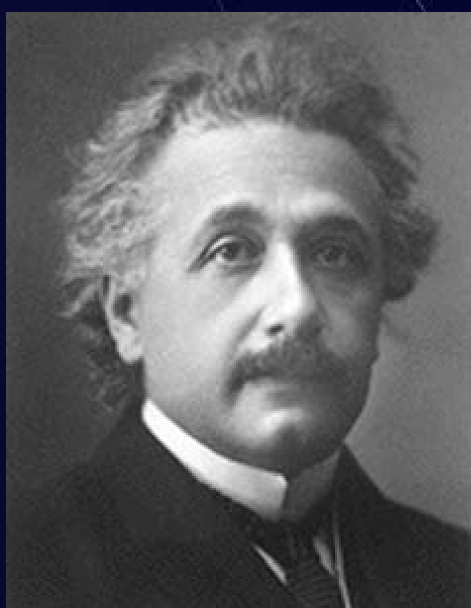
# Einstein's Universe

UNIVERSITY of GLASGOW



**Dr Martin Hendry**

*Dept of Physics and Astronomy*
*University of Glasgow, UK*

# Plan for remaining sessions

5) Introduction to General Relativity

6) GR, Black Holes and Cosmology

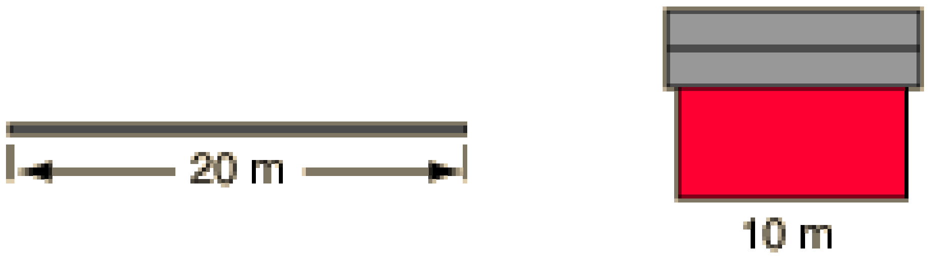
7) Hot topics in Cosmology

8) The Search for Gravitational Waves

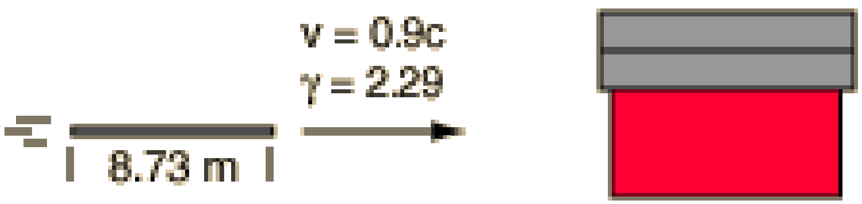
9) Einstein and the Quantum Revolution

10) The post-Einstein Universe

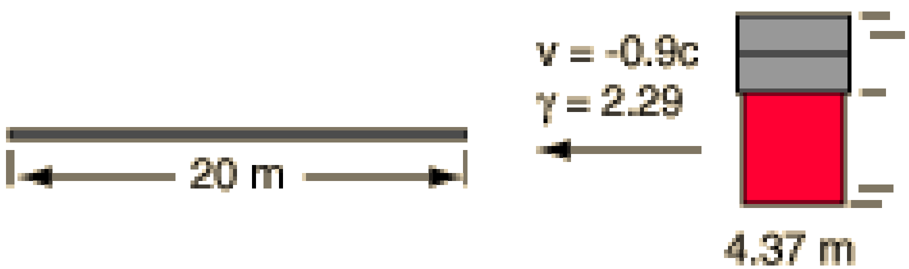
# The Pole in the Barn Paradox




A 20 meter pole and a 10 meter barn in their perspective when in the same rest frame.




If the pole has speed 0.9c, then it is length-contracted by a factor of 2.29 and short enough to fit momentarily within the barn, at least as seen by an observer in the barn.



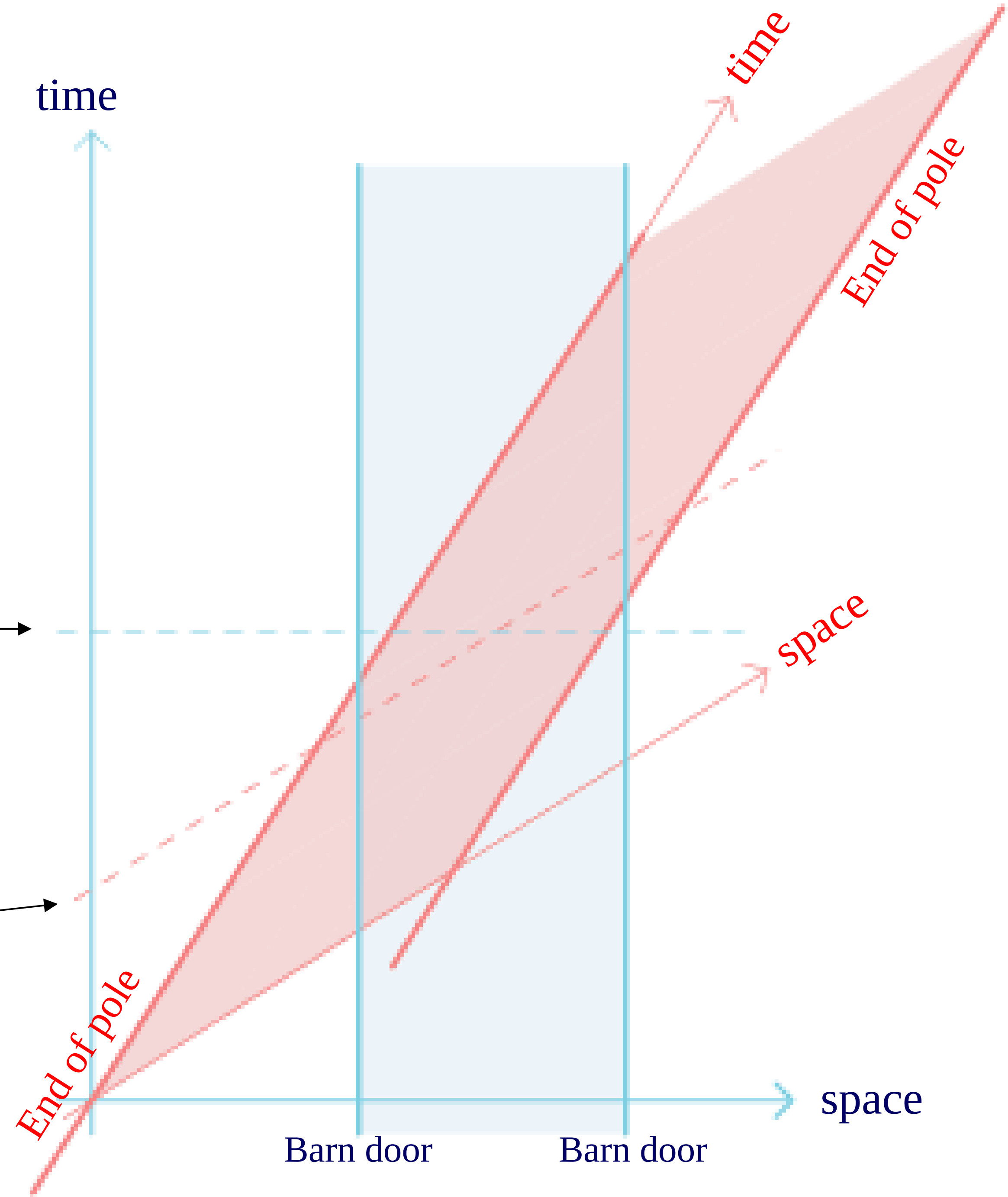

But from the point of view of the pole, the barn is contracted and the pole will never fit inside it.

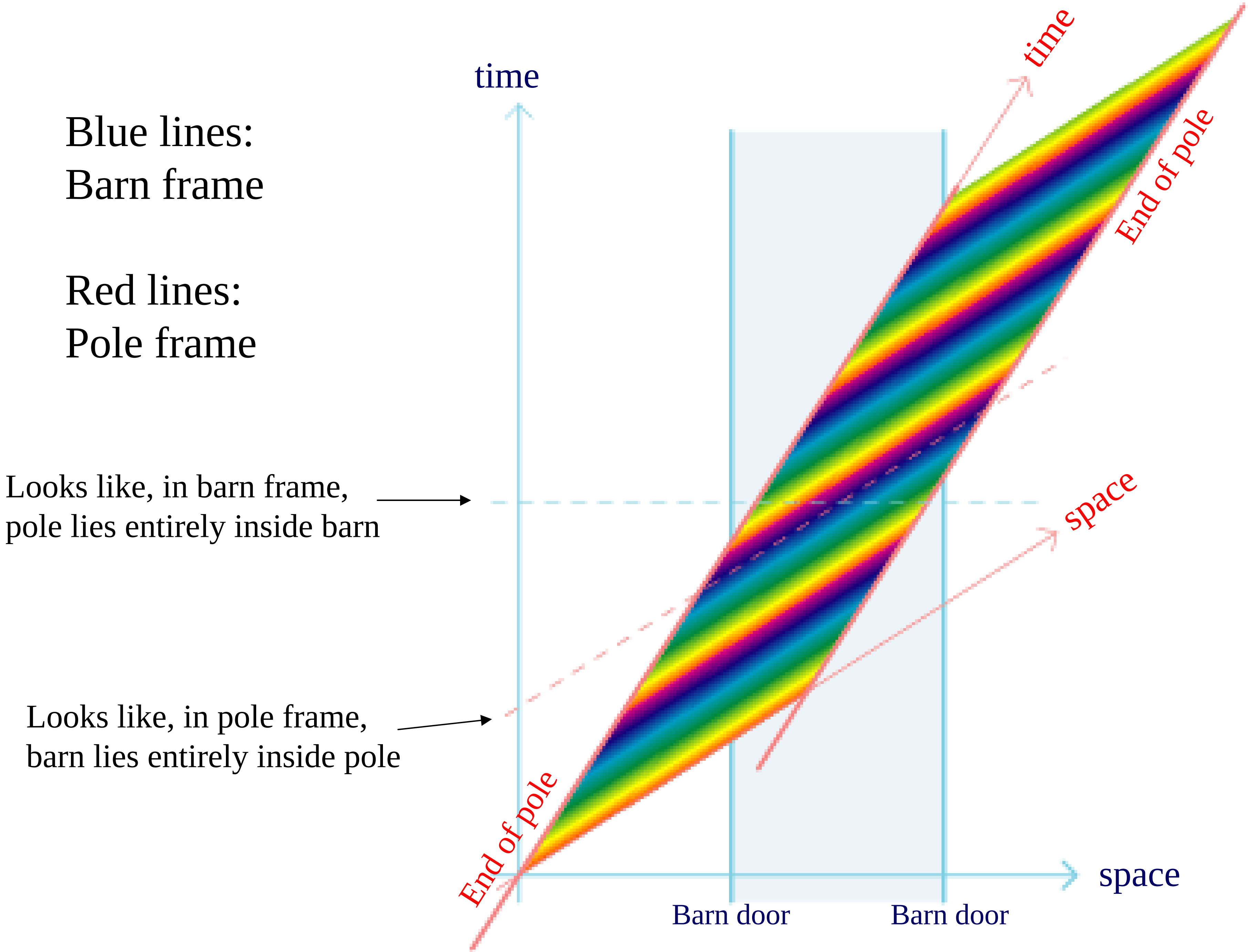
Blue lines:
Barn frame

Red lines:
Pole frame

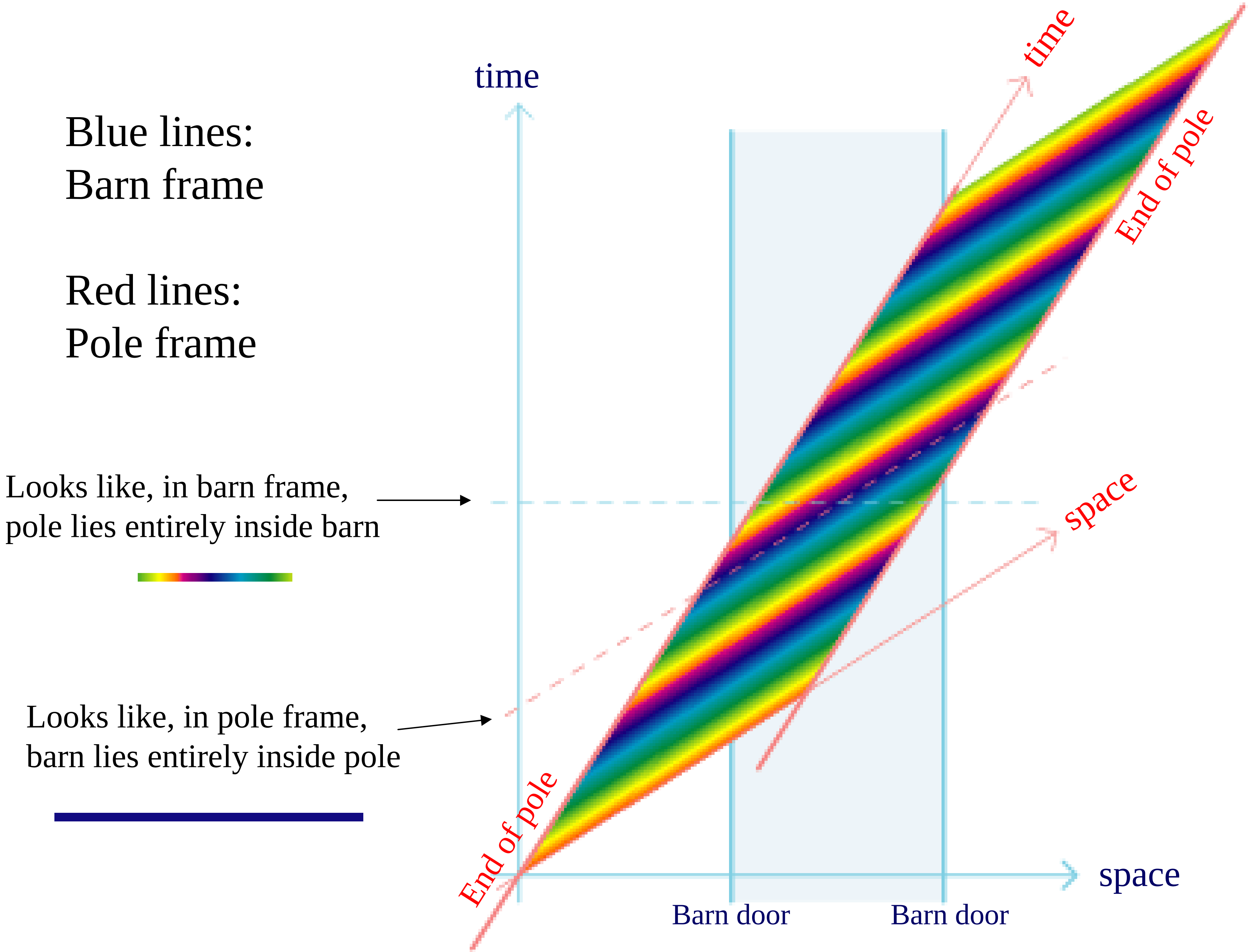
Looks like, in barn frame, pole lies entirely inside barn

Looks like, in pole frame, barn lies entirely inside pole





Blue lines:
Barn frame
Red lines:
Pole frame
Looks like, in barn frame,
pole lies entirely inside barn
Looks like, in pole frame,
barn lies entirely inside pole
time
space
Barn door
Barn door
time
space
End of pole
End of pole



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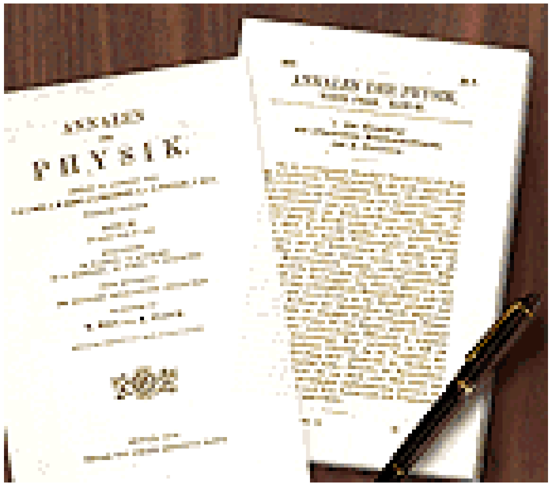
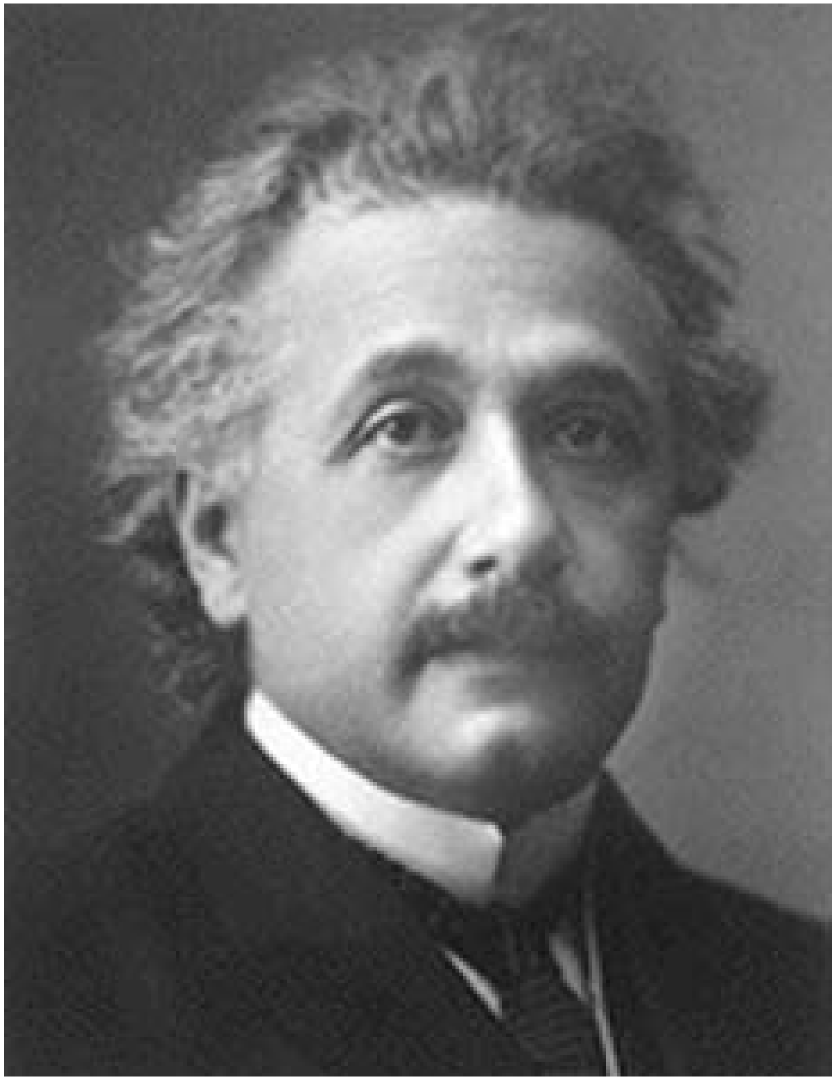
# Einstein's Relativity

How does gravity fit into this?




**General Relativity: 1916**





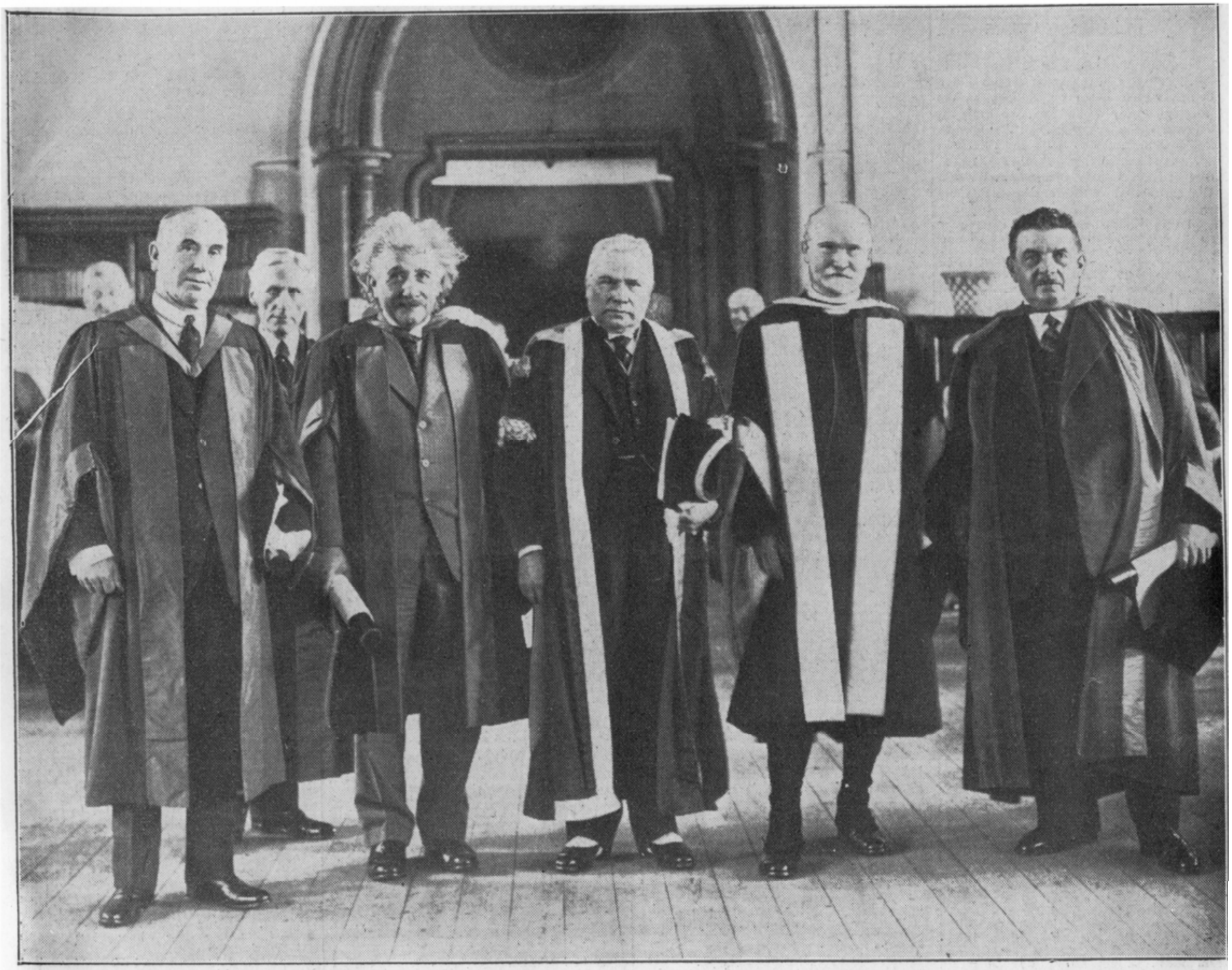
1916. № 7.

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.



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.


SPACETIME
GEOMETRY
Sean M. Carroll

# *How do things move?….*

**Newton built on Galileo's work and proposed 3 laws of motion:**

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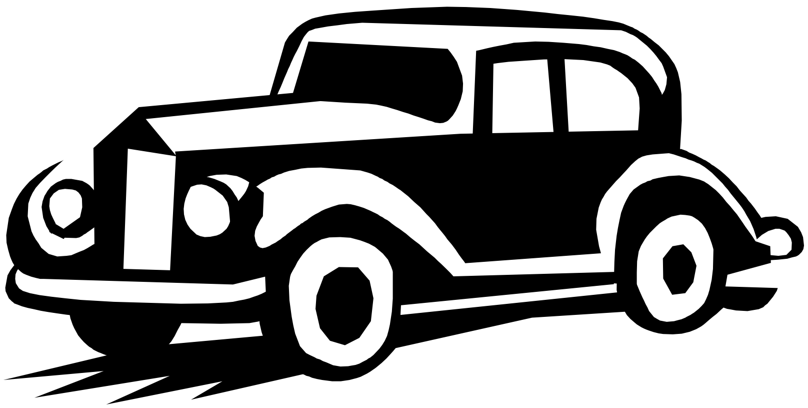
2. The acceleration of a body is proportional to the force on it

$$F = ma$$

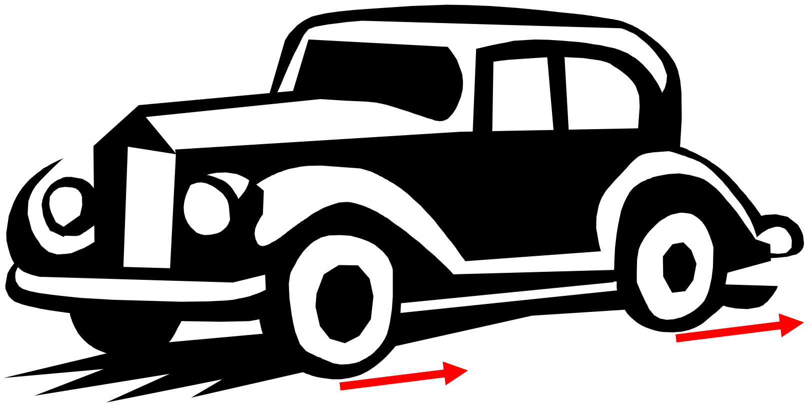
3. To every action there is an equal and opposite reaction

# *Getting from A to B…..*



Car engine burns petrol, releases chemical energy

# *Getting from A to B…..*



Car engine burns petrol, releases chemical energy

Applies a force to turn the car's wheels – they push against the road surface

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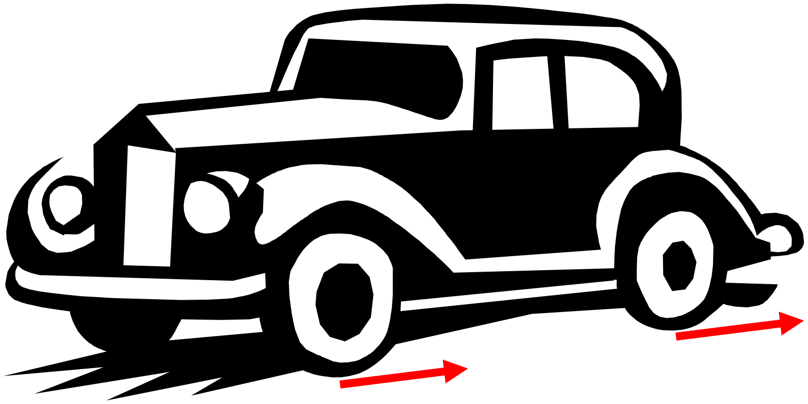

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**The car moves forward**

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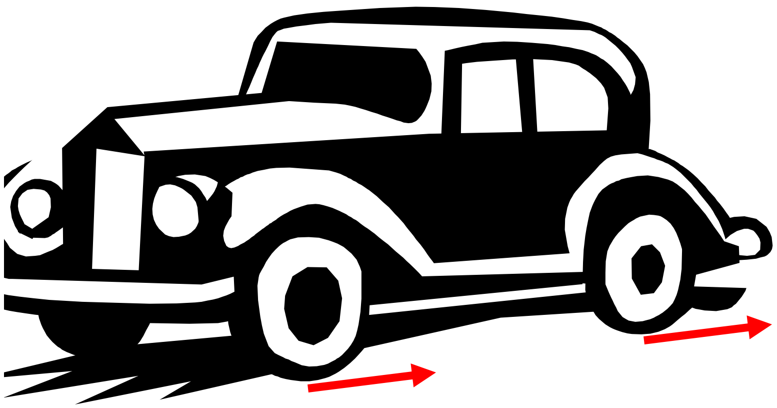

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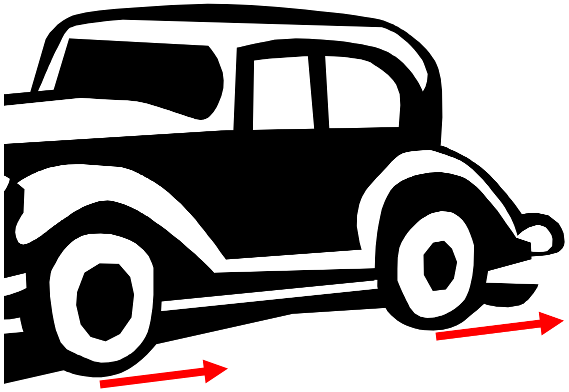

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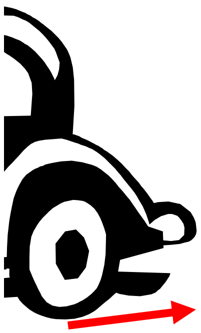

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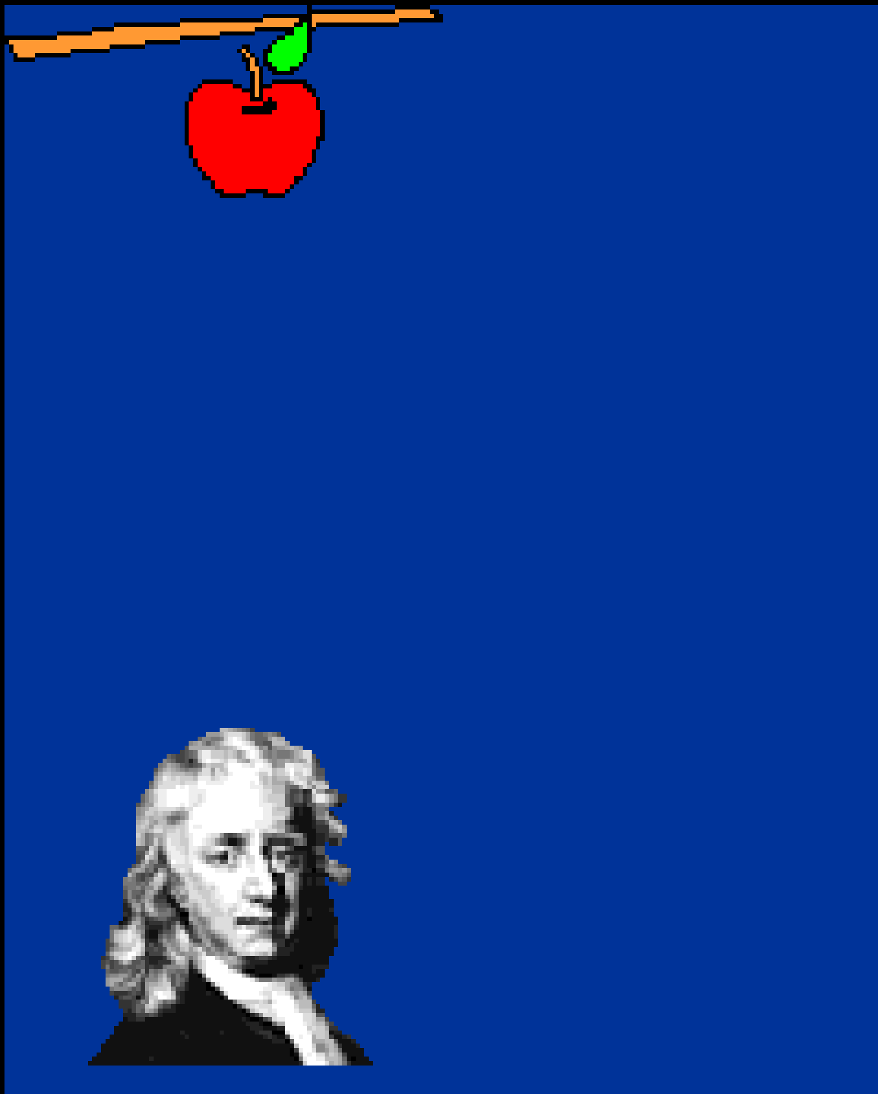


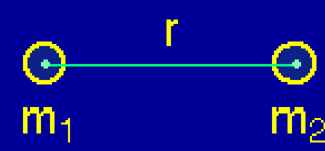
Isaac Newton:
1642 – 1727 AD

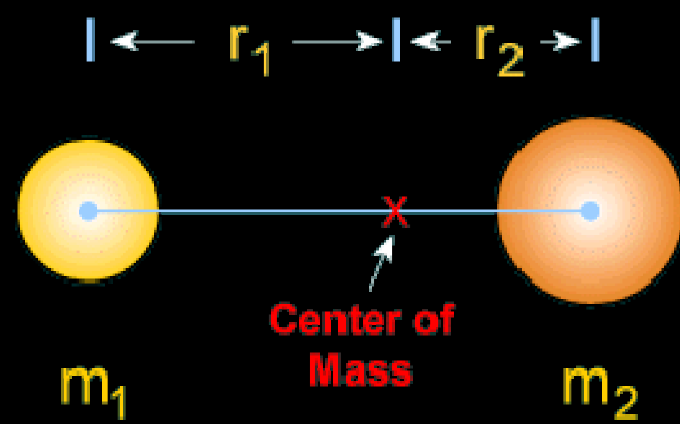
*The Principia: 1684 - 1686*

## 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.

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



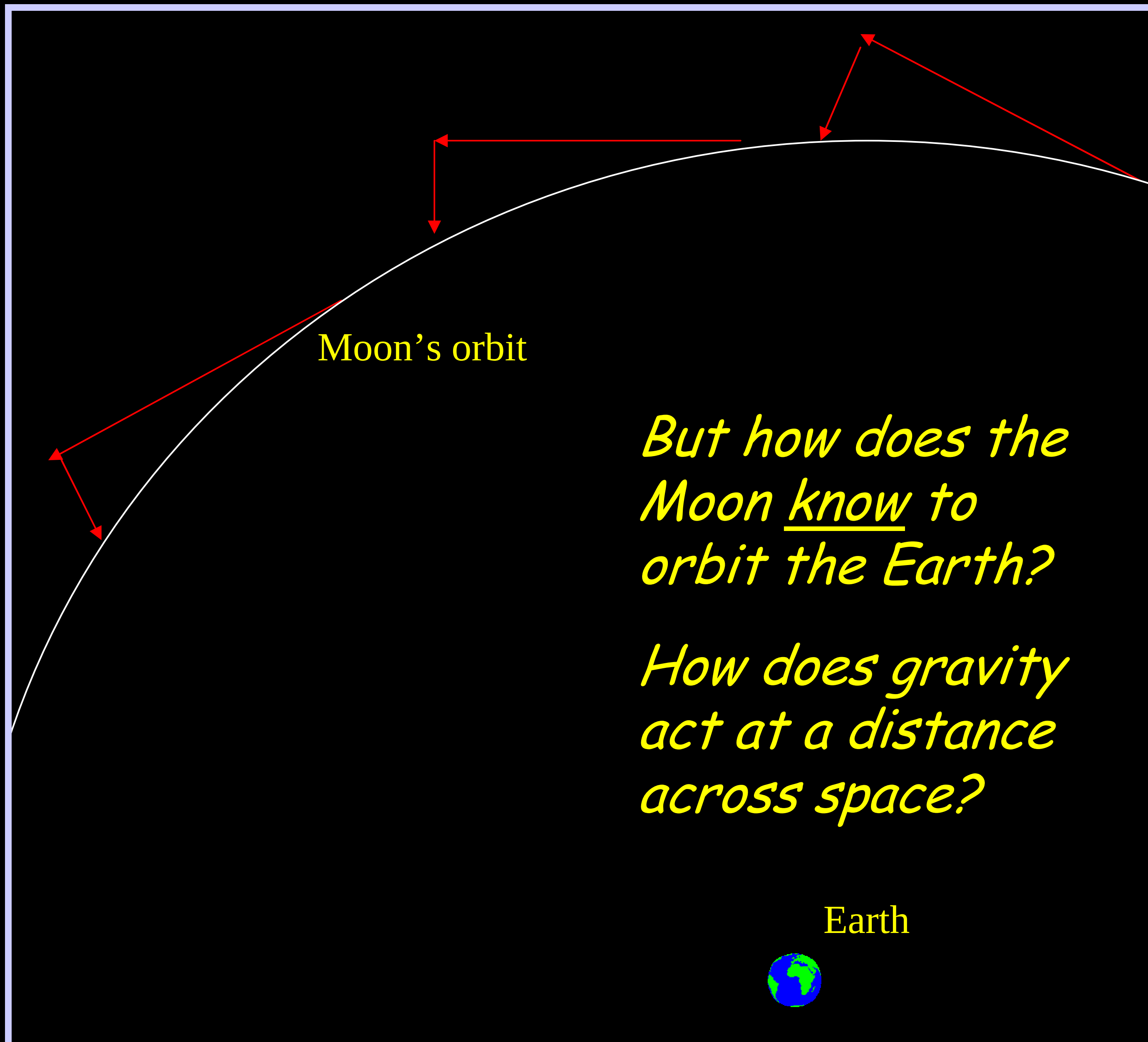



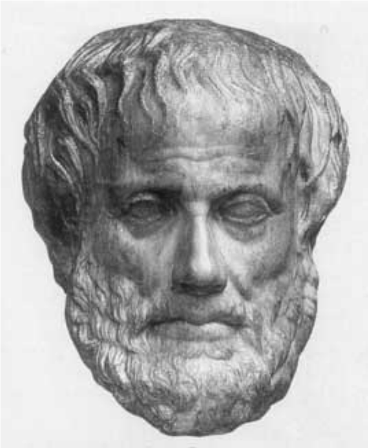
Schiehallion, from Loch Rannoch

Maskelyne's 1774 experiment to measure $G$

Charles Hutton

Neville Maskelyne


Moon's orbit
But how does the Moon know to orbit the Earth?
How does gravity act at a distance across space?
Earth




## *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*
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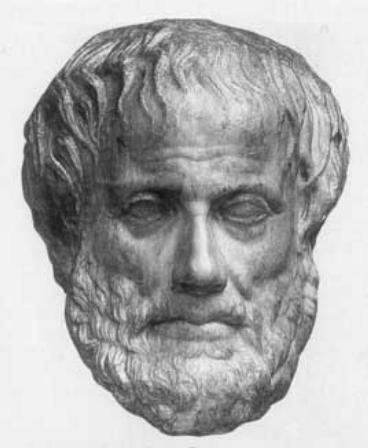
# Newton's Laws of Motion and Gravitation

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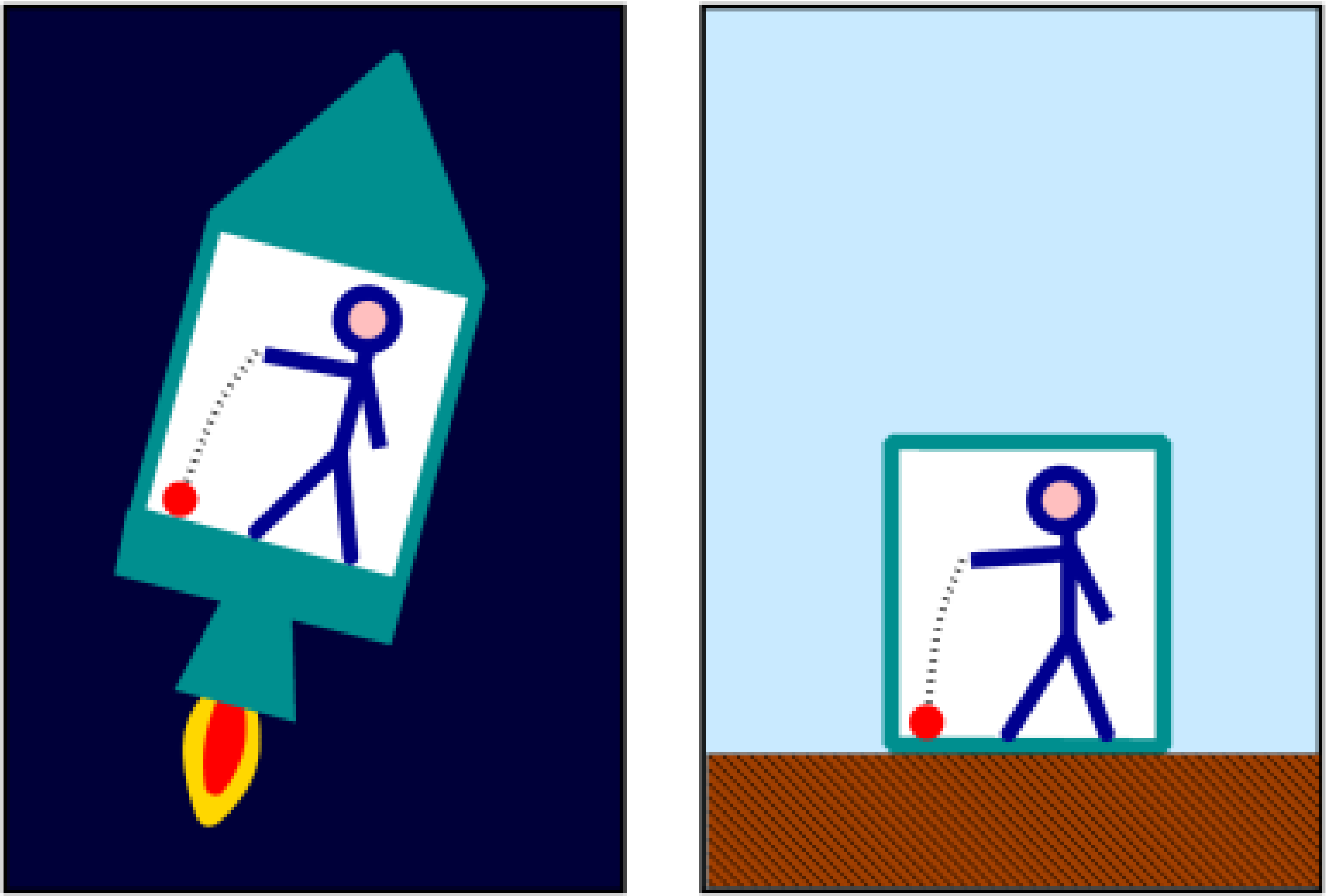
## The Equivalence Principle    Einstein (1907)



Acceleration due to **motion** and due to **gravity** are equivalent

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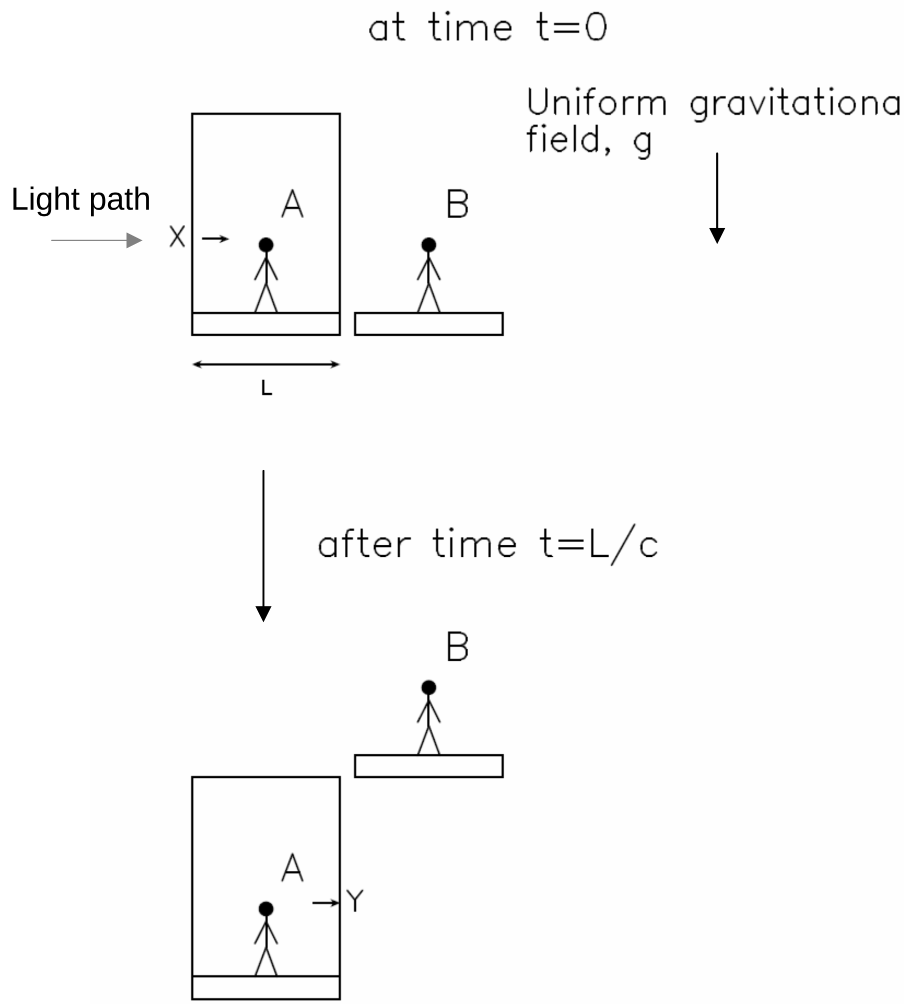
*But only local over region for which gravitational field is uniform.*

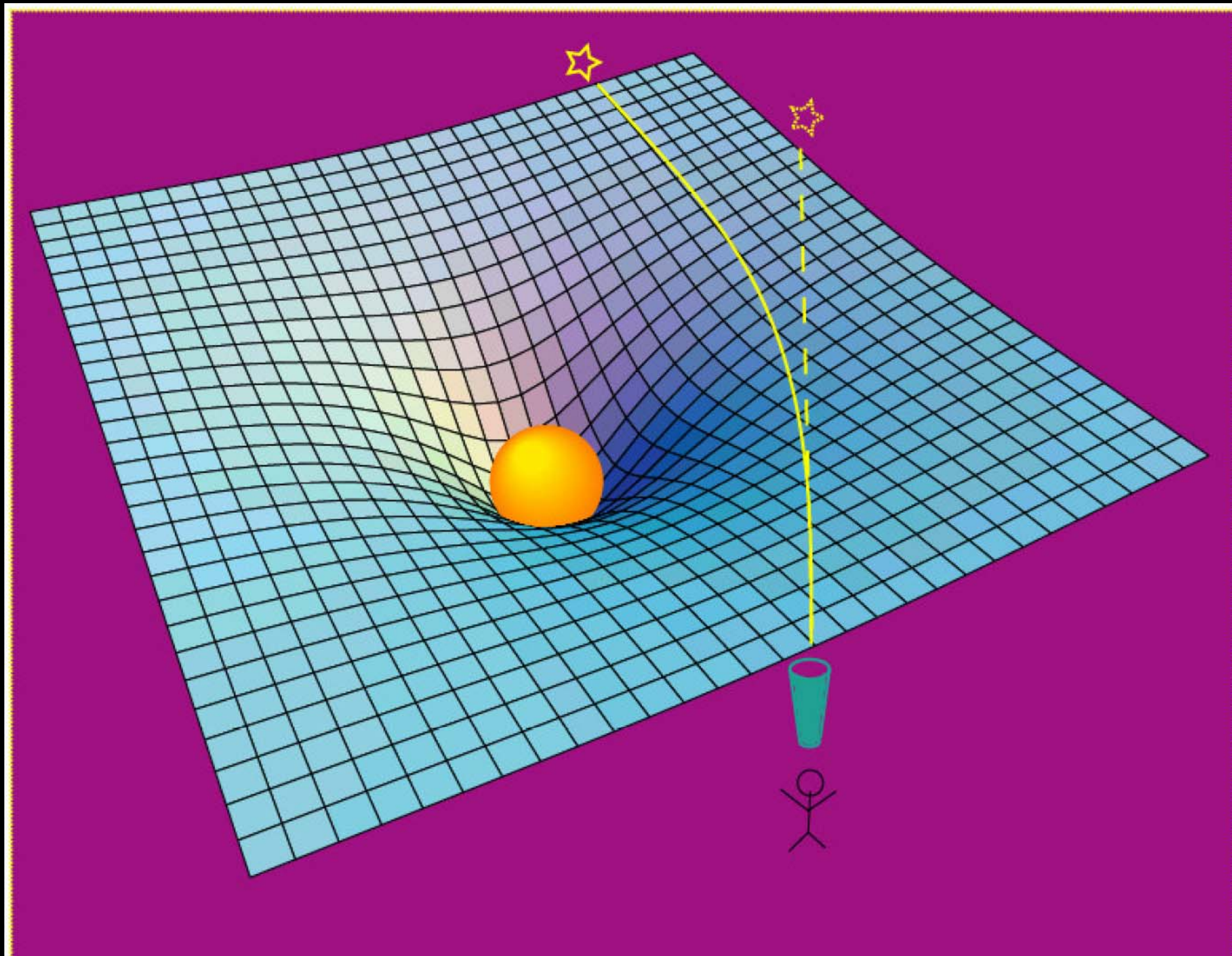
# The Equivalence principle also predicts the bending of light by a gravitational field… (Einstein 1911)

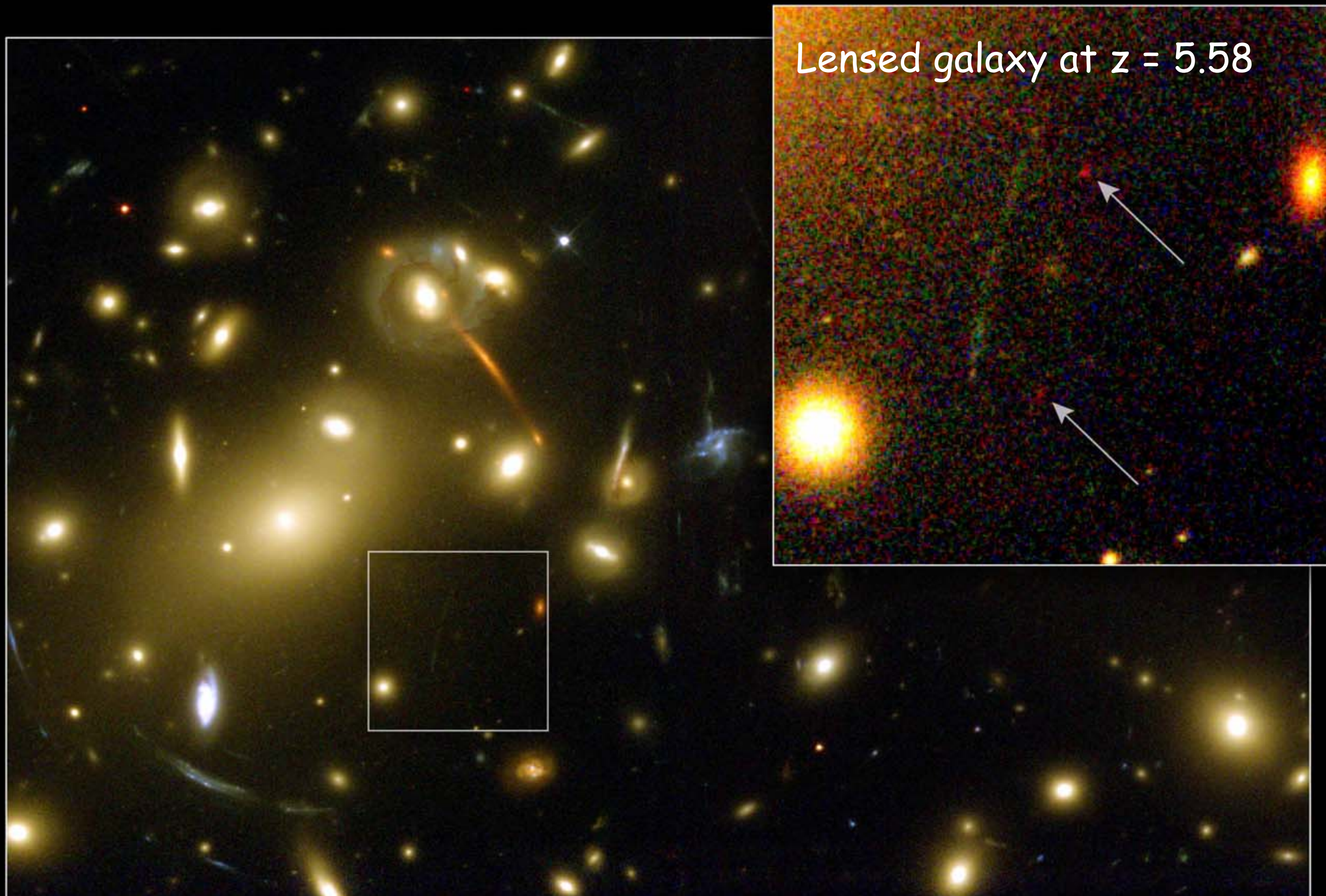
*Light enters lift horizontally at X, at instant when lift begins to free-fall.*

*Observer A is in an inertial frame. Must see light reach opposite wall at Y (same height as X), in agreement with Special Relativity.*

*To be consistent, observer B outside lift must see light path as* ***curved****, interpreting this as due to the gravitational field*








**Distant Object Gravitationally Lensed by Galaxy Cluster Abell 2218**
**Hubble Space Telescope** • WFPC2

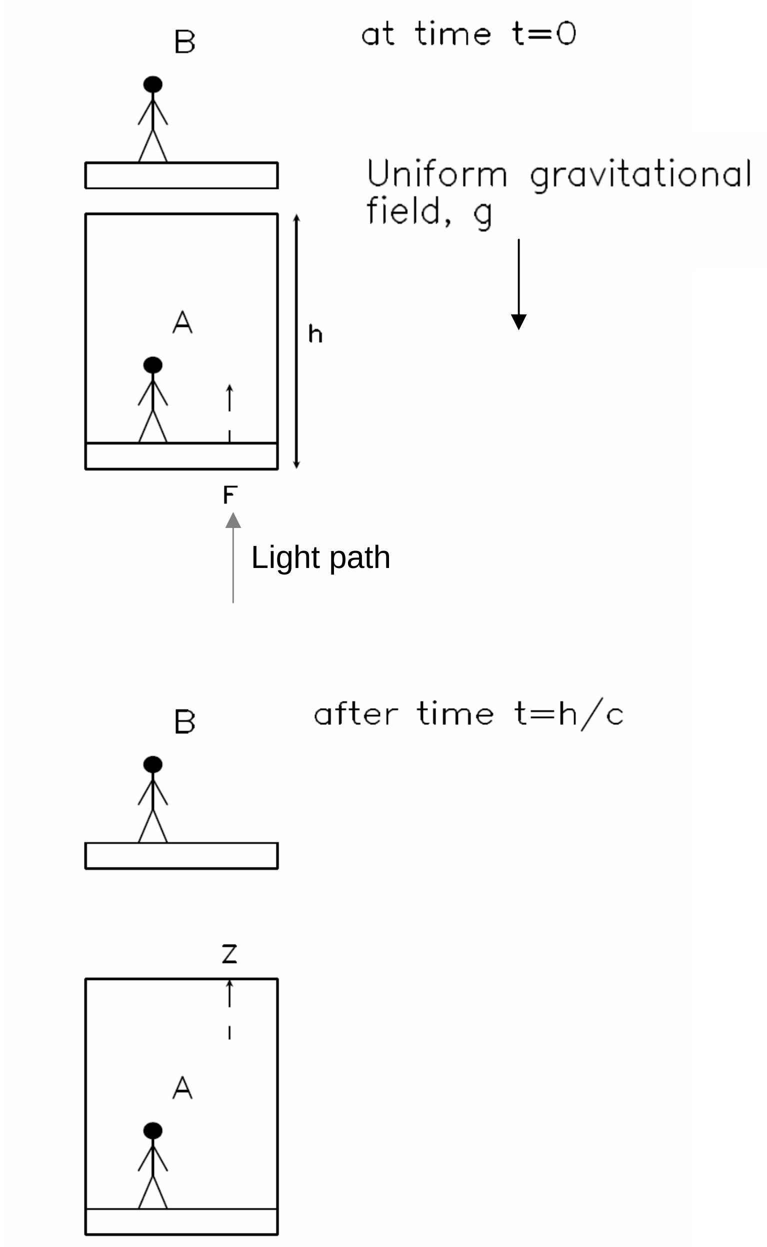
NASA, ESA, R. Ellis (Caltech) and J.-P. Kneib (Observatoire Midi-Pyrenees) • STScI-PRC01-32

# The Equivalence principle also predicts gravitational redshift…

*Light enters lift vertically at F, at instant when lift begins to free-fall.*

*Observer A is in LIF. Must see light reach ceiling at Z with unchanged frequency, in agreement with SR.*

*To be consistent,  observer B outside lift must see light as* ***redshifted****, interpreting this as due to gravitational field.*



## The Equivalence principle also predicts gravitational redshift…

Tiny effect, but measured at Harvard in the 1960s:
Pound-Rebka experiment

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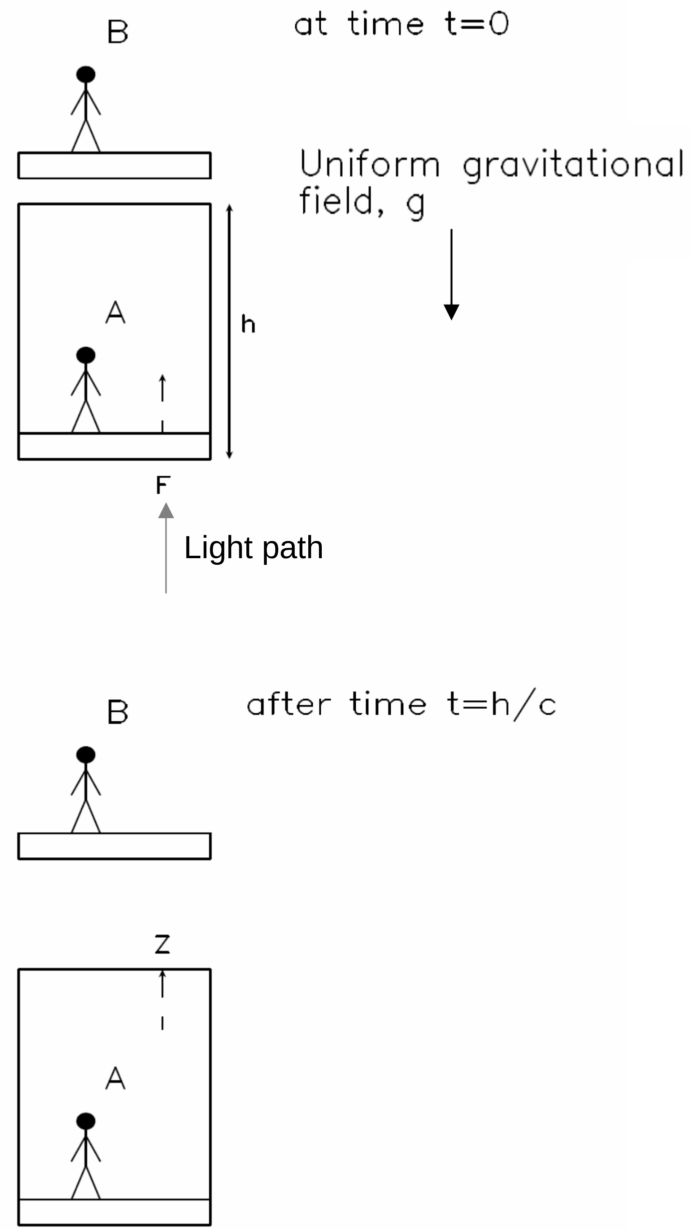
*If the frequency of light were used as a clock, this implies that clocks run more* ***slowly*** *in a stronger gravitation field.*

Einstein (1907)



# GLOBAL POSITIONING SYSTEM

*Serving the World*

www.gps.gov

The Global Positioning System (GPS) is a U.S. space-based radionavigation system that provides reliable positioning, navigation, and timing services to civilian users on a continuous worldwide basis -- freely available to all. For anyone with a GPS receiver, the system will provide location and time. GPS provides accurate location and time information for an unlimited number of people in all weather, day and night, anywhere in the world.

## Relativity

According to the theory of relativity, due to their constant movement and height relative to the Earth-centered inertial reference frame, the clocks on the satellites are affected by their speed (special relativity) as well as their gravitational potential (general relativity). For the GPS satellites, general relativity predicts that the atomic clocks at GPS orbital altitudes will tick more rapidly, by about 45.9 microseconds (μs) per day, because they are in a weaker gravitational field than atomic clocks on Earth's surface. Special relativity predicts that atomic clocks moving at GPS orbital speeds will tick more slowly than stationary ground clocks by about 7.2 μs per day. When combined, the discrepancy is about 38 microseconds per day; a difference of 4.465 parts in 1010.[23]. To account for this, the frequency standard onboard each satellite is given a rate offset prior to launch, making it run slightly slower than the desired frequency on Earth; specifically, at 10.22999999543 MHz instead of 10.23 MHz.[24] Since the atomic clocks on board the GPS satellites are precisely tuned, it makes the system a practical engineering application of the scientific theory of relativity in a real-world environment.

# GLOBAL POSITIONING SYSTEM

***Serving the World***

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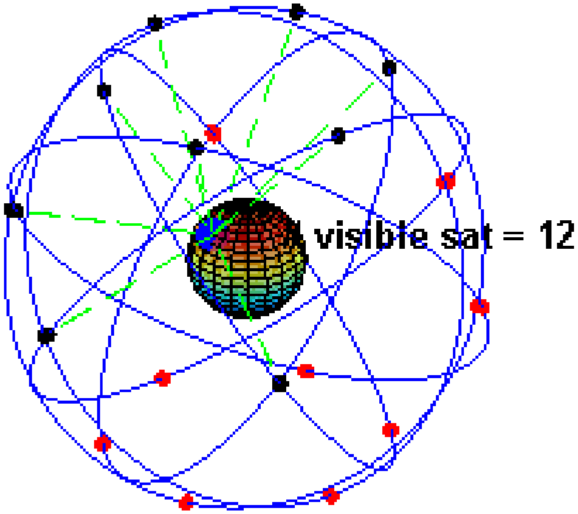


*There is no better illustration of the unpredictable payback of fundamental science than the story of Albert Einstein and the Global Positioning System [GPS] . . . the next time your plane approaches an airport in bad weather, and you just happen to be wondering "what good is basic science," think about Einstein and the GPS tracker in the cockpit, guiding you to a safe landing.*

—Clifford Will