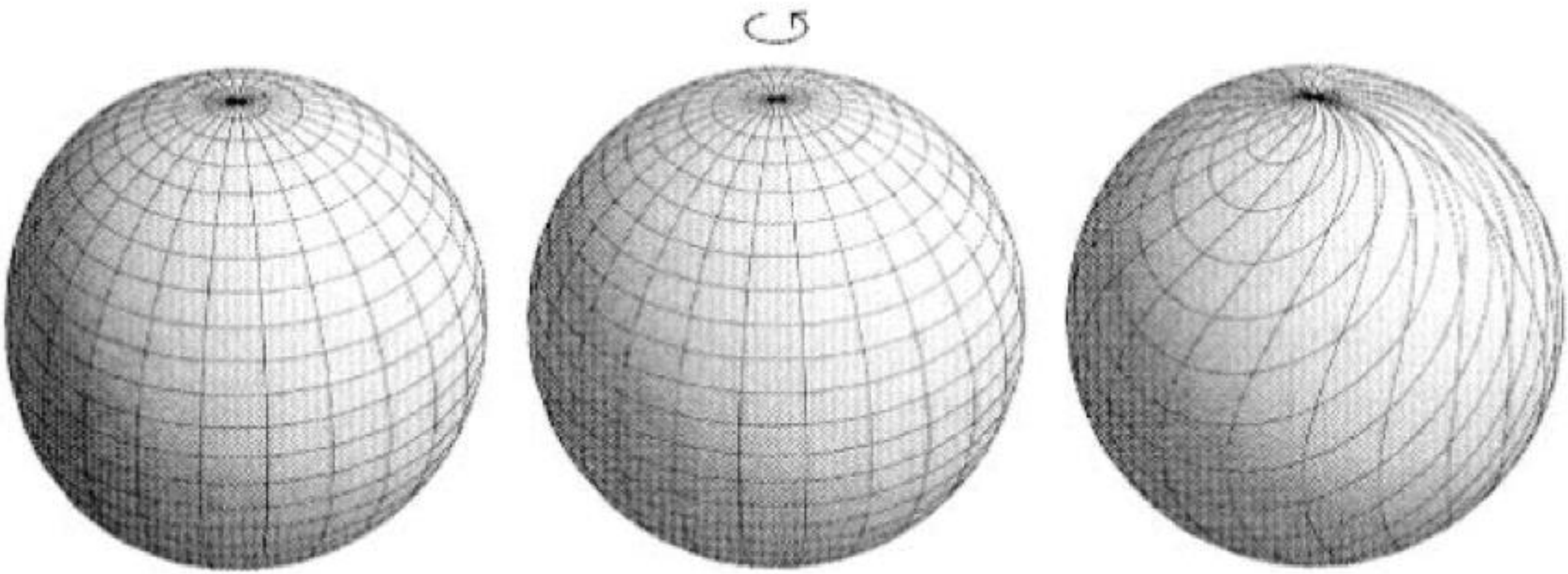
Symmetries in Physics



Andrea Banfi

University of Sussex

The Abdus Salam International Centre for Theoretical Physics
Physics Without Frontiers

IAEA
International Atomic Energy Agency

unesco
United Nations Educational, Scientific and Cultural Organization

Lecture 1: discrete symmetries

Introduction: a look at the table of elementary particles

Part I: general considerations on symmetries

- What is a symmetry?
- Discrete and continuous symmetries

Part II: discrete symmetries in particle physics

- Violation of parity
- Violation of parity and charge conjugation

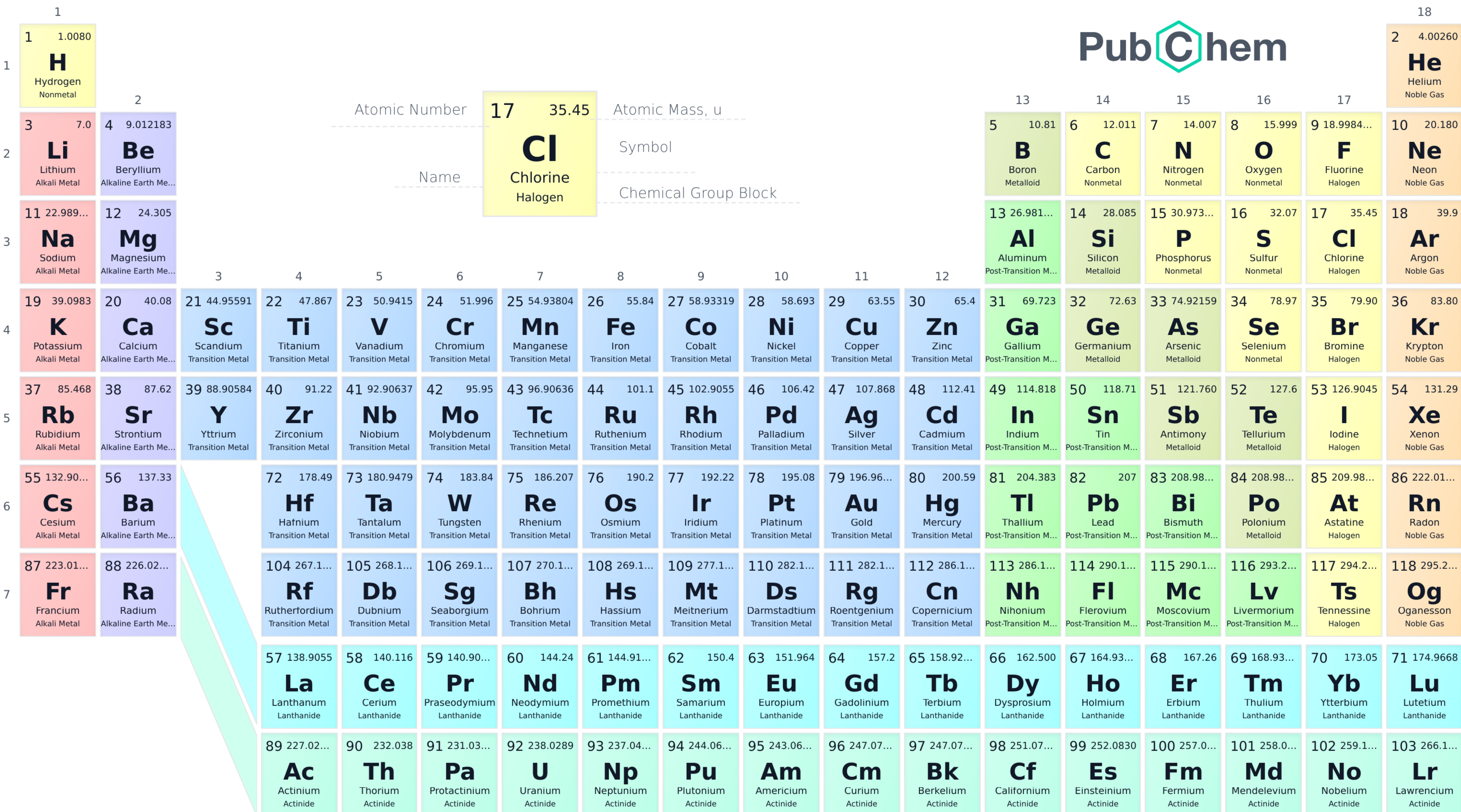
Periodic table of elements

PubChem

Atomic Number — 17 35.45 Cl Chlorine Halogen — Atomic Mass, u; Symbol; Name; Chemical Group Block

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 1.0080 H Hydrogen Nonmetal																	2 4.00260 He Helium Noble Gas
2	3 7.0 Li Lithium Alkali Metal	4 9.012183 Be Beryllium Alkaline Earth Me...											5 10.81 B Boron Metalloid	6 12.011 C Carbon Nonmetal	7 14.007 N Nitrogen Nonmetal	8 15.999 O Oxygen Nonmetal	9 18.9984... F Fluorine Halogen	10 20.180 Ne Neon Noble Gas
3	11 22.989... Na Sodium Alkali Metal	12 24.305 Mg Magnesium Alkaline Earth Me...											13 26.981... Al Aluminum Post-Transition M...	14 28.085 Si Silicon Metalloid	15 30.973... P Phosphorus Nonmetal	16 32.07 S Sulfur Nonmetal	17 35.45 Cl Chlorine Halogen	18 39.9 Ar Argon Noble Gas
4	19 39.0983 K Potassium Alkali Metal	20 40.08 Ca Calcium Alkaline Earth Me...	21 44.95591 Sc Scandium Transition Metal	22 47.867 Ti Titanium Transition Metal	23 50.9415 V Vanadium Transition Metal	24 51.996 Cr Chromium Transition Metal	25 54.93804 Mn Manganese Transition Metal	26 55.84 Fe Iron Transition Metal	27 58.93319 Co Cobalt Transition Metal	28 58.693 Ni Nickel Transition Metal	29 63.55 Cu Copper Transition Metal	30 65.4 Zn Zinc Transition Metal	31 69.723 Ga Gallium Post-Transition M...	32 72.63 Ge Germanium Metalloid	33 74.92159 As Arsenic Metalloid	34 78.97 Se Selenium Nonmetal	35 79.90 Br Bromine Halogen	36 83.80 Kr Krypton Noble Gas
5	37 85.468 Rb Rubidium Alkali Metal	38 87.62 Sr Strontium Alkaline Earth Me...	39 88.90584 Y Yttrium Transition Metal	40 91.22 Zr Zirconium Transition Metal	41 92.90637 Nb Niobium Transition Metal	42 95.95 Mo Molybdenum Transition Metal	43 96.90636 Tc Technetium Transition Metal	44 101.1 Ru Ruthenium Transition Metal	45 102.9055 Rh Rhodium Transition Metal	46 106.42 Pd Palladium Transition Metal	47 107.868 Ag Silver Transition Metal	48 112.41 Cd Cadmium Transition Metal	49 114.818 In Indium Post-Transition M...	50 118.71 Sn Tin Post-Transition M...	51 121.760 Sb Antimony Metalloid	52 127.6 Te Tellurium Metalloid	53 126.9045 I Iodine Halogen	54 131.29 Xe Xenon Noble Gas
6	55 132.90... Cs Cesium Alkali Metal	56 137.33 Ba Barium Alkaline Earth Me...		72 178.49 Hf Hafnium Transition Metal	73 180.9479 Ta Tantalum Transition Metal	74 183.84 W Tungsten Transition Metal	75 186.207 Re Rhenium Transition Metal	76 190.2 Os Osmium Transition Metal	77 192.22 Ir Iridium Transition Metal	78 195.08 Pt Platinum Transition Metal	79 196.96... Au Gold Transition Metal	80 200.59 Hg Mercury Transition Metal	81 204.383 Tl Thallium Post-Transition M...	82 207 Pb Lead Post-Transition M...	83 208.98... Bi Bismuth Post-Transition M...	84 208.98... Po Polonium Metalloid	85 209.98... At Astatine Halogen	86 222.01... Rn Radon Noble Gas
7	87 223.01... Fr Francium Alkali Metal	88 226.02... Ra Radium Alkaline Earth Me...		104 267.1... Rf Rutherfordium Transition Metal	105 268.1... Db Dubnium Transition Metal	106 269.1... Sg Seaborgium Transition Metal	107 270.1... Bh Bohrium Transition Metal	108 269.1... Hs Hassium Transition Metal	109 277.1... Mt Meitnerium Transition Metal	110 282.1... Ds Darmstadtium Transition Metal	111 282.1... Rg Roentgenium Transition Metal	112 286.1... Cn Copernicium Transition Metal	113 286.1... Nh Nihonium Post-Transition M...	114 290.1... Fl Flerovium Post-Transition M...	115 290.1... Mc Moscovium Post-Transition M...	116 293.2... Lv Livermorium Post-Transition M...	117 294.2... Ts Tennessine Halogen	118 295.2... Og Oganesson Noble Gas
				57 138.9055 La Lanthanum Lanthanide	58 140.116 Ce Cerium Lanthanide	59 140.90... Pr Praseodymium Lanthanide	60 144.24 Nd Neodymium Lanthanide	61 144.91... Pm Promethium Lanthanide	62 150.4 Sm Samarium Lanthanide	63 151.964 Eu Europium Lanthanide	64 157.2 Gd Gadolinium Lanthanide	65 158.92... Tb Terbium Lanthanide	66 162.500 Dy Dysprosium Lanthanide	67 164.93... Ho Holmium Lanthanide	68 167.26 Er Erbium Lanthanide	69 168.93... Tm Thulium Lanthanide	70 173.05 Yb Ytterbium Lanthanide	71 174.9668 Lu Lutetium Lanthanide
				89 227.02... Ac Actinium Actinide	90 232.038 Th Thorium Actinide	91 231.03... Pa Protactinium Actinide	92 238.0289 U Uranium Actinide	93 237.04... Np Neptunium Actinide	94 244.06... Pu Plutonium Actinide	95 243.06... Am Americium Actinide	96 247.07... Cm Curium Actinide	97 247.07... Bk Berkelium Actinide	98 251.07... Cf Californium Actinide	99 252.0830 Es Einsteinium Actinide	100 257.0... Fm Fermium Actinide	101 258.0... Md Mendelevium Actinide	102 259.1... No Nobelium Actinide	103 266.1... Lr Lawrencium Actinide

Periodic table of elements



- Elements are organised in a table according to their electronic structure

Table of elementary particles

- There are only 17 elementary particles, which are organised in a modern table of elements

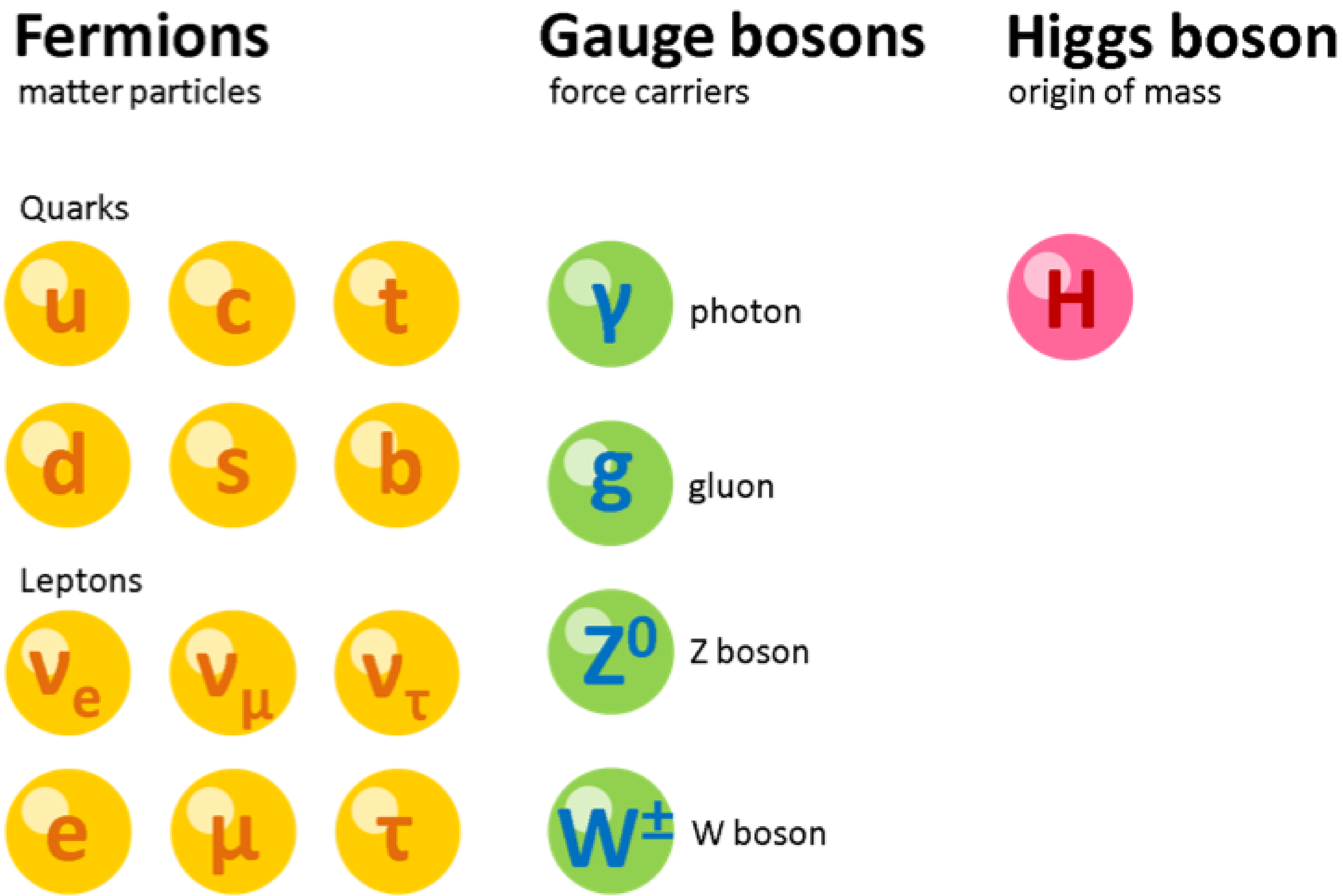
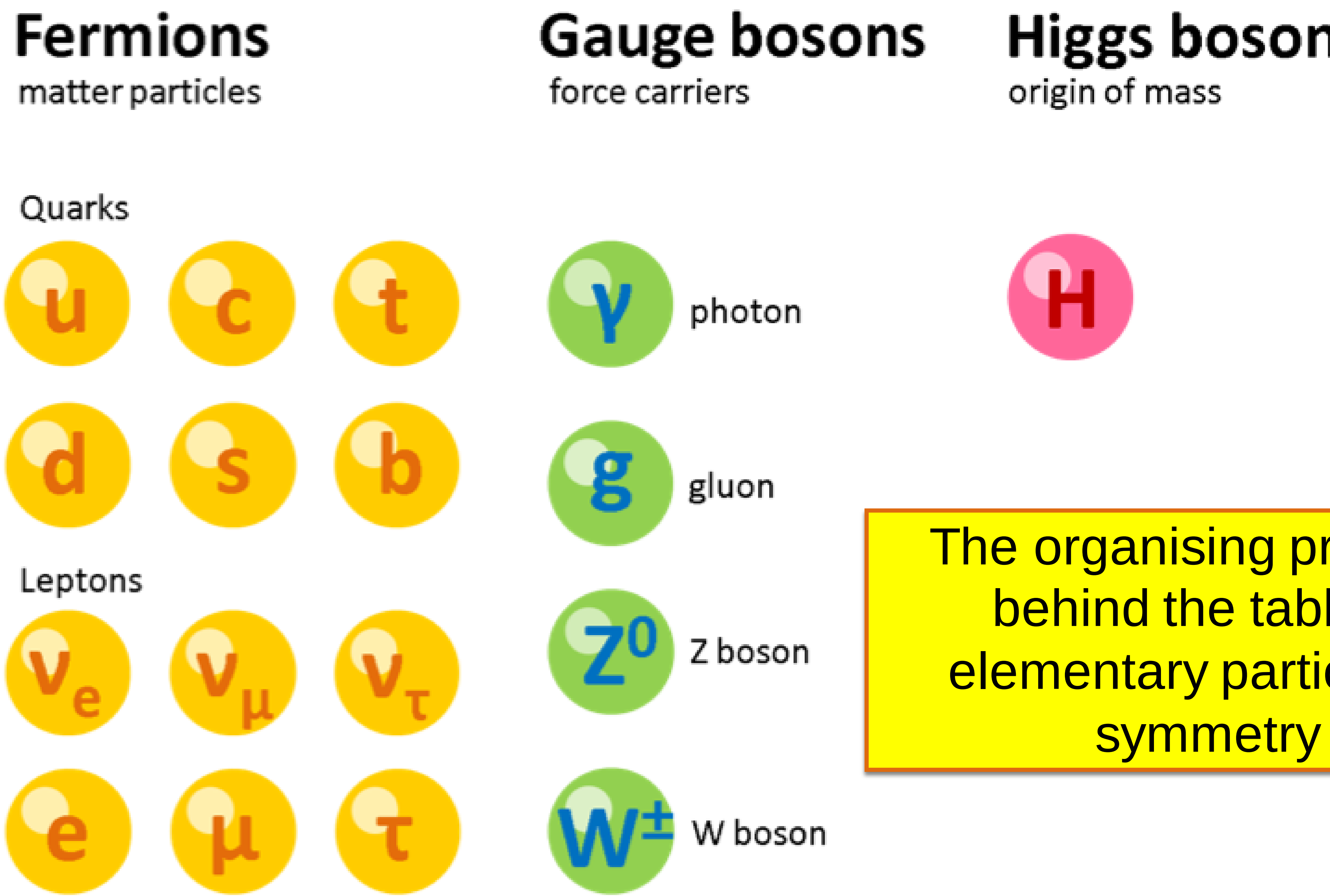


Table of elementary particles

- There are only 17 elementary particles, which are organised in a modern table of elements



The organising principle behind the table of elementary particles is symmetry

What is a symmetry?

Symmetries

- If an object does not change after some transformation, we say it possesses a symmetry
- Can you tell a common symmetry of the letters A and H?

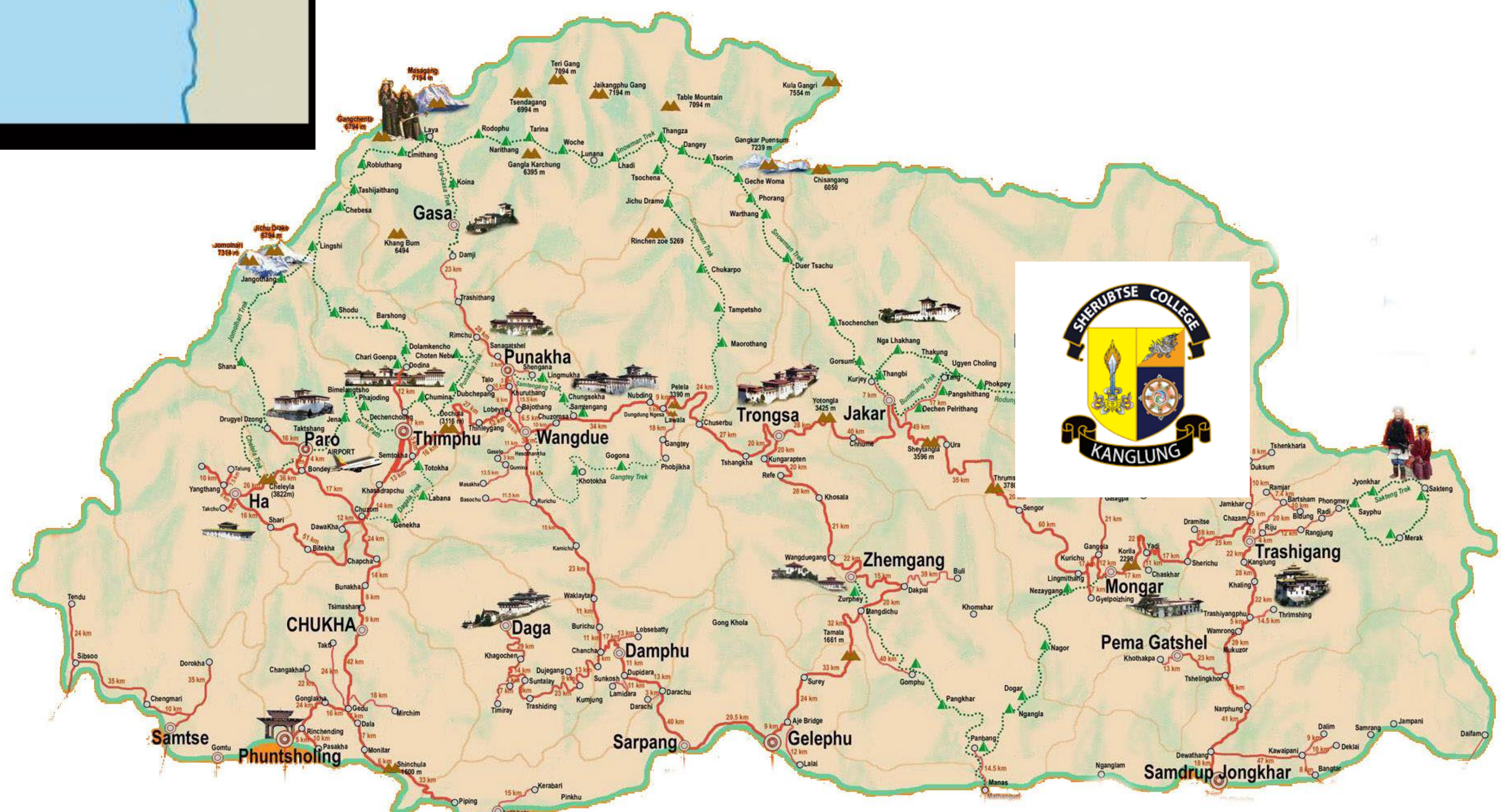
A H

Symmetries

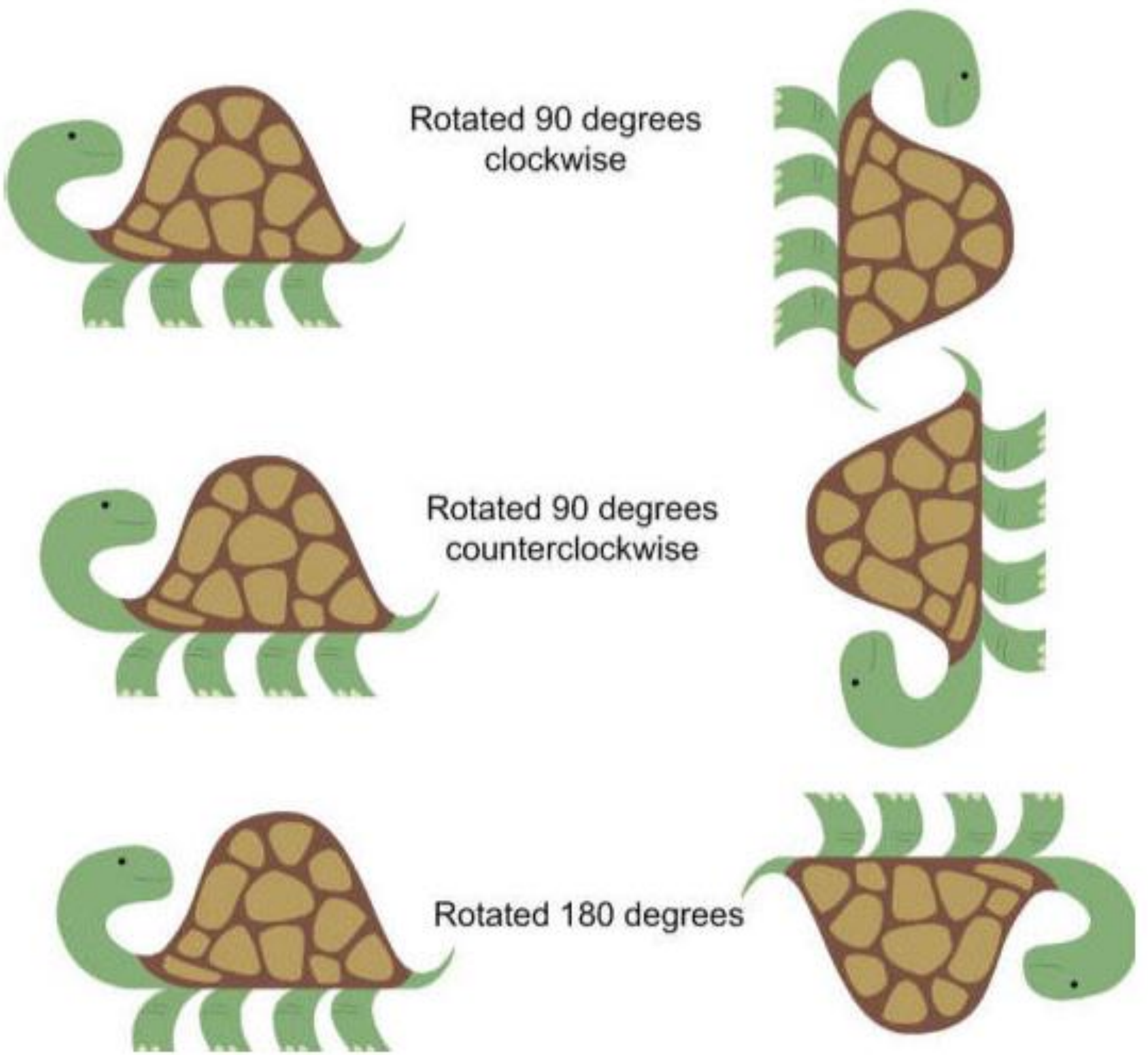
- If an object does not change after some transformation, we say it possesses a symmetry
- Letters A and H possess a mirror symmetry

What are the symmetries of physical systems?

Translations



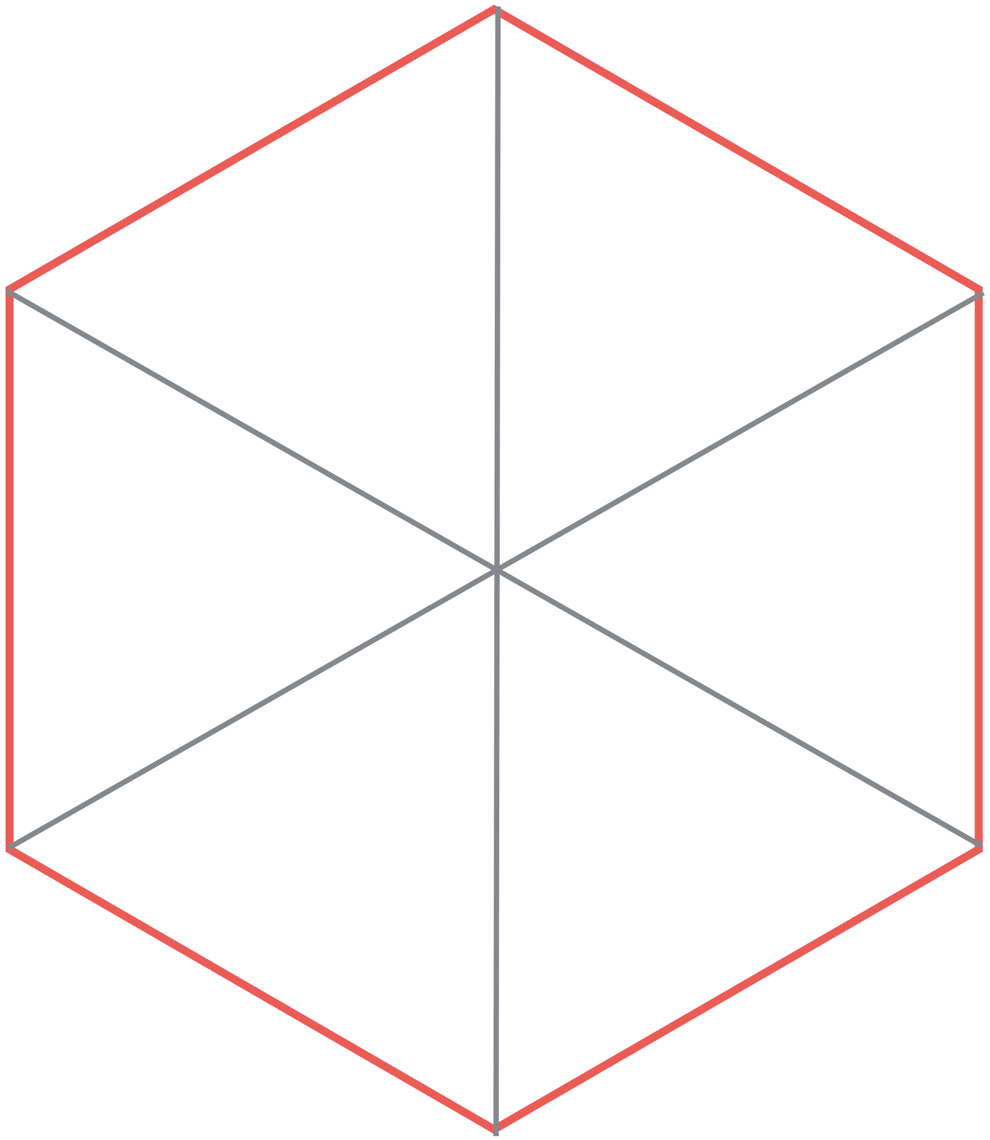
Rotations



Rotated 90 degrees clockwise
Rotated 90 degrees counterclockwise
Rotated 180 degrees

Discrete symmetries

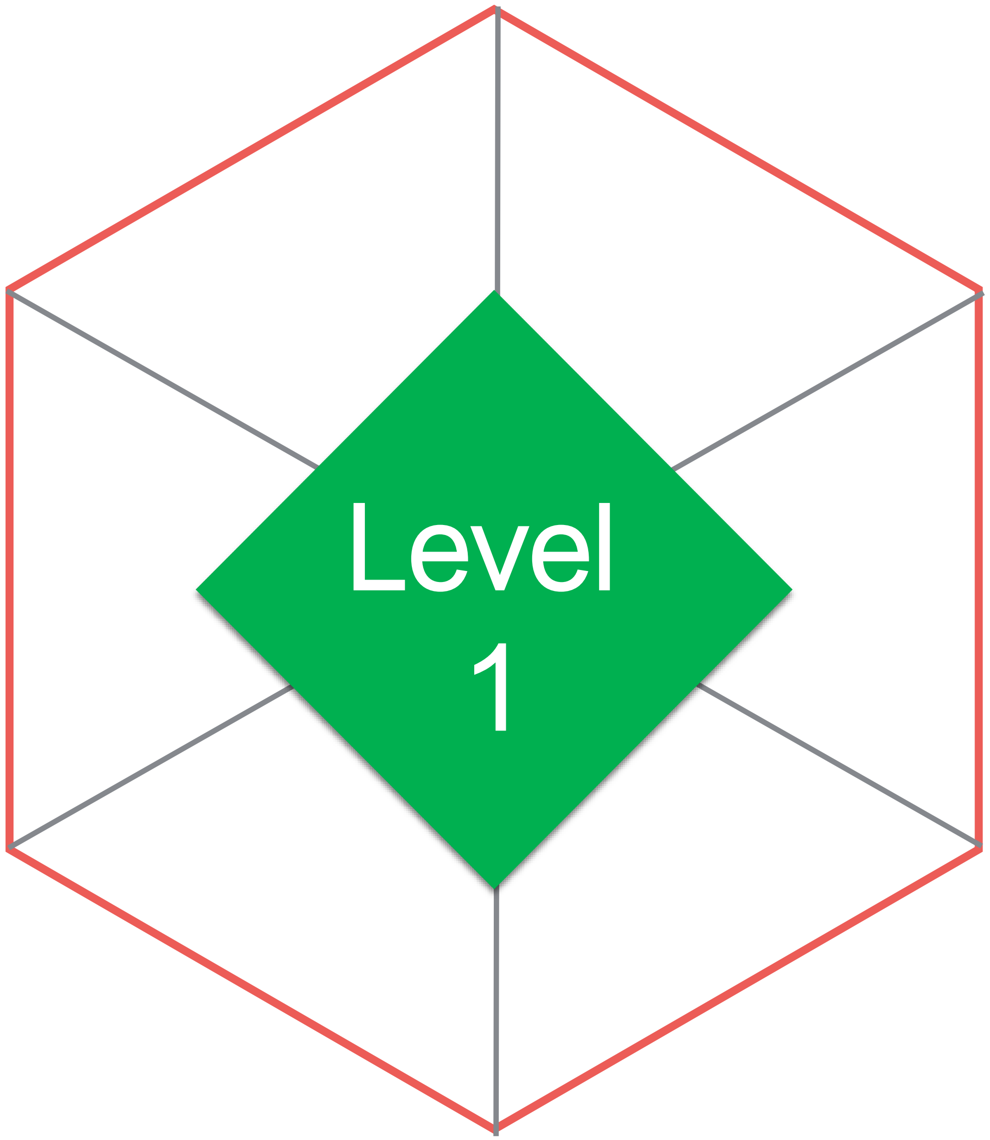
Only a finite number of transformations leave an object invariant



Example: the hexagon is invariant under rotations by 60 degrees only

Discrete symmetries

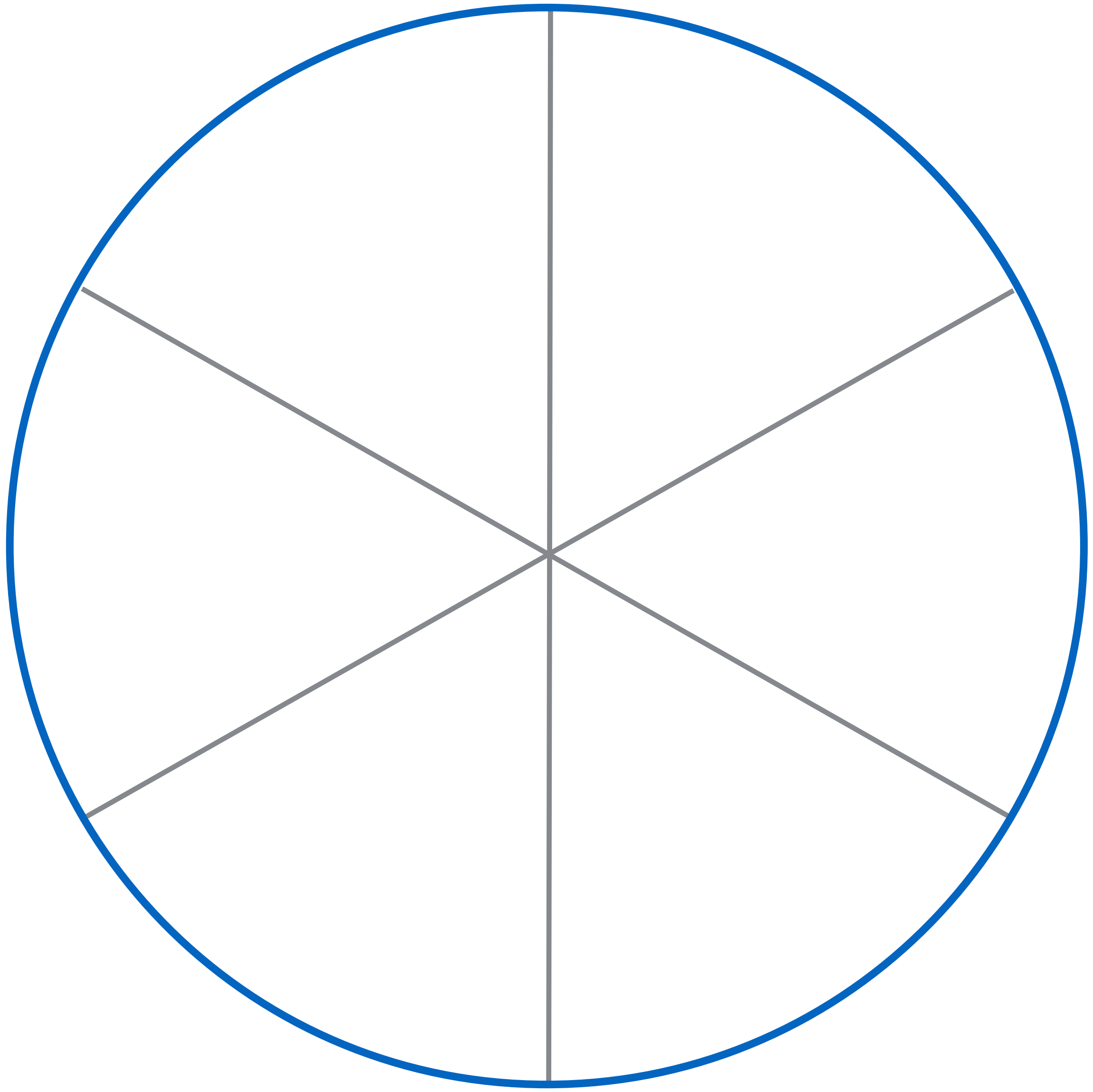
Only a finite number of transformations leave an object invariant



Example: the hexagon is invariant under rotations by 60 degrees only

Continuous symmetries

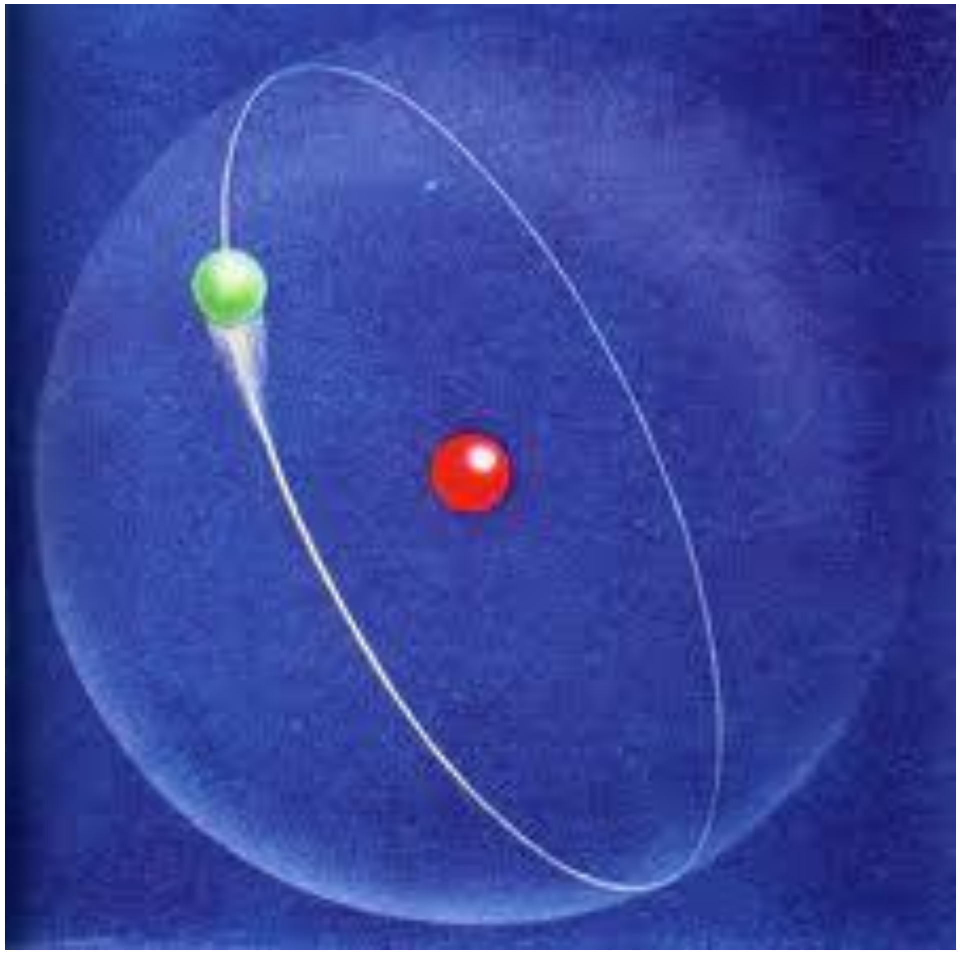
There exist infinitely many transformations that leave an object invariant



Example: the circle is invariant under rotations by any angle

Mirror symmetry

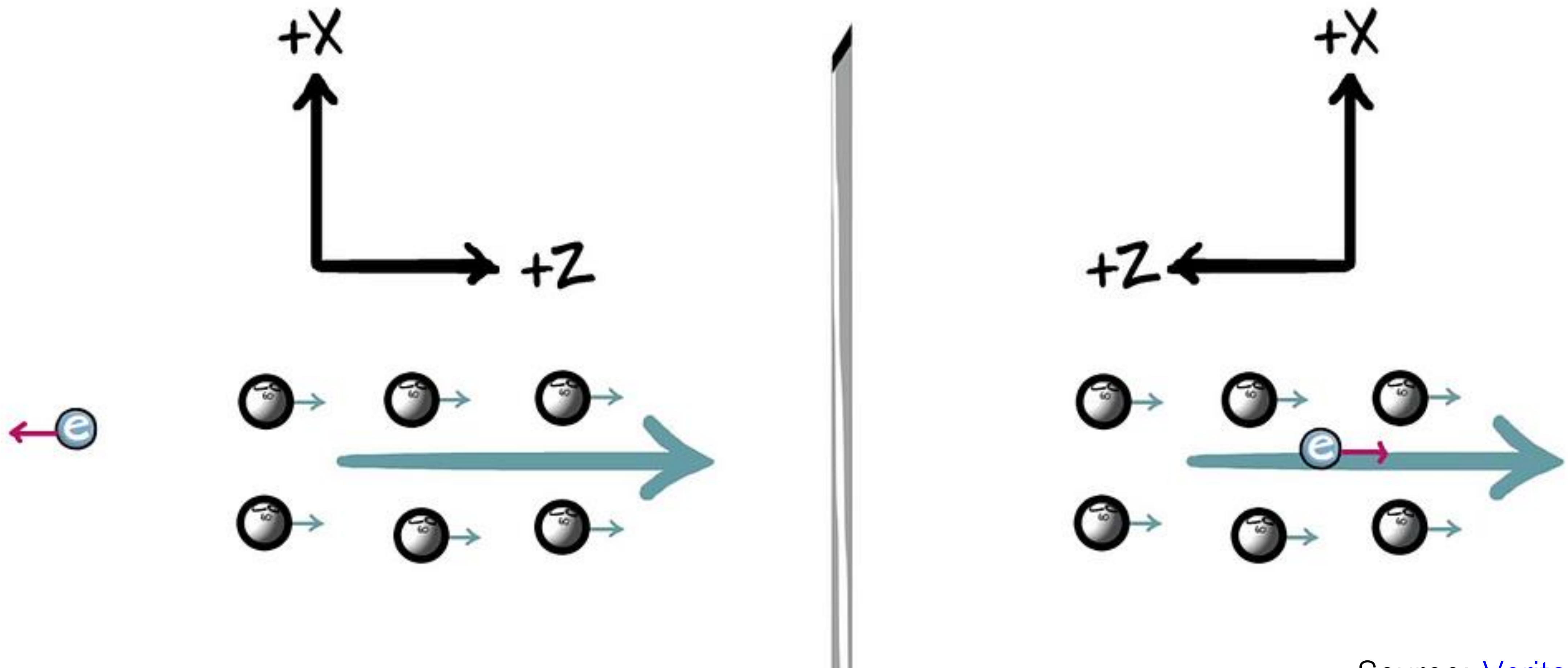
- Gravity, electromagnetism and the strong nuclear force act exactly in the same way on a physical system and on its mirror image



How can we tell left from right?

Parity in radioactive beta decay

- Let us consider the beta decay of Cobalt nuclei, and its mirror image

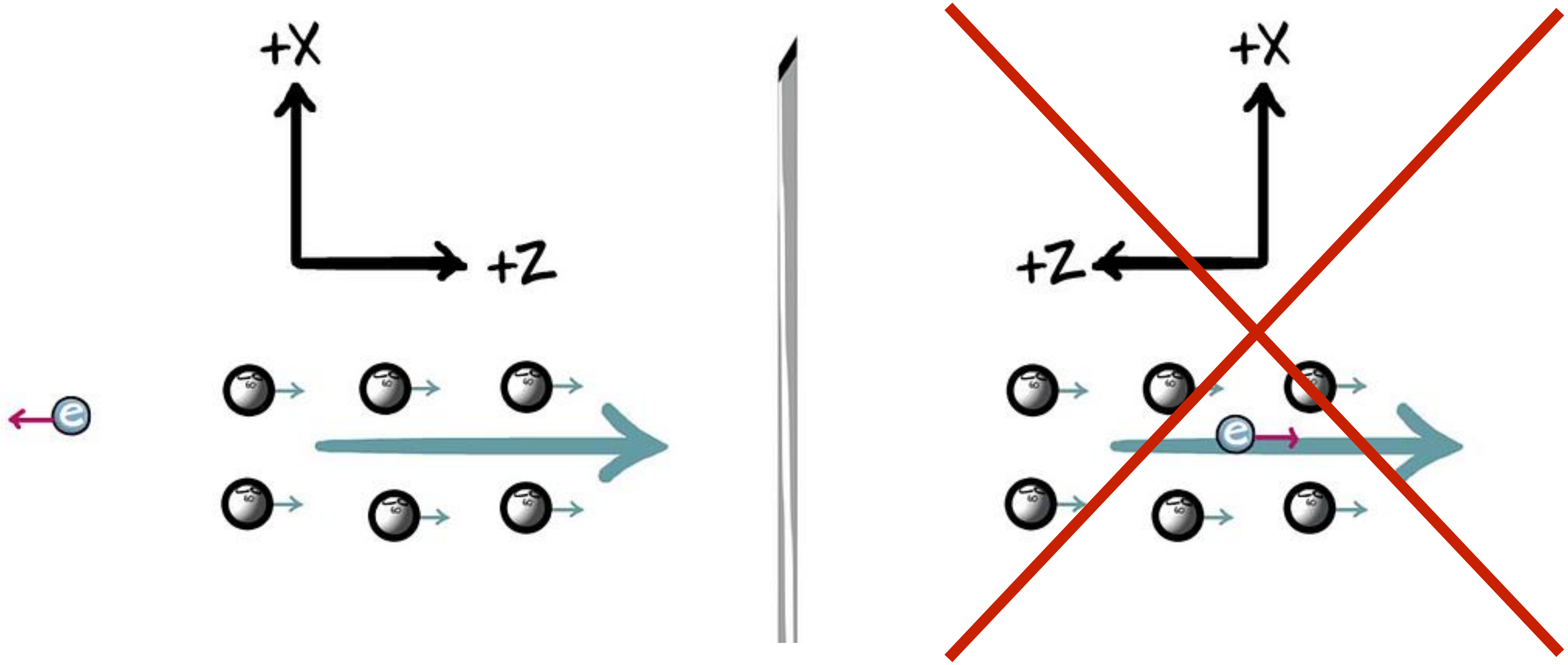


Source: [Veritasium]

- If mirror symmetry, or “parity”, were realised in beta decay, electrons would be emitted equally in the same direction and opposite the nuclear spin

Parity in radioactive beta decay

- Experiments tell us that electrons are predominantly emitted opposite to the nuclear spin



- This implies that parity is violated in beta decay, i.e. the world is not mirror-symmetric for weak interactions

Parity in radioactive beta decay

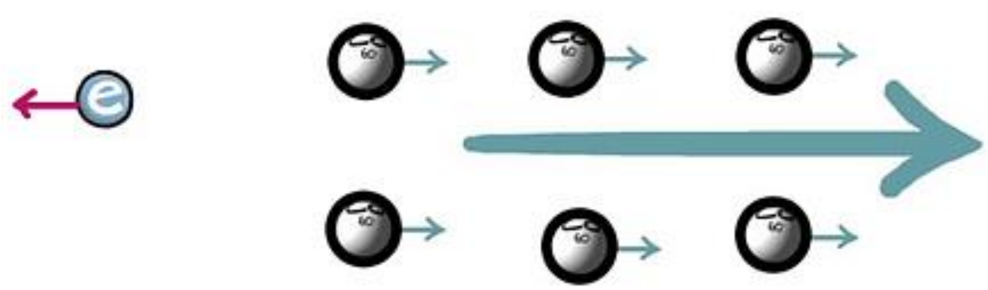
Experimental Test of Parity Conservation in Beta Decay*

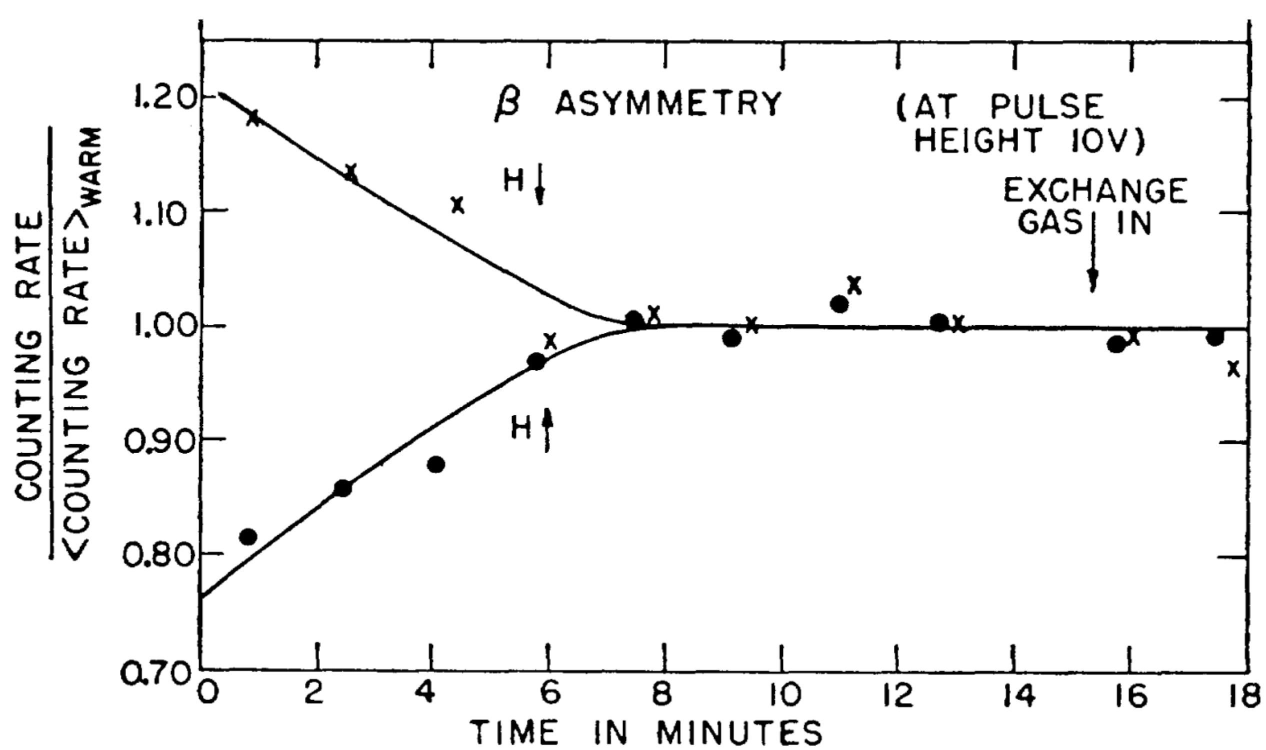
C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

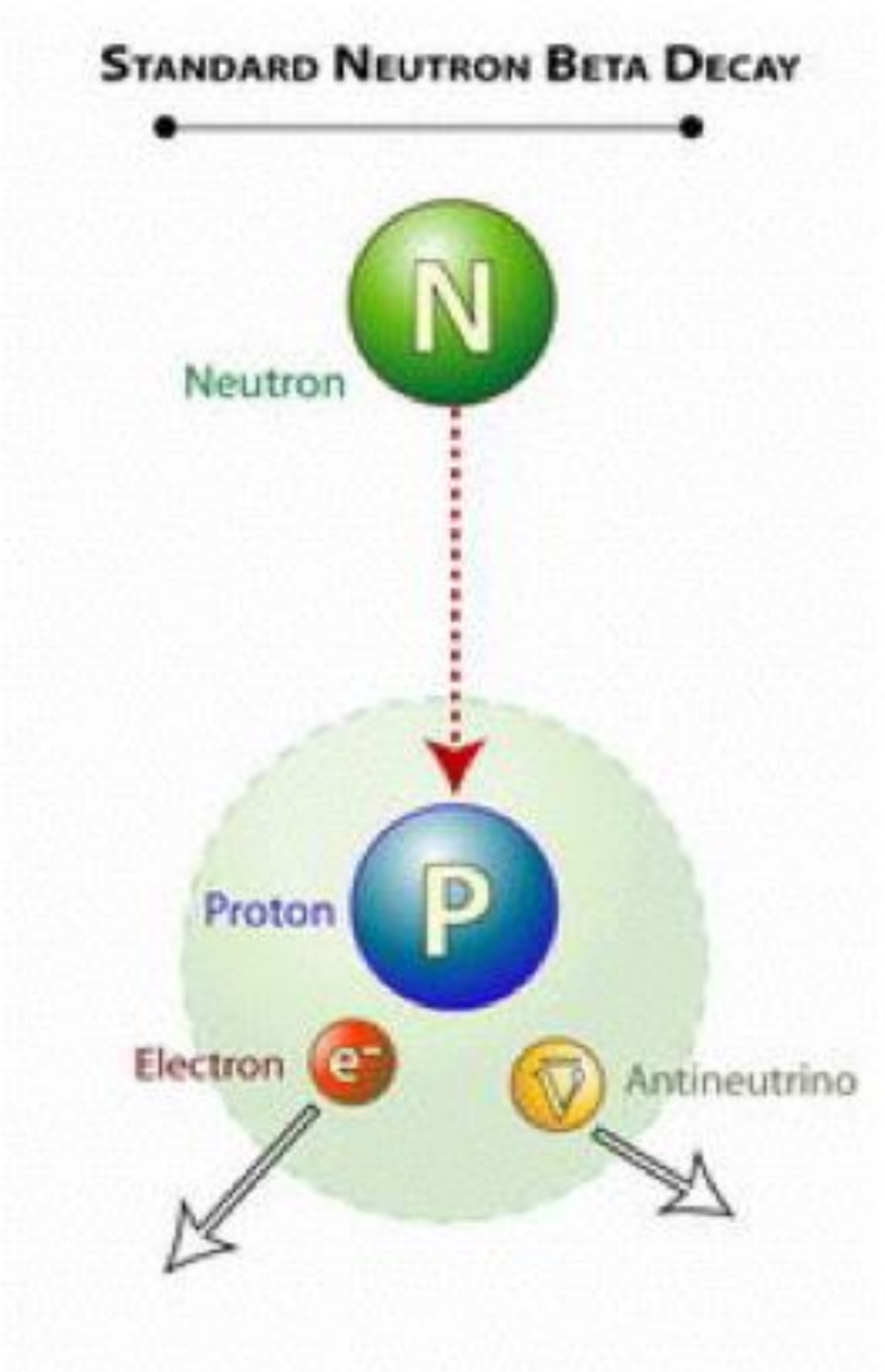
(Received January 15, 1957)





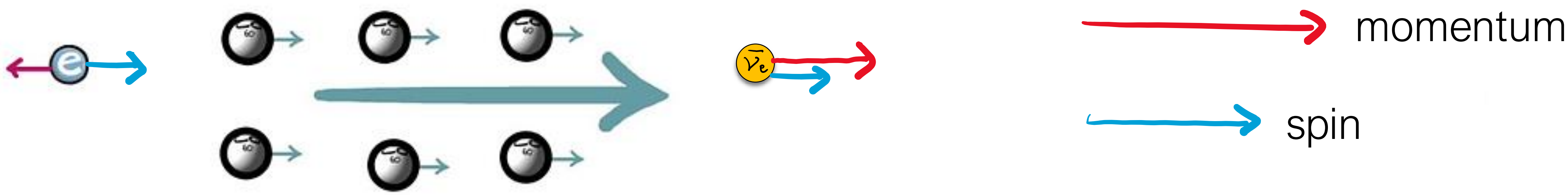
Radioactive decay

- Weak interactions are responsible for radioactive beta decay



Why is parity violated?

- Weak interactions involve only left-handed particles and right-handed antiparticles



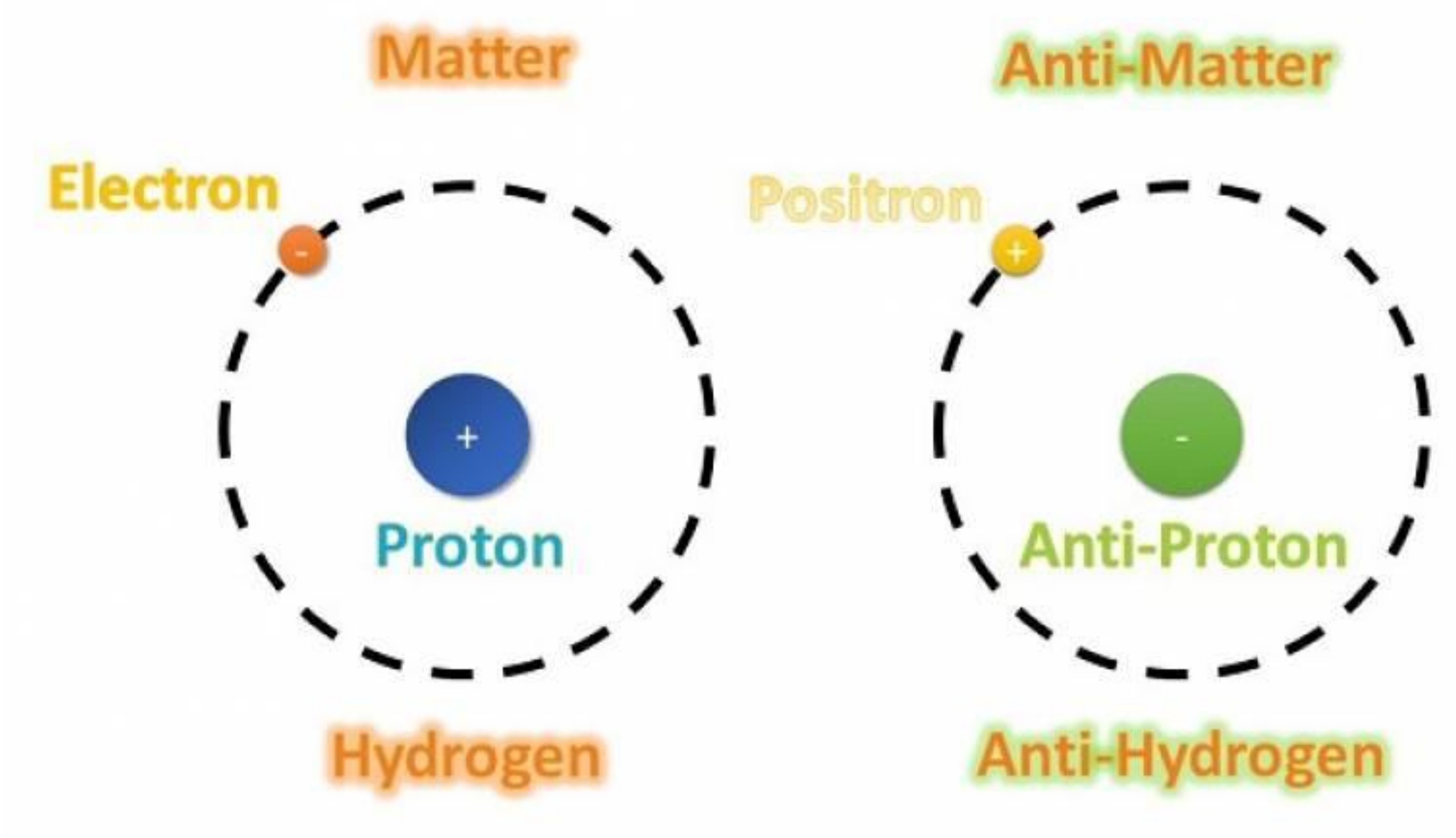
Right-handed: spin aligned in the same direction as momentum

Left-handed: spin aligned opposite to the momentum

- We could distinguish left from right using beta decay, right would be the direction of the nuclear spin, and left the direction of the electron

Charge conjugation

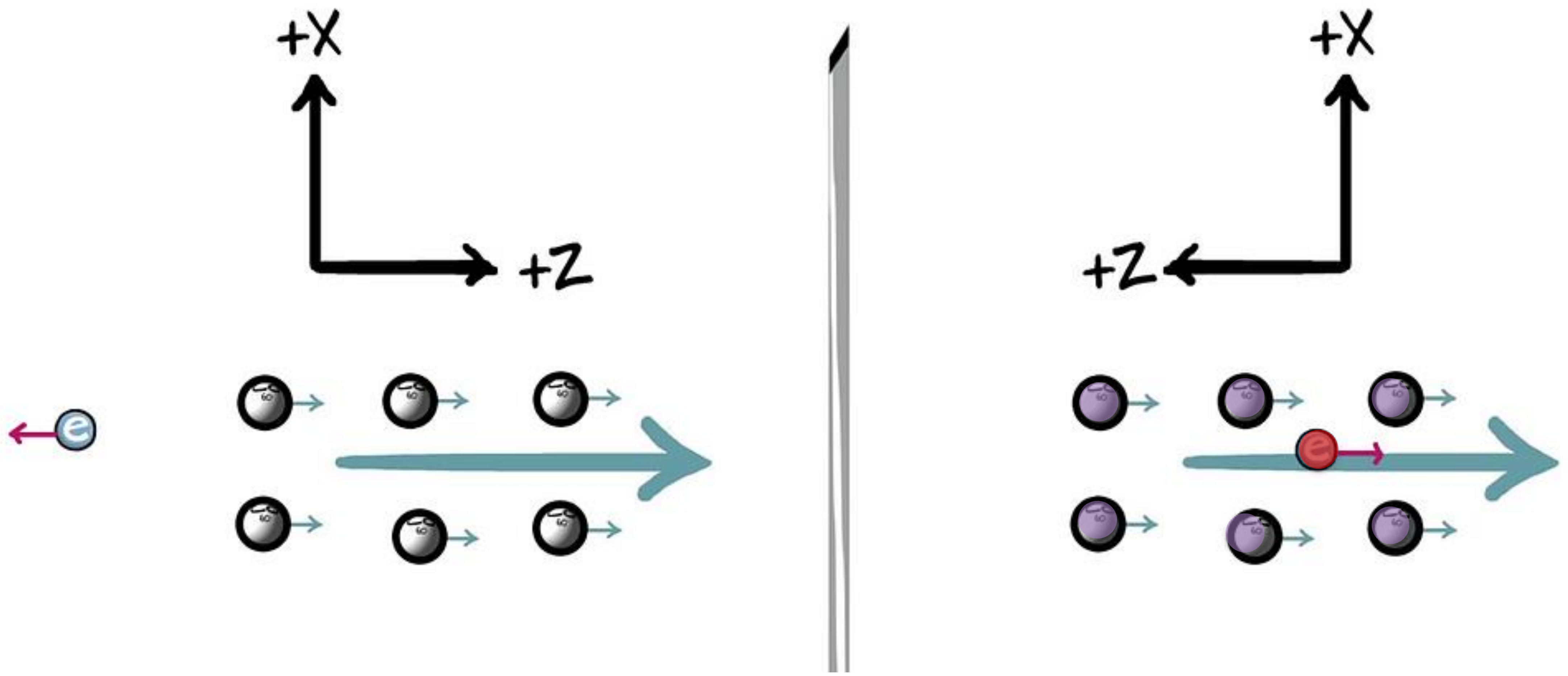
- Gravitational, electromagnetic and strong forces are the same whether they affect particles or anti-particles



- Anti-Hydrogen has the same atomic spectrum as hydrogen atom

Combining P and C

- We obtain a process allowed in nature if we not only mirror-image Cobalt decay, but we swap particles with antiparticles



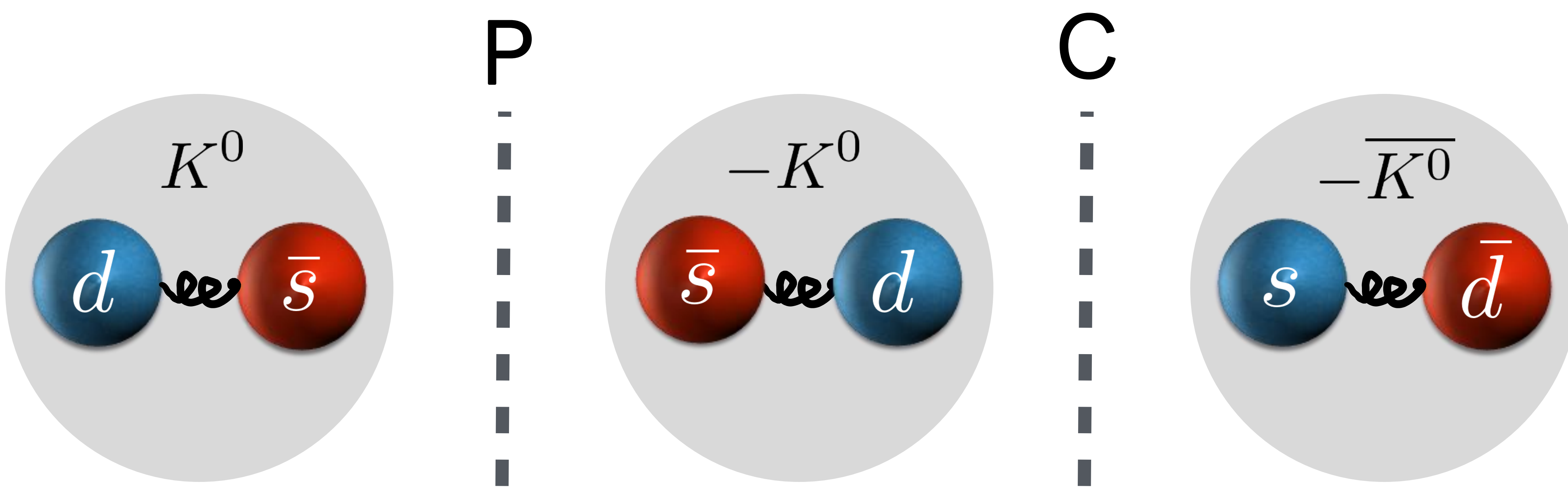
- If CP is conserved, and if we are made of anti-matter, we would see cobalt anti-nuclei emit positrons in the same direction as their spin, so again no chance of telling left from right

[Analogy taken from minutephysics]

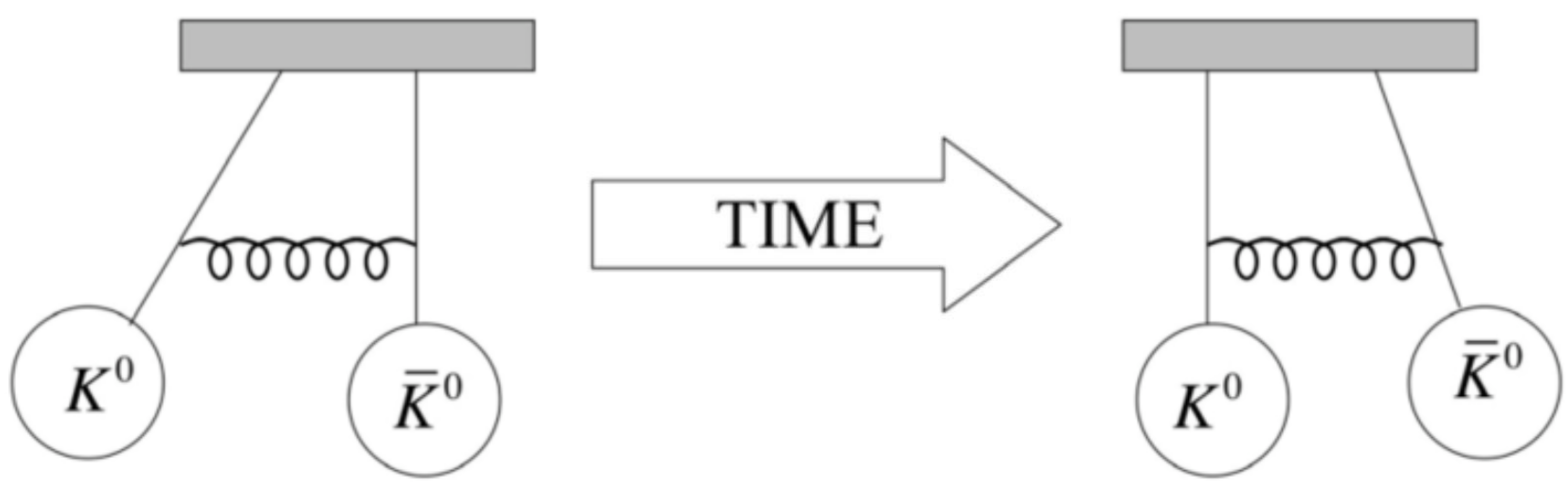
CP violation in kaons

Kaon mixing

- CP transforms spinless neutral particles called kaons (K^0) into (minus) their antiparticles ($\overline{K^0}$)



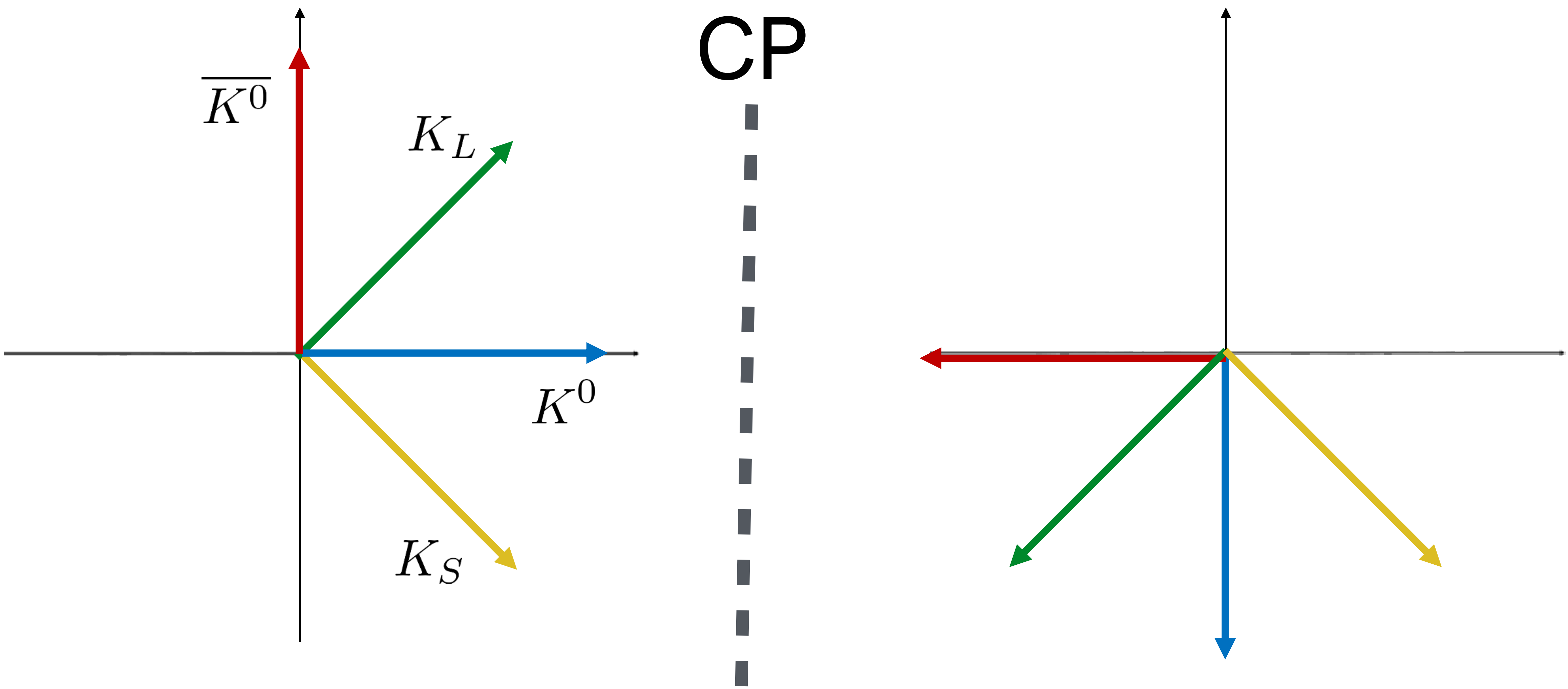
- Kaons and antikaons oscillate one into the other while they travel



Kaon mixing

- If CP is conserved, states with definite CP are mixtures of K^0 and $\overline{K^0}$ called K_S (short lifetime) and K_L (long lifetime)

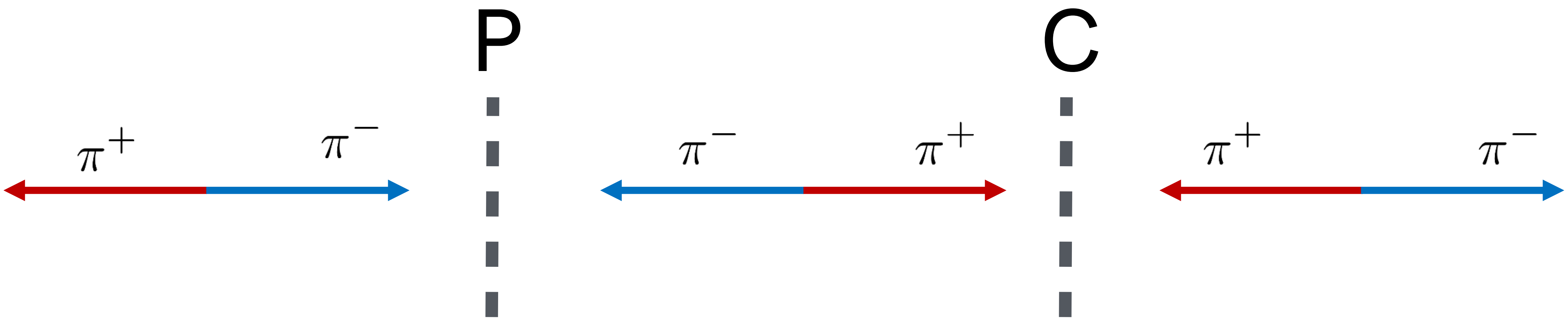
- It is useful to represent these particles as vectors in two dimensions

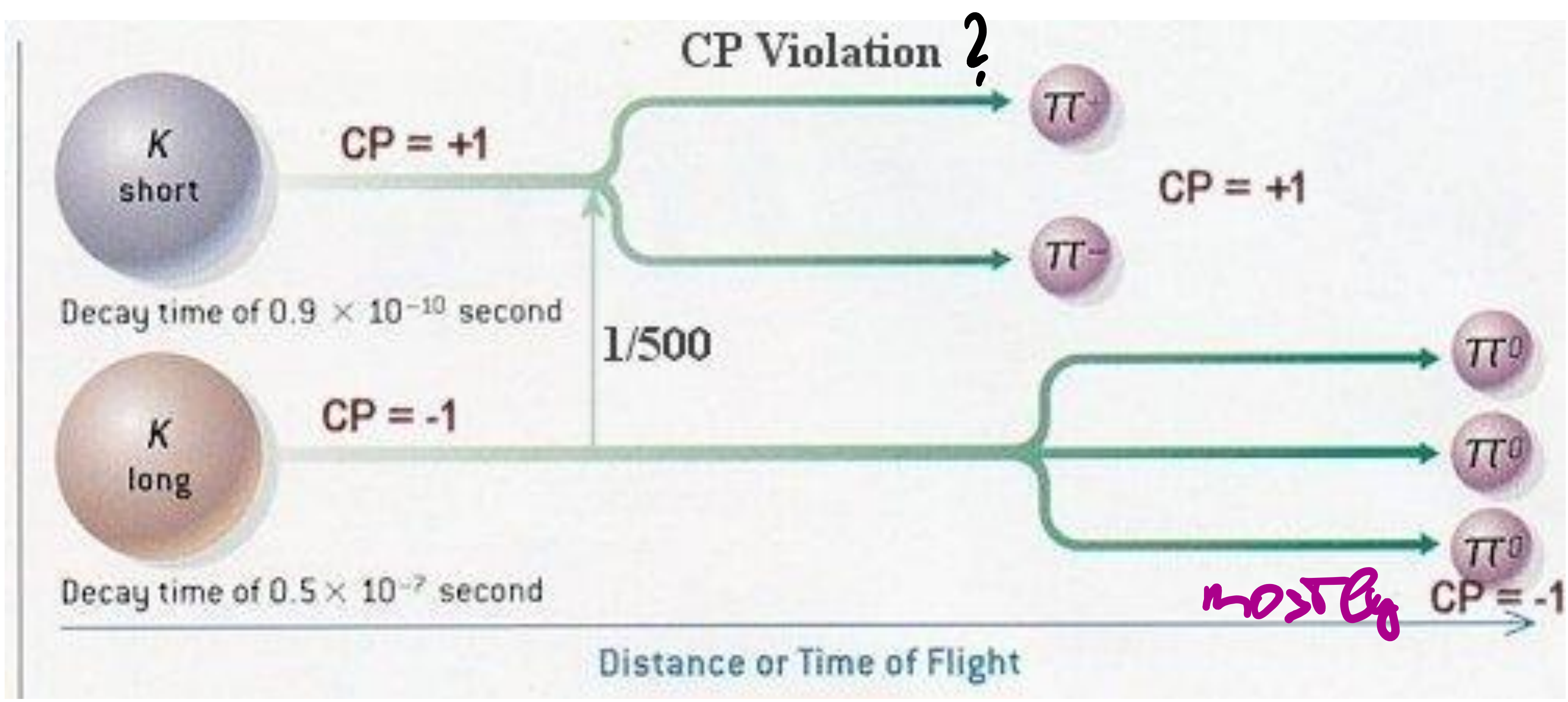


- We say that K_S is CP-even and K_L is CP-odd

CP violation

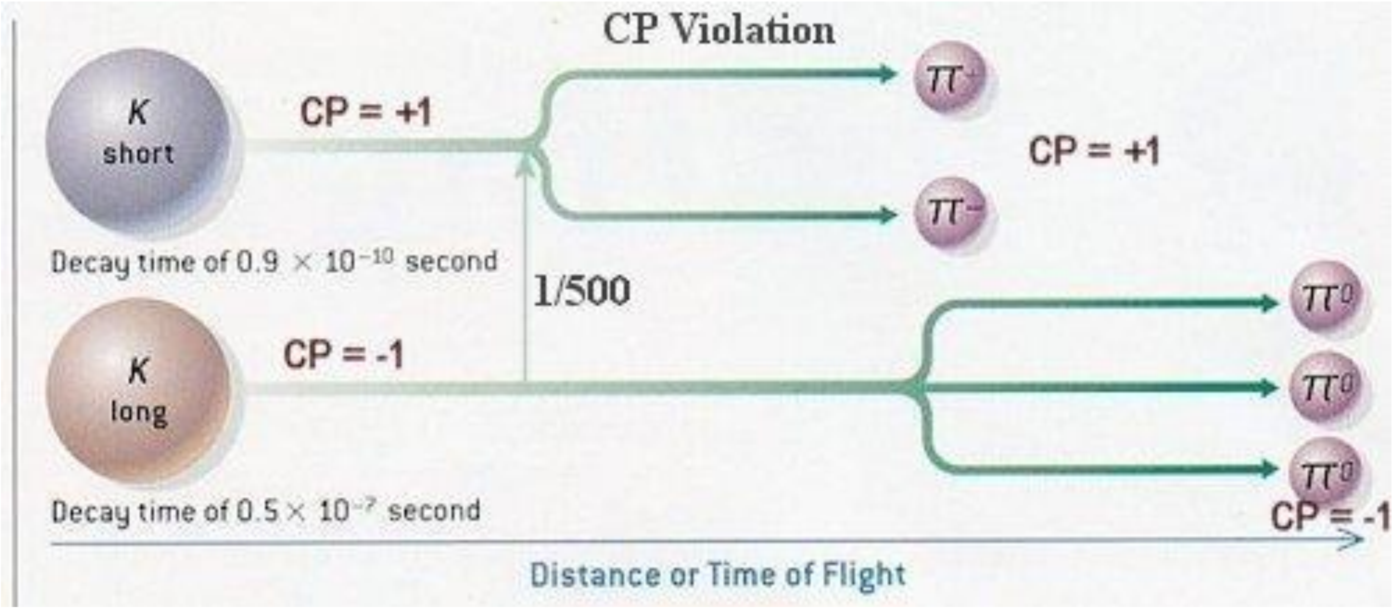
- If CP is conserved, K_L can never decay into two pions ($\pi^0\pi^0$ or $\pi^+\pi^-$) as this is a CP-even state, e.g.





CP violation

- If CP is conserved, K_L can never decay into two pions ($\pi^0\pi^0$ or $\pi^+\pi^-$) as this is a CP-even state



- This can be verified experimentally by measuring

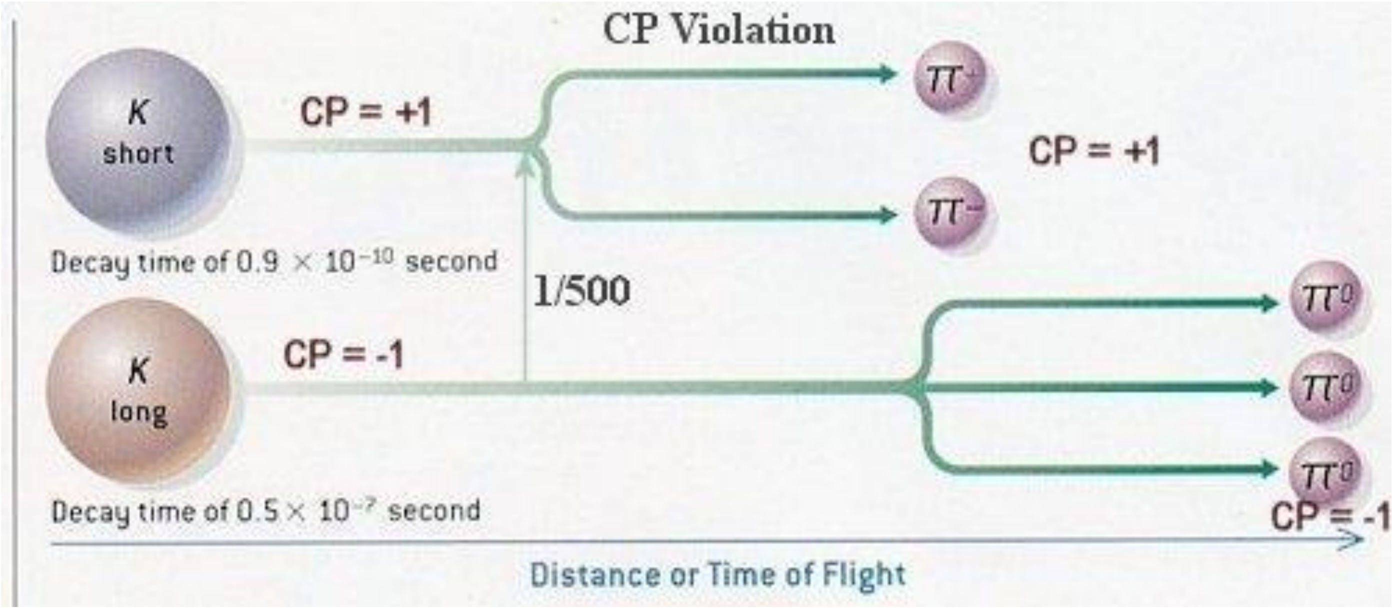
$$|\eta_{00}|^2 = \frac{N(K_L \to \pi^0\pi^0)}{N(K_S \to \pi^0\pi^0)} \qquad |\eta_{+-}|^2 = \frac{N(K_L \to \pi^+\pi^-)}{N(K_S \to \pi^+\pi^-)}$$

- In a CP-conserving universe, $\eta_{00} = \eta_{+-} = 0$, instead we find

$$|\eta_{00}| \simeq |\eta_{+-}| \simeq 2.2 \times 10^{-3} \neq 0$$

CP violation

- If CP is conserved, K_L can never decay into two pions ($\pi^0\pi^0$ or $\pi^+\pi^-$) as this is a CP-even state



- This can be verified experimentally by measuring

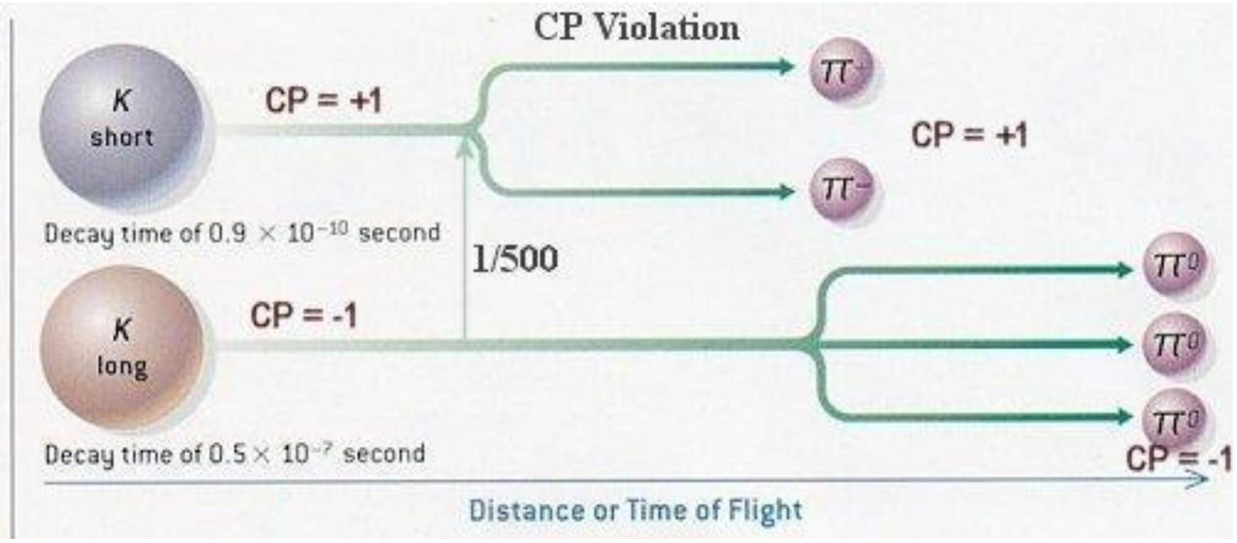
$$|\eta_{00}|^2 = \frac{N(K_L \to \pi^0\pi^0)}{N(K_S \to \pi^0\pi^0)} \qquad |\eta_{+-}|^2 = \frac{N(K_L \to \pi^+\pi^-)}{N(K_S \to \pi^+\pi^-)}$$

- In a CP-conserving universe, $\eta_{00} = \eta_{+-} = 0$, instead we find

$$|\eta_{00}| \simeq |\eta_{+-}| \simeq 2.2 \times 10^{-3} \neq 0$$

CP violation

- The fact that $|\eta_{00}| \simeq |\eta_{+-}| \neq 0$ implies that the mixing with K^0 and $\overline{K^0}$ does not give two particles with definite CP properties $\Rightarrow$ CP violation in the mixing



- Even if CP is violated in the mixing, it might be possible that the interactions responsible for kaon decay conserve CP $\Rightarrow$ $\eta_{00} = \eta_{+-} = \epsilon$

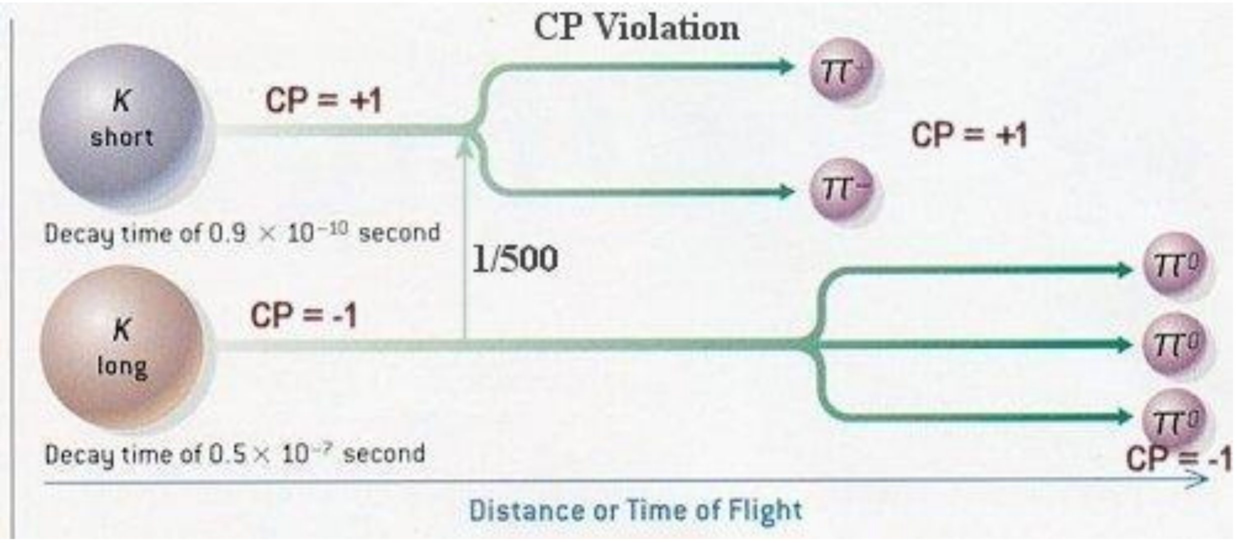
- This is not what is seen in data, which gives

$$\left|\frac{\eta_{00}}{\eta_{+-}}\right| = 0.9950 \pm 0.0007 \neq 1$$

- This phenomenon is known as CP violation in kaon decays

CP violation

- The fact that $|\eta_{00}| \simeq |\eta_{+-}| \neq 0$ implies that the mixing with K^0 and $\overline{K^0}$ does not give two particles with definite CP properties $\Rightarrow$ CP violation in the mixing



- Even if CP is violated in the mixing, it might be possible that the interactions responsible for kaon decay conserve CP $\Rightarrow$ $\eta_{00} = \eta_{+-} = \epsilon$

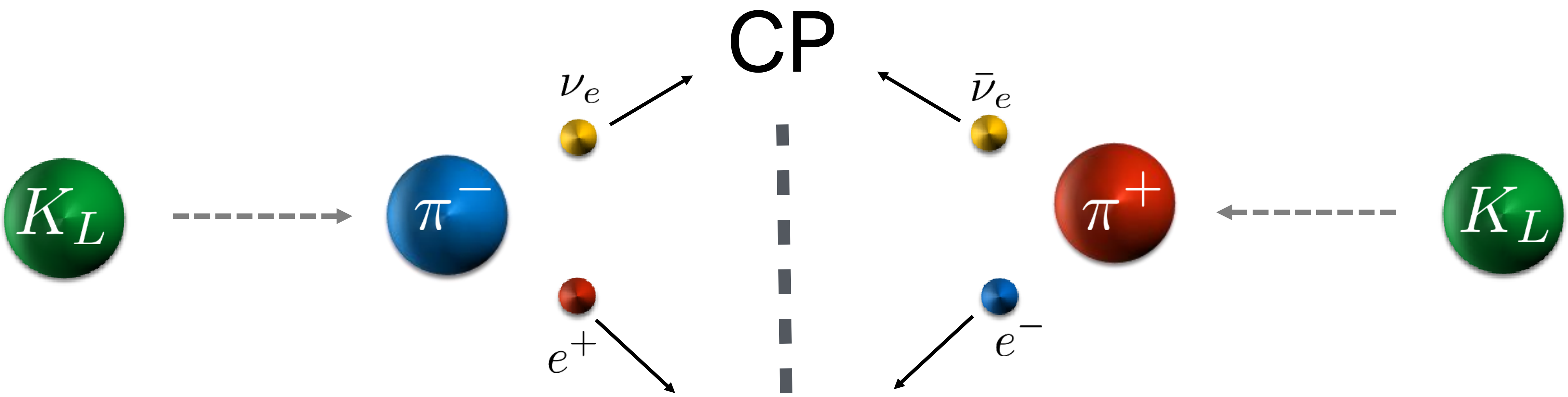
- This is not what is seen in data, which gives

$$\left| \frac{\eta_{00}}{\eta_{+-}} \right| = 0.9950 \pm 0.0007 \neq 1$$

- This phenomenon is known as CP violation in kaon decays

Distinguishing left from right

- After some time, any beam of K^0 or $\overline{K^0}$ will consist mostly of K_L
- One can look into the so-called semi-leptonic decays of K_L



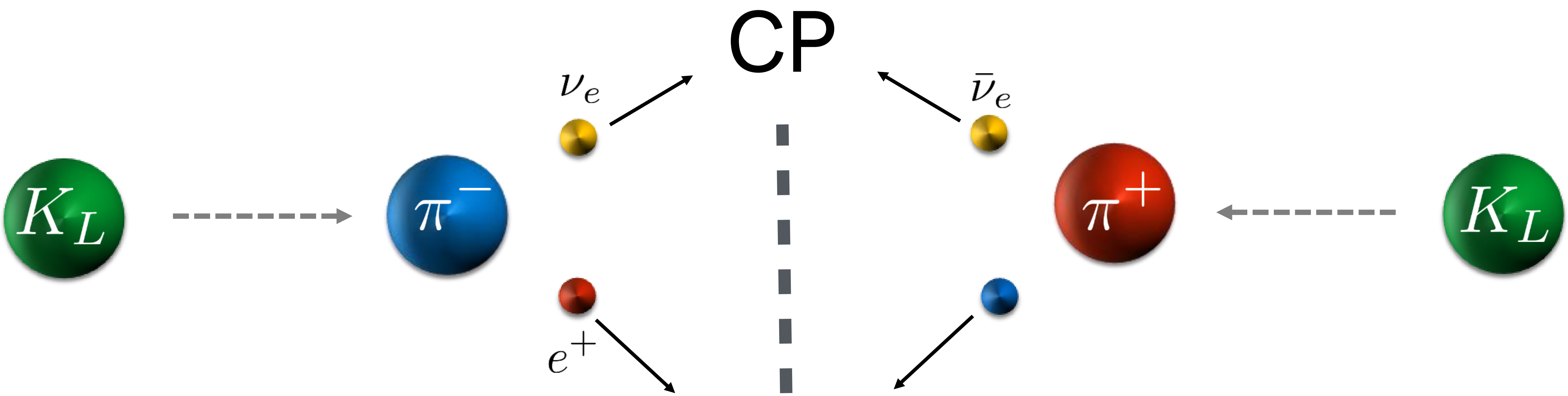
- If CP is conserved, the two decays should happen at the same rate (see Cobalt beta decay). This is not what is seen in the data

$$\delta_L = \frac{N(K_L \to \pi^- e^+ \nu_e) - N(K_L \to \pi^+ e^- \bar{\nu}_e)}{N(K_L \to \pi^- e^+ \nu_e) + N(K_L \to \pi^+ e^- \bar{\nu}_e)} \simeq 0.3\%$$

- Therefore, the left-handed electron is the particle into which K_L decays less frequently (albeit by a tiny amount)

Distinguishing left from right

- After some time, any beam of K^0 or $\overline{K^0}$ will consist mostly of K_L
- One can look into the so-called semi-leptonic decays of K_L



- If CP is conserved, the two decays should happen at the same rate (see Cobalt beta decay). This is not what is seen in the data

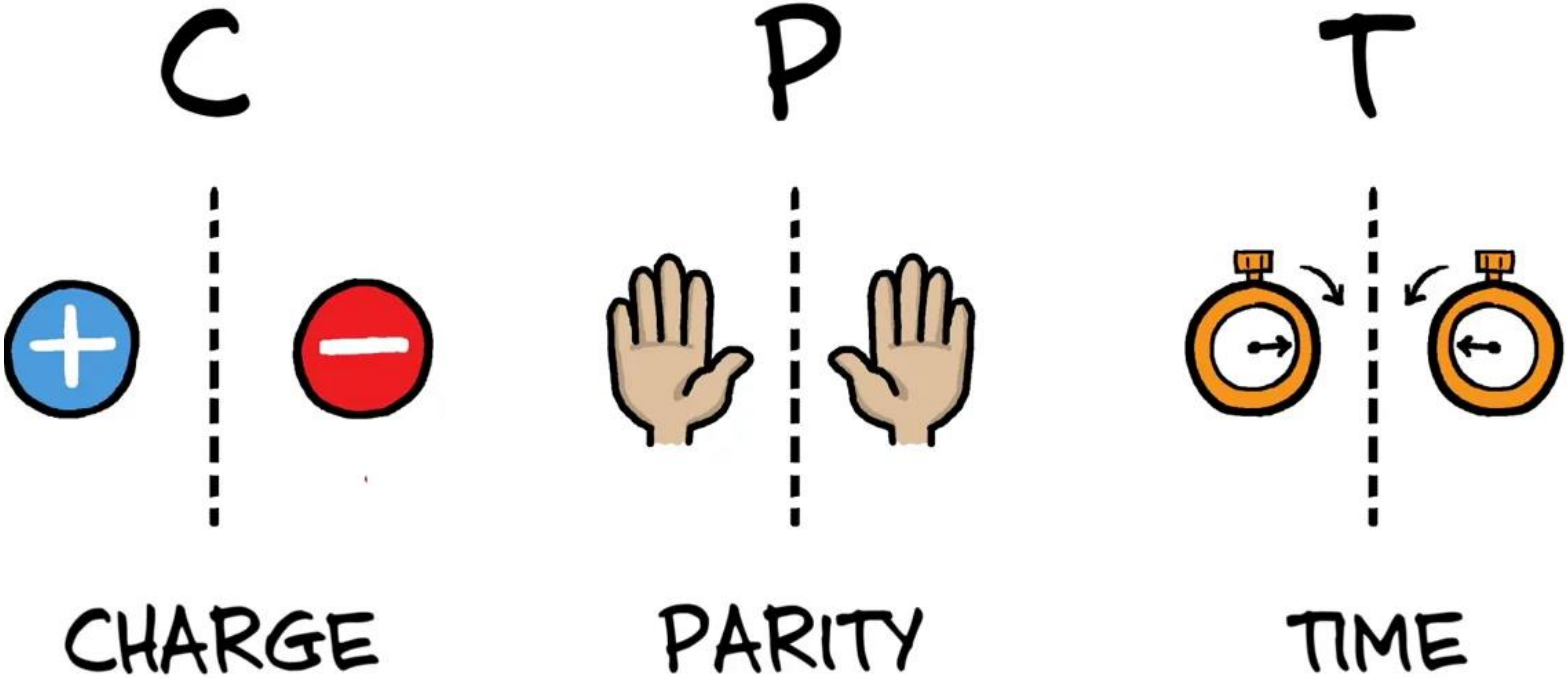
$$\delta_L = \frac{N(K_L \to \pi^- e^+ \nu_e) - N(K_L \to \pi^+ e^- \bar{\nu}_e)}{N(K_L \to \pi^- e^+ \nu_e) + N(K_L \to \pi^+ e^- \bar{\nu}_e)} \simeq 0.3\%$$

- Therefore, the left-handed electron is the particle into which K_L decays less frequently (albeit by a tiny amount)

Implications of CP violation

Time reversal

- After C and P, time reversal T is the last fundamental discrete symmetry

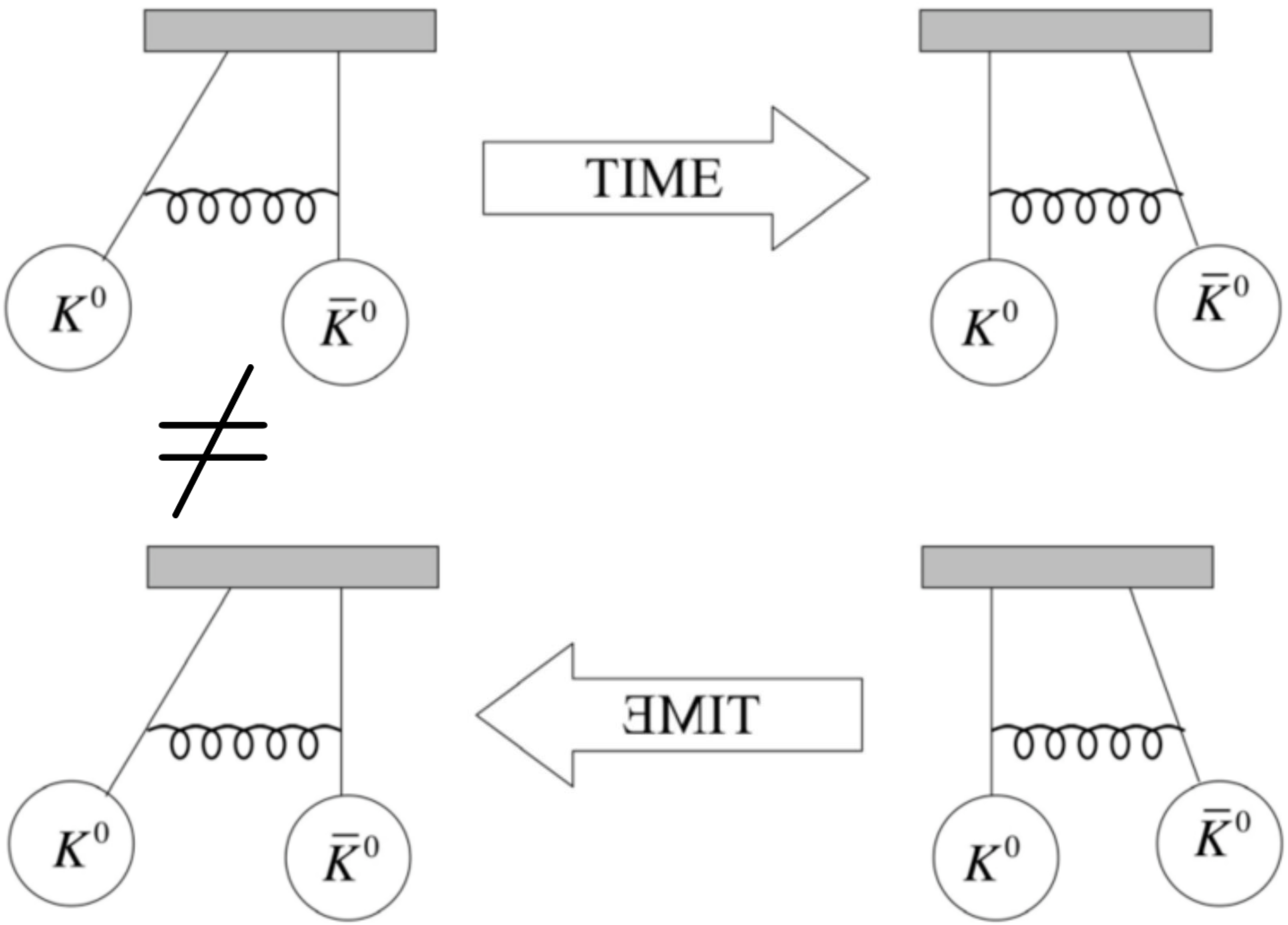


Source: Veritasium

- We can prove that CPT is always conserved, given some assumptions. Giving up those would require a major rewriting of many theories

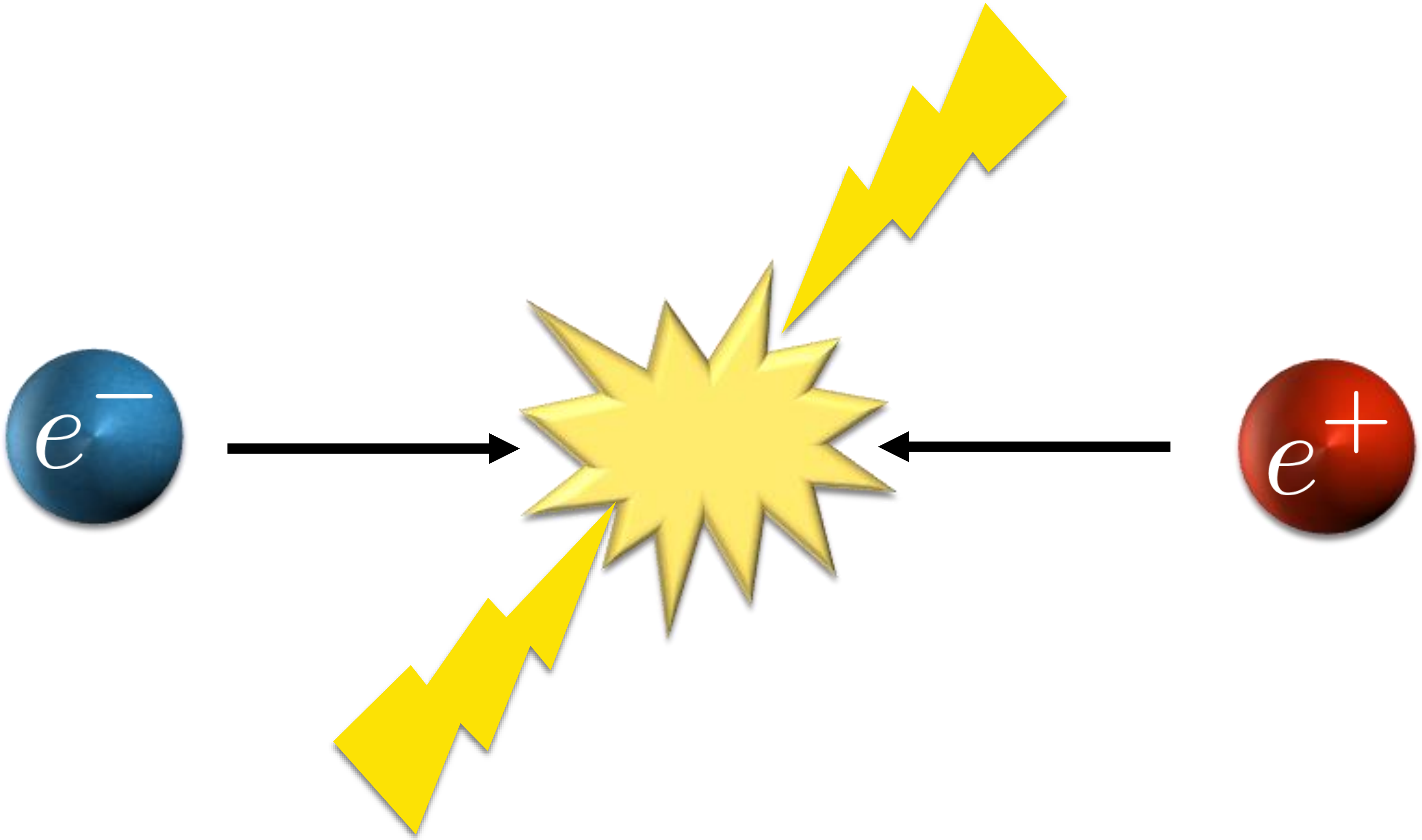
Violation of time reversal

- If CP is violated, and CPT is conserved, then T must be violated
- This means that kaon oscillations do not look the same if time reversed



Matter and antimatter

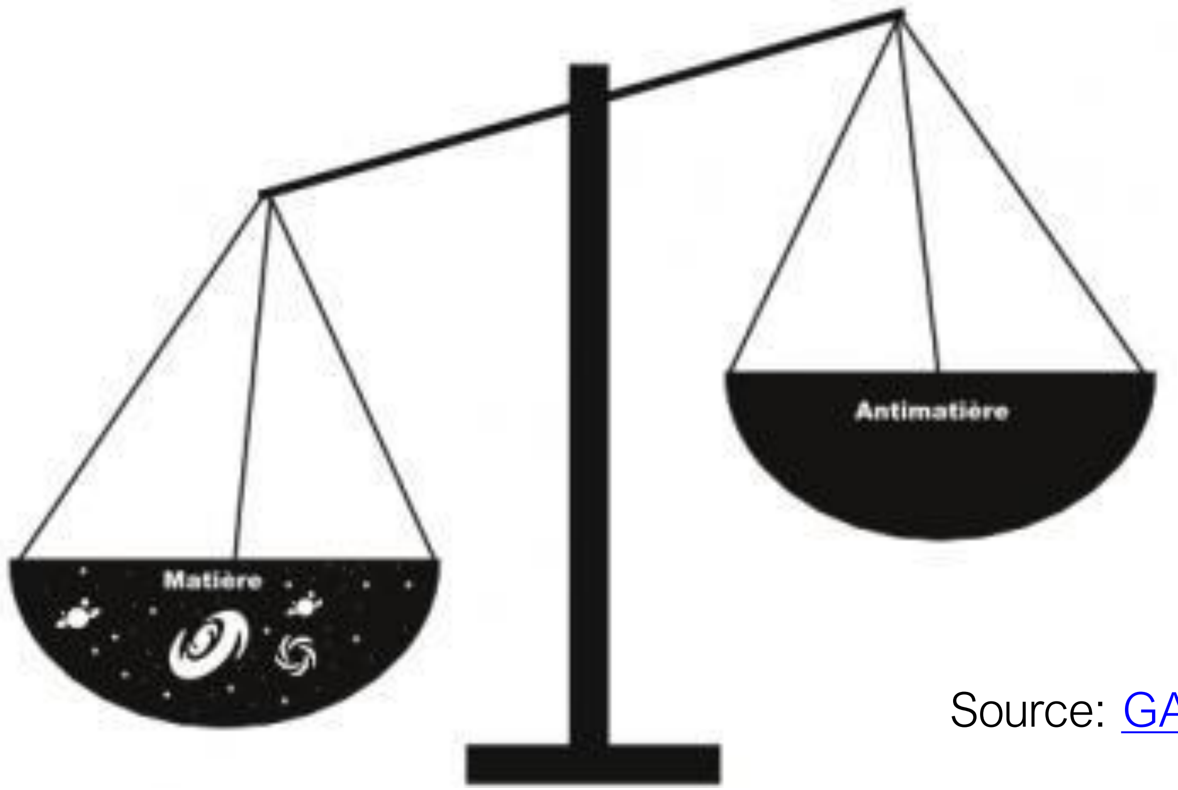
- Particles and antiparticles can annihilate, giving light (photons)



- If there were the same amount of matter and antimatter in the universe, they would annihilate and we would have only photons

Matter-antimatter asymmetry

- In the early universe, about 1/10000000000 more matter than antimatter was produced



Source: GANIL

- This is due to processes that violate CP, where matter and antimatter are not produced at equal rate (see e.g. kaon decays)
- Our Standard Model of elementary particles predicts a fraction of matter that is ten orders of magnitude less than that observed $\Rightarrow$ new physics!

Lecture 1: learning outcomes

In this lecture, we have learnt

- What a symmetry is and why it's important
- The difference between discrete and continuous symmetries
- Parity and its violation in weak decays
- Charge conjugation and the violation of CP in kaon decays
- Time reversal and the cosmological consequences of its violation