BSM Physics
Why are we looking for it?

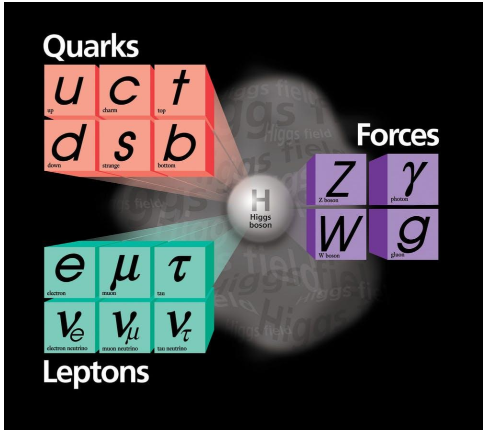
August 4, 2022
International Teacher Program

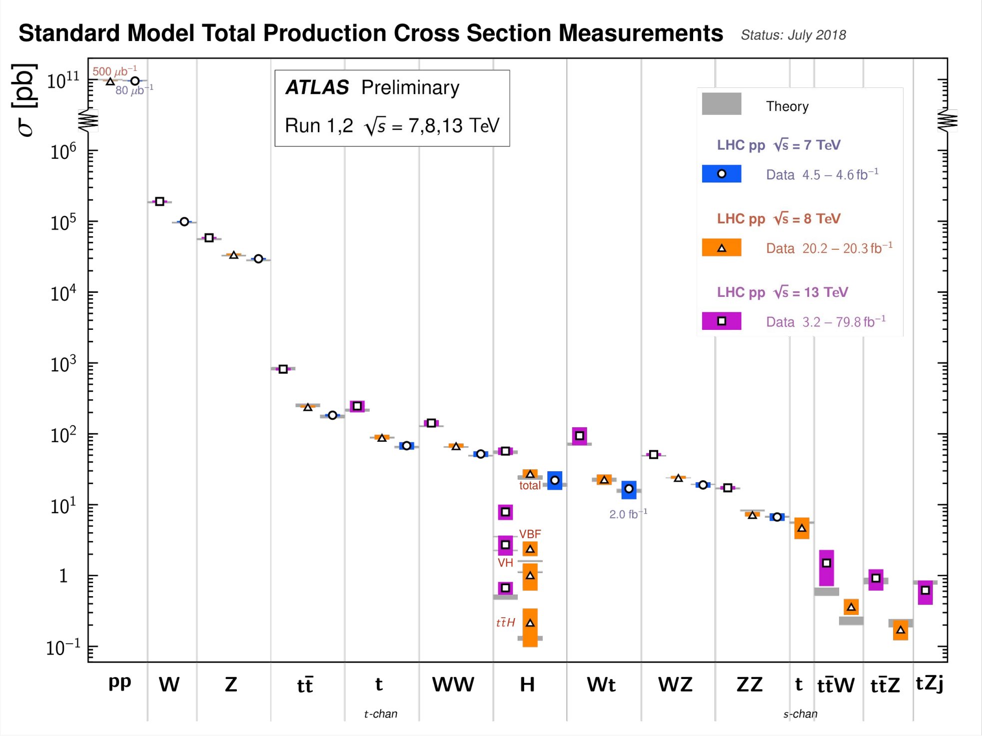
ATLAS EXPERIMENT

CERN

Das Standardmodell

- The **Standard Model (SM)** describes all **elementary particles** and their **interactions**.
- It has been tested at the LHC and various other experiments
- However, we cannot explain all known phenomena with the SM.





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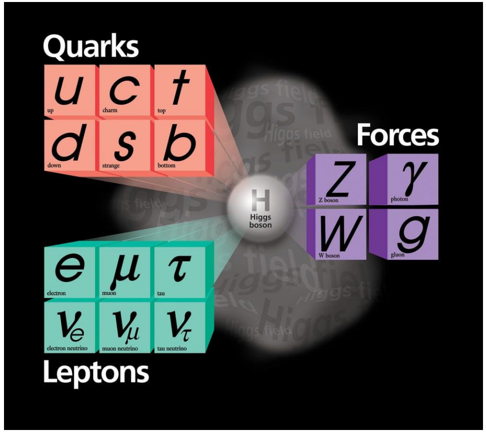


Fermions

- Quarks [(u,d), (s,c), (b,t)]
- Leptons [(e, ν_e), (μ, ν_μ). (τ, ν_τ)]

Bosons

- Gluons g
  - Strong interaction
- $W^{\mp}$, Z^0 bosons
  - Weak interactions
- Photons γ
  - Electromagnetic force
- Higgs H

Open questions

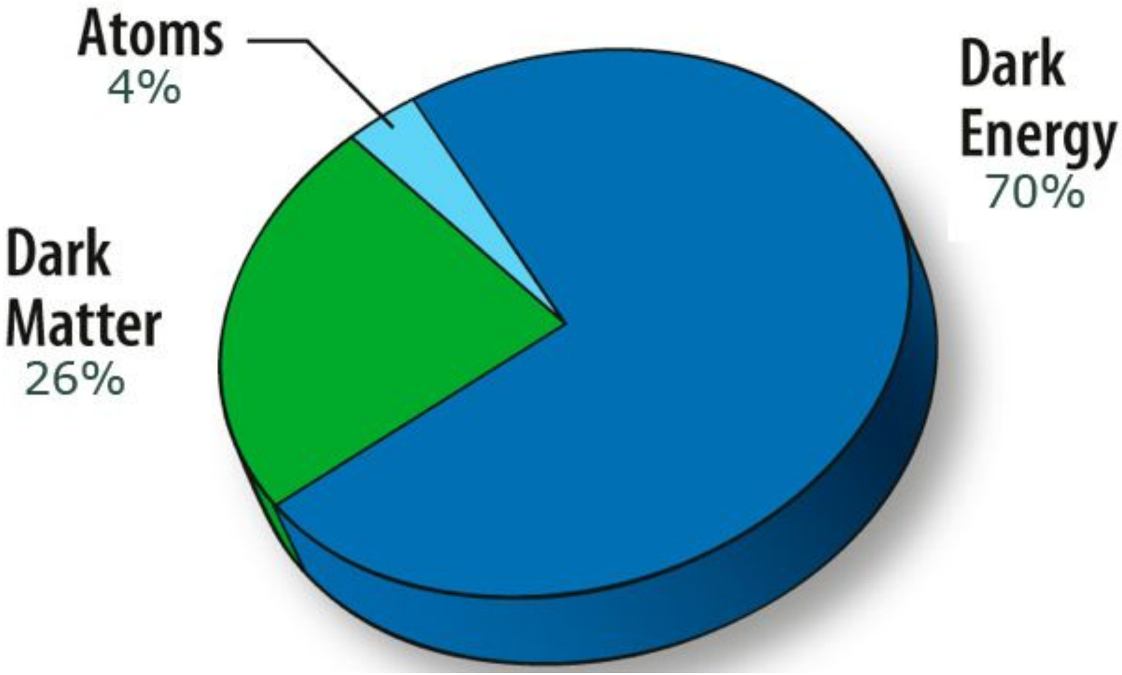
- Why is gravitation not contained in the SM?
- What about dark matter?
- What about dark energy?
- Antimatter
- Masses of neutrinos
- Unification of forces at high energies
- ….

Dark matter

Why do we think that there is dark matter?

- 1933: Fritz Zwicky observed, that a multiple of the observed mass of the COMA galaxy cluster would be needed in order to keep it together.

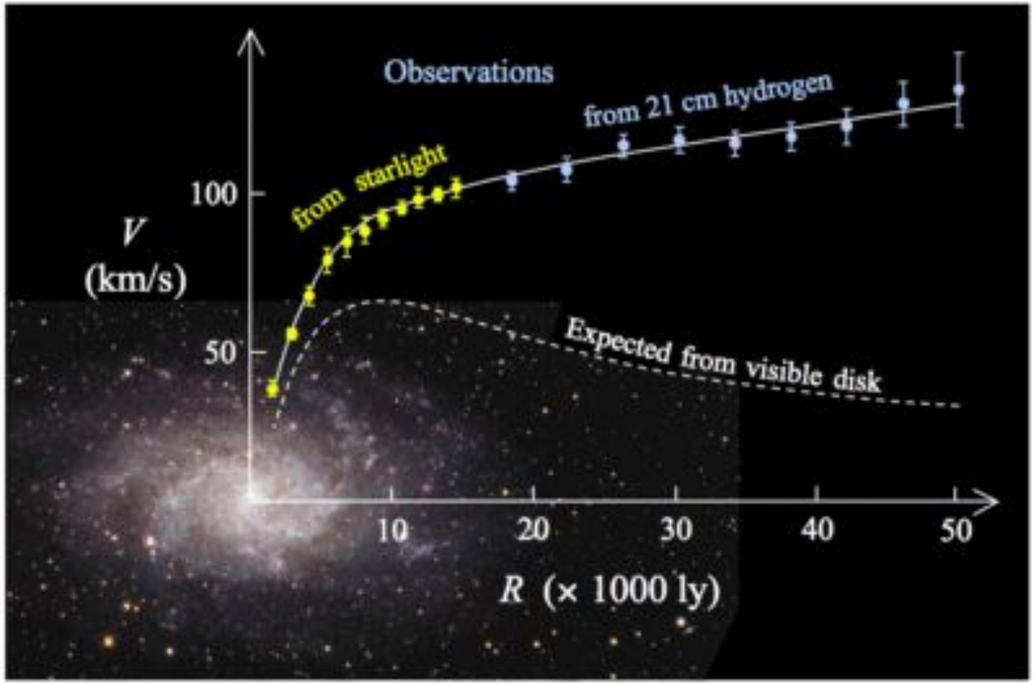
➔ **Dark (cold) matter**



Dark matter: Galaxy rotation

- **Estimated and observed rotation velocities of galaxies do not match!**

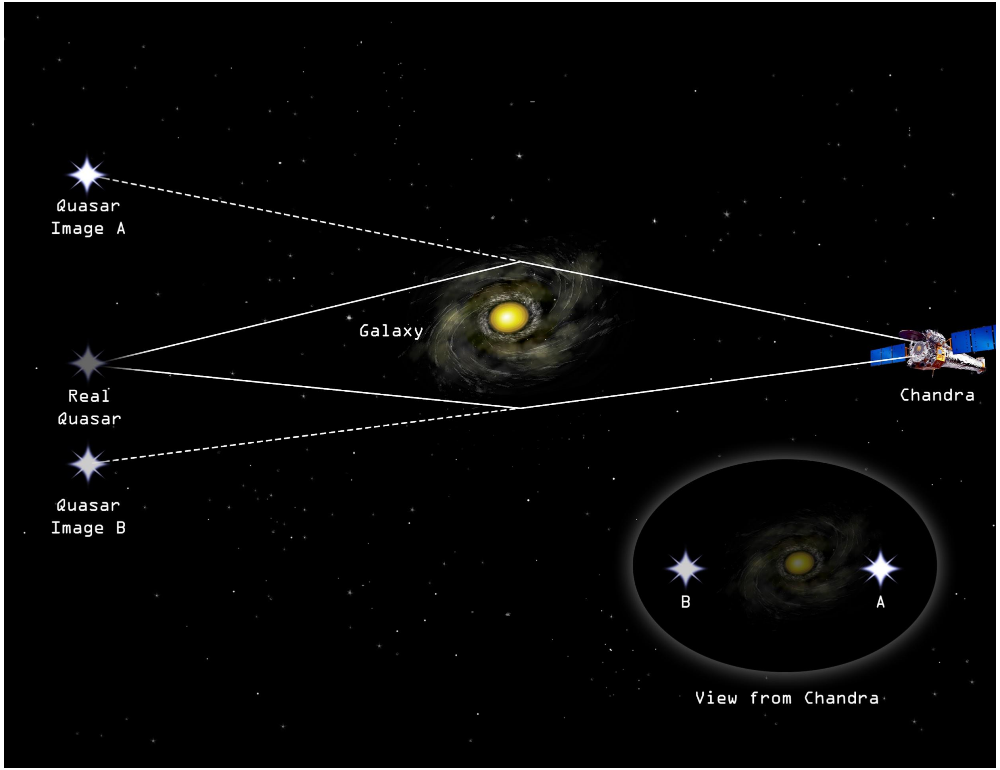
⇒ It seems that the bigger part of galaxy masses is **not visible** to us.



Dark matter: Gravitational lensing

- Big masses can **bend light**.
- This effect is based on **general relativity** (big masses or energies can **bend space-time**).
- Observed mass is not sufficient to explain the observed bending.

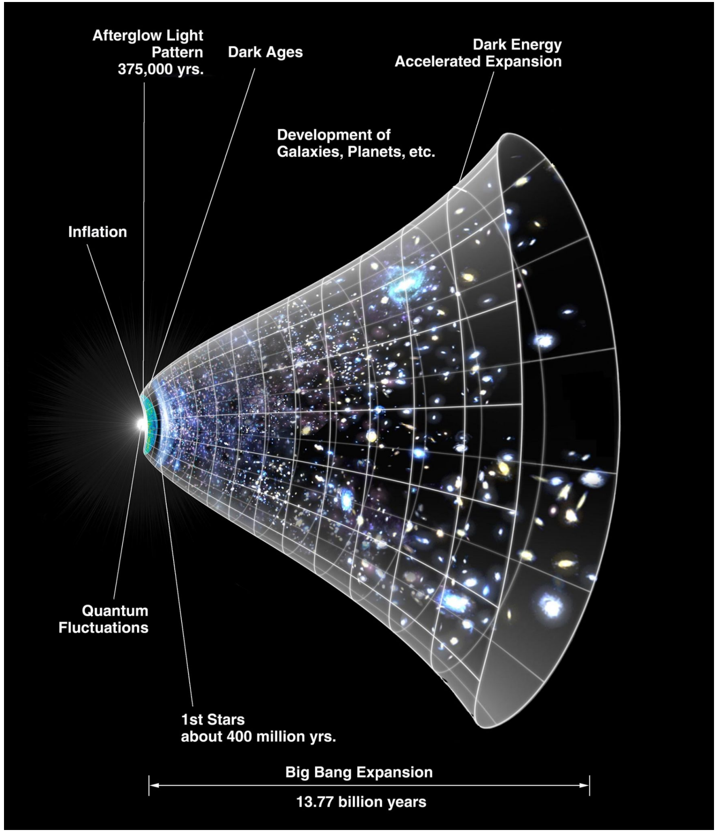
➔ Bending must be caused by matter that **cannot be directly observed** by us.



Dark energy

Why do we believe that there is dark energy?

- Observations of the expansion of the universe show, that the **expansion speed is increasing**.
- We have no idea, however, what dark energy is!



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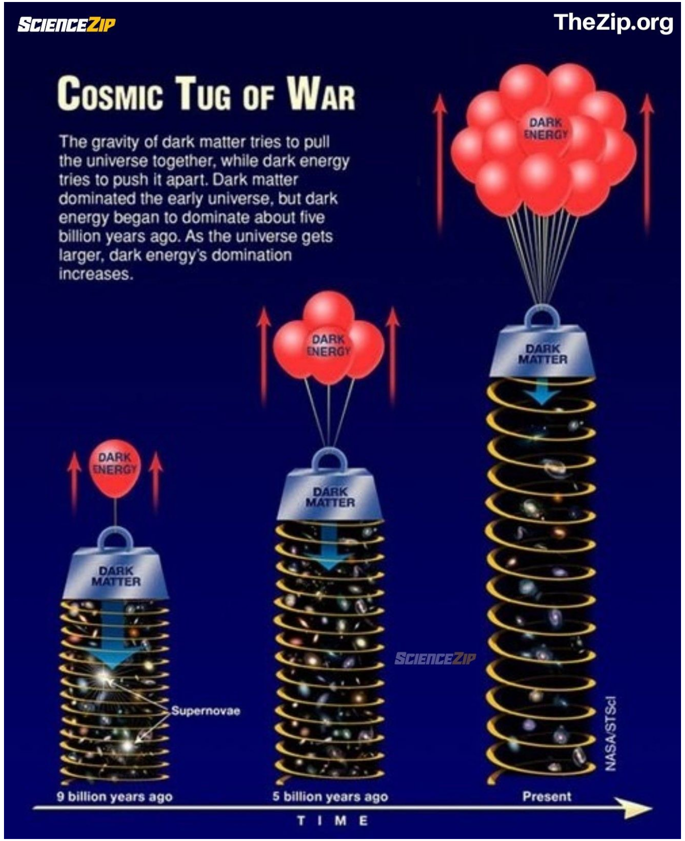
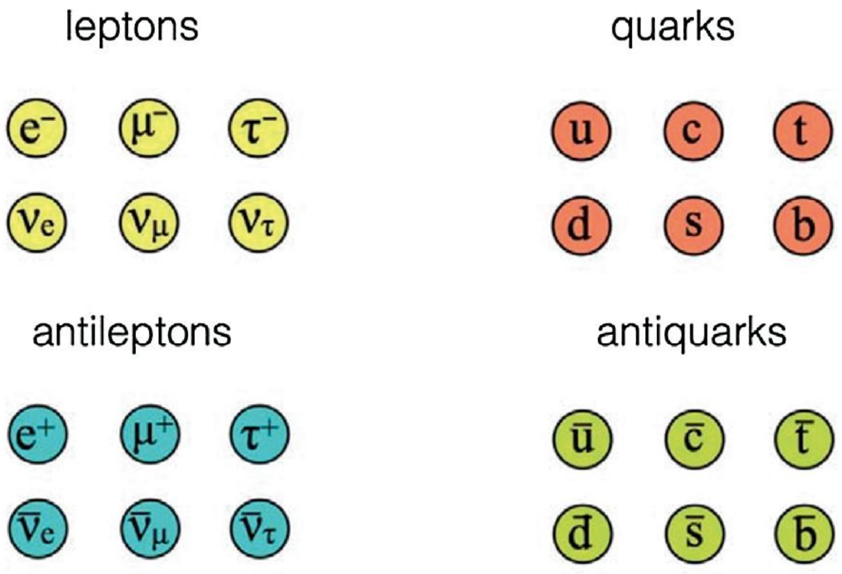


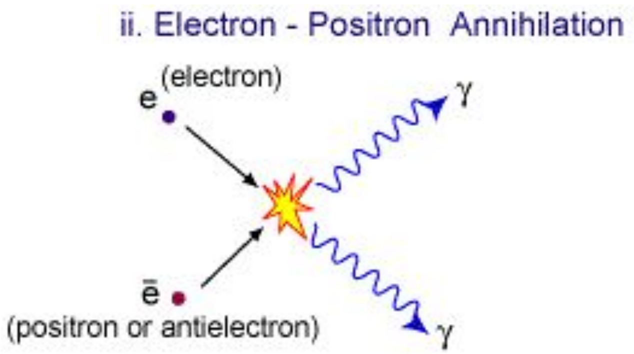
Antimatter

- For each particle there is an anti-particle with **equal mass**, but **opposite charge.**
- Anti-particles are for example produced in the **cosmic radiation** and the **beta-plus-decay**.
- **Antiatoms** have not been observed in nature and can only be produced in experiments.



Antimatter

- If a particle and its anti-particle interact, they annihilate and decay into **photons**.
- **Why did not all particles and antiparticles of the universe annihilate?**

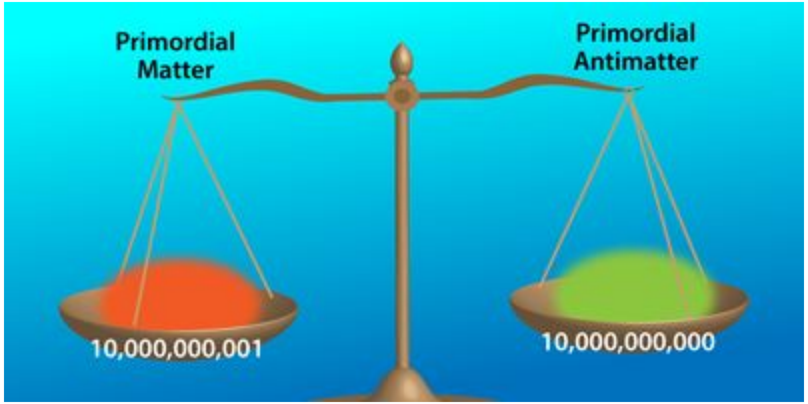


Antimatter

- If a particle and its anti-particle interact, they annihilate and decay into **photons**.

- **Why did not all particles and antiparticles of the universe annihilate?**

➔ **Symmetry breaking**:
For 10.000.000.001 particles there are 10.000.000.000 anti-particles!



Questions from cosmology to particle physics

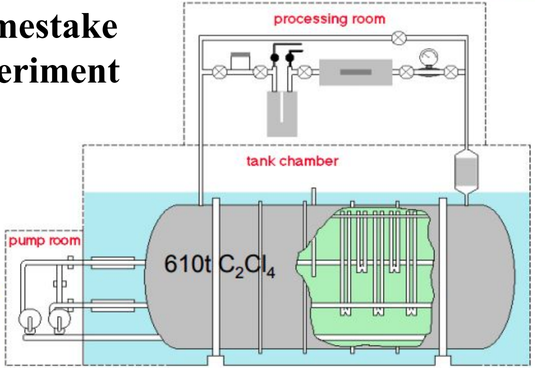
- Why is there more matter than antimatter in the universe?
- What is **dark energy**?
- What is **dark matter**?

Neutrinos

- **Neutrinos** (ν_e, ν_μ, ν_τ) in the SM are **massless** and **cannot transition from one kind of neutrino to another kind.**

- **Solar neutrino problem**
  - Was discovered at the **Homestake experiment.**
  - **Neutrinoflux** from the sun is smaller than expected.
  - Where are the missing neutrinos?

Homestake experiment



$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

Result:	
Measured flux:	**2.56 SNU**
Expected:	**8.5 SNU**

Neutrinos

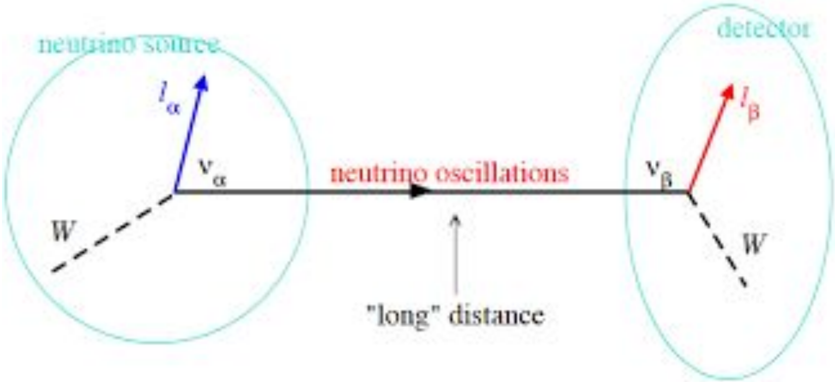
Conclusion:

Neutrino oscillations

Neutrino oscillations

- **Neutrino oscillations** = Transition of a neutrino with one to another neutrino with another lepton flavor.
  - At least two kind of neutrinos have a mass > 0!

- This was established for the first time at the **Super-Kamiokande** experiment.



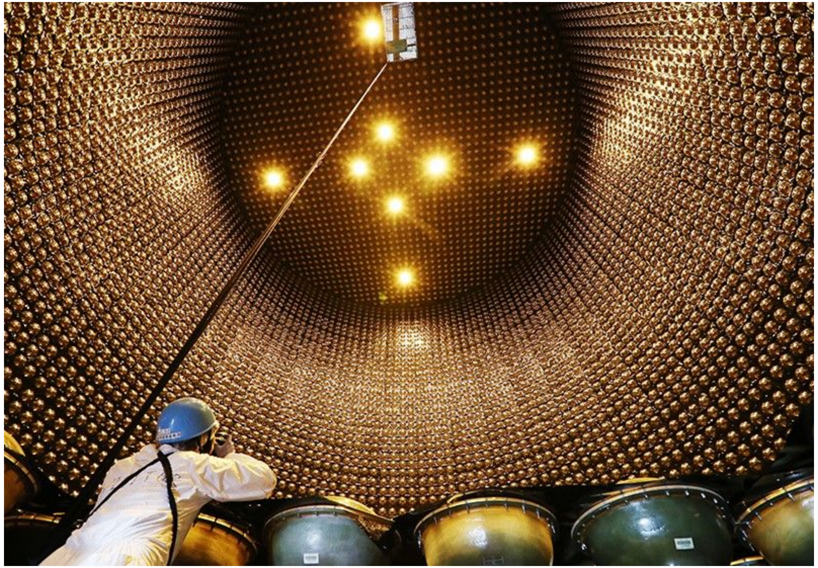
Super-Kamiokande

- **Experiment is located 1000m underground.**

- Tank filled with water. Using **photomultipliers** one can detect the following reactions:
  - $\nu_e + N \rightarrow e + X$
  - $\nu_\mu + N \rightarrow \mu + X$
  - $\nu_\tau + N \rightarrow \tau + X$

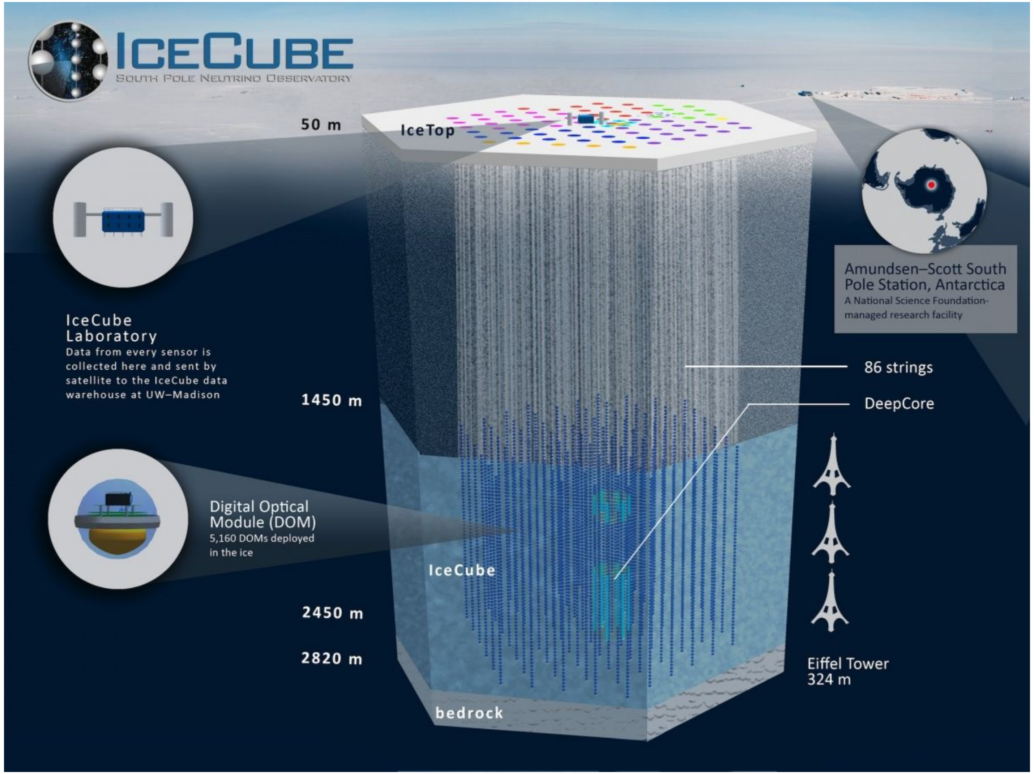
- **Discrepancy** between **expected and measured muon neutrino flux** observed!

➔ Proof for **neutrino oscillations!**



Ice cube

- Search for **high energy neutrinos** from outside our solar system.
- 2018 a first **high energy neutrino (290 TeV**) from a galaxy 4.5 ly away was detected!
- In total **28 extraterrestrial neutrinos** were detected.



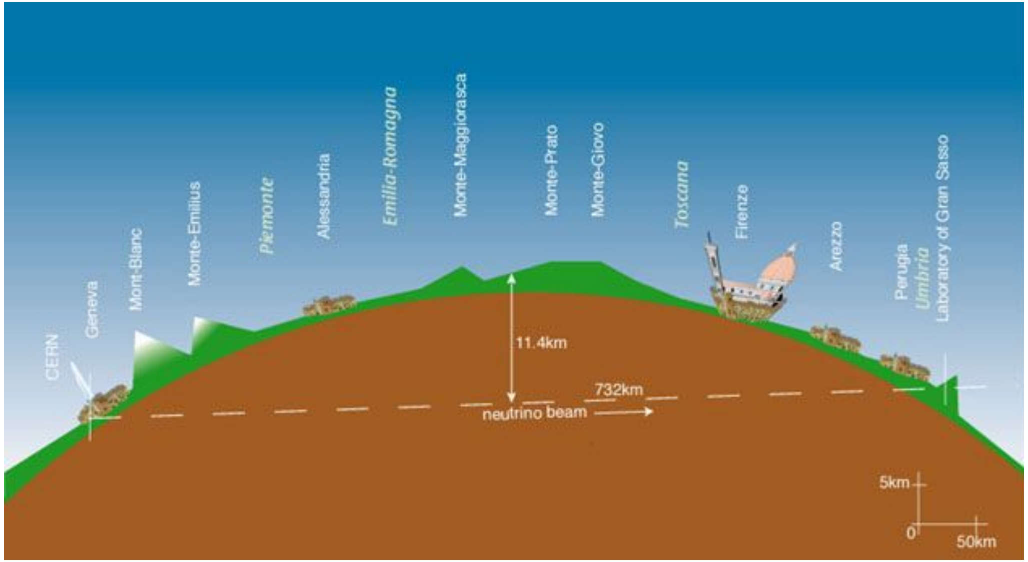
CNGS

- **CNGS - CERN Neutrinos to Gran Sasso**

- **Muon neutrino beam** sent from CERN to Gran Sasso.

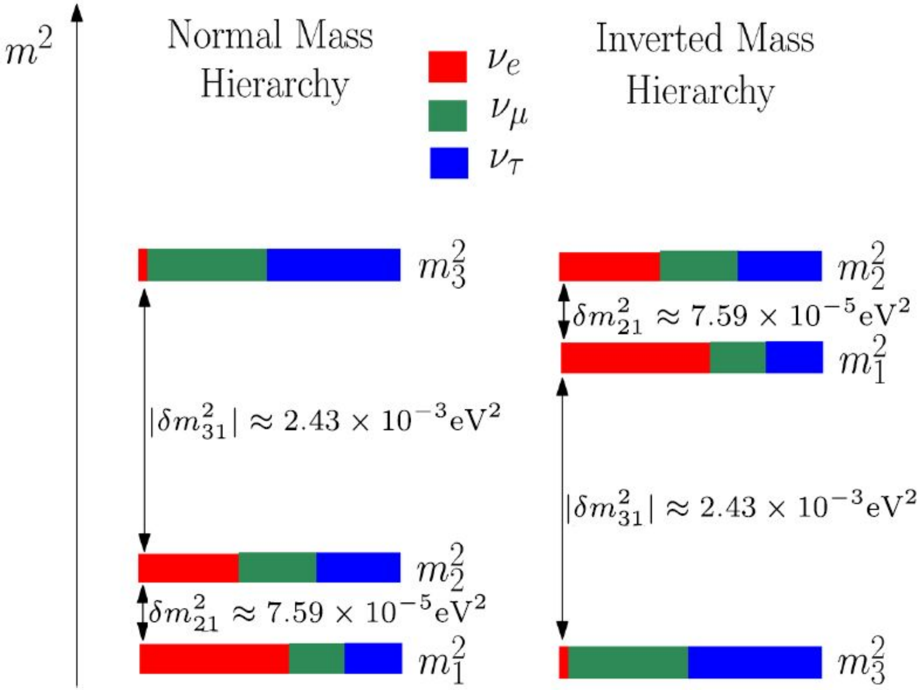
- There are two experiments in CNGS:
  - **OPERA**
  - **ICARUS**

- Both experiments were used to confirm **neutrino oscillations from ν_μ to ν_τ**.



Neutrino masses

- In all neutrino oscillation experiments we always measure the **mass difference** between two different neutrinos.
- Actually, we measure the difference of the **mass squared**! Hence, we cannot tell which neutrino has the largest mass!



Absolut neutrino mass measurement: Katrin

- One of the few experiments trying to measure the **absolut neutrino mass**!

- **KATRIN -** Karlsruhe Tritium Neutrino Experiment
  Measurements being conducted since 2018.

- Experiment to measure **electron anti-neutrino mass.**

- **Beta spectrum of tritium decay** is measured with a **sensitivity of 0.2 eV**.

$$H^{3}_{1} \xrightarrow[\text{12.3 years}]{} He^{3}_{2} + e^{0}_{-1} + \overline{\nu}^{0}_{0}$$

(tritium) (beta particle) (antineutrino)

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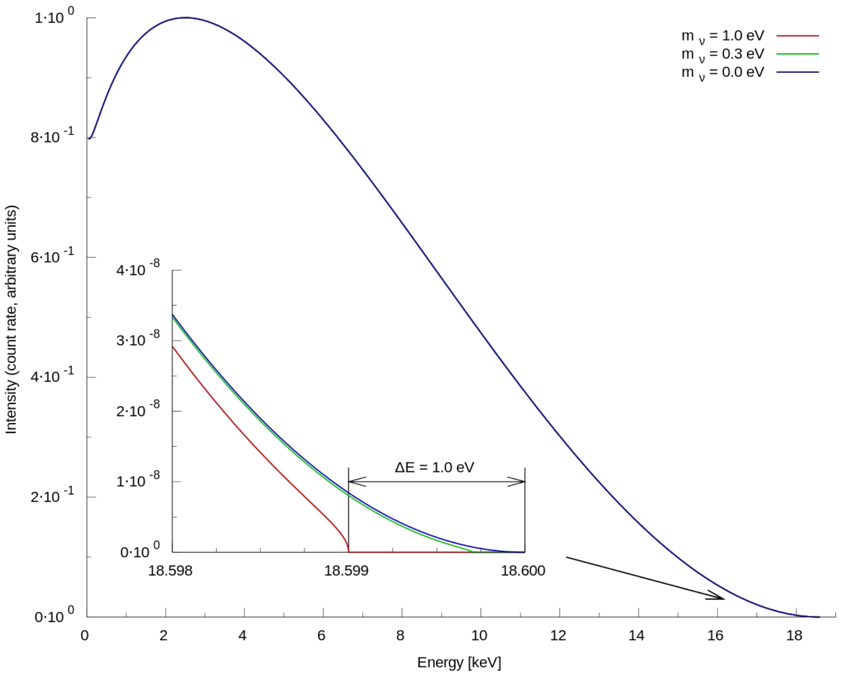


Hierarchy problem

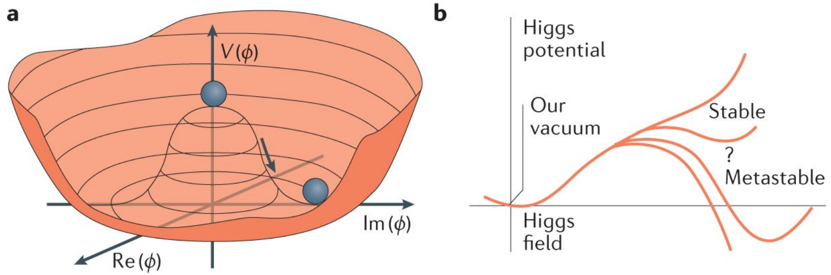
- For the Higgs mass **very big corrections** of all particles that couple to the Higgs field are needed.
  These are for example **loop corrections** of **fermionen *f*** or **scalars *S***.

- Corrections for a fermion are proportional to

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV} + \dots$$

- If the SM was correct for all energies, the Higgs mass would be **infinite**: $\Lambda_{UV} = \infty$, $m_H = \infty$
  Λ_{UV} is ultraviolet cutoff (energy scale for SM).

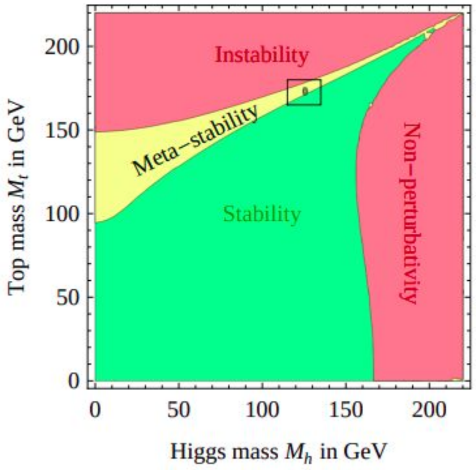
- This is apparently not the case! SM cannot be completely right!

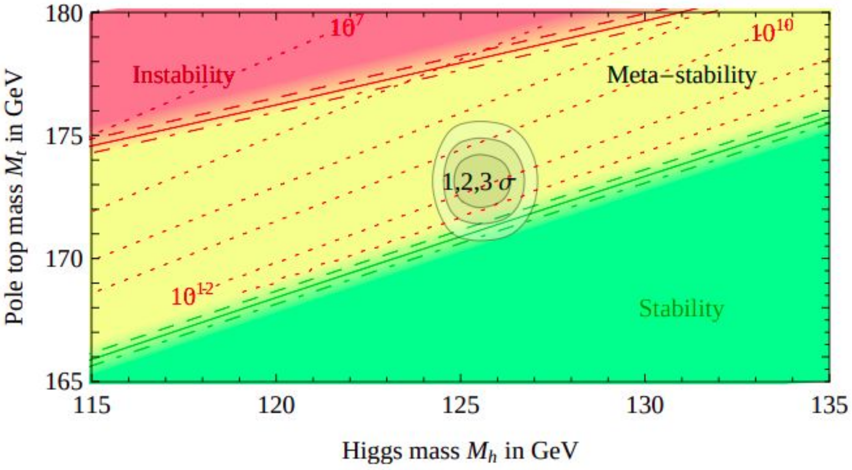


Fine tuning

- In order to explain the current state of the universe, the **universal constants have to be tuned to very specific values**.

➔ Either the whole universe is in a very unstable state, or we are (probably) lacking some knowledge **concerning new physics!**



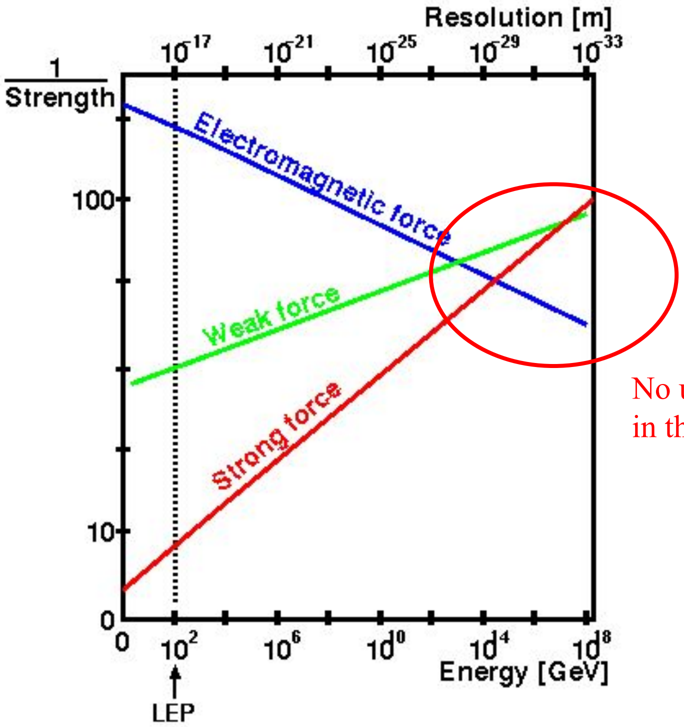


Unification (?) of coupling constants

- If the electromagnetic and strong force are unified, leptons and quarks can transition into each other.

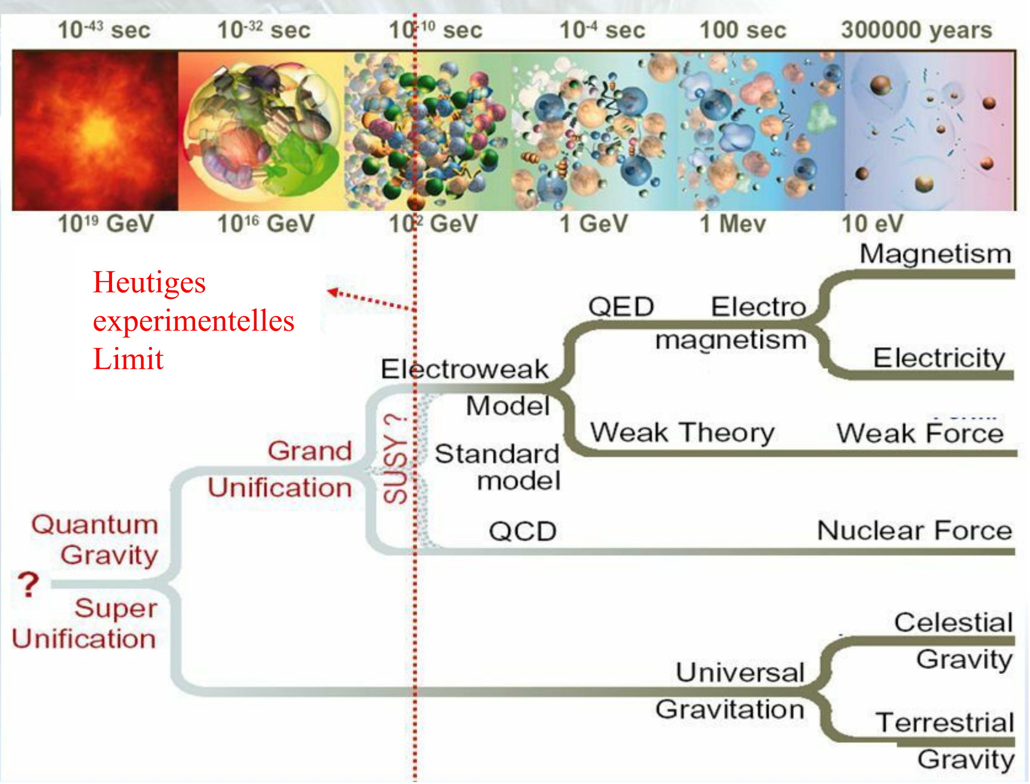
➔ The energy at which they unify must be large enough to be **compatible with the half-life of the proton** (atm > 10^{31} years).

- Unification of all forces is comprised in the **Grand Unified Theory (GUT)**.



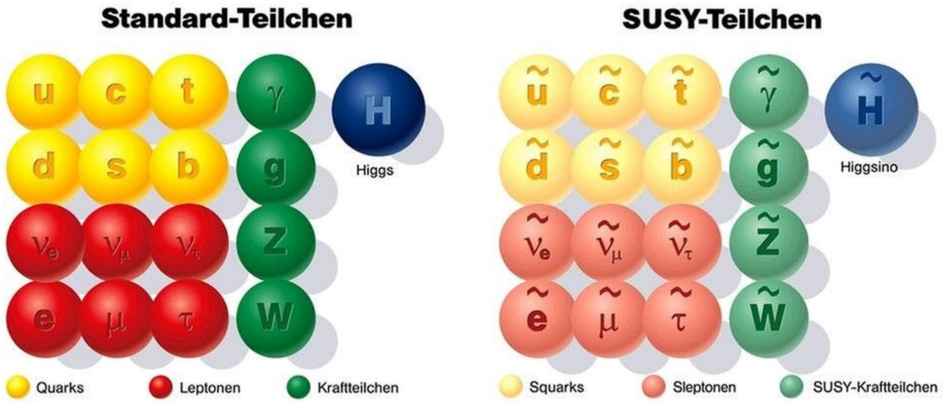
No unification in the SM :(

Grand Unified Theory (GUT)



Super Symmetrie (SUSY)

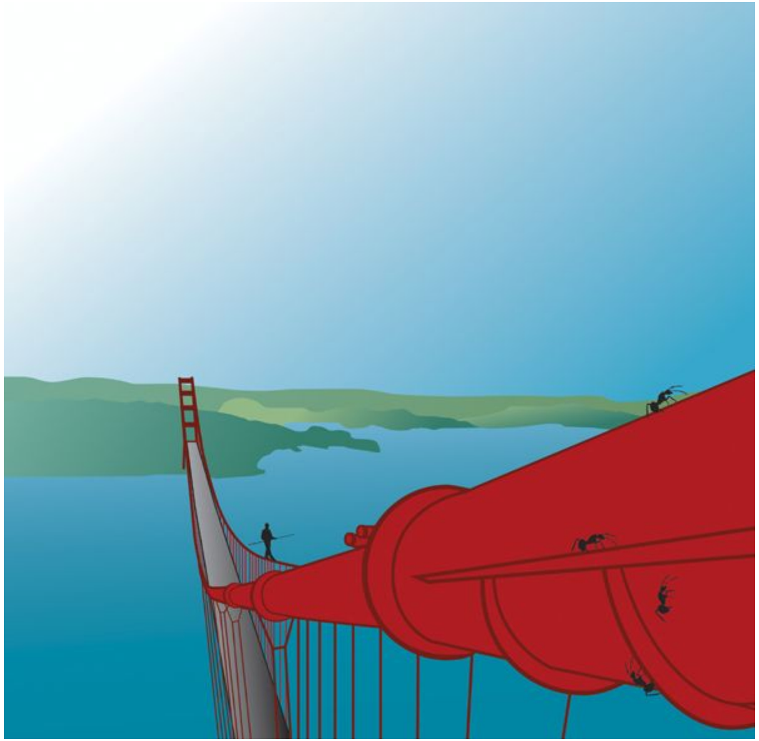
- Gravity is 10^{-38} times weaker than the weak force! Why?
- One possible explanation is **SUSY.**
- Each particle has a **supersymmetric partner.**
- SUSY would explain dark matter, unification of all forces at large energies etc.



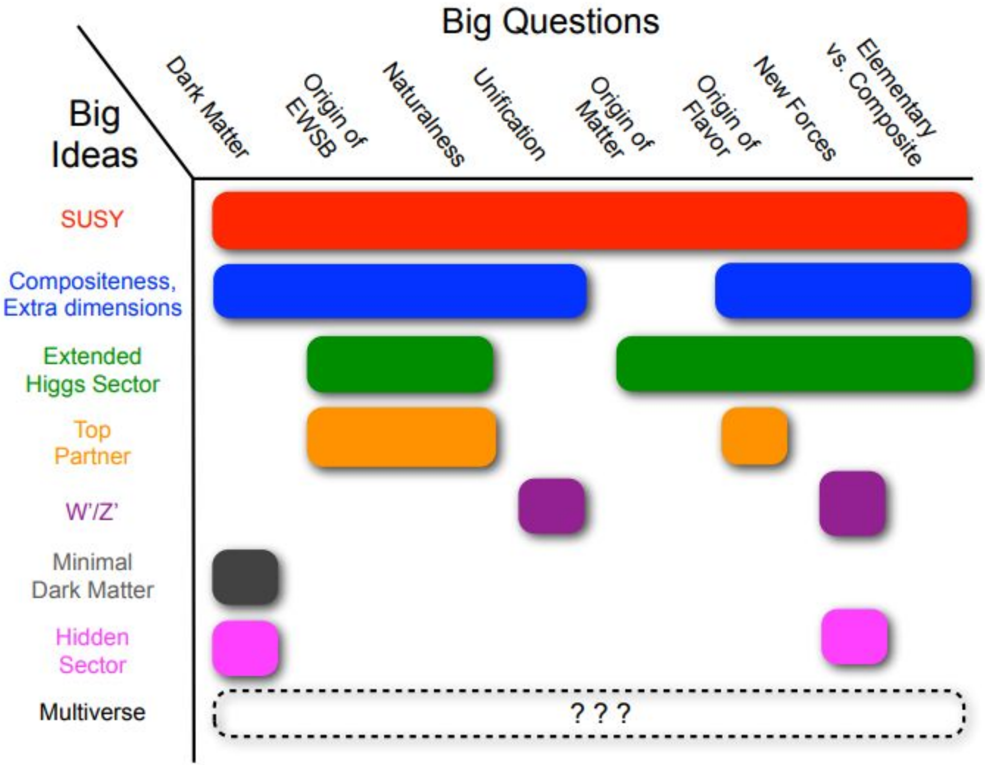
Extra dimensions

- Gravity is 10^{-38} times weaker than the weak force! Why?

- Other possible explanations are theories of **extra dimensions**, for example the string theory.
  - We and all to us known particles are located on a **subspace with 3+1 dimensions.**
  - The entire space consists of 3+1+d dimensions. In the string theory, the **graviton** also has access to the additional dimensions!



What are the open questions?



Backup

Neutrino masses

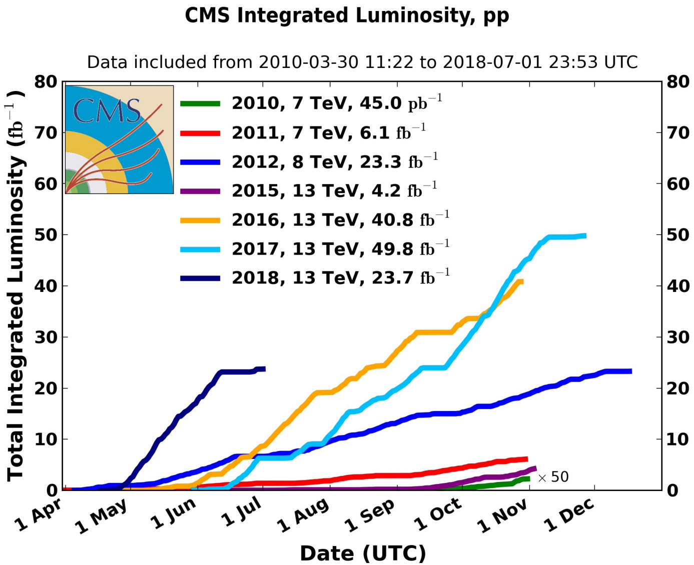
- Why are neutrino masses so small?

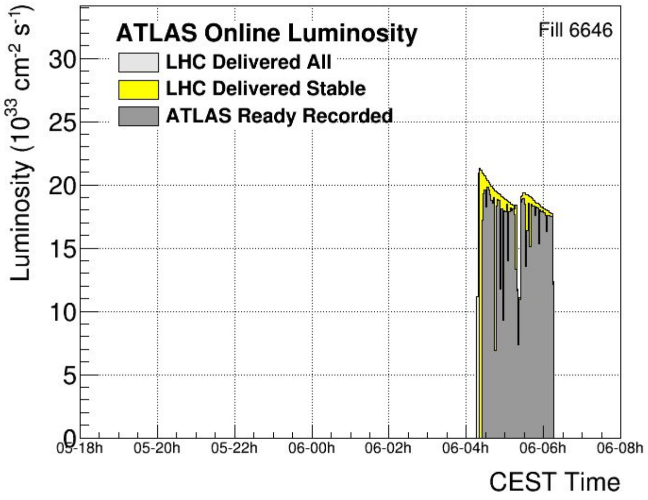
- There are many theories! One of the most popular ones is the "**Seesaw mechanism".**

- **Seesaw mechanism**:
  A heavy neutrino N (mass m_N) is postulated, and the light neutrino masses m_v are inversely proportional to it.
  - $m_v \sim y_v^2 v^2 / m_N$
  - y_v Yukawa coupling constant, v Higgs vacuum expectation value

How to look for new particles: The LHC

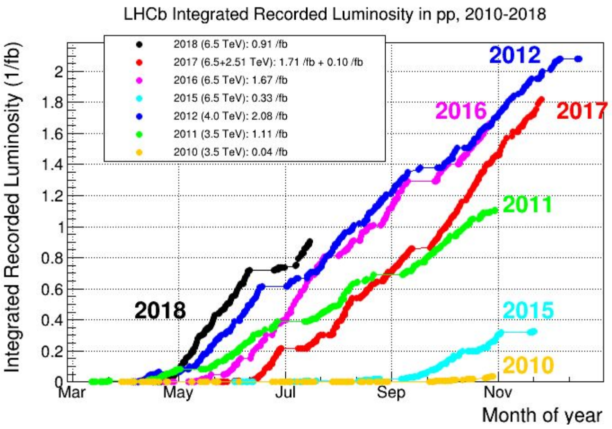
- The Large Hadron Collider (LHC) **collides protons and heavy ions**.
- 2010 - 2012: √s (proton-proton collisions) of 7-8 TeV, ATLAS and CMS collected ~30 fb^{-1} of data
- 2015 - 2018: √s = 13 TeV, accumulated data (as of ~July 2018): CMS ~113 fb^{-1} , ATLAS 136 fb^{-1}
- Target luminosity ~150 fb^{-1}

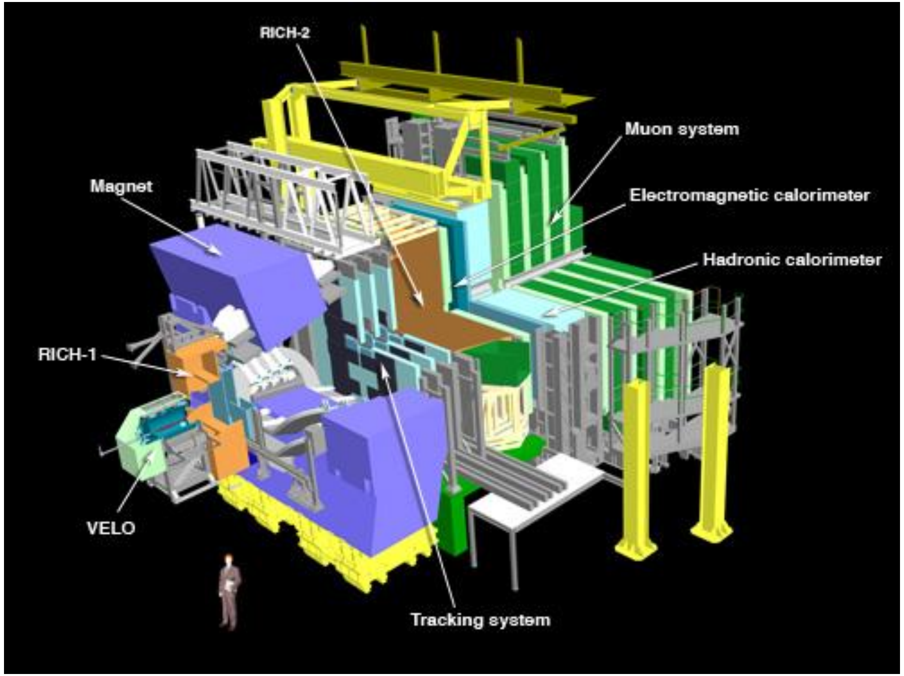




How to look for new particles: Experiments

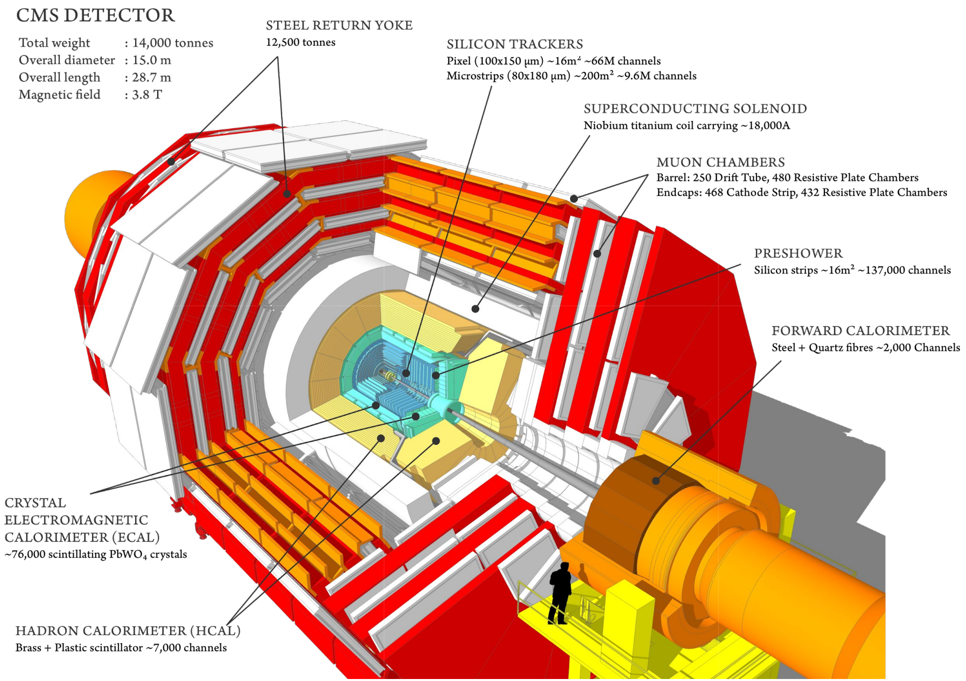
- LHCb is a **specialized b-physics experiment** for primarily investigating CP violation in b-hadron interactions.
- 2010 - 2012: ~ 3.23 fb^{-1} at √s = 3.5/4 TeV
- 2015 - 2018: ~4.62 fb^{-1} at √s = 6.5 TeV



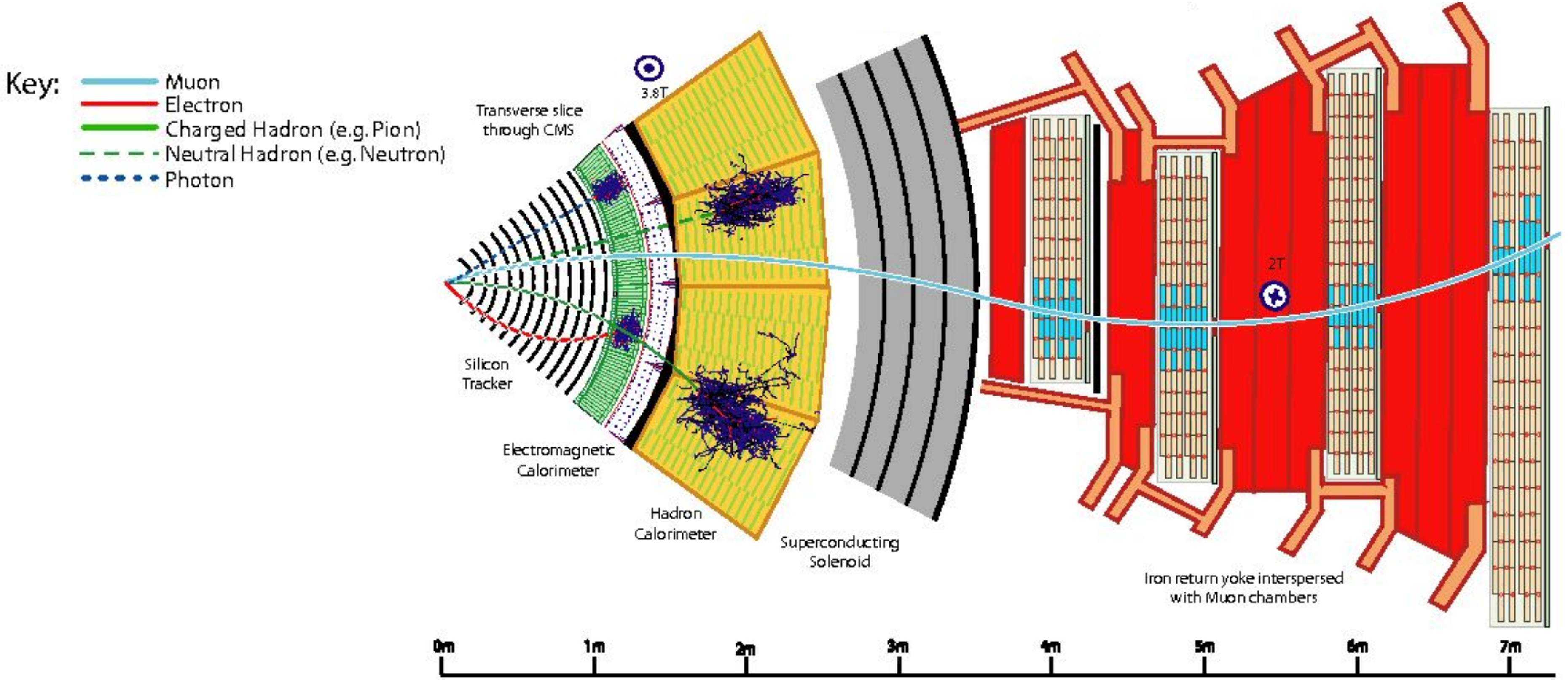


How to look for new particles: Experiments

- ATLAS and CMS are **general-purpose detectors**, both consisting of several subsystems, designed to exploit the physics potential at the LHC.

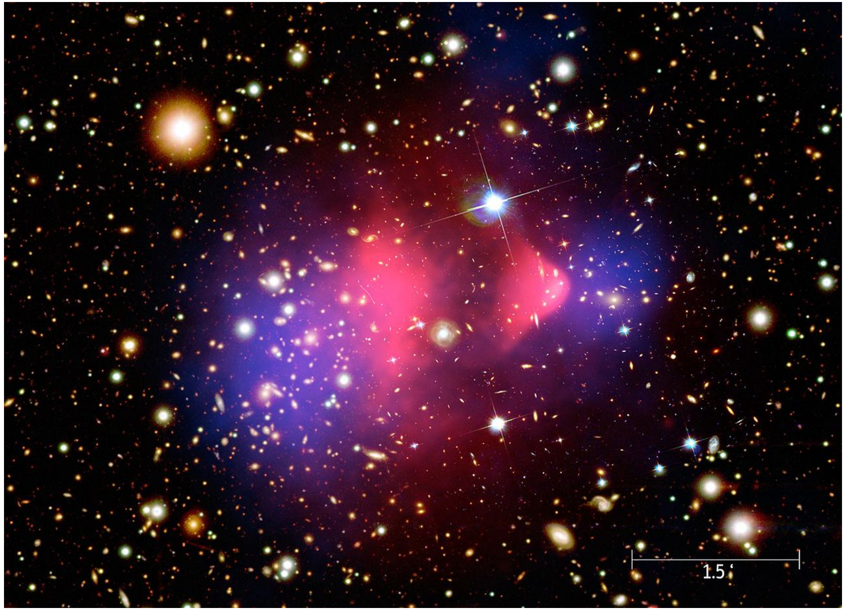


How to look for new particles: Particle reconstruction



Dunkle Materie: Bullet Cluster

- **Zwei Galaxienhaufen kollidieren (der kleinere der beiden = bullet cluster)**
- **Sterne** verändern ihre Laufbahn kaum und werden nur durch die Gravitationskraft abgelenkt.
- Großteil der **baryonischen Materie sind Gase (rot)**. Sie wechselwirken auch **elektromagnetisch** und werden um ein Vielfaches mehr abgebremst als Sterne.
- **Dunkle Materie** beobachtbar durch durch den **Gravitationslinseneffekt (blau)**. Wechselwirkt wahrscheinlich nur durch die Gravitation und durch die schwache Kraft.



Bullet-cluster “1E 0657−558”