Neutrinos - second lecture

importance of "*neutrinoless double beta decay*" process; global numbers; significance of neutrinos masses in particle physics; introduction to Majorana's formalism; extension of the standard model; implications

Francesco VISSANI - Laboratori Nazionali del Gran Sasso - July 21, 2022

a crucial process for particle physics

the importance of the search for process

$$(A, Z) \to (A, Z+2) + 2\ \mathrm{e}^-$$

receives consistent support from *several* argumentations, of different character

OBSERVATIONAL: the need to verify the global symmetries of SM

PHENOMENOLOGICAL: implications of evidences of physics beyond the SM

AXIOMATIC: the hypothesis posed in 1937 by Majorana for neutrino mass

EVOLUTIONARY: the development of gauge theories and search for their extensions

We expose these argumentations today, highlighting the many connections with ***neutrino*** *physics*

history of global symmetries in particle physics

Les Hypothèses moléculaires

Télécharger [masquer]

Jean Perrin

Les hypothèses moléculaires

La Revue Scientifique
13 Avril 1901

PHYSIQUE. — *Les hypothèses moléculaires.*
Jean Perrin, La Revue Scientifique

- 4e série — Tome XV:N°15 — 13 Avril 1901
- Conférence faite aux étudiants et aux amis de l'université de Paris, le 16 février 1901. par M. Jean Perrin, chargé du cours de Chimie à la Sorbonne.

In the section titled 'Division de l'atome en corpuscles' we read statements such as:

Every atom will consist, on the one hand, of various masses strongly charged with positive electricity, a kind of positive suns (soleils) *whose charge will be much greater than that of a corpuscle, and on the other hand, of a multitude of corpuscles, a kind of small negative planets* (planètes), *the whole of whose masses gravitate under the action of electrical forces, and the total negative charge exactly equals the total positive charge, so that the atom is electrically neutral.*

And also, equally impressive and eloquent,

- *Negative corpuscles* are all equal *to each other, whatever the chemical nature of the atom […]*
- *the mass […] is only the thousandth part of the hydrogen atom.*

from radioactivity to the nucleus

- **discovery of radioactivity** [Becquerel 1896]
- α, β, γ **rays** [Rutherford 1899, Villard 1900]
- **Th→Ra transmutation** [Soddy+Rutherford 1901]
- **energy mass equivalence** [Einstein 1905]
- **discovery of nucleus** [Geiger-Marsden+Rutherford 1911]

At this stage of the discussion, matter is thought to consist of nuclei and electrons. A first understanding of light quanta begins to emerge.

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NOW: if - based on $E = mc^2$ - someone had dared to raise the question, whether such a reaction could ever happen

$$\alpha \rightarrow p + p + \gamma \qquad \alpha \rightarrow p + p + p + \beta^-$$

the answer could have been that **"the mass-number is conserved,"** which is a corollary of *radioactive displacement law* (Russell, Fajans, Soddy)

which are the components of the nucleus?

(first attempts to devise a model)

van den Broek (1911) suggested that the nuclei consist of α and β particles

Harkins (1915) instead hypothesised that the basic components were H-nuclei and β particles

both are elegant models, that explain the main facts and exclude previous processes from occurring

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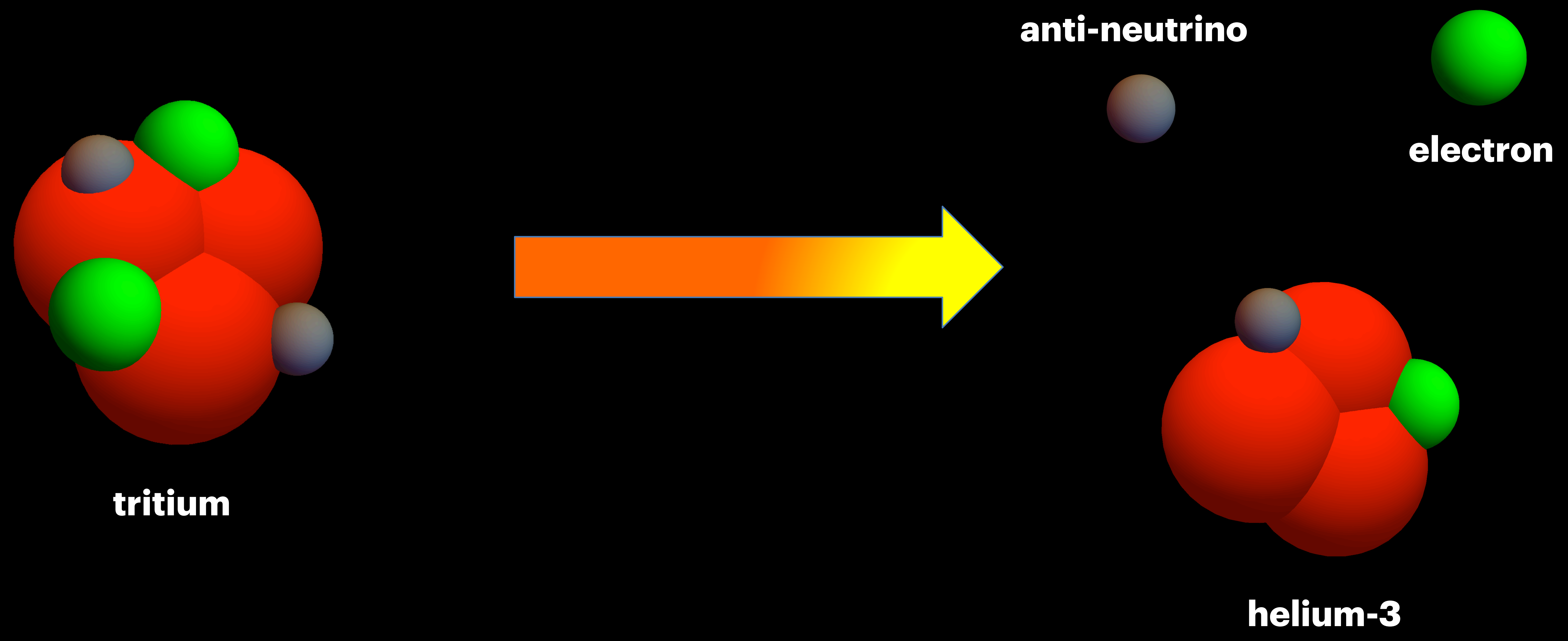
both are elegant models, that explain the main facts and exclude previous processes from occurring

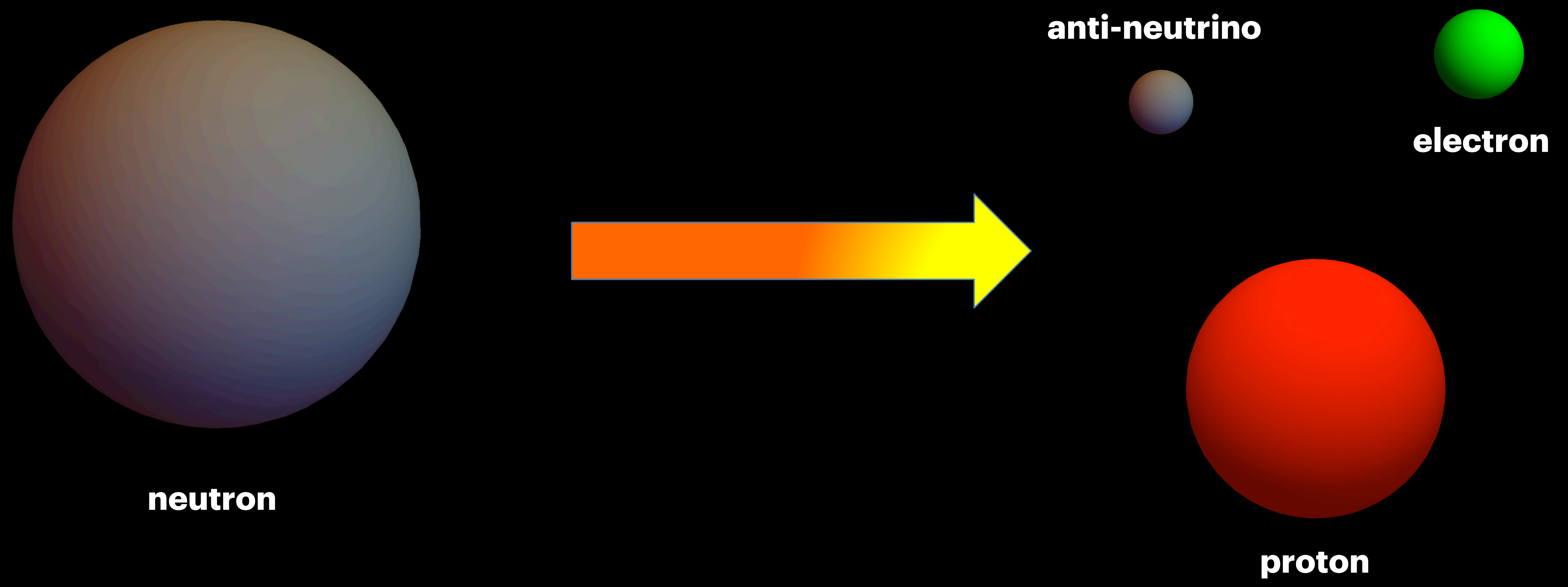
but these models contradict β rays observations!

a new model, a new particle (Pauli, 1930)



nuclei contain also neutrinos, that steal energy and spin
(in fact they have spin 1/2, as all other matter particles)

a relativistic theory of β-rays (Fermi, 1933)



some particles of matter disappear and others appear,
just as Einstein's "lichtquanten" do

this brings us back to matter stability dilemma

why disintegrations such as $p \to e^+ + \gamma$ do not occur?

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

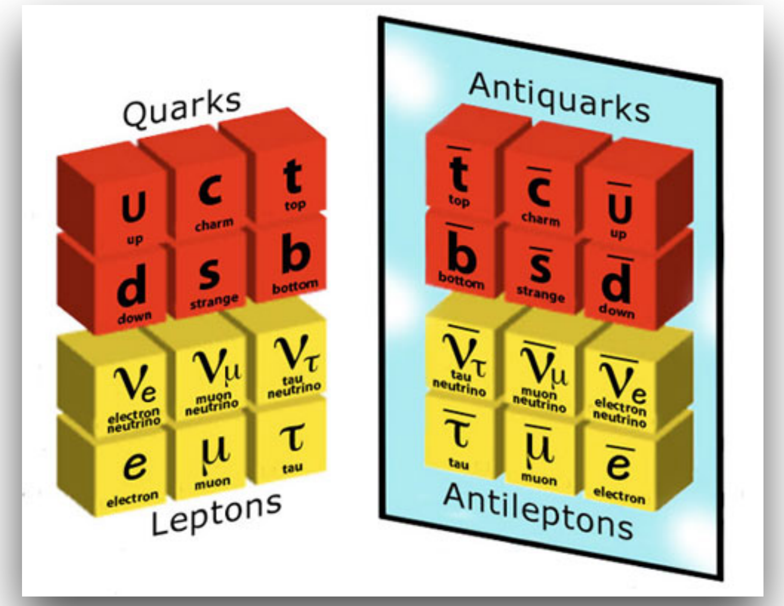
and similar dilemma for leptons

why disintegrations such as $\mu \rightarrow e + \gamma$ do not occur?

Marx; Zel’dovich; Konopinsky Mahmoud 52-53 - but also Pontecorvo 47, Puppi 48)

foundations of the standard model

- number of baryons **B** (1929-1949) and leptons **L** (1947-1953) are postulated to be conserved, to reconcile observations and theory
- after the discovery of parity violation (1956), a further hypothesis is invoked to proceed: that neutrinos are massless (1957)
- this paved the way to **V-A** theory of weak interaction (1957-1958) a cornerstone of the SM (1960-1967)



status of global numbers

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

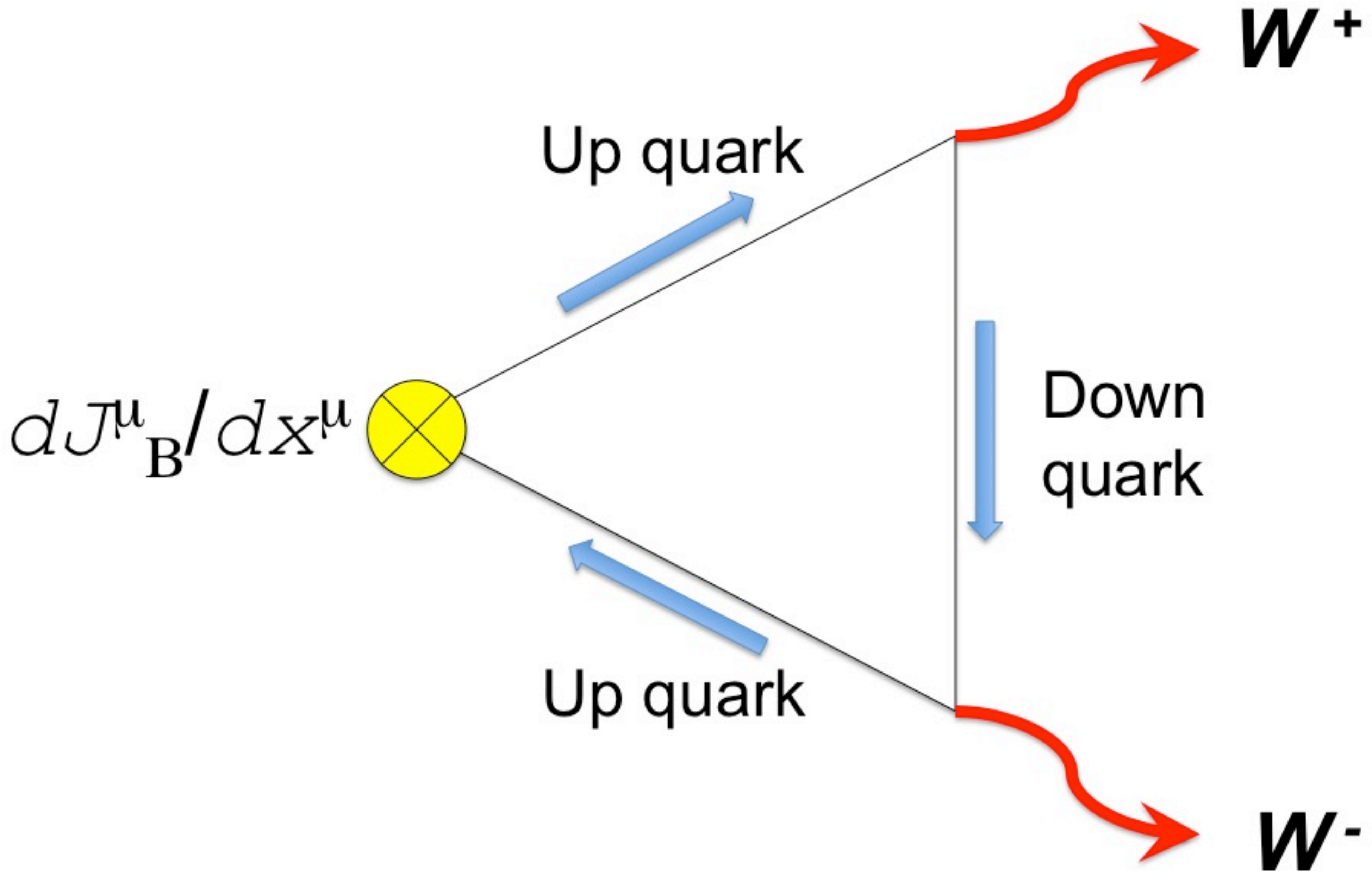
(=at the scrutiny of T2K, NOνA, OPERA, SK, DeepCore, only total lepton number L survived)

	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

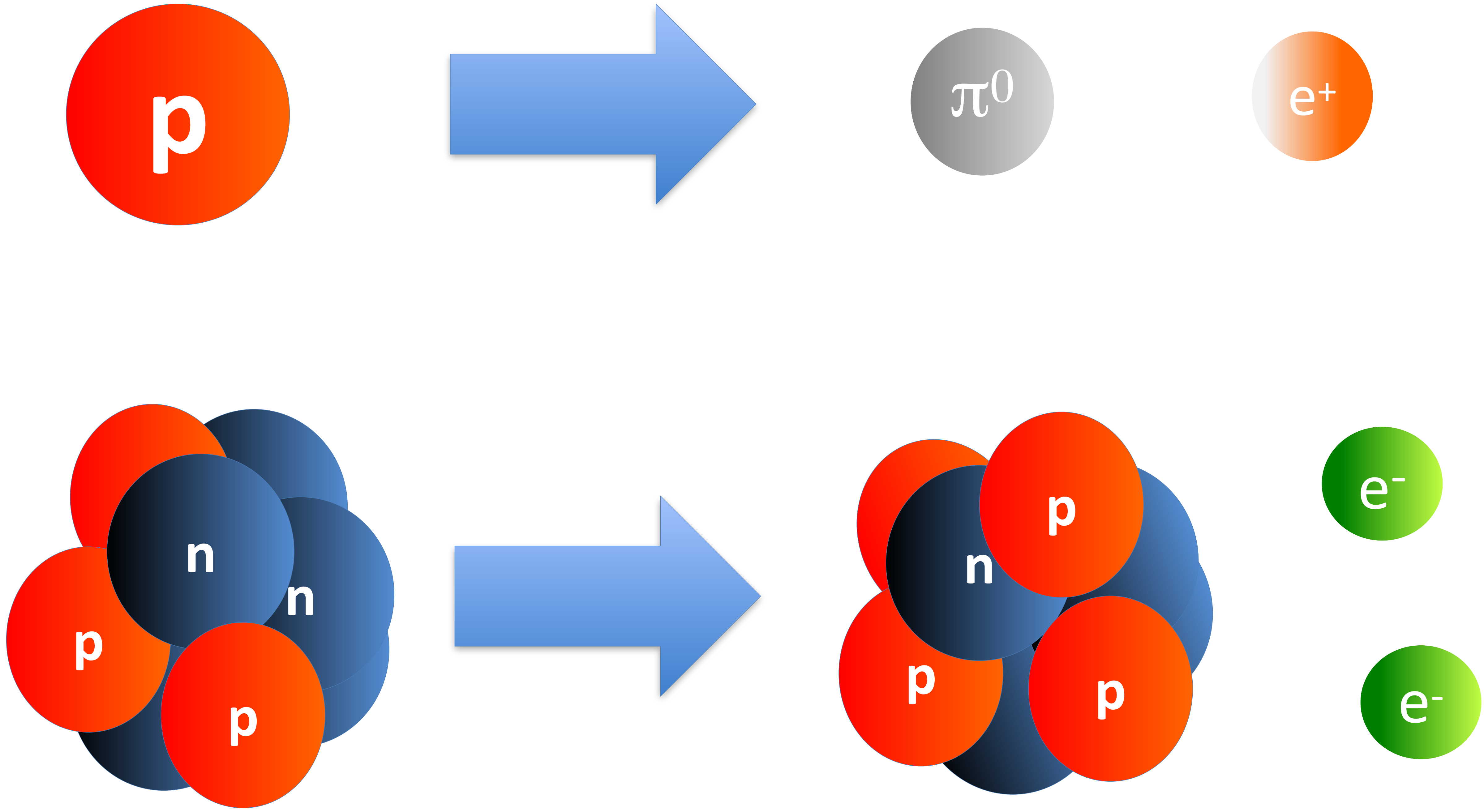


neutrino appearance experiments + SM imply that the only potentially exact symmetry is B-L

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

⇒ 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



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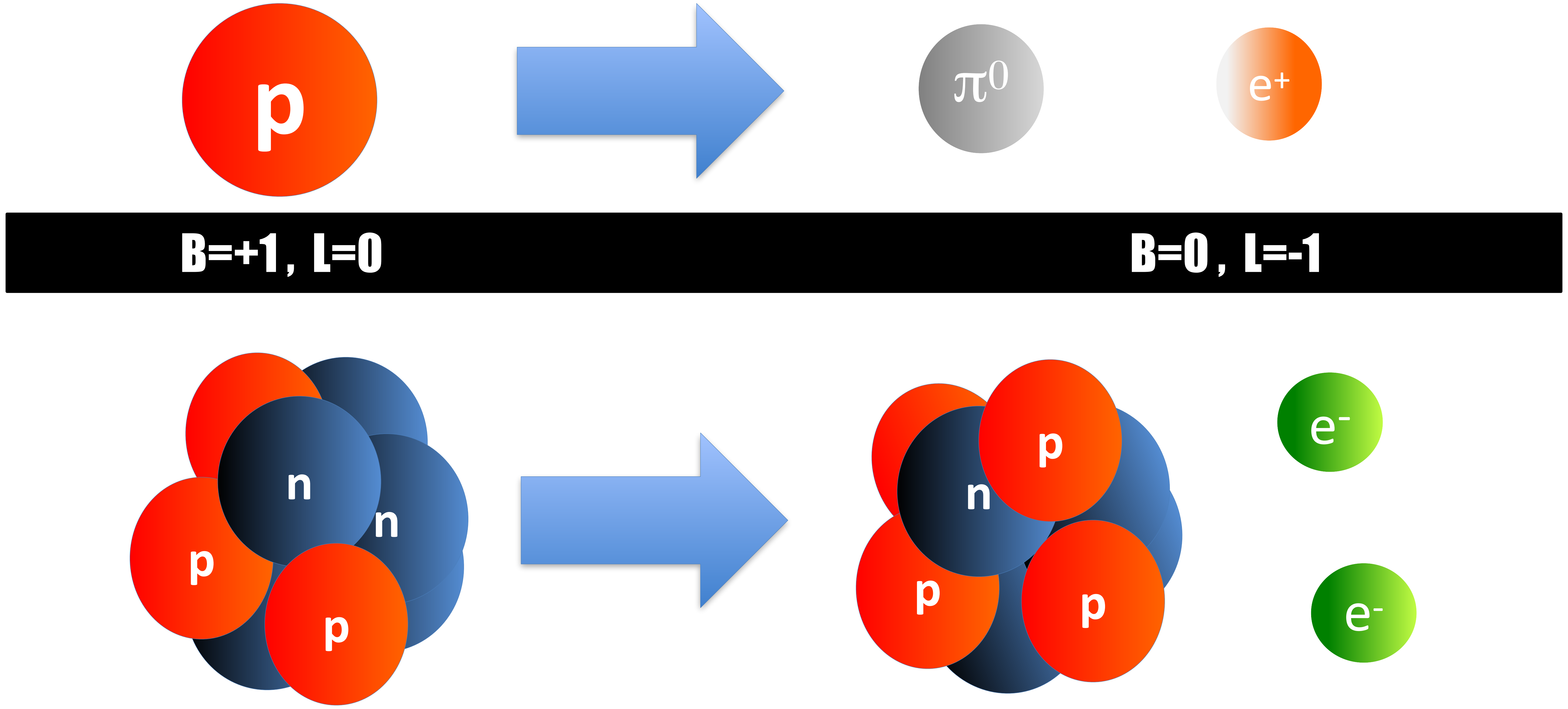

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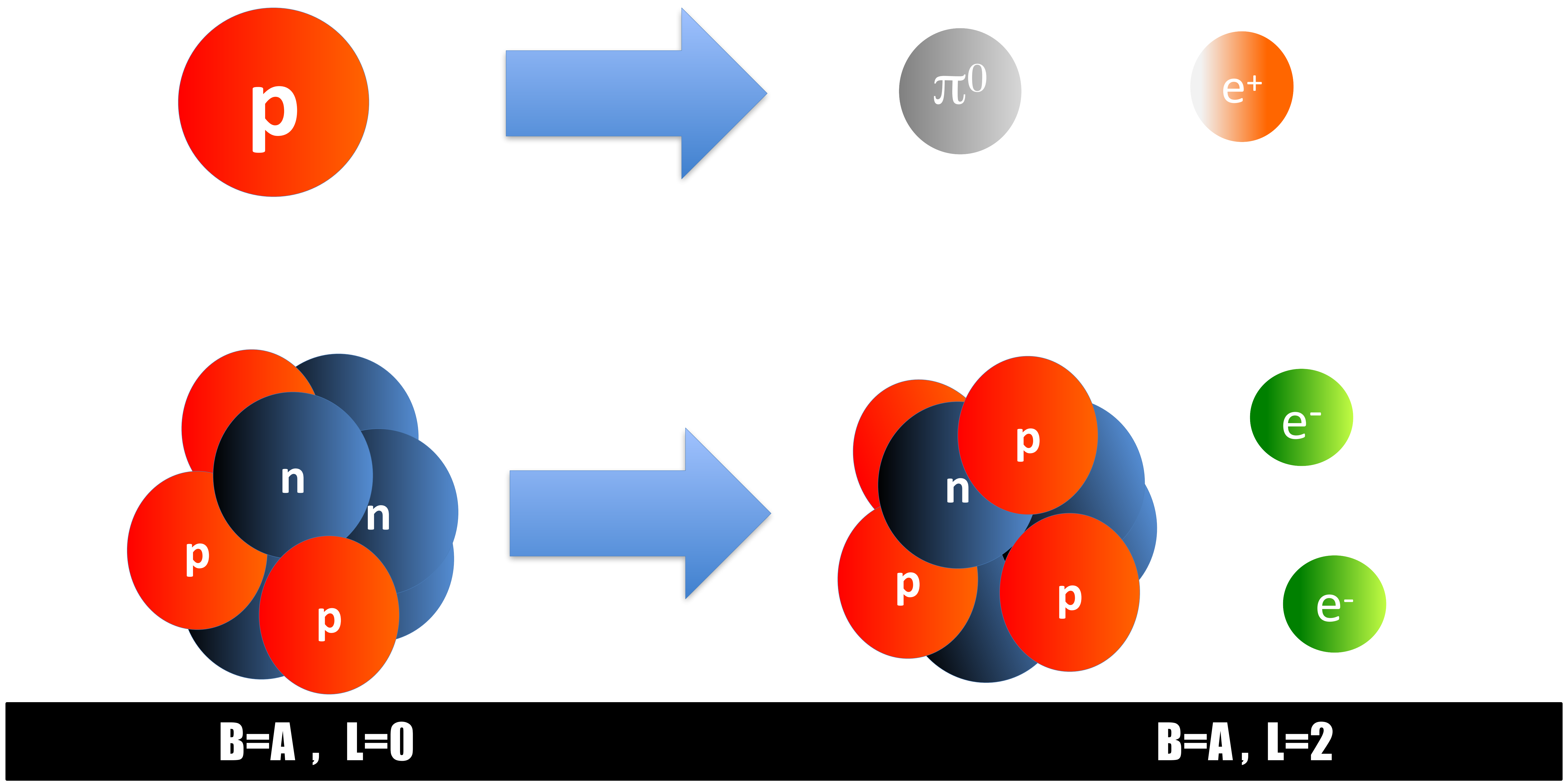

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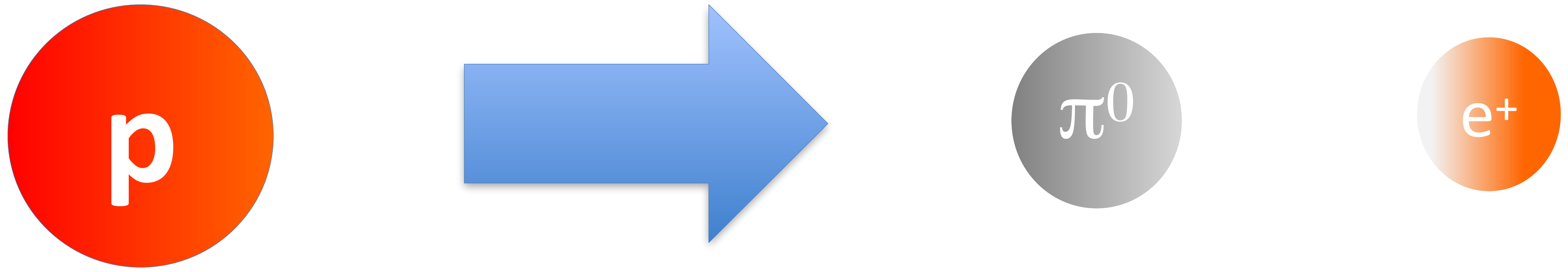
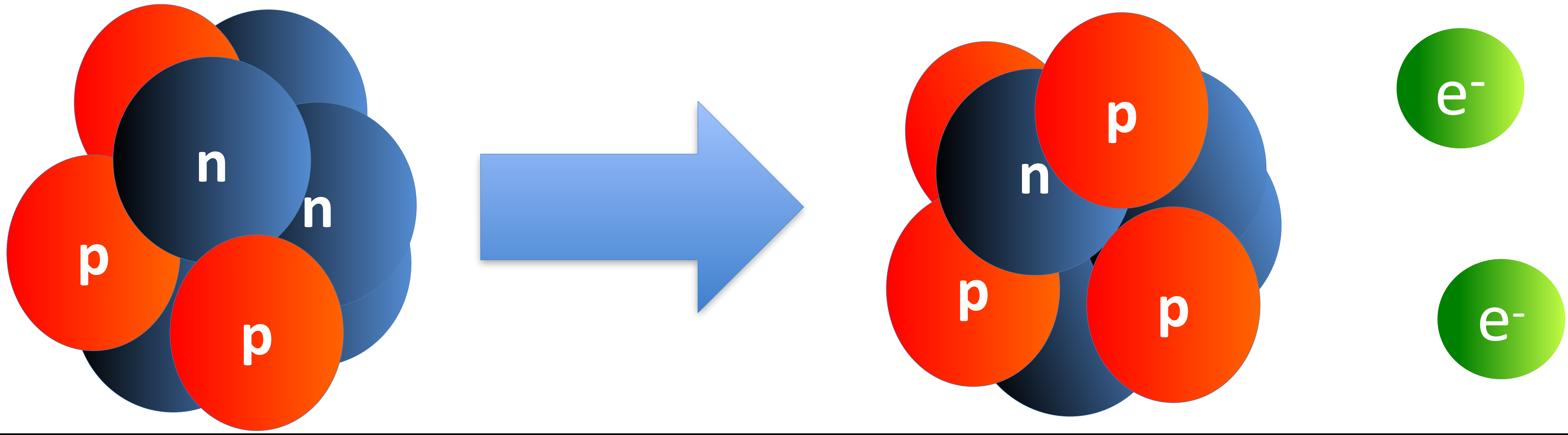
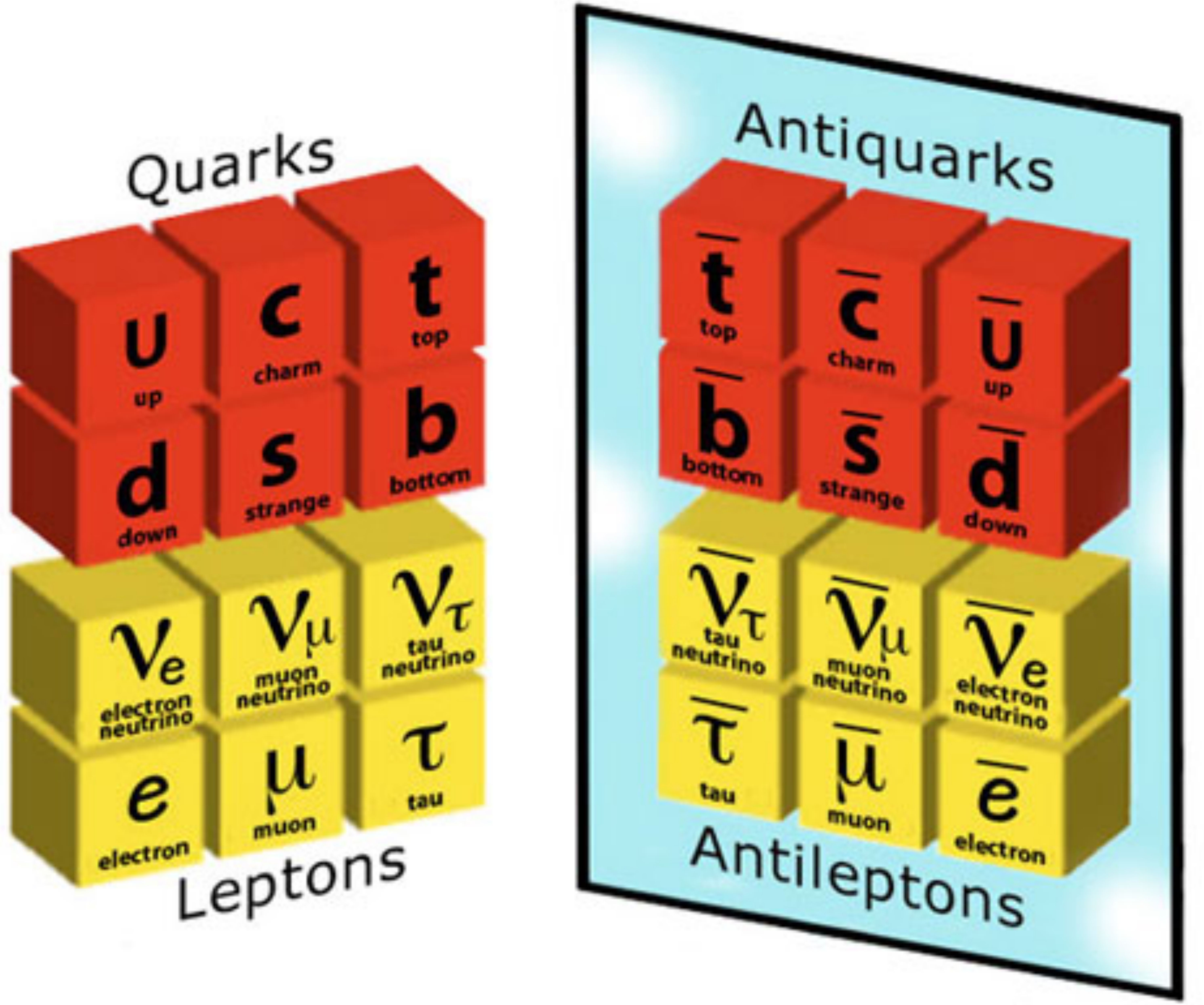


Proton decay (B-L conserved)



Electrons Creation (B-L violated)

features of the standard model and proof that it has to be extended



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:

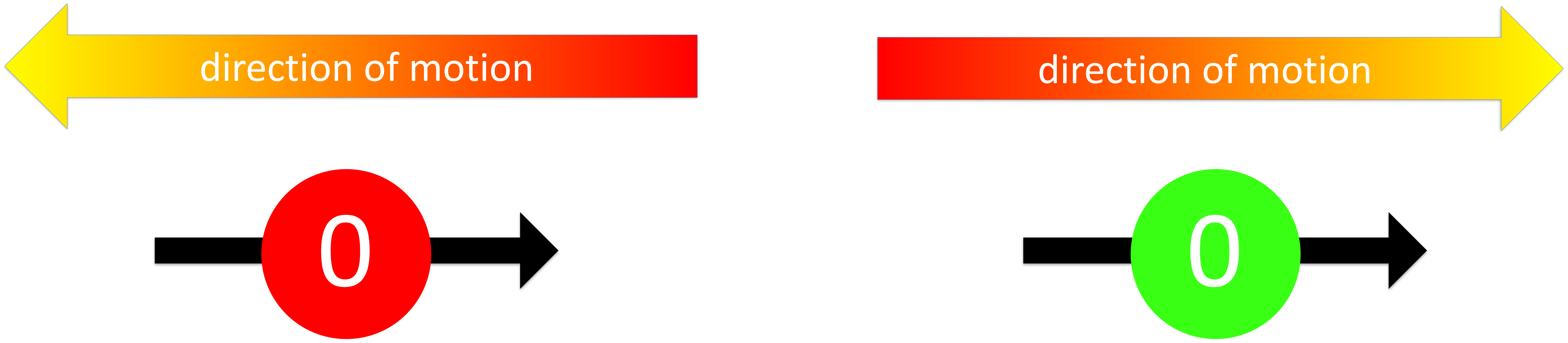
what distinguishes neutrinos and antineutrinos, as they are both chargeless?

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

on the structure of the standard model

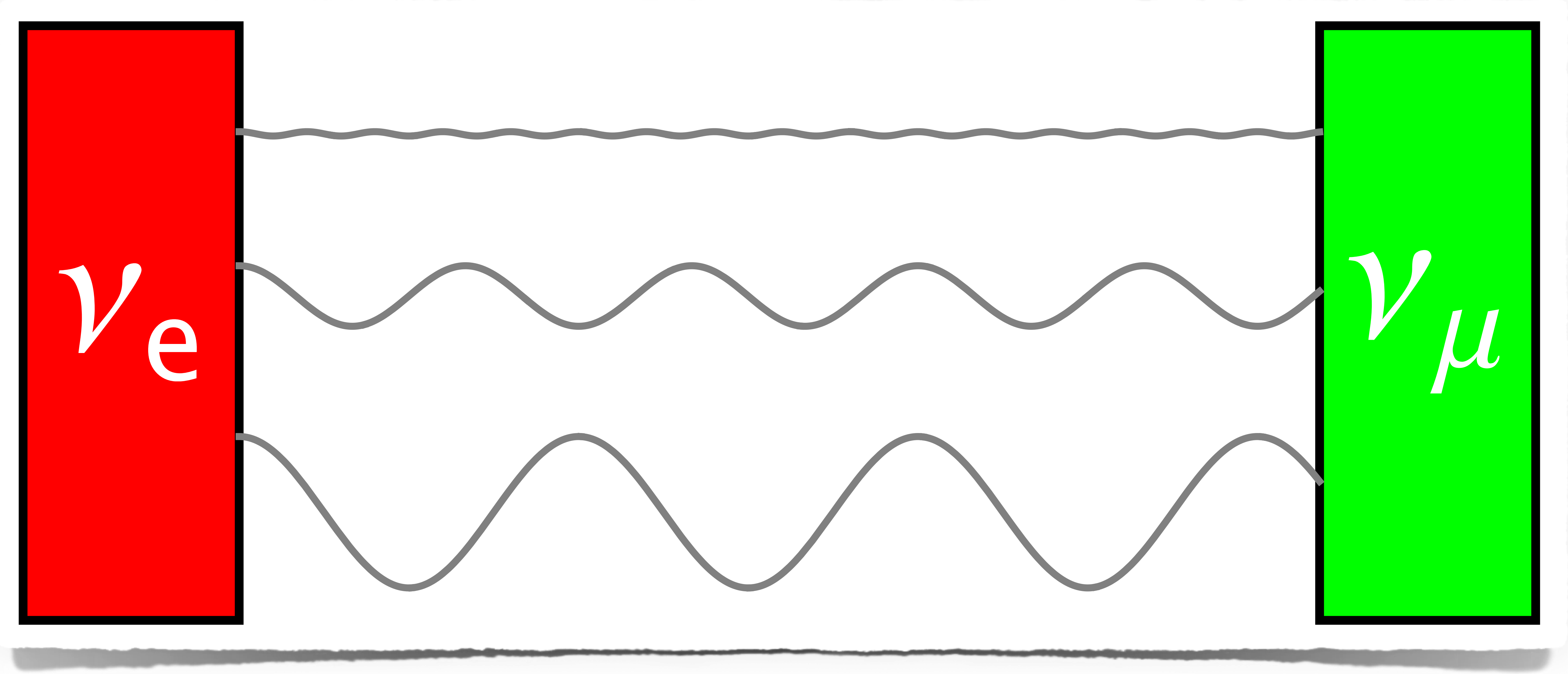
- the standard model <u>predicts</u> that the 3 lepton numbers are all conserved in perturbation theory. Their differences **L_i-L_j** and **B-L** are <u>exact</u>



- Helicity distinguishes neutrinos from antineutrinos - a feature of SM, based on the <u>masslessness</u> 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)

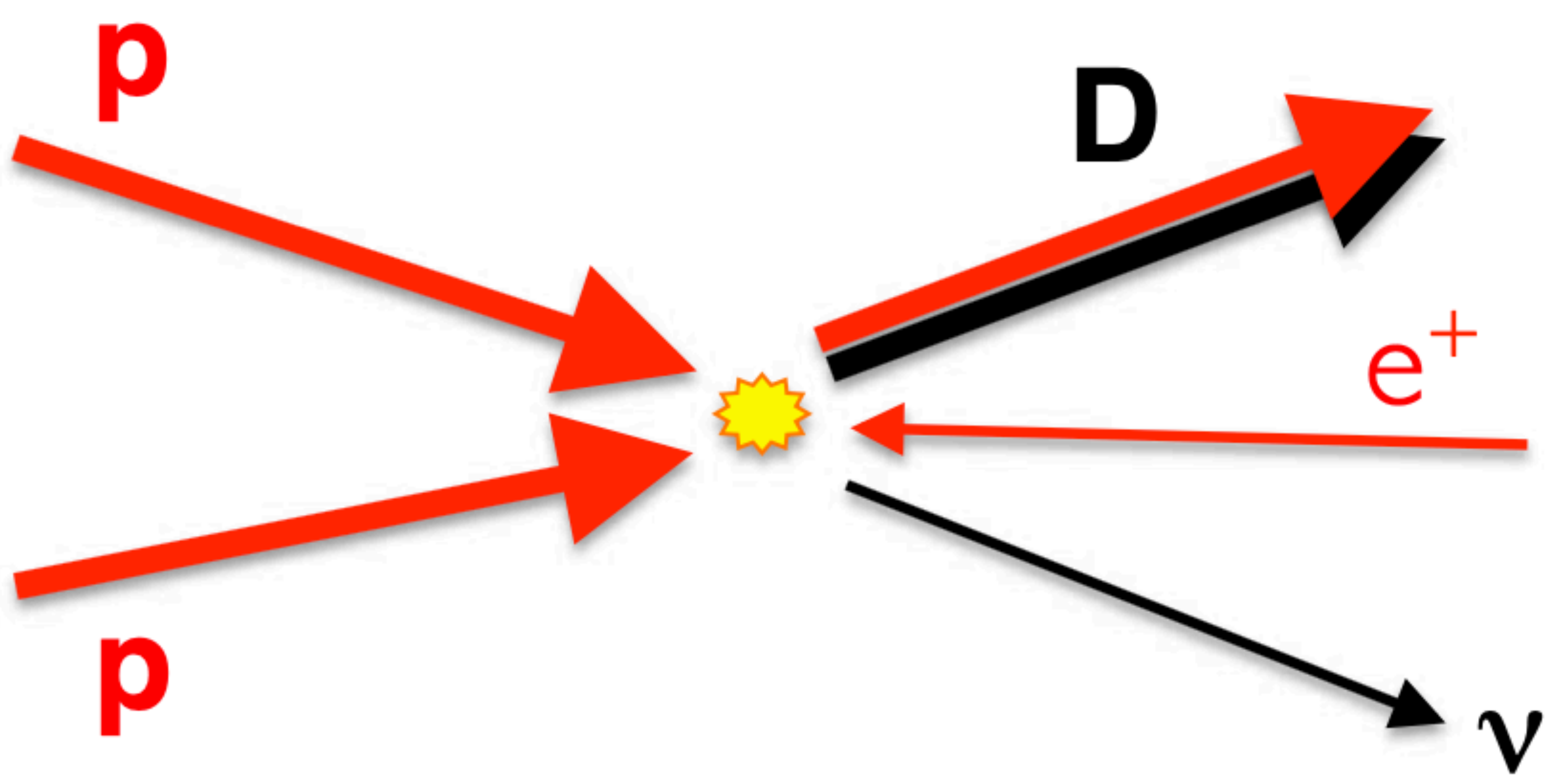
oscillations, B. Pontecorvo (1957-1967); **neutrino mixing**, Y. Katayama, K. Matumoto, S. Tanaka, E. Yamada (1962), Z. Maki, M. Nakagawa, S. Sakata (1962) M. Nakagawa, H. Okonogi, S. Sakata, A. Toyoda (1963) the evidence for neutrino mass implies physics beyond SM, and it shakes the foundations of the difference between neutrinos and antineutrinos

(inherent in the SM)

an argument for neutrino-antineutrino identity - or, introducing Majorana fermions

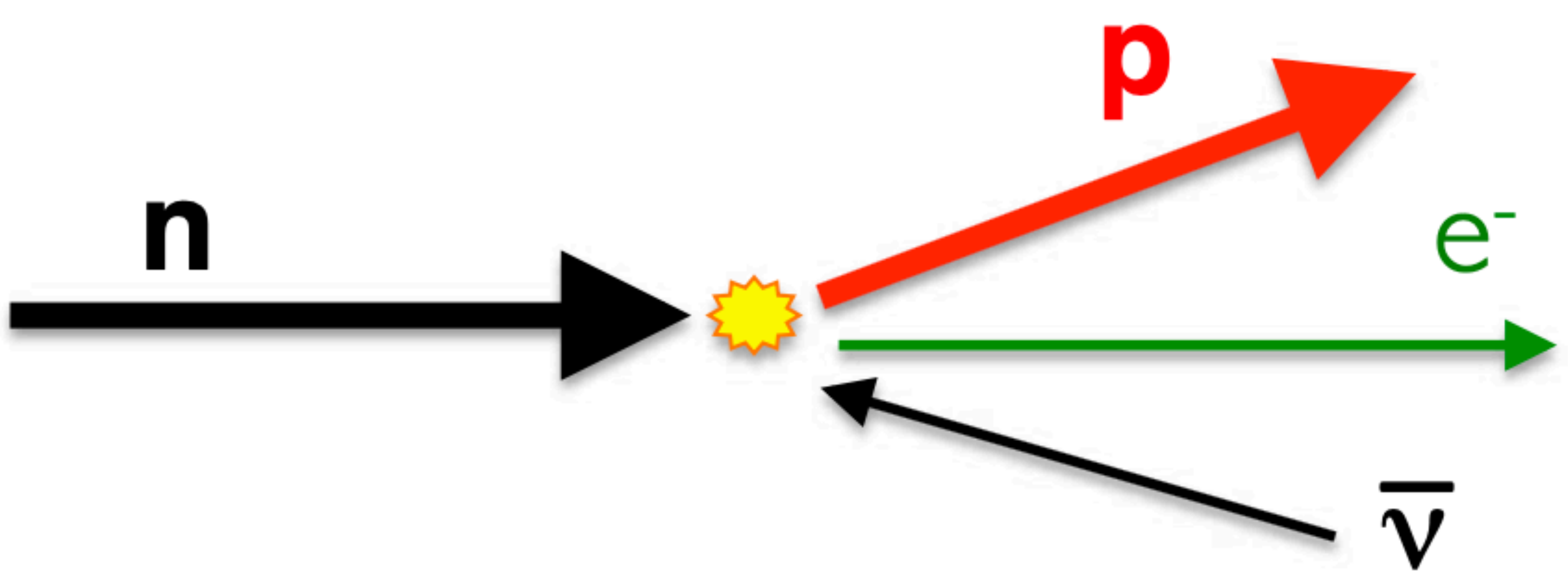
$p + p \rightarrow D + e^{+} + \nu$

The neutrino is the matter particle that accompanies the positron



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

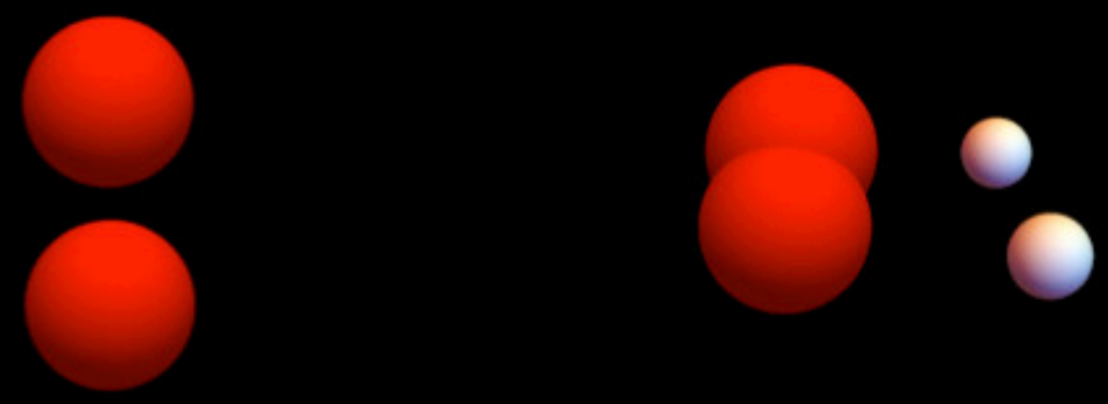
The antineutrino is the antimatter particle that accompanies the electron



proton fusion: $p+p \rightarrow D+e^{+}+\nu$

Electric charge is conserved:

$1+1=1+1+0$



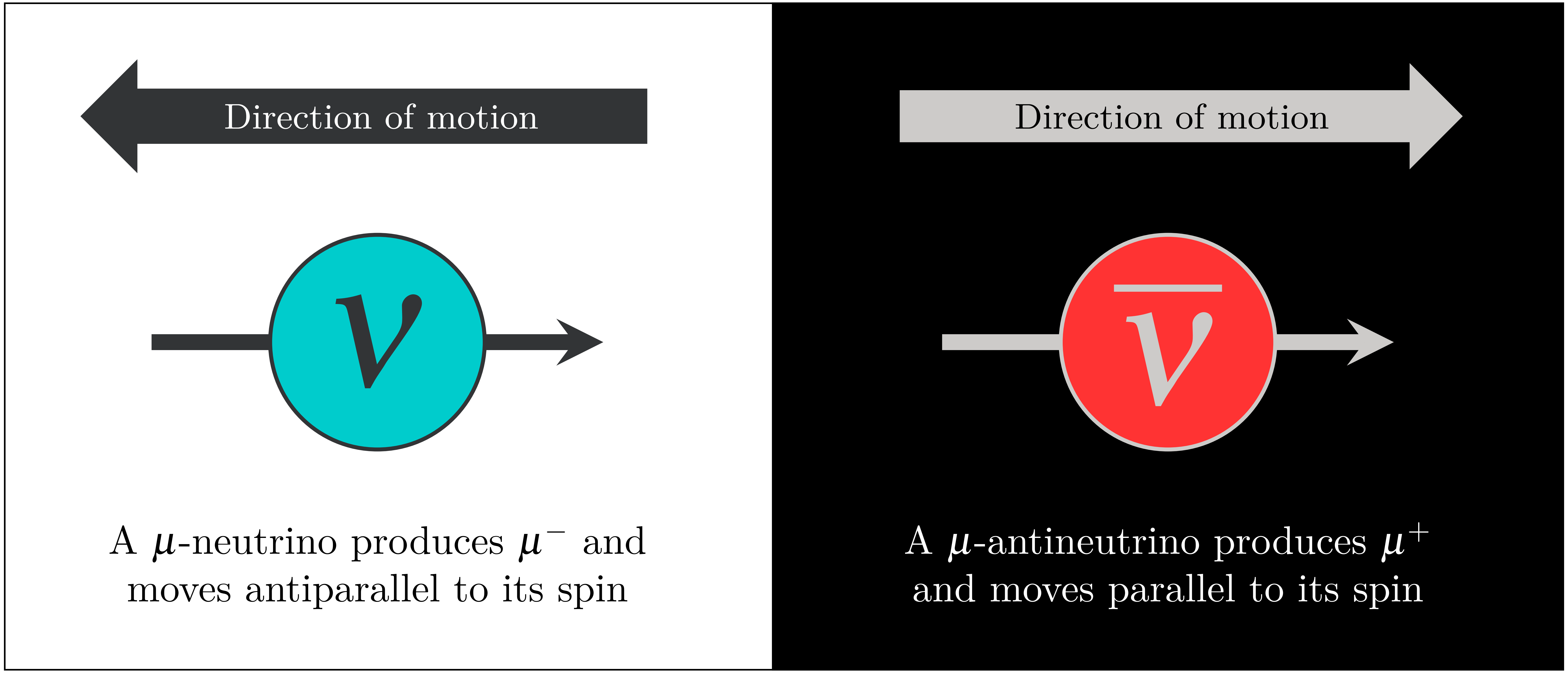
Baryon number is conserved :

$1+1=2+0+0$

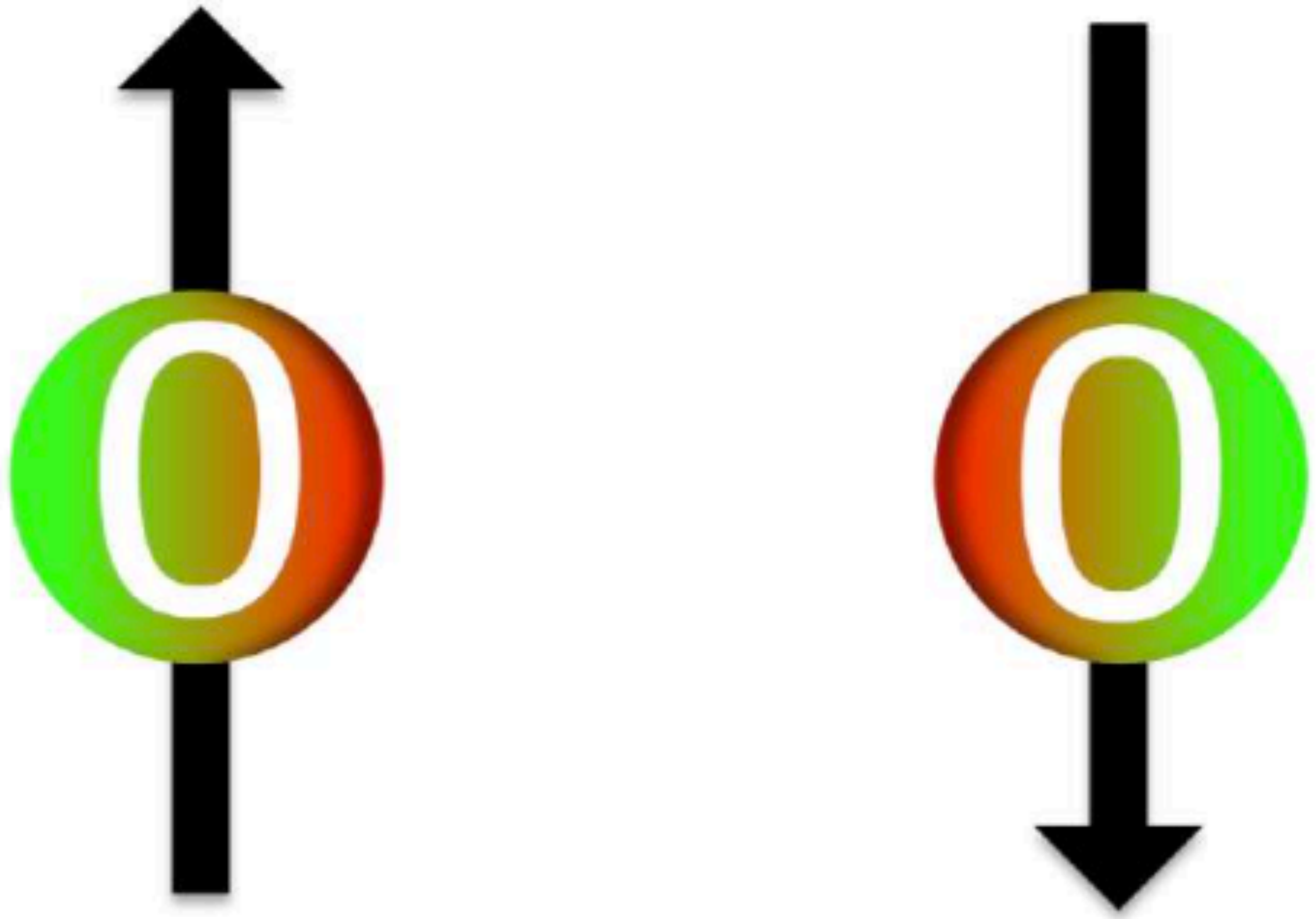
Lepton number is conserved:

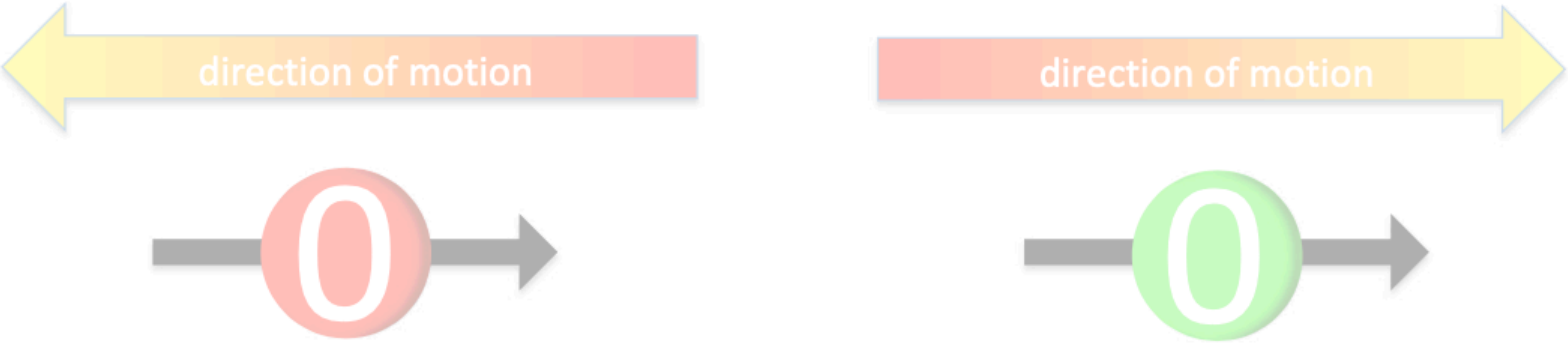
$0+0=0-1+1$

Therefore neutrinos should be classified among matter particles, aren’t them?

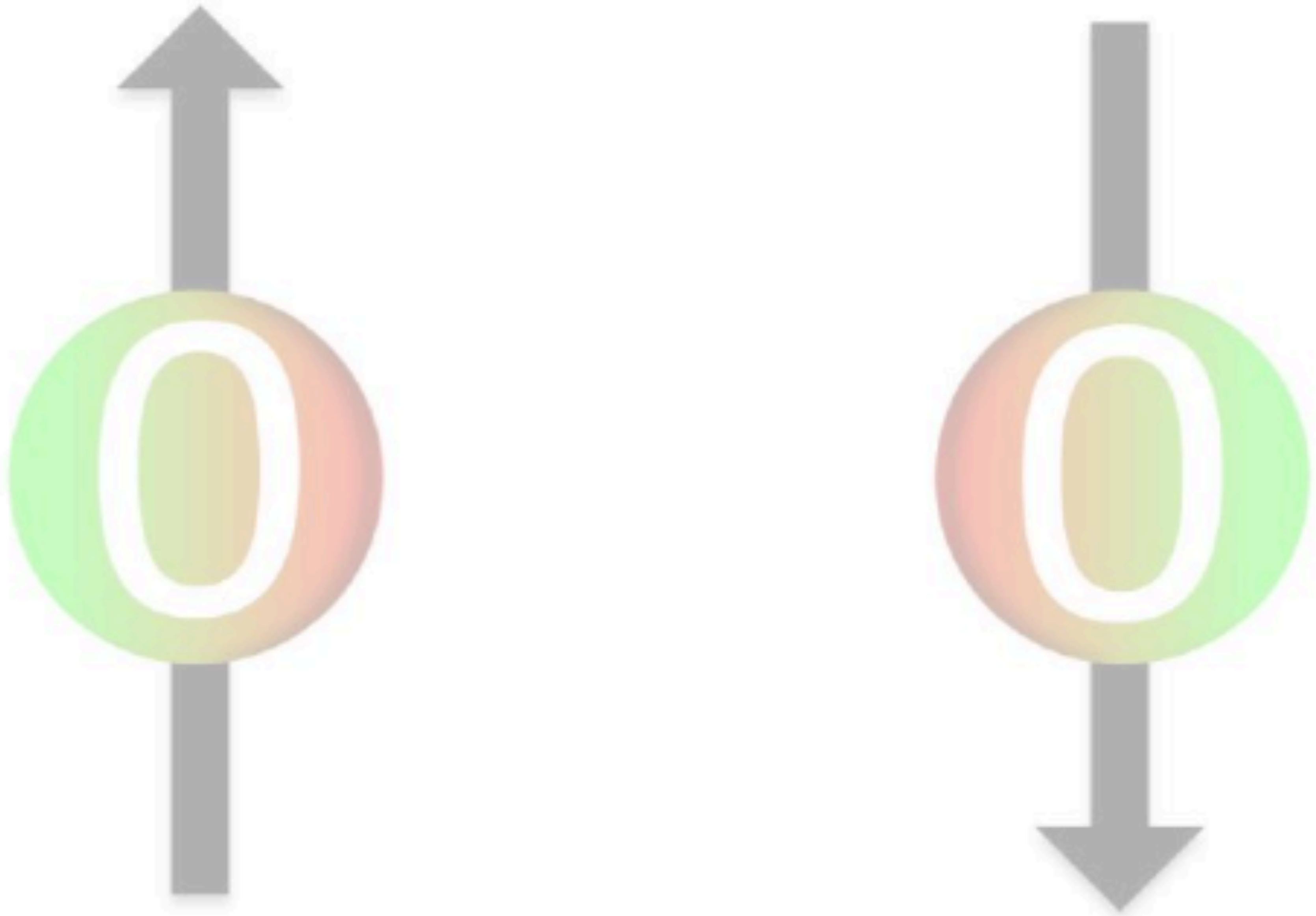

Direction of motion
ν
A μ-neutrino produces μ^- and moves antiparallel to its spin
Direction of motion
$\overline{\nu}$
A μ-antineutrino produces μ^+ and moves parallel to its spin

neutrinos and antineutrinos distinguished by their helicities and in their rest frame? they could be indistinguishable...

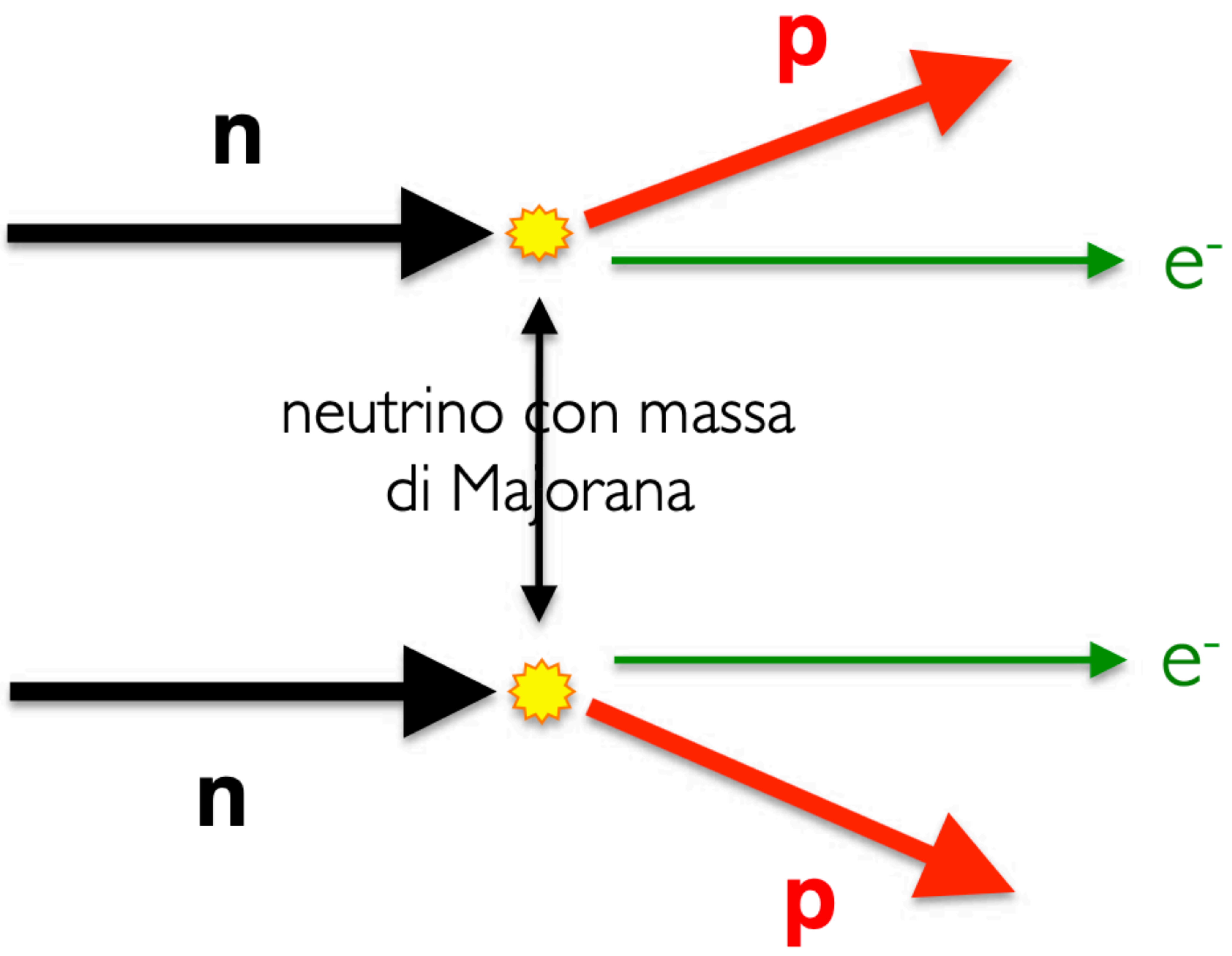




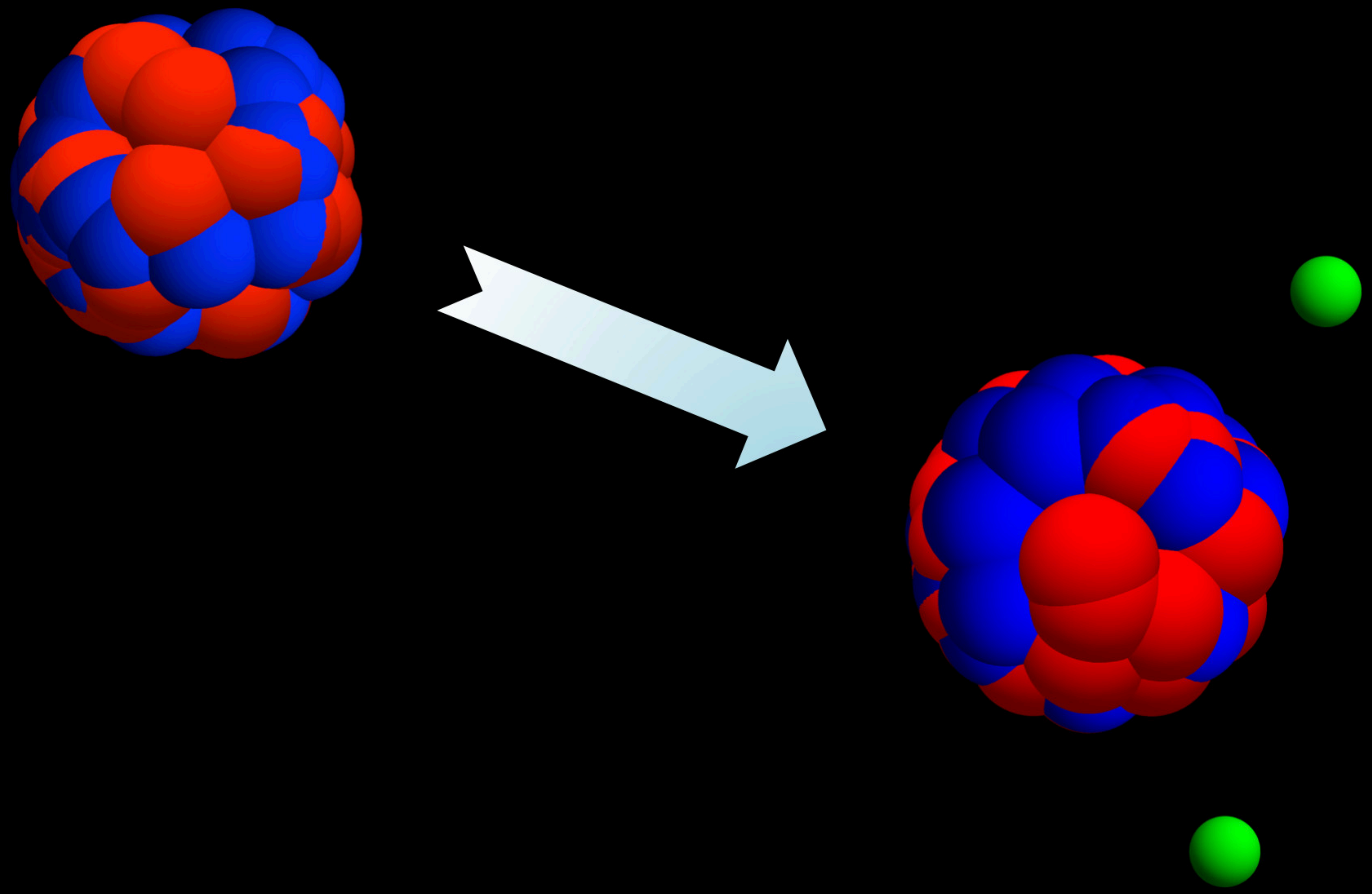
Majorana theory: they're matter & antimatter at once

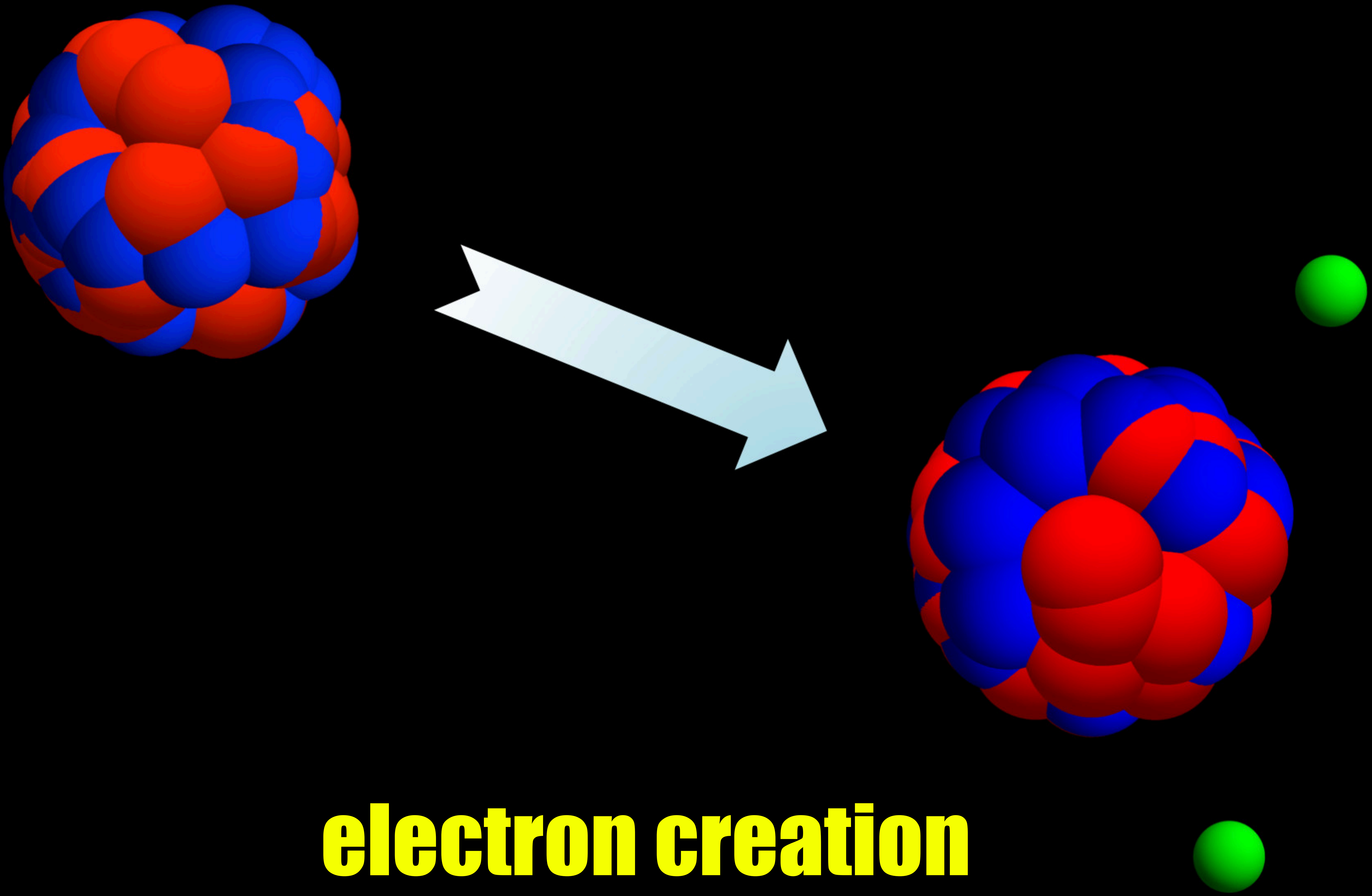


$2\,\mathbf{n} \rightarrow 2\,\mathbf{p} + 2\,e$

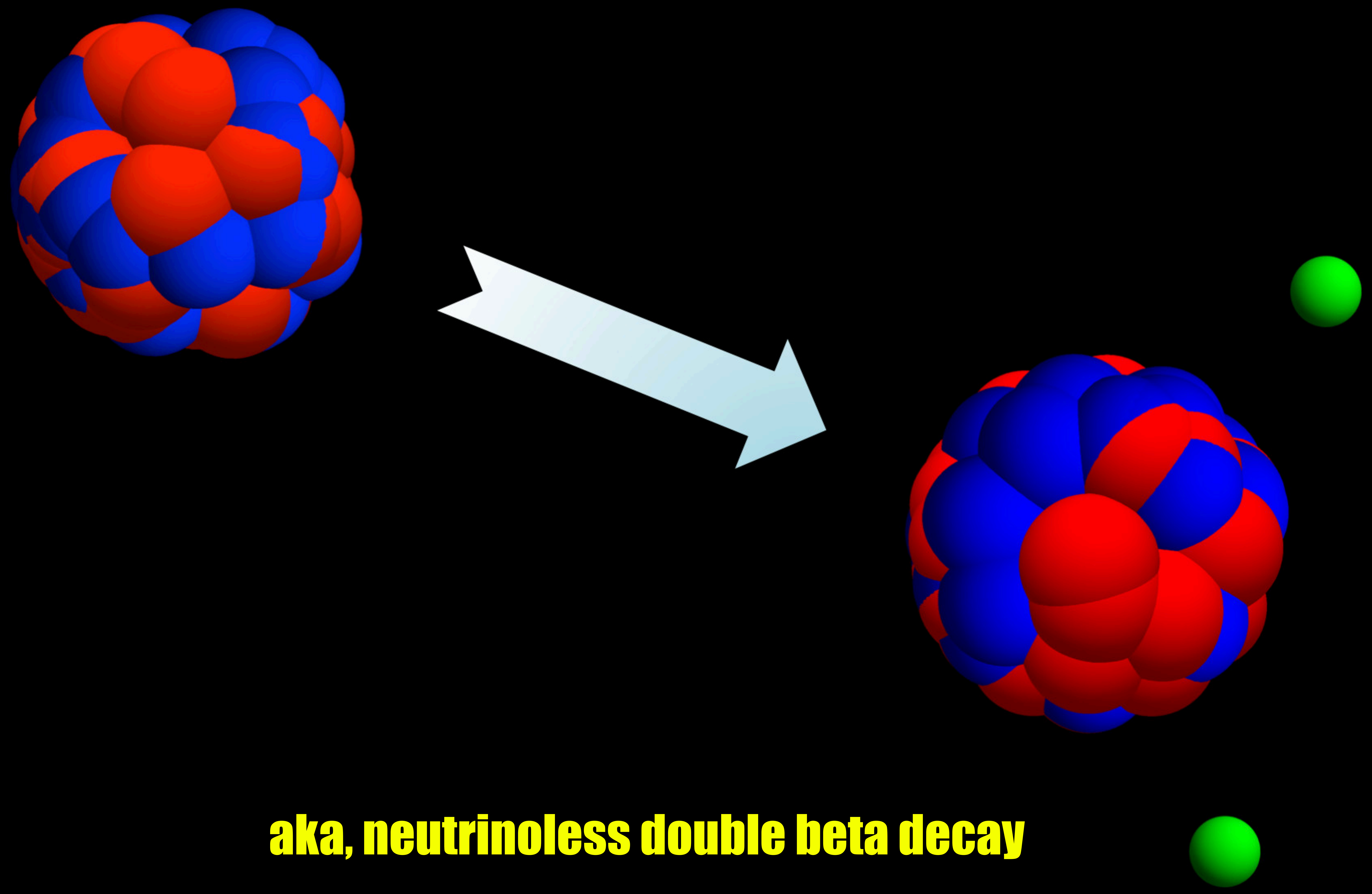


The neutrino of Majorana is matter and antimatter at the same time:
it leads to the creation of a couple of electrons





electron creation



aka, neutrinoless double beta decay

Several experiments at the Gran Sasso labs and elsewhere are looking for evidence…

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

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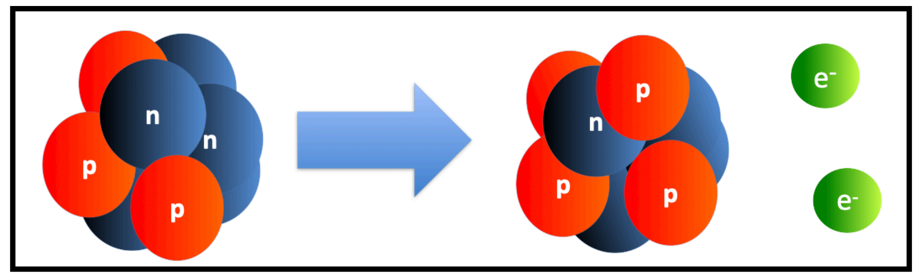
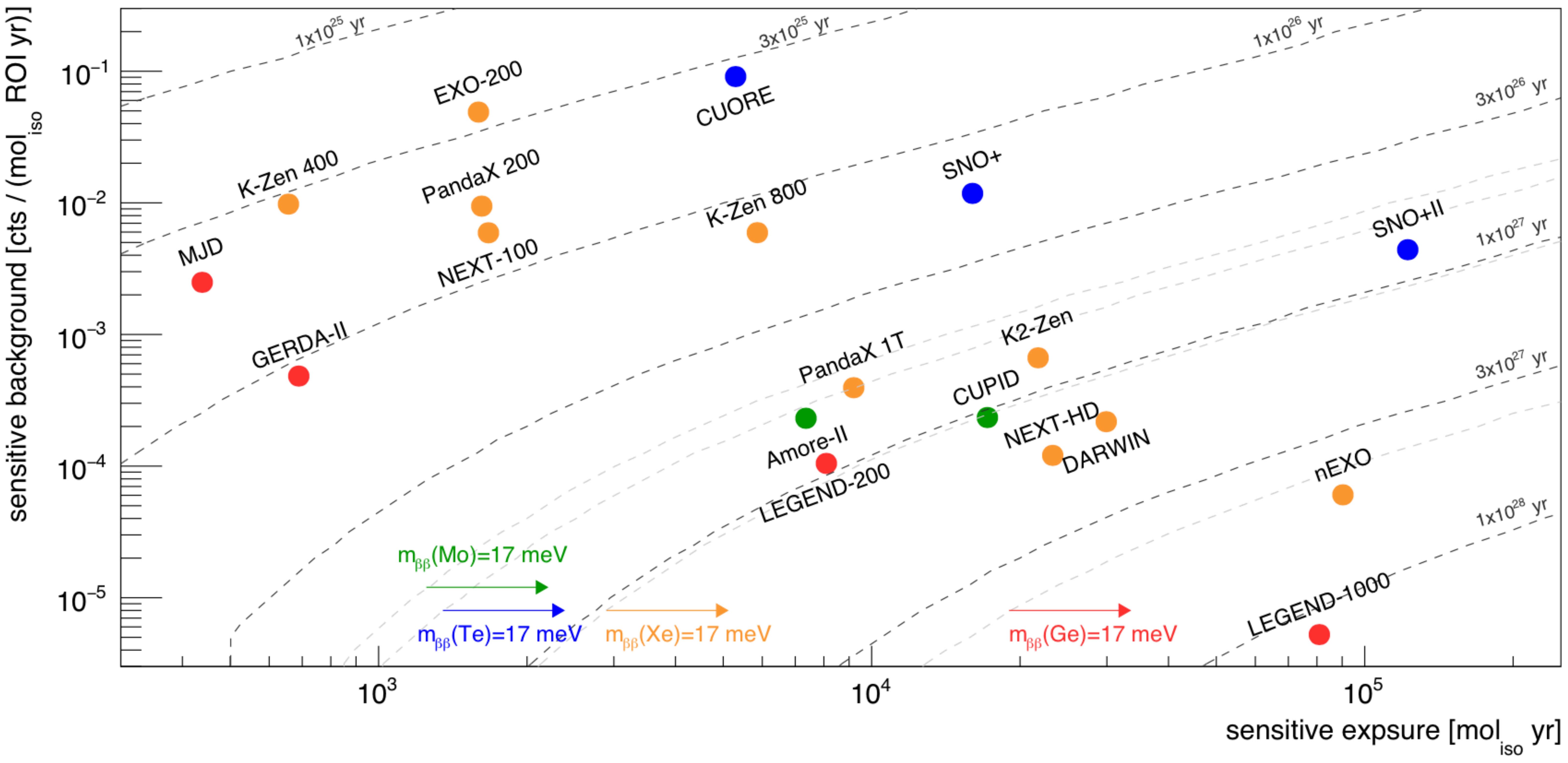
(Dated: September 24, 2021)

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.





insights on Dirac equation and formal introduction to Majorana ideas

insights into the Dirac equation
to reason about neutrinos instead of electrons

Dirac's equation is essential for dealing with fermions, including neutrinos.

insights into the Dirac equation

to reason about neutrinos instead of electrons

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But it was developed for atomic physics, where the motions are non-relativistic; initially Dirac stressed the theory of the spin and Landé factor (!)

The Quantum Theory of the Electron.

By P. A. M. Dirac, St. John's College, Cambridge.

(Communicated by R. H. Fowler, F.R.S.—Received January 2, 1928.)

The new quantum mechanics, when applied to the problem of the structure of the atom with point-charge electrons, does not give results in agreement with experiment. The discrepancies consist of " duplexity " phenomena, the observed number of stationary states for an electron in an atom being twice the number given by the theory. To meet the difficulty, Goudsmit and Uhlenbeck have introduced the idea of an electron with a spin angular momentum of half a quantum and a magnetic moment of one Bohr magneton. This model for the electron has been fitted into the new mechanics by Pauli,* and Darwin,†

insights into the Dirac equation

to reason about neutrinos instead of electrons

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But it was developed for atomic physics, where the motions are non-relativistic; initially Dirac stressed the theory of the spin and Landé factor (!)

To understand neutrinos well, it is useful to deepen at least these aspects

- its Lorentz structure **Weyl 1929**
- the formal origin of antiparticles **Stueckelberg 1941**
- the treatment of neutral particles **Majorana 1937**

spinors and relativity

let us begin with **rotations**, part of Lorentz group

As it is well-known, spinors transform with half-angles

$$\delta\psi = -\frac{i\,\vec{\theta}\,\vec{\sigma}}{2}\,\psi$$

With them, we can define one *scalar* and *axial vector* (=polarization)

$$S = \psi^\dagger\psi \qquad \text{and} \qquad \vec{V} = \psi^\dagger\vec{\sigma}\psi$$

that transform as expected, e.g.

$$\delta\vec{V} = \vec{\theta}\wedge\vec{V}$$

[check it]

spinors and relativity

let us continue with **velocity transformations**

Under **boosts**, spinors transform as

$$\delta\psi = +\frac{\vec{\eta}\,\vec{\sigma}}{2}\,\psi$$

One uses them with the quantity *already* defined

$$S = \psi^\dagger\psi \qquad \text{and} \qquad \vec{V} = +\psi^\dagger\vec{\sigma}\psi$$

and we find

$$\delta S = \vec{\eta}\,\vec{V} \qquad \text{and} \qquad \delta\vec{V} = \vec{\eta}\,S$$

[check it]

spinors and relativity

let us continue with **velocity transformations**

Under **boosts**, spinors transform (alternatively) as

$$\delta\psi = -\frac{\vec{\eta}\,\vec{\sigma}}{2}\,\psi$$

One uses them with the quantity *already* defined (in an alternative manner)

$$S = \psi^{\dagger}\psi \qquad \text{and} \qquad \vec{V} = -\,\psi^{\dagger}\vec{\sigma}\,\psi$$

and we find

$$\delta S = \vec{\eta}\;\vec{V} \qquad \text{and} \qquad \delta\vec{V} = \vec{\eta}\;S$$

[check it]

spinors and relativity

summary

There are **two types** of bi-spinors in relativity (Weyl)

$$\delta\psi_{\pm} = -\frac{i\,\vec{\theta}\,\vec{\sigma}}{2}\,\psi_{\pm} \quad , \quad \delta\psi_{\pm} = \pm\frac{\vec{\eta}\,\vec{\sigma}}{2}\,\psi_{\pm}$$

spinors and relativity

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we better think in terms of 4-vectors

$$V^0 \equiv S = \psi_{\pm}^{\dagger}\psi_{\pm} \qquad \text{and} \qquad \vec{V} = \pm\,\psi_{\pm}^{\dagger}\,\vec{\sigma}\,\psi_{\pm}$$

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and, with a suitable definition of the 6 parameters $\omega^{\mu\nu} = -\,\omega^{\nu\mu}$, we have

$$\delta V^{\mu} = \omega^{\mu}_{\ \nu}\, V^{\nu}$$

[obtain it by yourself]

spinors and relativity

one revision exercise

consider the lagrangian density

$$\mathscr{L} = i\, \psi_+^\dagger\, \sigma^\mu\, \partial_\mu \psi_+ \quad \text{with} \quad \sigma^\mu = (\sigma^0, \vec{\sigma})$$

and the associated wave-equation

$$i\, \sigma^\mu \partial_\mu\, \psi_+ = 0$$

show that the positive energy solution represents a massless particle with positive helicity

formal origin of antiparticles

generalities

The coupling to electromagnetic interactions is described replacing

$$P_\mu \to \mathscr{P}_\mu = P_\mu - qA_\mu \quad \text{where} \quad P_\mu = i\hbar\,\partial_\mu$$

formal origin of antiparticles

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Let us discuss the cases of scalar particles (described by Klein-Gordon equation) and the one of fermions (described by Dirac's equation)

formal origin of antiparticles

the case of scalar particles

Consider the simplest wave equation for an incoming wave

$$(\mathscr{P}_\mu \mathscr{P}^\mu - m^2)\ \varphi = ((P_\mu - qA_\mu)^2 - m^2)\ \varphi = 0$$

formal origin of antiparticles

the case of scalar particles

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the outgoing wave φ^* satisfies automatically

$$((\mathscr{P}_\mu \mathscr{P}^\mu)^* - m^2)\ \varphi^* = ((P_\mu + qA_\mu)^2 - m^2)\ \varphi^* = 0$$

formal origin of antiparticles

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waves with “negative energies” can be thought as regular waves with $q \to -q$

formal origin of antiparticles

the case of spinorial particles

Dirac' equation

$$(\mathscr{P}_\mu \gamma^\mu - m)\, \psi = ((P_\mu - qA_\mu)\, \gamma^\mu - m)\, \psi = 0$$

use Majorana representation, such as $\gamma_\mu^* = -\gamma_\mu$, finding

formal origin of antiparticles

the case of spinorial particles

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formal origin of antiparticles

the case of spinorial particles

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neutral particles

there are particles such as the photon or the π^0 which coincide with their own antiparticles, other instead such as the neutron or the K^0 that instead don't

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we do not know in which class neutrino is

Majorana (1937) proposed that they are in the first class (completely neutral, or real)

In this case their quantised field would obey,

$$\Psi = \Psi^*$$

[Majorana representation of gamma matrices]

neutral particles

there are particles such as the photon or the π^0 which coincide with their own antiparticles, other instead such as the neutron or the K^0 that instead don't

we do not know in which class neutrino is

Majorana (1937) proposed that they are in the first class (completely neutral, or real)

In this case their quantised field would obey,

$$\Psi = C\,\overline{\Psi}^t$$

[generic representation of gamma matrices]

consolidation exercises

- ✱ study the three most common representations of the gamma-matrices: Dirac's, Weyl's, Majorana and in particular:

1. obtain the expressions of the **charge conjugation** matrix C
2. obtain the expressions of the **chirality** matrix γ_5

- ✱ write down the equation of motion of free 4-fermions in the Weyl representation and compare it with that of 2-fermions
- ✱ show that a Majorana fermion does not couple to the photon, neither by charge, nor by magnetic moment

how we use this...

Given a set of masses m_i and of real fields, $\boldsymbol{\chi}_i = C\overline{\boldsymbol{\chi}_i}^t$,

$$\mathcal{L}_{\text{Majorana}} = -\frac{1}{2} m_i \, \overline{\boldsymbol{\chi}}_i \boldsymbol{\chi}_i$$

E.g., with the 3 known neutrinos $\boldsymbol{\nu}_\ell$ define

$$\boldsymbol{\chi}_i = U^*_{\ell i} \, \boldsymbol{\nu}_\ell + U_{\ell i} \, C\overline{\boldsymbol{\nu}_\ell}^t \quad \begin{cases} \ell = \mathrm{e}, \mu, \tau \\ i = 1, 2, 3 \end{cases}$$

then the Lagrangian density reads,

$$\mathcal{L}_{\text{Majorana}} = -\frac{1}{2} m_{\nu,\ell\ell'} \, \overline{\boldsymbol{\nu}_\ell} C \overline{\boldsymbol{\nu}_{\ell'}}^t + \frac{1}{2} m^*_{\nu,\ell\ell'} \, \boldsymbol{\nu}^t_\ell C^\dagger \boldsymbol{\nu}_{\ell'}$$

with the complex symmetric mass matrix

$$\boldsymbol{m}_\nu = \boldsymbol{U} \, \text{diag}(m) \boldsymbol{U}^t$$

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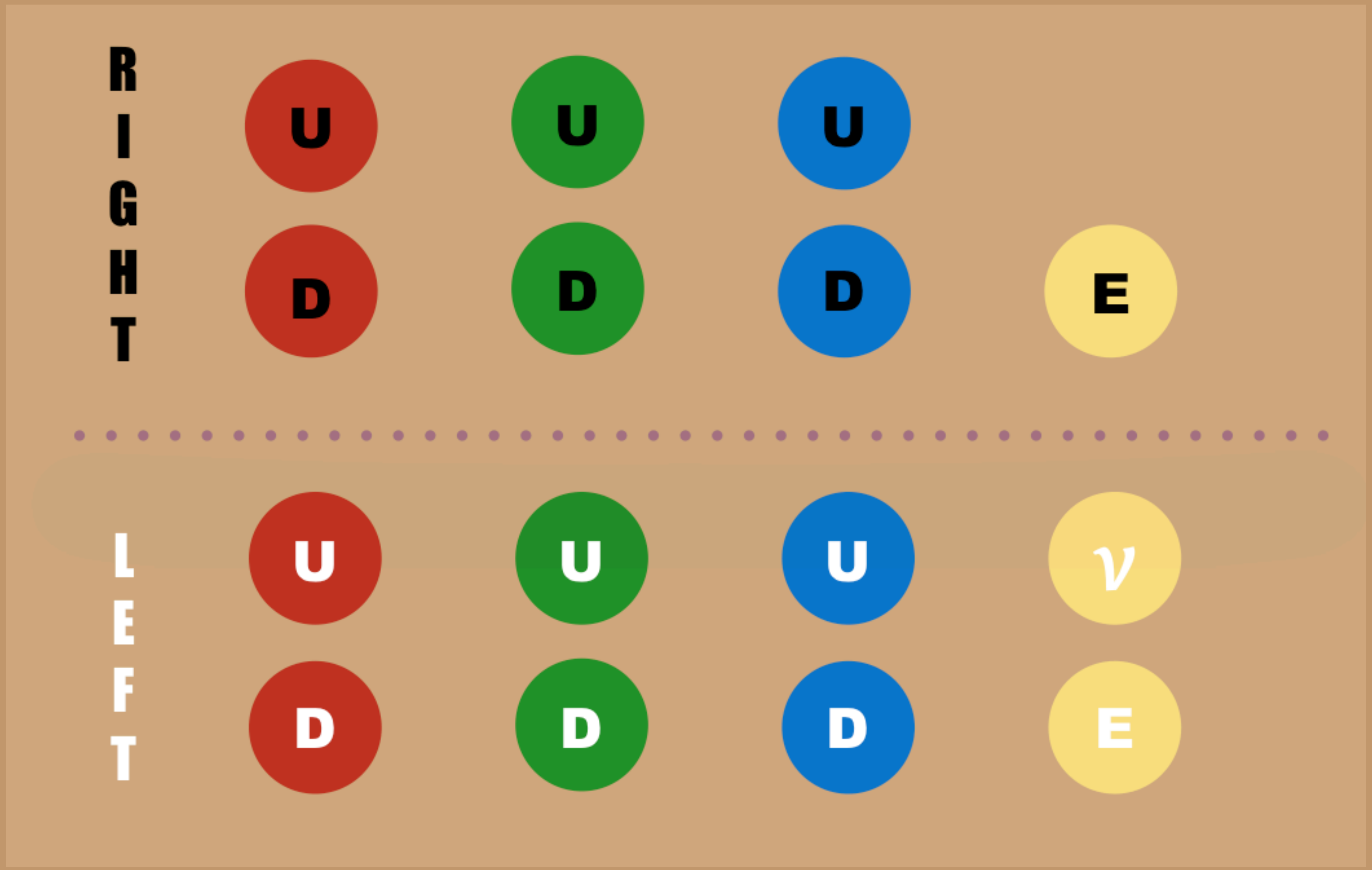
$$\boldsymbol{m}_\nu = \boldsymbol{U} \,\text{diag}(m) \boldsymbol{U}^t$$

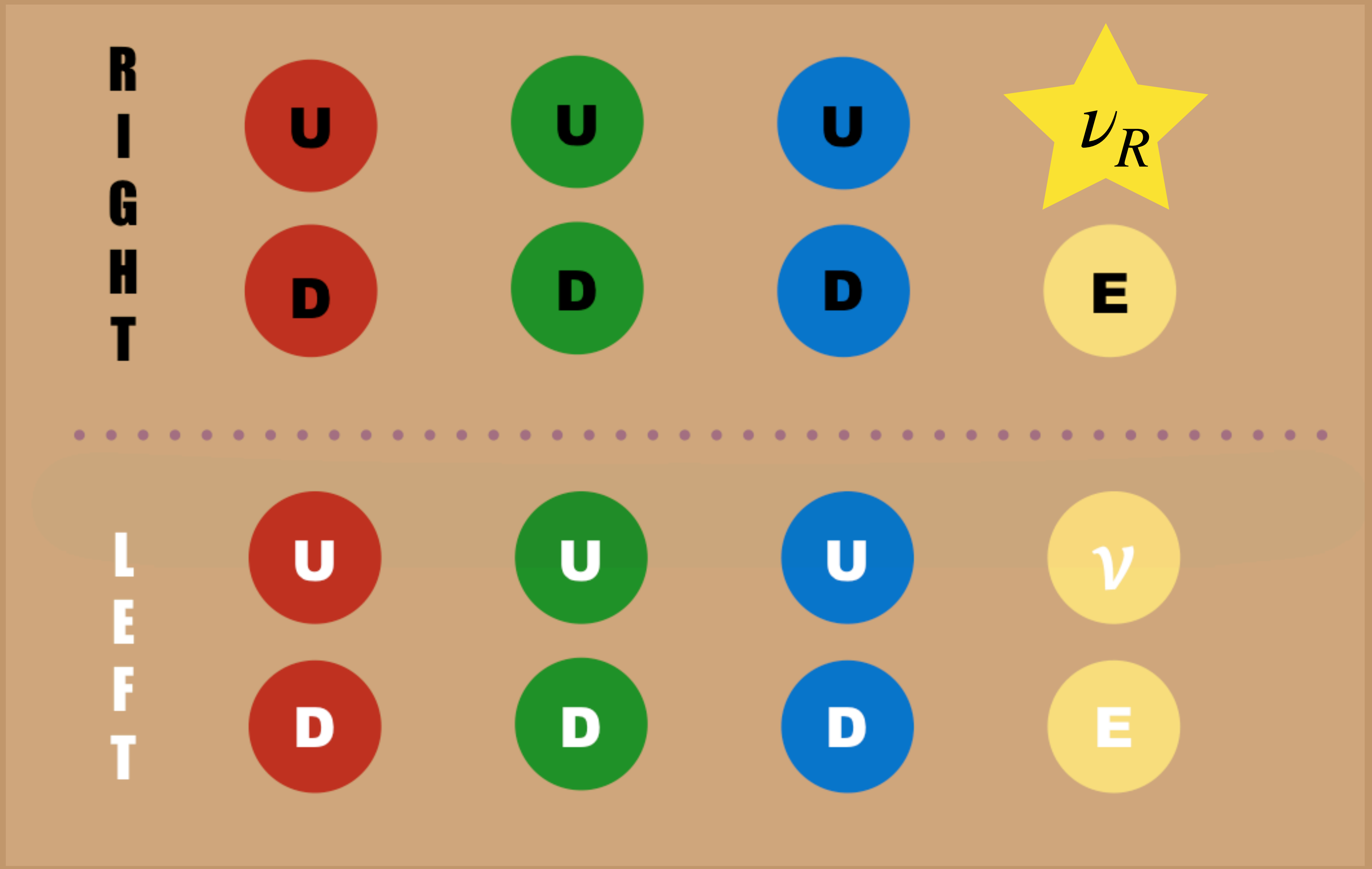
evolution of gauge models



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

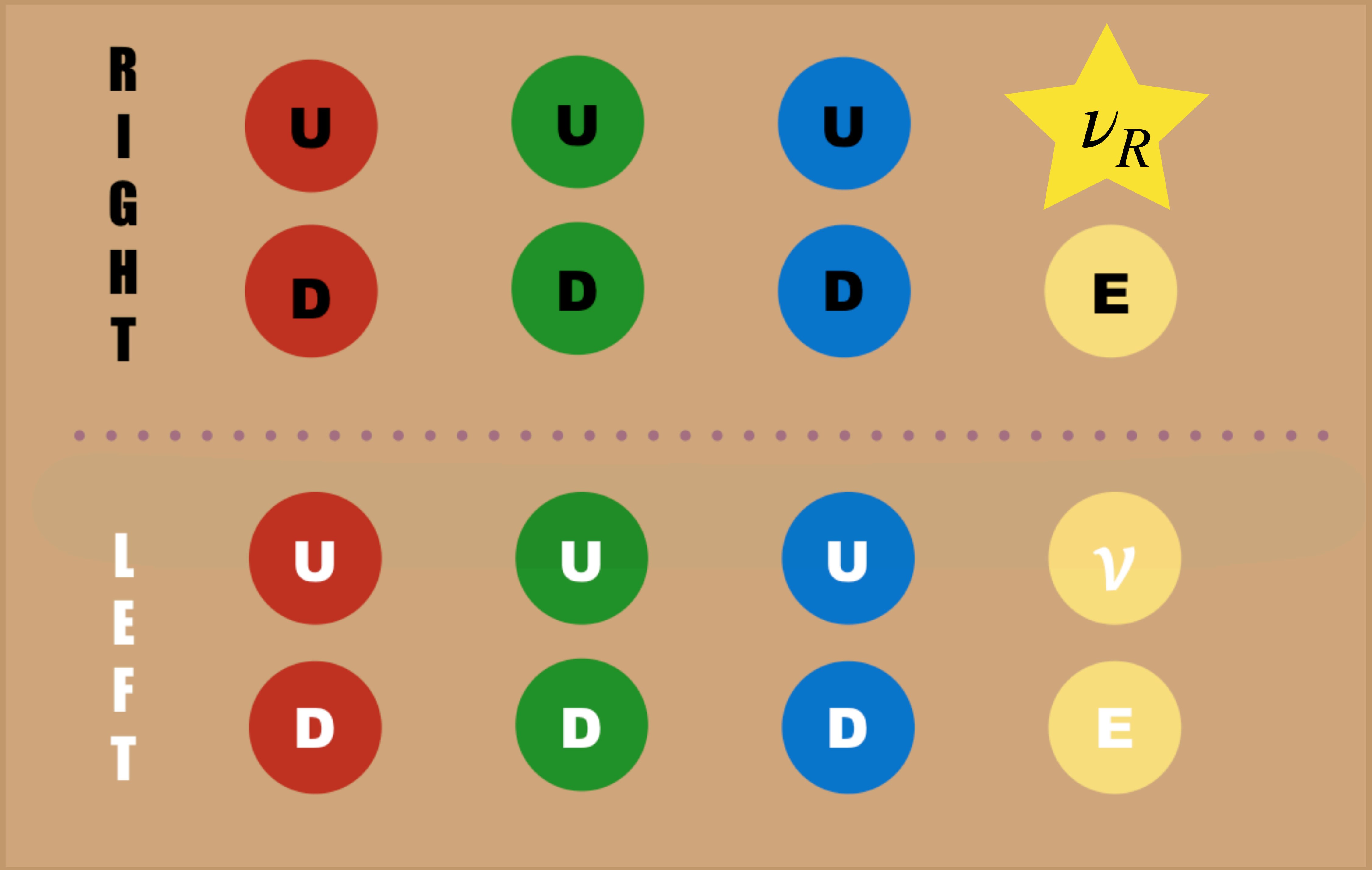
this new representation highlights
a significant asymmetry concerning neutrinos

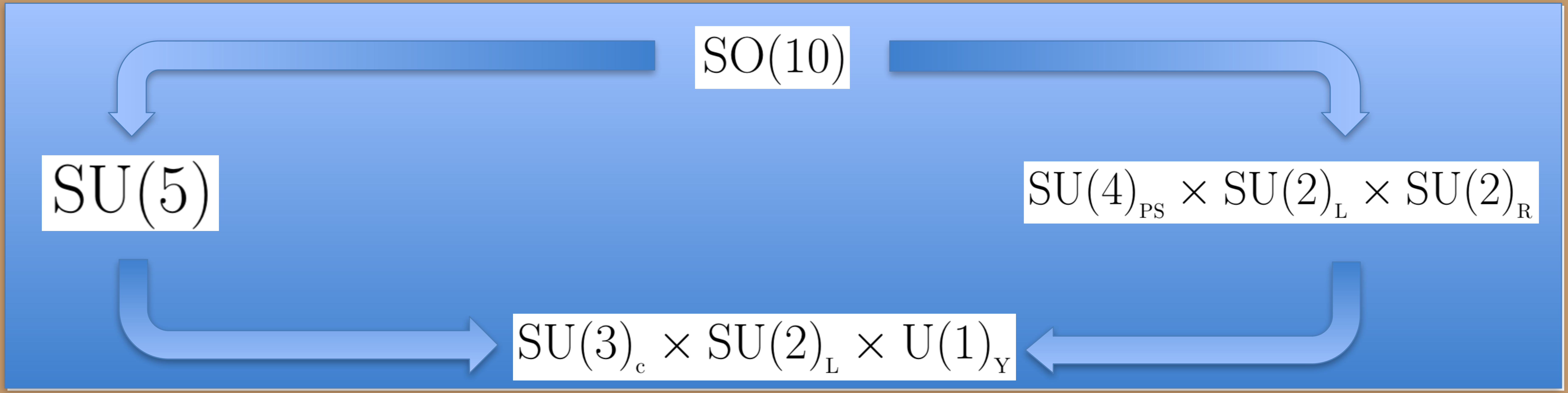
Glashow 1961; Weinberg 1967; Salam 1967; Gross & Wilczek 1973; Politzer 1973



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

Mohapatra & Pati 1975; Senjanovic & Mohapatra 1975





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

on the mass scale of heavy neutrinos

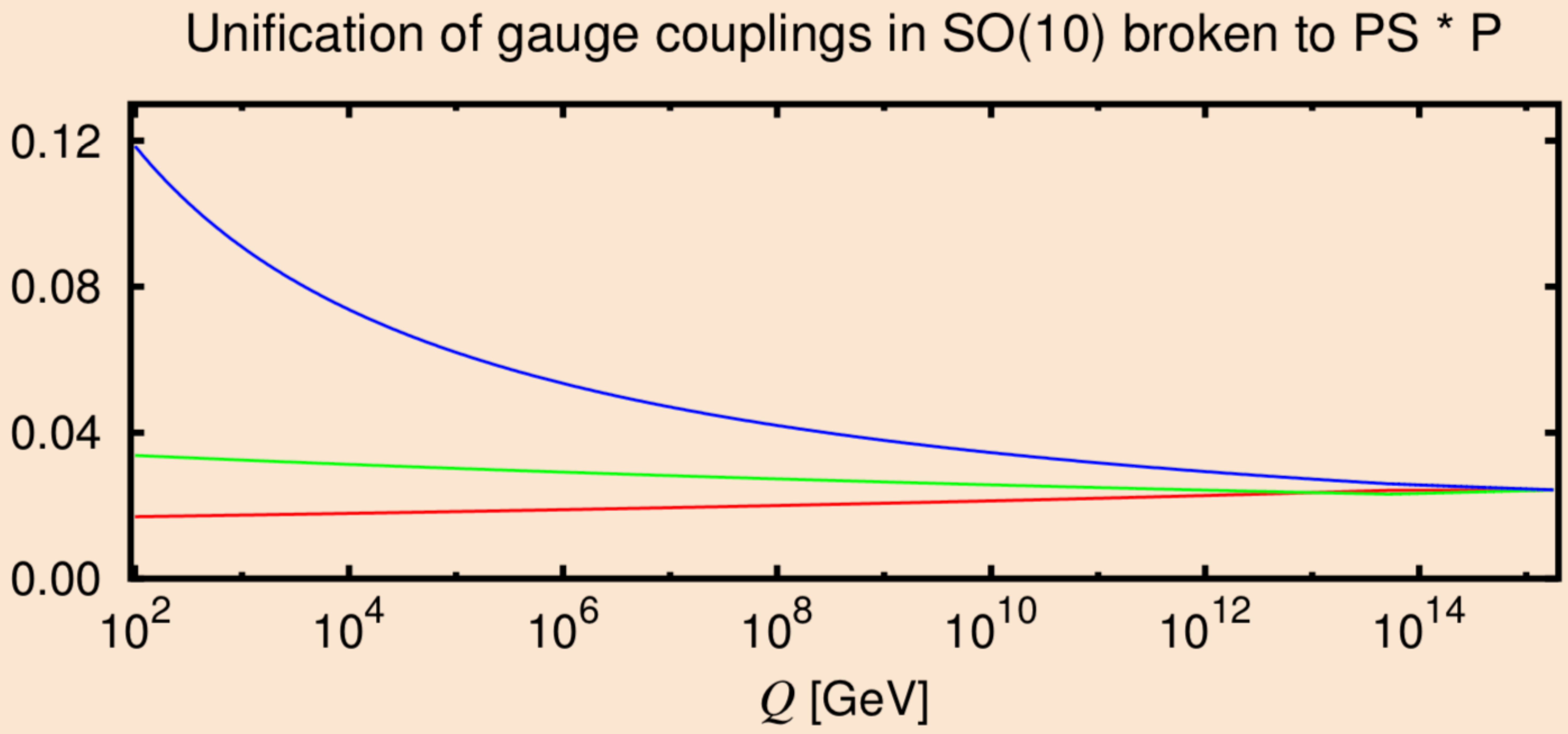
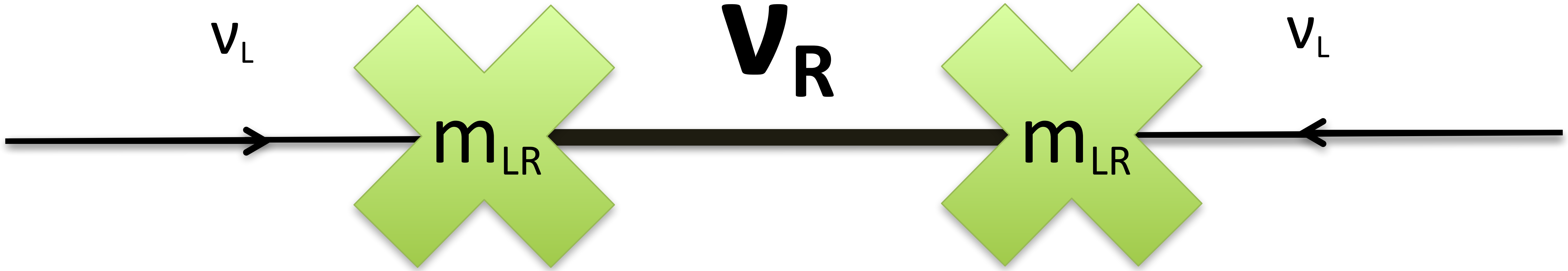


Figure 2: Evolution of the gauge coupling constants in a GUT model with intermediate scale. Here, $M_{\text{interm.}} \approx 5 \times 10^{13}$ GeV.

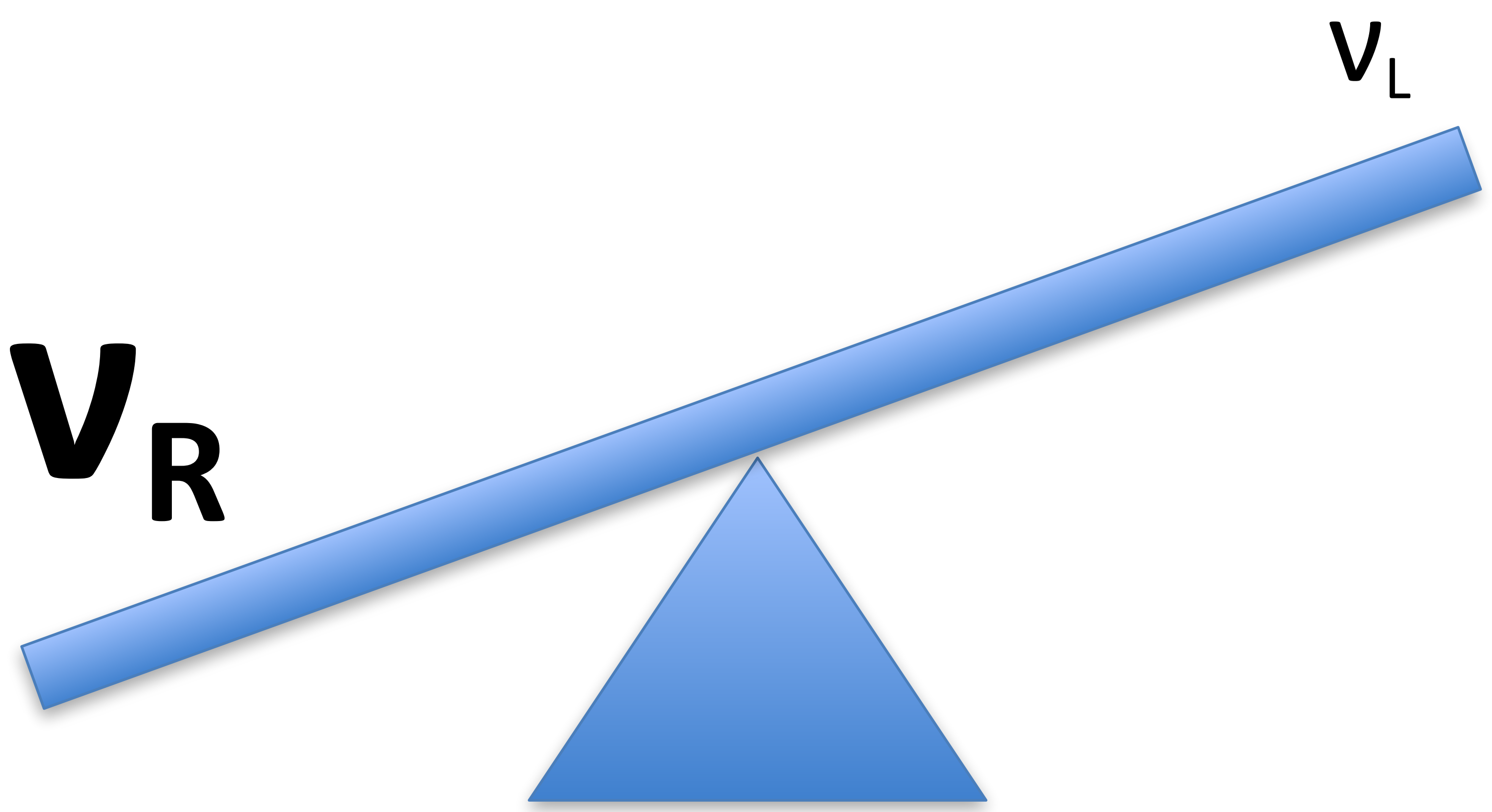
FV at the Cryodet meeting at Gran Sasso lab (2006) if the new neutrinos ν_R are heavy enough, the ordinary ones take on a small mass, just as we observe



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

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

$$\boldsymbol{H} = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \quad \boldsymbol{L}_\ell = \begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix} \text{ with } \ell = \text{e}, \mu, \tau$$

$$\boldsymbol{LH} = \boldsymbol{L}^t\, i\sigma_2\, \boldsymbol{H} = \boldsymbol{\nu}\langle H^0\rangle + \text{2 field}$$

$$\frac{\lambda^*_{\ell\ell'}}{2M}\, \boldsymbol{L}_\ell \boldsymbol{H}\, C^\dagger\, \boldsymbol{L}_{\ell'} \boldsymbol{H} = \lambda_{\ell\ell'} \frac{\langle H^0\rangle^2}{2M} \boldsymbol{\nu}_\ell C^\dagger \boldsymbol{\nu}_{\ell'} + \text{interactions}$$

$$\boldsymbol{m}_\nu = \frac{\langle H^0\rangle^2}{2M} \boldsymbol{\lambda}$$

dim5 operator…

$$\boldsymbol{H} = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \quad \boldsymbol{L}_\ell = \begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix} \text{ with } \ell = \text{e}, \mu, \tau$$

$$\boldsymbol{LH} = \boldsymbol{L}^t\, i\sigma_2\, \boldsymbol{H} = \boldsymbol{\nu}\langle H^0\rangle + 2 \text{ field}$$

$$\frac{\lambda^*_{\ell\ell'}}{2M} \boldsymbol{L}_\ell \boldsymbol{H}\, C^\dagger\, \boldsymbol{L}_{\ell'} \boldsymbol{H} = \lambda_{\ell\ell'} \frac{\langle H^0\rangle^2}{2M} \boldsymbol{\nu}_\ell C^\dagger \boldsymbol{\nu}_{\ell'} + \text{interactions}$$

$$\boldsymbol{m}_\nu = \frac{\langle H^0\rangle^2}{2M} \boldsymbol{\lambda}$$

…yields Majorana mass in SM!

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 $\Delta\mathbf{L}$

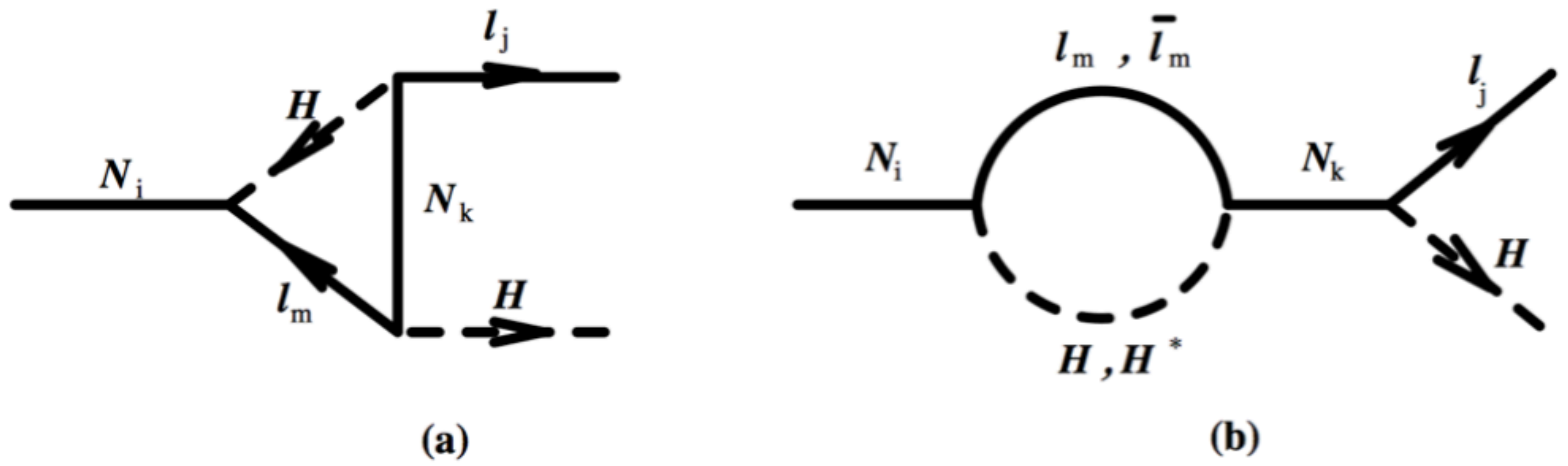


Figure 1: Diagrams contributing to the vertex (Fig. 1a) and wave function (Fig. 1b) CP violation in the heavy singlet neutrino decay.

Covi et al. '96

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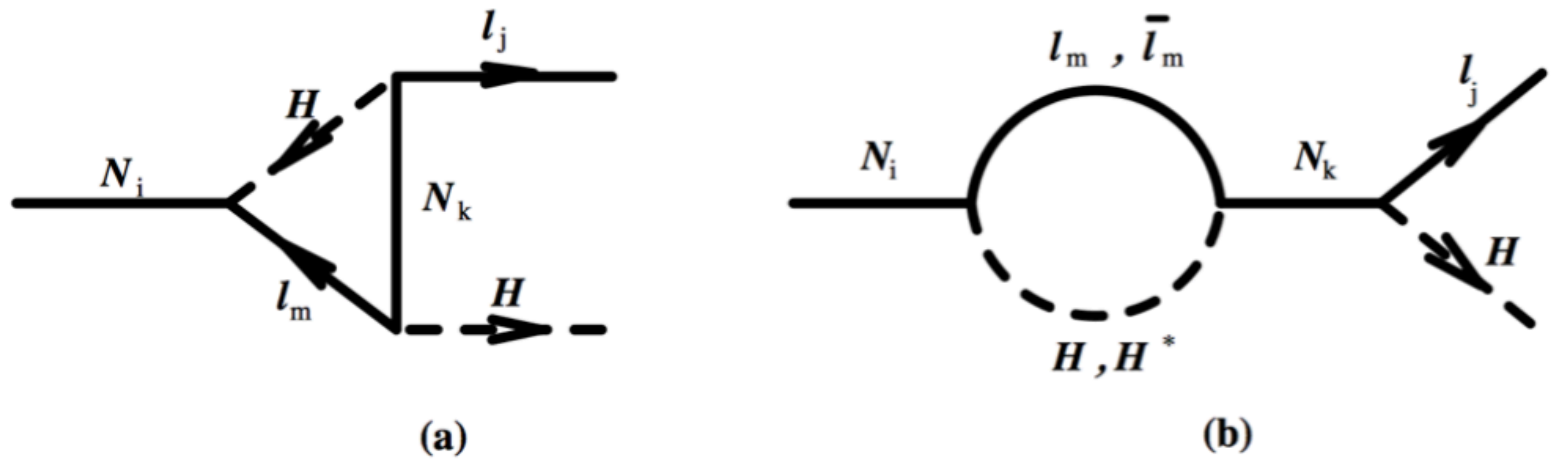
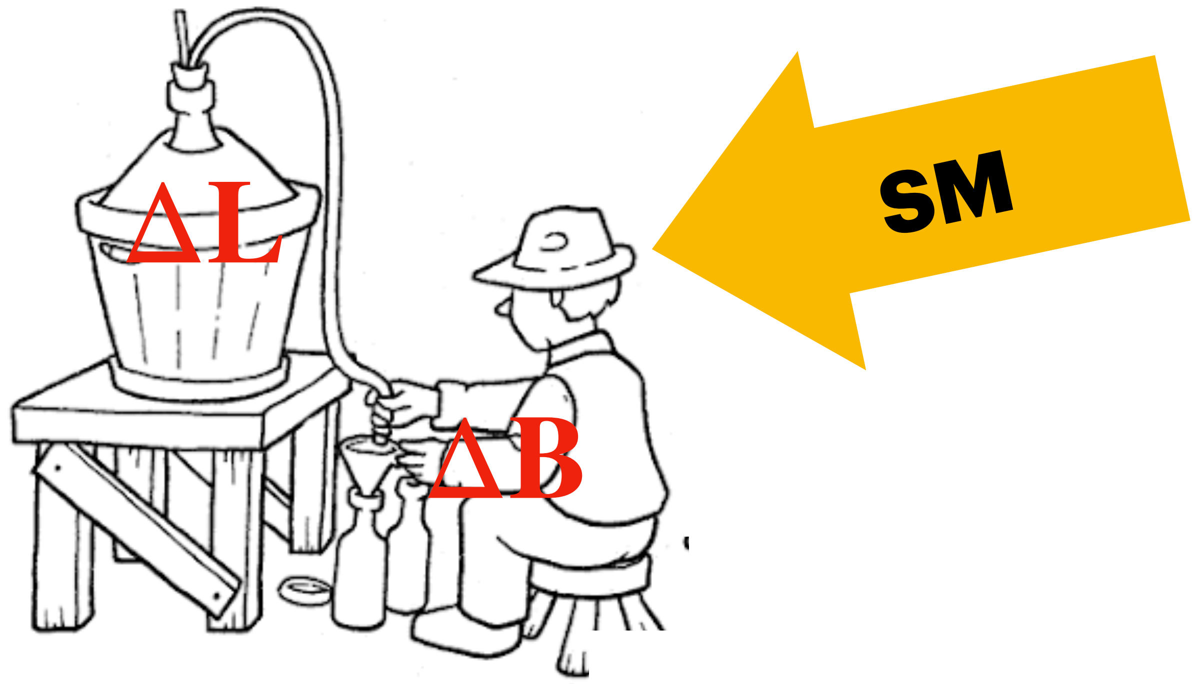


Figure 1: Diagrams contributing to the vertex (Fig. 1a) and wave function (Fig. 1b) CP violation in the heavy singlet neutrino decay.

Covi et al. '96

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

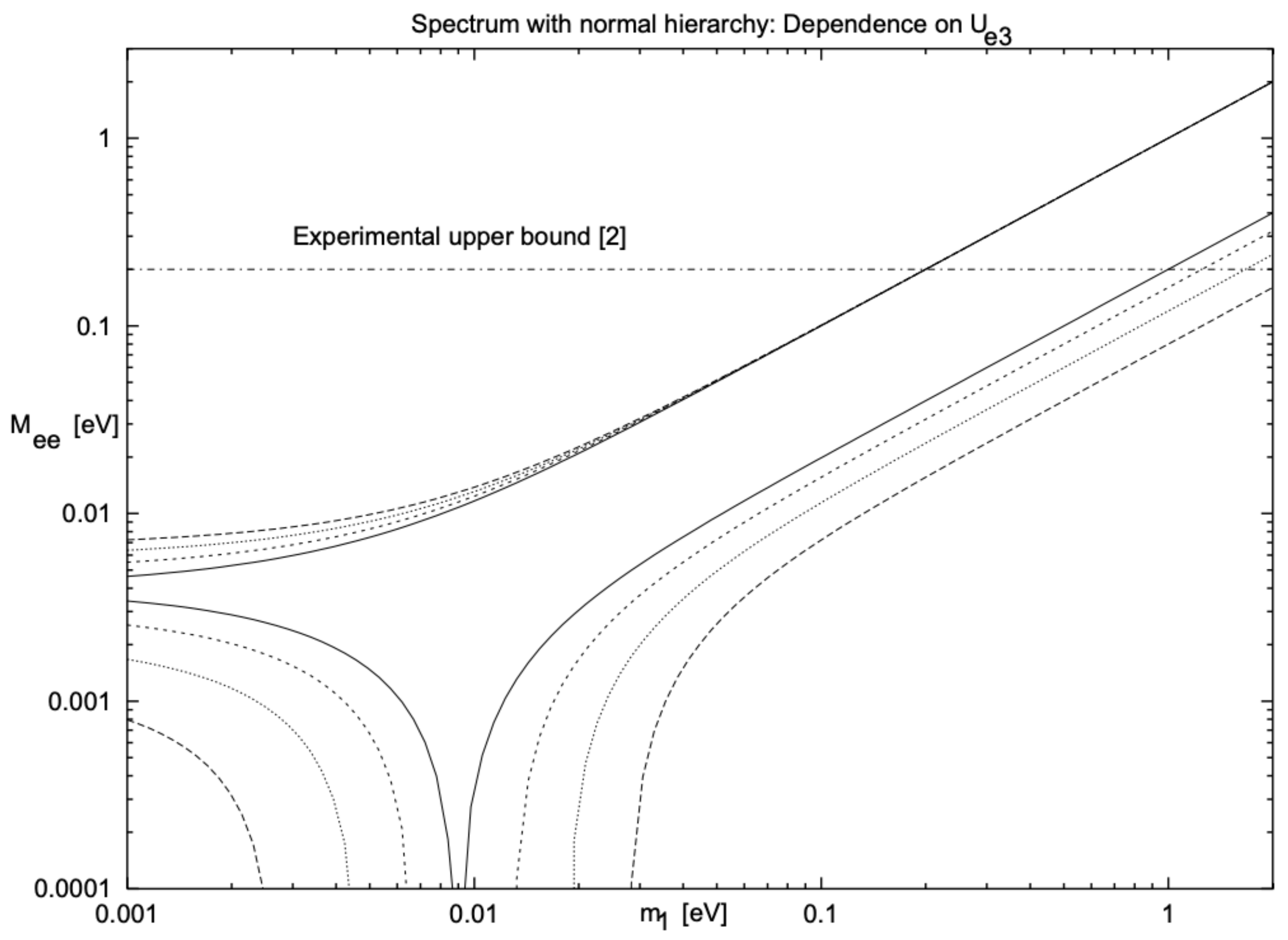


implications

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

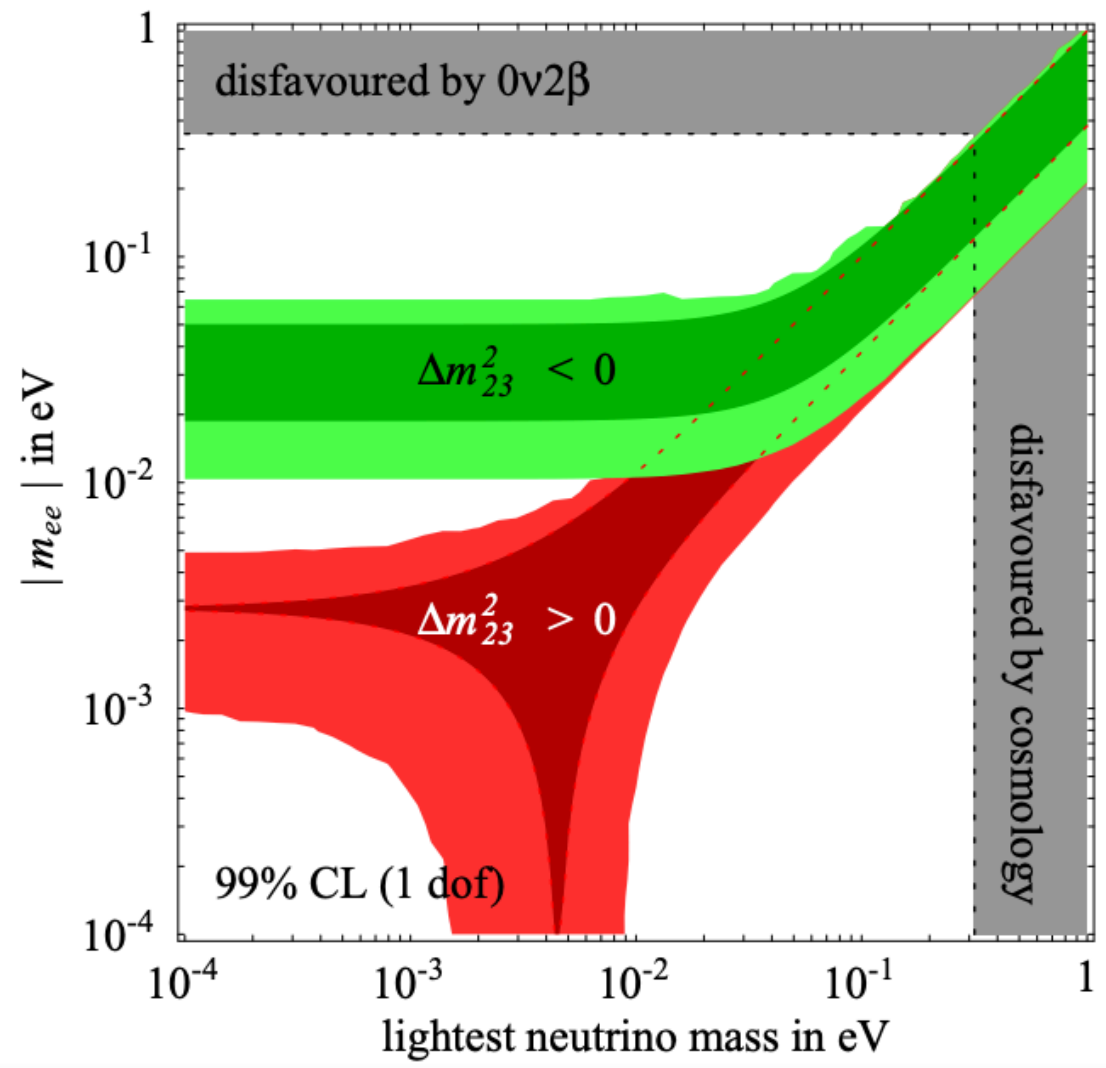
Vissani, JHEP

1999



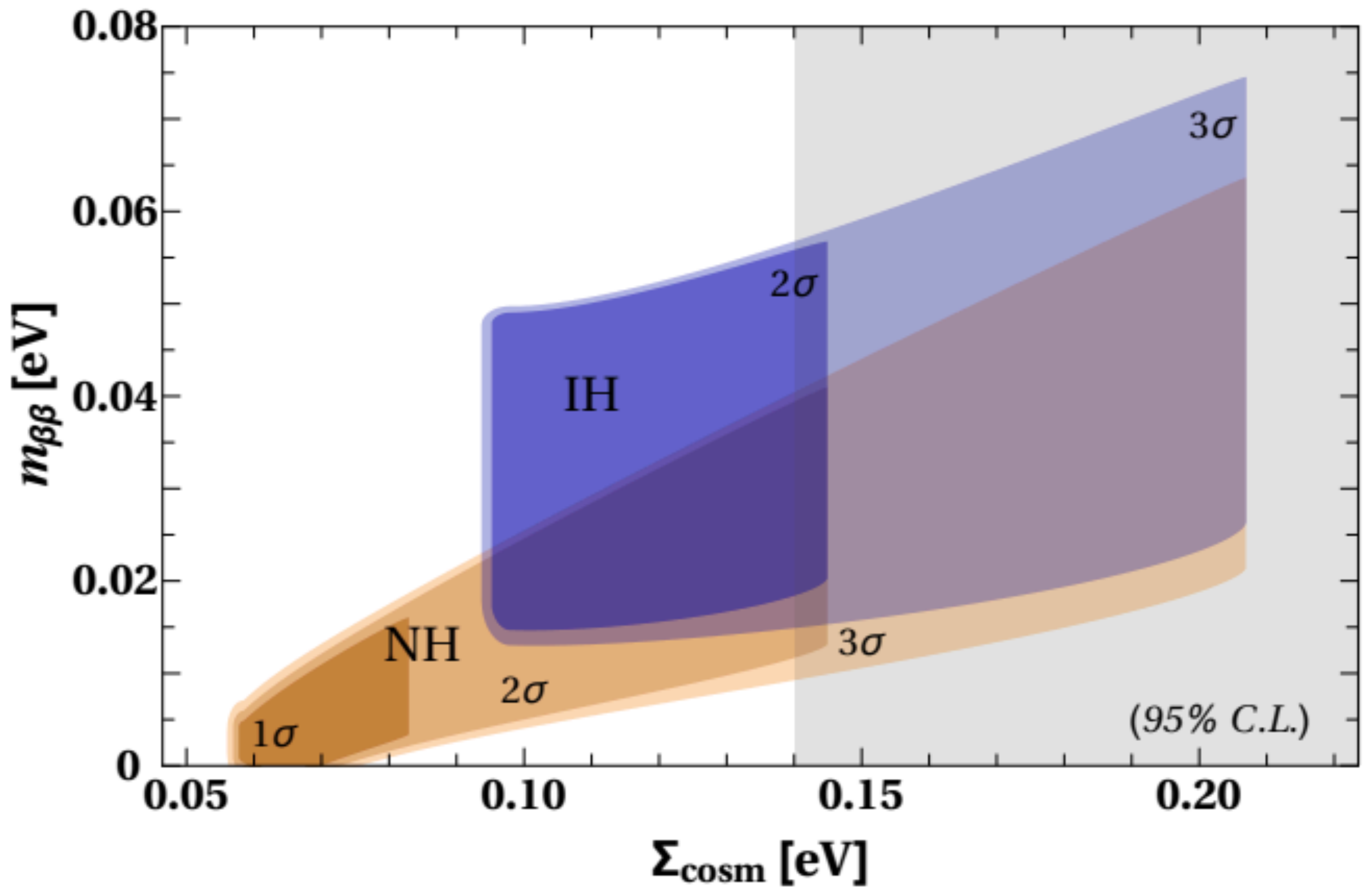
Strumia, Vissani NPB

2005



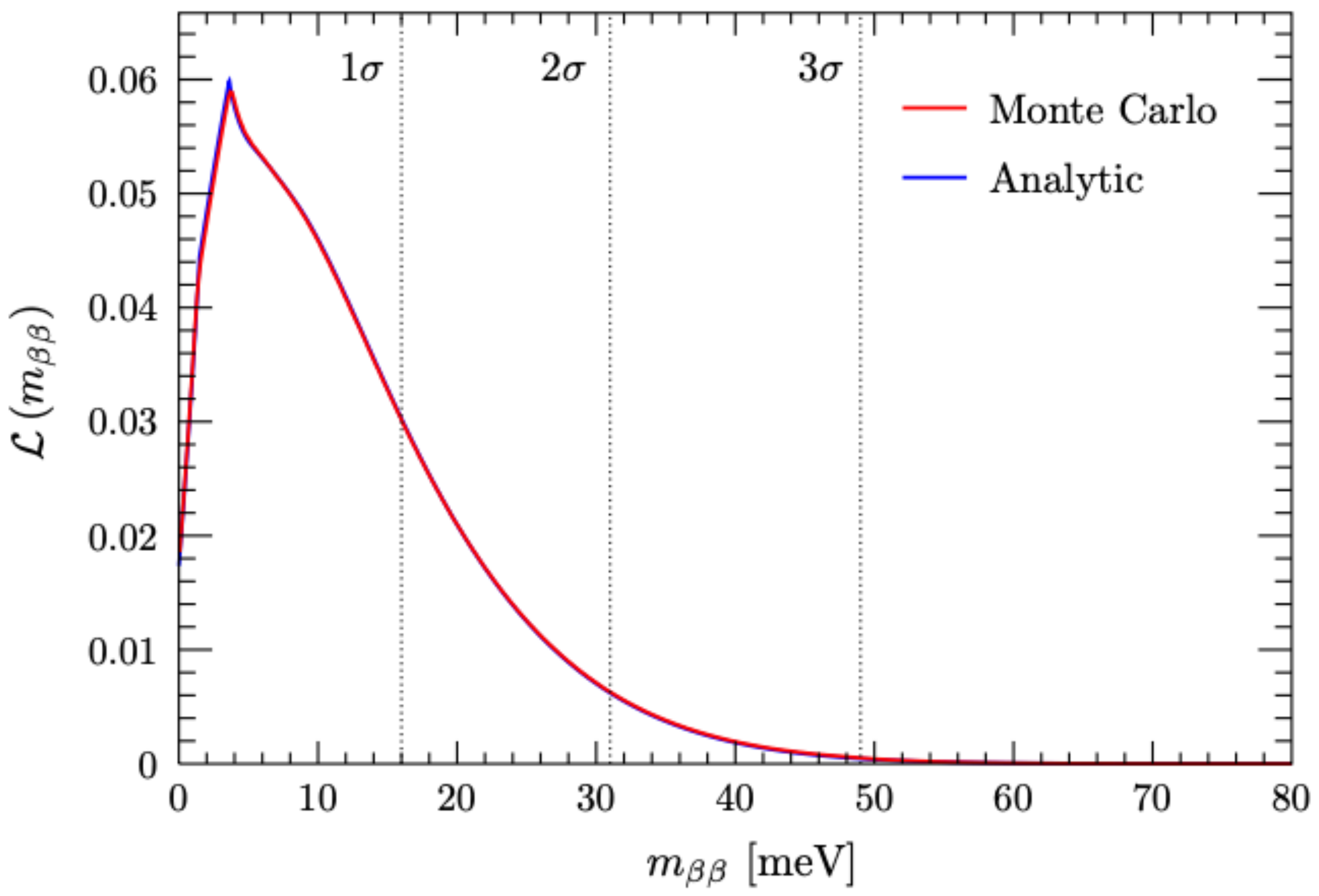
Dell'Oro, Marcocci, Vissani, PRD

2015



Dell'Oro, Marcocci, Vissani, PRD

2019



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

Matteo Agostini,[1,*] Giovanni Benato,[2,†] Jason A. Detwiler,[3,‡] Javier Menéndez,[4,§] and Francesco Vissani[2,5,¶]

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[2]*INFN, Laboratori Nazionali del Gran Sasso, 67100 Assergi, L'Aquila, Italy*
[3]*Center for Experimental Nuclear Physics and Astrophysics, and Department of Physics, University of Washington, Seattle, WA 98115 - USA*
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[5]*Gran Sasso Science Institute, 67100 L'Aquila, Italy*

(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.

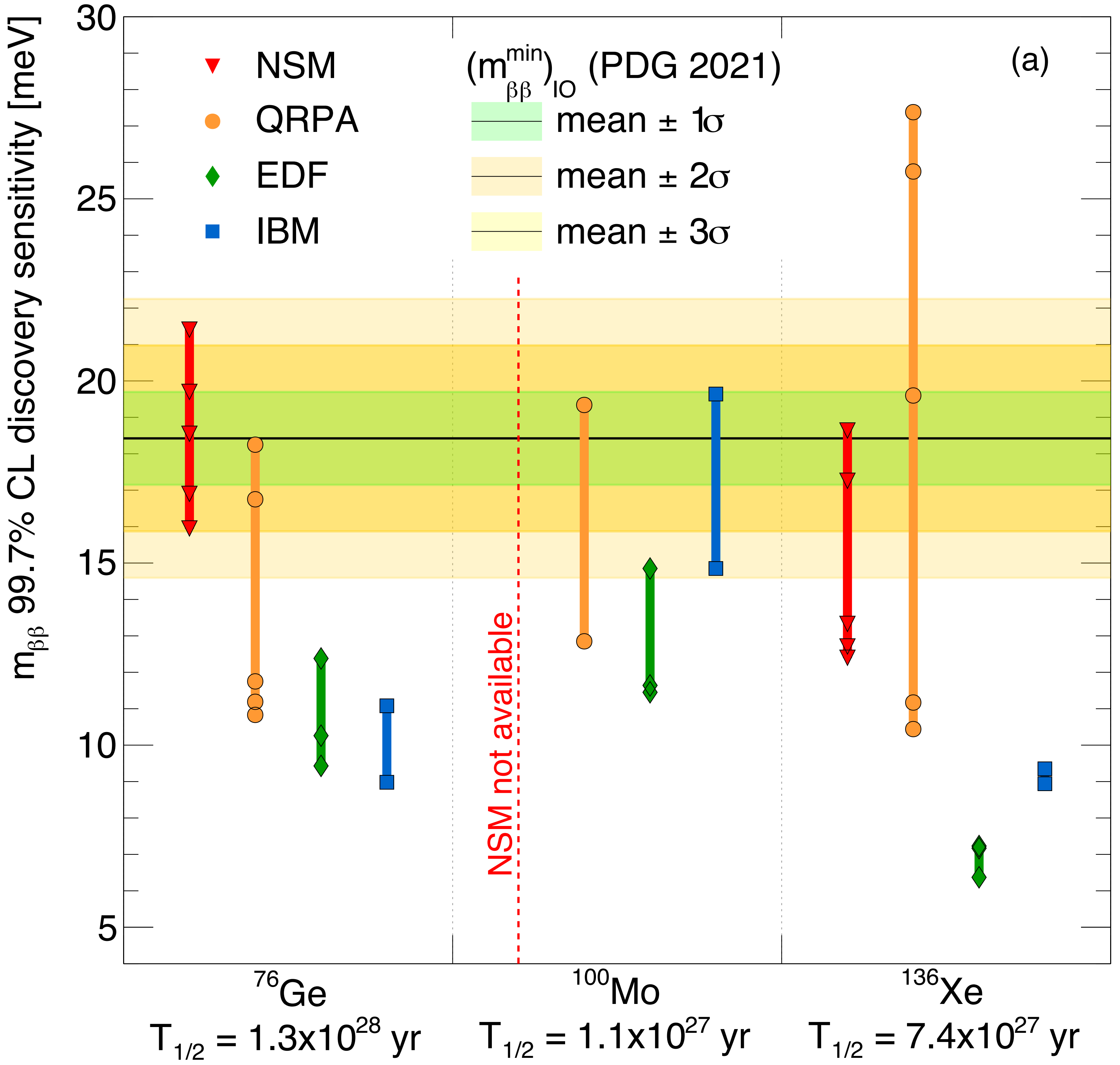
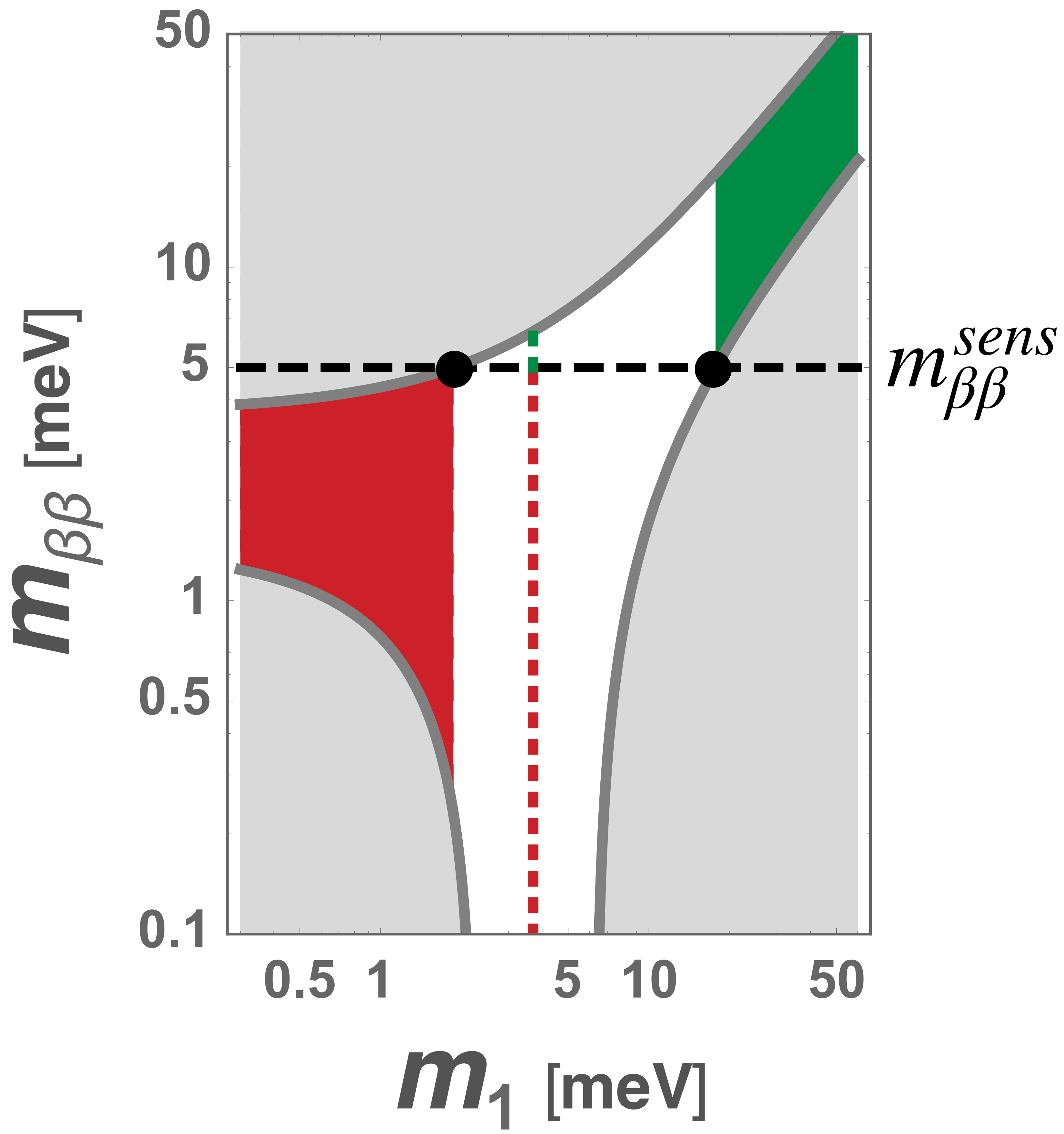


FIG. 1. Comparison of $m_{\beta\beta}$ 99.7%-CL discovery and 90%-CL median exclusion sensitivities for different isotopes at stated half-life sensitivities [30–32], grouped by nuclear many-body frameworks with matrix element ranges from Table I. The horizontal bands show the variation on $(m_{\beta\beta}^{min})_{IO}$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

Majorana neutrino masses

Given a sensitivity $m_{\beta\beta}^{sens}$ (horizontal line) the possible true values of m_1 fall in 3 subsets:

1. the true value $m_{\beta\beta}(m_1) < m_{\beta\beta}^{sens}$ (red)
2. it is more, $m_{\beta\beta}(m_1) > m_{\beta\beta}^{sens}$ (green),
3. it depends upon Majorana phases (white)



Majorana neutrino masses

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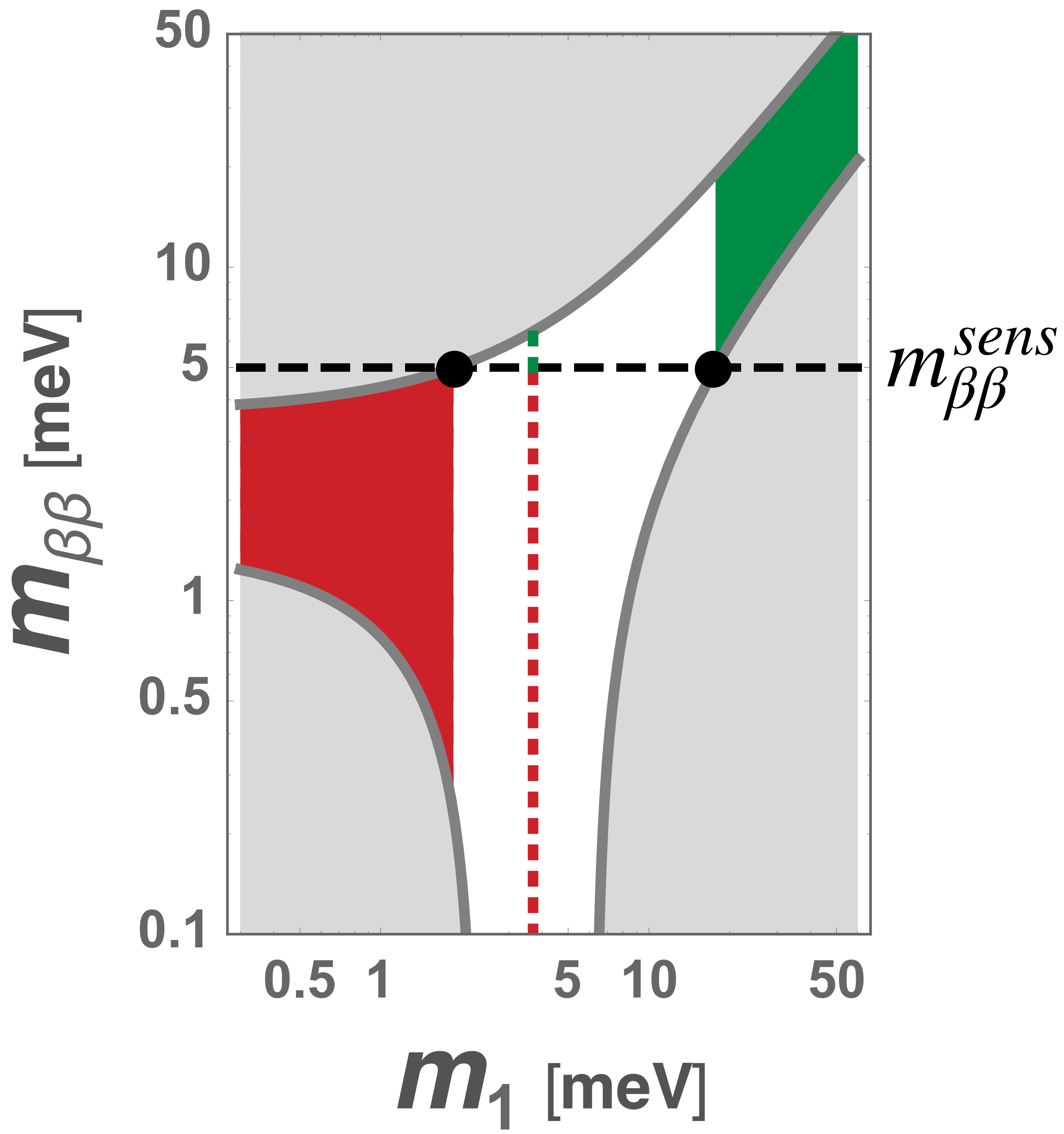
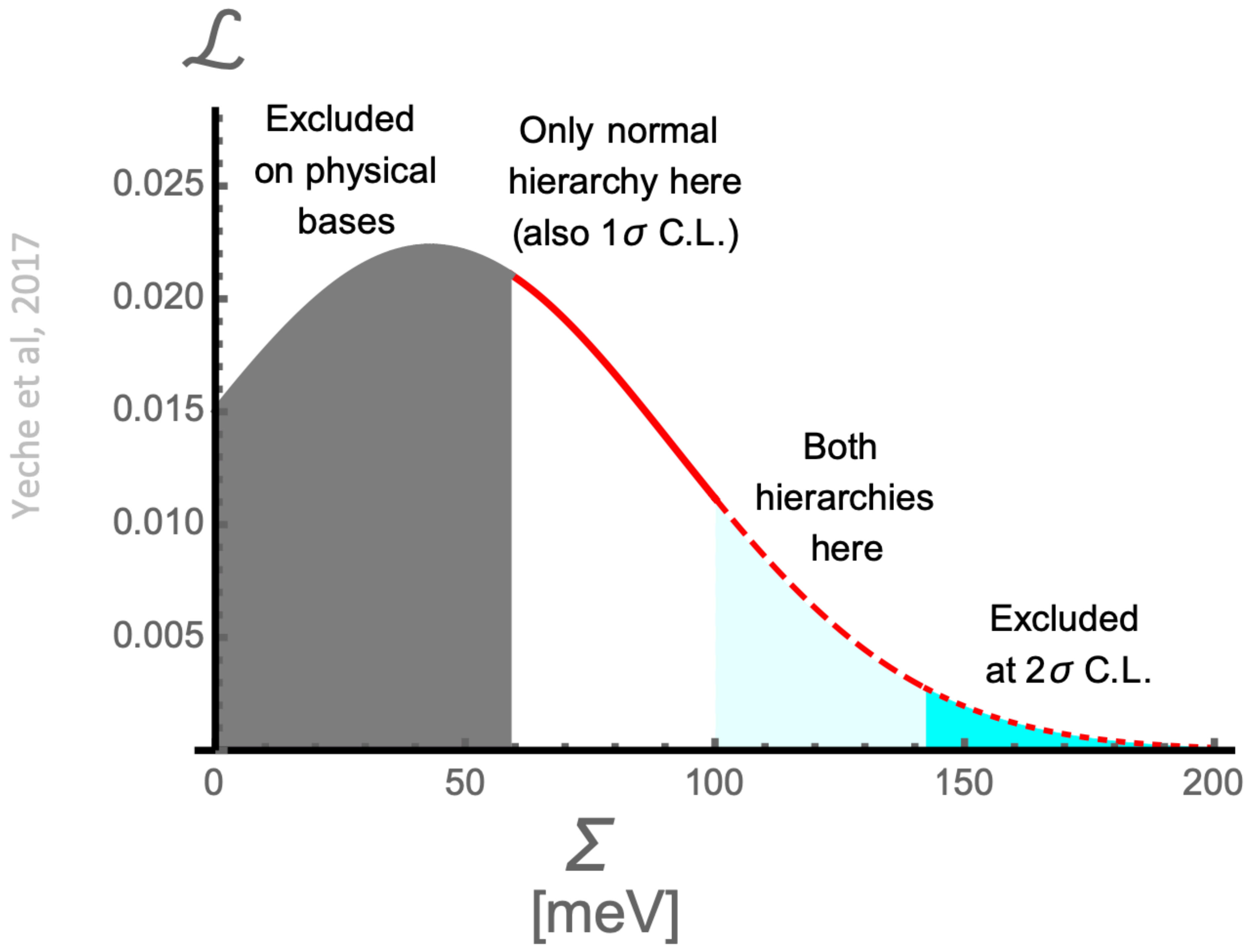
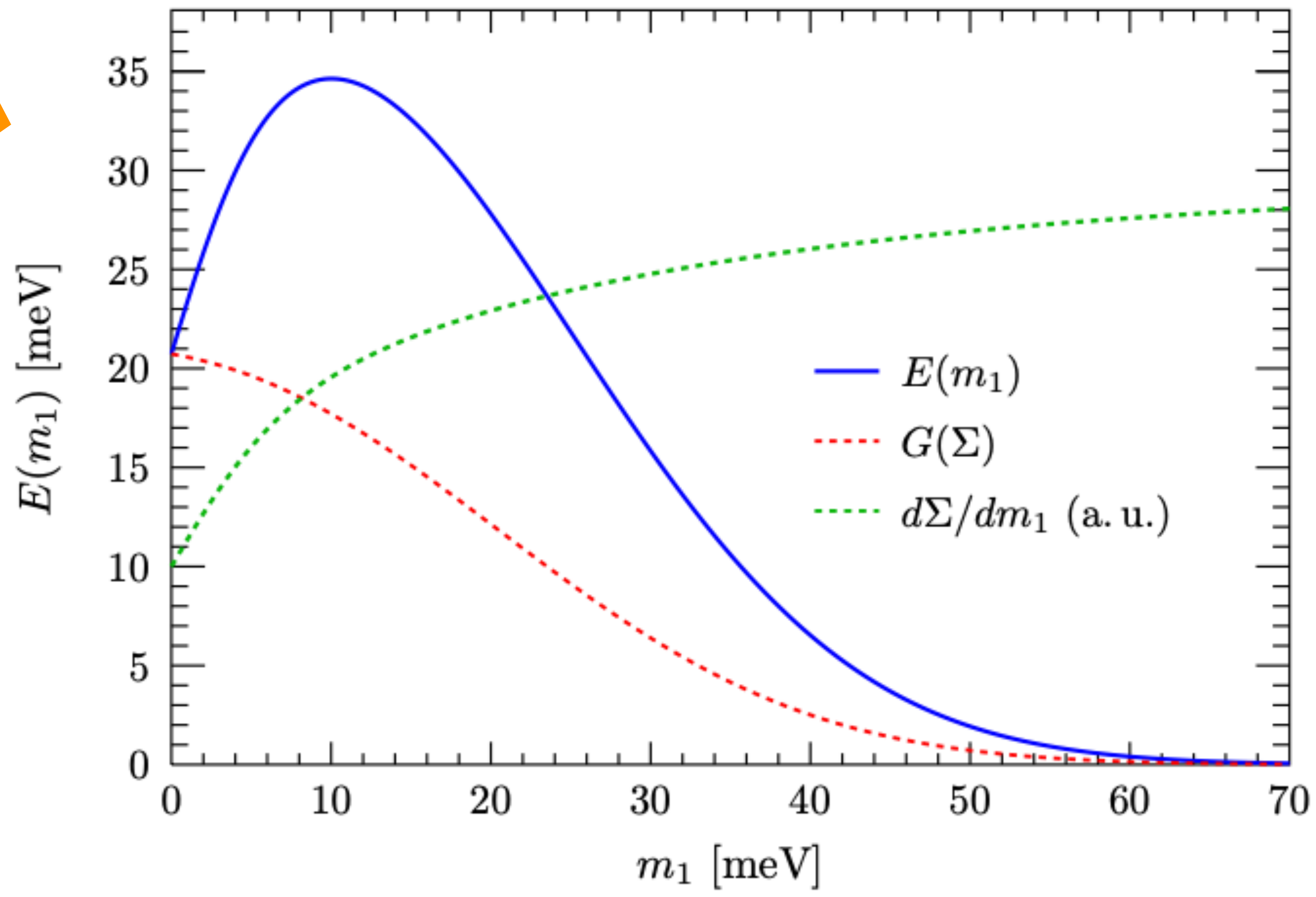
By measuring m_1 the probabilities of the 3 subsets can be quantified



CMB probes $\Sigma = m_1 + m_2 + m_3$



CMB probes m_1

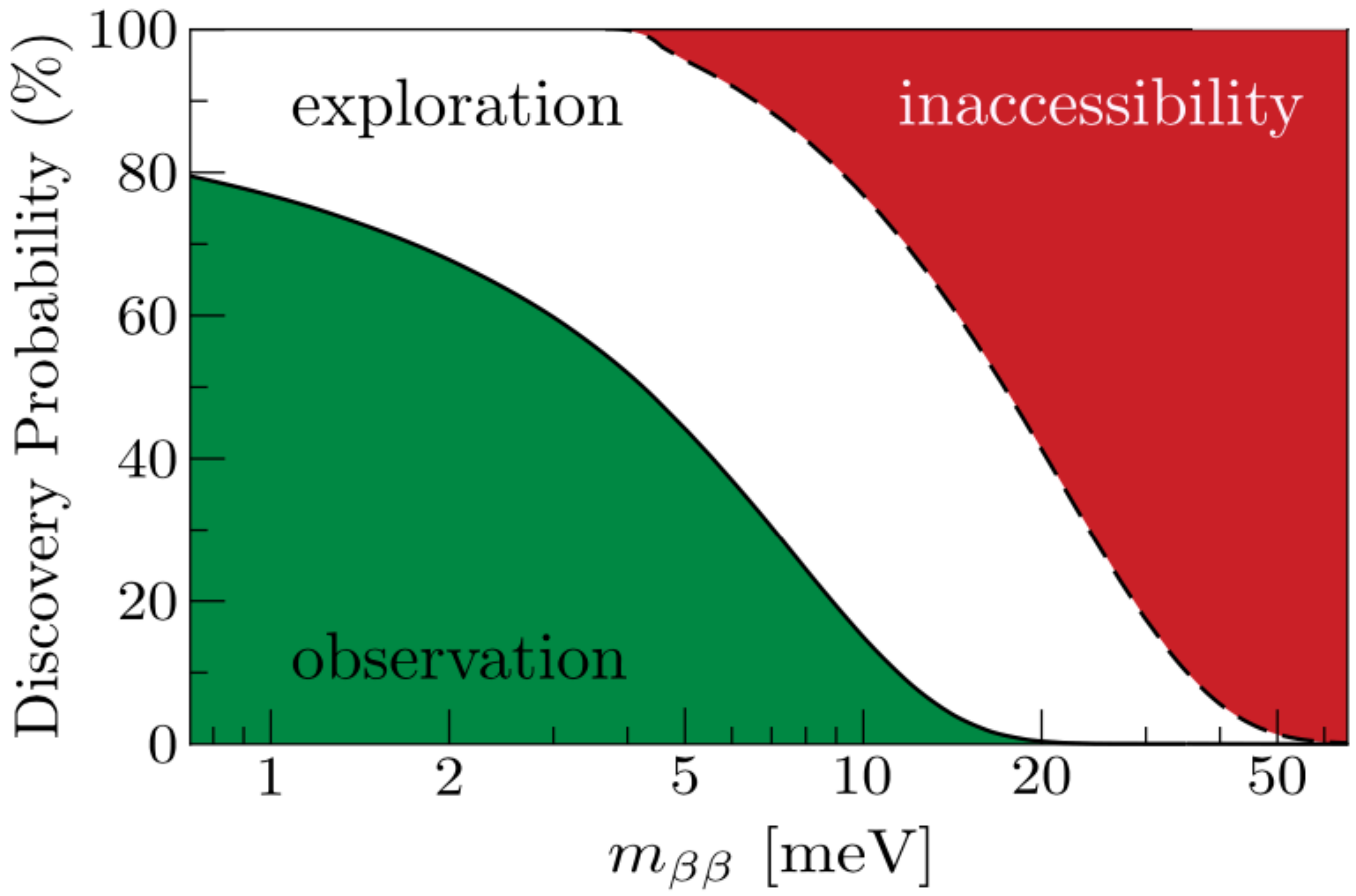


Dell'Oro, Marcocci, FV, 2019

the three probabilities & “flag viewgraph”

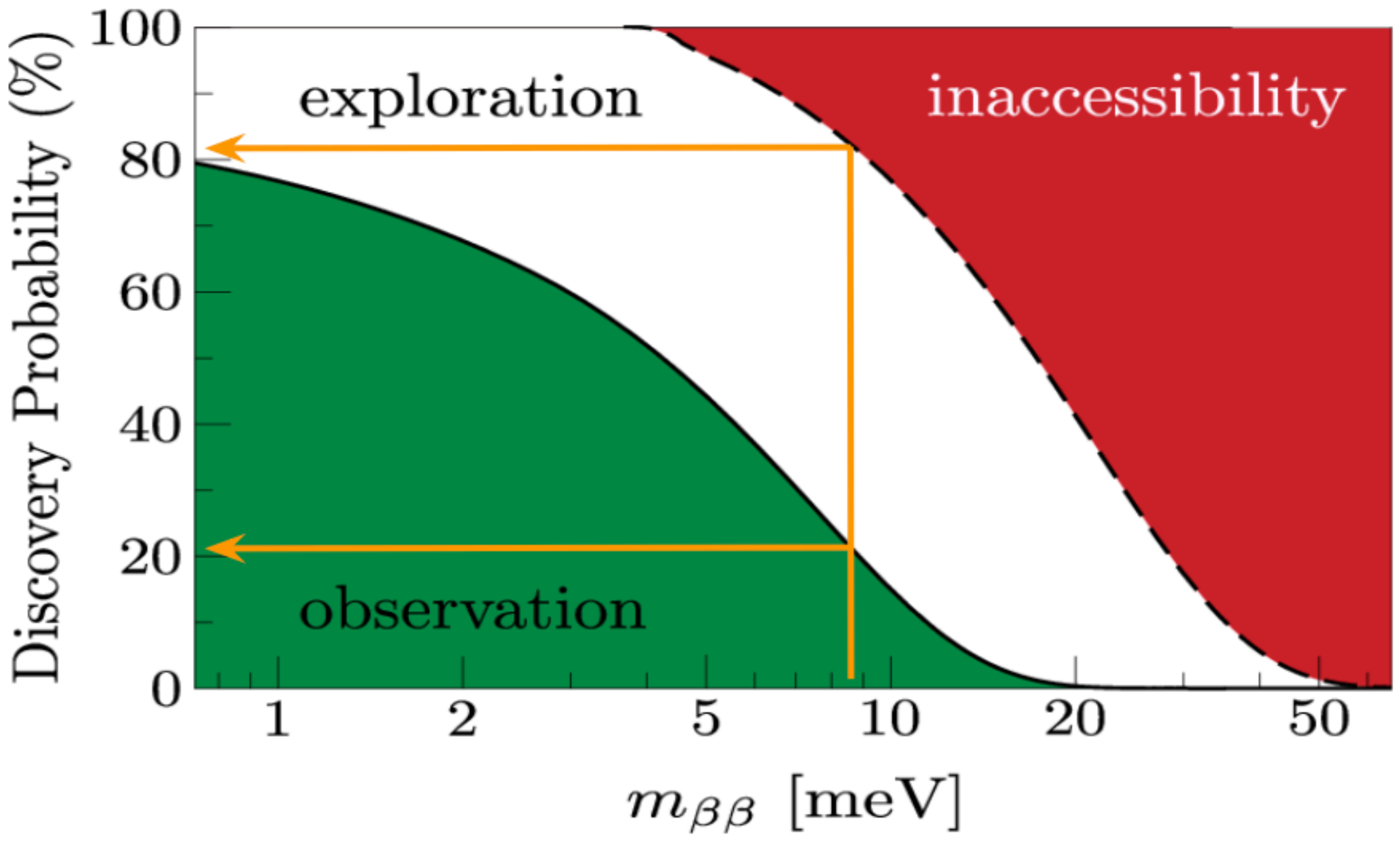
TABLE II. Probability (expressed in percent) of the possible outcomes of a search for $0\nu\beta\beta$ given as a function of the experimental sensitivity $m^*_{\beta\beta}$.

$m^*_{\beta\beta}$ [meV]	Inaccess.	Exploration	Observation
50	98.7%	1.3%	0.0%
20	58.6%	41.1%	0.3%
15	41.9%	55.1%	3.0%
10	23.1%	62.0%	14.9%
5	4.4%	51.4%	44.2%
2	0.0%	32.3%	67.7%
0	0.0%	12.4%	87.6%



current estimation of discovery probability:

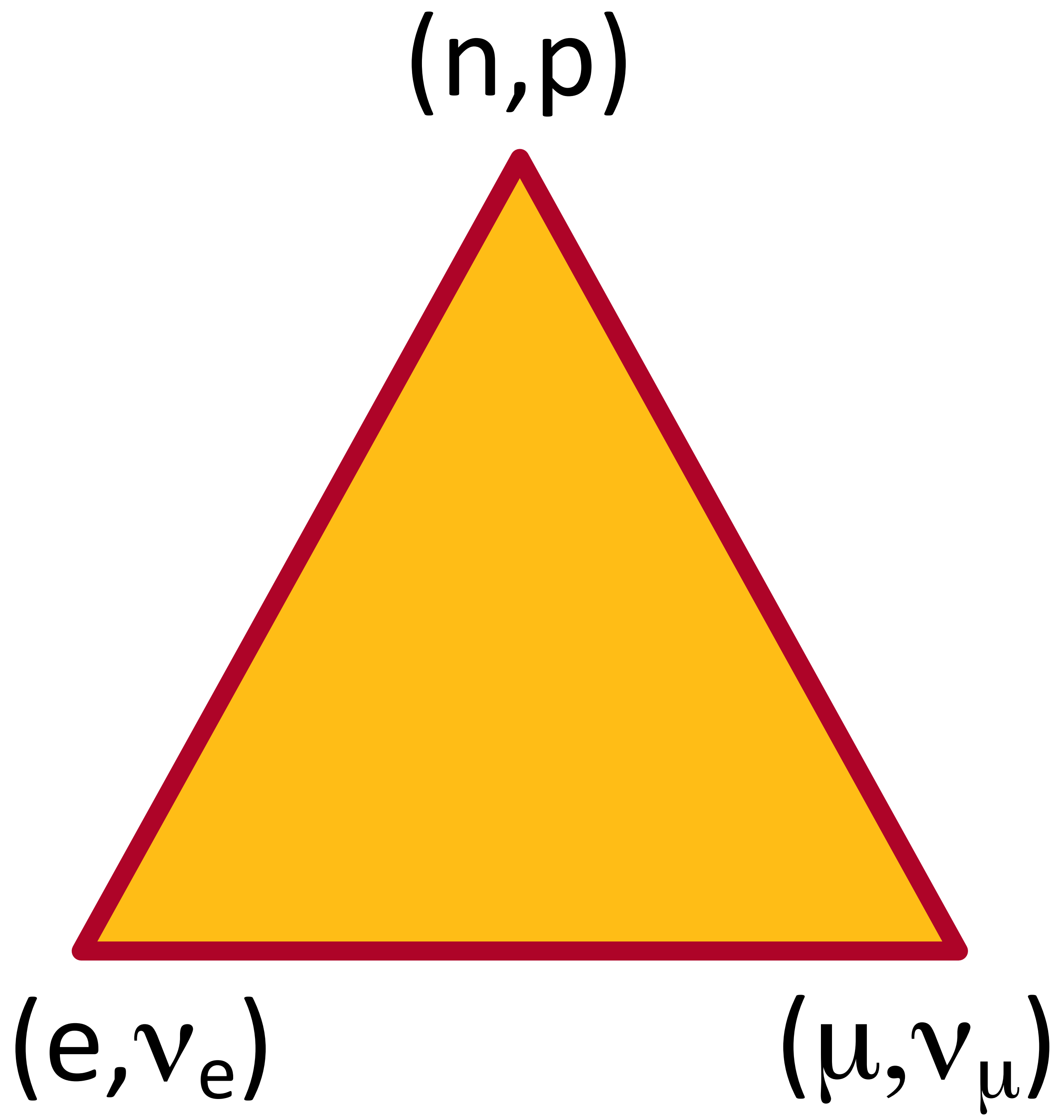
- 100% for inverted ordering;
- between 20% an 80% for normal ordering, if $m_{\beta\beta} = \sqrt{\Delta m^2_{12}} = 8.6$ meV is achieved



end of the
second lecture

Other types of neutrinos

- Pontecorvo studied e-capture and μ-capture and suggested that the **coupling is same** (1947)
- Puppi argued that the muon is associated to a **new type** of neutrino, as depicted in the triangle (1948)
- This indicates **universality**: weak interactions treat in the same way the various pairs of particles
- (For the pair (n,p), this is almost true)



Puppi's triangle

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?]** **???**

SM effective operators (Weinberg; Wilczek & Zee 79)

accept in the SM Lagrangian density also the operators with canonical dimension >4 that conserve gauge symmetry e.g.

$$\delta\mathcal{L} = \frac{(\ell H)^2}{M} + \frac{\ell q q q}{M'^2} + \frac{(\ell q d^c)^2}{M''^5}$$

SM effective operators (Weinberg; Wilczek & Zee 79)

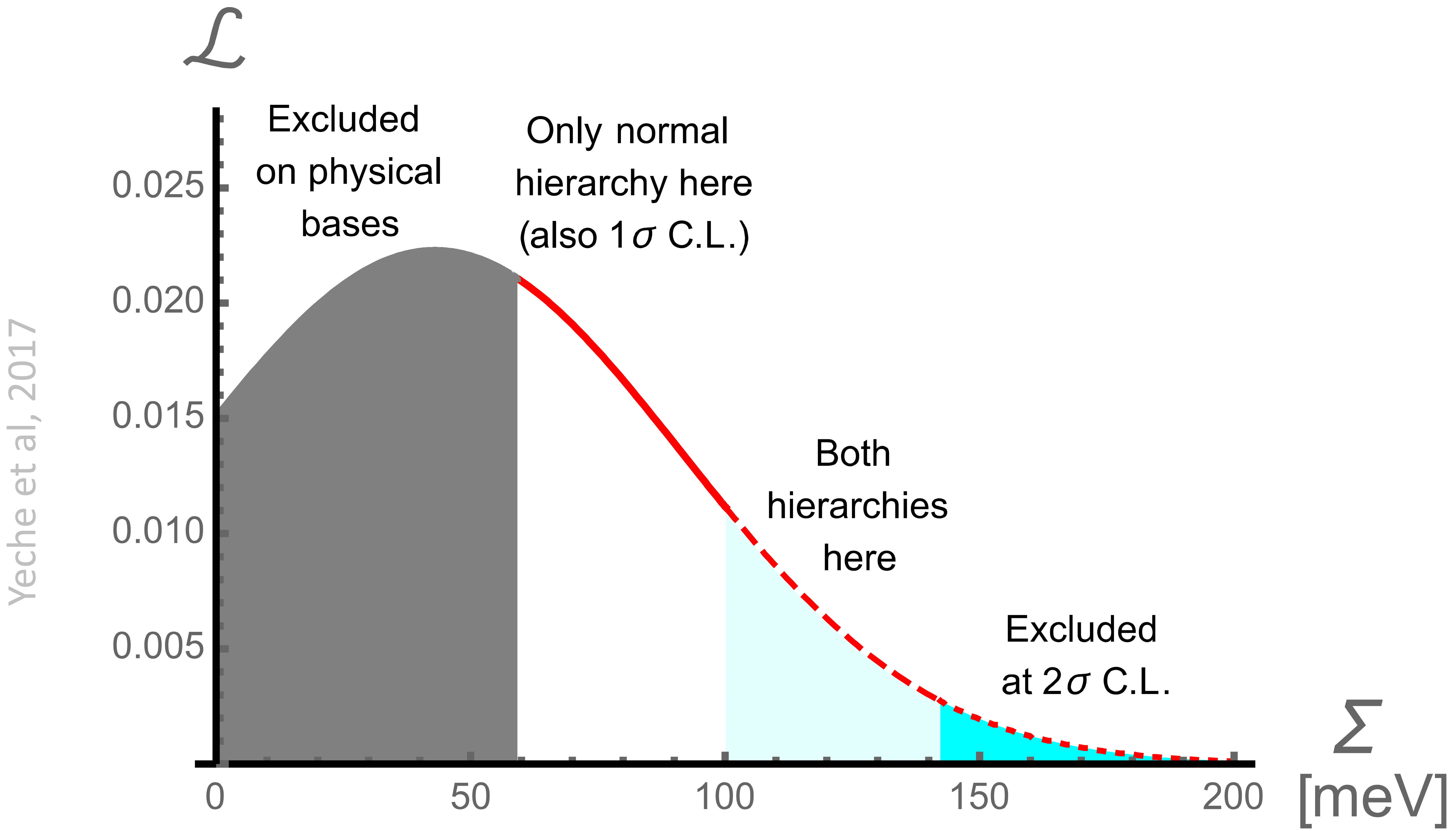
accept in the SM Lagrangian density also the operators with canonical dimension >4 that conserve gauge symmetry e.g.

B-L and L_i-L_j broken

$$\delta\mathcal{L} = \frac{(\ell H)^2}{M} + \frac{\ell qqq}{M'^2} + \frac{(\ell q d^c)^2}{M''^5}$$

B & L broken
B-L unbroken

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



Discovery probabilities of Majorana neutrinos based o cosmological data

M. Agostini,[1,2,*] G. Benato,[3,†] S. Dell'Oro,[4,5,‡] S. Pirro,[6,§] and F. Vissan
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(Received 5 January 2021; accepted 5 February 2021

We discuss the impact of the cosmological measurements on the p
neutrinos, the parameter probed by neutrinoless double-beta decay
assumptions, we quantify the probabilities of discovering neutrinoless
new graphical representation that could be of interest for the communi

DOI: 10.1103/PhysRevD.103.033008

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

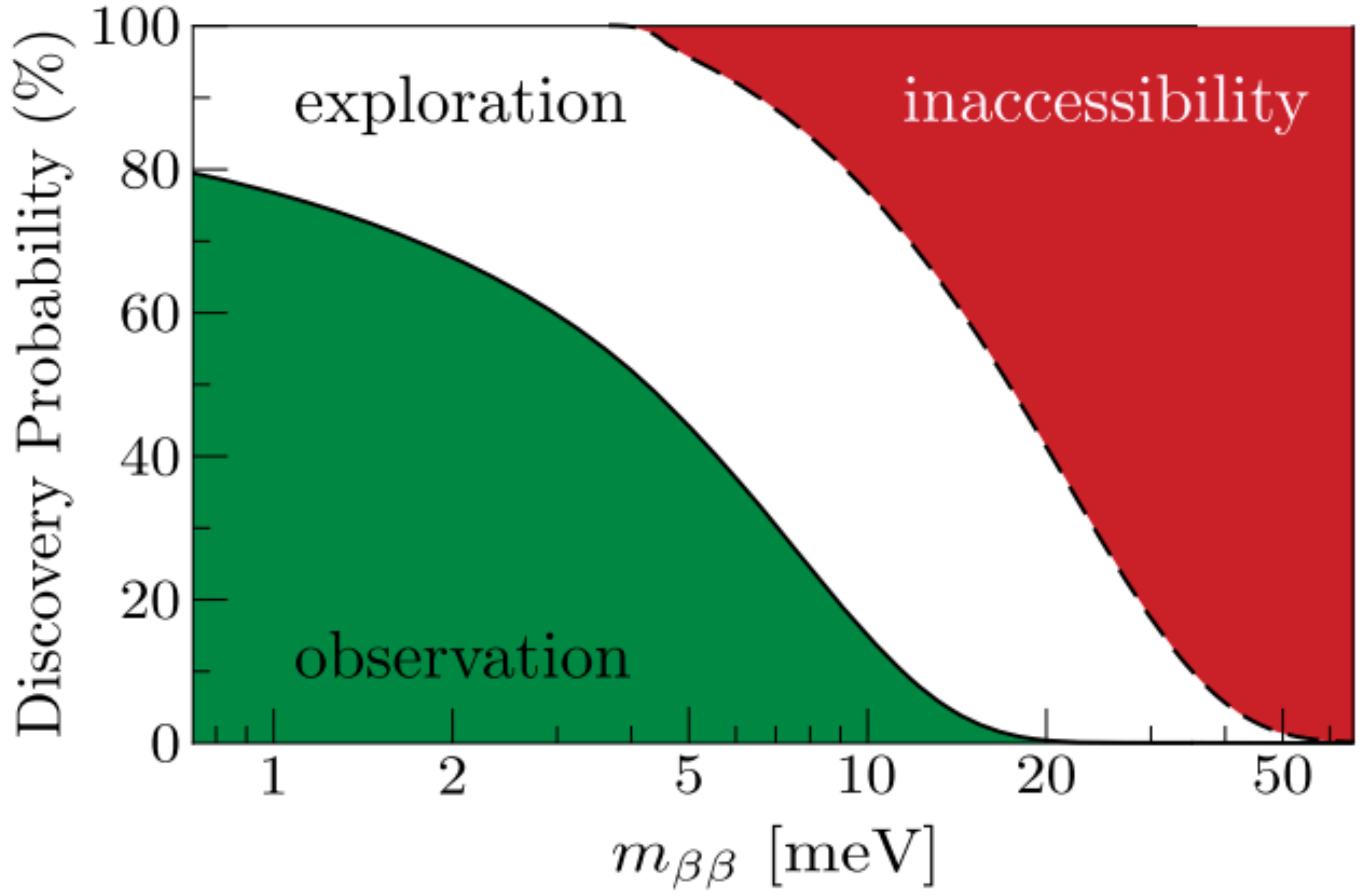

FIG. 2. Discovery probability as a function of the experimental sensitivities to $m_{\beta\beta}$ for the most unfavorable scenario (black solid line, $m_{\beta\beta}^{\min}$) and the most favorable one (black dashed line, $m_{\beta\beta}^{\max}$). The colored areas express the probability for the three 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).

references

Neutrino masses and mixings and...

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Francesco Vissani

INFN, Laboratori Nazionali del Gran Sasso, Theory Group, I-67010 Assergi (AQ), Italy

Abstract

We review experimental and theoretical results related to neutrino physics with emphasis on neutrino masses and mixings, and outline possible lines of development.

hep-ph/0606054 [hep-ph]

Contents

Open Access Review

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

by Francesco Vissani [1,2]

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Special Issue

Neutrino Masses and Oscillations 2015

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Neutrinoless Double Beta Decay: 2015 Review

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

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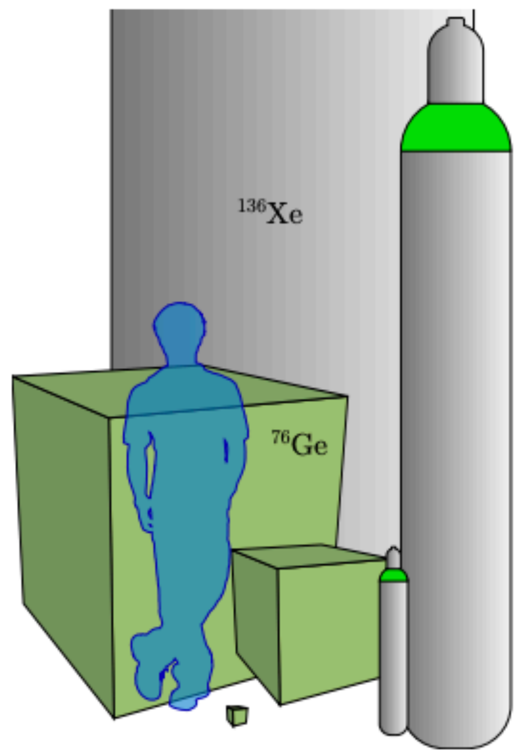

FIG. 18. Masses corresponding to present, mega and ultimate exposures, assuming zero background condition and 5 years of data acquisition. The cubes represent the amount of ^{76}Ge, the (150 bar) bottles the one of ^{136}Xe. The smallest masses depict the present exposure, while the biggest bottle is out of scale.

CONTENTS

Toward the discovery of matter creation with neutrinoless double-beta decay

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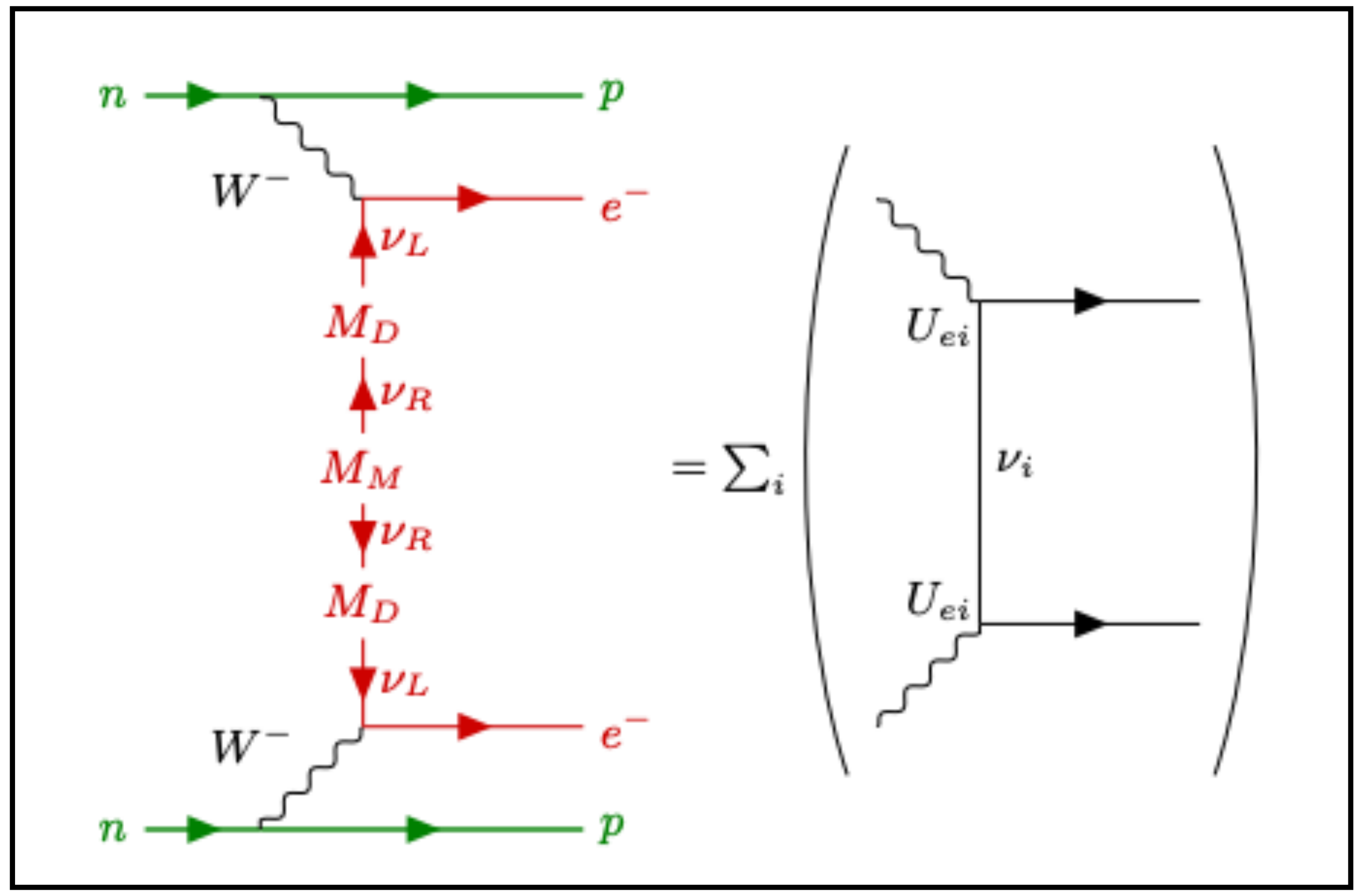
(Dated: February 7, 2022)



CONTENTS

I. INTRODUCTION

In all physical processes observed so far the creation or destruction of matter is compensated by that of antimatter. However, our universe contains an abundance of matter, a fact to which we owe our very existence. In various theories the balance of matter and antimatter can be broken, accounting for this asymmetry of our universe. At present, the most promising avenues for the detection in the laboratory of processes that alter the abundance of matter are proton decay, altering the number of baryons, and electron creation, altering the number of leptons.

The quest to observe electron creation is being pursued vigorously in the form of searches for a nuclear decay where the atomic number Z increases by two units while the nucleon number A remains constant: $(A,Z) \to (A, Z+2) + 2e$. This is commonly known as "neutrinoless $\beta\beta$ decay" ($0\nu\beta\beta$ decay). Here, the creation of electrons can be enabled by the "transmutation" of neutrinos into antineutrinos, which is only possible if the neutrino has a peculiar type of mass, named after Majorana. Thus the matter-antimatter imbalance and neutrino masses could have a common origin.

A symmetry between neutrinos and antineutrinos was postulated by Majorana and further discussed by Racah in 1937. This led Furry to propose the existence of $0\nu\beta\beta$ decay in 1939, building on Goeppert Mayer's ideas on $\beta\beta$ transitions. Pioneering searches for $0\nu\beta\beta$ decay started in the 40s using time-coincidence counting techniques or visual detection of tracks in cloud chambers and photographic emulsions. Since then, experiments have