University Lecture
2. The Birth of Matter
-Elementary Particles, Atoms, and the Universe-

The University of Tokyo, Theoretical Astrophysics Group (UTAP)

Research Center for the Early Universe (RESCEU)

Katsuhiko Sato

2. The Birth of Matter
-Elementary Particles, Atoms, and the Universe-

- Lecture 1 How do we conceive of the physical world? –structural hierarchy of matter-
- Lecture 2 The motion of the physical world –physical laws
- Lecture 3 Space-time –the "stage" of matter- Space-time and matter unite in motion to determine the structure of the world
- Lecture 4 The creation and evolution of the universe –for a comprehensive understanding of nature-

Space-time –the “Stage”of Matter-

- 1. What is time, what is space?
- 2. Special relativity established.
- 3. The worldview of general relativity.
- 4. Black holes and wormholes.
- 5. Time machines and closed time-like curve (CTC) problems.
- 6. What are the uses of general relativity?

1. What is Time, What is Space?

Saint Augustine of Hippo (Hippo Regius) bishop (354-430)

What then is time? If no one asks me, I know what it is. If I wish to explain it to him, I do not know.

Is there an end to space or time?

If there was a beginning of time, then what was there before the beginning of time?

If there is an end to space, then what is there at the end of space?

The Beginning of Time

- What did God do before he created the universe?

“God was preparing Hell for people who asked such questions.”

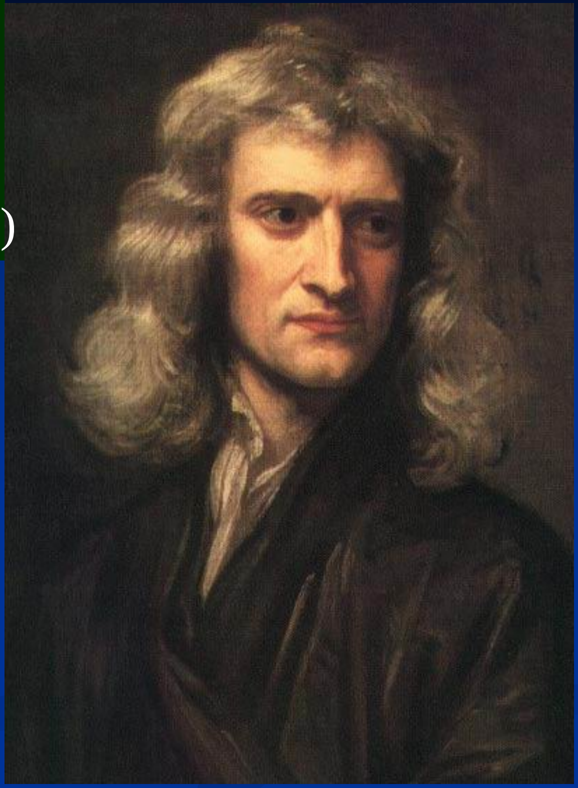
Saint Augustine of Hippo

“ Before God created the universe, there was nothing.”

Principia- Philosophiae Naturalis Principia Mathematica (1687)

Absolute time and absolute space.

- Time: from its own nature, runs at the same rate at all observing points without any relation to anything external, and can be called persistent.
- Space: from its own nature, remains homogeneous and isotropic without any relation to any external forces.

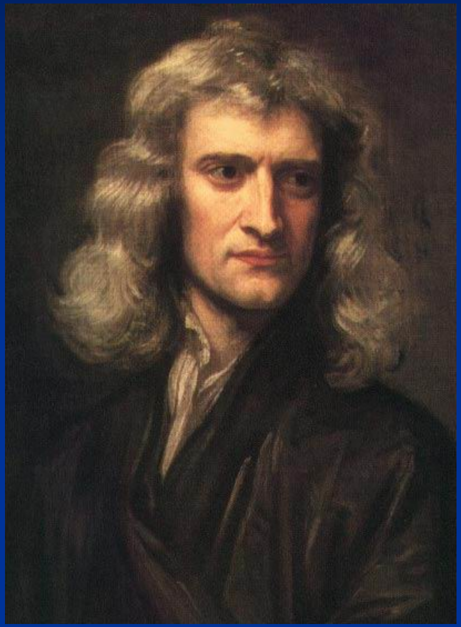


Newton (1642- 1727)

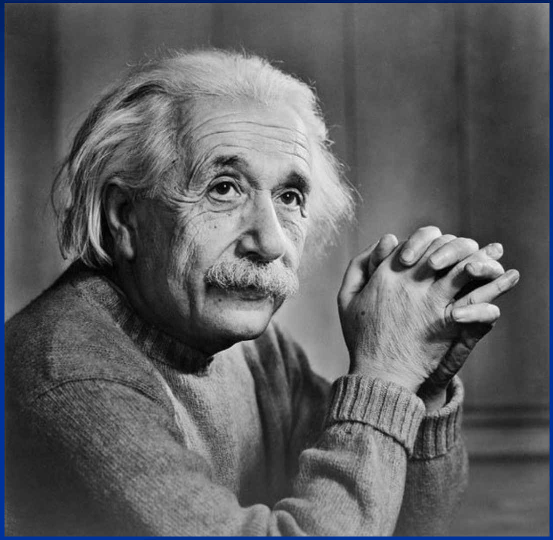
Kant (1740-1786): Space and time are both pure forms of intuition.

Until Einstein came along, Newtonian physics perceived space and time as a box, in which physics itself is put in, but not as a subject of physics.

Space and Time- The " Stage" of Matter



It is a stone stage where matter can dance without leaving any dents on the floor.



The stage is like a trampoline where matter has to dance carefully considering how big a dent it will leave on the floor. If matter is too heavy, the floor will collapse.

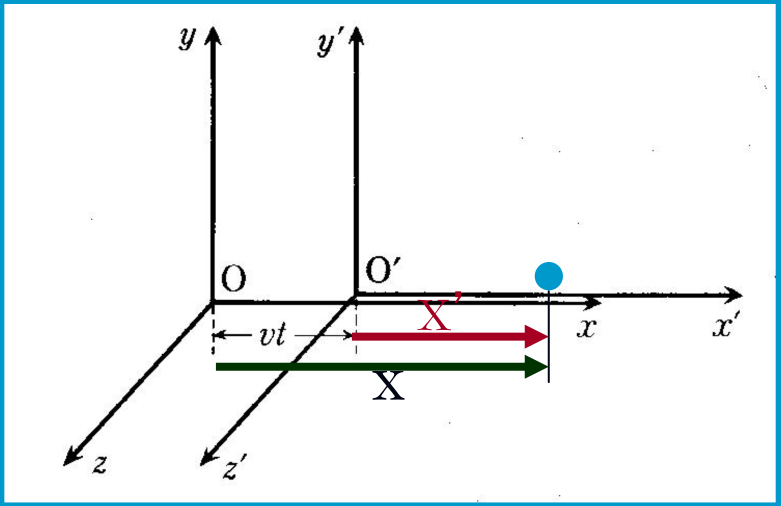
The Theory of Special and General Relativity

The theory of special relativity: physical laws can be written in the same mathematical forms for all inertial systems. (1905)

The theory of general relativity: physical laws can be written in invariable forms for all coordinate systems. (1915)

The Coordinate System and Relativity
Before Special Relativity Was Invented

The coordinate systems in uniform motion (inertial system) are identical and equal.



Galilei

$$x' = x - vt$$

$$y' = y$$

$$z' = z$$

$$m\frac{d^2x}{d^2t} = f$$

Newton's equation of motion remains constant regardless of the coordinate system.

$$m\frac{d^2x'}{d^2t} = f$$

Principles of relativity in the coordinate system: "human-made" coordinate systems do not apply to natural laws.

The Principle of the Constant Velocity of Light

Maxwell's equations (1861) of electromagnetism provided an unified understanding, which electromagnetic waves (light) propagate in the velocity of light. From what frame of reference is this velocity measured?

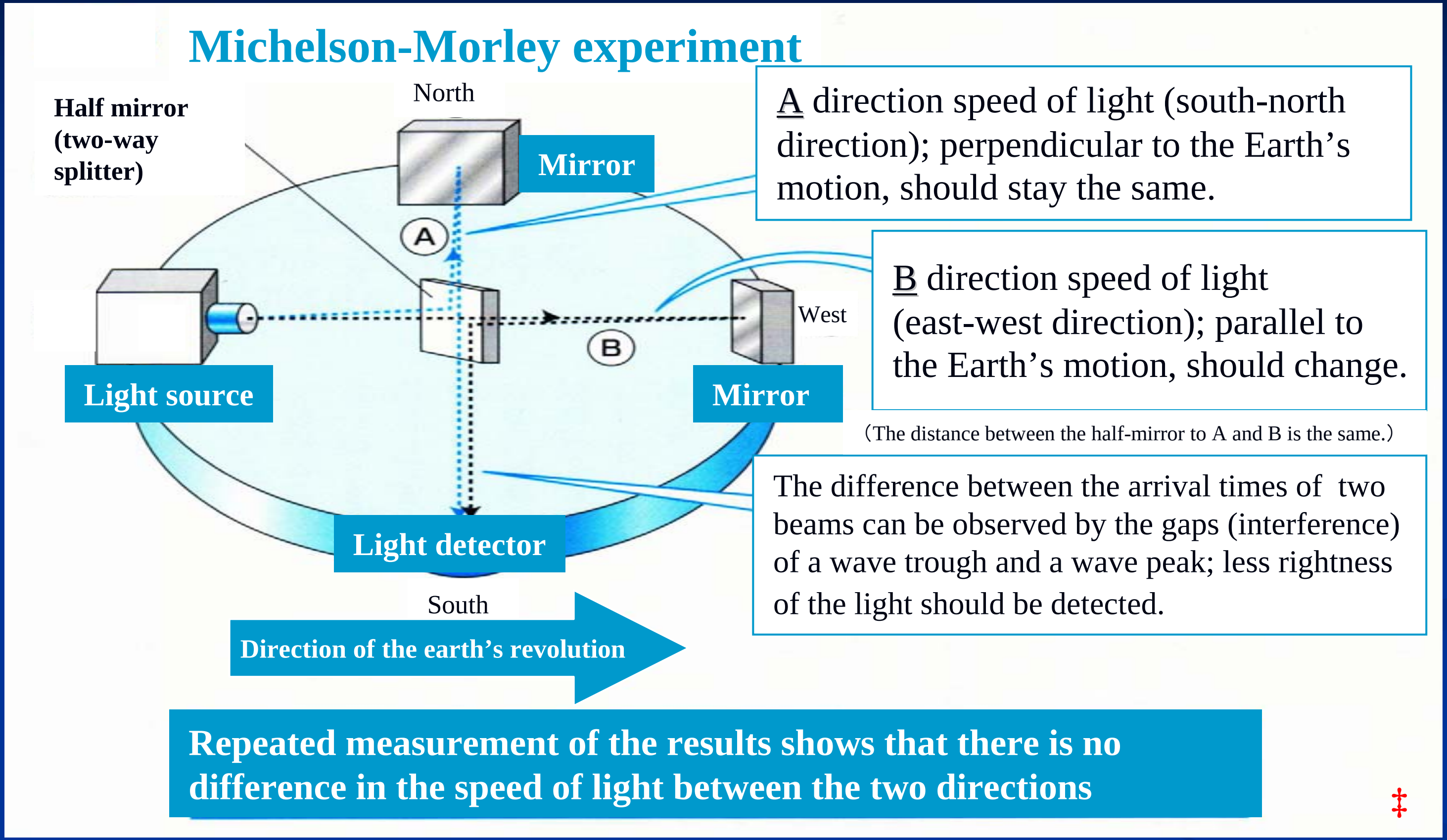
The two different viewpoints: which is correct?

1. If this physical law could apply to any inertial system, the constant velocity of light would be confirmed: the principle of the constant velocity of light.

2. This physical law may be applied to absolute inertial systems only: existence of ether.

Michelson-Morley experiment (1887) to prove the non-existence of ether.

Michelson-Morley Experiment (1887)



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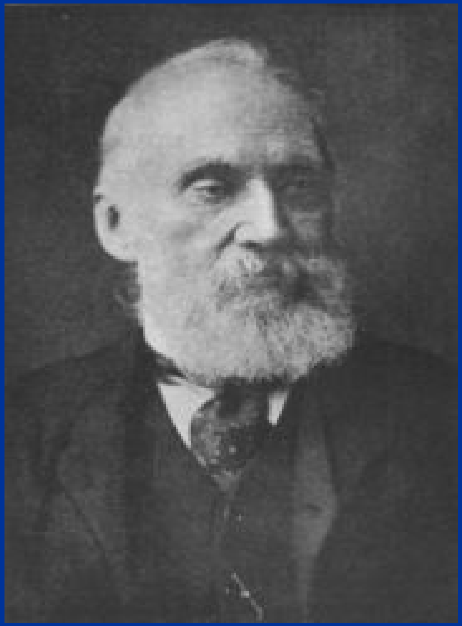
Proved non-existence of ether: experimentally secured the principle of the constant velocity of light.

In 1900, Lord Kelvin gave a lecture "*Nineteenth-Century Clouds over the Dynamical Theory of Heat and Light.*"

"*Beauty and clarity of theory*" was overshadowed by "*two clouds*", *the null result of the Michelson-Morley experiment* and the problems of blackbody radiation."



In the late 19th century, Lord Kelvin pointed out the existence of two clouds that overshadowed the clarity of physics at that time: detecting the non-existence of ether and blackbody radiation. Apparently, the two problems were the keys to modern physics: relativity theory and quantum theory.

2. Special Relativity Established (1905)

The principle of special relativity: physical laws are the same in any coordinate systems (inertial systems).

Arbitrary coordinate systems, which were made artificially, should not hold the physical laws.

The principle of the constant velocity of light: the velocity of light remains constant in all coordinate systems: C

The theory of special relativity is derived from two such simple principles.

Einstein's Great Contribution

Einstein showed that time is relative to the observer (frame of reference); it is not absolute. *"Your time and my time can be different."*

Galilean transformation

$$t' = t$$
$$x' = -vt + x$$
$$y' = y$$
$$z' = z$$

Lorenz transformation

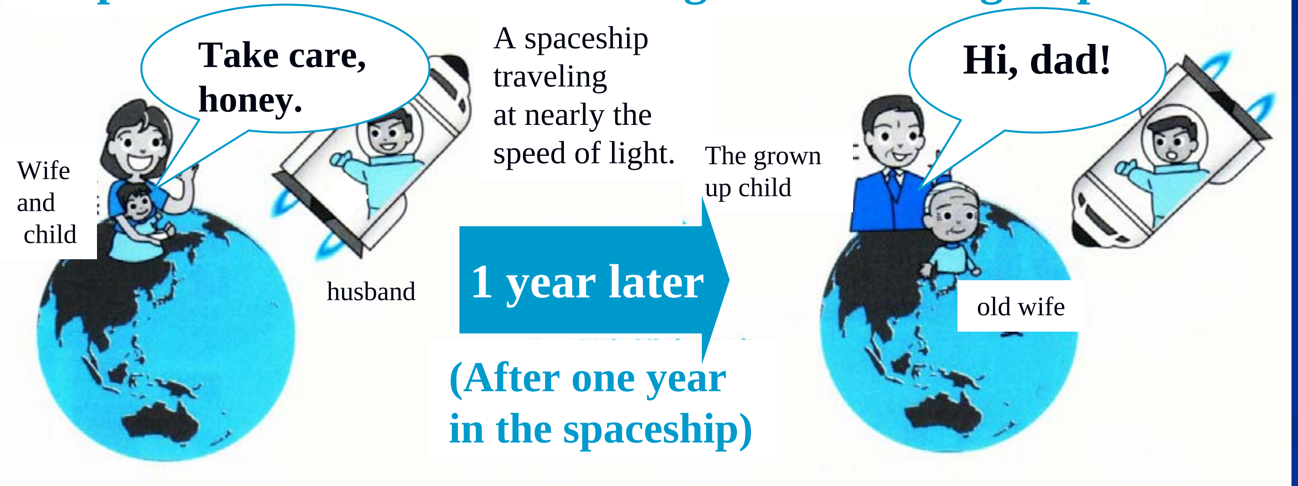
$$ct' = \frac{1}{\sqrt{1-(v/c)^2}}ct - \frac{v/c}{\sqrt{1-(v/c)^2}}x$$
$$x' = -\frac{v/c}{\sqrt{1-(v/c)^2}}ct + \frac{1}{\sqrt{1-(v/c)^2}}x$$
$$y' = y$$
$$z' = z$$

Infinite value of light velocity c matches Galilean transformation.

Therefore it satisfies both the "principle of special relativity" and the "principle of the constant velocity of light".

Rip van Winkle Effect

Rip van Winkle effect: traveling at near the light speed.



V=0.9998 x light speed, then one year in a spaceship is equal to fifty years of earth time.

$$T = \frac{t}{\sqrt{1-\left(v/c\right)^2}}$$

t: time on spaceship

T: time on the Earth

V: velocity of spaceship

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We can travel to the future but we cannot travel back in time.

Mass is a Form of Energy

$$E = \frac{mc^2}{\sqrt{1-\left(v/c\right)^2}} \approx mc^2 + \frac{1}{2}mv^2$$

When thermal energy ΔE is released in a chemical reaction, nuclear reaction, or gravitational collapse, the mass of the system is decreased by Δm（＝ΔE／c²）.

Rate of mass loss: chemical reaction 10^{-9} , nuclear reaction 10^{-3} , and a black hole forming 10^{-1} .

3. General Relativity

Limitations of Special Relativity Theory

1.Generalization of special relativity theory.

Accelerated frames of reference is excluded in this discussion. Physical laws should be written for all systems; inertial system and other coordinate systems.

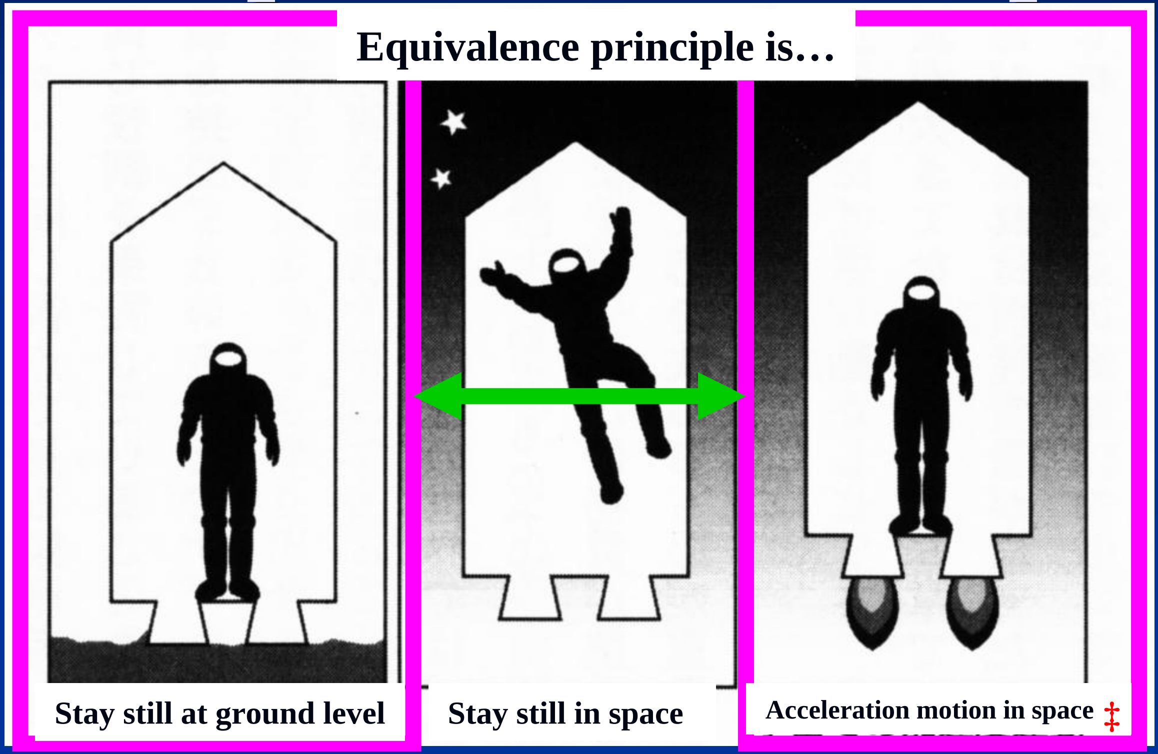
Einstein solved the problem by introducing Riemannian geometry (curved space geometry).
Collaboration with M. Grossman, a good friend of Einstein's.

2. Proper incorporation of gravity into the theory of relativity.

The fundamental physical laws should be written regardless of the coordinate systems (invariant to the coordinate transformation).

Three of the four fundamental forces (laws) were described by the theory of relativity but gravity was not included: electromagnetism, the strong (color) and weak forces.

General Relativity Derived by Equivalence Principle



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To stay still in a spaceship at ground level is the same as the motion with acceleration in a spaceship in space.

There is no gravity in a falling elevator.

Gravity is equivalent to acceleration.

Einstein's Equation (Einstein's Field Equation)

- Einstein's equation is determined by Poisson equation; an extension of Newton's law of gravity.

$T_{\mu\nu}$: Energy momentum tensor

$g_{\mu\nu}$:Metric tensor

$R_{\mu\nu}$: Ricci tensor

Newton's law of gravity

$$\phi = -\frac{GM}{r}$$

Φ: Gravity Potential

Poisson equation

$$\Delta\phi = 4\pi G\rho$$

Ρ: Density

Re-written in tensor components

$$\Delta g_{00} = \frac{8\pi G}{c^4} T_{00}$$

Tensor equation is obtained

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Einstein's Equation

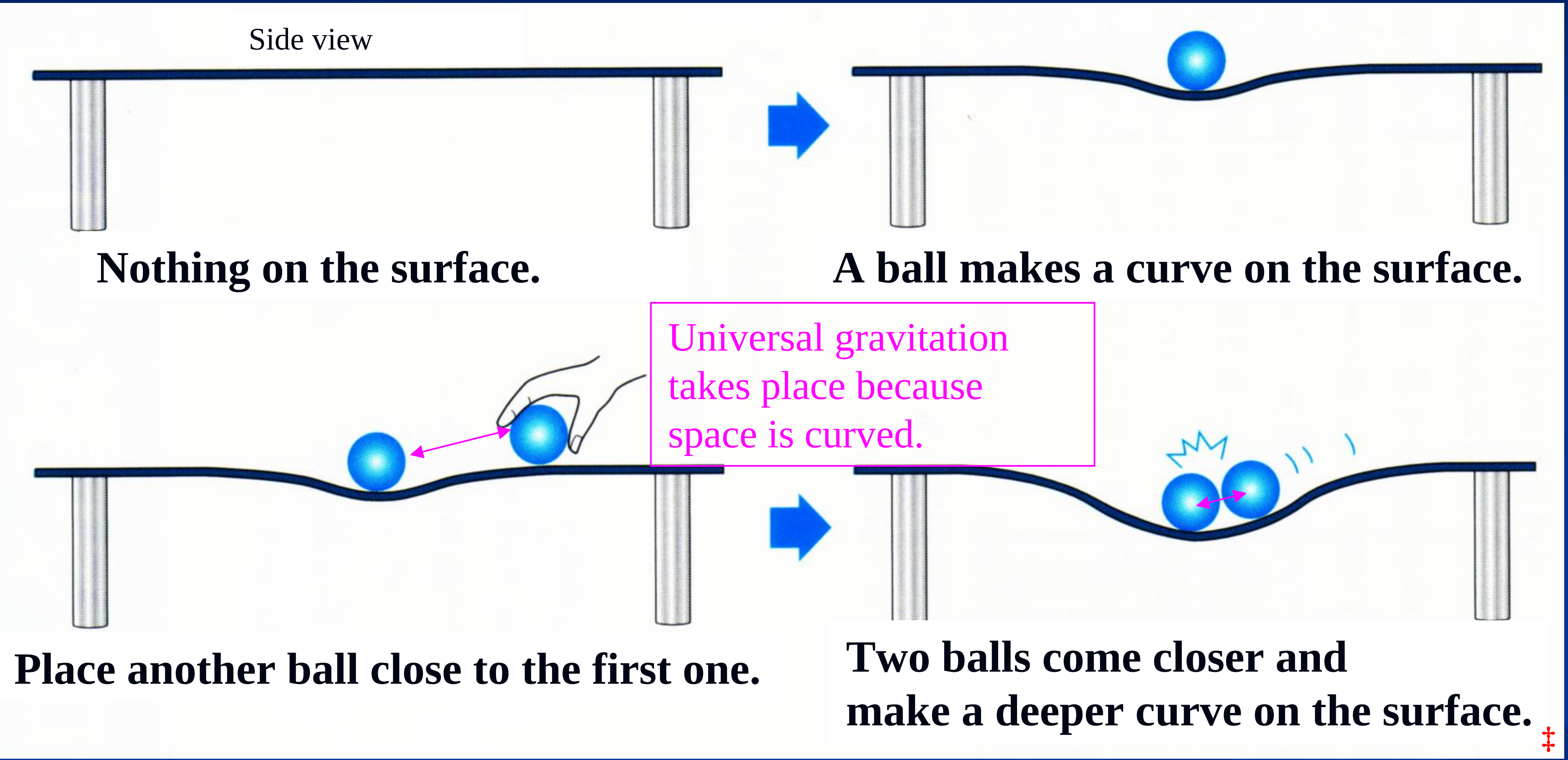
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Quantity that represents space and time geometry (curve).

Quantity that represents the matter-energy.

Matter-energy determines space and time geometry (time dilation and contraction, and a space curve).

Gravity Works in Curved Space



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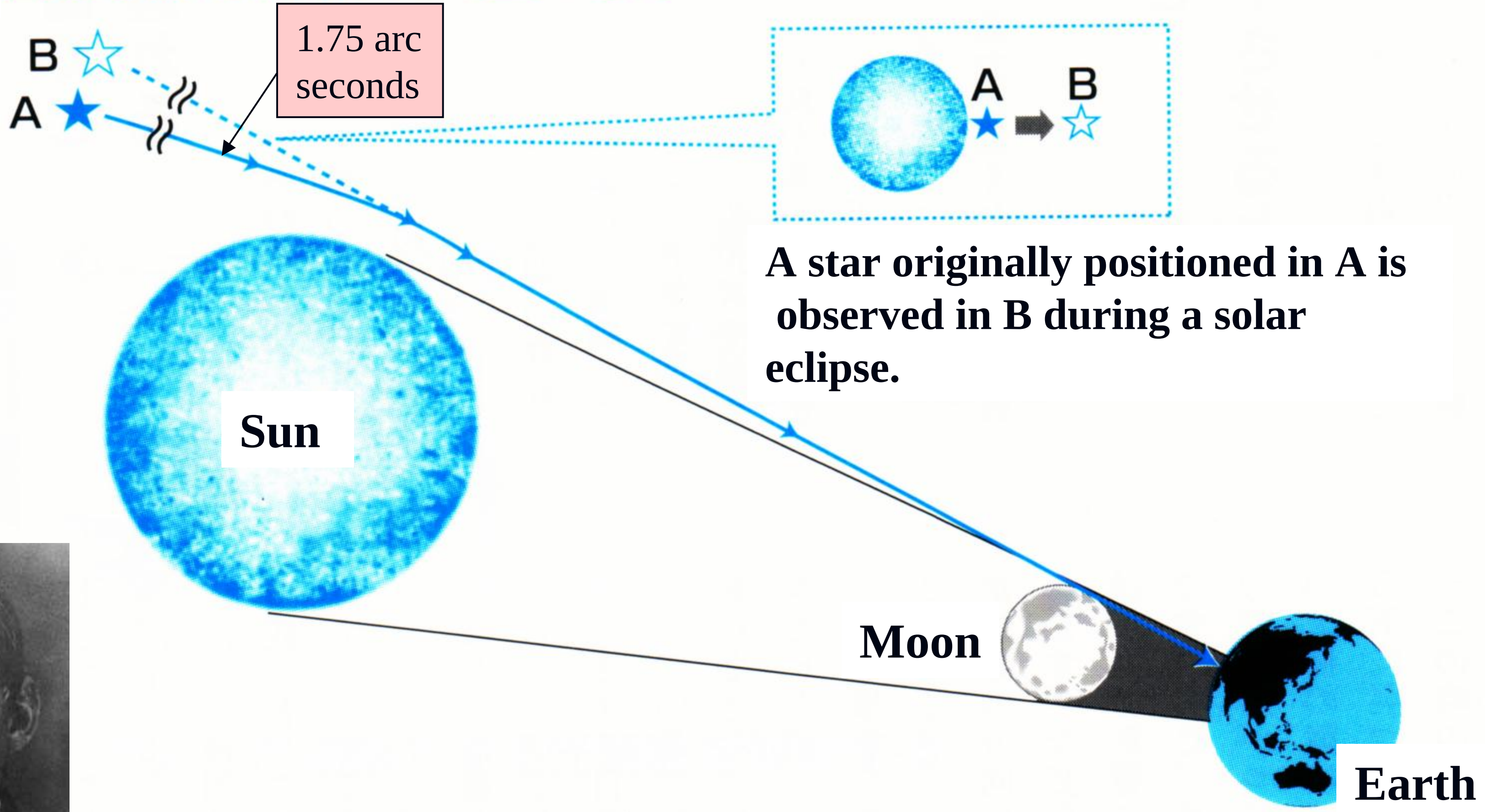
Matter-energy makes curves in space and time, and moves along the curves it makes. *Space and time is not simply the "stage" of the matter; it is a dance partner of matter.*

Deflection of Light by Curved Space

A star near a solar eclipse



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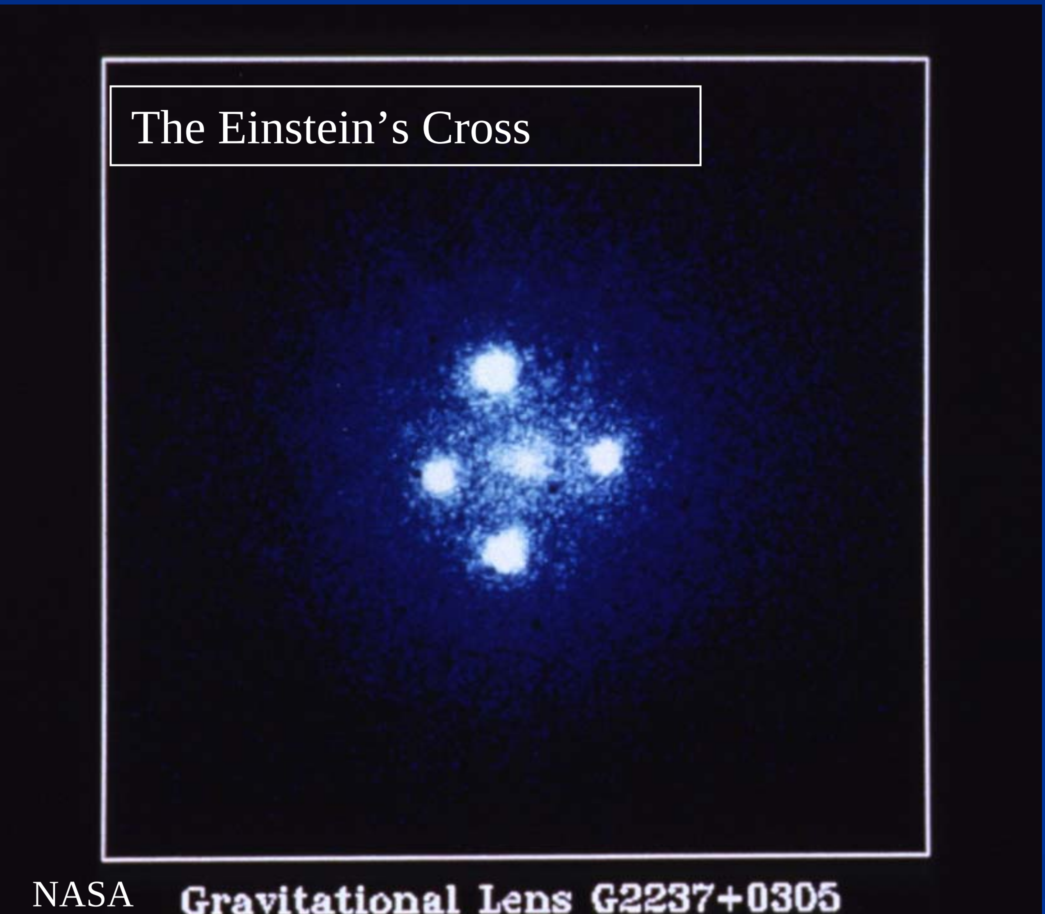
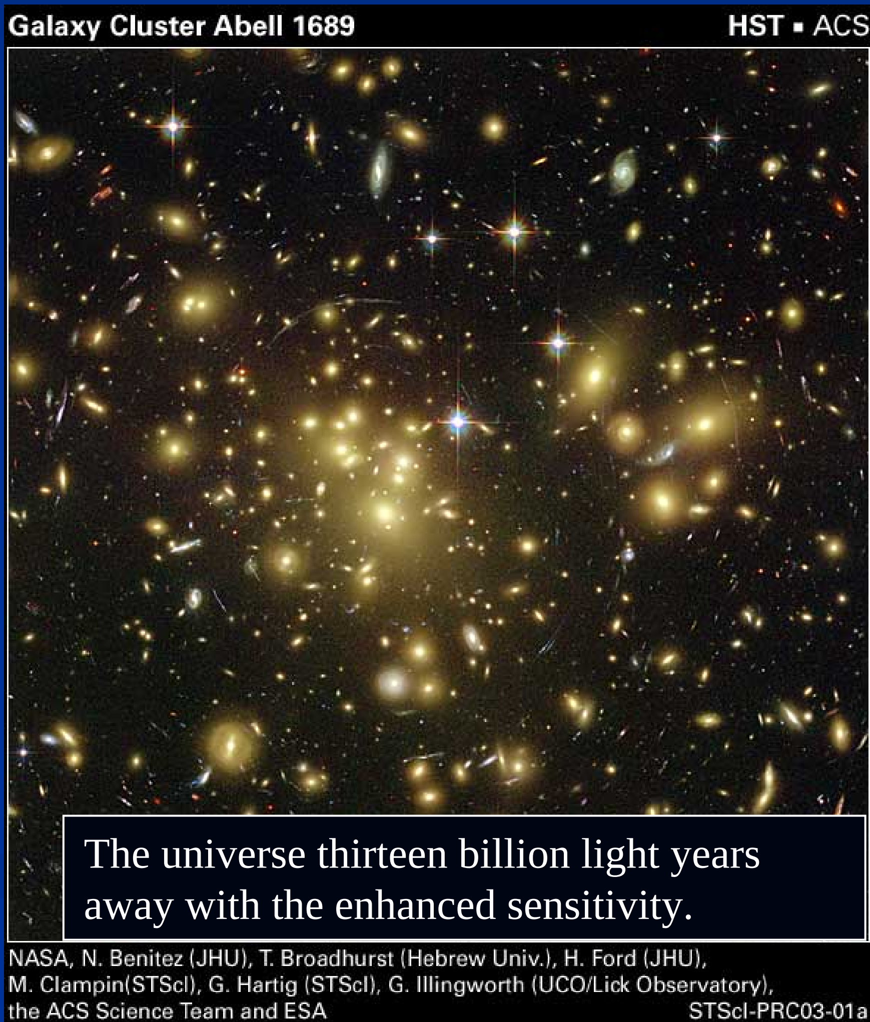
A.S.Eddington is thought to have proved this in his 1919 measurement.

The Gravitational Lens; An Important Step in Astronomical Observation

A single galaxy and a cluster of galaxies become lenses under gravity from a massive object.



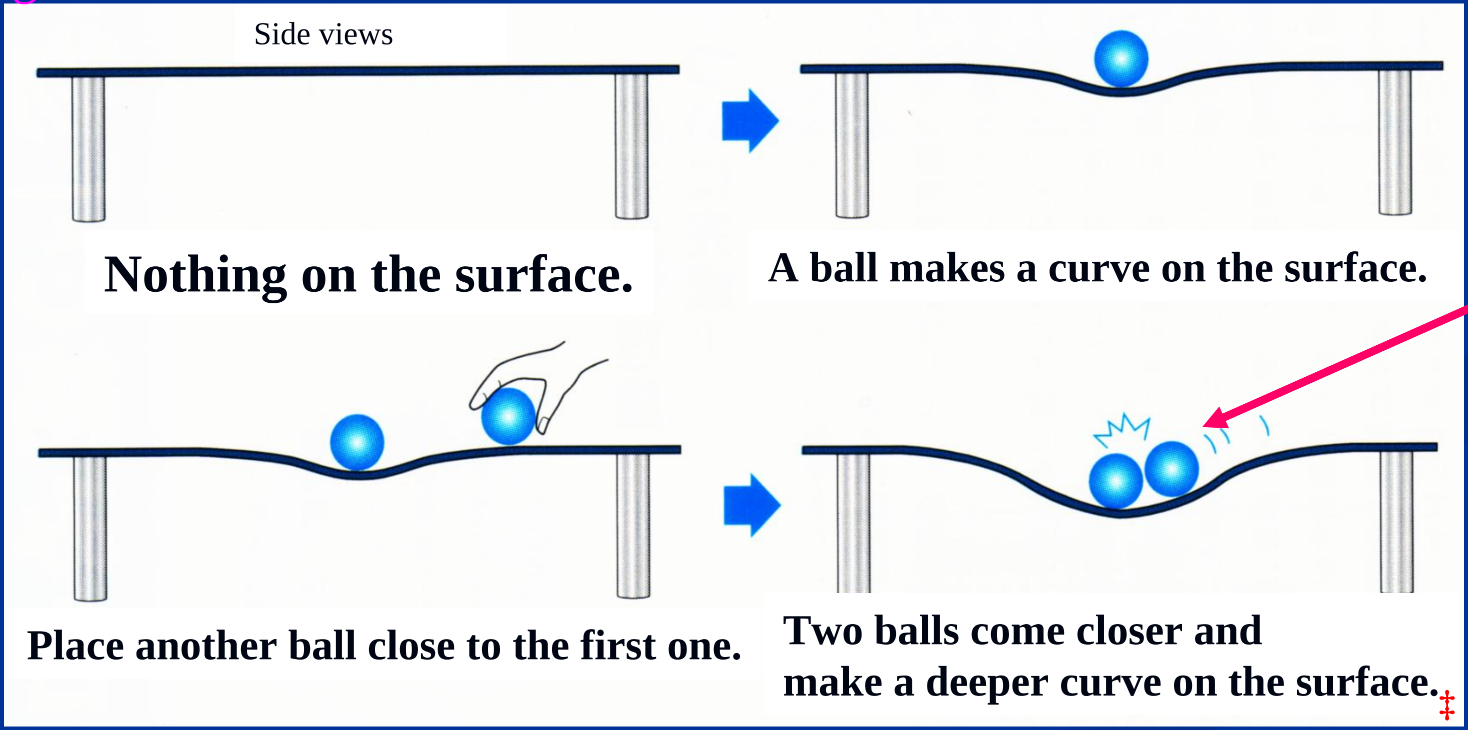
A single quasar eight billion light years away seems to be five quasars.



The universe thirteen billion light years away with the enhanced sensitivity.

Gravitational Waves Plays an Important Role in Astronomy

Intense movement of a massive star generates " ripples in space and time, i.e. gravitational waves."



Intense interaction generates ripples on the surface of the trampoline.

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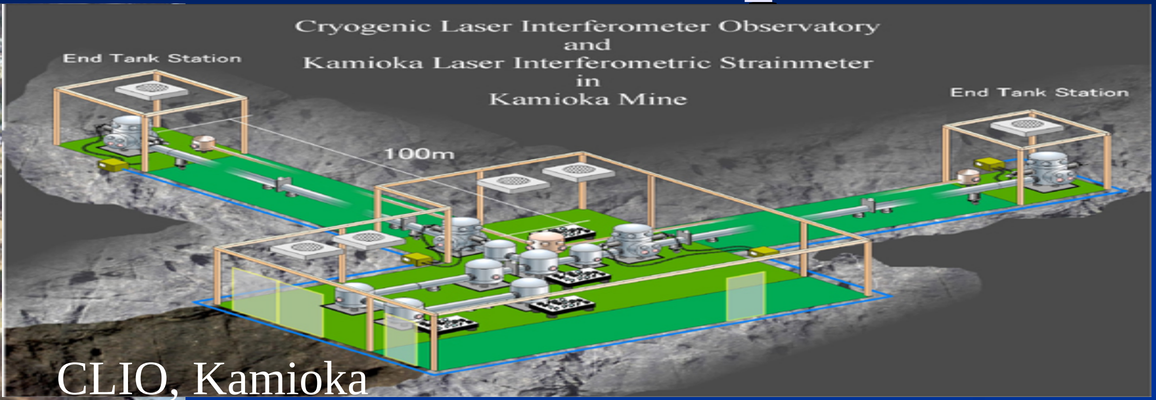
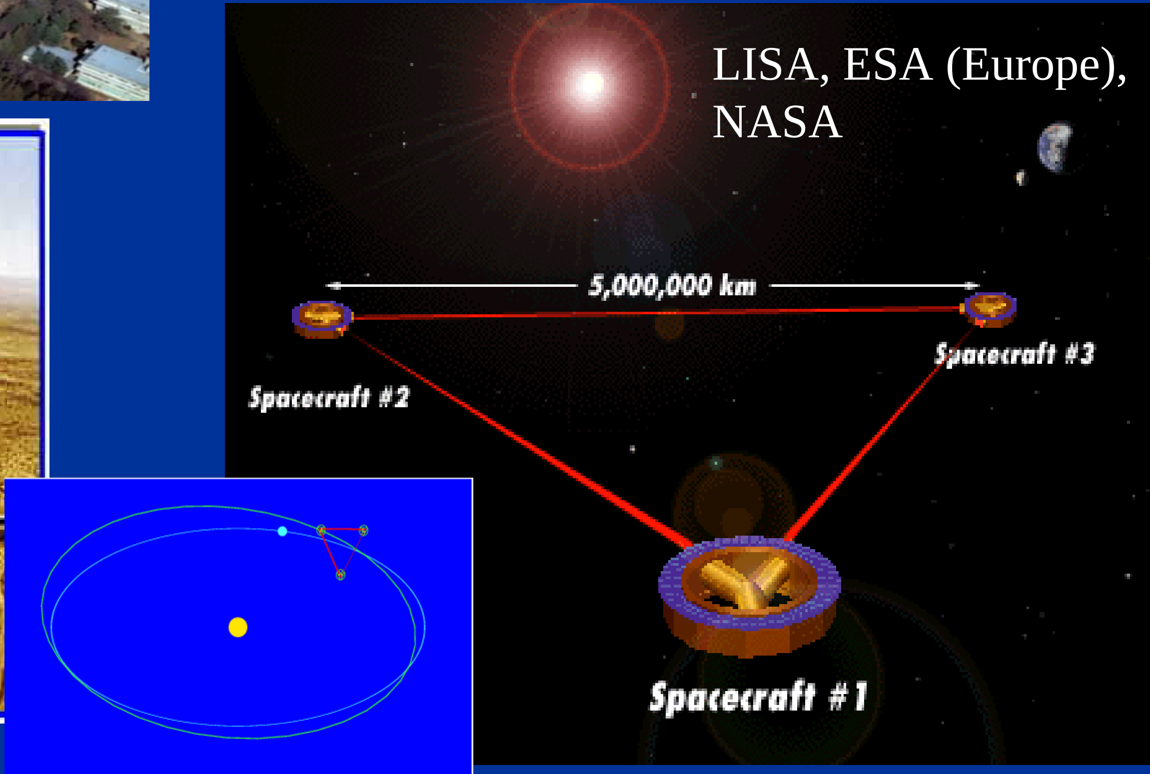
Intense gravitational waves are emitted during black hole formation and from approaching binary stars.

Gravitational-wave Detectors Under Operation and Under Development

TAMA, National



CLIO, Kamioka



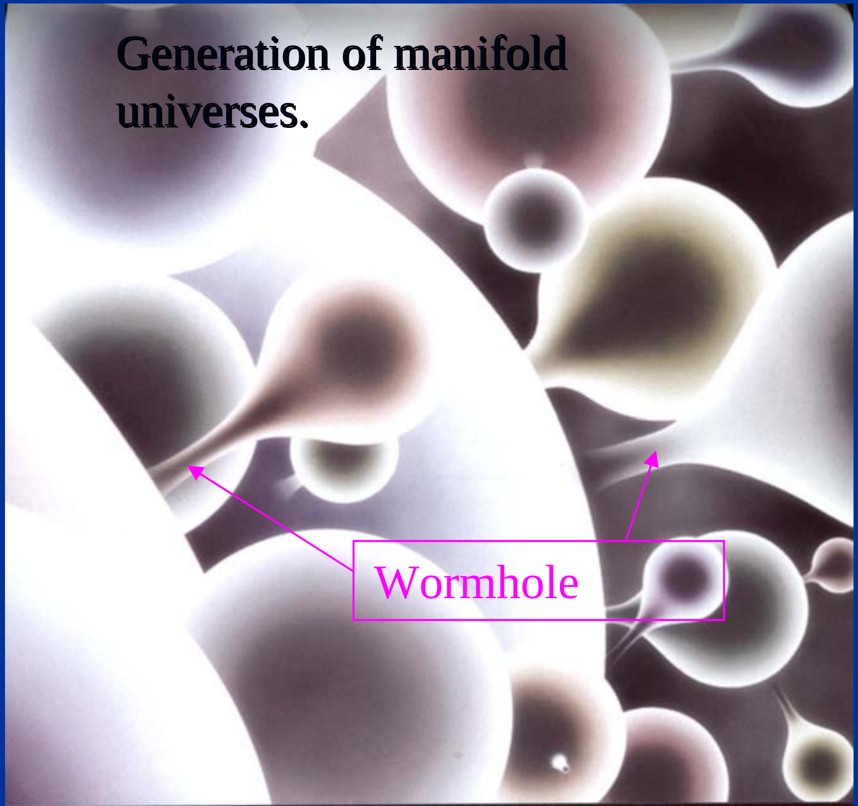
LISA, ESA (Europe), NASA

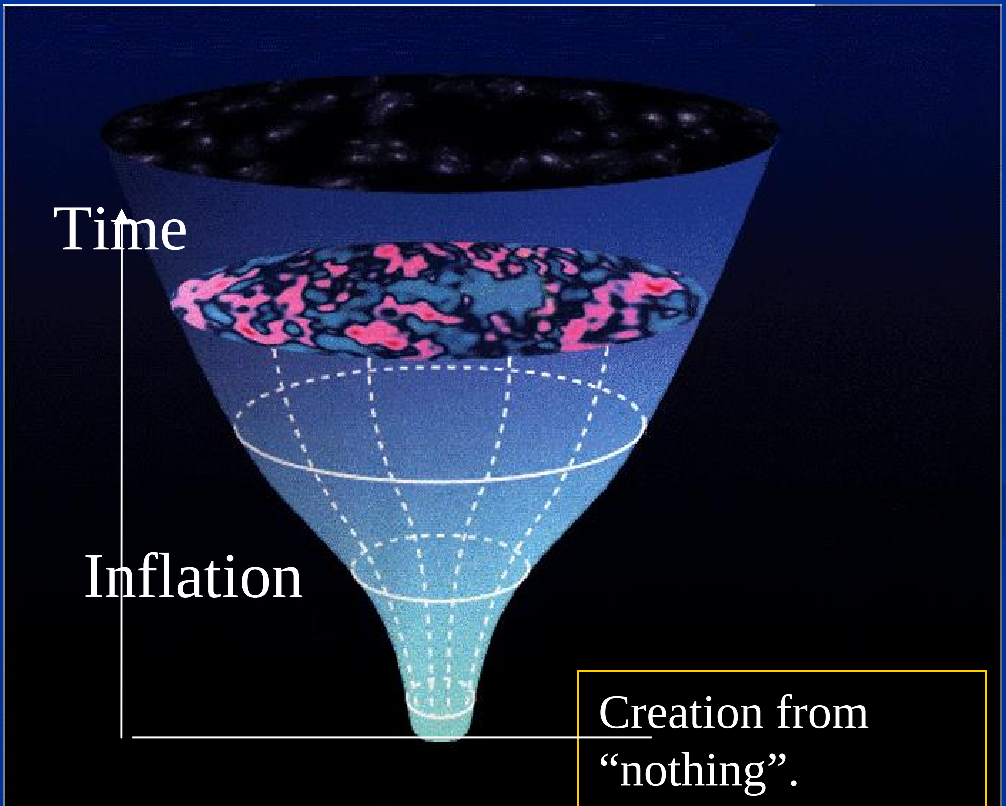
LIGO, U.S.A.

Space-time is Not Simply a “Stage” of Matter; it is a Dance Partner of Matter

- Creation and evolution of the universe.

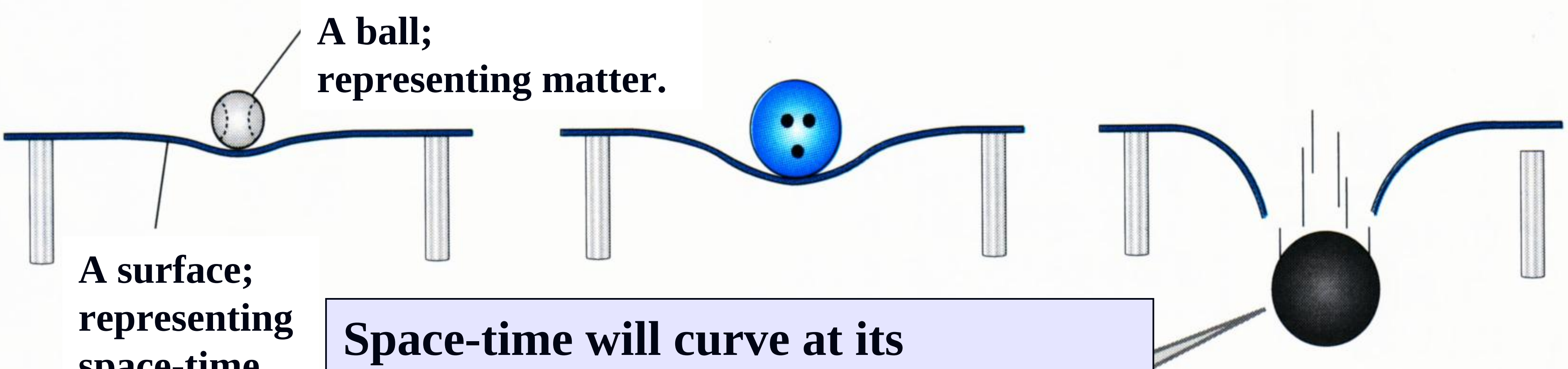
  Space-time coils round matter to evolve together.





4. Black Holes and Wormholes

Space-time and matter with a huge mass



Space-time will curve at its extreme limit around matter that retains such a huge mass; generating a very intense gravity field that even light cannot escape.
This is Black Hole formation.

‡

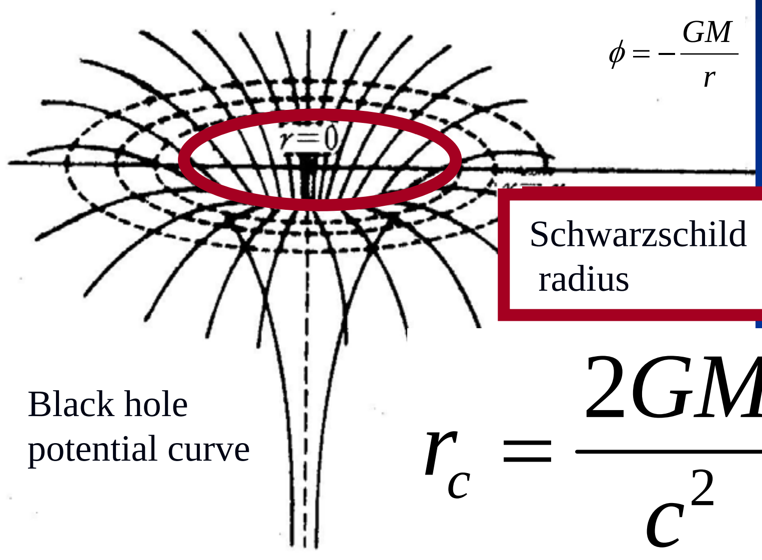
Schwarzschild Black Hole

The solution of Einstein's equation for the gravity field of a point mass. K. Schwarzschild (1915)

The solution has an event horizon (Schwarzschild surface) in which not even light can escape from it: a one- way zone.

Einstein never thought black holes existed.

(Ann. Math., 1939)



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

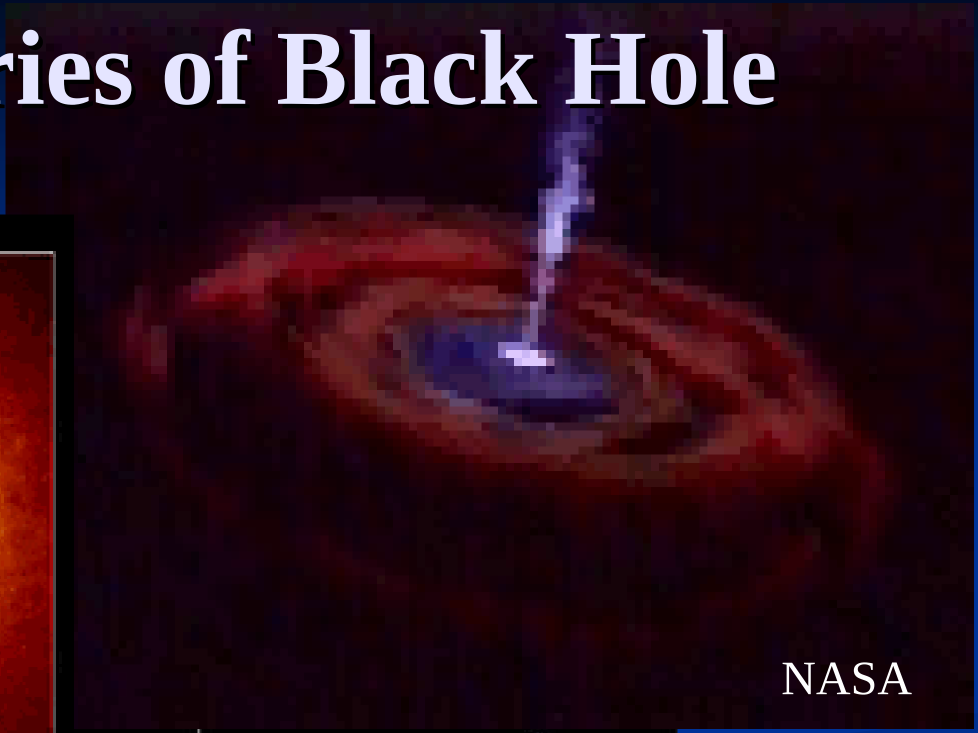
Schwarzschild radius: the radius at which escape velocity becomes the speed of light.

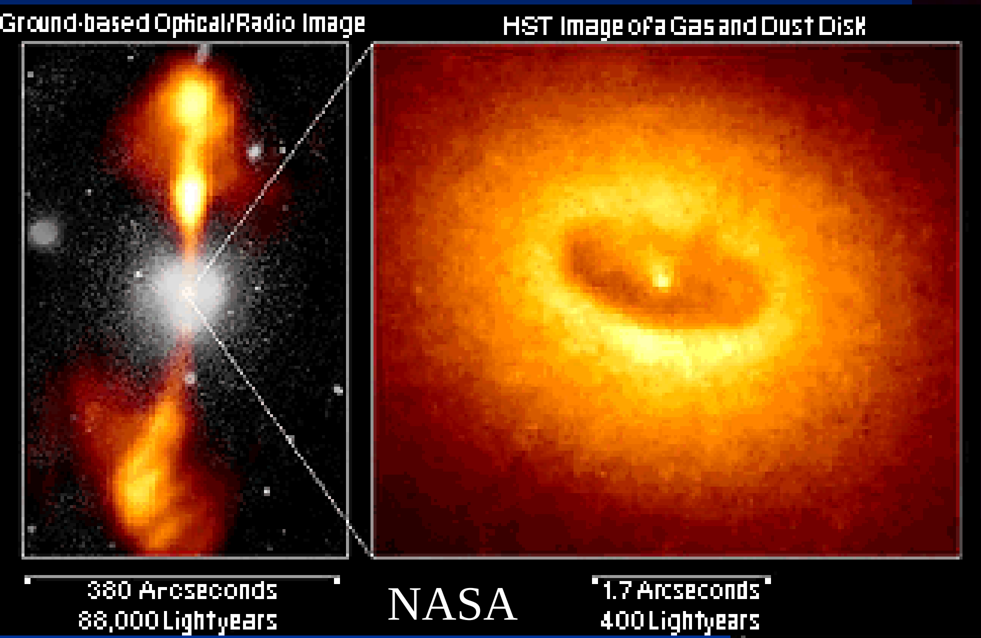
$$\frac{1}{2}mv^2 = \frac{GmM}{r_c}$$

$$v = c$$

J. Mitchell,1783

Many Discoveries of Black Hole





Black holes are universal in the cosmos.

After the explosion of stars and at the center of the galaxy.

Black Hole Evaporation

- Black hole area theorem (S.Hawking, 1973)
- Black hole surface area **A** increases proportionally even if multiple black holes combine together:

$$\Delta A \geq 0$$

Relates to the increase of black hole entropy.

- Black hole thermodynamics (J. Bekenstein, 1973)

$$dE = dMc^2 = T_{BH} dS_{BH}$$

$$S_{BH} \equiv \frac{kc^3}{4G\hbar} A$$

- Generalized black hole thermodynamics.

$$S = S_{matter} + S_{BH}$$

$$\Delta S \geq 0$$

- Temperature of the black hole.

(Hawking's temperature)

$$T_{BH} \equiv \frac{\hbar c^3}{8\pi GM}$$

Black Hole Evaporation

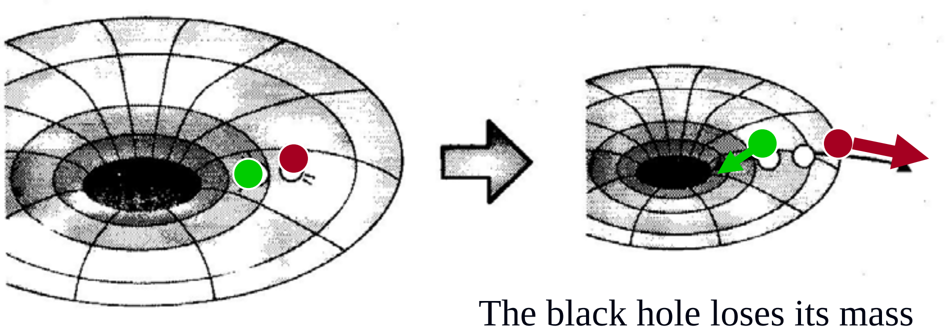
- Black holes have a temperature, and it evaporates away due to quantum effects.

$$T_{BH} \equiv \frac{\hbar c^3}{8\pi GM}$$

$$= 1.2 \times 10^{26} / M(g) K$$

$$= 6.2 \times 10^{-8} M / M_{Sun} K$$

Black hole evaporation



A pair of particles and antiparticle is created right outside the event horizon.

The black hole loses its mass when either the particle or antiparticle (the one with negative energy) is sucked into the event horizon.

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A primordial black hole might be created during the primordial state of universe. S. Hawking (1974)

If the mass of a black hole is greater than 10^{15} g, the time which takes for it to evaporate becomes longer than 14 billion years (the universe's age).

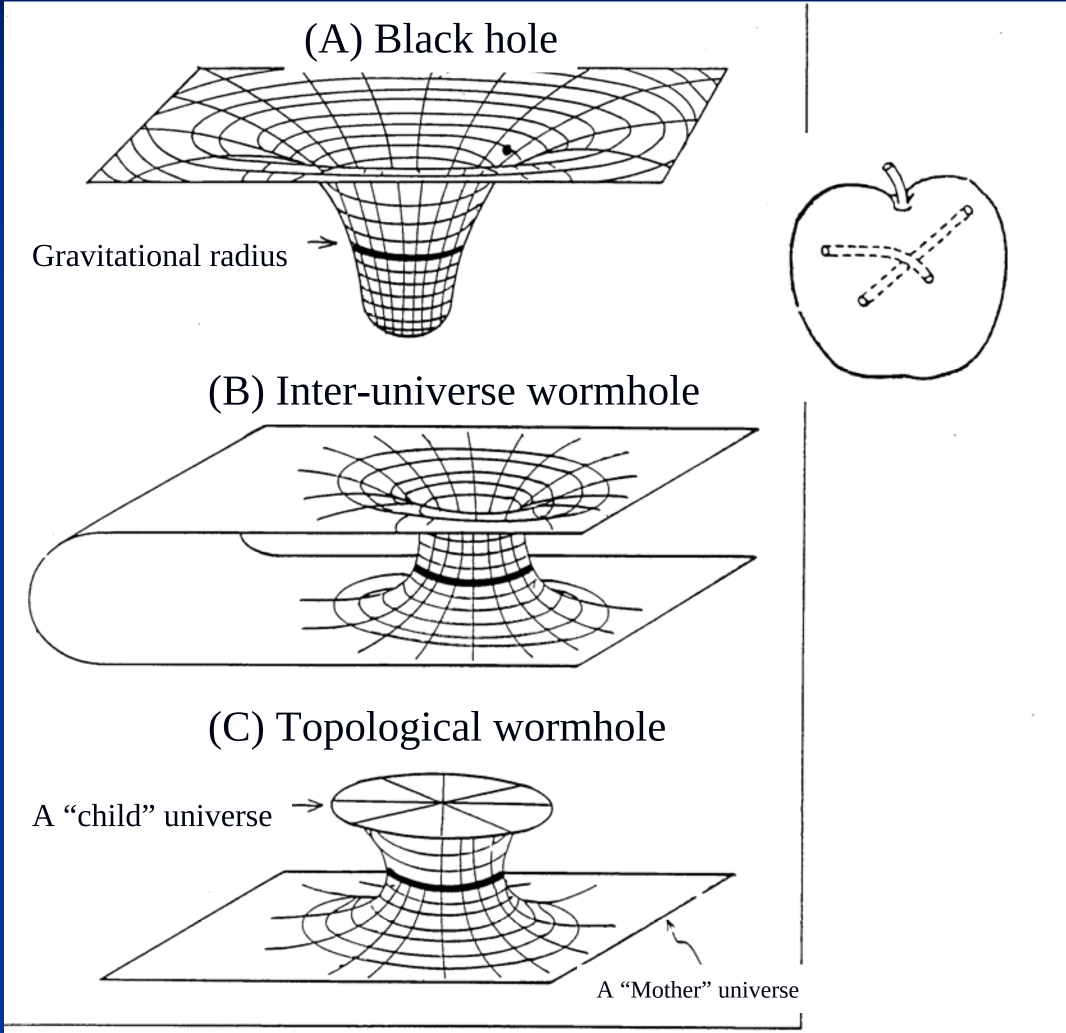
Wormhole

The lower half of the black hole is cut off and a copy of the upper half is connected to the cut off part.

It is a space-time structure containing a shortcut on the surface. Imagine a worm, traveling on an apple's skin as it burrows a wormhole.

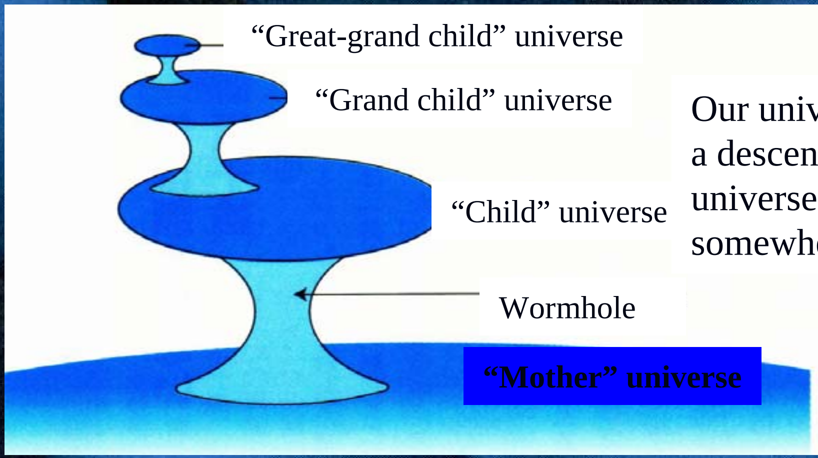
It is used as a shortcut (warp) for space travel in science fiction

Generally not traversable.



Models of black hole and worm holes

Multiple Birth of Universe



Our universe might be a descendant of “mother” universe found somewhere.

Sato, Sasaki, Kodama and Maeda. **(1982)**

A “mother” universe gives birth to a topological wormhole, which gives birth to a “child” and “grand child” universe

Sato, Nikkei Science

5. Time Machine Problems

- A very dominant SF theme.

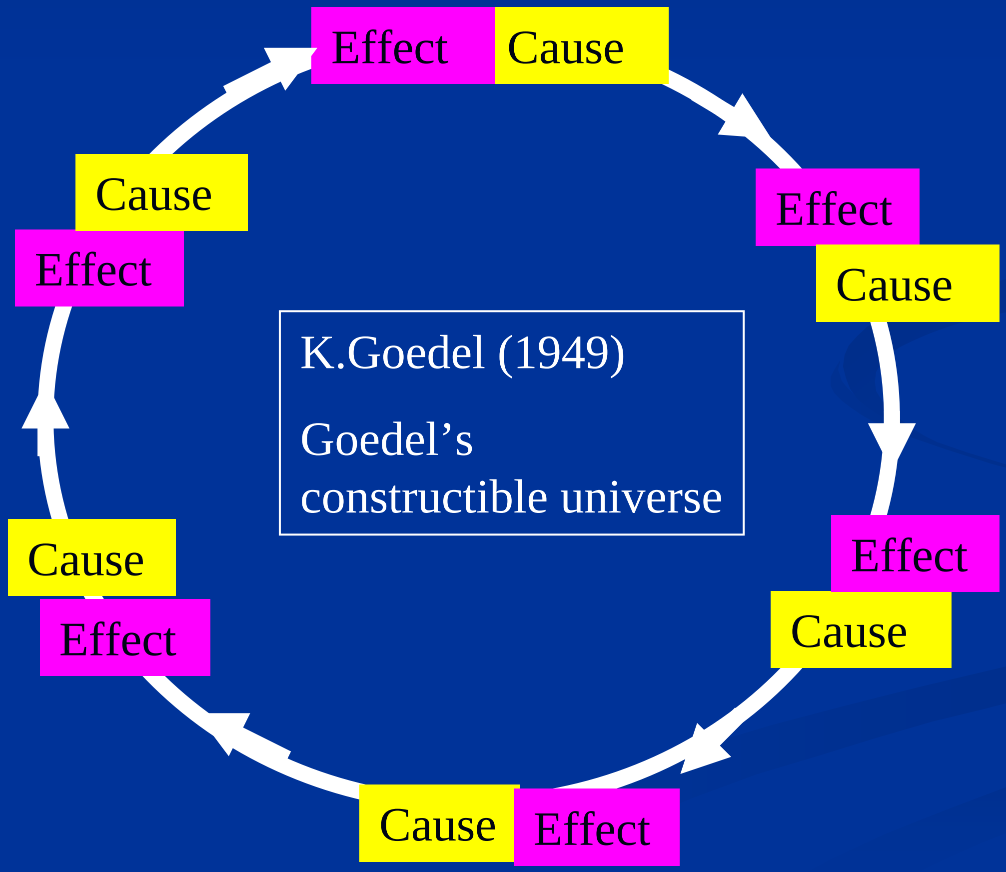
It gives rise to a the theoretical paradox known as the “grandfather paradox”:

“ What happens if a time traveler killed her mother before she was born? The time traveler herself would not have been born, thereby there is no way of killing her mother.”

- Surprisingly enough, the theory of general relativity never prohibits time travel.

Time Machine

The Existence of Closed Timelike Curves (CTC) in a Solution to Einstein's Equation



Einstein was surprised when Goedel, a mathematician and Einstein's counterpart found the existence of closed timelike curves (CTC) in a solution of Einstein's equation.

The Time Machine and Closed Timelike Curve (CTC) Problems

- Einstein was surprised by the discovery of a solution, that included CTC; the solution of Goedel’s universe (1949).
- He never thought a solution using CTC would be workable.
- However, K. Thorne (Phys. Rev. Lett. 1988) showed a way to create a time machine using wormholes.

K. Thorne's Time Machine

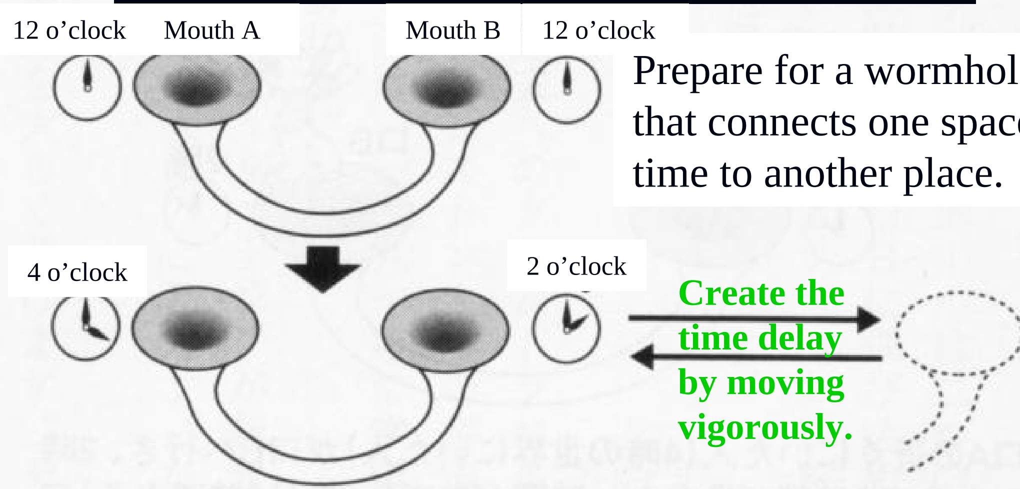
You cannot go back to the time prior to when the time machine is created.

In order to retain the wormhole to be traversable, the negative energy should be permeated.

Wormhole enlarges microscopic matter caused by quantum fluctuation.

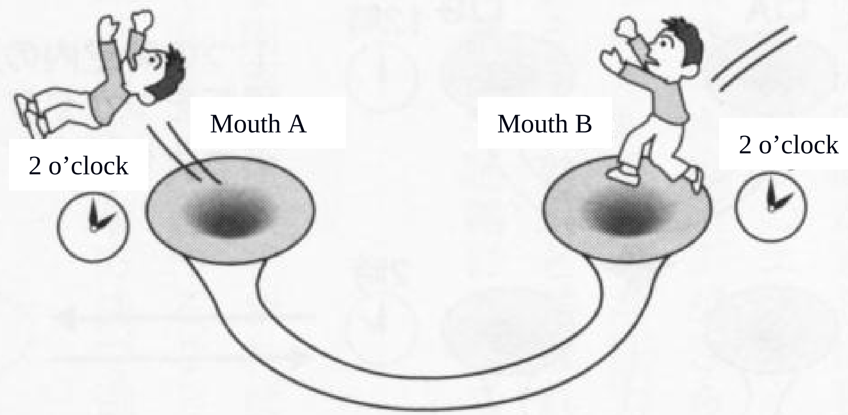
There is a future possibility of an intellectual creature existing in reality.

Wormhole time machine 1



Prepare for a wormhole that connects one space-time to another place.

Create a time gap between mouth A and mouth B by moving mouth B at the speed of light.



A person near mouth A (the person who was at 2 o'clock world) goes to mouth B and jumps into mouth B. In zero time (at 2 o'clock), he will come up form mouth A, thereby traveling back to the world two hours ago.

‡

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The Time Machine and Closed Timelike Curve (CTC) Problems

- 1. Is everything defined?

As long as causes are consistently connected, time can make a loop. (Principle of Self-consistency)

What seems to be free will may be an illusion. I. Novikov (1998)

- 2. Chronology Protection Conjecture

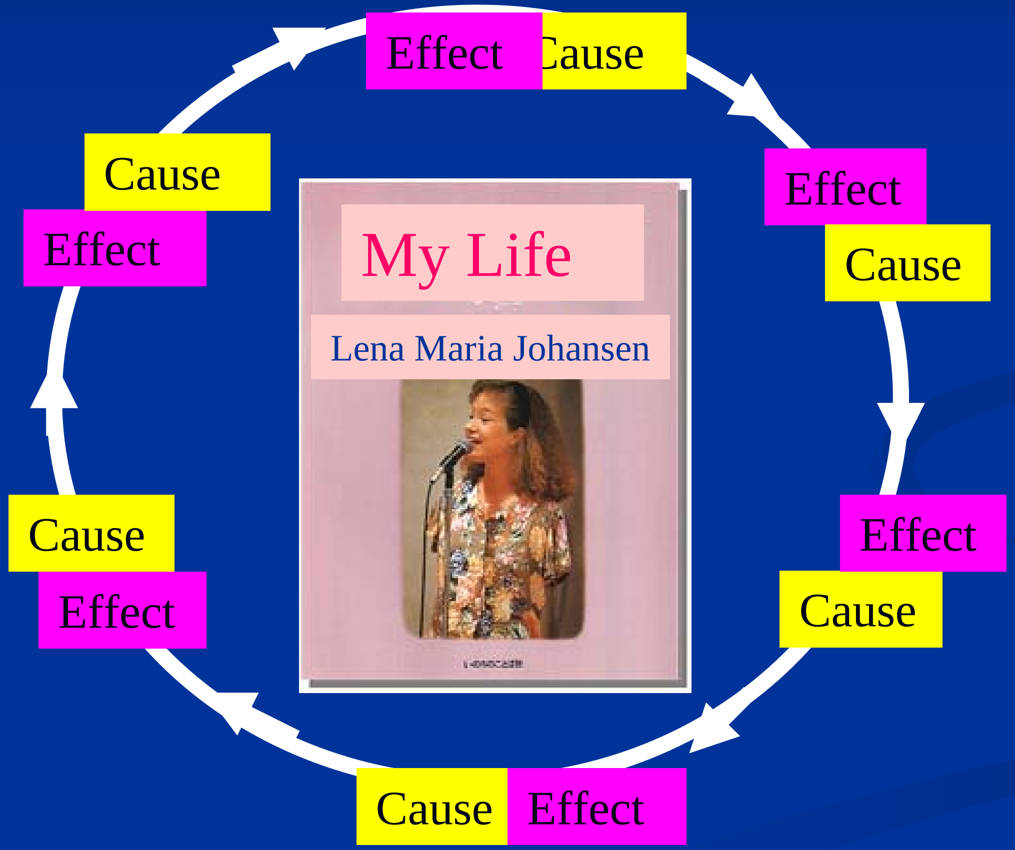
Even though the theory of relativity, one of the two pillars of modern physics allowed for the possibility of the existence of a time machine and CTC, quantum theory may not allow them. <u>Quantum-gravitational instability of the wormhole</u>. S.Hawking (1990)

- 3. Many world interpretation enables the possibility of a time machine without violating causality.

A person may travel backward to the past and change history and creating yet another universe.

D.Deutsch, M.Lockwood (1994)

Is Everything Defined?
(Principle of Self-consistency)



If there is consistent connection of cause and effect just like the water pools in Toshimaen which are connected like a loop, there should arise no problems.

Is free will an illusion?
Lena Maria Johansen
(1968 -)

"They say I am a disabled person however, I look at myself as a person with complete freedom. I am just trying to do what is capable within the limits of my abilities, and so are you.

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Chronology Protection Conjecture

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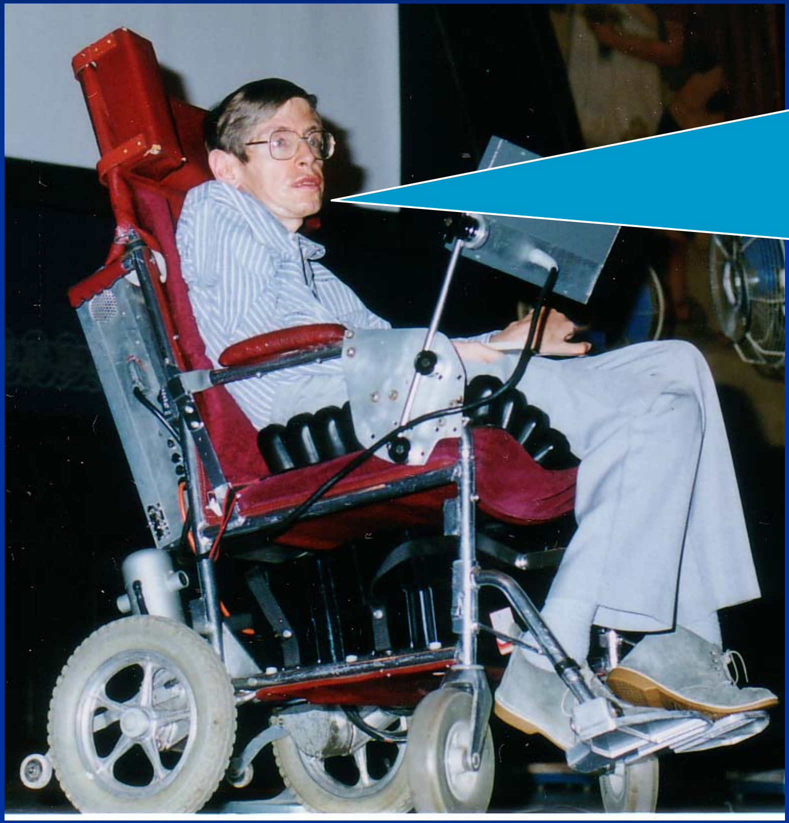

The University of Tokyo, Yasuda Auditorium, (1990)

If a time machine is possible in principle, the world would be filled with travelers from the future.

The wormhole collapses due to quantum-gravitational instability, and eventually becomes untraversable.

Quantum theory plays a role as a time patrol.

The Time Machine and Closed Timelike Curve (CTC) Problems

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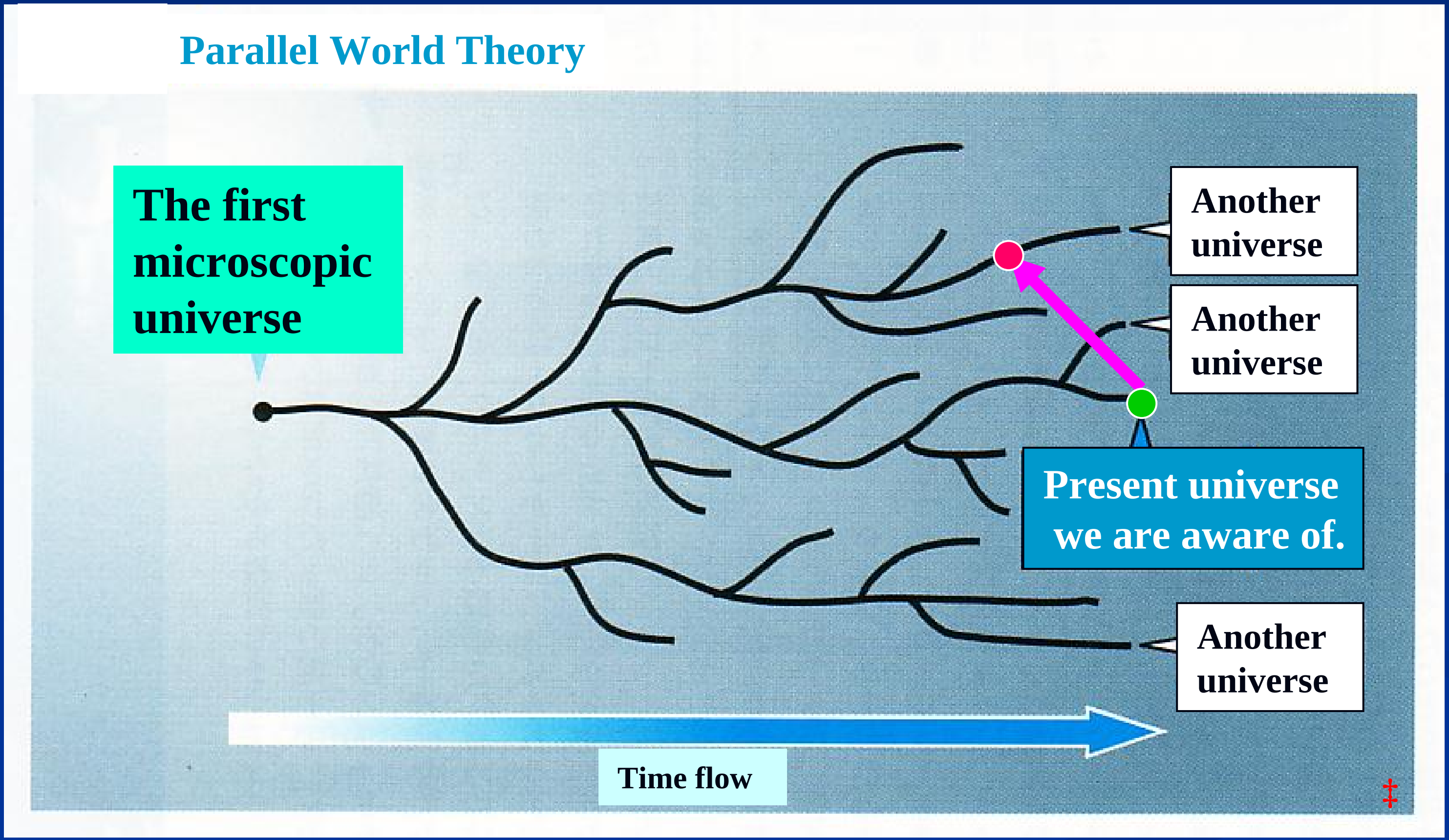
D.Deutsch's Many Worlds Time Machine Interpretation

- The universe split infinitely into branches following quantum theory.



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If you travel backward to the past and killed your mother, the mother you killed would belong to one of an infinite number of other universes.

Black Hole Evaporation Problem and the Time Machine Problem Suggest Larger Space-time Problems

- Superstring theory successfully derived the entropy of black holes.

$$S_{BH} \equiv \frac{kc^3}{4G\hbar} A \qquad T_{BH} \equiv \frac{\hbar c^3}{8\pi GM}$$

- Although the chronology protection conjecture remains a hypothesis, it suggests the instability of wormhole space-time.
- The time machine problem is recreation for quantum gravitational theorists. S. Hawking

6. What is the Use of General Relativity?

- It is an optional course for physics majors in the Department of Science; not a required course.
- Without the knowledge of space-time physics, there is no way of knowing this universe completely.
- It is indeed not needed in everyday life, yet there is a good operative example that provides convenience to our everyday life.

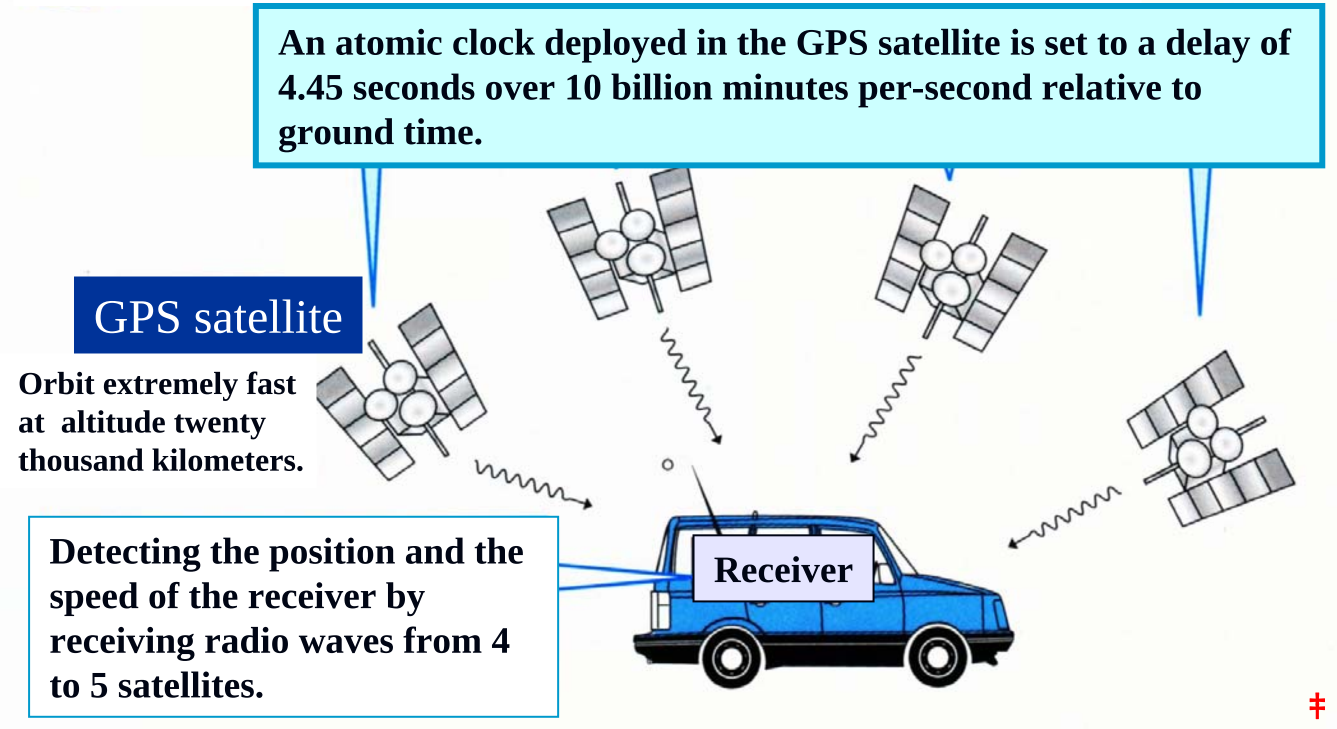
GPS (Global Positioning System)

Satellite time: t_{Satt}

Ground time: t_{Gro}

$$t_{Satt} = \left(1 + \frac{\phi_{Satt} - \phi_{Gro}}{c^2} - \frac{v^2_{Satt} - v^2_{Gro}}{2c^2}\right) t_{Gro}$$

GPS Satellite and an Onboard Navigating System



Sato, Katsuhiko, ed. Zukai: Soutaisei Riron. Tokyo: PHP Research Institute, 2003. p.65

General relativity correction is necessary for an accurate reading of one's position.

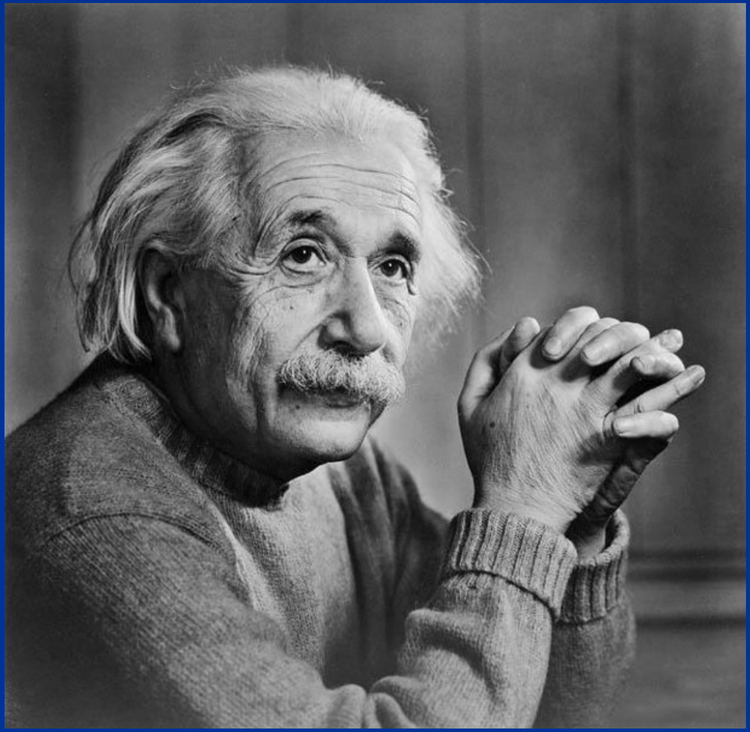
Summary

- Space-time was once thought as a stage for matter to dance: A box of matter.
  - Space-time is a priori. (Kant)
  - Absolute time and absolute space. (Newton)
- Space-time is rather a dance partner of matter.
- The theory of relativity along with quantum theory is a pillar of modern physics. We must understand space-time in order to investigate our universe and where in the universe we belong.
- The theory of relativity is not as practical as quantum theory these days, but by the end of 21st century, the theory of relativity will be needed in many technologies.

Quotation by A. Einstein

If matter were to disappear, space and time alone would remain behind (as a kind of stage for physical happening).
This standpoint was overcome ... with the “concept of field” and its final claim to replace, in principle, the idea of particle s (material points).
The inseparability of time and space emerged in connection with electrodynamics, or the law of the propagation of light.

Quotation by A. Einstein (2)



Gravitation cannot be held responsible for people falling in love.