How many new particles do we need?

Mikhail Shaposhnikov

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Based on works with

Takehiko Asaka, Fedor Bezrukov, Steve Blanchet, Alexey Boyarsky, Laurent Canetti, Marco Drewes, Shintaro Eijima, Juan Garcia-Bellido, Dmitry Gorbunov, Georgios Karananas, Juraj Klaric, Mikko Laine, Javier Rubio, Oleg Ruchayskiy, Andrey Shkerin, Inar Timiryasov, Sebastian Zell, and Daniel Zenhausern

How many particles exist in Nature?
Have we found all of them?
How many new particles still remain to be discovered?

These are different questions:

- If new particles are very heavy, we cannot make an accelerator to create them in collisions of protons or electrons. Example: Majorana see-saw neutrinos with masses above TeV.

- If new particles interact very weakly we will not be able to detect them. Example: axion with too weak coupling.

Possible clues for the answers:

- Theoretical prejudice - we may not like how the Standard Model is constructed, many “why’s”:
    - why 3 generations of fermions?
    - why the top quark is much heavier than electron?
    - how to unify all interactions with gravity?
    - etc, etc…
- Experimental guidance:
- Find where the Standard Model of particle physics cracks and cannot explain observations.
- Find what the cosmological observations need from particle physics.

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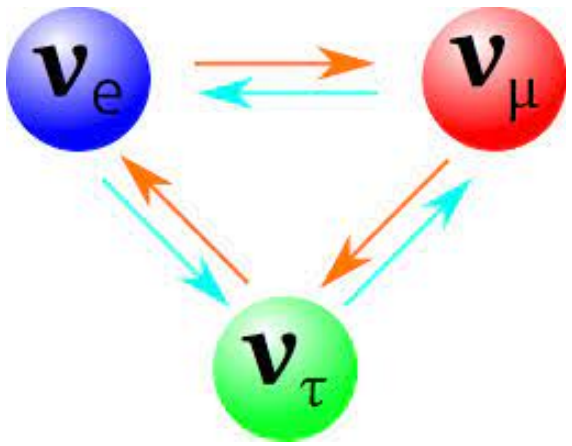
- 10^{32} new particles (e.g. suggested to solve the strong CP-problem in quantum chromodynamics).

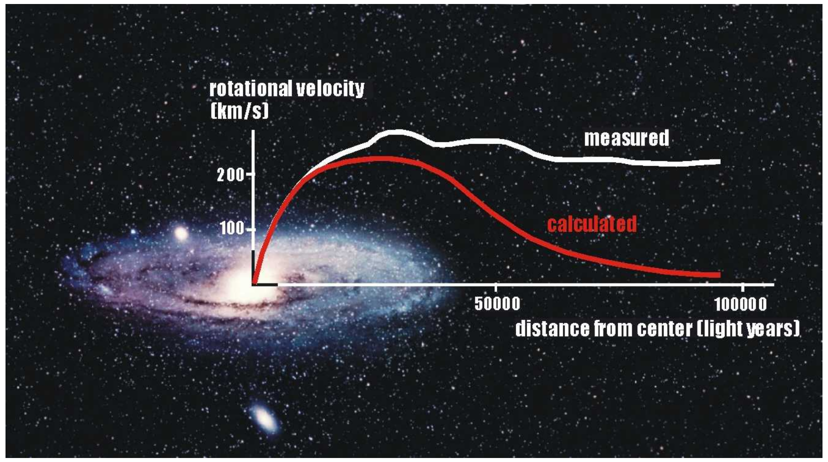
- Add ~ the same number as we already have in SM. Every particle has its supersymmetric partner. So far none were found, but many physicists were expected to see them at LEP and LHC.

Where the Standard Model of particle physics cracks

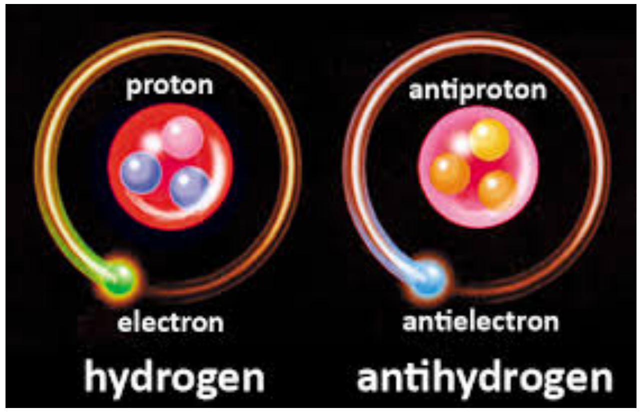
- In the Standard Model neutrinos are exactly massless. Experimentally neutrinos have tiny, but non-zero masses.



- Our Universe contains an unidentified substance: Dark Matter. None of the known particles can play the role of dark matter.

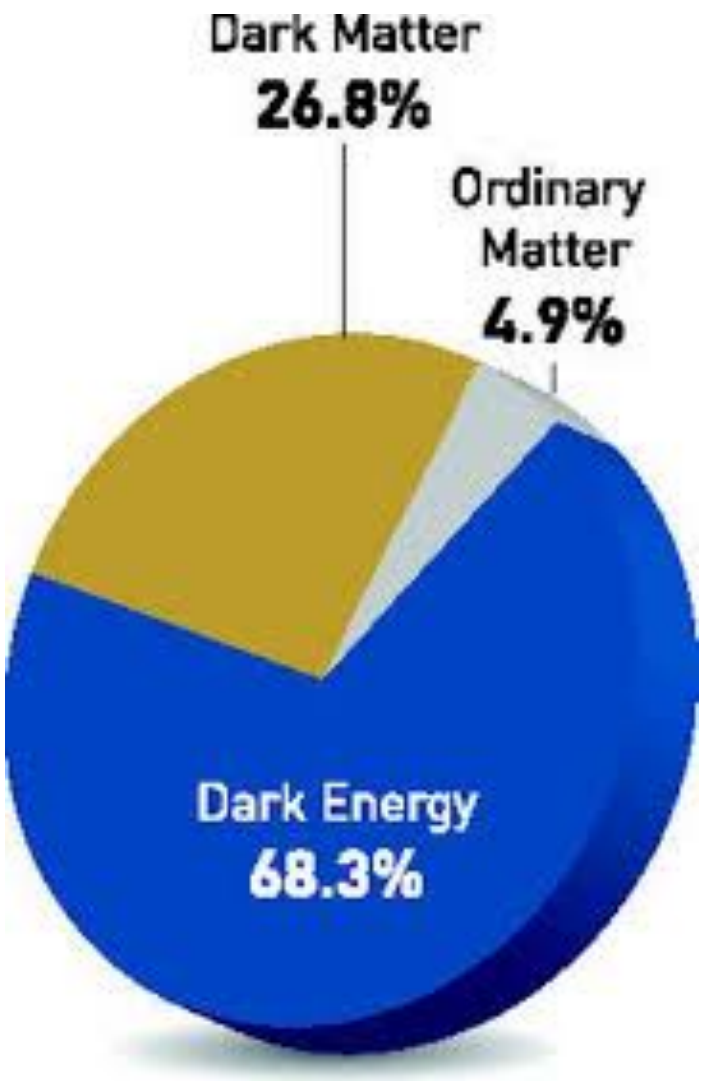


- Our Universe contains matter but no antimatter. The Standard Model fails to explain this.

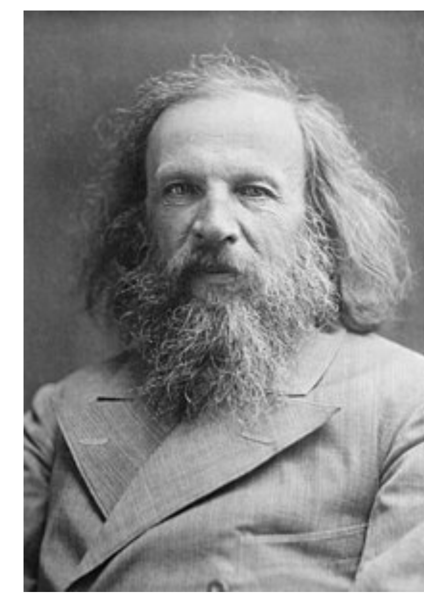


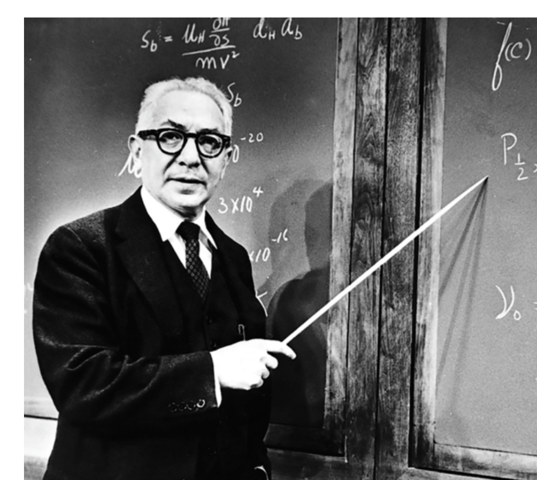
Early Universe: 50% matter, 50% antimatter. Now: everything annihilated.

Standard Model does not explain the composition of the Universe and therefore should be extended



Inspirations





- Ockham’s razor principle: “Frustra fit per plura quod potest fieri per pauciora” or “entities must not be multiplied beyond necessity” .

- Mendeleev in 1871 predicted several new elements by putting already known into a smart periodic table.

- Isaac Raby, when the muon was discovered in 1936, asked: “Who ordered that?” Everything should have a “Raison d’être”…

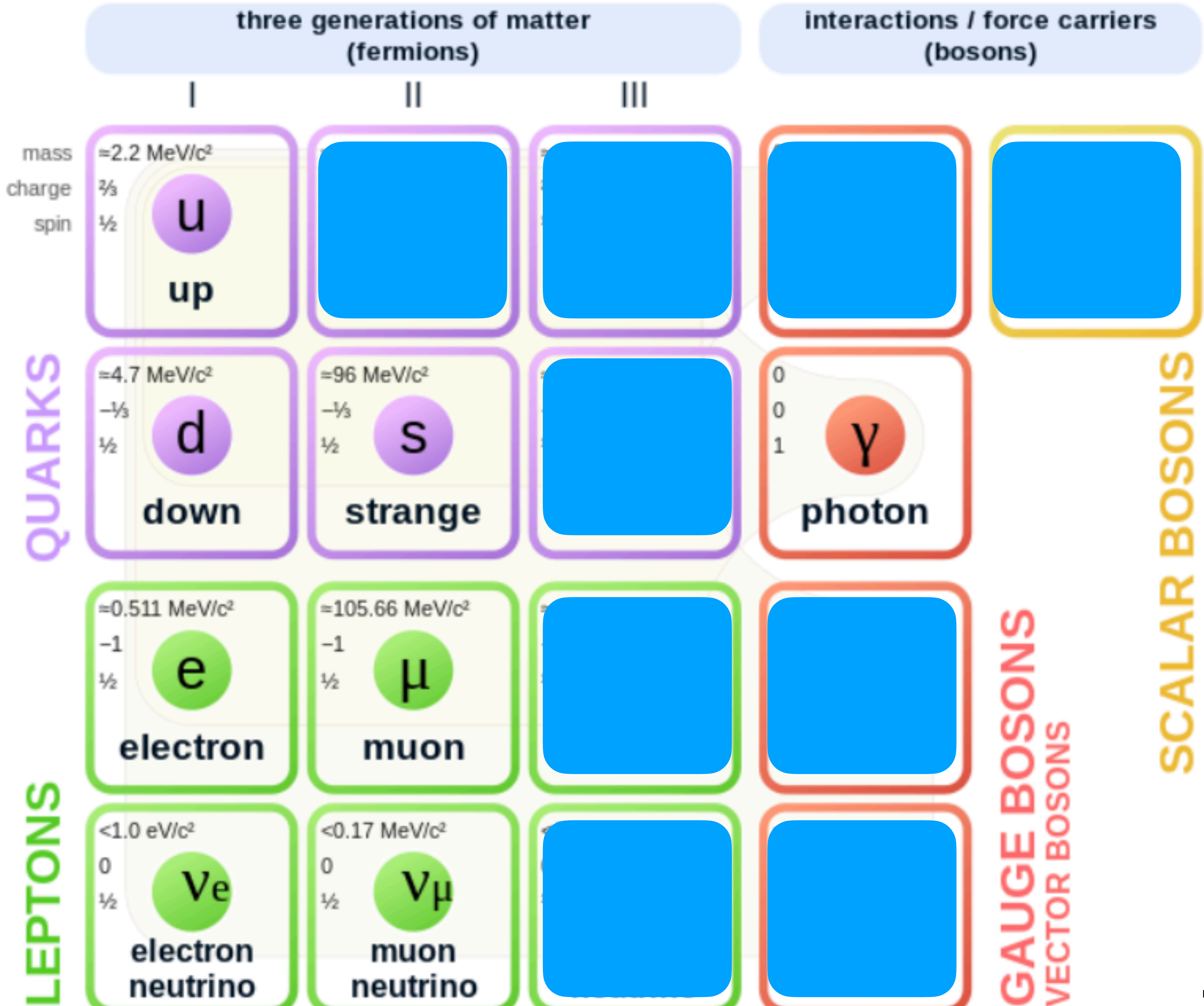
From Mendeleev to Standard Model

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	—	— — — —

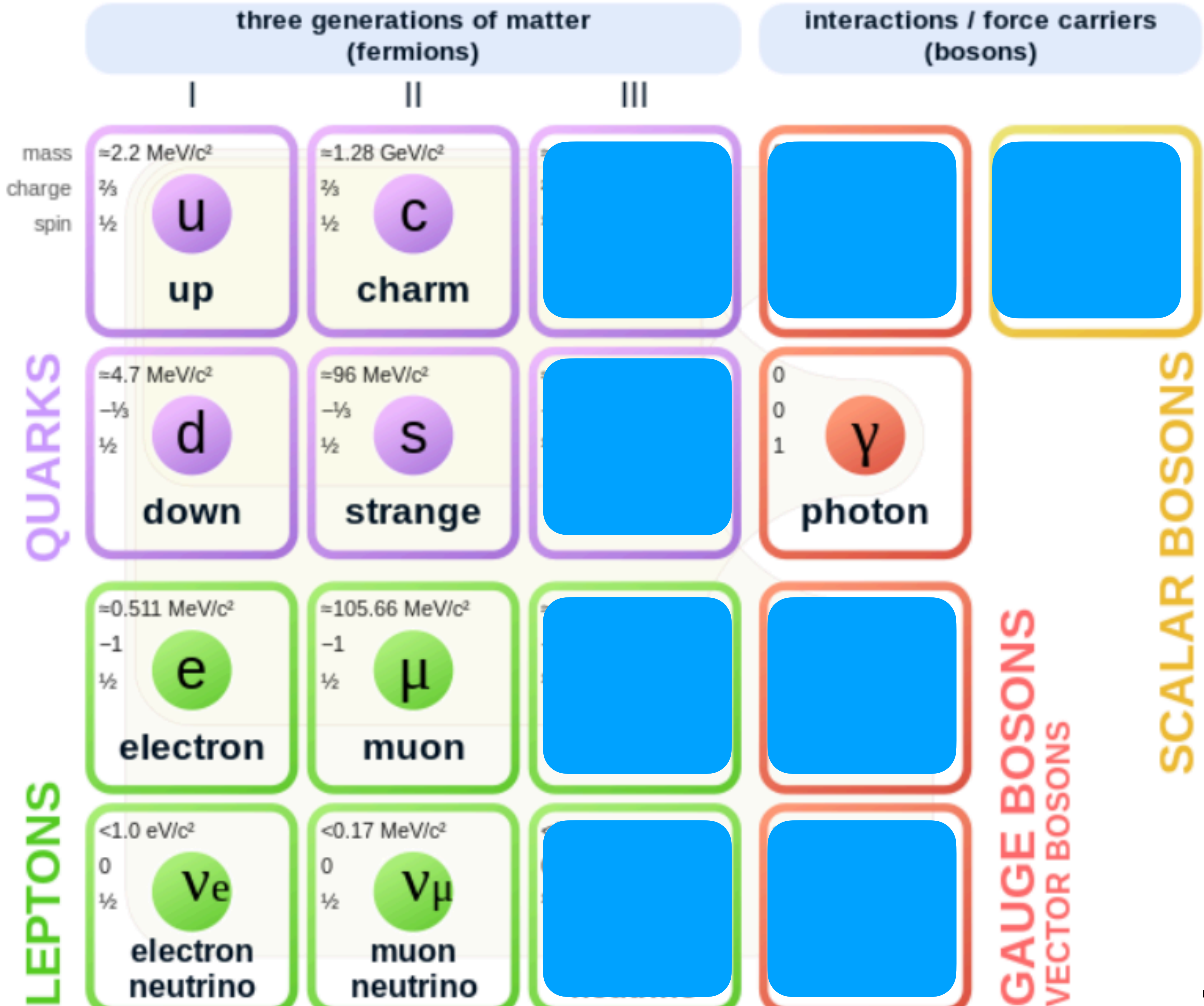
Predictions: eka-boron, eka-aluminium, eca-silicon, eka-manganese

Standard Model of Elementary Particles



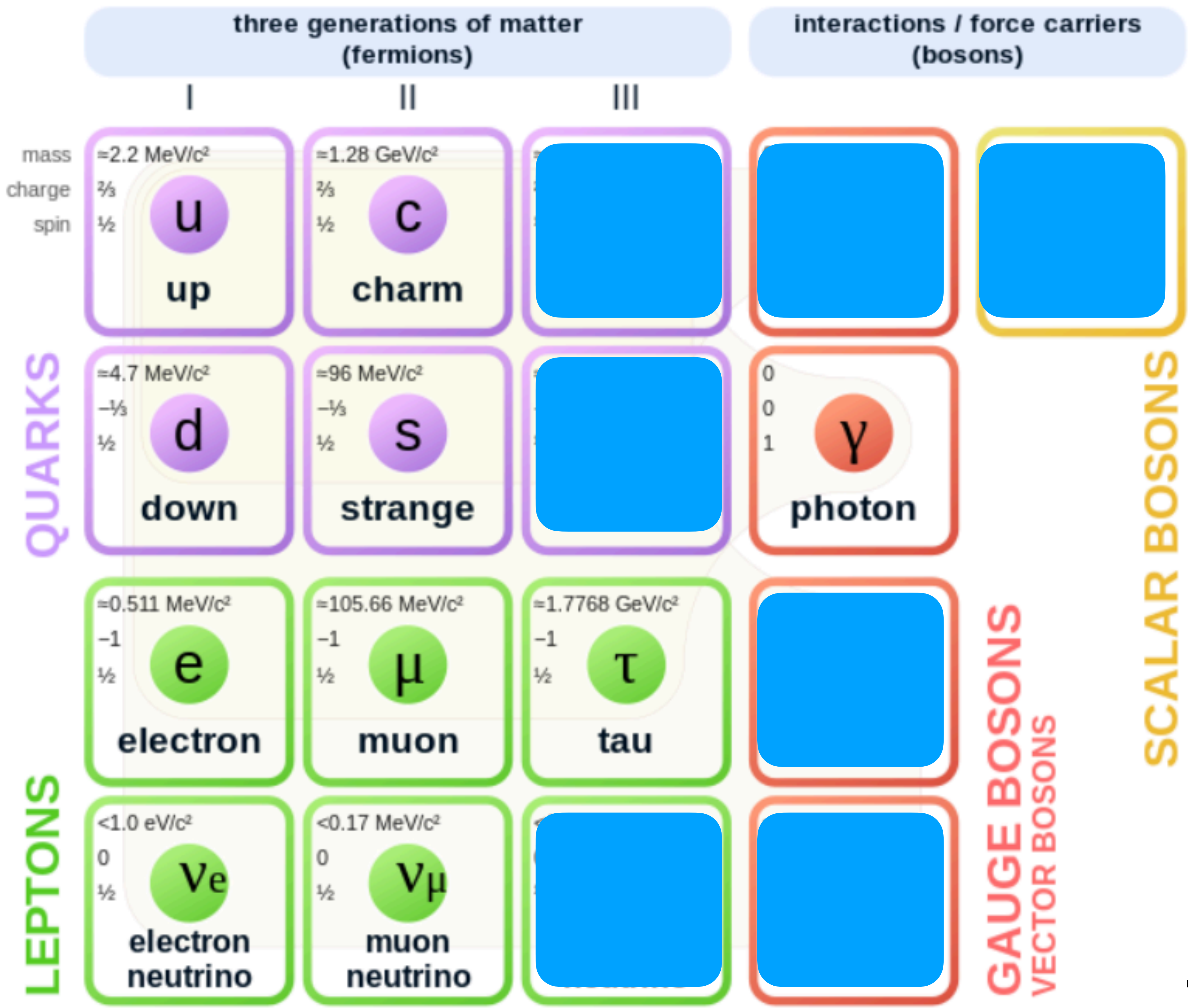
1973

Standard Model of Elementary Particles



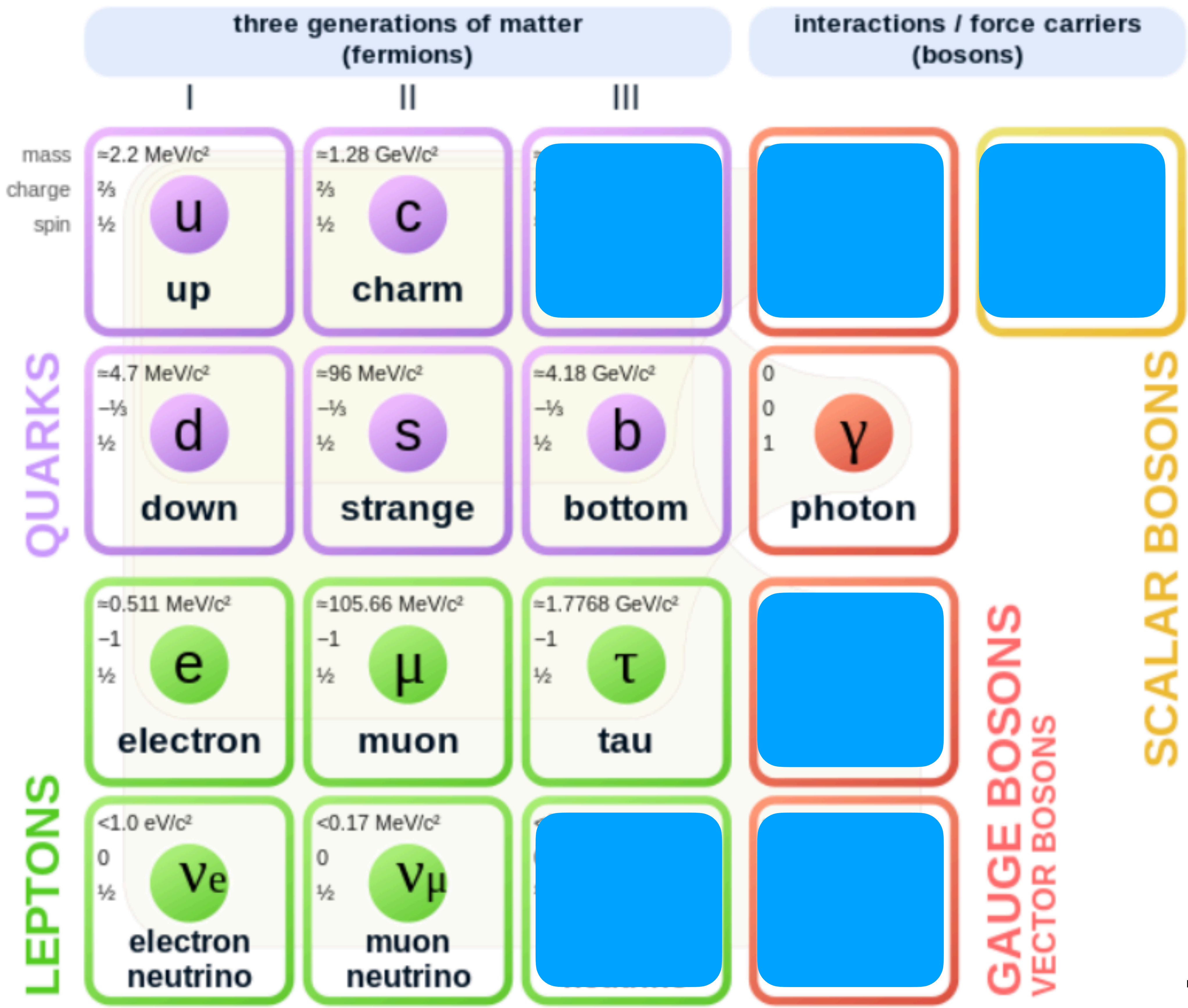
1974

Standard Model of Elementary Particles



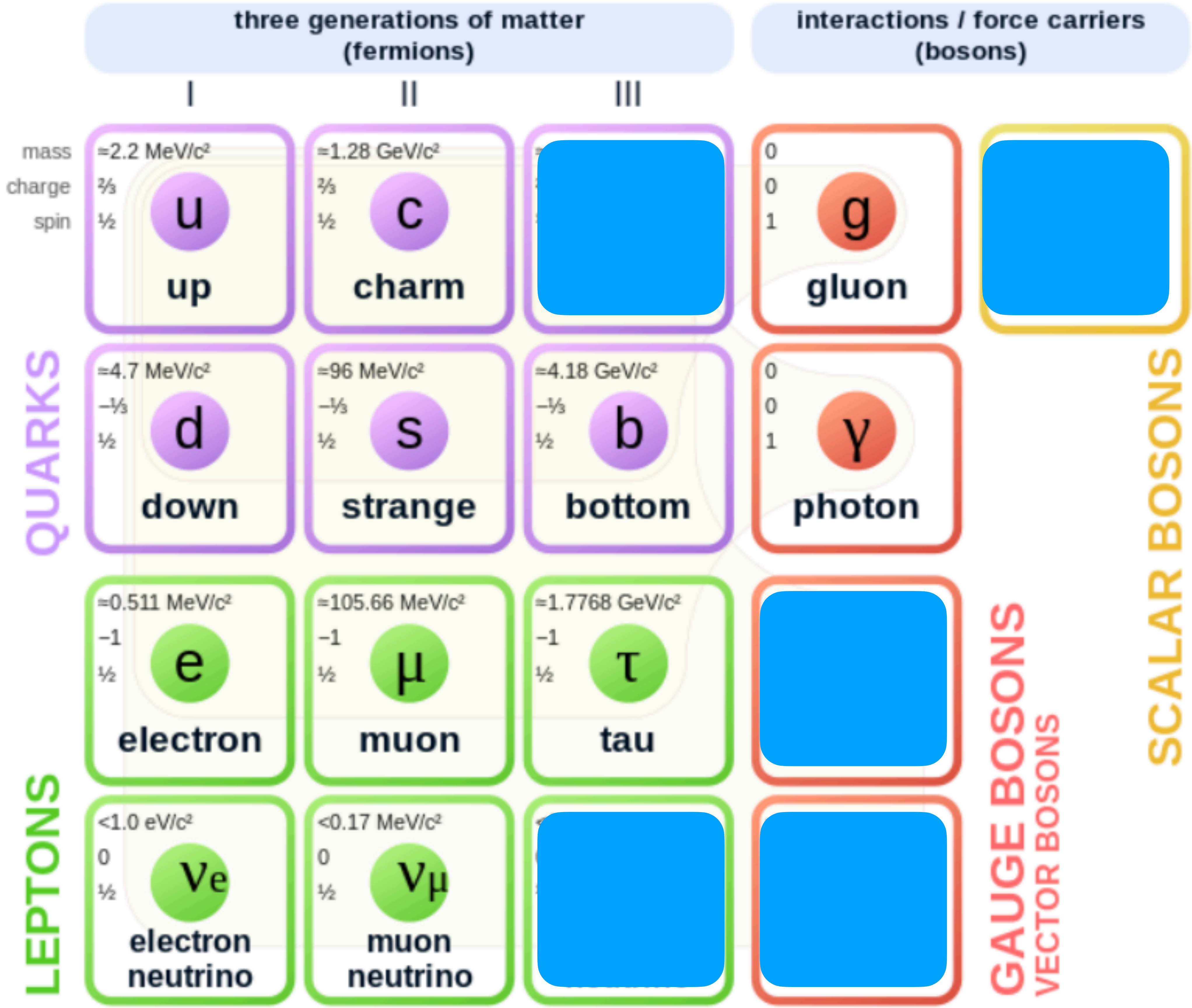
1975

Standard Model of Elementary Particles

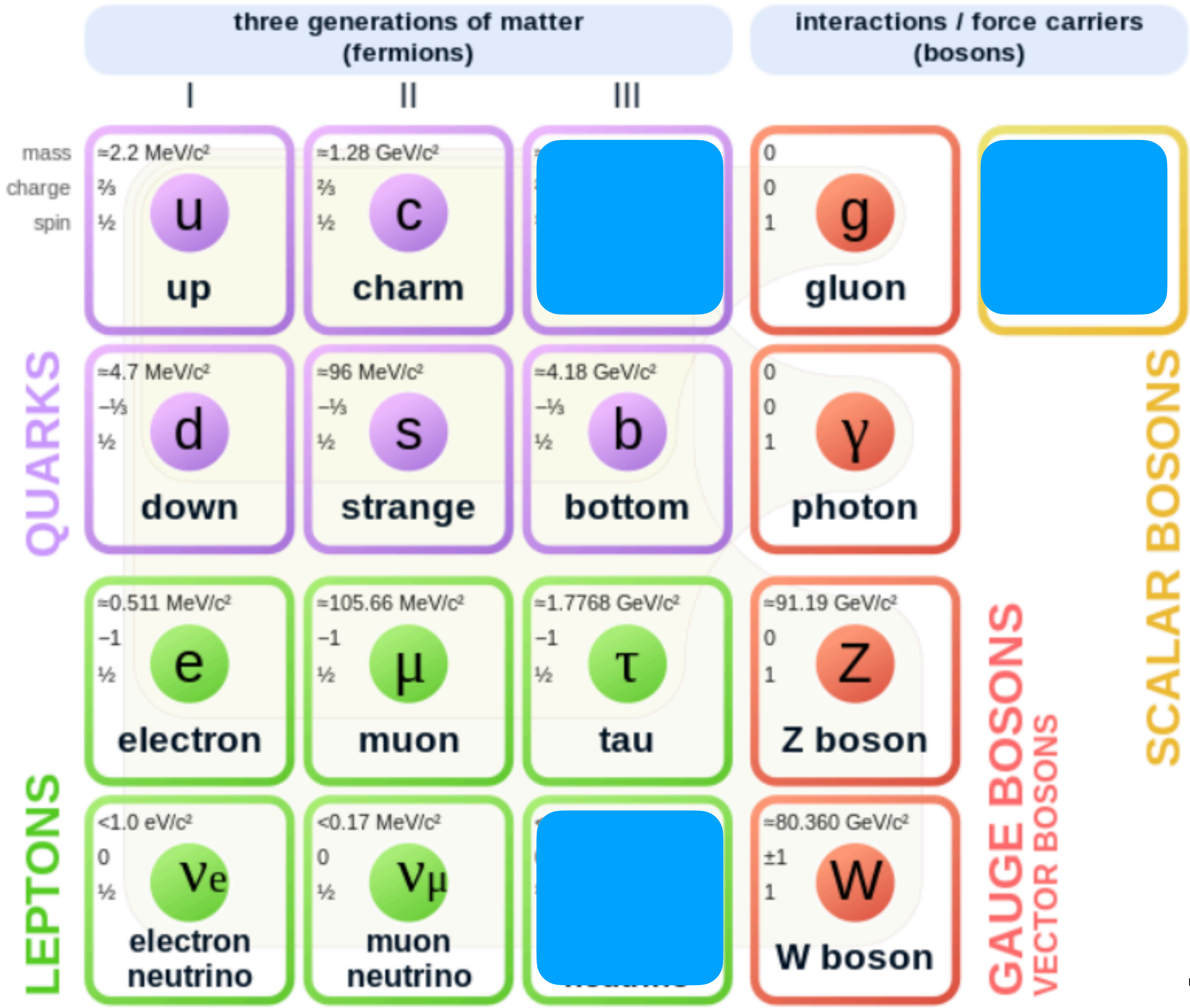


1977

Standard Model of Elementary Particles

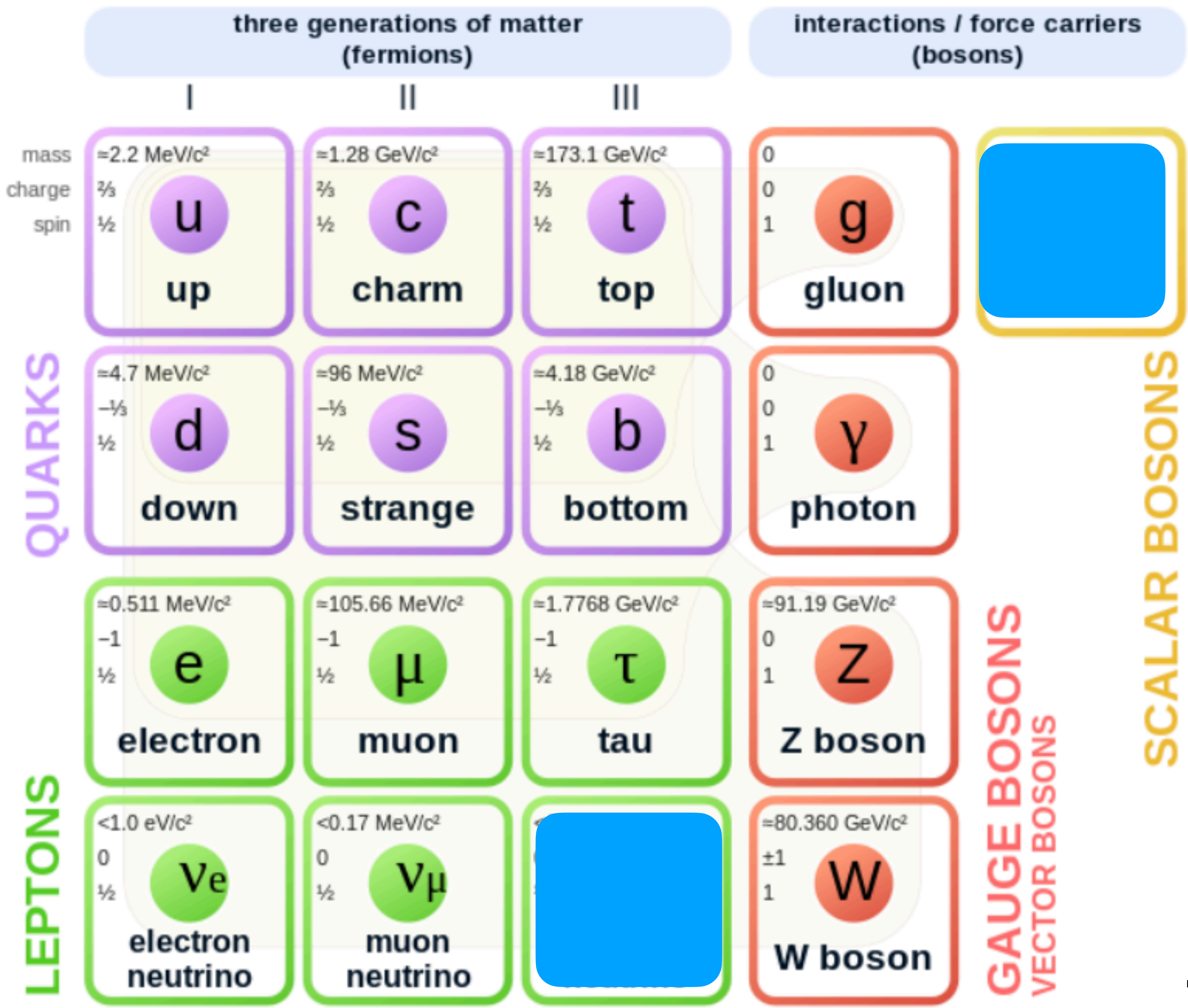


Standard Model of Elementary Particles



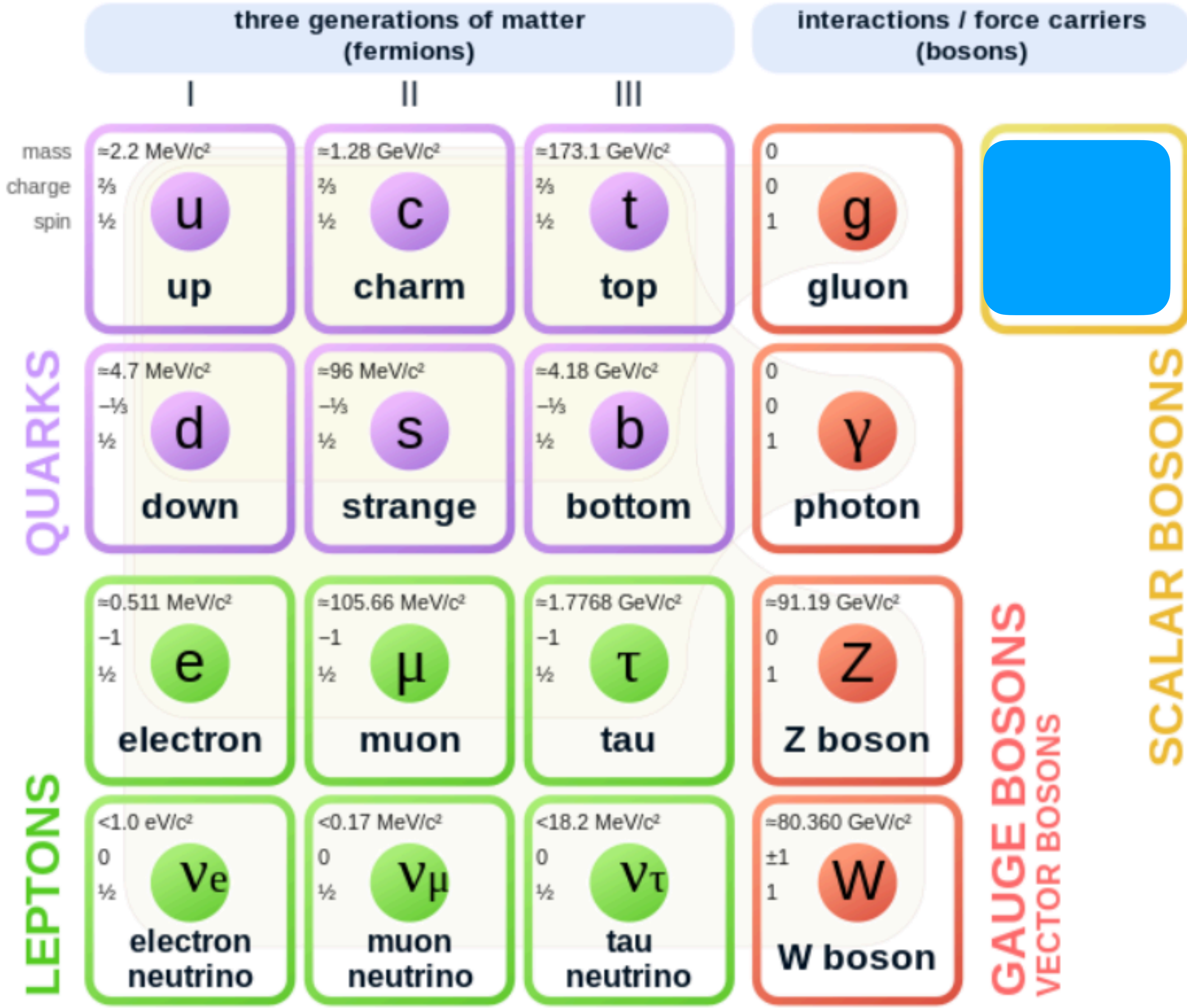
1983

Standard Model of Elementary Particles



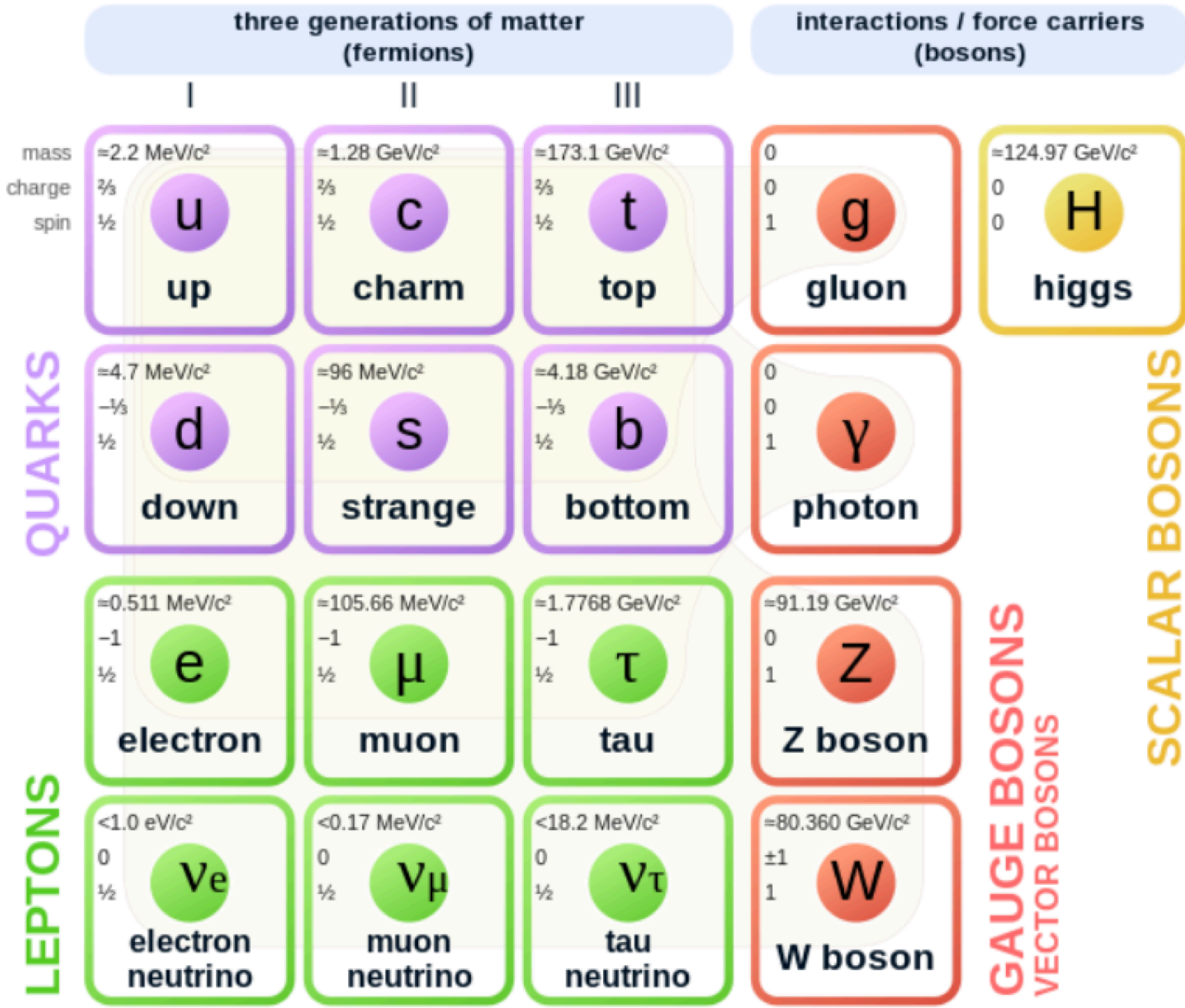
1995

Standard Model of Elementary Particles



2000

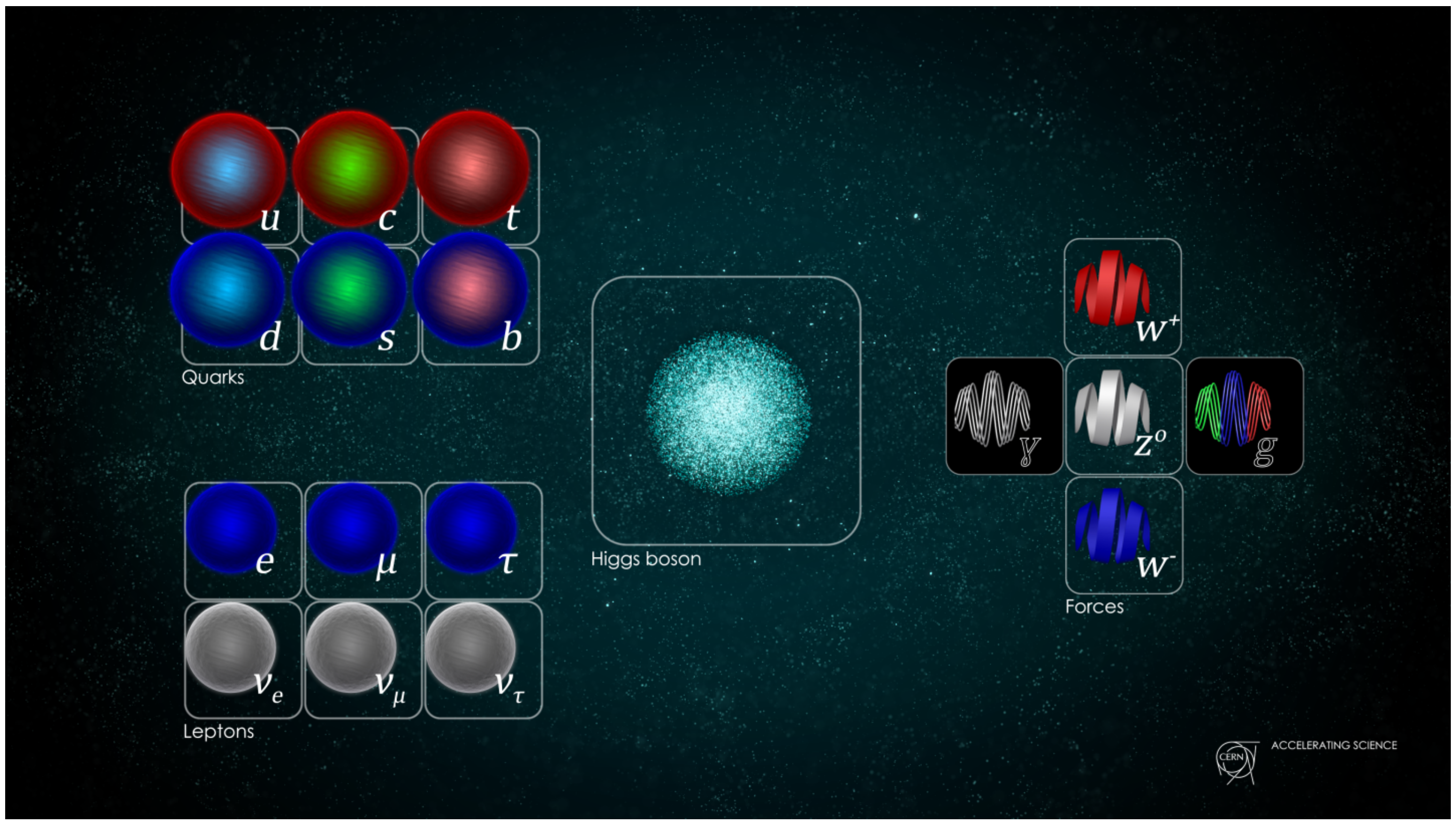
Standard Model of Elementary Particles

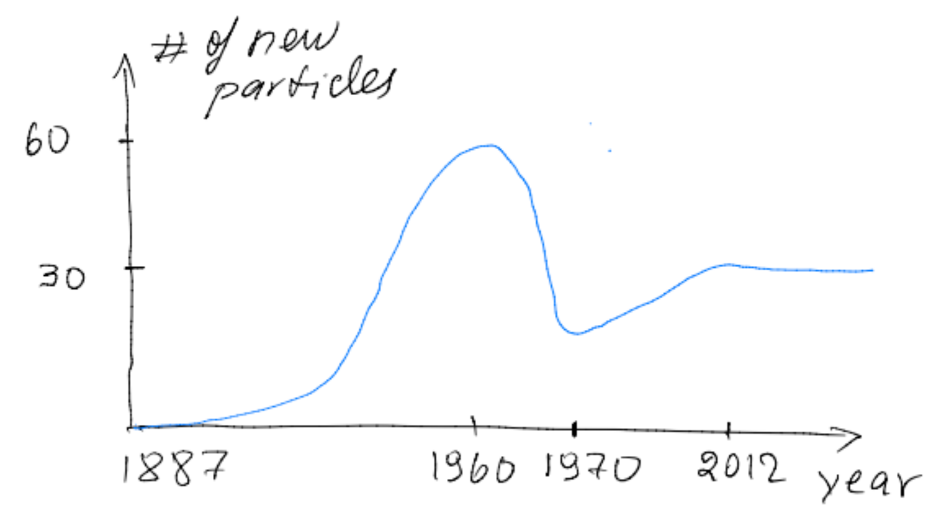


2012

New particle every 5 years (in average)!

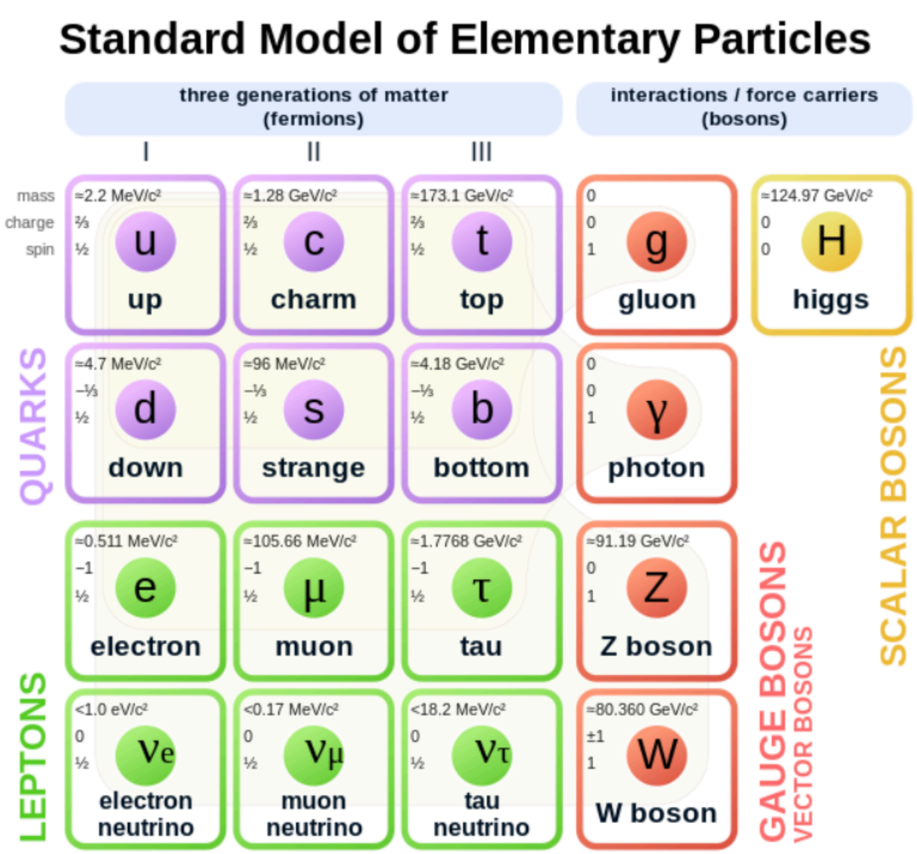
Plateau since the Higgs boson discovery in 2012





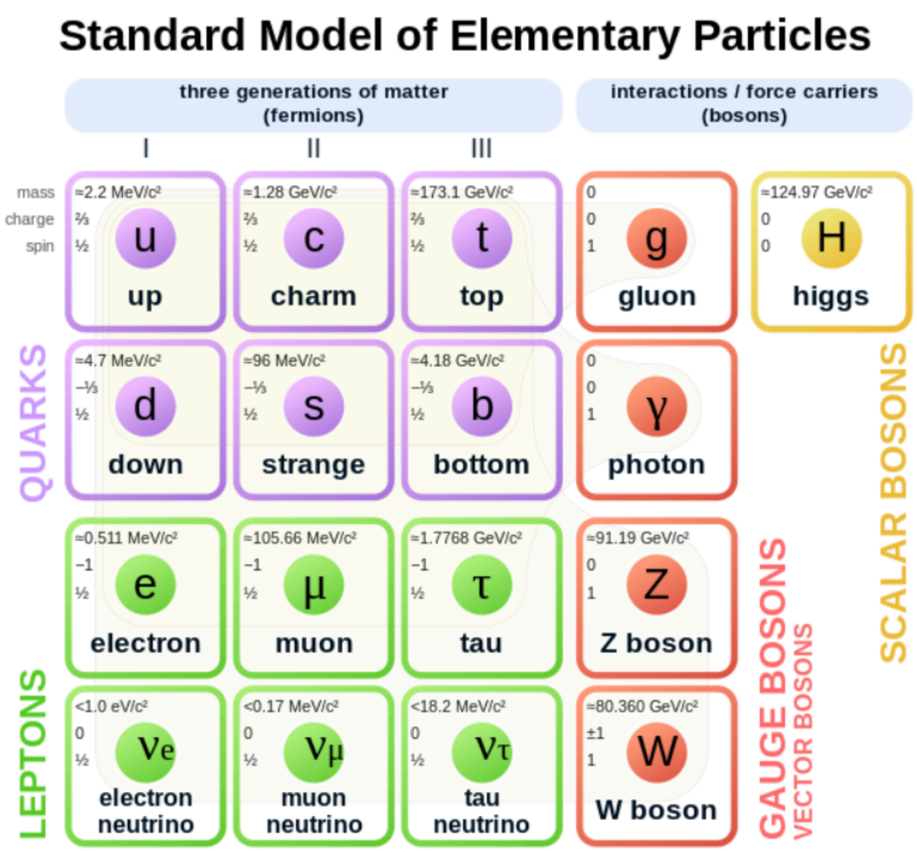
Standard Model in now complete with
3 families of quarks and leptons,
gluons,
W and Z bosons,
Higgs boson

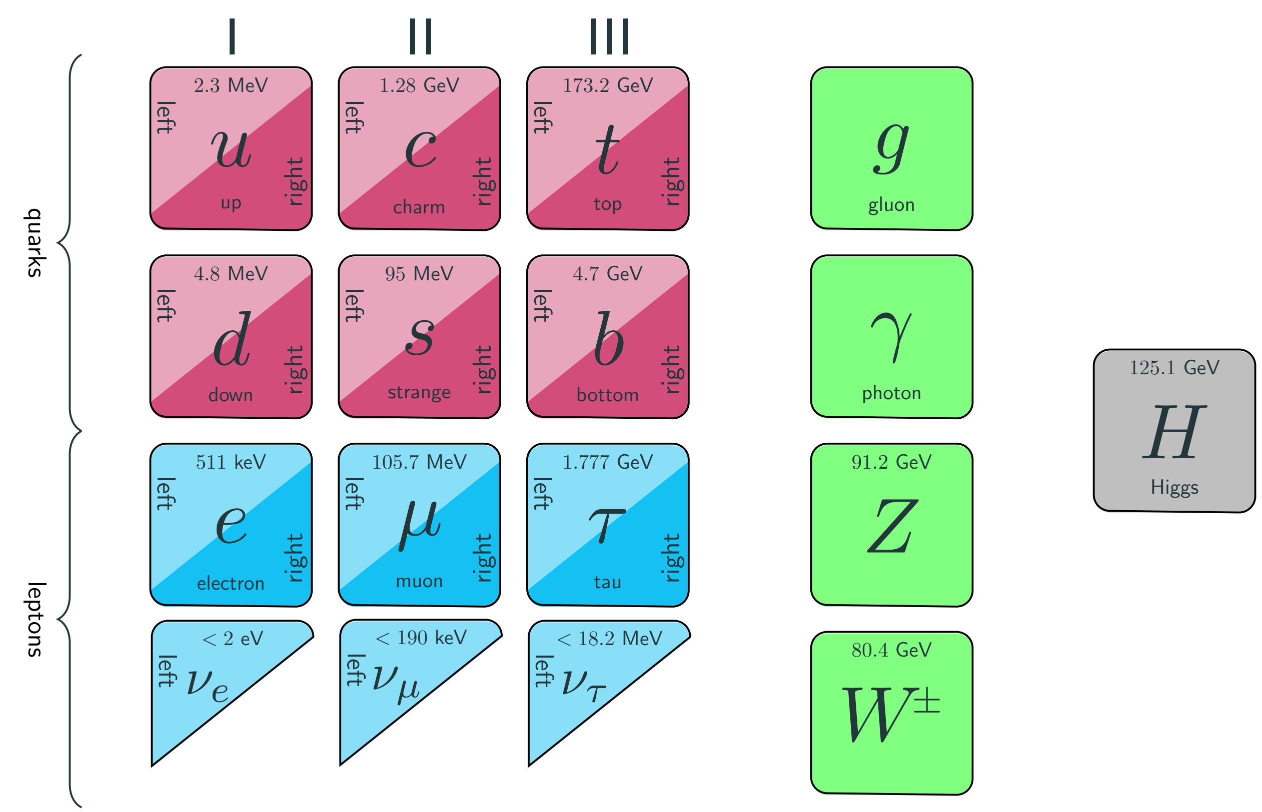
From Mendeleev to Standard Model



Wikipedia picture

From Mendeleev to Standard Model

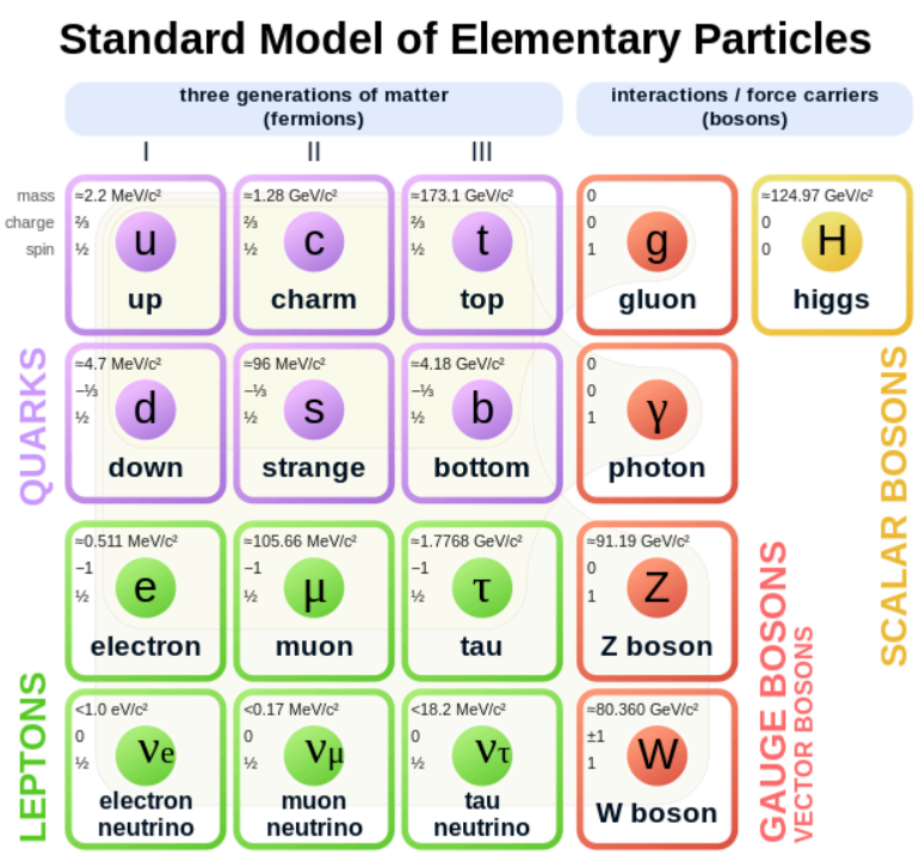


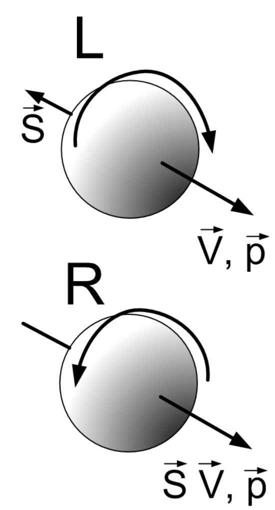


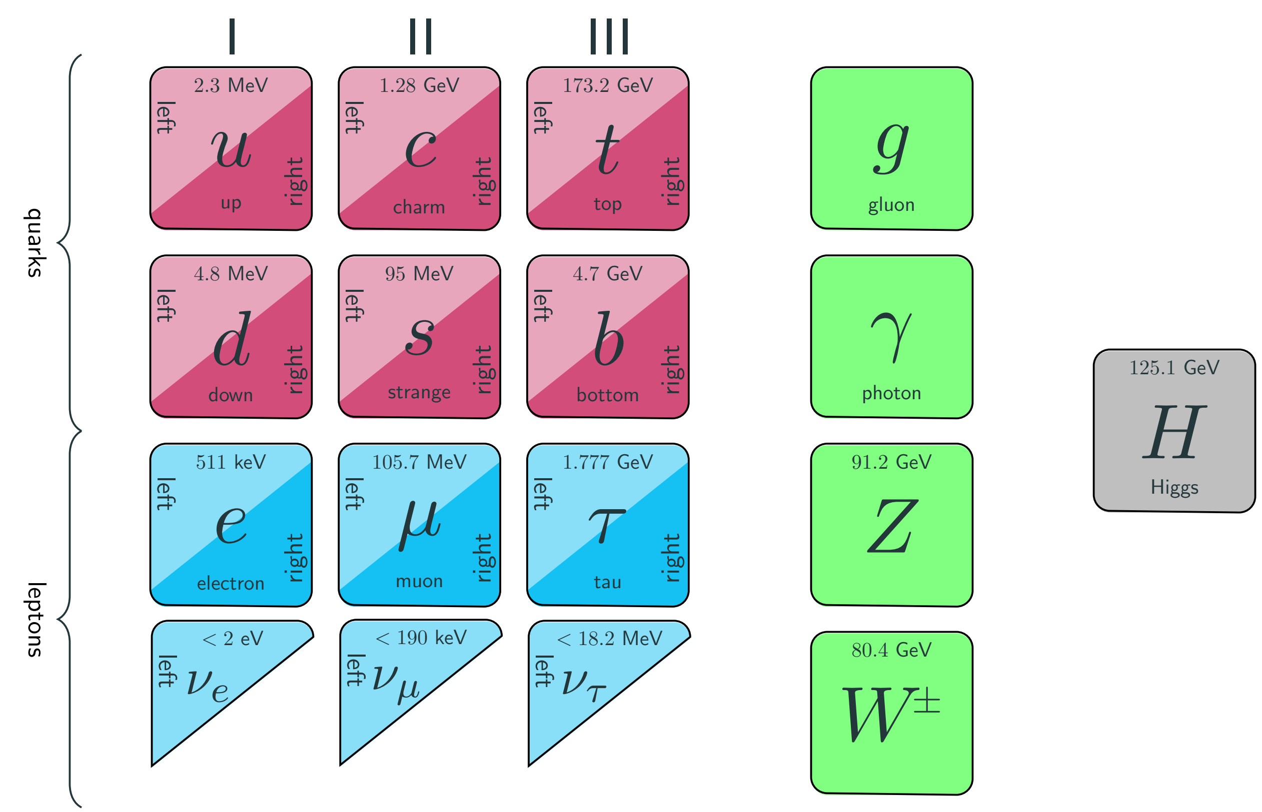
Wikipedia picture

Accurate picture

From Mendeleev to Standard Model







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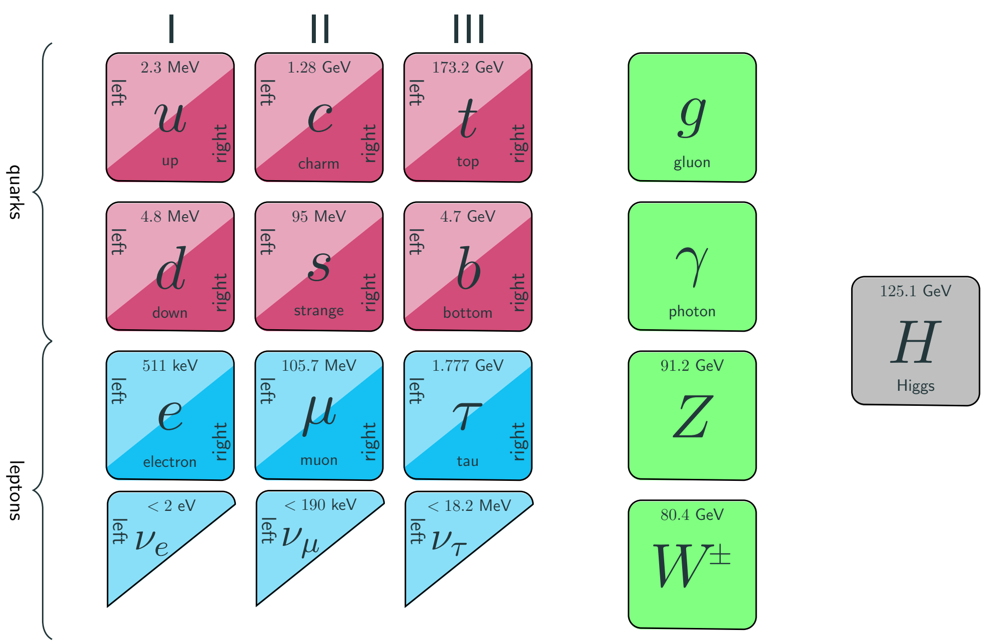
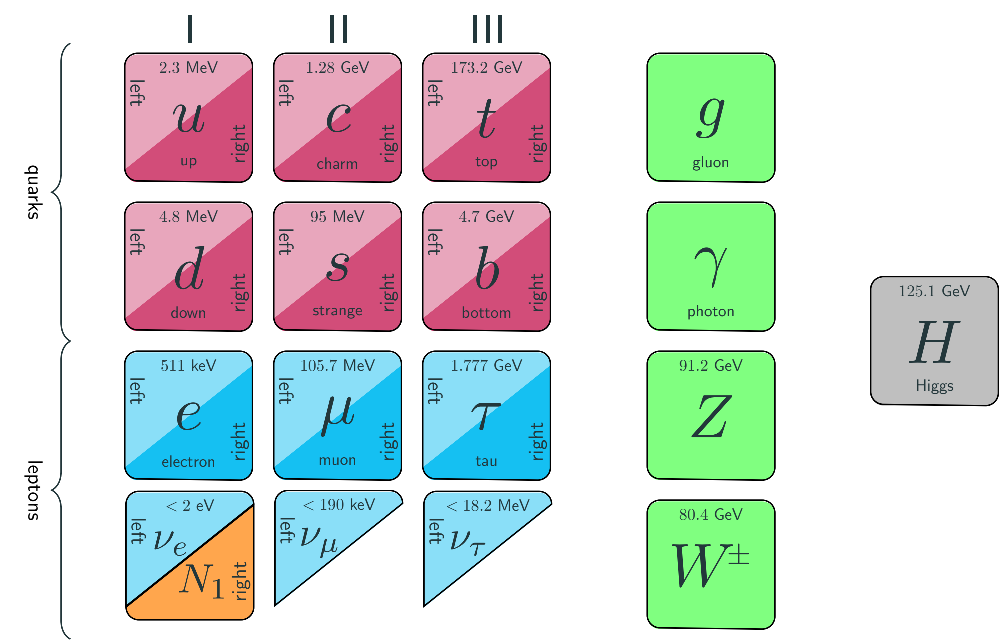
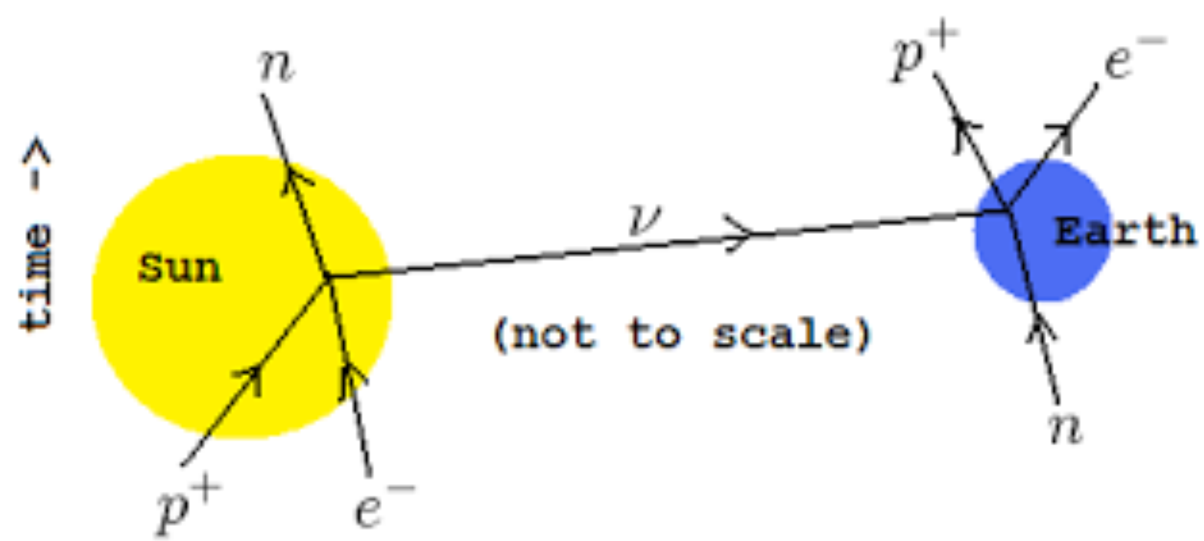
Filling the boxes





Who ordered that?

$\Rightarrow$ **Solar neutrino oscillations are explained**



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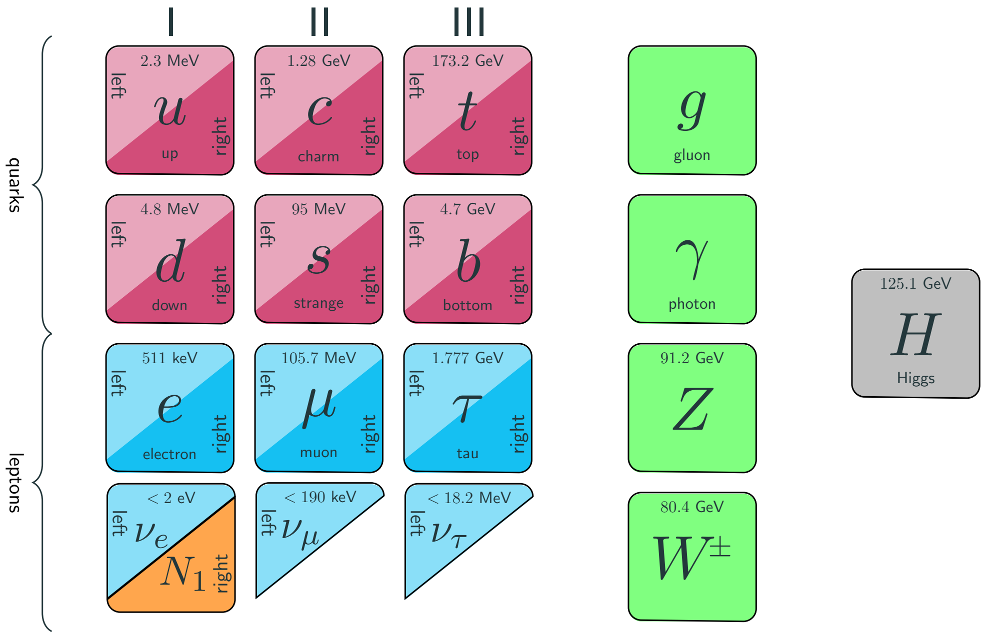
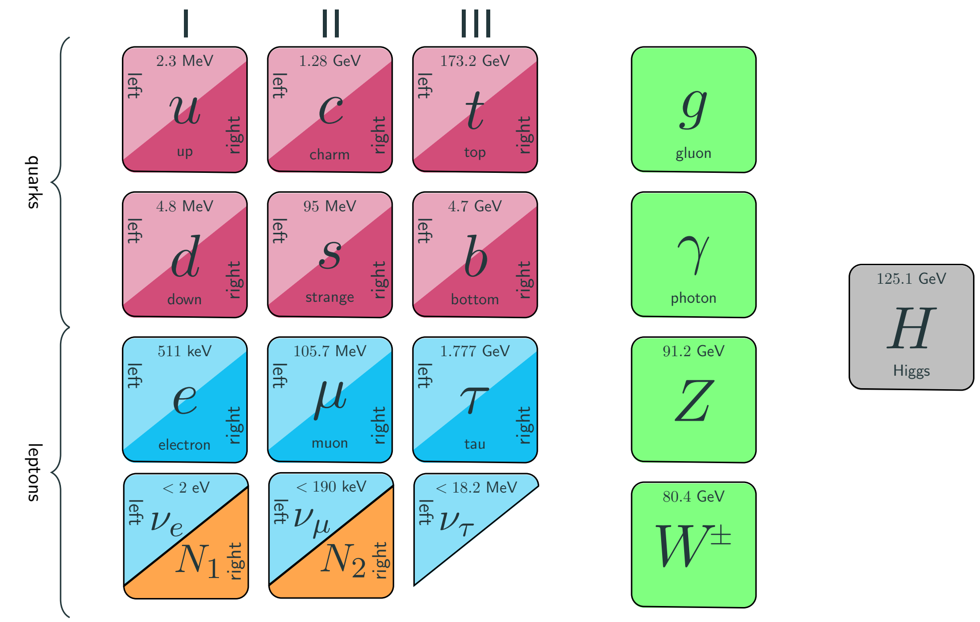
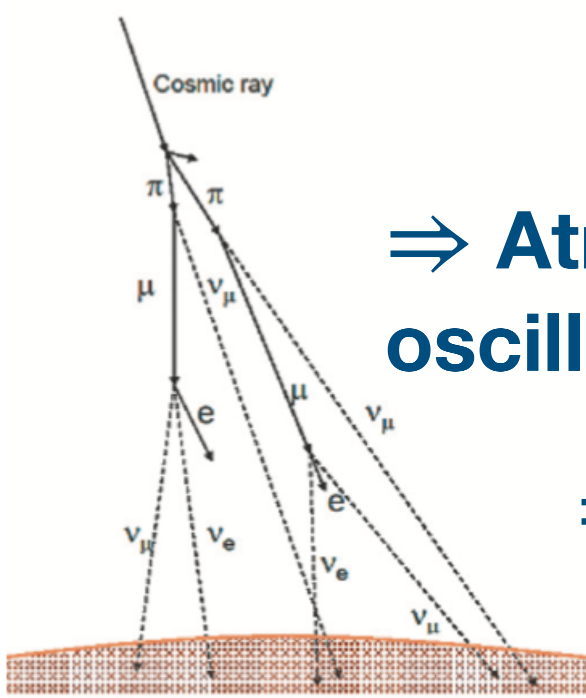


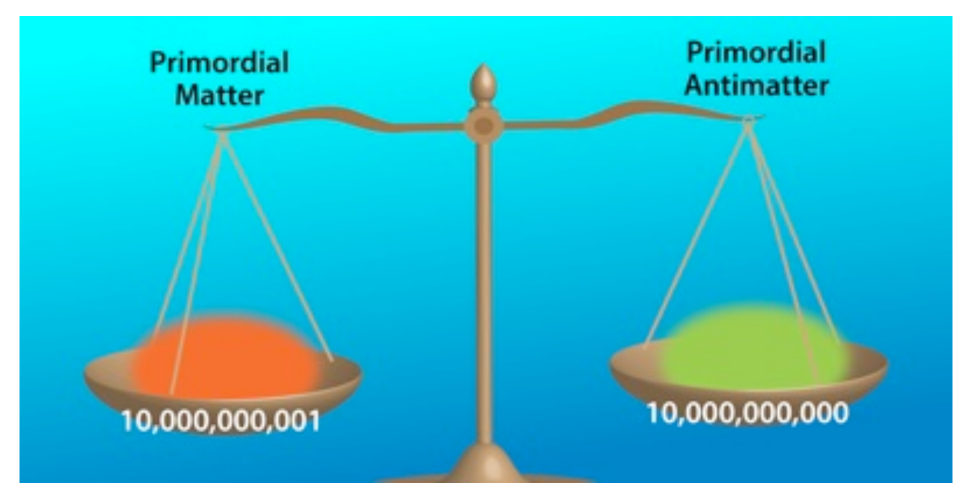


Who ordered that?



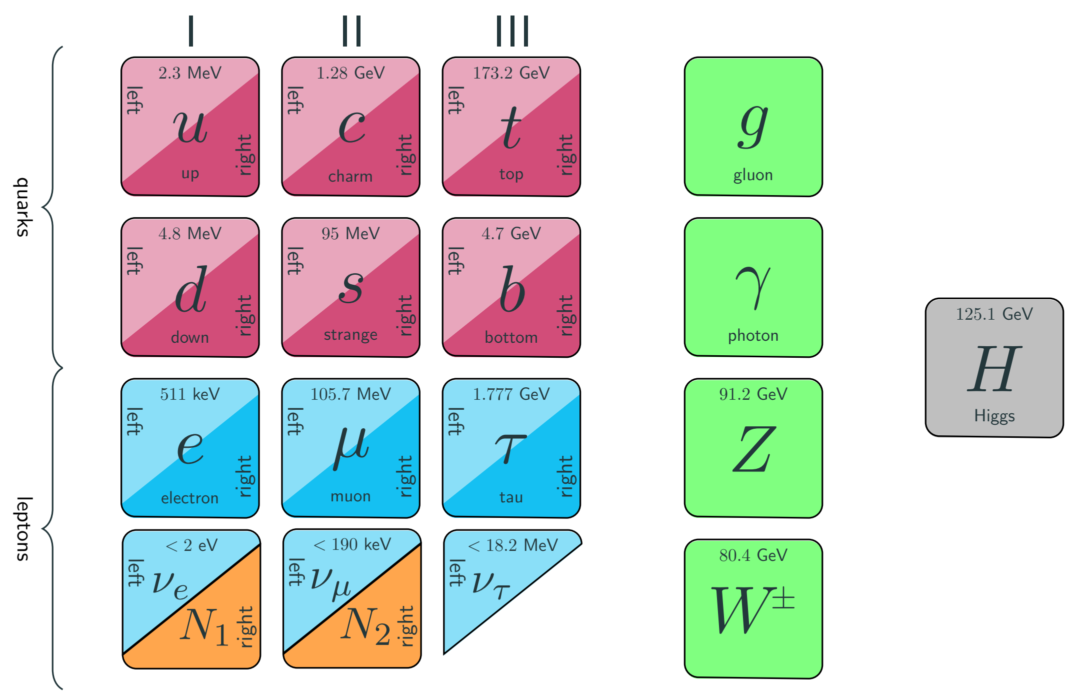
⇒ Atmospheric neutrino oscillations can be explained

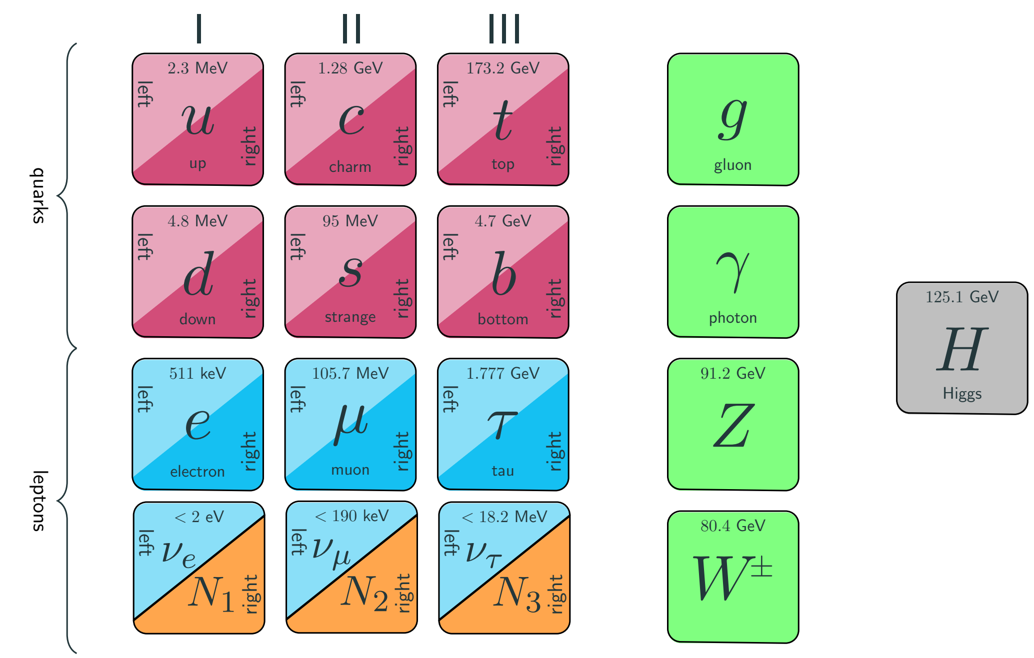
⇒ All neutrino physics can be understood

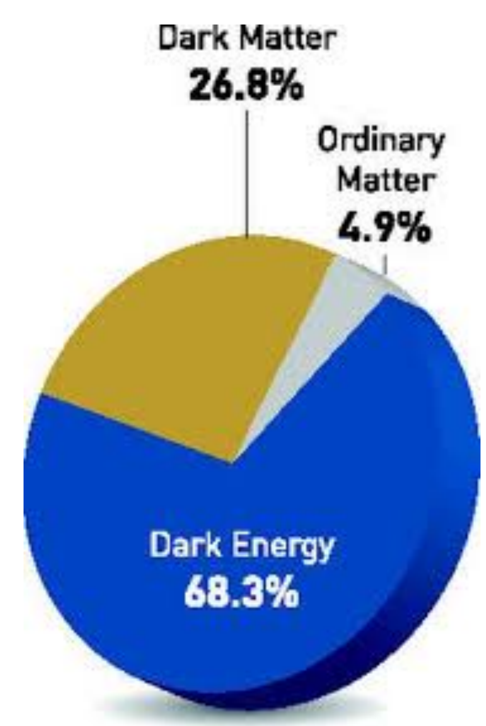


⇒ Baryon asymmetry of the Universe can be explained.

Filling the boxes







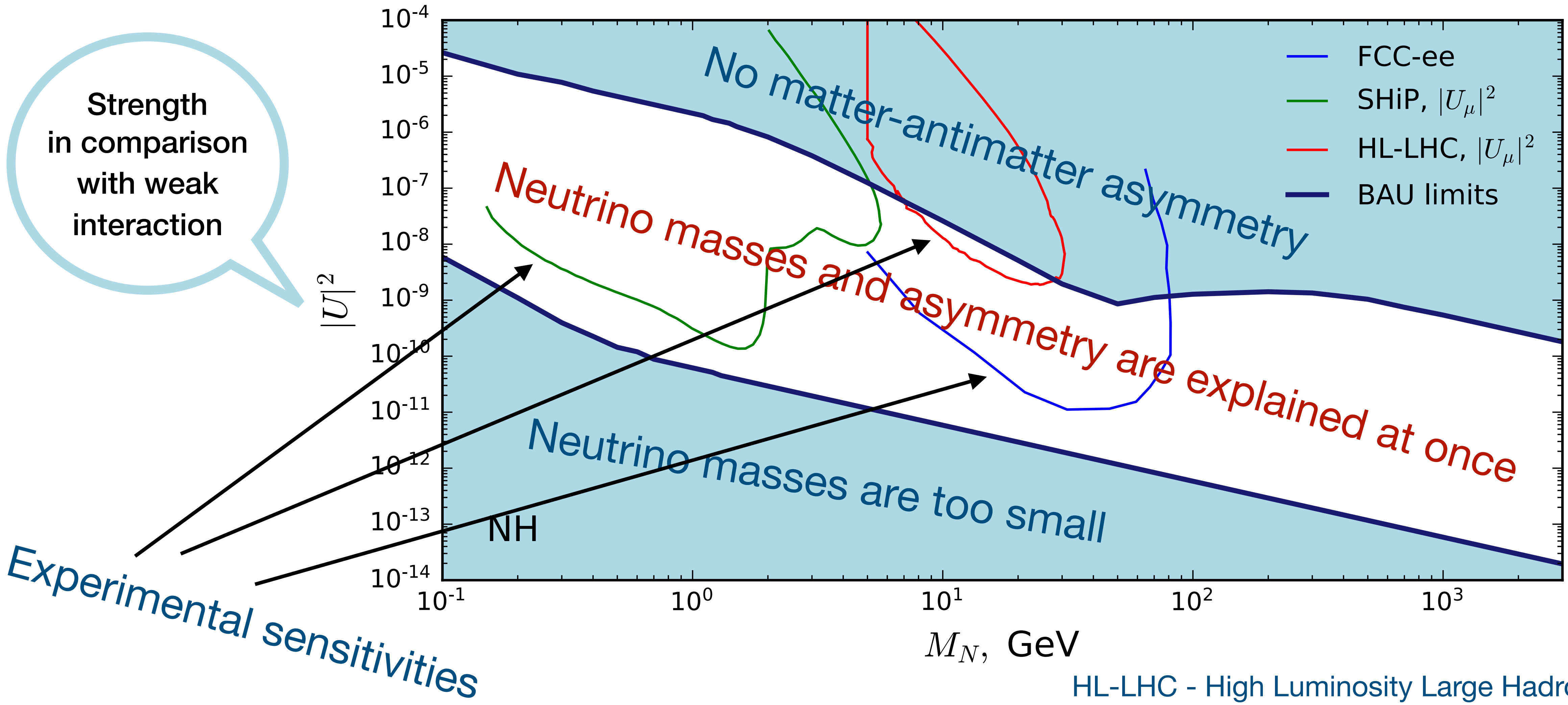
Who ordered that?

$\Rightarrow$ **Dark matter in the Universe can be explained.**

New particles are called "Heavy neutral leptons", sometimes sterile neutrinos. Model: the νMSM

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

figure from Klaric, MS, Timiryasov



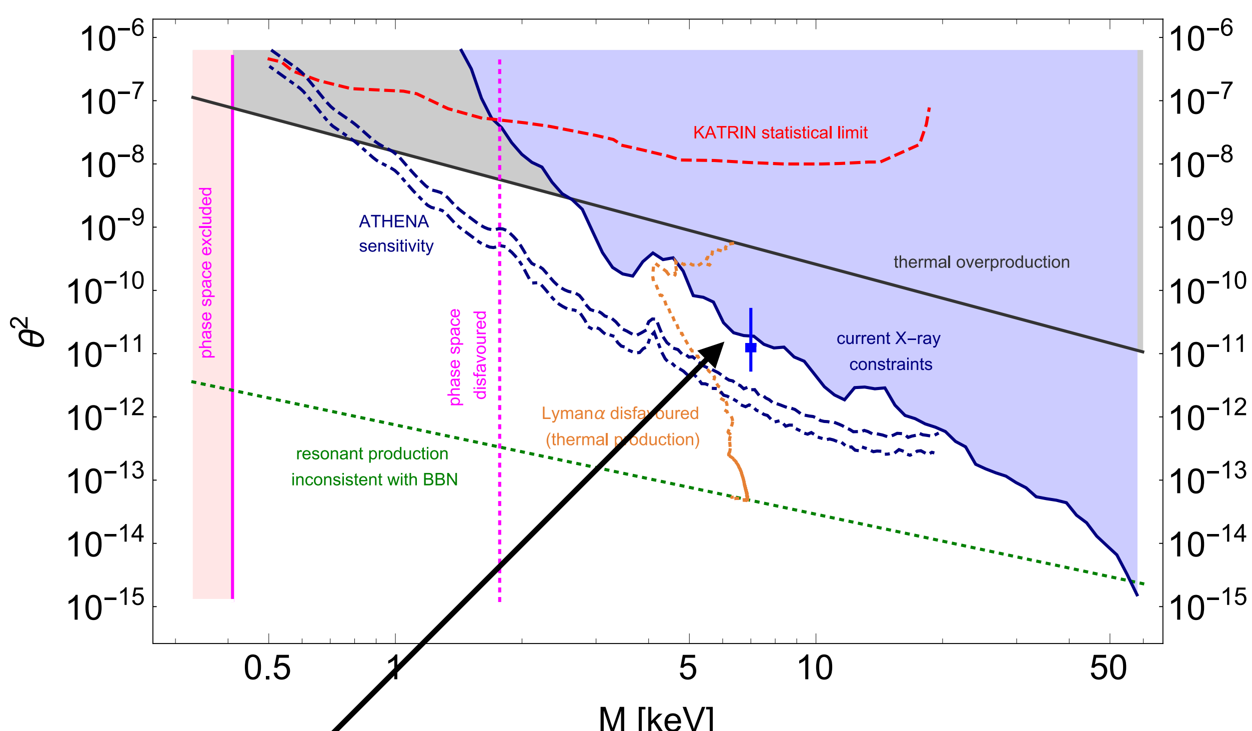
HL-LHC - High Luminosity Large Hadron Collider
BAU - Baryon asymmetry of the Universe
NH - normal neutrino hierarchy

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

Dark Matter in the νMSM: N_1

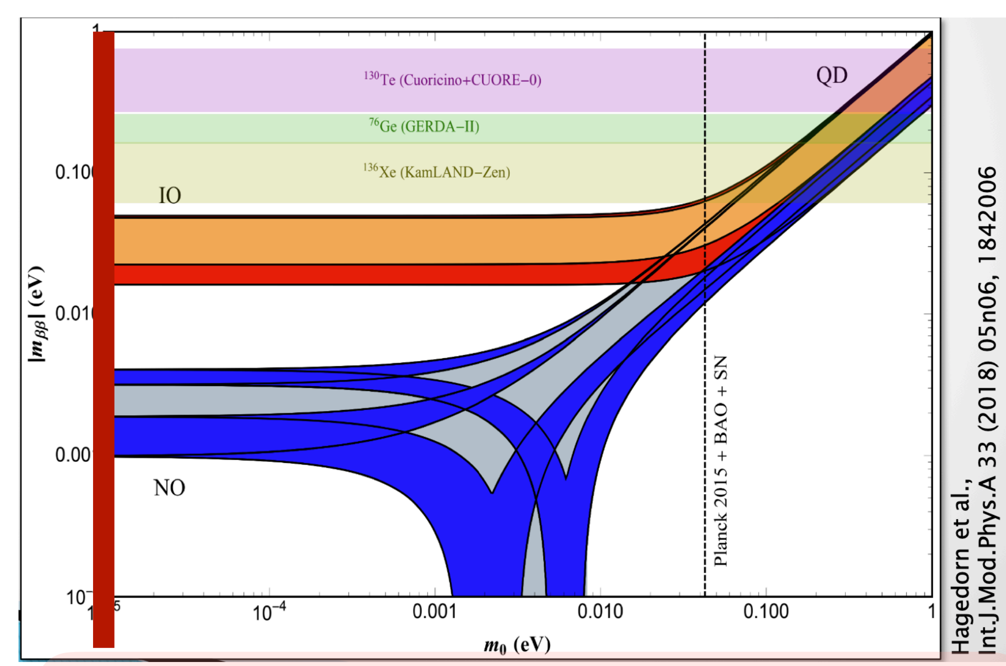
Dark matter sterile neutrino N_1: long-lived light particle (mass in the keV region) with the life-time greater than the age of the Universe. It can decay as $N_1 \to \gamma\nu$, what allows for experimental detection by X-ray telescopes in space. Future experimental searches: Hitomi-like satellite XRISM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



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

How much time it may take to discover Heavy Neutral Leptons?

Historical development of the SM: gradual adaptation of electroweak theory to experimental data during the past 50 years.

- Bosonic sector of the electroweak model remains intact from 1967, with the discoveries of the W and Z bosons in 1983 and the Higgs boson in 2012.
- The fermionic sector evolved from one to two and finally to three generations, revealing the remarkable symmetry between quarks and leptons.
- It took about 20 years to find all the quarks and leptons of the third generation.

Optimistic answer:

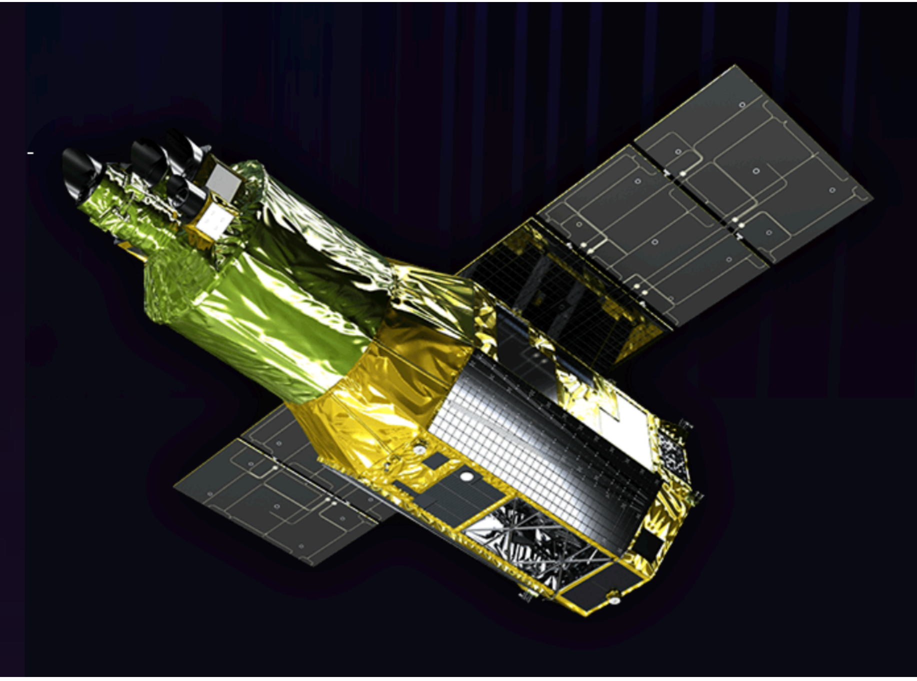
One, Dark matter, at XRISM

in 2024 (?)

Launch date: September 7, 2023
Launch Time : 8:42 (JST)

Two others at SHiP @ CERN in 2031 (?)

XRISM X-Ray Imaging and Spectroscopy Mission



The XRISM payload consists of two instruments:

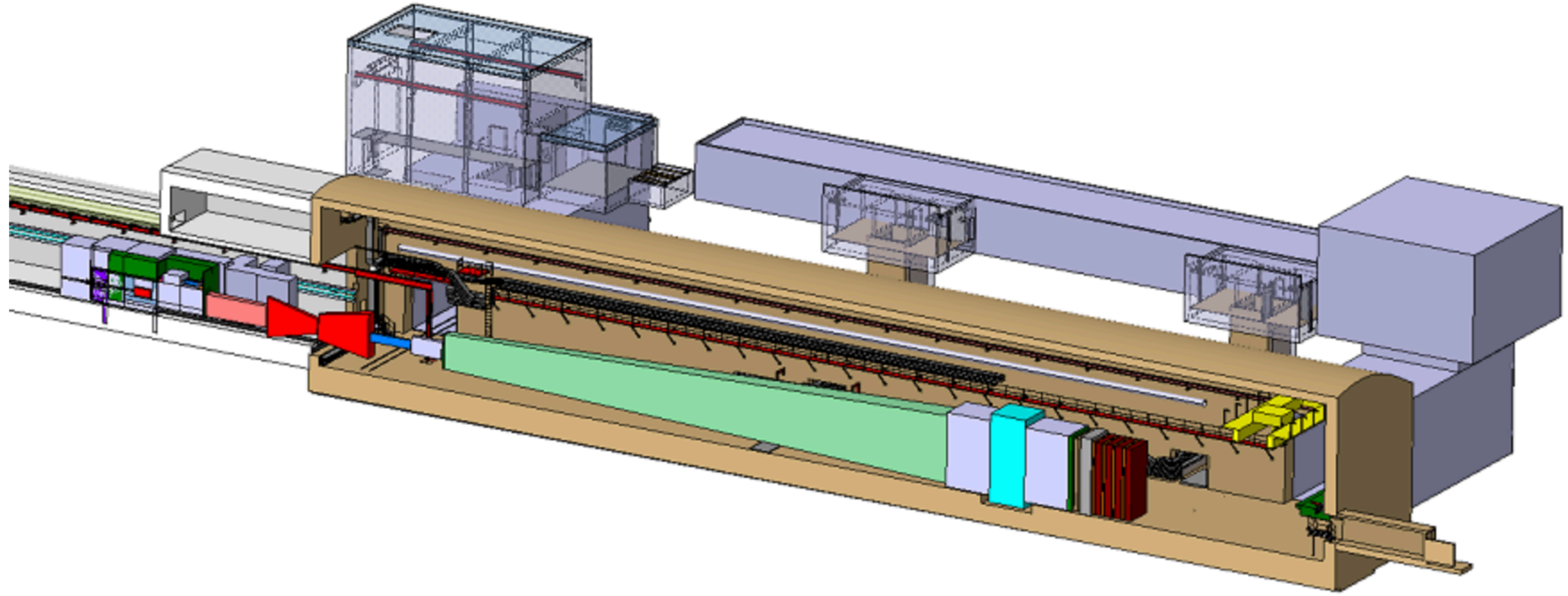
- Resolve, a soft X-ray spectrometer, which combines a lightweight X-ray Mirror Assembly (XMA) paired with an X-ray calorimeter spectrometer, and provides non-dispersive 5-7 eV energy resolution in the 0.3-12 keV bandpass with a field of view of about 3 arcmin.
- Xtend, a soft X-ray imager, is an array of four CCD detectors that extend the field of the observatory to 38 arcmin on a side over the energy range 0.4-13 keV, using an identical lightweight X-ray Mirror Assembly.

Spectral resolution is more than 10 times better than in XMM-Newton!

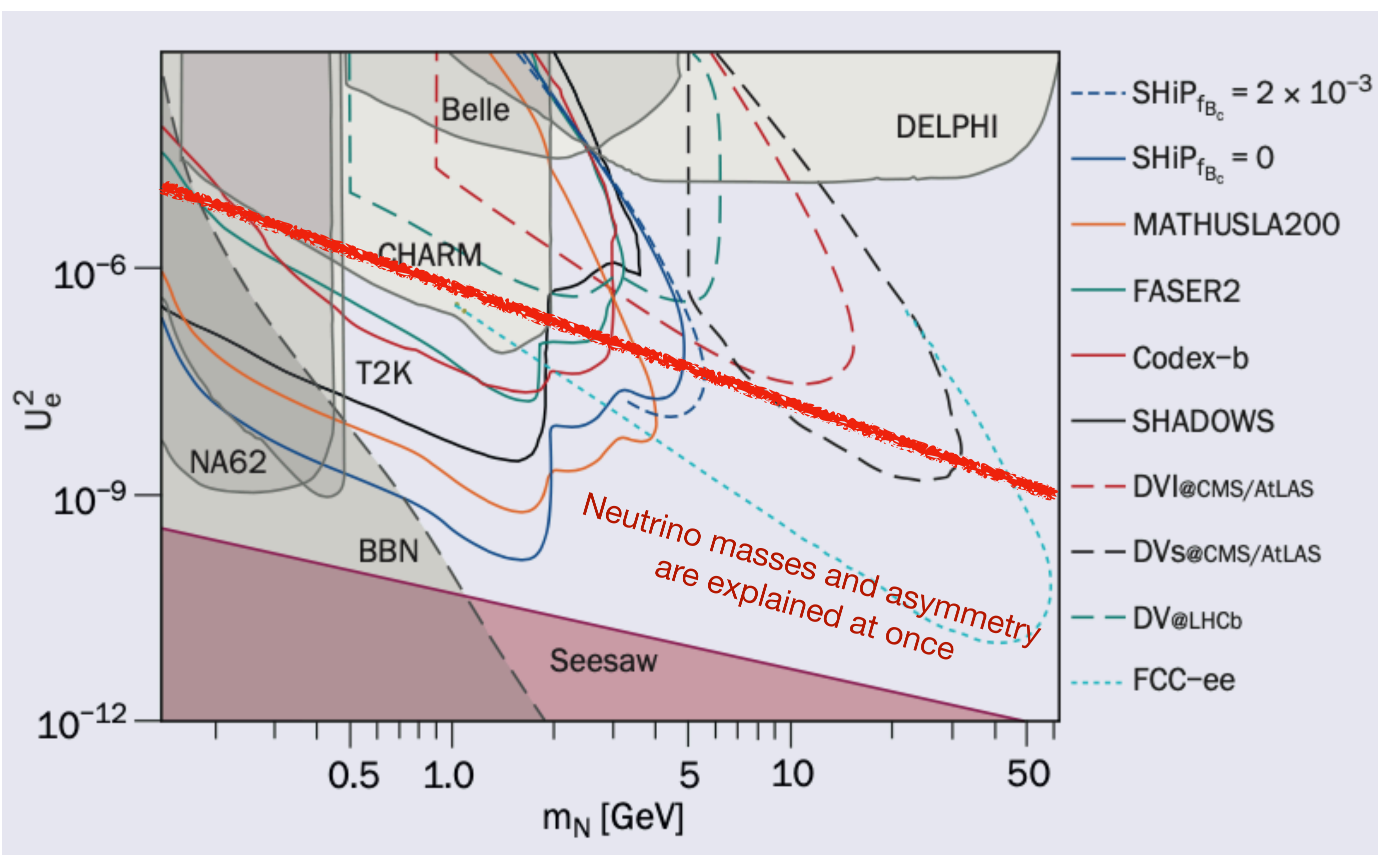
XRISM was launched by the H-IIA rocket from the Tanegashima Space Center at 8:42 a.m on September 7, 2023 JST, (23:42 on September 6, 2023 UT). Photo Credit: L. Hartz

SHiP

Search for Hidden Particles



Projection of bounds on HNLs



Sensitivity in number of events is 10’000 times better than in previous experiments!

Experiment approved at CERN last month

How many new particles do we need in particle physics?

Perhaps, just three. These are heavy neutral leptons which can be the key to all known experimental problems of the Standard Model:

- neutrino masses and oscillations
- baryon asymmetry of the Universe
- dark matter

May be more: some particles may not fit to the "periodic table", such as axions - strong CP problem.

Axion and simplicity

QCD without axion:

- One "unnatural" number, $\theta \lesssim 10^{-10}$

QCD with axion:

- 6 new degrees of freedom (KSVZ - one complex scalar field and a new massive quark, DFSZ - two complex scalar fields, one is the doublet with respect to the SU(2) weak isospin and another is a singlet).

- Two "unnatural" numbers:

 - Ratio of EW scale and PQ scale: $\left(v_{EW}/F_{PQ}\right)^2 \lesssim 10^{-14}$

- Quality of PQ symmetry: $\left(m_{PQ\ breaking}/F_{PQ}\right)^2 \lesssim 10^{-50}$

Universe at large scales and simplicity

Cosmological inflation

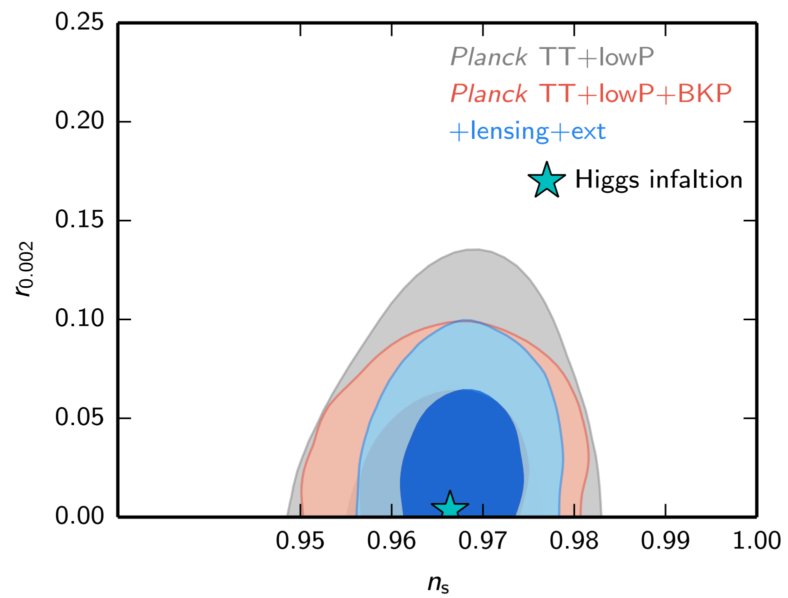
Most economical possibility - Higgs boson of the Standard Model drives inflation. Essential ingredient - non-minimal coupling of the Higgs to curvature scalar: $\xi\, H^\dagger H\, R, \quad \xi \gg 1$, making the theory scale-invariant at large values of the Higgs field.

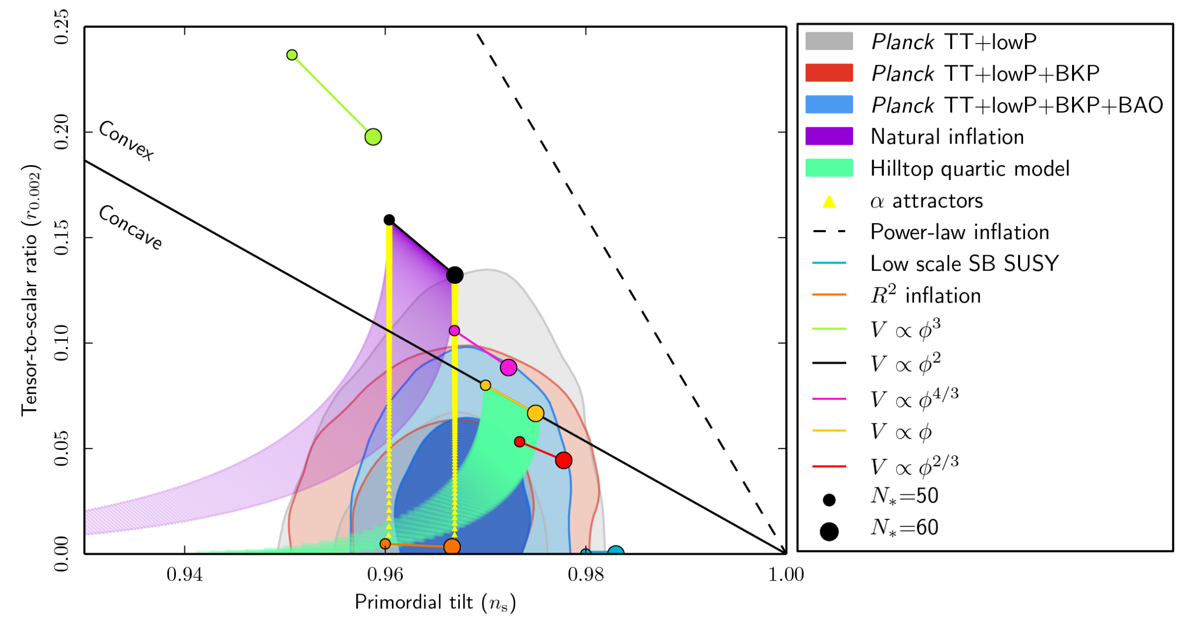
Predictions depend on the formulation of gravity

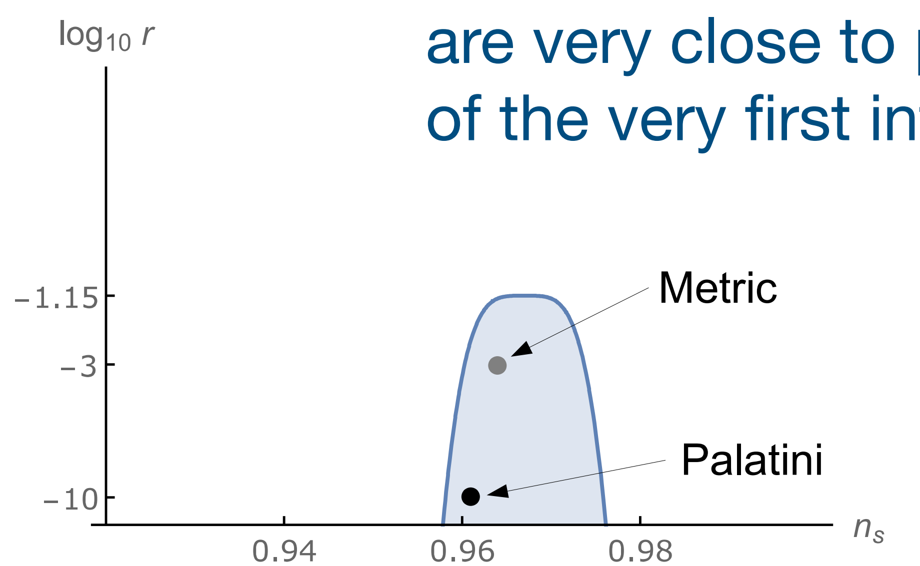
- metric gravity, $g_{\mu\nu}$ is the only dynamical variable
- Palatini gravity, $g_{\mu\nu}$ and symmetric connection
- Einstein-Cartan gravity, spin connection and tetrad
- …

Increasing complexity

Predictions of metric and Palatini Higgs inflations



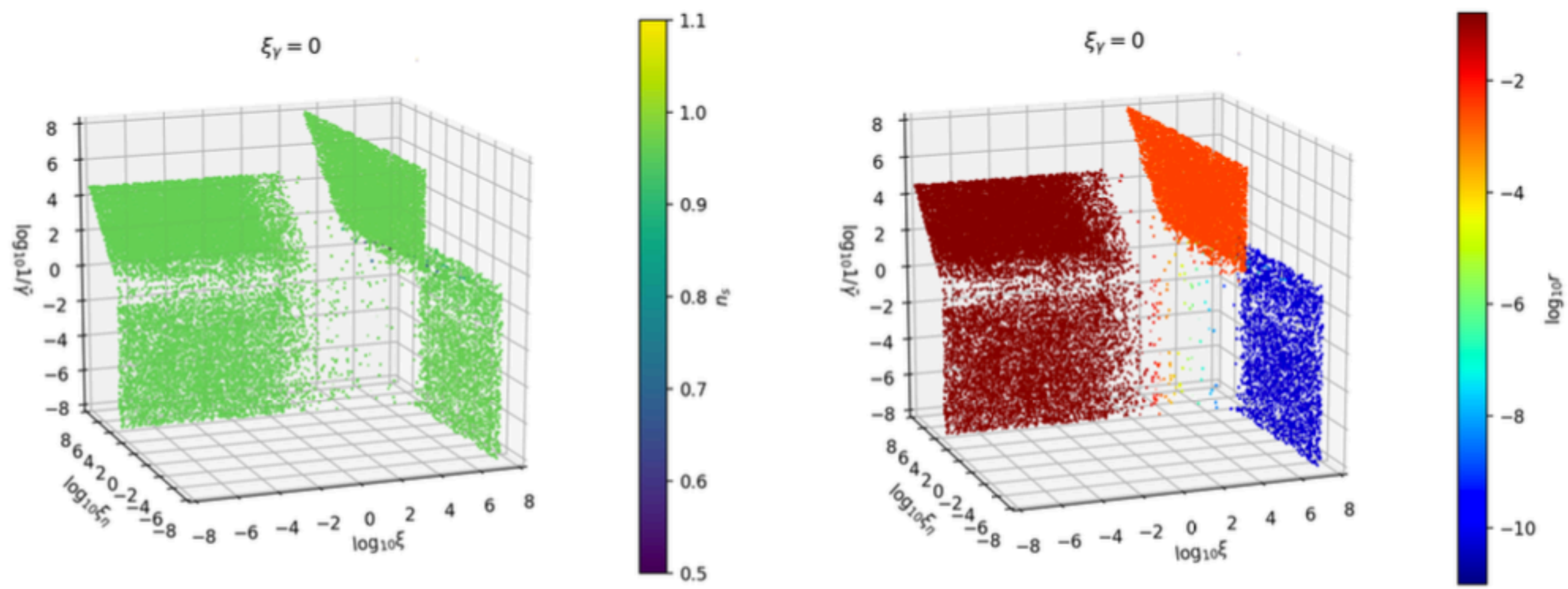




Predictions of metric Higgs inflation
are very close to predictions
of the very first inflationary model by Starobinsky

Generic Einstein-Cartan Higgs inflation

figure from MS, Shkerin, Timiryasov



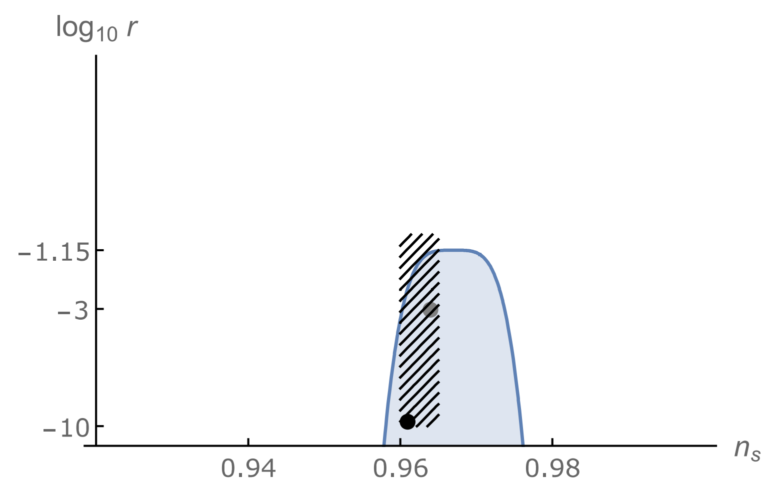
(a) (b)

Figure 5. Spectral tilt (a) and tensor-to-scalar ratio (b) in the case $\xi_\gamma = 0$. One can see that two regions in the right part of the plots reproduce metric and Palatini Higgs inflation. The left region is completely new. Note that due to the large values of the tensor-to-scalar ratio, this region is observationally excluded.

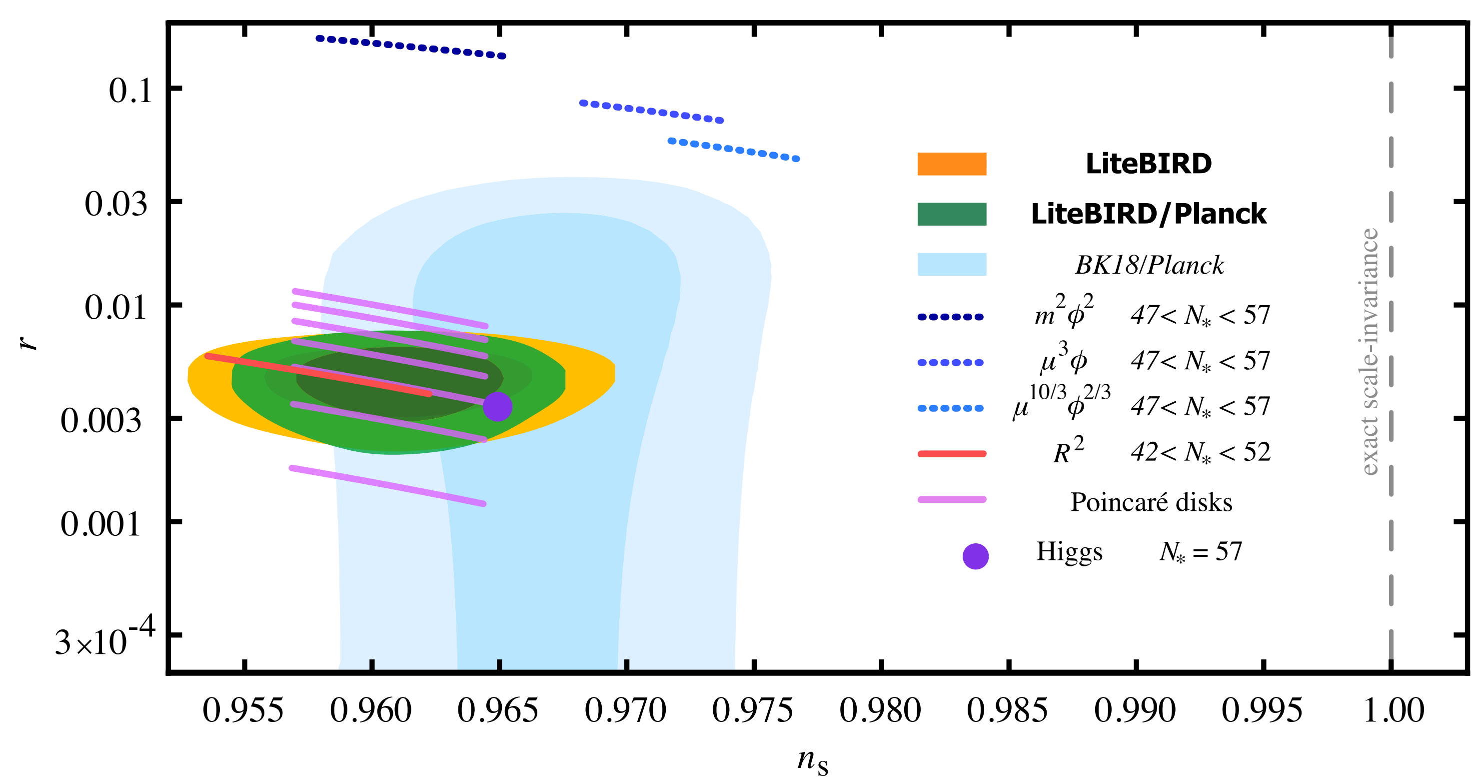
Generic Einstein-Cartan Higgs inflation

Observations:

- Inflation is a generic phenomenon.
- Large parts of the parameter space reproduce the predictions of either metric or Palatini Higgs inflation.
- The spectral index n_s is mostly independent of the choice of couplings and lies very close to $n_s = 1 - 2/N$.
- The tensor-to-scalar ratio r can vary between 1 and 10^{-10}. Detection of r in near future?



Future prospects



Einstein-Cartan gravity, scale and Weyl invariance

Extra symmetries lead to more definite predictions:

- EC gravity + scale invariance + Weyl symmetry below the Planck scale (MS, Karananas, Zell'23):

$$n_s \approx 1 - \frac{2}{N}, \quad r \gtrsim \frac{12}{N^2}\,,$$

Here N is the number of e-foldings.

Dark Energy

Equation of state of DE: $\epsilon = \omega p$

- if $\omega = -1$ - no new particle is needed, this is just cosmological constant, fits well to the SM (or the ν MSM)

- if $\omega \neq -1$ (DESI?), light or massless particle can do the job. Possible origin - dilaton of spontaneously broken exact scale invariance and unimodular gravity ($det[g_{\mu\nu}] = 1$). Also fits well to the SM (or the νMSM).

Unimodular gravity and scale-invariance

Scale-invariant action in unimodular gravity with dilaton:

$$S = \int d^4x \left[-\frac{1}{2}\xi_\chi \chi^2 R + \frac{1}{2}(\partial_\mu \chi)^2 - \frac{\beta}{4}\chi^4 \right].$$

Equivalent metric theory (no unimodular constraint):

$$S = \int \sqrt{-g}\, d^4x \left[-\frac{1}{2}M_P^2 R - \Lambda + \frac{1}{2}(\partial_\mu \tilde{\chi})^2 - U(\tilde{\chi}) \right],$$

with the potential of the thawing quintessence, leading to negative in w_0 and w_a ($\omega \approx w_0 + a w_a$, a is the scale factor)

$$U = \frac{\Lambda}{\xi_\chi^2} \exp\left(-\frac{\gamma \tilde{\chi}}{M_P} \right), \quad \gamma = \frac{4}{\sqrt{6 + \frac{1}{\xi_\chi}}}$$

Conclusions

How many new particles do we need?

Three is enough to explain neutrino masses, dark matter and baryon asymmetry of the Universe, while one more may be needed if Dark Energy is dynamical.