

From Particle Physics to Quantum Gravity

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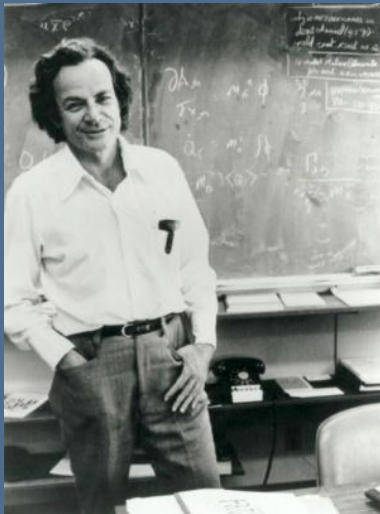
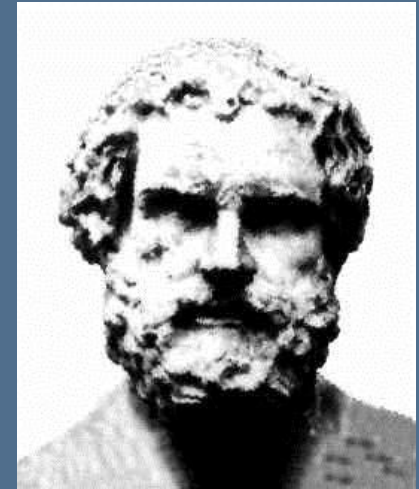
Atomists

- All matter is composed of atoms separated by vacuum

Immutable, Eternal

- Goal: explain similarities and differences
- “Atom” – the one that can not be divided in parts (indestructible)

Democritus (460-371 A.C.)



Feynman (Nobel 65)

Most important and far reaching hypothesis ever made about nature

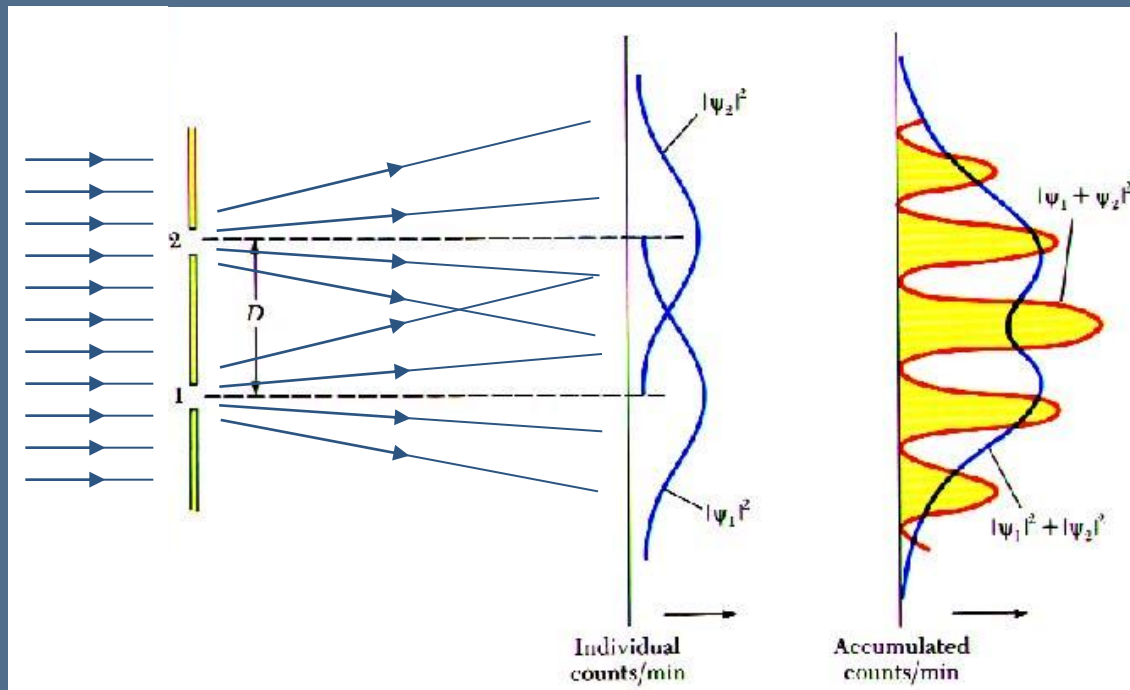
Particle/wave duality

Particles propagate like waves
of wave length

$$\lambda = \frac{h}{p}$$



de Broglie (Nobel 29)



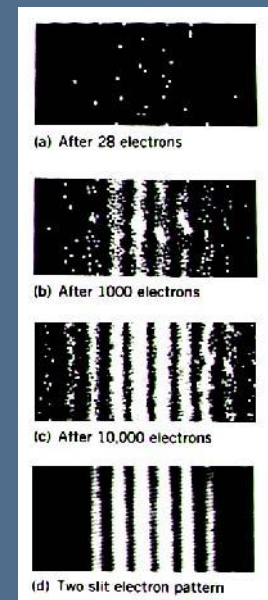
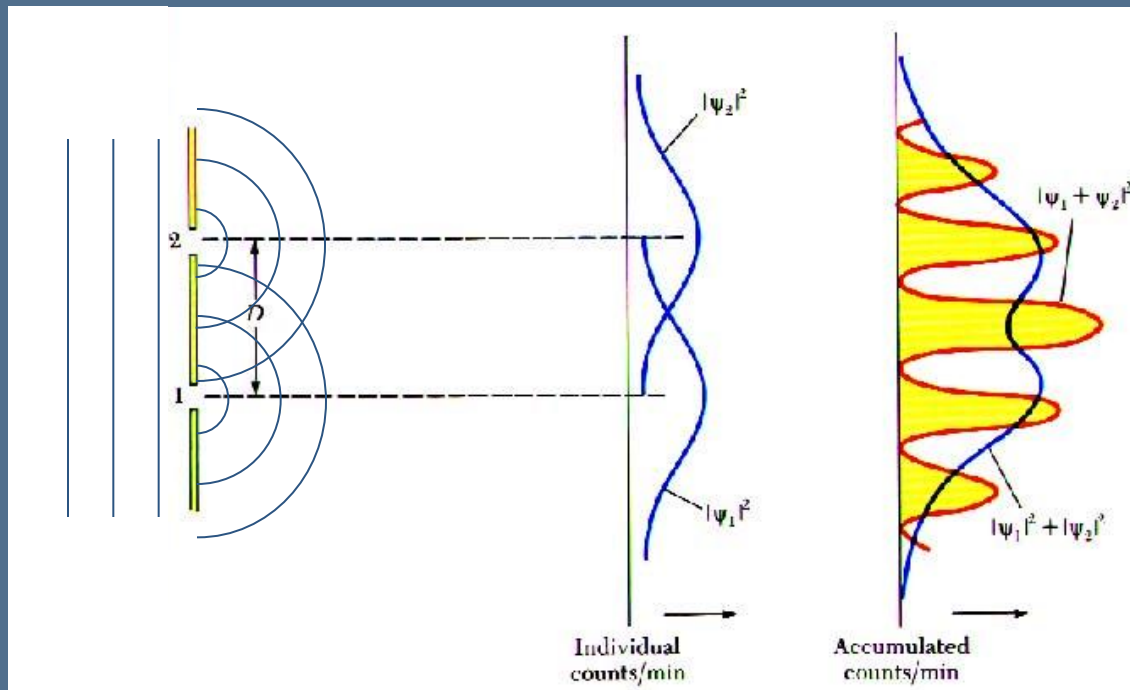
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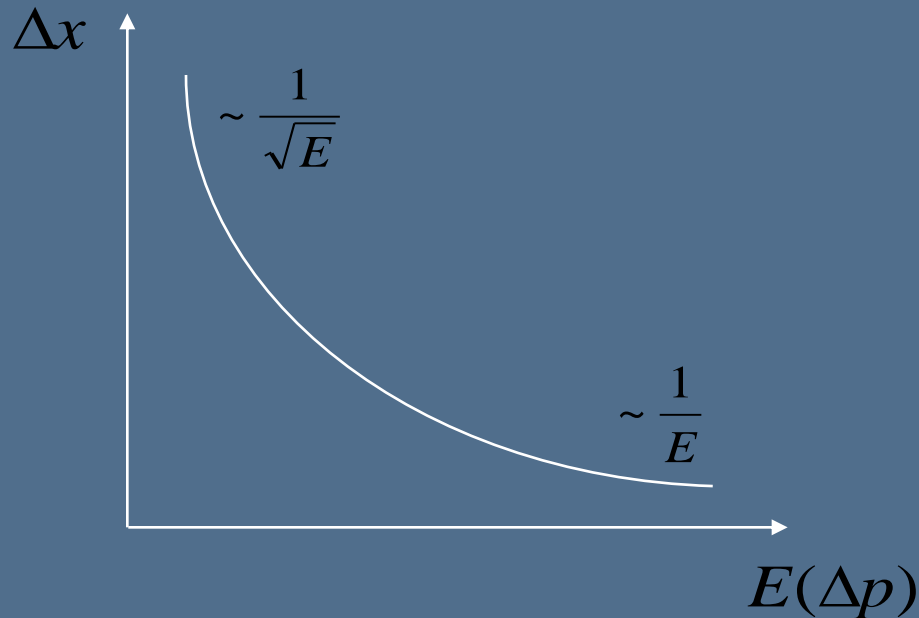
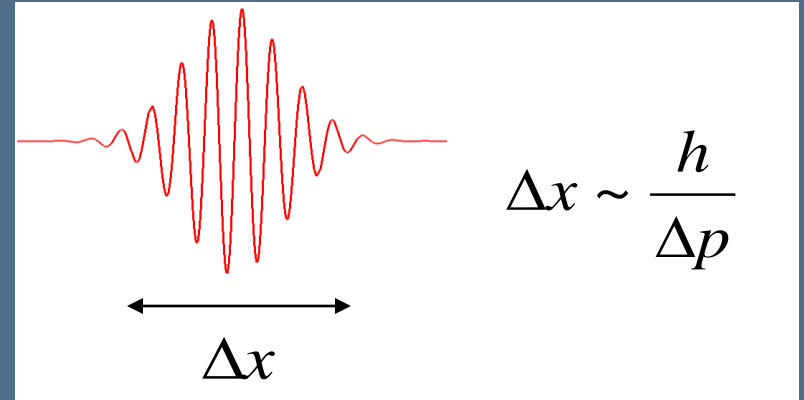


de Broglie (Nobel 29)

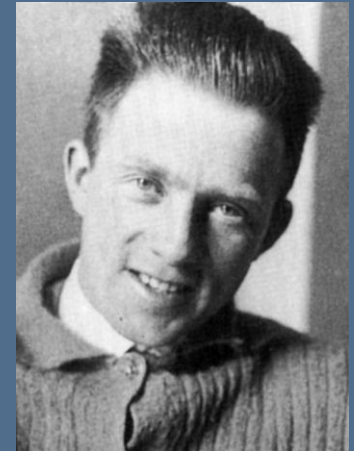


Uncertainty principle

Impossible to define simultaneously position and momentum of a particle



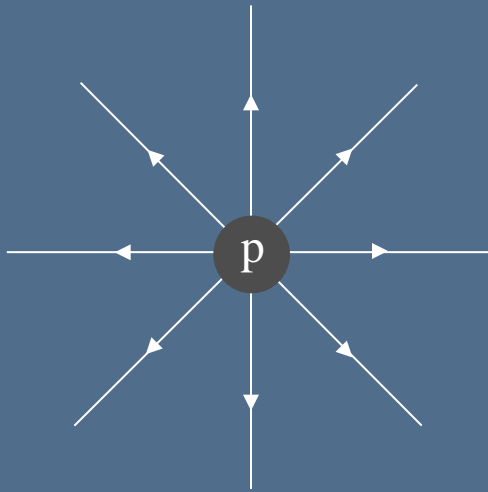
Heisenberg (Nobel 32)



To test Atomist hypothesis requires **high energies**

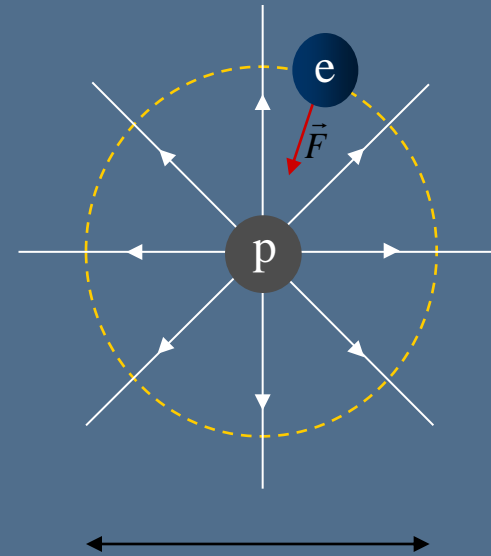
Fundamental interactions - EMG

Charges as **sources** of field



$$\vec{E} \sim \frac{1}{r^2} \vec{u}_r$$

Charges **suffer action** of field

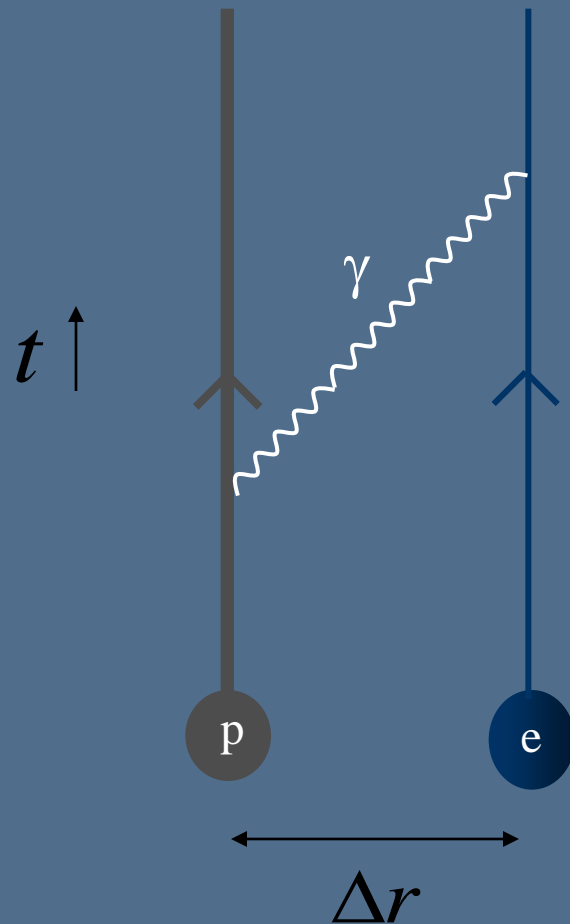


$$\Delta r \sim 10^{-8} \text{ cm}$$

$$E \sim 10 \text{ eV}$$

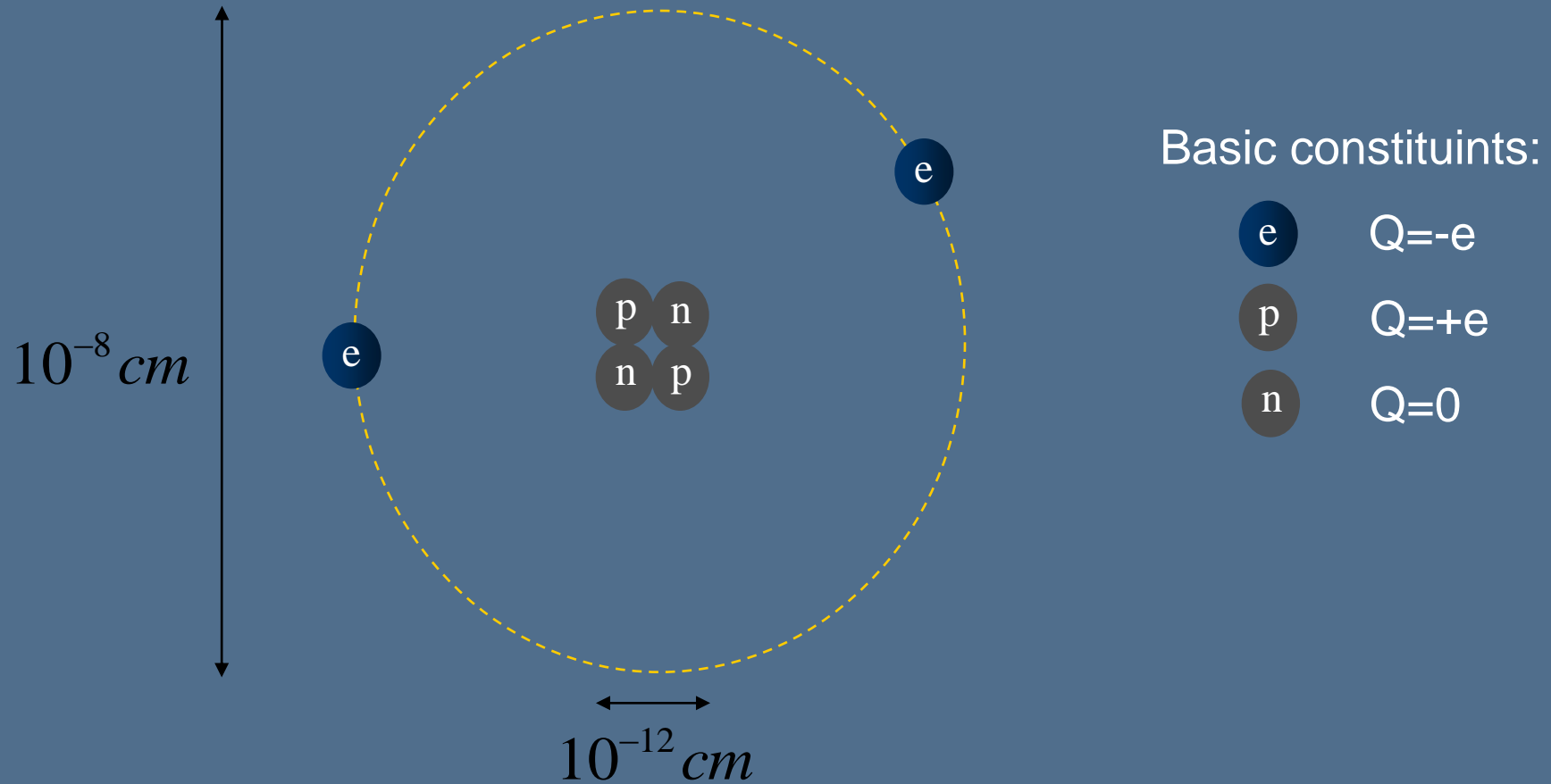
Photon: mediator of EMG interaction

Charges “communicate” through exchange of photons



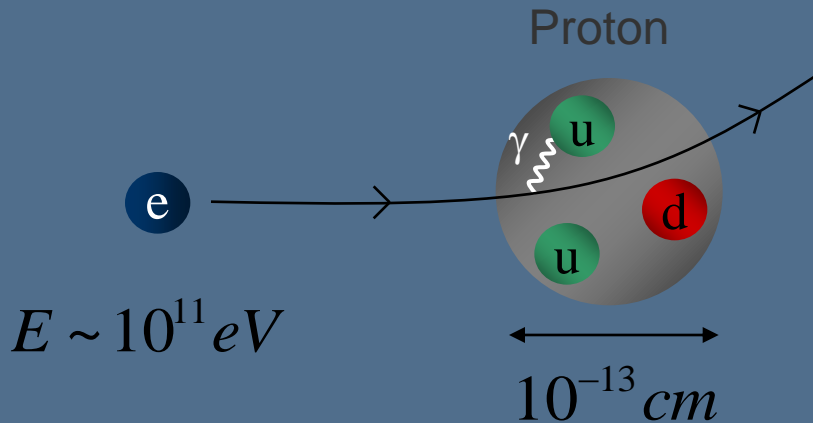
$$F \sim \frac{\Delta p}{\Delta t}$$
$$\sim \frac{h / \Delta r}{\Delta r / c}$$
$$\sim \frac{1}{\Delta r^2}$$

Atomic Physics – Atomist dream

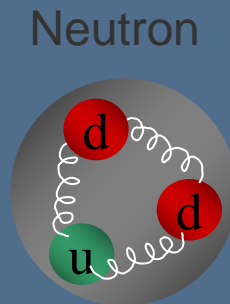
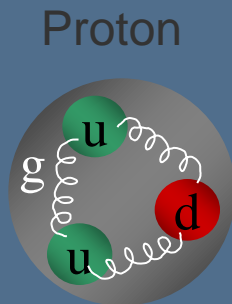
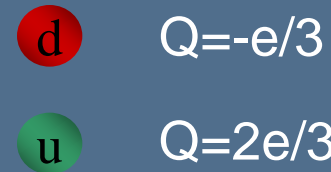


Chemical properties of matter (periodic table)

Particle Physics – strong force



SLAC: Friedman, Kendall, Taylor (Nobel 90)



Quarks are the basic constituents

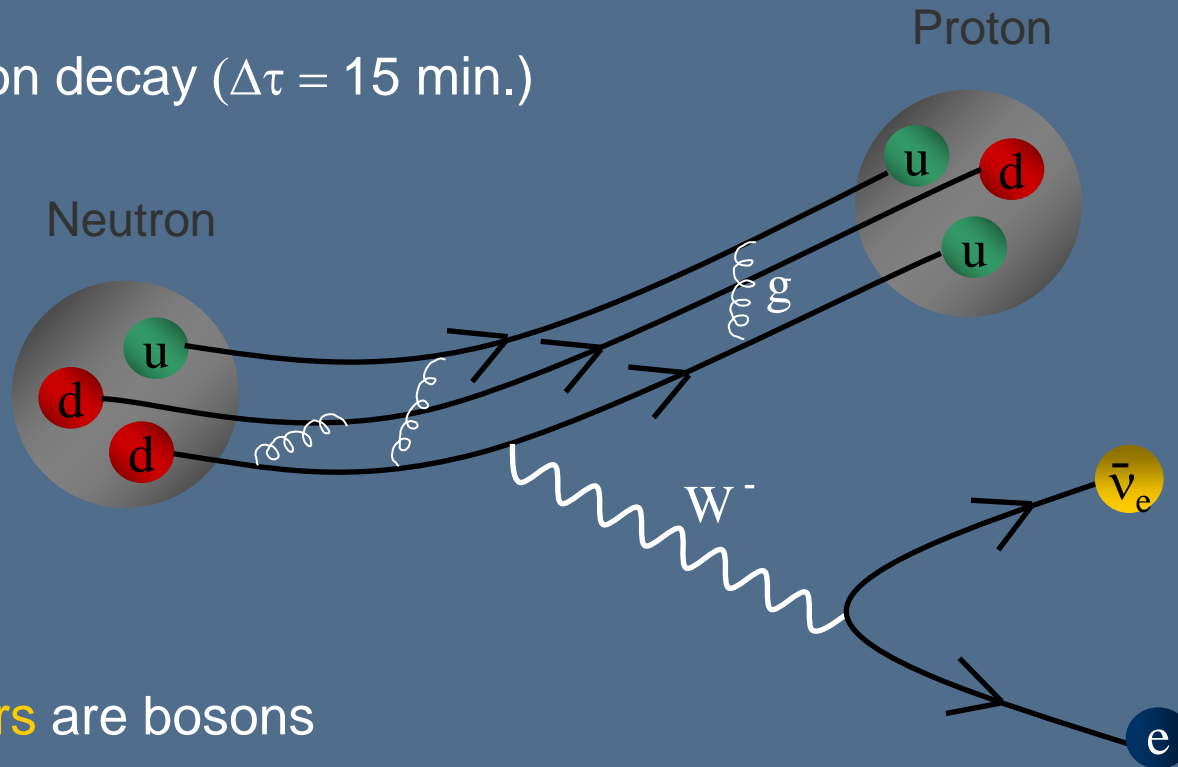
Mediators are the gluons

$$g_i \quad (i=1, \dots, 8)$$

Strong force is responsible for holding nuclei together
Other bound states, also observed, are called hadrons

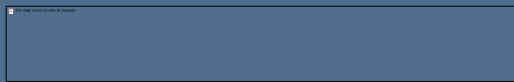
Particle Physics– weak force

Neutron decay ($\Delta\tau = 15 \text{ min.}$)



Mediators are bosons

Z, W^+, W^-



Glashow, Weinberg, Salam (Nobel 79)

CERN: Rubbia, van der Meer (Nobel 84)

Standard model of particle physics

Mediators of interactions

<i>Particle</i>	<i>Force</i>
<i>Photon</i> γ	<i>Electromagnetic</i>
<i>Gluon</i> g	<i>Strong</i>
<i>Z, W</i> $^{\pm}$ (91190, 80200)	<i>Weak</i>

(Masses in MeV= 10^6 eV)

Leptons (3 families)
(+ anti-particles)

<i>Electron</i> e^- (0.5)	<i>Neutrino</i> ν_e
<i>Muon</i> μ^- (106)	<i>Neutrino</i> ν_μ
<i>Tau</i> τ^- (1784)	<i>Neutrino</i> ν_τ

-1

Quarks (3 families)
(+ anti-particles)

<i>Up</i> u (4)	<i>Down</i> d (8)
<i>Charm</i> c (1500)	<i>Strange</i> s (150)
<i>Top</i> t (176000)	<i>Bottom</i> b (4700)

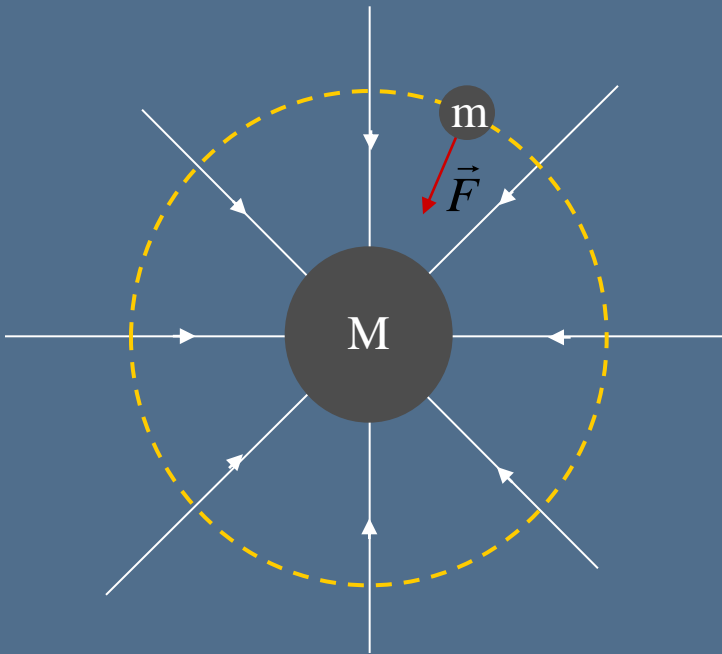
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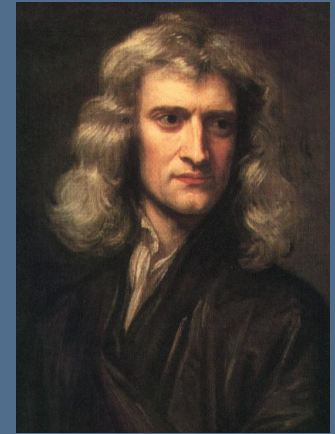
CERN ???

Higgs H^0 (>114000)

Gravitational force



$$\vec{F} = -G \frac{Mm}{r^2} \vec{u}_r$$

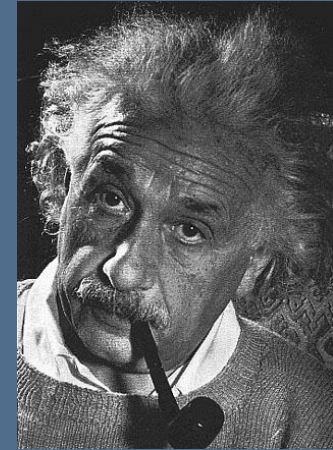
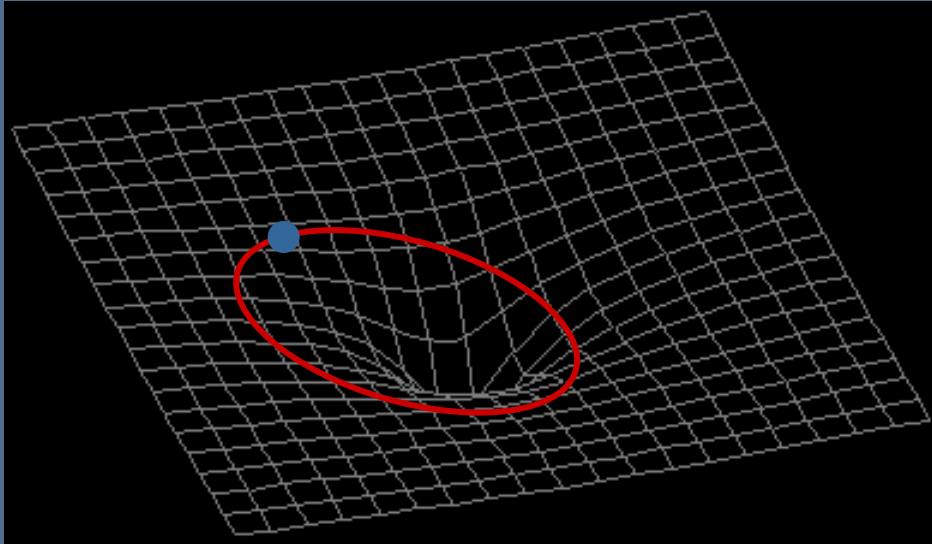


Newton (1642-1727)

Newton: “That one body may act upon another at a distance through a vacuum, without the mediation of anything else, by and through which their action and force may be conveyed from one another, is to me so great an absurdity, that I believe no man, who has in philosophical matters a competent faculty of thinking, can ever fall into it...”

Graviton – mediator of gravitational interaction

General Relativity



Einstein (Nobel 21)

Masses **deform** space-time

Masses follow straight lines in curved space (**geodesics**)

It is the **weakest** force

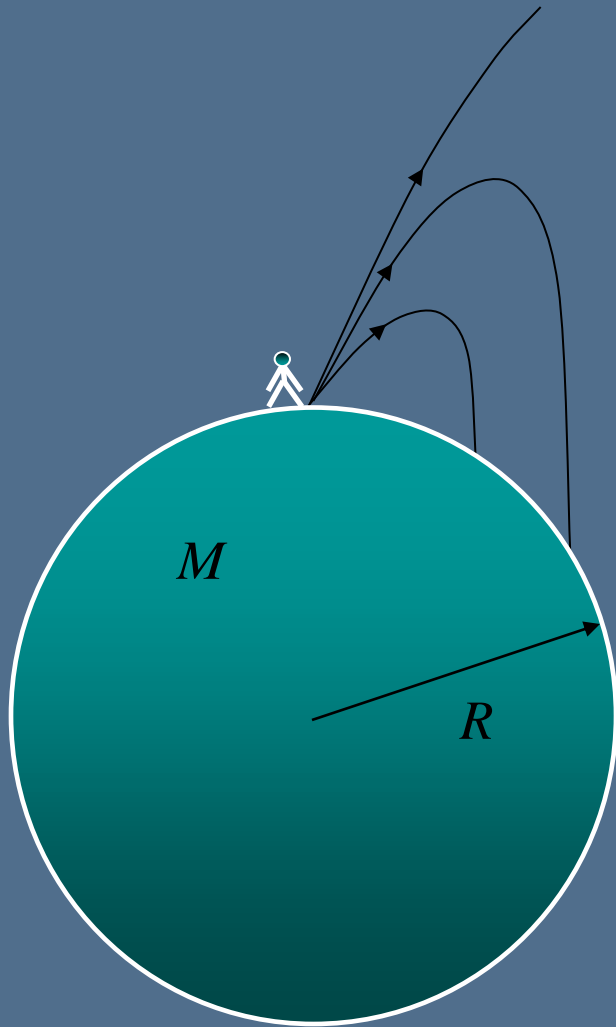
New physics for strong fields:

Black holes, big-bang, etc

Big Problem: theory is not renormalizable

Black holes: Mitchell stars

(1724-93)

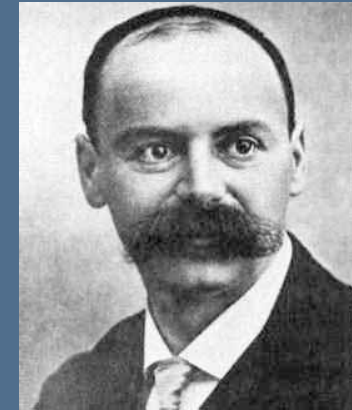
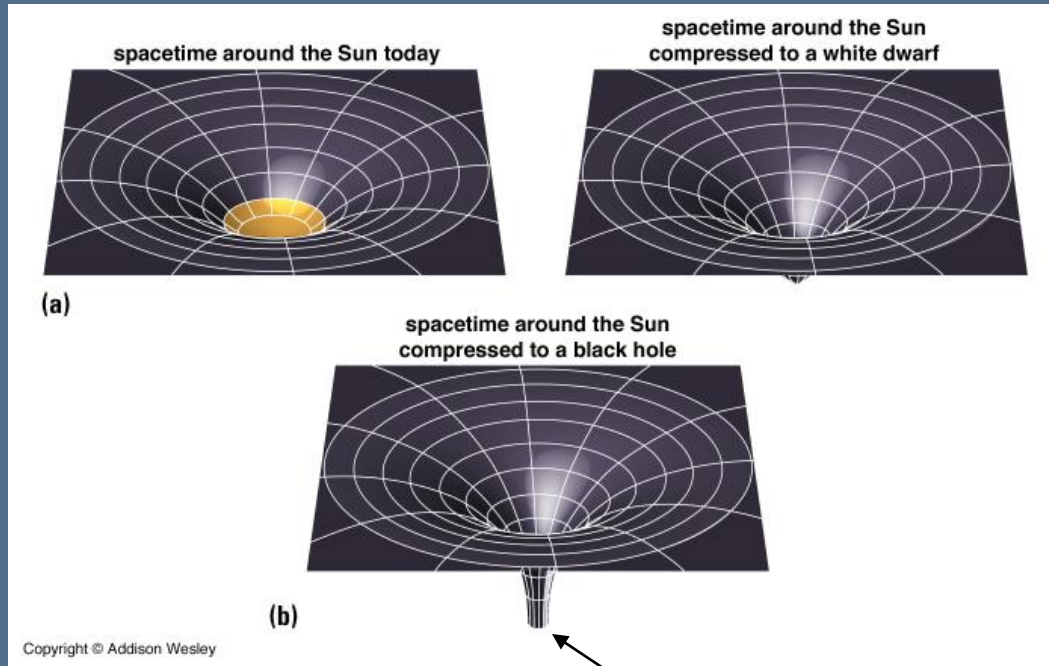


Escape velocity depends
of mass and radius of star

$$V = \sqrt{\frac{GM}{R}}$$

When $V > c$ not even light can
escape gravitational field!

Black Holes

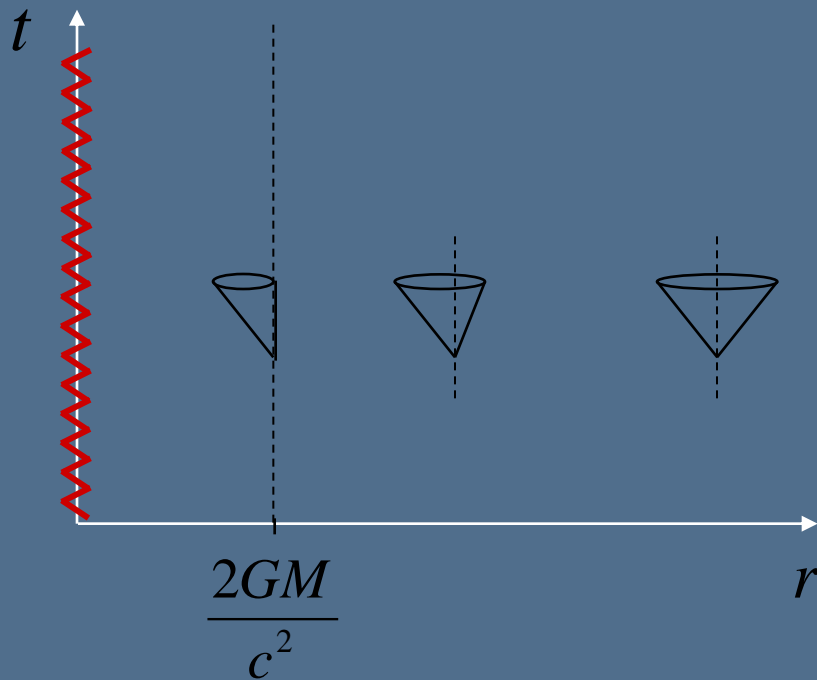


Schwarzschild
(1873-1916)

$$R_{Sch} = \frac{2GM}{c^2}$$

Sun radius is 700 000 *Km* ,
while its Schwarzschild radius is only 3 *Km*

Black Holes



Membrane of one direction

Causal structure of space-time profoundly changed

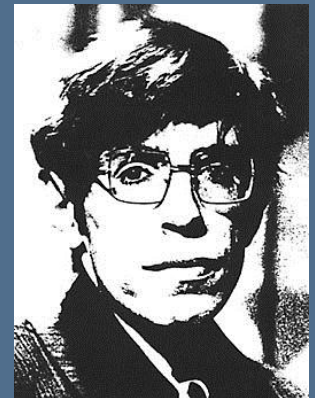
Singularity – gravity breakdown

Black hole emits radiation just like a black body at temperature

$$T_H = \frac{hc^3}{4GMk}$$

Black hole has entropy given by its area

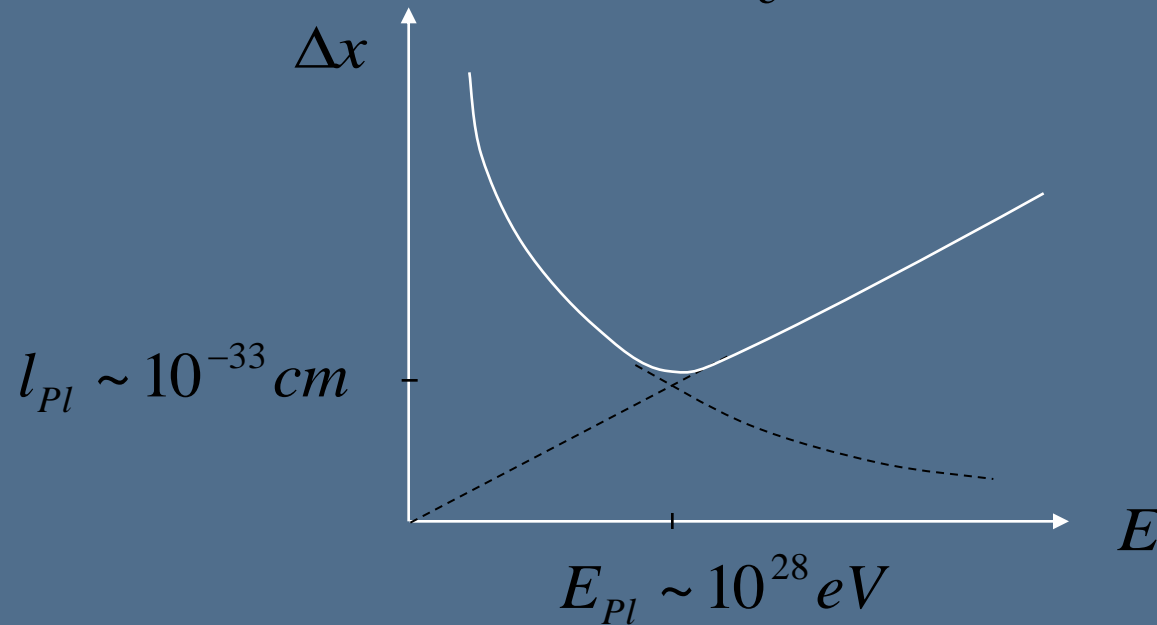
$$S \sim A \sim \ln N \quad \text{Microscopic interpretation?}$$



Hawking (1942-)

Quantum Gravity – Planck scale

If mass~energy concentrated in $\Delta x = \frac{2GM}{c^2}$ a black hole will form



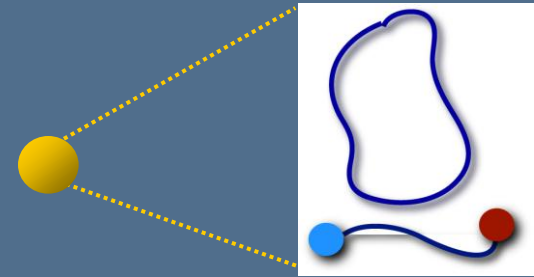
In a **fundamental** way $\Delta x > l_{Pl}$. It is not possible to measure smaller distances!

Space-time is a **derived** concept (low energy physics)

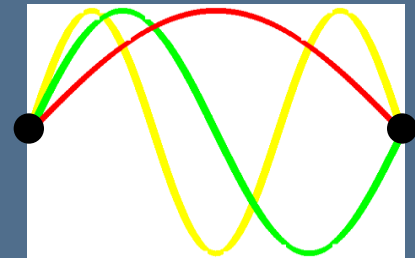
General Relativity is an effective theory

String Theory

Basic constituents are **one-dimensional** objects - strings



String vibrates in a linear combination of fundamental **harmonics**.



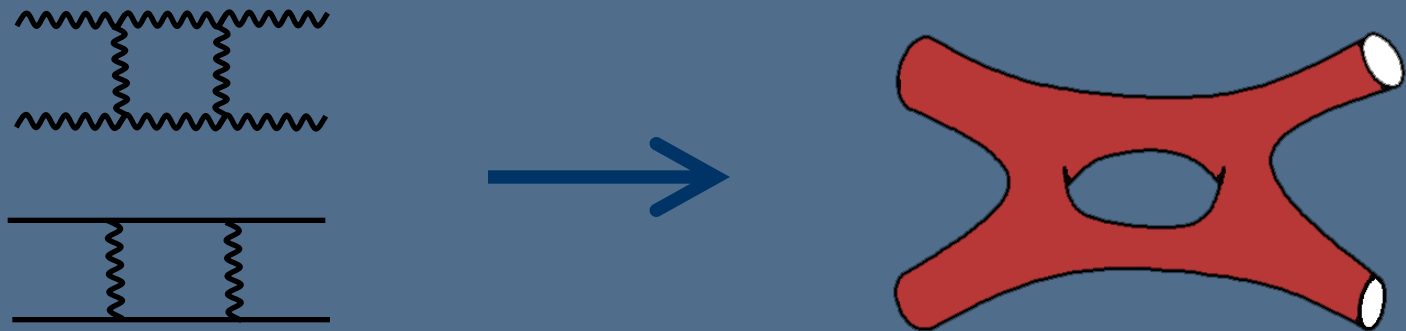
Fundamental particles
(including graviton)



String harmonics
(different oscillations
of a single string)

Quantum Gravity

Unification of fundamental interactions



Allows to analyse physics in the presence of very strong gravitational fields, like the case of **black holes** and **big bang**.

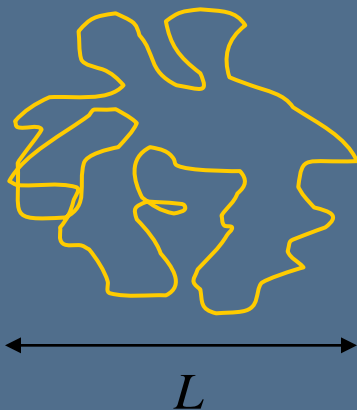
Strings and Black Holes

Highly excited string state $N \gg 1$

Free string

$$L^2 \sim \sqrt{N} \sim M$$

$$(G = 0)$$

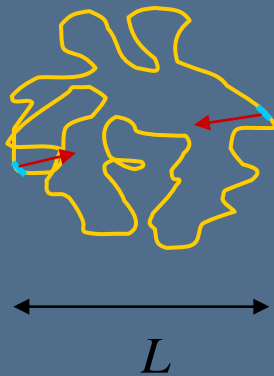


$$S = 4\pi\sqrt{N}$$

String weakly coupled

$$L \sim \frac{1}{G\sqrt{N}}$$

$$(G\sqrt{N} \ll 1)$$



Gravitational collapse toward a black hole

$$L < R_H$$

$$(G\sqrt{N} \gg 1)$$



$$S = \frac{A}{2} = 4\pi\sqrt{N}$$

Perspectives – where is the gold?!

Holography:

- QCD at strong coupling
- Quantum gravity

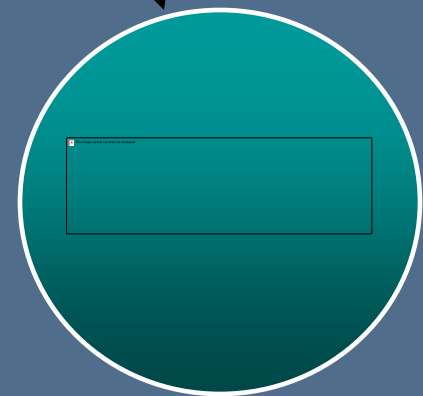
LHC:

- New physics? Supersymmetry, extra dimensions...

Cosmology:

- Universe is accelerating, but gives a very small (non-sense) value for cosmological constant
- Dark matter – what is its origin?

In gravitation configuration that maximizes entropy has



Gravitation, Cosmology & Particle Physics

P. Avelino, O. Bertolami, M. Costa, J. Oliveira, C. Santos - **Porto**