science case

An Introduction to the North America - Europe Workshop on Future of Double Beta Decay

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Topics:

Significance of the process under investigation

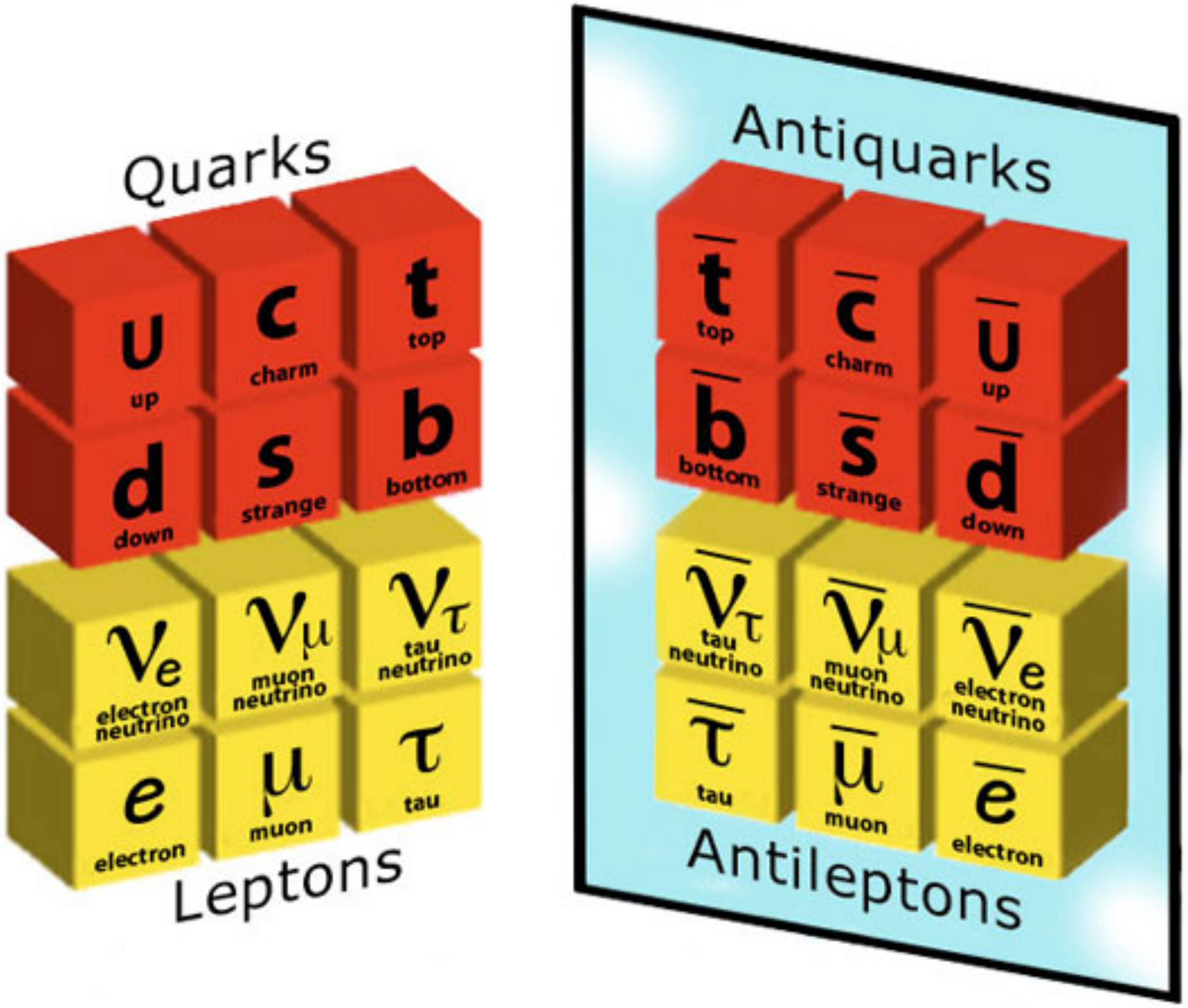
The role of (Majorana) neutrino mass

Relationship between experiment & theory

Bibliography, discussion, wrap up

on the significance of the process under investigation

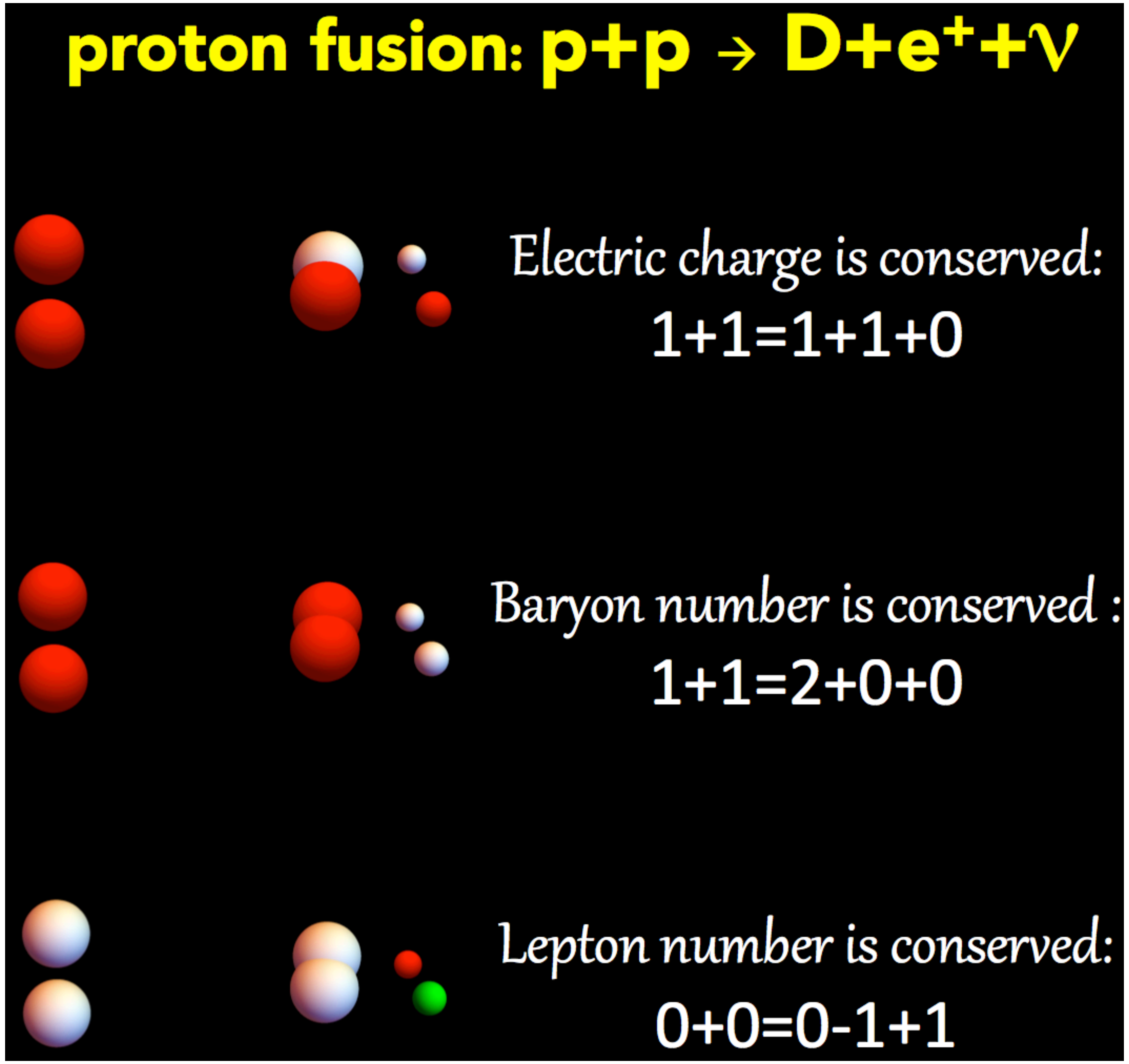
the particles that compose matter



matter stability

and the role of neutrinos

- Known physics ("standard model", SM) says: the numbers of baryons and leptons do not change
- This can be illustrated with the main reaction that powers the Sun, which implies that neutrinos are particles of matter - leptons
- Let us now consider the role of certain discoveries about neutrinos of last decade



from neutrino appearance experiments we have learned that there is only one basic type of lepton

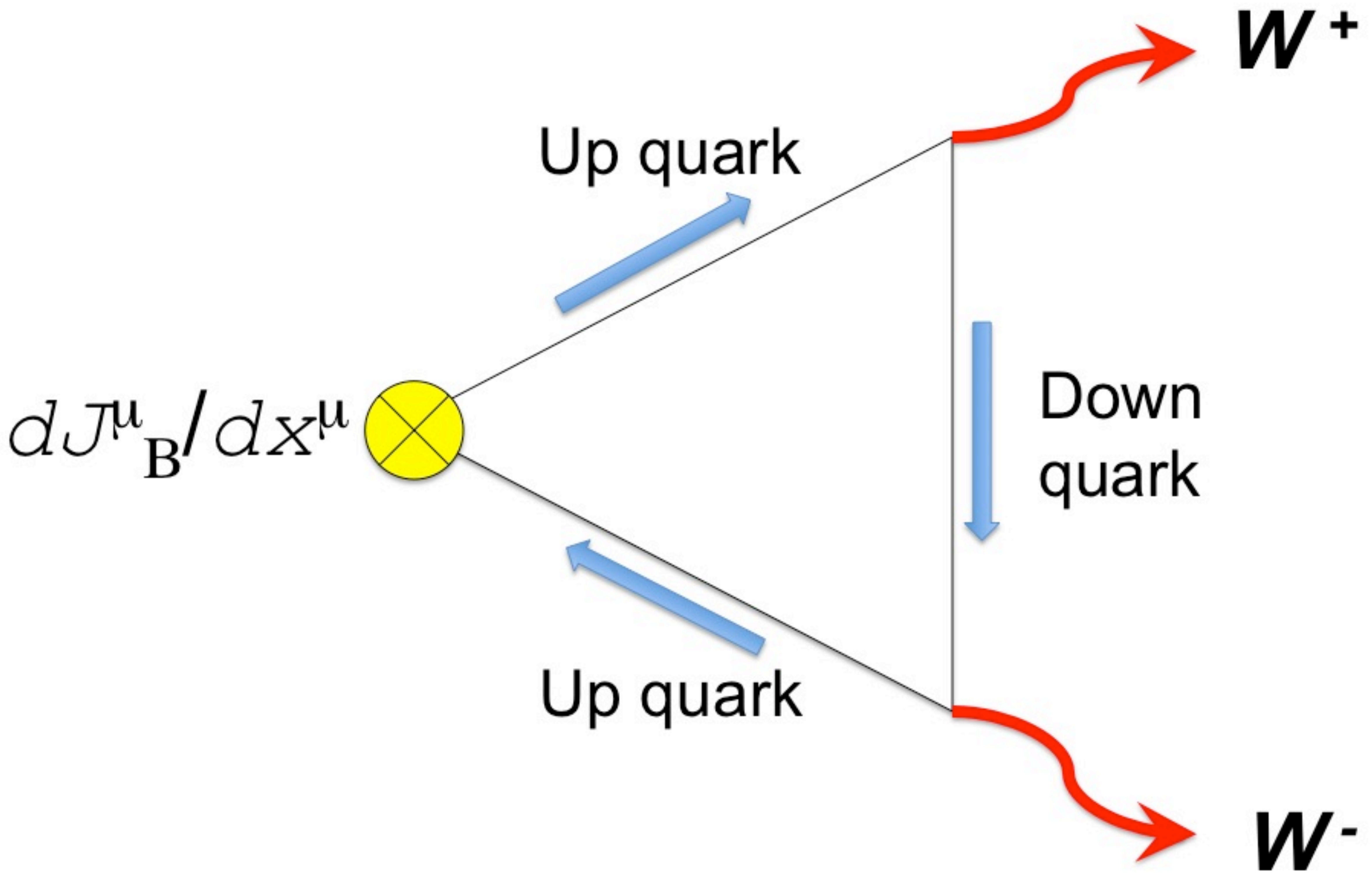
(=at the scrutiny of T2K, NOvA, OPERA, SK, DeepCore, only total lepton number L survived)

	ΔL_e	ΔL_μ	ΔL_τ	ΔL
$\nu_\mu \to \nu_e$	+1	-1	0	0
$\nu_\mu \to \nu_\tau$	0	-1	+1	0

We know empirically that all global symmetries of SM are violated, except **L** and **B**.
Conversion among families is possible, we have only two types of **matter particles**: leptons and quarks

In the accepted theory of matter (i.e., SM) B and L are not conserved alone

B+L is violated, only B-L is conserved exactly, thus: in SM, leptonic and baryonic matter is connected



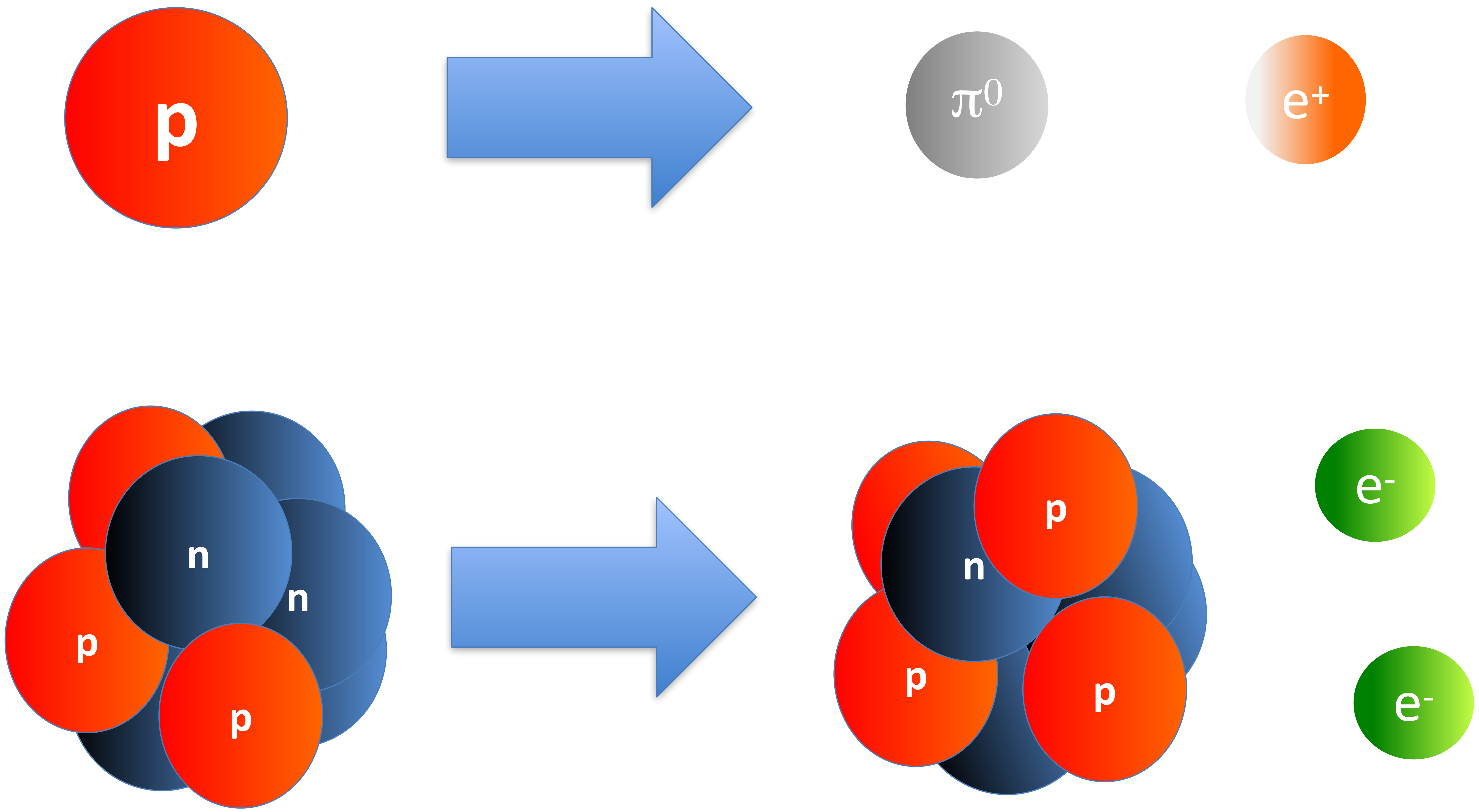
from neutrino appearance experiments we have learned that there is only one basic type of ~~lepton~~ fermion

(=at the scrutiny of T2K, NOvA, OPERA, SK, DeepCore, only total lepton number L survived)

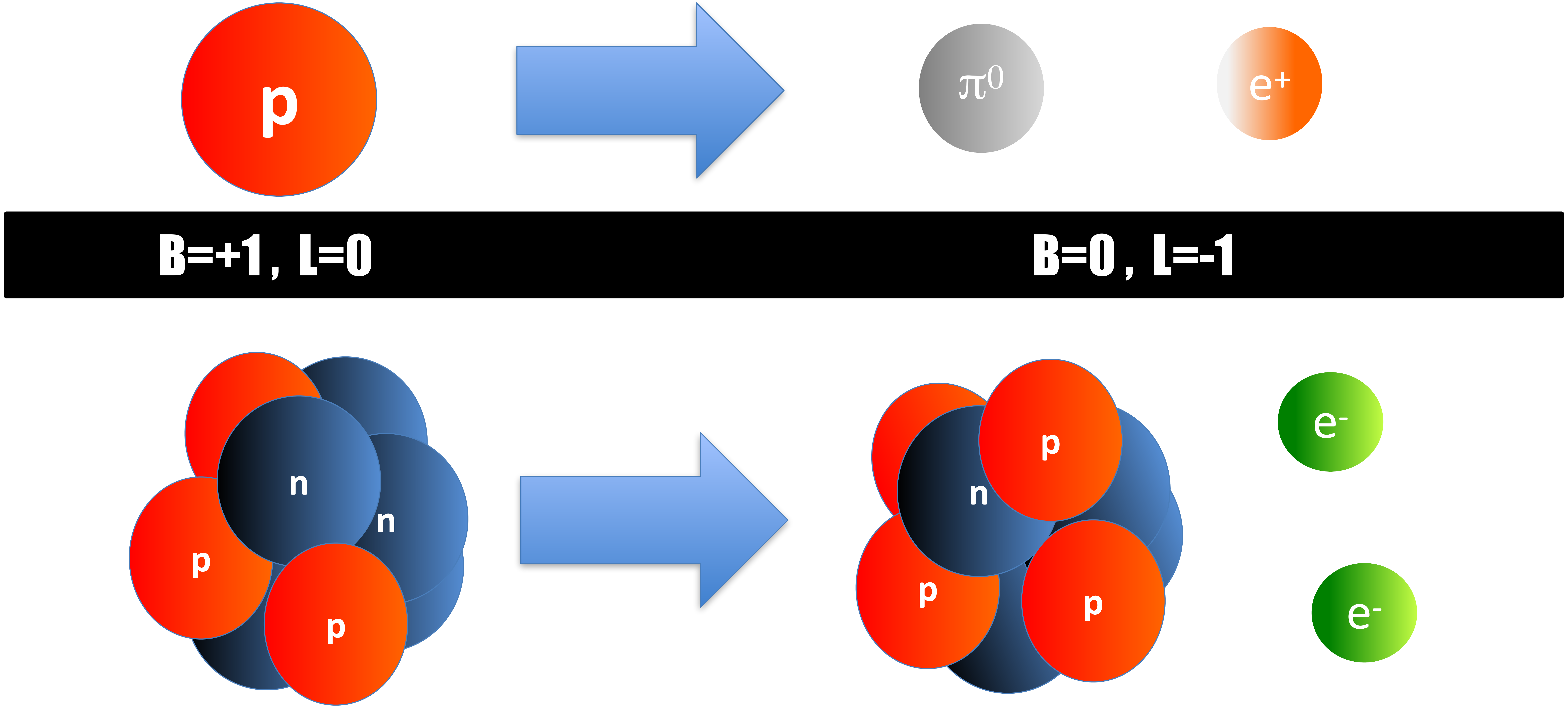
	$\Delta(L_e\text{-}L_\mu)$	$\Delta(L_\mu\text{-}L_\tau)$	$\Delta(L_\tau\text{-}L_e)$	$\Delta(B\text{-}L)$
$\nu_\mu \rightarrow \nu_e$	+2	-1	-1	0
$\nu_\mu \rightarrow \nu_\tau$	+1	-2	+1	0

B+L is not a conserved number in the Standard Model --- leptons and baryons conversion is possible. In other words, appearance experiments + theory (SM) prove that **all anomaly free symmetries** of SM are violated, except one, **B-L**

experimental tests of B and of L



experimental tests of B and of L



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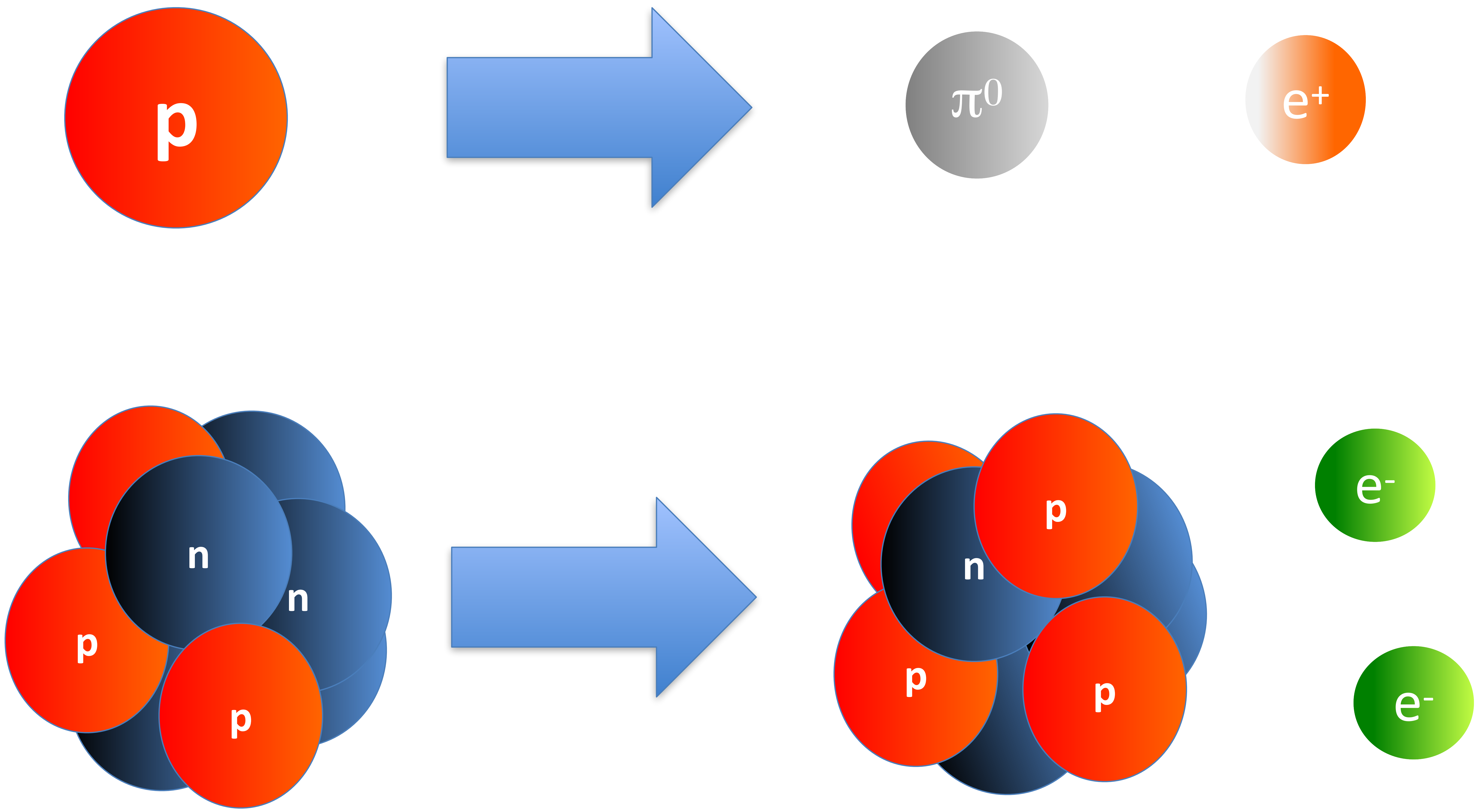
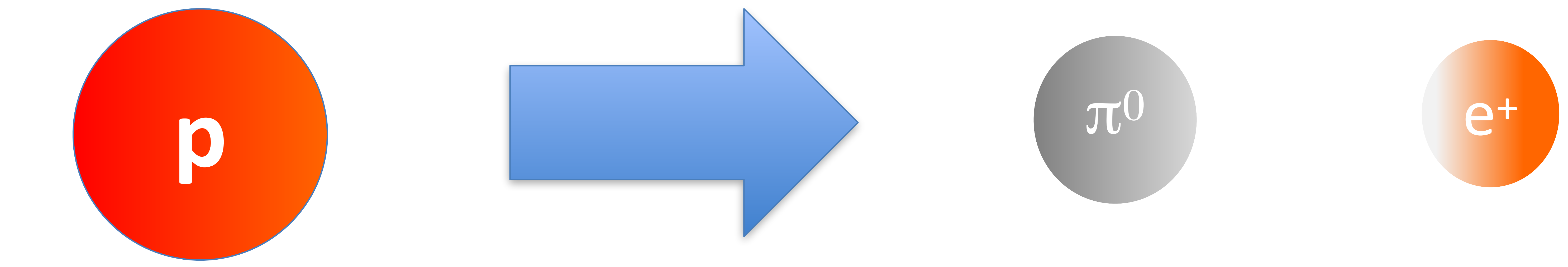


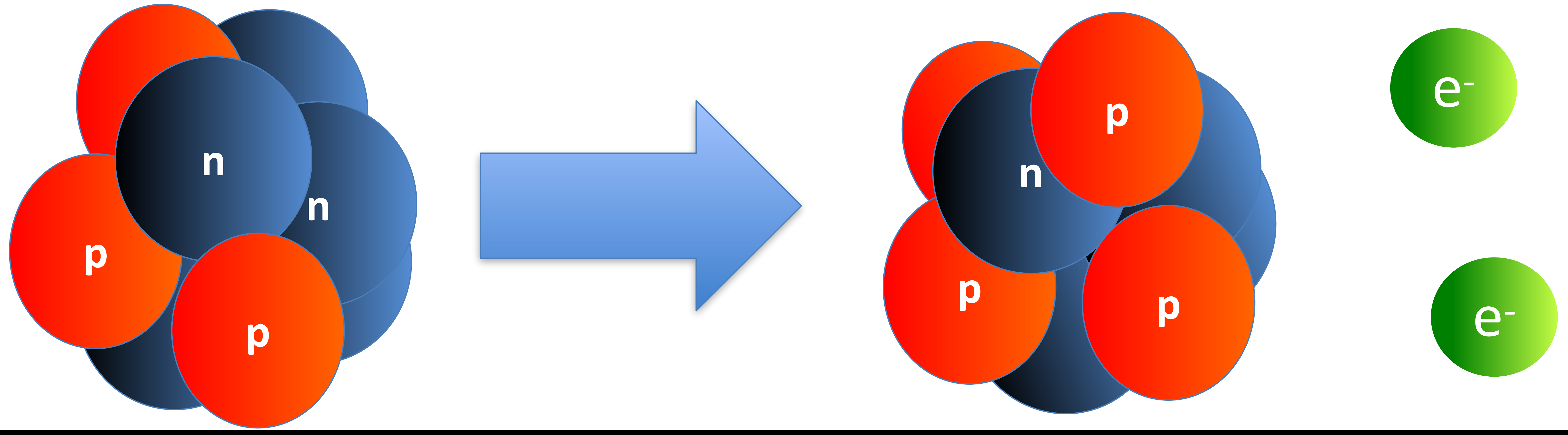
B=A , L=0

B=A , L=2

experimental tests of B and of L



Proton decay (B-L conserved)



Electrons Creation (B-L violated)

a remarkable - and probably related - scenario

(Fukugita-Yanagida's implementation of Sakharov's program)

(1) During big-bang, the decay of heavy (right-handed) neutrinos create ΔL

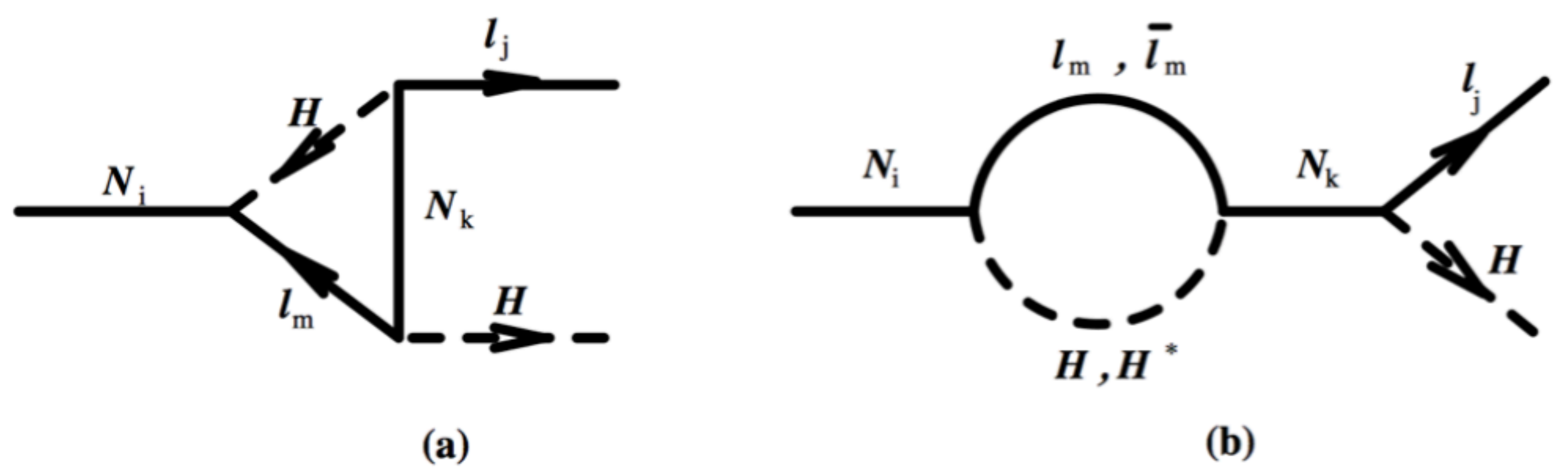


Figure 1: Diagrams contributing to the vertex (Fig. 1a) and wave function (Fig. 1b) CP violation in the heavy singlet neutrino decay.

Covi et al. '96

a remarkable - and probably related - scenario

(Fukugita-Yanagida's implementation of Sakharov's program)

(1) During big-bang, the decay of heavy (right-handed) neutrinos create $\Delta \mathbf{L}$

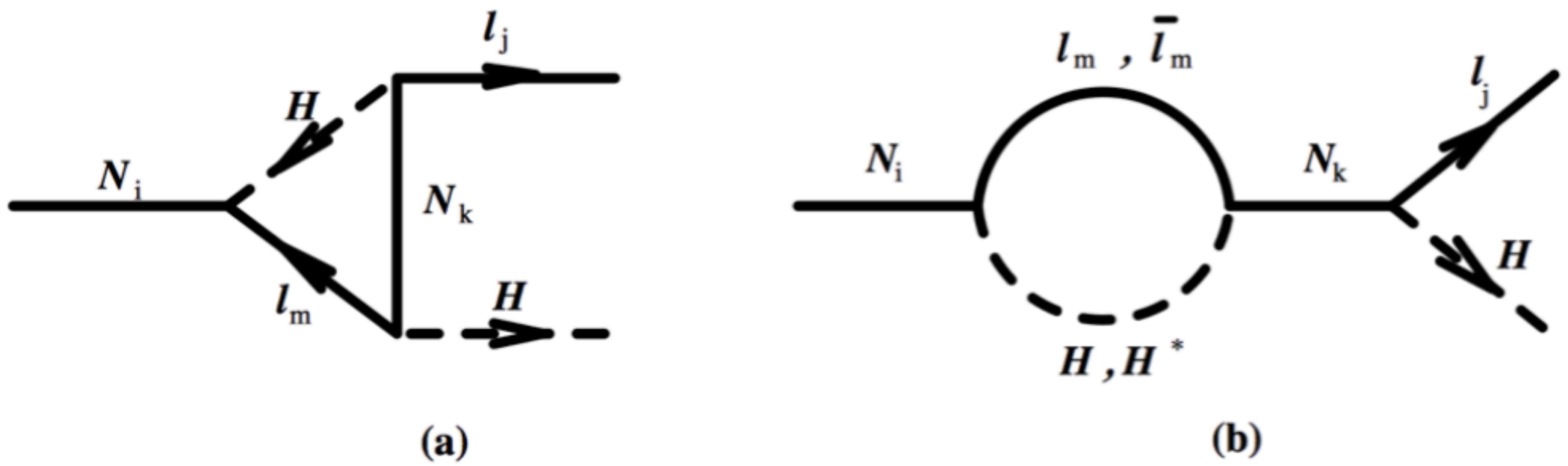
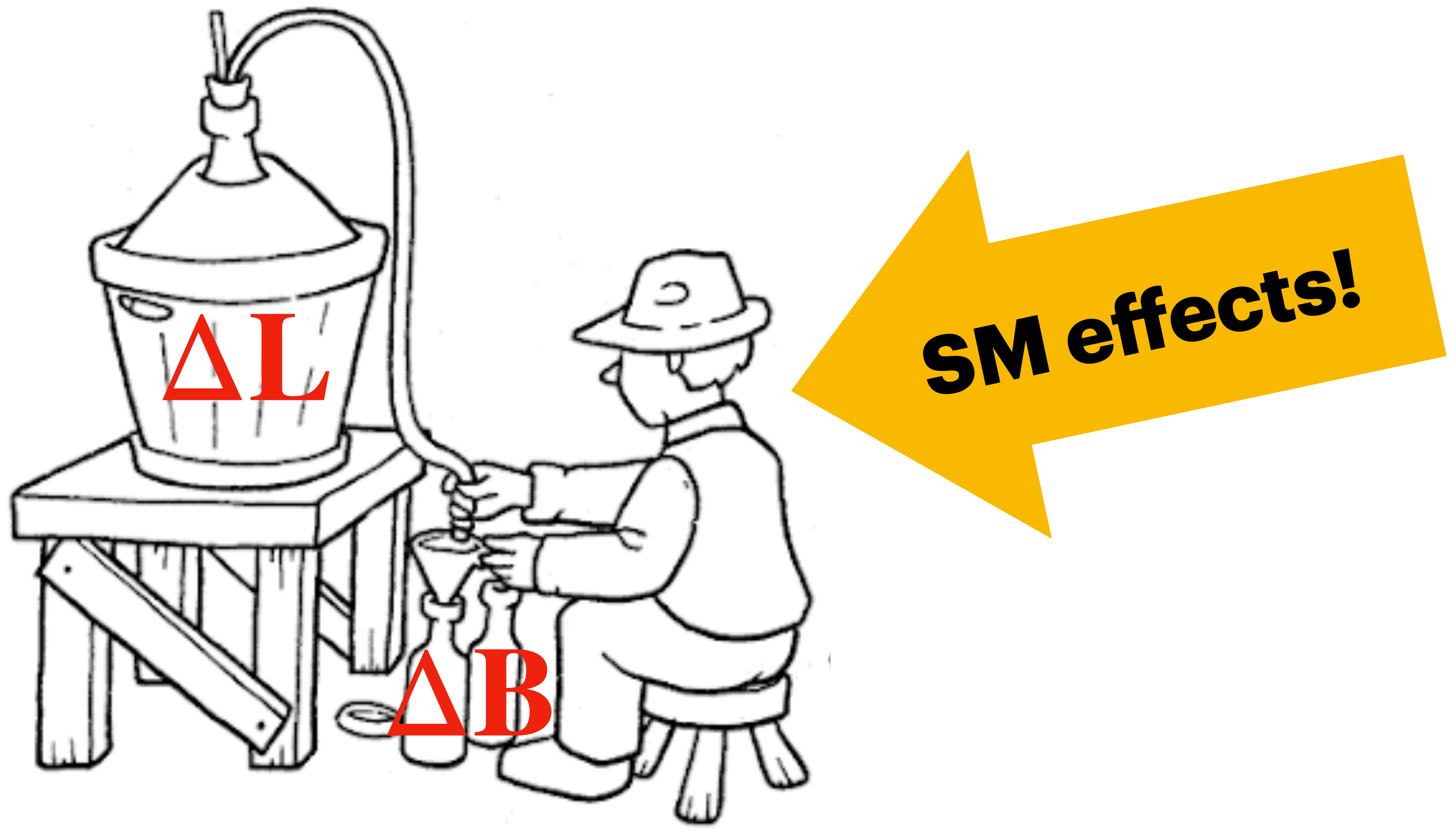


Figure 1: Diagrams contributing to the vertex (Fig. 1a) and wave function (Fig. 1b) CP violation in the heavy singlet neutrino decay.

Covi et al. '96

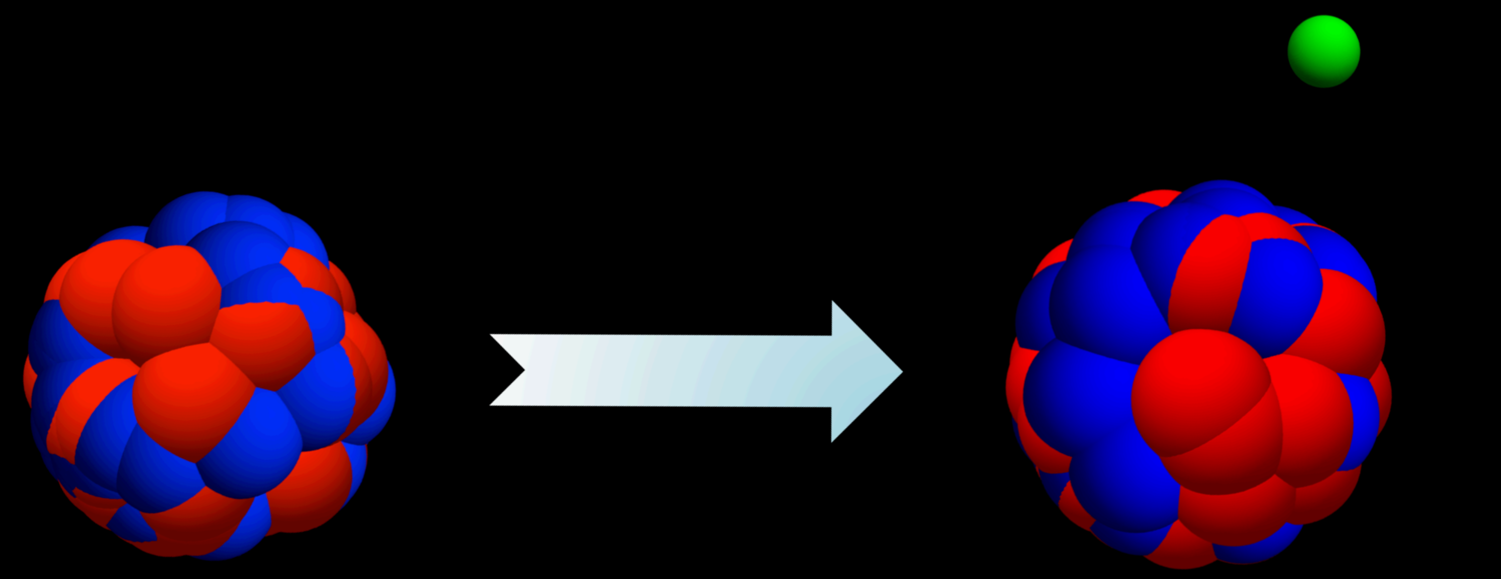
(2) Subsequently, $\mathbf{B} + \mathbf{L}$ violating effects convert it into $\Delta \mathbf{B}$



Summary

on the significance of the process under investigation

- this is a process of creation of matter particles - couple of electrons
- tests the only global symmetry of the SM not yet probed: **B-L**
- the traditional (jargonic) name of the process poorly conveys its meaning
- naturally connected with Sakharov's program, aimed at explaining the baryonic asymmetry (=creation of baryons)

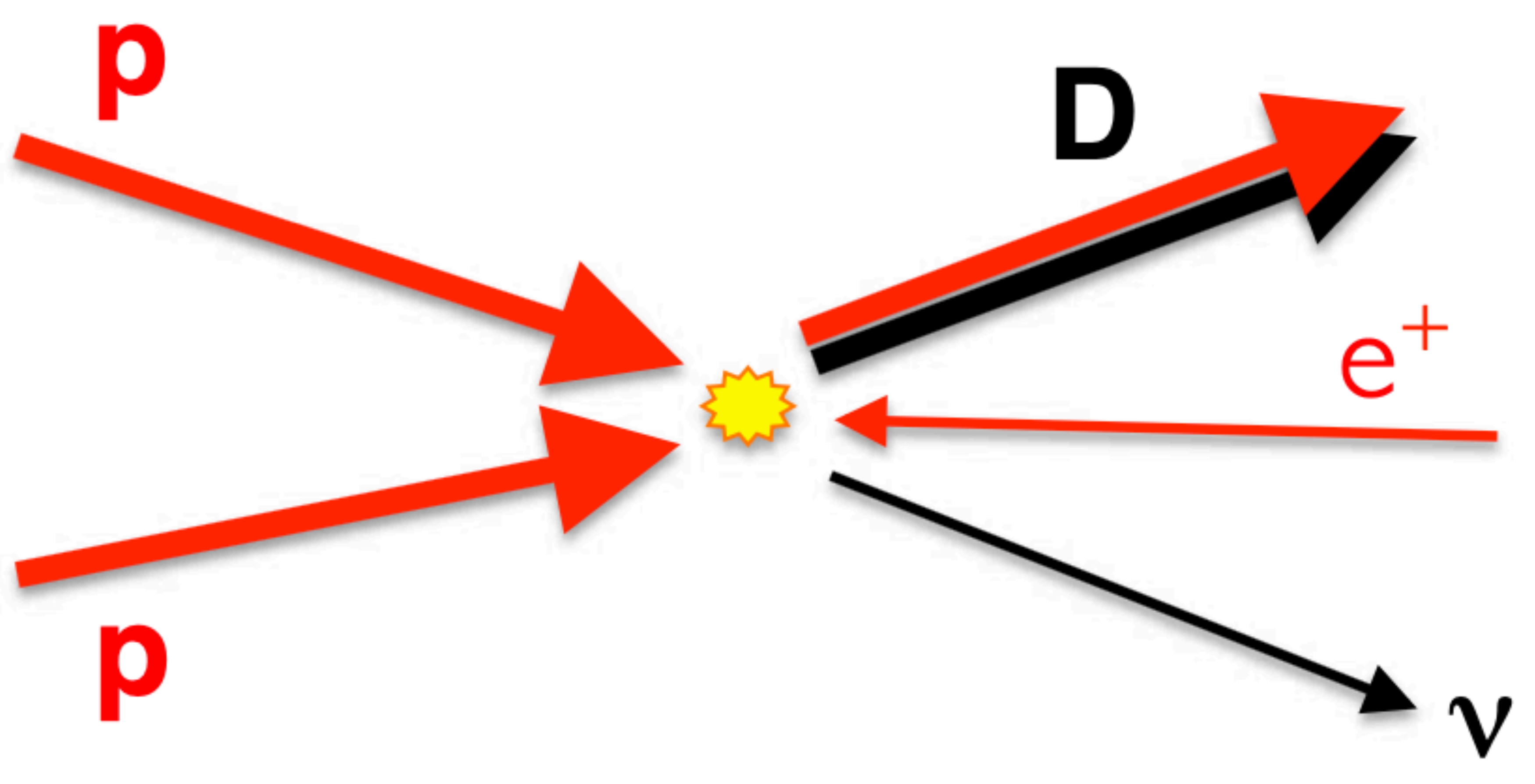


a discussion of the role of Majorana neutrino masses

on the difference between neutrinos and antineutrinos

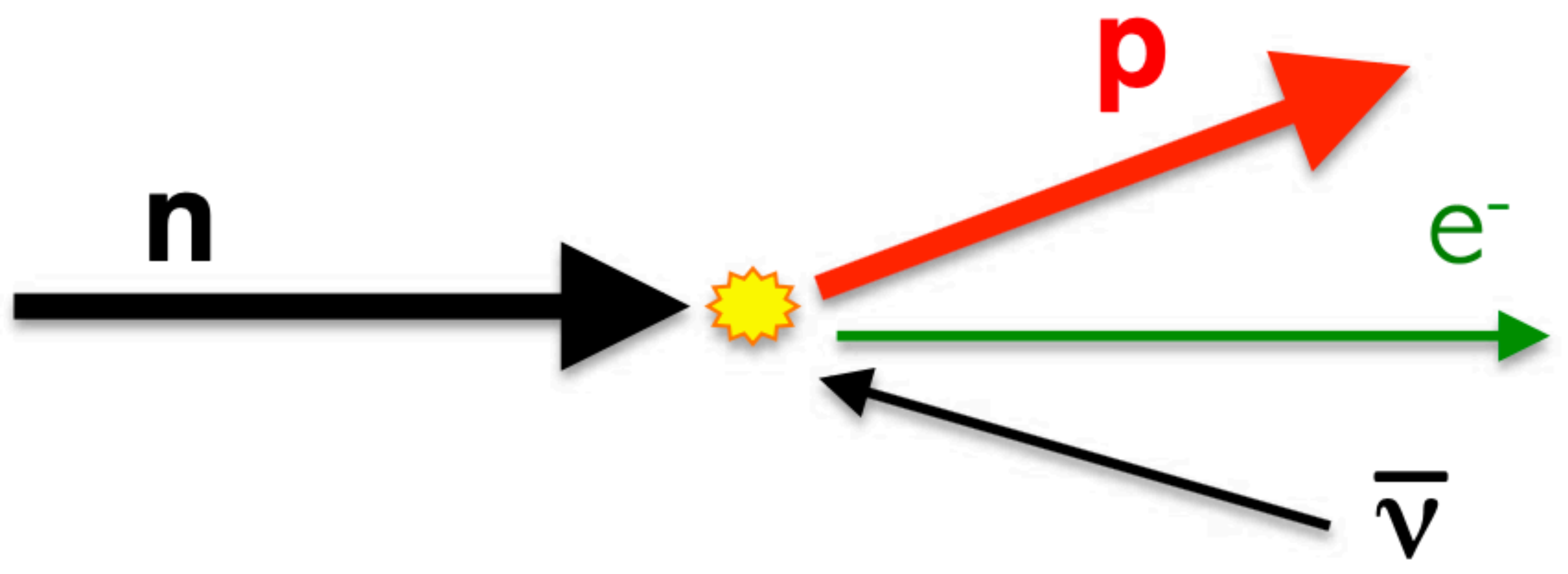
$p + p \rightarrow D + e^{+} + \nu$

The neutrino is the matter particle that accompanies the positron



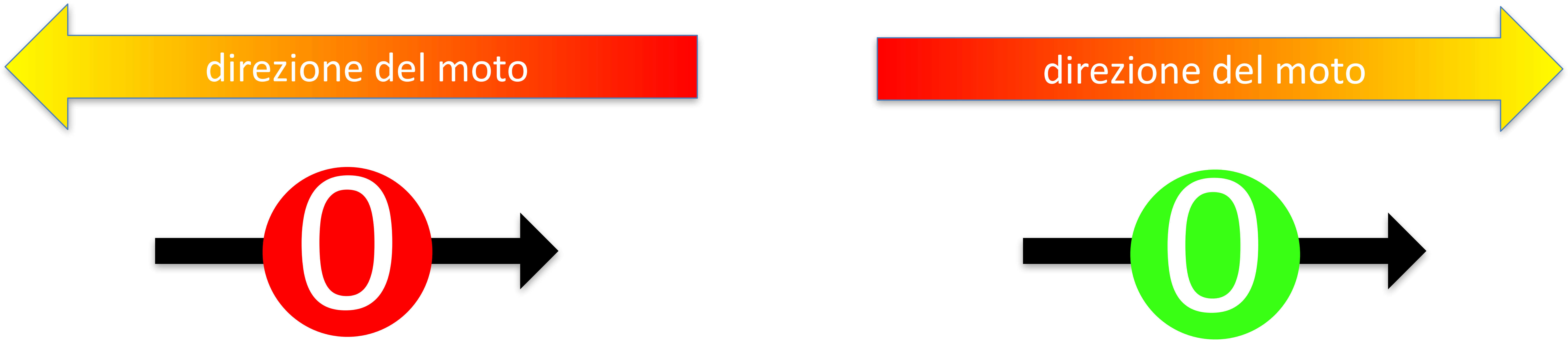
$n \rightarrow p + e + \bar{\nu}$

The antineutrino is the antimatter particle that accompanies the electron



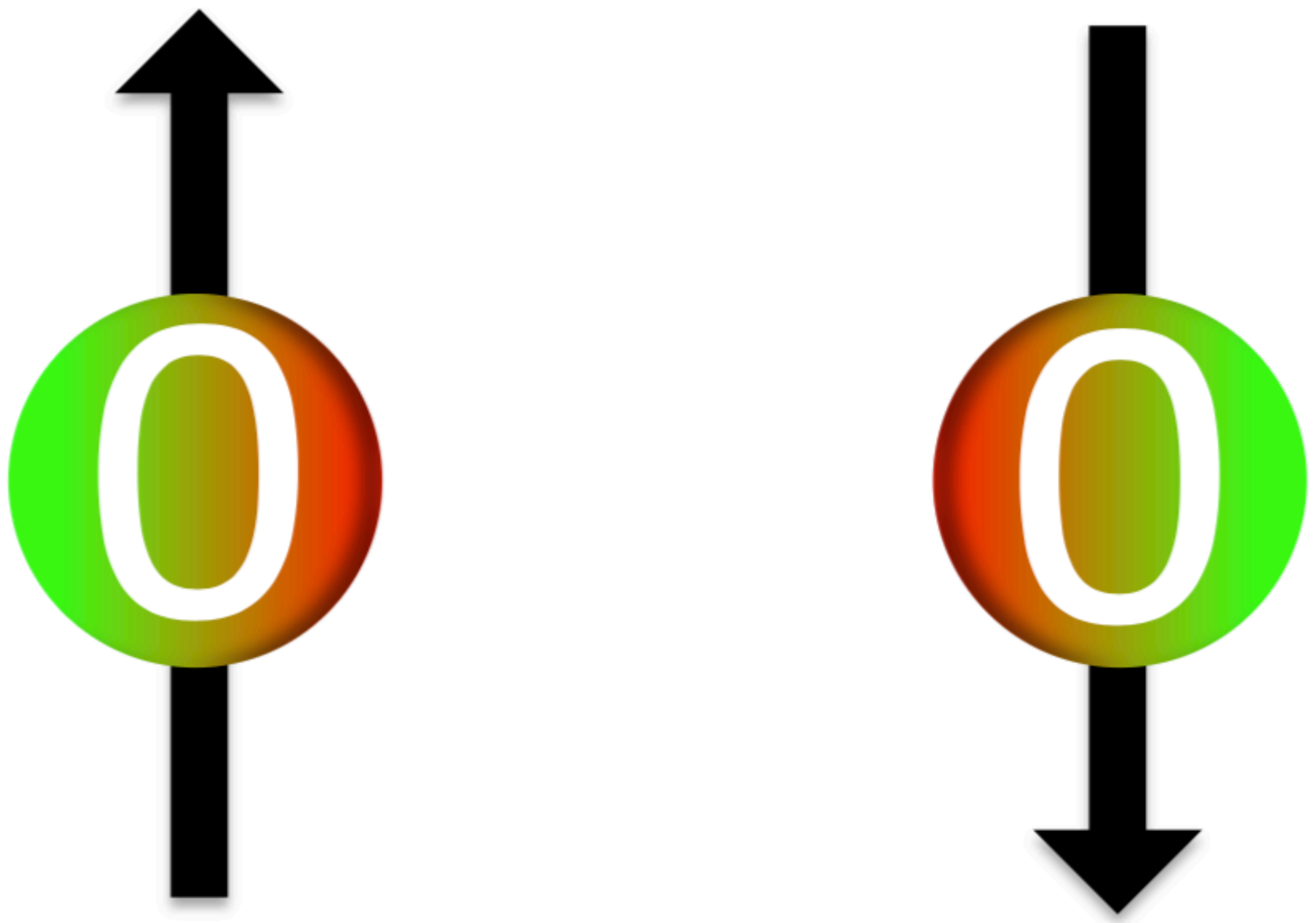
neutrinos and antineutrinos interactions at high energy are different.

How to distinguish them intrinsically, w/o referring to other particles?

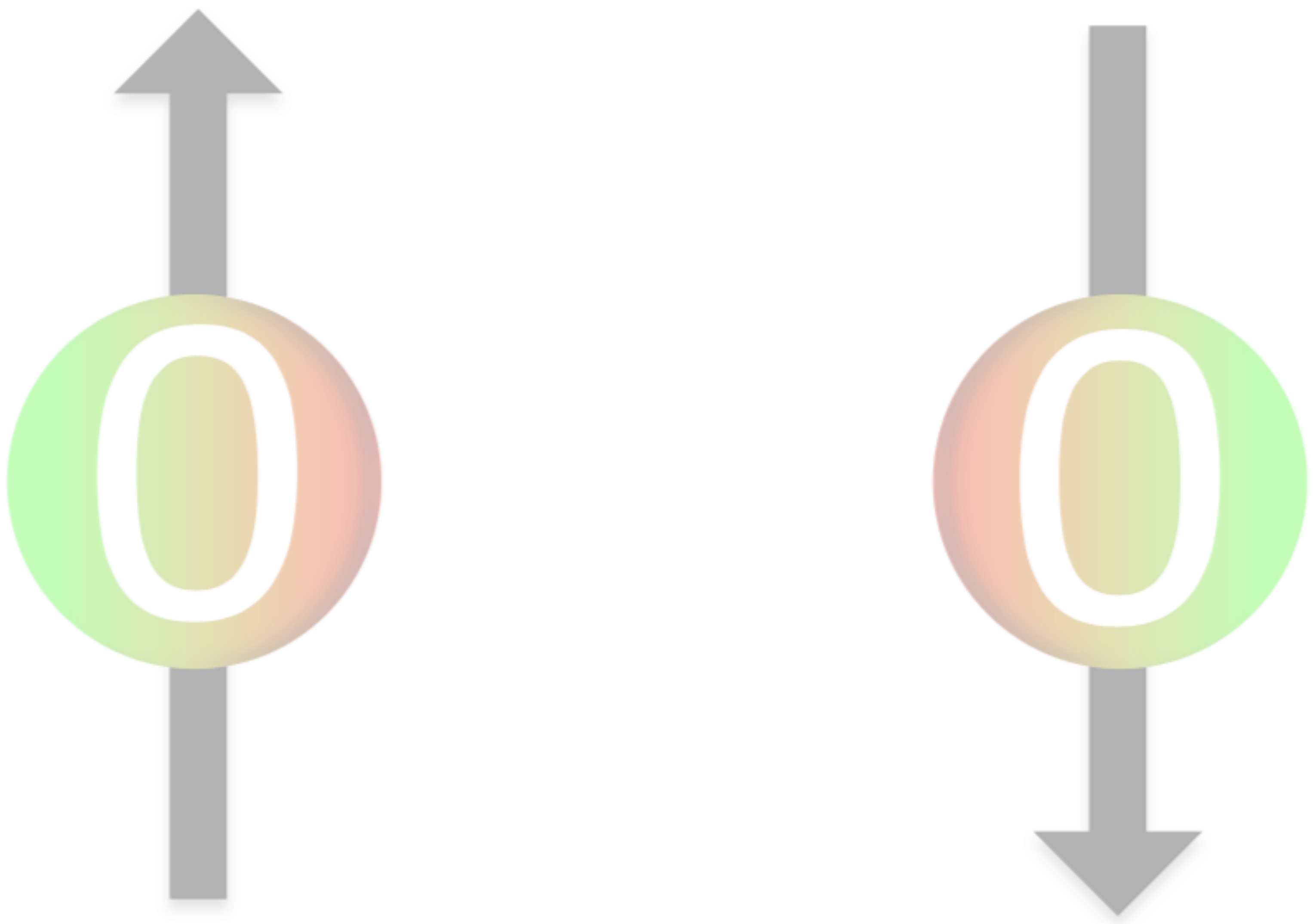


helicity tells neutrinos from antineutrinos

but in rest system that exists they seem equal

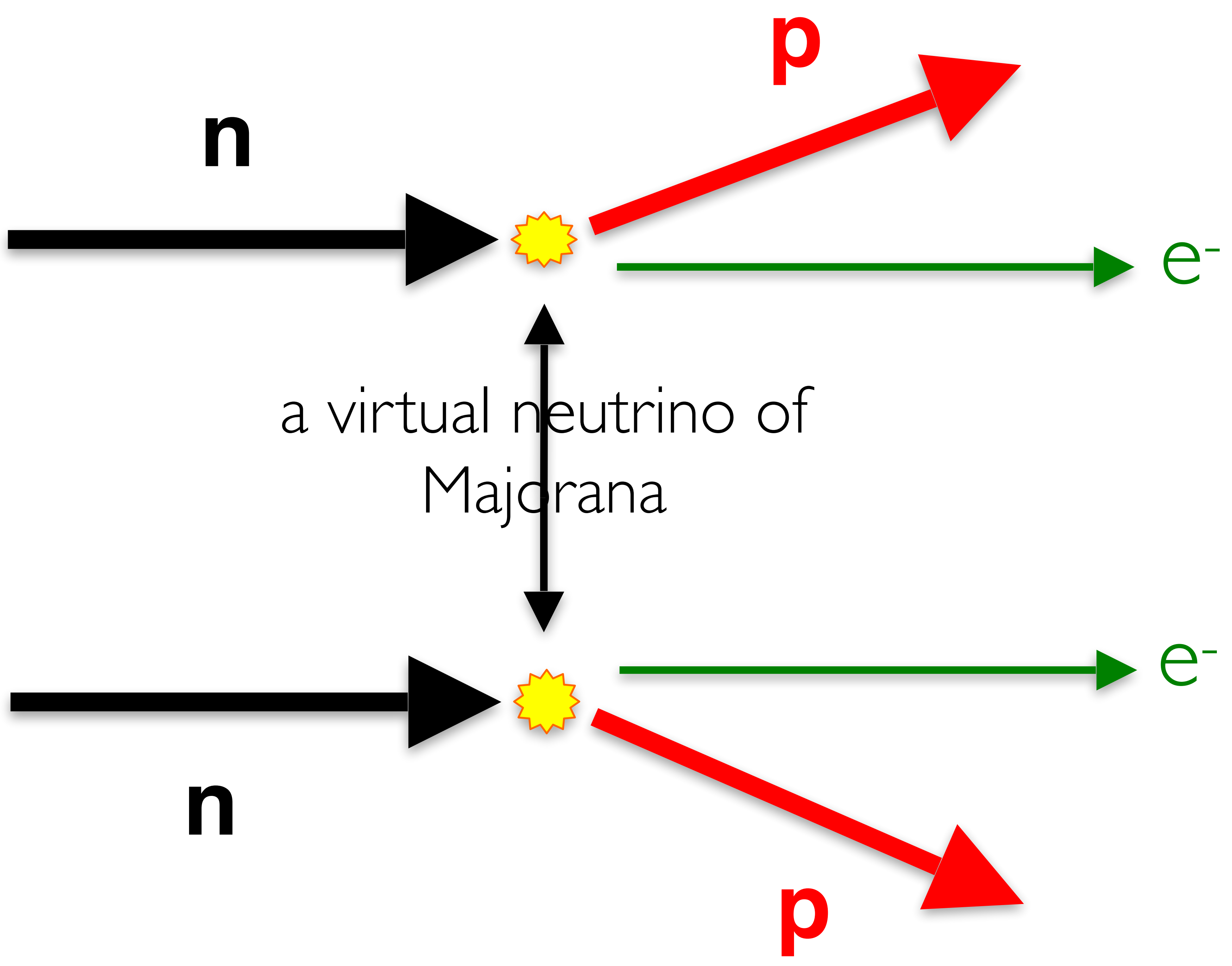


Majorana: neutrinos are matter & antimatter



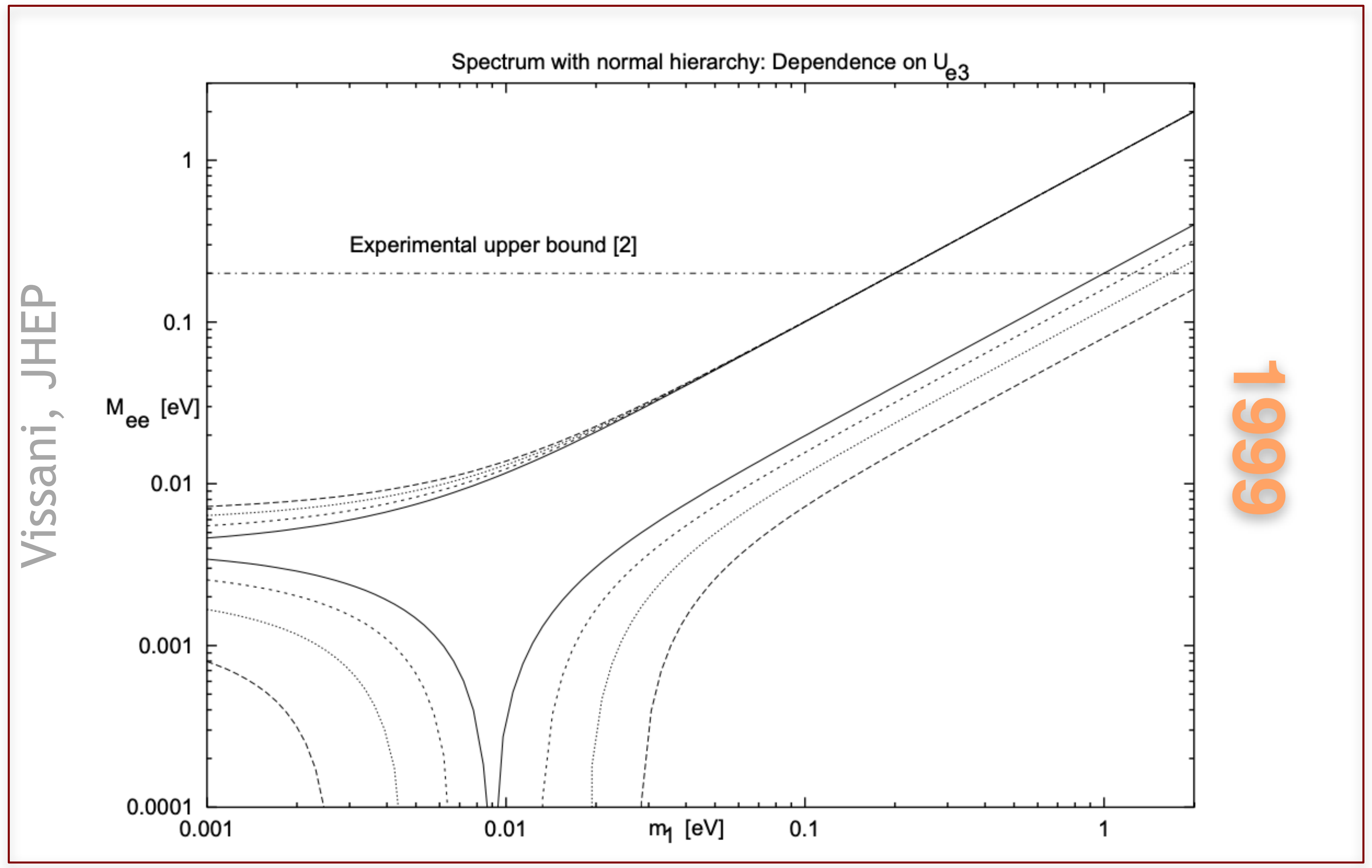
Majorana's neutrinos enable electron creation

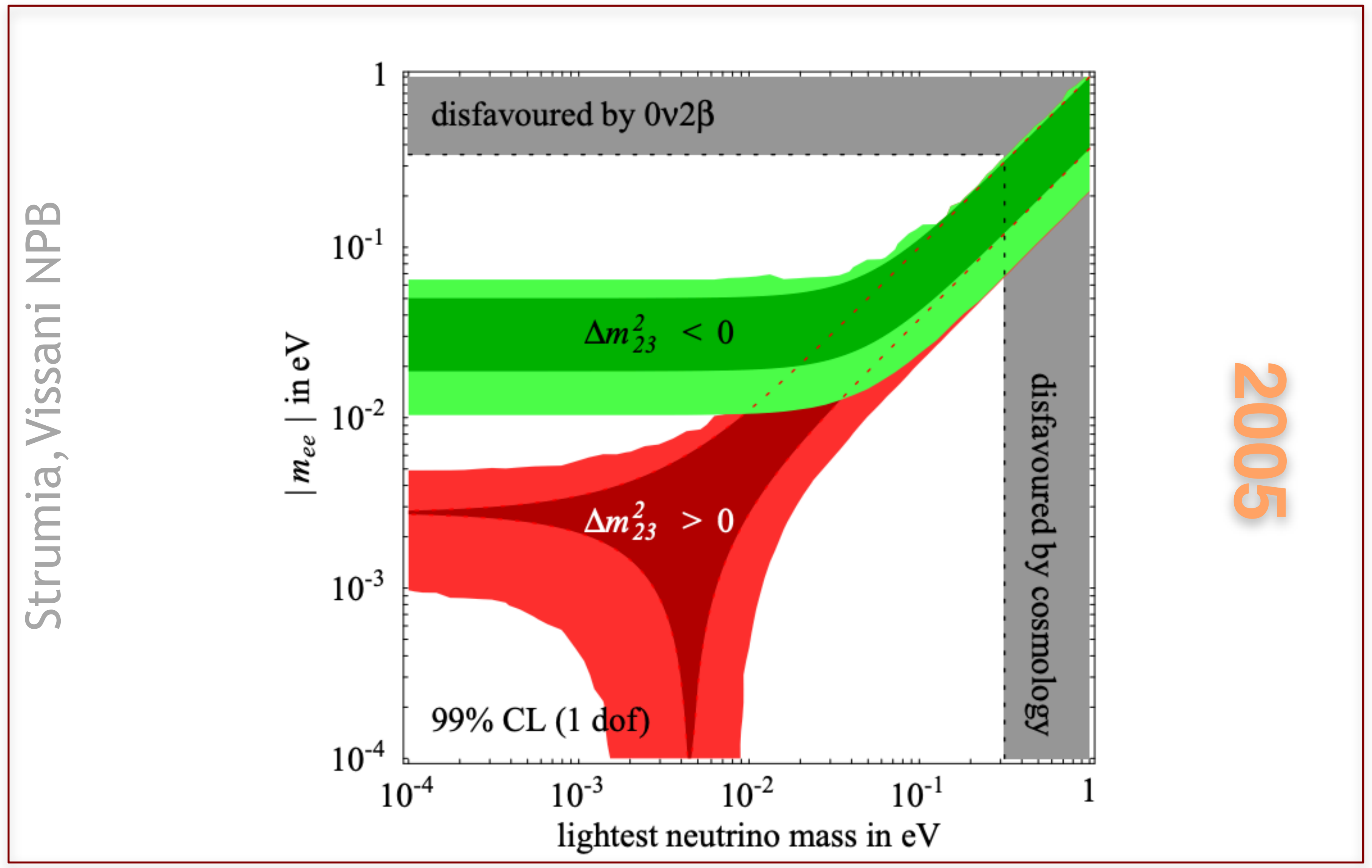
2 **n** → 2 **p** + 2 e

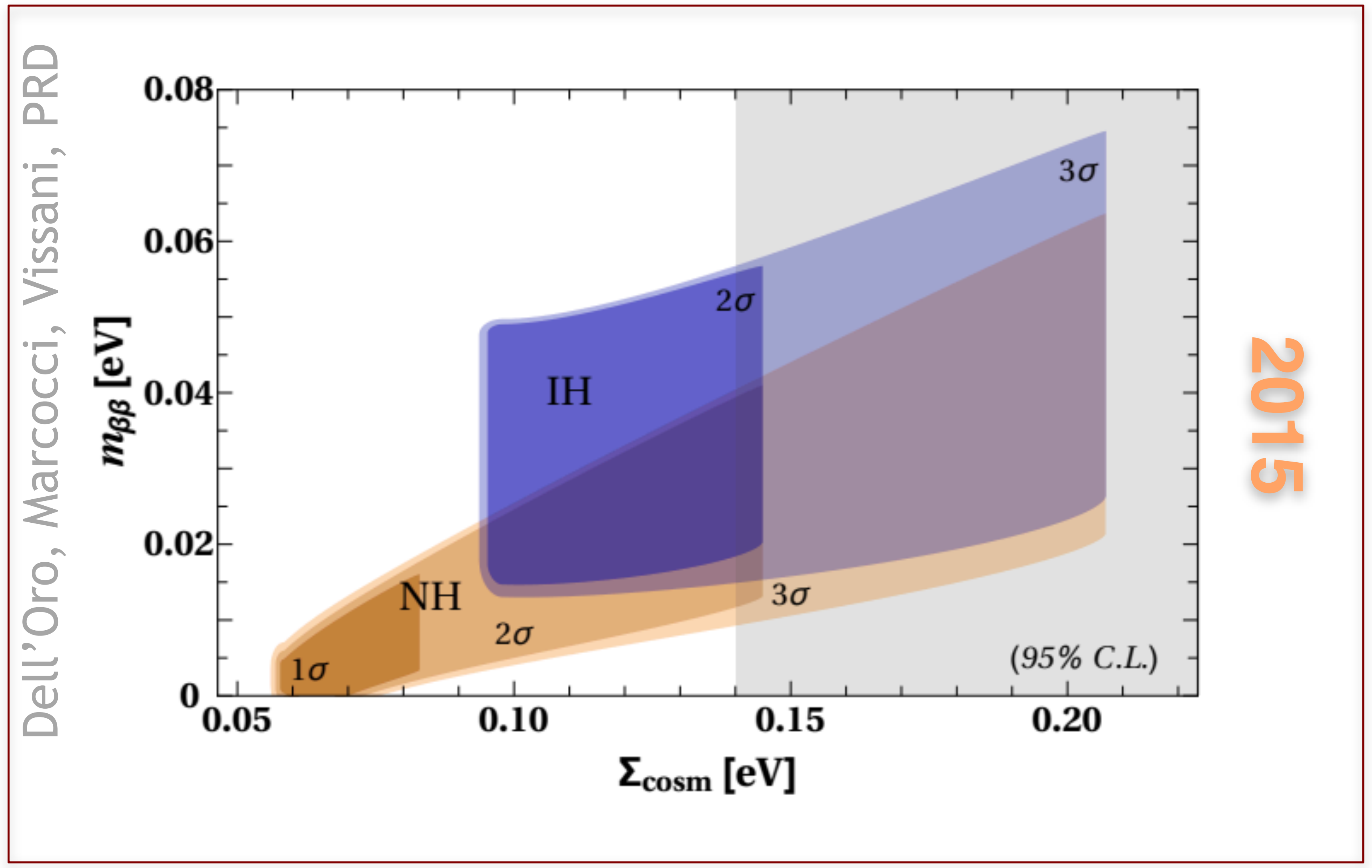


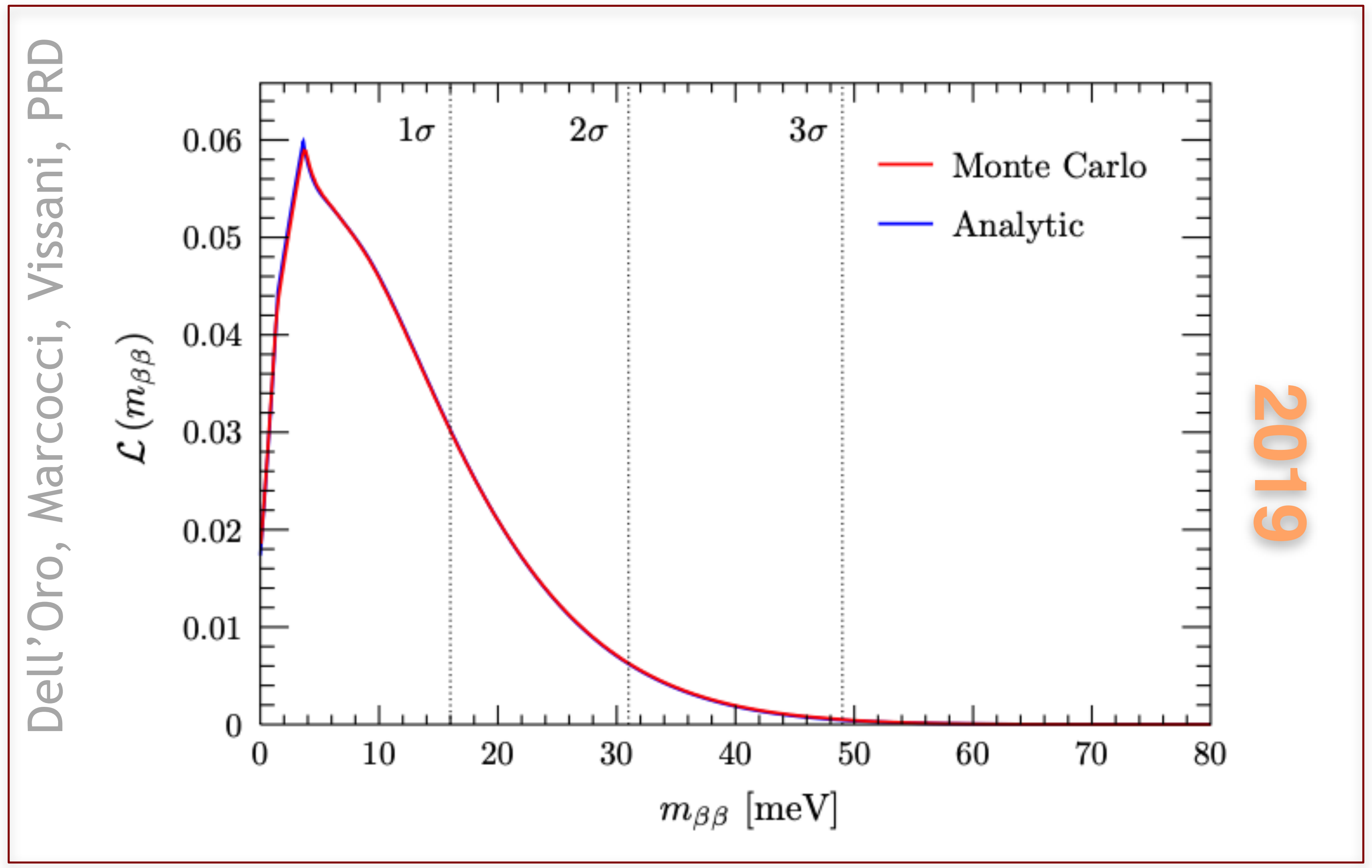
In fact, Majorana neutrinos act as a bridge between matter and antimatter.
For the reasons above, the amplitude is proportional to neutrino mass

20 yr of constraints on the Majorana mass relevant to 2n→2p+2e









Testing the Inverted Neutrino Mass Ordering with Neutrinoless Double-Beta Decay

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(Dated: July 21, 2021)

We quantify the extent to which future experiments will test the existence of neutrinoless double-beta decay mediated by light neutrinos with inverted-ordered masses. While it remains difficult to compare measurements performed with different isotopes, we find that future searches will fully test the inverted ordering scenario, as a global, multi-isotope endeavor. They will also test other possible mechanisms driving the decay, including a large uncharted region of the allowed parameter space assuming that neutrino masses follow the normal ordering.

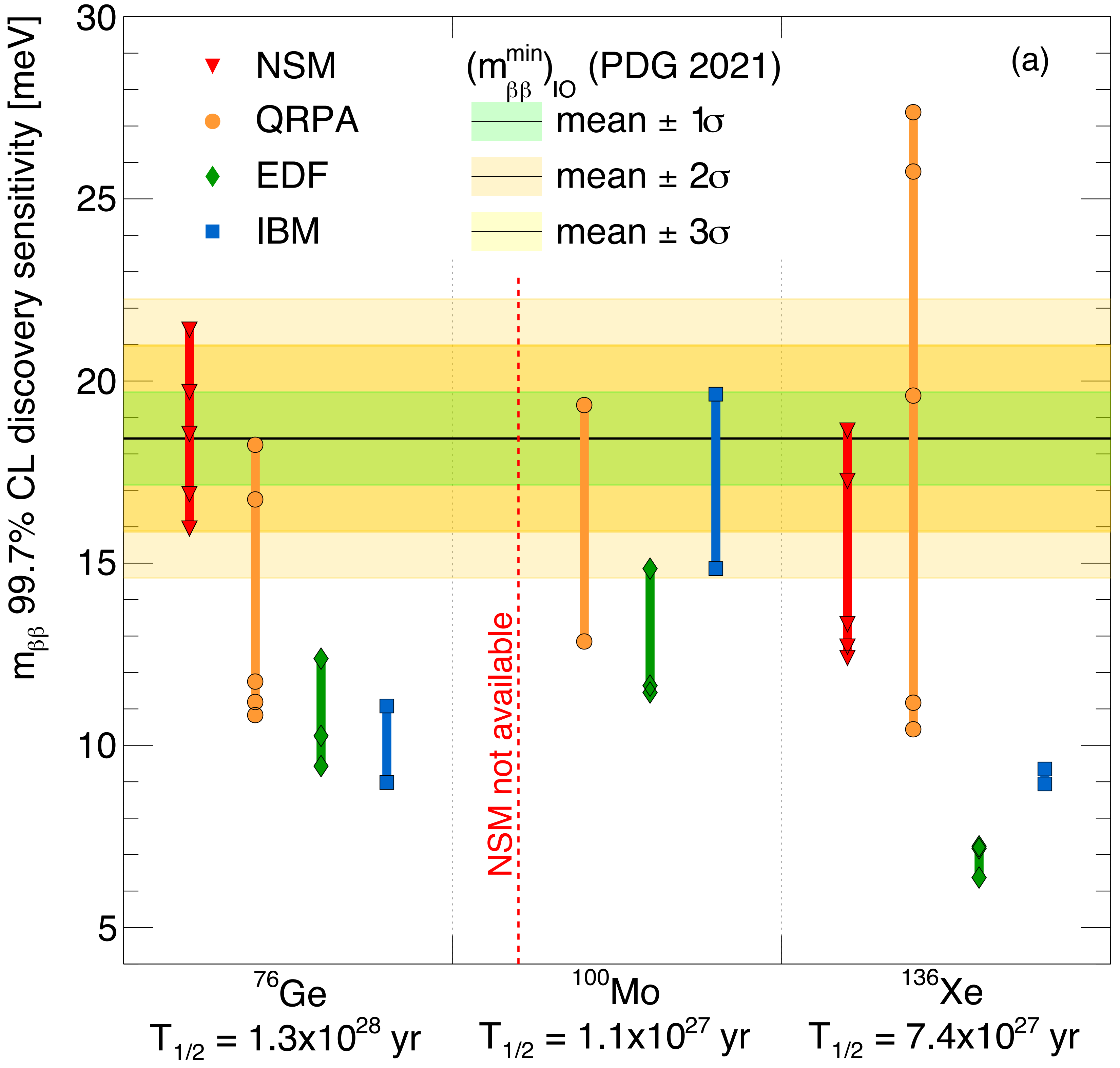

FIG. 1. Comparison of $m_{\beta\beta}$ 99.7%-CL discovery and 90%-CL median exclusion sensitivities for different isotopes at stated half-life sensitivities [30–32], grouped by nuclear many-body frameworks with matrix element ranges from Table I. The horizontal bands show the variation on $(m_{\beta\beta}^{min})_{IO}$ under variation of the neutrino oscillation parameters.

Discovery probabilities of Majorana neutrinos based on cosmological data

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(Received 5 January 2021; accepted 5 February 2021; published 26 February 2021)

We discuss the impact of the cosmological measurements on the predictions of the Majorana mass of the neutrinos, the parameter probed by neutrinoless double-beta decay experiments. Using a minimal set of assumptions, we quantify the probabilities of discovering neutrinoless double-beta decay and introduce a new graphical representation that could be of interest for the community

DOI: 10.1103/PhysRevD.103.033008

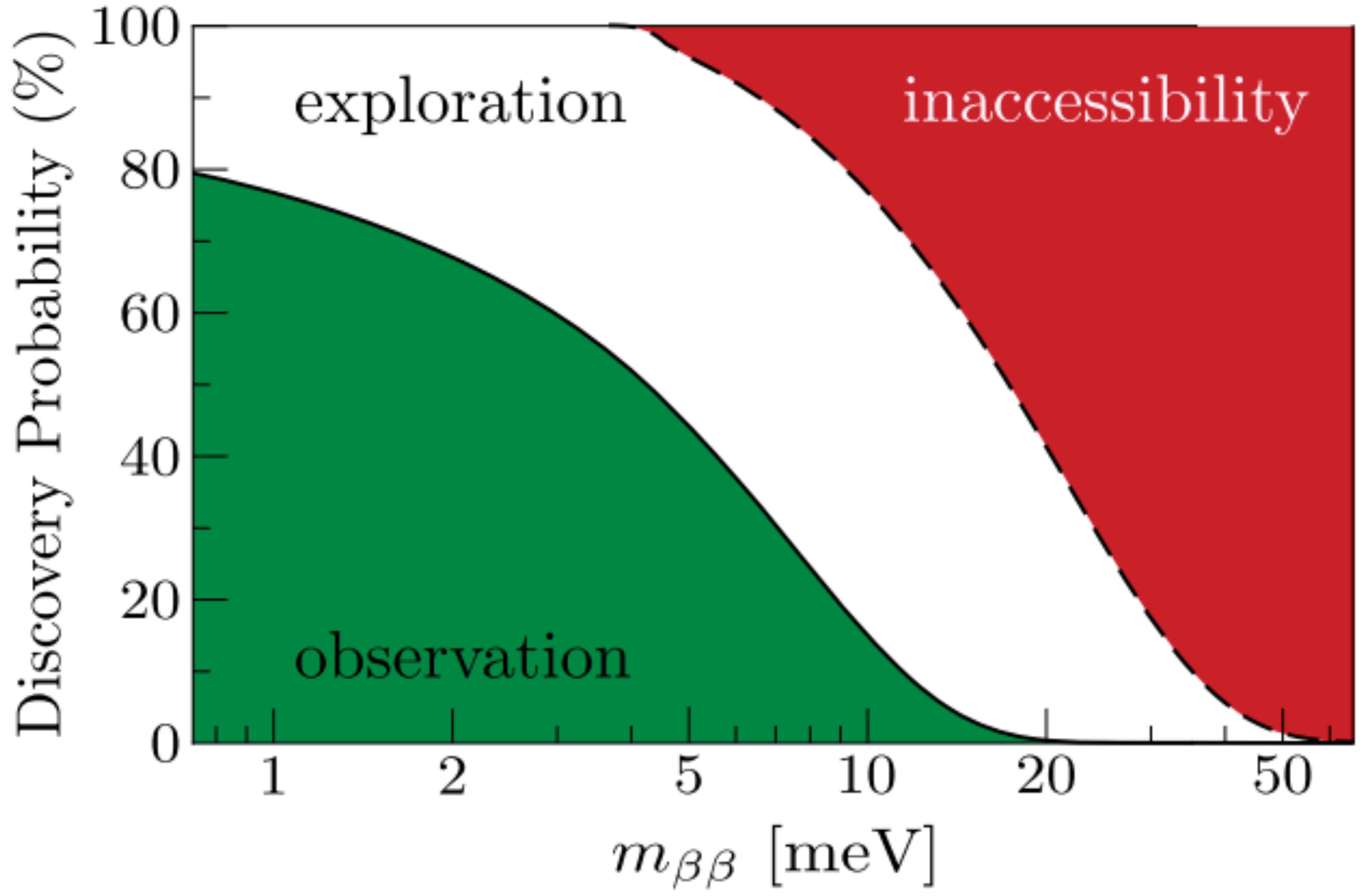
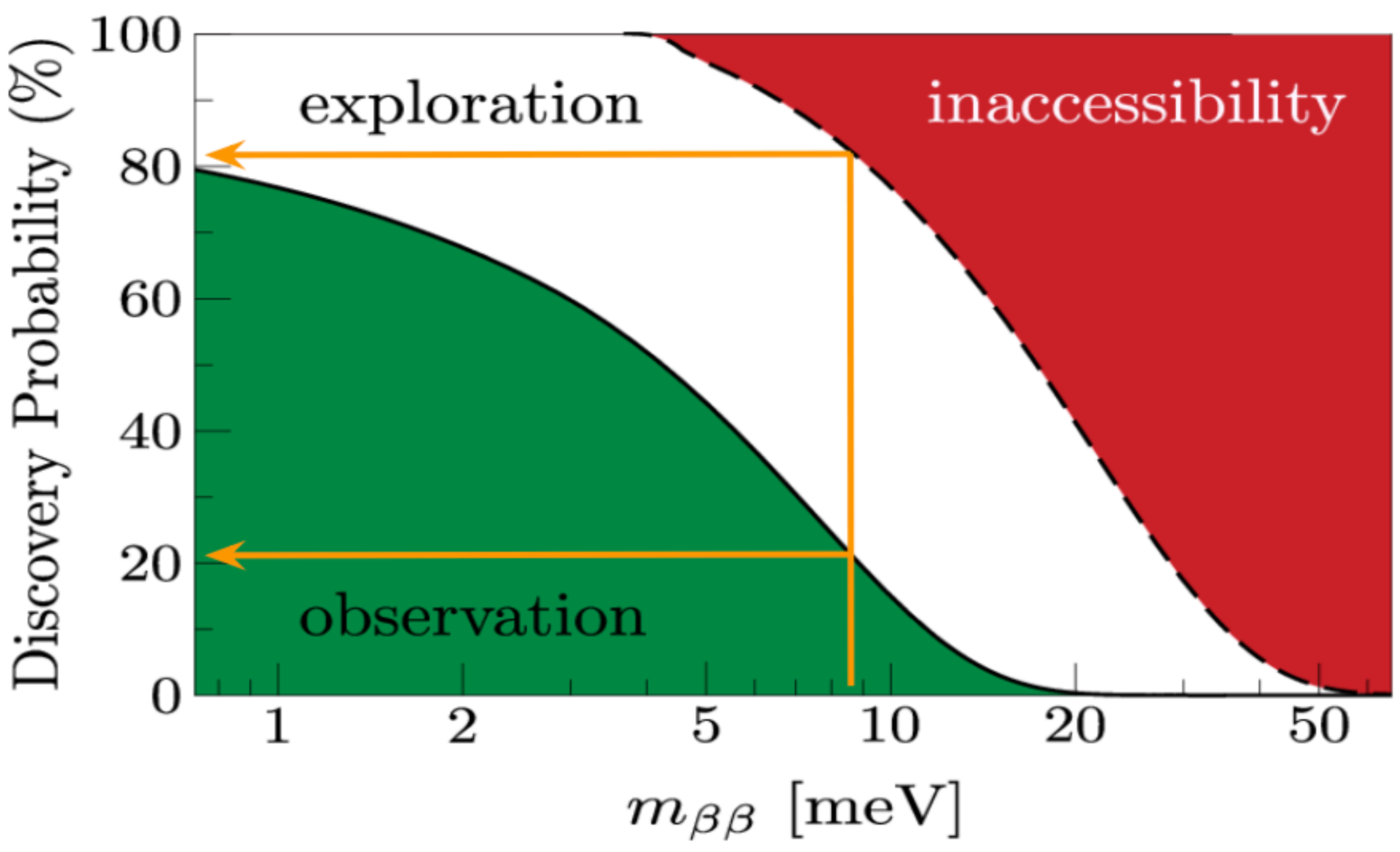


FIG. 2. Discovery probability as a function of the experimental sensitivities to $m_{\beta\beta}$ for the most unfavorable scenario (black solid line, $m_{\beta\beta}^{\min}$) and the most favorable one (black dashed line, $m_{\beta\beta}^{\max}$). The colored areas express the probability for the three possible outcomes of an experiment: observing a signal even in the worst case scenario (green, observation), not observing a signal even in the best case scenario (red, inaccessibility), and when observing a signal depends on the value of the Majorana phases (white, exploration).

discovery probability:

- 100% for inverted ordering;
- between 20% an 80% for normal ordering, if $m_{\beta\beta} = \sqrt{\Delta m^2_{12}} = 8.6$ meV is achieved



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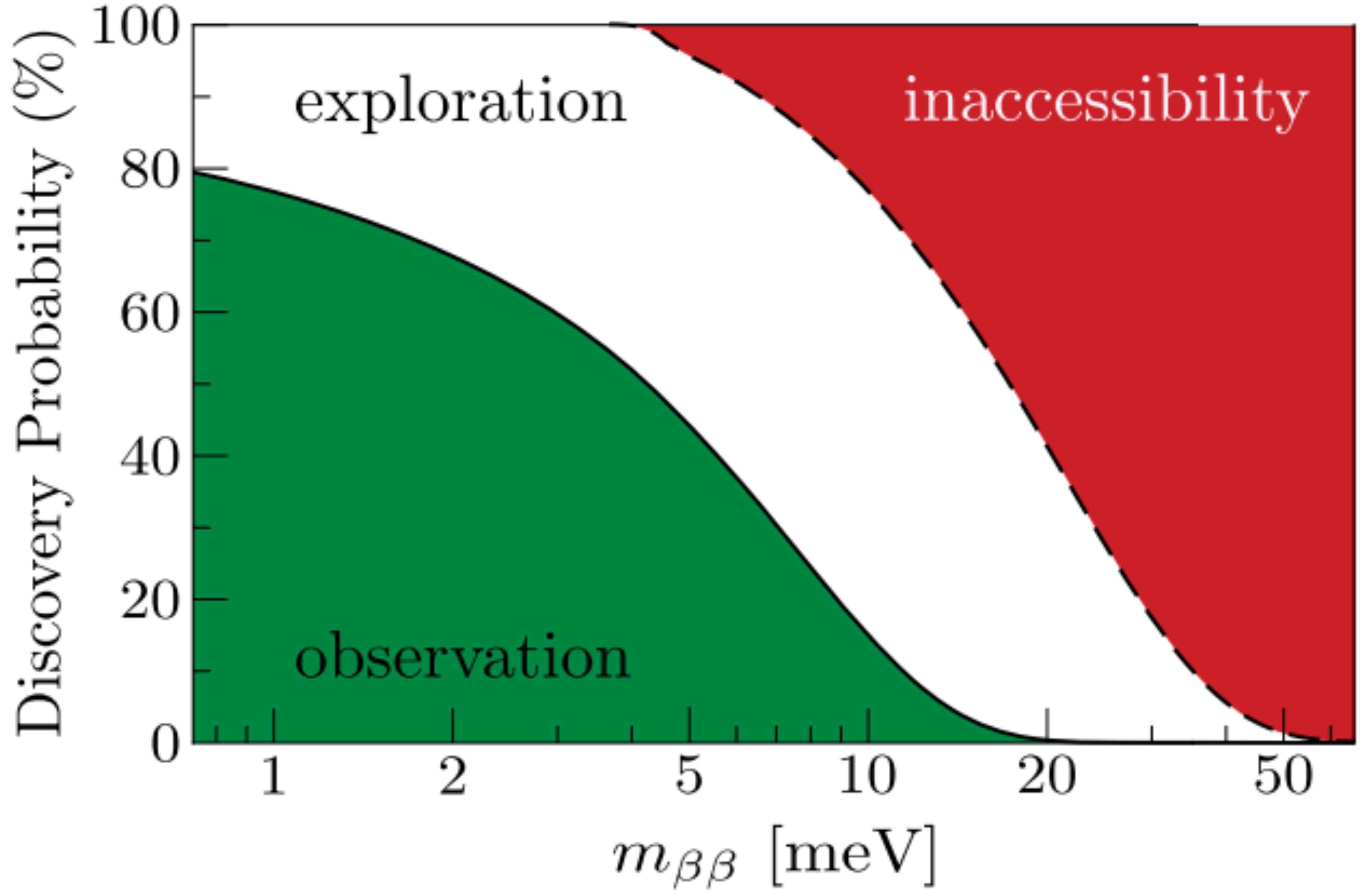
since Planck 2015 findings, this is the most sensitive probe of absolute neutrino masses, and the best chance of measuring them in the future



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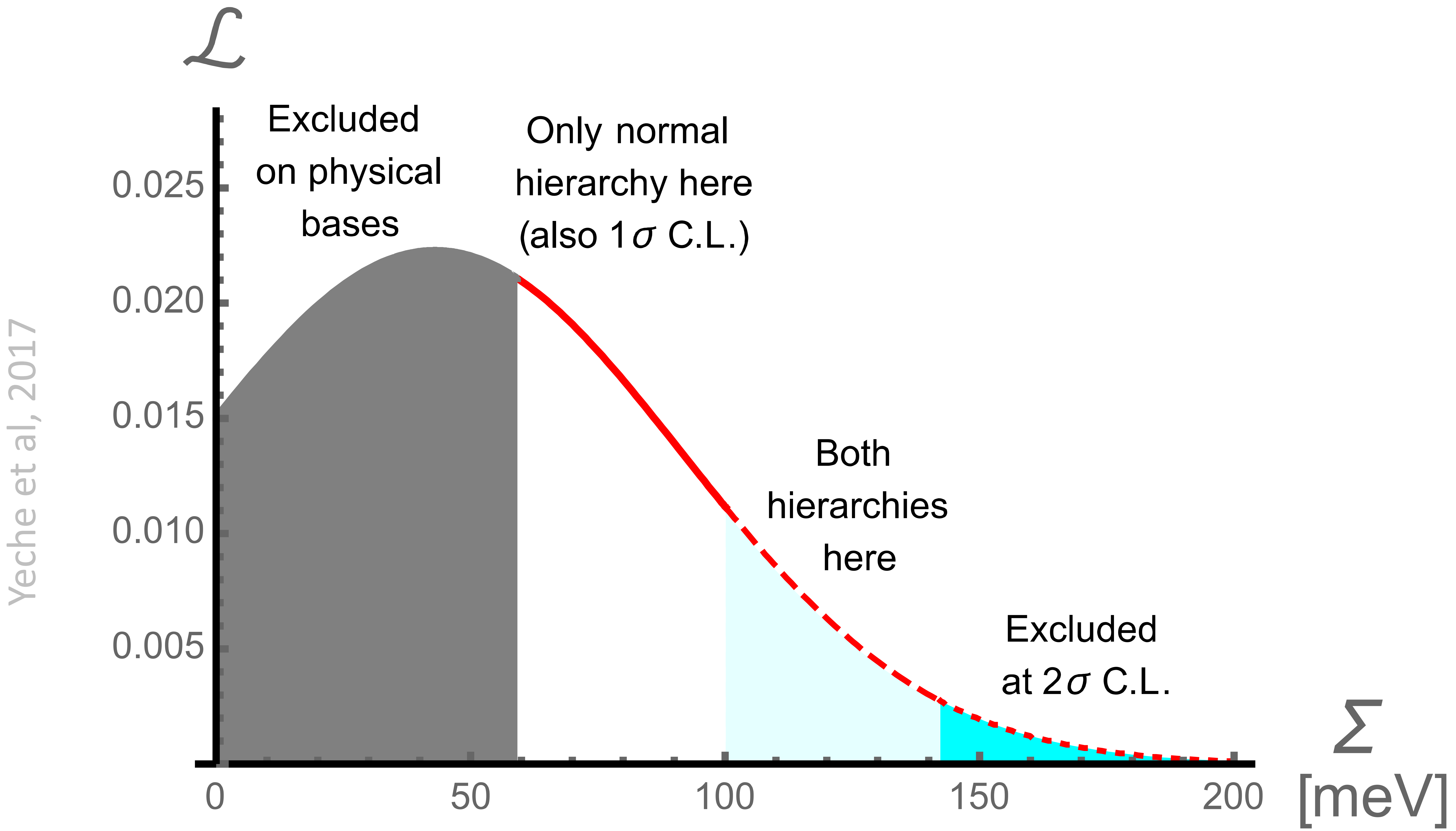
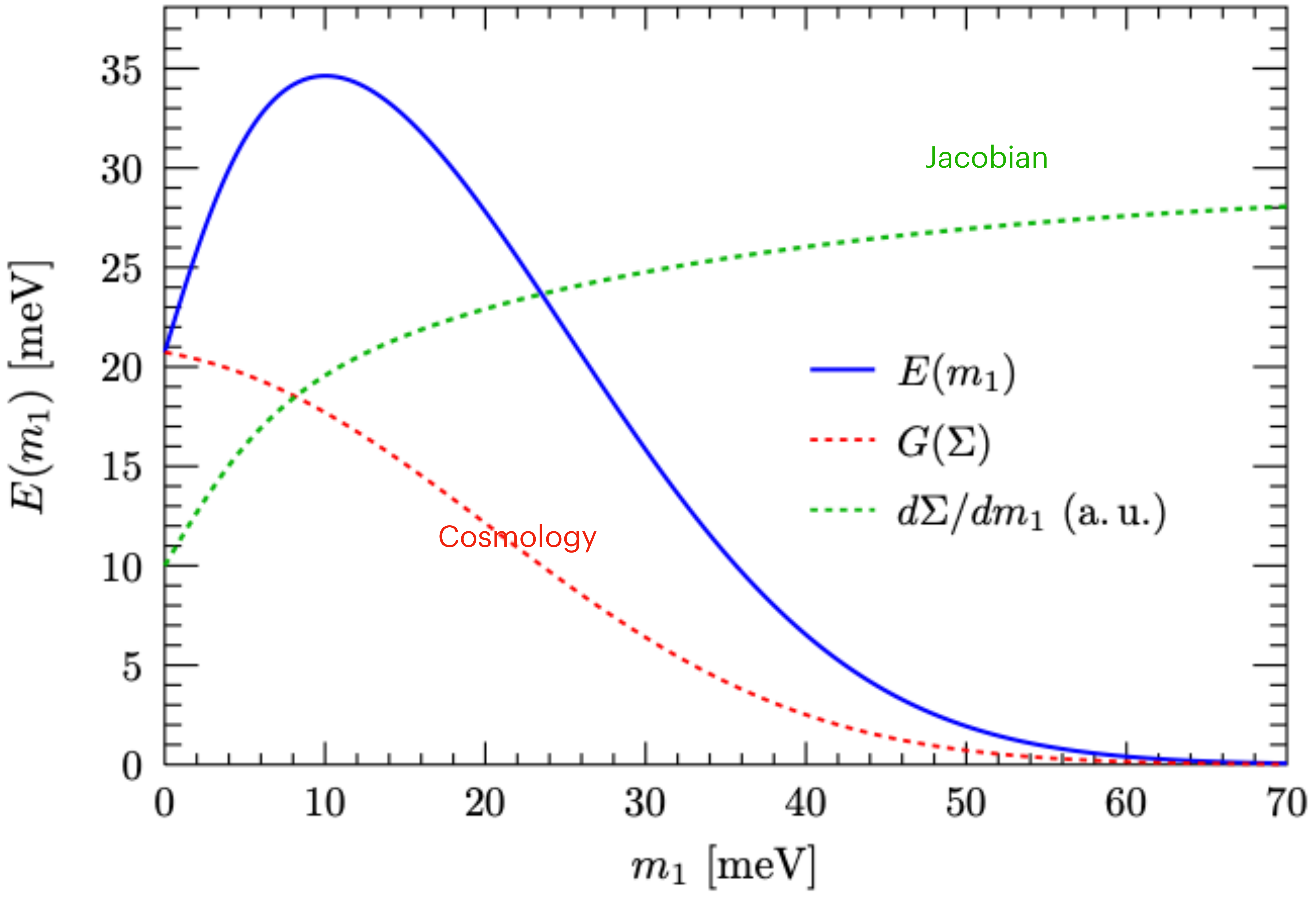
CMB is sensitive to $\Sigma = m_1 + m_2 + m_3$



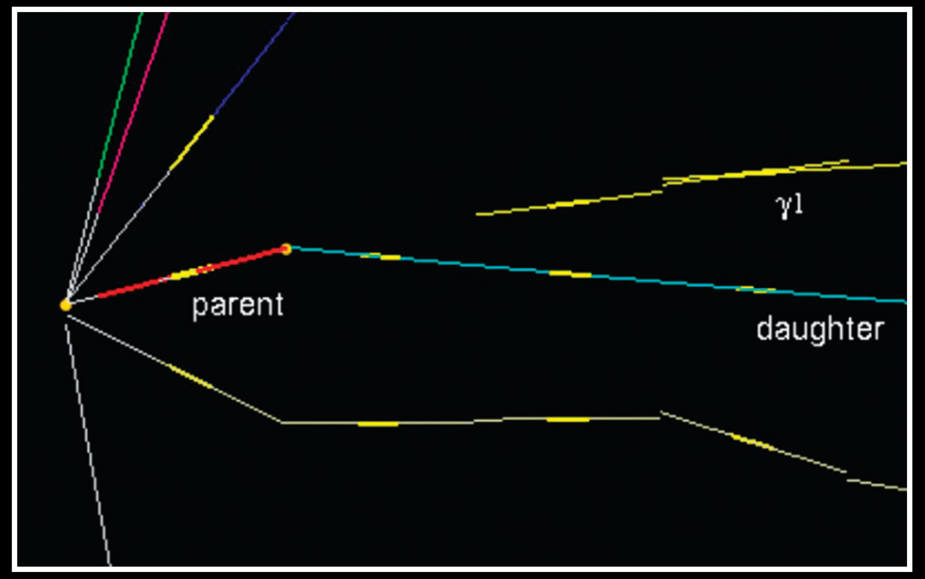
Resulting expectations on the mass of the lightest neutrino

Dell'Oro et al 2019

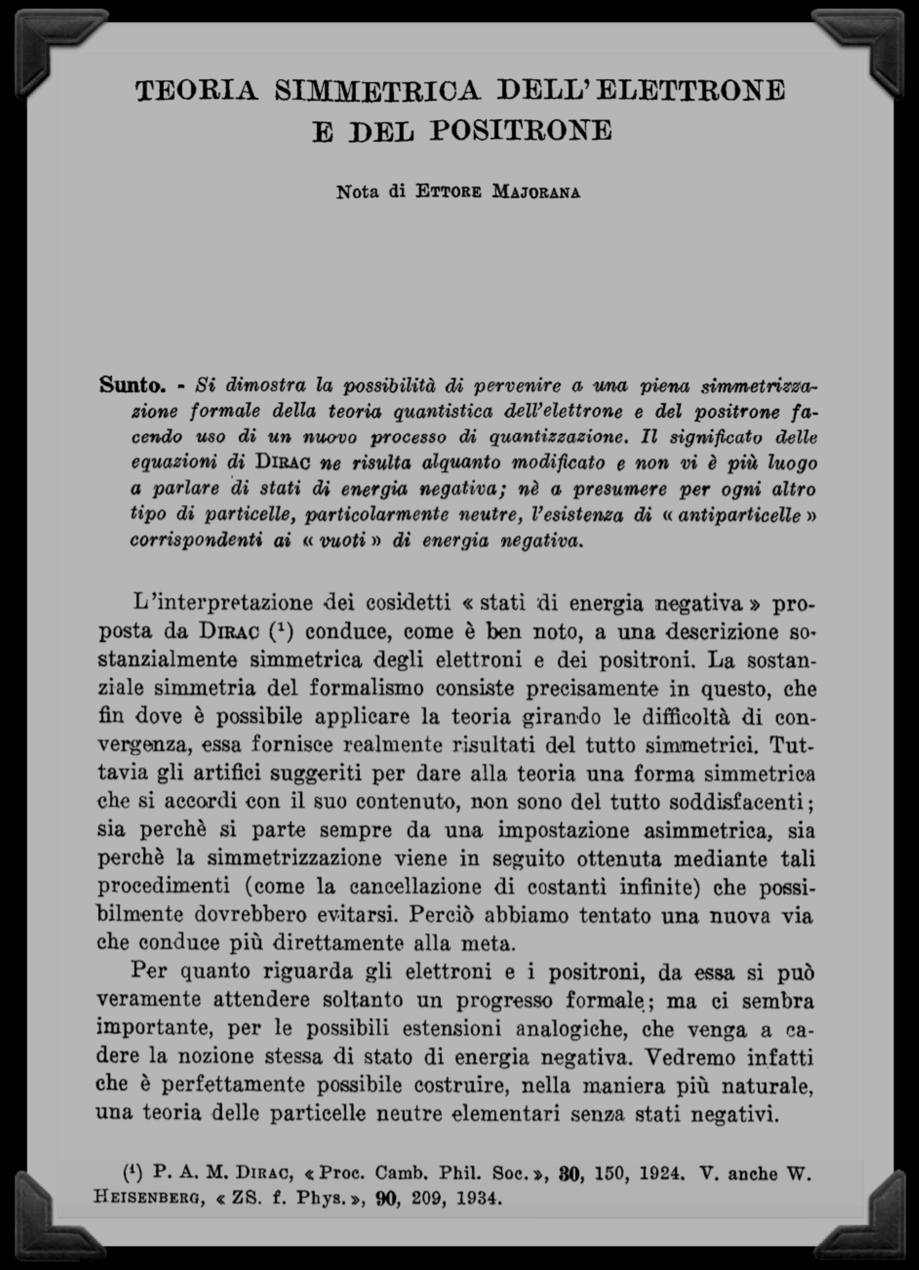


Summary

on the role of Majorana neutrino mass



- Majorana mass neutrinos are *very* plausible
- Definite goal in view: $m_{\beta\beta}^{\text{min}}(\text{inv}) = 18.4 \pm 1.3$ meV
- Next goal: $m_{\beta\beta} = \sqrt{\Delta m^2_{12}} = 8.6 \pm 0.1$ meV
- Keep an eye on (helping/guiding?) advances in other $\nu-$mass measurements cosmology included



TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

Nota di ETTORE MAJORANA

Sunto. - *Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di* DIRAC *ne risulta alquanto modificato e non vi è più luogo a parlare di stati di energia negativa; nè a presumere per ogni altro tipo di particelle, particolarmente neutre, l'esistenza di « antiparticelle » corrispondenti ai « vuoti » di energia negativa.*

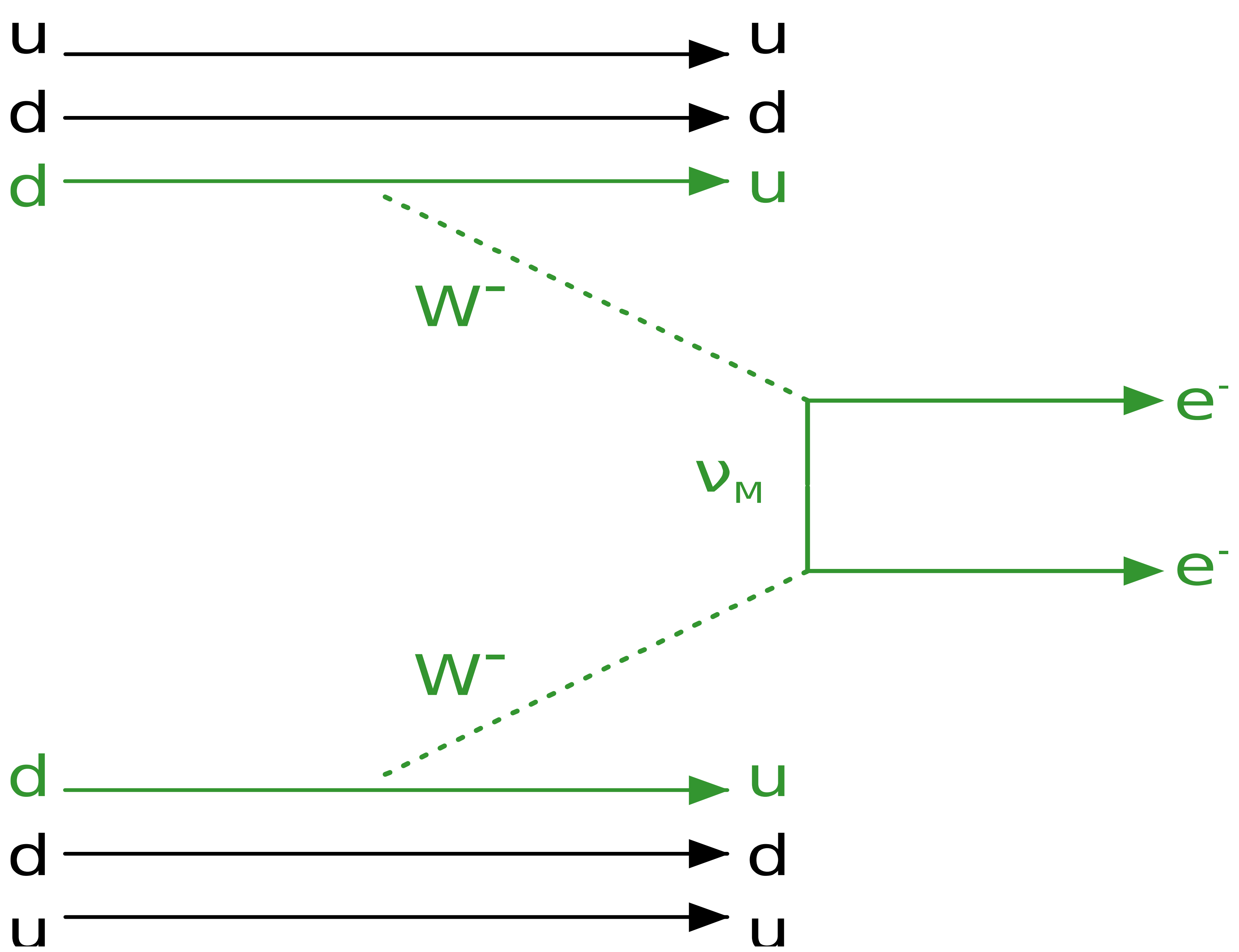
L'interpretazione dei cosidetti « stati di energia negativa » proposta da DIRAC (1) conduce, come è ben noto, a una descrizione sostanzialmente simmetrica degli elettroni e dei positroni. La sostanziale simmetria del formalismo consiste precisamente in questo, che fin dove è possibile applicare la teoria girando le difficoltà di convergenza, essa fornisce realmente risultati del tutto simmetrici. Tuttavia gli artifici suggeriti per dare alla teoria una forma simmetrica che si accordi con il suo contenuto, non sono del tutto soddisfacenti; sia perchè si parte sempre da una impostazione asimmetrica, sia perchè la simmetrizzazione viene in seguito ottenuta mediante tali procedimenti (come la cancellazione di costanti infinite) che possibilmente dovrebbero evitarsi. Perciò abbiamo tentato una nuova via che conduce più direttamente alla meta.

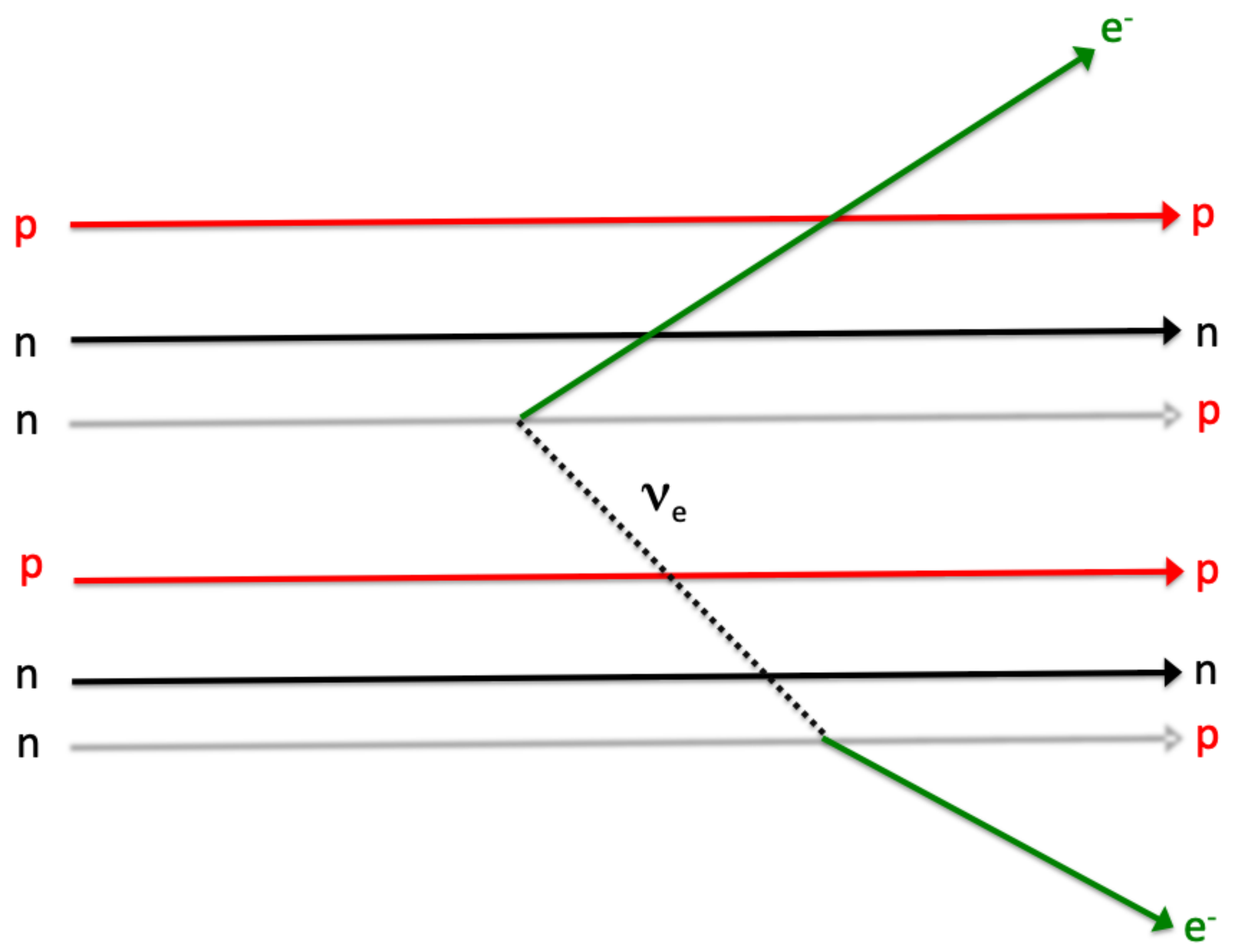
Per quanto riguarda gli elettroni e i positroni, da essa si può veramente attendere soltanto un progresso formale; ma ci sembra importante, per le possibili estensioni analogiche, che venga a cadere la nozione stessa di stato di energia negativa. Vedremo infatti che è perfettamente possibile costruire, nella maniera più naturale, una teoria delle particelle neutre elementari senza stati negativi.

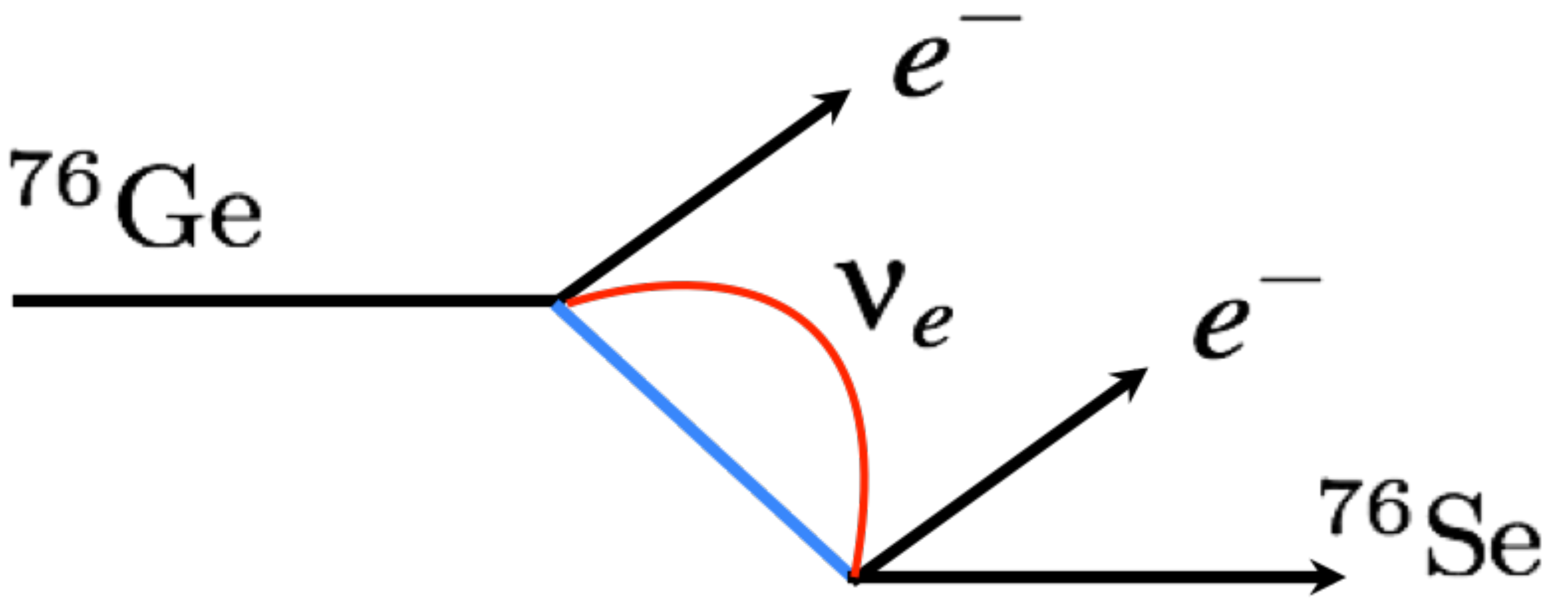
(1) P. A. M. DIRAC, « Proc. Camb. Phil. Soc. », **30**, 150, 1924. V. anche W. HEISENBERG, « ZS. f. Phys. », **90**, 209, 1934.

remarks on theory and relationship with experimental enquires

impact of the Majorana neutrinos on 0ν2β







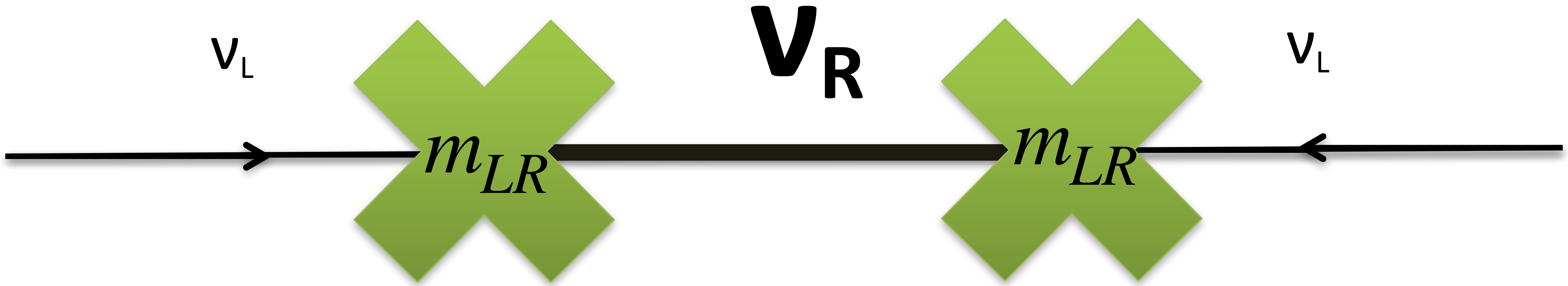
on nuclear physics aspects
work in progress and needs

- great numerical efforts are underway to know precisely the uncertainties and to produce *ab initio* estimates ... as far as possible

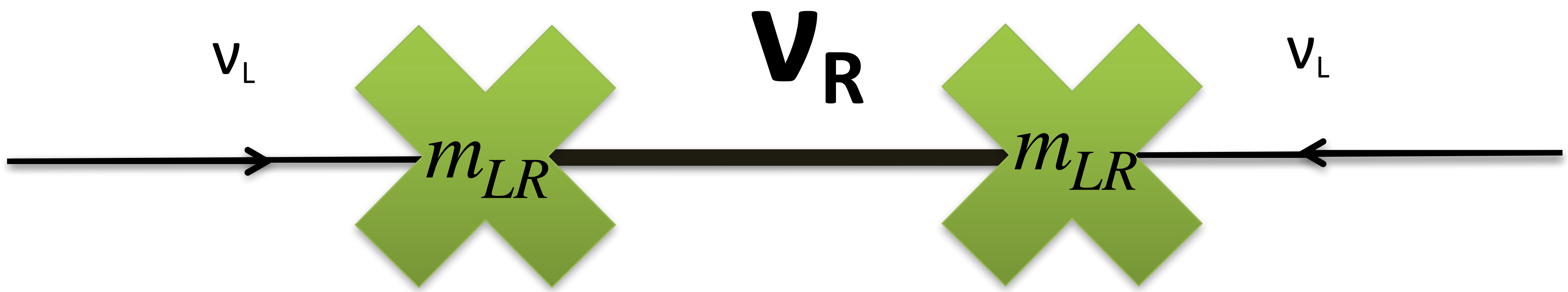
- comparably large experimental activity on $\Delta Z = \pm 1, \pm 2$ processes to validate and improve nuclear models

- important/necessary to study different nuclei and with different techniques to disambiguate various degenerations, from nuclear physics and possibly from fundamental physics

ideas on smallness of ν-mass

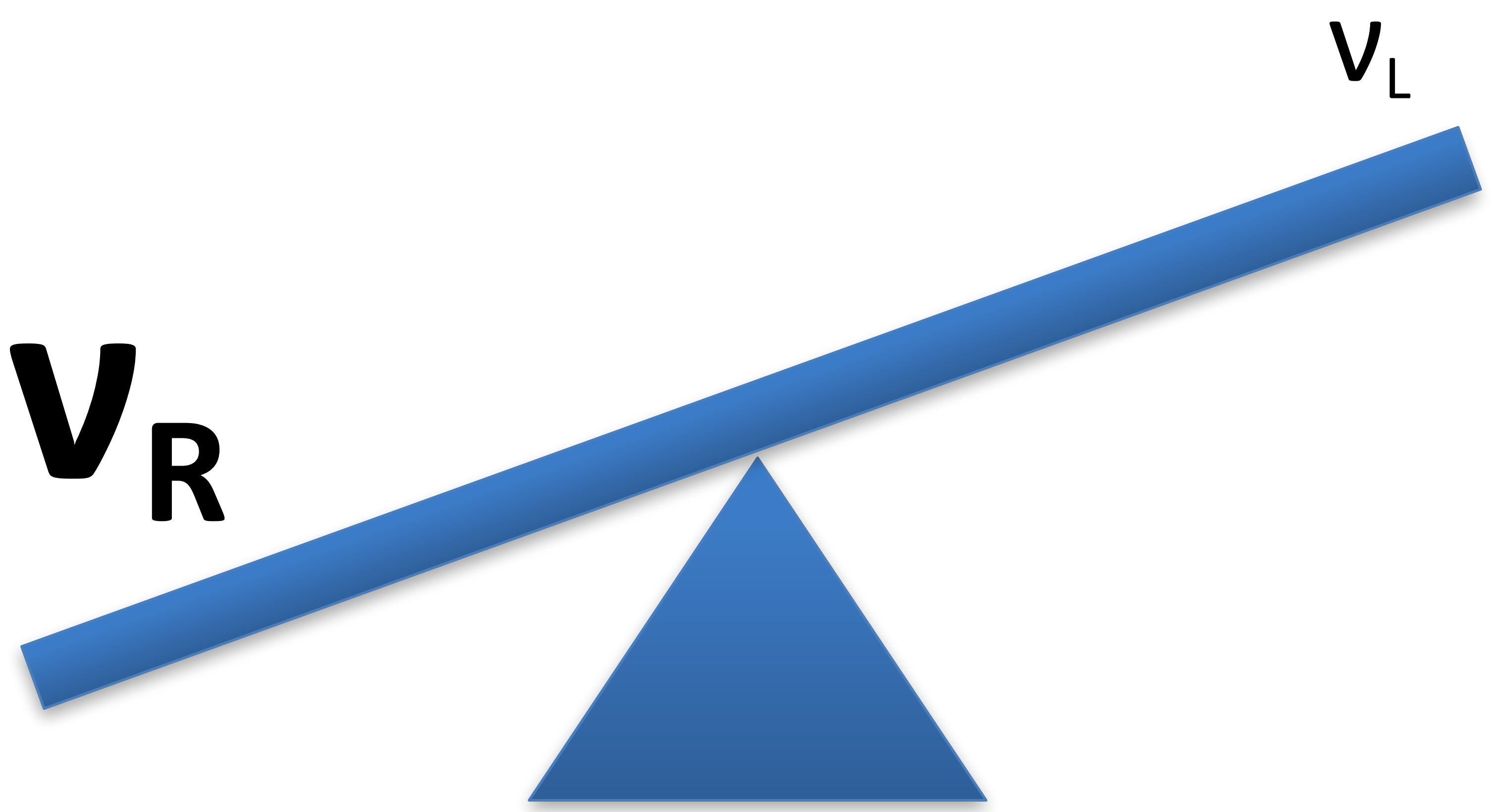


ideas on smallness of ν-mass



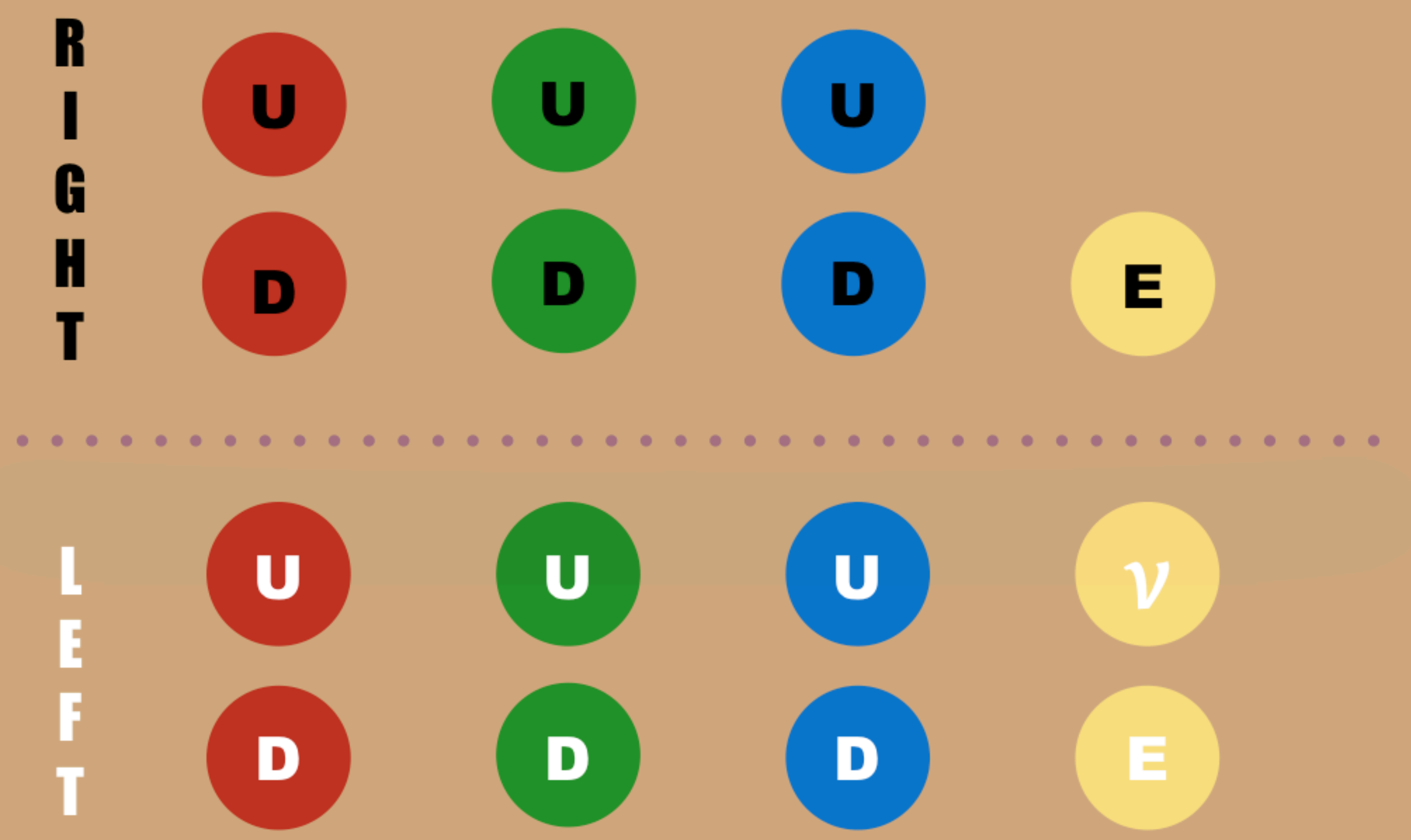
$$m_\nu \sim \frac{m_{LR}^2}{M_{RR}}$$

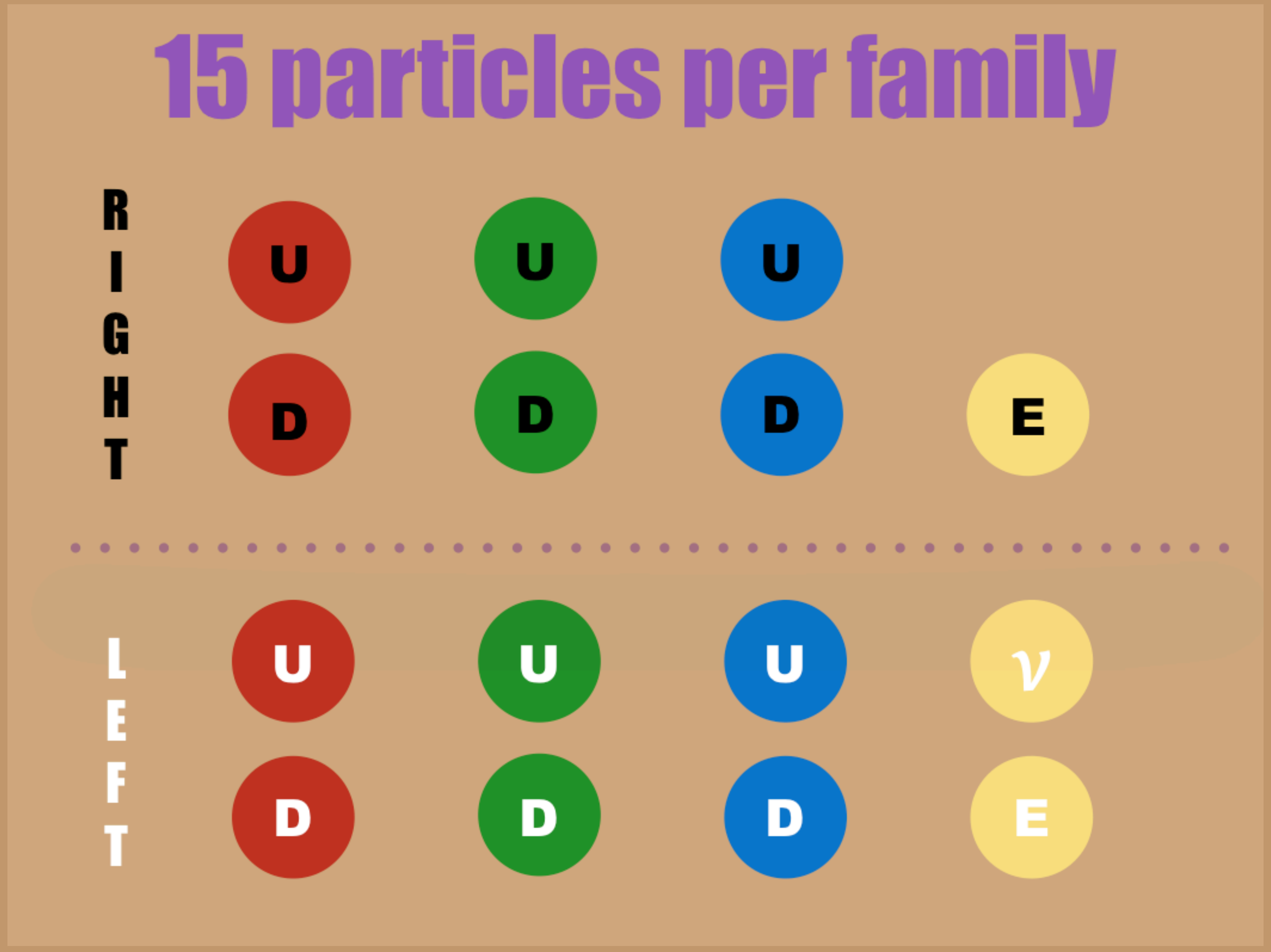
this is what we call "seesaw"



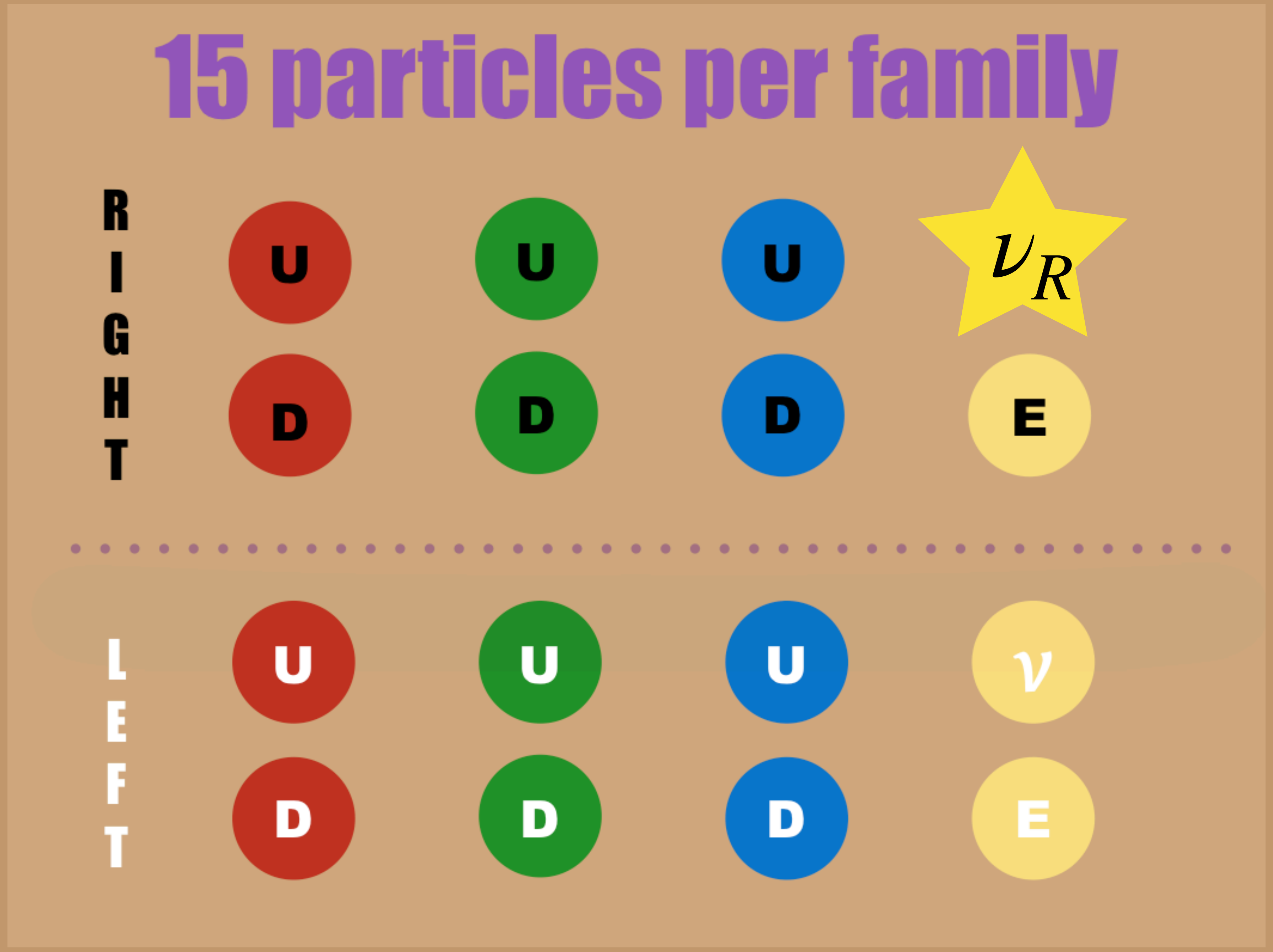
(Minkowski 1977; Yanagida 1979; Gell-Mann, Ramond, Slansky 1979; Mohapatra, Senjanovic 1980)

15 particles per family

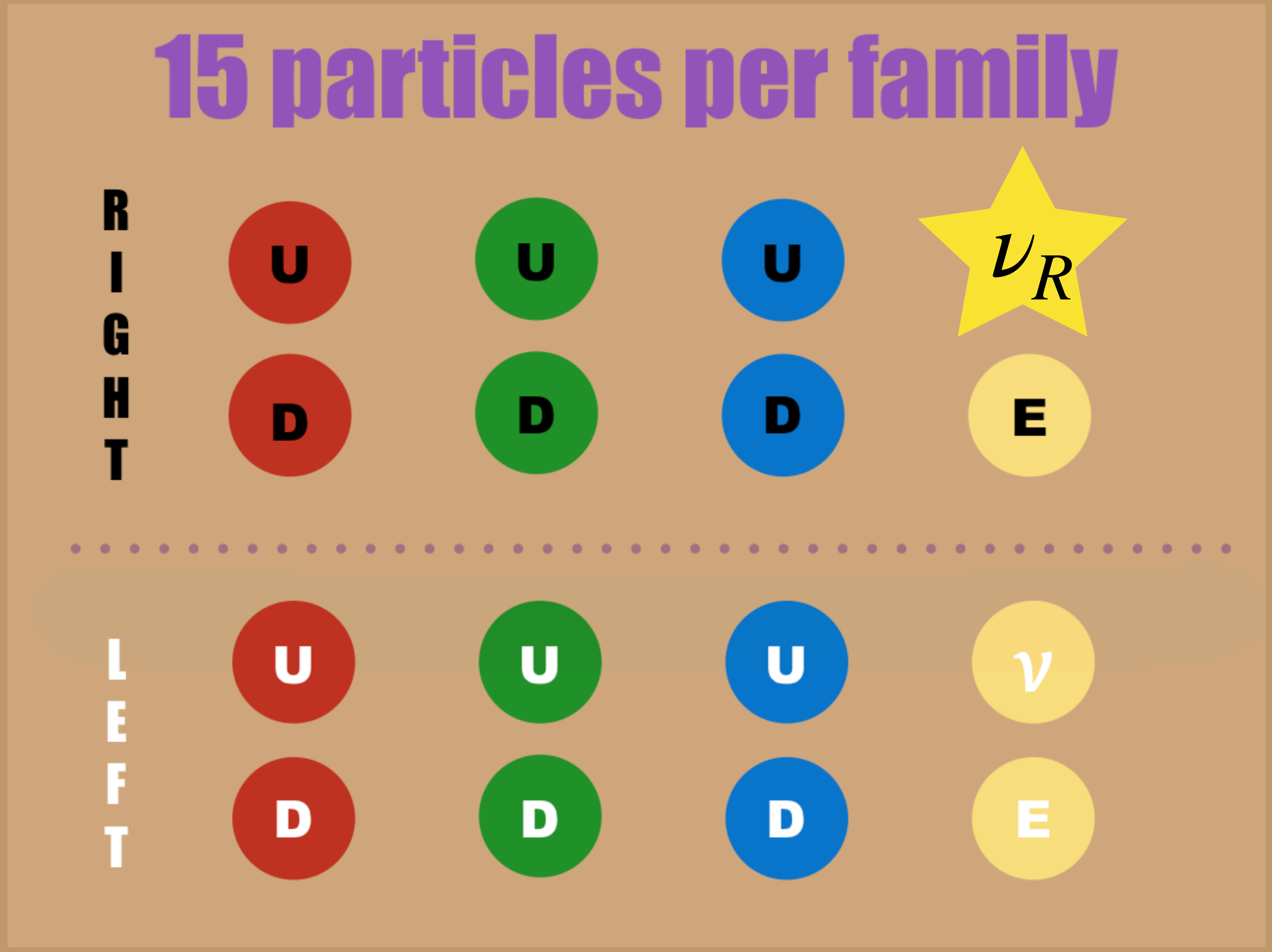


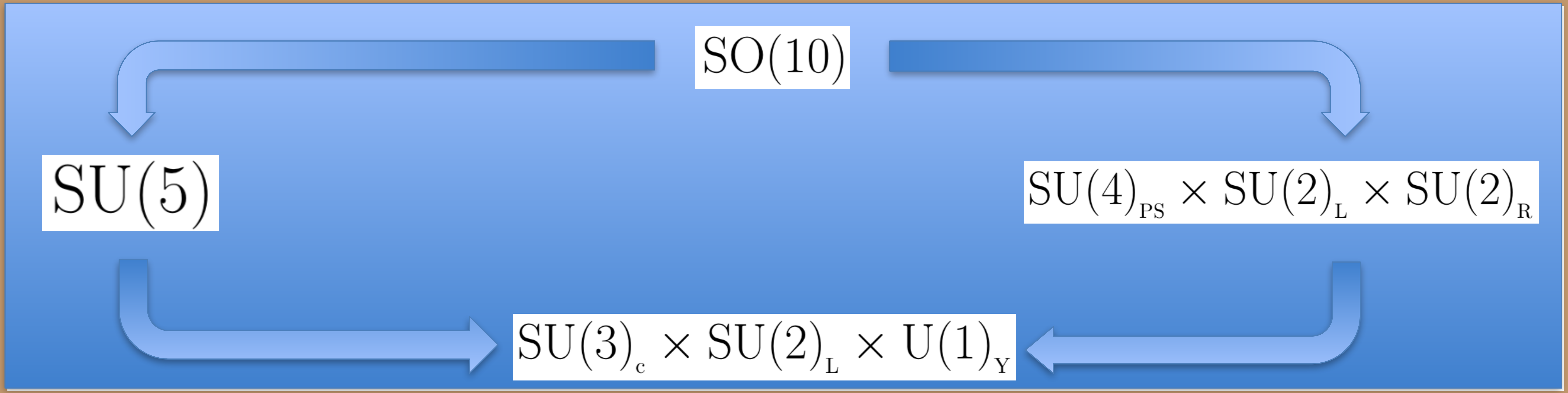


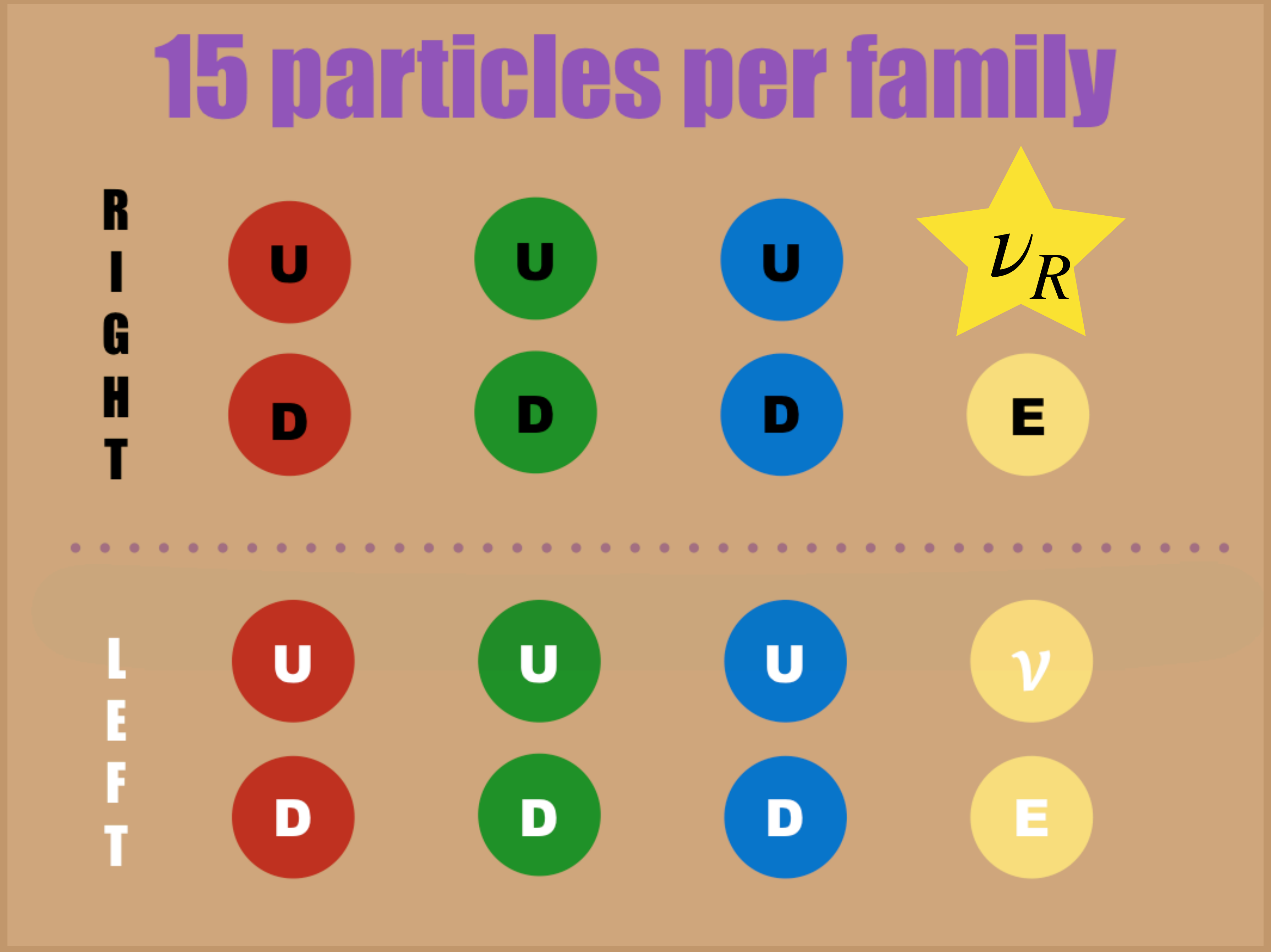
$$\mathrm{SU}(2)_{\mathrm{L}} \text{ acts on } \begin{pmatrix} \nu_{\mathrm{L}} \\ e_{\mathrm{L}} \end{pmatrix} \quad \text{while} \quad \mathrm{SU}(2)_{\mathrm{R}} \text{ acts on } \begin{pmatrix} \nu_{\mathrm{R}} \\ e_{\mathrm{R}} \end{pmatrix}$$

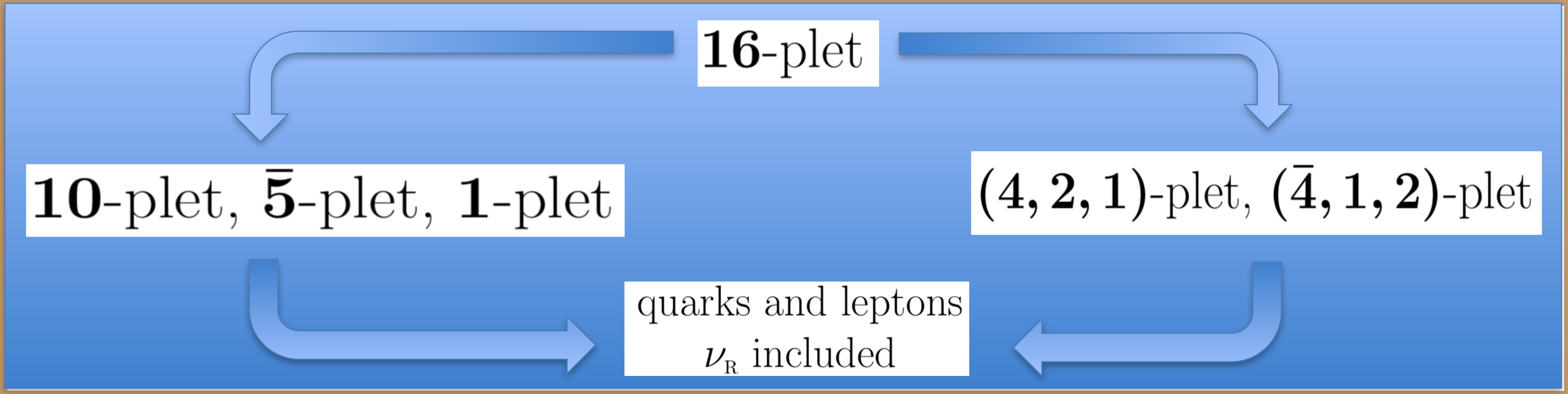


$$\mathrm{SU}(2)_{\mathrm{L}} \text{ acts on } \begin{pmatrix} \boldsymbol{\nu}_{\mathrm{L}} \\ \boldsymbol{e}_{\mathrm{L}} \end{pmatrix} \quad \text{while} \quad \mathrm{SU}(2)_{\mathrm{R}} \text{ acts on } \begin{pmatrix} \boldsymbol{\nu}_{\mathrm{R}} \\ \boldsymbol{e}_{\mathrm{R}} \end{pmatrix}$$


15 particles per family
RIGHT
U U U
ν_R
D D D E
LEFT
U U U ν
D D D E


$SO(10)$
$SU(5)$
$SU(4)_{PS} \times SU(2)_L \times SU(2)_R$
$SU(3)_c \times SU(2)_L \times U(1)_Y$


15 particles per family
RIGHT
U U U ν_R
D D D E
LEFT
U U U ν
D D D E


$\mathbf{16}$-plet
$\mathbf{10}$-plet, $\bar{\mathbf{5}}$-plet, $\mathbf{1}$-plet
$(\mathbf{4},\mathbf{2},\mathbf{1})$-plet, $(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$-plet
quarks and leptons
ν_R included

(from CRYODET meeting at LNGS - 2006)

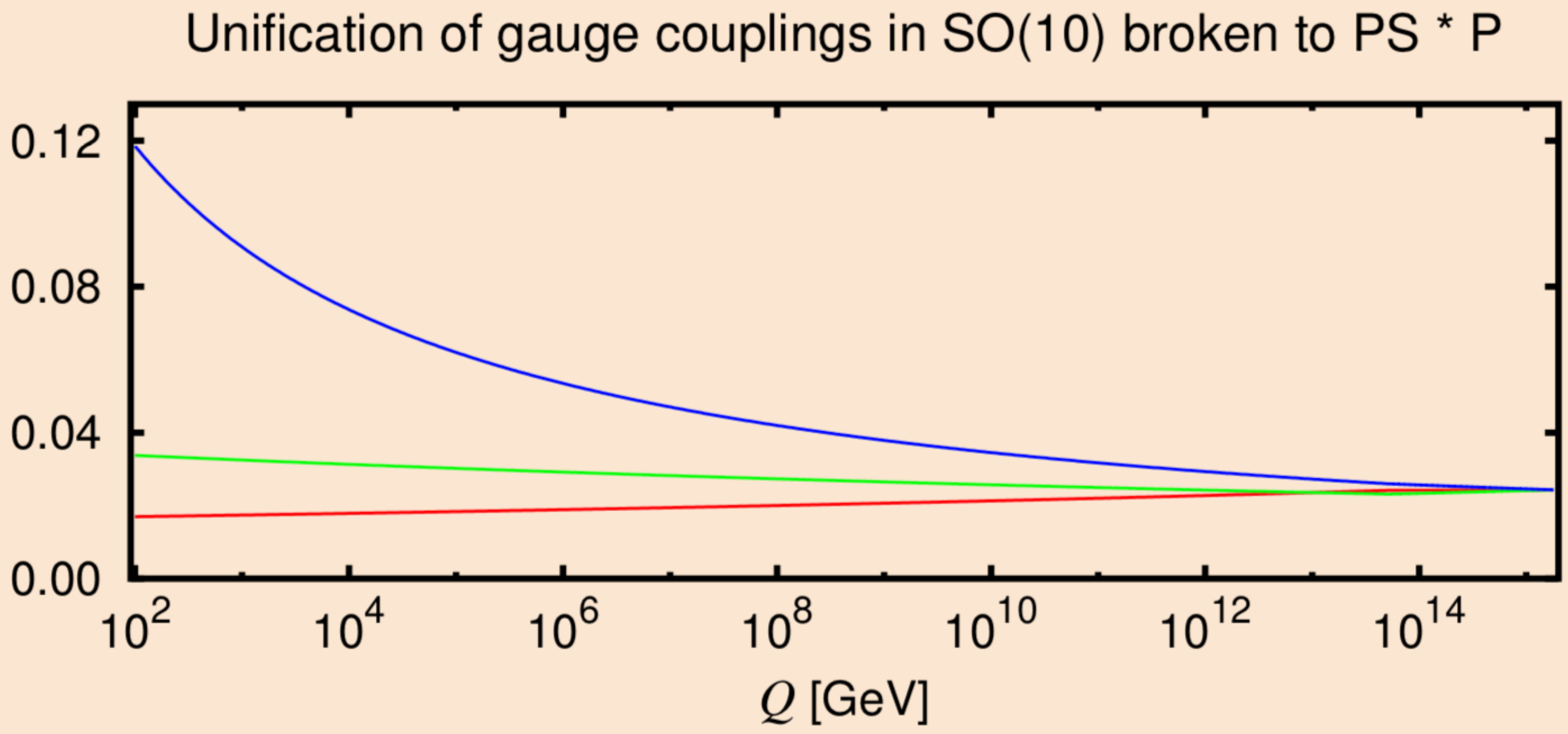


Figure 2: Evolution of the gauge coupling constants in a GUT model with intermediate scale. Here, $M_{\text{interm.}} \approx 5 \times 10^{13}$ GeV.

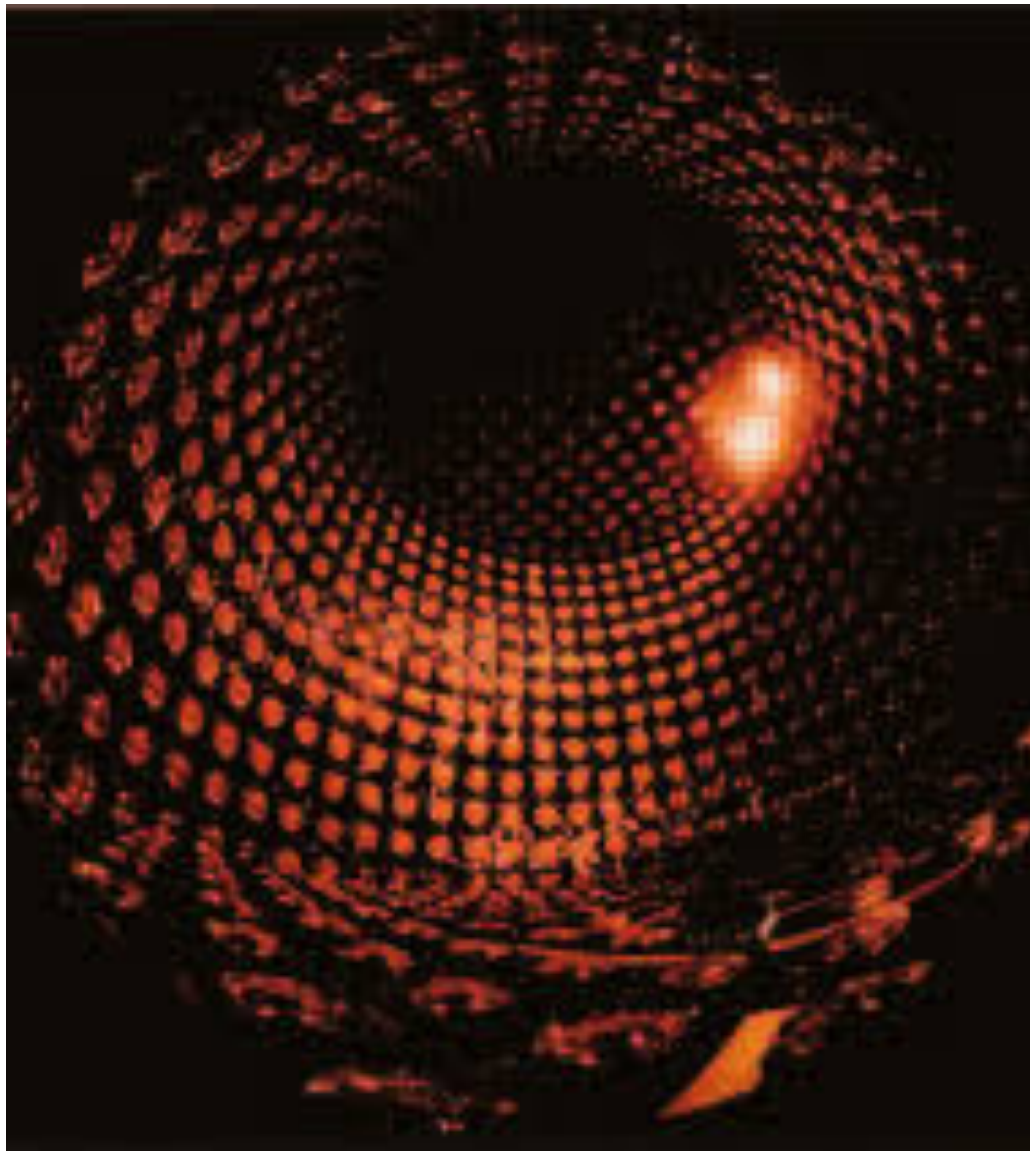
standard model inherits new phenomena

$$\delta\mathcal{L} = \frac{(\ell H)^2}{M} + \frac{\ell qqq}{M'^2} + \frac{(\ell q d^c)^2}{M''^5} \text{ with } \begin{cases} M < 10^{11} \text{ TeV} & \text{for } \texttt{dim.5} \\ M' > 10^{12} \text{ TeV} & \text{for } \texttt{dim.6} \\ M'' > 5 \text{ TeV} & \text{for } \texttt{dim.9} \end{cases}$$

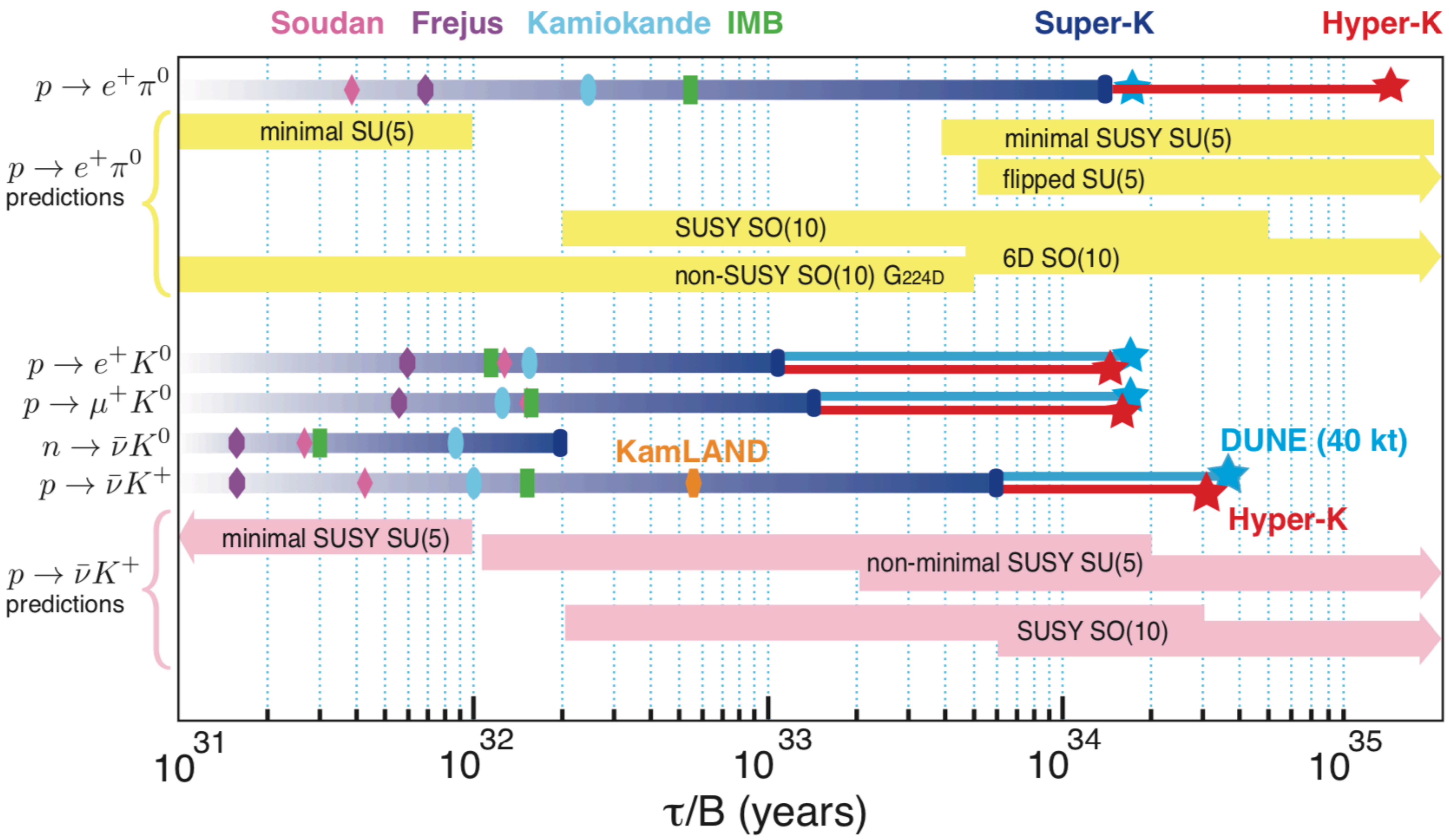
- the 1^{st} is the SM-invariant way to write a term for Majorana neutrino masses
- the 2^{nd} is one of the operators that cause the instability of the proton
- the 3^{rd} new contributes to $0\nu2\beta$ transition

(Weinberg 1979; Wilczek, Zee 1979)

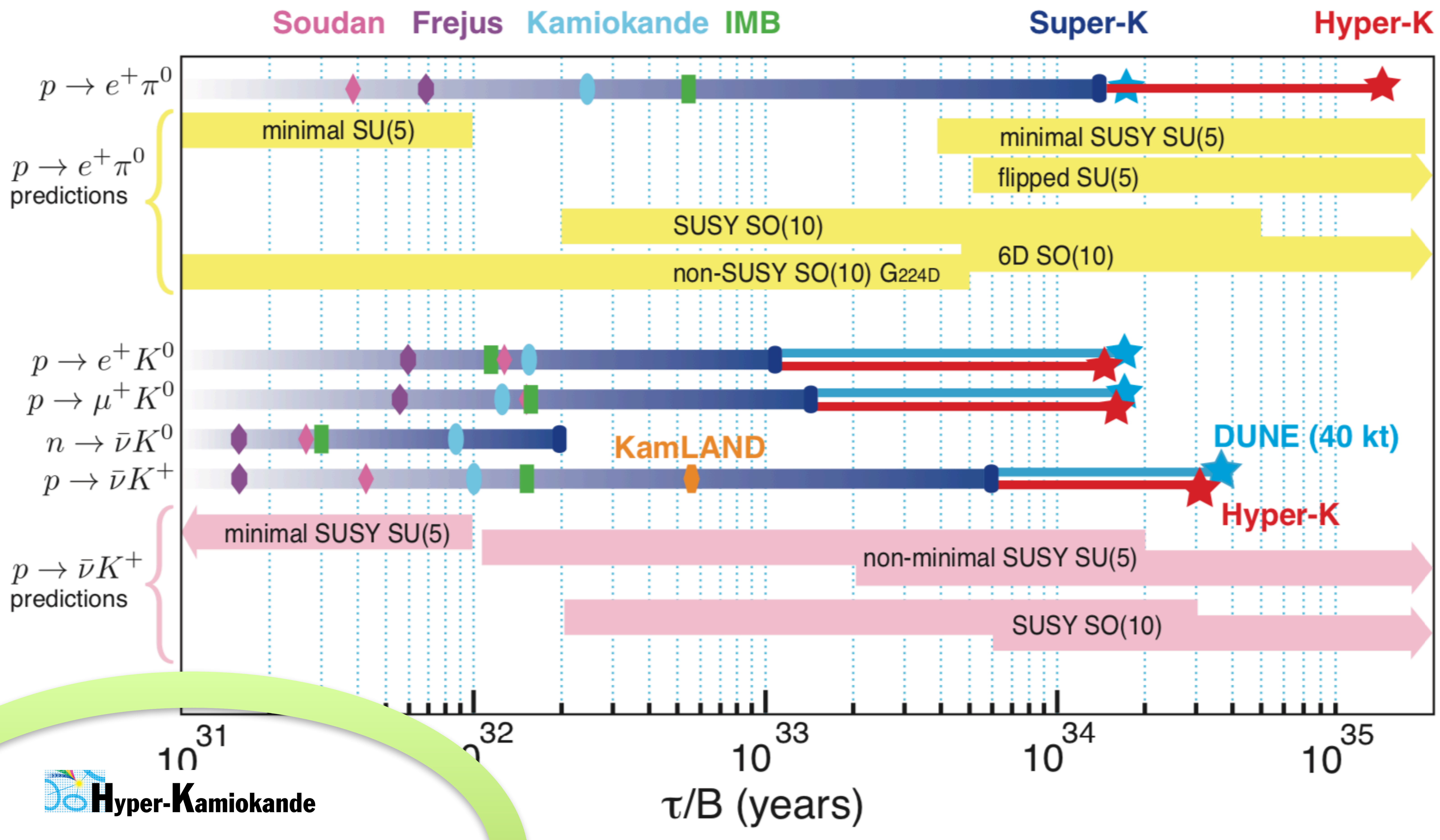
KGF, IMB, NUSEX, KAMIOKANDE, ICARUS…

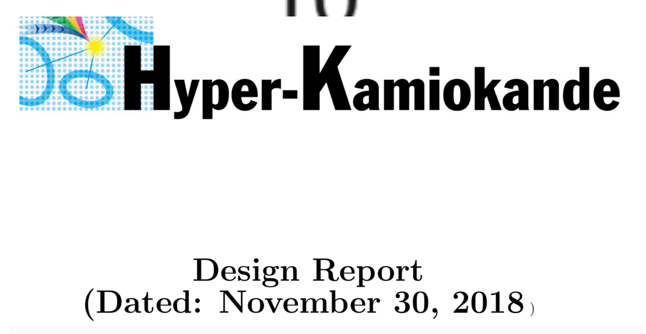


… JUNO, DUNE, HYPER-KAMIOKANDE



… JUNO, DUNE, HYPER-KAMIOKANDE





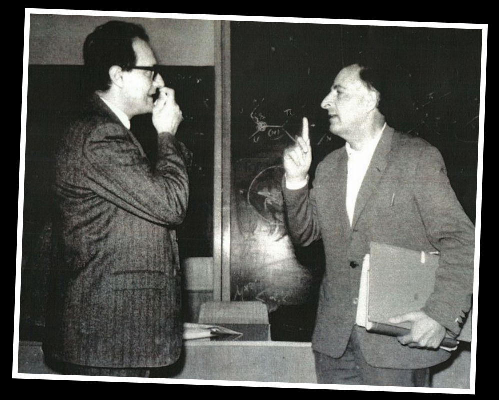
[no references to theory]

Summary

remarks on theory and relationship with experiment

- Progress in nuclear physics is tough but possible
- The idea that Majorana neutrino masses are related to large scale physics looks rather plausible
- It is important to continue to test SM and neutrino masses
- Theory offers clues but we still don't have anything as SM. Right-handed neutrinos, seesaw, leptogenesis, proton decay are likely linked to neutrino mass. Time to work on fermion masses






bibliography, discussion and wrap up

universe

MDPI

Review

What Is Matter According to Particle Physics, and Why Try to Observe Its Creation in a Lab?

Francesco Vissani [1,2]

[1] INFN, Laboratori Nazionali del Gran Sasso, 67100 L'Aquila, Italy; vissani@lngs.infn.it;
Tel.: +39-346-73-28-009
[2] Gran Sasso Science Institute, 67100 L'Aquila, Italy

Citation: Vissani, F. What Is Matter According to Particle Physics, and Why Try to Observe Its Creation in a Lab? *Universe* **2021**, *7*, 61. https://doi.org/10.3390/universe7030061

Abstract: The standard model of elementary interactions has long qualified as a theory of matter, in which the postulated conservation laws (one baryonic and three leptonic) acquire theoretical meaning. However, recent observations of lepton number violations—neutrino oscillations—demonstrate its incompleteness. We discuss why these considerations suggest the correctness of Ettore Majorana's ideas on the nature of neutrino mass and add further interest to the search for an ultra-rare nuclear process in which two particles of matter (electrons) are created, commonly called neutrinoless double beta decay. The approach of the discussion is mainly historical, and its character is introductory. Some technical considerations, which highlight the usefulness of Majorana's representation of gamma matrices, are presented in the appendix.

Keywords: standard model extensions; neutrino masses; Majorana neutrinos; lepton number violation universe MDPI

Review

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E.g.: one table

Table 2. The number of papers per decade citing a few seminal articles, including Majorana's, from their appearance to the present day. In the last two lines, a (incomplete) list of theoretical and observational facts that are of major relevance for current discussion. From https://inspirehep.net/ (accessed on December 2020). GUT, grand unified theory.

	'30s	**'40s**	**'50s**	**'60s**	**'70s**	**'80s**	**'90s**	**2000**	**2010**
Majorana [4]	3	3	8	5	17	43	67	159	745
Goeppert-M. [112]	2	2	6	0	0	18	19	41	221
Racah [18]	2	1	6	1	6	19	16	31	133
Furry [111]	0	2	6	0	1	25	30	71	351
Case [27]	-	-	1	10	10	36	43	34	36
theory	ν	**B, L**	V-A, SU(2)	SM, oscill.	SM	GUT, $\nu_\odot$	SUSY	glob.anal.	cosm.
exp. and obs.	n, e^+, μ	π, K	ν, V-A	$\nu_\odot$ anom.	SM, $\nu_\odot$	W, Z^0, ν_{atm}	oscill.	oscill.	Higgs, cosm.

universe MDPI

Review

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exp. and obs.	n, e^+, μ	π, K	ν, *V-A*	$\nu_\odot$ anom.	SM, $\nu_\odot$	W, Z^0, ν_{atm}	oscill.	oscill.	Higgs, cosm.

WHAT IS "MATTER" MADE OF?

Elementary Components Of Matter	Identifying Feature	End Vigence Of Model [Theory] Experiment	Reason For Inadequacy
Atoms	Type, Mass	[1838] 1909	[Atoms Of Electricity] Electrons
Electrons & Nuclei	Charge, Mass, Spin1/2	[1930] 1956	[Fermi' Theory] Neutrons & Neutrinos
p, n, e, ν_e, μ . . .	B, L_e, L_μ . . . , ""	[1961] 1968	[Standard Model] Quarks
Quarks & Leptons	B − L, $L_e - L_\mu$ . . . , ""	[1962] 2010	[Leptonic Mixing] Appearance Experiments
Quark-Leptons	B − L , ""	[1937] ?	[Majorana' Mass] $2n \to 2p + 2e$
Fermions	Mass, Spin1/2	[1977] ???	[Supersymmetry?] ???

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Volume 2016, Article ID 2162659, 37 pages
http://dx.doi.org/10.1155/2016/2162659

Review Article

Neutrinoless Double Beta Decay: 2015 Review

Stefano Dell'Oro,[1] Simone Marcocci,[1] Matteo Viel,[2,3] and Francesco Vissani[1,4]

[1] *INFN, Gran Sasso Science Institute, Viale F. Crispi 7, 67100 L'Aquila, Italy*
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Received 31 October 2015; Revised 13 January 2016; Accepted 27 January 2016

Academic Editor: Srubabati Goswami

The discovery of neutrino masses through the observation of oscillations boosted the importance of neutrinoless double beta decay ($0\nu\beta\beta$). In this paper, we review the main features of this process, underlining its key role from both the experimental and theoretical point of view. In particular, we contextualize the $0\nu\beta\beta$ in the panorama of lepton number violating processes, also assessing some possible particle physics mechanisms mediating the process. Since the $0\nu\beta\beta$ existence is correlated with neutrino masses, we also review the state of the art of the theoretical understanding of neutrino masses. In the final part, the status of current $0\nu\beta\beta$ experiments is presented and the prospects for the future hunt for $0\nu\beta\beta$ are discussed. Also, experimental data coming from cosmological surveys are considered and their impact on $0\nu\beta\beta$ expectations is examined.

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E.g.: After-discovery scenarios

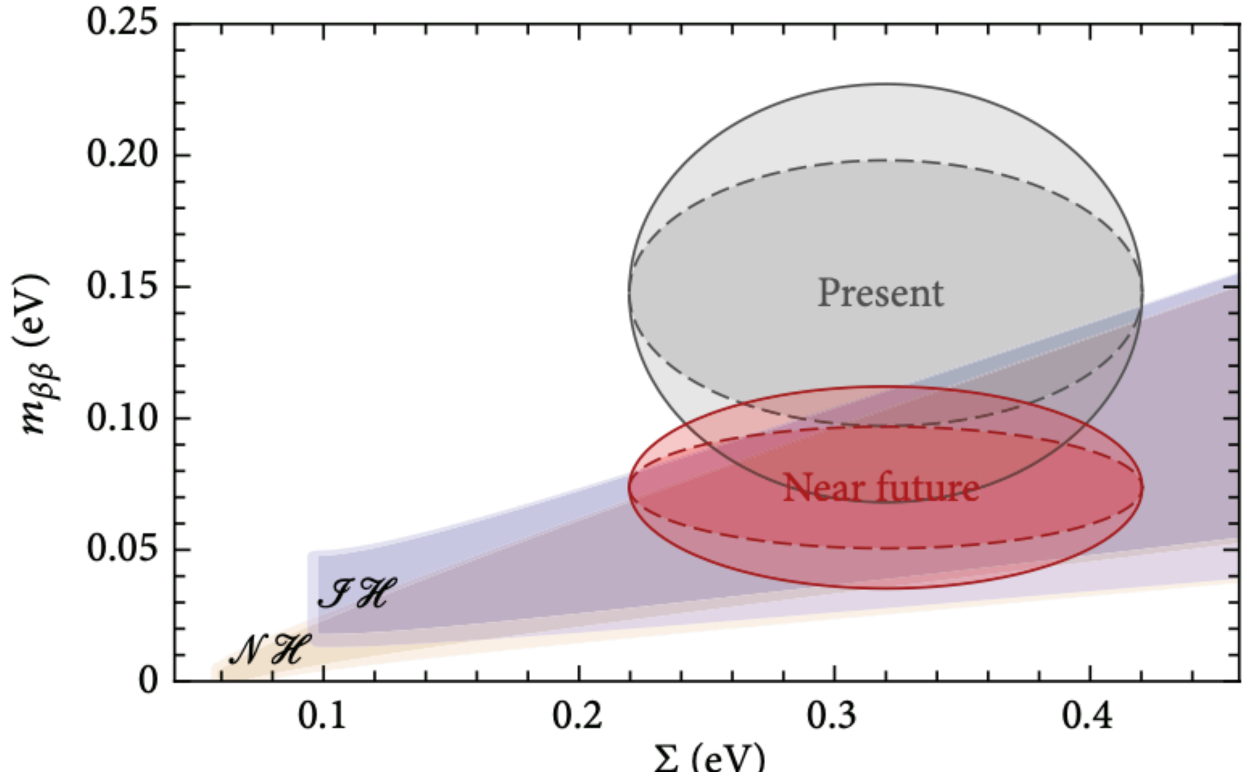

TABLE 6: 1σ ranges for both Gaussian and Poisson distributions for two different values of N_{peak}. In the former case, we assumed a standard deviation equal to $\sqrt{N_{peak}}$. To compute the error columns, we halved the total width of the range and divided it by N_{peak}.

Distribution	N_{peak}	Range	Relative error (%)
Gauss	5	2.8–7.2	44.7
	20	15.5–24.5	22.4
Poisson	5	3.1–7.6	45.0
	20	15.8–24.8	22.5

Toward the Discovery of Lepton Creation with Neutrinoless Double-β Decay

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Italy
Gran Sasso Science Institute, 67100 L'Aquila,
Italy

(Dated: September 24, 2021)

The discovery of neutrinoless double-β decay could soon be within reach. This hypothetical ultra-rare nuclear decay is a portal to new physics beyond the Standard Model. Its observation would constitute the discovery of a matter-creating process, corroborating leading theories of why the universe contains more matter than antimatter. It would also prove that neutrinos and anti-neutrinos are not two distinct particles, but can transform into each other, generating their own mass in the process. The recognition that neutrinos are not massless necessitates an explanation and has boosted interest in neutrinoless double-β decay. The field is now at a turning point. A new round of experiments is currently being proposed for the next decade to cover an important region of the parameter space. Advancements in nuclear theory are laying the groundwork to connect the nuclear decay with its underlying mechanisms. Meanwhile, the particle theory landscape continues to find new motivations for neutrinos to be their own antiparticle. This review brings together the experimental, nuclear theory, and particle theory aspects connected to neutrinoless double-β decay, with the goal of exploring the path toward – and beyond – its discovery.

Toward the Discovery of Lepton Creation with Neutrinoless Double-β Decay

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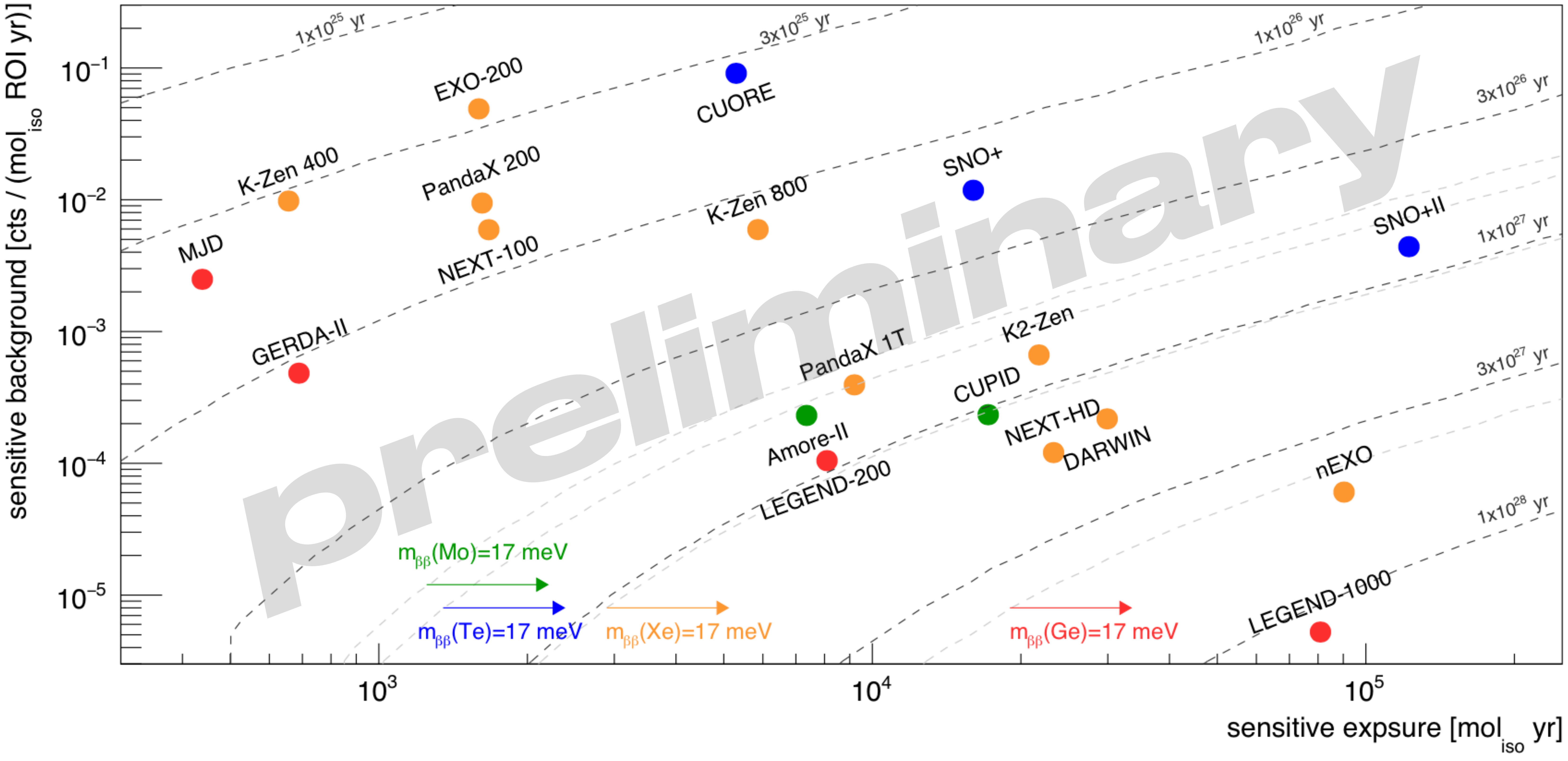


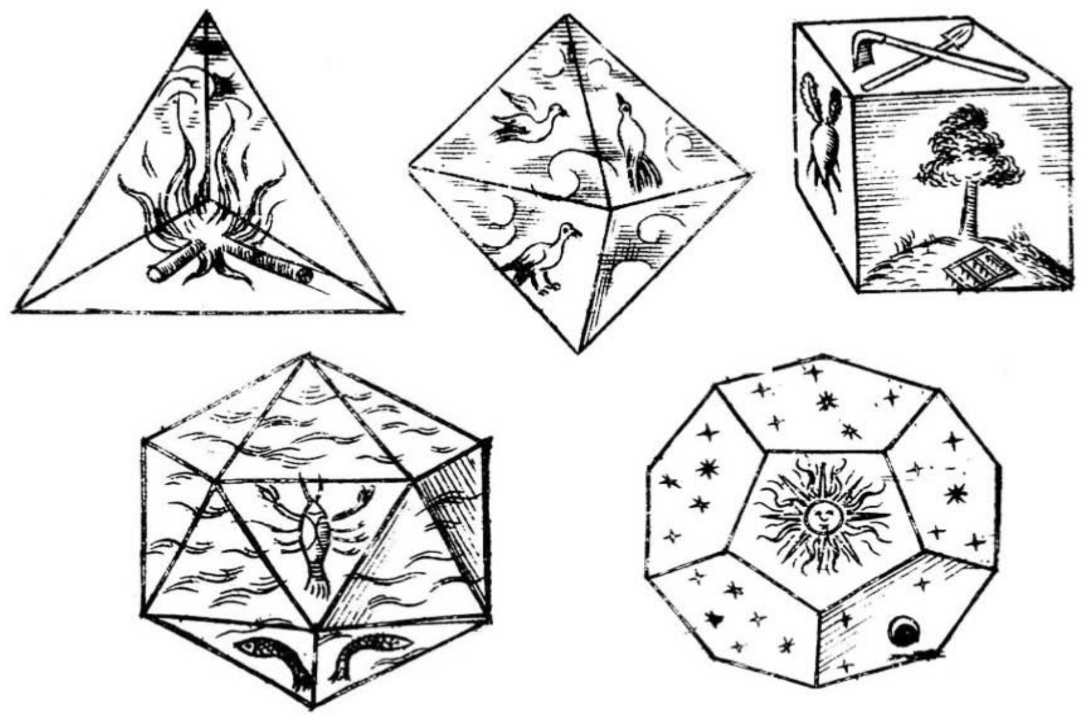
grazie e buon lavoro!

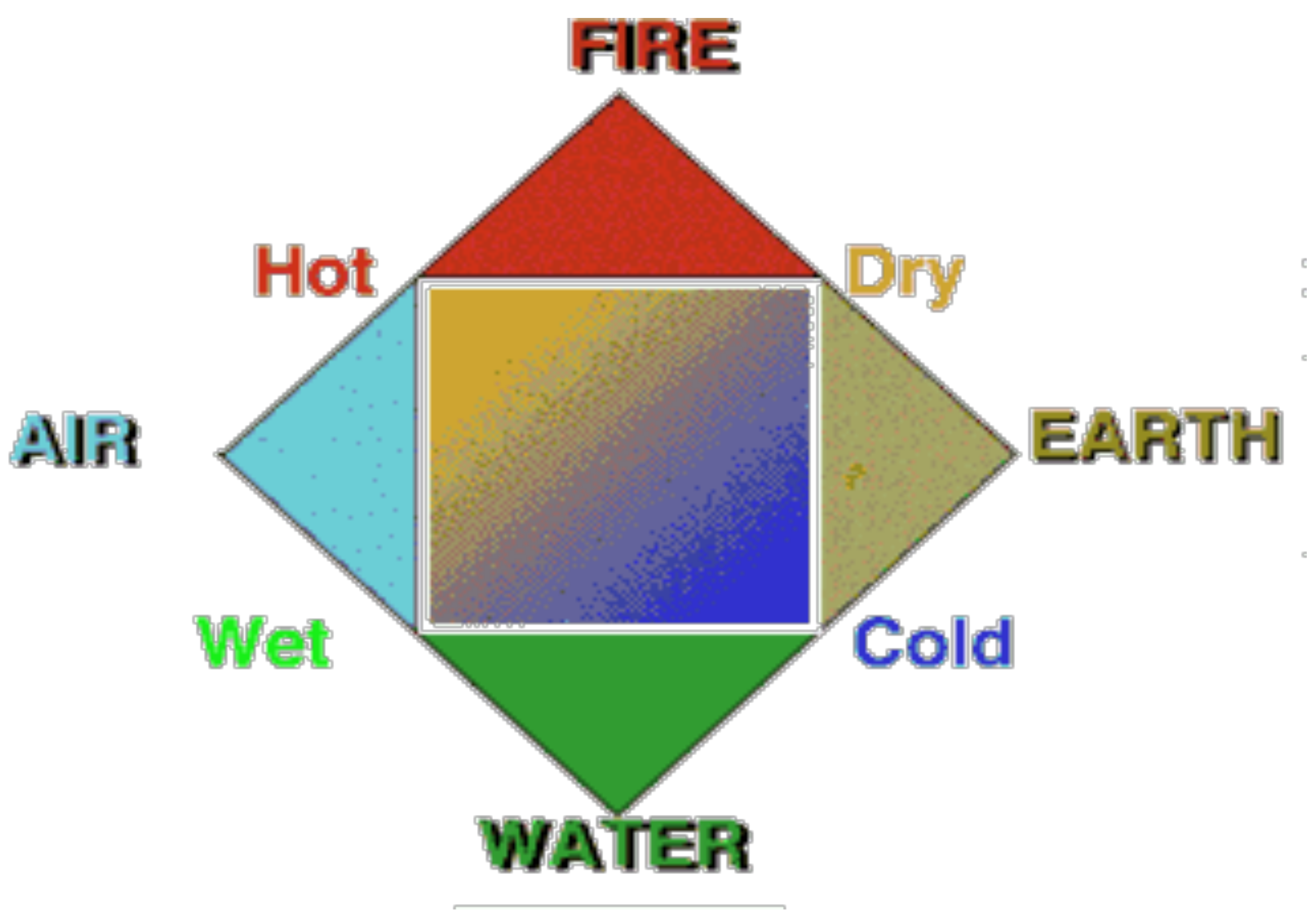
An Introduction to the North America - Europe Workshop on Future of Double Beta Decay

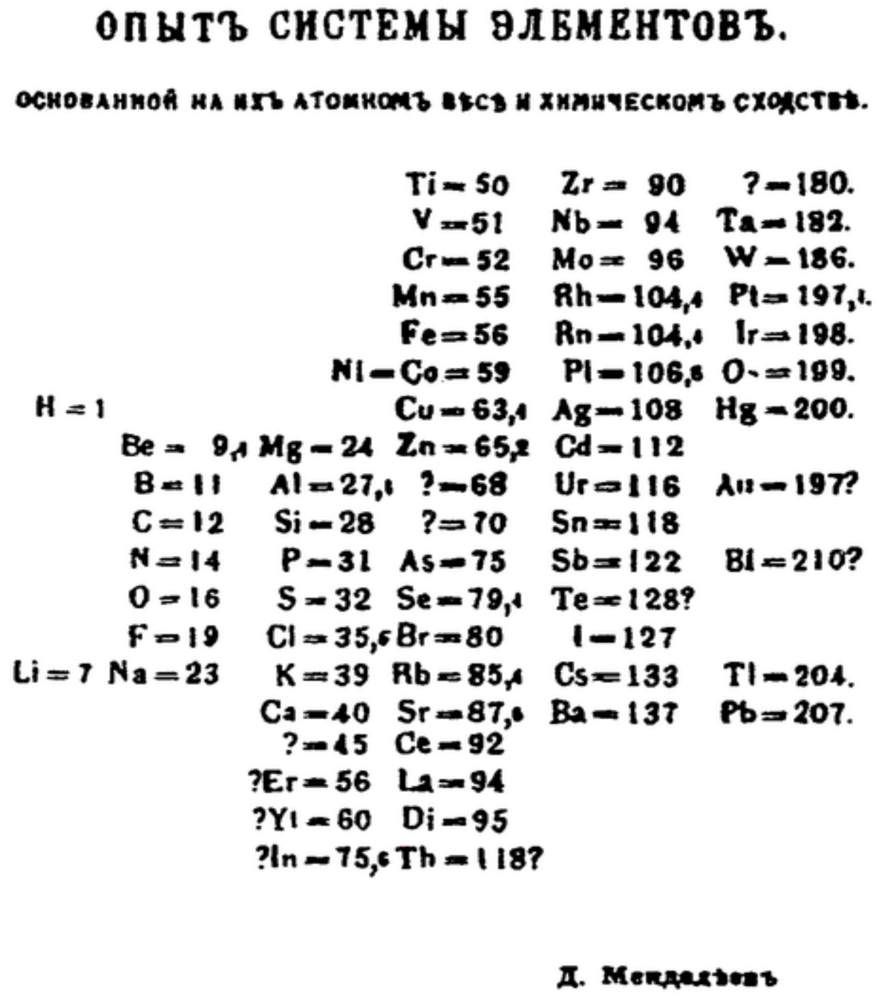
Francesco VISSANI, INFN, Gran Sasso

more on matter

Leucippus, Democritus, Pythagoras, Heraclitus, Plato, Aristotle…





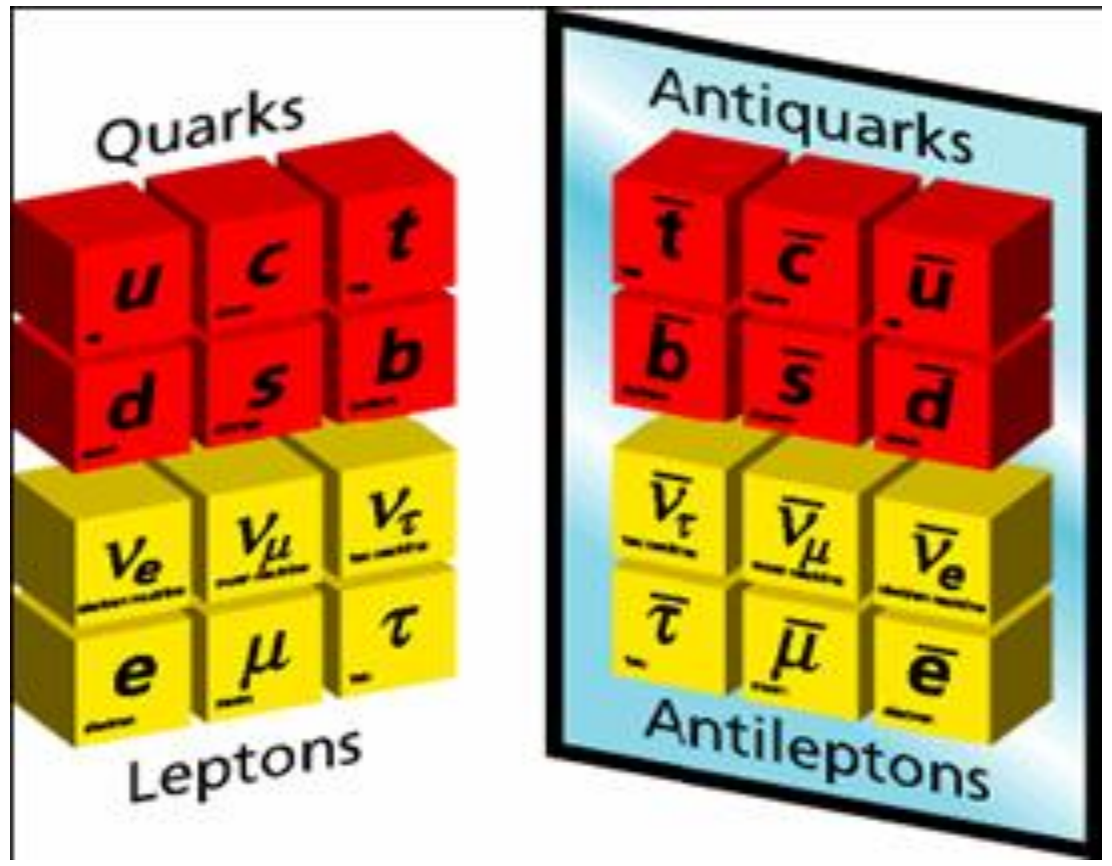


ОПЫТЪ СИСТЕМЫ ЭЛЕМЕНТОВЪ.

ОСНОВАННОЙ НА ИХЪ АТОМНОМЪ ВѢСѢ И ХИМИЧЕСКОМЪ СХОДСТВѢ.

			Ti=50	Zr=90	?=180.
			V=51	Nb=94	Ta=182.
			Cr=52	Mo=96	W=186.
			Mn=55	Rh=104,4	Pt=197,4.
			Fe=56	Rn=104,4	Ir=198.
			Ni=Co=59	Pl=106,6	Os=199.
H=1			Cu=63,4	Ag=108	Hg=200.
	Be=9,4	Mg=24	Zn=65,2	Cd=112	
	B=11	Al=27,4	?=68	Ur=116	Au=197?
	C=12	Si=28	?=70	Sn=118	
	N=14	P=31	As=75	Sb=122	Bi=210?
	O=16	S=32	Se=79,4	Te=128?	
	F=19	Cl=35,5	Br=80	I=127	
Li=7	Na=23	K=39	Rb=85,4	Cs=133	Tl=204.
		Ca=40	Sr=87,6	Ba=137	Pb=207.
		?=45	Ce=92		
		?Er=56	La=94		
		?Yt=60	Di=95		
		?In=75,6	Th=118?		

Д. Менделѣевъ



…Dalton, Lavoisier, Mendeleev, Thomson, Pauli, Fermi, Zweig, Gell-Mann…

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Matter

From Wikipedia, the free encyclopedia

This article is about the concept in the physical sciences. For other uses, see Matter (disambiguation).

In classical physics and general chemistry, **matter** is any substance that has mass and takes up space by ha
ultimately composed of atoms, which are made up of interacting subatomic particles, and in everyday as we
made up of them, and any particles (or combination of particles) that act as if they have both rest mass and
photons, or other energy phenomena or waves such as light or sound.[1][2] Matter exists in various states (al
as solid, liquid, and gas – for example water exists as ice, liquid water, and gaseous steam – but other state
fermionic condensates, and quark–gluon plasma.[3]

Usually atoms can be imagined as a nucleus of protons and neutrons, and a surrounding "cloud" of orbiting
correct, because subatomic particles and their properties are governed by their quantum nature, which mea
like waves as well as particles and they do not have well-defined sizes or positions. In the Standard Model o
elementary constituents of atoms are quantum entities which do not have an inherent "size" or "volume" in a
other fundamental interactions, some "point particles" known as fermions (quarks, leptons), and many comp
particles under everyday conditions; this creates the property of matter which appears to us as matter taking

For much of the history of the natural sciences people have contemplated the exact nature of matter. The id
particulate theory of matter, was first put forward by the Greek philosophers Leucippus (~490 BC) and Demo

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Matter

From Wikipedia, the free encyclopedia

This article is about the concept in the physical sciences. For other uses, see Matter (disambiguation).

In classical physics and general chemistry, **matter** is any substance that has mass and takes up space by ha
ultimately composed of atoms, which are made up of interacting subatomic particles, and in everyday as we
made up of them, and any particles (or combination of particles) that act as if they have both rest mass and
photons, or other energy phenomena or waves such as light or sound.[1][2] Matter exists in various states (al
as solid, liquid, and gas – for example water exists as ice, liquid water, and gaseous steam – but other state
fermionic condensates, and quark–gluon plasma.[3]

Usually atoms can be imagined as a nucleus of protons and neutrons, and a surrounding "cloud" of orbiting
correct, because subatomic particles and their properties are governed by their quantum nature, which mea
like waves as well as particles and they do not have well-defined sizes or positions. In the Standard Model o
elementary constituents of atoms are quantum entities which do not have an inherent "size" or "volume" in a
other fundamental interactions, some "point particles" known as fermions (quarks, leptons), and many comp
particles under everyday conditions; this creates the property of matter which appears to us as matter taking

For much of the history of the natural sciences people have contemplated the exact nature of matter. The ide
particulate theory of matter, was first put forward by the Greek philosophers Leucippus (~490 BC) and Demo

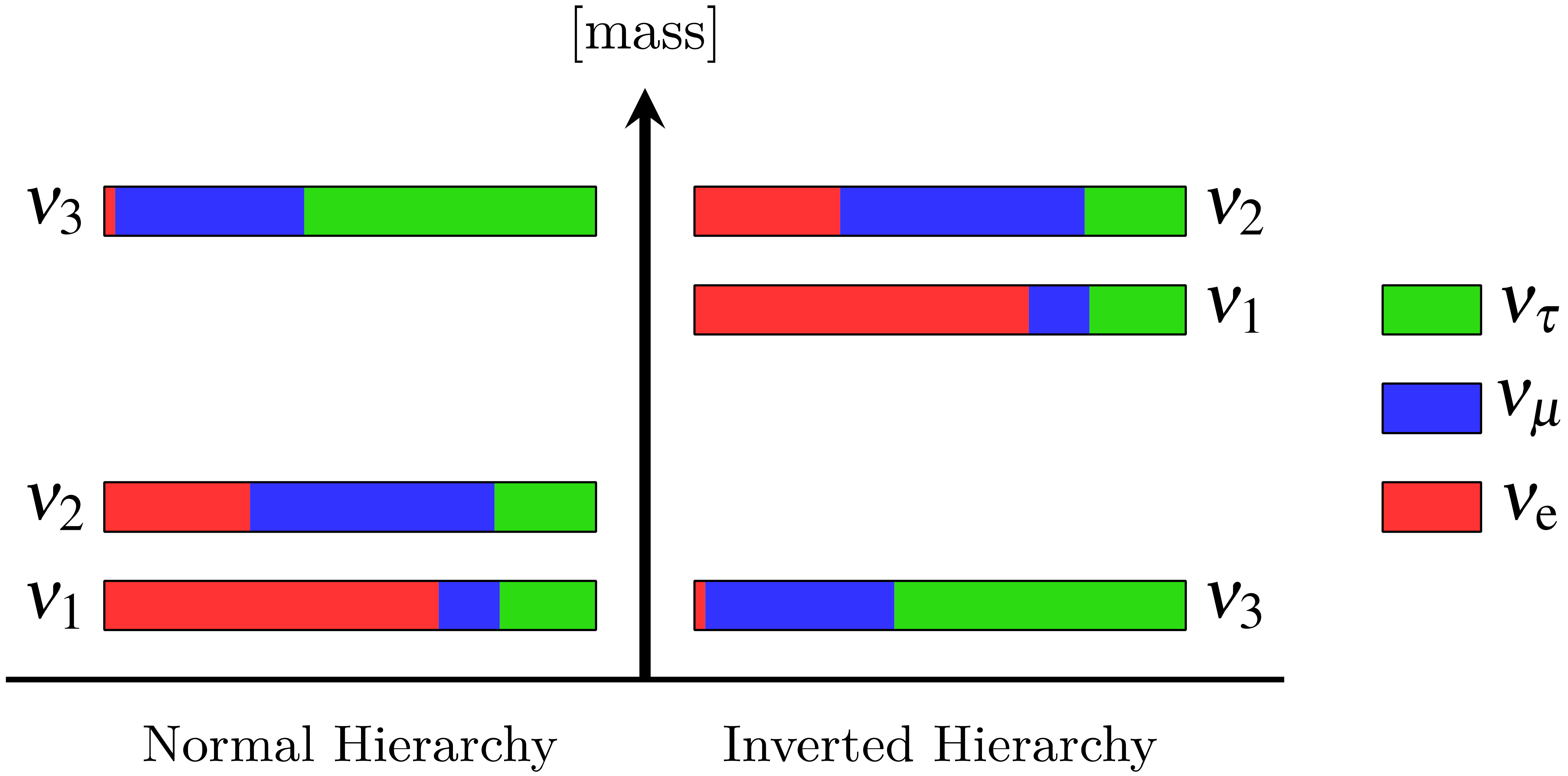
WHAT IS "MATTER" MADE OF?

Elementary Components Of Matter	Identifying Feature	End Vigence Of Model [Theory] Experiment	Reason For Inadequacy
Atoms	Type, Mass	[1838] 1909	**[Atoms Of Electricity] Electrons**
Electrons & Nuclei	Charge, Mass, Spin1/2	[1930] 1956	**[Fermi' Theory] Neutrons & Neutrinos**
p, n, e, ν_e, μ . . .	B, L_e, L_μ . . . , " "	[1961] 1968	**[Standard Model] Quarks**
Quarks & Leptons	$B - L, L_e - L_\mu$, . . ., " "	[1962] 2010	**[Leptonic Mixing] Appearance Experiments**
Quark-Leptons	$B - L$, " "	[1937] ?	**[Majorana' Mass]** $2n \rightarrow 2p + 2e$
Fermions	Mass, Spin1/2	[1977] ???	**[Supersymmetry?] ???**

more on neutrinos

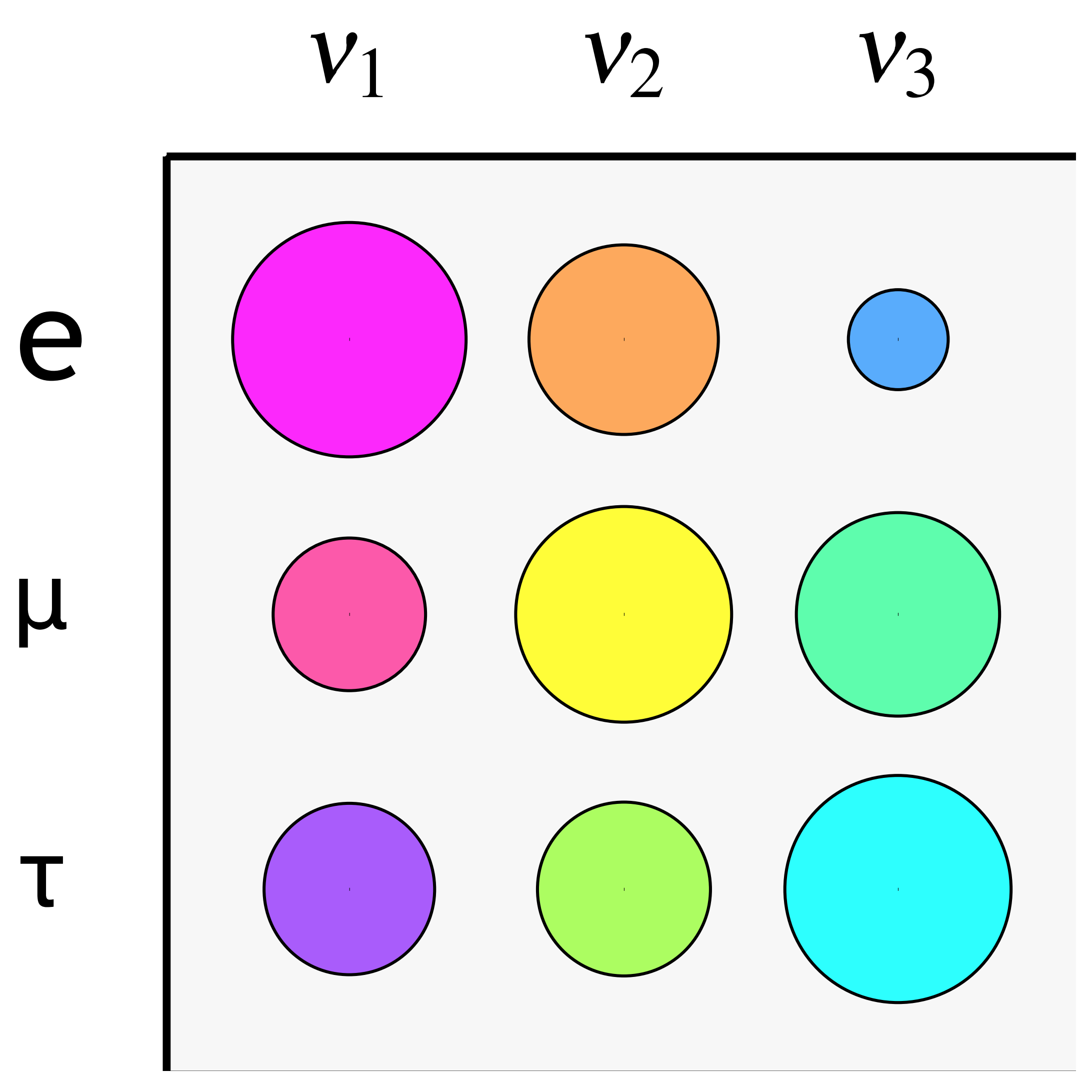
three flavor model [1/2]

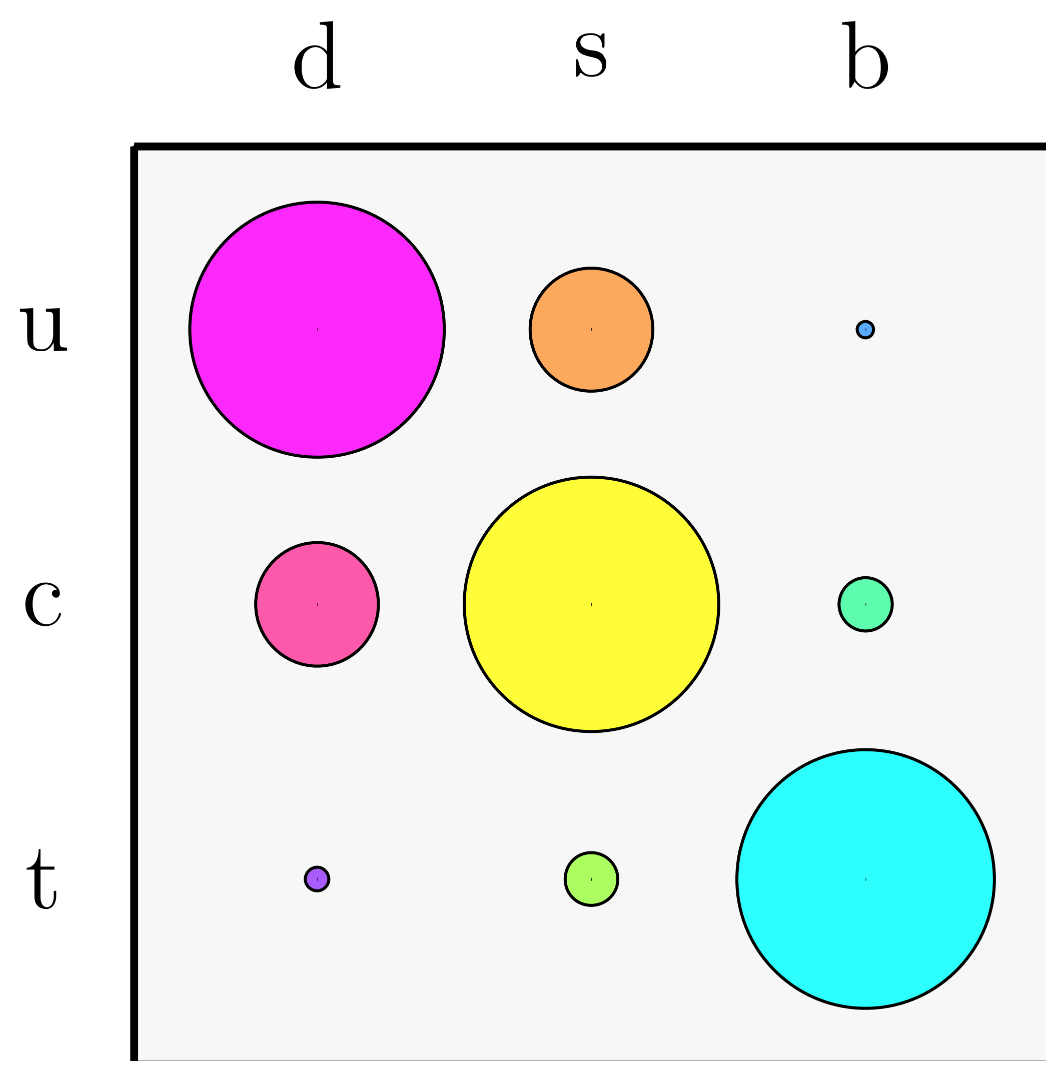
Fantini, Gallo Rosso et al, 2018



three flavor model [2/2]

Fantini, Gallo Rosso et al, 2018





The unfinished fabric of the three neutrino paradigm

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TABLE I: Global 3ν analysis of oscillation parameters: best-fit values and allowed ranges at $N_\sigma = 1$, 2 and 3, for either NO or IO, including all data. The latter column shows the formal "1σ fractional accuracy" for each parameter, defined as 1/6 of the 3σ range, divided by the best-fit value and expressed in percent. We recall that $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$ and that $\delta \in [0, 2\pi]$ (cyclic). The last row reports the difference between the χ^2 minima in IO and NO.

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	"1σ" (%)
$\delta m^2/10^{-5}$ eV^2	NO, IO	7.36	7.21 – 7.52	7.06 – 7.71	6.93 – 7.93	2.3
$\sin^2\theta_{12}/10^{-1}$	NO, IO	3.03	2.90 – 3.16	2.77 – 3.30	2.63 – 3.45	4.5
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.485	2.454 – 2.508	2.427 – 2.537	2.401 – 2.565	1.1
	IO	2.455	2.430 – 2.485	2.403 – 2.513	2.376 – 2.541	1.1
$\sin^2\theta_{13}/10^{-2}$	NO	2.23	2.17 – 2.30	2.11 – 2.37	2.04 – 2.44	3.0
	IO	2.23	2.17 – 2.29	2.10 – 2.38	2.03 – 2.45	3.1
$\sin^2\theta_{23}/10^{-1}$	NO	4.55	4.40 – 4.73	4.27 – 5.81	4.16 – 5.99	6.7
	IO	5.69	5.48 – 5.82	4.30 – 5.94	4.17 – 6.06	5.5
δ/π	NO	1.24	1.11 – 1.42	0.94 – 1.74	0.77 – 1.97	16
	IO	1.52	1.37 – 1.66	1.22 – 1.78	1.07 – 1.90	9
$\Delta\chi^2_{\mathrm{IO-NO}}$	IO−NO	+6.5				

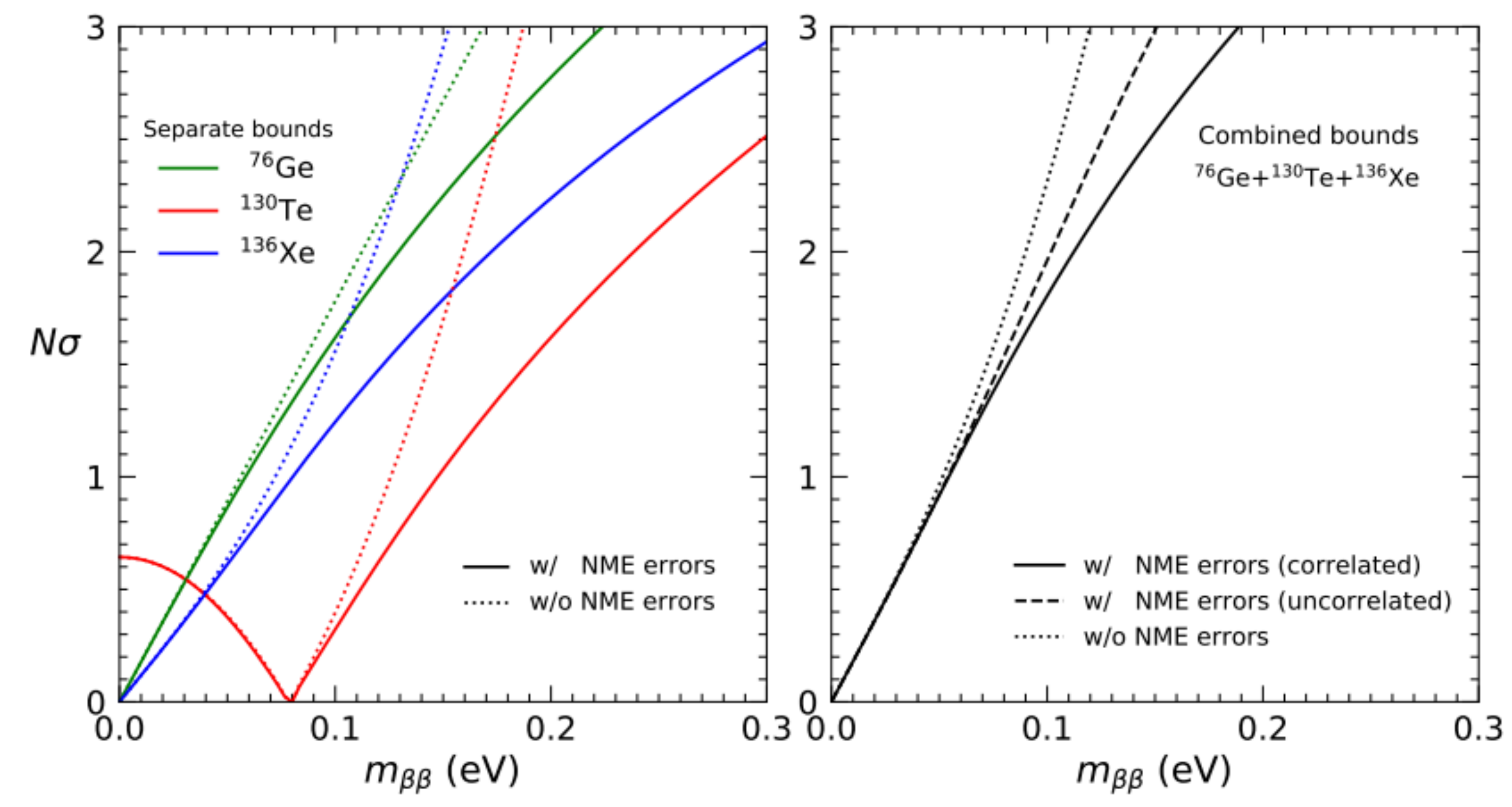


FIG. 10: Neutrinoless double beta decay: Our estimated bounds on $m_{\beta\beta}$, expressed in terms of $N_\sigma = \sqrt{\Delta\chi^2}$. The left and right panels refer, respectively, to separate and combined bounds from the three nuclides, with (solid) or without (dotted) NME uncertainties. In the right panel, the case with uncorrelated uncertainties is also shown (dashed).

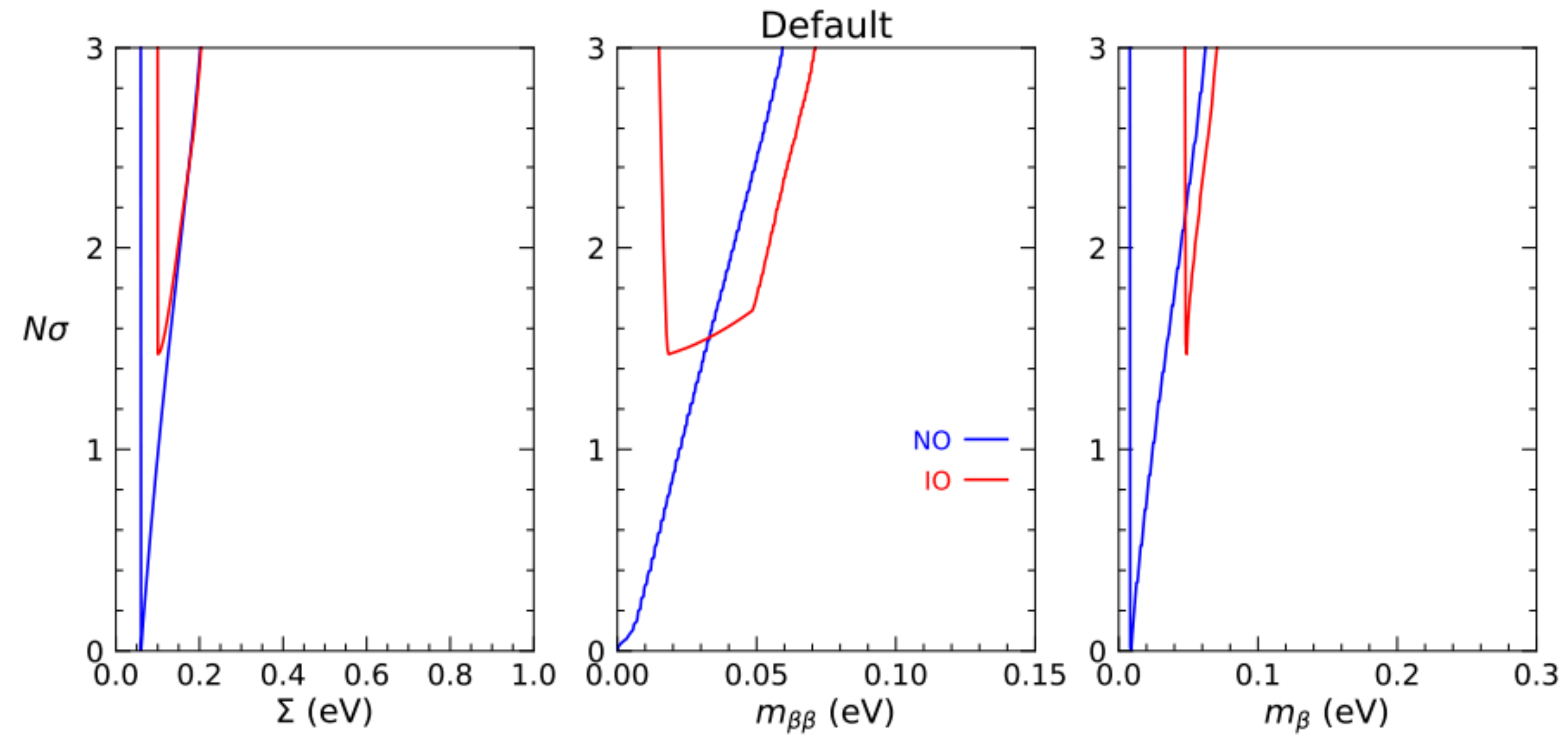
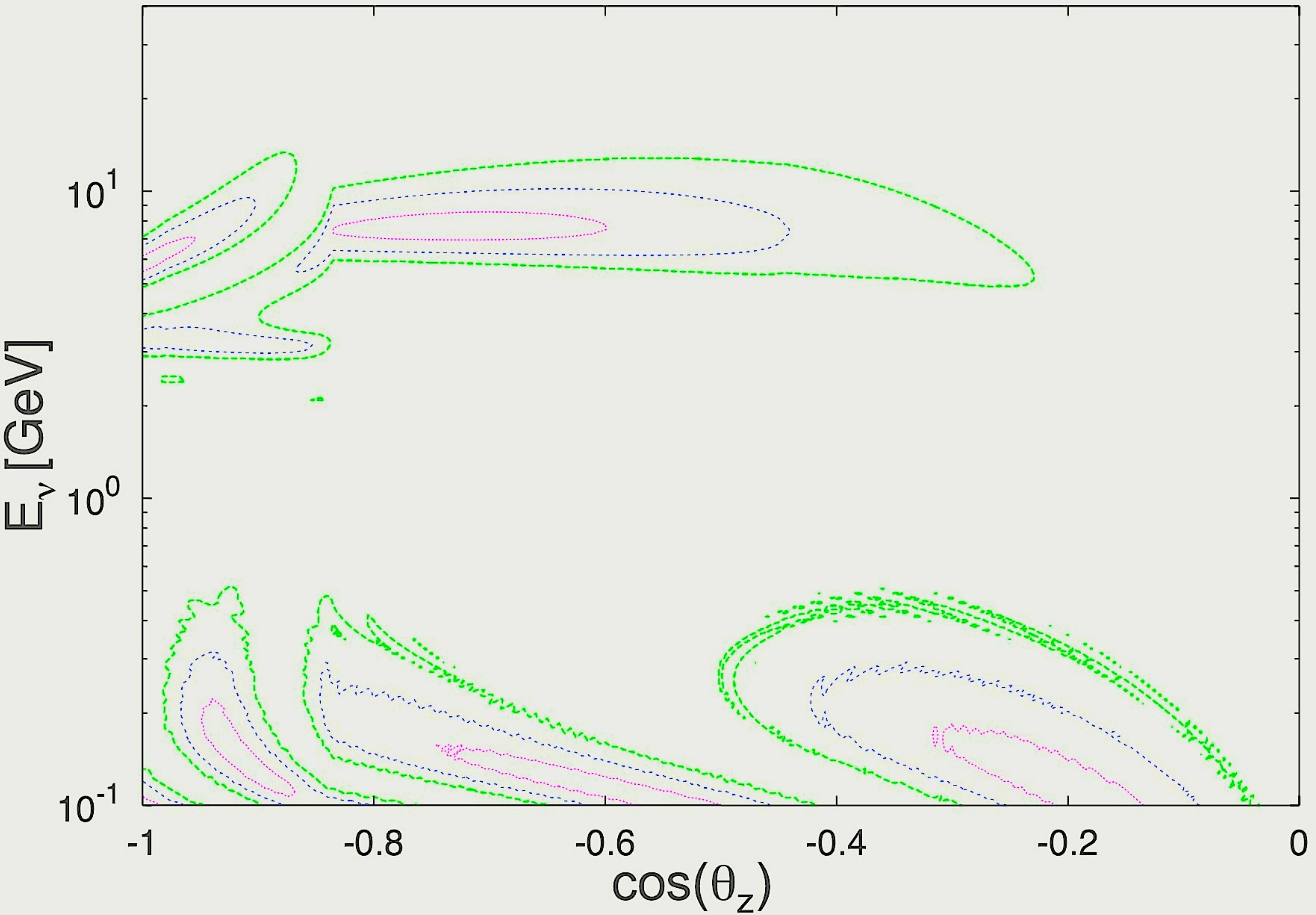


FIG. 14: N_σ bounds on the single nonoscillation parameters Σ (left), $m_{\beta\beta}$ (center) and m_β (right), assuming default cosmological inputs. The combination of nonoscillation data induces the offset between the absolute minima in IO (red) and NO (blue).

NH→NO

Normal hierarchy → Normal ordering

P_{ee}=0.7, 0.5, 0.3 through the Earth (La Thuile 2003)



NO → YES

Normal ordering → Yearningly Expected Spectrum

more on theory

round table "Einstein and the physics of the future"
published in Some Strangeness in the Proportion, ed. H. Woolf, 1980

Weinberg:

[…] the lifetime of the proton (this has been worked on by a number of people now) comes out to be of the order 10^{30} to 10^{32} years. The present experimental lower bound is 10^{29} years. Thus the time is ripe for an assault on the next few orders of magnitude in the proton lifetime.

Dyson:

[…] the modern view of particle theory, with the sub-nuclear world a playground of interlocking broken and unbroken symmetries, had its roots in Felix Klein's Erlanger Program of 1872 […]

I predict that in the next 25 years we shall see the emergence of unified physical theories in which general relativity, group theory, and field theory are tied together with bonds of rigorous maths.

Yang:

beautiful mathematics is the language of fundamental physics […]

Maybe it is my prejudice - maybe it is my ignorance - but I do not believe that any of these graded Lie algebras has the intrinsic and fundamental beauty of Lie algebras and Lie groups, not as yet!

from 1979 Nobel lectures

Salam:

That summer [1973, ed] Jogesh Pati and I had predicted proton decay within the context of what is now called GUT.

Glashow:

GUT - perhaps along the lines of the original SU(5) theory of Georgi and me - must be essentially correct. This implies that the proton, and indeed all nuclear matter, must be inherently unstable.

Weinberg:

If effects of a tiny non-conservation of baryon or lepton number such as proton decay or neutrino masses are discovered experimentally, we will then be left with gauge symmetries as the only true internal symmetries of nature, a conclusion that I would regard as most satisfactory.

PHYSICAL REVIEW D VOLUME 57, NUMBER 11 1 JUNE 1998

Do experiments suggest a hierarchy problem?

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(Received 18 September 1997; published 14 April 1998)

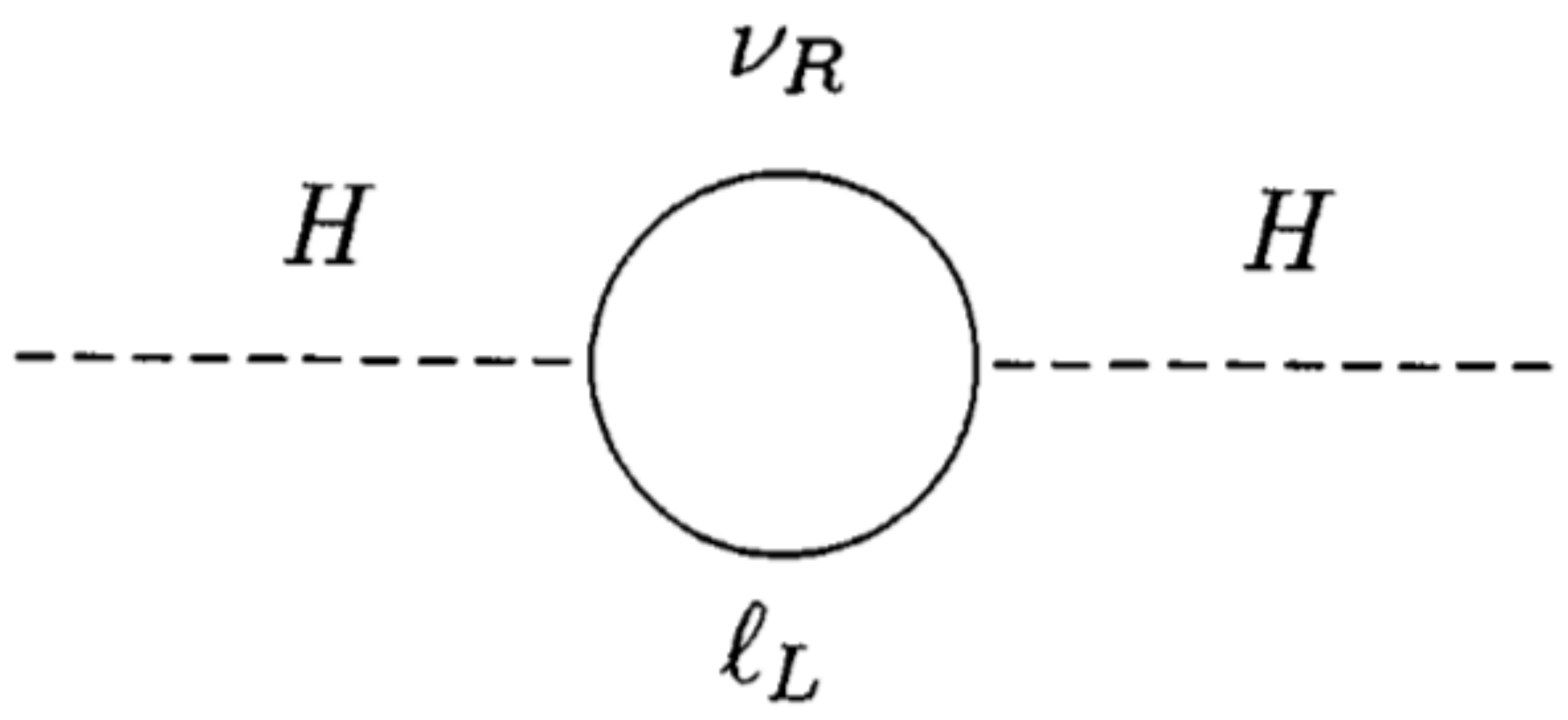

FIG. 1. The Feynman diagram originating the corrections in Eq. (1); ν_R denotes the right-handed neutrino of mass M_R, $\ell_L = (\nu_L, e_L)$ the leptonic and H the Higgs doublets.

OK, but what about the cosmological constant?

A few modern example of non supersymmetric grand unified models, suited to describe fermion masses:

- Matsuda et al 2001;
- Bajc et al 2005;
- Bertolini et al 2009-2011;
- Joshipura et al 2011;
- Buccella et al 2012;
- Dueck et al 2013;
- Altarelli et al 2013;
- Ohlsson et al 2019-2021

JHEP

Published for SISSA by Springer

Received: July 28, 2021
Revised: August 25, 2021
Accepted: September 1, 2021
Published: September 17, 2021

Flavor symmetries in the Yukawa sector of non-supersymmetric SO(10): numerical fits using renormalization group running

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Abstract: We consider a class of SO(10) models with flavor symmetries in the Yukawa sector and investigate their viability by performing numerical fits to the fermion masses and mixing parameters. The fitting procedure involves a top-down approach in which we solve the renormalization group equations from the scale of grand unification down to the electroweak scale. This allows the intermediate scale right-handed neutrinos and scalar triplet, involved in the type I and II seesaw mechanisms, to be integrated out at their corresponding mass scales, leading to a correct renormalization group running. The result is that, of the 14 models considered, only two are able to fit the known data well. Both these two models correspond to $\mathbb{Z}_2$ symmetries. In addition to being able to fit the fermion masses and mixing parameters, they provide predictions for the sum of light neutrino masses and the effective neutrinoless double beta decay mass parameter, which are both within current observational bounds.

JHEP09(2021)111

remarks

- ⭐the idea that SM is the low energy limit of a more complete theory has emerged in 70's
- ⭐neutrinos mass expected (observed); proton decay is possible (not yet observed)
- ⭐Majorana mass of neutrinos: one of the most interesting characteristic features
- ⭐one can argue for a “hierarchy problem" (e.g. heavy ν) but what we learn from this?
- ⭐these theories are compatible with new light particles observable in laboratories
- ⭐important to proceed with systematic studies of principled models

discussion

Q **[Lindner] how to make statement on discovery probability w/o theory?**

A *I agree this is not desirable: we better have a theory. Still, using oscillations and cosmological likelihood, it is possible to quantify the probability of the 3 cases: observation, inaccessibility, exploration, as we did with "flag-plot" (page 25-29)*

Q **[Previtali] a) nuclear uncertainty can be reduced? b) what is the nature of the problem?**

A *I am not sure I am competent to discuss this usefully. But I see that after a long period where only few theorist work on that, now there is a much increased activity. This comes with a lot of experimental efforts. (page 33). I believe we should be aware that an important investment on* $0\nu2\beta$ *should be accompanied by theoretical progresses*

Q **[Cremonesi] what is wrong with Dirac mass?**

A *Nothing fundamental in principle. However if you add right handed neutrinos to SM particles, there is no reason to forbid Majorana mass for them. Likewise in models such as SO(10) you do not expect Dirac neutrinos. This is why we better invest time on studying principled model; mathematically, the number of possibilities is just too large. Just for completeness if we play w/o principles, many possibilities arise e.g.,* $0\nu2\beta$ *can be due* ν_R *to not to* ν_L *mass*

Q **[Nakahata] a) is it possible to exclude mixing between Dirac and Majorana neutrinos? b) can measuring e.m. dipole help to tell Dirac from Majorana?**

A *a) it is not possible to exclude, but we have no neat evidence from oscillations; maybe, new neutrinos are useful for dark matter (Shaposhnikov's model) but dark matter is warm not cold b) it is not clear we can reach the sensitivity. Furthermore, neutrino masses have been measured and arise in SM at dimension five; this simple consideration make the search for* $0\nu2\beta$ *a priority*