Introduction to Particle Physics

SIST2023 Summer Lecture Series

Christina Gao

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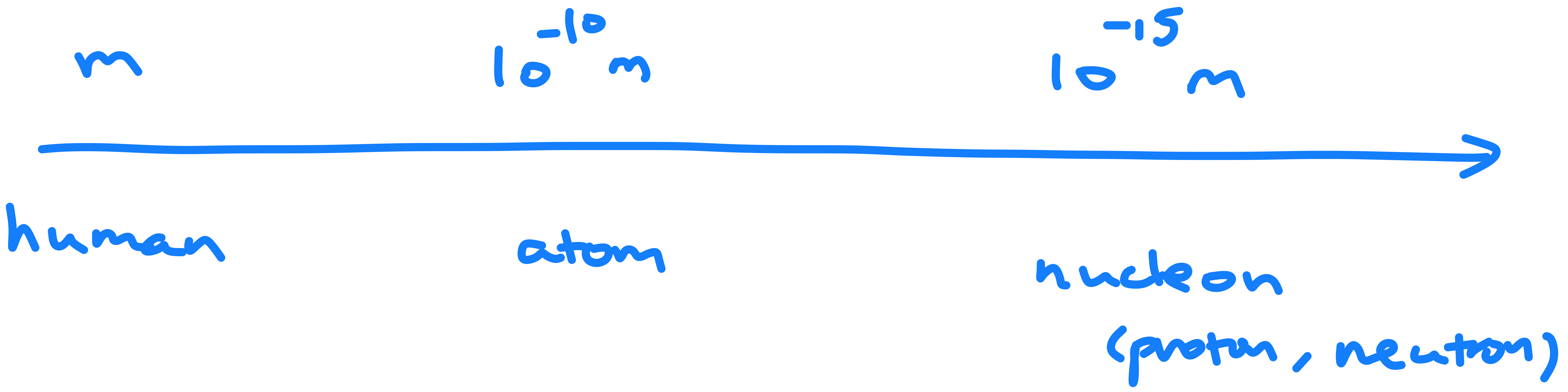
What is particle physics



- These are all composite objects.
- They can be made up from elementary particles.

What is particle physics

ex

Hydrogen = proton + electron

p^+ e^- → leptons

proton = up + up + down

p^+ (u u d)

u, d → quarks

neutron = (u d d)

n

What is particle physics: quarks and leptons

ex

Hydrogen = proton + electron

p^+ e^- → leptons

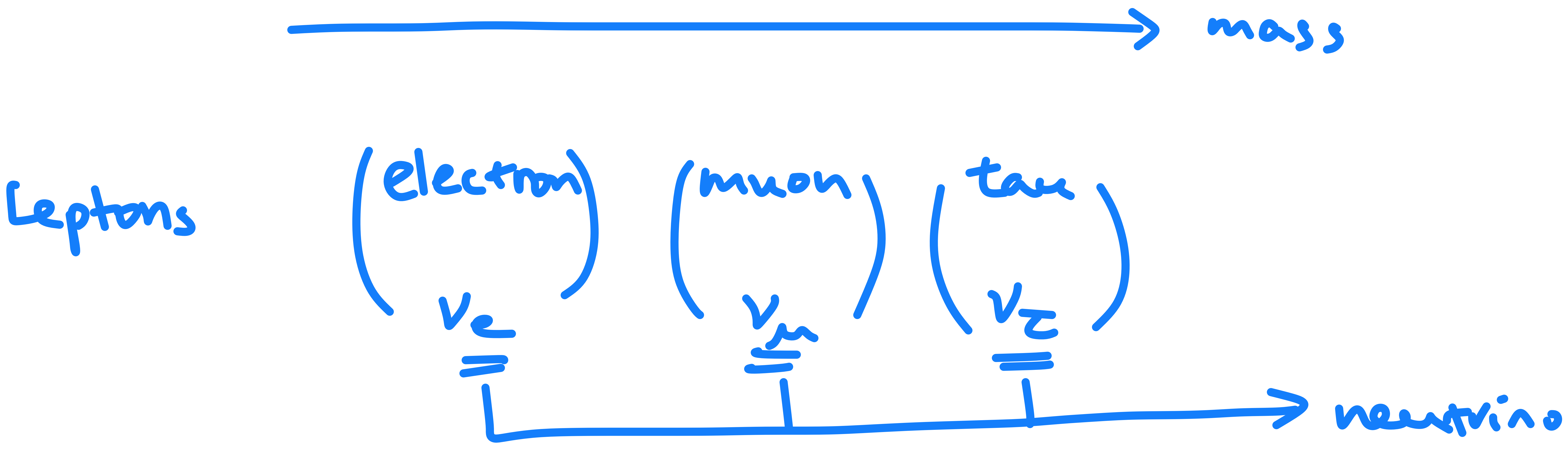
proton = up + up + down

p^+ (u u d) → quarks

neutron = (u d d)

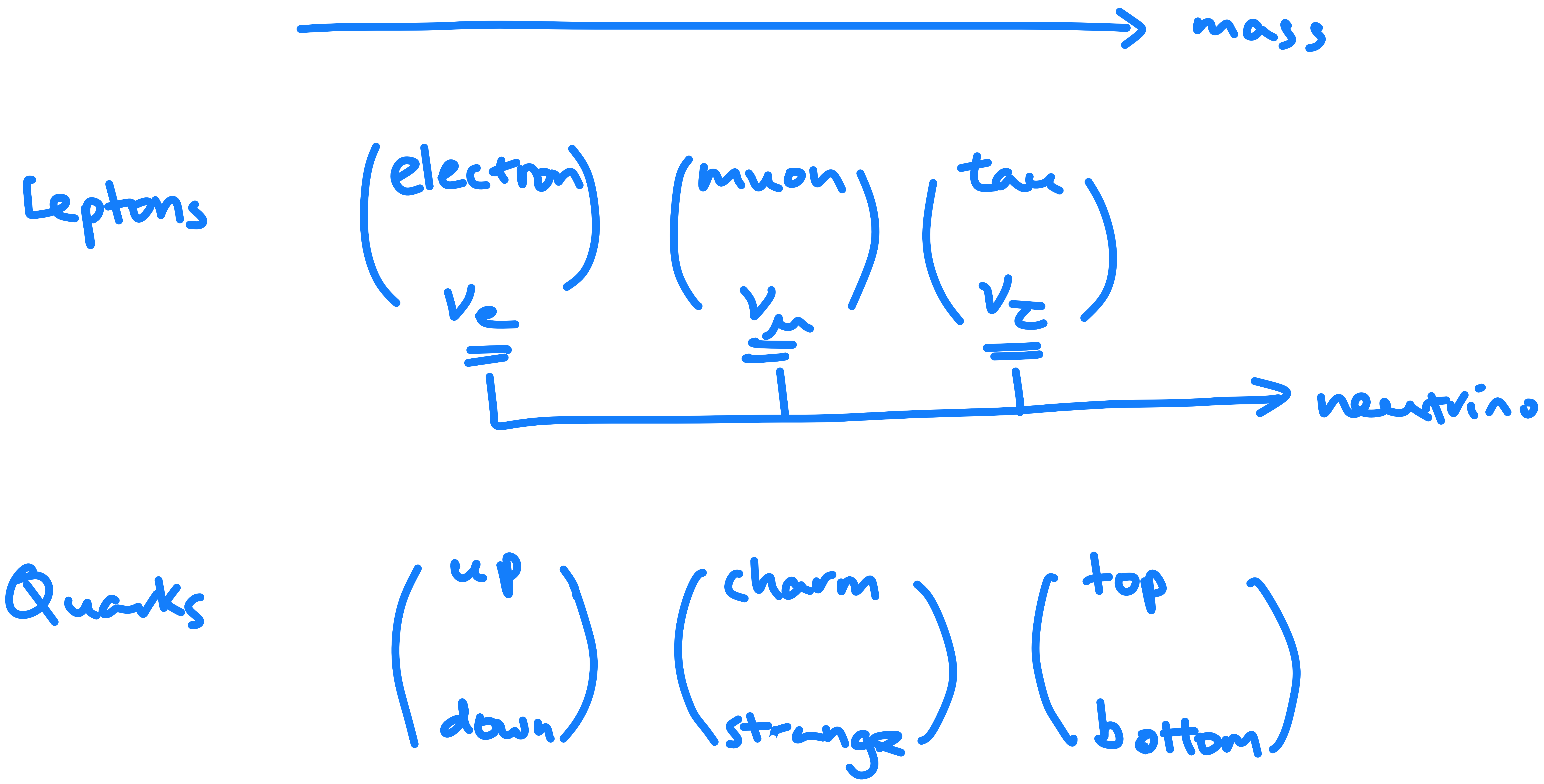
n

How many quarks and leptons



- Fermilab observed the tau neutrino.
- Neutrino mass ordering is still unknown today.

How many quarks and leptons

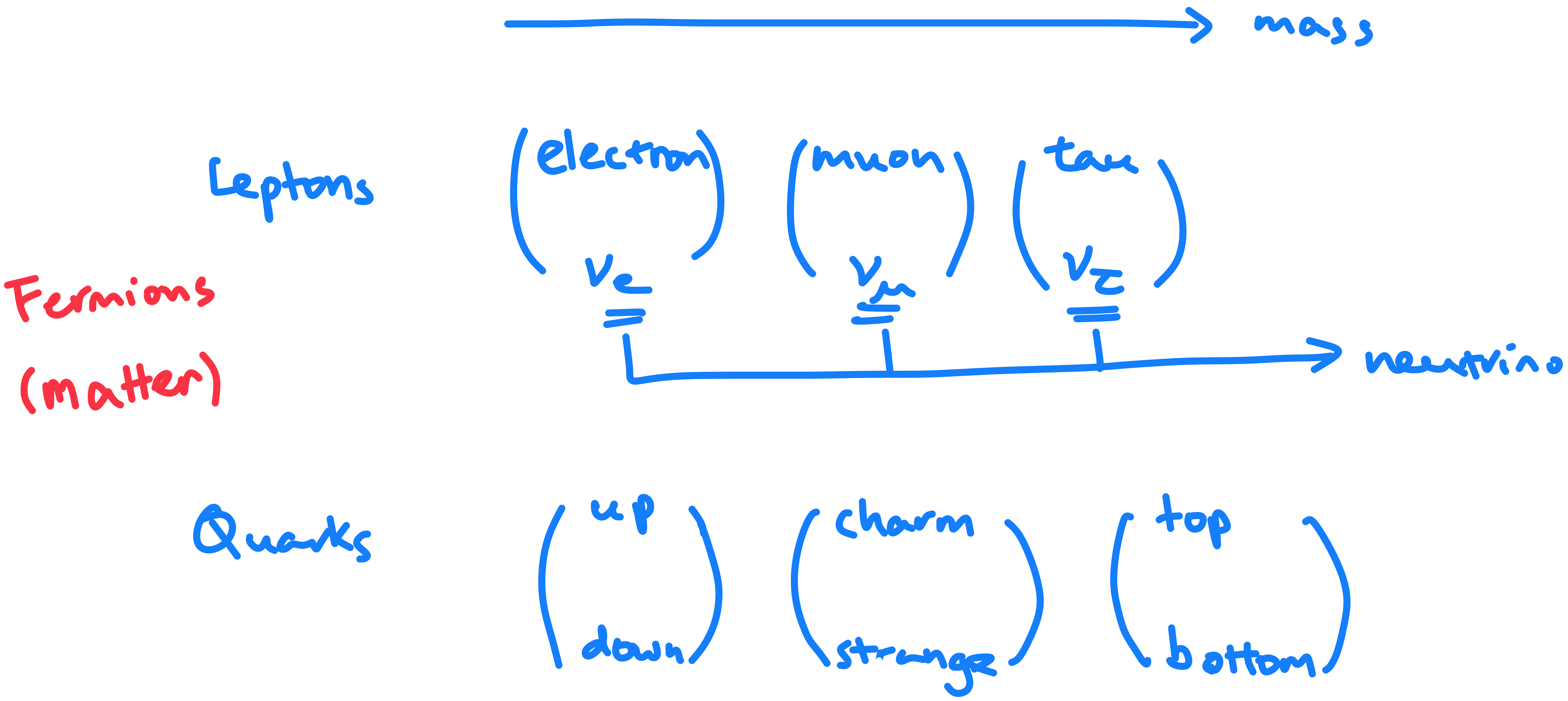


How many quarks and leptons

- Fermilab discovered top and bottom quarks
- Quarks can form baryons (proton: uud) and mesons (pion+: u anti-d)

Quarks $\begin{pmatrix} \text{up} \\ \text{down} \end{pmatrix} \begin{pmatrix} \text{charm} \\ \text{strange} \end{pmatrix} \begin{pmatrix} \text{top} \\ \text{bottom} \end{pmatrix}$

How many quarks and leptons



Quarks and leptons are fermions

- Fermions have half-integer spins.
- All the known elementary quarks and leptons have spin-1/2.
- We can study their

ex

mass

charge (NOT just electric)

decay (they may be unstable)

scattering (how they interact with each other)

Quarks and leptons are fermions

- Fermions have half-integer spins.
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mass

charge (NOT just electric)

determined by forces { decay (they may be unstable)

scattering (how they interact with each other)

How many fundamental forces

- Hydrogens are bounded by the **electromagnetic force** between the electrons and protons
- Protons are bounded by the **strong** nuclear **force** between the up and down quarks
- Neutrons can decay to protons (a.k.a. beta decay) via the **weak force**

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All these fundamental forces are mediated by force carriers,
i.e. more particles…

How many fundamental forces

Electromagnetic	photon	Maxwell Equations
Strong	gluons	Can be studied using Quantum Field Theory !
Weak	$W^{\pm}$, Z bosons	
gravity	graviton	Newtonian gravity General Relativity

How many fundamental forces

Electromagnetic — photon — Maxwell Equations

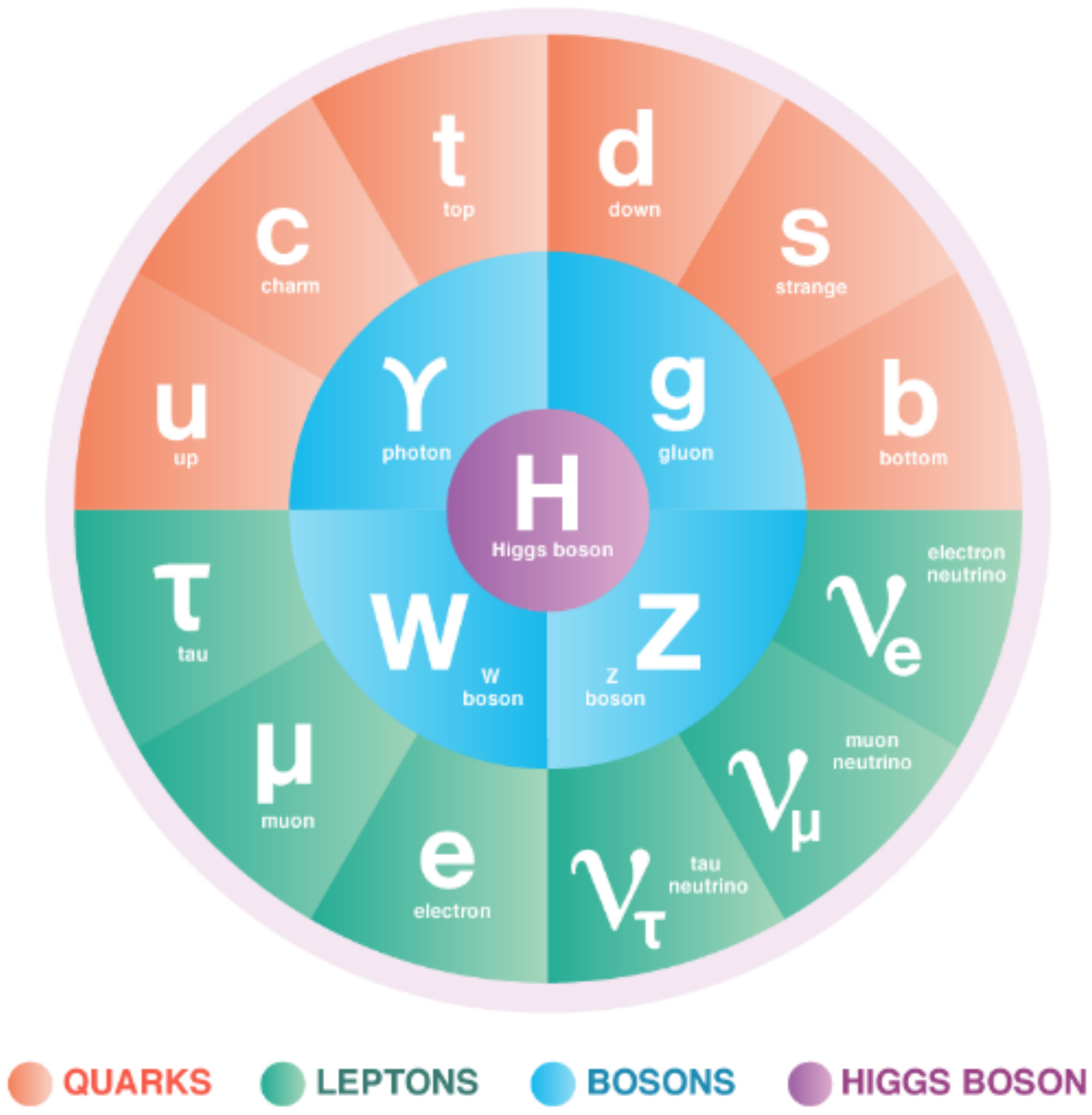
Strong — gluons

Weak — $W^{\pm}, Z$ bosons

gauge bosons (spin 1) — Can be studied using Quantum Field Theory!

gravity — spin-2 — graviton — Newtonian gravity, General Relativity

Standard Model of particle physics



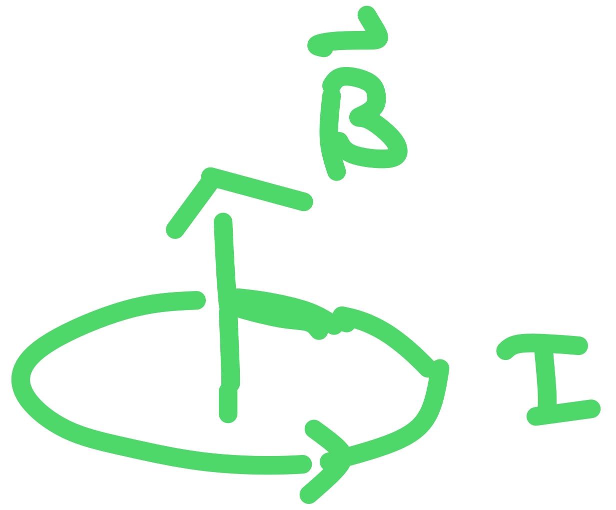
- We discovered six leptons, six quarks, and force carriers of the three fundamental forces.
- What is the Higgs boson?
- To talk about Higgs, we need talk about symmetries.

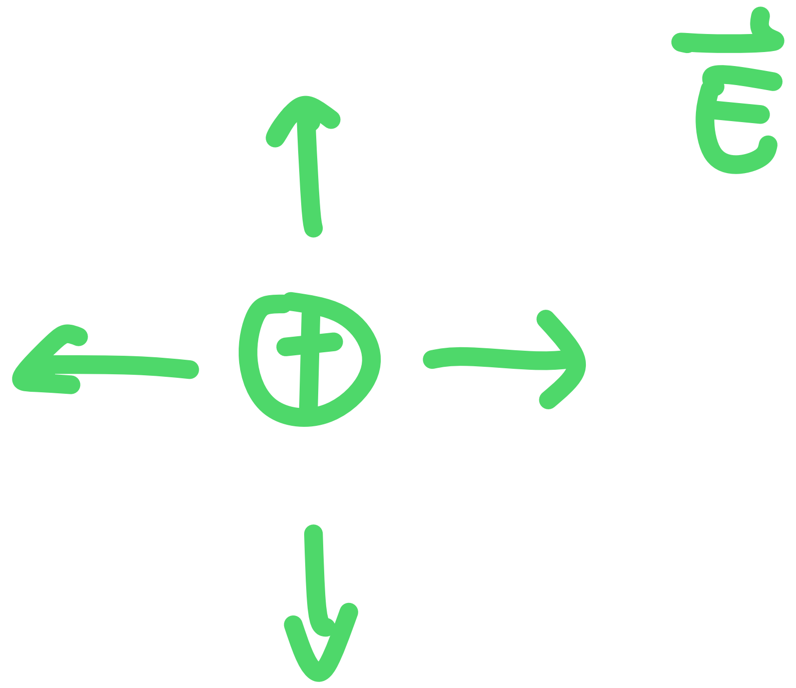
Symmetry and symmetry breaking

Symmetries in particle physics

- Discrete symmetry

ex: time reversal $T: t \to -t$





$T: \vec{B} \to -\vec{B}$ $\vec{E} \to \vec{E}$

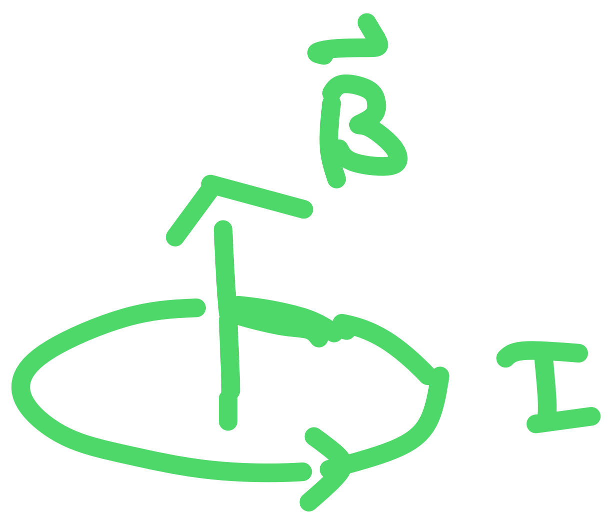
odd even

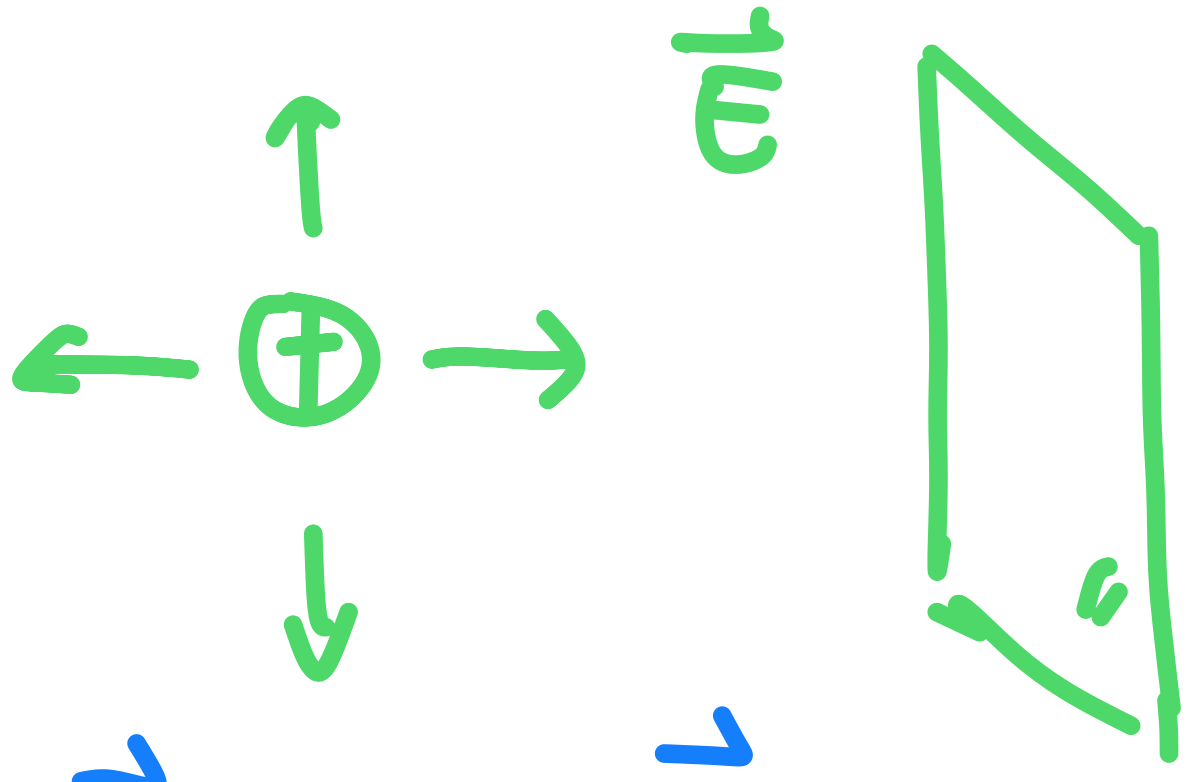
Symmetries in particle physics

- Discrete symmetry

ex — parity

$P : x \to -x$





$P : \vec{B} \to \vec{B}$

even

$\vec{E} \to -\vec{E}$

odd

Symmetries in particle physics

- Discrete symmetry

ex: Charge conjugation

$$C: \quad e^- \to e^+$$

* do not depend on space or time
* act on the "internal space" of the particle

Symmetries in particle physics

- Discrete symmetries, e.g. parity (P), time-reversal (T), charge conjugation (C)
- We see under these symmetries, fields (and therefore particles) may transform differently (even or odd).
- The physics laws may break P, CP (or T), but always seem to obey CPT.

Symmetries in particle physics

- Discrete symmetries, e.g. parity (P), time-reversal (T), charge conjugation (C)
- Continuous symmetries

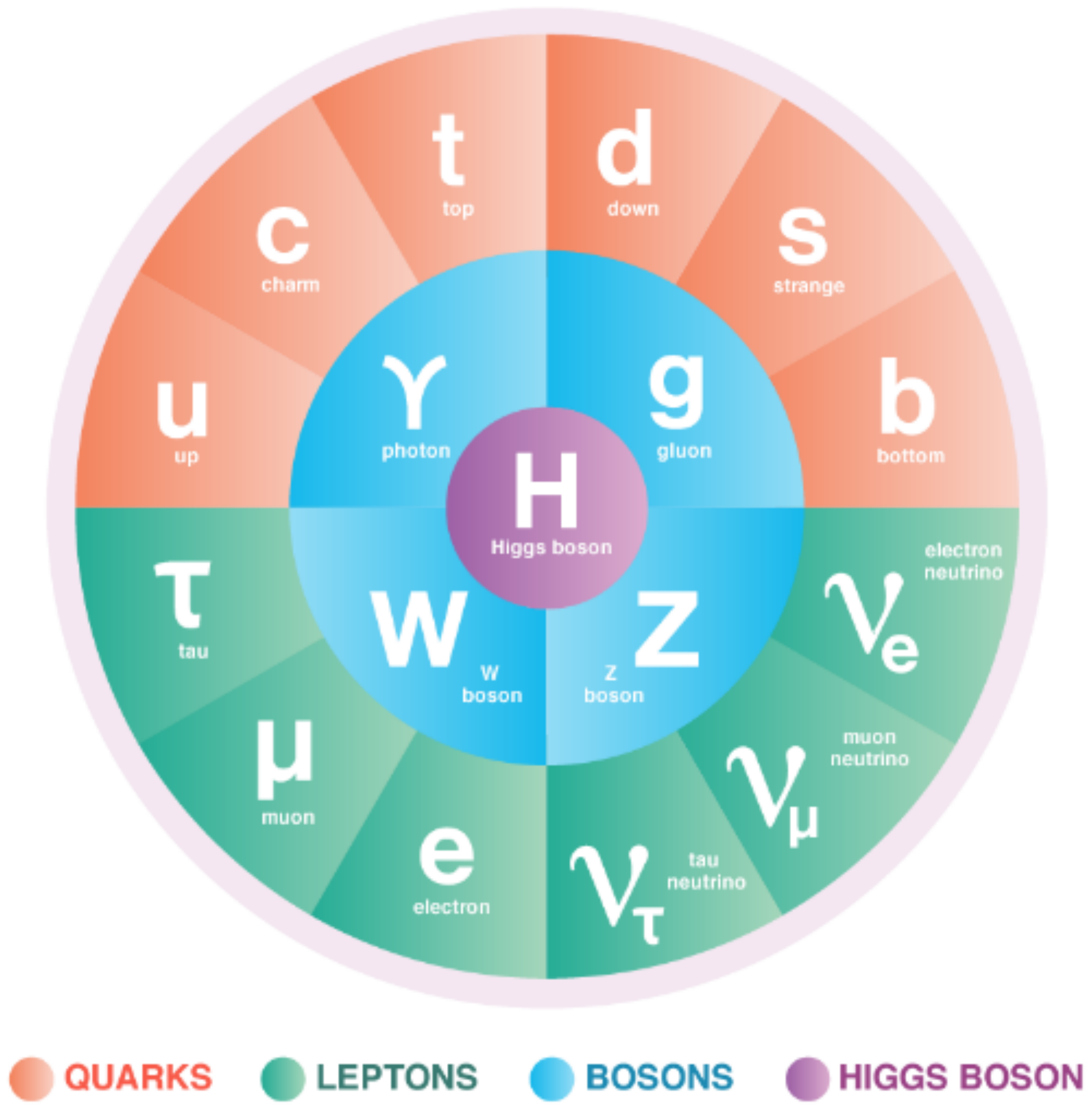
ex * Lorentz transformations < boost / rotation

* Rotations can happen in the "internal space" of the fields and particles !

Symmetries in particle physics

- Discrete symmetries, e.g. parity (P), time-reversal (T), charge conjugation (C)
- Continuous symmetries (e.g. rotations) can happen in the internal space of the fields and particles, but how much they can rotate may be different at the different spacetime.
- Global symmetry vs local (gauge) symmetry.
- A gauge symmetry is the mathematical structure behind a fundamental force!

Gauge symmetries in the Standard Model



$$SU(3)_{color} \times SU(2)_{weak} \times U(1)_Y$$

gauge bosons	strong	weak	EM ?
Leptons	✗	✓	✓
quarks	✓	✓	✓
Higgs	✗	✓	✓

Gauge symmetries in the Standard Model

- Standard Model: $SU(3)_{color} \times SU(2)_{weak} \times U(1)_Y$

a rotation in plane
1 . d.o.f.

a rotation in 3-D space, 3 d.o.f.

Gauge symmetries in the Standard Model

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  a rotation in plane 1 . d.o.f.

  a rotation with 8 d.o.f.

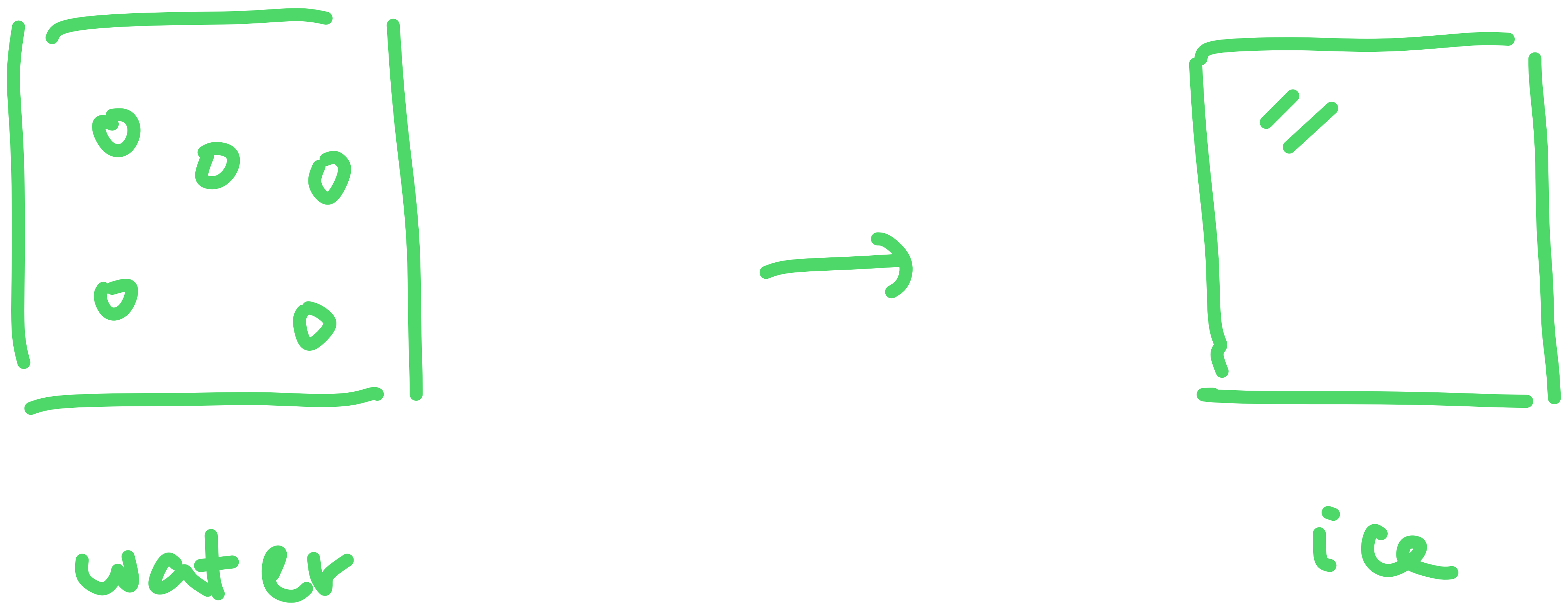
  a rotation in 3-D space, 3 d.o.f.

- By specifying the charges of leptons and quarks under these gauge transformations, we can write down a theory using quantum field theory, and work out how they interact with one another.

- Symmetries can be broken!

Broken symmetries

ex



* translation invariance

* phase transition

Broken symmetries in the Standard Model

- Standard Model $SU(2)_{weak} \times U(1)_Y \rightarrow U(1)_{EM}$
- This breaking is achieved through the Higgs, a spin-0 boson
- Higgs potential $V(H) \sim \frac{m^2}{2} H^2 + \frac{\lambda}{4!} H^4 \quad (\lambda > 0)$

$$0 = \frac{\partial V}{\partial H} = m^2 H + \frac{\lambda}{6} H^3 = \left(m^2 + \frac{\lambda}{6} H^2\right) H \Rightarrow \langle H \rangle = 0 \text{ OR } \langle H \rangle = \pm\sqrt{\frac{-6m^2}{\lambda}}$$

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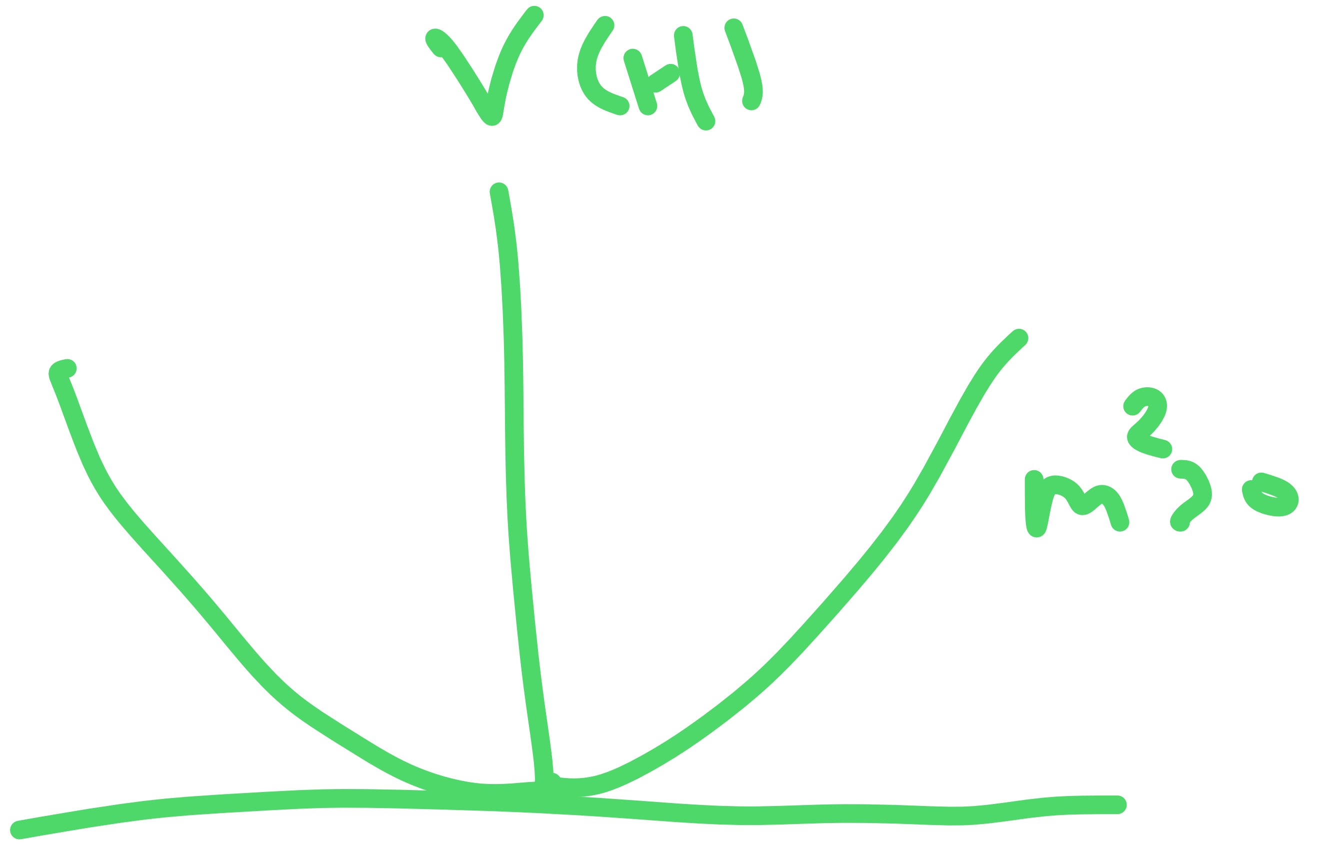

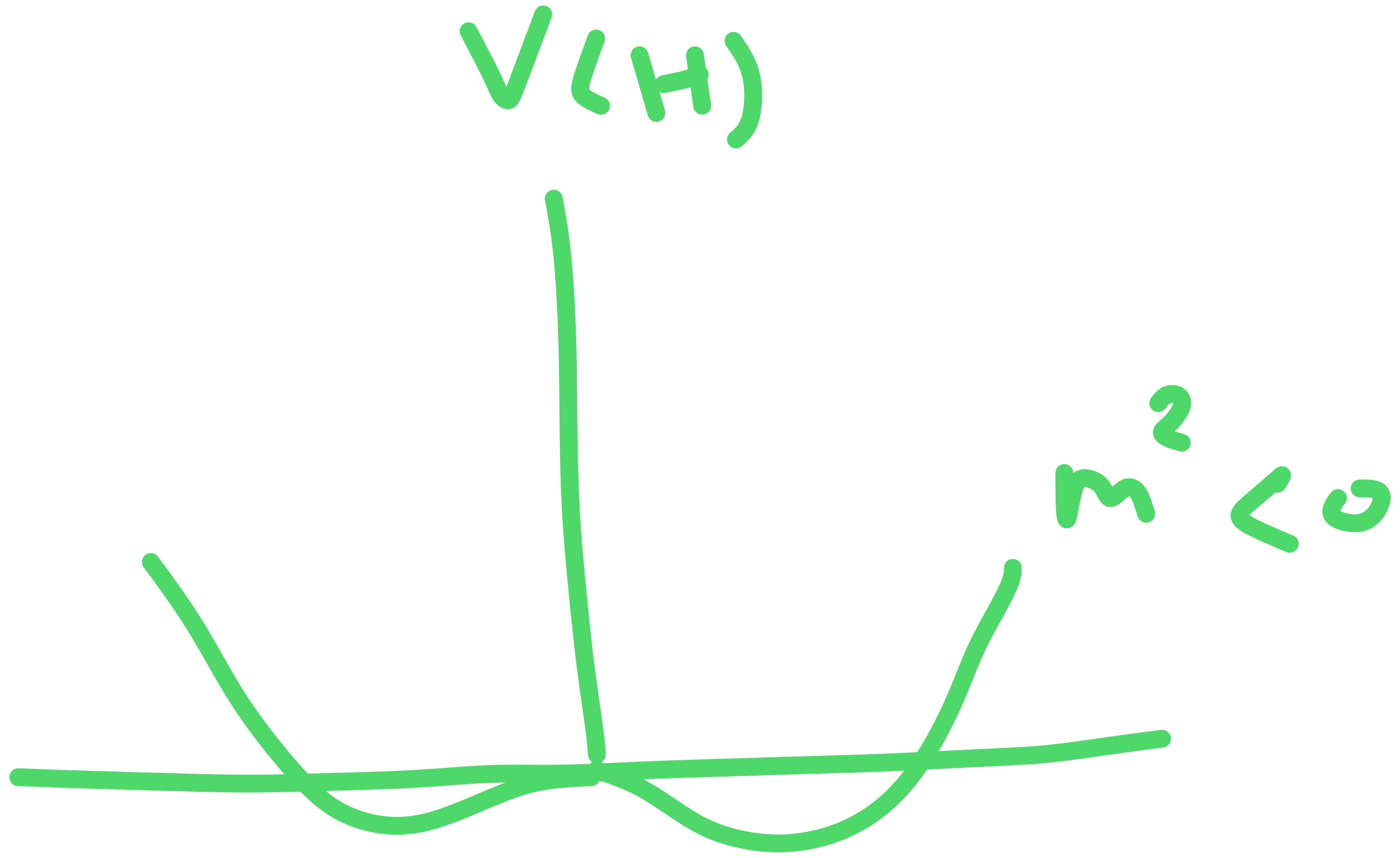

$$\langle H \rangle = 0$$

OR

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Broken symmetries in the Standard Model

- Standard Model $SU(2)_{weak} \times U(1)_Y \to U(1)_{EM}$
- This breaking is achieved via Higgs Mechanism
- The “mass” of the Higgs depends on the temperature of the Universe. As the universe cools down, the mass parameter becomes negative, which triggers the electroweak phase transition.
- After the electroweak phase transition (today), we only experience electromagnetic force in everyday life. What about the strong force?

Broken symmetries

- We just saw an example of **spontaneous symmetry breaking**, which happens in the Standard Model.
- Spontaneous symmetry breaking is a very powerful idea in particle physics, and guides us explore the vast territories of beyond the Standard Model physics.

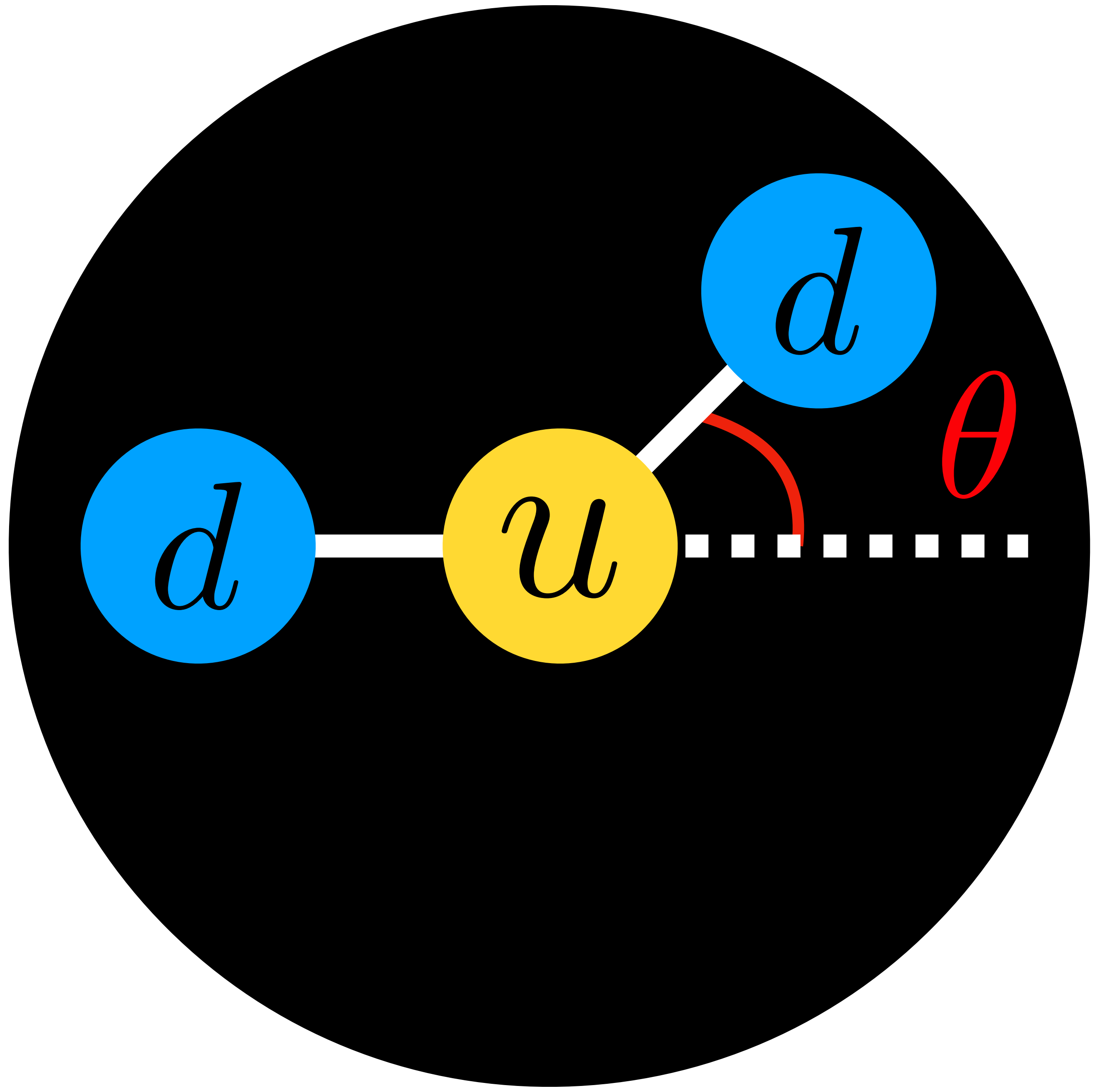
Broken symmetries

- We just saw an example of **spontaneous symmetry breaking**, which happens in the Standard Model.
- Spontaneous symmetry breaking is a very powerful idea in particle physics, and guides us explore the vast territories of beyond the Standard Model physics.
- Why is the Standard Model not enough?

* All known matter constitutes 4% of the Universe
* Neutrinos have mass
* gravity ? ...

An example of symmetry breaking beyond the Standard Model: axion

Axions were proposed to solve the strong CP problem



neutron (udd)

≃ ⊖ → ⊕ an electric dipole

- A neutron electric dipole moment breaks P and CP
- Measurement of the electric dipole moment of neutron $\rightarrow \theta \lesssim 10^{-10}$
- The strong force seems to obey CP.
- Solution: make θ dynamical, i.e. a particle!

Axions can arise in symmetry breaking

$$V(H) \sim m^2 H^* H + \frac{\lambda}{2} (H^* H)^2$$

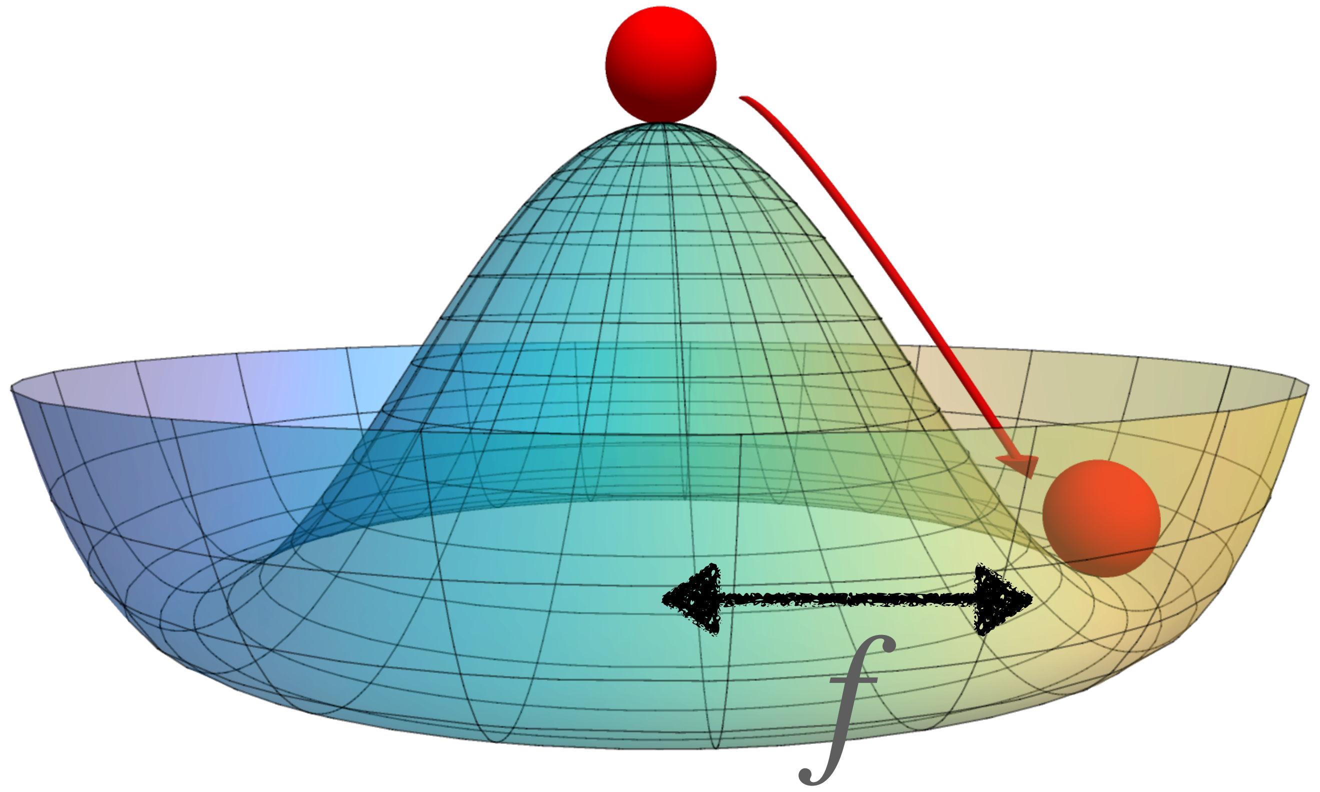
$H = |H| e^{i\theta}$ is a complex field

* $\langle H \rangle = f$

* But θ can take any values

→ a very light particle, can be axion

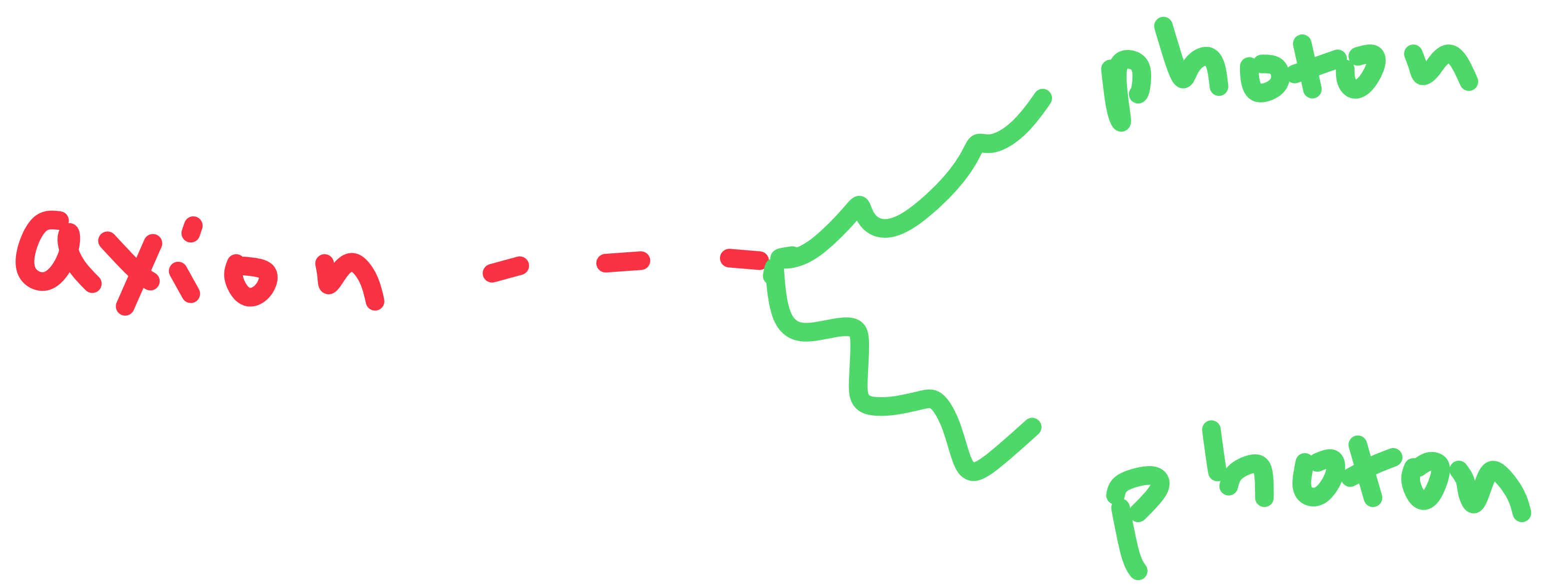
$m^2 < 0$



Why are we interested in axions

- Can solve the strong CP problem
- Many axion like particles exist in string theory
- Can be dark matter
- Can address many other issues in fundamental physics and cosmology, such as inflation, baryogenesis, dark energy…
- Can be searched both in laboratories and through astrophysical observations

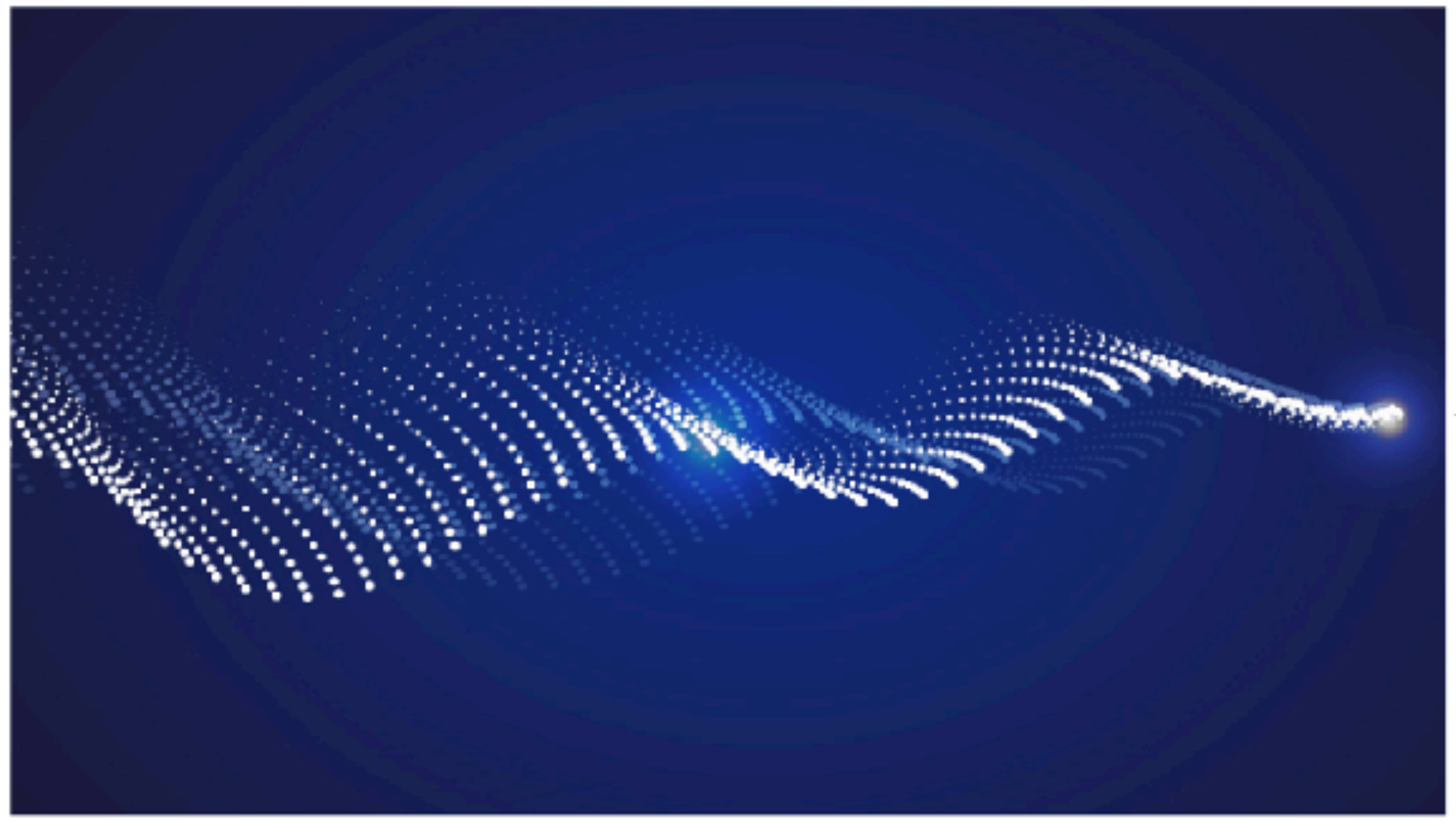
How to look for axions

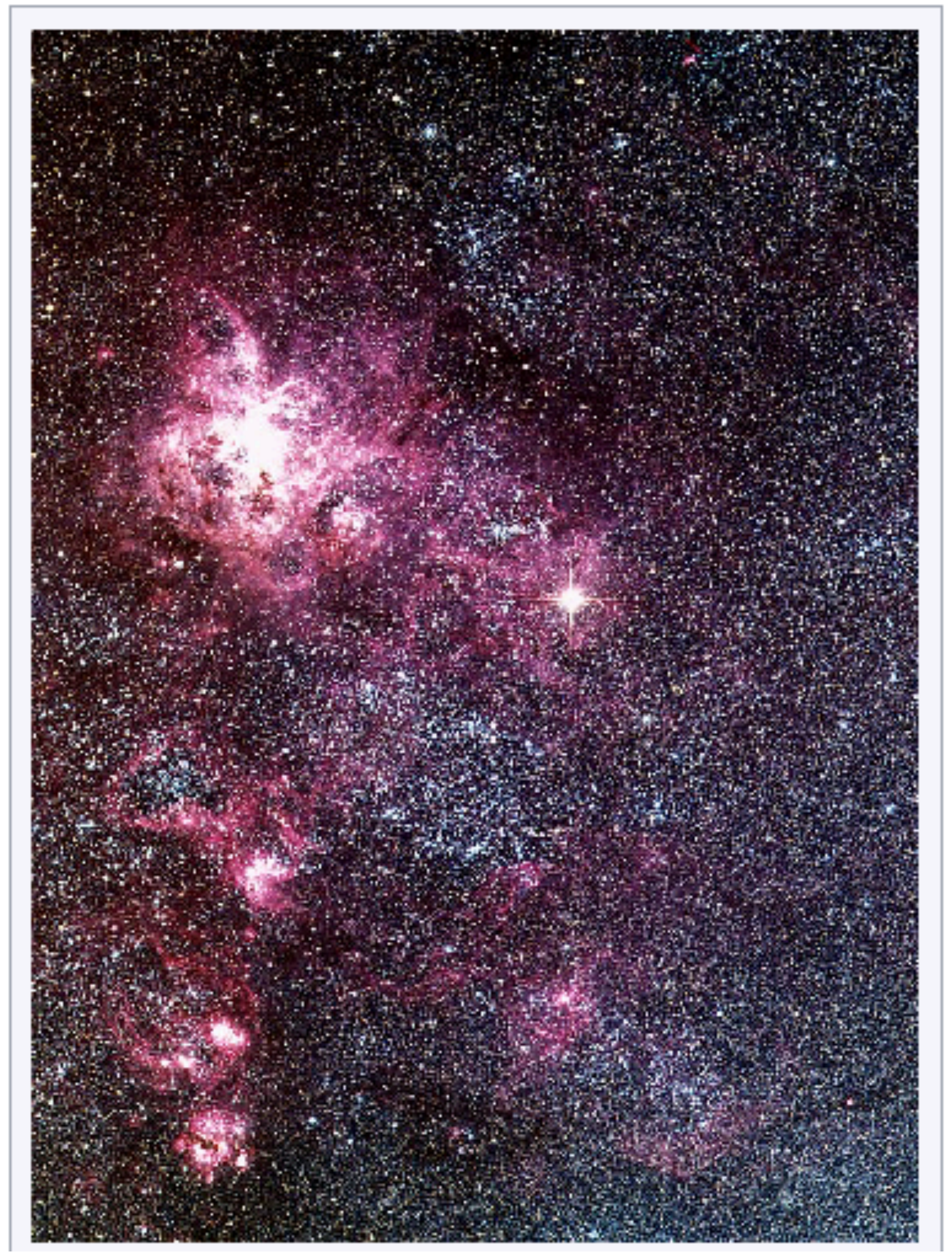


$$a \vec{E} \cdot \vec{B}$$

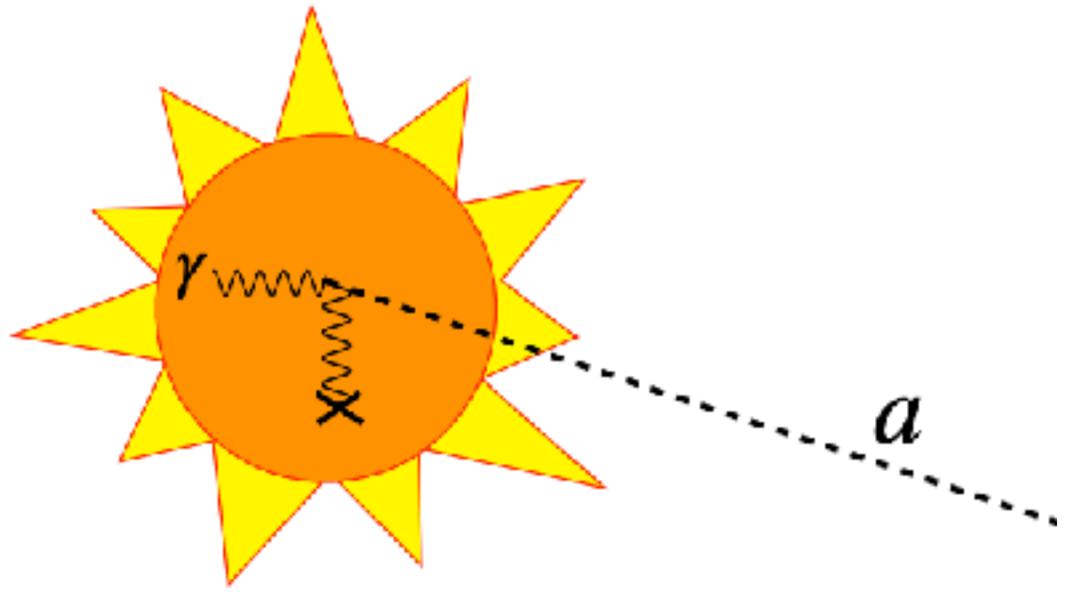
- Axions can convert to photons in the background of a constant magnetic field.
- Axions can decay to a pair of photons.
- If we have a source of axions, we can look for those axion converted photons with a very sensitive photon detector, a telescope, etc..

Sources of axions



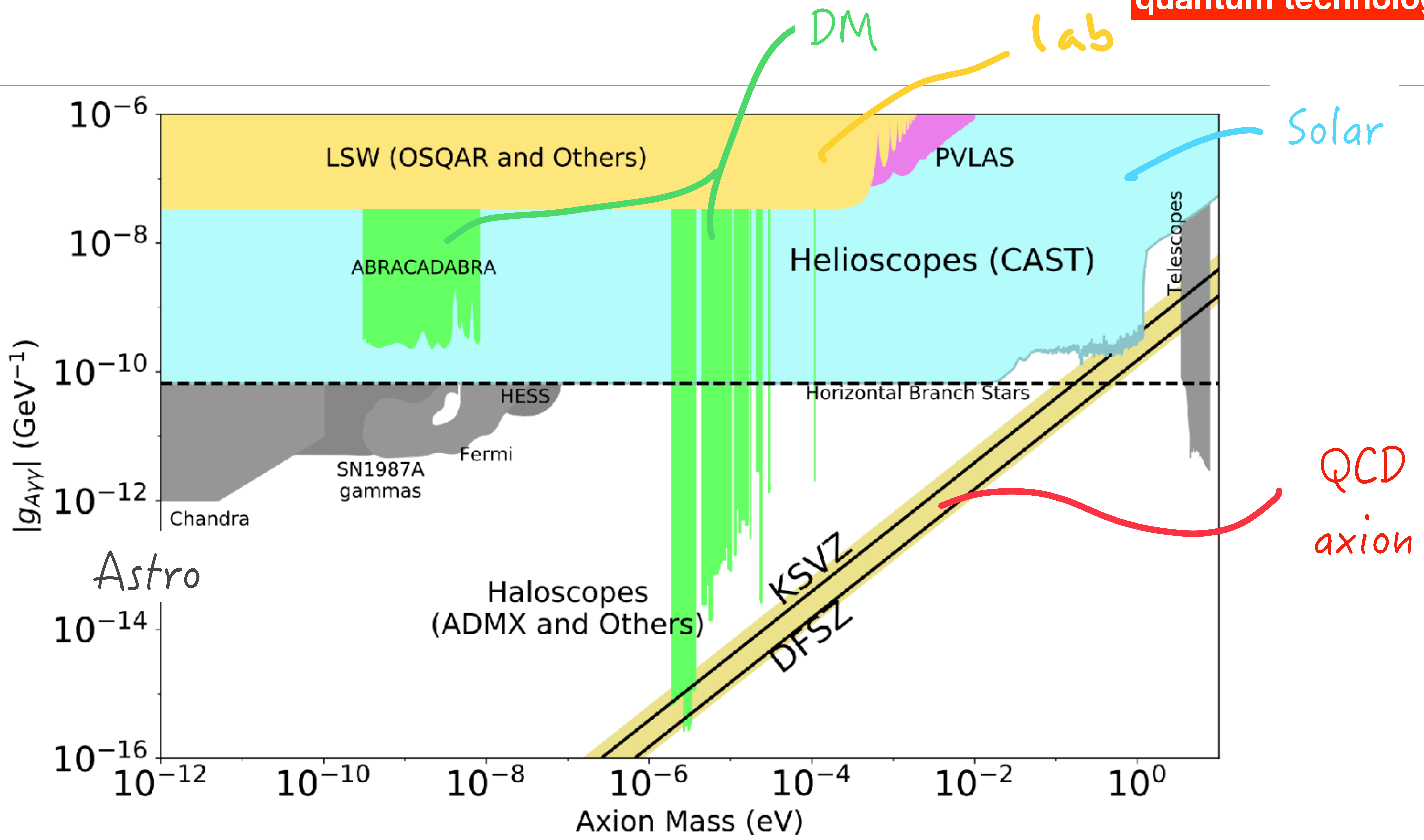


- Solar axion (helioscope)
- Axion dark matter (haloscope)
- Other astronomical sources, e.g. Supernova 1987A
- Produced in the laboratory (light-shining-through-walls)

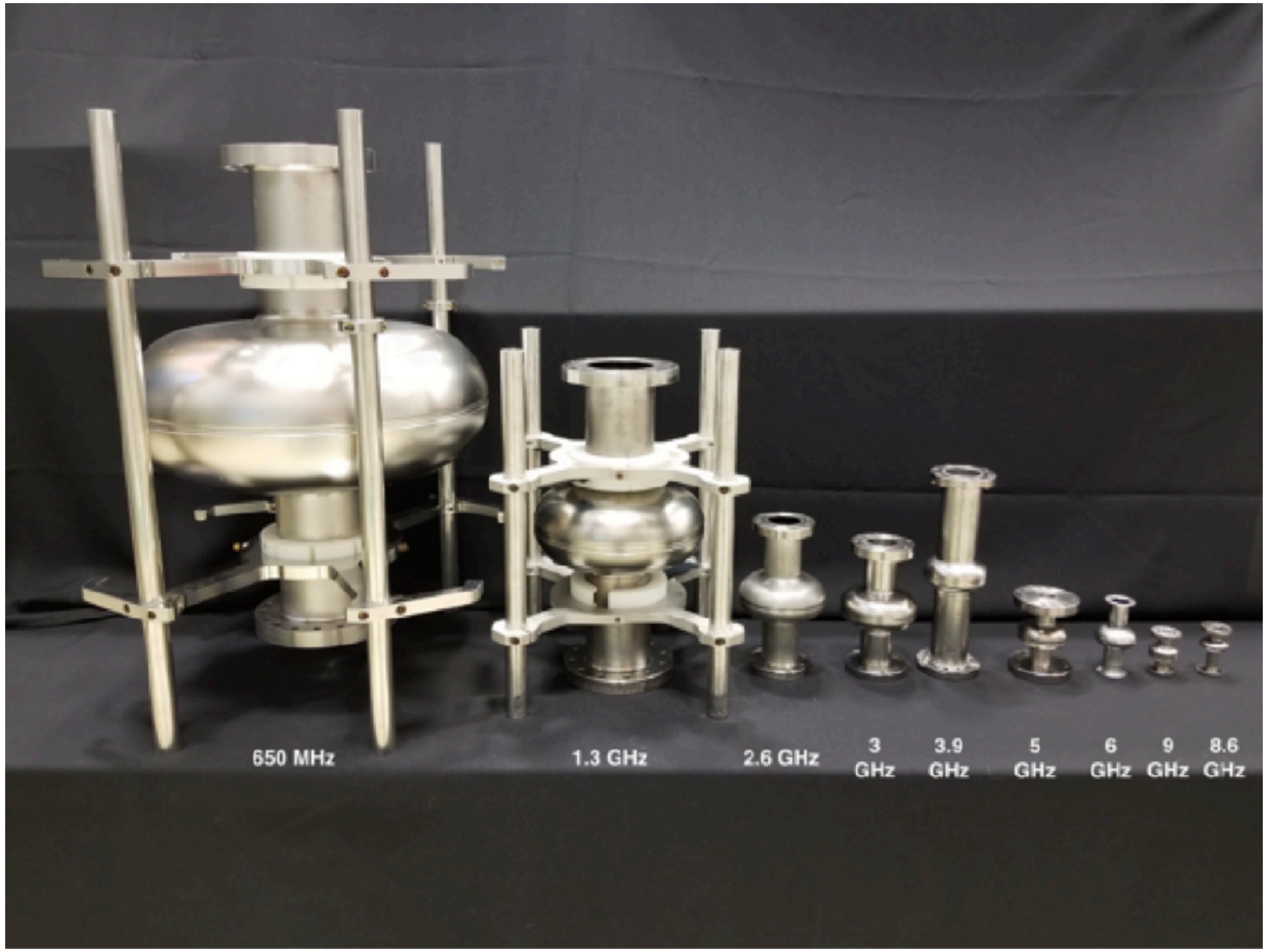


From The Review of Particle Physics (2020)

may be improved by quantum technology!



There are many ongoing efforts on axion searches at the Fermilab

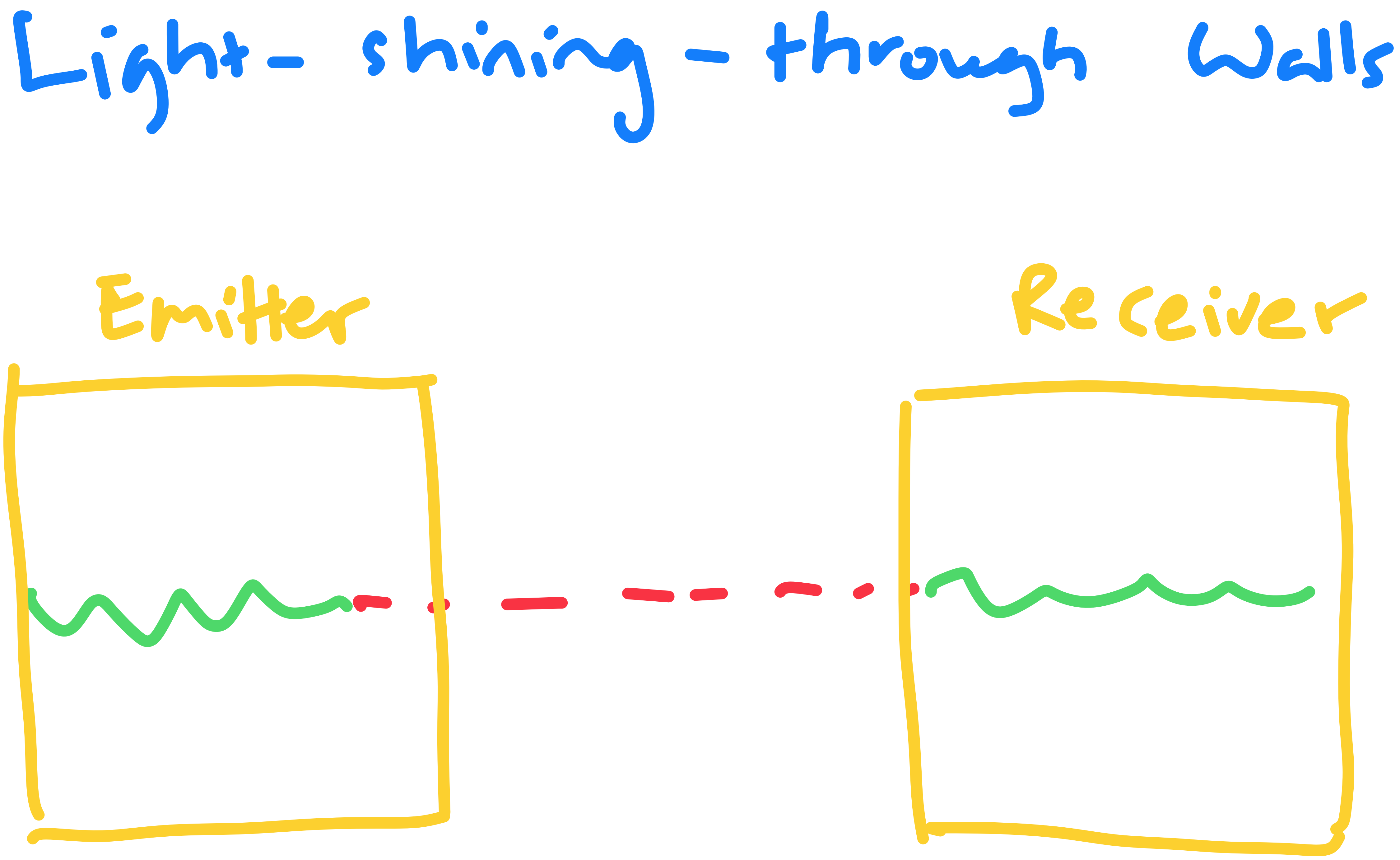


- A radio wave cavity acts as a photon resonator, thus can store a lot of photons
- Fermilab has superconducting radio-frequency cavities that have quality factor as high as $Q \sim 10^{11}$
- Can be used to search for axion dark matter or axion light-shining-through-walls experiments

New exclusion limit for dark photons (Dark SRF)

Emitter

Receiver



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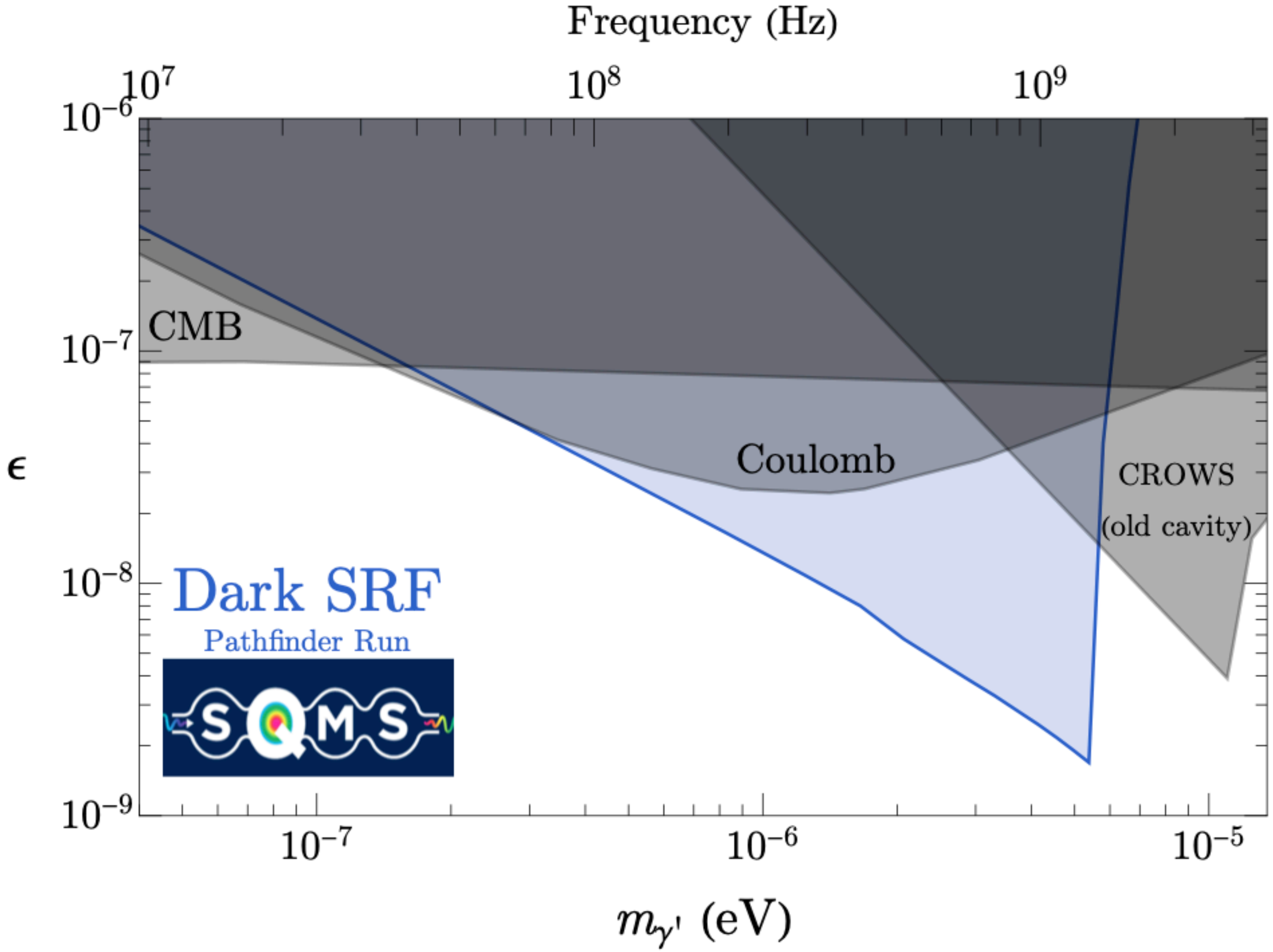

Summary

- Standard Model of particle physics is a success.
- Symmetry and symmetry breaking are powerful tools in the study of particle physics.
- Particle physics still has many unanswered questions, such as the origin of neutrino mass, dark matter, theory of quantum gravity… that require us to go beyond the Standard Model.
- One well motivated beyond the Standard Model physics is axion and we are actively searching for it at the Fermilab.