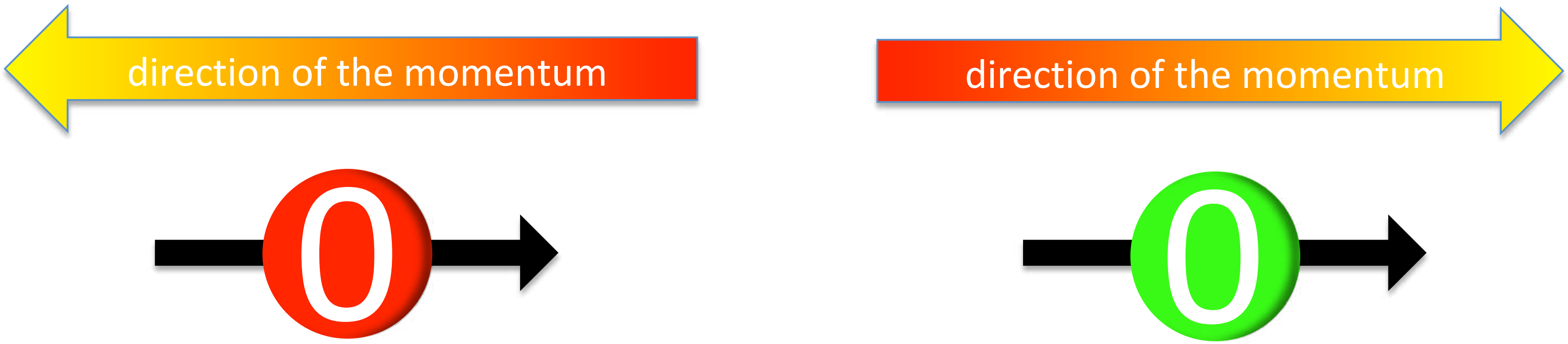
Majorana Neutrinos: What, Why, Where?

Francesco Vissani
GSSI & LNGS

WIN 2019 Conference, Bari, June 7, 2019

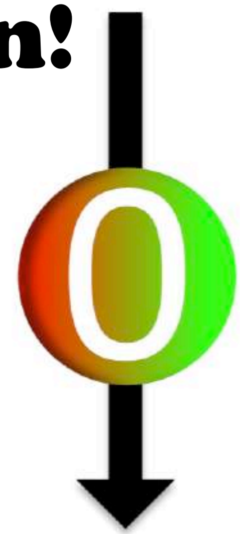
why known neutrinos could well be Majorana particles; the minimal formalism; relevance of the issue for the direct search of big-bang neutrinos

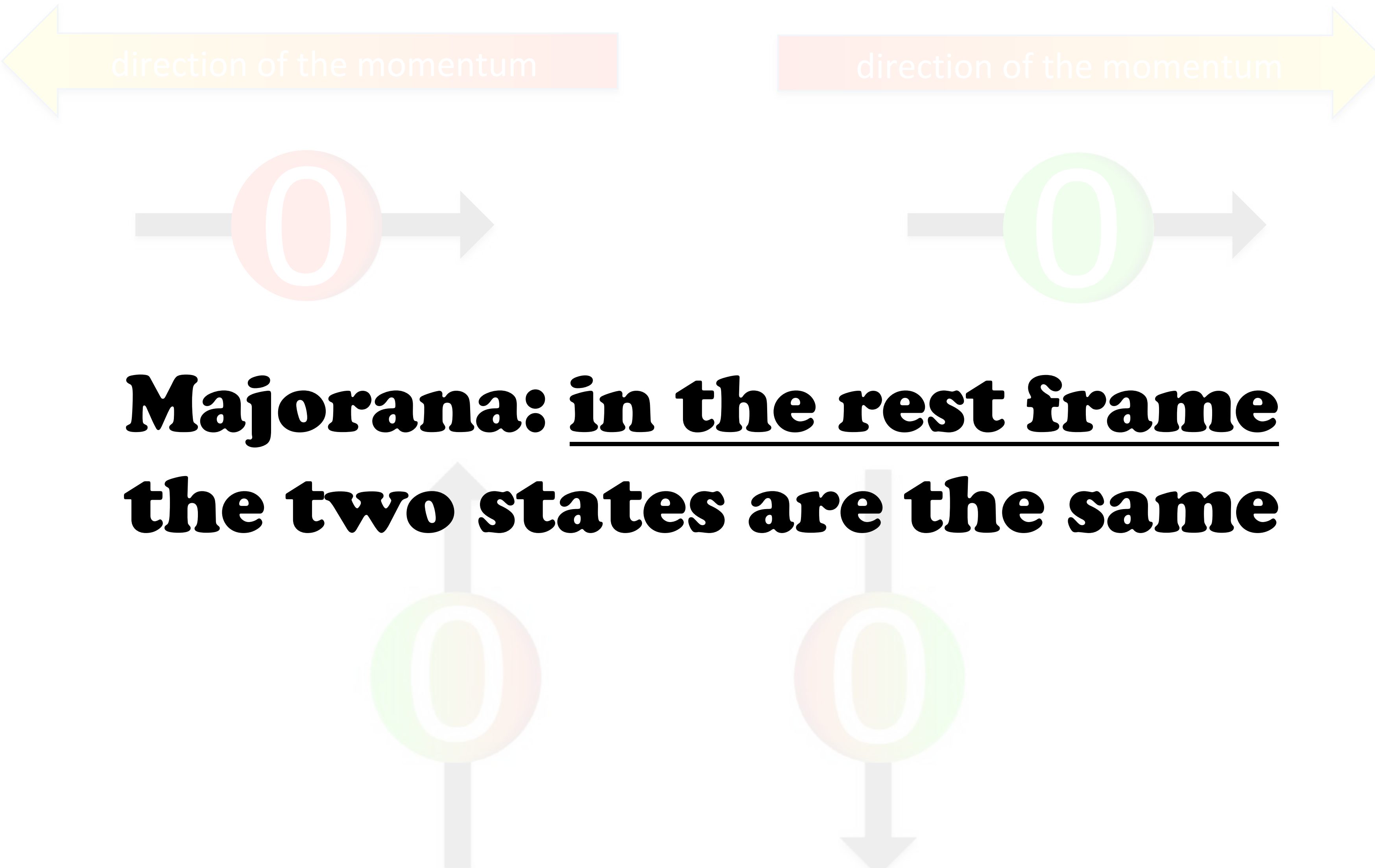
MAJORANA'S HYPOTHESIS ON NEUTRINOS



helicity distinguishes neutrinos from antineutrinos

but in the rest frame there is only the spin!





Majorana: <u>in the rest frame</u> the two states are the same

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

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

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

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

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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comments

- recall: neutrino masses are necessary to explain oscillations
- neutrino mass + V-A nature makes Majorana hypothesis plausible
- “unusual appearance” means just “we are used to Dirac”

next, one manifestation of Majorana mass – see M. Messina’s talk

direct search of big-bang neutrinos

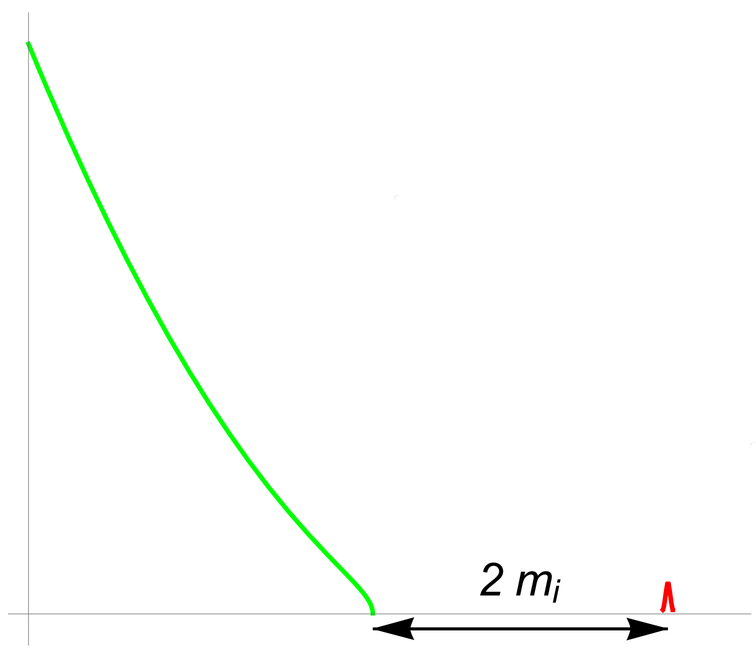
big-bang neutrinos produce 3 **neutrino-capture** lines for a radioactive target

their positions depend on m_i ; their intensity on $|U_{ei}^2|$

lightest neutrino gives the most intense line for normal hierarchy

Needs

- great energy resolution
- big target mass, ≥100g of tritium



Majorana means more events

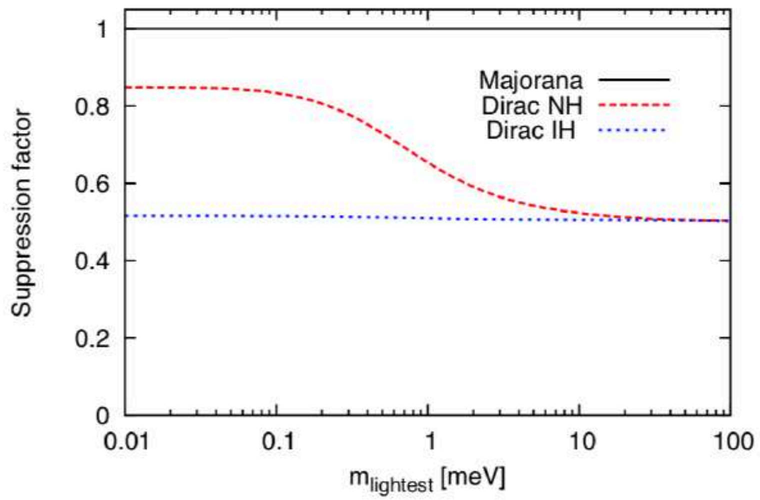


Figure 1: Numerical calculation of the suppression factor for the Dirac neutrino capture process, as a function of the lightest neutrino mass and for the two neutrino mass hierachies (normal and inverted). For comparison, also the case of Majorana neutrinos is shown, for which the suppression is 1 or, in other words, there is no suppression.

Roulet & FV, 2018

remarks on the features of the standard model (SM); effective operators that violate lepton and baryon numbers; observable manifestations

ON SM EXTENSIONS

remarks on SM standard model

- in SM **B-L** , $\mathbf{L_e} - \mathbf{L_\mu}$ and $\mathbf{L_\mu} - \mathbf{L_\tau}$ are exact symmetries

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- But $\mathbf{L_e - L_\mu}$ and $\mathbf{L_\mu - L_\tau}$ are violated in oscillations

conclusion:

SM needs to be modified/improved/extended

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.

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

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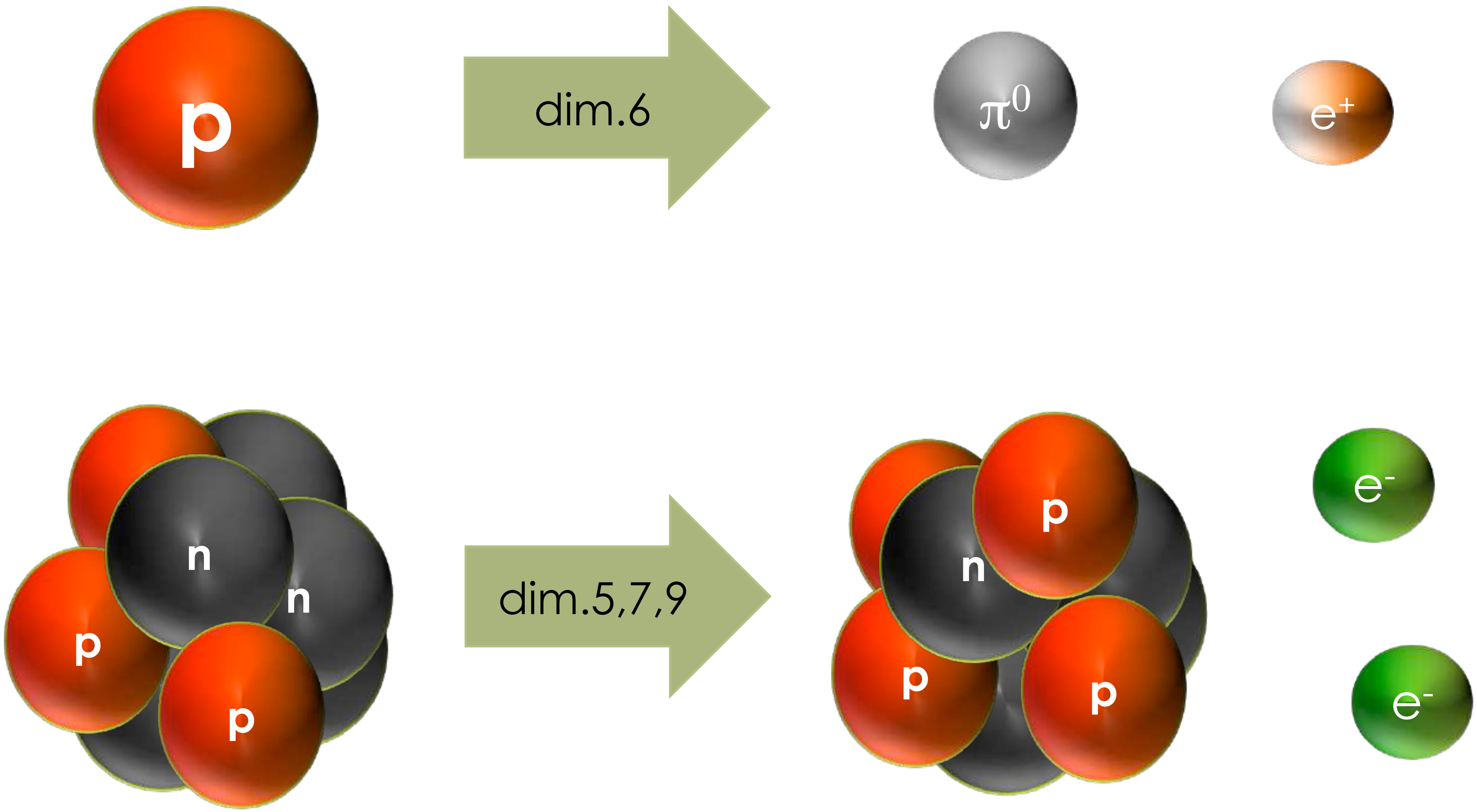
B-L and L_i-L_j broken

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

B & L broken
B-L unbroken

manifestations



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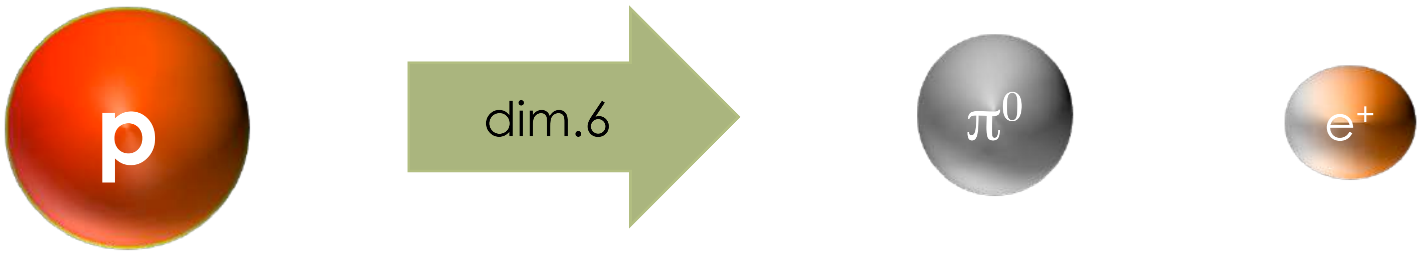
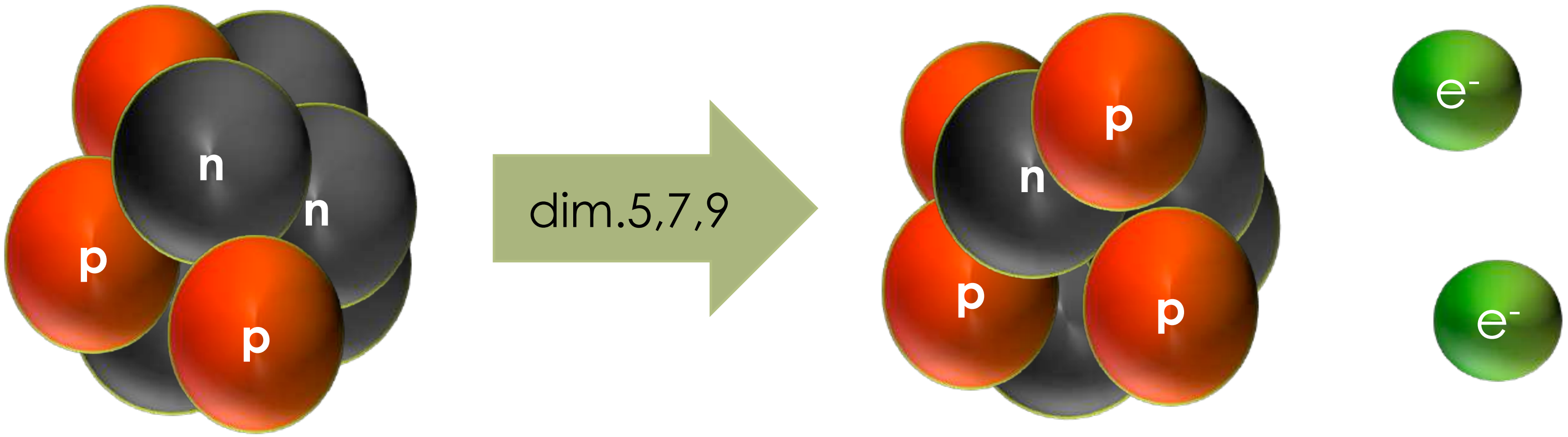


B=+1 , L=0 **B=0 , L=-1**



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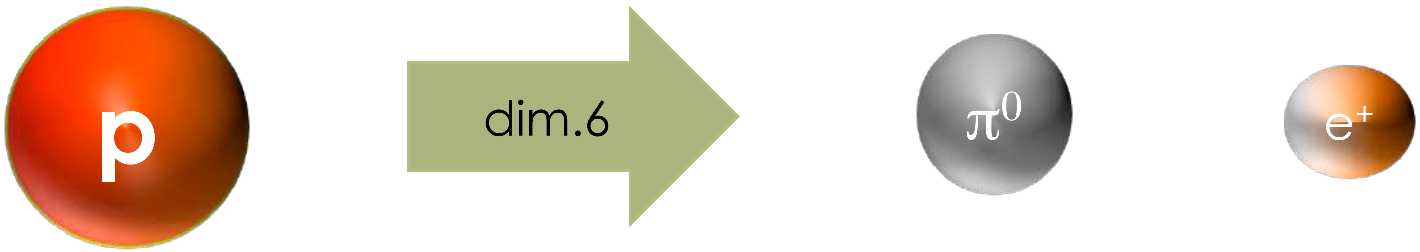

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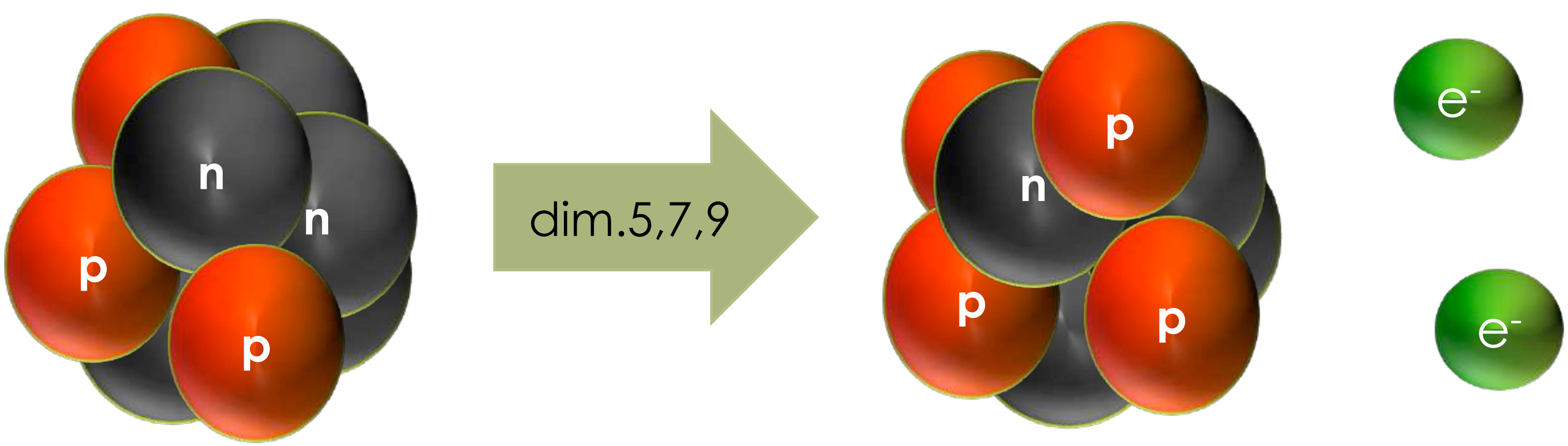
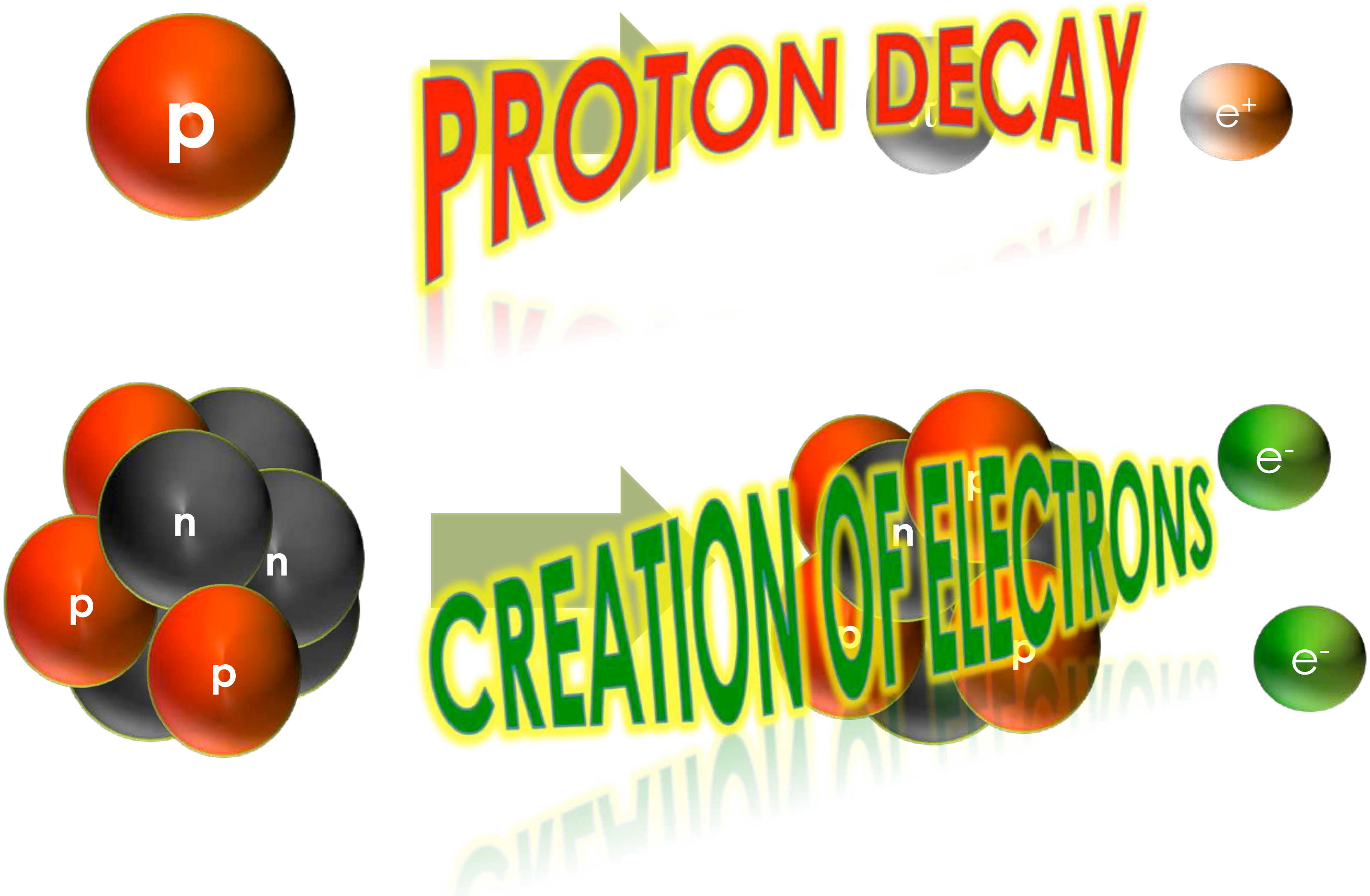


B=A, L=0 **B=A, L=2**

manifestations



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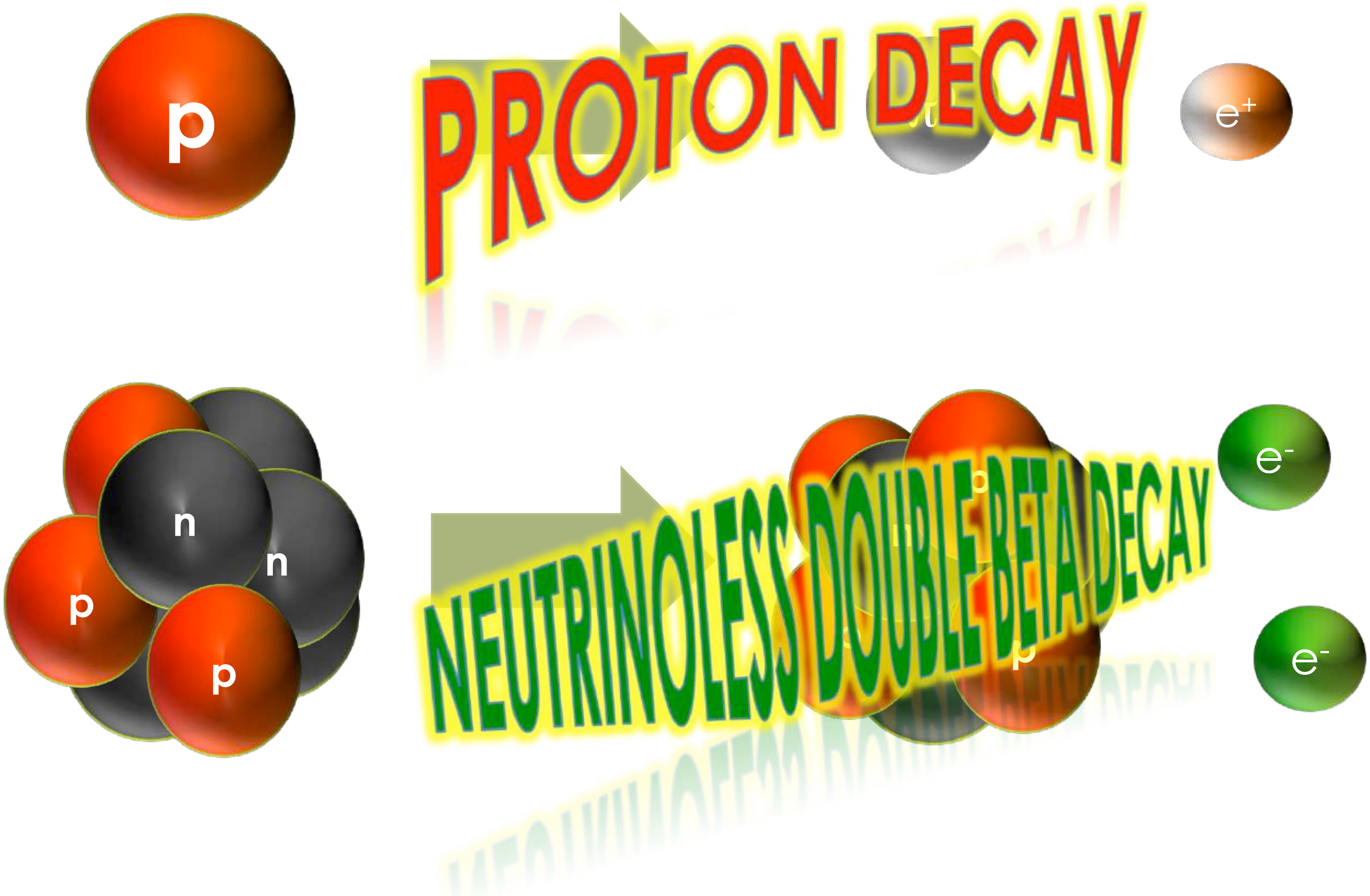

the process of interest; connection with Majorana neutrino masses; theoretical discussion of the most plausible mechanism

TESTING B-L SYMMETRY

the process of interest

A very promising process to test B-L is,

$$(A,Z) \rightarrow (A,Z+2) + 2\ e^-$$

Actively searched (see G. Gratta and next talks)

its selection rules

(A,Z) → (A,Z+2) + 2 e^-

- **It violates L_e , also violated in T2K & NOνA's oscillations**
- **It violates L , being a creation of two electrons (NEW!)**
- **It conserves B**
- **It violates B-L, the residual SM symmetry (NEW!)**
- **Potentially due to many SM effective operators: dim.5, 7, 9 *etc***

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

dim5 operator...

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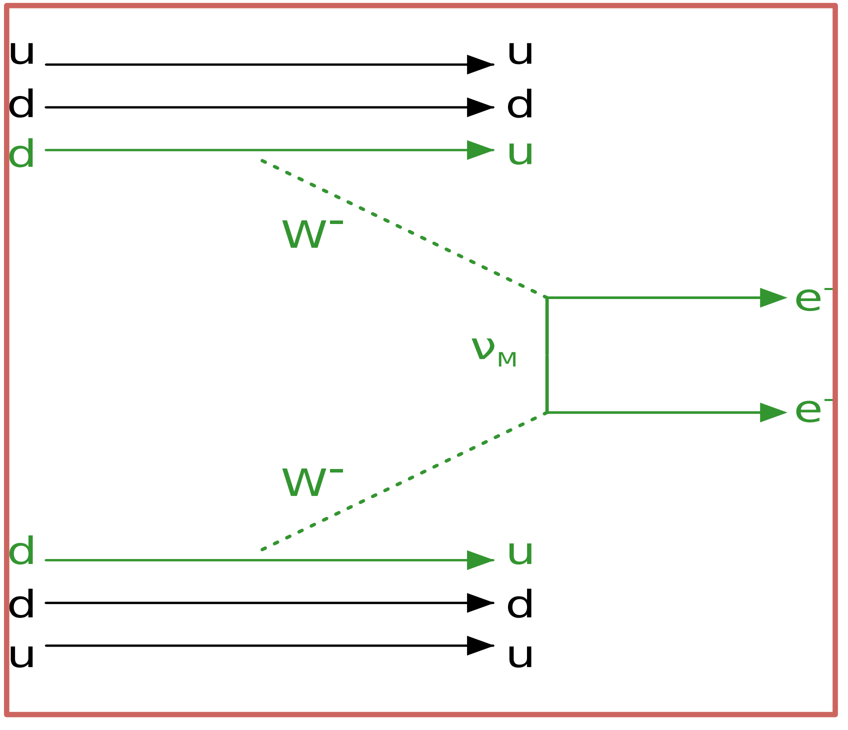
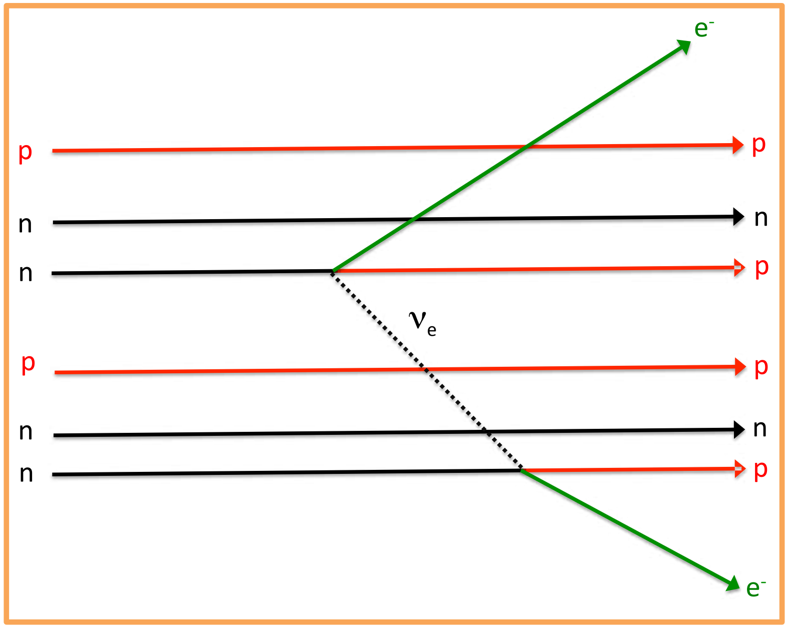
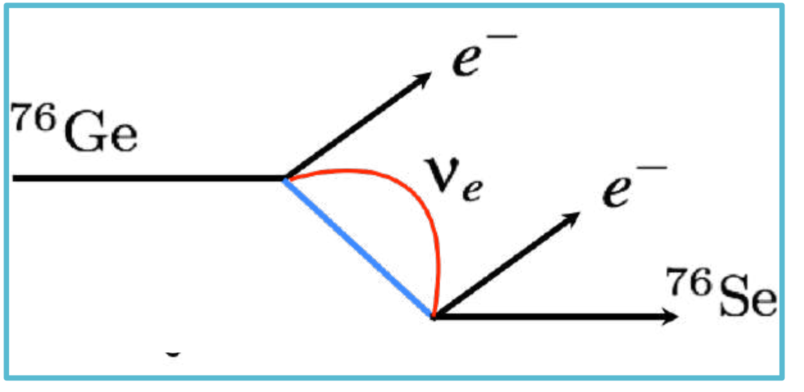
...yields Majorana mass in SM!

Majorana neutrinos and $0\nu2\beta$







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- SM gauge symmetry constrains hypothetical phenomena that break **L** & **B**. These are described by higher-order operators, ordered in powers of new physics masses

- many operators can break **B-L** causing $0\nu2\beta$, w/o giving big contributions to neutrino masses

- the lowest order operator causes $0\nu2\beta$ ("neutrinoless double beta decay") **and** gives Majorana mass: a plausible extension of the SM -- oscillations are explained

$$\mathcal{A}_{0\nu2\beta}(\text{dim5}) \sim G_F^2 \times \frac{m_{\beta\beta}}{\langle q^2 \rangle}$$

$$\mathcal{A}_{0\nu2\beta}(\text{dim9}) \sim G_F^2 \times \frac{M_W^4}{\Lambda^5}$$

are comparable when $\Lambda \sim$ TeV,

but then,

$$m_\nu \sim \frac{M_W^2}{\Lambda} \times 10^{-11}$$

unexpectedly small in unified models

for the couplings

summary: the reasons of assuming light neutrino dominance

- First, we have evidence of light neutrino masses and not of new physics at TeV scale.
- Moreover, higher dimensional operators would point to new physics at TeV scale (Tello et al 2011) but would also indicate that the couplings of the neutrinos are rather different from the other ones − much smaller.

the relevant parameter - “electron neutrino mass”, aka “effective mass”, aka $m_{\beta\beta}$; theoretical remarks on its value; again on alternative theoretical possibilities

THEORETICAL REMARKS

the "electron neutrino" mass

If light Majorana ν leads the transition, the parameter that counts for 0ν2β is,

$$m_{\beta\beta} = |(m_\nu)_{ee}| = \left| \sum_{j=1}^{3} |U_{ej}^2| \times e^{i\,\xi_j} \times m_j \right|$$

The first is the traditional symbol; the second, is the ee-element of the ν mass matrix. Sometimes indicated also as $\langle m_\nu \rangle$

(there are also other symbols, that always indicate the very same thing!)

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Only the mass differences m_i^2-m_j^2 and

electronic mixing $|U_{ej}^2|$ are measured by oscillations.

Lightest neutrino mass & Majorana phases ξ_i aren't.

fourty years ago

Volume 107B, number 1,2 PHYSICS LETTERS 3 December 1981

CP PROPERTIES OF MAJORANA NEUTRINOS AND DOUBLE BETA DECAY

Lincoln WOLFENSTEIN
Carnegie-Mellon University, Pittsburgh, PA 15213, USA

Received 8 September 1981

$$M_{ee} = \sum_{np} O^{T}_{en} \eta_n m_n \delta_{np} O_{pe} = \sum_{n} \eta_n m_n O^2_{ne} .$$

Thus, the decay rate Γ from eq. (8) is directly proportional to M^2_{ee}. Therefore, in models such as the Zee model, in which the diagonal Majorana mass of ν_e vanishes, the decay rate Γ vanishes identically. In such

twenty years ago

28 Jun 1999

Signal of neutrinoless double beta decay, neutrino spectrum and oscillation scenarios

Francesco Vissani

Deutsches Elektronen-Synchrotron, DESY
Notkestraße 85, D-22603 Hamburg, Germany, and
International Centre for Theoretical Physics, ICTP

[5] On the contrary, one might argue that the case [$\mathcal{N}$] is more likely than [$\mathcal{I}$], and this latter more likely than [$\mathcal{D}$], again on the basis of an analogy between the neutrino spectrum and the spectra of the charged fermions.

today

Physics Letters B
Volume 786, 10 November 2018, Pages 410-417

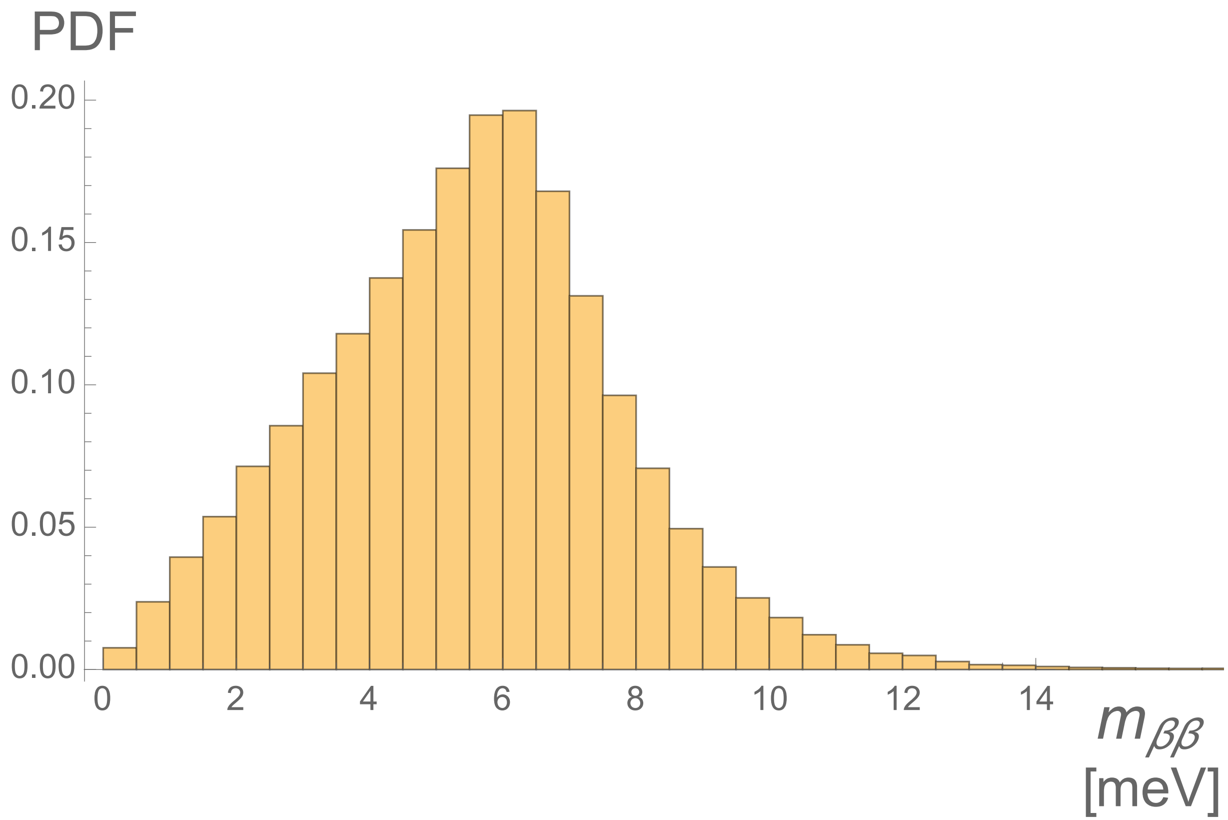
The 10^{-3} eV frontier in neutrinoless double beta decay

J.T. Penedo [a], S.T. Petcov [a, b, 1]

effective Majorana mass $|\langle m \rangle|$. For a neutrino mass spectrum with normal ordering, which is favoured over the spectrum with inverted ordering by recent global fits, $|\langle m \rangle|$ can be significantly suppressed. Taking into account updated data on the neutrino

is $m_{\beta\beta} = |\ (m_\nu)_{ee}\ |$ predictable?

- Yes, in a definite theoretical context
- However, it is difficult to believe that this can be achieved w/o understanding charged fermions masses
- Which principles should be adopted?
- Do we have credible models to tackle such problems?
- To illustrate these considerations we discuss a few attempts



$$(m_\nu)_{ee} \sim \sqrt{\Delta m_{atm}} \times \theta_C$$ (guesswork)

Vissani 1998-2001; Dell'Oro et al 2018

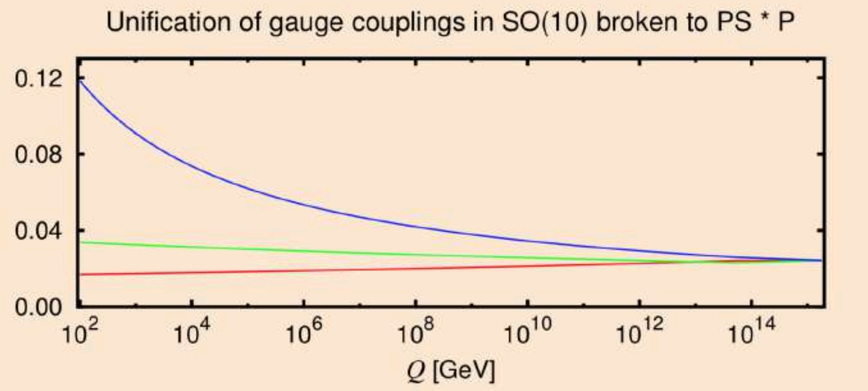


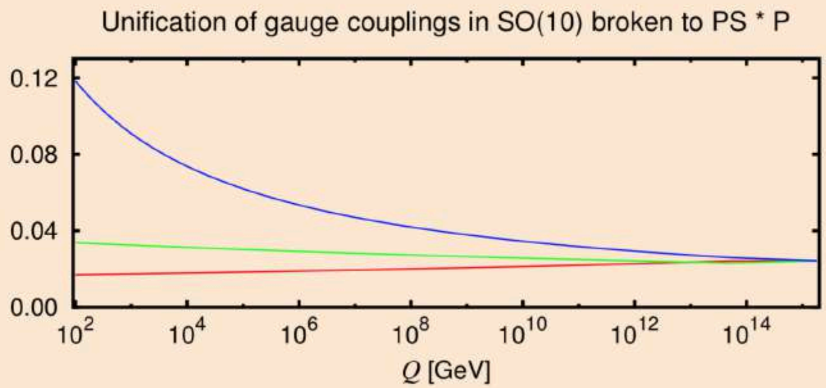
Figure 2: Evolution of the gauge coupling constants in a GUT model with intermediate scale. Here, $M_{\text{interm.}} \approx 5 \times 10^{13}$ GeV.

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

minimal SO(10)

(principled model)

- ★ 16-plet coupled to 10 and 126 higgs: heavy right-handed neutrinos
- ★ (Peccei Quinn symmetry to address strong CP and dark matter)



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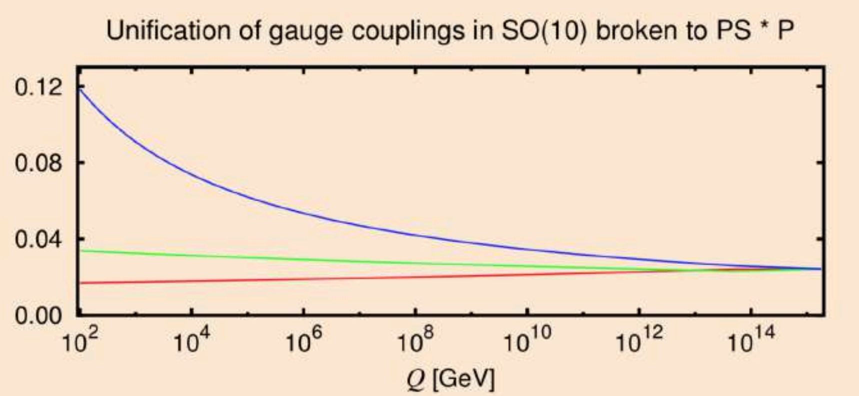

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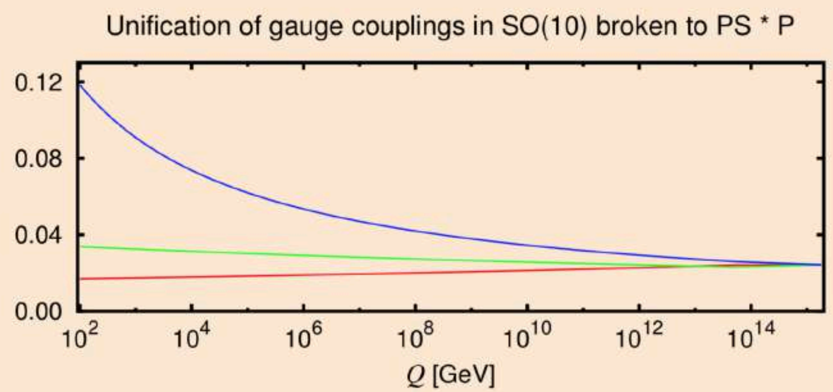

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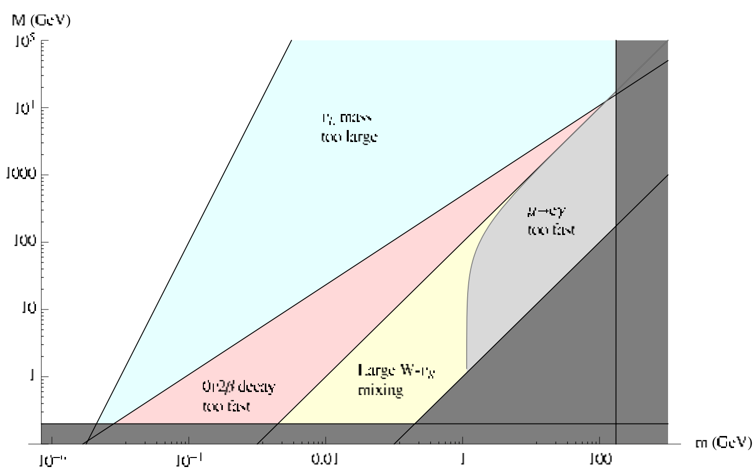
- ★ normal mass hierarchy; $m_{\beta\beta}$ in the few meV range
- ★ (potentially interesting expectations for proton decay)

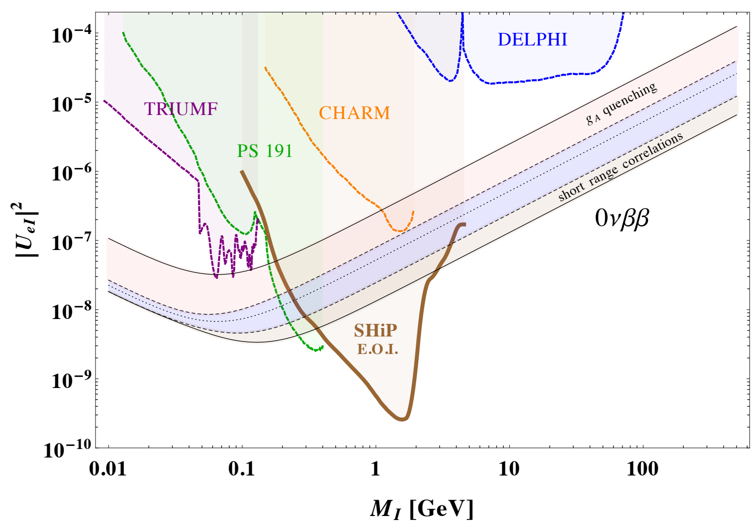
another contribution from heavy (“right-handed”) neutrinos?

Atre et al 2009’ Mitra et al 2011; SHiP 2016

naively, not a likely option



with some gym, maybe



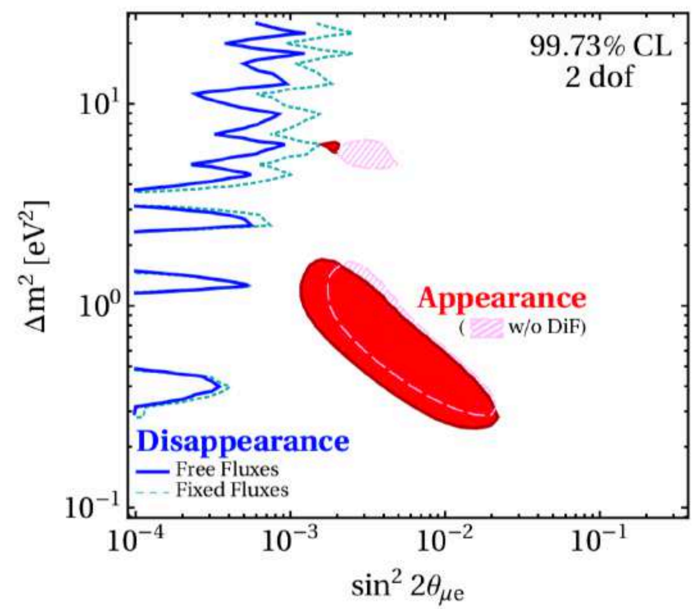
other contributions from light ("sterile") neutrinos?

new light neutrinos could lead to new manifestations

e.g. the case $m_\nu \sim 1$ eV was regarded with interest

minor relevance for $0\nu2\beta$: $m_{\beta\beta}(\text{new}) \sim m_\nu \cdot \theta^2_{ee} \sim 10$ meV

incompatible with other experimental facts (fig & refs)



Bilenky et al 1996 Grimus & Schwetz 2001; Cirelli et al 2005; Dentler et al 2018; Giunti &Lasserre 2019 the connection with oscillations; the constraints due to cosmological measurements; nuclear physics issues

EMPIRICAL INFERENCES

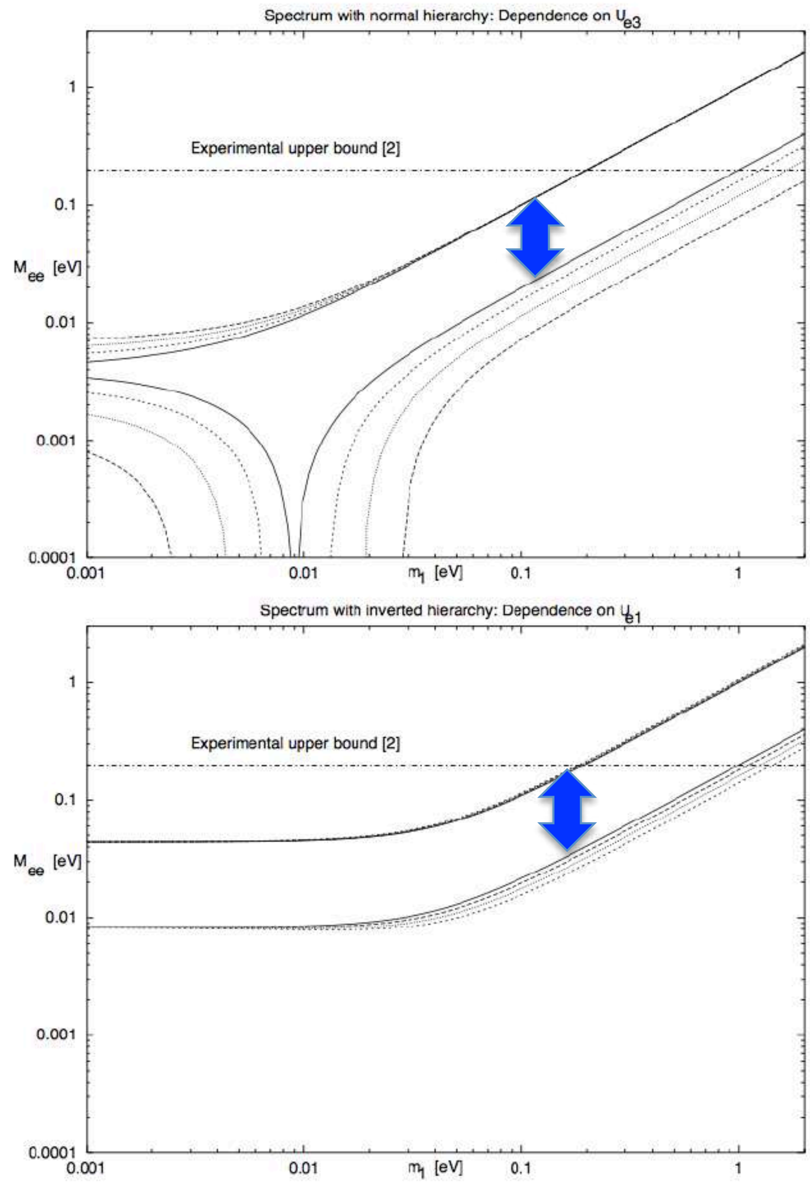
lesson from neutrino oscillations

Vertical span – indicated by the arrows - obtained varying Majorana phases;

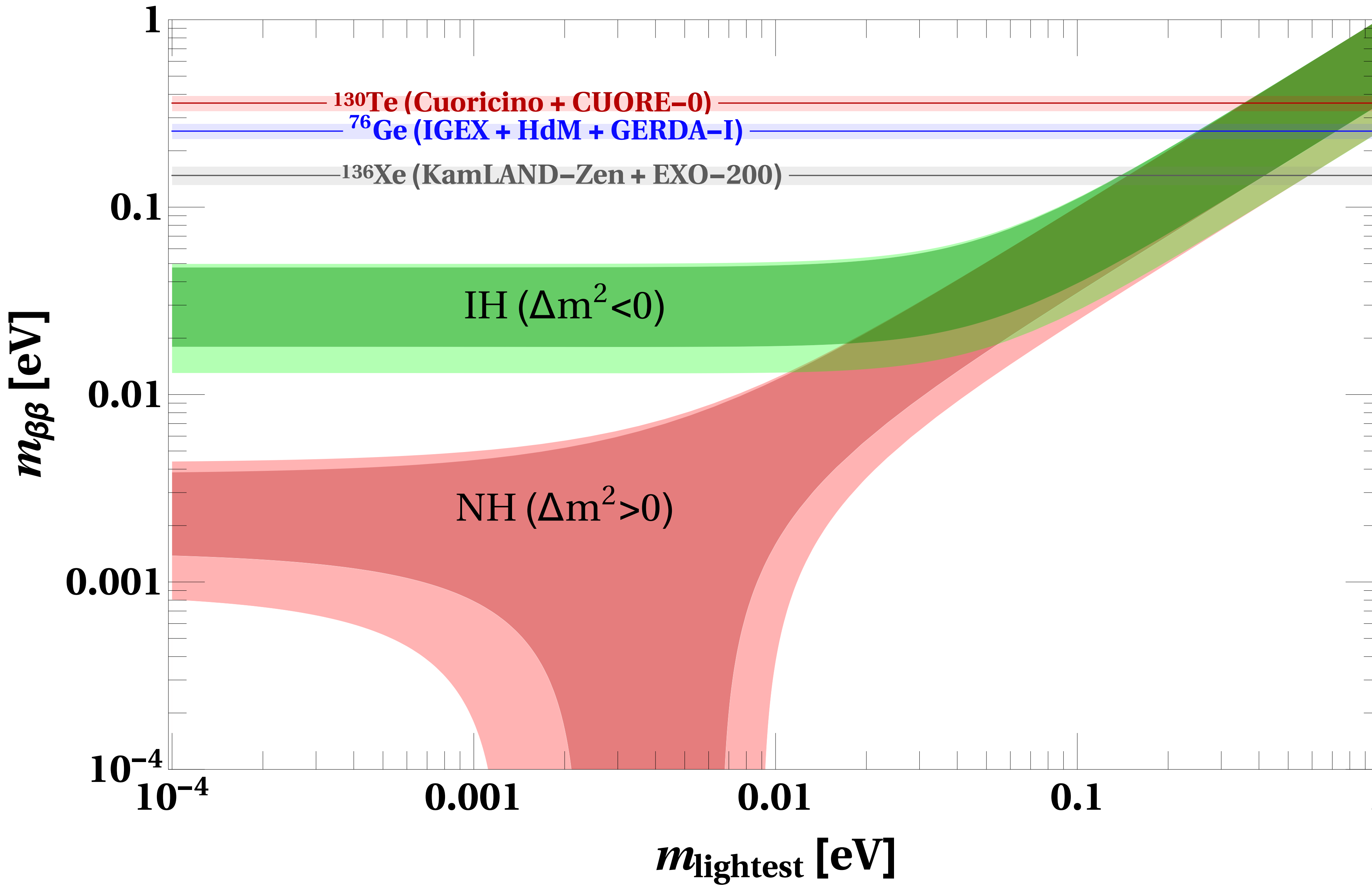
horizontal span, varying the minimum mass

Some – minor - uncertainty due to oscillation parameters

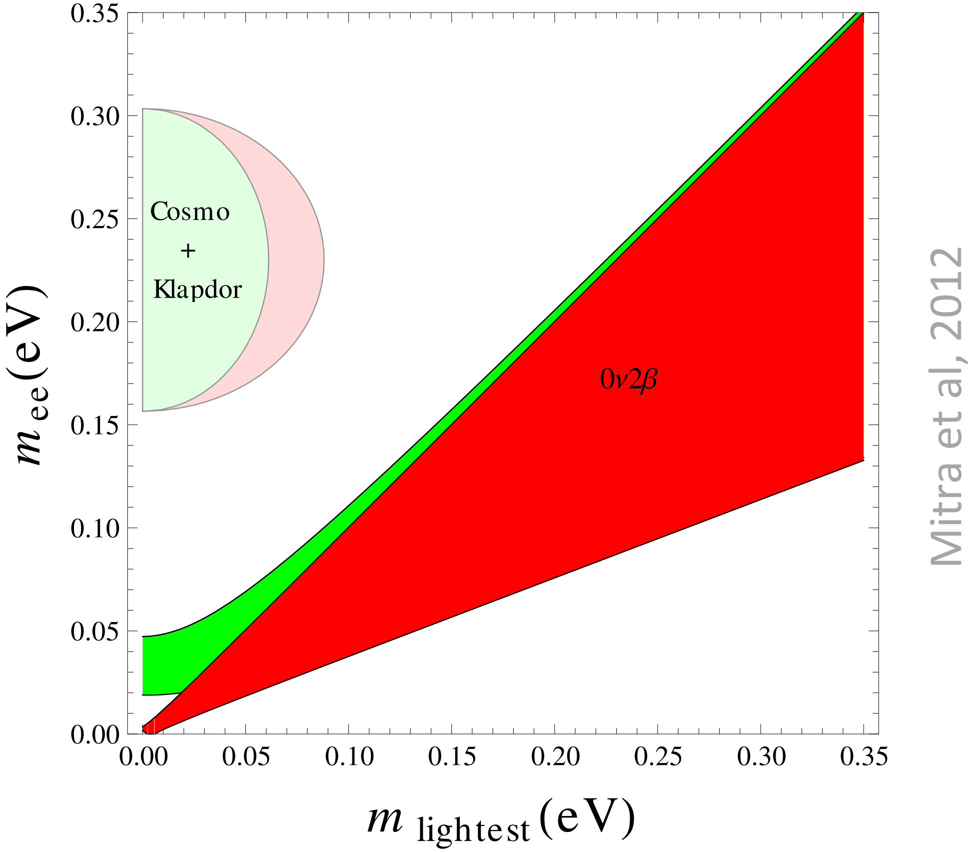
(Called sometimes "lobster plot" or also "bikini plot")



Vissani, 1999



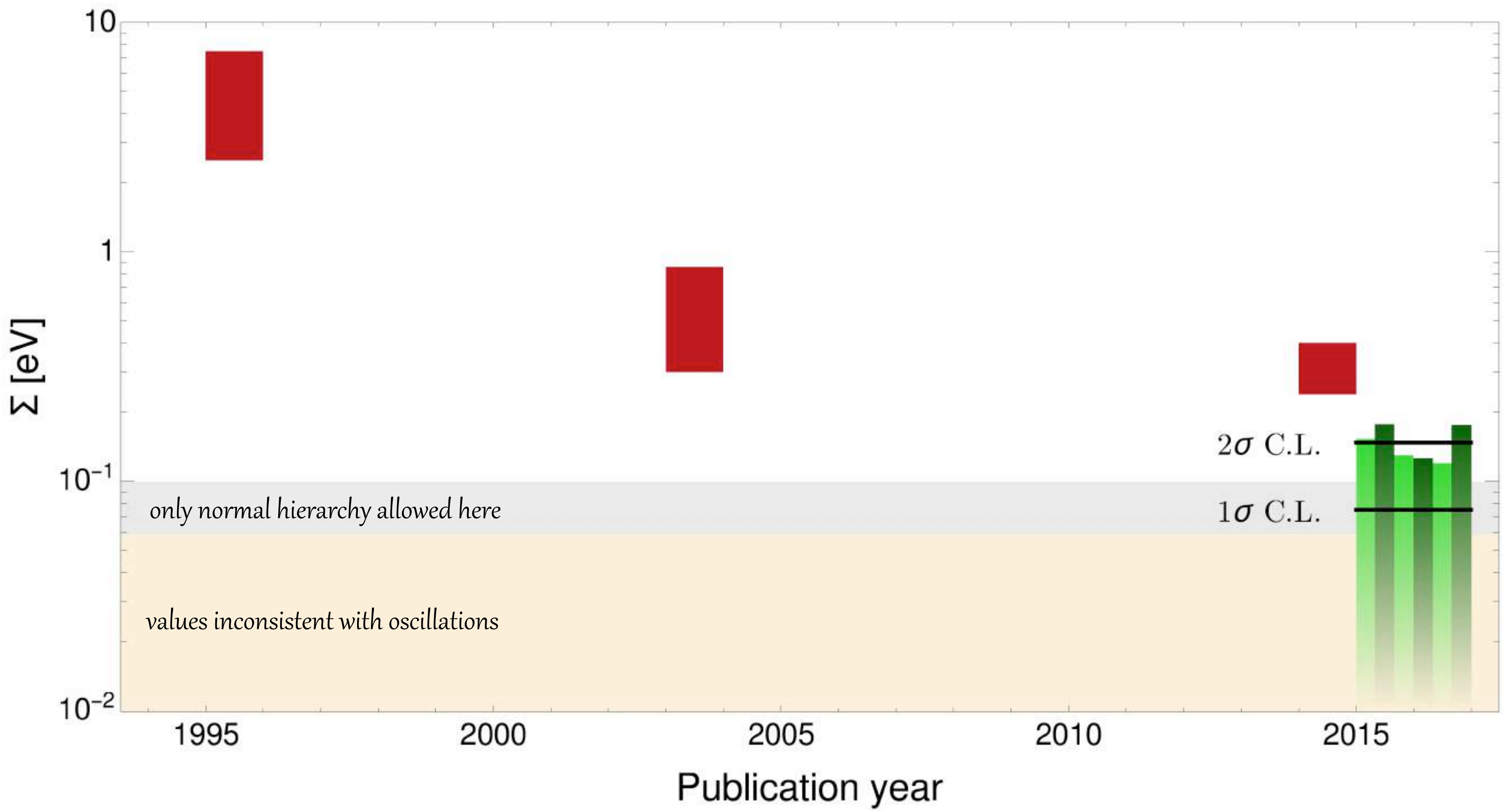
1
0.1
0.01
0.001
10−4
$m_{\beta\beta}$ [eV]
130Te (Cuoricino + CUORE−0)
76Ge (IGEX + HdM + GERDA−I)
136Xe (KamLAND−Zen + EXO−200)
IH (Δm2<0)
NH (Δm2>0)
10−4
0.001
0.01
0.1
1
$m_{\rm lightest}$ [eV]



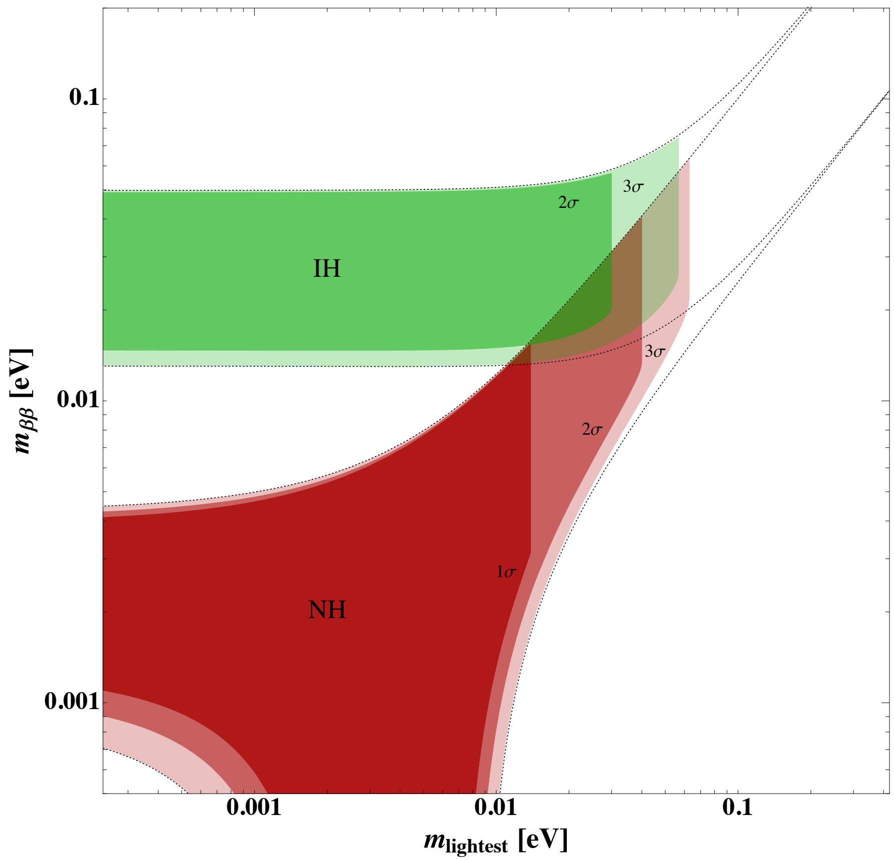
the ($m_{lightest}$, $m_{\beta\beta}$)-plot proved its usefulness

This drawing reminds us that Klapdor et al's result did not agree with light Majorana neutrino interpretation. A priori, a similar situation can signify that the findings are not reliable or that an alternative interpretation works; this could be very interesting if lepton number violation will be observed in LHC or other accelerators in future.

cosmology yields $\Sigma = m_1 + m_2 + m_3$



Dell'Oro et al, 2015

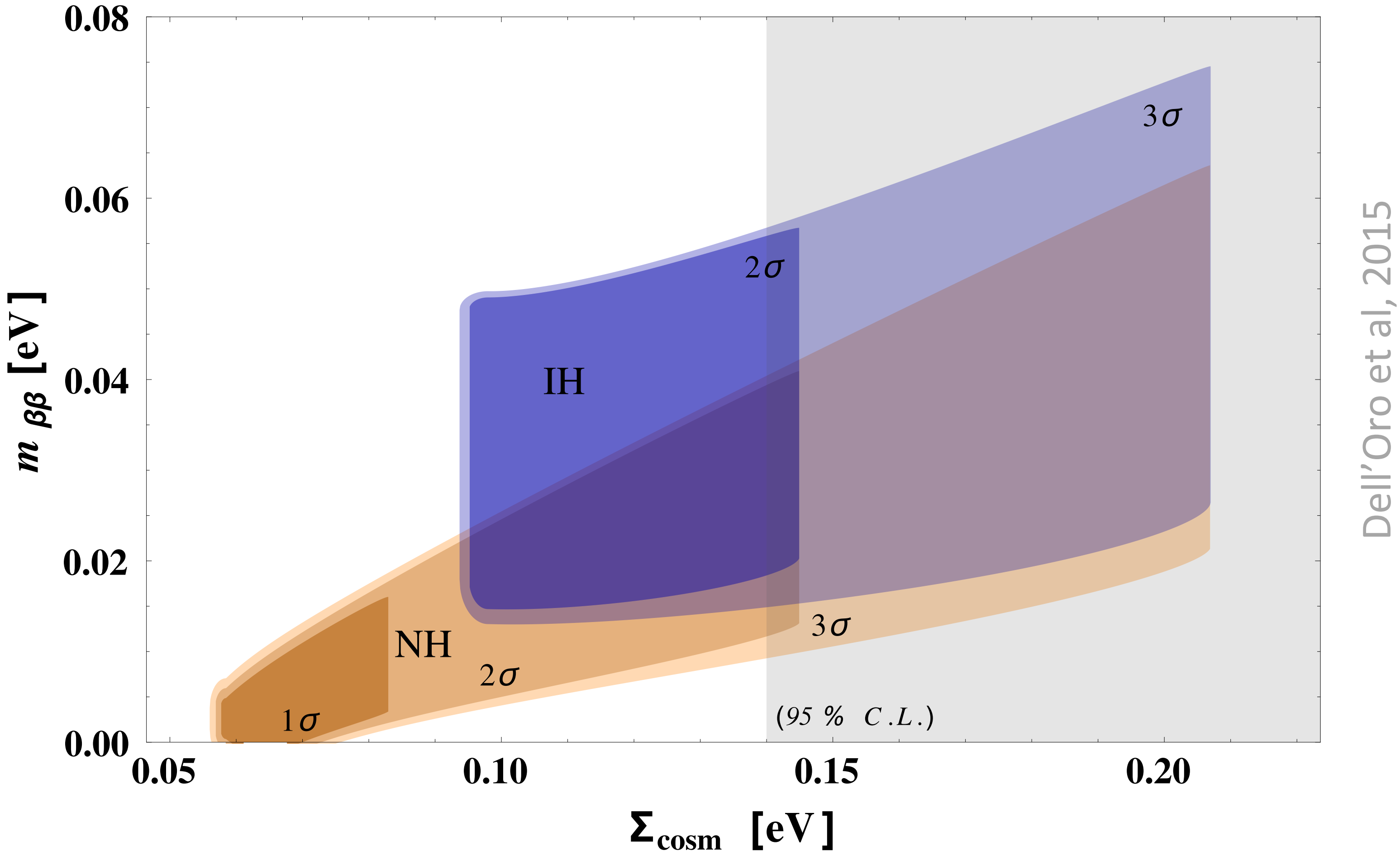


Dell'Oro et al, 2015

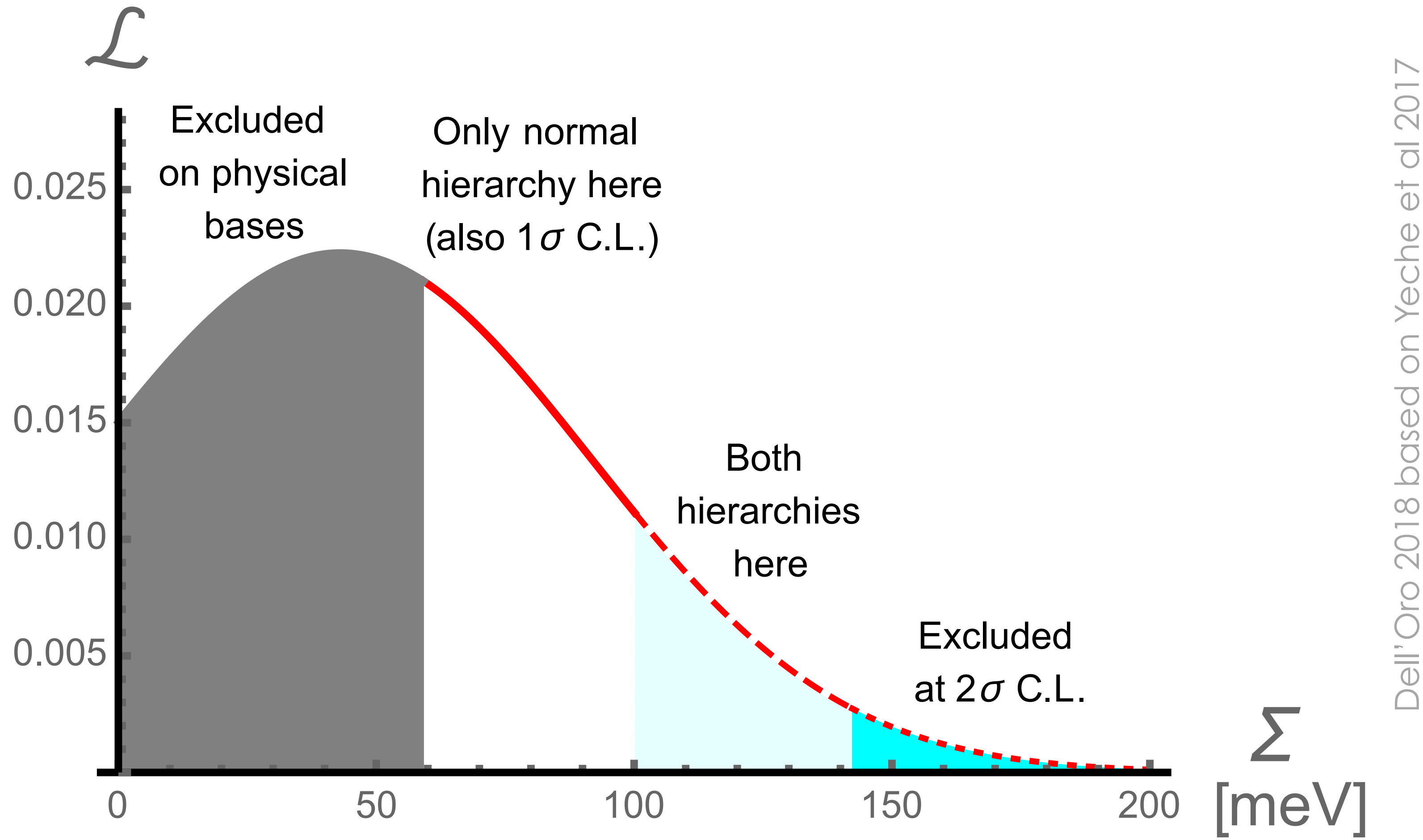
Cosmological bound and allowed regions

Cosmological analyses favors slightly the case of normal mass hierarchy. This indication preceded (2015) and it is consistent with the one from oscillations (2016, 2017).

impact of cosmology, illustrated using Bari group type plot



improved & confirmed by Planck



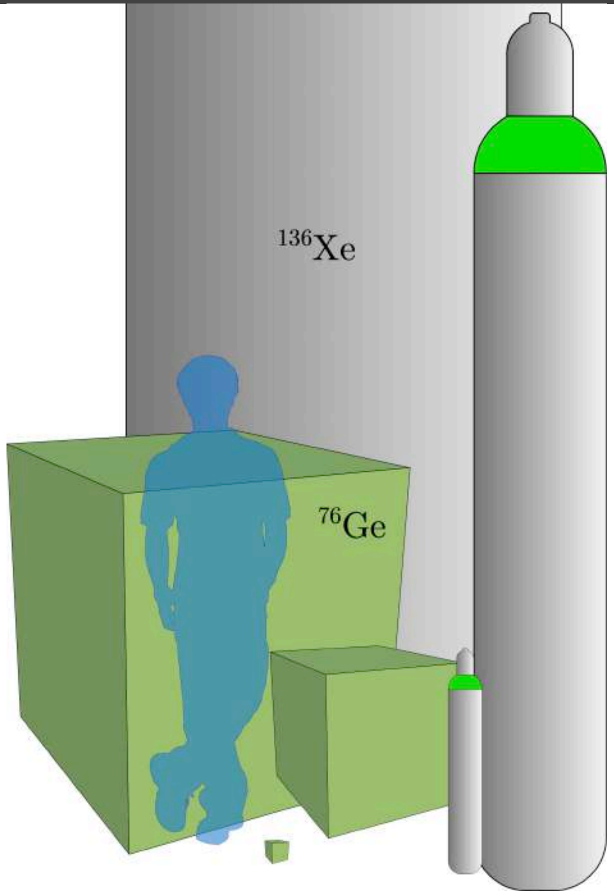
on nuclear matrix elements

nuclear matrix elements are uncertain, since nuclear structure is

different calculations agree well on $0\nu 2\beta$; but do not reproduce well $2\nu 2\beta$ or single-β

thus, uncertainty is likely to be large. quenching?

tests with double charge exchange process (NUMEN)



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IOP Conf. Series: Journal of Physics: Conf. Series **888** (2017) 012178 doi:10.1088/1742-6596/888/1/012178

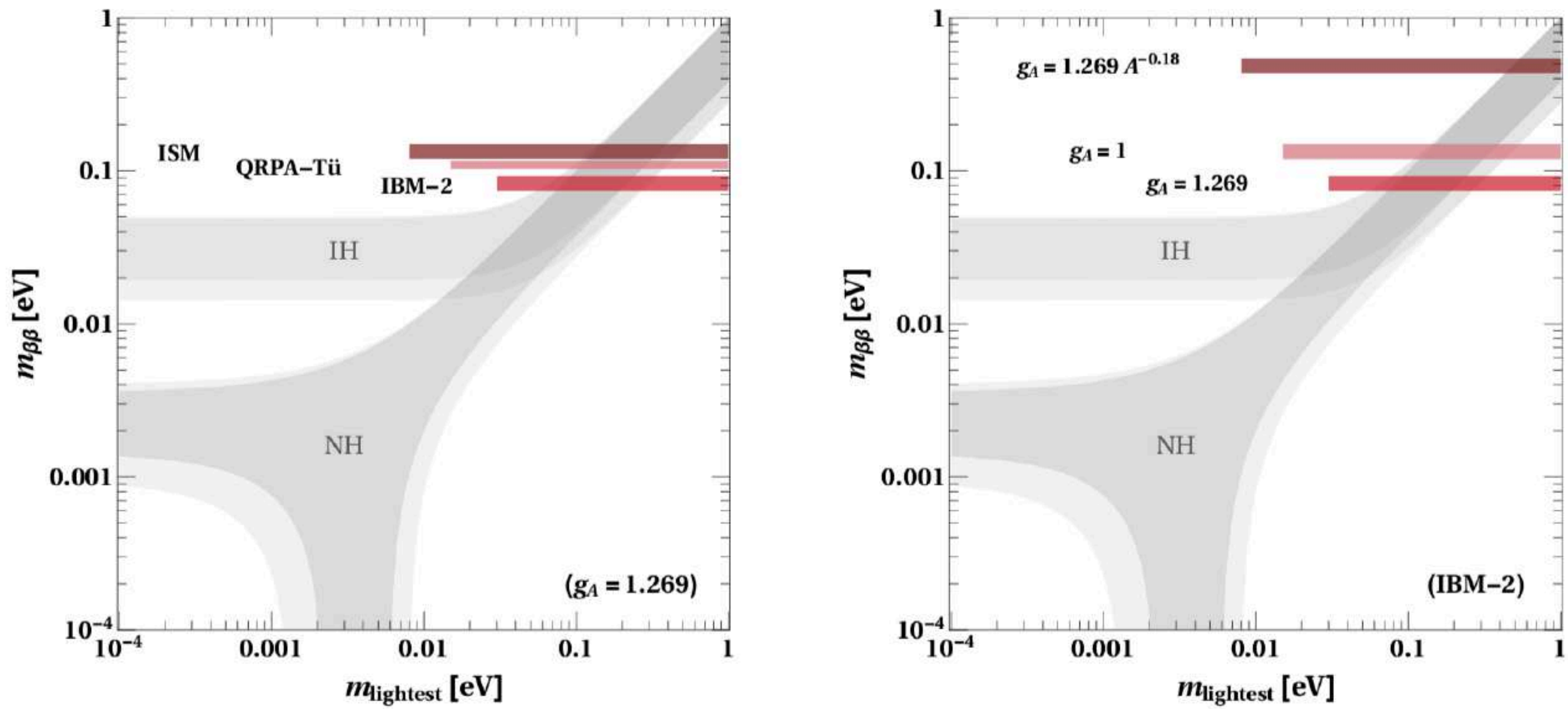


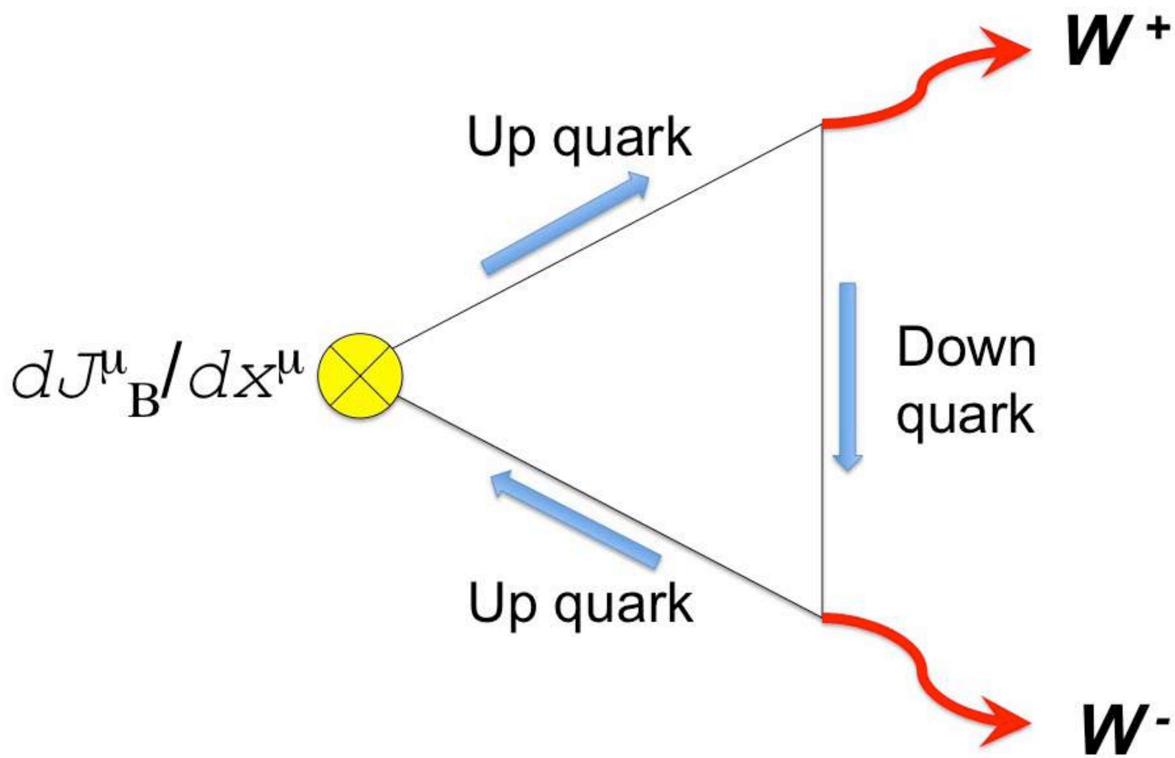
Figure 2. Uncertainty of the current $m_{\beta\beta}$ bound from ^{136}Xe [8]. (Left) Dependence on the NME (QRPA [11], IBM-2 [12], ISM [13]). (Right) Dependence on the value of the axial vector coupling constant. See Ref. [2] for an extensive discussion.

final remarks; summary and discussion

CONCLUSION

In "standard model" B and L are not conserved individually.

Only B-L is conserved exactly, thus: light & heavy matter types are connected



"neutrinoless etc": a misnamer?

- it is funny to define a process in terms of something absent (i.e., neutrinos) - hippo is not a trunkless elephant
- the name "creation of electrons" is much neater and reminds us that **B-L** is broken
- the term β comes from Rutherford times, when the β was used for "nuclear electrons" – i.e., a wrong model!!

"neutrinoless etc": a misnamer?

- it is funny to define a process in terms of something absent (i.e., neutrinos) - hippo is not a trunkless elephant
- the name "creation of electrons" is much neater and reminds us that **B-L** is broken
- the term β comes from Rutherford times, when the β was used for "nuclear electrons" – i.e., a wrong model!!
- this name reminds us one theoretical belief: that BSM physics is at ultra-high scale, and therefore, mechanism of (virtual) light Majorana neutrino exchange drives $0\nu2\beta$

what makes “matter”?

elementary components	identifying feature	time period theory (exp.)	reason of inadequacy
atoms	mass, type	till 1838 (1909)	“atoms of electricity”
nuclei & electrons	mass, charge	till 1933 (1956)	neutrons & neutrinos
p, n, e, ν_e	**B**, **L_e**, spin	till 1961 (1968)	quarks / SM
quarks, leptons	**B**, **L_e**, **L_μ**, **L_τ**, spin	till 1967 (2010)	neutrino appearance
quarks-antileptons	**B-L**, spin	till 1937!!! (??)	Majorana mass/$0\nu2\beta$
fermions	spin	till ???? (?????)	???????????

summary and discussion

- in the light of SM & of experimental knowledge, Majorana hypothesis is more plausible than ever
- motivations for the search for creation of electrons (aka, neutrinoless double beta decay) are very strong, at least as those for the proton decay search
- we have no solid theoretical expectations and, in principle, the signal could also be observed by current generation of detectors
- however, the most convincing arguments, based on cosmological bounds and Majorana hypothesis, lead us to believe that multi-tons detectors are needed

capture rate for Dirac/Majorana cosmological neutrinos; matter stability; on dim.5 operator; GUT patterns; random Majorana phases; definitions of “matter” on Wiki; again on terminology & acronyms

SUPPORTING MATERIAL

proof [1/2]

Roulet & FV, 2018

Dirac field:

$$\mathbf{\Psi}^{\mathrm{D}} = \sum_{\vec{p},\lambda} \mathbf{a}_{\vec{p},\lambda}\ \psi_{\vec{p},\lambda} + \mathbf{b}^{\dagger}_{\vec{p},\lambda}\ \psi^{\mathrm{C}}_{\vec{p},\lambda}$$

Initial states (hot Big-Bang):

$$|\nu^{\mathrm{D}}\rangle = \mathbf{a}^{\dagger}_{\vec{p},-}|0\rangle \text{ and } |\bar{\nu}^{\mathrm{D}}\rangle = \mathbf{b}^{\dagger}_{\vec{p},+}|0\rangle$$

Matrix elements for the transition:

$$\langle 0|P_{\mathrm{L}}\mathbf{\Psi}^{\mathrm{D}}|\nu^{\mathrm{D}}\rangle = P_{\mathrm{L}}\psi_{\vec{p},-}$$

and

$$\langle 0|P_{\mathrm{L}}\mathbf{\Psi}^{\mathrm{D}}|\bar{\nu}^{\mathrm{D}}\rangle = 0$$

Majorana field:

$$\mathbf{\Psi}^{\mathrm{M}} = \sum_{\vec{p},\lambda} \mathbf{c}_{\vec{p},\lambda}\ \psi_{\vec{p},\lambda} + \mathbf{c}^{\dagger}_{\vec{p},\lambda}\ \psi^{\mathrm{C}}_{\vec{p},\lambda}$$

Initial states (hot Big-Bang):

$$|\nu^{\mathrm{M}}\rangle = \mathbf{c}^{\dagger}_{\vec{p},-}|0\rangle \text{ and } |\bar{\nu}^{\mathrm{M}}\rangle = \mathbf{c}^{\dagger}_{\vec{p},+}|0\rangle$$

Matrix elements for the transition:

$$\langle 0|P_{\mathrm{L}}\mathbf{\Psi}^{\mathrm{M}}|\nu^{\mathrm{M}}\rangle = P_{\mathrm{L}}\psi_{\vec{p},-}$$

and

$$\langle 0|P_{\mathrm{L}}\mathbf{\Psi}^{\mathrm{M}}|\bar{\nu}^{\mathrm{M}}\rangle = P_{\mathrm{L}}\psi_{\vec{p},+}$$

proof [2/2]

Roulet & FV, 2018

Dirac field:

$$\langle 0|P_{\rm L}\boldsymbol{\Psi}^{\rm D}|\nu^{\rm D}\rangle = P_{\rm L}\psi_{\vec{p},-}$$

and

$$\langle 0|P_{\rm L}\boldsymbol{\Psi}^{\rm D}|\bar{\nu}^{\rm D}\rangle = 0$$

Probability:

If $\int d^3x|\psi^2_{\vec{p},\lambda}| = 1,$

then $\int d^3x|P_{\rm L}\psi^2_{\vec{p},-}| = \frac{1+\beta}{2}$

Majorana field:

$$\langle 0|P_{\rm L}\boldsymbol{\Psi}^{\rm M}|\nu^{\rm M}\rangle = P_{\rm L}\psi_{\vec{p},-}$$

and

$$\langle 0|P_{\rm L}\boldsymbol{\Psi}^{\rm M}|\bar{\nu}^{\rm M}\rangle = P_{\rm L}\psi_{\vec{p},+}$$

Probability:

If $\int d^3x|\psi^2_{\vec{p},\lambda}| = 1,$

then $\int d^3x|P_{\rm L}\psi^2_{\vec{p},-}| = \frac{1+\beta}{2}$

and $\int d^3x|P_{\rm L}\psi^2_{\vec{p},+}| = \frac{1-\beta}{2}$

another proof

Consider one Dirac neutrino with mass m_i produced in the big-bang, whose momentum is subject to adiabatic expansion of the Universe, and consider helicity states. We need to evaluate the polarized density matrix bracketed between two chirality projectors,

$$P_L\ u_i\overline{u_i}\ P_R = P_L\ (\not{p}_i + m_i)\frac{1+\gamma_5\not{\xi}_i}{2}P_R = P_L\frac{\not{p}_i - m_i\not{\xi}_i}{2}P_R \qquad (1)$$

Thus the usual calculations have to be modified trivially: we should include systematically a factor 1/2 in the calculation of the interaction rate, and moreover we should replace the 4-momentum

$$p_i \to p_i - m_i\,\xi_i$$

Considering helicity $\lambda = \pm 1$, we have $p_i = (E_i, \vec{n}\,p)$ and $m_i\,\xi_i = \lambda(p, \vec{n}\,E_i)$, where E_i is the energy and $\vec{n}$ the direction of the motion of the neutrino, $\vec{p} = p\,\vec{n}$. We get,

$$\frac{p_i - m_i\,\xi_i}{2} = \frac{1 \mp \lambda\beta_i}{2} \times p_i \text{ where } \beta_i = \frac{p}{E_i} \qquad (2)$$

The overall factor on the right-hand side is the one in which we are interested. The unpolarized neutrino density matrix $\rho_i(\nu) \equiv \not{p}_i$ has to be modified trivially

$$\rho_i(\nu) \to \frac{1 \mp \lambda\beta_i}{2} \times \rho_i(\nu)$$

Reliability of the predictions of the "standard model"; search for new phenomena: creation of electrons & proton decay; remarks on the names

MATTER STABILITY NEEDS TESTS

in *Standard model* we trust – or not?

SM ensures matter stability, but it has its own shortcomings

Matter stability is not for granted

We should test experimentally if matter appears in some process / disappears in some other

Glancing beyond SM

- High dim. operators, invariant under SM symmetry, summarize new physics at ultra-high scales
- (They play exactly the same role of Fermi interactions)
- The one with lowest dimension describes Majorana neutrino masses
- Oscillations are matched by a huge mass, say, of GUT

$$m^{\nu}_{\text{overall}} \sim \frac{M_W^2}{M_{\text{GUT}}} = 65\ \text{meV} \times \frac{10^{14}\ \text{GeV}}{M_{\text{GUT}}}$$

SM effective operators (Weinberg; Wilczek & Zee 79)

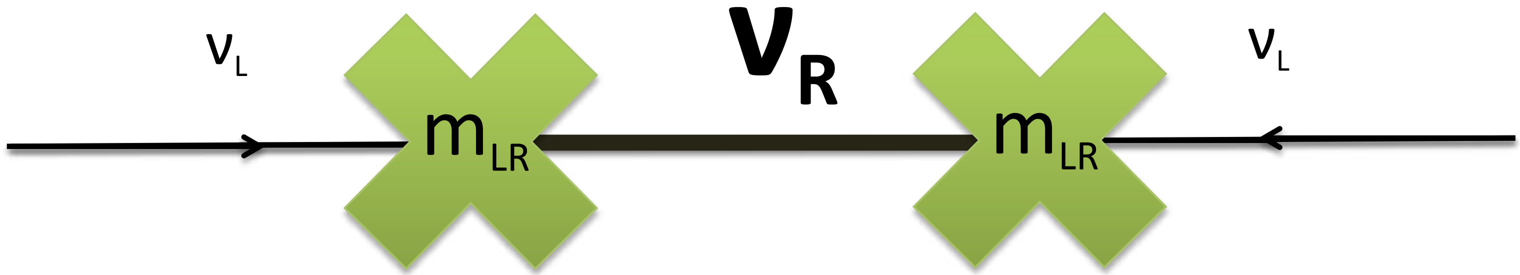
accept in the SM Lagrangian density also the operators with canonical dimension >4 that conserve SM gauge symmetry

B-L and L_i-L_j broken

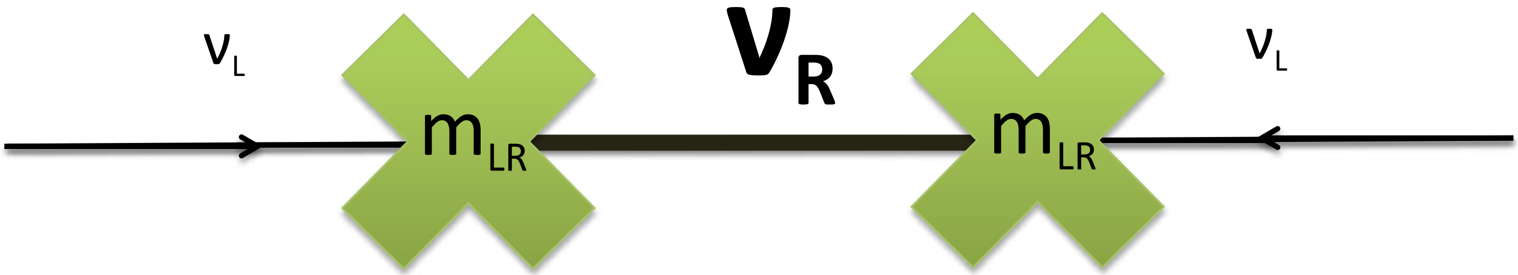
$$\delta\mathcal{L} = \frac{(\ell H)^2}{M} + \frac{\ell qqq}{M'^2} + \frac{(\ell q d^c)^2}{M''^5} \text{ with } \begin{cases} M < 10^{11} \text{ TeV} & \text{for } \texttt{dim.5} \\ M' > 10^{12} \text{ TeV} & \text{for } \texttt{dim.6} \\ M'' > 5 \text{ TeV} & \text{for } \texttt{dim.9} \end{cases}$$

B & L broken
B-L unbroken

an explanation of small of neutrino masses

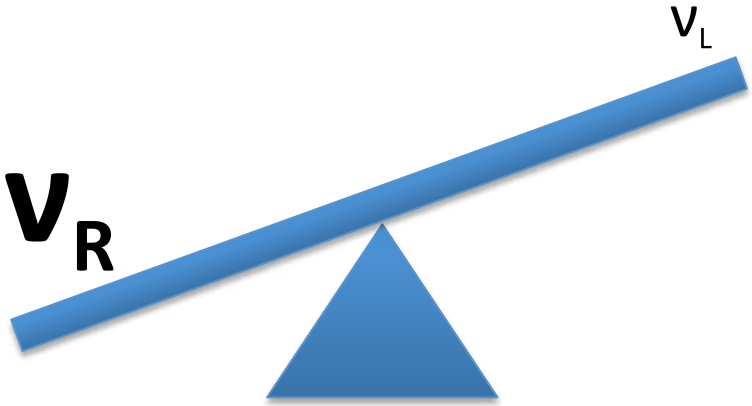


an explanation of small of neutrino masses

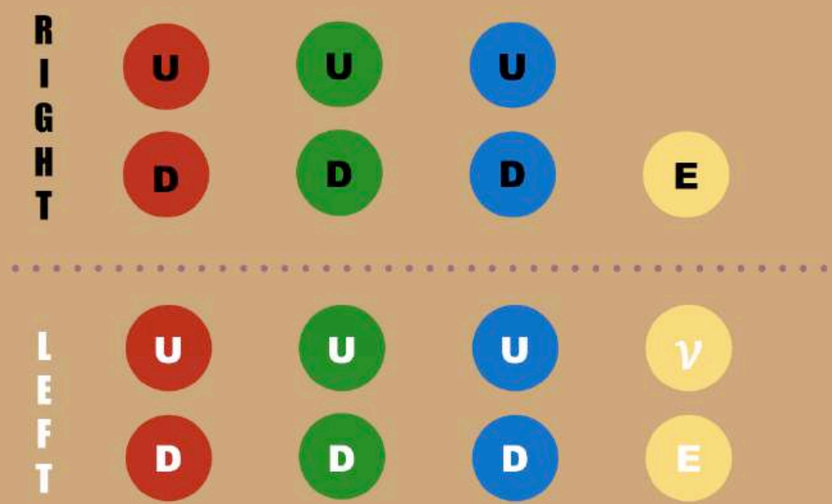


$$\frac{1}{m_{RR}}$$

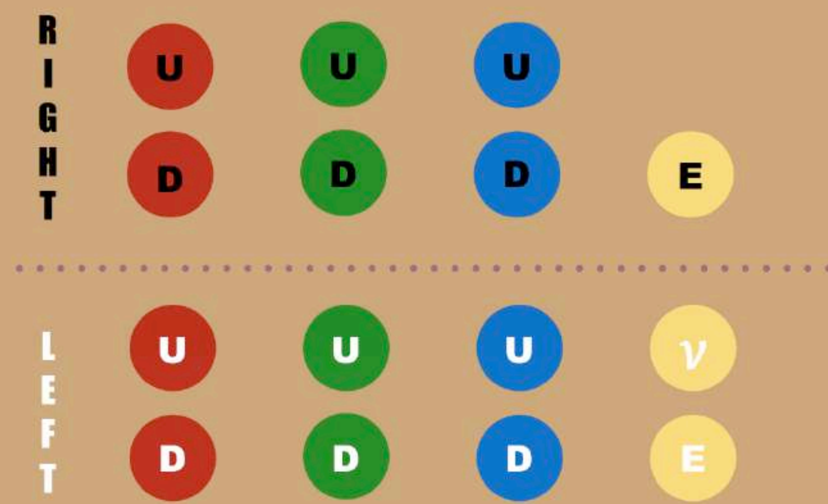
this is called “seesaw”



15 particles per family

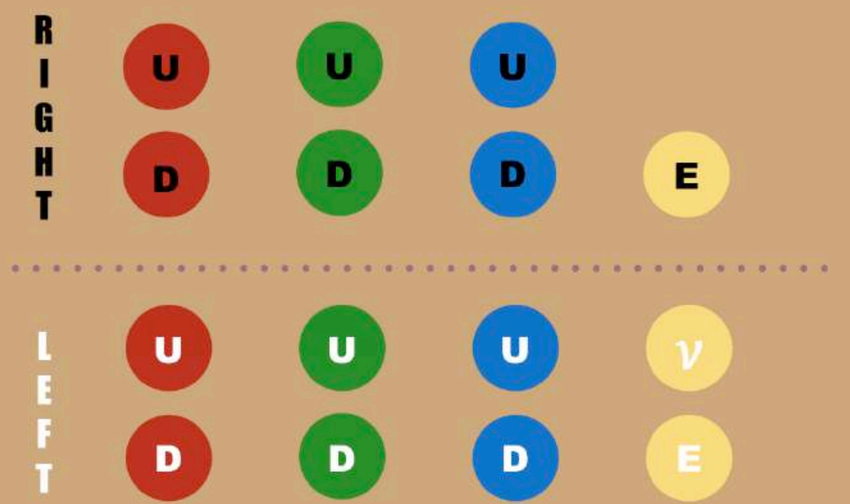


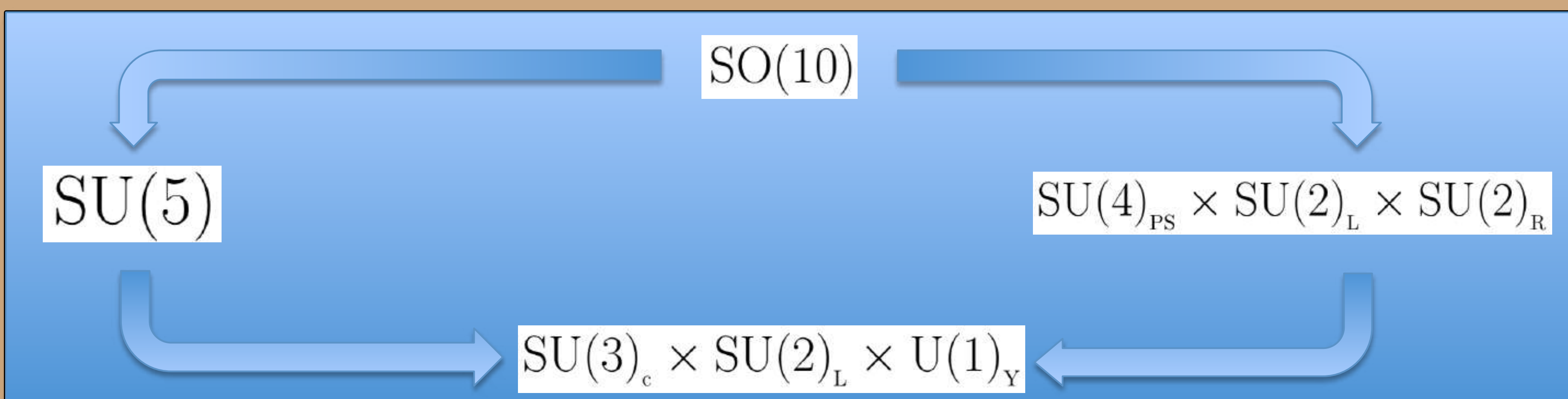
15 particles per family



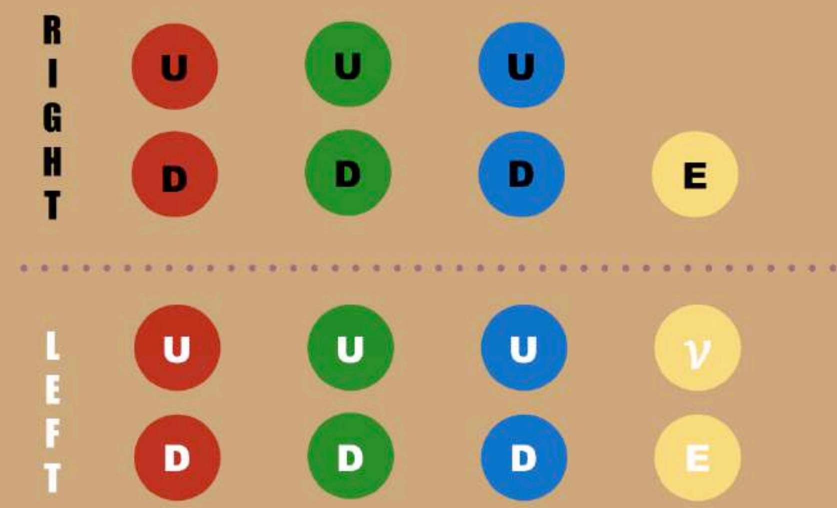
$$\mathrm{SU}(2)_{\mathrm{L}} \text{ acts on } \begin{pmatrix} \nu_{\mathrm{L}} \\ e_{\mathrm{L}} \end{pmatrix} \quad \text{while} \quad \mathrm{SU}(2)_{\mathrm{R}} \text{ acts on } \begin{pmatrix} \nu_{\mathrm{R}} \\ e_{\mathrm{R}} \end{pmatrix}$$

15 particles per family





15 particles per family



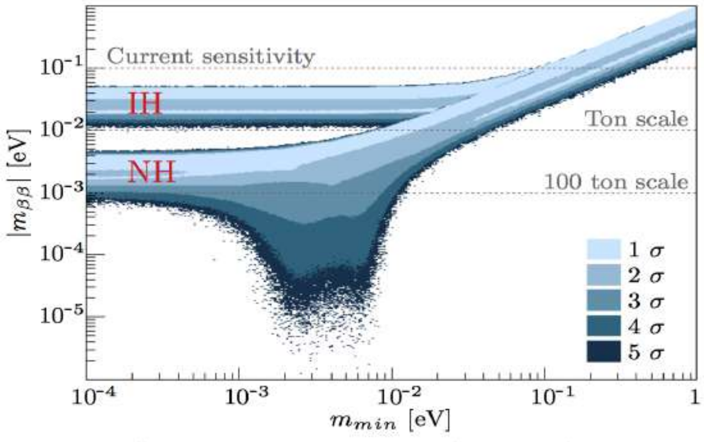
16-plet

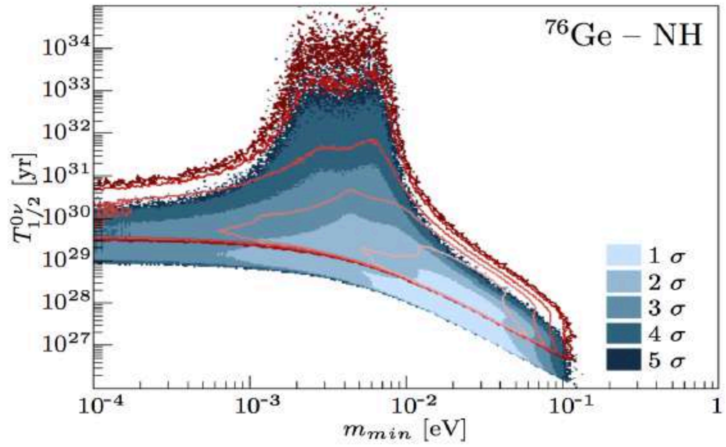
10-plet, $\bar{\mathbf{5}}$-plet, **1**-plet

$(\mathbf{4}, \mathbf{2}, \mathbf{1})$-plet, $(\bar{\mathbf{4}}, \mathbf{1}, \mathbf{2})$-plet

quarks and leptons
ν_R included

hypothesis of random phases





Benato, 2015

See also Caldwell, Merle, Schultz, Totzauer; Agostini, Benato, Detwiler 2017

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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 h
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]

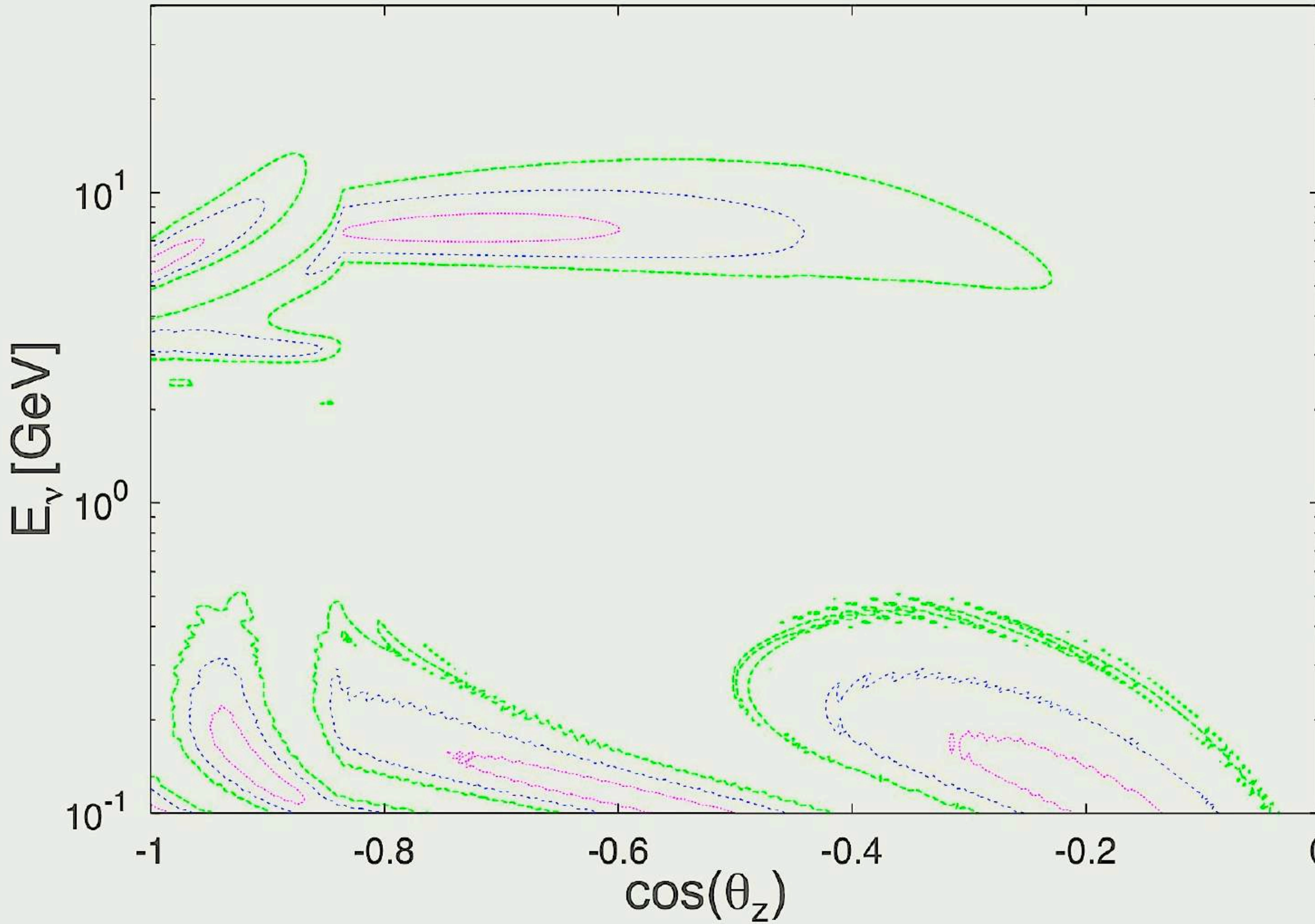
Usually atoms can be imagined as a nucleus of protons and neutrons, and a surrounding "cloud" of orbiting
correct, because subatomic particles and their properties are governed by their quantum nature, which mea
like waves as well as particles and they do not have well-defined sizes or positions. In 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 Dem

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

Alternative designations for 0ν2β?
the suffix "-genesis" seems apt, but

"Electrogenesis" is already used in biochemistry

English [edit]

Etymology [edit]

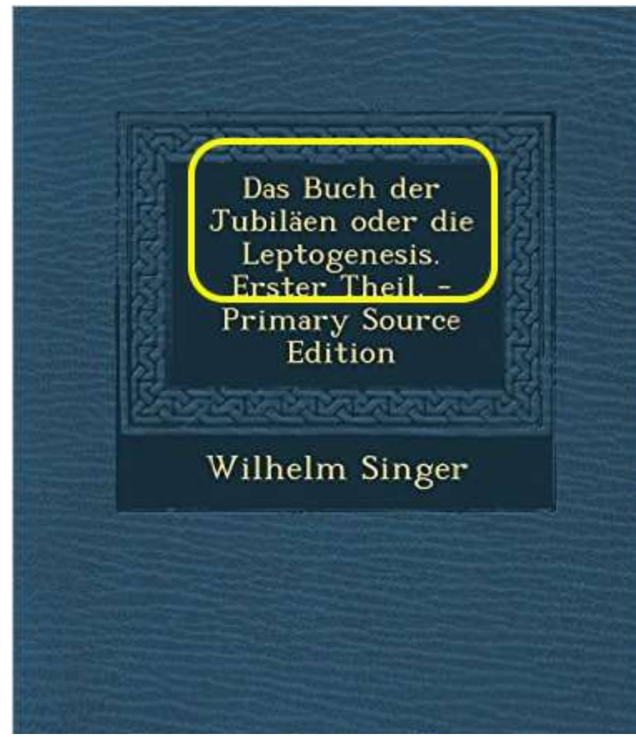
electro- + *-genesis*

Noun [edit]

electrogenesis (*usuall* *uncountable*, *plural* **electrogeneses**)

1. (*biochemistry*, *physics*) The production of electricity (or the transfer o electrons) in the tissues of a living organism

"Leptogenesis" is taken by copts & particle theorists



a few discussions at WIN2019, with editing, on: other designations for neutrinoless double beta decay; more possible effects of Majorana masses; impact of new neutrinos on neutrinoless double beta decay

QUESTIONS AND ANSWERS

Q/A

Q: *Why not to use the words "lepton creation" to denote "neutrinoless double beta decay"?*

A: This is an excellent choice when talking to colleagues who know exactly how important lepton number is.[1]

For general usage, other choices are possible. The term "electron" is much better known (atomic theory is taught early in schools); "matter creation" is an equally valid locution.

The best term depends upon the context in my view.

[1] E.g., as I emphasized in the talk, the SM links via **B-L** the leptons and the baryons, so lepton number is as important as the baryon number (this is well-known to people studying "leptogenesis").

Q/A

Q: *Shouldn't neutron decay be termed "electron creation" as well? This is just what happens in Fermi's theory (1933).*[1]

A: In Fermi's theory an electron is not created alone.

Calling neutron decay "electron creation" - rather than, say, "weak decay" - means forgetting the antineutrino, which is an antimatter particle in current thinking (i.e., what remains of SM)

Neutron decay does not imply matter creation. This is true not only for what concerns heavy particles (i.e. baryons) but also for what concerns light matter particles (i.e., leptons).

[1] The first theory with particle creation/annihilation is Einstein's theory of light (1905) but then, nobody believed that matter particles could be created: E.g., in Pauli theory (1930) the electron and the (anti)neutrino are in the nucleus.

Q/A

Q: *Is it conceivable that Majorana nature of neutrinos shows up in other cosmological/astrophysical context?*

A: I do not know for sure if asked in these very general terms, so I just touch a few points for the discussion.

1. Typically neutrinos are produced at high energy and in that case the mass plays no role.
2. Whenever gravity is the leading force (e.g., for what concerns structure formation, or CMB) the two chiral states are treated in the same manner.
3. If we have Dirac mass and there is an initial neutrino-antineutrino asymmetry, this will be conserved while it will be violated in the case of Majorana mass.
4. Another interesting possibility to tell Majorana from Dirac is if magnetic neutrino moment is large and measurable.

Q/A

Q: *Light right-handed neutrinos are potentially relevant for neutrinoless double β decay as remarked by Rodejohann.*

A: I agree, if they exist. In the talk I pointed out that we do not have convincing evidence that this situation applies.[1]

Note that in some model as νSM (Shaposhnikov's) the contribution of the additional neutrinos, differently from the so called 3+1 model, is negligible instead.

[1] Incidentally I think that the traditional nomenclature reserves the words "sterile neutrino" for some light particles that could mix with the ordinary neutrinos, e.g., those with a mass of 1 eV, whereas "right handed neutrino" is usually considered much heavier, say above Λ_{QCD}. I prefer to use "heavy neutrino" for the second situation, since this term is a bit more explicit, and moreover we could turn a right field into a left one by charge conjugation.