Why is the neutrino mass important

- The rise and fall of massless neutrinos
- Implications of neutrino oscillations
- Majorana's mass and how to test it
- Significance of mass and perspectives

Francesco Vissani,
INFN, Laboratori Nazionali del Gran Sasso, Italy

Bonjour à tous et merci pour l’invitation!

Je suis désolé de ne pas pouvoir être avec vous en personne, mais hier j'étais occupé à présenter un séminaire général à l'APS à New York, qui avait un but.

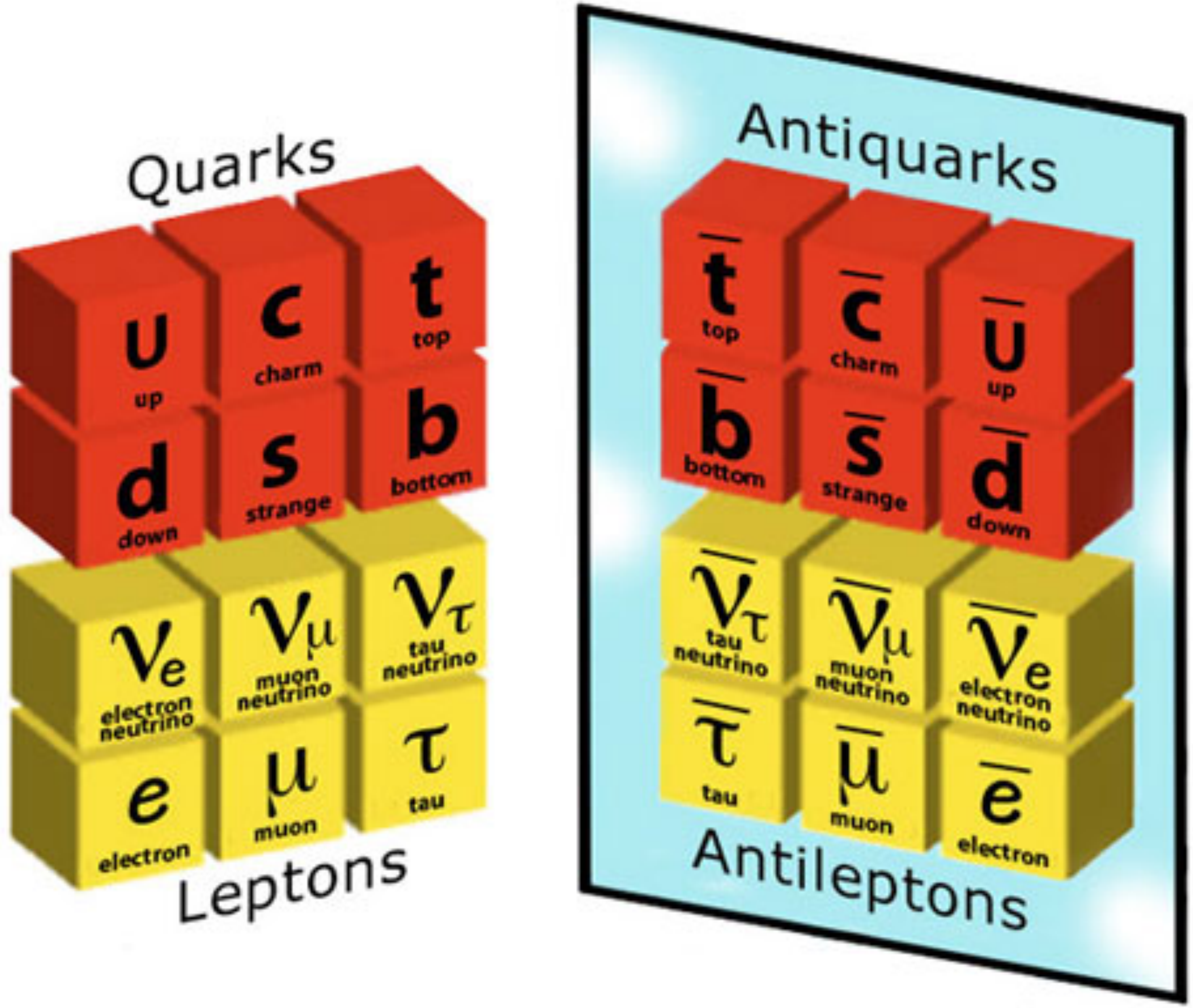
J'essayais de convaincre les communautés scientifiques, qui ne travaillent pas sur la "désintégration double bêta sans neutrino", qu'un processus élémentaire portant un nom aussi laid et non encore observé est néanmoins très important.

J'ai fait ce que j'ai pu, et j'aimerais partager le résultat avec vous.

PS : je ne pense pas que nous ayons besoin de convaincre Andrea, Léonard, Anastasiia, Giovanni, etc. — mais il y a le reste du monde.

the rise and fall of massless neutrinos

neutrinos and the standard model of elementary particles



Matter and antimatter particles
Credit: Fermilab

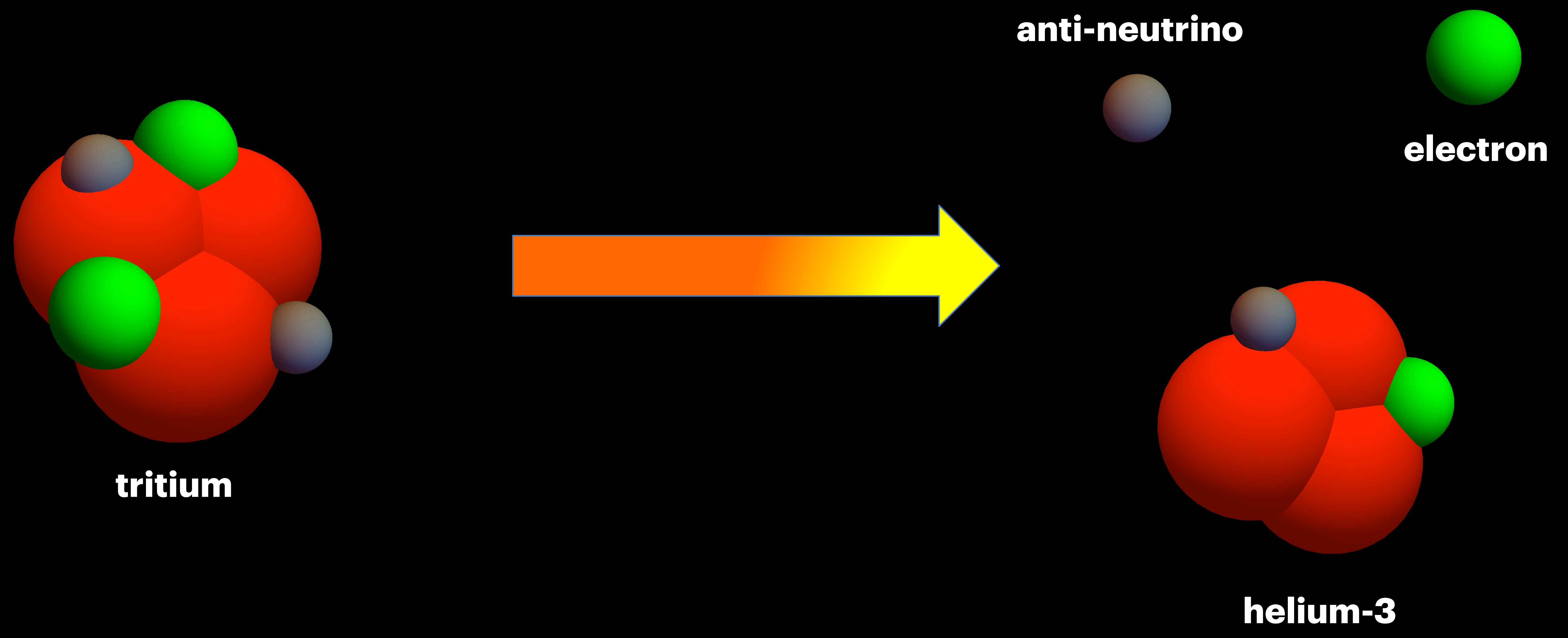
This useful picture conveys a huge amount of information, evoking the concepts of:

- *particles/antiparticles*
- *quarks/leptons*
- *family replication*

But it raises a question:

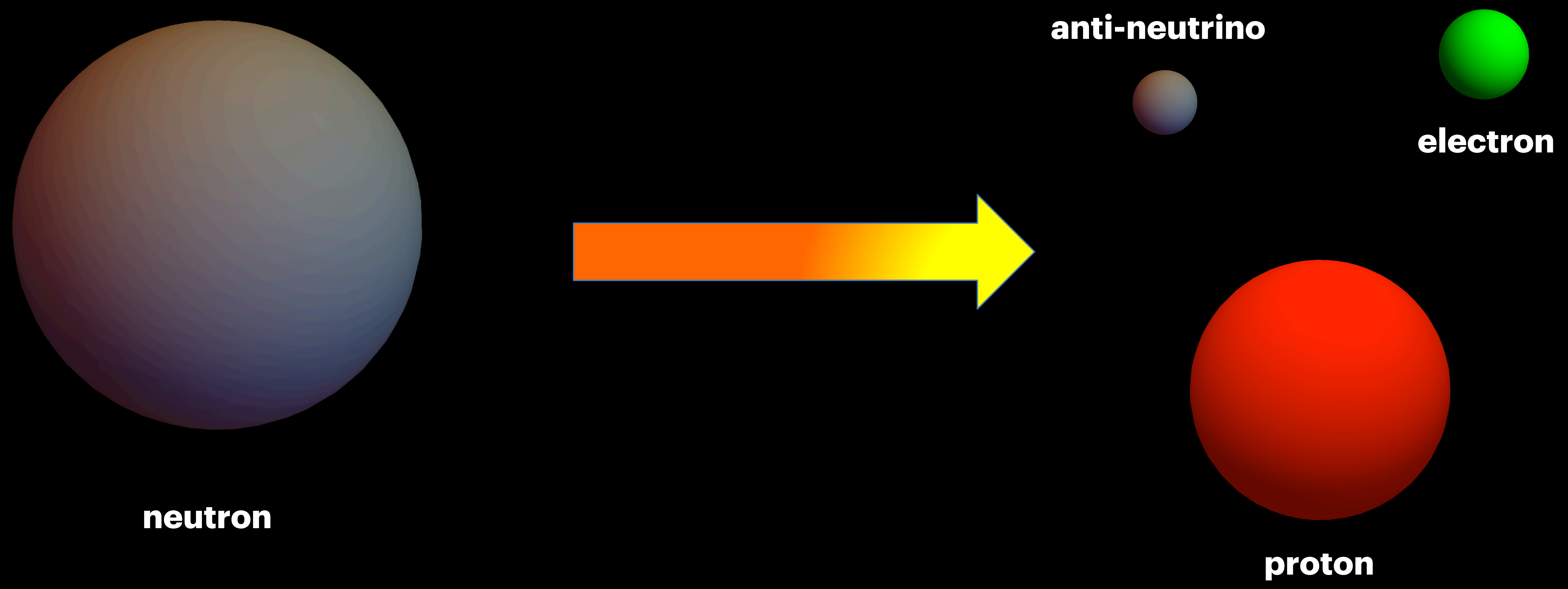
what distinguishes neutrinos and antineutrinos, as they are both chargeless?

how neutrinos were introduced (Pauli, 1930)



the nuclei contains electrons, protons & **neutrinos**; the latter steal some energy and (as all other matter particles) have spin 1/2

the theory of β-rays (Fermi, 1933)



for the first time, some particles of matter disappear, others appear: just like photons do!

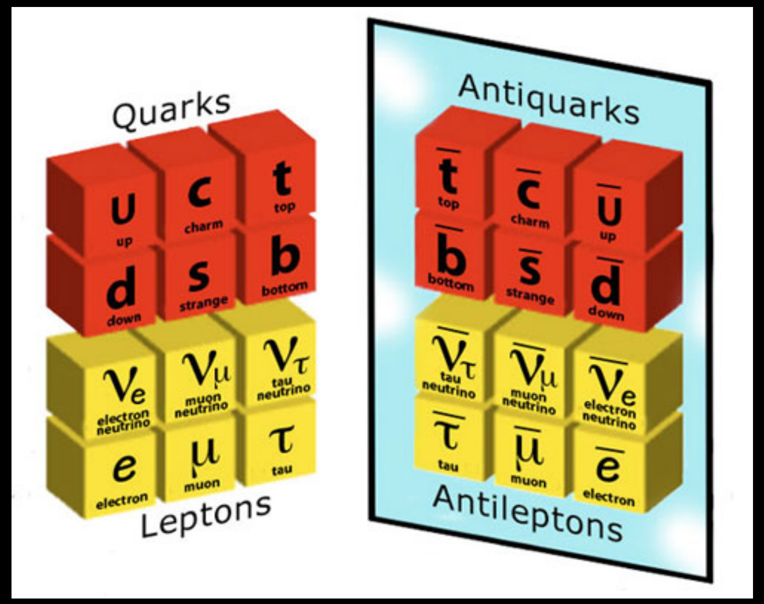
this behavior raised a theoretical dilemma

why disintegrations such as $p \rightarrow e^{+} + \gamma$ do not occur?

Weyl (1929); Stuckelberg (1936); Wigner (1949)

foundations for the standard model are laid in fifties

- to rescue theory, number of baryons **B** (1929-1949) and leptons **L** (1952-1953) are assumed to be conserved
- after the discovery of parity violation (1956), a further hypothesis is invoked: neutrinos are <u>massless</u> (1957)
- this paves the way to **V-A** theory of weak interaction (1957-1958) a cornerstone of the standard model (1960-1967)



on the structure of the standard model

- the standard model predicts that the 3 lepton numbers are all conserved in perturbation theory. Their differences $\mathbf{L_i - L_j}$ and **B-L** are exact

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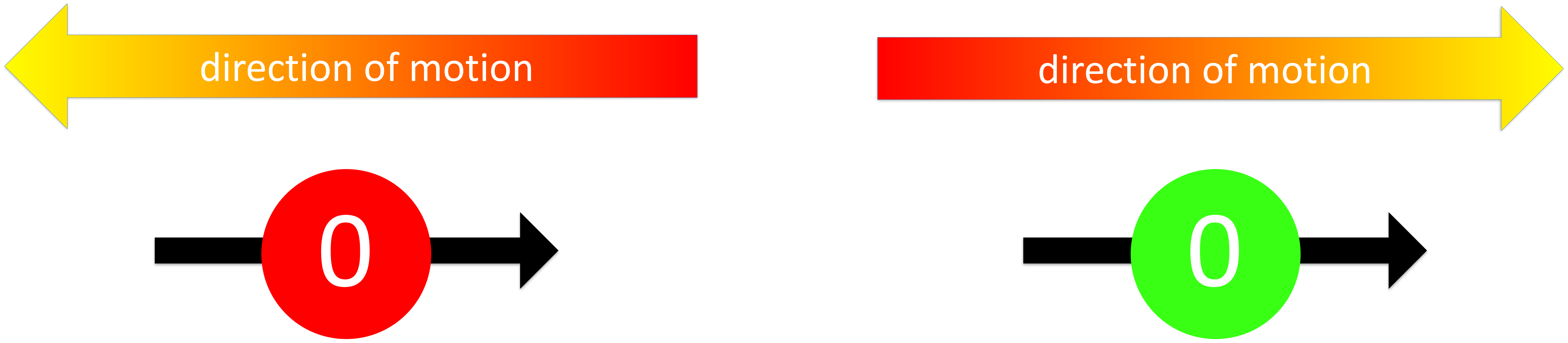
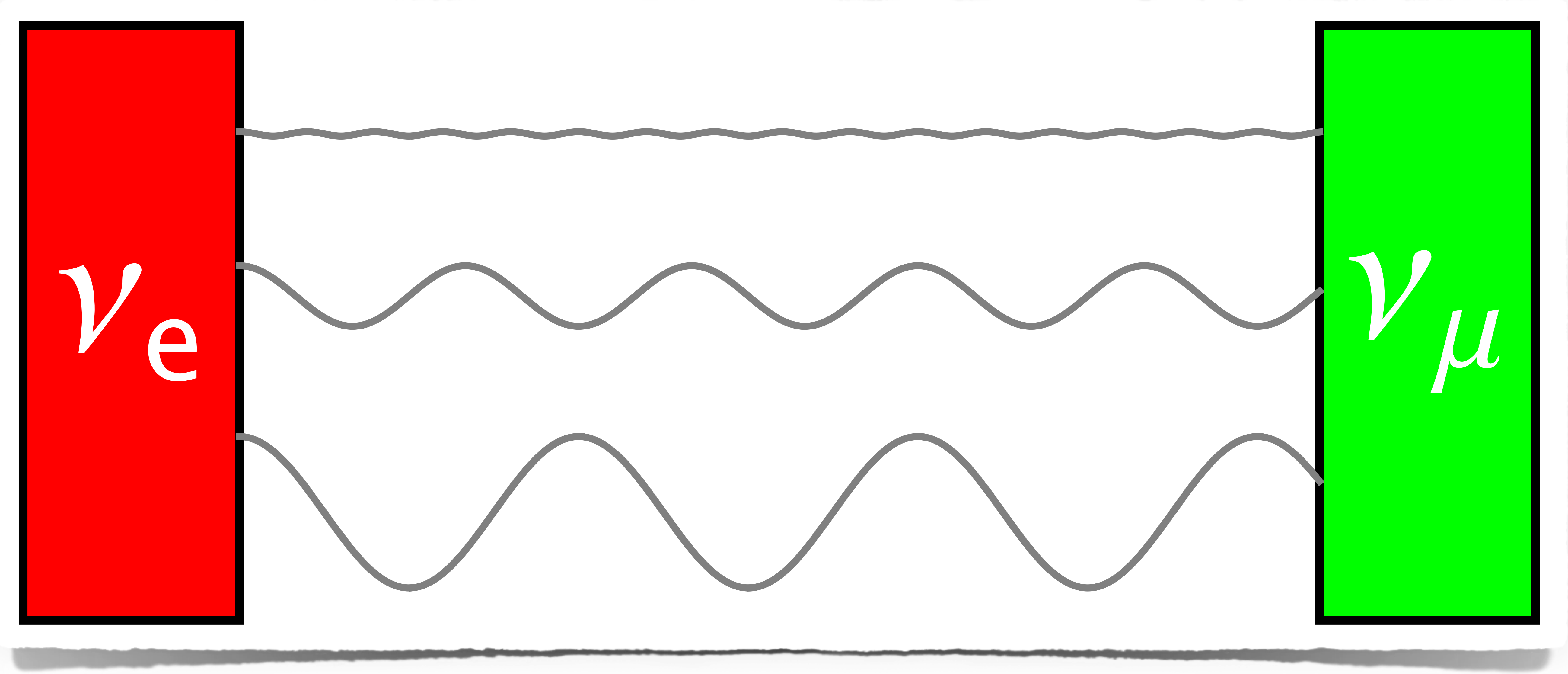


- Helicity distinguishes neutrinos from antineutrinos - a feature of SM, based on the masslessness of neutrinos.

however, neutrinos do have mass.

a quantum phenomenon, neutrino oscillations (1957-1967), indicates this beyond any doubt.



the proof, achieved with great efforts lasting more than 30 years, was recognized by the Nobel Prize awarded to Kajita and McDonald (2015)

oscillations, B. Pontecorvo (1957-1967); **neutrino mixing**, Y. Katayama, K. Matumoto, S. Tanaka, E. Yamada (1962), Z. Maki, M. Nakagawa, S. Sakata (1962) M. Nakagawa, H. Okonogi, S. Sakata, A. Toyoda (1963)

implications of neutrino oscillations

remarks on neutrino appearance experiments, status of the lepton and baryon numbers

neutrino appearance experiments proved that there is only one basic type of lepton

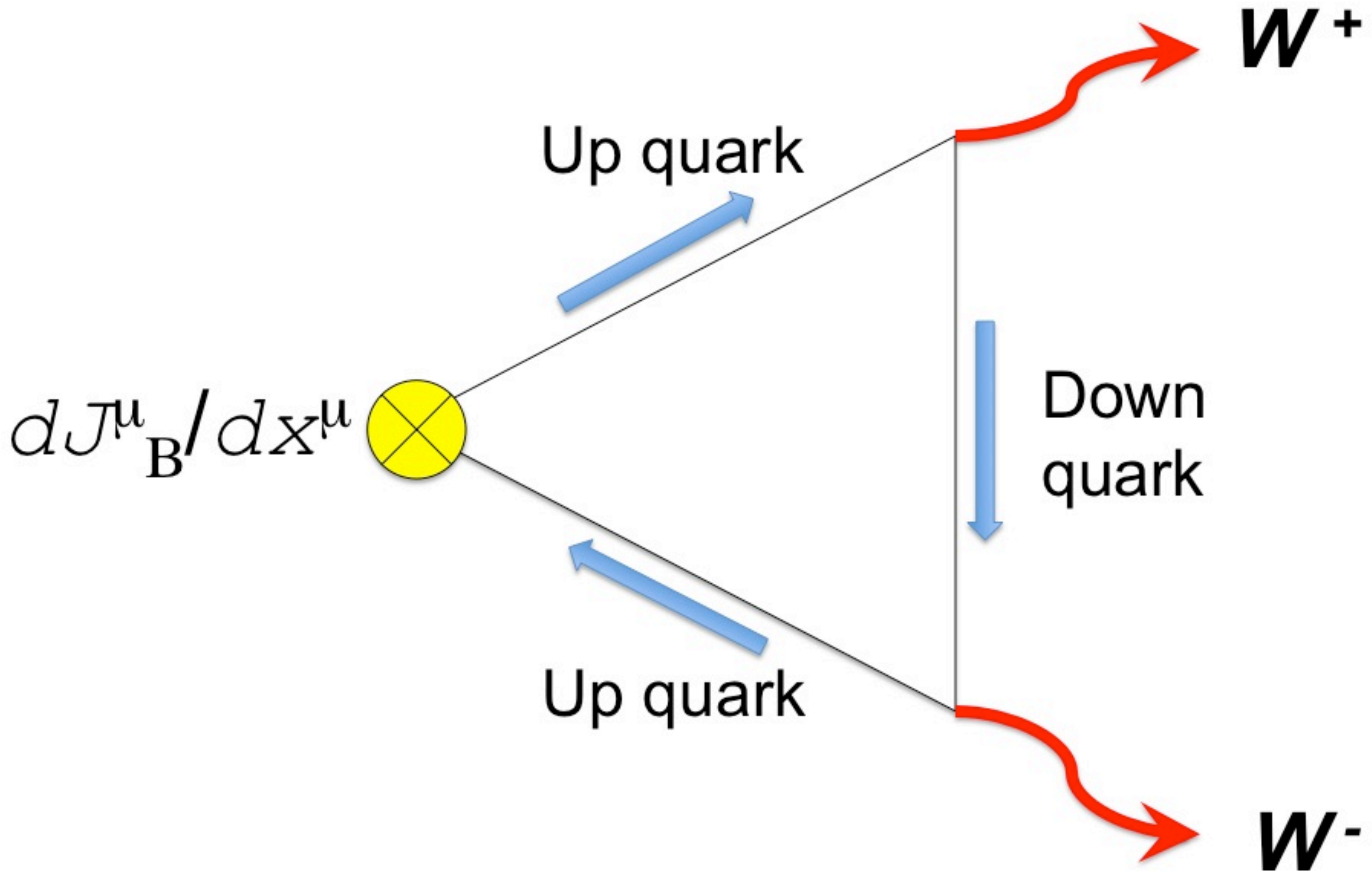
(=at the scrutiny of T2K, NOνA, OPERA, SK, DeepCore, only total lepton number L survived)

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

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

but in the SM, B and L are not separately conserved: B-L is conserved exactly; instead, B, L, B+L are not.

thus, in SM L and B are intimately connected

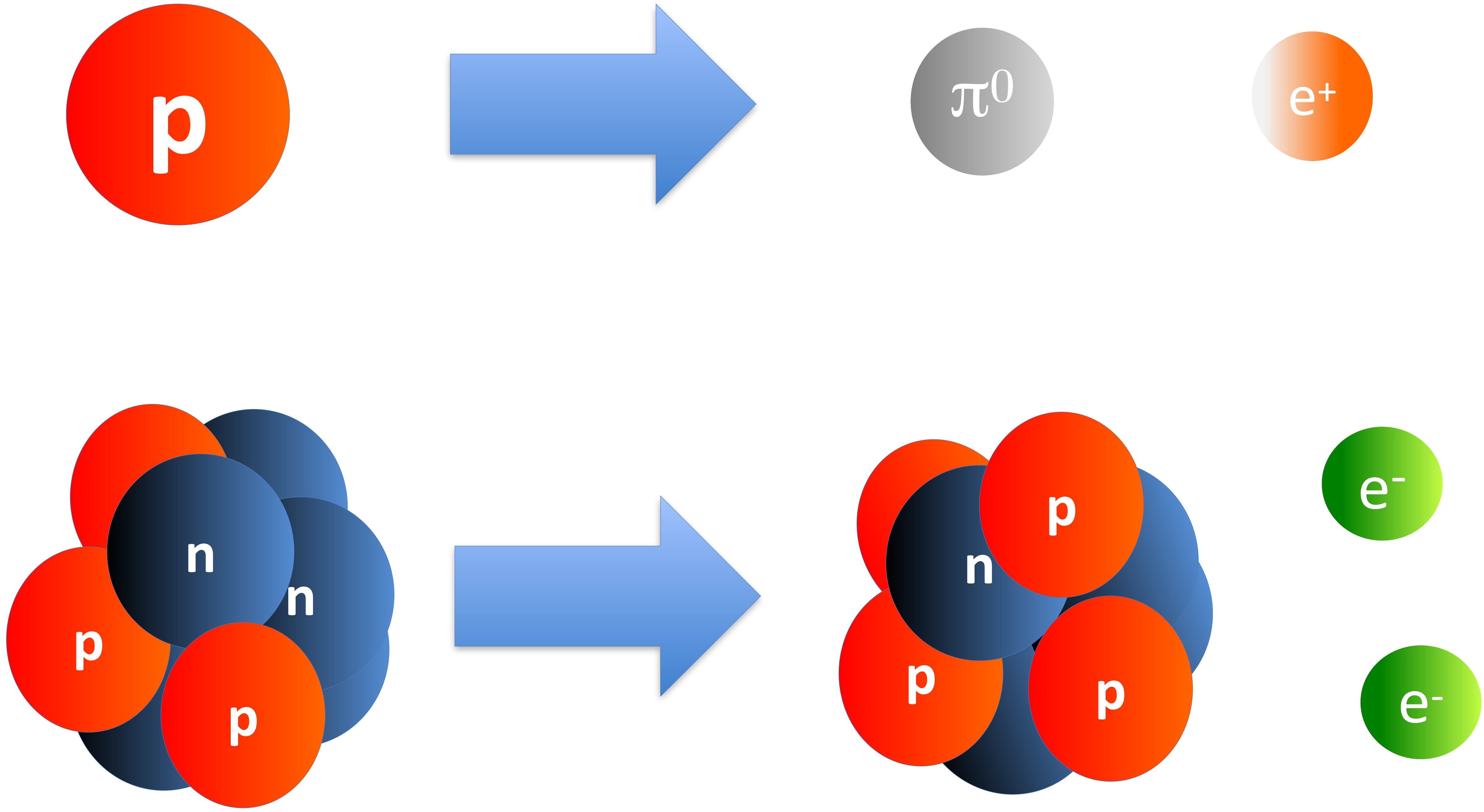


neutrino appearance experiments + SM imply that the only potentially exact symmetry is B-L

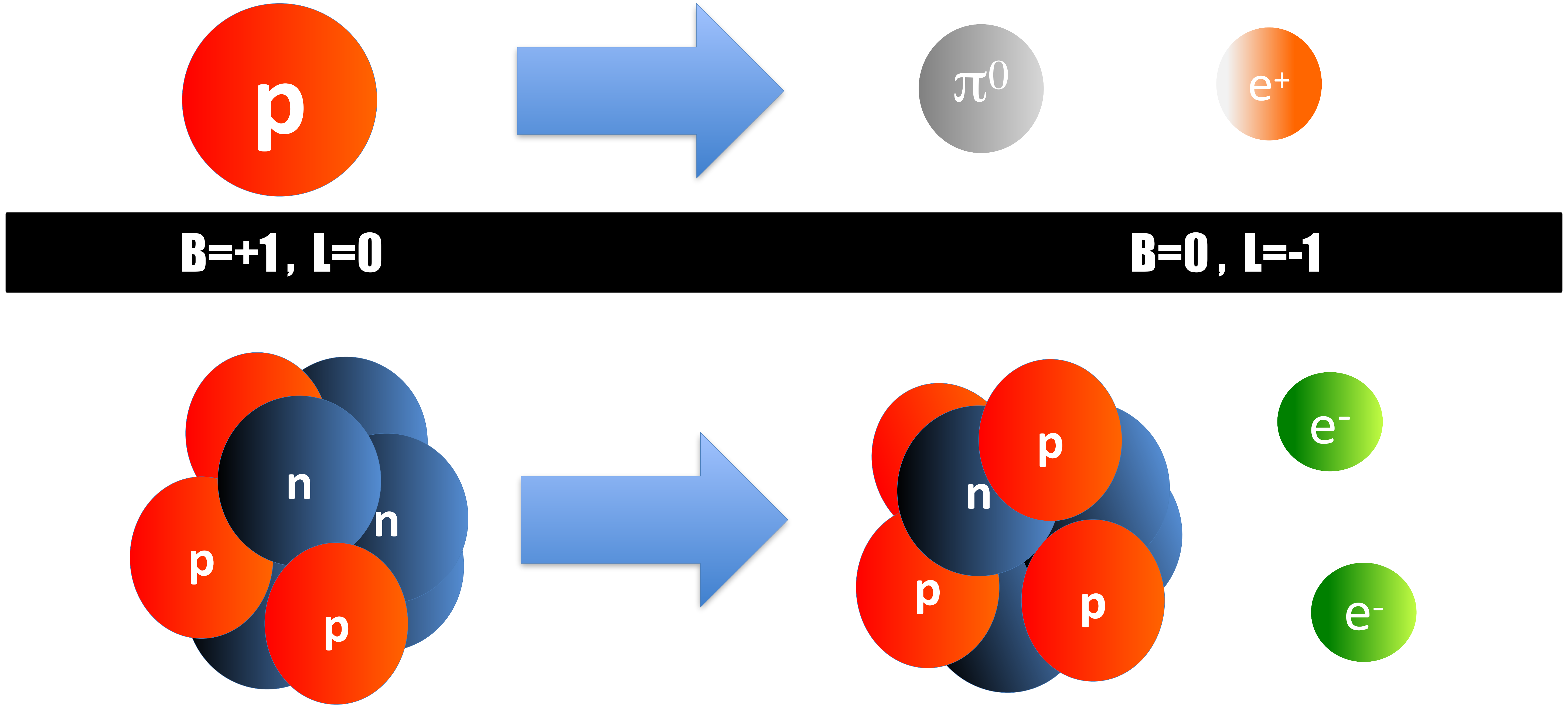
	$\Delta(L_e-L_\mu)$	$\Delta(L_\mu-L_\tau)$	$\Delta(L_\tau-L_e)$	$\Delta(B-L)$
$\nu_\mu \to \nu_e$	+2	-1	-1	0
$\nu_\mu \to \nu_\tau$	+1	-2	+1	0

$\Rightarrow$ there is an intimate connection between leptons and quarks.
One question that immediately arises is what is the degree of violation of **B**, **L**, etc

experimental tests of B and of L



experimental tests of B and of L



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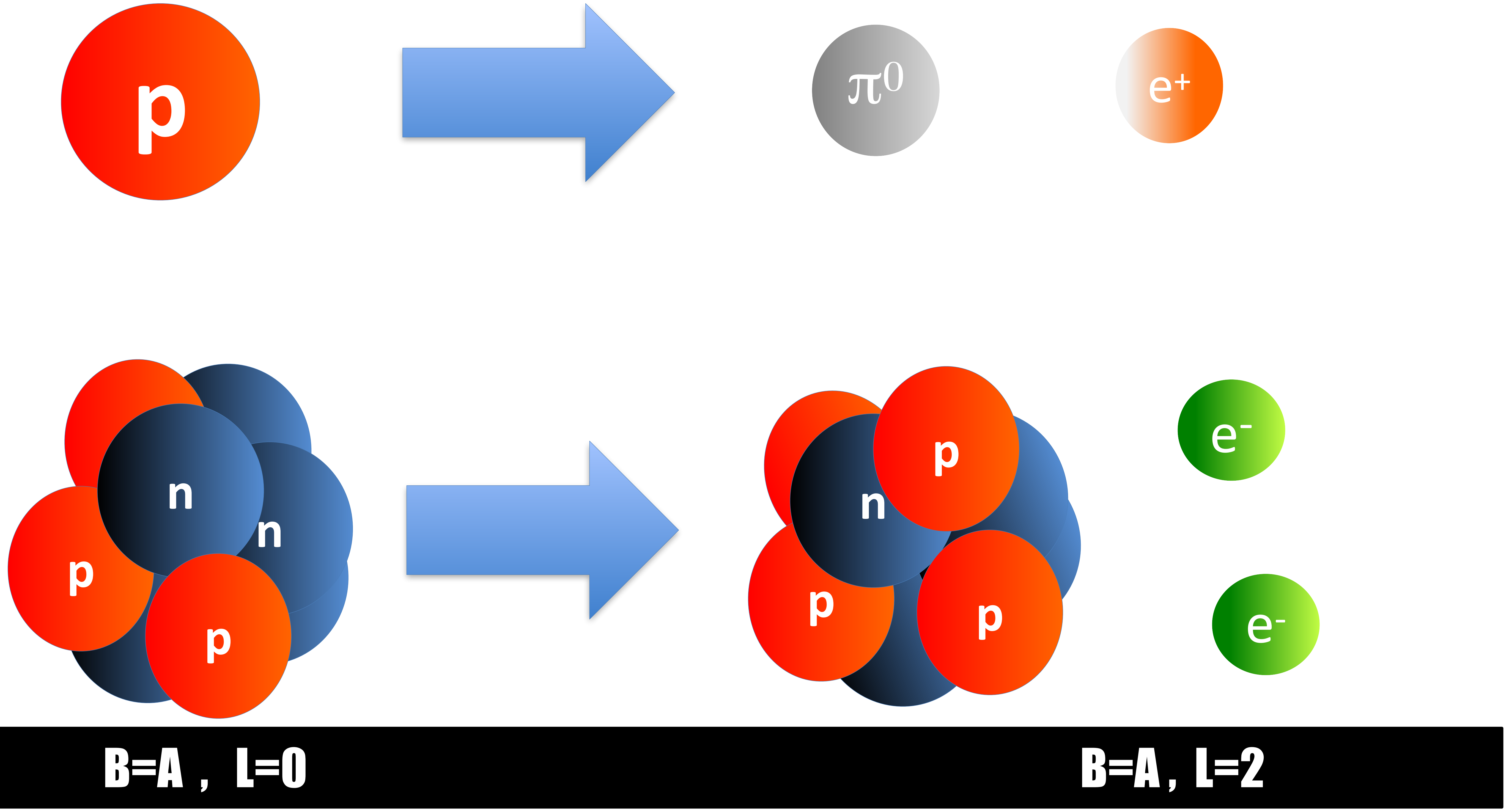
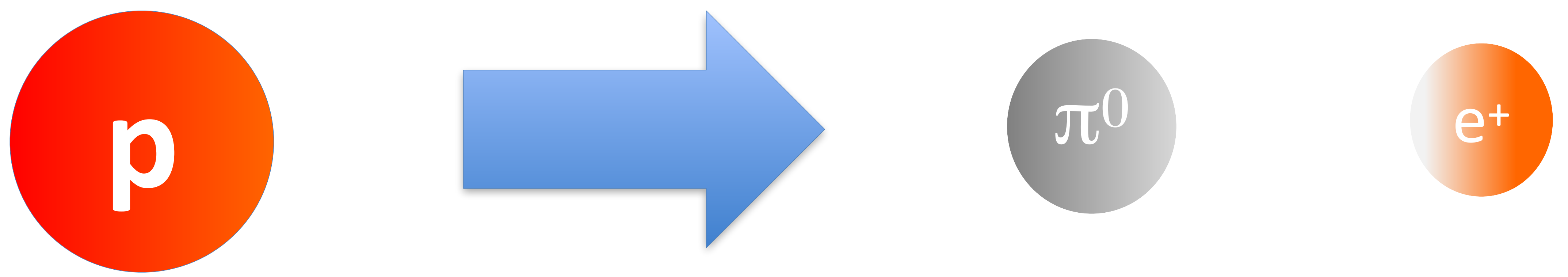
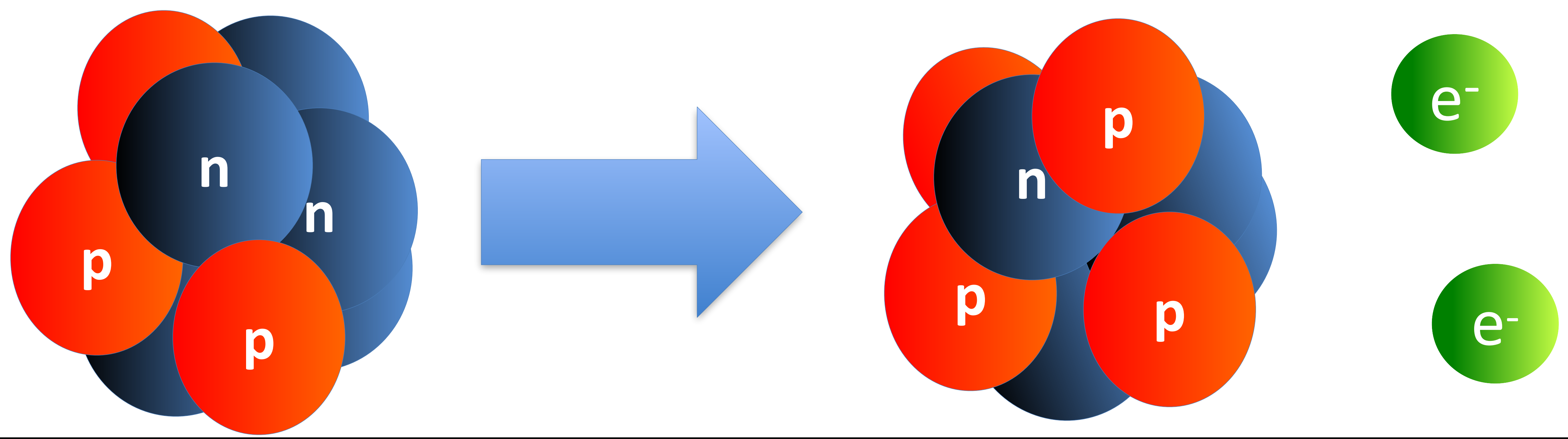


experimental tests of B and of L



Proton decay (B-L conserved)



Electrons Creation (B-L violated)

Electrons Creation - aka - Neutrinoless Double Beta Decay

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

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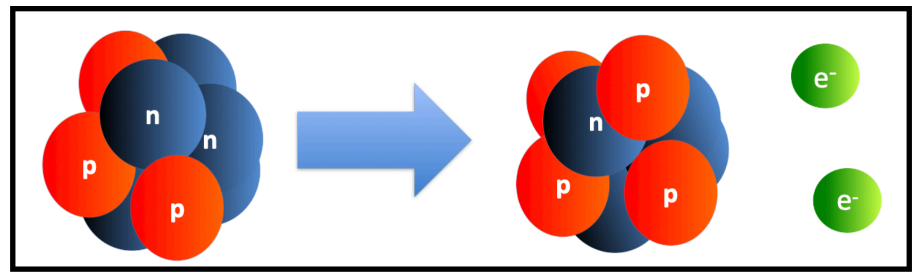
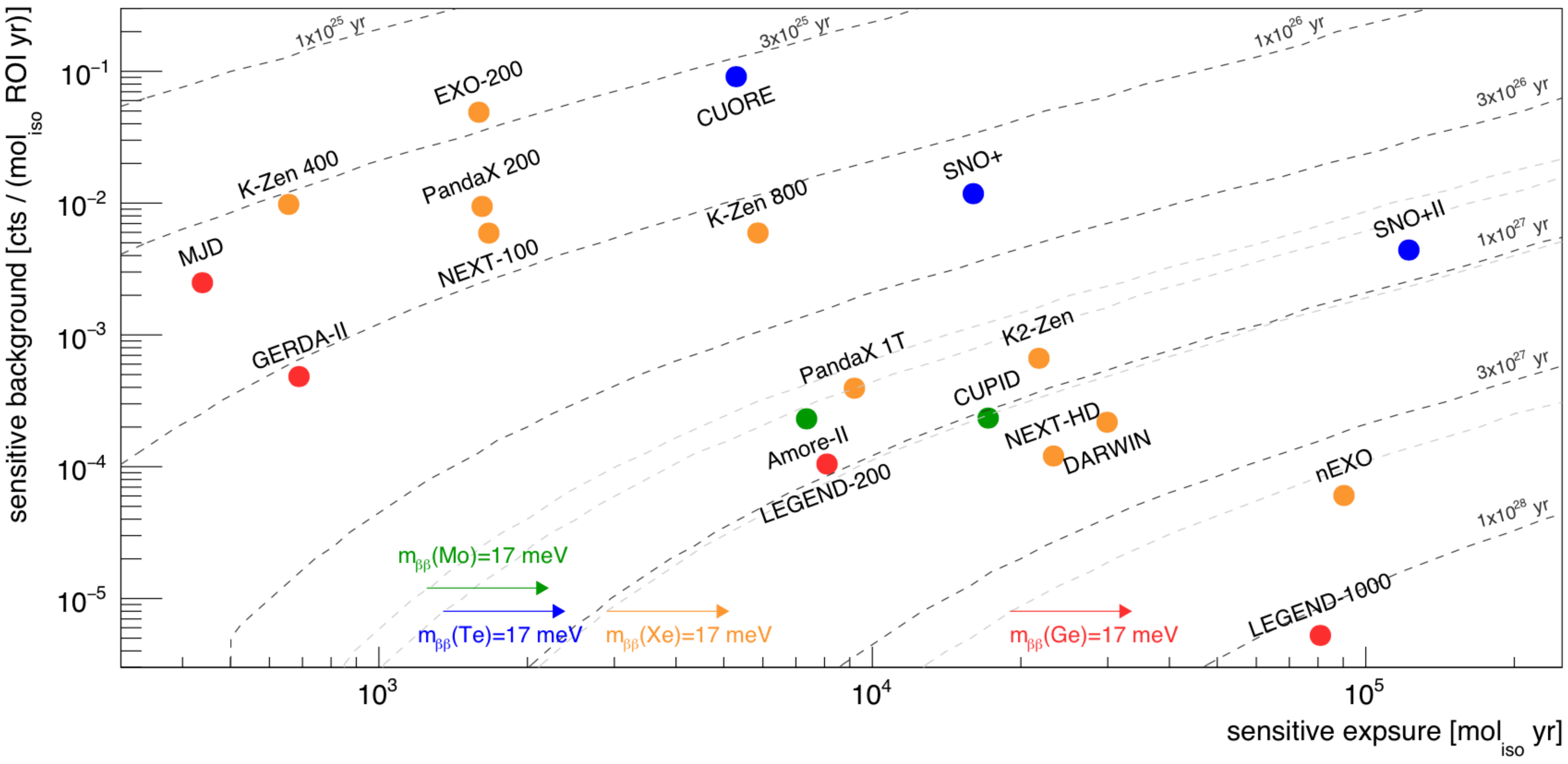
(Dated: September 24, 2021)

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.

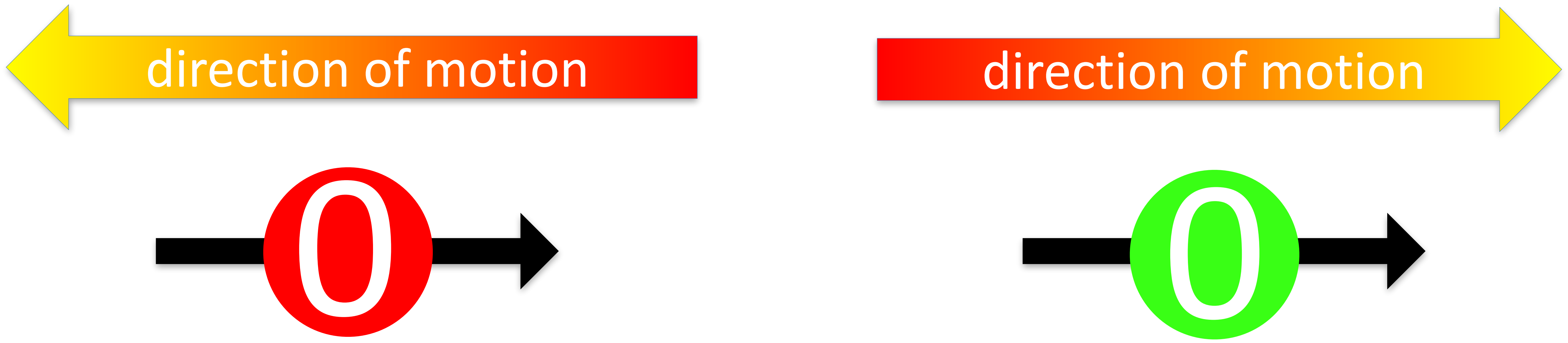




the link with neutrino mass

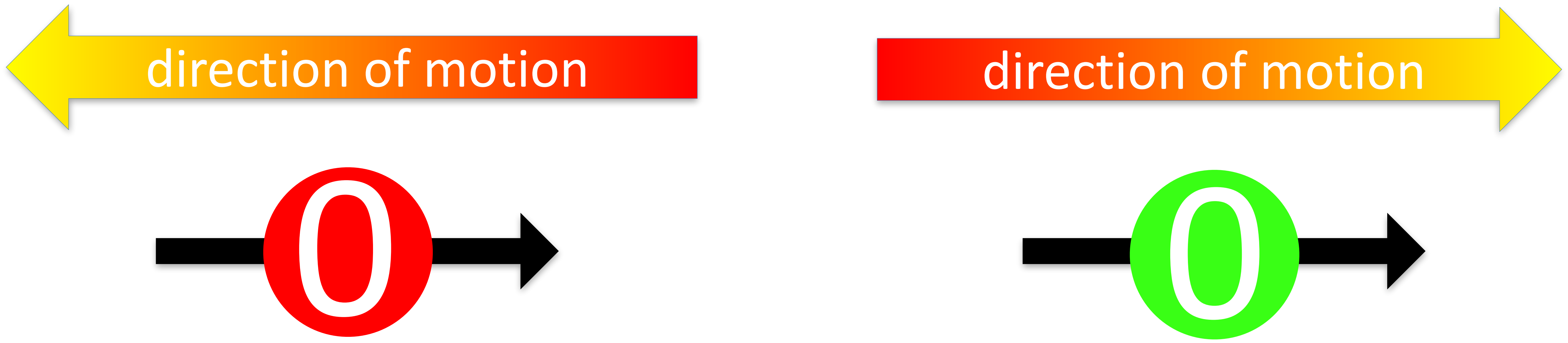
Majorana' mass and the structure of the standard model, how to test it with neutrinoless double beta decay / electron creation

the case for Majorana neutrinos

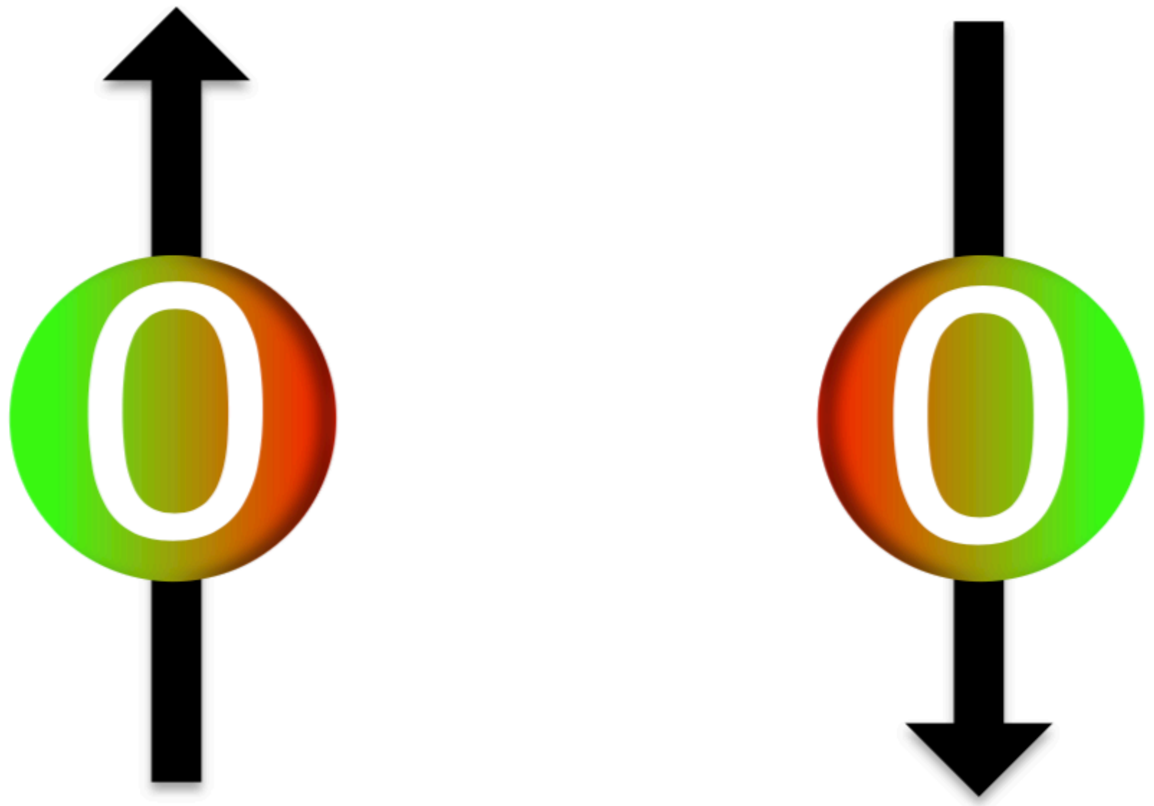


helicity tells neutrinos from antineutrinos

the case for Majorana neutrinos

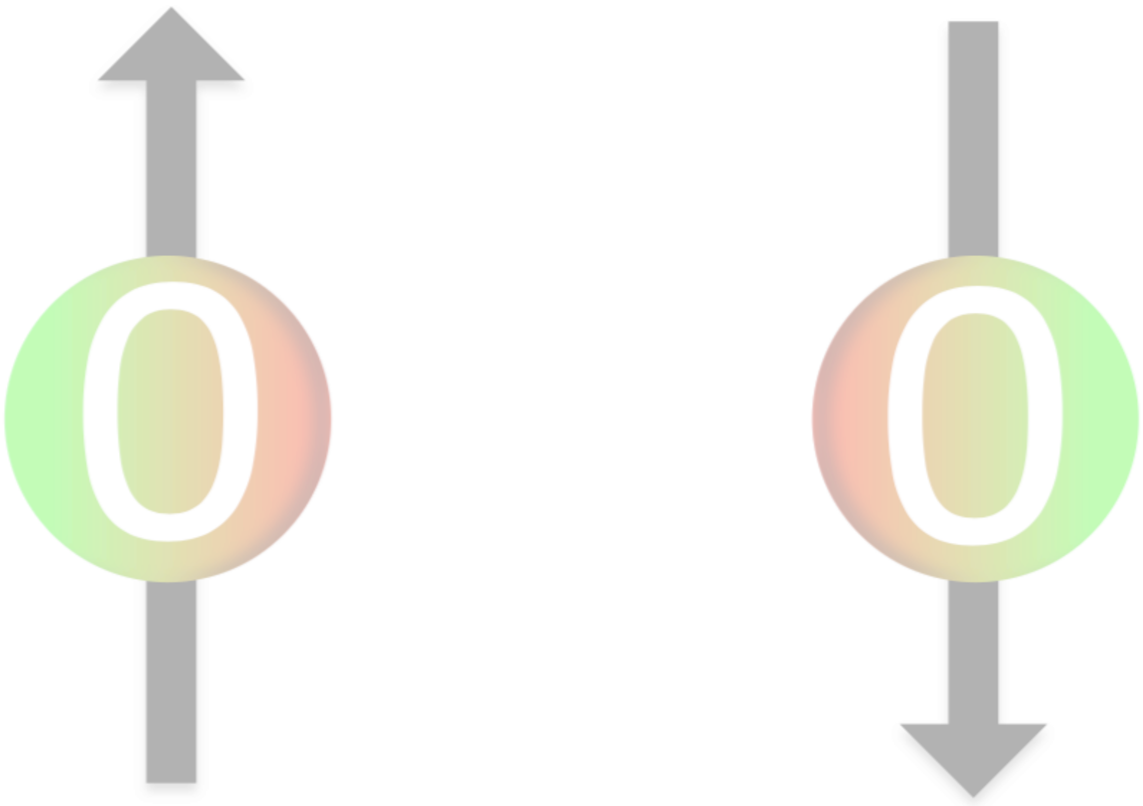


but in rest system that exists they look the same



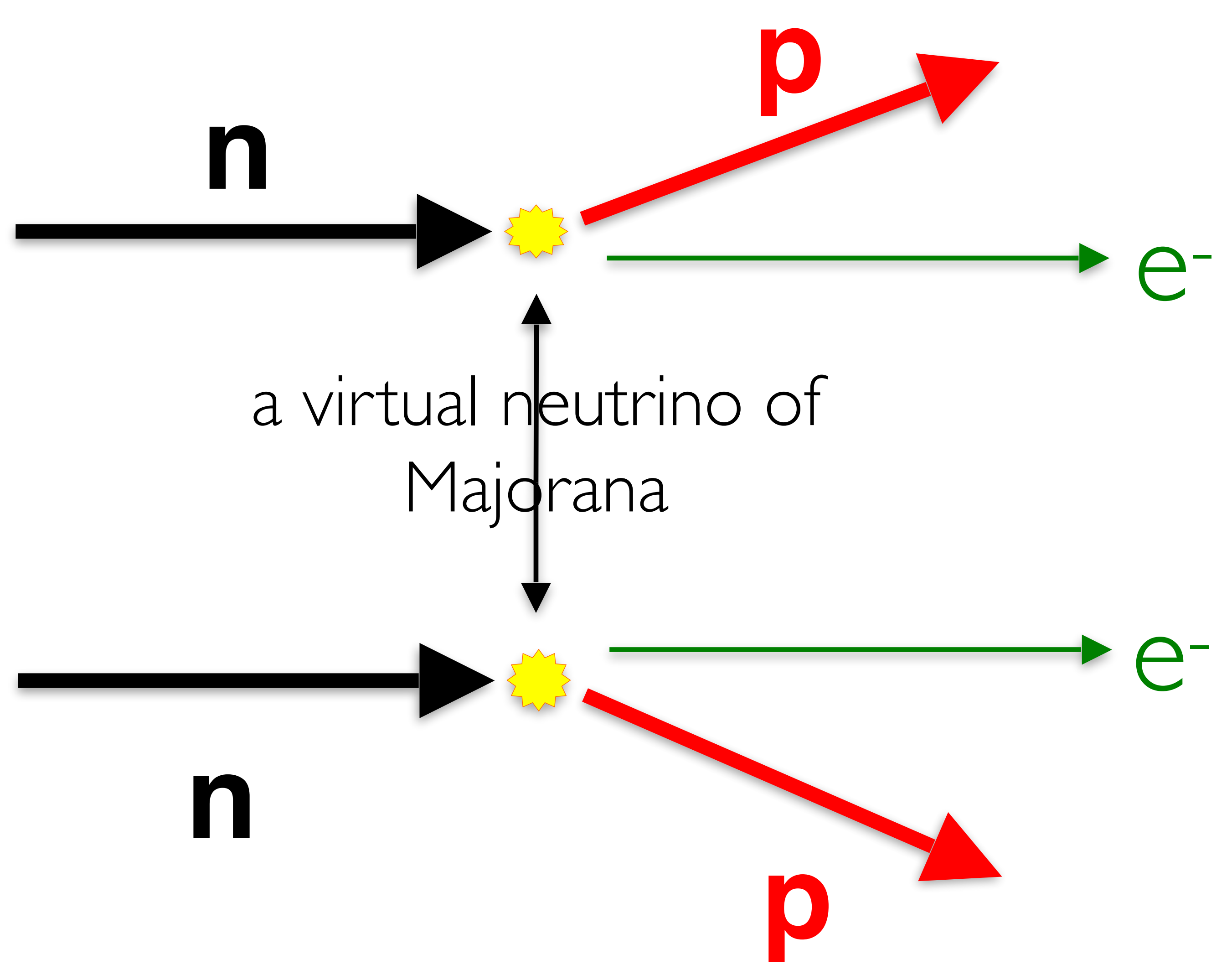
the case for Majorana neutrinos

hypothesis: neutrinos are matter & antimatter



Majorana's neutrinos enable electron creation

$2\,\mathbf{n} \rightarrow \quad 2\,\mathbf{p} + 2\,e^-$



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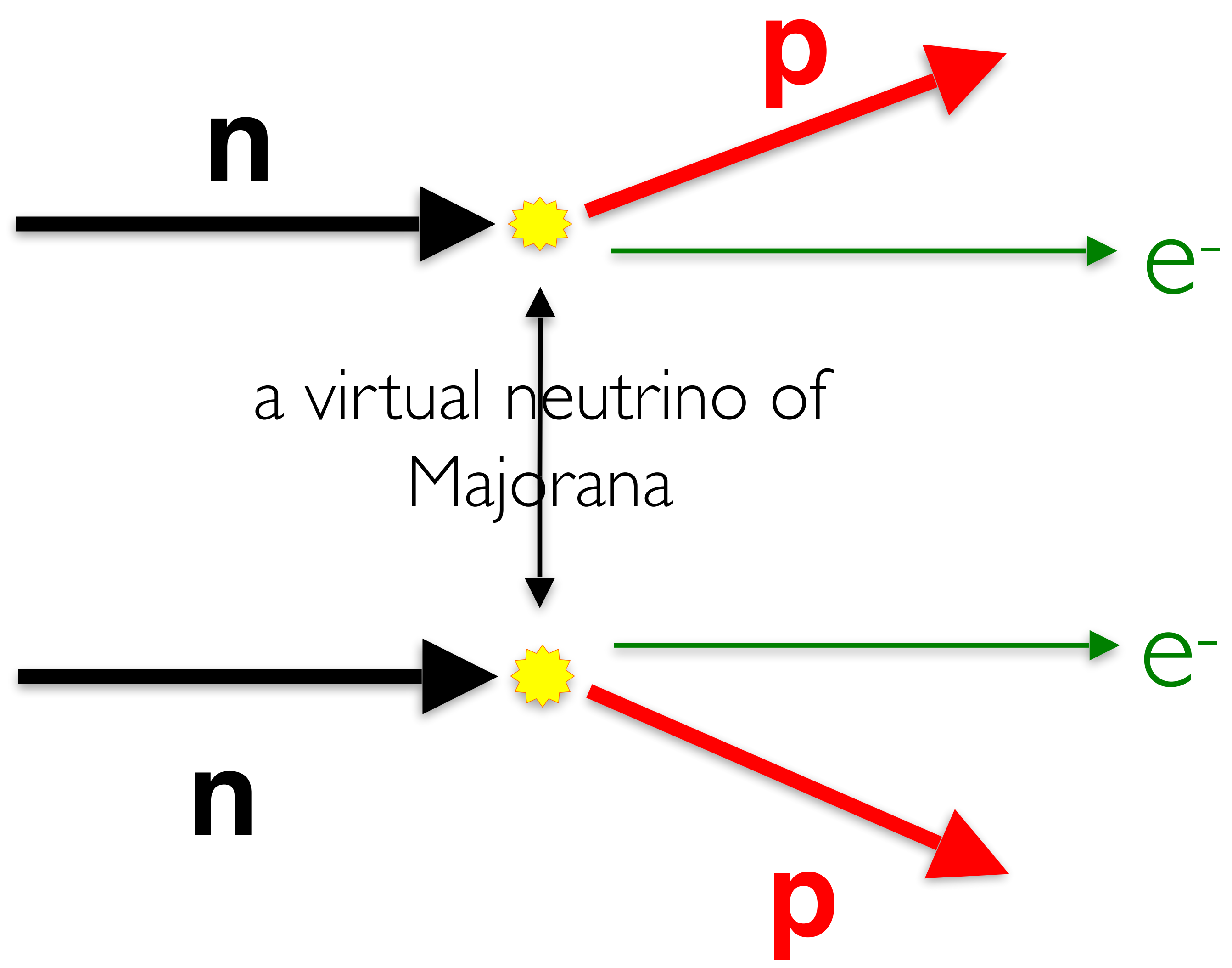
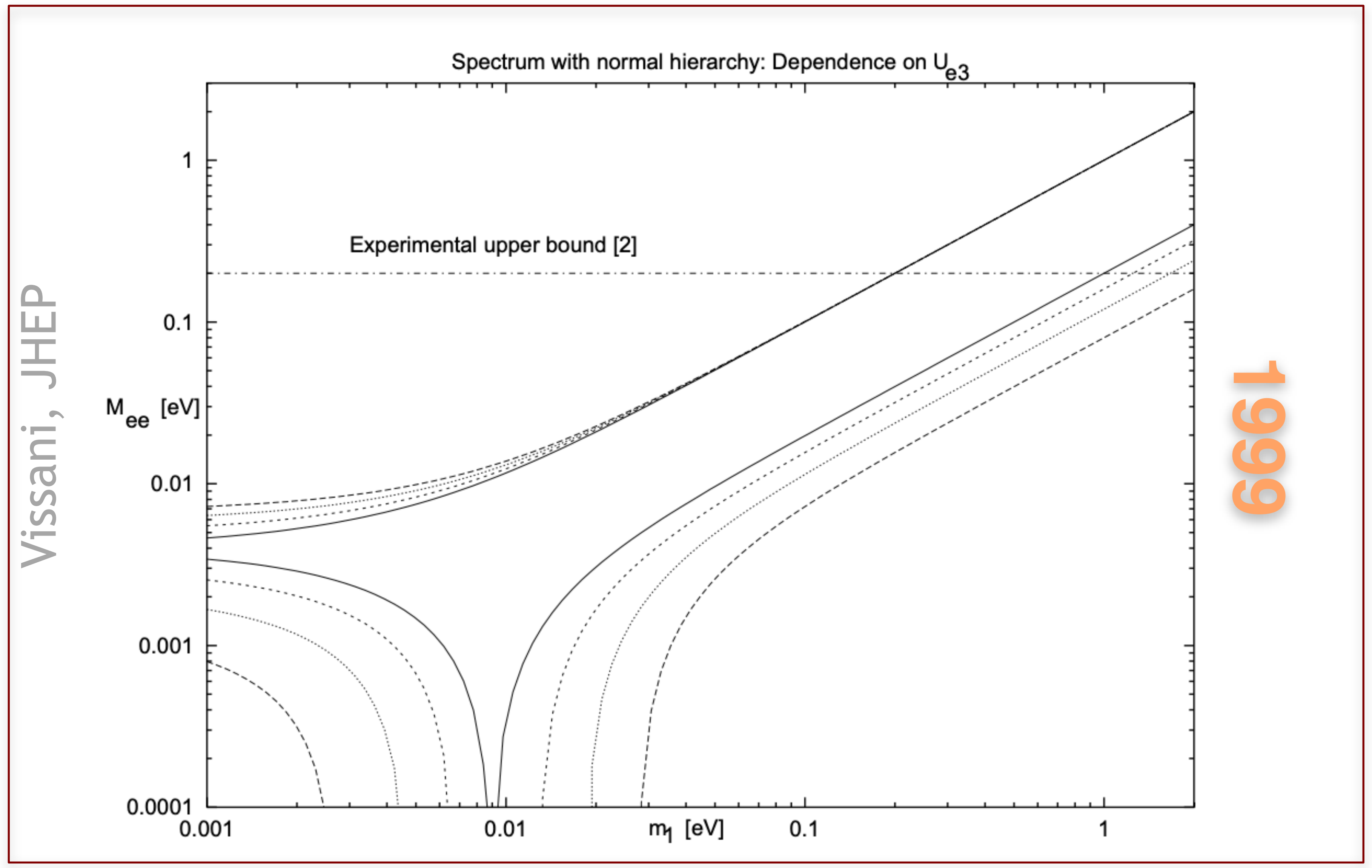
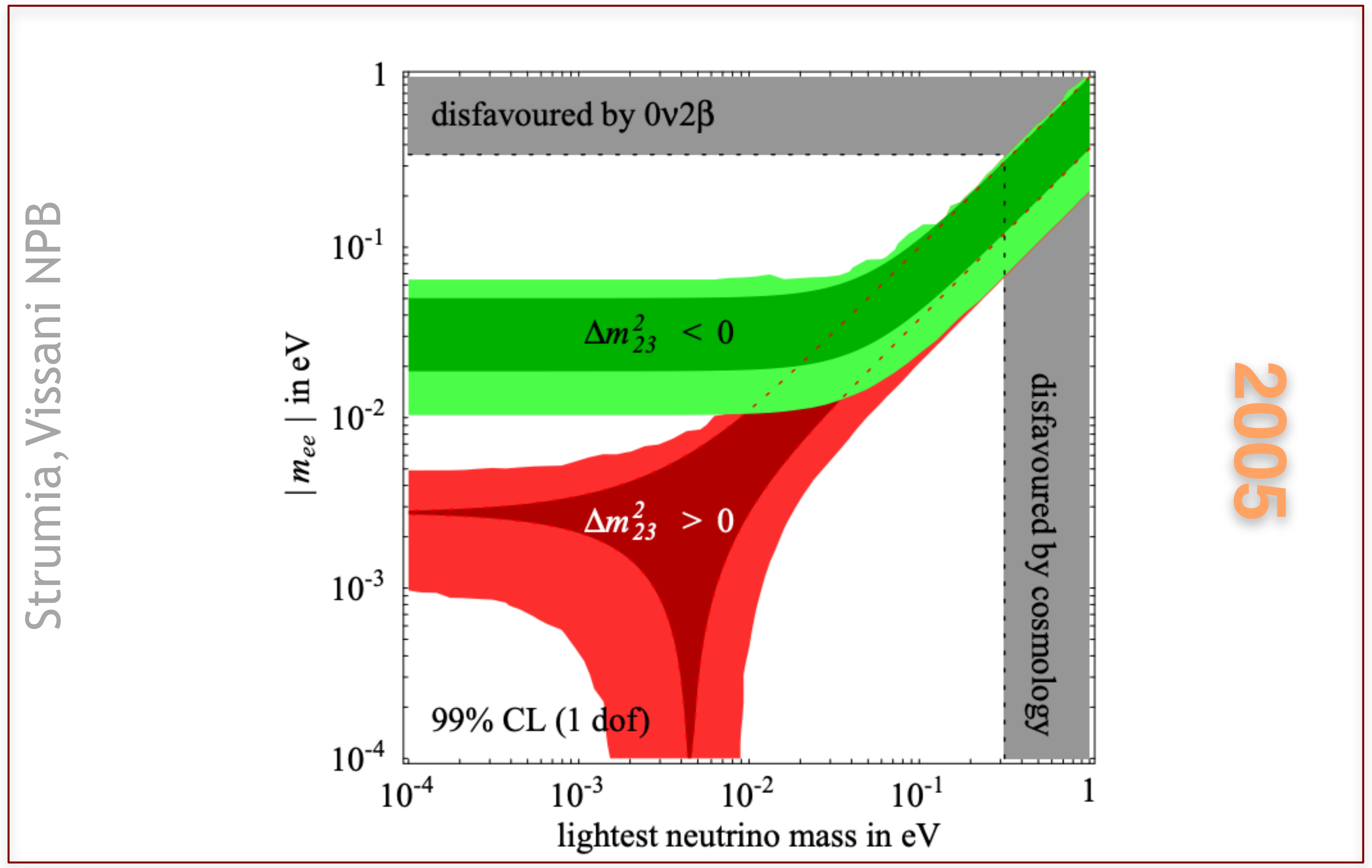
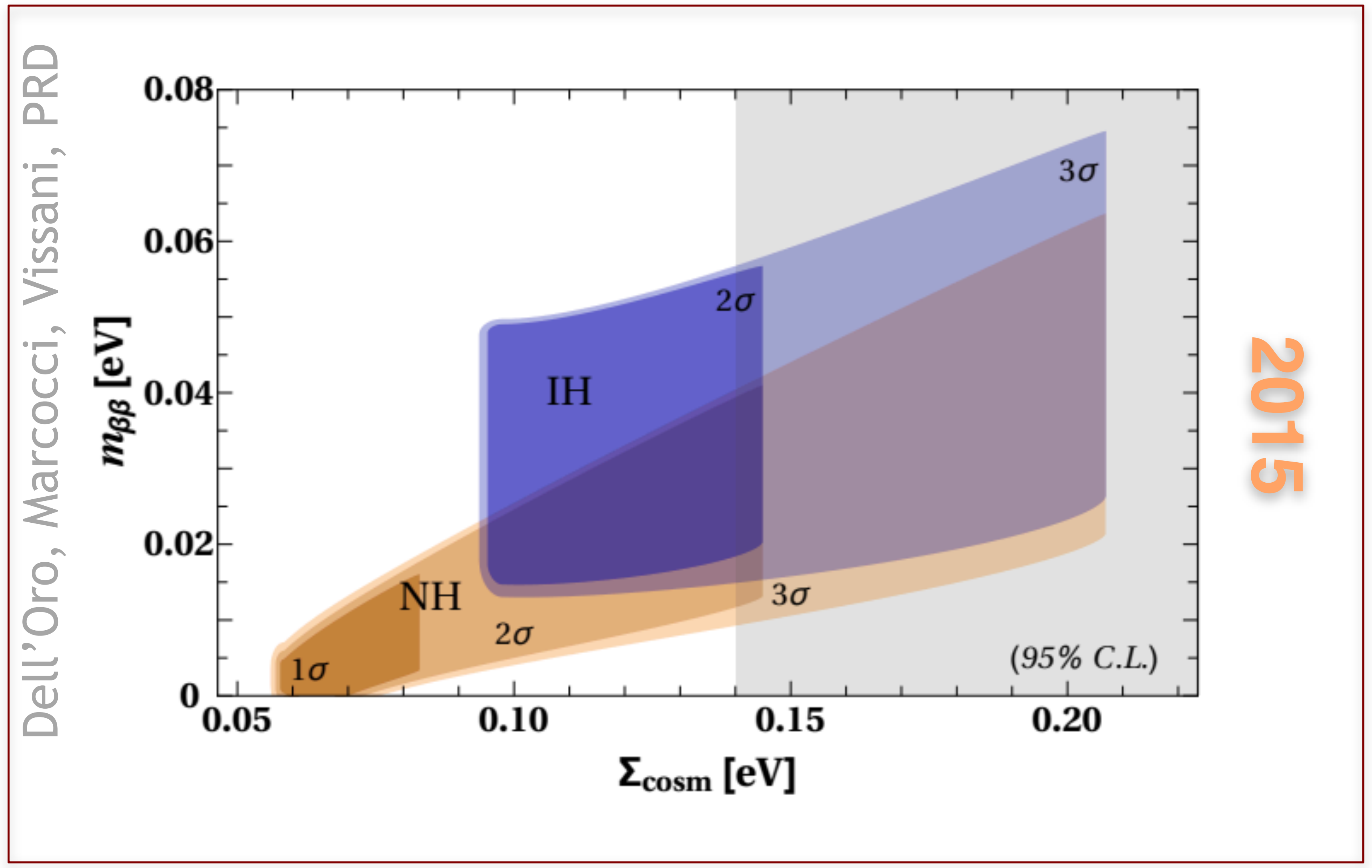


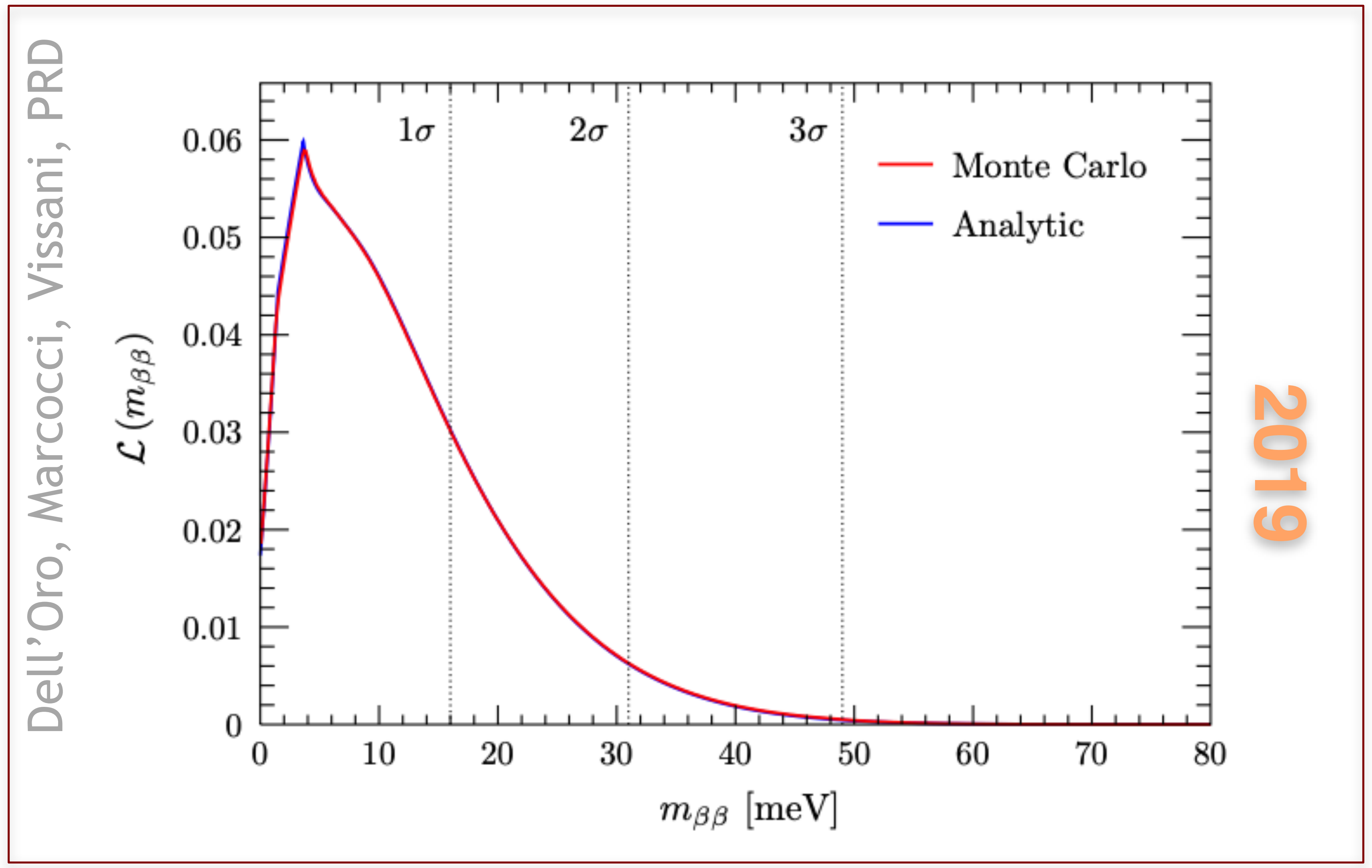
Neutrinos with Majorana mass are matter and antimatter, as seen in the system at rest. They can act as a **bridge** between matter and antimatter, in transformations whose amplitude is proportional to the neutrino mass

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.

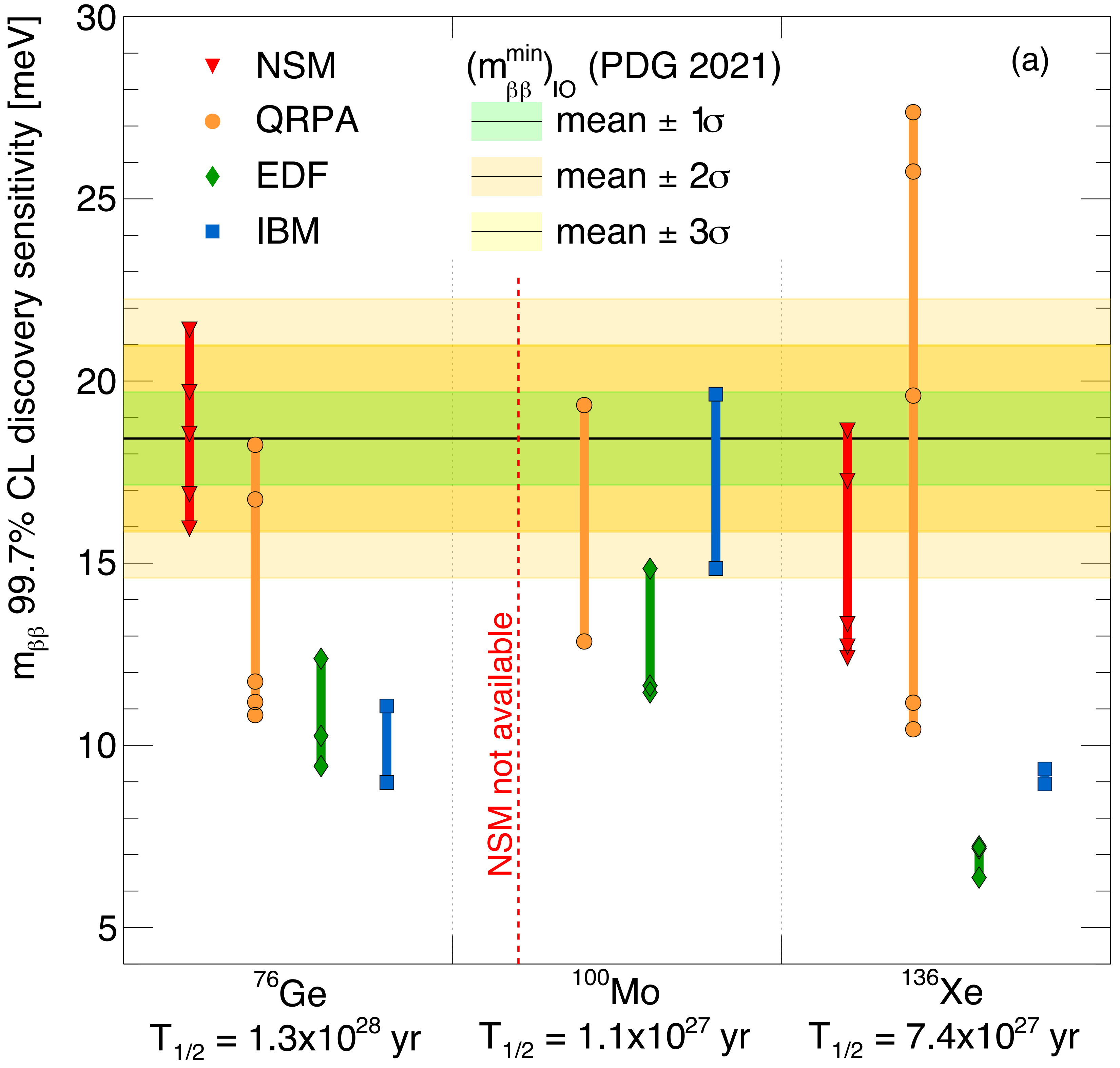

FIG. 1. Comparison of $m_{\beta\beta}$ 99.7%-CL discovery and 90%-CL median exclusion sensitivities for different isotopes at stated half-life sensitivities [30–32], grouped by nuclear many-body frameworks with matrix element ranges from Table I. The horizontal bands show the variation on $(m_{\beta\beta}^{min})_{\rm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

Discovery probabilities of Majorana neutrinos based on cosmological data

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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

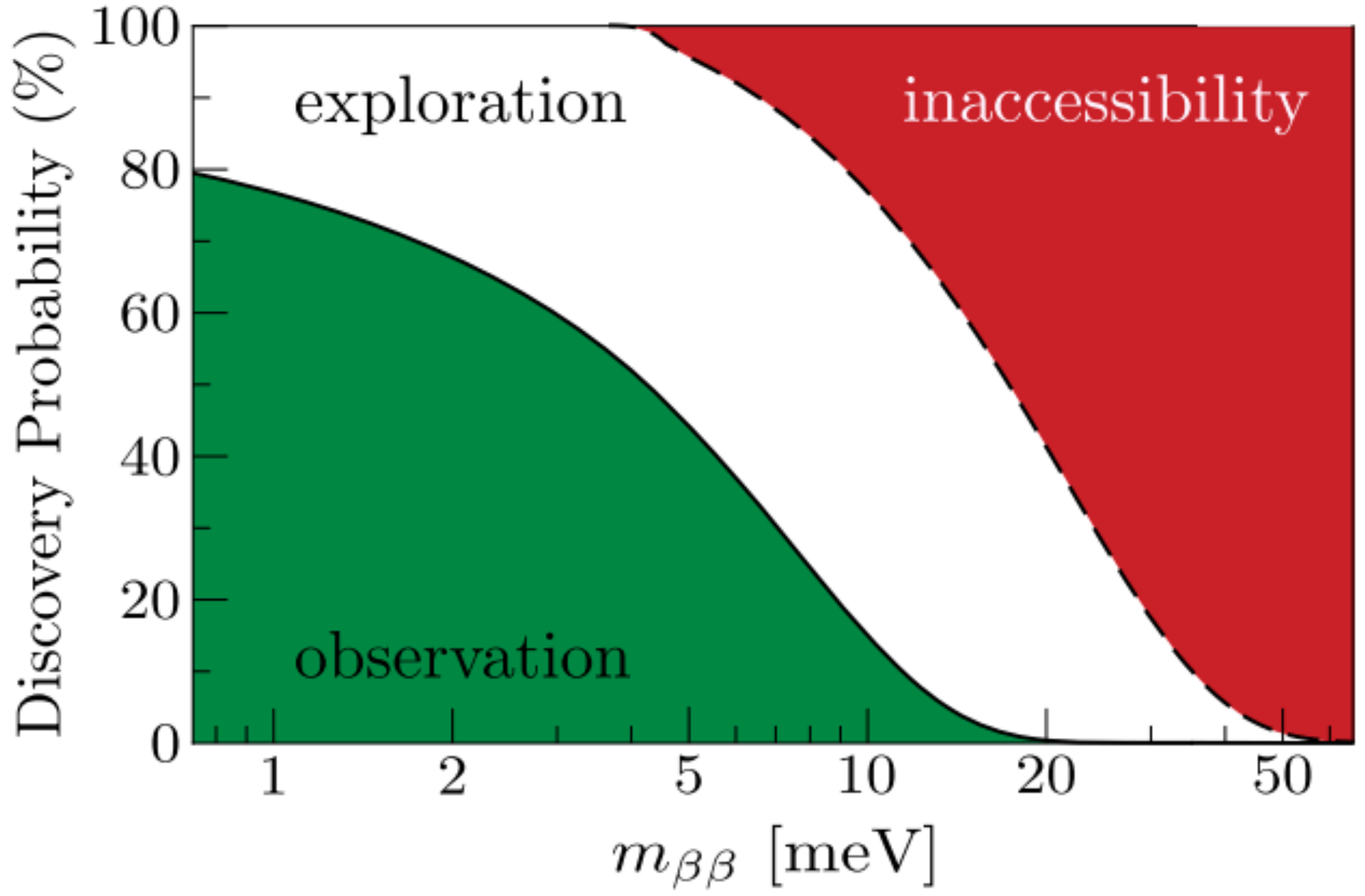
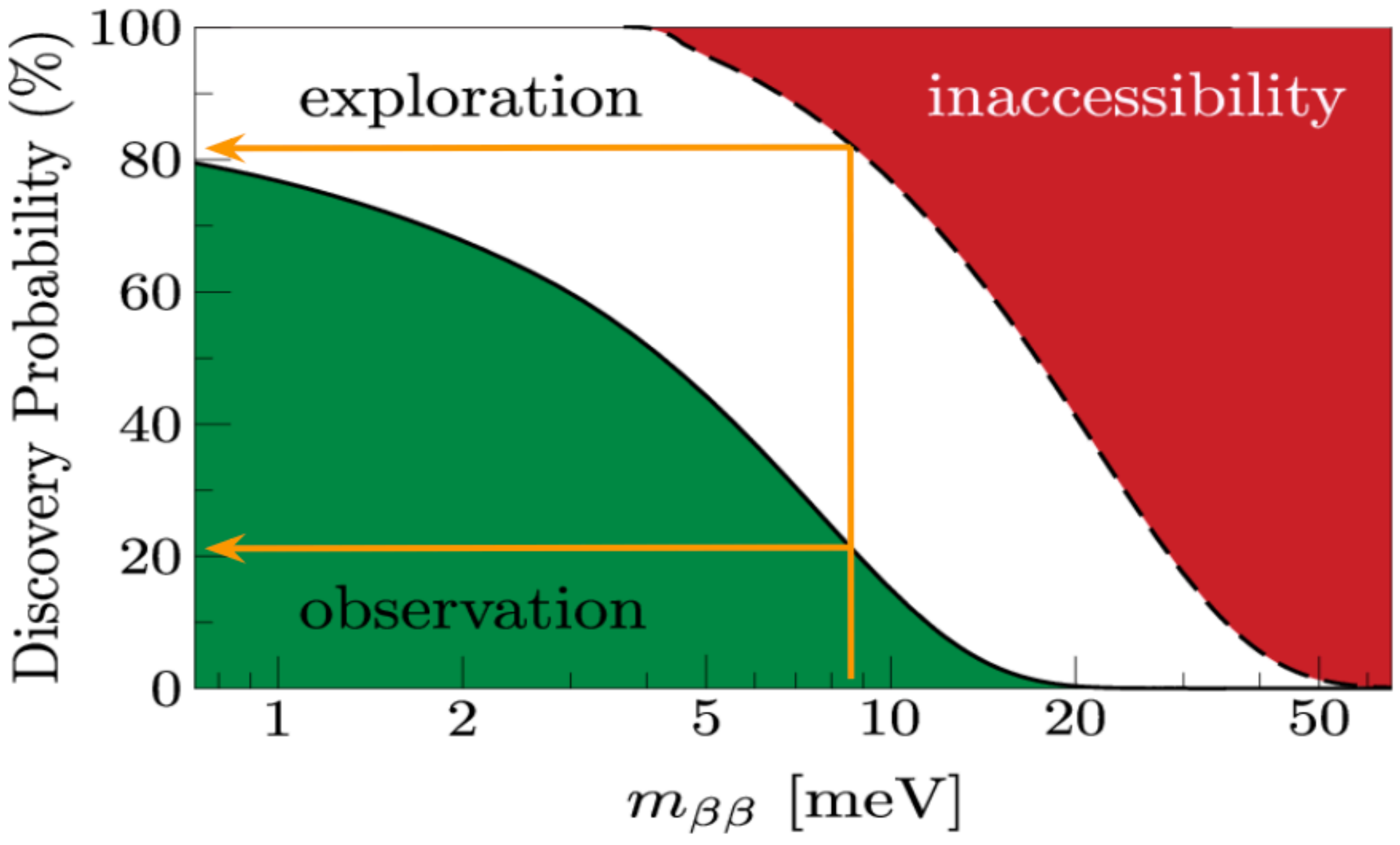


FIG. 2. Discovery probability as a function of the experimental sensitivities to $m_{\beta\beta}$ for the most unfavorable scenario (black solid line, $m_{\beta\beta}^{\text{min}}$) and the most favorable one (black dashed line, $m_{\beta\beta}^{\text{max}}$). The colored areas express the probability 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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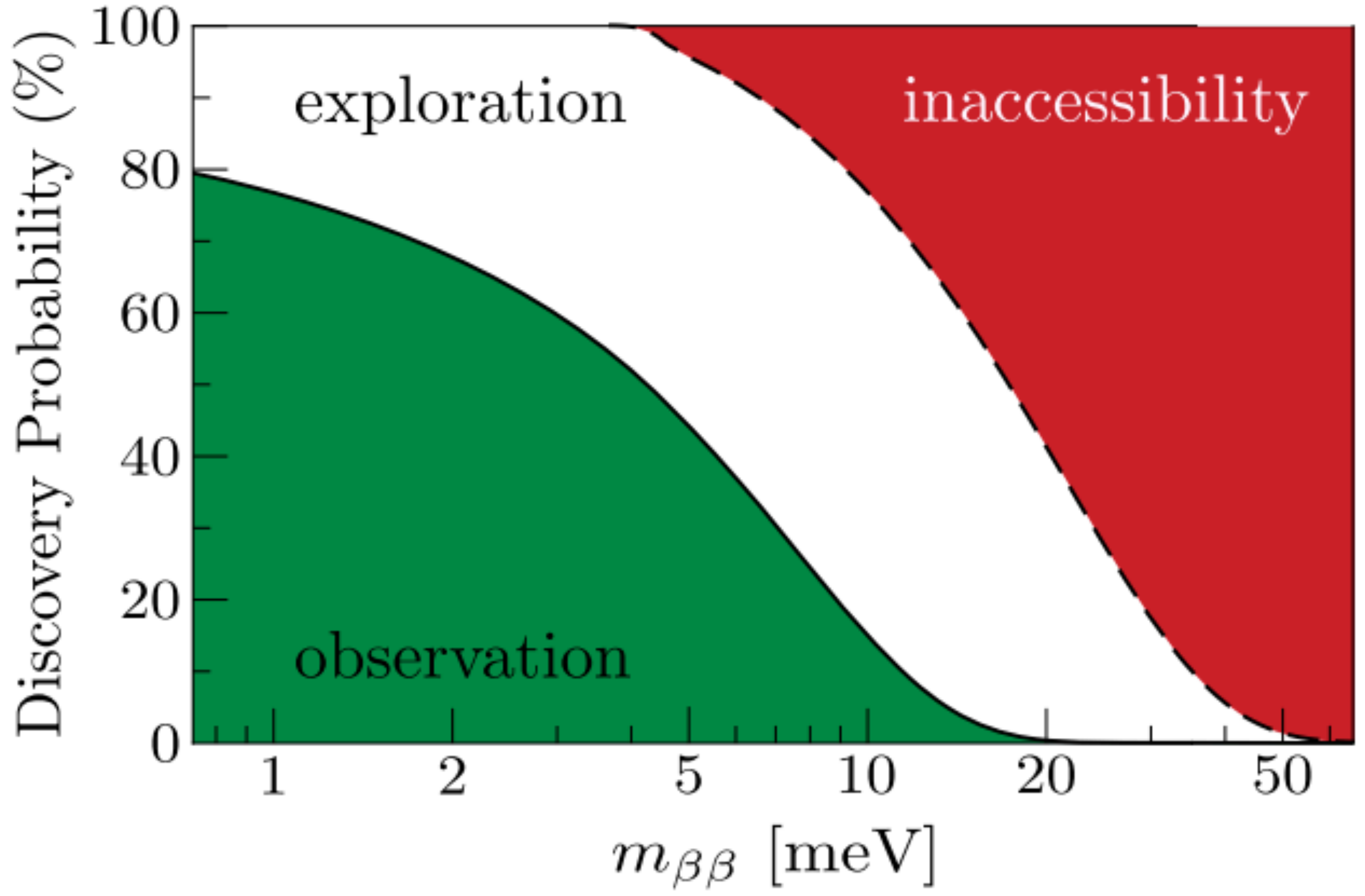
since Planck 2015 findings, this is the most sensitive probe of absolute neutrino masses, and the best chance of measuring them in the future



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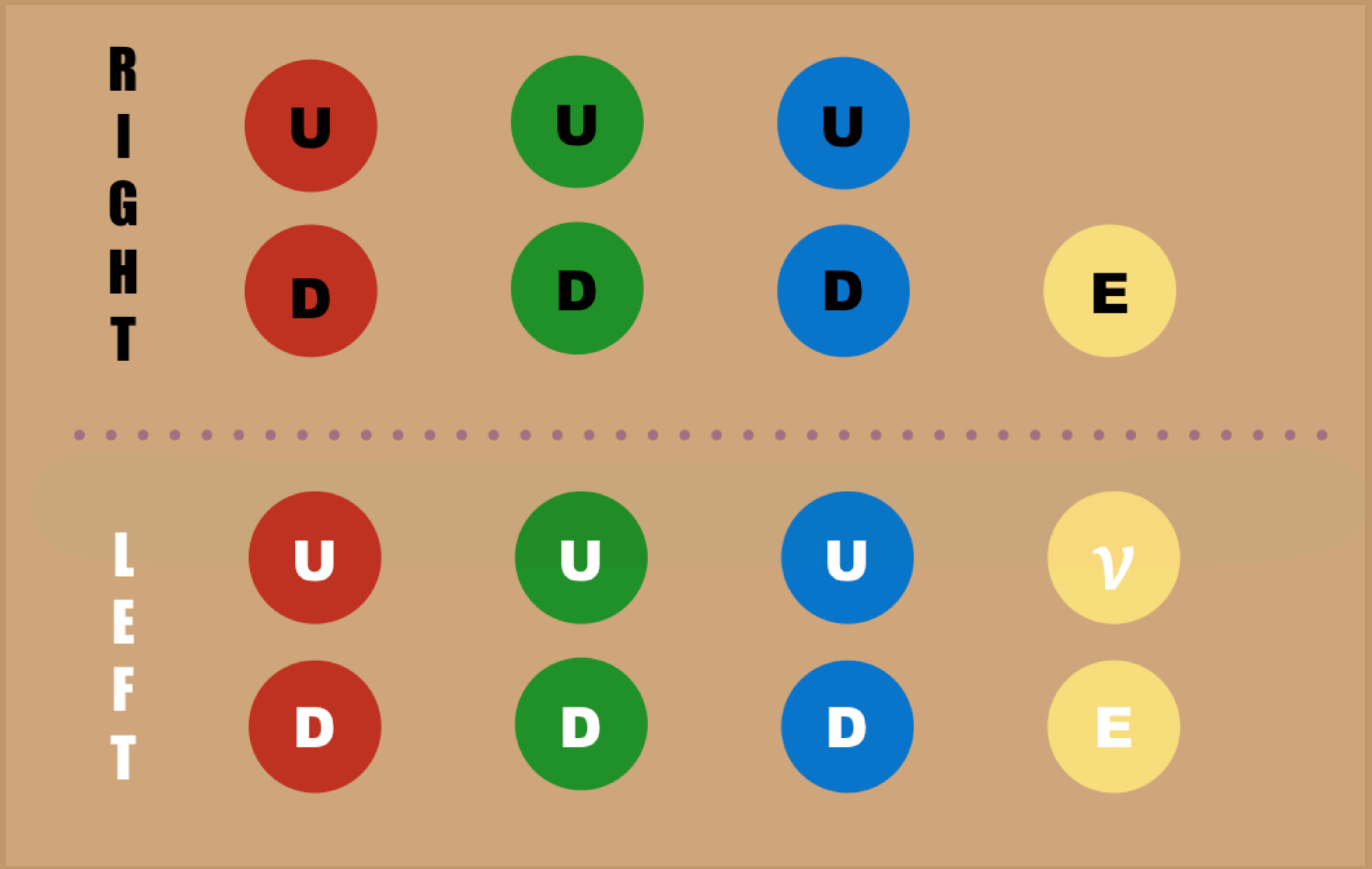
significance and perspectives

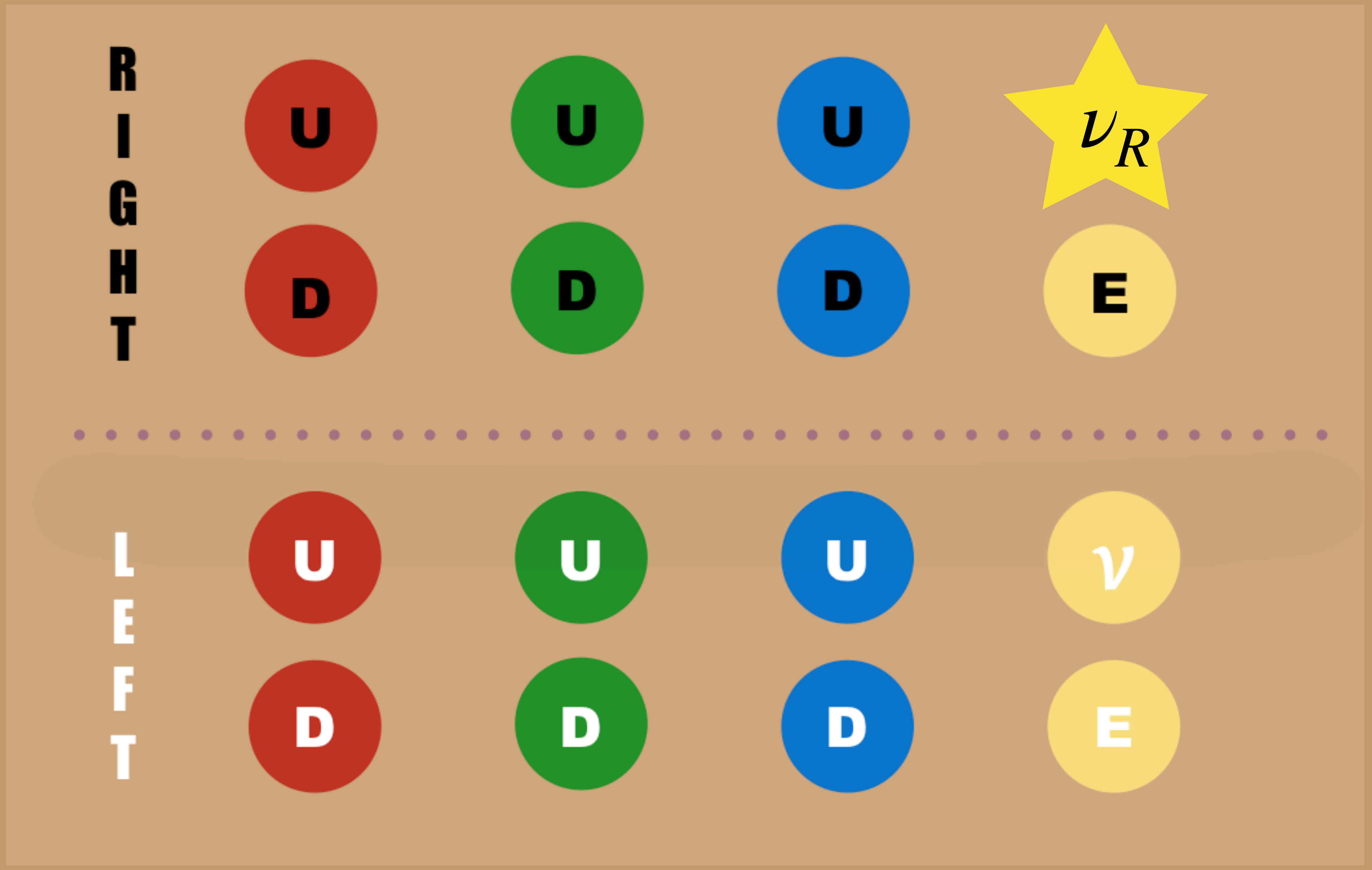
extended gauge models / grand unification; heavy neutrinos; something else?



this diagram depicts more accurately which are
the particles of the standard model in each family

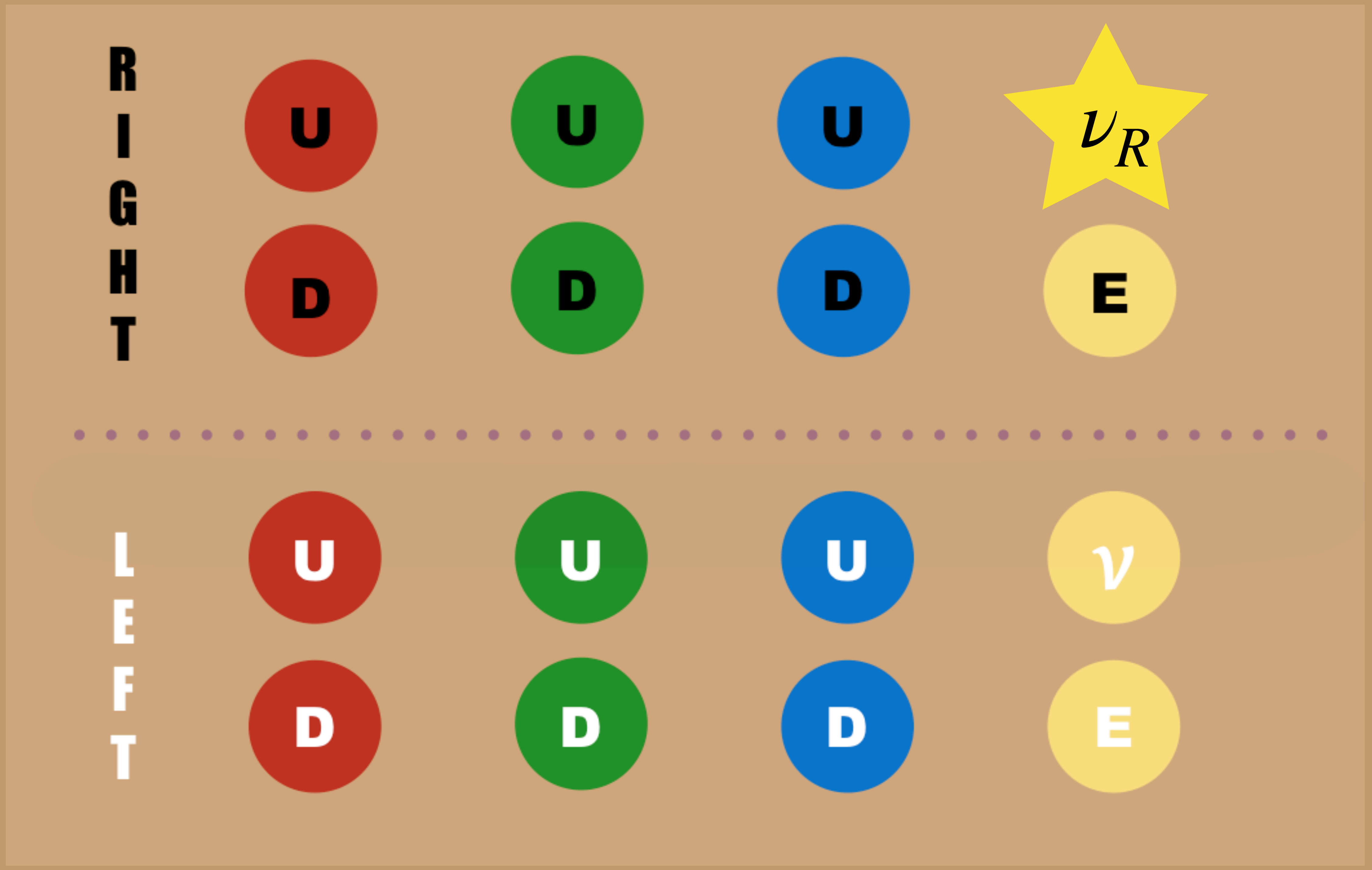
this new representation highlights
a significant asymmetry concerning neutrinos

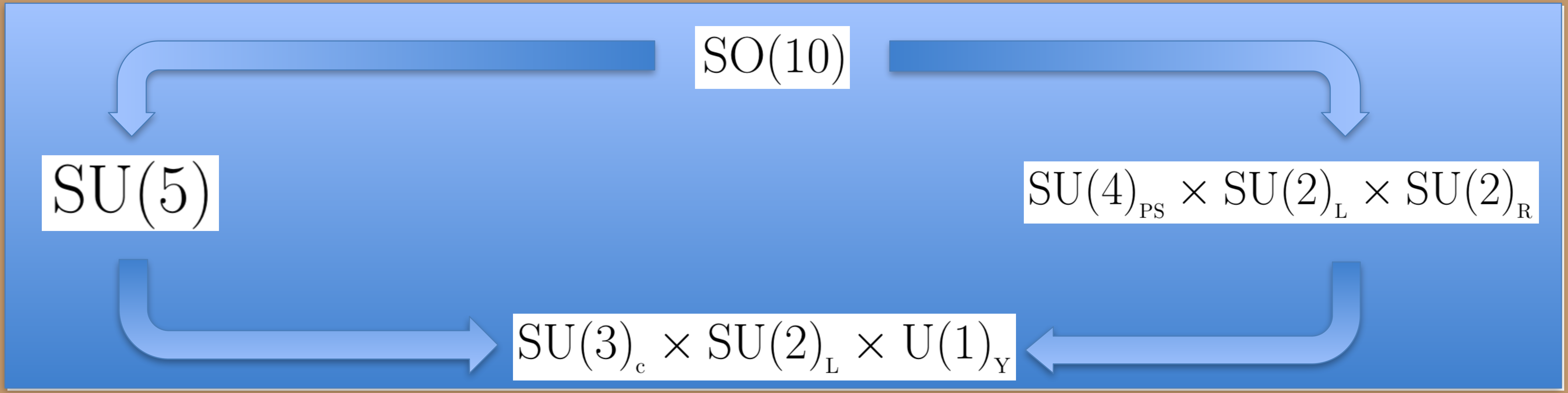
Glashow 1961; Weinberg 1967; Salam 1967; Gross & Wilczek 1973; Politzer 1973



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

Mohapatra & Pati 1975; Senjanovic & Mohapatra 1975





Georgi & Glashow 1974; Pati & Salam 1974; Georgi 1975; Fritzsch & Minkowski 1975

on the mass scale of heavy neutrinos

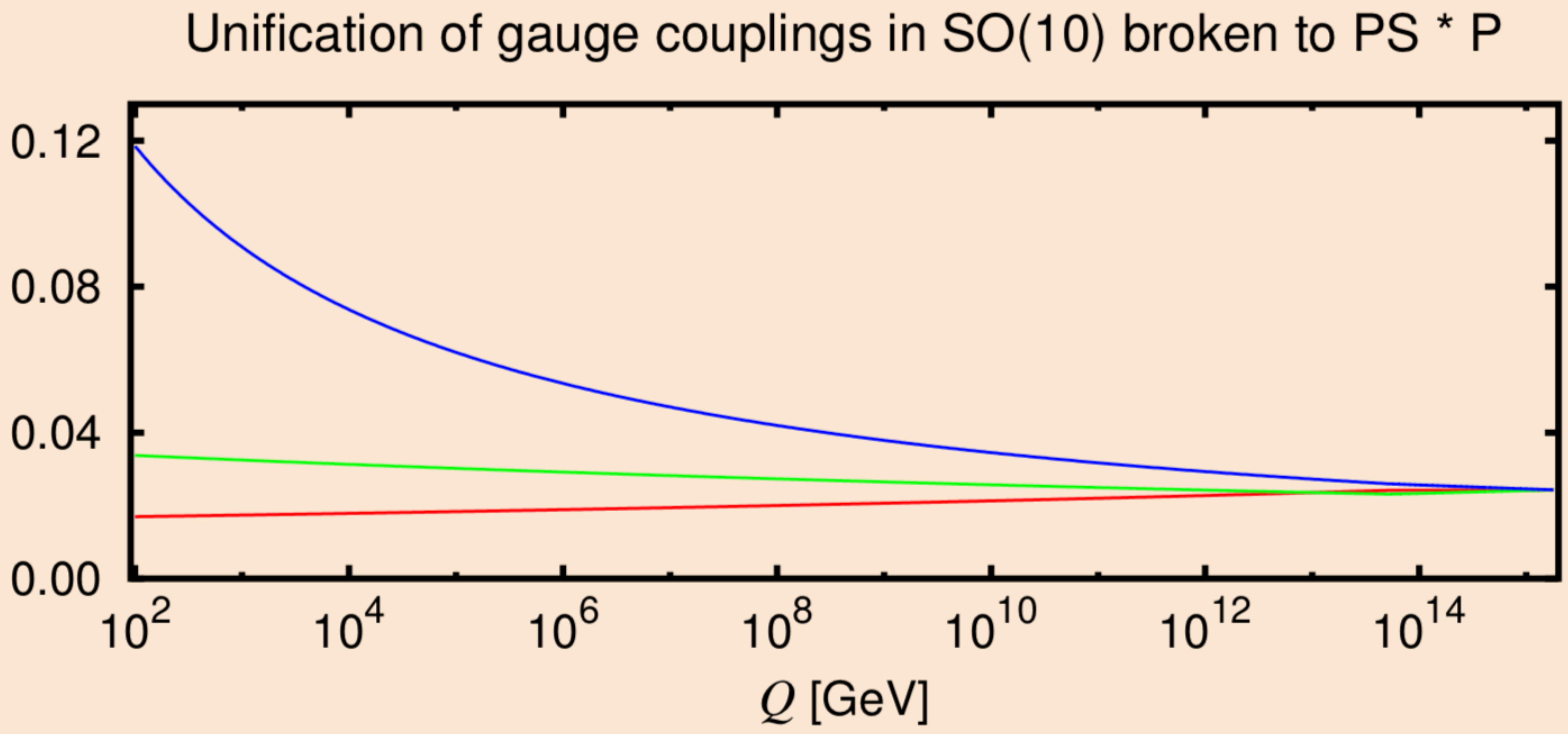
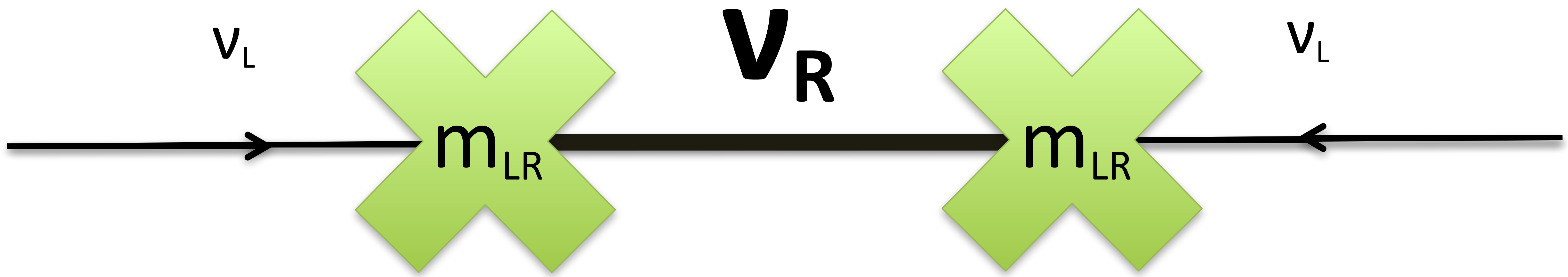


Figure 2: Evolution of the gauge coupling constants in a GUT model with intermediate scale. Here, $M_{\text{interm.}} \approx 5 \times 10^{13}$ GeV.

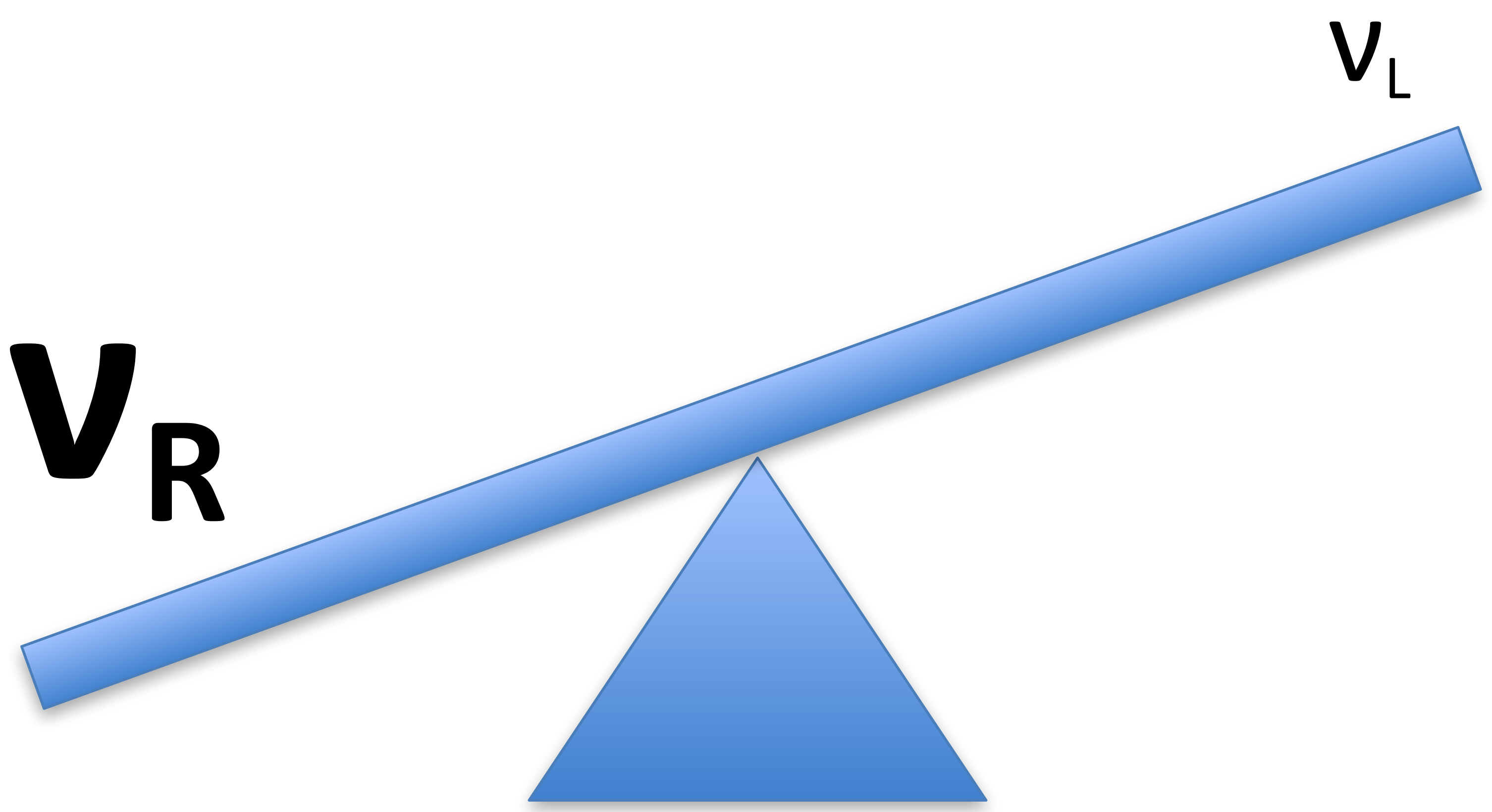
FV at the Cryodet meeting at Gran Sasso lab (2006) if the new neutrinos ν_R are heavy enough, the ordinary ones take on a small mass, just as we observe



$$\frac{1}{m_{RR}}$$

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

this is called “seesaw”



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

a plausible scenario for baryogenesis

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

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

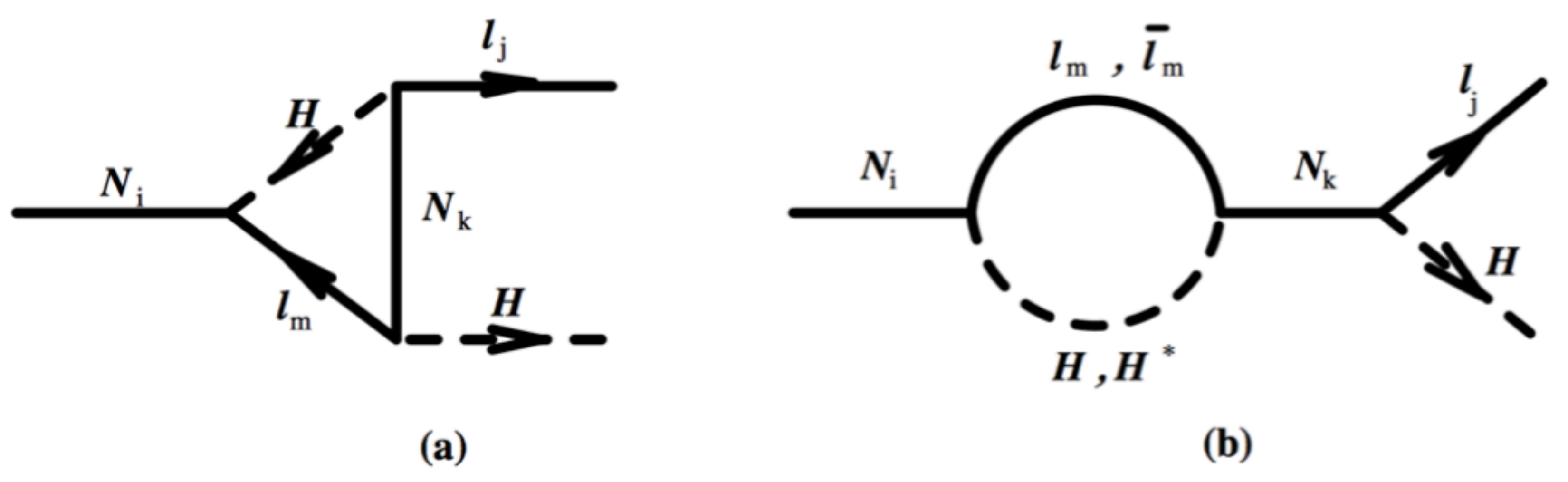


Figure 1: Diagrams contributing to the vertex (Fig. 1a) and wave function (Fig. 1b) CP violation in the heavy singlet neutrino decay.

Covi et al. '96

a plausible scenario for baryogenesis

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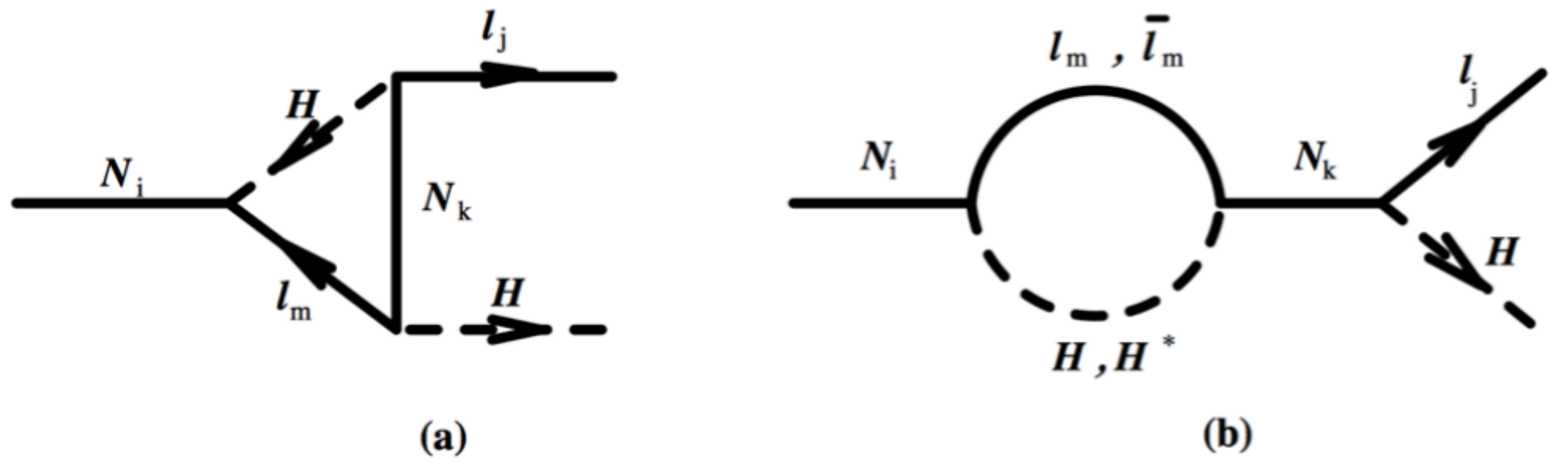
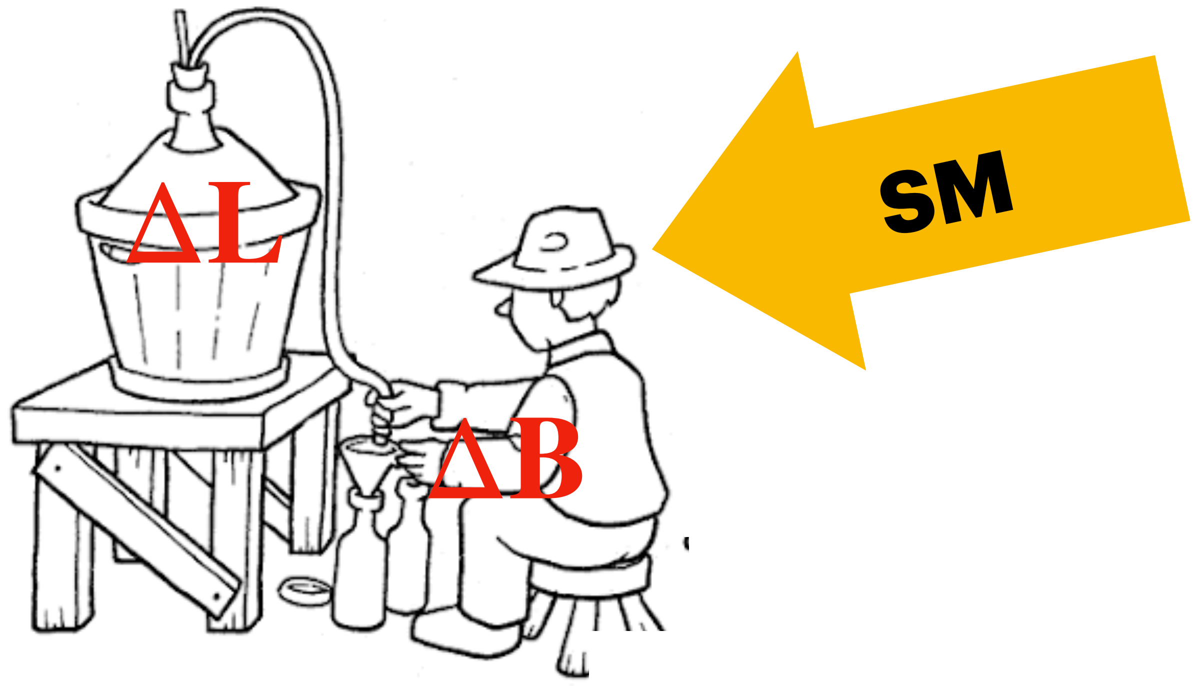


Figure 1: Diagrams contributing to the vertex (Fig. 1a) and wave function (Fig. 1b) CP violation in the heavy singlet neutrino decay.

Covi et al. '96

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



discussion: from the minimalistic outlook...

Grand unified (gauge) models suggest that ν_R masses are heavy, far from electroweak scale, which controls SM fermion masses instead. This is called the "great desert" scenario.

Ordinary neutrino masses would have Majorana nature. This would be a **unique experimental test** of physics beyond SM.

Potential to explain baryogenesis and proton decay.

Key remark: in this case, the particle spectrum would be just that of the SM.

…to more exciting prospects

We may be close to observing particles beyond the SM, that could be the reason for anomalies, such as g-2, W mass, b-physics… or "dark matter". Fun times are back?

How to proceed? Acquire new facts and harmonize them with caution.

Certainly, neutrino masses remain an important acquired fact, still worthy of investigation, and a valuable test bed for theories beyond the SM.

E.g.: the direct correlation of the decay rate of $2\mathrm{n} \to 2\mathrm{p} + 2\mathrm{e}$ and absolute neutrino mass scale holds if **L** is violated only at ultra-high scale. This might be not the case.

to conclude, a few thoughts on:
how important is it to probe B and L?

from 1979 Nobel lectures for the standard model

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.

thanks for your attention!

questions

Question-1

Sotiris Loucatos

What is the ν_R good for? Can it be dark matter?

This depends on the type of ν_R we are discussing. In the grand unified option emphasised above, ν_Rs are heavy and unstable, since their Yukawa couplings are similar to those of up quarks (within an order of magnitude) even though they can leave a significant footprint in the cosmos - baryonic asymmetry.

If one abandons this theoretical framework, it is possible to adjust the parameters to allow the three ν_Rs to play the role of dark matter (of a few keV) and also ensure a different form of leptogenesis. This possibility has been emphasized by Shaposhnikov and co-workers; its drawback is that it is difficult or impossible to reconcile with principled (grand unified gauge) models.

Question-2

Adrien Blanchet

What should we measure to test the ν_R hypothesis? In particular what is the connection with leptonic CP violation that we can measure?

It is not possible to measure the parameters of ν_R directly, if the particles are very heavy, as with the models I have emphasized in most of the talk.

The connection to the low-energy CP violation depends on the model. A proper evaluation requires the formulation of a complete theory that extends and replaces the standard model, including at least neutrino masses, but possibly also dark matter particles.

However, based on similar considerations (i.e., baryogenesis) the importance of measuring hadronic CP violation was widely recognized when meson factories were proposed; the leptonic CP violation is at least as important, and probably more so.

Question-3

Sara Bolognesi

How gauge coupling unification works with new particles?

The example I showed assumes the existence of new particles, which appear in the "Pati-Salam" model based on the gauge symmetry $\mathrm{SU}(4)_c \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{P}$ *. This possibility is appealing as it gives a reasons why ordinary neutrinos are light, and* $\mathrm{SO}(10)$ *is undeniably an interesting option.*

A much better known example is based on the assumption that near to electroweak scale, supersymmetry becomes manifest.

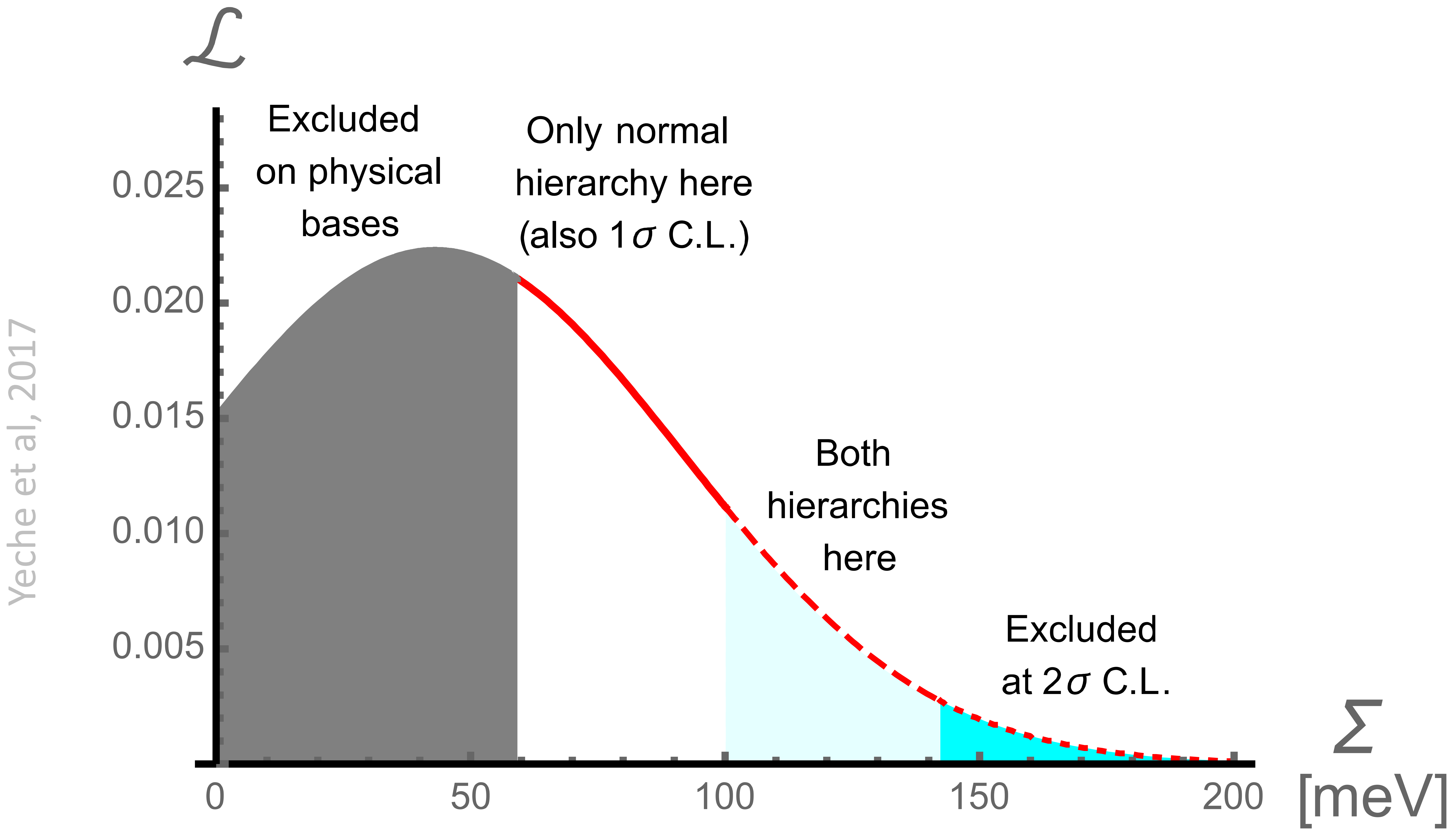
These are not the only possibilities; and unfortunately we have little information to decide if any of these are the correct ones.

spare slides

contents

- cosmological constraints on neutrino masses
- remarks on the terminology (hierarchy, spectrum and ordering)
- more on neutrinoless double beta decay
- evolution of the theory of mass
- fermions in grand unified models
- effective operators
- heavy neutrinos and "naturalness"

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

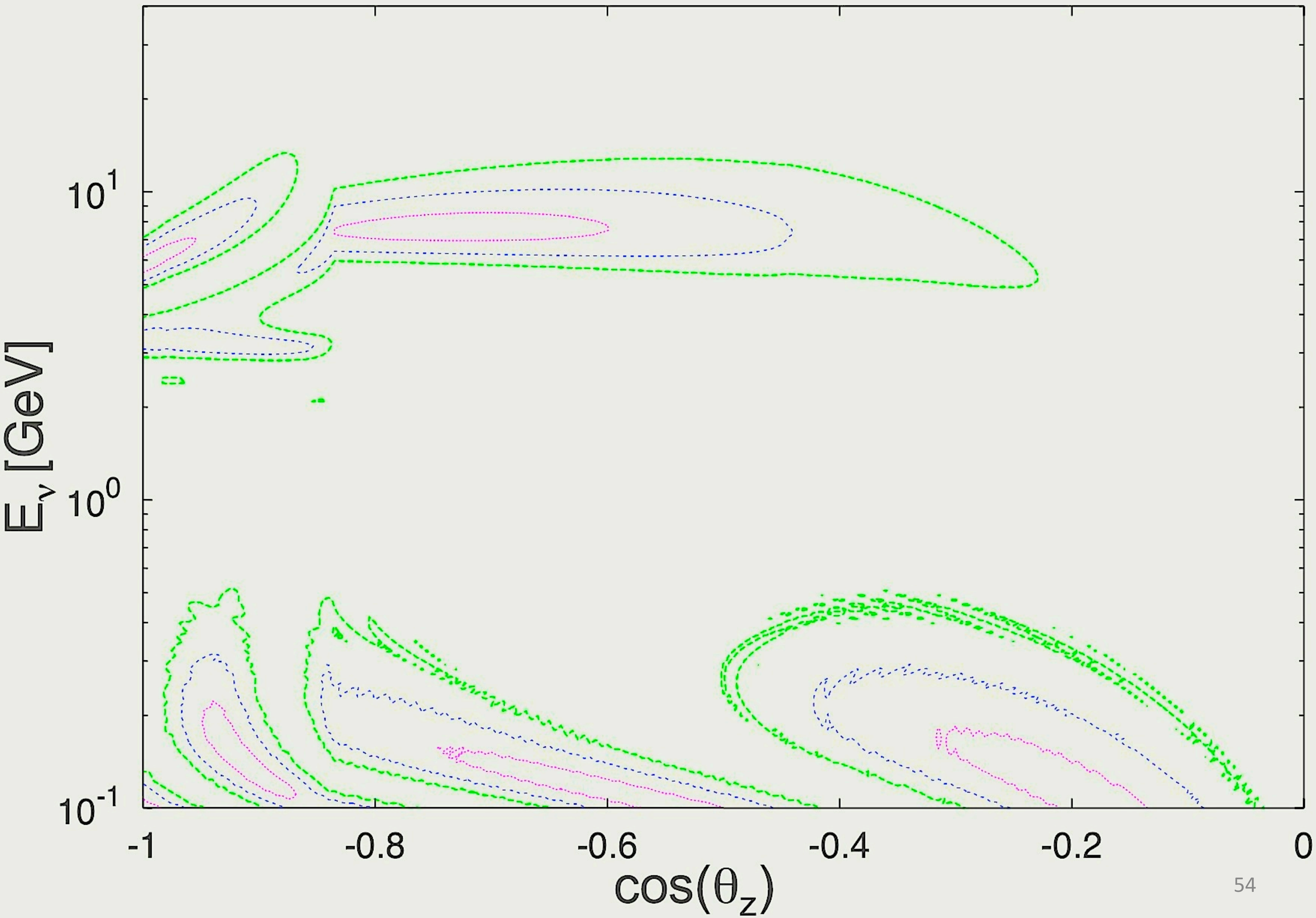


on modern terminology

NH→NO

Normal hierarchy → Normal ordering

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

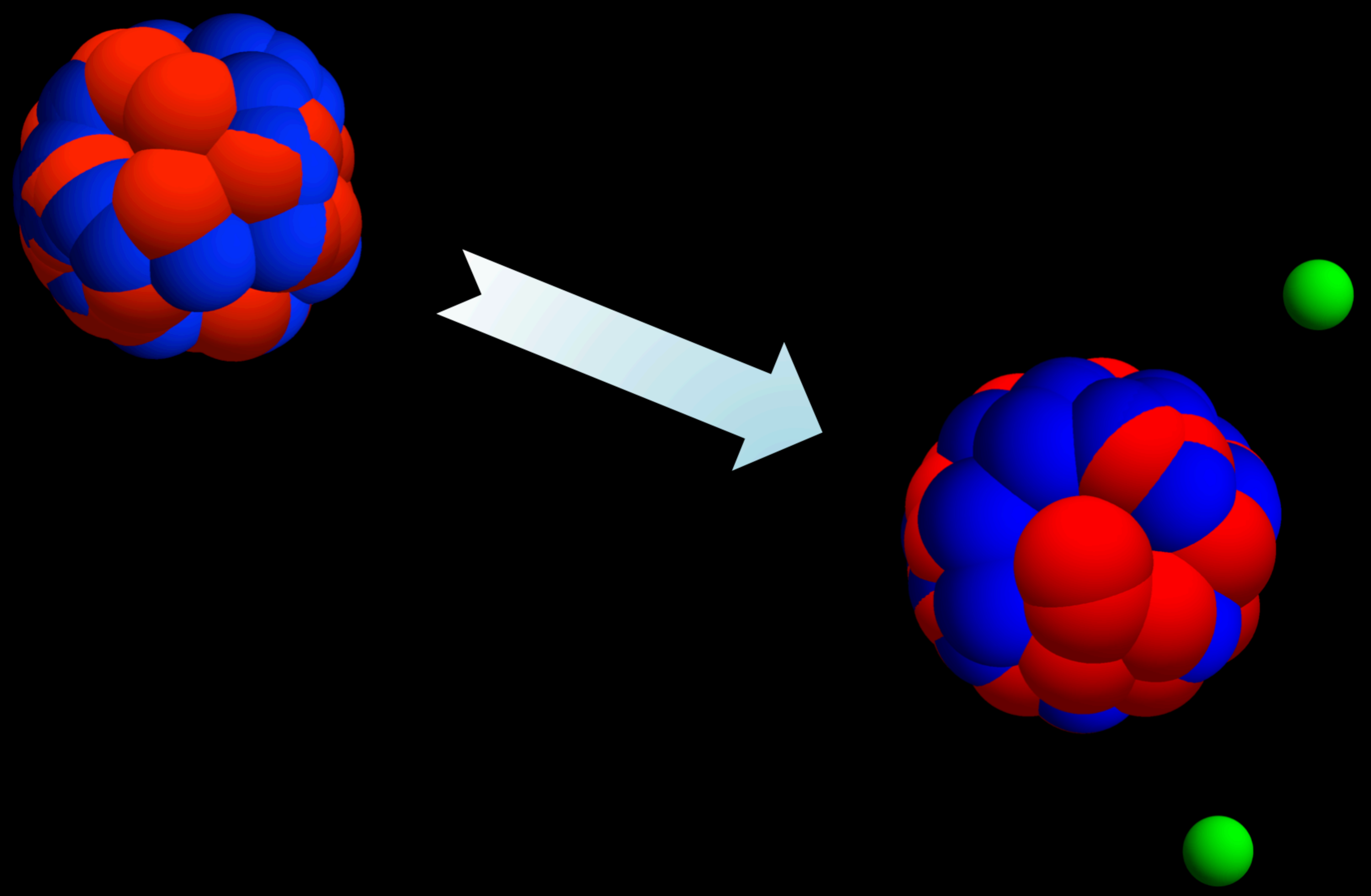


on modern terminology

NO → YES

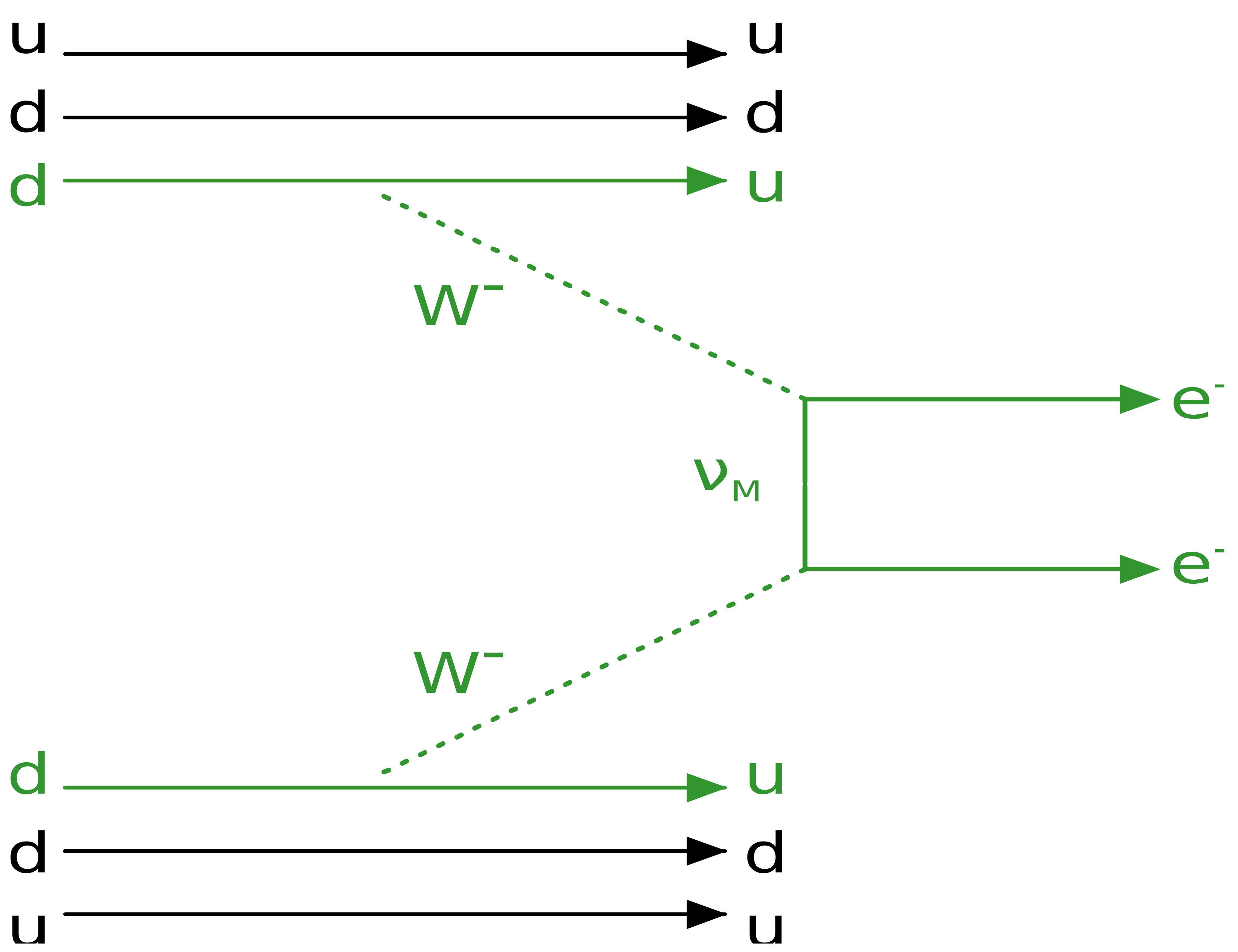
Normal ordering → Yearningly Expected Spectrum

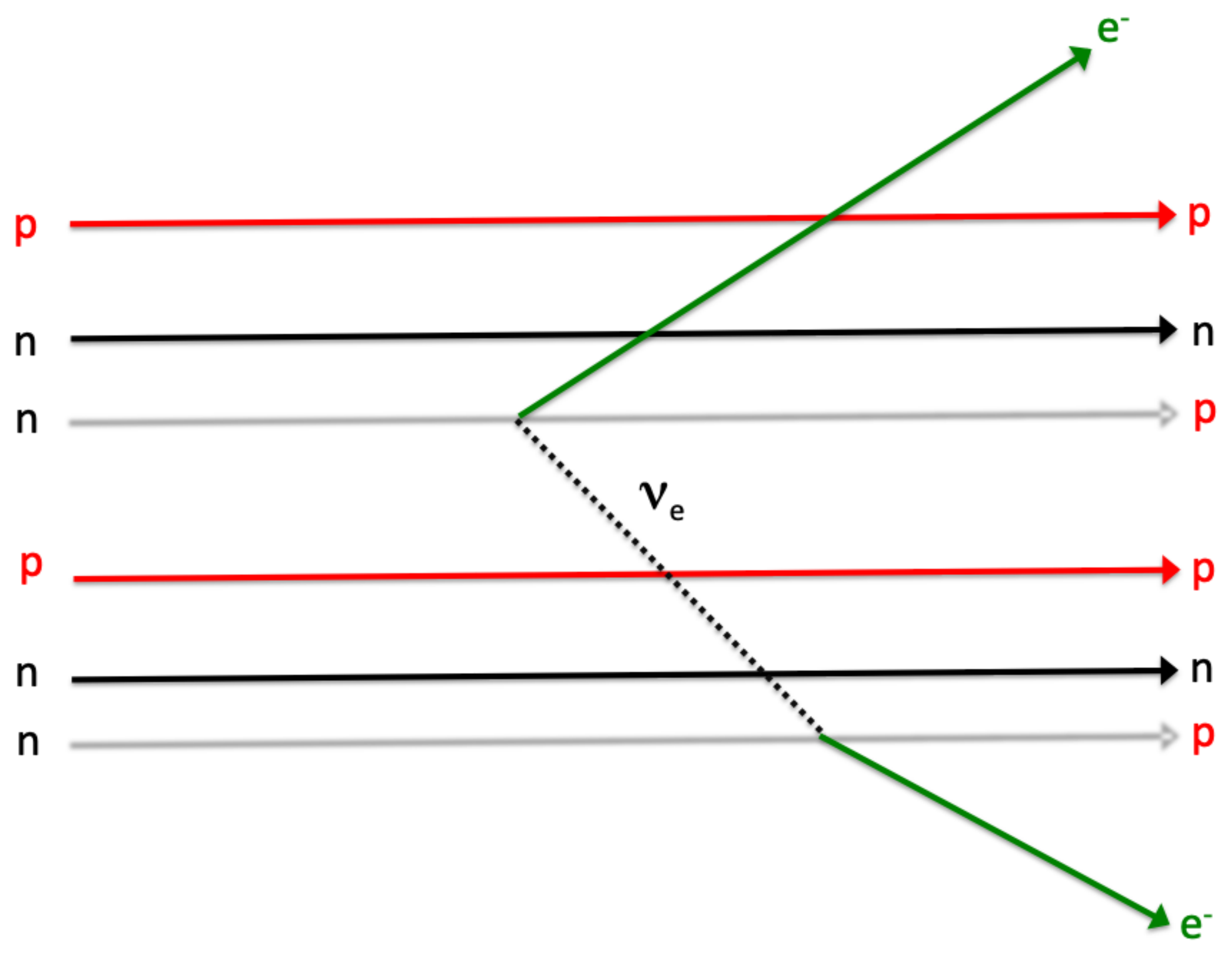
Majorana neutrinos work as bridges between matter & antimatter

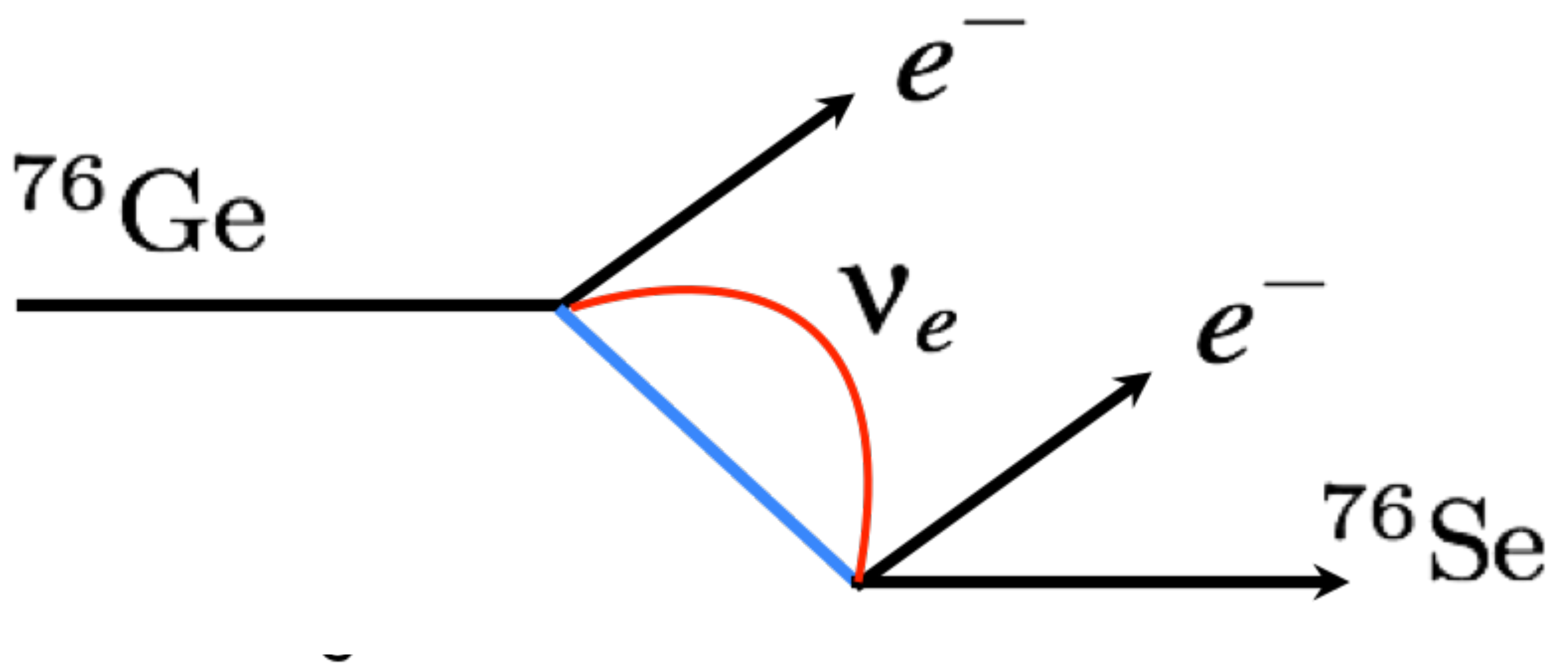


2 matter particles can be created !!!

Majorana neutrinos & creation of electrons (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

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Hindawi

Review Article

Neutrinoless Double Beta Decay: 2015 Review

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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.

E.g.: After-discovery scenarios

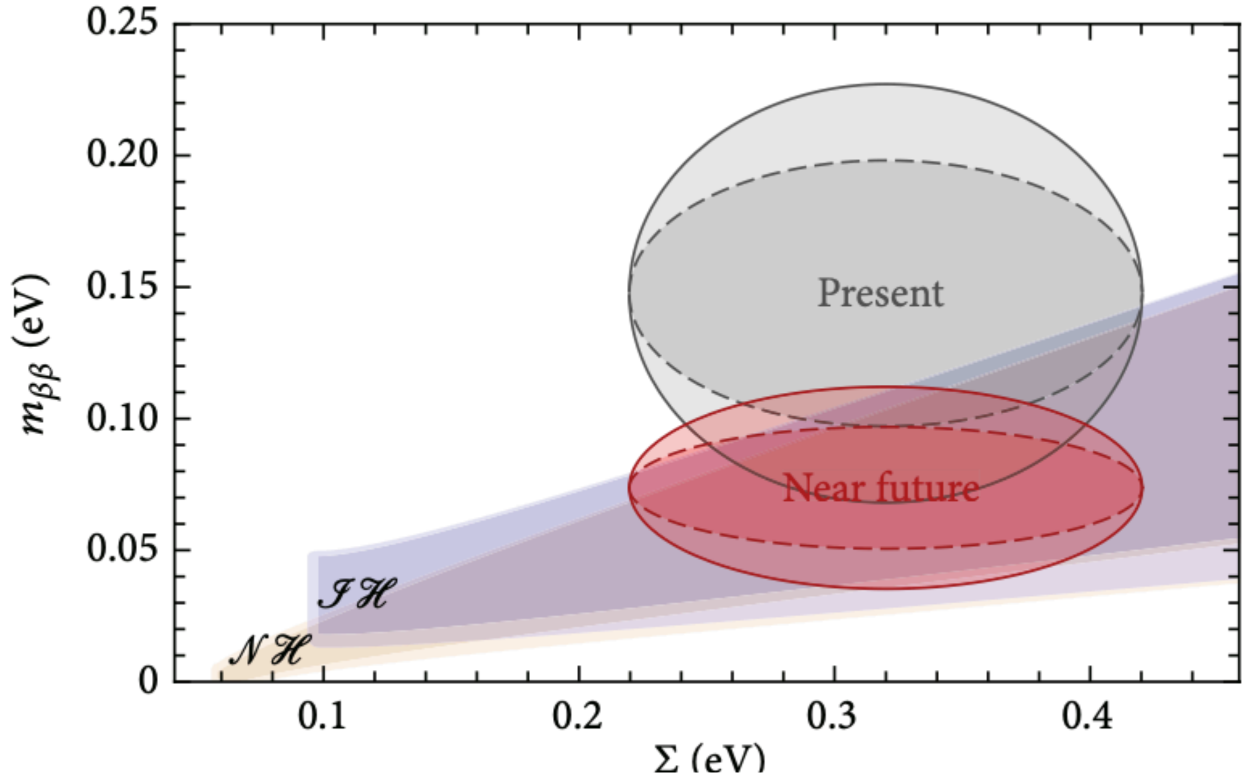
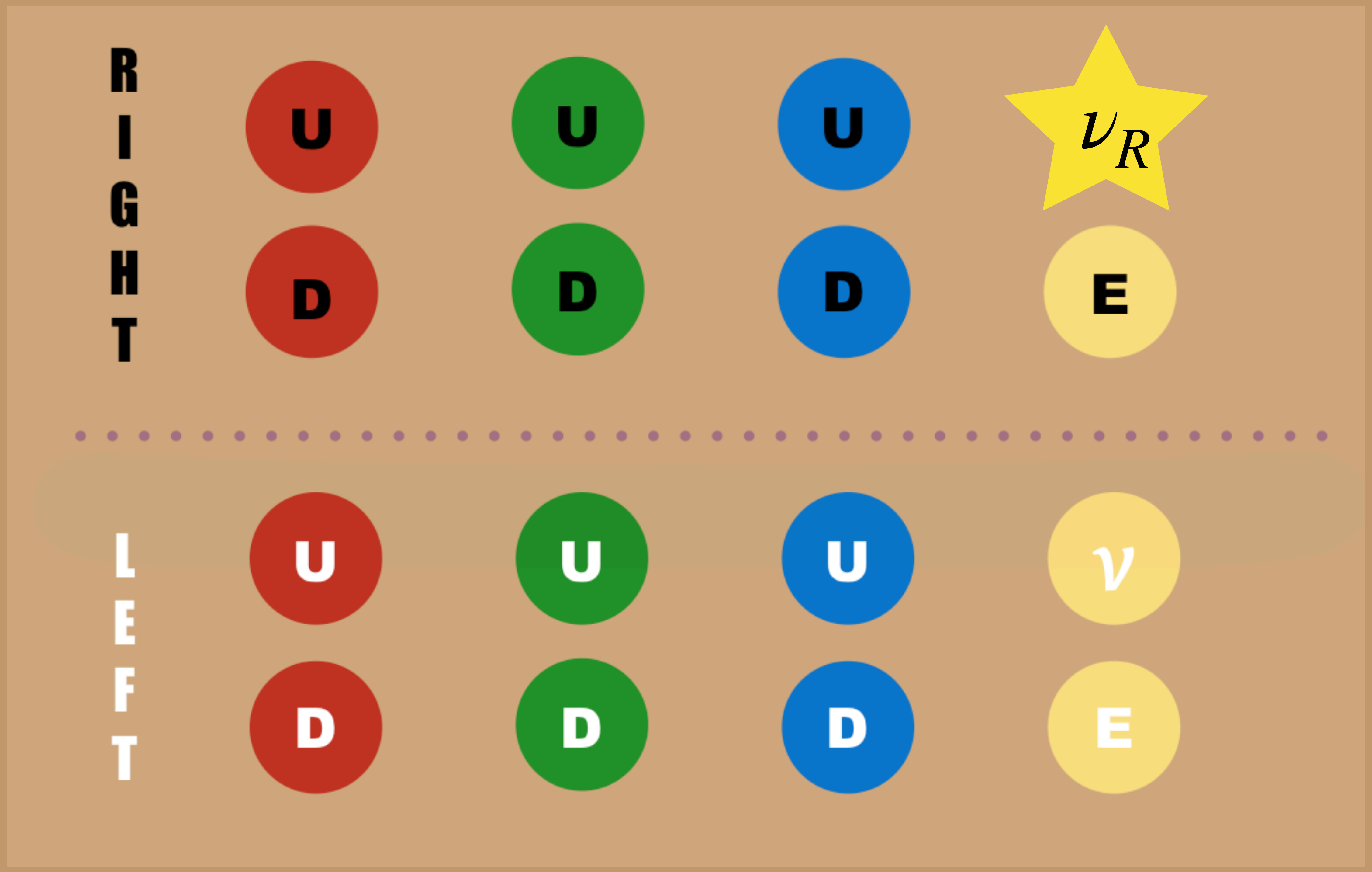


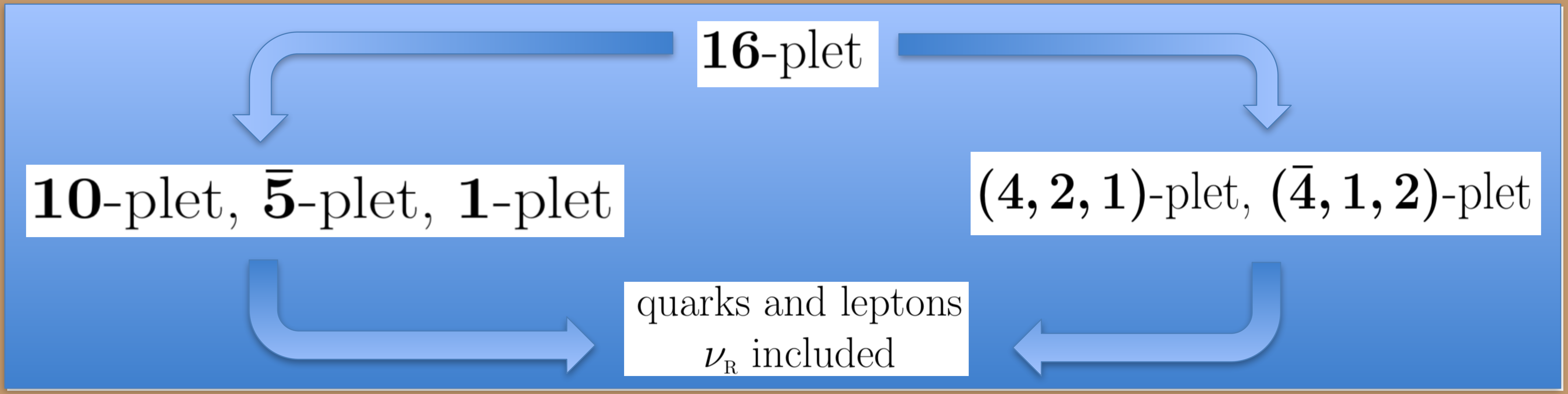
TABLE 6: 1σ ranges for both Gaussian and Poisson distributions for two different values of N_{peak}. In the former case, we assumed a standard deviation equal to $\sqrt{N_{peak}}$. To compute the error columns, we halved the total width of the range and divided it by N_{peak}.

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

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
$p, n, e, \nu_e, \mu \ldots$	$B, L_e, L_\mu \ldots$, " "	[1961] 1968	[Standard Model] Quarks
Quarks & Leptons	$B-L, L_e-L_\mu, \ldots$, " "	[1962] 2010	[Leptonic Mixing] Appearance Experiments
Quark-Leptons	$B-L$, " "	[1937] ?	[Majorana' Mass] $2n \rightarrow 2p + 2e$
Fermions	Mass, Spin1/2	[1977] ???	[Supersymmetry?] ???


R I G H T
U U U ν_R
D D D E
L E F T
U U U ν
D D D E


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

SM seen as an effective theory

Weinberg 79

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

- the 1st is SM-invariant formulation of neutrino masses
- the 2nd is one of operator that implies proton instability
- the 3rd an example of a source of new observable phenomena

SM seen as an effective theory

Weinberg 79

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

- the 1st is the SM-invariant description of Majorana neutrino masses which **violates B-L**
- the 2nd is one of the operators that cause the instability of the proton **but conserves B-L**
- the 3rd violates lepton number **and contributes to** 2n→2p + 2e **(0ν2β)**
- At dim.7 **B-L is broken**; at dim.9 also **B violation** appears

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Do experiments suggest a hierarchy problem?

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(Received 18 September 1997; published 14 April 1998)

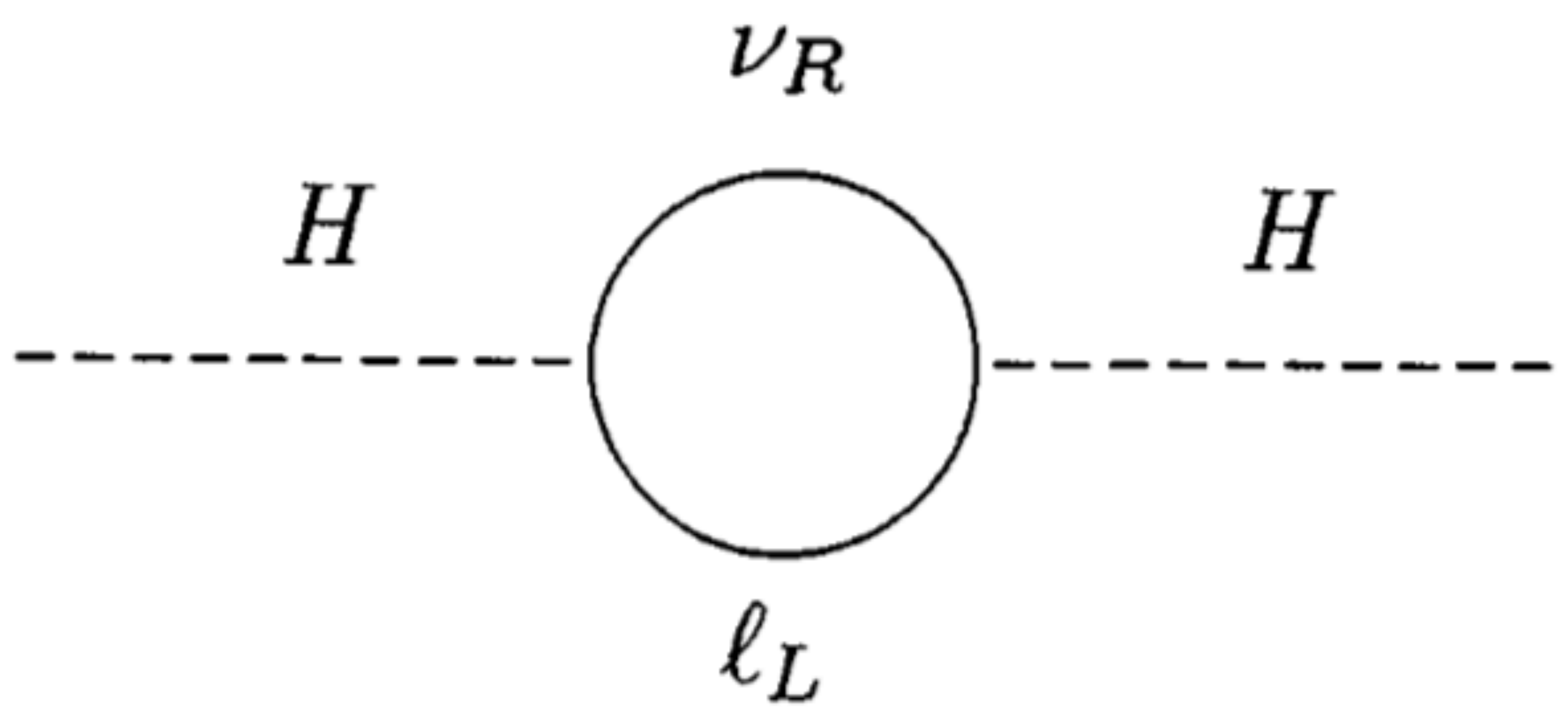

FIG. 1. The Feynman diagram originating the corrections in Eq. (1); ν_R denotes the right-handed neutrino of mass M_R, $\ell_L = (\nu_L, e_L)$ the leptonic and H the Higgs doublets.

OK, but what about the cosmological constant?