Cosmological matter-antimatter asymmetry and neutrino physics

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Matter-antimatter asymmetry

Main questions:

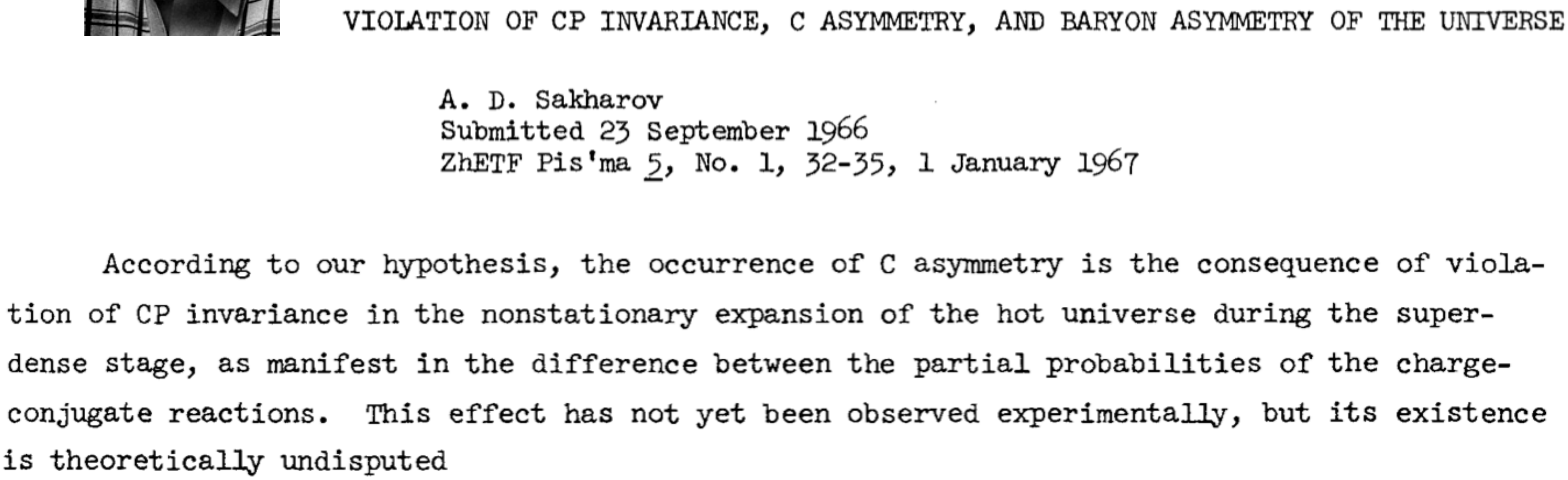
- Why do the Earth, the Solar system and our galaxy consists of matter and not of antimatter?
- Why we do not see any traces of antimatter in the universe except of those where antiparticles are created in collisions of ordinary particles?

This looks really strange, as the properties of matter and antimatter are very similar.

Problems to solve:

- Why in the early universe the number of baryons is greater than the number of anti-baryons ?
- How to compute the primordial baryon asymmetry? (from observations baryon to photon ratio is $n_B/n_\gamma \simeq 10^{-10}$)

Sakharov proposal, 1967



VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

According to our hypothesis, the occurrence of C asymmetry is the consequence of violation of CP invariance in the nonstationary expansion of the hot universe during the superdense stage, as manifest in the difference between the partial probabilities of the charge-conjugate reactions. This effect has not yet been observed experimentally, but its existence is theoretically undisputed

The source of baryon asymmetry:
decays of Markov's maximons with masses $\sim 10^{19}$ GeV

Sakharov conditions:

- **Baryon number non-conservation, to produce net baryon number**
- **C and CP-violation, to have difference between particles and antiparticles**
- **Departure from thermal equilibrium, "arrow of time", to kill static CPT prediction**

Technology is highly elaborated nowadays: take a specific Lagrangian, embed it into expanding Universe, and make a computation. However, to have a prediction, we should know the theory to start with.

Standard Model?

Potentially BAU could be generated (Sakharov conditions are satisfied):

- Difference between matter and anti-matter: CP-violation present in the Standard Model (experimentally detected)
- Baryon number non-conservation in the Standard Model : rapid “sphaleron” transitions in the early Universe and very slow at normal conditions, may lead to creation of excess of baryons over anti-baryons
- Non-equilibrium: OK, Universe expansion, electroweak phase transition?

BAU in the Standard Model

In the Standard Model: everything is known (all parameters, CP-violation, mechanism of baryon number non-conservation). No true computation has been done for asymmetry, but we are convinced that it does not work.

- CP violation is too small
- No phase transition for Higgs mass above 73 GeV.

⬇

BAU tells that there is physics beyond the SM!

Baryogenesis: window to BSM physics

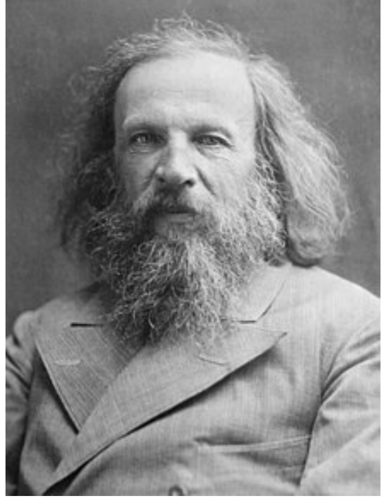
But the window is wide open. There is just one number n_B/n_γ to explain, and therefore many possibilities.

Epistemology tells that the

$$\text{\# of theories} \sim \text{const}/(\text{\# of data points})^\alpha, \alpha > 0$$

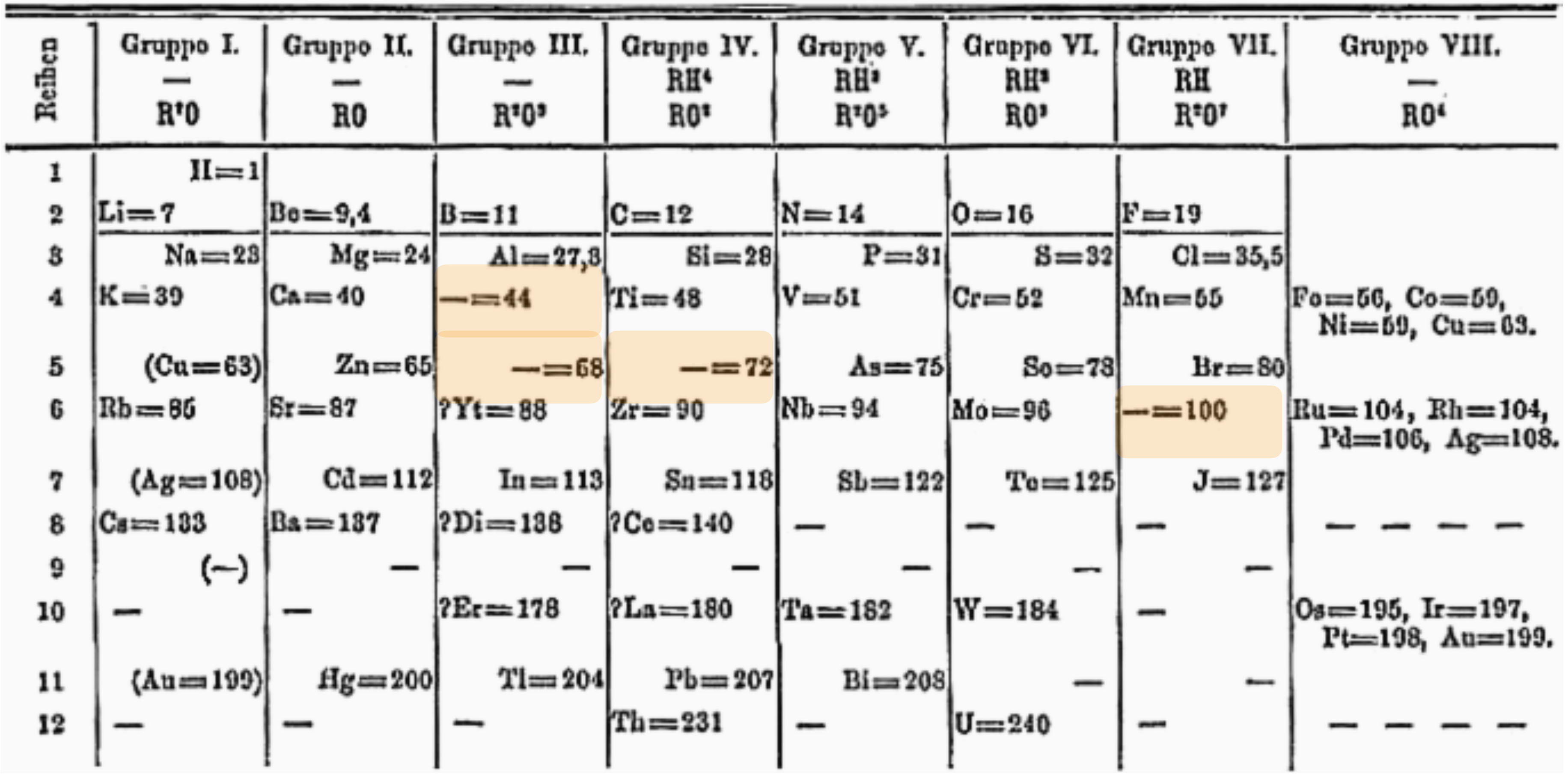
To narrow the search, we should look at other indications that the Standard model is not complete

Deficiency of the Standard Model:
neutrino masses and oscillations, Dark Matter



Mendeleev: example of successful approach

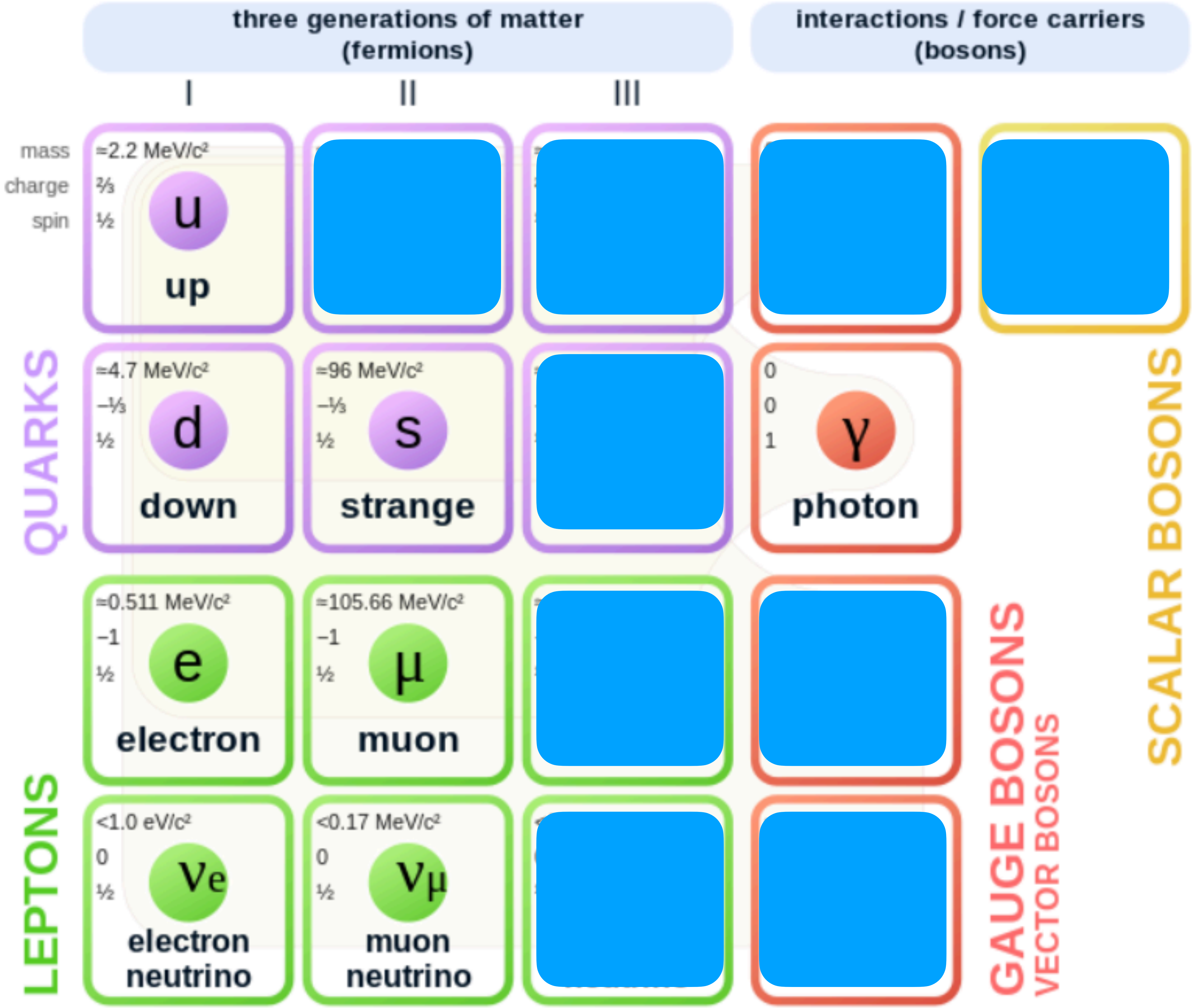
From 1871 Mendeleev article



Reihen	Gruppo I. — R^2O	Gruppo II. — RO	Gruppo III. — R^2O^3	Gruppo IV. RH^4 RO^2	Gruppo V. RH^3 R^2O^5	Gruppo VI. RH^2 RO^3	Gruppo VII. RH R^2O^7	Gruppo VIII. — RO^4
1	H=1							
2	Li=7	Be=9,4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27,3	Si=28	P=31	S=32	Cl=35,5	
4	K=39	Ca=40	—=44	Ti=48	V=51	Cr=52	Mn=55	Fe=56, Co=59, Ni=59, Cu=63.
5	(Cu=63)	Zn=65	—=68	—=72	As=75	Se=78	Br=80	
6	Rb=85	Sr=87	?Yt=88	Zr=90	Nb=94	Mo=96	—=100	Ru=104, Rh=104, Pd=106, Ag=108.
7	(Ag=108)	Cd=112	In=113	Sn=118	Sb=122	Te=125	J=127	
8	Cs=133	Ba=137	?Di=138	?Ce=140	—	—	—	— — — —
9	(—)	—	—	—	—	—	—	
10	—	—	?Er=178	?La=180	Ta=182	W=184	—	Os=195, Ir=197, Pt=198, Au=199.
11	(Au=199)	Hg=200	Tl=204	Pb=207	Bi=208	—	—	
12	—	—	—	Th=231	—	U=240	—	— — — —

Predictions: eka-boron, eka-aluminium, eca-silicon, eka-manganese

Standard Model of Elementary Particles



three generations of matter (fermions)

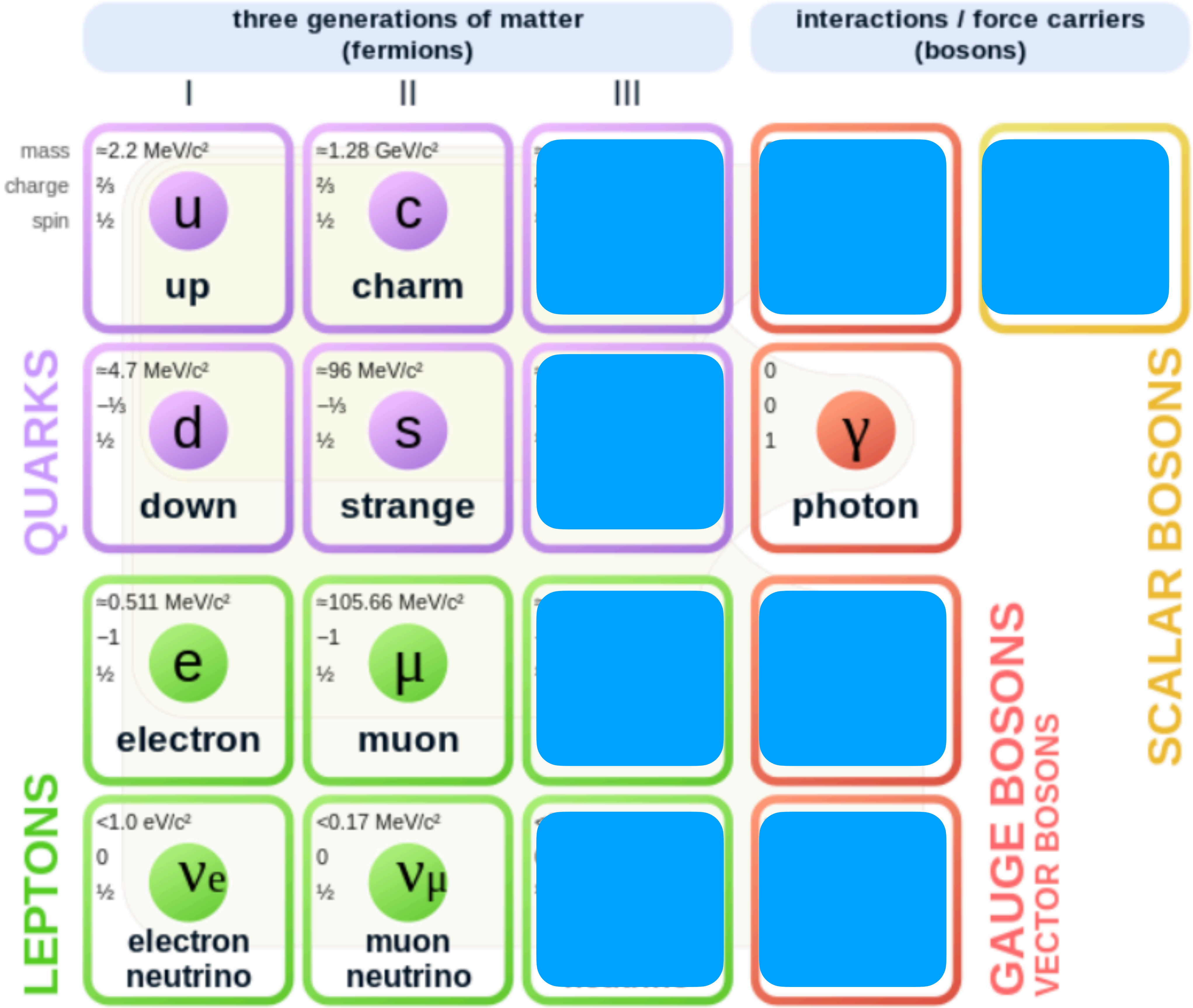
interactions / force carriers (bosons)

	I	II	III		
mass charge spin	≈2.2 MeV/c² ⅔ ½ u **up**				
QUARKS	≈4.7 MeV/c² −⅓ ½ d **down**	≈96 MeV/c² −⅓ ½ s **strange**		0 0 1 γ **photon**	
	≈0.511 MeV/c² −1 ½ e **electron**	≈105.66 MeV/c² −1 ½ μ **muon**			
LEPTONS	<1.0 eV/c² 0 ½ ν_e **electron neutrino**	<0.17 MeV/c² 0 ½ ν_μ **muon neutrino**			

GAUGE BOSONS
VECTOR BOSONS

SCALAR BOSONS

Standard Model of Elementary Particles



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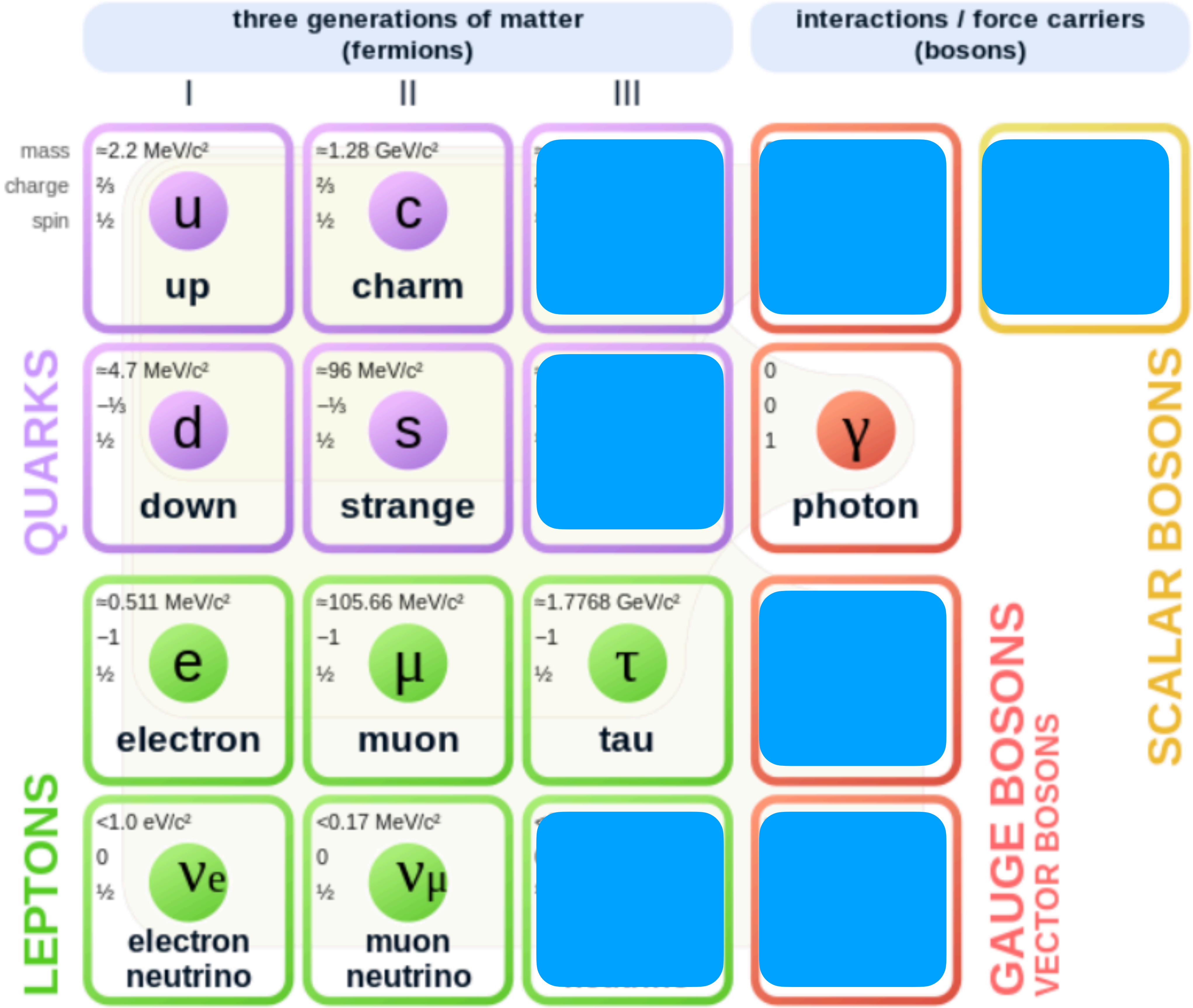

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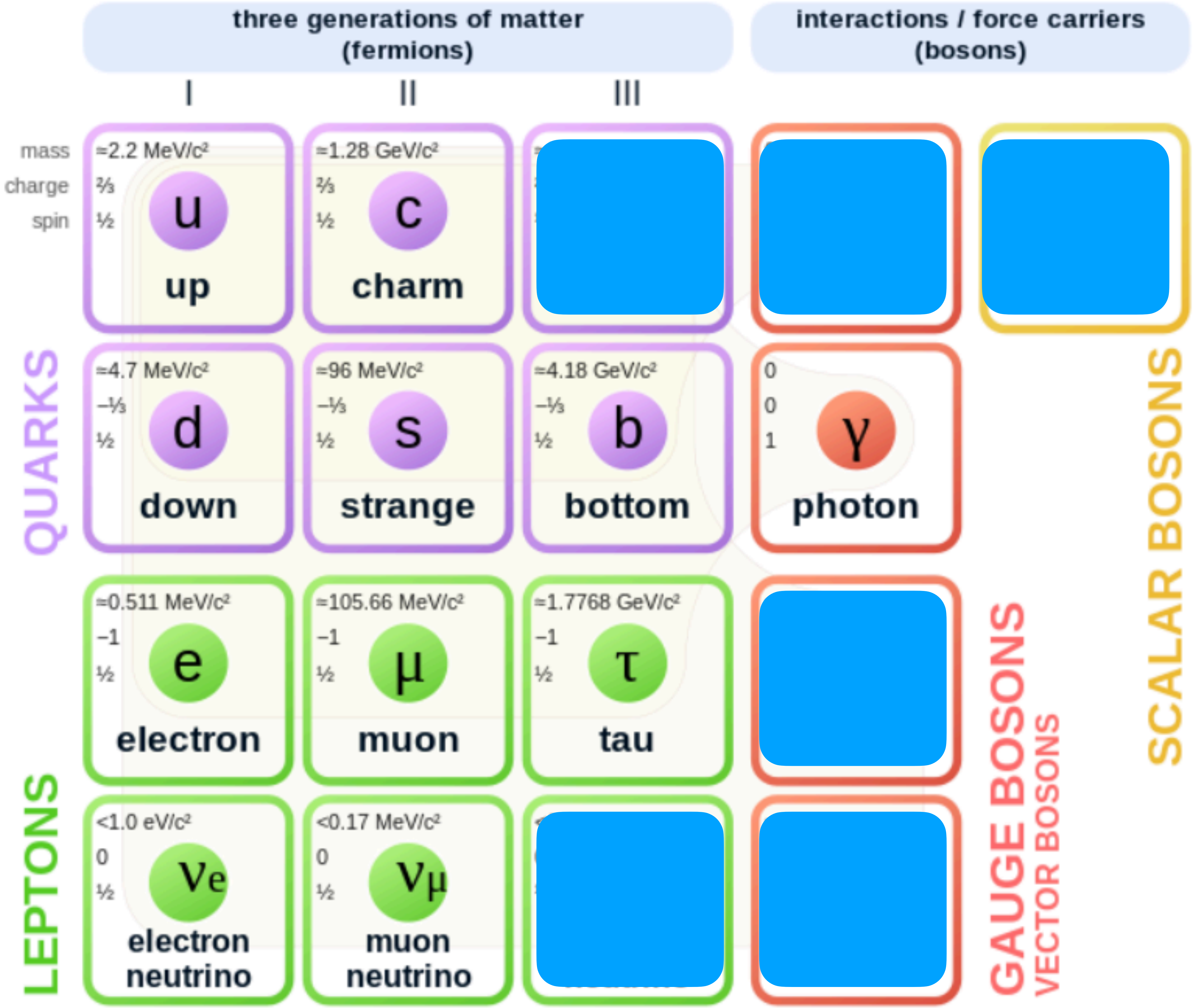

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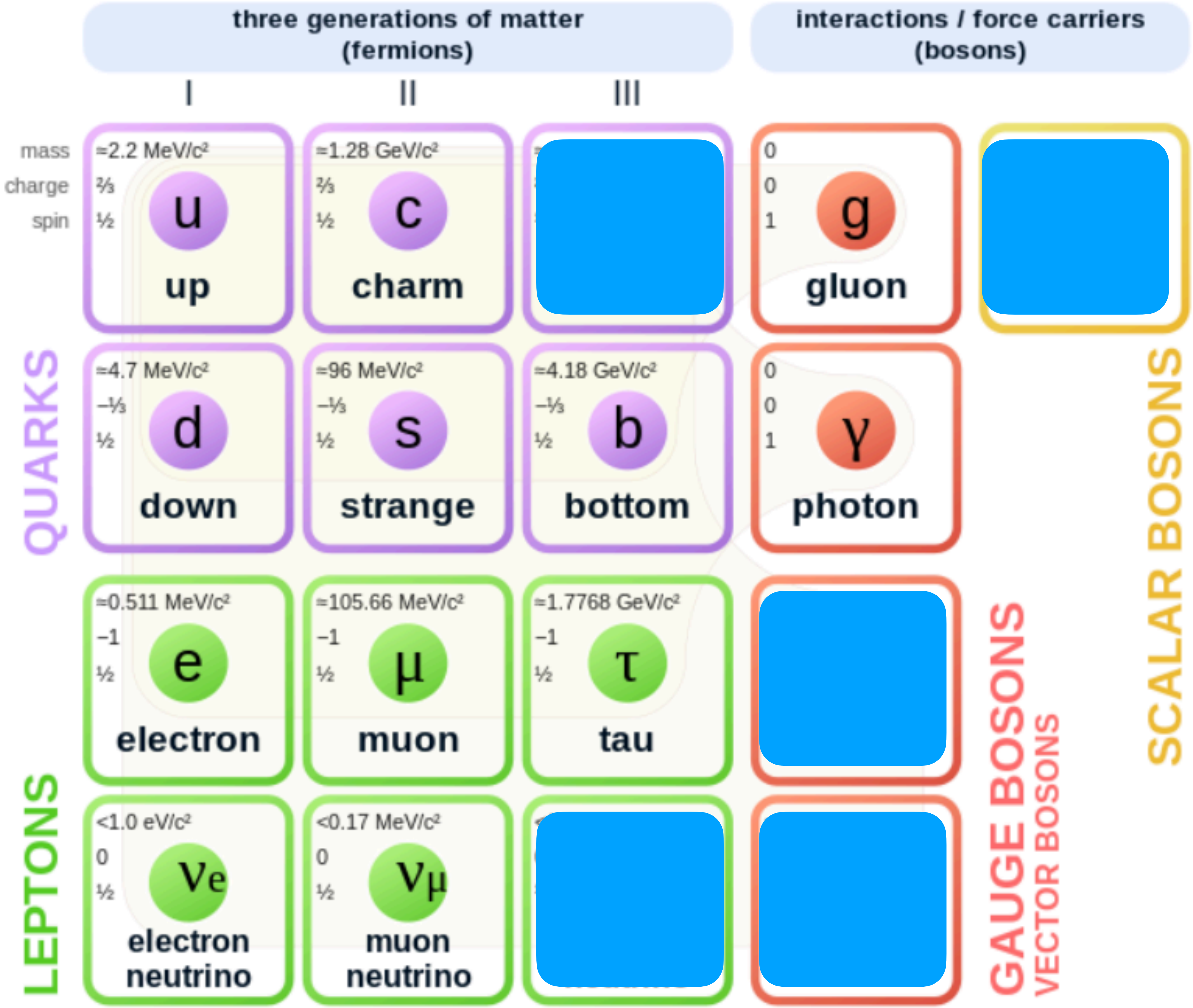

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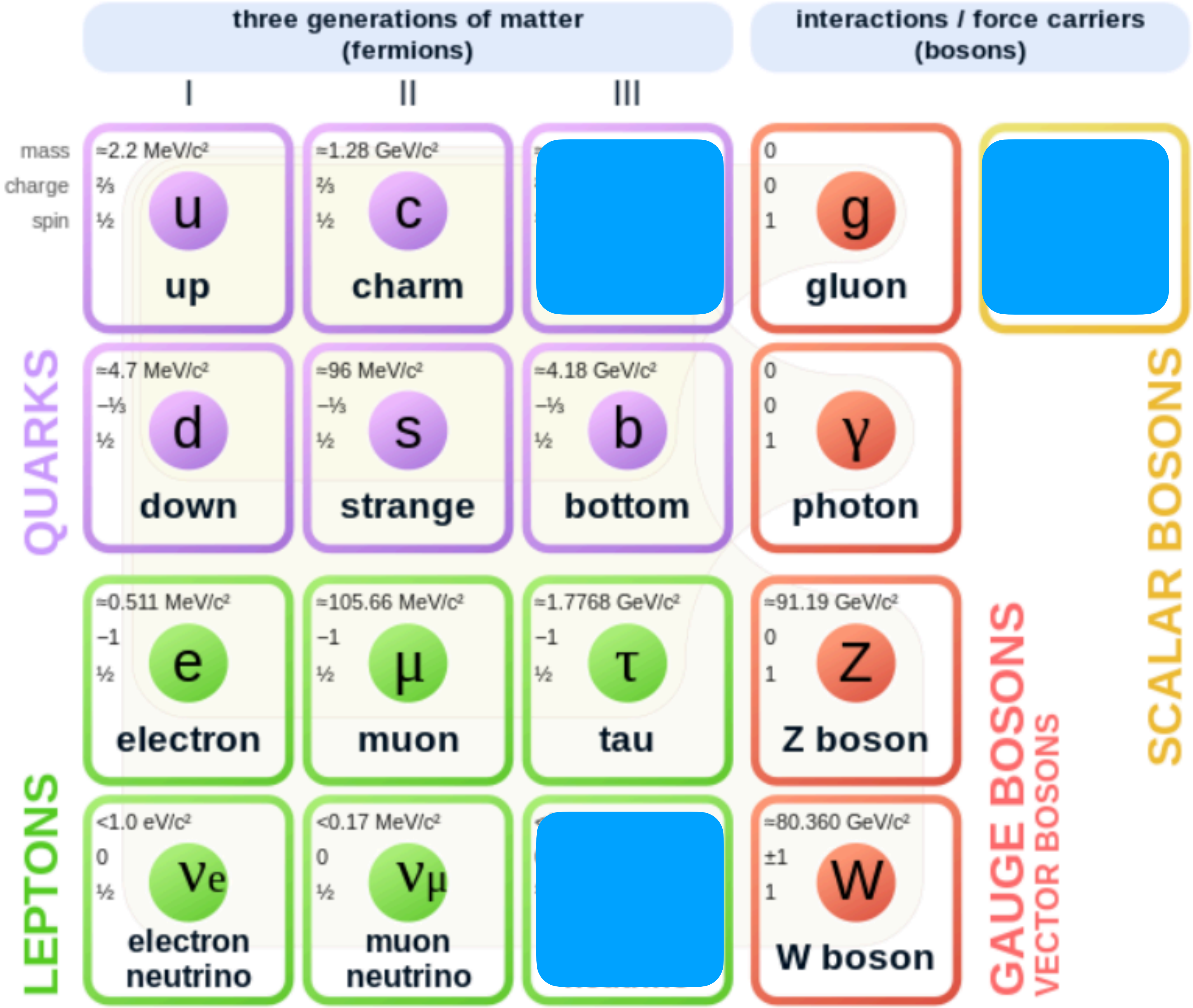

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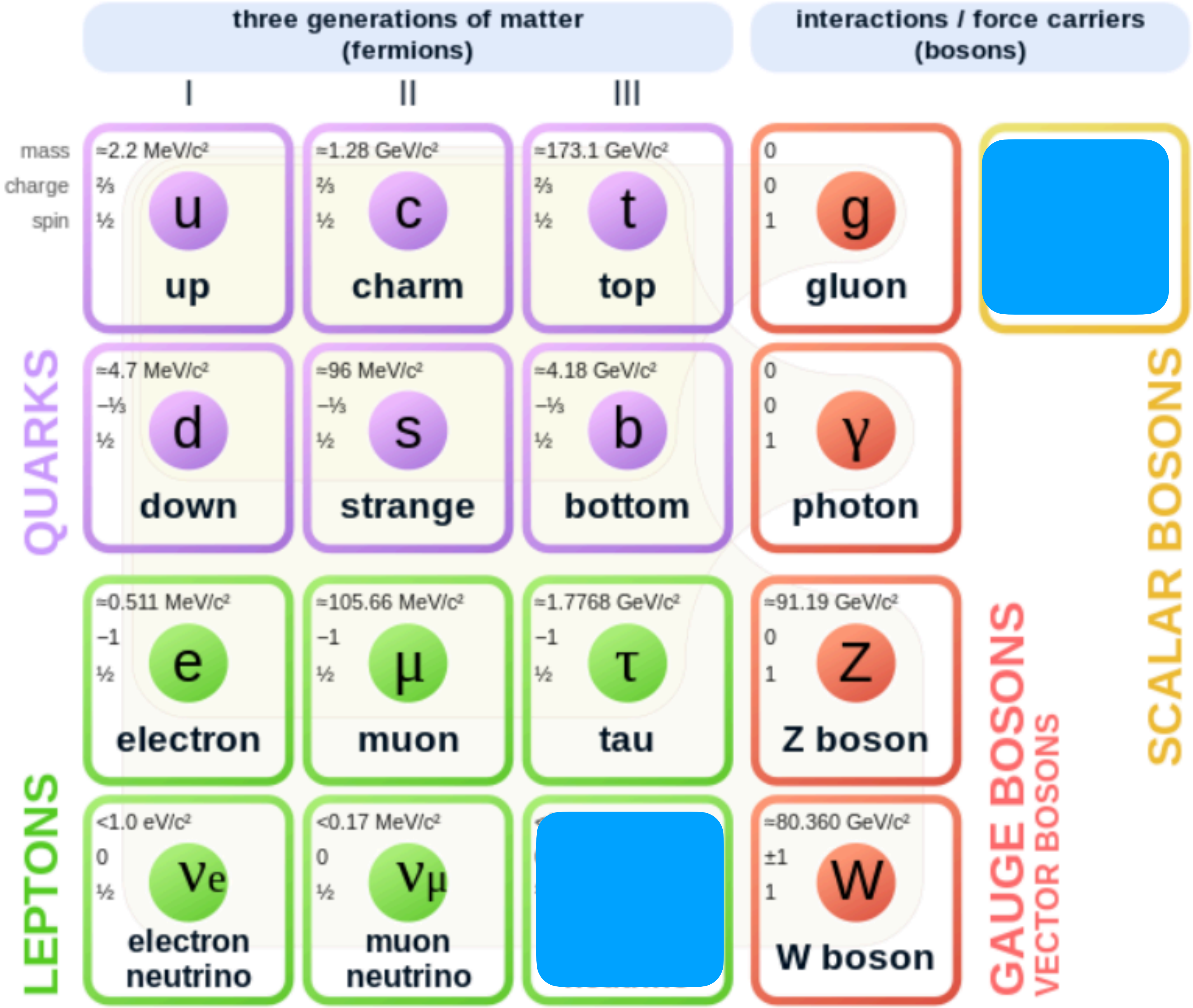

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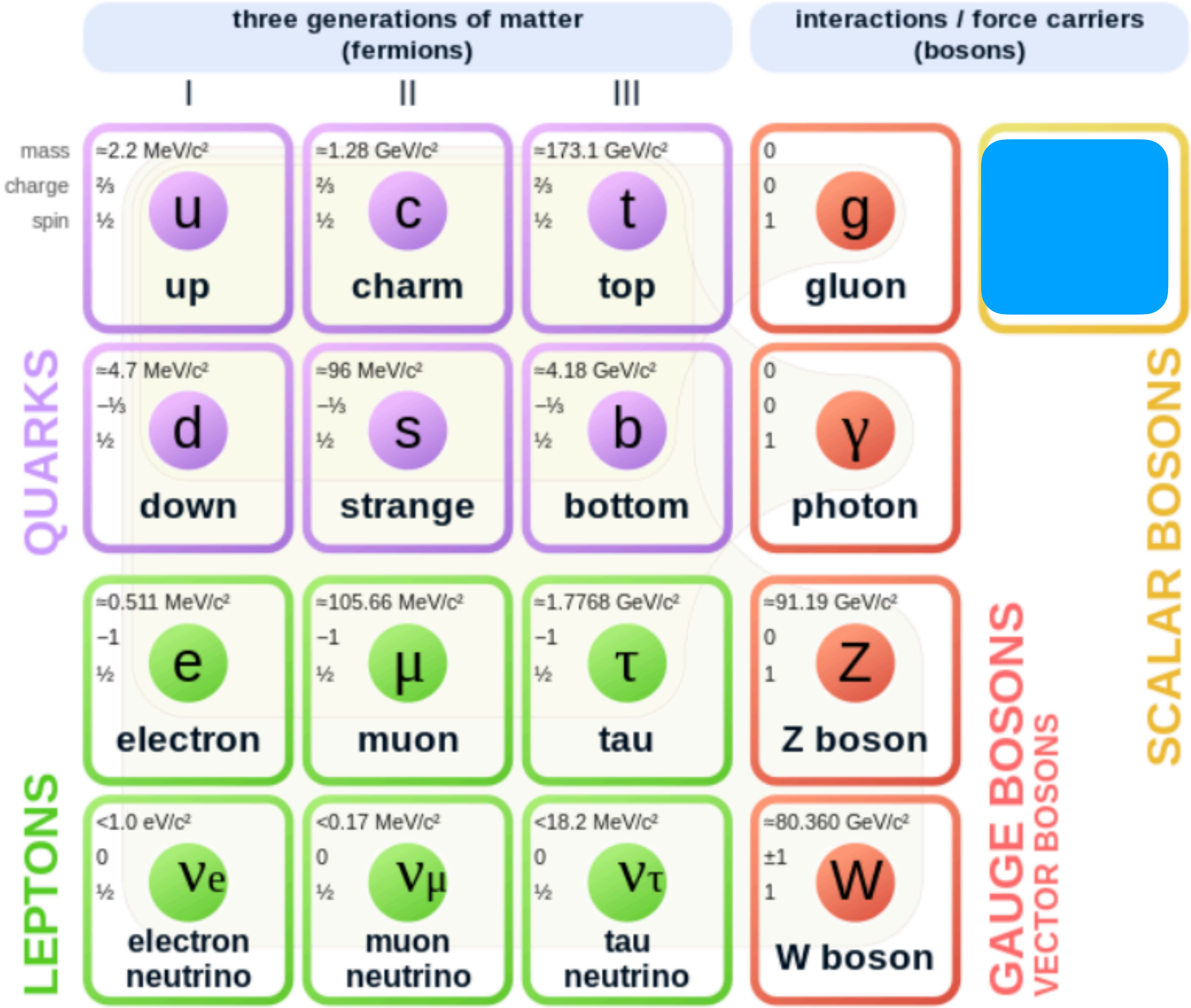

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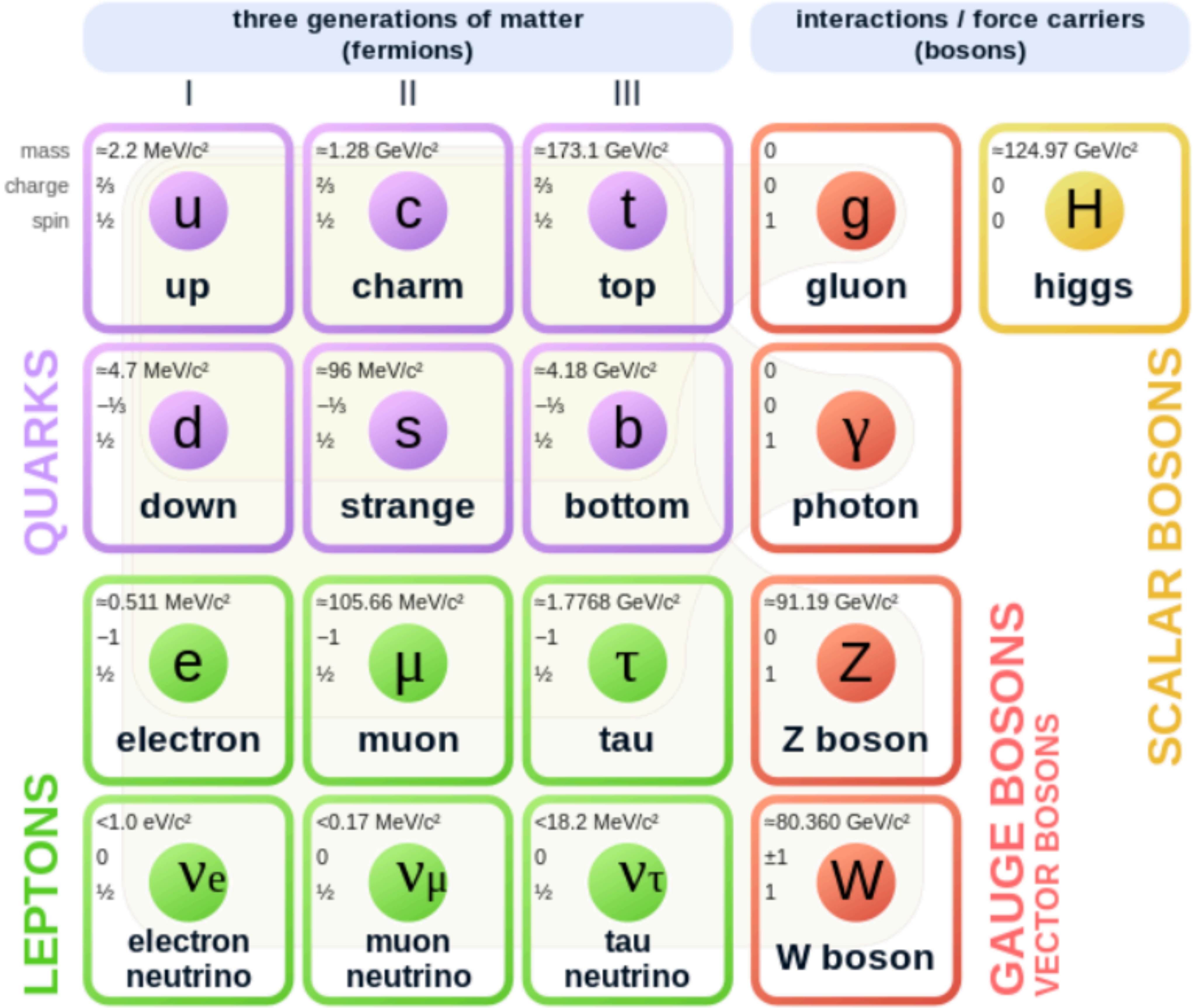

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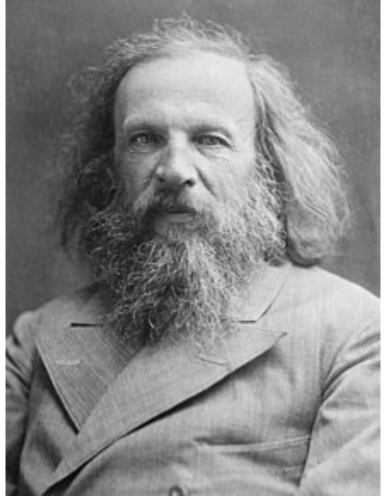
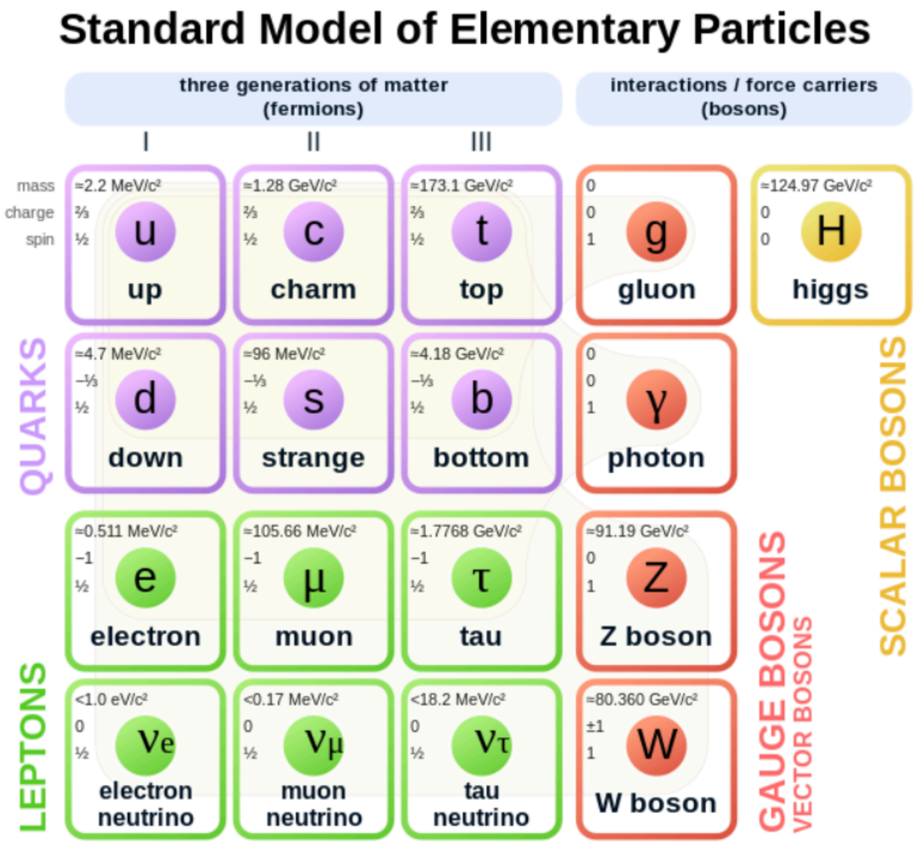
New particle every 5 years (in average, 1974-2012)!



Mendeleev approach to Standard Model



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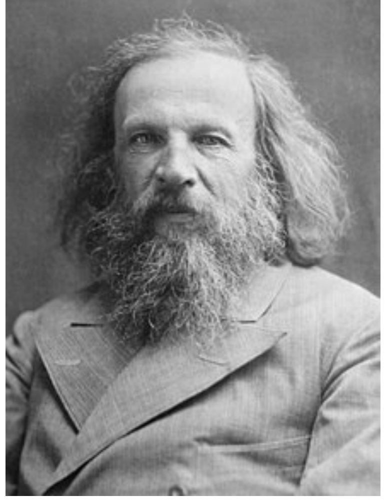
Wikipedia picture



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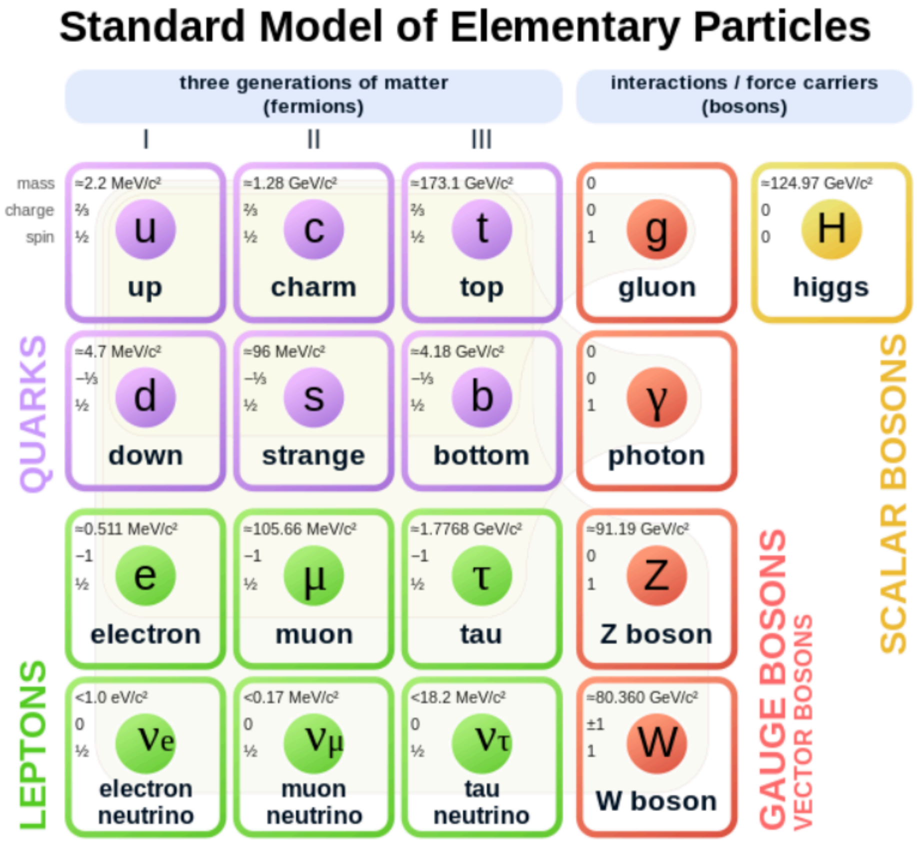
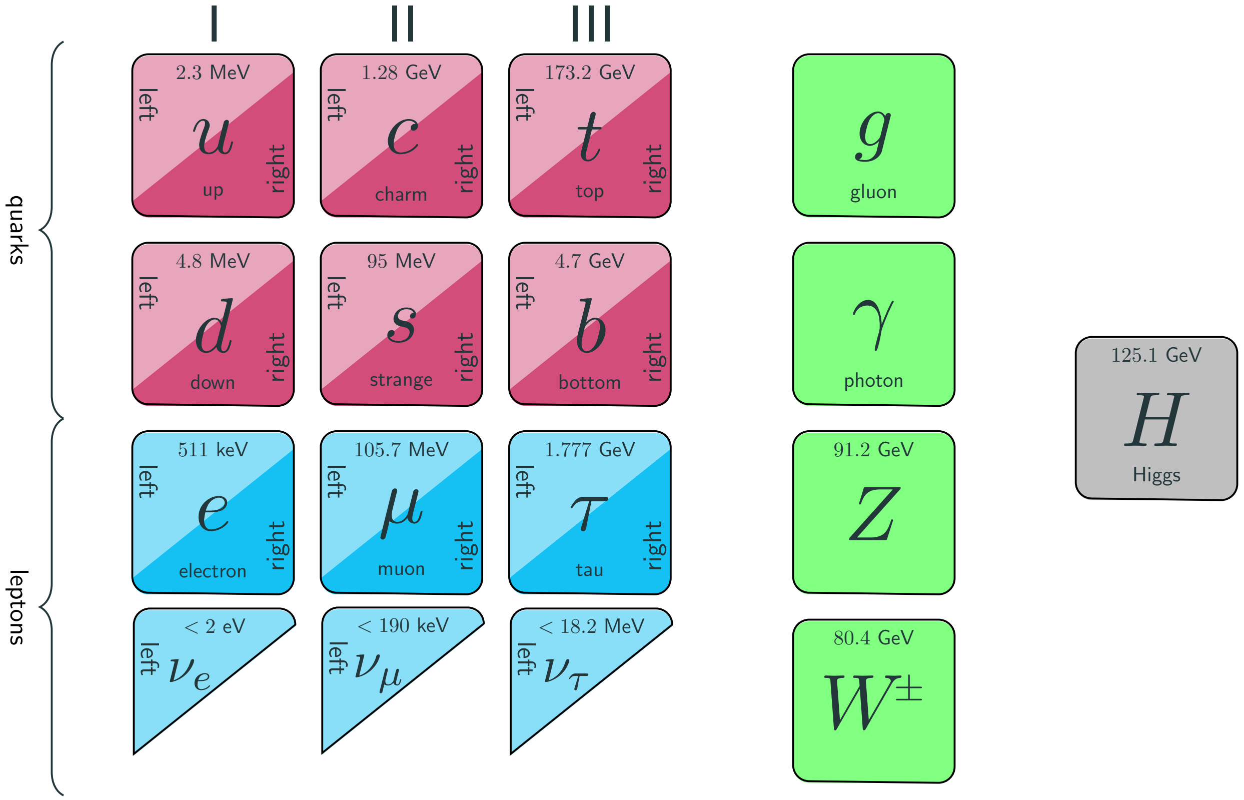
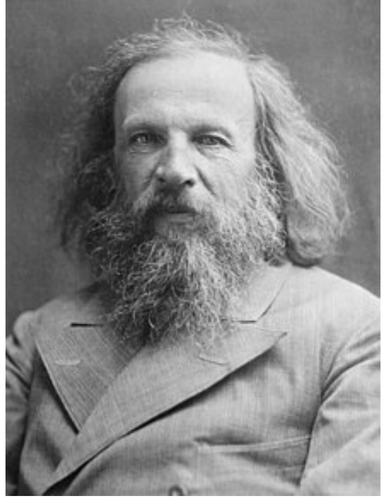




Wikipedia picture

Accurate picture



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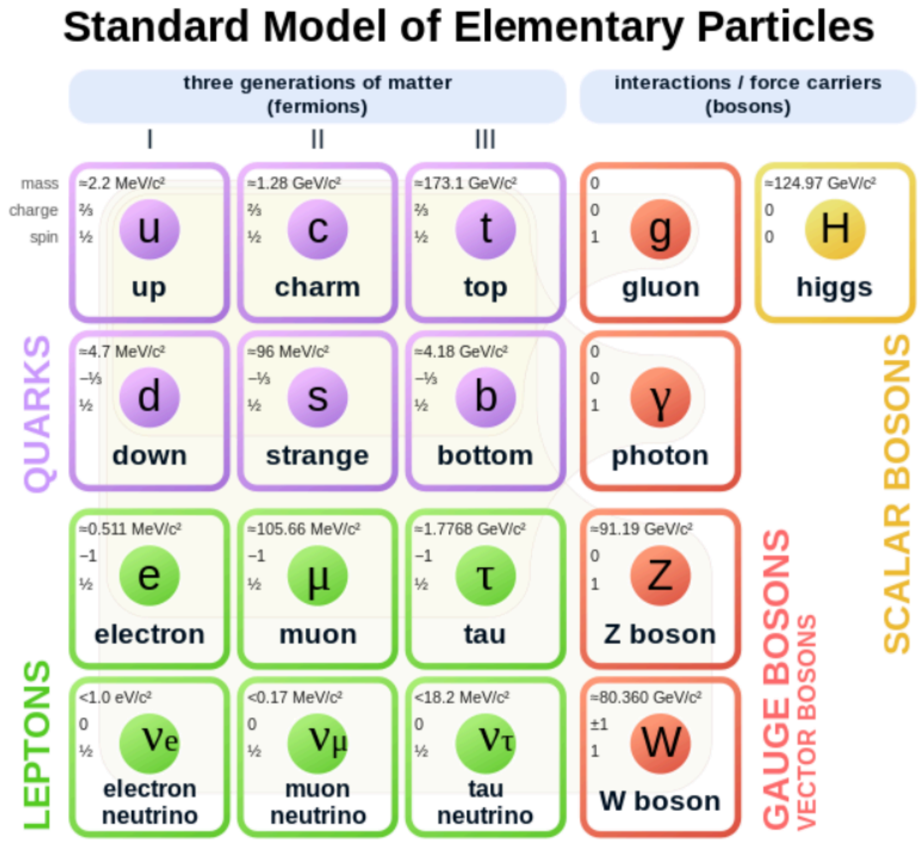

Standard Model of Elementary Particles

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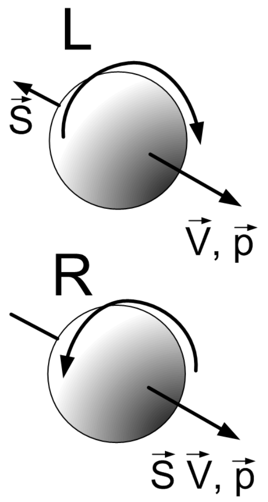
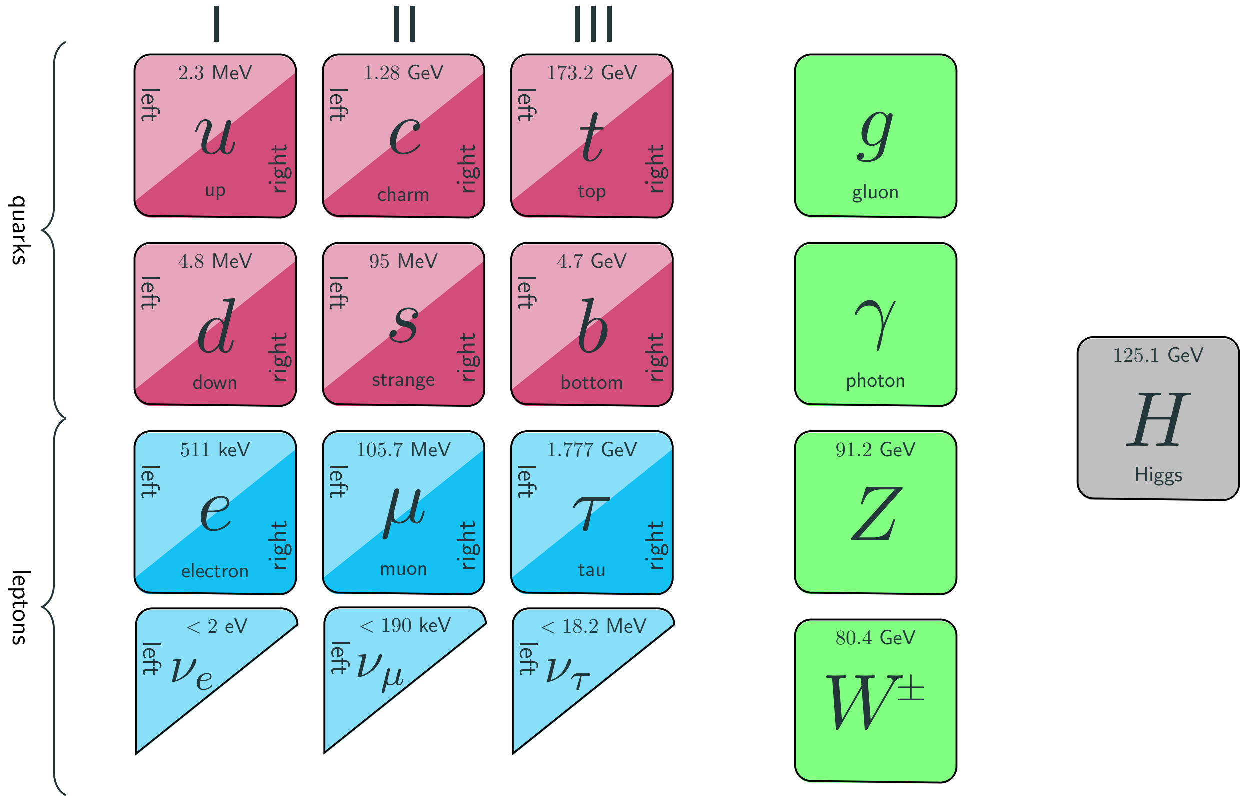


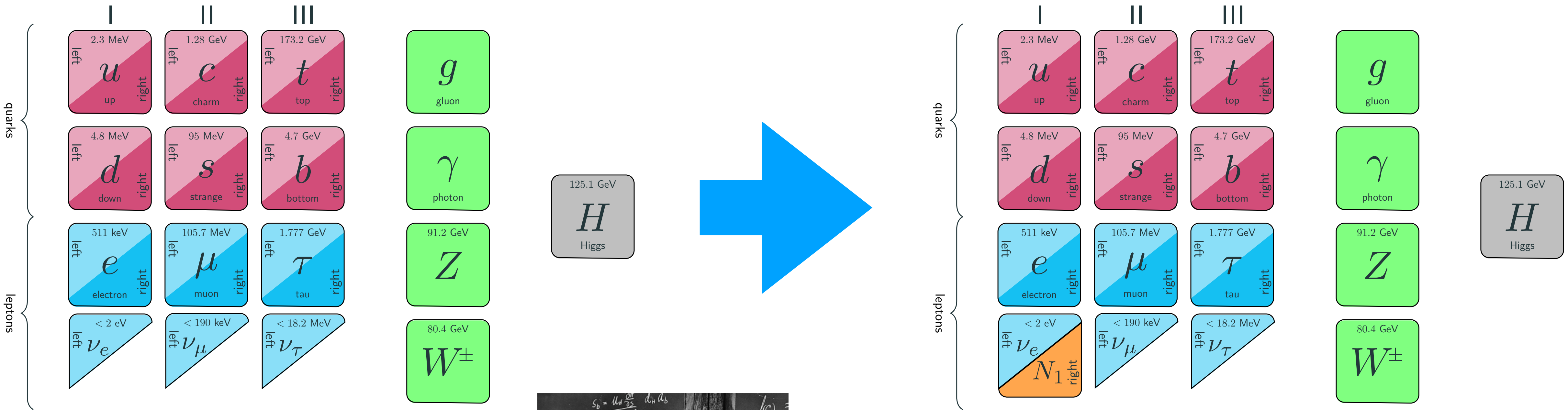


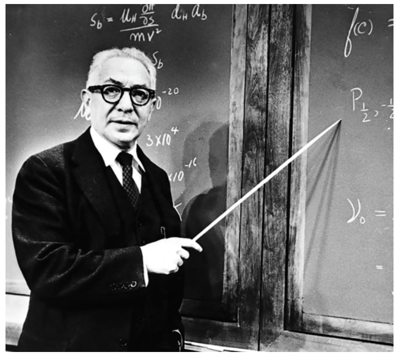
	I	II	III		
quarks	2.3 MeV left u right up	1.28 GeV left c right charm	173.2 GeV left t right top	g gluon	
	4.8 MeV left d right down	95 MeV left s right strange	4.7 GeV left b right bottom	γ photon	125.1 GeV H Higgs
leptons	511 keV left e right electron	105.7 MeV left μ right muon	1.777 GeV left τ right tau	91.2 GeV Z	
	< 2 eV left ν_e	< 190 keV left ν_μ	< 18.2 MeV left ν_τ	80.4 GeV $W^\pm$	

Wikipedia picture

Accurate picture

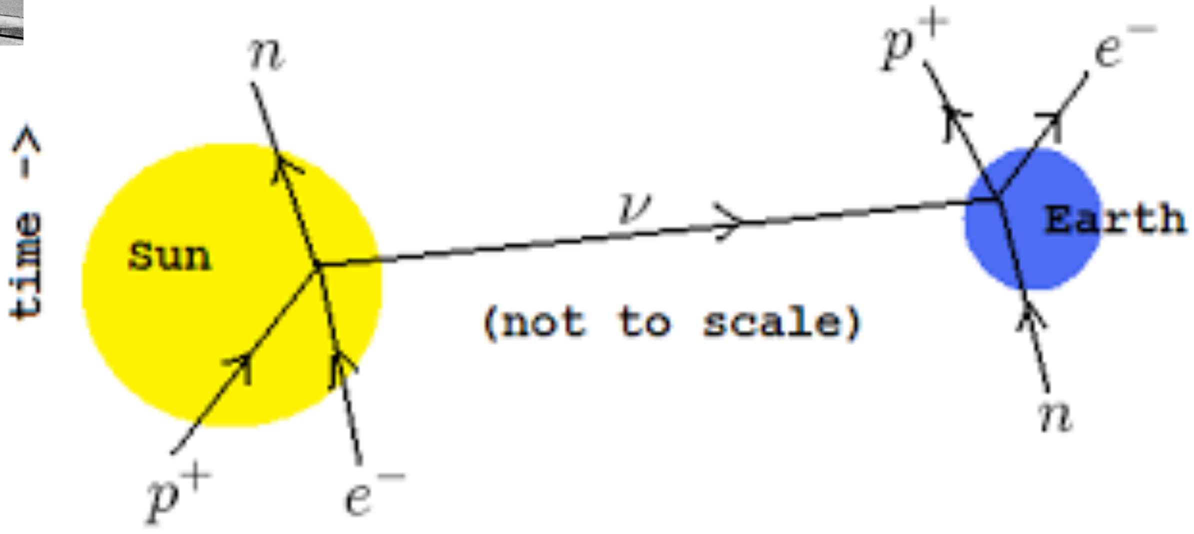
Filling the boxes





Who ordered that?

⇒ Solar neutrino oscillations are explained



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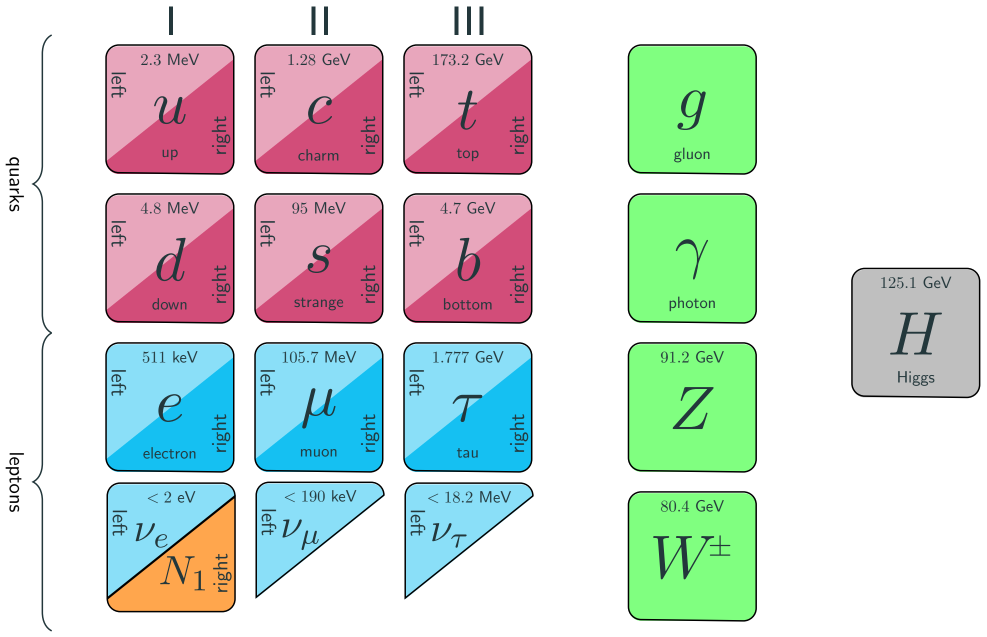

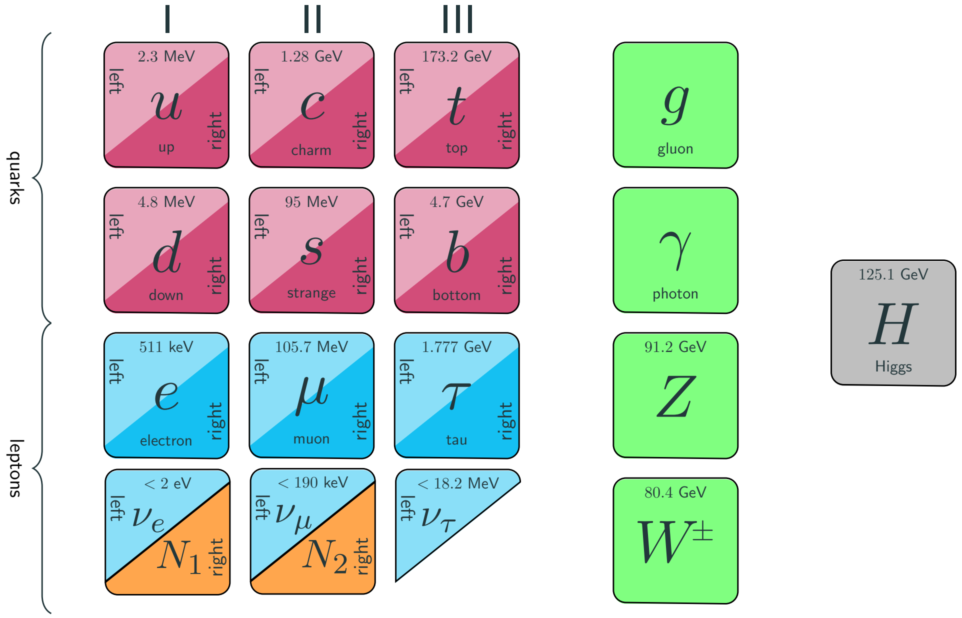

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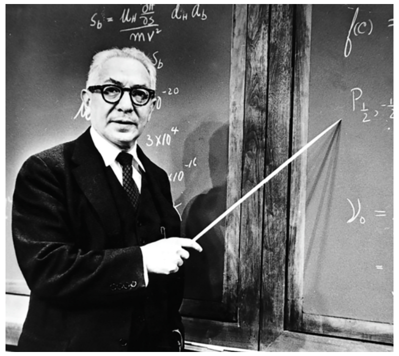
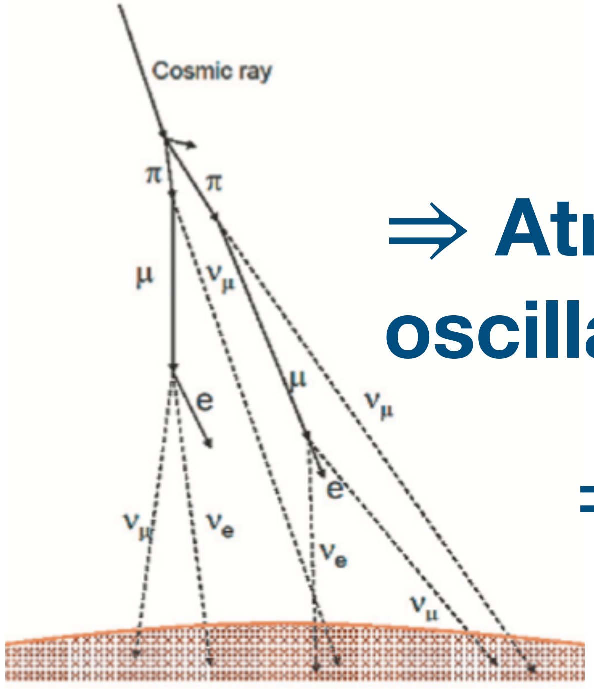
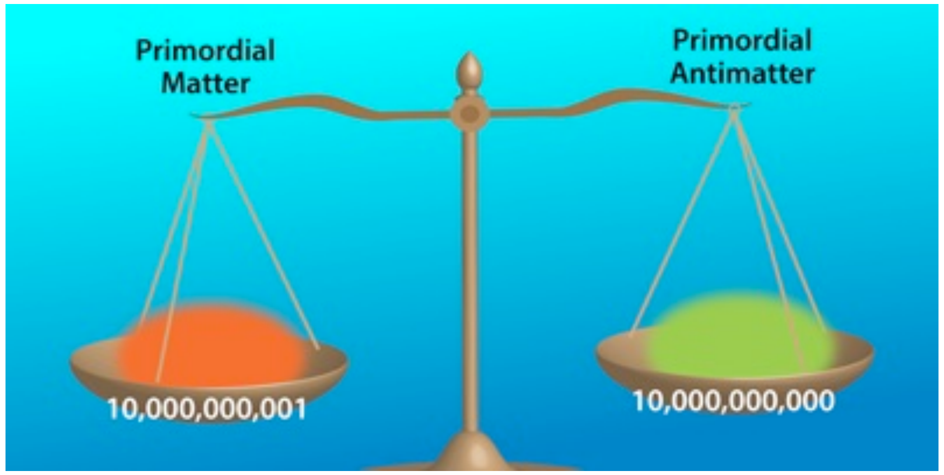




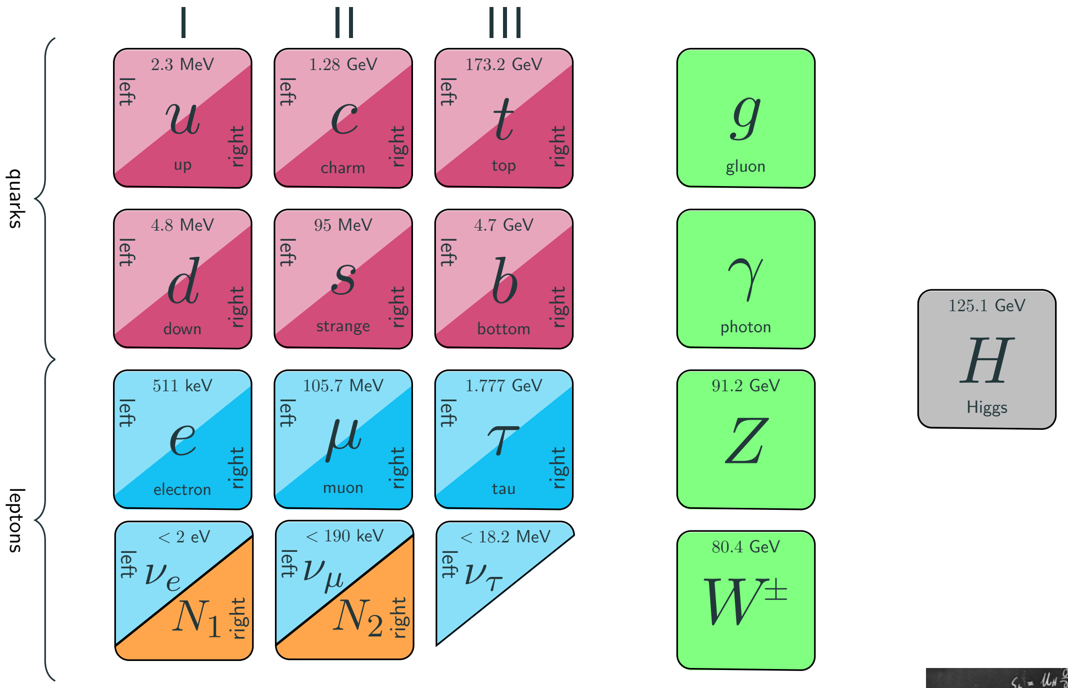
⇒ Atmospheric neutrino oscillations can be explained

⇒ All neutrino physics can be understood



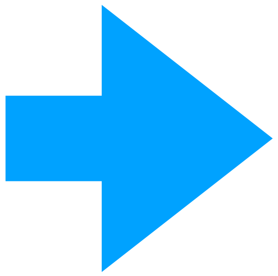
⇒ Baryon asymmetry of the Universe can be explained.

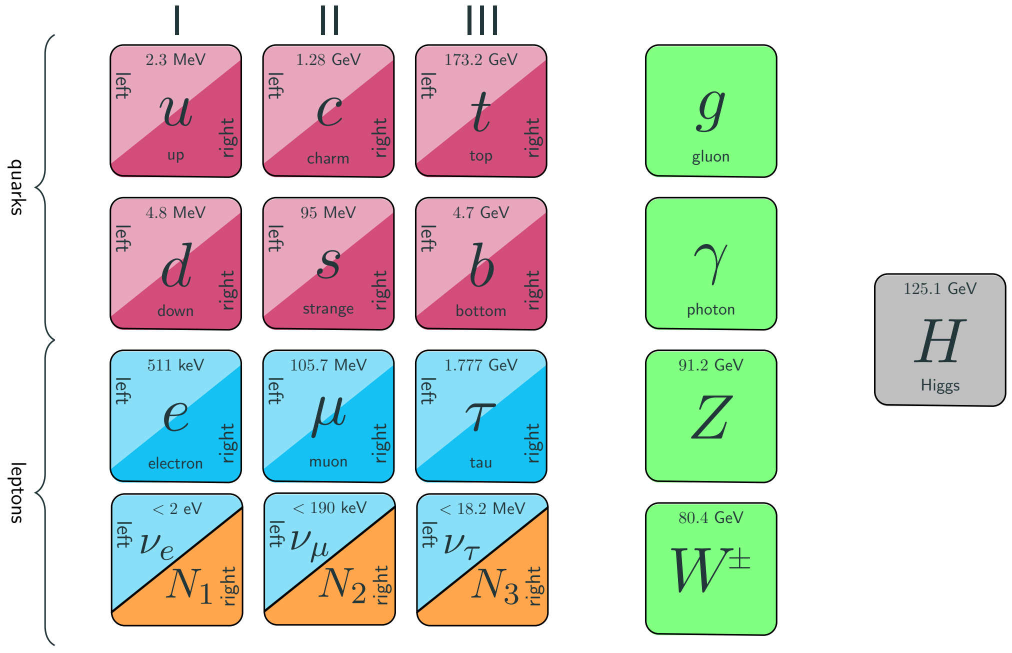
Filling the boxes



	I	II	III	
quarks	2.3 MeV u up	1.28 GeV c charm	173.2 GeV t top	g gluon
	4.8 MeV d down	95 MeV s strange	4.7 GeV b bottom	γ photon
leptons	511 keV e electron	105.7 MeV μ muon	1.777 GeV τ tau	91.2 GeV Z
	< 2 eV ν_e N_1	< 190 keV ν_μ N_2	< 18.2 MeV ν_τ	80.4 GeV $W^\pm$

125.1 GeV
H
Higgs





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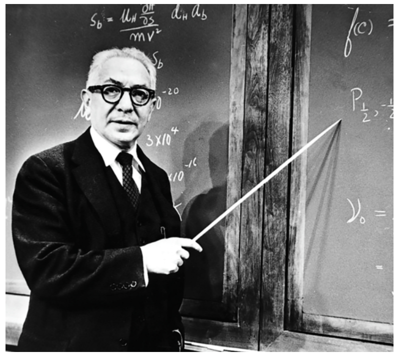
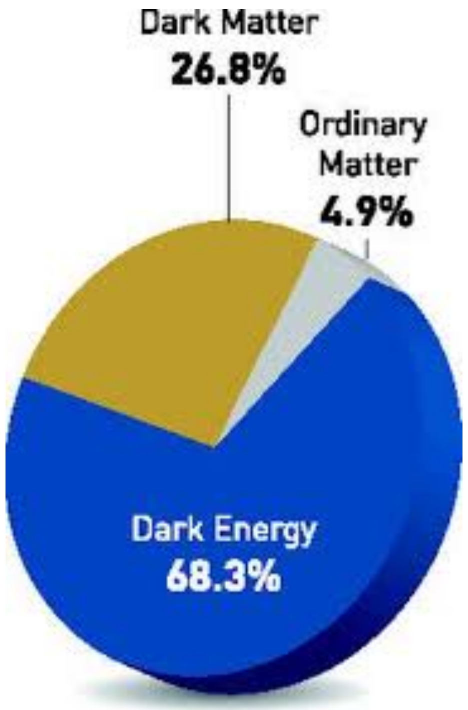




Who ordered that?

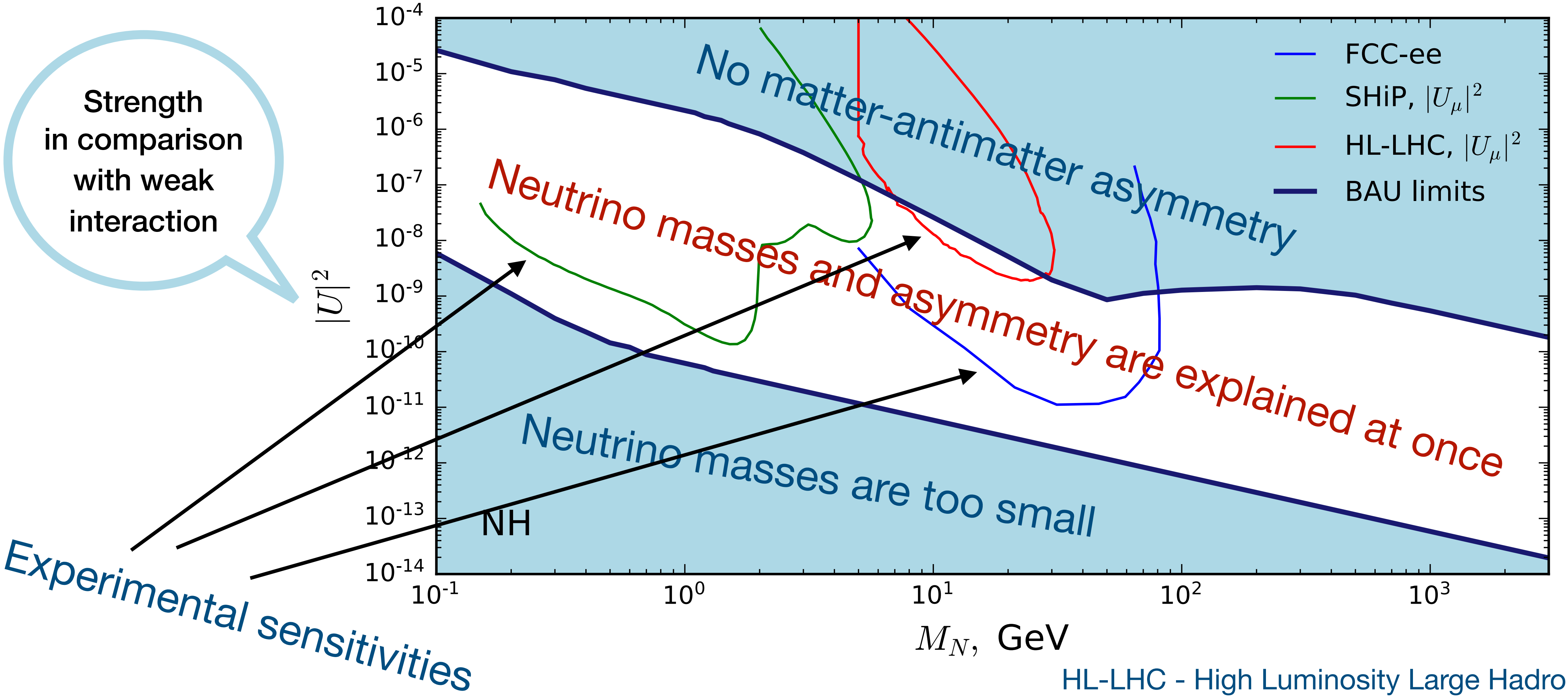
⇒ Dark matter in the Universe can be explained.

New particles are called “Heavy neutral leptons”, sometimes sterile neutrinos.

νMSM-neutrino minimal SM, or low scale minimal type I see-saw model.

Matter-antimatter asymmetry and neutrino masses in the νMSM: $N_{2,3}$

figure from Klaric, Timiryasov, MS



HL-LHC - High Luminosity Large Hadron Collider
BAU - Baryon asymmetry of the Universe
NH - normal neutrino hierarchy

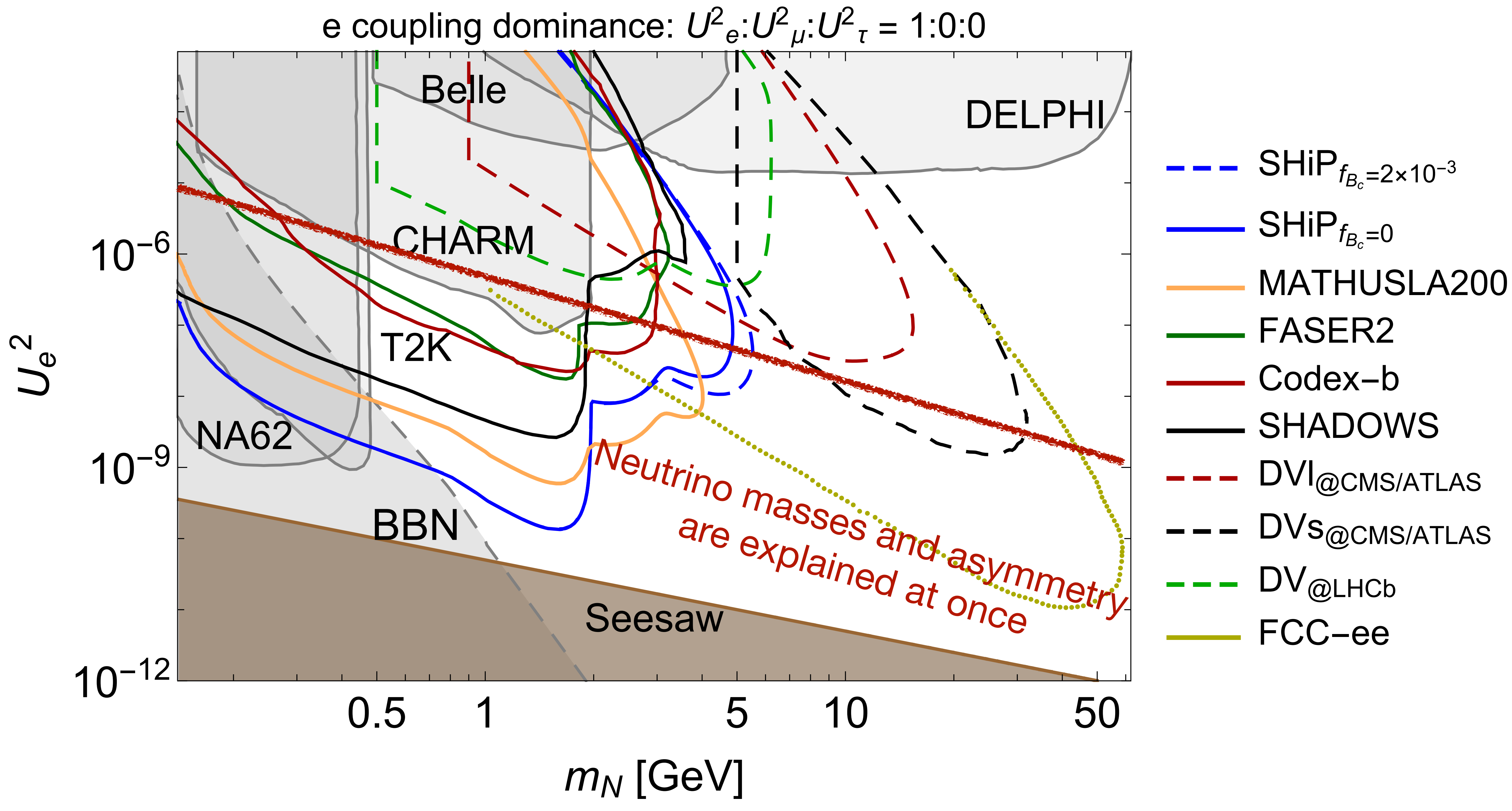
The mechanisms of neutrino mass and matter-antimatter asymmetry generation can be verified experimentally!

Experimental challenges of HNL searches:

HNL production and decays are highly suppressed – dedicated experiments are needed:

- Mass below ~ 5 GeV - Intensity frontier, CERN SPS: SHiP
- Mass above ~ 5 GeV - FCC in e+e– mode in Z-peak, LHC

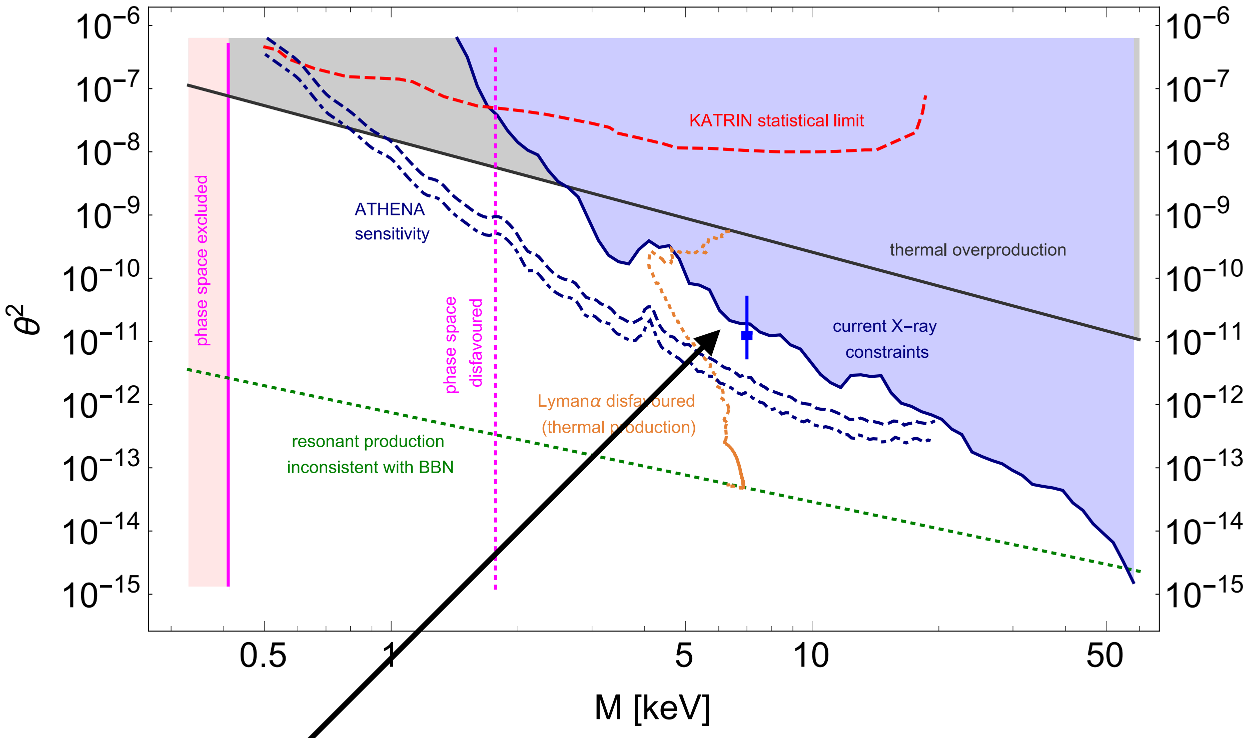
Projection of bounds on HNLs



Dark Matter in the νMSM: N$_1$

Dark matter sterile neutrino N$_1$: long-lived light particle (mass in the keV region) with the life-time greater than the age of the Universe. It can decay as $N_1 \to \gamma\nu$, what allows for experimental detection by X-ray telescopes in space. Future experimental searches: Hitomi-like satellite XRISM (2023), Large ESA X-ray mission, Athena + (2028?)

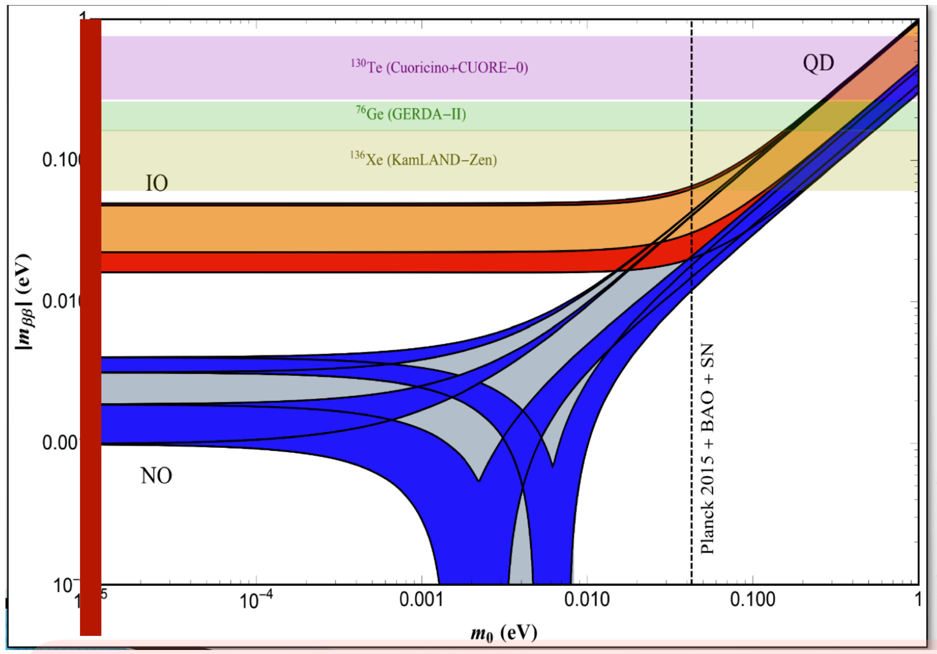
Available parameter space, current situation



Possible detection (?), controversial

Bulbul et al; Boyarsky et al

Prediction for neutrinoless double beta decay:



Hagedorn et al., Int.J.Mod.Phys.A 33 (2018) 05n06, 1842006

Prediction from Dark Matter: minimal neutrino mass $< 10^{-5}$ eV

Conclusions

- Both baryon asymmetry of the Universe and Dark Matter may have their roots in neutrino physics.
- Traditional goals of neutrino physics should be supplemented by the HNL searches. PMNS+neutrino masses are not enough to uncover the origin of neutrino masses, dark matter and baryon asymmetry.

The planned future experiments such as SHiP and FCC-ee in the Z-resonance mode have chances to uncover the origin of neutrino masses and baryon asymmetry of the Universe, whereas X-ray telescopes have chances to find sterile neutrino dark matter.