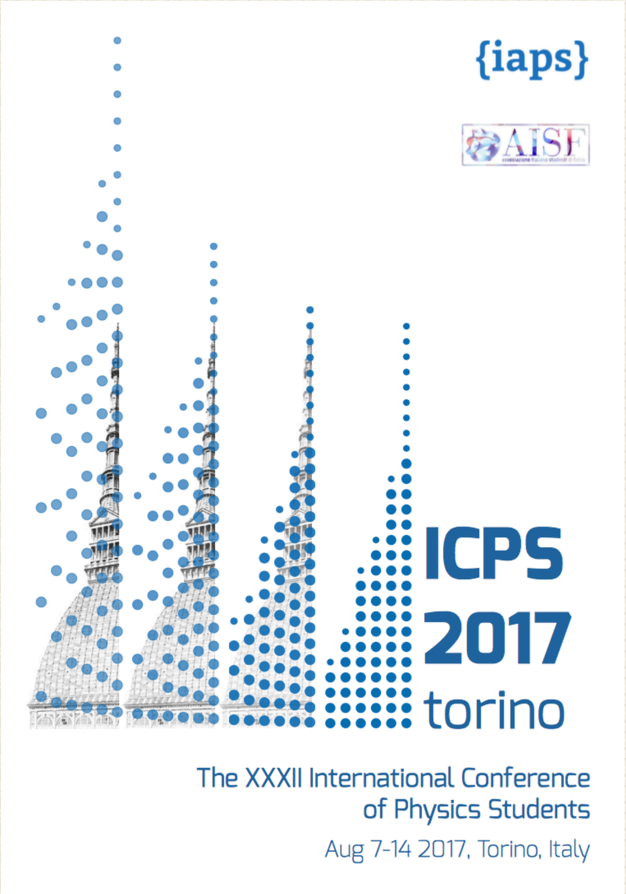
A JOURNEY INTO THEORETICAL PHYSICS

AGNESE BISSI
HARVARD UNIVERSITY

ICPS2017, TORINO AUGUST 9TH



A BRIEF JOURNEY INTO HIGH ENERGY THEORETICAL PHYSICS

AGNESE BISSI
HARVARD UNIVERSITY

ICPS2017, TORINO AUGUST 9TH

{iaps}
AISF
ICPS 2017 torino
The XXXII International Conference of Physics Students
Aug 7-14 2017, Torino, Italy

E=mc 2

WHERE DO WE COME FROM? WHAT ARE WE? WHERE ARE WE GOING?

PAUL GAUGUIN, 1897

E=mc 2

WHAT IS THEORETICAL PHYSICS?

- Theoretical physics is the development of mathematical formalisms for describing fundamental objects around us and their interactions

- Both providing models for understanding empirical results or constructing theories to predict phenomena beyond current experiments.

- Today's theoretical physicists are often working on the boundaries of known mathematics.

WHAT IS THEORETICAL PHYSICS?

- In the past, there was little difference between theoretical and experimental physics
- Nowadays scientists are much more specialised and experiments are mostly driven by theory.

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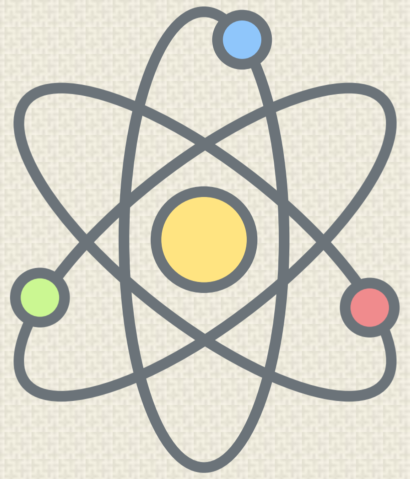
PLAN FOR TODAY

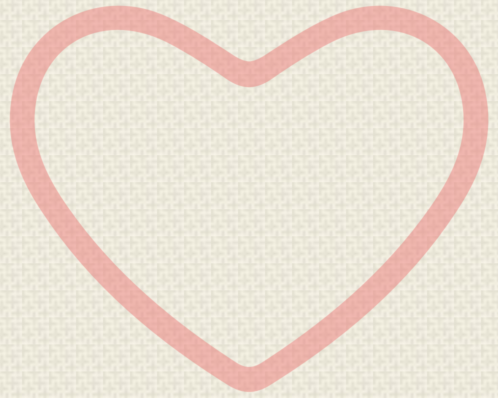
1) PARTICLE PHYSICS



2) GRAVITY

$E=mc^2$

3) PARTICLE PHYSICS AND GRAVITY



PARTICLE PHYSICS

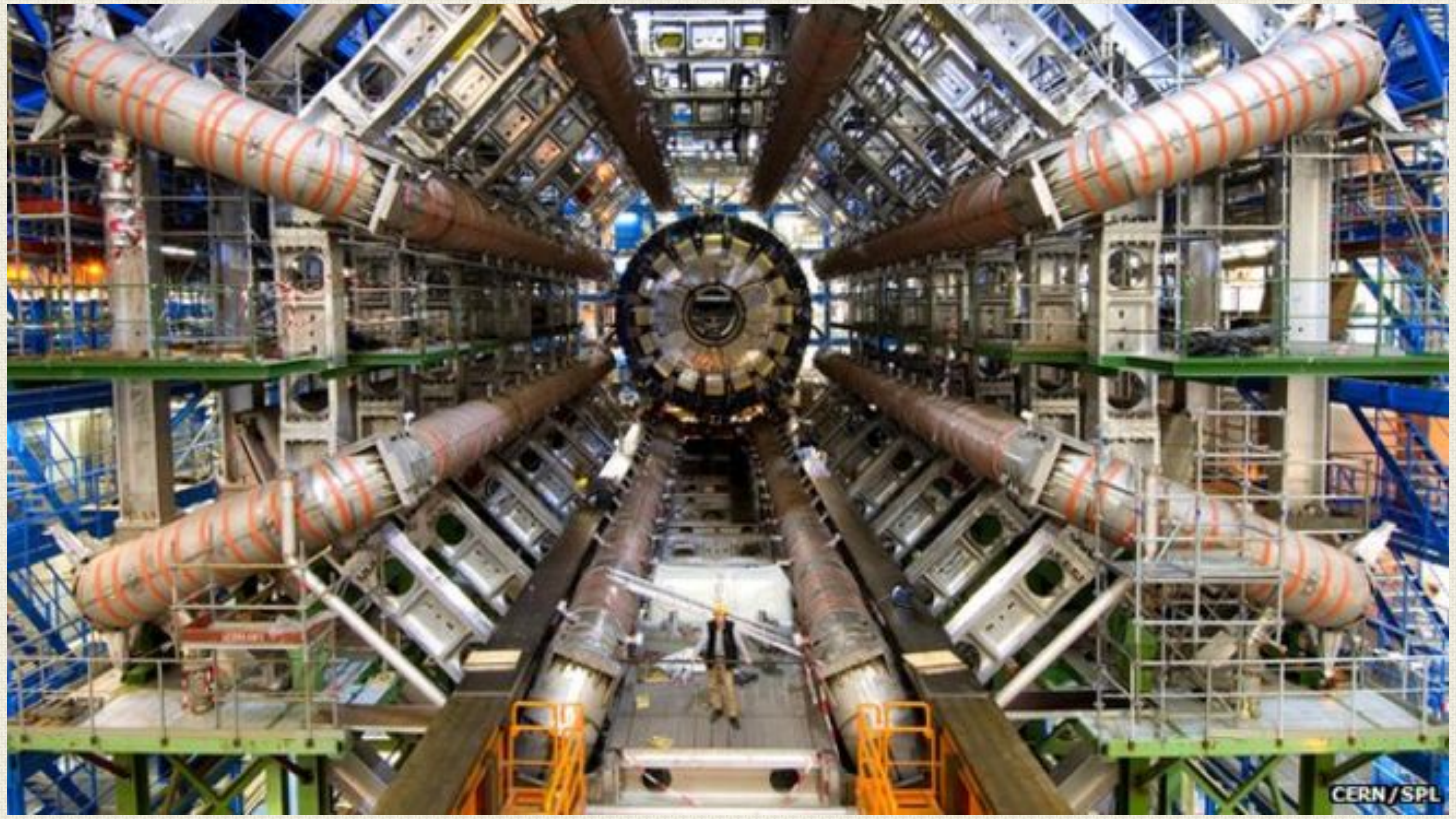
This content is archived on the CERN Document Server

CERN's main focus is particle physics – the study of the fundamental constituents of matter – but the physics programme at the laboratory is much broader, ranging from nuclear to high-energy physics, from studies of antimatter to the possible effects of cosmic rays on clouds.

Since the 1970s, particle physicists have described the fundamental structure of matter using an elegant series of equations called the Standard Model. The model describes how everything that they observe in the universe is made from a few basic blocks called fundamental particles, governed by four forces. Physicists at CERN use the world's most powerful particle accelerators and detectors to test the predictions and limits of the Standard Model. Over the years it has explained many experimental results and precisely predicted a range of phenomena, such that today it is considered a well-tested physics theory.

But the model only describes the 4% of the known universe, and questions remain. Will we see a unification of forces at the high energies of the Large Hadron Collider (LHC)? Why is gravity so weak? Why is there more matter than antimatter in the universe? Is there more exotic physics waiting to be discovered at higher energies? Will we discover evidence for a theory called supersymmetry at the LHC? Or understand the Higgs boson that gives particles mass?

Physicists at CERN are looking for answers to these questions and more – find out more below.



from https://home.cern/about/physics

ELEMENTARY PARTICLES

FERMIONS

QUARKS

COLOR CHARGE

$\boxed{u}$ $\boxed{d}$

$\boxed{c}$ $\boxed{s}$

$\boxed{t}$ $\boxed{b}$

LEPTONS

+ ANTIPARTICLES

NO COLOR CHARGE

e^- ν_e

μ^- ν_μ

τ^- ν_τ

BOSONS

GAUGE

SPIN $\neq$ ZERO

γ

W^+, W^-, Z

GLUON

GRAVITON

SCALAR

SPIN ZERO

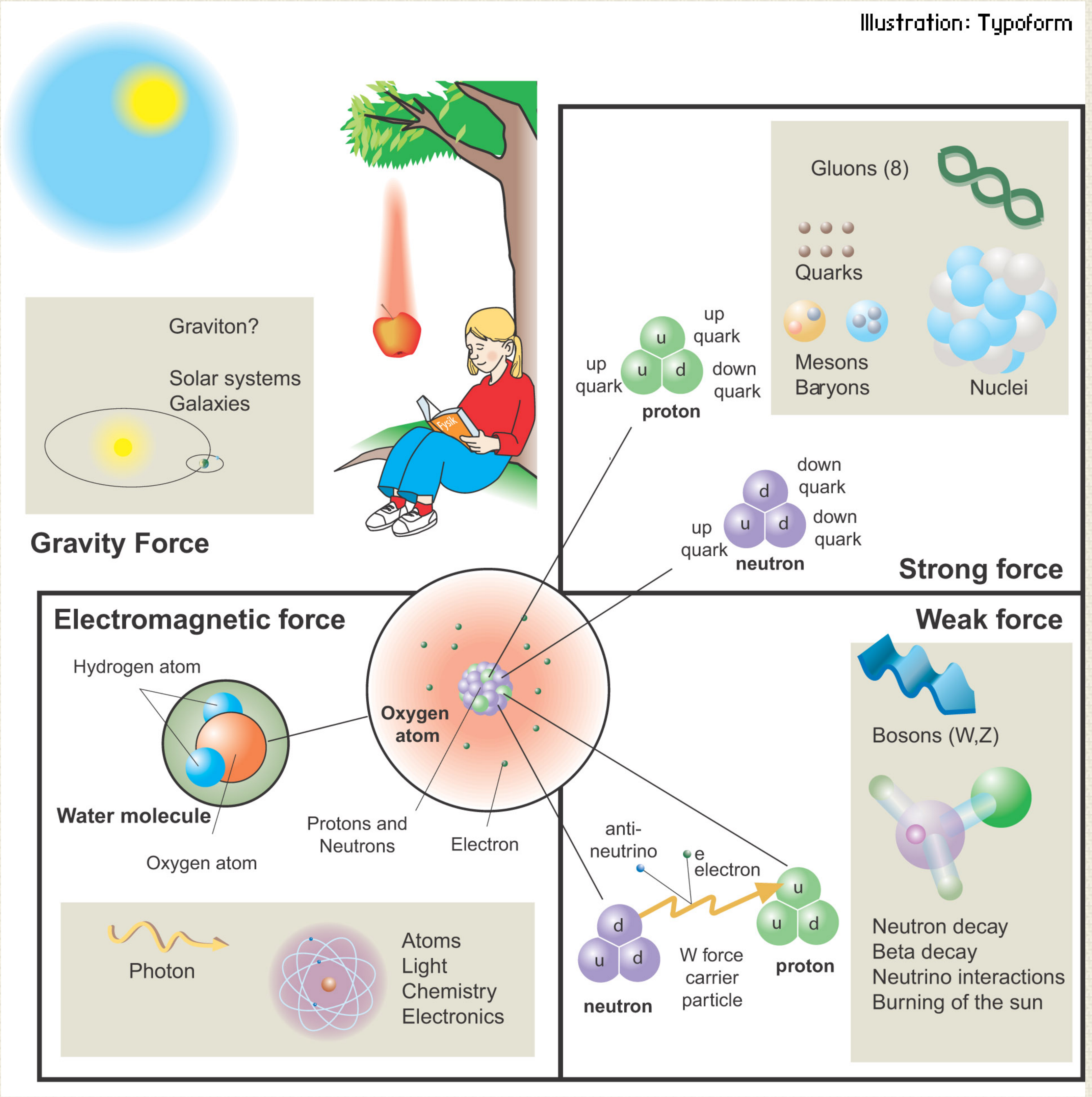
HIGGS

CURIOSITY!

WHY THE NAME "QUARK"?

THE WORD "QUARK" APPEARED IN THE NOVEL FINNEGANS WAKE, BY JAMES JOYCE. THE PROTAGONIST OF THE BOOK IS A PUBLICAN WHO DREAMS THAT HE IS SERVING BEER TO A DRUNKEN SEAGULL. INSTEAD OF ASKING FOR "THREE QUARTS FOR MISTER MARK" THE INEBRIATED BIRD SAYS "THREE QUARKS FOR MUSTER MARK".

4 ELEMENTARY FORCES



- WEAK FORCE
- STRONG FORCE
- ELECTROMAGNETIC FORCE
- GRAVITATIONAL FORCE

STANDARD MODEL

4 ELEMENTARY FORCES

INTERACTIONS	STRENGTH	RANGE
GRAVITATIONAL	10^{-38}	INFINITE
STRONG	1	$10^{-15}m$
WEAK	10^{-6}	$10^{-18}m$
ELECTROMAGNETIC	10^{-2}	INFINITE

4 ELEMENTARY FORCES

INTERACTIONS	RANGE
GRAVITATIONAL	INFINITE
STRONG	$10^{-15}m$
WEAK	$10^{-18}m$
ELECTROMAGNETIC	INFINITE

4 ELEMENTARY FORCES

INTERACTIONS		RANGE
GRAVITATIONAL		INFINITE
STRONG	THIS IS WHY THEY ARE DETECTABLE	$10^{-15}m$
WEAK	IN EVERYDAY LIFE	$10^{-18}m$
ELECTROMAGNETIC		INFINITE

4 ELEMENTARY FORCES

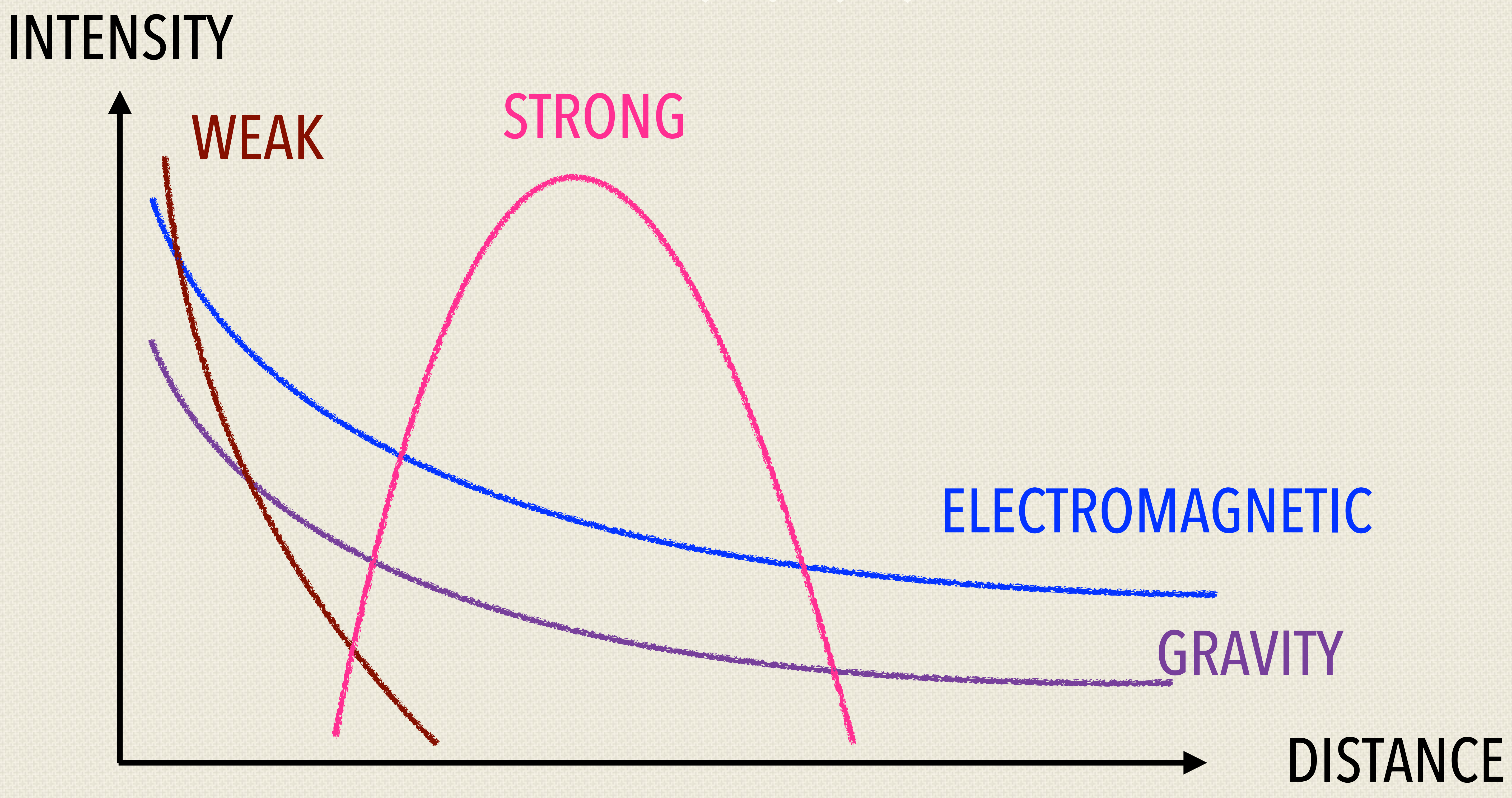
INTERACTIONS	RANGE
GRAVITATIONAL	INFINITE
STRONG	$10^{-15}m$
WEAK	$10^{-18}m$
ELECTROMAGNETIC	INFINITE

4 ELEMENTARY FORCES

INTERACTIONS	RANGE
GRAVITATIONAL	INFINITE
STRONG	PROTON ← $10^{-15}m$
WEAK	QUARKS ← $10^{-18}m$
ELECTROMAGNETIC	INFINITE

E=mc 2

LONG DISTANCE BEHAVIOUR



MEDIATORS: FORCE CARRIERS MUST BE EMITTED FROM ONE PARTICLE AND REACH ANOTHER TO CREATE A FORCE

FERMIONS

QUARKS

COLOR CHARGE

$\boxed{u}$ $\boxed{d}$

$\boxed{c}$ $\boxed{s}$

$\boxed{t}$ $\boxed{b}$

LEPTONS

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BOSONS

GAUGE

SPIN $\neq$ ZERO

$\boxed{\gamma}$

$\boxed{W^+, W^-, Z}$

GLUON

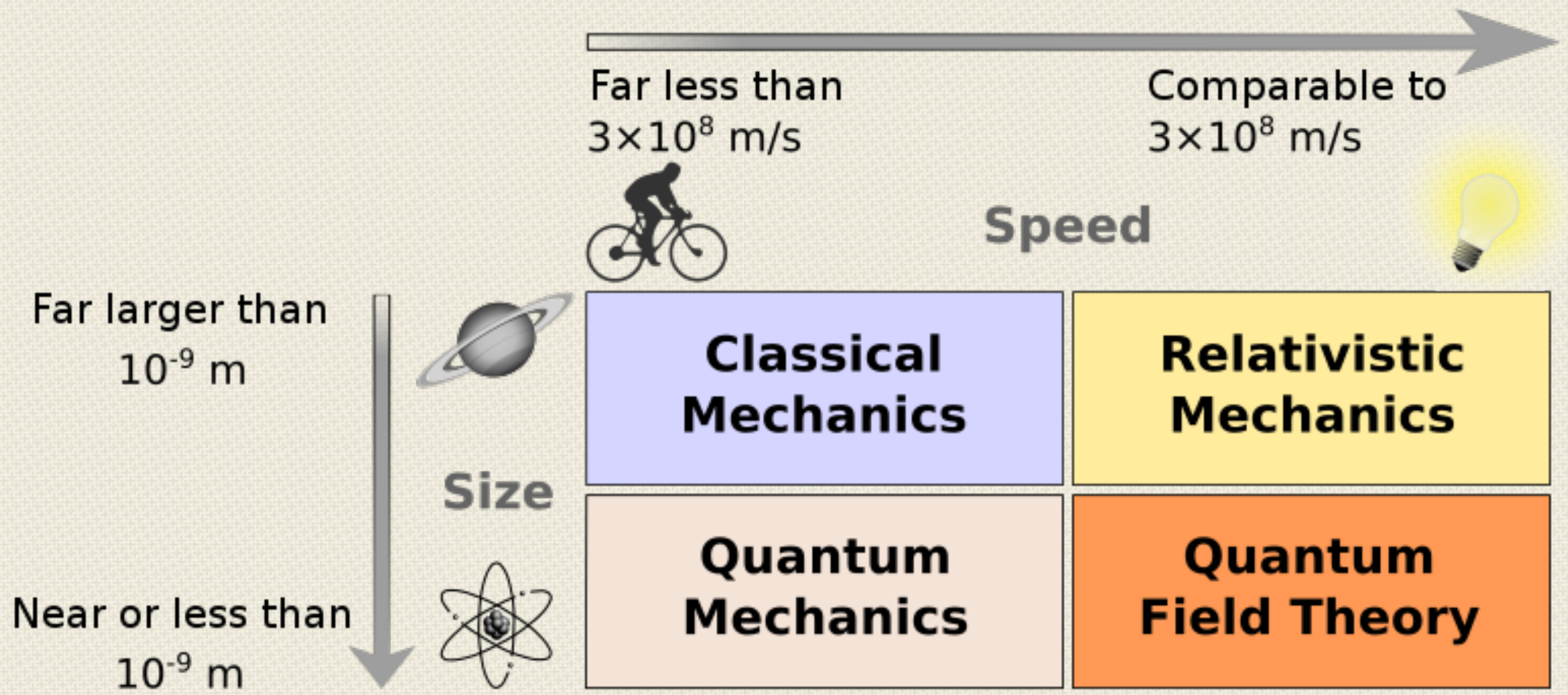
GRAVITON

SCALAR

SPIN ZERO

HIGGS

INTERMEZZO: QUANTUM FIELD THEORY



<u>QUANTUM FIELD THEORY</u> PROVIDES A CONSISTENT FRAMEWORK TO DESCRIBE ALL KNOWN PARTICLES AND INTERACTIONS, EXCEPT GRAVITY!

STANDARD MODEL

- The Standard Model is a successful description of particle physics nowadays.
- It is a **gauge quantum field theory** that explains the dynamics of our universe through matter and forces.
- It includes all different types of particles

WEAK ↘ ELECTROMAGNETIC ↙

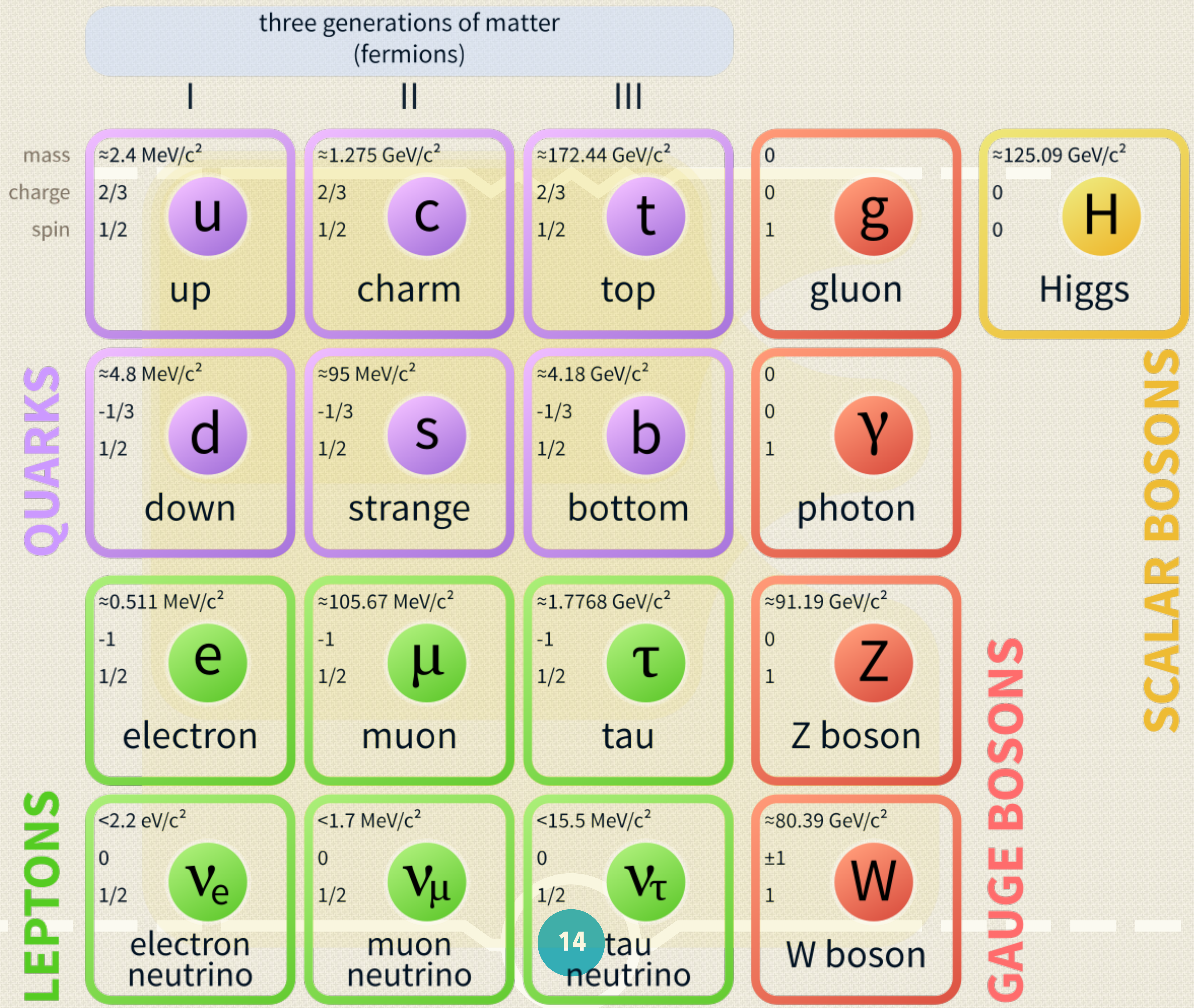
ELECTROWEAK

STRONG ↓

QUANTUM CHROMODYNAMICS (QCD)

STANDARD MODEL

Standard Model of Elementary Particles



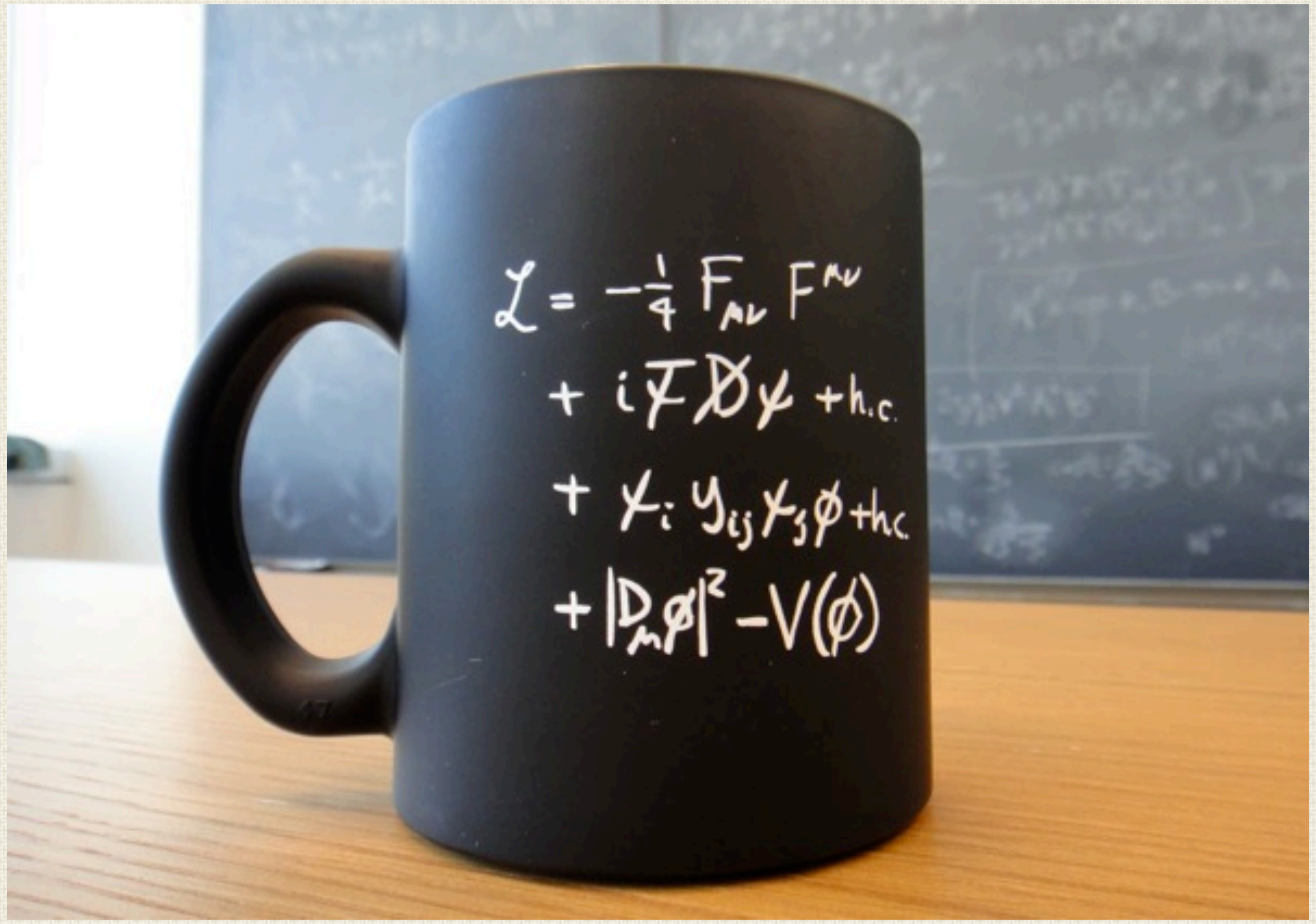
STANDARD MODEL- GAUGE?

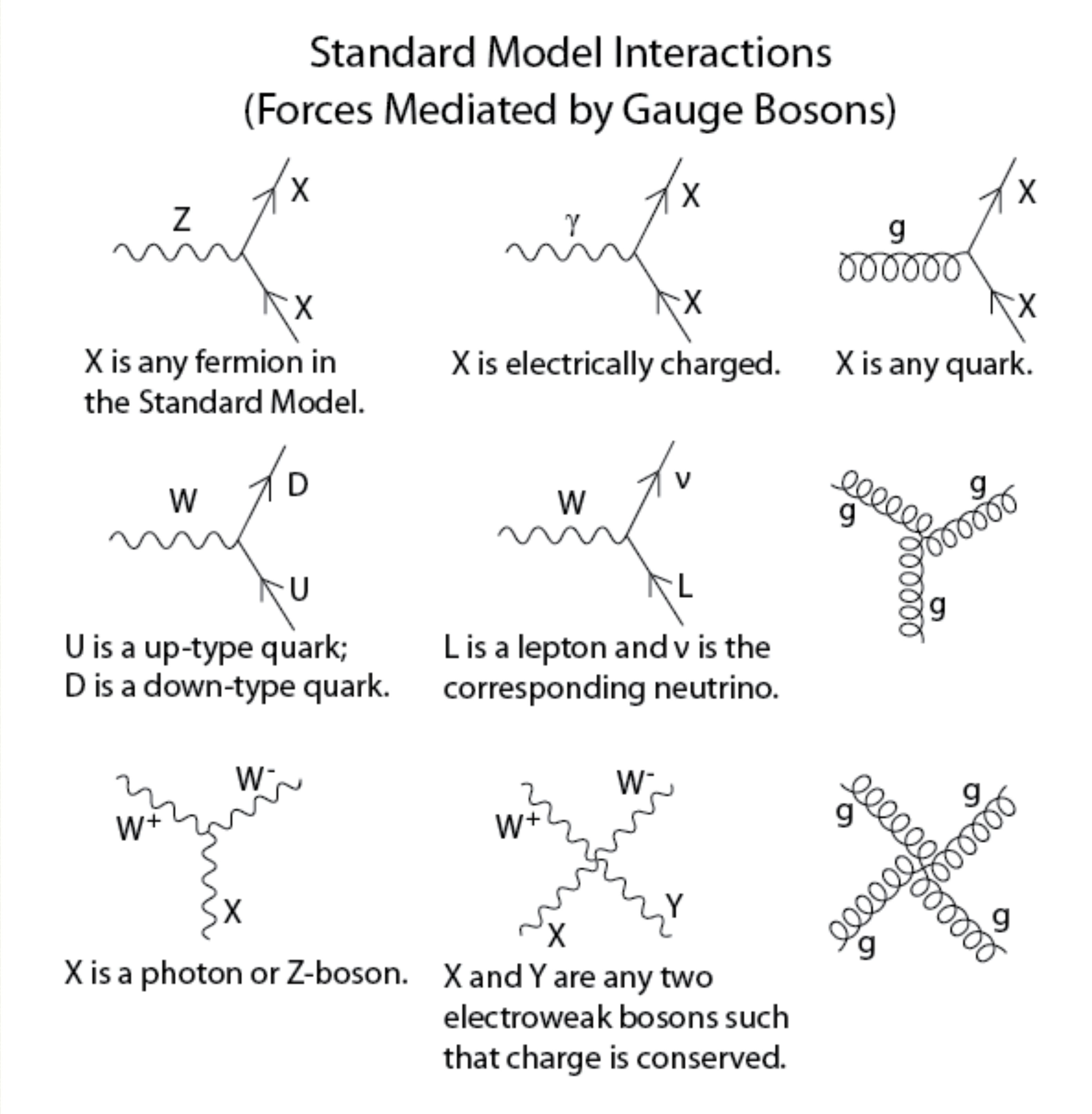
$$SU(3) \times SU(2) \times U(1)$$

QCD ELECTROWEAK

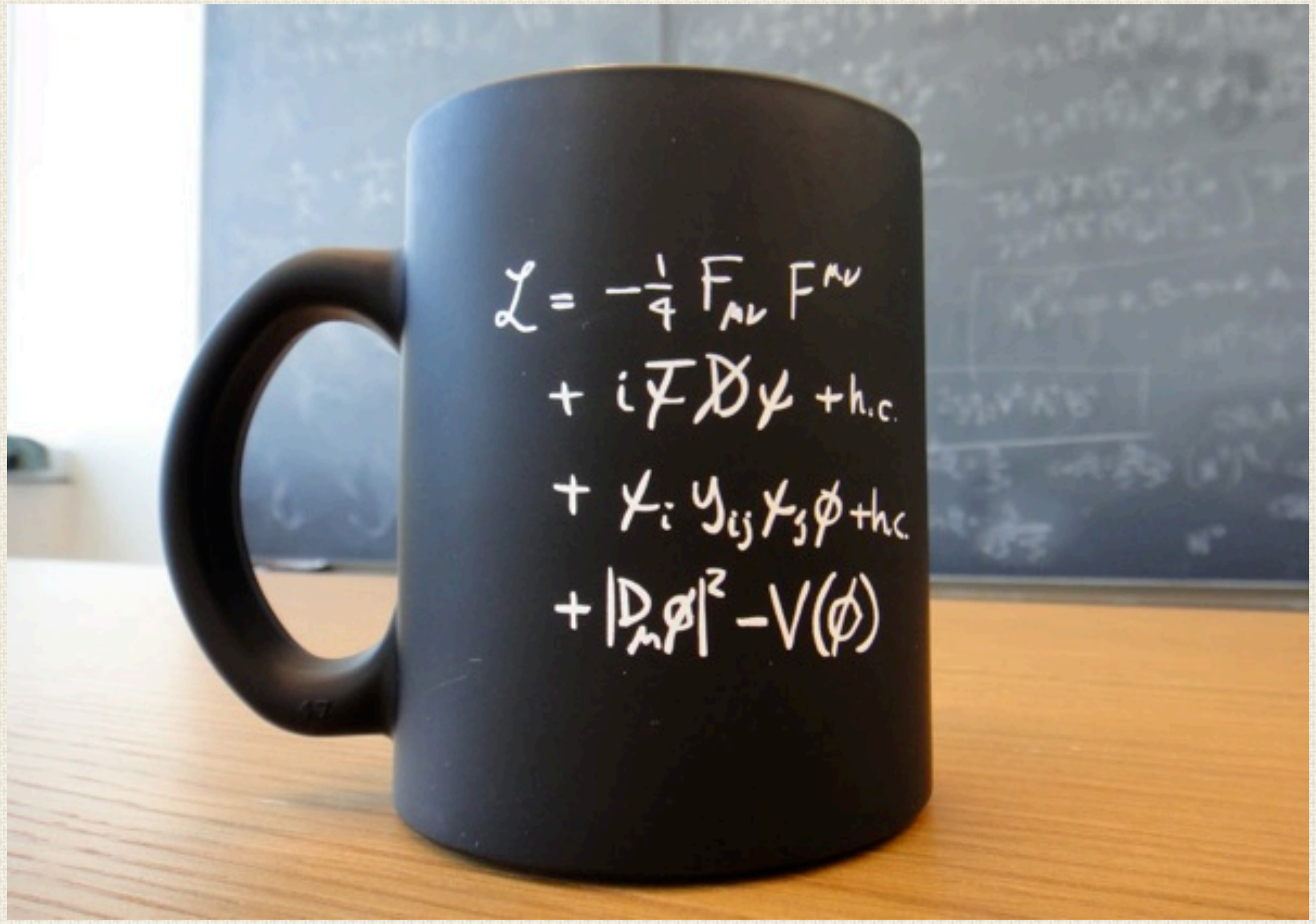
- Very interesting: the symmetry structure fixes the form of the lagragian of the theory!
- This is a common feature in theoretical physics: symmetries (almost) fix the lagrangian.

STANDARD MODEL LAGRANGIAN

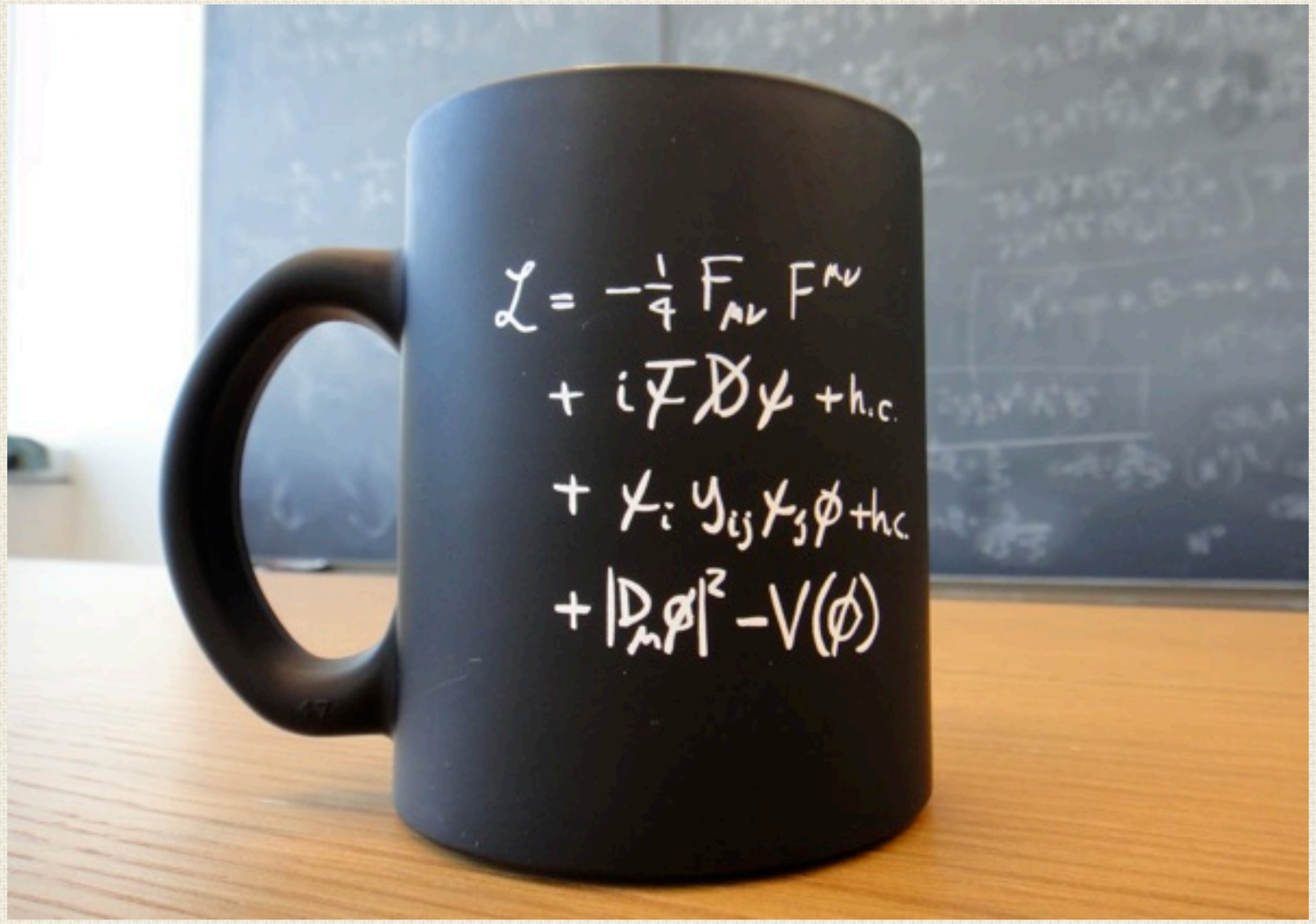




STANDARD MODEL LAGRANGIAN



STANDARD MODEL LAGRANGIAN



RENORMALIZABLE

1971

19 FREE PARAMETERS

• 19 FREE PARAMETERS •

9: PARTICLE MASSES

4: 3 MIXING ANGLES+ 1 PHASE VIOLATION

3: GAUGE COUPLINGS

1: QCD VACUUM ANGLE

2: 1 HIGGS MASS + 1 HIGGS VEV

19 FREE PARAMETERS

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TO BE FIXED WITH EXPERIMENTS!!

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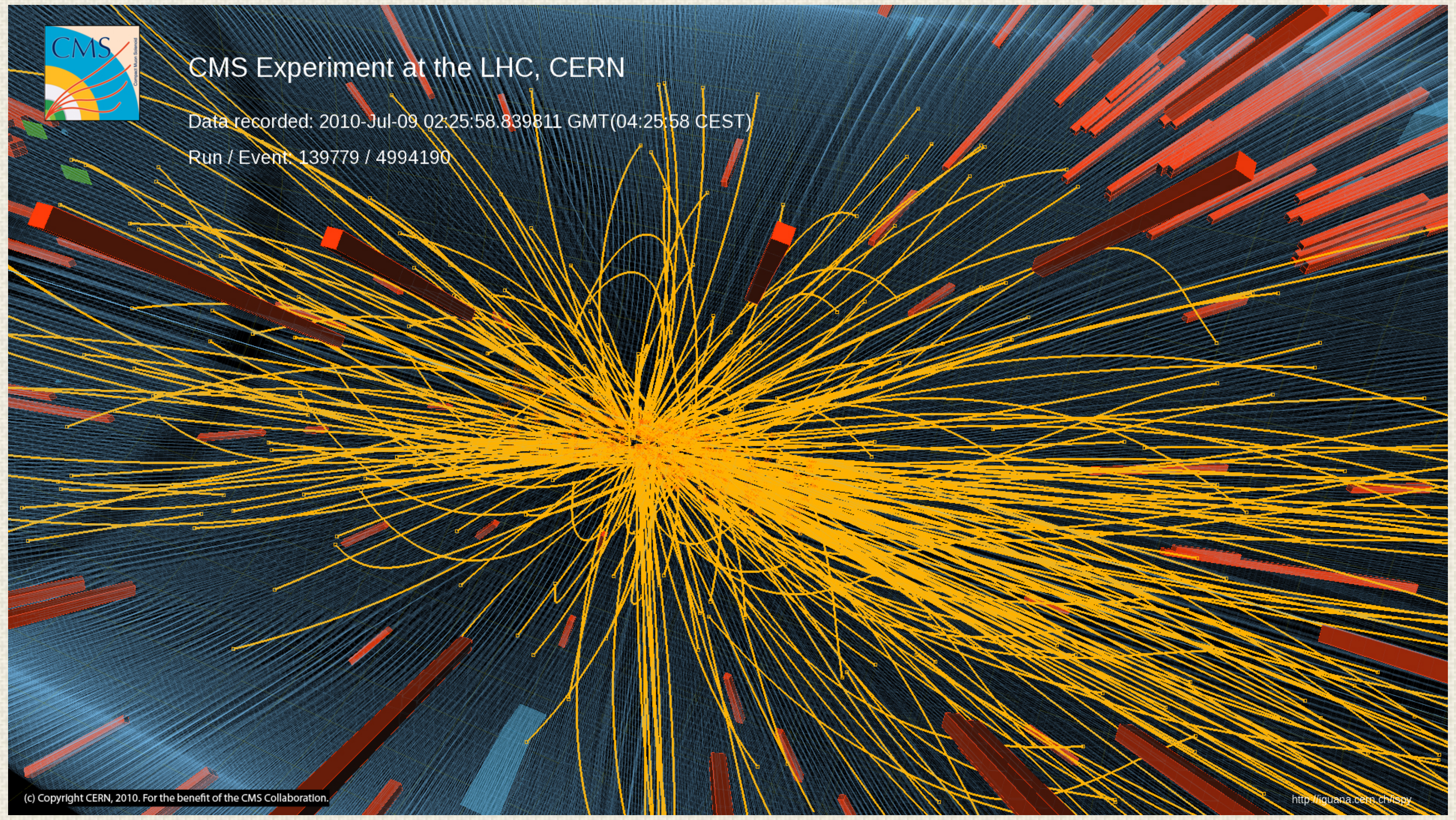

HIGGS DISCOVERY

E=mc 2

HIGGS DISCOVERY

THE STANDARD MODEL IS EXTREMELY ACCURATE AND....WE HAVE PROOF!

UNSOLVED PROBLEMS

- Despite the fact that it is one of the most successful theory we know….

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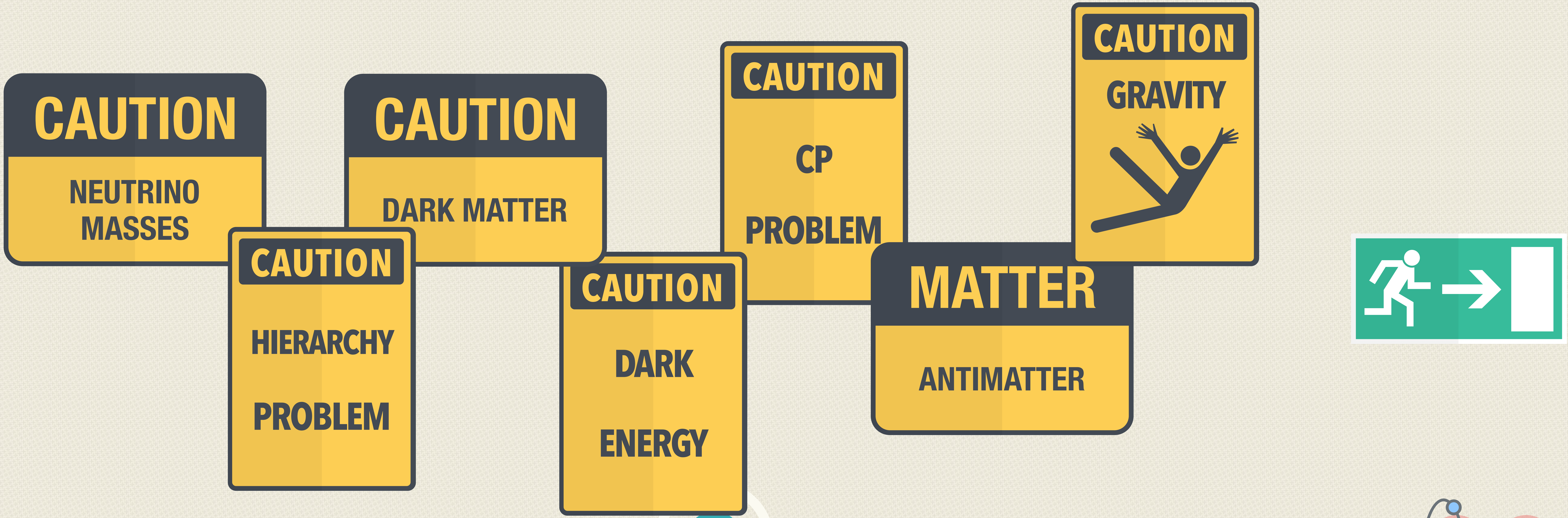
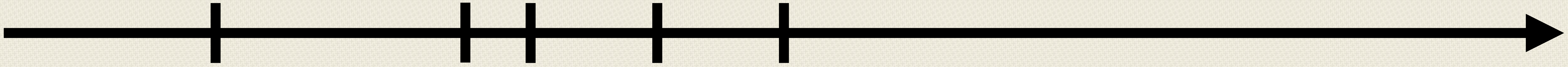


WHY GRAVITY IS IMPORTANT?

- **Gravity is a UNIVERSAL FORCE**: couples to any form of mass and energy
- **Gravity is LONG RANGE:** contrary to weak and strong forces
- **Gravity is UNSCREENED**: no negative charge or mass

BRIEF HISTORY OF GRAVITY



1687

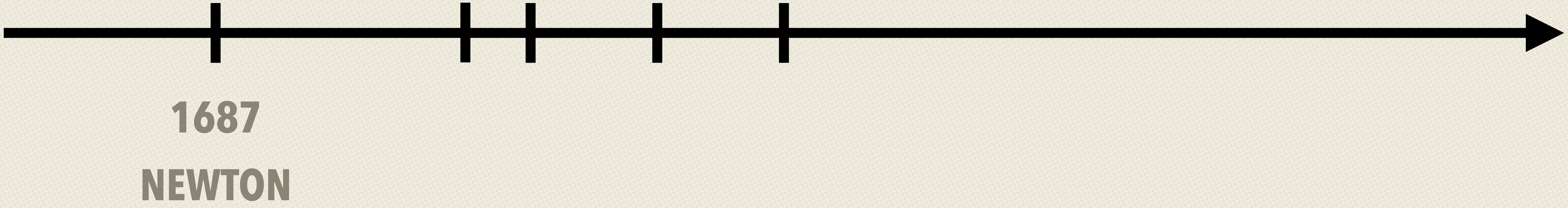
NEWTON

Comprehensive account of gravity.

Toolbook for astronomers, predicting the motion of planets.

Precession of Mercury doesn't work!! The discrepancy is small but big enough for astronomers to know it was there

BRIEF HISTORY OF GRAVITY



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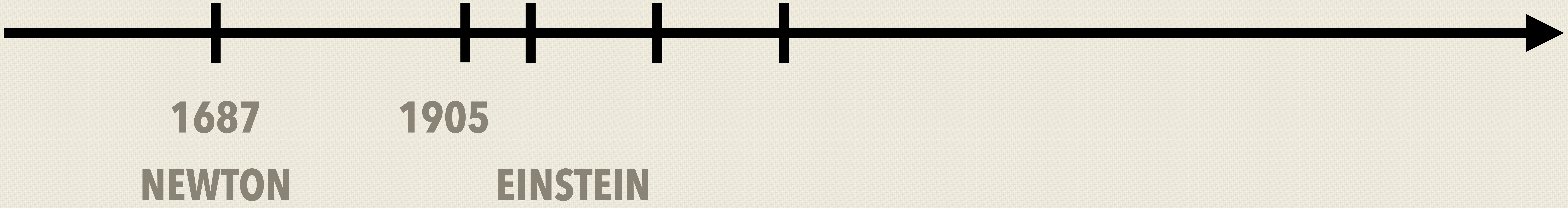


BRIEF HISTORY OF GRAVITY

1687

NEWTON

1905

EINSTEIN

Theory of special relativity:

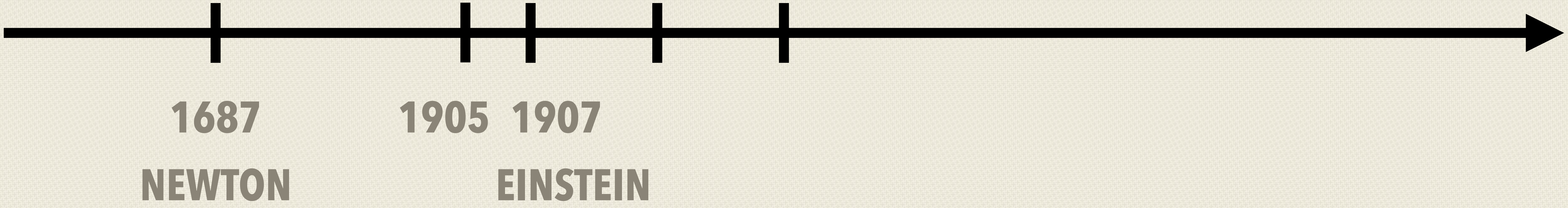
Model of motion at any speed when gravitational effects are negligible

BRIEF HISTORY OF GRAVITY

1687 NEWTON

1905 EINSTEIN

BRIEF HISTORY OF GRAVITY



BRIEF HISTORY OF GRAVITY

1687 1905 1907

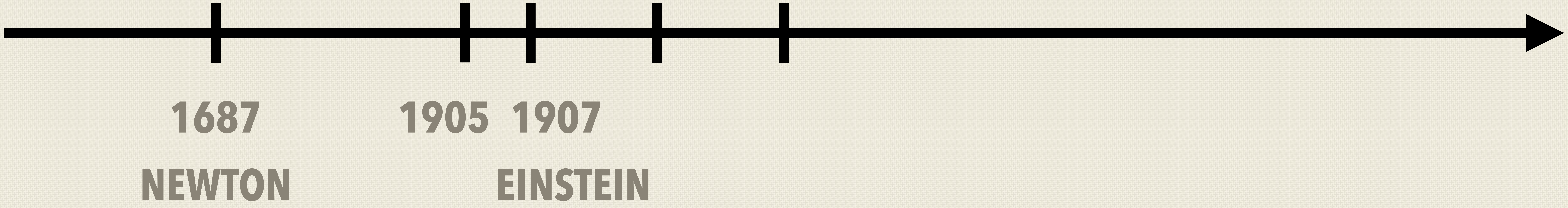
NEWTON EINSTEIN

Gravitational redshift:

electromagnetic radiation from a source in a gravitational field is reduced in frequency when observed in a region at higher gravitation potential

E=mc 2

BRIEF HISTORY OF GRAVITY



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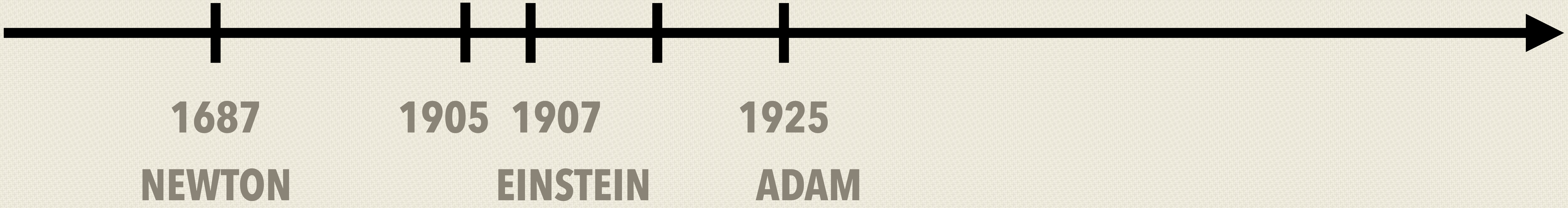


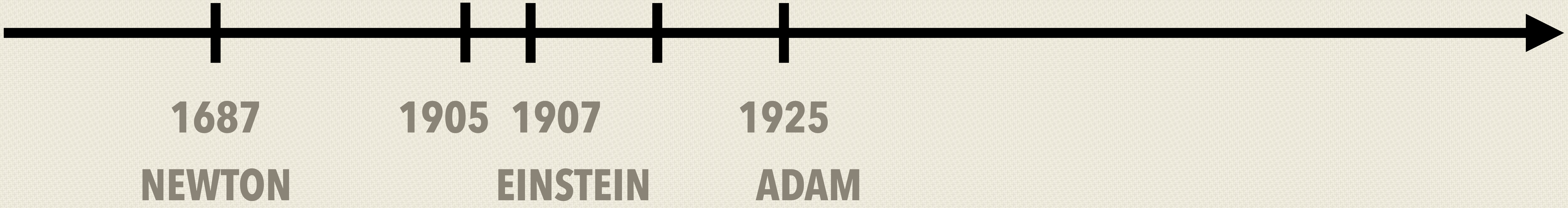
BRIEF HISTORY OF GRAVITY

1687 1905 1907 1925

NEWTON EINSTEIN ADAM

Measurement of gravitational redshift from the surface of a massive star

BRIEF HISTORY OF GRAVITY



BRIEF HISTORY OF GRAVITY

1687 1905 1907 1925

NEWTON ADAM

Theory of general relativity:

"Matter tells space how to curve, space tells matter how to move" (Wheeler)

- Existence of black hole
- Precession of Mercury (*1st test of GR*)
- Gravitational waves
- Gravitational lensing

BRIEF HISTORY OF GRAVITY

1687 NEWTON

1905 1907 EINSTEIN

1925 ADAM

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E=mc ^{2}

BRIEF HISTORY OF GRAVITY

1687	1905	1907	1915	1925
NEWTON		EINSTEIN		ADAM

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E=mc 2

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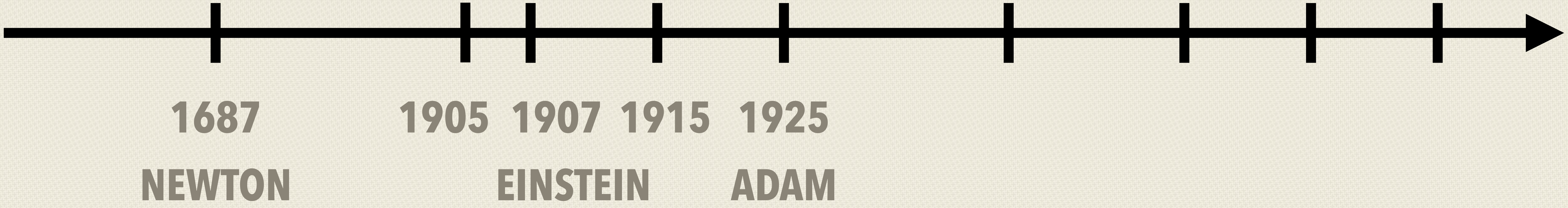

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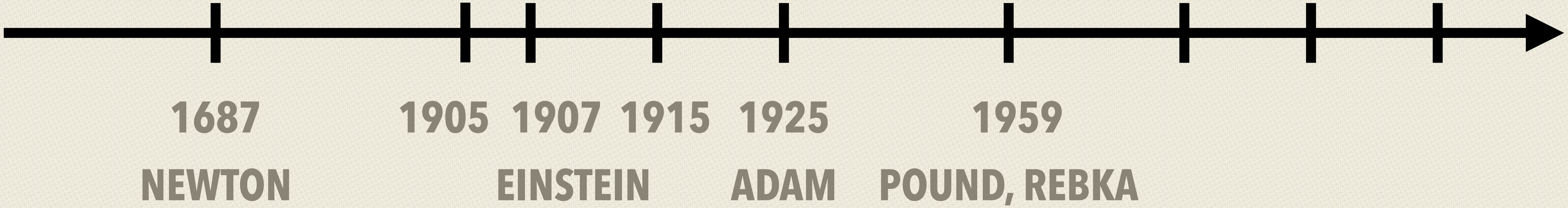


BRIEF HISTORY OF GRAVITY

1687 — **NEWTON**

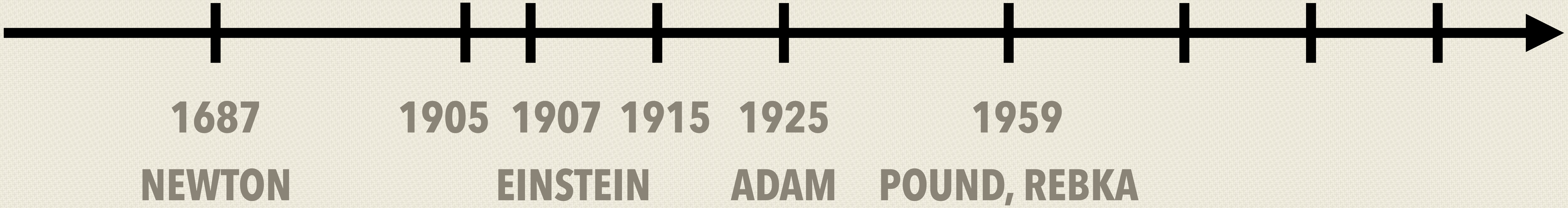
1905 **1907** **1915** — **EINSTEIN**

1925 — **ADAM**

1959 — **POUND, REBKA**

Gravitational lensing verified

BRIEF HISTORY OF GRAVITY



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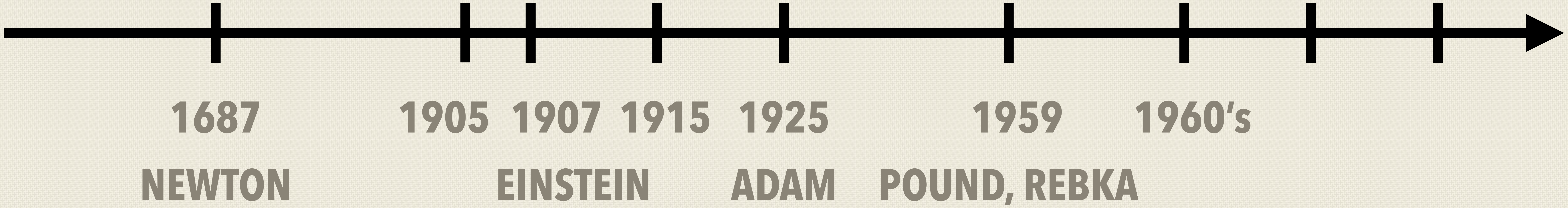

BRIEF HISTORY OF GRAVITY

1687 1905 1907 1915 1925 1959 1960's

NEWTON EINSTEIN ADAM POUND, REBKA

Evidence for the presence of black holes at the center of galaxies

BRIEF HISTORY OF GRAVITY

1687	1905	1907	1915	1925	1959	1960's
NEWTON		EINSTEIN		ADAM	POUND, REBKA	

BRIEF HISTORY OF GRAVITY

1687 1905 1907 1915 1925 1959 1960's 1973

NEWTON EINSTEIN ADAM POUND, REBKA

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1687 1905 1907 1915 1925 1959 1960's 1973

NEWTON

EINSTEIN

ADAM

POUND, REBKA

TAYLOR, HULSE

BRIEF HISTORY OF GRAVITY

1687	1905	1907	1915	1925	1959	1960's	1973
NEWTON		EINSTEIN		ADAM	POUND, REBKA		TAYLOR, HULSE

Indirect evidence for gravitational waves from pulsars

BRIEF HISTORY OF GRAVITY

1687 1905 1907 1915 1925 1959 1960's 1973

NEWTON

EINSTEIN

ADAM

POUND, REBKA

TAYLOR, HULSE

BRIEF HISTORY OF GRAVITY

1687	1905	1907	1915	1925	1959	1960's	1973
NEWTON		EINSTEIN		ADAM	POUND, REBKA		TAYLOR, HULSE

NOBEL PRIZE IN 1993

BRIEF HISTORY OF GRAVITY

1687	1905	1907	1915	1925	1959	1960's	1973
NEWTON	EINSTEIN			ADAM	POUND, REBKA		TAYLOR, HULSE

BRIEF HISTORY OF GRAVITY

1687 1905 1907 1915 1925 1959 1960's 1973 2016

NEWTON

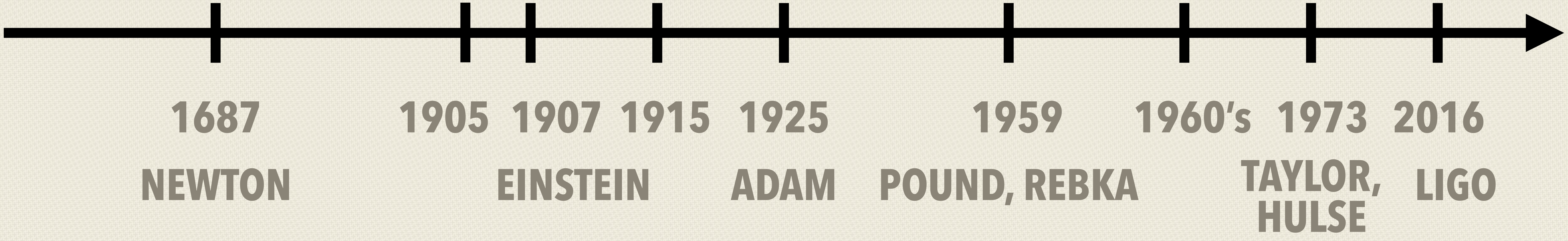
EINSTEIN

ADAM

POUND, REBKA

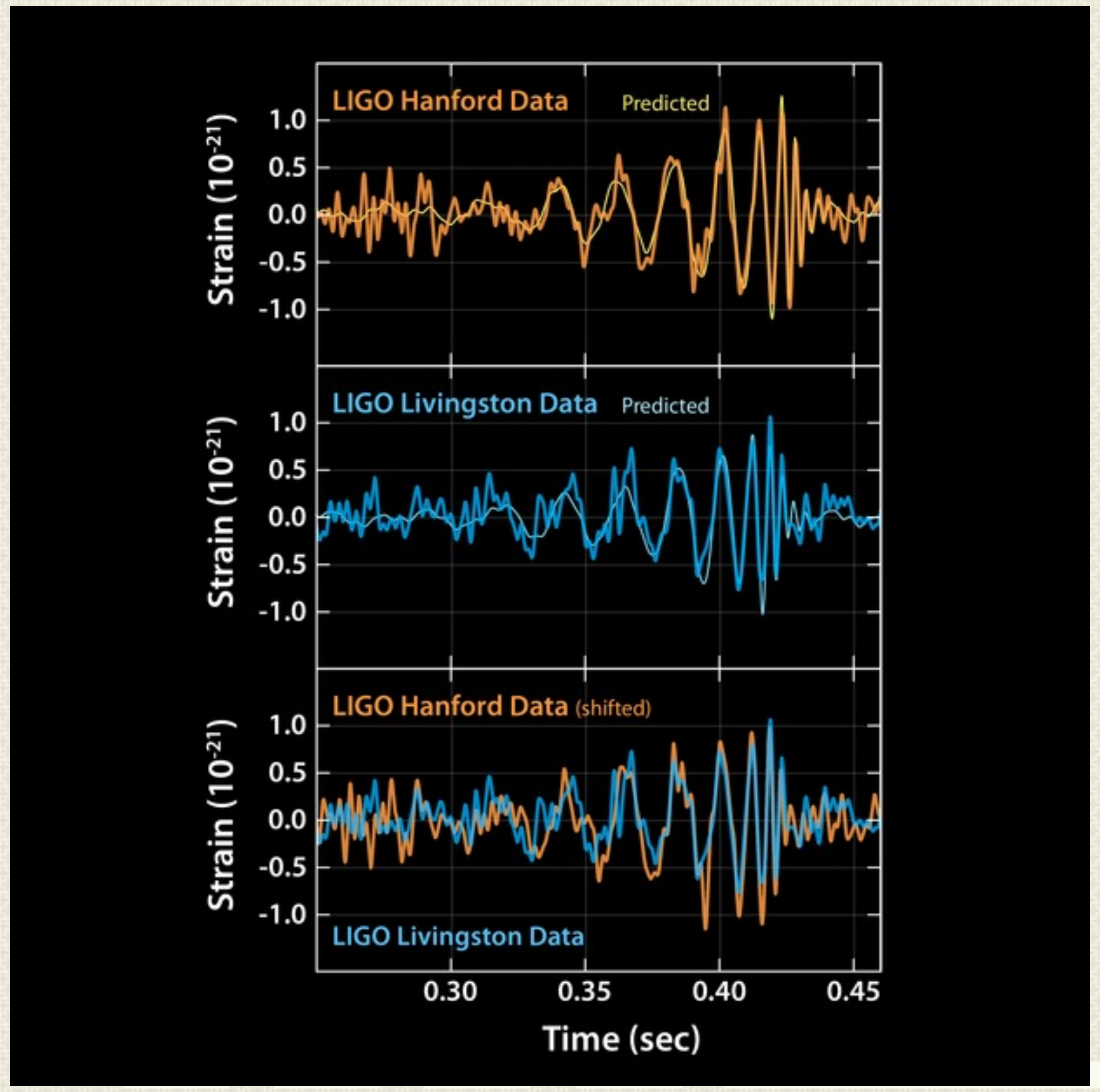
TAYLOR,
HULSE

BRIEF HISTORY OF GRAVITY



BRIEF HISTORY OF GRAVITY

1687	1905	1907	1915	1925	1959	1960's	1973	2016
NEWTON		EINSTEIN		ADAM	POUND, REBKA		TAYLOR, HULSE	LIGO



Direct measurement of gravitational waves

one of the most impressive measurements of recent years

BRIEF HISTORY OF GRAVITY

1687 NEWTON

1905 1907 1915 EINSTEIN

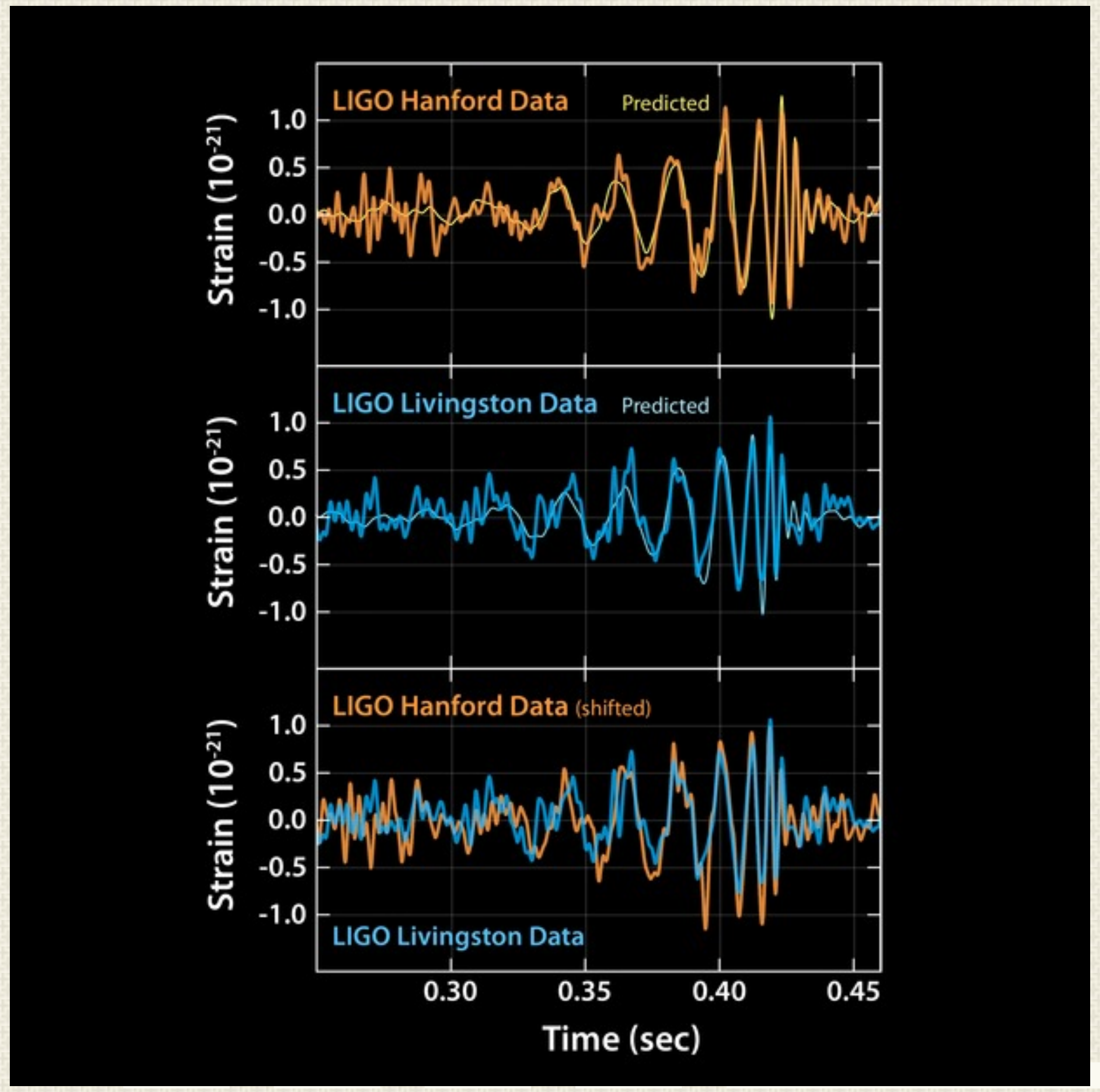
1925 ADAM

1959 POUND, REBKA

1960's

1973 TAYLOR, HULSE

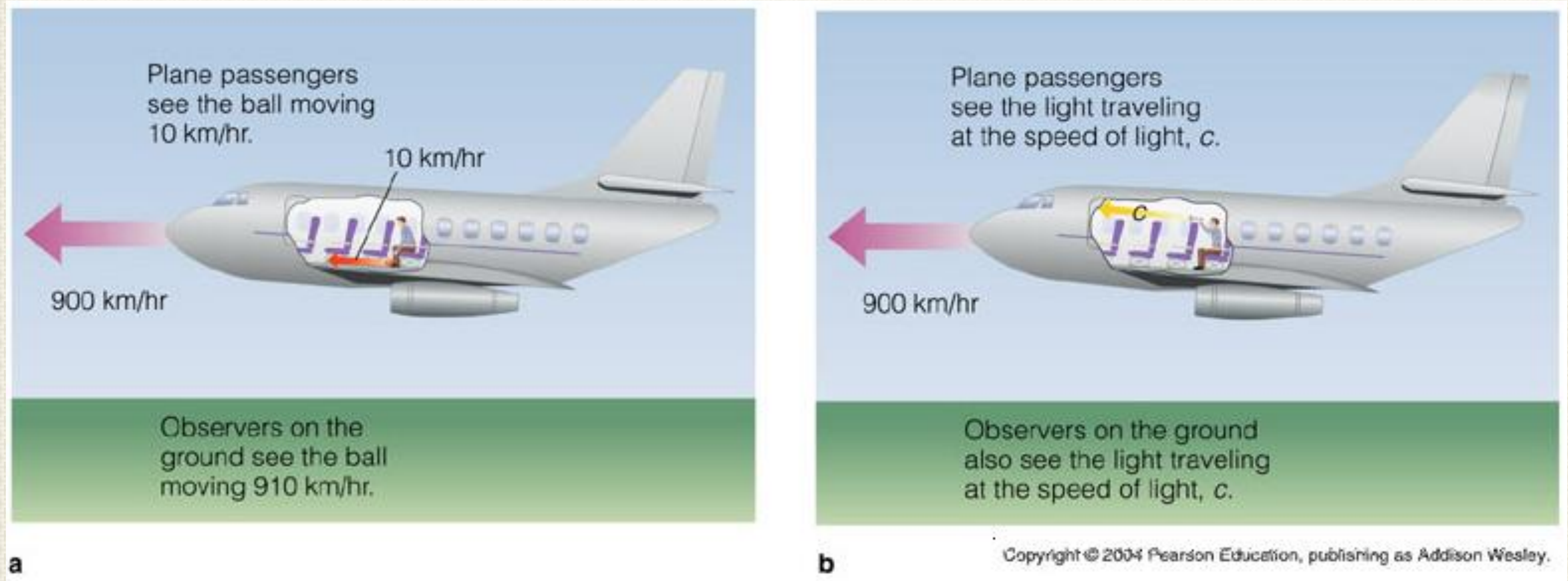
2016 LIGO



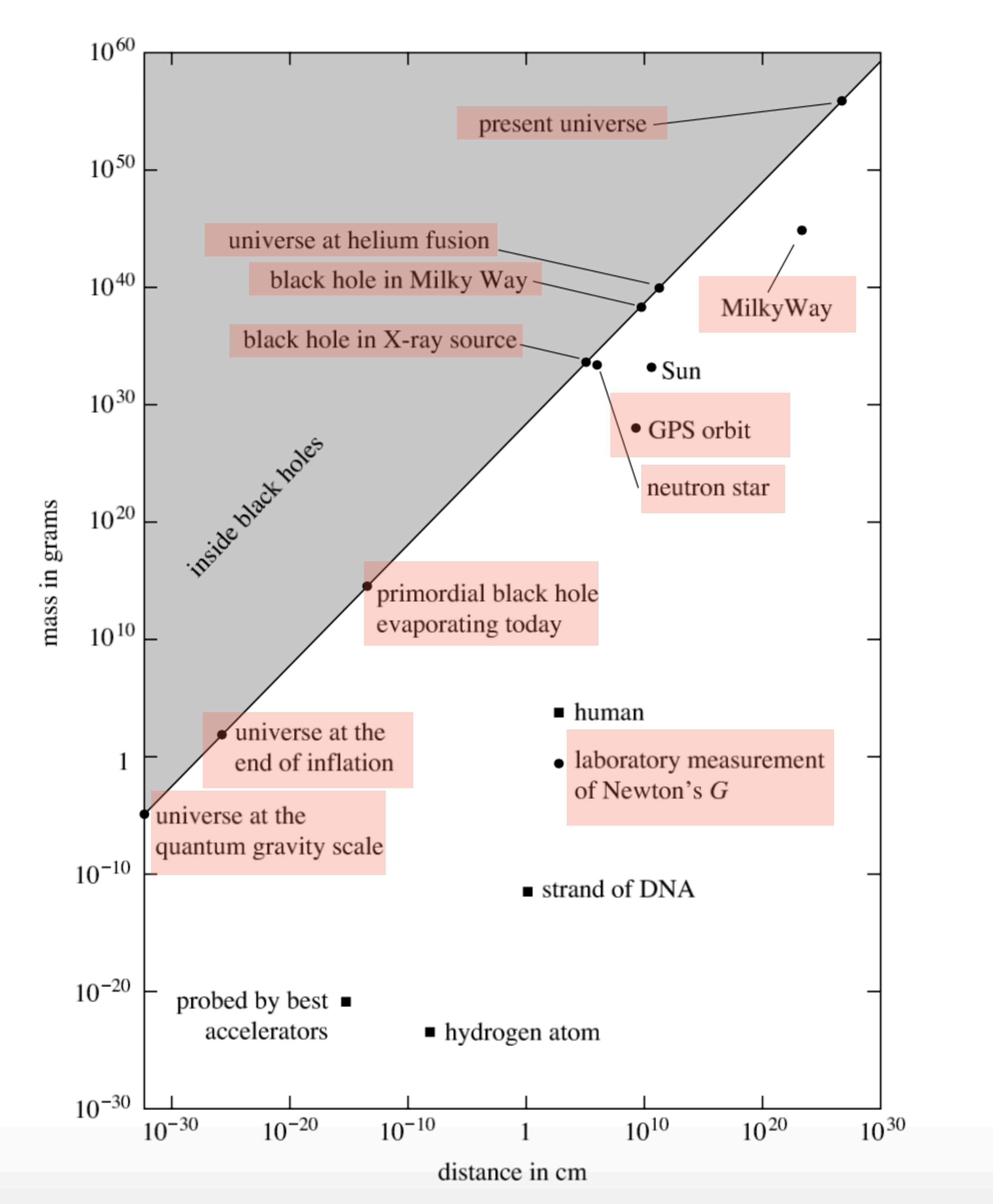
SPECIAL RELATIVITY

PILLARS OF SPECIAL RELATIVITY

- The laws of physics are invariant in all INERTIAL (not accelerating) reference frames
- Gravitational effects are negligible
- The speed of light in vacuum is constant for all observers



WHEN IS GENERAL RELATIVITY IMPORTANT?



NEWTON CONSTANT

MASS OF THE OBJECT

$$q = \frac{G_N M}{Rc^2} \sim 1$$

SPEED OF LIGHT

RADIUS OF THE OBJECT

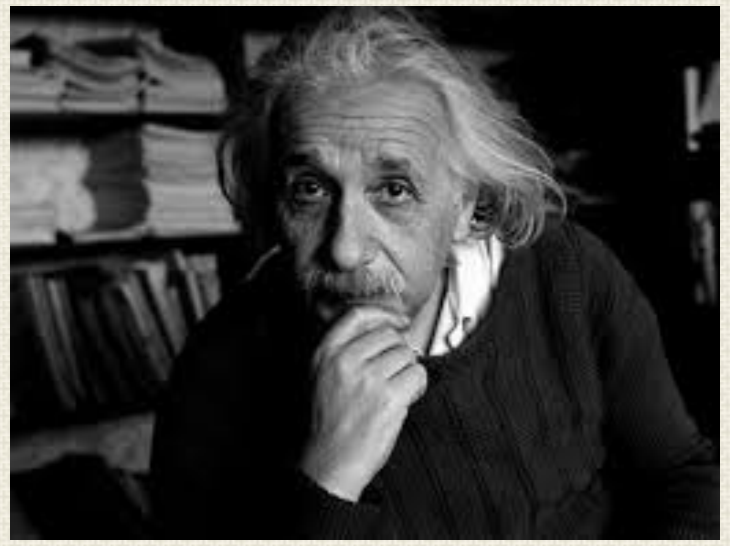
$$\ell_{PL} = \left(\frac{G_N \hbar}{c^3}\right)^{\frac{1}{2}} \sim 10^{-33} cm \ll 10^{-13} cm$$

STRONG FORCE RANGE

GENERAL RELATIVITY

CARL FRIEDRICH GAUSS

- What happens if the system is accelerating?
- What happens when gravity is not a small effect?
- What is the origin of gravity?



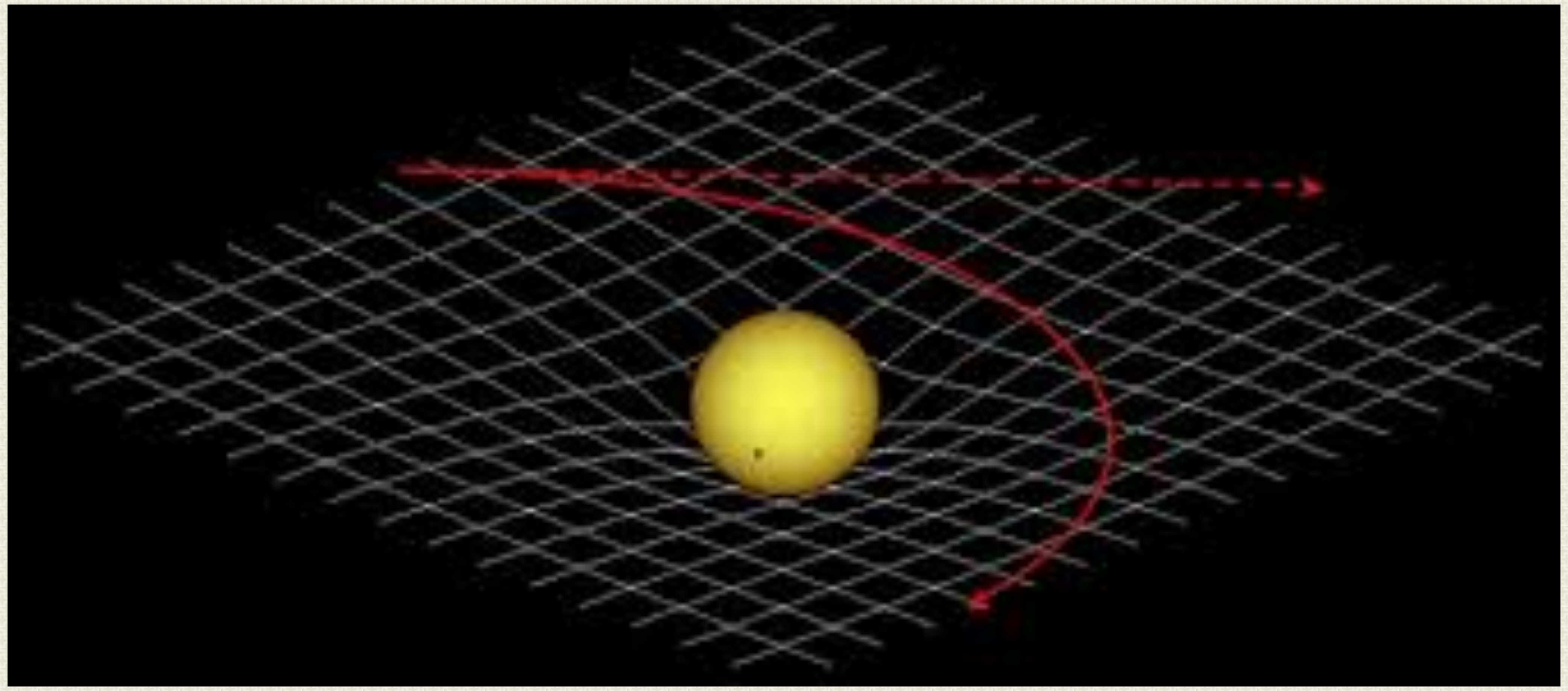
BERNHARD RIEMANN

GENERAL RELATIVITY

- **Gravity is geometry**: phenomena seen as arising from gravitational forces in Newtonian geometry are due to the curvature of the geometry of 4 dimensional spacetime

- **Mass-energy**: is the source of space time curvature

- Free masses move on **straight paths in curved spacetime**



EINSTEIN'S FIELD EQUATIONS

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

METRIC=
GEOMETRY OF THE
SPACE TIME

ENERGY
MOMENTUM
TENSOR

MEASURE OF CURVATURE

MATTER

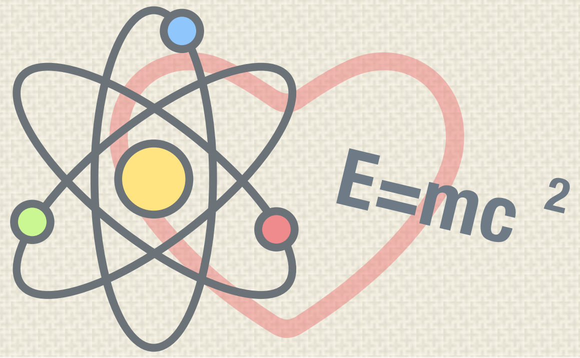
- 10 non linear, coupled, partial differential equations for the metric!

BLACK HOLES AND REVELATIONS

- **Black holes are solutions of Einsteins' equations!** (the simplest solution of Einstein's equation is a -special- black hole)

- We can infer the presence of black holes and study them by detecting their effect on matter nearby

- Main character for the study of quantum gravity: very strong gravitational field



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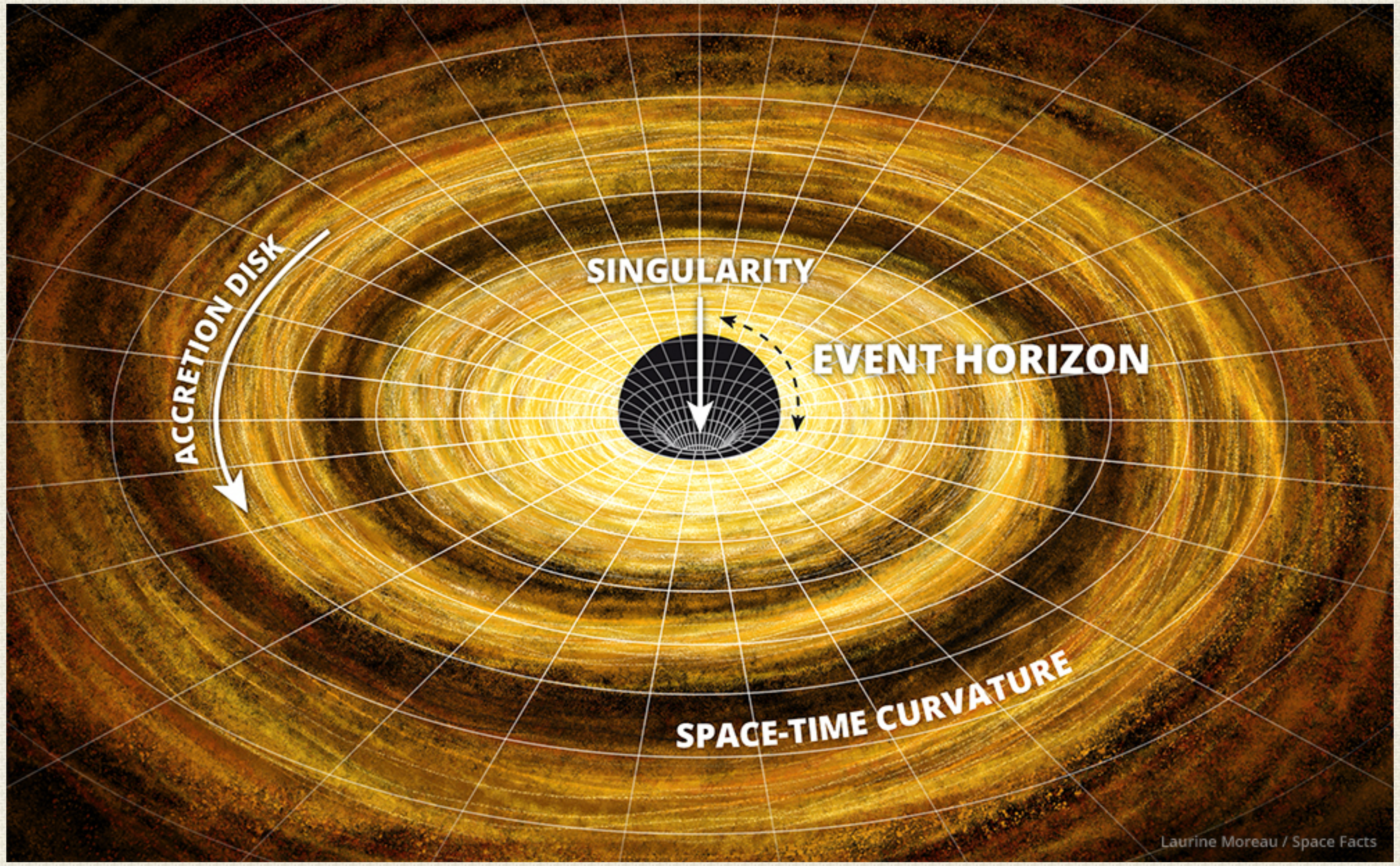
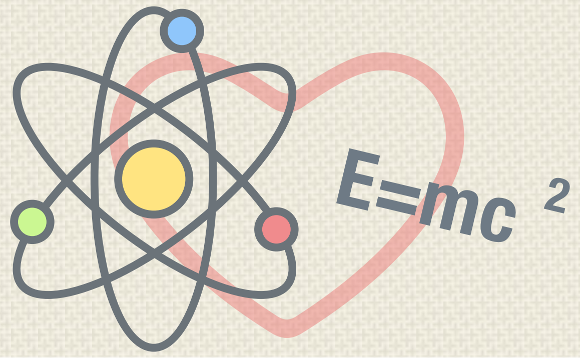
- Main character for the study of quantum gravity: very strong gravitational field





INTERMEZZO: RENORMALIZABILITY

- Consider the total energy of an electron in isolation

$$E_T = m + \int d^3x |\vec{E}|^2 \sim m + 4\pi \int dr\, r^2 \frac{e^2}{r^4}$$

- This integral diverges when r=0
- Put a cutoff and then send the cutoff to 0
- The observable is not m!!!

$$E_T \sim m + \frac{\kappa e^2}{\Lambda}$$

- There is a bare mass (parameter in the lagrangian) and the physical mass (outcome of a measurement)
- There is a cancelation between infinities to get the physical mass! Each infinity to be canceled needs one measurement.

DIVERGENCES

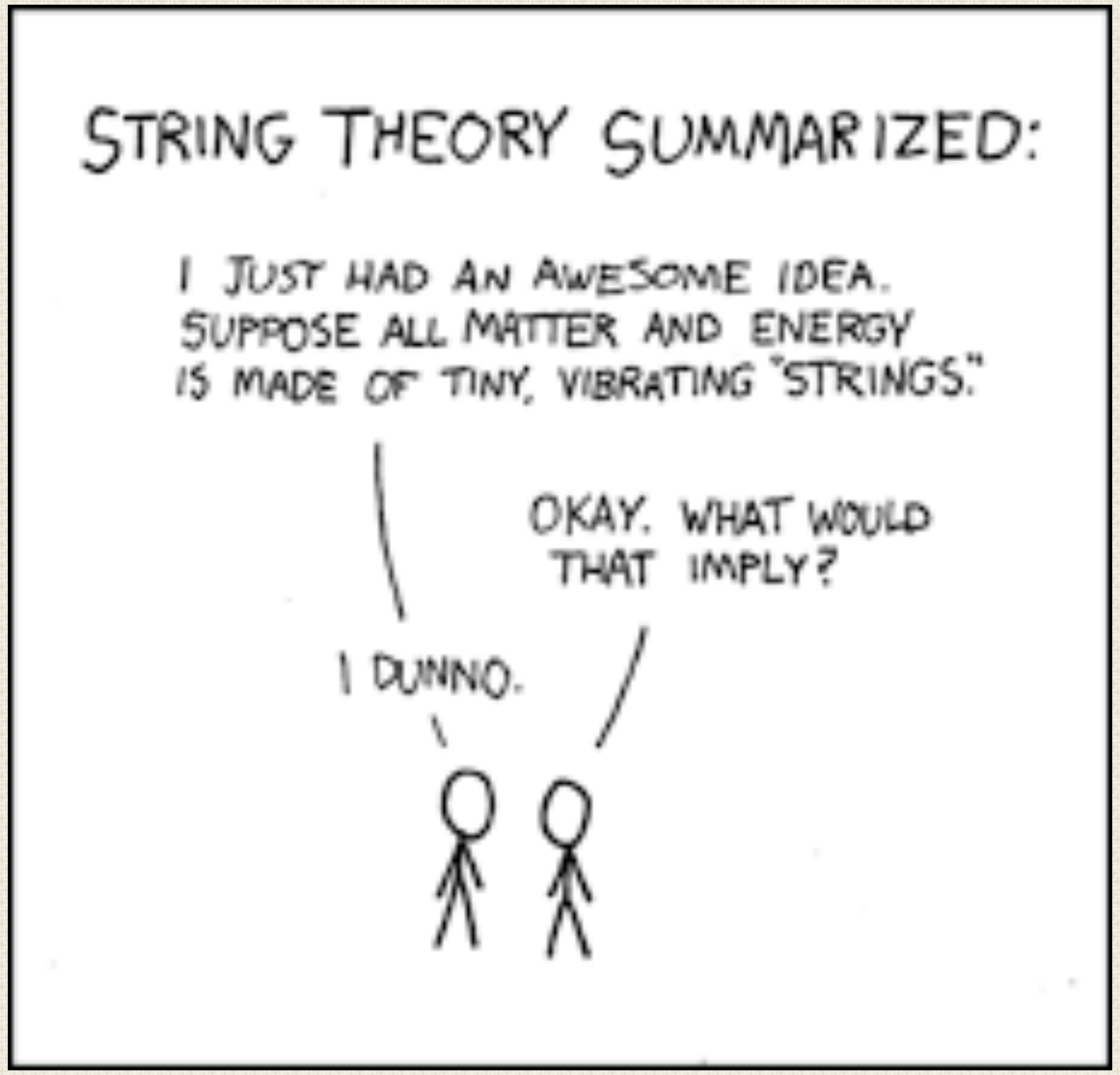
- We can calculate quantum corrections to gravity as long as we are at energies below the Plank mass
- At energy of order of the Plank mass we need more and more parameters to absorb the infinities
- The divergence comes from the fact that point particles can be arbitrarily close to each other

NON RENORMALIZABLE !!!

GENERAL RELATIVITY IS NOT A COMPLETE THEORY

STRING THEORY

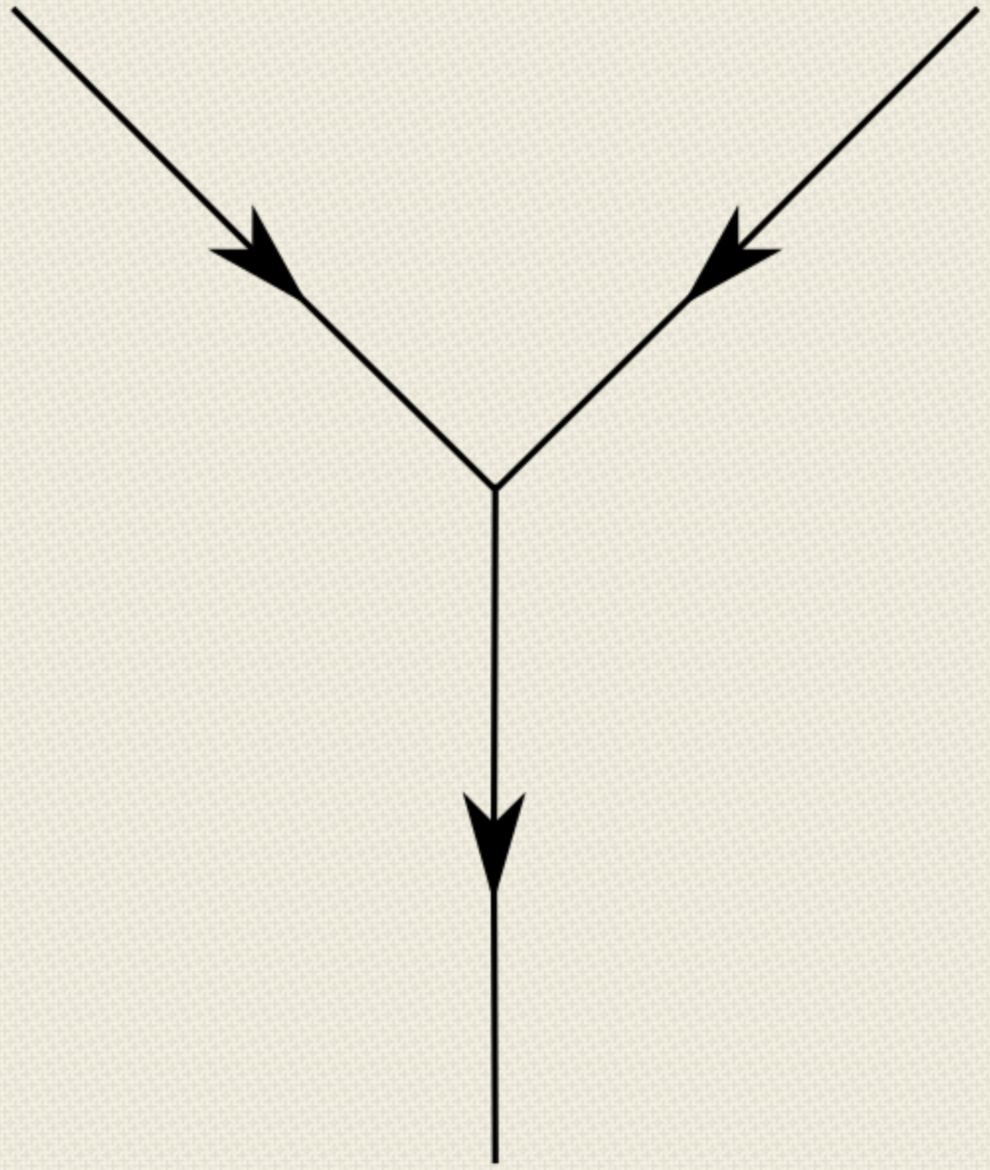
- String theory replaces point particles by strings
- Strings can be **closed** or **open** (depends on the particular type of particle being replaced by the string)
- Only one parameter: Length of the string (Planck length)

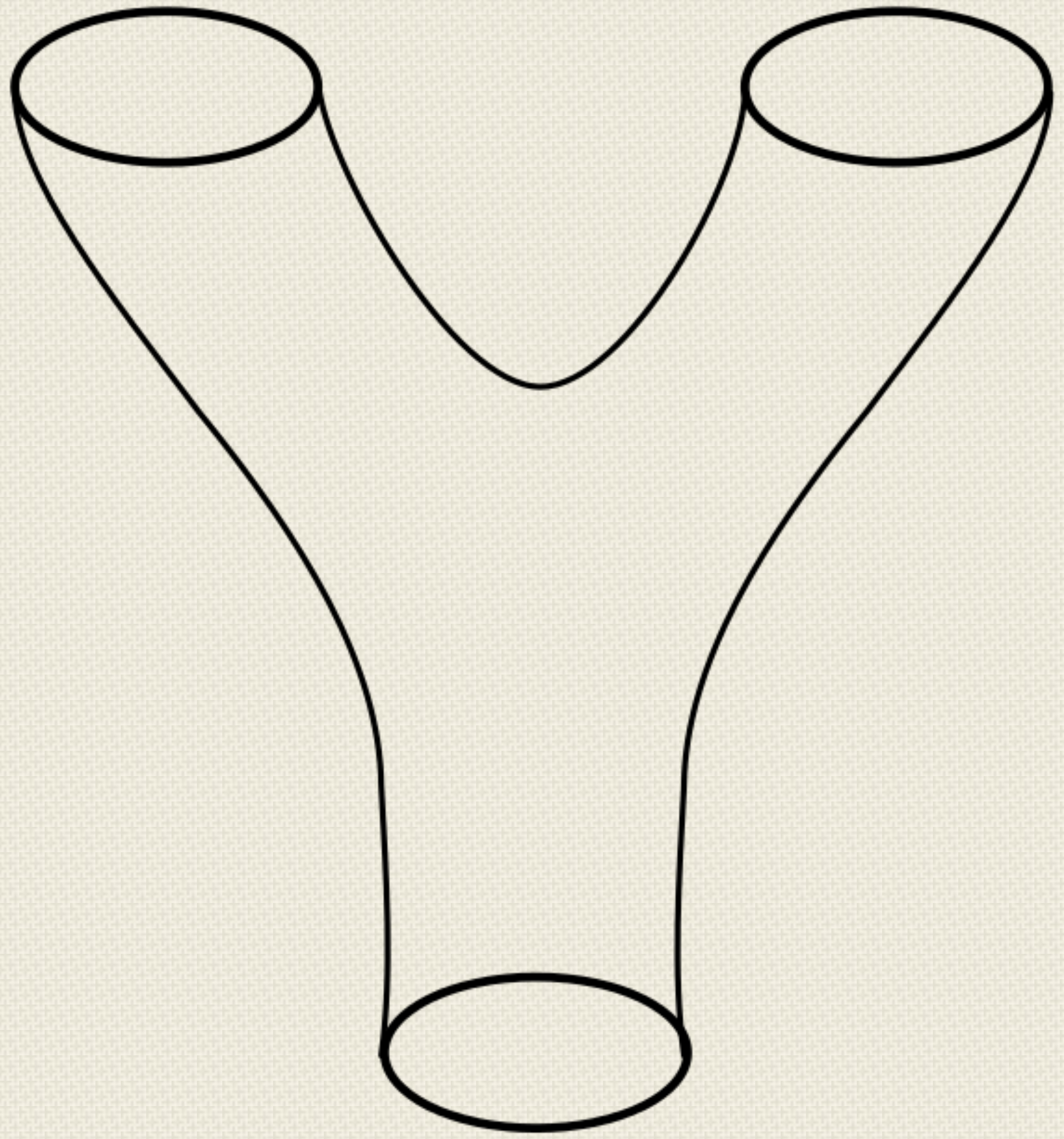


INFINITIES

- Since we are dealing with strings (characteristic length) and not with point particles, the **integrals are naturally regulated!**

- **String theory provides a UV completion theory of gravity!**





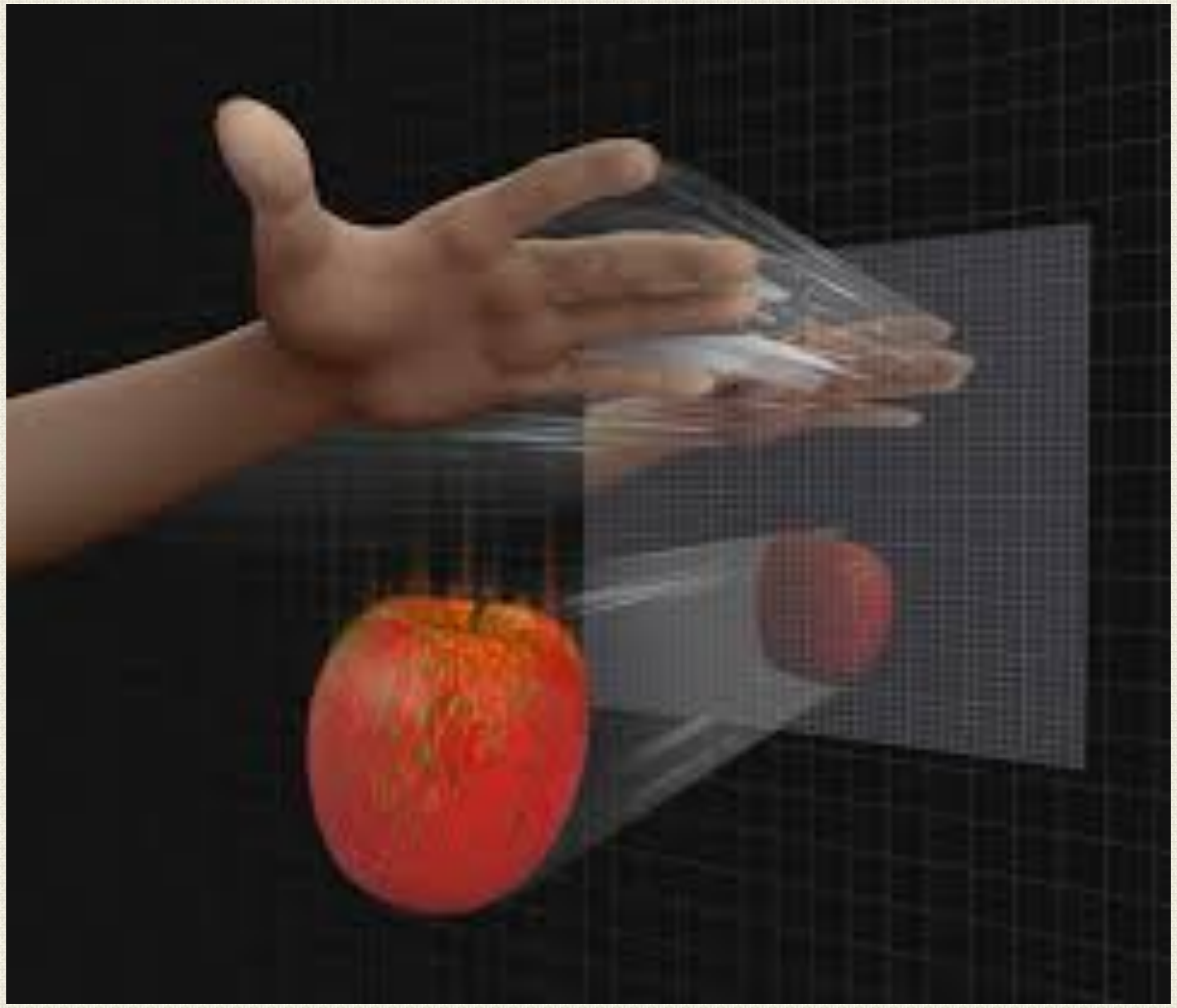
PRO AND CONS

- Provides a unified and complete theory for matter and interactions
- Complete theory of general relativity
- Only consistent theory of quantum gravity
- Predicts the existence of supersymmetry
- Next section….

- Very hard to do computations
- Consistent in 10 dimensions
- Extremely hard to prove/disprove

GAUGE-GRAVITY DUALITY

- HOLOGRAPHIC PRINCIPLE: In a quantum theory of gravity, the physical information in an a region of space is completely encoded in it's boundary



GAUGE-GRAVITY DUALITY

QUANTUM FIELD THEORY (WITHOUT GRAVITY) IN D-1 DIMENSIONS

DUAL TO

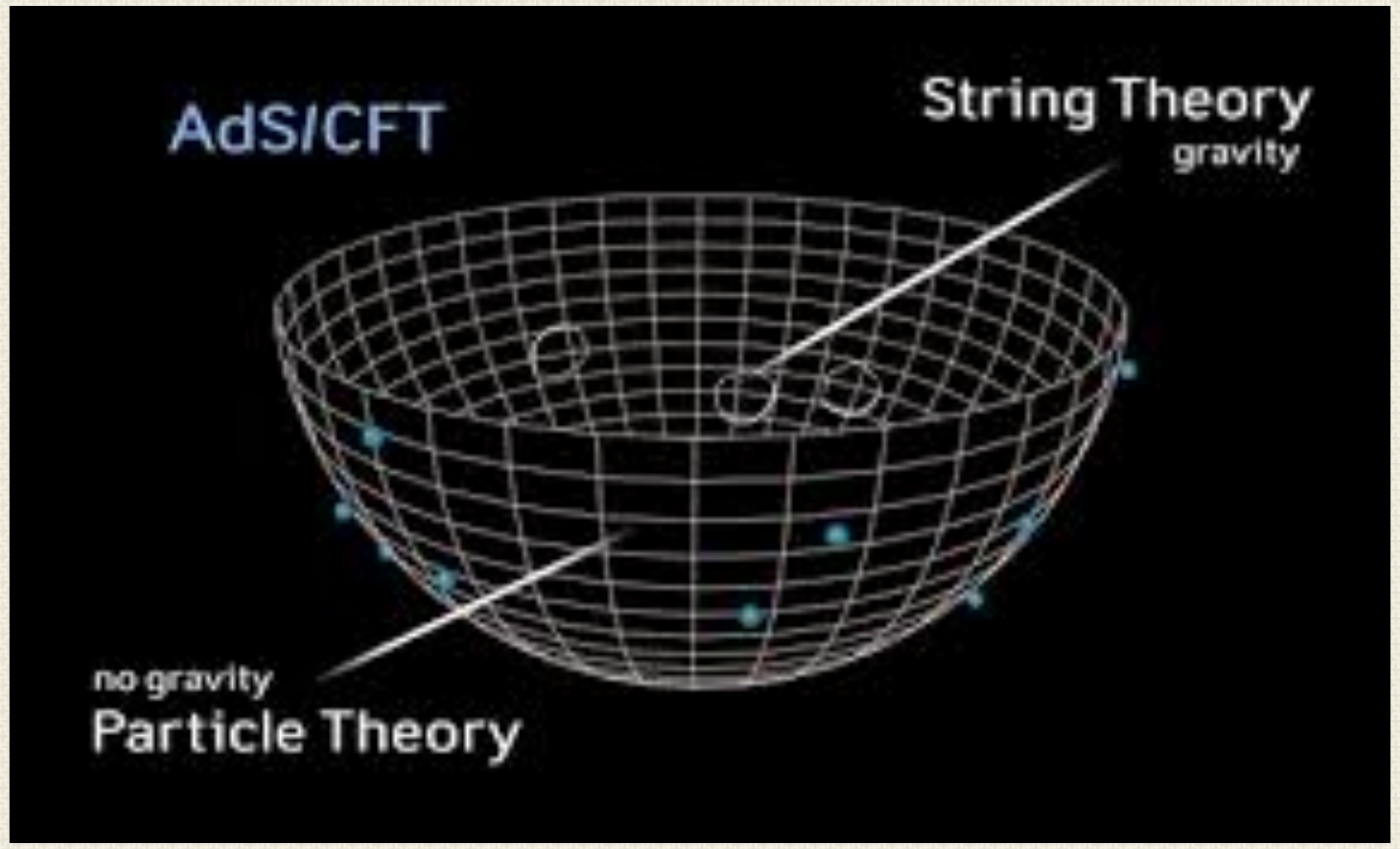
THEORY OF GRAVITY IN D DIMENSIONS

LEARN ABOUT QUANTUM GRAVITY BY STUDYING A QUANTUM FIELD THEORY WITHOUT GRAVITY

IN A REGIME IN WHICH WE KNOW HOW TO CARRY OUT COMPUTATIONS!!

GAUGE-GRAVITY DUALITY

- Passed hundreds of (non trivial) tests
- Powerful tool to both study quantum gravity and quantum field theories
- Applies to several systems, with and without supersymmetry
- Applies to a huge variety of contexts: from quark gluon plasma to strange metals , from quantum entanglement to quantum information
- The biggest development of last twenty years!



E=mc 2

CONCLUSIONS

- I have covered only (or maybe less) 0.001% of developments over the last 40 years
- There is also a beautiful mathematical/ geometrical structure behind which is a field itself
- Several open problems in quantum gravity and mysteries about black holes to be solved
- There is always need of new energy and creative ideas to be able to unravel and eventually understand quantum gravity!