Strings, Membranes and Quantum foam

Dr Martin Hendry

Dept of Physics and Astronomy
University of Glasgow

Einstein's Universe

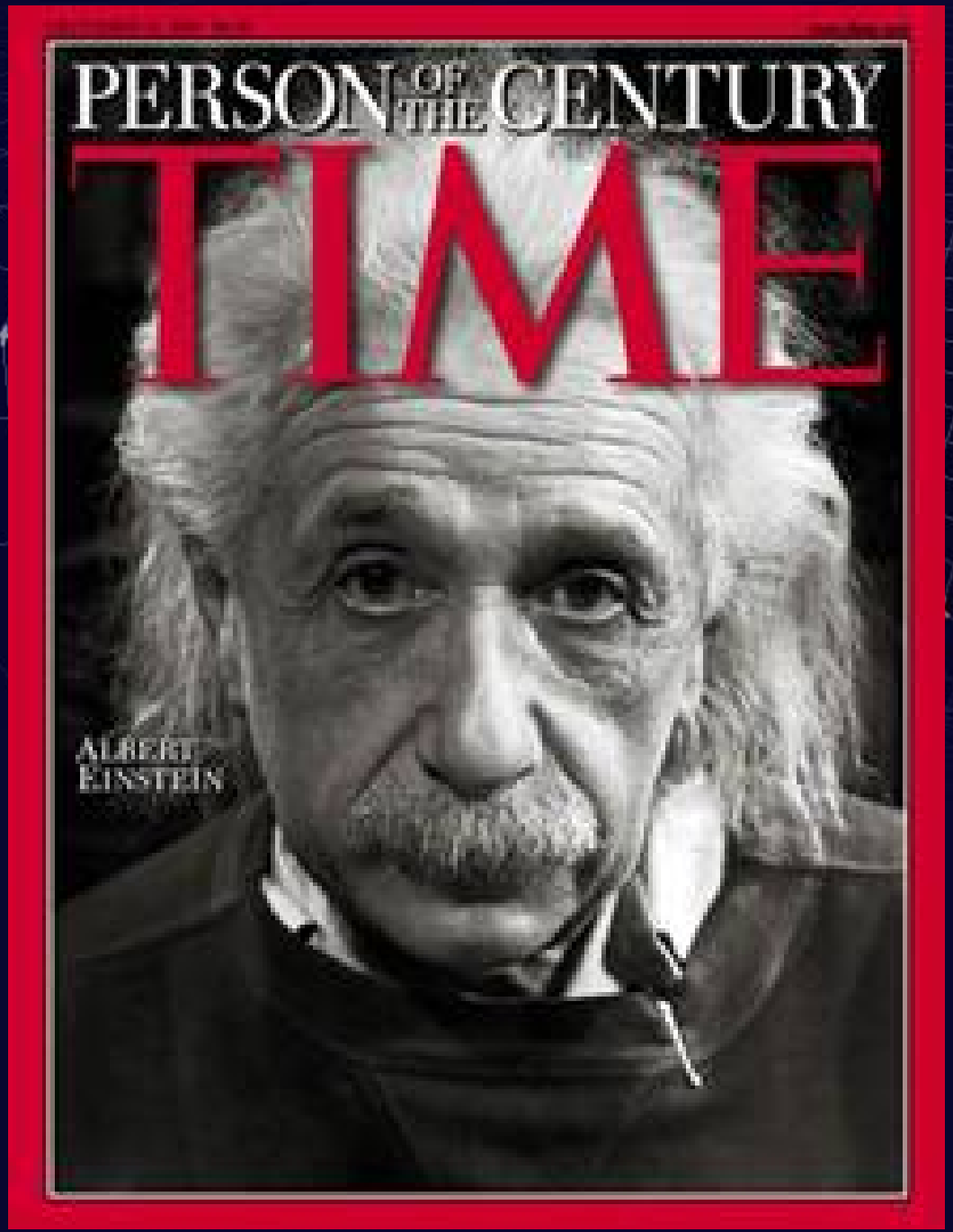
Dr Martin Hendry

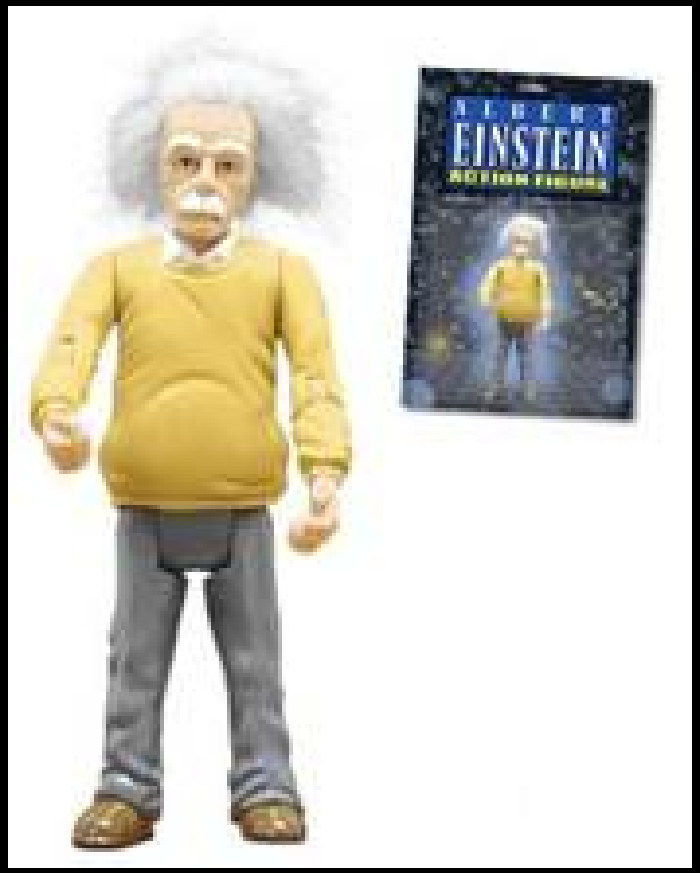
Dept of Physics and Astronomy
University of Glasgow

Post-Einstein's Universe

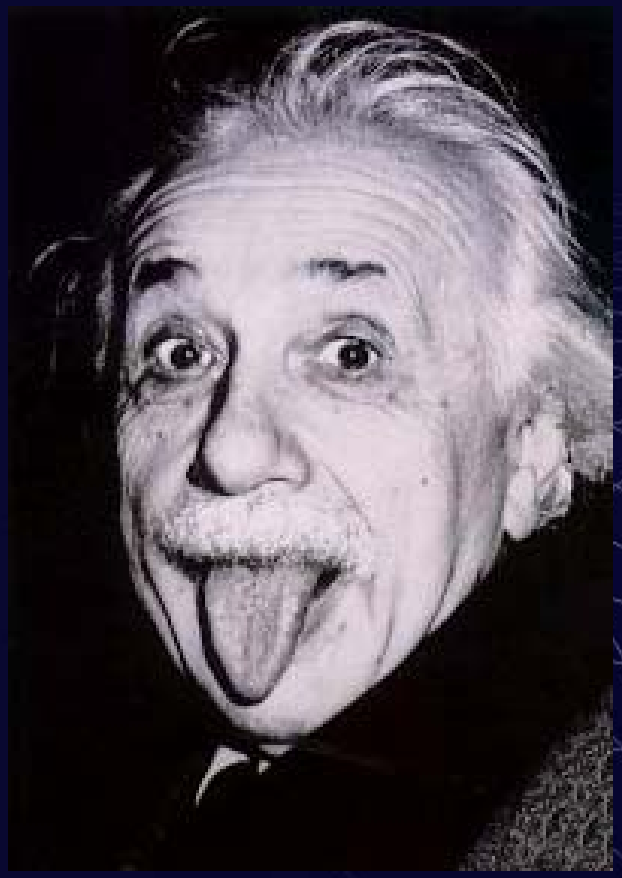
Dr Martin Hendry

Dept of Physics and Astronomy
University of Glasgow


PERSON OF THE CENTURY
TIME
ALBERT EINSTEIN


ALBERT
EINSTEIN
ACTION FIGURE

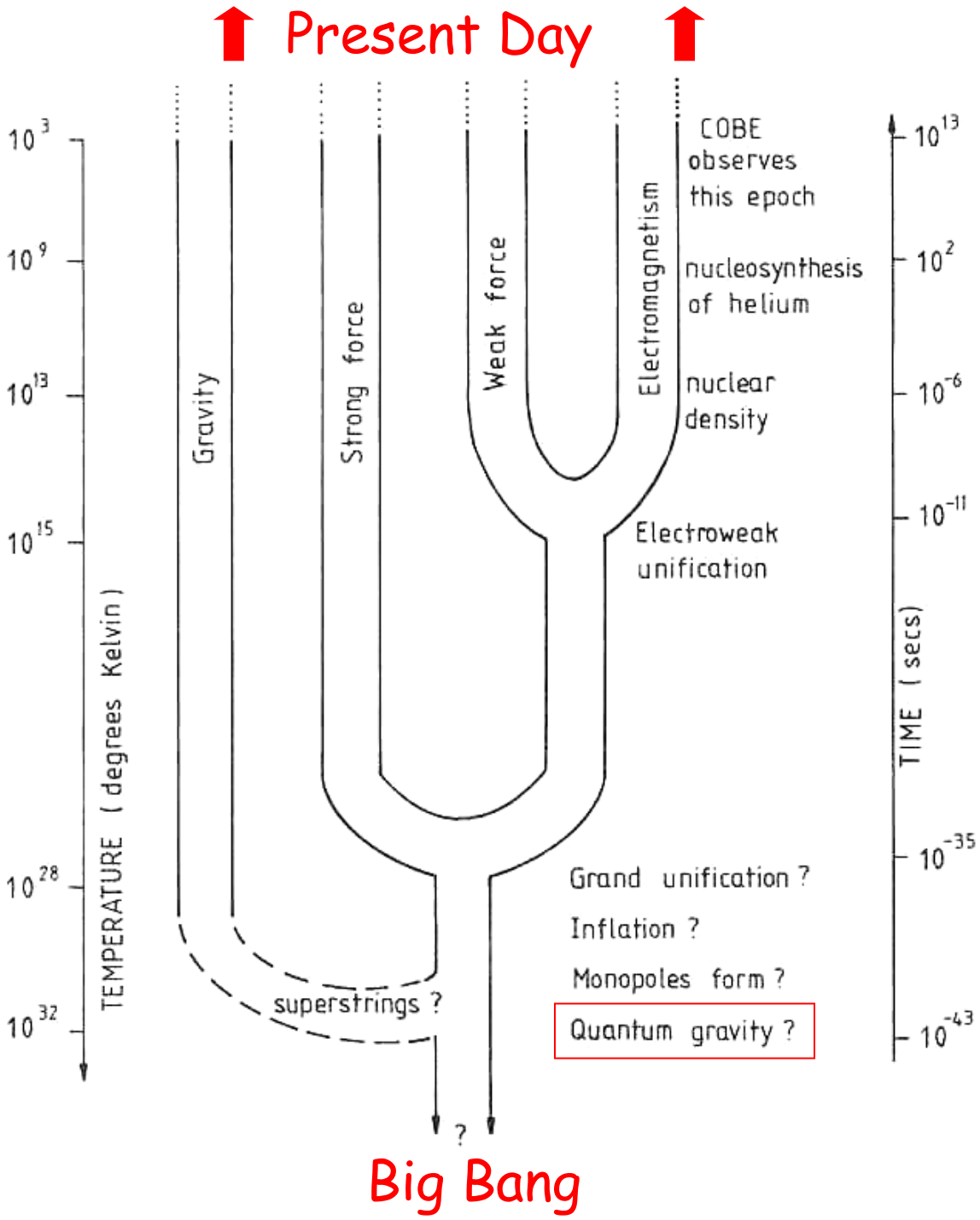

If A equals success,
then the formula is:
A=X+Y+Z
X is work. Y is play.
Z is keep your
mouth shut.



"The generalisation of the theory of gravitation has occupied me unceasingly since 1916"

Einstein, 1953

Space:
The Final Frontier


Present Day
10^{3}
10^{9}
10^{13}
10^{15}
10^{28}
10^{32}
TEMPERATURE (degrees Kelvin)
Gravity
Strong force
Weak force
Electromagnetism
COBE observes this epoch
nucleosynthesis of helium
nuclear density
Electroweak unification
Grand unification ?
Inflation ?
Monopoles form ?
Quantum gravity ?
superstrings ?
?
10^{13}
10^{2}
10^{-6}
10^{-11}
10^{-35}
10^{-43}
TIME (secs)
Big Bang

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

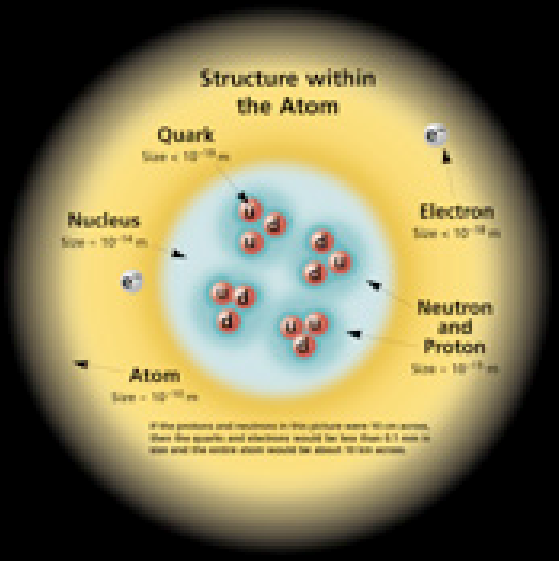
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-22}$ MeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c²	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and W and Z bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** ($q\bar{q}$) and **baryons** (qqq).

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromagnetic for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromagnetic for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons. There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	−1	1.672	3/2

Mesons $q\bar{q}$
Mesons are bosonic hadrons. There are about 140 types of mesons.

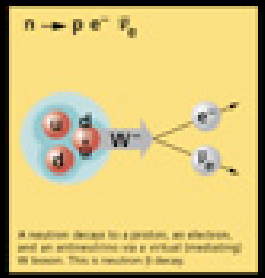
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^0	rho	$u\bar{u}$, $d\bar{d}$	0	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

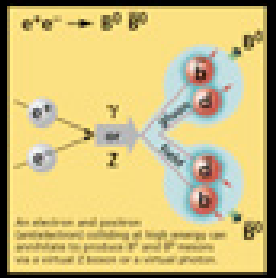
Matter and Antimatter

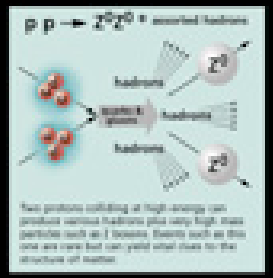
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless a or − charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

These diagrams are an artist's conception of physical processes. They are **not** exact and have **no** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.







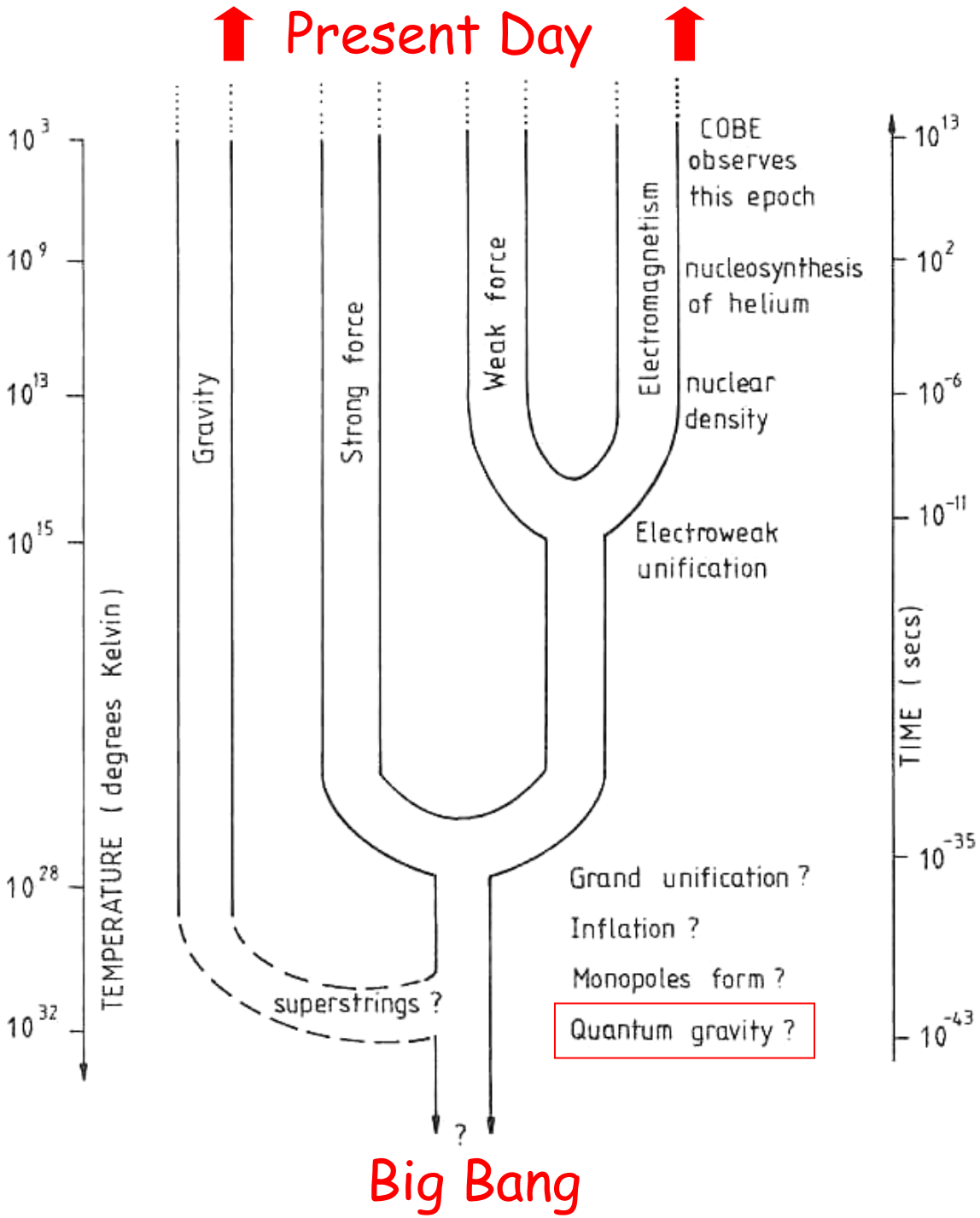
The Particle Adventure

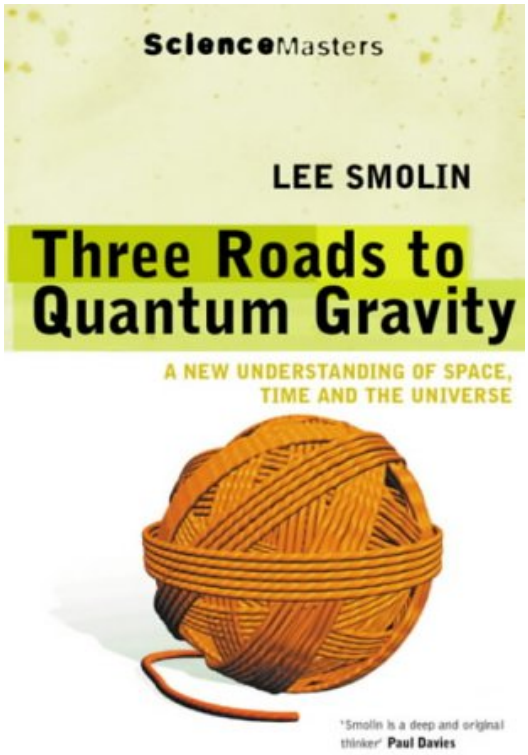
Visit the award-winning web feature *The Particle Adventure* at http://pdg.lbl.gov/cpep/adventure.html

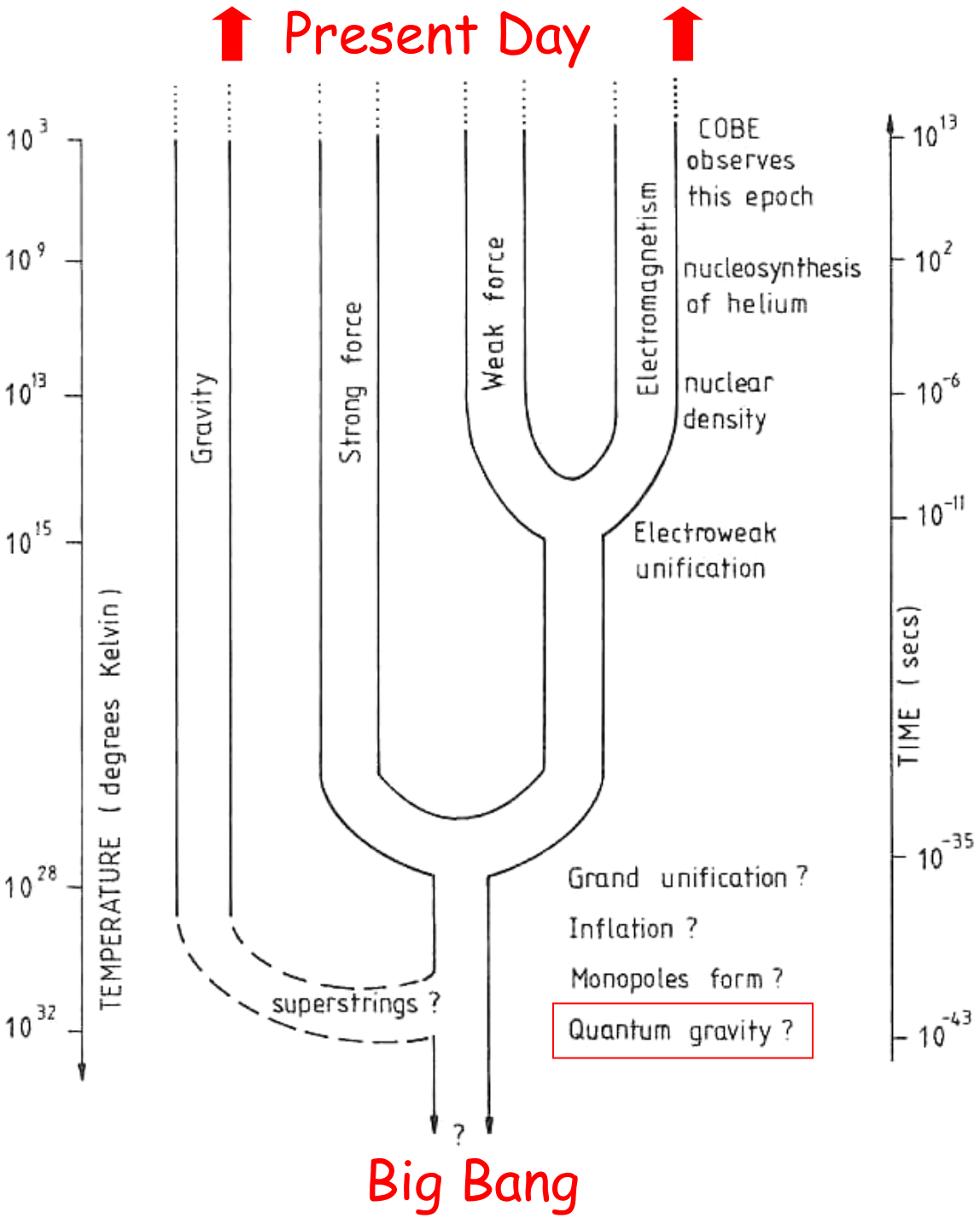
Sponsors

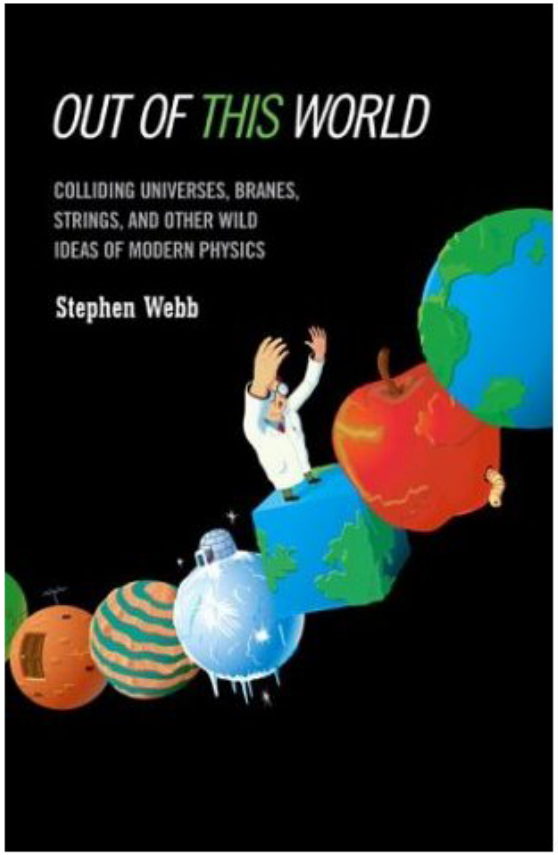
This chart has been made possible by the generous support of:
U.S. Department of Energy
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

http://pdg.lbl.gov/cpep.html


Present Day
10^{3}
10^{9}
10^{13}
10^{15}
10^{28}
10^{32}
TEMPERATURE (degrees Kelvin)
Gravity
Strong force
Weak force
Electromagnetism
COBE observes this epoch
nucleosynthesis of helium
nuclear density
Electroweak unification
Grand unification ?
Inflation ?
Monopoles form ?
Quantum gravity ?
superstrings ?
?
10^{13}
10^{2}
10^{-6}
10^{-11}
10^{-35}
10^{-43}
TIME (secs)
Big Bang


ScienceMasters
LEE SMOLIN
Three Roads to Quantum Gravity
A NEW UNDERSTANDING OF SPACE, TIME AND THE UNIVERSE
'Smolin is a deep and original thinker' Paul Davies


Present Day
10^{3}
10^{9}
10^{13}
10^{15}
10^{28}
10^{32}
TEMPERATURE (degrees Kelvin)
Gravity
Strong force
Weak force
Electromagnetism
COBE observes this epoch
nucleosynthesis of helium
nuclear density
Electroweak unification
Grand unification ?
Inflation ?
Monopoles form ?
Quantum gravity ?
superstrings ?
?
10^{13}
10^{2}
10^{-6}
10^{-11}
10^{-35}
10^{-43}
TIME (secs)
Big Bang


OUT OF THIS WORLD
COLLIDING UNIVERSES, BRANES, STRINGS, AND OTHER WILD IDEAS OF MODERN PHYSICS
Stephen Webb

What should a theory of Quantum Gravity encapsulate?...

- General Relativity:

  No absolute background of space and time

- Quantum Physics:

  On small scales, things are 'fuzzy'

Classical Physics:
All the World's A Stage

- Newton's physics assumes absolute space and time, for all observers.

Classical Physics:
All the World's A Stage

- Newton's physics assumes absolute space and time, for all observers.

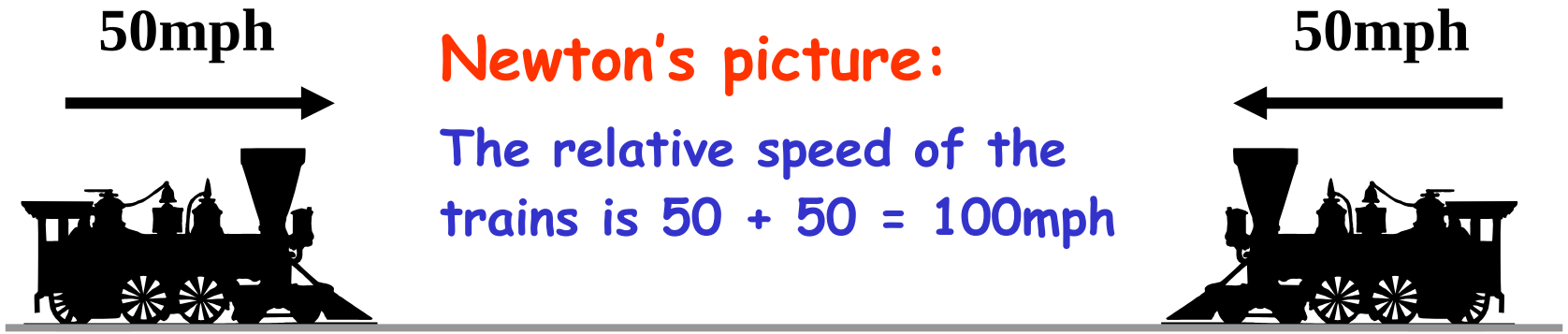
Classical Physics:
All the World's A Stage

- Newton's physics assumes absolute space and time, for all observers.
- Working out how things look to different observers follows simple rules, in different *reference frames*

Classical Physics:
All the World's A Stage

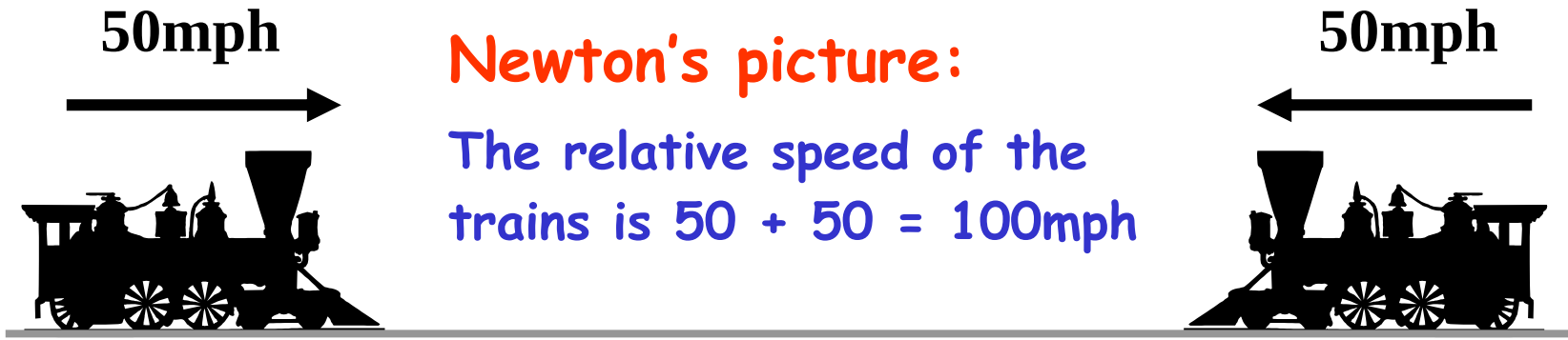
- Newton's physics assumes absolute space and time, for all observers.
- Working out how things look to different observers followed simple rules, in different *reference frames*

Viewed from the blue car's rest frame



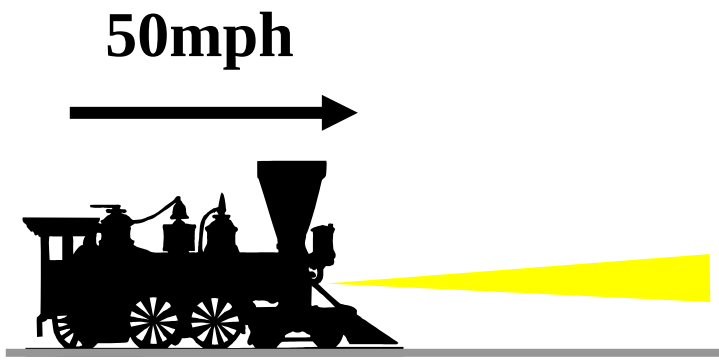
Newton's picture:

The relative speed of the trains is 50 + 50 = 100mph



Newton's picture:

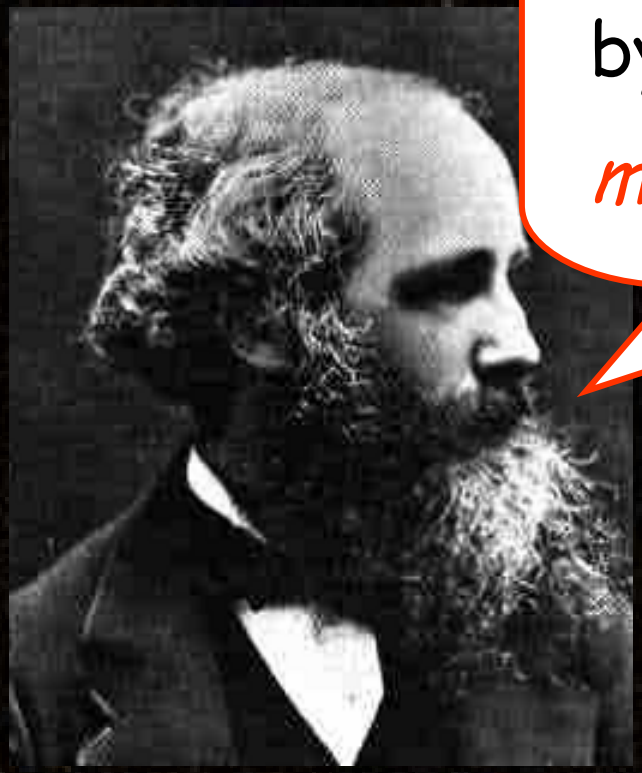
The relative speed of the trains is 50 + 50 = 100mph



What about the light from the train's headlamp?...

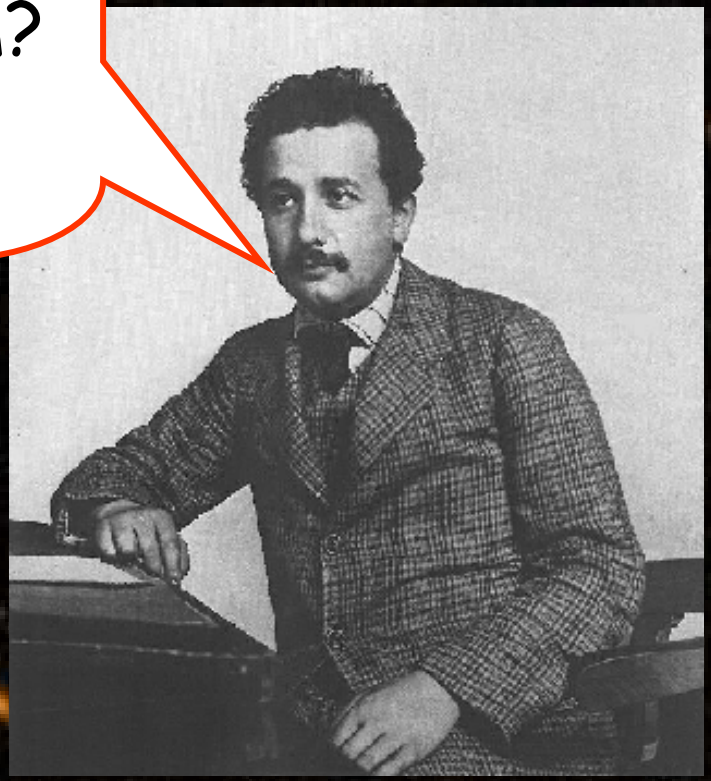
Classical Physics:

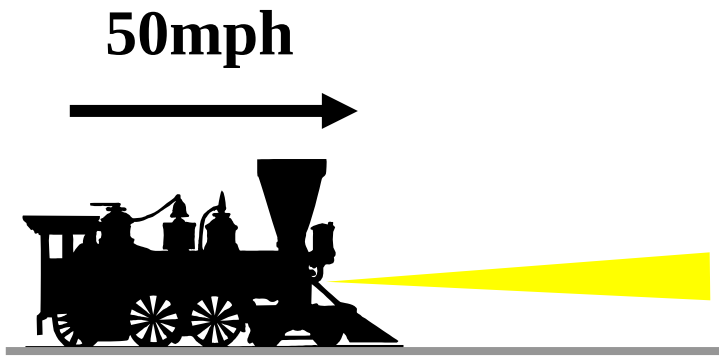
James Clerk Maxwell's theory of light



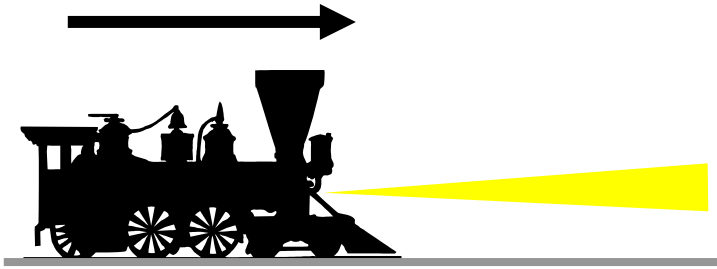
Light is a *wave* caused by varying *electric* and *magnetic* fields

But what if I travelled *alongside* a light beam? Would it still wave?





In Einstein's relativity, the speed of light is *unchanged* by the motion of the train



In Einstein's relativity, the speed of light is *unchanged* by the motion of the train

ON THE ELECTRODYNAMICS OF MOVING BODIES

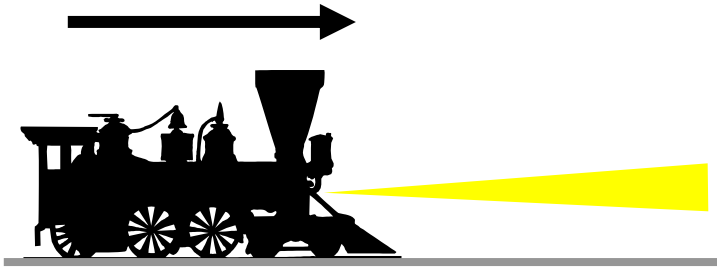
By A. EINSTEIN

June 30, 1905

It is known that Maxwell's electrodynamics—as usually understood at the present time—when applied to moving bodies, leads to asymmetries which do not appear to be inherent in the phenomena. Take, for example, the reciprocal electrodynamic action of a magnet and a conductor. The observable phenomenon here depends only on the relative motion of the conductor and the magnet, whereas the customary view draws a sharp distinction between the two cases in which either the one or the other of these bodies is in motion. For if the magnet is in motion and the conductor at rest, there arises in the neighbourhood of the magnet an electric field with a certain definite energy, producing a current at the places where parts of the conductor are situated. But if the magnet is stationary and the conductor in motion, no electric field arises in the neighbourhood of the magnet. In the conductor, however, we find an electromotive force, to which in itself there is no corresponding energy, but which gives rise—assuming equality of relative motion in the two cases discussed—to electric currents of the same path and intensity as those produced by the electric forces in the former case.

Examples of this sort, together with the unsuccessful attempts to discover any motion of the earth relatively to the "light medium," suggest that the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest. They suggest rather that, as has already been shown to the first order of small quantities, the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good.[1] We will raise this conjecture (the purport of which will hereafter be called the "Principle of Relativity") to the status of a postulate, and also introduce another postulate, which is only apparently irreconcilable with the former, namely, that light is always propagated in empty space with a definite velocity c which is independent of the state of motion of the emitting body. These two postulates suffice for the attainment of a simple and consistent theory of the electrodynamics of moving bodies based on Maxwell's theory for stationary bodies. The introduction of a "luminiferous ether" will prove to be superfluous inasmuch as the view here to be developed will not require an "absolutely stationary space" provided with special properties, nor

[1]The preceding memoir by Lorentz was not at this time known to the author.



In Einstein's relativity, the speed of light is *unchanged* by the motion of the train

ON THE ELECTRODYNAMICS OF MOVING BODIES

By A. EINSTEIN

June 30, 1905

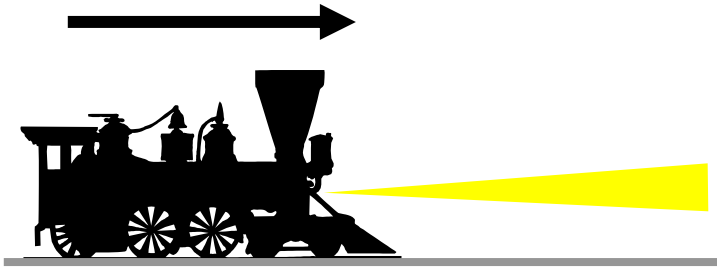
It is known that Maxwell's electrodynamics—as usually understood at the present time—when applied to moving bodies, leads to asymmetries which do not appear to be inherent in the phenomena. Take, for example, the reciprocal electrodynamic action of a magnet and a conductor. The observable phenomenon here depends only on the relative motion of the conductor and the magnet, whereas the customary view draws a sharp distinction between the two cases in which either the one or the other of these bodies is in motion. For if the magnet is in motion and the conductor at rest, there arises in the neighbourhood of the magnet an electric field with a certain definite energy, producing a current at the places where parts of the conductor are situated. But if the magnet is stationary and the conductor in motion, no electric field arises in the neighbourhood of the magnet. In the conductor, however, we find an electromotive force, to which in itself there is no corresponding energy, but which gives rise—assuming equality of relative motion in the two cases discussed—to electric currents of the same path and intensity as those produced by the electric forces in the former case.

Examples of this sort, together with the unsuccessful attempts to discover any motion of the earth relatively to the "light medium," suggest that the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest. They suggest rather that, as has already been shown to the first order of small quantities, the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good.[1] We will raise this conjecture (the purport of which will hereafter be called the "Principle of Relativity") to the status of a postulate, and also introduce another postulate, which is only apparently irreconcilable with the former, namely, that light is always propagated in empty space with a definite velocity c which is independent of the state of motion of the emitting body. These two postulates suffice for the attainment of a simple and consistent theory of the electrodynamics of moving bodies based on Maxwell's theory for stationary bodies. The introduction of a "luminiferous ether" will prove to be superfluous inasmuch as the view here to be developed will not require an "absolutely stationary space" provided with special properties, nor

[1]The preceding memoir by Lorentz was not at this time known to the author.

1

- Measurements of space and time are ***relative*** and depend on our motion



In Einstein's relativity, the speed of light is *unchanged* by the motion of the train

ON THE ELECTRODYNAMICS OF MOVING BODIES

By A. EINSTEIN

June 30, 1905

It is known that Maxwell's electrodynamics—as usually understood at the present time—when applied to moving bodies, leads to asymmetries which do not appear to be inherent in the phenomena. Take, for example, the reciprocal electrodynamic action of a magnet and a conductor. The observable phenomenon here depends only on the relative motion of the conductor and the magnet, whereas the customary view draws a sharp distinction between the two cases in which either the one or the other of these bodies is in motion. For if the magnet is in motion and the conductor at rest, there arises in the neighbourhood of the magnet an electric field with a certain definite energy, producing a current at the places where parts of the conductor are situated. But if the magnet is stationary and the conductor in motion, no electric field arises in the neighbourhood of the magnet. In the conductor, however, we find an electromotive force, to which in itself there is no corresponding energy, but which gives rise—assuming equality of relative motion in the two cases discussed—to electric currents of the same path and intensity as those produced by the electric forces in the former case.

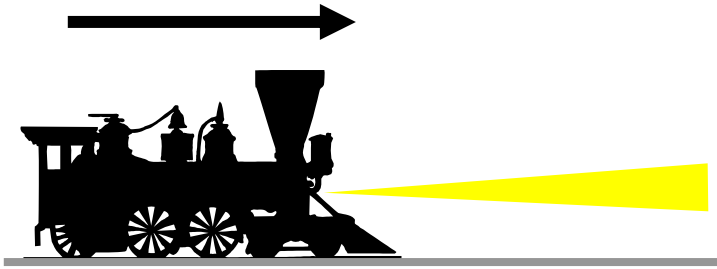
Examples of this sort, together with the unsuccessful attempts to discover any motion of the earth relatively to the "light medium," suggest that the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest. They suggest rather that, as has already been shown to the first order of small quantities, the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good.[1] We will raise this conjecture (the purport of which will hereafter be called the "Principle of Relativity") to the status of a postulate, and also introduce another postulate, which is only apparently irreconcilable with the former, namely, that light is always propagated in empty space with a definite velocity c which is independent of the state of motion of the emitting body. These two postulates suffice for the attainment of a simple and consistent theory of the electrodynamics of moving bodies based on Maxwell's theory for stationary bodies. The introduction of a "luminiferous ether" will prove to be superfluous inasmuch as the view here to be developed will not require an "absolutely stationary space" provided with special properties, nor

[1]The preceding memoir by Lorentz was not at this time known to the author.

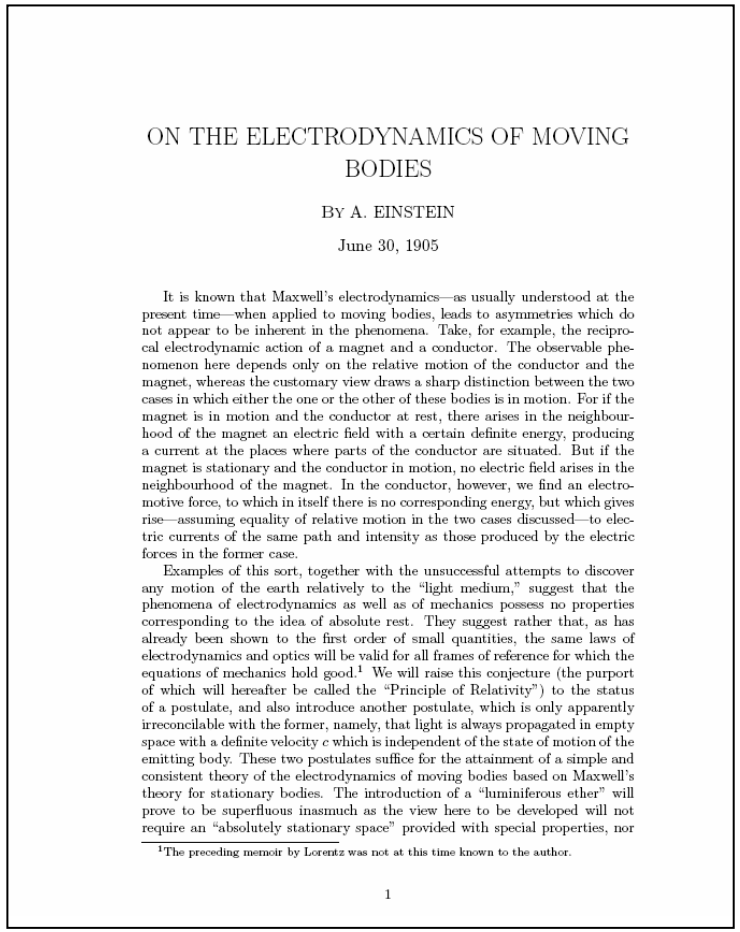
1

- Measurements of space and time are ***relative*** and depend on our motion

"The only reason for time is so that everything doesn't happen at once."



In Einstein's relativity, the speed of light is *unchanged* by the motion of the train



ON THE ELECTRODYNAMICS OF MOVING BODIES

BY A. EINSTEIN

June 30, 1905

It is known that Maxwell's electrodynamics—as usually understood at the present time—when applied to moving bodies, leads to asymmetries which do not appear to be inherent in the phenomena. Take, for example, the reciprocal electrodynamic action of a magnet and a conductor. The observable phenomenon here depends only on the relative motion of the conductor and the magnet, whereas the customary view draws a sharp distinction between the two cases in which either the one or the other of these bodies is in motion. For if the magnet is in motion and the conductor at rest, there arises in the neighbourhood of the magnet an electric field with a certain definite energy, producing a current at the places where parts of the conductor are situated. But if the magnet is stationary and the conductor in motion, no electric field arises in the neighbourhood of the magnet. In the conductor, however, we find an electromotive force, to which in itself there is no corresponding energy, but which gives rise—assuming equality of relative motion in the two cases discussed—to electric currents of the same path and intensity as those produced by the electric forces in the former case.

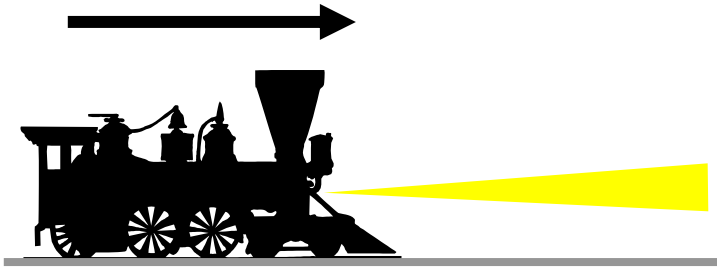
Examples of this sort, together with the unsuccessful attempts to discover any motion of the earth relatively to the "light medium," suggest that the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest. They suggest rather that, as has already been shown to the first order of small quantities, the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good.[1] We will raise this conjecture (the purport of which will hereafter be called the "Principle of Relativity") to the status of a postulate, and also introduce another postulate, which is only apparently irreconcilable with the former, namely, that light is always propagated in empty space with a definite velocity c which is independent of the state of motion of the emitting body. These two postulates suffice for the attainment of a simple and consistent theory of the electrodynamics of moving bodies based on Maxwell's theory for stationary bodies. The introduction of a "luminiferous ether" will prove to be superfluous inasmuch as the view here to be developed will not require an "absolutely stationary space" provided with special properties, nor

[1]The preceding memoir by Lorentz was not at this time known to the author.

1

- Measurements of space and time are ***relative*** and depend on our motion

"Put your hand on a hot stove for a minute, and it seems like an hour. Sit with a pretty girl for an hour and it seems like a minute. THAT'S relativity."



In Einstein's relativity, the speed of light is *unchanged* by the motion of the train

ON THE ELECTRODYNAMICS OF MOVING BODIES

BY A. EINSTEIN

June 30, 1905

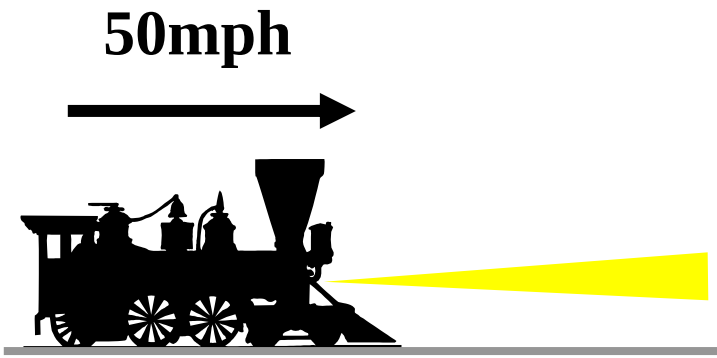
It is known that Maxwell's electrodynamics—as usually understood at the present time—when applied to moving bodies, leads to asymmetries which do not appear to be inherent in the phenomena. Take, for example, the reciprocal electrodynamic action of a magnet and a conductor. The observable phenomenon here depends only on the relative motion of the conductor and the magnet, whereas the customary view draws a sharp distinction between the two cases in which either the one or the other of these bodies is in motion. For if the magnet is in motion and the conductor at rest, there arises in the neighbourhood of the magnet an electric field with a certain definite energy, producing a current at the places where parts of the conductor are situated. But if the magnet is stationary and the conductor in motion, no electric field arises in the neighbourhood of the magnet. In the conductor, however, we find an electromotive force, to which in itself there is no corresponding energy, but which gives rise—assuming equality of relative motion in the two cases discussed—to electric currents of the same path and intensity as those produced by the electric forces in the former case.

Examples of this sort, together with the unsuccessful attempts to discover any motion of the earth relatively to the "light medium," suggest that the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest. They suggest rather that, as has already been shown to the first order of small quantities, the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good.[1] We will raise this conjecture (the purport of which will hereafter be called the "Principle of Relativity") to the status of a postulate, and also introduce another postulate, which is only apparently irreconcilable with the former, namely, that light is always propagated in empty space with a definite velocity c which is independent of the state of motion of the emitting body. These two postulates suffice for the attainment of a simple and consistent theory of the electrodynamics of moving bodies based on Maxwell's theory for stationary bodies. The introduction of a "luminiferous ether" will prove to be superfluous inasmuch as the view here to be developed will not require an "absolutely stationary space" provided with special properties, nor

[1]The preceding memoir by Lorentz was not at this time known to the author.

1

- Measurements of space and time are ***relative*** and depend on our motion
- Unified ***spacetime*** - only measurements of the ***spacetime*** interval are invariant



In Einstein's relativity, the speed of light is *unchanged* by the motion of the train

ON THE ELECTRODYNAMICS OF MOVING BODIES

BY A. EINSTEIN

June 30, 1905

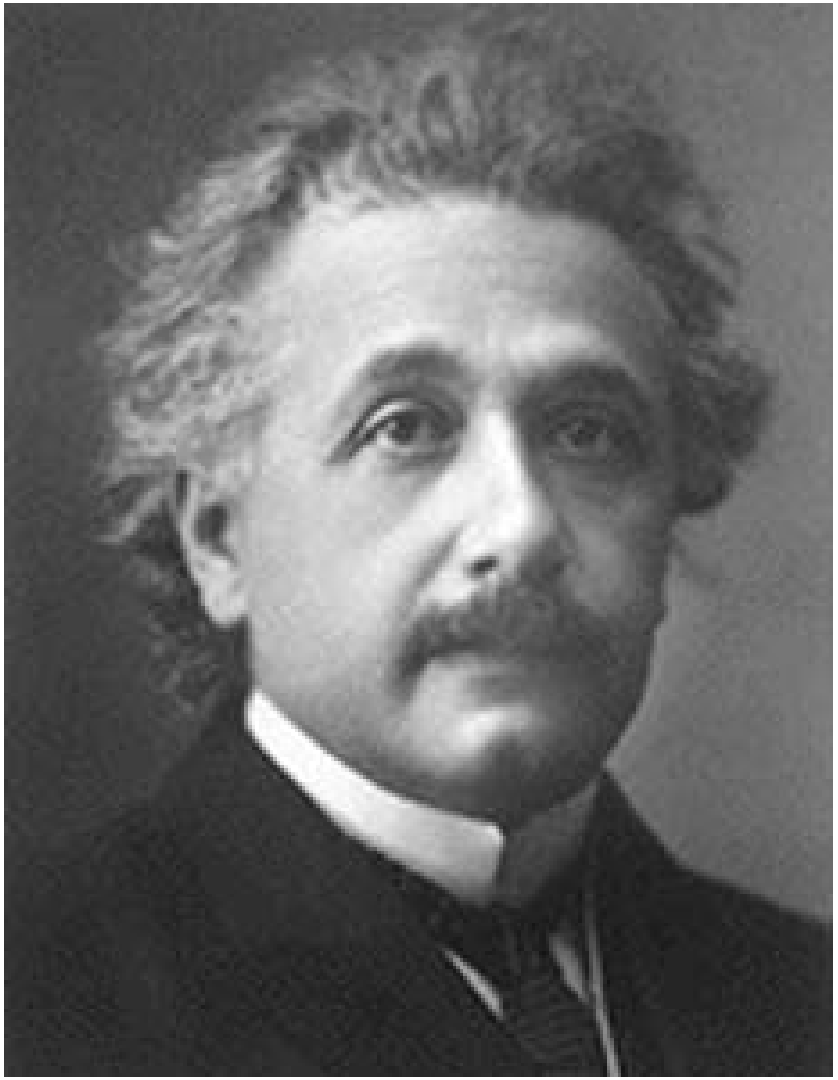
It is known that Maxwell's electrodynamics—as usually understood at the present time—when applied to moving bodies, leads to asymmetries which do not appear to be inherent in the phenomena. Take, for example, the reciprocal electrodynamic action of a magnet and a conductor. The observable phenomenon here depends only on the relative motion of the conductor and the magnet, whereas the customary view draws a sharp distinction between the two cases in which either the one or the other of these bodies is in motion. For if the magnet is in motion and the conductor at rest, there arises in the neighbourhood of the magnet an electric field with a certain definite energy, producing a current at the places where parts of the conductor are situated. But if the magnet is stationary and the conductor in motion, no electric field arises in the neighbourhood of the magnet. In the conductor, however, we find an electromotive force, to which in itself there is no corresponding energy, but which gives rise—assuming equality of relative motion in the two cases discussed—to electric currents of the same path and intensity as those produced by the electric forces in the former case.

Examples of this sort, together with the unsuccessful attempts to discover any motion of the earth relatively to the "light medium," suggest that the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest. They suggest rather that, as has already been shown to the first order of small quantities, the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good.[1] We will raise this conjecture (the purport of which will hereafter be called the "Principle of Relativity") to the status of a postulate, and also introduce another postulate, which is only apparently irreconcilable with the former, namely, that light is always propagated in empty space with a definite velocity c which is independent of the state of motion of the emitting body. These two postulates suffice for the attainment of a simple and consistent theory of the electrodynamics of moving bodies based on Maxwell's theory for stationary bodies. The introduction of a "luminiferous ether" will prove to be superfluous inasmuch as the view here to be developed will not require an "absolutely stationary space" provided with special properties, nor

[1]The preceding memoir by Lorentz was not at this time known to the author.

1

- Measurements of space and time are ***relative*** and depend on our motion
- Unified ***spacetime*** - only measurements of the ***spacetime*** interval are invariant
- Equivalence of **matter** and **energy**



1916. № 7.

ANNALEN DER PHYSIK.

VIERTE FOLGE. BAND 49.

1. *Die Grundlage der allgemeinen Relativitätstheorie;* von *A. Einstein.*

Die im nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie" bezeichneten Theorie; die letztere nenne ich im folgenden zur Unterscheidung von der ersteren „spezielle Relativitätstheorie" und setze sie als bekannt voraus. Die Verallgemeinerung der Relativitätstheorie wurde sehr erleichtert durch die Gestalt, welche der speziellen Relativitätstheorie durch Minkowski gegeben wurde, welcher Mathematiker zuerst die formale Gleichwertigkeit der räumlichen Koordinaten und der Zeitkoordinate klar erkannte und für den Aufbau der Theorie nutzbar machte. Die für die allgemeine Relativitätstheorie nötigen mathematischen Hilfsmittel lagen fertig bereit in dem „absoluten Differentialkalkül", welcher auf den Forschungen von Gauss, Riemann und Christoffel über nichteuklidische Mannigfaltigkeiten ruht und von Ricci und Levi-Civita in ein System gebracht und bereits auf Probleme der theoretischen Physik angewendet wurde. Ich habe im Abschnitt B der vorliegenden Abhandlung alle für uns nötigen, bei dem Physiker nicht als bekannt vorauszusetzenden mathematischen Hilfsmittel in möglichst einfacher und durchsichtiger Weise entwickelt, so daß ein Studium mathematischer Literatur für das Verständnis der vorliegenden Abhandlung nicht erforderlich ist. Endlich sei an dieser Stelle dankbar meines Freundes, des Mathematikers Grossmann, gedacht, der mir durch seine Hilfe nicht nur das Studium der einschlägigen mathematischen Literatur ersparte, sondern mich auch beim Suchen nach den Feldgleichungen der Gravitation unterstützte.

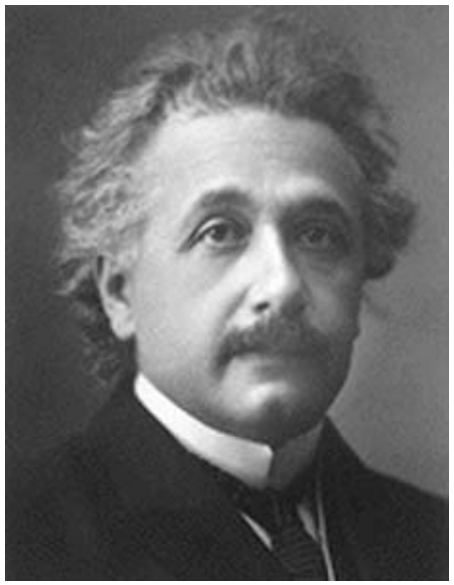
1916. № 7.

ANNALEN DER PHYSIK.
VIERTE FOLGE. BAND 49.

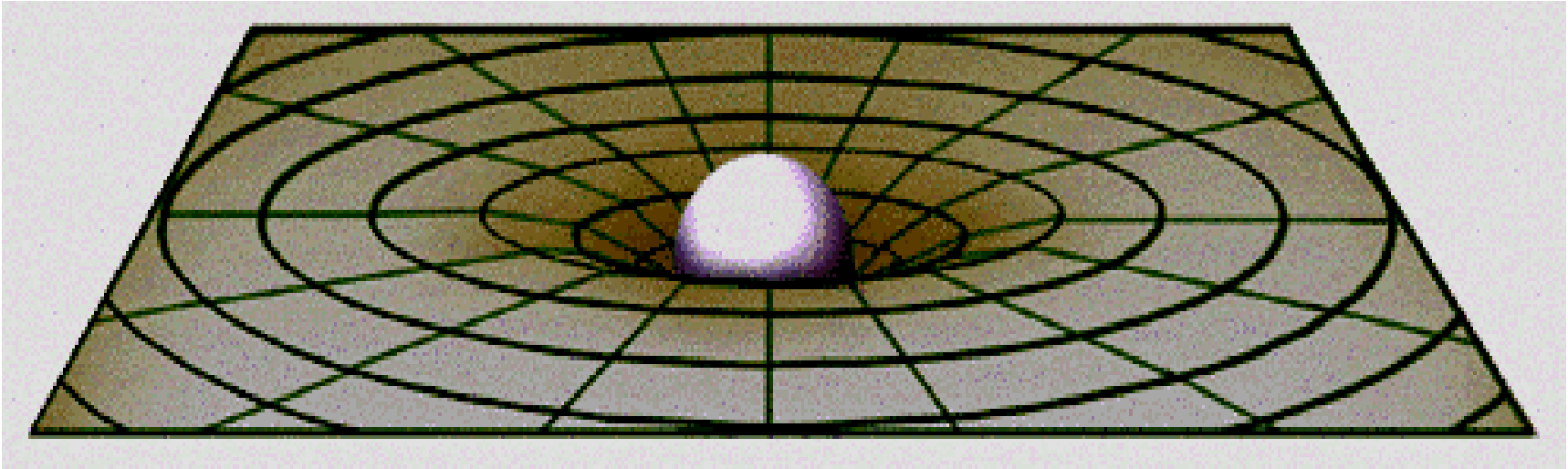
1. *Die Grundlage der allgemeinen Relativitätstheorie;* von *A. Einstein.*

Die im nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie" bezeichneten Theorie; die letztere nenne ich im folgenden zur Unterscheidung von der ersteren „spezielle Relativitätstheorie" und setze sie als bekannt voraus. Die Verallgemeinerung der Relativitätstheorie wurde sehr erleichtert durch die Gestalt, welche der speziellen Relativitätstheorie durch Minkowski gegeben wurde, welcher Mathematiker zuerst die formale Gleichwertigkeit der räumlichen Koordinaten und der Zeitkoordinate klar erkannte und für den Aufbau der Theorie nutzbar machte. Die für die allgemeine Relativitätstheorie nötigen mathematischen Hilfsmittel lagen fertig bereit in dem „absoluten Differentialkalkül", welcher auf den Forschungen von Gauss, Riemann und Christoffel über nichteuklidische Mannigfaltigkeiten ruht und von Ricci und Levi-Civita in ein System gebracht und bereits auf Probleme der theoretischen Physik angewendet wurde. Ich habe im Abschnitt B der vorliegenden Abhandlung alle für uns nötigen, bei dem Physiker nicht als bekannt vorauszusetzenden mathematischen Hilfsmittel in möglichst einfacher und durchsichtiger Weise entwickelt, so daß ein Studium mathematischer Literatur für das Verständnis der vorliegenden Abhandlung nicht erforderlich ist. Endlich sei an dieser Stelle dankbar meines Freundes, des Mathematikers Grossmann, gedacht, der mir durch seine Hilfe nicht nur das Studium der einschlägigen mathematischen Literatur ersparte, sondern mich auch beim Suchen nach den Feldgleichungen der Gravitation unterstützte.

Gravity in Einstein's Universe



"Spacetime tells matter how to move, and matter tells spacetime how to curve"

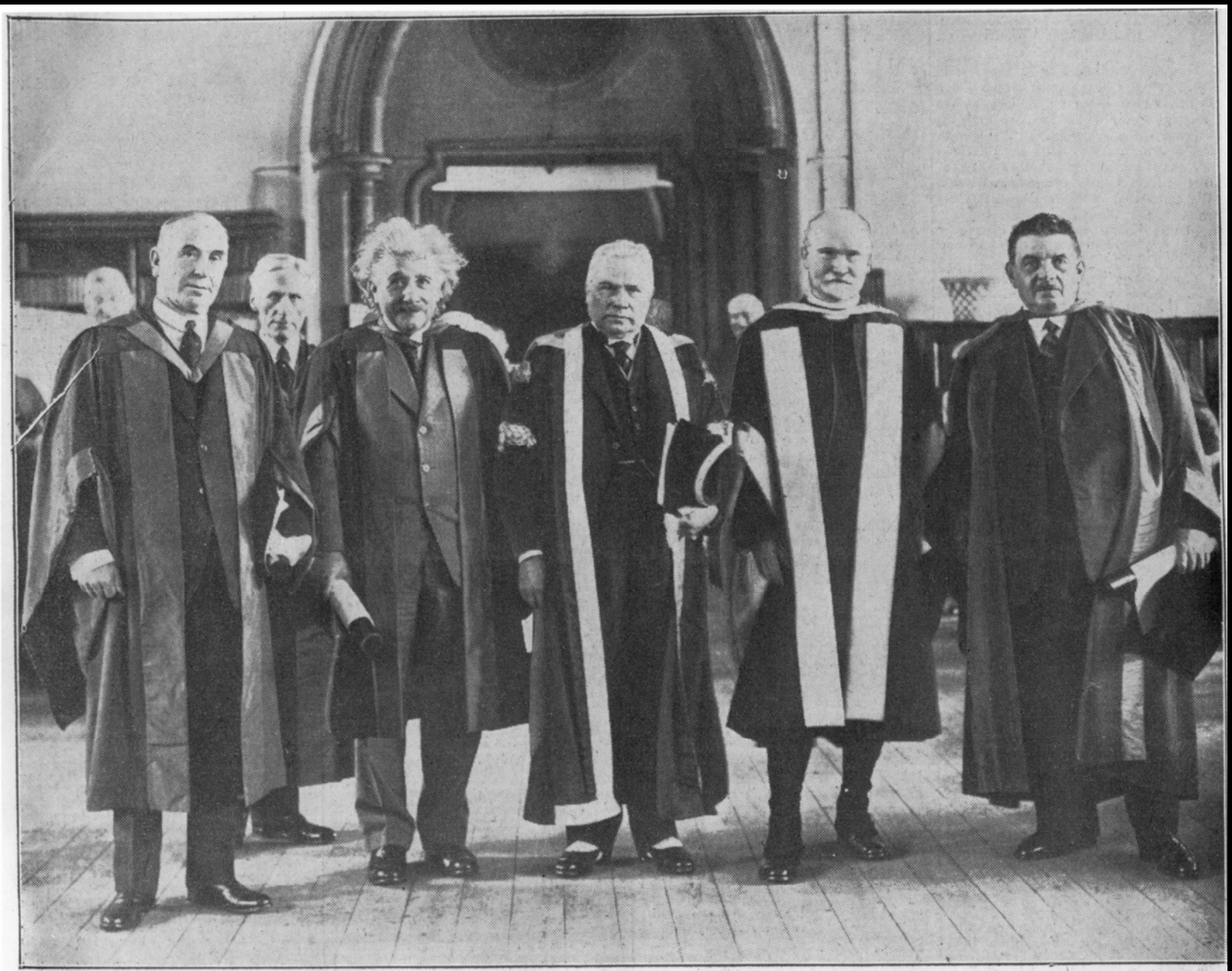


Colleague: *"Professor Eddington, you must be one of only three persons in the world who understand relativity!"*

Eddington: *" oh, I don't know..."*

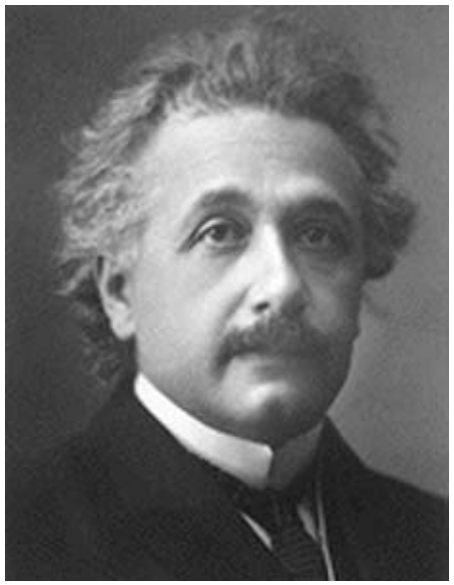
Colleague: *" Don't be modest Eddington."*

Eddington: *" On the contrary, I am trying to think who the third person is."*



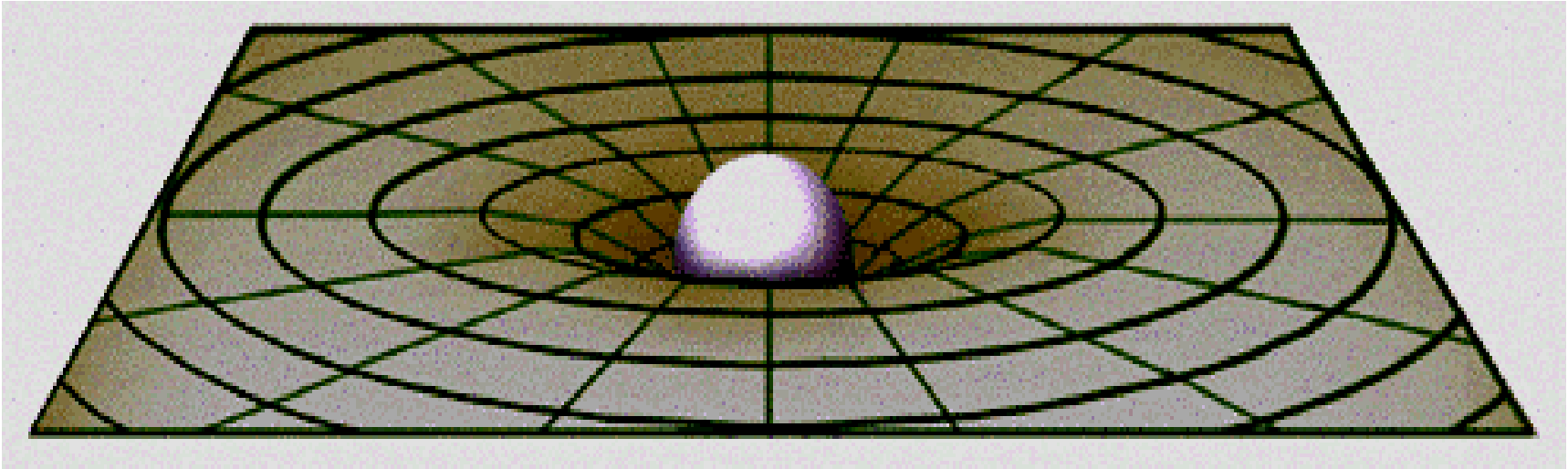
A group of some of the honorary graduates taken after the ceremony in the Bute Hall of Glasgow University yesterday. Left to right—The Right Hon. Sir Robert S. Horne; Emeritus Professor William Blair-Bell, University of Liverpool; Professor Albert Einstein; Principal Sir Robert S. Rait; the Archbishop of Armagh and Primate of All Ireland; and M. Edouard Herriot, former Prime Minister of France.

Gravity in Einstein's Universe

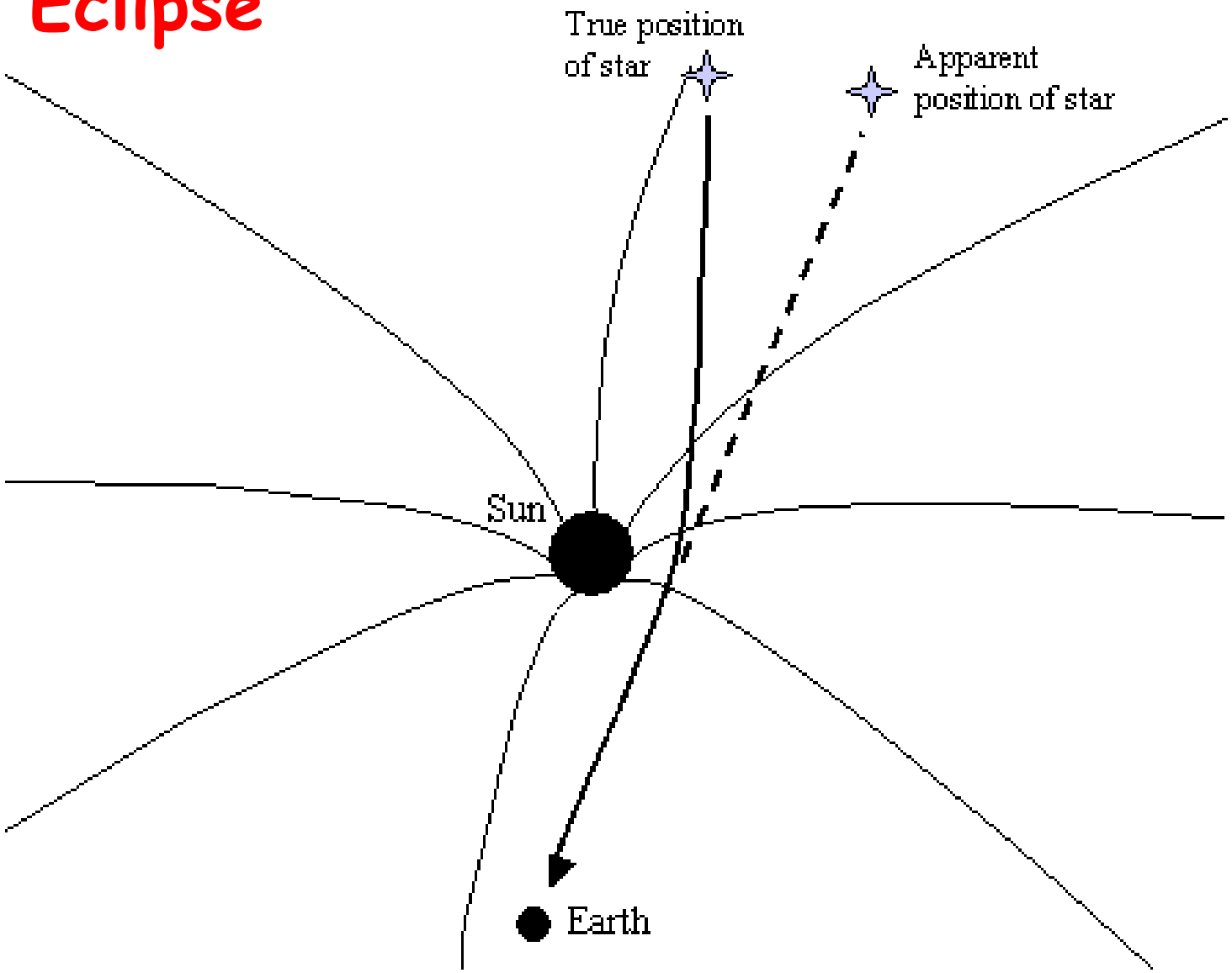


As light passes close to a star its path is bent by the curved spacetime

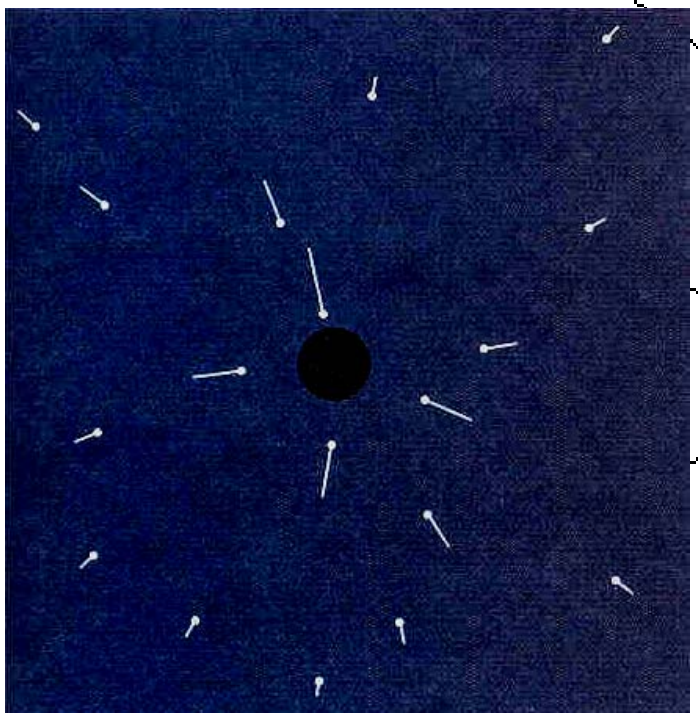
Gravitational Lensing



We can see this during a Solar Eclipse



We can see this during a Solar Eclipse

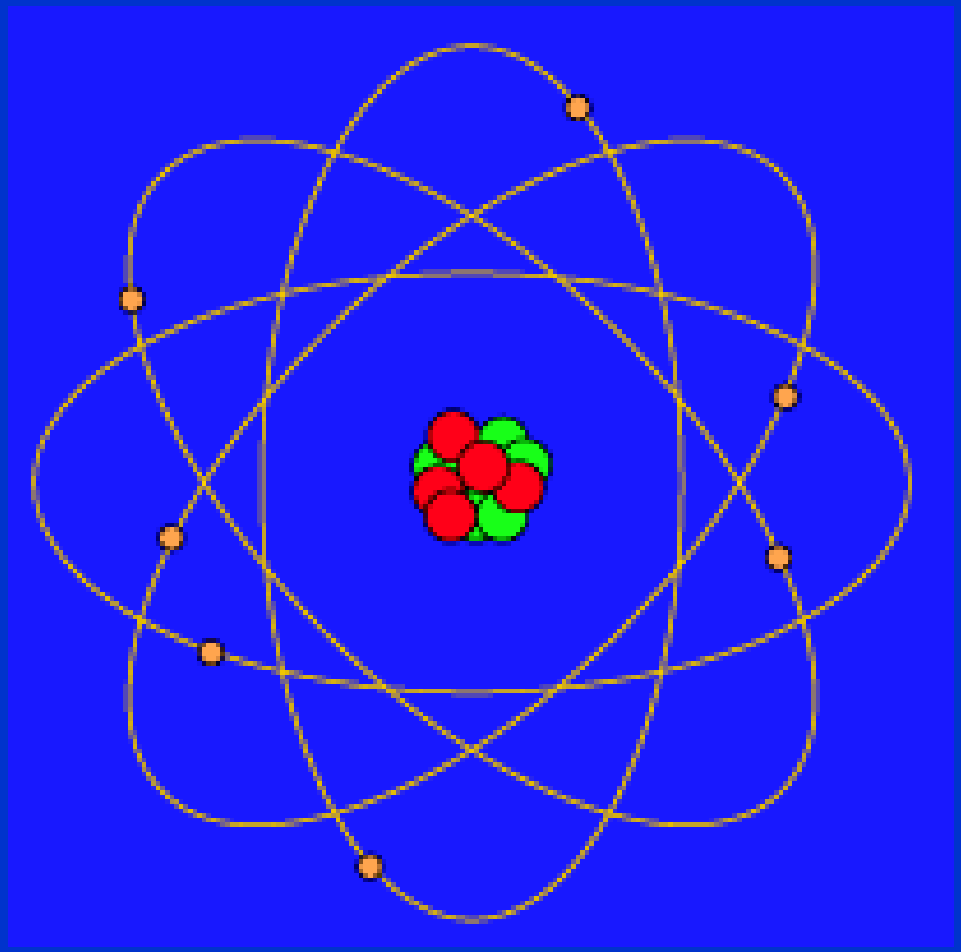


In 1919 Eddington's expedition to the Southern Hemisphere confirmed Einstein's theory

“He was one of the finest people I have ever known….but he didn’t really understand physics. During the eclipse…he stayed up all night to see if it would confirm the bending of light by the gravitational field. If he had really understood general relativity, he would have gone to bed the way I did.”


SPACETIME
GEOMETRY
Sean M. Carroll

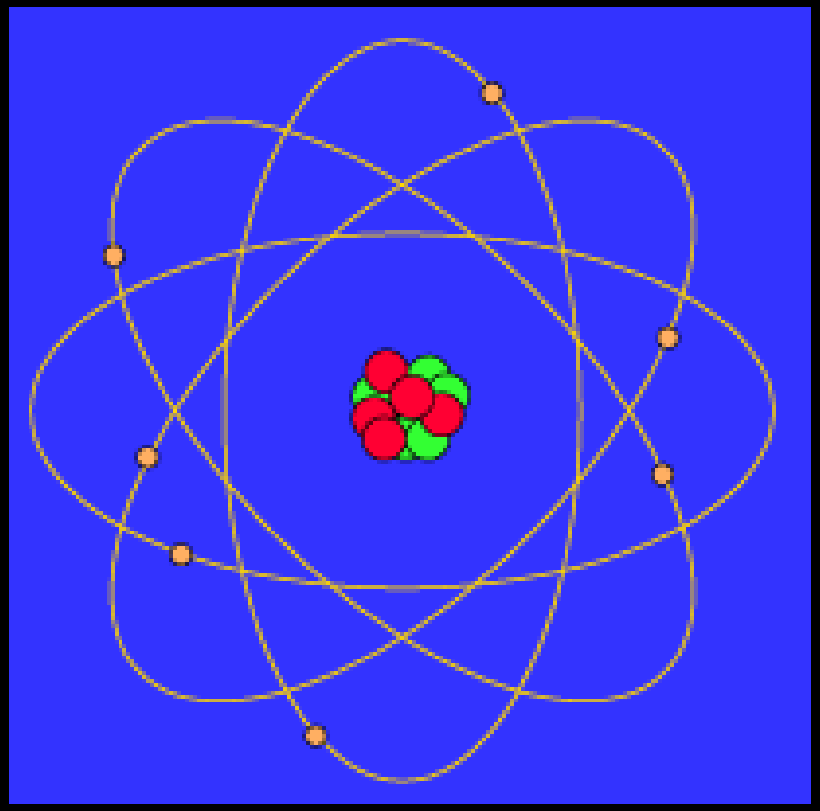
The Quantum World



Bohr atom, 1913

Light energy is ***quantised*** in packets, or ***photons*** of energy

The Quantum World



Heisenberg Uncertainty Principle

The precision of measurements in a quantum system is limited ***in principle***

Heisenberg Uncertainty Principle

The precision of measurements in a quantum system is limited ***in principle***

$$\Delta p \, \Delta x \sim \hbar$$

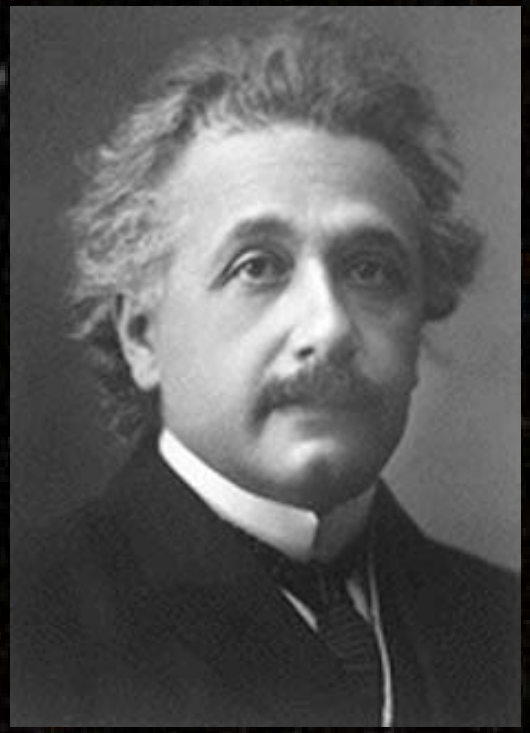
Heisenberg Uncertainty Principle

The precision of measurements in a quantum system is limited ***in principle***

$$\Delta p \Delta x \sim \hbar$$

Position and momentum are *complementary* properties: the action of measurement determines which of the two properties the quantum system possesses

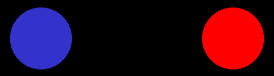
"God does not play dice"



Thought experiment, proposed by Einstein Podolsky & Rosen (1935)

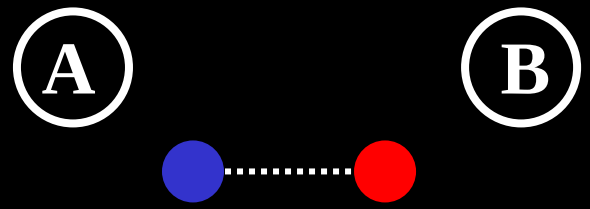
designed to expose the paradox of complementarity

The EPR 'Paradox'



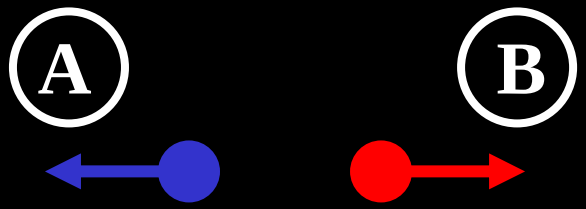
Quantum system: two particles,
initially coupled, then fly apart

The EPR 'Paradox'



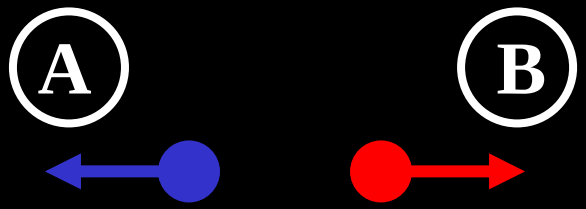
Quantum system: two particles, initially coupled, then fly apart

The EPR 'Paradox'



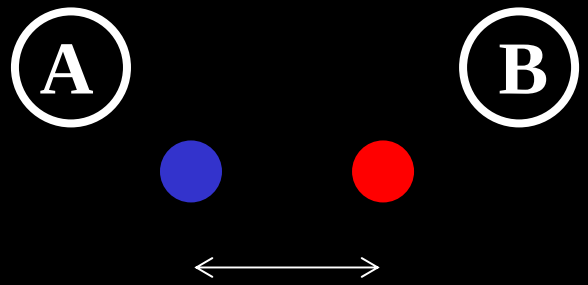
Quantum system: two particles, initially coupled, then fly apart

The EPR 'Paradox'



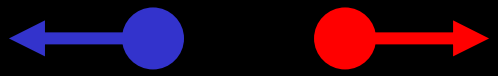
Quantum system: two particles, initially coupled, then fly apart

The EPR 'Paradox'

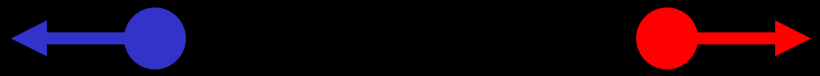


We can set things up so that initially the **total** momentum is zero (say).

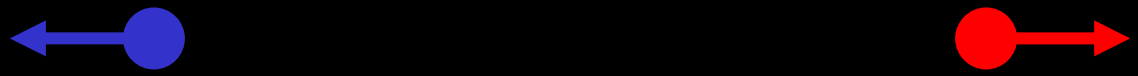
The EPR 'Paradox'



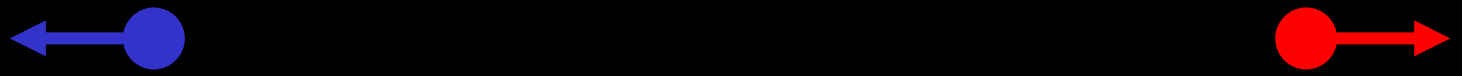
The EPR 'Paradox'



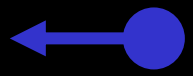
The EPR 'Paradox'

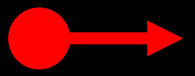


The EPR 'Paradox'



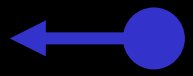
The EPR 'Paradox'

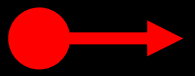




We decide to measure the momentum of (A)

The EPR 'Paradox'





We decide to measure the momentum of (A)

(B) *instantaneously* adopts 'momentum' state

How does it know?

The EPR 'Paradox'

EPR regarded this prediction as unreasonable, as it violated causality.

"[It] makes the reality of position and momentum in the second system depend upon the measurement carried out in the first system, which does not disturb the second system in any way. *No reasonable definition of reality could be expected to permit this.*"

But this is exactly what ***does*** happen

Quantum Entanglement

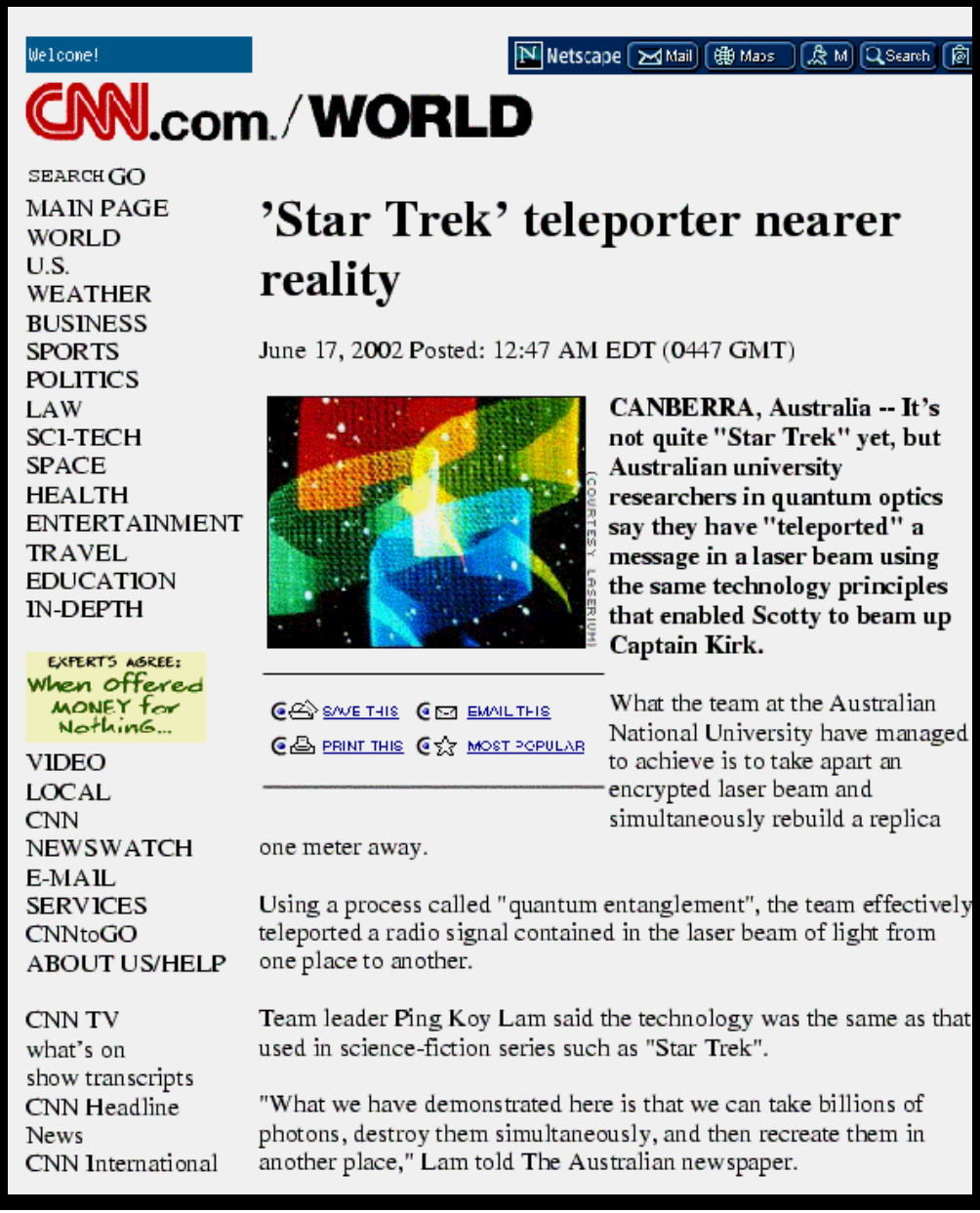
Quantum states are 'entangled': they can influence each other instantaneously, even when separated by great distances

This is the idea behind the Star Trek 'teleporter'

Quantum Entanglement

Quantum states are 'entangled': they can influence each other instantaneously, even when separated by great distances

This is the idea behind the Star Trek 'teleporter'



Welcome!

Netscape Mail Maps M Search

CNN.com/WORLD

SEARCH GO

MAIN PAGE
WORLD
U.S.
WEATHER
BUSINESS
SPORTS
POLITICS
LAW
SCI-TECH
SPACE
HEALTH
ENTERTAINMENT
TRAVEL
EDUCATION
IN-DEPTH

EXPERTS AGREE: When offered MONEY for Nothing...

VIDEO
LOCAL
CNN
NEWSWATCH
E-MAIL
SERVICES
CNNtoGO
ABOUT US/HELP

CNN TV
what's on
show transcripts
CNN Headline News
CNN International

'Star Trek' teleporter nearer reality

June 17, 2002 Posted: 12:47 AM EDT (0447 GMT)

(COURTESY LASERIUM)

CANBERRA, Australia -- It's not quite "Star Trek" yet, but Australian university researchers in quantum optics say they have "teleported" a message in a laser beam using the same technology principles that enabled Scotty to beam up Captain Kirk.

SAVE THIS EMAIL THIS
PRINT THIS MOST POPULAR

What the team at the Australian National University have managed to achieve is to take apart an encrypted laser beam and simultaneously rebuild a replica one meter away.

Using a process called "quantum entanglement", the team effectively teleported a radio signal contained in the laser beam of light from one place to another.

Team leader Ping Koy Lam said the technology was the same as that used in science-fiction series such as "Star Trek".

"What we have demonstrated here is that we can take billions of photons, destroy them simultaneously, and then recreate them in another place," Lam told The Australian newspaper.

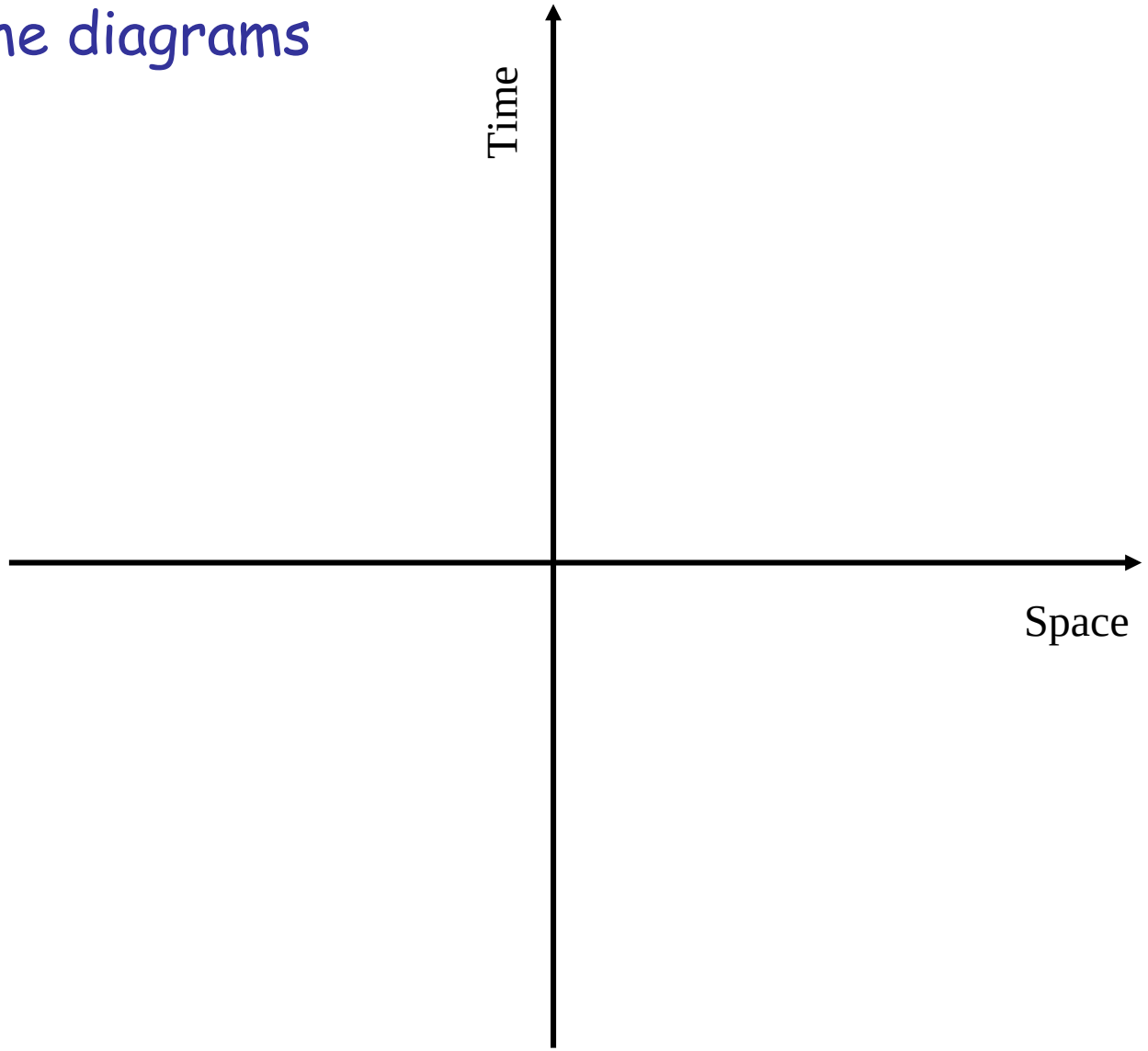
Gravity in Einstein's Universe

A 'Black Hole' warps spacetime so much that even light can't escape

A Black Hole has an 'event horizon'

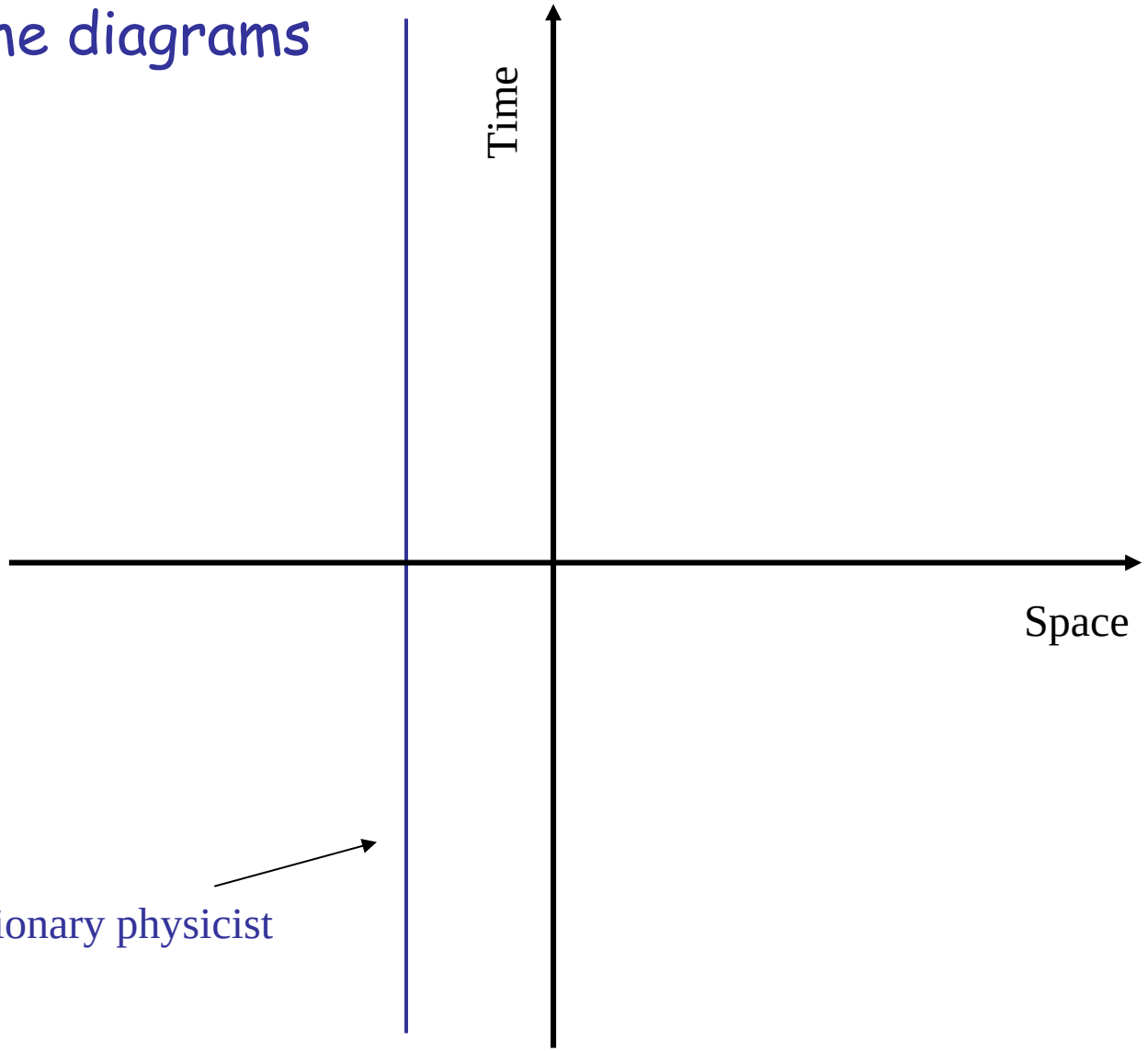
Making Sense of Einstein's Universe

Spacetime diagrams



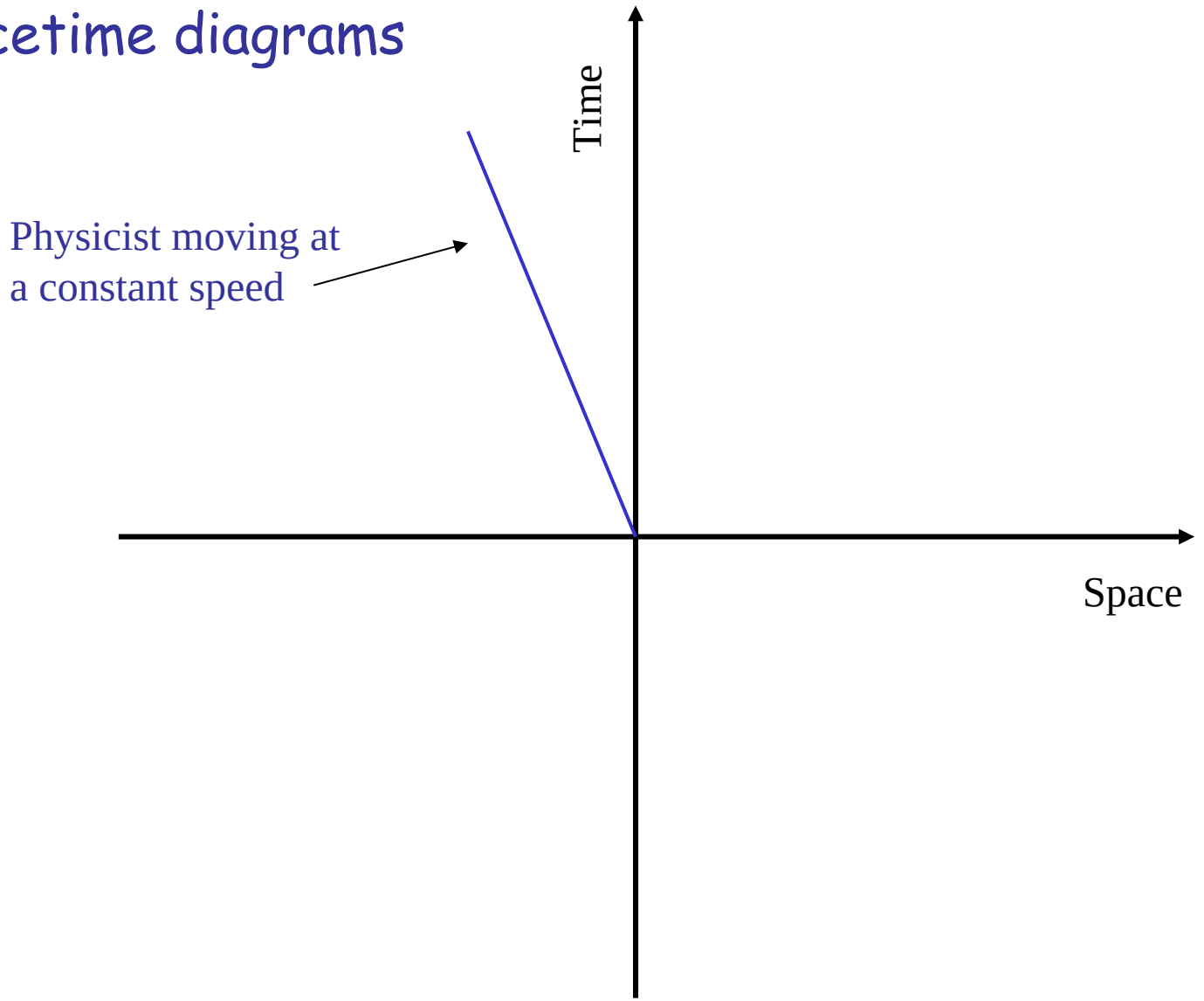
Making Sense of Einstein's Universe

Spacetime diagrams



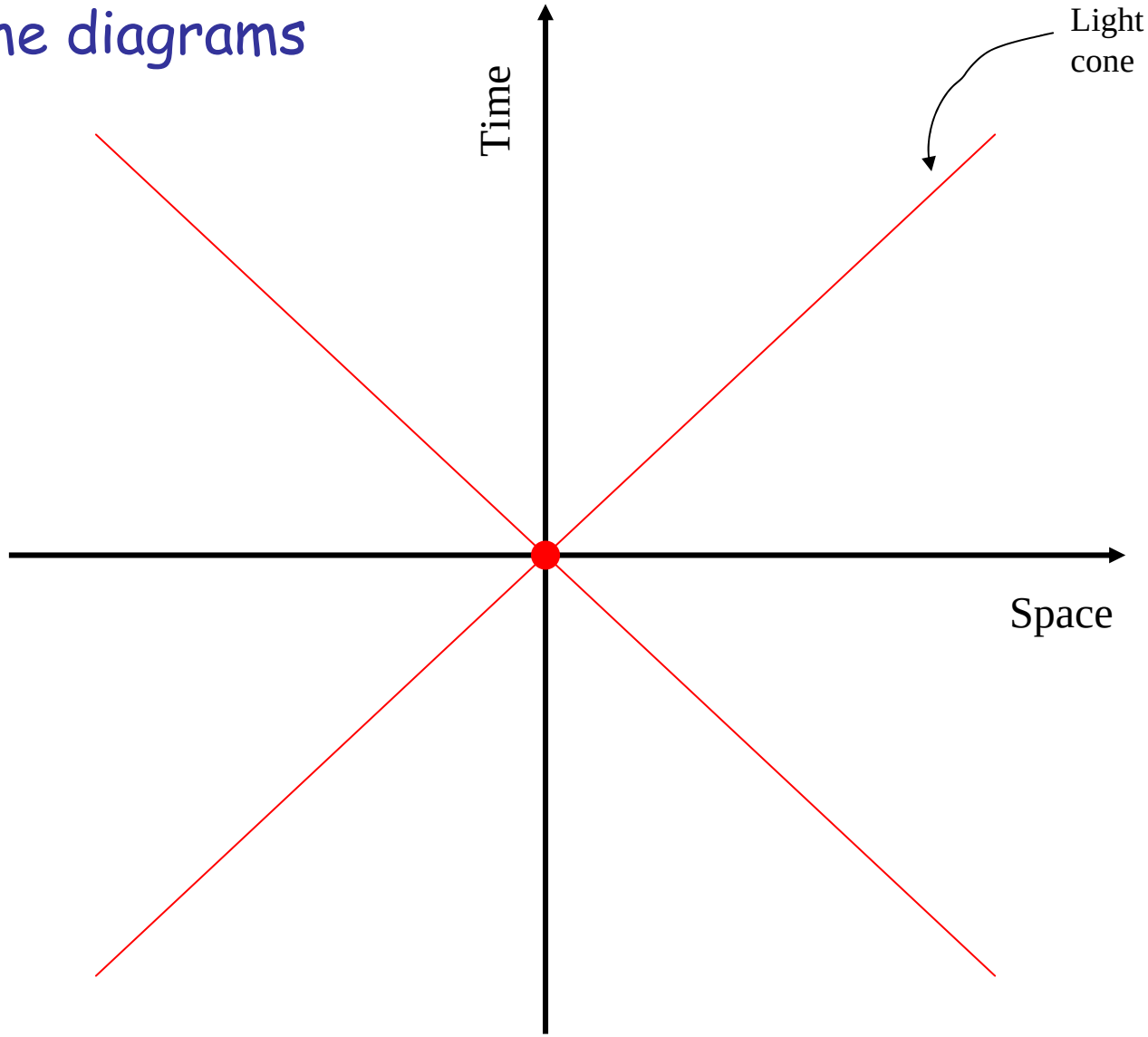
Making Sense of Einstein's Universe

Spacetime diagrams



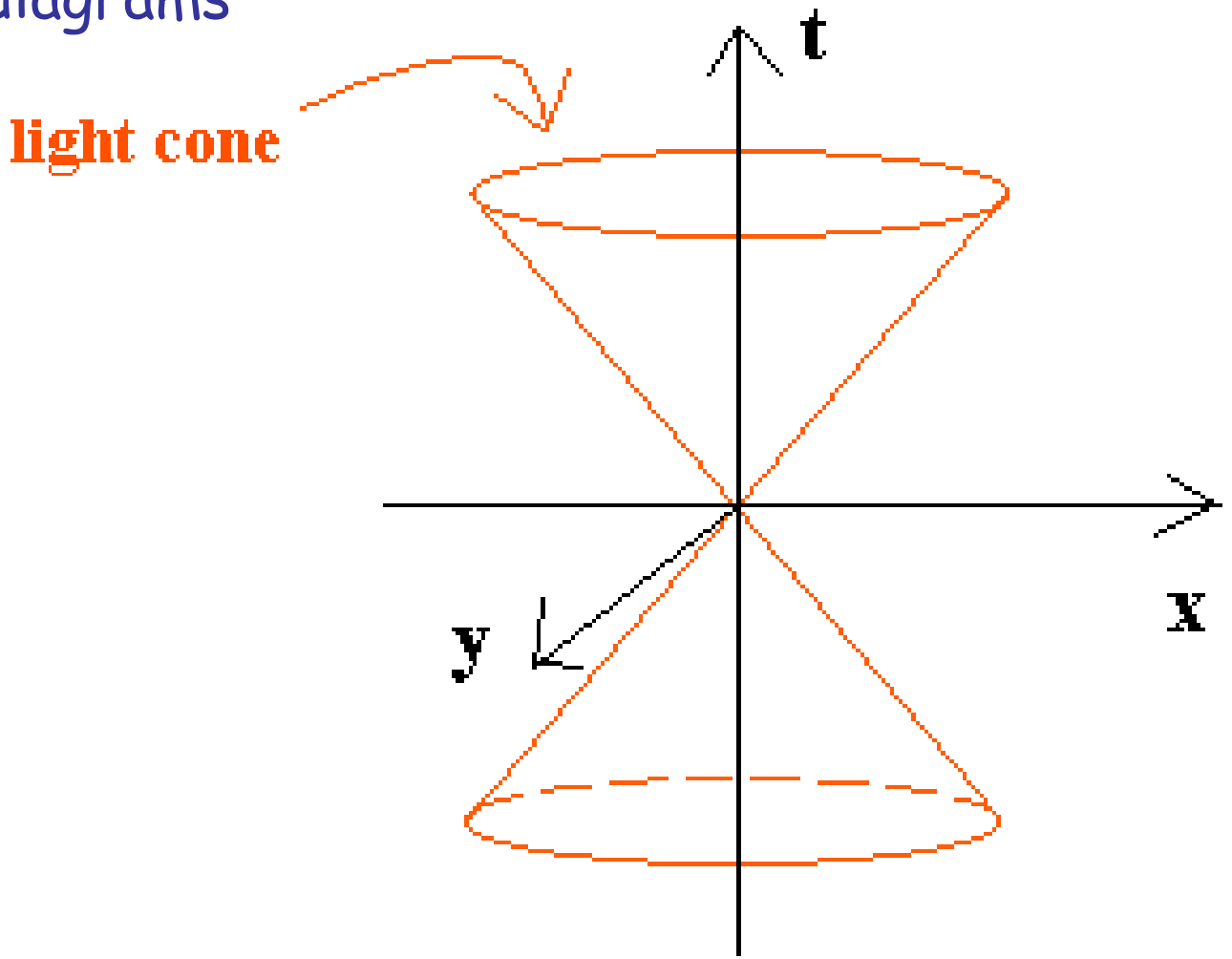
Making Sense of Einstein's Universe

Spacetime diagrams



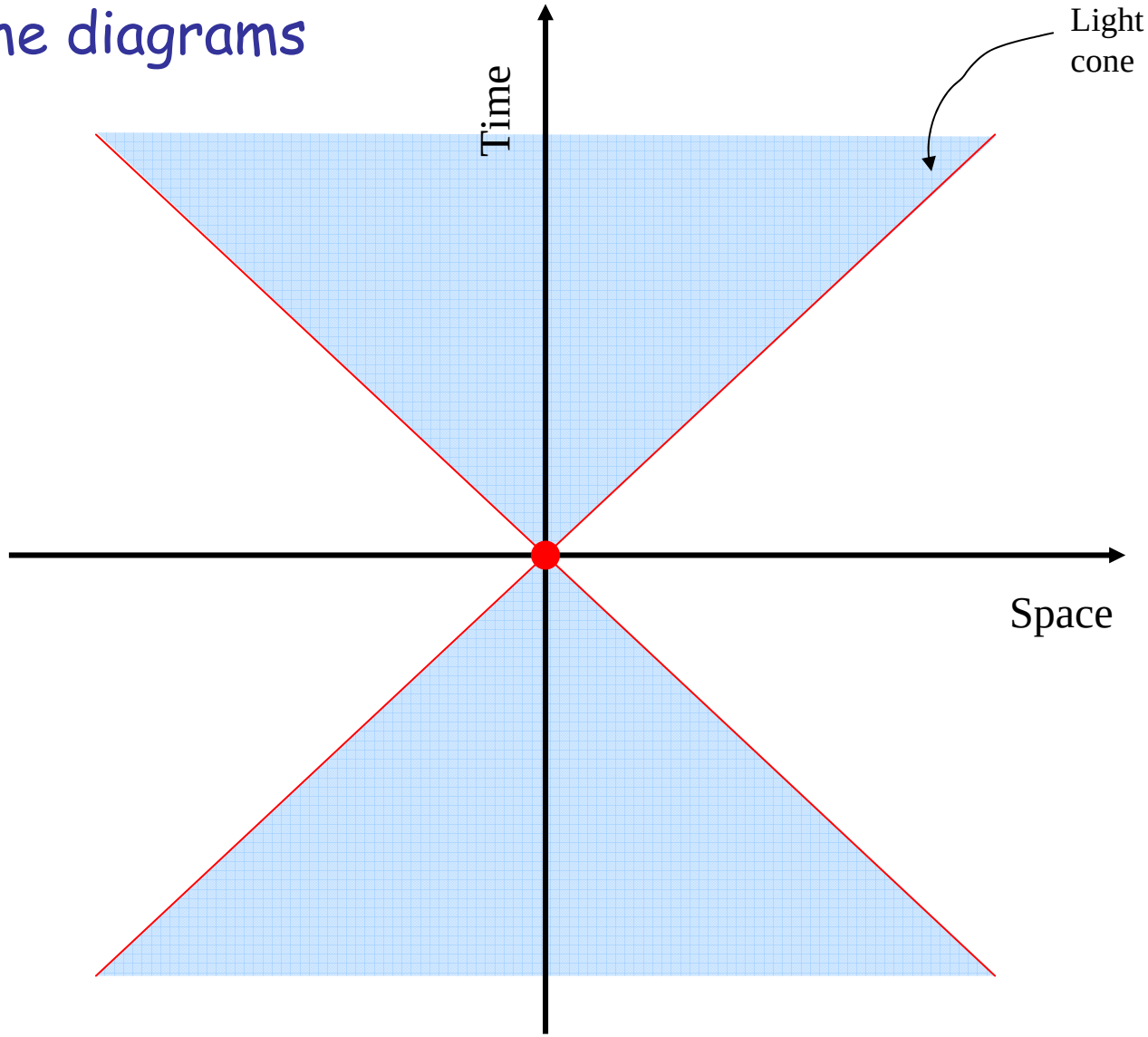
Making Sense of Einstein's Universe

Spacetime diagrams



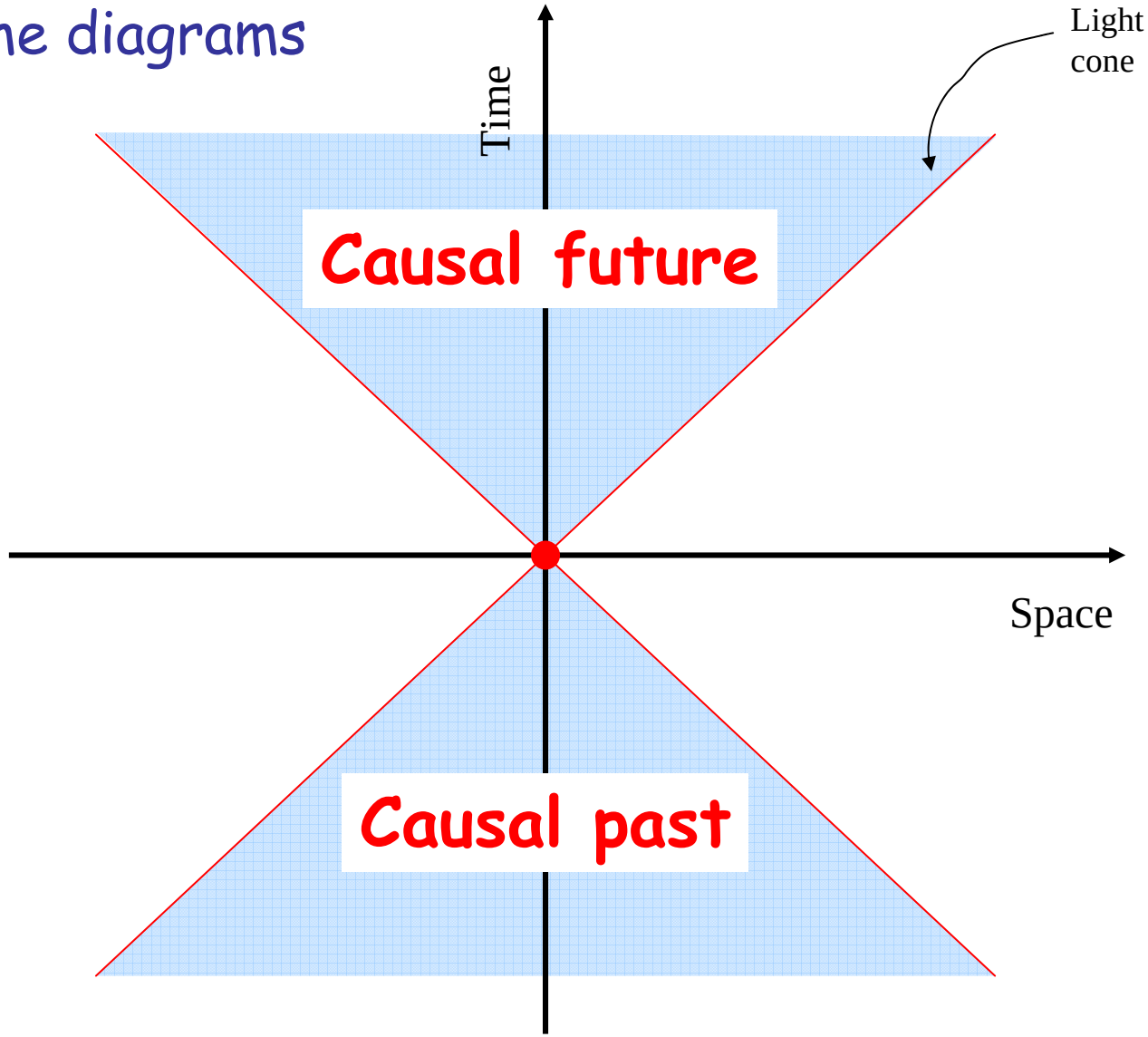
Making Sense of Einstein's Universe

Spacetime diagrams



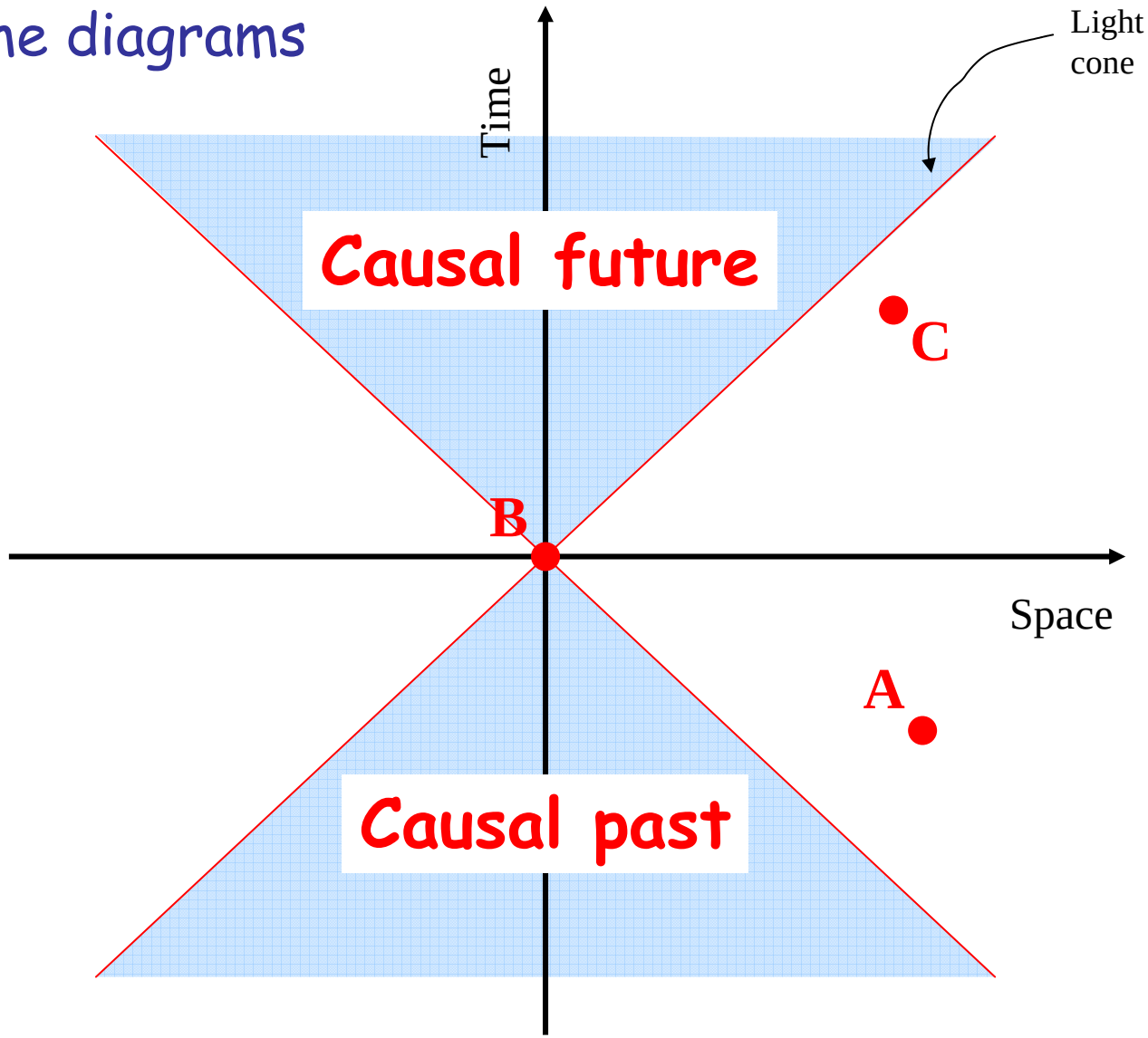
Making Sense of Einstein's Universe

Spacetime diagrams



Making Sense of Einstein's Universe

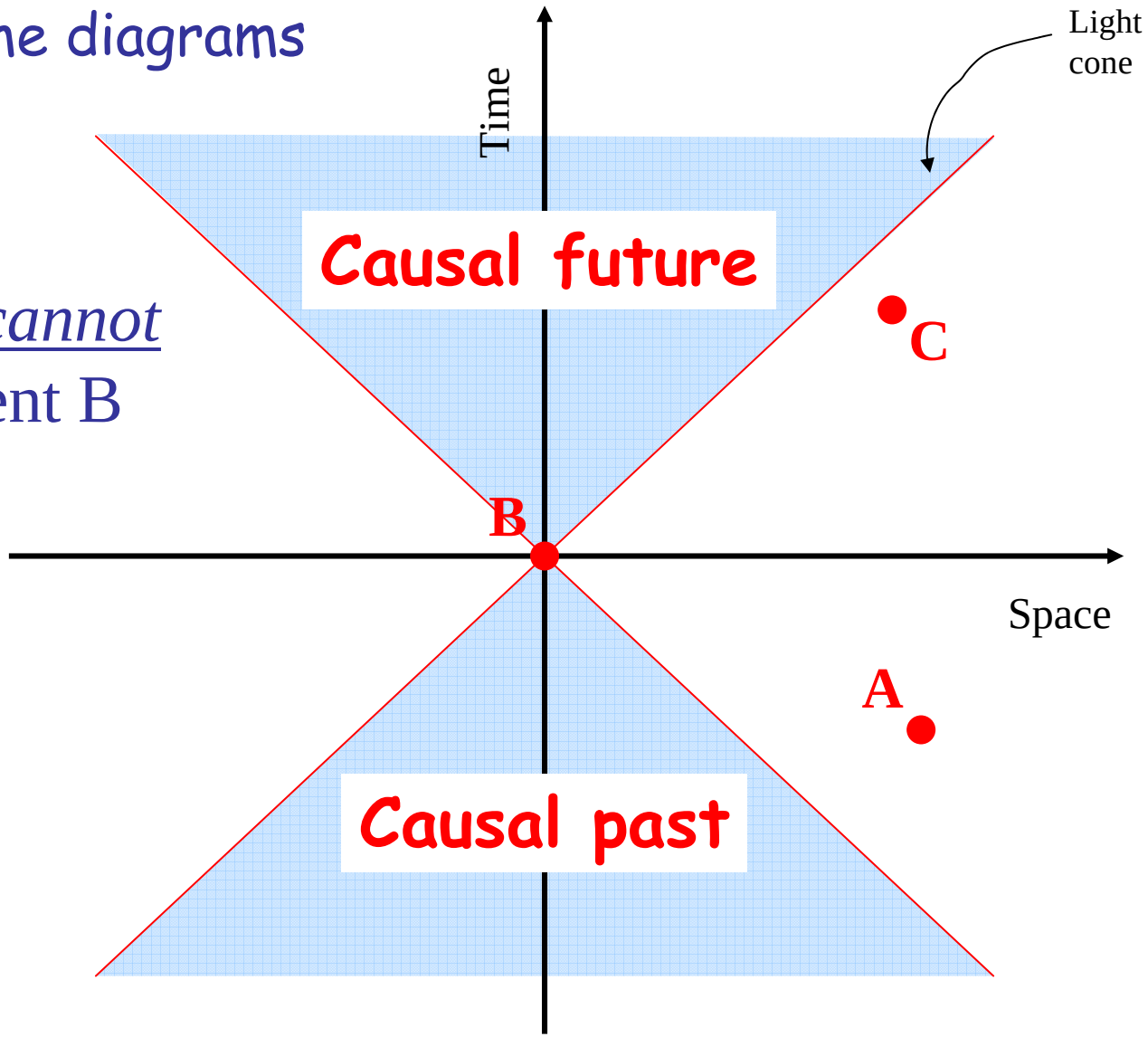
Spacetime diagrams



Making Sense of Einstein's Universe

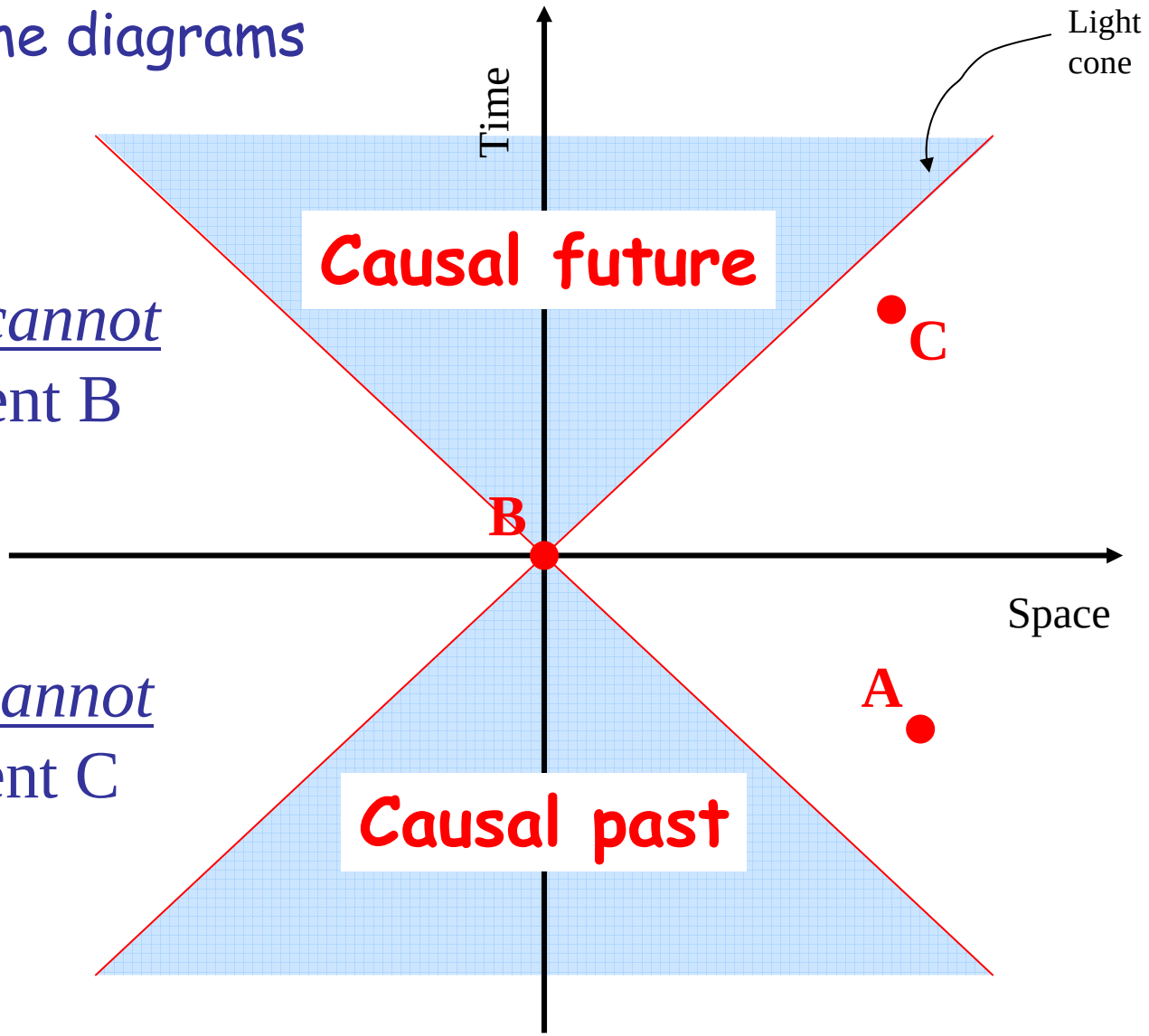
Spacetime diagrams

Event A *cannot* cause Event B



Making Sense of Einstein's Universe

Spacetime diagrams



Event A *cannot* cause Event B

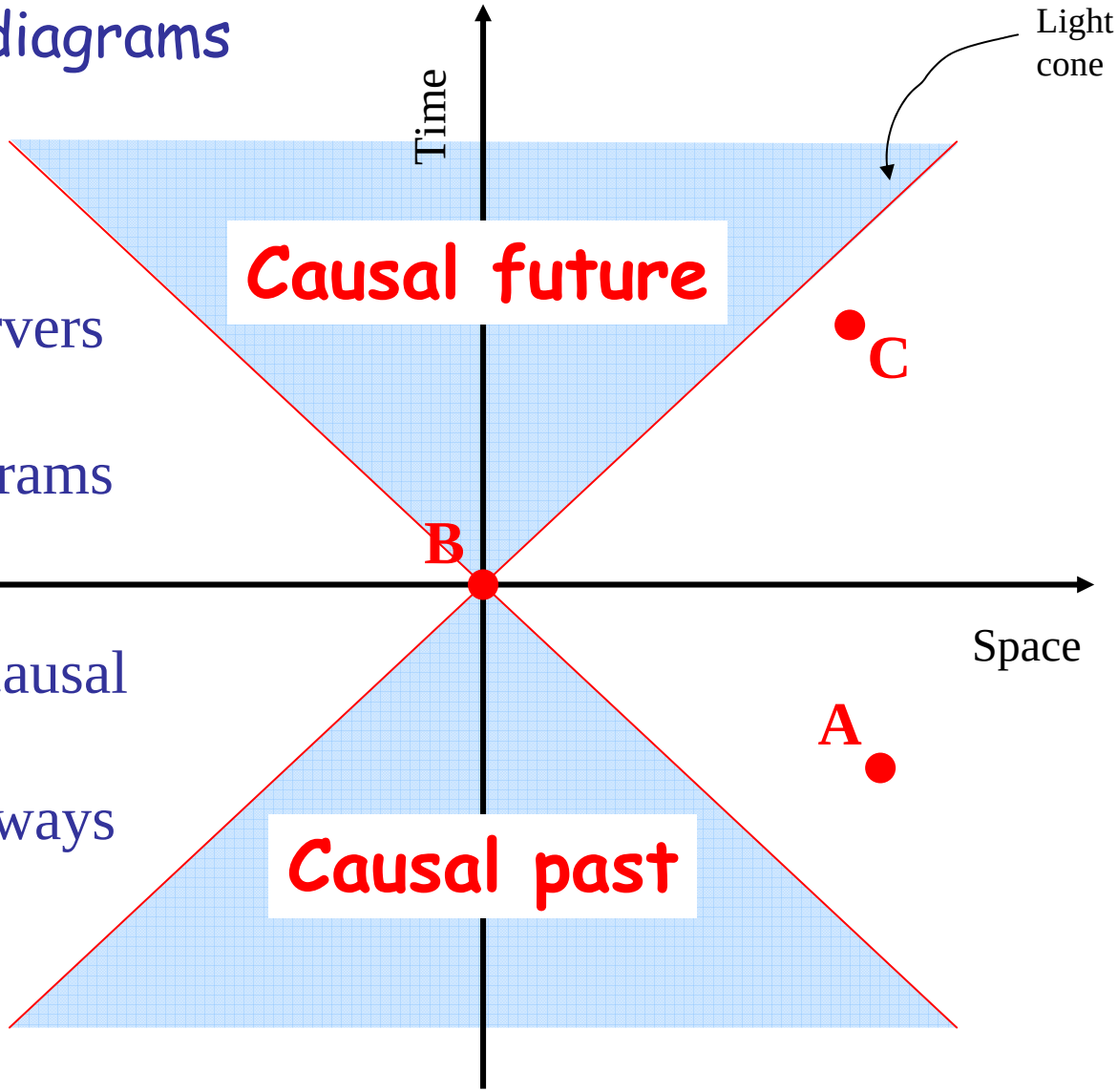
Event B *cannot* cause Event C

Making Sense of Einstein's Universe

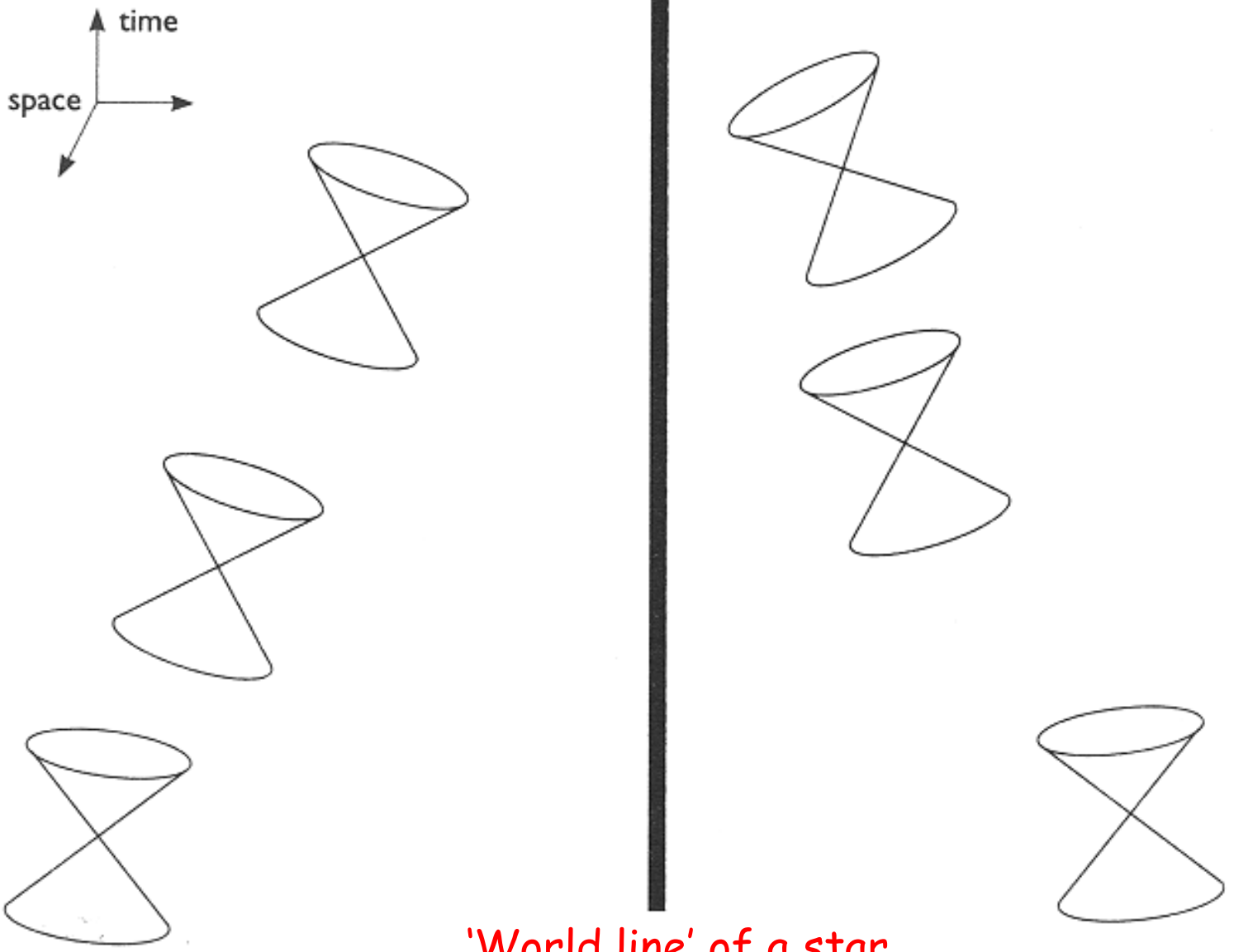
Spacetime diagrams

Different observers see different spacetime diagrams

However, the causal structure of spacetime is always preserved…



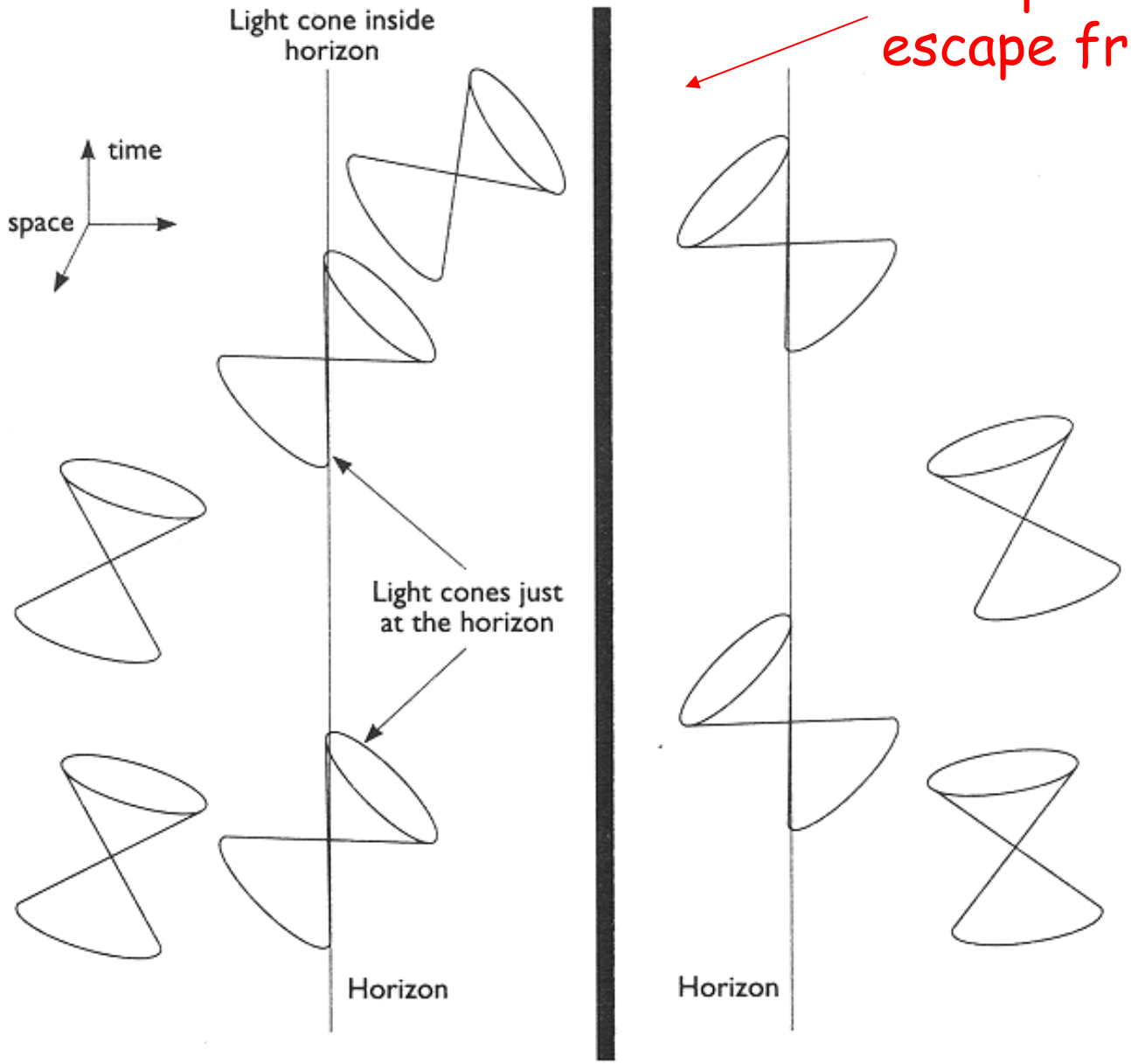
Gravity 'tilts' light cones



'World line' of a star

Gravity 'tilts' light cones

Even photons can't escape from here

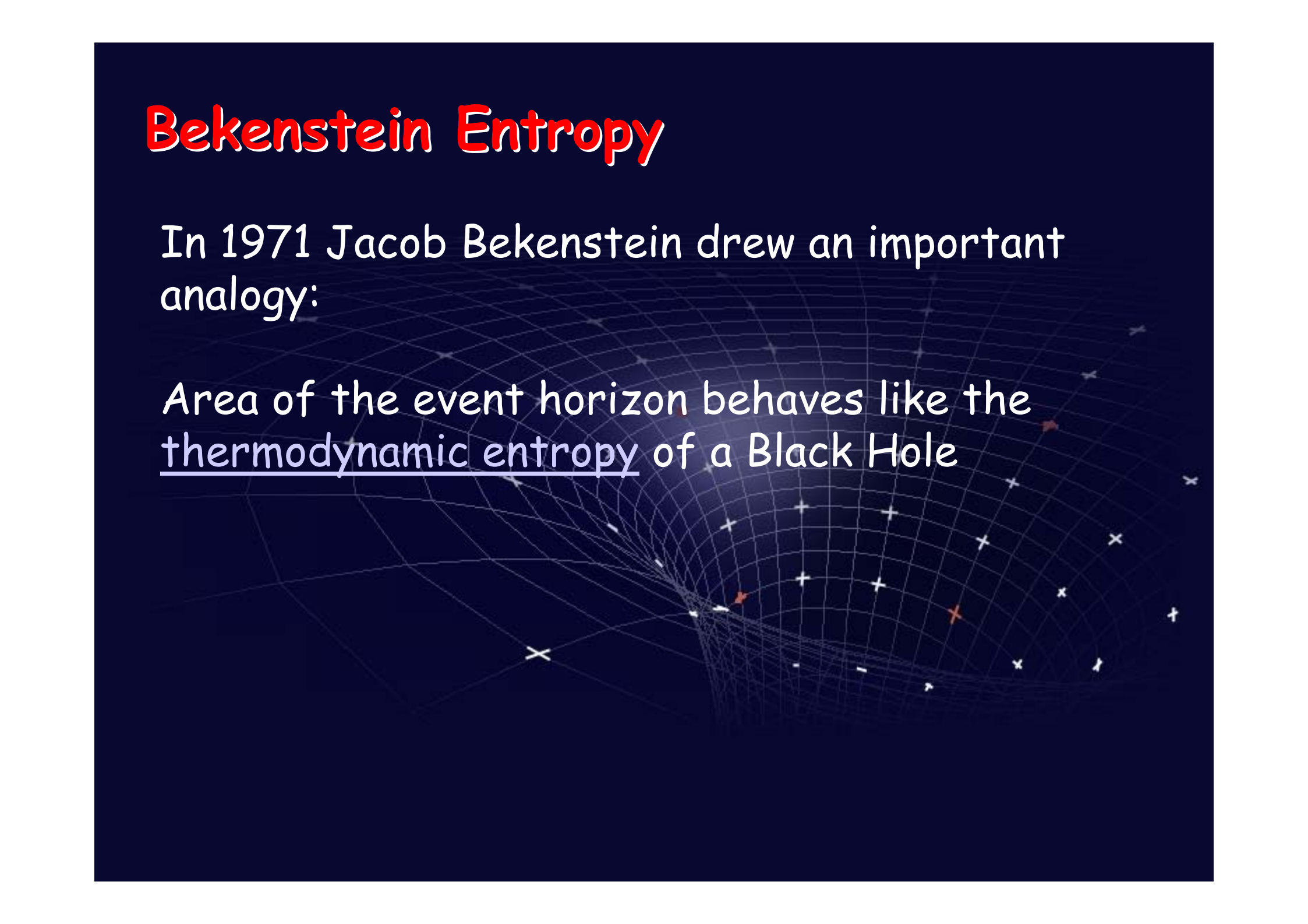


'World line' of a black hole

Bekenstein Entropy

In 1971 Jacob Bekenstein drew an important analogy:

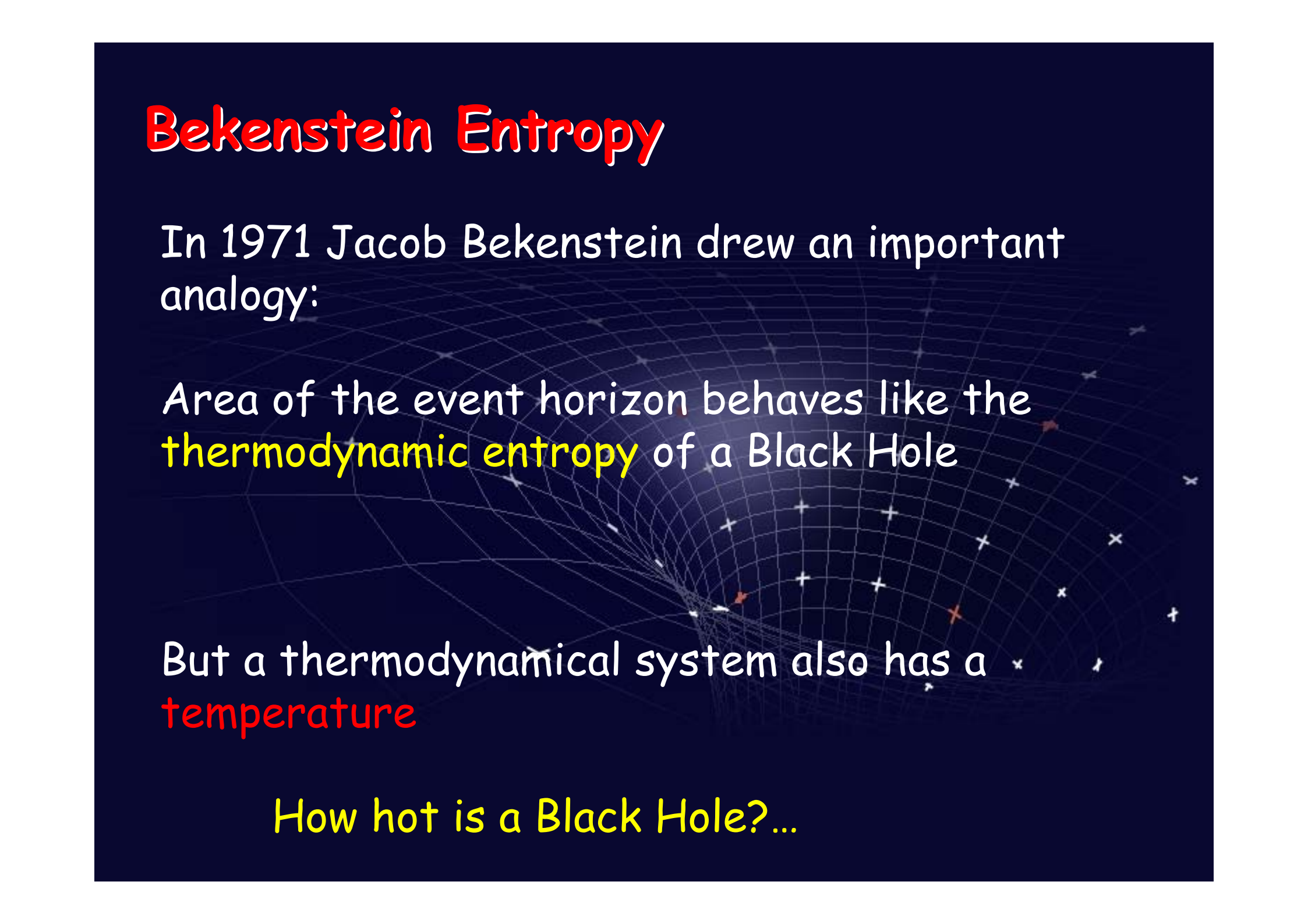
Area of the event horizon behaves like the thermodynamic entropy of a Black Hole



Bekenstein Entropy

In 1971 Jacob Bekenstein drew an important analogy:

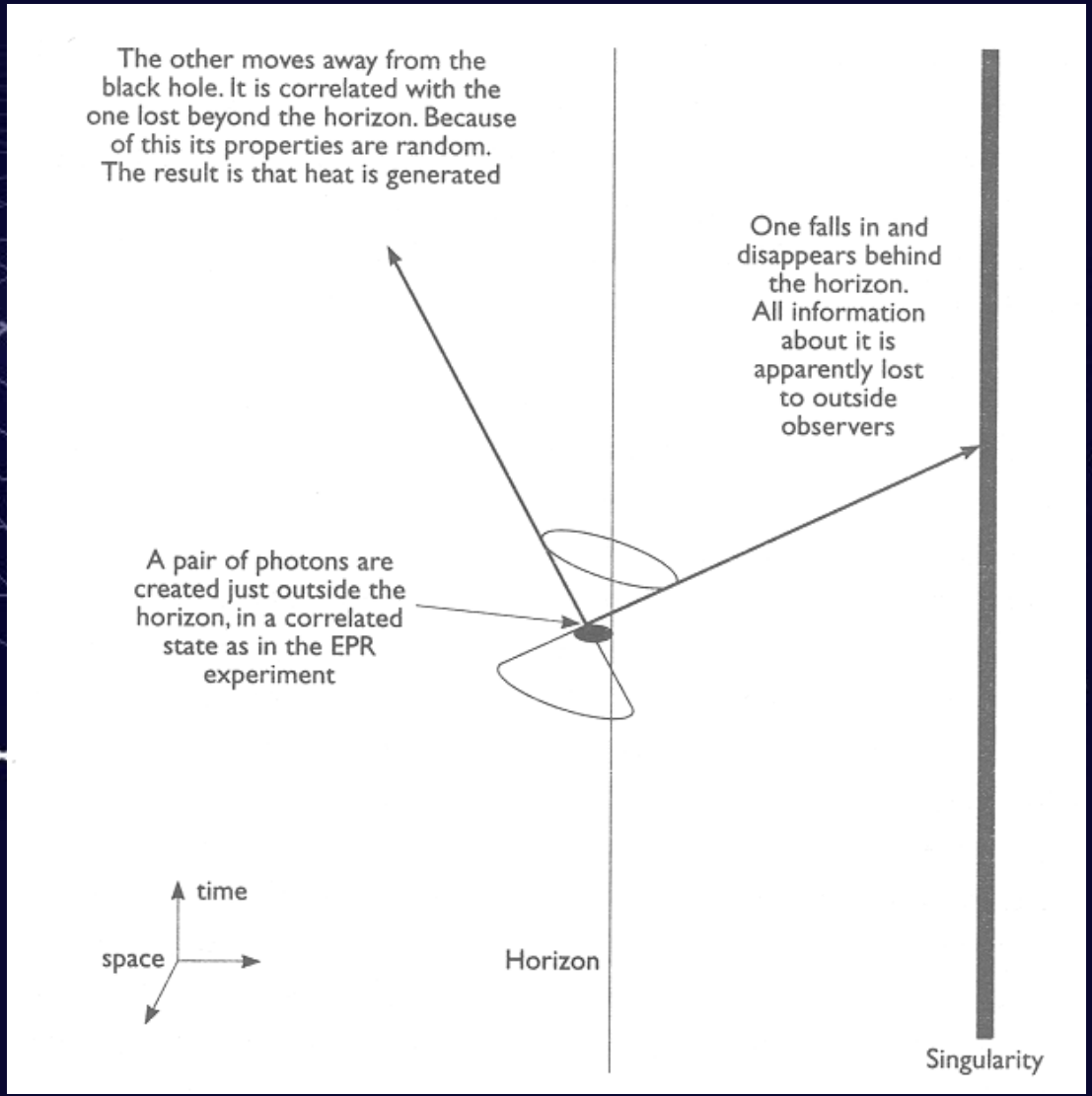
Area of the event horizon behaves like the thermodynamic entropy of a Black Hole



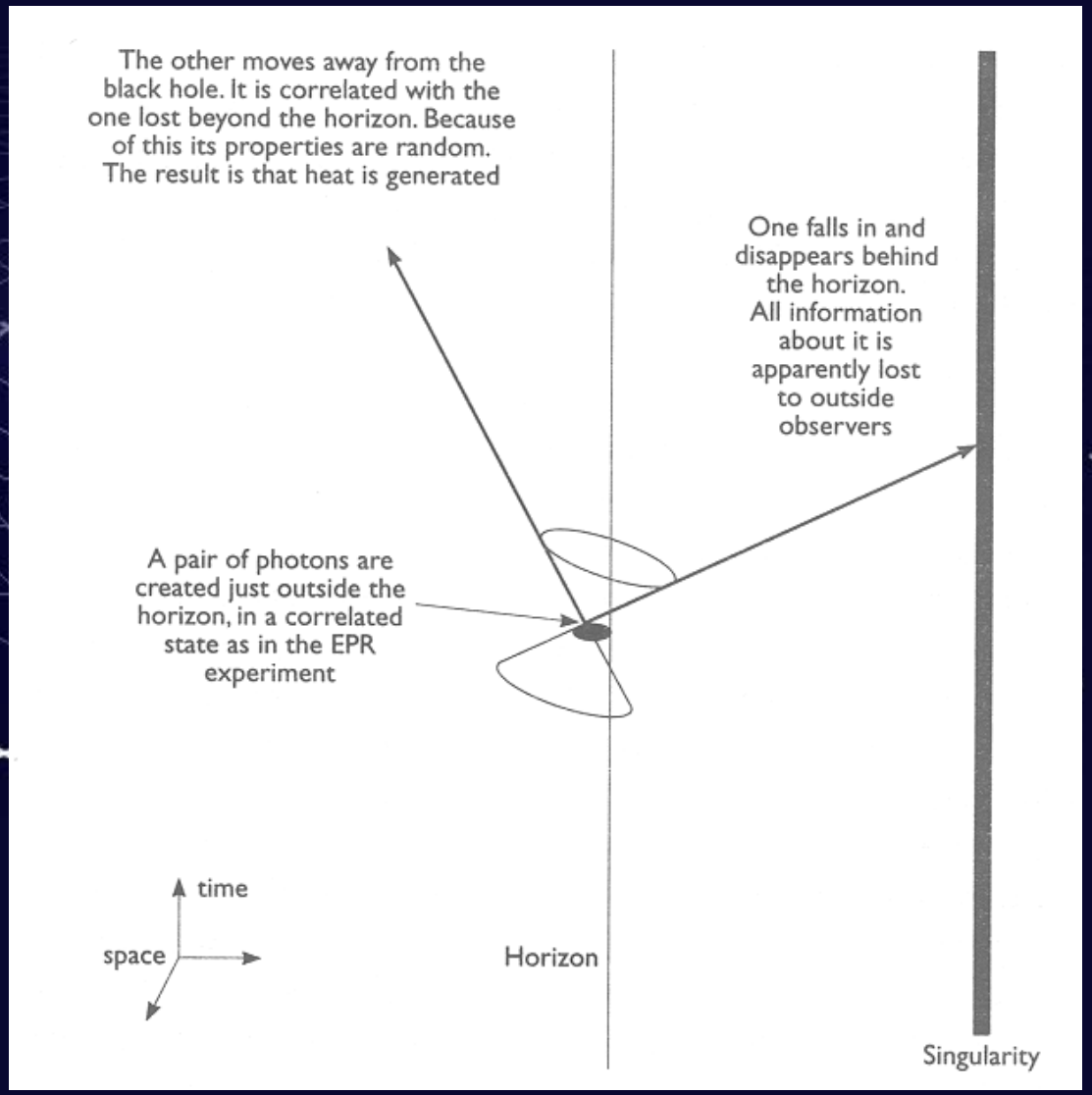
But a thermodynamical system also has a temperature

How hot is a Black Hole?...

By studying them as quantum objects, Stephen Hawking showed that Black Holes radiate

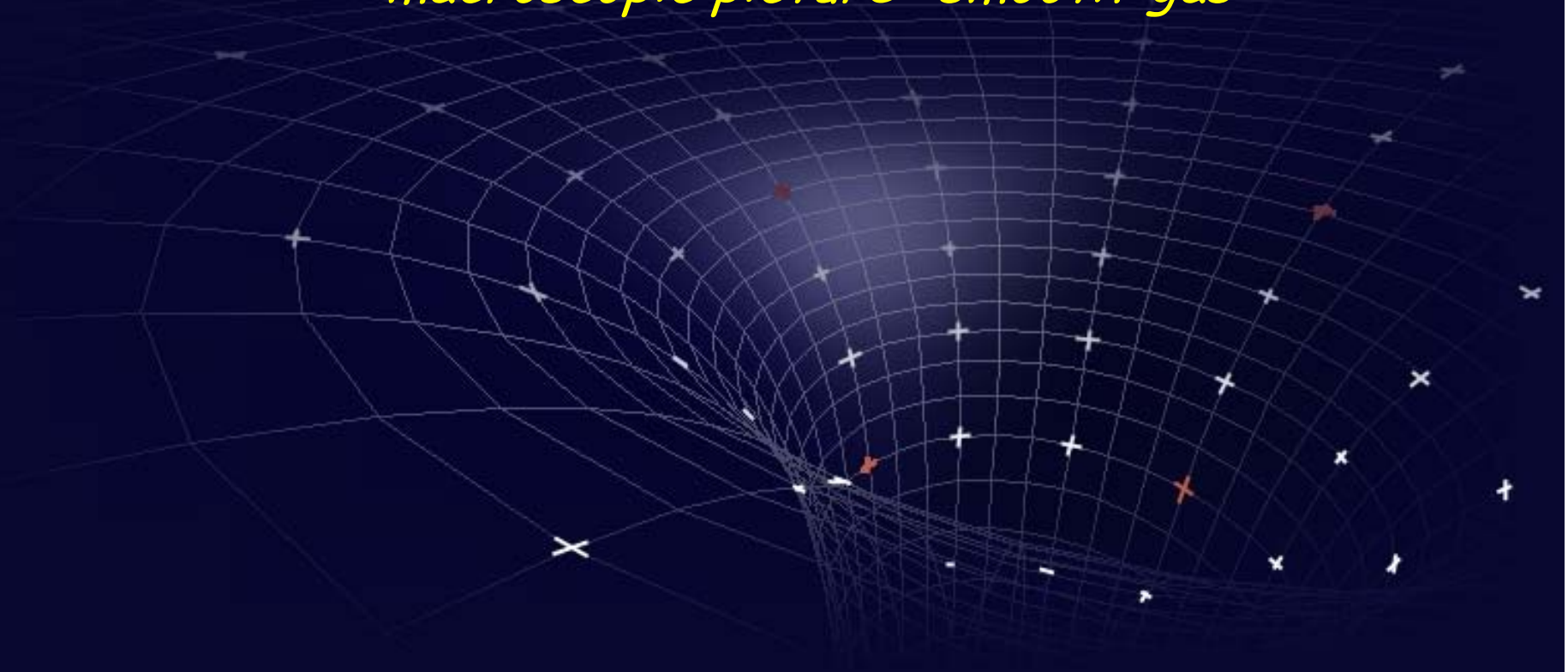


This completed the link between Black Holes and thermodynamics



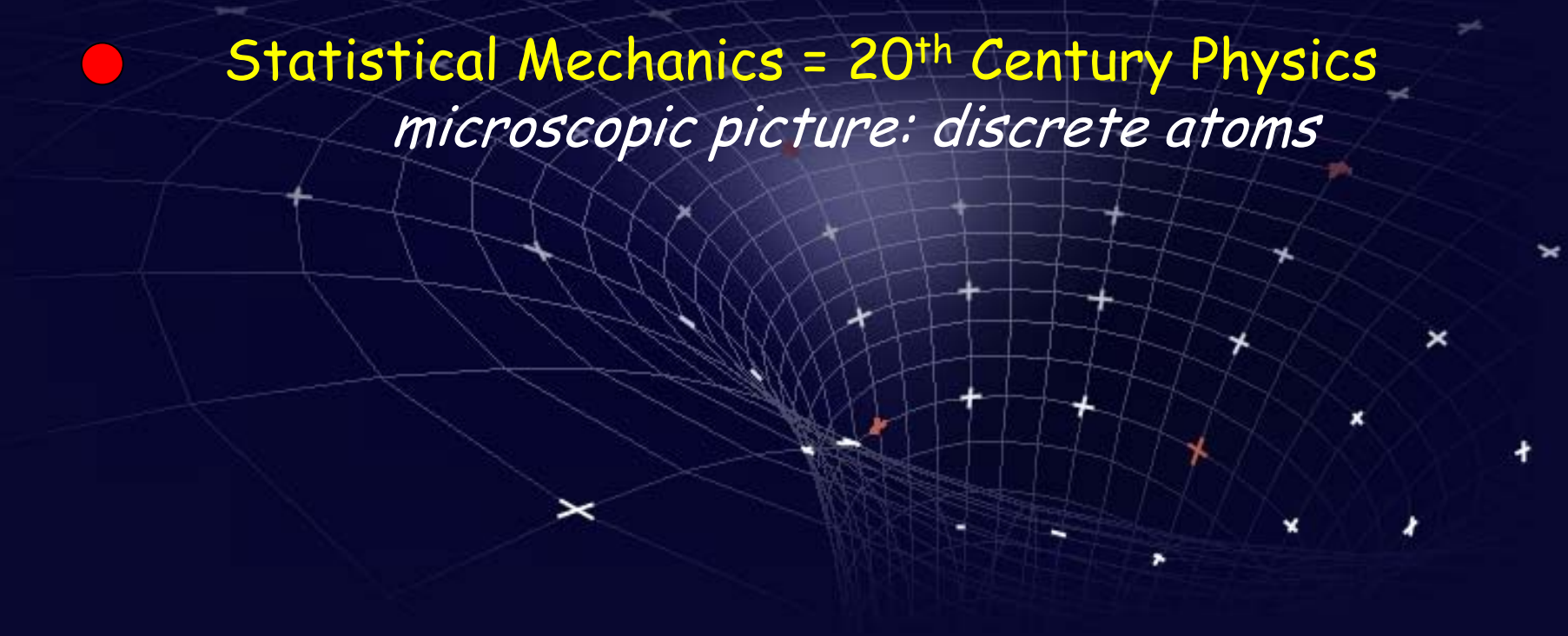
Quantised spacetime

- Thermodynamics = 19th Century Physics
  macroscopic picture: 'smooth' gas



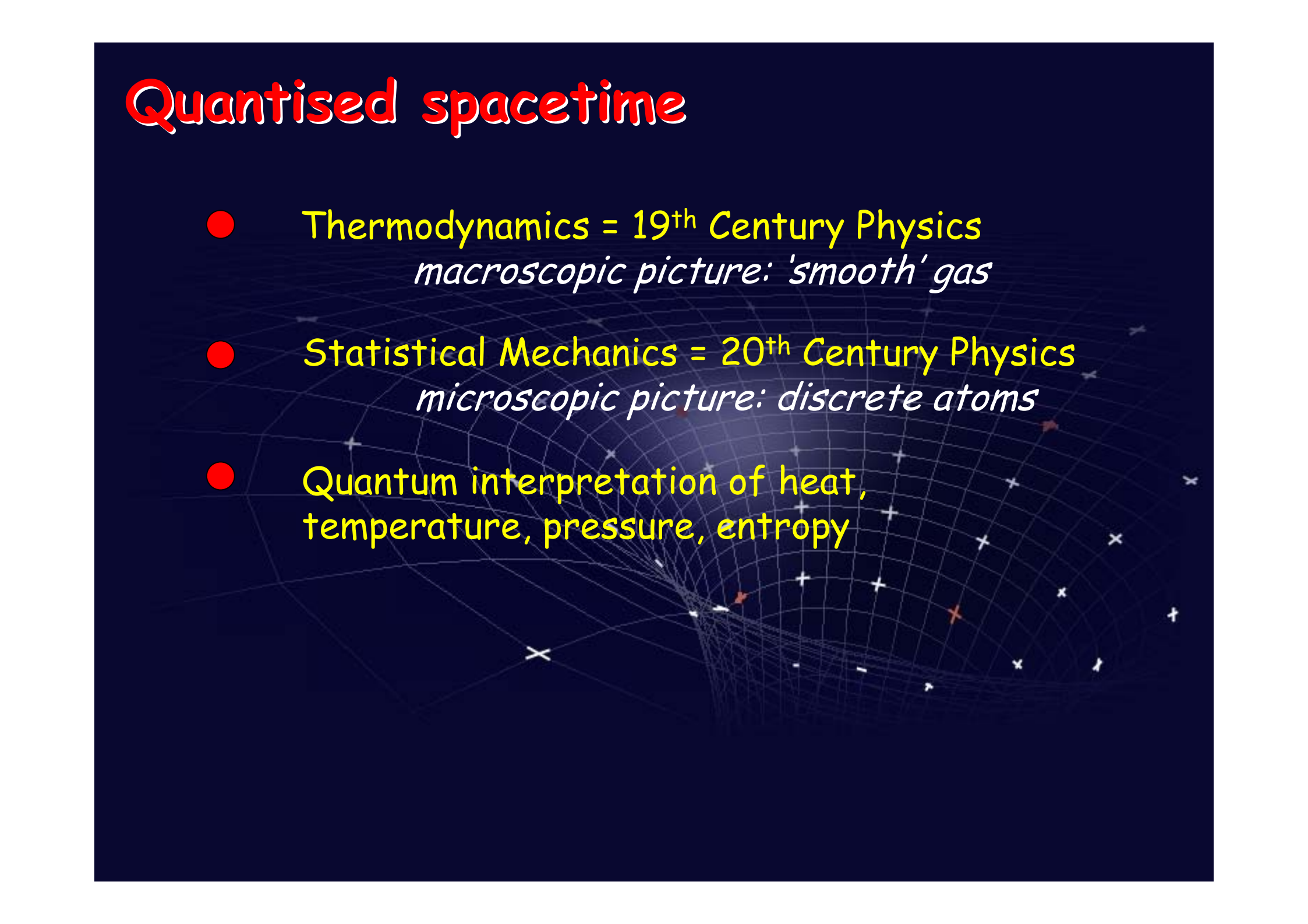
Quantised spacetime

- Thermodynamics = 19th Century Physics
  macroscopic picture: 'smooth' gas
- Statistical Mechanics = 20th Century Physics
  microscopic picture: discrete atoms



Quantised spacetime

- Thermodynamics = 19th Century Physics
  macroscopic picture: 'smooth' gas
- Statistical Mechanics = 20th Century Physics
  microscopic picture: discrete atoms
- Quantum interpretation of heat, temperature, pressure, entropy



Quantised spacetime

- Thermodynamics = 19th Century Physics
  macroscopic picture: 'smooth' gas
- Statistical Mechanics = 20th Century Physics
  microscopic picture: discrete atoms
- Quantum interpretation of heat, temperature, pressure, entropy
- Entropy measures our information about the motions of individual atoms

Quantised spacetime

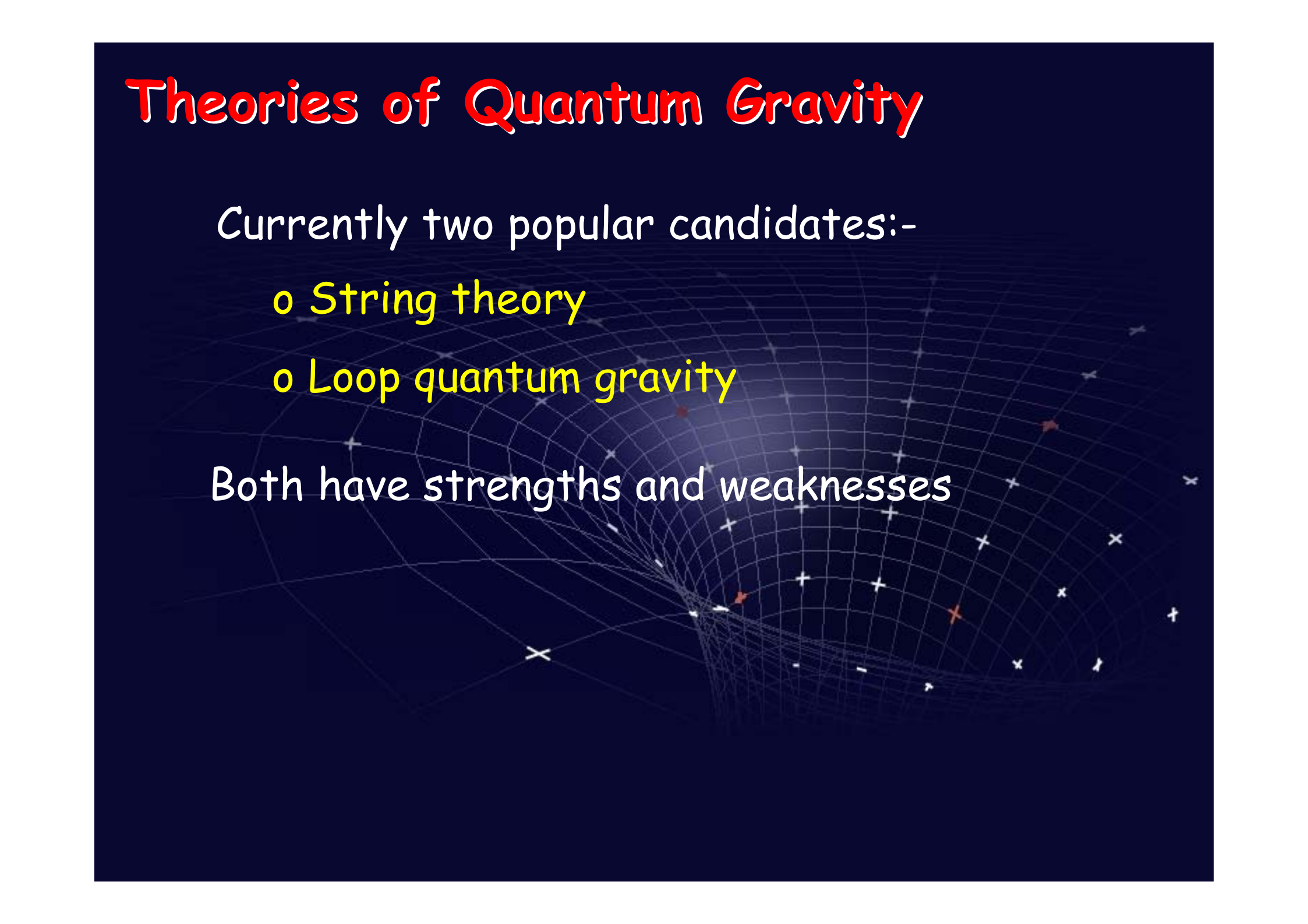
- Thermodynamics = 19th Century Physics
  macroscopic picture: 'smooth' gas
- Statistical Mechanics = 20th Century Physics
  microscopic picture: discrete atoms
- Quantum interpretation of heat, temperature, pressure, entropy
- Entropy measures our information about the motions of individual atoms
- Does Bekenstein Entropy indicate a quantum interpretation of spacetime?

Theories of Quantum Gravity

Currently two popular candidates:-

- String theory
- Loop quantum gravity

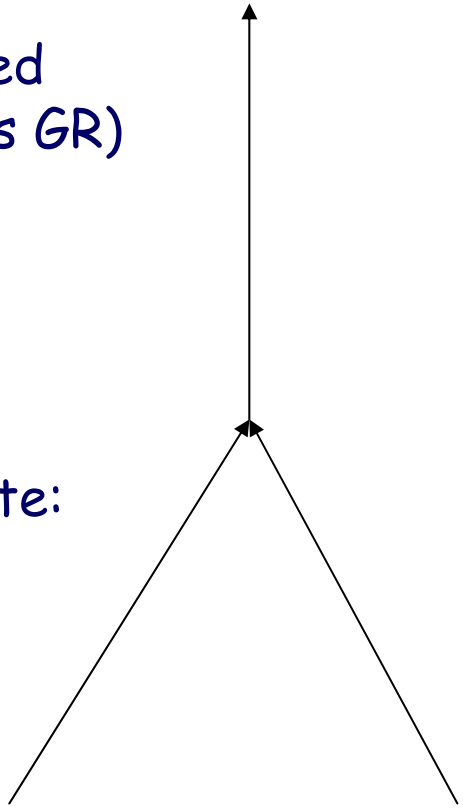
Both have strengths and weaknesses



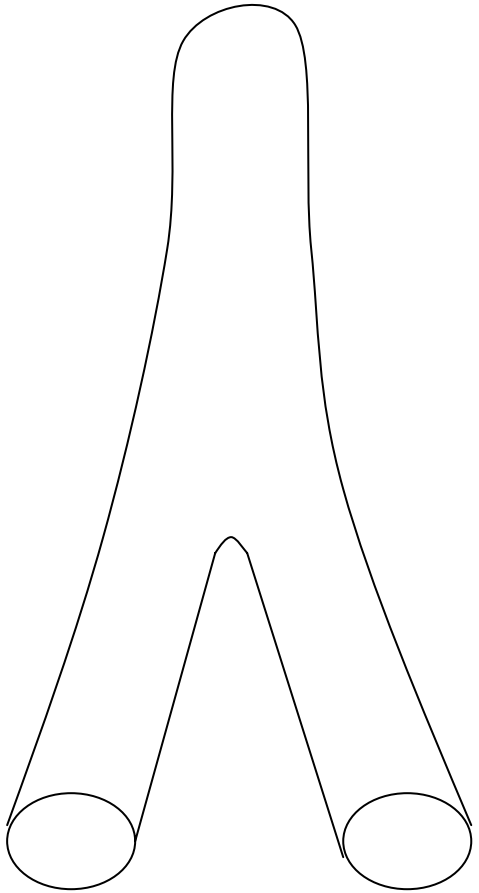
String Theory

- Point particles replaced by string loops
- Avoids 'infinities'
- BUT defined on fixed background (violates GR)
- No unique theory (e.g. *Membranes* in higher dimensions)
- Spacetime is discrete:

$$\Delta x \sim \frac{\hbar}{\Delta p} + C\Delta p$$



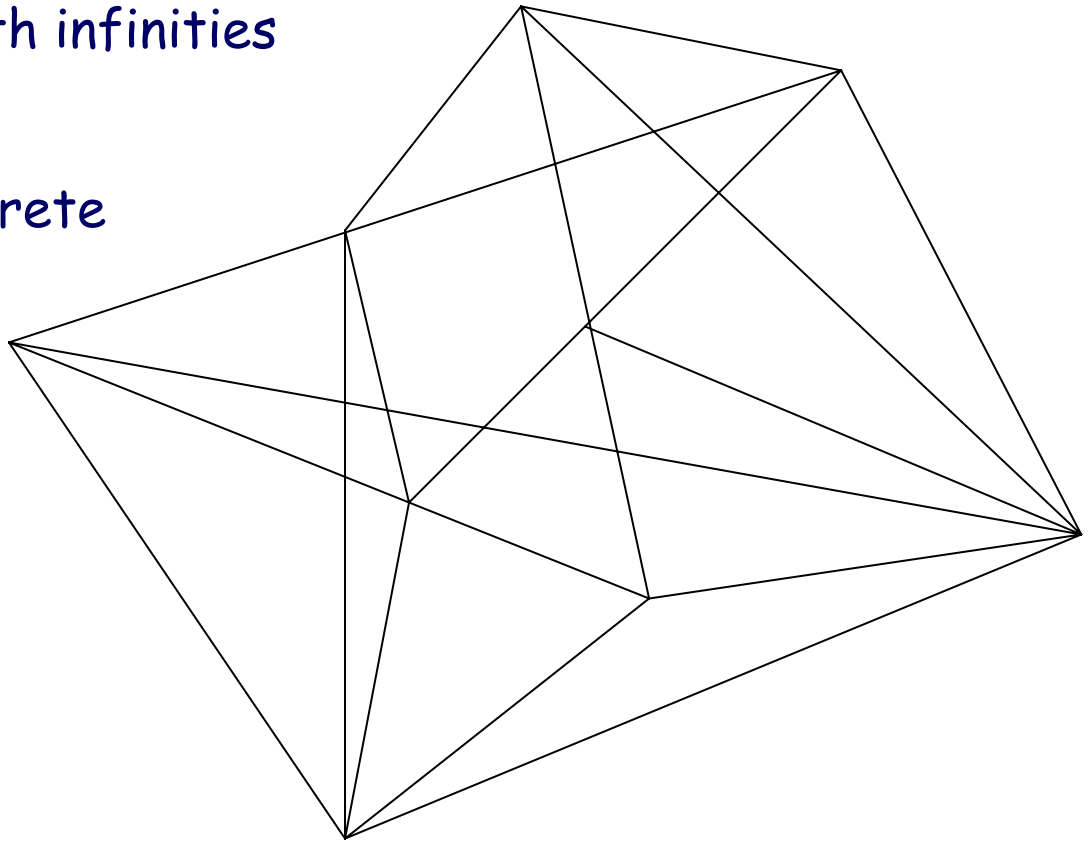
Particle representation



String representation

Loop Quantum Gravity

- Network of relations between events
- Quantum correlations built in
- BUT problems with infinities (gravitons)
- Spacetime is discrete

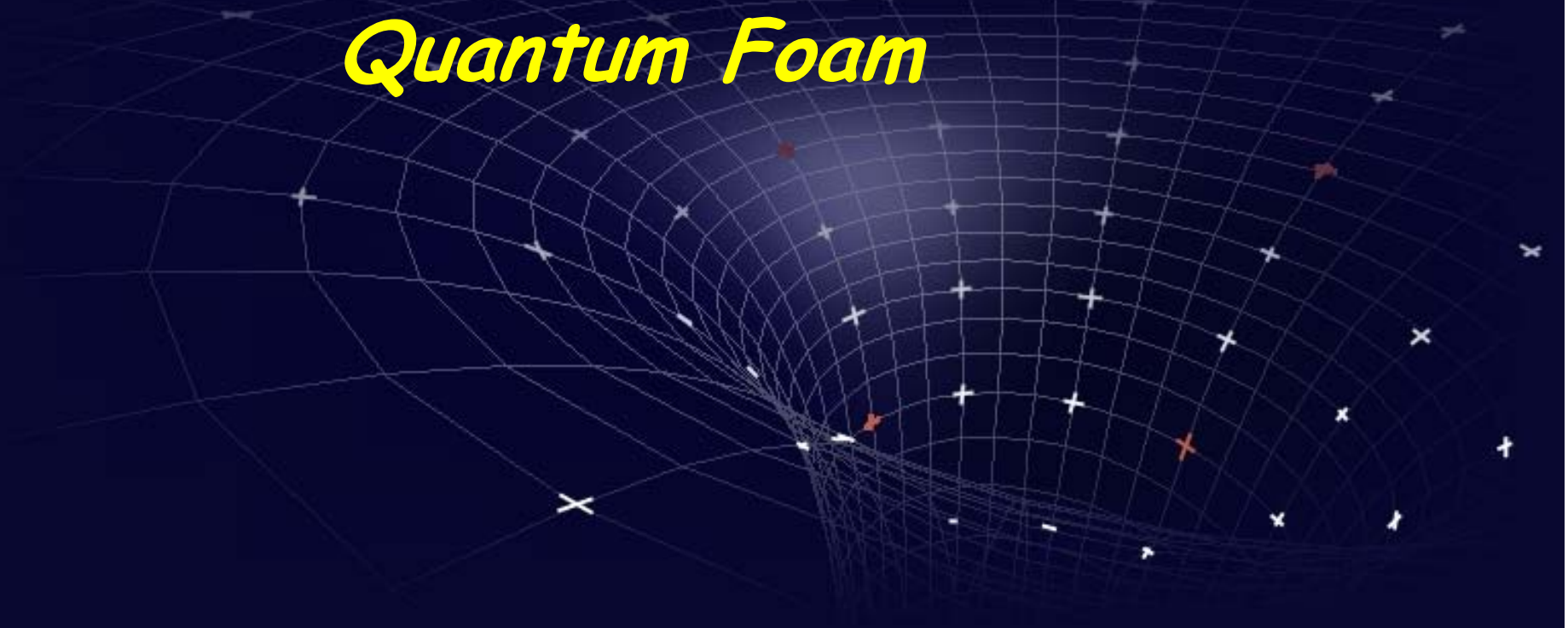


Quantum loop network

Three roads to same result:-

Spacetime comes in discrete chunks

Quantum Foam



Three roads to same result:-

Spacetime comes in discrete chunks

Quantum Foam

Holographic principle:-

Three roads are different manifestations of same quantum gravity theory

Three roads to same result:-

Spacetime comes in discrete chunks

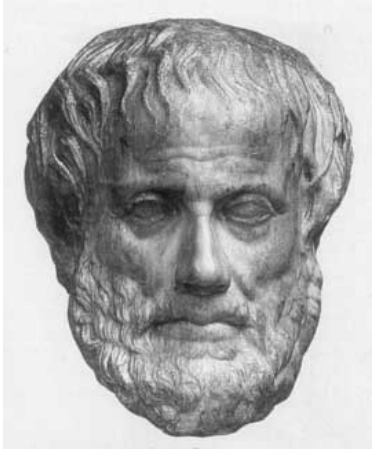
Quantum Foam

Holographic principle:-

Three roads are different manifestations of same quantum gravity theory

Analogous to Galileo and Kepler

How do things move?….



Aristotle's Theory:

1. *Objects move only as long as we apply a force to them*
2. *Falling bodies fall at a constant rate*
3. *Heavy bodies fall faster than light ones*

Galileo's Experiment:

1. *Objects keep moving after we stop applying a force (if no friction)*
2. *Falling bodies accelerate as they fall*
3. *Heavy bodies fall at the same rate as light ones*

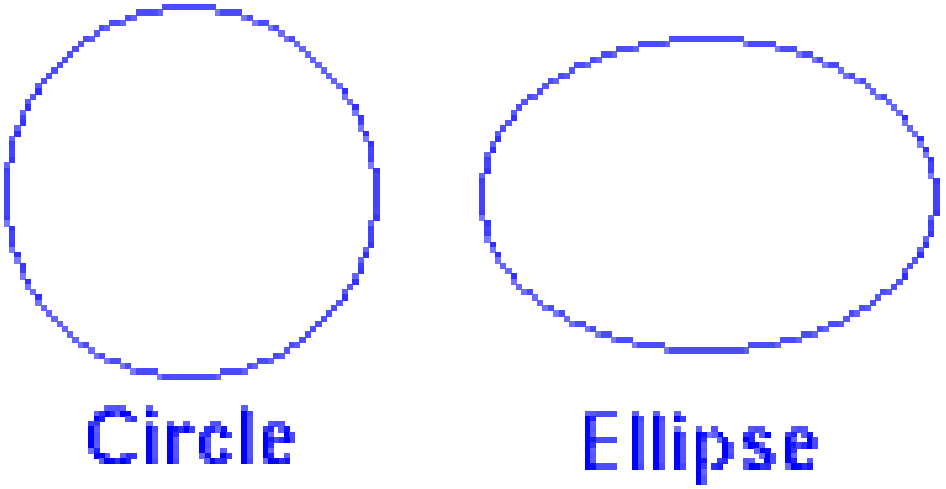
How do things move?….

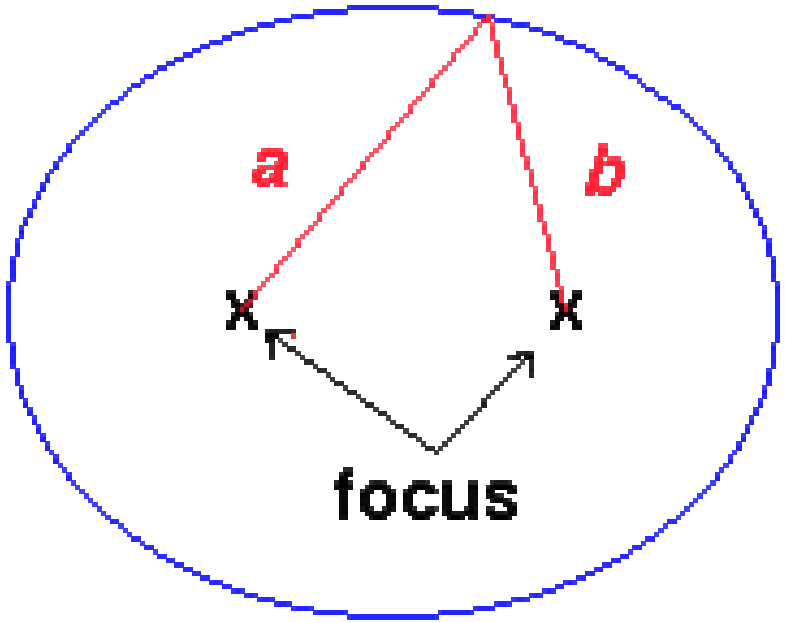
Aristotle's Theory:

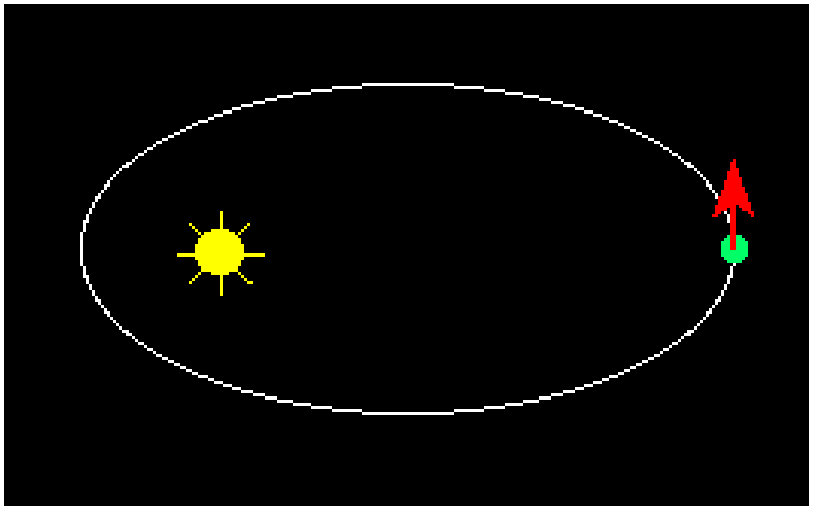
1. *Objects move only as long as we apply a force to them*
2. *Falling bodies fall at a constant rate*
3. *Heavy bodies fall faster than light ones*

Galileo's Experiment:

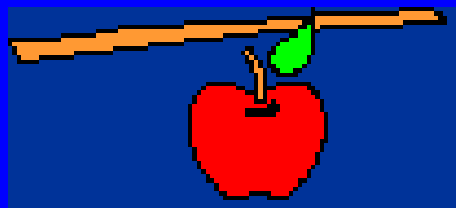
1. *Objects keep moving after we stop applying a force (if no friction)*
2. *Falling bodies accelerate as they fall*
3. *Heavy bodies fall at the same rate as light ones*







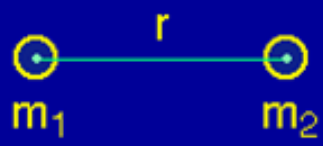
Kepler’s laws, published 1609, 1619



Law of Universal Gravitation

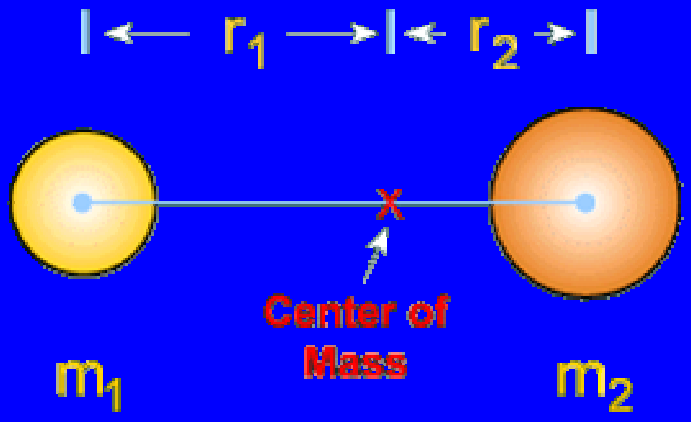
Every object in the Universe attracts every other object with a force directed along the line of centers for the two objects that is proportional to the product of their masses and inversely proportional to the square of the separation between the two objects.

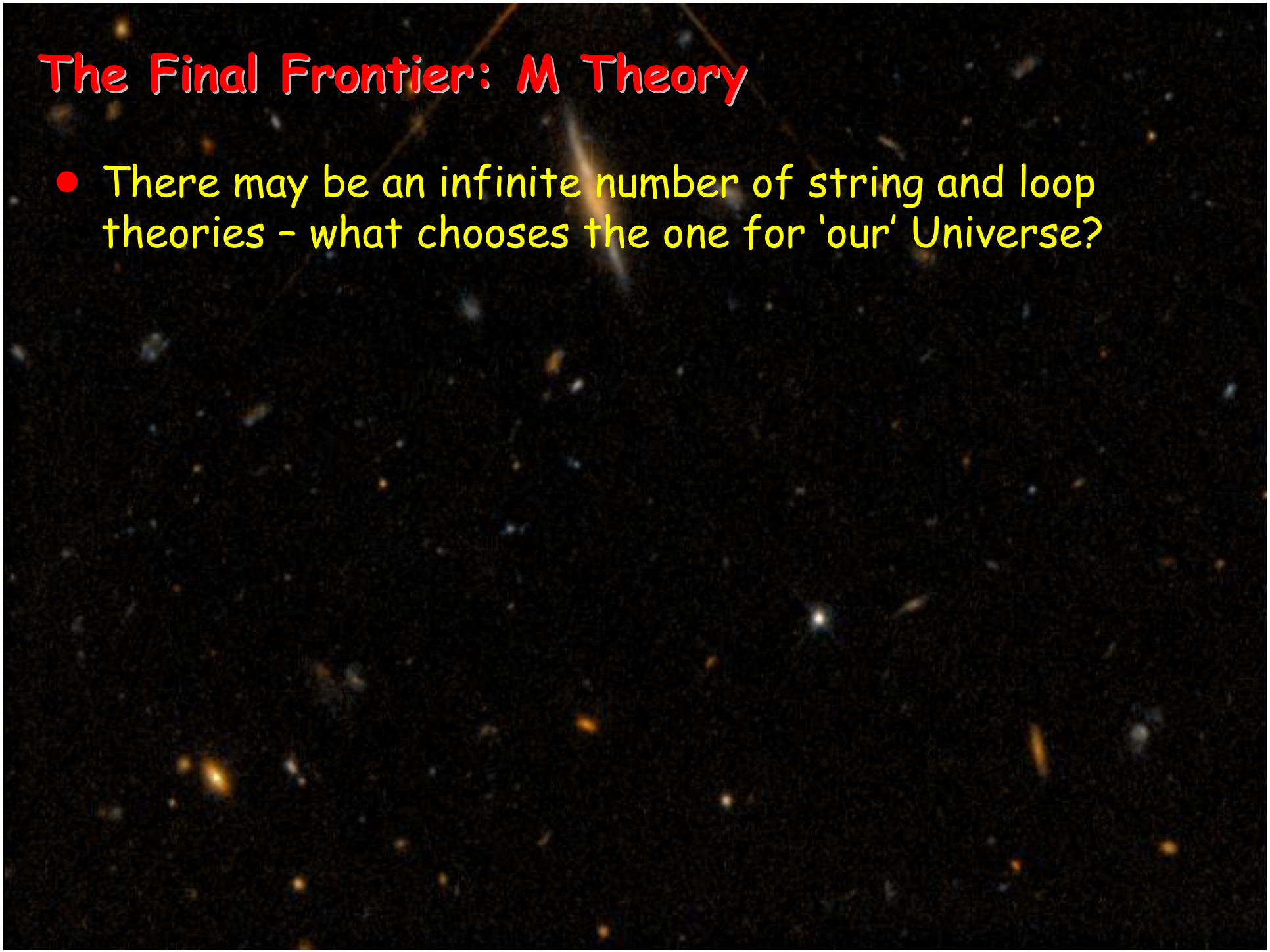
$$F_g = G\frac{m_1 m_2}{r^2}$$



Isaac Newton:
1642 – 1727 AD

The Principia: 1684 - 1686





The Final Frontier: M Theory

- There may be an infinite number of string and loop theories – what chooses the one for 'our' Universe?

The Final Frontier: M Theory

- There may be an infinite number of string and loop theories – what chooses the one for 'our' Universe?
- We need a meta-theory which can explain:-
  - why do we live in a (3+1)-D Universe?
  - why is the Universe so large and old?
  - why does spacetime look smooth on large scales?

The Final Frontier: M Theory

- There may be an infinite number of string and loop theories – what chooses the one for 'our' Universe?
- We need a meta-theory which can explain:-
  - why do we live in a (3+1)-D Universe?
  - why is the Universe so large and old?
  - why does spacetime look smooth on large scales?
- Do we need an Anthropic Principle for M-theory?

The Final Frontier: M Theory

- There may be an infinite number of string and loop theories – what chooses the one for 'our' Universe?
- We need a meta-theory which can explain:-
  - why do we live in a (3+1)-D Universe?
  - why is the Universe so large and old?
  - why does spacetime look smooth on large scales?
- Do we need an Anthropic Principle for M-theory?
- Can we test the prediction of quantised spacetime?

The Final Frontier: M Theory

- There may be an infinite number of string and loop theories – what chooses the one for 'our' Universe?
- We need a meta-theory which can explain:-
  - why do we live in a (3+1)-D Universe?
  - why is the Universe so large and old?
  - why does spacetime look smooth on large scales?
- Do we need an Anthropic Principle for M-theory?
- Can we test the prediction of quantised spacetime?

Watch this space!