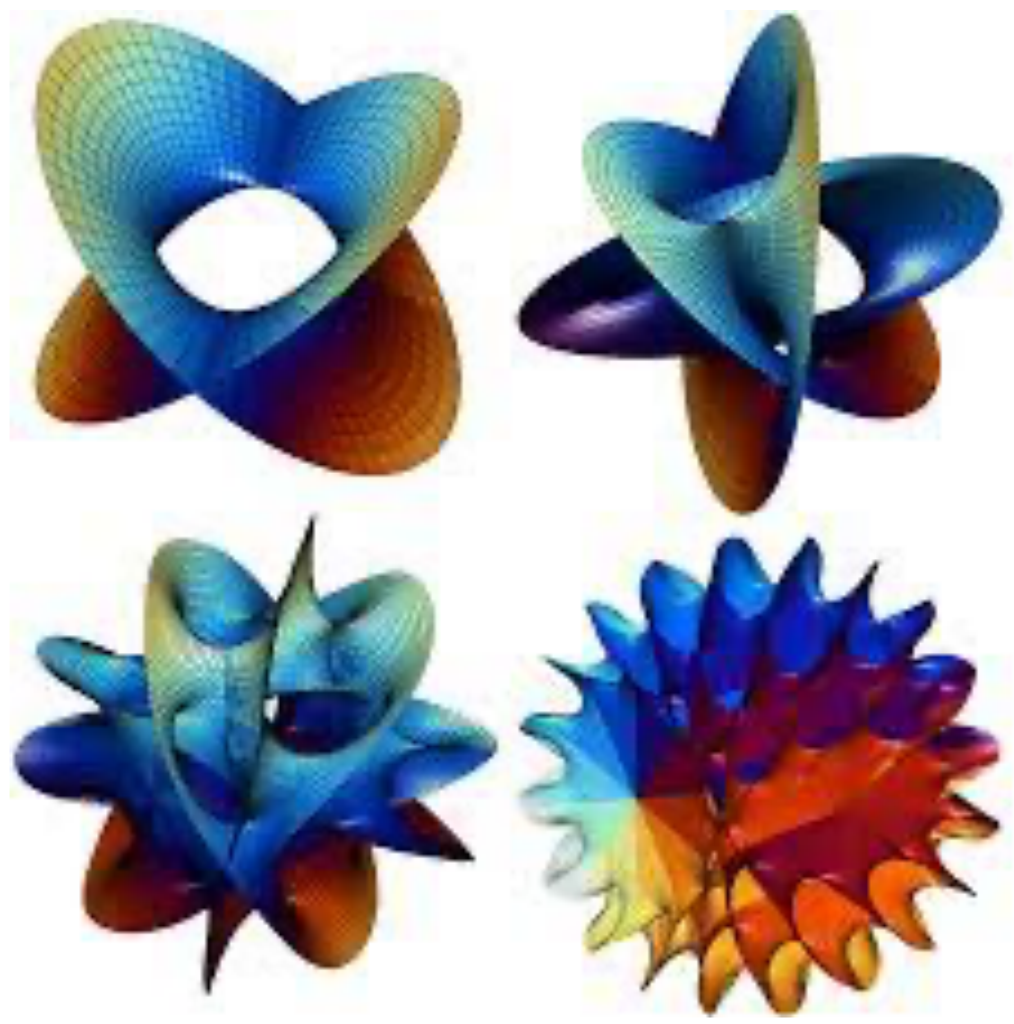
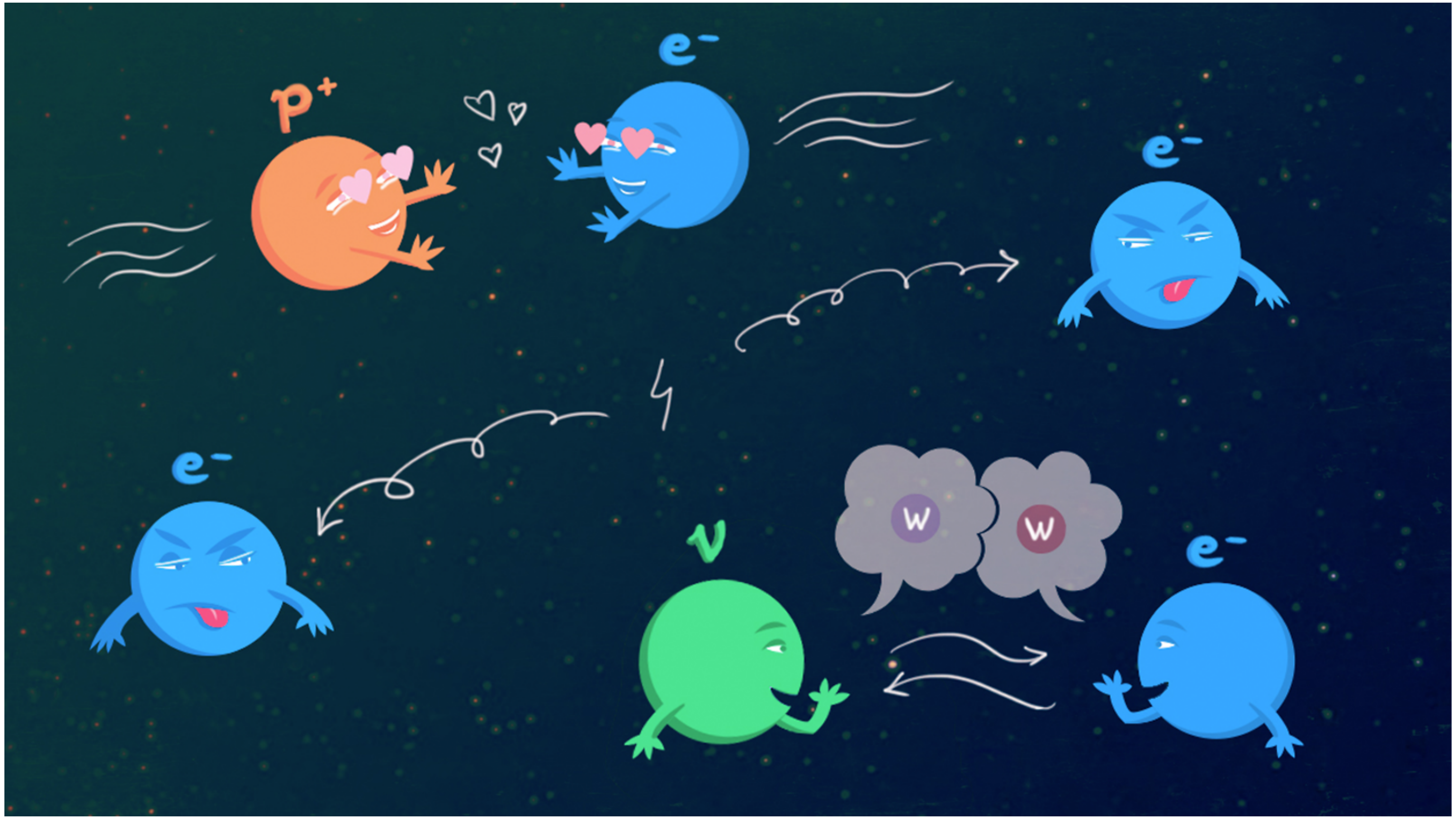
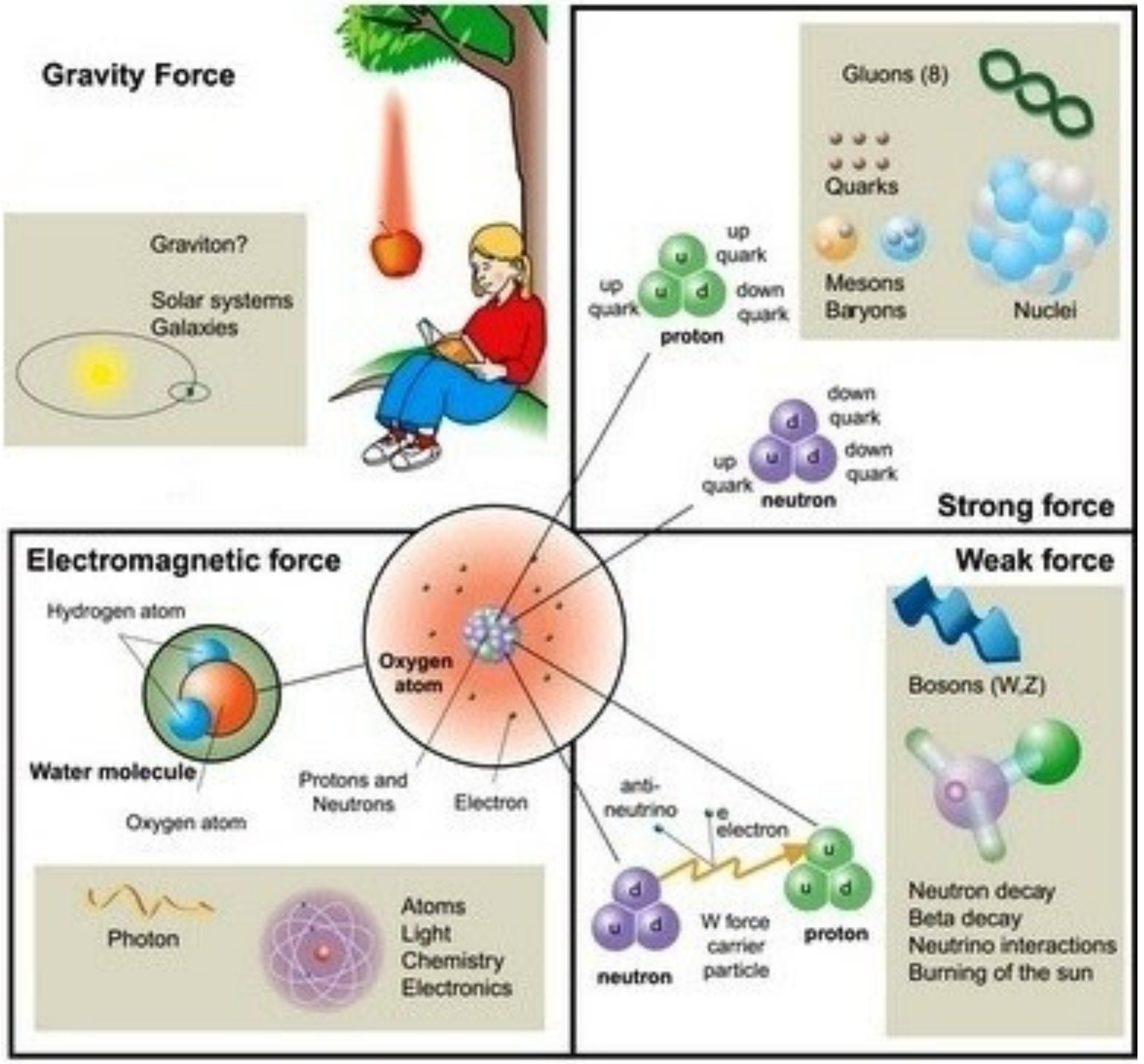
Journeys in Standard Model (and beyond)

Dipan Sengupta

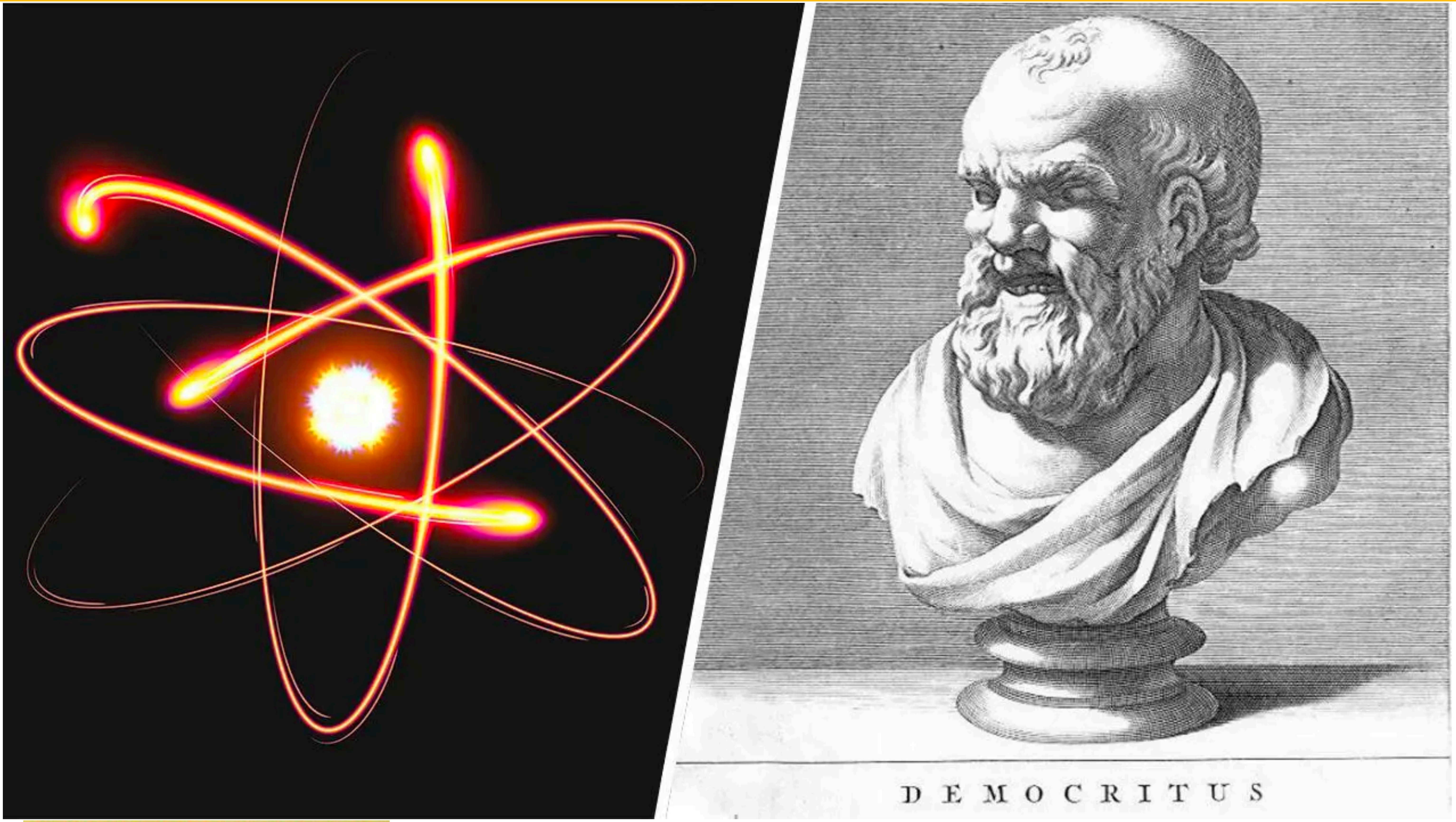


Particles and Forces

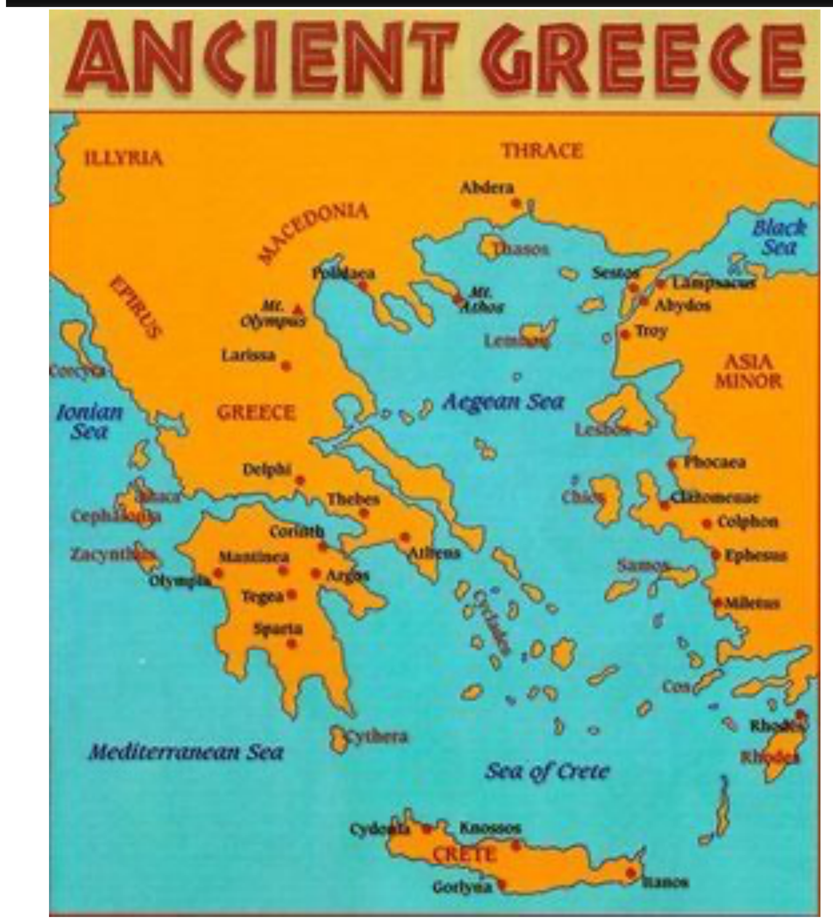


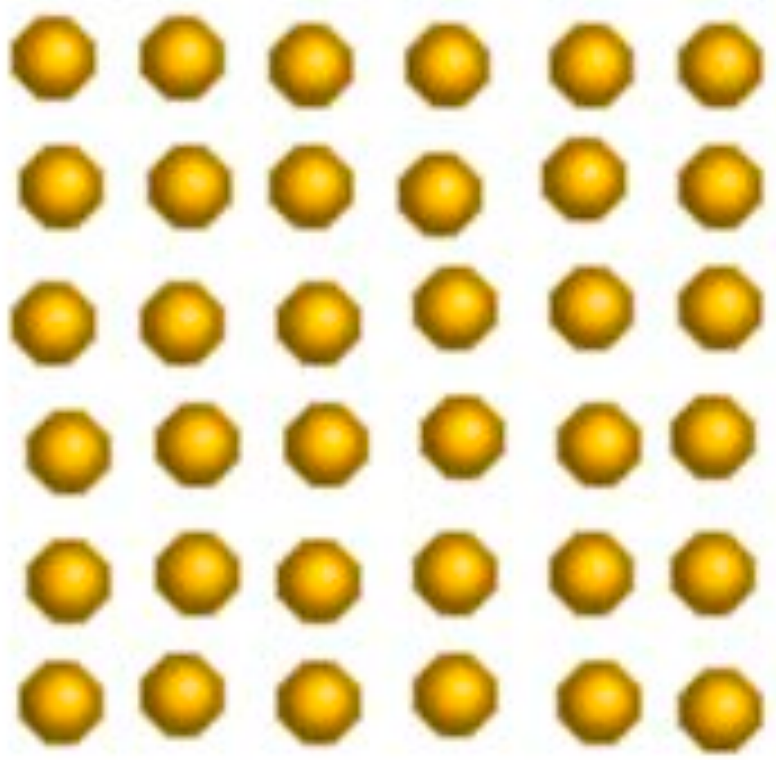


Particles

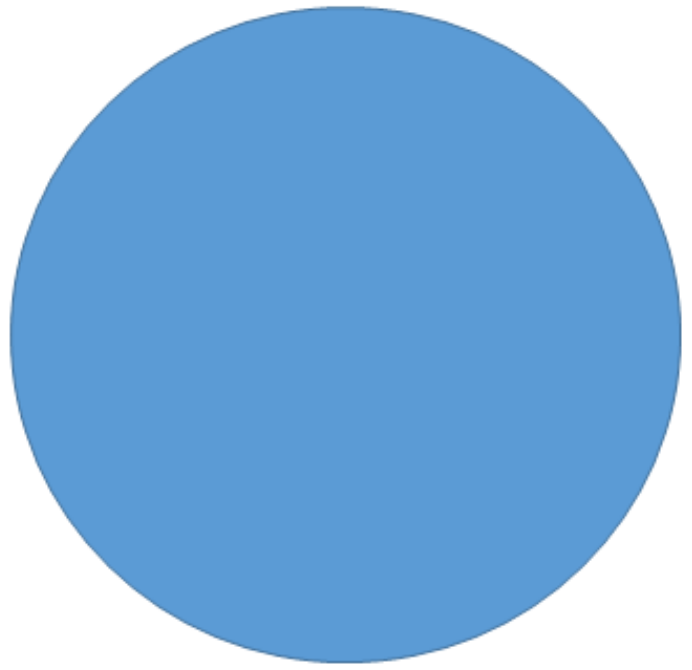


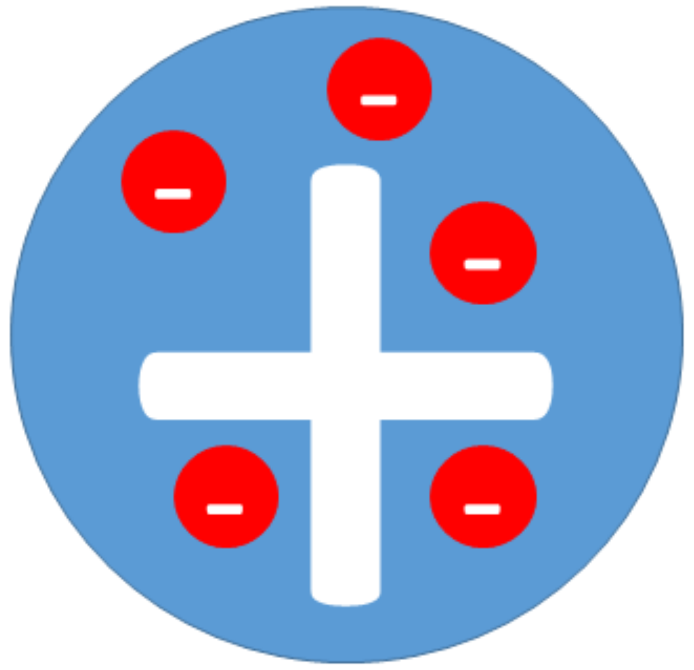
- Greek philosopher, 400 BC
- Named the smallest piece of matter "atomos," meaning "not to be cut."
- Democritus' atoms were small, hard particles that were all made of the same material but were different shapes and sizes.
- Atoms were infinite in number, always moving and capable of joining together.

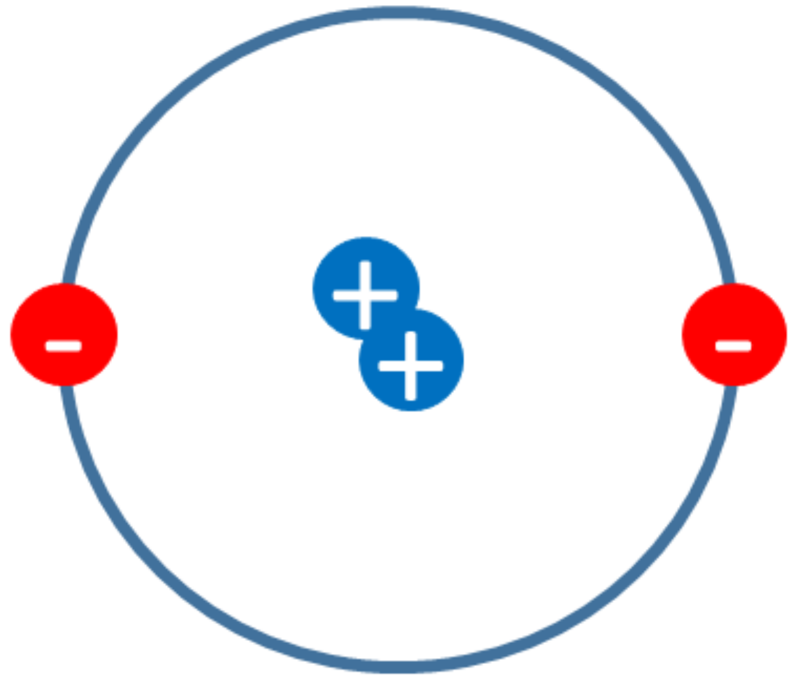




Particles



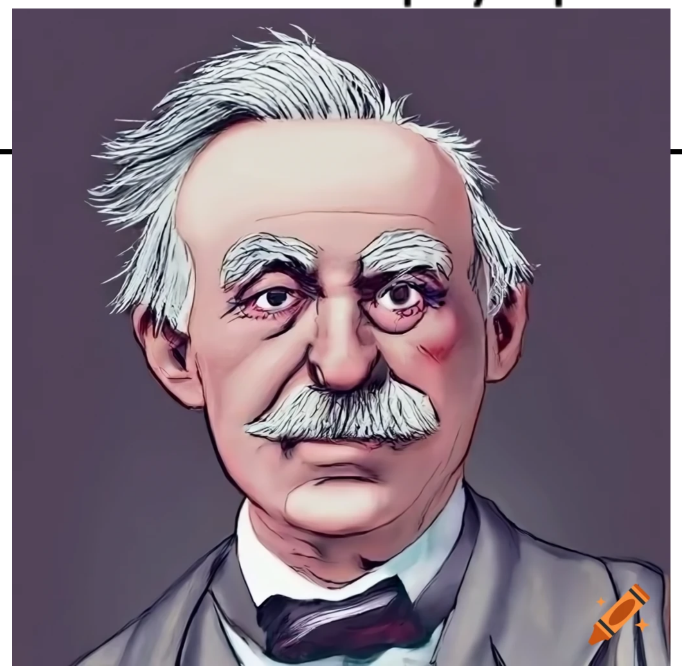




<u>John Dalton (1803):</u>
Atoms are tiny, hard spheres that cannot be split up.

<u>J.J. Thomson (1897):</u>
Electrons are distributed inside a positive mass like raising in a plum pudding.

<u>Ernest Rutherford (1909):</u>
Most of the atom's mass is inside the nucleus. Electrons circle the nucleus. Most of the atom is empty space.



Until Rutherford particles were thought of as

classical rigid objects, a point

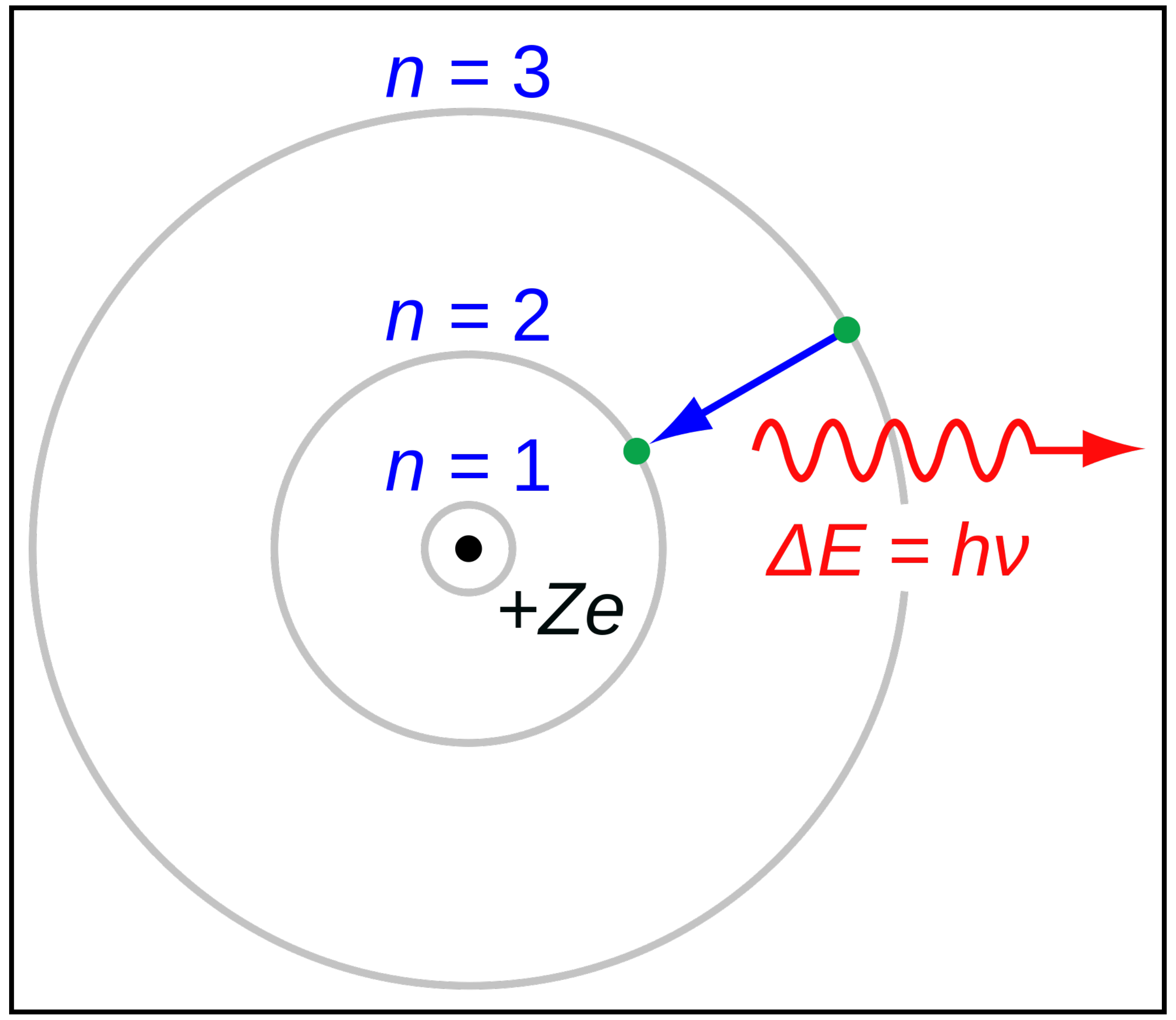
or a spherical object that can be broken down

Particles

Bohr's model + de-Broglie's quantization condition gave a quantum interpretation to the particle.

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

Fun fact : Bohr never believed in the photon



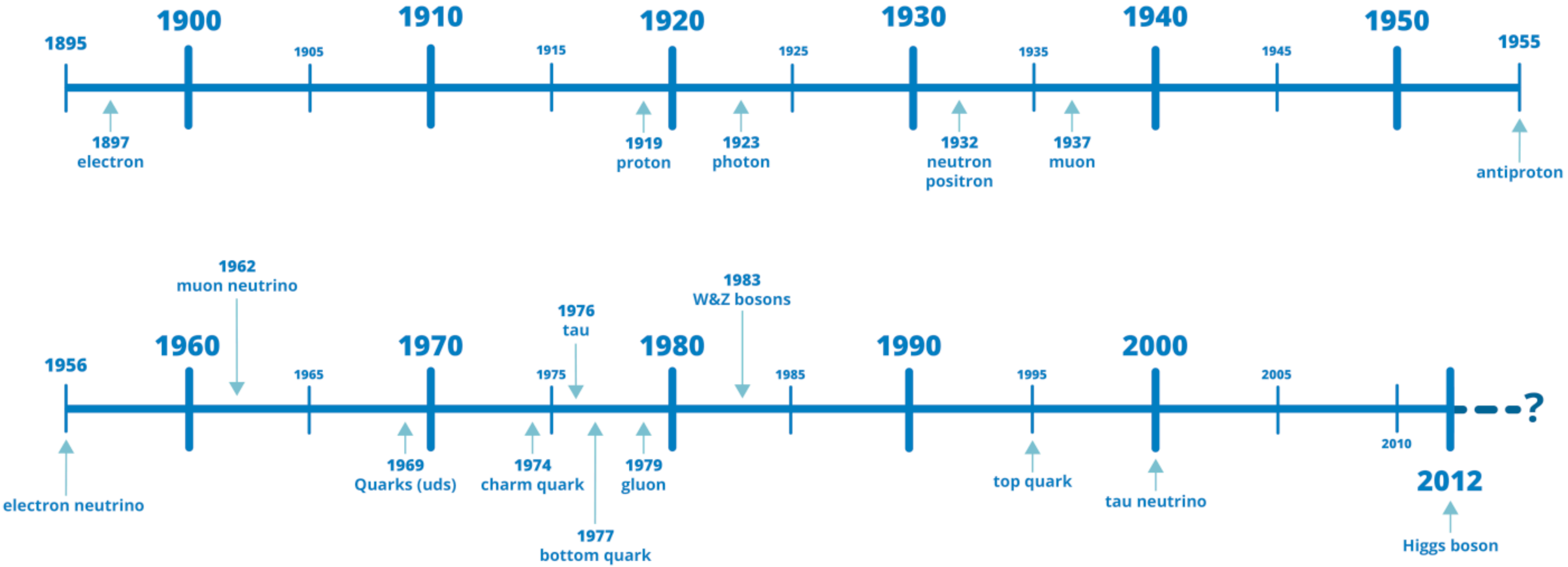
Bohr model was still semi-classical, A full quantum treatment required us to think of electron clouds, issues with Zeeman Effect/ Stark effect ...

No new particles untill fundamental particles untill the 1930's

Particles

ATLAS EXPERIMENT

Key particle discoveries



Schrodinger-Heisenberg-Dirac :

Werner Heisenberg: “matrix mechanics”

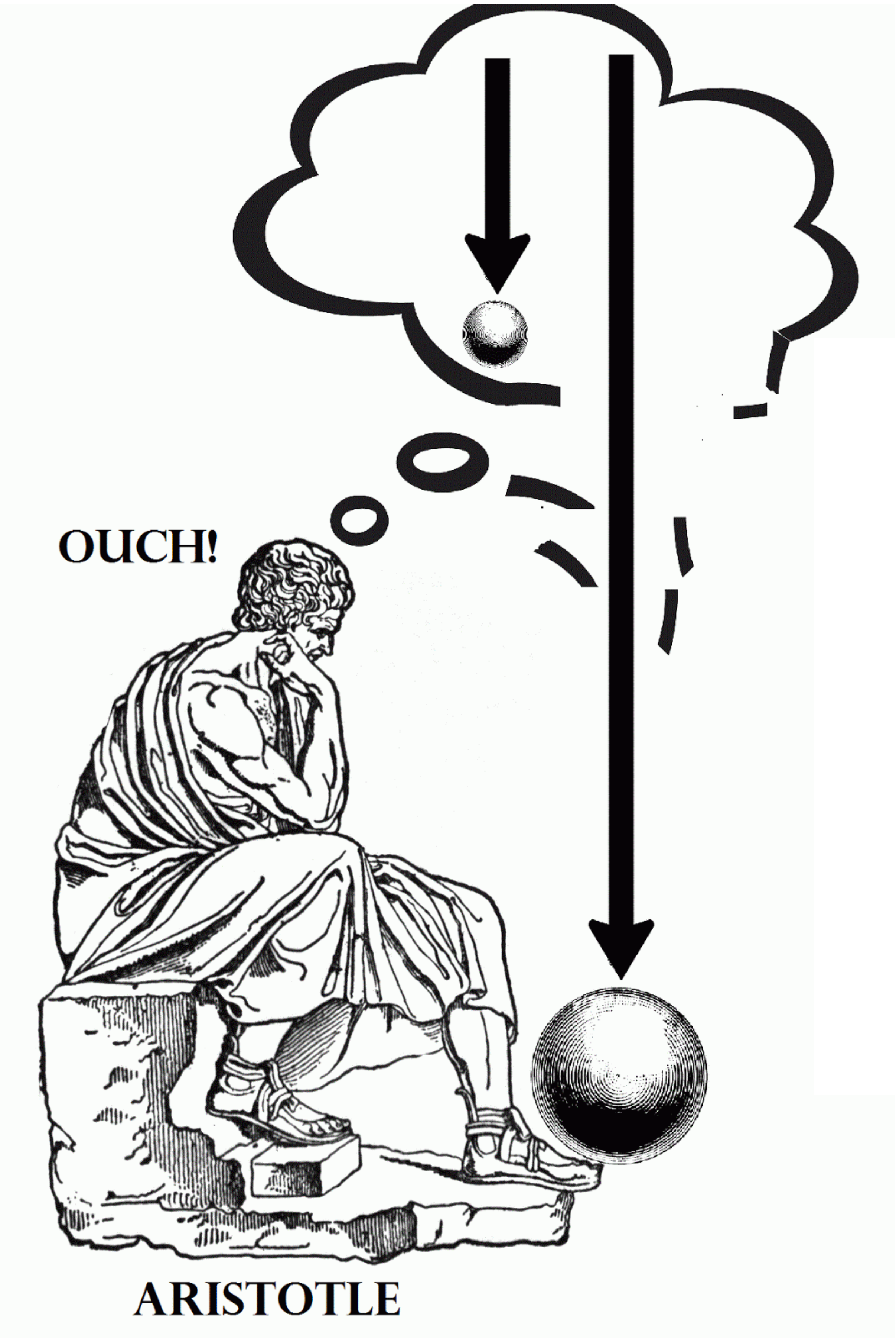
Erwin Schrödinger: “wave mechanics”

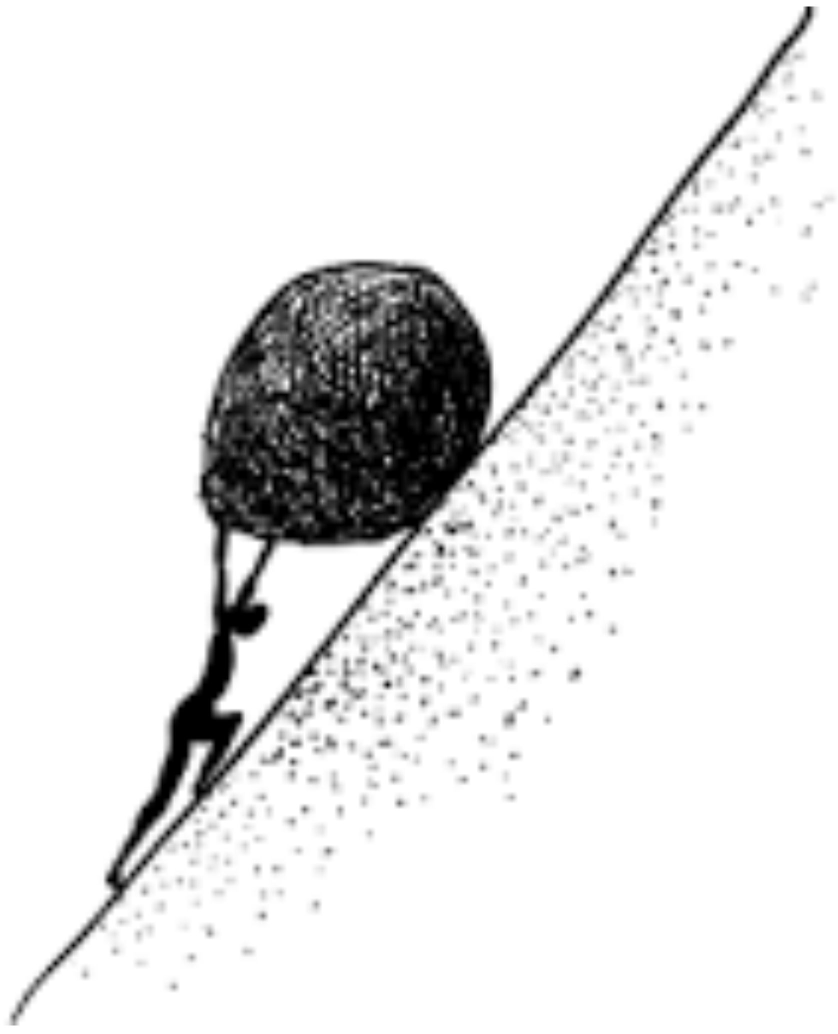
Paul Dirac: Heisenberg’s and Schrödinger’s formalisms are equivalent

Newton’s Laws are replaced by the Schrödinger Equation for the quantum state:

$$H|\Psi\rangle = i\partial_t|\Psi\rangle$$

Forces

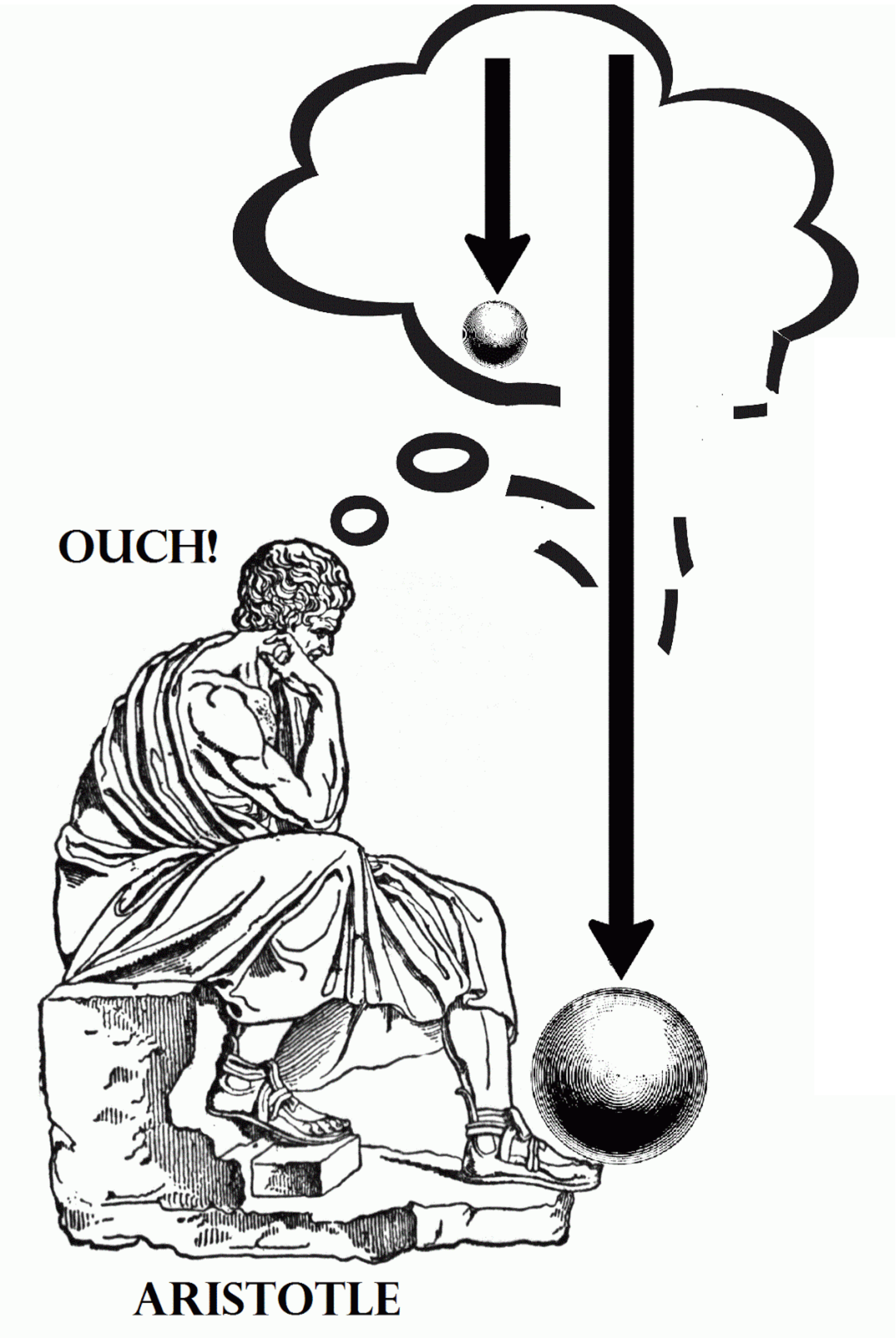


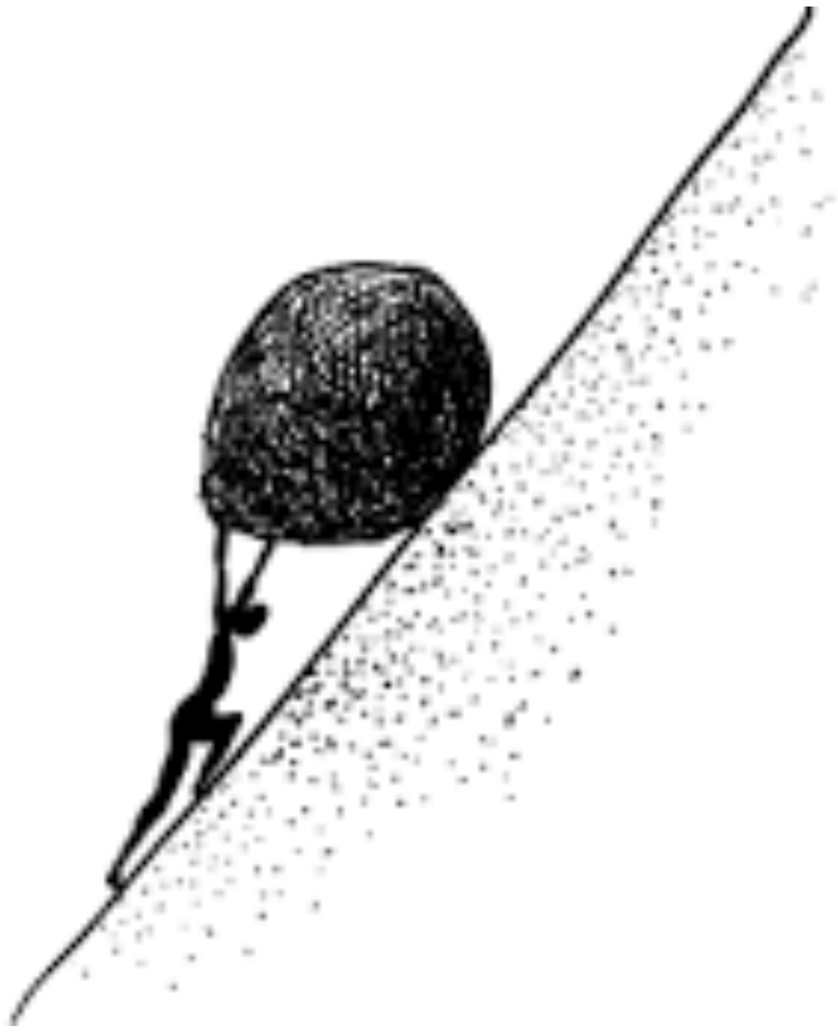


Galileo: Objects accelerate

at the same rate down the slope

Forces

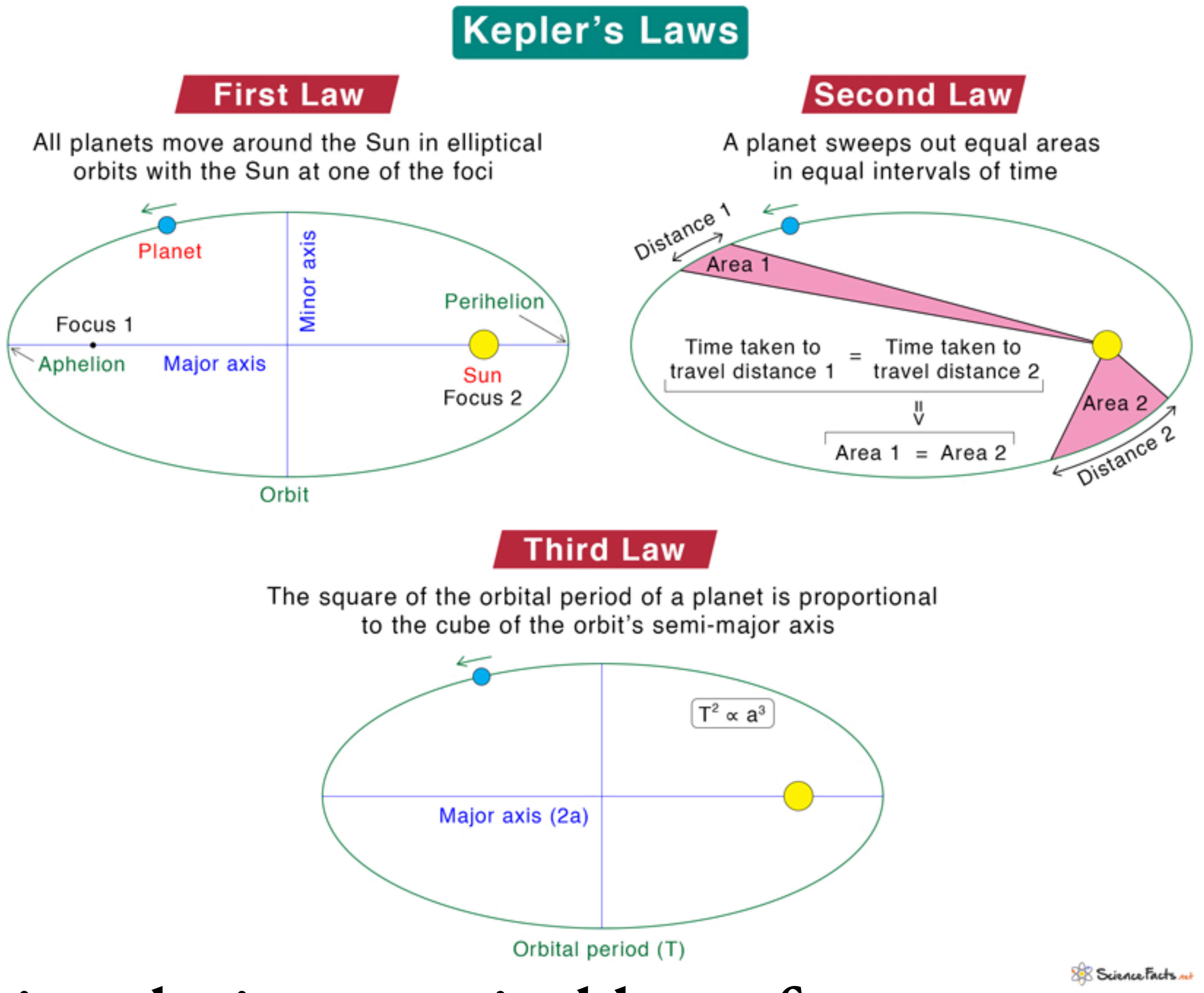




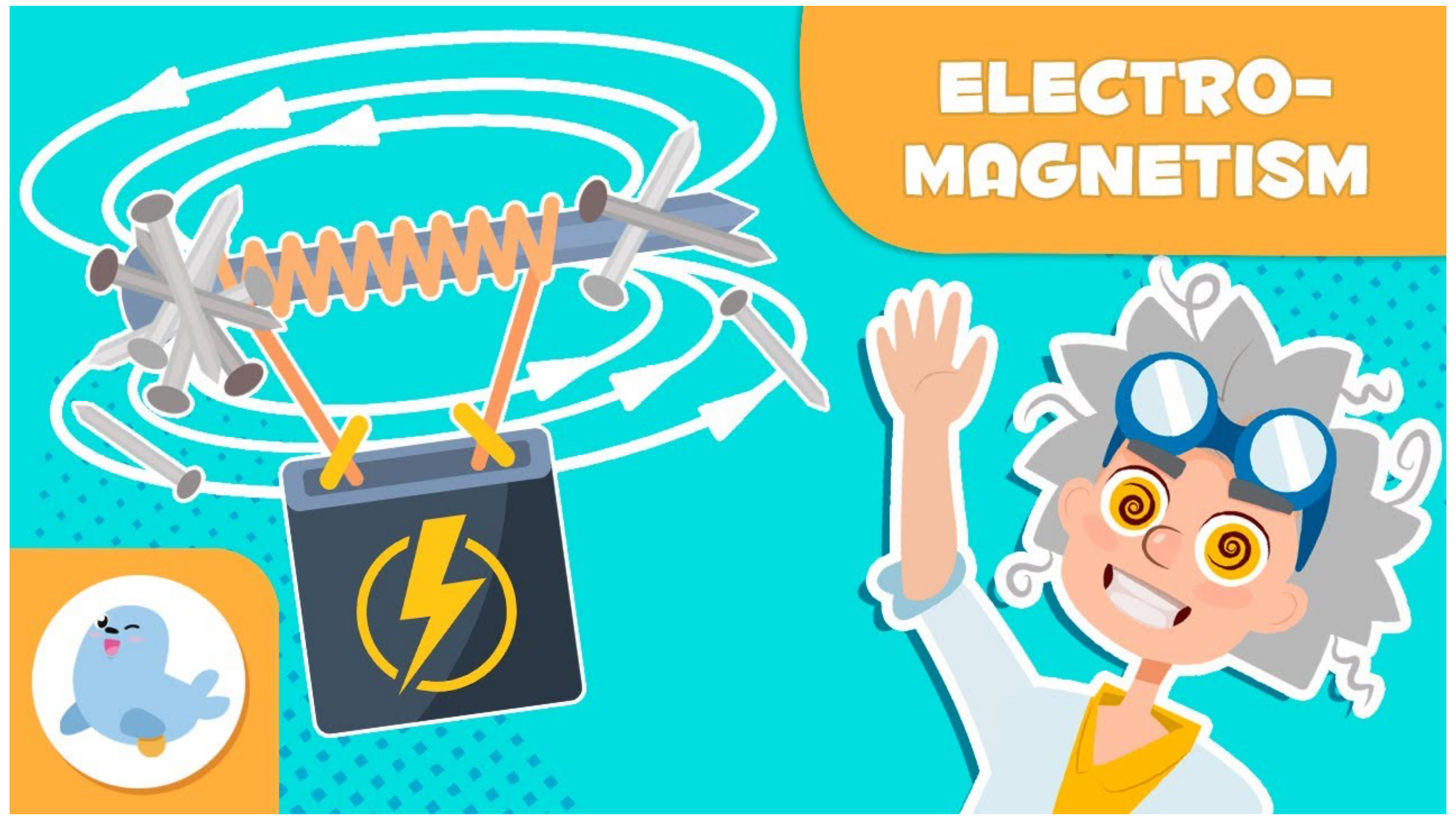
Galileo: Objects accelerate

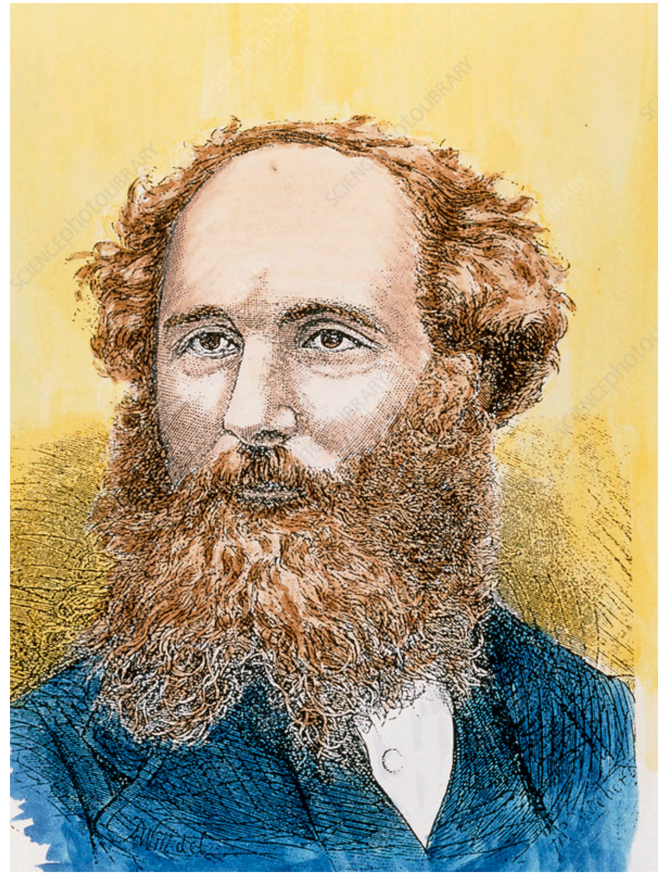
at the same rate down the slope

Forces : Newton-Kepler-Copernicus



No new forces untill Maxwell interpreted electromagnetism being carried by a force



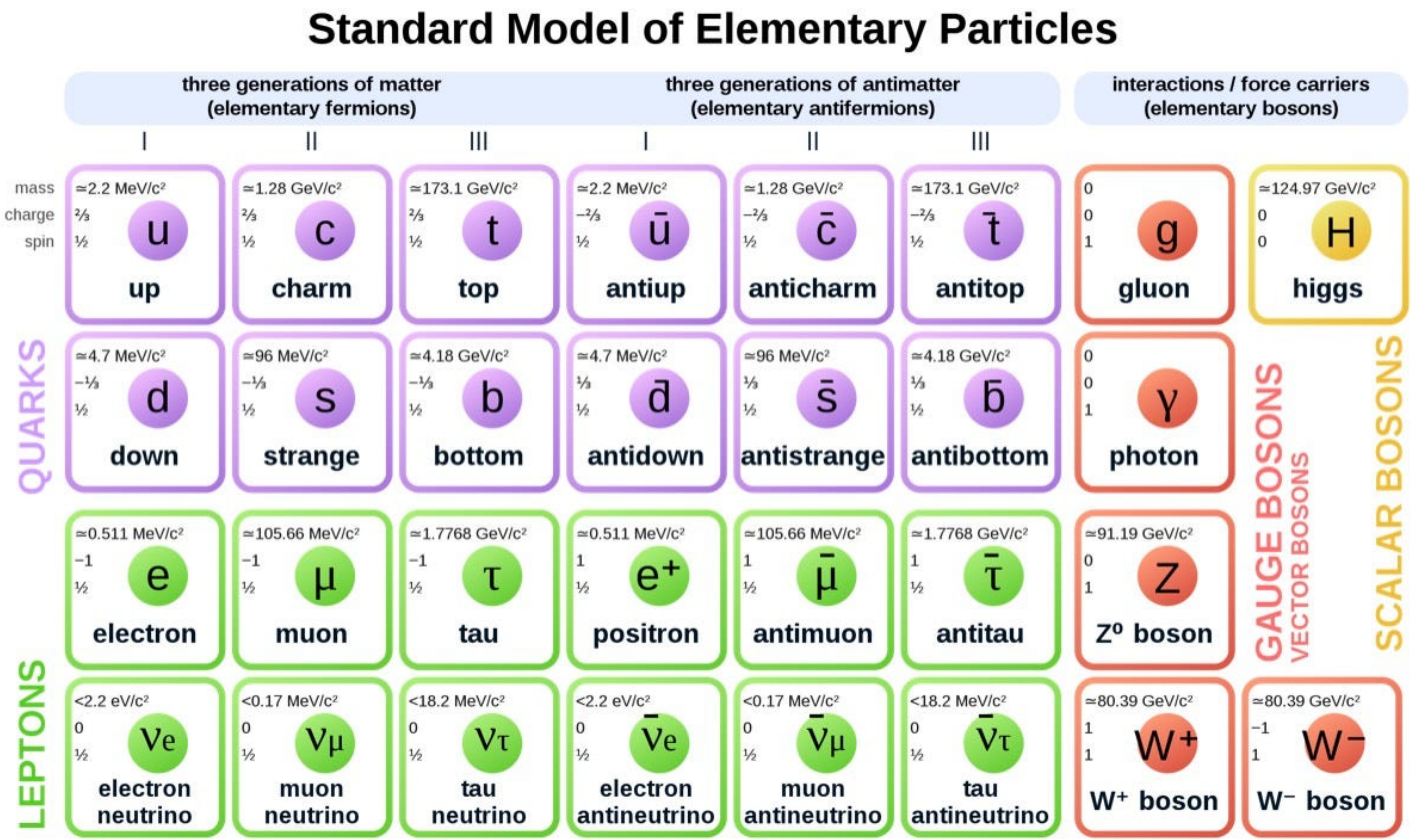


Forces

Interaction	Current theory	Mediators	Relative strength[20]	Long-distance behavior (potential)	Range (m) [21]
Weak	Electroweak theory (EWT)	W and Z bosons	10^{33}	$\frac{1}{r}\, e^{-m_{\mathrm{W,Z}}\, r}$	10^{-18}
Strong	Quantum chromodynamics (QCD)	gluons	10^{38}	$\sim r$ (Color confinement, see discussion below)	10^{-15}
Gravitation	General relativity (GR)	gravitons (hypothetical)	1	$\frac{1}{r^2}$	∞
Electromagnetic	Quantum electrodynamics (QED)	photons	10^{36}	$\frac{1}{r^2}$	∞

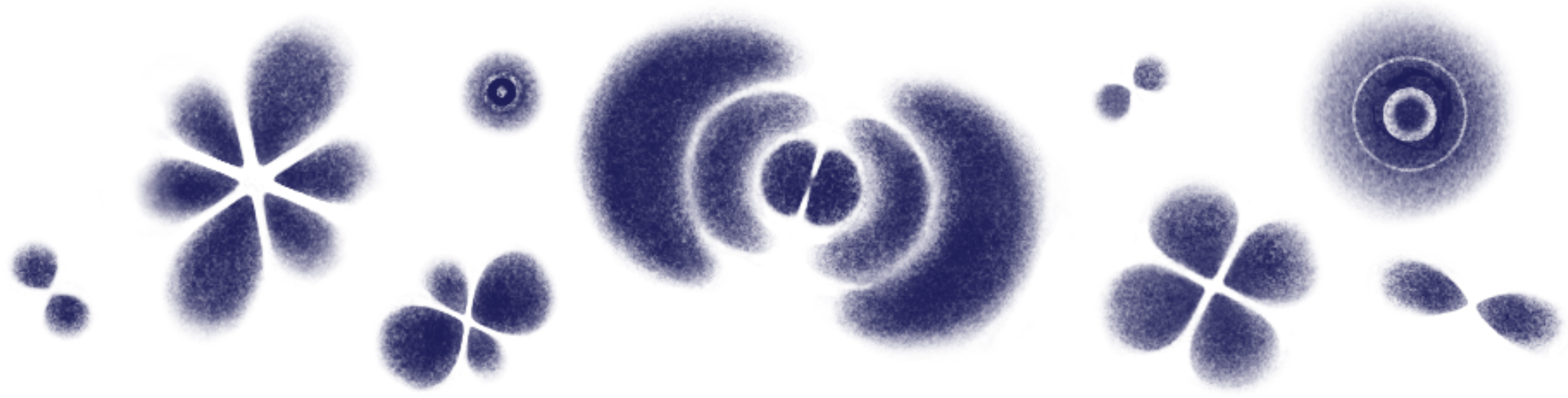
Source Wikipedia

Standard Model of Particle Physics

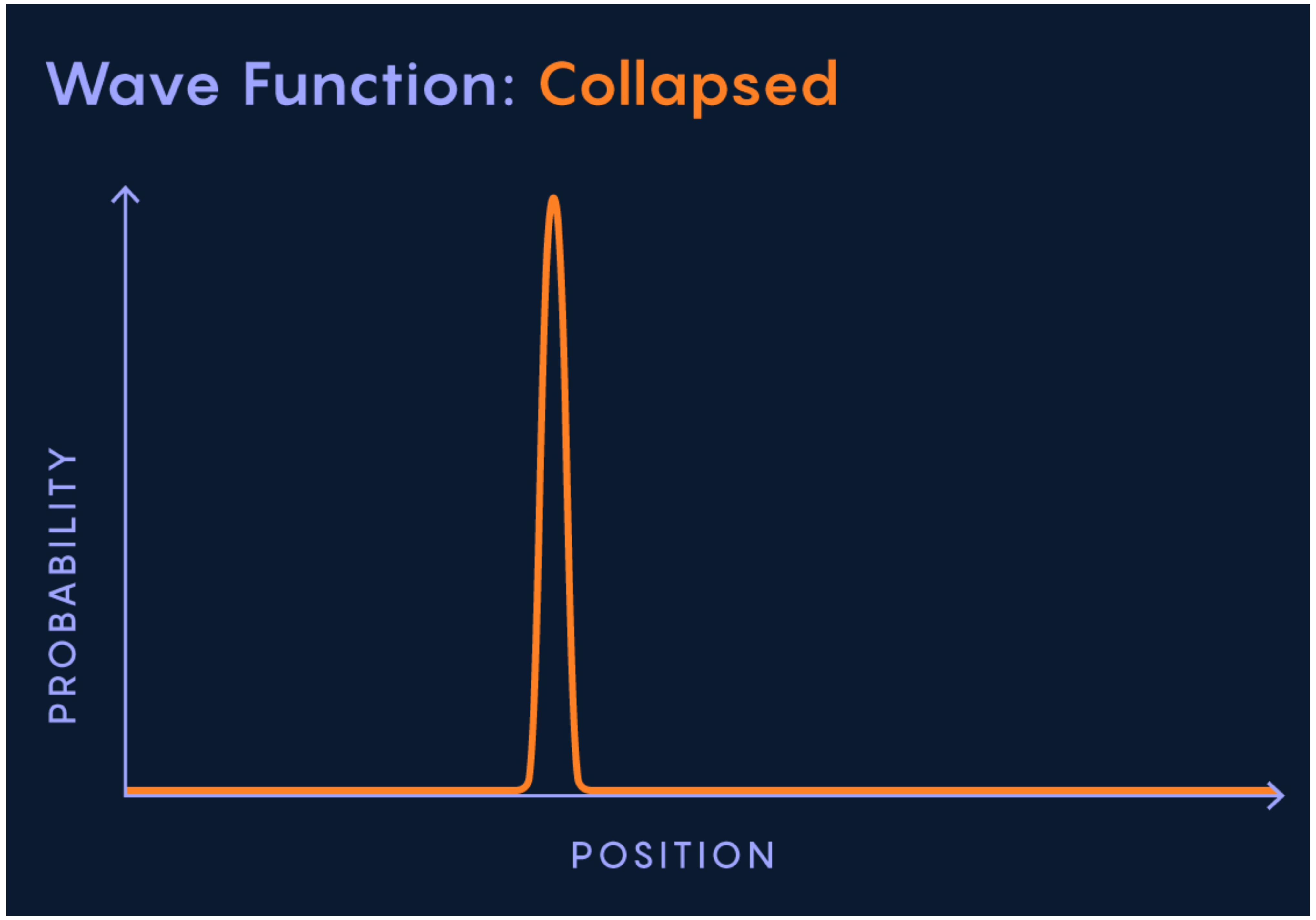


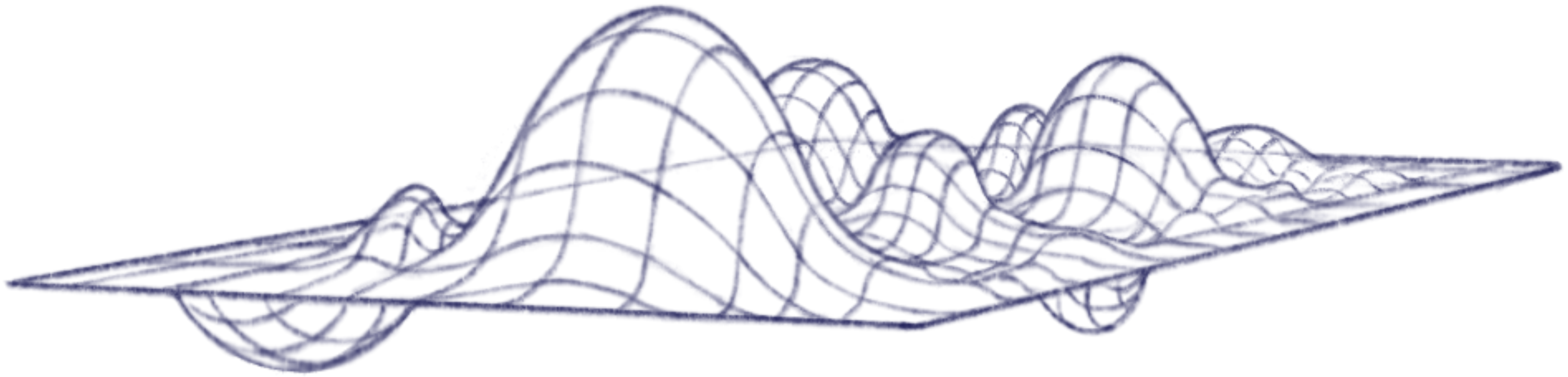
Organizing particles and forces : QM to QFT

Particles and fields : Classically a particle is a rigid sphere of sorts



QM : A particle is a collapsed wave function

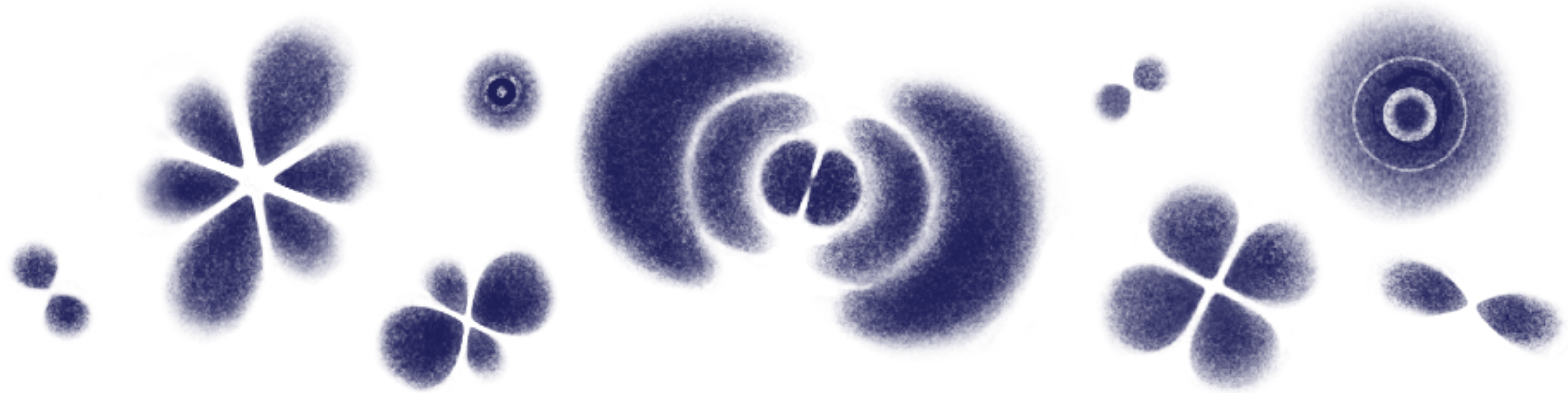


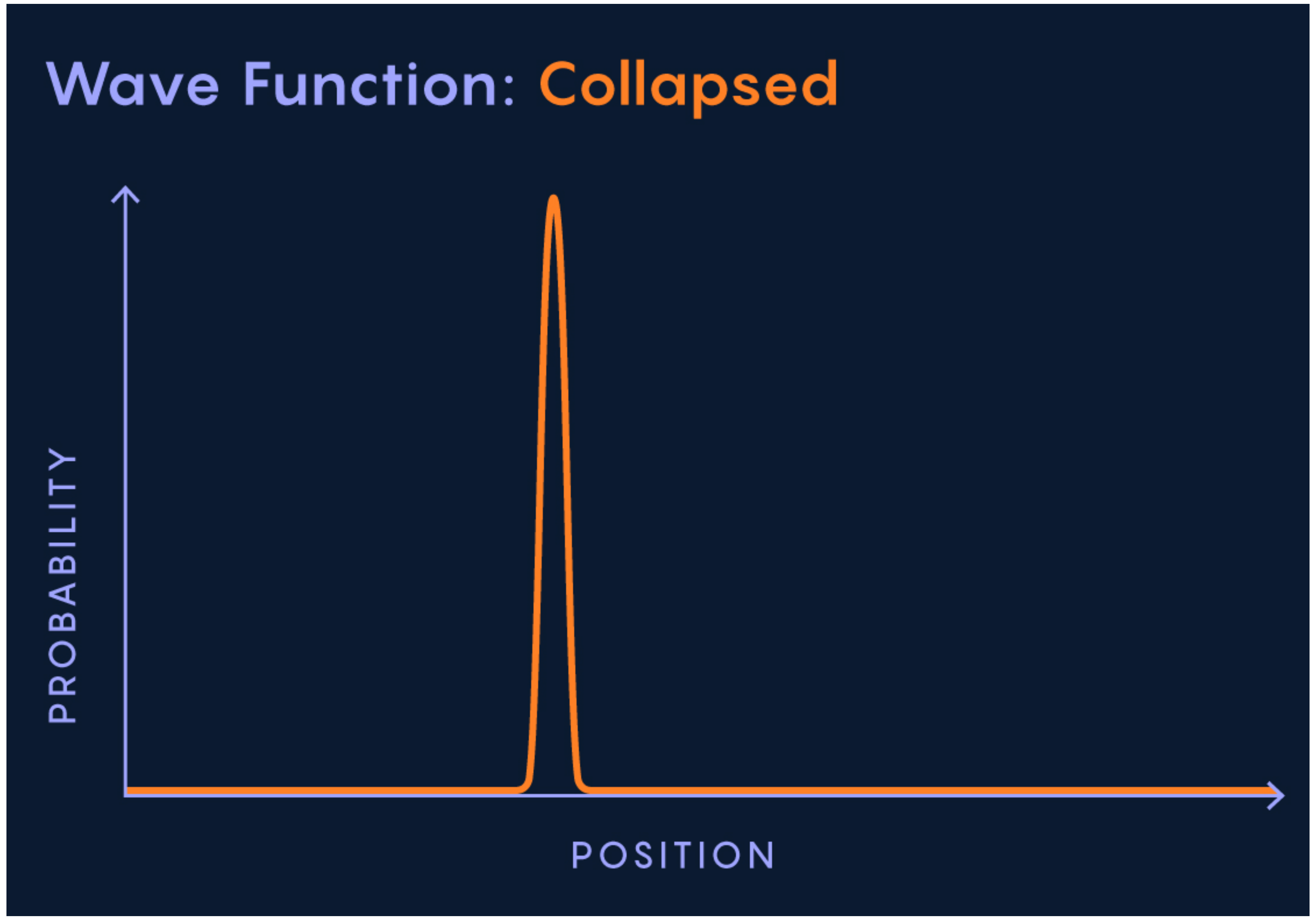


A field pervades space and time   QFT: A particle is a localized quantum excitation of a field

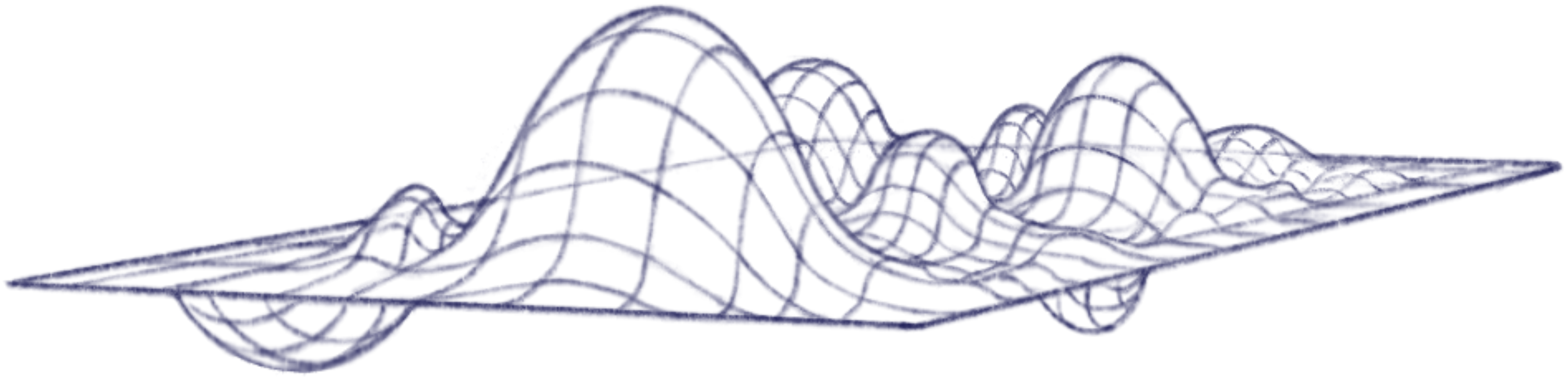
Organizing particles and forces : QM to QFT

Particles and fields : Classically a particle is a rigid sphere of sorts





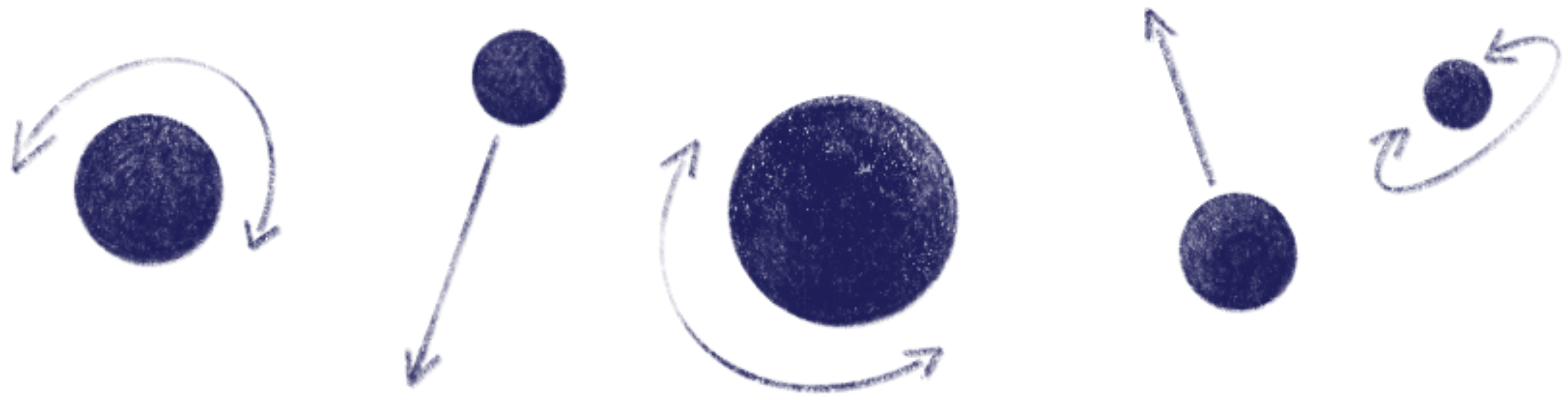
QM : A particle is a collapsed wave function



A field pervades space and time

QFT: A particle is a localized quantum excitation of a field

Organizing Particles : Group them



At the very least,

A particle is an irreducible representation of a poincare group

$$[P^\mu,\ P^\nu] = 0,$$
$$[M^{\mu\nu},\ P^\lambda] = i(\eta^{\lambda\nu}\ P^\mu - \eta^{\lambda\mu}\ P^\nu),$$
$$[M^{\mu\nu},\ M^{\lambda\rho}] = i(\eta^{\mu\rho}\ M^{\nu\lambda} - \eta^{\mu\lambda}\ M^{\nu\rho} + \eta^{\nu\lambda}\ M^{\mu\rho} - \eta^{\nu\rho}\ M^{\mu\lambda})$$

The Poincare' algebra $L(\mathcal{P})$ *contains*

10 generators = 4-translations, 3-rotations and 3-boosts

Organizing Particles : Group them like Wigner

Wigner got his Nobel in 1963, but not for his 1939 paper addressing issues on internal space-time symmetries.

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ON UNITARY REPRESENTATIONS OF THE INHOMOGENEOUS LORENTZ GROUP*

BY E. WIGNER

(Received December 22, 1937)

1. ORIGIN AND CHARACTERIZATION OF THE PROBLEM

Eugene Paul Wigner

Wigner's Little Groups: Subgroups of the Lorentz group whose transformations keep the given momentum of a particle invariant.

A massive particle can be brought to its rest frame. The momentum is invariant under rotations, but its spin can be rotated. Thus the little group is like O(3).

A massless particle cannot be brought to the rest frame. Rotations around the momentum leaves it invariant . The dynamical quantity associated with this rotation is called the helicity.

Organizing Particles : Group them like Wigner

For a massive particle at rest, it is O(3). If the particle gains Its momentum, it is a Lorentz-boosted O(3). Thus, if the momentum is not zero, the Little group is a Lorentz-boosted O(3) or O(3)-like little group.

If a particle is massless, the little group consists of rotations around the momentum.

In addition, Wigner showed that this ugly matrix leaves the four-momentum of the massless particle invariant.

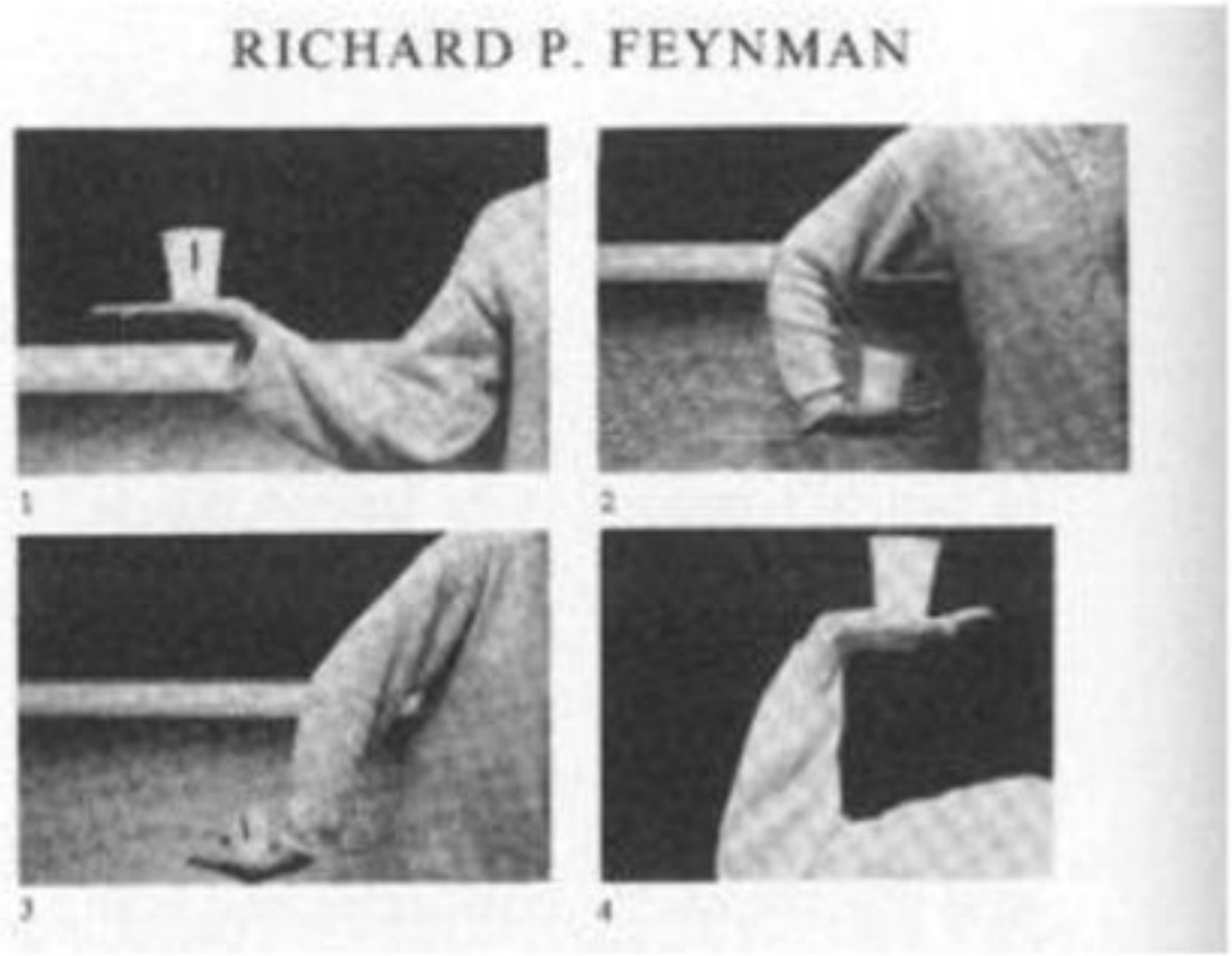
$$\Lambda_e(\gamma) = \left\| \begin{matrix} 1 & 0 & 0 & 0 \\ 0 & 1 & \gamma & \gamma \\ 0 & -\gamma & 1 - \frac{1}{2}\gamma^2 & -\frac{1}{2}\gamma^2 \\ 0 & \gamma & \frac{1}{2}\gamma^2 & 1 + \frac{1}{2}\gamma^2 \end{matrix} \right\|$$

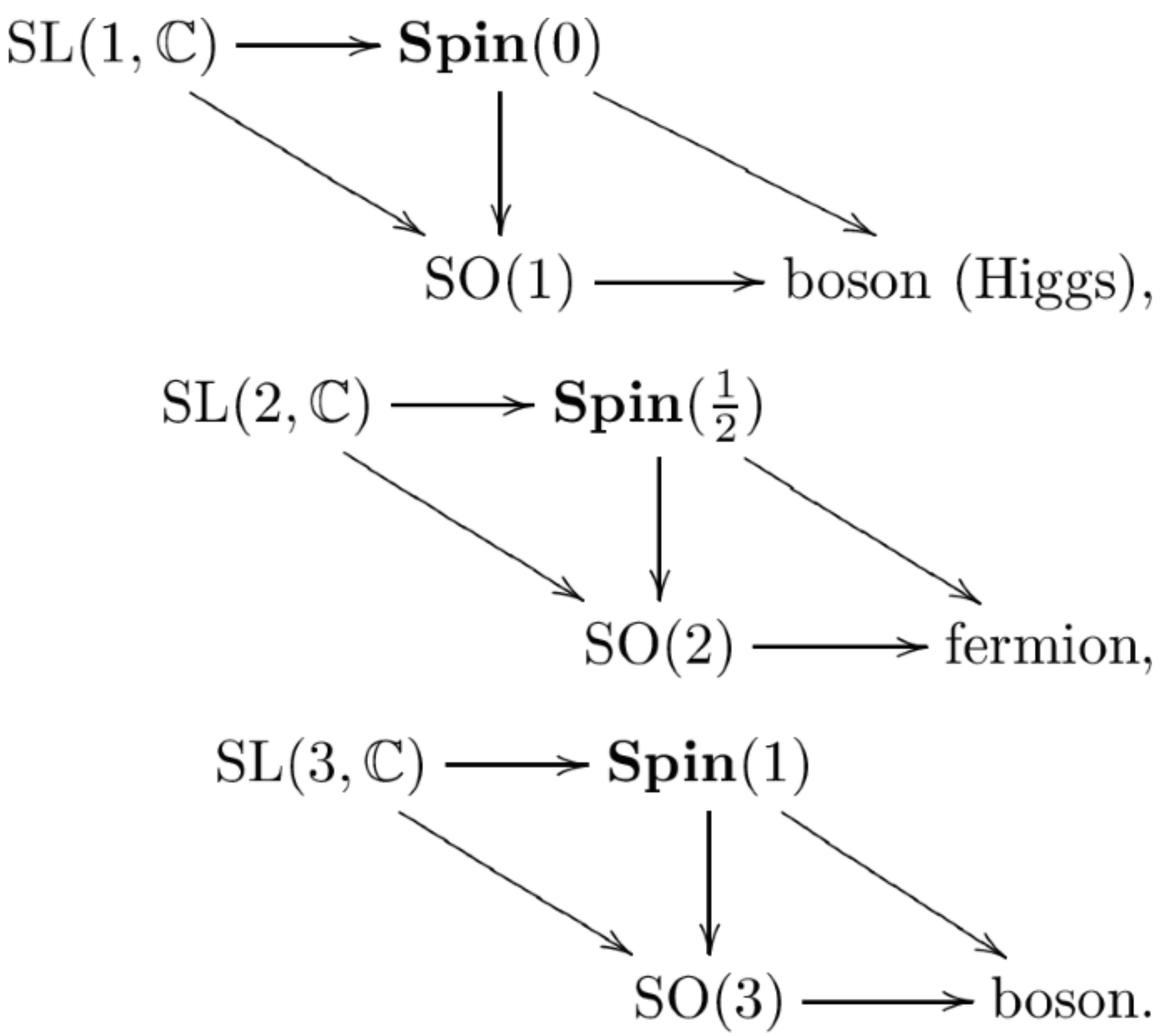
Organizing Particles : Use Spin to group them

Spin operator

$$\Psi(s_n+\theta_0) = e^{i\theta_0 s.n/\hbar}\,\Psi(s_n), \quad s = \hbar\sigma/2$$

$$R(\theta) = e^{i\theta_0 s/\hbar}$$





Spin-Statistics theorem

$\frac{1}{2}$ integer spins are fermions

$$R(2\pi) = -1$$

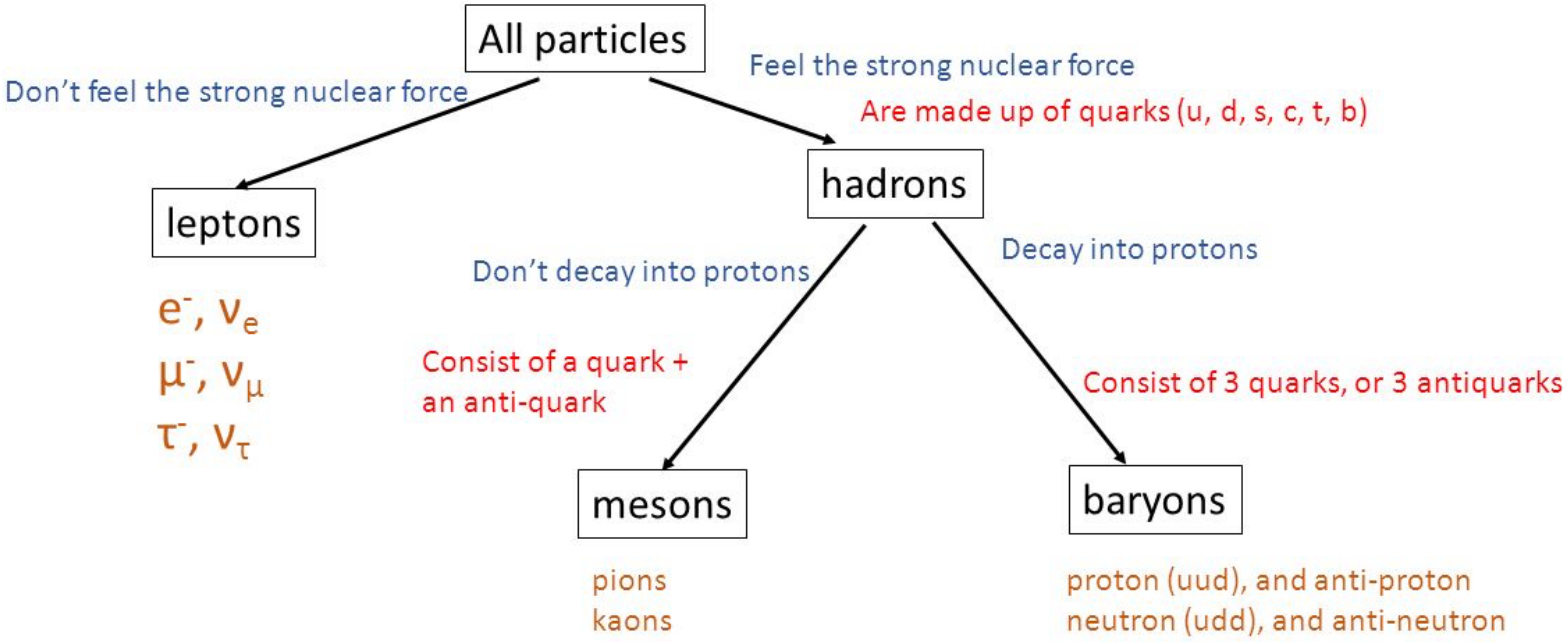
$$\Psi(1,2) = -\Psi(2,1)$$

Integer spins are bosons (including s = 0)

$$R(2\pi) = 1$$

$$\Psi(1,2) = \Psi(2,1)$$

Organizing Particles : Hadrons and Leptons



Hadron "zoo"

mesons

LIGHT UNFLAVORED ($S = C = B = 0$)

	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^{\pm}$	$1^-(0^-)$	• $\phi(1680)$	$0^-(1^{--})$
• π^0	$1^-(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• η	$0^+(0^{-+})$	• $\rho(1700)$	$1^+(1^{--})$
• $f_0(600)$	$0^+(0^{++})$	$a_2(1700)$	$1^-(2^{++})$
• $\rho(770)$	$1^+(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\omega(782)$	$0^-(1^{--})$	$\eta(1760)$	$0^+(0^{-+})$
• $\eta'(958)$	$0^+(0^{-+})$	• $\pi(1800)$	$1^-(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	$f_2(1810)$	$0^+(2^{++})$
• $a_0(980)$	$1^-(0^{++})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $\phi(1020)$	$0^-(1^{--})$	$\eta_2(1870)$	$0^+(2^{-+})$
• $h_1(1170)$	$0^-(1^{+-})$	$\rho(1900)$	$1^+(1^{--})$
• $b_1(1235)$	$1^+(1^{+-})$	$f_2(1910)$	$0^+(2^{++})$
• $a_1(1260)$	$1^-(1^{++})$	$f_2(1950)$	$0^+(2^{++})$
• $f_2(1270)$	$0^+(2^{++})$	$\rho_3(1990)$	$1^+(3^{--})$
• $f_1(1285)$	$0^+(1^{++})$	$X(2000)$	$1^-(?^{?+})$
• $\eta(1295)$	$0^+(0^{-+})$	• $f_2(2010)$	$0^+(2^{++})$
• $\pi(1300)$	$1^-(0^{-+})$	$f_0(2020)$	$0^+(0^{++})$
• $a_2(1320)$	$1^-(2^{++})$	• $a_4(2040)$	$1^-(4^{++})$
• $f_0(1370)$	$0^+(0^{++})$	• $f_4(2050)$	$0^+(4^{++})$
$h_1(1380)$	$?^-(1^{+-})$	$\pi_2(2100)$	$1^-(2^{-+})$
$\pi_1(1400)$	$1^-(1^{-+})$	$f_0(2100)$	$0^+(0^{++})$
• $f_1(1420)$	$0^+(1^{++})$	$f_2(2150)$	$0^+(2^{++})$
• $\omega(1420)$	$0^-(1^{--})$	$\rho(2150)$	$1^+(1^{--})$
$f_2(1430)$	$0^+(2^{++})$	$f_0(2200)$	$0^+(0^{++})$
• $\eta(1440)$	$0^+(0^{-+})$	$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
• $a_0(1450)$	$1^-(0^{++})$	$\eta(2225)$	$0^+(0^{-+})$
• $\rho(1450)$	$1^+(1^{--})$	$\rho_3(2250)$	$1^+(3^{--})$
• $f_0(1500)$	$0^+(0^{++})$	• $f_2(2300)$	$0^+(2^{++})$
$f_1(1510)$	$0^+(1^{++})$	$f_4(2300)$	$0^+(4^{++})$
• $f_2'(1525)$	$0^+(2^{++})$	$f_0(2330)$	$0^+(0^{++})$
$f_2(1565)$	$0^+(2^{++})$	• $f_2(2340)$	$0^+(2^{++})$
$h_1(1595)$	$0^-(1^{+-})$	$\rho_5(2350)$	$1^+(5^{--})$
$\pi_1(1600)$	$1^-(1^{-+})$	$a_6(2450)$	$1^-(6^{++})$
$X(1600)$	$2^+(2^{++})$	$f_6(2510)$	$0^+(6^{++})$
$a_1(1640)$	$1^+(1^{++})$	**OTHER LIGHT UNFLAVORED** ($S = C = B = 0$)	
$f_2(1640)$	$0^+(2^{++})$	Further States	
$\eta_2(1645)$	$0^+(2^{-+})$		
• $\omega(1650)$	$0^-(1^{--})$		
• $\omega_3(1670)$	$0^-(3^{--})$		
• $\pi_2(1670)$	$1^-(2^{-+})$		

STRANGE ($S = \pm1$, $C = B = 0$)

	$I(J^P)$
• $K^{\pm}$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K^0_S	$1/2(0^-)$
• K^0_L	$1/2(0^-)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K^*_0(1430)$	$1/2(0^+)$
• $K^*_2(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K^*_3(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K^*_0(1950)$	$1/2(0^+)$
$K^*_2(1980)$	$1/2(2^+)$
• $K^*_4(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K^*_5(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED ($C = \pm1$)

• $D^{\pm}$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^{\pm}$	$1/2(1^-)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^{\pm}$	$1/2(?^?)$
• $D^*_2(2460)^0$	$1/2(2^+)$
• $D^*_2(2460)^+$	$1/2(2^+)$
$D^*(2640)^{\pm}$	$1/2(?^?)$

CHARMED, STRANGE ($C = S = \pm1$)

• $D_s^{\pm}$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s1}(2536)^{\pm}$	$0(1^+)$
• $D_{sJ}(2573)^{\pm}$	$0(?^?)$

BOTTOM ($B = \pm1$)

	$I^G(J^{PC})$
• $B^{\pm}$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^{\pm}/B^0$ ADMIXTURE	
• $B^{\pm}/B^0/B^0_s/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
$B^*_J(5732)$	$?(?^?)$

BOTTOM, STRANGE ($B = \pm1$, $S = \mp1$)

• B^0_s	$0(0^-)$
B^*_s	$0(1^-)$
$B^*_{sJ}(5850)$	$?(?^?)$

BOTTOM, CHARMED ($B = C = \pm1$)

• $B_c^{\pm}$	$0(0^-)$

$c\bar{c}$

• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
$h_c(1P)$	$?^?(?^{??})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
$\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
$\psi(3836)$	$0^-(2^{--})$
• $\psi(4040)$	$0^-(1^{--})$
• $\psi(4160)$	$0^-(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$

$b\bar{b}$

$\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\Upsilon(4S)$	$0^-(1^{--})$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

baryons

p	P_{11}	****
n	P_{11}	****
$N(1440)$	P_{11}	****
$N(1520)$	D_{13}	****
$N(1535)$	S_{11}	****
$N(1650)$	S_{11}	****
$N(1675)$	D_{15}	****
$N(1680)$	F_{15}	****
$N(1700)$	D_{13}	***
$N(1710)$	P_{11}	***
$N(1720)$	P_{13}	****
$N(1900)$	P_{13}	**
$N(1990)$	F_{17}	**
$N(2000)$	F_{15}	**
$N(2080)$	D_{13}	**
$N(2090)$	S_{11}	*
$N(2100)$	P_{11}	*
$N(2190)$	G_{17}	****
$N(2200)$	D_{15}	**
$N(2220)$	H_{19}	****
$N(2250)$	G_{19}	****
$N(2600)$	$I_{1,11}$	***
$N(2700)$	$K_{1,13}$	**

$\Delta(1232)$	P_{33}	****
$\Delta(1600)$	P_{33}	***
$\Delta(1620)$	S_{31}	****
$\Delta(1700)$	D_{33}	****
$\Delta(1750)$	P_{31}	*
$\Delta(1900)$	S_{31}	**
$\Delta(1905)$	F_{35}	****
$\Delta(1910)$	P_{31}	****
$\Delta(1920)$	P_{33}	***
$\Delta(1930)$	D_{35}	***
$\Delta(1940)$	D_{33}	*
$\Delta(1950)$	F_{37}	****
$\Delta(2000)$	F_{35}	**
$\Delta(2150)$	S_{31}	*
$\Delta(2200)$	G_{37}	*
$\Delta(2300)$	H_{39}	**
$\Delta(2350)$	D_{35}	*
$\Delta(2390)$	F_{37}	*
$\Delta(2400)$	G_{39}	**
$\Delta(2420)$	$H_{3,11}$	****
$\Delta(2750)$	$I_{3,13}$	**
$\Delta(2950)$	$K_{3,15}$	**

Λ	P_{01}	****
$\Lambda(1405)$	S_{01}	****
$\Lambda(1520)$	D_{03}	****
$\Lambda(1600)$	P_{01}	***
$\Lambda(1670)$	S_{01}	****
$\Lambda(1690)$	D_{03}	****
$\Lambda(1800)$	S_{01}	***
$\Lambda(1810)$	P_{01}	***
$\Lambda(1820)$	F_{05}	****
$\Lambda(1830)$	D_{05}	****
$\Lambda(1890)$	P_{03}	****
$\Lambda(2000)$		*
$\Lambda(2020)$	F_{07}	*
$\Lambda(2100)$	G_{07}	****
$\Lambda(2110)$	F_{05}	***
$\Lambda(2325)$	D_{03}	*
$\Lambda(2350)$	H_{09}	***
$\Lambda(2585)$		**

Σ^+	P_{11}	****
Σ^0	P_{11}	****
Σ^-	P_{11}	****
$\Sigma(1385)$	P_{13}	****
$\Sigma(1480)$		*
$\Sigma(1560)$		**
$\Sigma(1580)$	D_{13}	**
$\Sigma(1620)$	S_{11}	**
$\Sigma(1660)$	P_{11}	***
$\Sigma(1670)$	D_{13}	****
$\Sigma(1690)$		**
$\Sigma(1750)$	S_{11}	***
$\Sigma(1770)$	P_{11}	*
$\Sigma(1775)$	D_{15}	****
$\Sigma(1840)$	P_{13}	*
$\Sigma(1880)$	P_{11}	**
$\Sigma(1915)$	F_{15}	****
$\Sigma(1940)$	D_{13}	***
$\Sigma(2000)$	S_{11}	*
$\Sigma(2030)$	F_{17}	****
$\Sigma(2070)$	F_{15}	*
$\Sigma(2080)$	P_{13}	**
$\Sigma(2100)$	G_{17}	*
$\Sigma(2250)$		***
$\Sigma(2455)$		**
$\Sigma(2620)$		**
$\Sigma(3000)$		*
$\Sigma(3170)$		*

Ξ^0, Ξ^-	P_{11}	****
$\Xi(1530)$	P_{13}	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	D_{13}	***
$\Xi(1950)$		***
$\Xi(2030)$		***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-		****
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**
Λ_c^+		****
$\Lambda_c(2593)^+$		***
$\Lambda_c(2625)^+$		***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2880)^+$		**
$\Sigma_c(2455)$		****
$\Sigma_c(2520)$		***
Ξ_c^+, Ξ_c^0		***
$\Xi_c'^+$, $\Xi_c'^0$		***
$\Xi_c(2645)$		***
$\Xi_c(2790)$		***
$\Xi_c(2815)$		***
Ω_c^0		***
Λ_b^0		***
Ξ_b^0, Ξ_b^-		*

Organizing Particles : Family and Friends

Organizing particles and forces together

1. Photons carry Electromagnetism and interact with charged particles

It is described at a classical level by Maxwell's Equation and by a

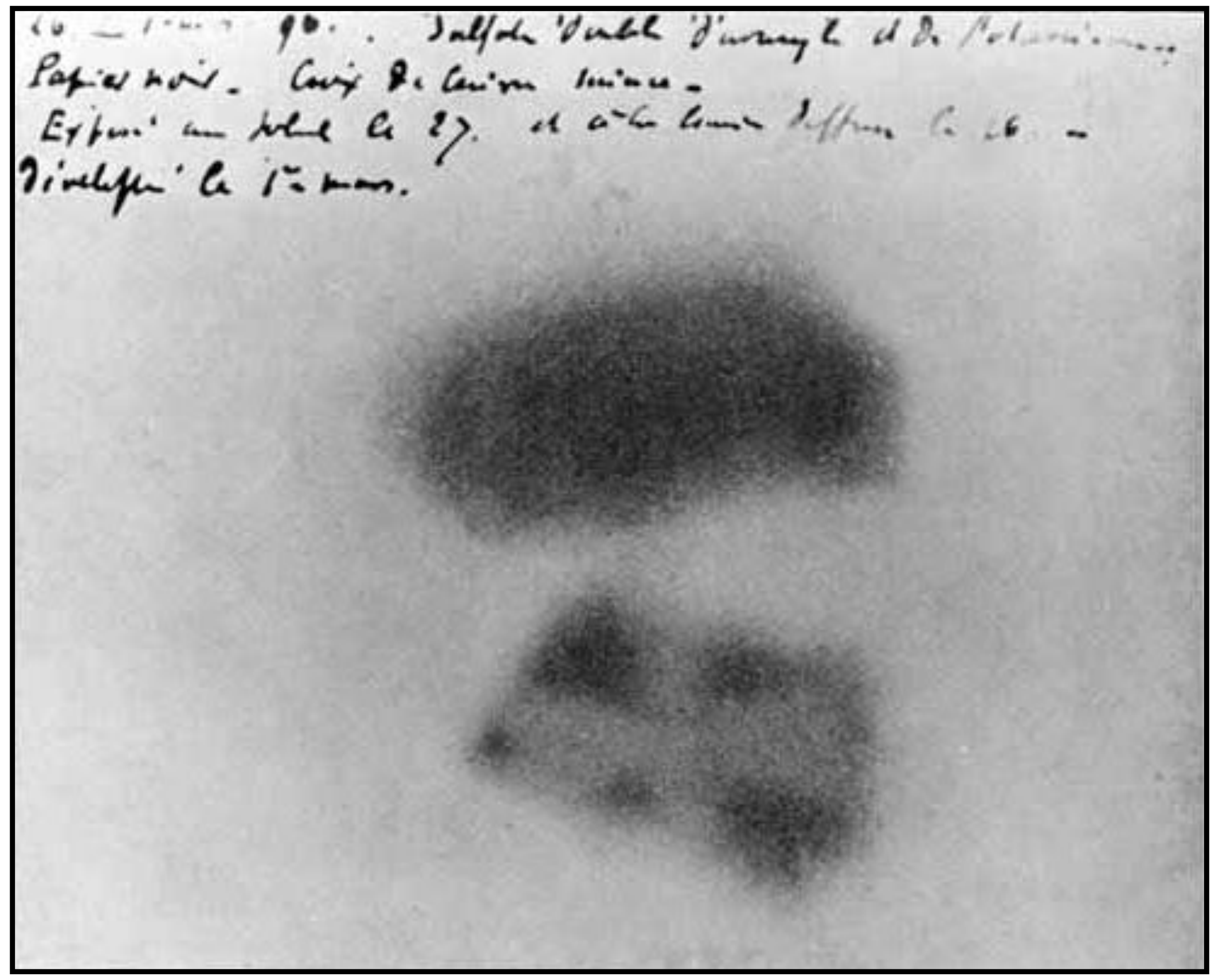
Spin-1 bosonic field invariant under a phase (U(1)) transformation.

2. Massive Gauge Bosons are responsible for the weak force, interacts with

'Left-handed' Particles of the Universe. Invariant under rotations of a 2-sphere (SU(2)).

3. Gluons are responsible for carrying the strong force and interact with quarks and themselves.

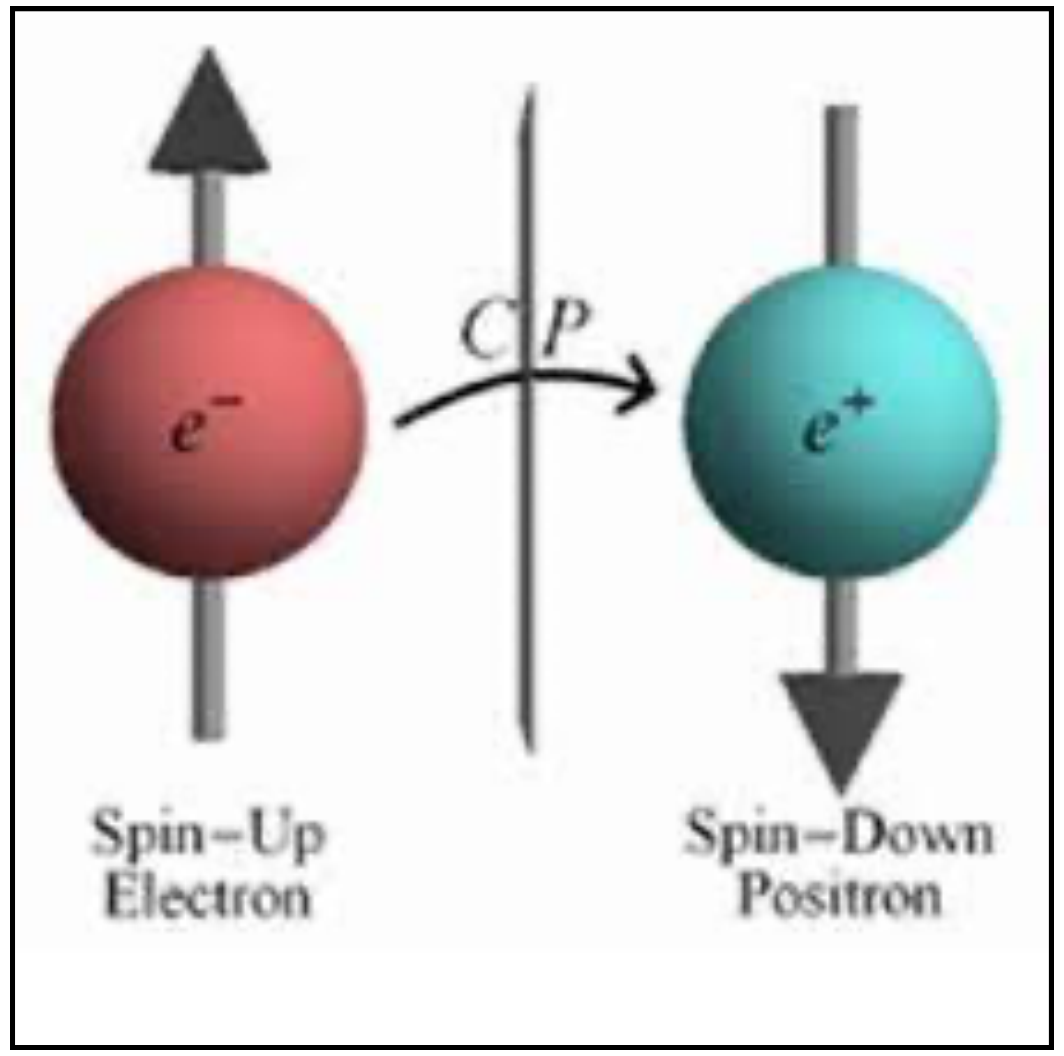
The Electroweak Theory : Unification of Weak and EM forces



Weak Interactions : Curie/Becquerel to Fermi

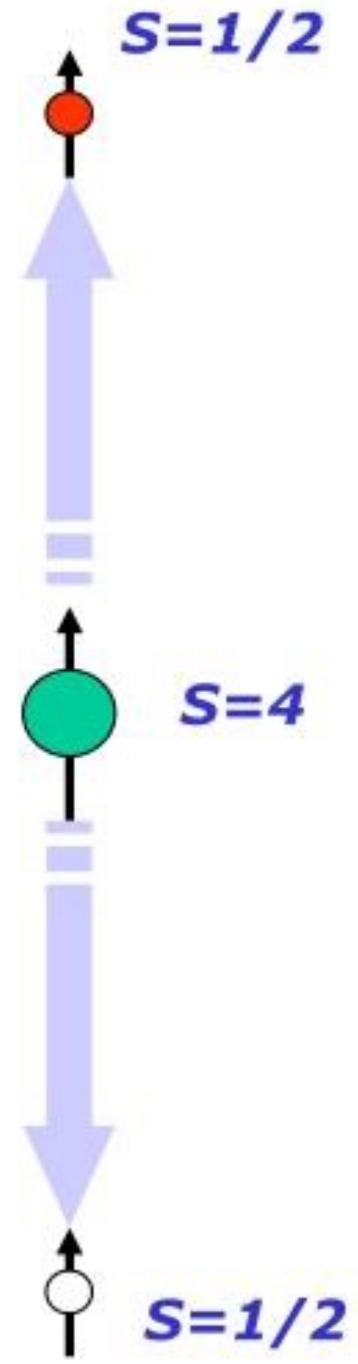
- Becquerel 1896 : discovered uranium salts spontaneously emit radiation
- that could be captured on plates.
- Marie/Pierre Curie 18989-1910 : New Radioactive elements
- Fermi theory 1933 : Beta decay can be explained by four fermi contact interactions mediated by a force without range
- 1954 : Yang and Lee suggested that weak interactions violate Charge and Parity
- 1957 : Wu experimentally confirmed symmetry violation

A realistic experiment: the Wu experiment (1956)



- Observe radioactive decay of Cobalt-60 nuclei
  - The process involved: ${}^{60}_{27}Co \rightarrow {}^{60}_{28}Ni + e^- + \overline{\nu_e}$
  - **${}^{60}_{27}Co$ is spin-5 and ${}^{60}_{28}Ni$ is spin-4, both e- and ν_e are spin-½**
  - If you start with fully polarized Co (S_Z=5) the experiment is essentially the same (i.e. there is only one spin solution for the decay)

|5,+5> → |4,+4> + |½ ,+½> + |½,+½>

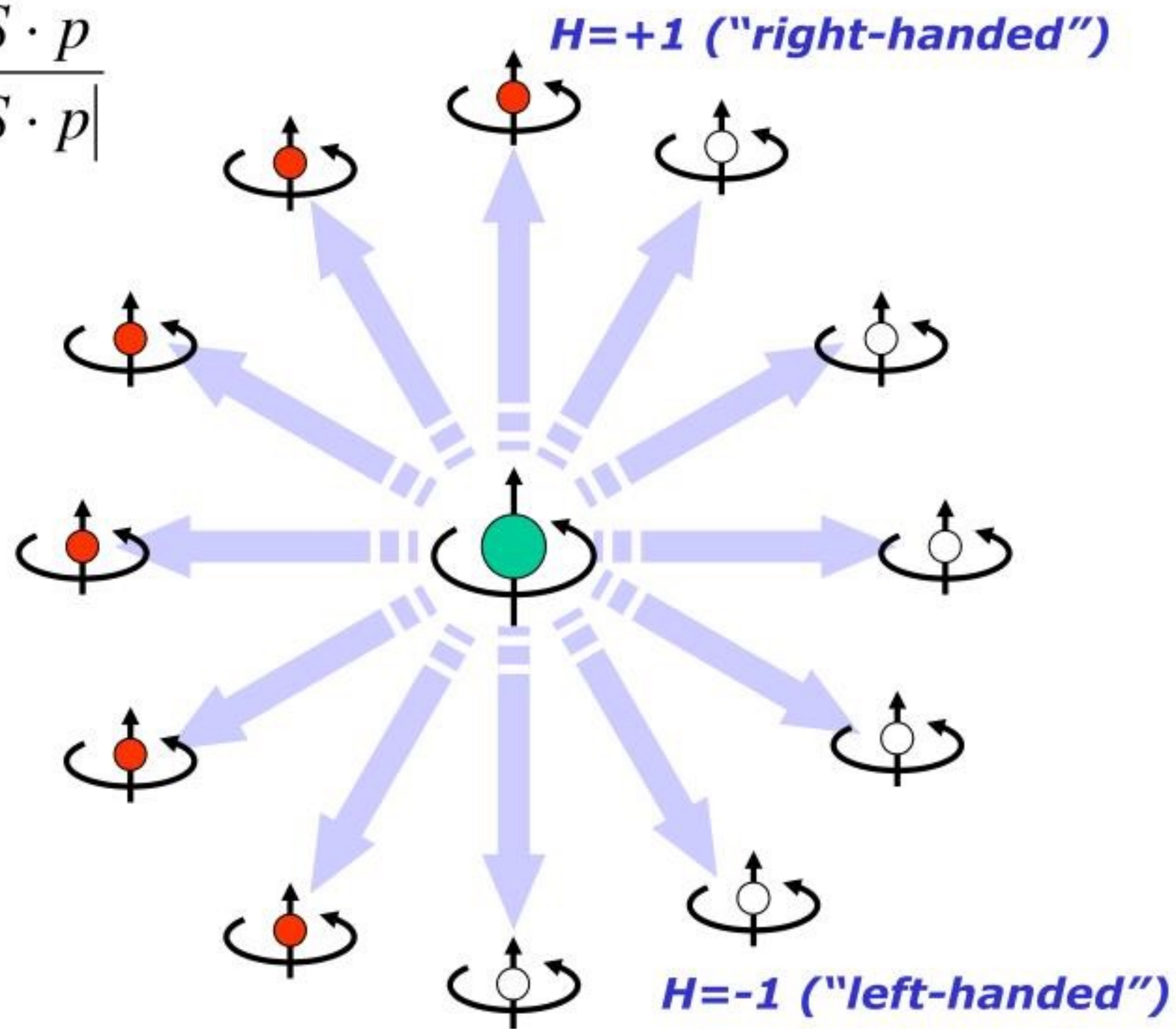


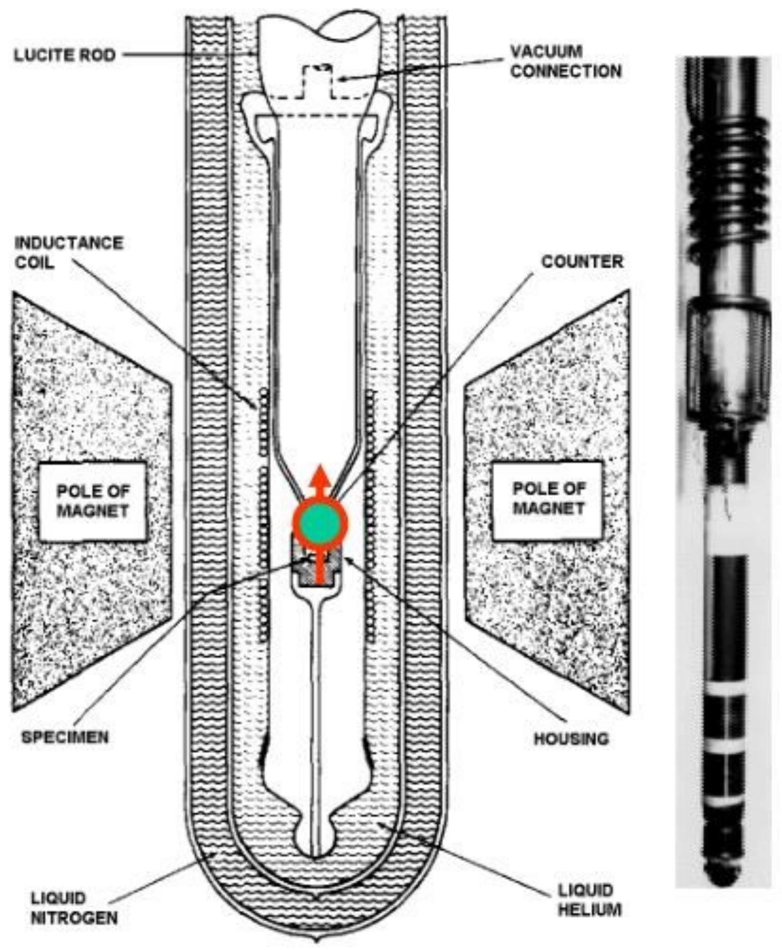
- We introduce a new quantity: Helicity = the projection of the spin on the direction of flight of a particle

$$H \equiv \frac{S \cdot p}{|S \cdot p|}$$

The making of Standard Model : C and P violation in weak interactions

$$H \equiv \frac{S \cdot p}{|S \cdot p|}$$





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)

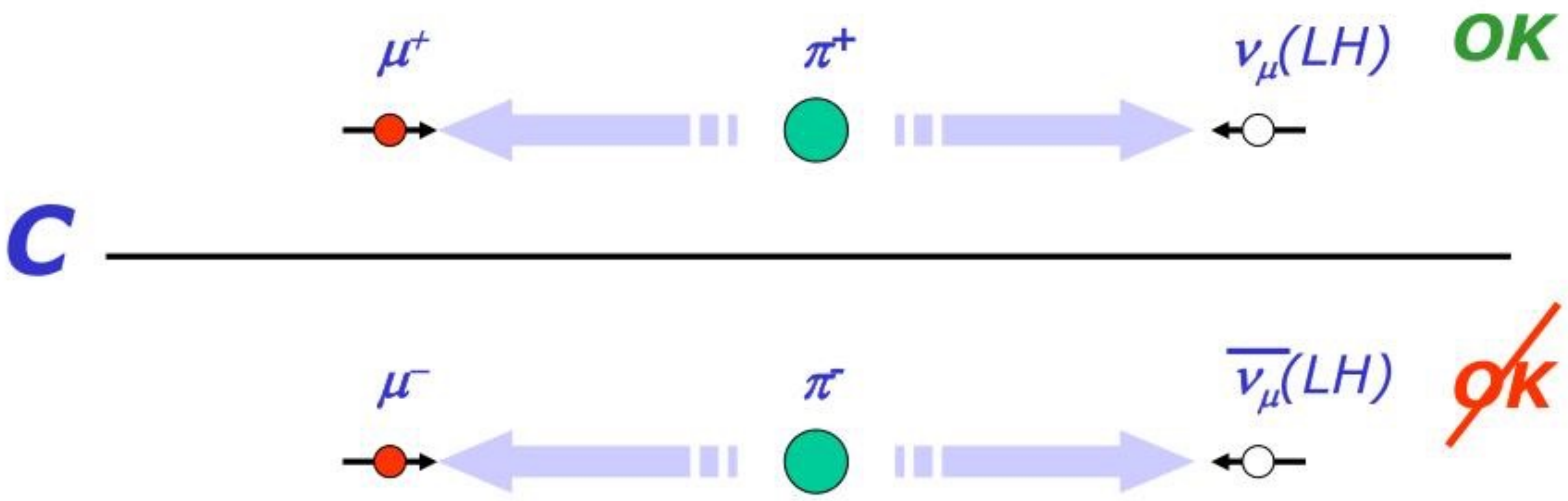
- The surprising result: the counting rate is different
  - **Electrons are preferentially emitted in direction opposite of ^{60}Co spin!**
  - Careful analysis of results shows that experimental data is consistent with emission of left-handed (H=-1) electrons only at any angle!!

- Physics conclusion:
  - Angular distribution of electrons shows that only pairs of left-handed electrons / right-handed anti-neutrinos are emitted regardless of the emission angle
  - Since right-handed electrons are known to exist (for electrons H is not Lorentz-invariant anyway), this means **no left-handed anti-neutrinos are produced in weak decay**

- **Parity is violated in weak processes**
  - **Not just a little bit but 100%**

The making of Standard Model : C and P violation in weak interactions

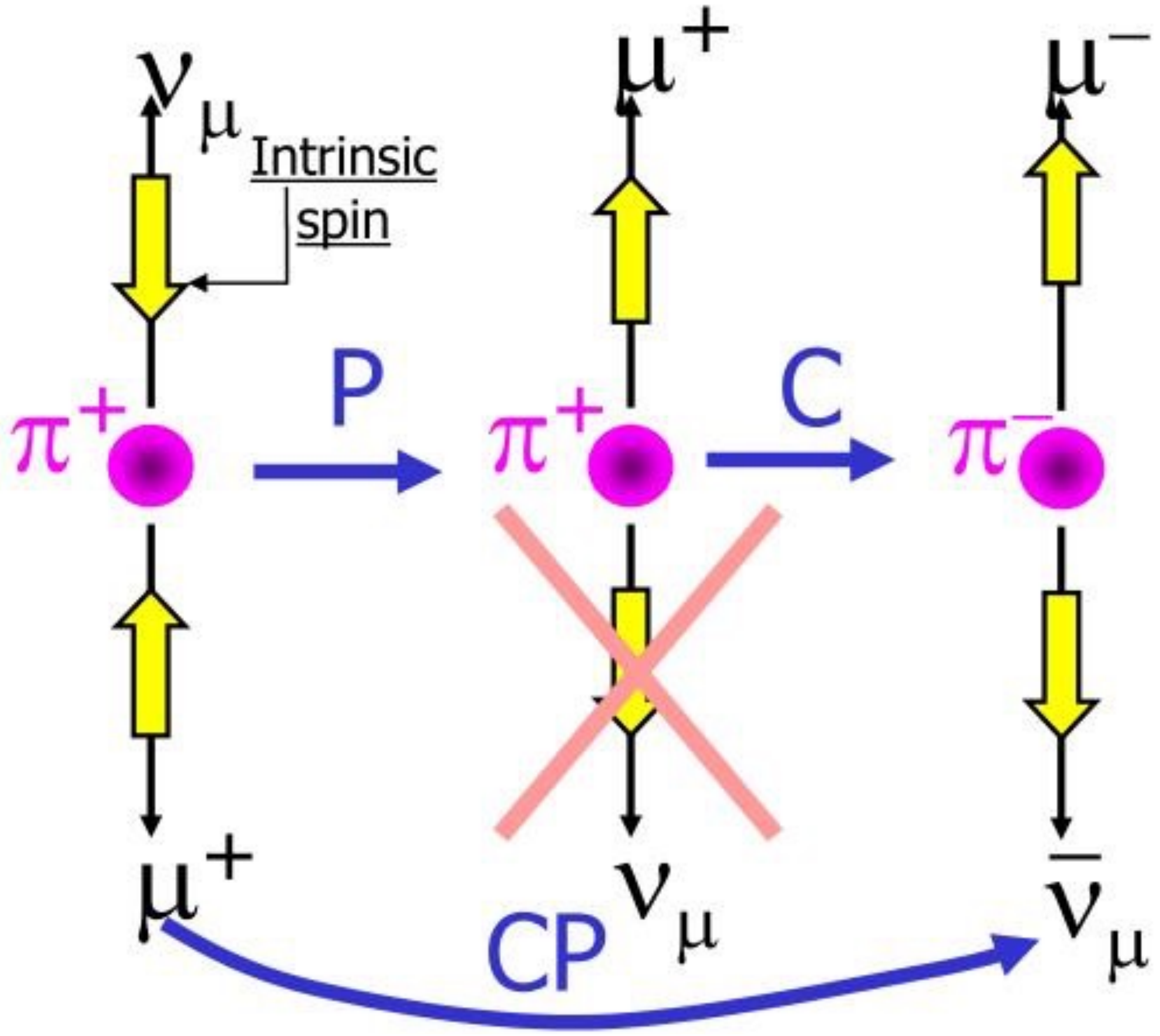
- Wu's experiment was shortly followed by another clever experiment by L. Lederman: Look at decay $\pi^+ \rightarrow \mu^+ \nu_\mu$
  - Pion has spin 0, μ,ν_μ both have spin ½
    → spin of decay products must be oppositely aligned
    → Helicity of muon is same as that of neutrino.



- Ledermans result: All neutrinos are left-handed and all anti-neutrinos are right-handed

- C symmetry is broken by the weak interaction,
  - just like P

- What about C+P ≡ CP symmetry?
  - CP symmetry is parity conjugation (x,y,z → -x,-y,z) followed by charge conjugation ($X \rightarrow \overline{X}$)

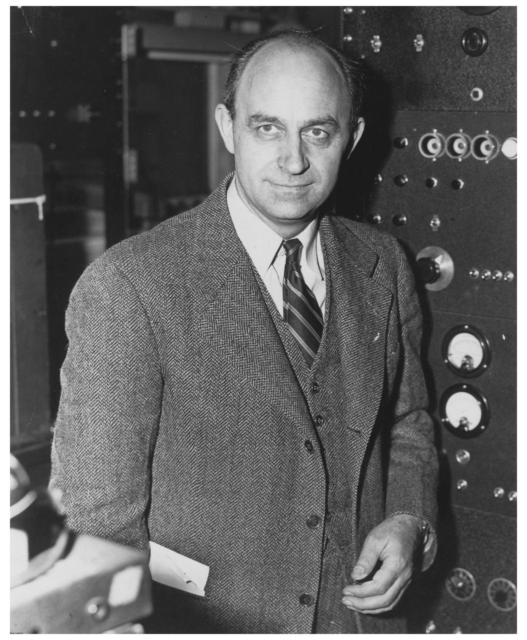


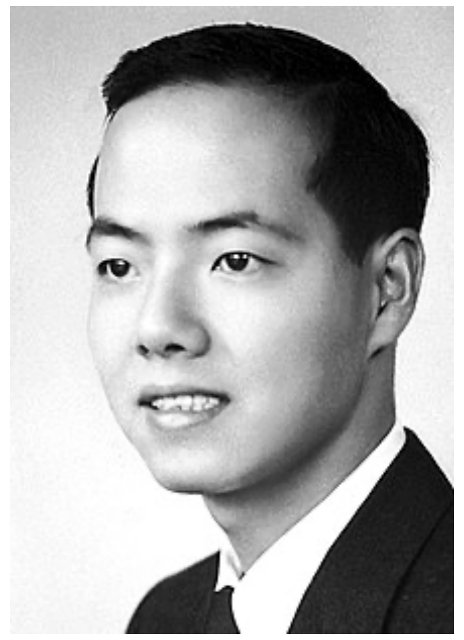
CP appears to be preserved in weak interaction!

The Electroweak SU(2) X U(1) Theory

- Bolstered by the success of quantizing Electrodynamics (QED) in 1940's, the stock of early QFT rose a lot, and then crashed in the 1950's since 4-fermi EW interactions led to infinities in perturbation theory, i.e can't be "re-normalized"
- Early theories of strong interactions (Yukawa theory) had another problem, perturbation theory was useless. (The age of "Radial" and "Azimuthal" physicists described by Weinberg)
  - Three good ideas emerged in the 1950's: a) Quark Model (Gell-Mann, Zweig)
    b) Idea of local (gauge) symmetries (Yang-Mills)
    c) Idea of Spontaneously broken symmetry (Landau-Ginzburg-Nambu-Goldstone)
- Famously Weinberg didn't believe in quarks so he started with leptons and the problem of masses of fermions and gauge bosons

The Electroweak SU(2) X U(1) Theory

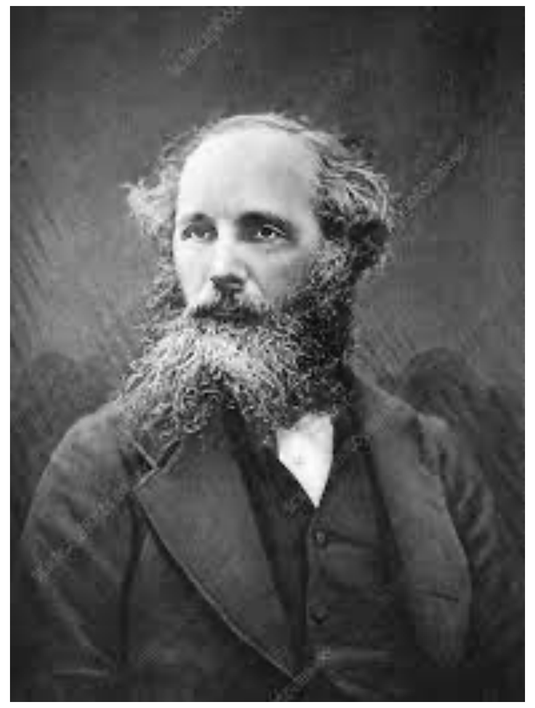



Weak Force

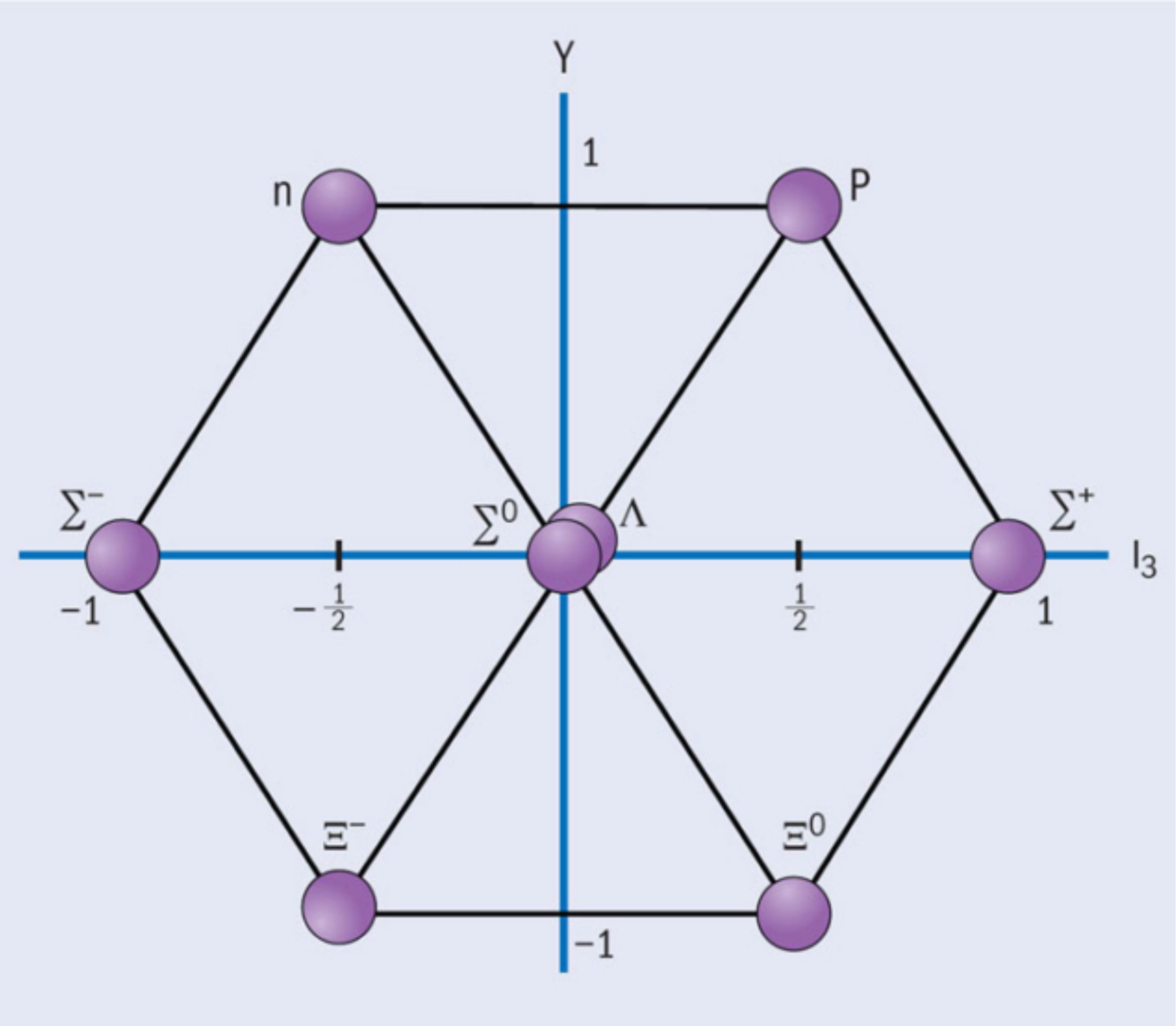
Electromagnetic Force

Unified Electroweak theory



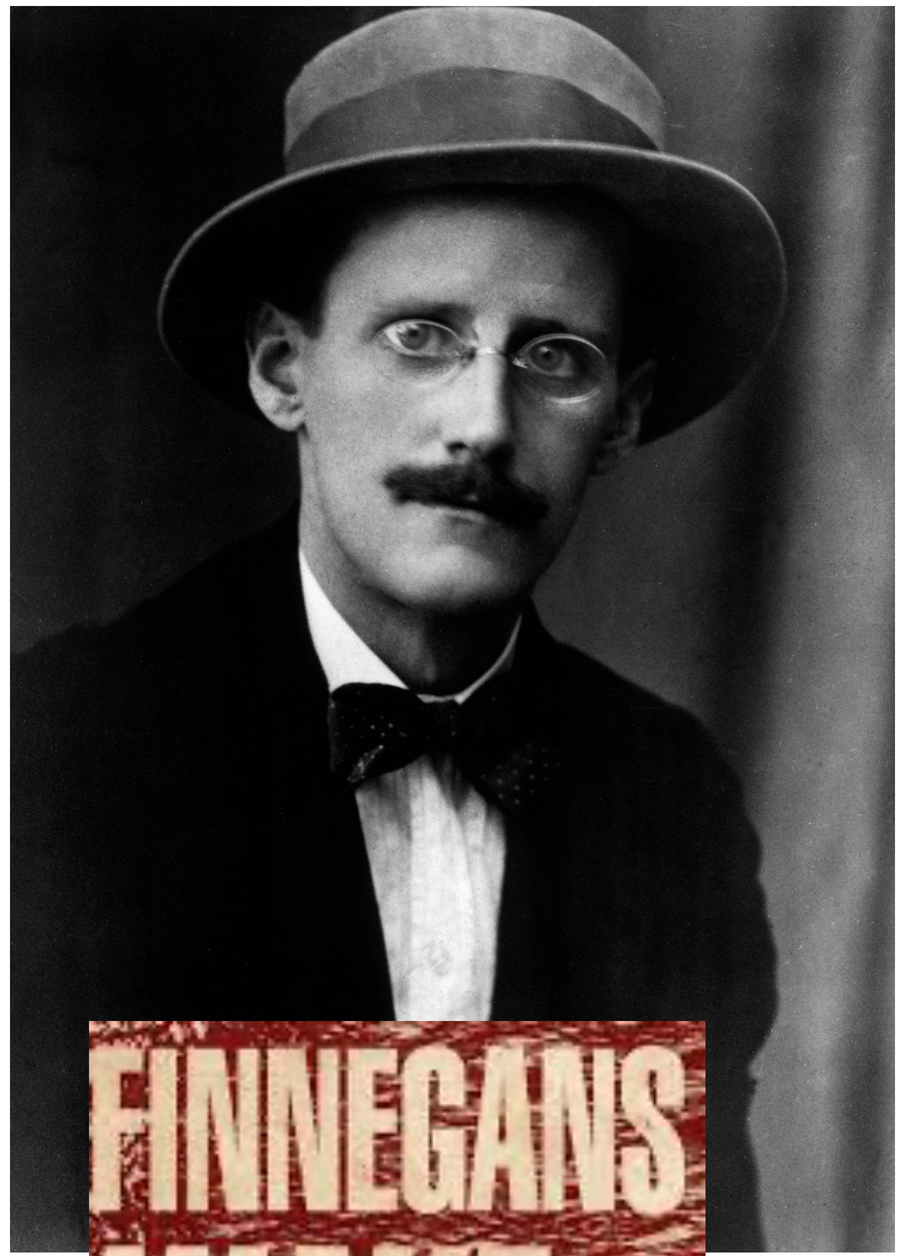


QCD and SU(3)



The 1950's and 60's were golden times for QFT. A new particle was found every second day, and fuelled by the cold war, many new accelerators and experiments came along.

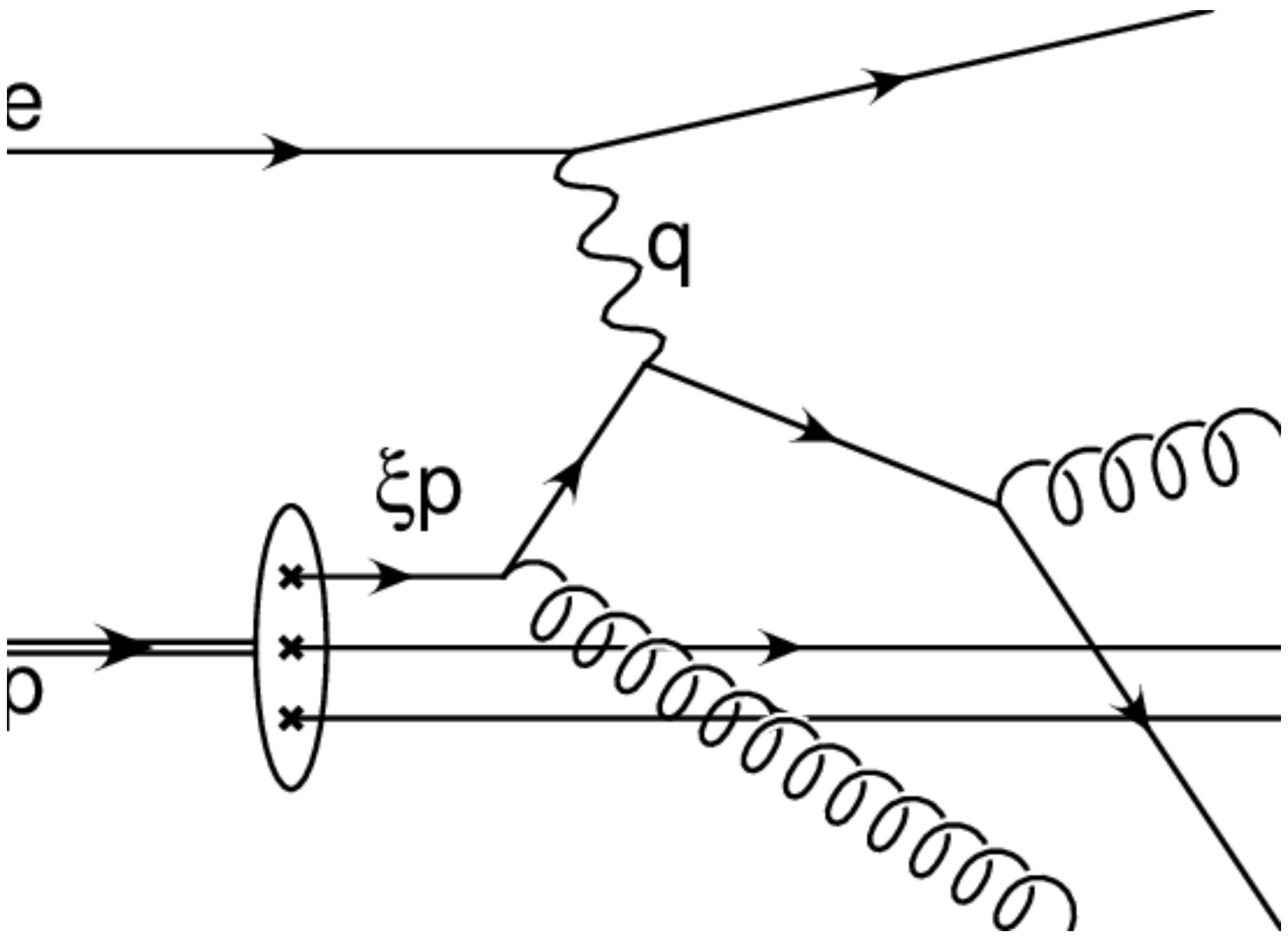
- Gell-Mann and Ne'eman (1961-62) described the octet of baryons in an SU(3) group described by 3 X 3 Unitary matrices with determinant 1. Baryons come in octets and decuplets, mesons are octets and singlets.
- Gell-Mann and Zweig (1964) proposed the quark model , stating that Baryons and Mesons are composed of fundamental particles called quarks.

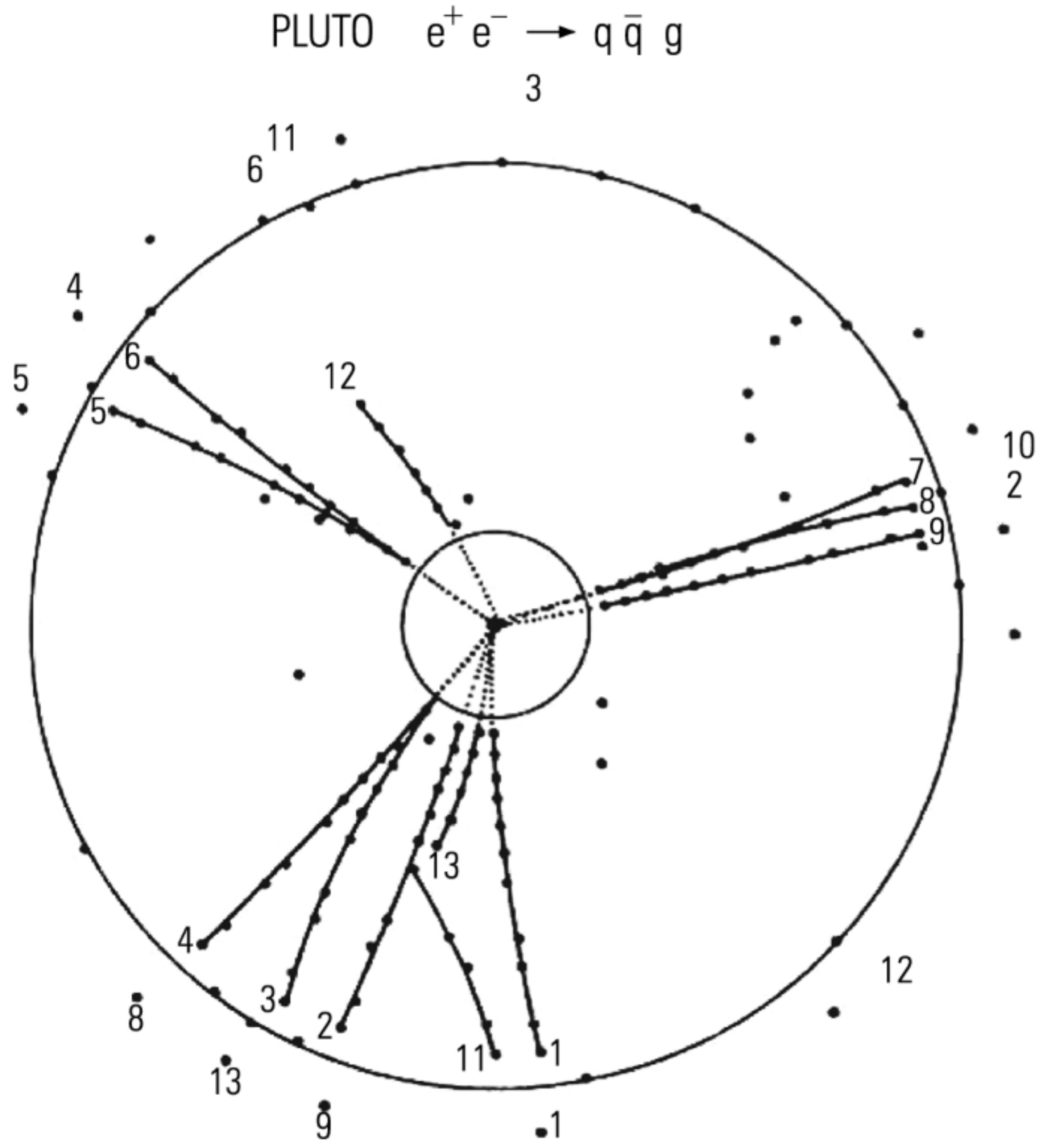


QCD and gluons

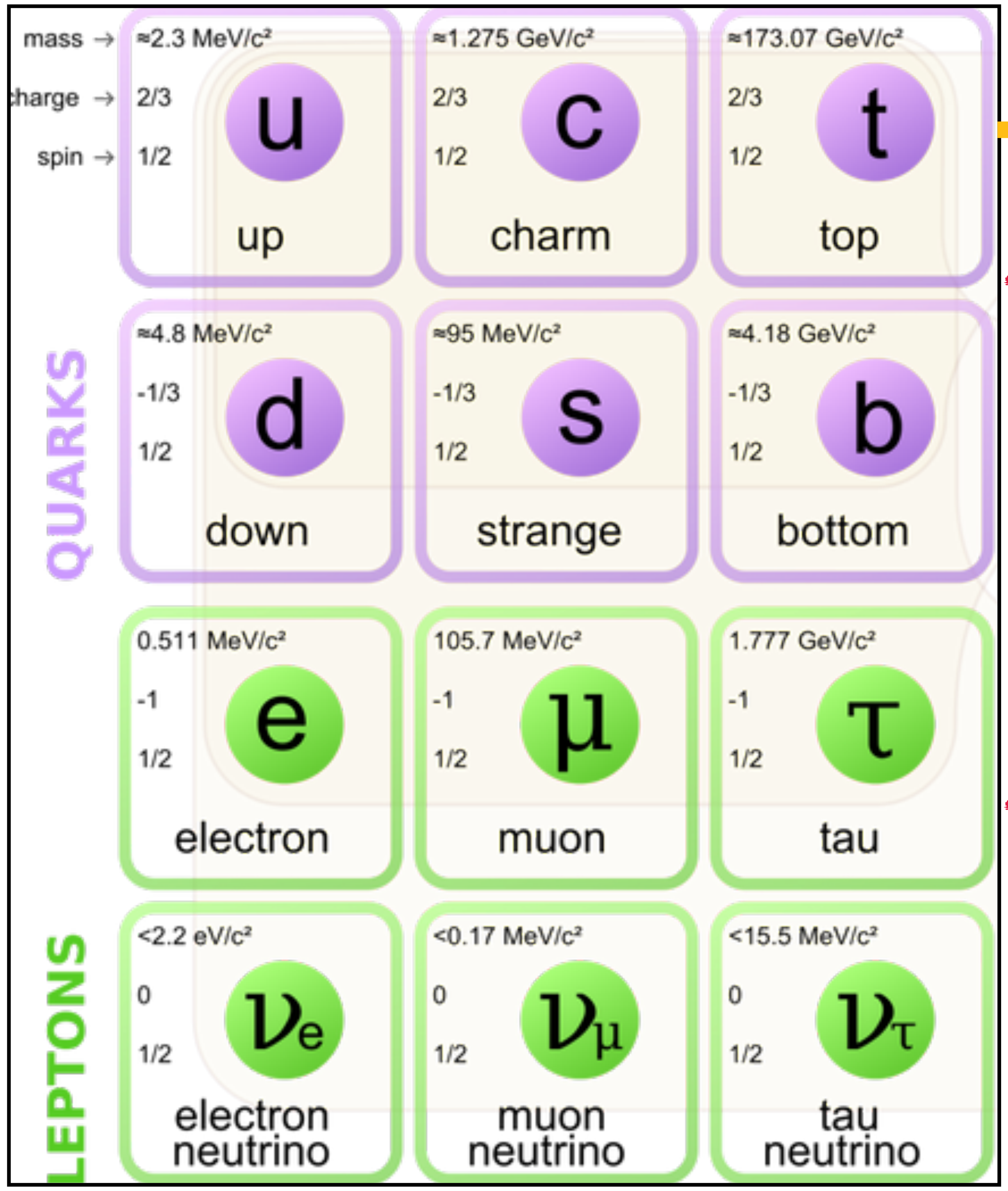
Deep Inelastic Scattering Experiments 1974 3 jet process

Confirmed gluons as the force careers of strong interactions





Standard Model of Particle Physics in a nutshell



Quarks are charged under SU(3) color. Left Handed quarks are also charged under SU(2)XU(1). Right handed quarks are charged under U(1)

8 gluons carry SU(3 force)

3 doublets of left handed fermions + 6 right handed quarks+ 3 right handed leptons

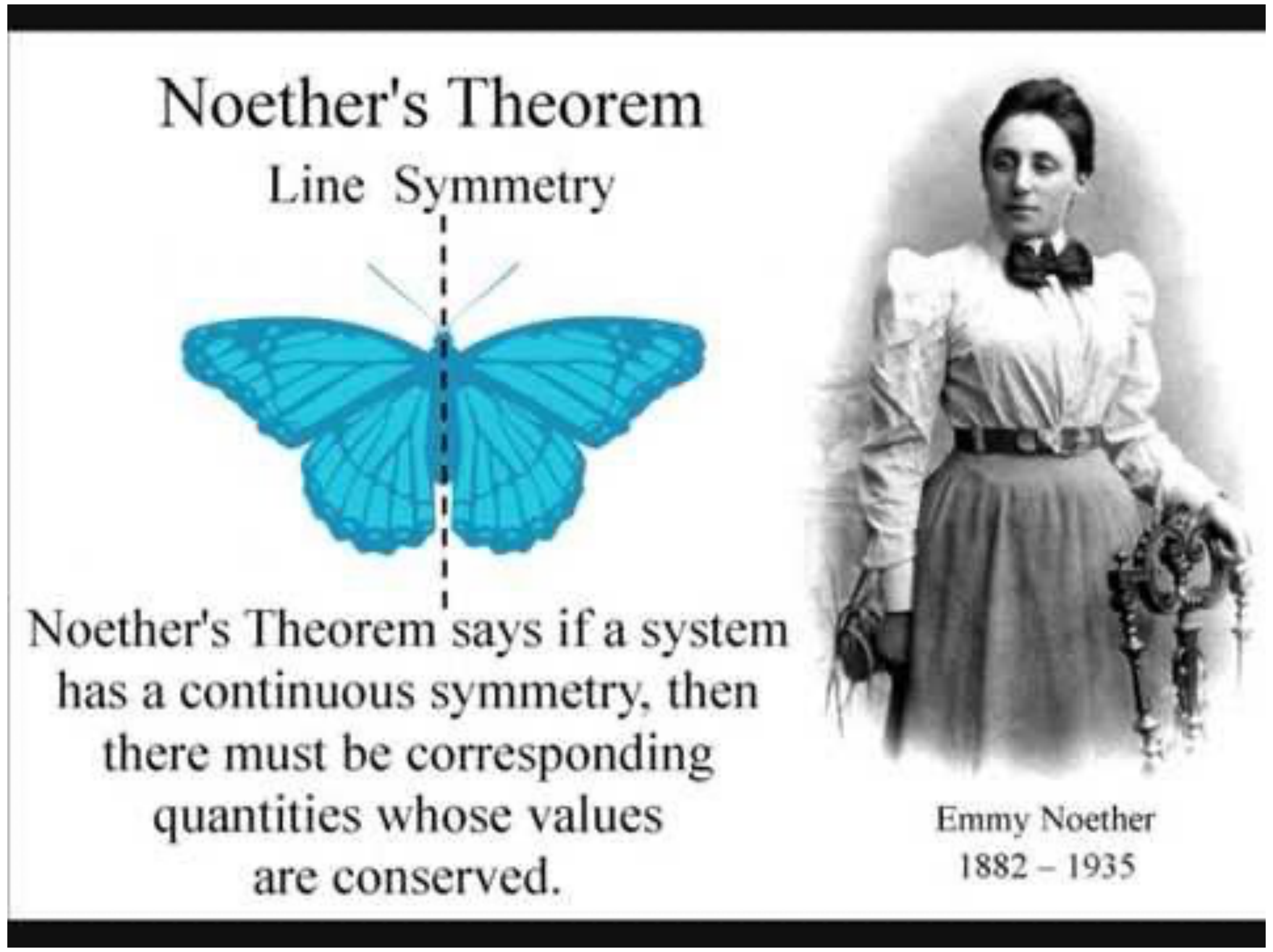
Left-handed leptons are charged under both SU(2) and U(1). Right handed leptons are charged only under U(1).

Photon and W/Z carry the EW force

No masses for Electroweak gauge bosons and fermions in unbroken SM

SU(2)XU(1) breaks to U(1) electromagnetic via Higgs mechanism

Noether's theorem and Standard Model Charges



$$T : \phi \longmapsto \phi + \Delta\phi$$

$$\& \qquad \mathcal{L} \overset{T}{\longmapsto} \mathcal{L}$$

$$\Longrightarrow \quad \boxed{\partial_\mu j^\mu = 0 \quad , \quad j^\mu = \frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi)} \Delta\phi}$$

$$\begin{aligned} Q(\nu_L) &= I_3(\nu_L) + Y/2 = \tfrac{1}{2} - \tfrac{1}{2} = 0 \\ Q(e_L^-) &= I_3(e_L^-) + Y/2 = -\tfrac{1}{2} - \tfrac{1}{2} = -1. \end{aligned}$$

Interaction mediated	Boson	Electric charge Q	Weak isospin T_3	Weak hypercharge Y_W
Weak	$W^\pm$	±1	±1	0
	Z^0	0	0	0
Electromagnetic	γ^0	0	0	0
Strong	g	0	0	0
Higgs	H^0	0	$-\frac{1}{2}$	+1

Fermion family	Left-chiral fermions				Right-chiral fermions			
		Electric charge Q	Weak isospin T_3	Weak hyper-charge Y_W		Electric charge Q	Weak isospin T_3	Weak hyper-charge Y_W
Leptons	ν_e, ν_μ, ν_τ	0	$+\frac{1}{2}$	−1	No interaction, if they even exist			0
	e^-, μ^-, τ^-	−1	$-\frac{1}{2}$	−1	e_R^-, μ_R^-, τ_R^-	−1	0	−2
Quarks	u, c, t	$+\frac{2}{3}$	$+\frac{1}{2}$	$+\frac{1}{3}$	u_R, c_R, t_R	$+\frac{2}{3}$	0	$+\frac{4}{3}$
	d, s, b	$-\frac{1}{3}$	$-\frac{1}{2}$	$+\frac{1}{3}$	d_R, s_R, b_R	$-\frac{1}{3}$	0	$-\frac{2}{3}$

Standard Model of Particle Physics in a nutshell

The problem of massive fermions

- Check $U(1)$:

> - Transformation: $\psi \to \psi' = e^{i\vartheta} \ \psi \qquad \overline{\psi} \to \overline{\psi}' = \overline{\psi} e^{-i\vartheta}$
> - In mass term : $m_\psi \overline{\psi}\psi \to m_{\psi'} \overline{\psi'}\psi' = m_\psi \overline{\psi}\psi$

- No obvious problem with fermion masses here. So is it a problem of non-abelian gauge symmetries?

- Check $SU(3)$:

  Similarly no problem in $SU(3) \to$ no problem of non-Abelian gauge field theories.

- It is the distinction between left- (ψ_L) and right-handed (e_R) fermions, with different coupling structure:

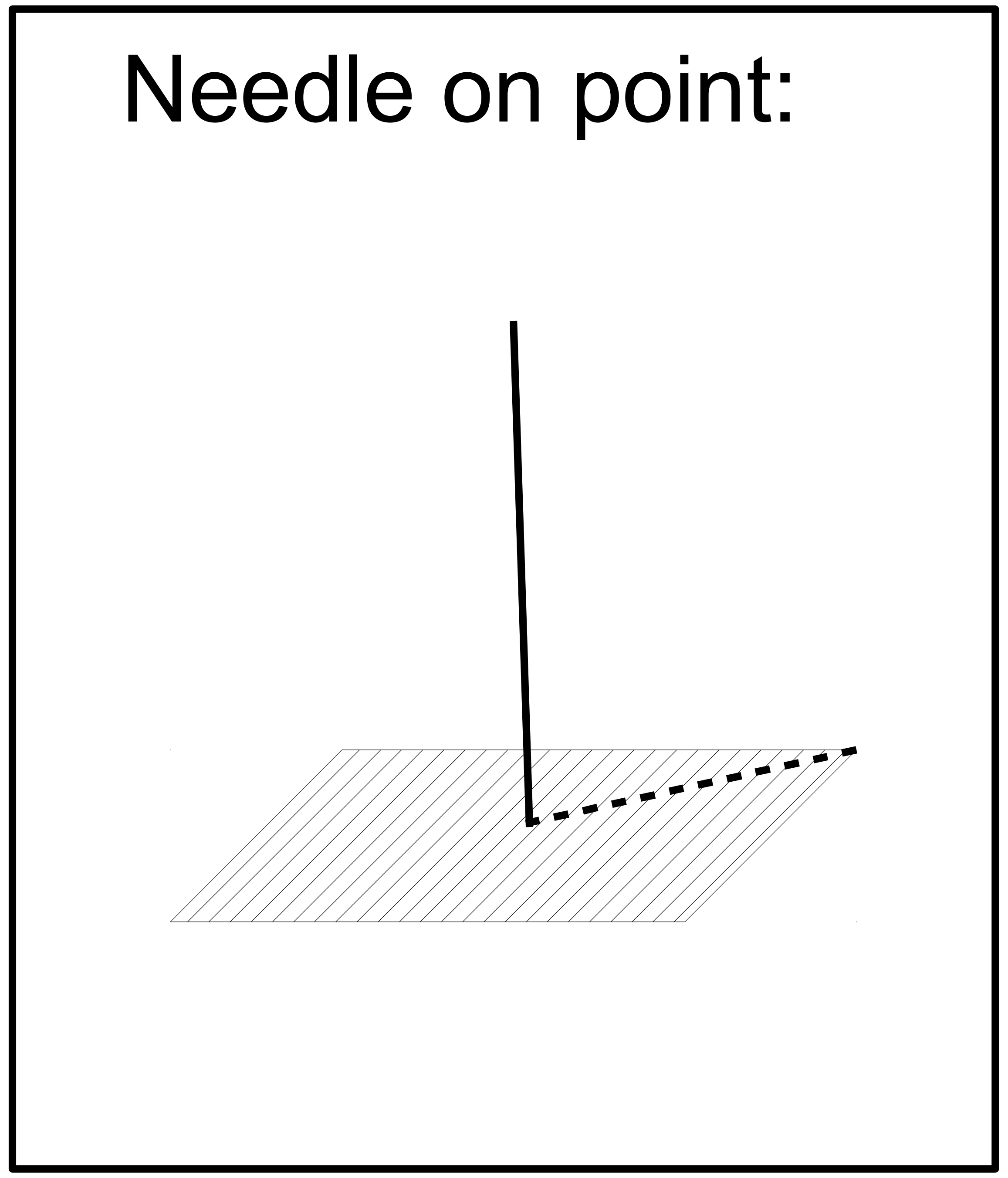
$$m_e \bar{e} e = m_e \overline{(e_L + e_R)}(e_L + e_R) = \overbrace{m_e \bar{e}_R e_L + m_e \bar{e}_L e_R}^{(1)}$$

$SU(2)$ singlet

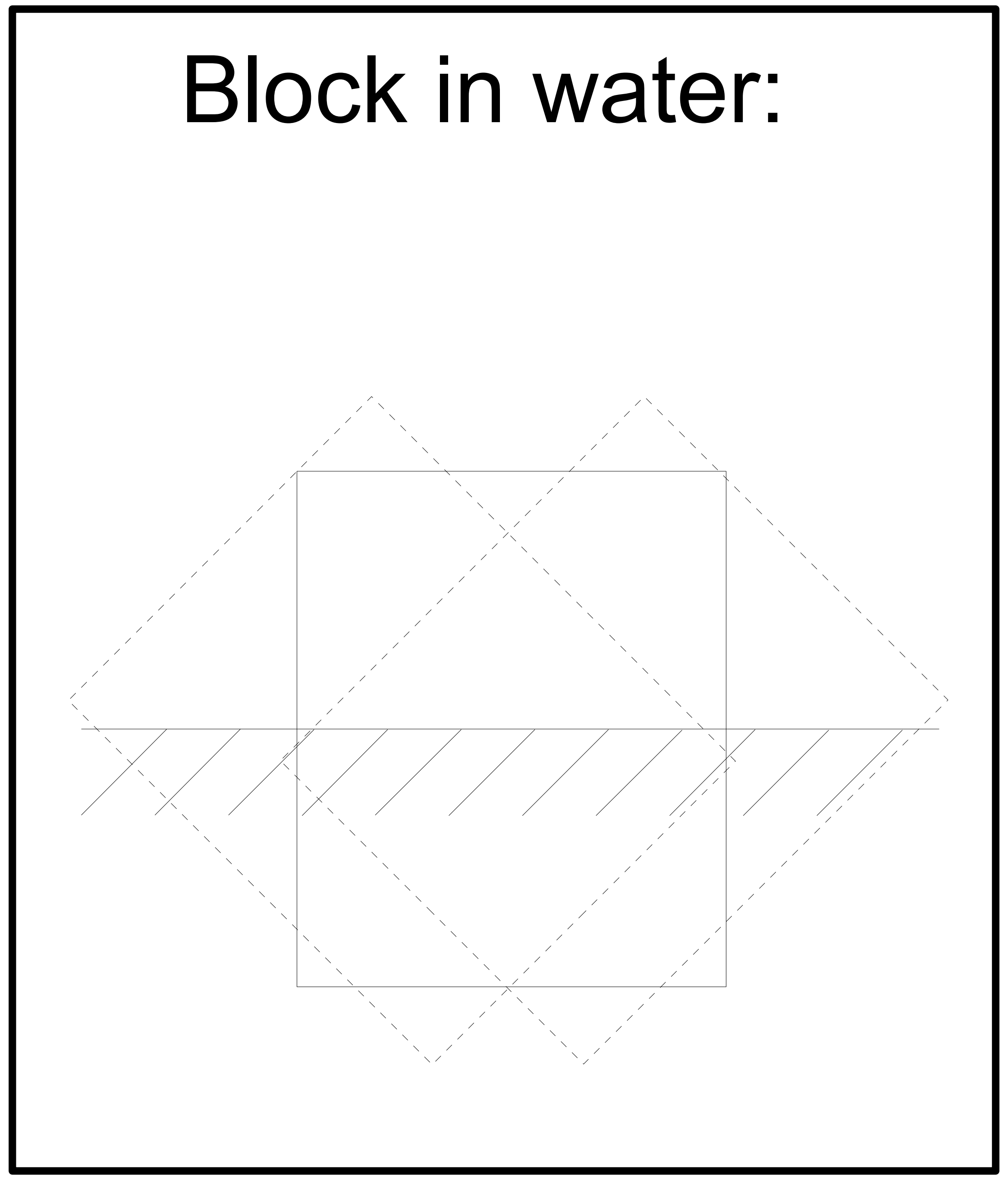
lower component of $SU(2)$ doublet.

Standard Model of Particle Physics in a nutshell

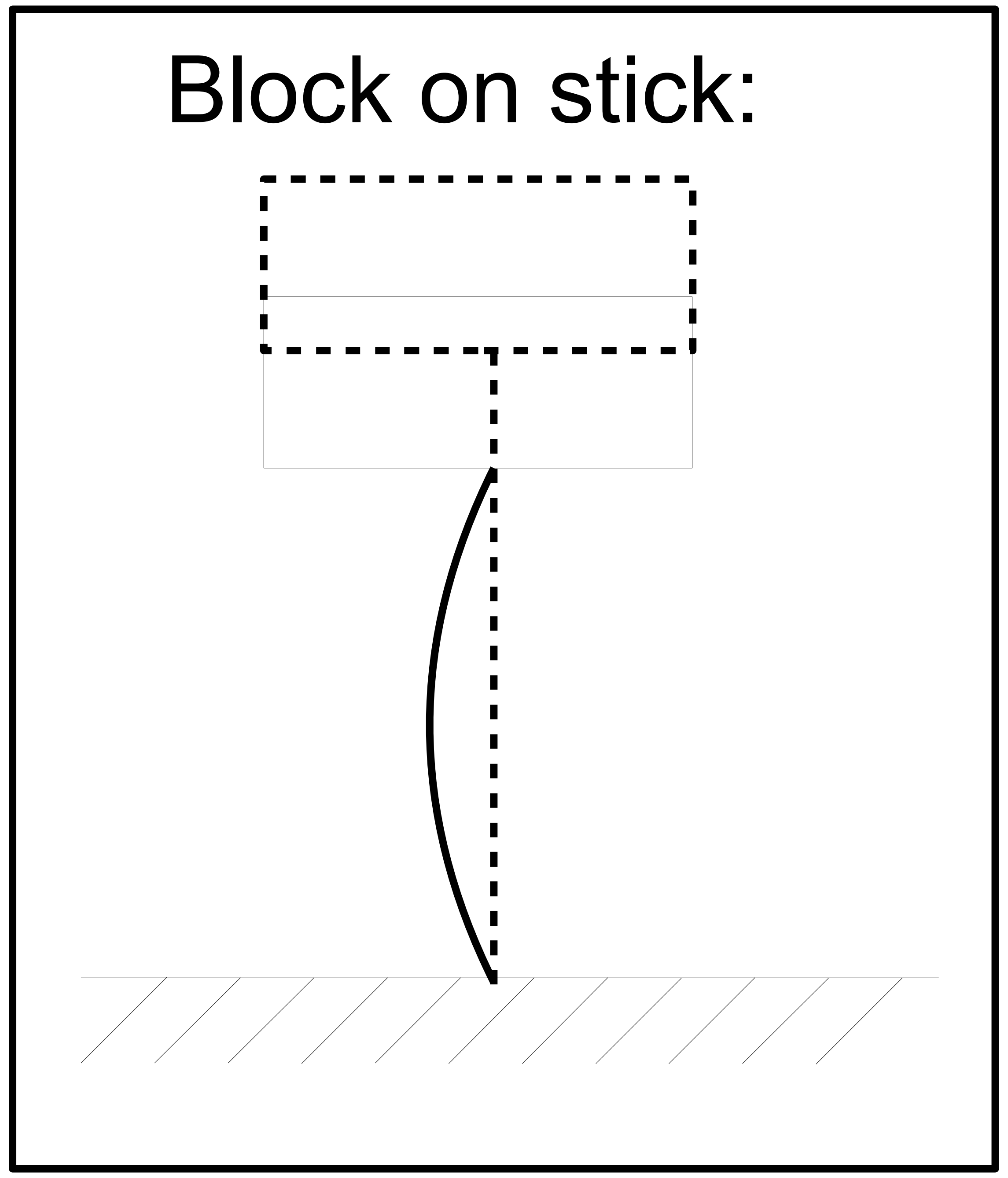
- Symmetry is present in the system (i.e. in the Lagrangian density $\mathcal{L}$).
- BUT it is broken in the ground state (i.e. in the quantum vacuum).
- Three examples (from classical mechanics):



φ symmetry

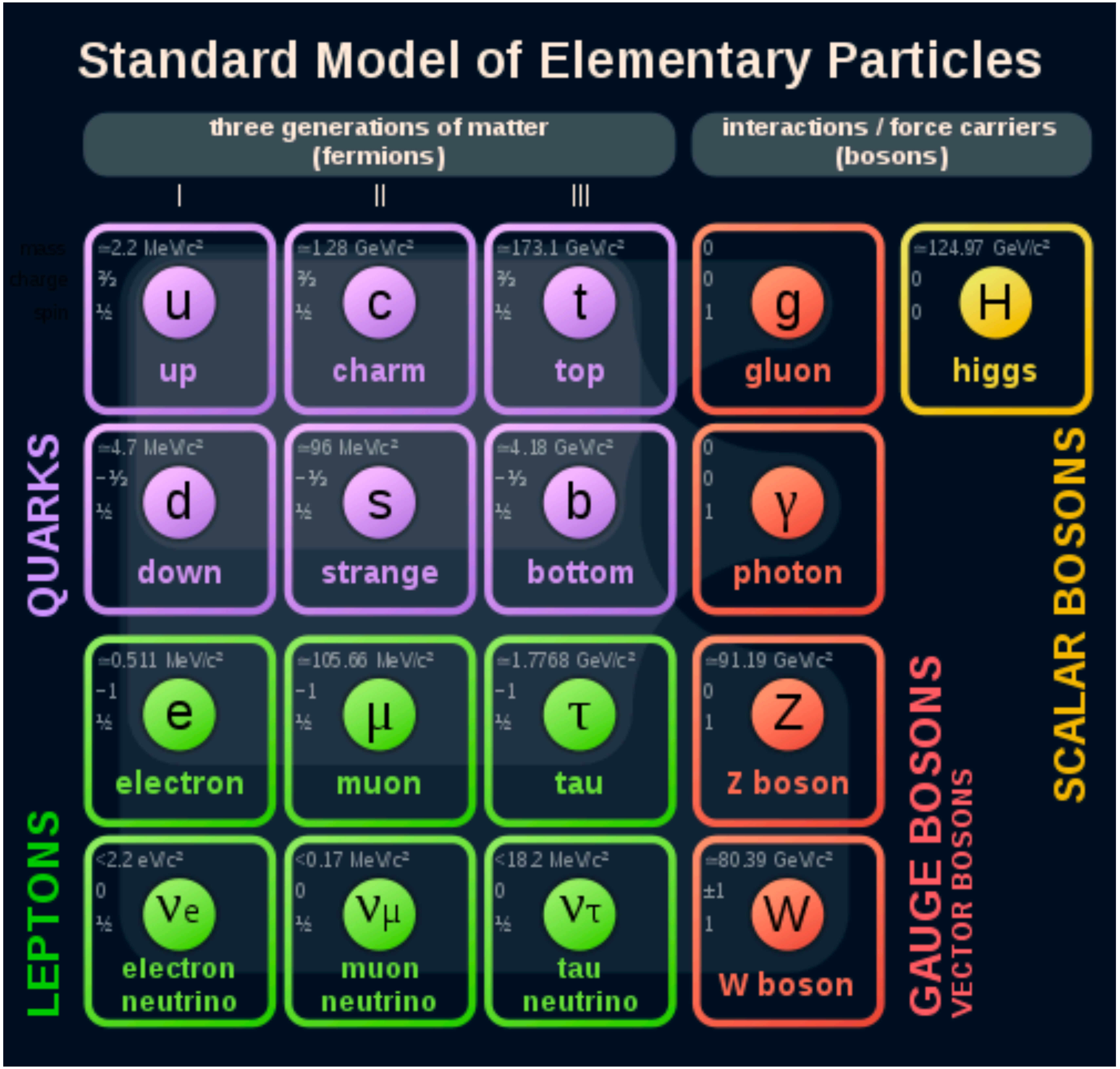


axis-symmetry

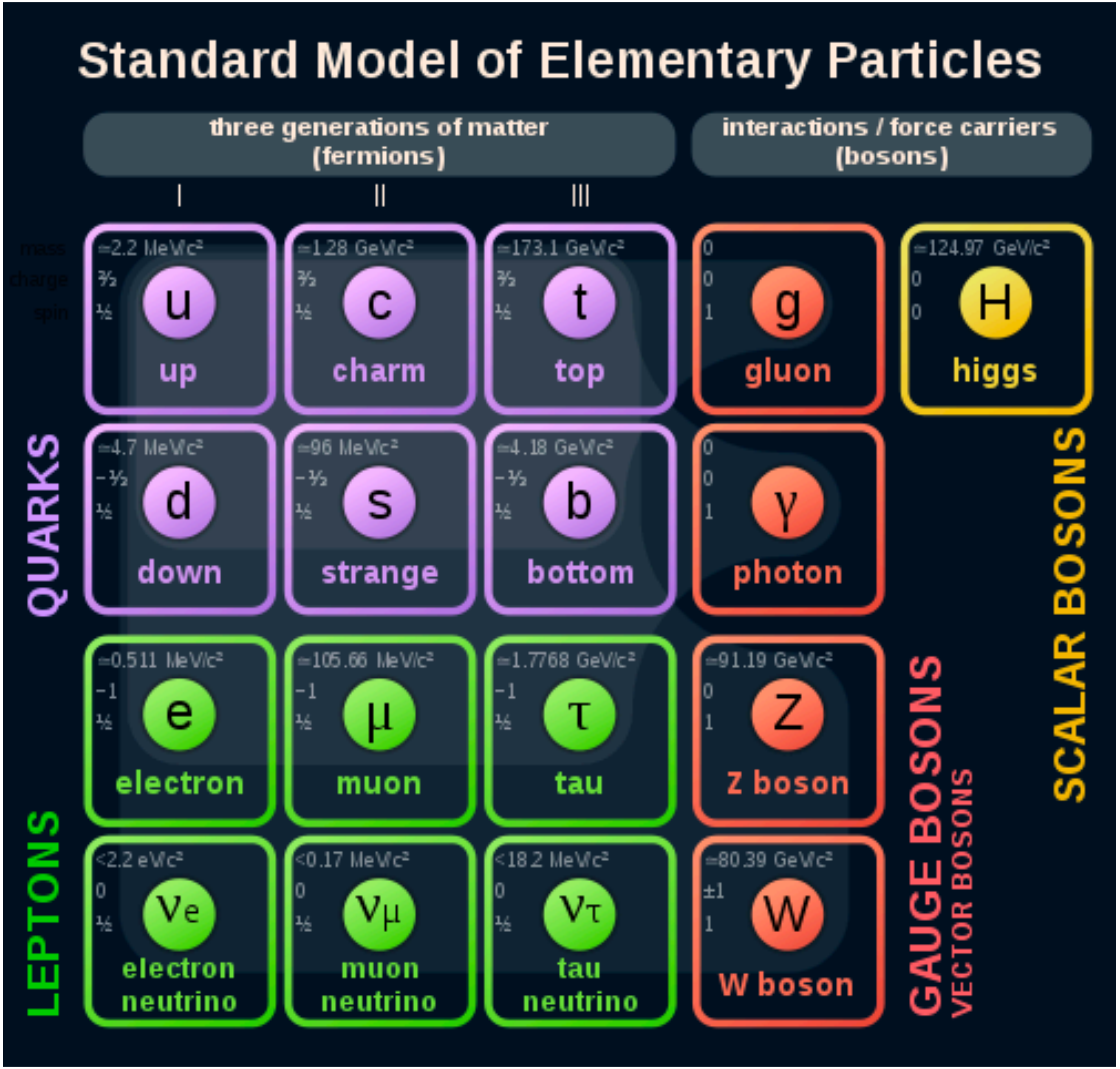


φ symmetry

Standard Model of Particle Physics in a nutshell

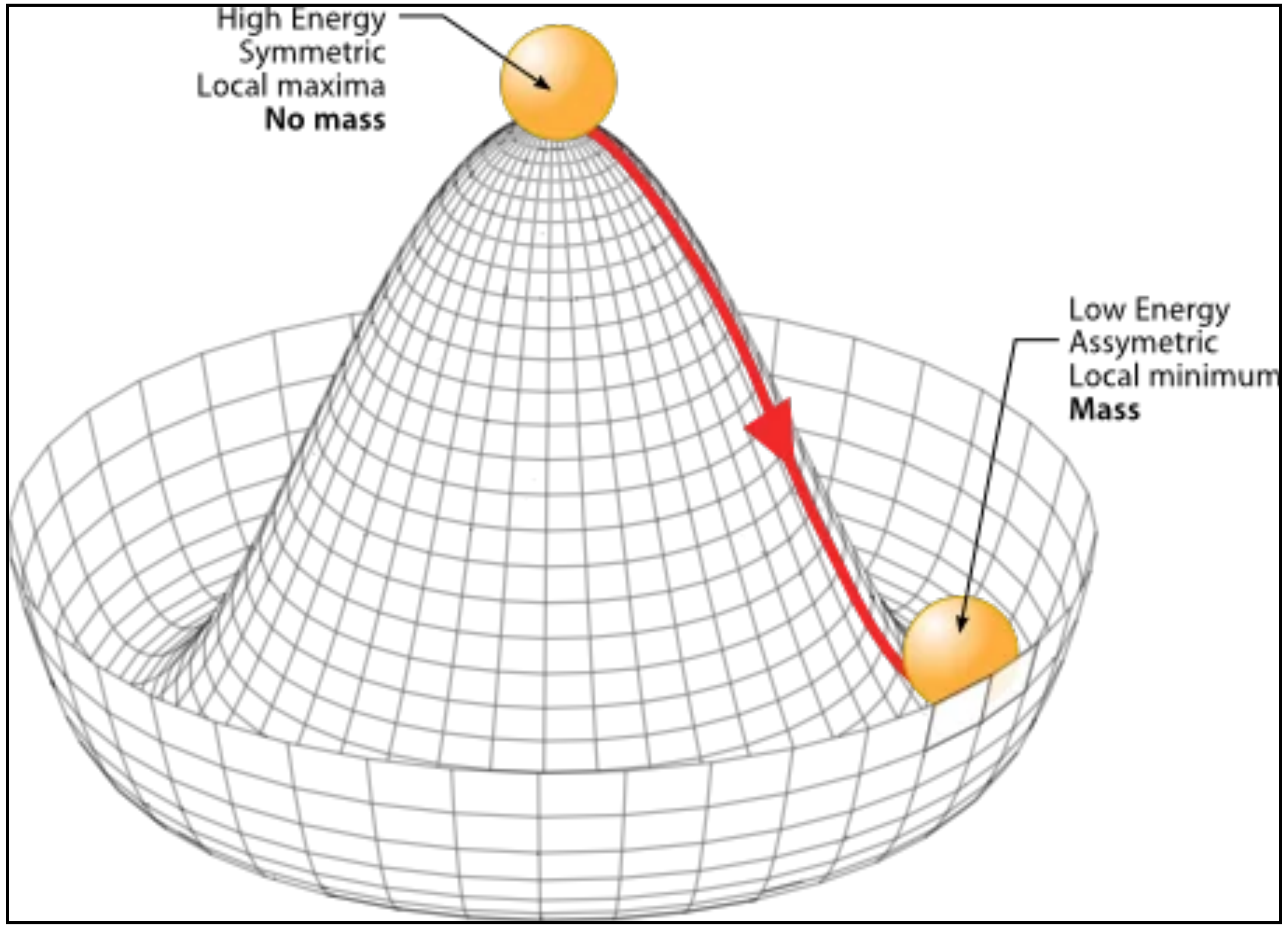


Standard Model of Particle Physics in a nutshell



No gauge invariant mass terms.
How do I give a mass ?

$$\mathcal{L}_{\rm SM} = -\frac{1}{4} W^a_{\mu\nu} W_a^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \overline{L}\, i D_\mu \gamma^\mu\, L + \overline{e}_R\, i D_\mu \gamma^\mu\, e_R \;\cdots$$



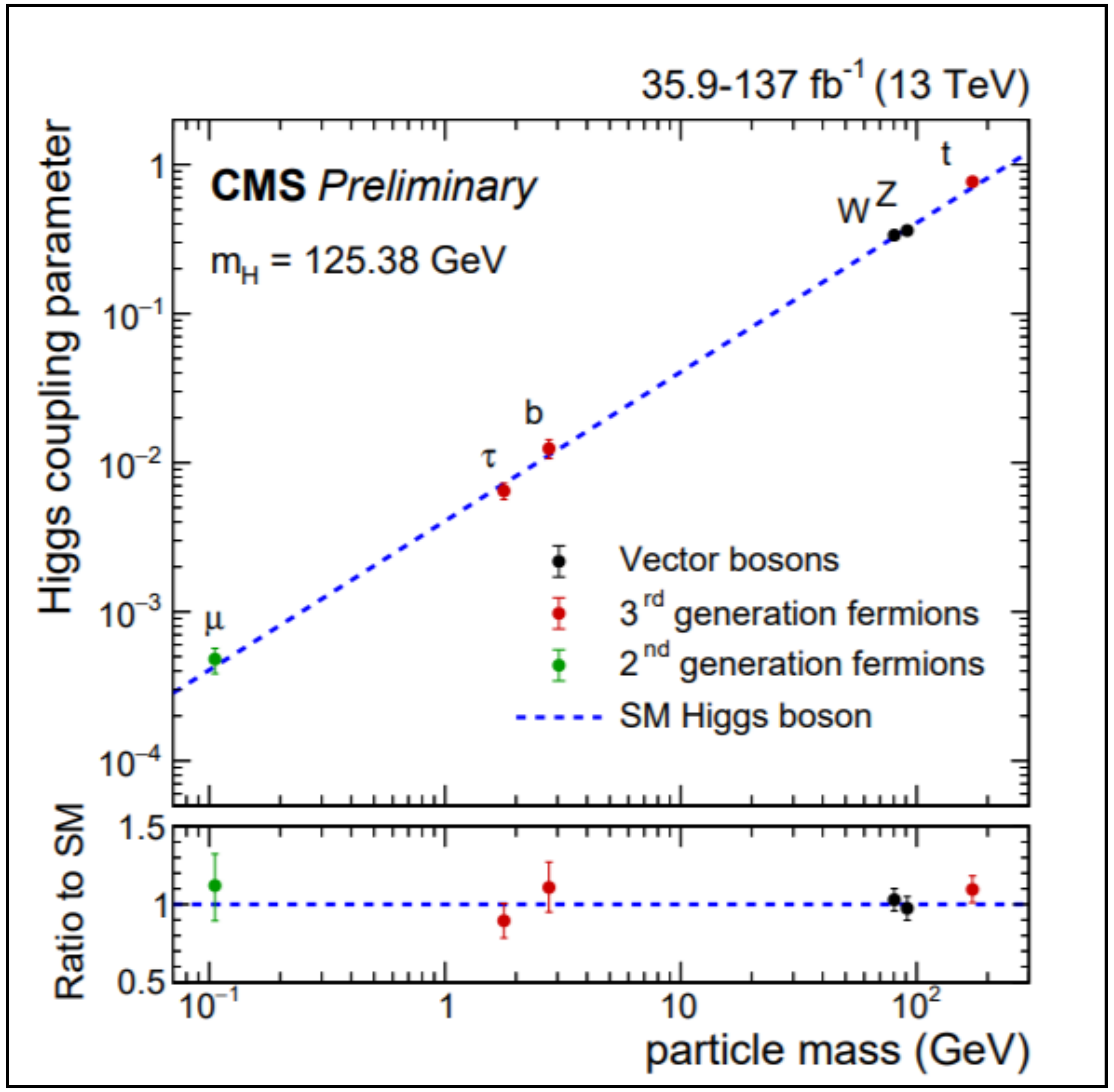
The Higgs field provides mass by interacting with SM particles at a classical (tree) level.

An SM particle gets more or less mass depending on how strongly it interacts with the field at this minimum.

The Remarkable Success of the Standard Model

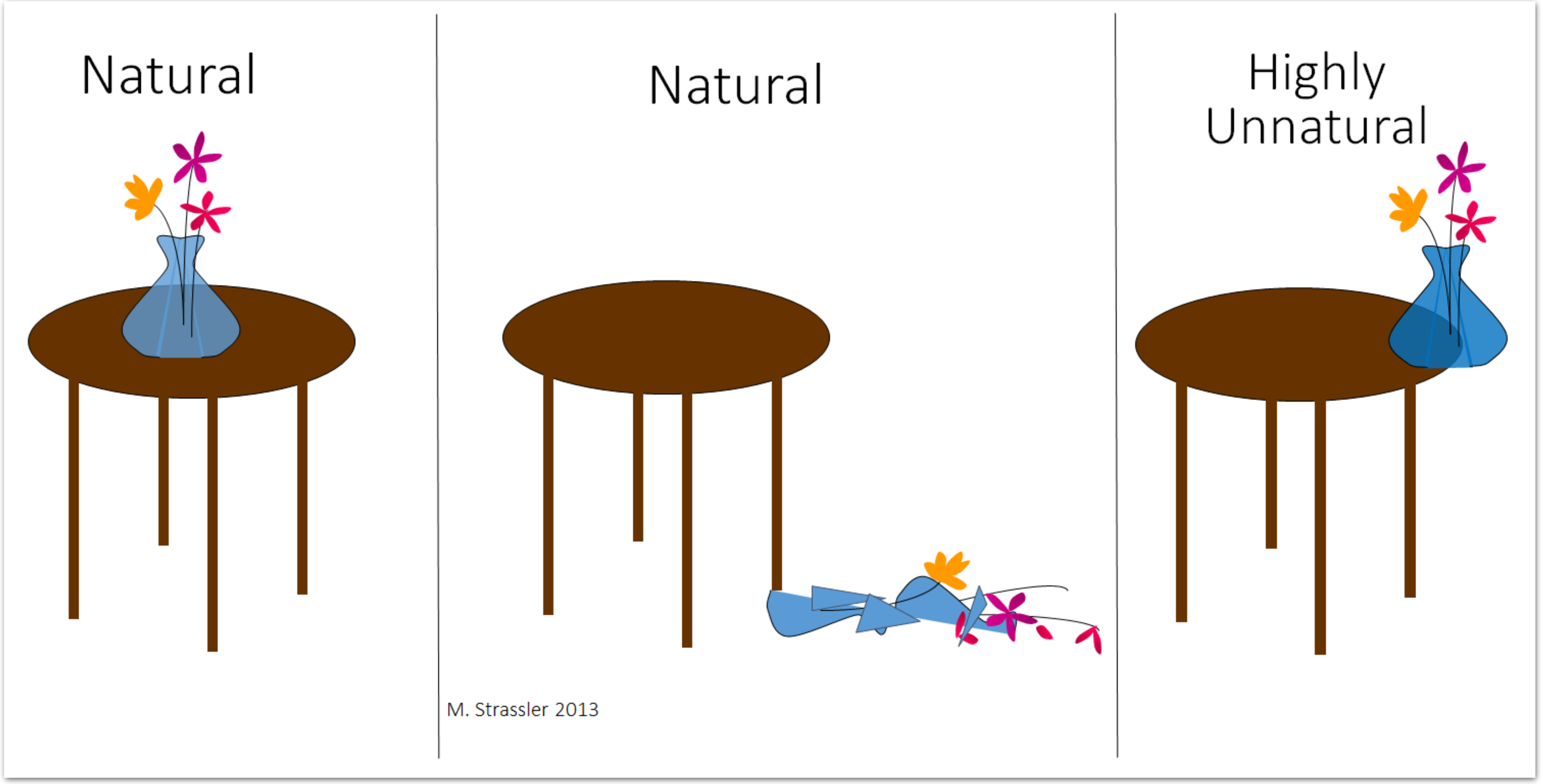
Quantity	Value	standard model
M_Z (GeV)	91.187 ± 0.007	input
Γ_Z (GeV)	2.491 ± 0.007	$2.490 \pm 0.001 \pm 0.005 \pm [0.006]$
$R = \Gamma_{had}/\Gamma_{l\bar{l}}$	20.87 ± 0.07	$20.78 \pm 0.01 \pm 0.01 \pm [0.07]$
$\sigma_p^h(nb)$	41.33 ± 0.18	$41.42 \pm 0.01 \pm 0.01 \pm [0.06]$
$\Gamma_{b\bar{b}}$ (MeV)	373 ± 9	$375.9 \pm 0.2 \pm 0.5 \pm [1.3]$
$A_{FB}(\mu)$	0.0152 ± 0.0027	$0.0141 \pm 0.0005 \pm 0.0010$
$A_{pol}(\tau)$	0.140 ± 0.018	$0.137 \pm 0.002 \pm 0.005$
$A_e(P_\tau)$	0.134 ± 0.030	$0.137 \pm 0.002 \pm 0.005$
$A_{FB}(b)$	0.093 ± 0.012	$0.096 \pm 0.002 \pm 0.003$
$A_{FB}(c)$	0.072 ± 0.027	$0.068 \pm 0.001 \pm 0.003$
A_{LR}	0.100 ± 0.044	$0.137 \pm 0.002 \pm 0.005$
$\Gamma_{l\bar{l}}$ (MeV)	83.43 ± 0.29	$83.66 \pm 0.02 \pm 0.13$
Γ_{had} (MeV)	1741.2 ± 6.6	$1739 \pm 1 \pm 4 \pm [6]$
Γ_{inv} (MeV)	499.5 ± 5.6	$500.4 \pm 0.1 \pm 0.9$
N_ν	3.004 ± 0.035	3
$\bar{g}_A$	-0.4999 ± 0.0009	-0.5
$\bar{g}_V$	-0.0351 ± 0.0025	$-0.0344 \pm 0.0006 \pm 0.0013$
$\bar{s}_W^2$ $(A_{FB}(q))$	0.2329 ± 0.0031	$0.2328 \pm 0.0003 \pm 0.0007 \pm$?
M_W (GeV)	79.91 ± 0.39	$80.18 \pm 0.02 \pm 0.13$
M_W/M_Z	0.8813 ± 0.0041	$0.8793 \pm 0.0002 \pm 0.0014$
$Q_W(Cs)$	$-71.04 \pm 1.58 \pm [0.88]$	$-73.20 \pm 0.07 \pm 0.02$
$g_A^e(\nu e \to \nu e)$	-0.503 ± 0.017	$-0.505 \pm 0 \pm 0.001$
$g_V^e(\nu e \to \nu e)$	-0.025 ± 0.020	$-0.036 \pm 0.001 \pm 0.001$
$\sin^2\theta_W$	$0.2242 \pm 0.0042 \pm [0.0047]$	$0.2269 \pm 0.0003 \pm 0.0025$

Standard Model Global Fit Parameters from gfitter group 2021



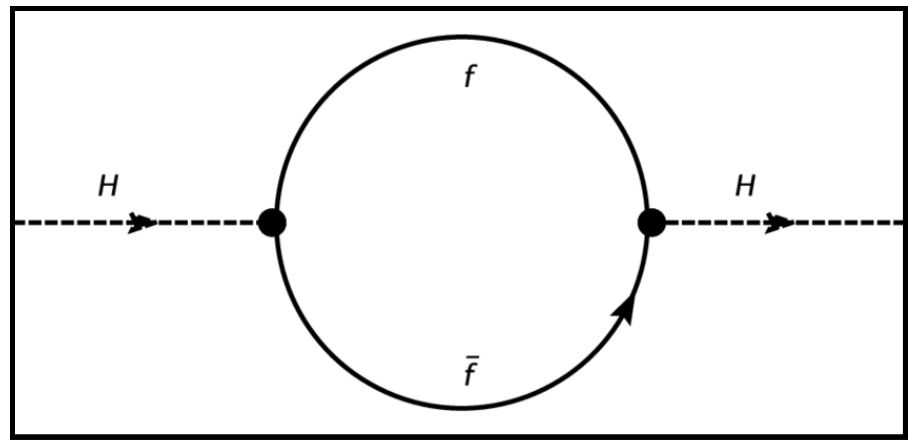
Standard Model Higgs Couplings

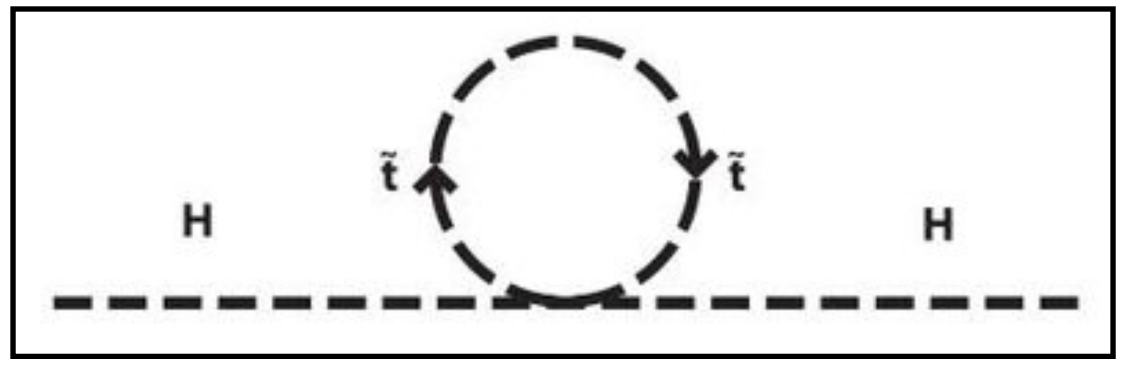
The “Unnatural” Higgs



Higgs is always hungry for more because it is really social. We have to send it to a gym

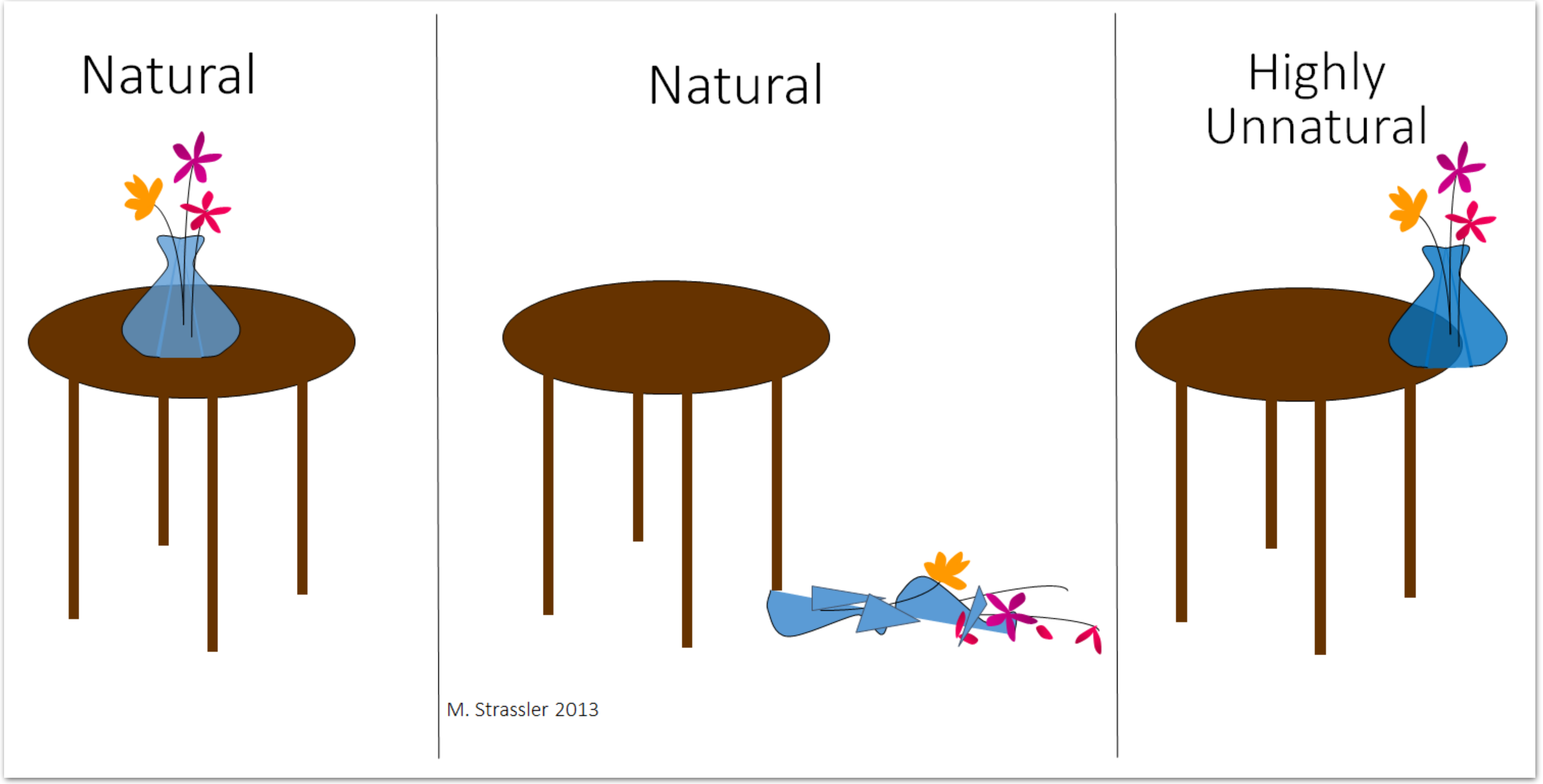
- Quantum corrections to the Higgs lead to “large fine-tunings”
- The bare mass parameter must be tuned to get a physical mass
- **Unless there is a “Natural” metabolism of the Higgs that keeps it light**
- **A symmetry that protects it from using the gym, à la “New Physics”**





A scalar partner to “work-out”

The “Unnatural” Higgs



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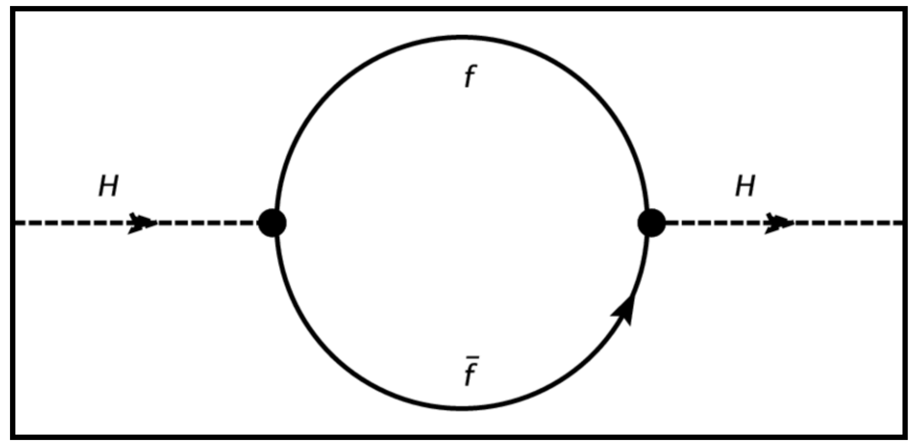
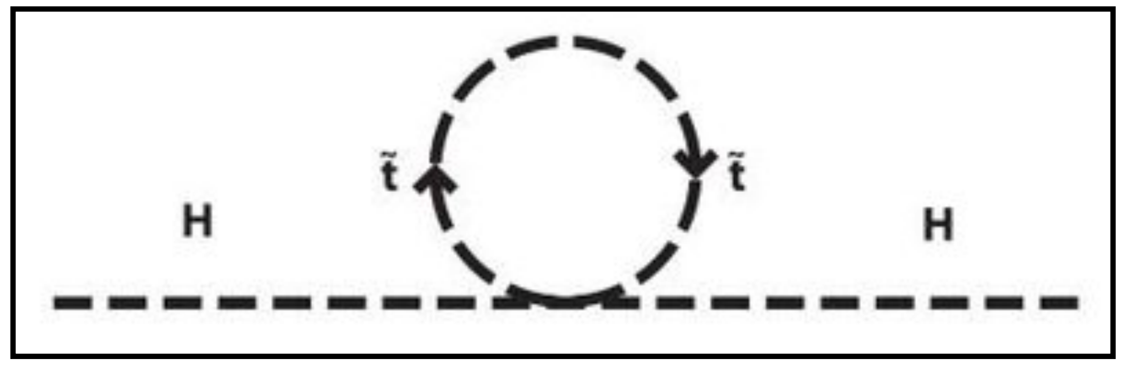




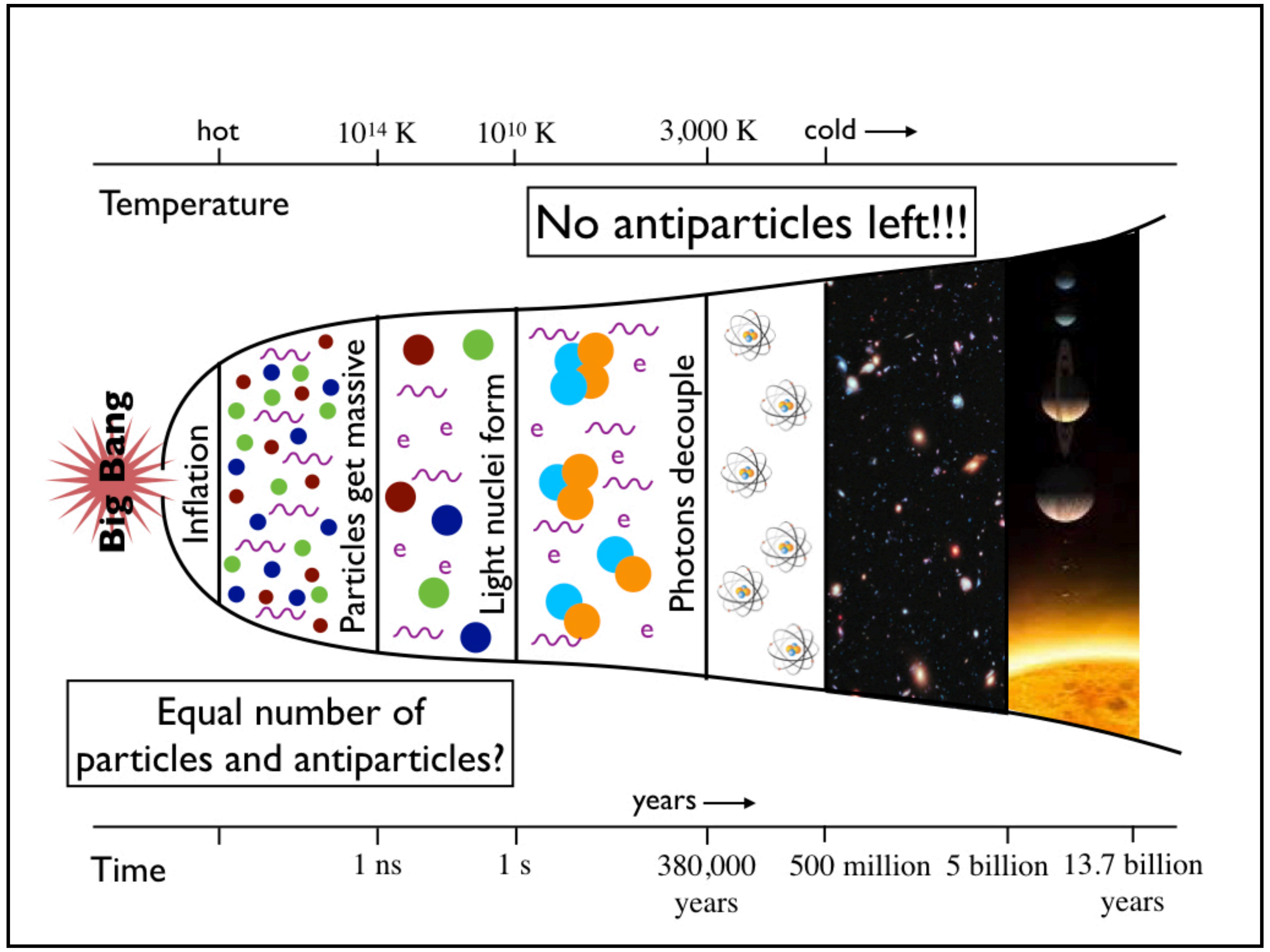
A scalar partner to “work-out”

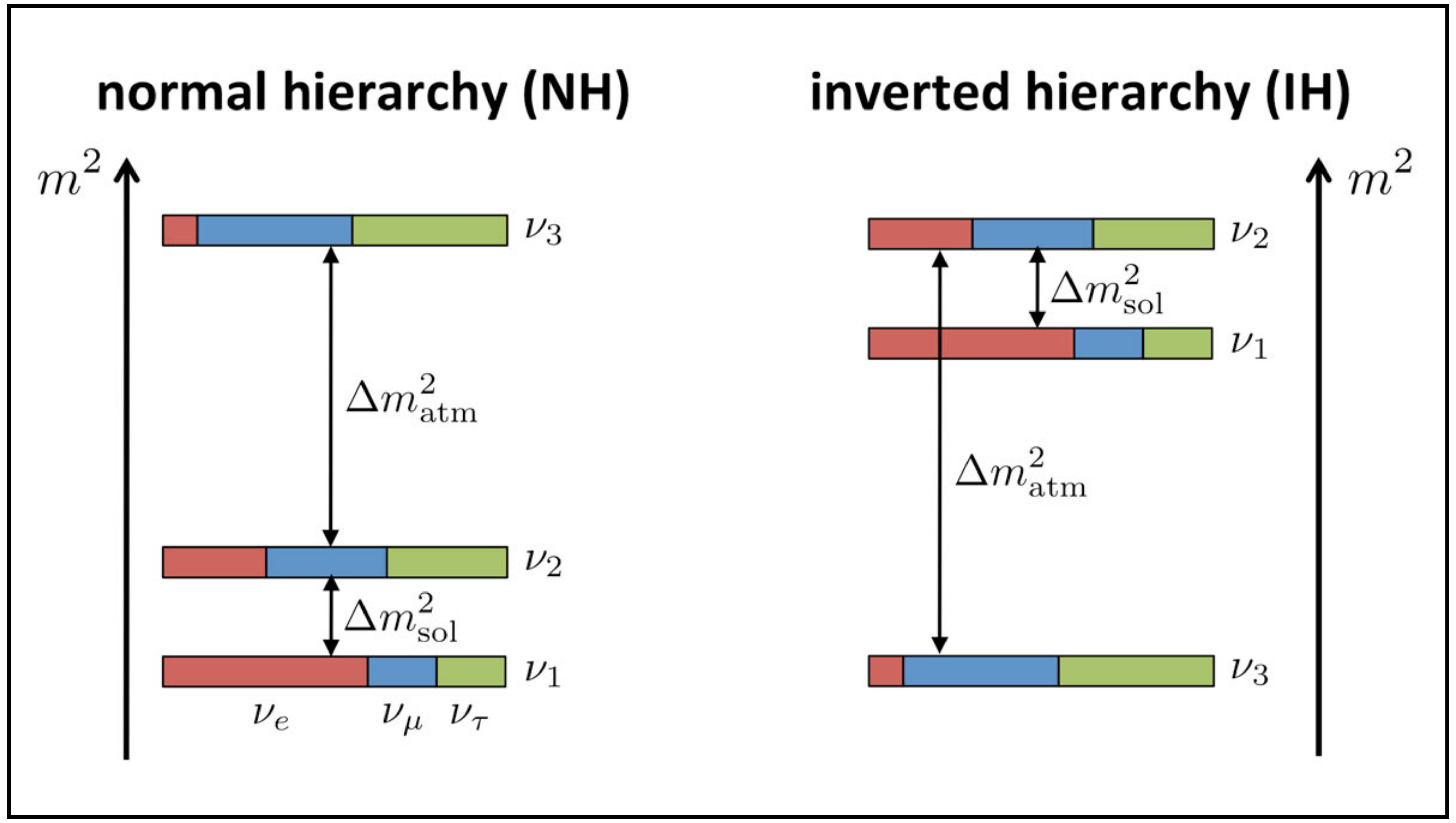
Expectation : New Physics at GeV-TeV scale, within reach of LHC

The Naturalness Olympics

See for example Nathaniel Craig's summary (2205.05708) for Snowmass 2023

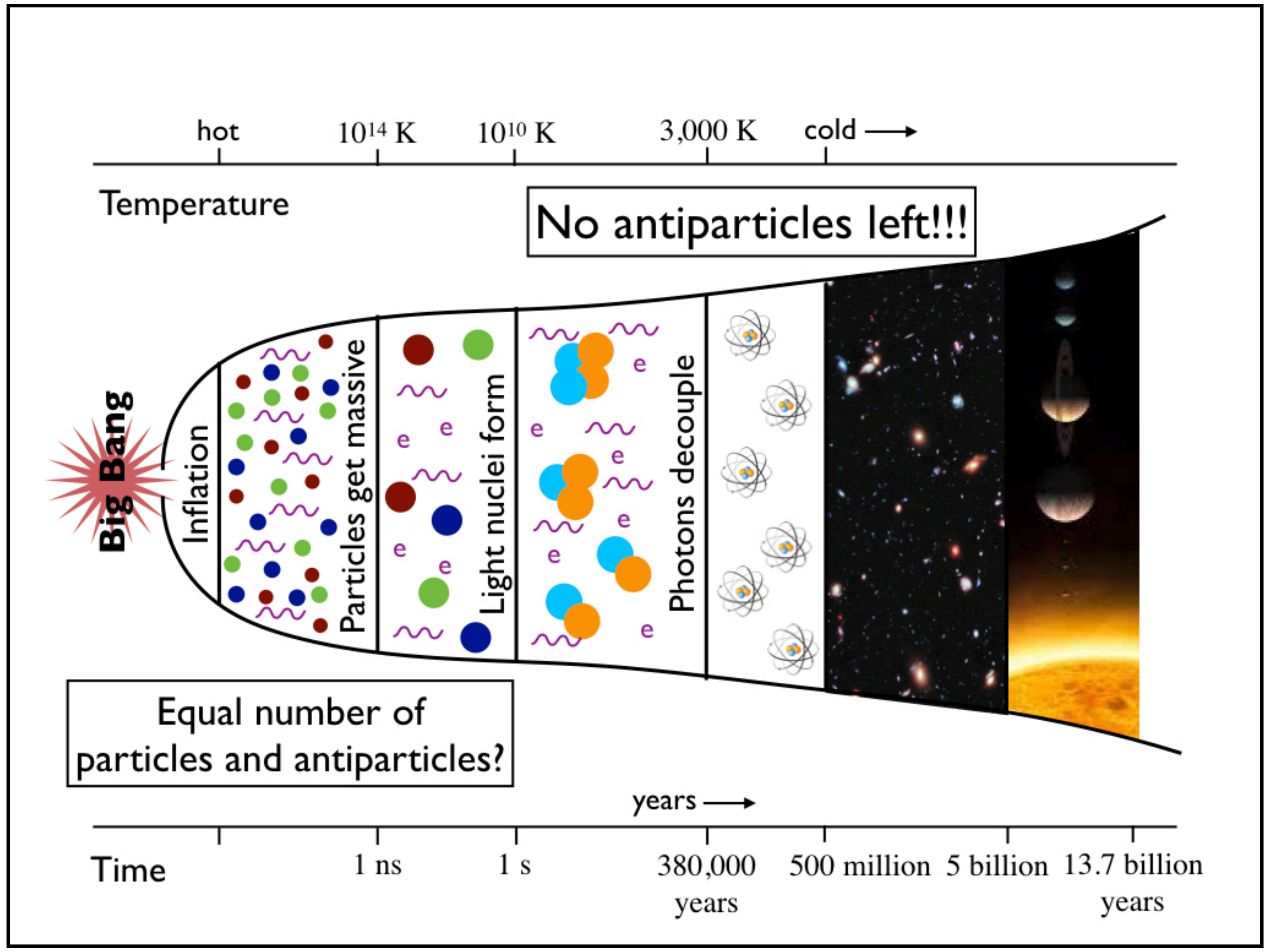
Real Problems of the Standard Model



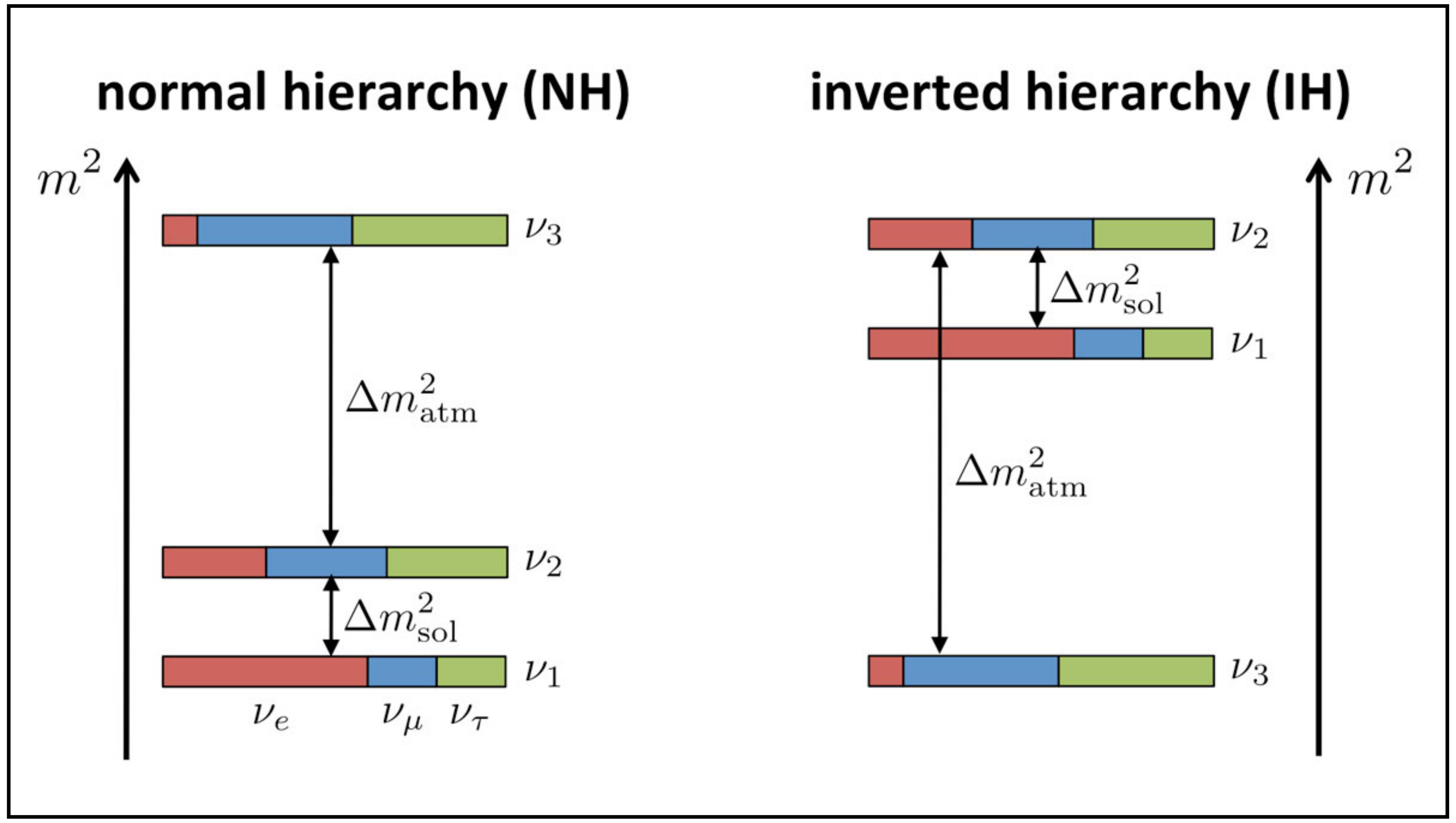


“Interstellar” Black Hole

Real Problems of the Standard Model



Needs new sources
of Charge and Parity violation

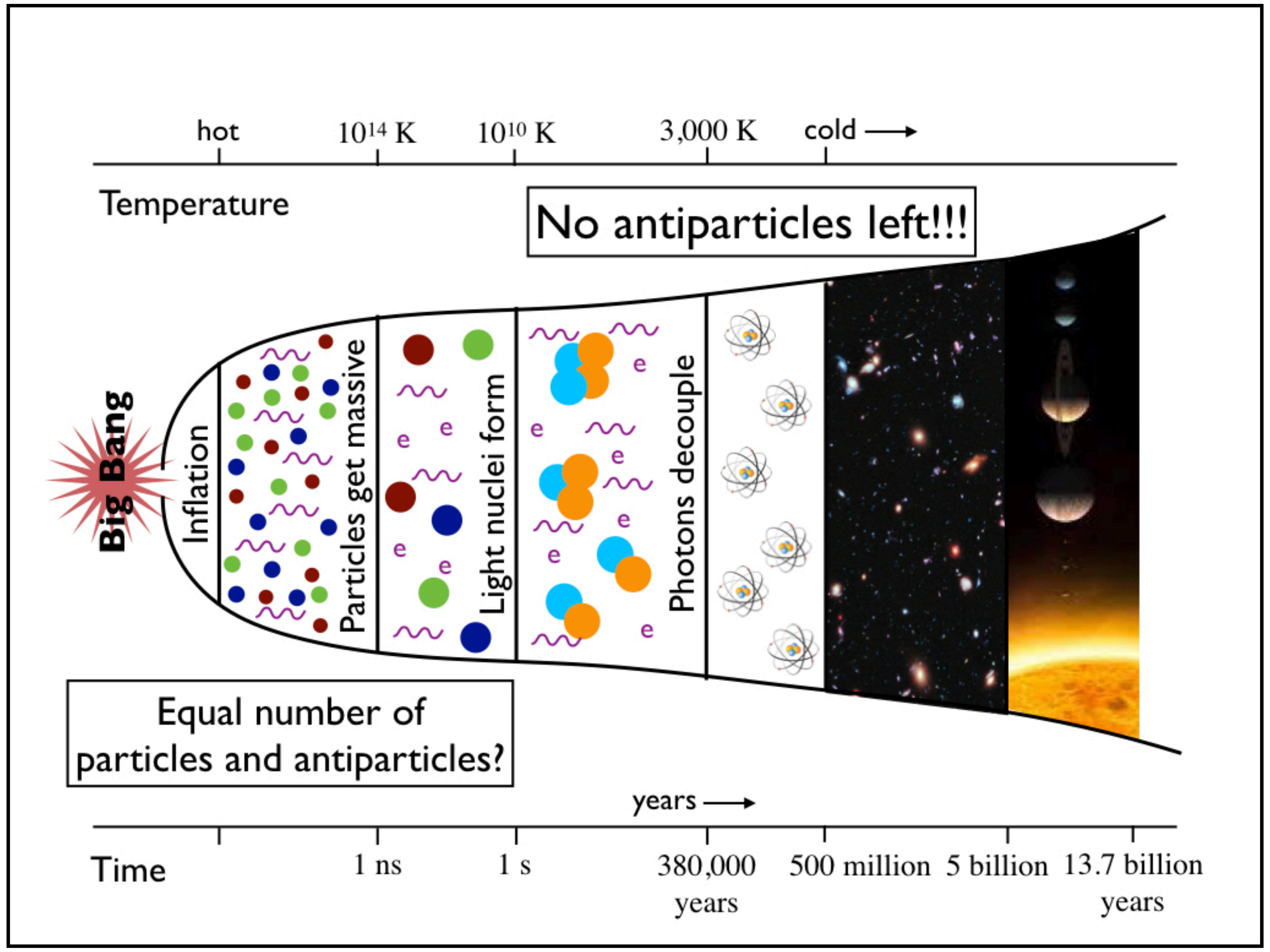


A mechanism for
Neutrino masses

"Interstellar" Black Hole

A theory of quantum gravity

Real Problems of the Standard Model



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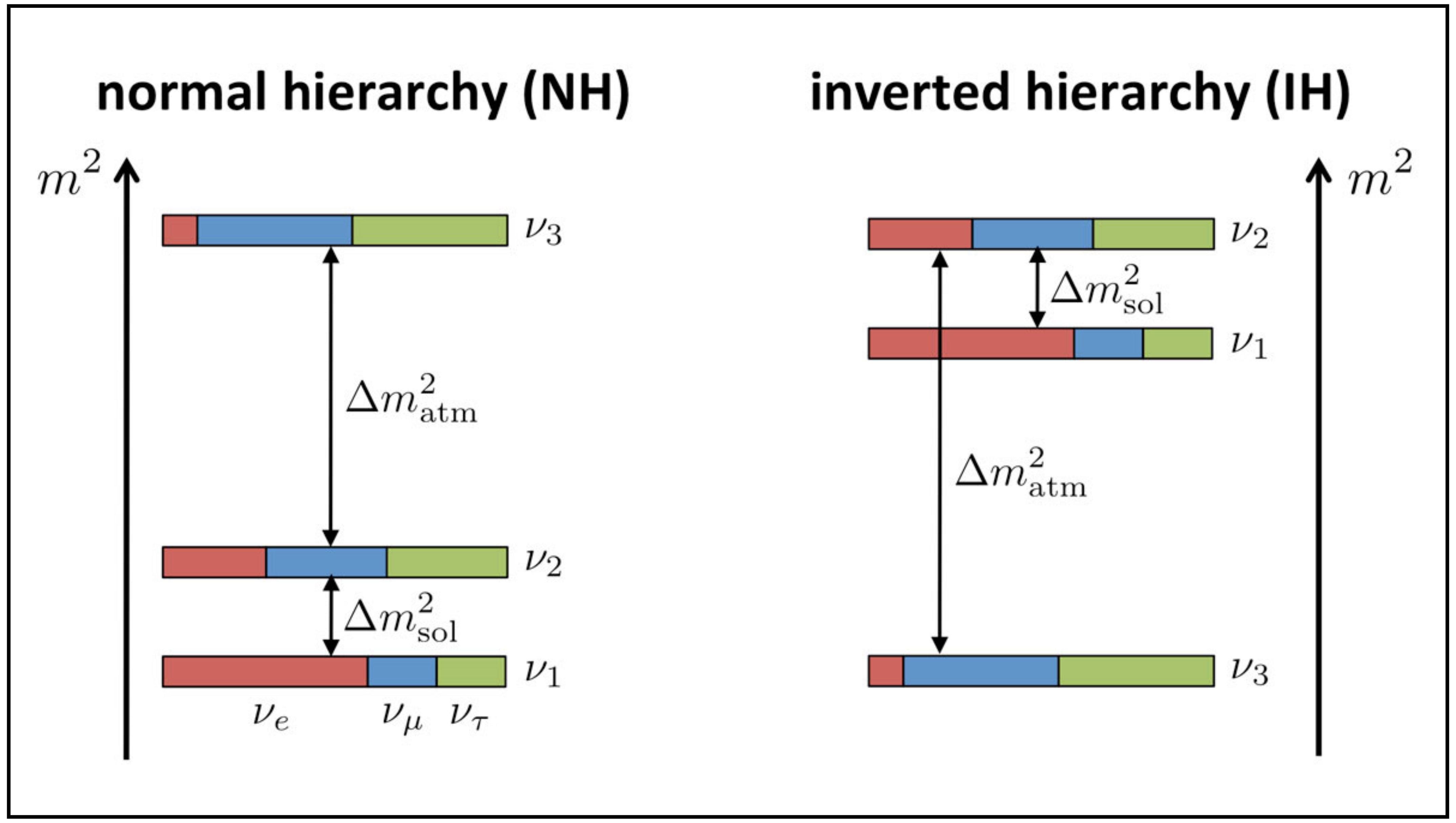


A mechanism for
Neutrino masses

"Interstellar" Black Hole

The biggest deficiency of them all:
Dark Matter

A theory of quantum gravity

Is String Theory the Ultimate Answer

- Two keystones of fundamental physics:

  1. Einstein's theory of gravity [1915]
  2. Quantum theory: [1920-1930]

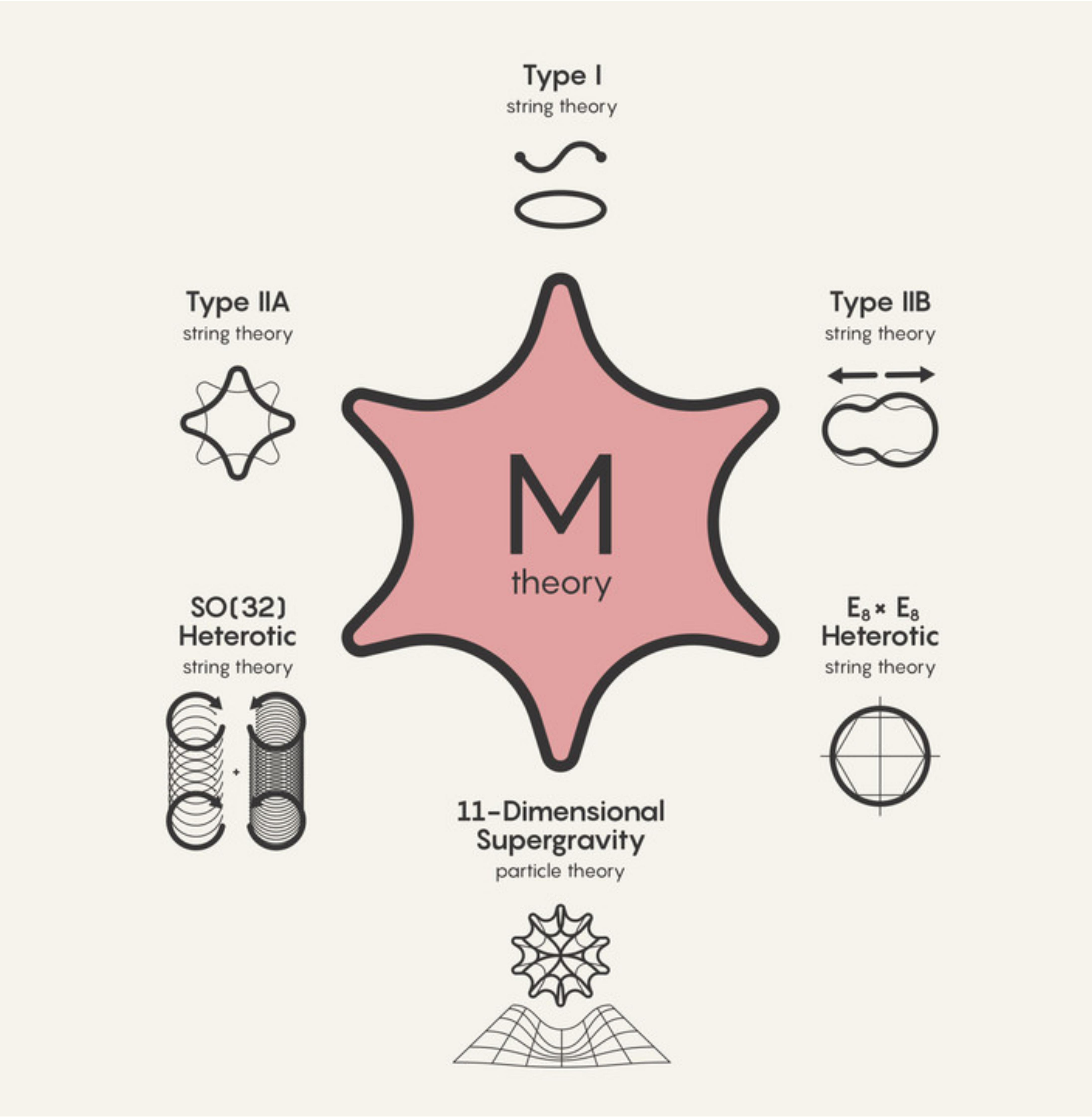
  ⇒ Standard model of elementary particle physics [1950-75]
  Electromagnetic, weak and strong forces

- **Not known how to combine the two!** ⇒ "unified theory"

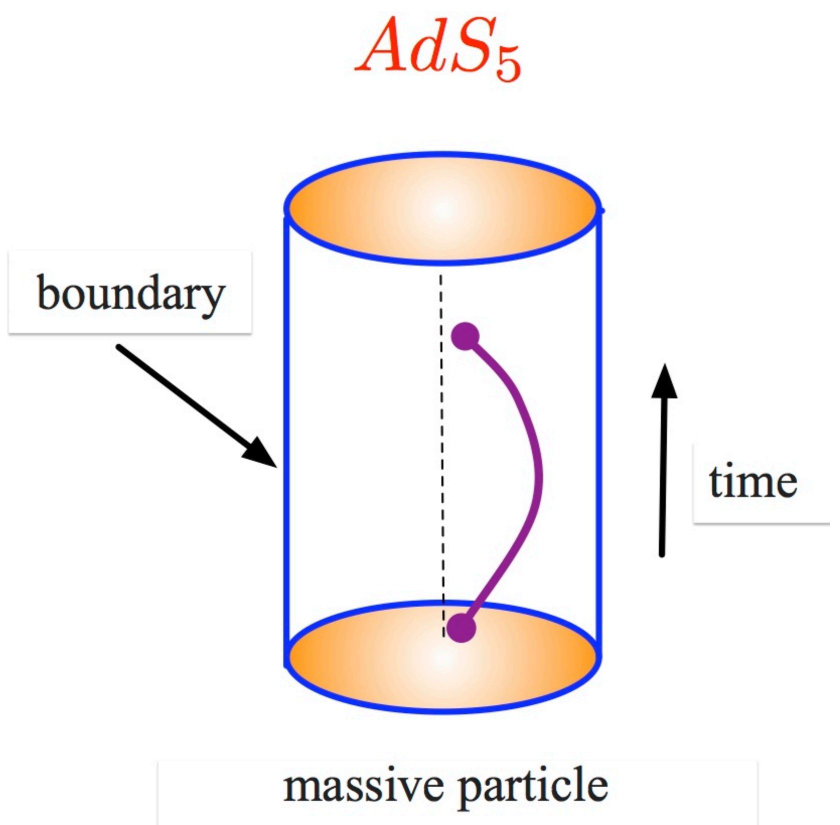
- The most promising ansatz: **String theory** [since 1984]

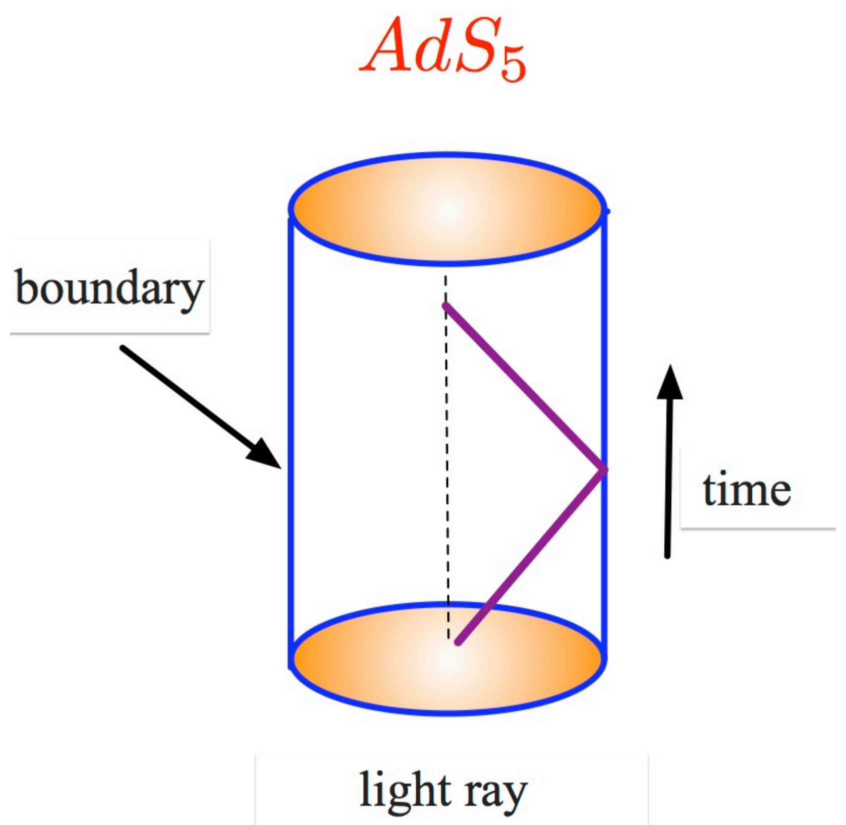
- Both keystones are intimately connected

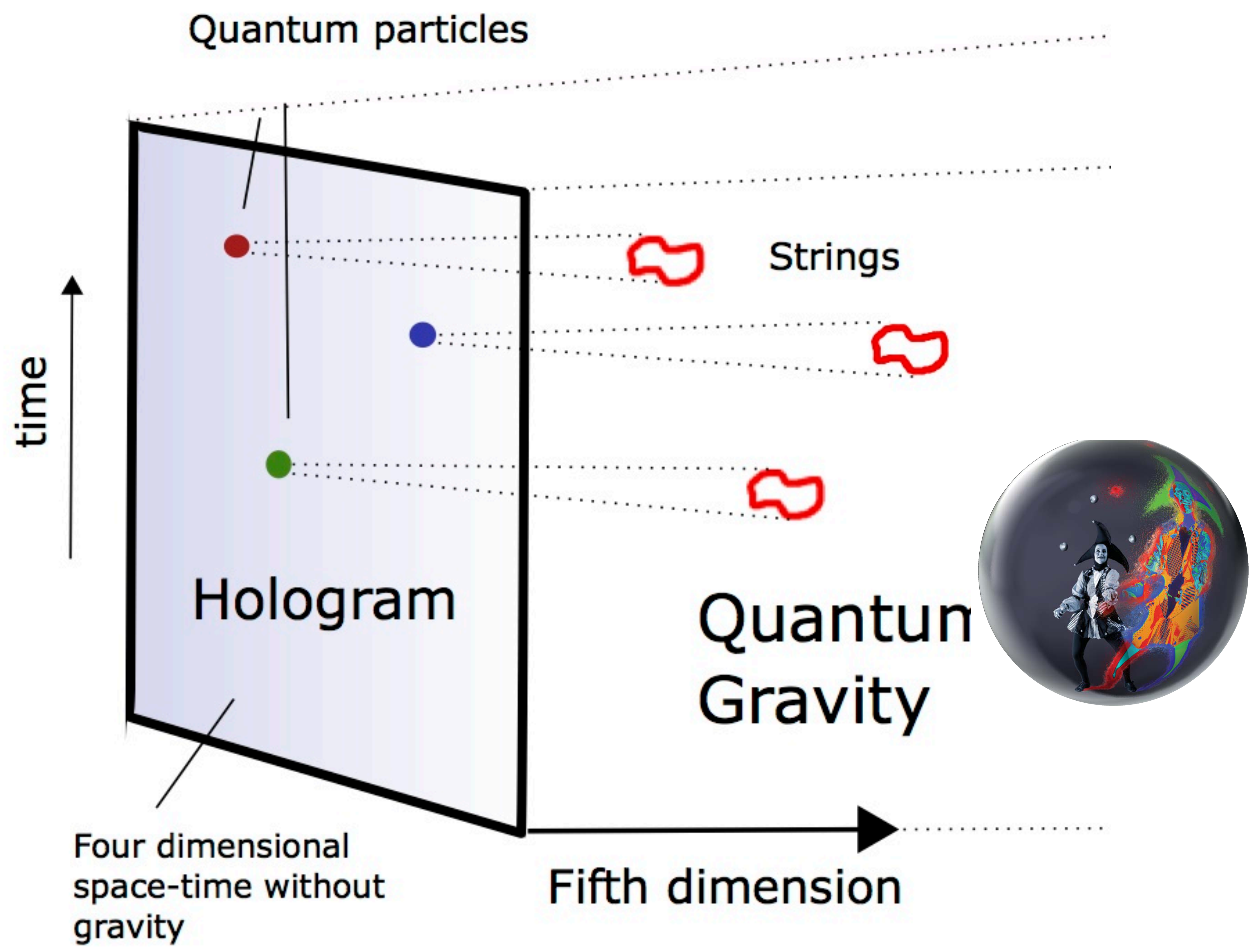
  ⇒ Holographic principle of quantum gravity [since 1997]



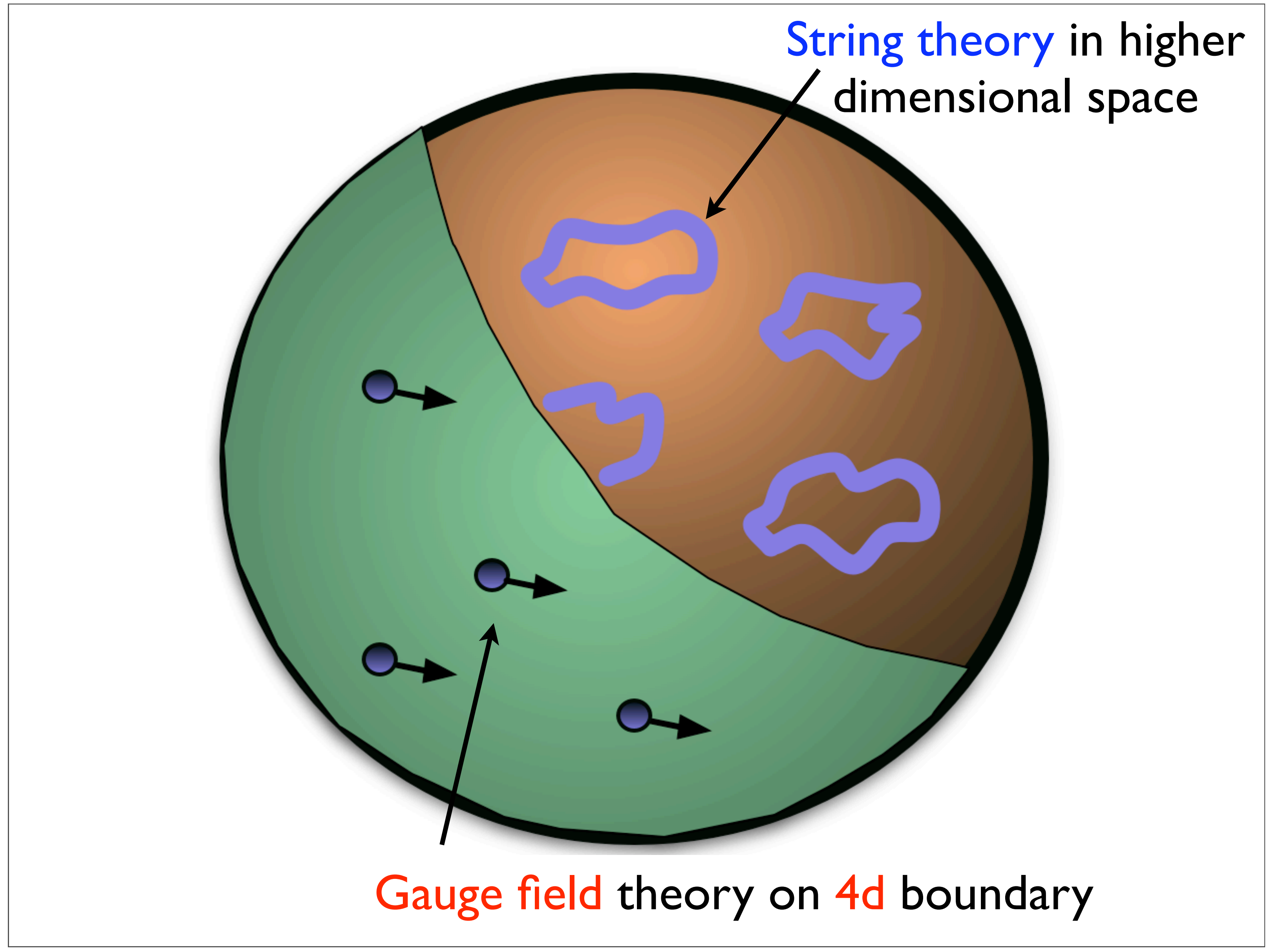
Holographic Universe







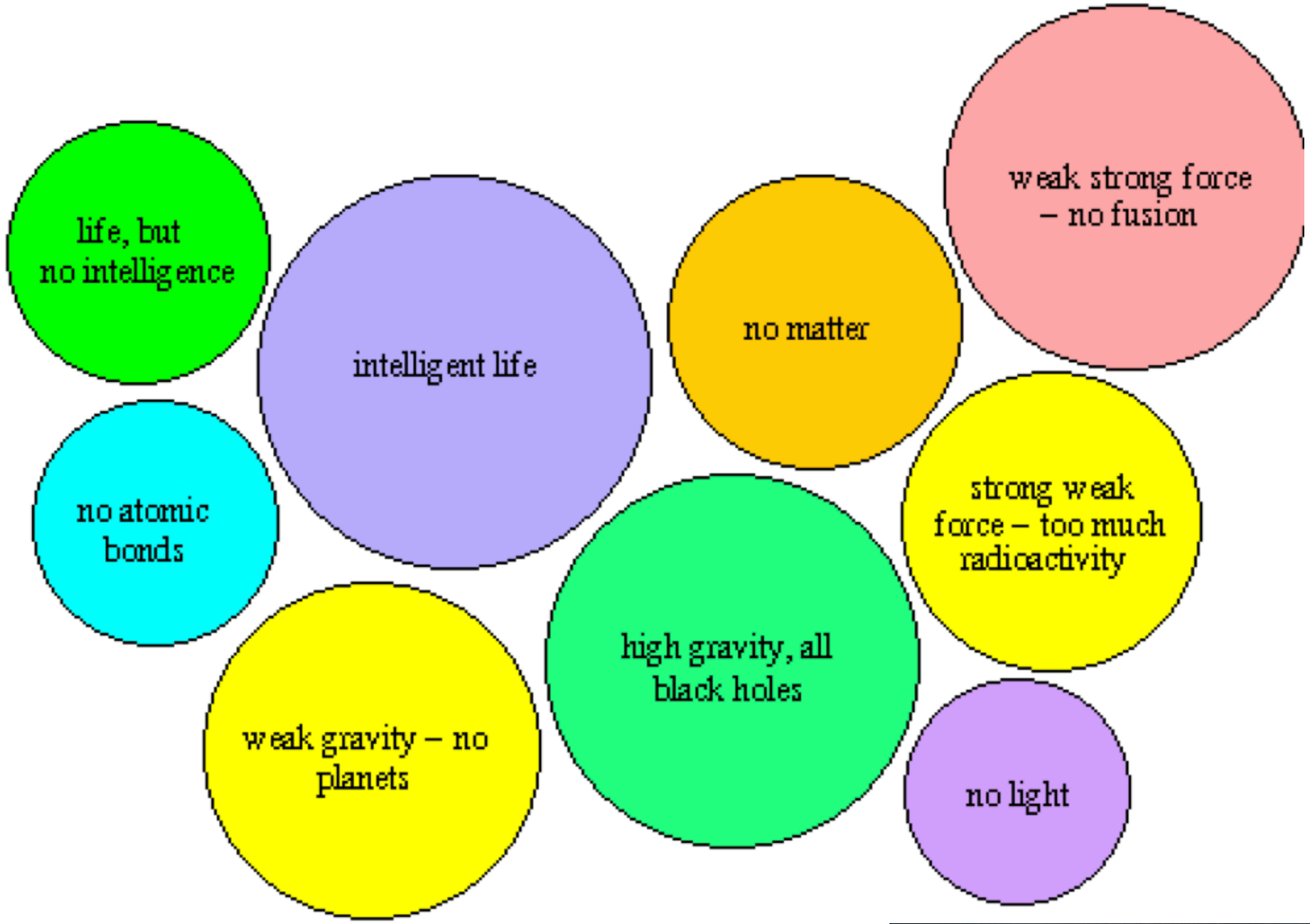
Holographic principle: Strings in the bulk of space-time (Anti-de-Sitter space), quantum particles (gluons) on the boundary

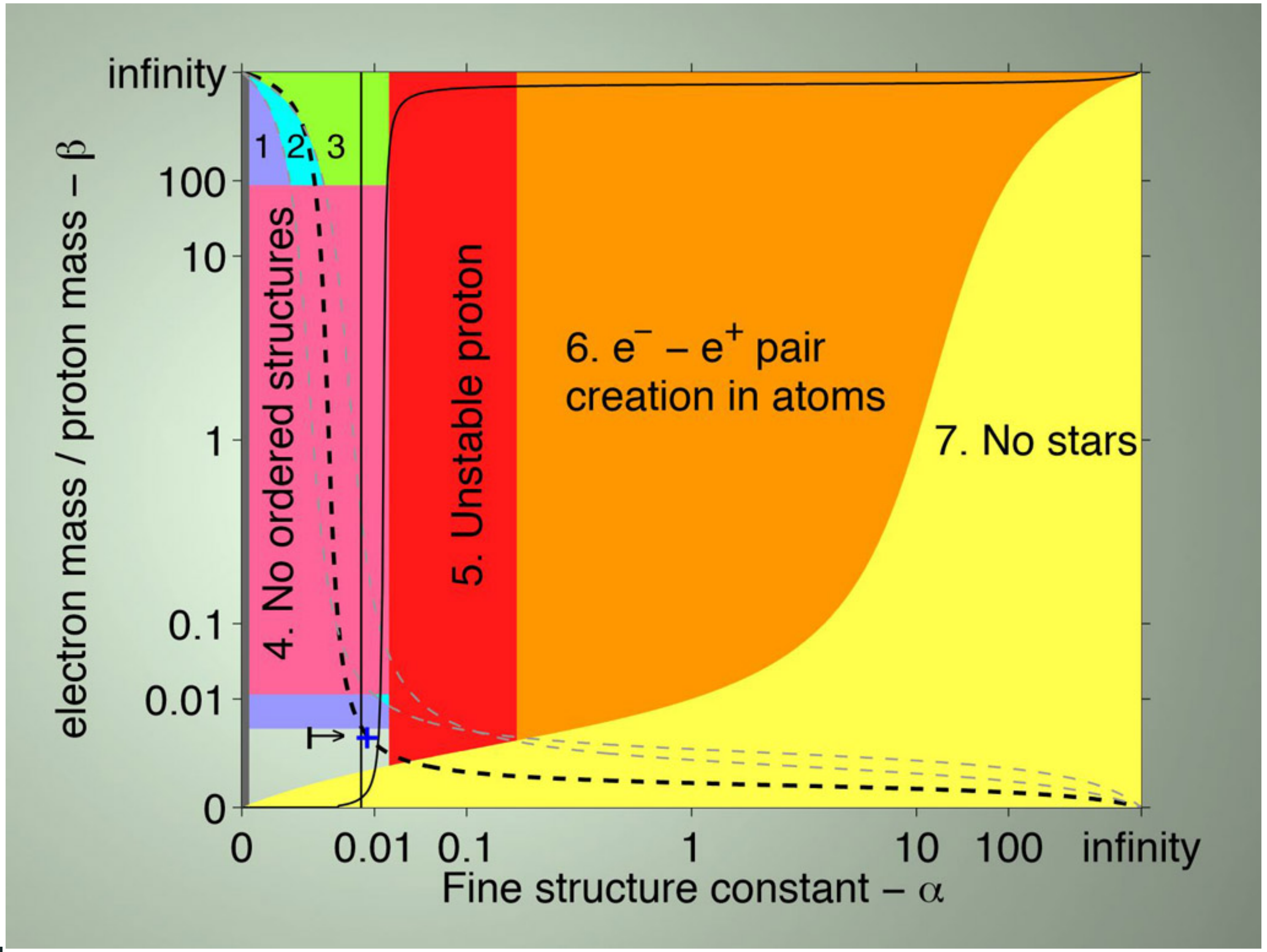


Two dual descriptions of **one** physical entity: Gauge theory $\hat{=}$ String theory in AdS

Maldacena 1997

Multiverses

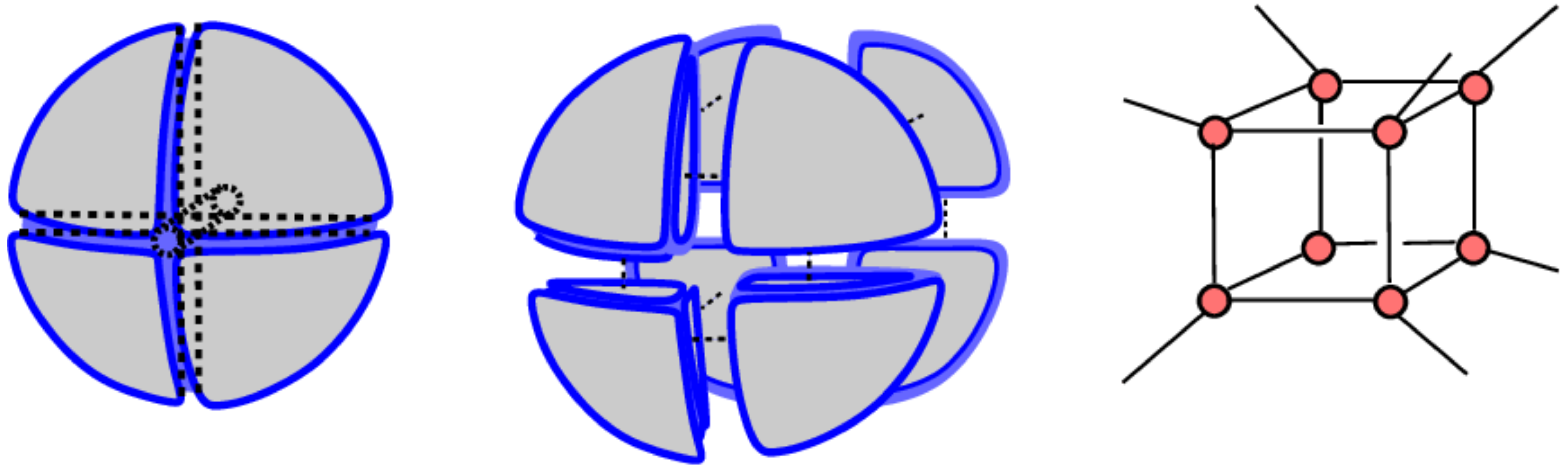


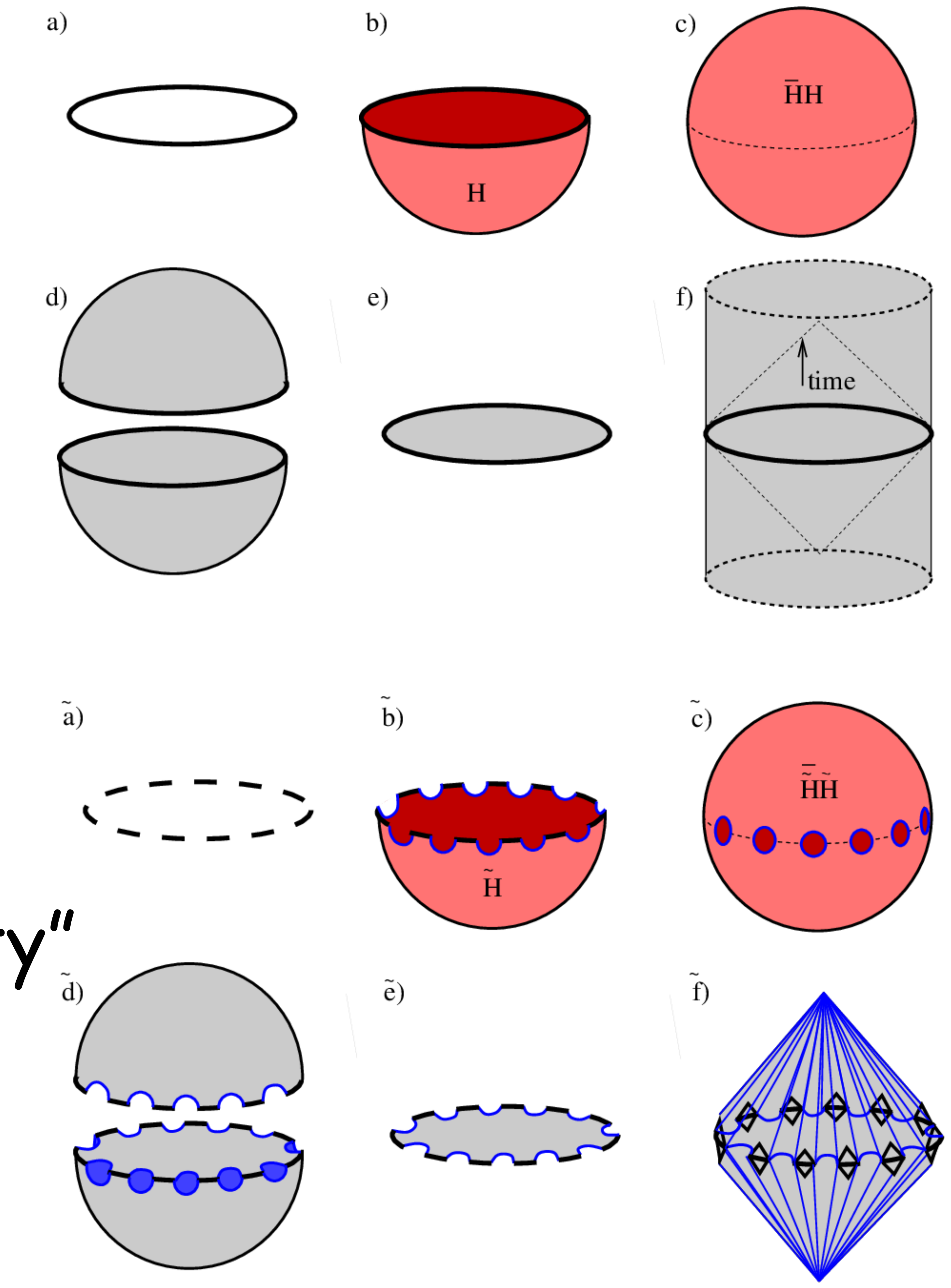


Barne's diagram

The It from Qubit

Spacetime from Entanglement : van Raamsdonck 2011,2019





"Emergence of classically connected spacetimes is Intimately related to quantum entanglement of degrees of freedom in a non-perturbative description on quantum gravity"

Tasi lectures : 1609.00026


There is nothing new to be discovered in physics. All that remains is more and more precise measurement.
Lord Kevin
Relativity
Quantum Mechanics
Nuclear Physics
Quantum Field Theory
Beyond the Standard Model
Grand Unified Theory