Quantum Gravity

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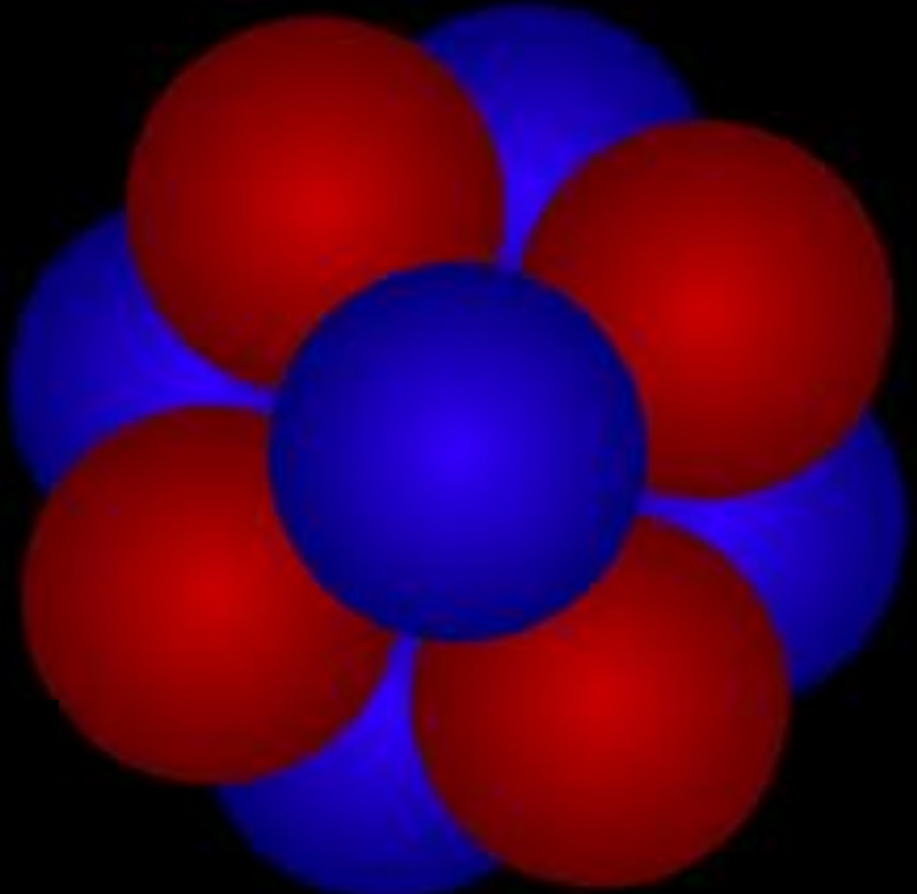
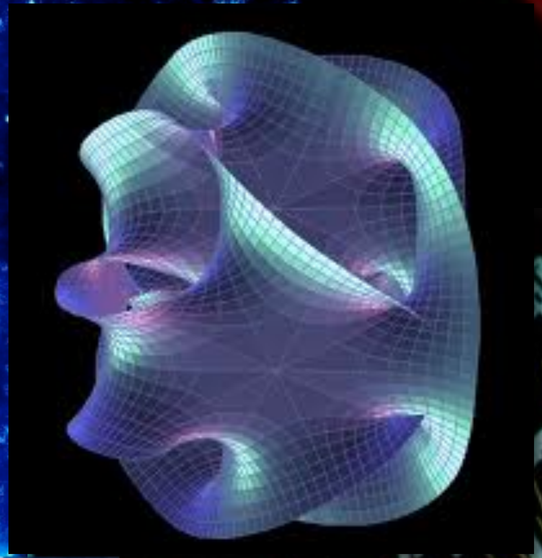
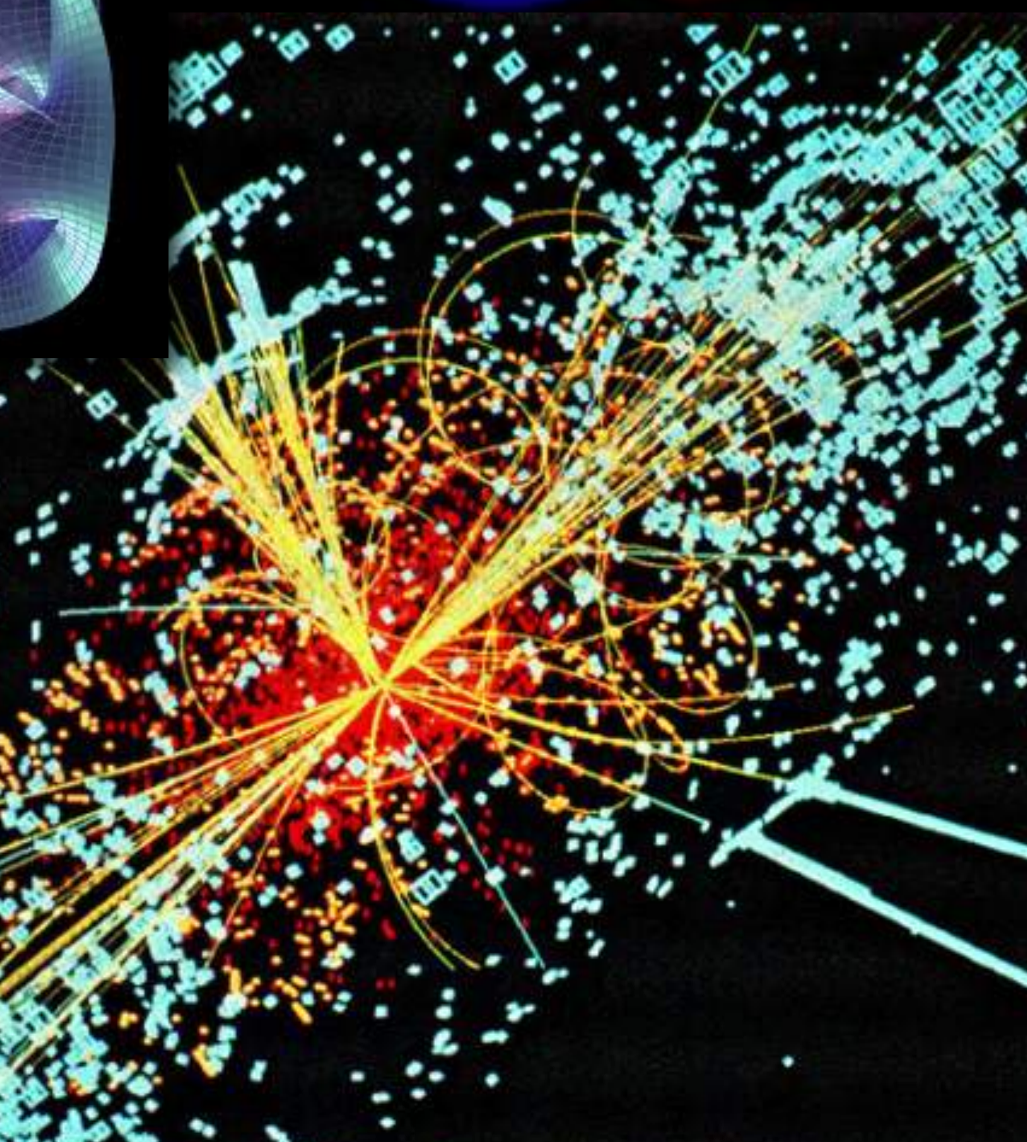






PART I

Classical gravity

What is Gravity?

- We all had *encounters* with gravity in our daily lives

- Gravity is an extremely important factor in shaping our Universe

- Still: a most mysterious force .....

A quick history of gravity

- Aristotle: There is no *motion* without cause! (Force)

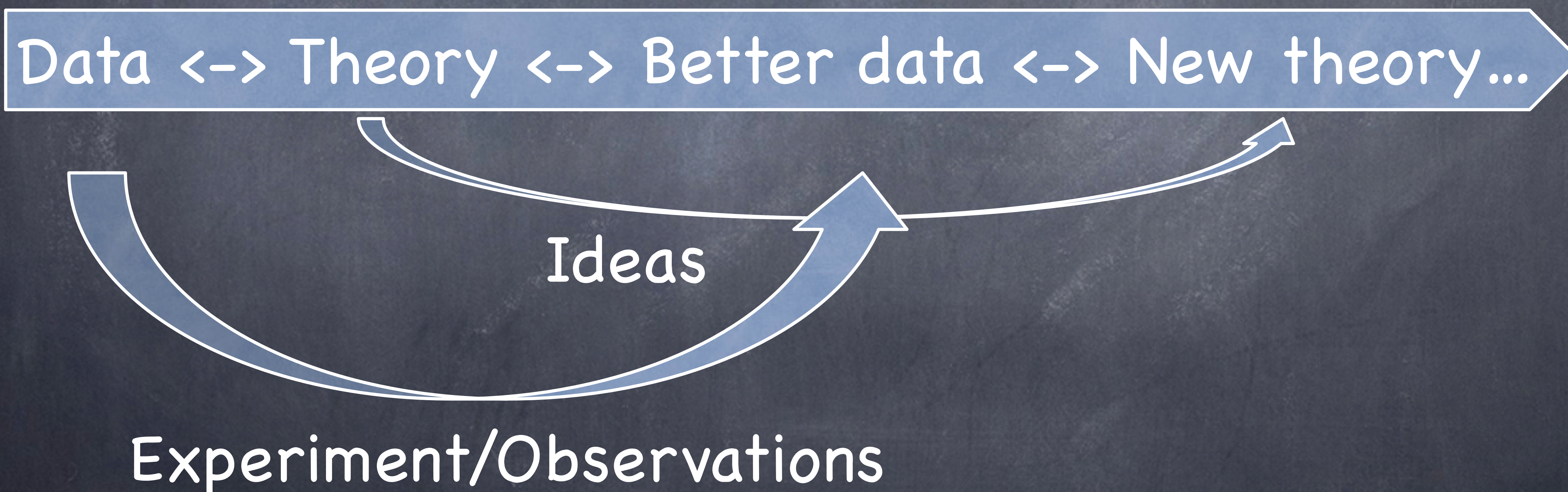
- Vituvius: Gravity not dependent on *weight* rather on *substance!* (Acceleration)

- Brahmagupta: Earth is spherical and attract things! (Uniformity)

Scientific method

Gravity- no exception!

Standard scientific method endless cycle of explaining results of experiments through new theories:



Observations and new theory

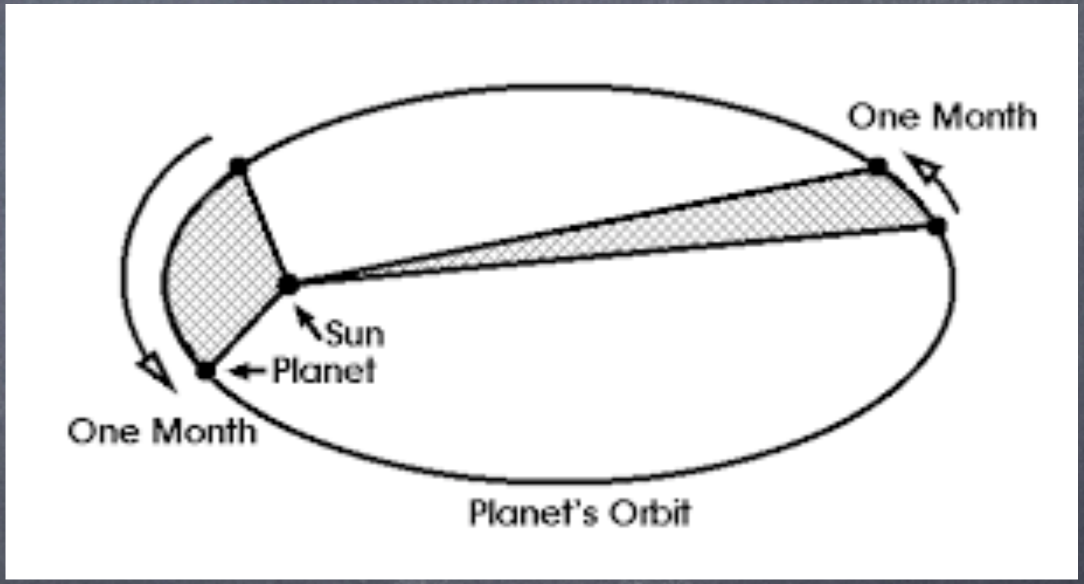
- Tycho Bache: Direct observations of orbital anomalies for planets
  - Question: Helicentric system?
  - Difficult questions and challenge to "accepted" truths...

- Kepler: Through careful analysis of Tycho Brahe's results: laid the ground for Newton's work through his laws for the motion of planets in the solar system.

Kepler's work

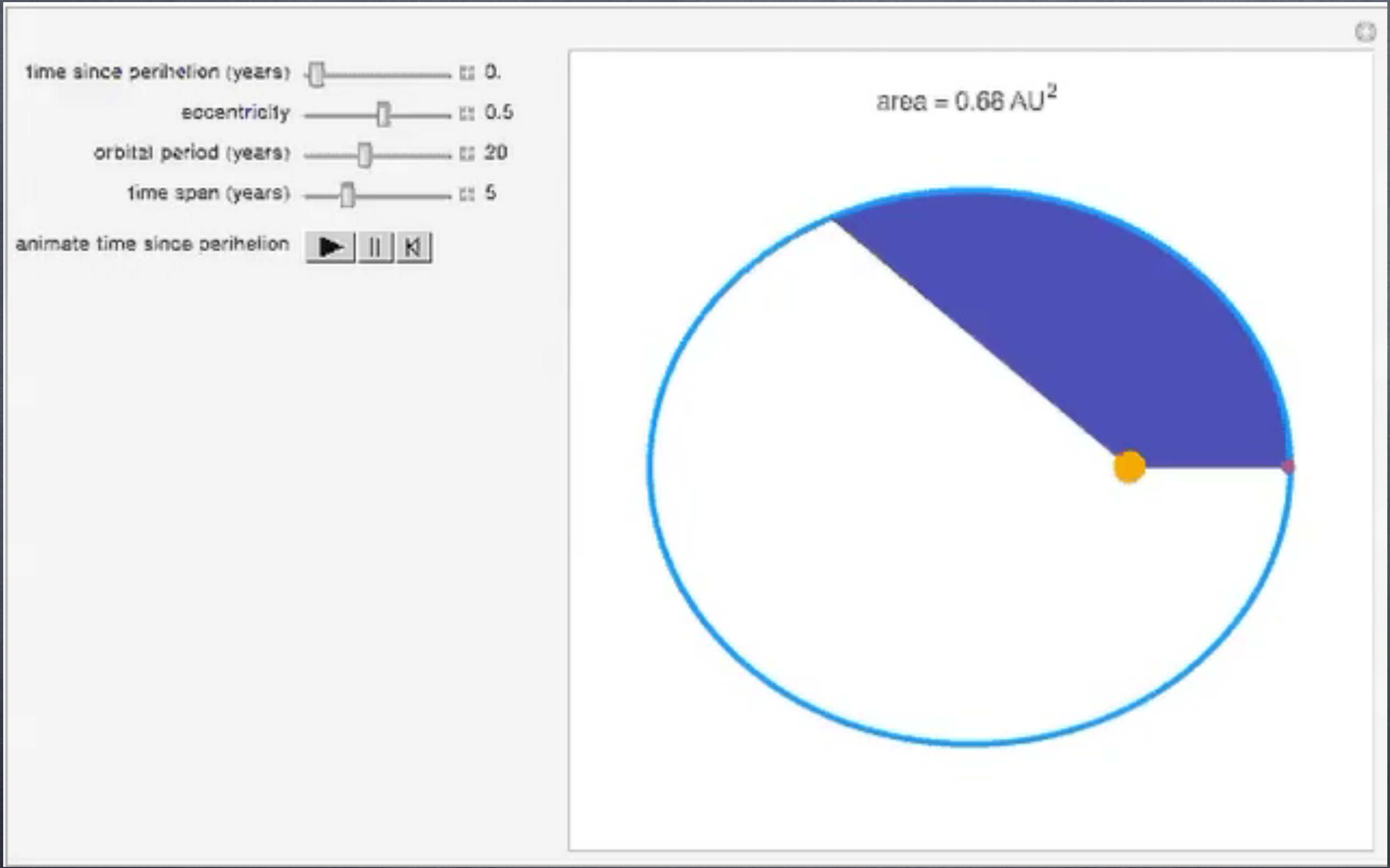
- The orbits of the planets are ellipses

- A line drawn from a planet to the sun sweeps out equal areas in equal intervals of time



- The square of the Planets orbital period (T) is proportional to the cube of its average Distance (D) from the Sun.

$$T^2 \sim D^3$$


time since perihelion (years) 0.
eccentricity 0.5
orbital period (years) 20
time span (years) 5
animate time since perihelion
area = 0.66 AU^2

Newton

Gravity attraction: between matter.

Newton: gravity fundamental force, same force on apple as for the moon.

New way of thinking..

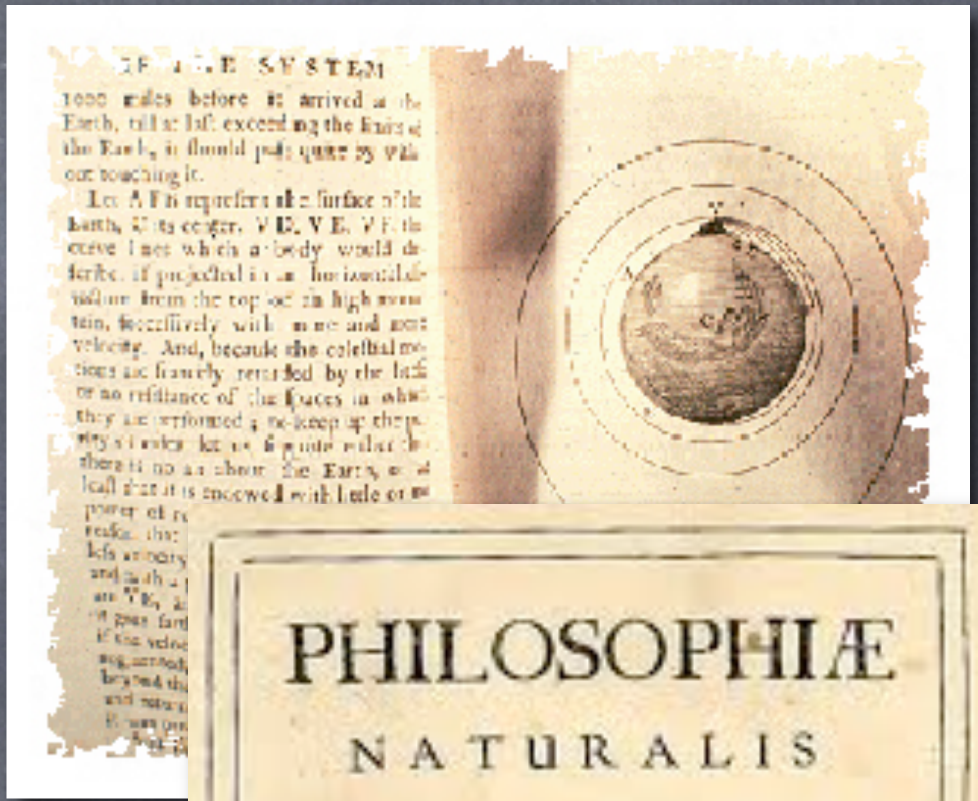
Birth of modern physics: Newton's theory confirmed by numerous observations and experiments.

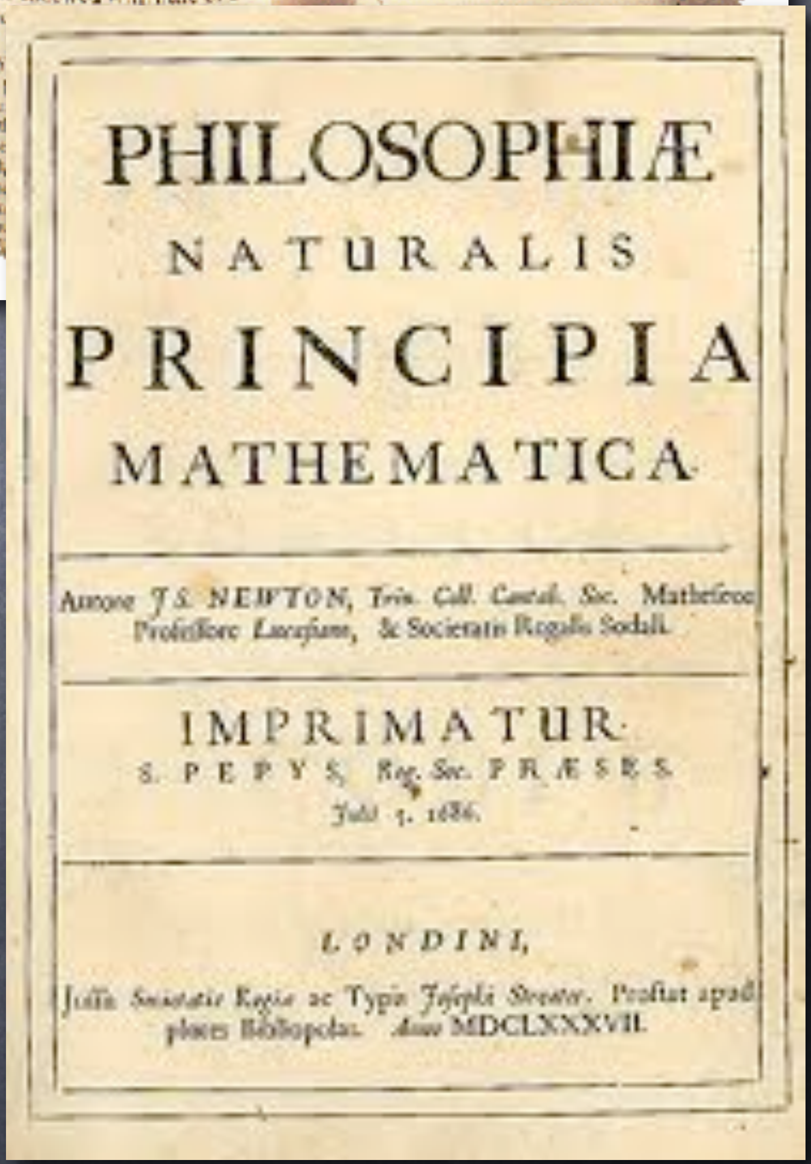
Newton's work

- Gives a direct way to compute the effects of gravity

  Force = mass x acceleration

- Explains a number of observations from theoretical reasons, derives Keplers law!
- Introduces the important notion: A universal force (a new concept)





PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA

Autore J S. NEWTON, Trin. Coll. Cantab. Soc. Matheseos Professore Lucasiano, & Societatis Regalis Sodali.

IMPRIMATUR
S. PEPYS, Reg. Soc. PRÆSES.
Julii 5. 1686.

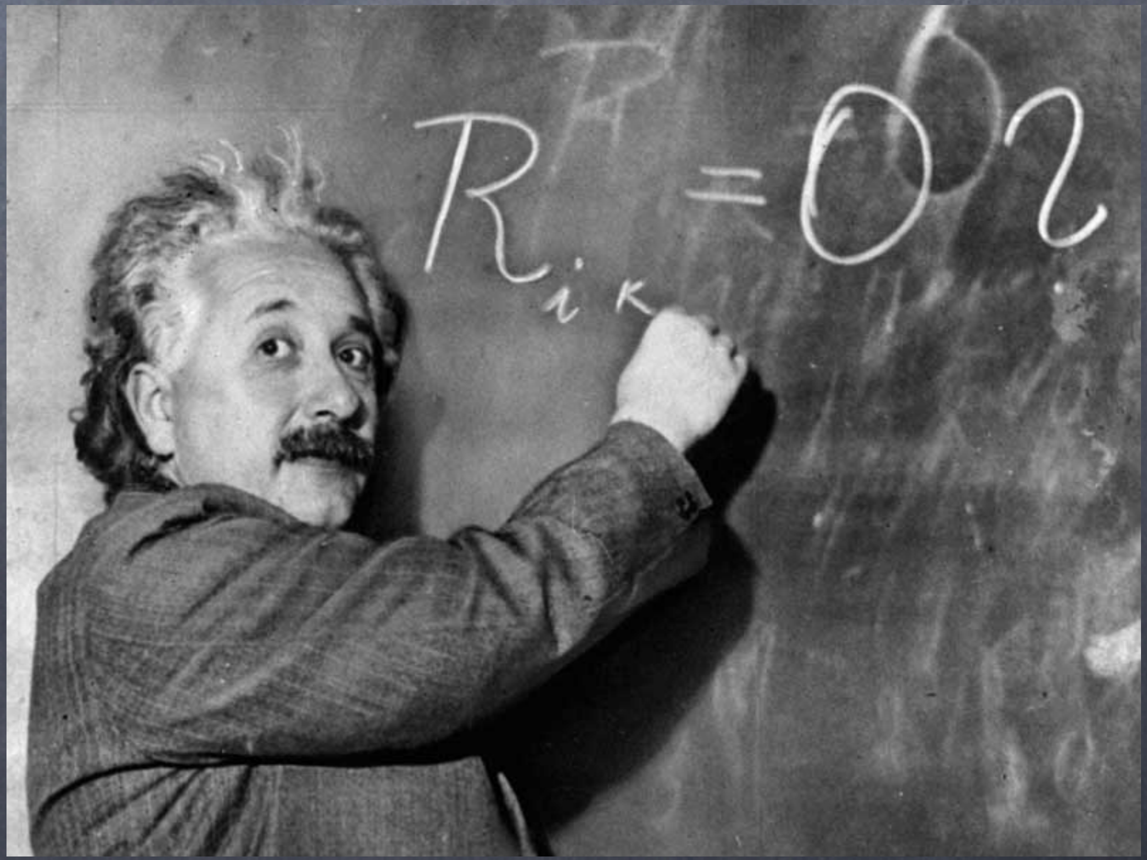
LONDINI,
Jussu Societatis Regiæ ac Typis Josephi Streater. Prostat apud plures Bibliopolas. Anno MDCLXXXVII.

Inertia

Einstein's theories

- The concept of universal forces in Nature is inspiration for Maxwell who combines Electric and Magnetic forces as one force of Nature.

- The theory of Electromagnetism is problematic to combine with Newtonian mechanics, but leads Einstein on the track to formulate special relativity…



Einstein's general theory

- Derived from the principles of special relativity but introducing new concepts

- Basic equation is the Einstein equation:

Curvature is connected to the energy-density

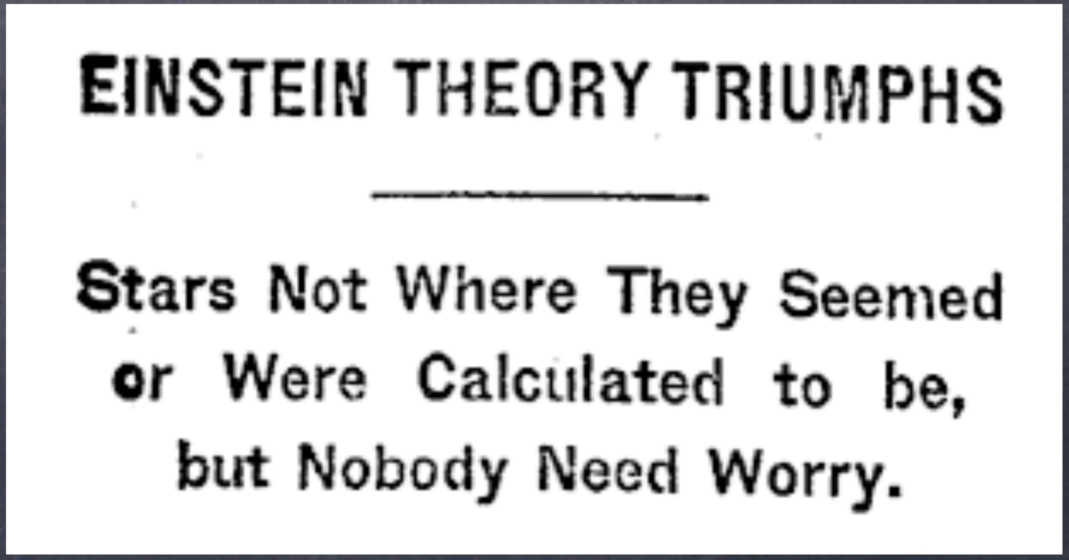
Leads to the notion of curvature of space!

- Gravity is a result of attraction between densities of energy, curvature of space is given by solving the Einstein equation.

Experimentel verification

Einstein predicts: Bending of light

- Light bends around massive objects
- Deflection can be measured
- Gives clear justification to Einstein's theory!


EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

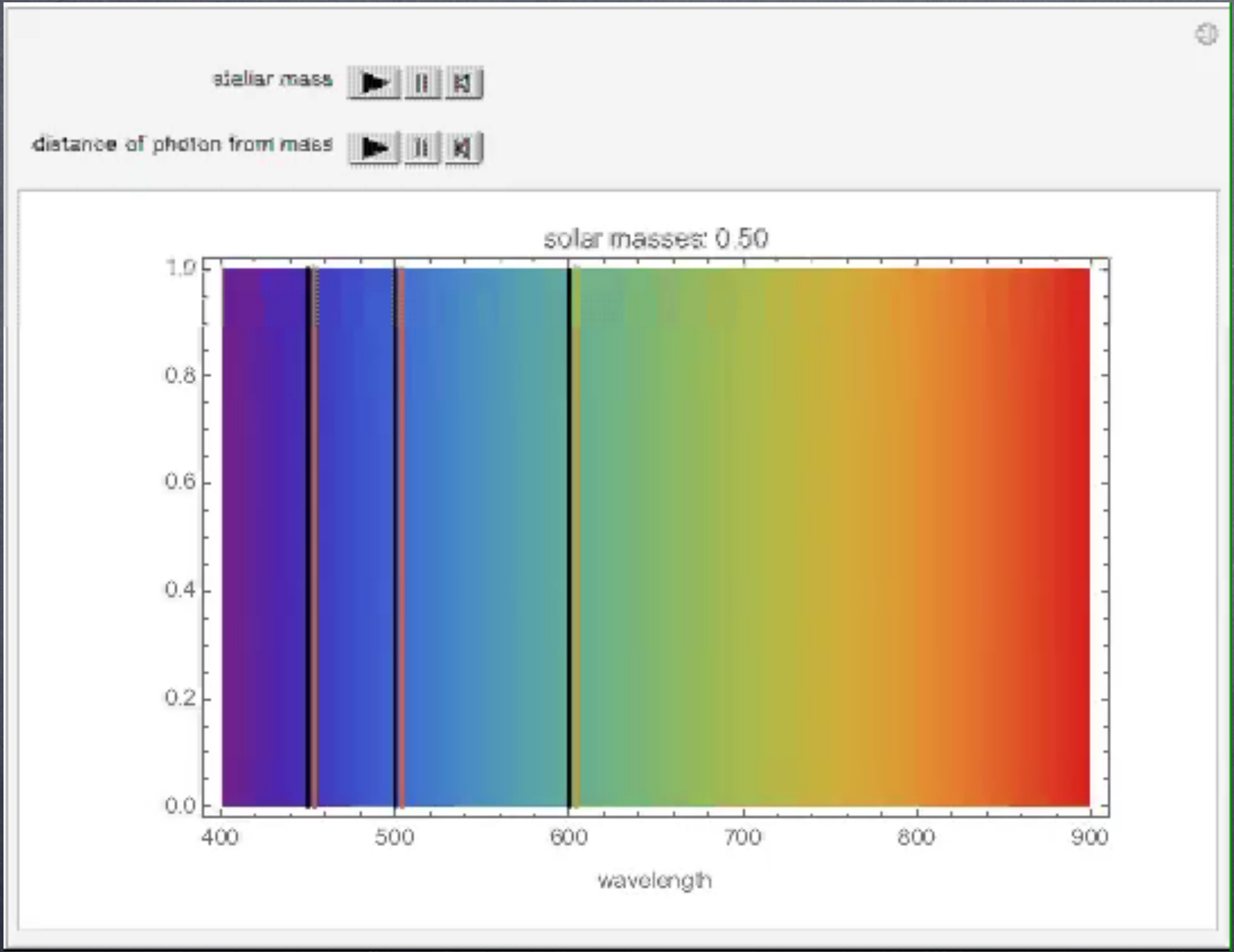
Experimentel verification

Einstein predicts: Perihelion distortion

- Planet orbits are generally a little distorted from their Newtonian form (ellipses).
- This is due to the Newtonian mechanics neglect of energy as a source of gravity.
- Can be measured rather precisely.

Experimentel verification

- Gravitational time dilatation:
  - Time goes little slower on the surface of a massive object, this can be observed as a small time delay!
  - Plays a crucial role for GPS systems
  - Gives a gravitational redshift for light

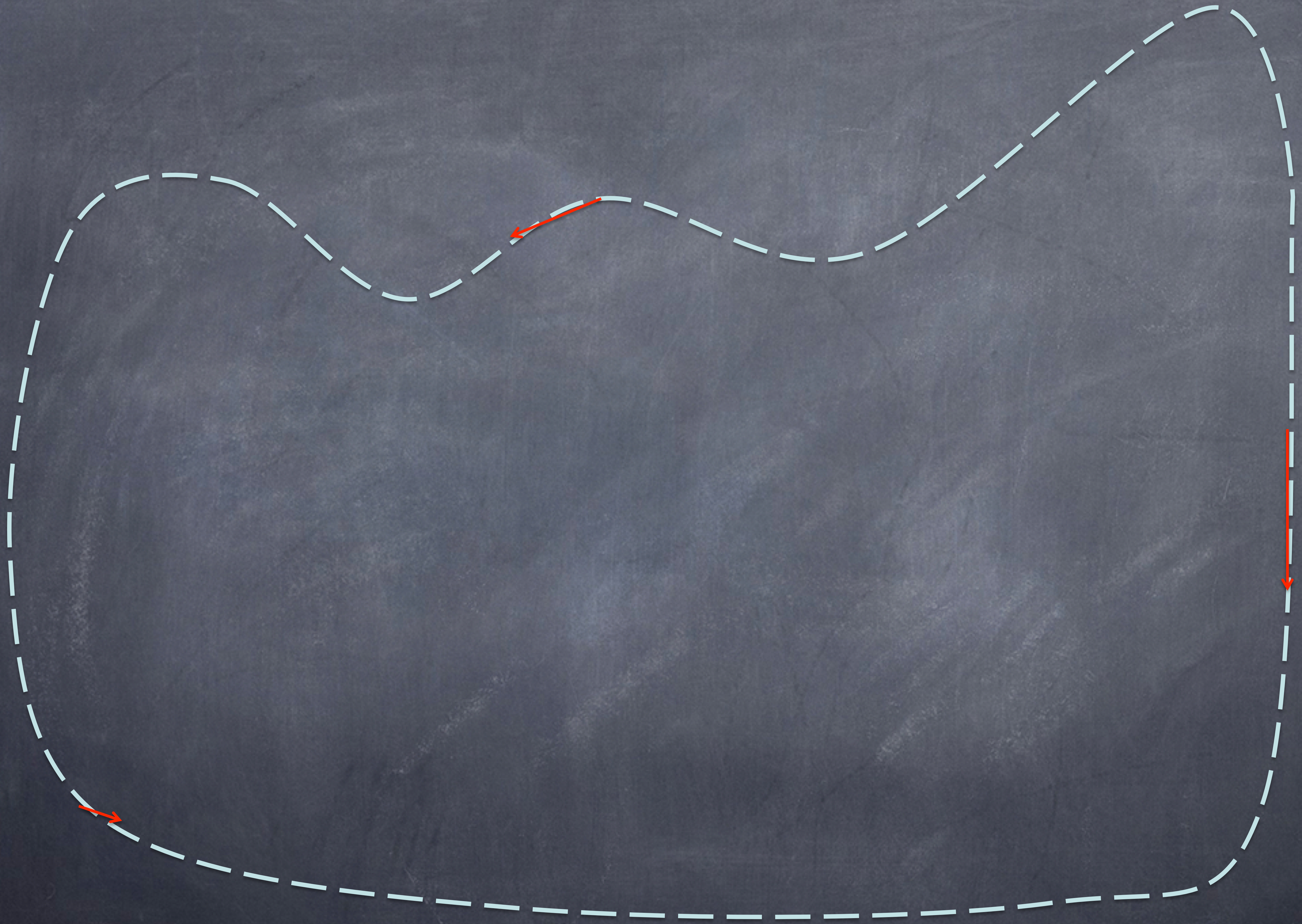

stellar mass
distance of photon from mass
solar masses: 0.50
1.0
0.8
0.6
0.4
0.2
0.0
400
500
600
700
800
900
wavelength

Einstein's theory

- A beautiful theory based on one equation, explaining all theories before and giving important new theoretical results

  - Everything we know about gravity is in correlation with the general theory of relativity

  - Deterministic theory like Newton's theory: given initial conditions everything is known in future!



PART II

Deterministic vs. Non deterministic

Deterministic vs. Non-deterministic

In order to understand how this question becomes important in theoretical physics – one has to understand matter better

Eventually this question comes down is matter really dividable forever or does smallest quantities appear at some scale.

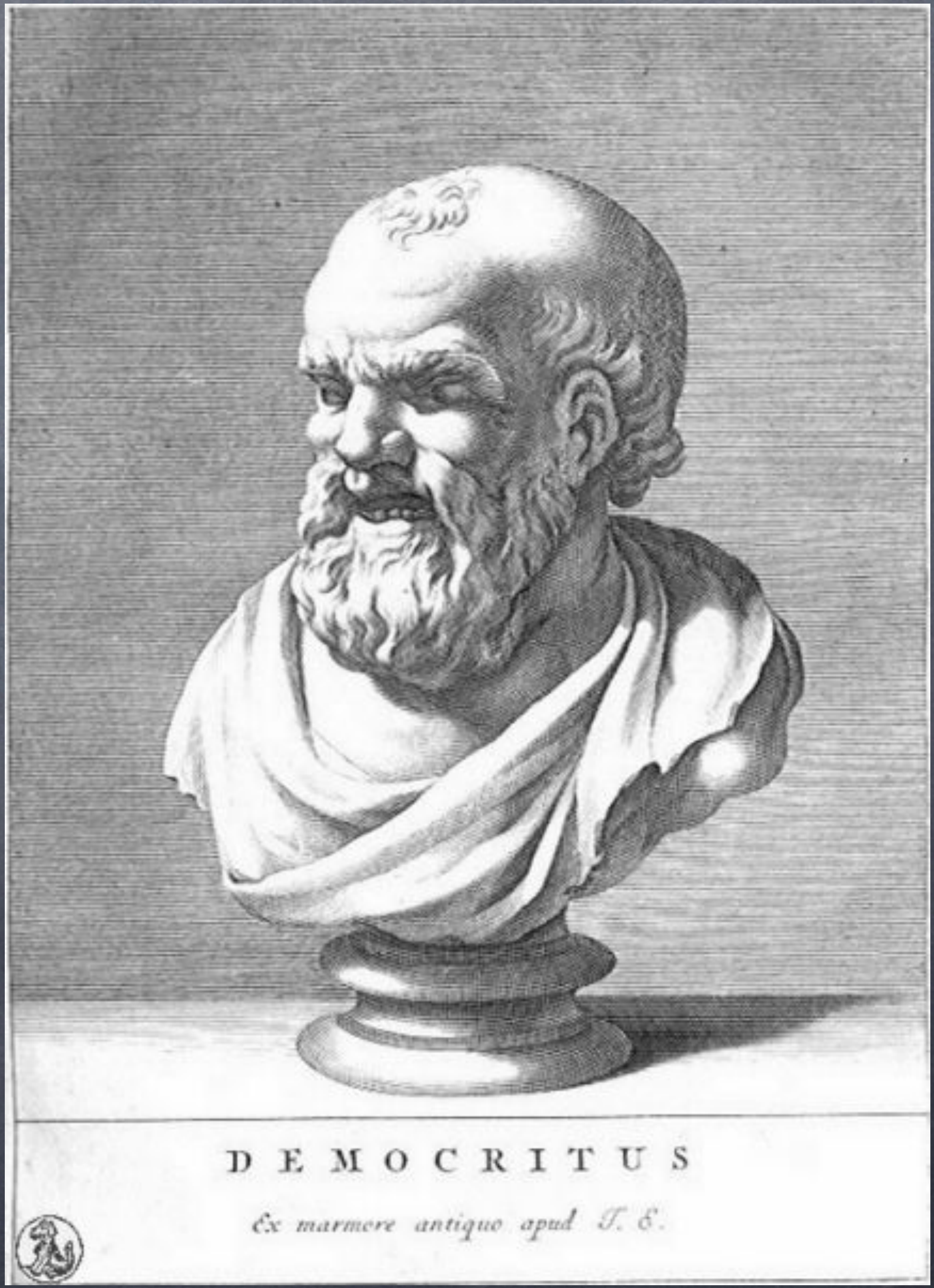
Birth: Quantum mechanics

History of atoms

Idea: matter containing undividable particles (atoms)

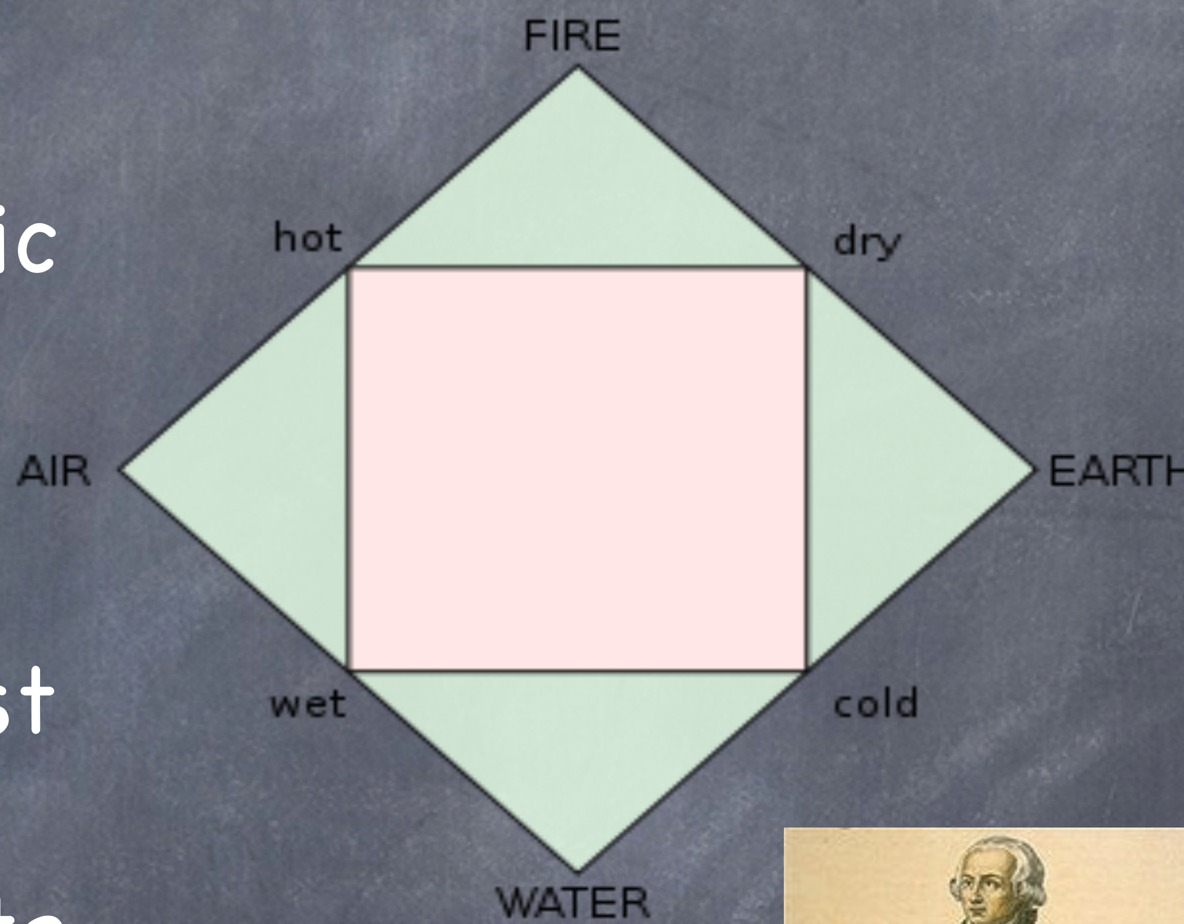
Close to modern knowledge of atoms constituting matter

Philosophical work: no direct experiments to establish if theory is correct...



Air, Fire, Earth, Water

In the middle ages, alchemy, Aristotle's elements – based on basic observations (data)



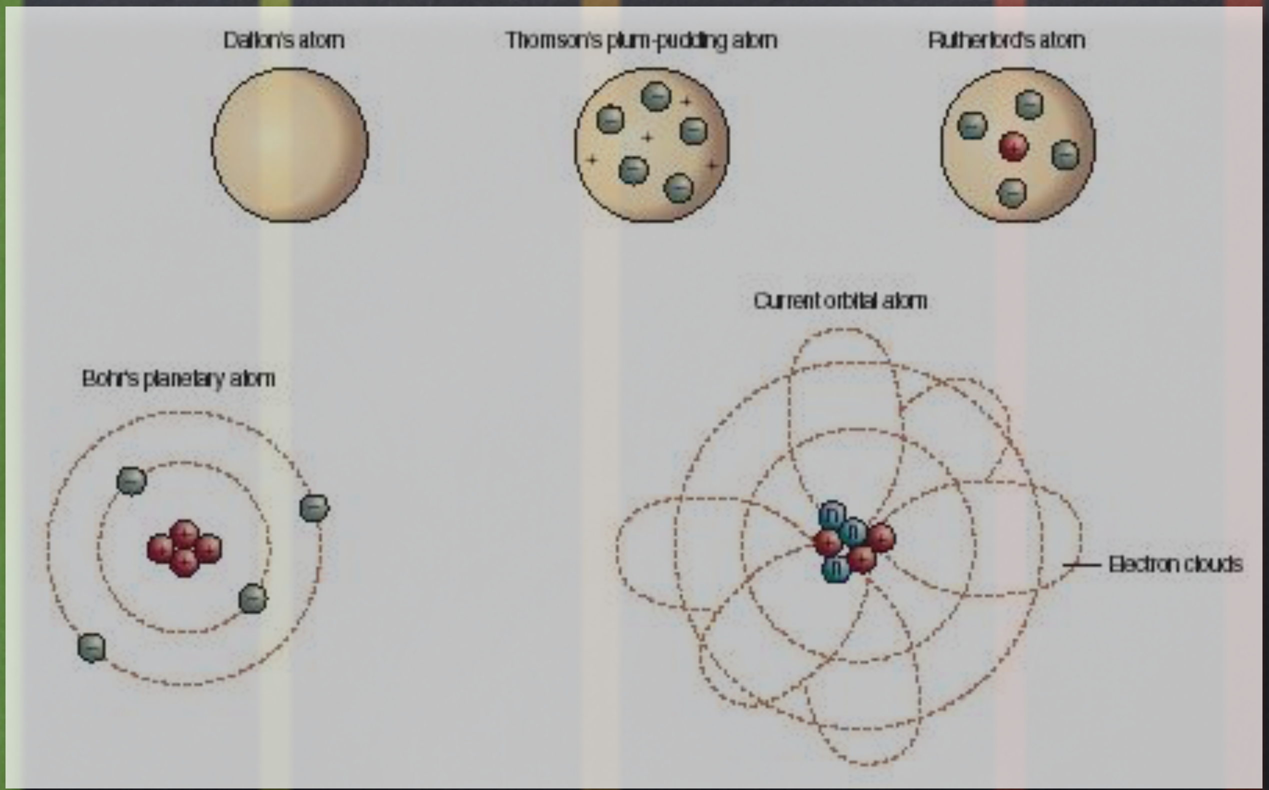
Lavoisier: creator of modern chemistry (against the phlogiston theory)

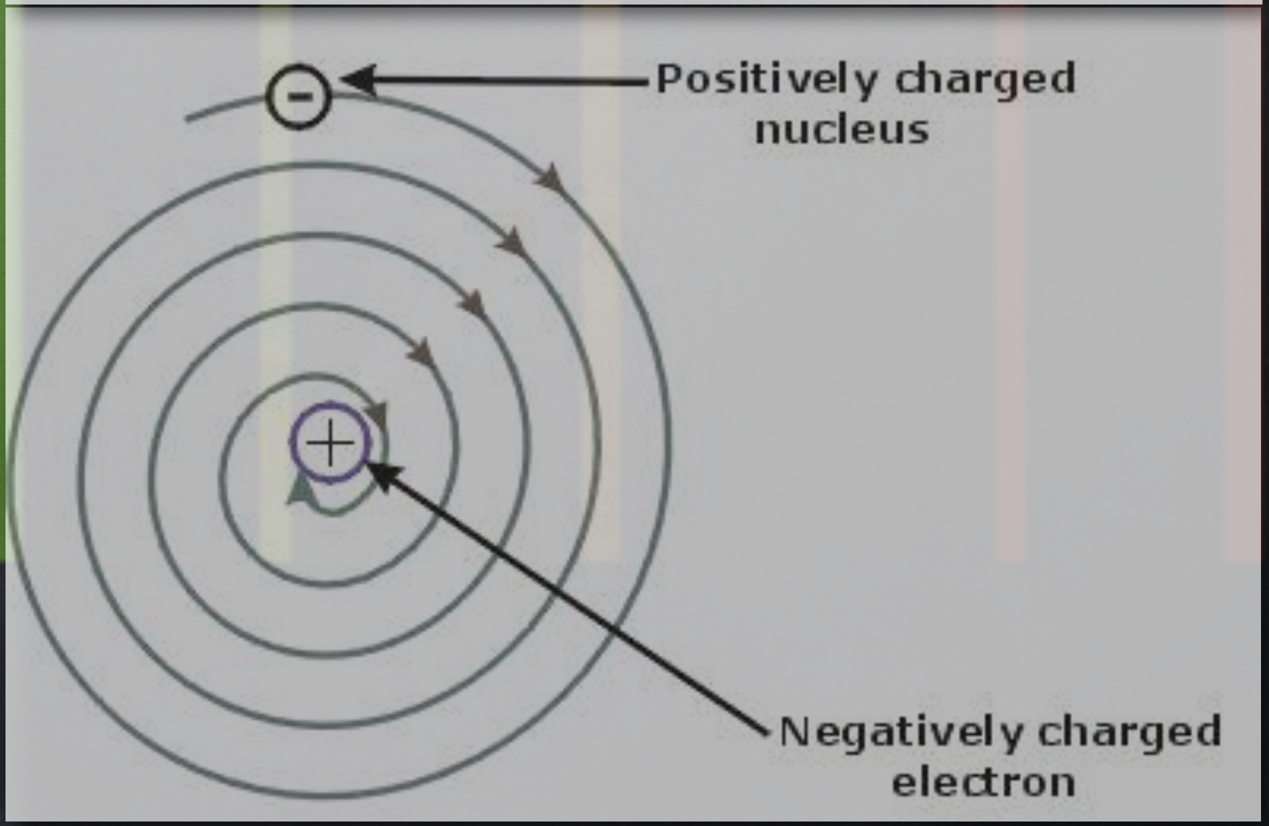
Idea: elements constitute matter and interact through chemistry -> idea of a periodic table of elements

1913 Atoms and Nuclei

Properties of atoms and nuclei

- Spectral lines
- A very hard and small nucleus
- Challenge: To understand of the concept of interactions at the quantum level.

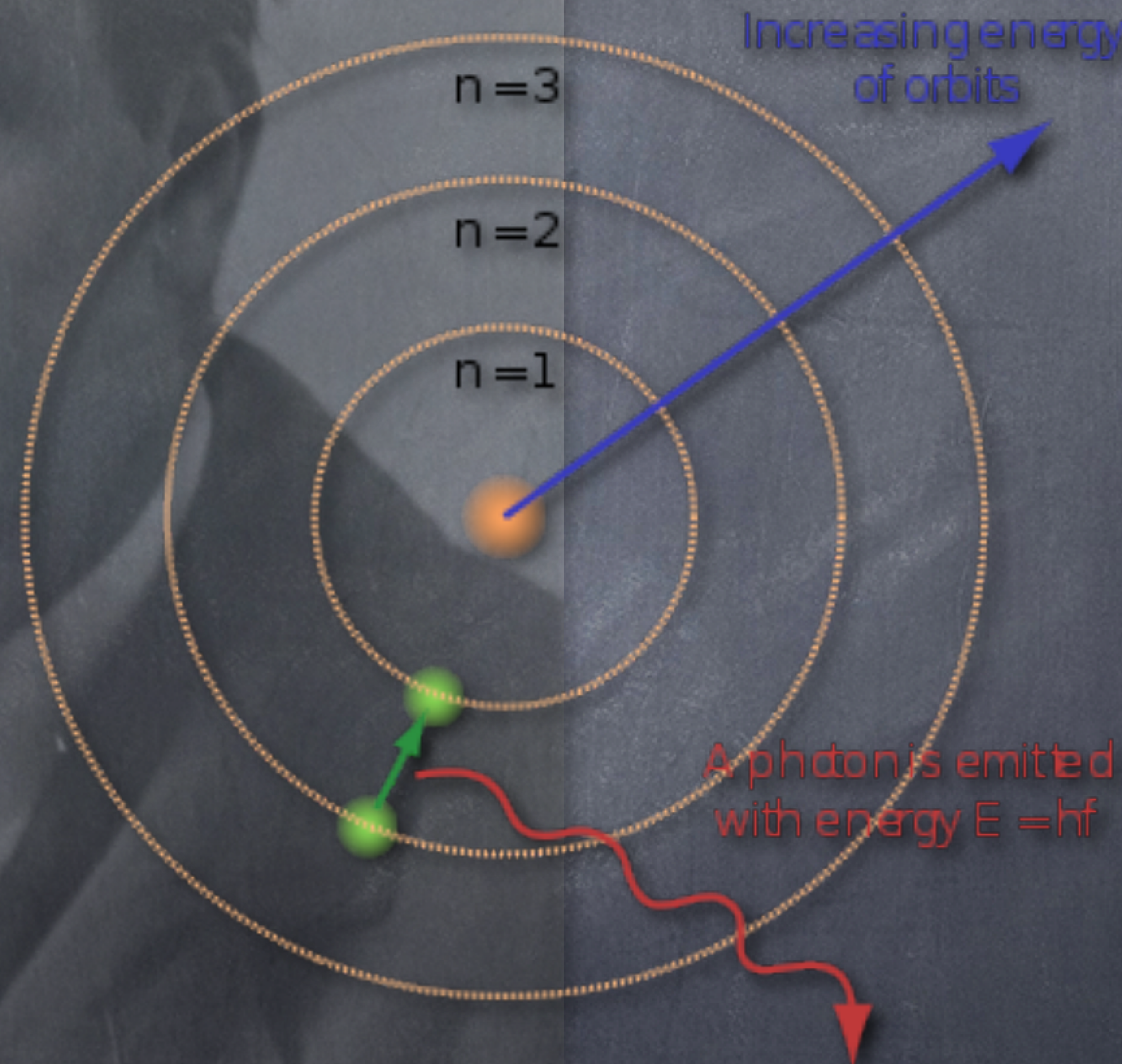




Niels Bohr's model for the atom

Creative new solution to problem of stability and explanation of spectra:

- Fixed energy levels between shells
- Quantum jumps between shells: light (photon) emission

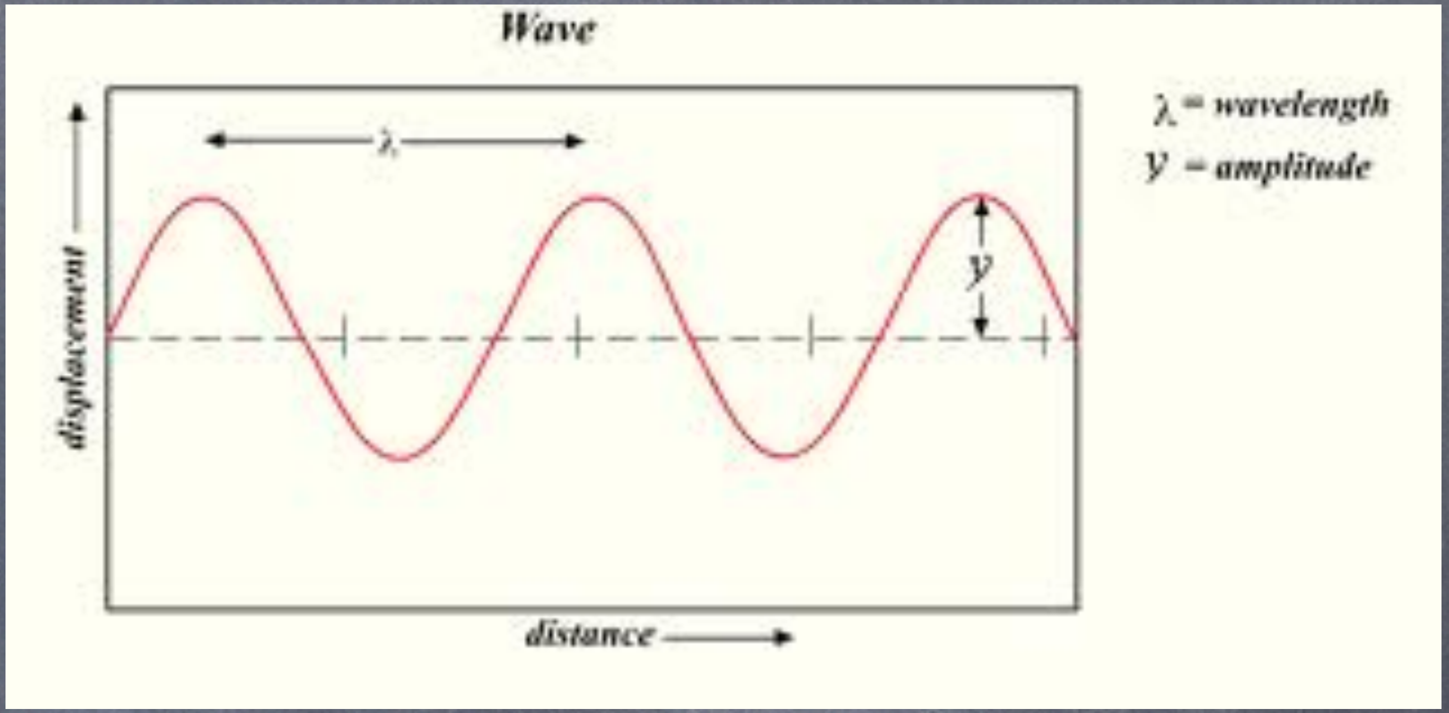


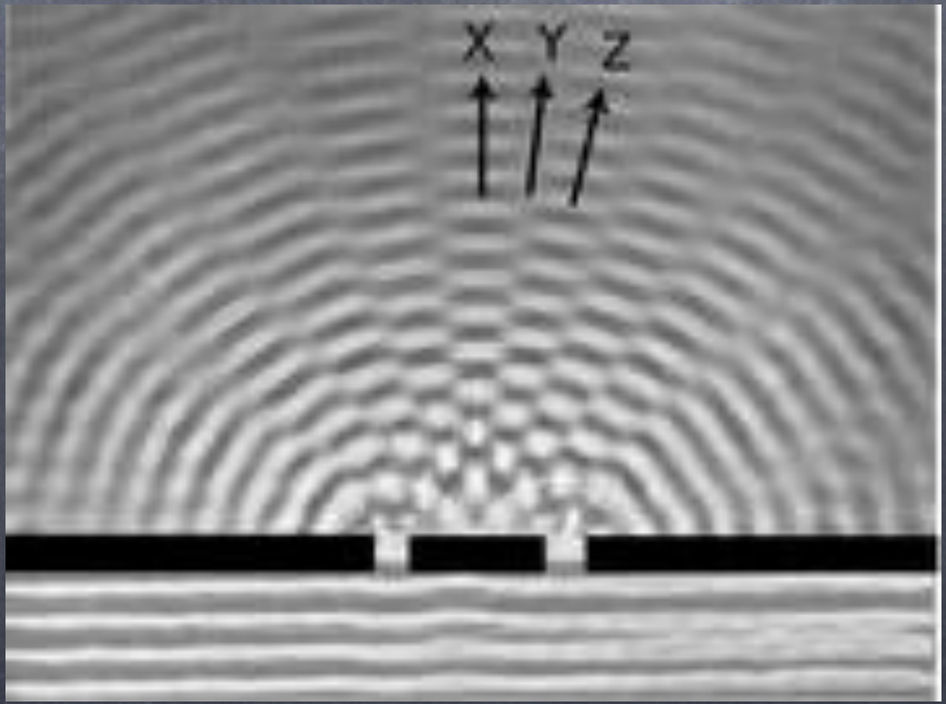
Amplitudes

Fundamental object in quantum mechanics

Matter described as waves/amplitudes

Squaring the amplitude gives quantum probability





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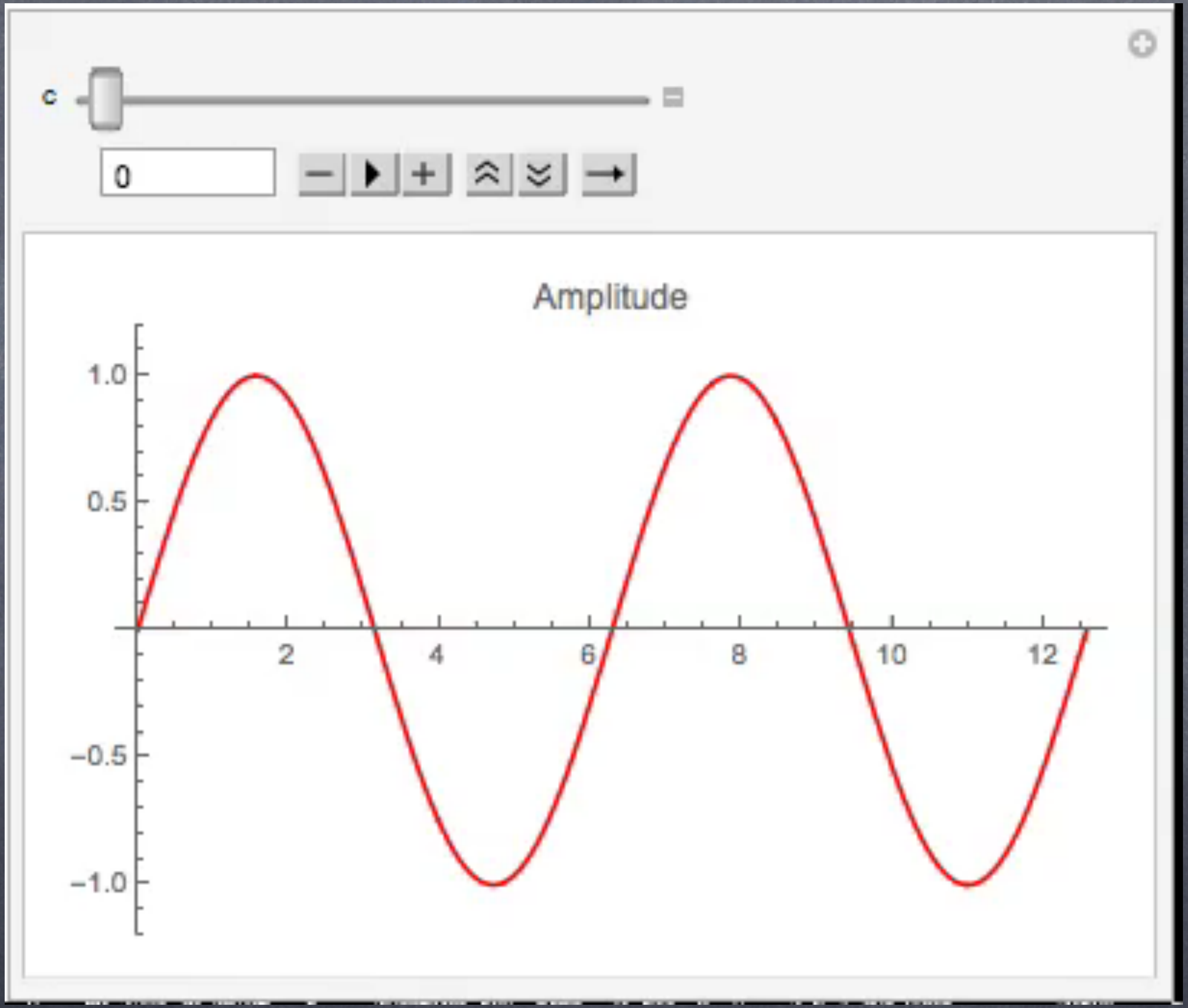
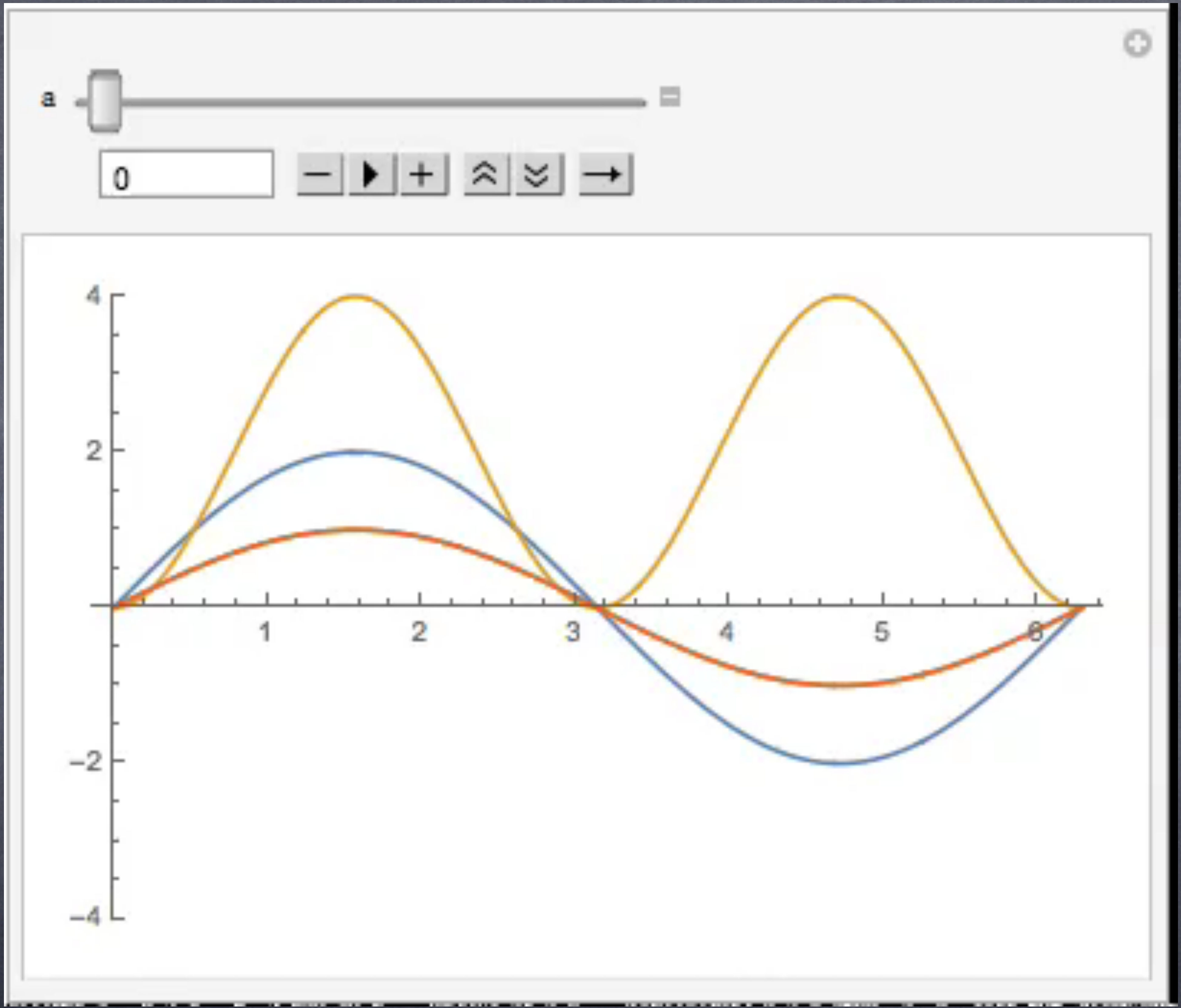
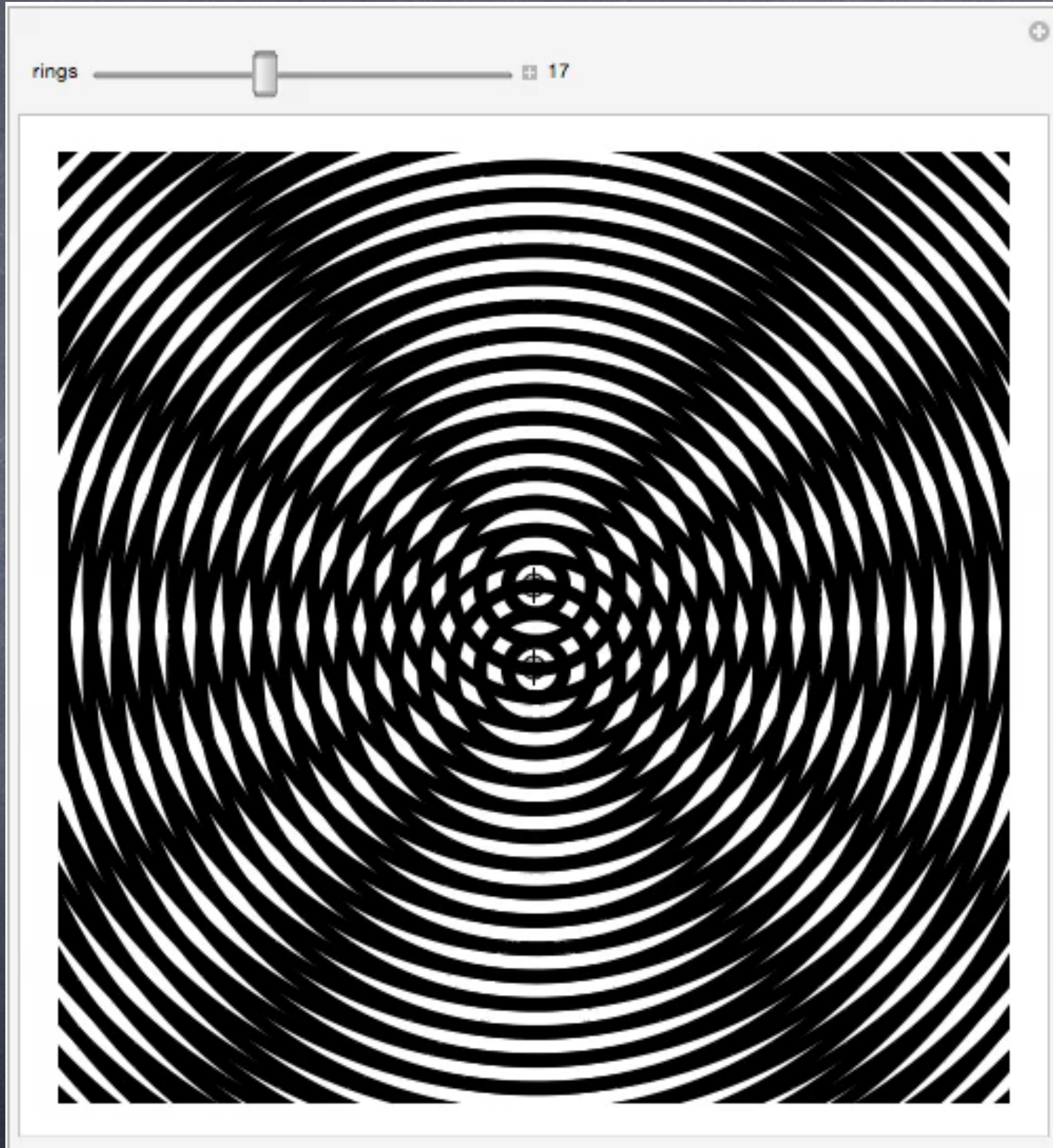
Amplitudes and probability




a
0
4
2
−2
−4
1
2
3
4
5
6


rings
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Quantum Mechanics

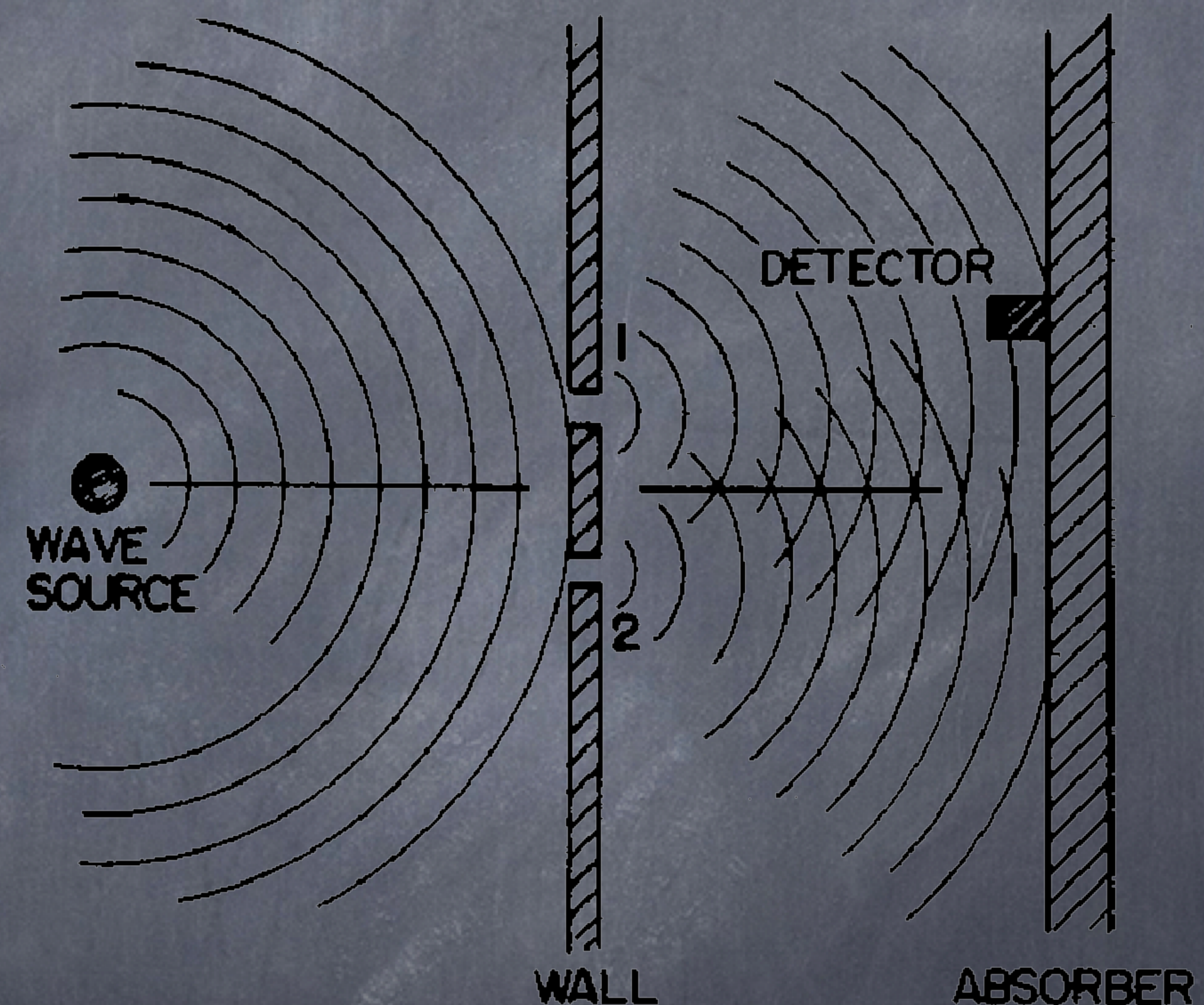
Unique importance for physics

Completely new concepts

Complimentary interpretation

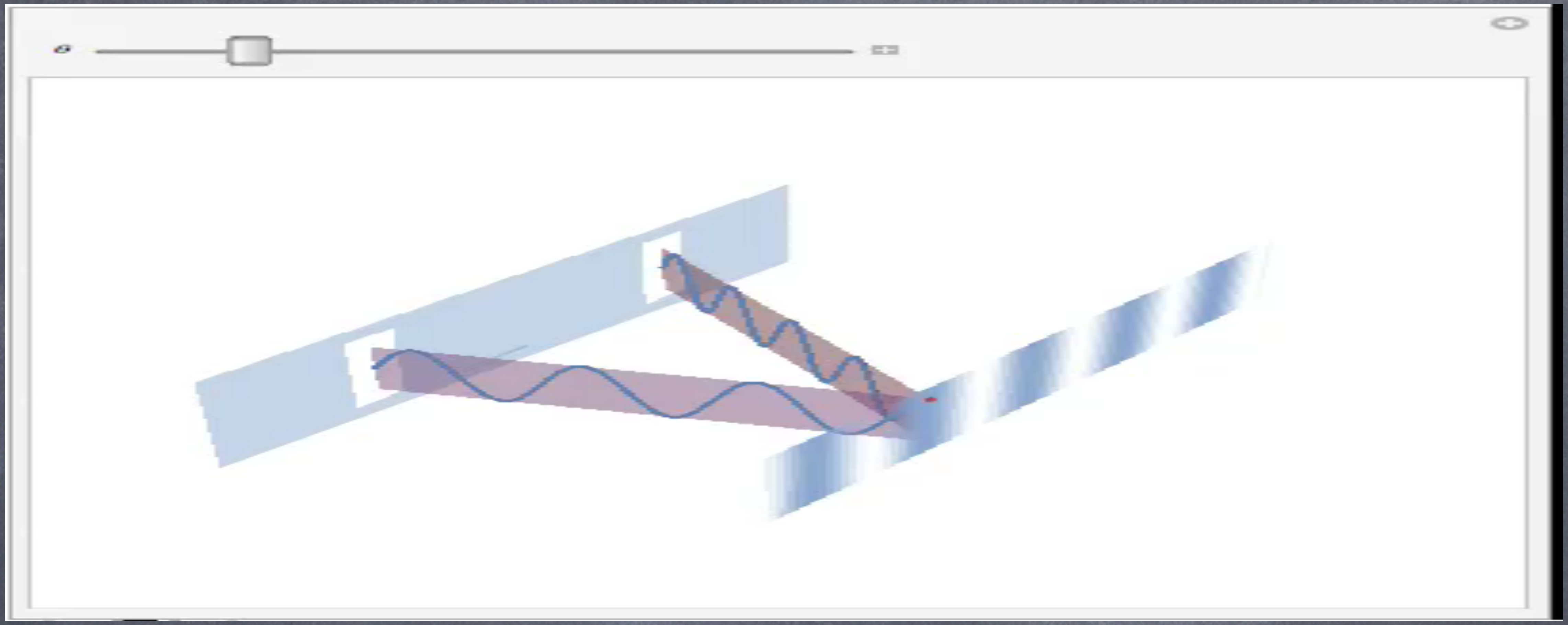
Extremely successful: Match of theory to experiment with unseen high precision

The quantum path forward for Theoretic Physics even today



Position and momentum cannot be measured at the same time

Interference properties

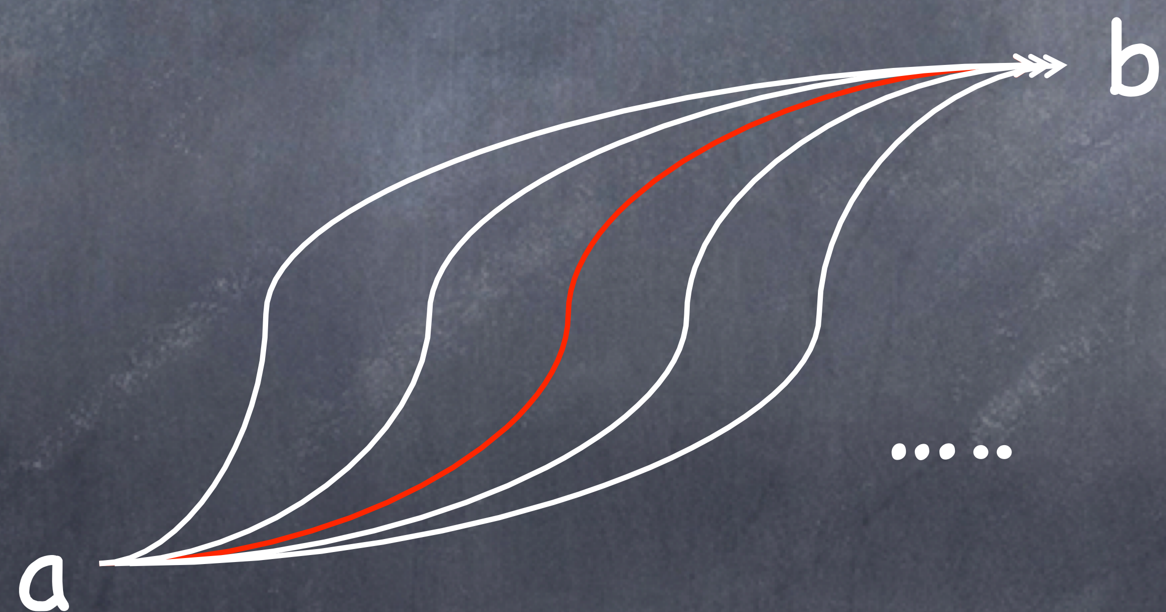


Distinct break between quantum and classical physics –
Wave properties hold for single particles

Deterministic vs. Non-deterministic

Classical interaction

Have to integrate/sum over all paths



Feynman path integral

Particle wave duality

Absolutely crucial in Quantum Mechanics

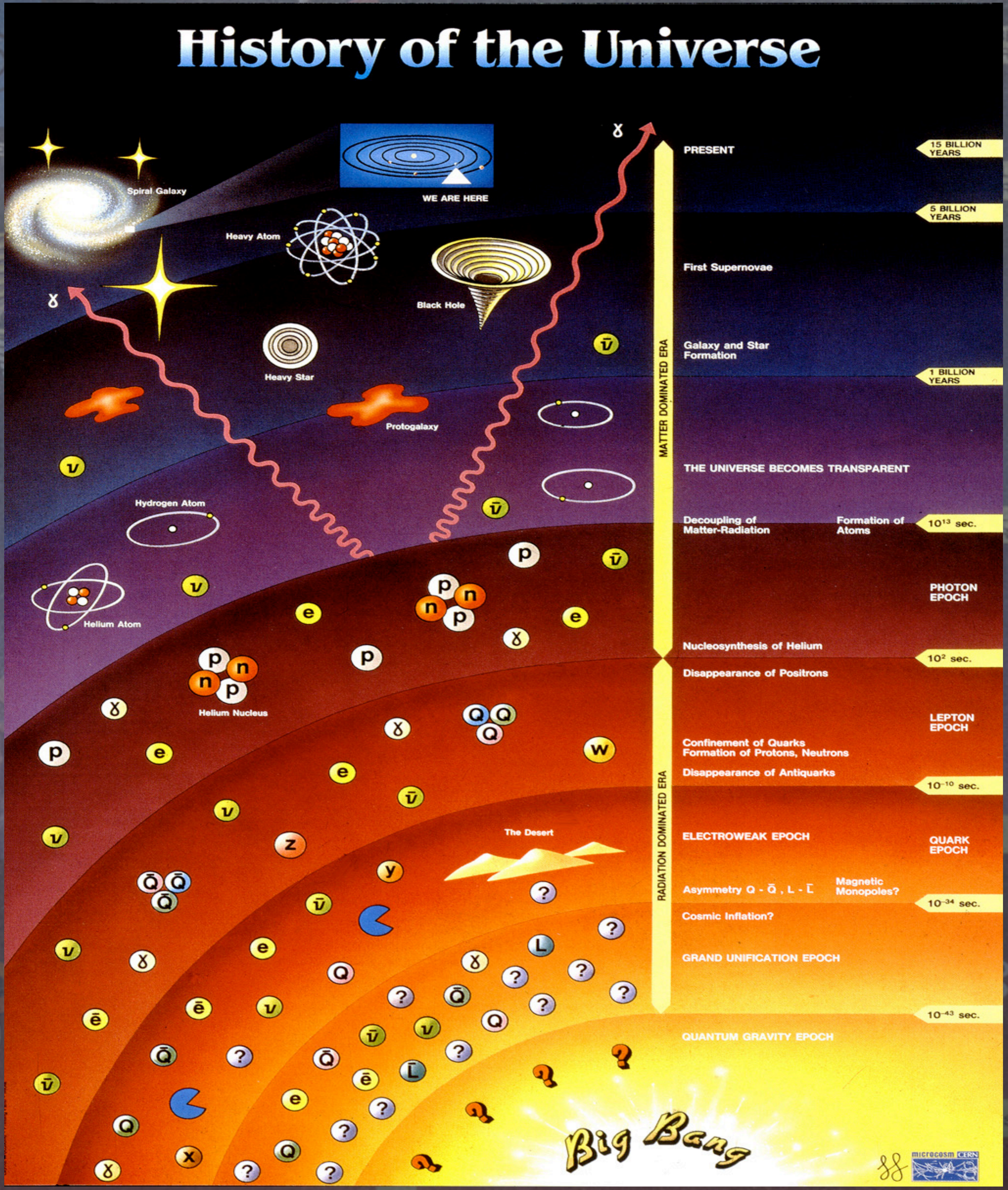
- Particle properties are as real as wave properties. It is the same fundamental manifestation of matter.
- What we have grasp is that this is fundamental break with classical mechanics where all variables can be measured at the same time to all times
- Problem: Quantum gravity? What framework?

PART III

Modern Particle physics

High Energy Physics

Concerned with a large number of topics ranging from the sub-nuclear scales to the cosmological



High Energy Physics

Some current goals and ongoing investigations:

New physics

New particles and symmetries (esp. Supersymmetry)

Understanding "Dark matter"

Extra dimensions of spacetime?

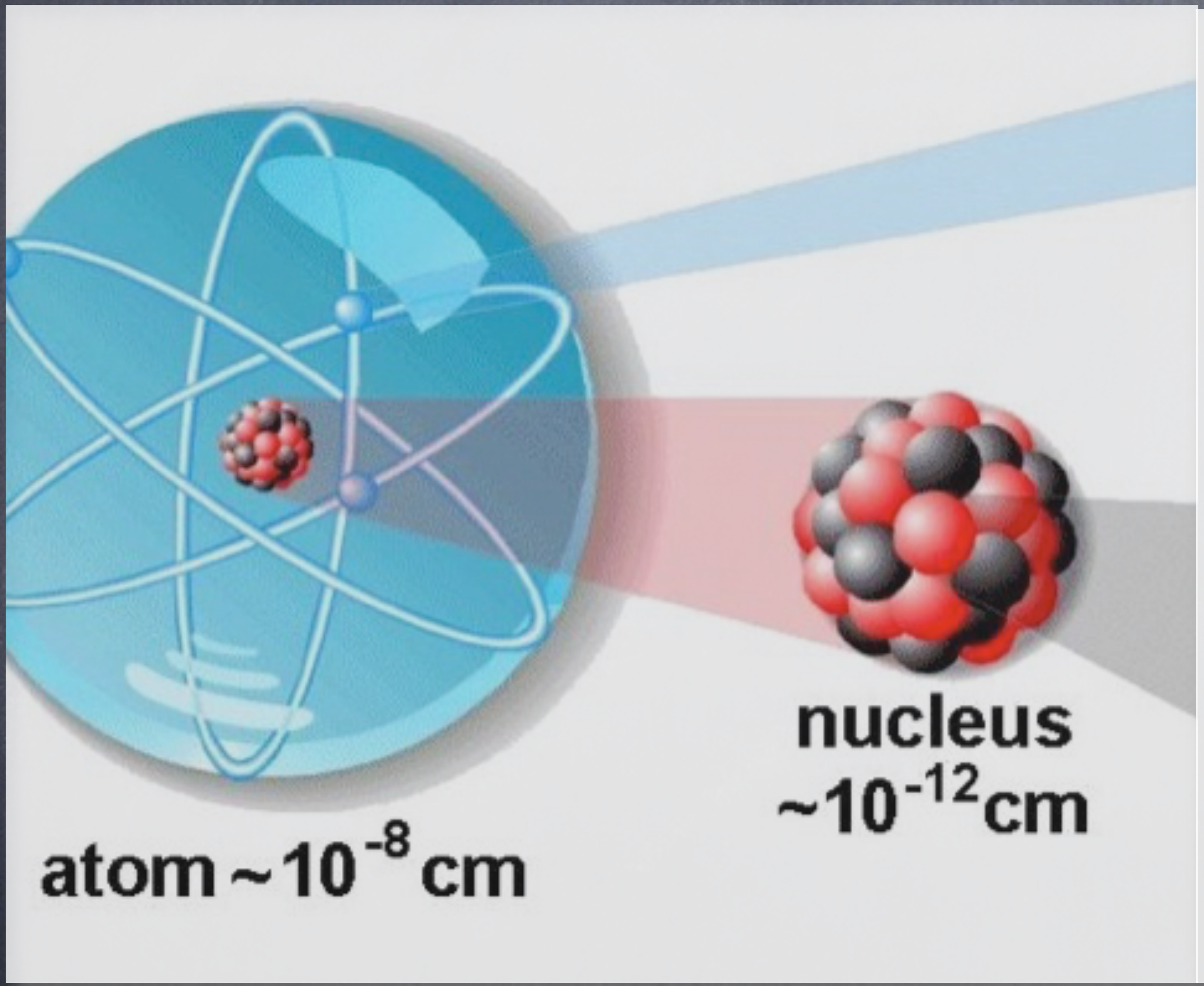
Masses of neutrinos

Anti-symmetry of matter

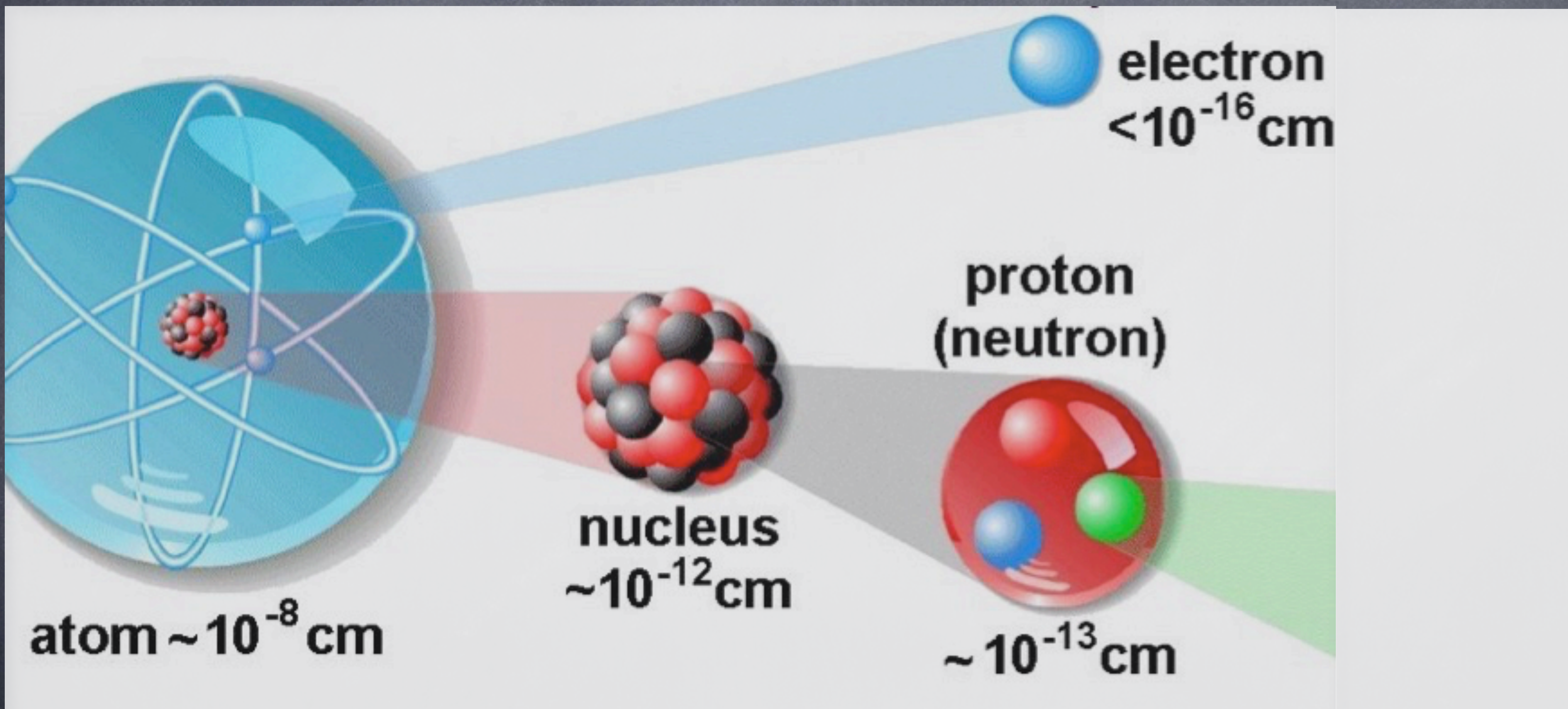
Quantum gravity

Unification of forces

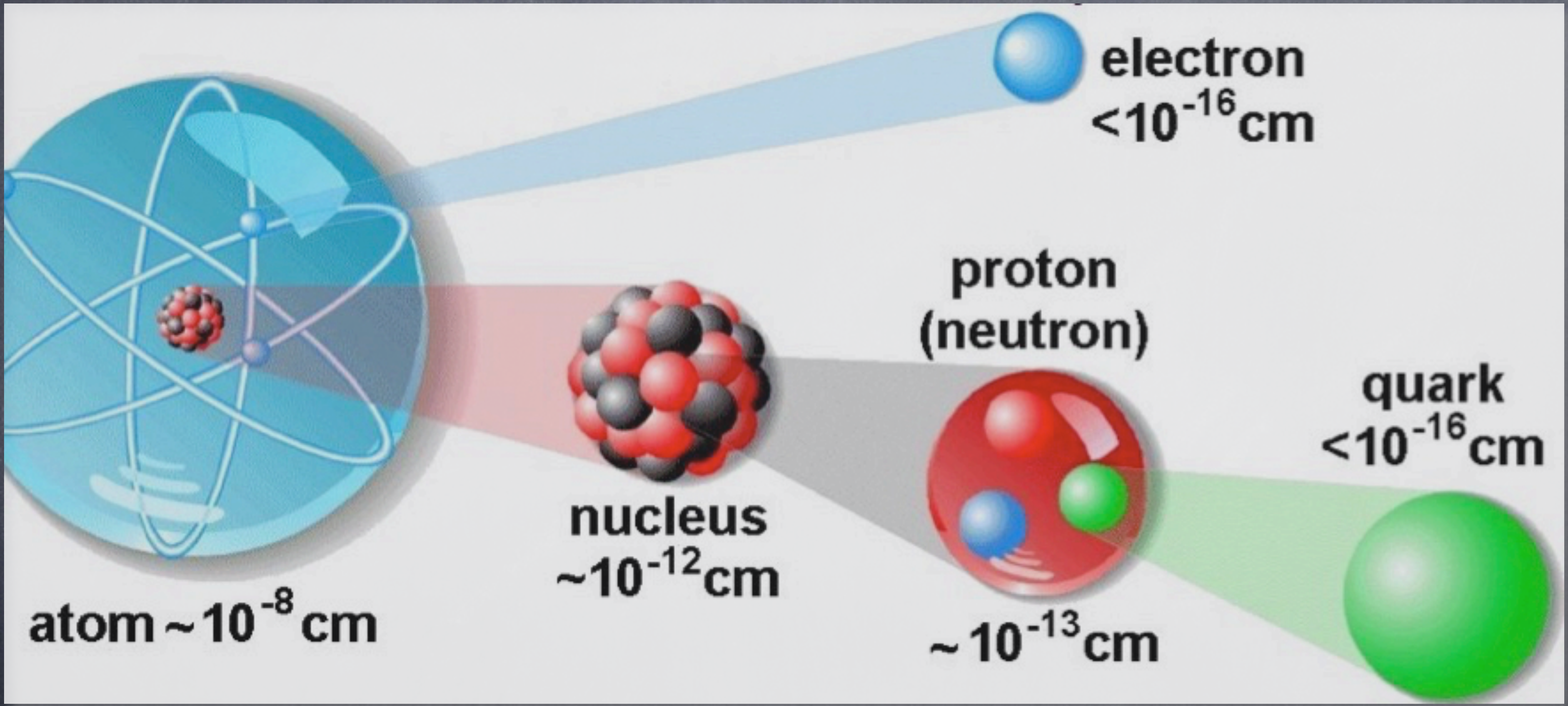
From the atom to the nucleus



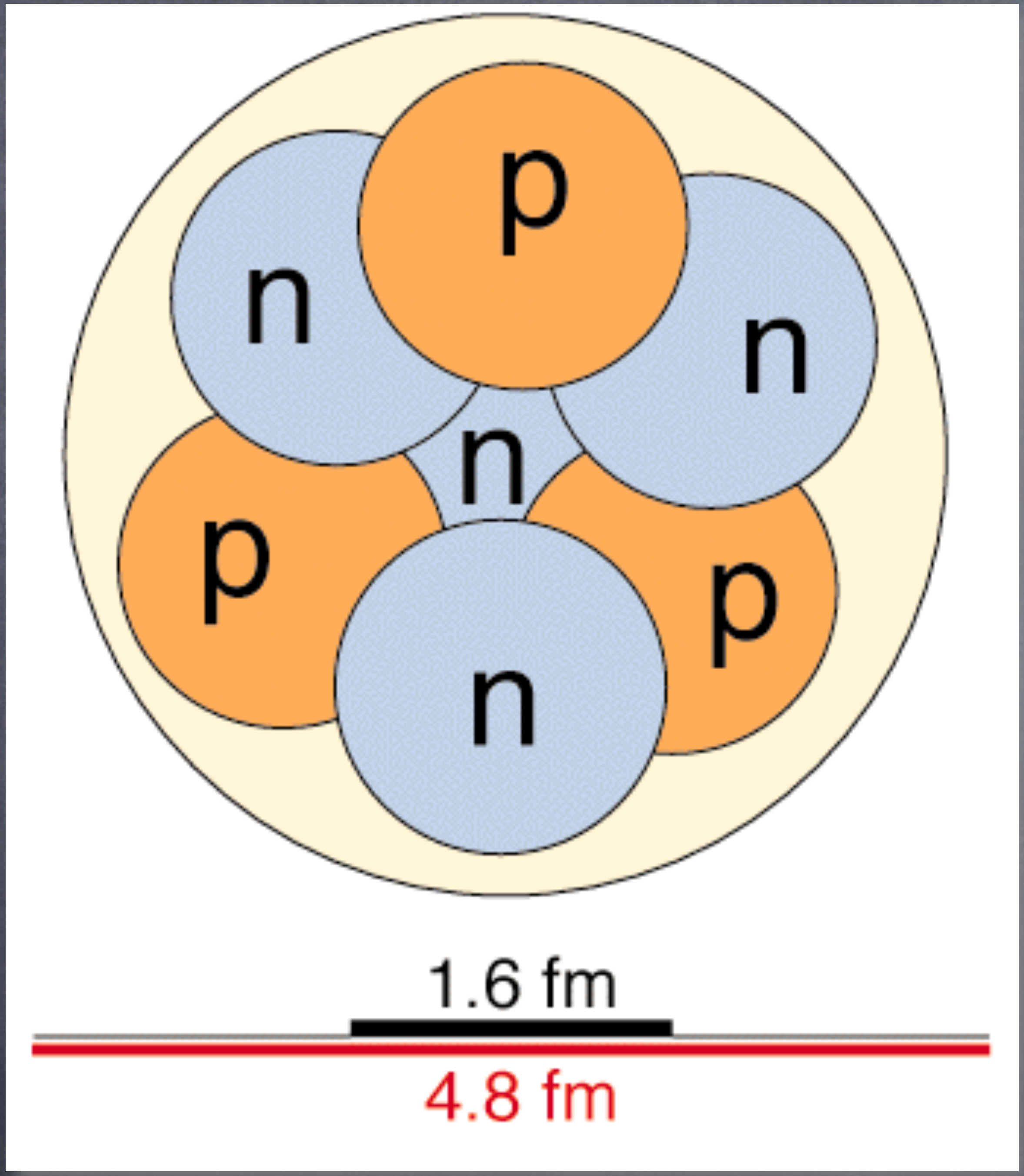
From the atom to the proton



From the atom to the quark



Nucleus



Atom: Nucleus and Electrons, held together by Electromagnetic forces.

Nucleus: Protons and Neutrons held together by much stronger nuclear forces.

Possible: in many cases to reuse solutions from atomic physics

Nuclear forces

Weak nuclear interactions

Force particle: W and Z bosons

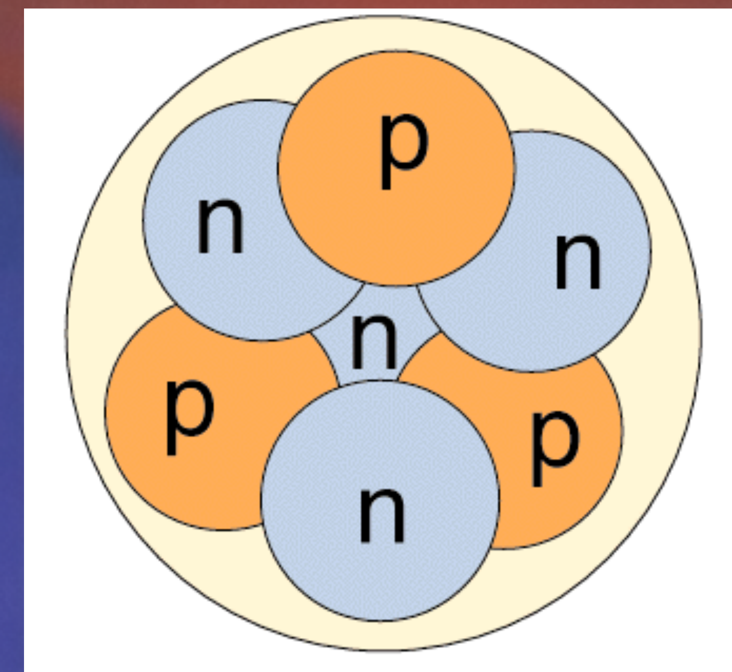
Neutrons decay into Protons: new particle: neutrino

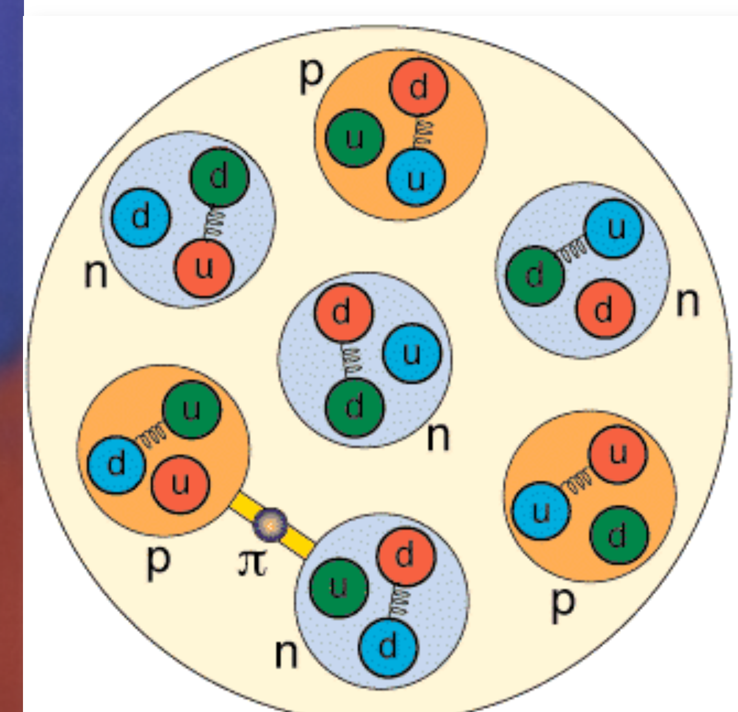
Strong nuclear interactions

Force particle: gluon

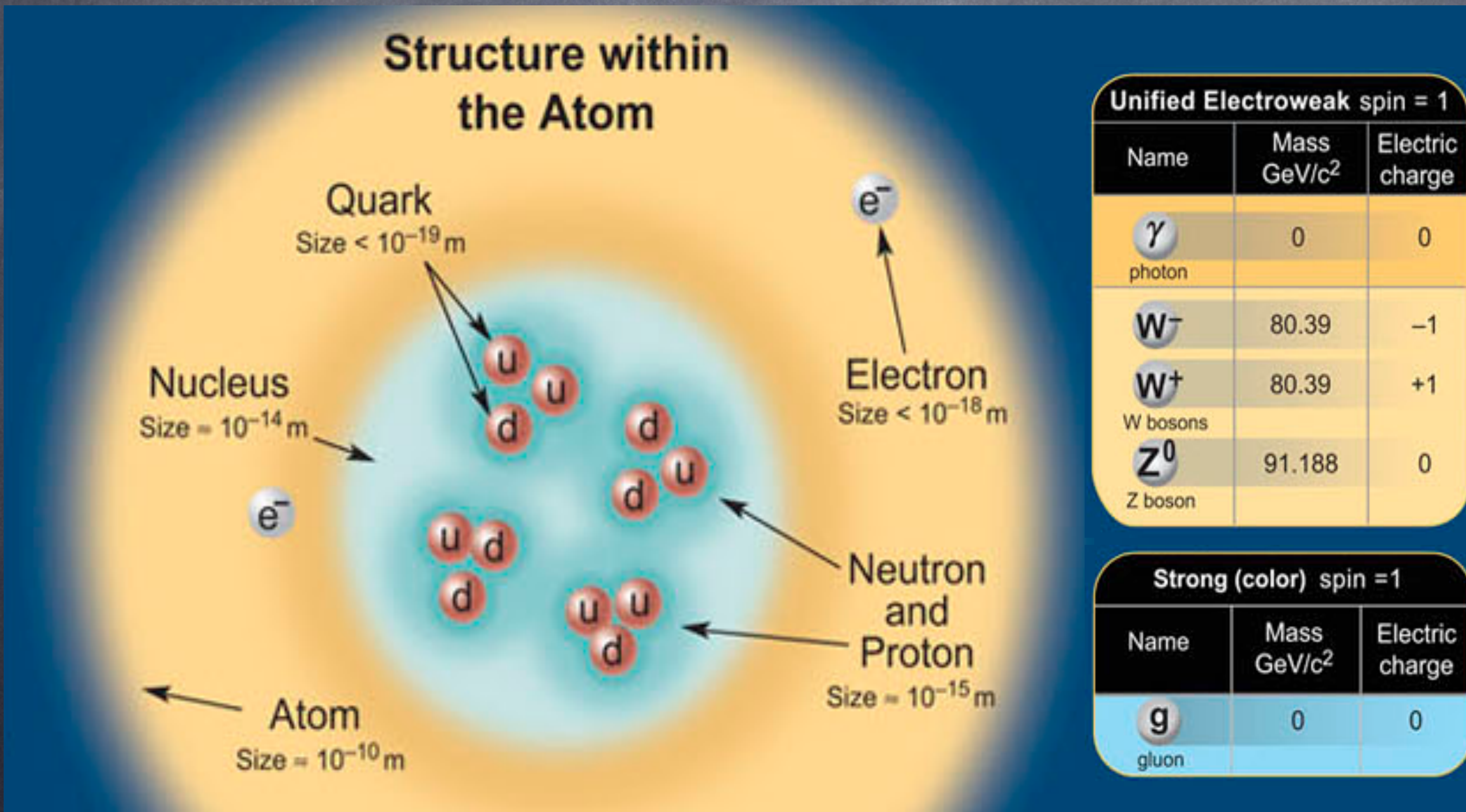
Quarks interacts via gluons

New concept: Asymptotic freedom





Standard Model of particle physics: Bosons, leptons and quarks - gravity?



Three generations for matter:

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

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Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Amazing cookbook for all matter

Hydrogen

2x

Leptons spin =1/2		
Flavor	Mass GeV/c^2	Electric charge
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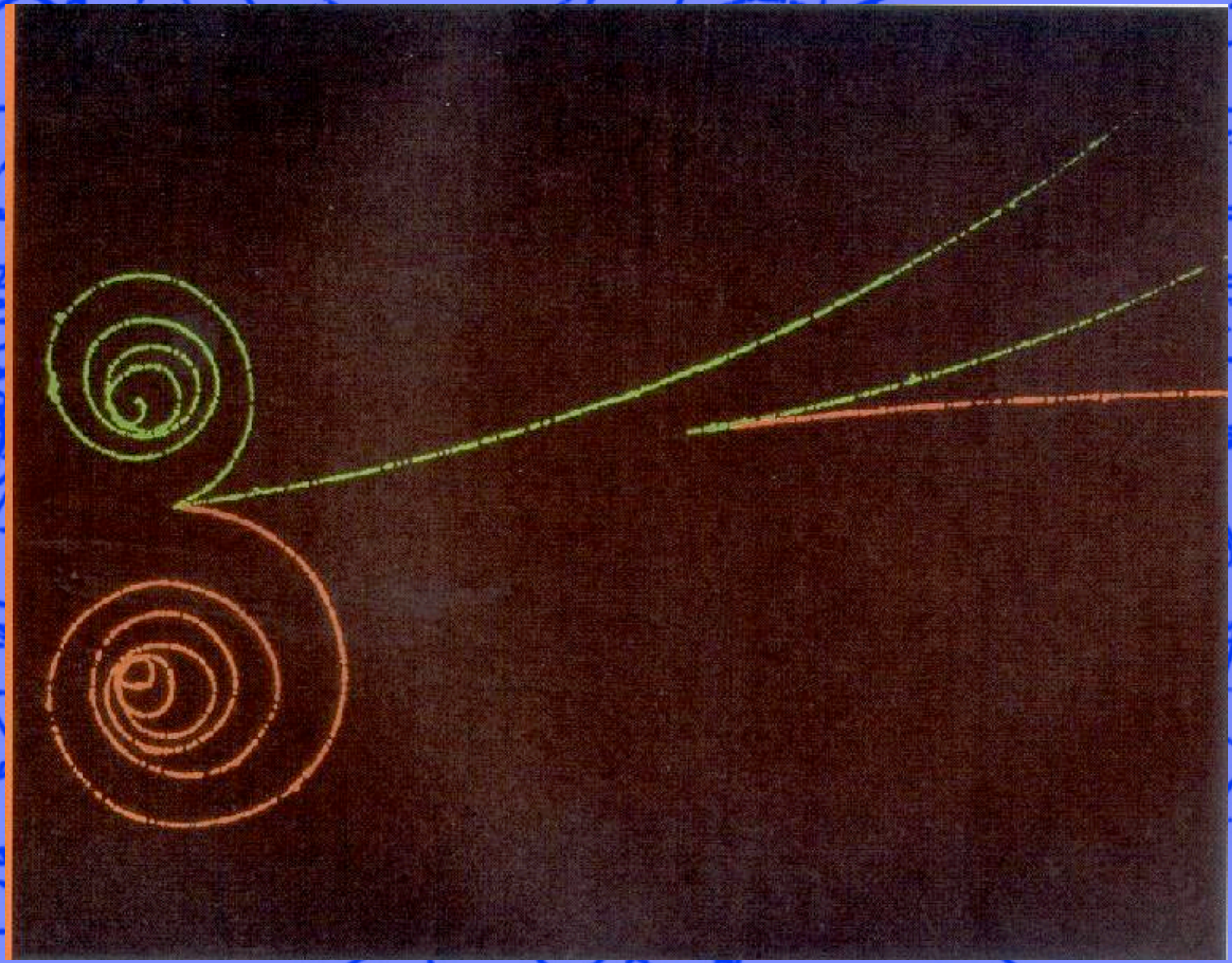
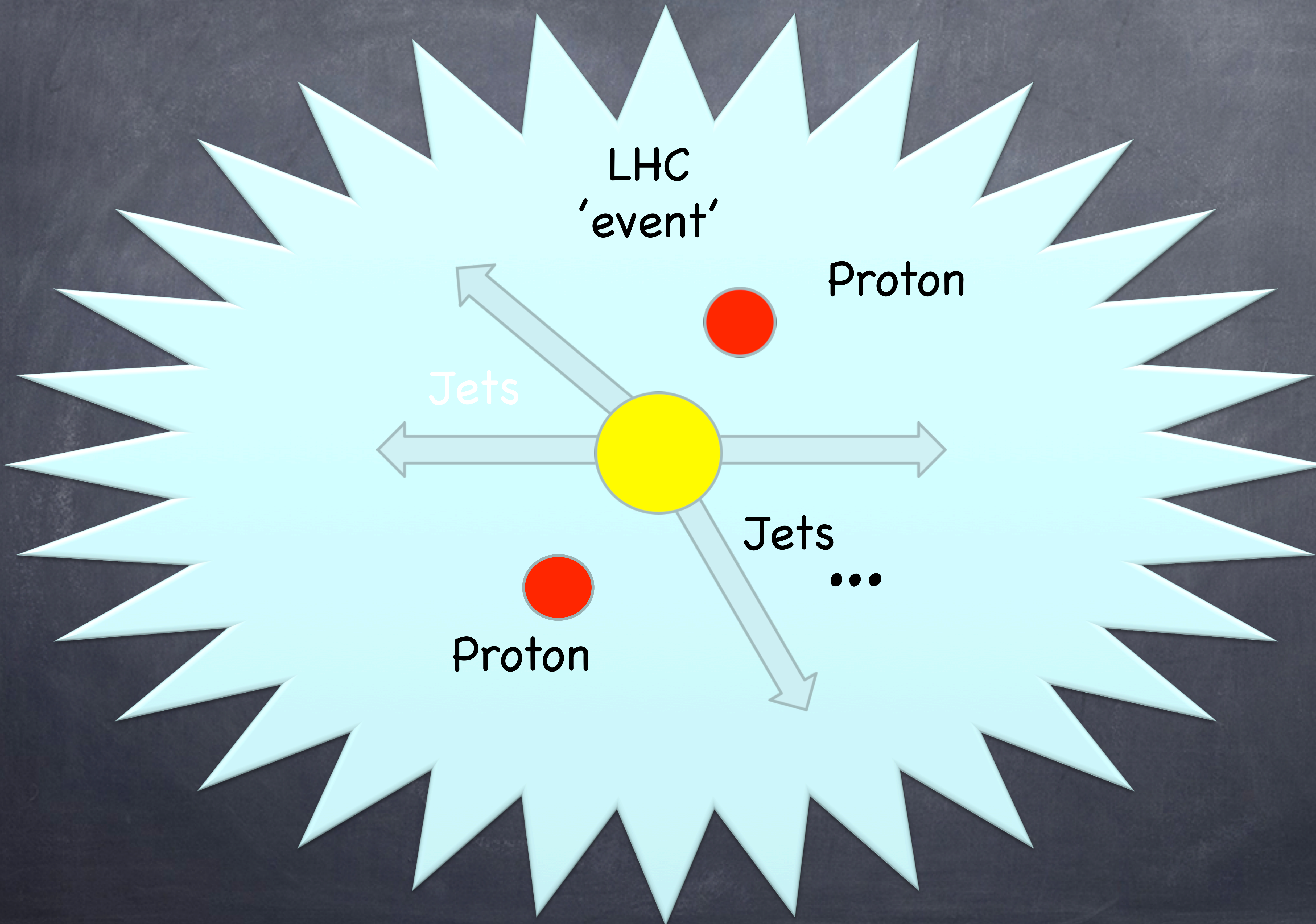
Bubble chamber

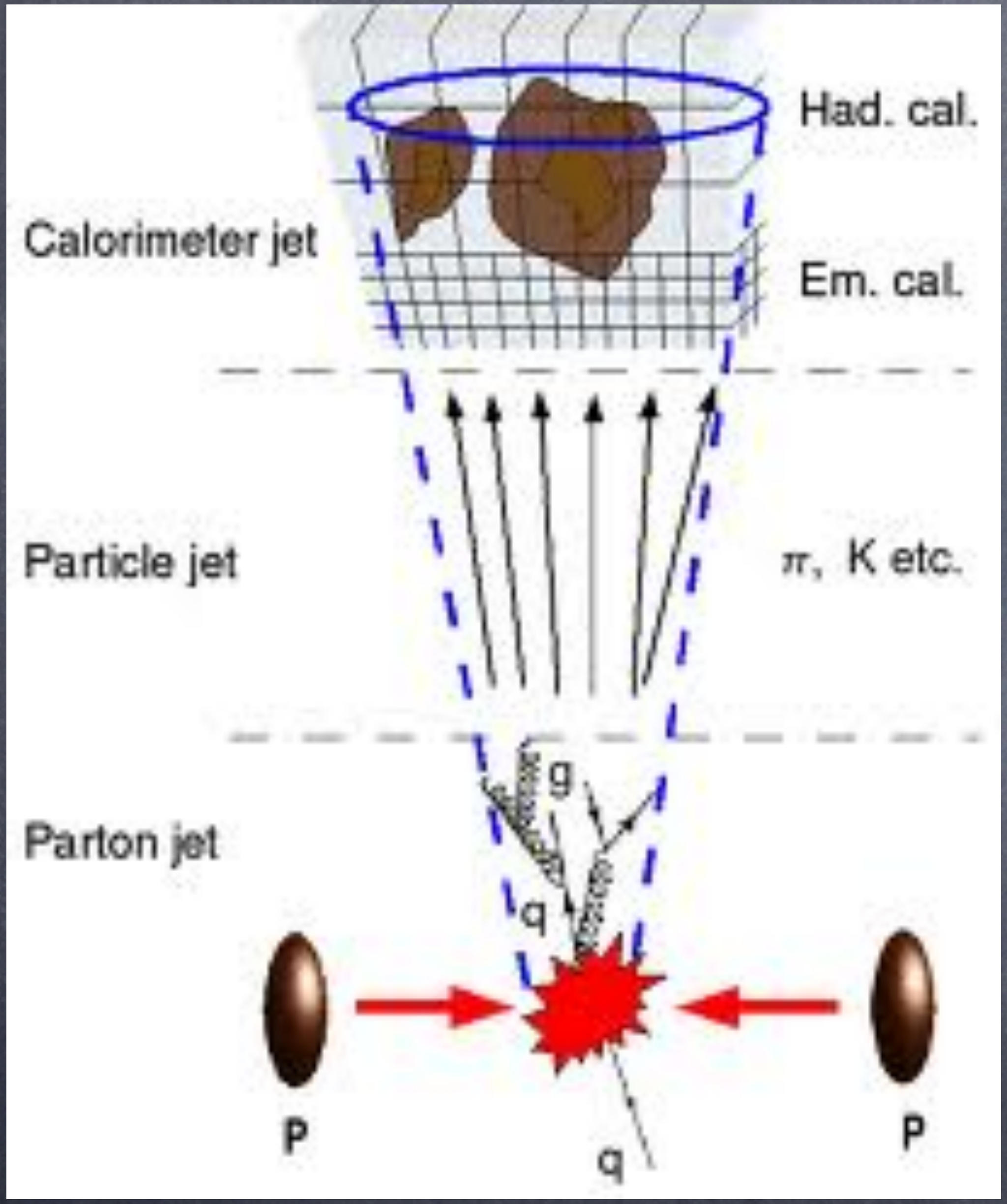


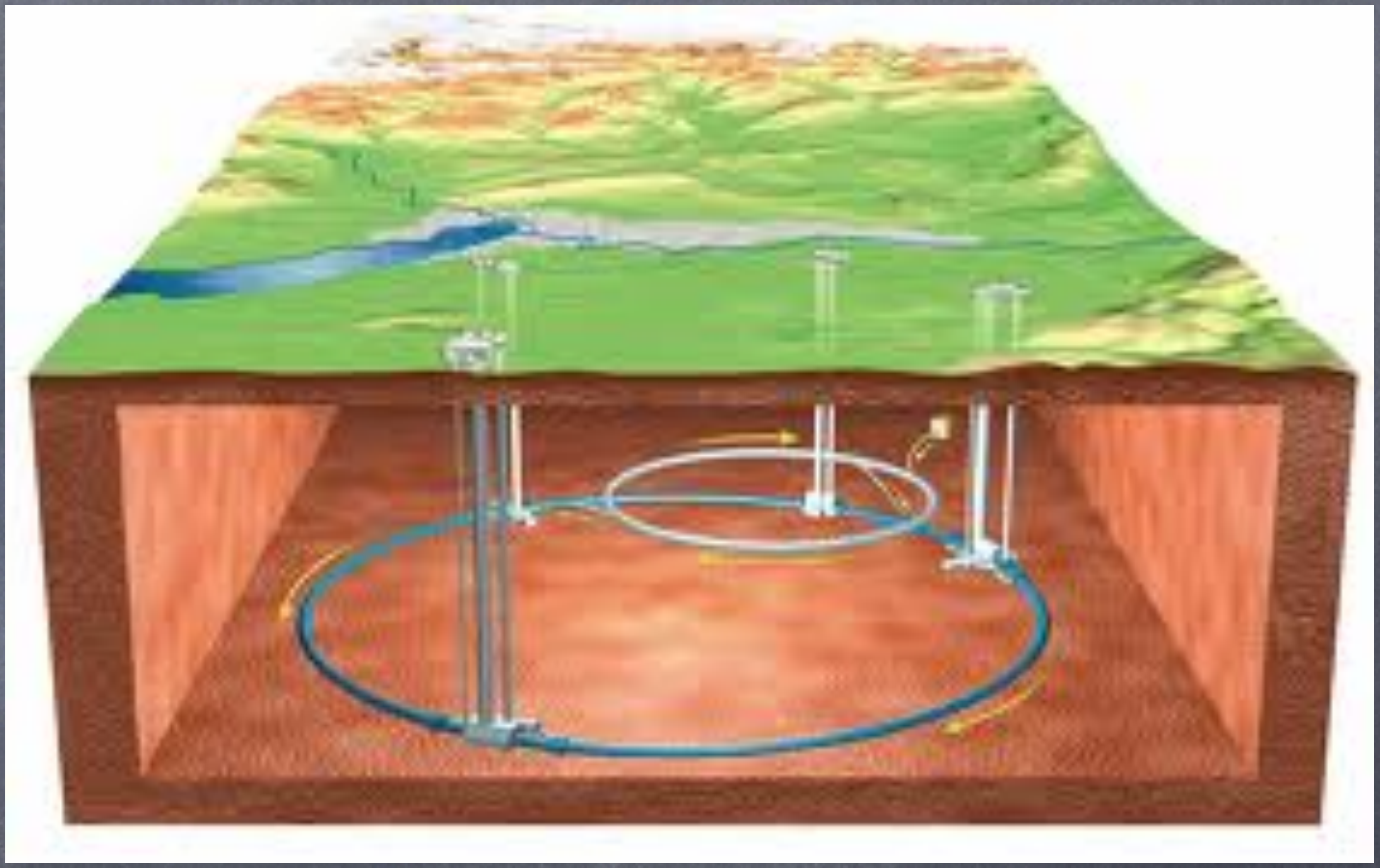
LHC CERN

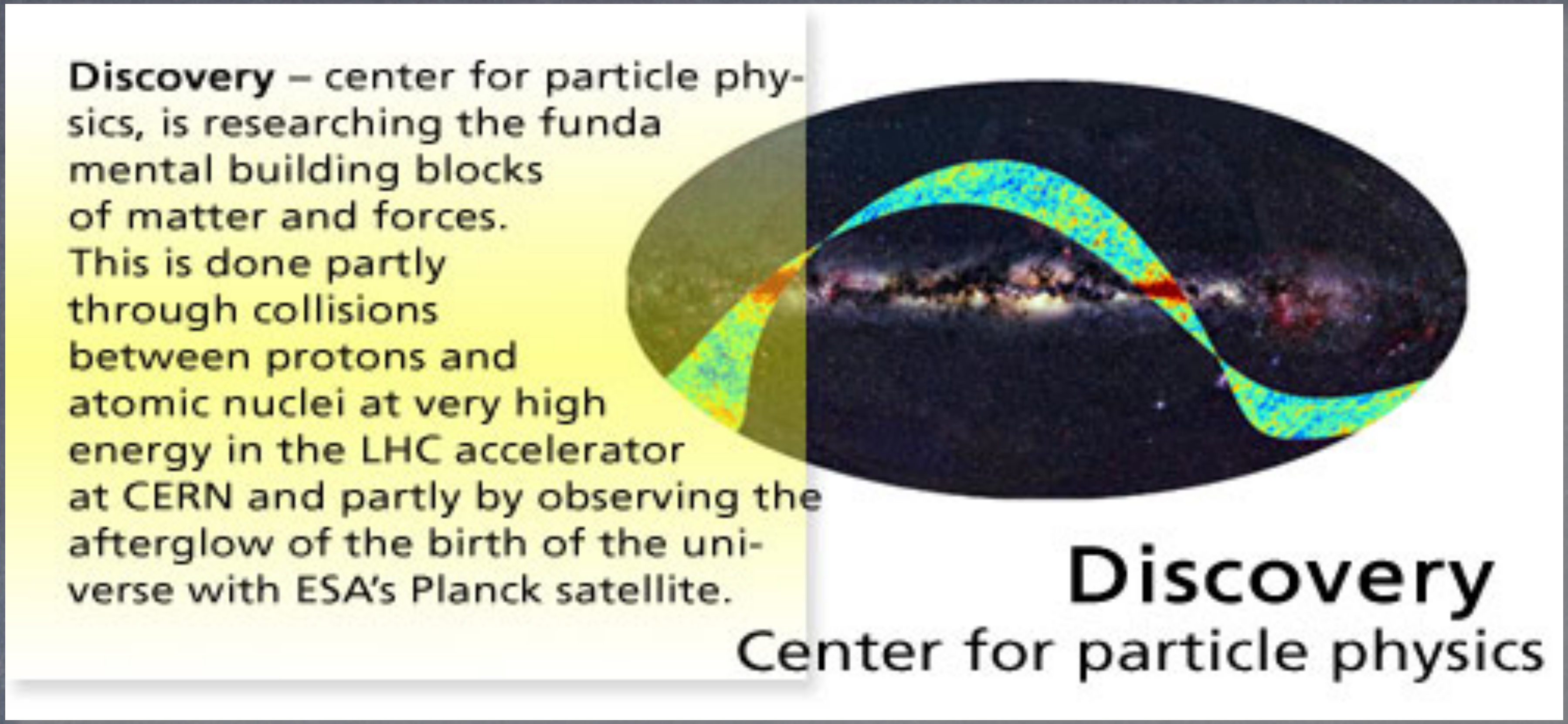
Large Hadron Collider

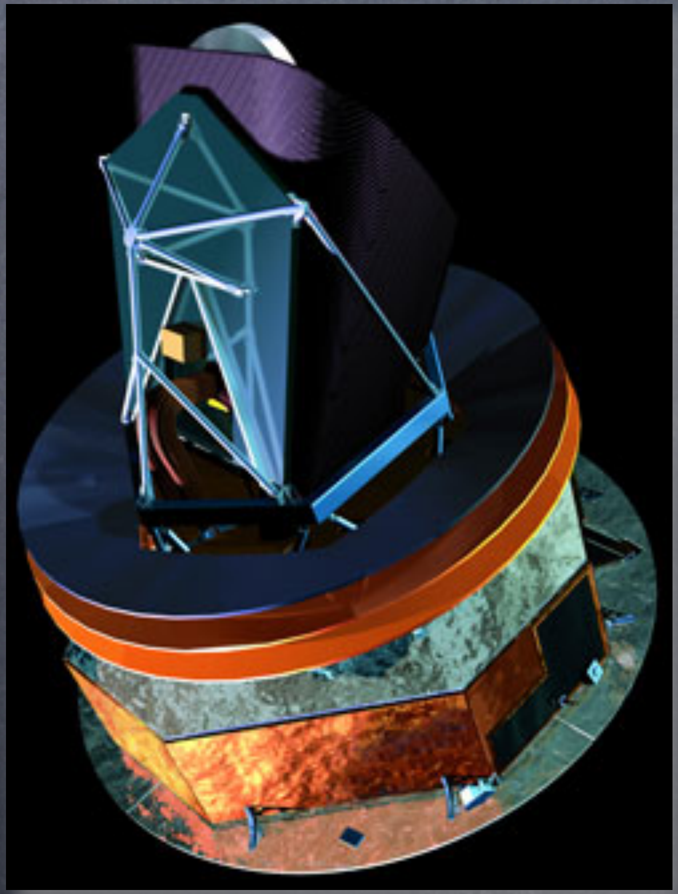


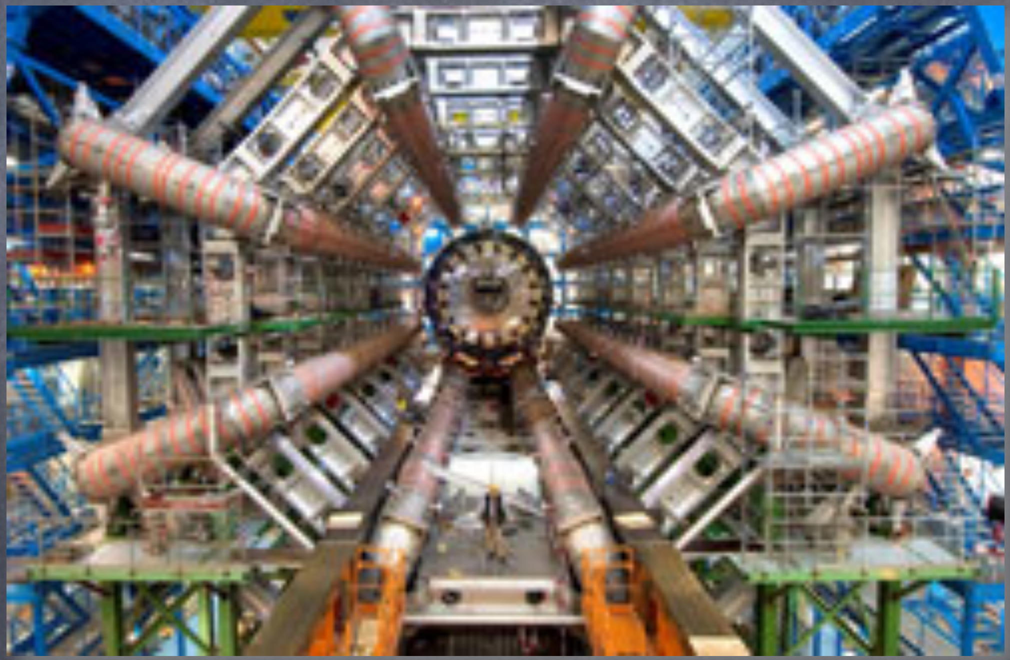
LHC


Had. cal.
Calorimeter jet
Em. cal.
Particle jet
π, K etc.
Parton jet
g
q
P
P
q

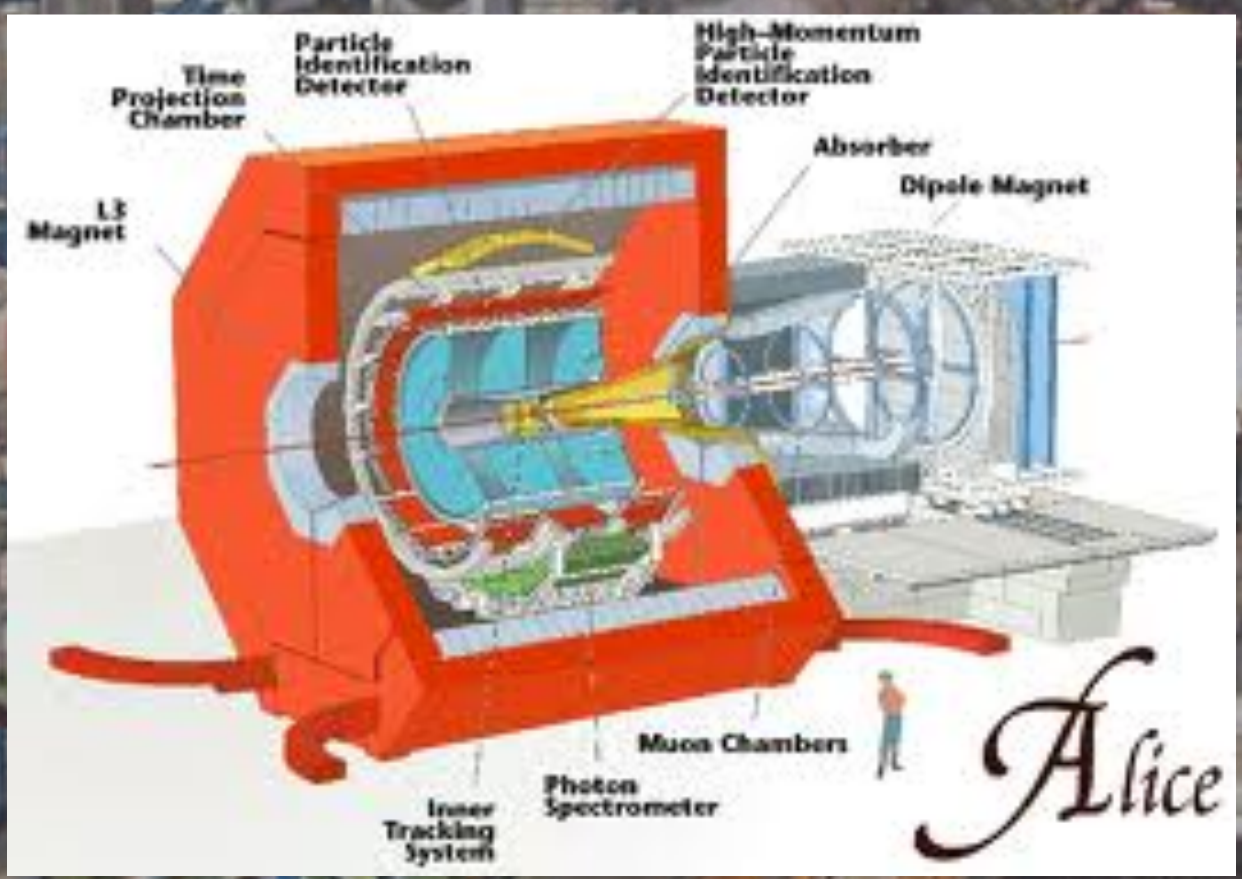


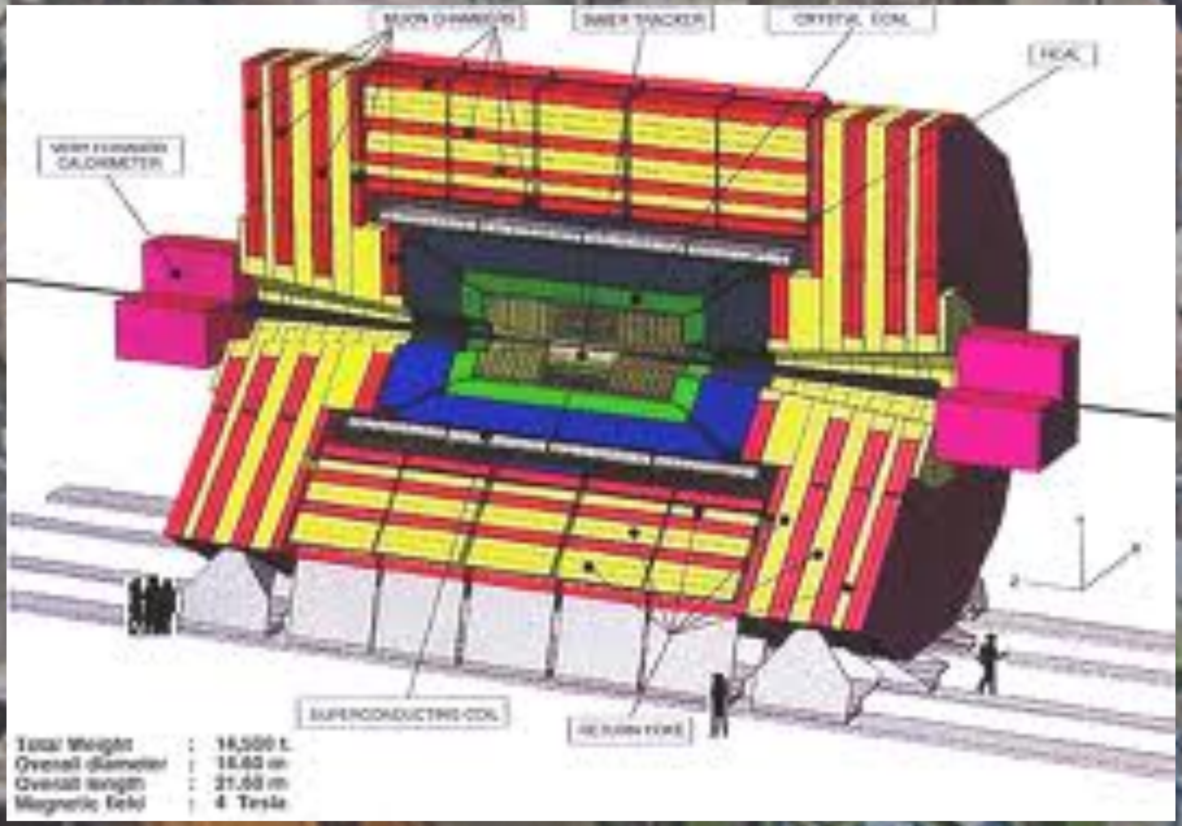

Discovery – center for particle physics, is researching the fundamental building blocks of matter and forces. This is done partly through collisions between protons and atomic nuclei at very high energy in the LHC accelerator at CERN and partly by observing the afterglow of the birth of the universe with ESA's Planck satellite.
Discovery
Center for particle physics



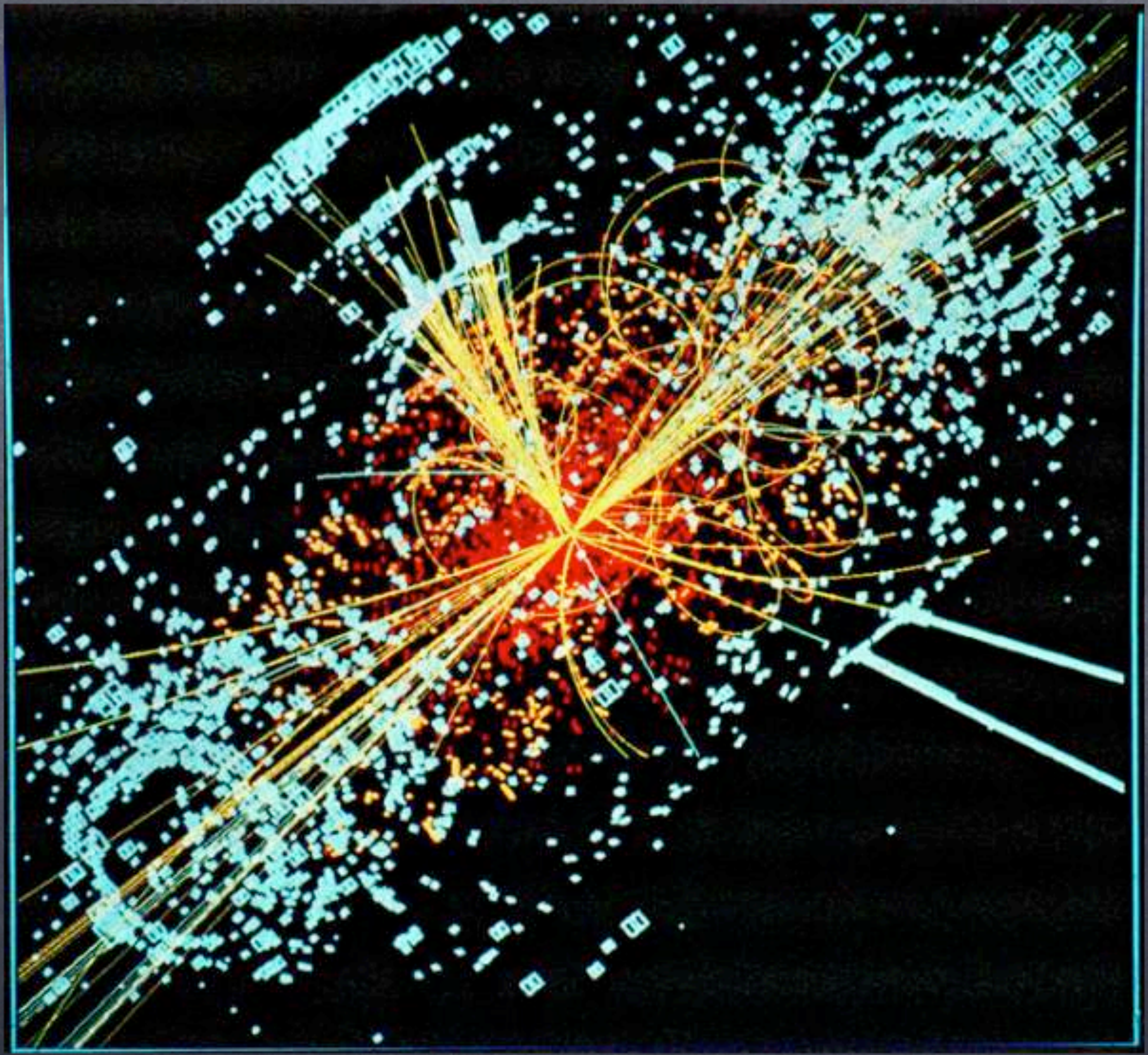


Detektorer

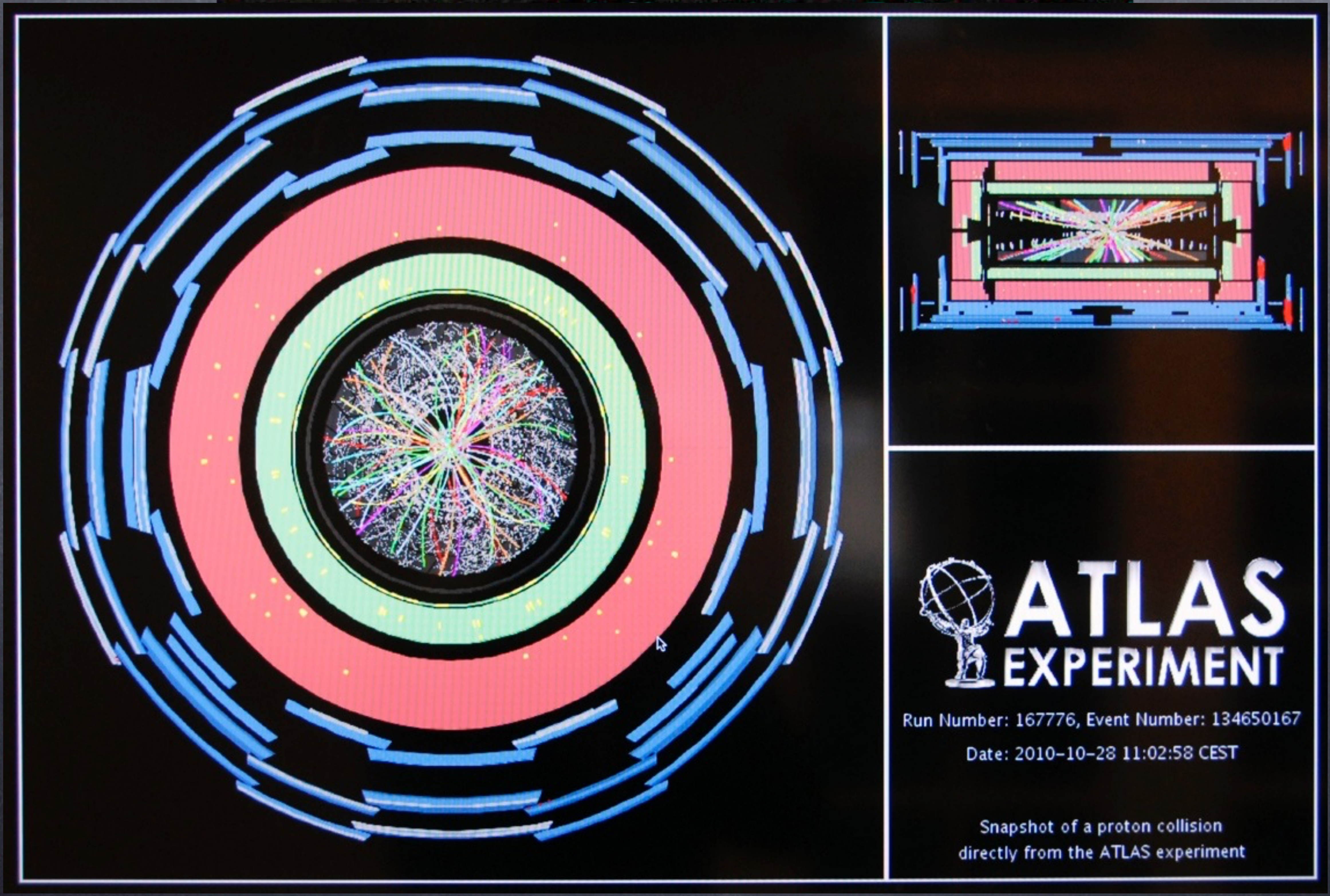

Particle
Identification
Detector
High-Momentum
Particle
Identification
Detector
Time
Projection
Chamber
Absorber
Dipole Magnet
L3
Magnet
Muon Chambers
Photon
Spectrometer
Inner
Tracking
System
Alice


CRYSTAL ECAL
HCAL
SUPERCONDUCTING COIL
Total Weight : 14,500 t.
Overall diameter : 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

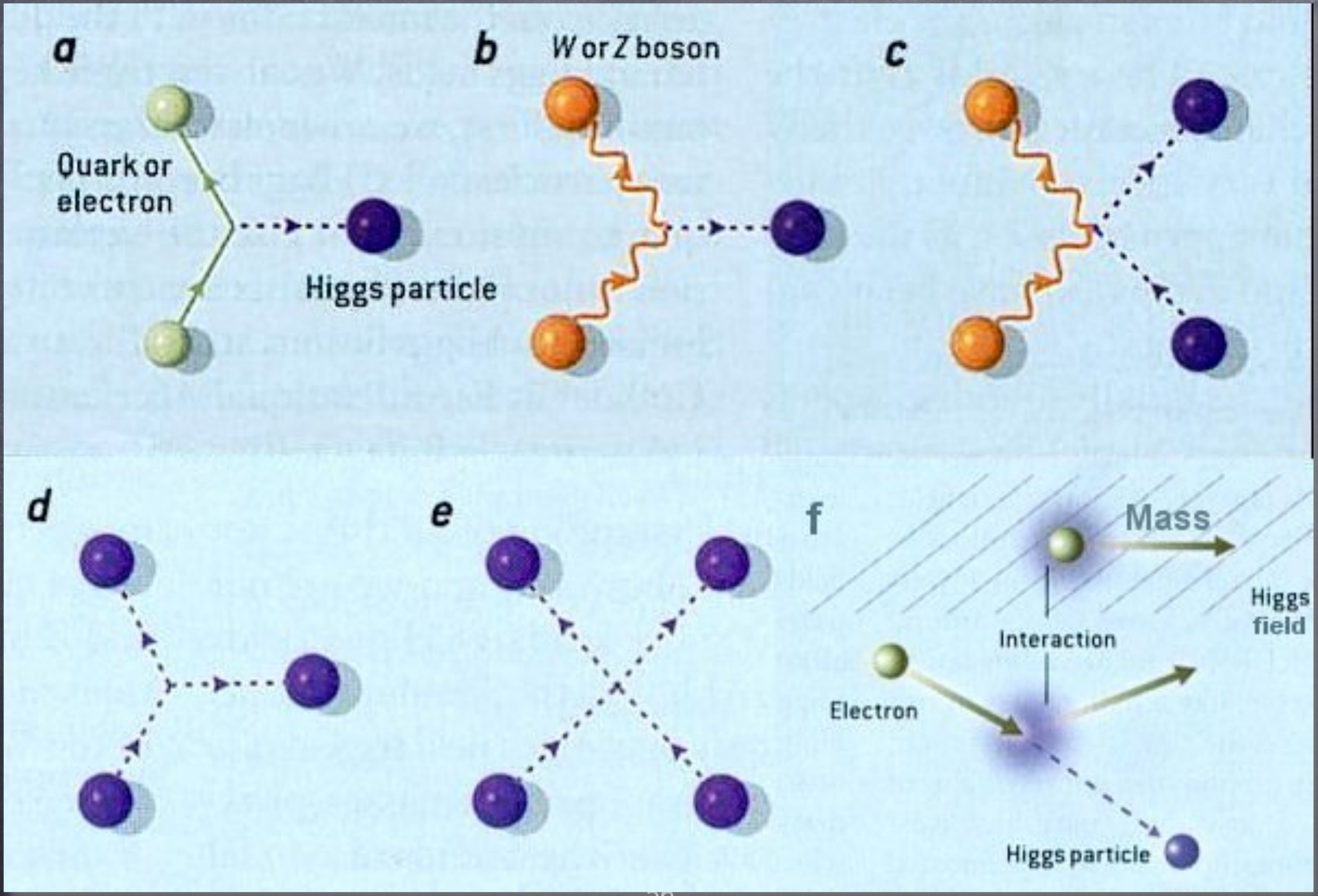
Electronic detectors



Electronic detectors

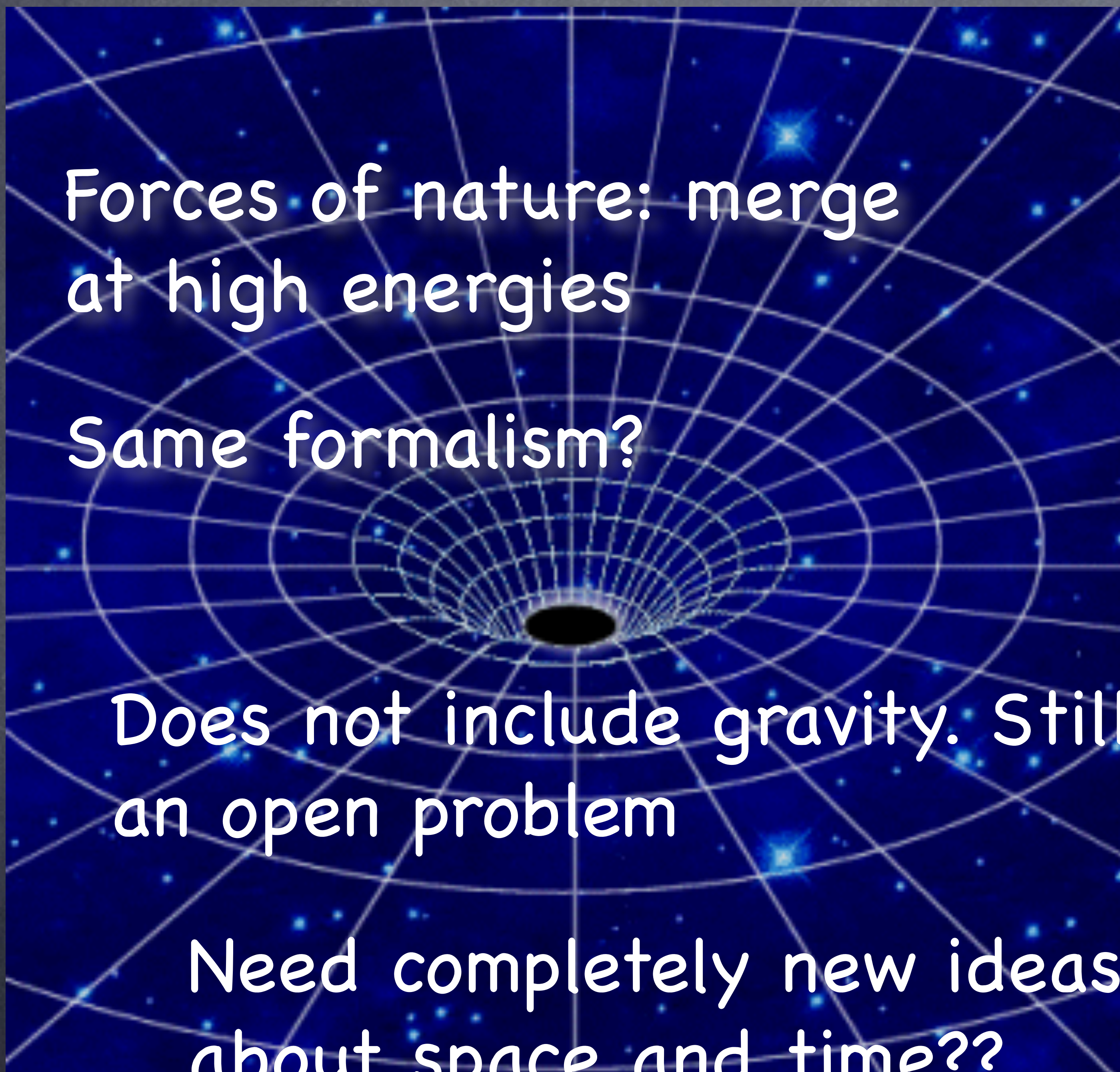


Higgs partikel



So where is the graviton in all this??

Grand-unified theory

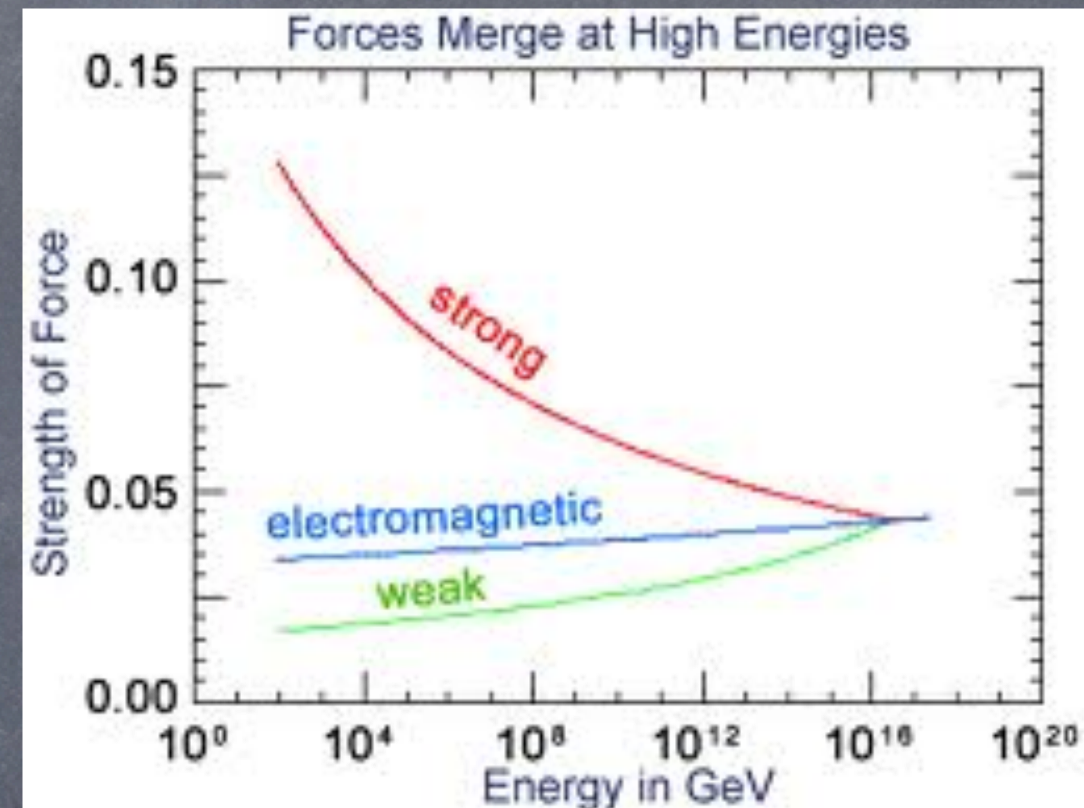


Forces of nature: merge at high energies

Same formalism?

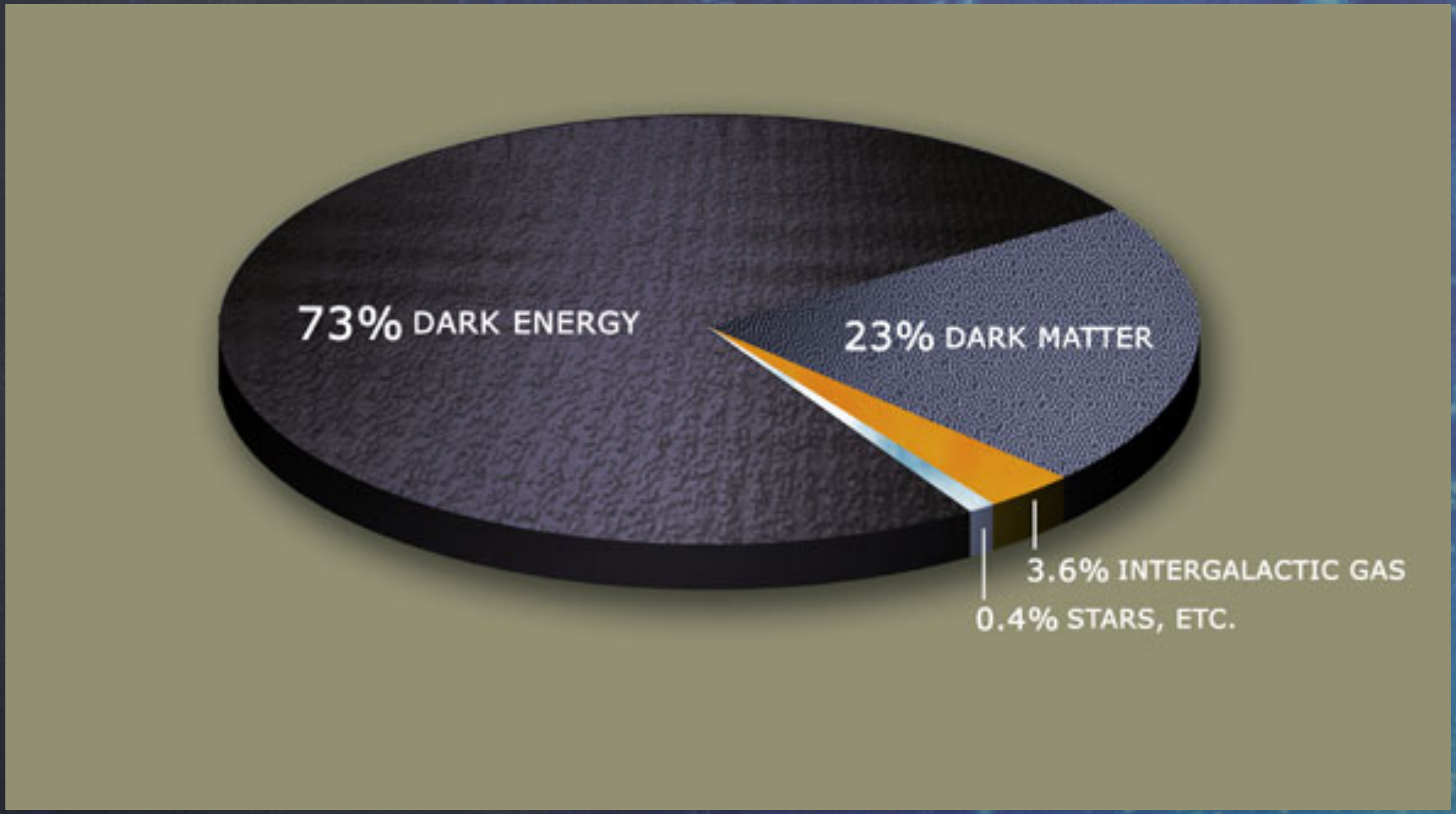
Does not include gravity. Still an open problem

Need completely new ideas about space and time??



Dark matter and antimatter

Universe : Expanding forever



Why more matter than antimatter in universe?

Fundamental antisymmetry??..Current tests

Masses of neutrinos?

What is Dark matter?

PART IV

Quantum gravity as a Particle Theory

How to think of gravity as a quantum theory

- Gravity is mediating the attraction of matter
- We know other theories:
- Electromagnetism: Photons
- Strong interactions: Gluons

Graviton

- Graviton should be emitted from all matter not 'charged' like photons
- It should be an attractive force, not mixed repulsive / attractive like electro-magnetism
- The optimal candidate particle is a spin-2 particle (photons are spin-1)

Einstein-Hilbert

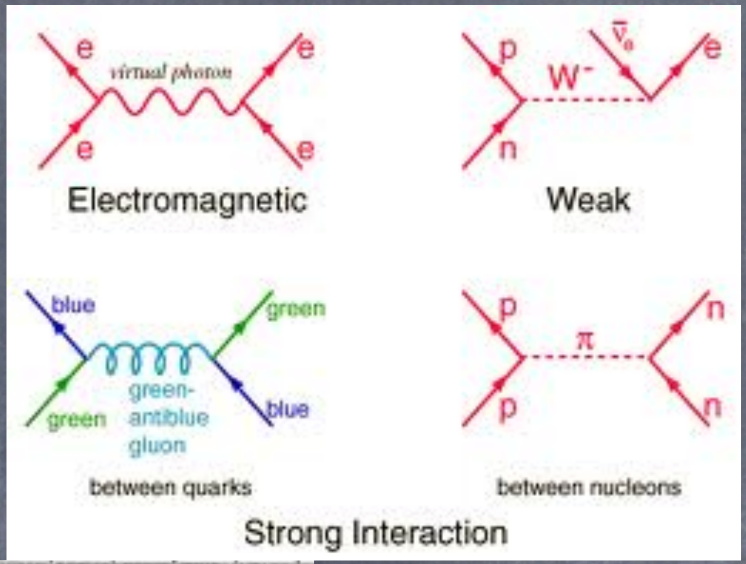
- Einstein equation can be derived from a classical action theory
- The offers a starting point for particle physics.
- Idea is to proceed as if the theory was one we know well like electro-magnetism or strong interactions

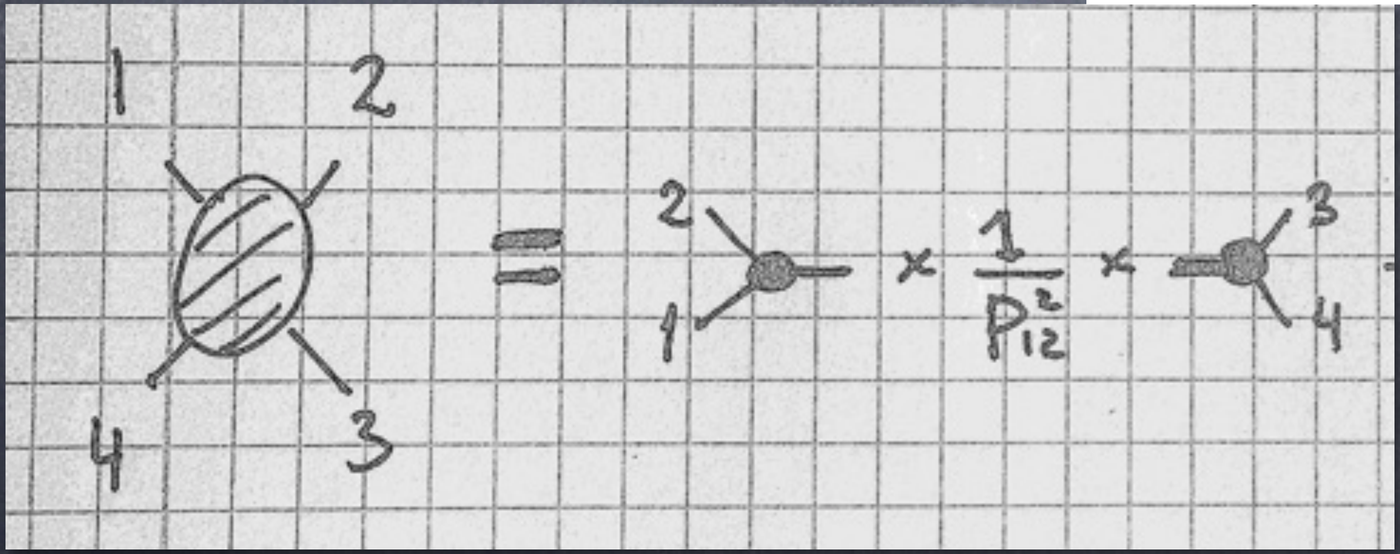
Amplitudes and Feynman diagrams

In particle physics: amplitudes from diagrams

Feynman diagrams

Example



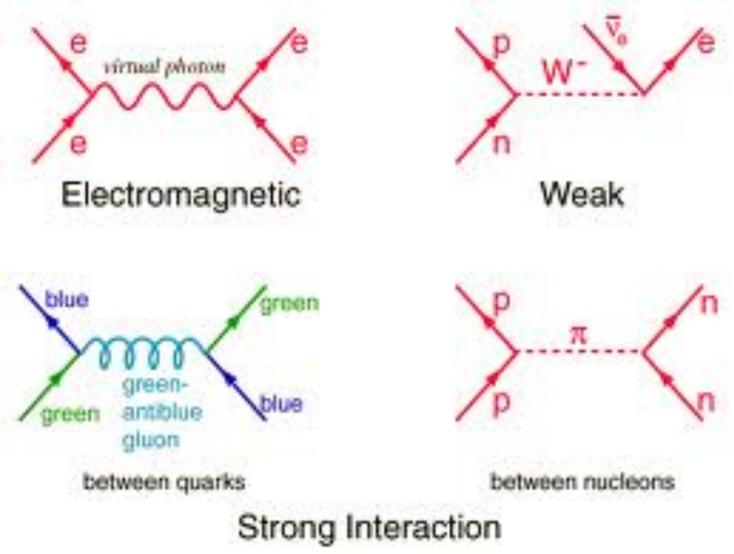


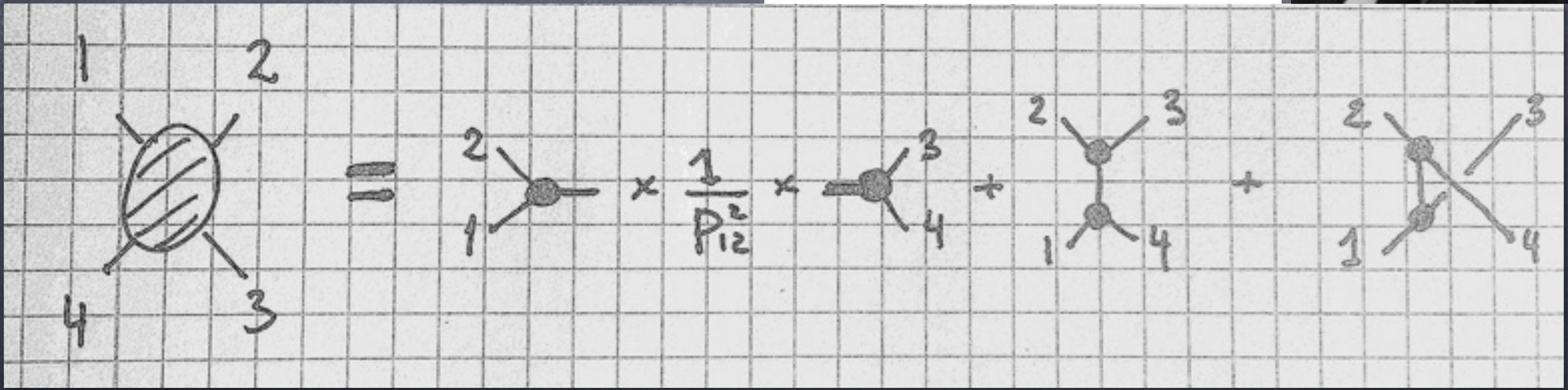
Amplitudes and Feynman diagrams

In particle physics: amplitudes from diagrams

Feynman diagrams

Example





Amplitudes and Feynman diagrams

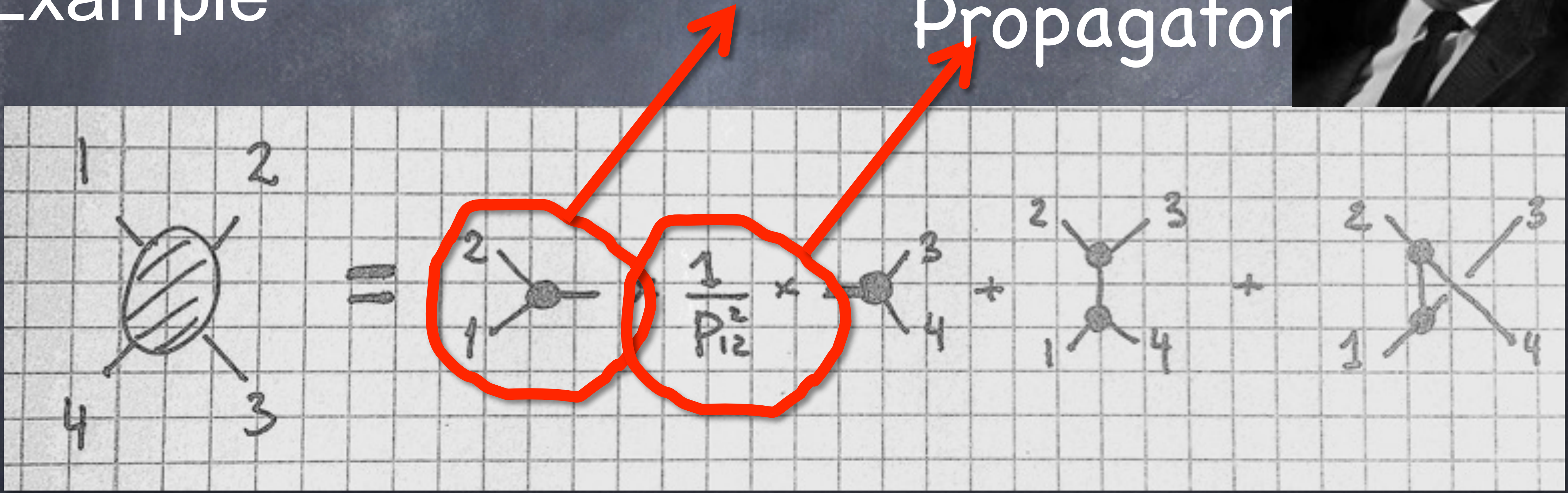
In particle physics: amplitudes from diagrams

Feynman diagrams

Example

Vertex

Propagator



Amplitudes and Feynman diagrams

- Feynman's method not flawless
- Diagrammatic expansion : huge permutational problem!
  - Scalar field theory : constant vertex (i.e. 1 term)
  - Gluons : momentum dependent vertex (i.e. 3 terms)
  - Gravitons : momentum dependent vertex (i.e. 100 terms)
- Naïve basic 4pt diagram count (graviton exchange) :

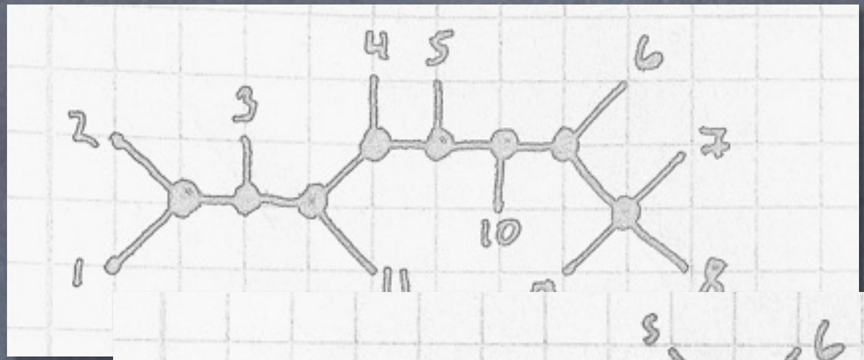
100 x 100 i.e. 10^4 terms + index contractions (i.e. 36 pr diagram)
Number of diagrams: (4 !) 10^5 terms i.e. 10^6 index contractions
n-point: (n !) i.e. more atoms in your brain!

Too much clutter.....

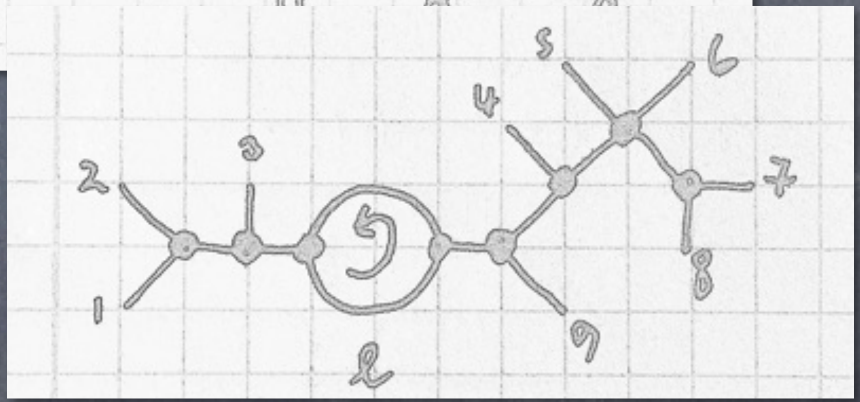
Topologies of amplitudes

- Feynman diagrams have different topologies:

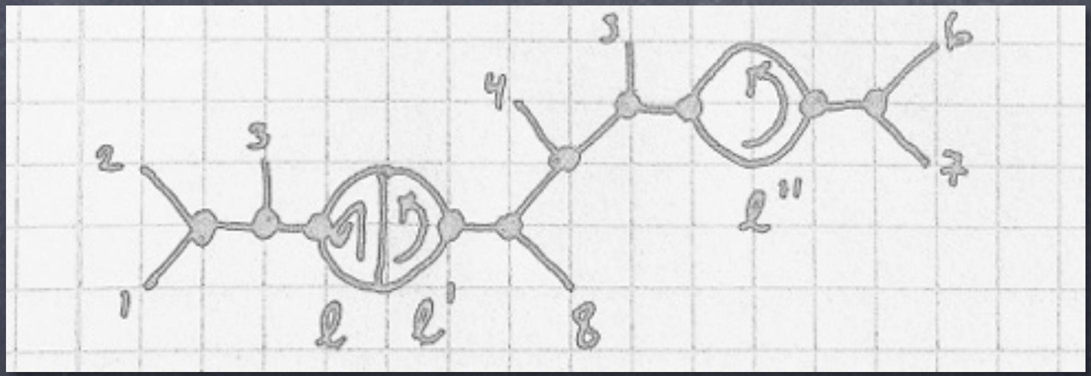
- Tree diagrams :



- One-loop diagrams :



- Multi-loop diagrams :

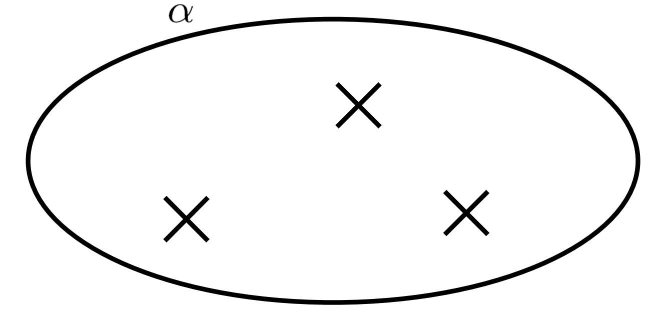


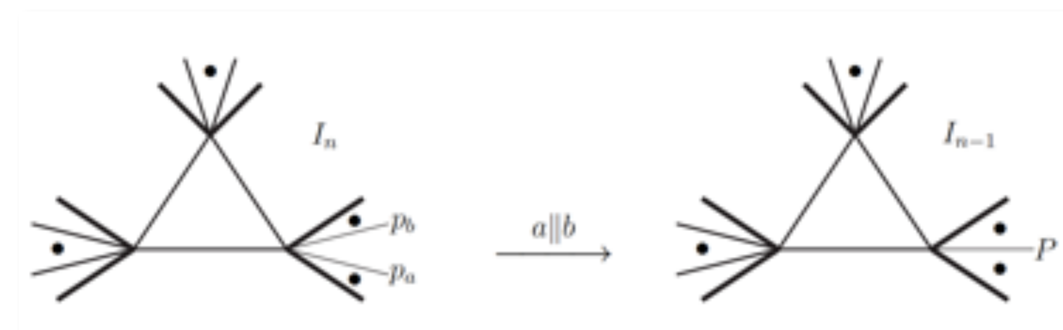
Amplitude cookbook!

1 Unitarity: Fuse tree amplitudes into loops

2 Recursion: Extend trees and loops into more complicated amplitudes

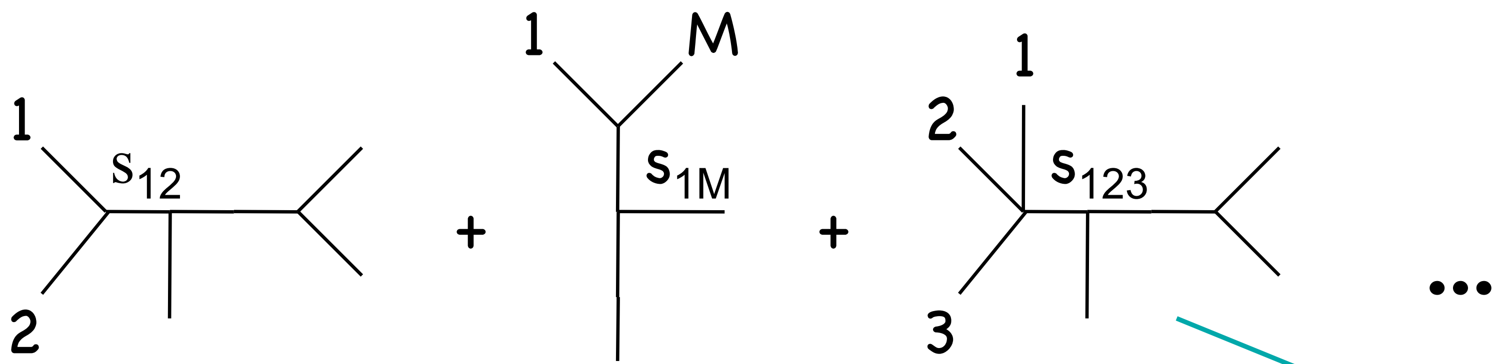
$$A(0) = -\sum_{\alpha} \mathrm{Res}_{z=z_\alpha} \frac{A(z)}{z}$$



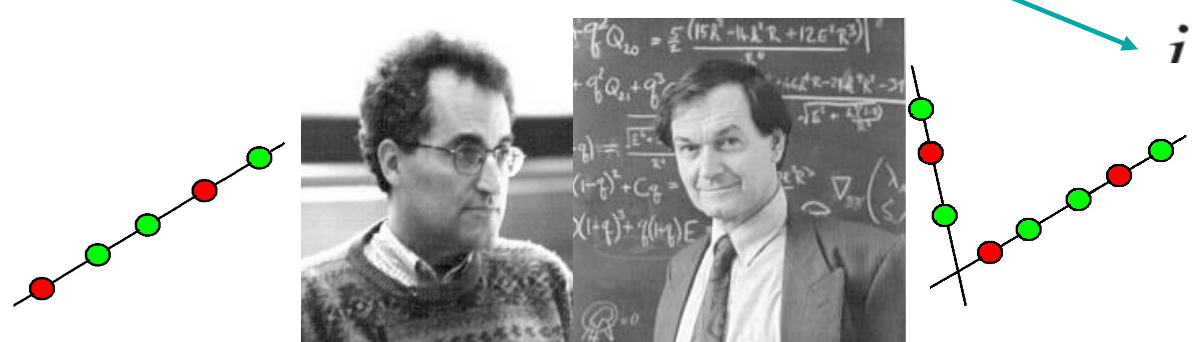


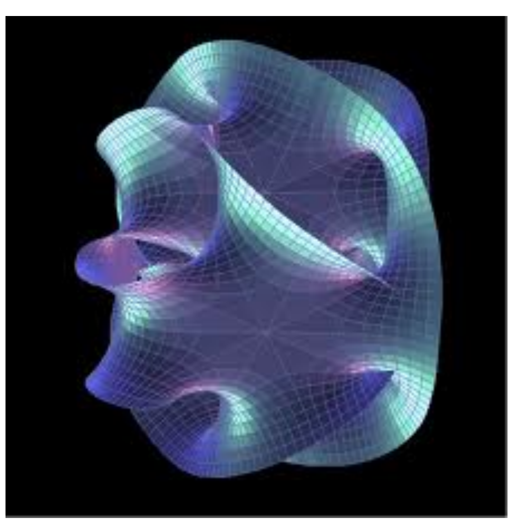
3 String theory: Complete the picture and link concepts

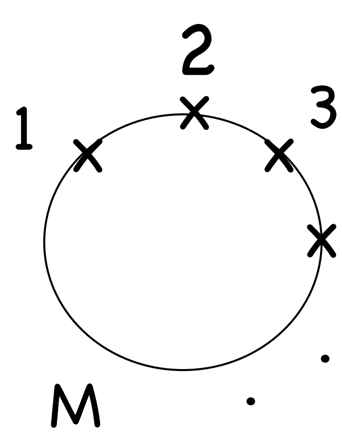
Research

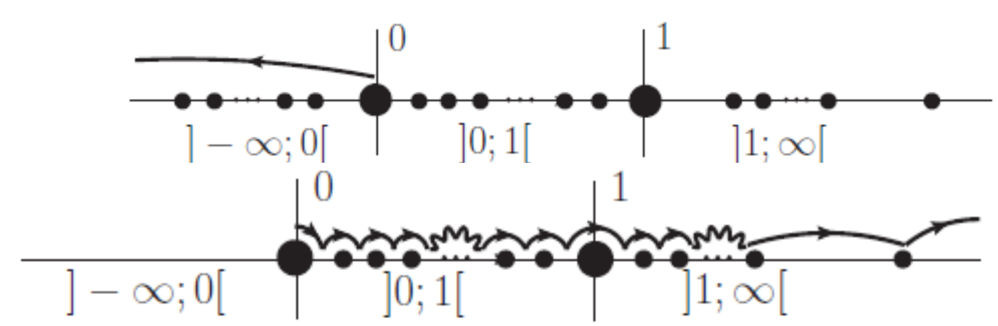


$$i\,\frac{\langle j\,k\rangle^4}{\langle 1\,2\rangle\langle 2\,3\rangle\cdots\langle n\,1\rangle}$$

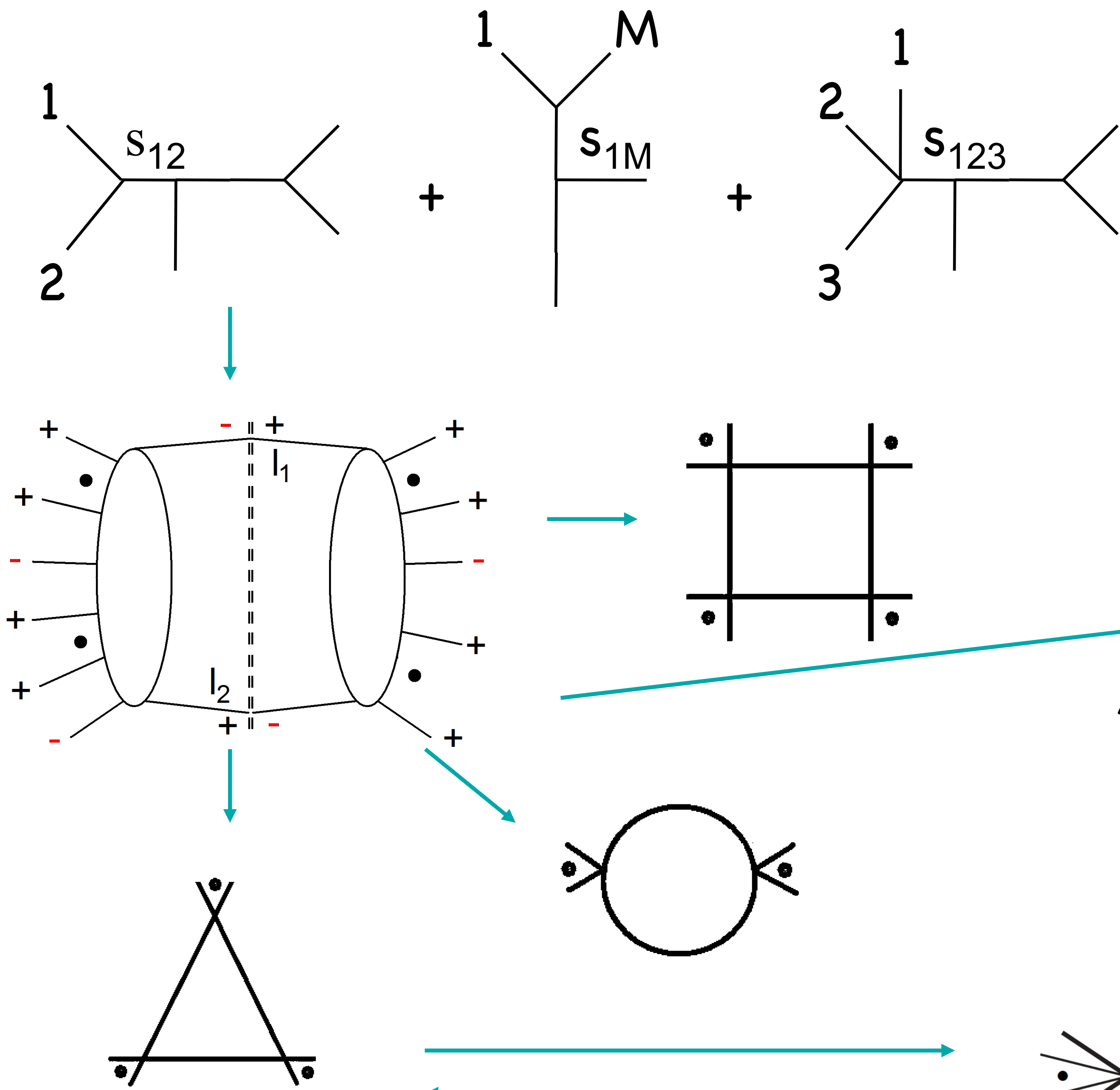


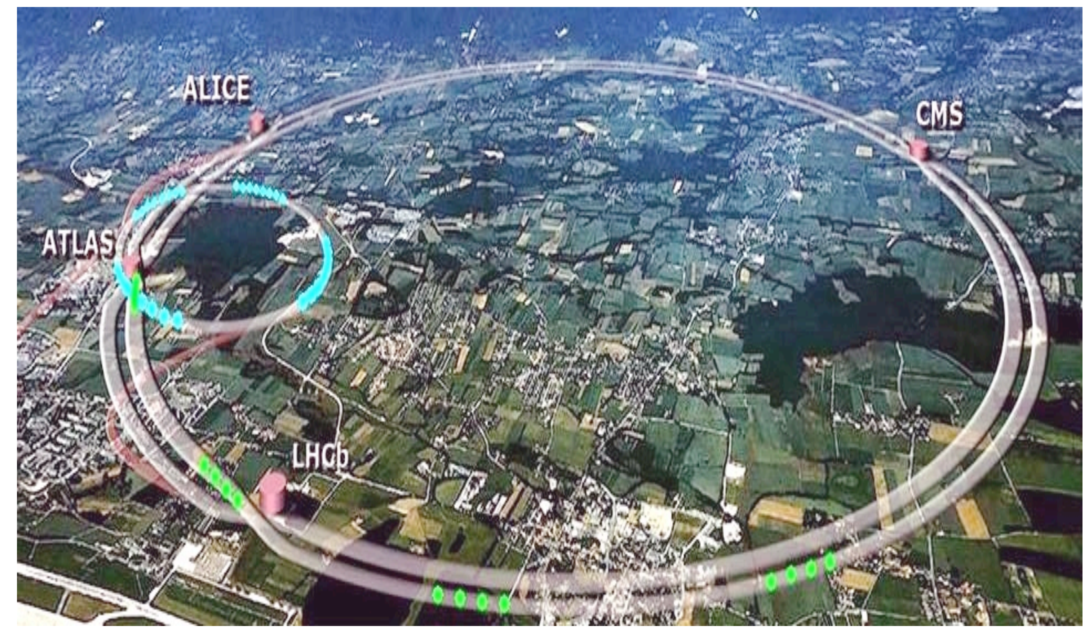




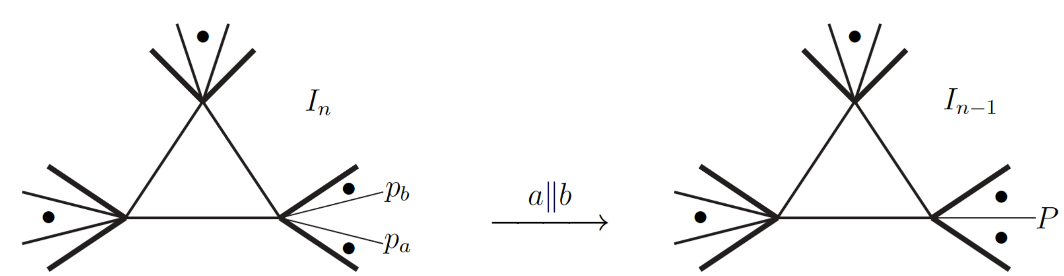


Research



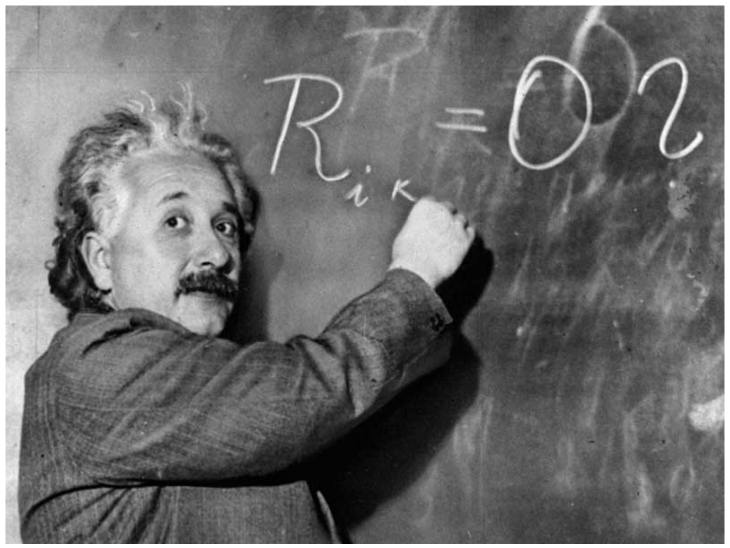


Amplitudes$^2 \sim$ Probabliity

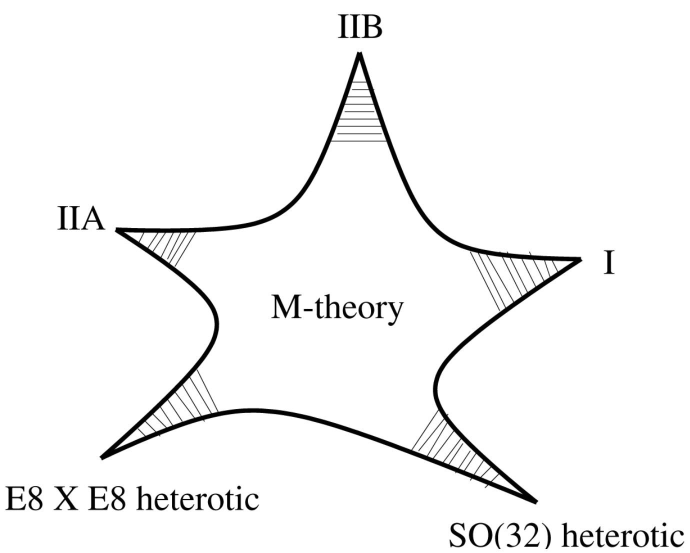


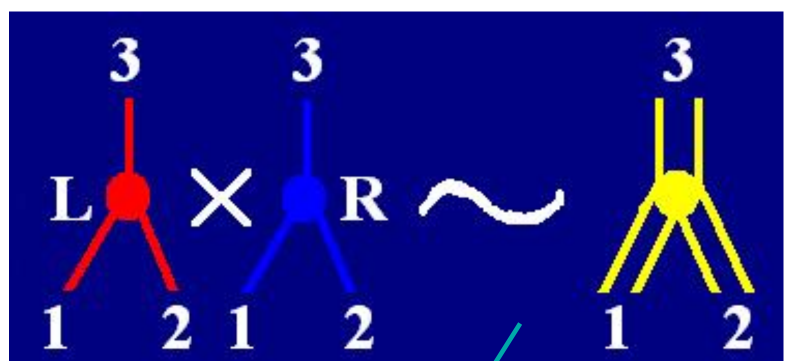
Research

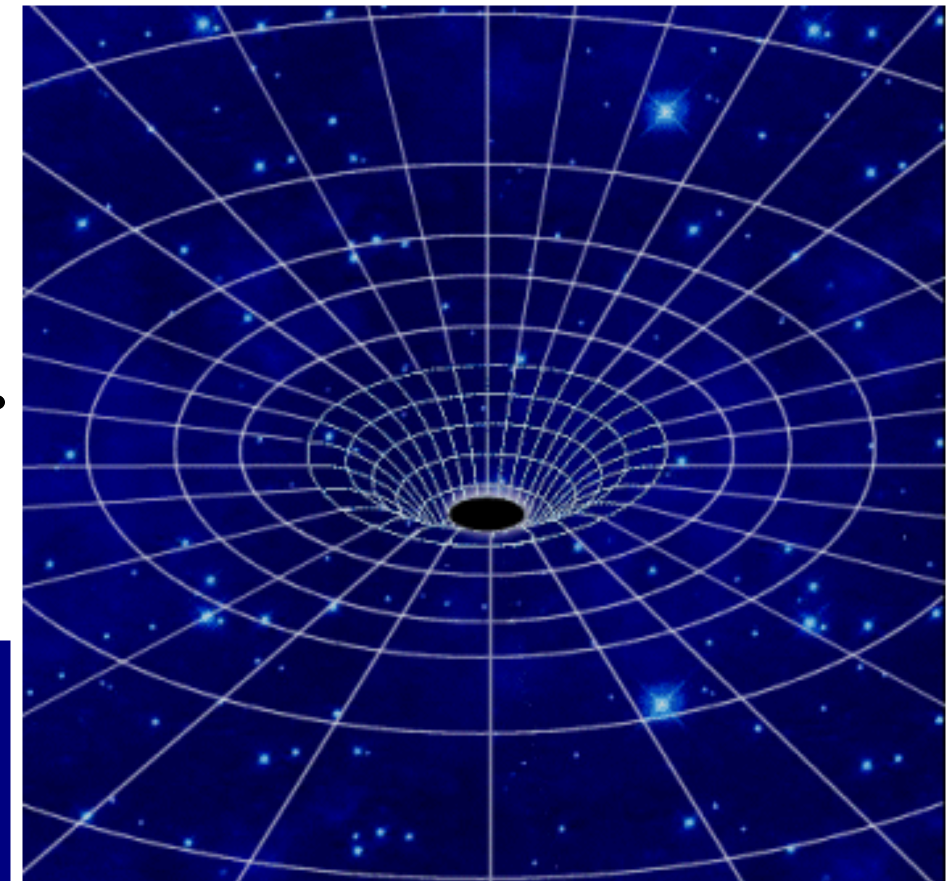
Gravity



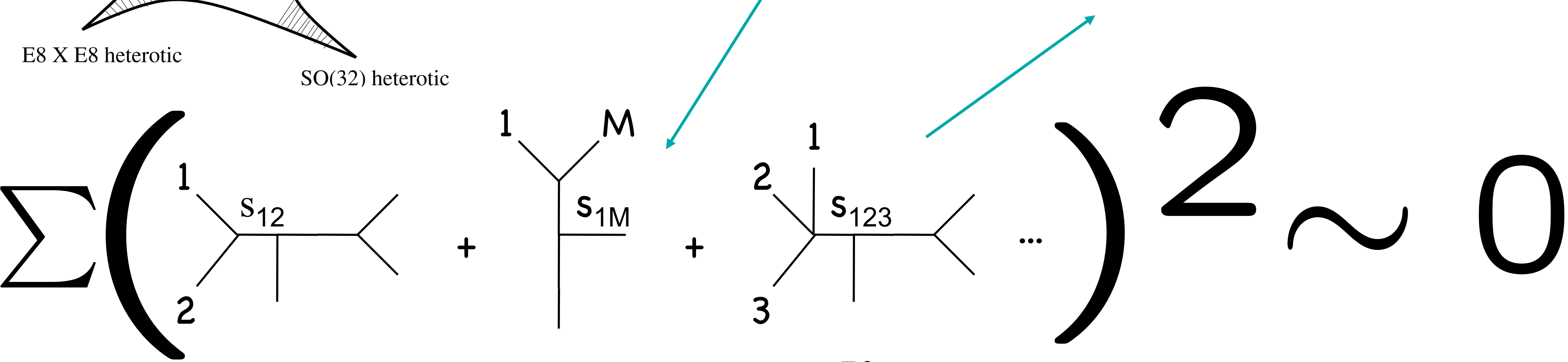
Highly creative and experimental..

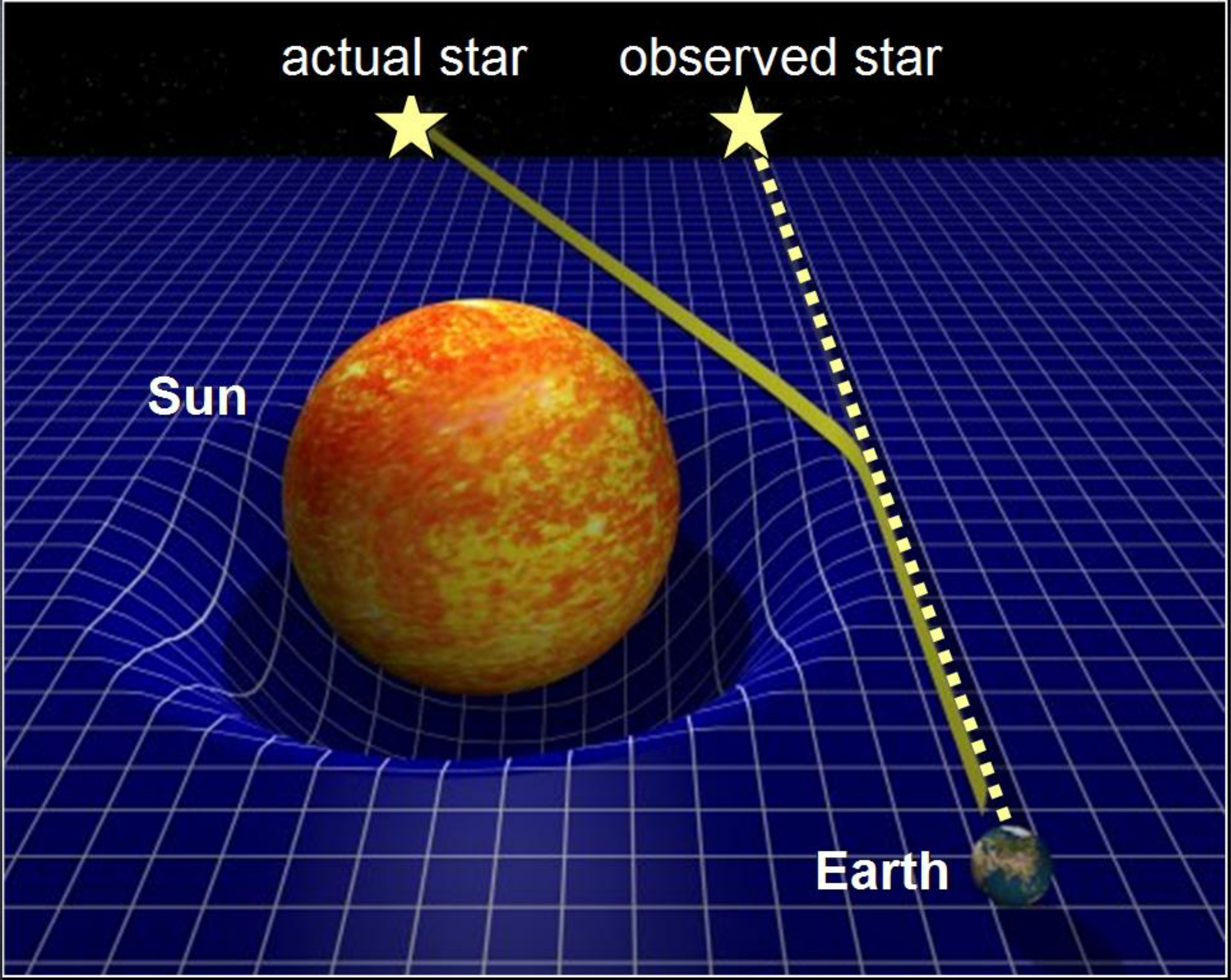






'Vanishing' relations!!!




actual star
observed star
Sun
Earth

Quantum gravity from particle physics

PRL **114,** 061301 (2015) PHYSICAL REVIEW LETTERS week ending 13 FEBRUARY 2015

Bending of Light in Quantum Gravity

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We consider the scattering of lightlike matter in the presence of a heavy scalar object (such as the Sun or a Schwarzschild black hole). By treating general relativity as an effective field theory we directly compute the nonanalytic components of the one-loop gravitational amplitude for the scattering of massless scalars or photons from an external massive scalar field. These results allow a semiclassical computation of the bending angle for light rays grazing the Sun, including long-range $\hbar$ contributions. We discuss implications of this computation, in particular, the violation of some classical formulations of the equivalence principle.

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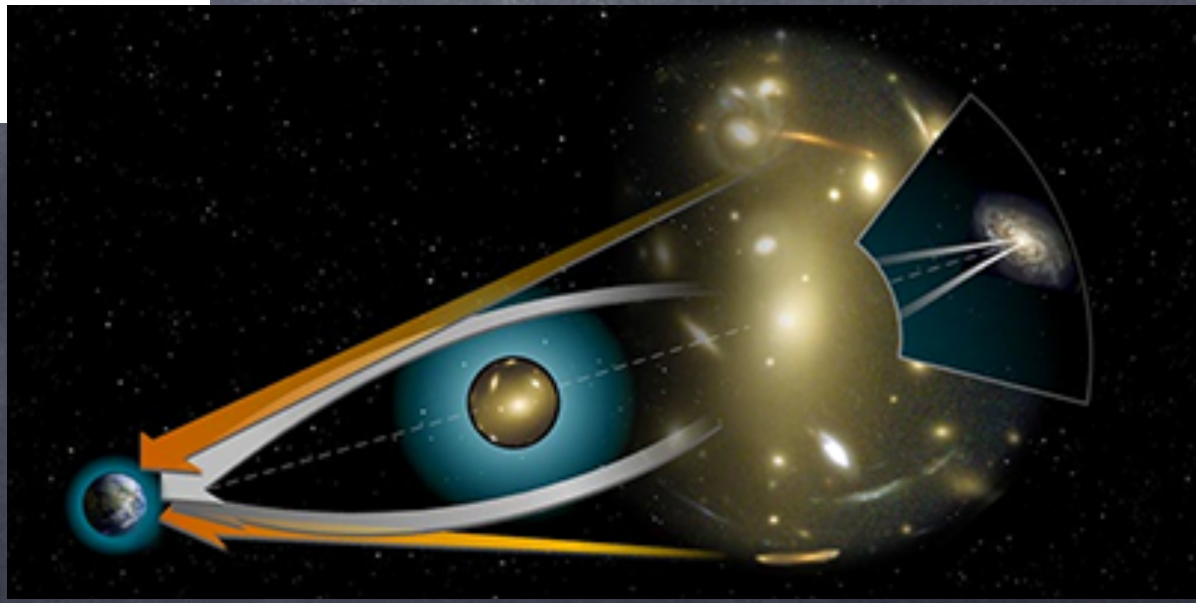
Using only particle theory plus computational tricks!

Reproduces Einstein's result plus quantum effects!

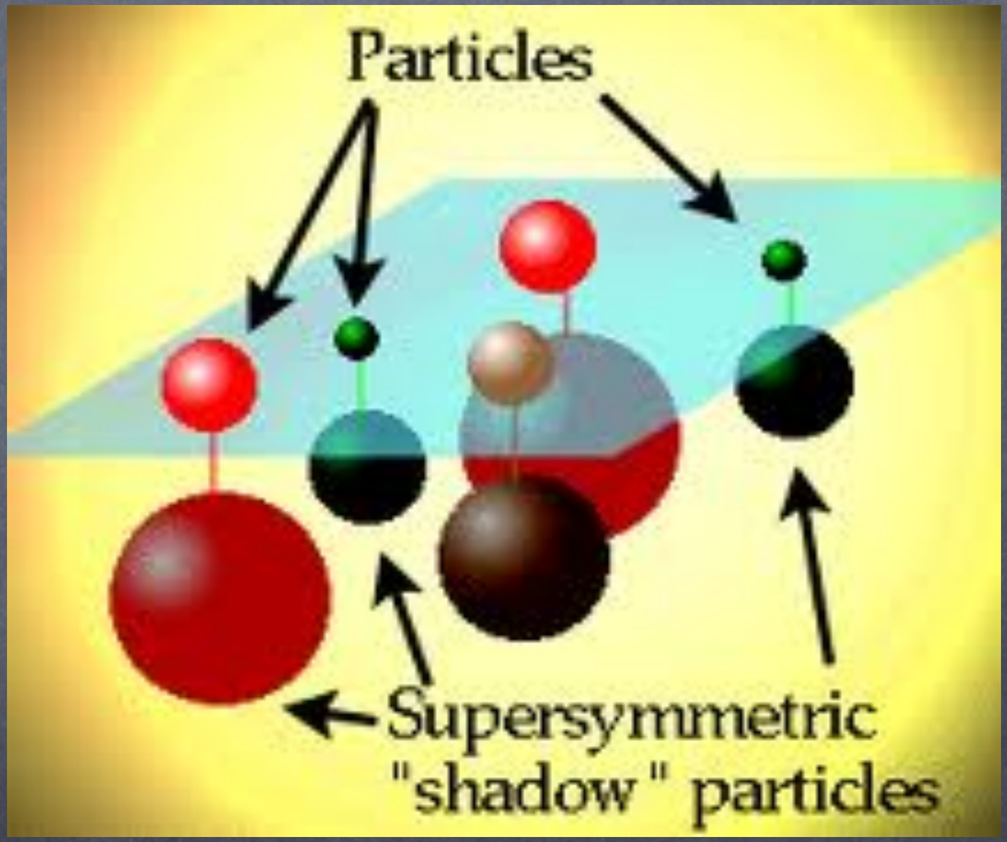


Quantum gravity from particle physics

- Solves part of the problem: how to combine particle physics and general relativity
- There is a framework where it is possible to compute in quantum mechanical valid way.
- Very high-energy limit: still a problem, here new non-perturbative effects are needed + it appears fundamental obstacles hinders valid computations. String theory??

Extensions of the Standard Model

- Big changes in concepts of standard model difficult
  - Extra symmetry?
- Super-symmetry exciting possibility
  - Solves many issues...
  - Funny new dimensions with anti commuting variables: X Y = - Y X (Grassman)



Supersymmetry

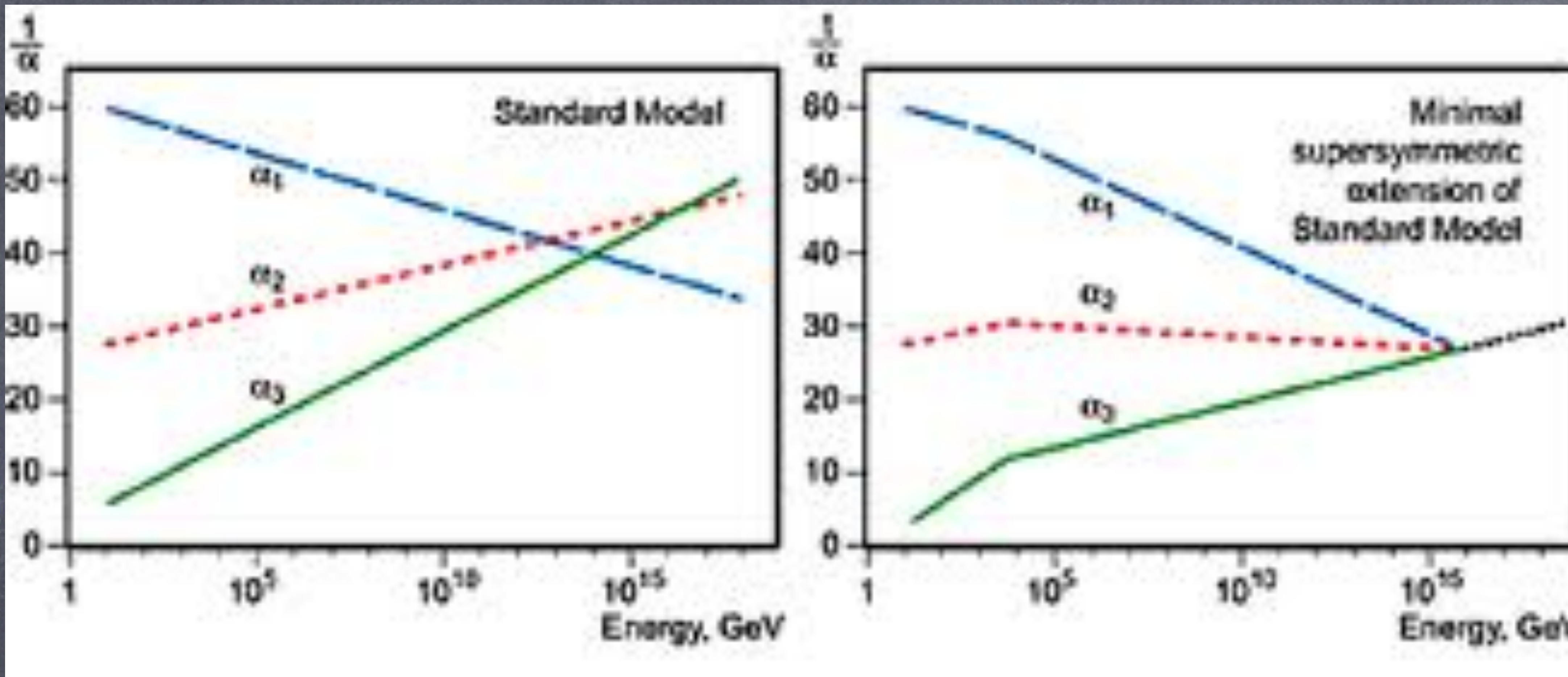
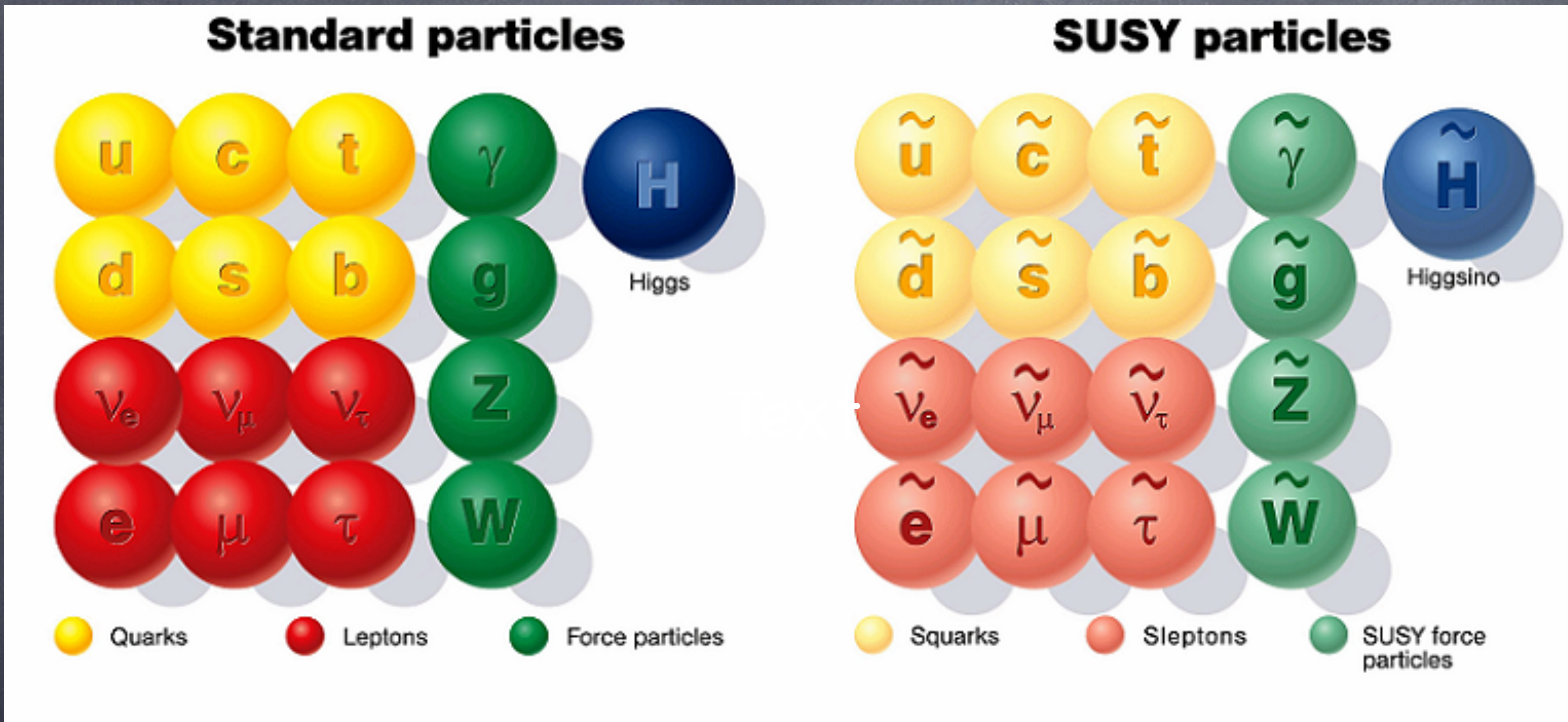


FIG. 8: Unification of interactions helped by SUSY

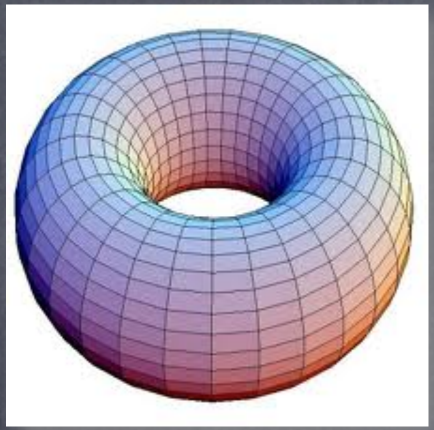
Problem: forces of nature seems to not meet in a point if we try to reach unification scales (with supersymmetry they do...)

Supersymmetry

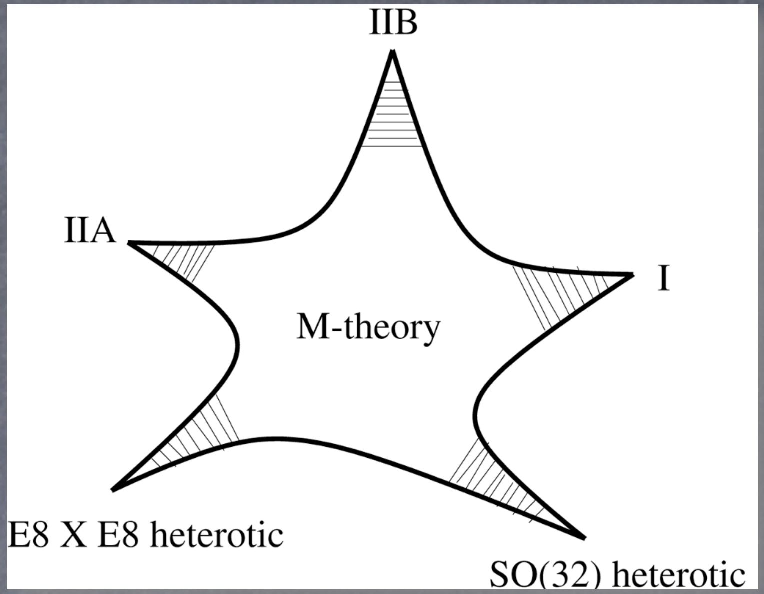


New model(s), couplings, fields

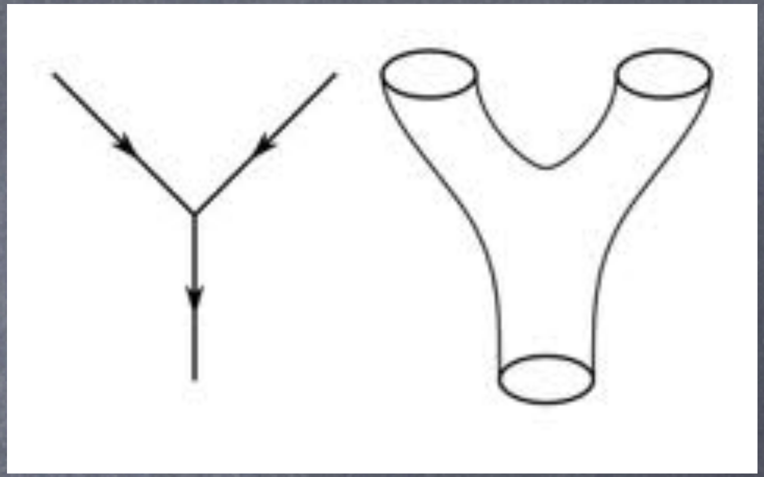
Quantum gravity?

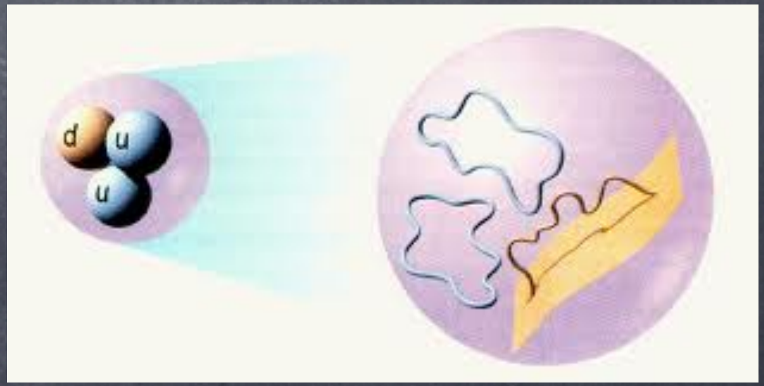


String theory



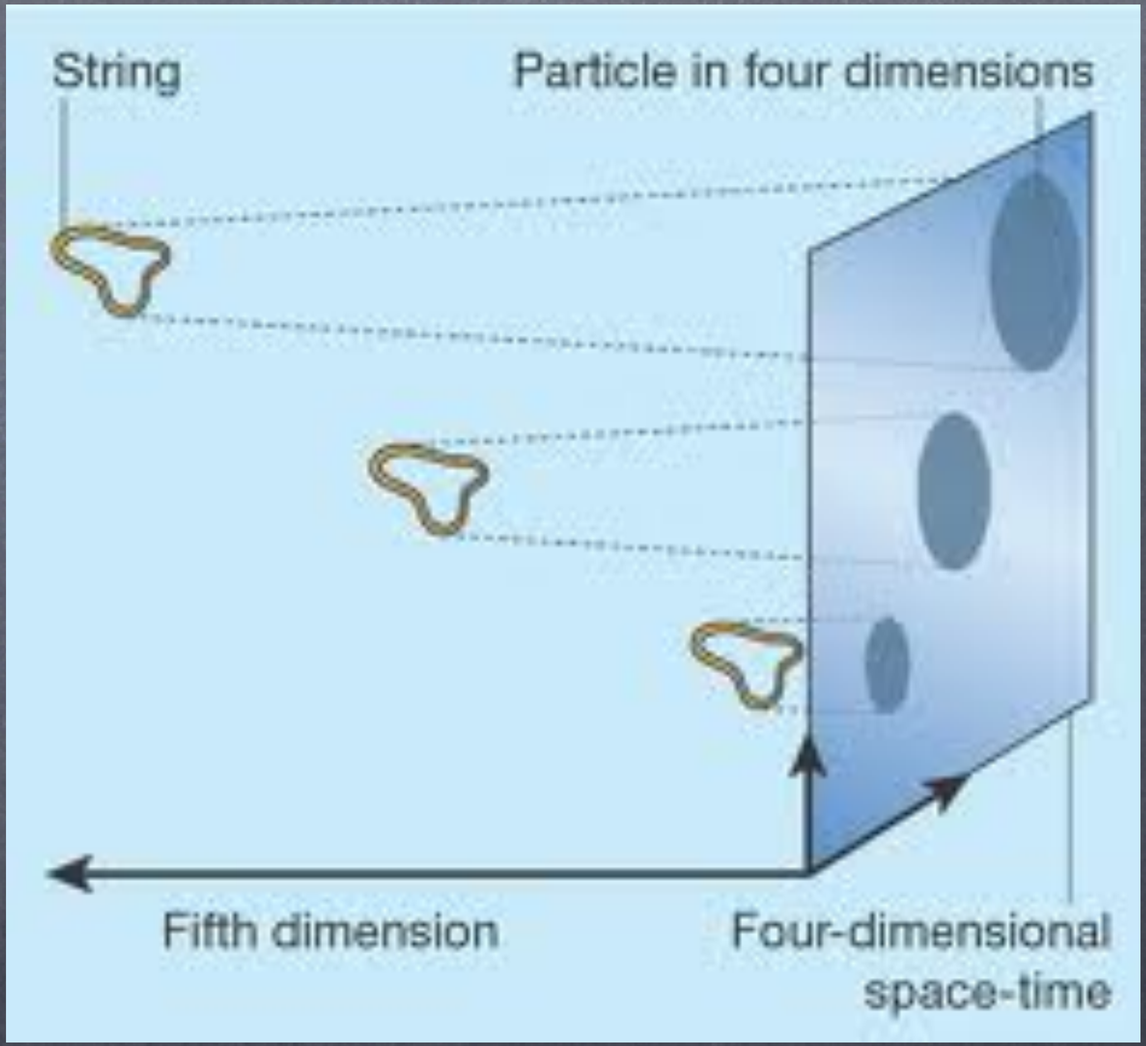
- Natural quantum gravity
- Particles as vibrations on strings
- M-theory in 10 Dimensions
- From creative point of view: Natural idea: extend the concept of interaction point into a interaction surface...





Extra dimensions

If we are creative we can understand particles in 4D as shadows of particles living in higher dimensions.



Quantum gravity visions going ahead

Still many things we do not know..

But we are making progress all the time.

We are seeing deep connections in quantum mechanics - between gauge and gravity theories

Developments no one would have believed of a few years ago.

Very exciting times in physics ahead!

Every great and deep difficulty bears in itself its own solution. It forces us to change our thinking in order to find it.

Niels Bohr

Learn from yesterday, live for today, hope for tomorrow. The important thing is not to stop questioning

Albert Einstein


Tak fordi De lyttede med

International Linear Collider