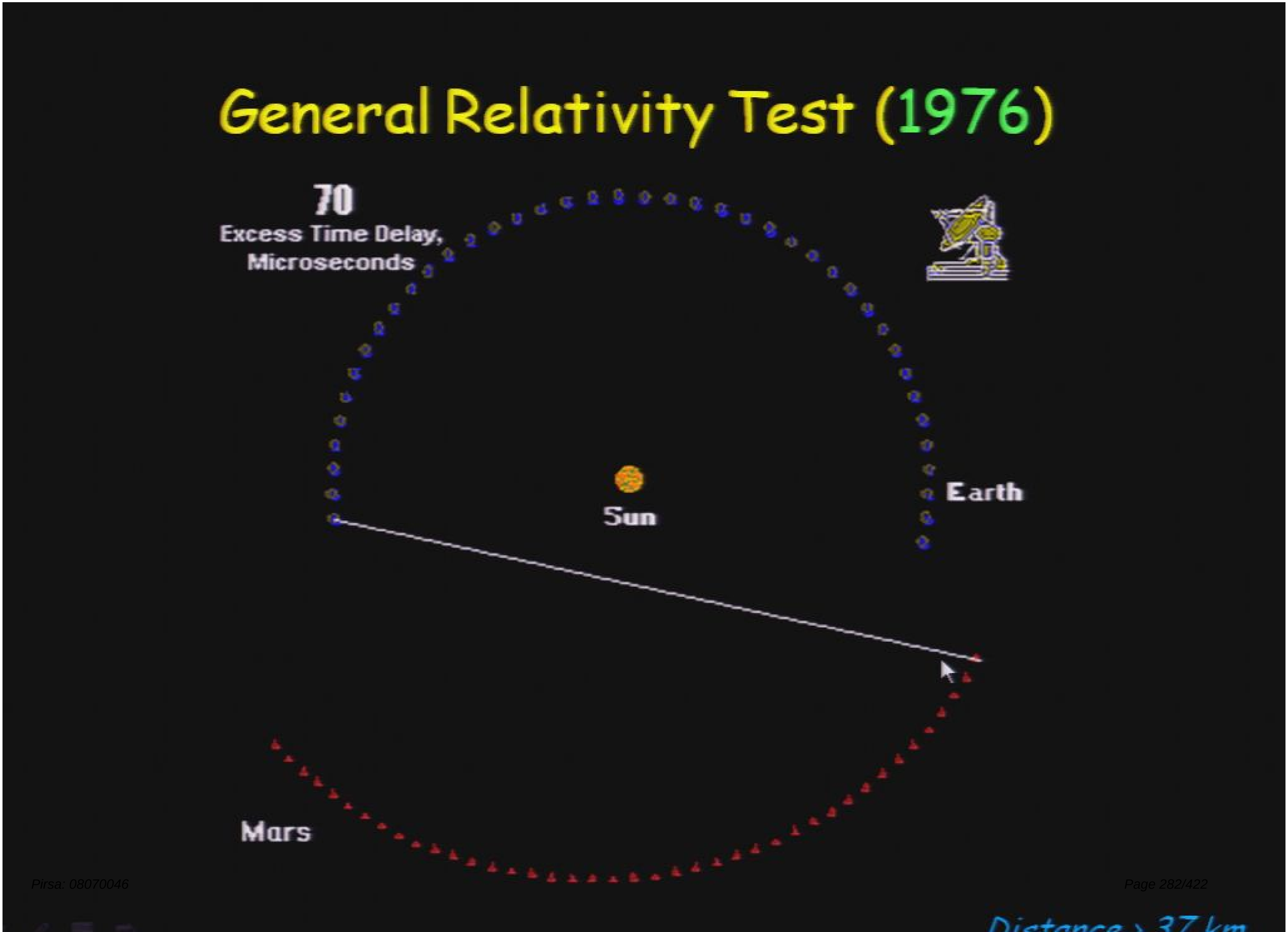



General Relativity Test (1976)
159
Excess Time Delay, Microseconds
Earth
Sun
Mars

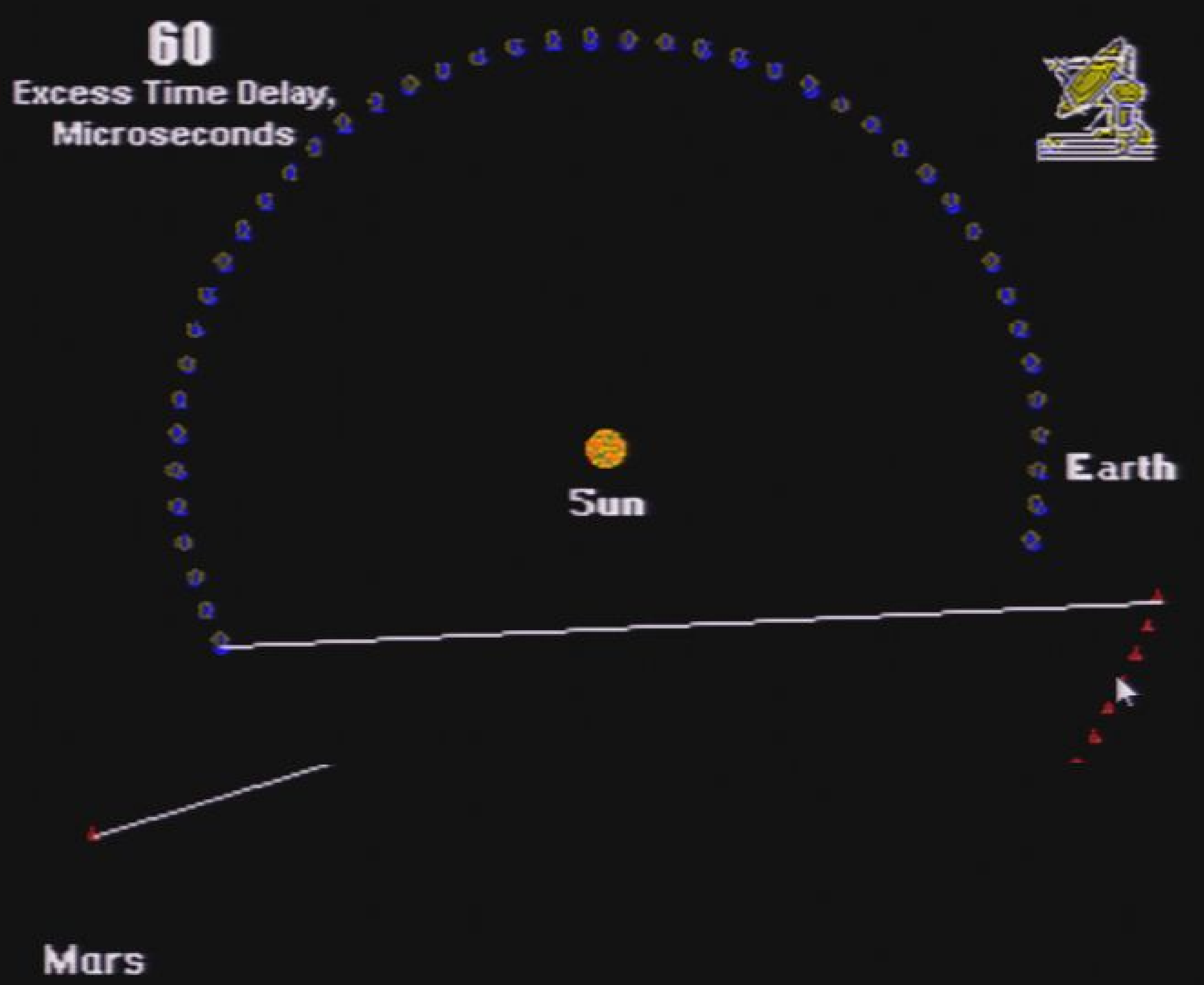

General Relativity Test (1976)
96
Excess Time Delay,
Microseconds
Earth
Sun
Mars

General Relativity Test (1976)

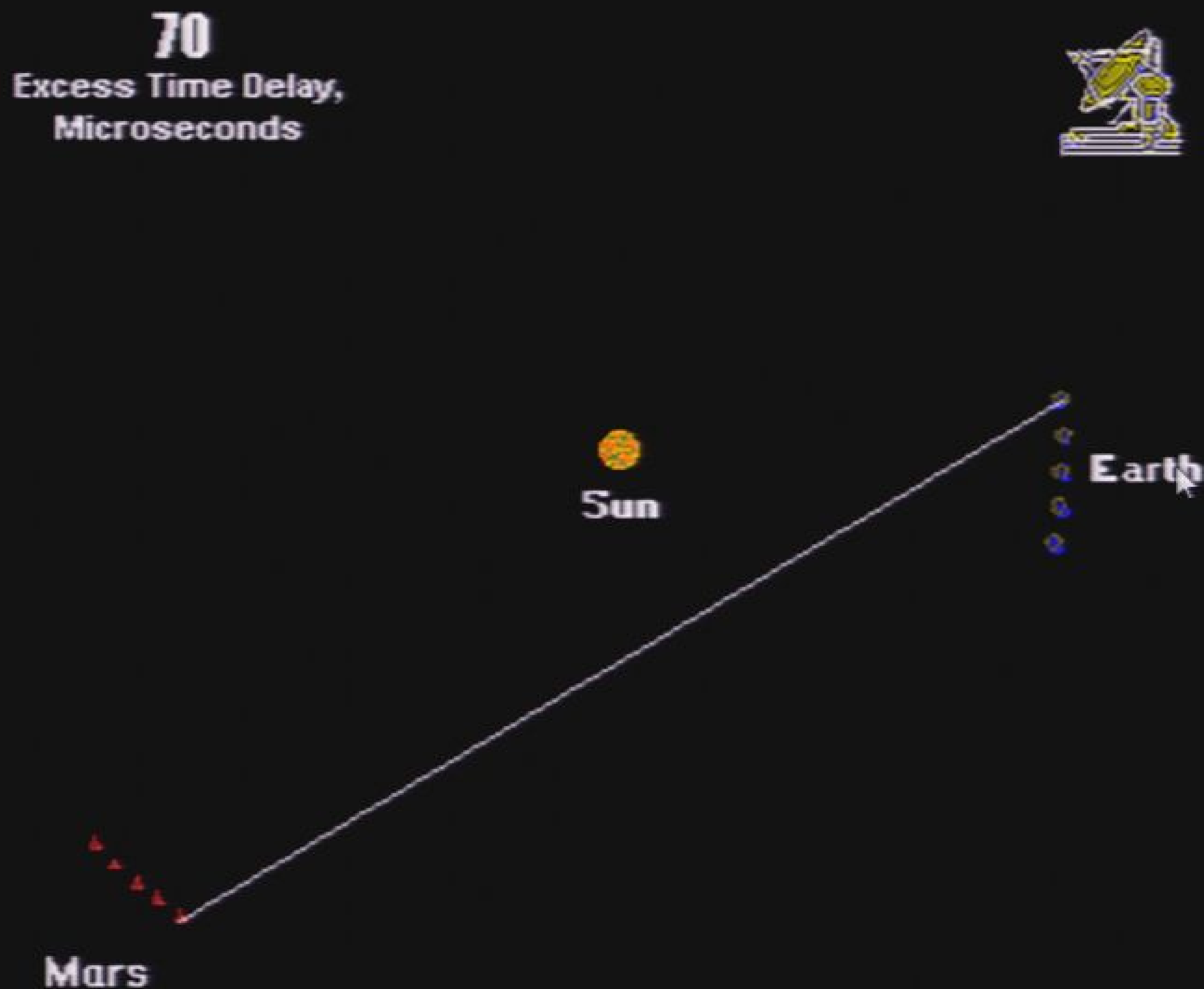



General Relativity Test (1976)
70
Excess Time Delay,
Microseconds
Earth
Sun
Mars

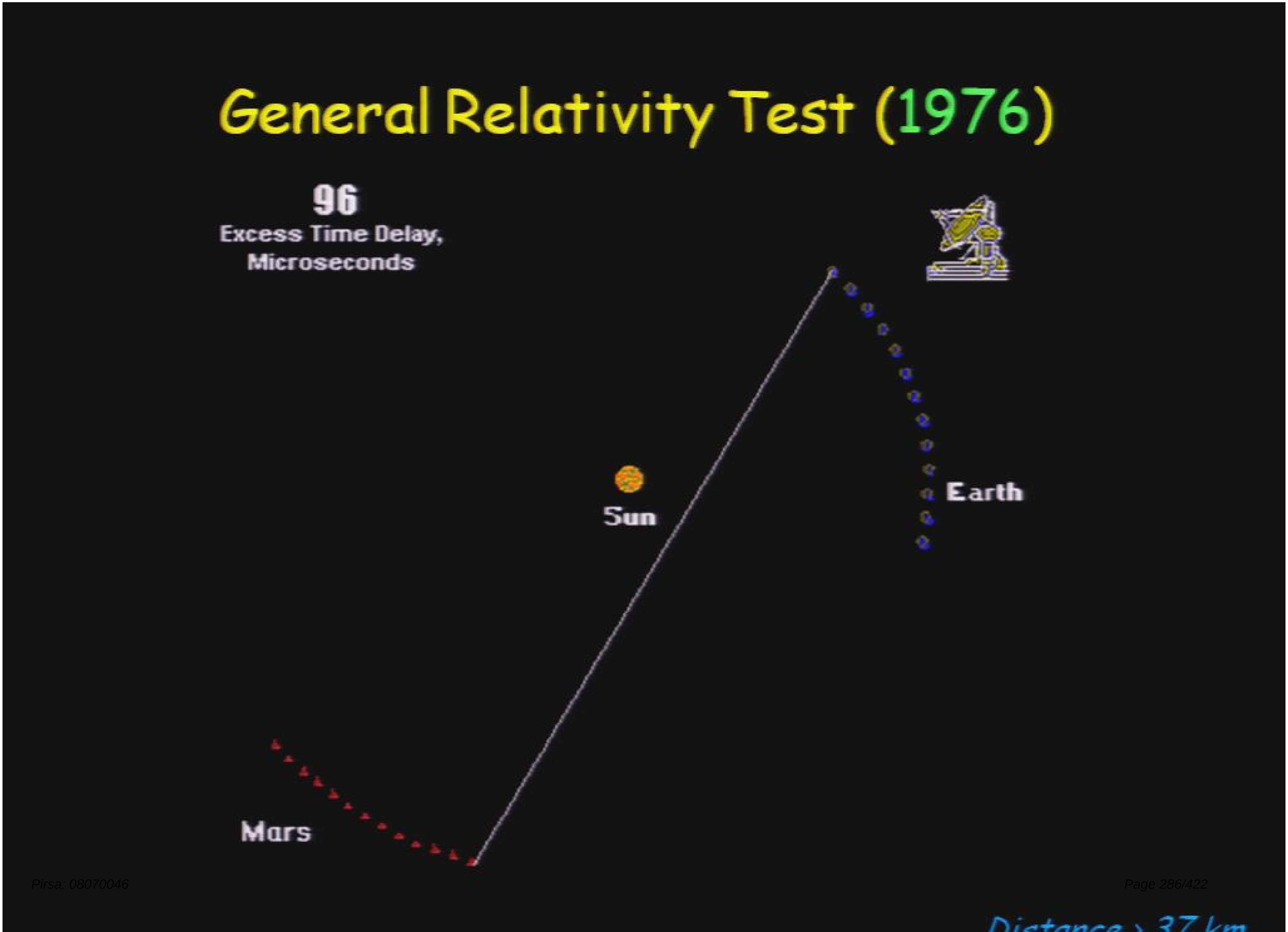
General Relativity Test (1976)



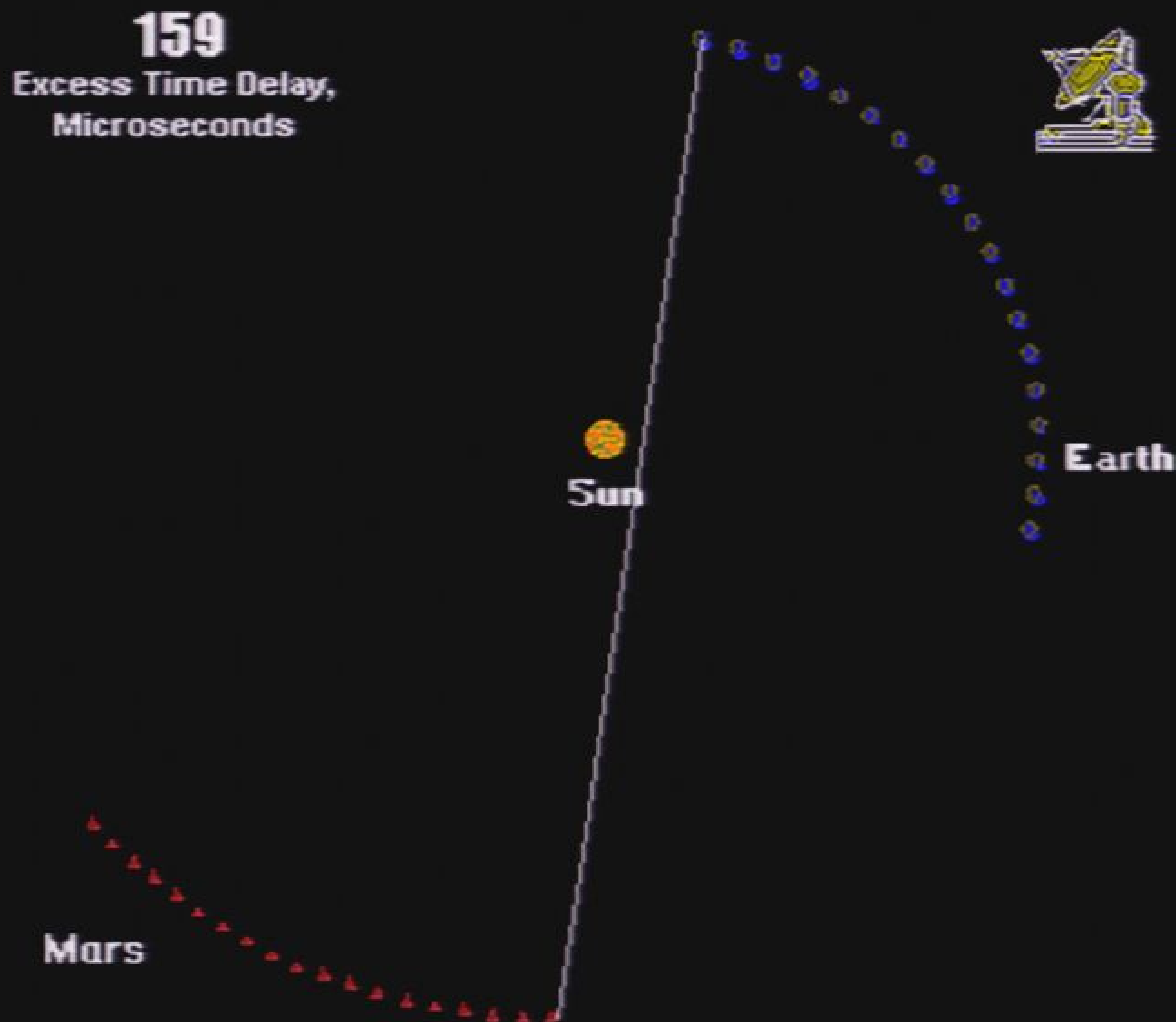
General Relativity Test (1976)



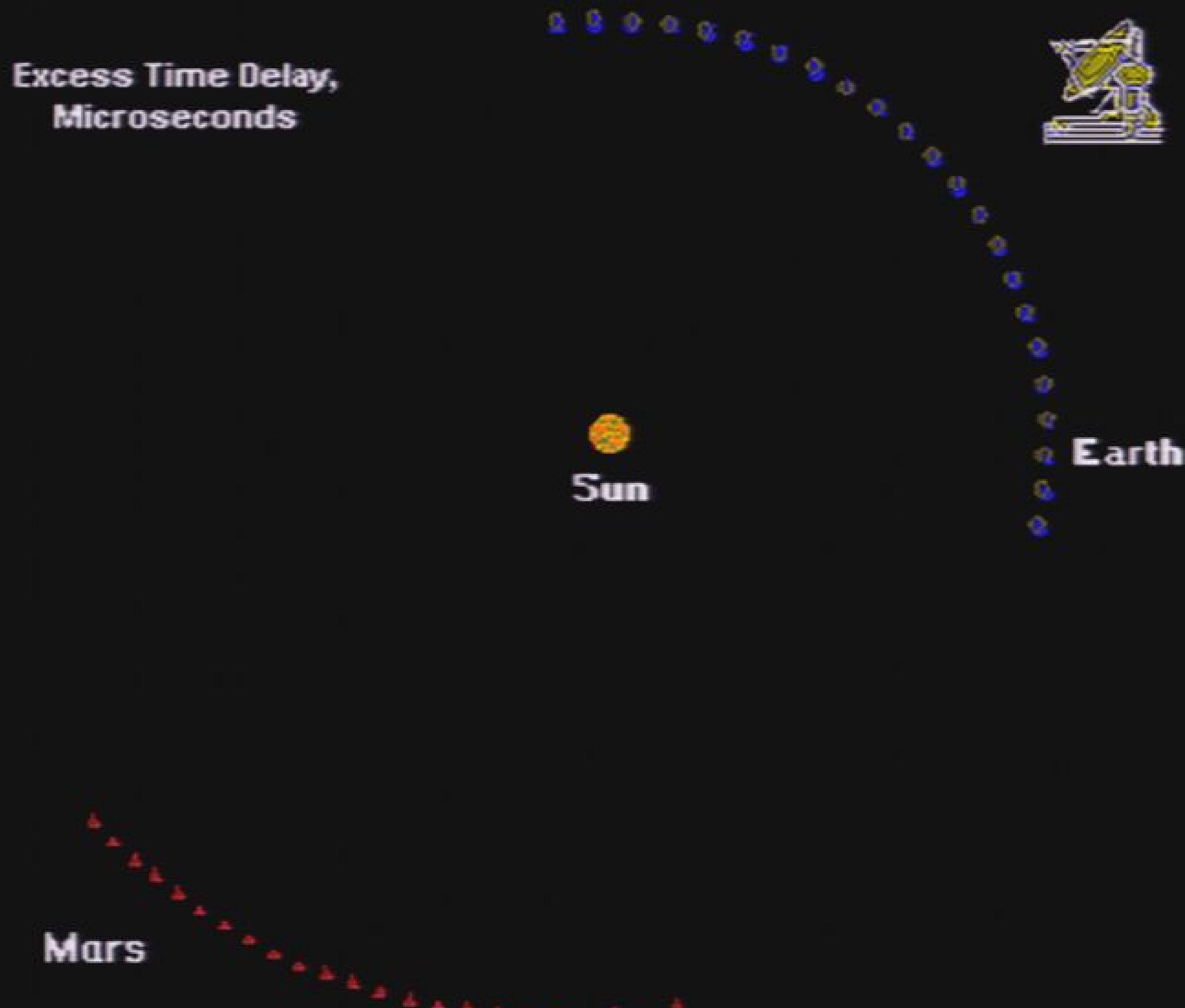
General Relativity Test (1976)

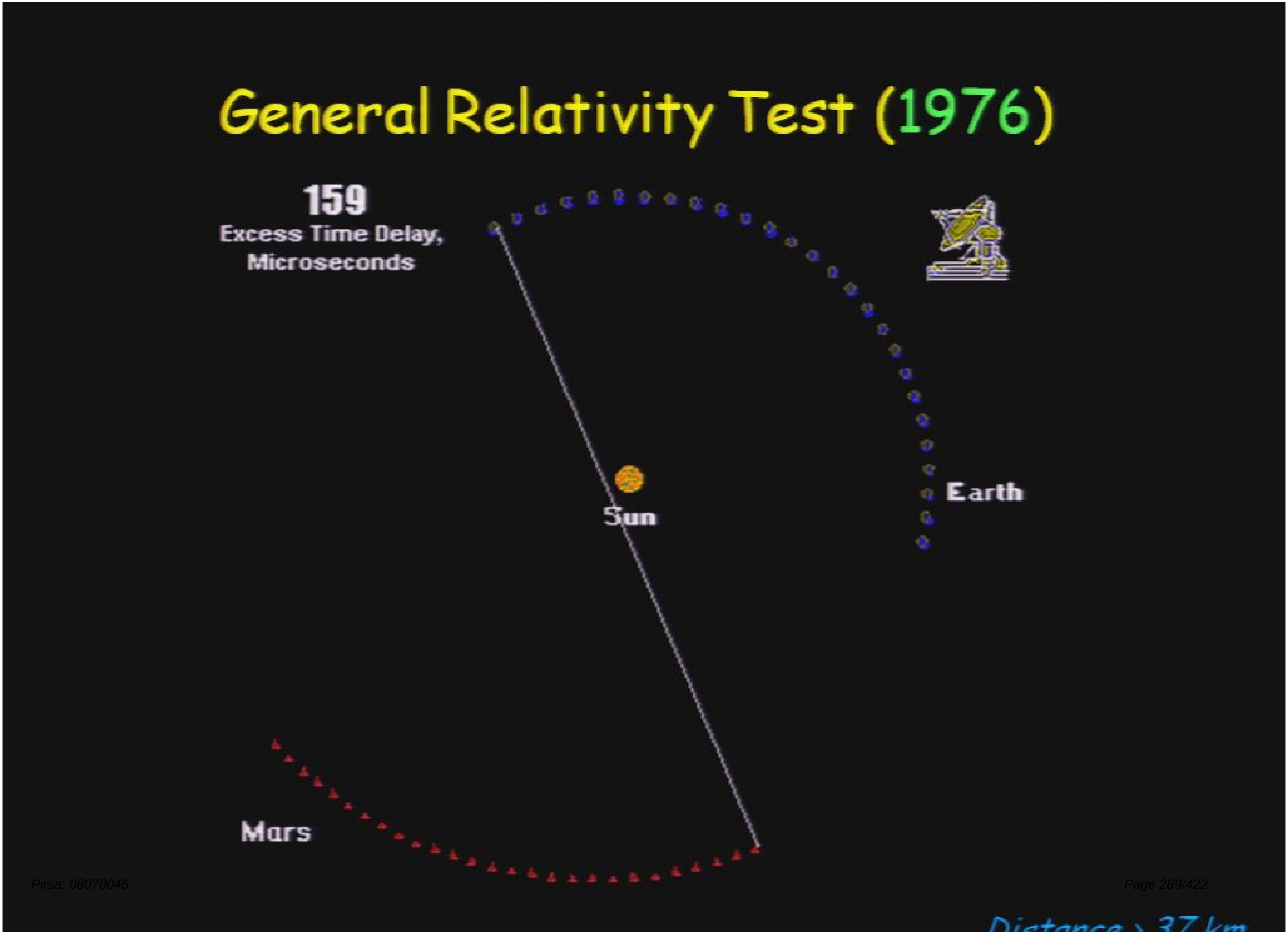

General Relativity Test (1976)
96
Excess Time Delay,
Microseconds
Sun
Earth
Mars

General Relativity Test (1976)

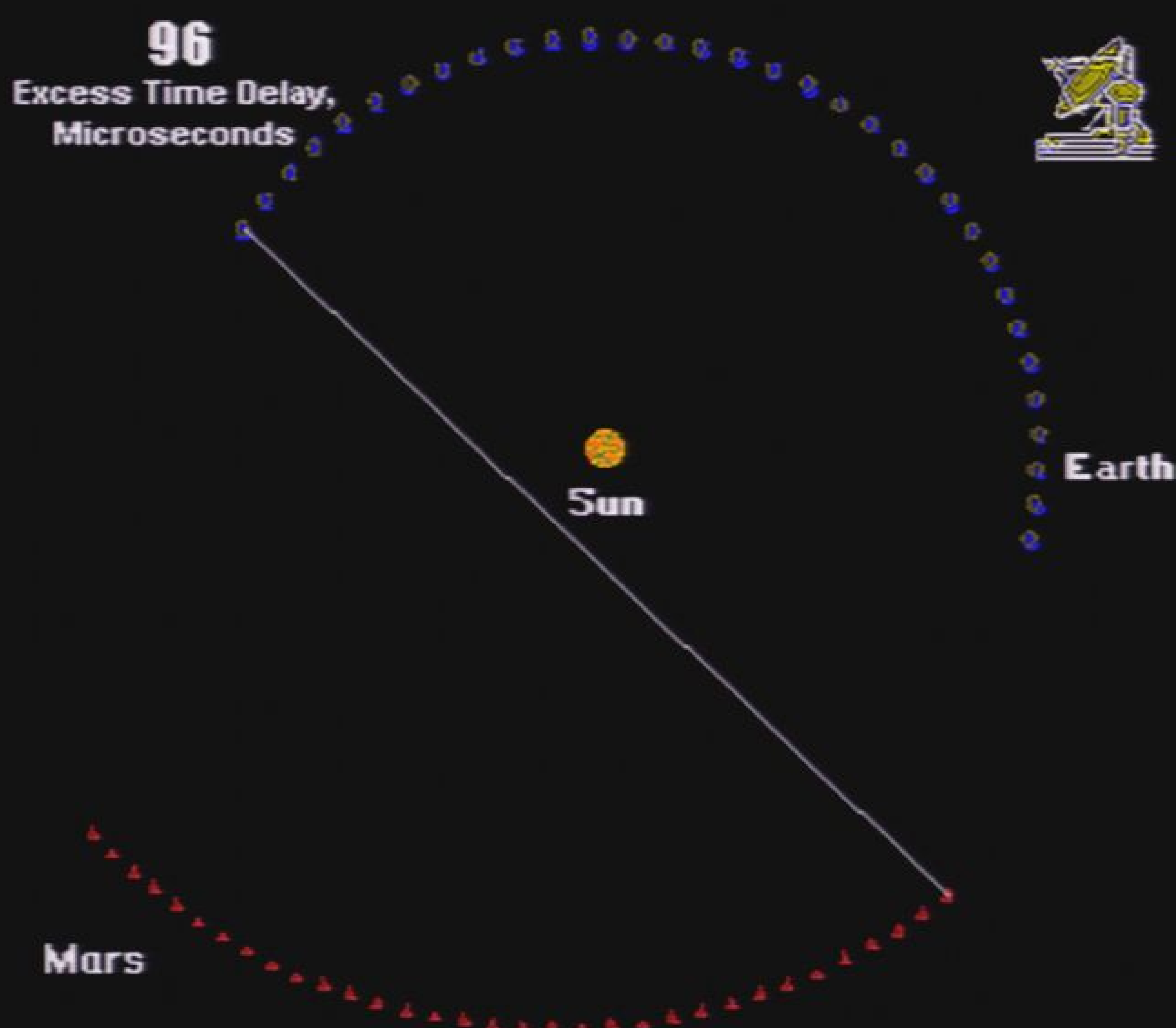


General Relativity Test (1976)



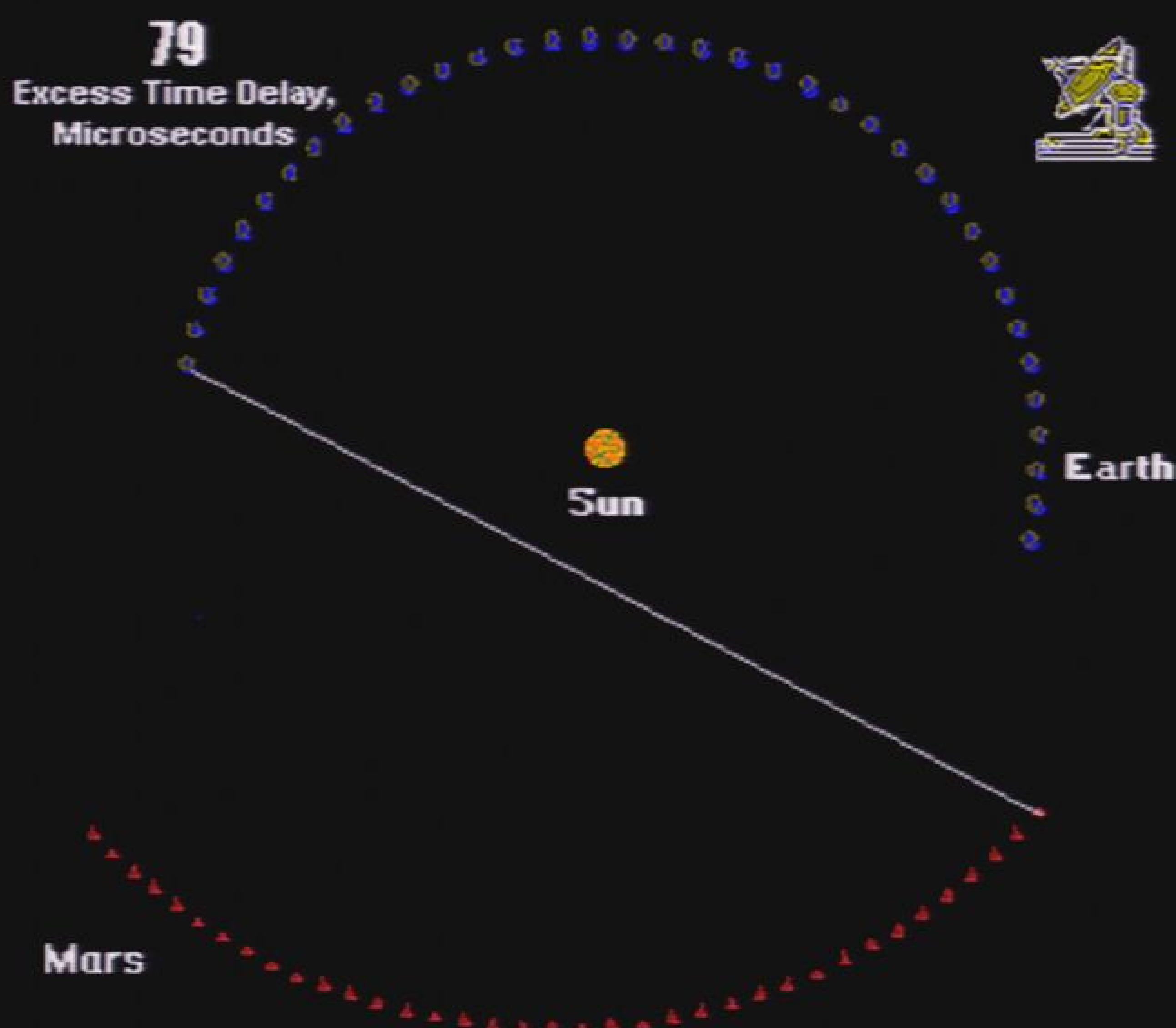

General Relativity Test (1976)
159
Excess Time Delay, Microseconds
Earth
Sun
Mars

General Relativity Test (1976)



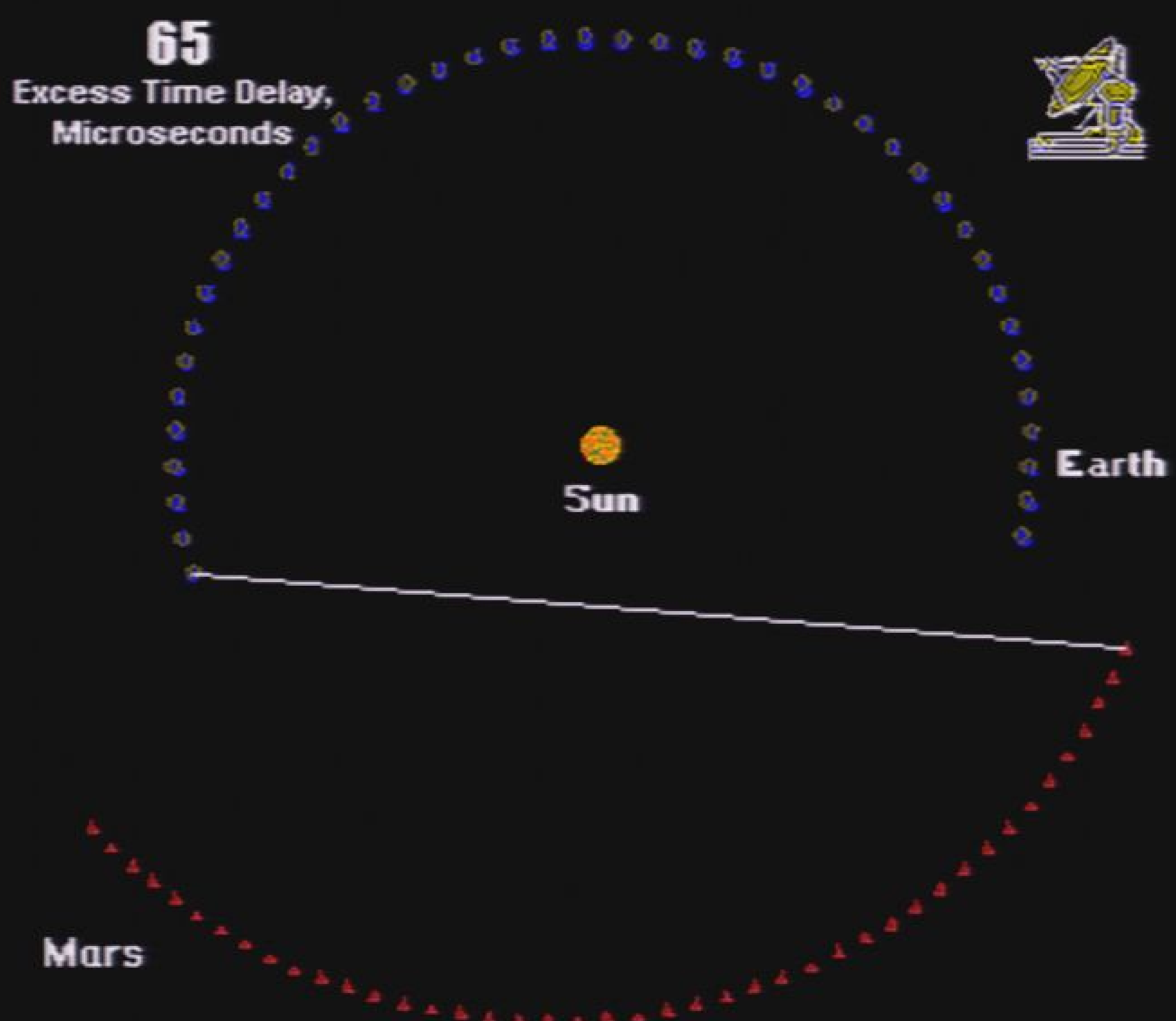
Distance > 37 km

General Relativity Test (1976)

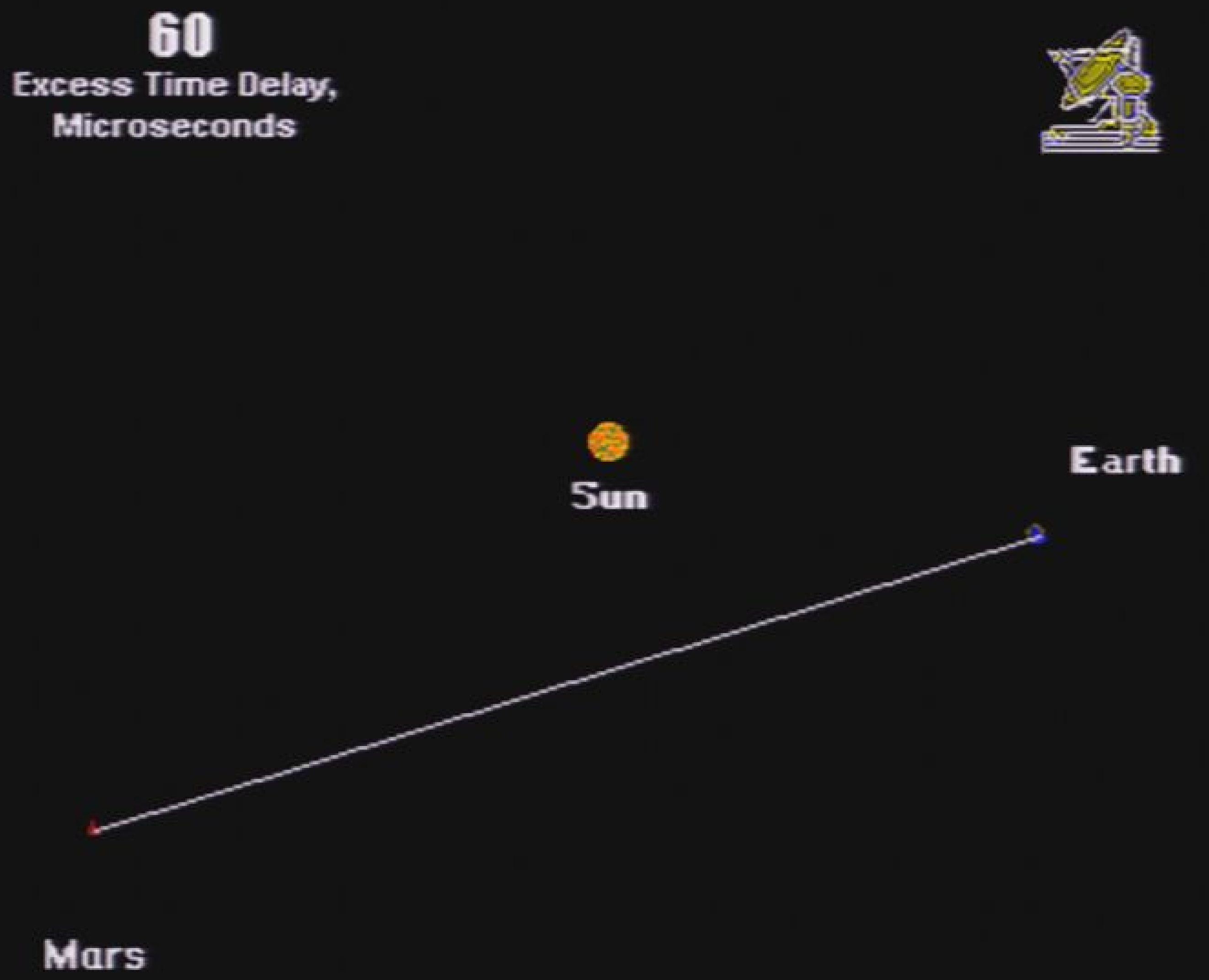


Distance > 37 km

General Relativity Test (1976)



General Relativity Test (1976)

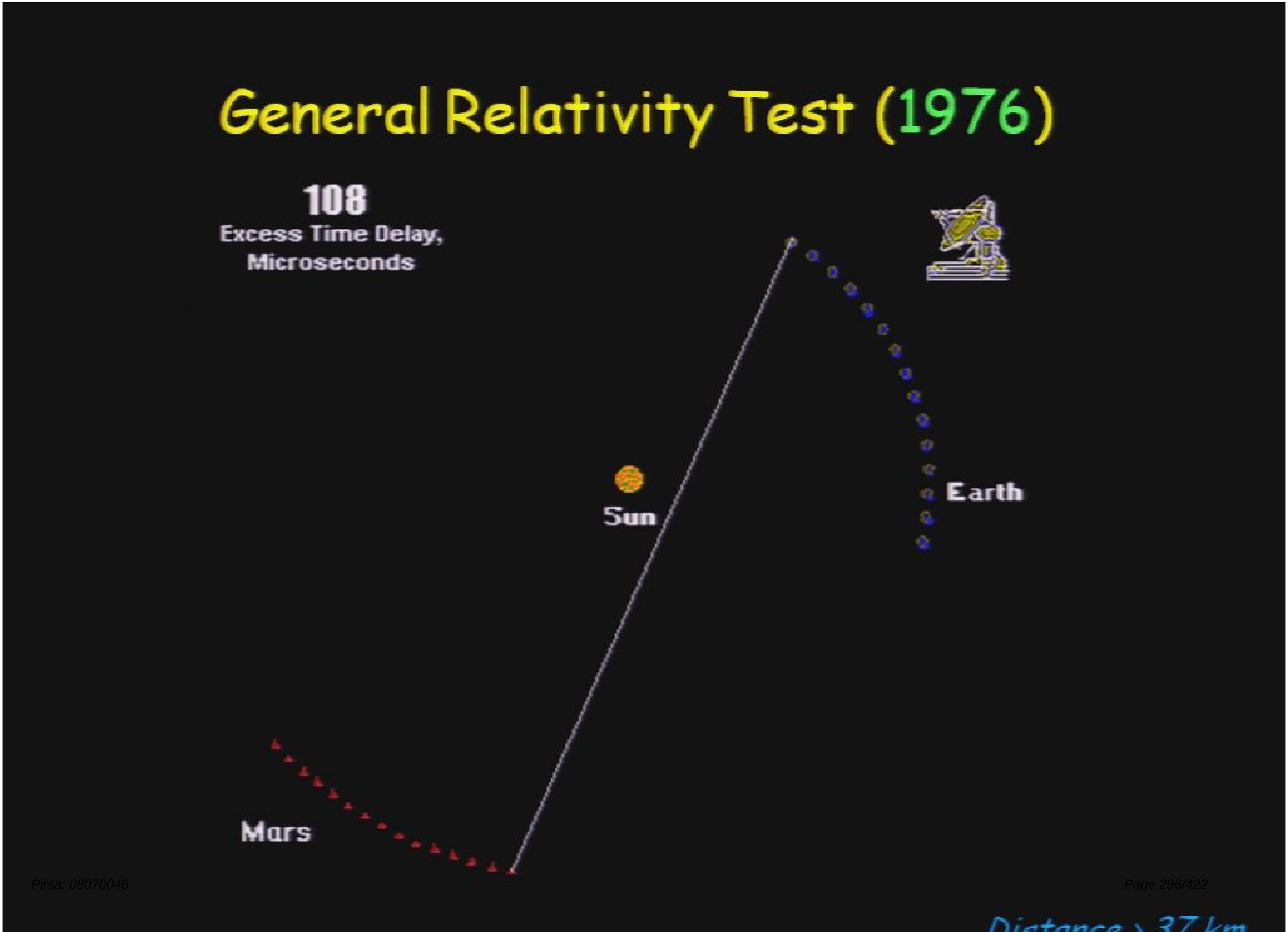


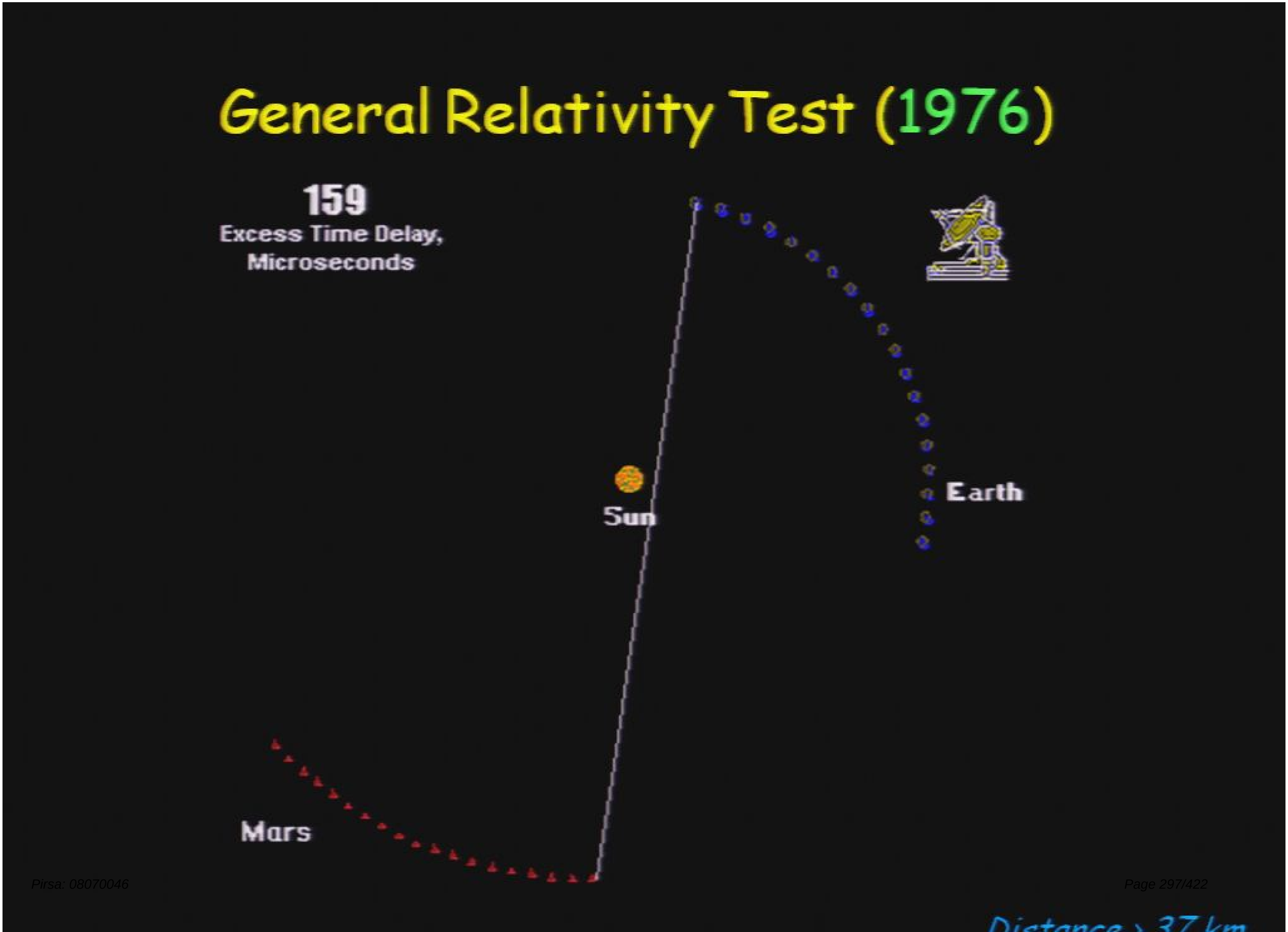
Distance > 37 km

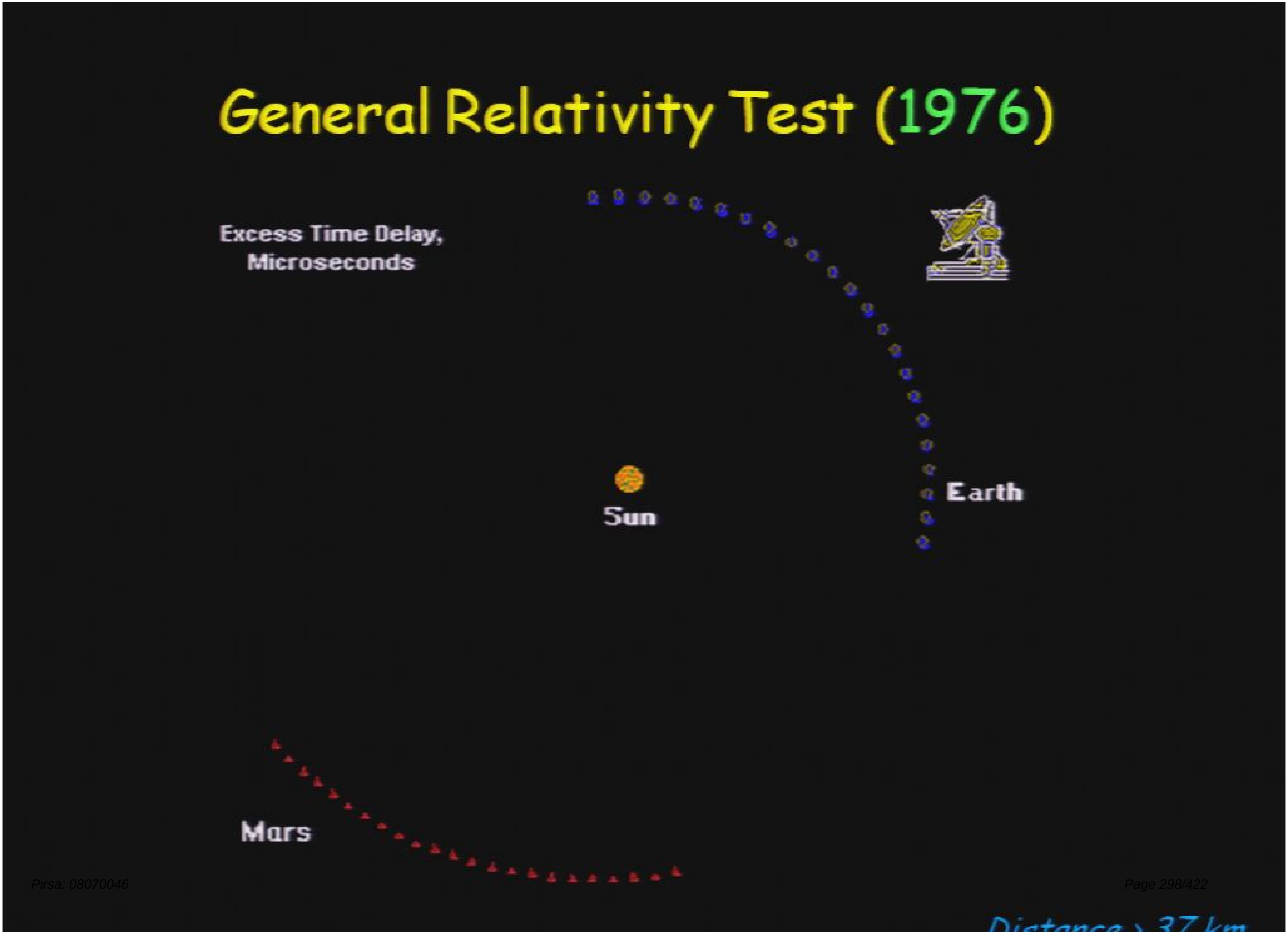
General Relativity Test (1976)

General Relativity Test (1976)

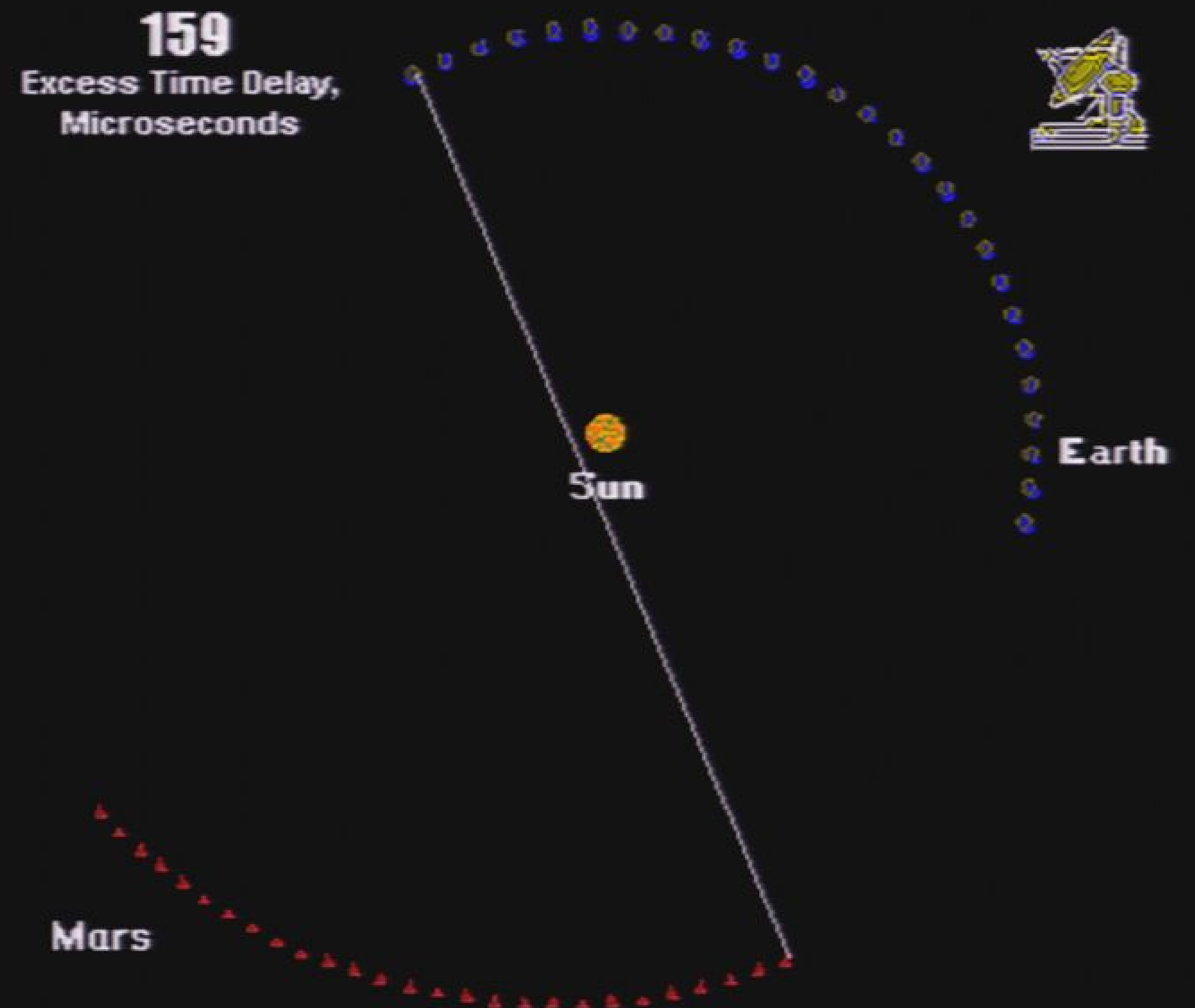
Distance > 37 km


General Relativity Test (1976)
108
Excess Time Delay,
Microseconds
Sun
Earth
Mars


General Relativity Test (1976)
159
Excess Time Delay,
Microseconds
Earth
Sun
Mars

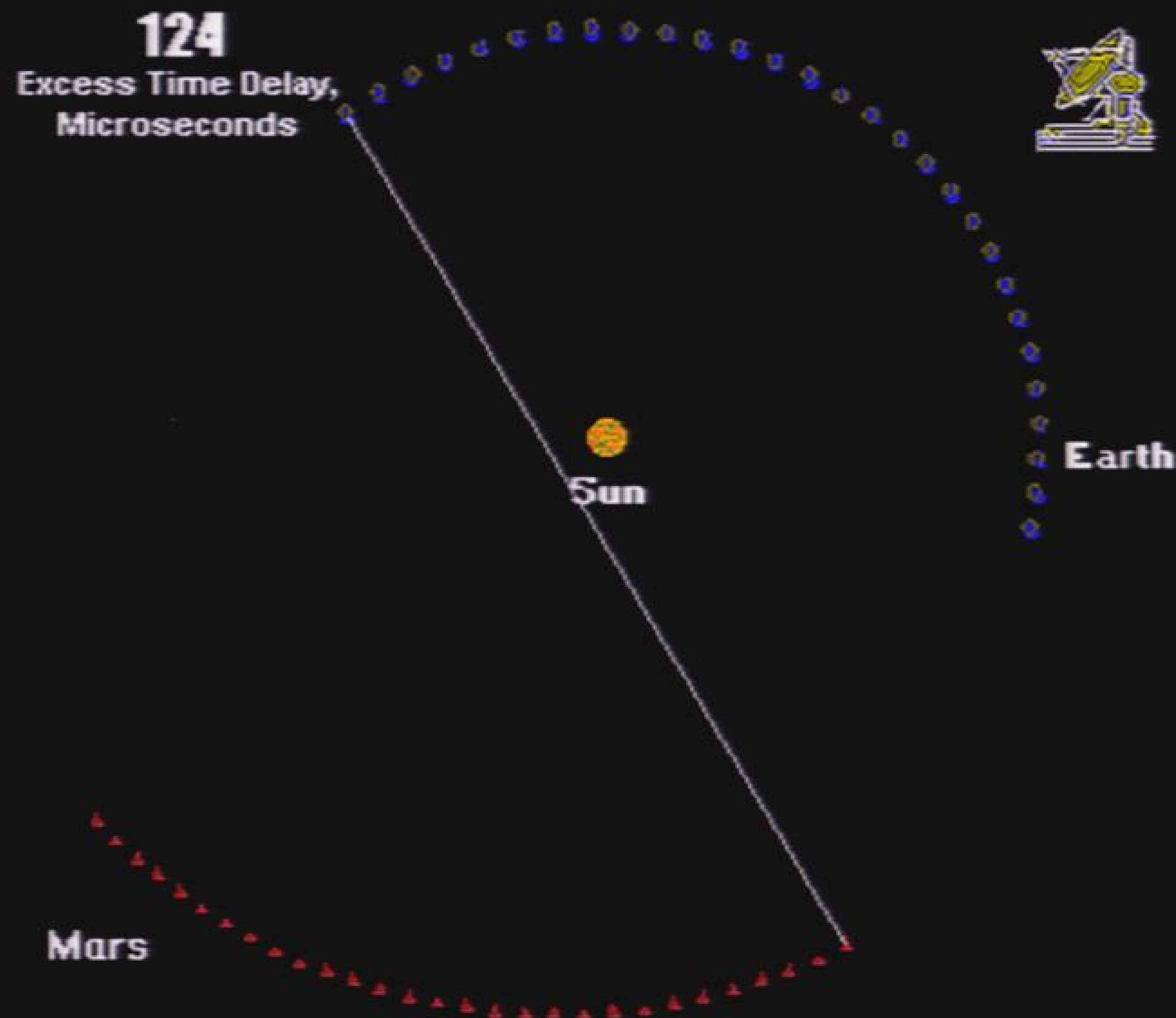

General Relativity Test (1976)
Excess Time Delay,
Microseconds
Sun
Earth
Mars

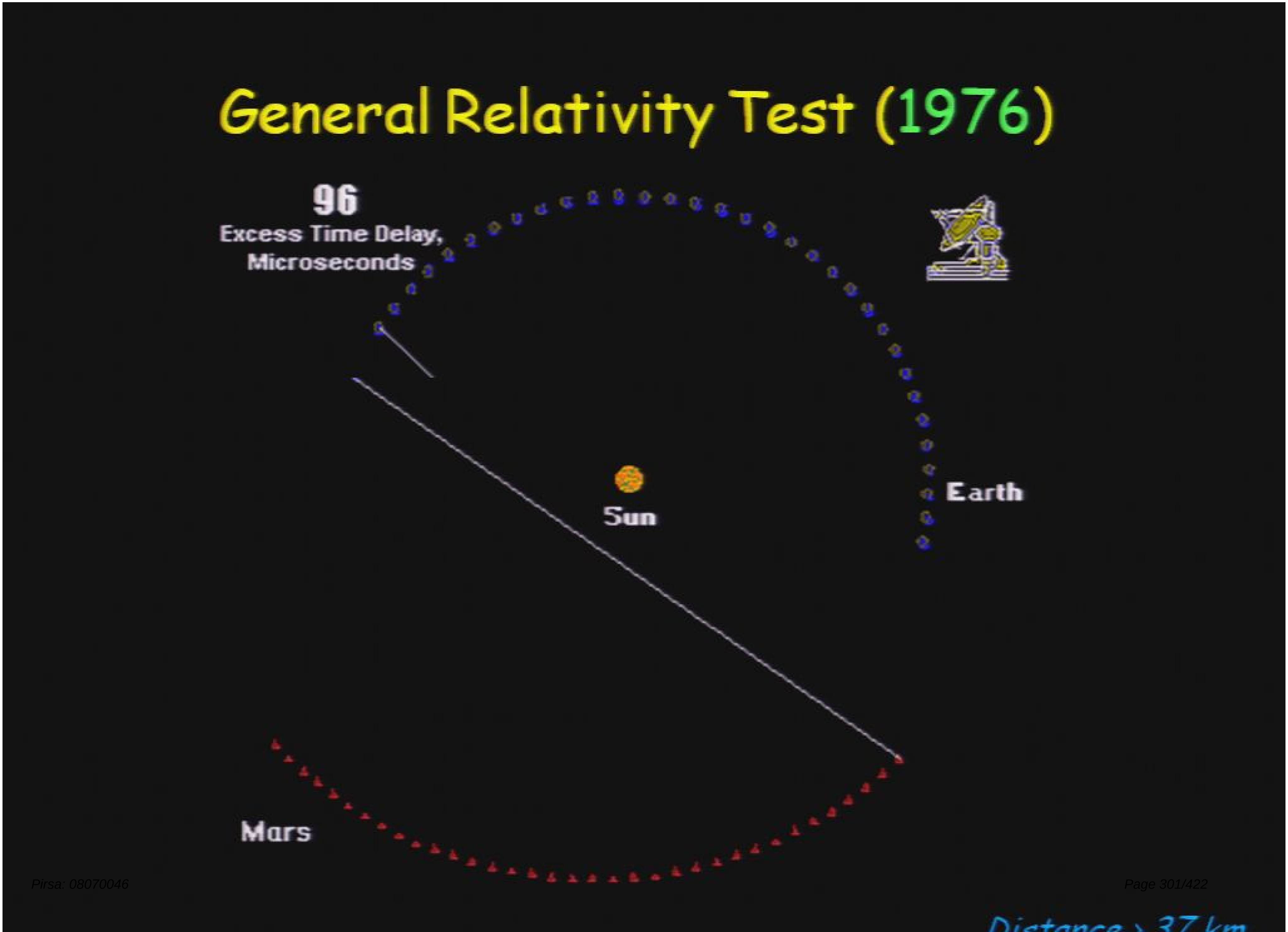
General Relativity Test (1976)



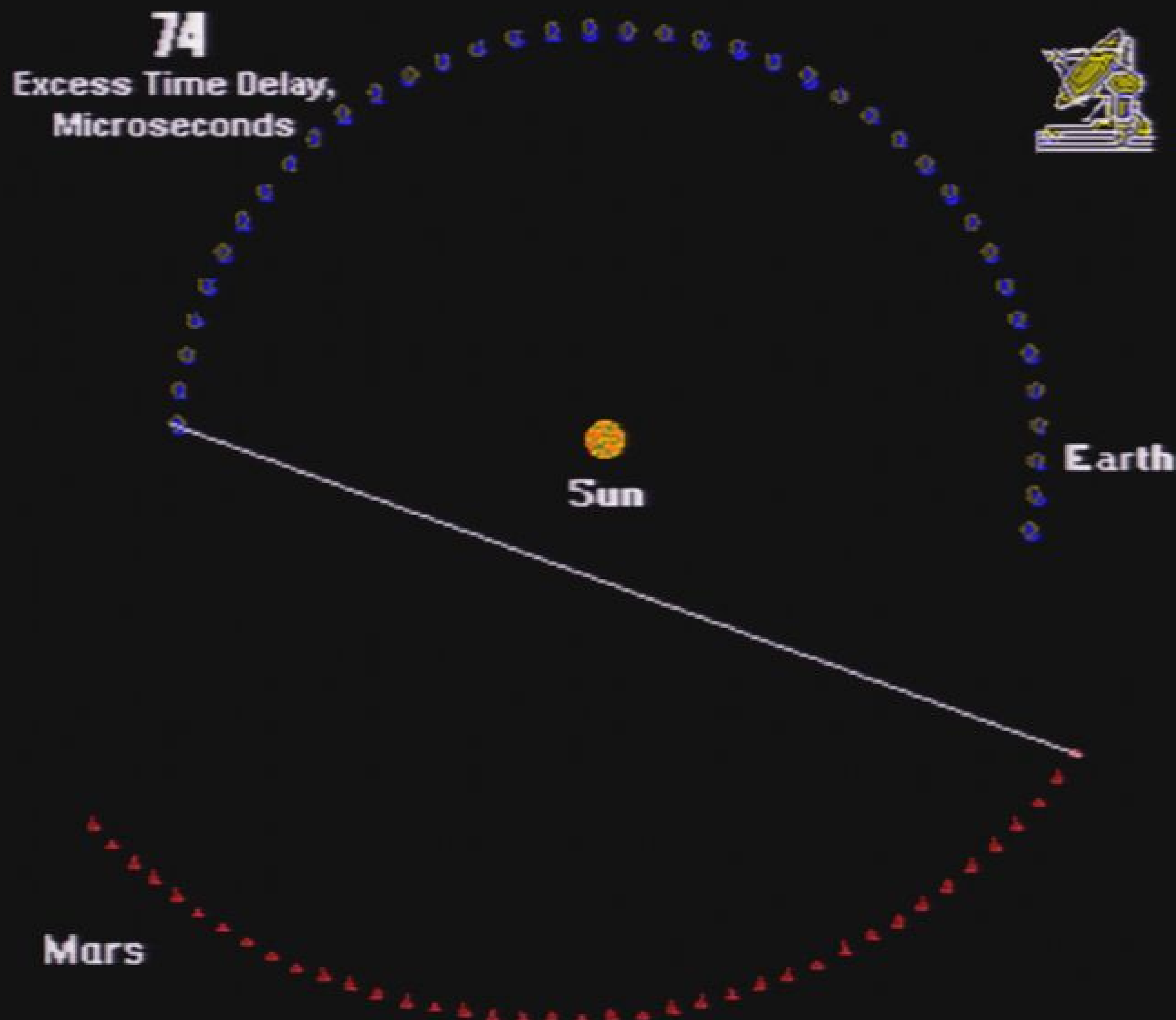
Distance > 37 km

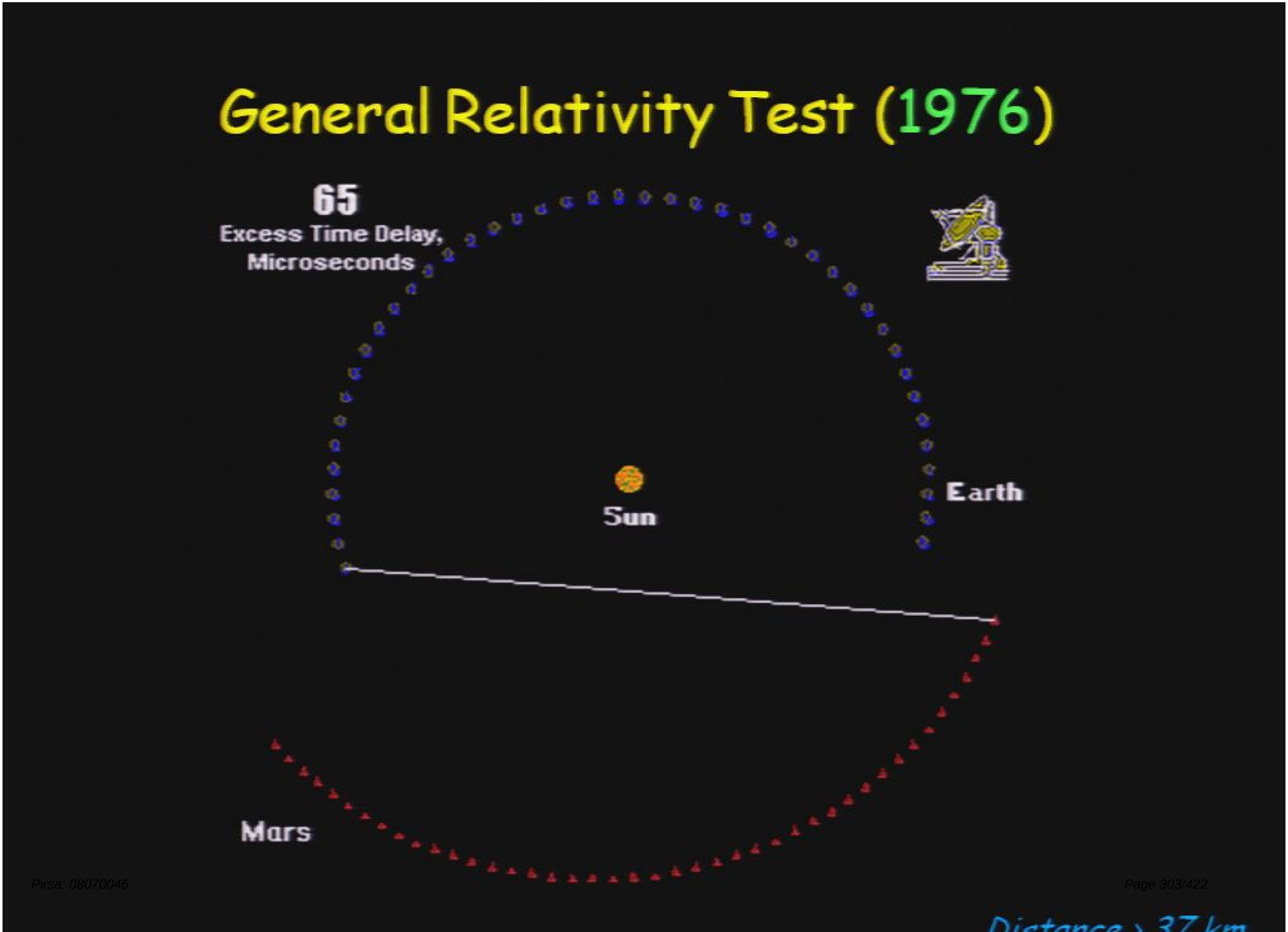
General Relativity Test (1976)

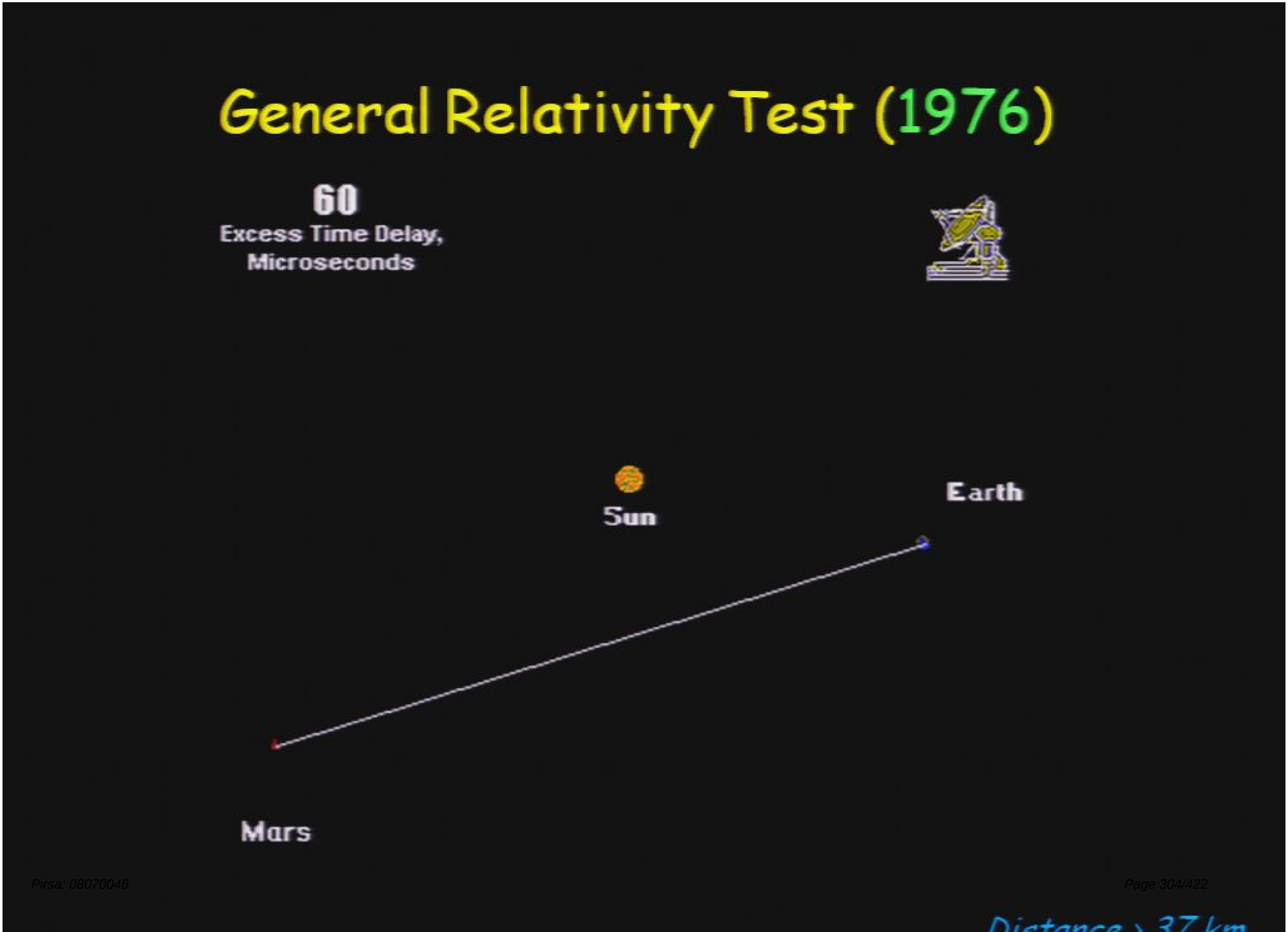



General Relativity Test (1976)
96
Excess Time Delay,
Microseconds
Earth
Sun
Mars

General Relativity Test (1976)

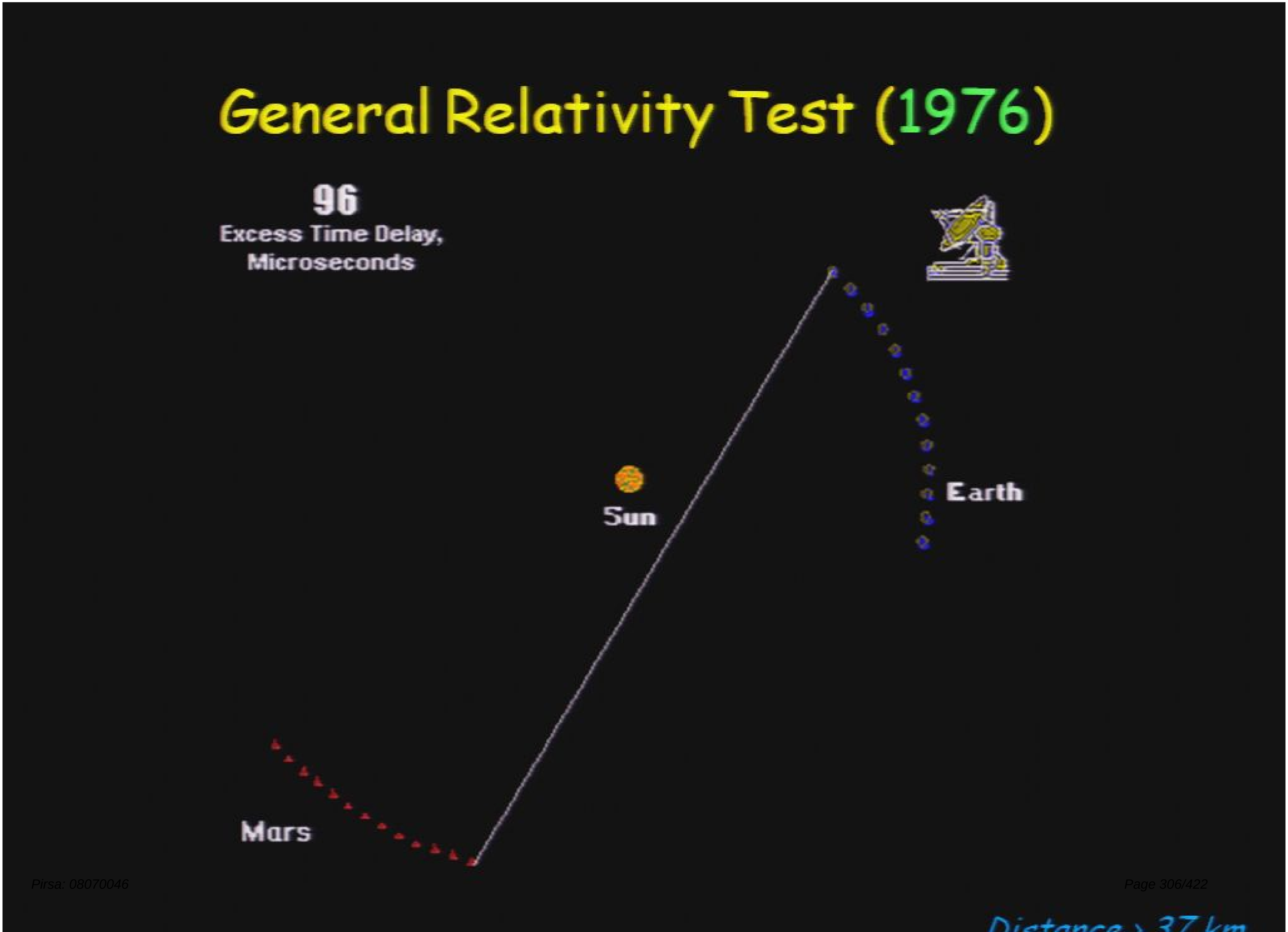


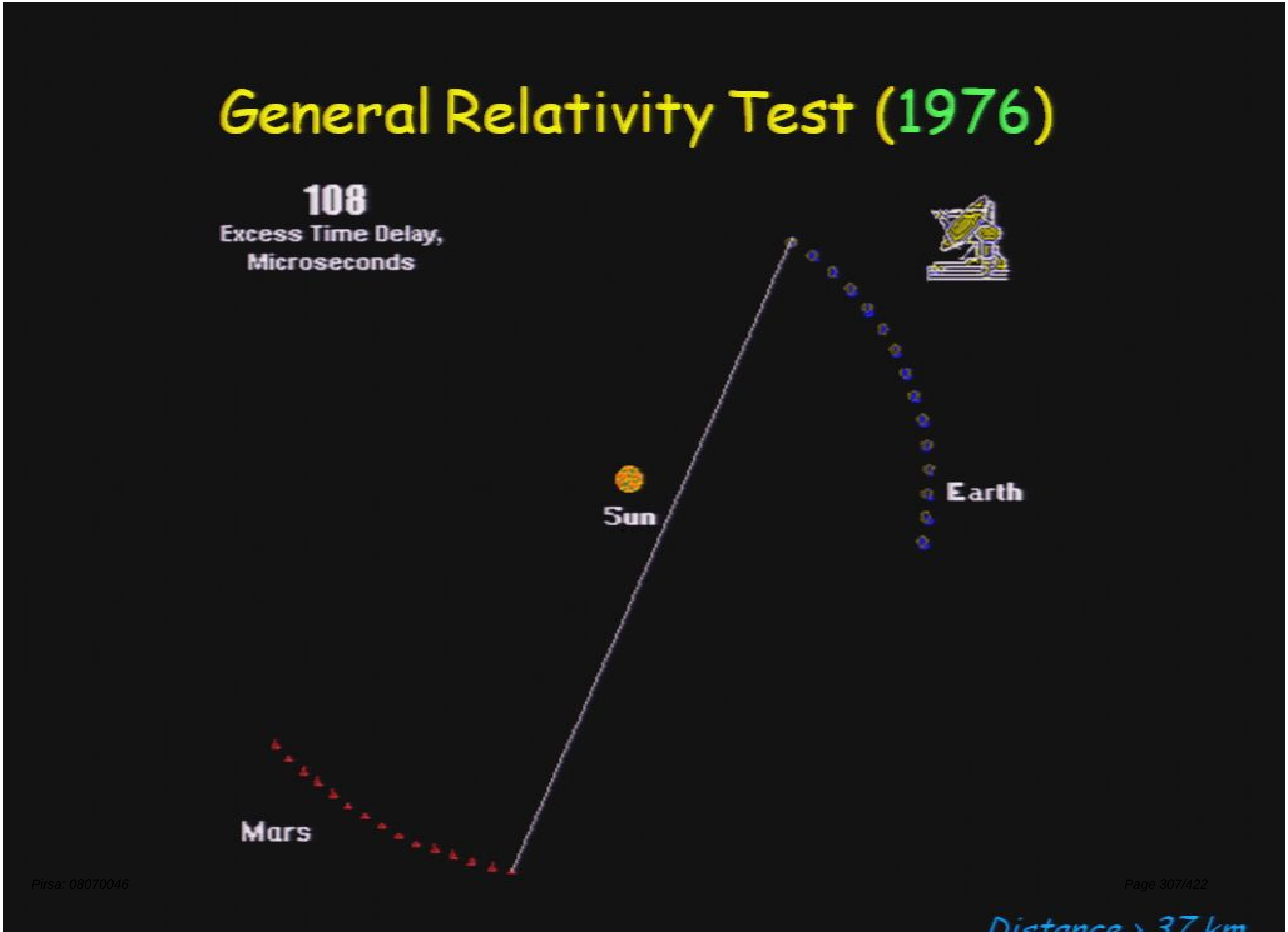

General Relativity Test (1976)
65
Excess Time Delay,
Microseconds
Earth
Sun
Mars


General Relativity Test (1976)
60
Excess Time Delay,
Microseconds
Sun
Earth
Mars

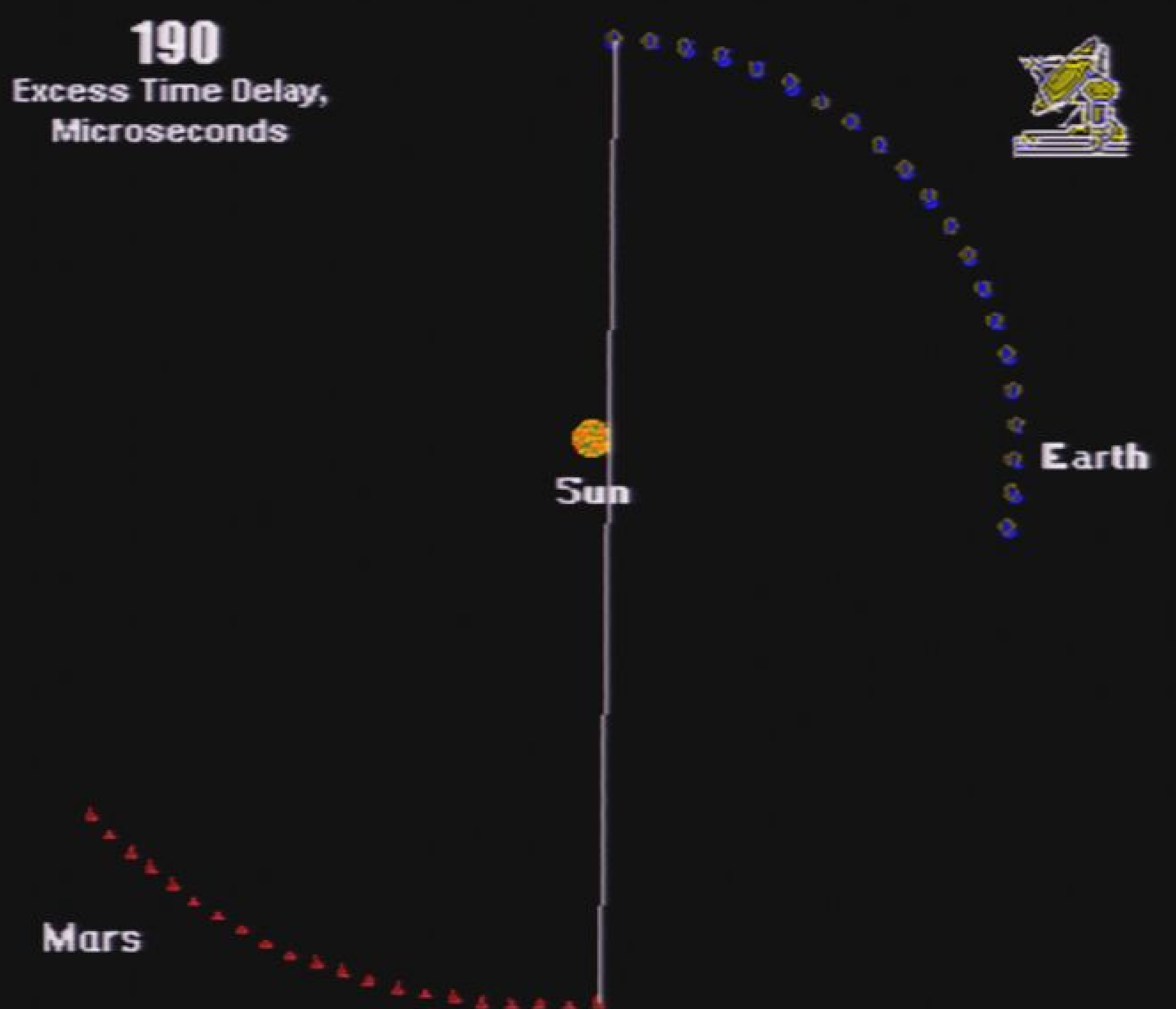
General Relativity Test (1976)

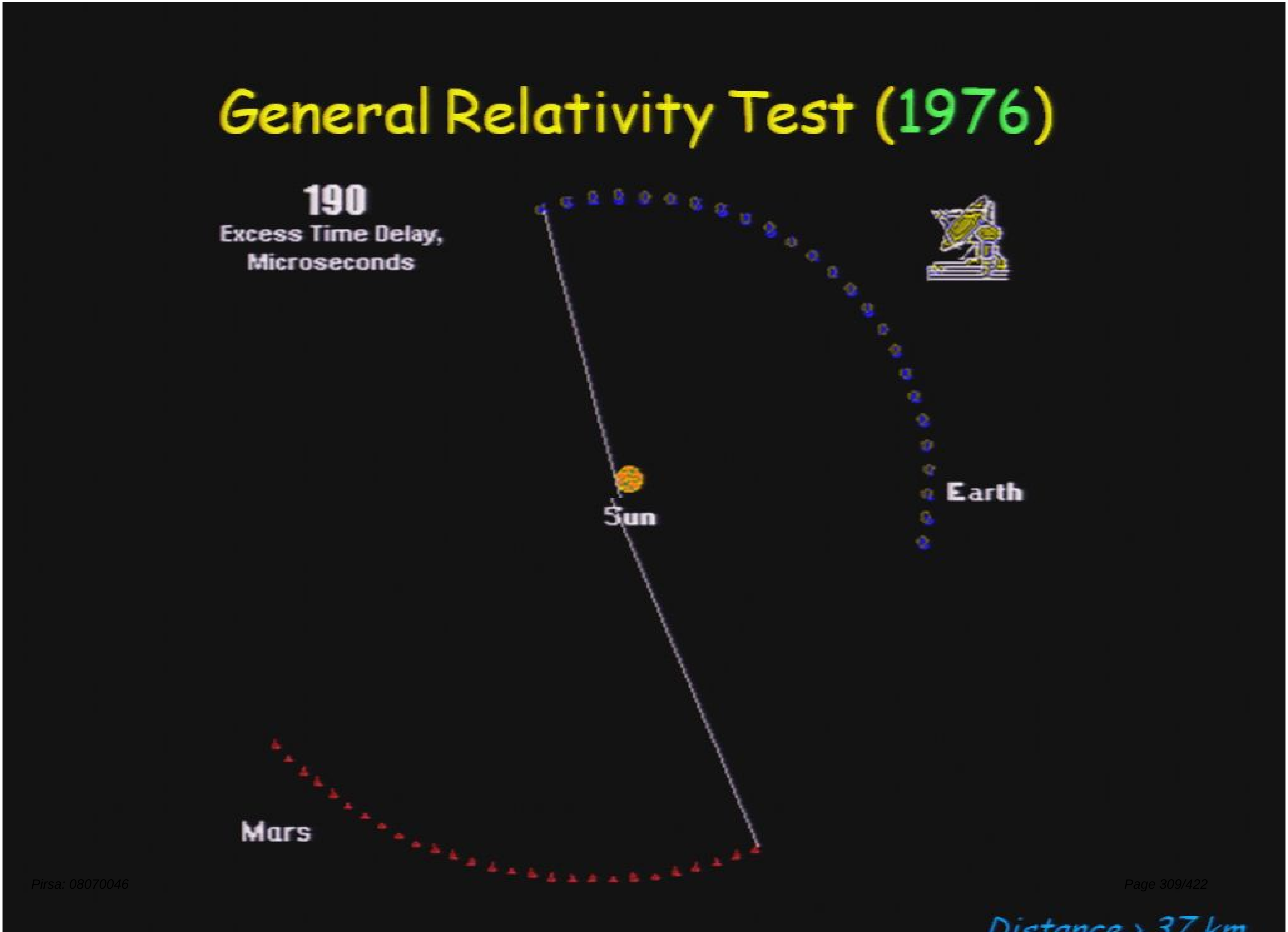
Distance > 37 km

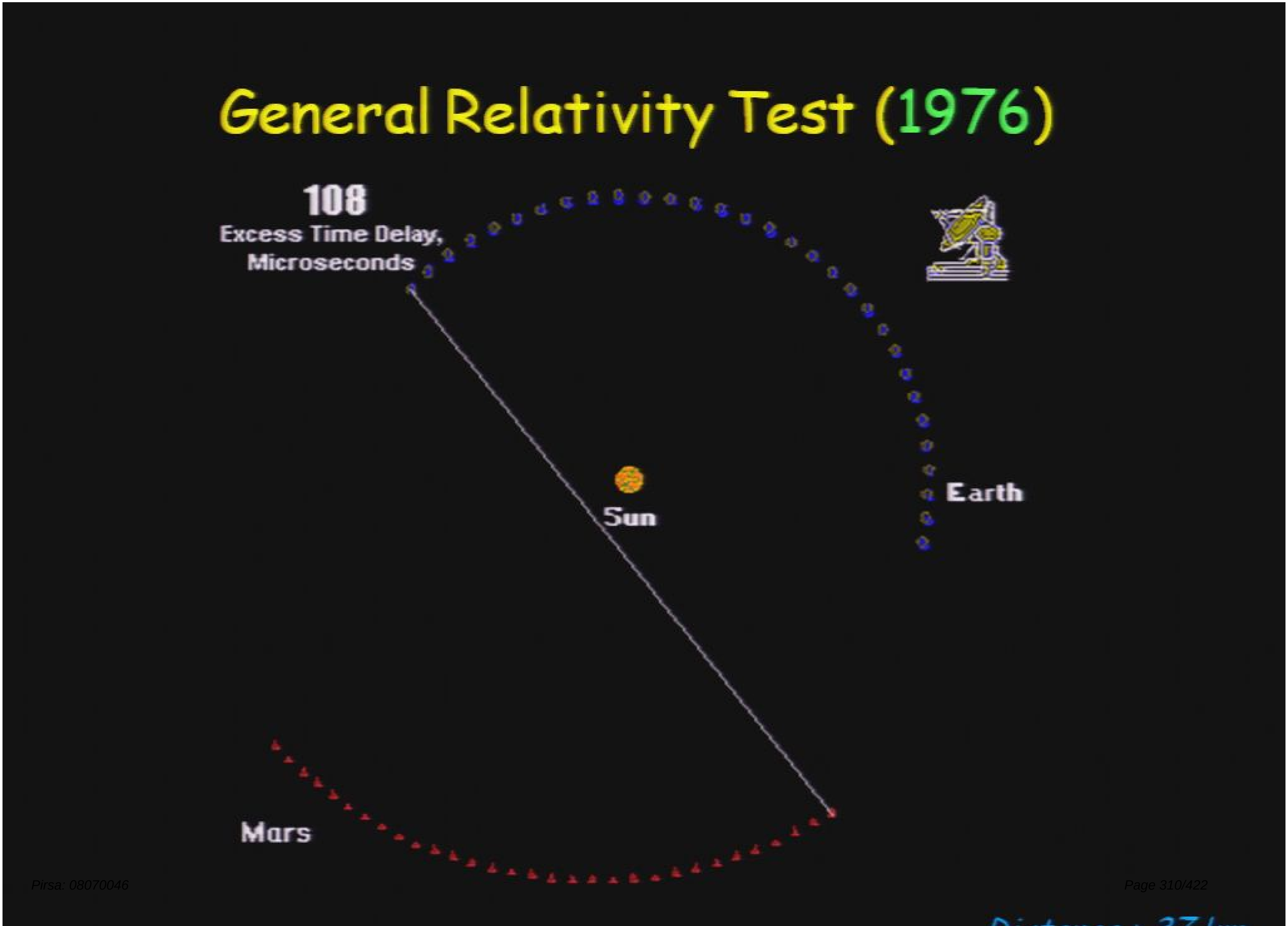

General Relativity Test (1976)
96
Excess Time Delay,
Microseconds
Sun
Earth
Mars

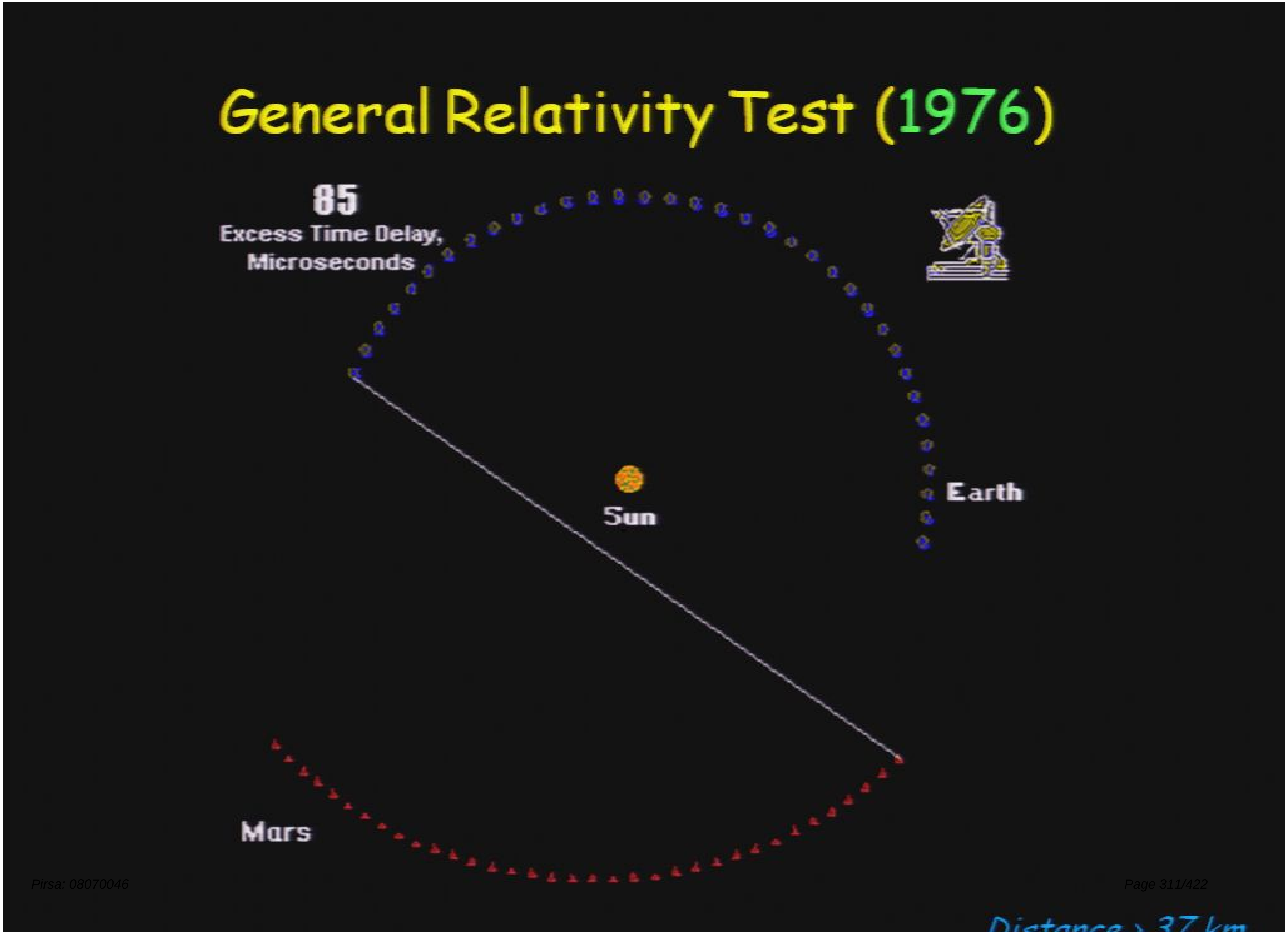

General Relativity Test (1976)
108
Excess Time Delay,
Microseconds
Sun
Earth
Mars

General Relativity Test (1976)

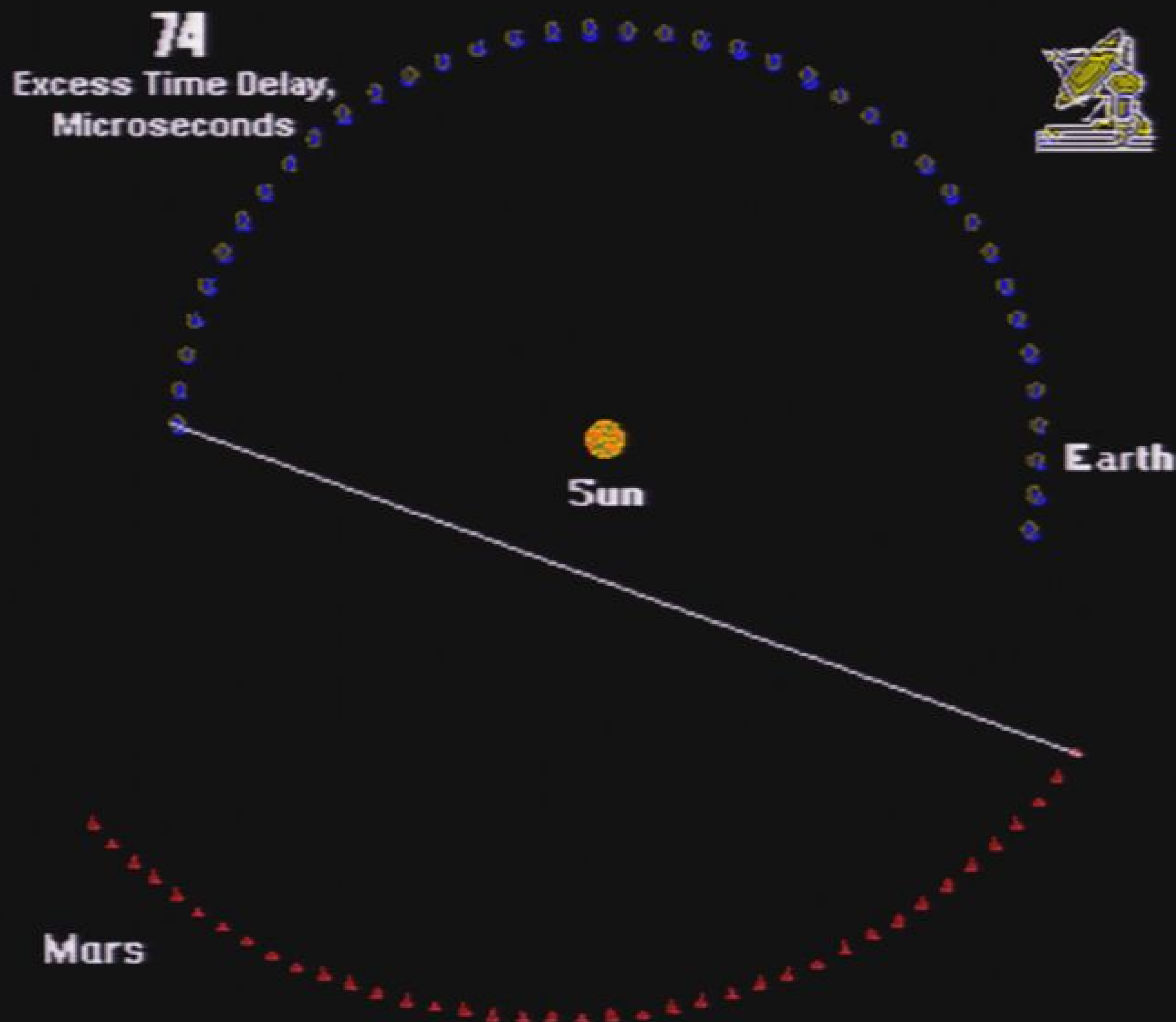



General Relativity Test (1976)
190
Excess Time Delay,
Microseconds
Earth
Sun
Mars

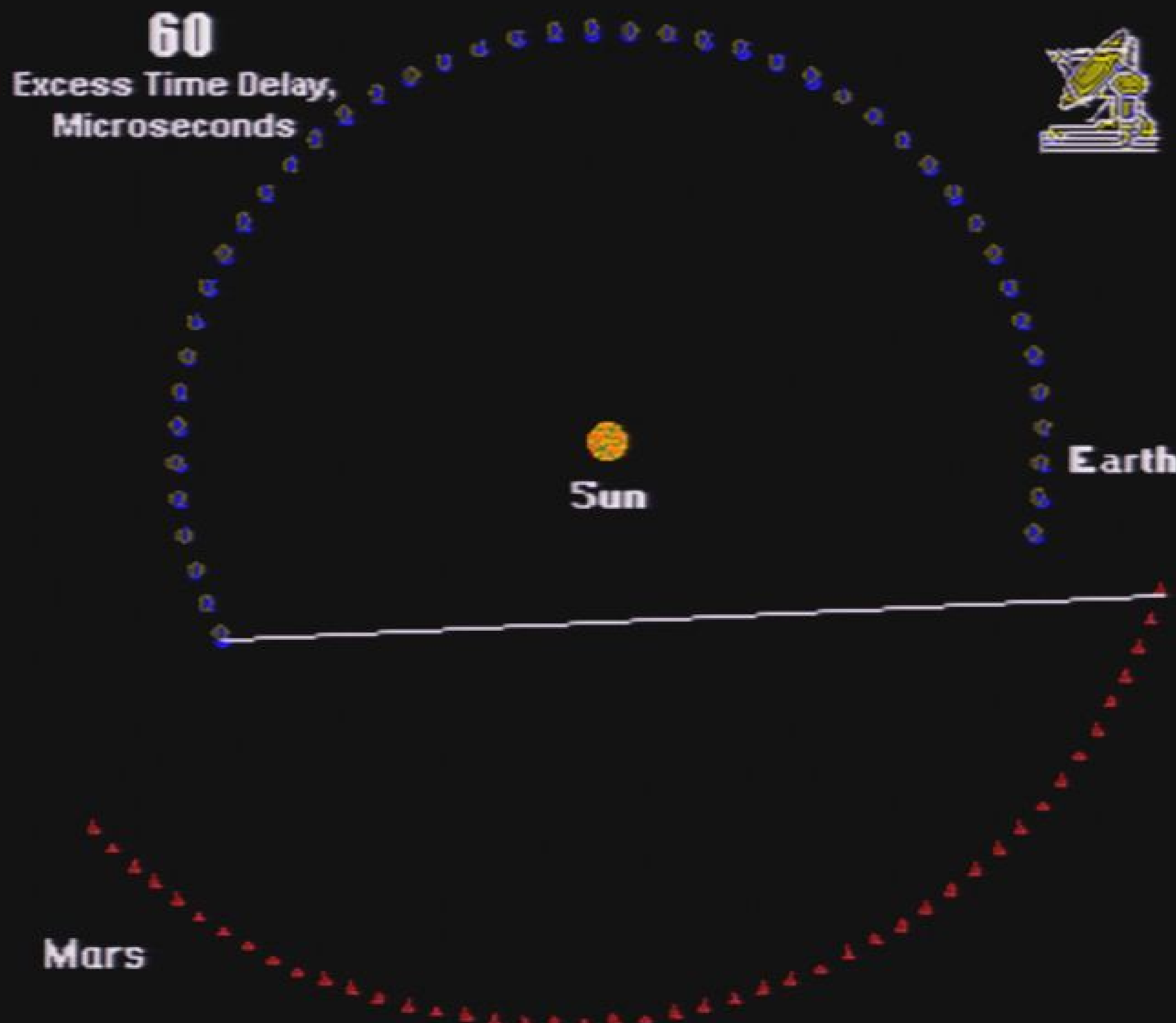

General Relativity Test (1976)
108
Excess Time Delay,
Microseconds
Earth
Sun
Mars
Distance > 37 km

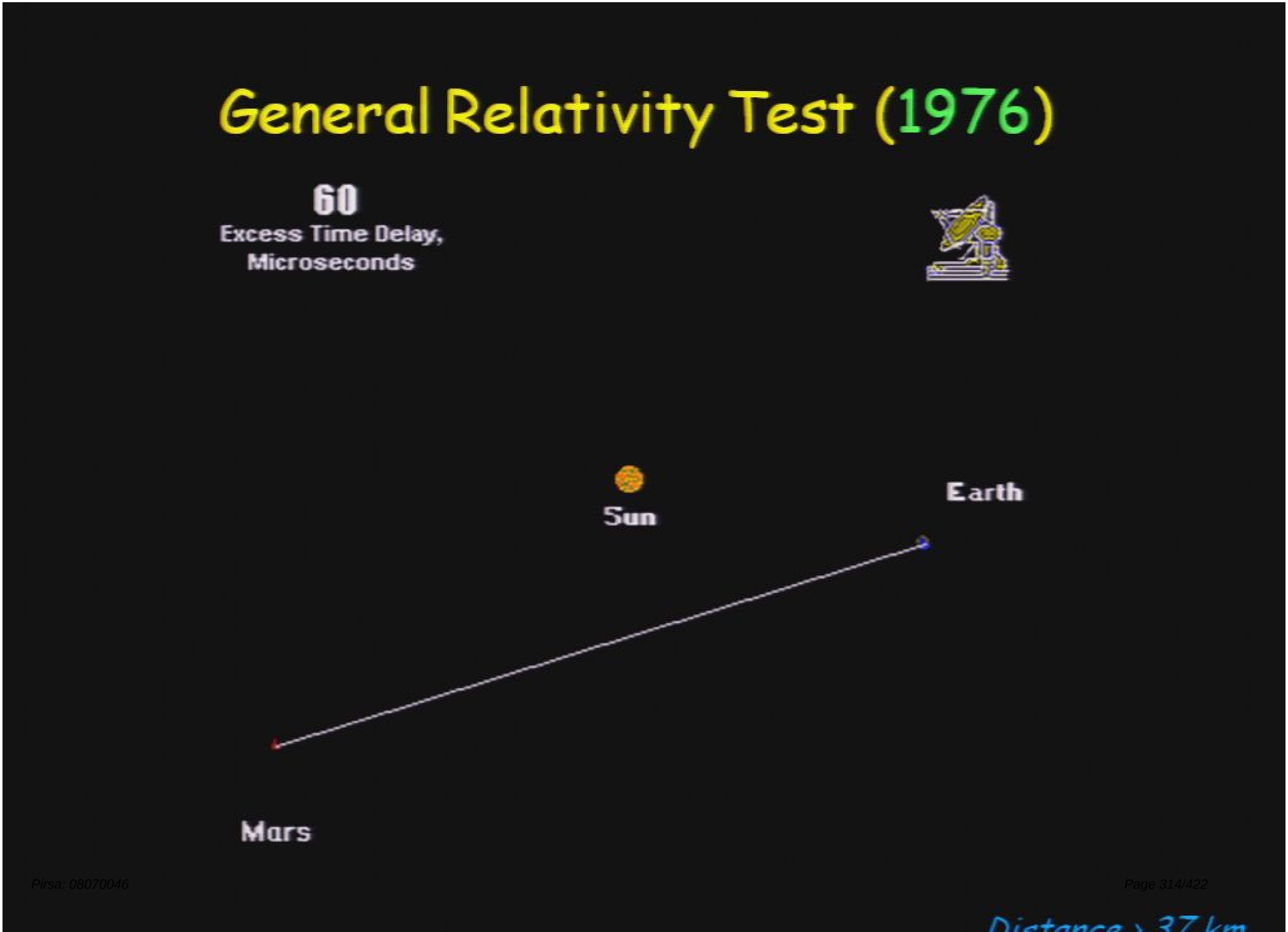

General Relativity Test (1976)
85
Excess Time Delay, Microseconds
Earth
Sun
Mars

General Relativity Test (1976)

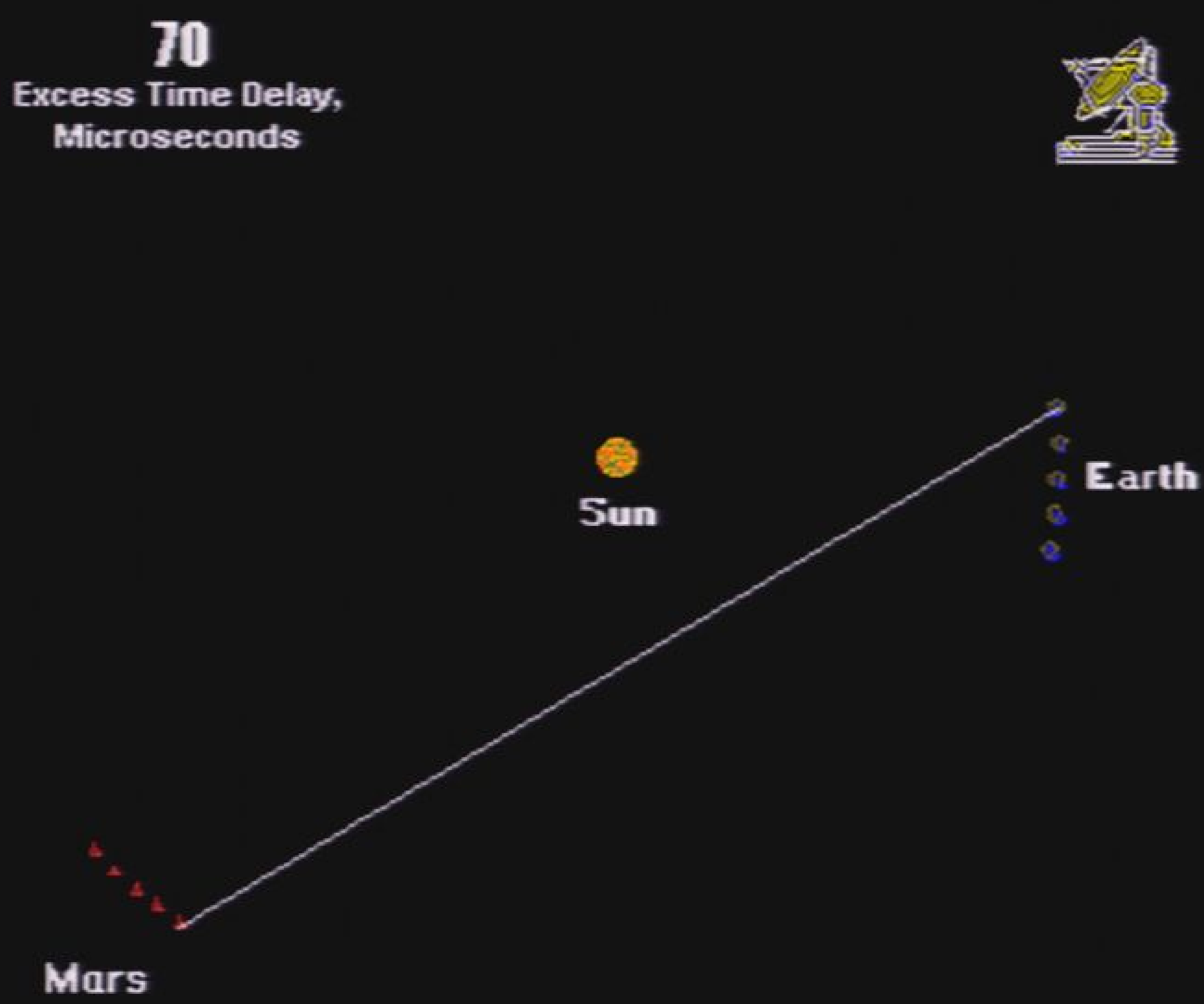


General Relativity Test (1976)

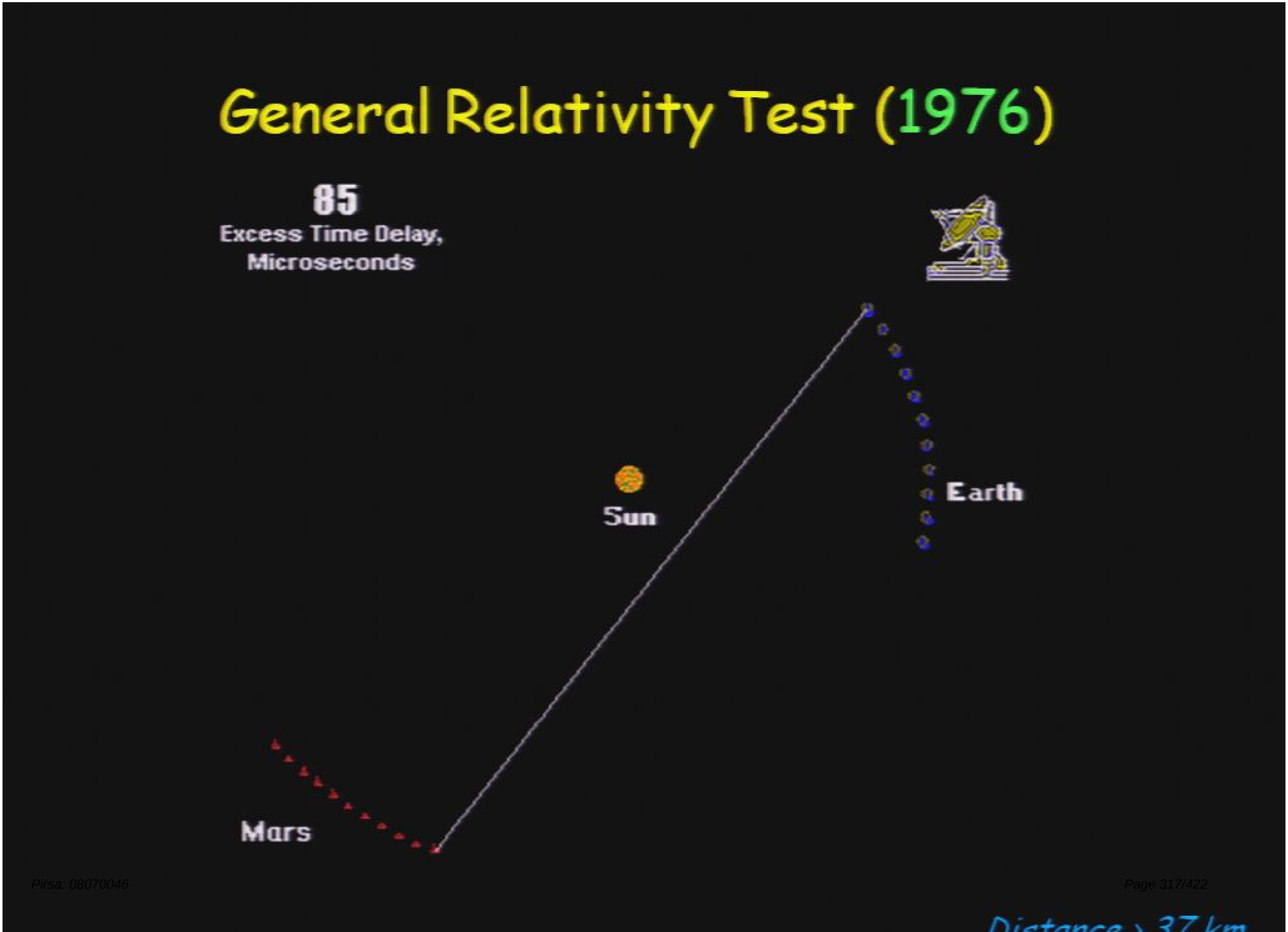


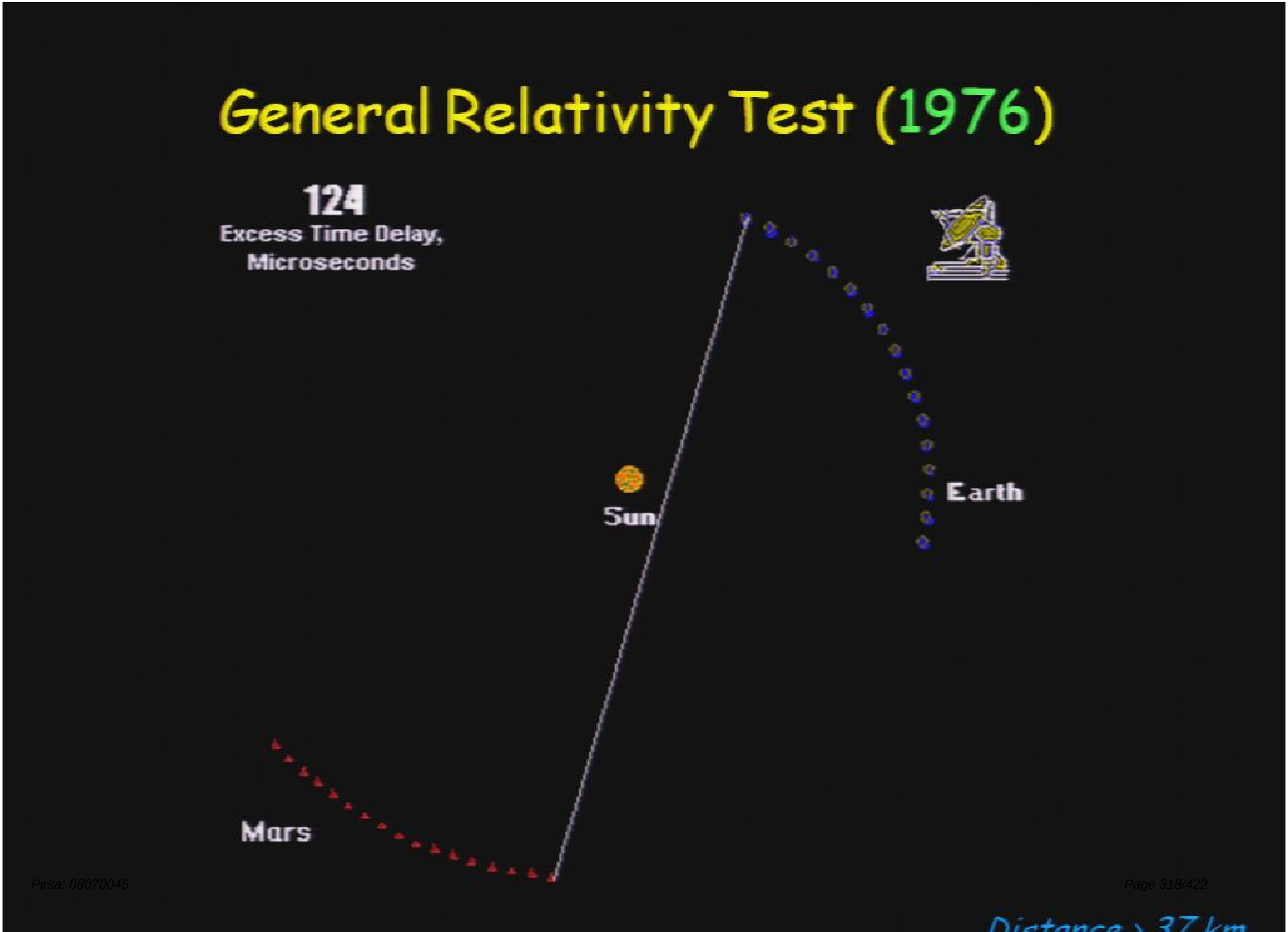

General Relativity Test (1976)
60
Excess Time Delay,
Microseconds
Sun
Earth
Mars

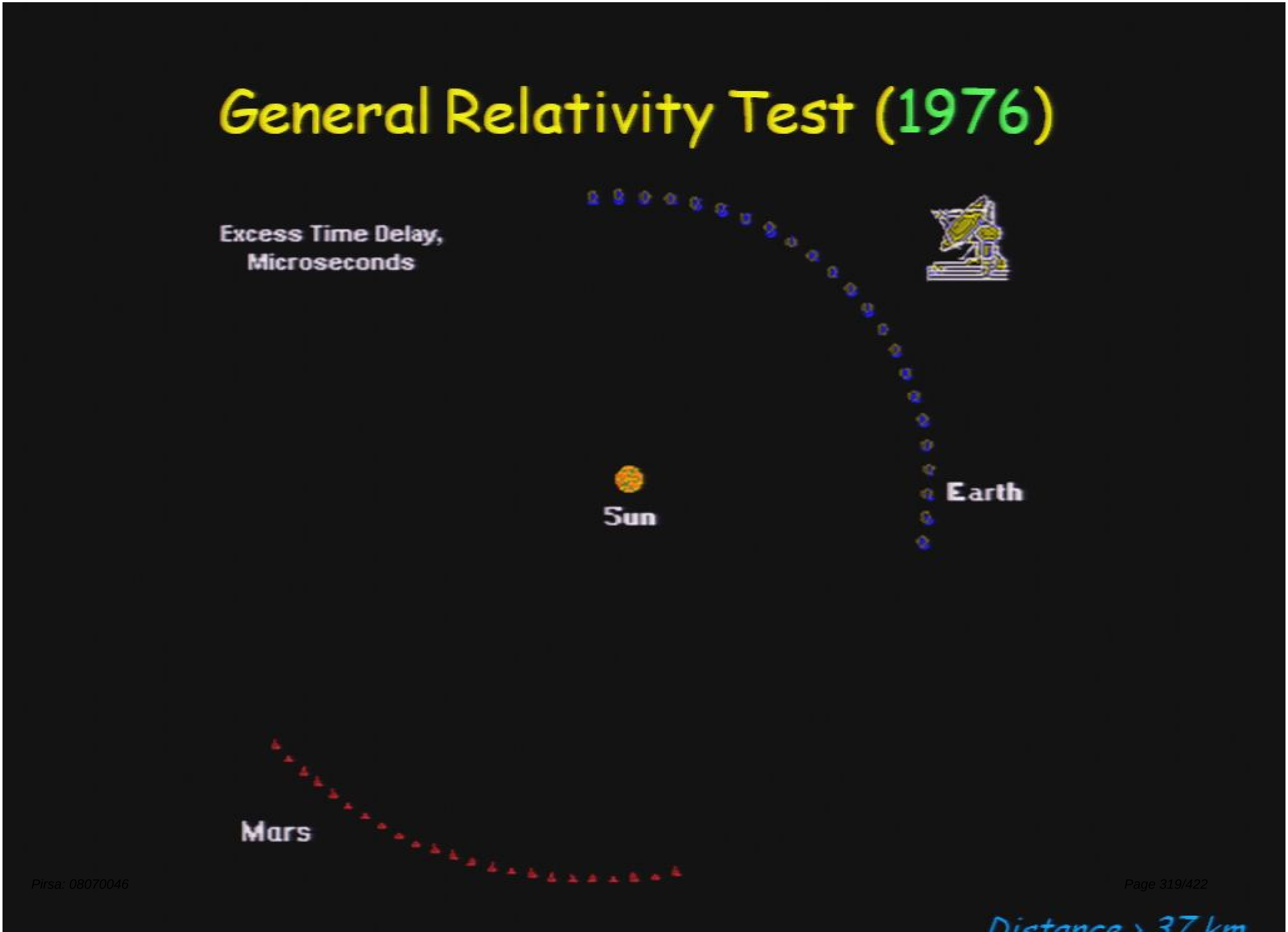
General Relativity Test (1976)



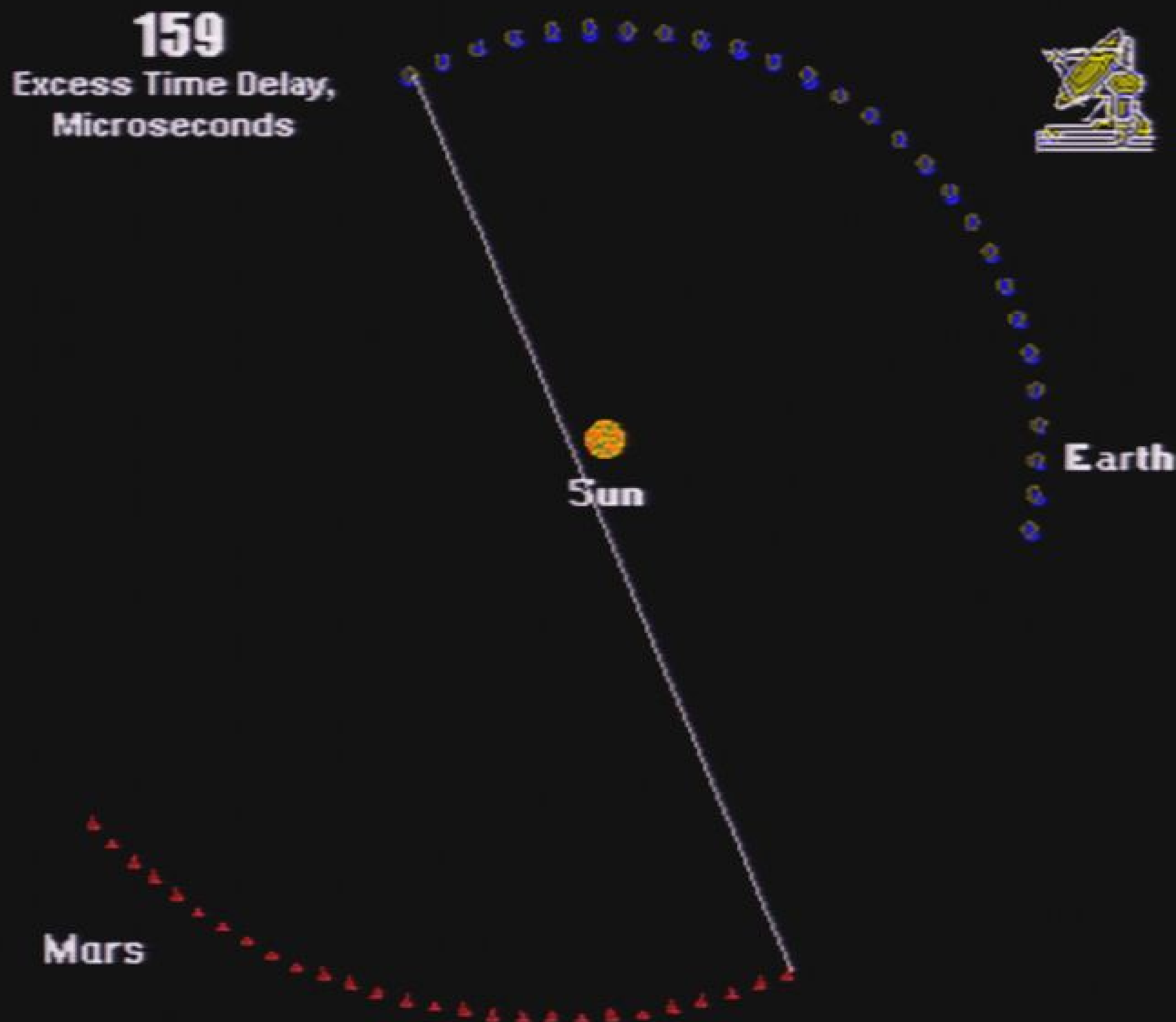
General Relativity Test (1976)


General Relativity Test (1976)
85
Excess Time Delay,
Microseconds
Sun
Earth
Mars

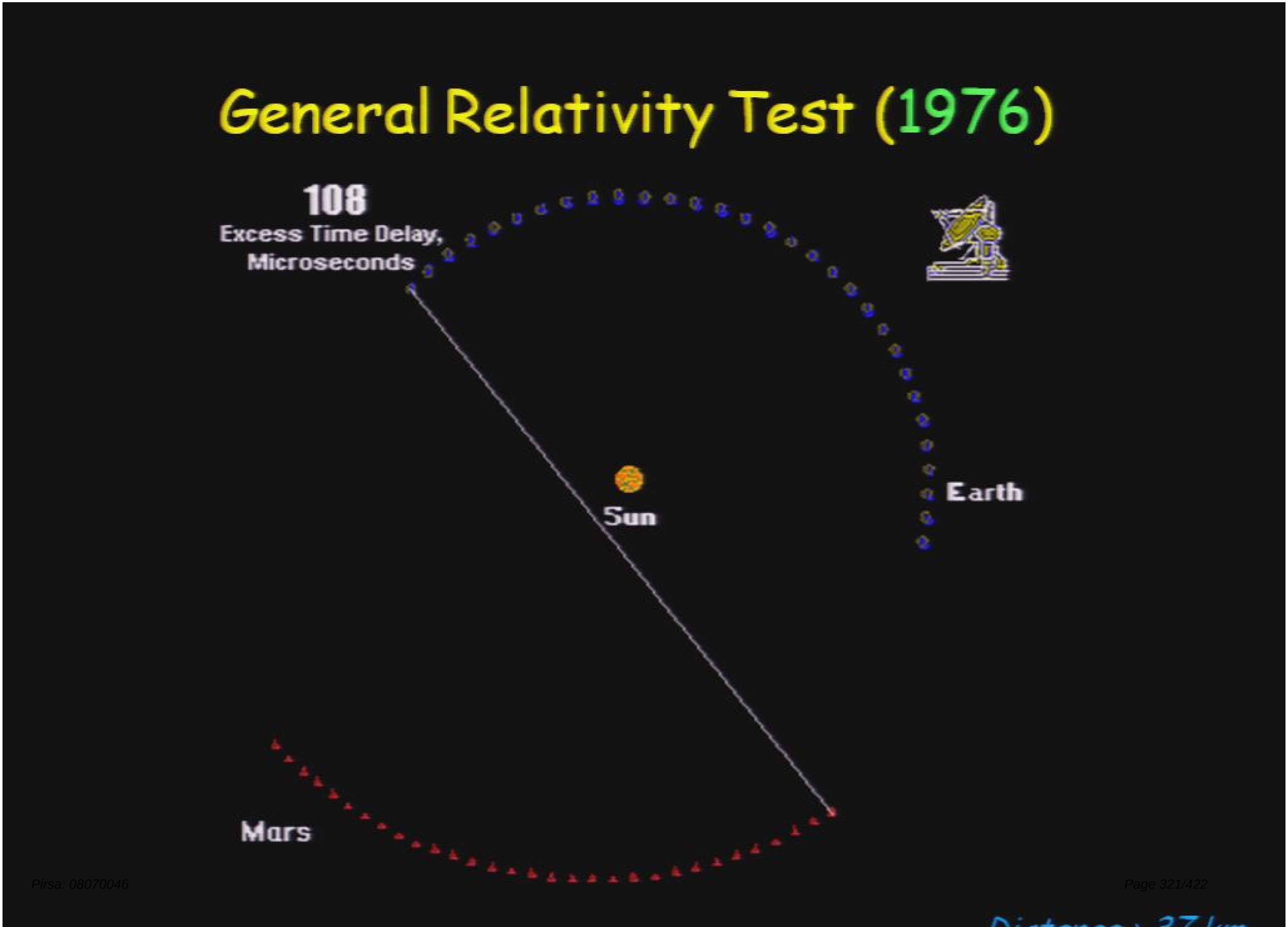

General Relativity Test (1976)
124
Excess Time Delay,
Microseconds
Sun
Earth
Mars


General Relativity Test (1976)
Excess Time Delay,
Microseconds
Earth
Sun
Mars

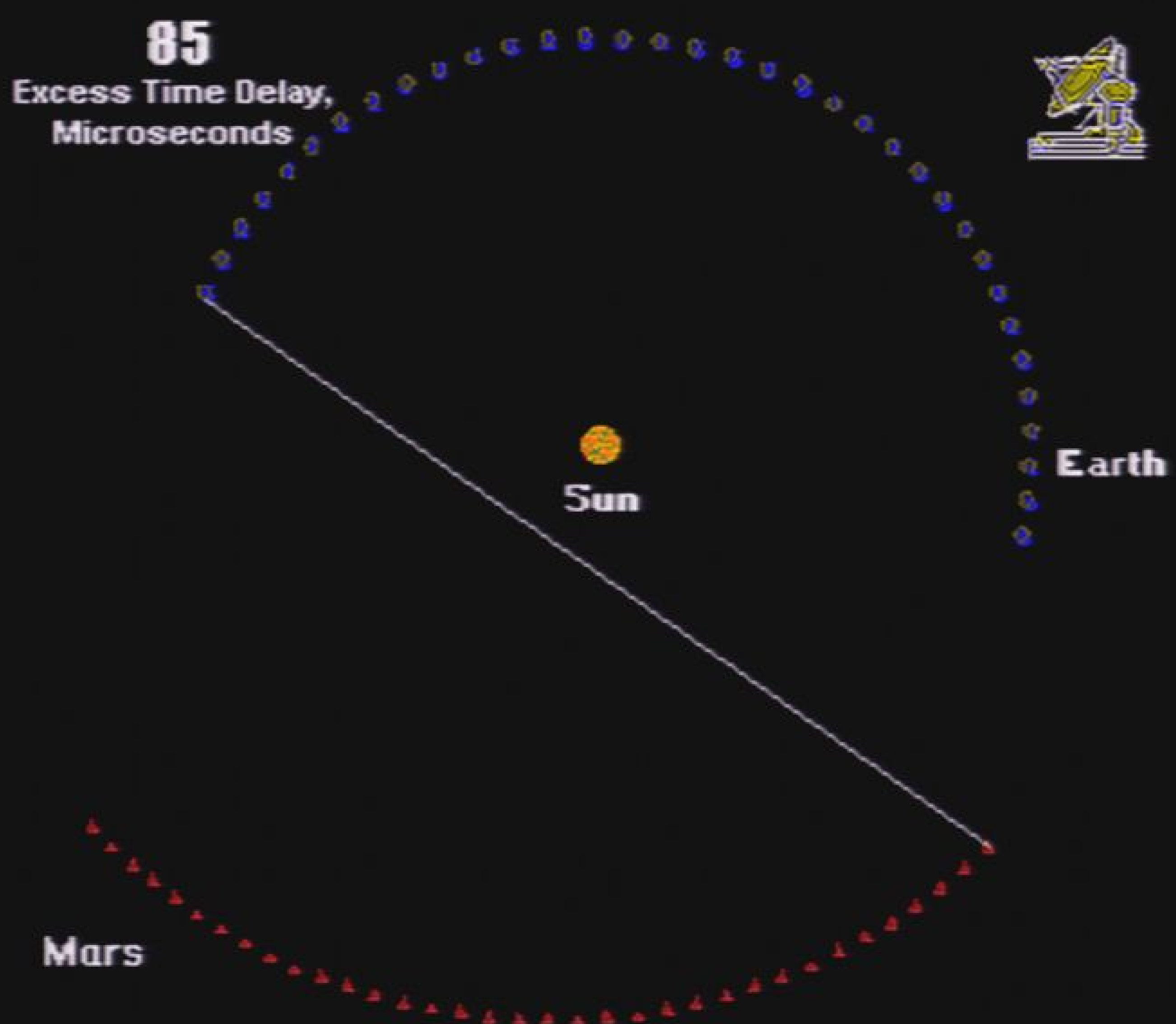
General Relativity Test (1976)

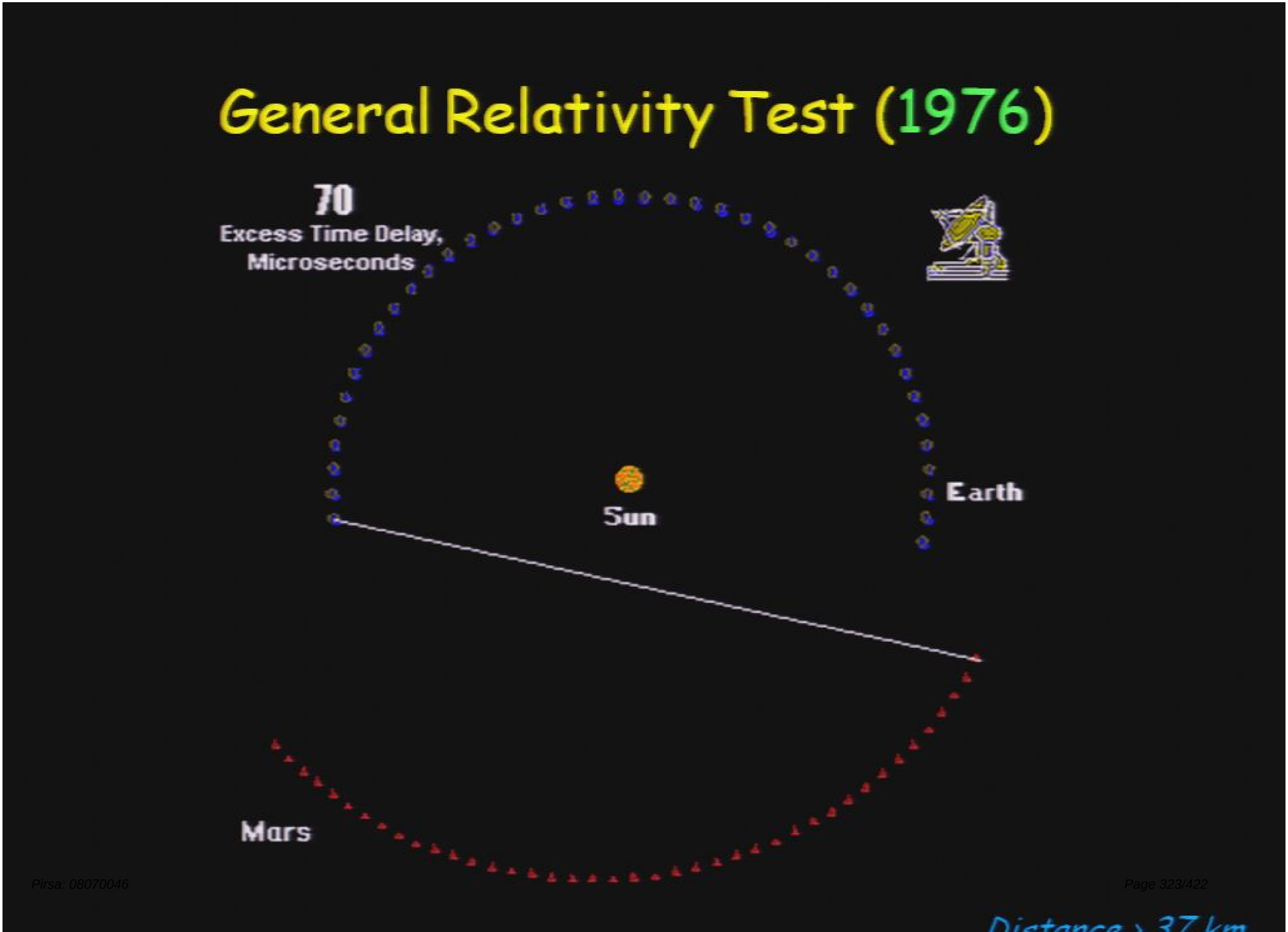


Distance > 37 km


General Relativity Test (1976)
108
Excess Time Delay,
Microseconds
Earth
Sun
Mars

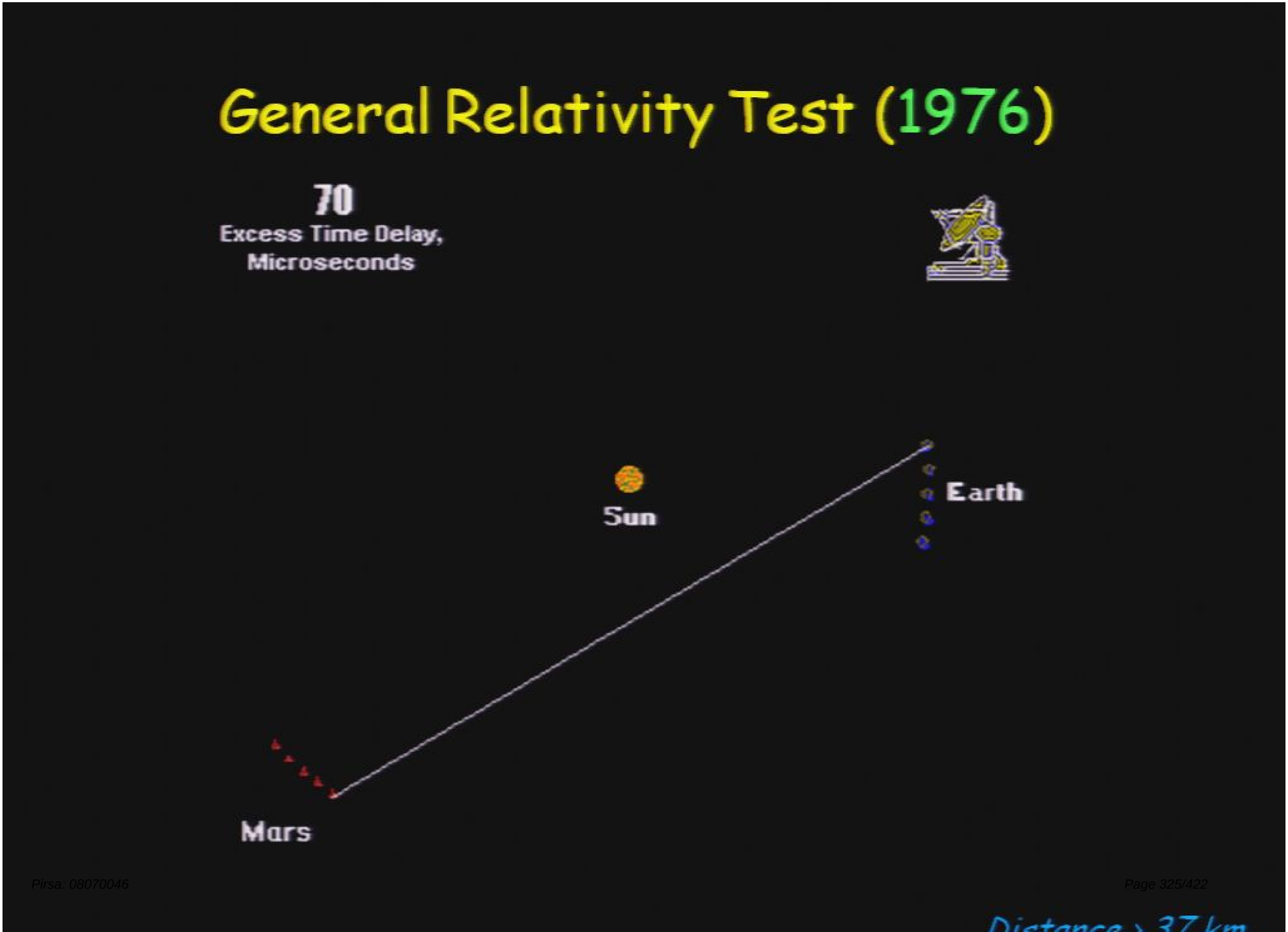
General Relativity Test (1976)




General Relativity Test (1976)
70
Excess Time Delay, Microseconds
Earth
Sun
Mars

General Relativity Test (1976)

Distance > 37 km

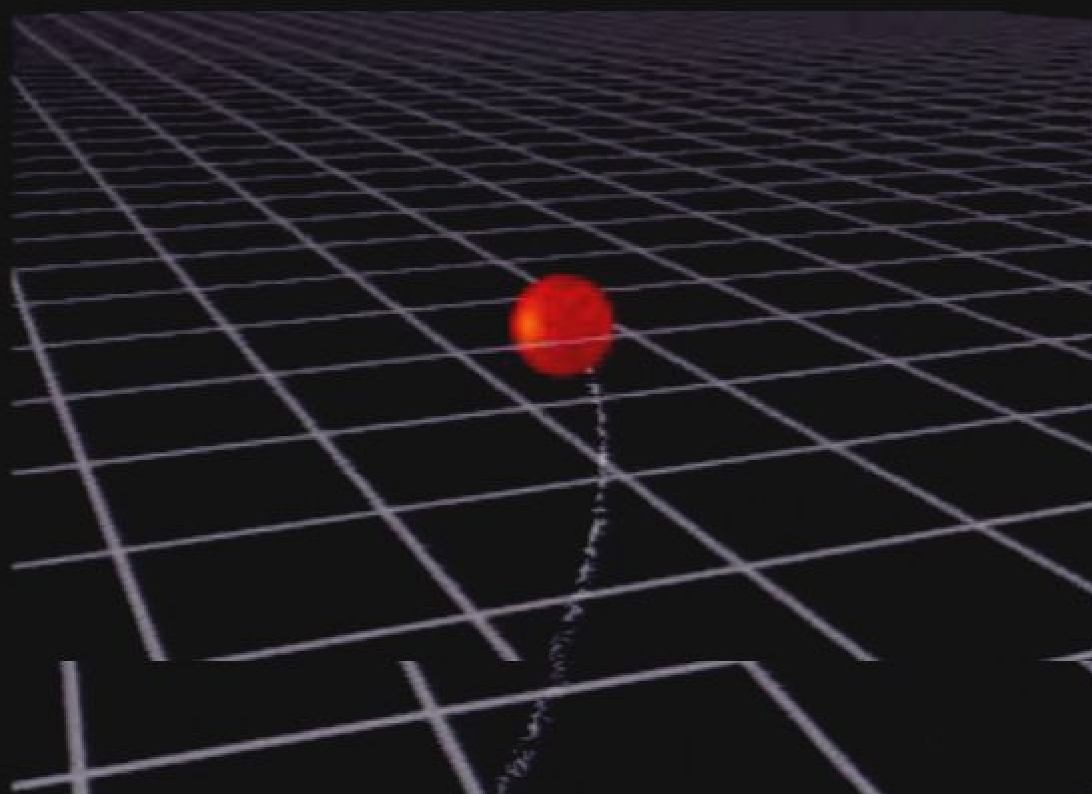

General Relativity Test (1976)
70
Excess Time Delay,
Microseconds
Sun
Earth
Mars

Mercury's Precession of axis

- Mercury's precession did not agree with Newton's Laws
- Out by 43 arc seconds per century.
- Einstein's Theory accounted for this 43 arc seconds

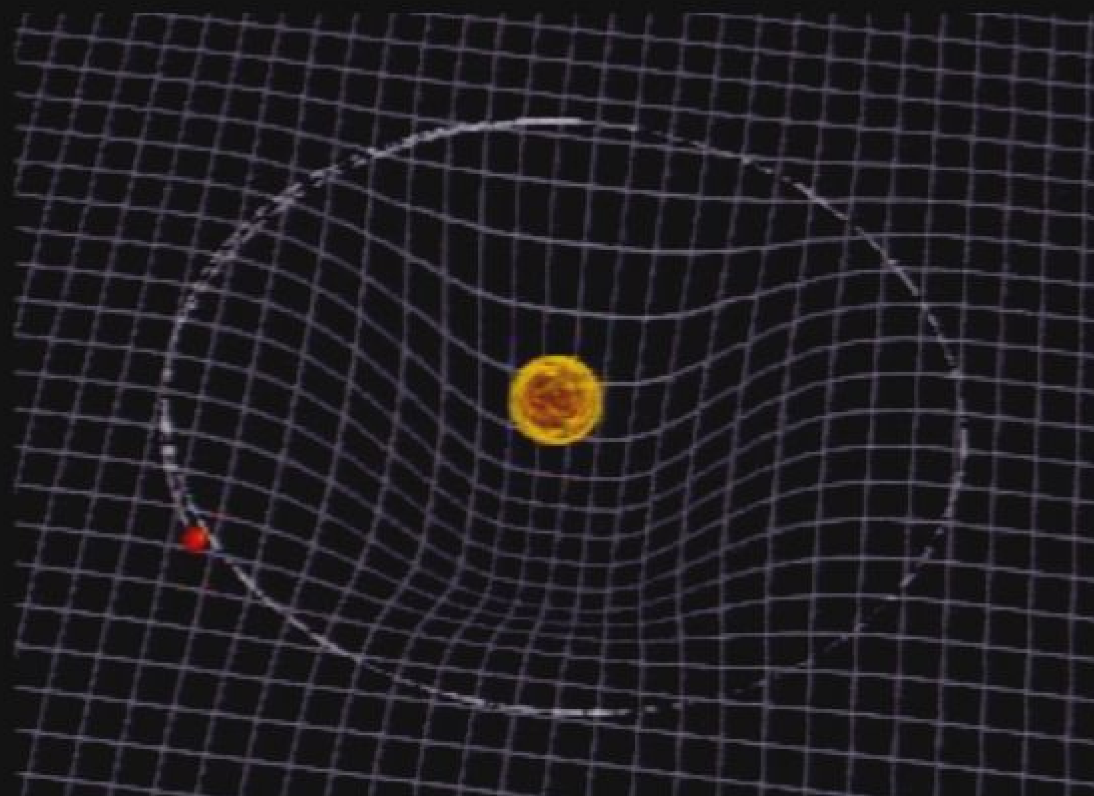
Mercury's Precession of axis

- Mercury's precession did not agree with Newton's Laws
- Out by 43 arc seconds per century.
- Einstein's Theory accounted for this 43 arc seconds



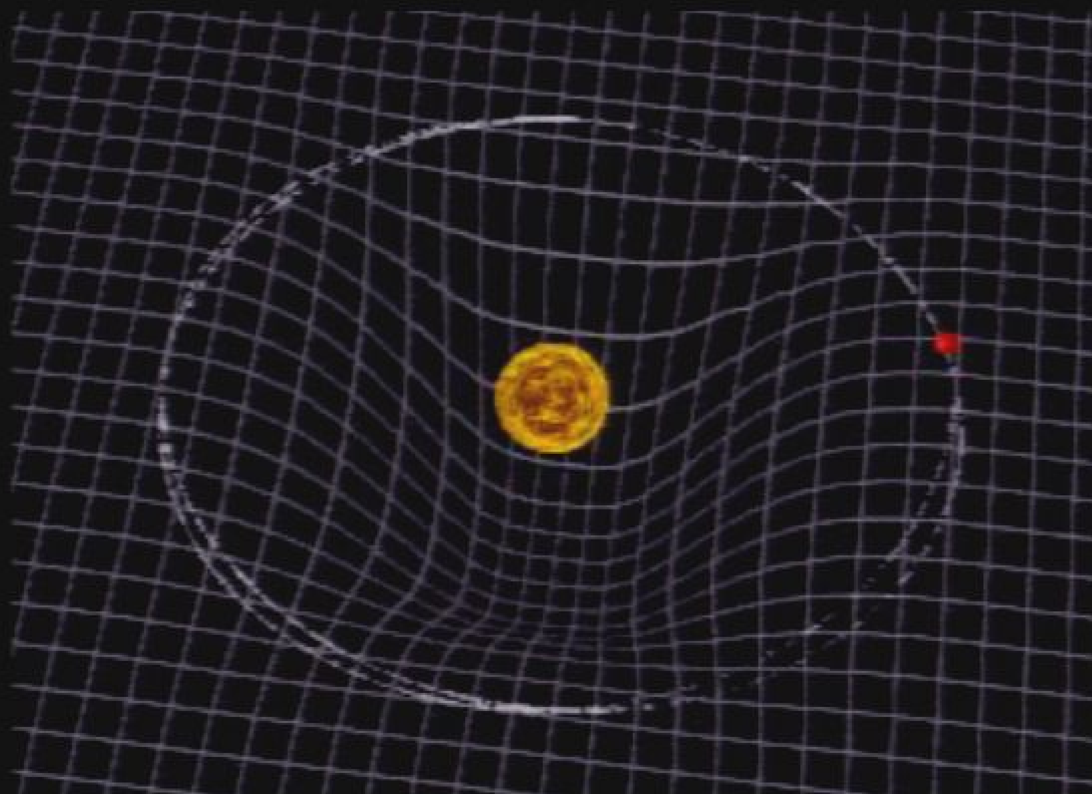
Mercury's Precession of axis

- Mercury's precession did not agree with Newton's Laws
- Out by 43 arc seconds per century.
- Einstein's Theory accounted for this 43 arc seconds



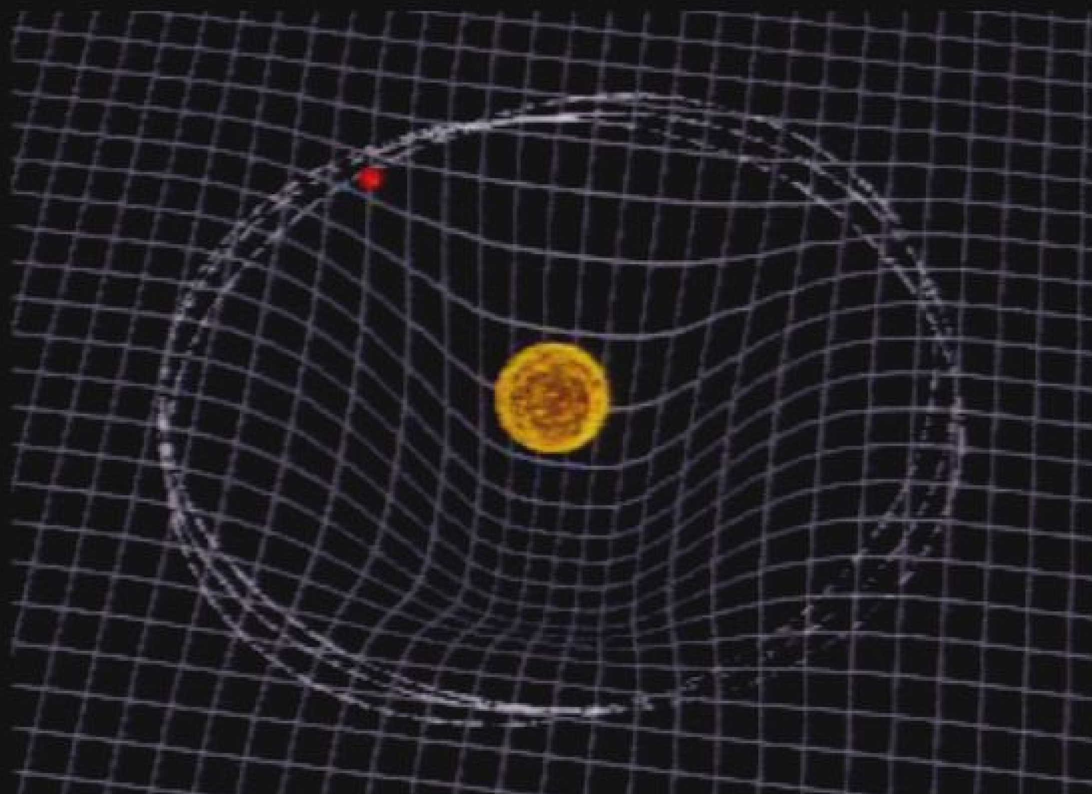
Mercury's Precession of axis

- Mercury's precession did not agree with Newton's Laws
- Out by 43 arc seconds per century.
- Einstein's Theory accounted for this 43 arc seconds



Mercury's Precession of axis

- Mercury's precession did not agree with Newton's Laws
- Out by 43 arc seconds per century.
- Einstein's Theory accounted for this 43 arc seconds



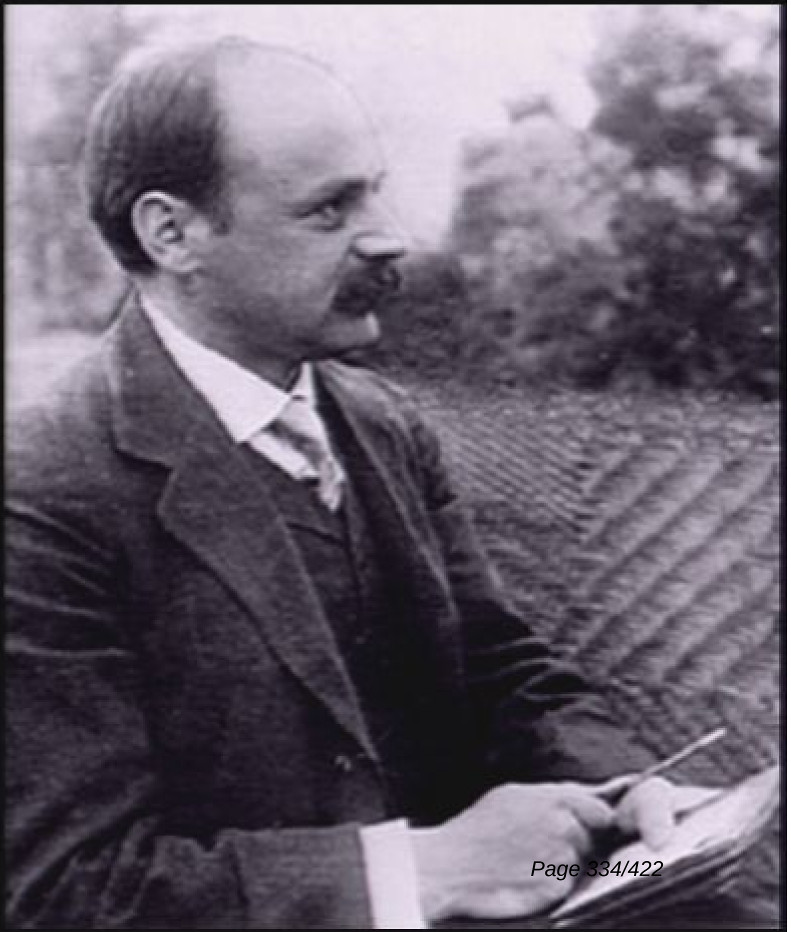
Calculation of Schwarzschild radius

What to do with the Field Equations

Calculation of Schwarzschild radius

Calculation of Schwarzschild radius

In 1916 Karl Schwarzschild discovers a solution of the Einstein field equation, which describes a nonspinning, uncharged spherical body.



Calculation of Schwarzschild radius

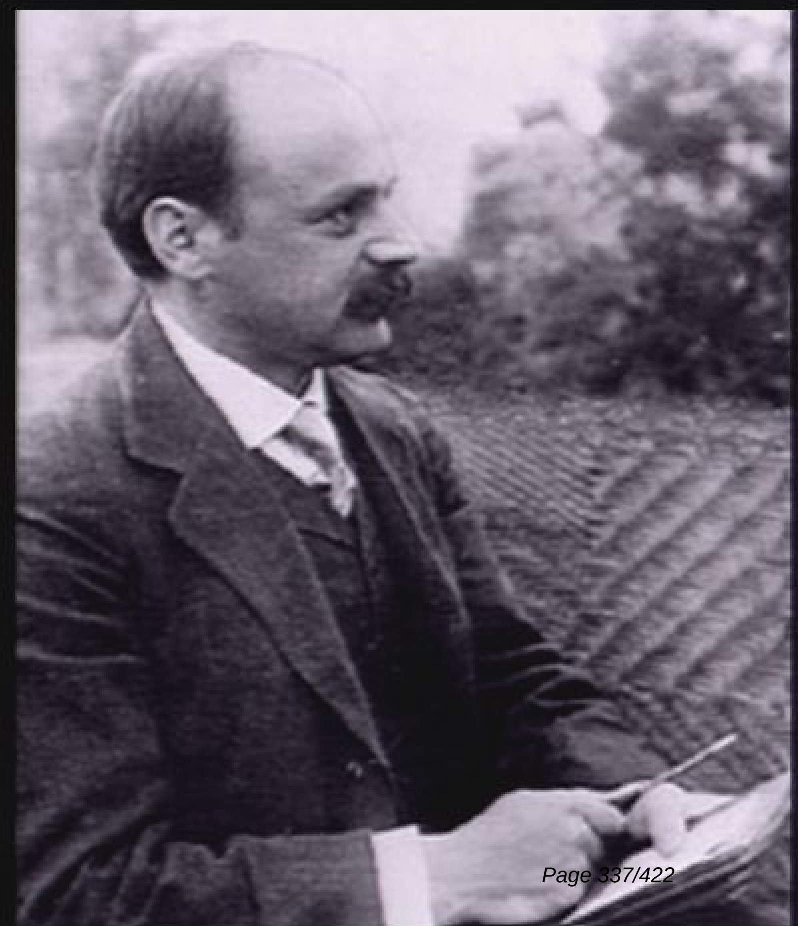
•In 1916 Karl Schwarzschild discovers a solution of the Einstein field equation, which describes a nonspinning, uncharged spherical body.

Calculation of Schwarzschild radius

- In 1916 Karl Schwarzschild discovers a solution of the Einstein field equation, which describes a nonspinning, uncharged spherical body.
- Did this when serving in the German Army on the Russian front of World War I

Calculation of Schwarzschild radius

- In 1916 Karl Schwarzschild discovers a solution of the Einstein field equation, which describes a nonspinning, uncharged spherical body.
- Did this when serving in the German Army on the Russian front of World War I
- Only required a few days to solve equation and describe spacetime curvature.



Calculation of Schwarzschild radius

- In 1916 Karl Schwarzschild discovers a solution of the Einstein field equation, which describes a nonspinning, uncharged spherical body.
- Did this when serving in the German Army on the Russian front of World War I
- Only required a few days to solve equation and describe spacetime curvature.
- Einstein presented solution on behalf of Schwarzschild to the Academy of Sciences.

Calculation of Schwarzschild radius

- In 1916 Karl Schwarzschild discovers a solution of the Einstein field equation, which describes a nonspinning, uncharged spherical body.
- Did this when serving in the German Army on the Russian front of World War I
- Only required a few days to solve equation and describe spacetime curvature.
- Einstein presented solution on behalf of Schwarzschild to the Academy of Sciences.
- Schwarzschild died on the front 4 months later.

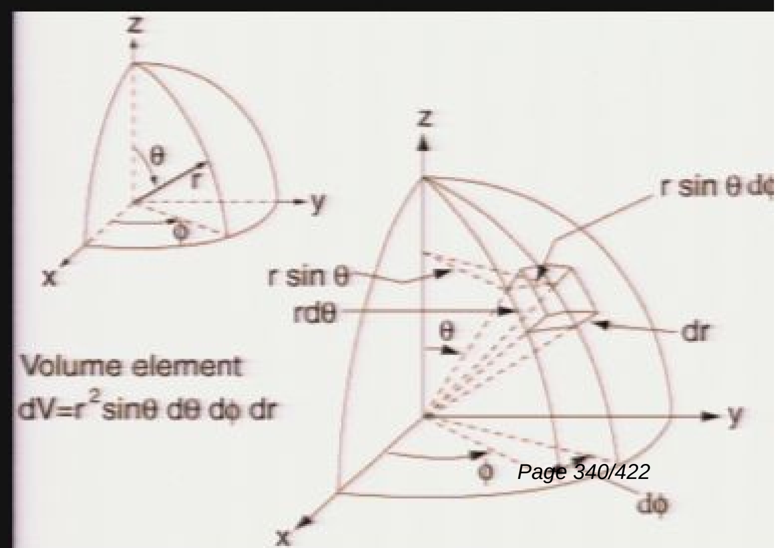
The Schwarzschild Radius

$$d\sigma^2 = -\left(1-\frac{r_s}{r}\right)c^2dt^2 + \frac{dr^2}{\left(1-\frac{r_s}{r}\right)} + r^2\left(d\theta^2 + \sin^2(\theta)\,d\phi^2\right)$$

Curvature factor

$$r_s = \frac{2GM}{c^2}$$

r, θ, ϕ are the polar coordinates



The Schwarzschild Radius

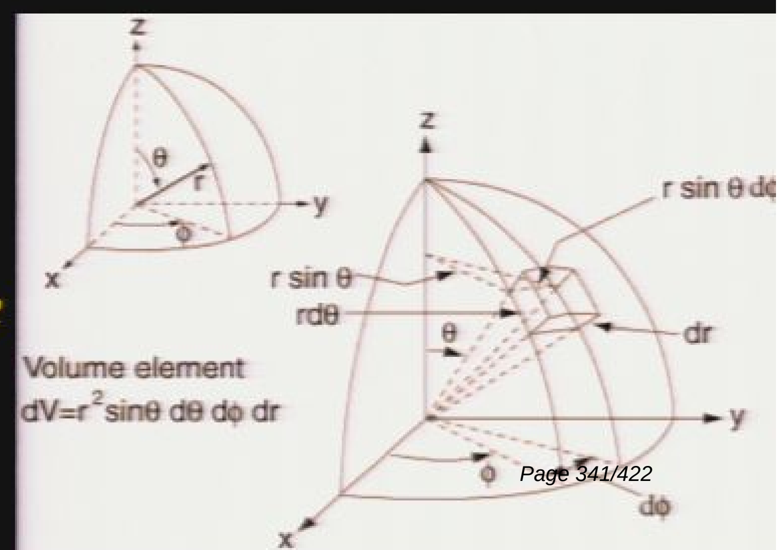
$$d\sigma^2 = -\left(1-\frac{r_s}{r}\right)c^2dt^2 + \frac{dr^2}{\left(1-\frac{r_s}{r}\right)} + r^2\left(d\theta^2 + \sin^2(\theta)d\phi^2\right)$$

Curvature factor

$$r_s = \frac{2GM}{c^2}$$

r, θ, ϕ are the polar coordinates

$$_{\mu\nu} = \begin{pmatrix} -\left(1-\frac{2MG}{rc^2}\right) & 0 & 0 & 0 \\ 0 & \left(1-\frac{2MG}{rc^2}\right)^{-1} & 0 & 0 \\ 0 & 0 & r^2 & 0 \\ 0 & 0 & 0 & r^2\sin(\theta) \end{pmatrix} \begin{matrix} \}\,time \\ \\ \}\,space \\ \end{matrix}$$



Schwarzschild Metric

$$d\sigma^2 = -\left(1-\frac{r_s}{r}\right)c^2dt^2 + \frac{dr^2}{\left(1-\frac{r_s}{r}\right)} + r^2\left(d\theta^2 + \sin^2(\theta)\,d\phi^2\right)$$

$$d\tau^2 = \left(1-\frac{r_s}{r}\right)c^2dt^2 - \frac{dr^2}{\left(1-\frac{r_s}{r}\right)} - r^2\left(d\theta^2 + \sin^2(\theta)\,d\phi^2\right)$$

is the proper time (time measured by a clock moving along path)

Schwarzschild Metric

$$d\sigma^2 = -\left(1-\frac{r_s}{r}\right)c^2dt^2 + \frac{dr^2}{\left(1-\frac{r_s}{r}\right)} + r^2\left(d\theta^2 + \sin^2(\theta)\,d\phi^2\right)$$

$$d\tau^2 = \left(1-\frac{r_s}{r}\right)c^2dt^2 - \frac{dr^2}{\left(1-\frac{r_s}{r}\right)} - r^2\left(d\theta^2 + \sin^2(\theta)\,d\phi^2\right)$$

is the proper time (time measured by a clock moving along path)

Schwarzschild Metric

$$d\sigma^2 = -\left(1-\frac{r_s}{r}\right)c^2dt^2 + \frac{dr^2}{\left(1-\frac{r_s}{r}\right)} + r^2\left(d\theta^2 + \sin^2(\theta)d\phi^2\right)$$

$$d\tau^2 = \left(1-\frac{r_s}{r}\right)c^2dt^2 - \frac{dr^2}{\left(1-\frac{r_s}{r}\right)} - r^2\left(d\theta^2 + \sin^2(\theta)d\phi^2\right)$$

- is the proper time (time measured by a clock moving along path)
- is the proper distance (distance measured by a clock moving along path)

Schwarzschild Metric

$$d\sigma^2 = -\left(1-\frac{r_s}{r}\right)c^2dt^2 + \frac{dr^2}{\left(1-\frac{r_s}{r}\right)} + r^2\left(d\theta^2 + \sin^2(\theta)\,d\phi^2\right)$$

$$d\tau^2 = \left(1-\frac{r_s}{r}\right)c^2dt^2 - \frac{dr^2}{\left(1-\frac{r_s}{r}\right)} - r^2\left(d\theta^2 + \sin^2(\theta)\,d\phi^2\right)$$

is the proper time (time measured by a clock moving along path)

is the proper distance (distance measured by a clock moving along path)

is the time coordinate (measured by a far away stationary observer)

Schwarzschild Metric

$$d\sigma^2 = -\left(1-\frac{r_s}{r}\right)c^2dt^2 + \frac{dr^2}{\left(1-\frac{r_s}{r}\right)} + r^2\left(d\theta^2 + \sin^2(\theta)\,d\phi^2\right)$$

$$d\tau^2 = \left(1-\frac{r_s}{r}\right)c^2dt^2 - \frac{dr^2}{\left(1-\frac{r_s}{r}\right)} - r^2\left(d\theta^2 + \sin^2(\theta)\,d\phi^2\right)$$

is the proper time (time measured by a clock moving along path)

is the proper distance (distance measured by a clock moving along path)

is the time coordinate (measured by a far away stationary observer)

is the radial coordinate (circumference of a circle centered on star divided by 2π

Schwarzschild Metric

$$d\sigma^2 = -\left(1 - \frac{r_s}{r}\right)c^2 dt^2 + \frac{dr^2}{\left(1 - \frac{r_s}{r}\right)} + r^2\left(d\theta^2 + \sin^2(\theta)\, d\phi^2\right)$$

$$d\tau^2 = \left(1 - \frac{r_s}{r}\right)c^2 dt^2 - \frac{dr^2}{\left(1 - \frac{r_s}{r}\right)} - r^2\left(d\theta^2 + \sin^2(\theta)\, d\phi^2\right)$$

is the proper time (time measured by a clock moving along path)

is the proper distance (distance measured by a clock moving along path)

is the time coordinate (measured by a far away stationary observer)

is the radial coordinate (circumference of a circle centered on star divided by 2π)

Schwarzschild Metric

$$d\sigma^2 = -\left(1-\frac{r_s}{r}\right)c^2dt^2 + \frac{dr^2}{\left(1-\frac{r_s}{r}\right)} + r^2\left(d\theta^2 + \sin^2(\theta)\,d\phi^2\right)$$

$$d\tau^2 = \left(1-\frac{r_s}{r}\right)c^2dt^2 - \frac{dr^2}{\left(1-\frac{r_s}{r}\right)} - r^2\left(d\theta^2 + \sin^2(\theta)\,d\phi^2\right)$$

is the proper time (time measured by a clock moving along path)

is the proper distance (distance measured by a clock moving along path)

is the time coordinate (measured by a far away stationary observer)

is the radial coordinate (circumference of a circle centered on star divided by 2π)

is the Schwarzschild radius

Schwarzschild Metric

Schwarzschild Metric

$\tau^2 = t^2 - s^2$ ← Timelike *Spacetime Metric*

Schwarzschild Metric

$$d\tau^2 = dt^2 - dx^2 - dy^2$$ ← 2D flat Spacetime in Cartesian

It is the square of the wristwatch time between two events as marked by x, y, t

Schwarzschild Metric

$$d\tau)^2 = (dt)^2 - (dr)^2 - (rd\phi)^2$$ ← *2D flat Spacetime in Polar*

Schwarzschild Metric

$$d\tau)^2 = (dt)^2 - (dr)^2 - (rd\phi)^2$$

← *2D flat Spacetime in Polar*

$$d\tau^2 = \left(1 - \frac{r_s}{r}\right)c^2dt^2 - \frac{dr^2}{\left(1 - \frac{r_s}{r}\right)} - r^2d\phi^2$$

← *Curvature added, now Schwarzschild timelike Spacetime Metric*

$$r_s = \frac{2GM}{c^2}$$

Schwarzschild Metric

$$d\sigma^2 = -\left(1-\frac{2M}{r}\right)dt^2 + \frac{dr^2}{\left(1-\frac{2M}{r}\right)} + r^2 d\phi^2$$

The metric describes the shape of spacetime outside of matter. Once you hit matter, be it some gas, a star, a planet, or a rock, this metric no longer applies.

You can see that, if $r = 2M$, dt term would be zero. That is to say that at the event horizon there would be no change in time. Makes sense; you can look at the event horizon as being the place where time "stops". The dr factor deals with how close to something you are. You'll notice that it "blows up" when $r = 2M$.

Schwarzschild Metric

$$d\sigma^2 = -\left(1 - \frac{2M}{r}\right)dt^2 + \frac{dr^2}{\left(1 - \frac{2M}{r}\right)} + r^2 d\phi^2$$ ← *Spacelike Form*

$$d\tau^2 = \left(1 - \frac{2M}{r}\right)dt^2 - \frac{dr^2}{\left(1 - \frac{2M}{r}\right)} - r^2 d\phi^2$$ ← *Timelike Form*

The metric describes the shape of spacetime outside of matter. Once you hit matter, be it some gas, a star, a planet, or a rock, this metric no longer applies.

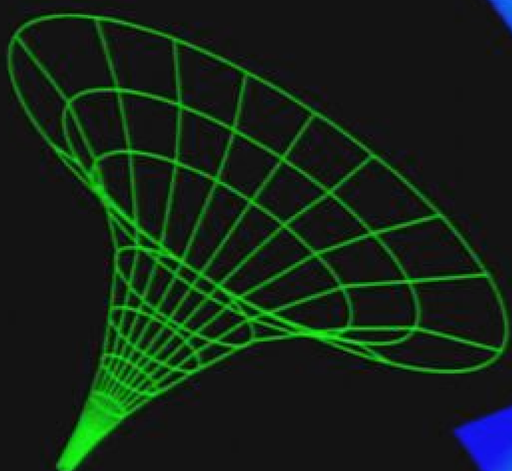
You can see that, if $r = 2M$, dt term would be zero. That is to say that at the event horizon there would be no change in time. Makes sense; you can look at the event horizon as being the place where time "stops". The dr factor deals with how close to something you are. You'll notice that it "blows up" when $r = 2M$.

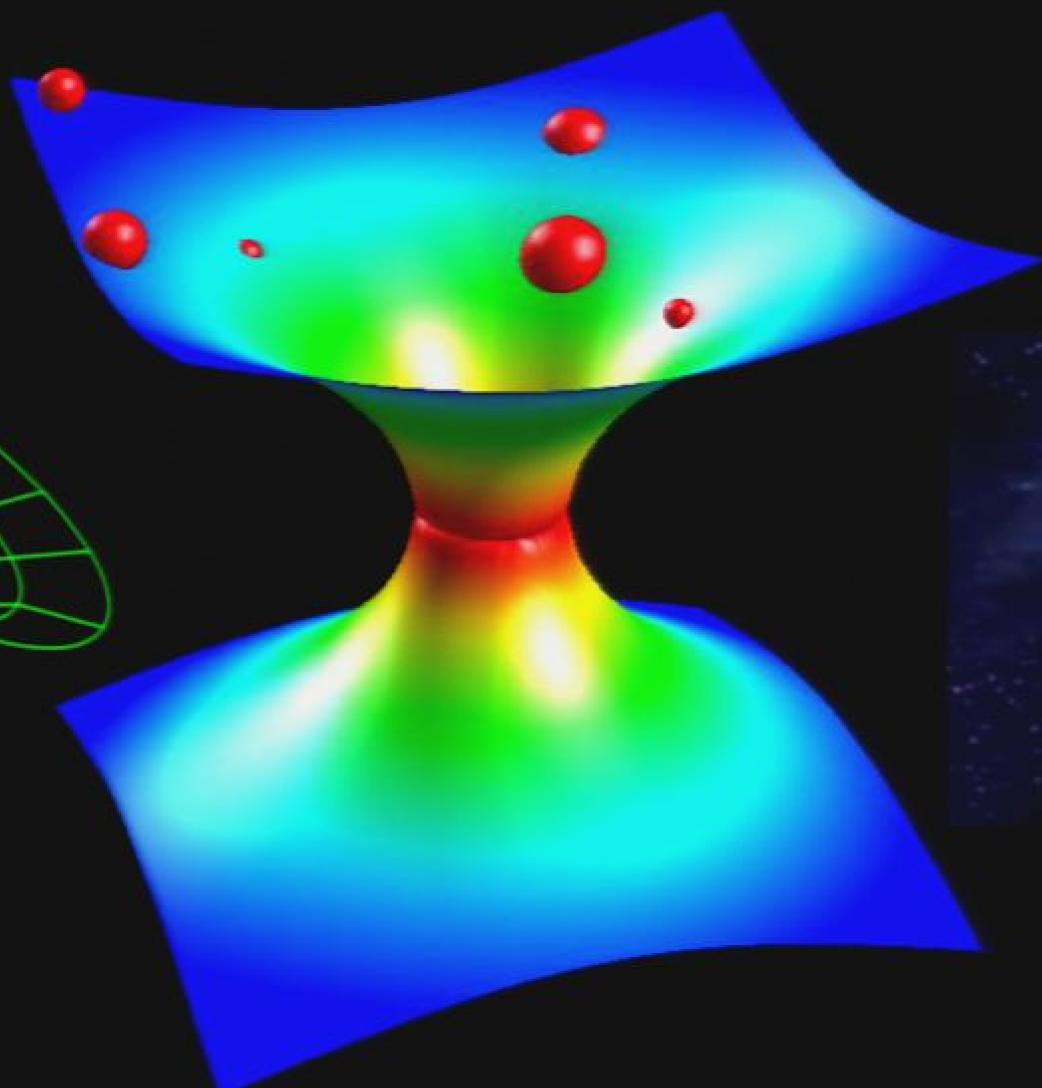
Schwarzchild radii for different objects

Object	Mass	R_S
Atom	10^{-26} kg	10^{-51} cm
Human Being	70 kg	10^{-23} cm
Earth	6.0×10^{24} kg	0.89 cm
Sun	2.0×10^{30} kg	3.0 km
Galaxy	10^{11} M_S	10^{-2} l.y.
Universe (if closed)	10^{23} M_S	10^{10} l.y.

$$r_s = \frac{2GM}{c^2}$$

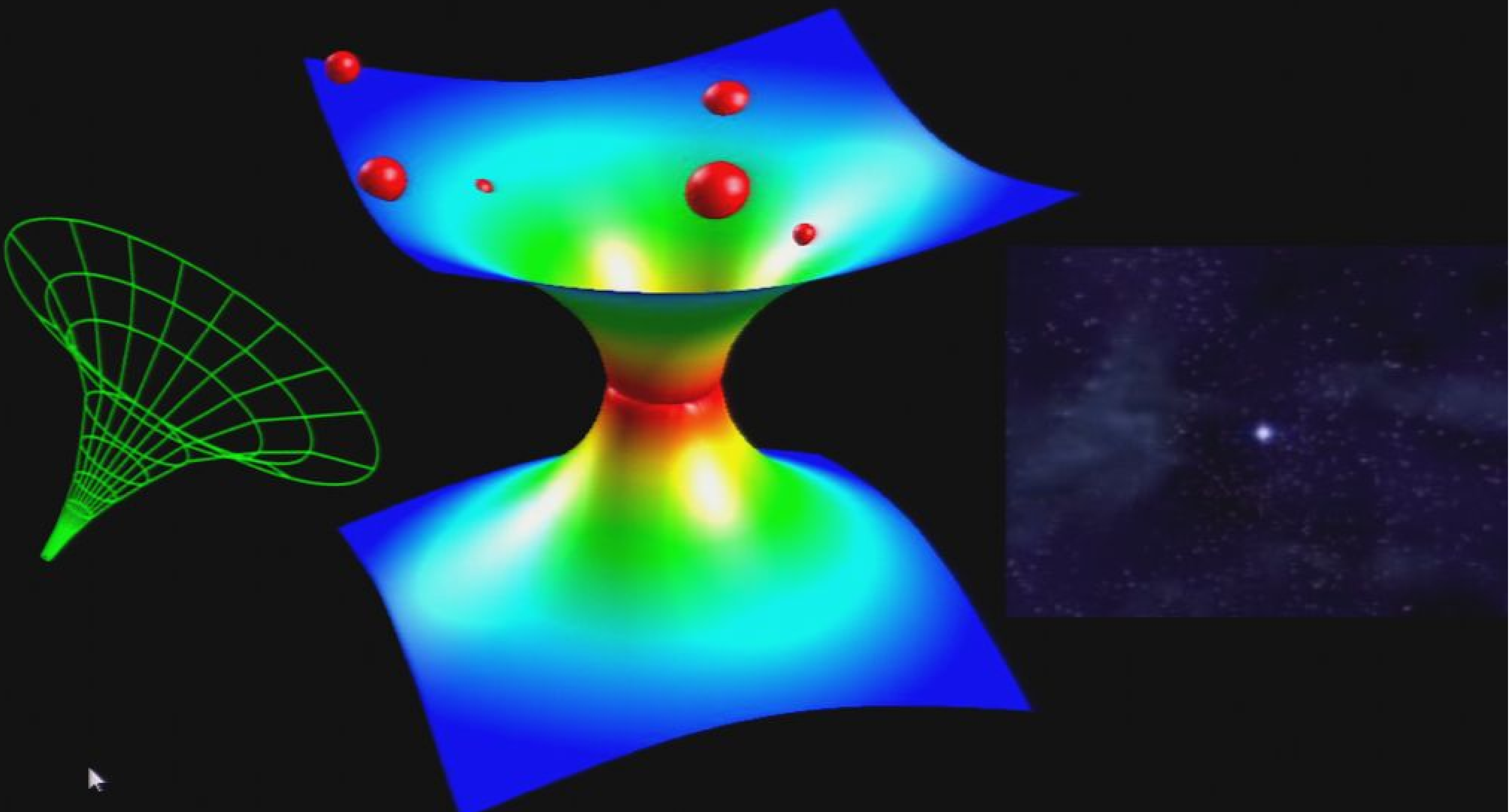
Embedding Diagrams





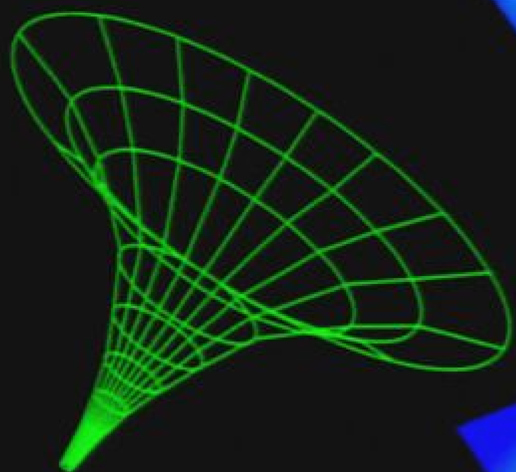
Emphasis on Spatial rather than temporal interpretations

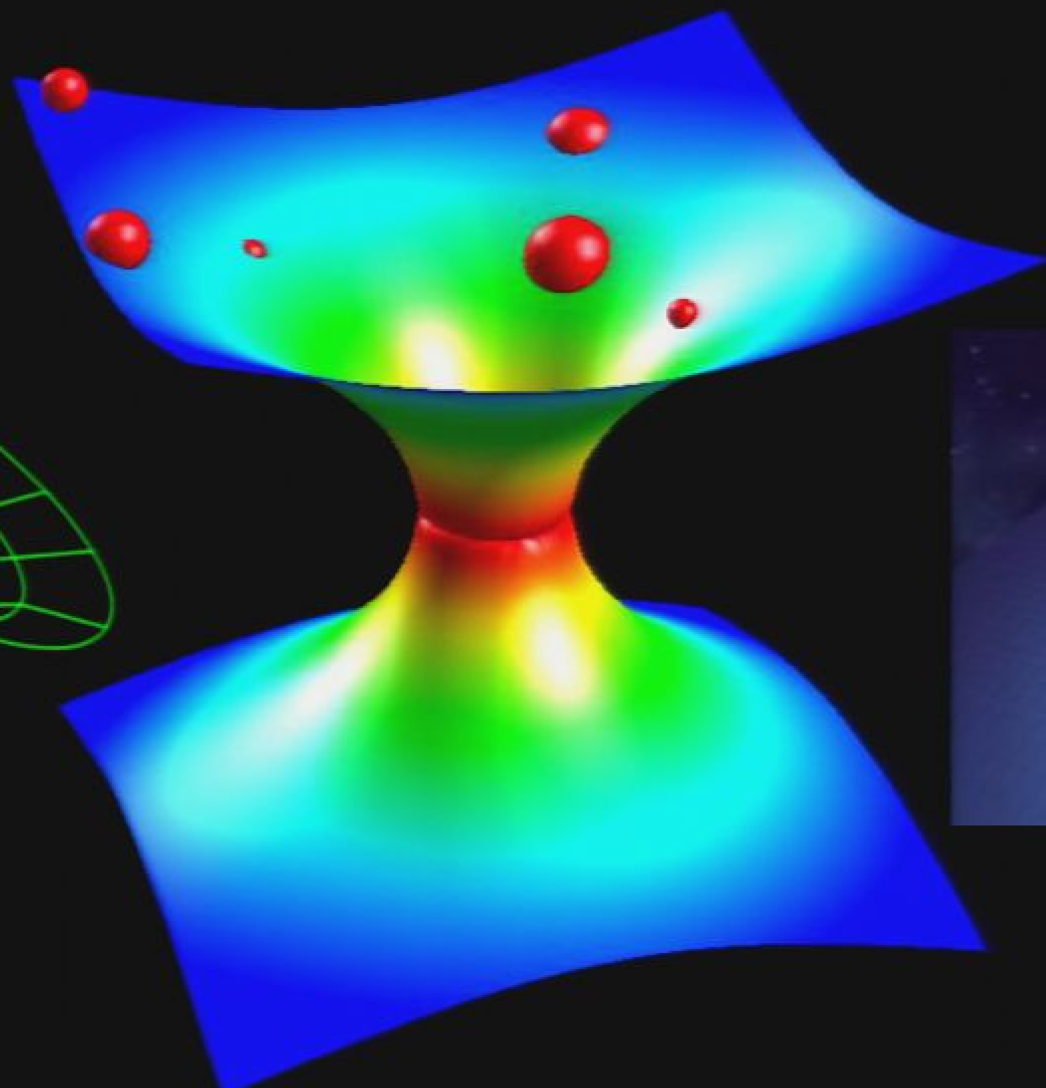
Embedding Diagrams

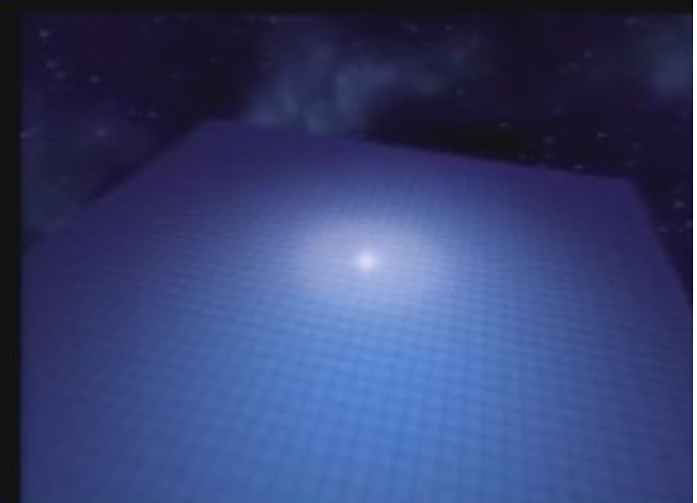


Emphasis on Spatial rather than temporal interpretations

Embedding Diagrams

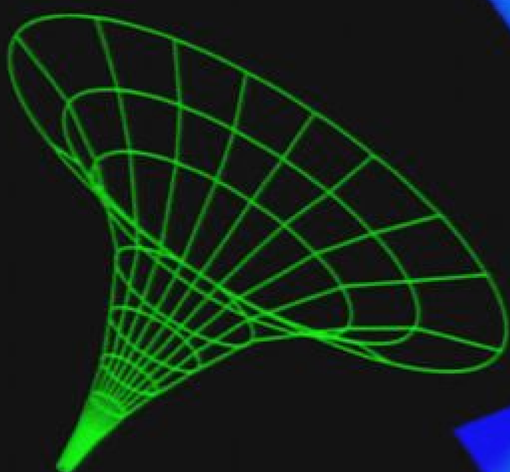


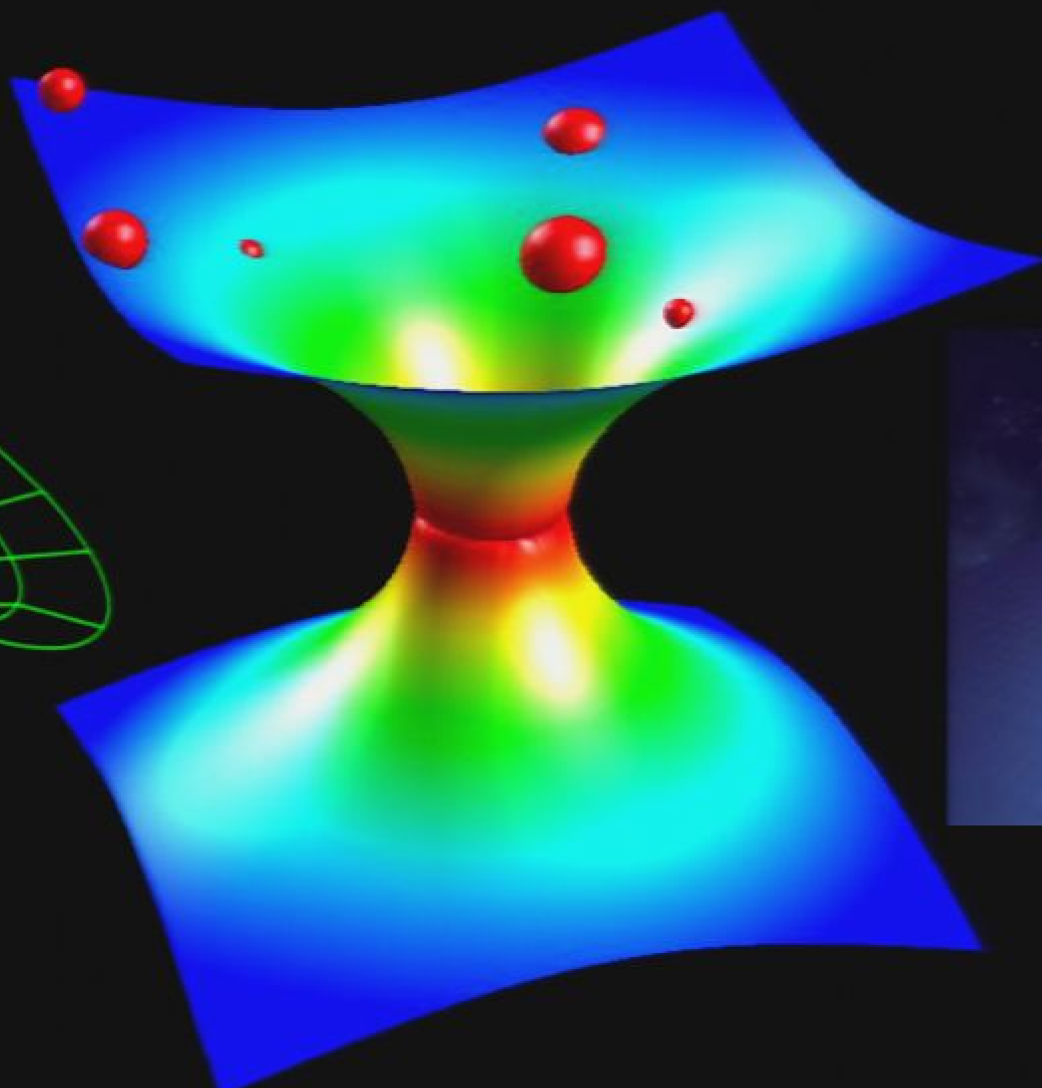


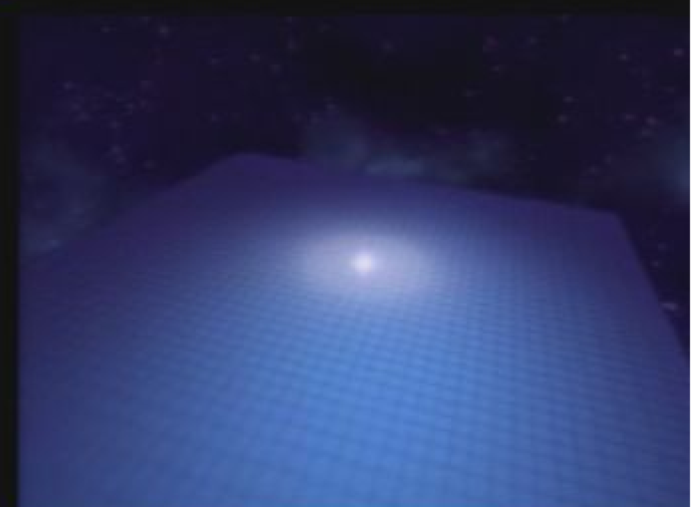


Emphasis on Spatial rather than temporal interpretations

Embedding Diagrams

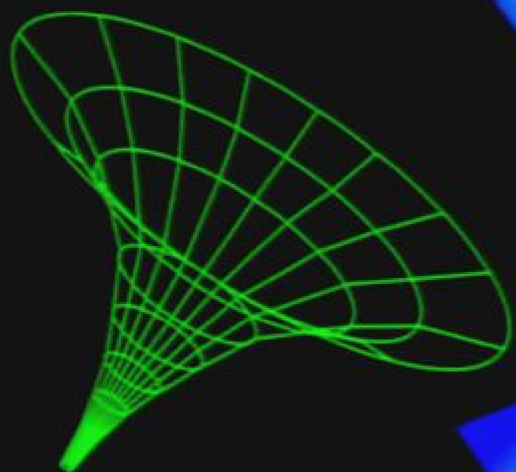


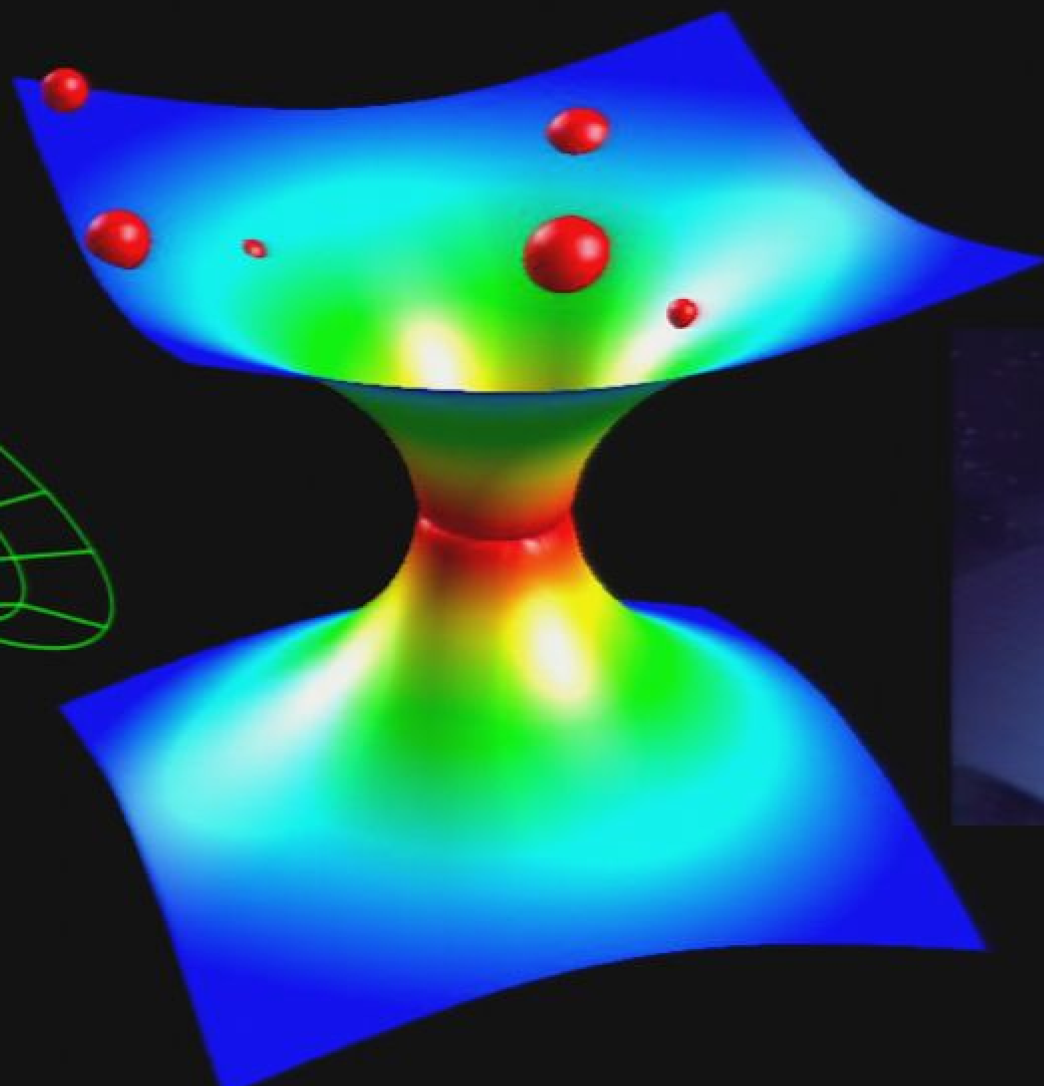


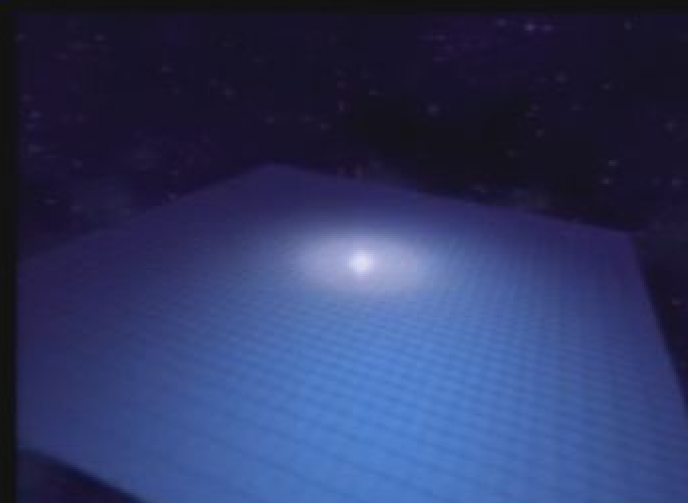


Emphasis on Spatial rather than temporal interpretations

Embedding Diagrams

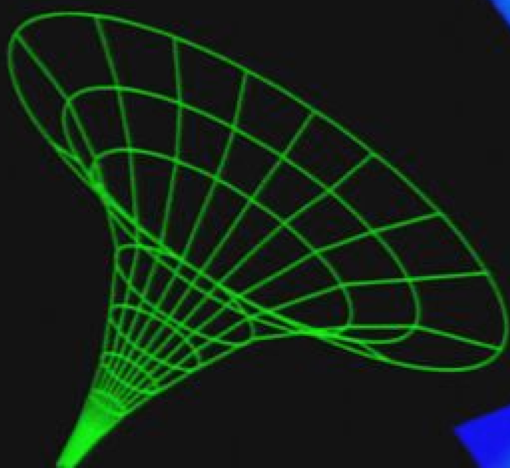


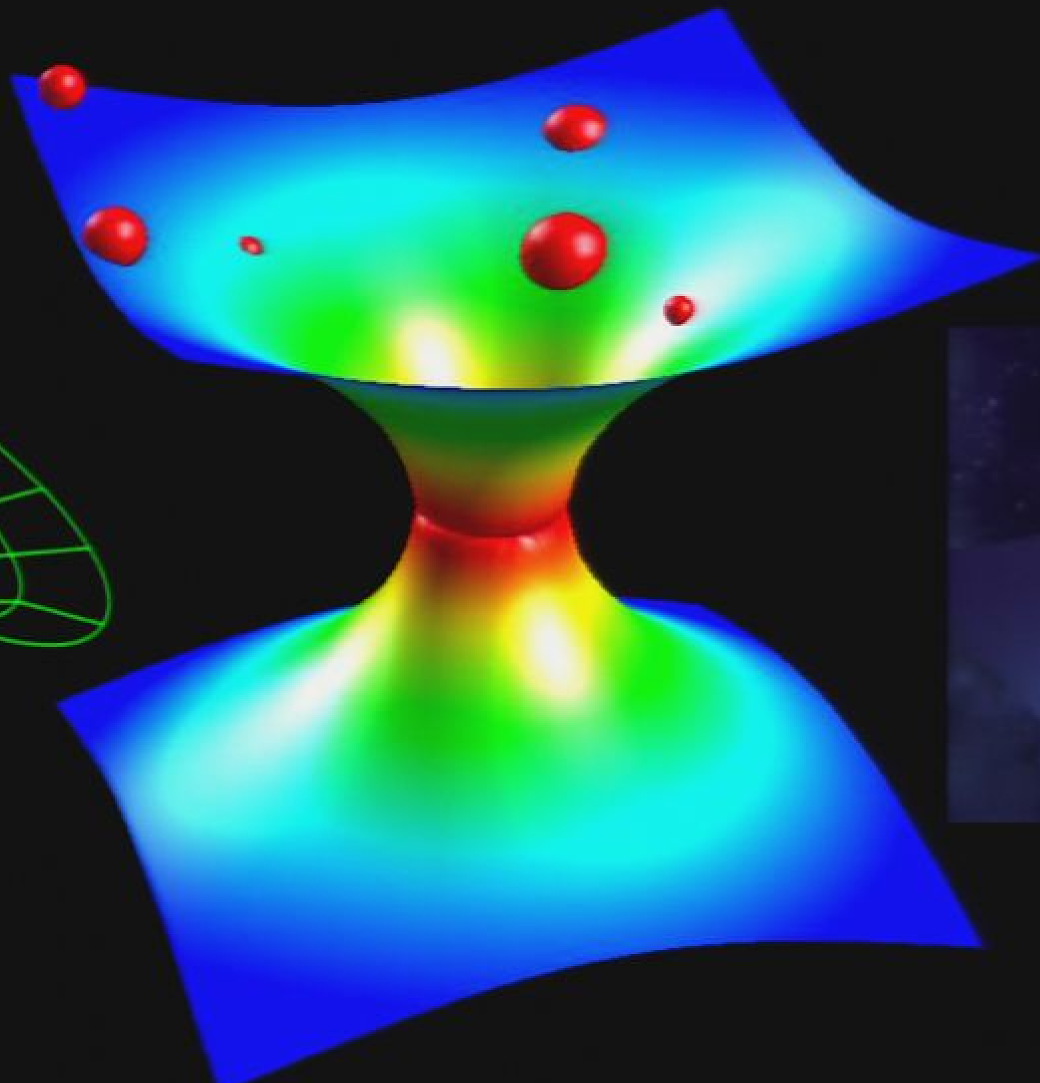


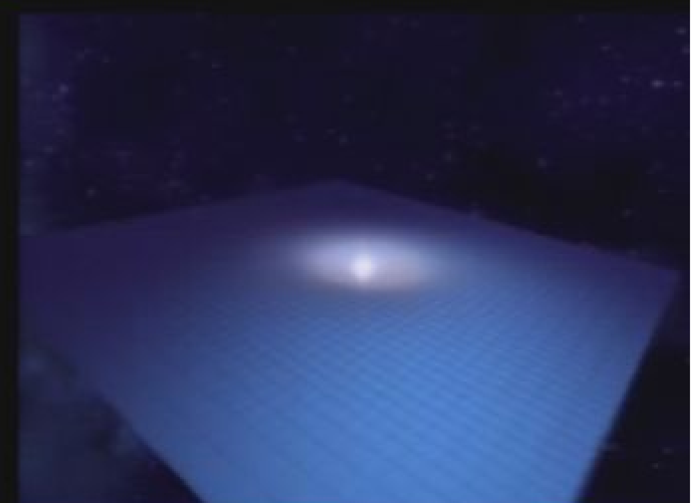


Emphasis on Spatial rather than temporal interpretations

Embedding Diagrams

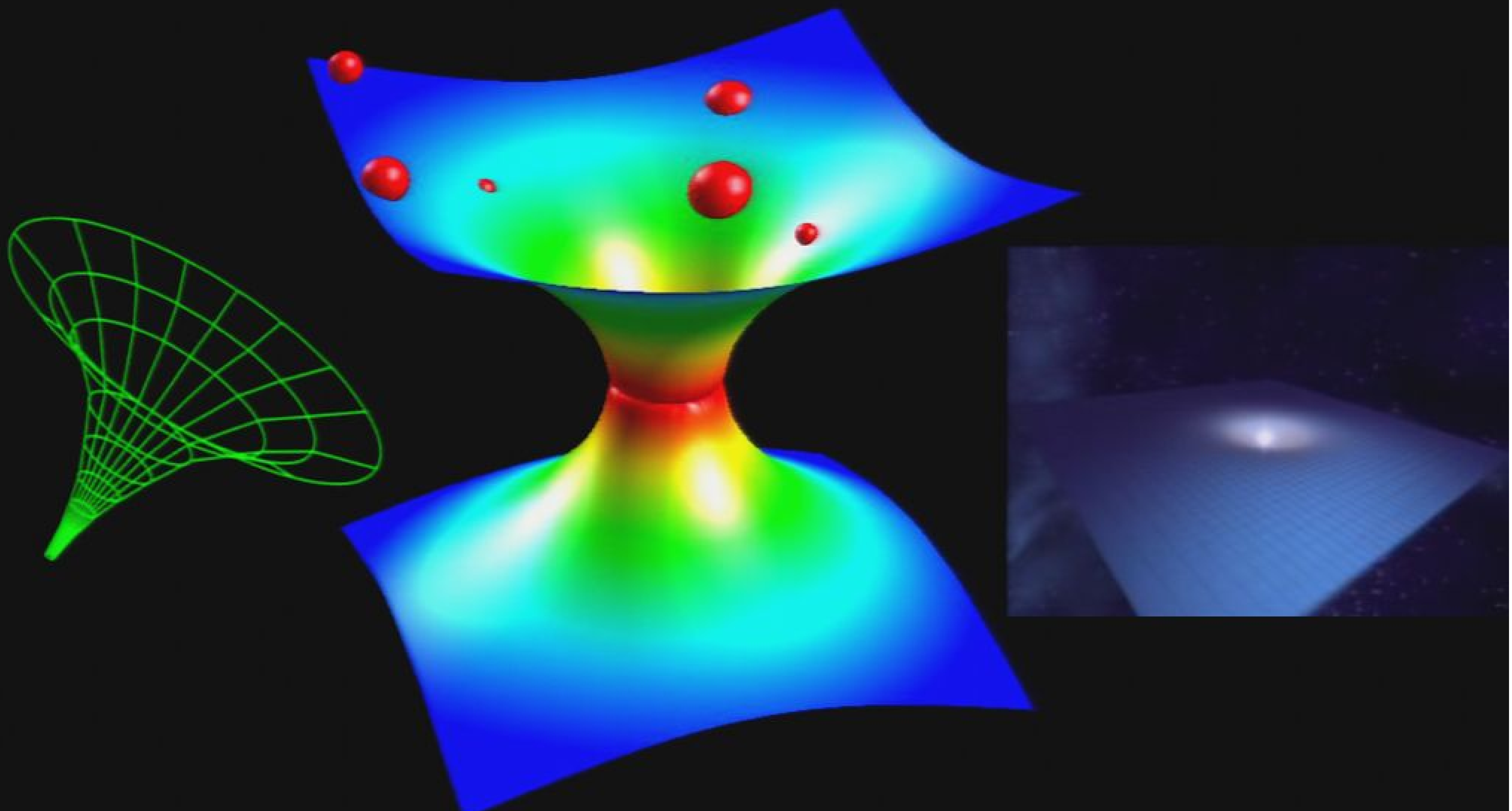






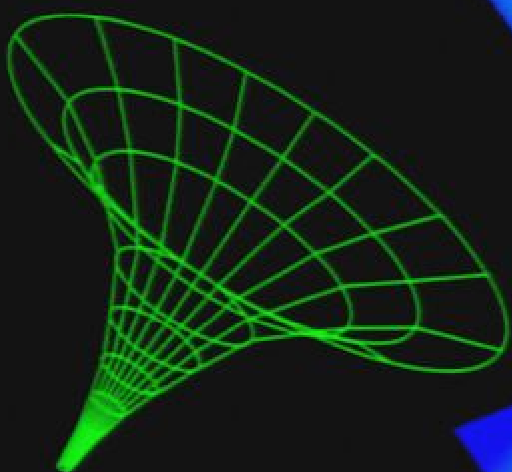
Emphasis on Spatial rather than temporal interpretations

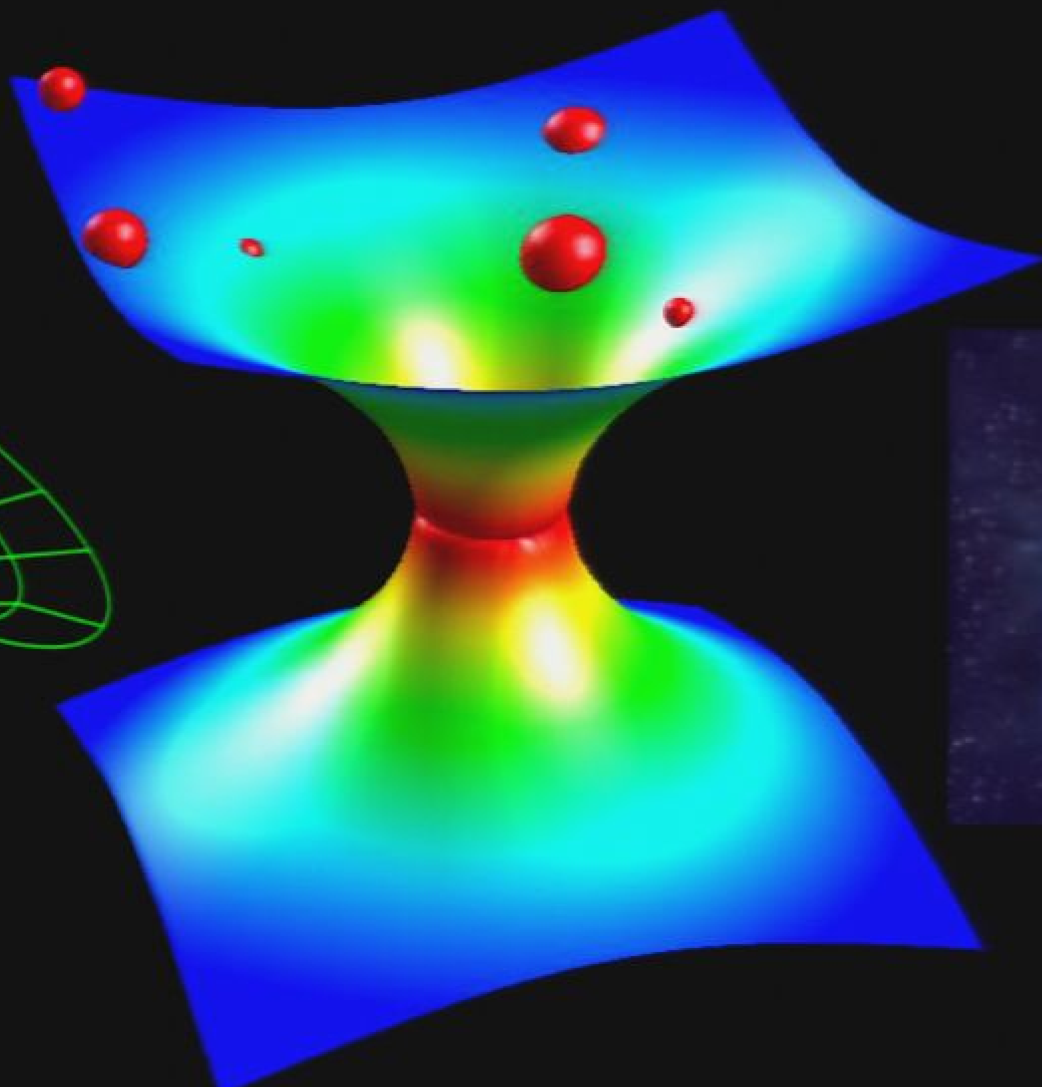
Embedding Diagrams



Emphasis on Spatial rather than temporal interpretations

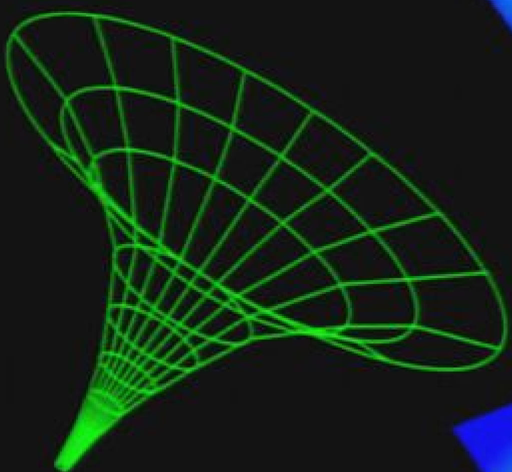
Embedding Diagrams

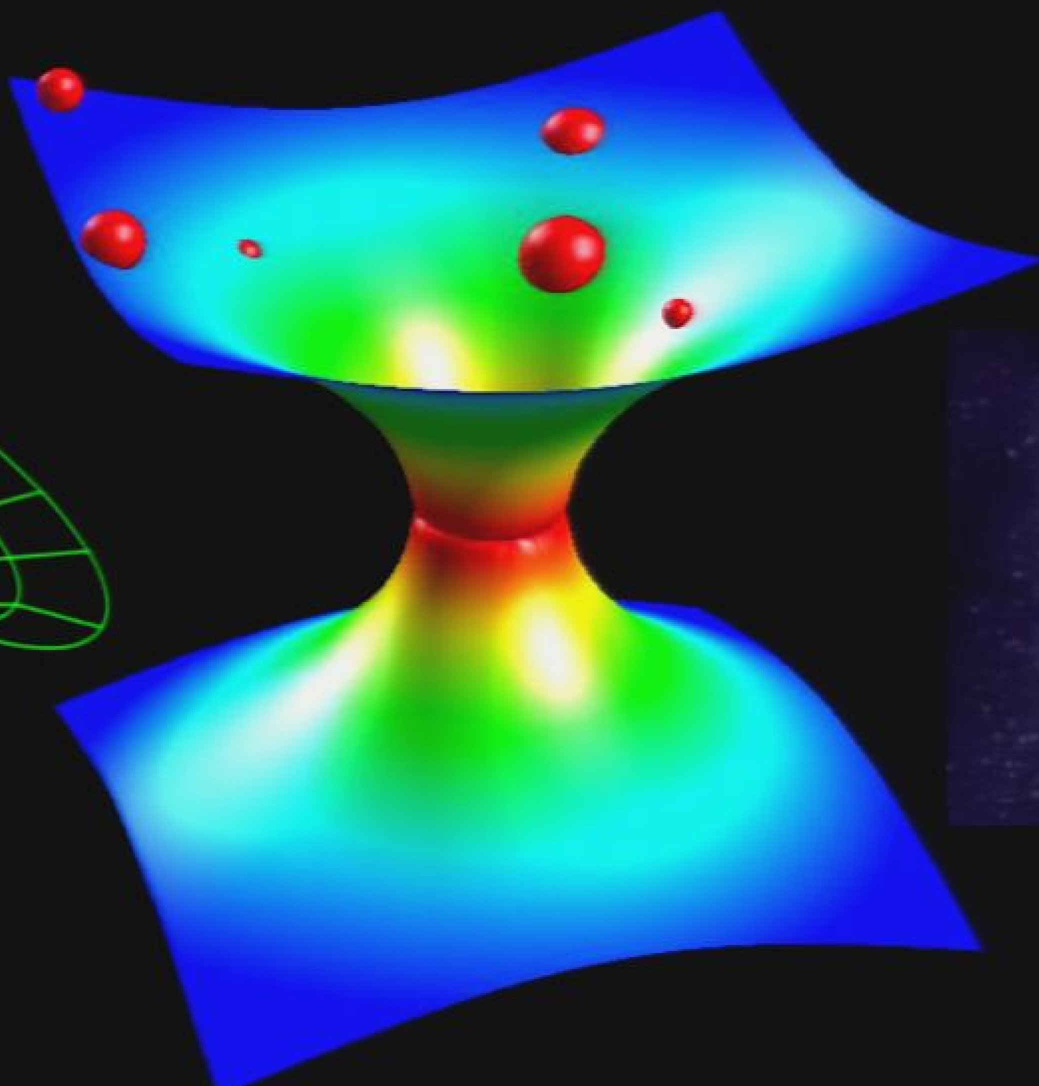




Emphasis on Spatial rather than temporal interpretations

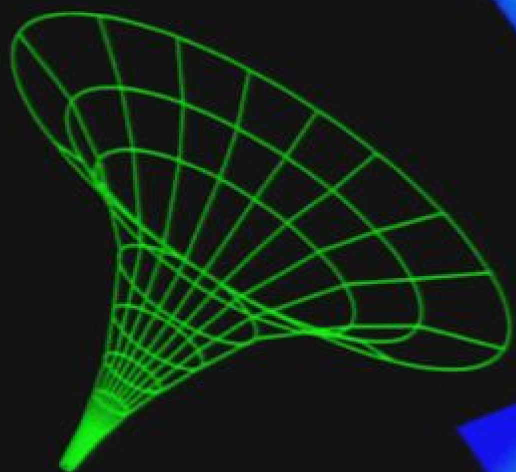
Embedding Diagrams

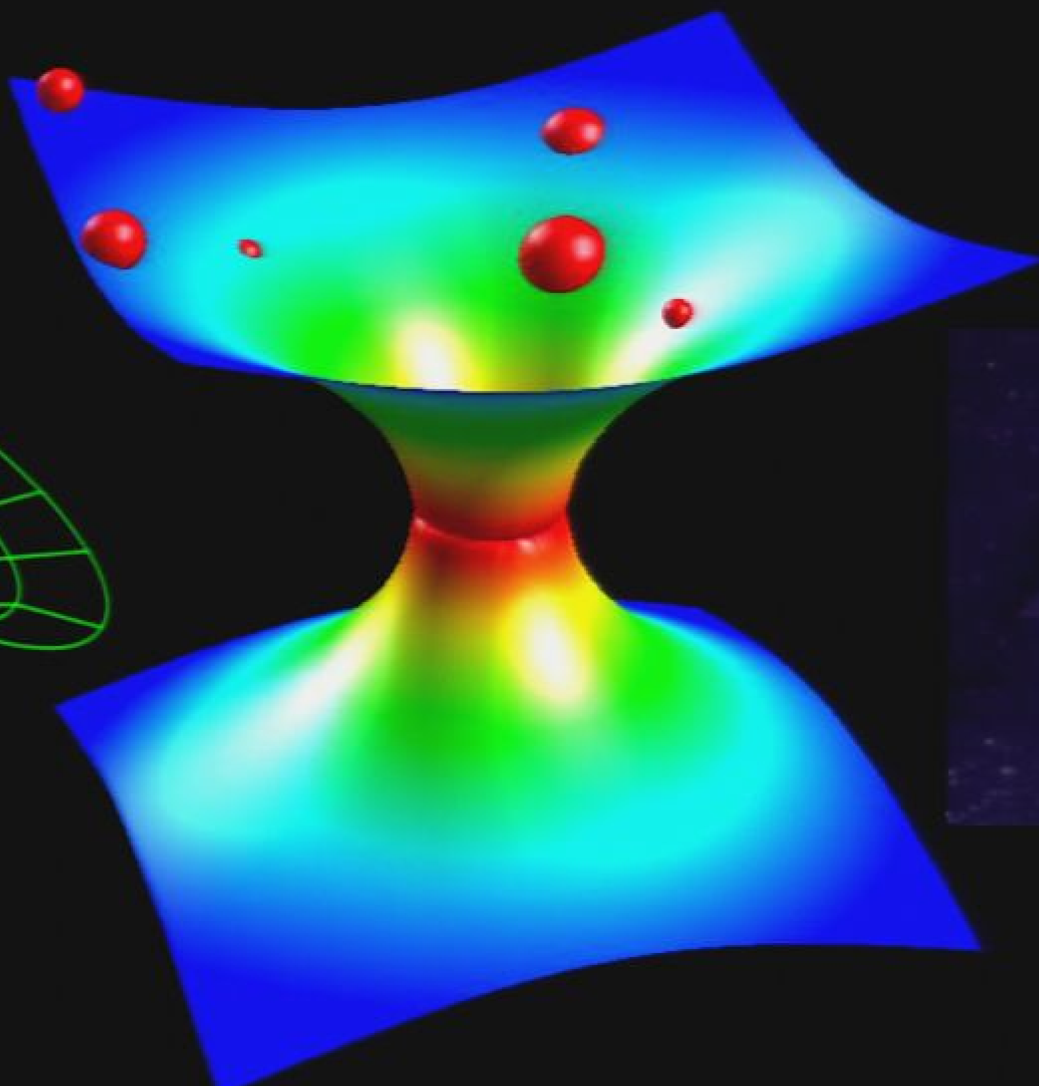




Emphasis on Spatial rather than temporal interpretations

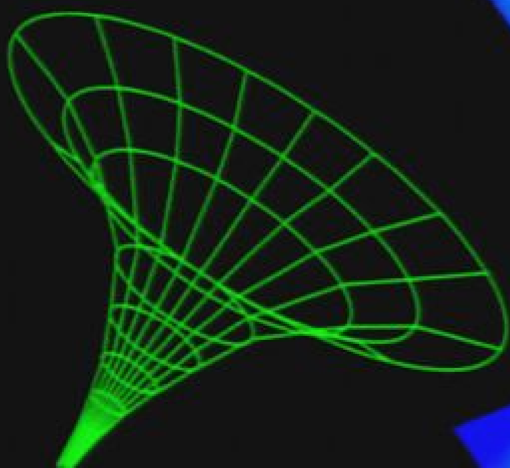
Embedding Diagrams

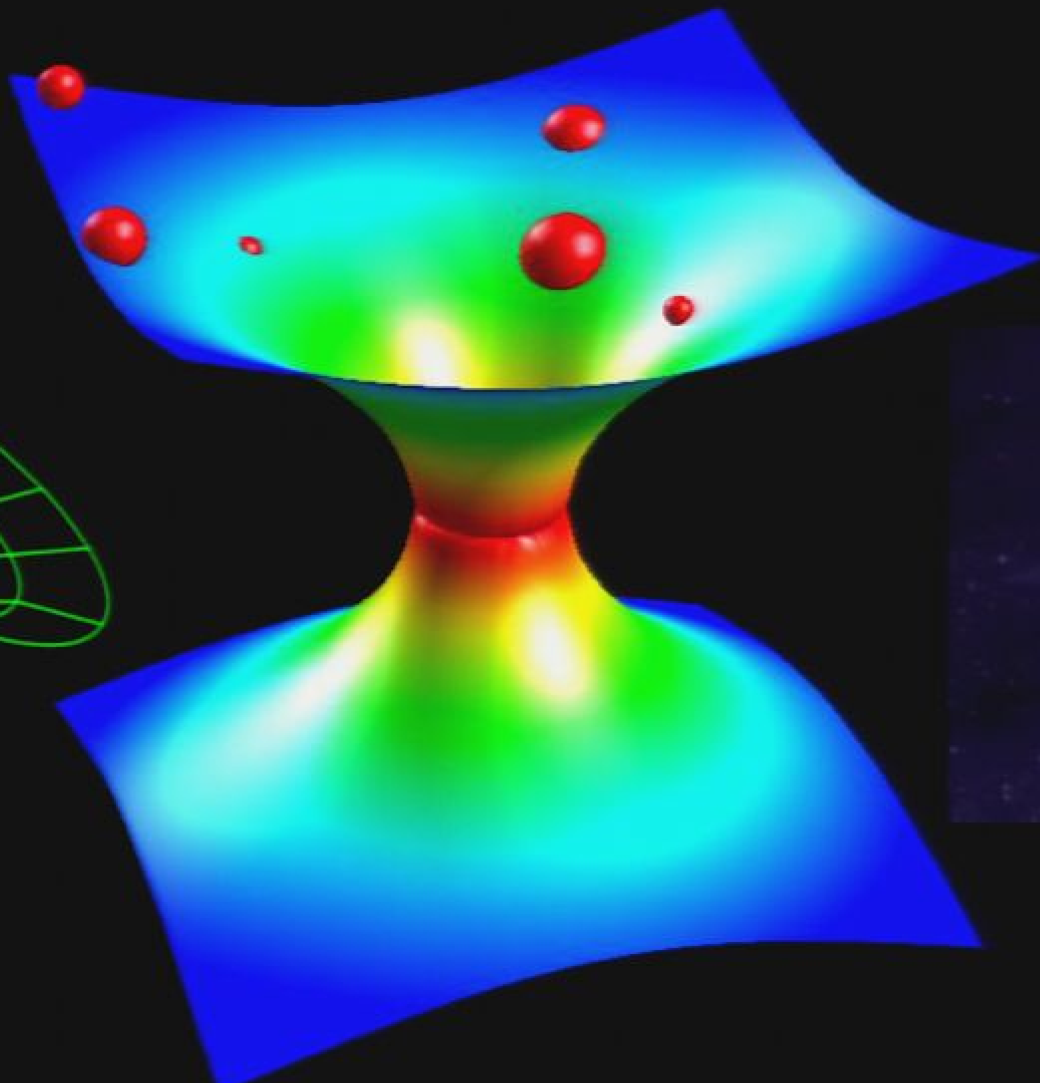




Emphasis on Spatial rather than temporal interpretations

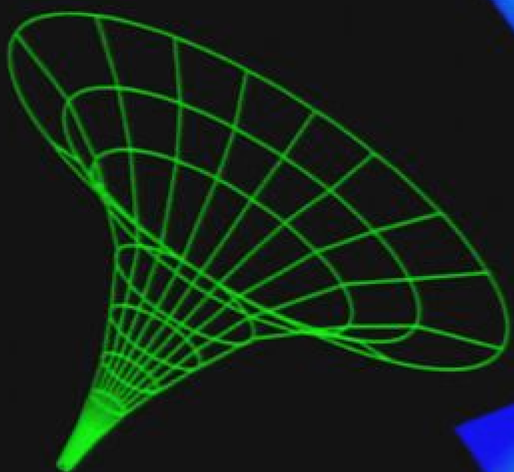
Embedding Diagrams

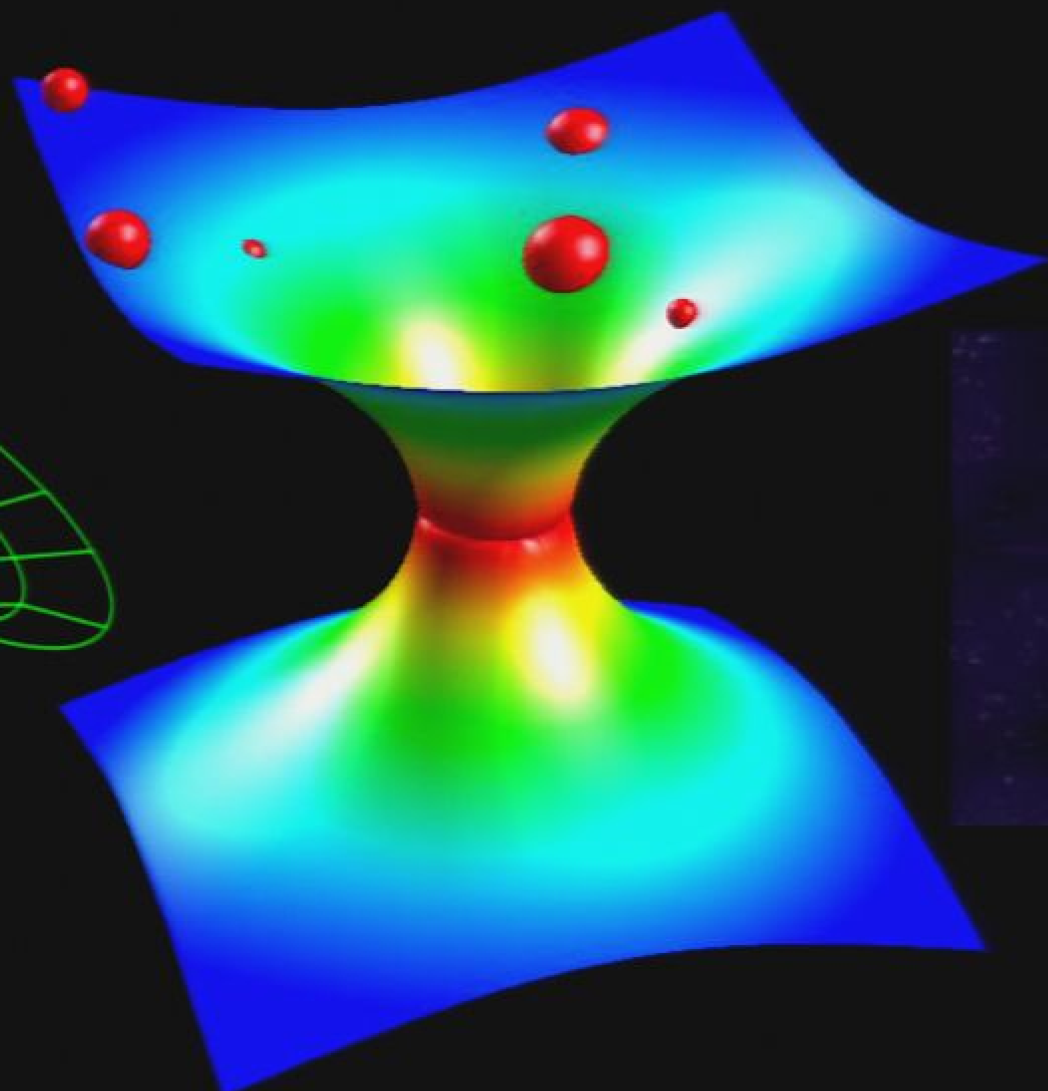




Emphasis on Spatial rather than temporal interpretations

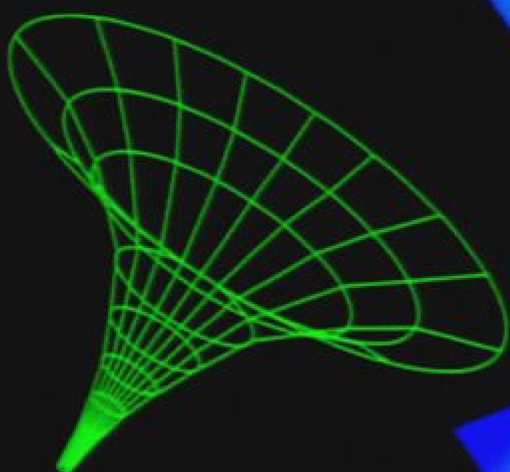
Embedding Diagrams

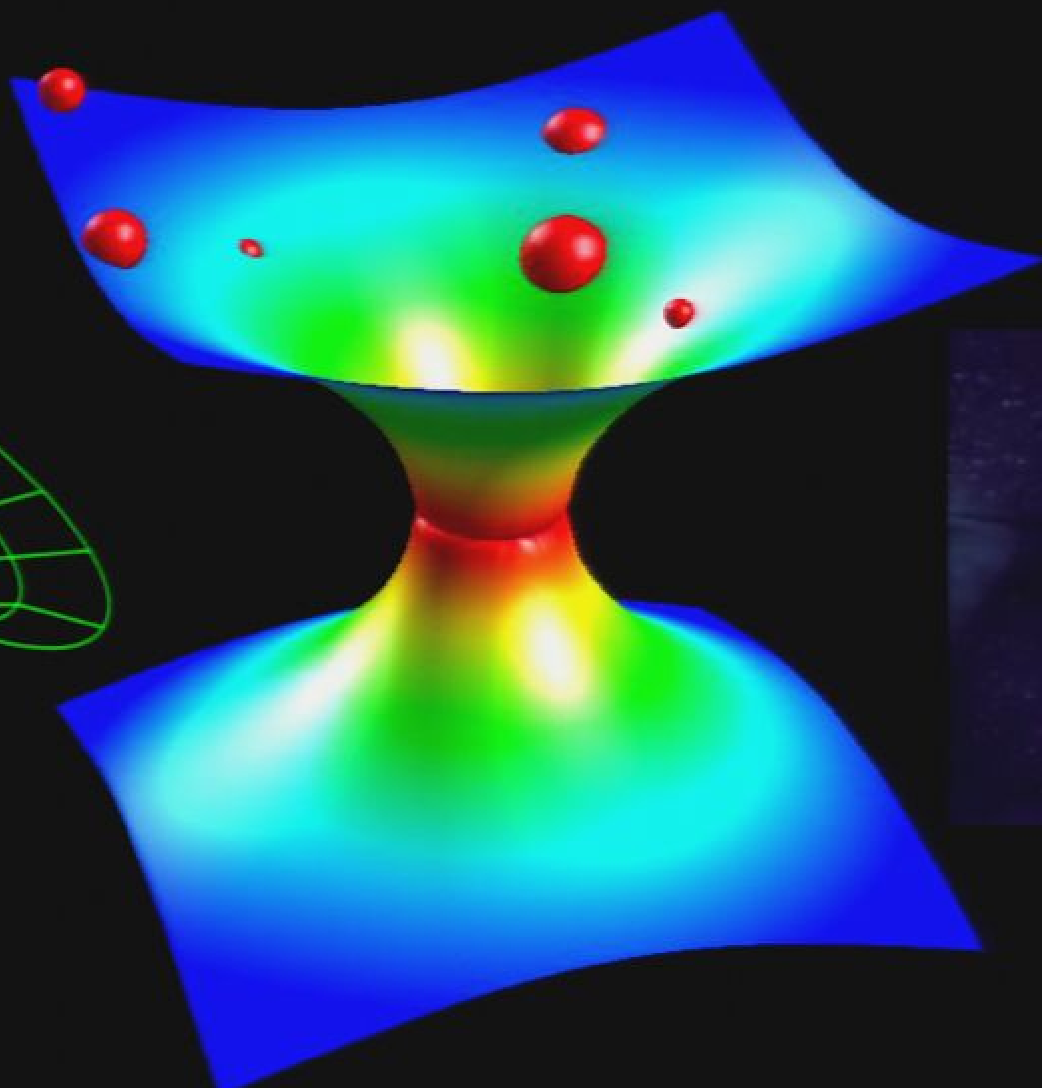




Emphasis on Spatial rather than temporal interpretations

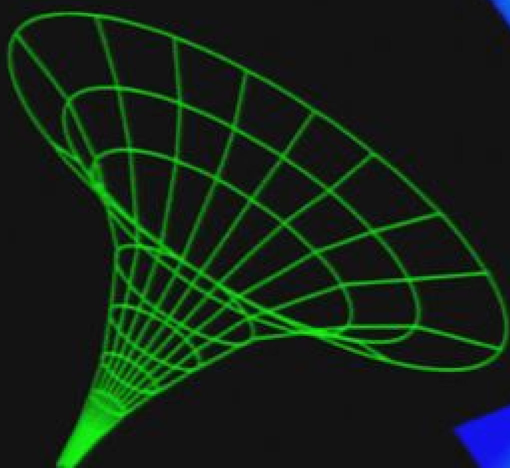
Embedding Diagrams

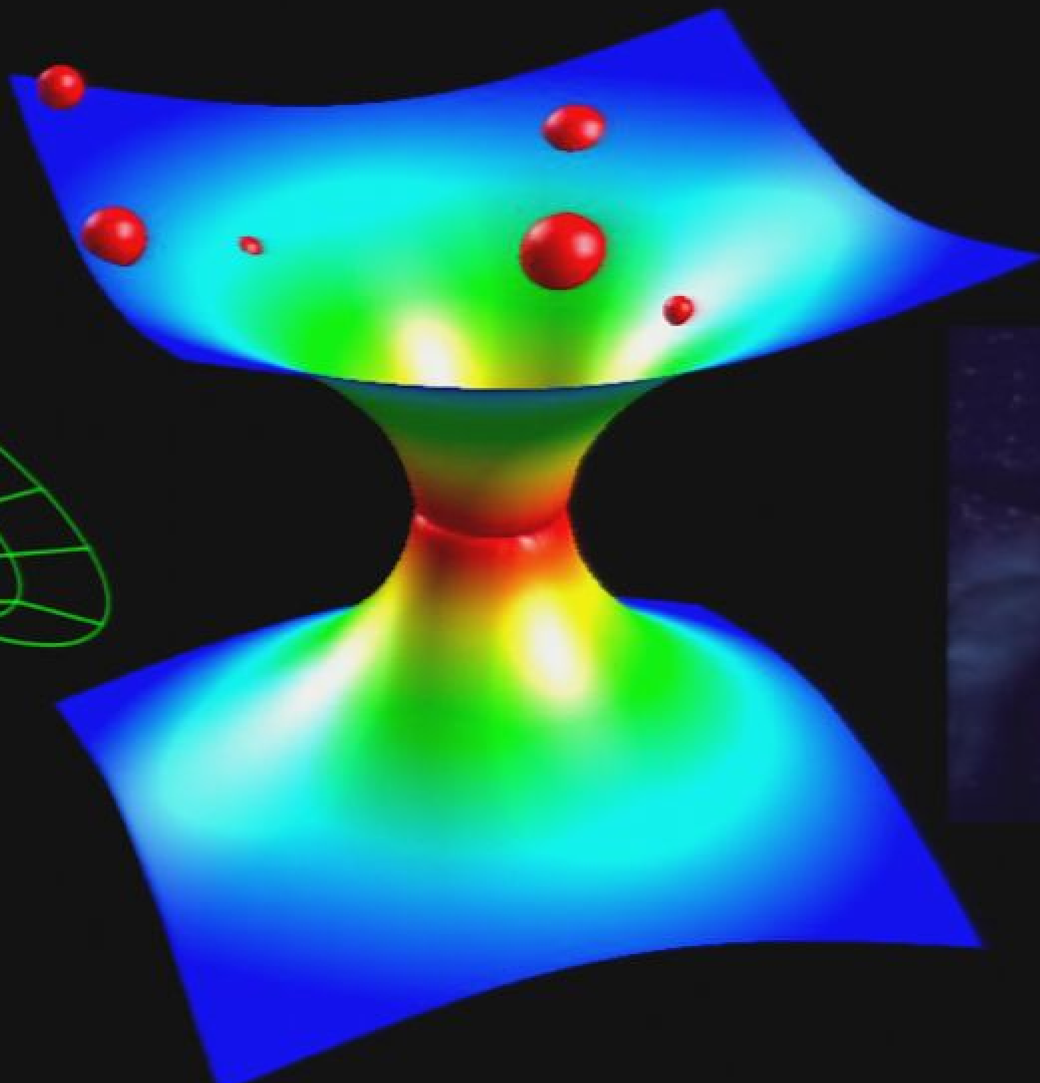




Emphasis on Spatial rather than temporal interpretations

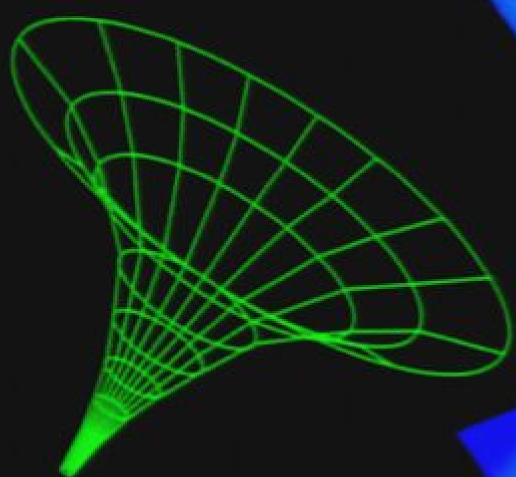
Embedding Diagrams

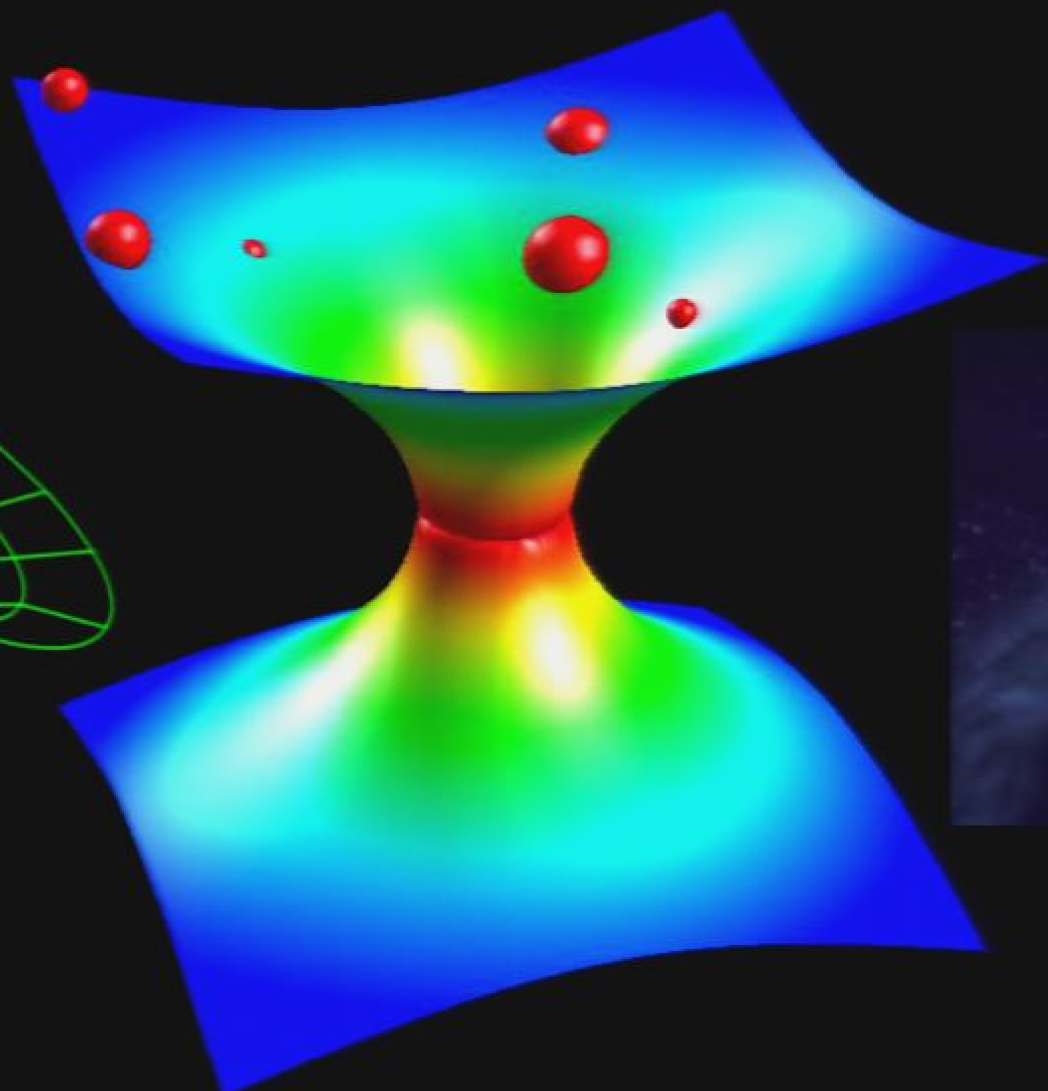




Emphasis on Spatial rather than temporal interpretations

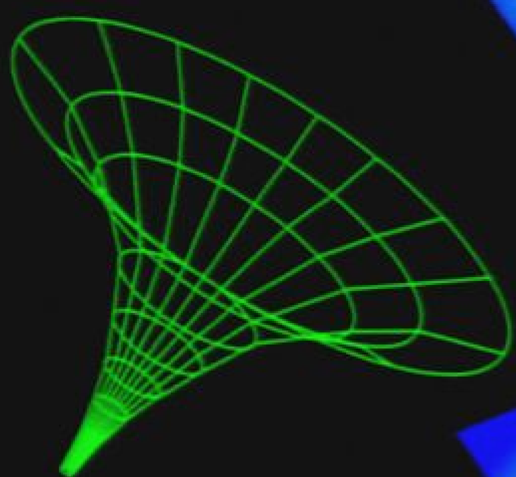
Embedding Diagrams

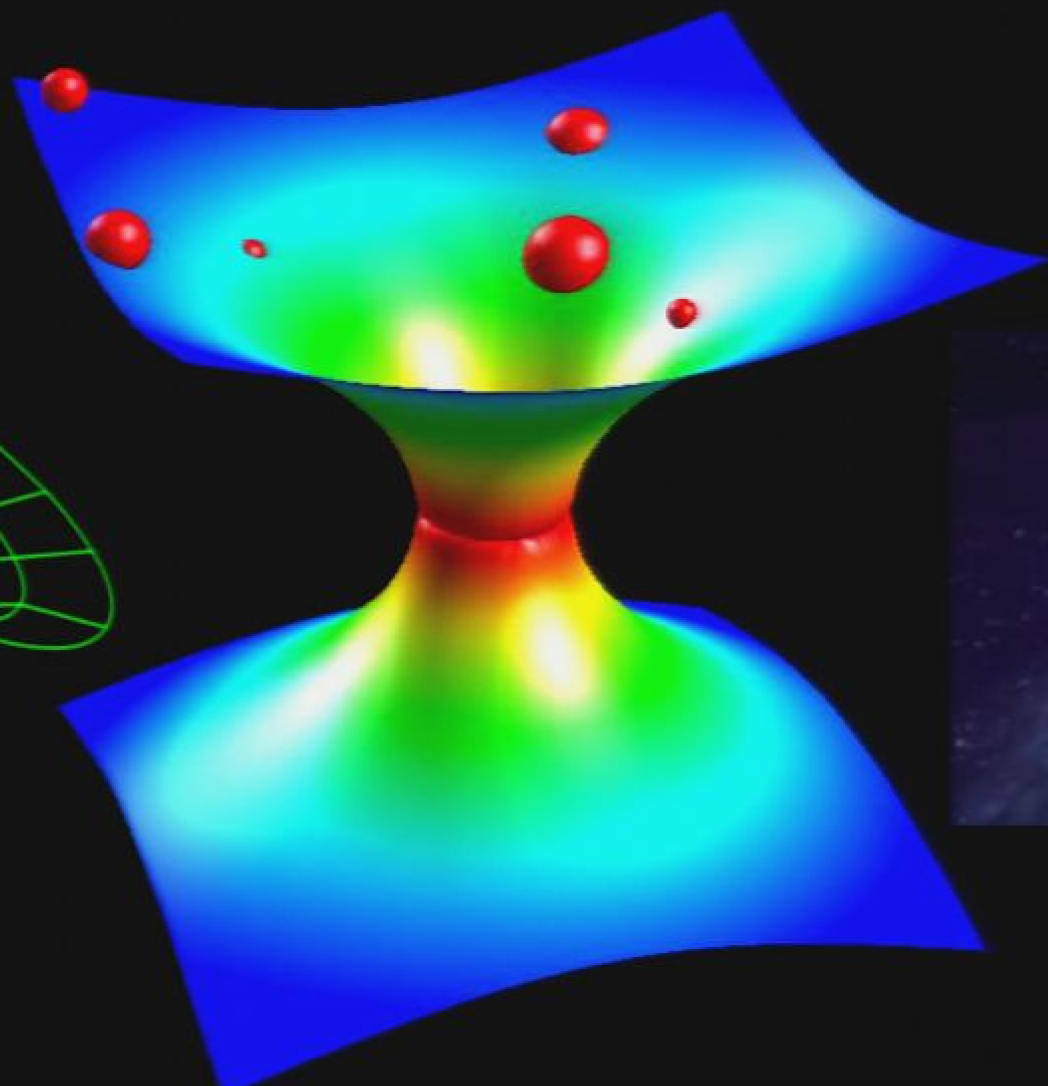




Emphasis on Spatial rather than temporal interpretations

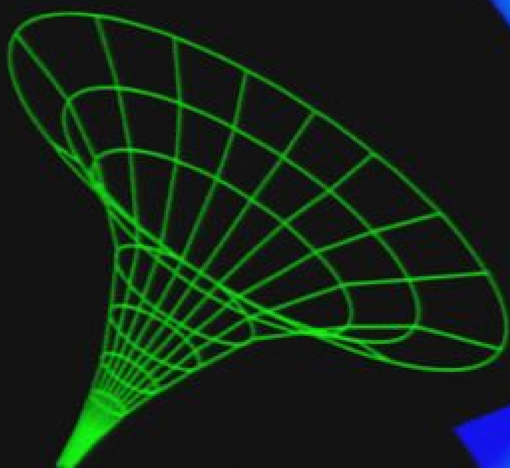
Embedding Diagrams

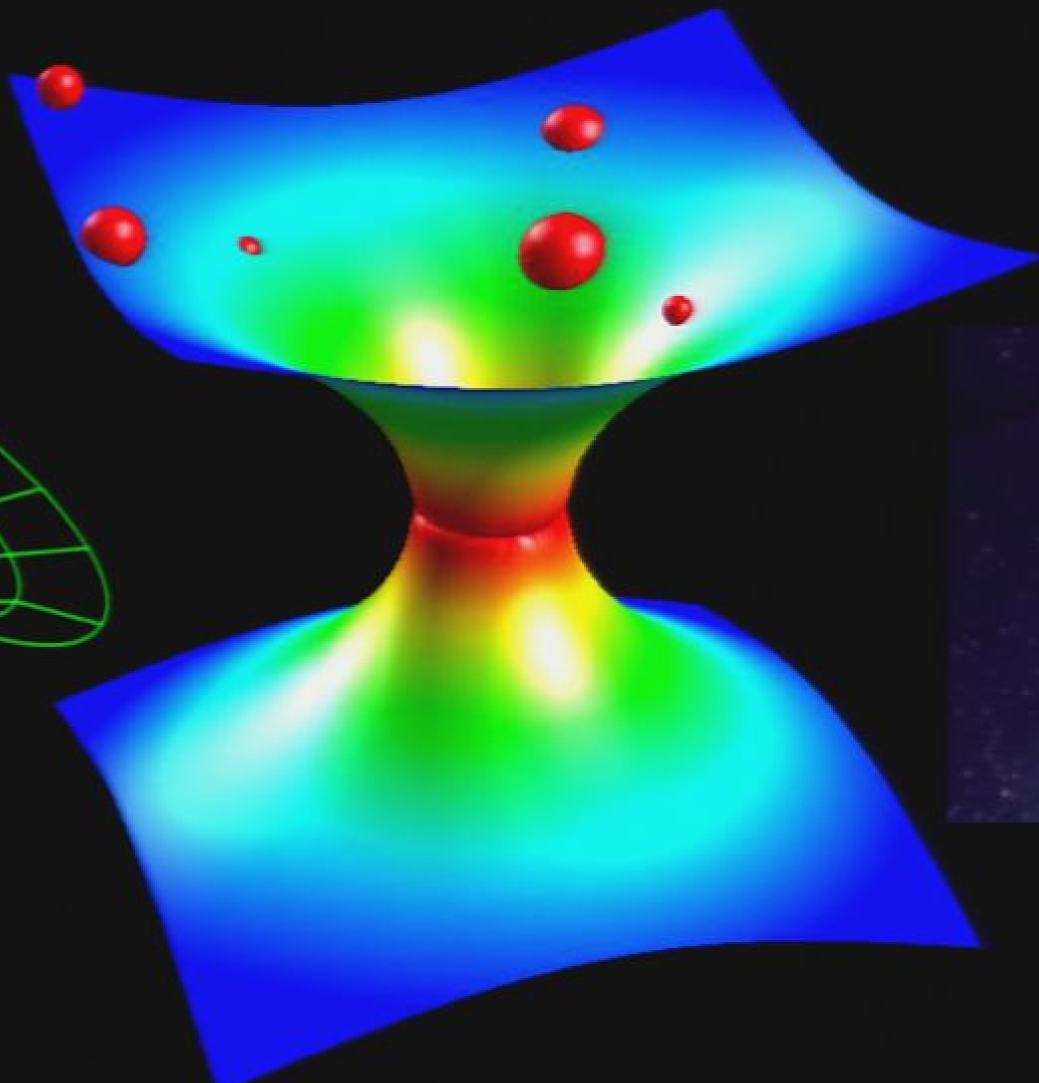




Emphasis on Spatial rather than temporal interpretations

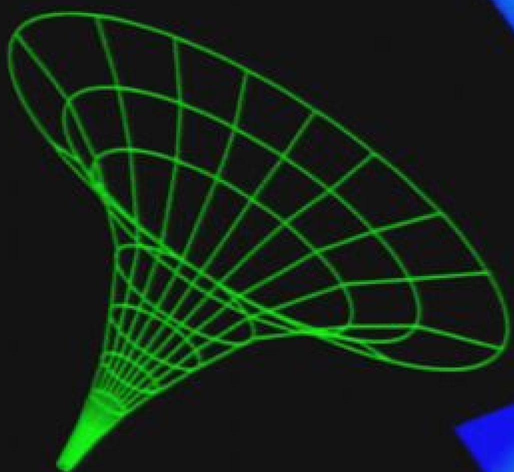
Embedding Diagrams

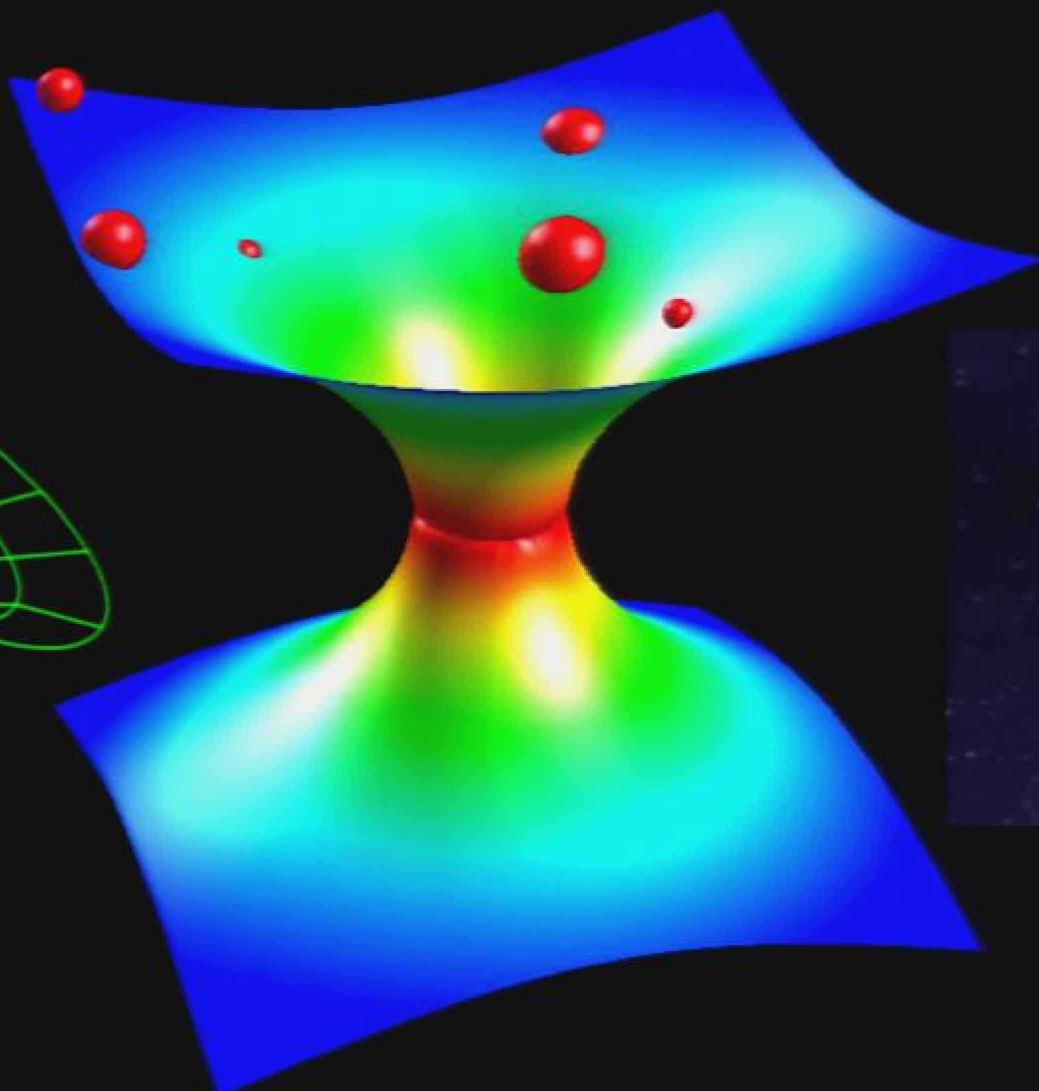




Emphasis on Spatial rather than temporal interpretations

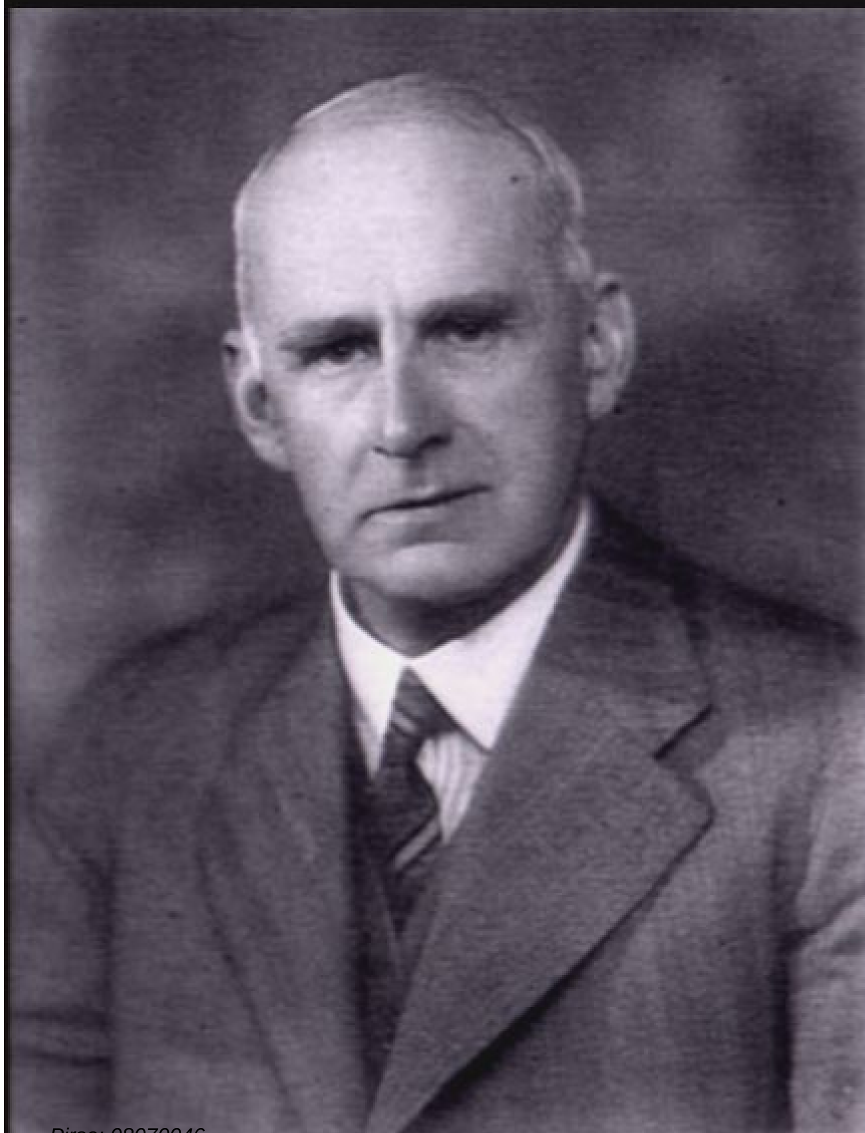
Embedding Diagrams





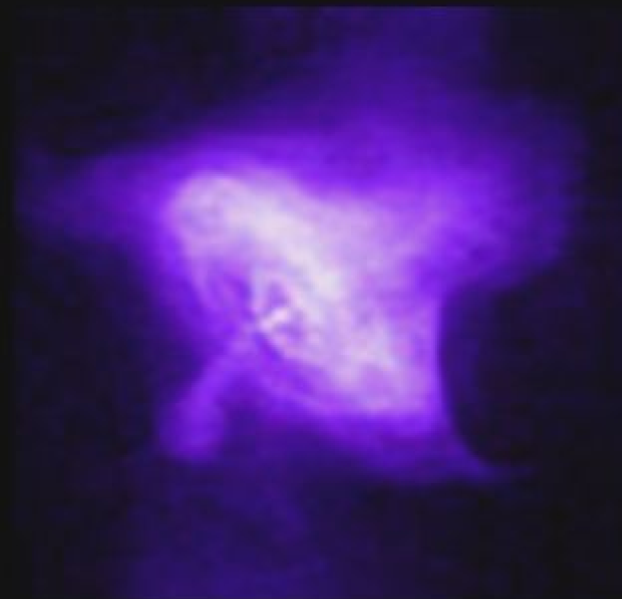
Emphasis on Spatial rather than temporal interpretations

Sir Arthur Eddington



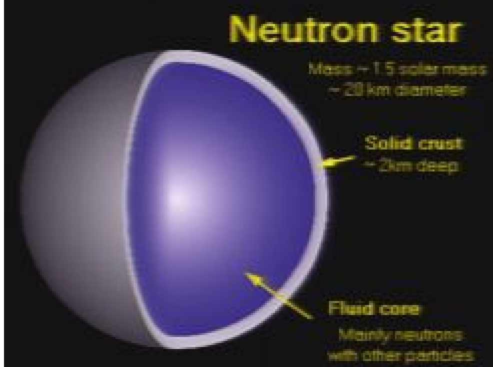
- 1926 Book – The internal constitution of the Stars
- Early proponent of Einstein's Theory of General Relativity (next to Einstein best expert on General Relativity)
- Poses the mystery of white dwarfs and attacks the reality of black holes predicted by Schwarzschild.
- Believed White Dwarf was last state in a stars life (rock Star)
- Paradox with White Dwarf

Subrahmanyan Chandrasekhar

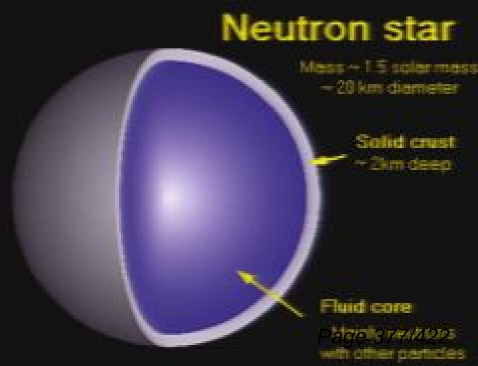


- *Idolized Eddington, resolved Eddington;s paradox*
- *In 1930 he showed that there is a maximum mass for White Dwarfs*
- *1935 Eddington attacks his work. "Chandra" left the field of Blackholes until 1970's*
- *Nobel Prize in Physics 1983*

Walter Baade and Fritz Zwicky



- Identifies the process of a supernovae, predicted that this collapse strips the atoms of their electrons, packing the nuclei together as a neutron star.
- Neutron stars would not be verified observably until 1968.
- Identified the galaxies associated with cosmic radio sources.
- Still something was missing that took a star from fusion to supernovae.

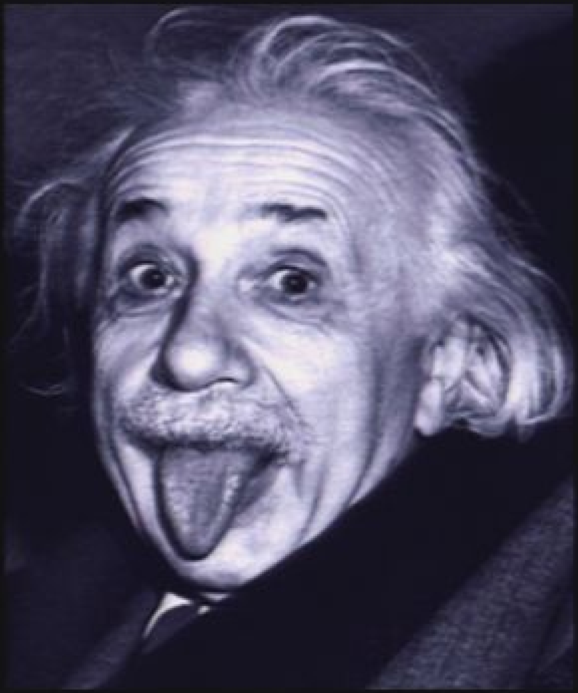


Robert J. Oppenheimer

- *Showed that there is a maximum mass for a neutron star from 1.5 to about 3 solar masses (1938).*
- *In a highly idealized calculation, showed that an imploding star forms a black hole.*
- *Led the American atomic bomb project.*
- *Which provided the opportunity to experimentally verify and test theories (too expensive for the universities) and the development of the atomic bombs which mimic the power source for the sun to come up with the mathematics and understanding of stellar mechanics*
- *Major battle with Wheeler.*

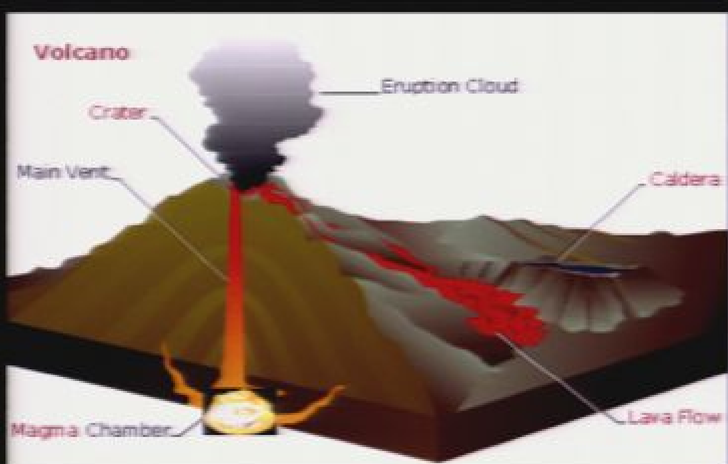
Robert J. Oppenheimer

In 1939 Einstein wrote a paper about his concerns about Oppenheimer's paper and the Schwarzschild radius and states "Schwarzschild singularities do not exist in physical reality". He demonstrated that a collapsing star is unstable when it reaches the Schwarzschild radius, which ended up being mute since that star collapses into a singularity there anyway.



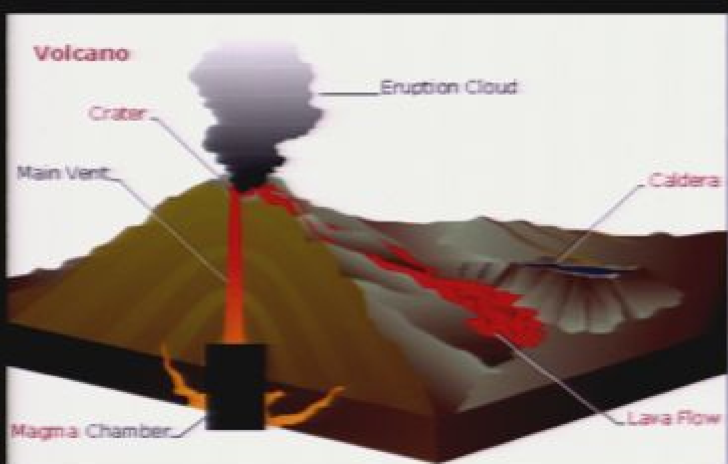
Yakov Zel'dovich

- *Soviet counterpart to Oppenheimer.*
- *Developed the theory of nuclear chain reactions. (1939)*
- *Lead theorist on USSR atomic bomb (1945)*
- *Creates black hole research team (1962).*
- *Super massive black holes power Quasars (1960's).*



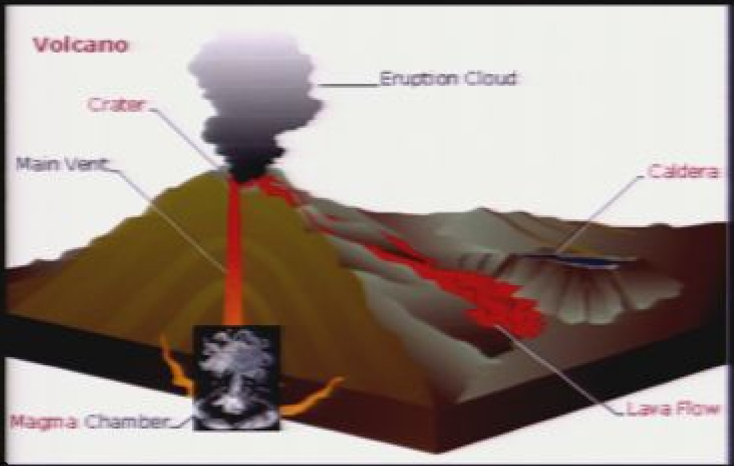
Yakov Zel'dovich

- *Soviet counterpart to Oppenheimer.*
- *Developed the theory of nuclear chain reactions. (1939)*
- *Lead theorist on USSR atomic bomb (1945)*
- *Creates black hole research team (1962).*
- *Super massive black holes power Quasars (1960's).*



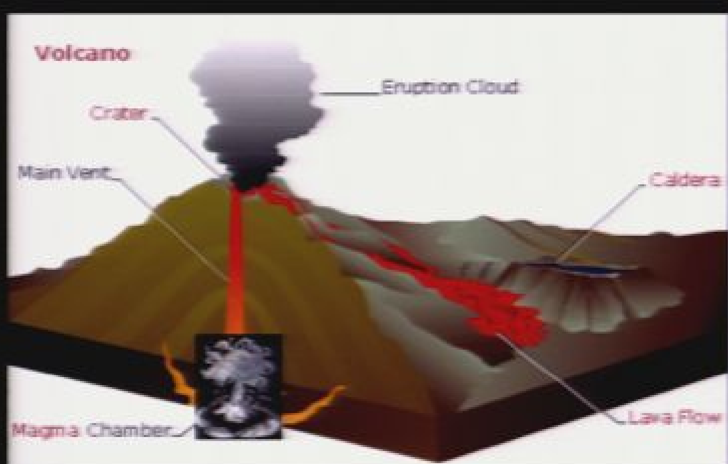
Yakov Zel'dovich

- *Soviet counterpart to Oppenheimer.*
- *Developed the theory of nuclear chain reactions. (1939)*
- *Lead theorist on USSR atomic bomb (1945)*
- *Creates black hole research team (1962).*
- *Super massive black holes power Quasars (1960's).*



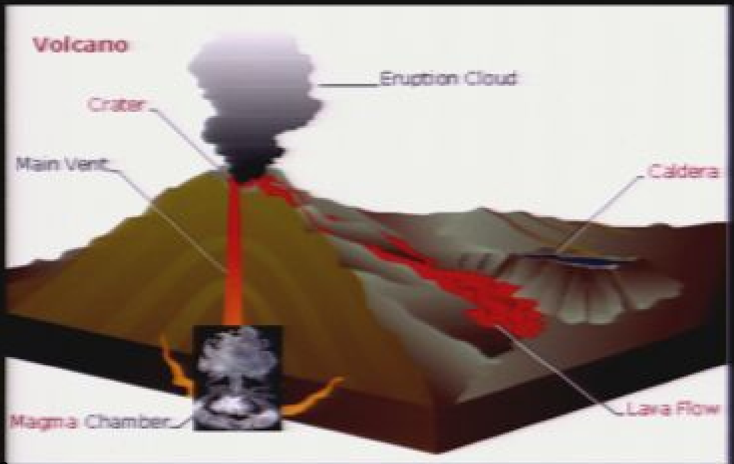
Yakov Zel'dovich

- *Soviet counterpart to Oppenheimer.*
- *Developed the theory of nuclear chain reactions. (1939)*
- *Lead theorist on USSR atomic bomb (1945)*
- *Creates black hole research team (1962).*
- *Super massive black holes power Quasars (1960's).*



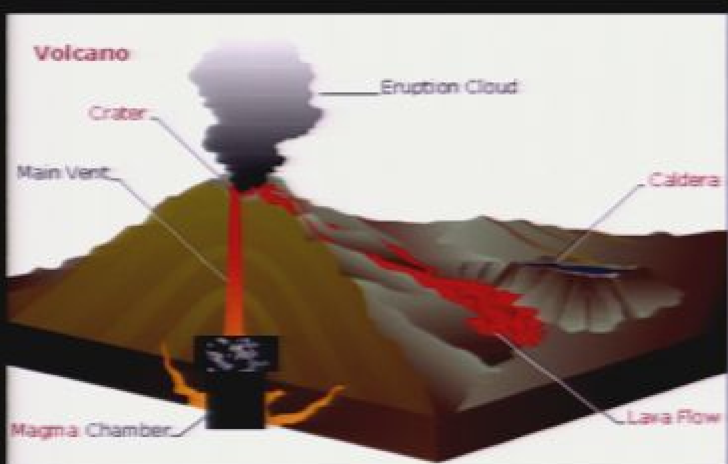
Yakov Zel'dovich

- *Soviet counterpart to Oppenheimer.*
- *Developed the theory of nuclear chain reactions. (1939)*
- *Lead theorist on USSR atomic bomb (1945)*
- *Creates black hole research team (1962).*
- *Super massive black holes power Quasars (1960's).*



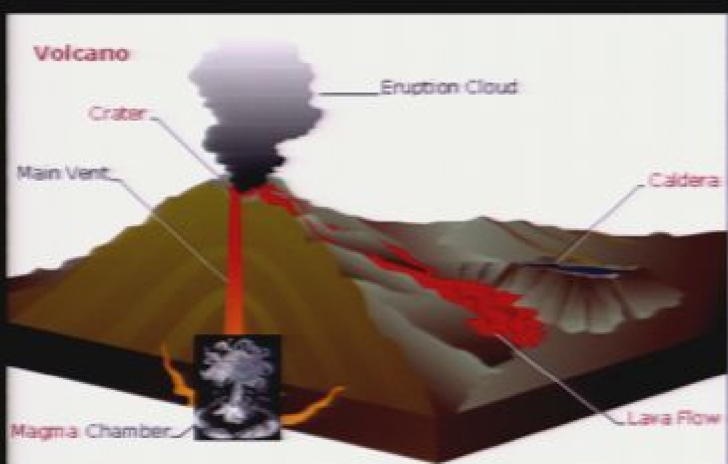
Yakov Zel'dovich

- Soviet counterpart to Oppenheimer.
- Developed the theory of nuclear chain reactions. (1939)
- Lead theorist on USSR atomic bomb (1945)
- Creates black hole research team (1962).
- Super massive black holes power Quasars (1960's).



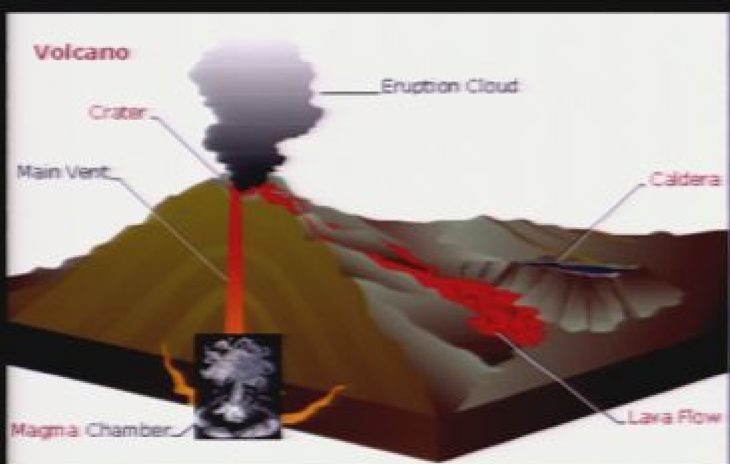
Yakov Zel'dovich

- *Soviet counterpart to Oppenheimer.*
- *Developed the theory of nuclear chain reactions. (1939)*
- *Lead theorist on USSR atomic bomb (1945)*
- *Creates black hole research team (1962).*
- *Super massive black holes power Quasars (1960's).*



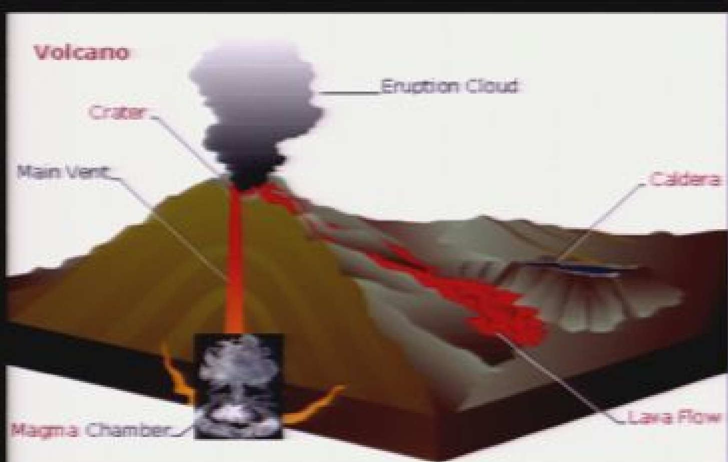
Yakov Zel'dovich

- *Soviet counterpart to Oppenheimer.*
- *Developed the theory of nuclear chain reactions. (1939)*
- *Lead theorist on USSR atomic bomb (1945)*
- *Creates black hole research team (1962).*
- *Super massive black holes power Quasars (1960's).*



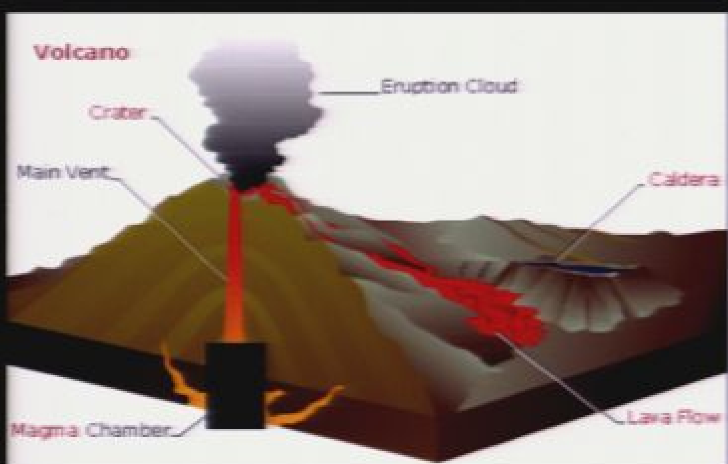
Yakov Zel'dovich

- Soviet counterpart to Oppenheimer.
- Developed the theory of nuclear chain reactions. (1939)
- Lead theorist on USSR atomic bomb (1945)
- Creates black hole research team (1962).
- Super massive black holes power Quasars (1960's).



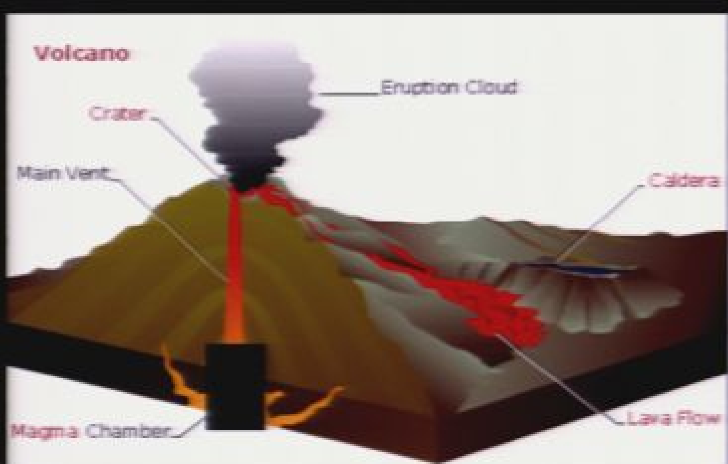
Yakov Zel'dovich

- *Soviet counterpart to Oppenheimer.*
- *Developed the theory of nuclear chain reactions. (1939)*
- *Lead theorist on USSR atomic bomb (1945)*
- *Creates black hole research team (1962).*
- *Super massive black holes power Quasars (1960's).*



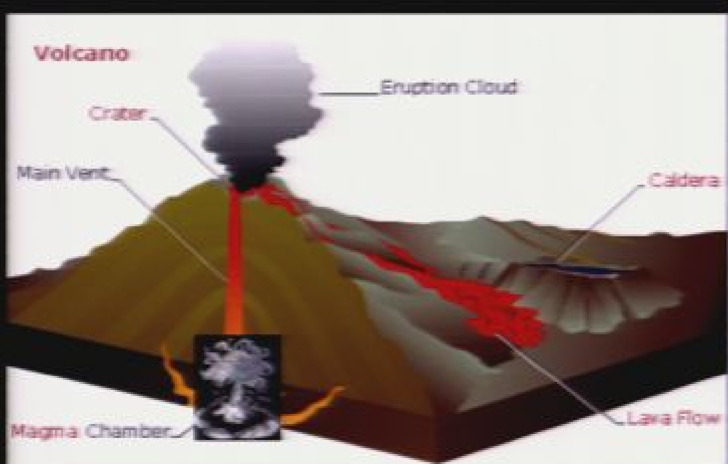
Yakov Zel'dovich

- *Soviet counterpart to Oppenheimer.*
- *Developed the theory of nuclear chain reactions. (1939)*
- *Lead theorist on USSR atomic bomb (1945)*
- *Creates black hole research team (1962).*
- *Super massive black holes power Quasars (1960's).*



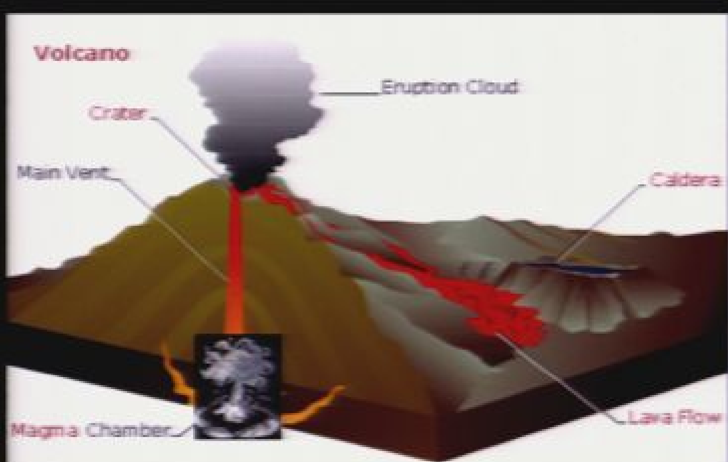
Yakov Zel'dovich

- *Soviet counterpart to Oppenheimer.*
- *Developed the theory of nuclear chain reactions. (1939)*
- *Lead theorist on USSR atomic bomb (1945)*
- *Creates black hole research team (1962).*
- *Super massive black holes power Quasars (1960's).*



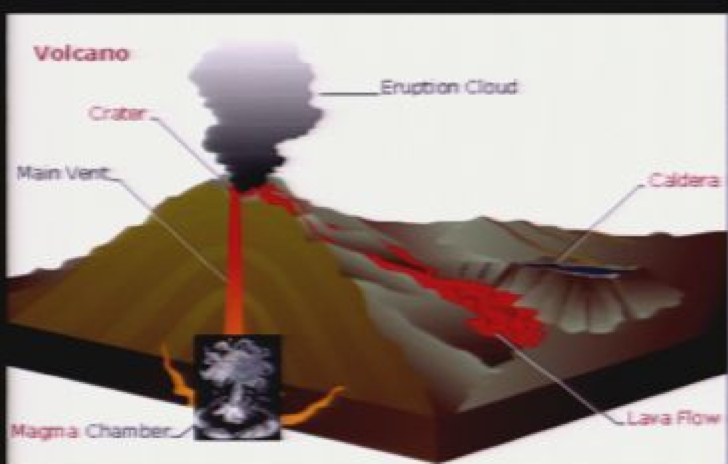
Yakov Zel'dovich

- *Soviet counterpart to Oppenheimer.*
- *Developed the theory of nuclear chain reactions. (1939)*
- *Lead theorist on USSR atomic bomb (1945)*
- *Creates black hole research team (1962).*
- *Super massive black holes power Quasars (1960's).*



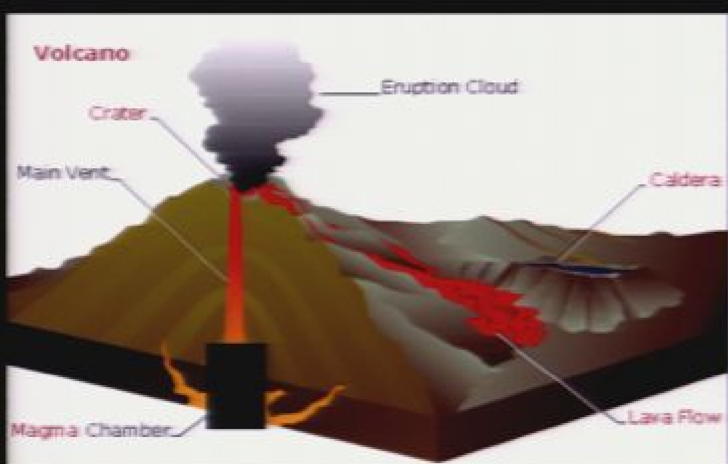
Yakov Zel'dovich

- *Soviet counterpart to Oppenheimer.*
- *Developed the theory of nuclear chain reactions. (1939)*
- *Lead theorist on USSR atomic bomb (1945)*
- *Creates black hole research team (1962).*
- *Super massive black holes power Quasars (1960's).*



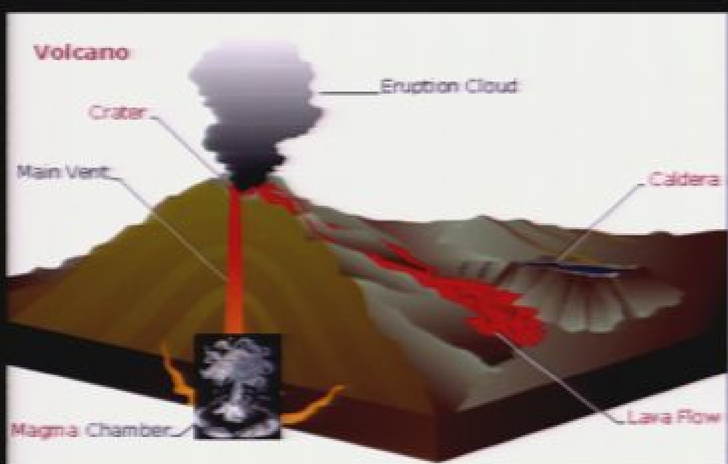
Yakov Zel'dovich

- *Soviet counterpart to Oppenheimer.*
- *Developed the theory of nuclear chain reactions. (1939)*
- *Lead theorist on USSR atomic bomb (1945)*
- *Creates black hole research team (1962).*
- *Super massive black holes power Quasars (1960's).*



Yakov Zel'dovich

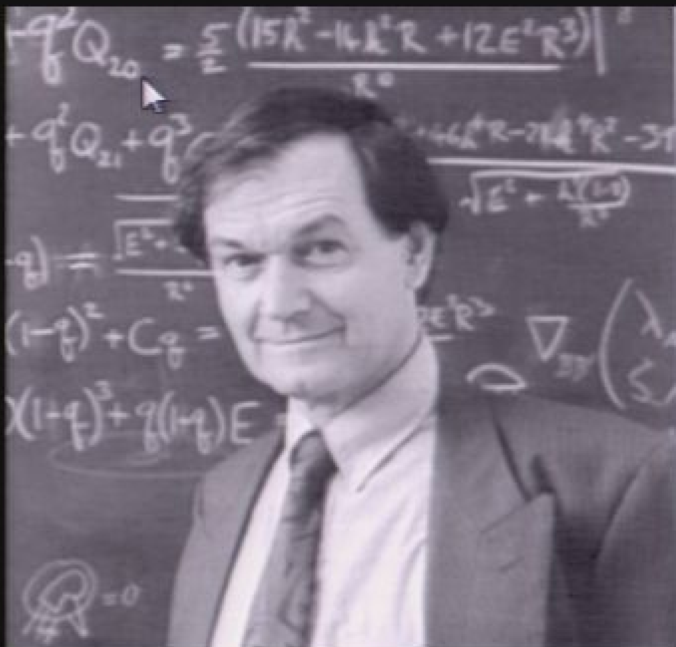
- *Soviet counterpart to Oppenheimer.*
- *Developed the theory of nuclear chain reactions. (1939)*
- *Lead theorist on USSR atomic bomb (1945)*
- *Creates black hole research team (1962).*
- *Super massive black holes power Quasars (1960's).*



John Wheeler

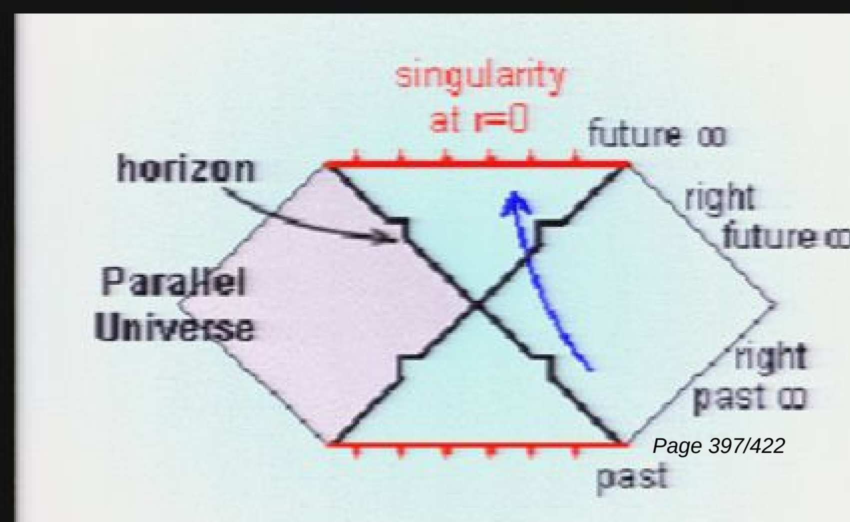
- With Bohr develops the theory of nuclear fission.
- Completes a catalog cold, dead stars firming up evidence of destiny of dead stars. (1957)
- Major battle with Oppenheimer about existence of black holes. (1957)
- Retracted argument and became the leading proponent of black hole. (1960)
- Coined the phrase "Black Hole".
- Coined the phrase "a Black Hole has no hair" (1968).

Roger Penrose

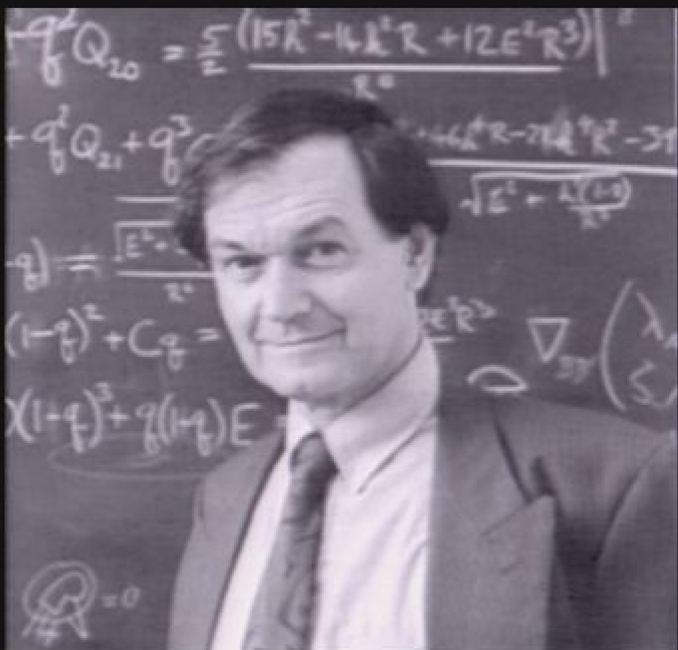


- Speculated black holes loose their hair by radiating it away.
- Discovered that spinning black holes store energy in space outside their horizon (1969).
- Discovered surface area of black holes must increase.
- Proved that black holes must have singularities at their core (1964).
- Proposed cosmic censorship conjecture (1969).

Topology

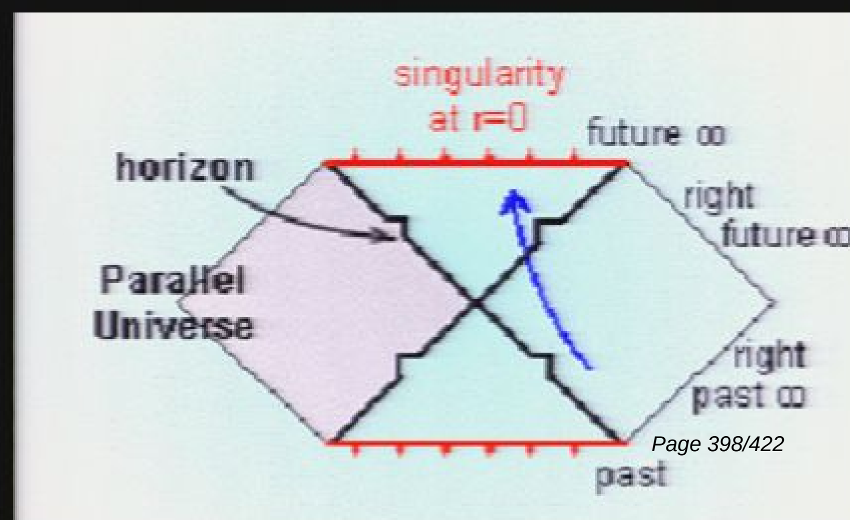


Roger Penrose

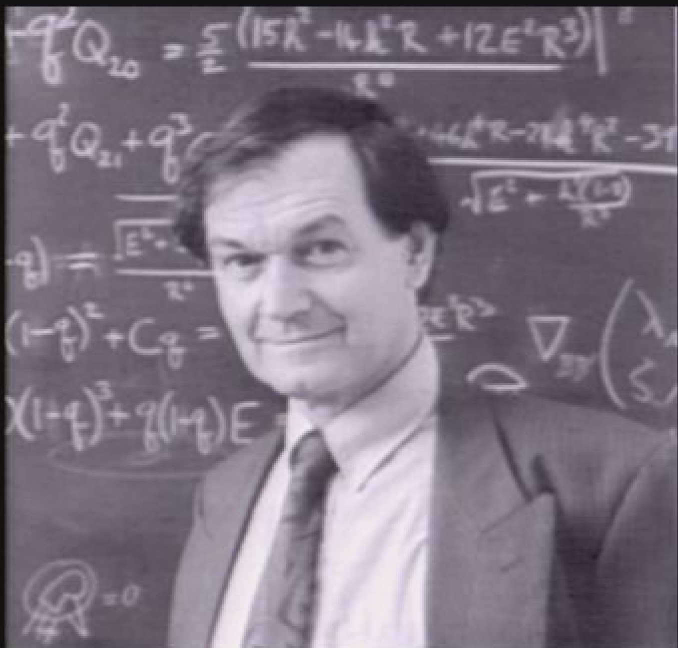


- Speculated black holes loose their hair by radiating it away.
- Discovered that spinning black holes store energy in space outside their horizon (1969).
- Discovered surface area of black holes must increase.
- Proved that black holes must have singularities at their core (1964).
- Proposed cosmic censorship conjecture (1969).

Topology

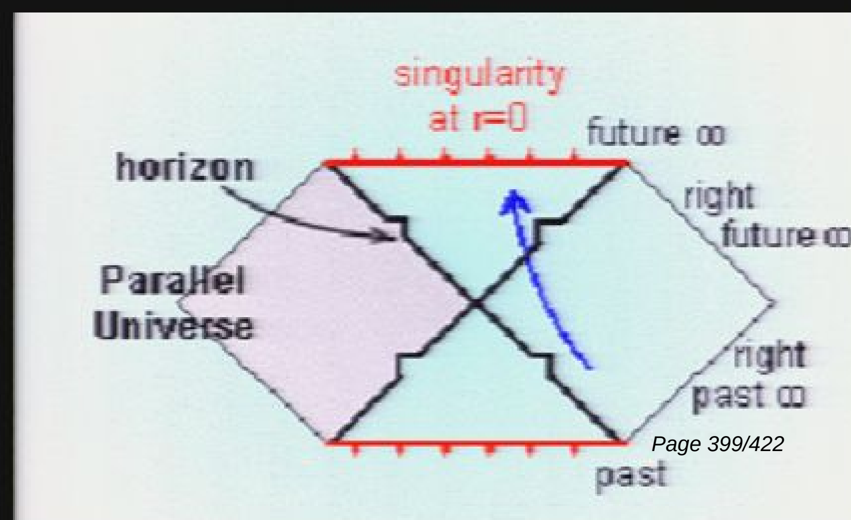


Roger Penrose

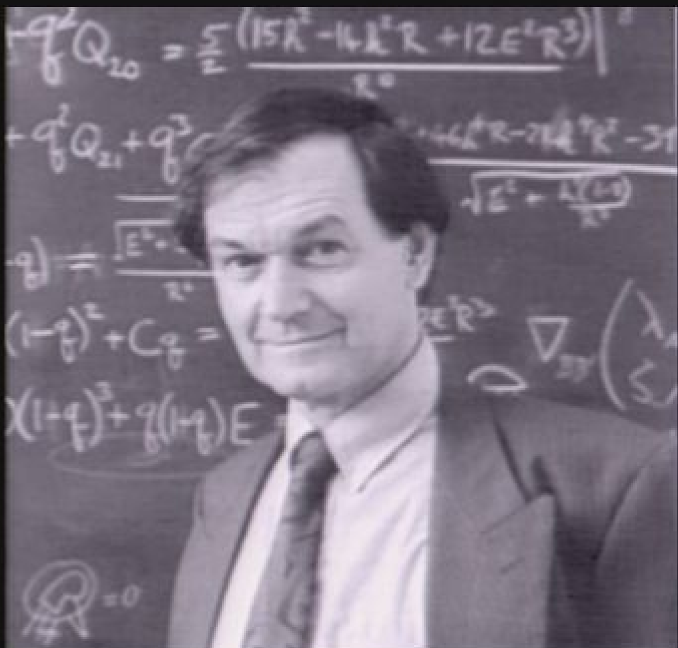


- *Speculated black holes loose their hair by radiating it away.*
- *Discovered that spinning black holes store energy in space outside their horizon (1969).*
- *Discovered surface area of black holes must increase.*
- *Proved that black holes must have singularities at their core (1964).*
- *Proposed cosmic censorship conjecture (1969).*

Topology

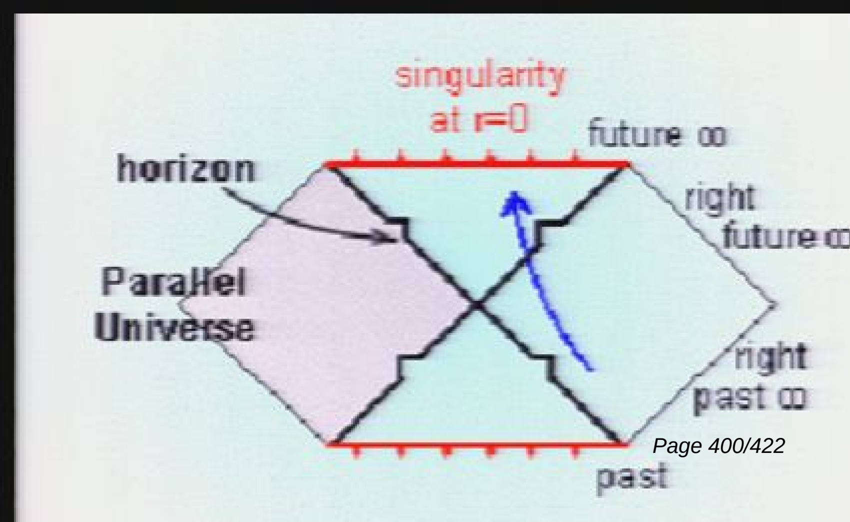


Roger Penrose

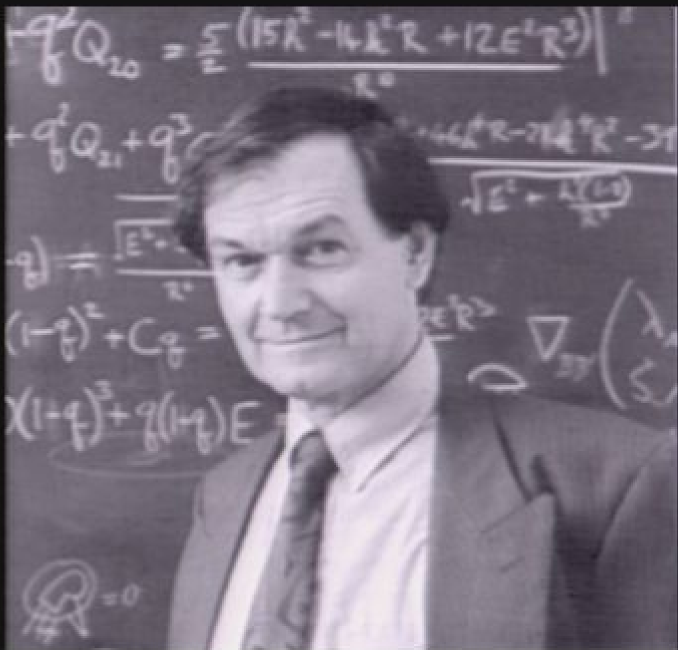


- Speculated black holes loose their hair by radiating it away.
- Discovered that spinning black holes store energy in space outside their horizon (1969).
- Discovered surface area of black holes must increase.
- Proved that black holes must have singularities at their core (1964).
- Proposed cosmic censorship conjecture (1969).

Topology

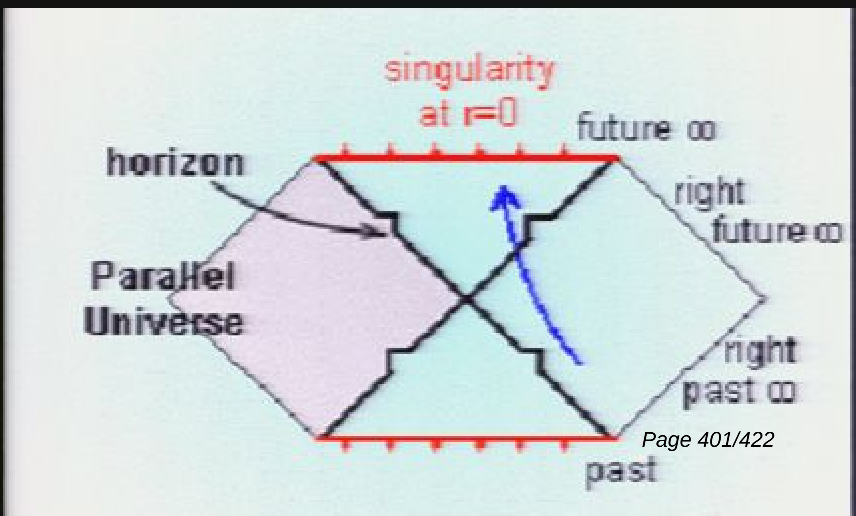


Roger Penrose

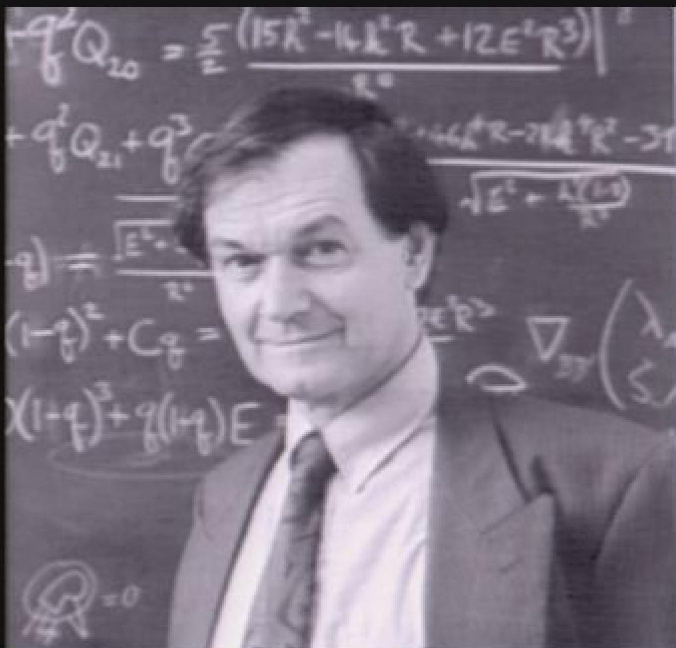


- *Speculated black holes loose their hair by radiating it away.*
- *Discovered that spinning black holes store energy in space outside their horizon (1969).*
- *Discovered surface area of black holes must increase.*
- *Proved that black holes must have singularities at their core (1964).*
- *Proposed cosmic censorship conjecture (1969).*

Topology

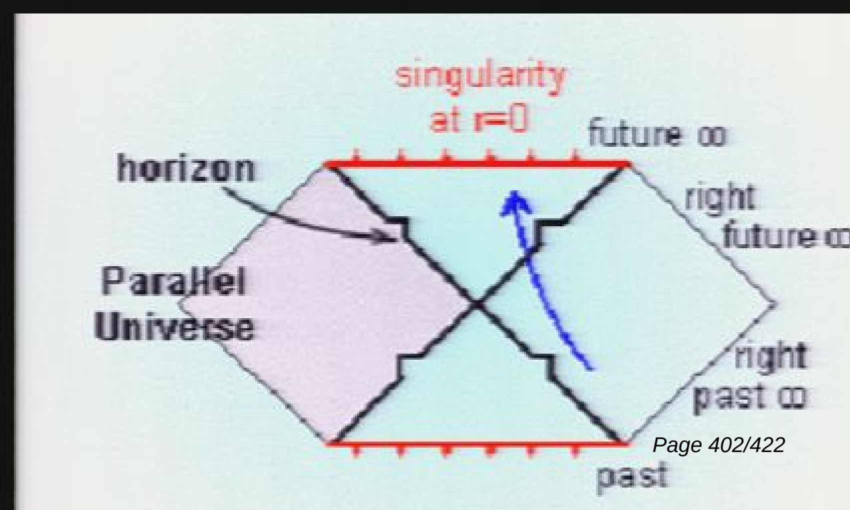


Roger Penrose

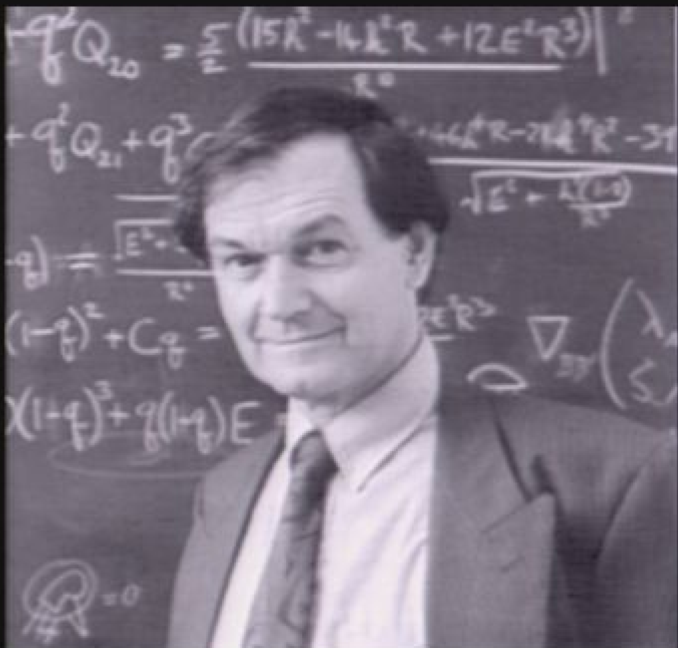


- Speculated black holes loose their hair by radiating it away.
- Discovered that spinning black holes store energy in space outside their horizon (1969).
- Discovered surface area of black holes must increase.
- Proved that black holes must have singularities at their core (1964).
- Proposed cosmic censorship conjecture (1969).

Topology

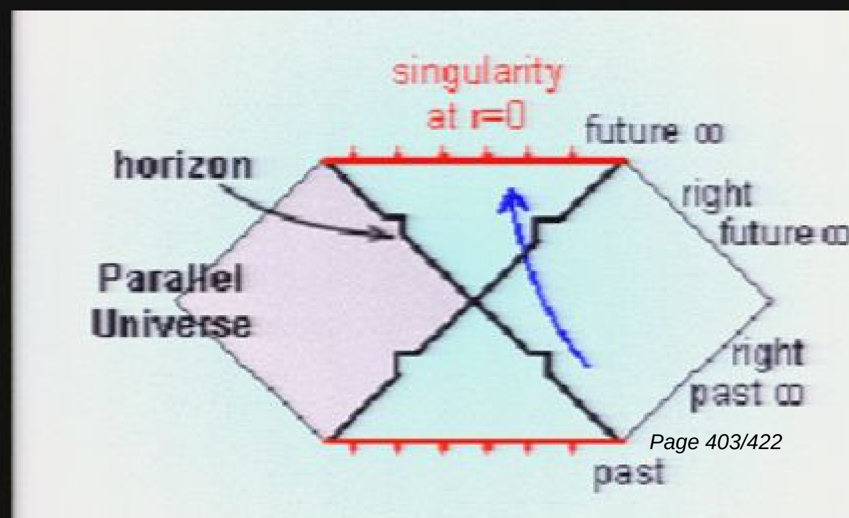


Roger Penrose

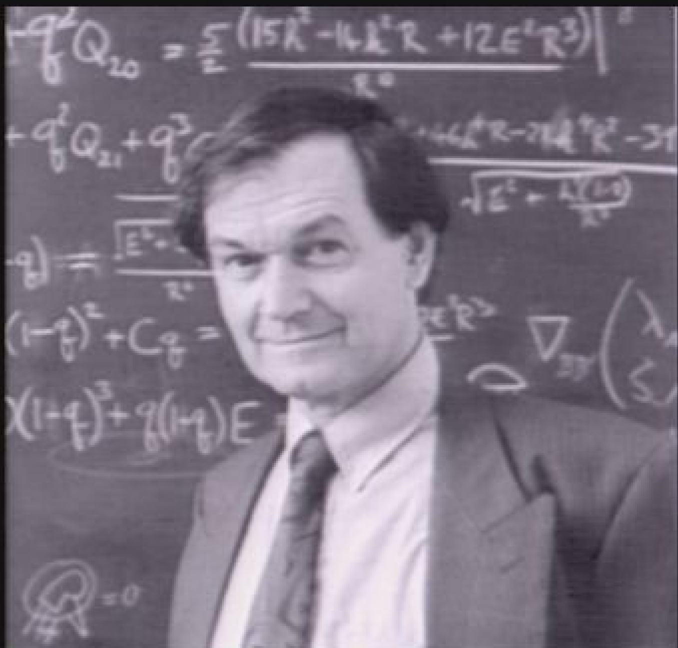


- Speculated black holes loose their hair by radiating it away.
- Discovered that spinning black holes store energy in space outside their horizon (1969).
- Discovered surface area of black holes must increase.
- Proved that black holes must have singularities at their core (1964).
- Proposed cosmic censorship conjecture (1969).

Topology

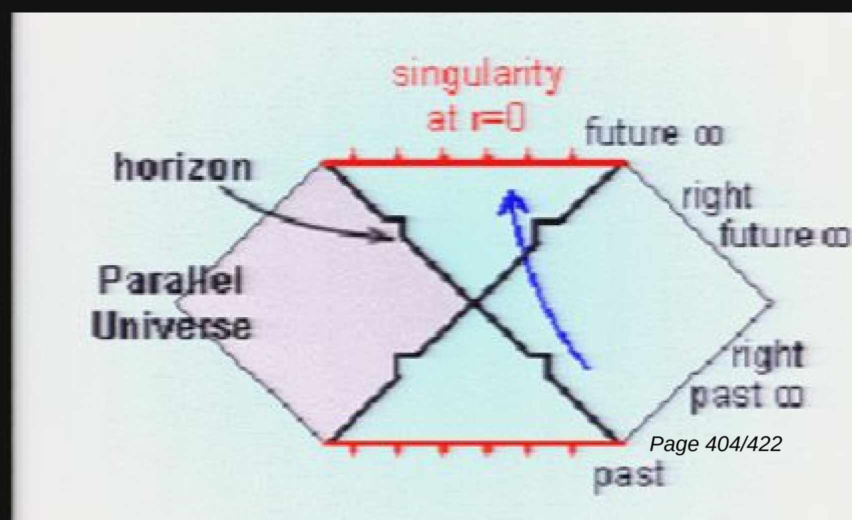


Roger Penrose

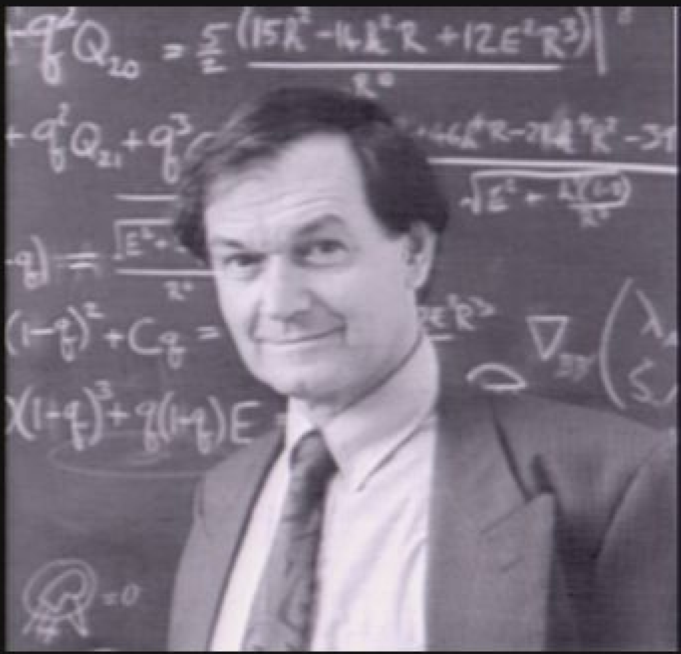


- *Speculated black holes loose their hair by radiating it away.*
- *Discovered that spinning black holes store energy in space outside their horizon (1969).*
- *Discovered surface area of black holes must increase.*
- *Proved that black holes must have singularities at their core (1964).*
- *Proposed cosmic censorship conjecture (1969).*

Topology

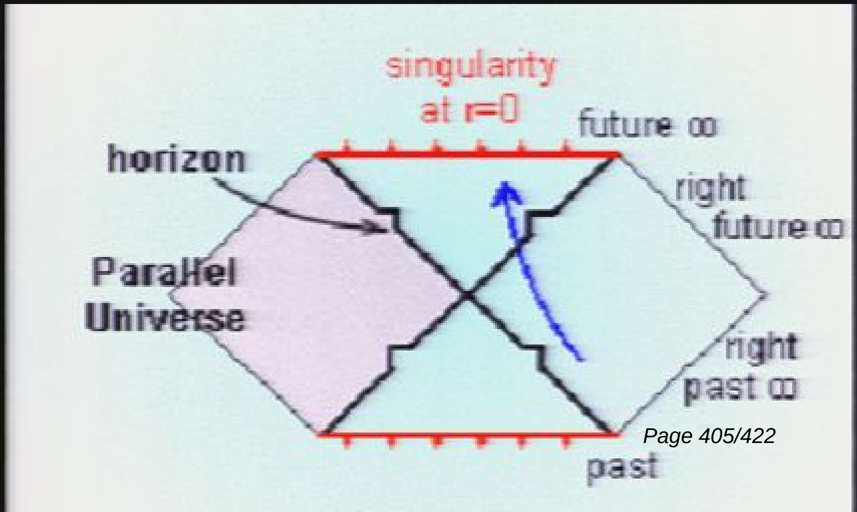


Roger Penrose

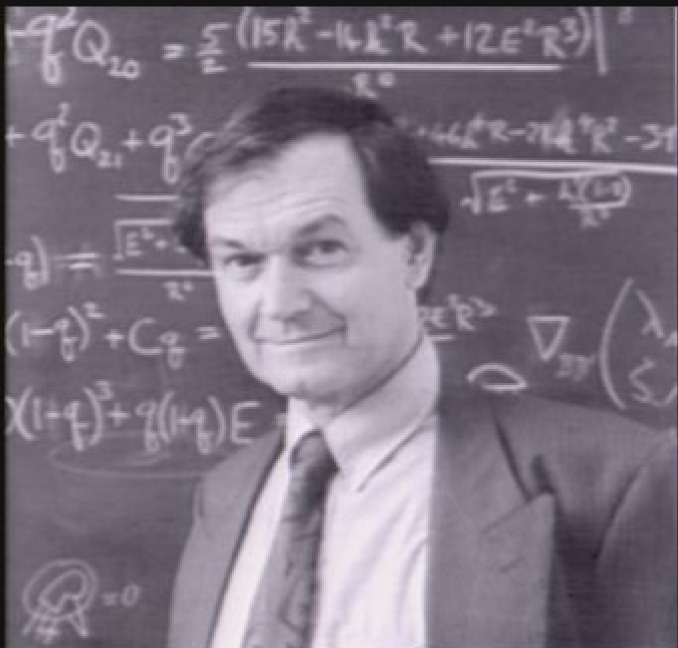


- Speculated black holes loose their hair by radiating it away.
- Discovered that spinning black holes store energy in space outside their horizon (1969).
- Discovered surface area of black holes must increase.
- Proved that black holes must have singularities at their core (1964).
- Proposed cosmic censorship conjecture (1969).

Topology

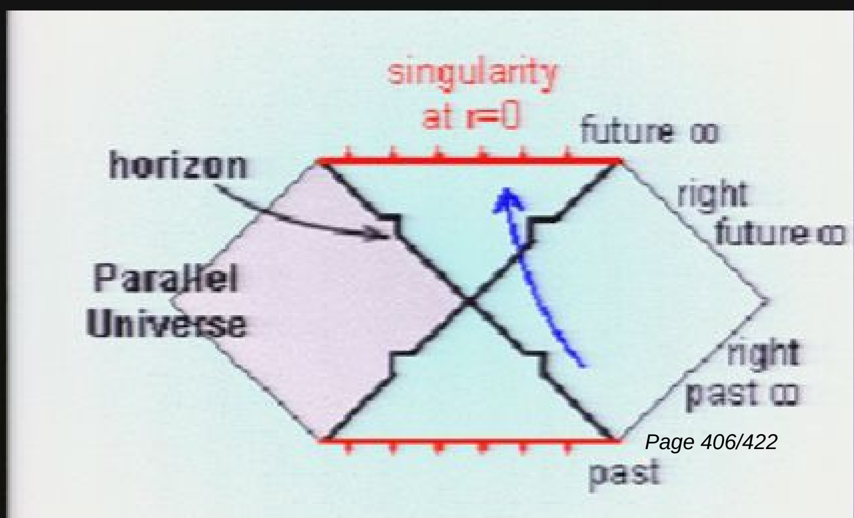


Roger Penrose

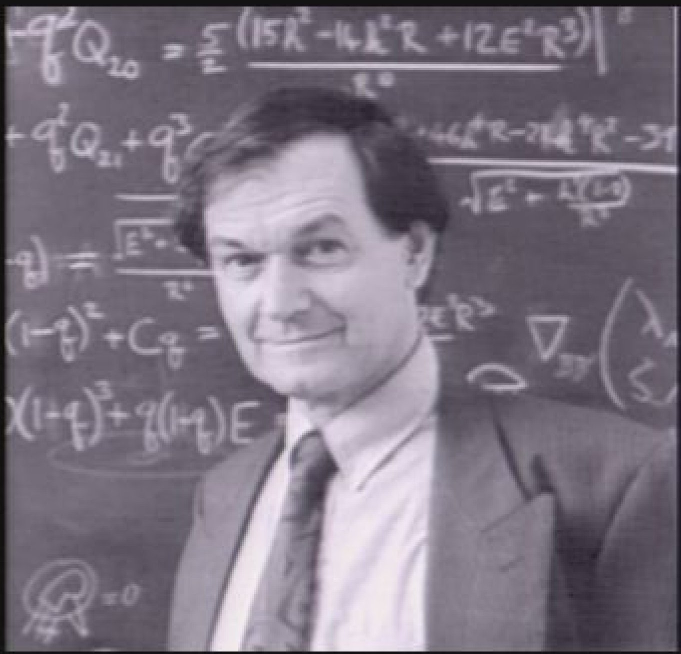


- Speculated black holes loose their hair by radiating it away.
- Discovered that spinning black holes store energy in space outside their horizon (1969).
- Discovered surface area of black holes must increase.
- Proved that black holes must have singularities at their core (1964).
- Proposed cosmic censorship conjecture (1969).

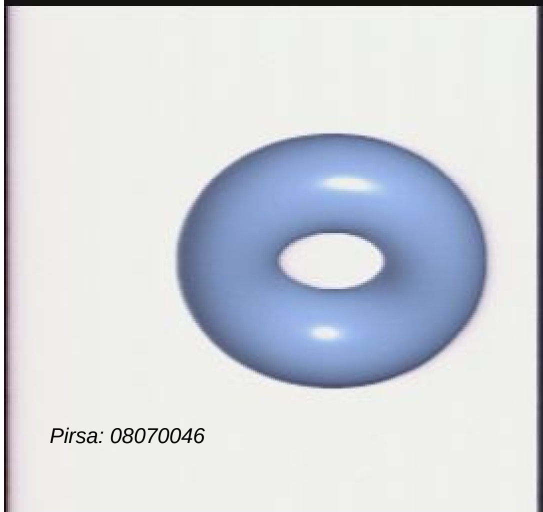
Topology



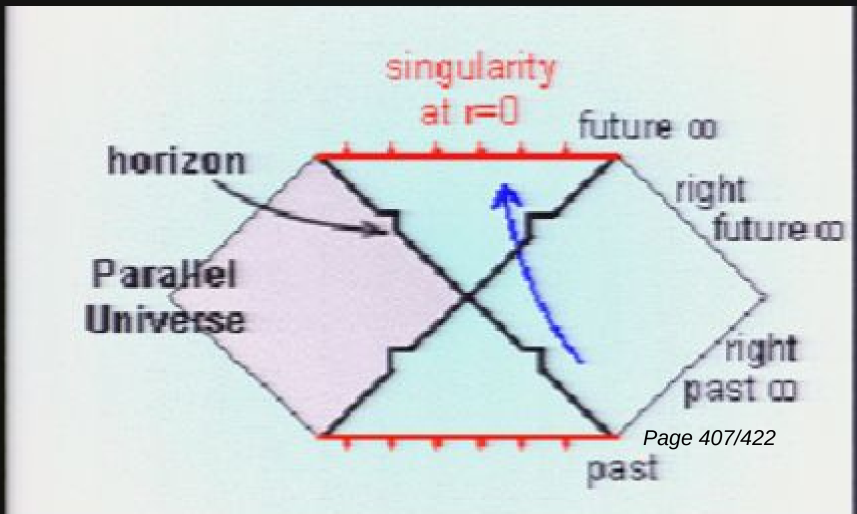
Roger Penrose



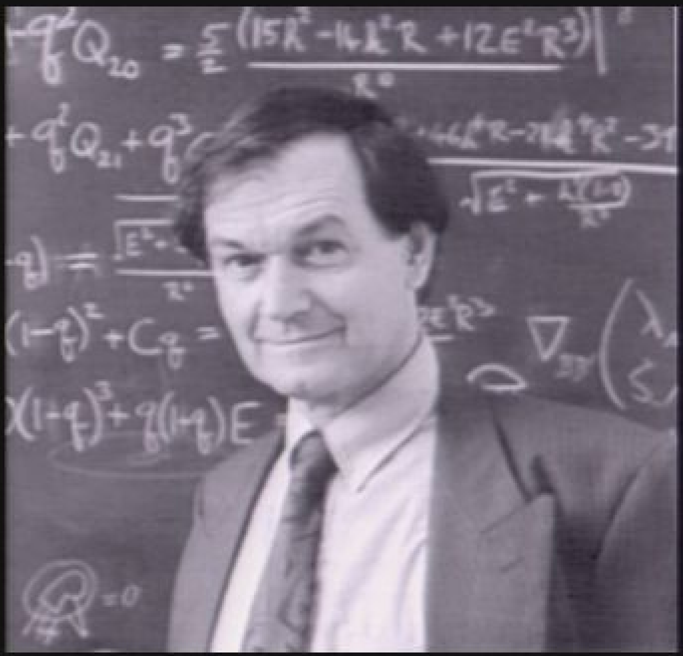
- Speculated black holes loose their hair by radiating it away.
- Discovered that spinning black holes store energy in space outside their horizon (1969).
- Discovered surface area of black holes must increase.
- Proved that black holes must have singularities at their core (1964).
- Proposed cosmic censorship conjecture (1969).



Topology

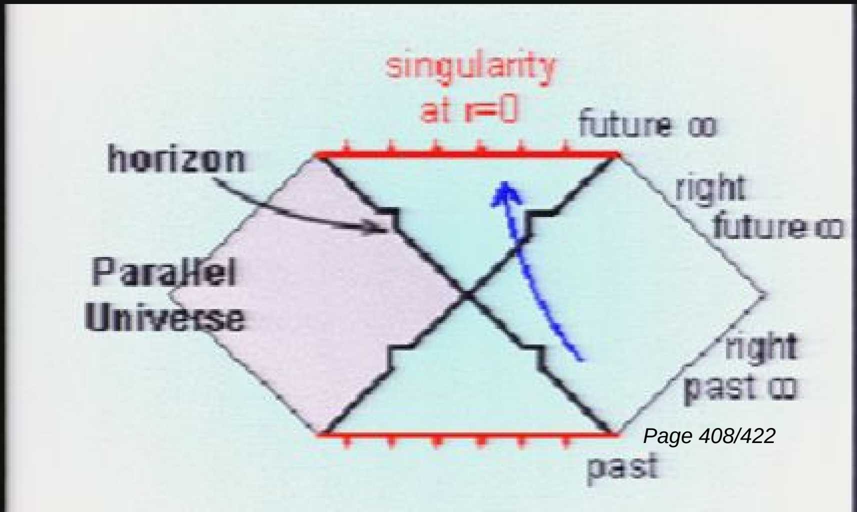


Roger Penrose

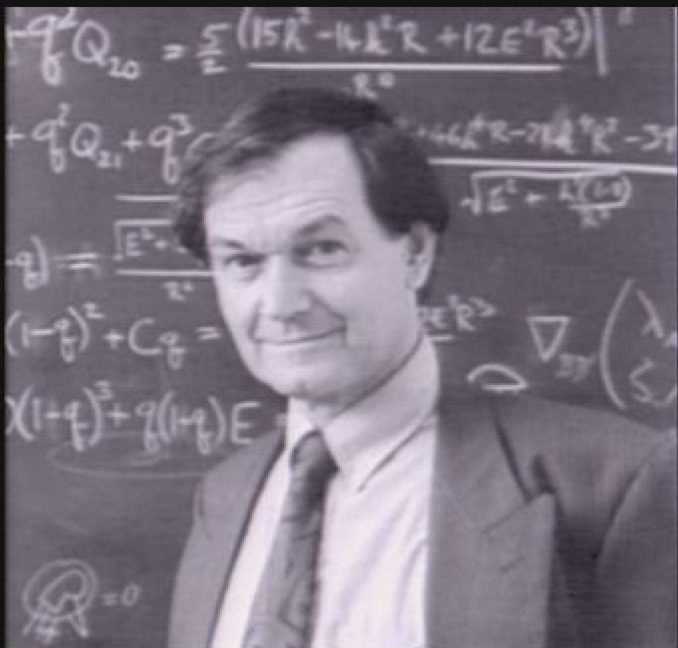


- Speculated black holes loose their hair by radiating it away.
- Discovered that spinning black holes store energy in space outside their horizon (1969).
- Discovered surface area of black holes must increase.
- Proved that black holes must have singularities at their core (1964).
- Proposed cosmic censorship conjecture (1969).

Topology

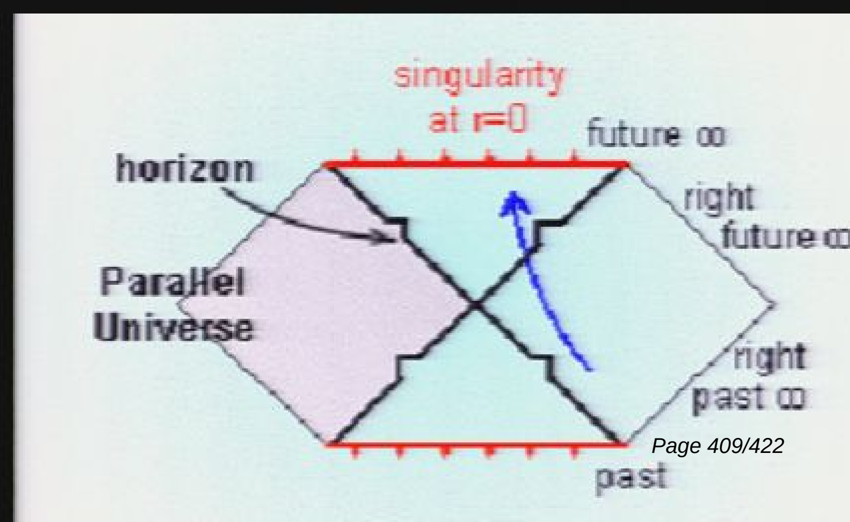


Roger Penrose

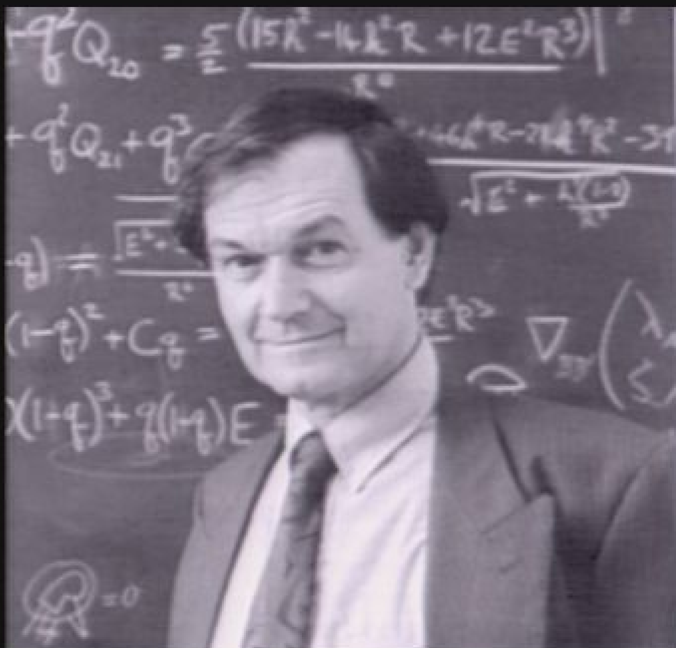


- Speculated black holes loose their hair by radiating it away.
- Discovered that spinning black holes store energy in space outside their horizon (1969).
- Discovered surface area of black holes must increase.
- Proved that black holes must have singularities at their core (1964).
- Proposed cosmic censorship conjecture (1969).

Topology

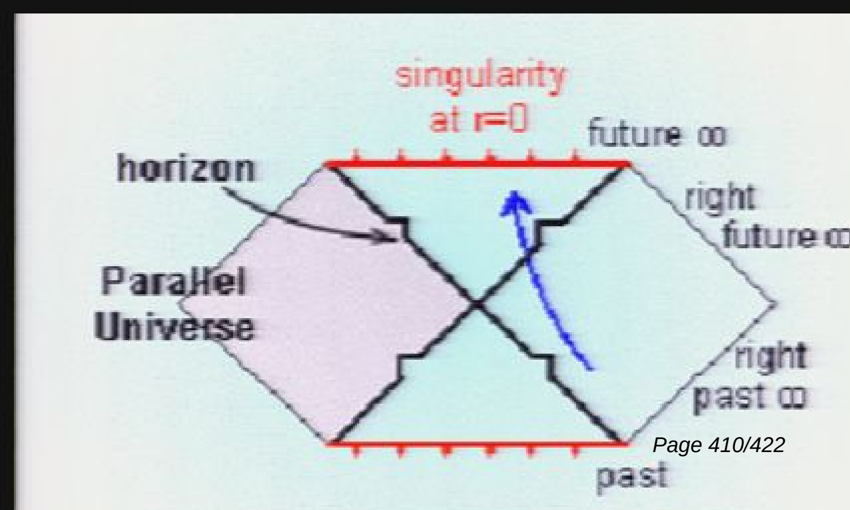


Roger Penrose

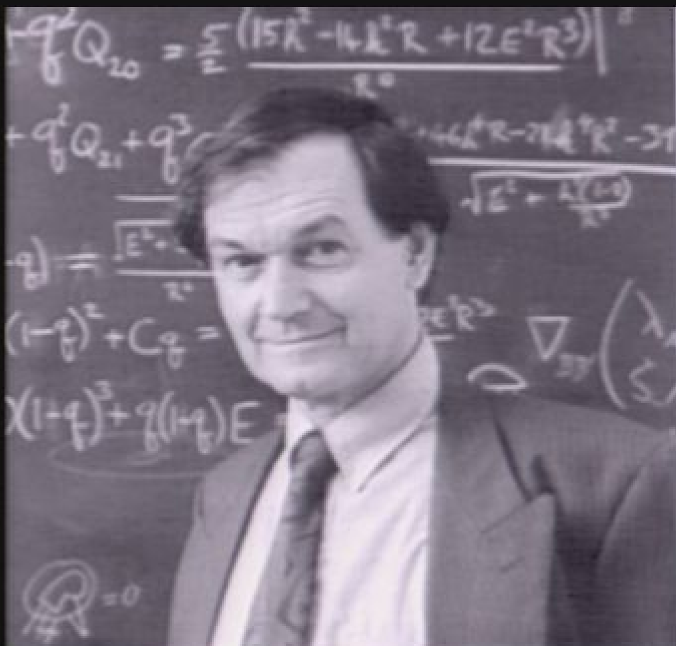


- *Speculated black holes loose their hair by radiating it away.*
- *Discovered that spinning black holes store energy in space outside their horizon (1969).*
- *Discovered surface area of black holes must increase.*
- *Proved that black holes must have singularities at their core (1964).*
- *Proposed cosmic censorship conjecture (1969).*

Topology

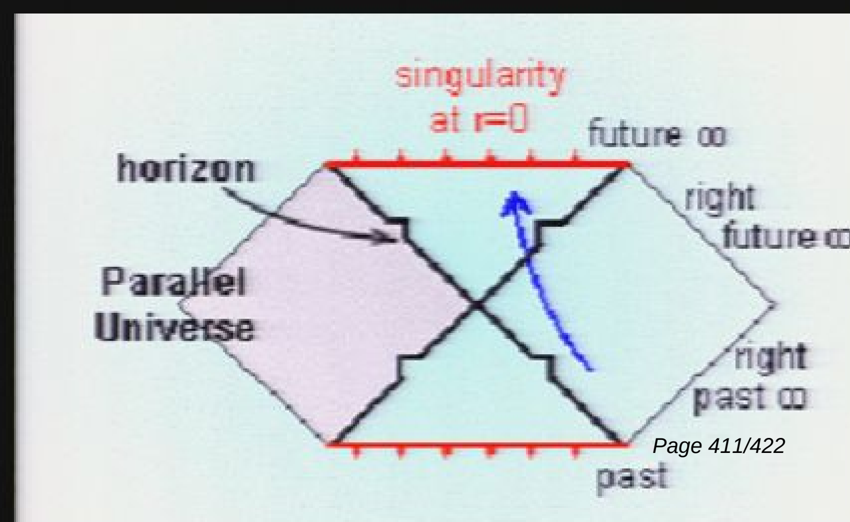


Roger Penrose

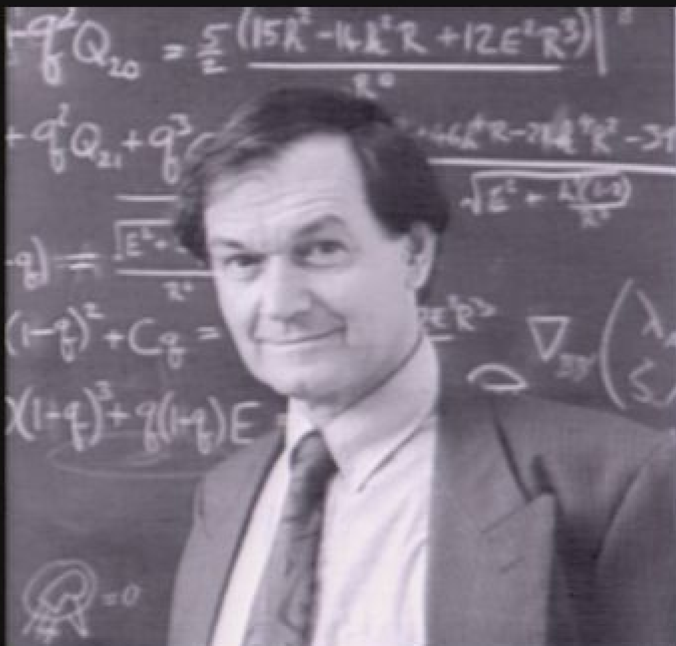


- *Speculated black holes loose their hair by radiating it away.*
- *Discovered that spinning black holes store energy in space outside their horizon (1969).*
- *Discovered surface area of black holes must increase.*
- *Proved that black holes must have singularities at their core (1964).*
- *Proposed cosmic censorship conjecture (1969).*

Topology

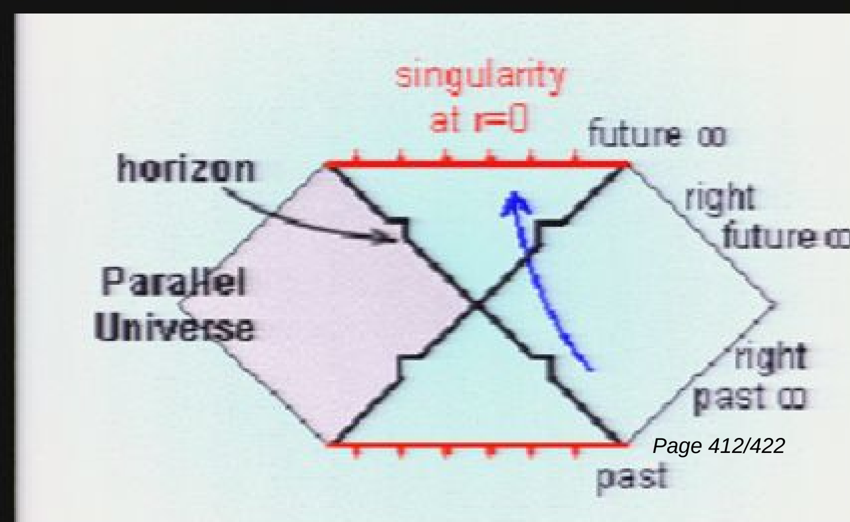


Roger Penrose

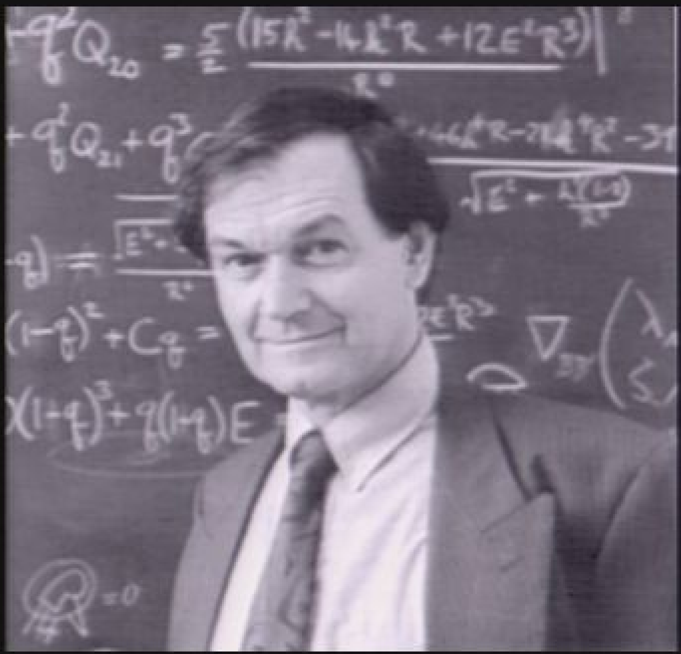


- Speculated black holes loose their hair by radiating it away.
- Discovered that spinning black holes store energy in space outside their horizon (1969).
- Discovered surface area of black holes must increase.
- Proved that black holes must have singularities at their core (1964).
- Proposed cosmic censorship conjecture (1969).

Topology

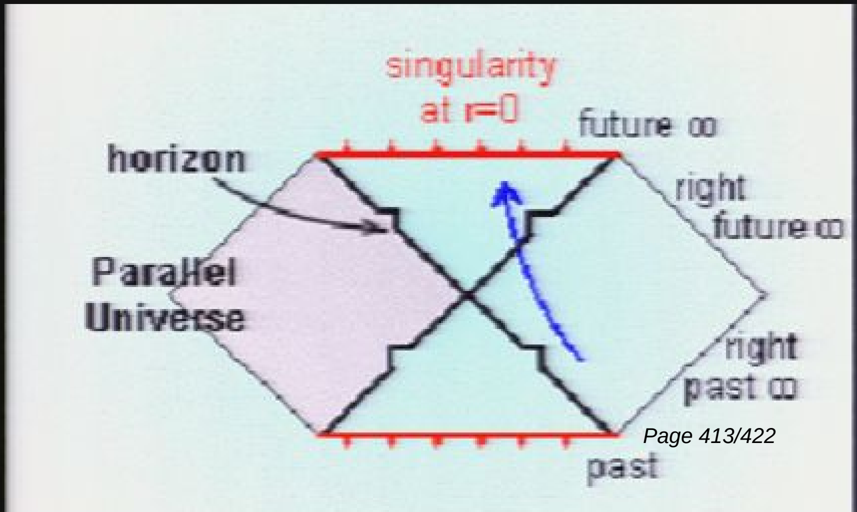


Roger Penrose

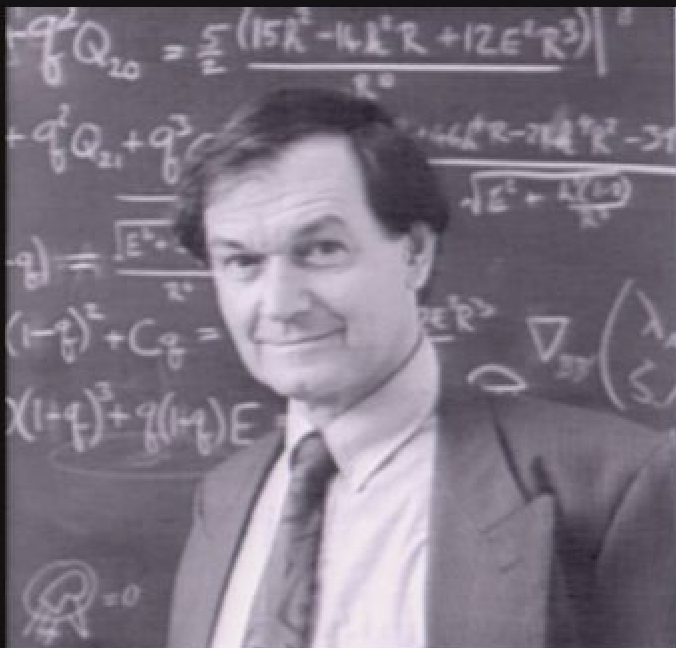


- Speculated black holes loose their hair by radiating it away.
- Discovered that spinning black holes store energy in space outside their horizon (1969).
- Discovered surface area of black holes must increase.
- Proved that black holes must have singularities at their core (1964).
- Proposed cosmic censorship conjecture (1969).

Topology

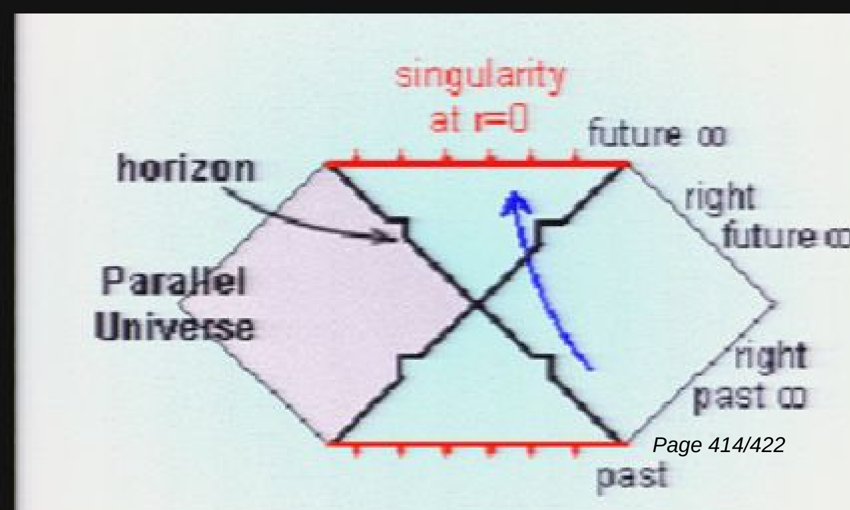


Roger Penrose

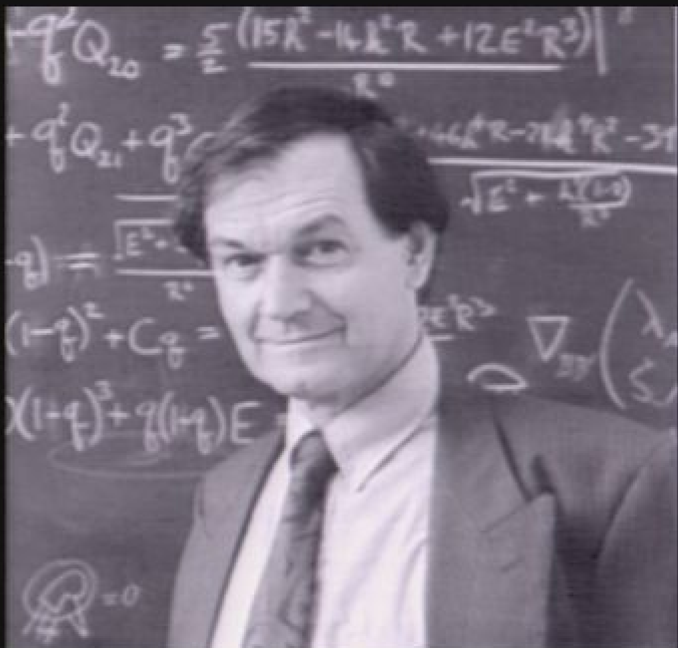


- *Speculated black holes loose their hair by radiating it away.*
- *Discovered that spinning black holes store energy in space outside their horizon (1969).*
- *Discovered surface area of black holes must increase.*
- *Proved that black holes must have singularities at their core (1964).*
- *Proposed cosmic censorship conjecture (1969).*

Topology

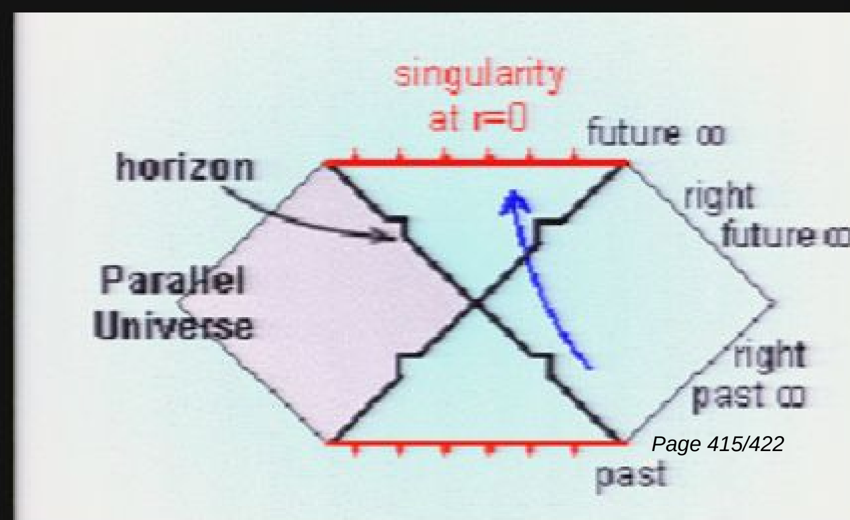


Roger Penrose

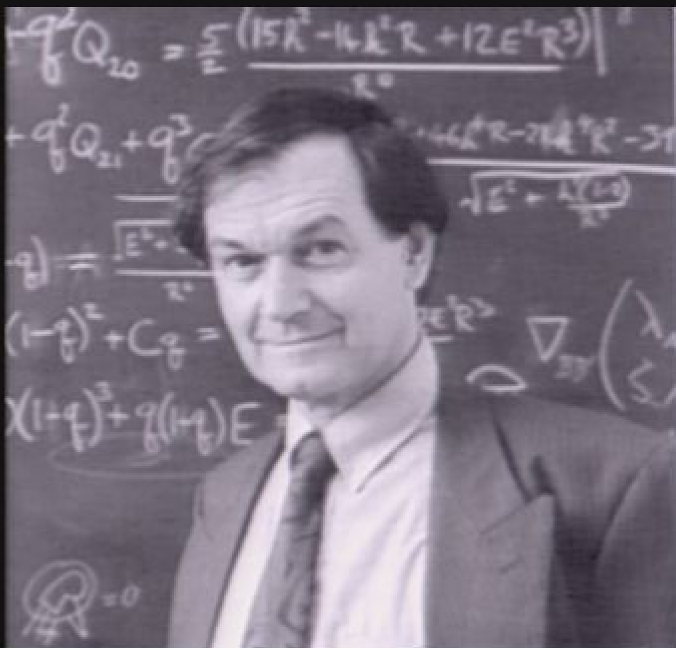


- Speculated black holes loose their hair by radiating it away.
- Discovered that spinning black holes store energy in space outside their horizon (1969).
- Discovered surface area of black holes must increase.
- Proved that black holes must have singularities at their core (1964).
- Proposed cosmic censorship conjecture (1969).

Topology

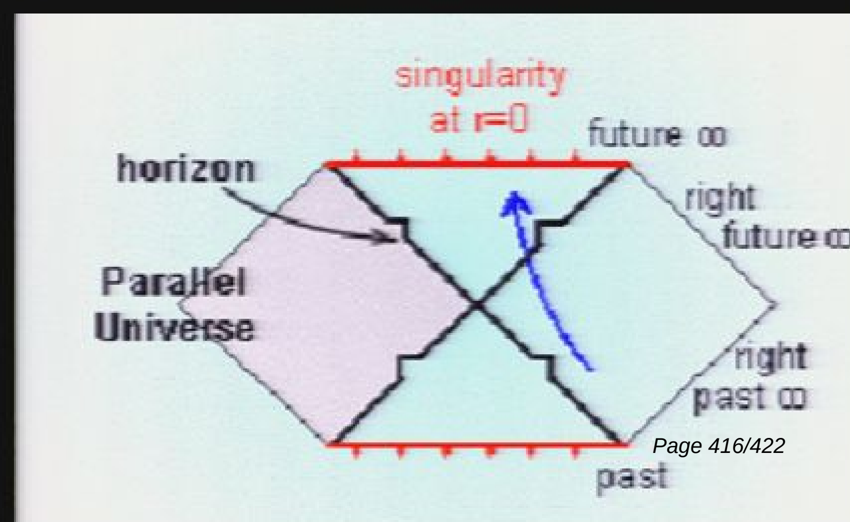


Roger Penrose

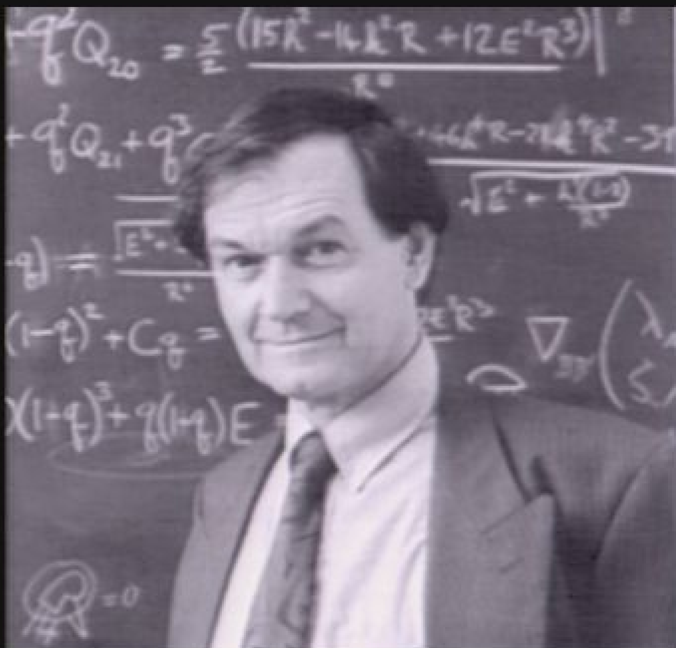


- Speculated black holes loose their hair by radiating it away.
- Discovered that spinning black holes store energy in space outside their horizon (1969).
- Discovered surface area of black holes must increase.
- Proved that black holes must have singularities at their core (1964).
- Proposed cosmic censorship conjecture (1969).

Topology

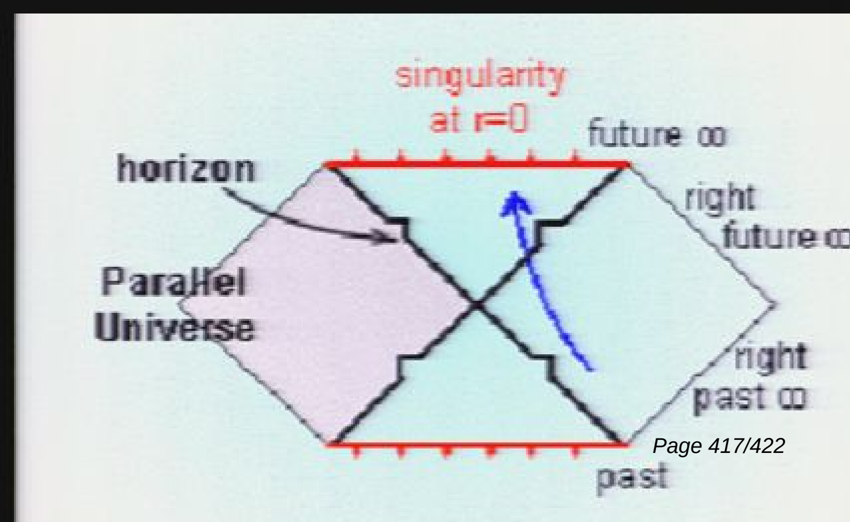


Roger Penrose

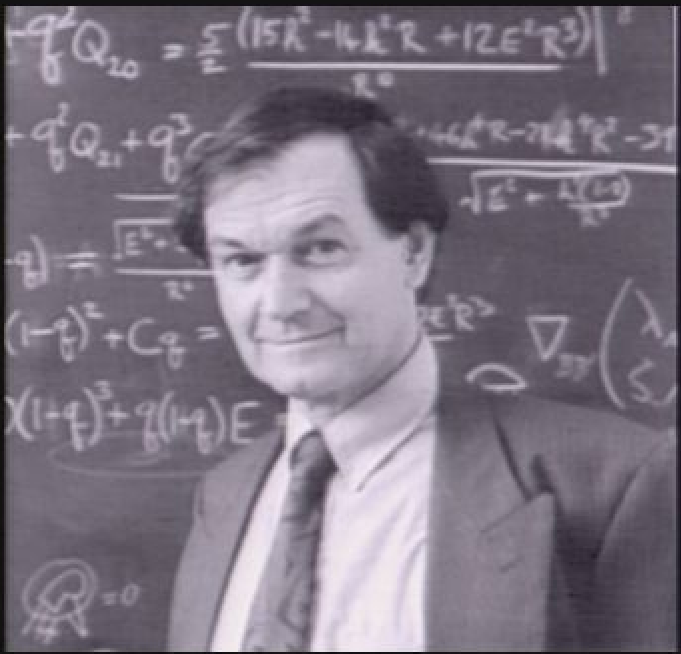


- Speculated black holes loose their hair by radiating it away.
- Discovered that spinning black holes store energy in space outside their horizon (1969).
- Discovered surface area of black holes must increase.
- Proved that black holes must have singularities at their core (1964).
- Proposed cosmic censorship conjecture (1969).

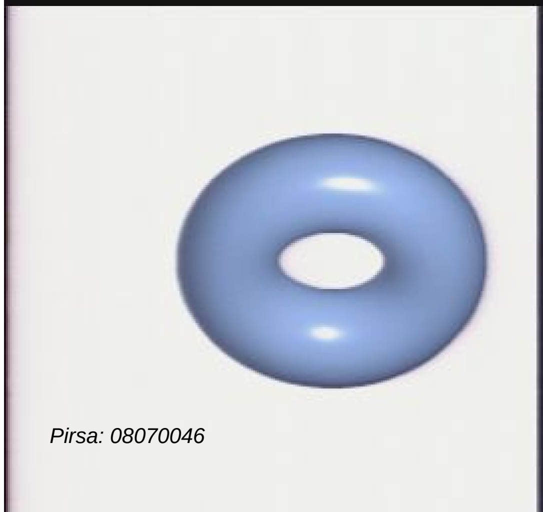
Topology



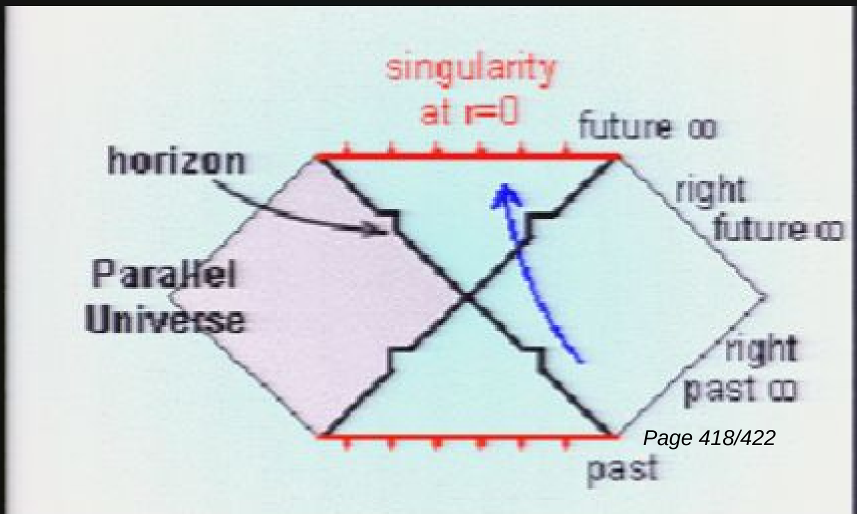
Roger Penrose



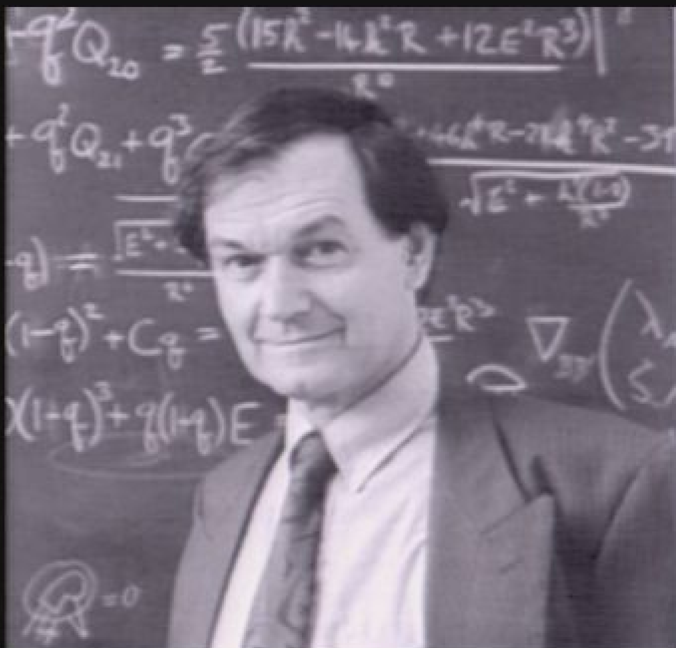
- Speculated black holes loose their hair by radiating it away.
- Discovered that spinning black holes store energy in space outside their horizon (1969).
- Discovered surface area of black holes must increase.
- Proved that black holes must have singularities at their core (1964).
- Proposed cosmic censorship conjecture (1969).



Topology

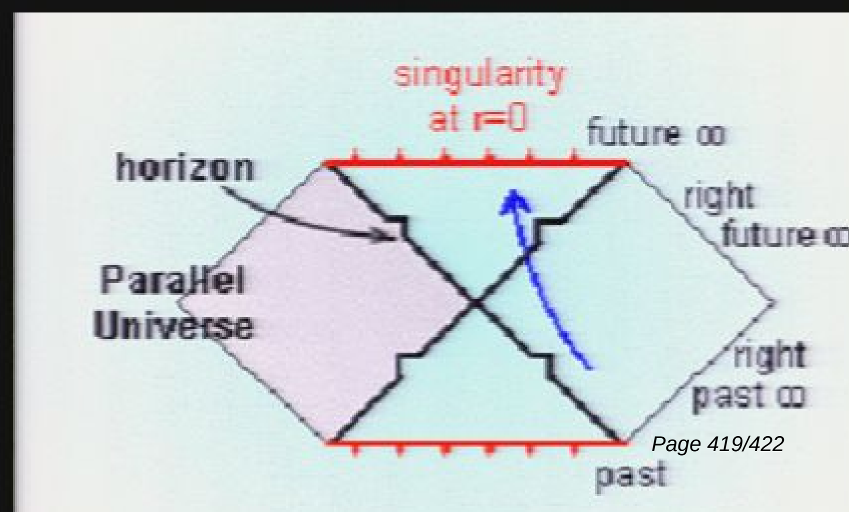


Roger Penrose

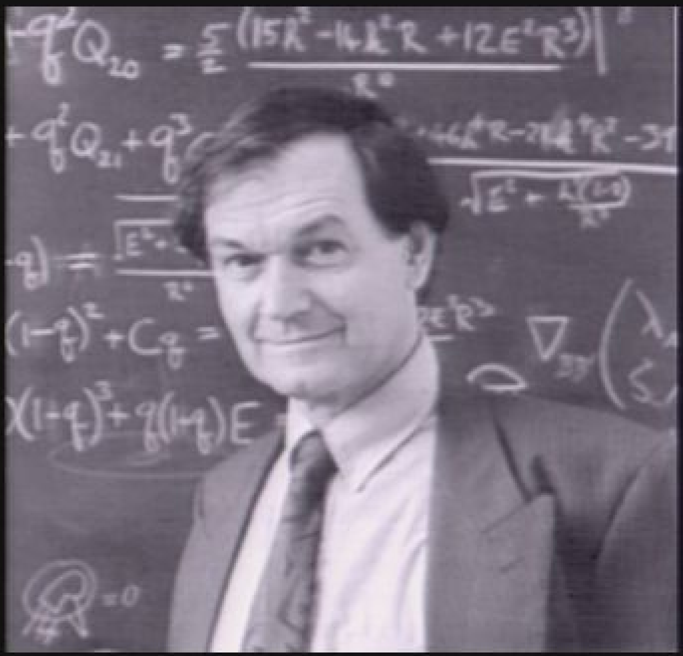


- Speculated black holes loose their hair by radiating it away.
- Discovered that spinning black holes store energy in space outside their horizon (1969).
- Discovered surface area of black holes must increase.
- Proved that black holes must have singularities at their core (1964).
- Proposed cosmic censorship conjecture (1969).

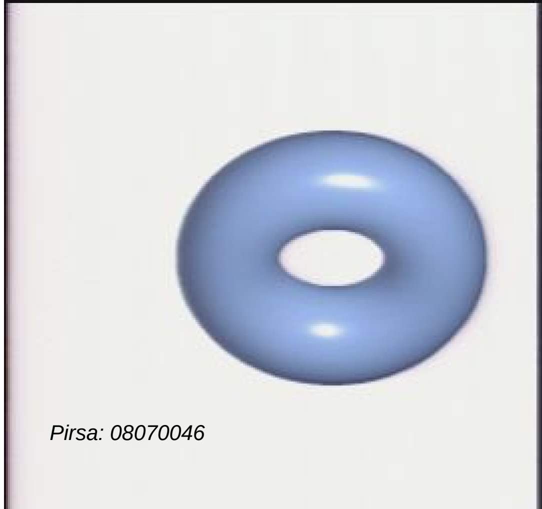
Topology



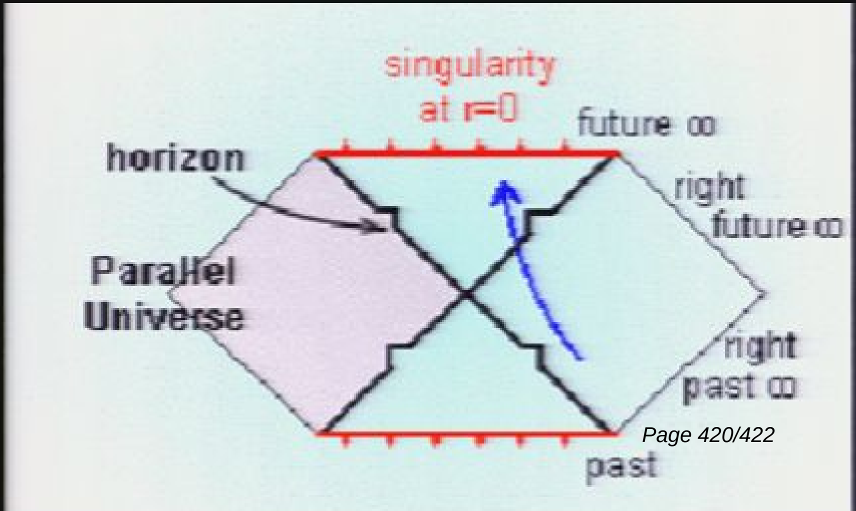
Roger Penrose



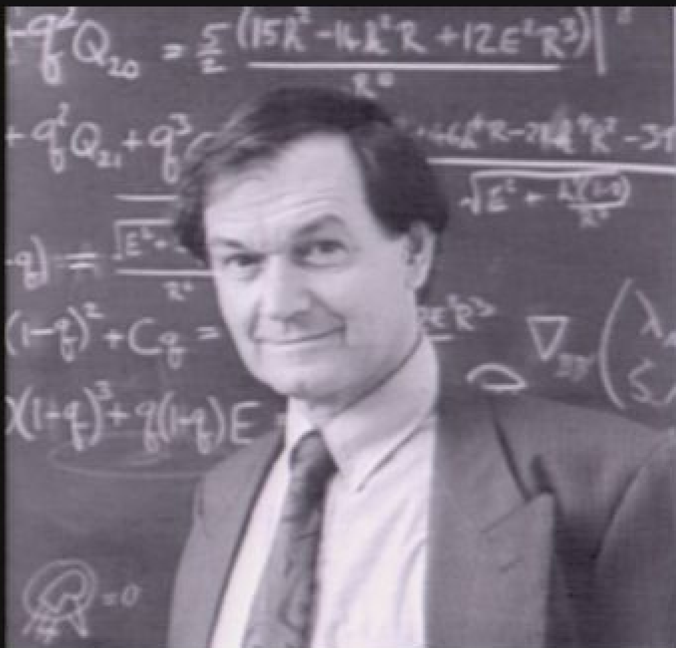
- Speculated black holes loose their hair by radiating it away.
- Discovered that spinning black holes store energy in space outside their horizon (1969).
- Discovered surface area of black holes must increase.
- Proved that black holes must have singularities at their core (1964).
- Proposed cosmic censorship conjecture (1969).



Topology

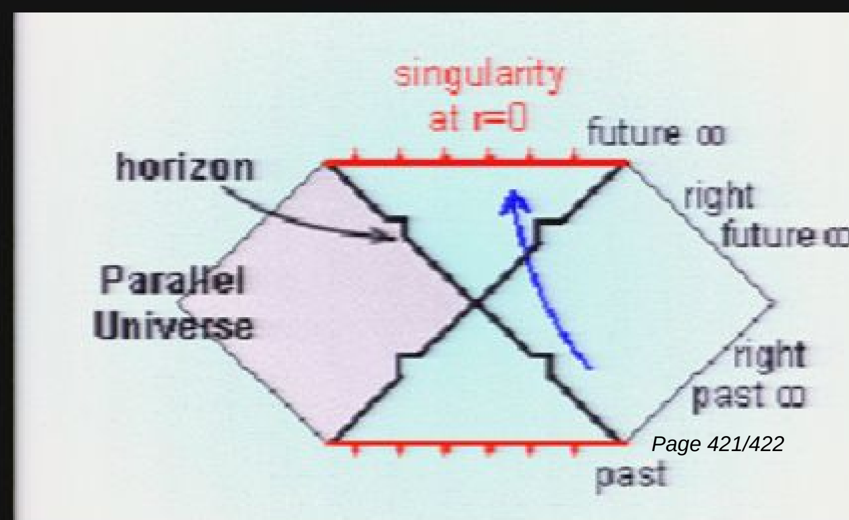


Roger Penrose



- Speculated black holes loose their hair by radiating it away.
- Discovered that spinning black holes store energy in space outside their horizon (1969).
- Discovered surface area of black holes must increase.
- Proved that black holes must have singularities at their core (1964).
- Proposed cosmic censorship conjecture (1969).

Topology



The Blackhole Stars Today