PHL424: 4 fundamental forces in nature

The familiar force of **gravity** pulls you down into your seat, toward the Earth's center. You feel it as your weight.

Why don't you fall through your seat?

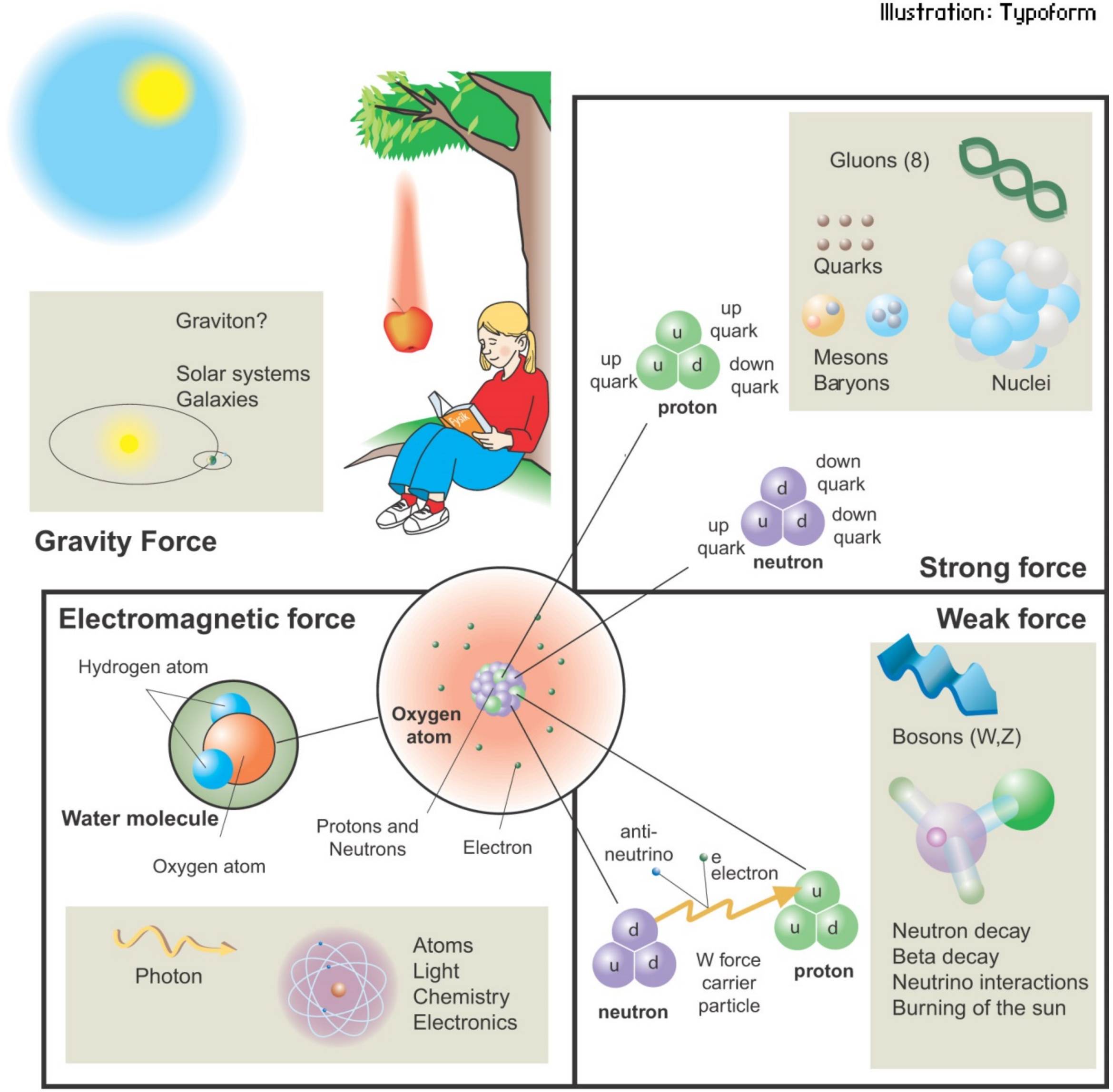
Well, another force, **electromagnetism**, holds the atoms of your seat together, preventing your atoms from intruding on those of your seat.

The remaining two forces work at the atomic level, which we never feel, despite being made of atoms.

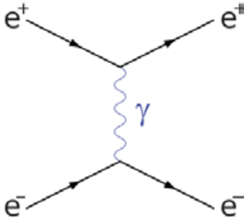
The **strong force** holds the nucleus together.

Lastly, the **weak force** is responsible for radioactive decay, specifically, β-decay where a neutron within the nucleus changes into a proton and an electron, which is ejected from the nucleus.

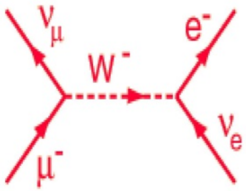
Illustration: Typoform



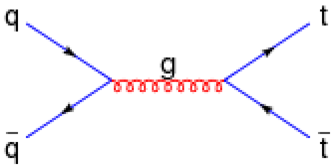
➢ Forces are ´carried´ or ´mediated´ by particles: exchange force



Electromagnetic



Weak



Strong

BOSONS force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Matter and forces

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction (Electroweak)	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

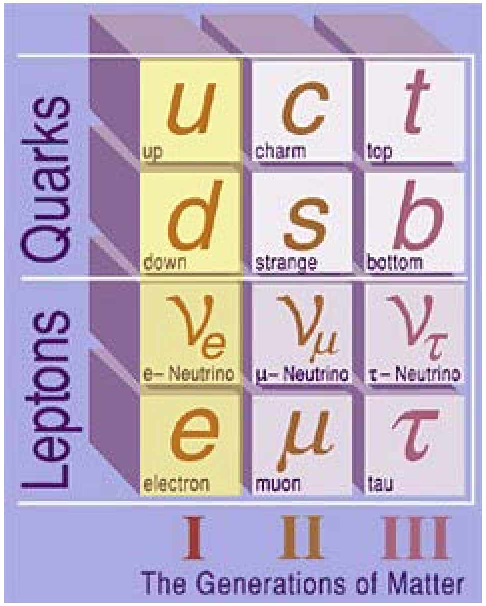
Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

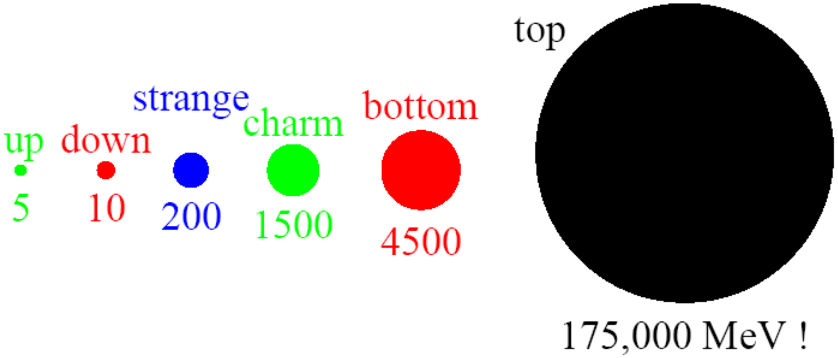
Quarks spin =1/2

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

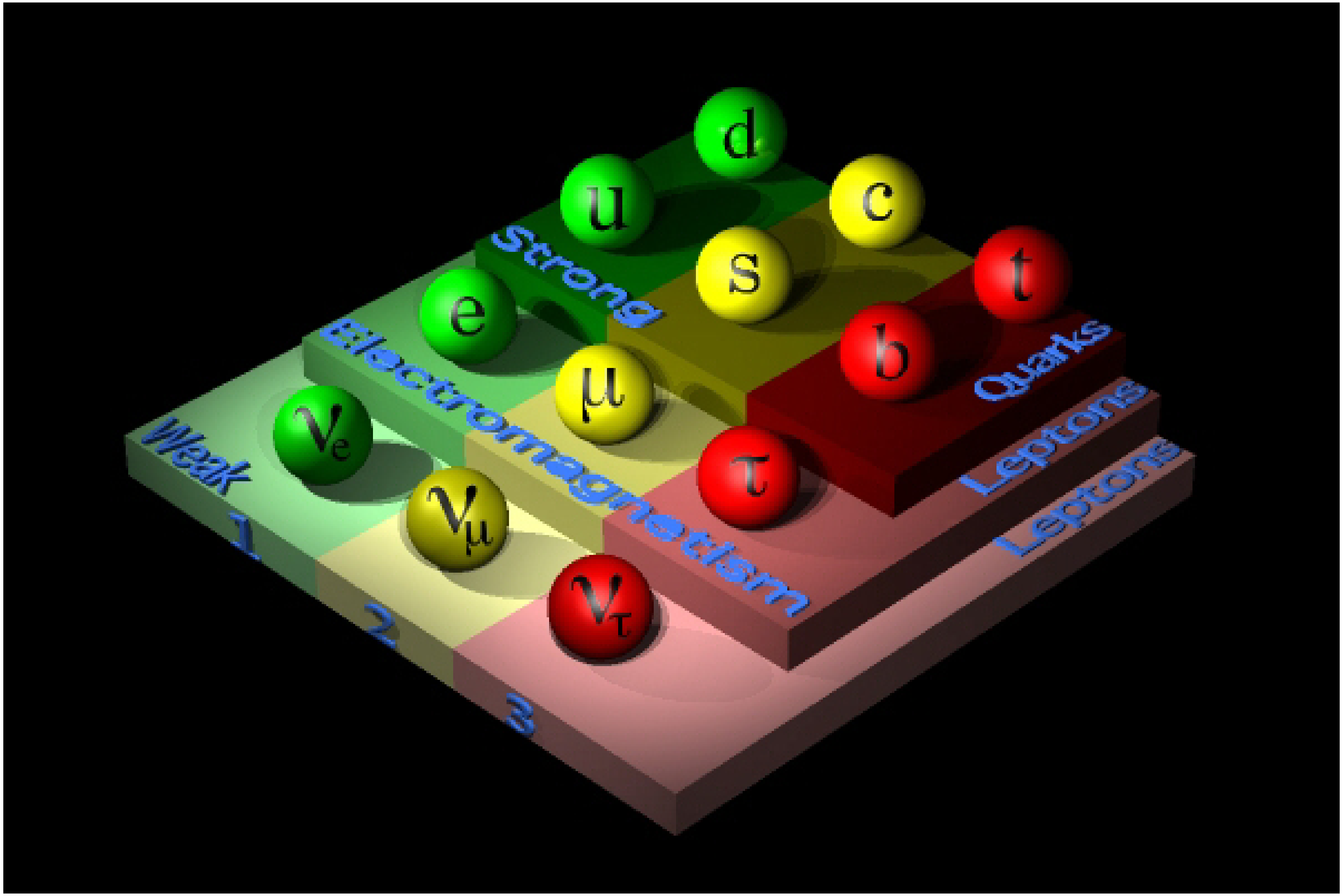
Three families

- **up** and **down** quarks make protons and neutrons …
- They bind with **electrons** to make atoms …
- And **neutrinos**, partner with electron …
- So what´s all the staff to the right?
- There just appear to be three copies of all the matter that really matters …
- All that distinguishes the ´generations´ is their mass





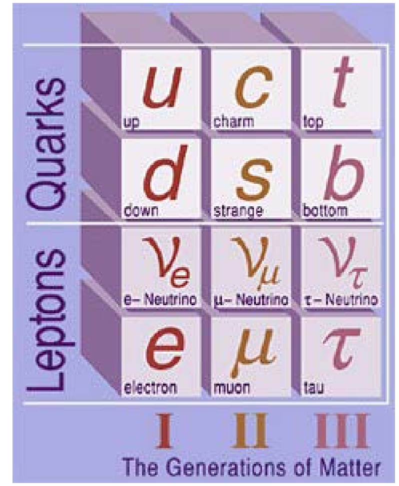
The complete set of particles

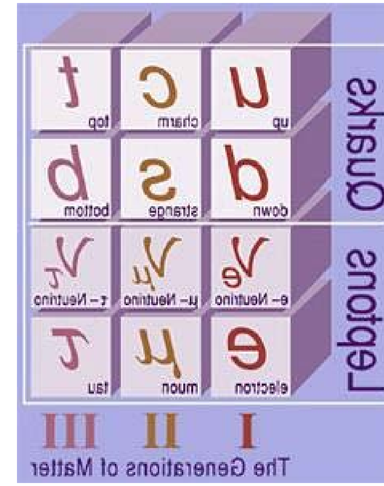


The first generation of 4 particles repeats only twice. Nobody knows why!!!

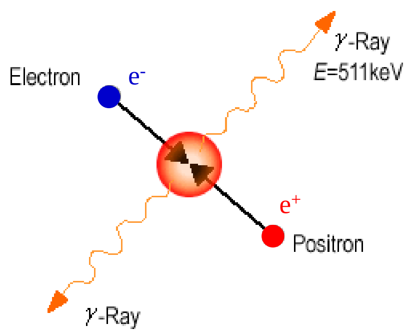
Antimatter

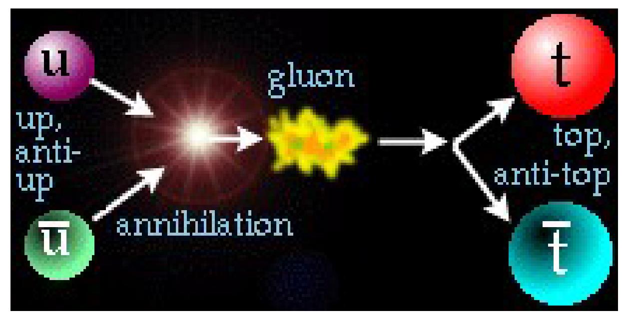
- All particles have antiparticles!
- Antimatter has the same properties as matter
  - Same mass, same spin, same interactions
  - But opposite electric charge
- Has another weird property…
  - It can annihilate with matter to create pure energy!
  - Or, conversely, energy can create matter and antimatter pairs. $E = mc^2$





particle – anti-particle annihilation



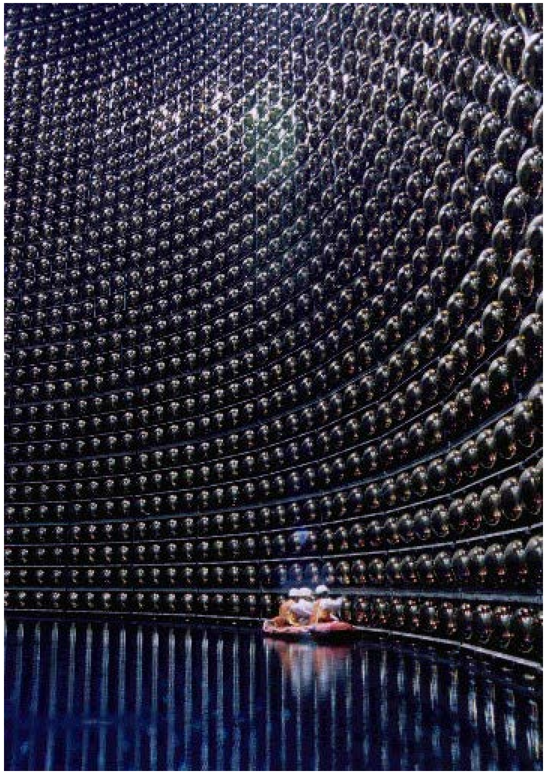


- The early Universe had a lot of energy … where is the antimatter in the Universe?

How weak are Weak interactions?

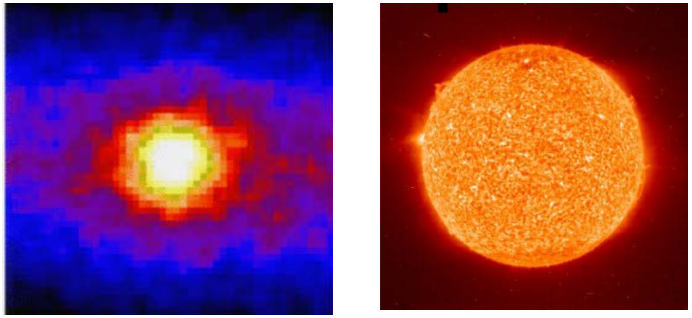
- Weak is, in fact, way weak

- A 3 MeV neutrino produced in fusion from the sun will travel through water, on average **53 light years**, before interacting
    - A 3 MeV positron (anti-matter electron) produced in the same fusion process will travel 3 cm on average



- Moral: to find neutrinos, one needs a lot of neutrinos and a lot of detectors!

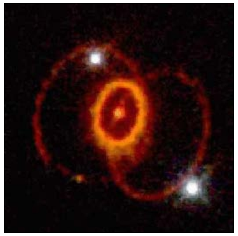
- Super-Kamiokande: confirms the existence of the sun in neutrino image!

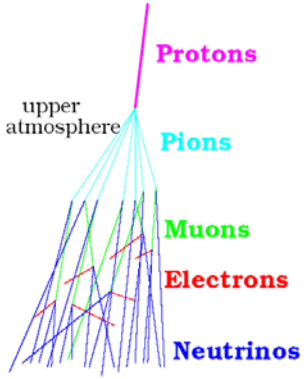


The sun, imaged in neutrinos, by Super-Kamiokande and optical

Where are neutrinos found?

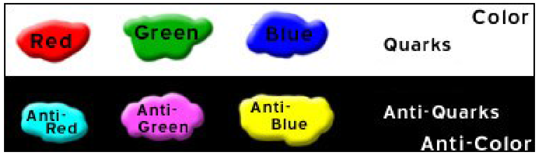
- In the early Universe
  - The heavy things to the right decay (weakly), leaving a waste trail of 100/cm^3 of each neutrino species
  - Even if they have a very small mass, they make up much of the weight of the Universe
- In the sun
  - 100 billion neutrinos per cm^2 per second rain on us
- Supernova 1987A (150 000 light years away)
  - When it exploded, it released 100 times the neutrinos the sun will emit in its whole lifetime
- Bananas?
  - We each contain about 20 mg of ^{40}K which is unstable and undergoes β-decay
  - So each of us emits 0.3 billion neutrinos/s
- For the same reason, the natural radioactivity of the earth results in 10 million neutrinos per cm^2 per second
- Nuclear reactors (6% of energy is anti-neutrinos)
  - Average plant produces 10^{20} anti-neutrinos/s
- Cosmic Rays



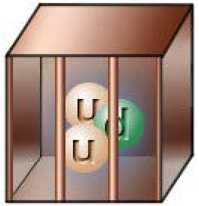


The Strong Force

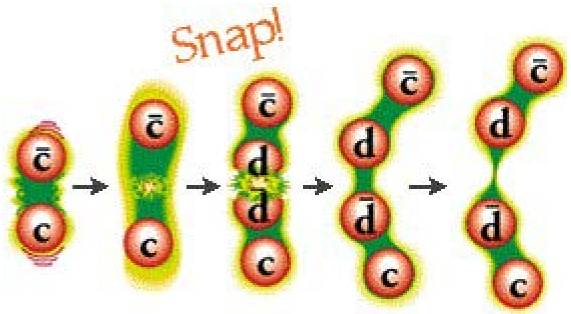
- This force is so strong that it can effectively be thought of as glue
  - Force carrier is named the ´gluon´
  - Gluons connect to ´color´
  - Can think of these colors as combining like light
  - ´White´(colorless) things do not feel the strong force



- If you think of this as ´glue´ then these colorless combinations stick together
  - this is called ´confinement´
  - The proton is one such ´confined combination of quarks´
    Red + Green + Blue → Colorless

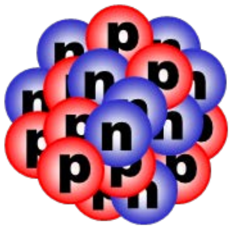


- Two questions follow from this picture
  - What happens if you try to pull things apart?
  - How do protons stick to each other?

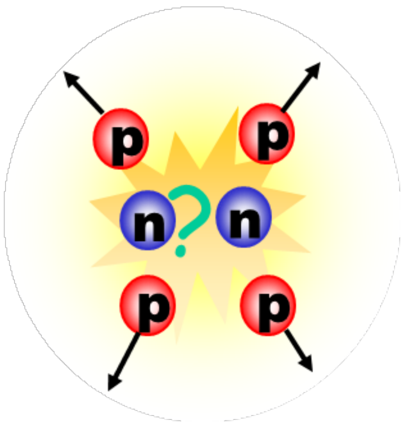


What binds the nucleus together?

neutrons: no charge
protons: positively charged – repel one another.

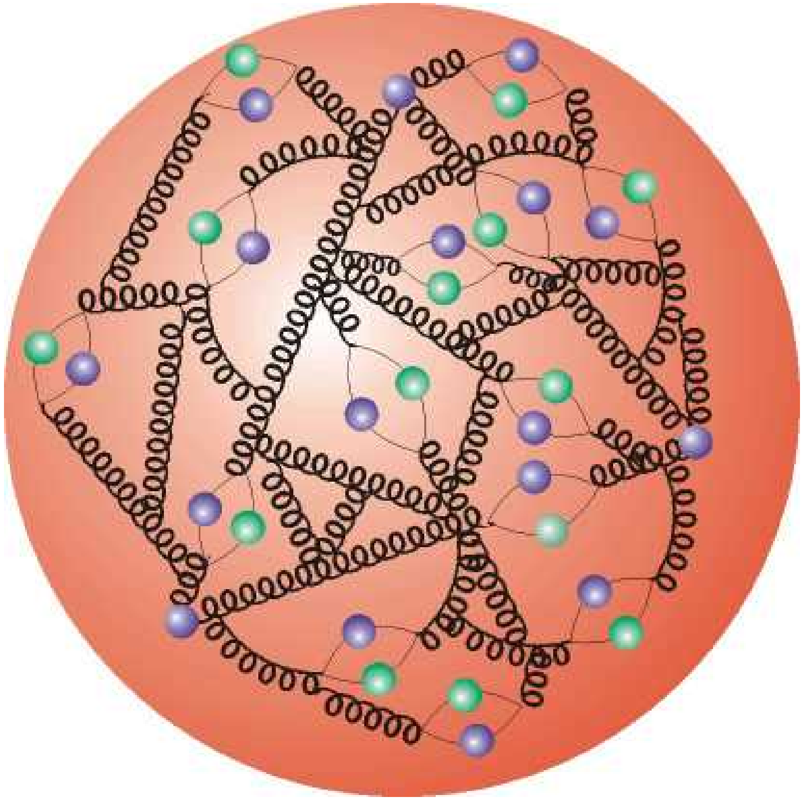


Why doesn´t the nucleus blow apart?



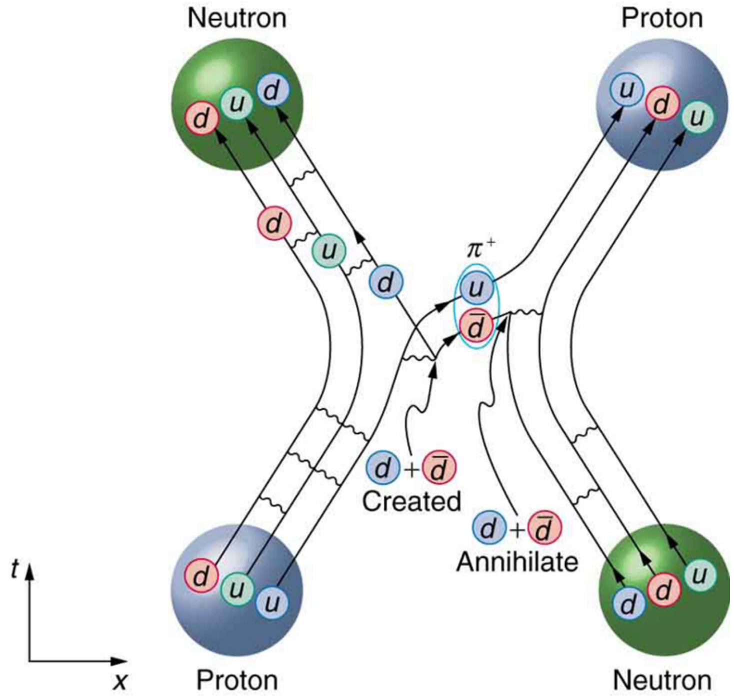
The strong force holds quarks together to form hadrons, so its carrier particles are whimsically called **gluons** because they so tightly “glue” quarks together

Interaction of nucleons



proton´s internal structure

Only about 1% of the mass of a nucleon is made up of the rest – mass energies of its constituent particles with mass, the quarks. The rest is the kinetic energy of those quarks and the gluons

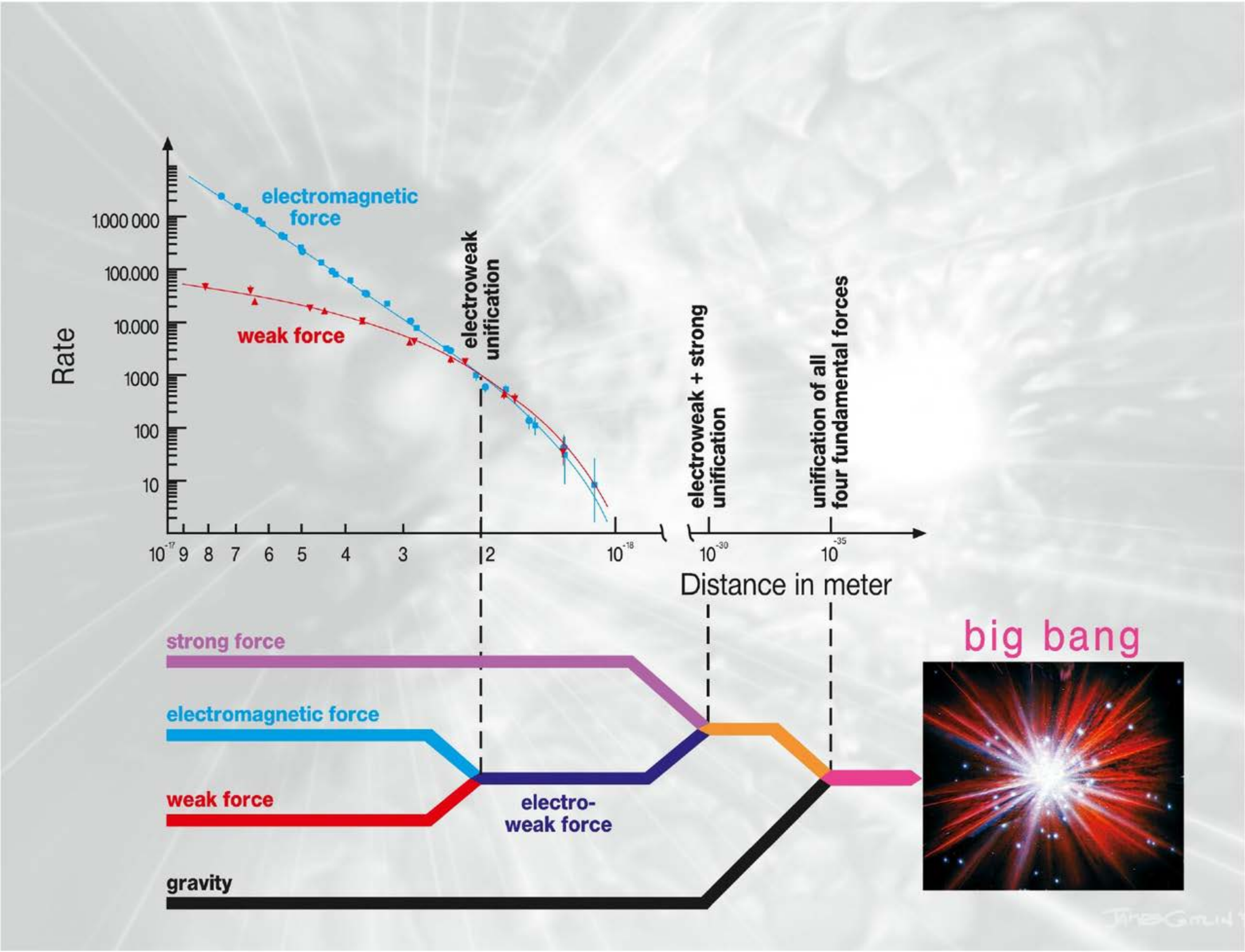


The fundamental forces

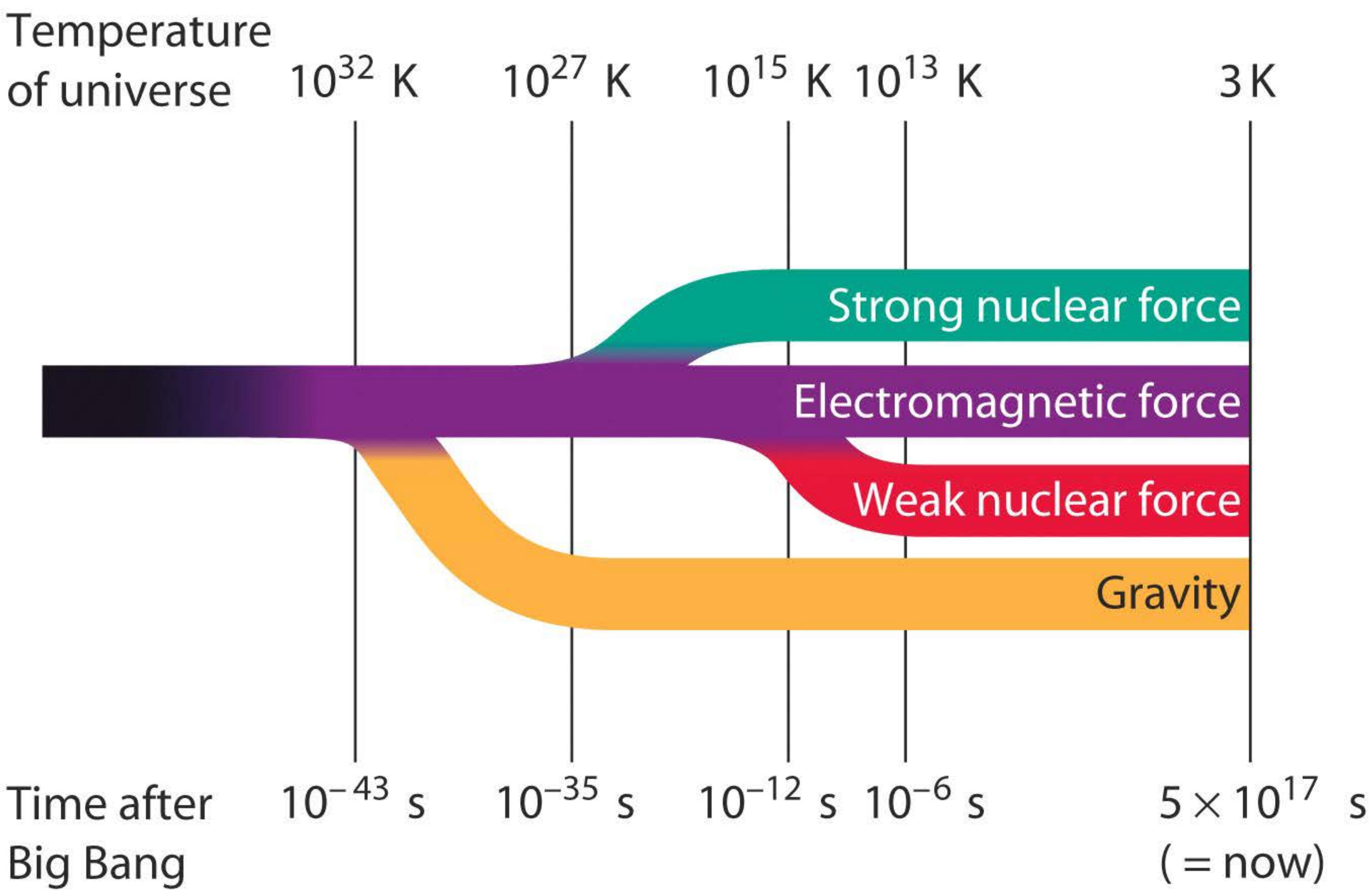
Force	Theory	Mediator	Relative Strength	Range (m)
Strong	QCD	gluon (g)	1	$\sim 10^{-15}$
Electromagnetic	QED	photon (γ)	$\alpha = \frac{1}{137} \approx 10^{-2}$	∞
Weak	Electroweak	$W^{\pm}$ and Z bosons	$\sim 10^{-5}$	$\sim 10^{-18}$
Gravitational	Gravity	unknown	$\sim 10^{-38}$	∞

http://hyperphysics.phy-astr.gsu.edu/hbase/forces/funfor.html

Forces and the history of the universe

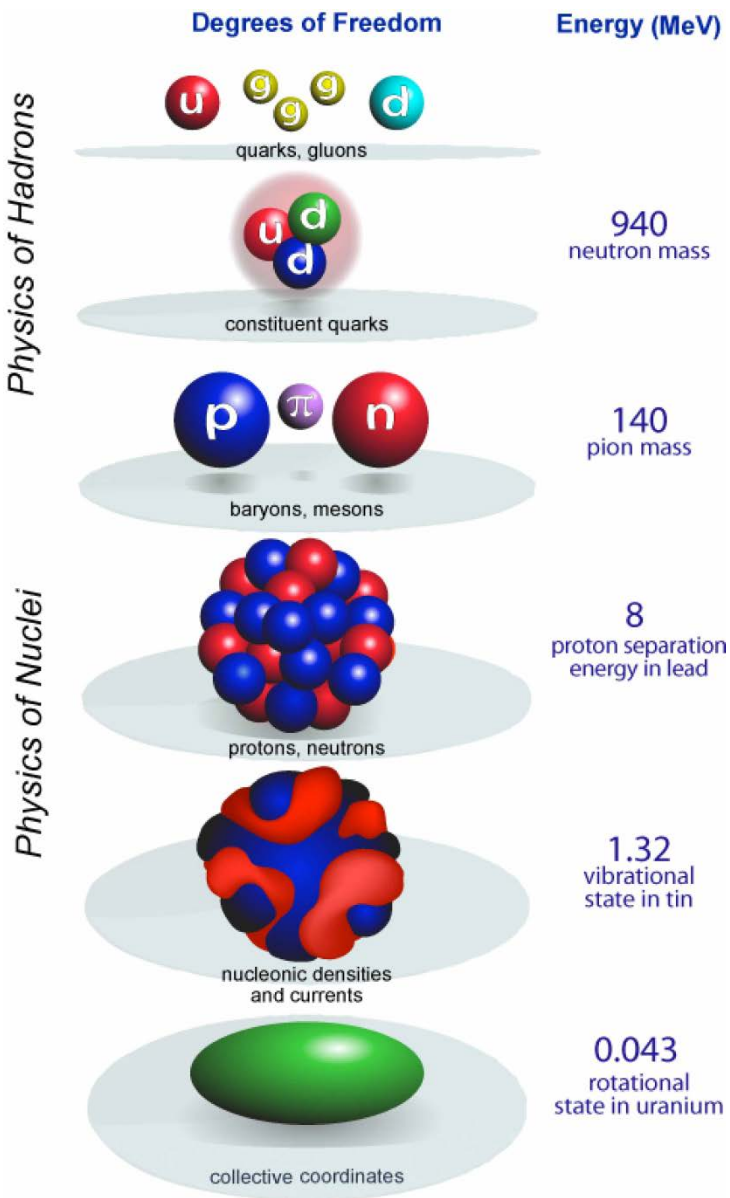


Known fundamental forces

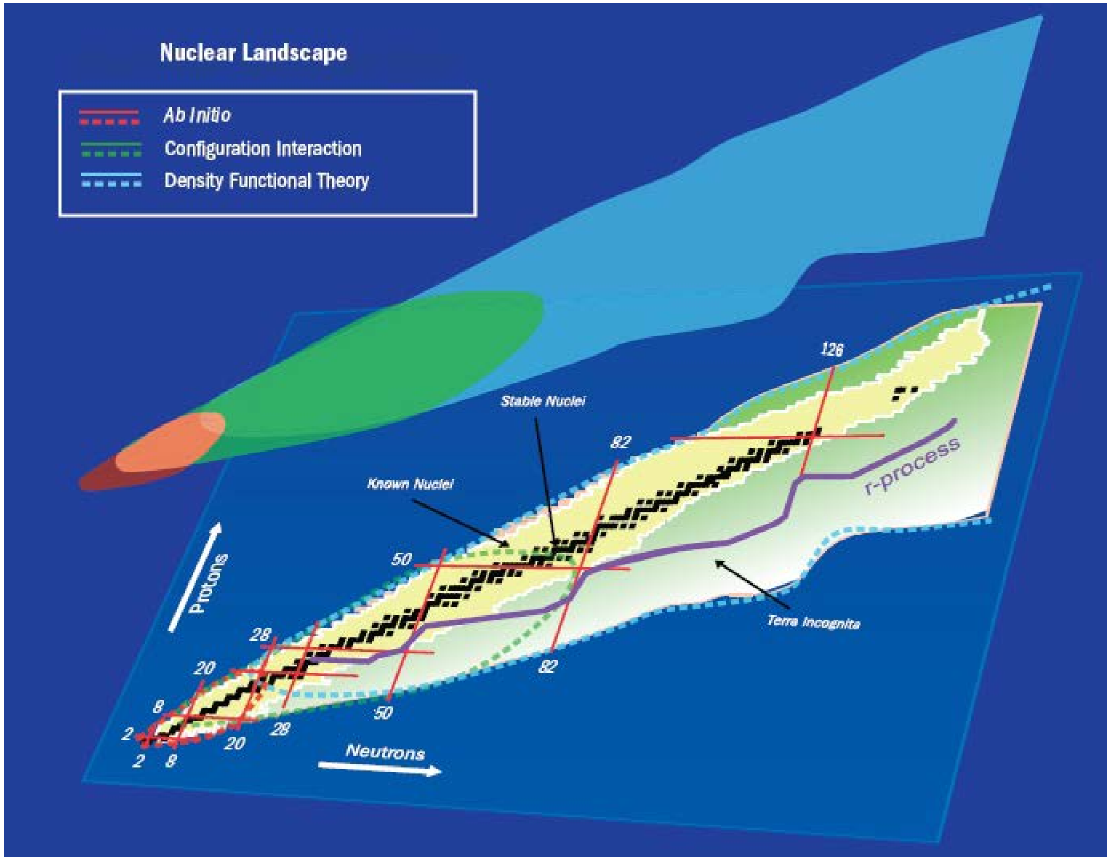


Sheldon Glashow, Abdus Salam, Steven Weinberg

Why can´t we use the fundamental interaction to describe all nuclei?



Many-Body Problem



Conclusion: If we consider only the bare nucleon-nucleon potential, with so many interactions, we quickly run into the quantum many-body problem. Although there are some systems today that can be calculated using the bare nucleon-nucleon interaction, it is typically limited to very light nuclei (A < 15).

The force between nucleons

Some forms of nuclear theory are able to use the residual interaction between nucleons. We'll start by comparing what we know about the nucleon-nucleon interaction to atomic physics.

Electrons and atoms

- Coulomb interaction
- Electrons in classical orbits that have large (relative) energy spacings
- Electron distances are large (i.e. small e-e interaction probabilities)

Nucleon-nucleon interaction

- Strong interaction
- Nuclear orbits (shells) have small (relative) energy spacings
- Due to the small nuclear size, a given nucleon will strongly interact with all nearest-neighbor nucleons