What is Gravity?

Hirosi Ooguri

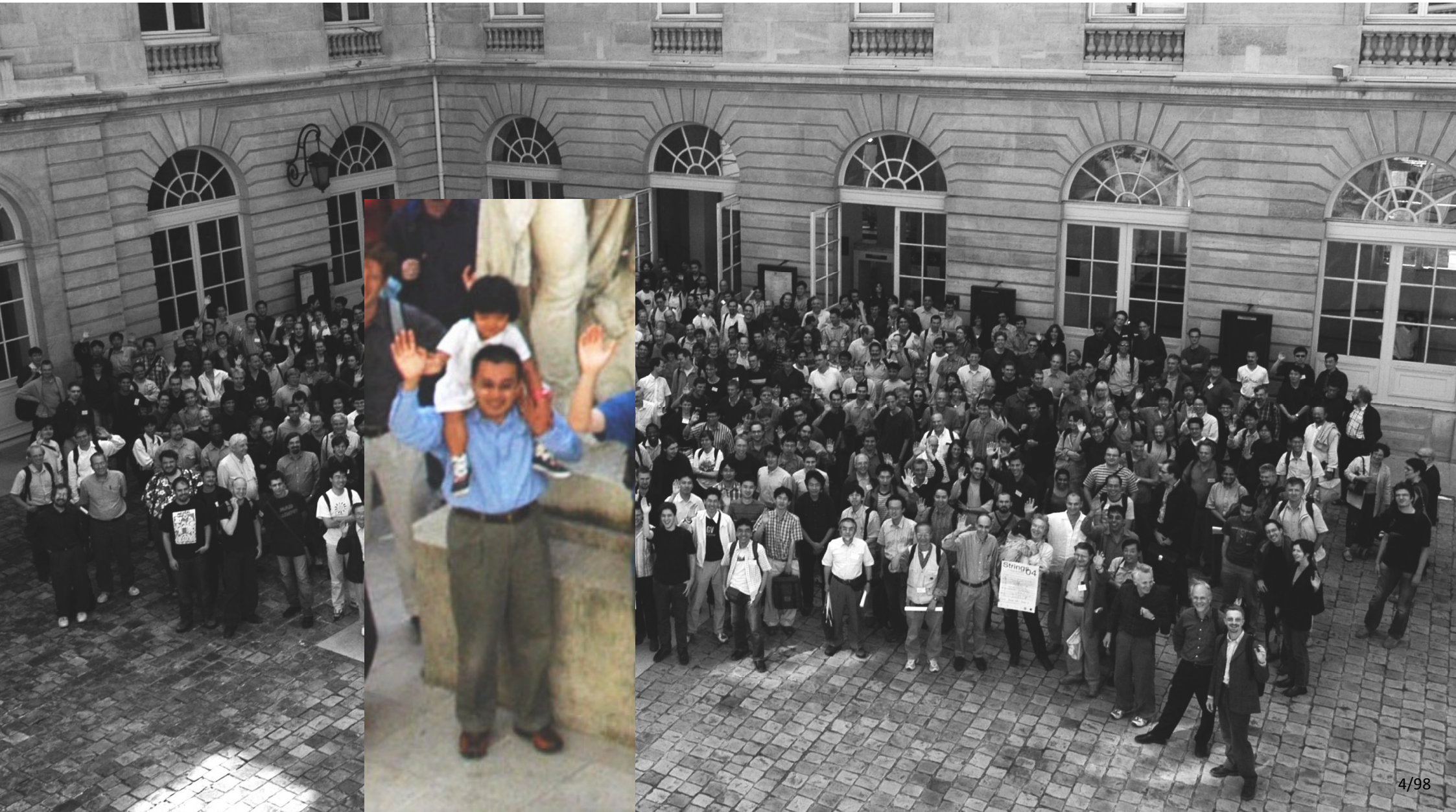
Walter Burke Institute for Theoretical Physics
California Institute of Technology

Kavli Institute for the Physics and Mathematics of the Universe
University of Tokyo

String-Math 2016, College de France, Paris

Strings 2004, College de France, Paris

Strings 2004, College de France, Paris



Gravity is the most familiar force.

Gravity is the most familiar force.

It is also the most mysterious.

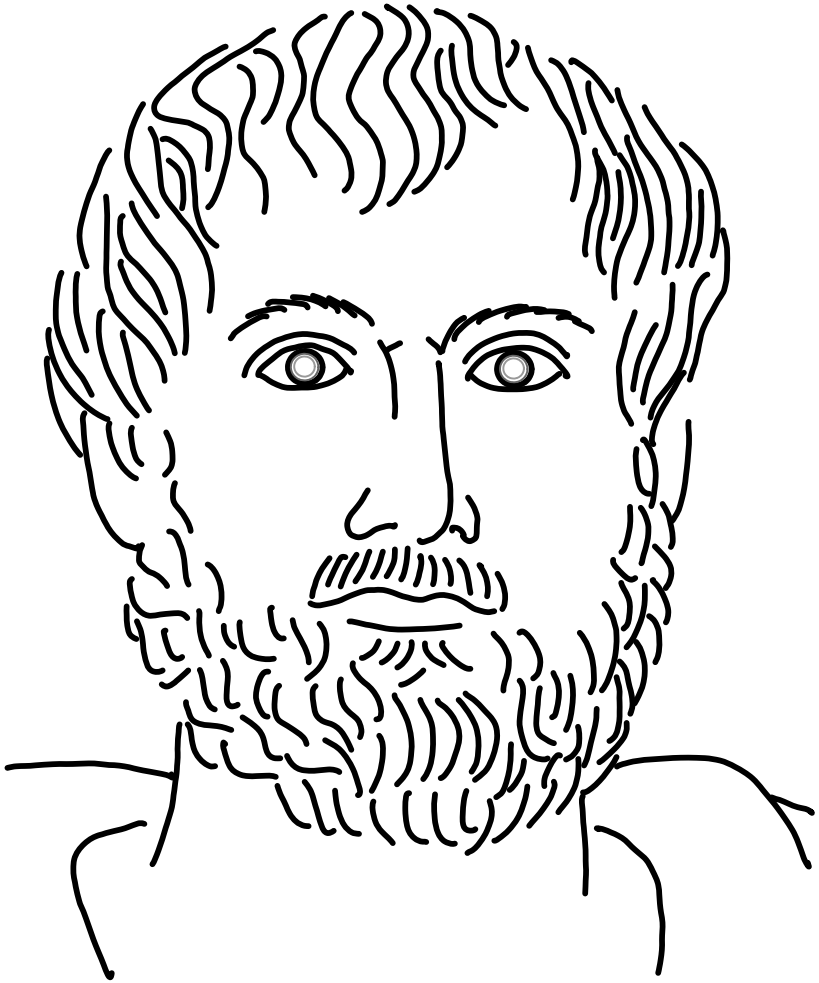
Gravity is the most familiar force.

It is also the most mysterious.

It holds the key to some of
the deepest secrets of the Universe.

Seven Wonders of Gravity

1. Gravity is a Force



Aristotle

This was not obvious to ancient Greeks.

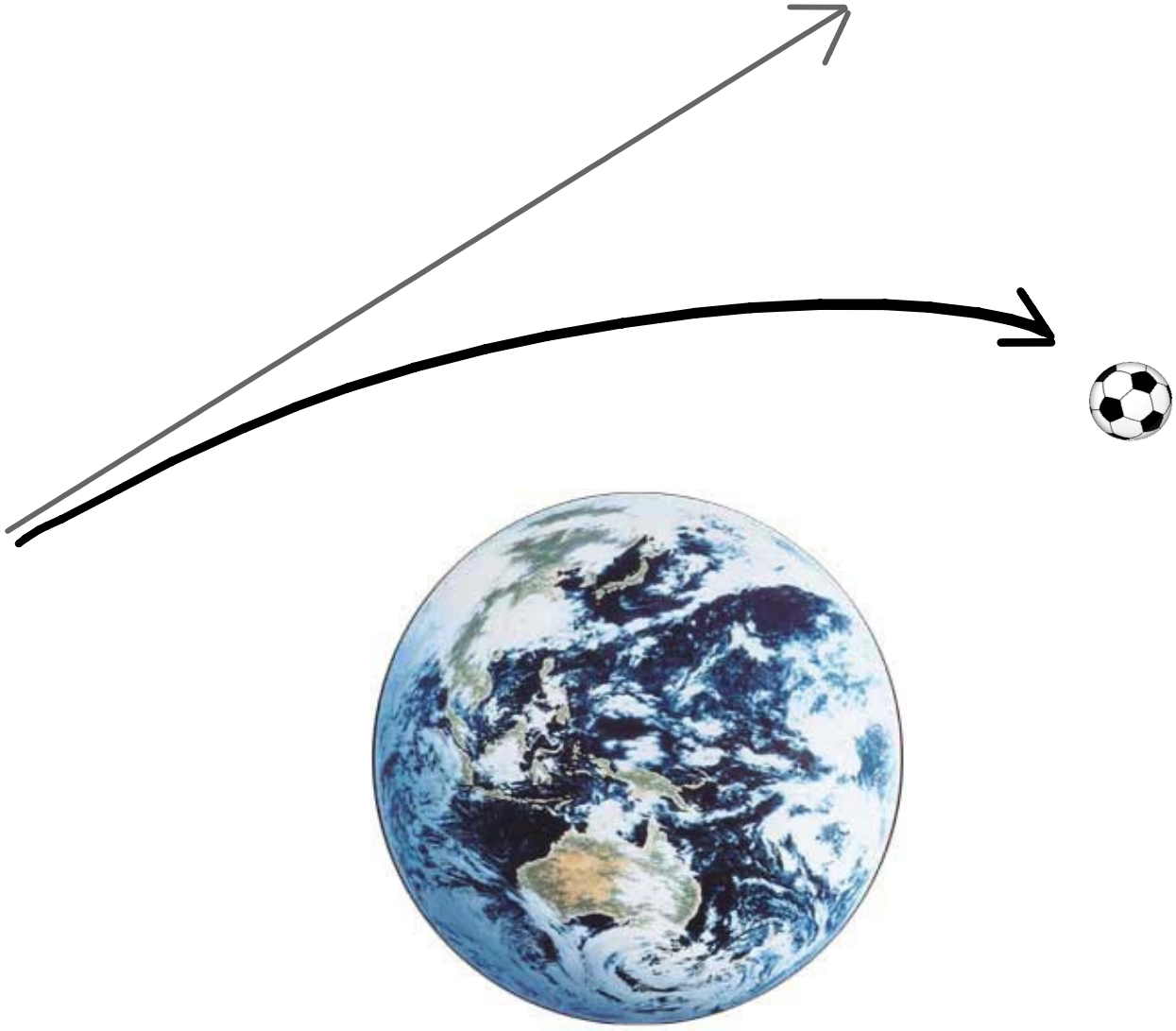
Each of the four elements has its natural place.

All that is earthly tends toward the center of the Earth.

Aristotle's view lasted for 2000 years.

What are Forces?

Aristotle's view lasted for 2000 years until Newton defined "Force" as something that changes motion.



We now understand that there are **4 forces** in Nature:

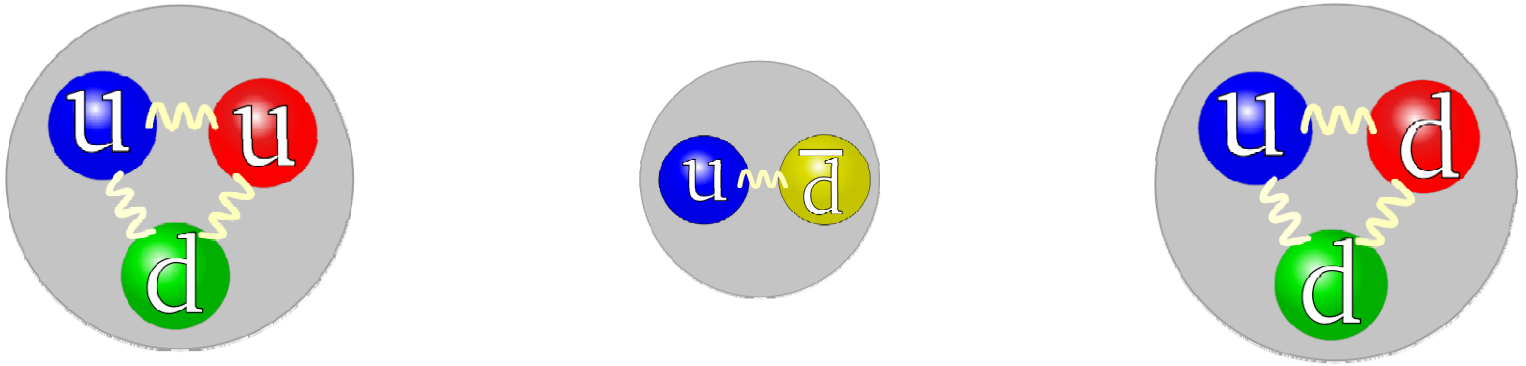
Gravitational Force

Electromagnetic Force

Strong Force } *discovered in the 20th century*

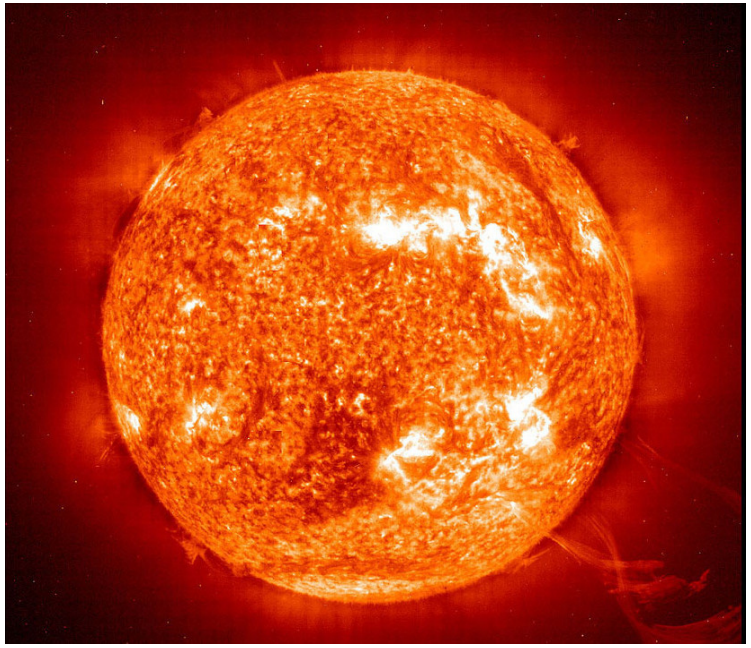
Weak Force }

Strong Force



attracts quarks to each other
and makes proton, neutron, etc.

Weak Force



is responsible for radioactivities, sunshine, etc.

We now understand that
there are **4 forces** in Nature:

Gravity ＜ Weak ＜ E & M ＜ Strong

2. Gravity is Weak

A magnet (a few gram) is stronger

than the Earth (billion x billion x billion gram).

The cup does not fall through the table. ... Why?

Gravity is much weaker than any other forces in Nature:

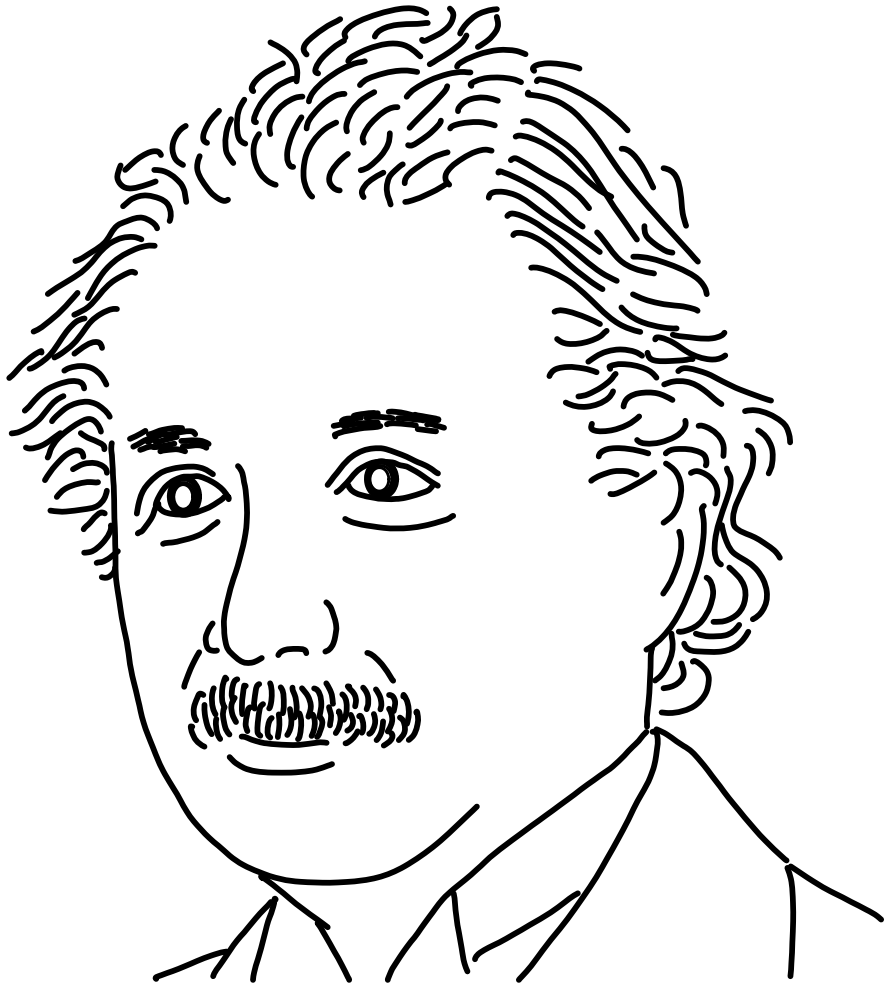
Gravity $<$ Weak $<$ E & M $<$ Strong

3. Gravity is in the eye of the beholder


www.joZeroG.com

Einstein's **happiest thought** of his life:

For an observer falling freely from the roof of a house, the gravitational force does not exist.



4. Gravity is Warping of Space and Time

It took ten years for Einstein to turn his **happiest thought** into General Relativity.

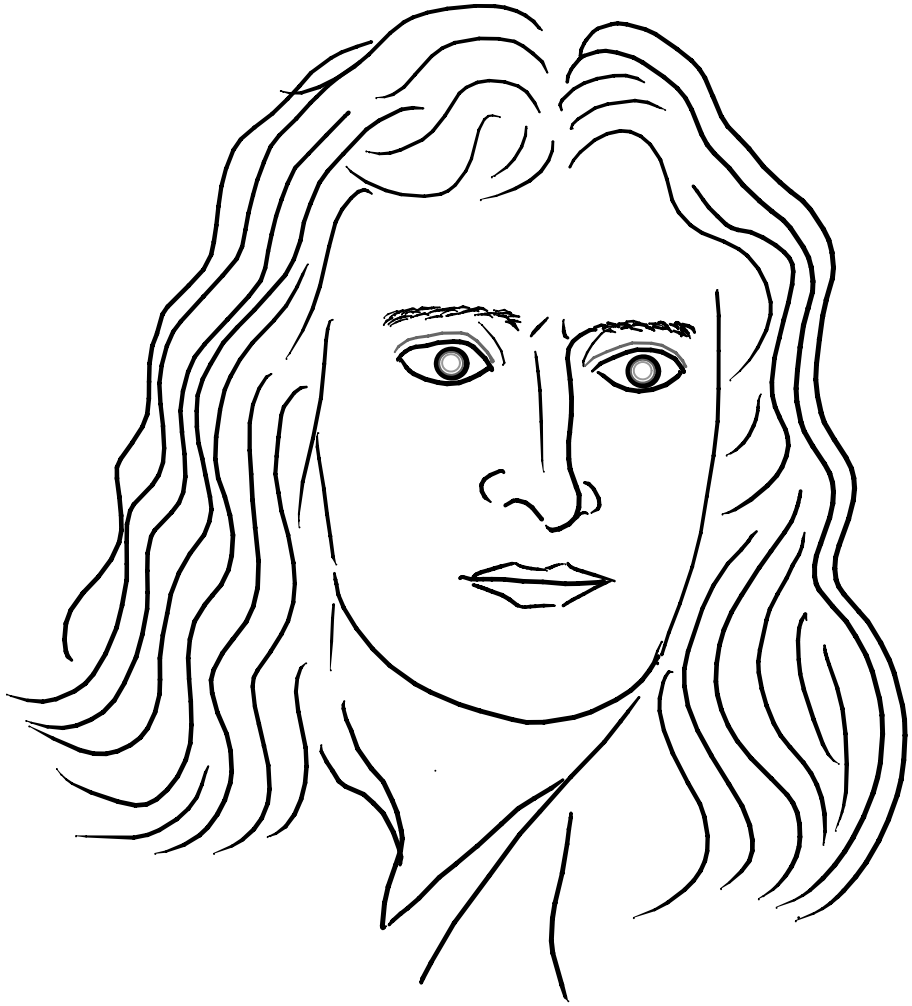
What is Space?

What is Time?

Nature abhors a vacuum.

Space and time do not exist independently of matter in them.

Newton's First Revolution



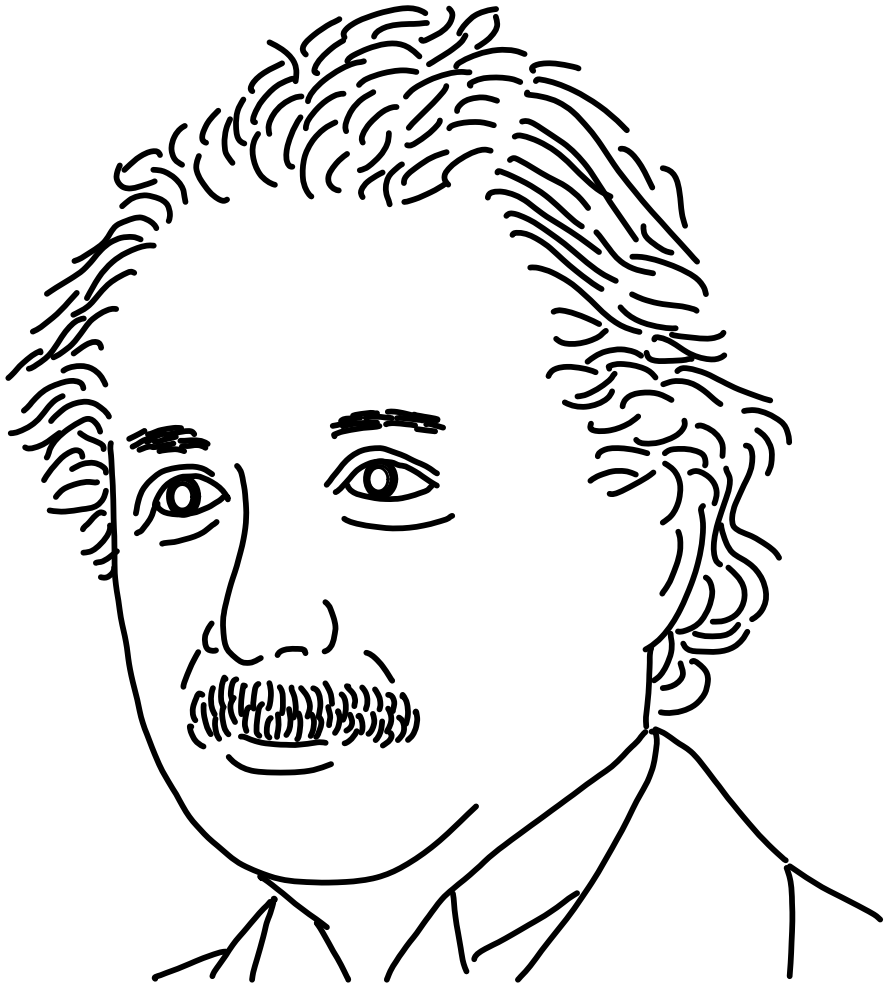
Absolute time
flows uniformly.

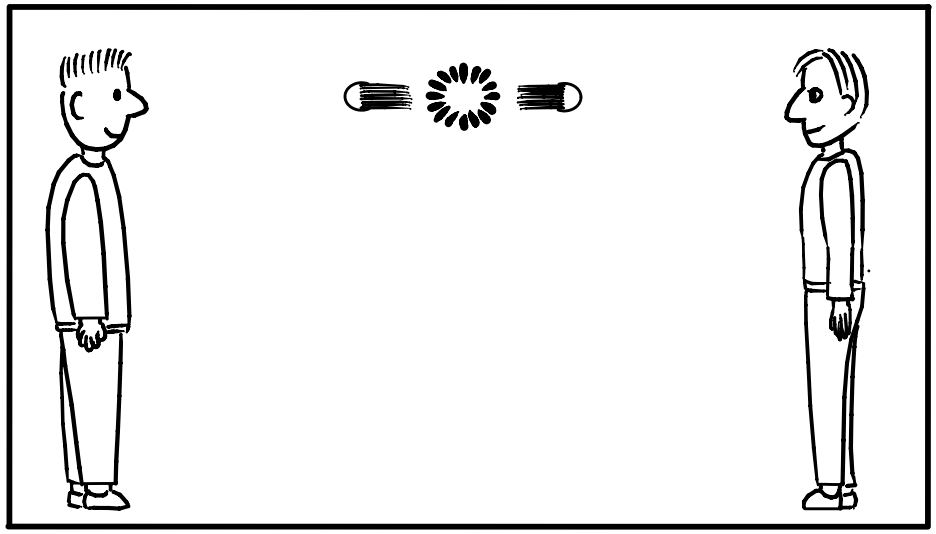
Absolute space
does not depend
on physical events.

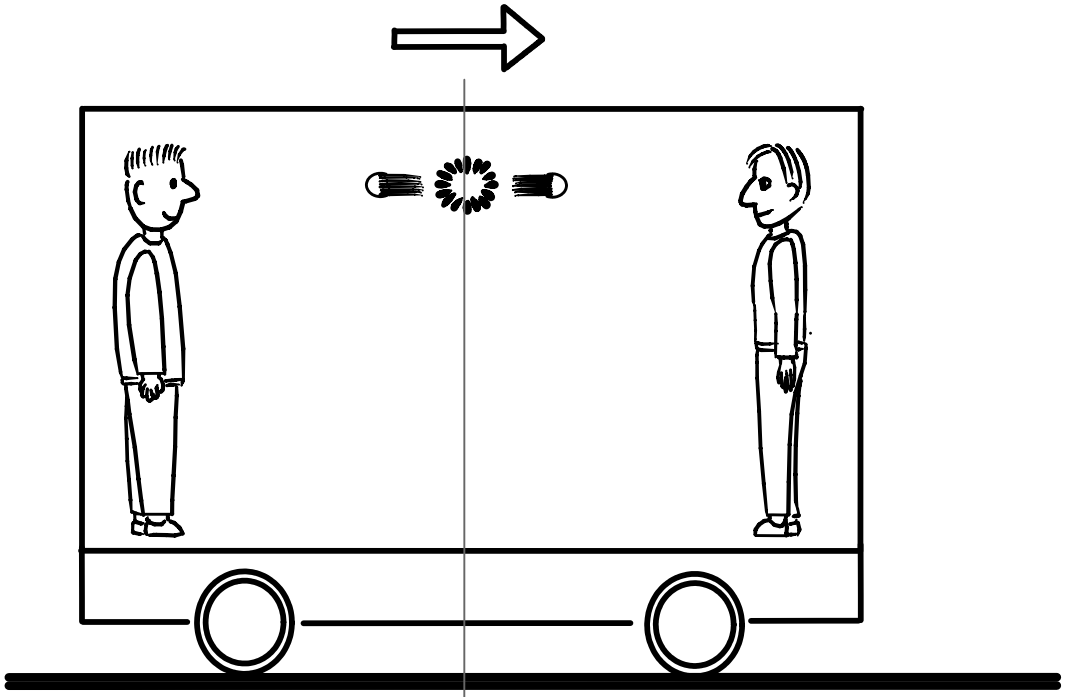
Einstein's Second Revolution

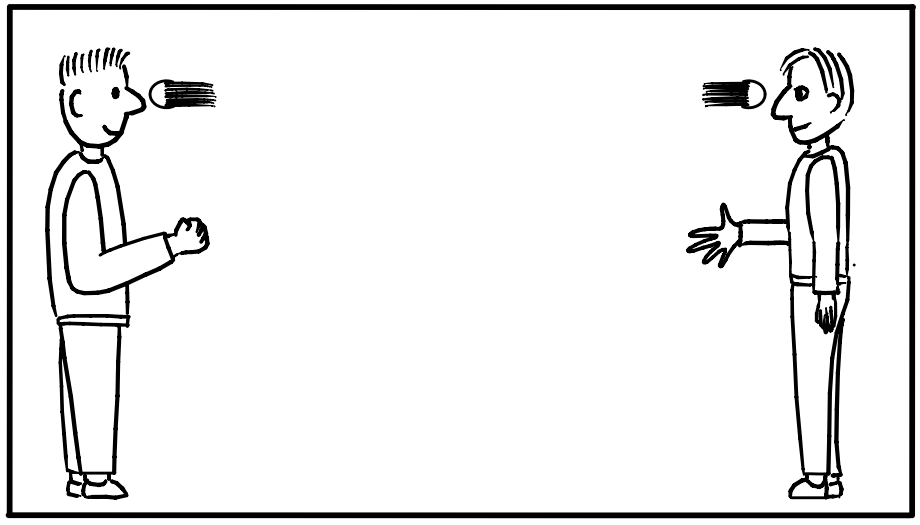
Special Relativity:

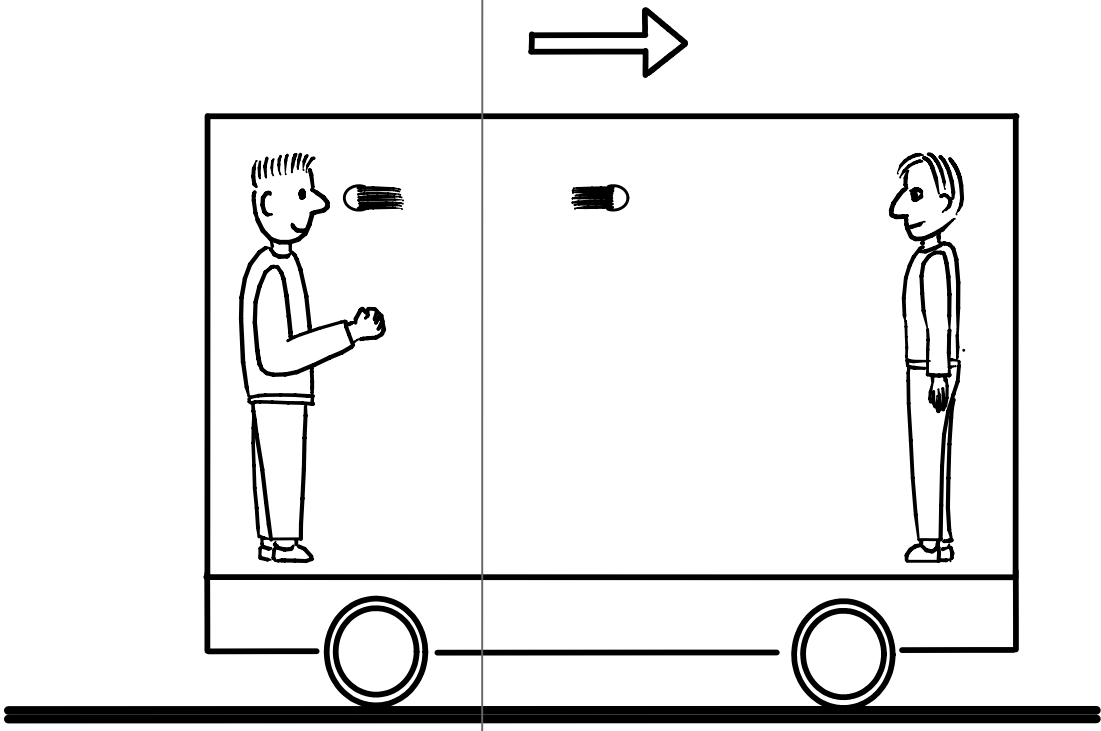
Space and time depend on how you observe them.







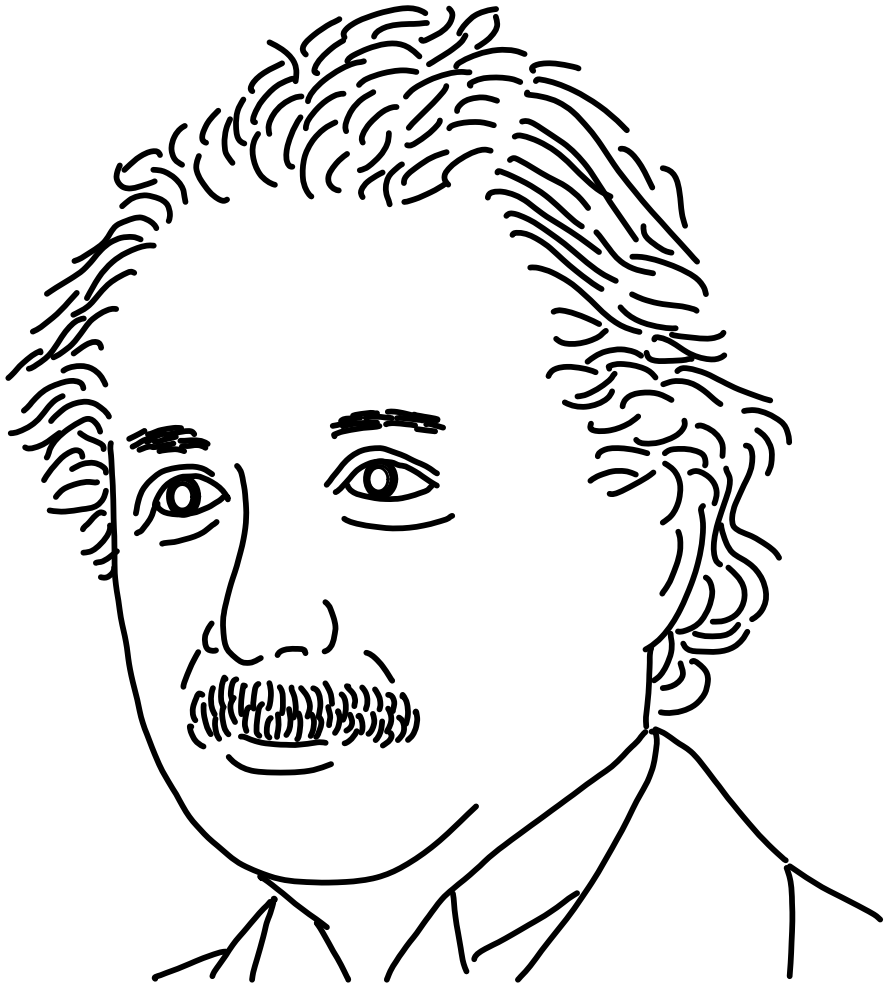


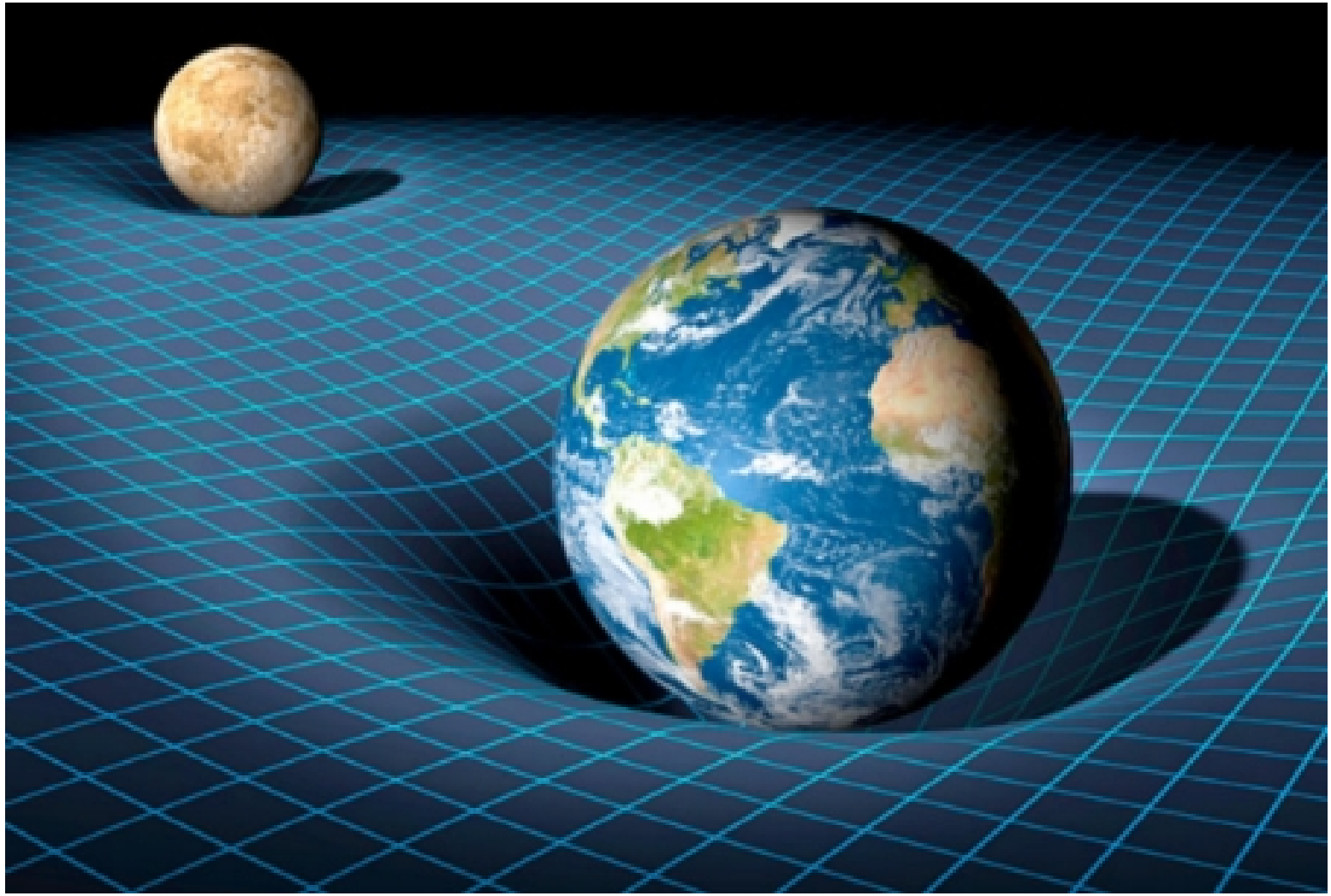


Einstein's Second Revolution

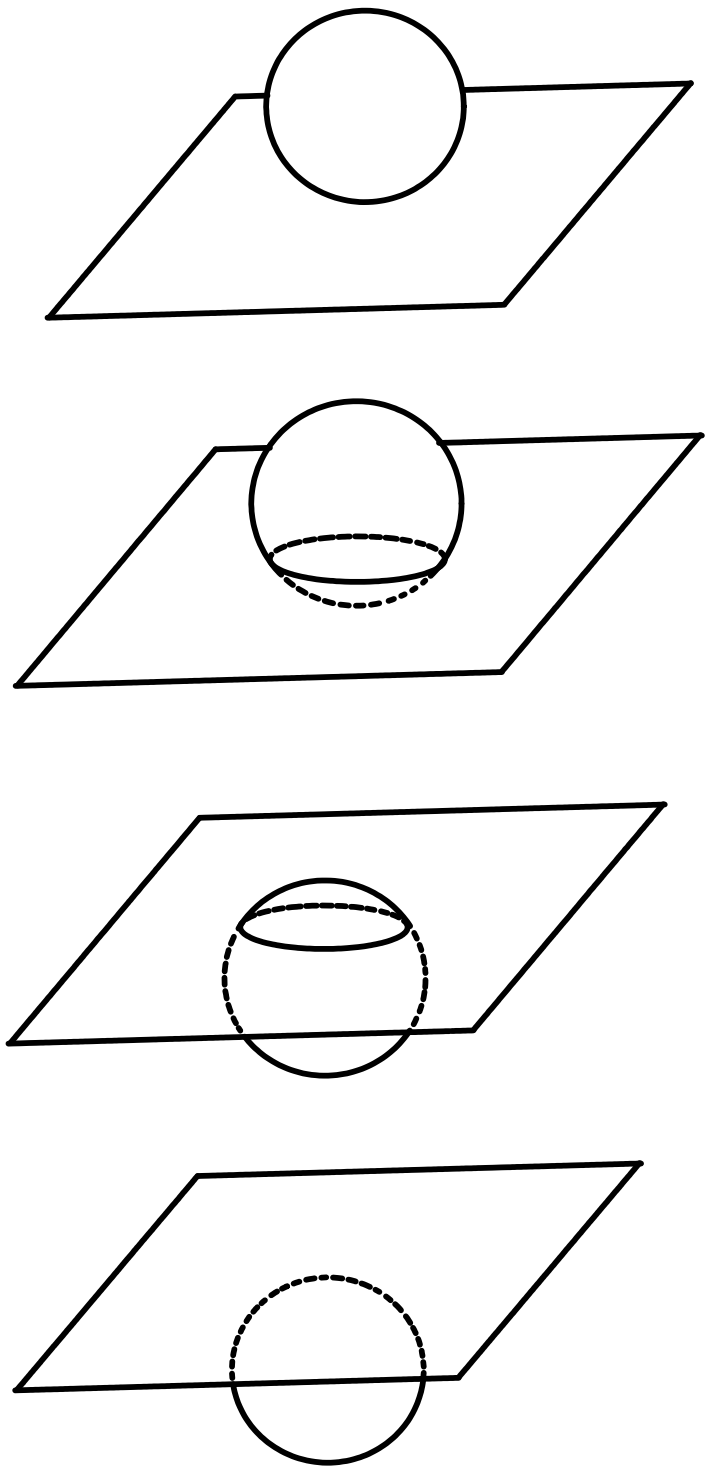
General Relativity:

Gravity is warping
of space and time





General Relativity in our three dimensions may be complicated, but things are a little easier in **Flatland**.

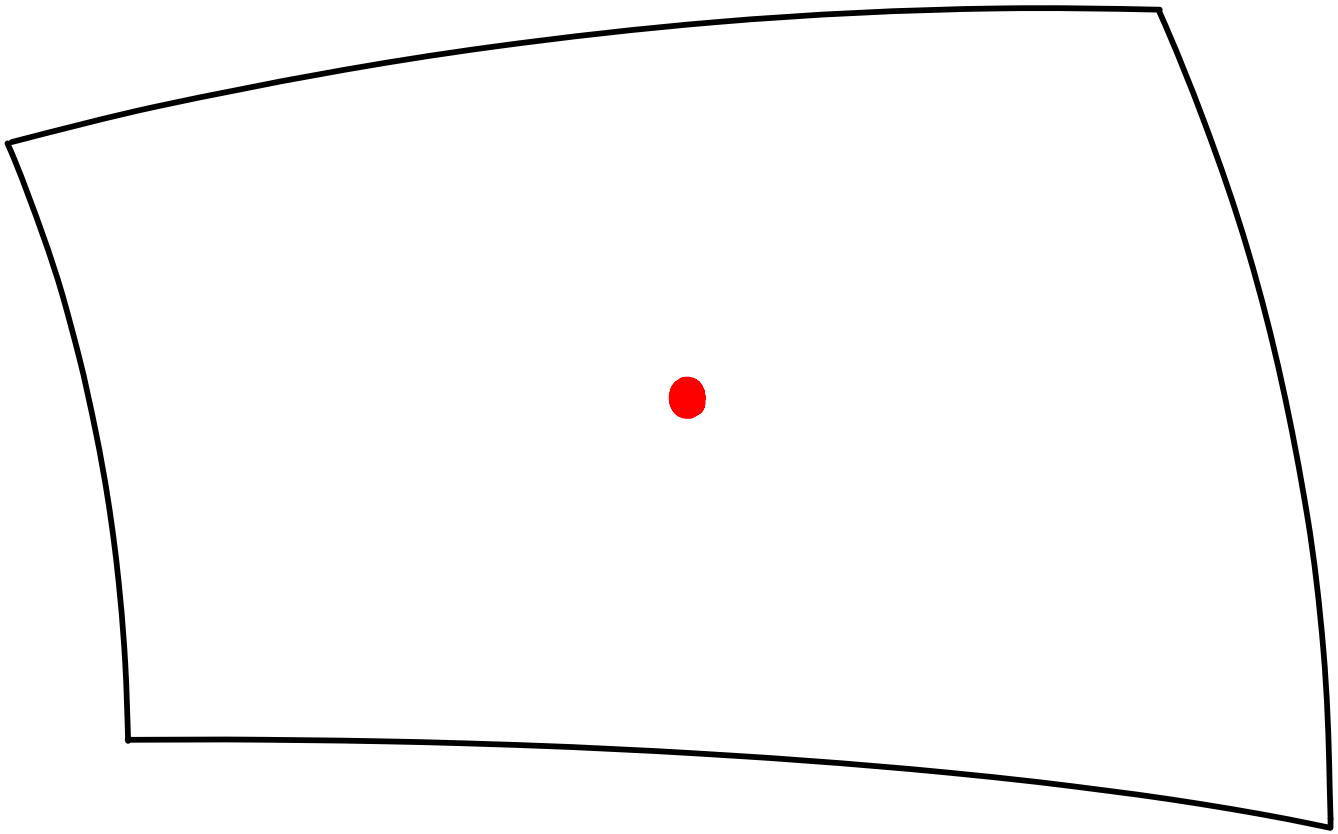


It is a story of a humble **Square** in Flatland.

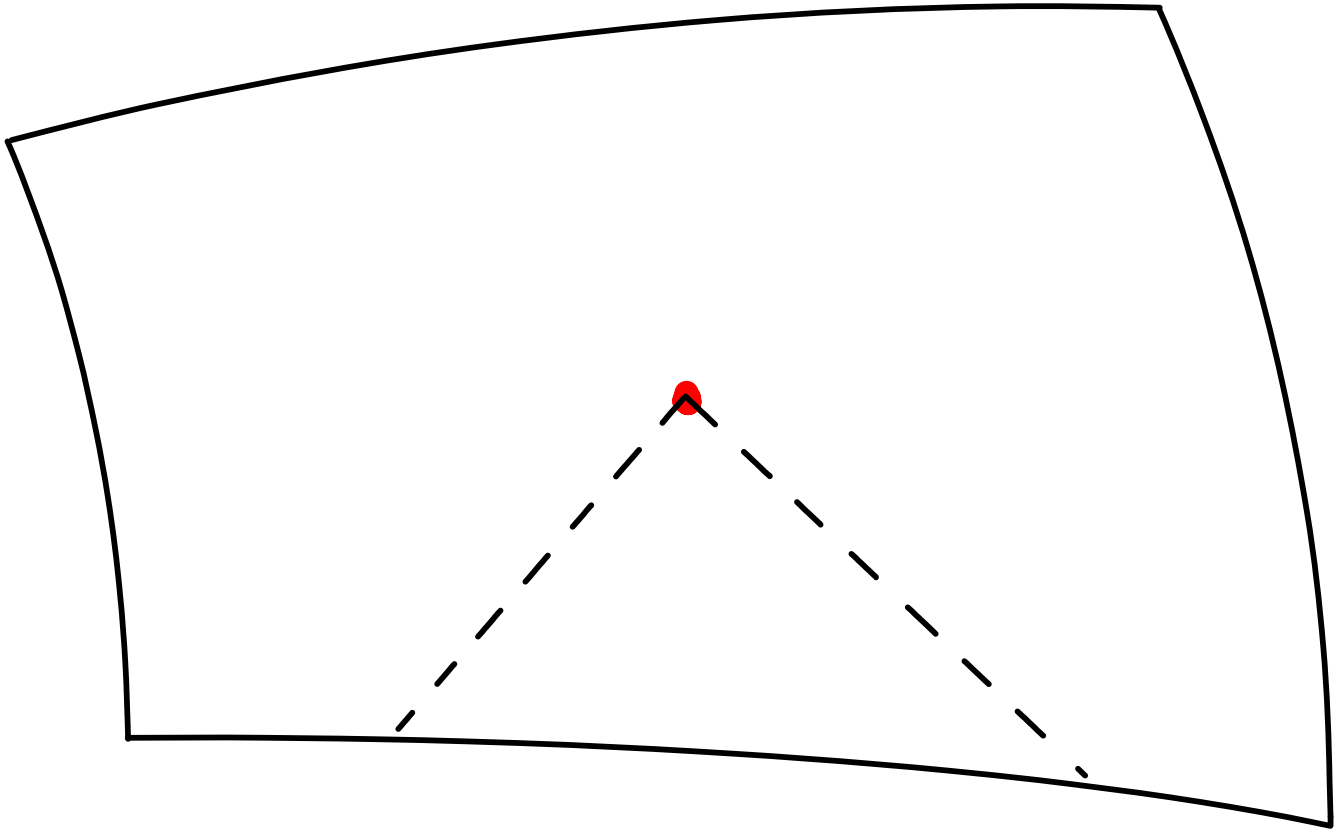
One day,
Sphere in **Spaceland** visits **Flatland** and opens Square's mind to higher dimensions.

What would Einstein in Flatland have done?

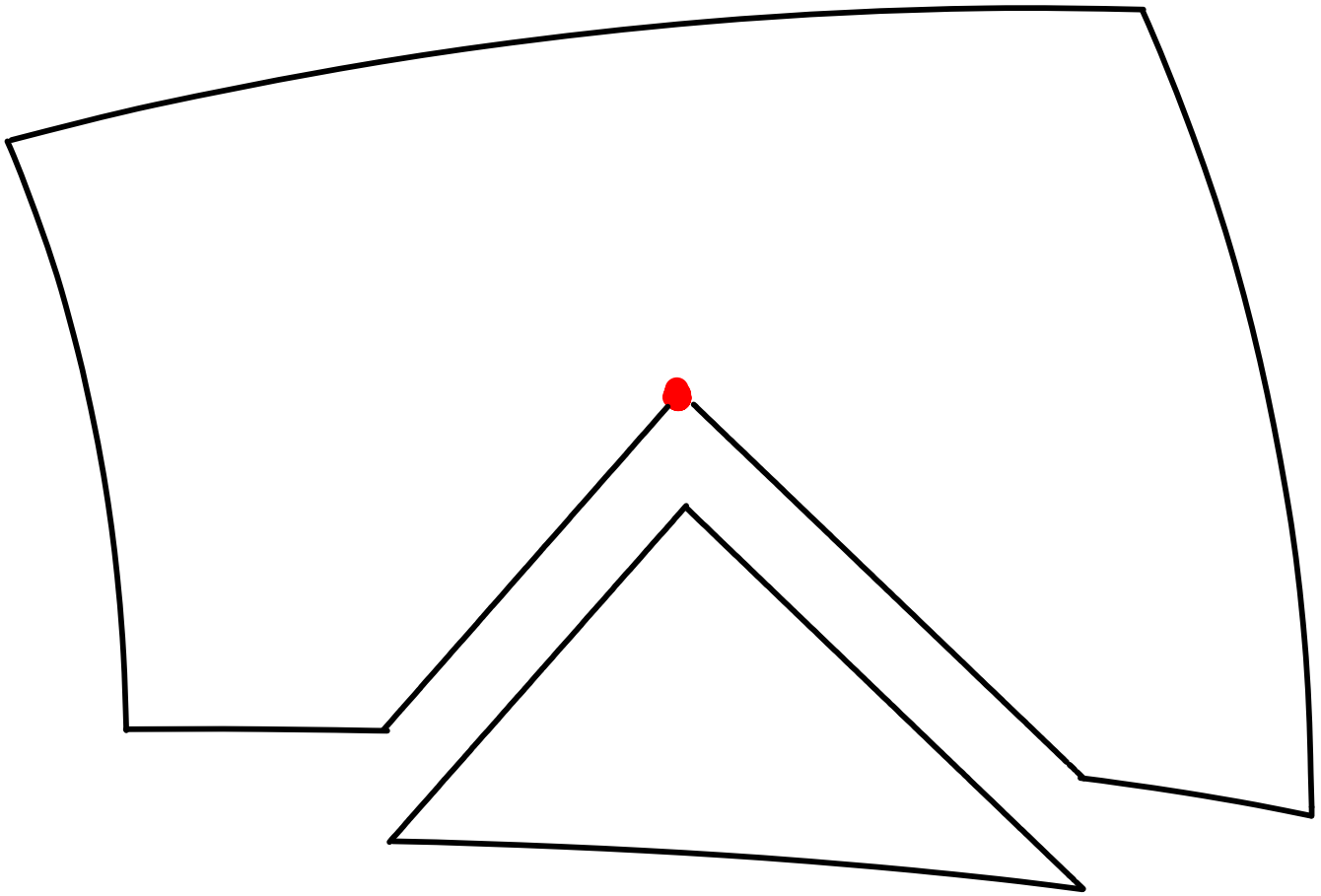
Get a piece of paper.



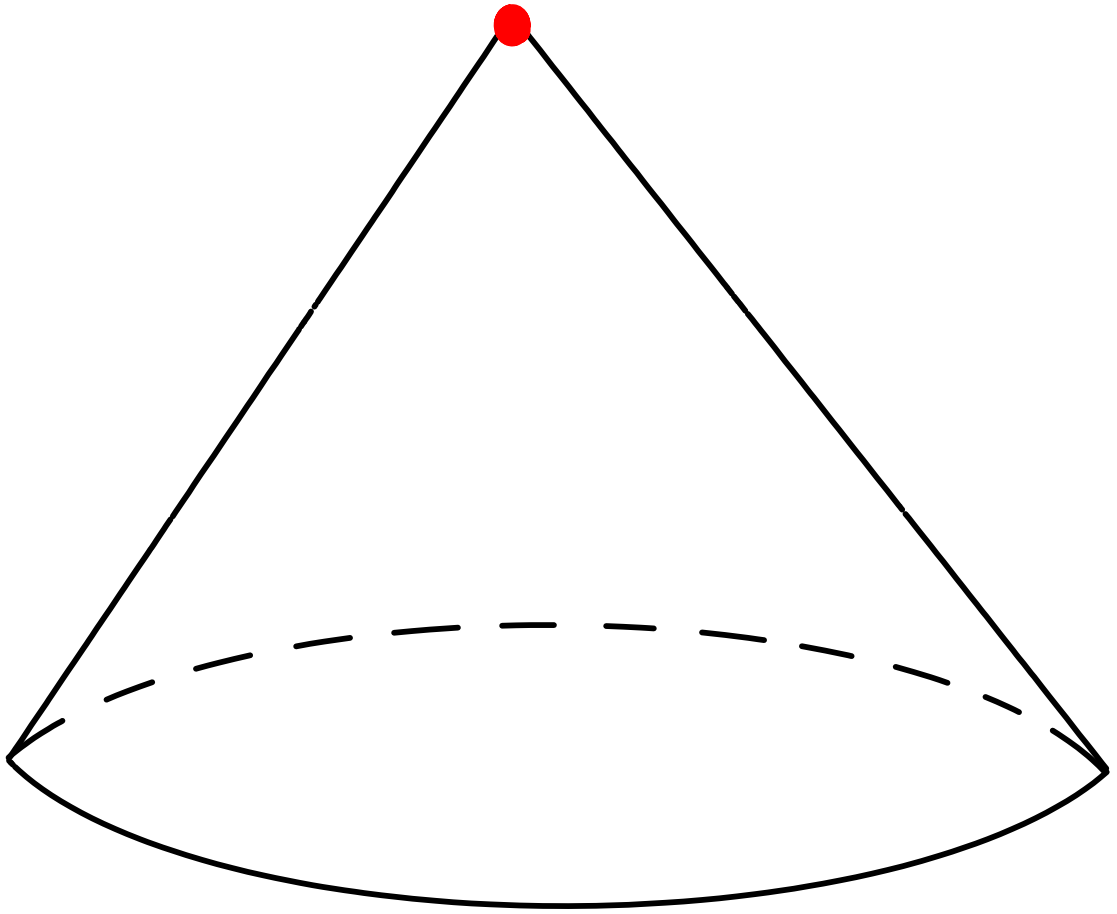
In Flatland, a point mass generates a *deficit angle*.



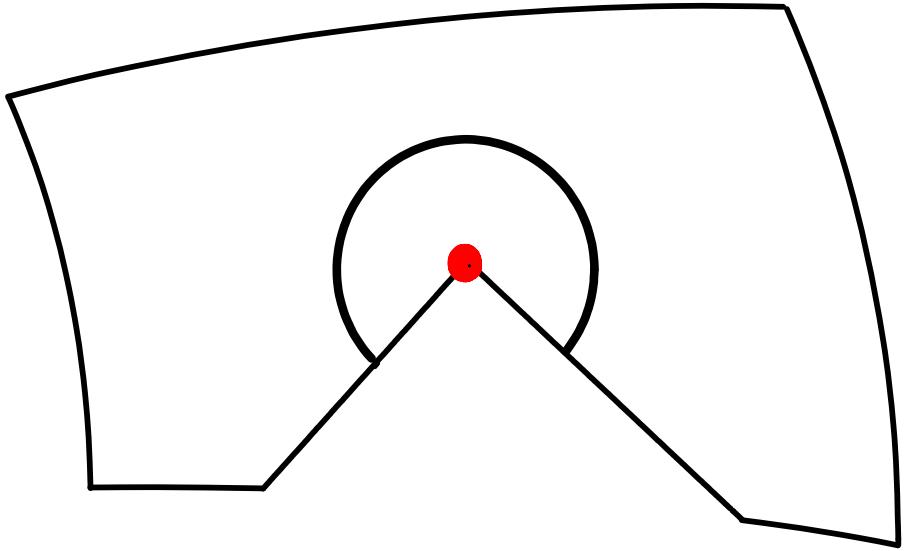
In Flatland, a point mass generates a *deficit angle*.

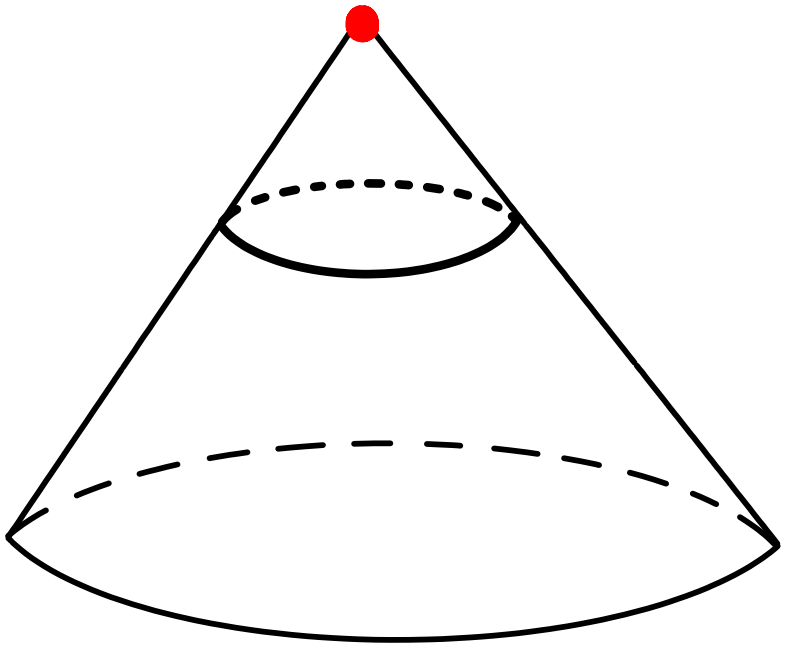


In Flatland, a point mass generates a *deficit angle*.

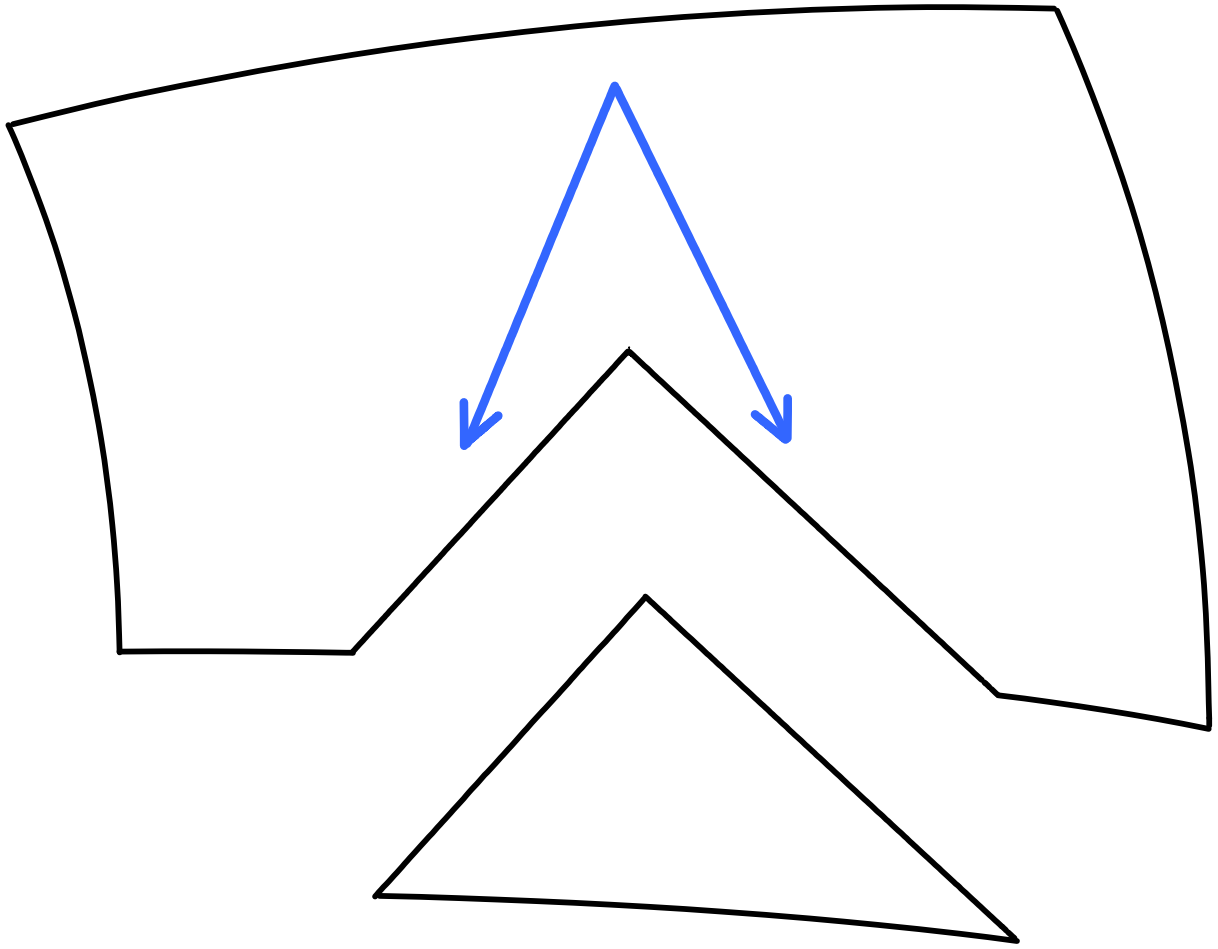


In Flatland, a point mass generates a *deficit angle*.

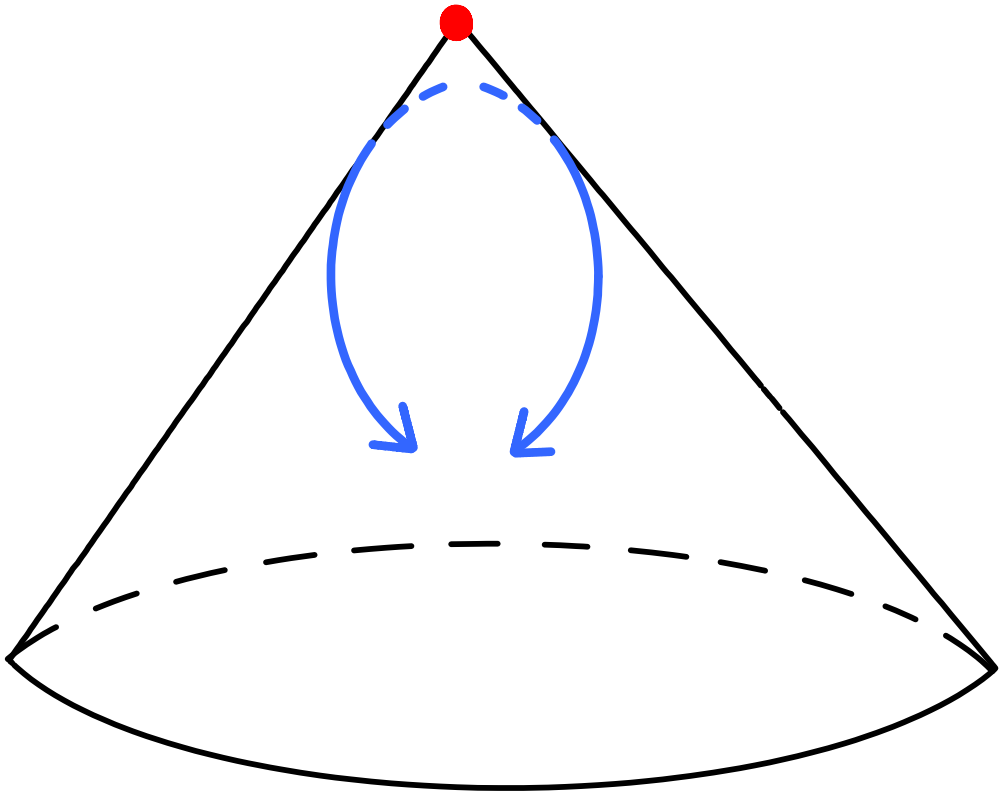




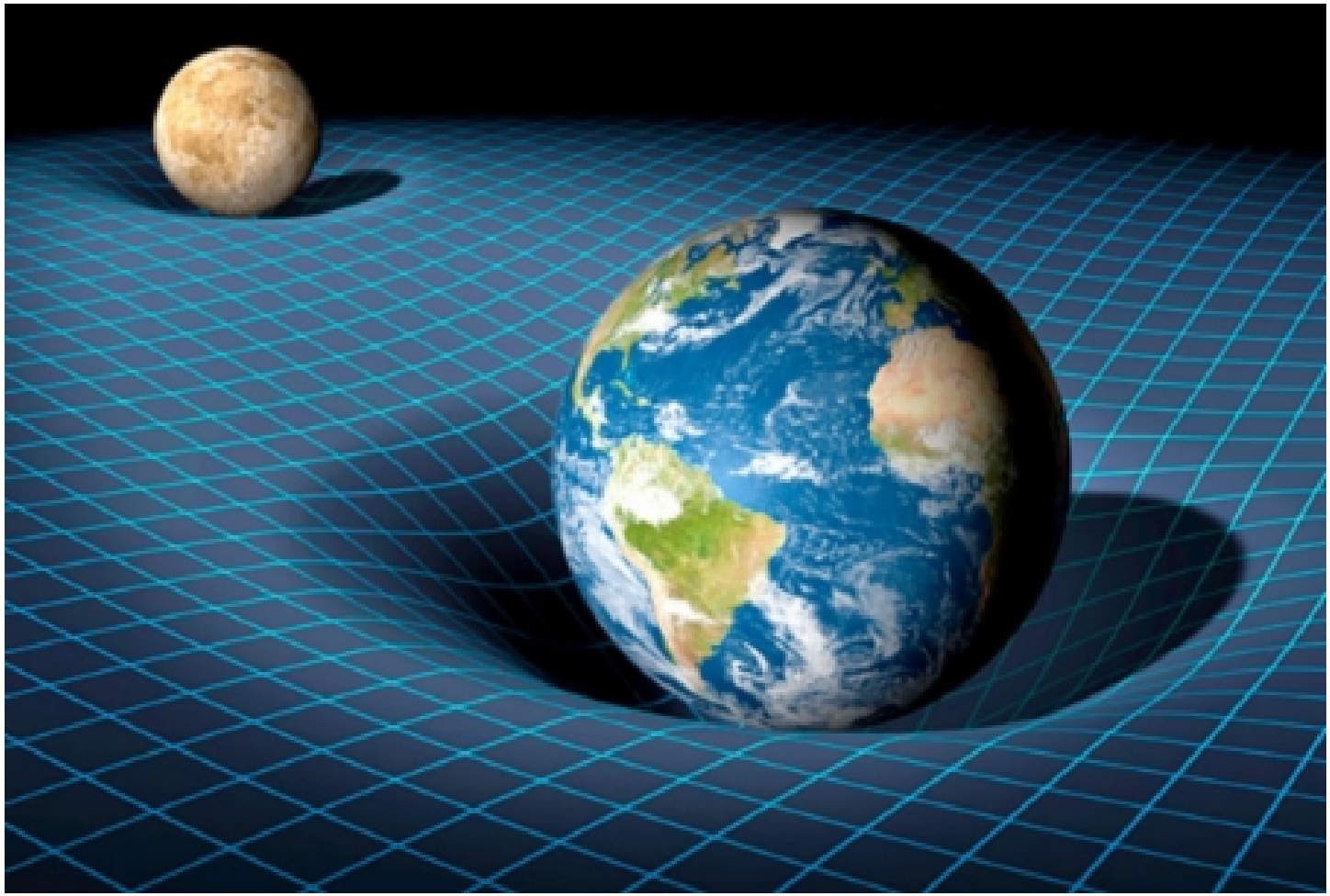
Two straight trajectories ...



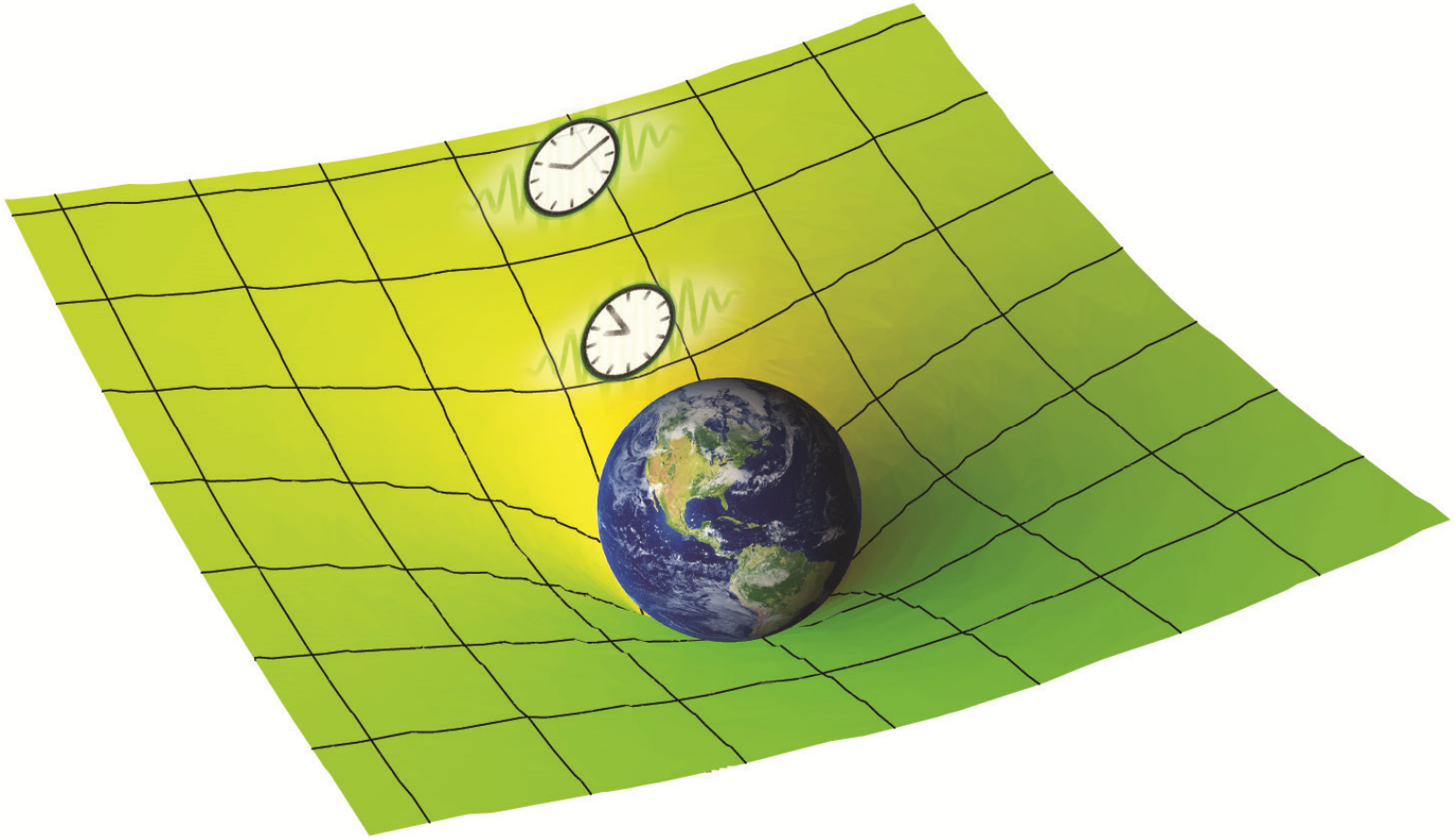
are attracted to each other as if by gravitational force.

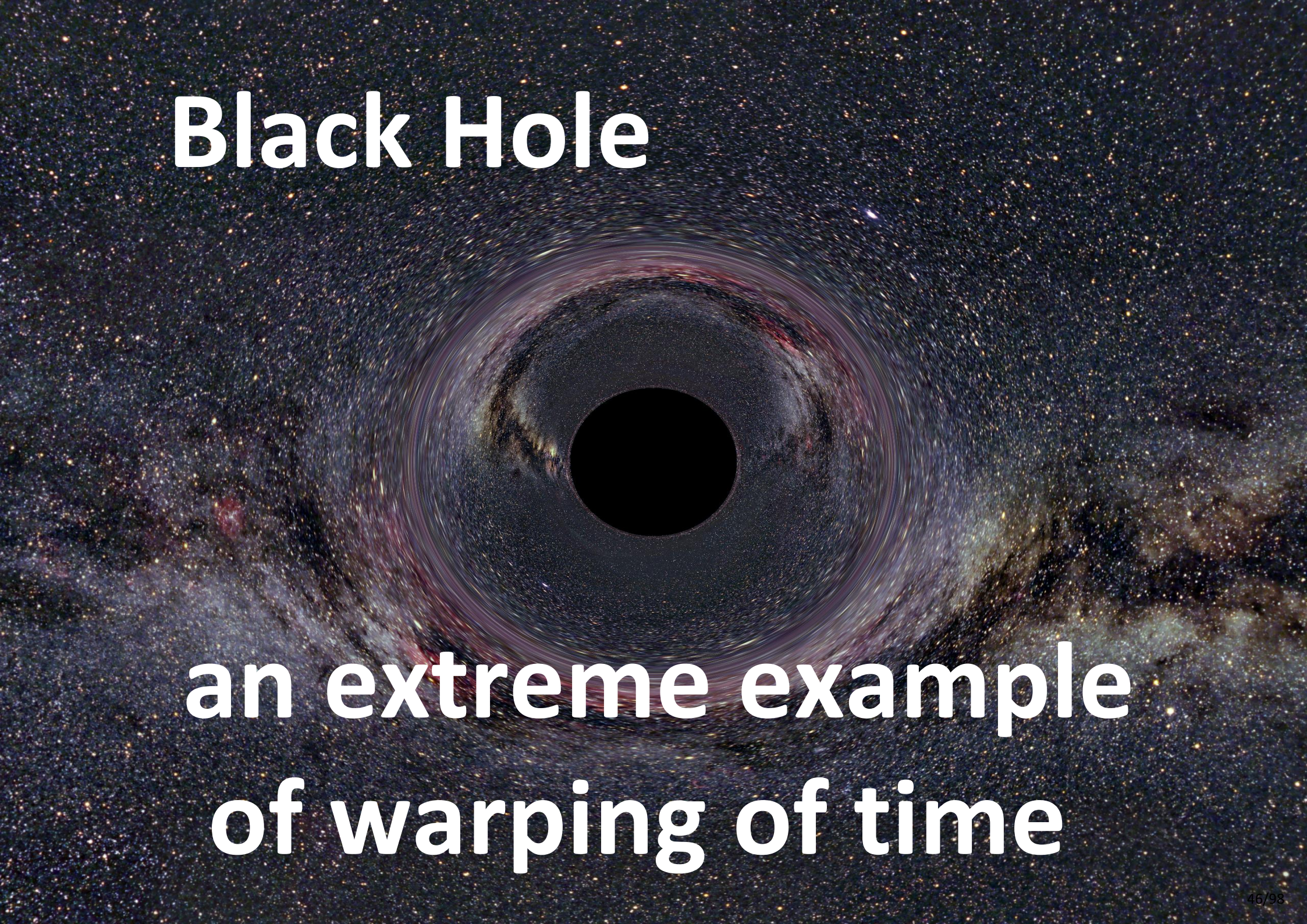


Einstein's idea is the same in our three dimensions, just with a little more math.

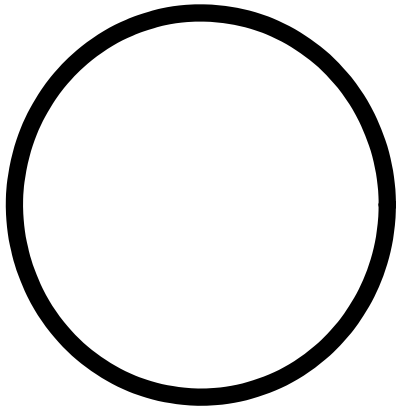


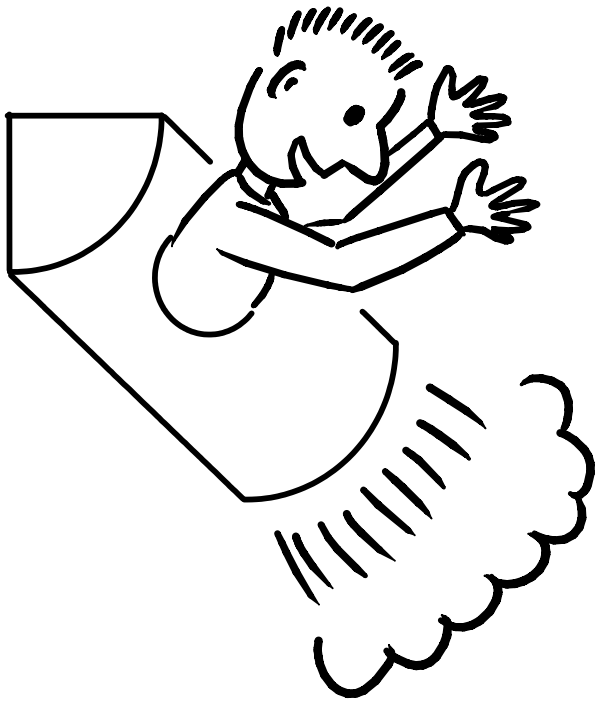
Gravity also warps time.




Black Hole
an extreme example
of warping of time

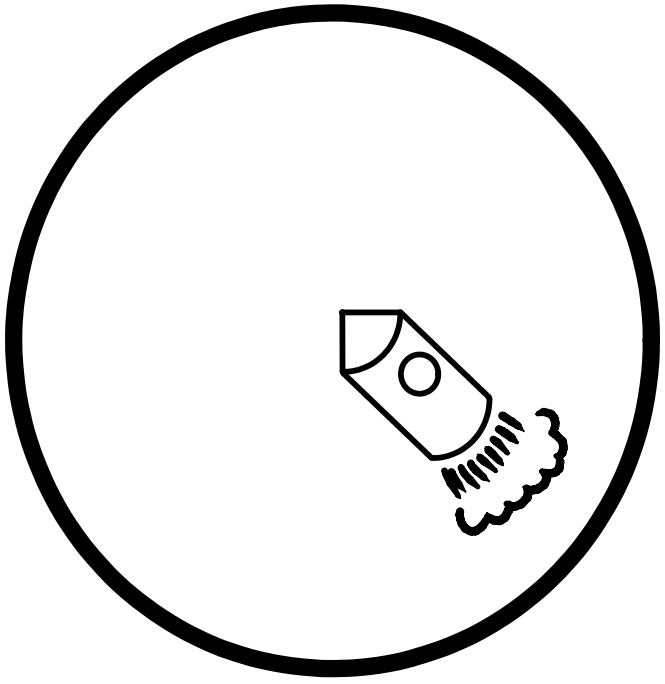

Nothing can come out
from a Black Hole.

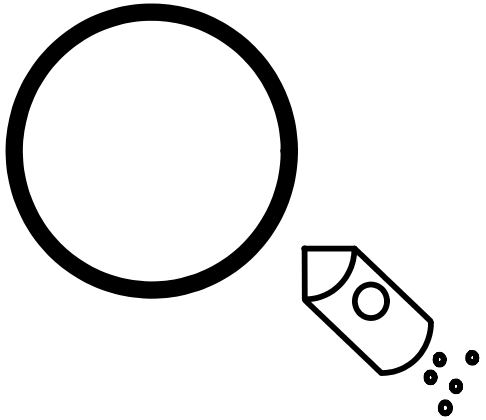




I will email you every day.

Just crossed the event horizon!

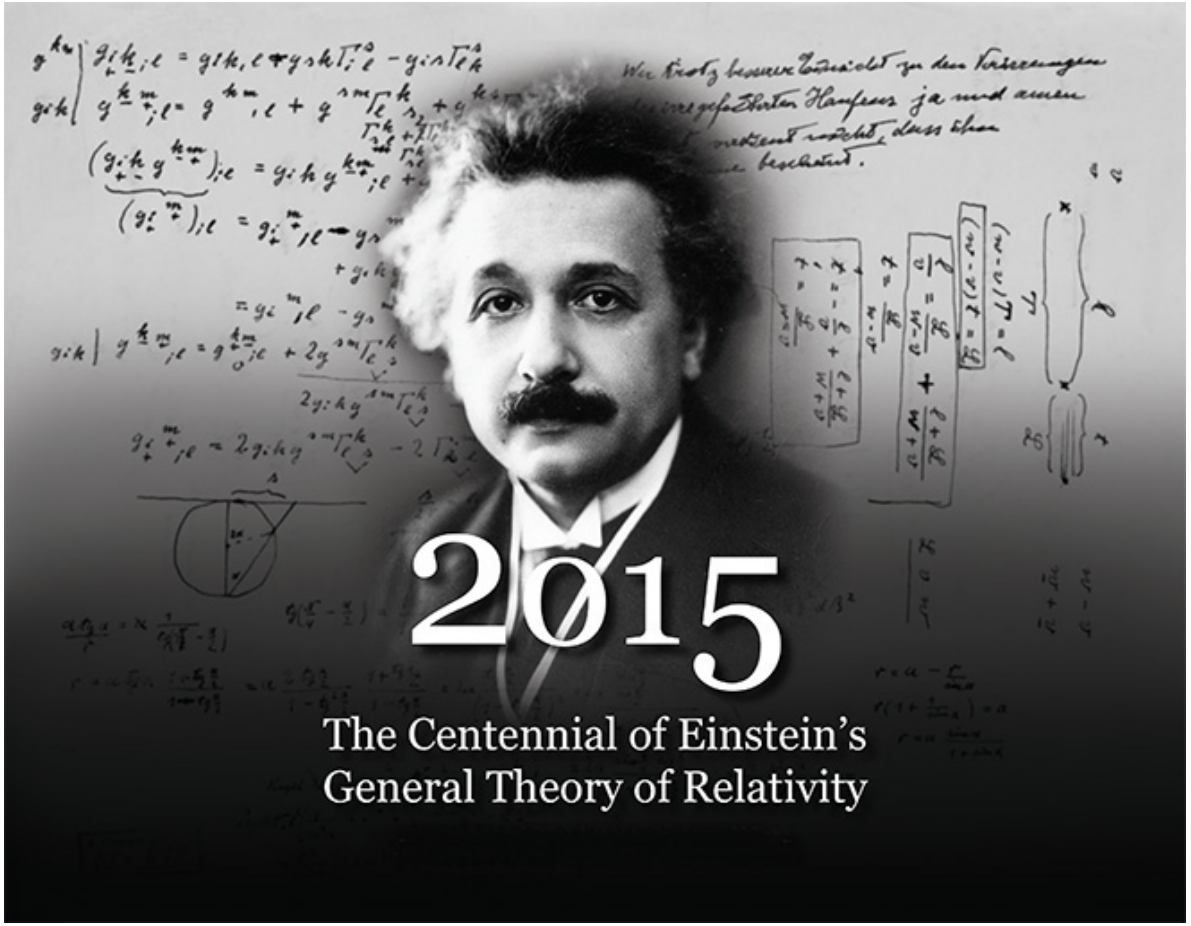




Why is he procrastinating?

GPS would not work without taking into account warping of space and time.

Special and general relativity effects would cause errors of 12 km/day.



In November 1915,
Einstein presented his gravity equations at the Prussian Academy of Science in Berlin.

York Times

National Edition

RIDAY, FEBRUARY 12, 2016

Printed in California $2.50

WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

A RIPPLE IN SPACE-TIME

An Echo of Black Holes Colliding a Billion Light-Years Away

By DENNIS OVERBYE

A team of scientists announced on Thursday that they had heard and recorded the sound of two black holes colliding a billion light-years away, a fleeting chirp that fulfilled the last prediction of Einstein's general theory of relativity.

That faint rising tone, physicists say, is the first direct evidence of gravitational waves, the ripples in the fabric of space-time that Einstein predicted a century ago. It completes his vision of a universe in which space and time are interwoven and dynamic, able to stretch, shrink and jiggle. And it is a ringing confirmation of the nature of black holes, the bottomless gravitational pits from which not even light can escape, which were the most foreboding (and unwelcome) part of his theory.

More generally, it means that a century of innovation, testing, questioning and plain hard work

CALTECH-M.I.T.-LIGO LABORATORY

Interferometer Gravitational-Wave Observatory in Hanford, Wash.

s Notice Sanders

candidate she barely knew. "It makes me feel good," she said, chuckling, "that young people are listening to the elderly people." She now said she was an undecided voter and planned to do some homework on Mr. Sanders.

Mrs. Clinton has long looked forward to the Feb. 27 Democratic contest in South Carolina, he first state where blacks will

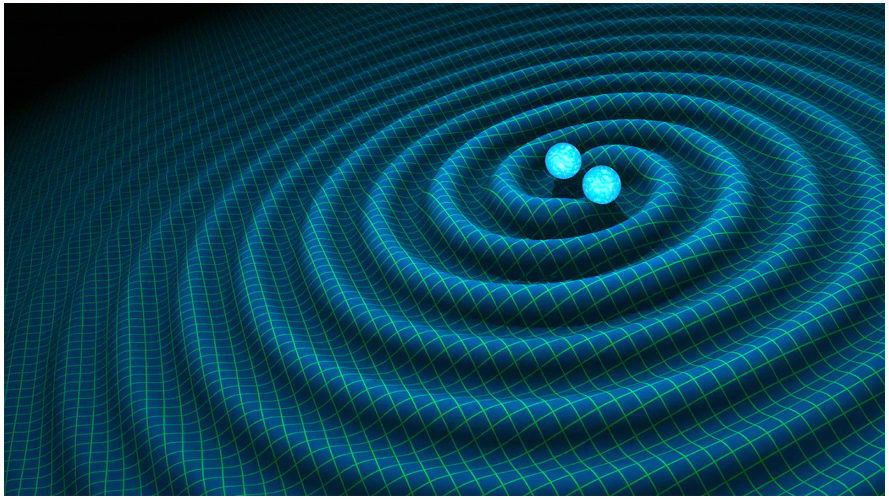
Last Occupier In Rural Oregon Is Coaxed Out

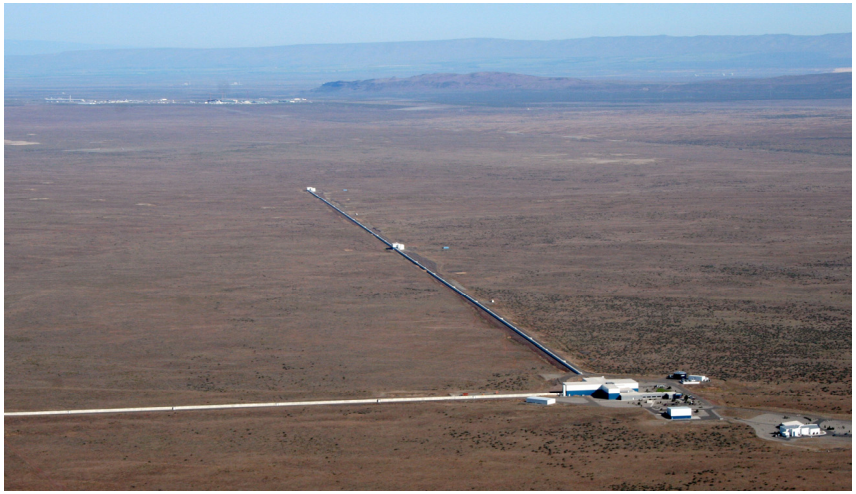
This article is by ***Dave Seminara, Richard Pérez-Peña*** *and* ***Kirk Johnson.***

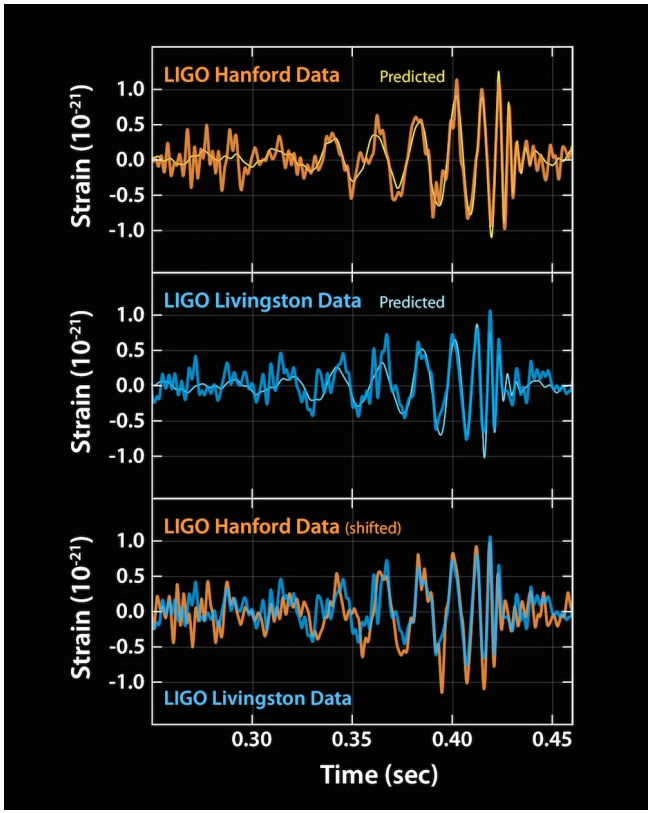
PRINCETON, Ore. — They im-

Gravitational waves were predicted in 1916.

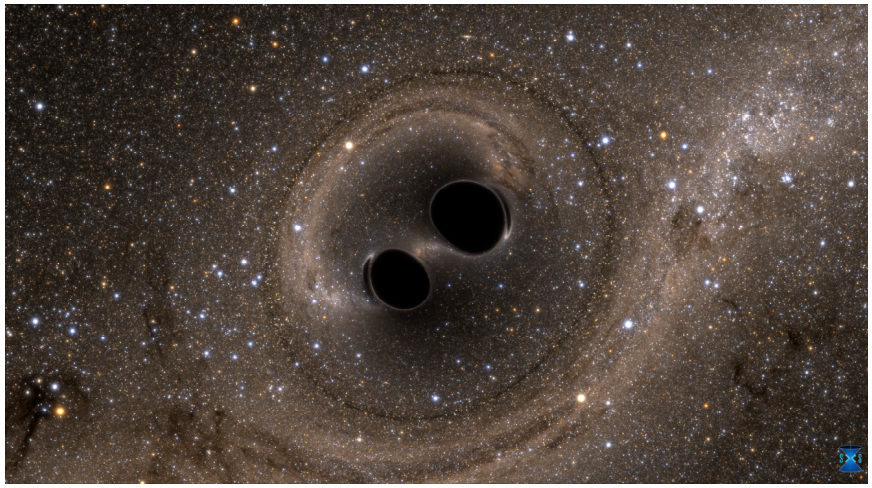
99 years later, on 14 September 2015, LIGO observatories made the first direct detection.

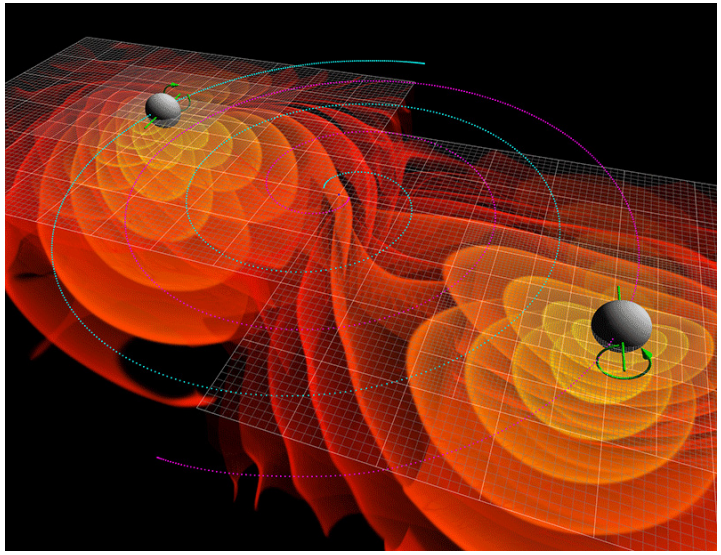






The gravitational waves were emitted by a pair of black holes, about 30 solar mass each, 1.3 billion light years away, and identical signals were detected at the two LIGO observatories.





LIGO's detection of gravitational waves,

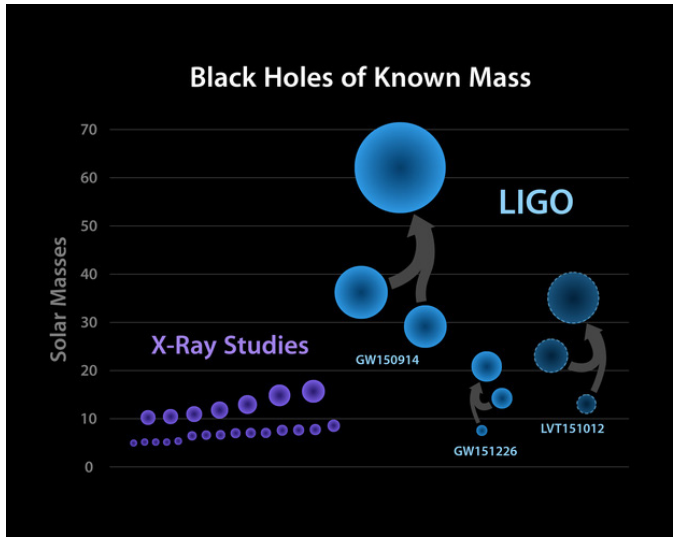
◎ confirmed Einstein's prediction.

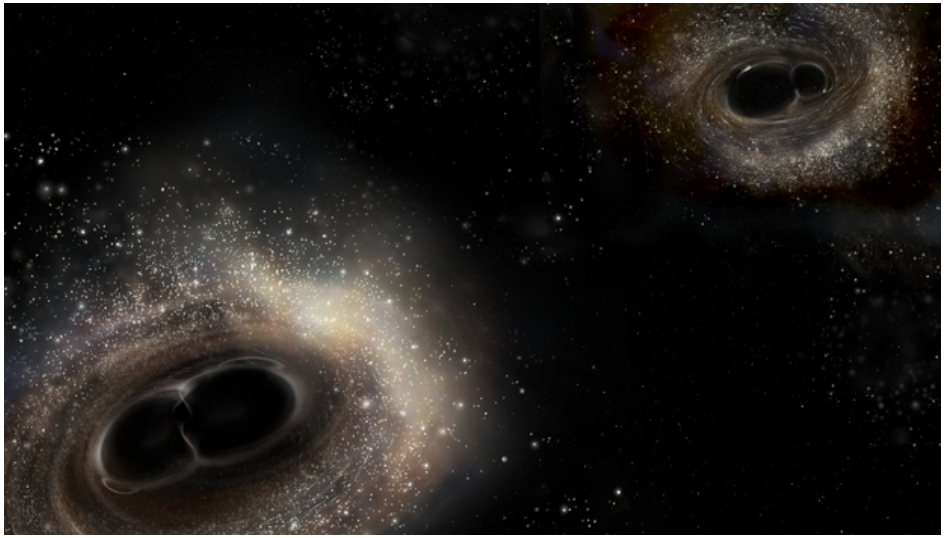
◎ opened a new window to the Universe.

◎ opened a possibility to test Einstein's theory at strong gravitational fields.

News Flash:

Second Detection on 26 December 2015.





It is estimated that LIGO will detect about 1,000 gravitational wave events from black hole mergers per year.

1. Gravity is **a Force.**
2. Gravity is **Weak.**
3. Gravity is **in the eye of the beholder.**
4. Gravity is **Warping of Space and Time.**

Gravity is Warping of Space and Time

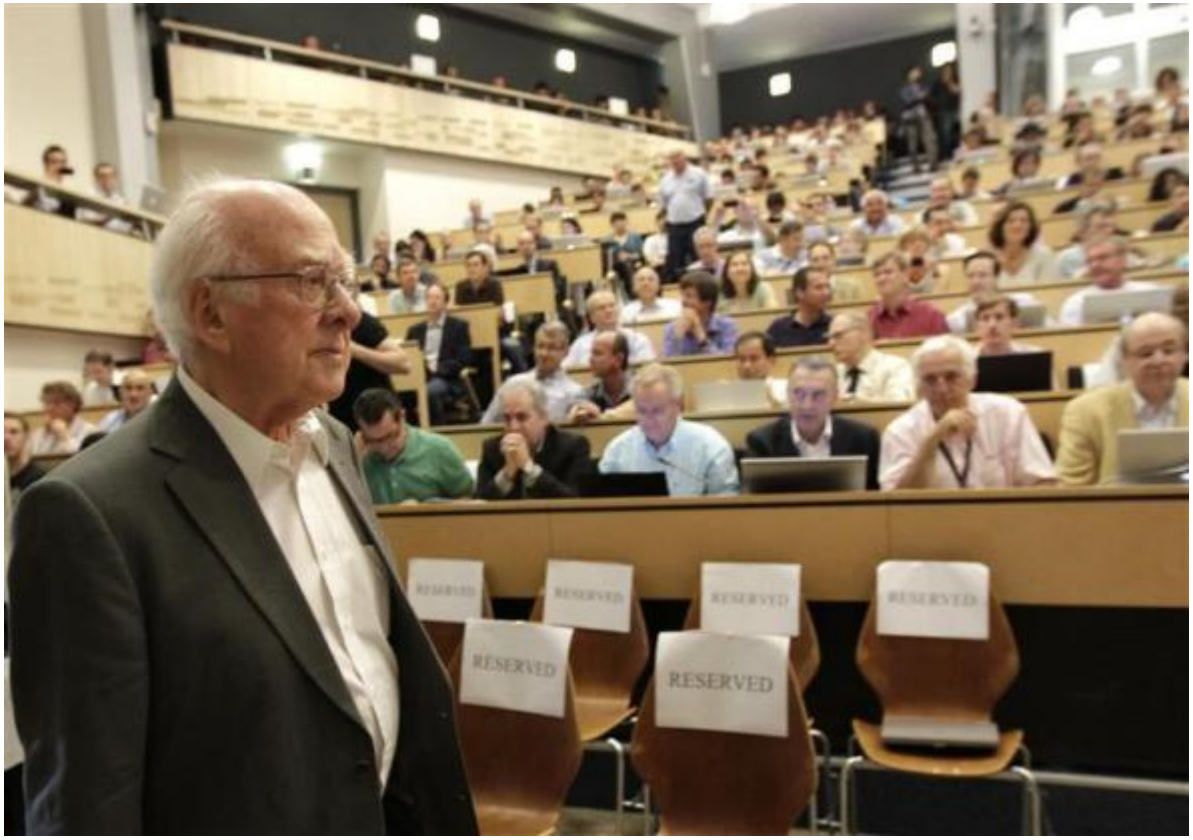
This would have been a fine answer to the question, "What is Gravity?"

Gravity is Warping of Space and Time

This would have been a fine answer to the question, "What is Gravity?"

... until **Quantum Mechanics** was discovered.

5. Gravity is hard to marry with Quantum Mechanics



On 4 July 2012, CERN announced the discovery of the Higgs particle.

Front Page of New York Times signed by Peter Higgs

Best wishes! Peter Higgs

New York Times

Late Edition

Today, sunny to partly cloudy, rather hot, high 92. Tonight, mostly clear, low 72. Tomorrow, mostly sunny, hot and humid, high 90. Weather map appears on Page B16.

NEW YORK, THURSDAY, JULY 5, 2012 $2.50

Physicists Find Elusive Particle Seen as Key to Universe

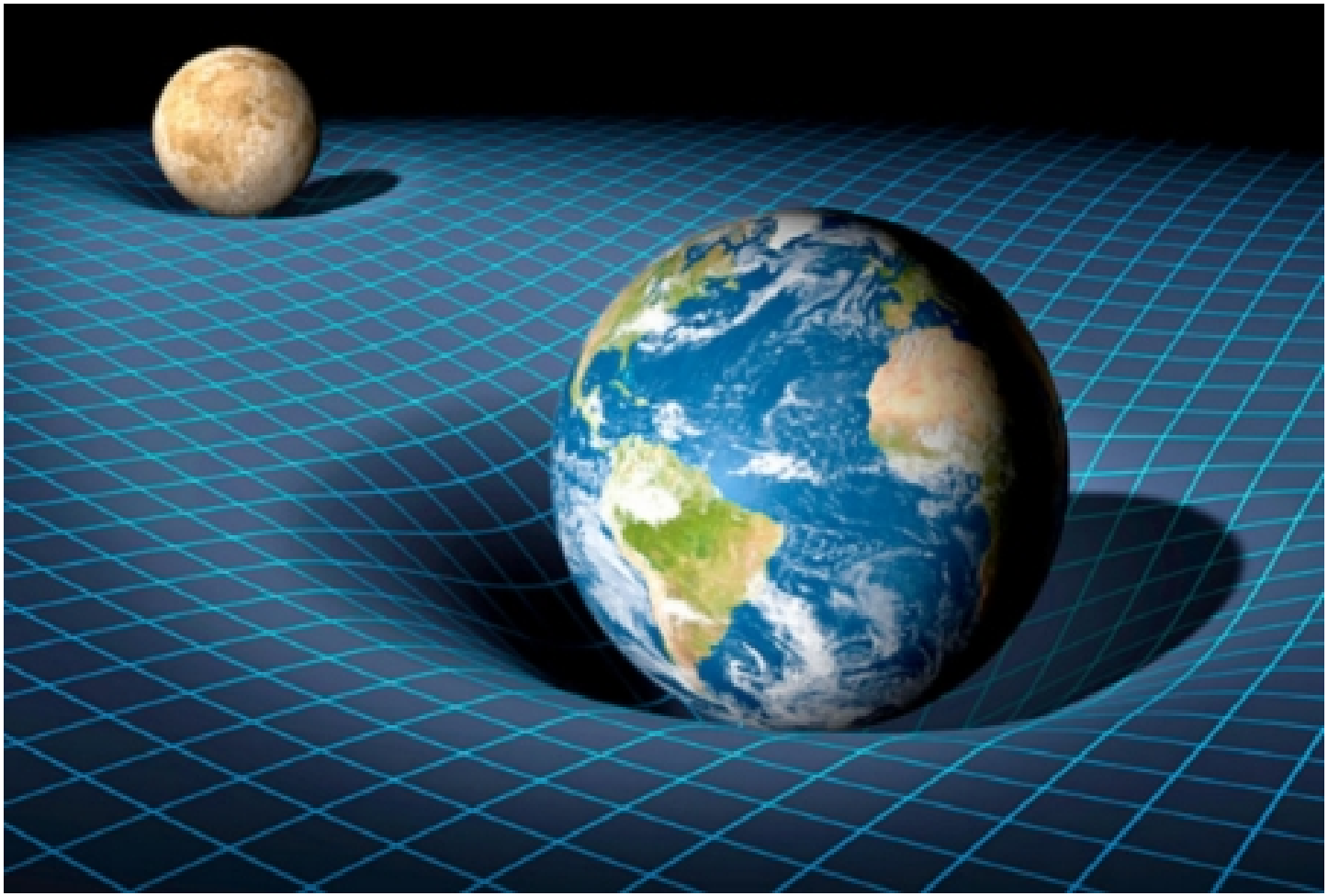
The Higgs discovery completes the Standard Model of Particle Physics.

But,...

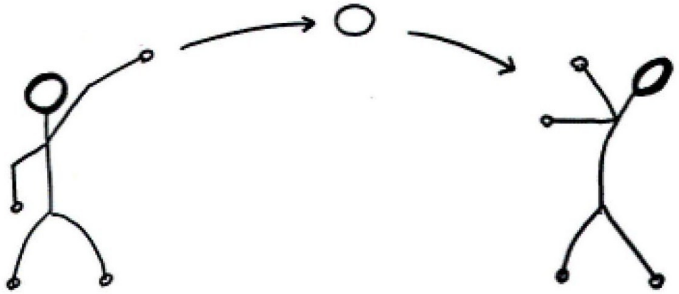
The Standard Model of Particle Physics

does not contain Gravity.

Gravity is Warping of Space and Time.

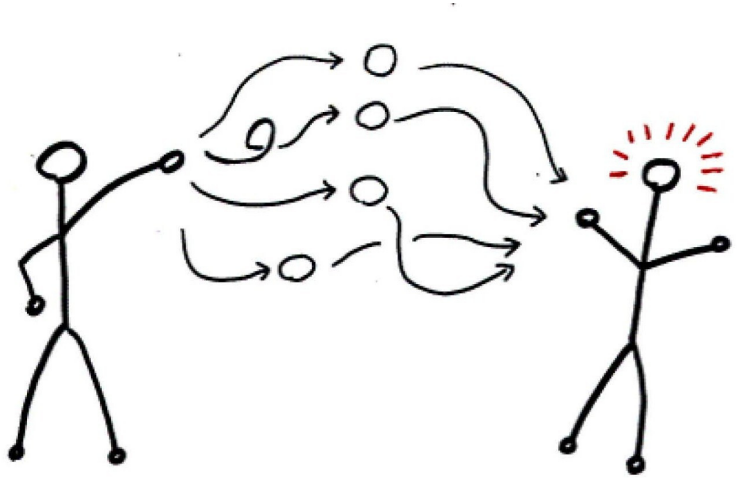


Things are **uncertain** in Quantum Mechanics

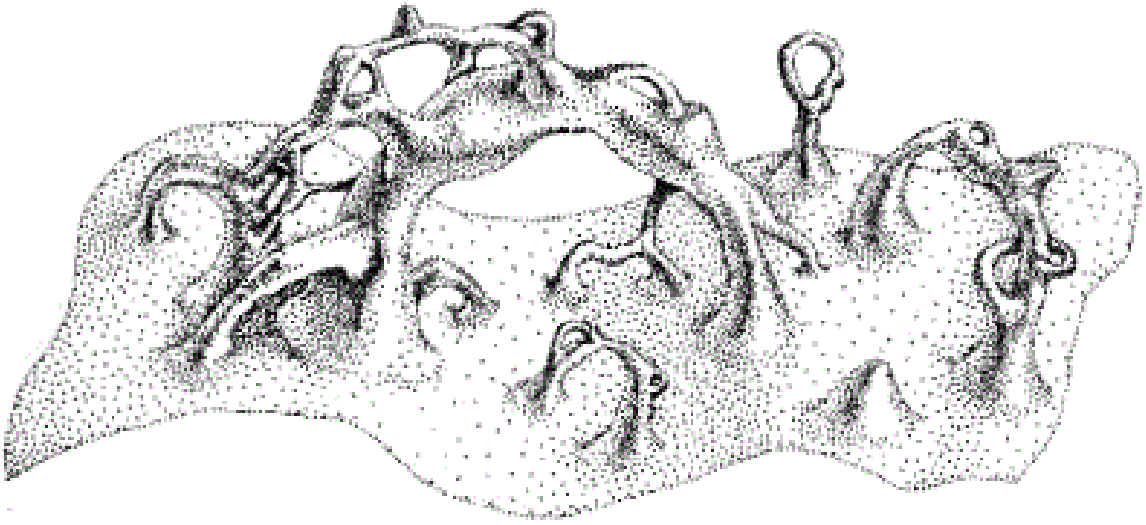


Classical World

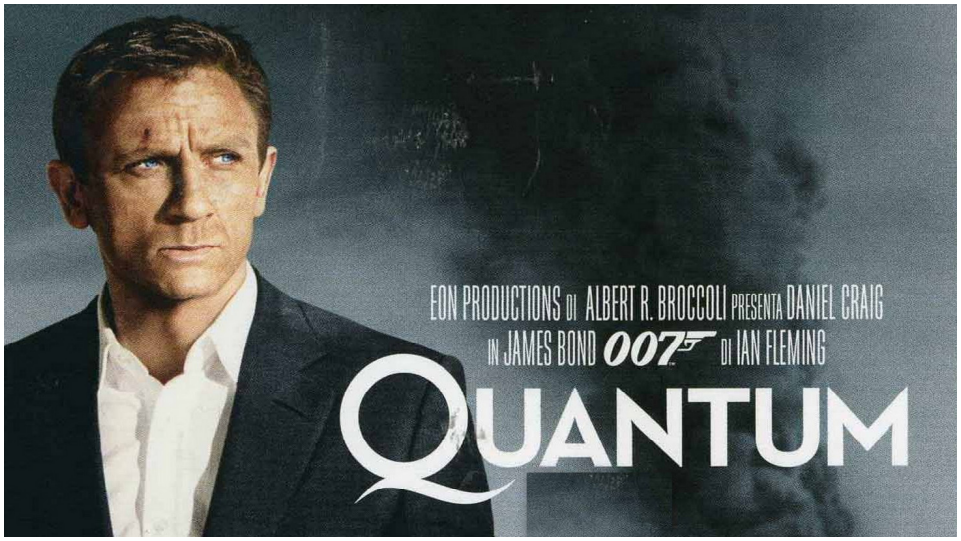
Quantum World

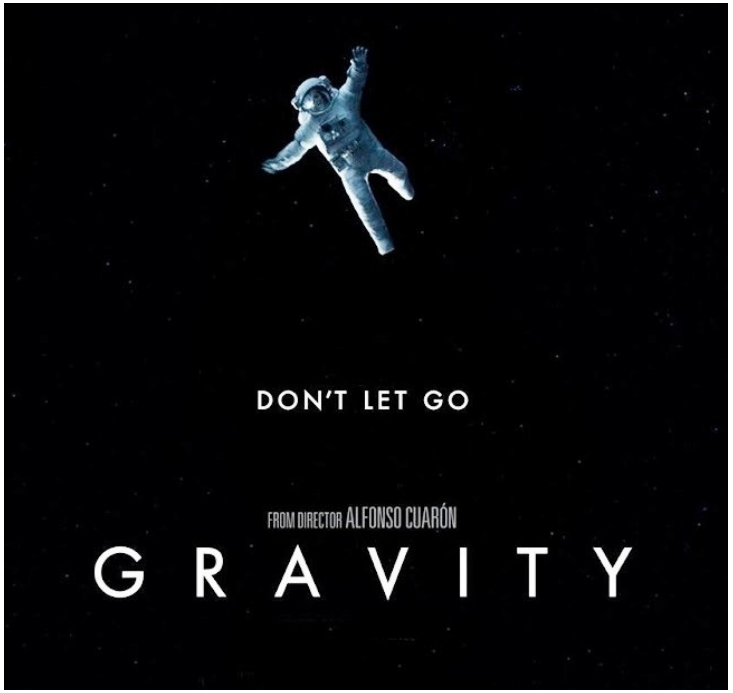


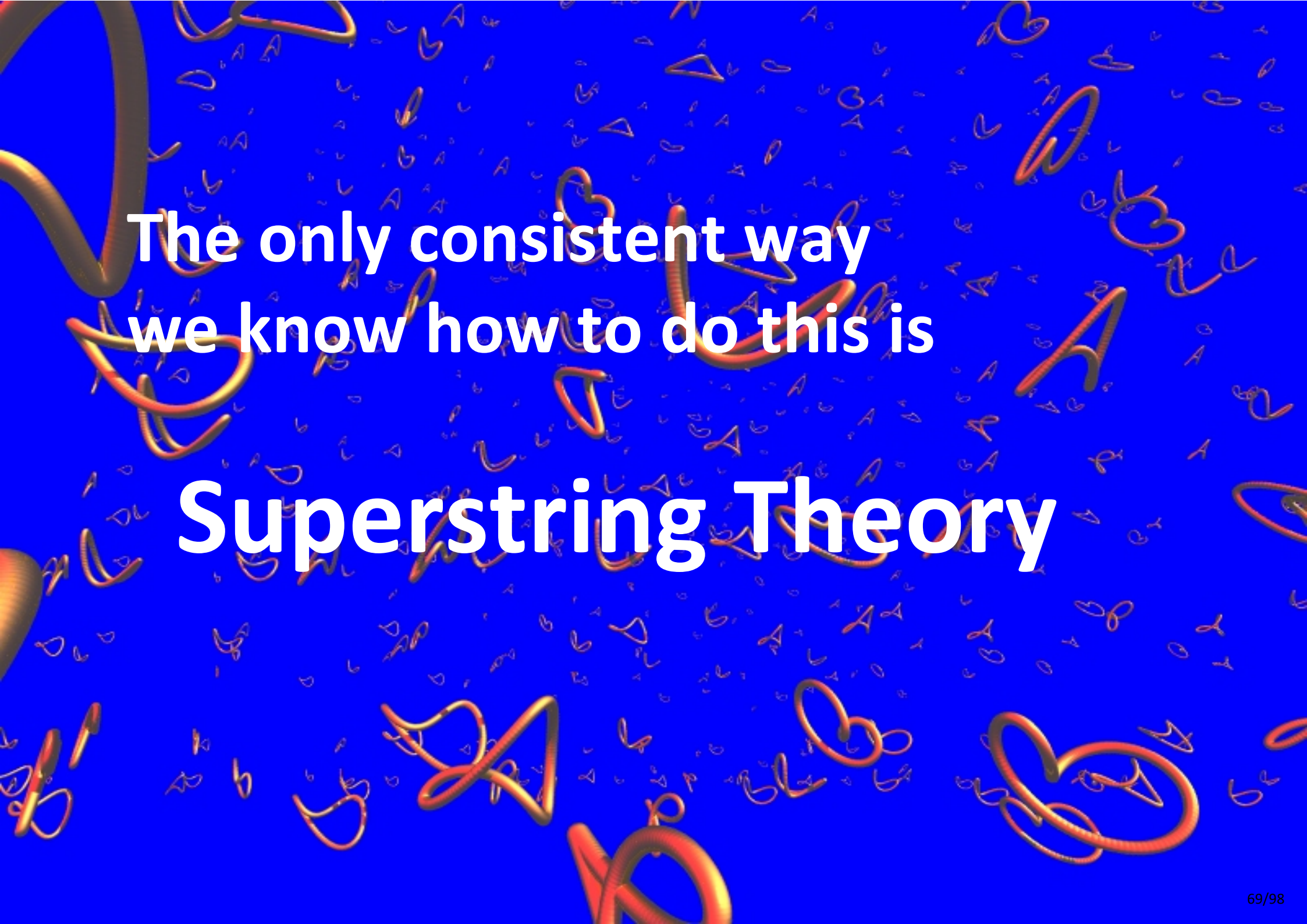
An attempt to marry gravity with quantum mechanics would make space and time uncertain.



Reconciling Quantum and Gravity has been the Holy Grail of modern physics.






The only consistent way
we know how to do this is
Superstring Theory

Superstring Theory postulates fundamental building blocks are not point particles but strings.

Superstring Theory contains
all the ingredients needed to build
the Standard Model of Particle Physics,
including Gravity.

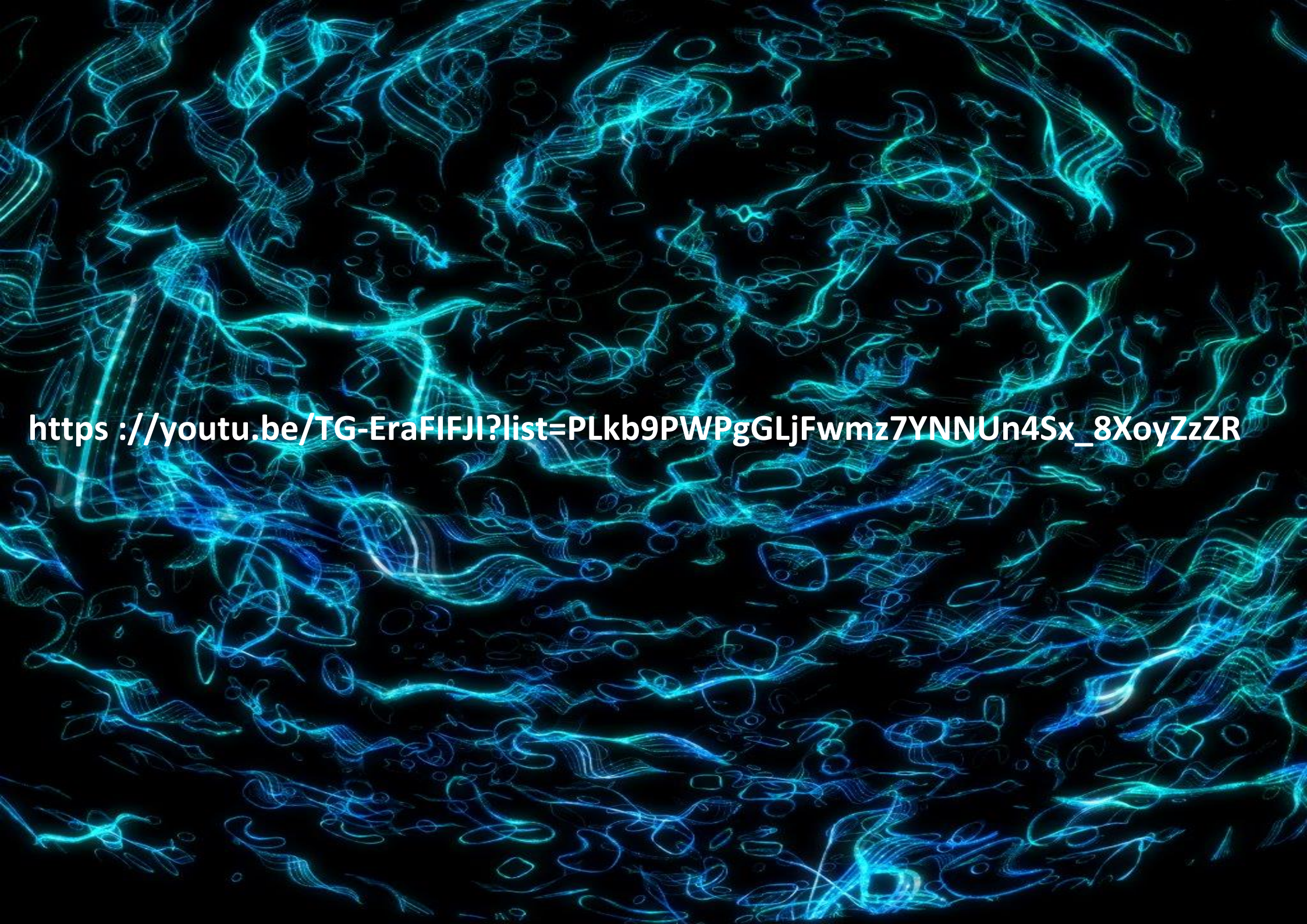
Superstring Theory helped solve some of the deepest mysteries of quatum gravity, such as the origin of the Hawking radiation from a black hole.

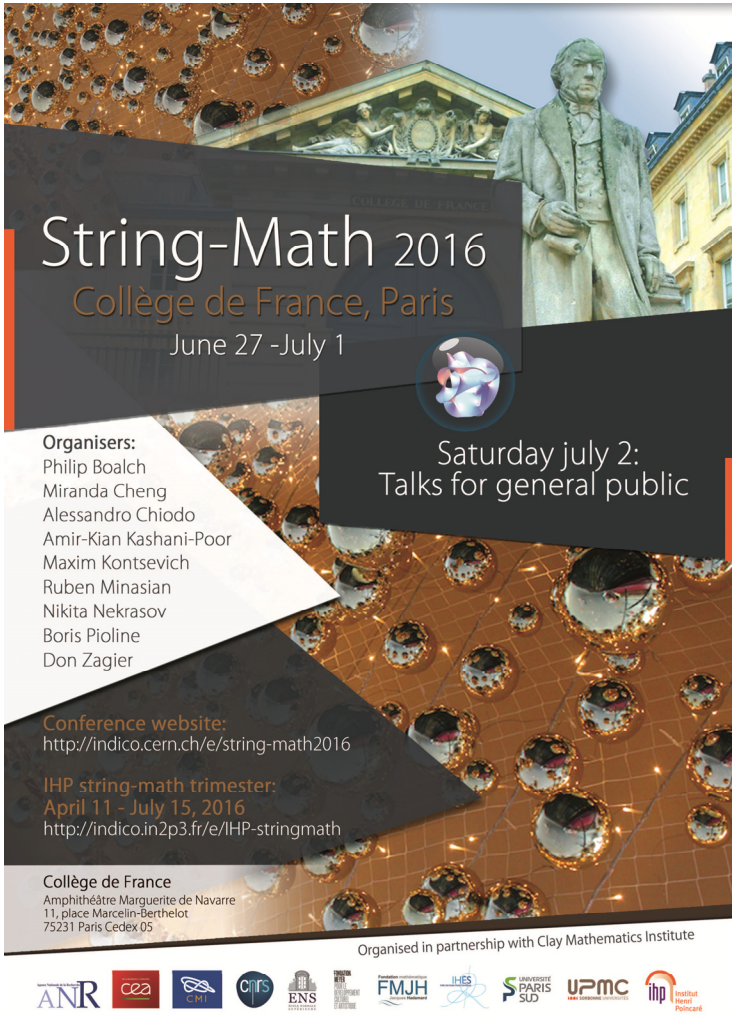
3D Dome Theater Movie

The Man
from the 9 Dimensions

debuted in Tokyo
on April 20, 2016

"The Man from the 9 Dimensions" received the 2016 **Best Educational Product Award** from the International Planetarium Society, from 66 films submitted from 15 countries.


https ://youtu.be/TG-EraFIFJI?list=PLkb9PWPgGLjFwmz7YNNUn4Sx_8XoyZzZR



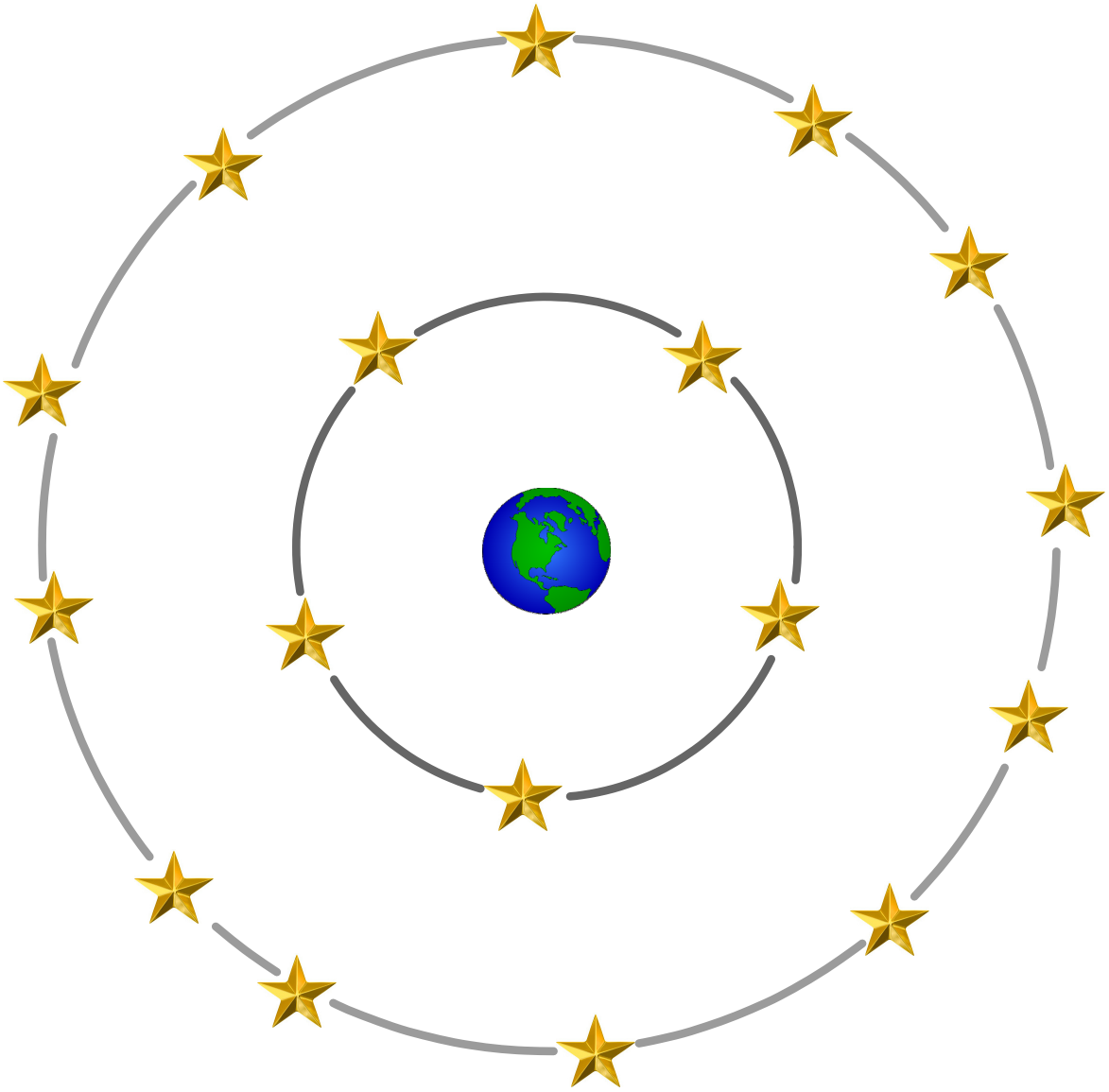
General relativity
describes gravity as **geometry**.

Quantum mechanics
describes the microscopic world in terms of **algebra**.

Study of quantum gravity and string theory is opening new lines of research in mathematics connecting **geometry** and **algebra** in unexpected ways.

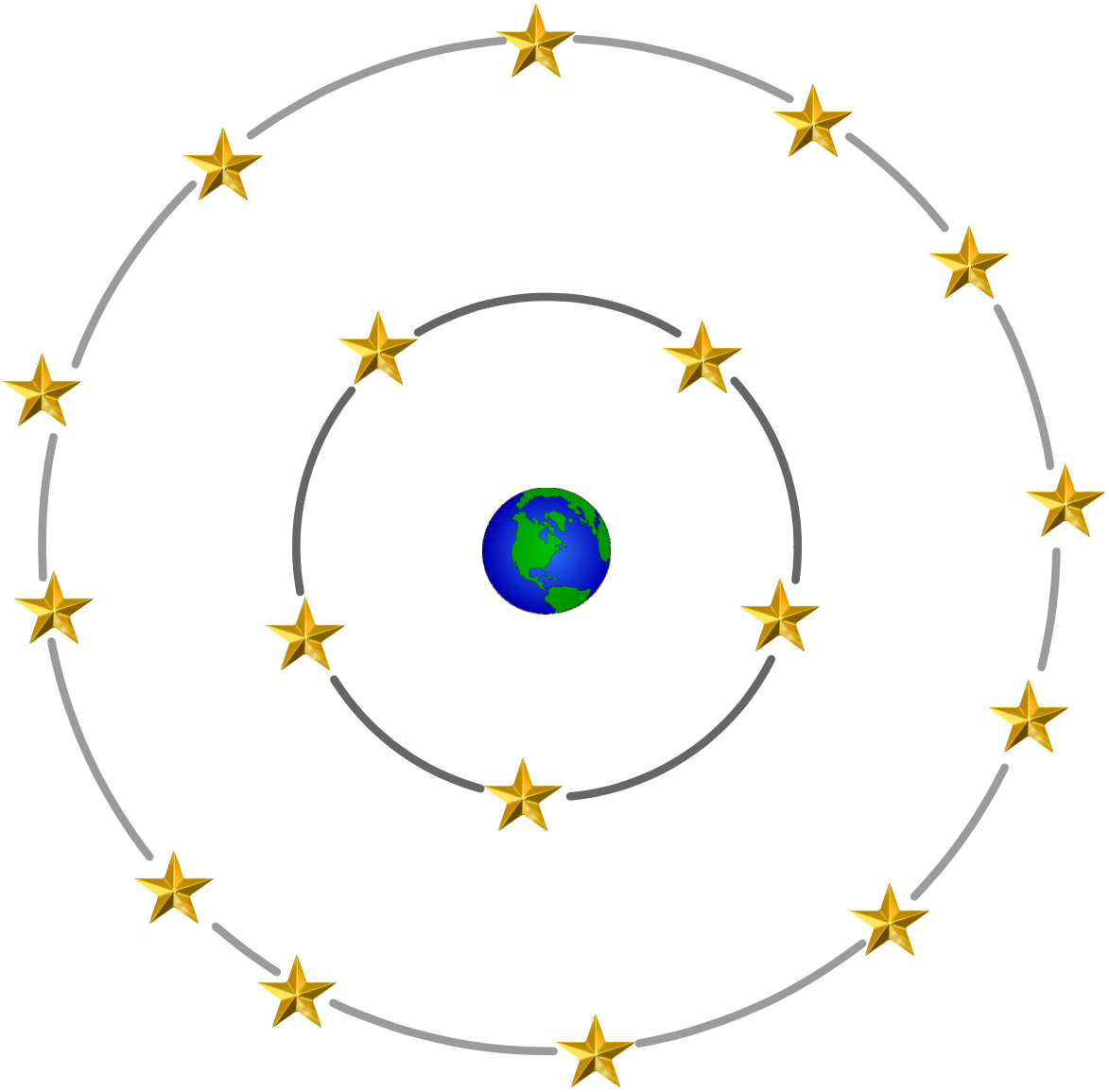
6. Why is the Sky Dark at Night?

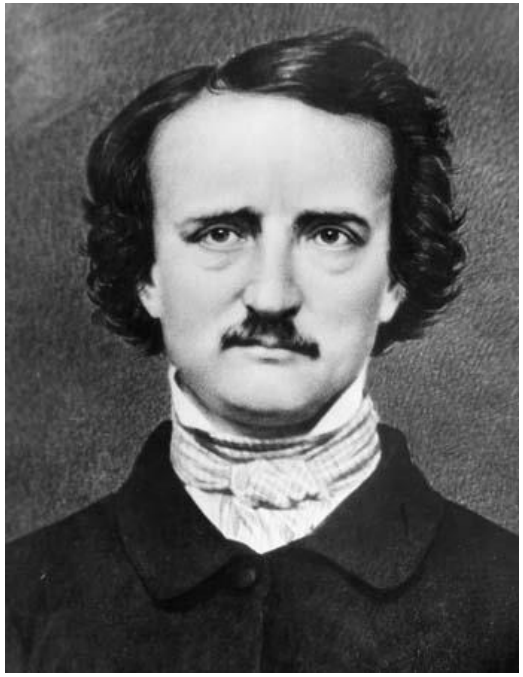
Luminosity of a star twice distance away is 1/4.
However, there are 4 times as many stars.



Olbers' Paradox (1823):

Why is the sky dark at night?





Edgar Allan Poe
"Eureka" (1848)

Were the succession of stars endless, then the background of the sky would present us a uniform luminosity, like that displayed by the Galaxy – since there could be absolutely no point, in all that background, at which would not exist a star. The only mode, therefore, in which, under such a state of affairs, we could comprehend the voids which our telescopes find in innumerable directions, would be ***by supposing the distance of the invisible background so immense that no ray from it has yet been able to reach us at all****.*

In 1929, Edwin Hubble of Mount Wilson Observatory discovered that distant galaxies are receding and the recession velocity increases with distance, implying that the Universe is expanding.

If the Universe is expanding,
it must have been hotter and denser
in the past.

Einstein's gravitational equations predict:

Big Bang

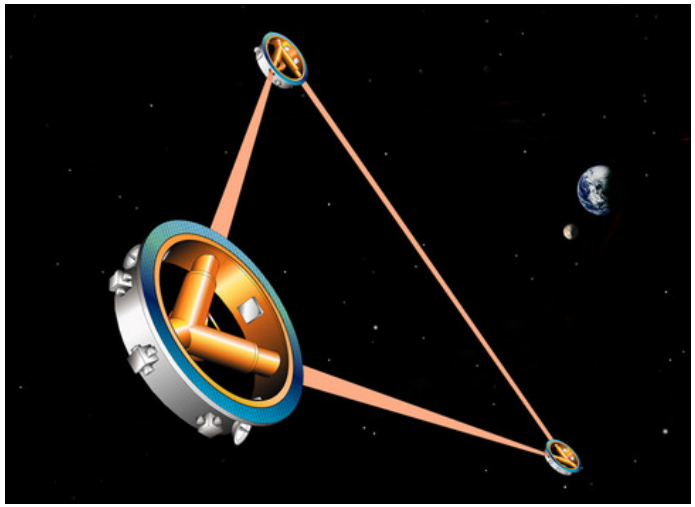
The Universe began
13.8 billion years ago.

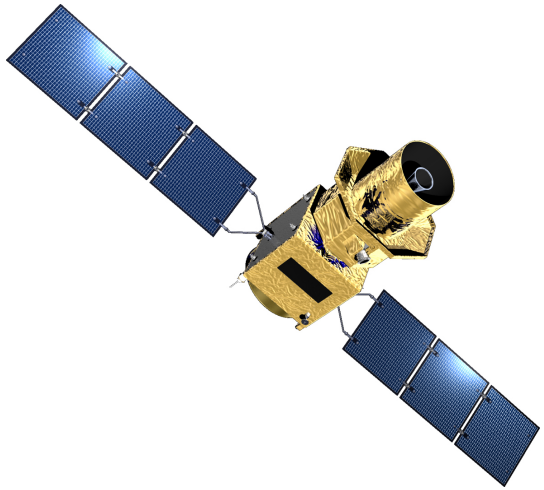
Light from stars beyond
13.8 billion light years
has not reached us.

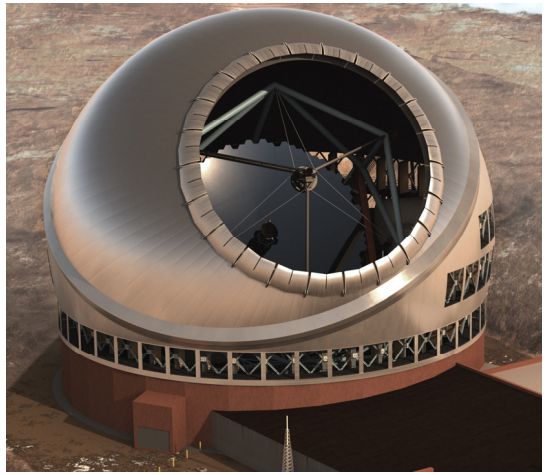
Why is the sky dark at night?

This simple question had a surprising answer.

Experiments and observations in the next decade will significantly advance our understanding of the beginning of the Universe and may provide ways to test superstring theory, too.

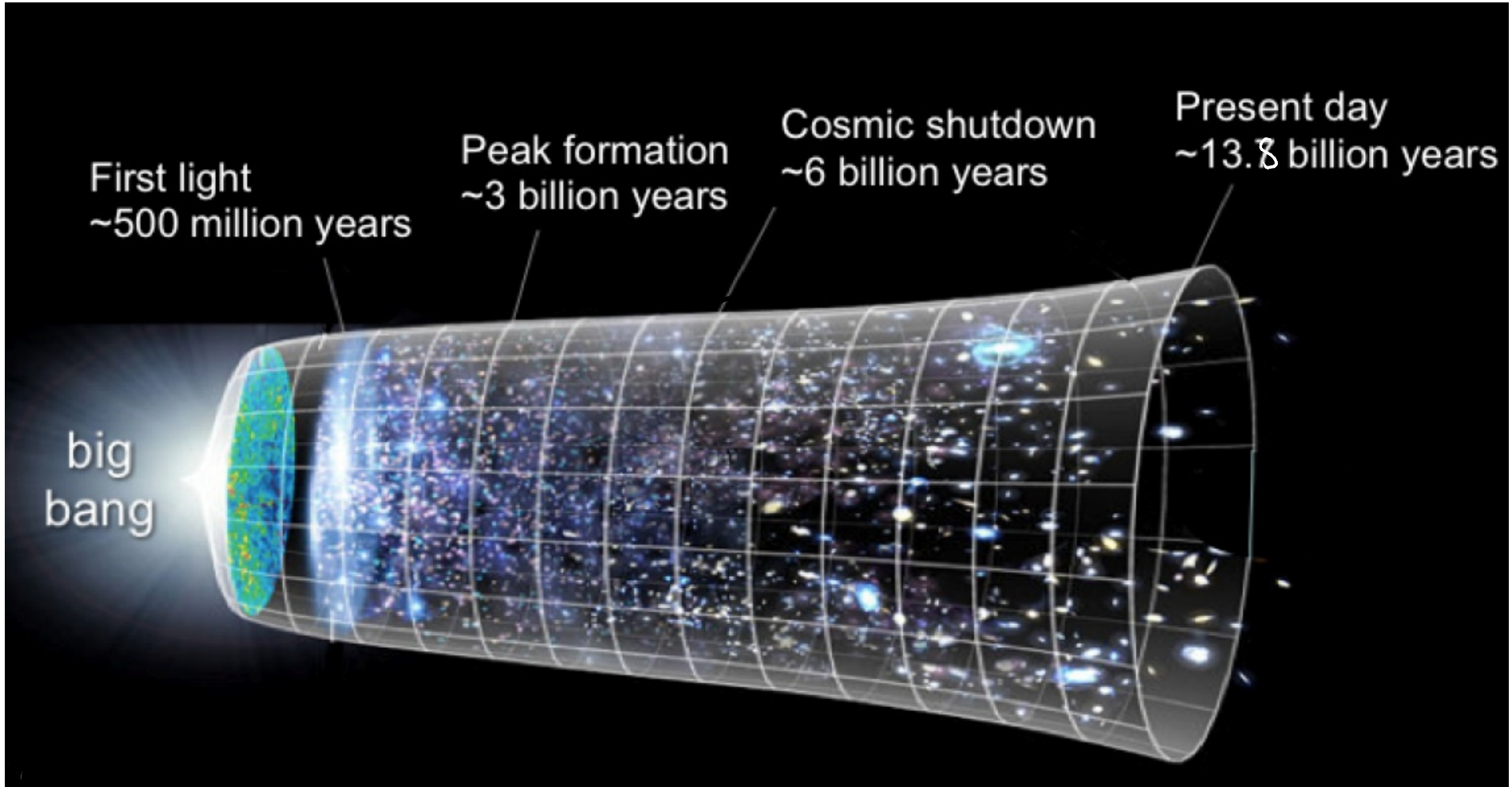




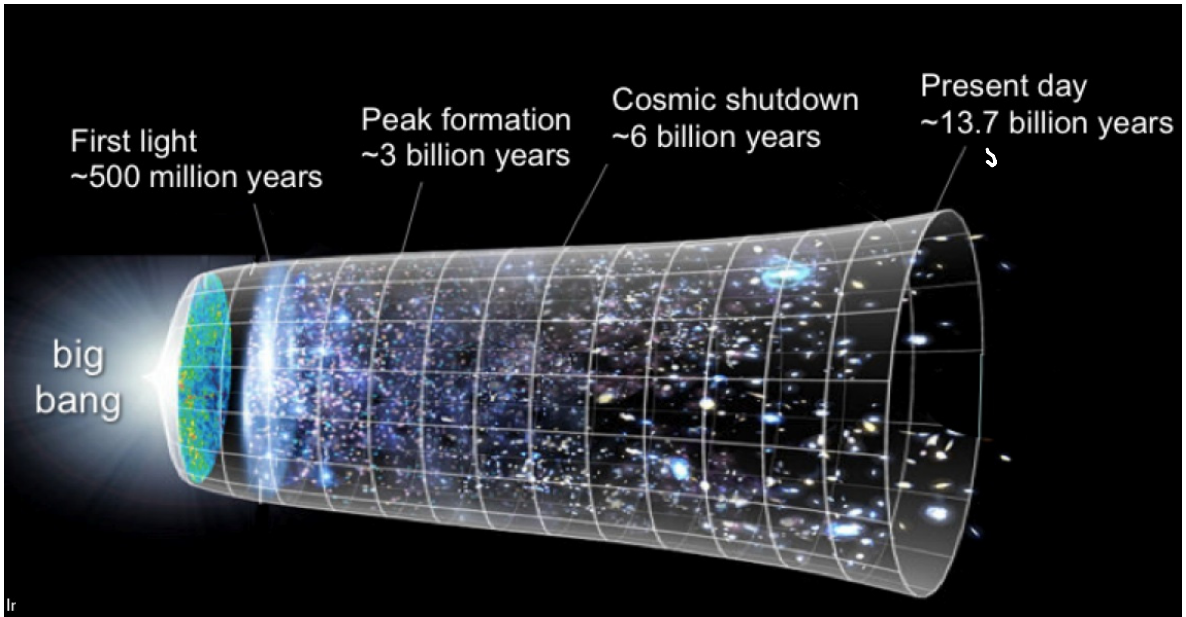


7. Why is Gravity … just so?

The Universe was born 13.8 billion years ago.



It gave us home on this beautiful planet
and 3.5 billion years to evolve
from microbes to Homo sapiens
intellectual enough to ask,
"what is gravity?"



Gravity is weak

If Gravity were weaker,
stars and planets would
not have formed.

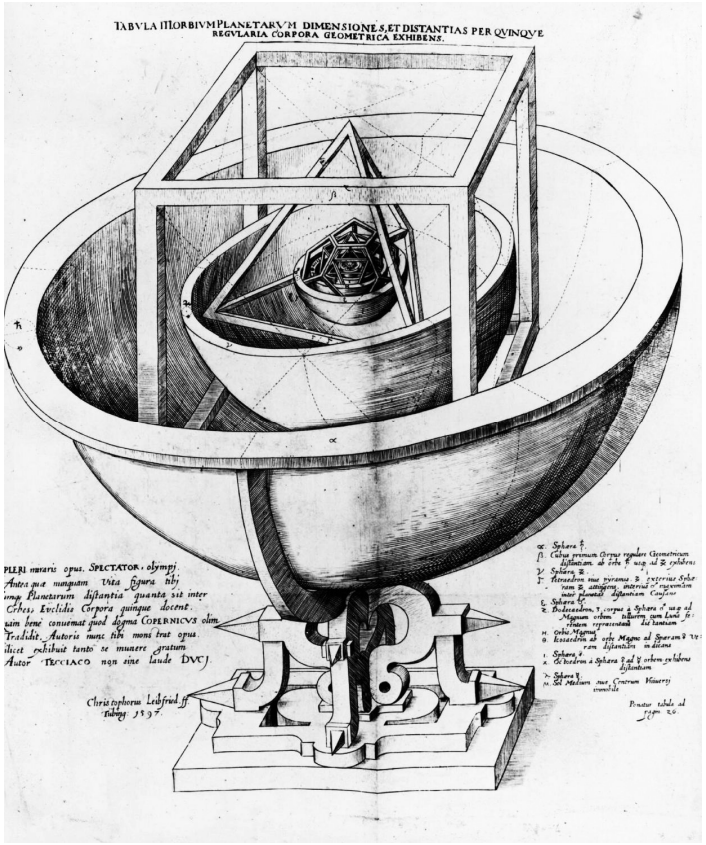
If Gravity were stronger,
most stars would have
collapsed into black holes.

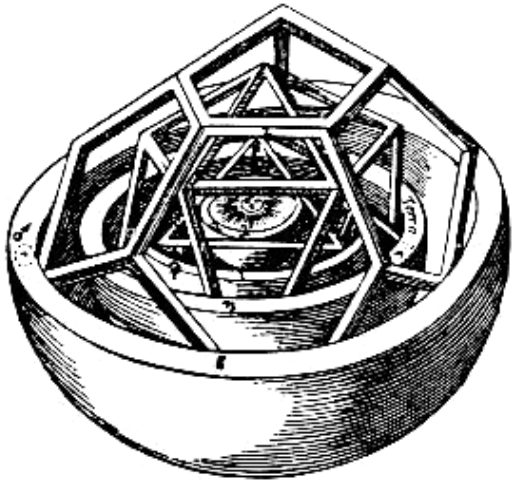
Why is Gravity

… just so?

Anthropic Principle?

The Anthropic Principle gives the correct explanationation for the distance between the Sun and the Earth.





In *Mysterium Cosmographicum* (1596) , Johannes Kelper speculated that the six planets known at the time have orbits on the six spheres inscribing and circumscribing the five Platonic solids appropriately ordered and that it suggests God's geometric plan for the Universe.

Do we have to employ the Anthropic Principle to explain the Fundamental Laws of Nature?

Should we give up deriving them from the Basic Principle?

Seven Wonders of Gravity

1. Gravity is **a Force**.
2. Gravity is **Weak**.
3. Gravity is **in the Eye of the Beholder**.
4. Gravity is **Warping of Space and Time**.
5. Gravity is **Hard to Marry with Quantum Mechanics**.
6. Why is the sky dark at night?
7. Why is Gravity ... **Just So ?**

String-Math 2018

Tohoku University, Sendai

18 - 22 June 2018

Strings 2018

OIST, Okinawa

25 - 29 June 2018

We look forward to welcoming you
in Japan in 2018.