Title: Relativity 5

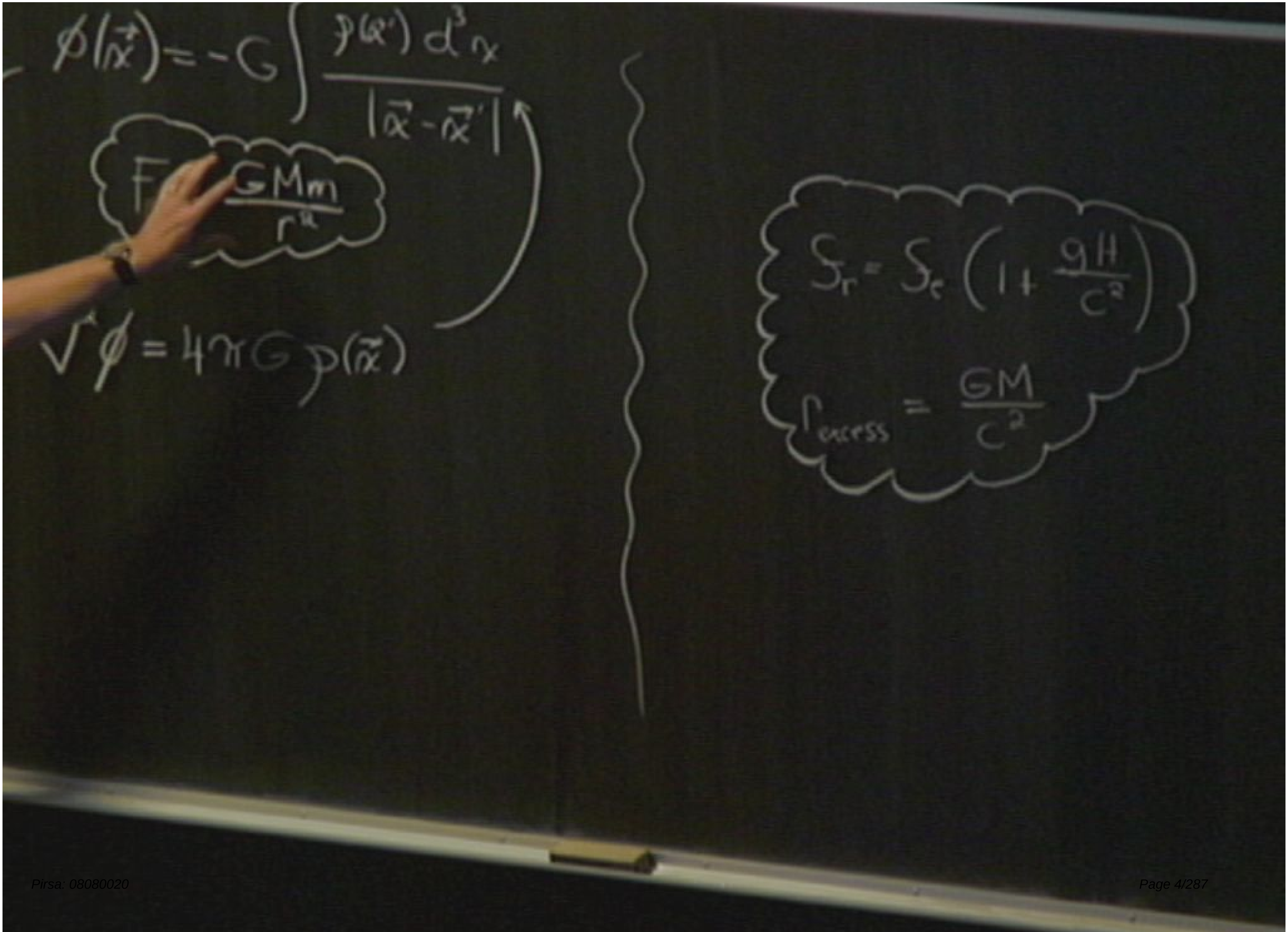
Date: Aug 15, 2008 02:00 PM

URL: http://pirsa.org/08080020

Abstract:


Black Holes


φ(x⃗) = -G ∫ ρ(x′) d³x / |x⃗ - x⃗′|
F_G = GMm
∇²φ = 4π
S_r = S_e (1 + gH/c²)
= GM/c²


$\phi(\vec{x}) = -G\int \frac{\rho(\vec{x}')\,d^3x}{|\vec{x}-\vec{x}'|}$
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$\nabla^2\phi = 4\pi G\rho(\vec{x})$
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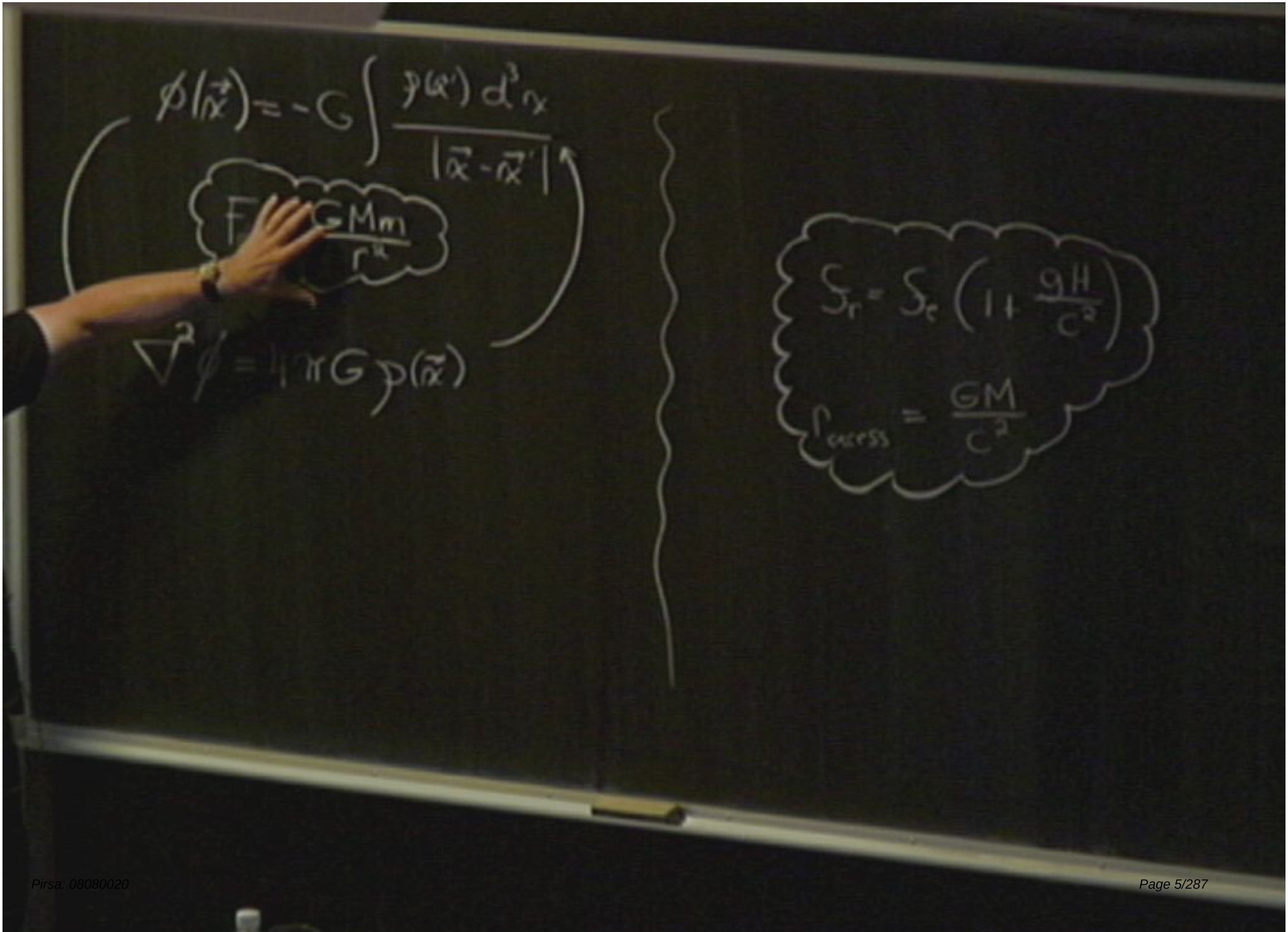
$r_{excess} = \frac{GM}{c^2}$



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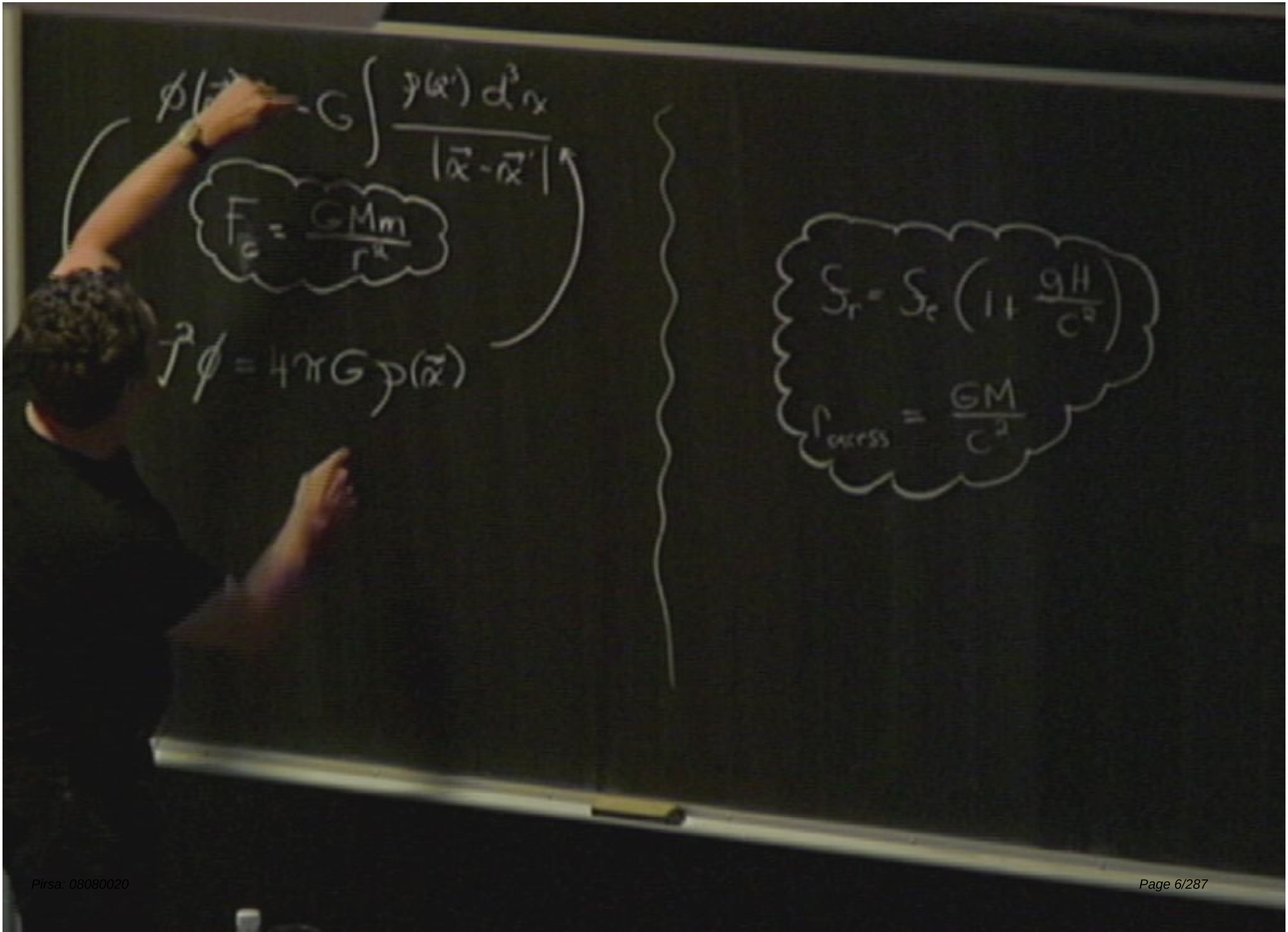
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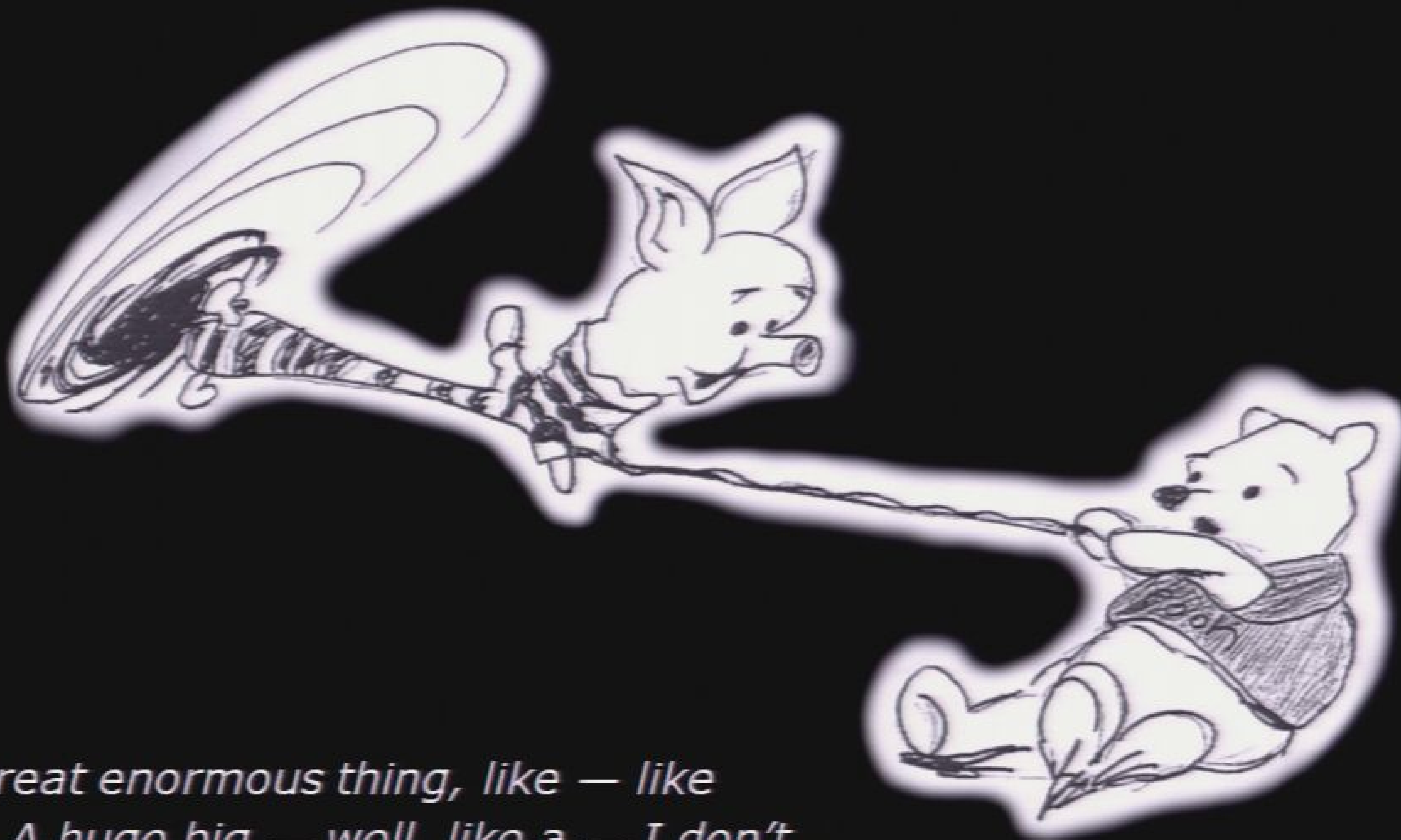

A huge great enormous thing, like — like nothing. A huge big — well, like a — I don't know — like an enormous big nothing ...

Piglet describes the Heffalump,
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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.

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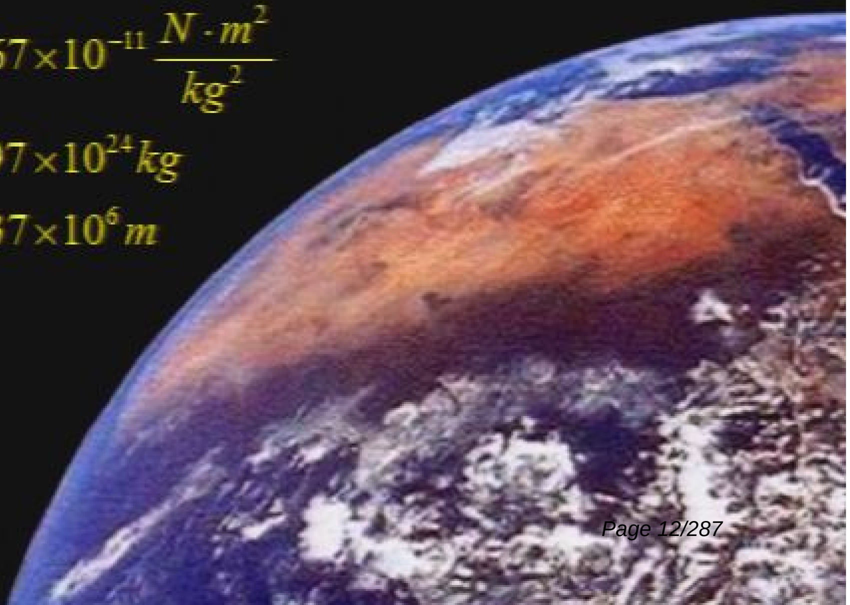

Calculate Escape Velocity

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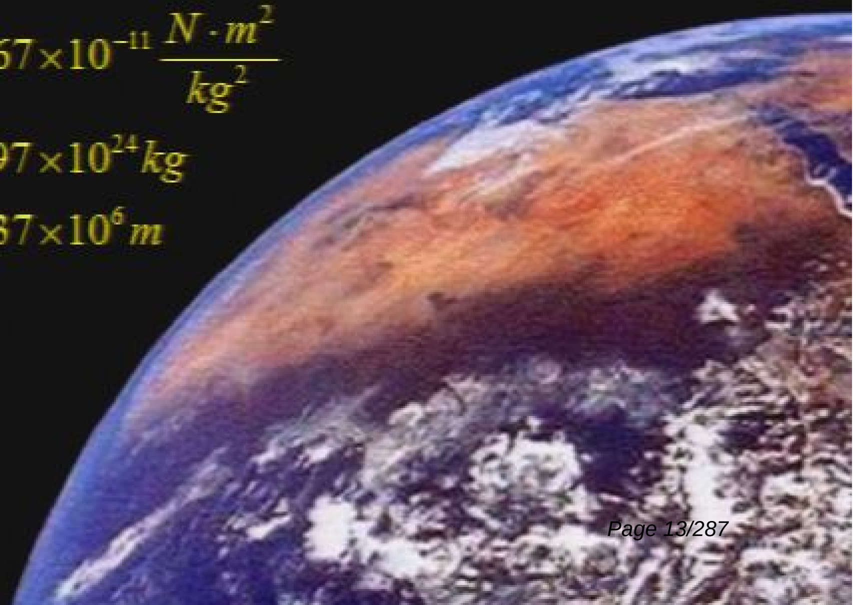

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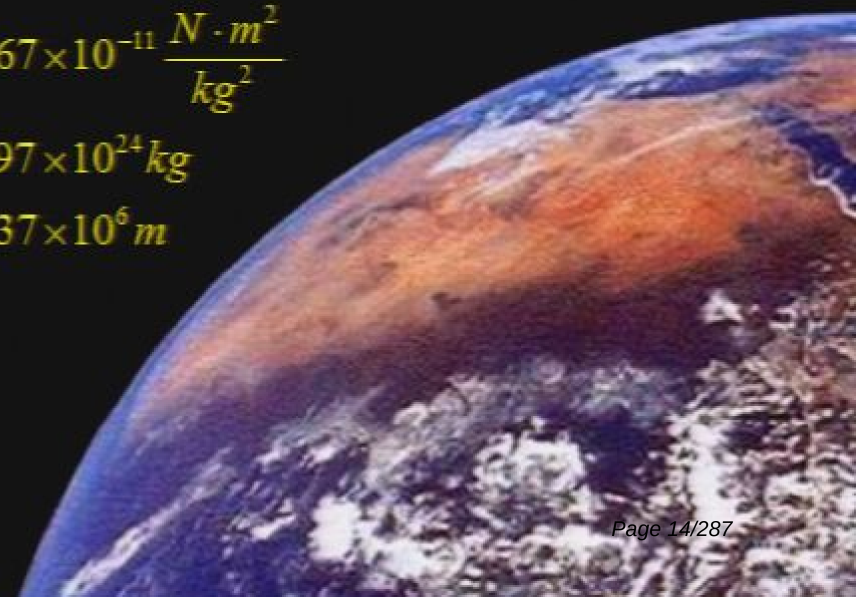

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11.2 km/s

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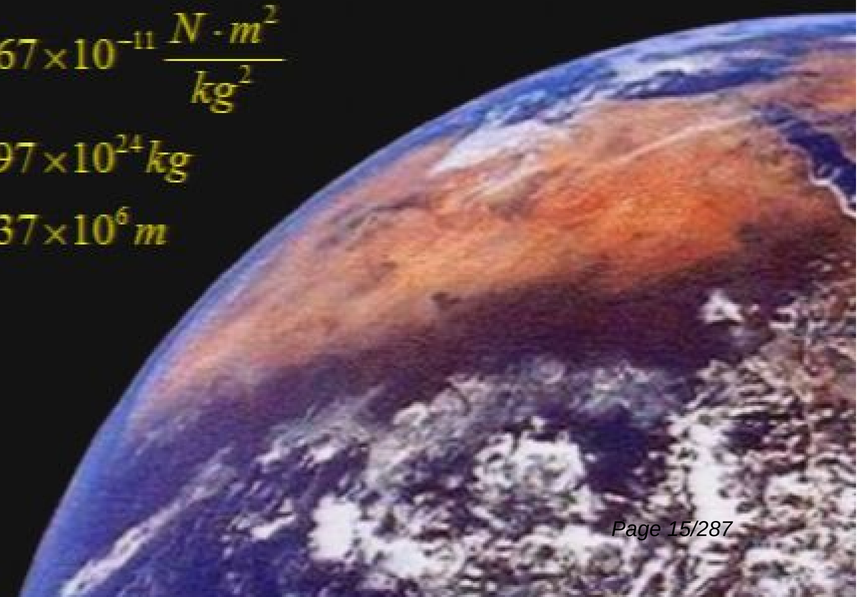

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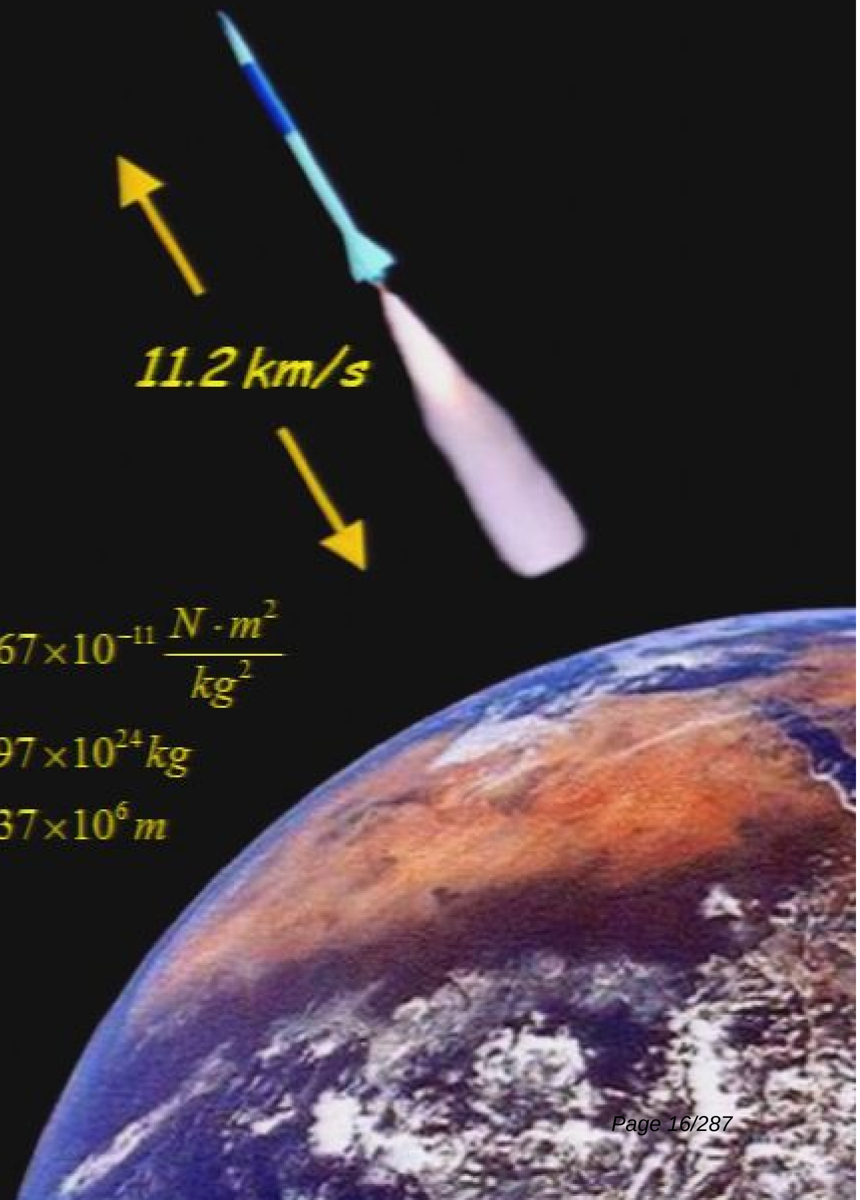

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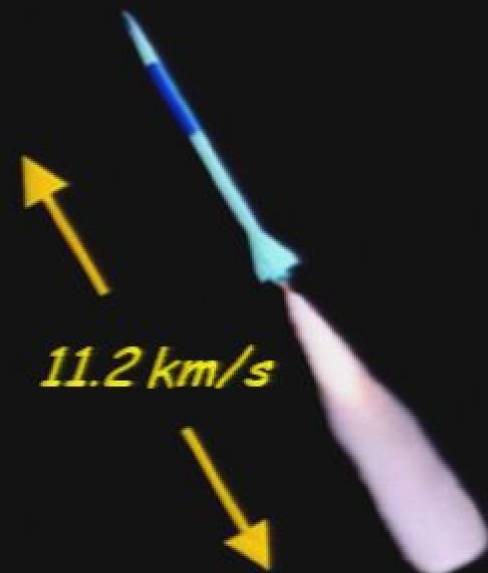

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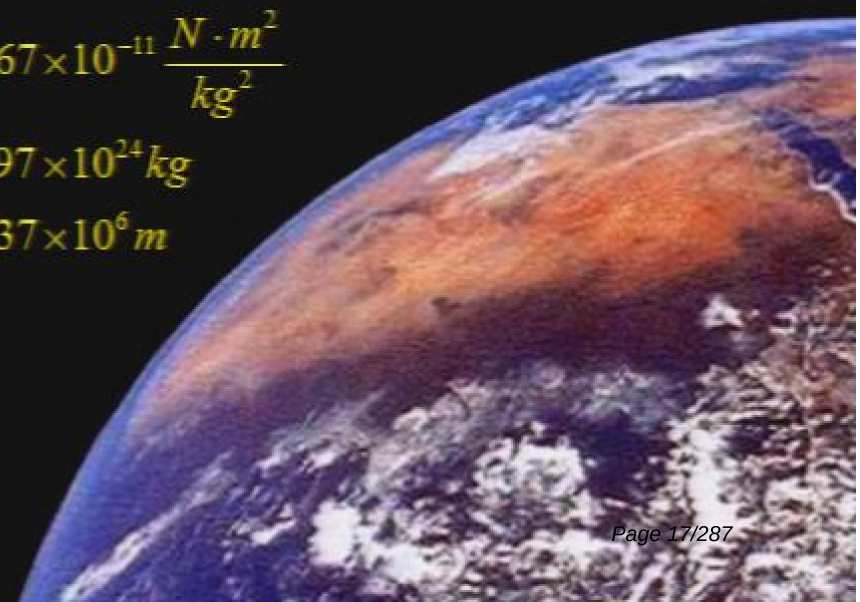
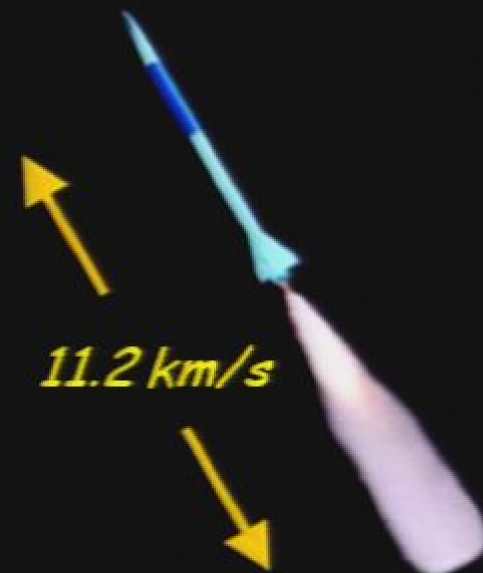


What is Earth's r when escape velocity is $3x10^8$ m/s

$$\boxed{\sim 8.9\ mm}$$



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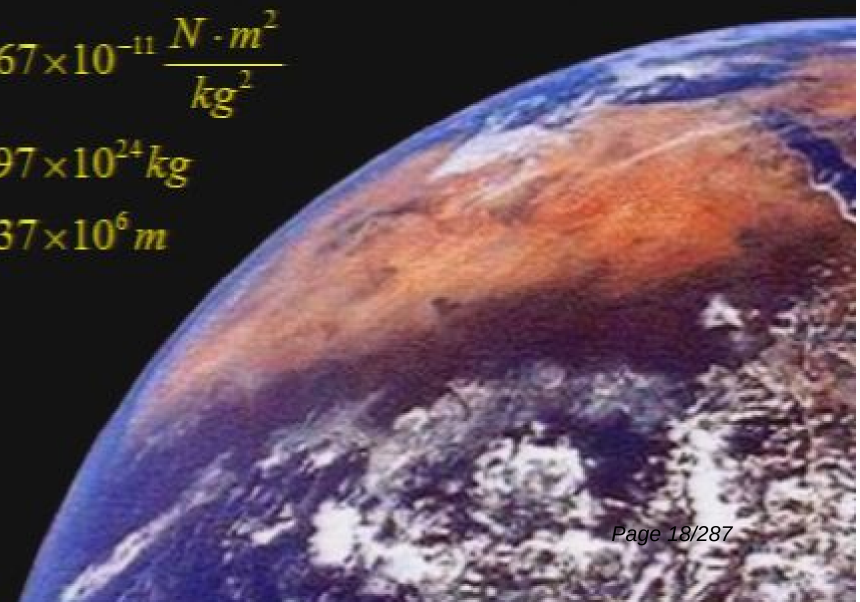
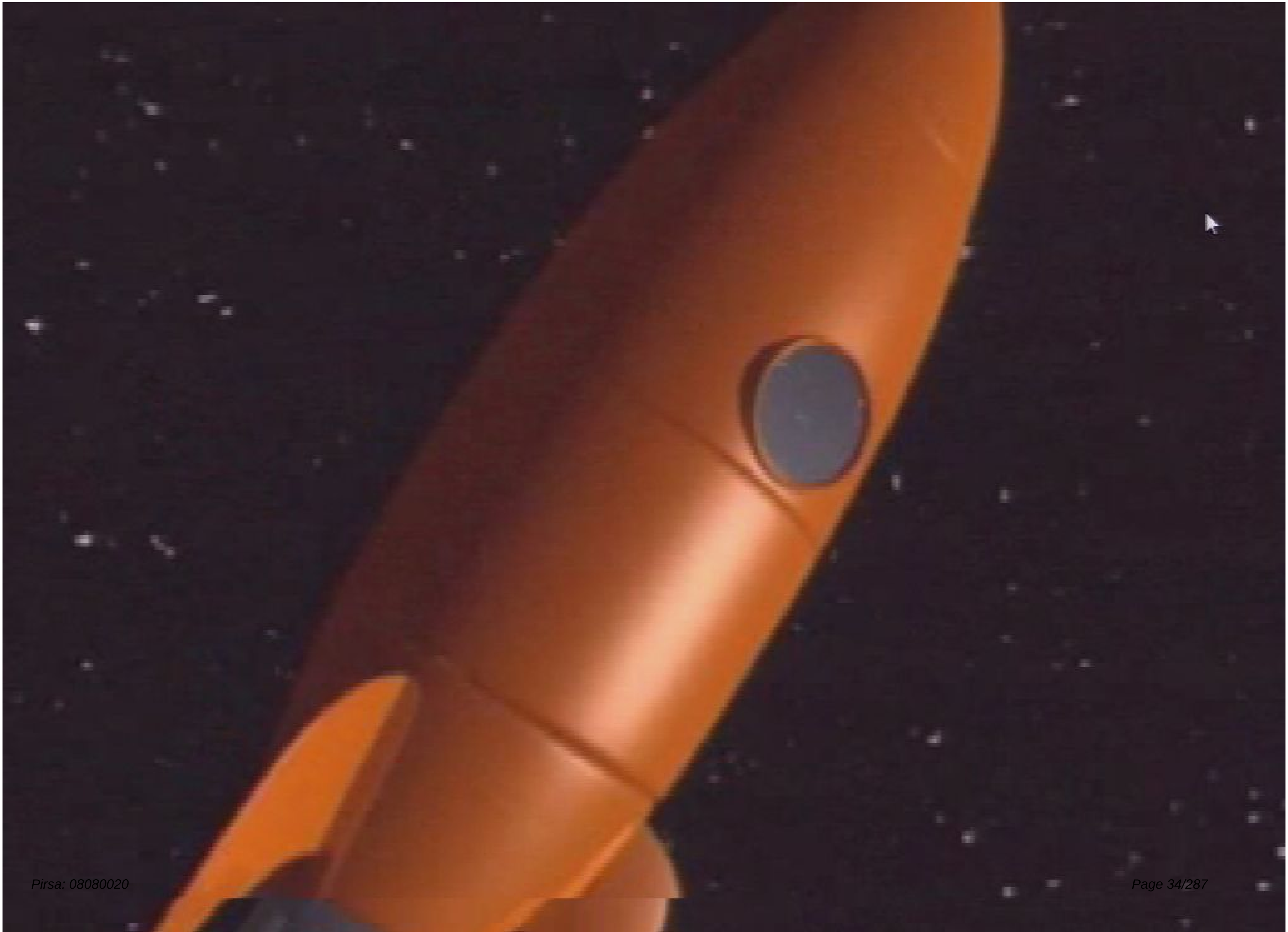
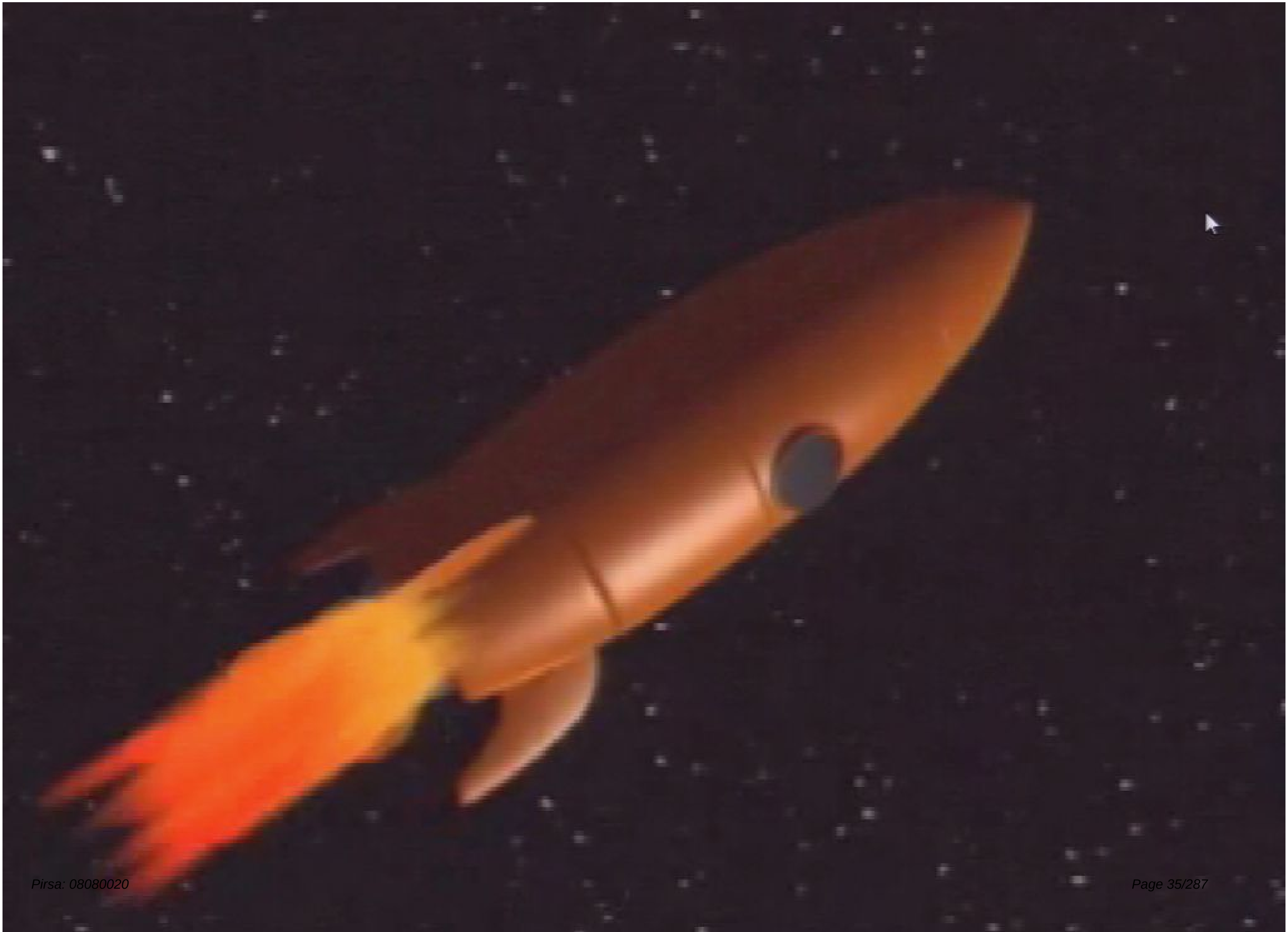
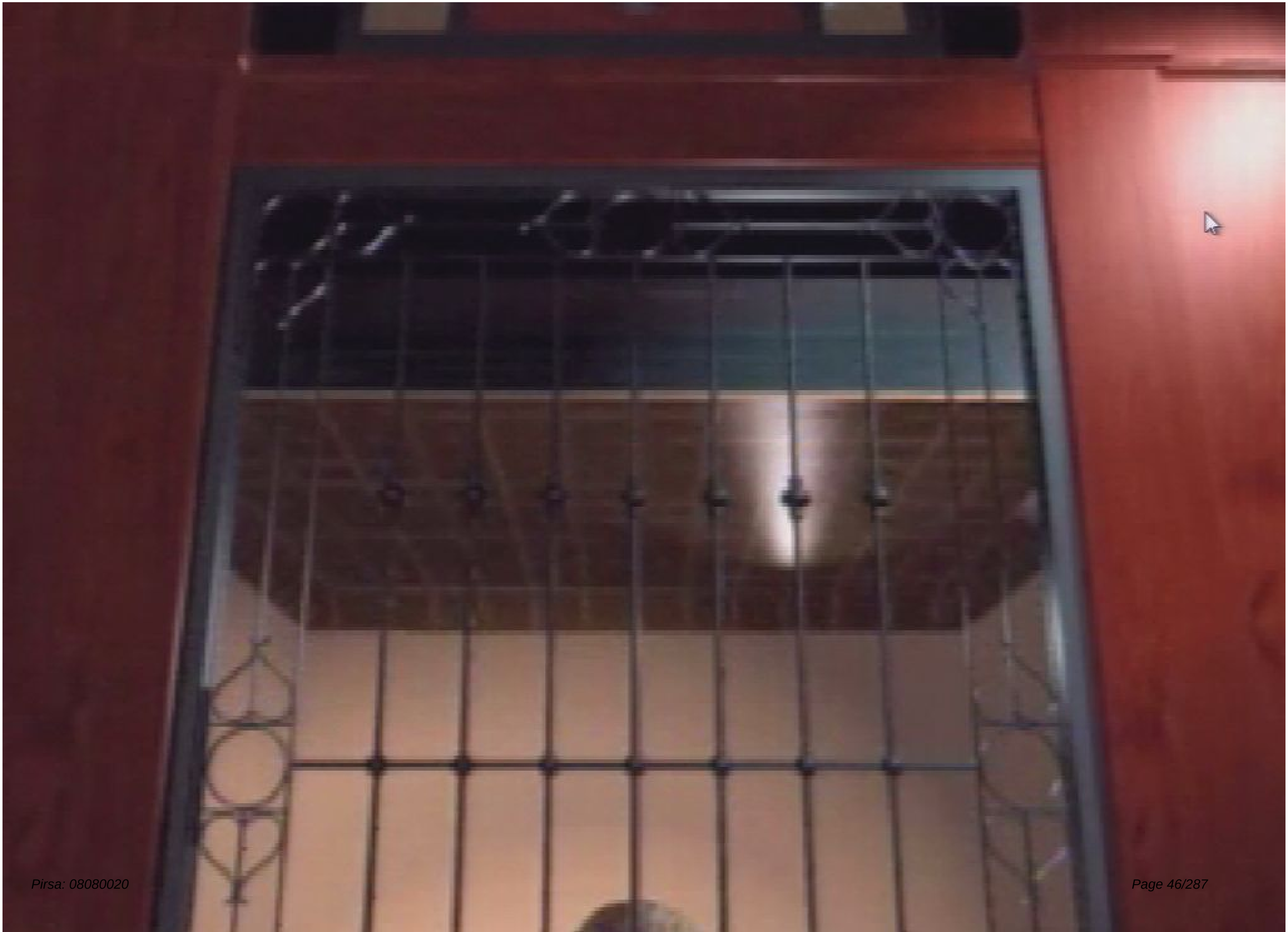


Einstein's Equivalence Principle

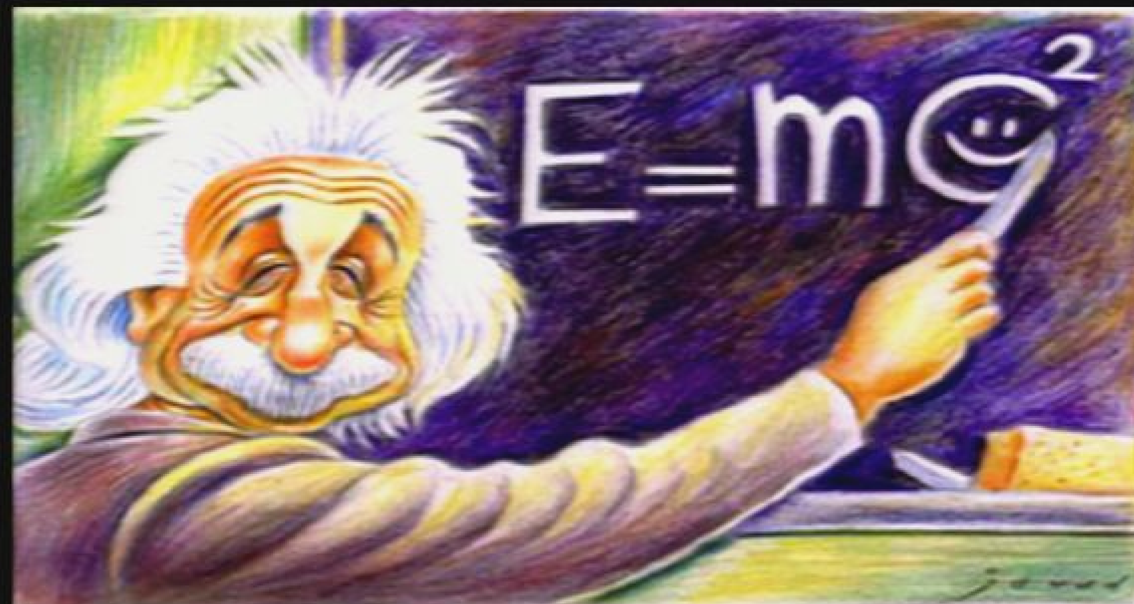
- There is no experiment that you can perform that will distinguish these two diagrams







Gravity as a Curvature of Spacetime



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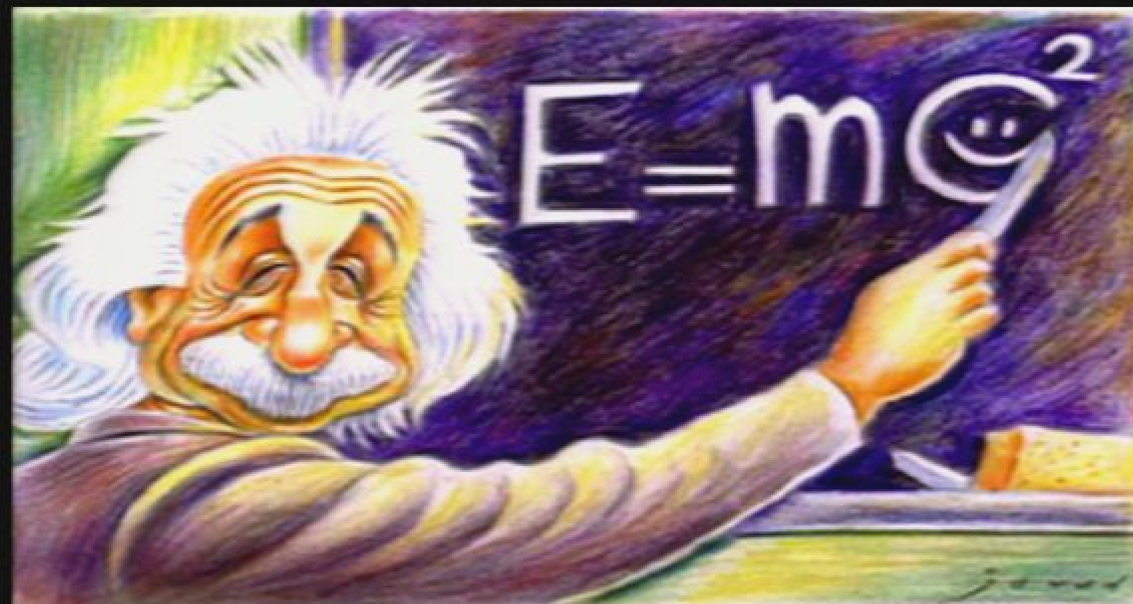

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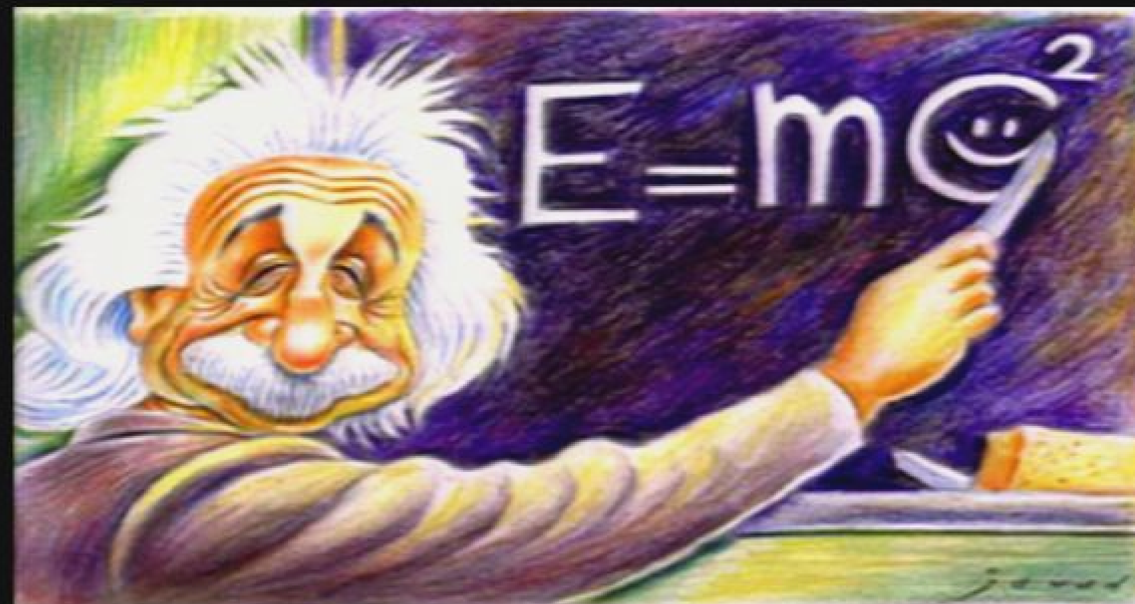

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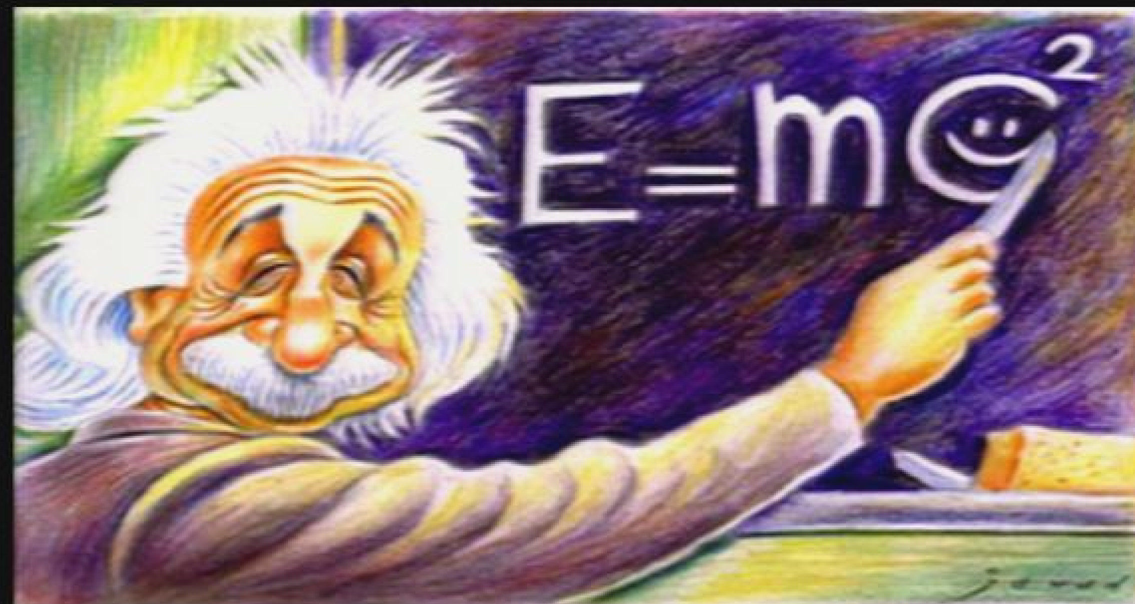

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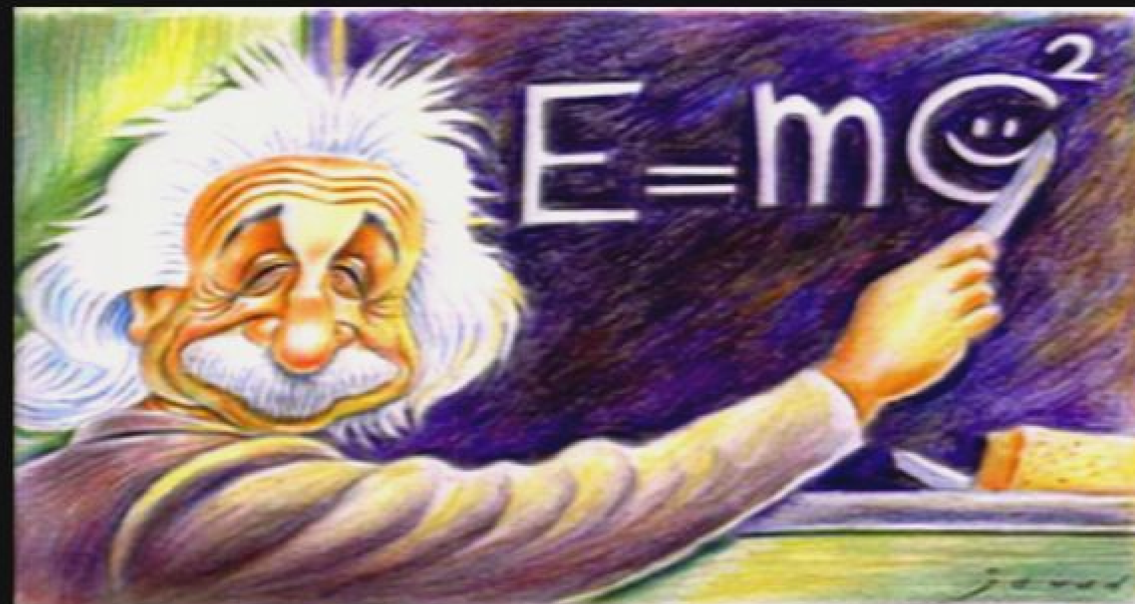

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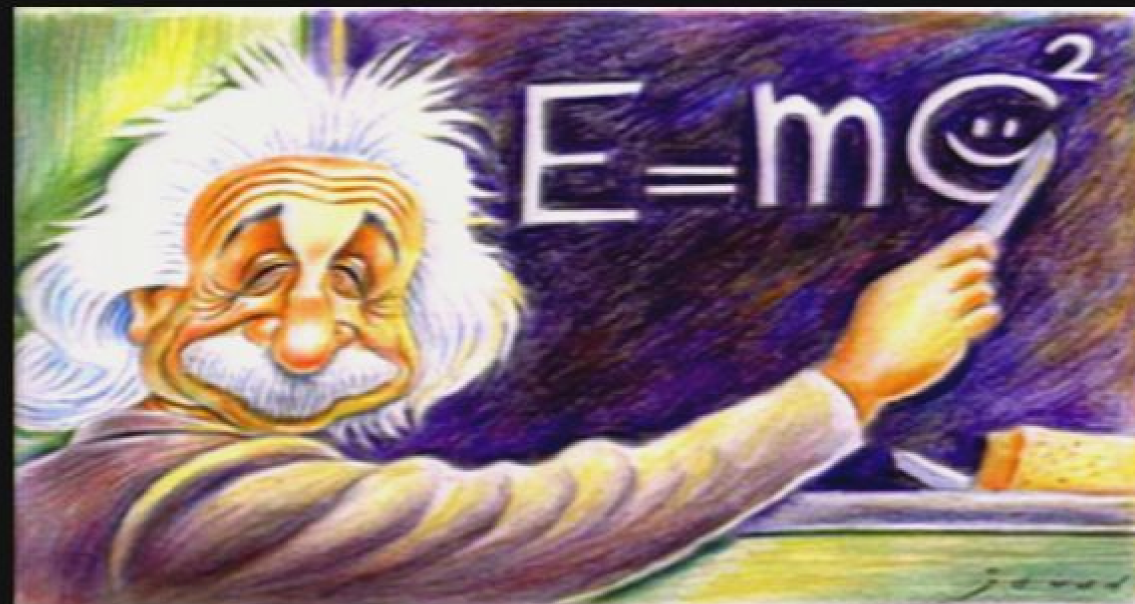

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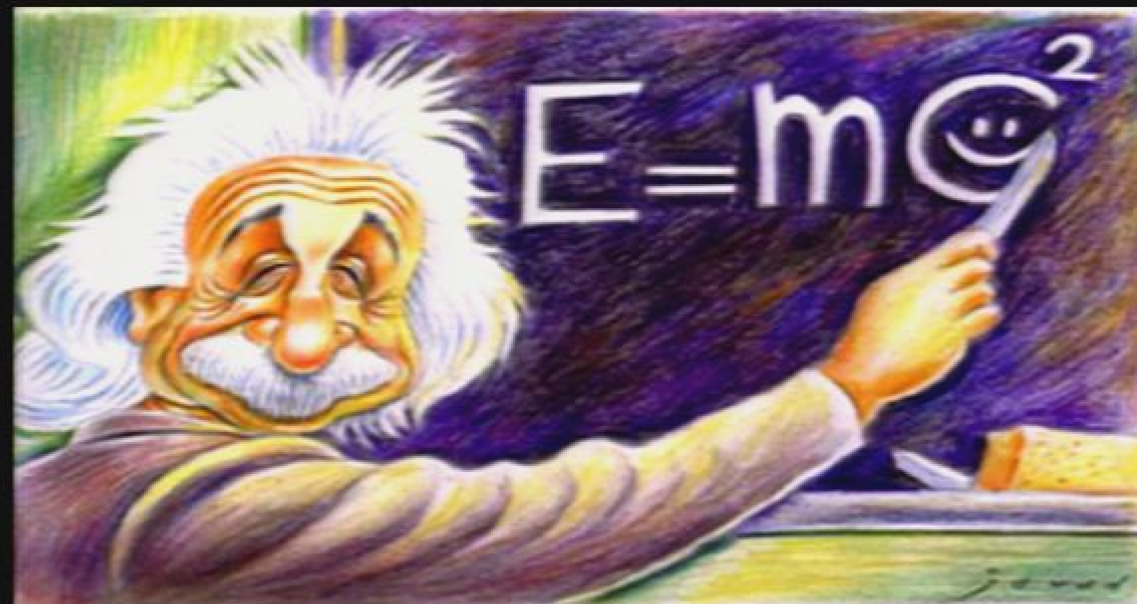

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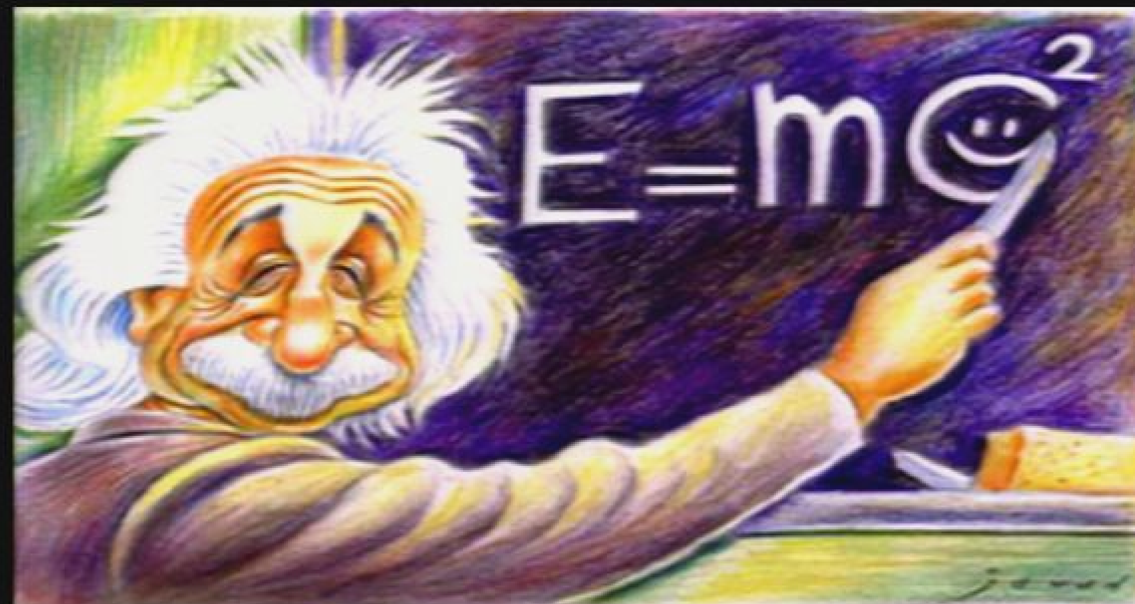

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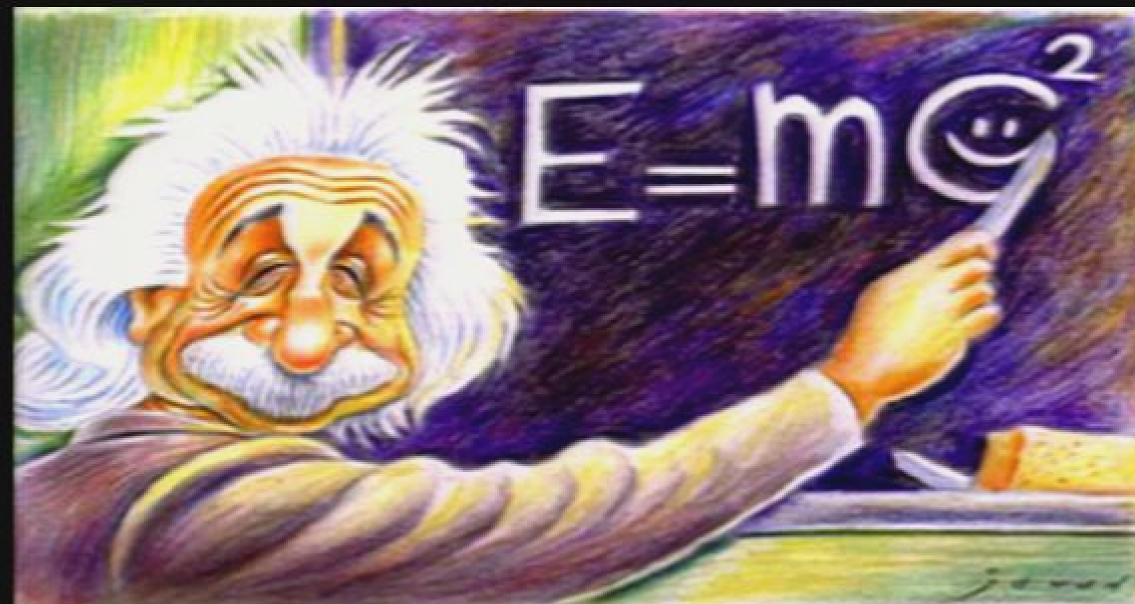

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Einstein Field Equation: another dissection

- 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:

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

Let's Review

SPACETIME

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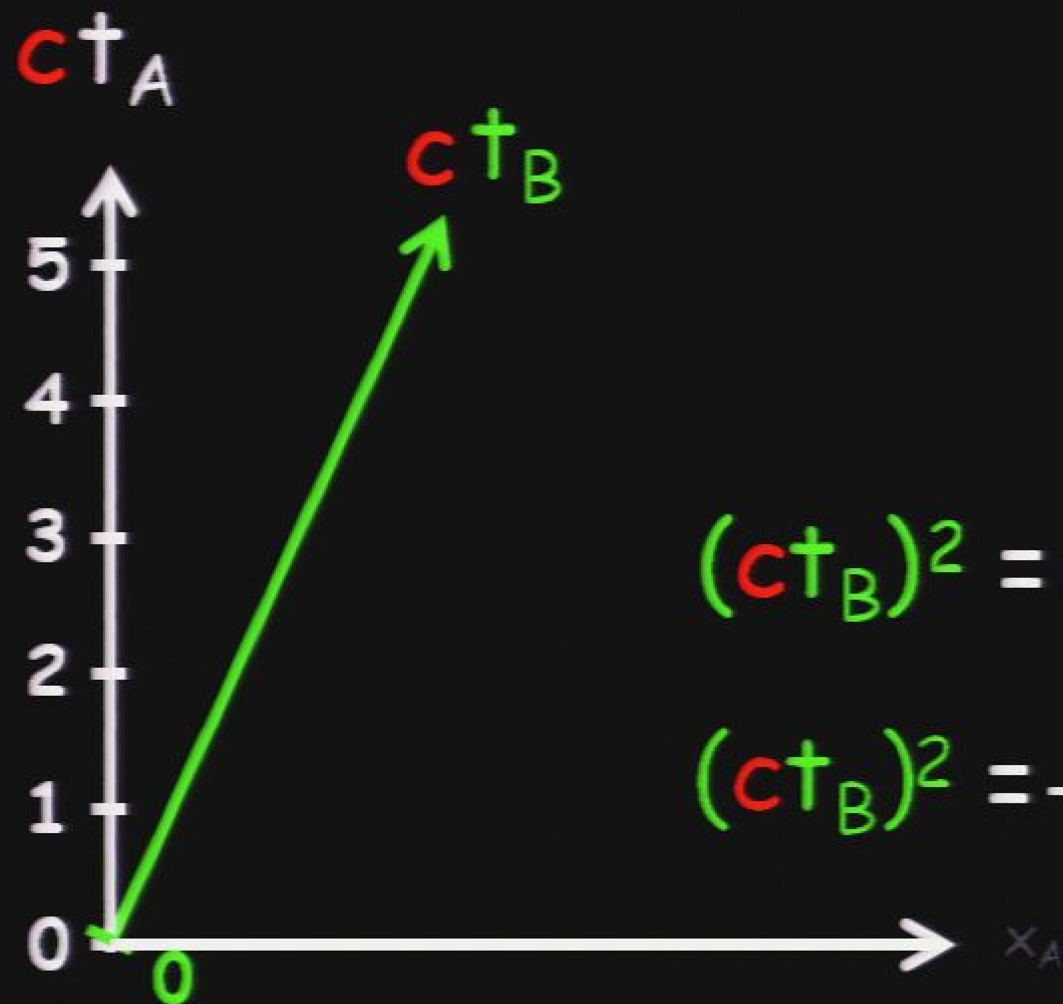
The Geometry of Spacetime



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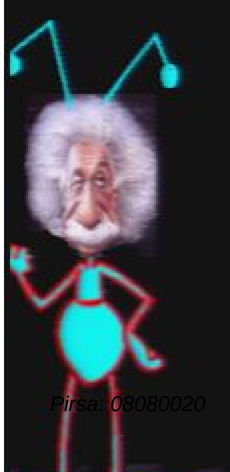
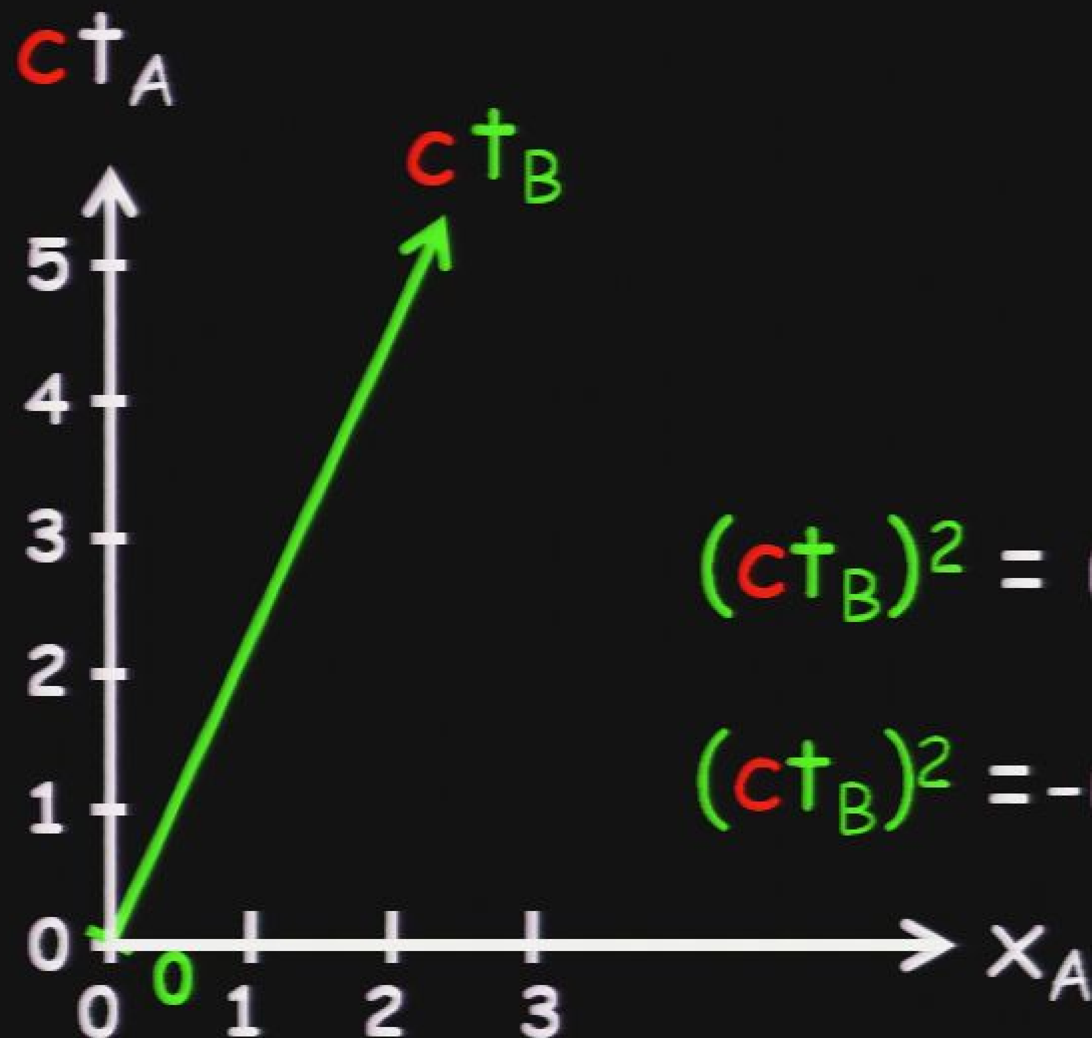


The Geometry of Spacetime



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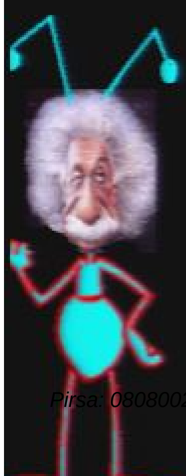

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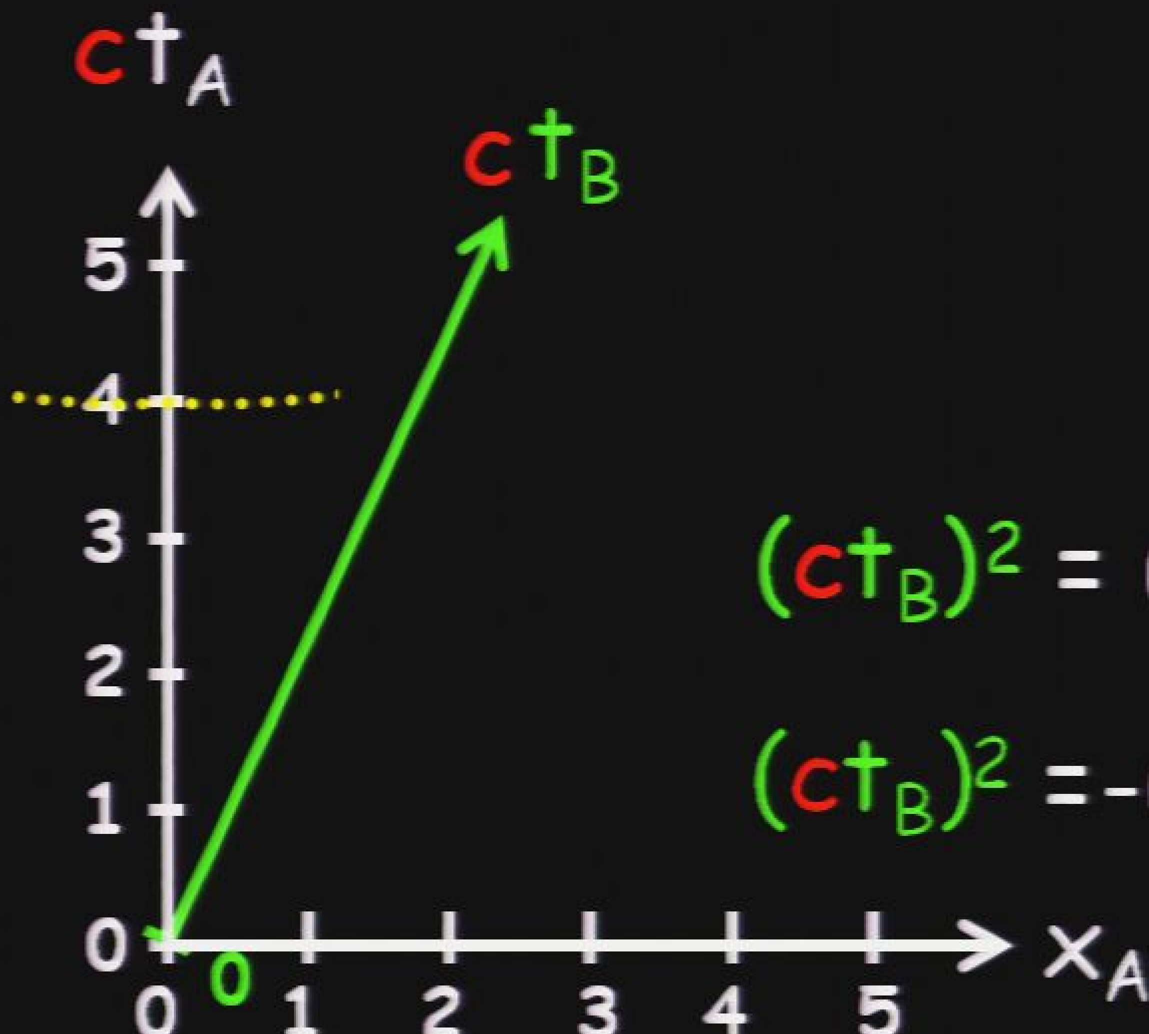

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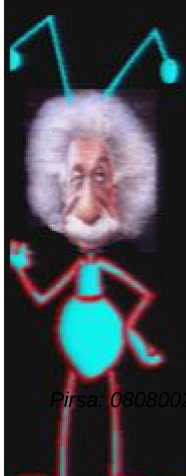

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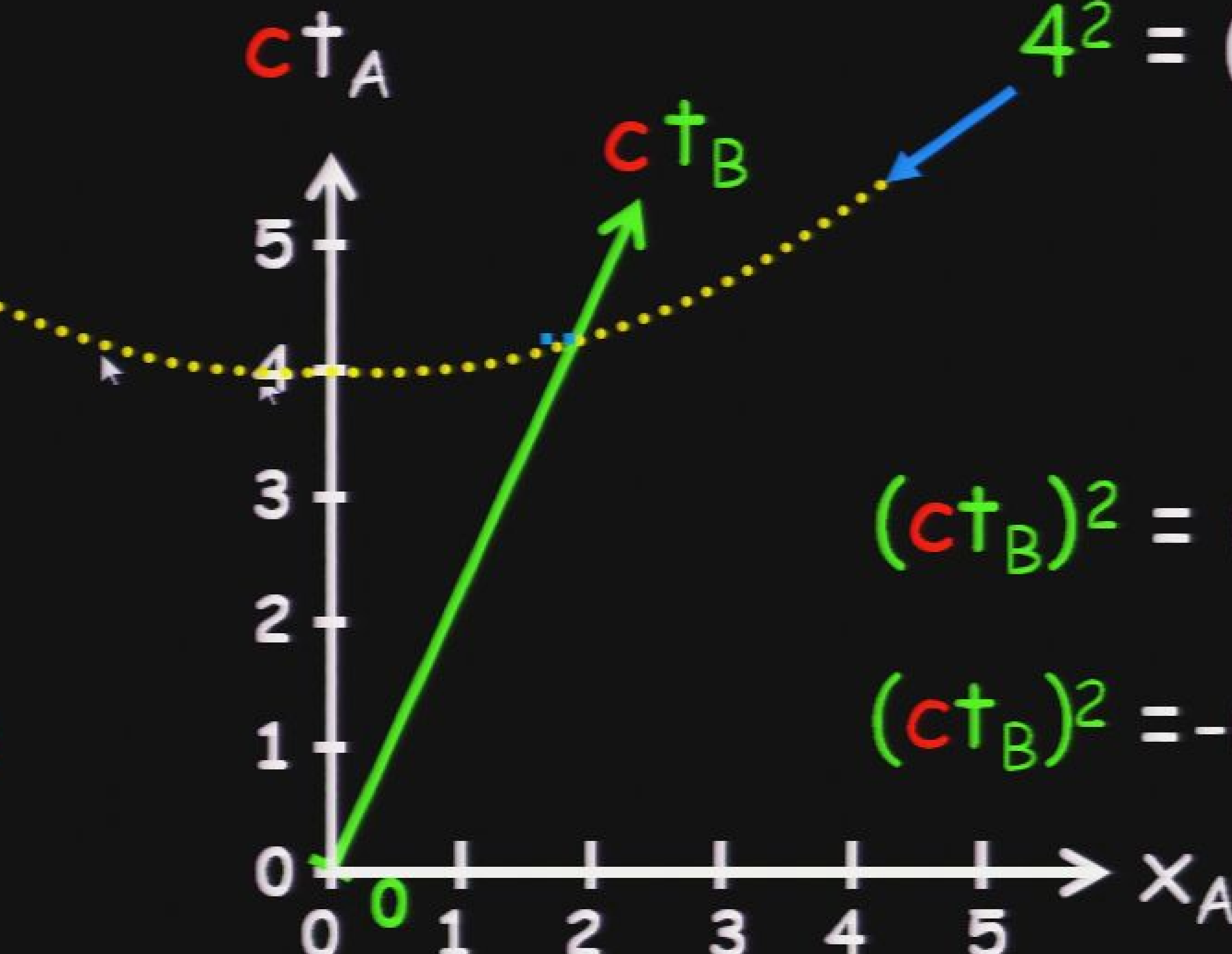

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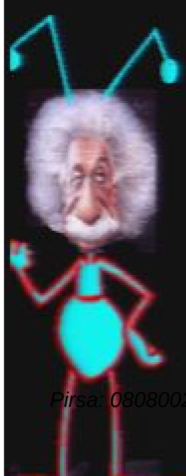

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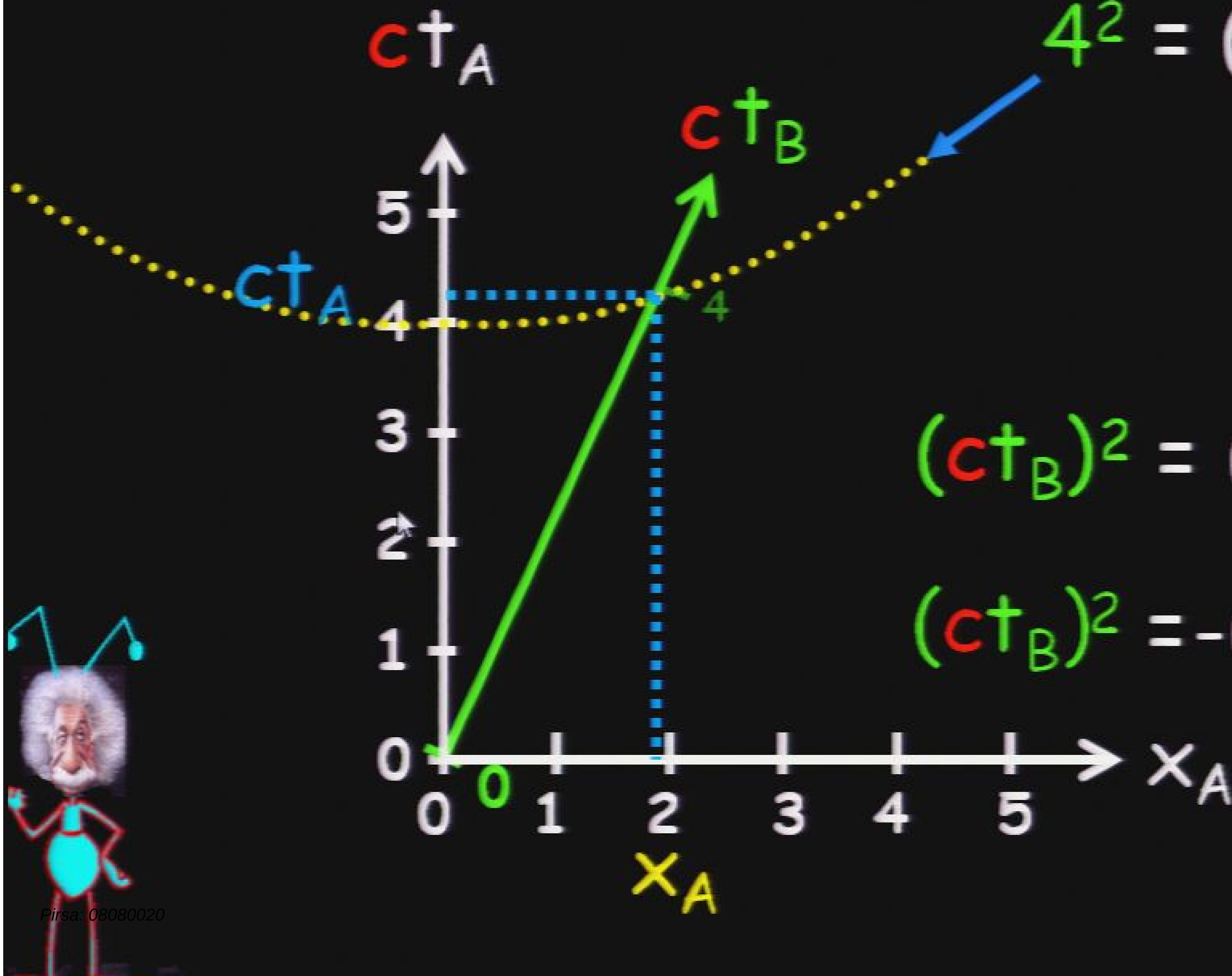

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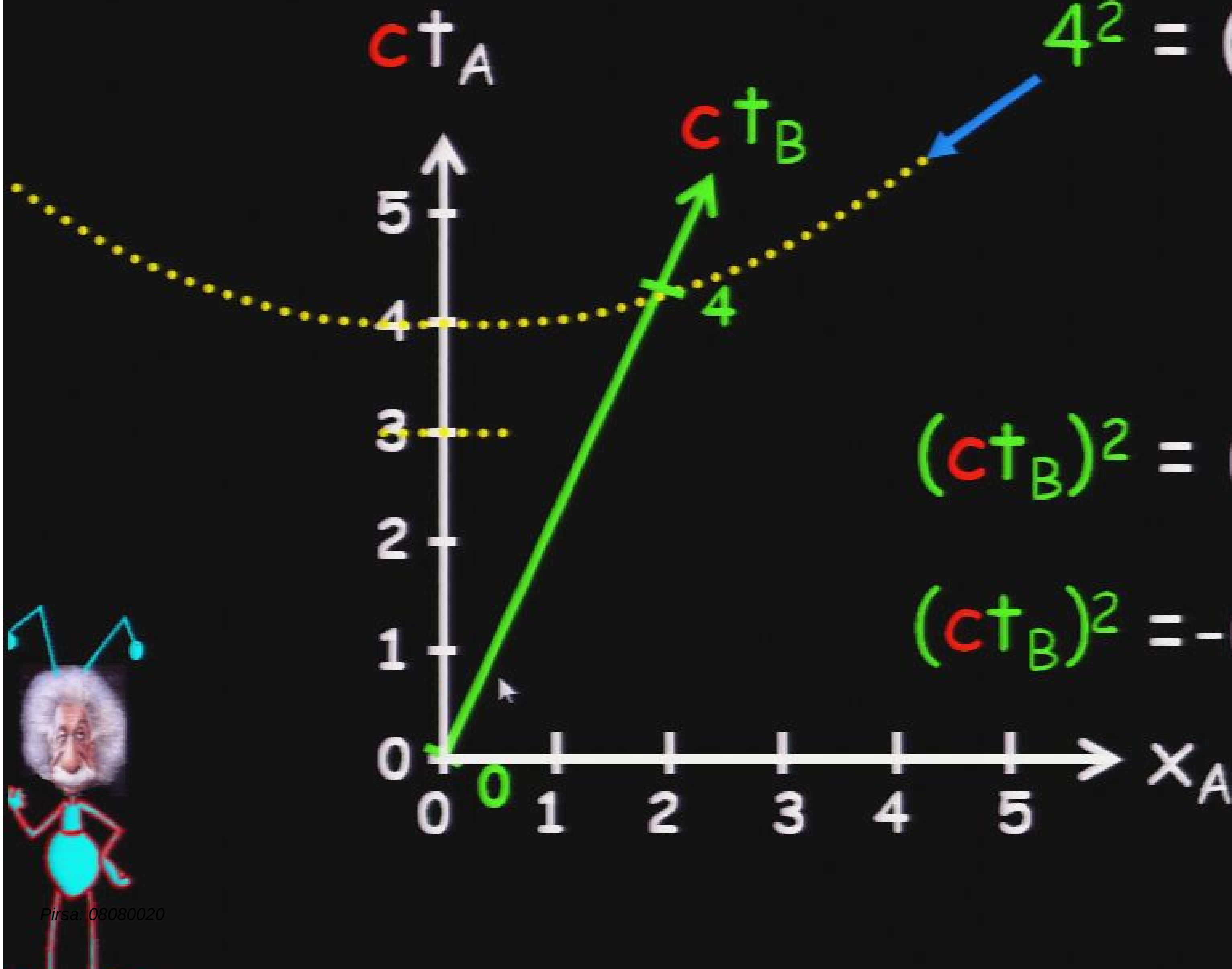

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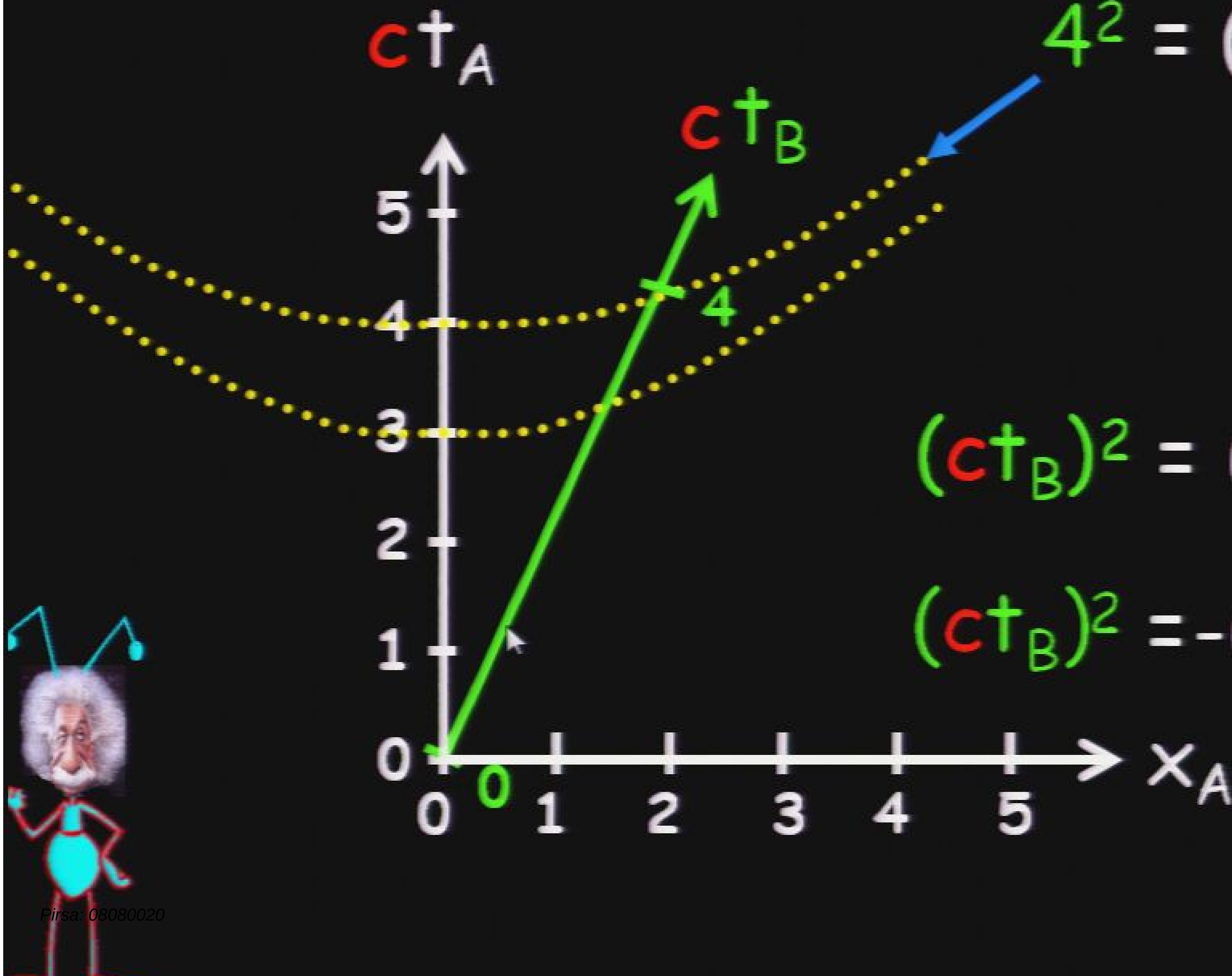

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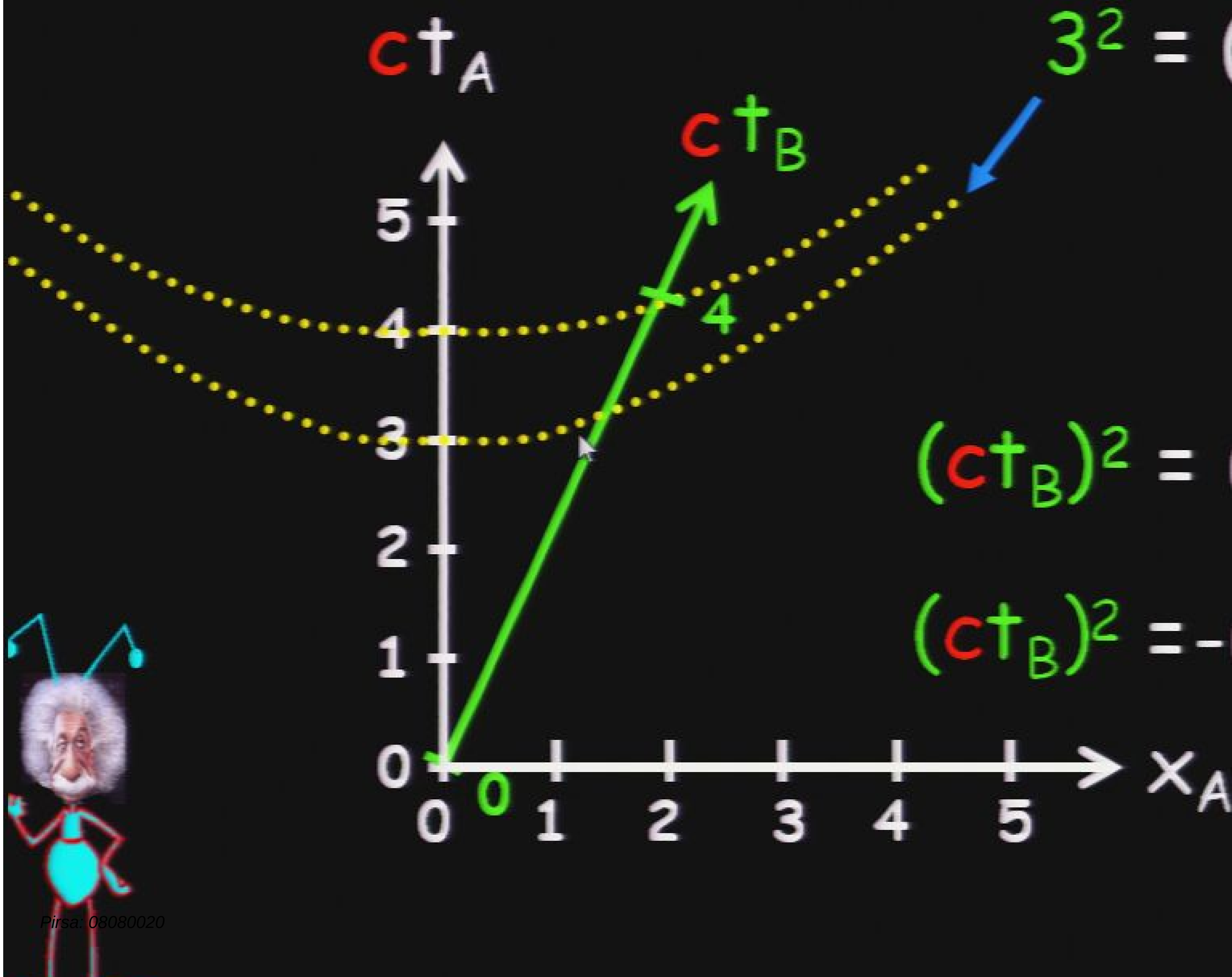
The Geometry of Spacetime



$$3^2 = (ct_A)^2 - x_A^2$$

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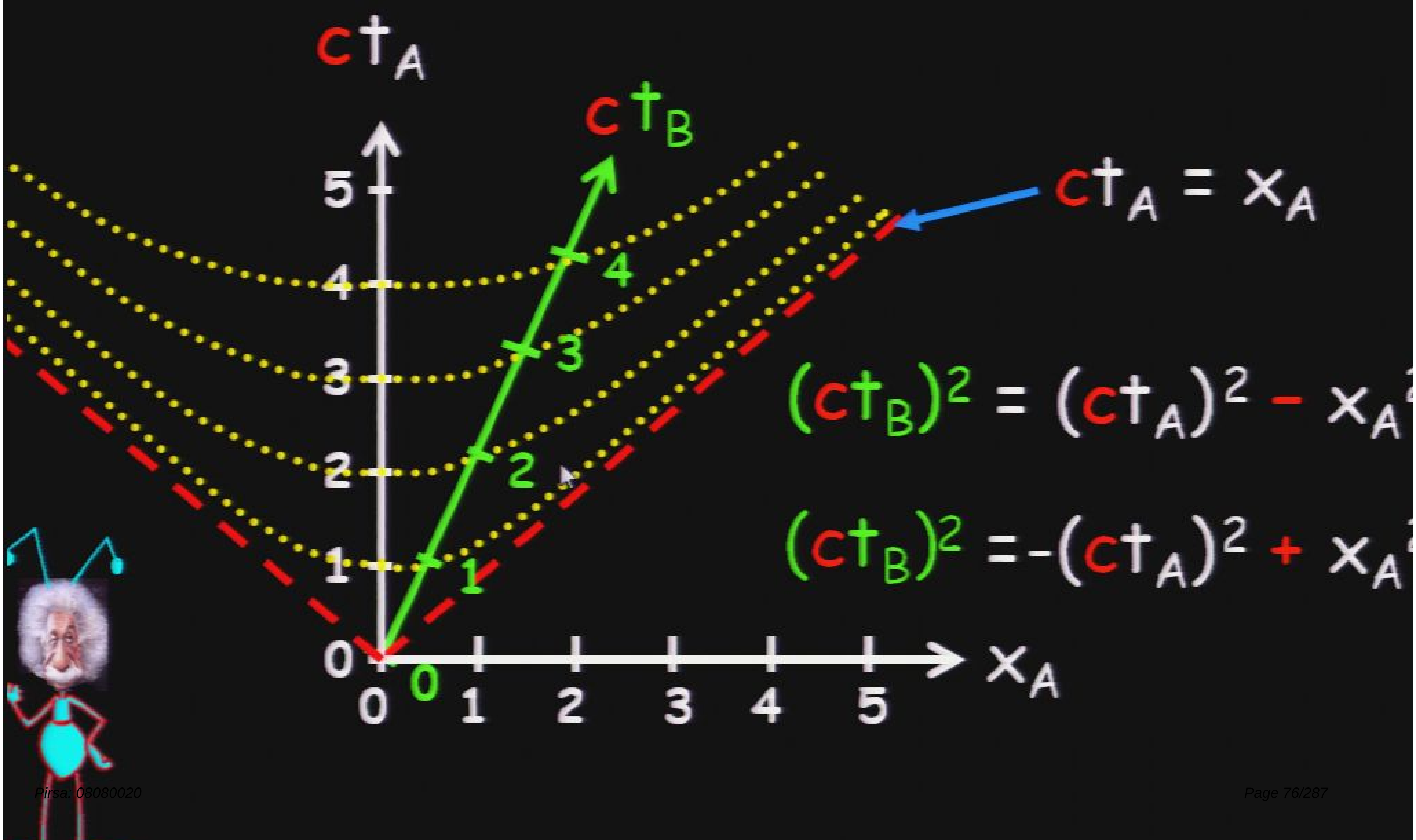
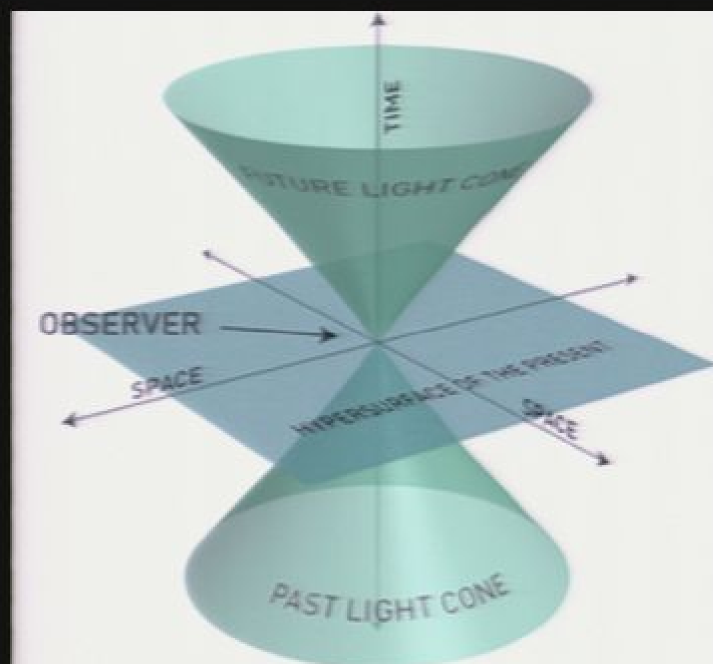


Spacelike, Null, Timelike

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* $P(t,x,y,z)$

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- *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 in one line:

The Geodesics

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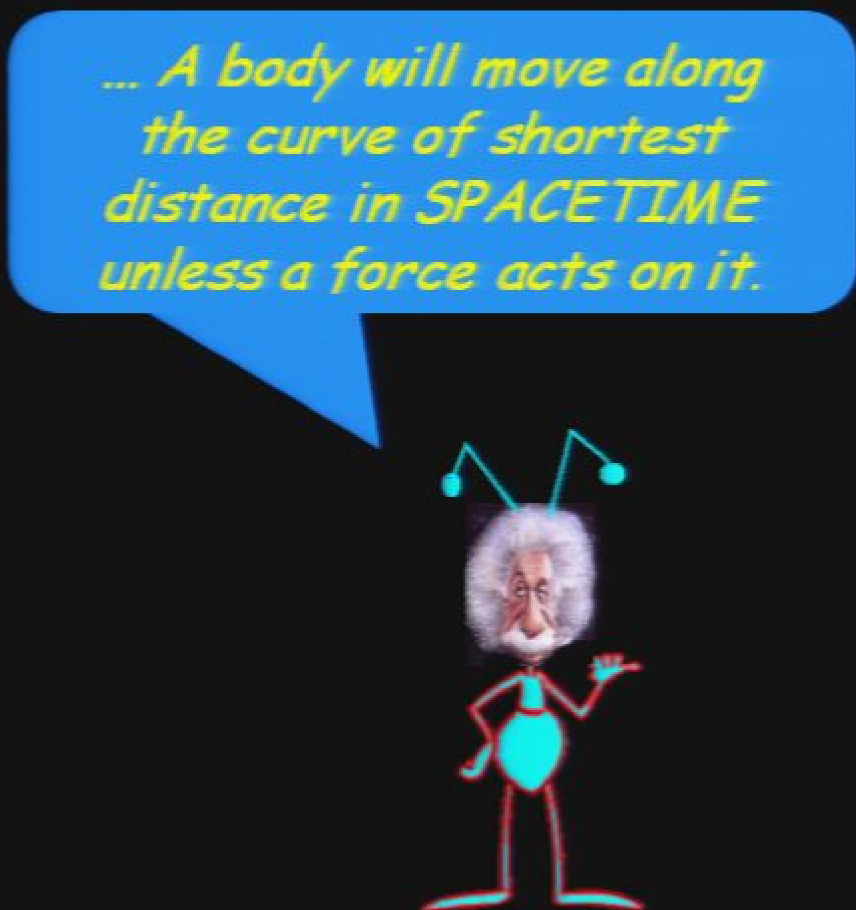

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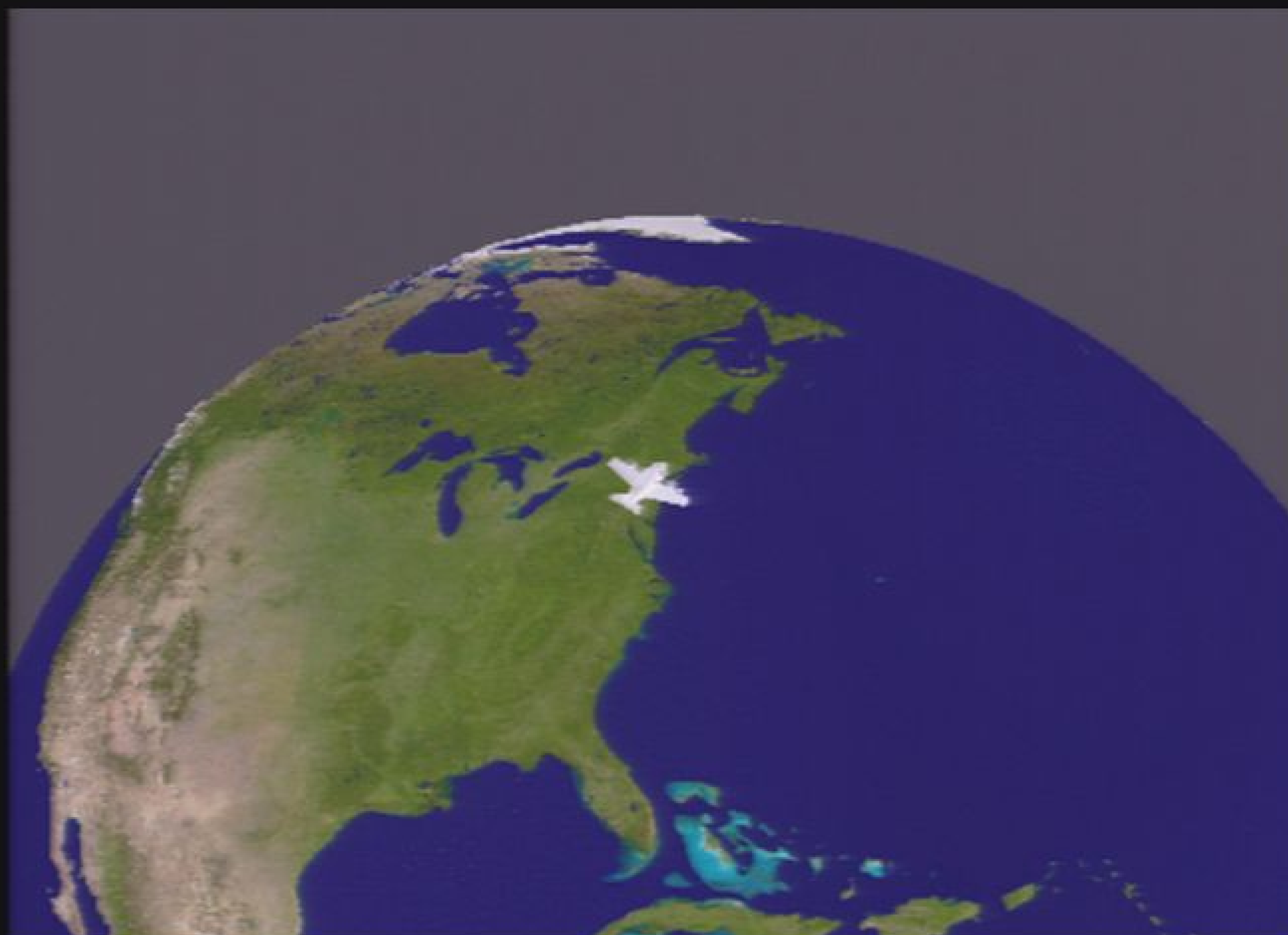
... A body will move along the curve of shortest distance in SPACETIME unless a force acts on it.

... 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



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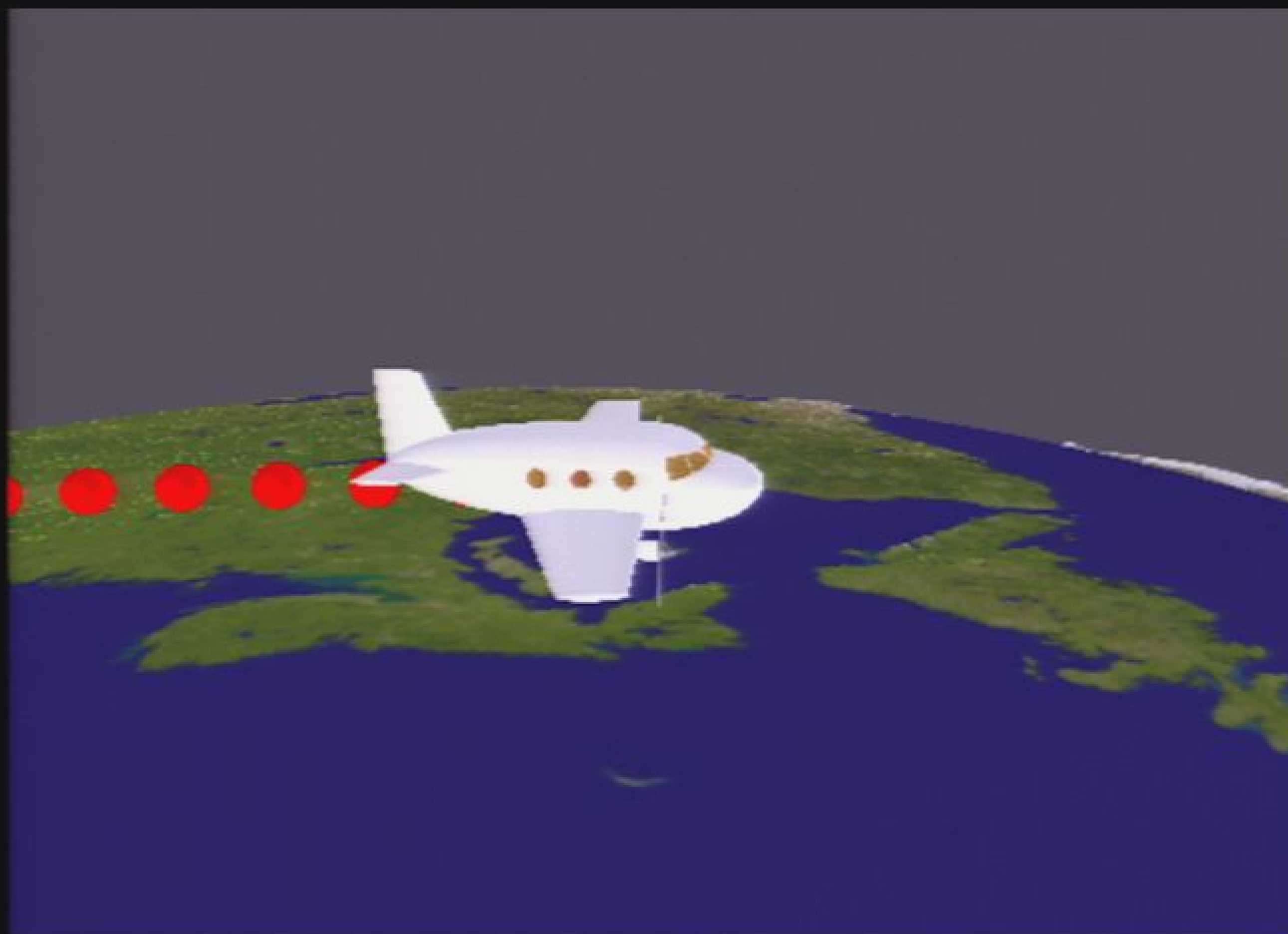

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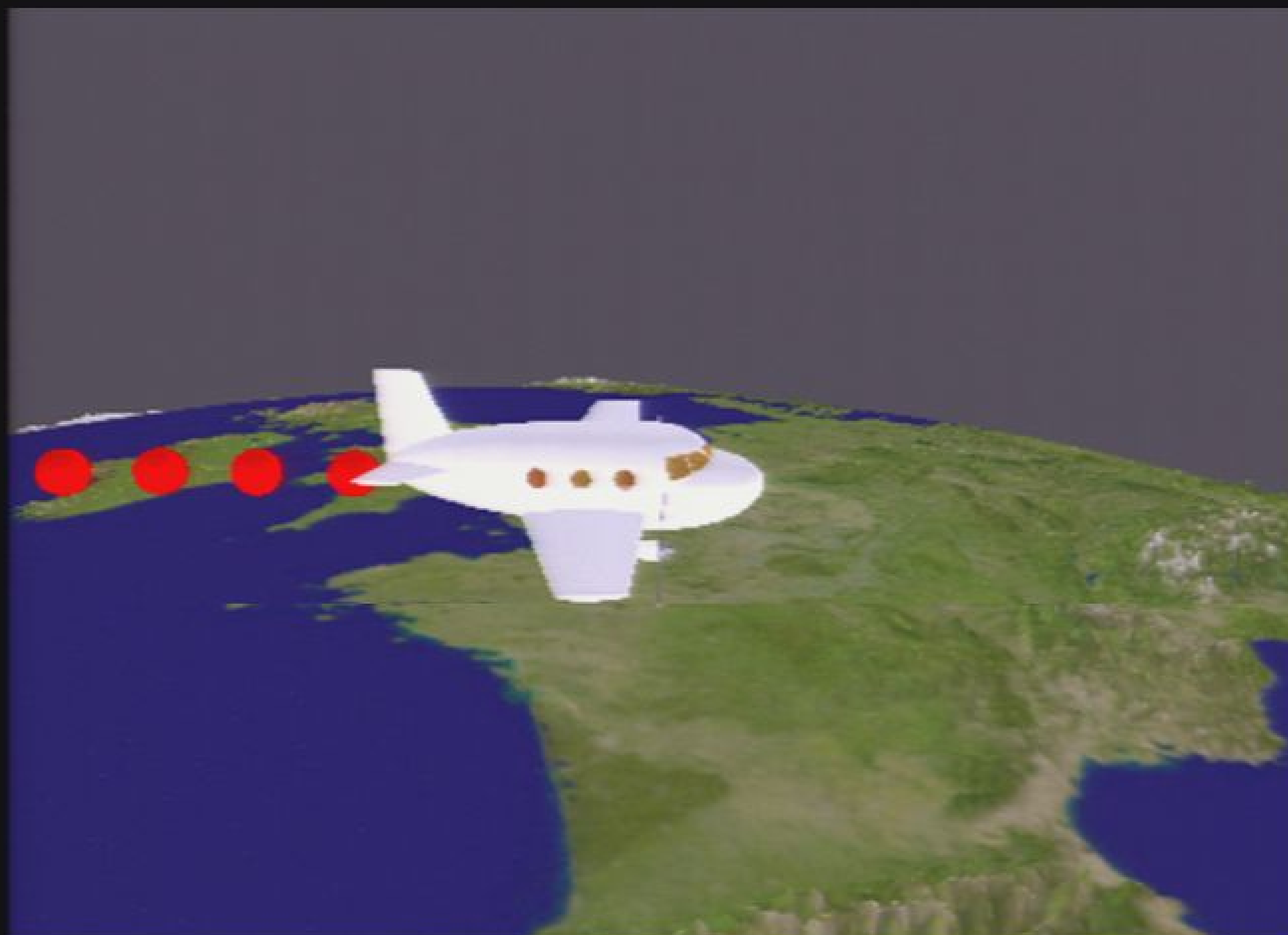

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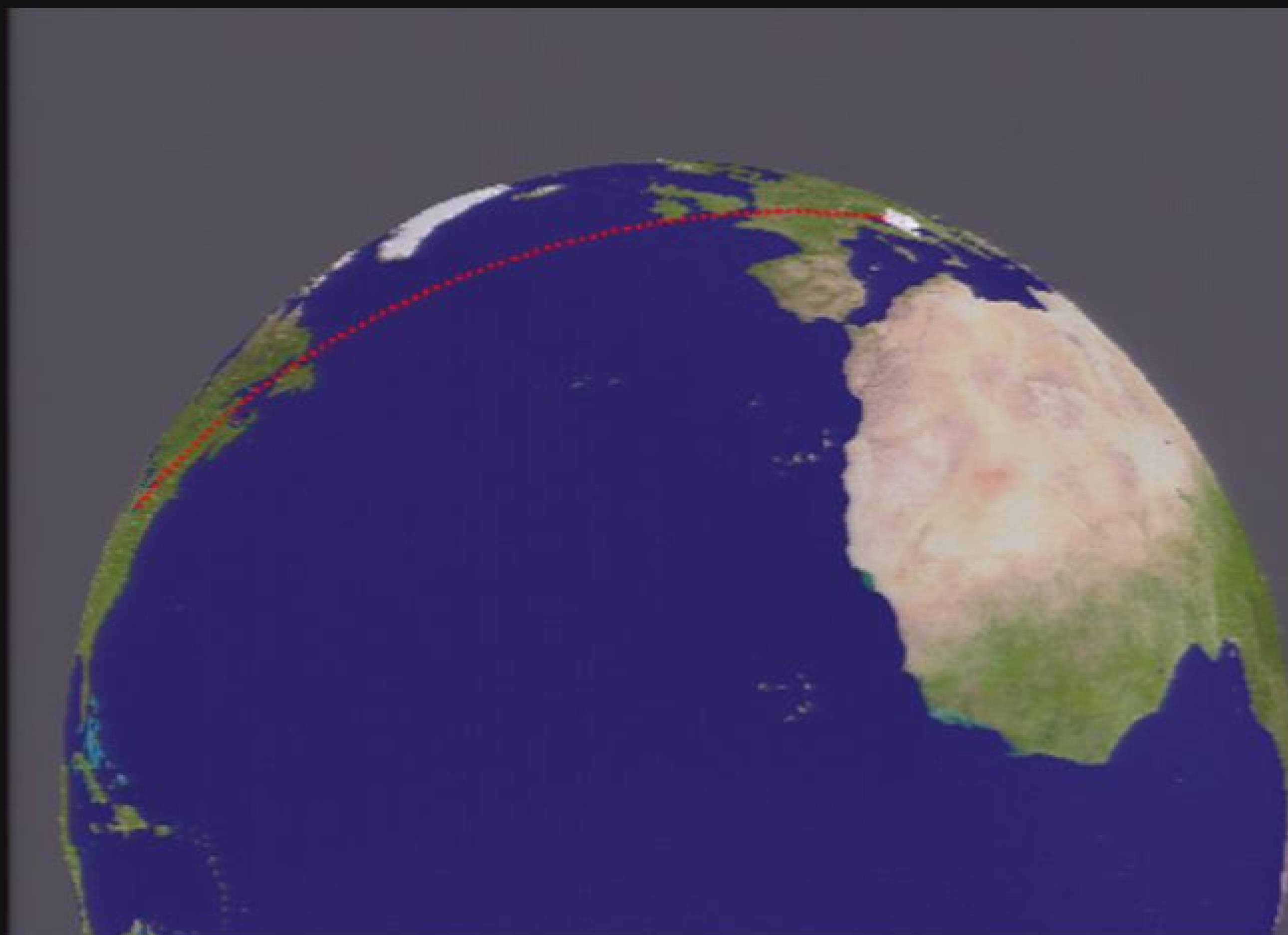

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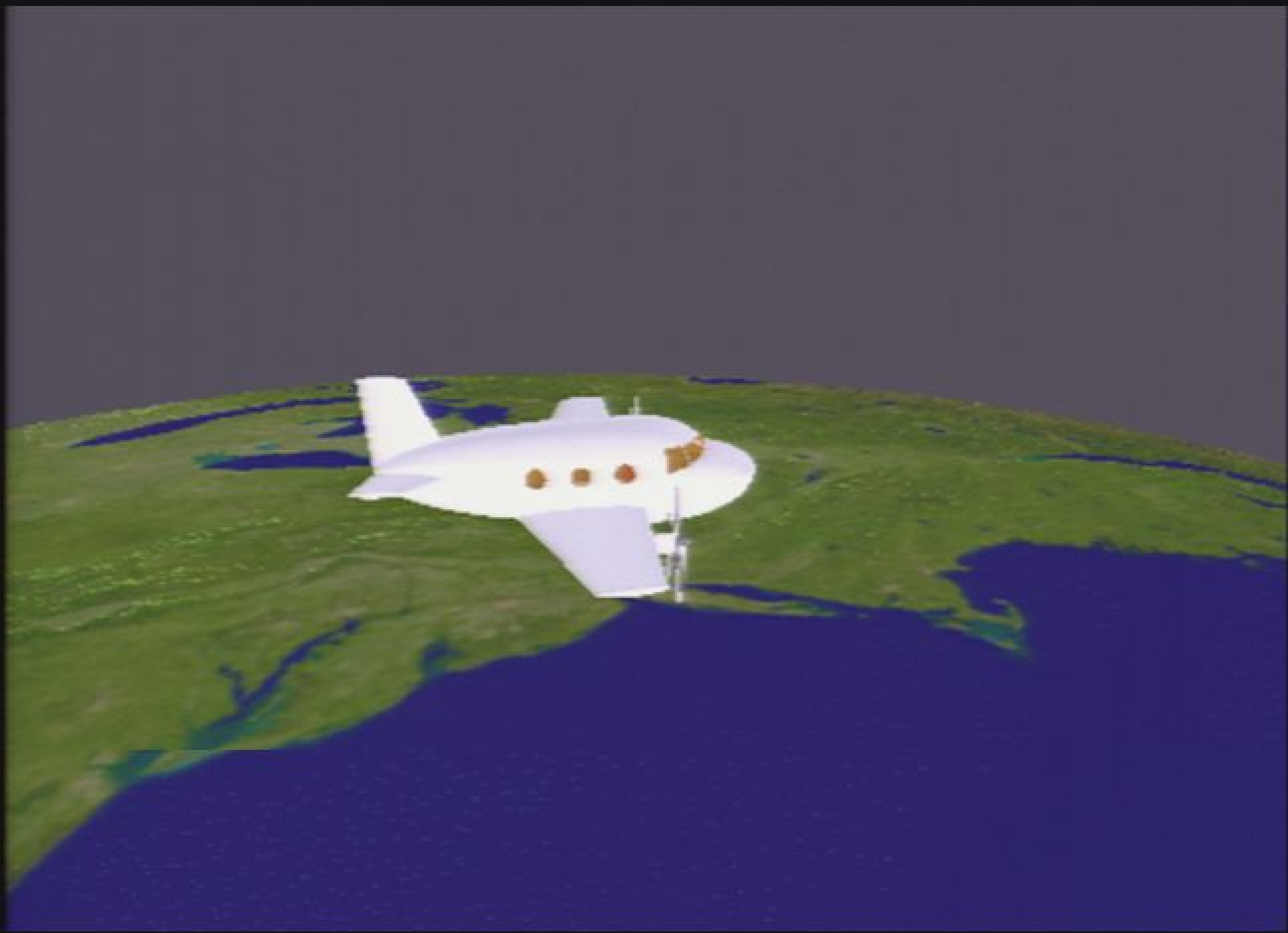

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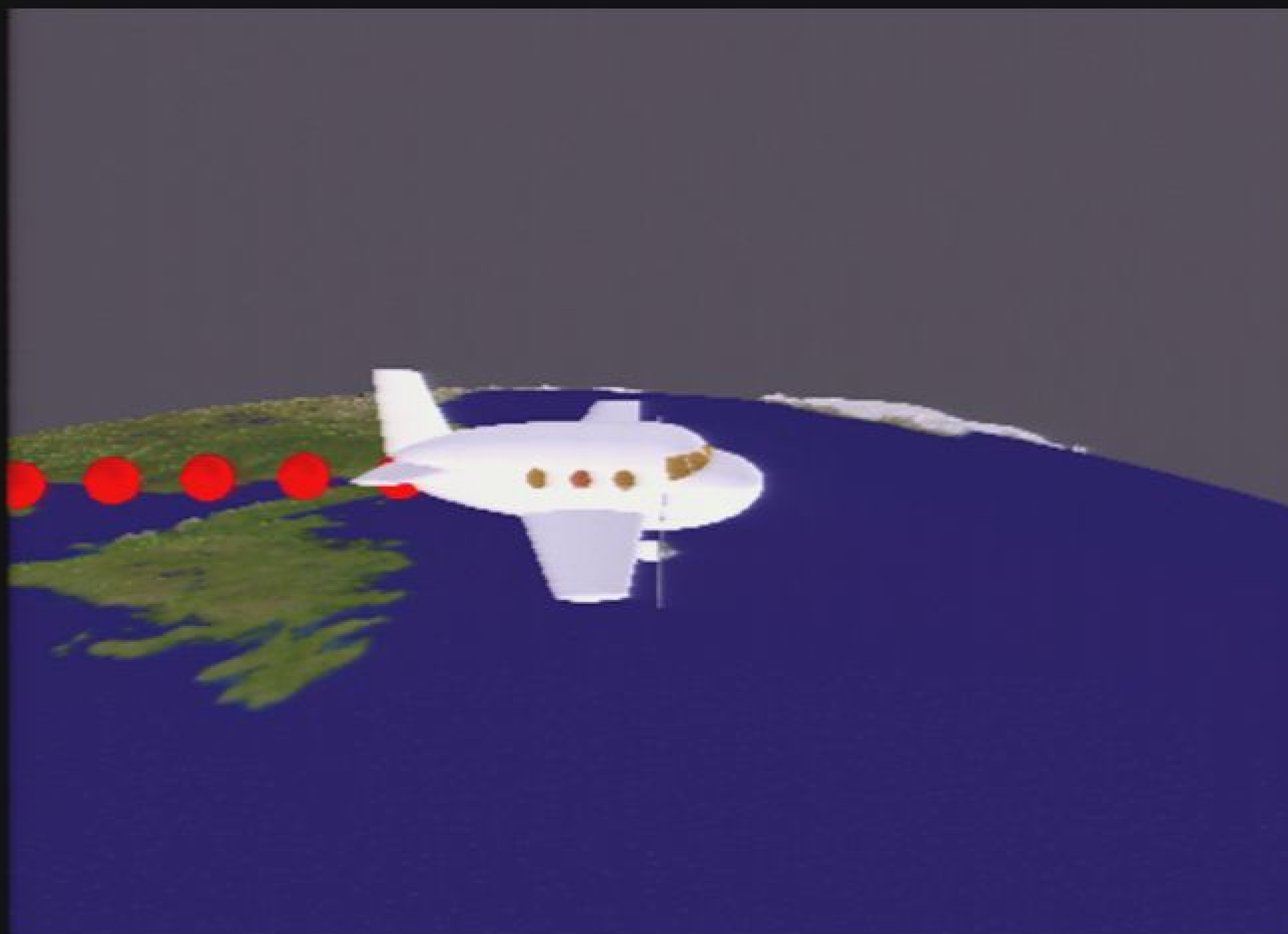

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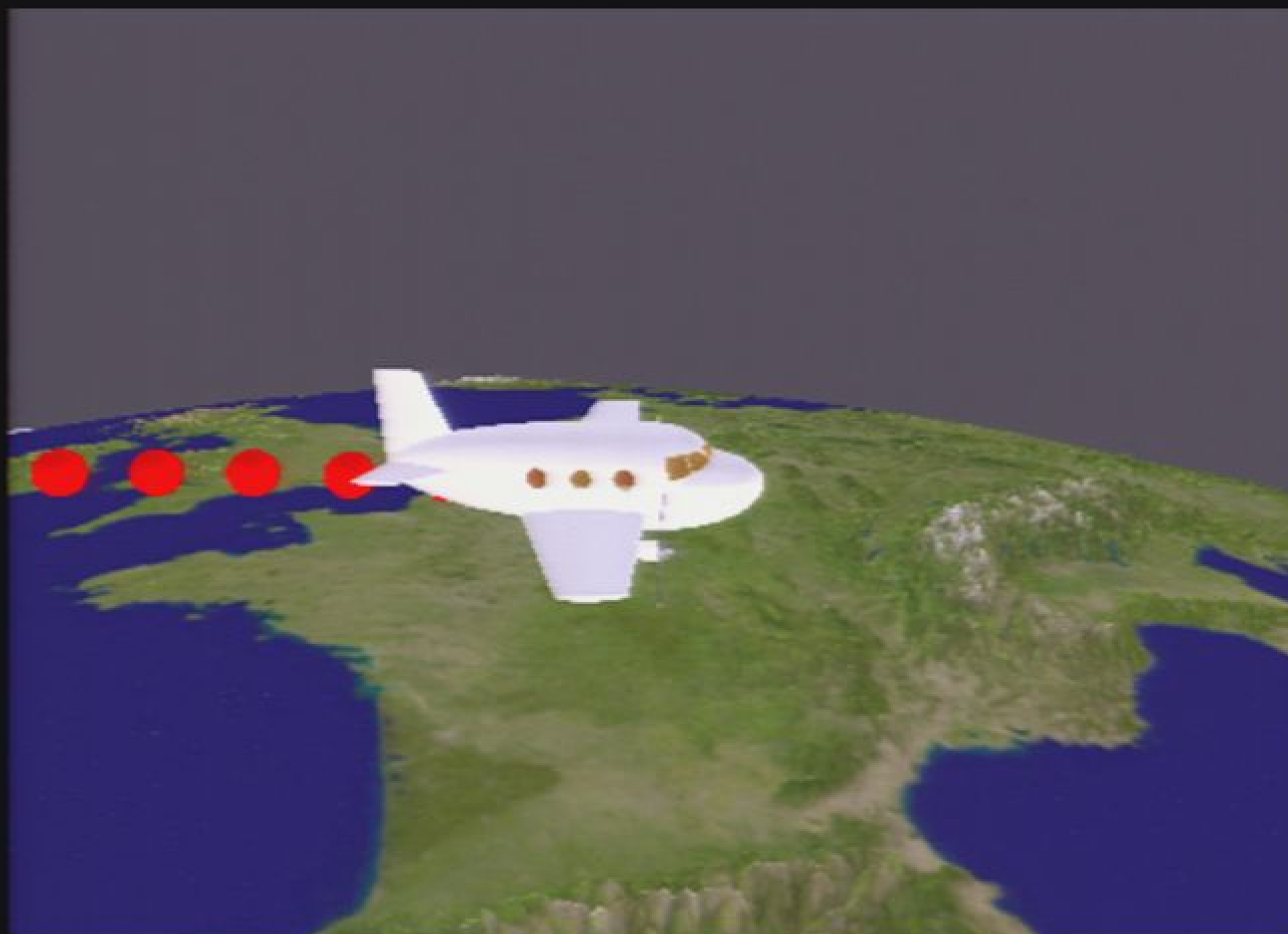

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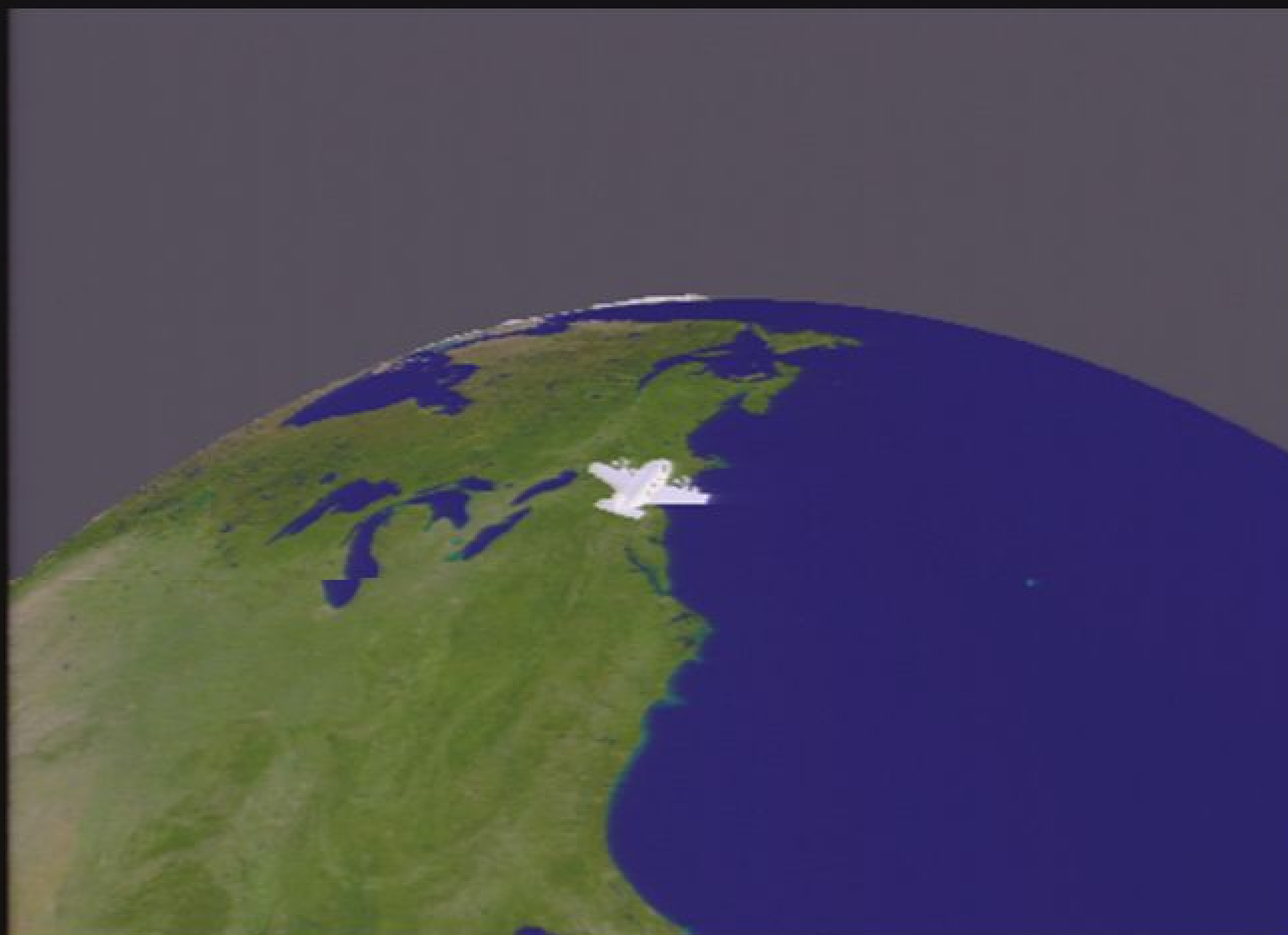

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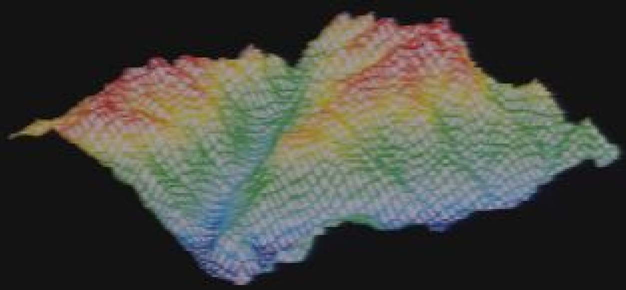

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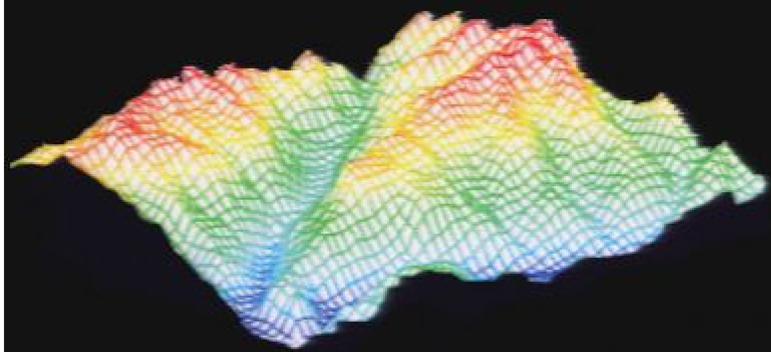

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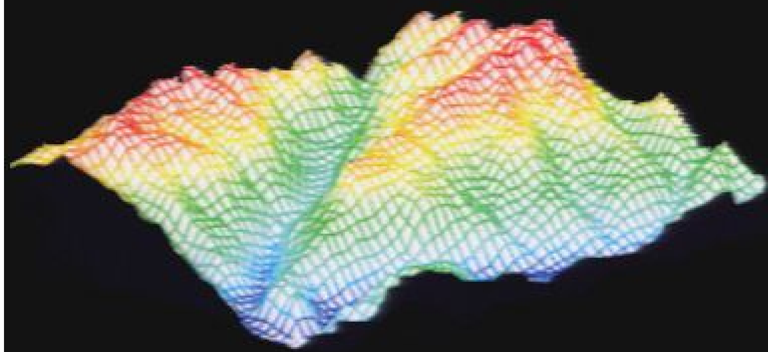

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...but I needed the distance in *SPACETIME*, so I used a mathematical quantity which converts the flat map distances into actual distances on our curved space. This is the *METRIC* of the space. Denoted by "*g*".

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.

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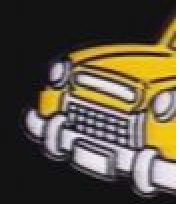

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The "taxi metric" can depend on time, it can depend on location.

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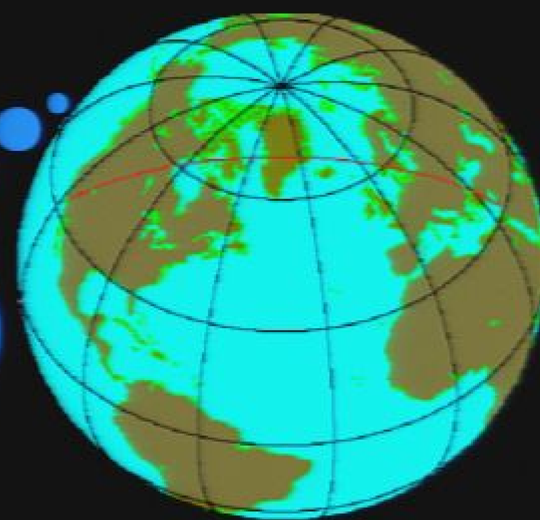

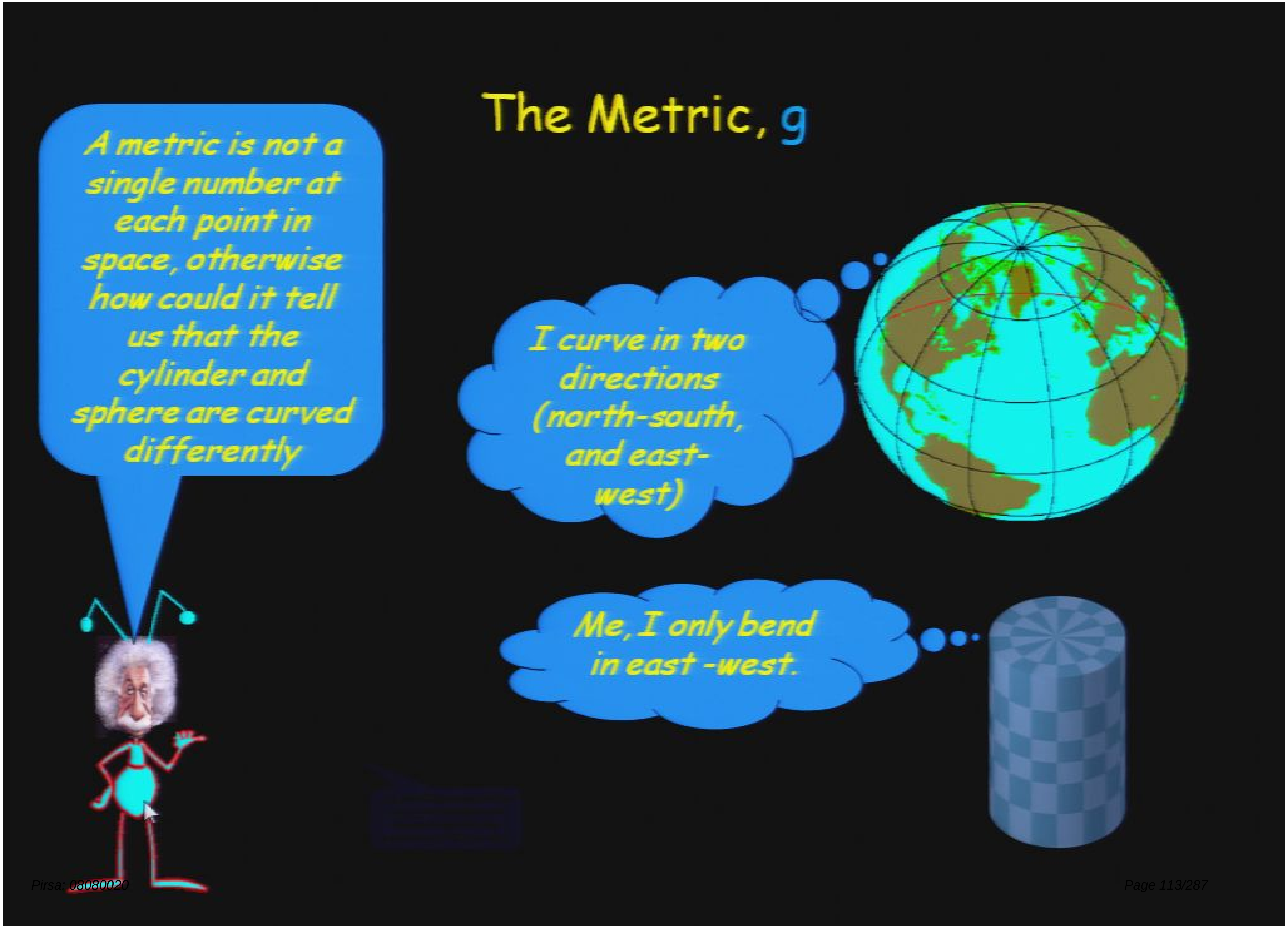
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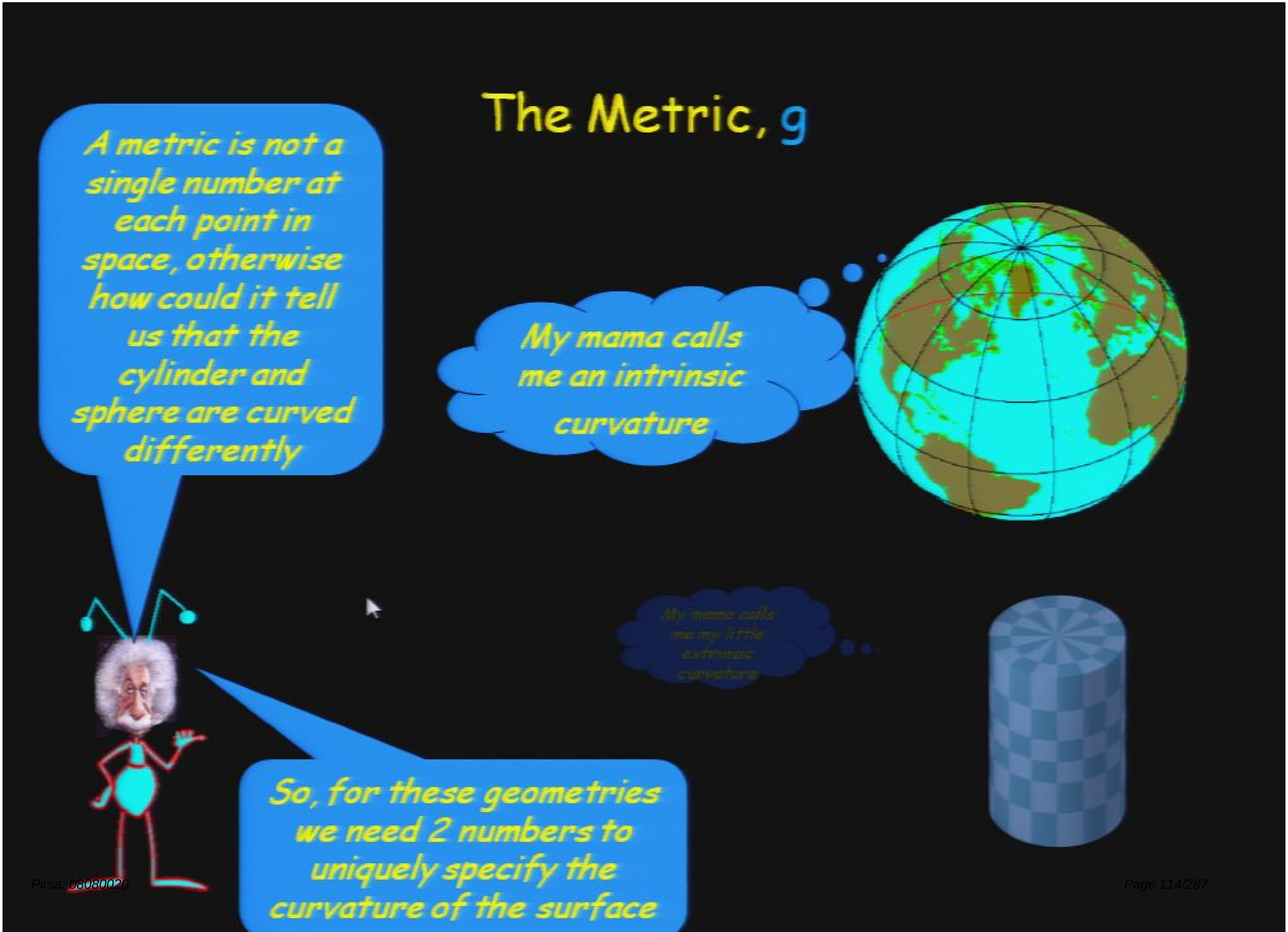
I curve in two directions (north-south, and east-west)
Me, I only bend in east -west.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My mama calls me an intrinsic curvature
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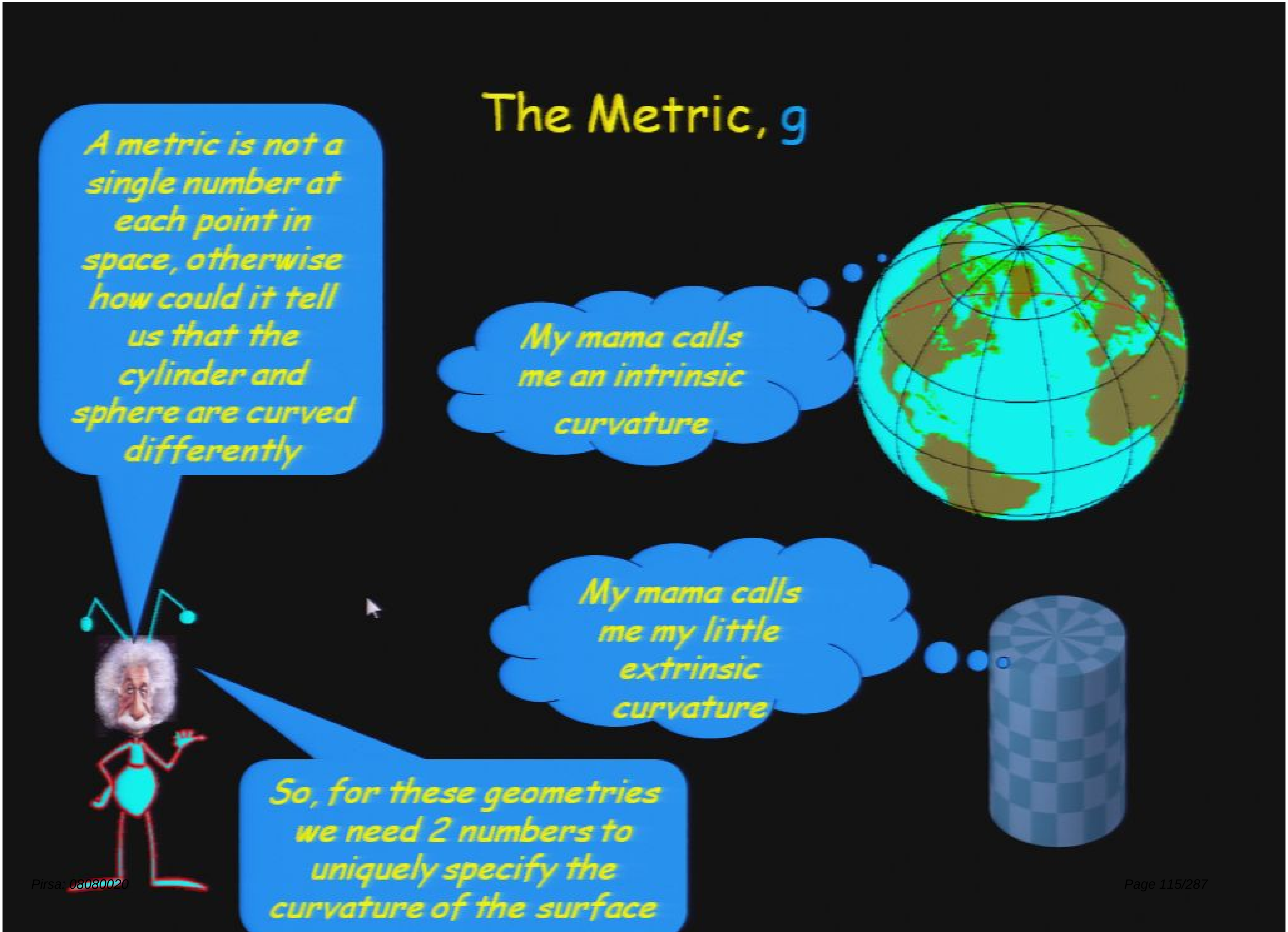
So, for these geometries we need 2 numbers to uniquely specify the curvature of the surface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2- tensor is a matrix of 4x4=16 numbers

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

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

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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

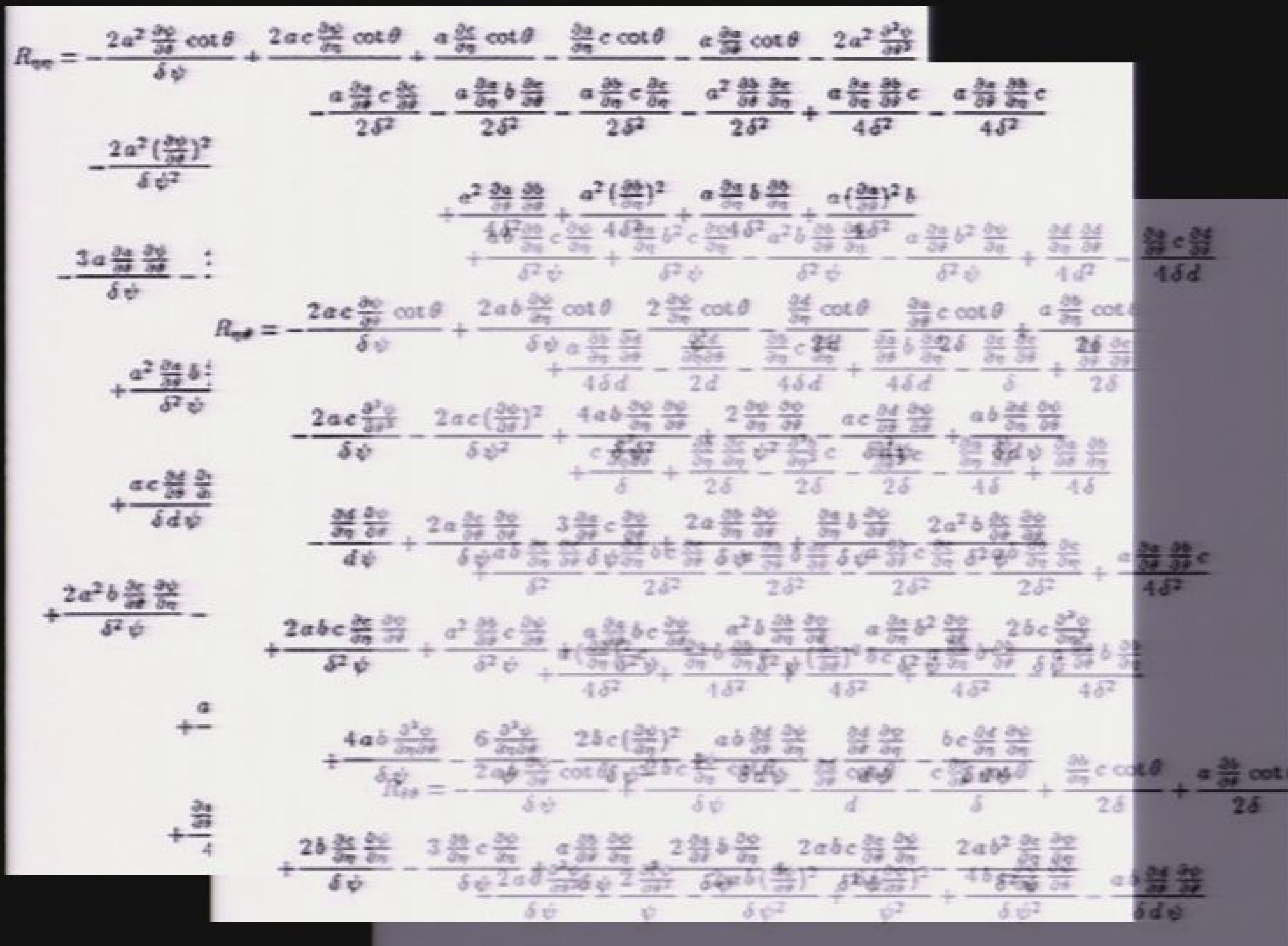
The EFE is a tensor equation relating a set of symmetric 4 x 4 tensors. Einstein's equations are actually 16 equations in the form: $G_{11} = 8\pi T_{11} + \Lambda g_{11}$

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:

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

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

... and just a little bit more.



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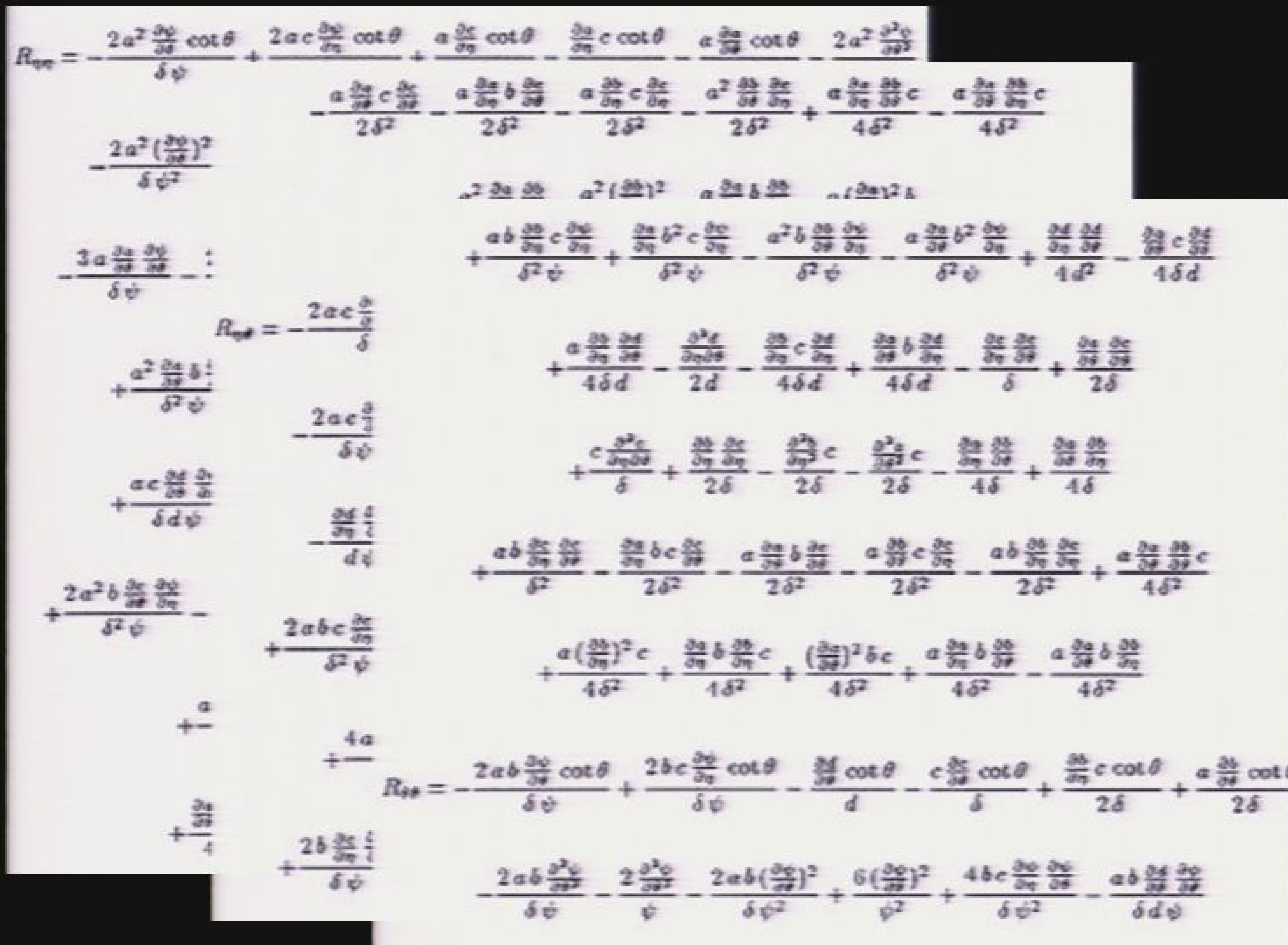


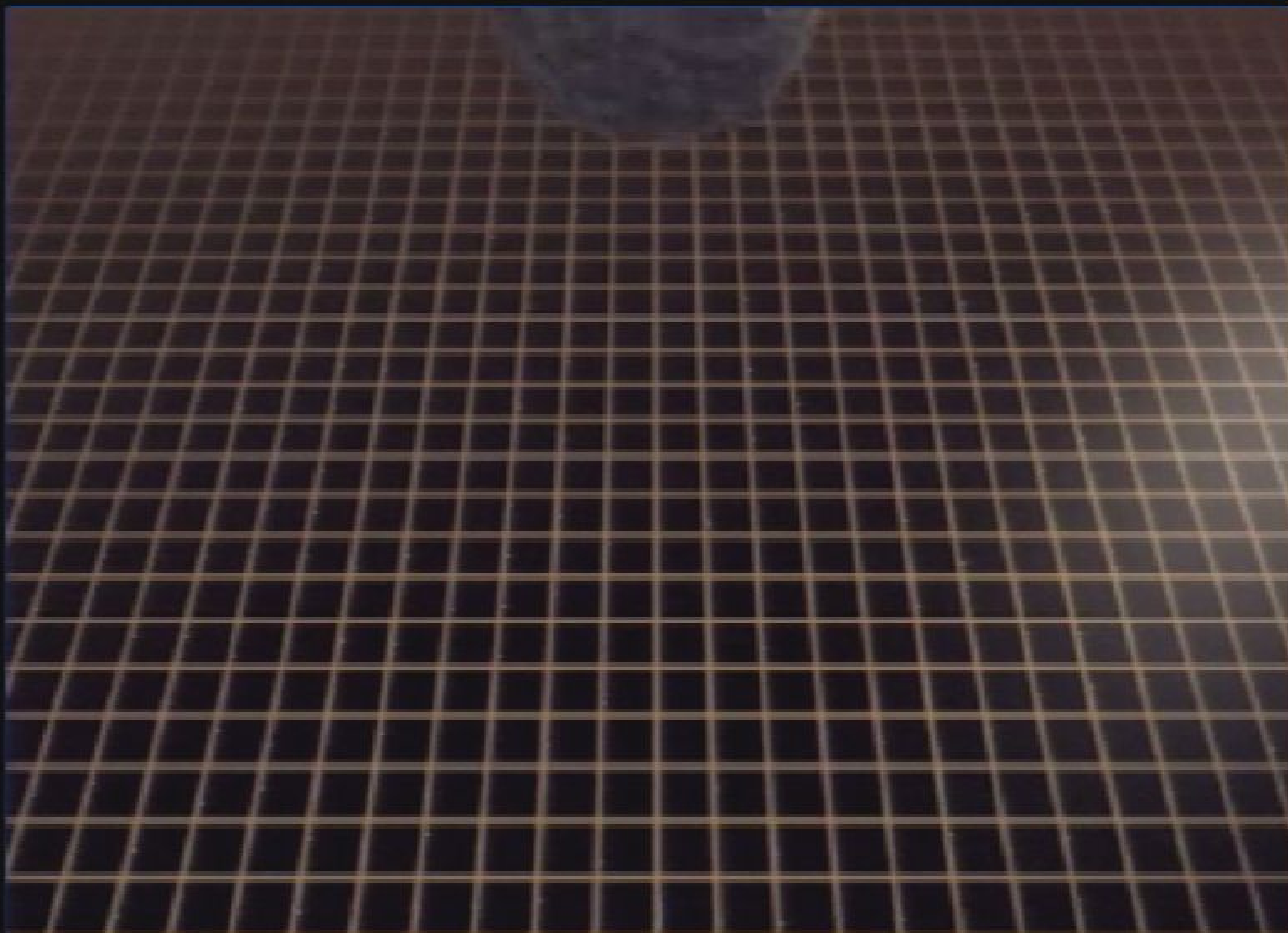
This is a general expression for Ricci tensor R_{mn} in only two dimensions, with axial symmetry.

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

What does all this say?

Curvature

Curvature



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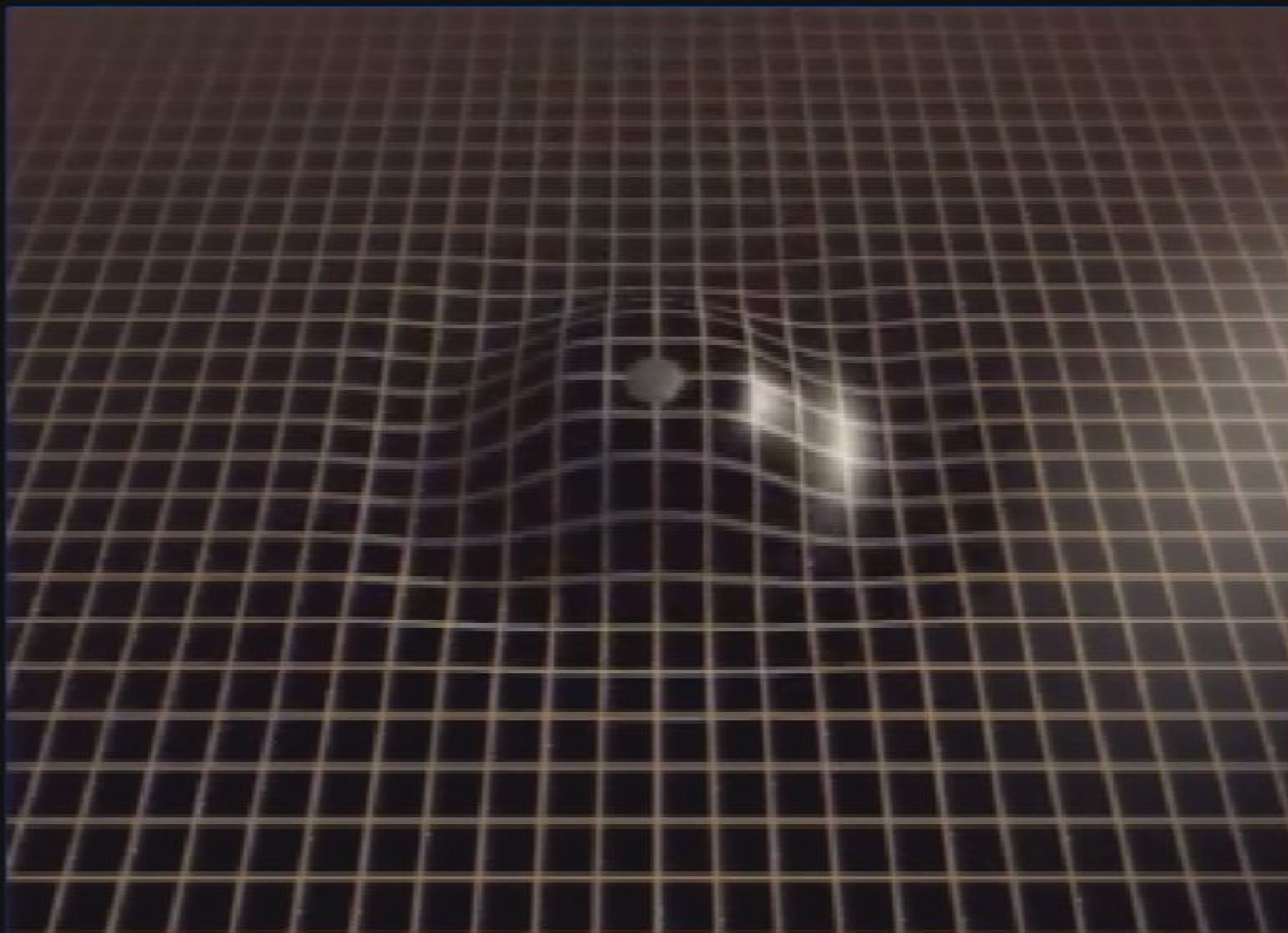

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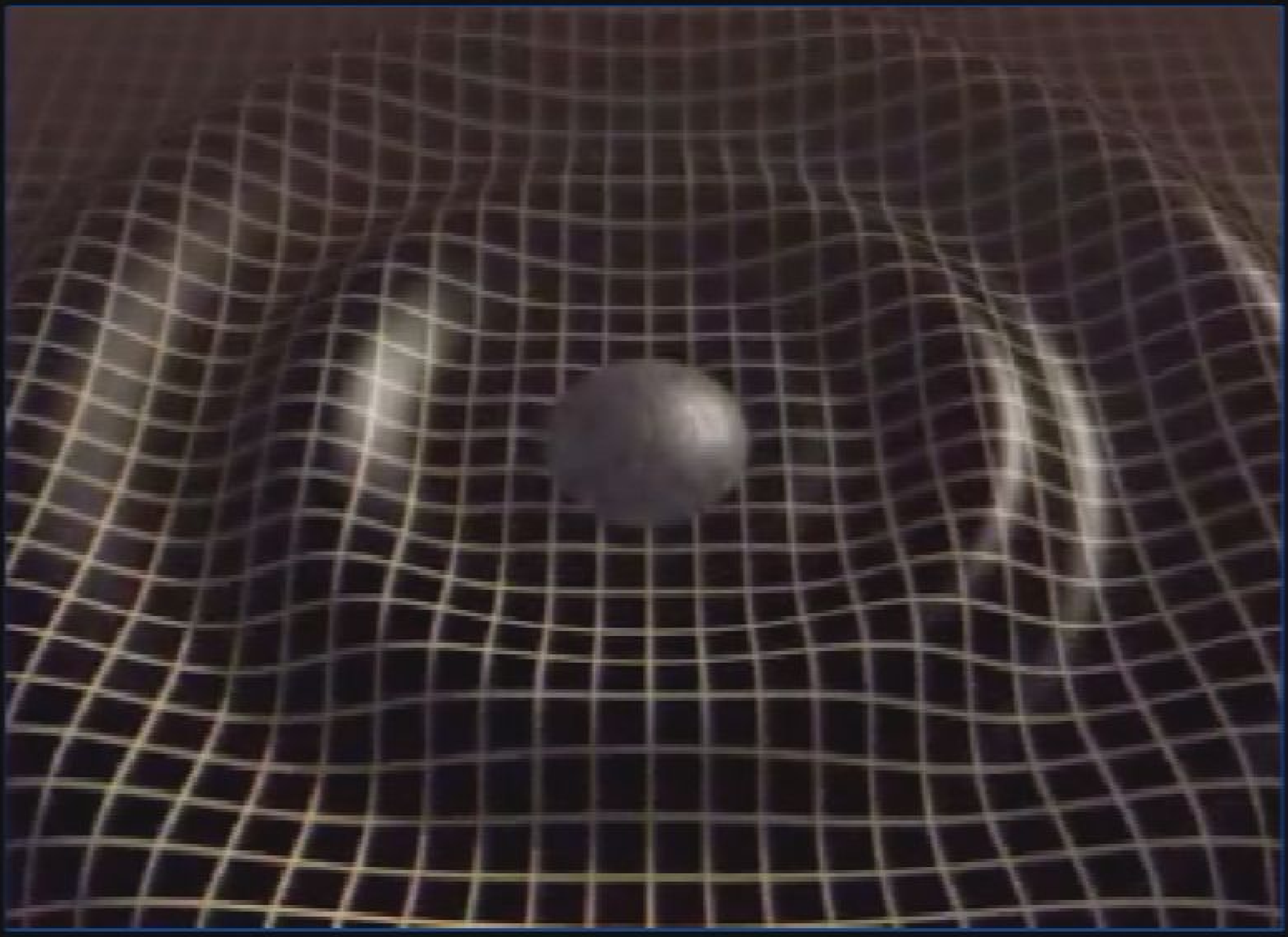

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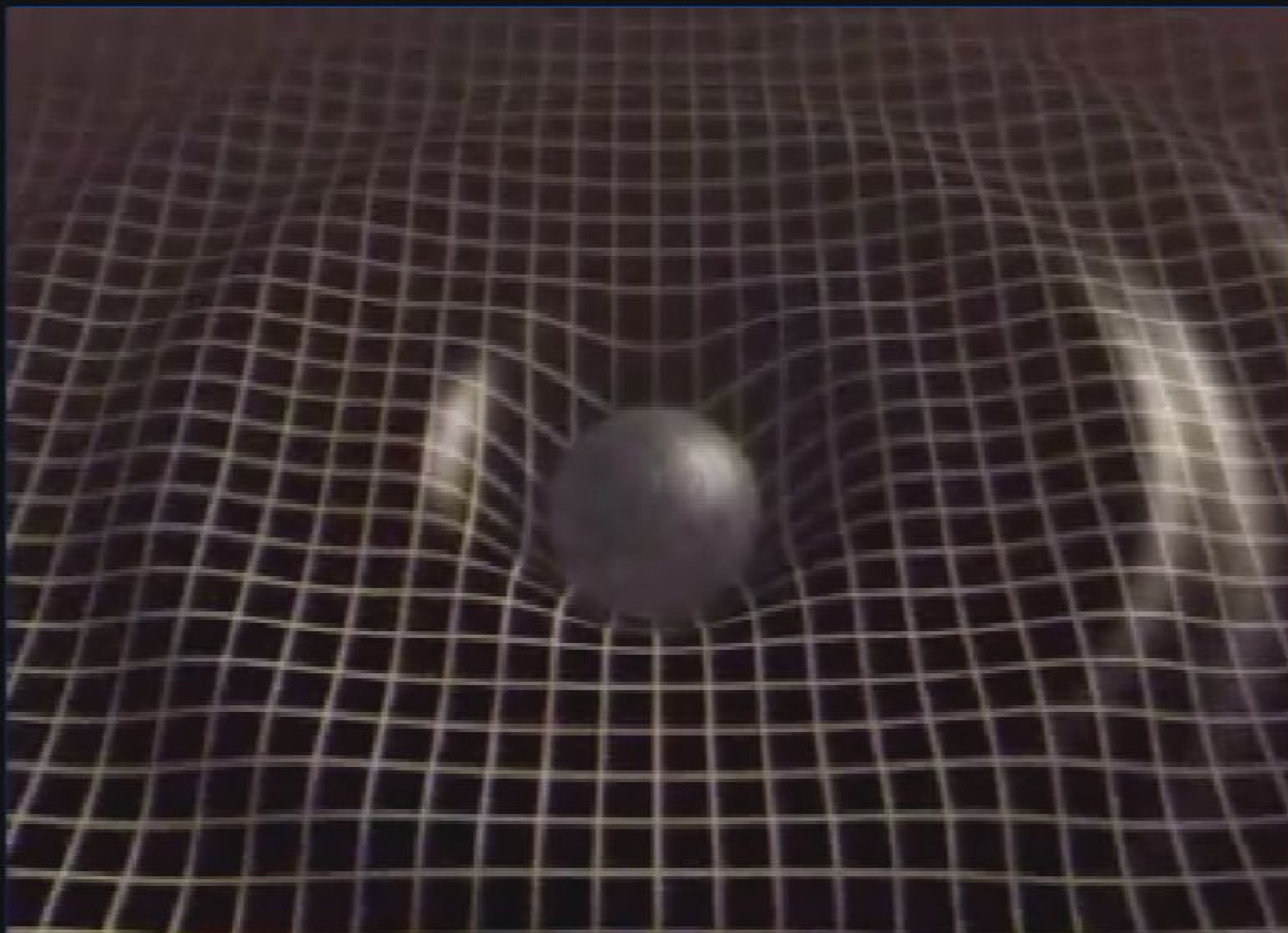

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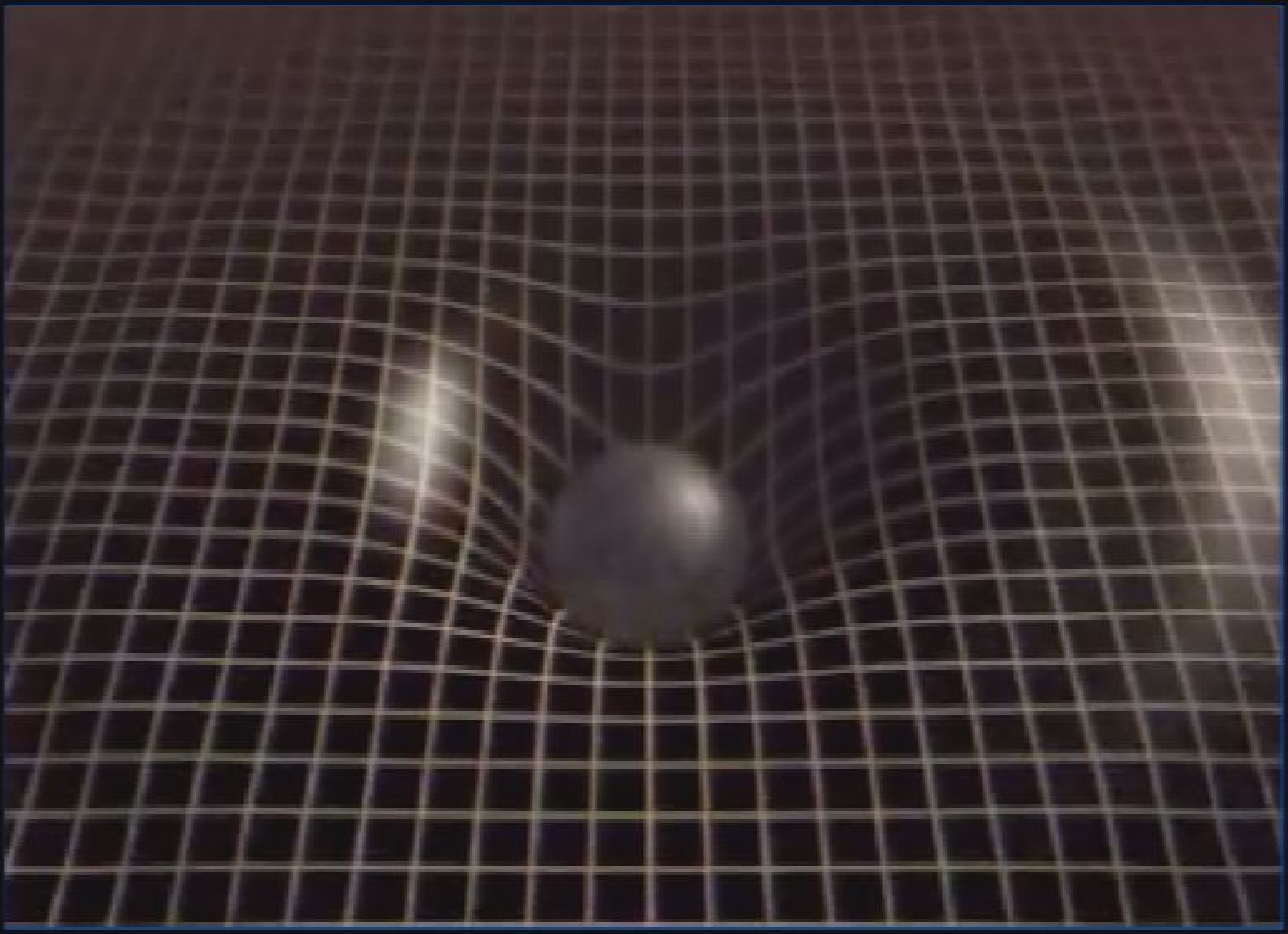

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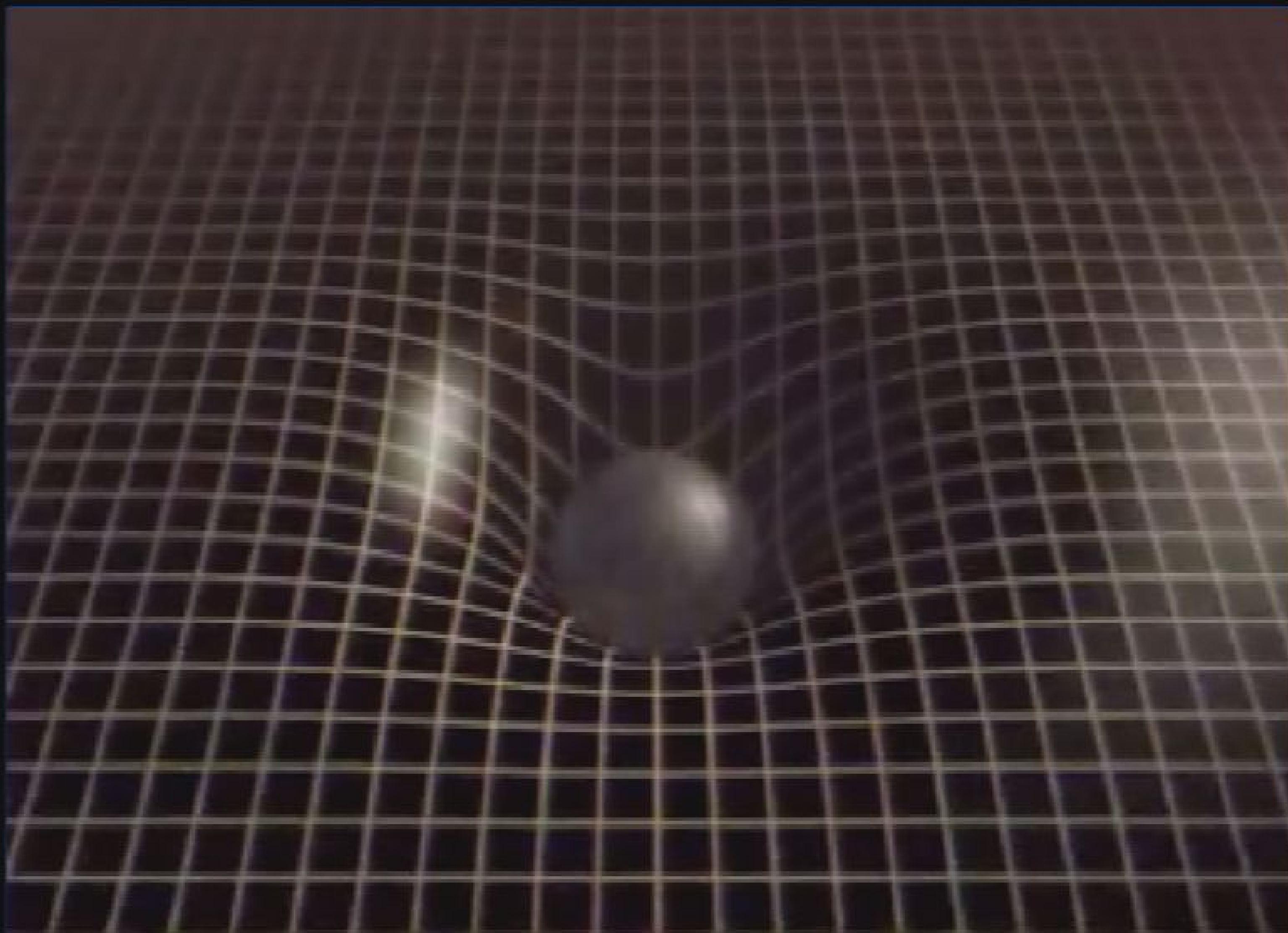

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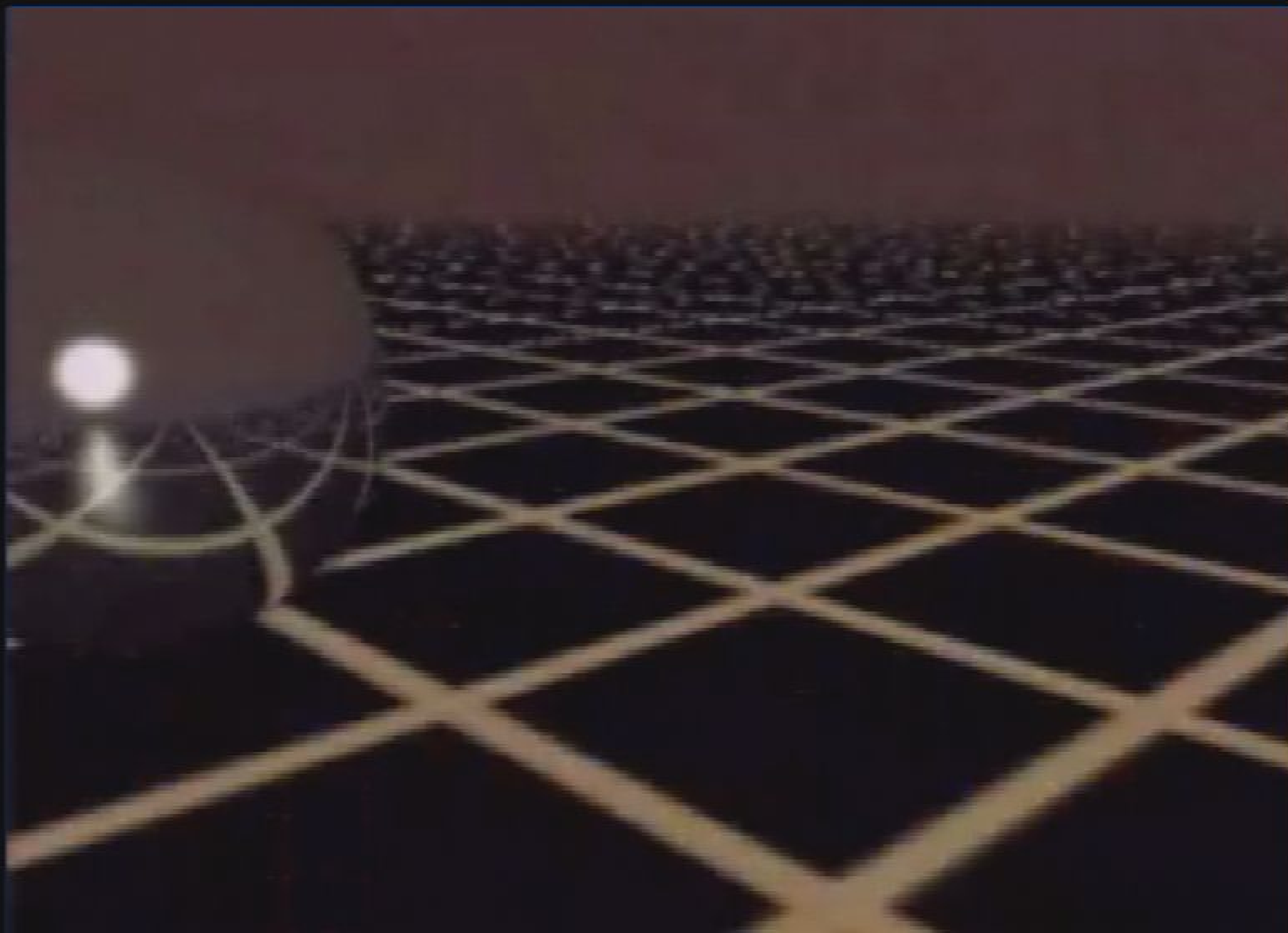

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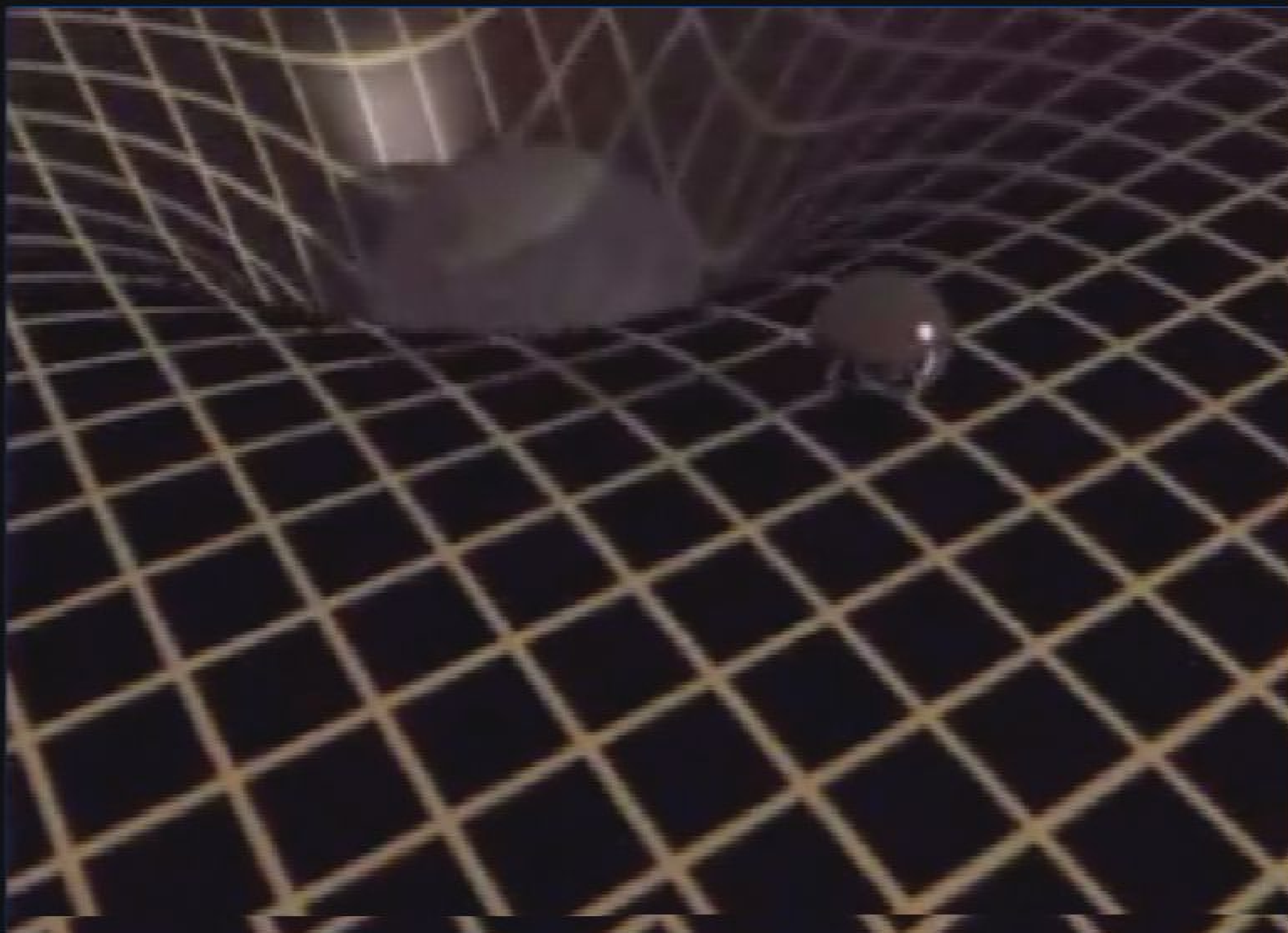

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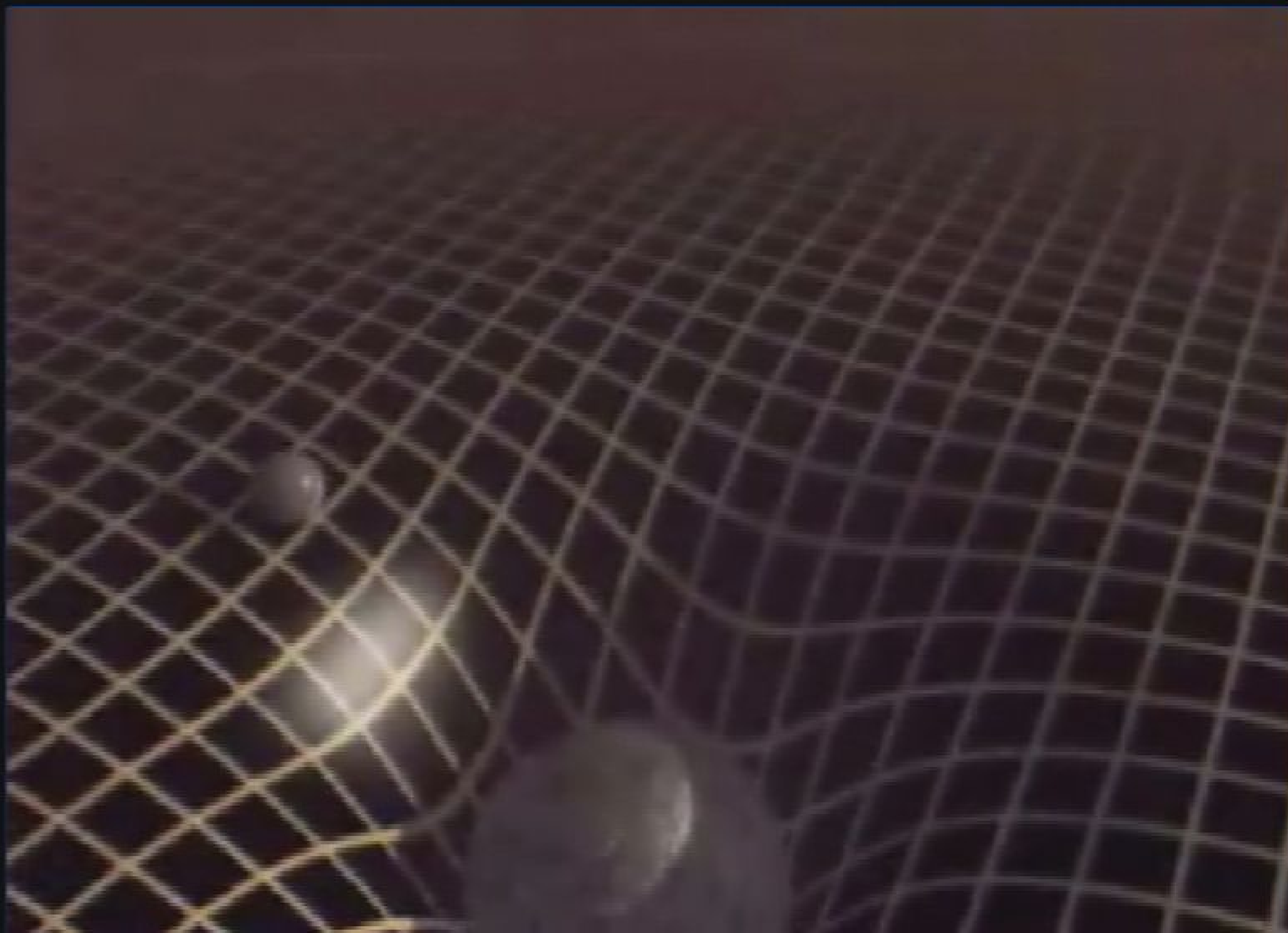

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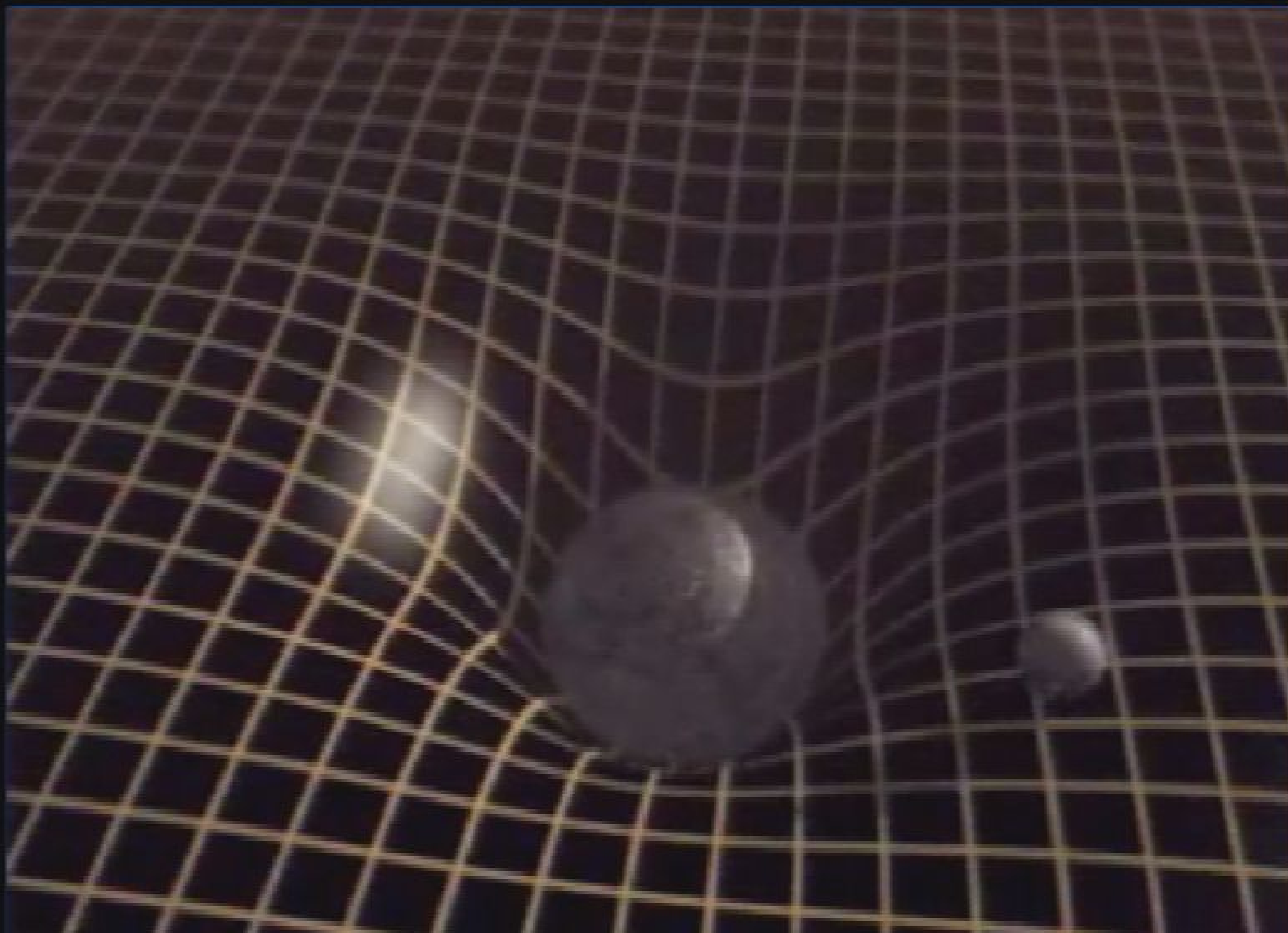

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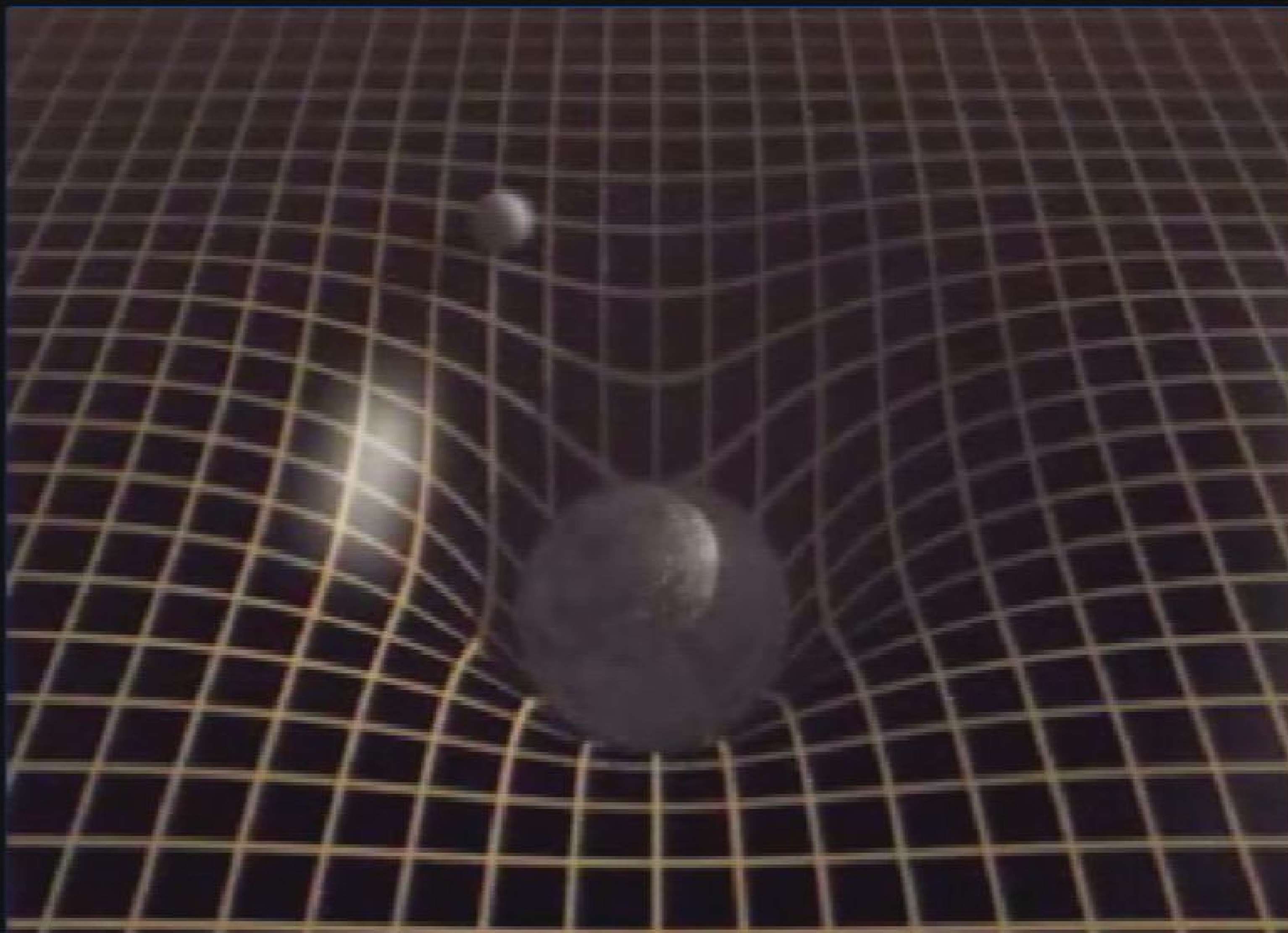

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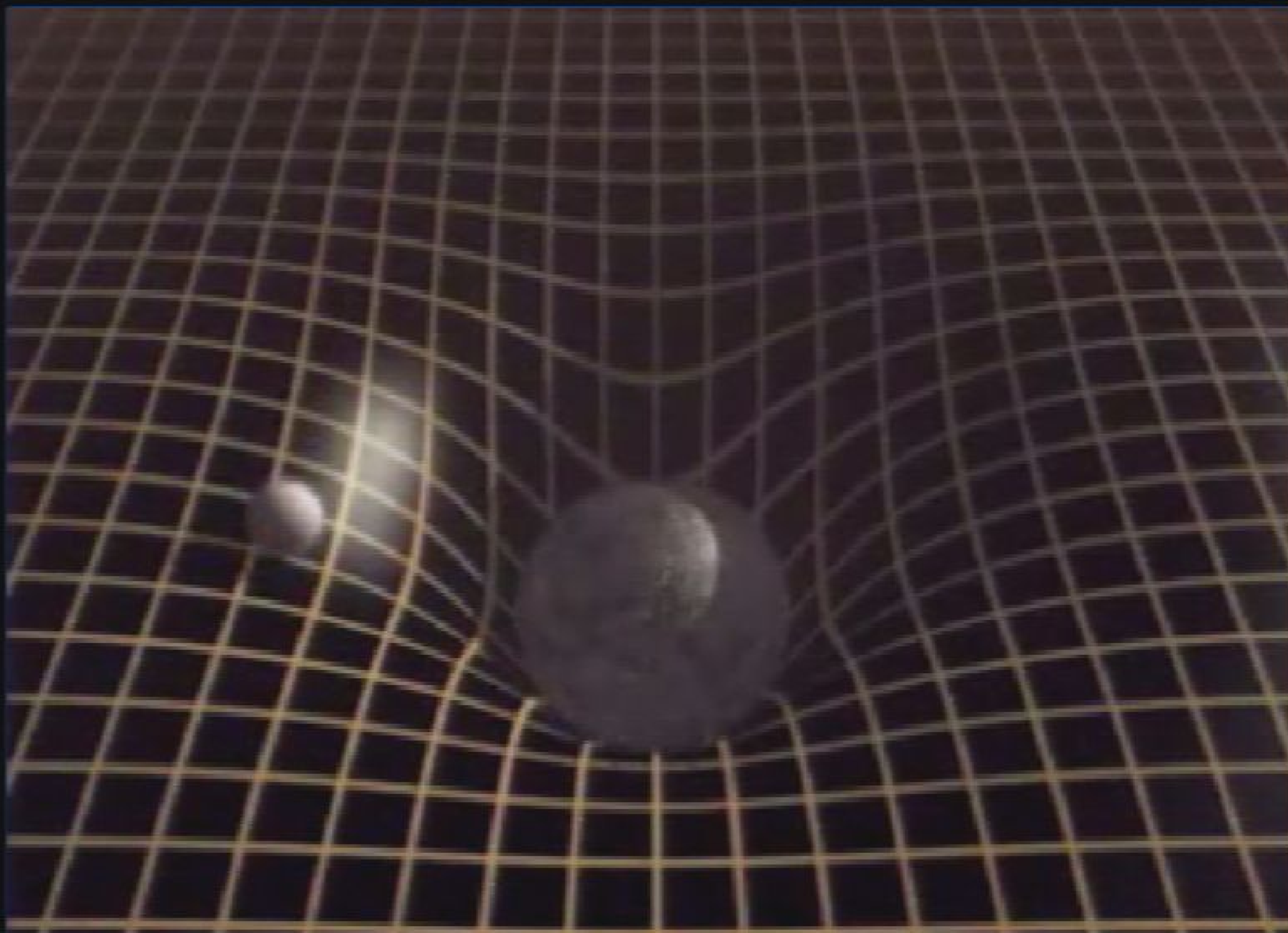

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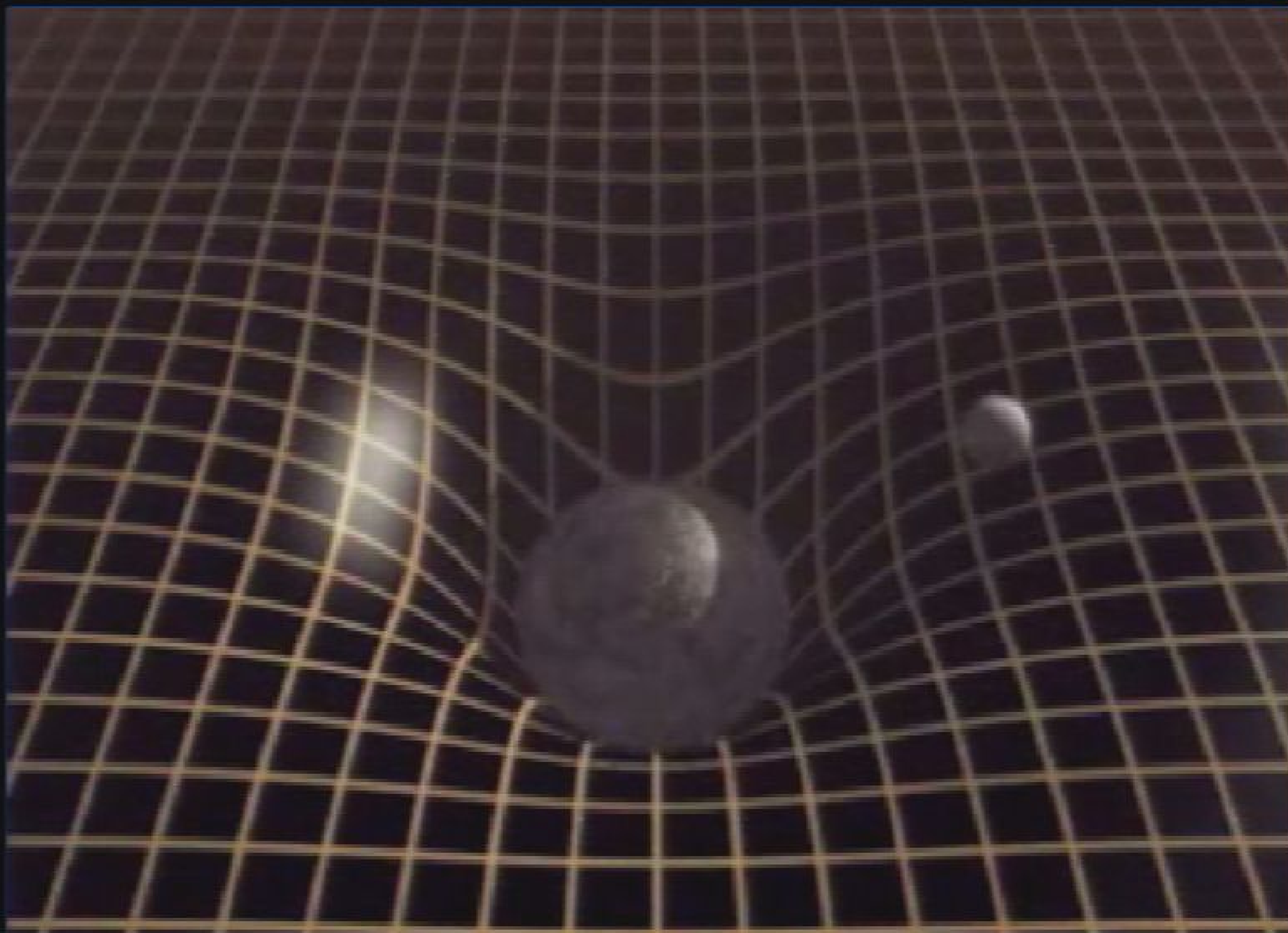

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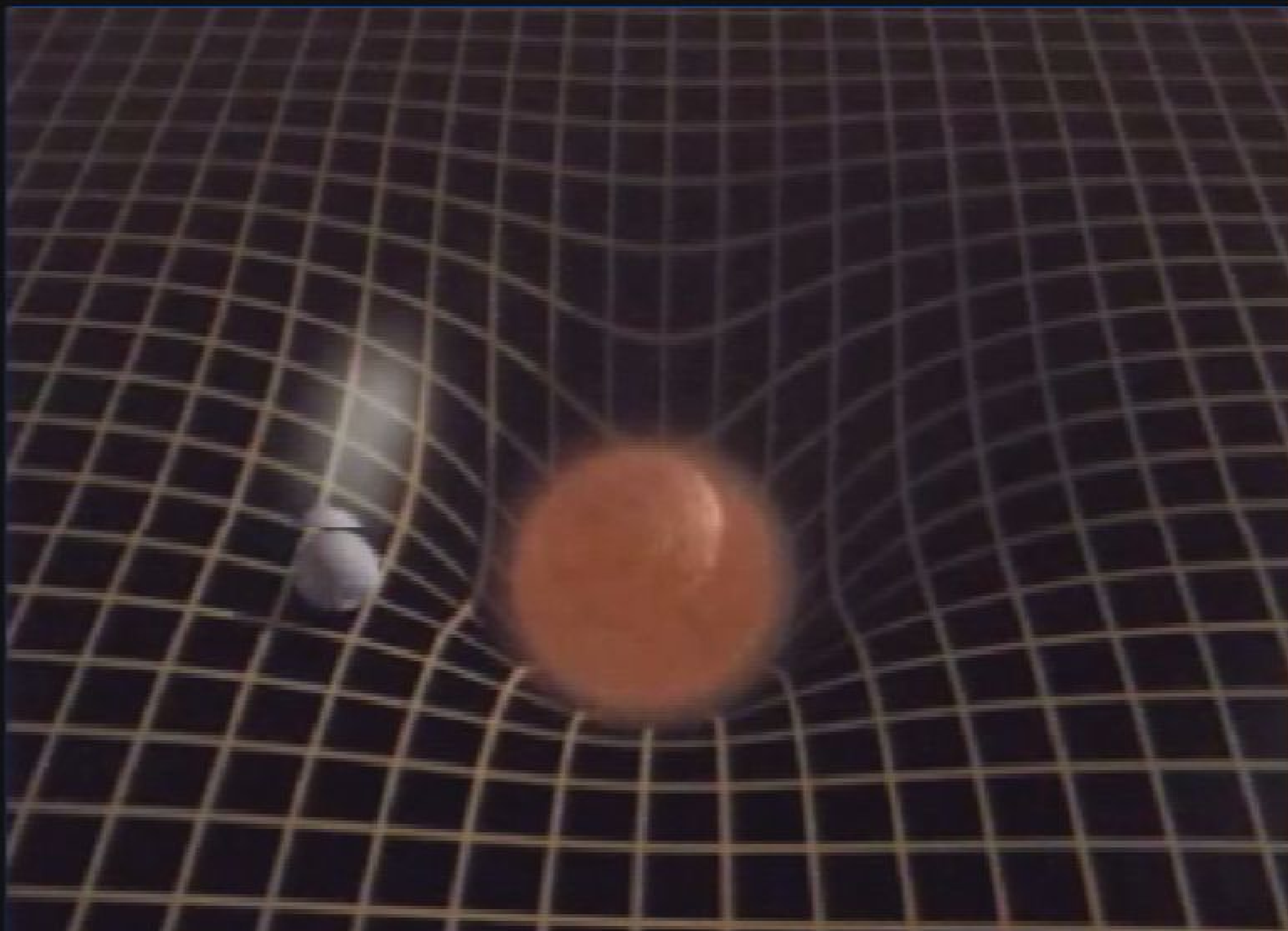

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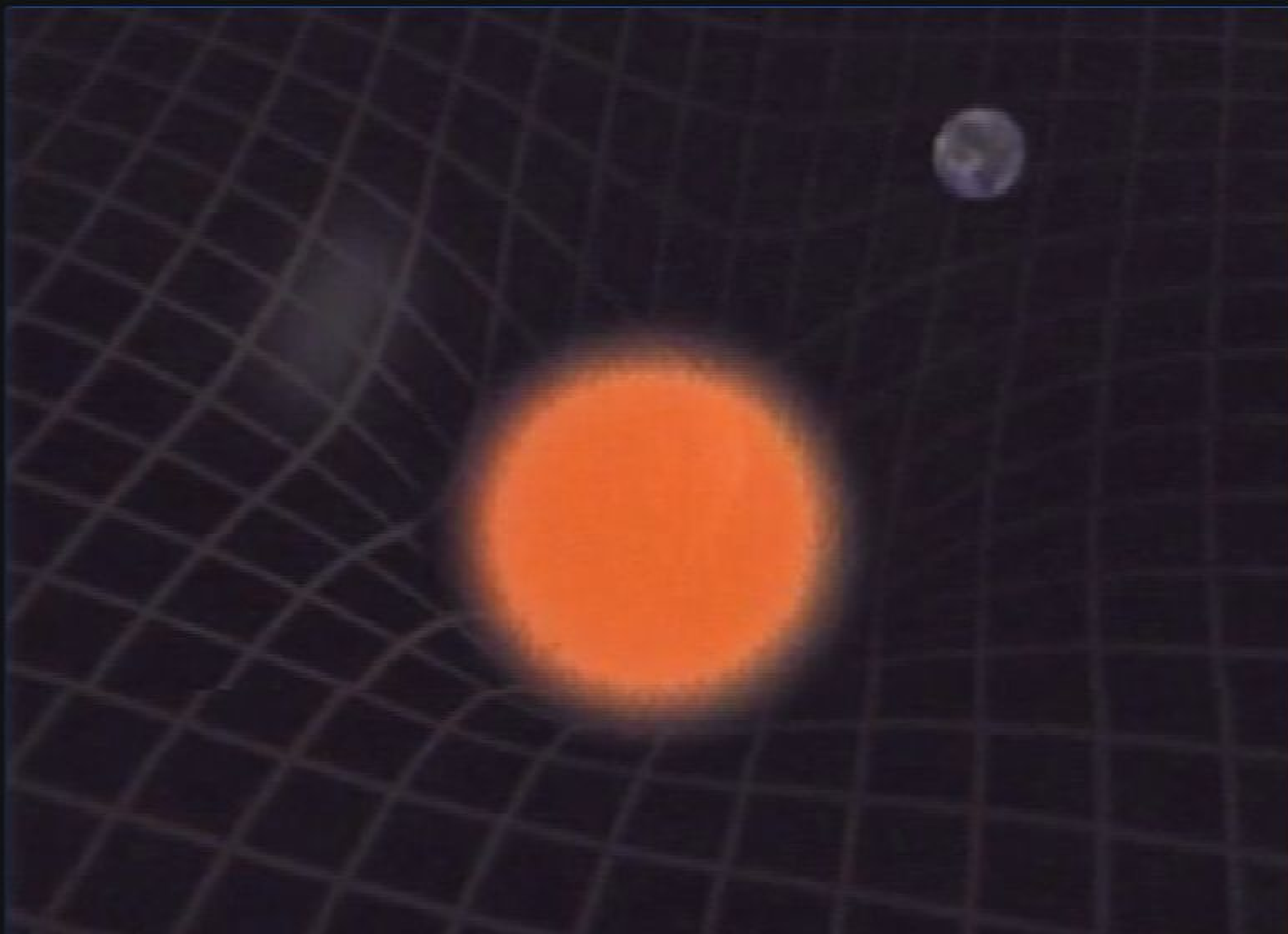

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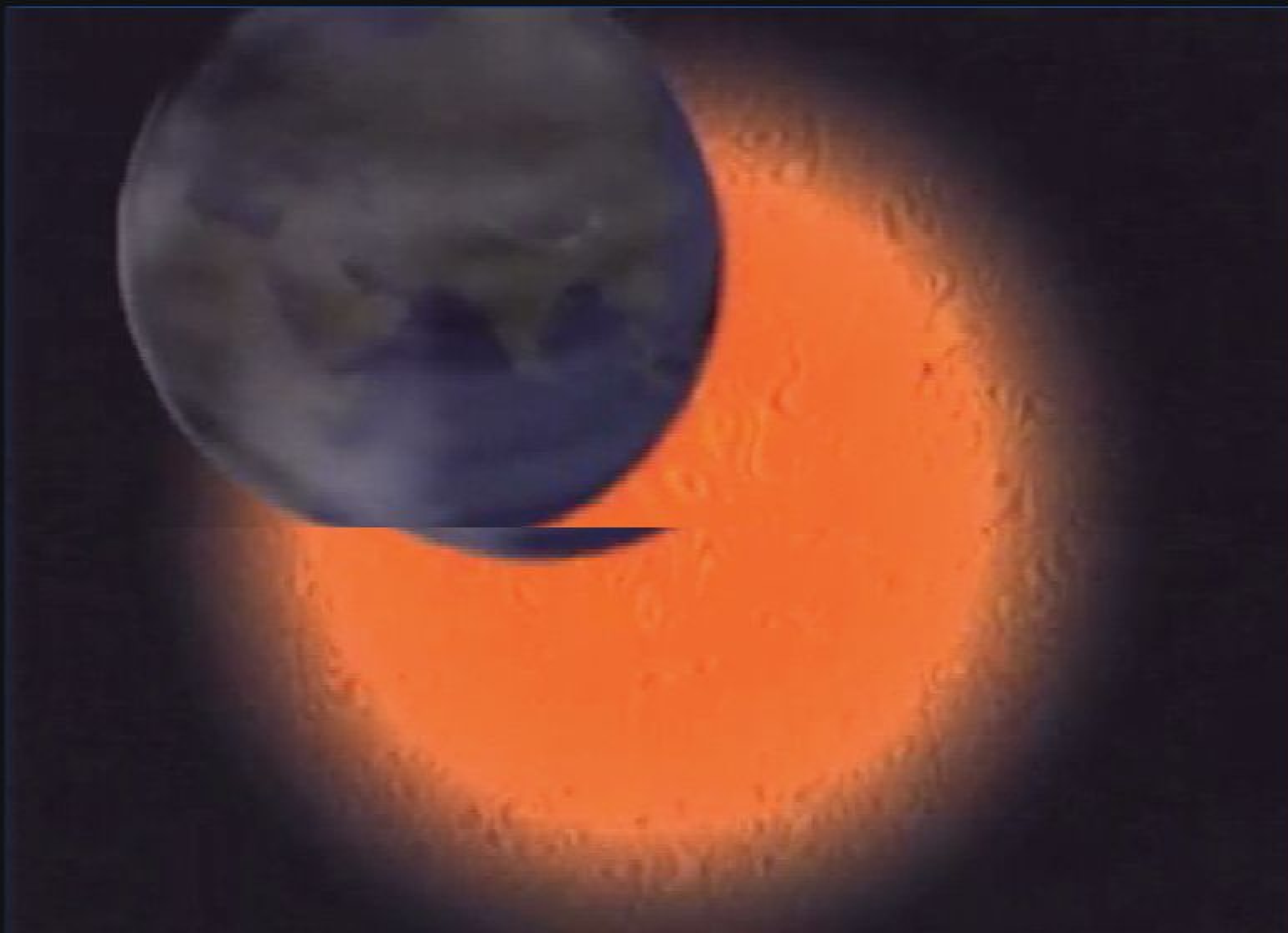

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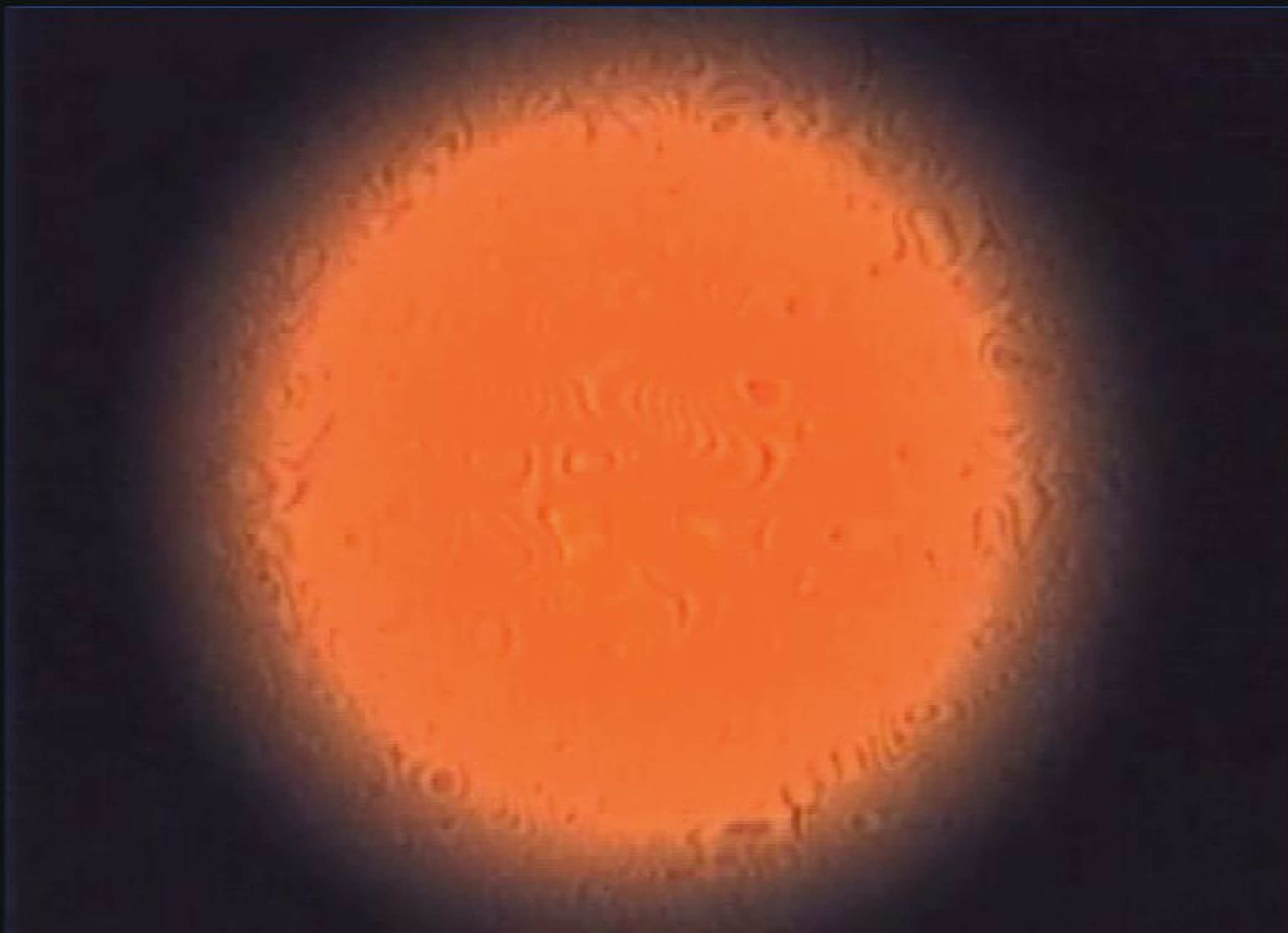

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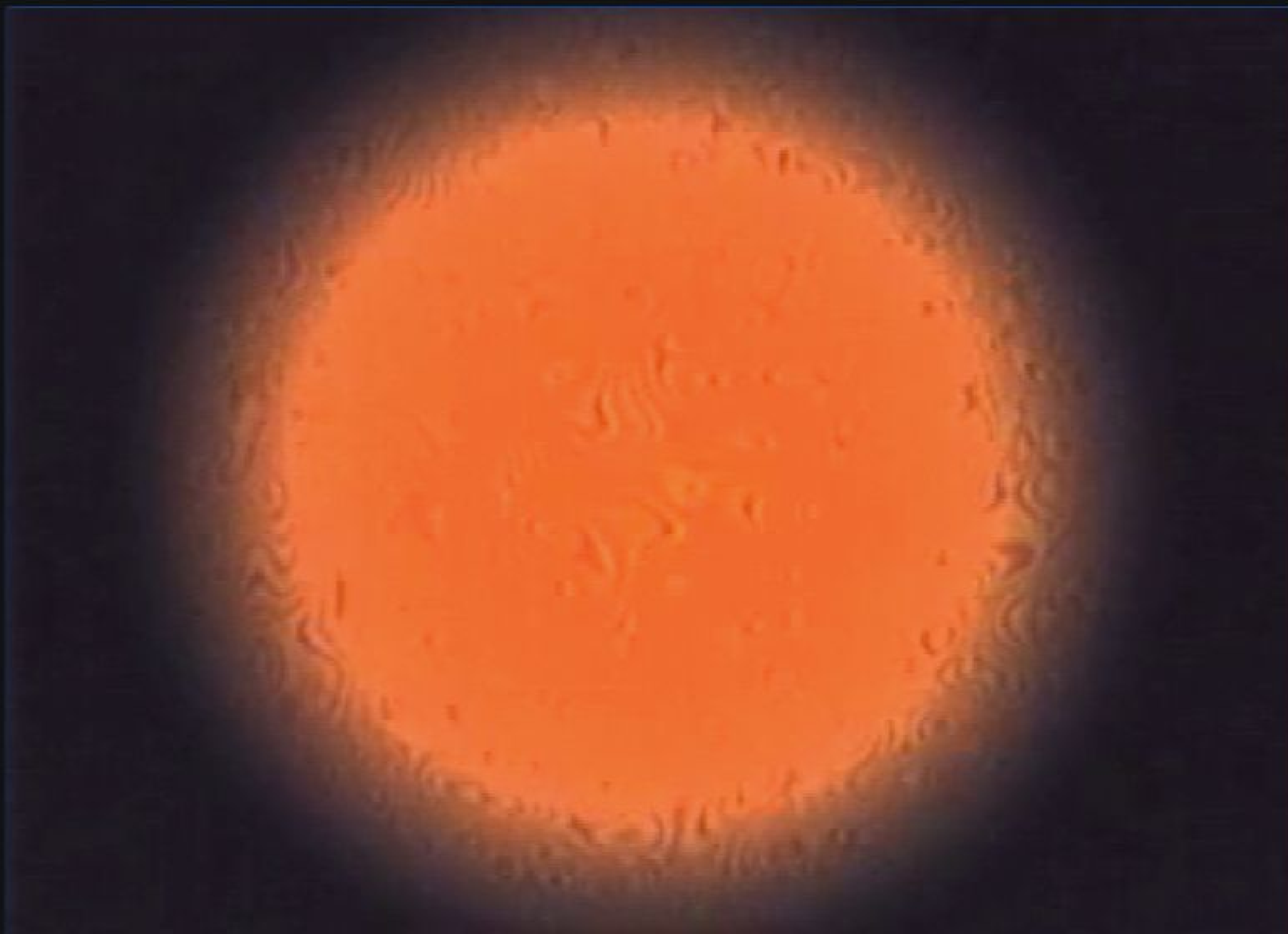

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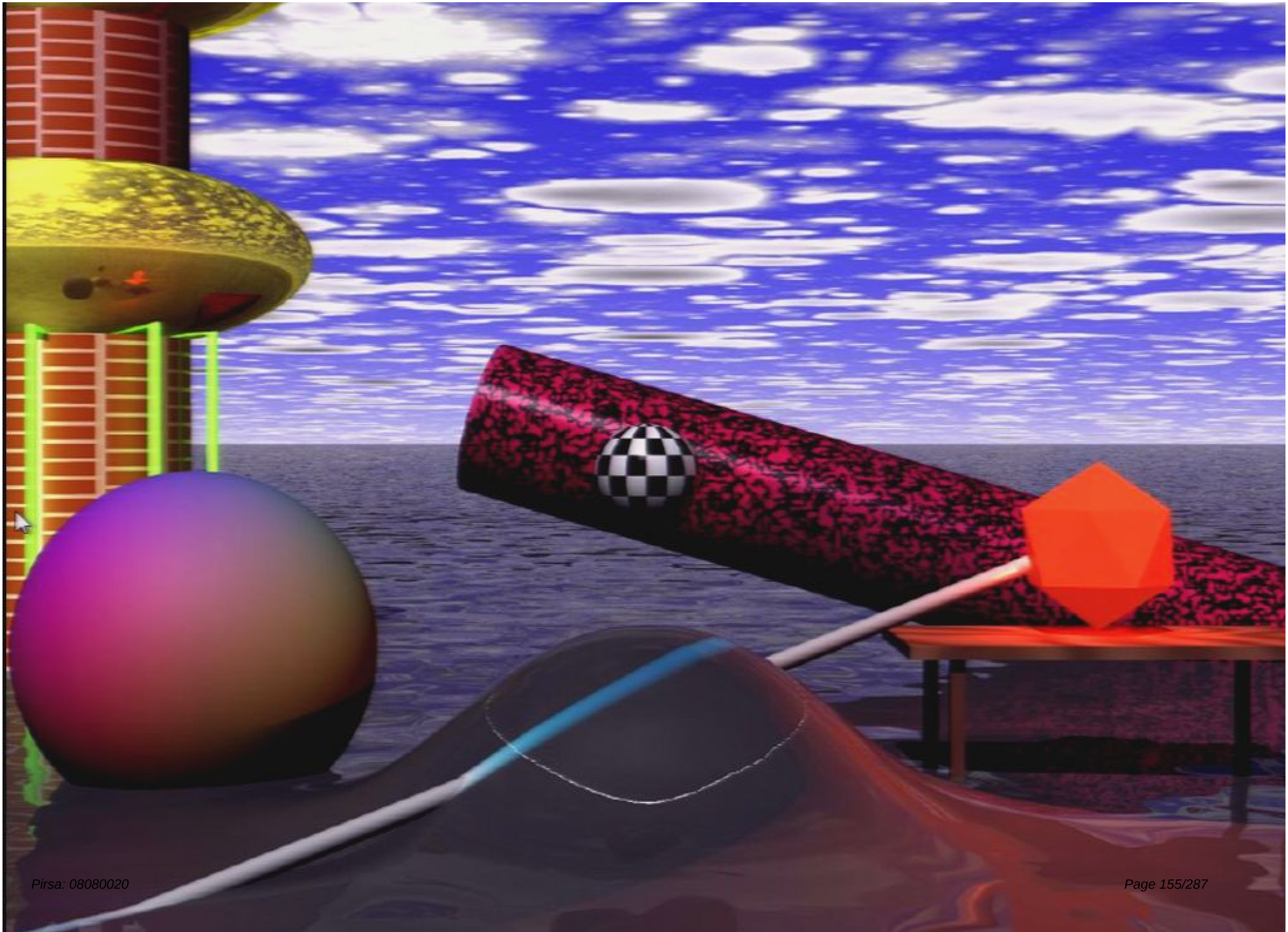
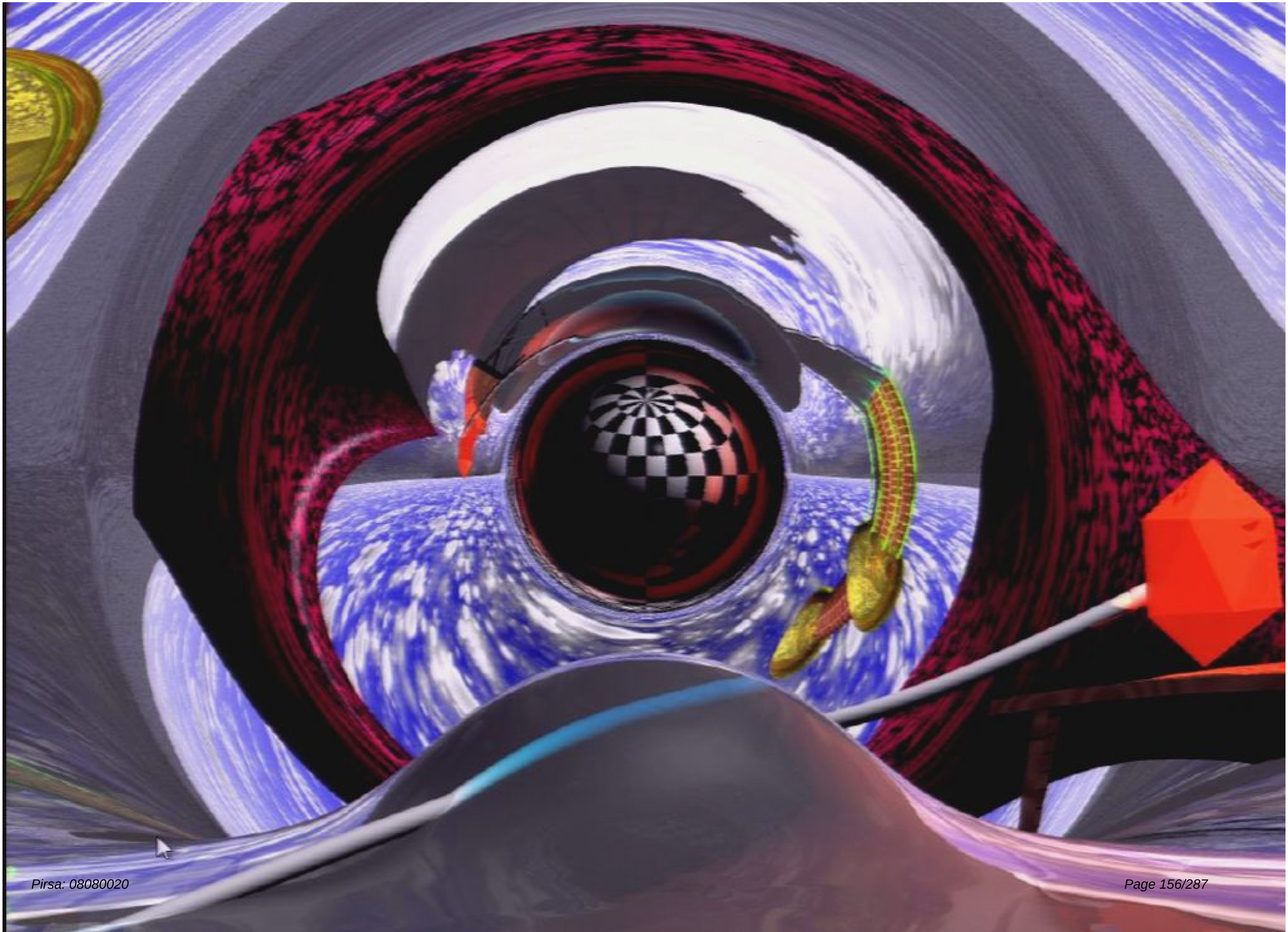
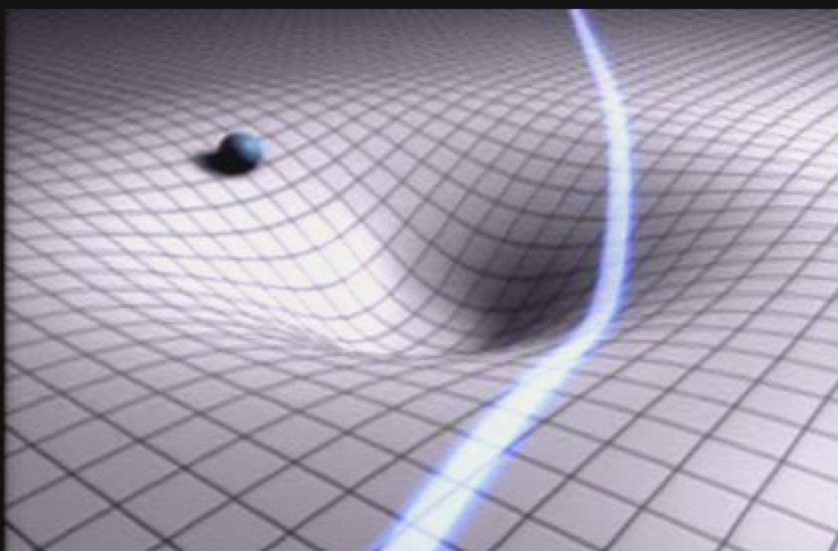
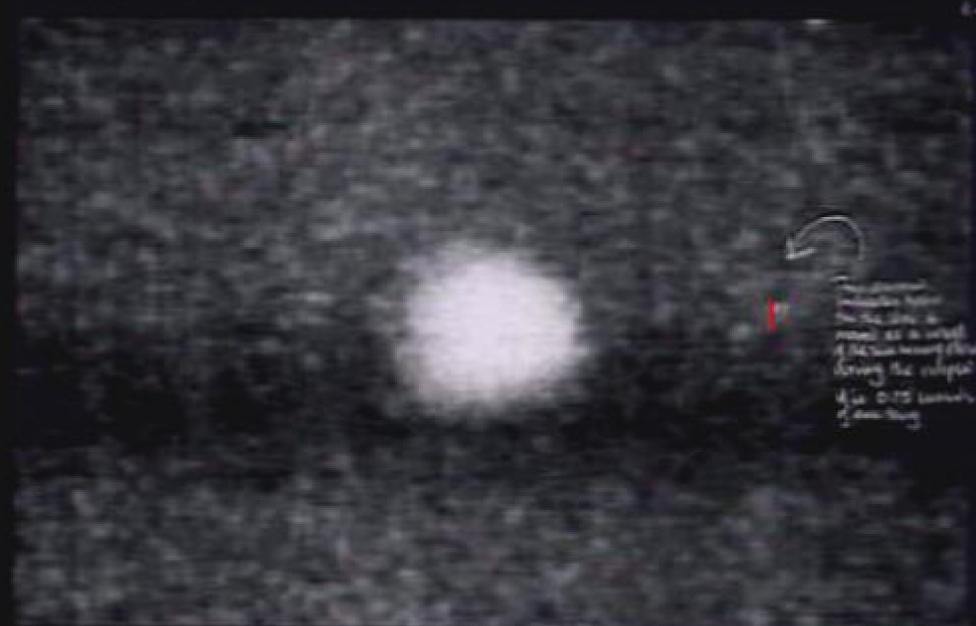


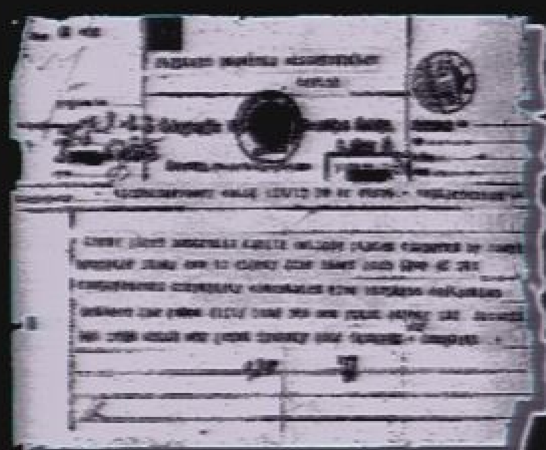


1919 Verification



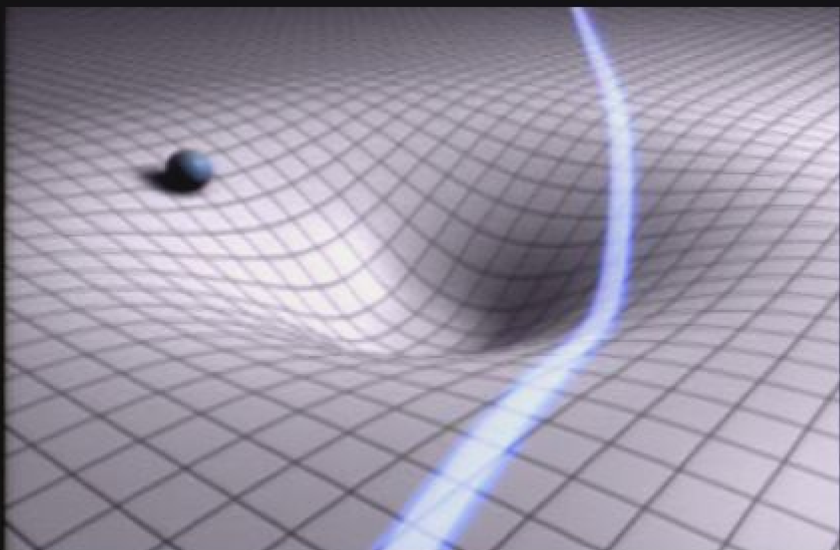


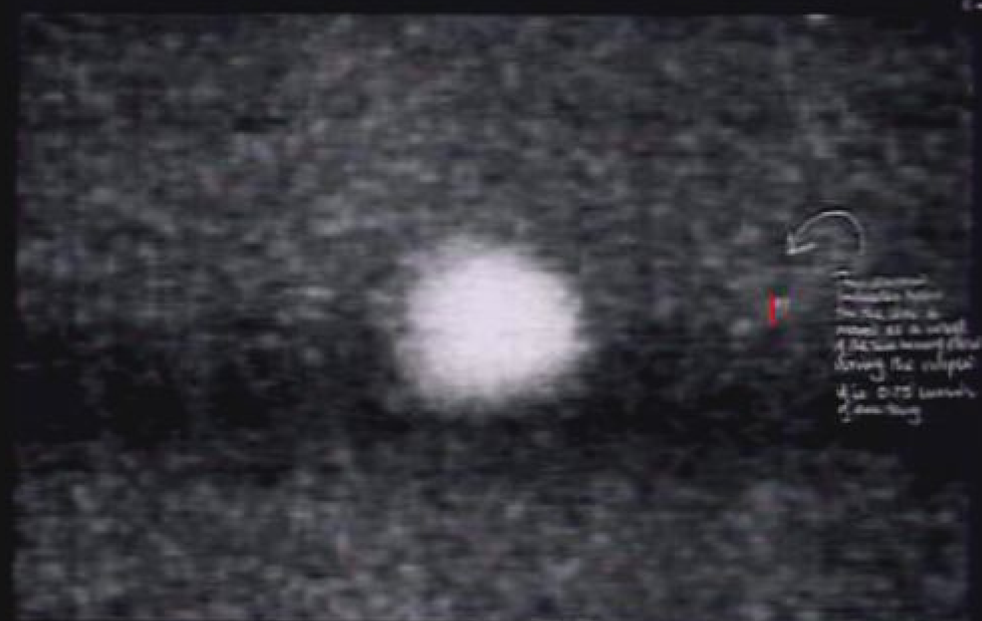
This image is magnified 281 times, compared with glass plate



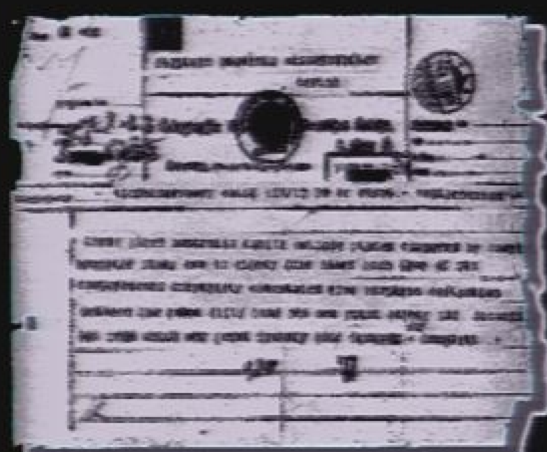
The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.

1919 Verification



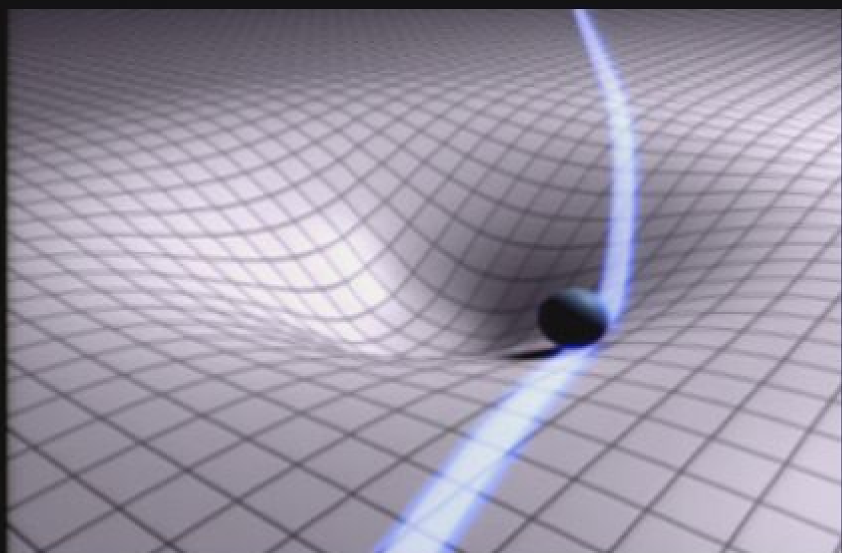


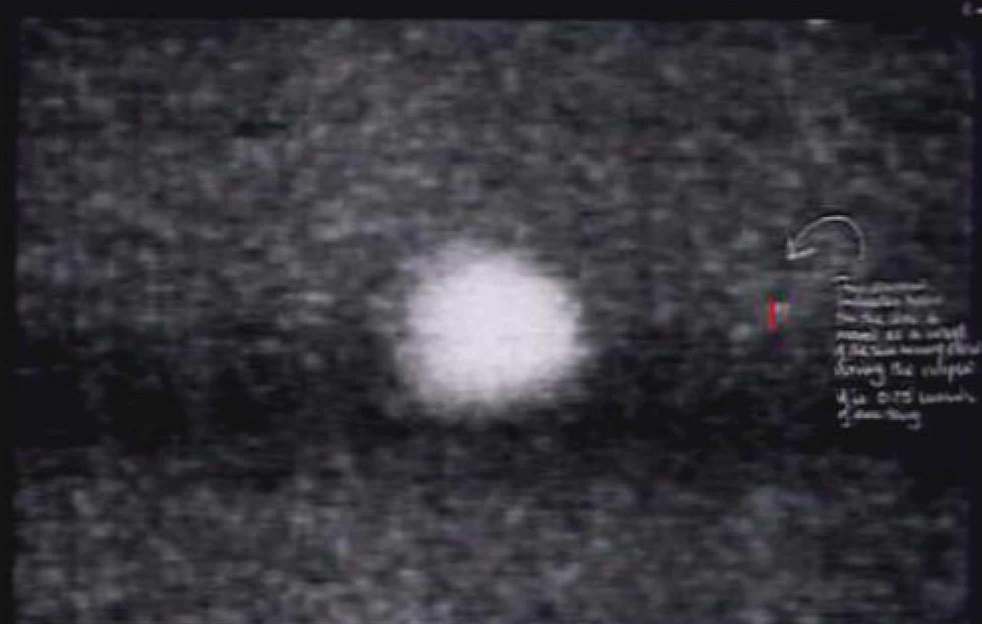
This image is magnified 231 times, compared with glass plate

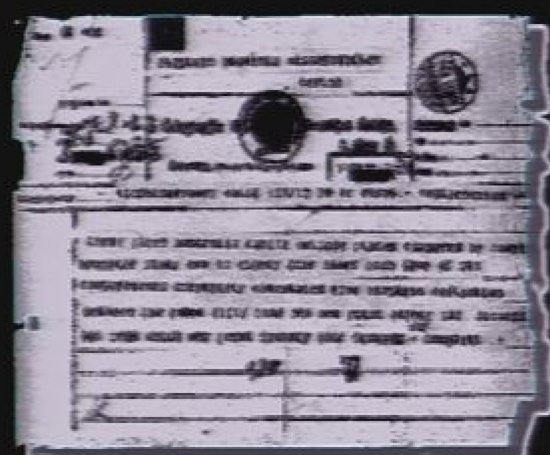


The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.

1919 Verification

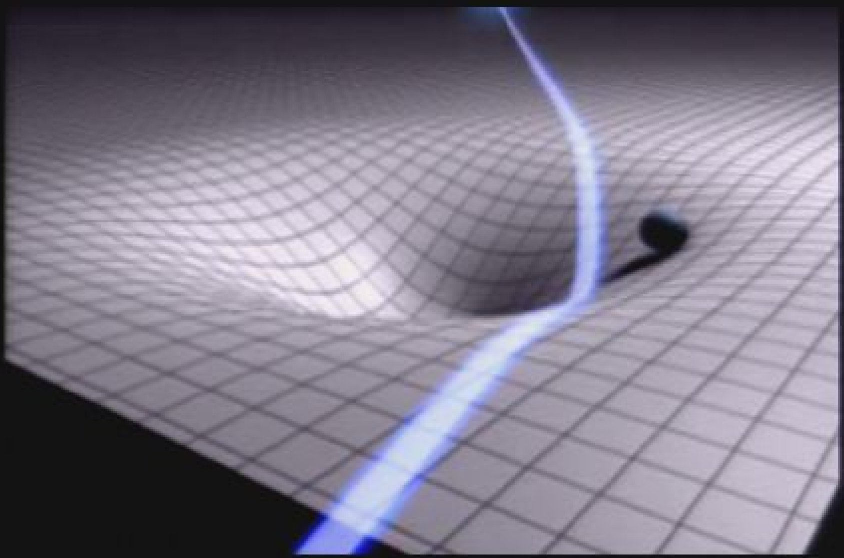


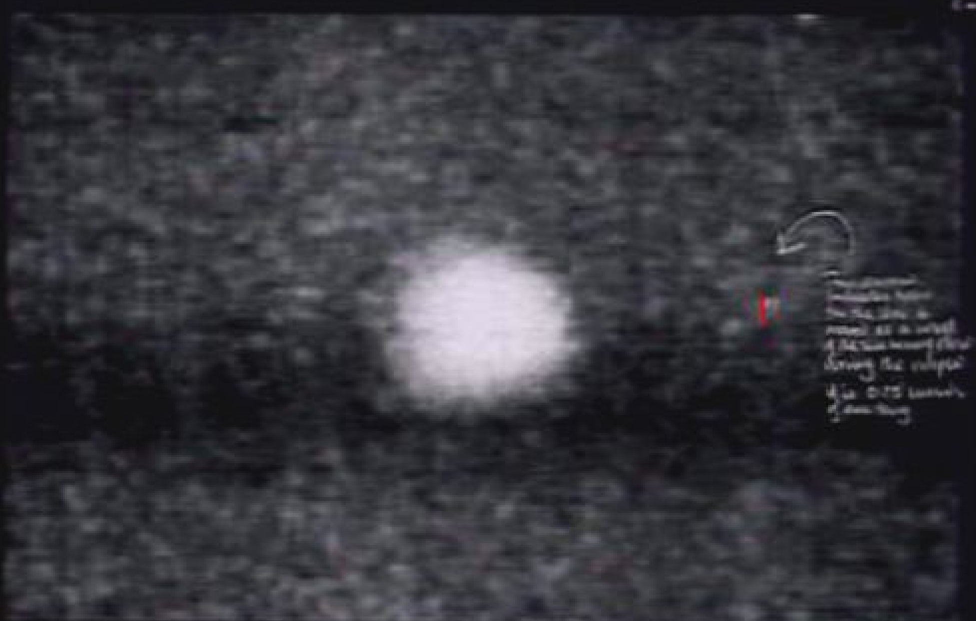




The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.

1919 Verification

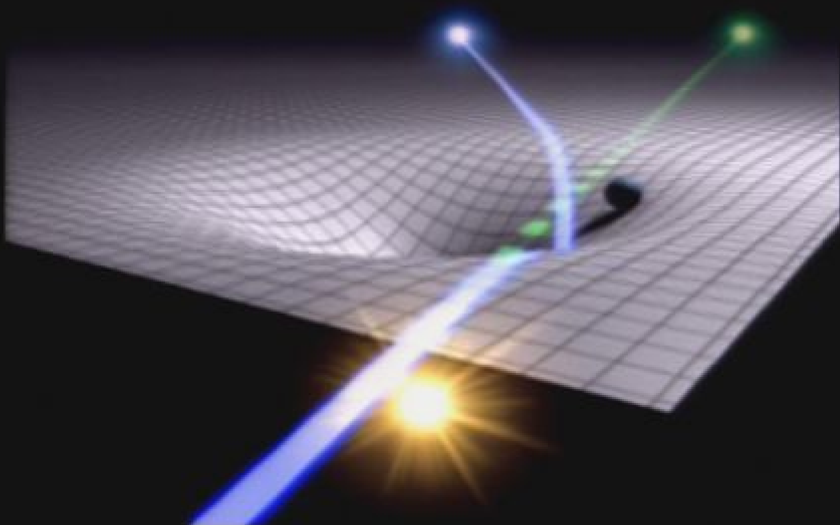


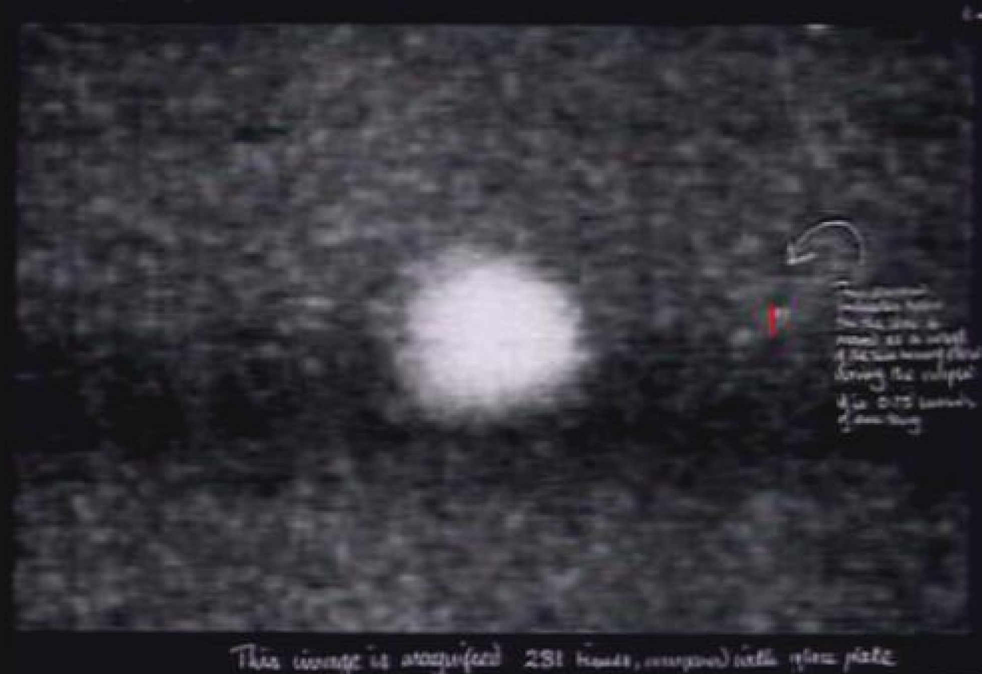


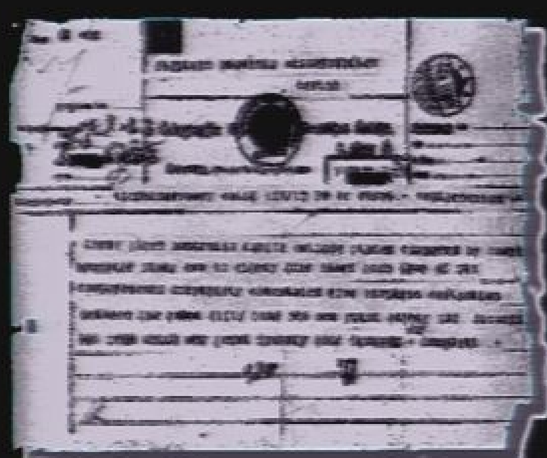
This image is magnified 231 times, compared with glass plate

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

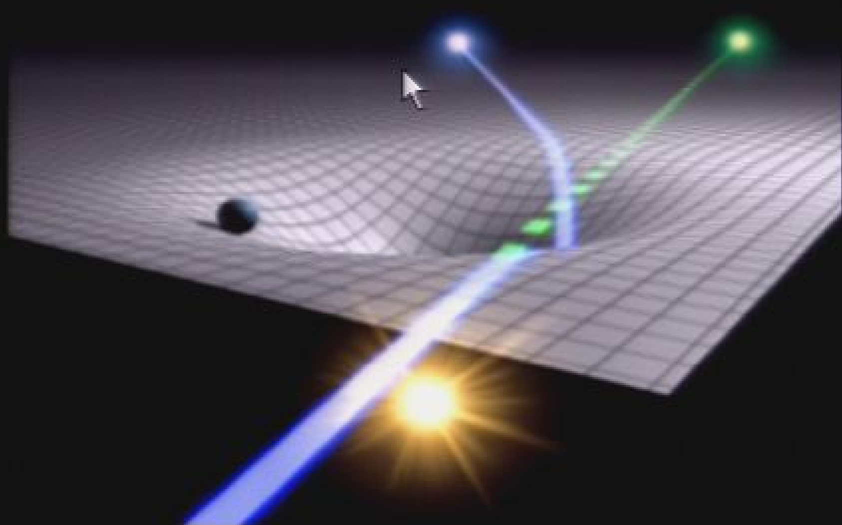


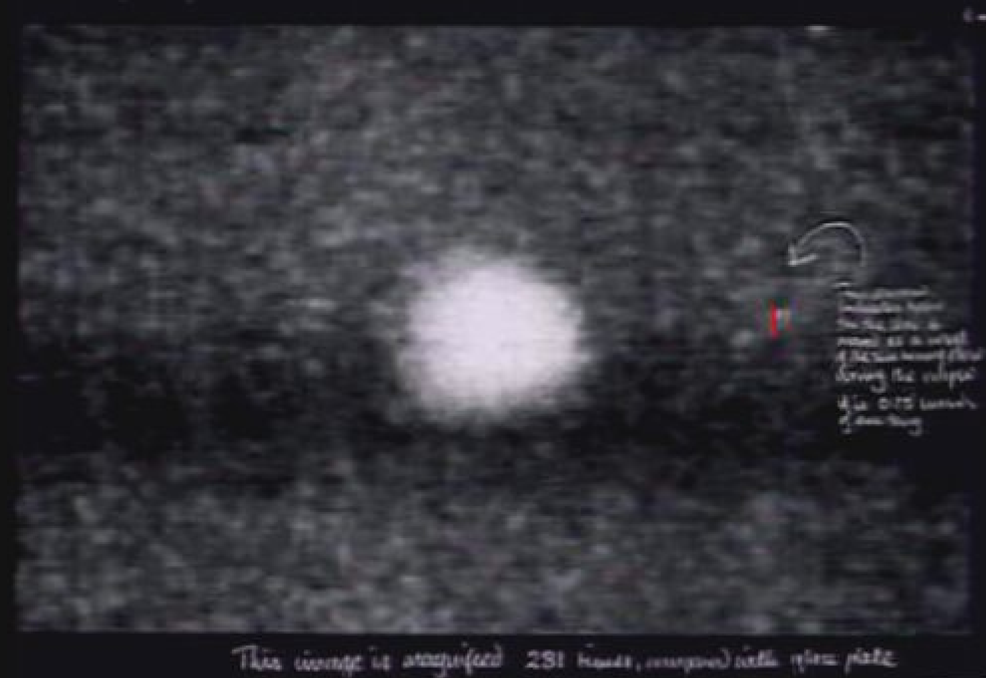


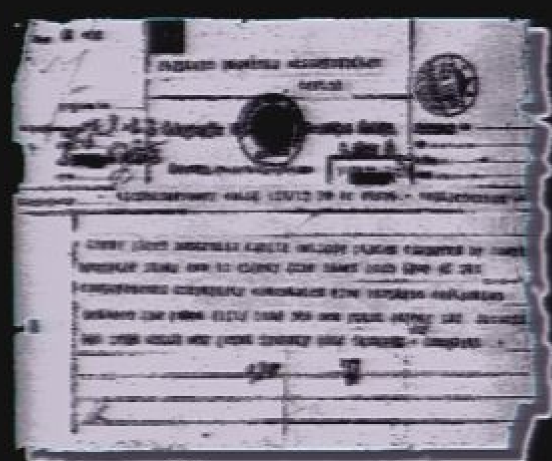


The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.

1919 Verification

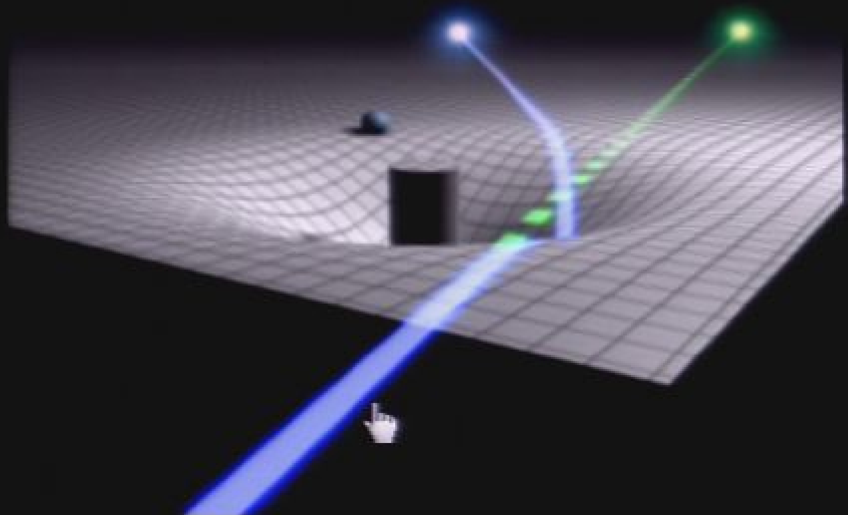


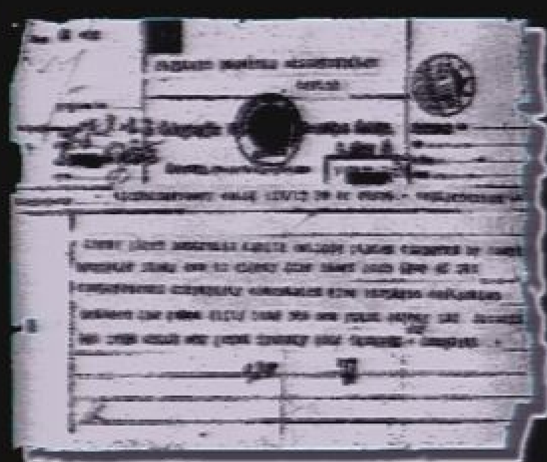




The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.

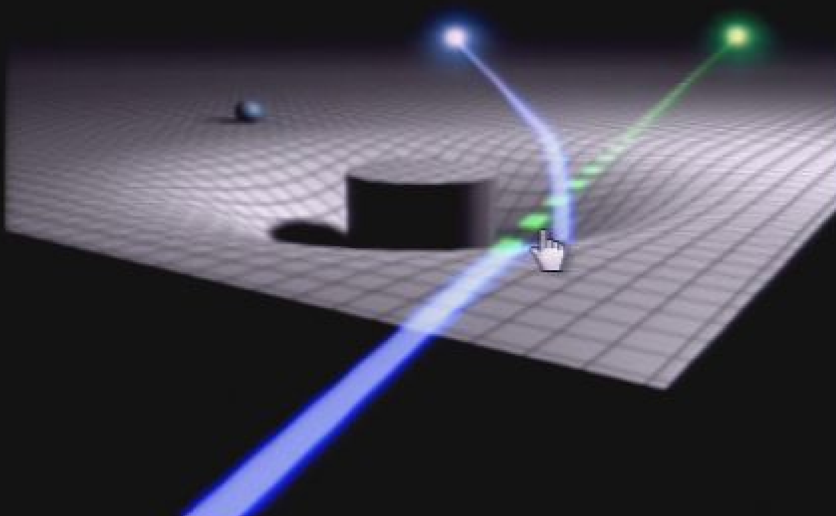
1919 Verification

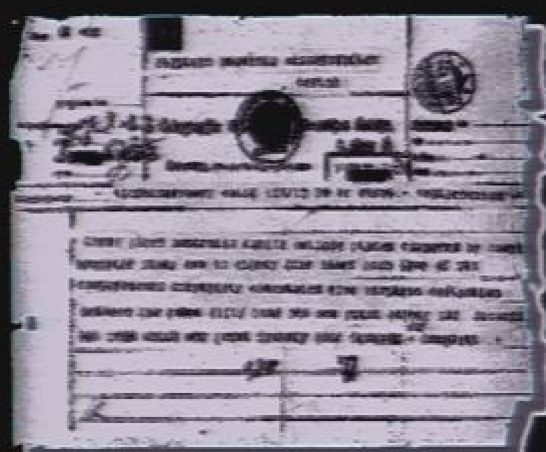




The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.

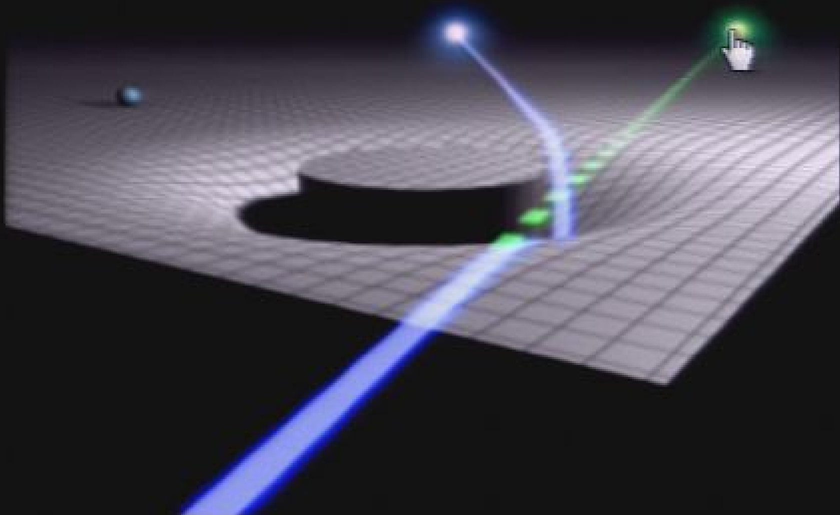
1919 Verification

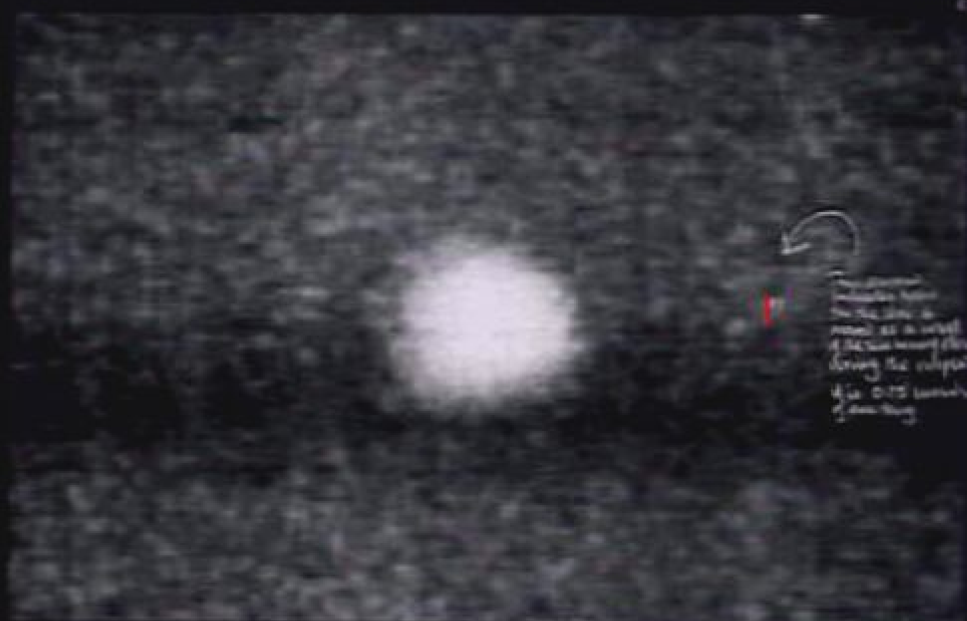


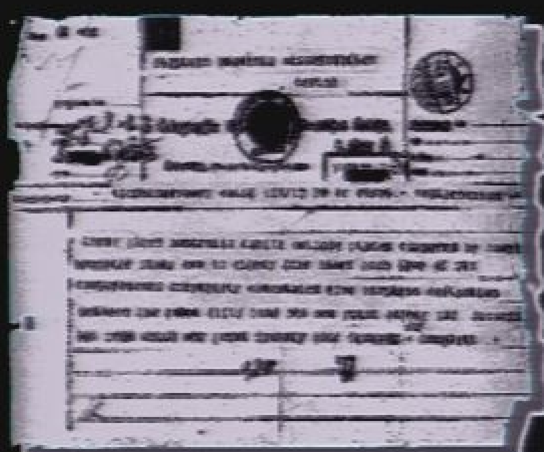


The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.

1919 Verification

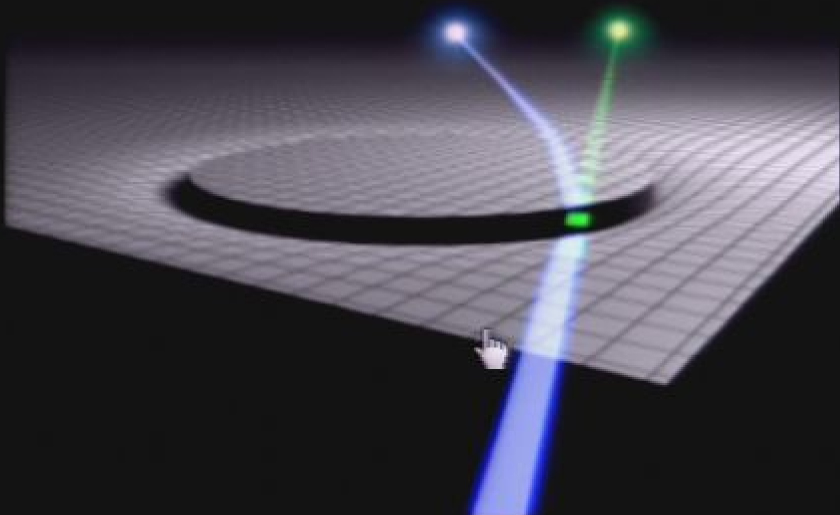


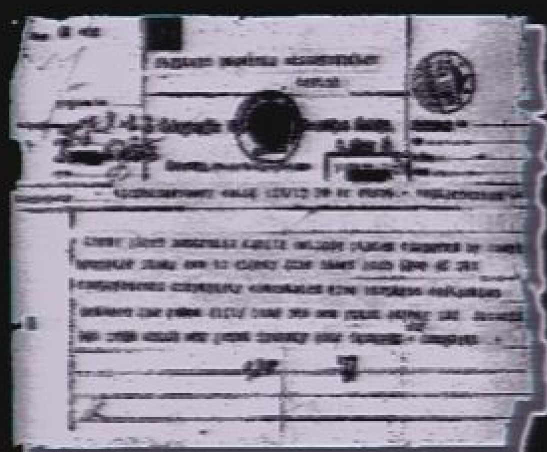




The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.

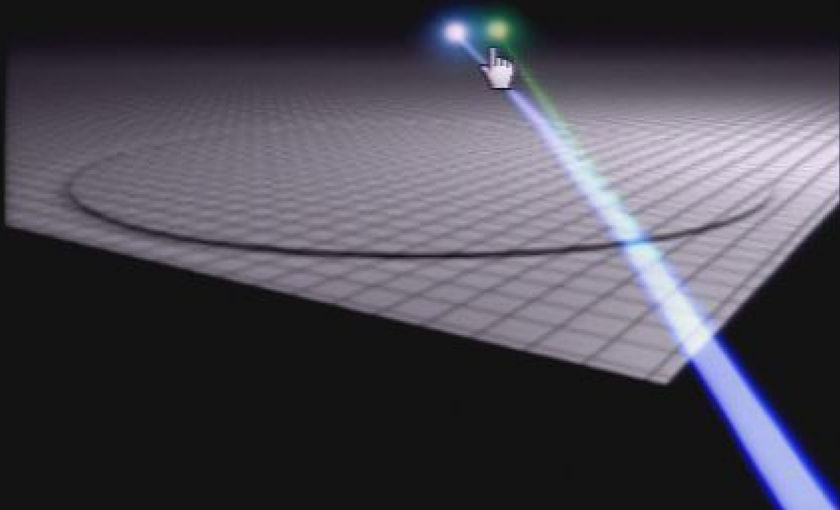
1919 Verification

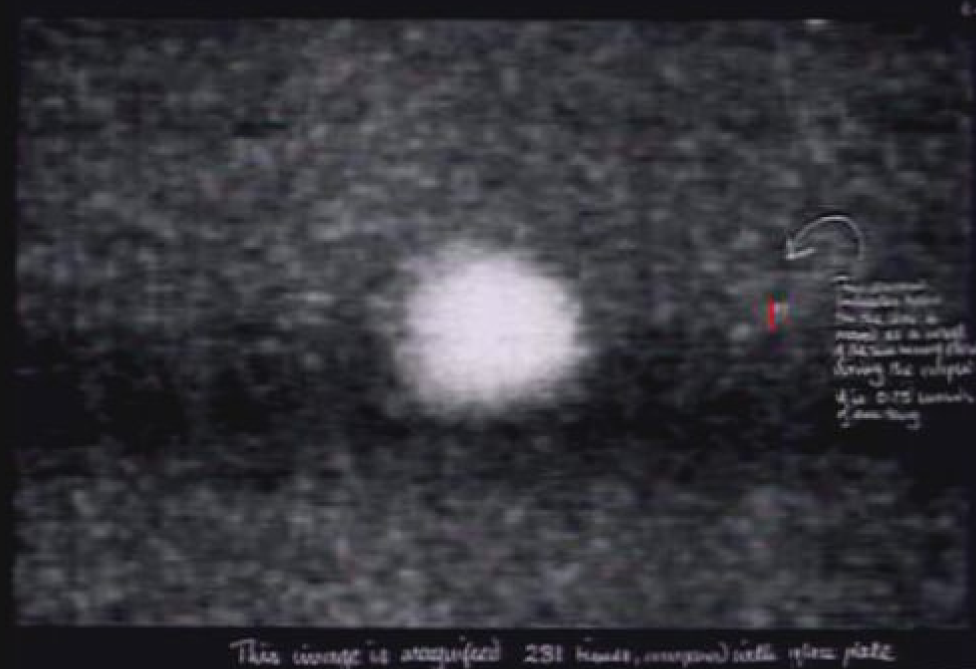


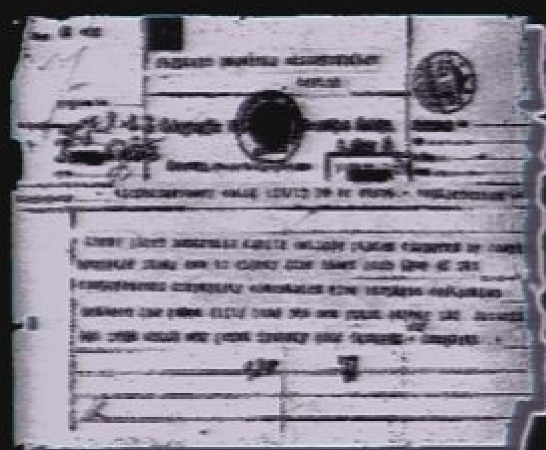


The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.

1919 Verification

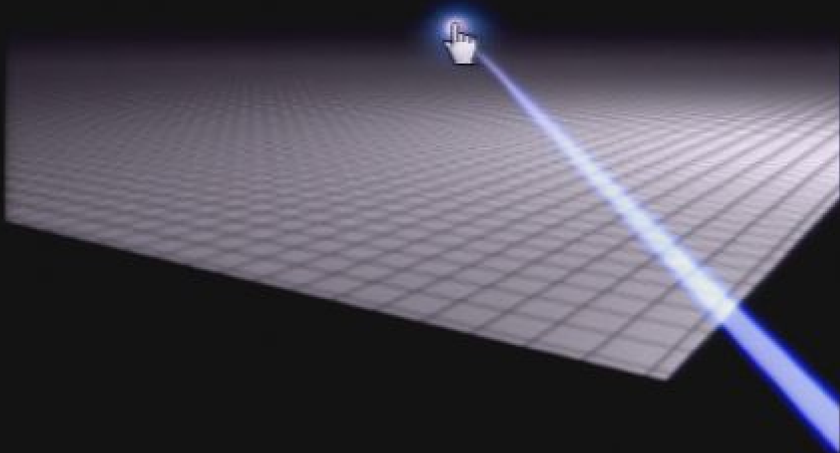


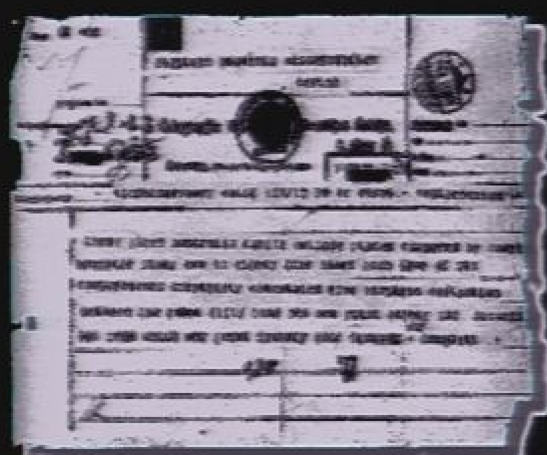




The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.

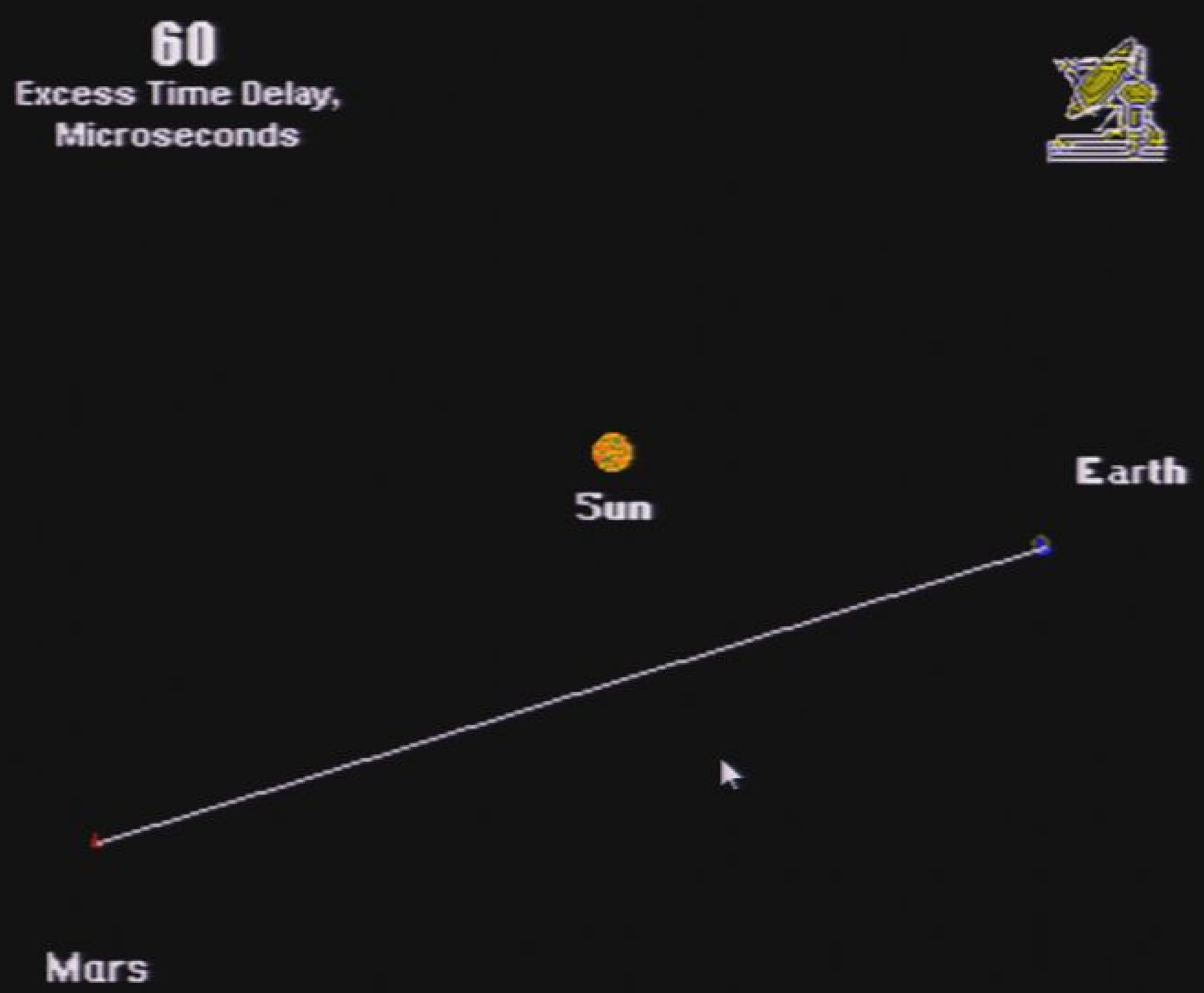
1919 Verification



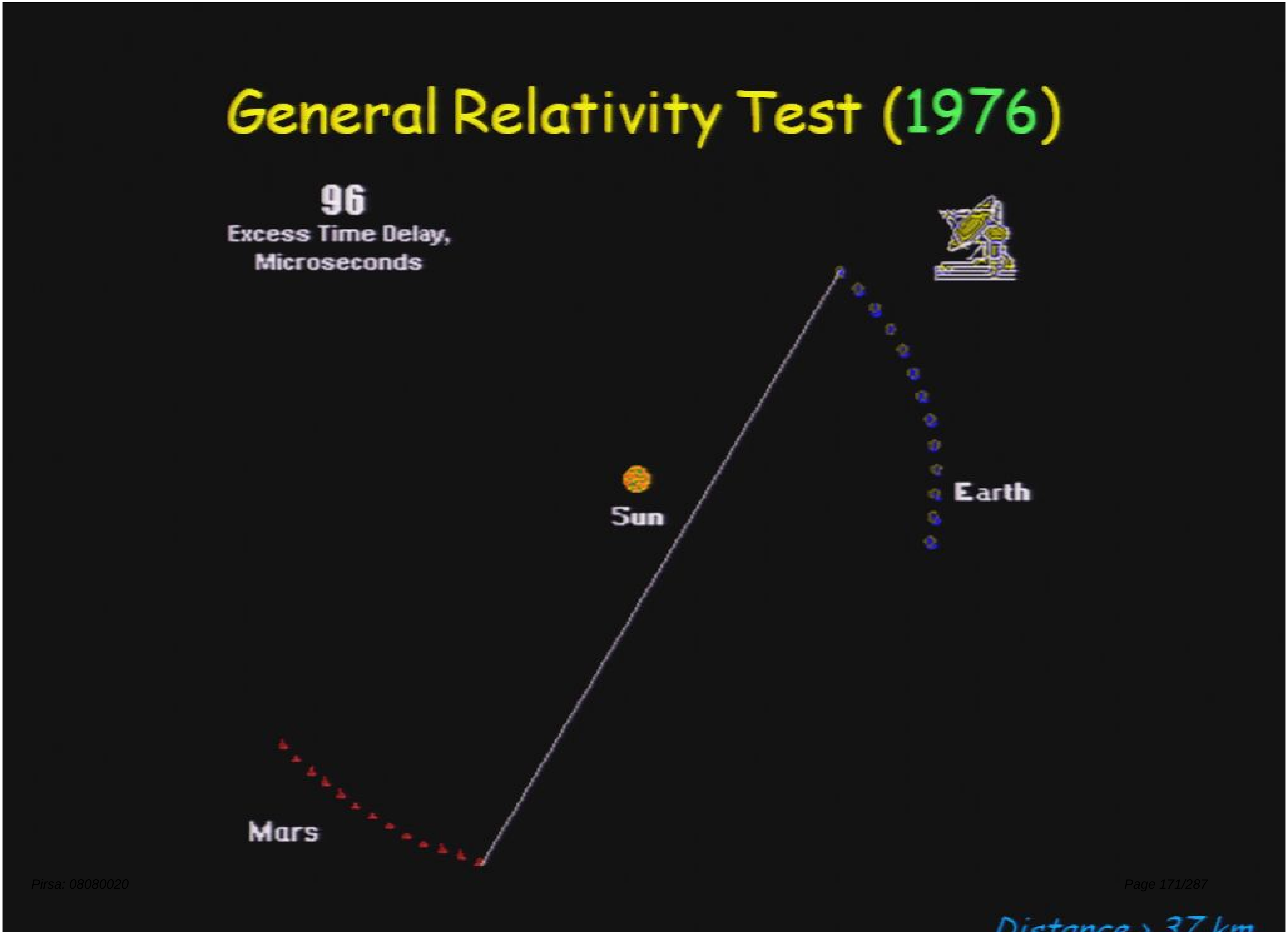


The final proof: the small red line shows how far the position of the star has been shifted by the Sun's gravity.

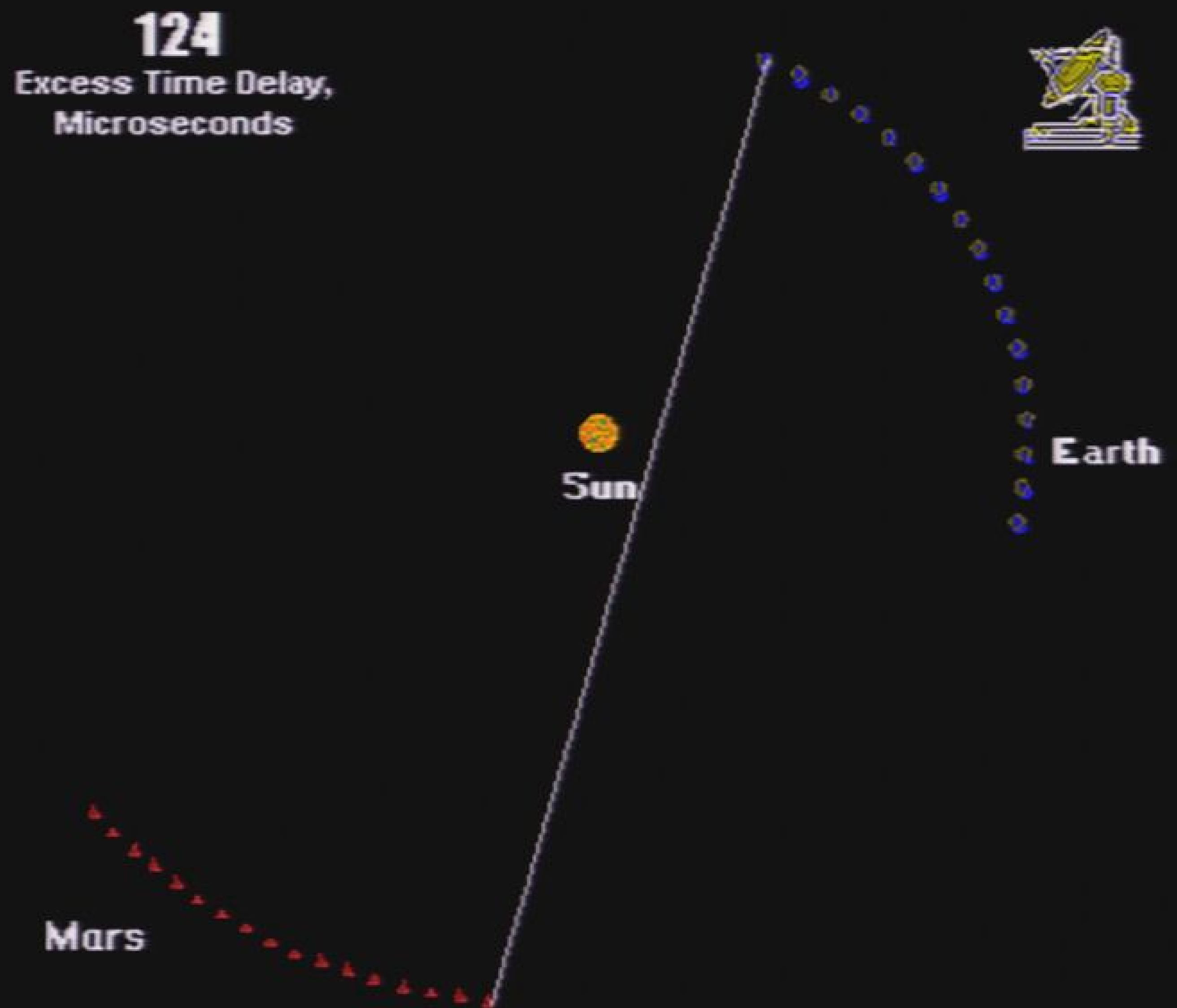
General Relativity Test (1976)



General Relativity Test (1976)

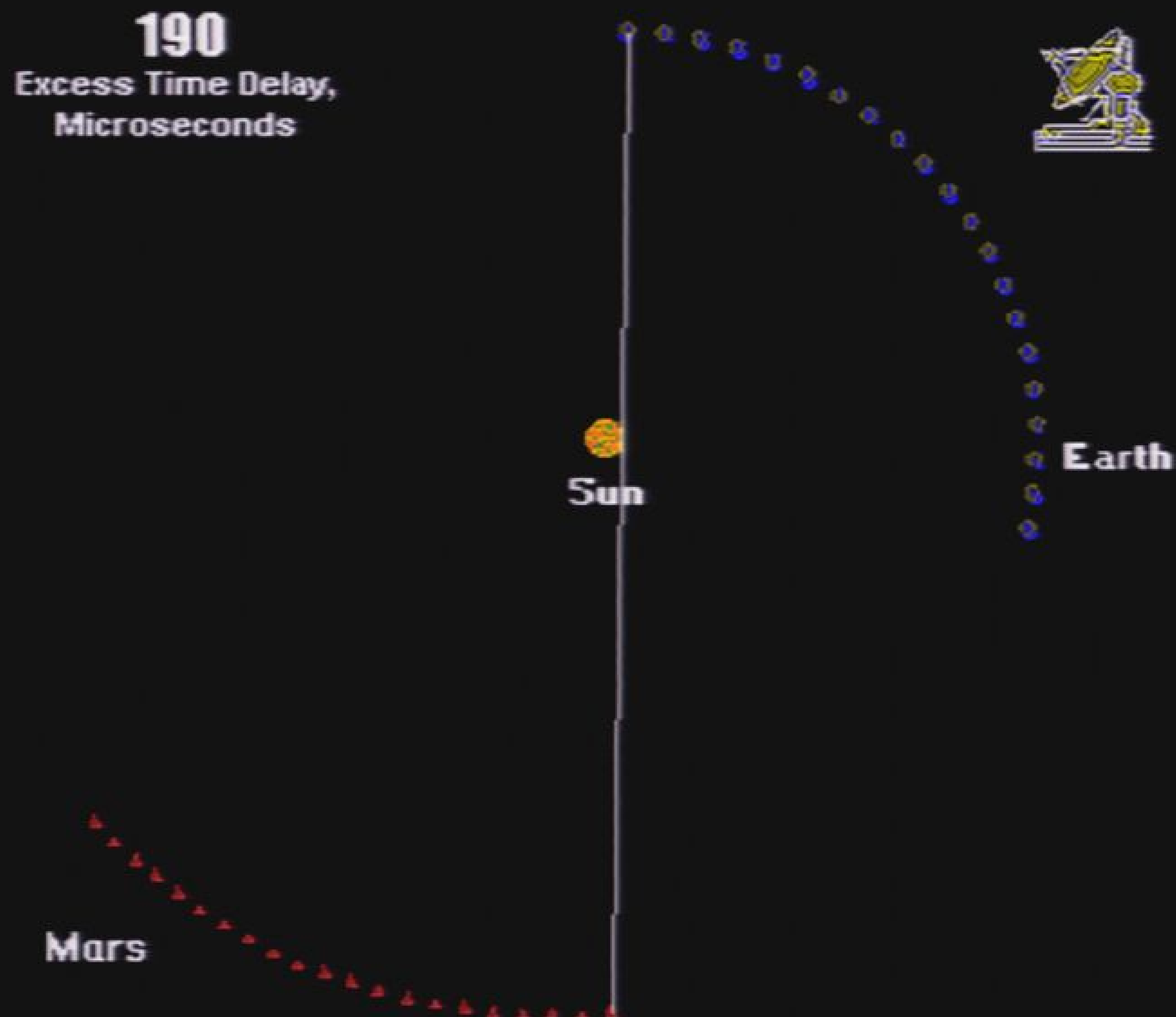

General Relativity Test (1976)
96
Excess Time Delay,
Microseconds
Earth
Sun
Mars

General Relativity Test (1976)

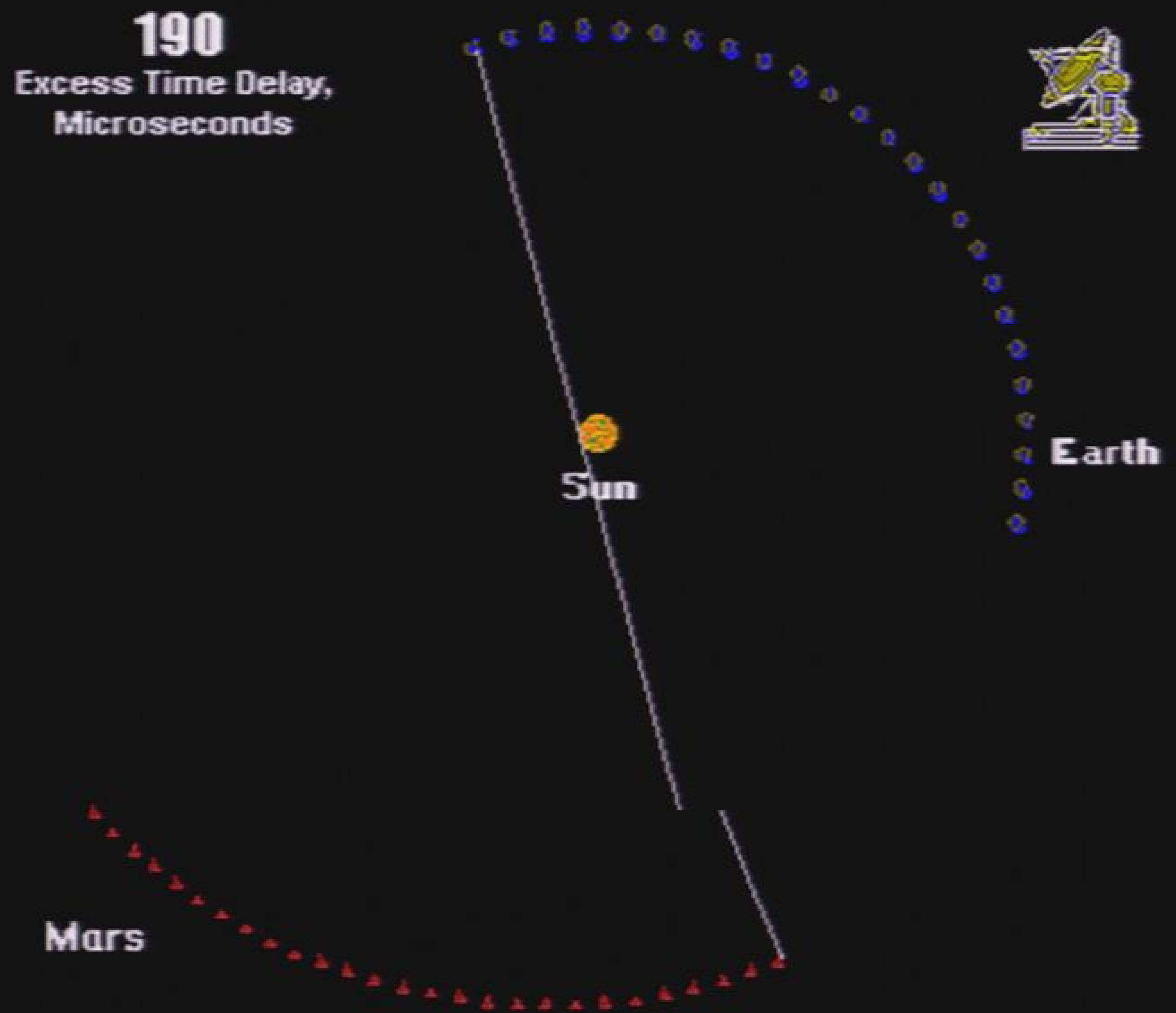


Distance > 37 km

General Relativity Test (1976)

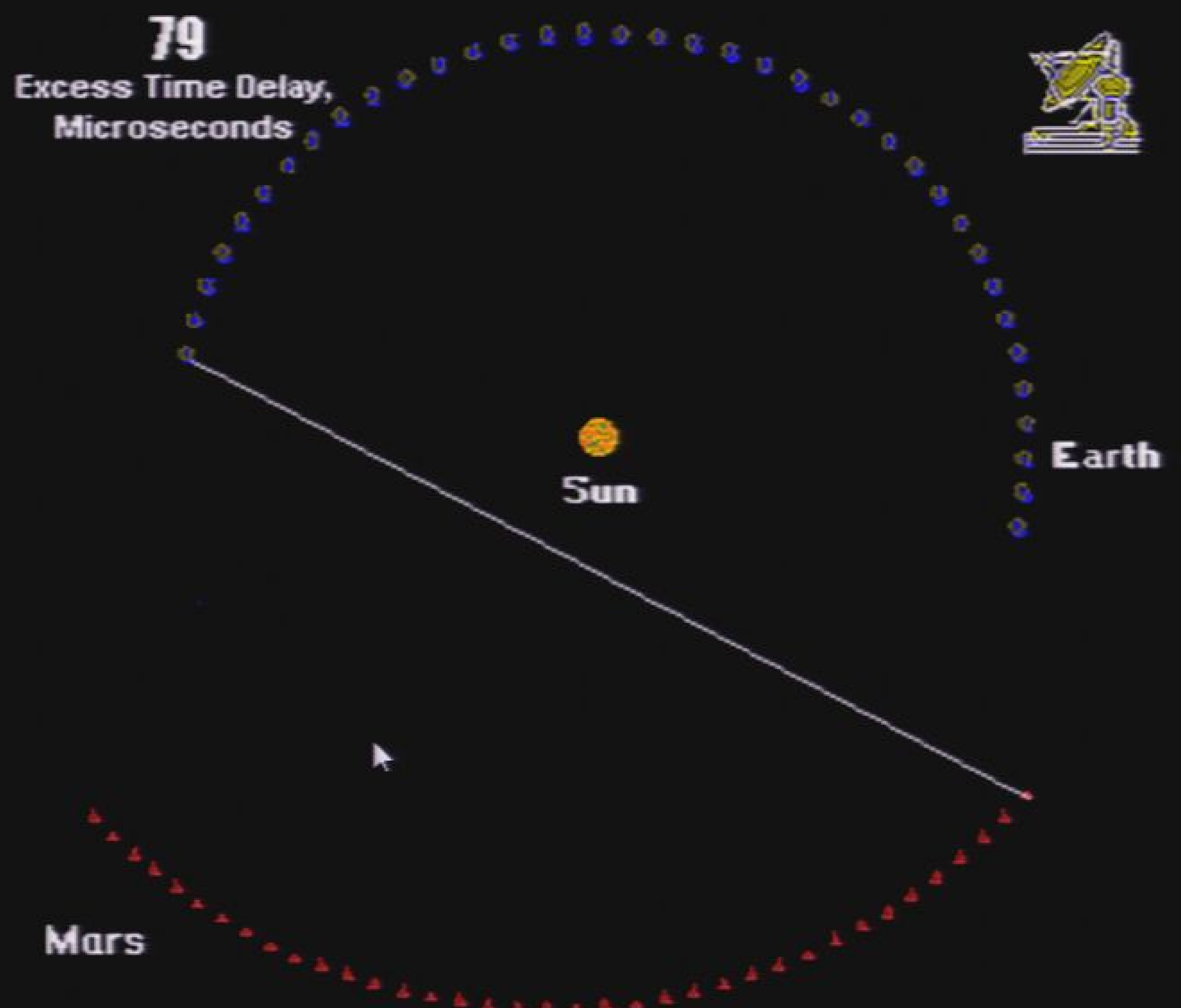


General Relativity Test (1976)

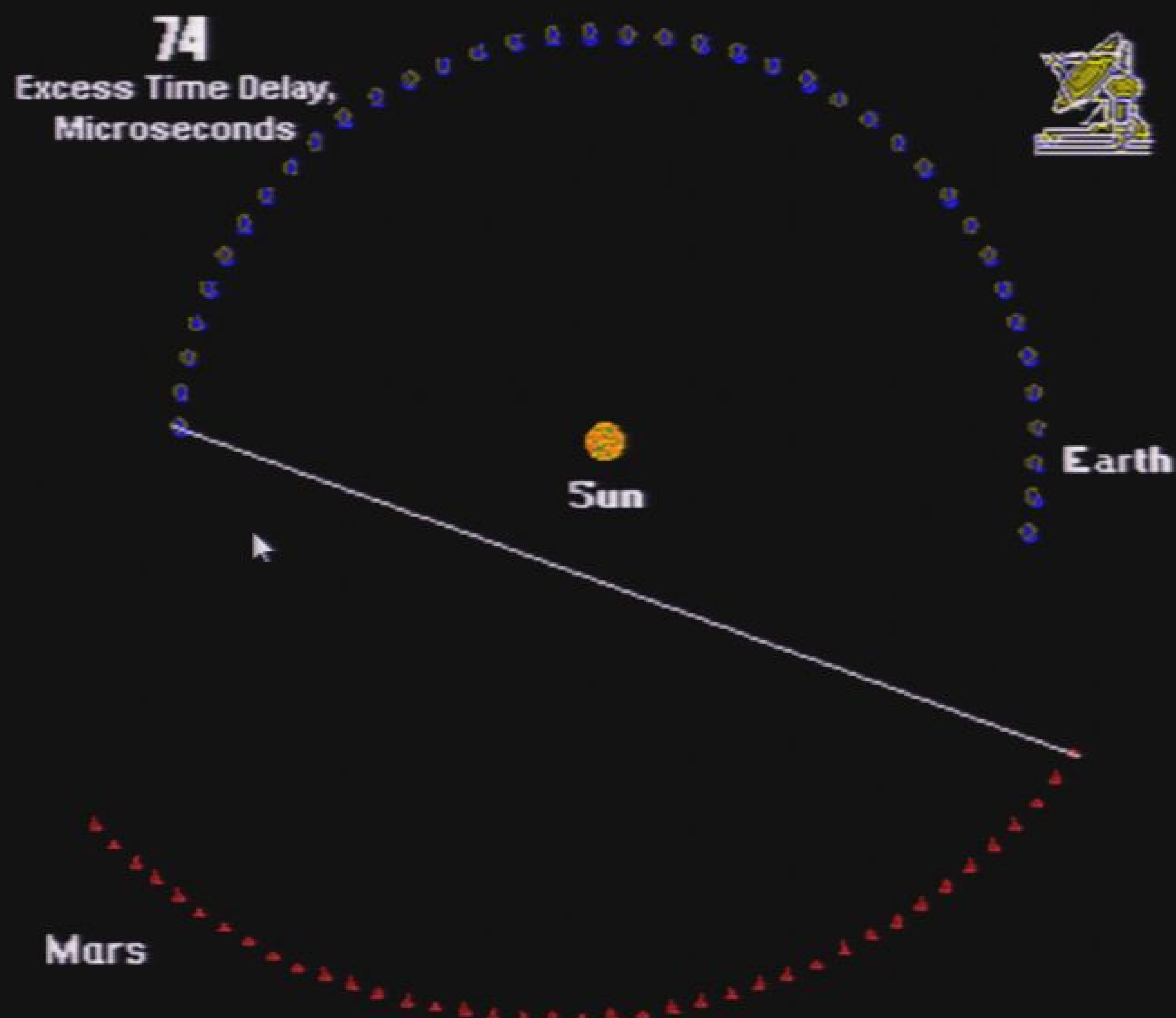


General Relativity Test (1976)

General Relativity Test (1976)



General Relativity Test (1976)



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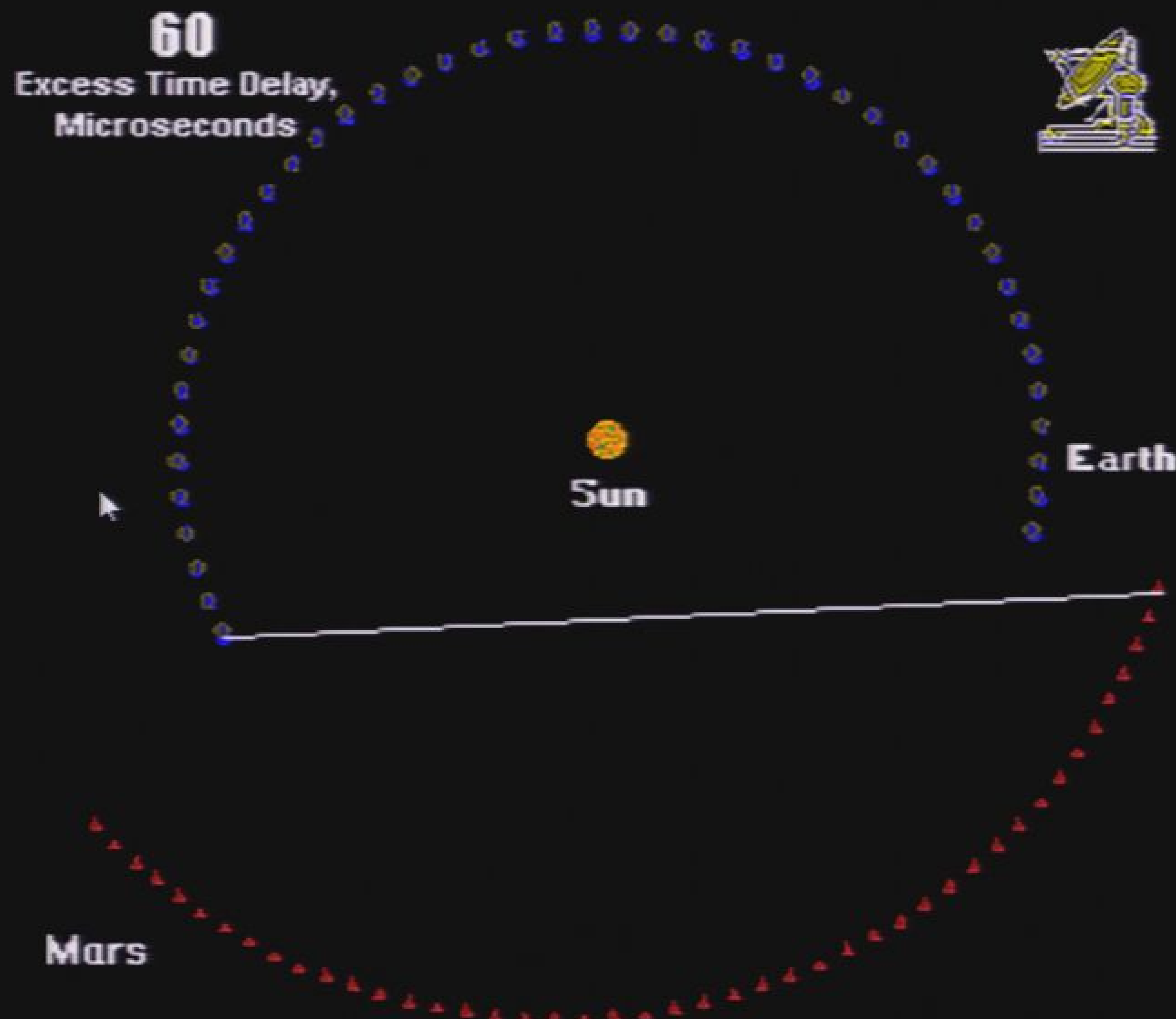
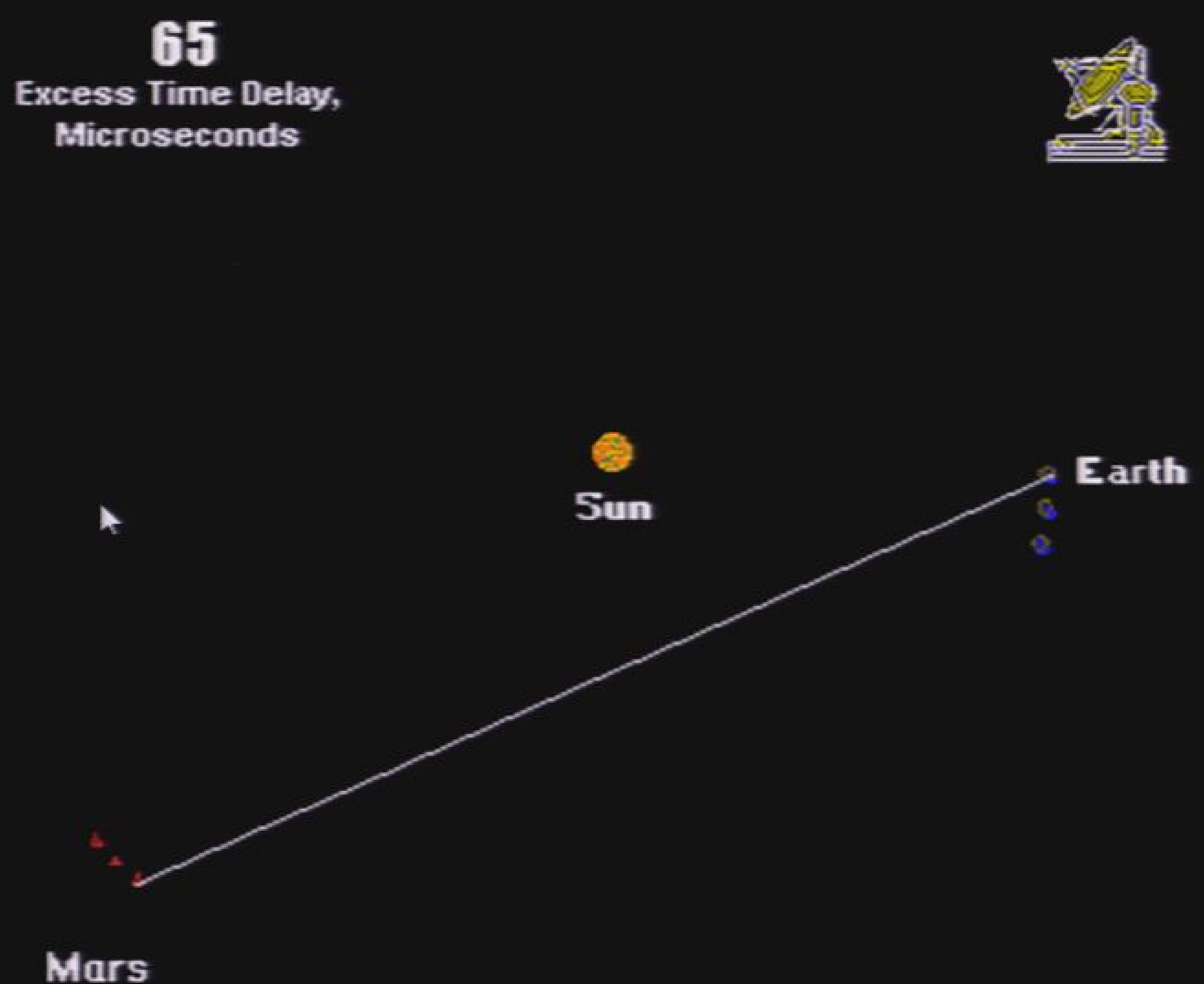
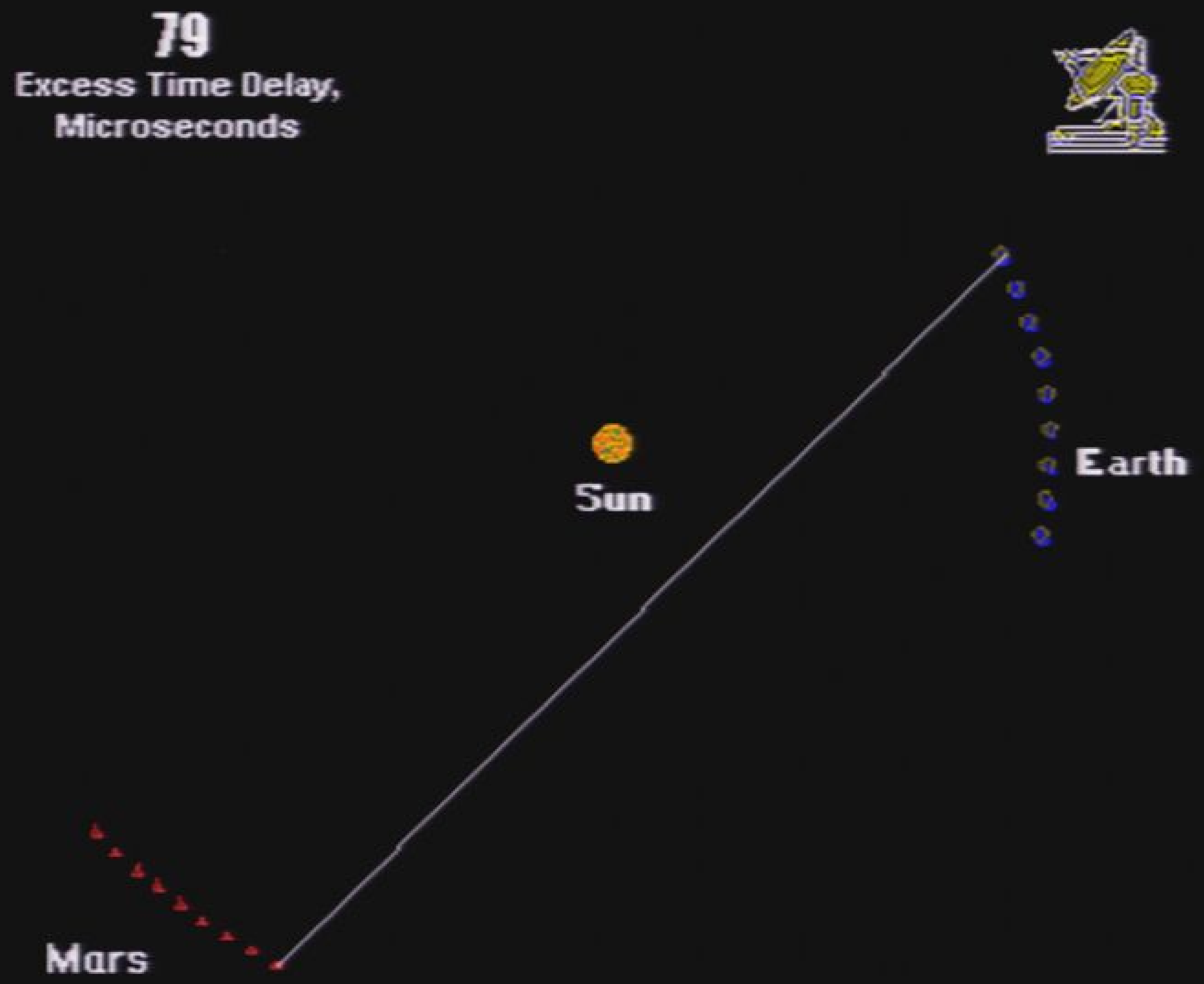


General Relativity Test (1976)

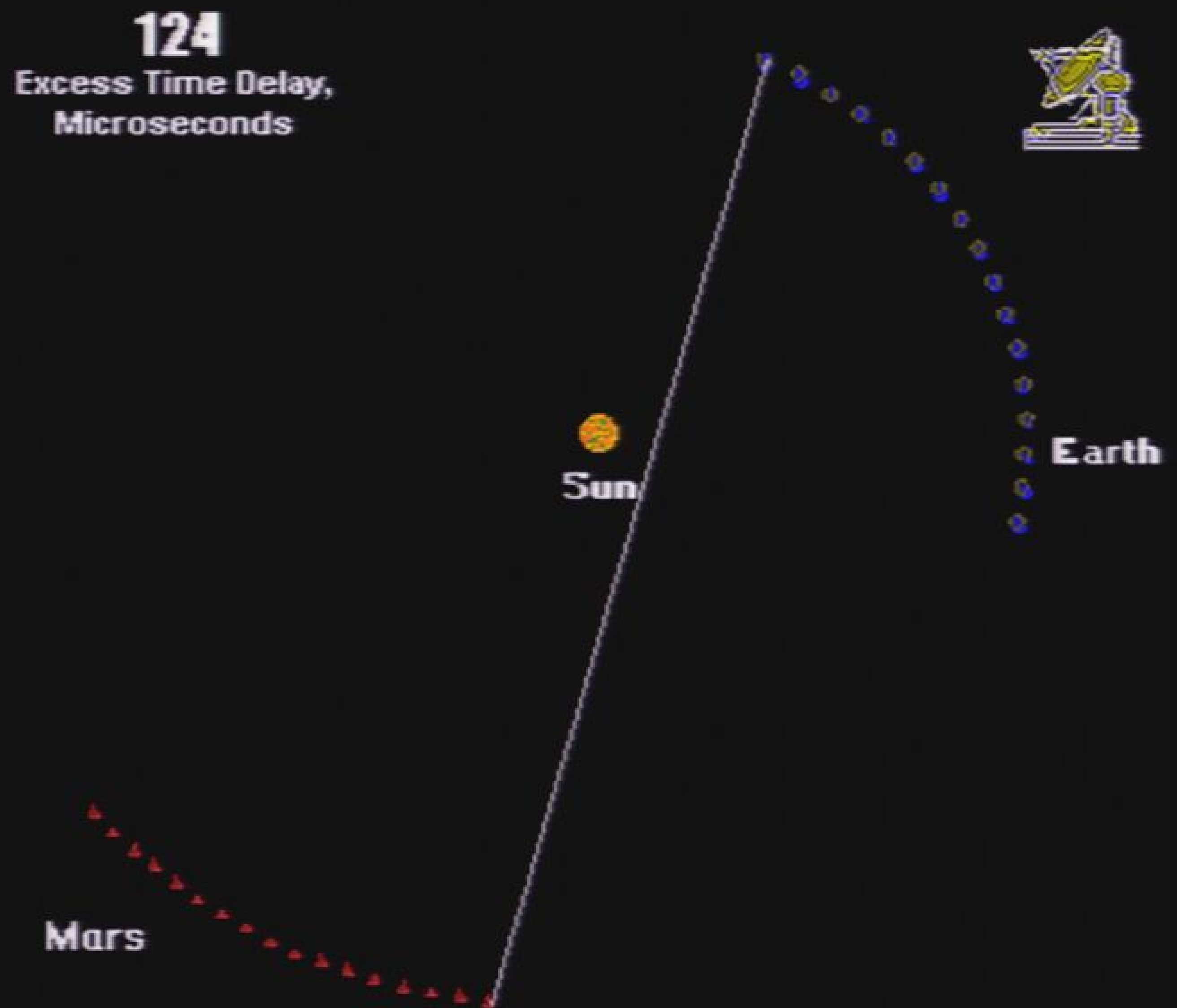


General Relativity Test (1976)



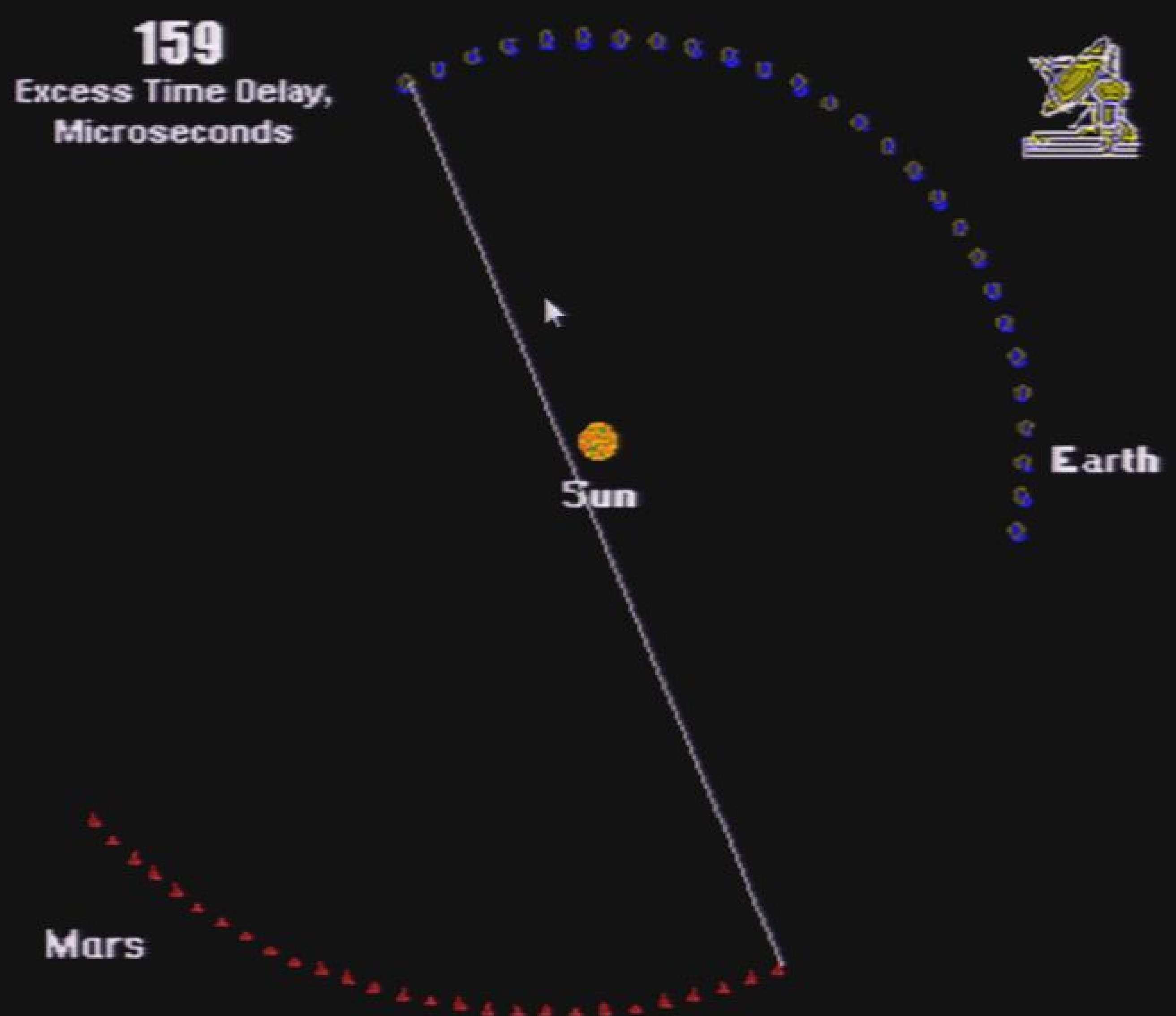
General Relativity Test (1976)

General Relativity Test (1976)

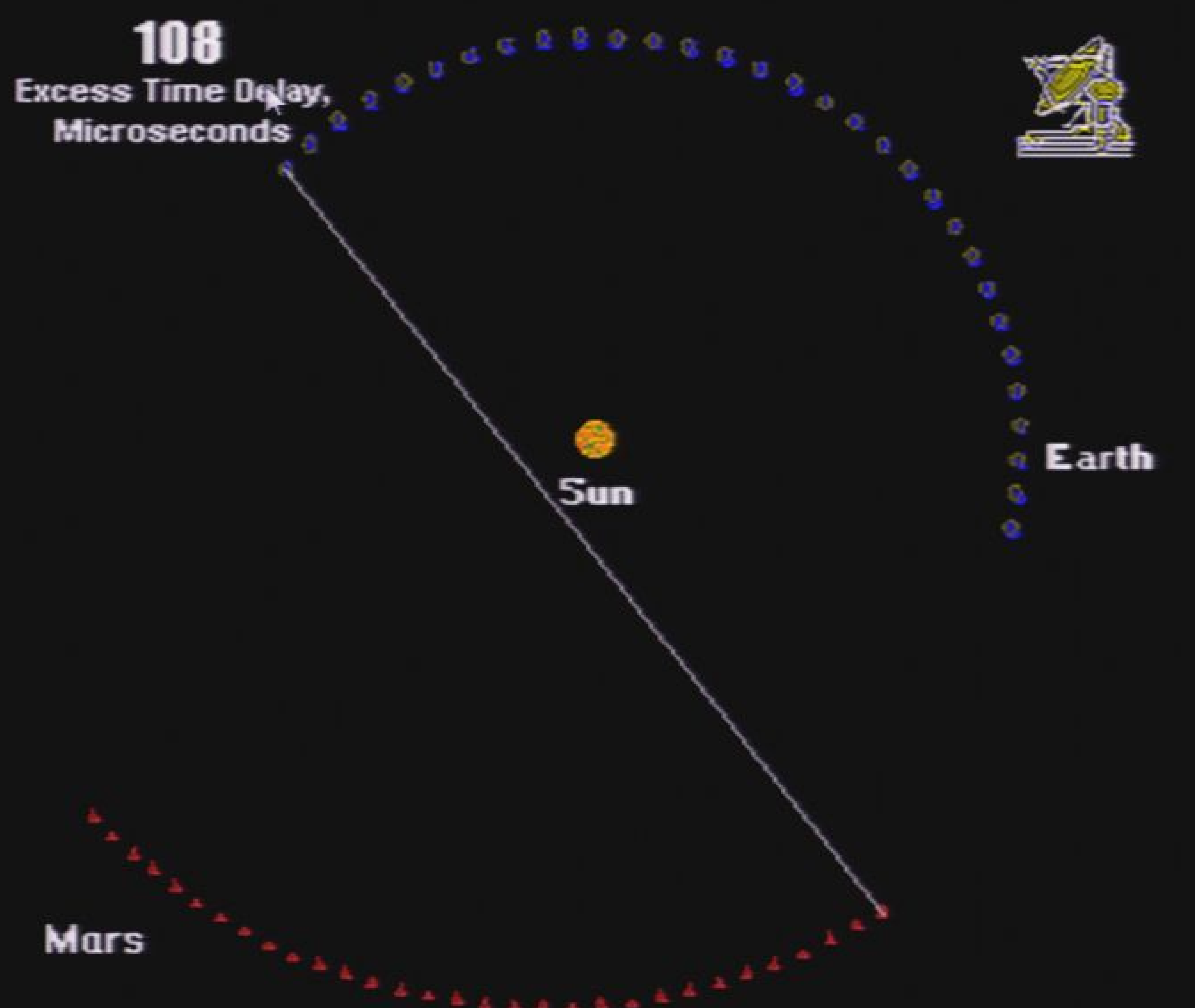


General Relativity Test (1976)

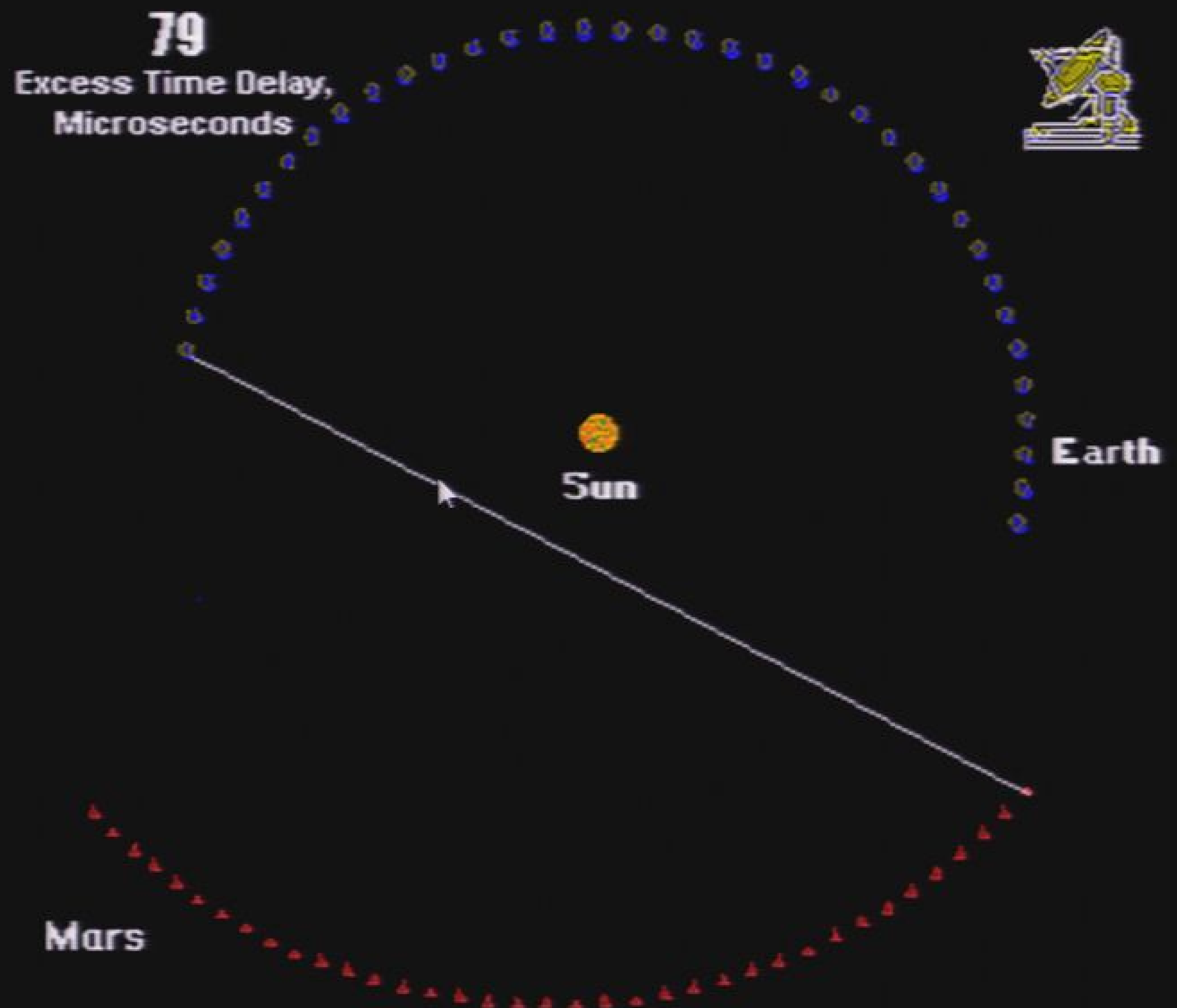
General Relativity Test (1976)



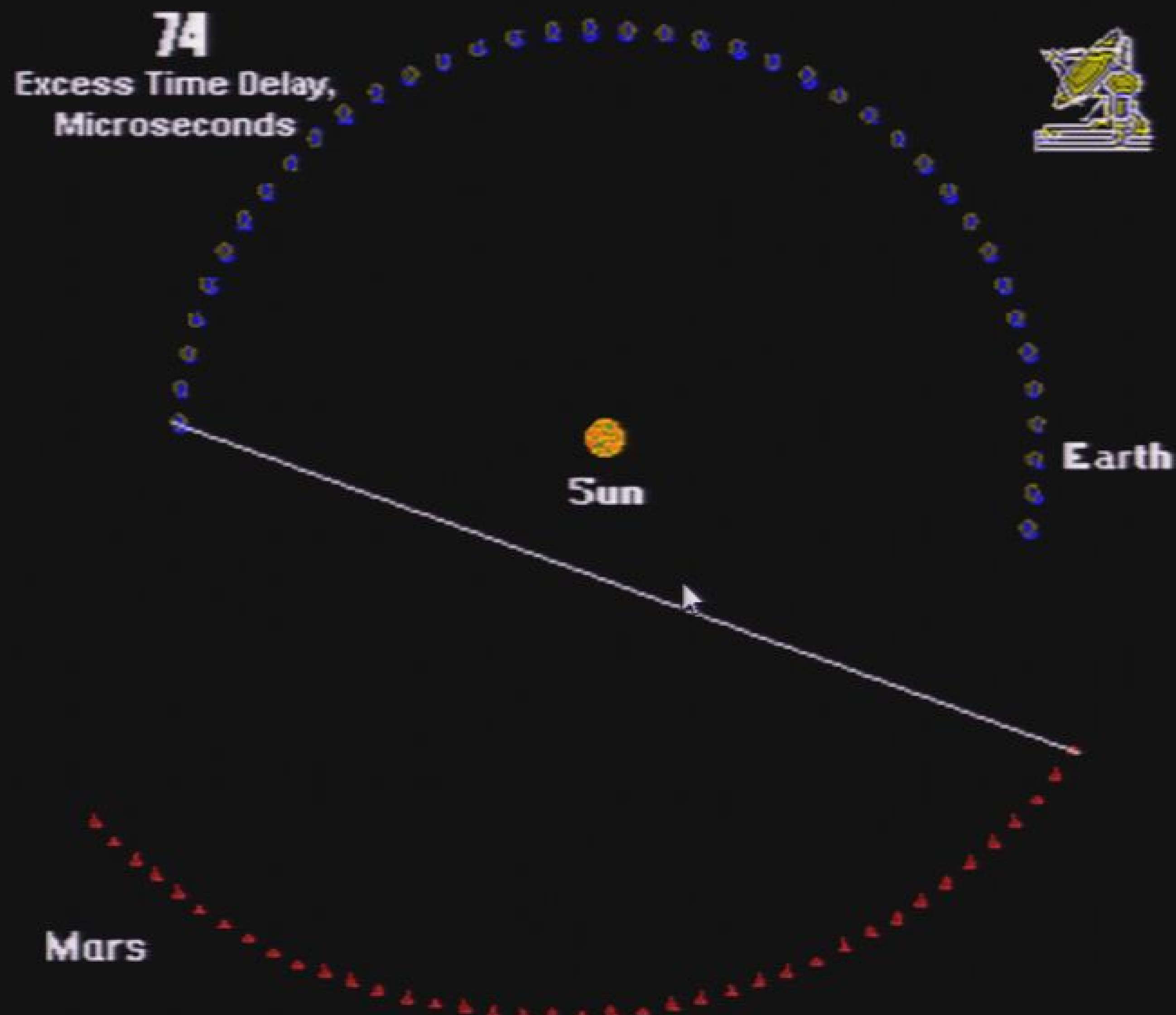
General Relativity Test (1976)

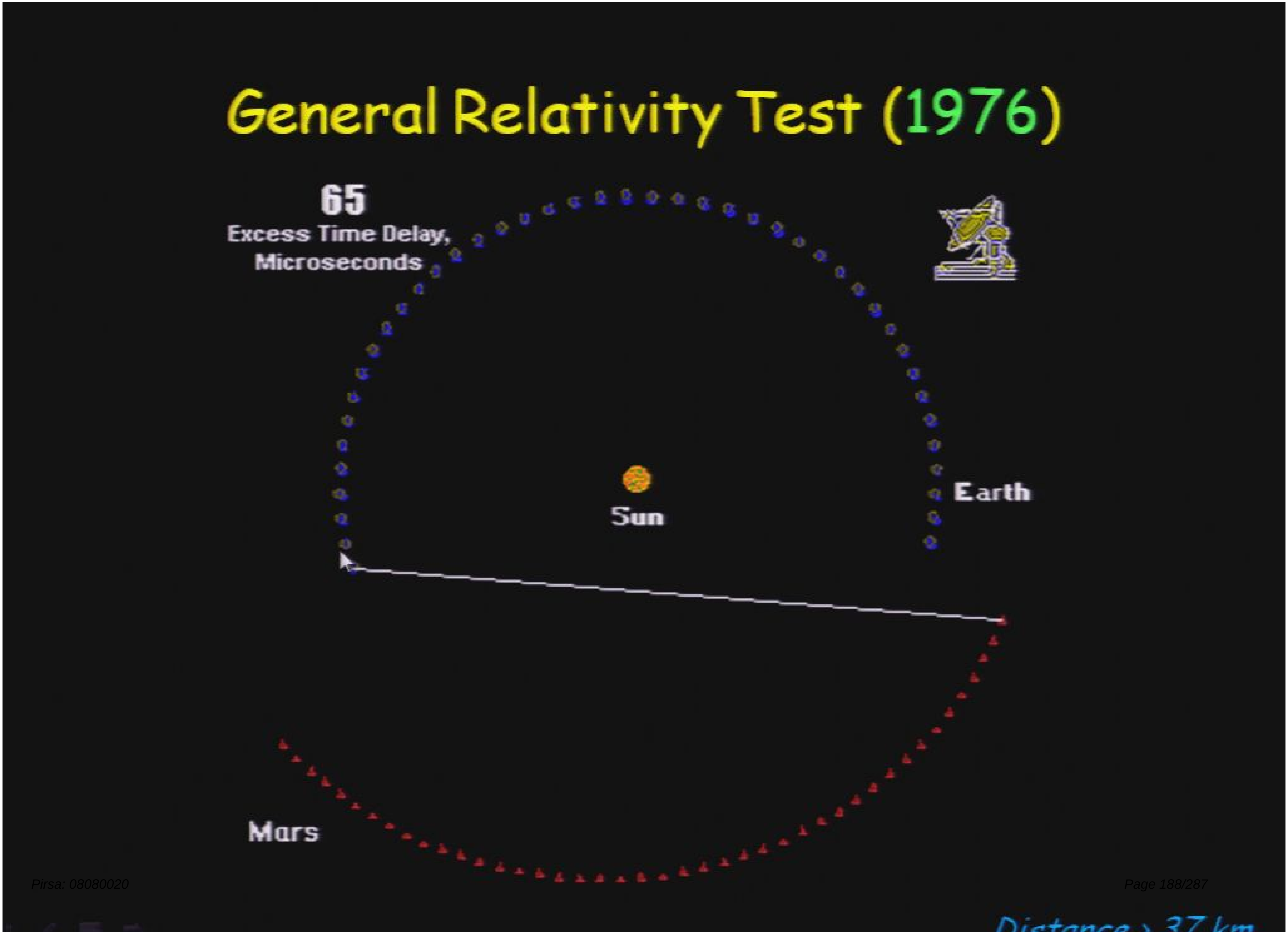


General Relativity Test (1976)



General Relativity Test (1976)

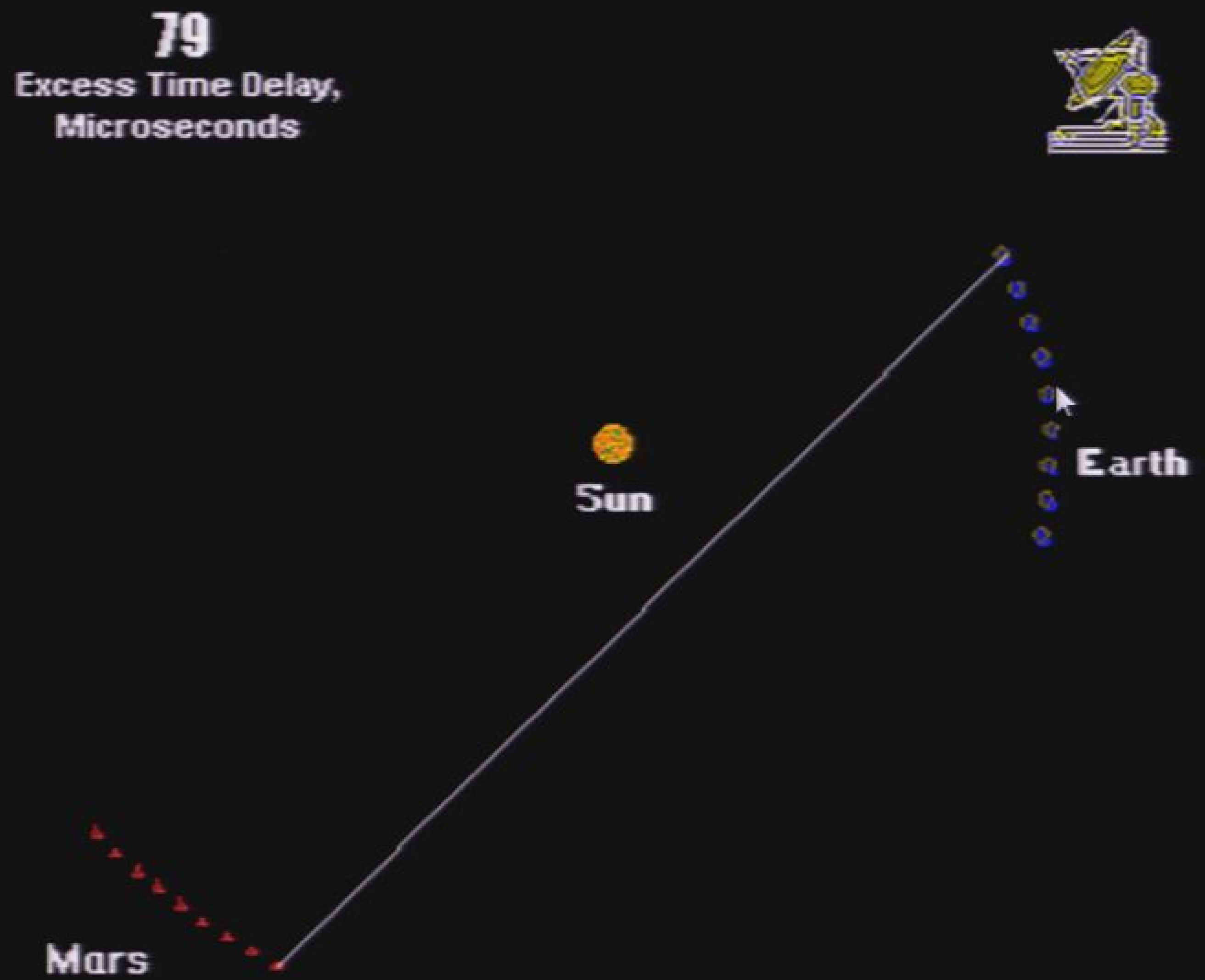



General Relativity Test (1976)
65
Excess Time Delay,
Microseconds
Earth
Sun
Mars

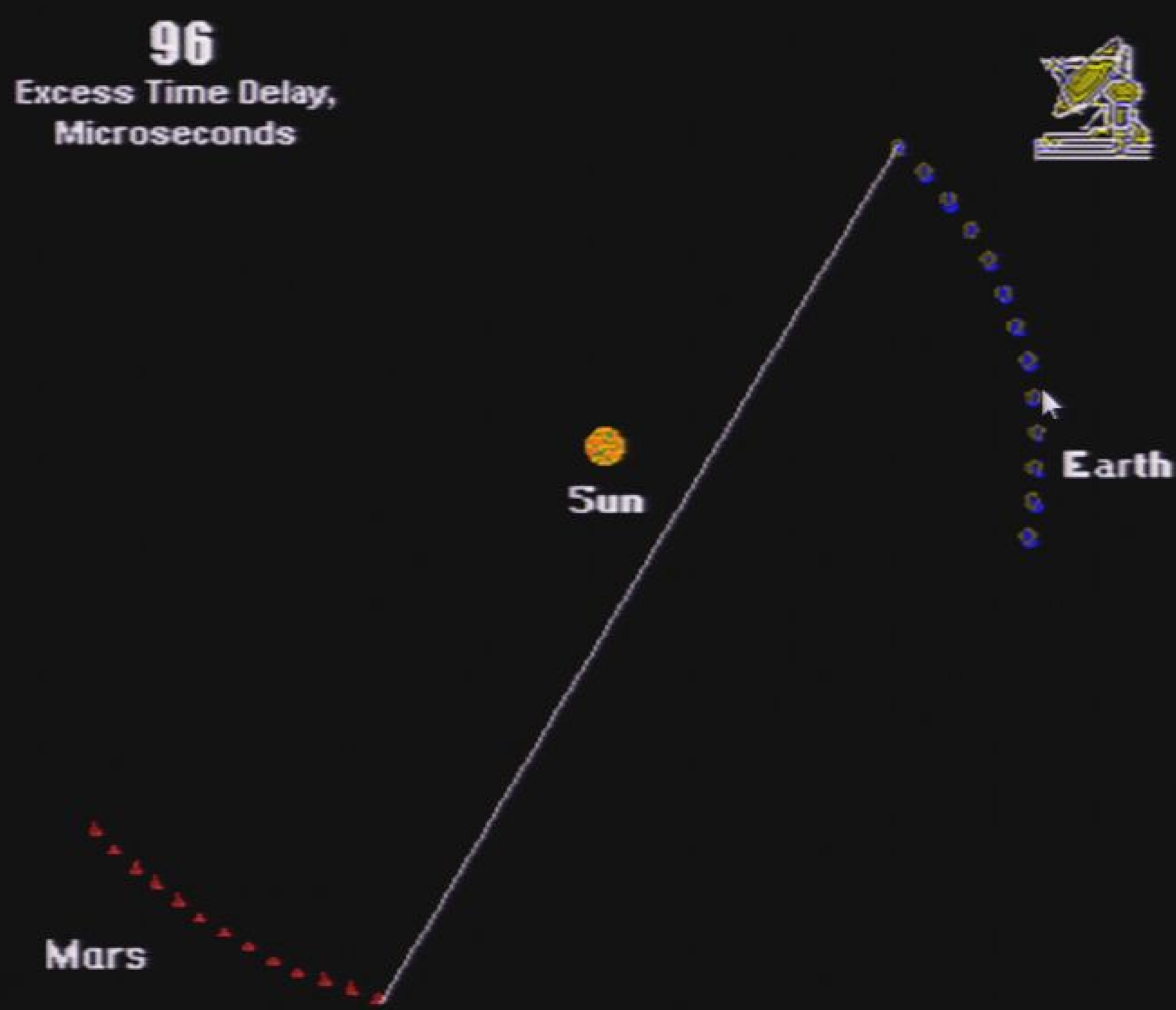
General Relativity Test (1976)

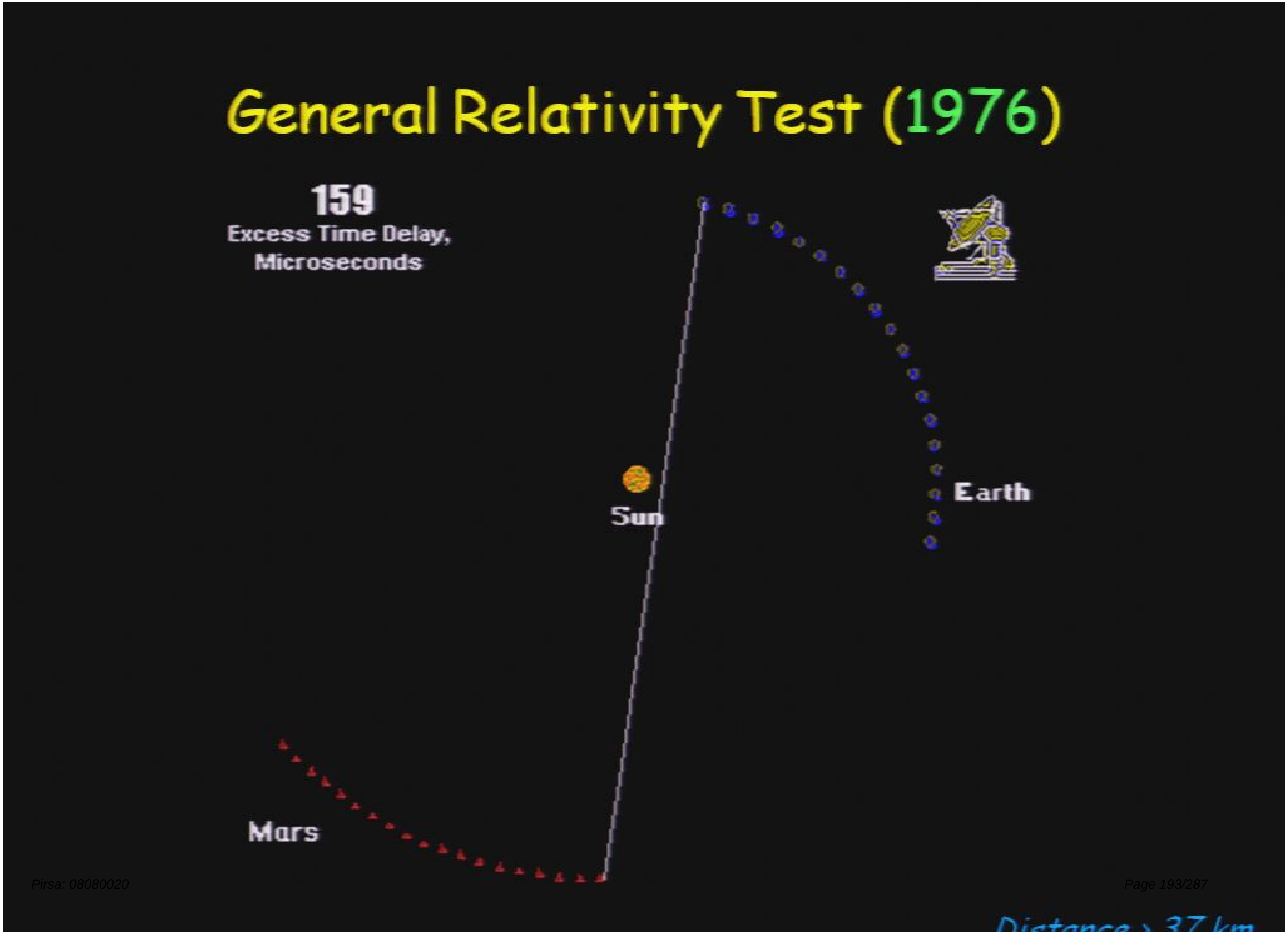
General Relativity Test (1976)

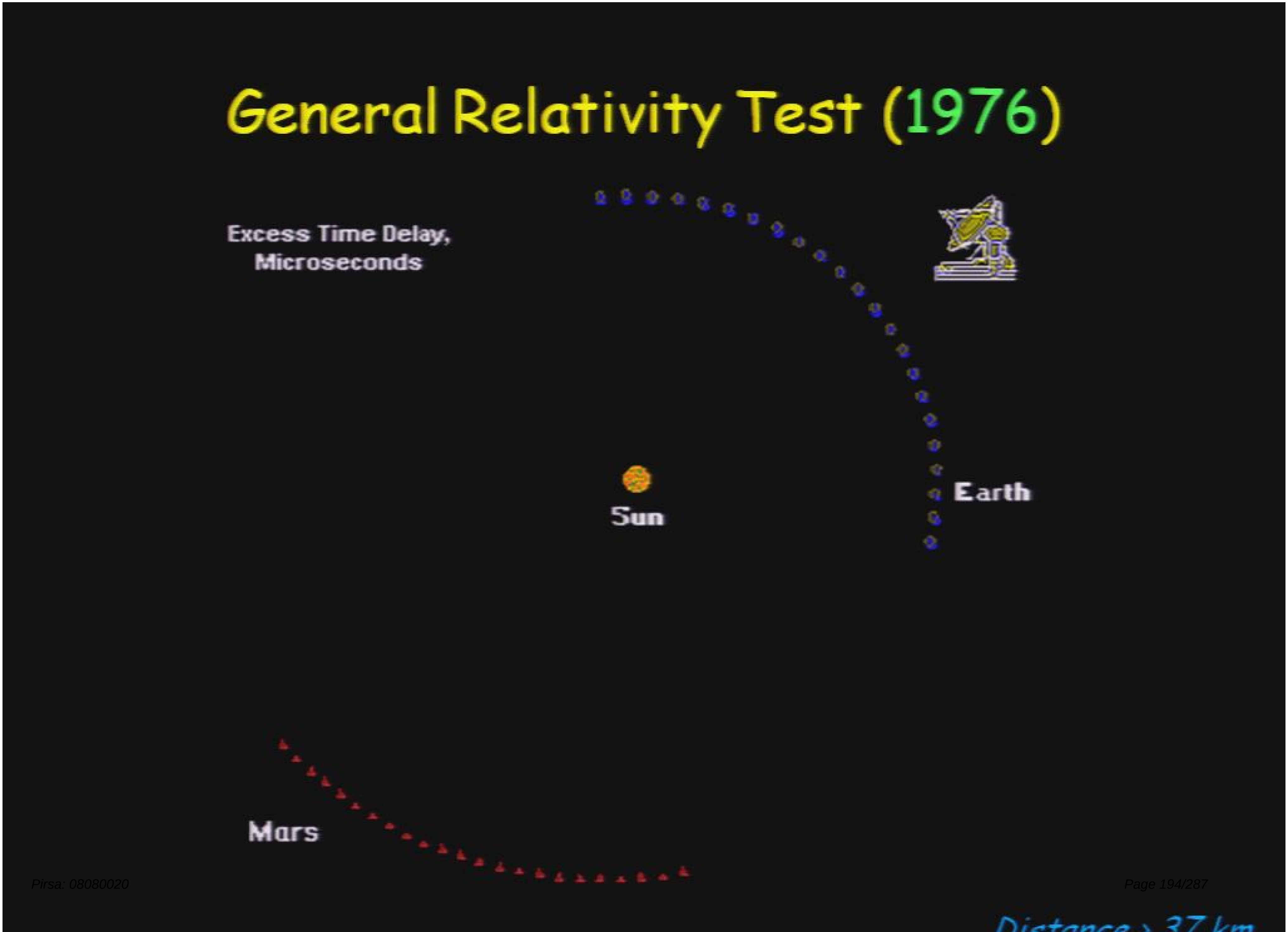
General Relativity Test (1976)



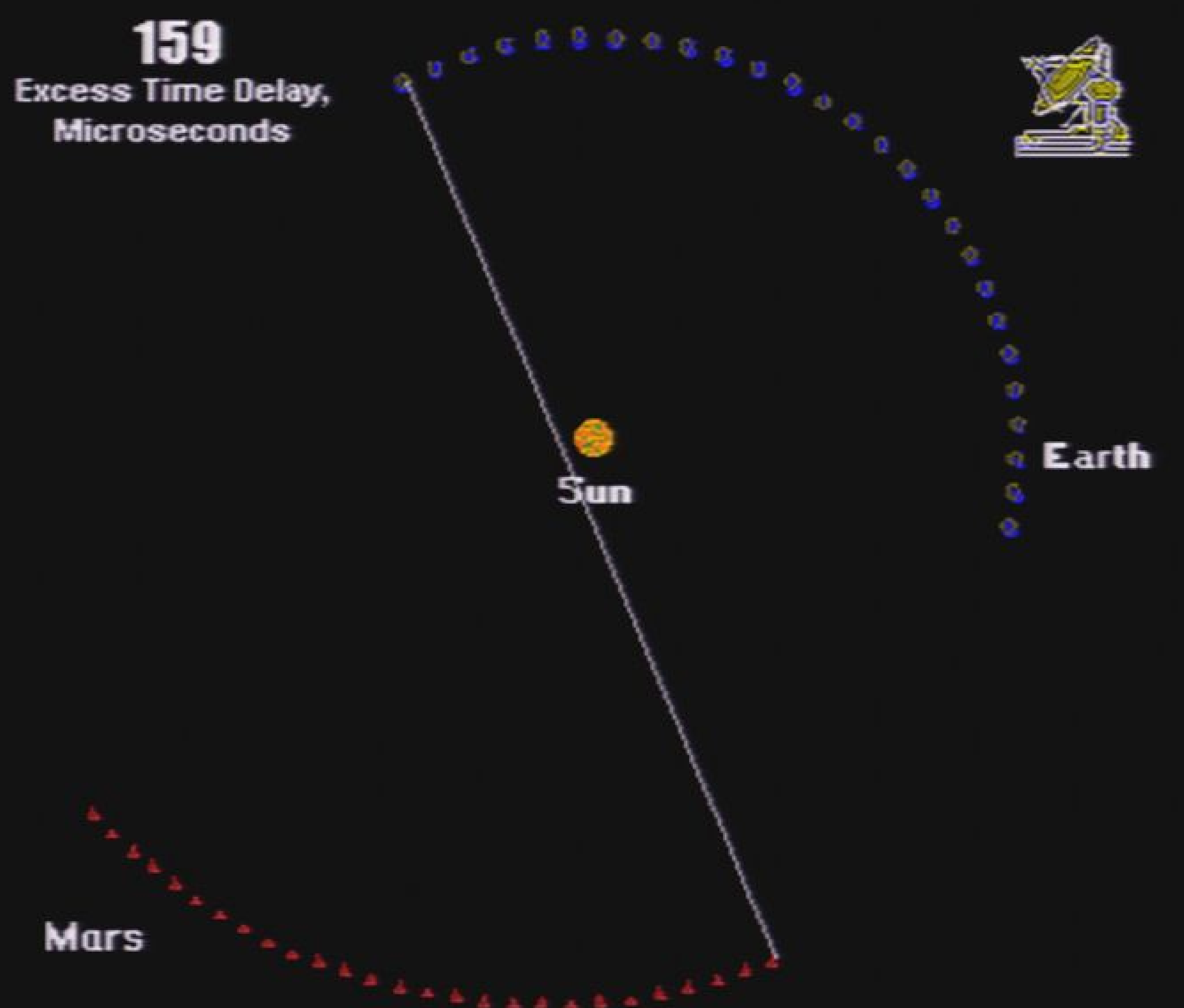
General Relativity Test (1976)



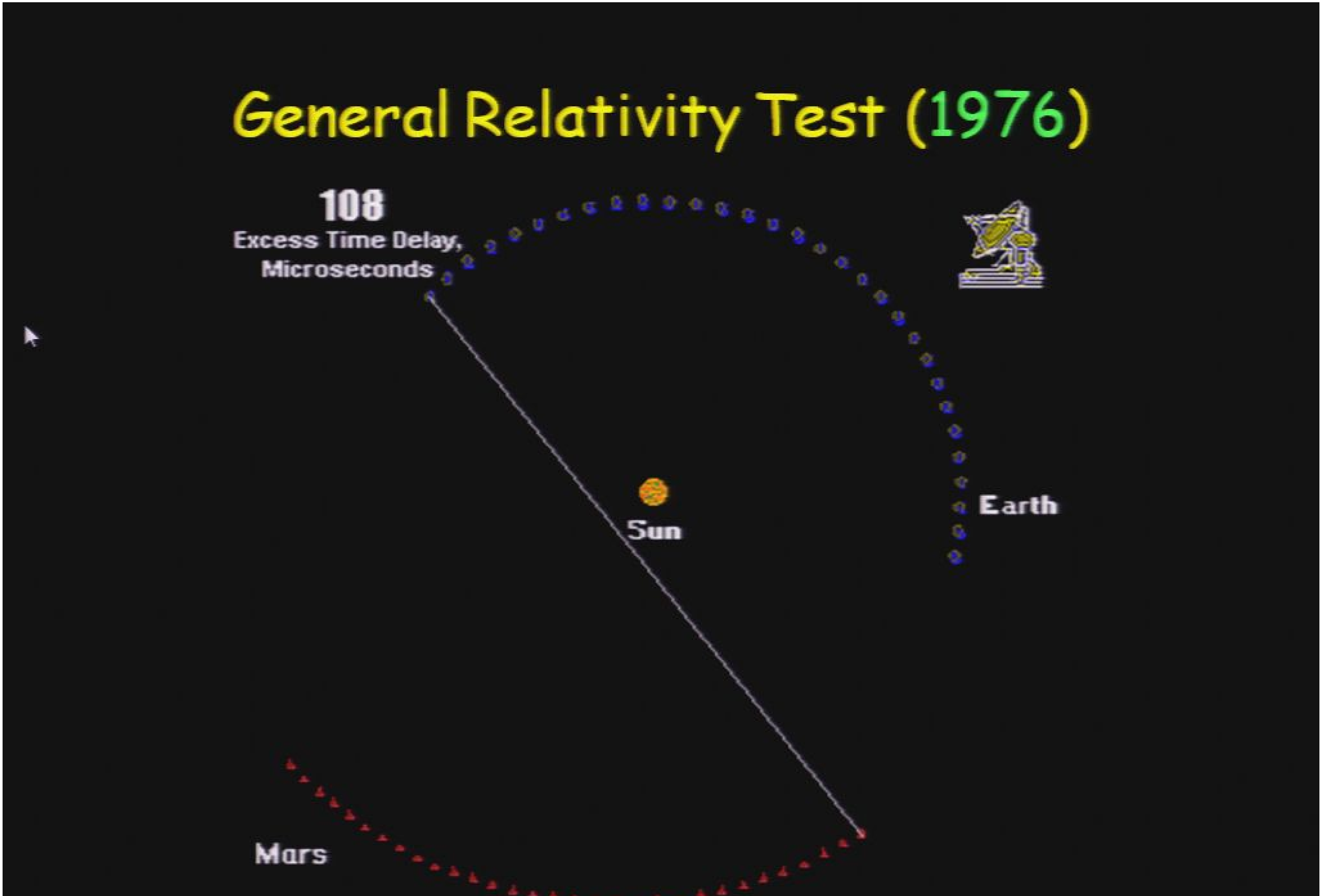

General Relativity Test (1976)
159
Excess Time Delay,
Microseconds
Sun
Earth
Mars


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

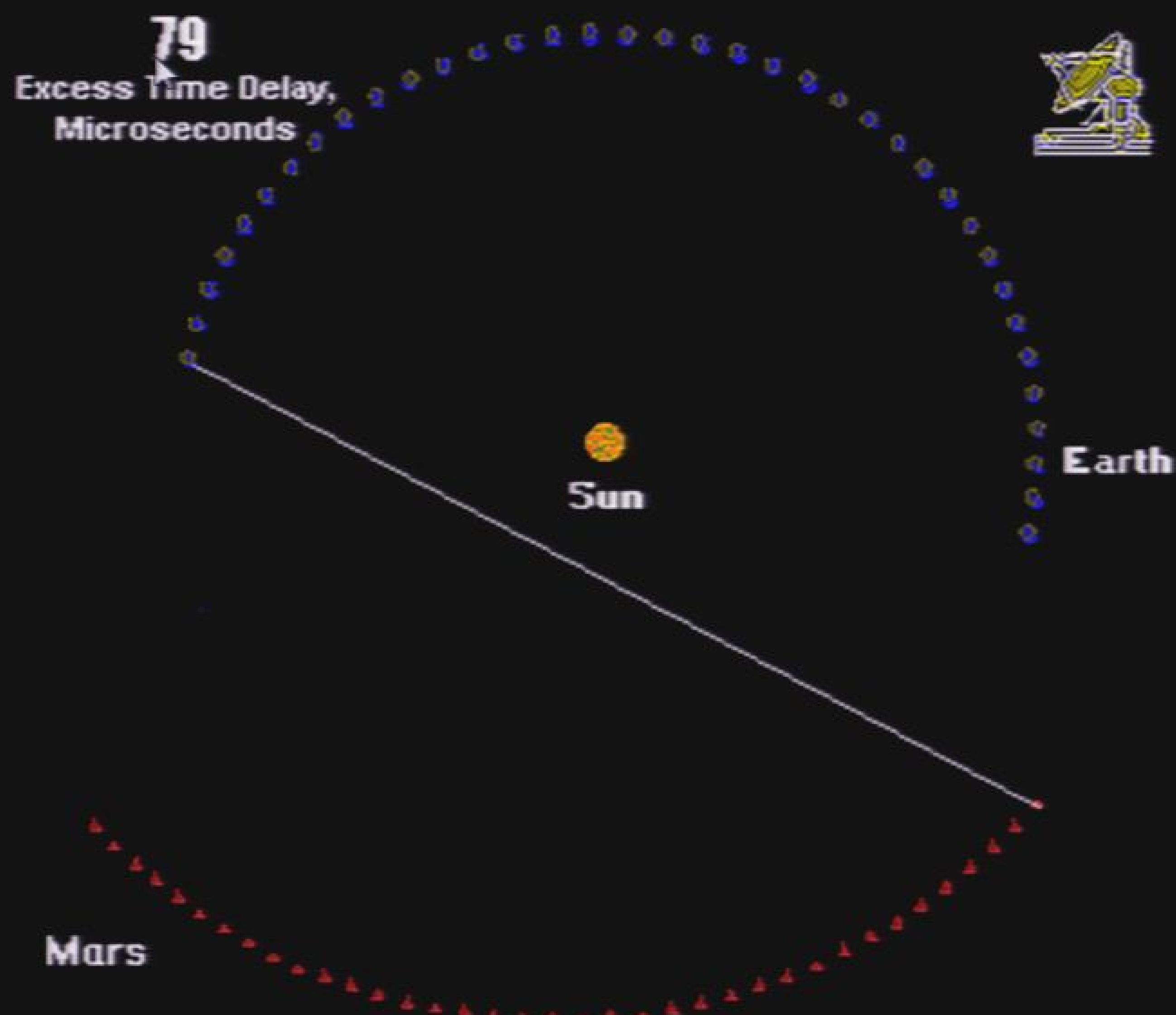
General Relativity Test (1976)

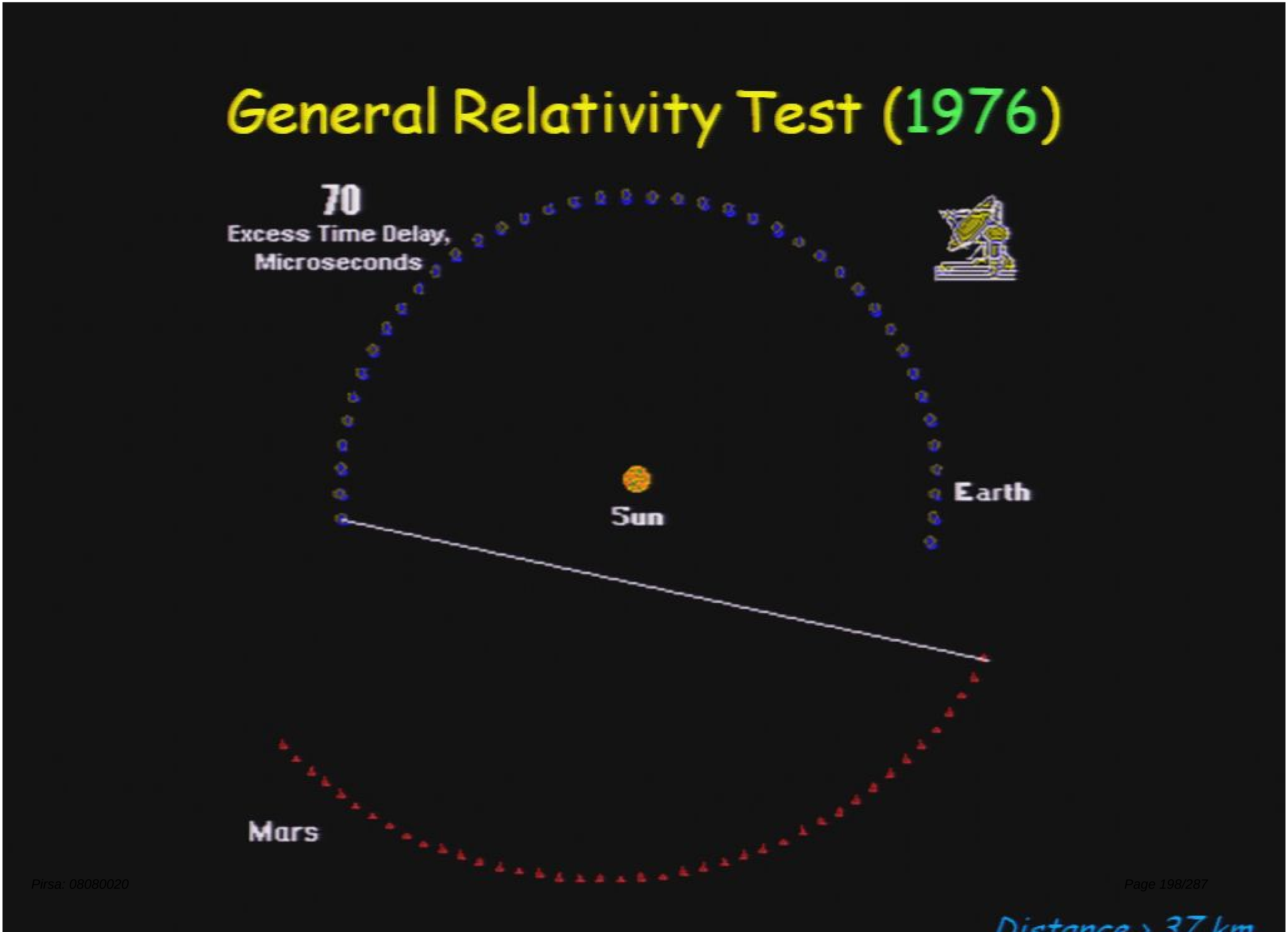


Distance > 37 km

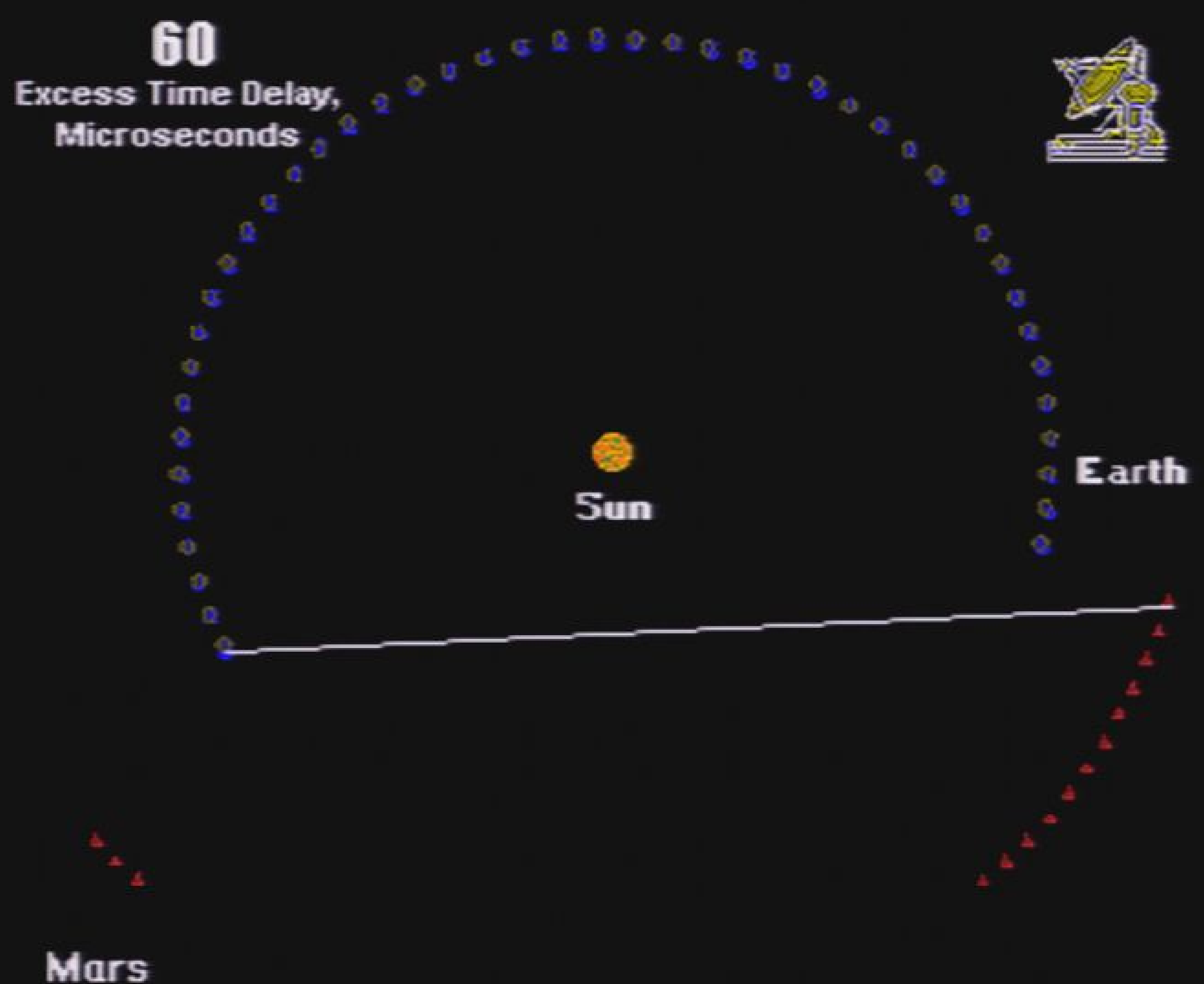

General Relativity Test (1976)
108
Excess Time Delay,
Microseconds
Earth
Sun
Mars

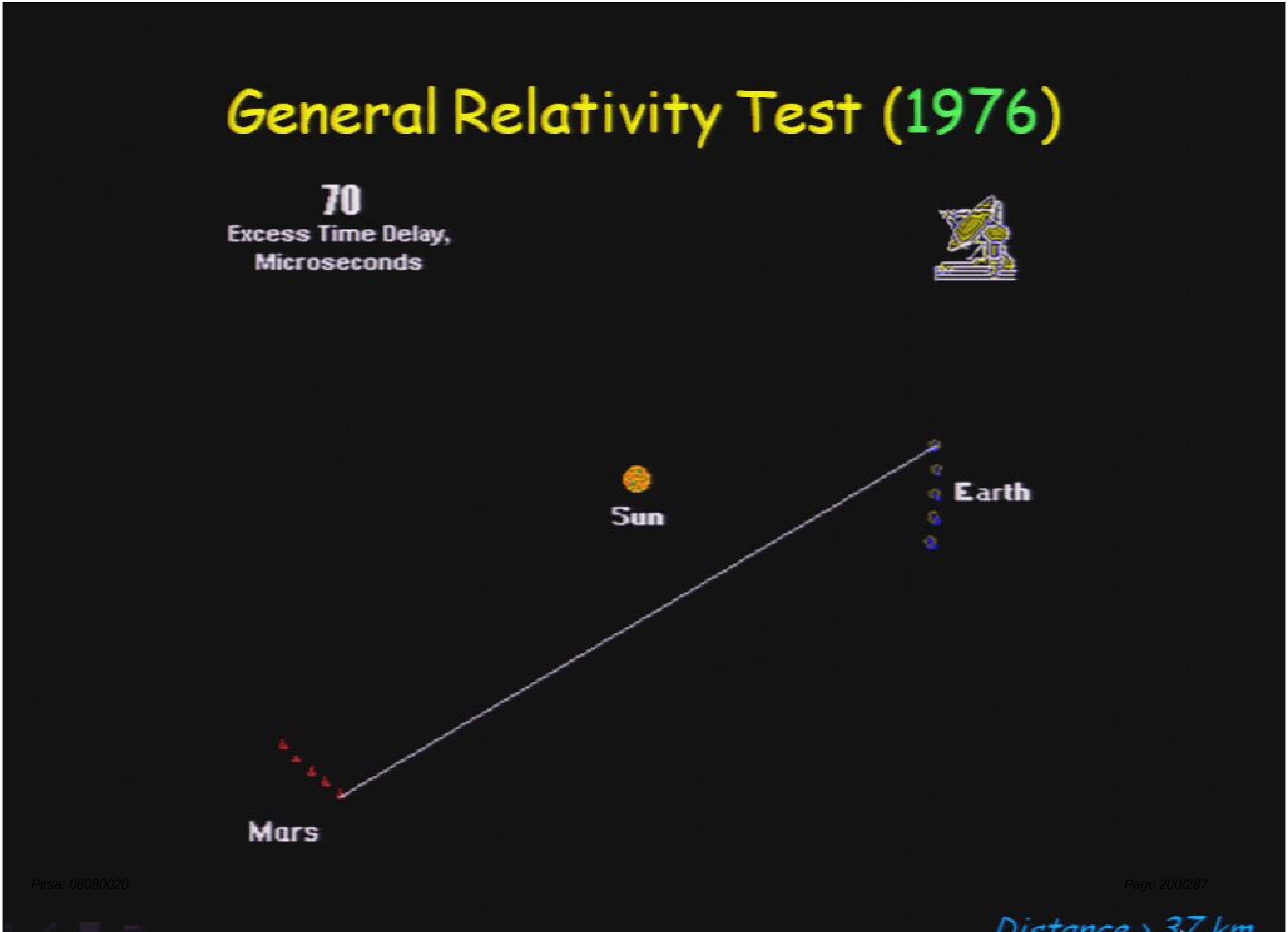
General Relativity Test (1976)

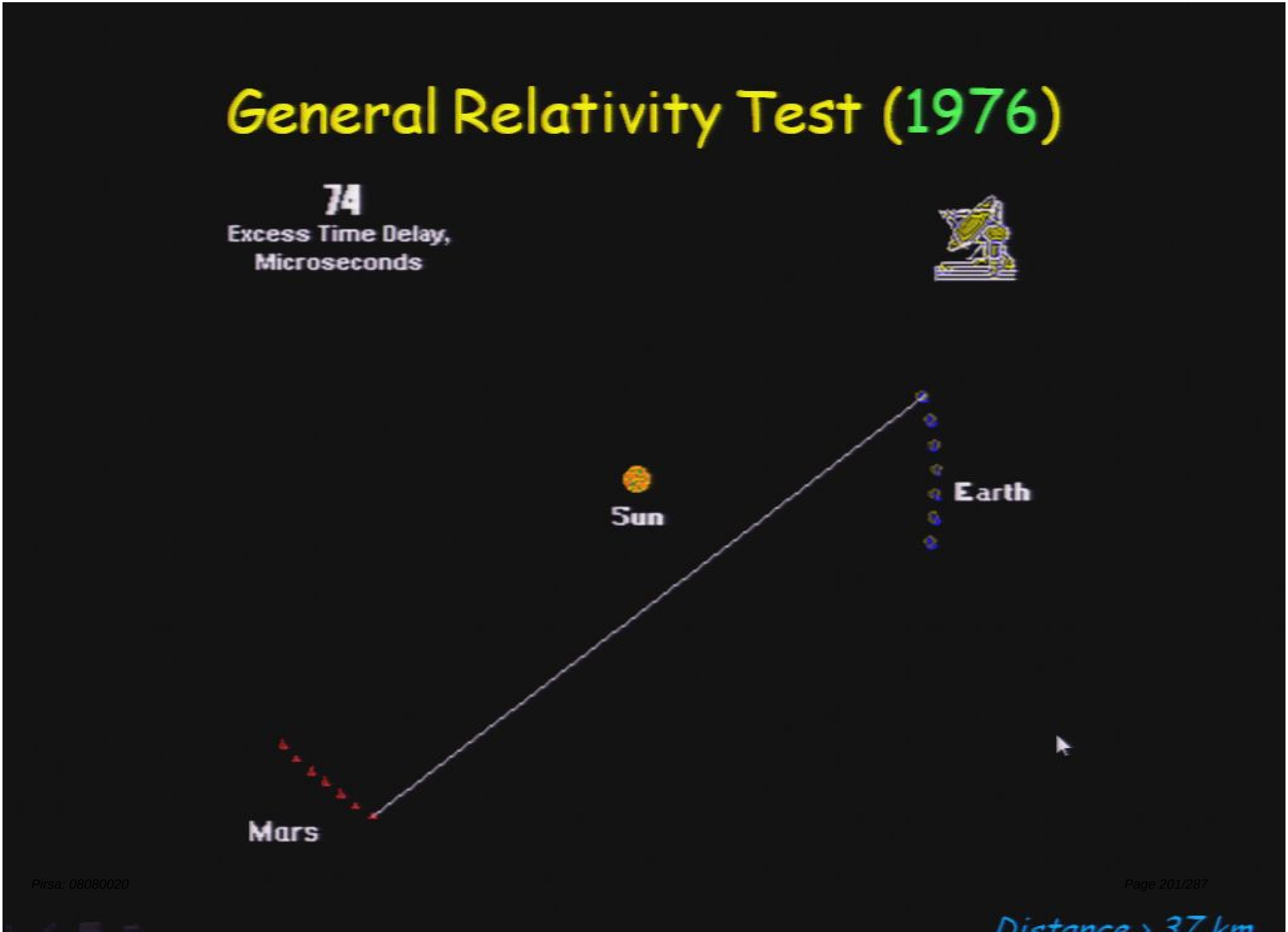



General Relativity Test (1976)
70
Excess Time Delay,
Microseconds
Earth
Sun
Mars

General Relativity Test (1976)



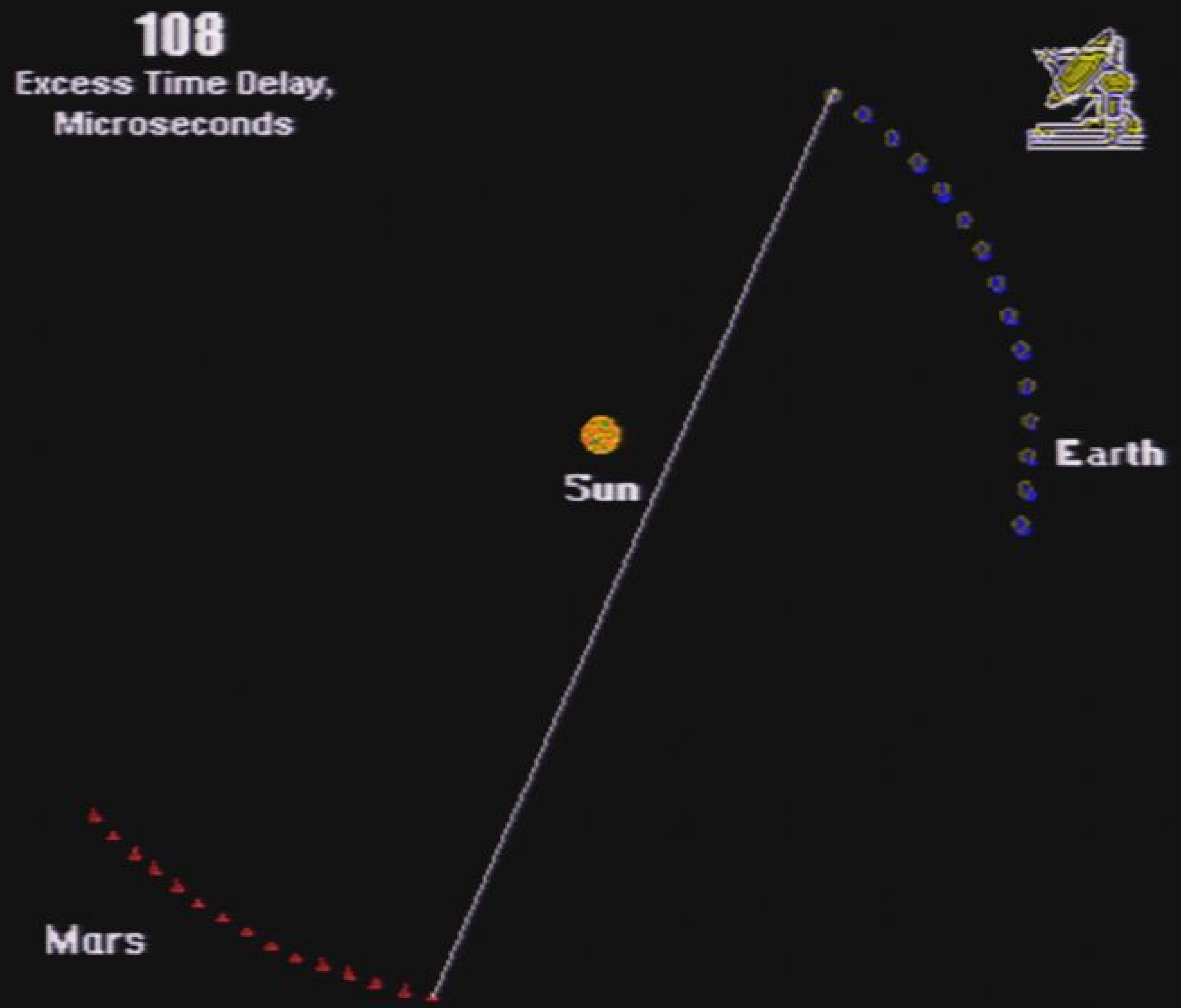

General Relativity Test (1976)
70
Excess Time Delay,
Microseconds
Sun
Earth
Mars

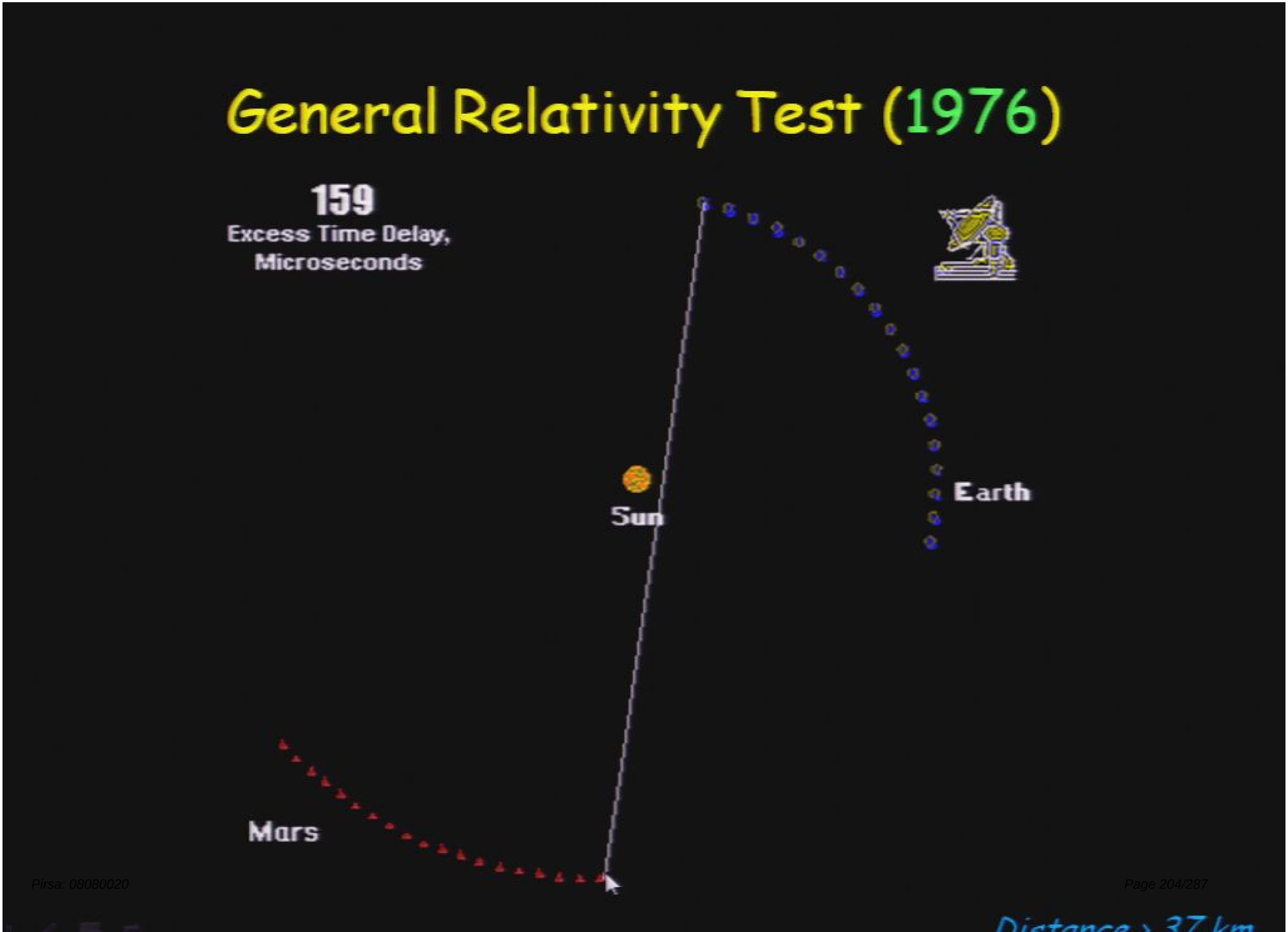

General Relativity Test (1976)
74
Excess Time Delay,
Microseconds
Sun
Earth
Mars

General Relativity Test (1976)

Distance > 37 km

General Relativity Test (1976)

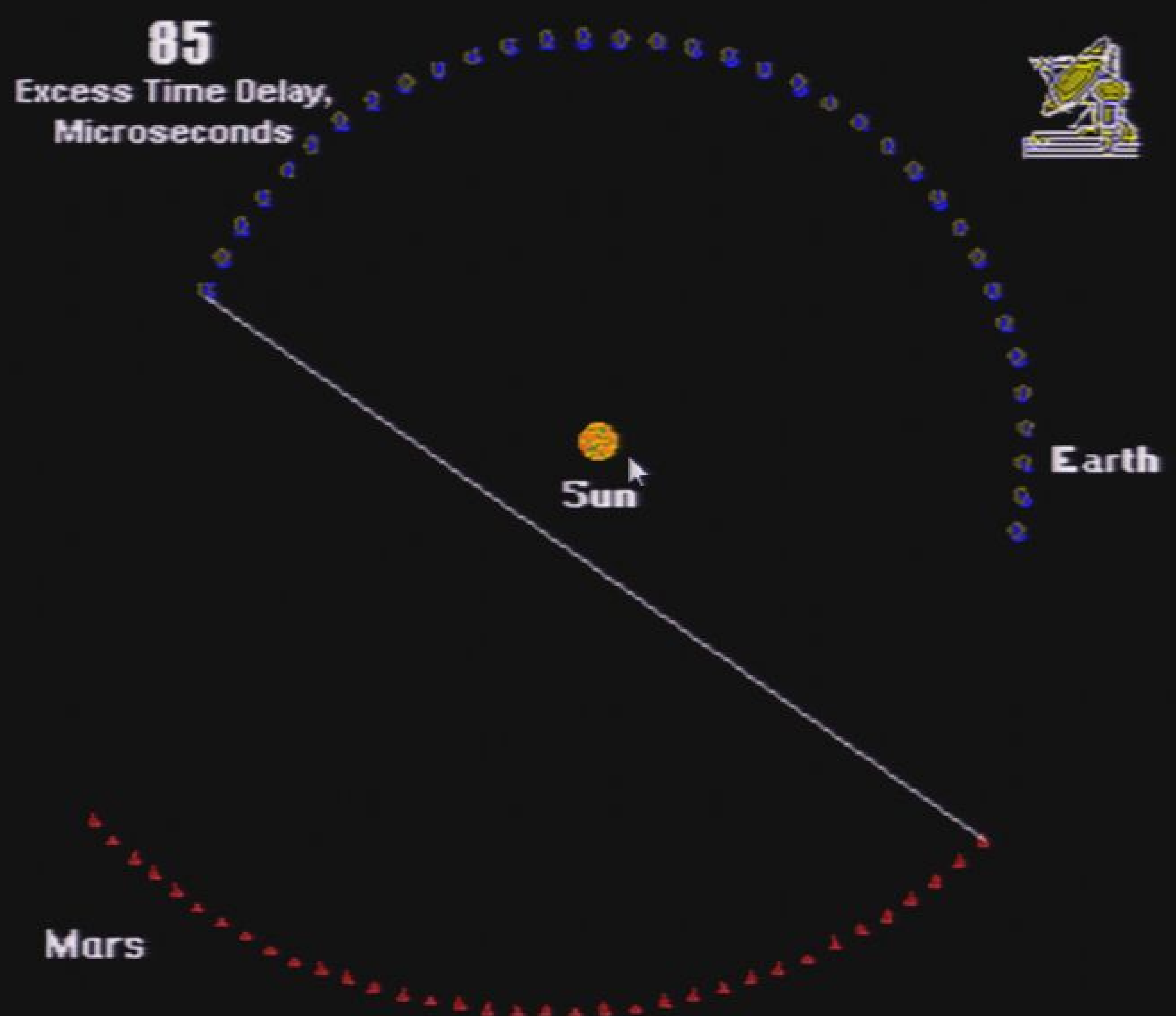


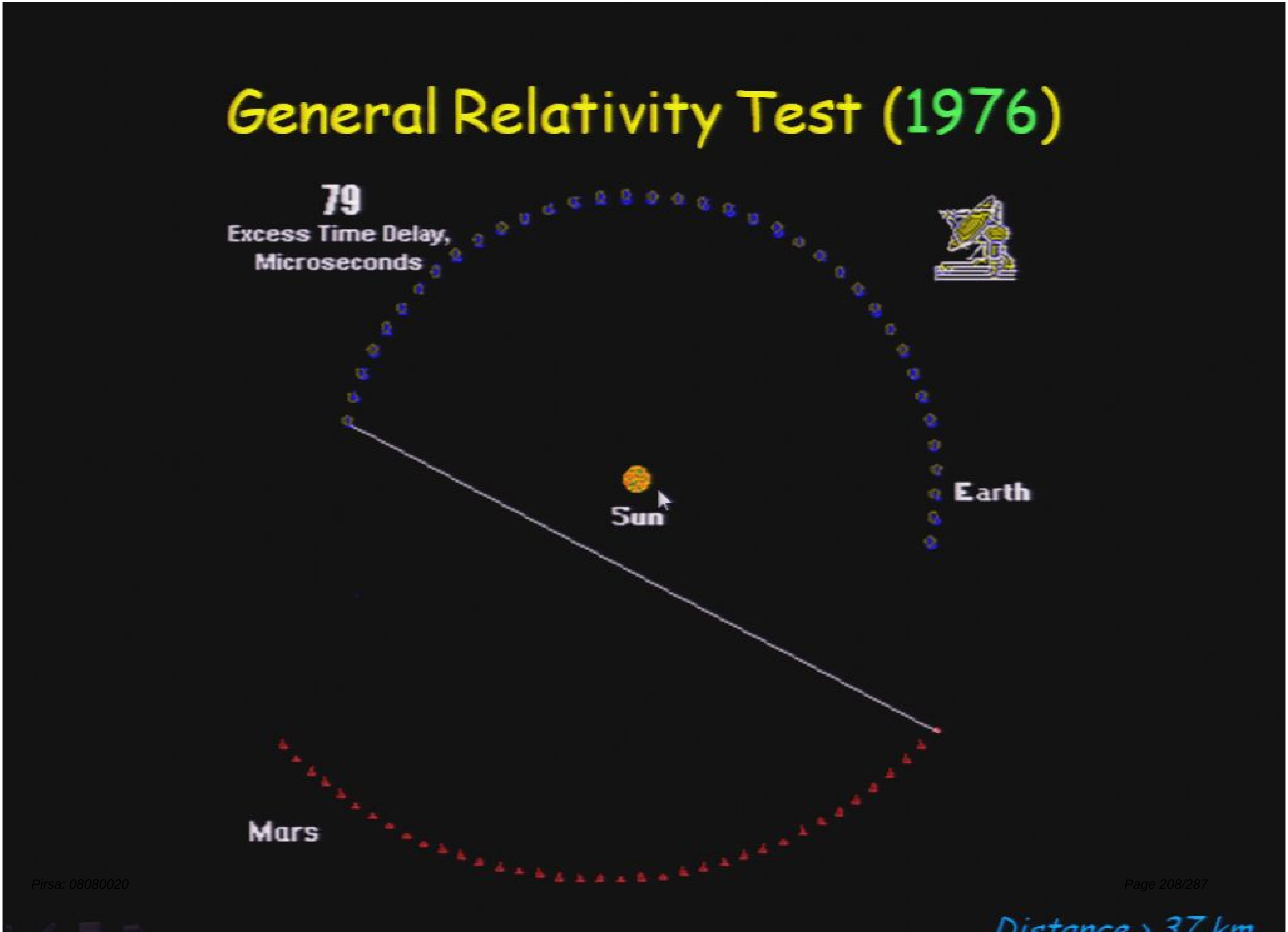

General Relativity Test (1976)
159
Excess Time Delay,
Microseconds
Earth
Sun
Mars

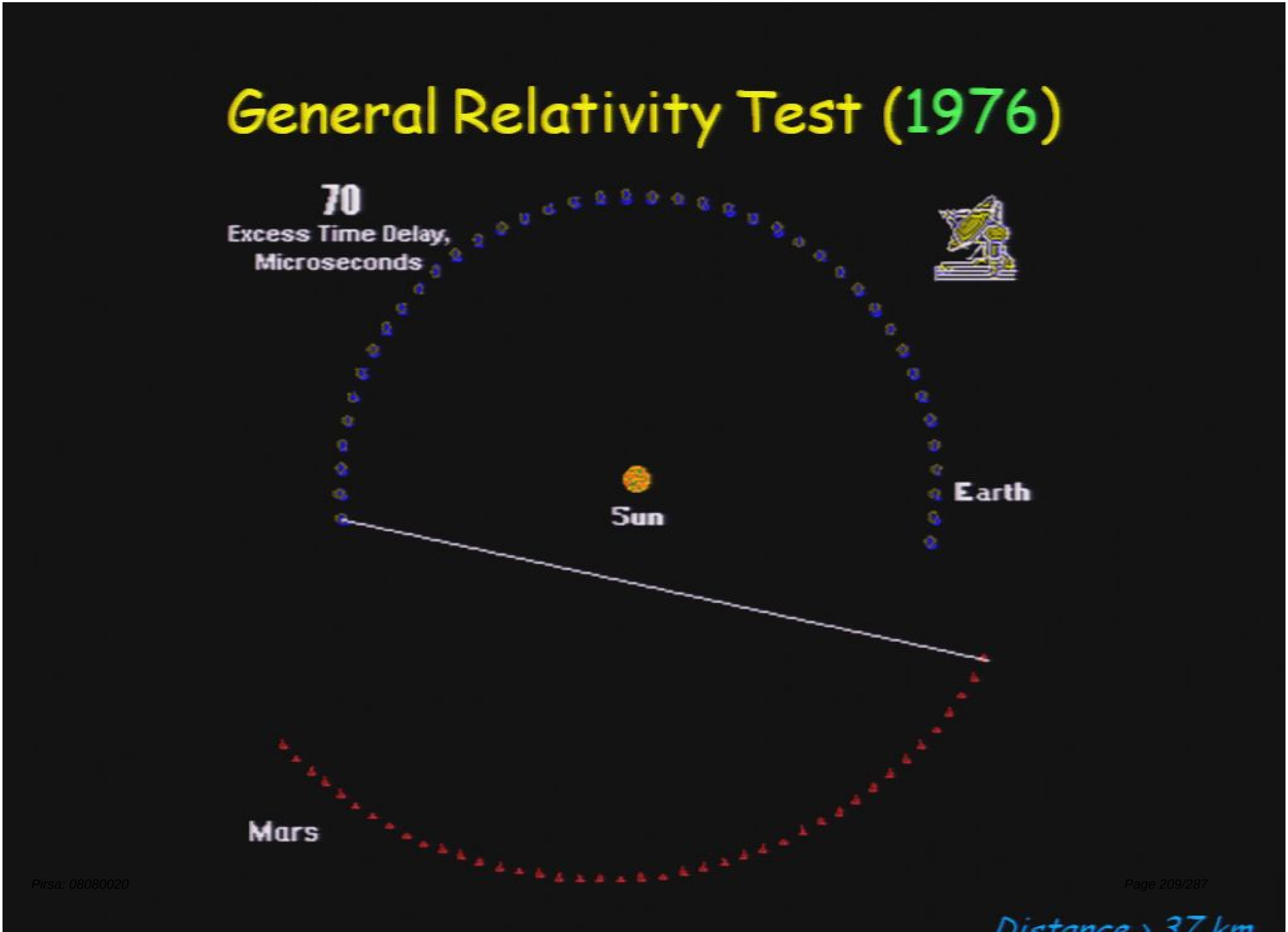
General Relativity Test (1976)

General Relativity Test (1976)

General Relativity Test (1976)

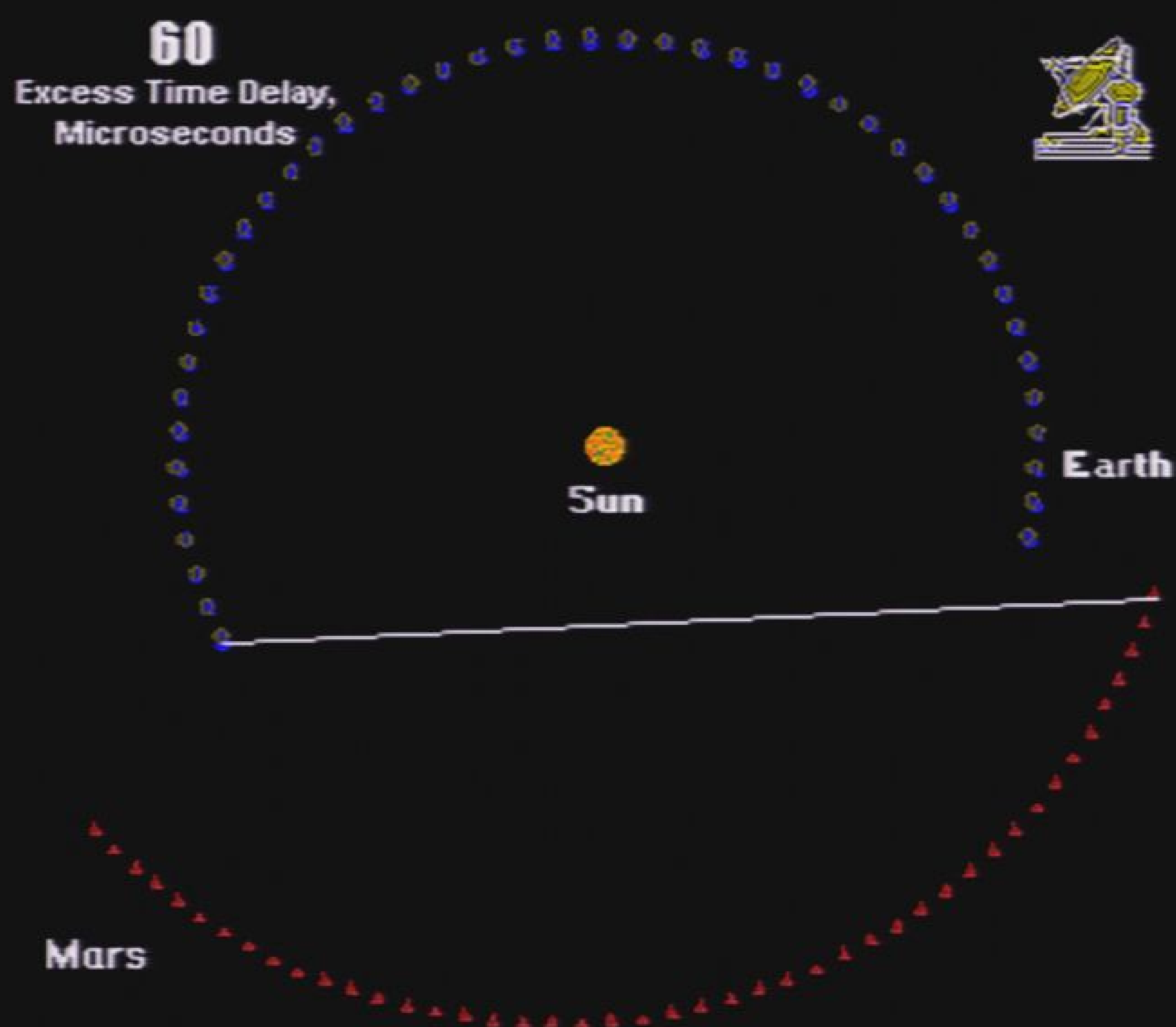



General Relativity Test (1976)
79
Excess Time Delay,
Microseconds
Earth
Sun
Mars



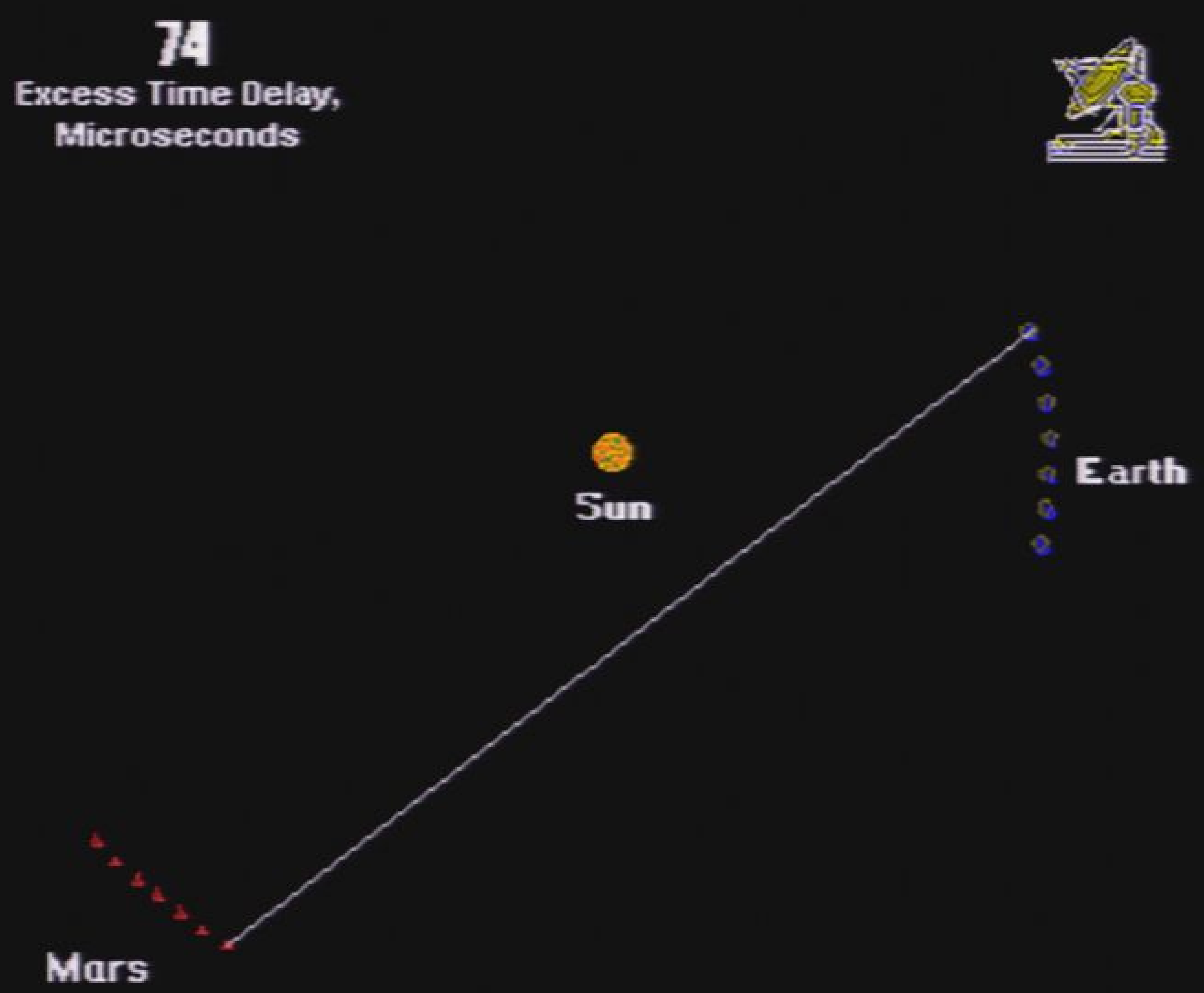
General Relativity Test (1976)
70
Excess Time Delay, Microseconds
Earth
Sun
Mars

General Relativity Test (1976)

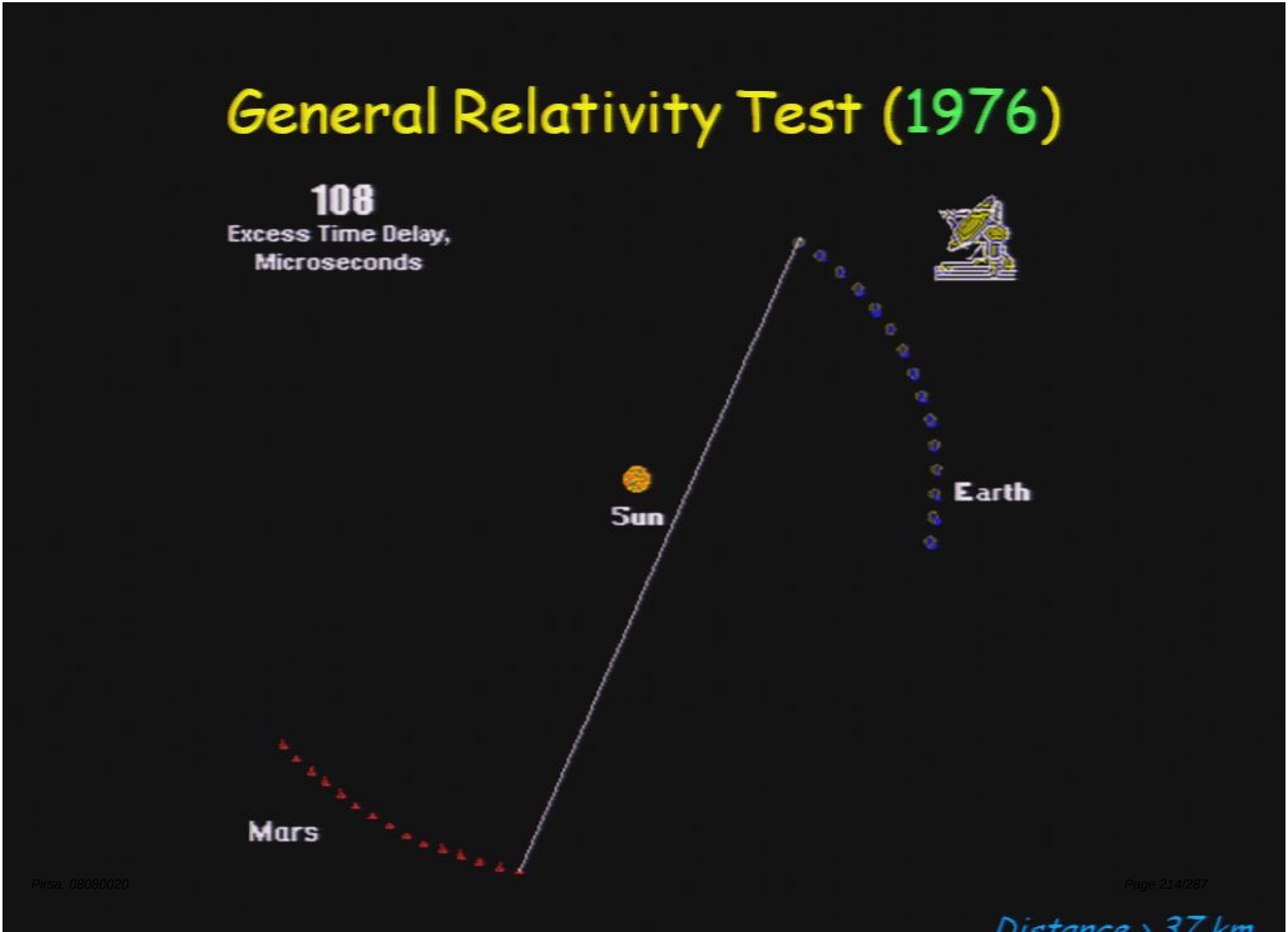


General Relativity Test (1976)

General Relativity Test (1976)

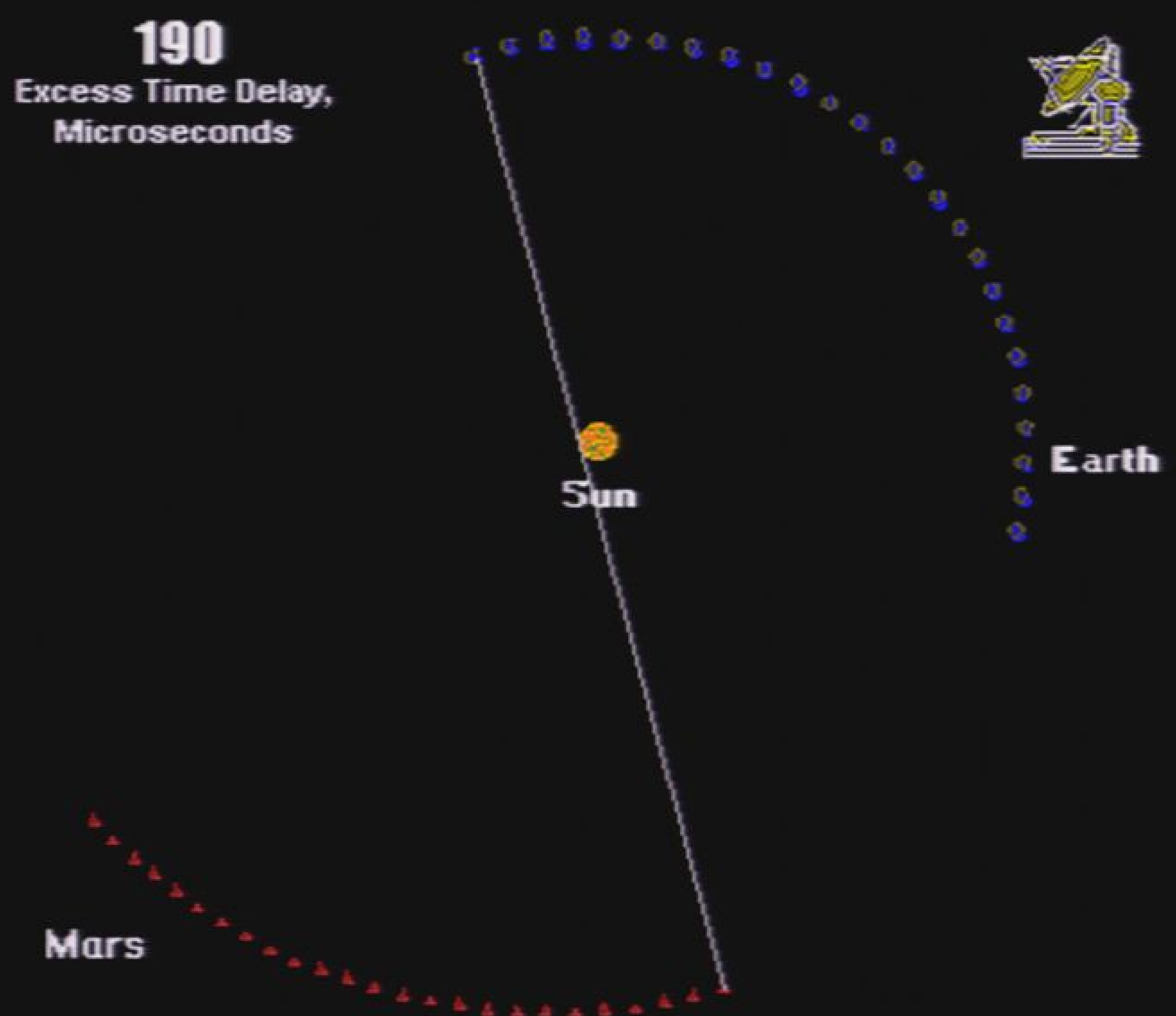


General Relativity Test (1976)


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

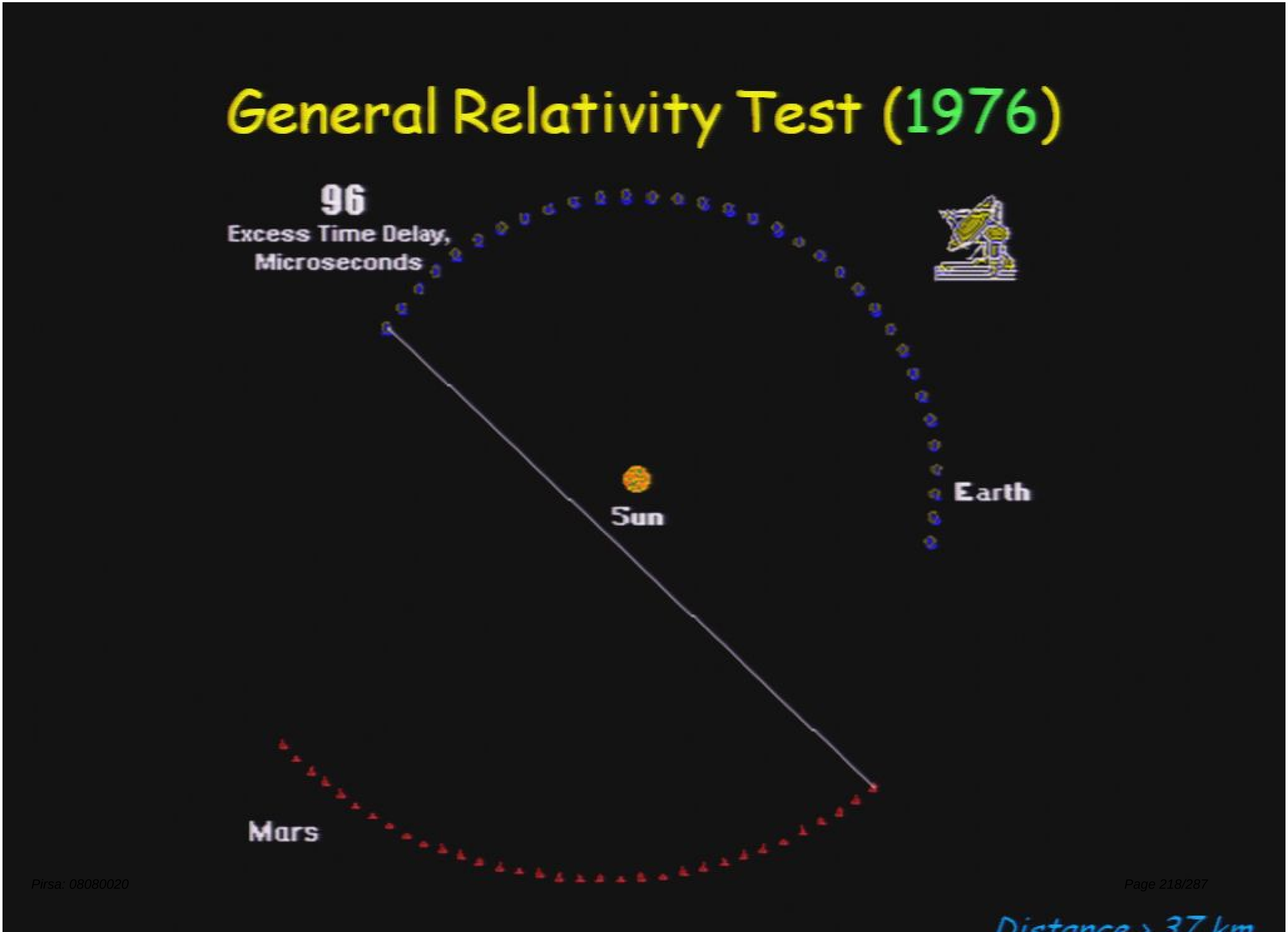
General Relativity Test (1976)

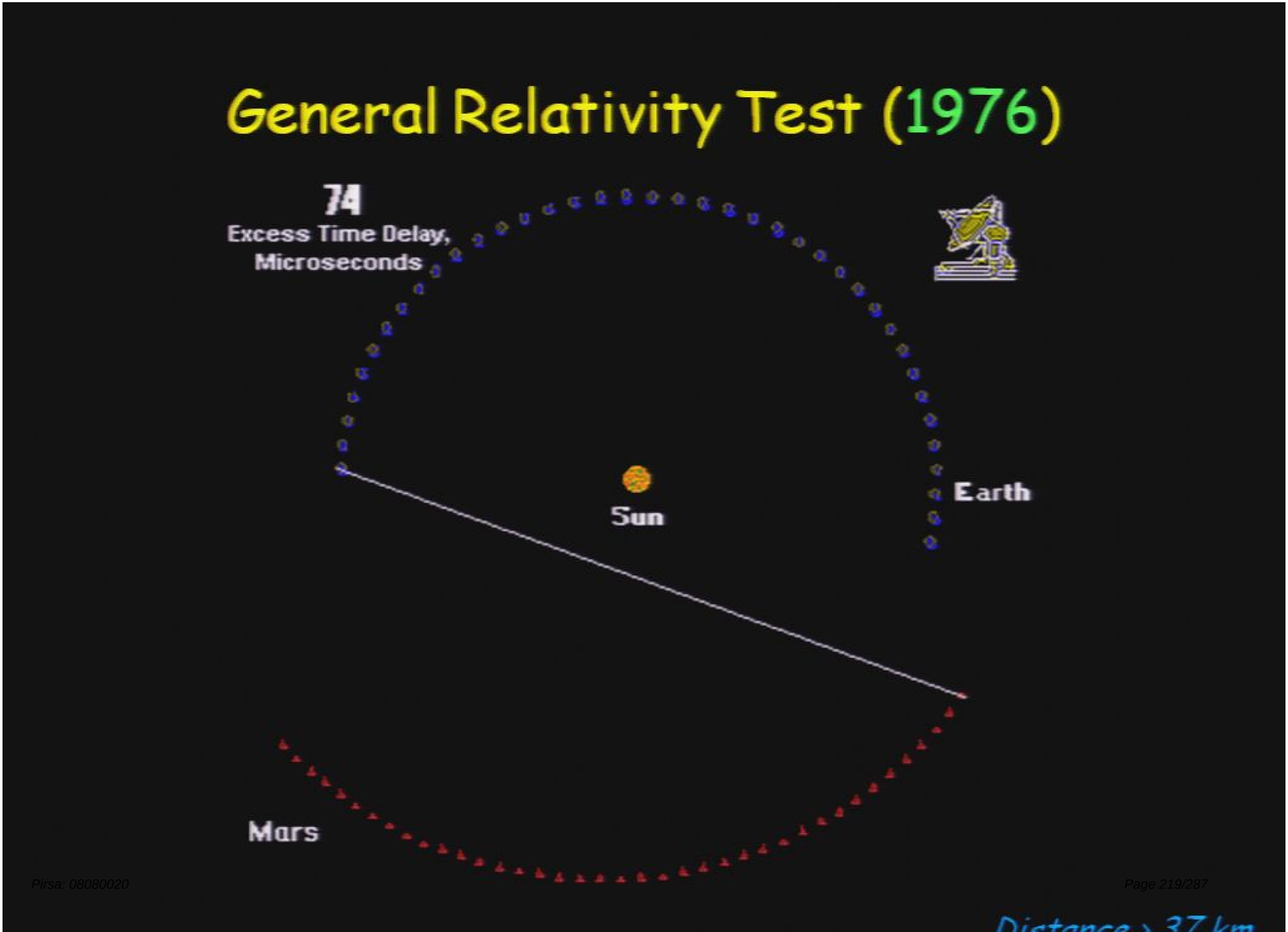
General Relativity Test (1976)



General Relativity Test (1976)

Distance > 37 km


General Relativity Test (1976)
96
Excess Time Delay,
Microseconds
Earth
Sun
Mars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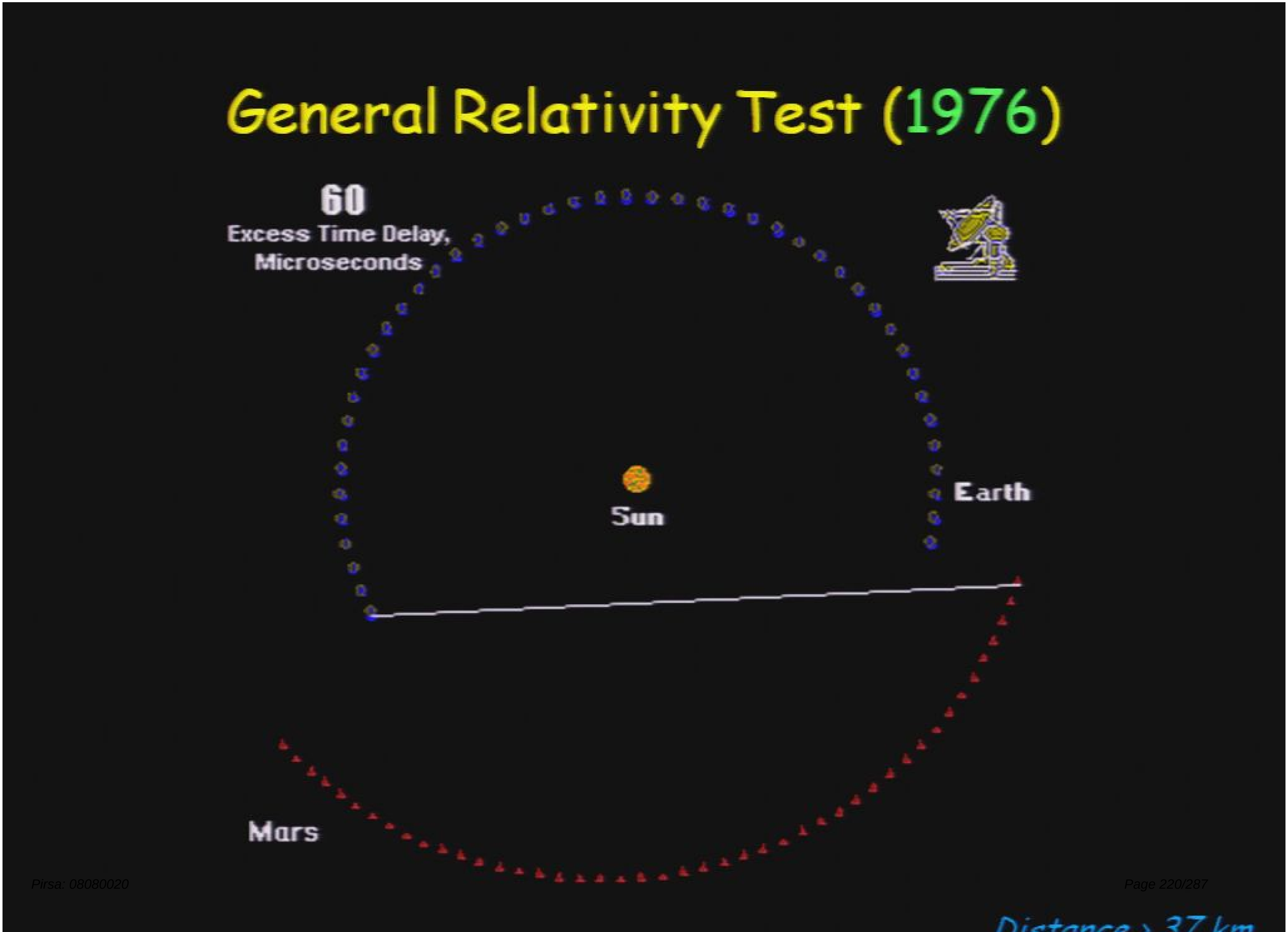
74
Excess Time Delay,
Microseconds
Earth
Sun
Mars


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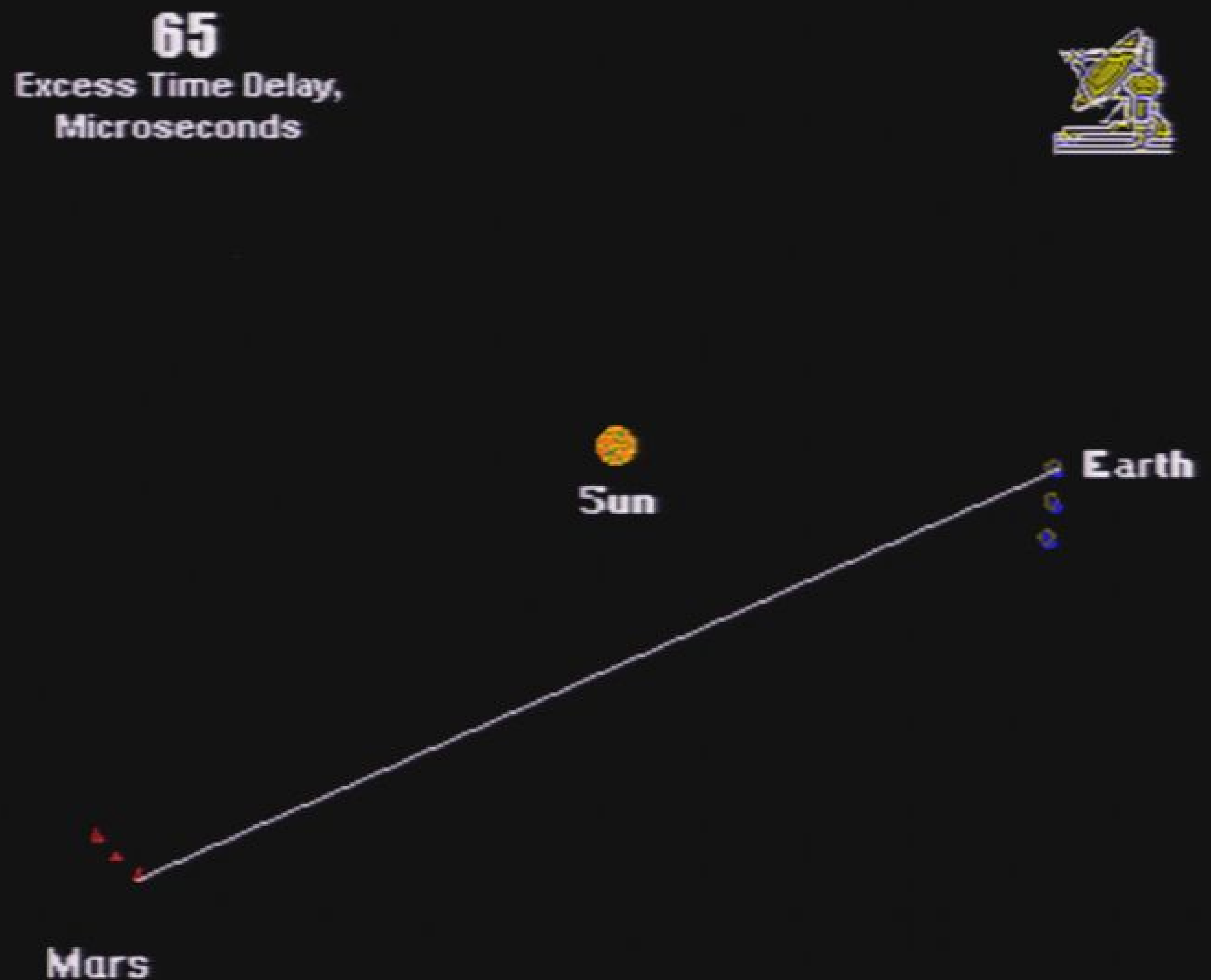
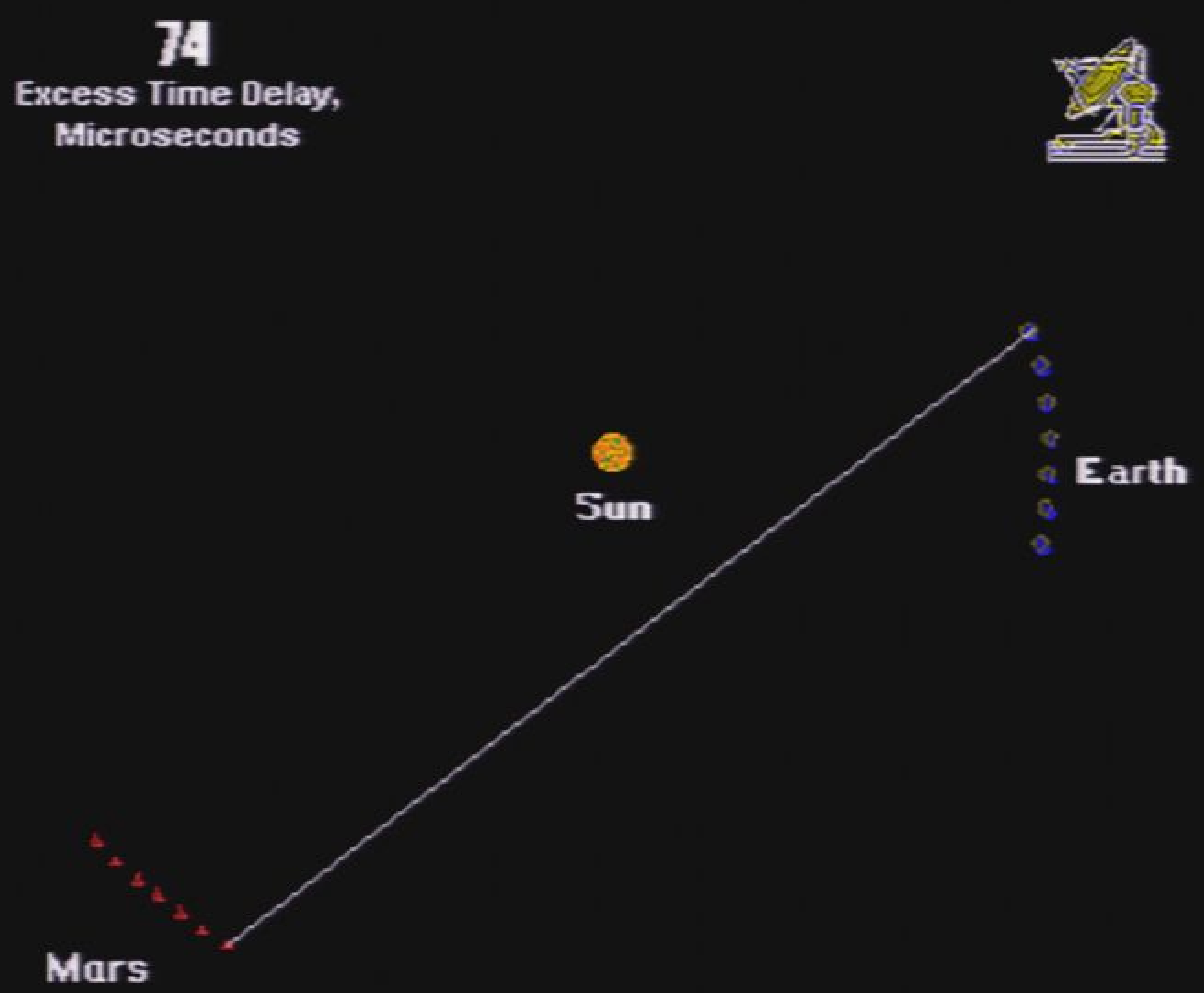
Excess Time Delay,
Microseconds
Earth
Sun
Mars

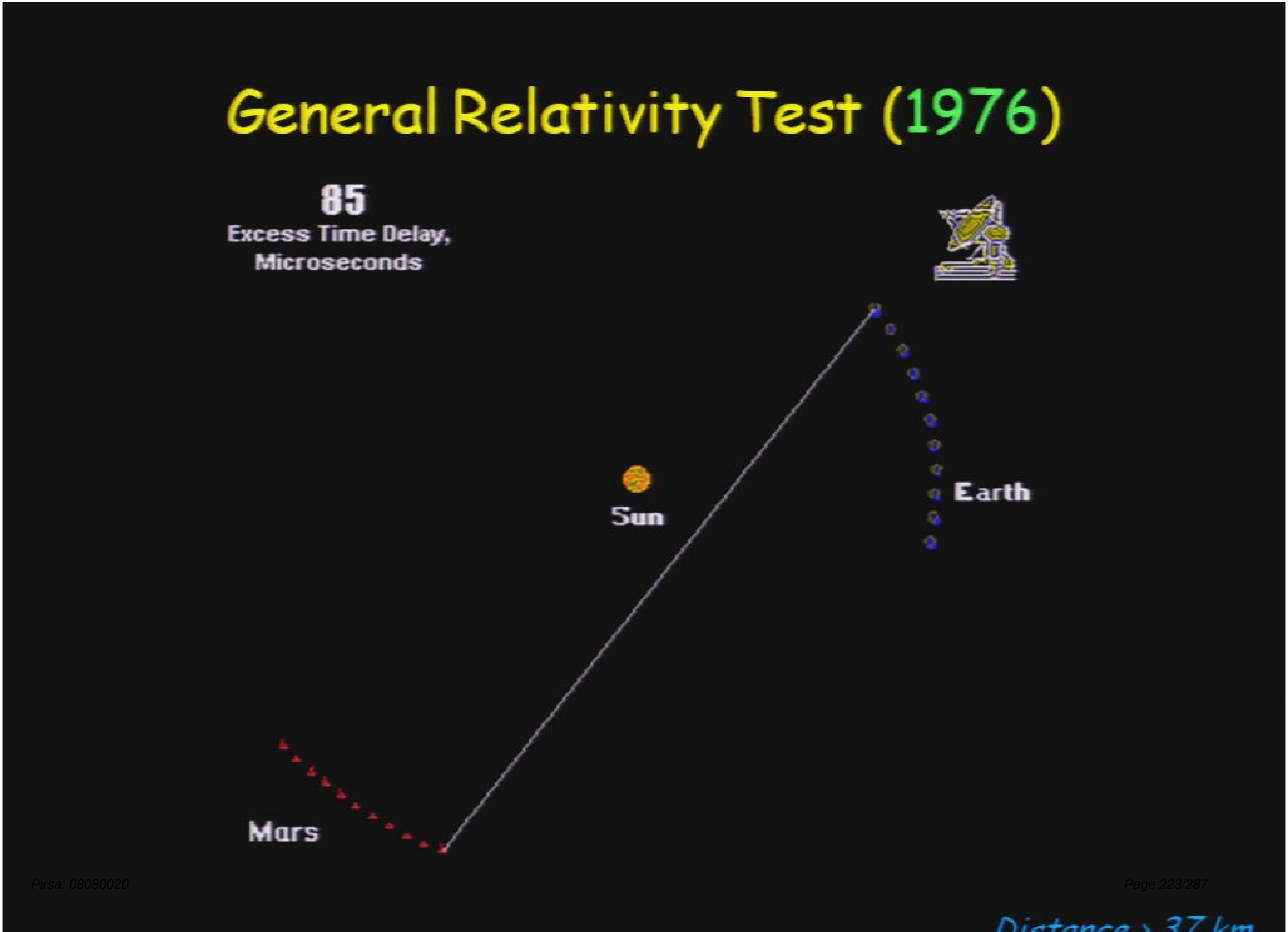
General Relativity Test (1976)

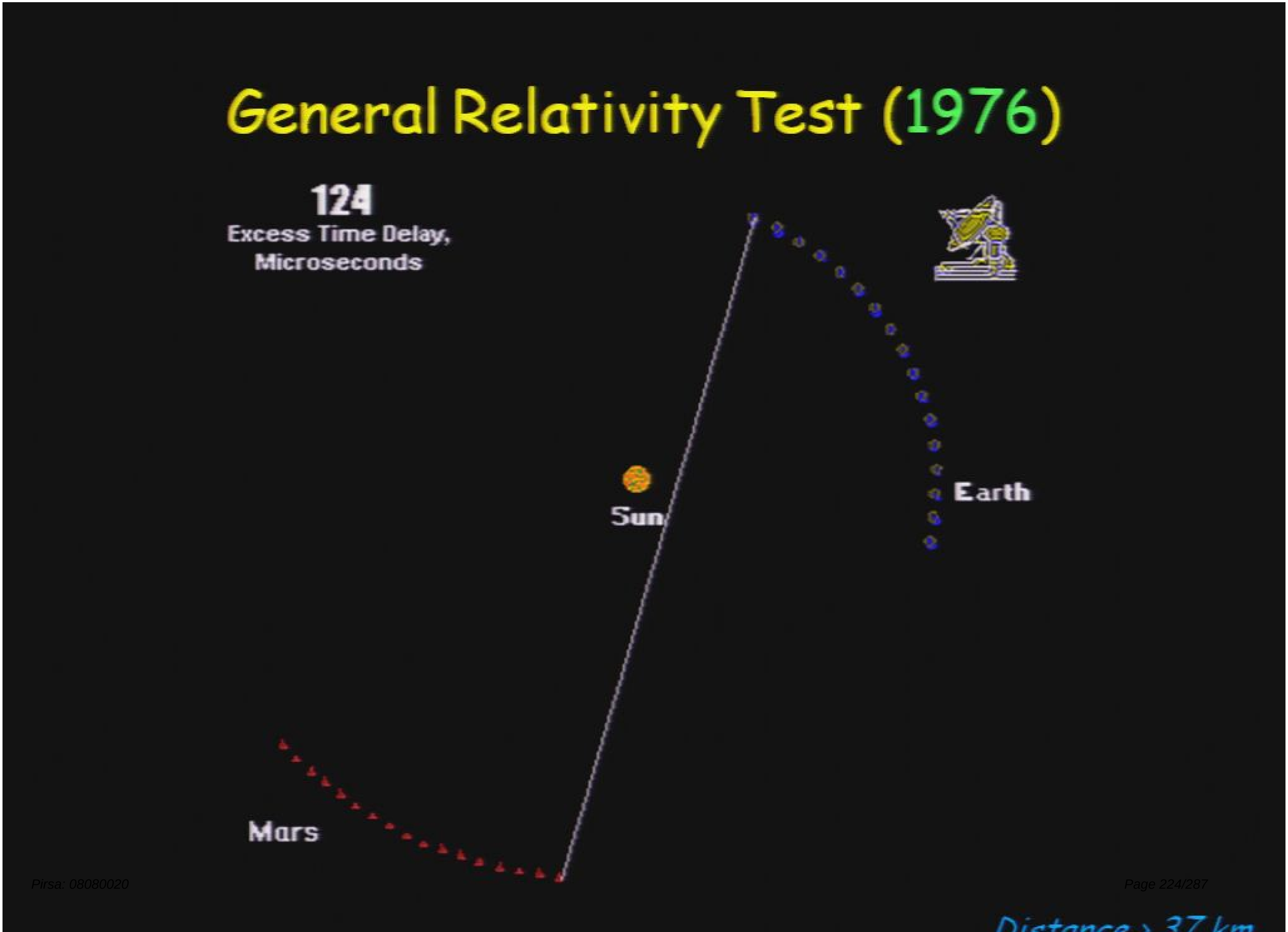


Distance > 37 km

General Relativity Test (1976)

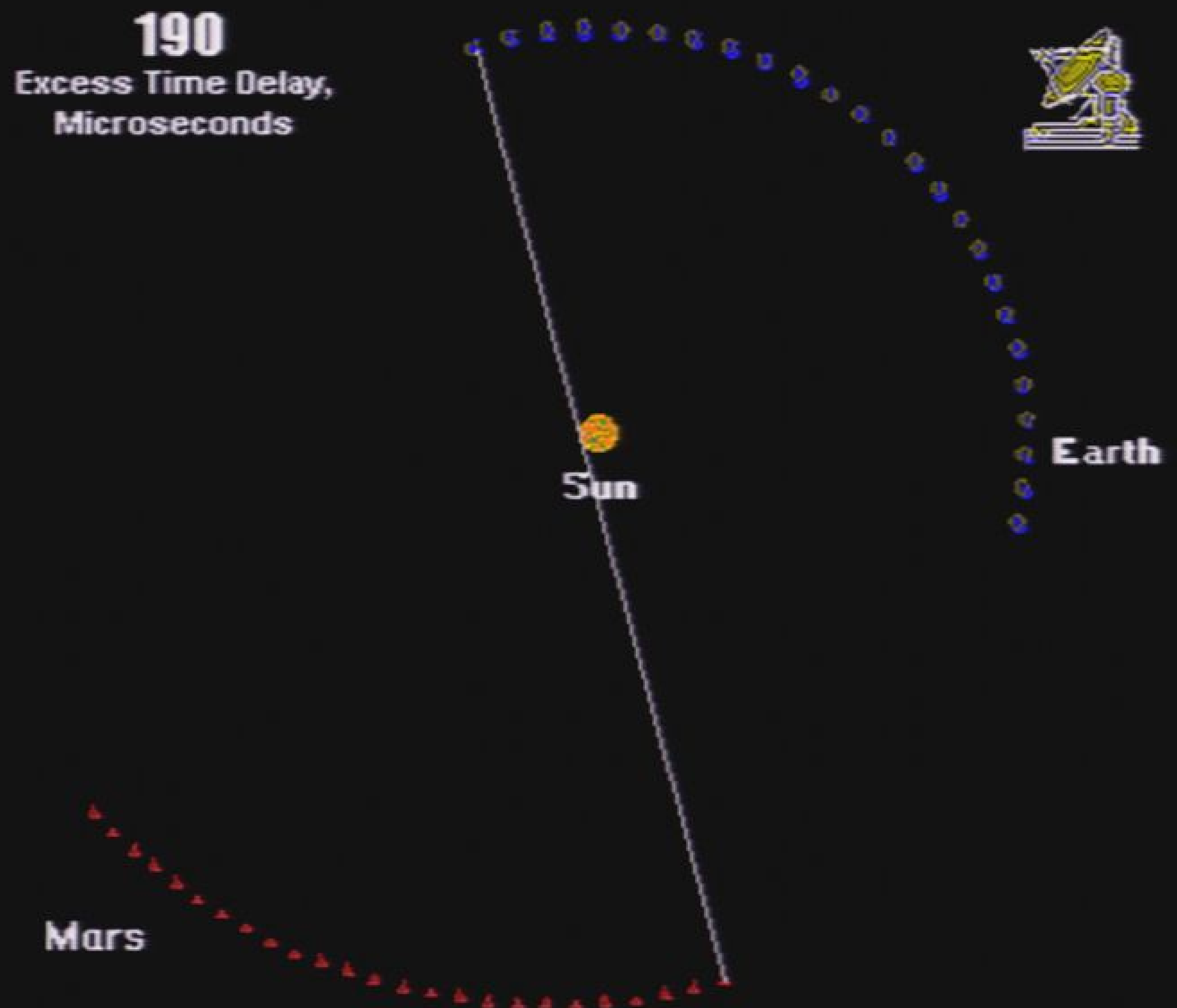



General Relativity Test (1976)
85
Excess Time Delay,
Microseconds
Sun
Earth
Mars


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

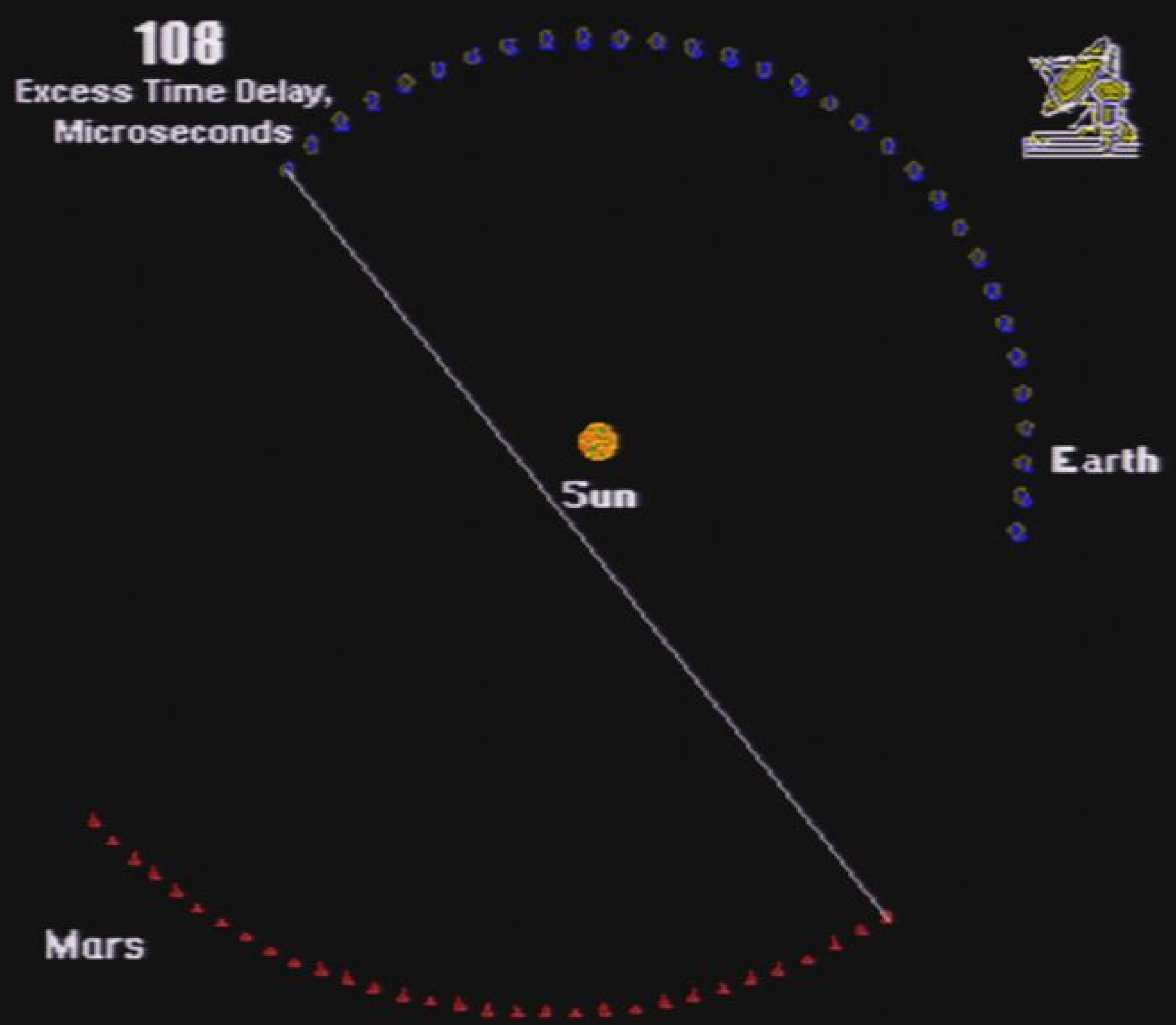
General Relativity Test (1976)

General Relativity Test (1976)



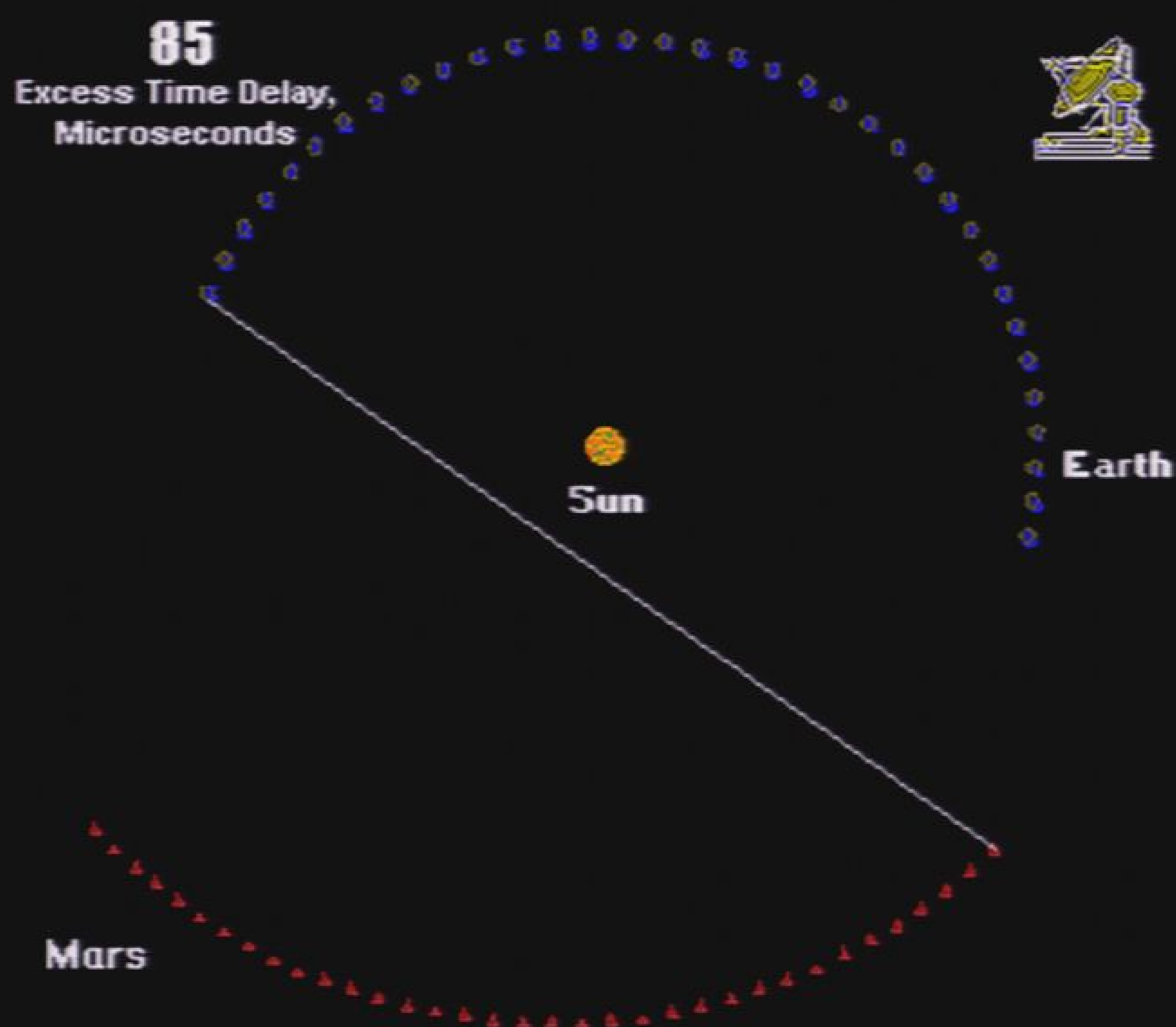
Distance > 37 km

General Relativity Test (1976)



Distance > 37 km

General Relativity Test (1976)



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.

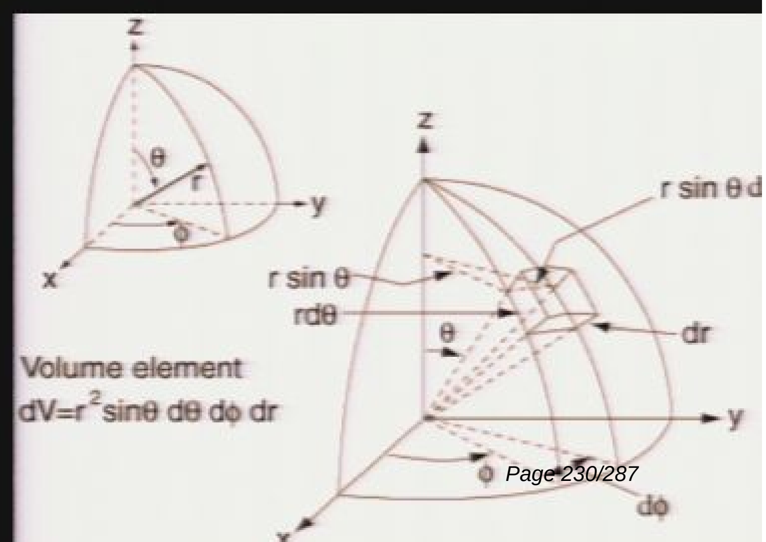
The Schwarzschild Radius

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

Curvature factor

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

r, θ, ϕ are the polar coordinates



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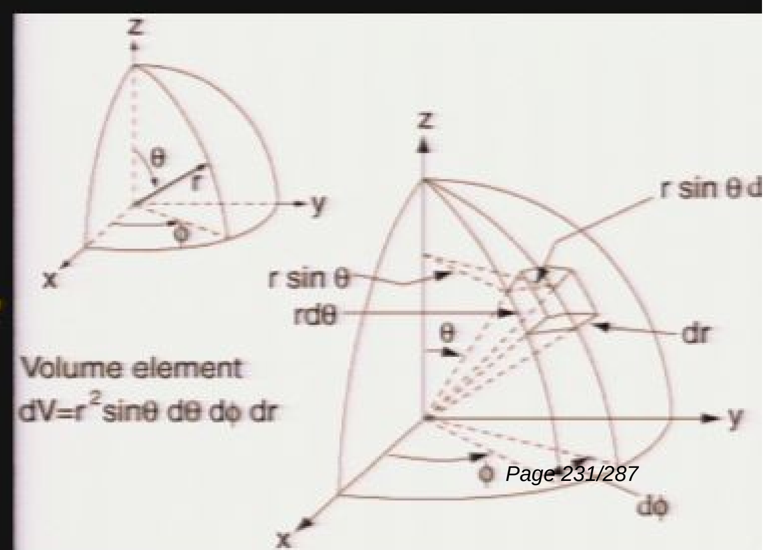
r, θ, ϕ are the polar coordinates

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



Schwarzschild Metric

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

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

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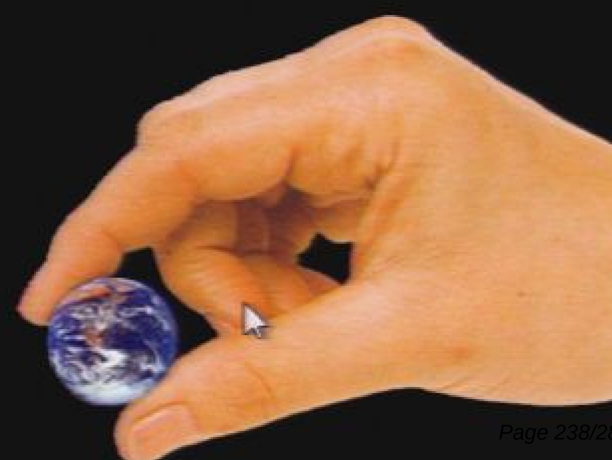
is the Schwarzschild radius

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.

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



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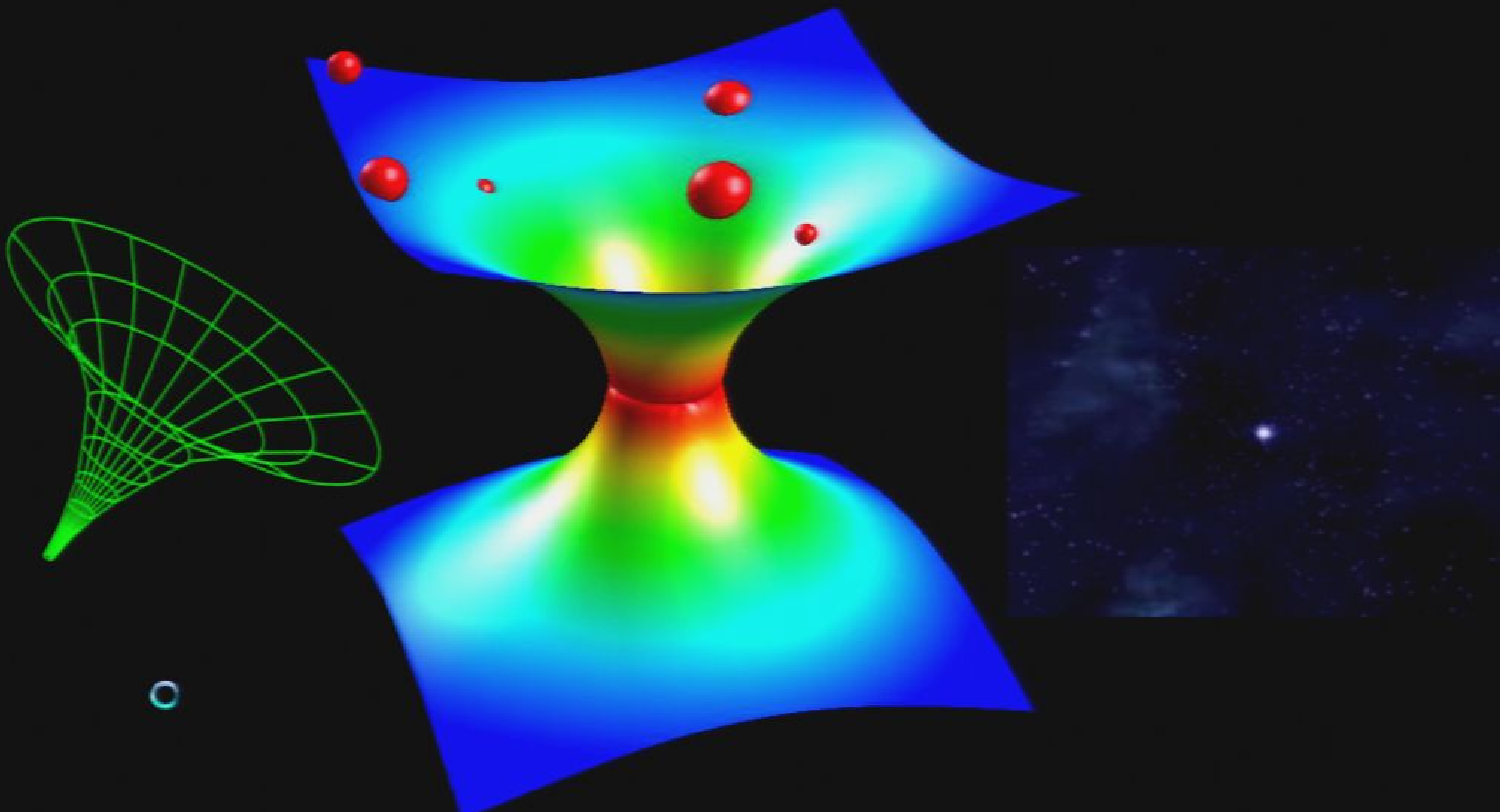

Emphasis on Spatial rather than temporal interpretations

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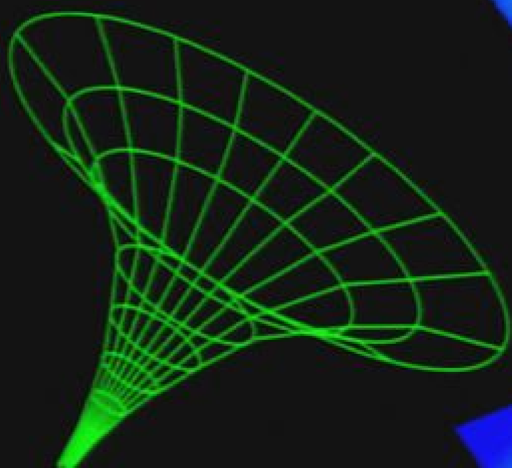

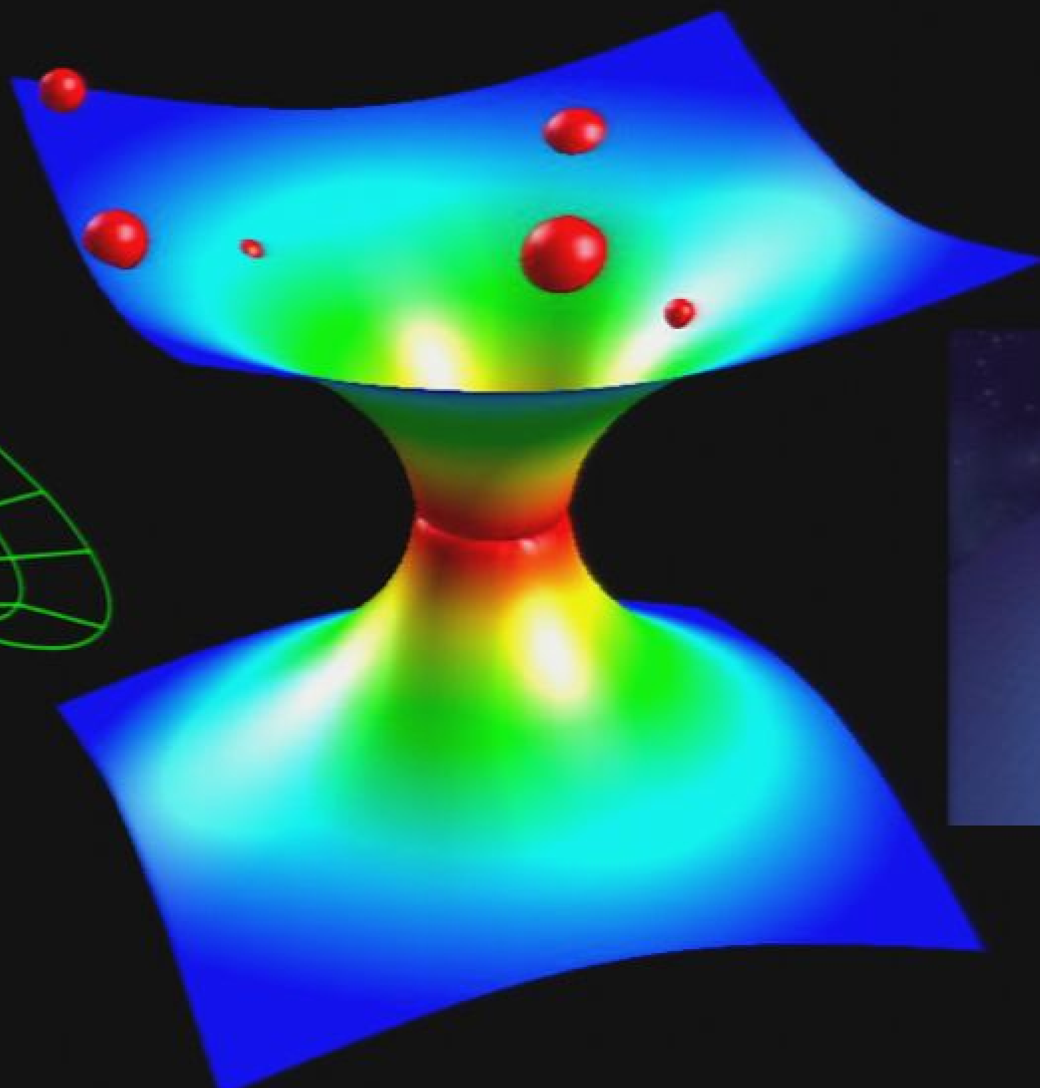

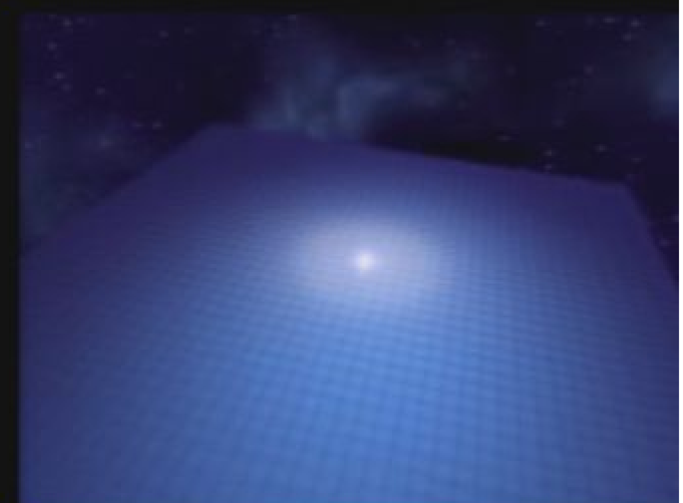

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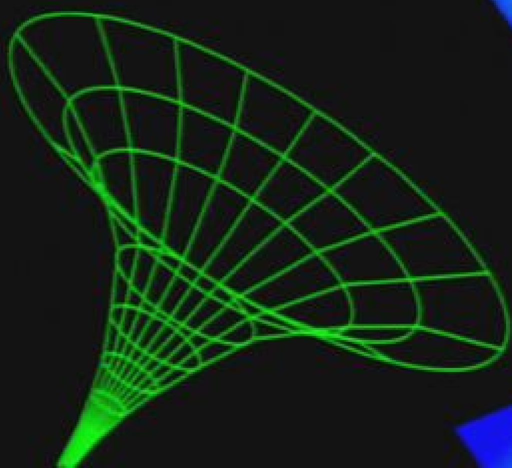

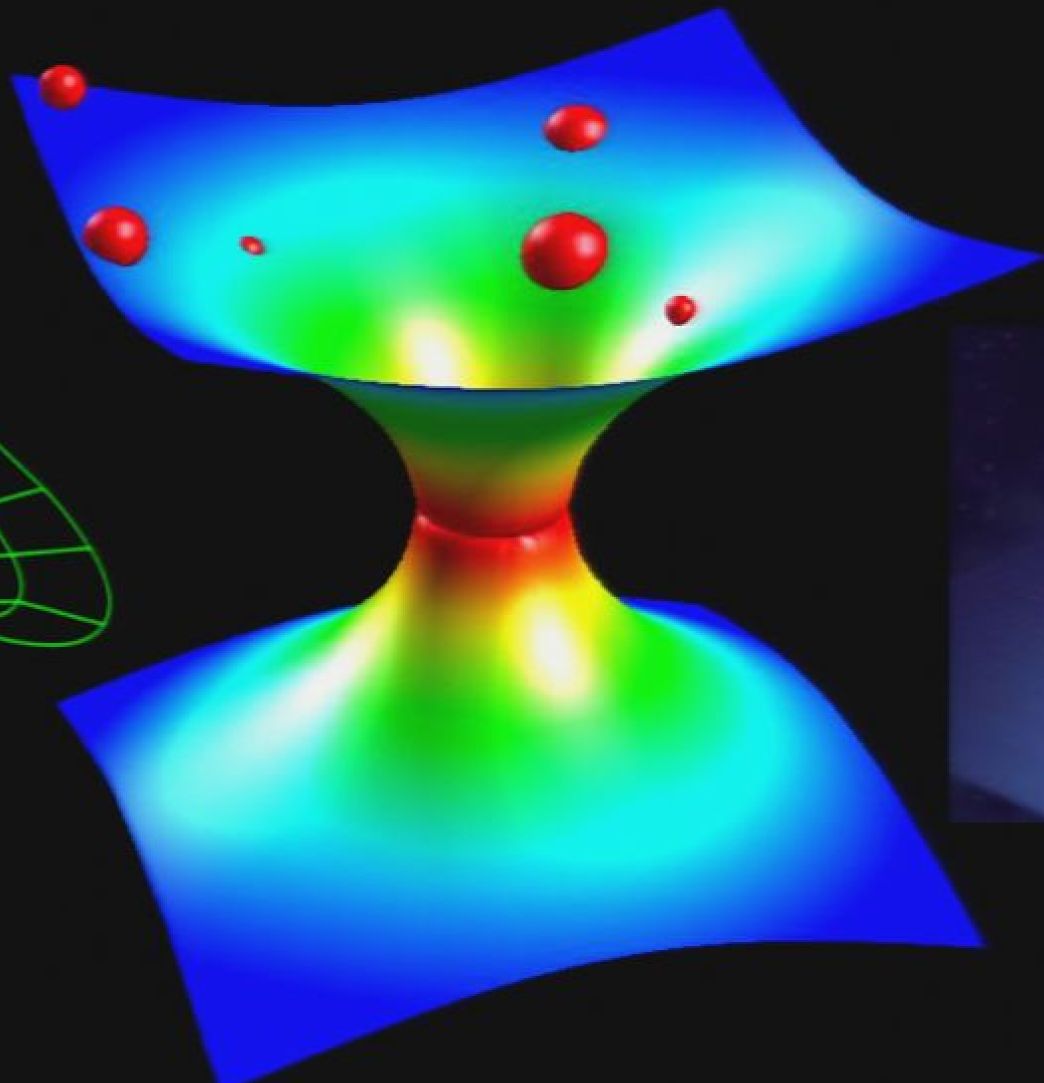

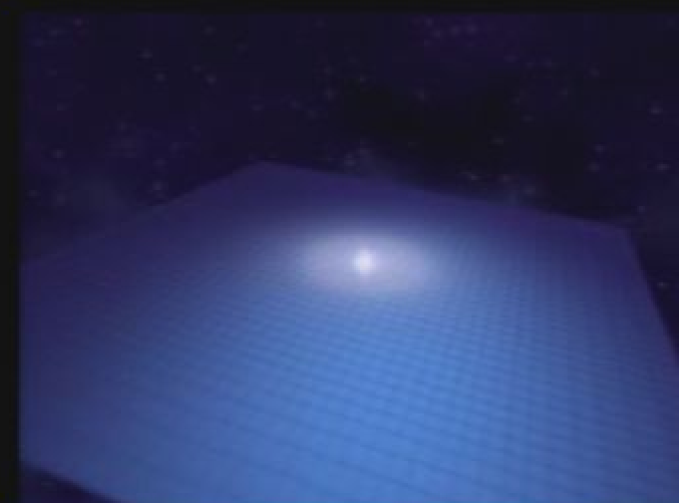

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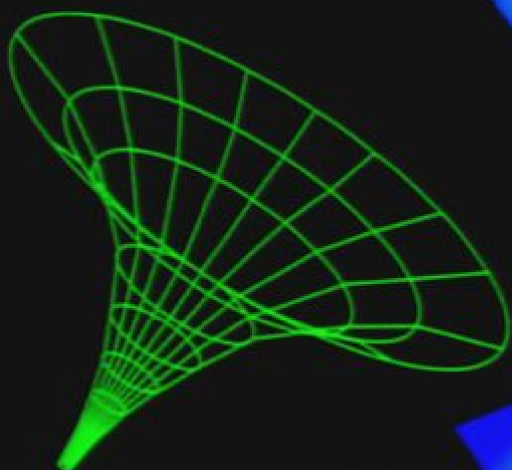

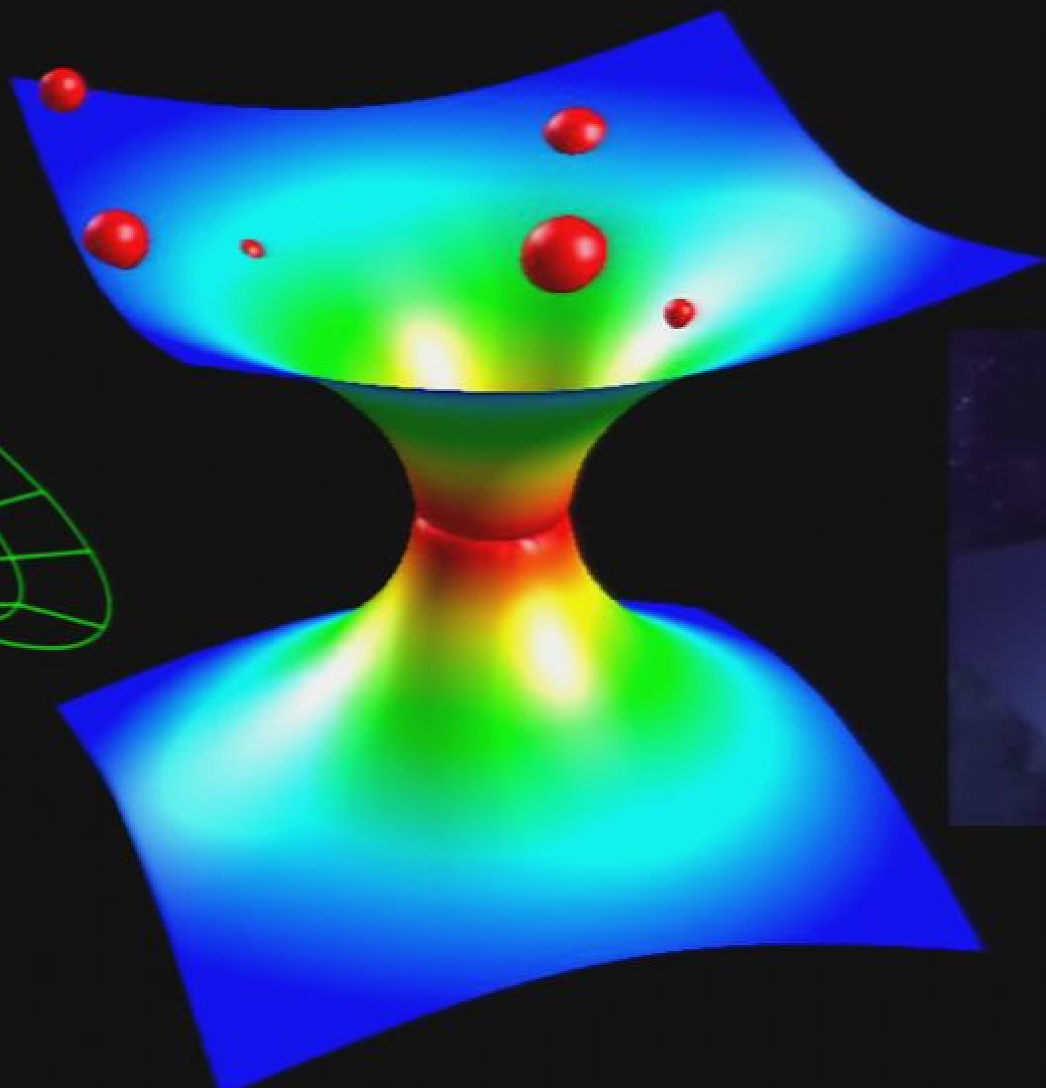

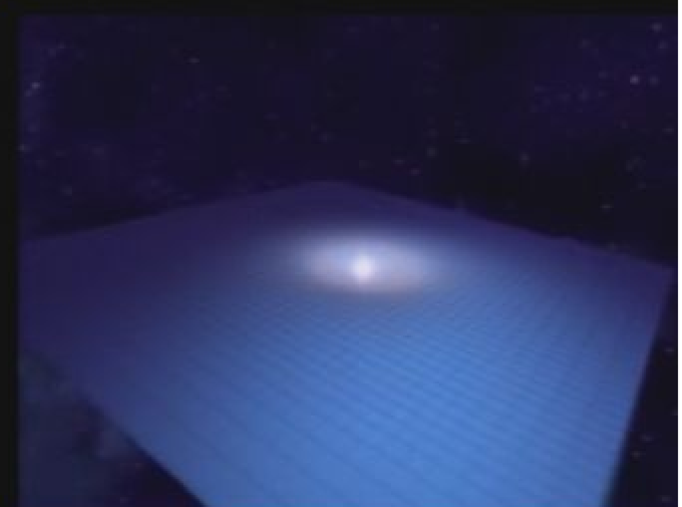

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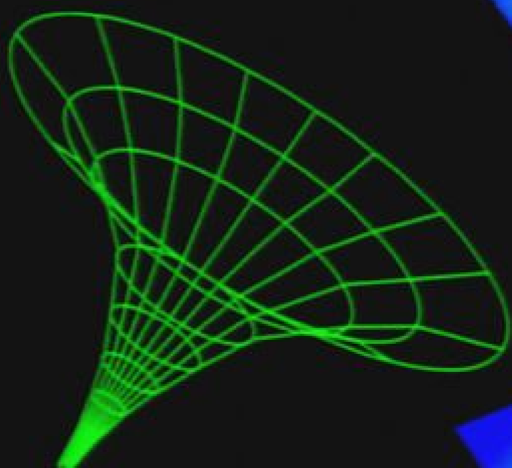

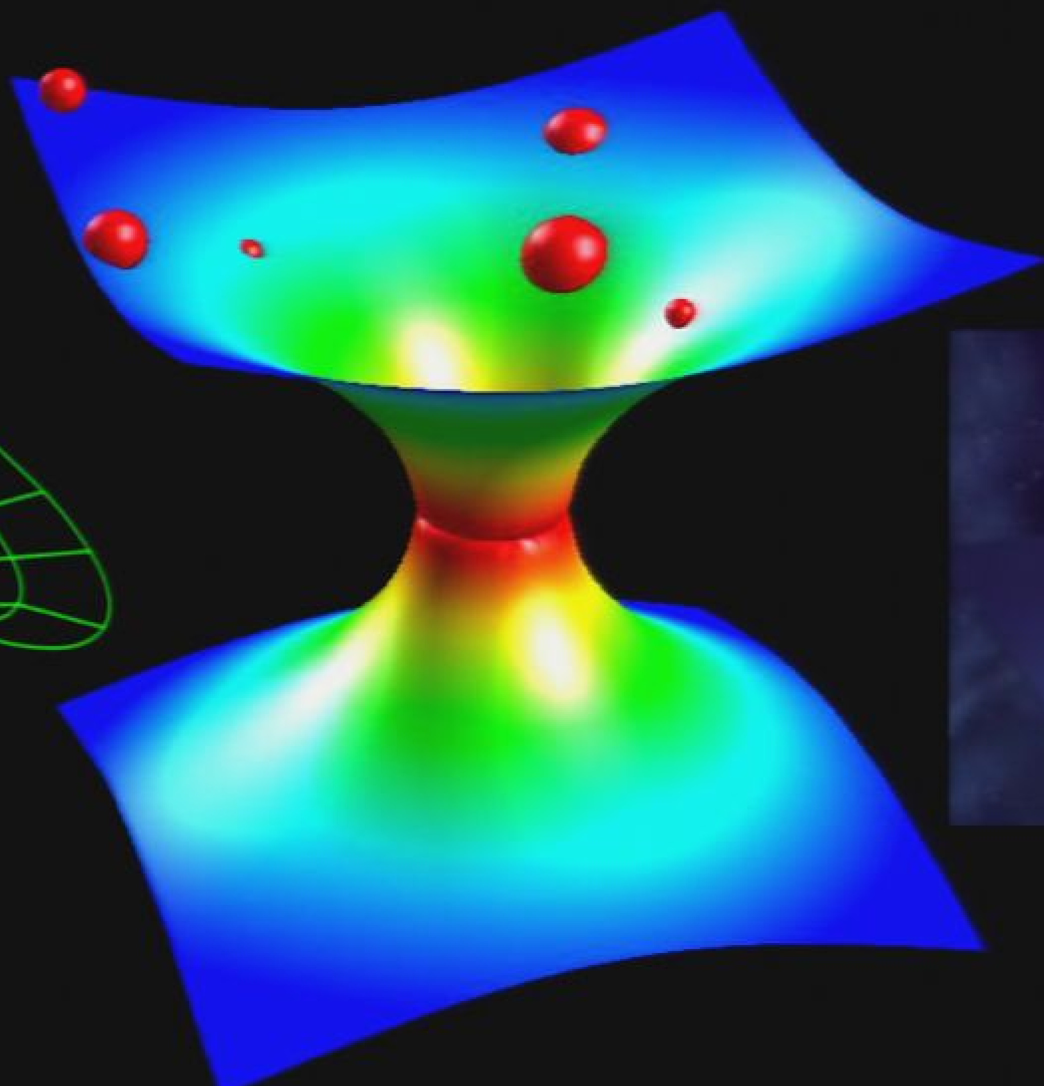

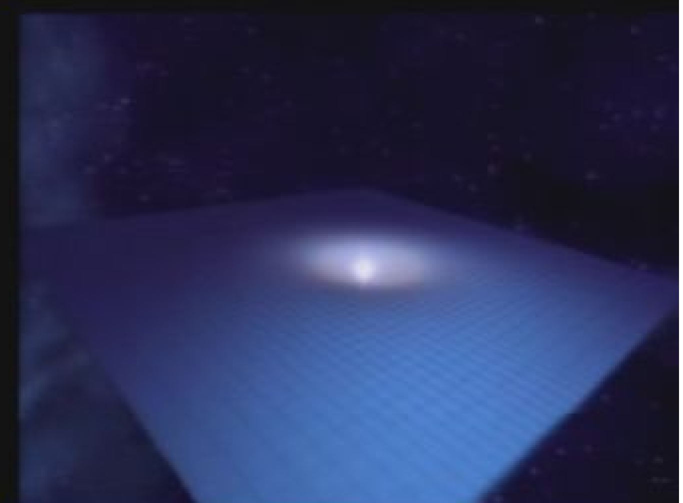

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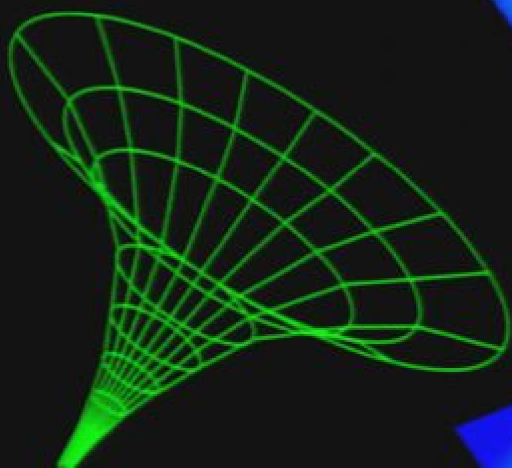

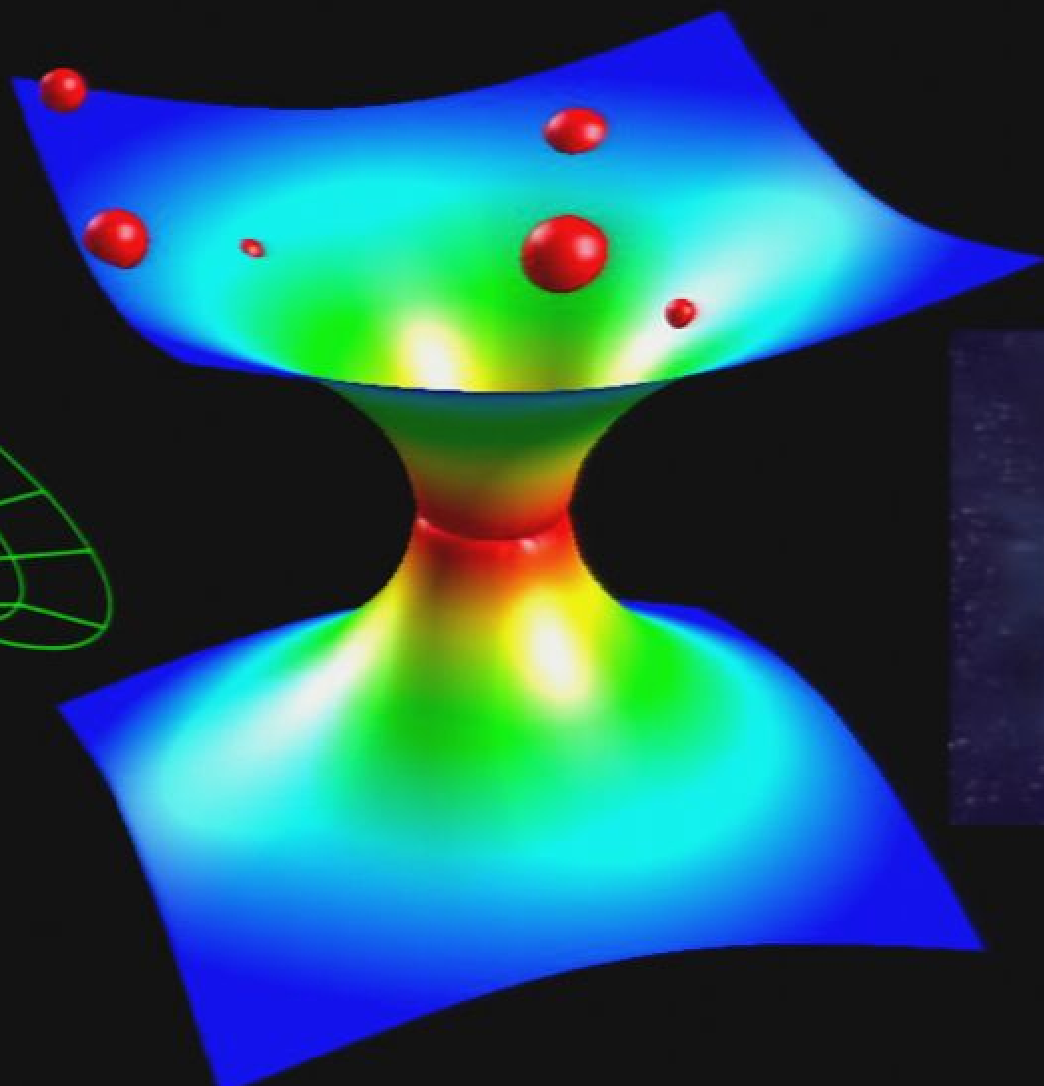

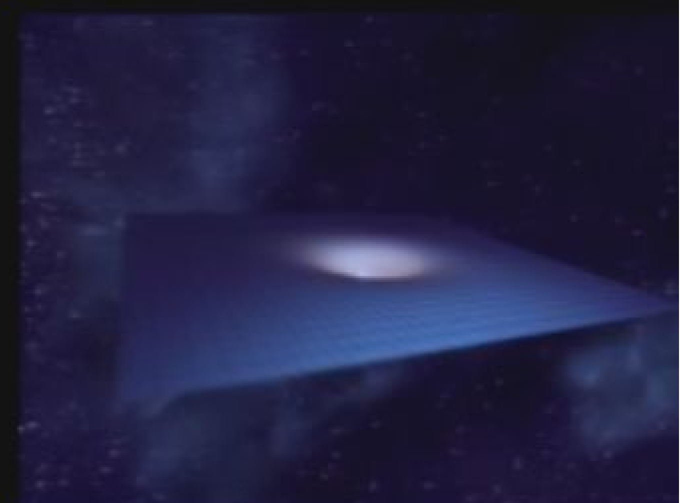

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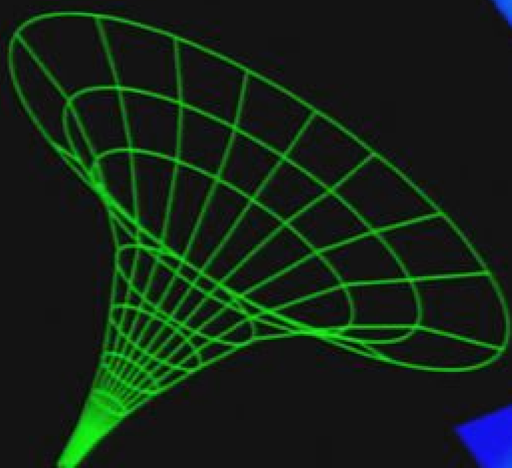

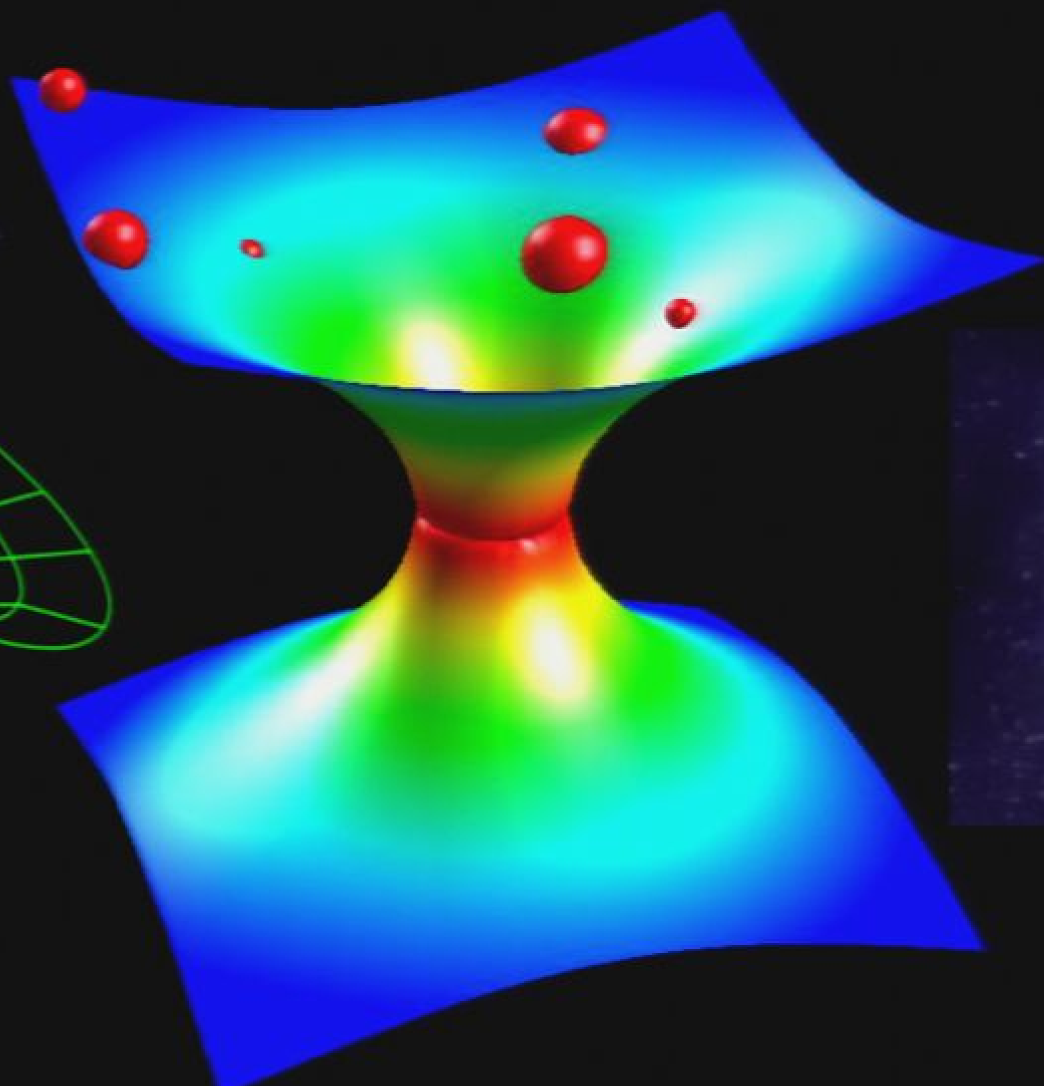

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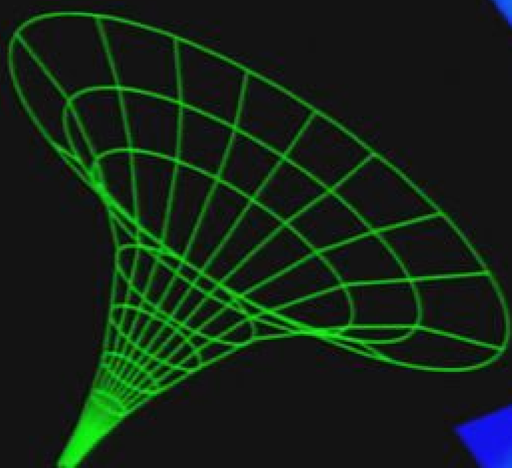

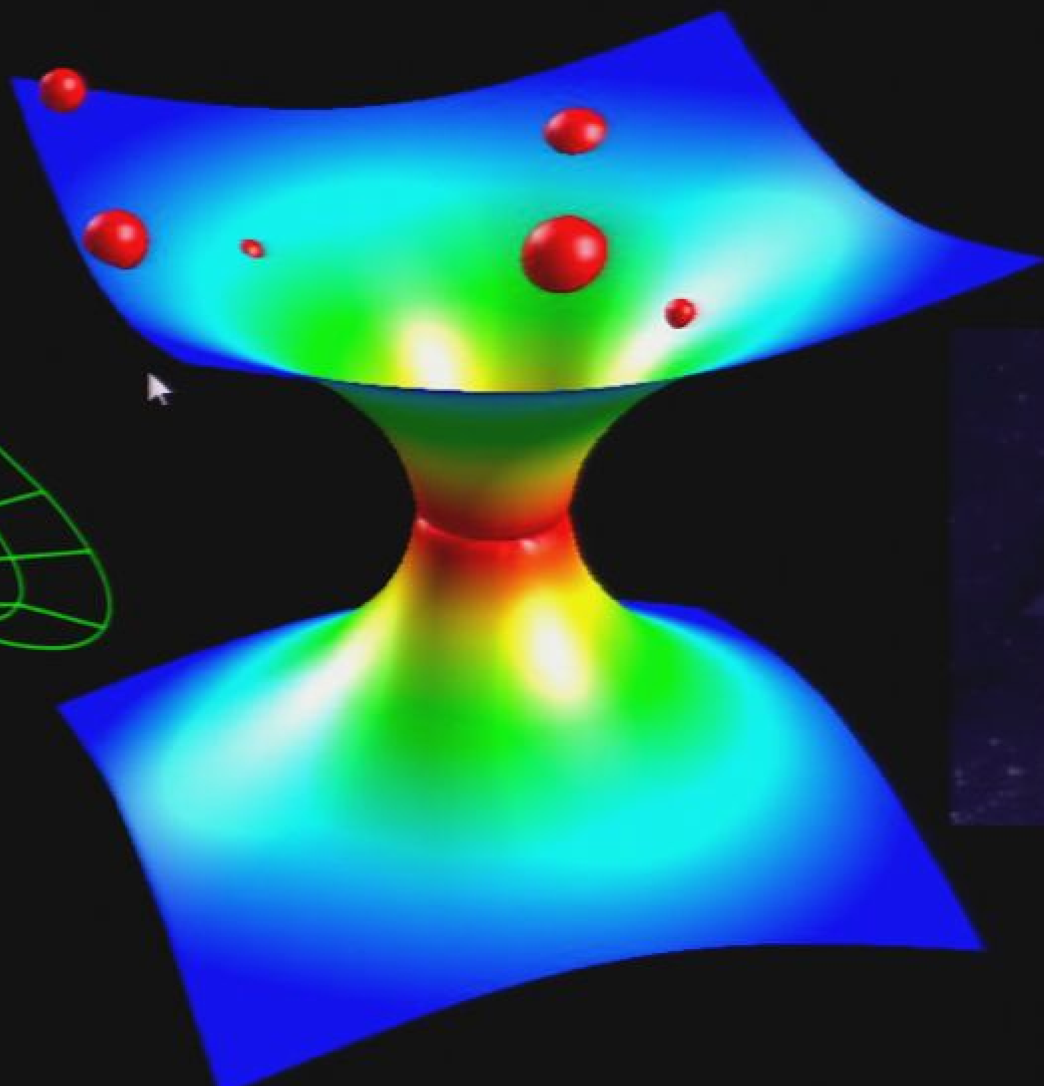

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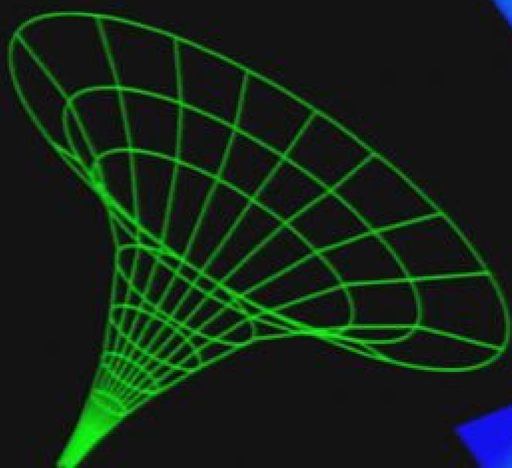

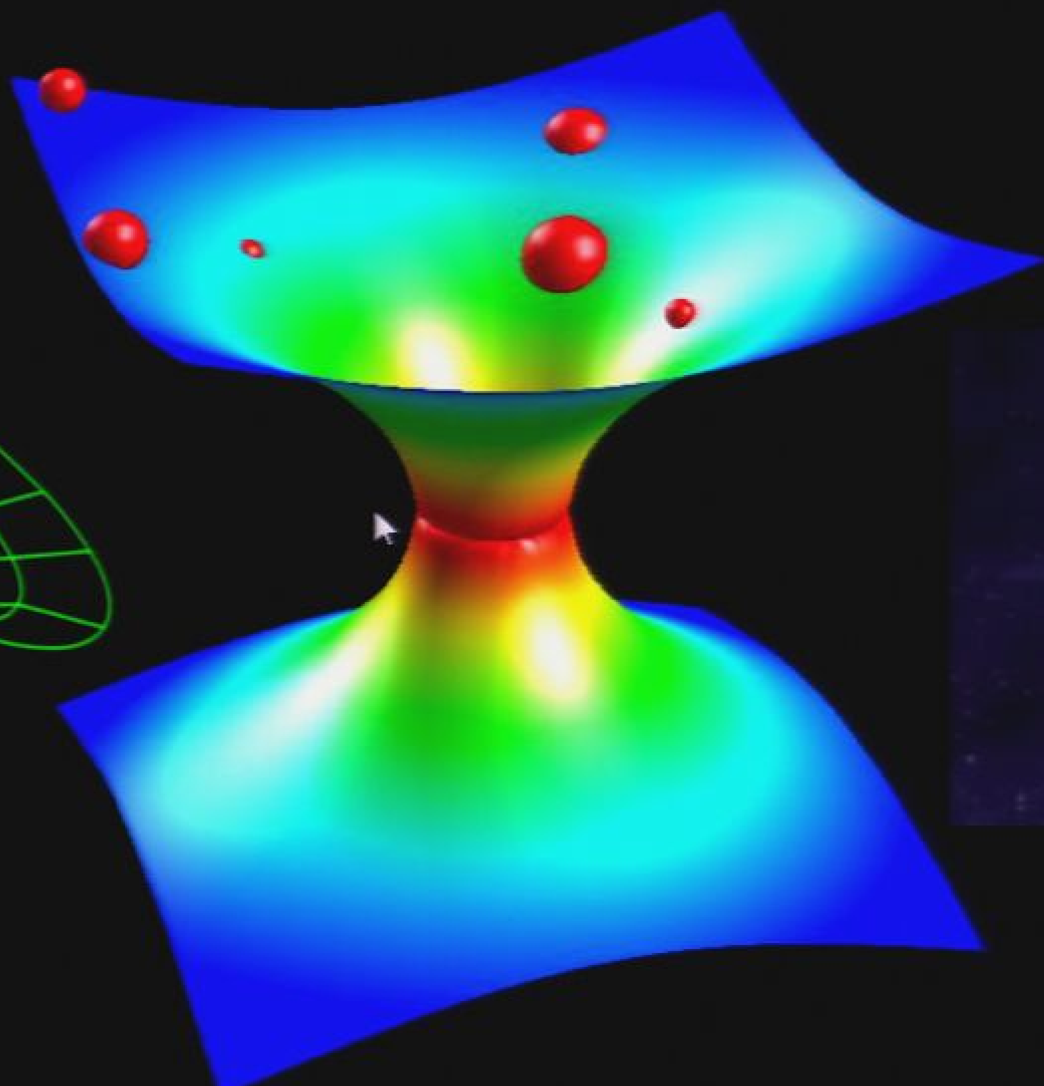

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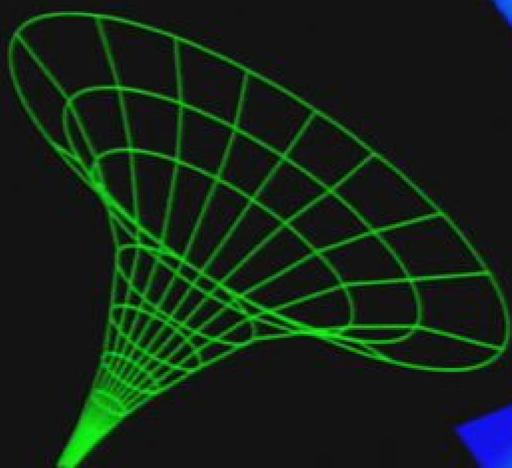

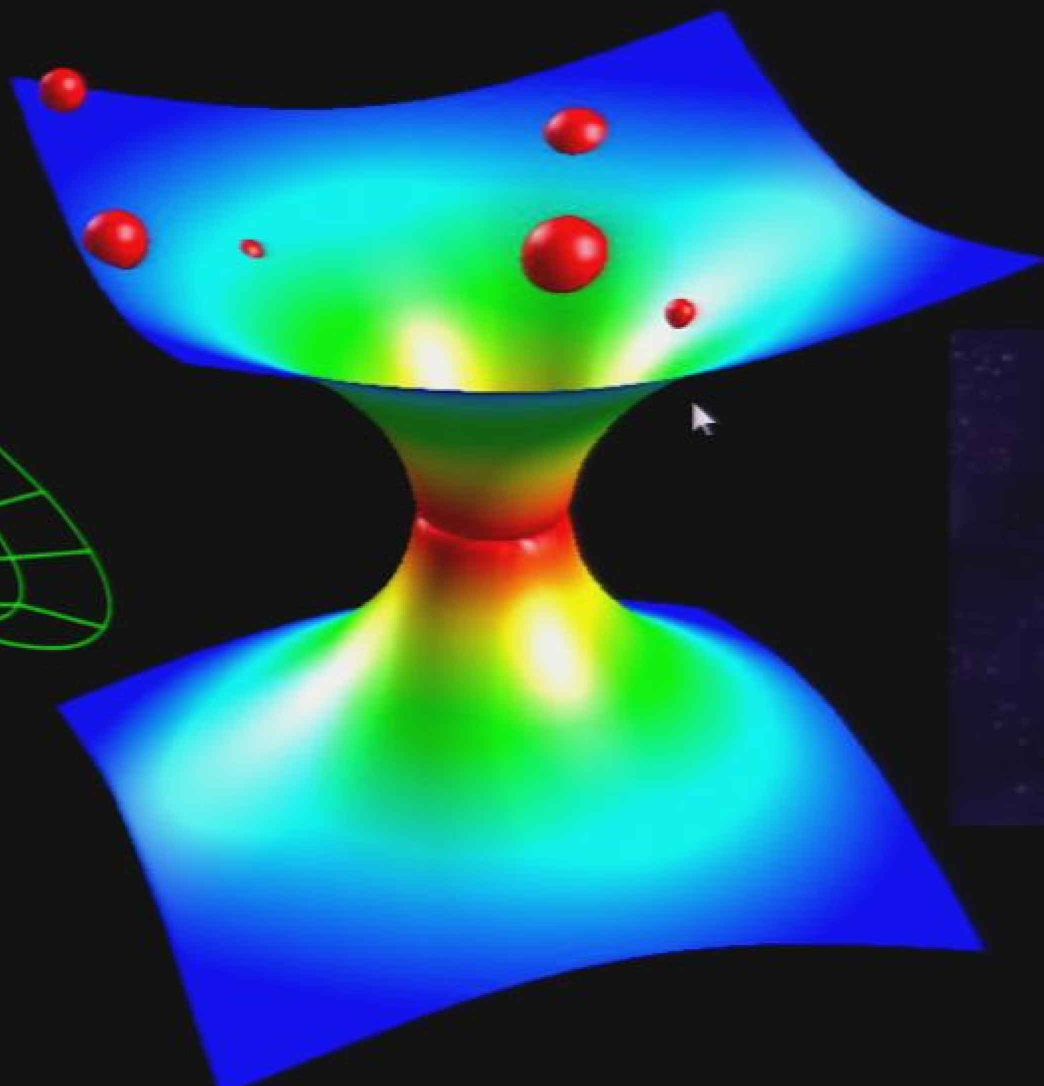

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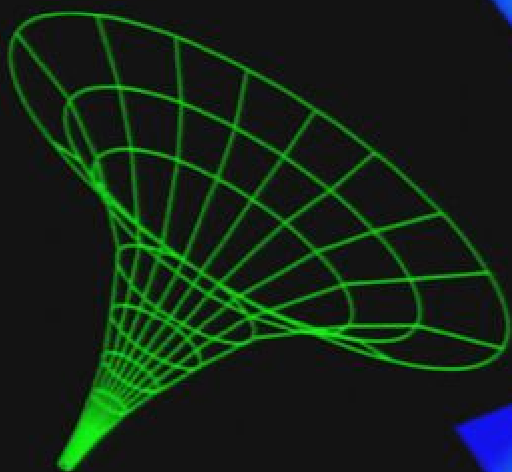

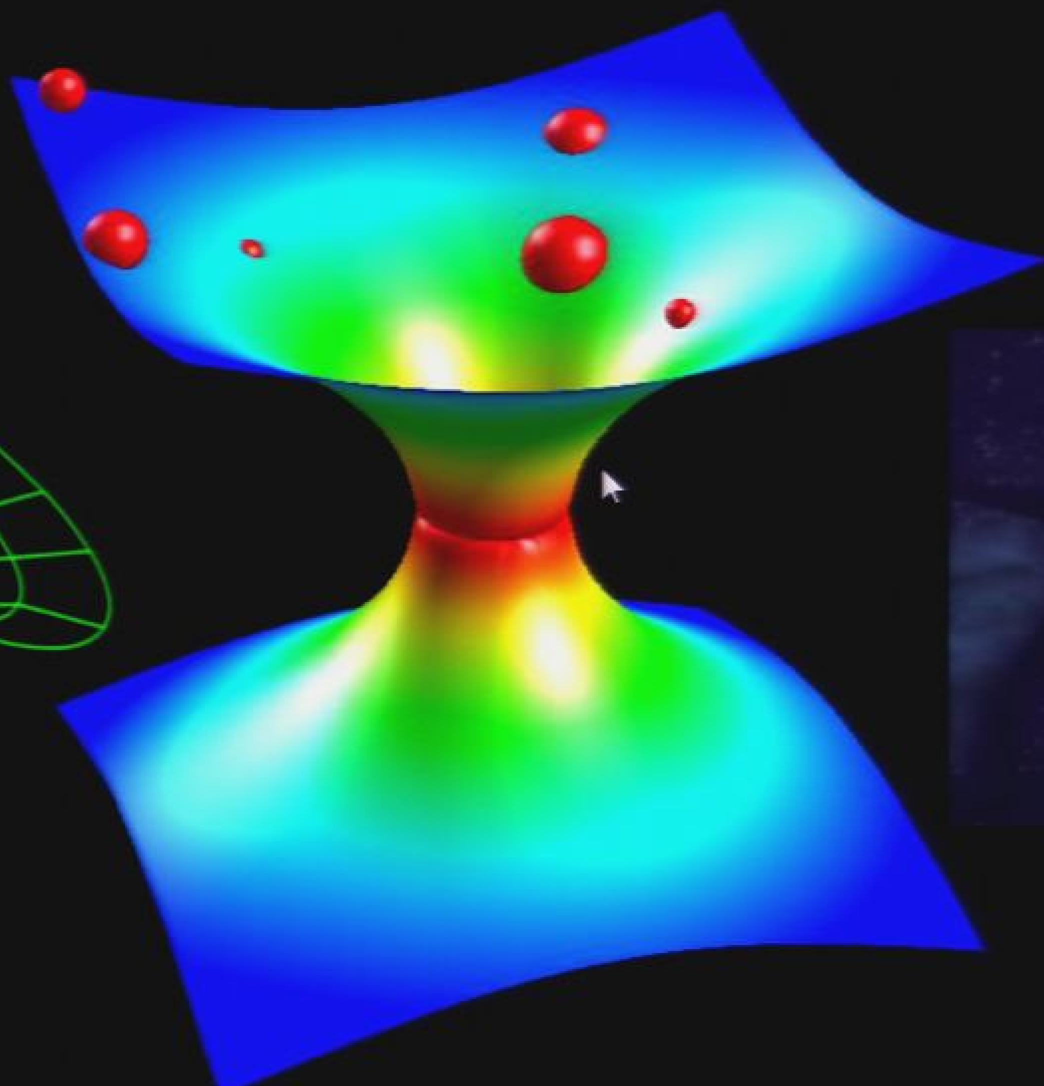

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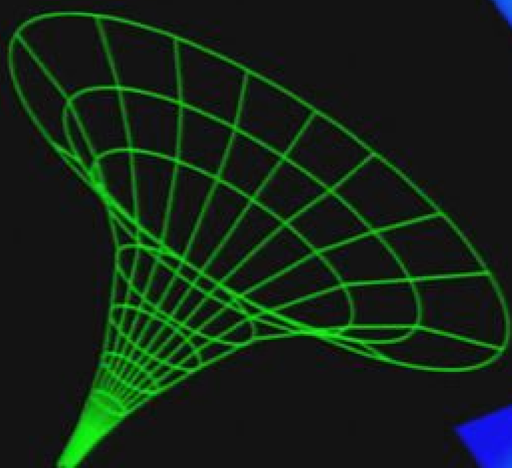

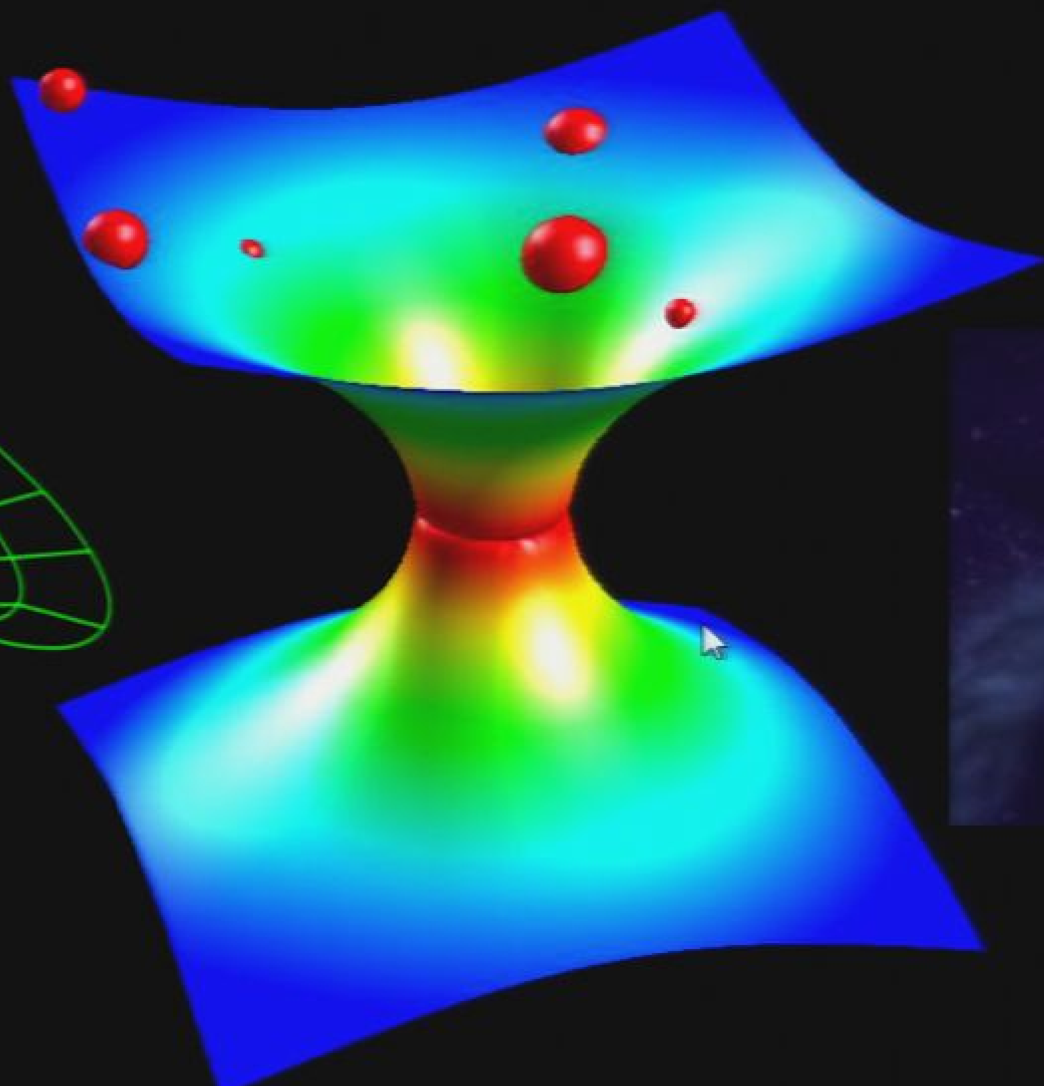

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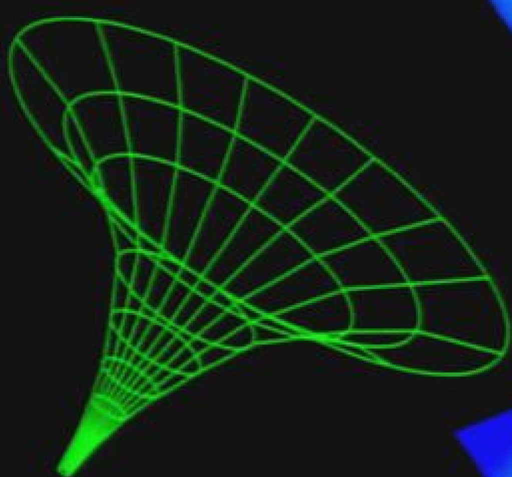

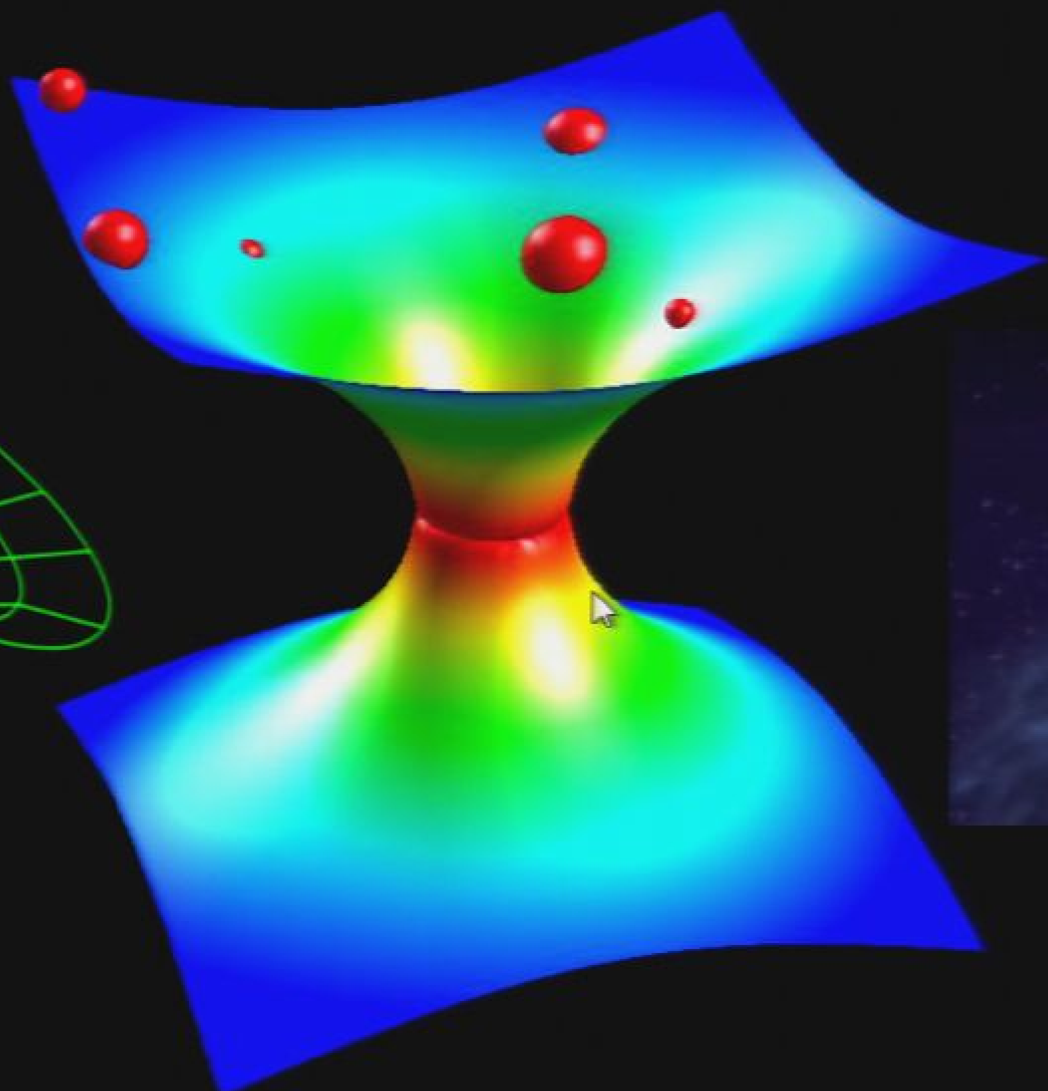

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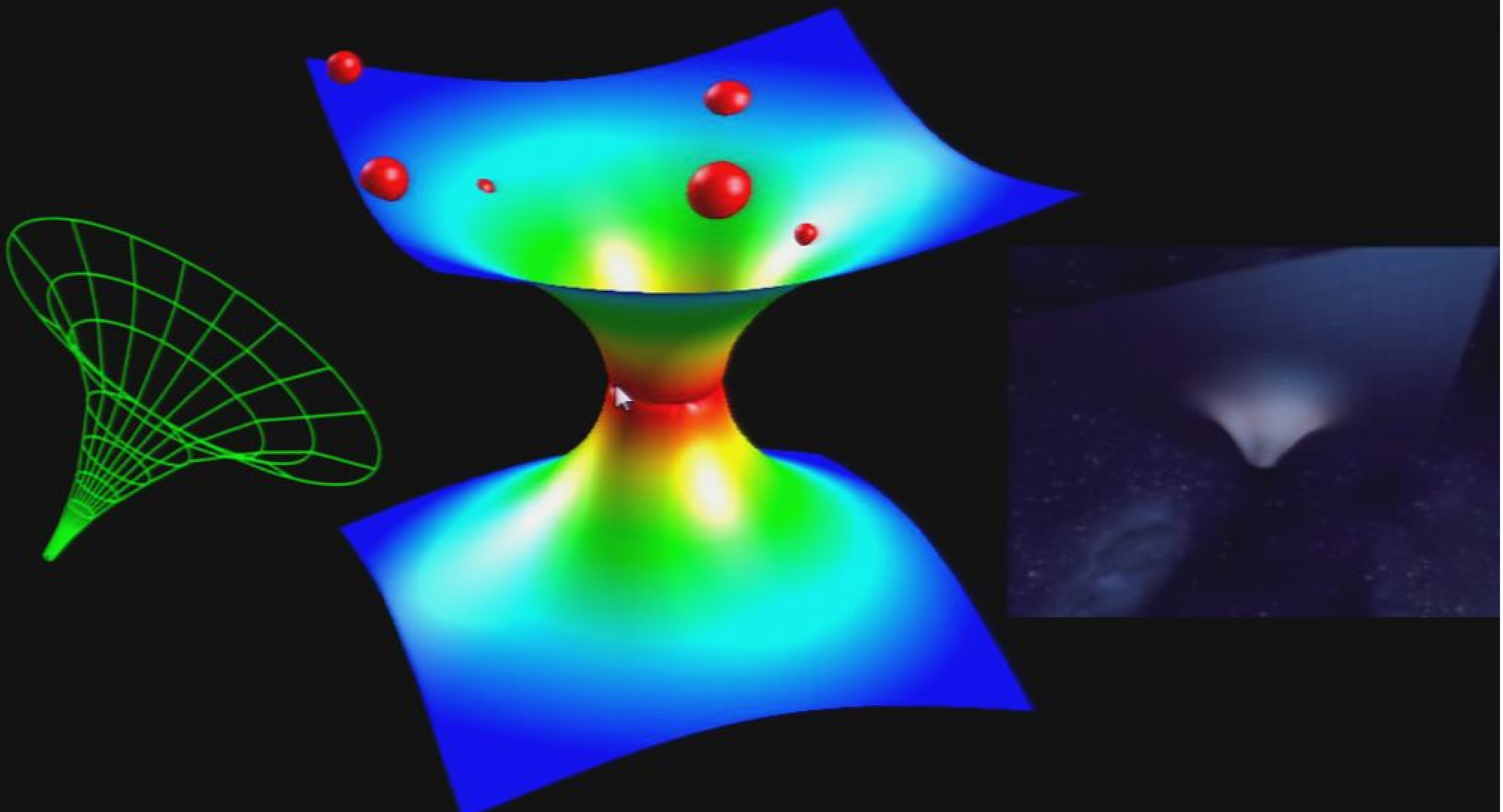

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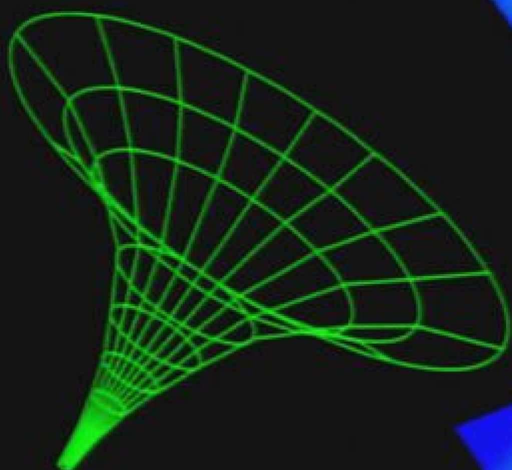
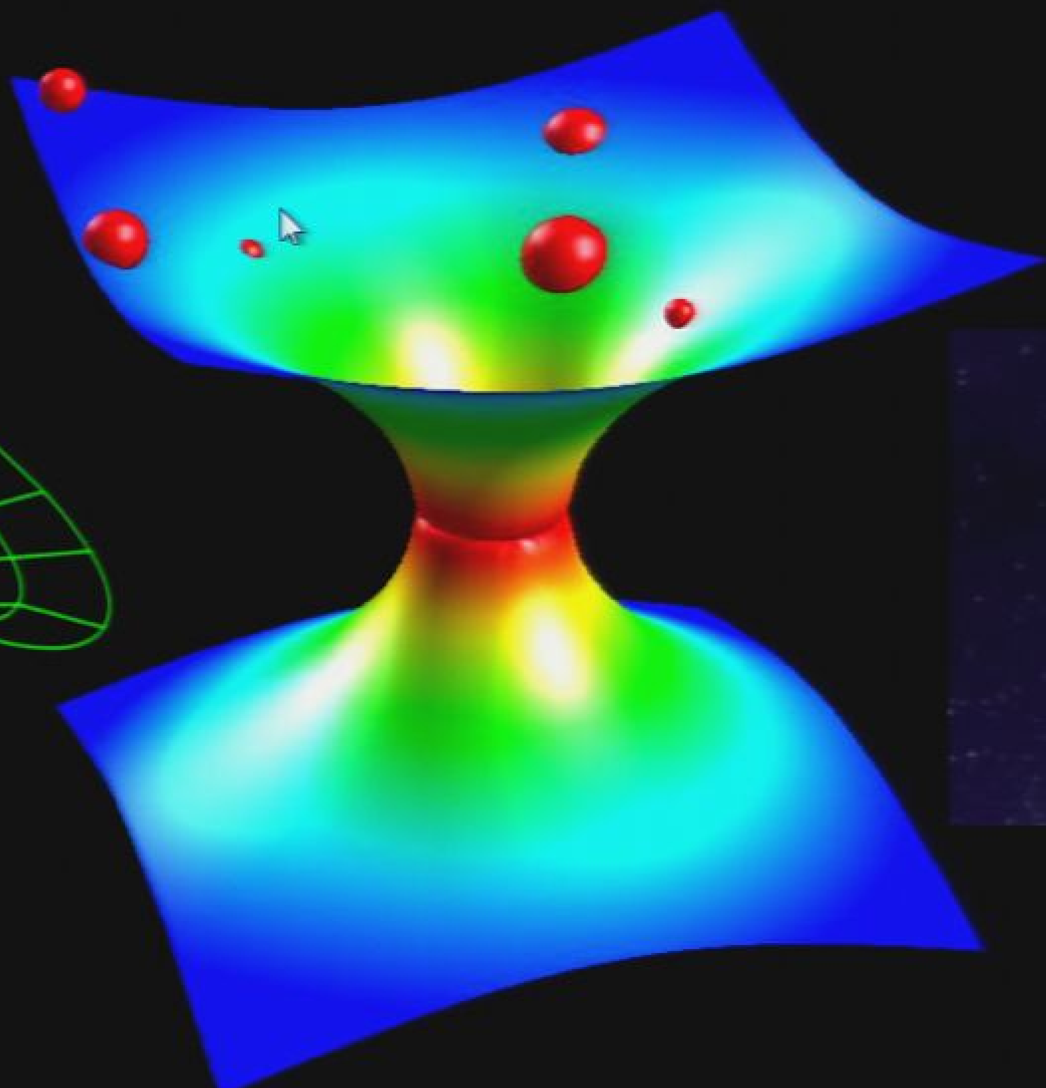
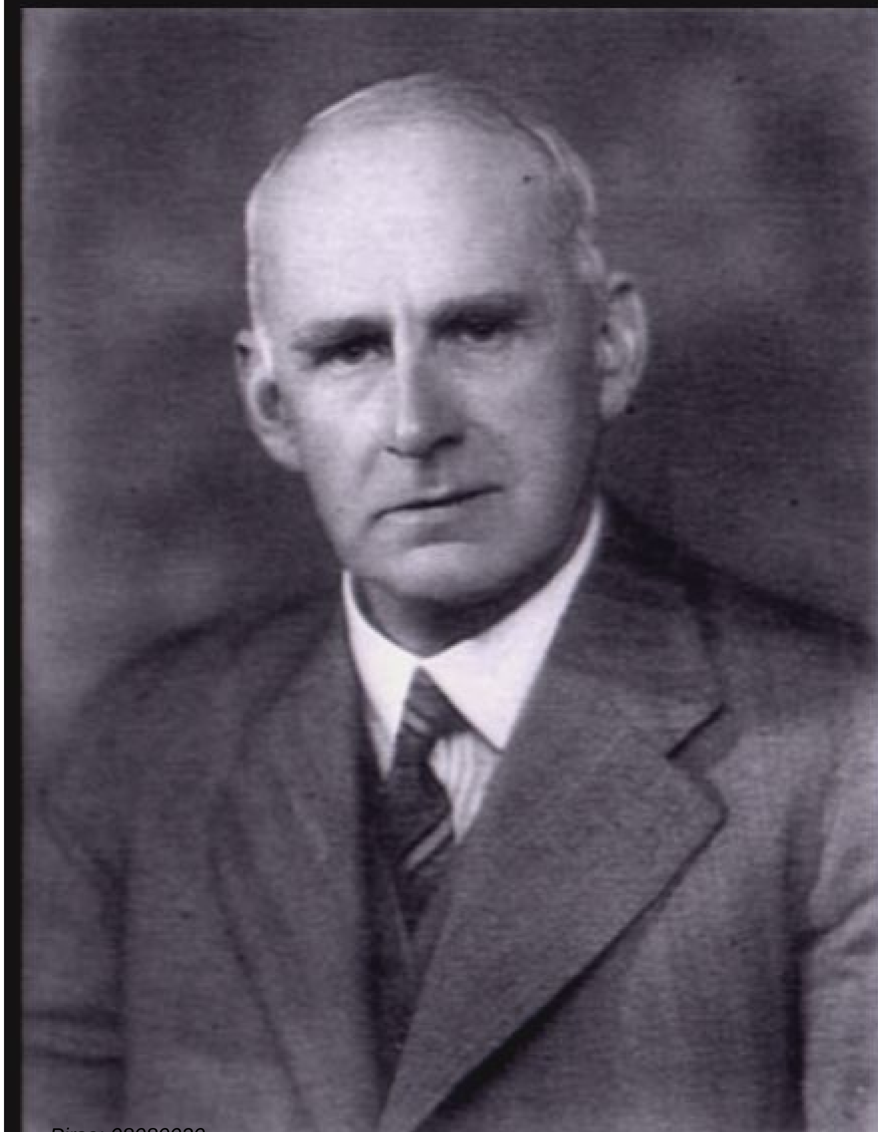




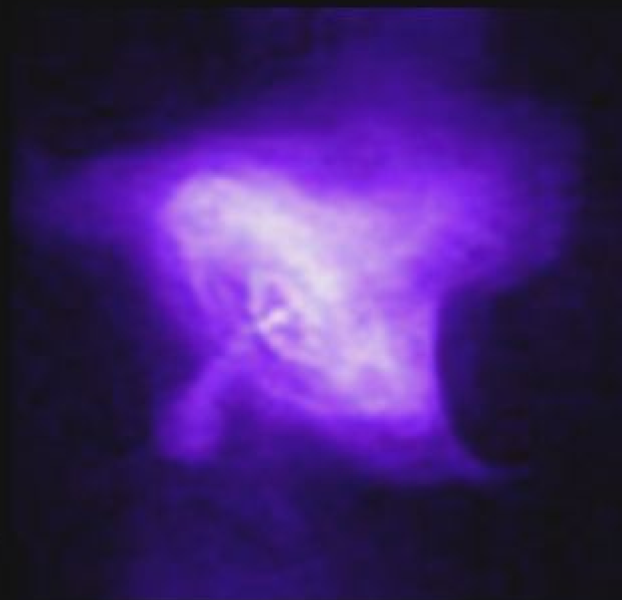
Emphasis on Spatial rather than temporal interpretations

Sir Arthur Eddington



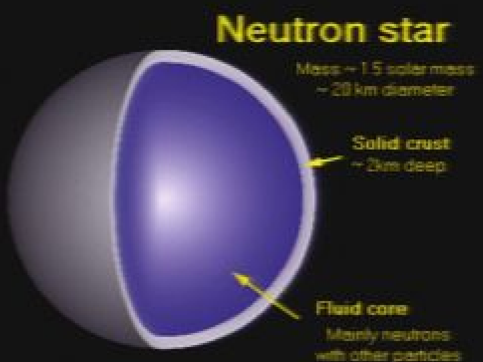
- 1926 Book – The internal constitution of the Stars
- Early proponent of Einstein's Theory of General Relativity (next to Einstein best expert on General Relativity)
- Poses the mystery of white dwarfs and attacks the reality of black holes predicted by Schwarzschild.
- Believed White Dwarf was last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

Subrahmanyan Chandrasekhar

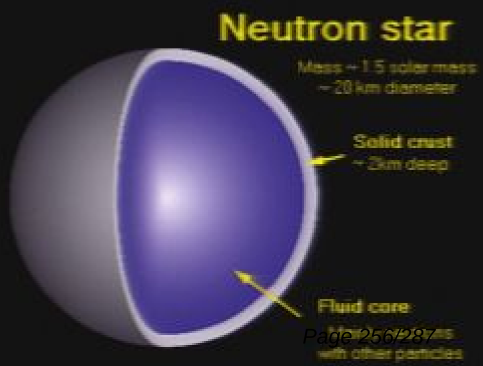


- *Idolized Eddington, resolved Eddington's paradox*
- *In 1930 he showed that there is a maximum mass for White Dwarfs*
- *1935 Eddington attacks his work. "Chandra" left the field of Blackholes until 1970's*
- *Nobel Prize in Physics 1983*

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.*

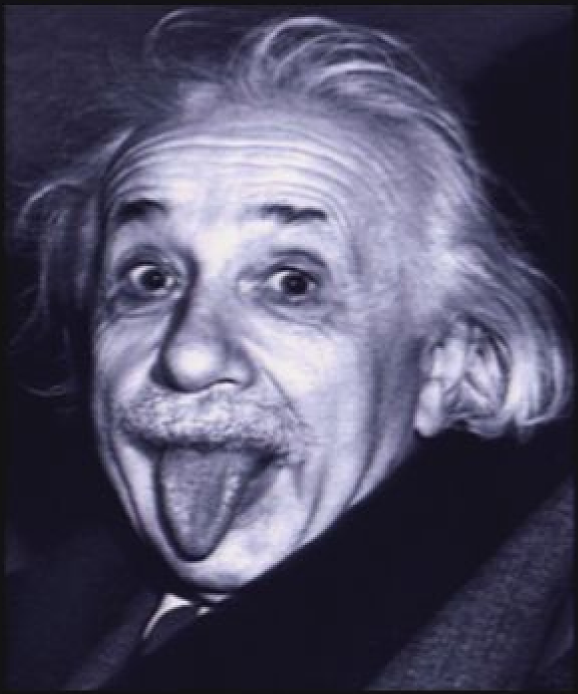


Robert J. Oppenheimer

- 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.*
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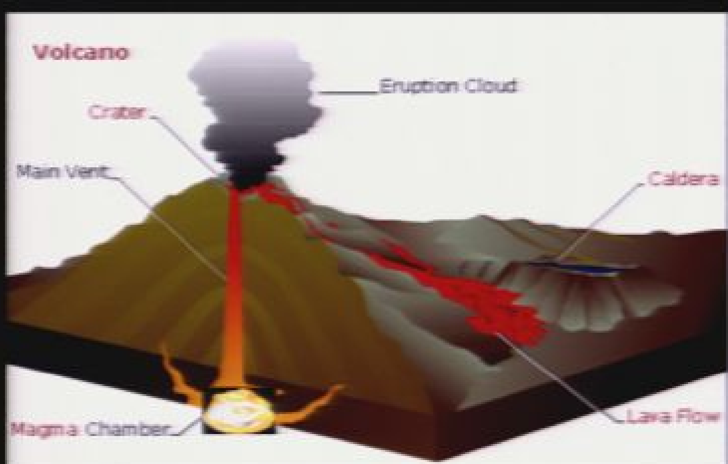

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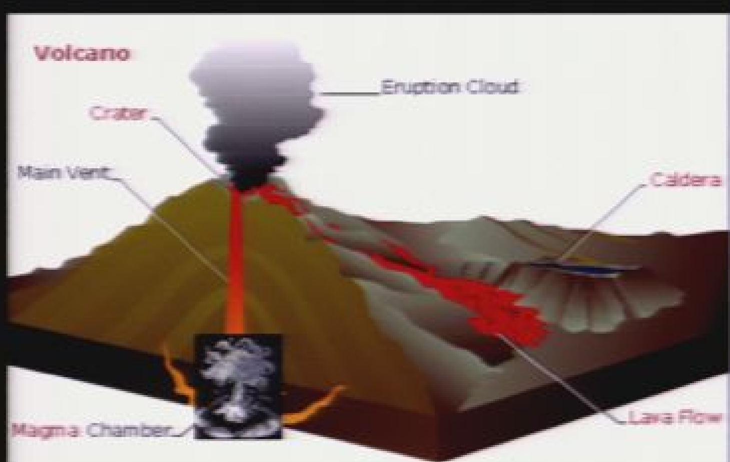

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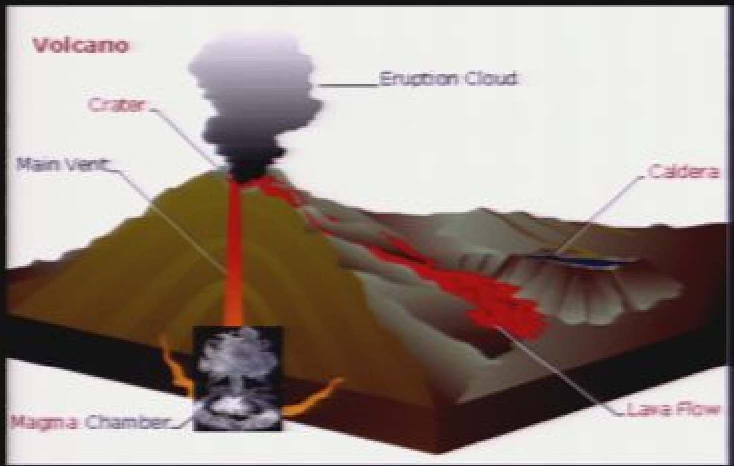

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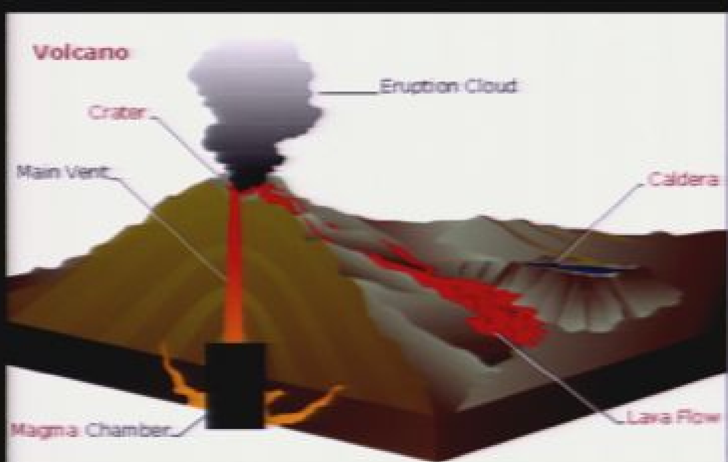

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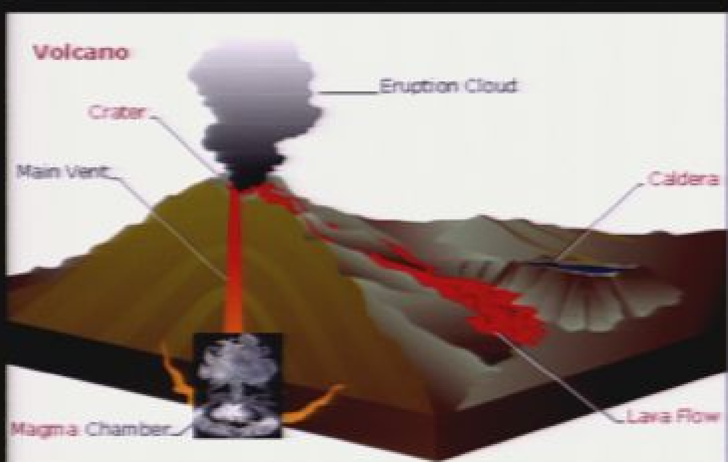

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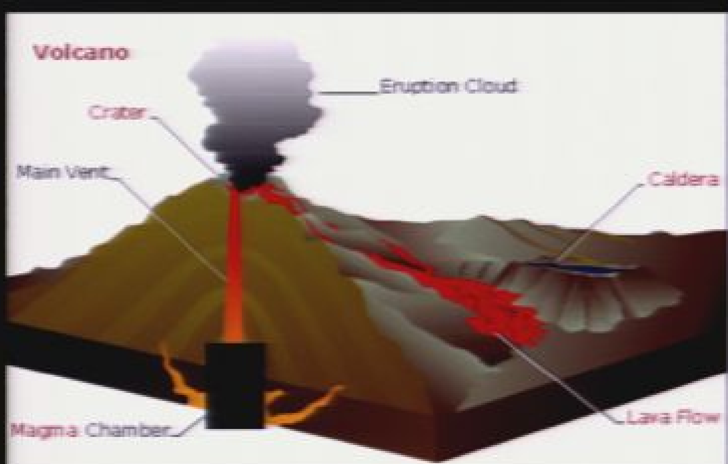

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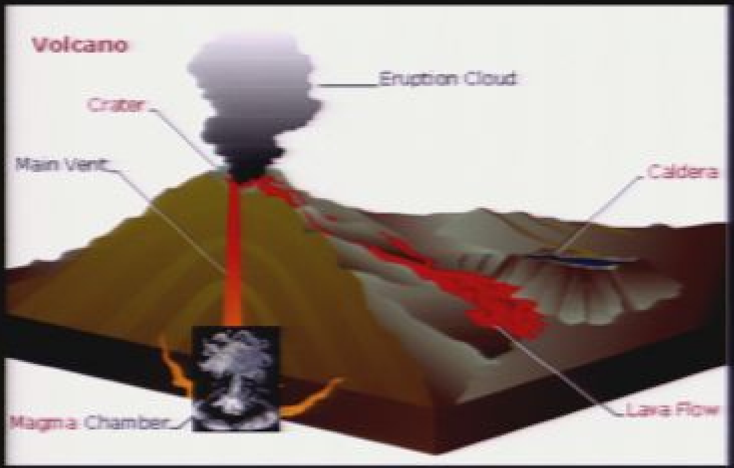

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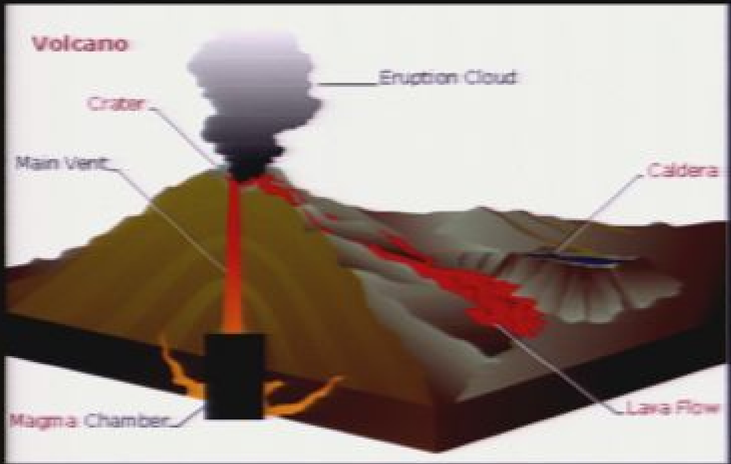

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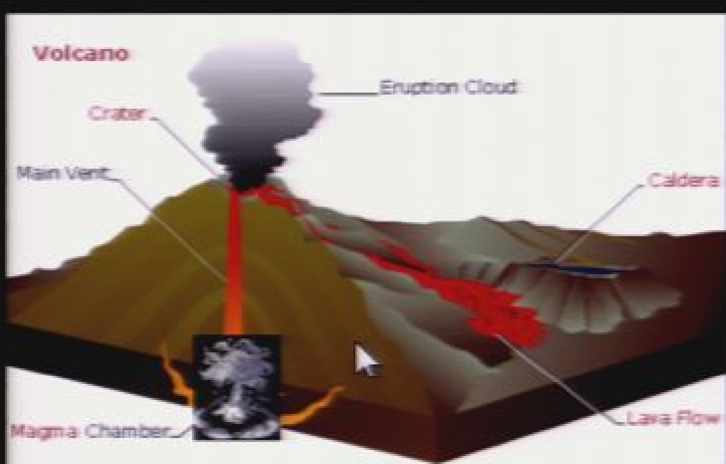
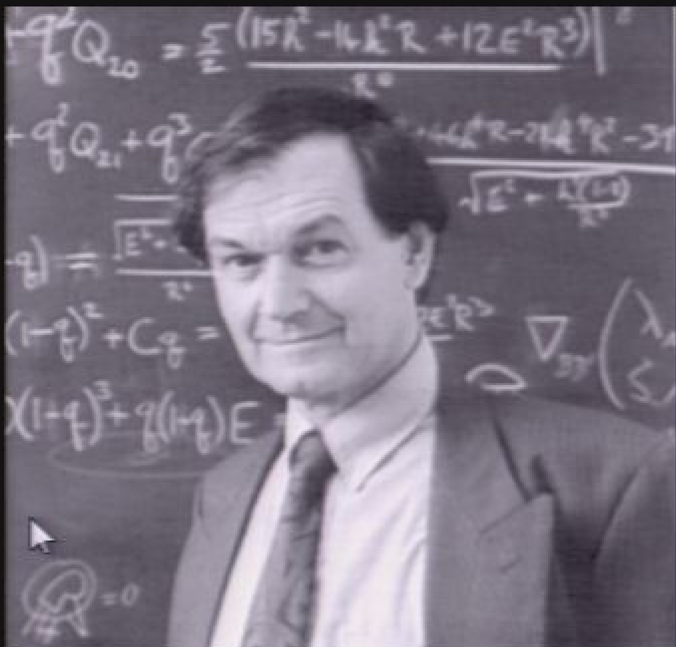


John Wheeler

- *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



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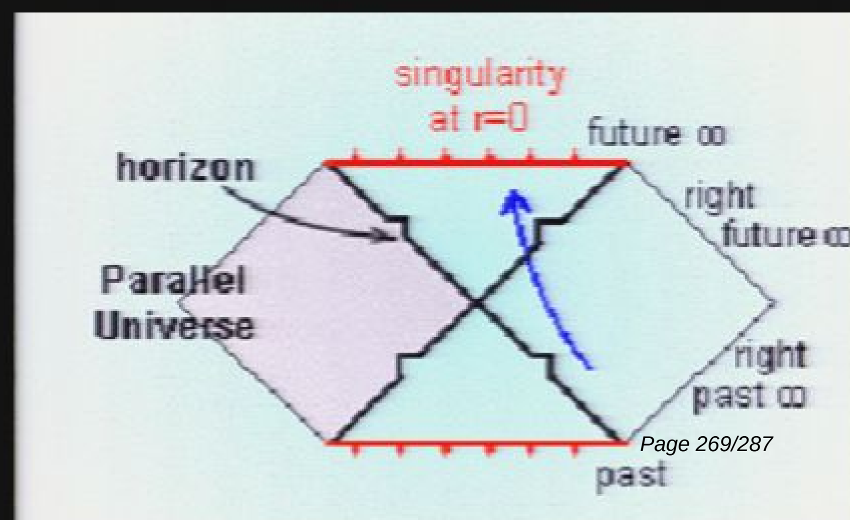

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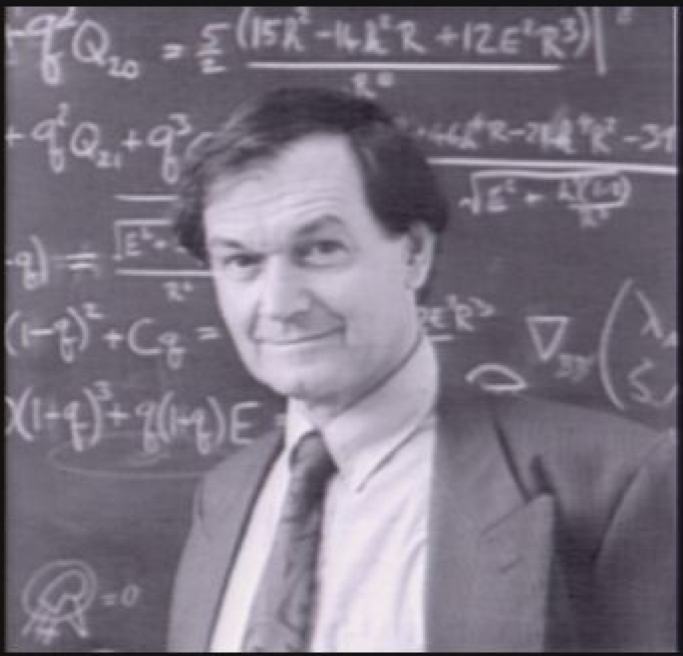

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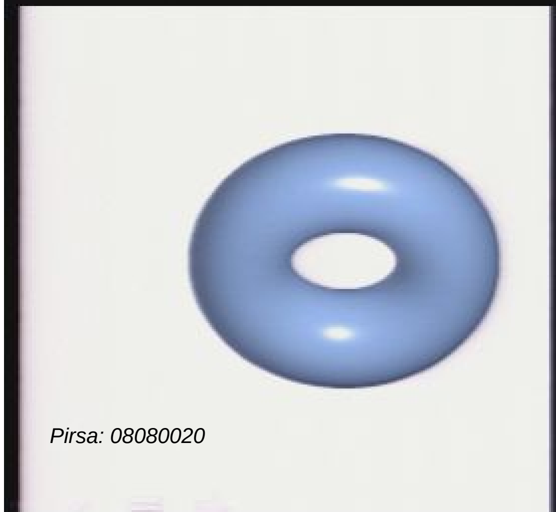

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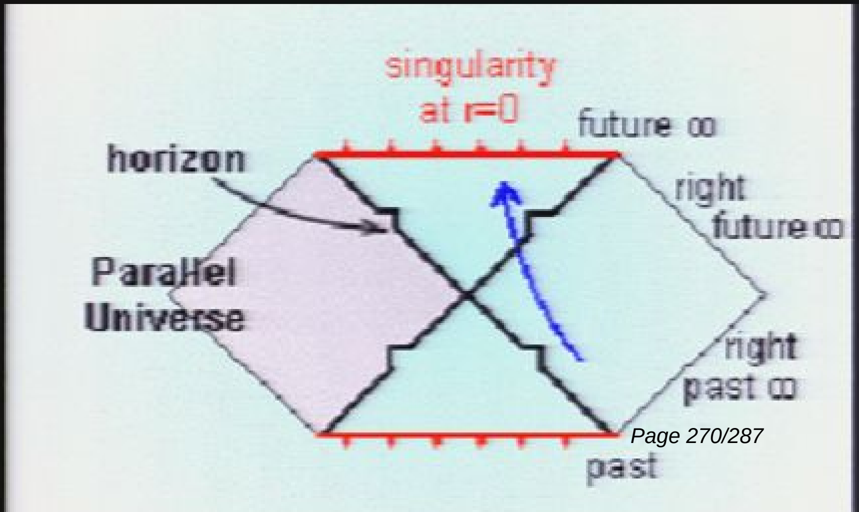

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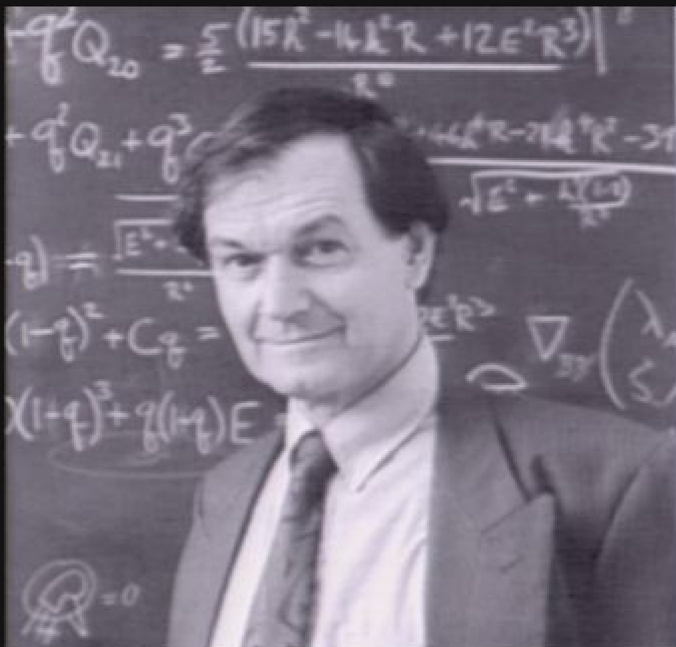

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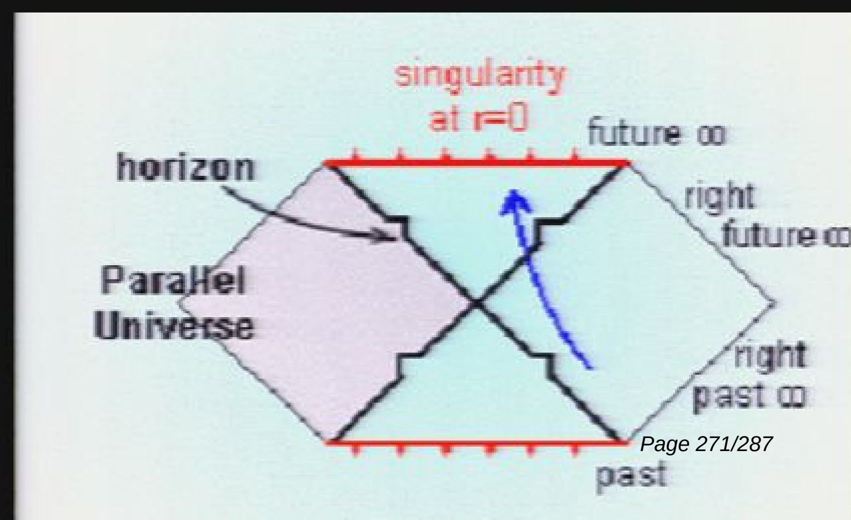

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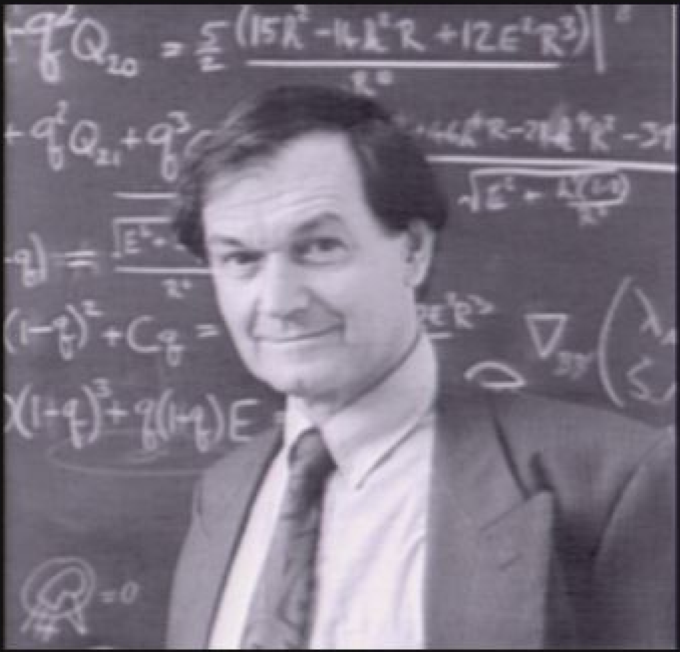

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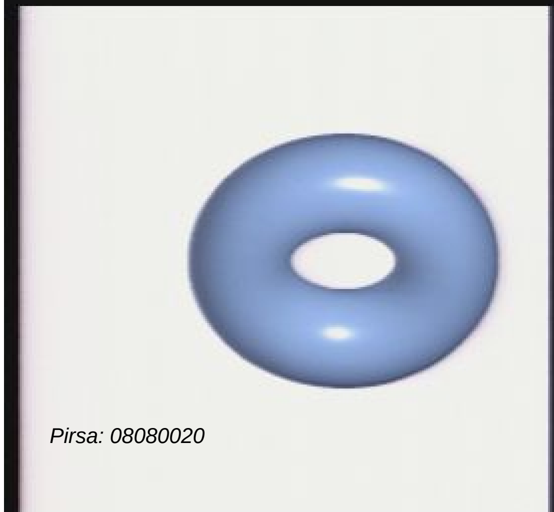

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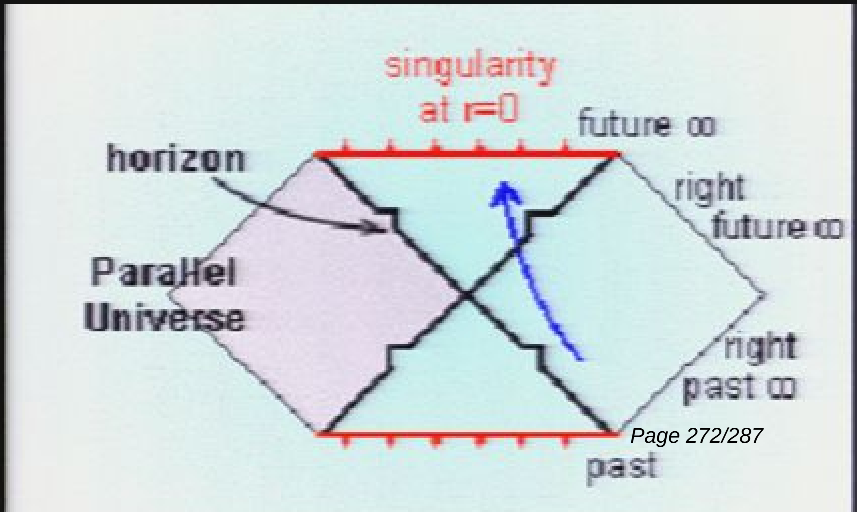

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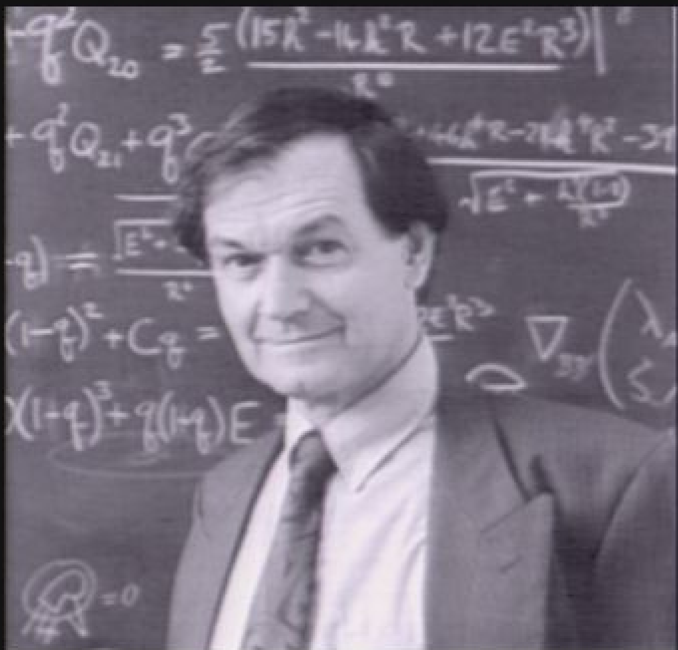

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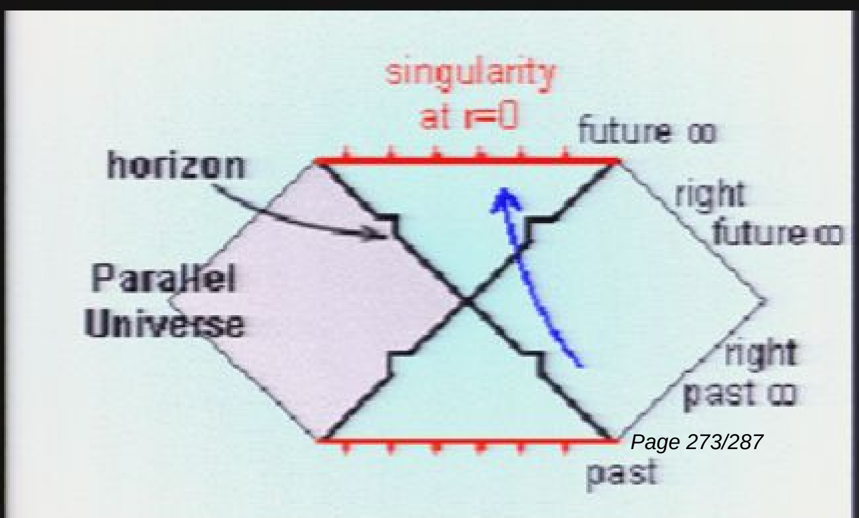

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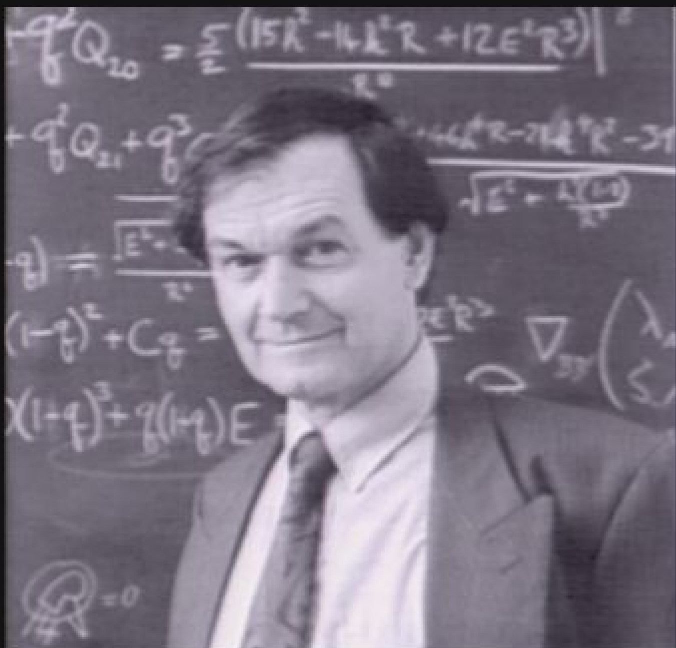

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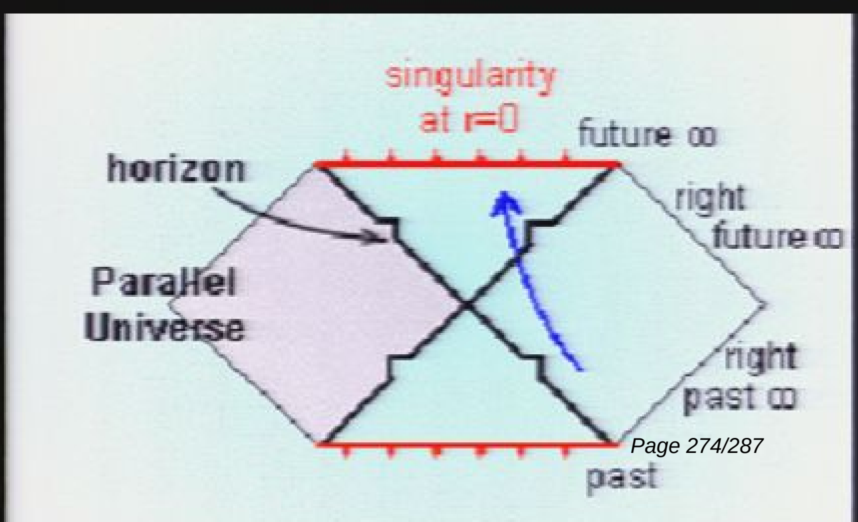

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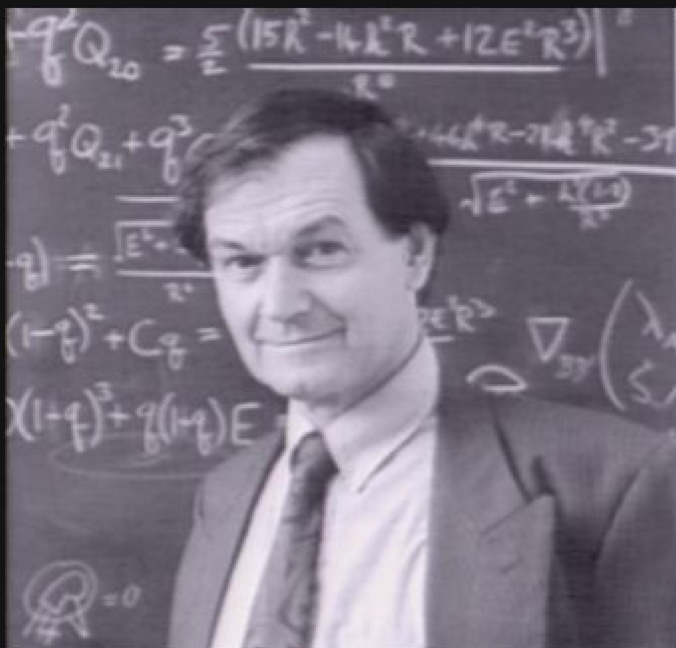

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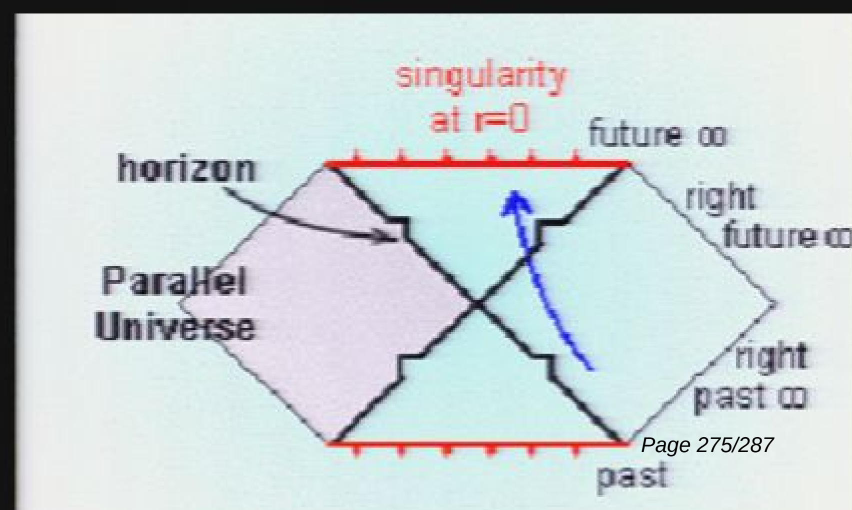

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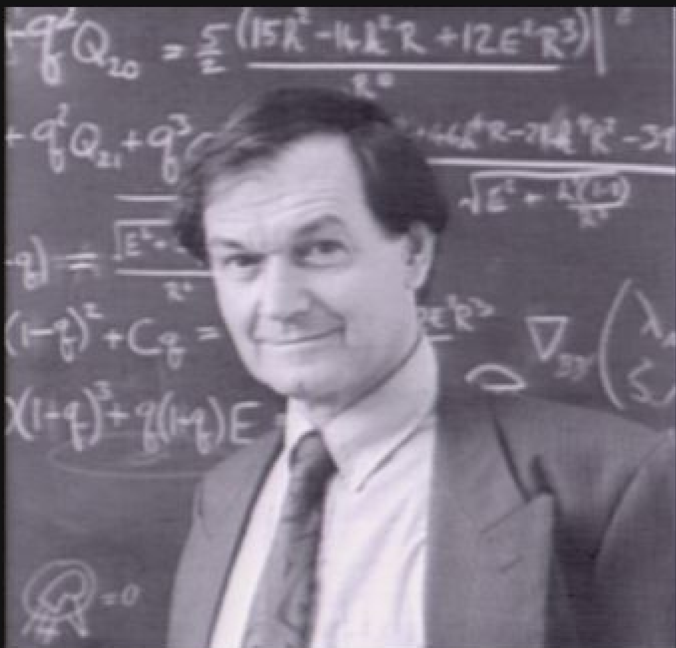

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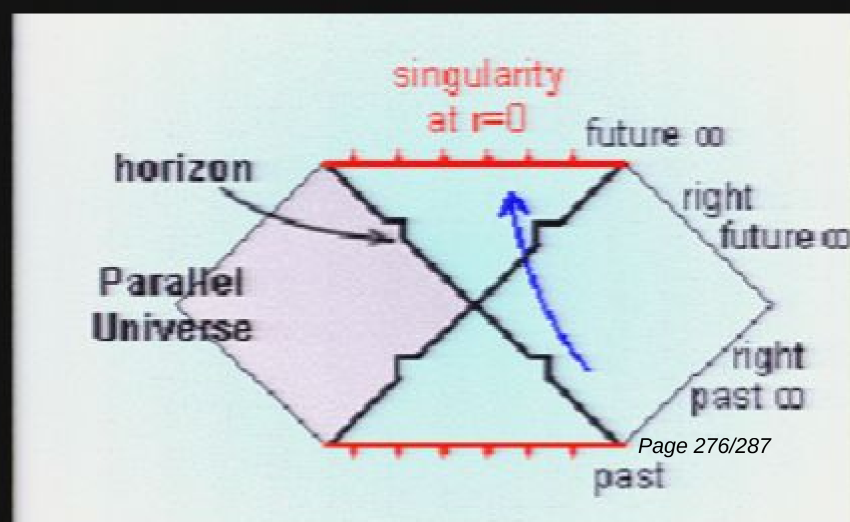

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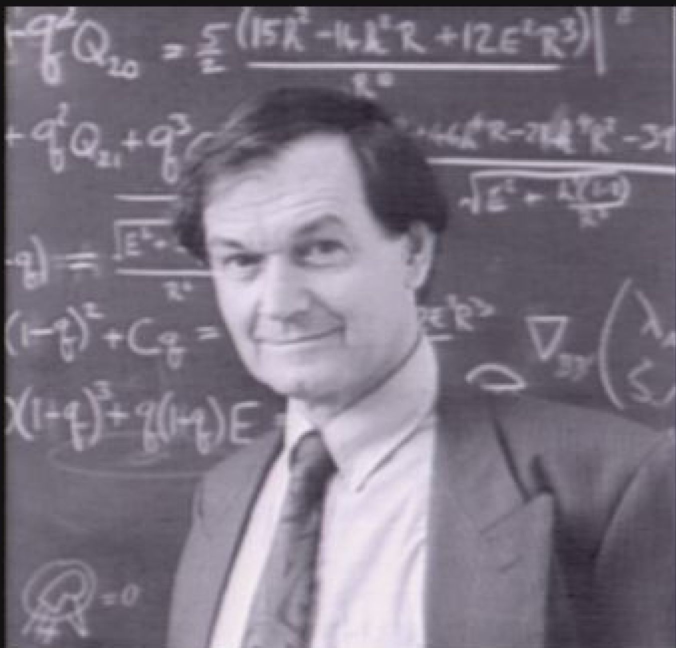

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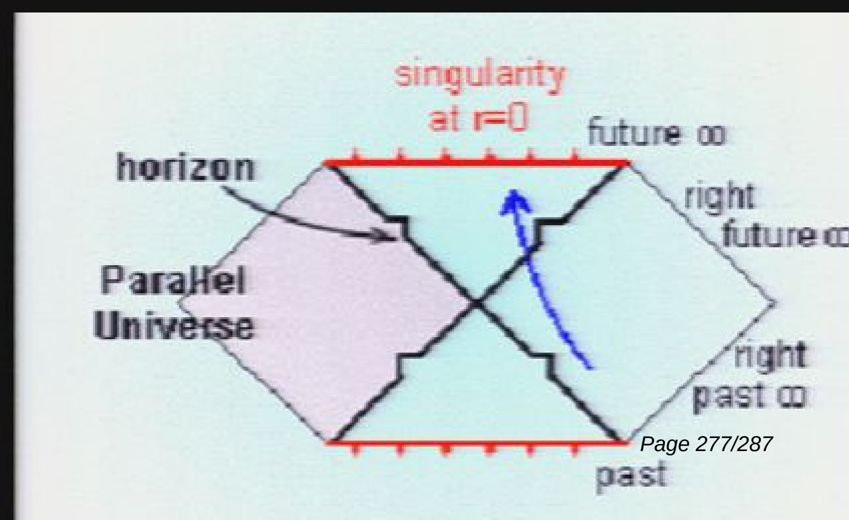

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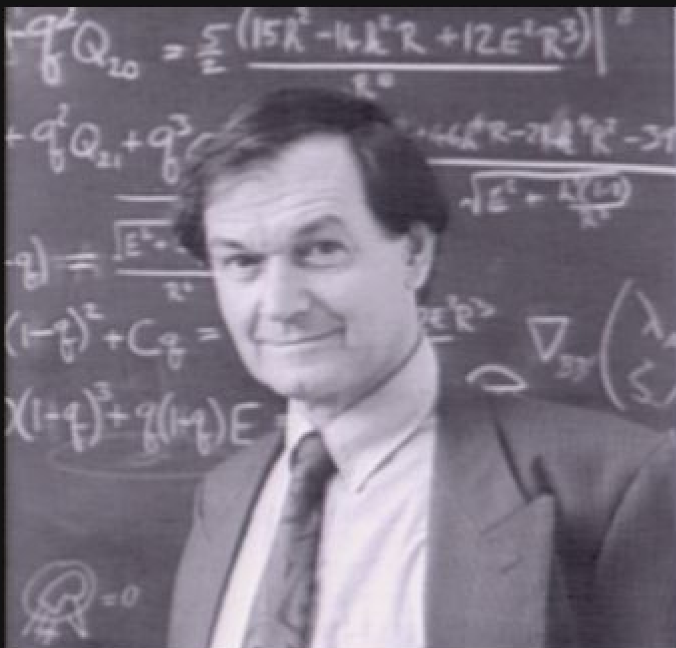

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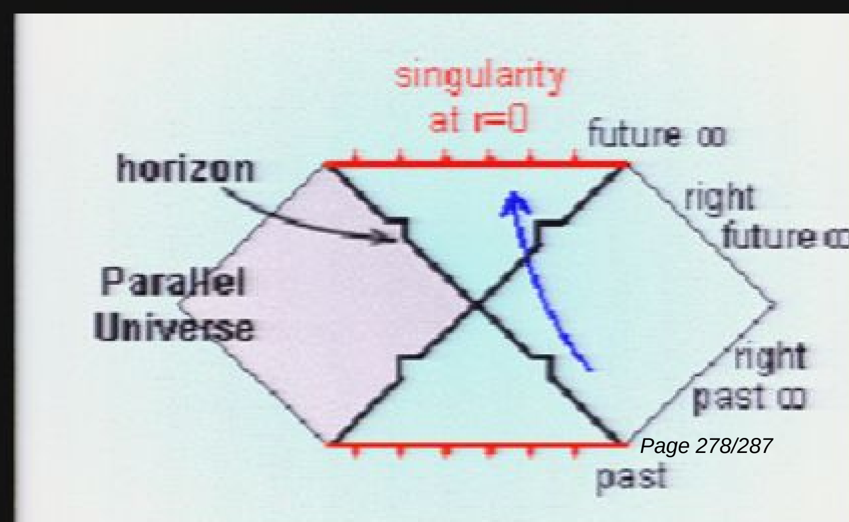

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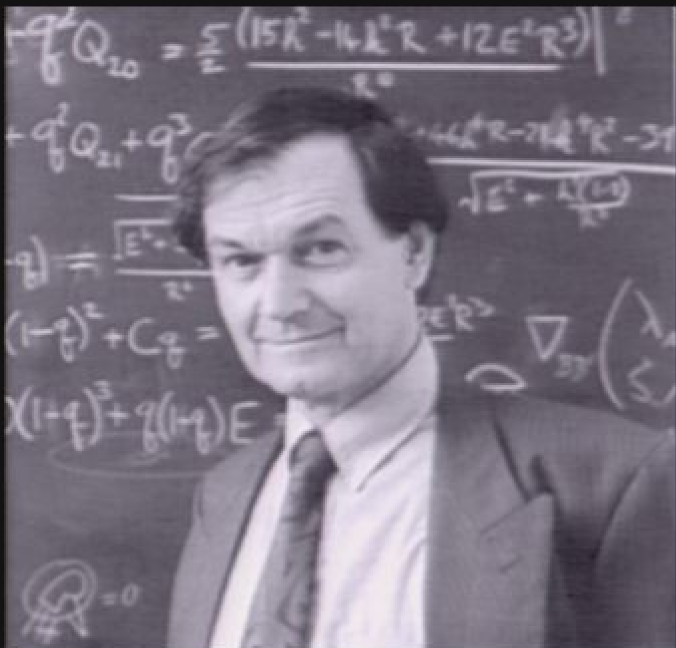

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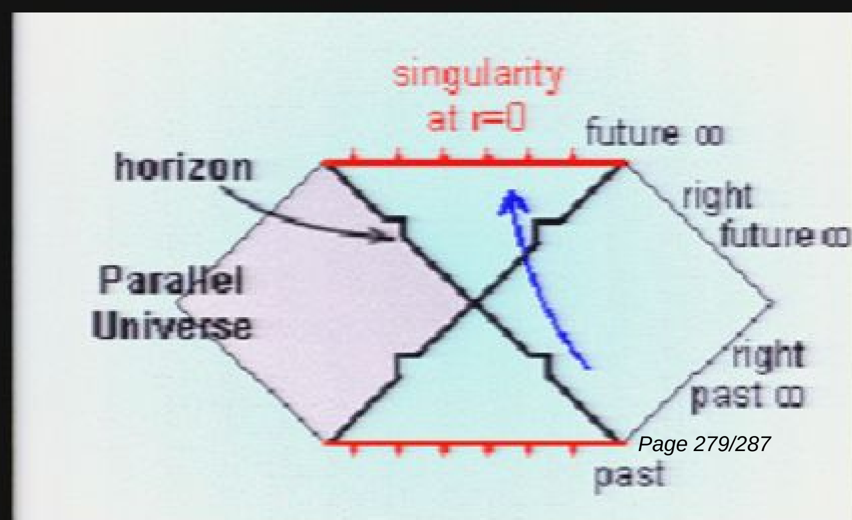

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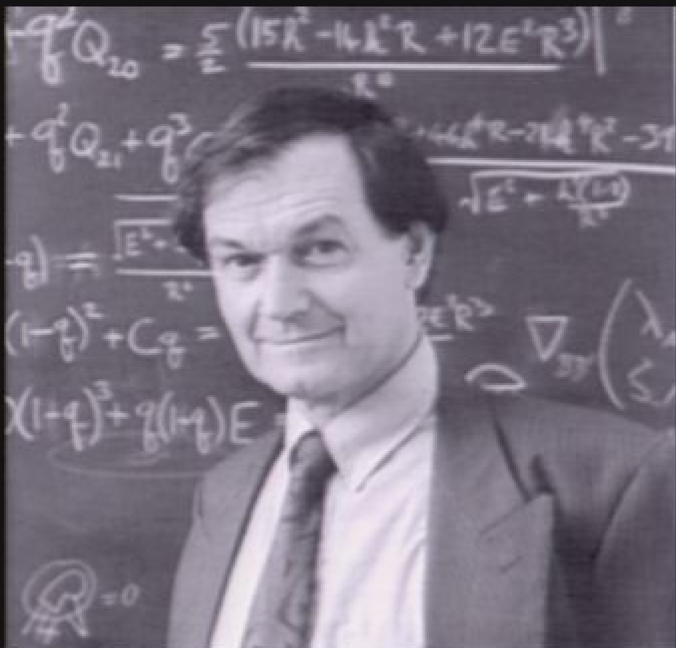

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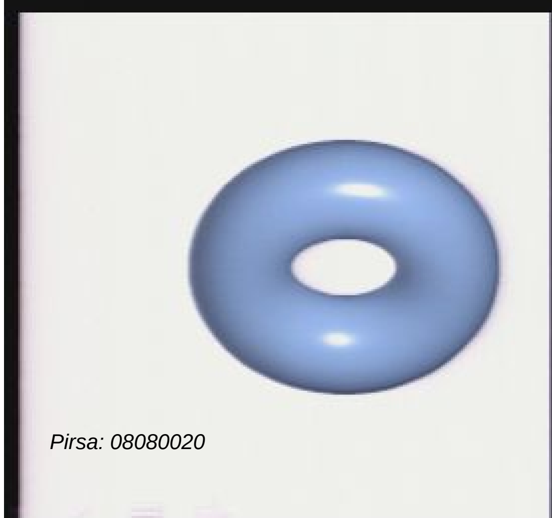

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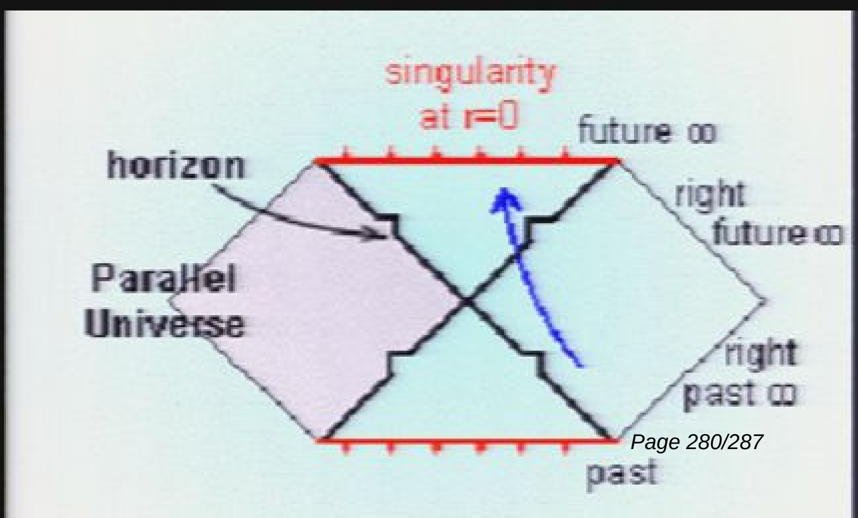

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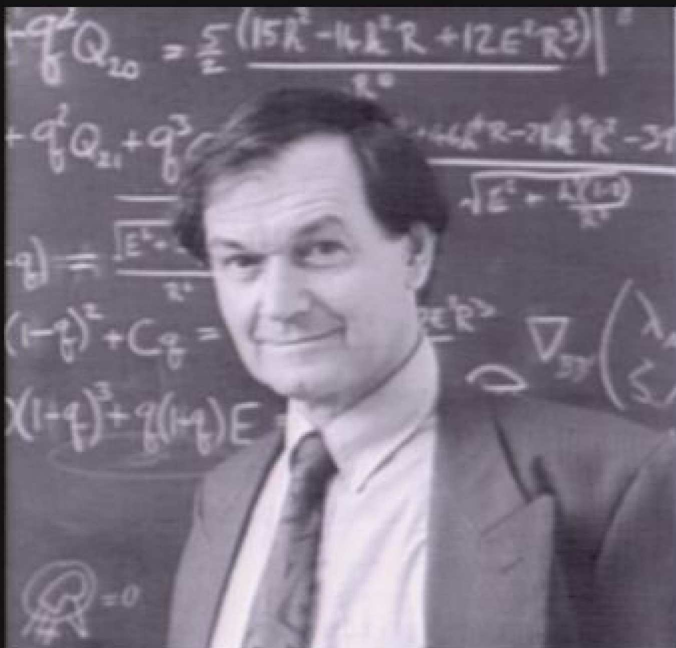

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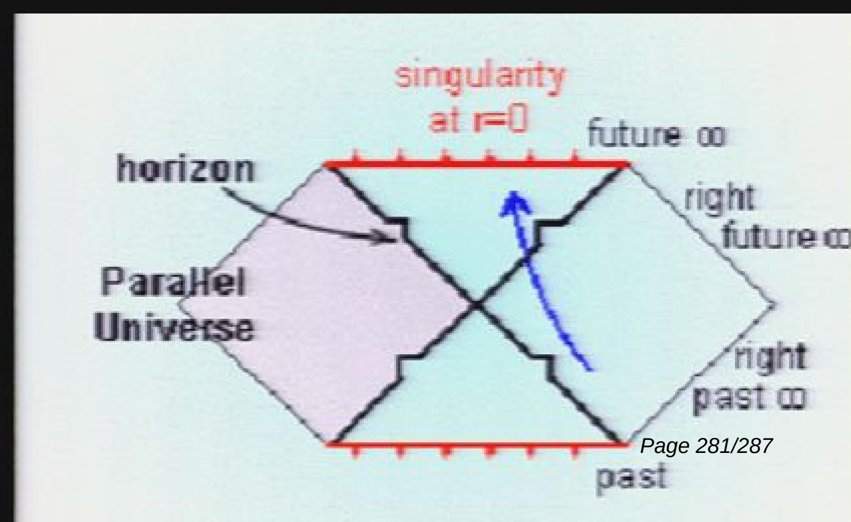

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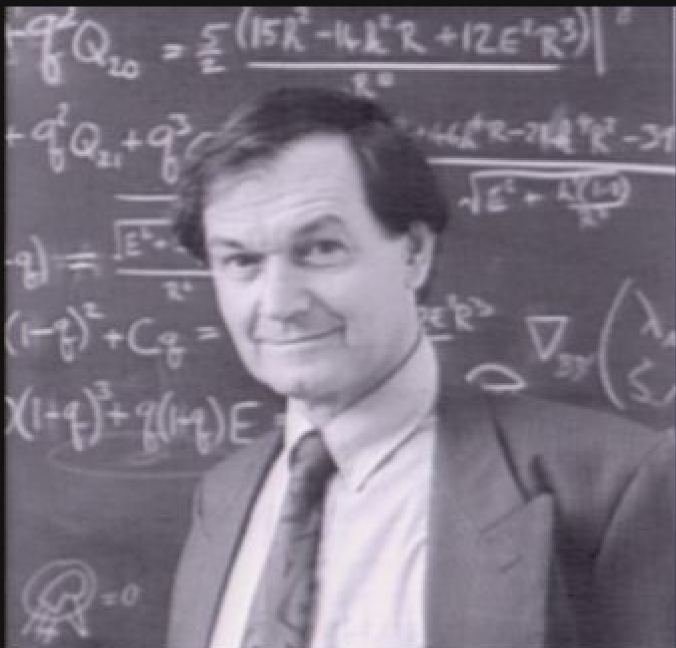

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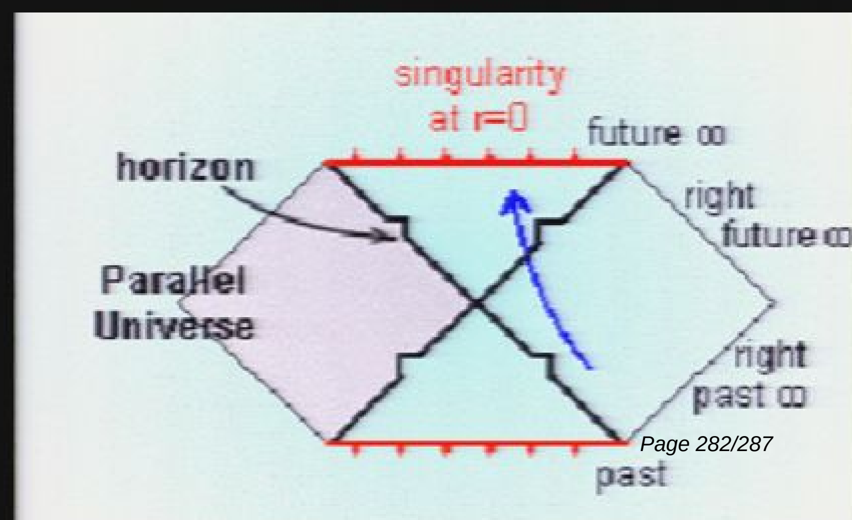

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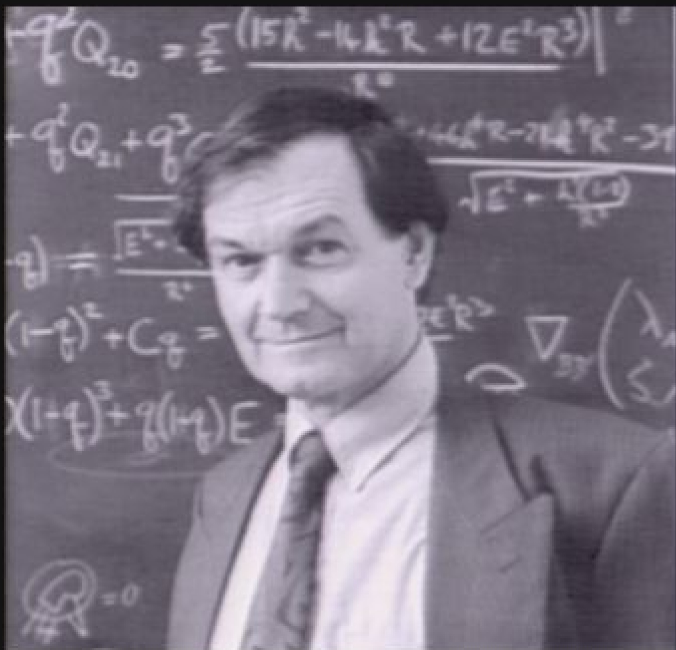

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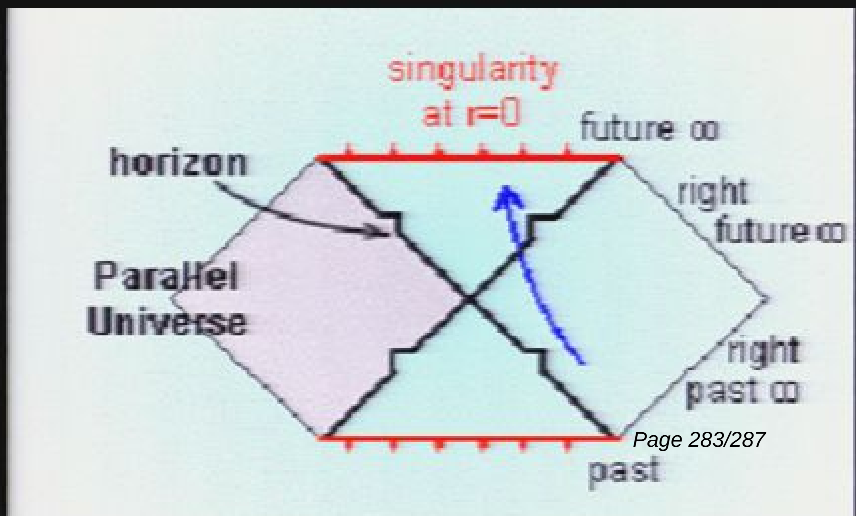

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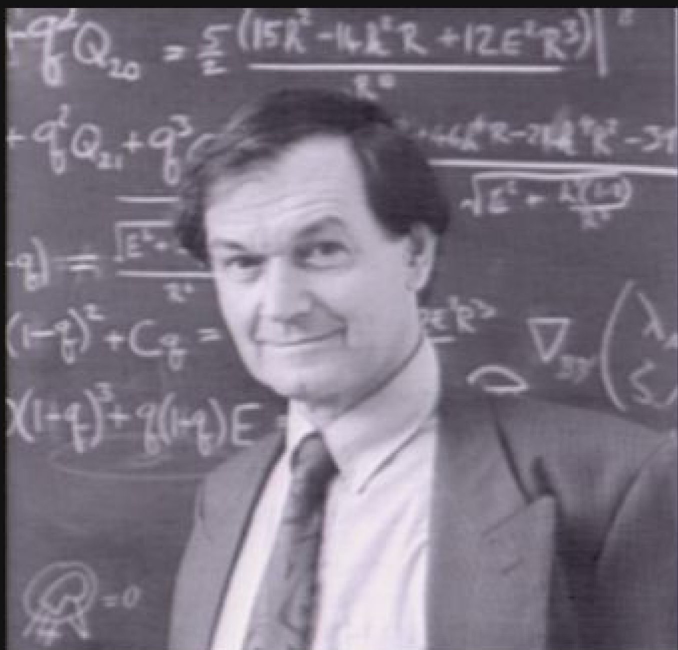

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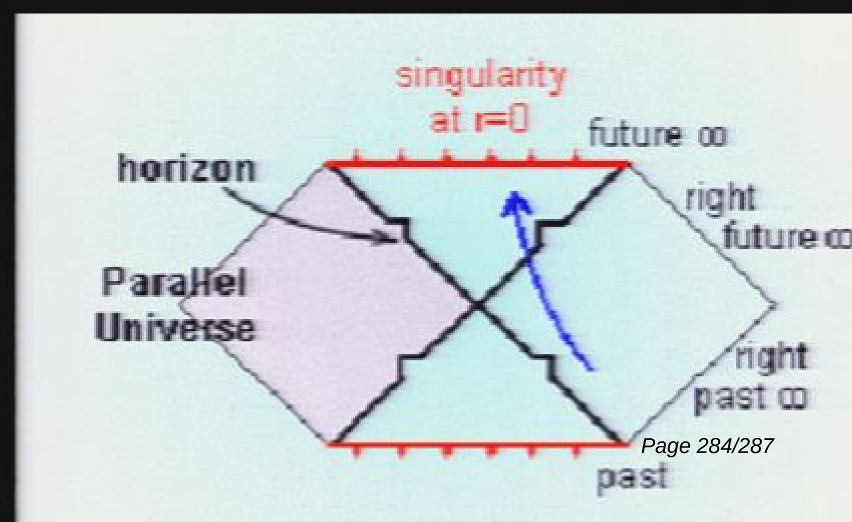

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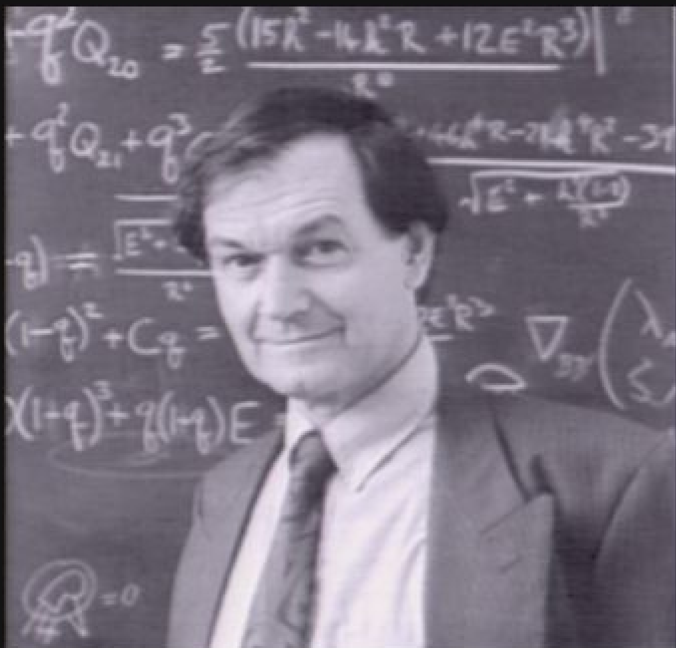

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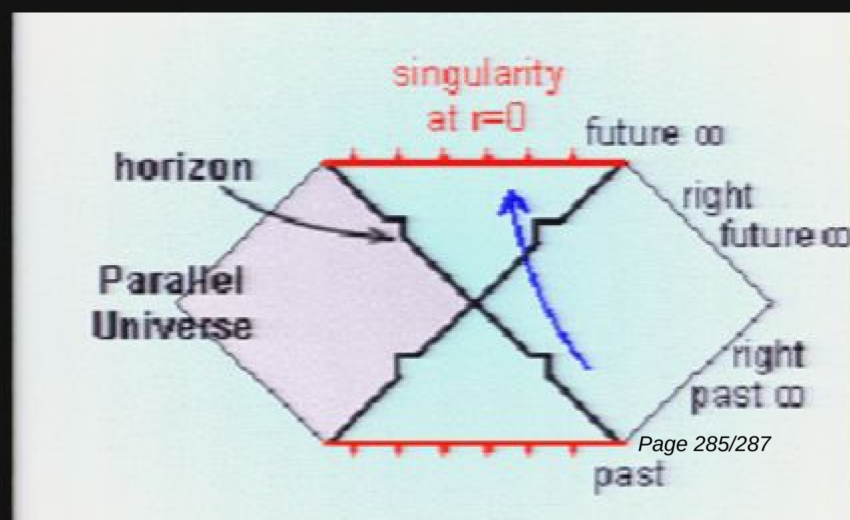

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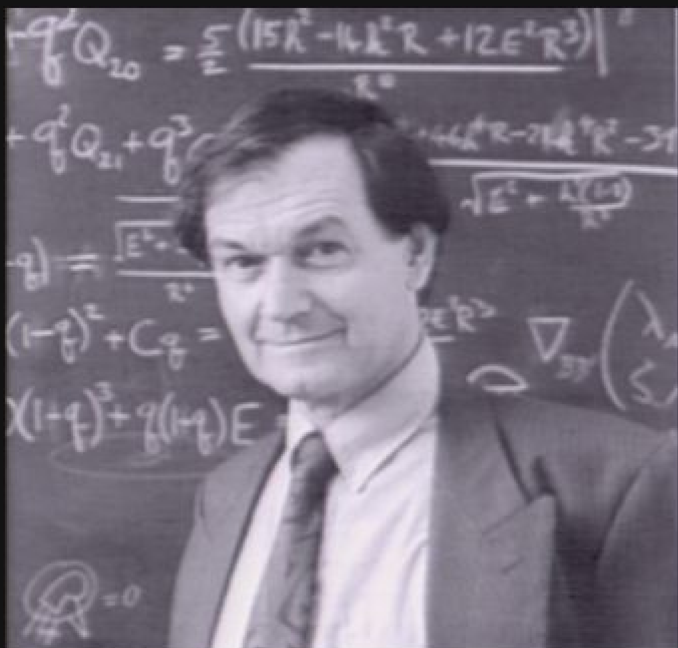

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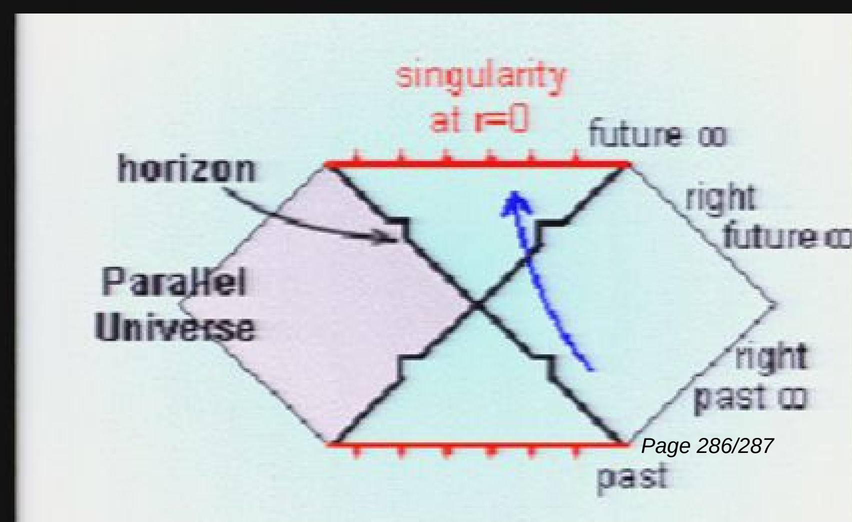
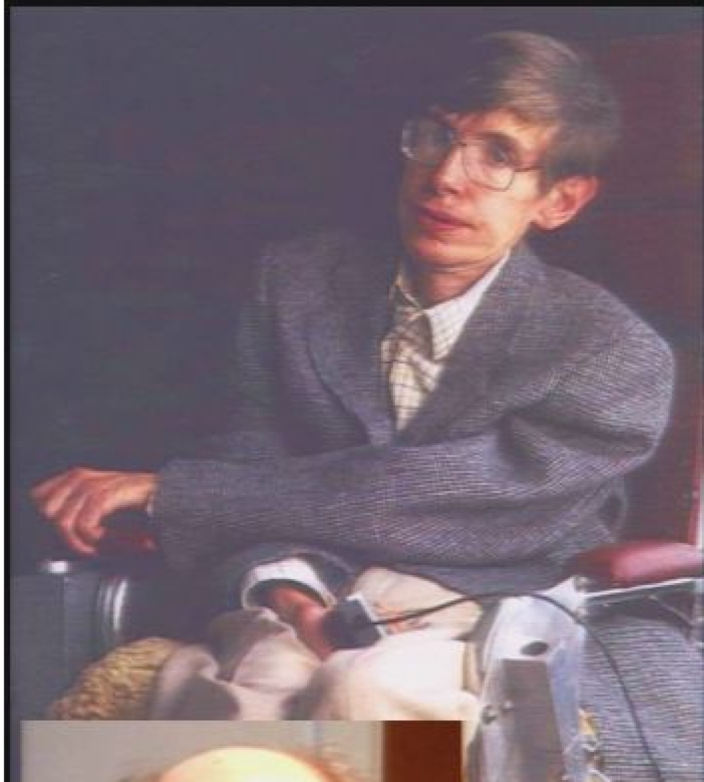
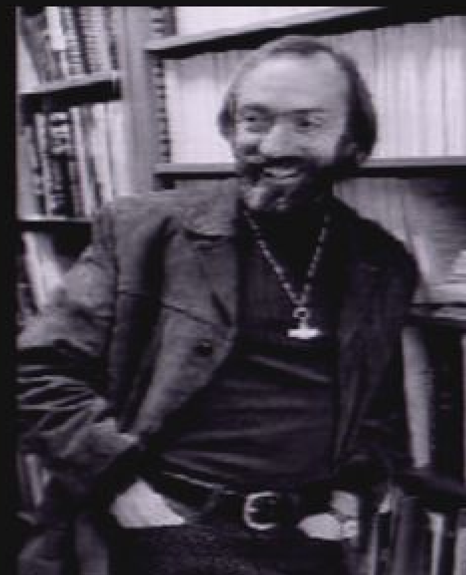


The Blackhole Stars Today

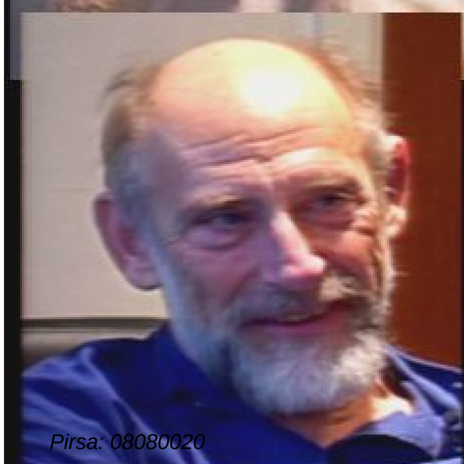


Hawking

Bekenstein



Thorne



Susskind

Werner Israel

Robert Wald