Title: Audience Night

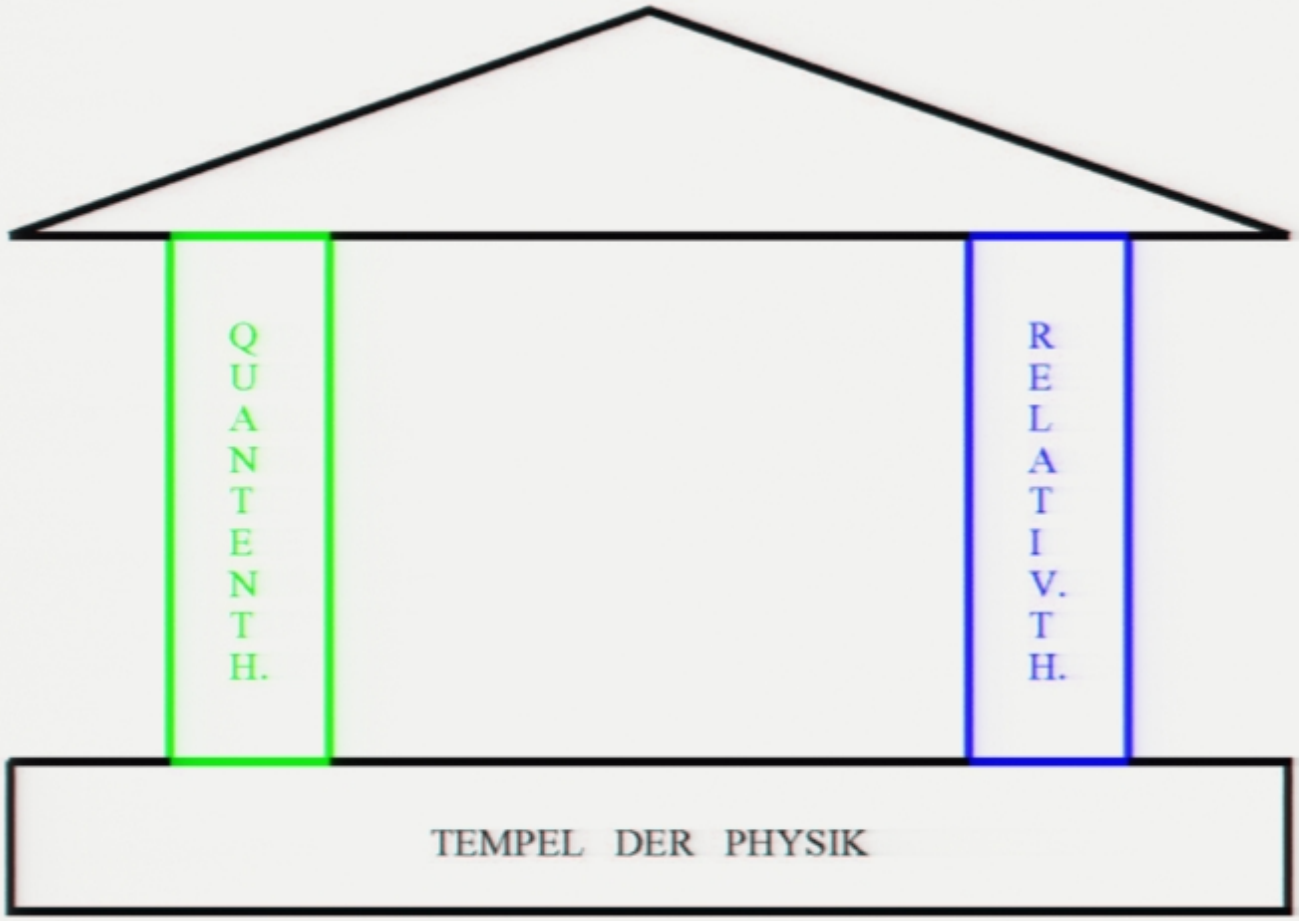
Date: Jun 01, 2005 07:00 PM

URL: http://pirsa.org/05060057

Abstract: The final part of the 04-05 Public Events series turns the spotlight on you. ItÂ’s your chance to ask a panel of Perimeter researchers for their thoughts on a wide variety of scientific topics. <kw>Heisenberg, uncertainty principle, discrete theory, space-time, Thiemann, quantum, relativity, special relativity, quantum theory, Emerson, coherent superpostions, Shrodinger, Sorkin, clock, Freidel, gravity, Romelsberger, Burgess, Einstein, string theory, quantum entanglement </kw>

# Heisenberg Uncertainty Principle from Discrete Theories of Spacetime ?

T. Thiemann, AEI and PI


QUANTENTH.
RELATIV. TH.
TEMPEL DER PHYSIK

## Quantum Theory: Heisenberg Uncertainty

Consider:

I. $X$: Position of a particle.

II. $P$: Momentum of a particle.

III. Set up identical experiments and measure $X, P$ simultaneously.

IV. Get values $X_1,\ X_2,\ ..,\ X_N$ and $P_1,\ P_2,\ ..,\ P_N$

V. Compute the averages

$$< X >:= \frac{1}{N}(X_1 + X_2 + .. + X_N),$$

VI. Compute average errors

$$(\Delta X)^2 := \frac{1}{N}([X_1 - < X >]^2 + .. + [X_N - < X >]^2),$$

No matter how precisely you set up the measurement, you can never beat the Heisenberg uncertainty bound

$$[\Delta X]\ [\Delta P] \geq \hbar$$

Consequence:

Physically, particles always have a spatial extension, point particles are a mathematical abstraction. The spatial extension of a particle of momentum $P$ is of the order of the de Broglie wavelength

$$\Delta X \propto \frac{\hbar}{P}$$

This is, e.g. the best possible resolution of a electron microscope.

## Special Relativity: Energy – Momentum – Mass

Ever faster moving particles become more and more massive:

$$E = Pc = Mc^2$$

## General Relativity: Gravitational Collapse

If you squeeze a lump of energy $E$ into a region of spatial extension smaller than its Schwarzschild radius

$$R = \frac{2GM}{c^2} = \frac{2GE}{c^4}$$

then a black hole forms, i.e. a region in space and time out of which no information can escape.

## Quantum General Relativity: Discrete Spacetime

Increasing the energy of a particle decreases its de Broglie wavelength

$$\Delta X \propto \frac{\hbar}{P} = \frac{\hbar c}{E}$$

while its Schwarzschild radius increases

$$R = \frac{2GE}{c^4}$$

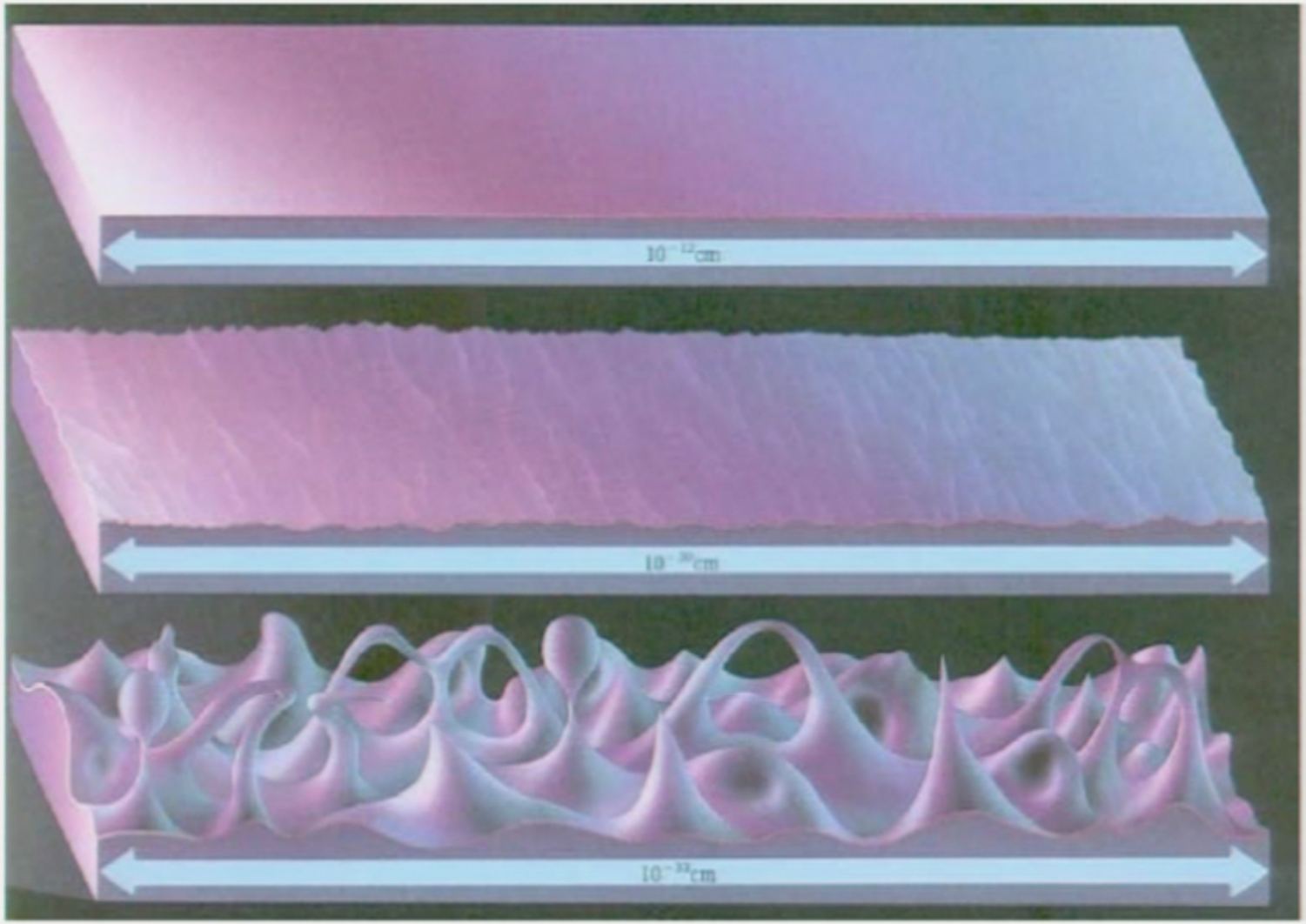
so that eventually a tiny black hole must form at the Planck length

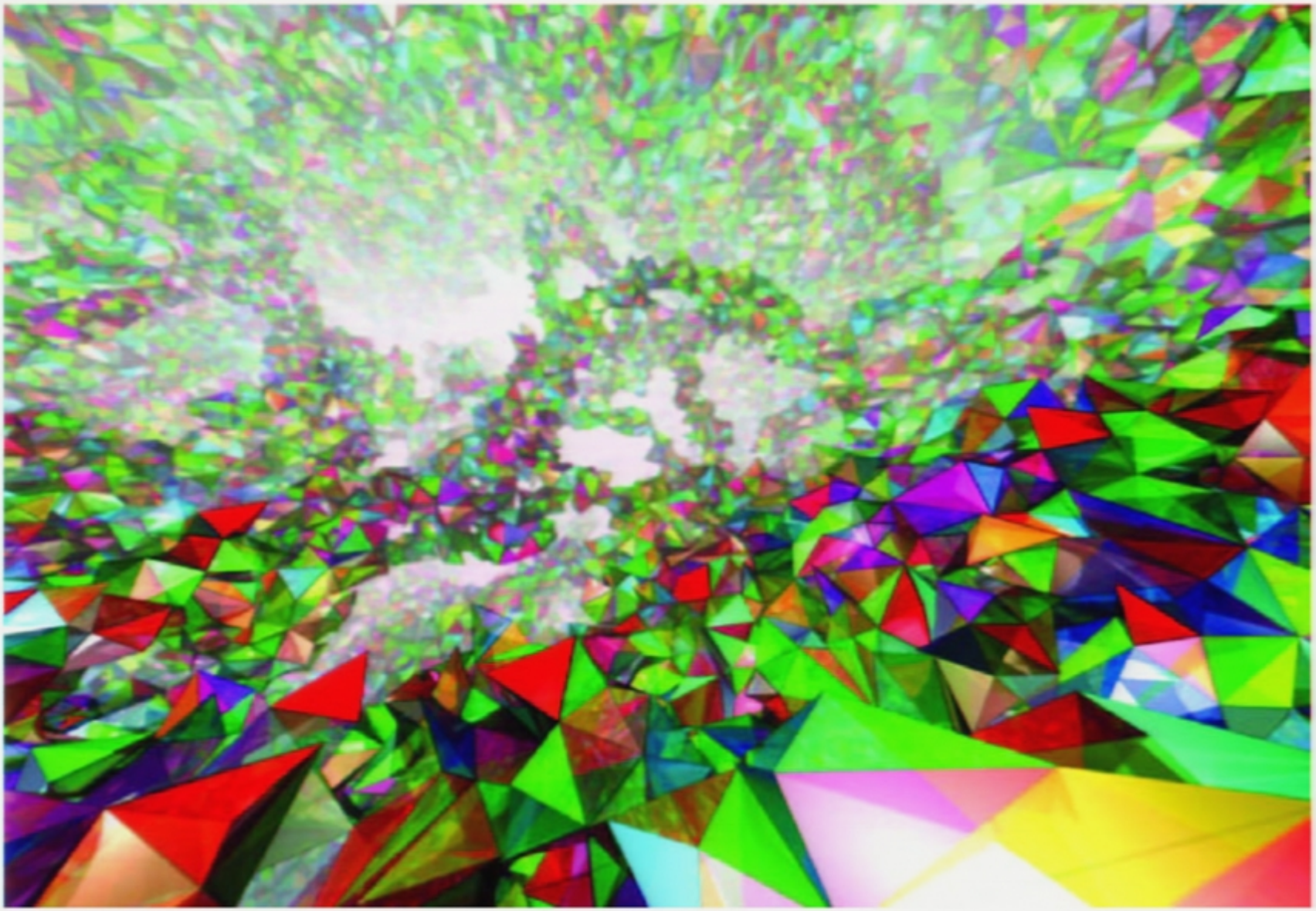
$$\ell_P \approx \sqrt{\frac{\hbar G}{c^3}} \approx 10^{-33} cm$$

which, according to Heisenberg, immediately decays within a Planck time

$$\tau_P \propto \hbar/E = \ell_P/c \approx 10^{-43} s$$

It is principally impossible to build a microscope with a better resolution than $\ell_P$.
Physically then, spacetime consists of "atoms", i.e. spatial length and temporal duration can change only in discrete steps $\propto \ell_P,\ \tau_P$.


$10^{-12}$cm
$10^{-30}$cm
$10^{-33}$cm



Joseph Emerson
Perimeter Institute

# Quantum Theory

**Quantum theory** exhibits many **unusual features** in its description of fundamental properties:

The dynamical properties of elementary particles are described by a **wave-function**, given by the fundamental **Schroedinger wave-equation**, which is analogous to the equations describing water and sound waves (*particle-wave duality*).

**Measurement** is associated with a **necessary disturbance** to the system under observation (*Heisenberg's uncertainty principle*).

Generally only **probabilistic** predictions are possible (*Born's rule*).

# Coherent Superpositions

The feature most relevant to the question being asked:

> **Quantum theory admits the possibility of *coherent superpositions* of observable states.**

*What are coherent superpositions?*

Consider two **position states** of a particle: {**up**, **down**}

The coherent superposition state '**up + down**' means that the particle will sometimes be found to be '**up**' and sometimes '**down**'.

However, the coherent superposition state '**up + down**' is *measurably different* from the *classical* state '**either up or down**'.

# Coherent Superpositions

Coherent superposition states such as '**up + down**' have important properties that are impossible for the state '**either up or down**':

They produce interference patterns (**wave-like phenomena**) for individual particles whose paths are separated and recombined!

- Anton Zeilinger has described to us how these interference effects can be observed even for large macromolecules.

The creation of such states is essential for the **advantages of quantum communication and quantum computation**

- Ray Laflamme has described to us how these states can be created in the lab in prototype quantum computers.

# Coherent Superpositions

What are coherent superpositions *really* like?

***This* is the fundamental question of interpretation!**

One conception is that a coherent superposition means that the particles possess *both* properties at once, for example, the idea that a particle can be in *two places at once*.

This idea implies some kind of **'blurred reality'** for microscopic particles.

However, this idea of a 'blurred reality' leads to other conceptual difficulties…

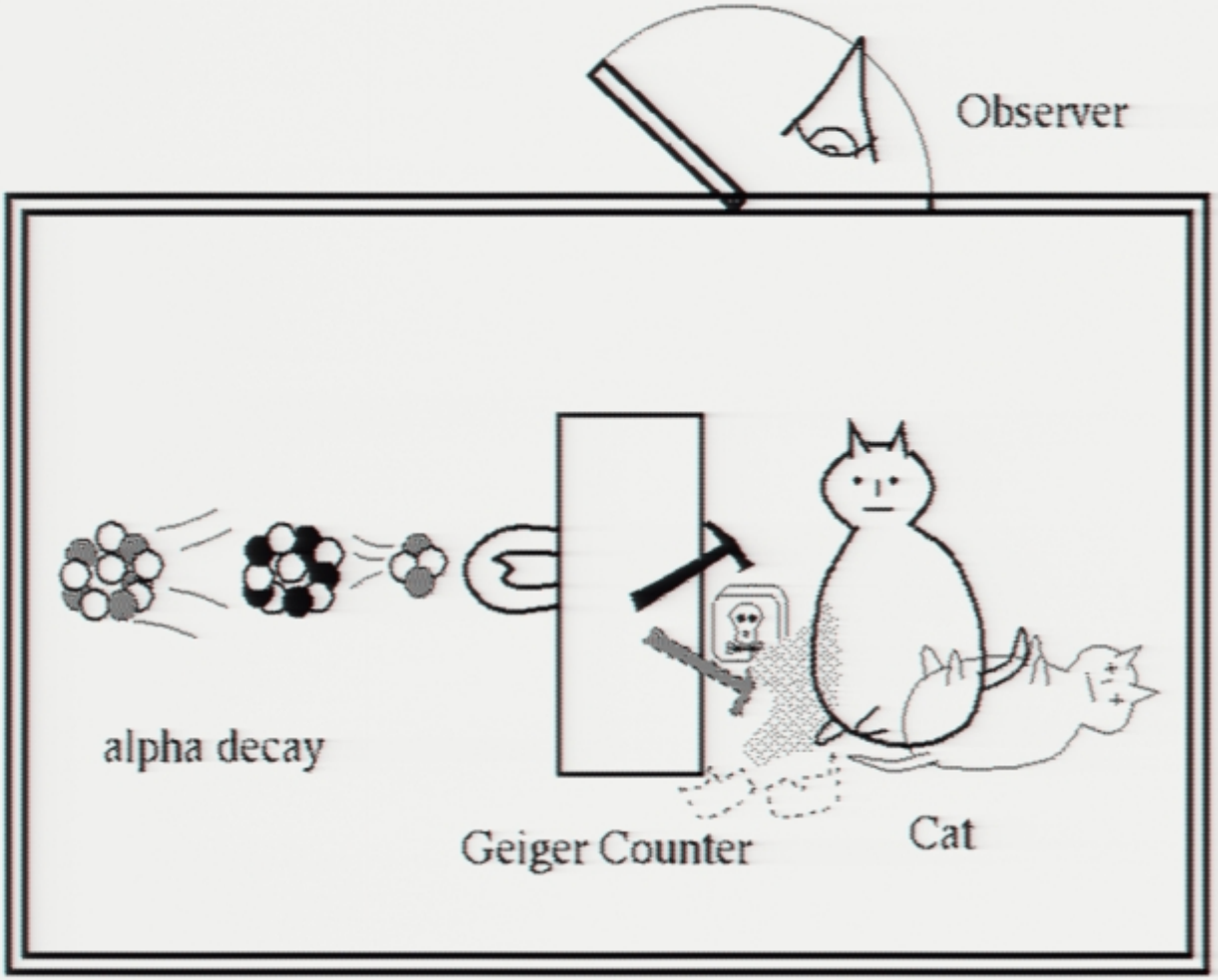
# Shroedinger's Famous "Cat"

**Problem 1:** The "blurring" of reality due to coherent superpositions must also occur at the macroscopic level (prior to observation) !

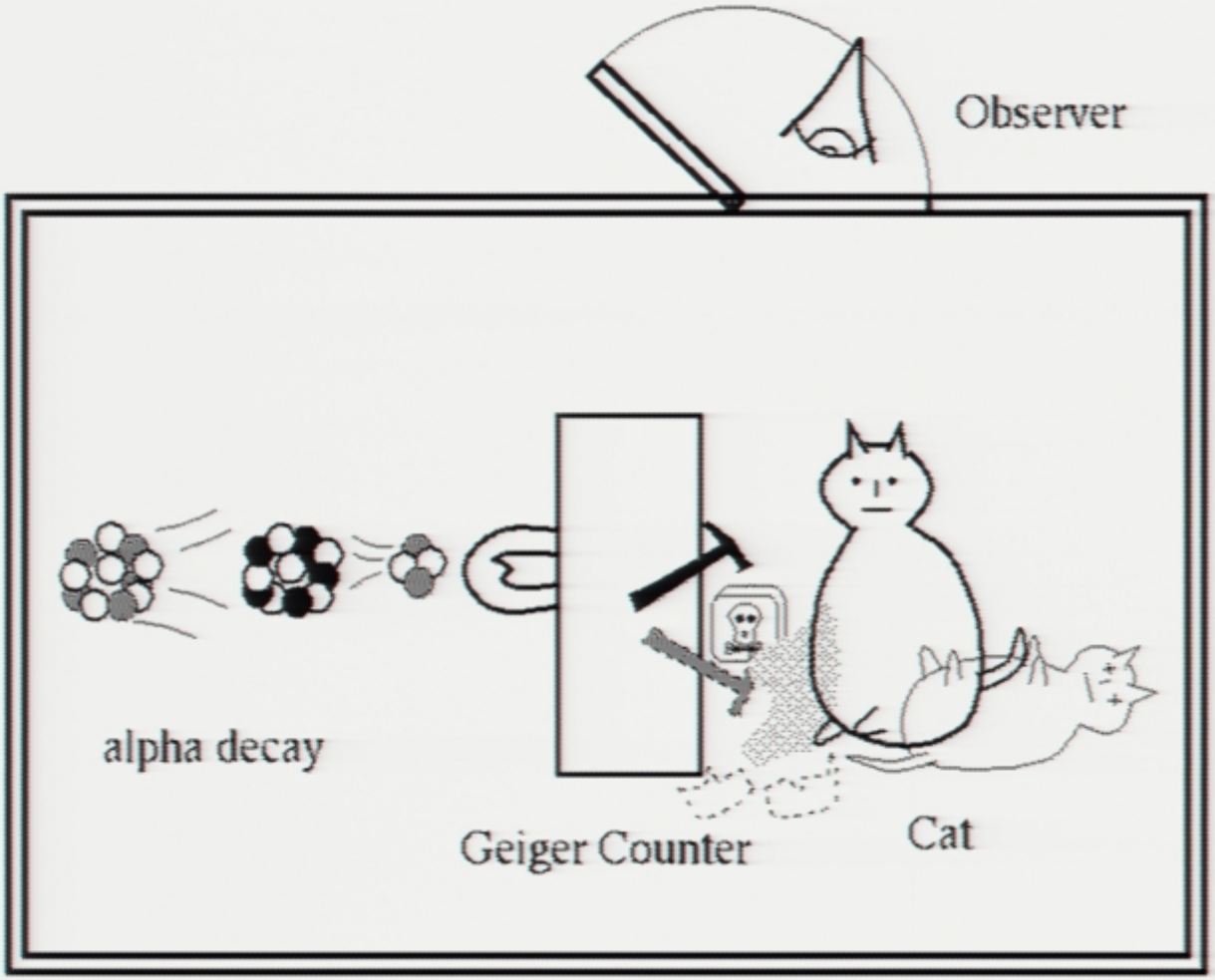
*"One can even set up quite ridiculous cases… [ Imagine a cat in a sealed box with a small mechanism which releases hydrocyanic acid only on the condition of one of two equally probable atomic states initially prepared in a coherent superposition ]… The wave-function of the entire system would express this by having in it the living and the dead cat (pardon the expression) mixed or smeared out in equal parts."*

Schrodinger (1935)

# Shroedinger's Famous "Cat"



# Shroedinger's Famous "Cat"




**Only a "thought" experiment!**

# The Collapse of the Wave-Function

**Problem 2: *Observed* properties are never 'blurred', so how and why does the 'blurriness' disappear upon observation?**

When John von Neumann developed the first full axiomatization of the new quantum theory in 1932, he found it necessary to postulate a ***discontinuous collapse*** of the wave-function to one of the observable states whenever a ***'measurement'*** takes place.

*"We have then answered the question as to what happens in the measurement of [an observable]. **To be sure, the 'how' remains unexplained for the present.** This discontinuous transition from the wave-function into one of [the observable states] is certainly not of the type described by the time-dependent Schroedinger equation."*

von Neumann (1932)

# John Bell's Quip

**Tonight's question: how can it be that the human *act of observation* can produce a change to the cat's state of being?**

**John Bell**, who demonstrated the non-locality of entangled states, asked, with his typical wit, a similar question:

# John Bell's Quip

**Tonight's question: how can it be that the human *act of observation* can produce a change to the cat's state of being?**

**John Bell**, who demonstrated the non-locality of entangled states, asked, with his typical wit, a similar question:

> *"What exactly qualifies some physical system to play the role of 'measurer'? Was the wave-function of the world waiting to jump for thousands of millions of years until a single-celled living creature appeared? Or did it have to wait a little longer, for some better qualified system … with a PhD?"*
>
> John Bell (1990)

# Opinion of the Man of the Year

For Einstein, these conceptual puzzles arise from the **incorrect assumption** that the 'blurred' quantum states provide a complete description of reality:

*"One arrives at very implausible theoretical conceptions, if one attempts to maintain the thesis that the statistical quantum theory is in principle capable of producing a complete description of an individual physical system. I am convinced that everyone who will take the trouble to carry through such reflections conscientiously will find himself finally driven to [ the view that the wave-function is not to be understood as the complete description of a single system ] … it appears unavoidable to look elsewhere for a complete description of the individual system … I am rather firmly convinced that the development of theoretical physics will be of that type; but the path will be lengthy and difficult."*

A. Einstein

# Current Approaches

Efforts to find a theoretical and conceptual framework which can avoid these difficulties is a subject of **active research** at the Perimeter Institute. Some current approaches are:

**Many-worlds Interpretation:** the different properties in coherent superpositions are not a blurring of reality in this world, but correspond to parallel worlds. There is a world in which the cat is found dead and one in which the cat is found alive.

**Statistical or Informational Interpretations:** the blurriness associated with coherent superpositions is not a blurriness of reality but a *blurriness of our knowledge of reality*. But then how can we explain the (wavelike) interference effects, and other technical constraints, with any additional 'hidden variables' which are needed to specify the micro-reality?

# Current Approaches

Efforts to find a theoretical and conceptual framework which can avoid these difficulties is a subject of **active research** at the Perimeter Institute. Some current approaches are:

**Many-worlds Interpretation:** the different properties in coherent superpositions are not a blurring of reality in this world, but correspond to parallel worlds. There is a world in which the cat is found dead and one in which the cat is found alive.

**Statistical or Informational Interpretations:** the blurriness associated with coherent superpositions is not a blurriness of reality but a *blurriness of our knowledge of reality*. But then how can we explain the (wavelike) interference effects, and other technical constraints, with any additional 'hidden variables' which are needed to specify the micro-reality?


desert.mov
File Edit Movie Favorites Window Help
C
1 m/s
Highway
✓ Aberration
✓ Doppler
✓ Intensity
00:00:00


desert.mov
File Edit Movie Favorites Window Help
0.000c
γ = 1
00:00:00


desert.mov
File Edit Movie Favorites Window Help
0.944c
γ=3.03
00:00:37

A reference frame for what I will say

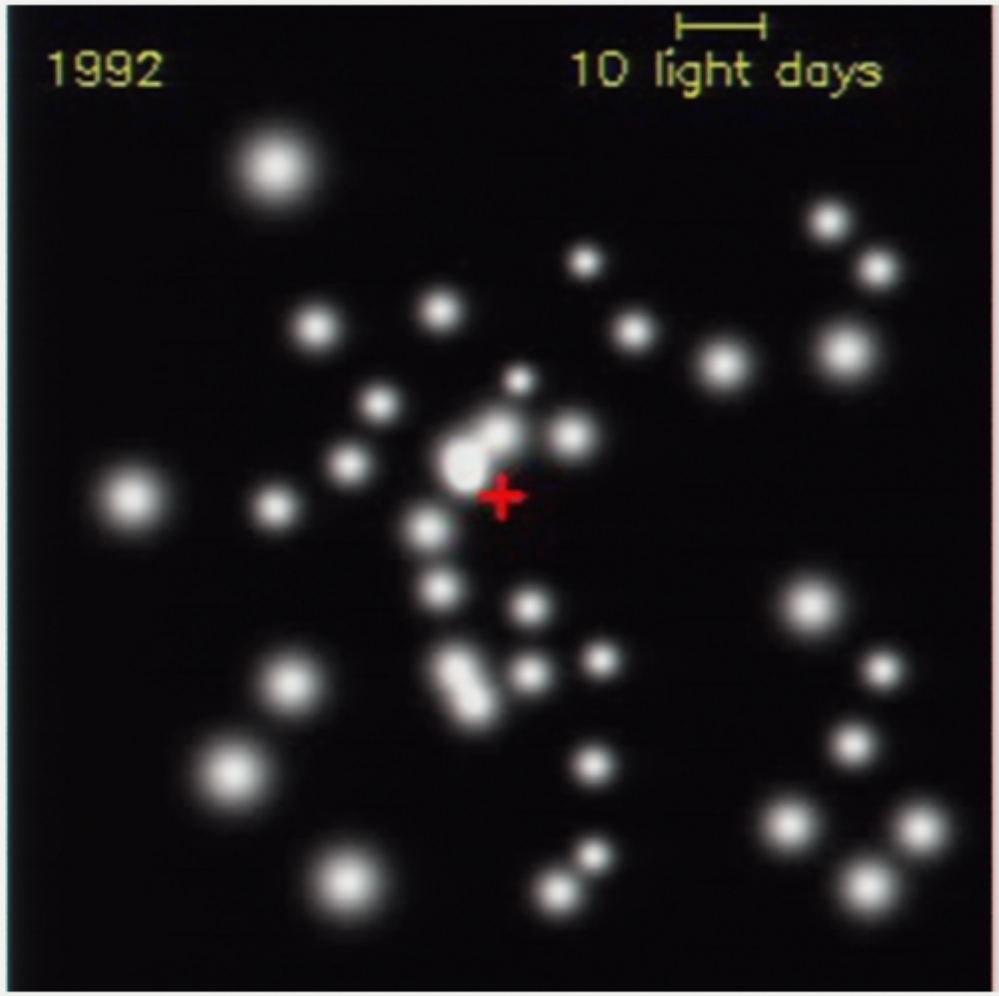
APPROACHING CLOCK APPEARS TO SPEED UP, APPROACHING BODY TO LENGTHEN

UNIVERSE WOULD NOT LOOK FROZEN OR THIN AS A SHEET OF PAPER

A STAR IS CLOSER THAN YESTERDAY

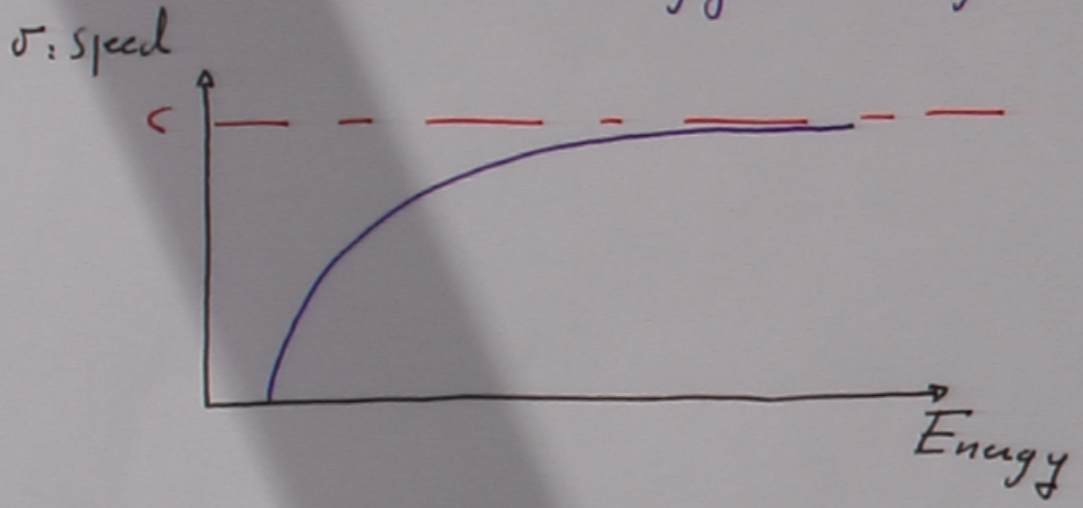
AN EVENT IN OUR EYE IS IN IMMEDIATE CAUSAL CONTACT WITH AN EVENT IN THE STAR


desert.mov
File Edit Movie Favorites Window Help
0.944c
γ=3.03
00:00:37


1992
10 light days

# Special Relativity

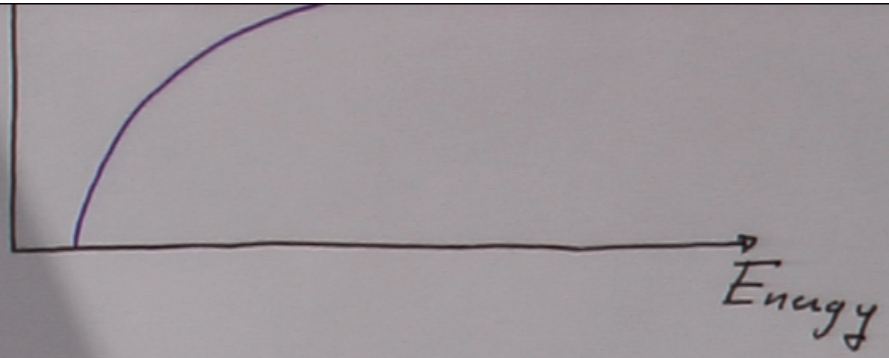
No massive object can go faster than the speed of light no matter how much energy this object is given.




- At rest $v = 0$ $\quad E = mc^2$

- moving $v \neq 0$ $\quad E = m_v c^2 = \dfrac{m}{\sqrt{1 - \frac{v^2}{c^2}}} c^2$

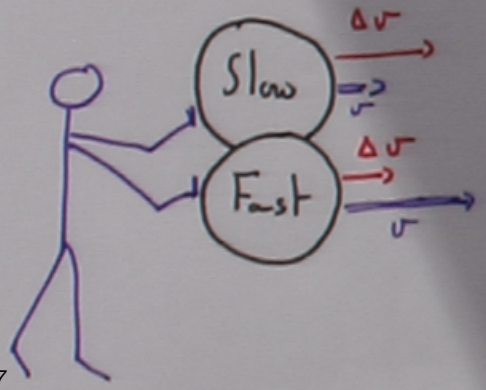
$m_v$ : rest mass + Kinetic energy : inertial mass




- At rest $v = 0$ $\quad E = mc^2$

- moving $v \neq 0$ $\quad E = m_v c^2 = \dfrac{m}{\sqrt{1 - \frac{v^2}{c^2}}} c^2$

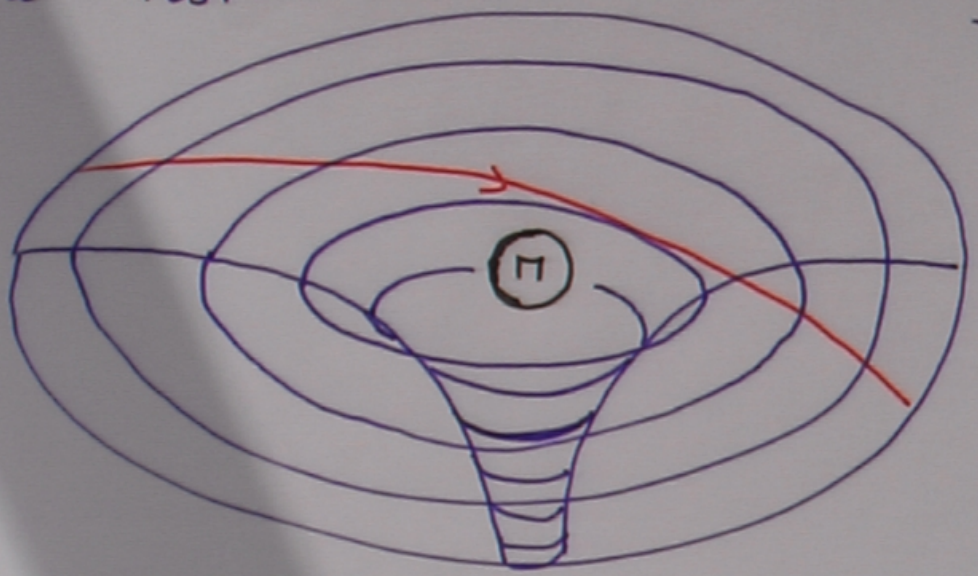
$m_v$ : rest mass + Kinetic energy : inertial mass




$$m_v = \frac{\Delta \text{ Force}}{\Delta \text{ acceleration}}$$

Special Relativity

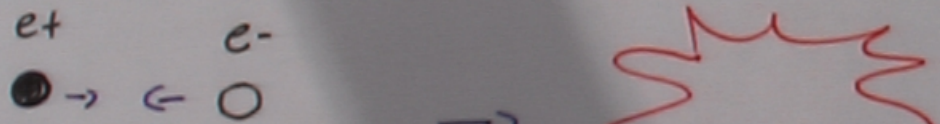
- Mass at rest

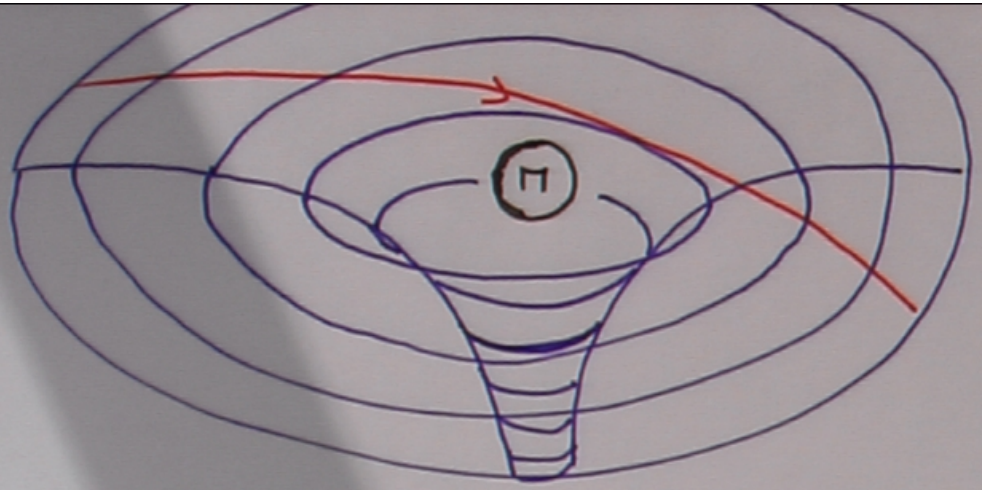



→ warping of spacetime

- Curvature and gravity are generated by any form of energy.

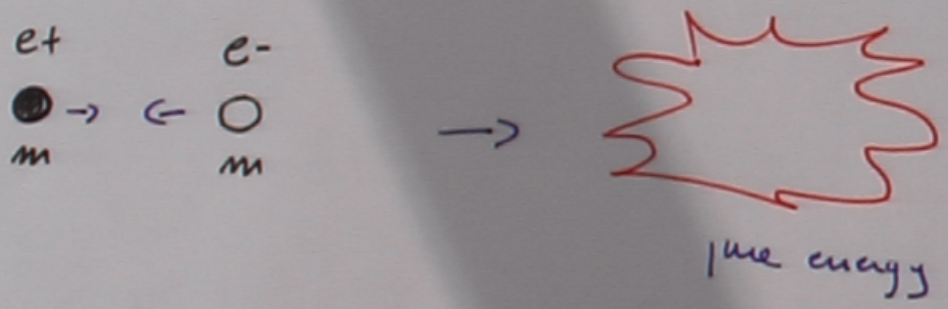
Special relativity + Quantum mechanics → antiparticle

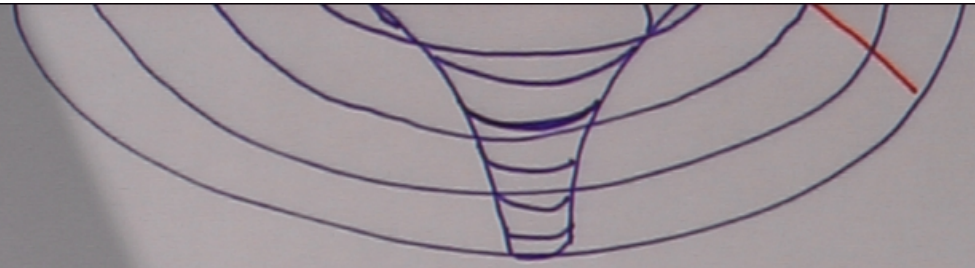




Curvature and gravity are generated by any form of energy.

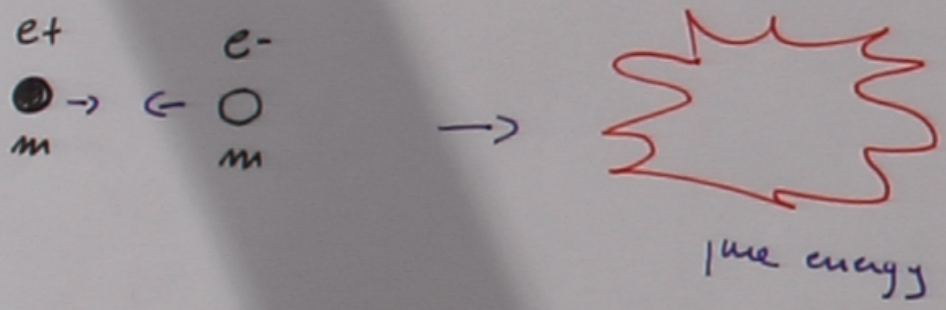
Special relativity + Quantum mechanics → antiparticle



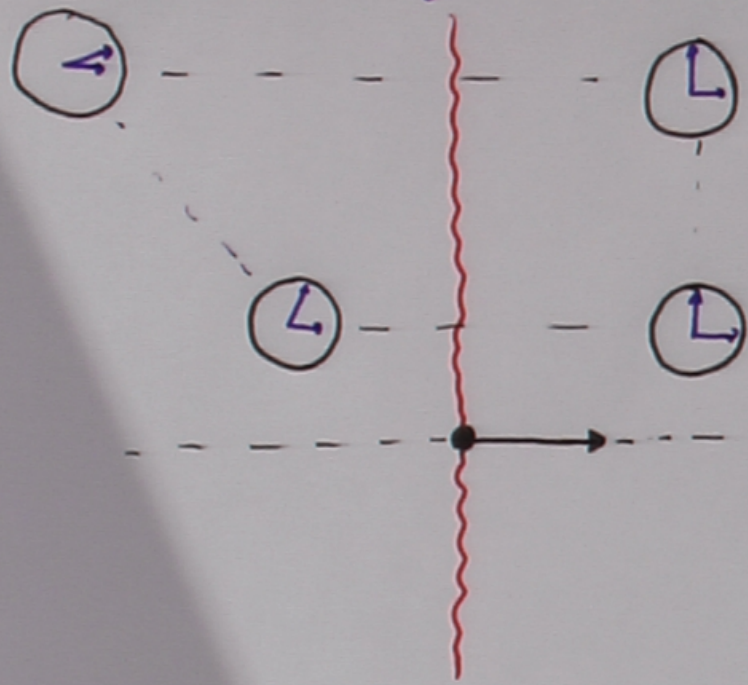


- Curvature and gravity are generated by any form of energy.

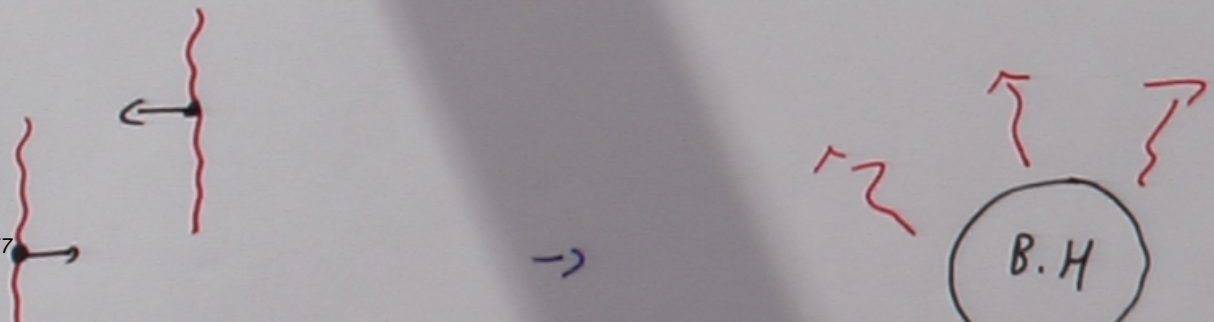
Special relativity + Quantum mechanics → antiparticle



• Mass moving at extremely high velocity: shock wave

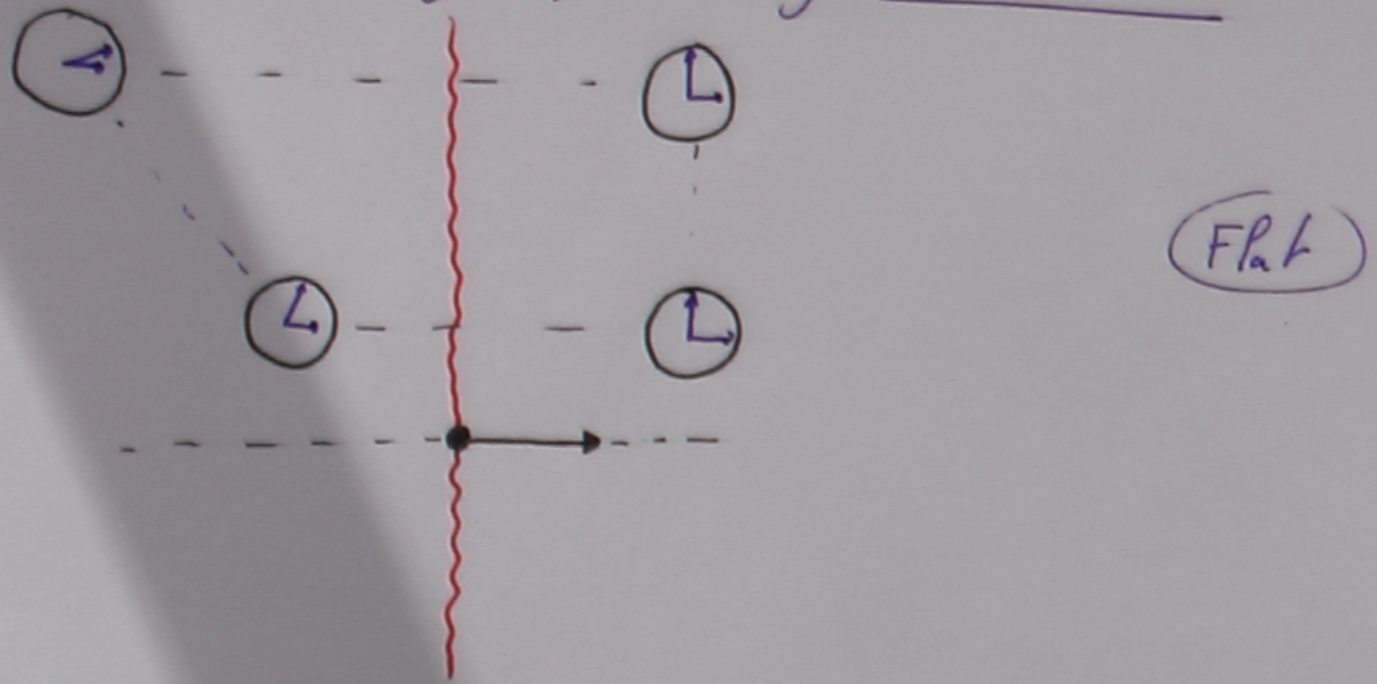



• Warping:



# General Relativity

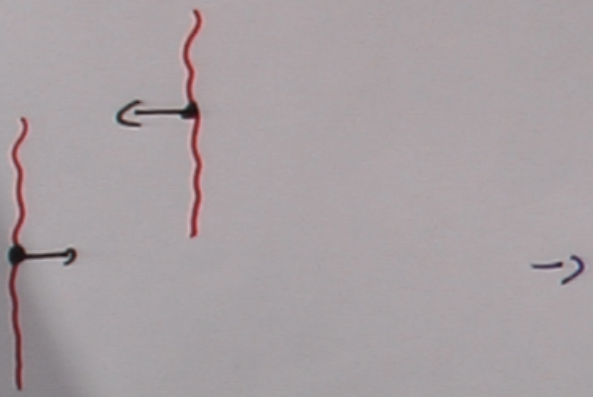
- Mass moving at extremely high velocity: shock wave

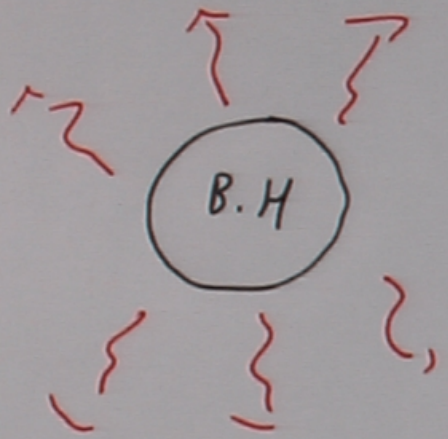





- Warping:

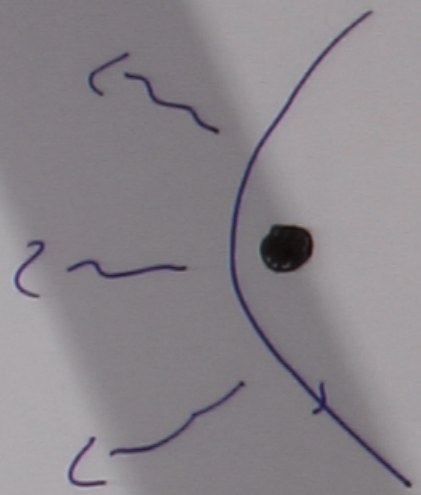
• Warping:

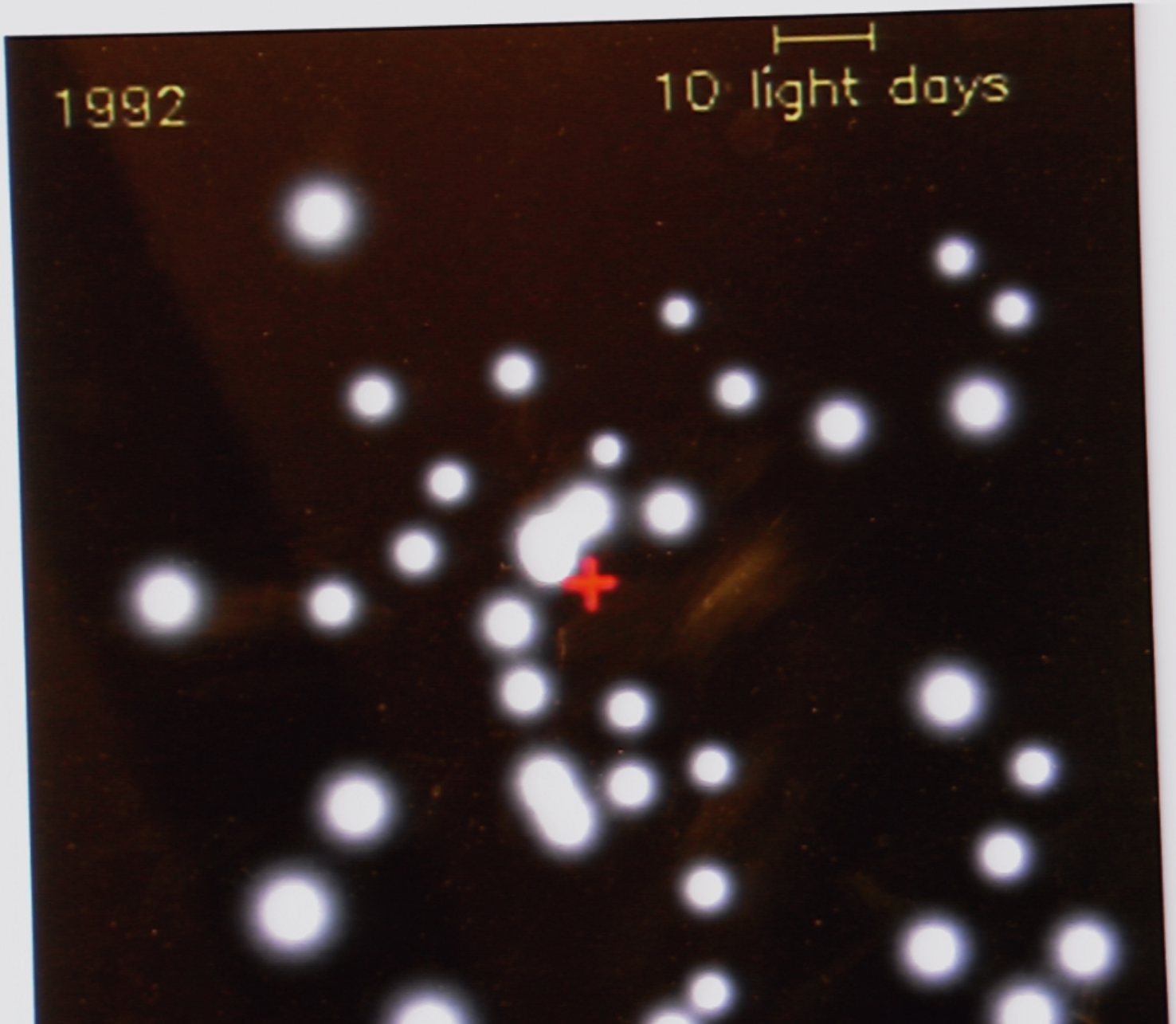


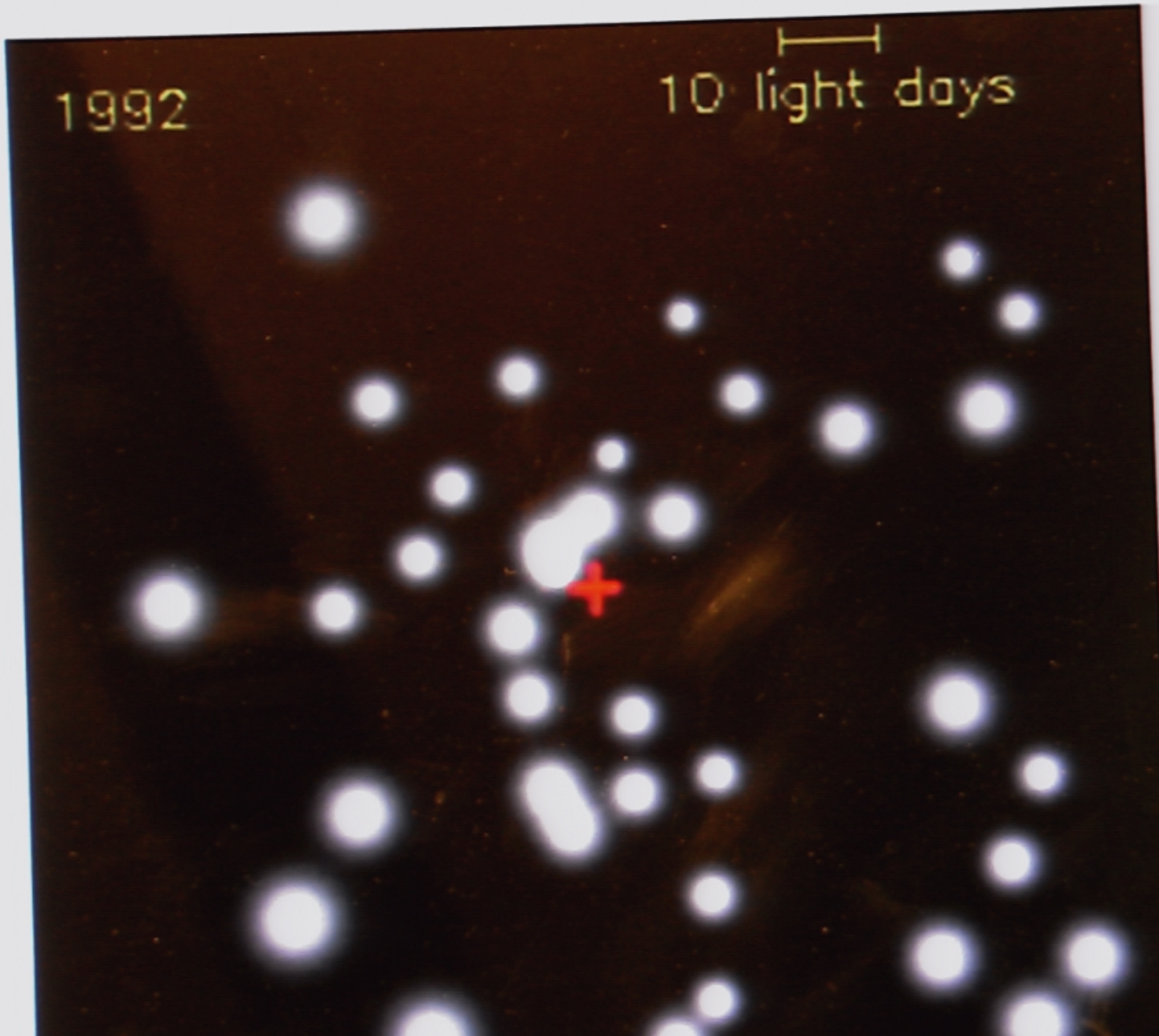


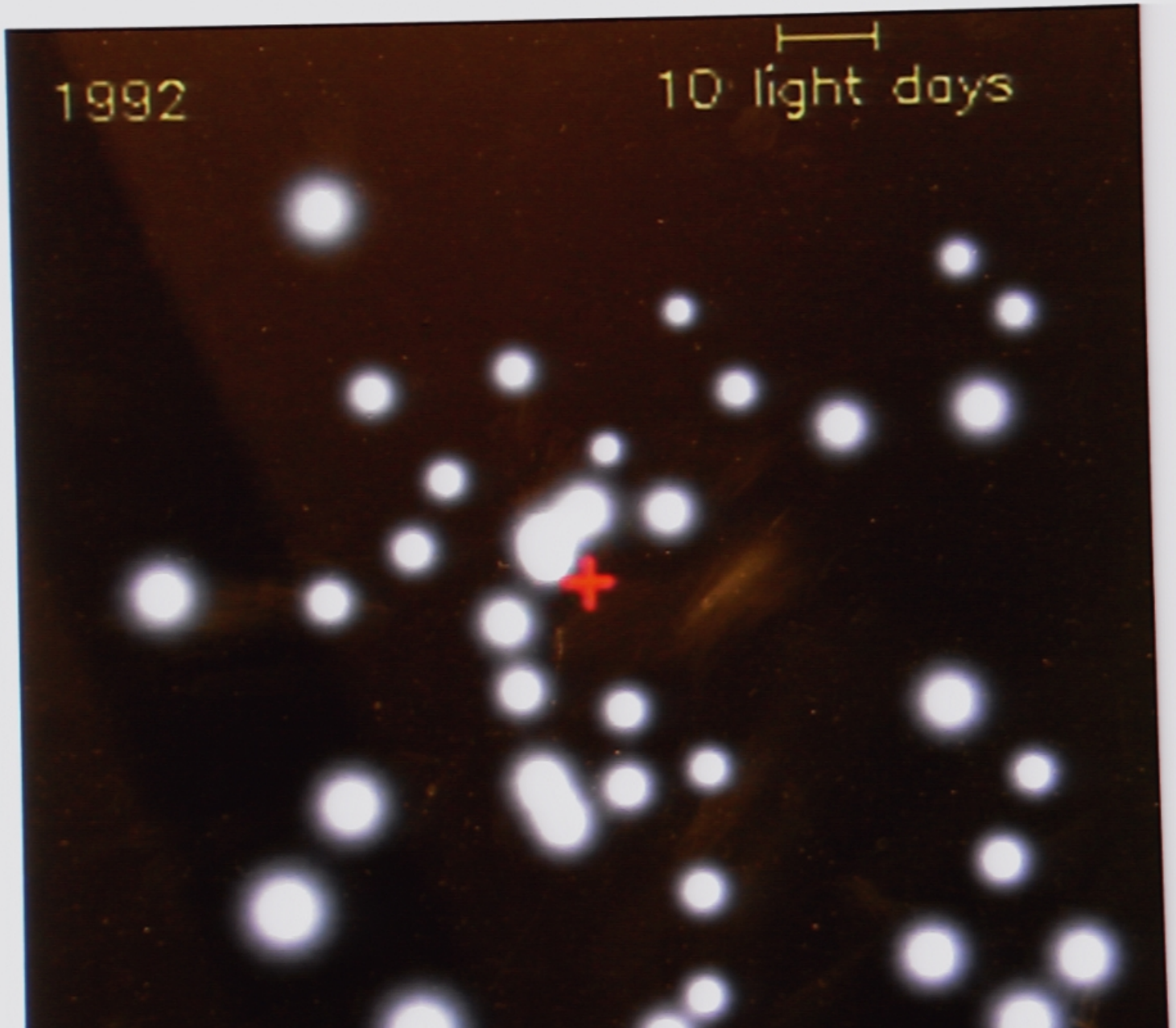

Blackhole formation
+ gravitational radiation.

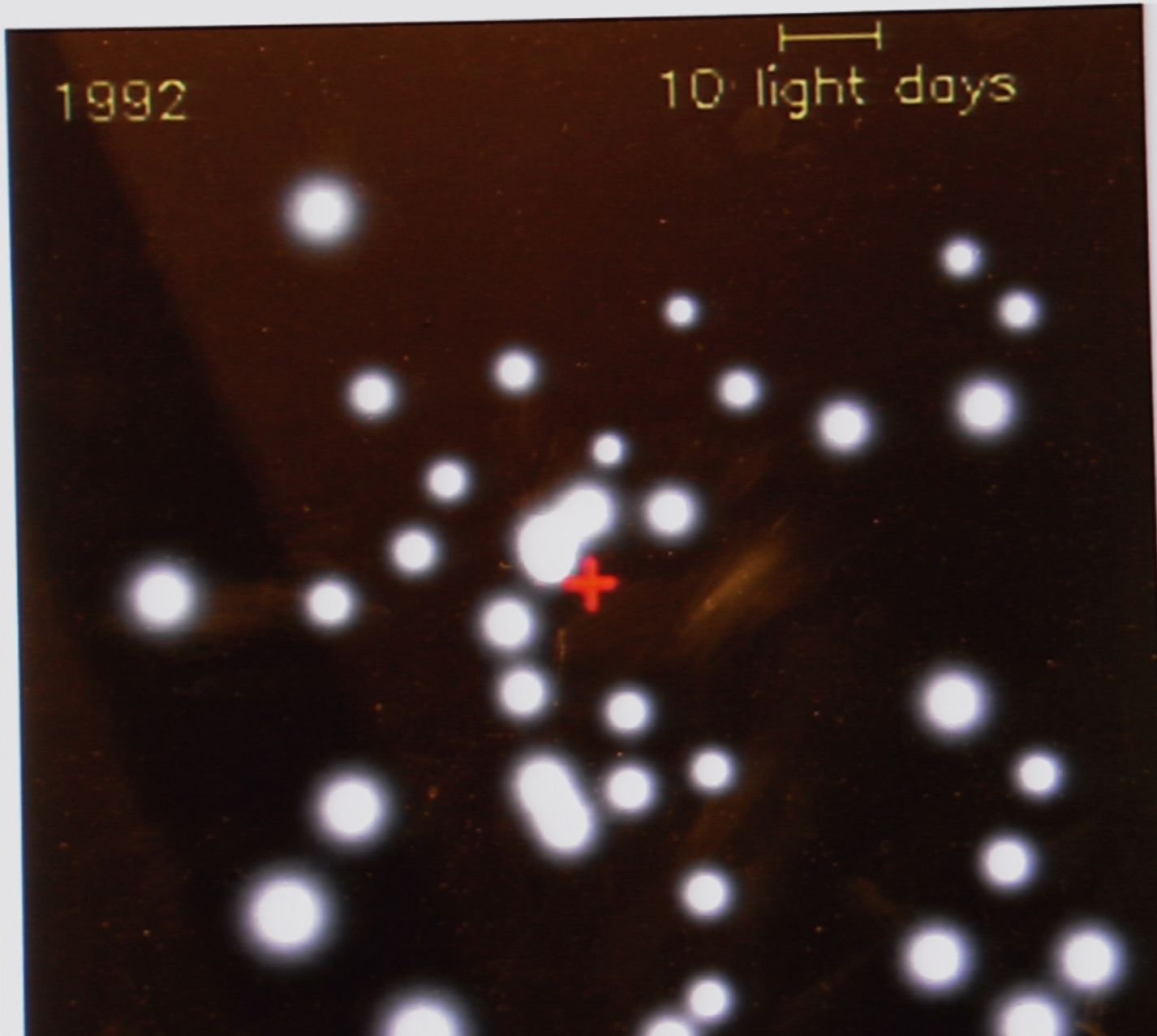
• In a realistic system: Star accelerated by a Black Hole will emit gravitational radiation

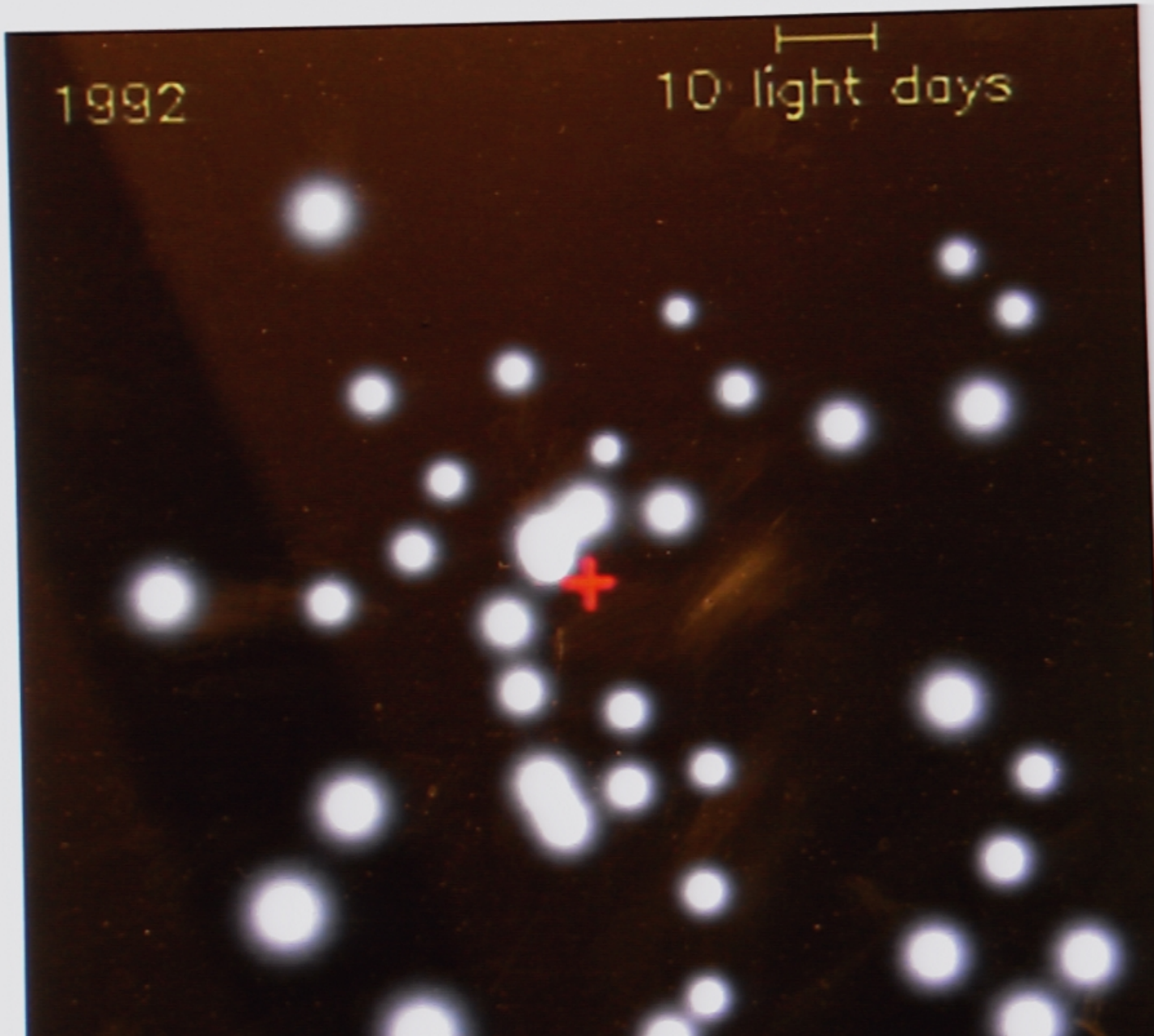


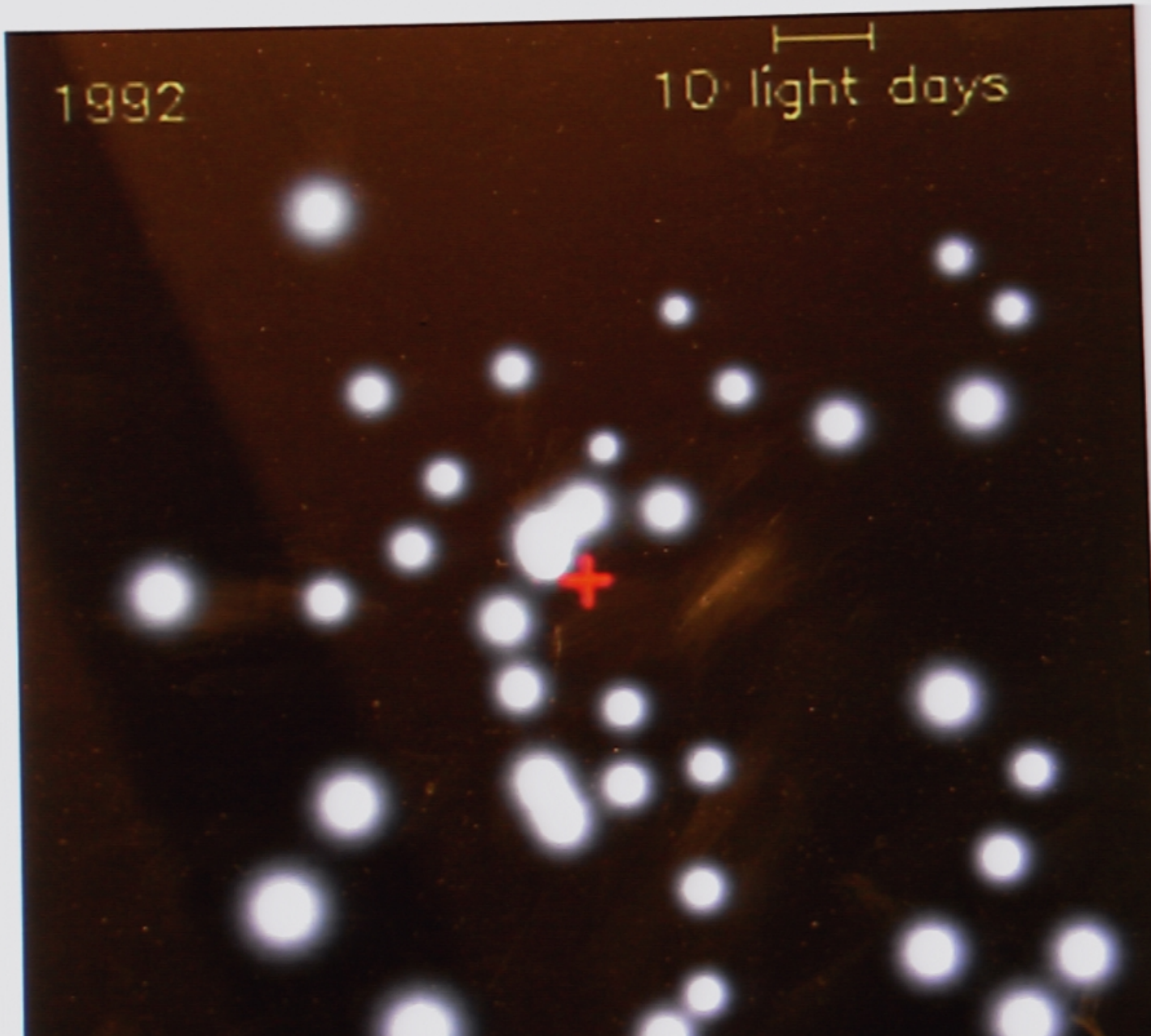

1992
10 light days

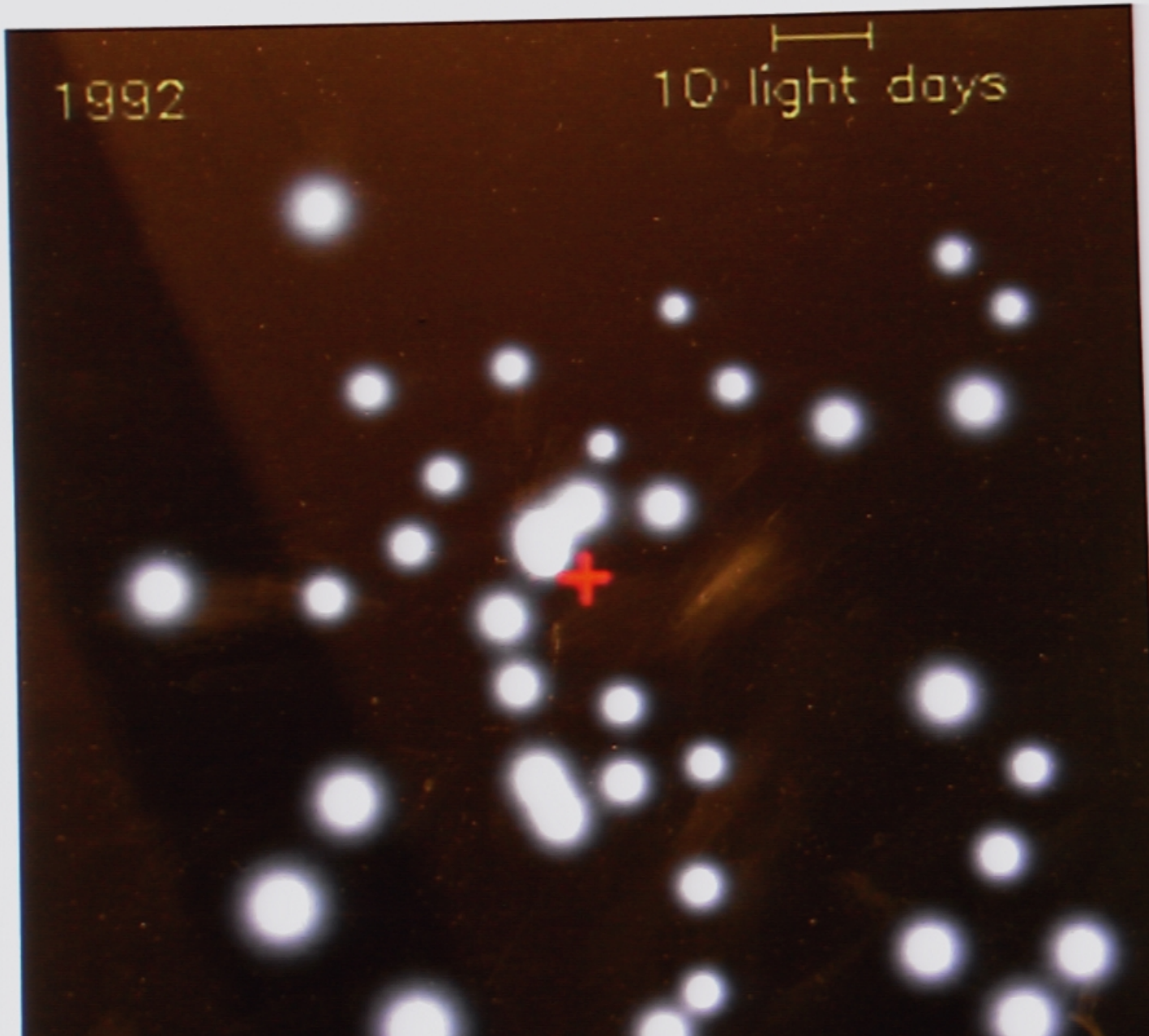

1992
10 light days

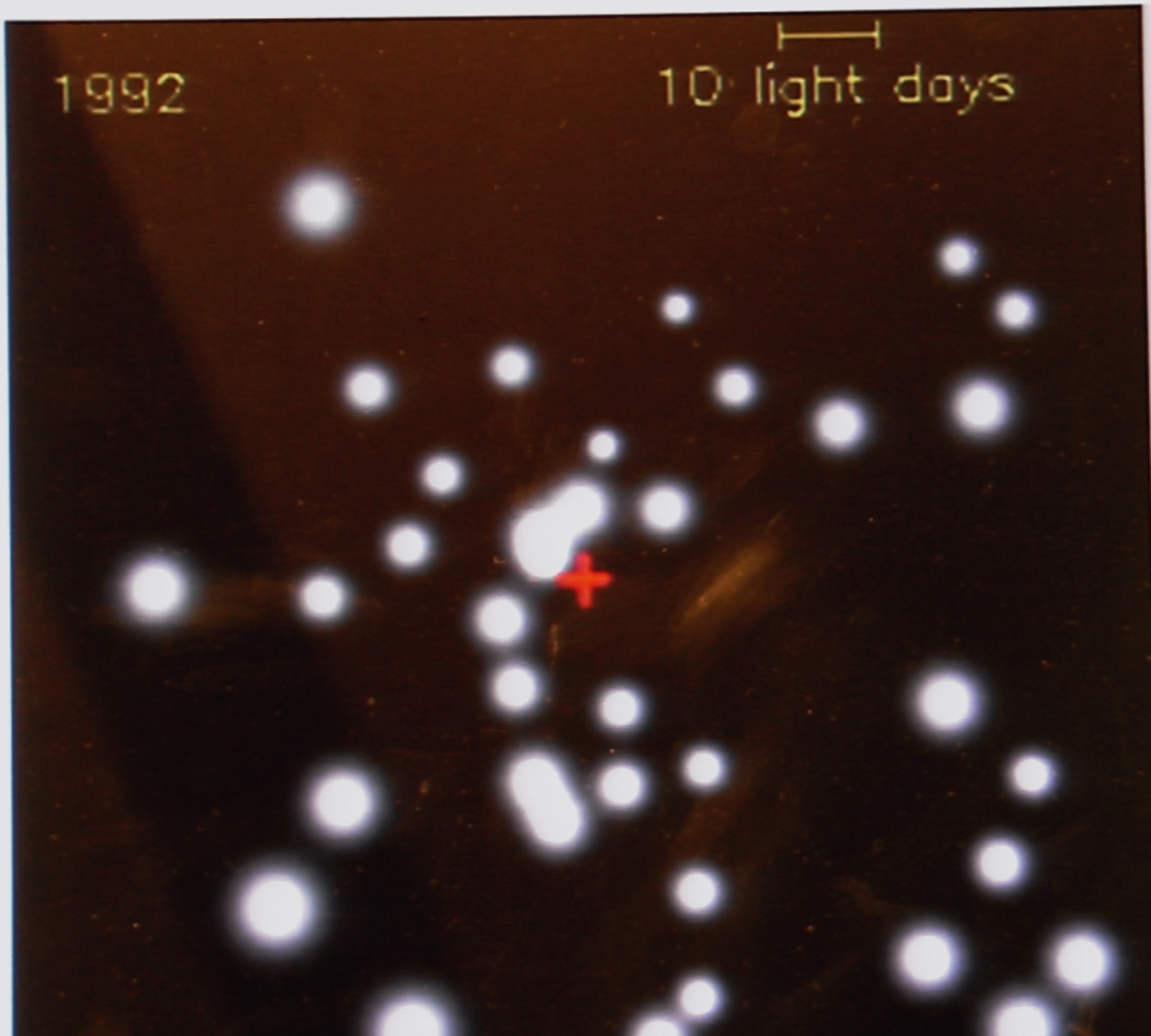

1992
10 light days

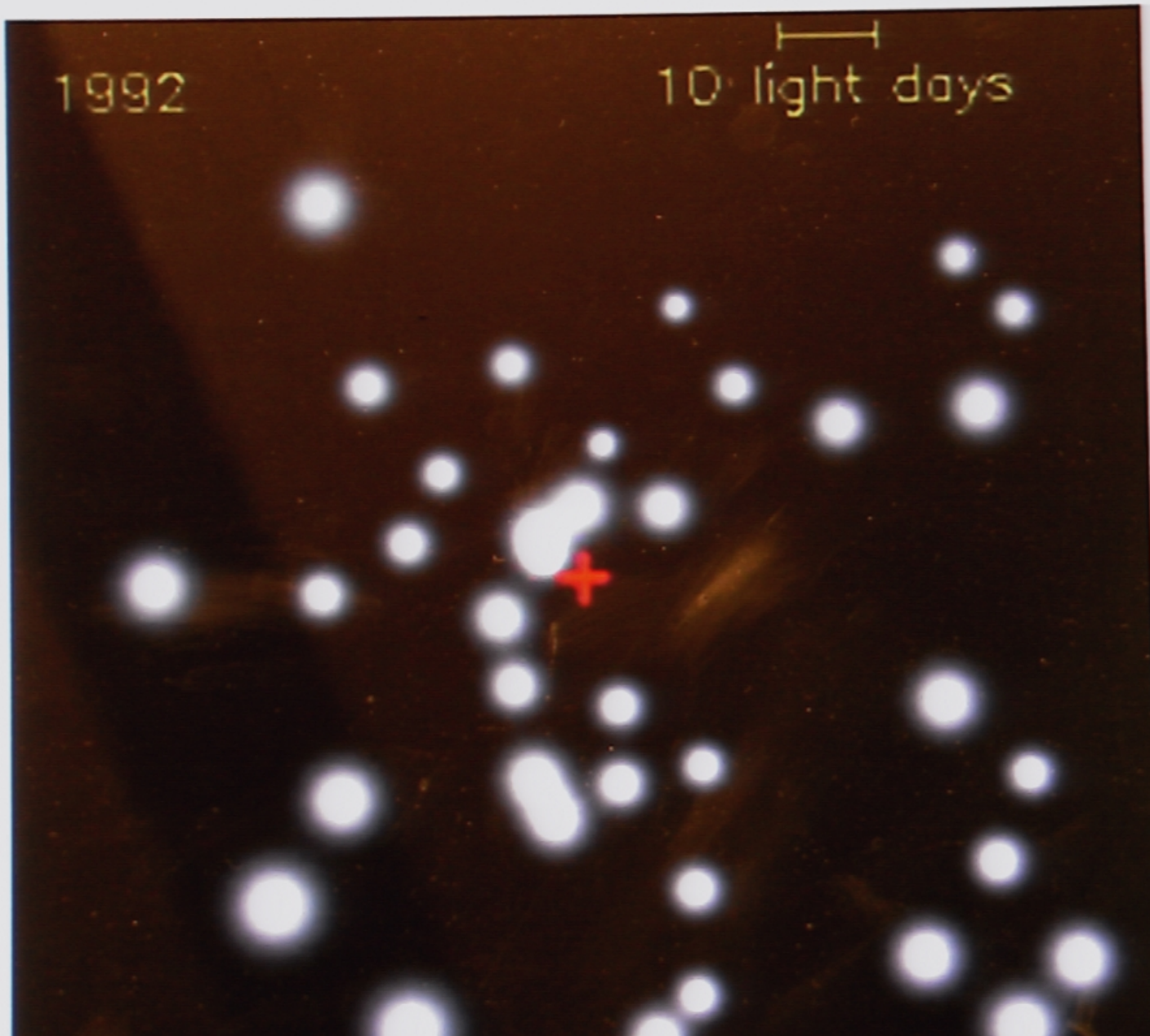

1992
10 light days


1992
10 light days

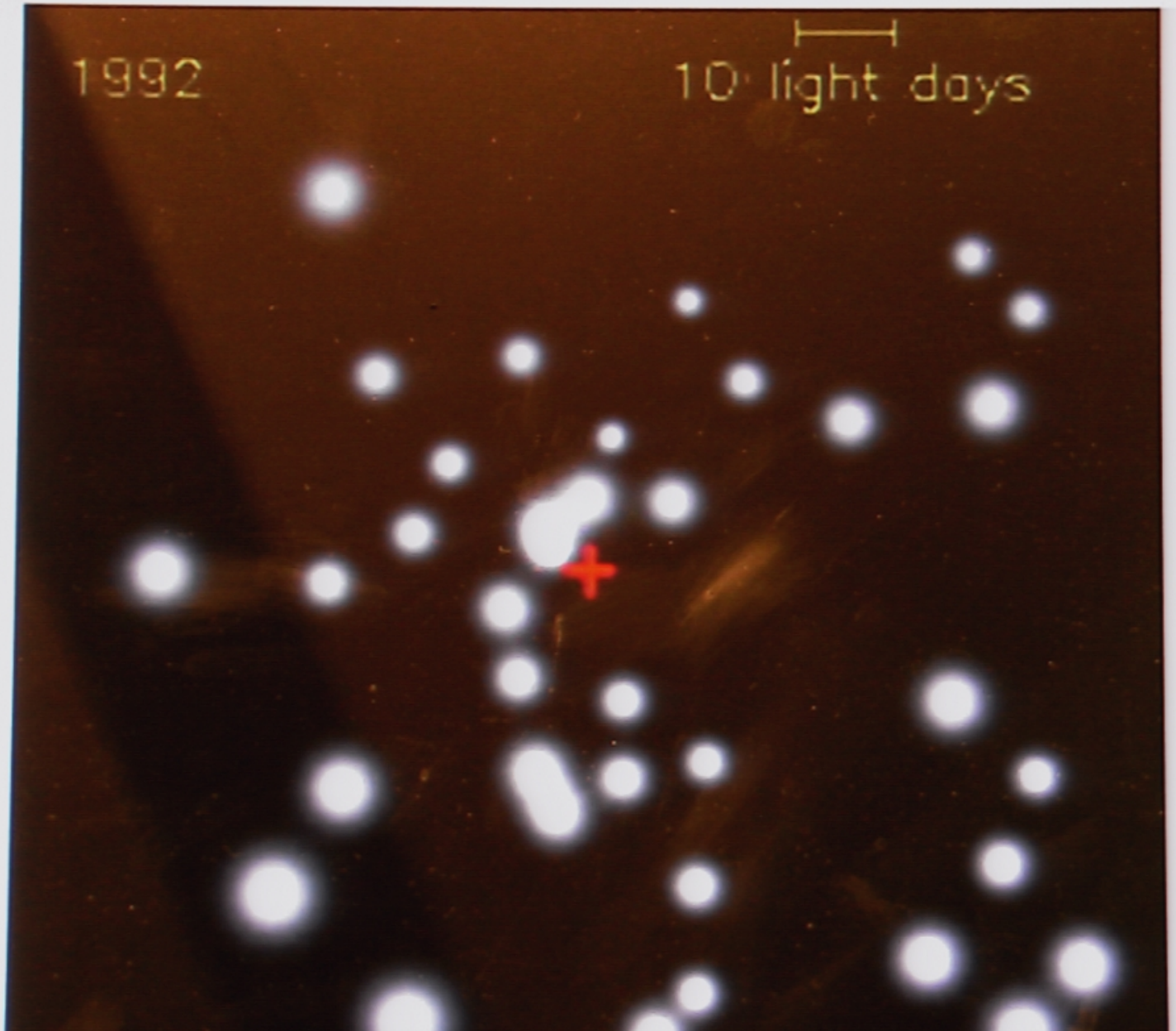

1992
10 light days

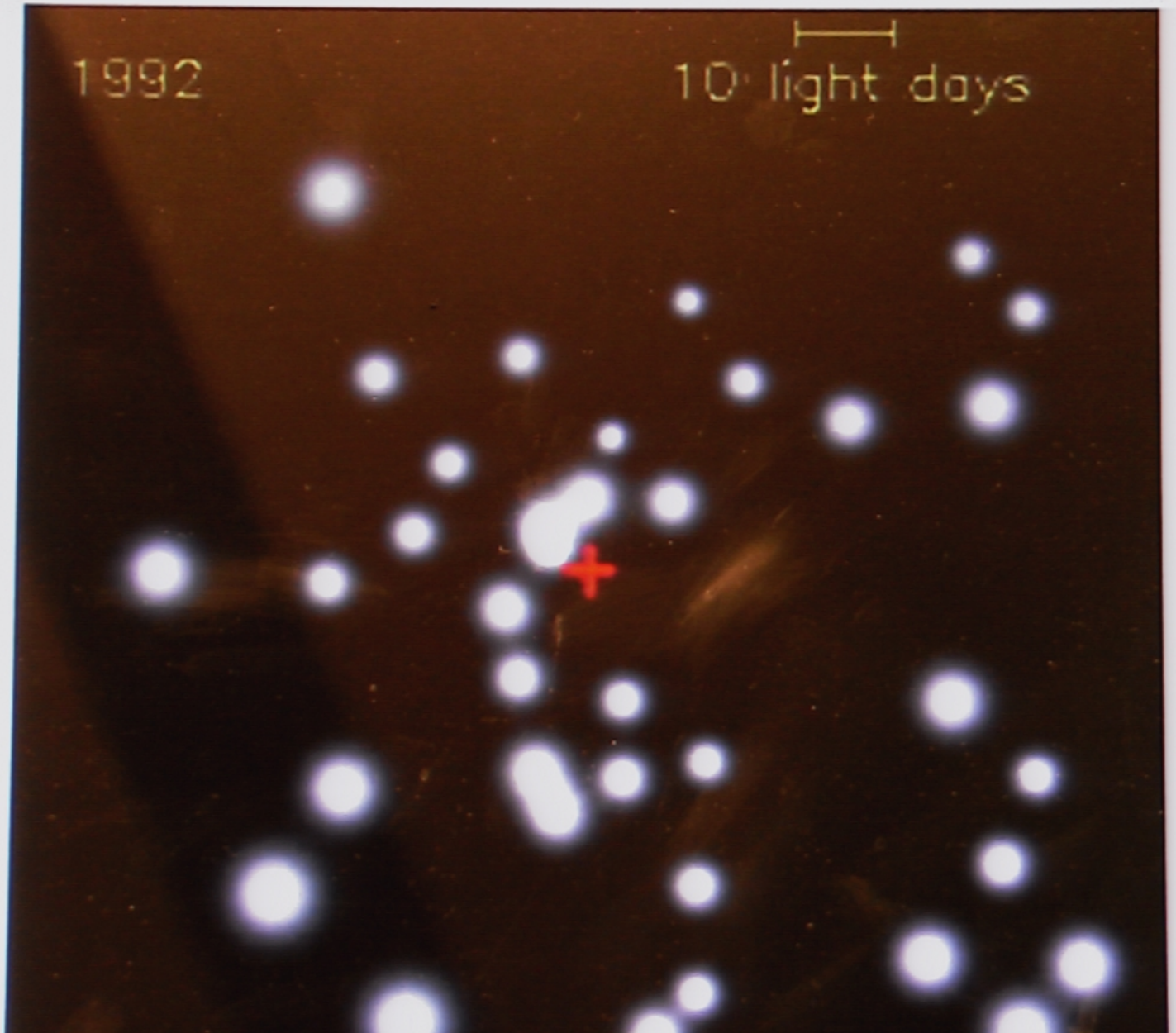

1992
10 light days

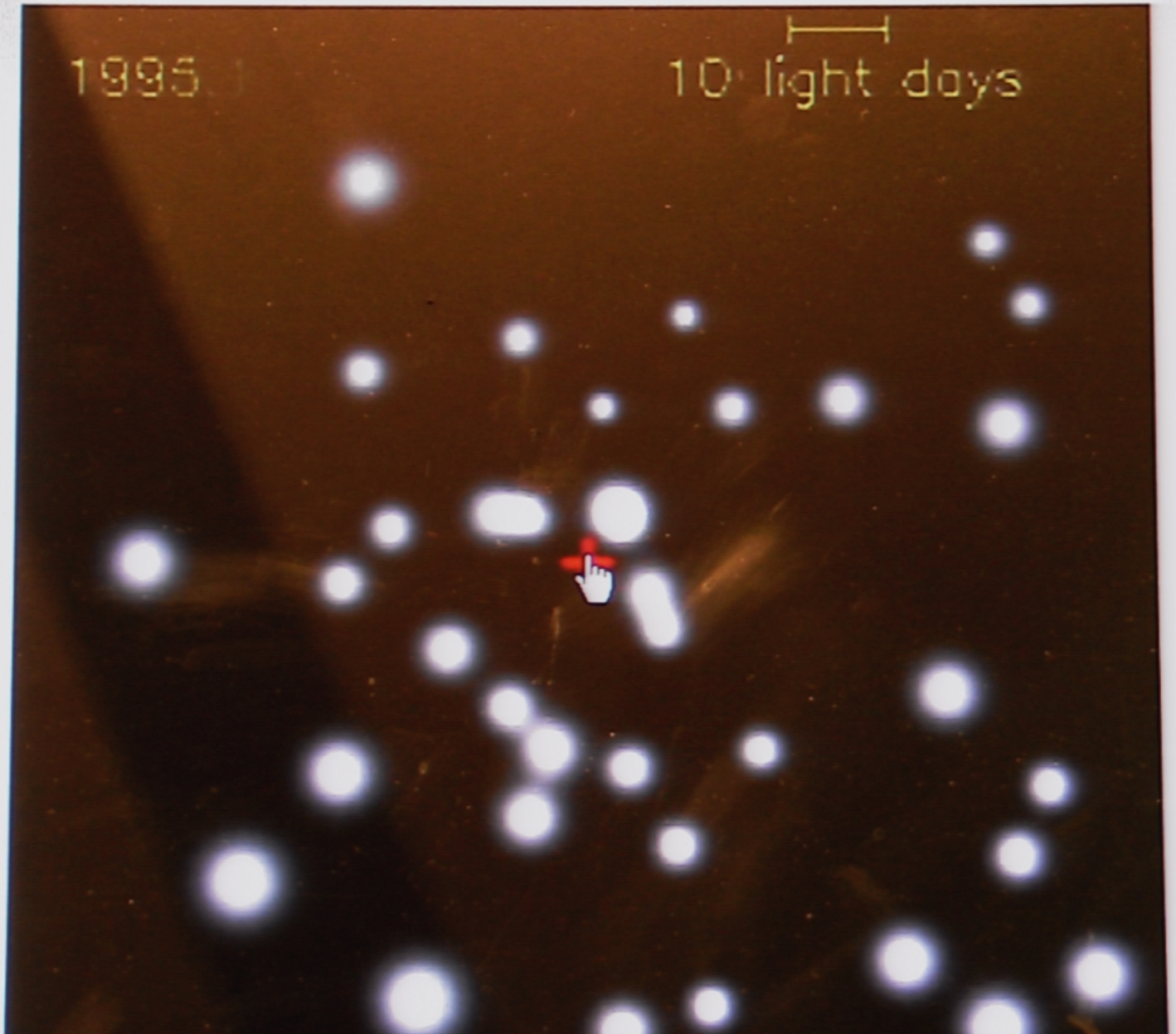

1992
10 light days

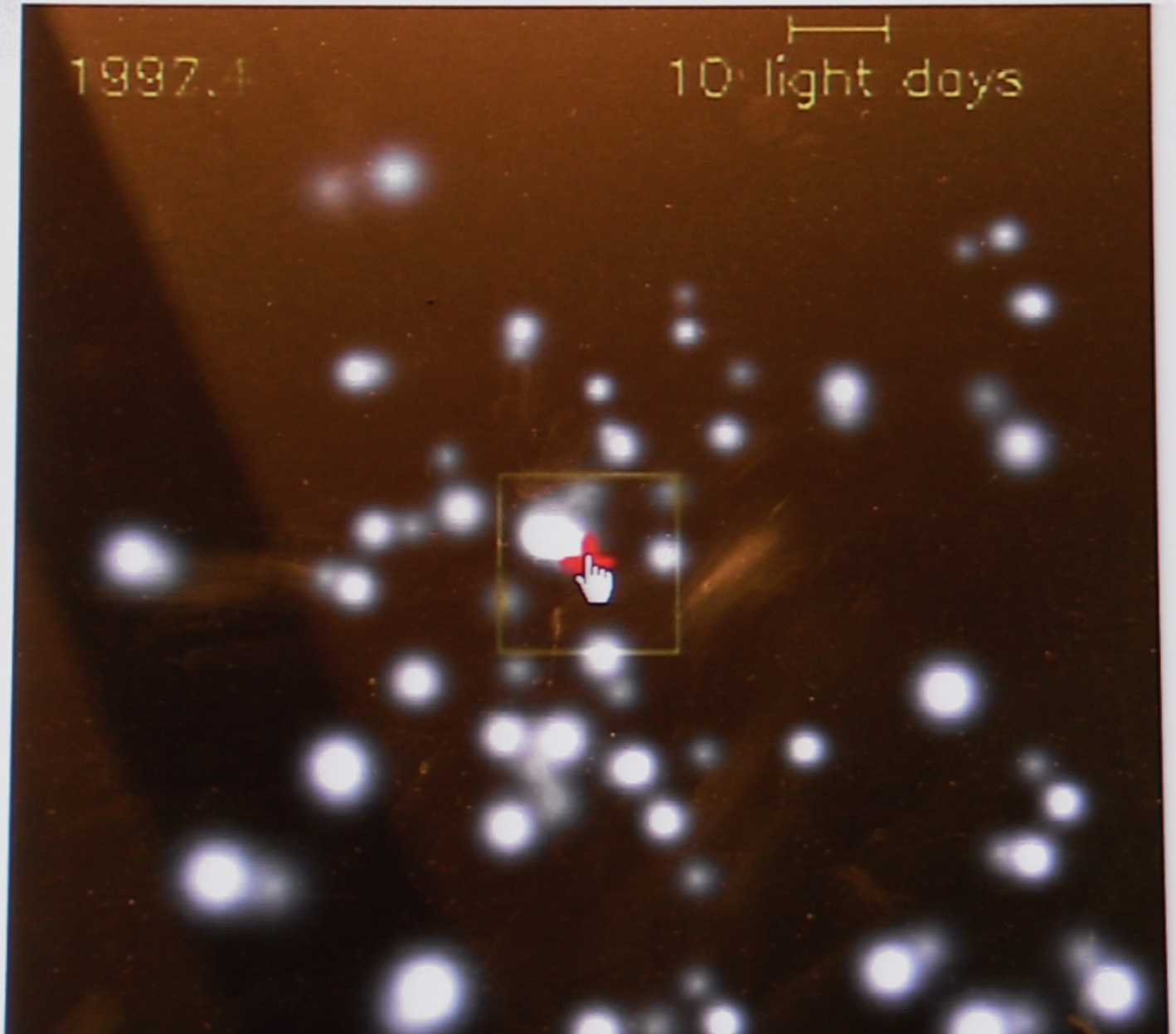

1992
10 light days

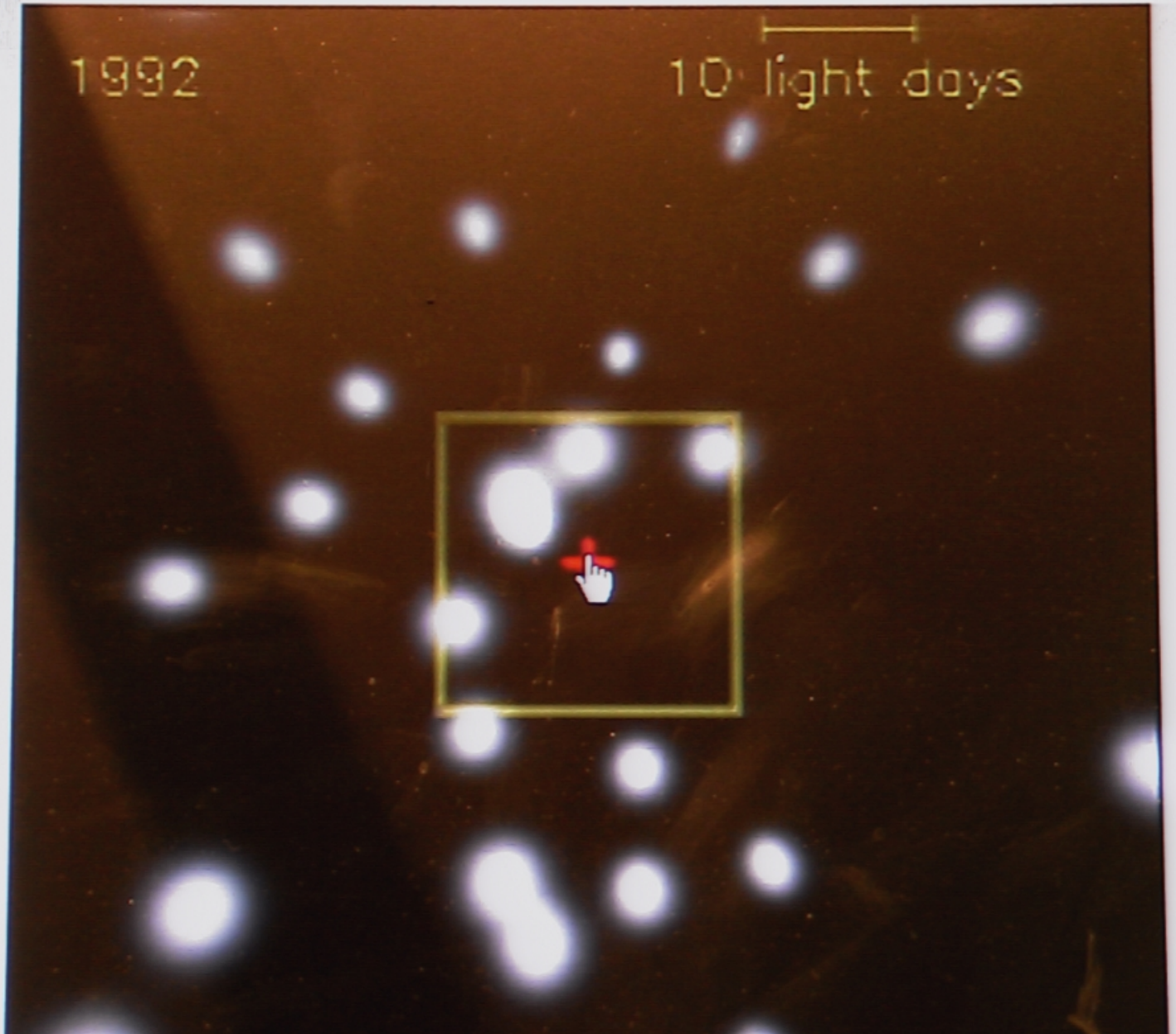

1992
10 light days

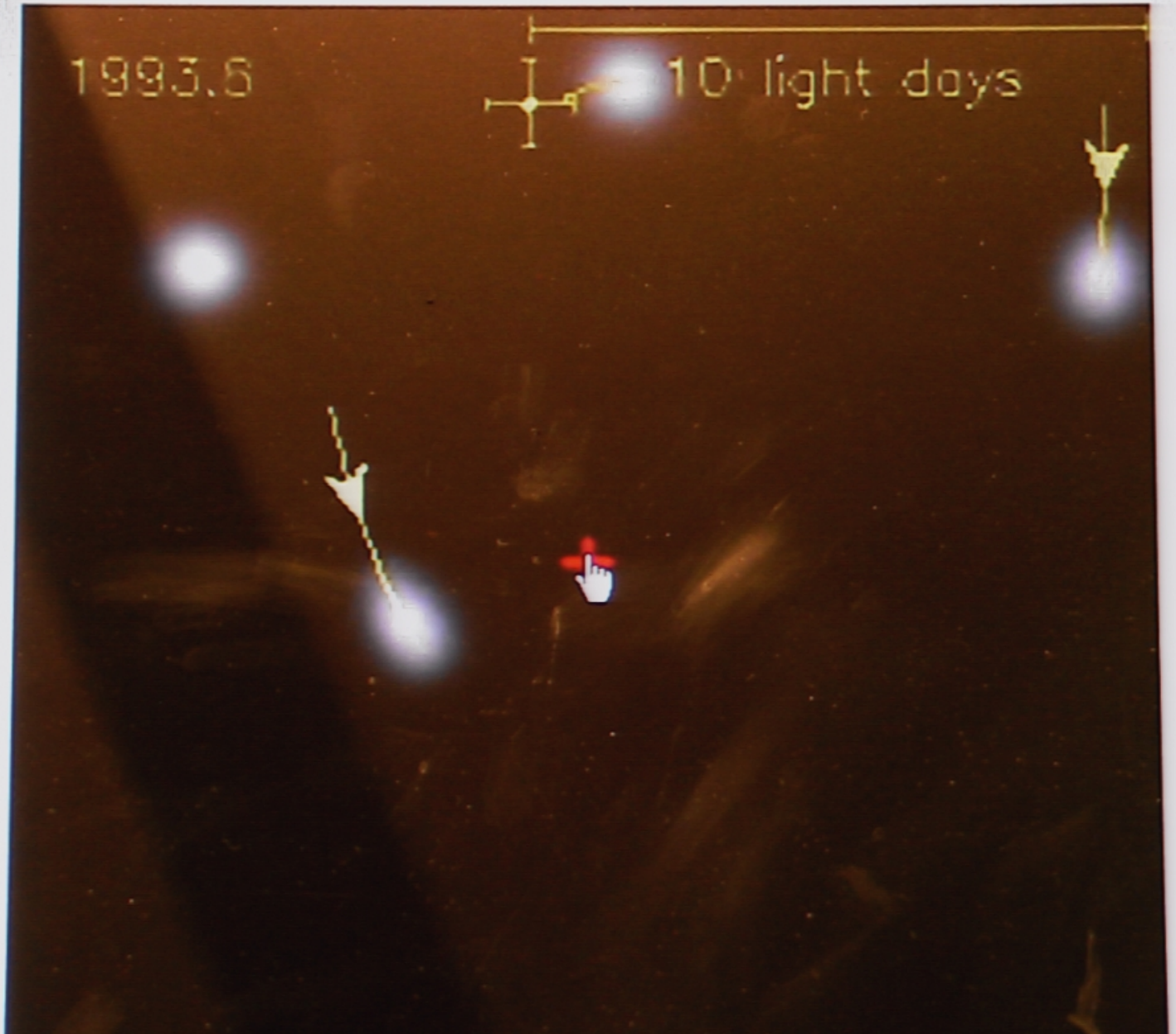

1992
10 light days

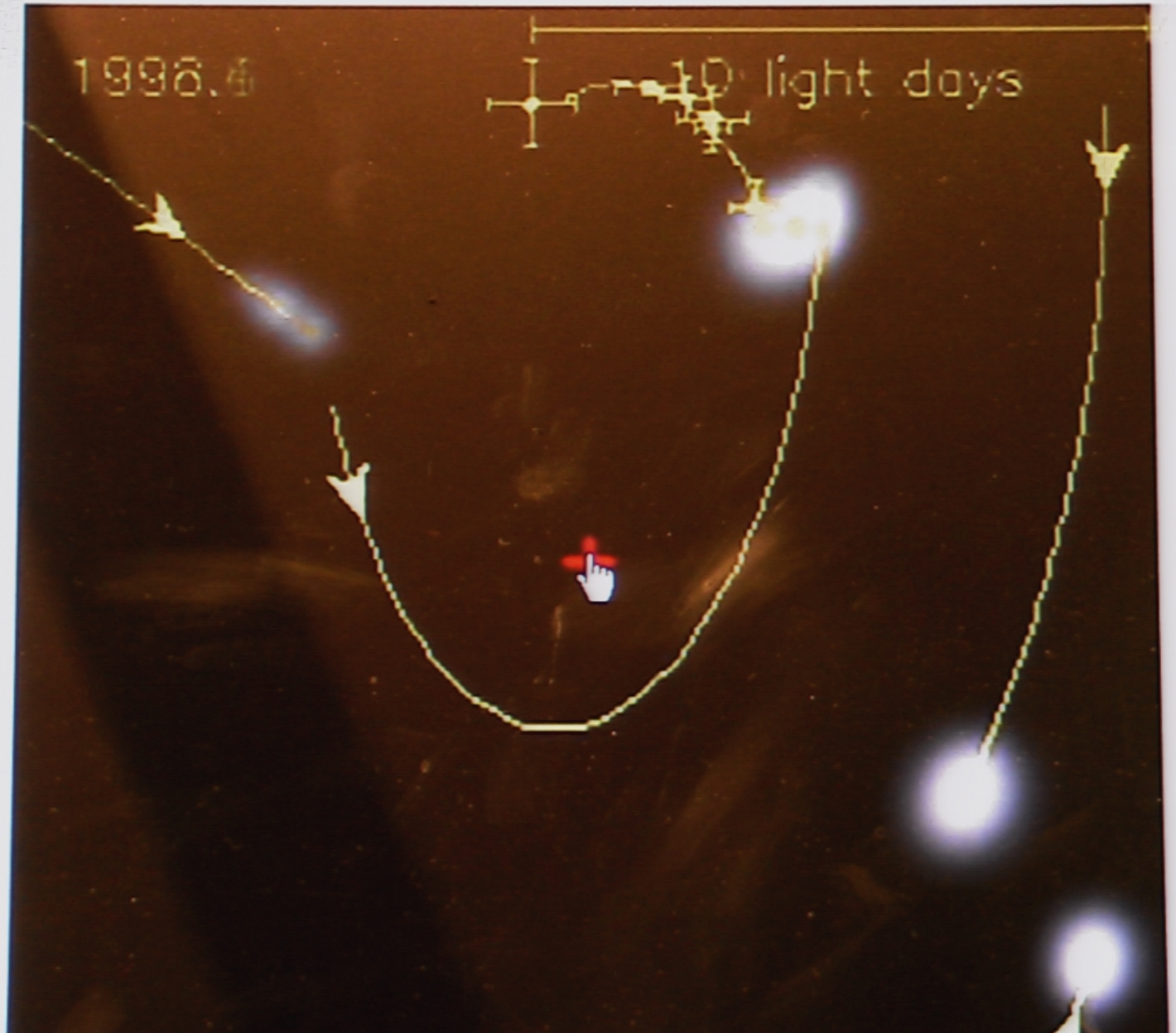

1992
10 light days

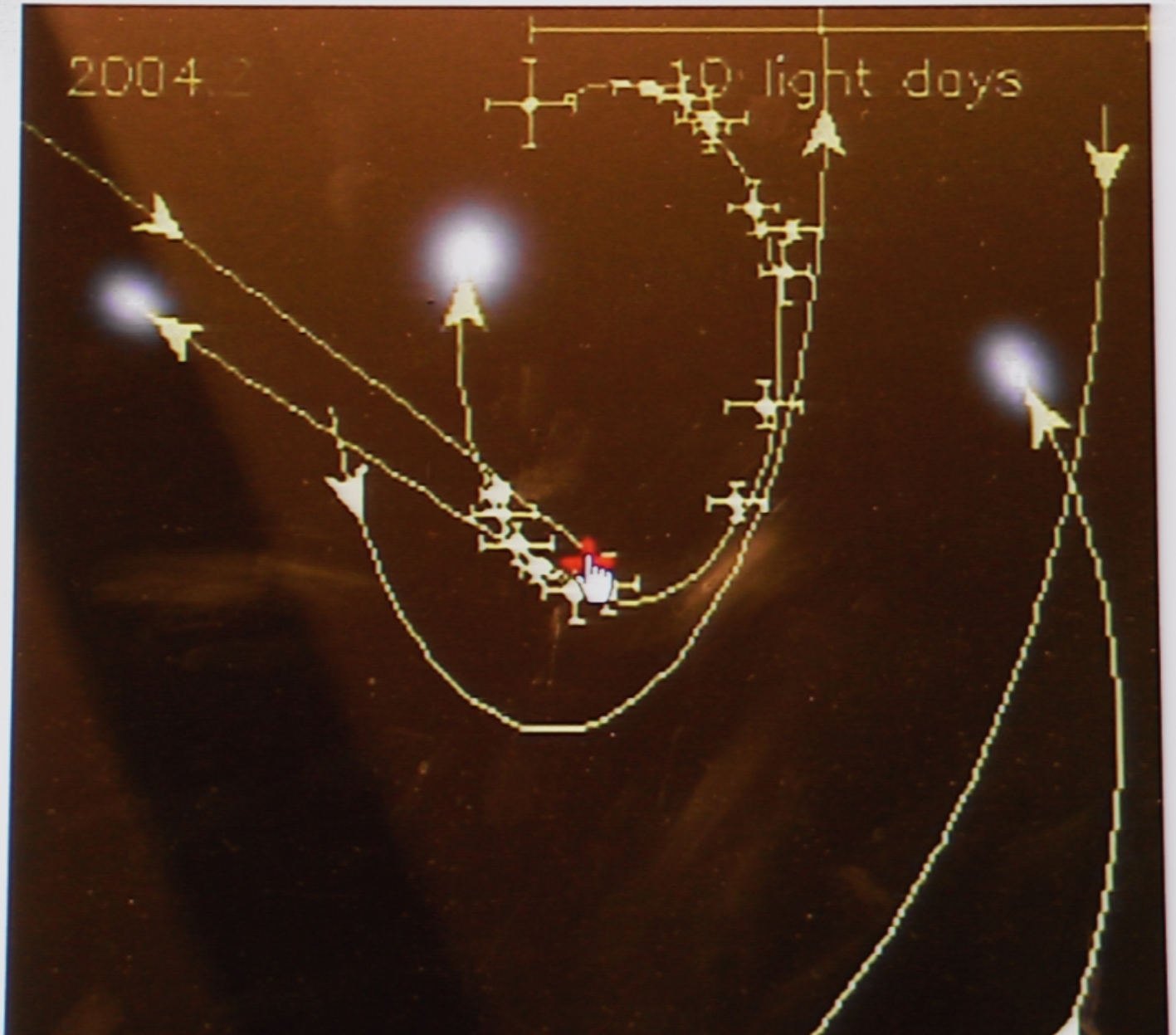

1995
10 light days

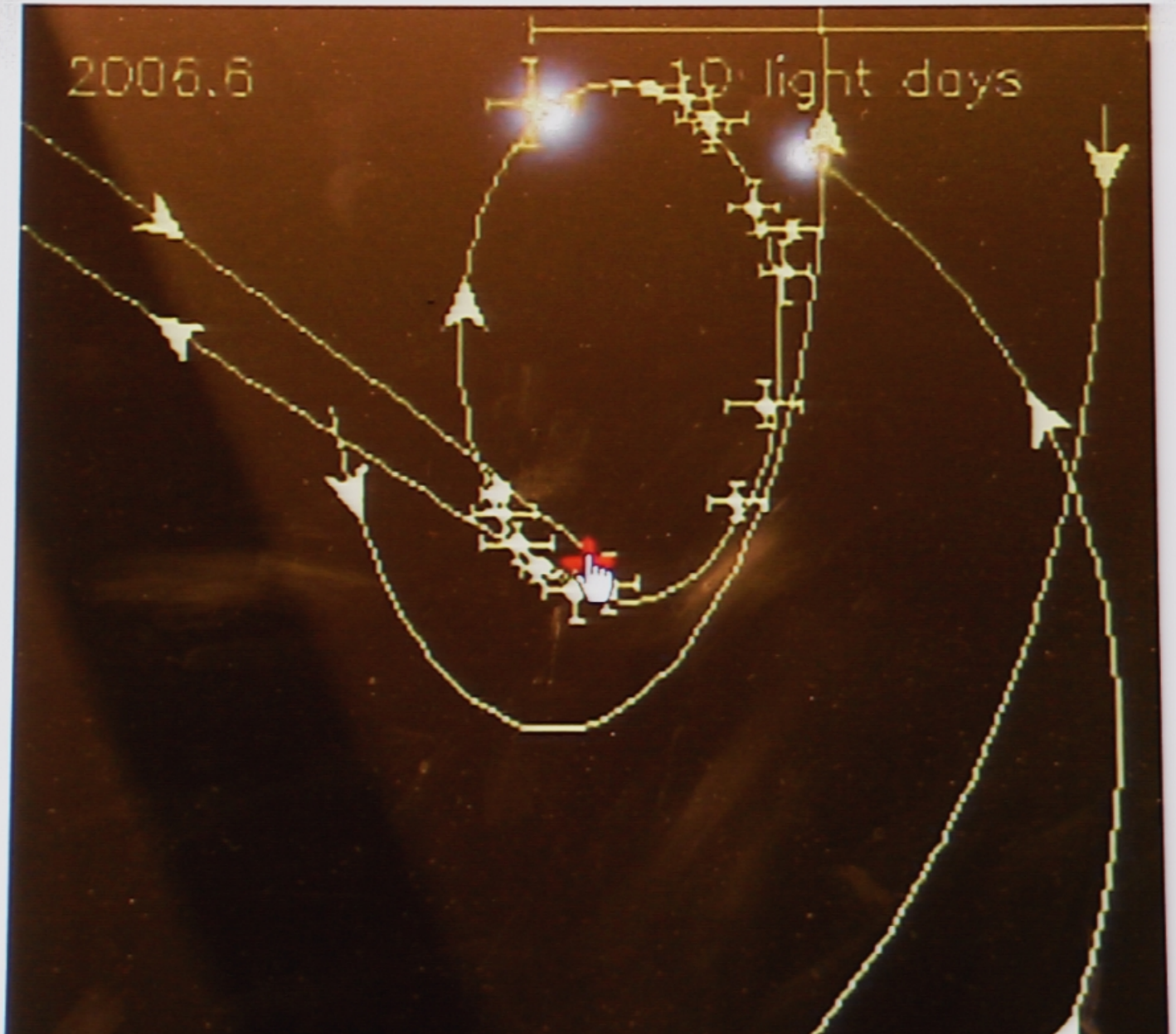

1997.1
10 light days

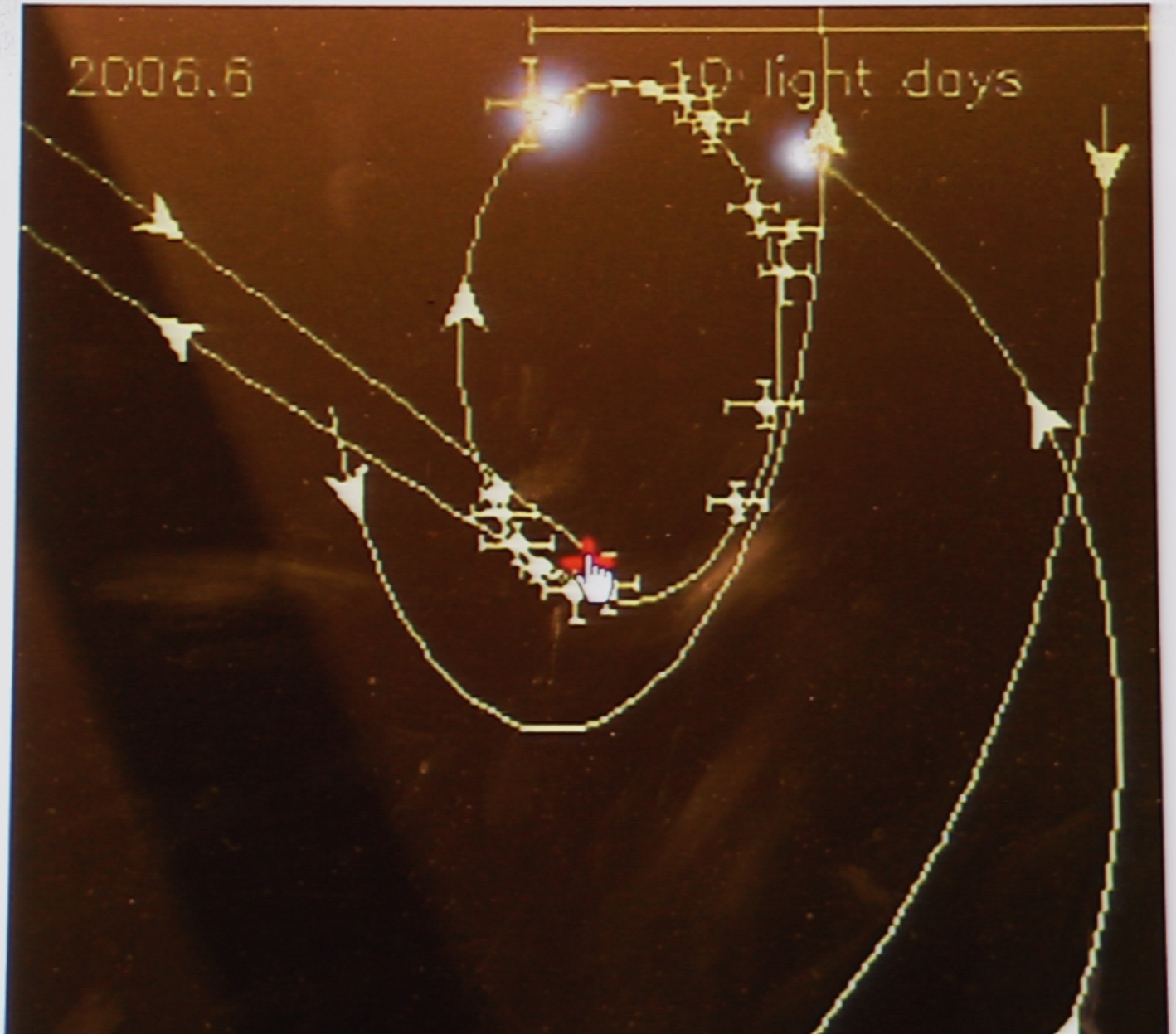

1992
10 light days


1993.6
10 light days


1996.4
10 light days

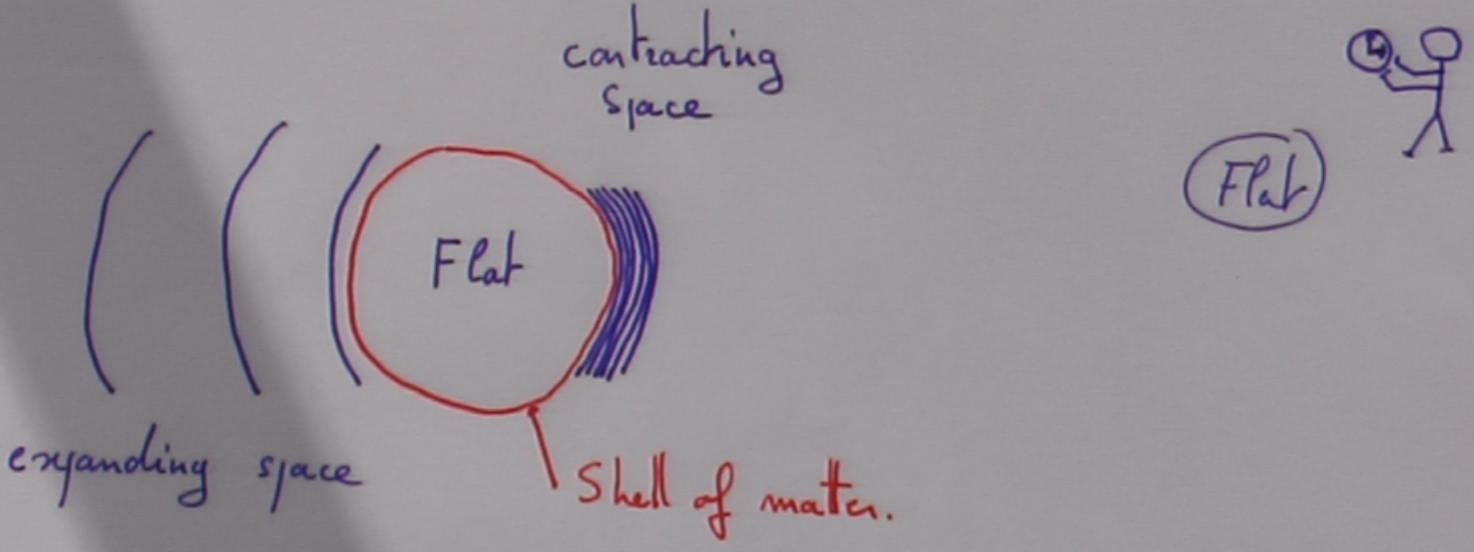

2004
10 light days


2006.6
10 light days

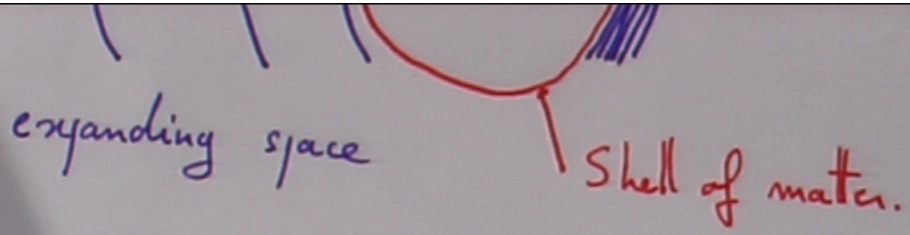

2006.6
10 light days

## Warp drive Spacetime:

A mathematical but unphysical solution of Einstein's equations:




- the bubble travels locally slower than the speed of light
but a round trip can be made in an arbitrary short time




- the bubble travels locally slower than the speed of light
  but a round trip can be made in an arbitrary short time
  as viewed by an asymptotic observer

But: The shell is made of <u>exotic</u> matter
violating the positive energy condition : not physical.

Question:

Is there a viable string theoretic explanation of quantum entanglement?

## (I) Quantum entanglement

### (Standard) Example:

Spin 0 particle (i.e. not rotating)

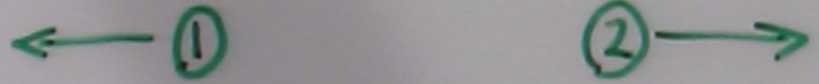
Decays into two rotating particles

# (I) Quantum entanglement

## (Standard) Example:

Spin 0 particle (i.e. not rotating)

Decays into two rotating particles




For each of the two particles the axis of rotation is not known.

Measure how much particle (1) is rotating along a given axis

What can be predicted about the measurement of the rotation of particle ② around another given axis ?

In a quantum theory the result of a rotation along a given axis can only be that it

- either rotates in the direction of the axis with strength 1
- or rotates in the opposite direction with strenth 1

If the axes of measurement are aligned for the two particles then one of the two particles is going to be rotating along this axis with strength 1

axis with strength 1

• or rotates in the opposite direction with strength 1

If the axes of measurement are aligned for the two particles, then one of the two particles is going to be rotating along this axis with strength 1 and the other particle is going to be rotating in the opposite direction with strength 1.

However, if the two axes are not aligned, then the results are correlated in a way that cannot be explained by a (local) classical theory.

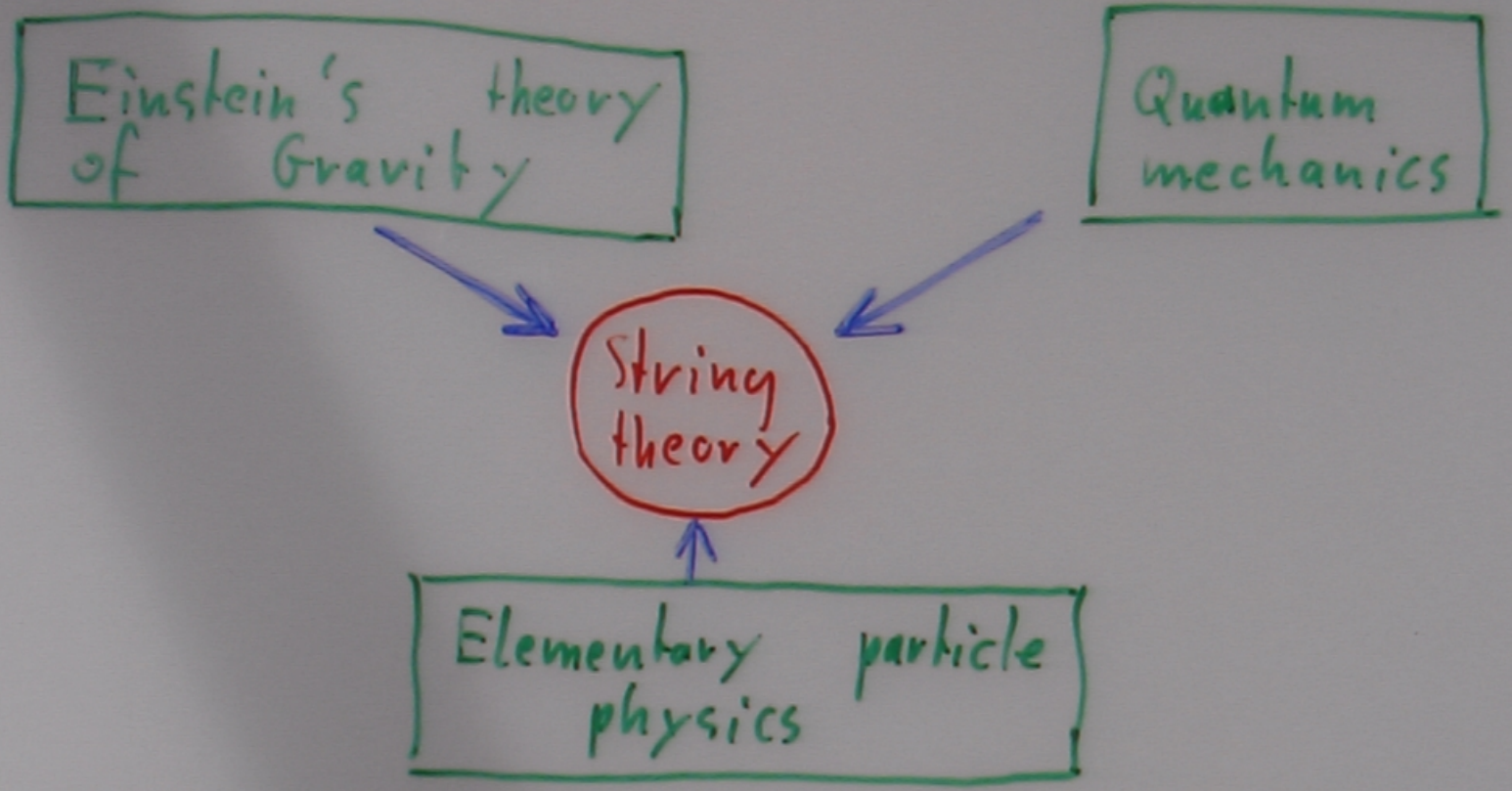
the axis with strength 1

- or rotates in the opposite direction with strength 1

If the axes of measurement are aligned for the two particles, then one of the two particles is going to be rotating along this axis with strength 1 and the other particle is going to be rotating in the opposite direction with strength 1.

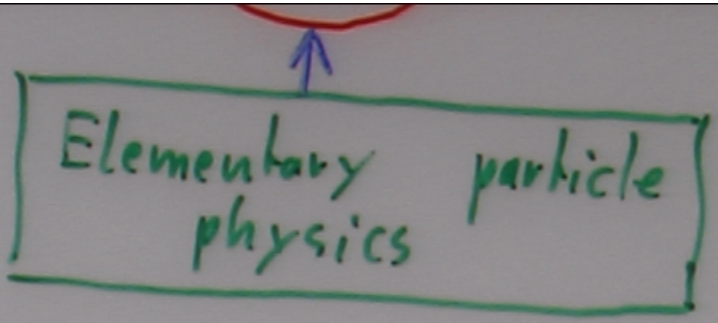
However, if the two axes are not aligned, then the results are correlated in a way that cannot be explained by a (local) classical theory.

# (II) String theory




Official Advertisement:

String theory unifies Einstein's theory of gravity, Quantum mechanics and elementary particle physics into a single




**Official Advertisement:**

String theory unifies Einstein's theory of gravity, Quantum mechanics and elementary particle physics into a single "Theory of Everything"

→ This allows to do physics under extreme conditions:

- Big Bang and Cosmology
- Black holes
- Colliding particles at extremely high energies.

! Put as much energy into a single electron as is needed to shoot a cow to the moon!

! In calories of food this is as much as an adult eats in 6 months!

Caveat: - We don't understand string theory as a full theory yet.

- We can't calculate any realistic and/or really interesting scenarios.

Basic Idea: Replace pointlike particles

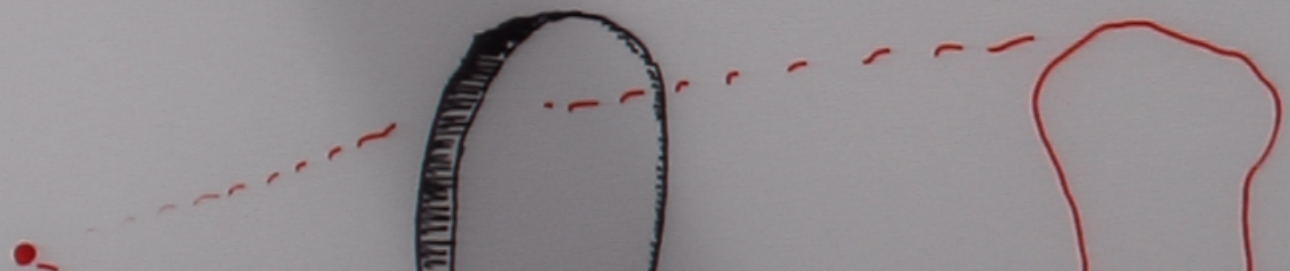
single electron as ⁽⁽ is needed to shoot a cow to the moon!

! In calories of food this is as much as an adult eats in 6 months!

Caveat: - We don't understand string theory as a full theory yet.

- We can't calculate any realistic and/or really interesting scenarios.

Basic Idea: Replace pointlike particles by strings

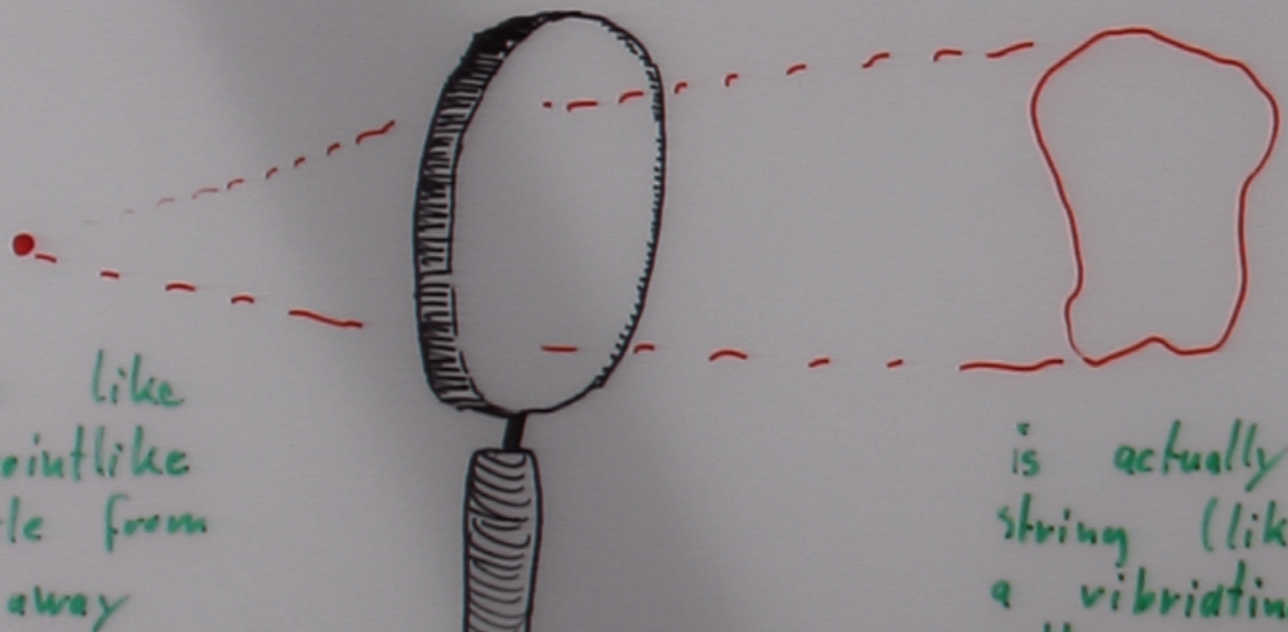


much as an adult eats in 6 months!

Caveat: - We don't understand string theory as a full theory yet.

- We can't calculate any realistic and/or really interesting scenarios.

Basic Idea: Replace pointlike particles by strings



looks like a pointlike particle from far away

is actually a string (like a vibriating

can be in different vibrational modes.

→ This corresponds to particles of different masses and spins.

Some of those "string states" correspond to gravitons, the excitations of gravity

Other string states correspond to particles similar to the ones found in elementary particle physics.

Facts:

- There appear other objects in string theory apart from strings.

  e.g. Membranes on which strings can end

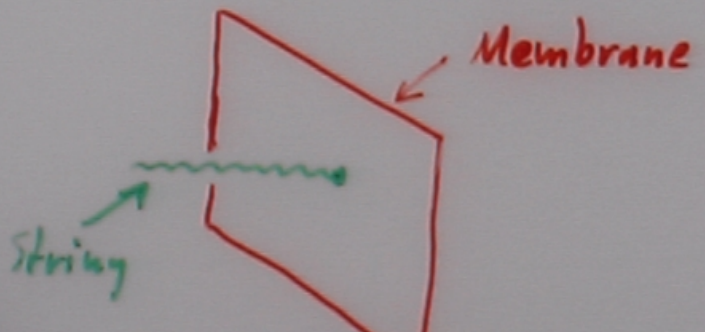
Some of those "string states" correspond to gravitons, the excitations of gravity

Other string states correspond to particles similar to the ones found in elementary particle physics.

**Facts:**

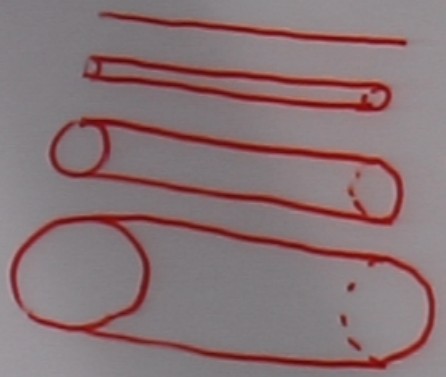
- There appear other objects in string theory apart from strings.

  e.g. Membranes on which strings can end



- String theory lives in 10 dimensions (1 time and 9 space)

→ need to roll up 6 dimensions



looks 1-dimensional

looks 2-dimensional

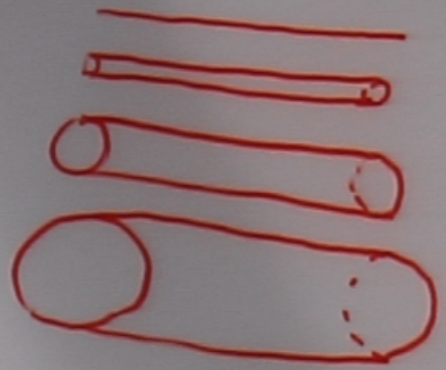
- Strings interact by joining and splitting

String 1'

String 2'

time

→ need to roll up 6 dimensions



looks 1-dimensional

looks 2-dimensional

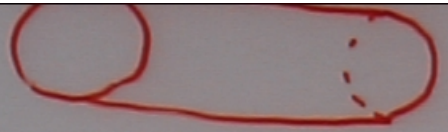
- Strings interact by joining and splitting

String 1'

String 2'

time

world sheet

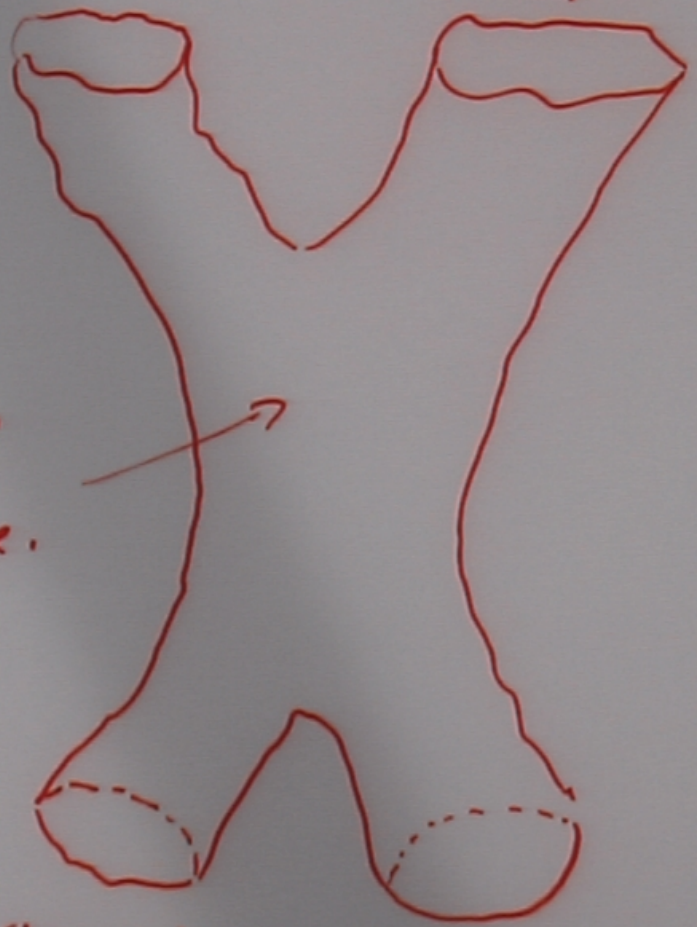


looks 2-dimensional

- Strings interact by joining and splitting

String 1'

String 2'



"worldsheet" in space-time.

time

# (III) Entanglement in string theory

String theory is formulated in the framework of Quantum mechanics.

For this reason it has Quantum entanglement.

It uses the Quantum framework
→ It cannot explain entanglement ☹

However it allows to test and experiment with entanglement under extreme conditions: ☺

String theory is formulated in the framework of Quantum mechanics.

For this reason it has Quantum entanglement.

It uses the Quantum framework
→ It cannot explain entanglement ☹

However it allows to test and experiment with entanglement under extreme conditions: ☺

- Can try to understand entanglement

For this reason it has Quantum entanglement.

It uses the Quantum framework
→ It cannot explain entanglement ☹

However it allows to test and experiment with entanglement under extreme conditions: ☺

- Can try to understand entanglement in the presence of Black Holes (Hawking radiation ...). Or vice versa.
- Play with entanglement in

entanglement.

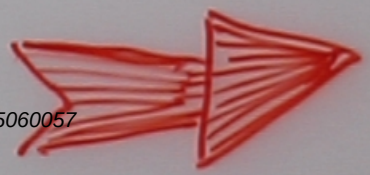
It uses the Quantum framework
→ It cannot explain entanglement ☹

However it allows to test and experiment with entanglement under extreme conditions: ☺

- Can try to understand entanglement in the presence of Black Holes (Hawking radiation ...). Or vice versa.
- Play with entanglement in cosmological scenarios

Other big open problems in string theory:

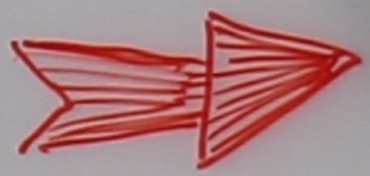
- What is String theory really?
- Understand Gravity and Quantum theory under extreme conditions.
- Derive physics of the world that we observe from string theory.
  (Compare to results at the new Collider LHC in 2008)



There is still

... under extreme conditions.

- Derive physics of the world that we observe from string theory.
  (Compare to results at the new Collider LHC in 2008)



There is still a lot of work for us to do here at PI and elsewhere!

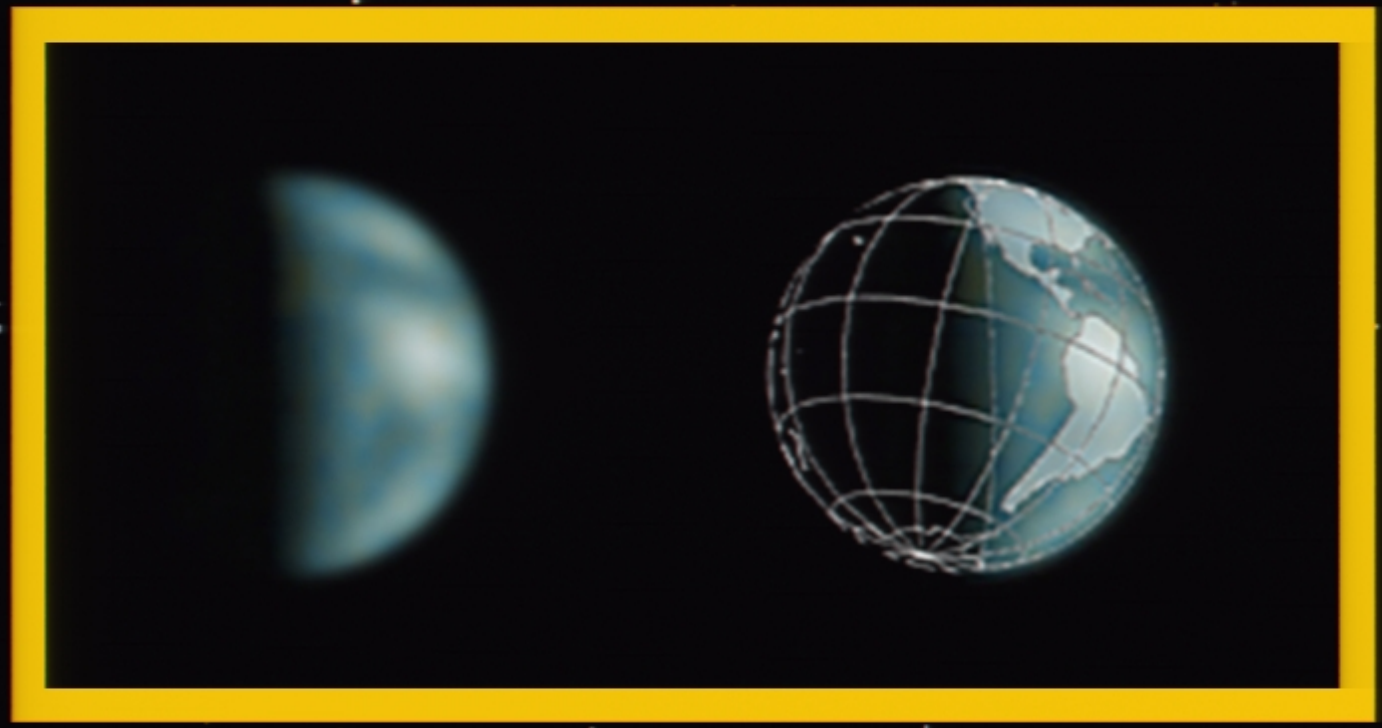
# SETI

*Search for Extra-Terrestrial Intelligence:* scans the heavens searching for extraterrestrial intelligence.

# Looking for Extraterrestrial Intelligence

Signals could be ‘wasted’ energy leaking into space, or deliberate signals directed into space.

# Telescopic Searches?



Direct searches for planets are difficult because of the immensity of interstellar distances

# The Drake Equation

How many planets could have intelligent life which we might detect from space?

$$N = R_* f_p n_e f_l f_i f_c L$$

- $R_*$: rate of formation of solar-type stars
- $f_p$: fraction of stars having planets
- $n_e$: number of planets per star suitable for life
- $f_l$: fraction of habitable planets on which life arises
- $f_i$: fraction of life forms which evolve to intelligent forms
- $f_c$: fraction which can and choose to send signals into space
- $L$: Lifetime of this technologically advanced civilization

# The Drake Equation

How many planets could have intelligent life which we might detect from space?

$$N = R_* f_p n_e f_l f_i f_c L$$

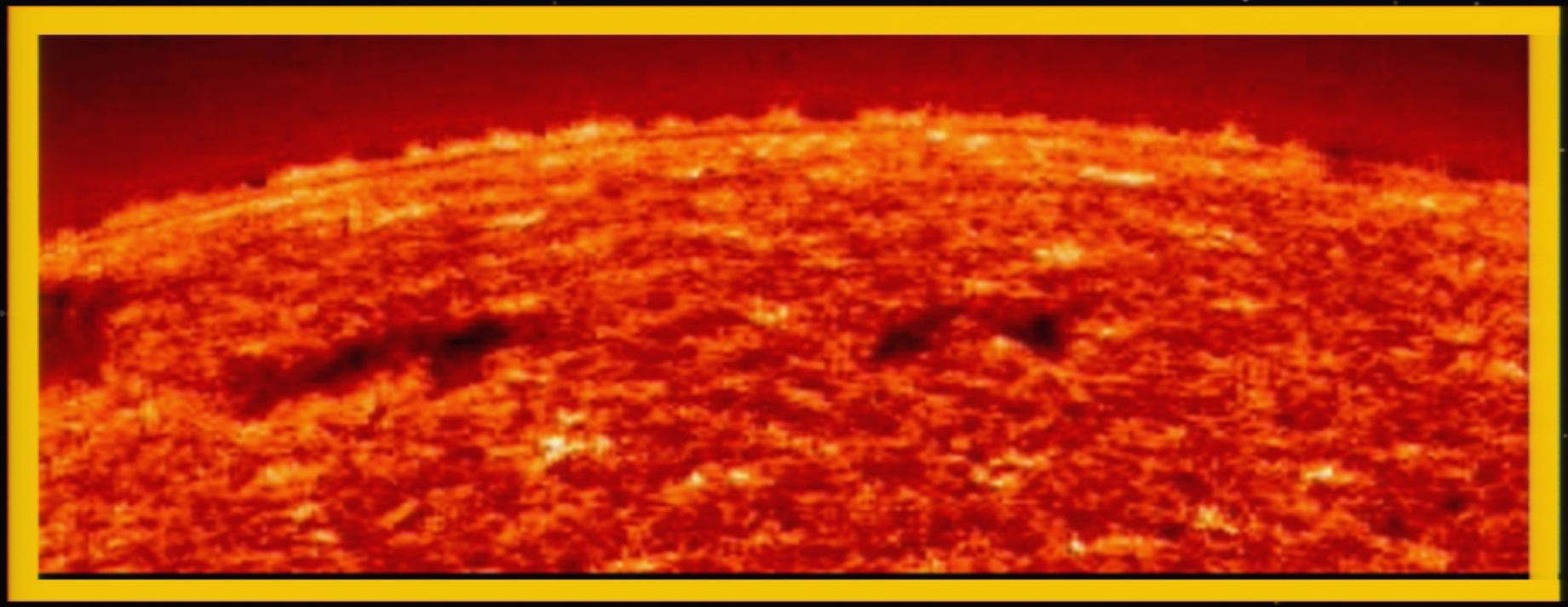
- $R_*$: rate of formation of solar-type stars
- $f_p$: fraction of stars having planets
- $n_e$: number of planets per star suitable for life
- $f_l$: fraction of habitable planets on which life arises
- $f_i$: fraction of life forms which evolve to intelligent forms
- $f_c$: fraction which can and choose to send signals into space
- $L$: Lifetime of this technologically advanced civilization

# Intelligent Guesses

Rate of formation of Sun-like stars: Around 100 billion stars in the Milky Way, and each lives roughly 10 billion years:

$$R_* \sim 10/year$$

# Intelligent Guesses



Fraction of stars having planetary systems: More than 100 planets have been found orbiting nearby stars:

$$f_p \sim 1$$

# Intelligent Guesses

The number of planets per solar system which are suitable for life:

Most planets found so far are Jupiter-like, but as close to their star as Mercury is to ours

$$n_e \sim 0.01$$

# Intelligent Guesses

Likelihood of life starting given a habitable planet: On Earth there is evidence for life almost immediately after surface cooled.

$f_l \sim 1$

# Imponderables

- How likely is intelligence once life evolves?
  - There is no evidence that evolution prefers complexity or intelligence in life.

# Imponderables


Even if it evolves, intelligent life may hide itself:

- On Earth the first meeting of two civilizations usually resulted in the destruction of one, usually by disease. (eg: Homo Sapiens meeting Neanderthals in Europe, European colonization of Australia and the Americas, Bantu migration to southern Africa, Polynesian colonizations)

# Imponderables

Other suprises?

# In My Opinion…

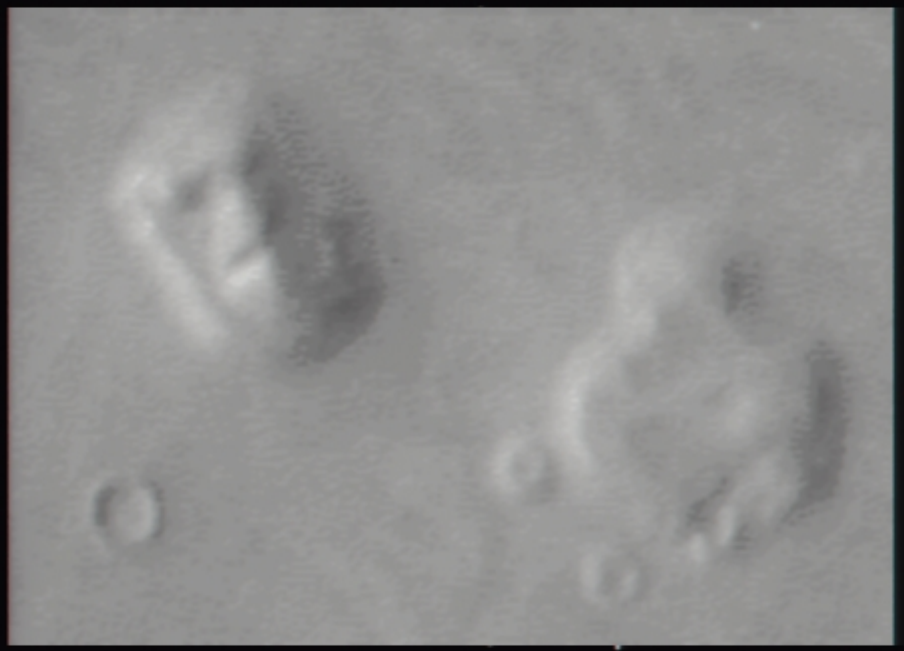
- Extraterrestrial Life is unlikely to be:
  - Vaguely human shaped
  - Watching us with UFOs
  - Kept secret by the US government in Area 51
  - Cute like ET…

# In My Opinion…

- Extraterrestrial Life is unlikely to be:
  - Vaguely human shaped
  - Watching us with UFOs
  - Kept secret by the US government in Area 51
  - Cute like ET…

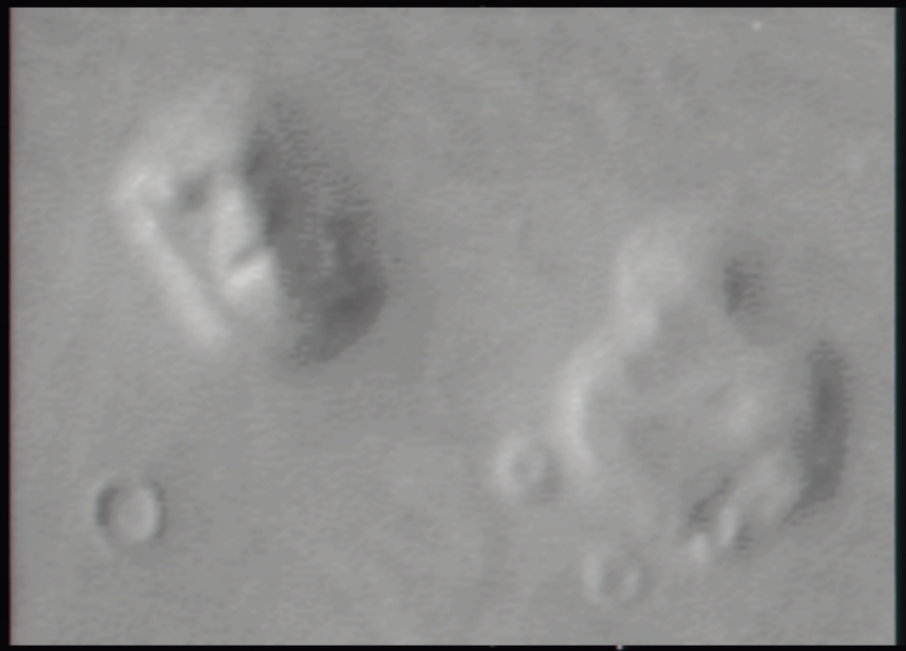
- Extraterrestrial Life is likely to be:
  - Single-celled.
- Extraterrestrial Intelligent Life is likely to be:
  - Multicellular
  - Sexually reproducing
  - Mortal
  - Dangerous

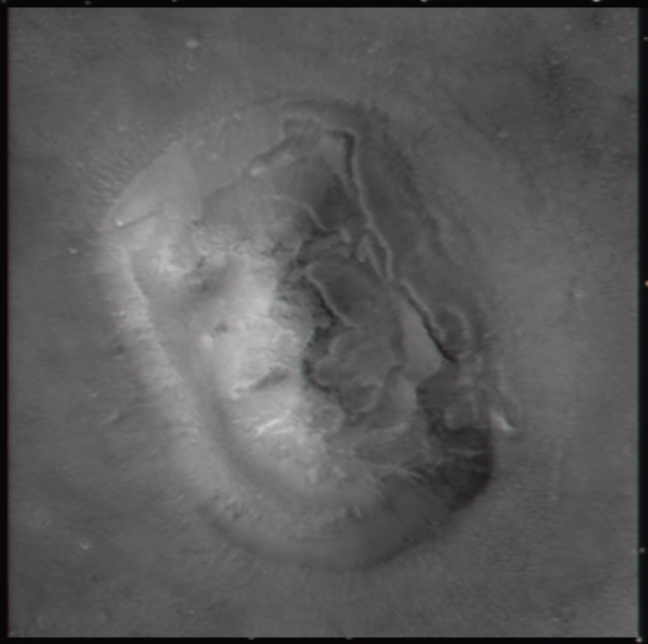
# *Caveat Emptor*



- The ‘Face on Mars’ illustrates the pitfalls it is easy to fall into when looking for life elsewhere.

# *Caveat Emptor*





- The ‘Face on Mars’ illustrates the pitfalls it is easy to fall into when looking for life elsewhere.


Thanks for coming!