Neutrino-less ββ−decay: Motivations, Expectations, Uncertainties
(or: our opportunity to study the creation of matter in lab)

Stefano Dell'Oro, Simone Marcocci, Francesco Vissani
INFN-LNGS & GSSI

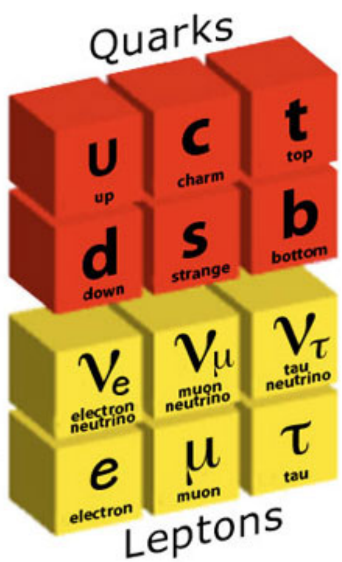
(based mostly on the review Adv. in HEP, 2016, 2162659 & on 1710.06732)

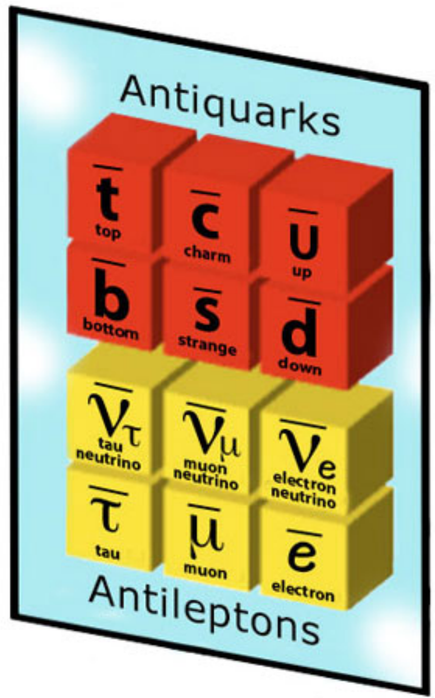
17th Int Workshop on Next Generation Nucleon Decay and Neutrino Detectors,
The University of Warwick, Oct 26-28, 2017

On the nature of matter, shortcomings of the “standard model”, search for new phenomena: creation of electrons & proton decay

WHY MATTER STABILITY NEEDS TESTS


What is
“matter”?


Quarks
u up
c charm
t top
d down
s strange
b bottom
ν_e electron neutrino
ν_μ muon neutrino
ν_τ tau neutrino
e electron
μ muon
τ tau
Leptons


Antiquarks
$\bar{t}$ top
$\bar{c}$ charm
$\bar{u}$ up
$\bar{b}$ bottom
$\bar{s}$ strange
$\bar{d}$ down
$\bar{\nu}_\tau$ tau neutrino
$\bar{\nu}_\mu$ muon neutrino
$\bar{\nu}_e$ electron neutrino
$\bar{\tau}$ tau
$\bar{\mu}$ muon
$\bar{e}$ electron
Antileptons

the best theory of matter we have

is the "Standard Model". Some features relevant for us,

- neutrino masses are zero
- B-L , L_e-L_μ , L_e-L_τ , L_τ-L_μ are exactly conserved; B , L , L_e , L_μ , L_τ only perturbatively
- matter ≠ antimatter, neutrinos included
- (no explanation of cosmic matter unbalance)

the best theory of matter we have

is the "Standard Model". Some features relevant for us,

- neutrino masses are zero **(false)**
- B-L , L_e-L_μ , L_e-L_τ , L_τ-L_μ are exactly conserved; B , L , L_e , L_μ , L_τ only perturbatively **(mostly false)**
- matter ≠ antimatter, neutrinos included **(dubious)**
- (no explanation of cosmic matter unbalance)

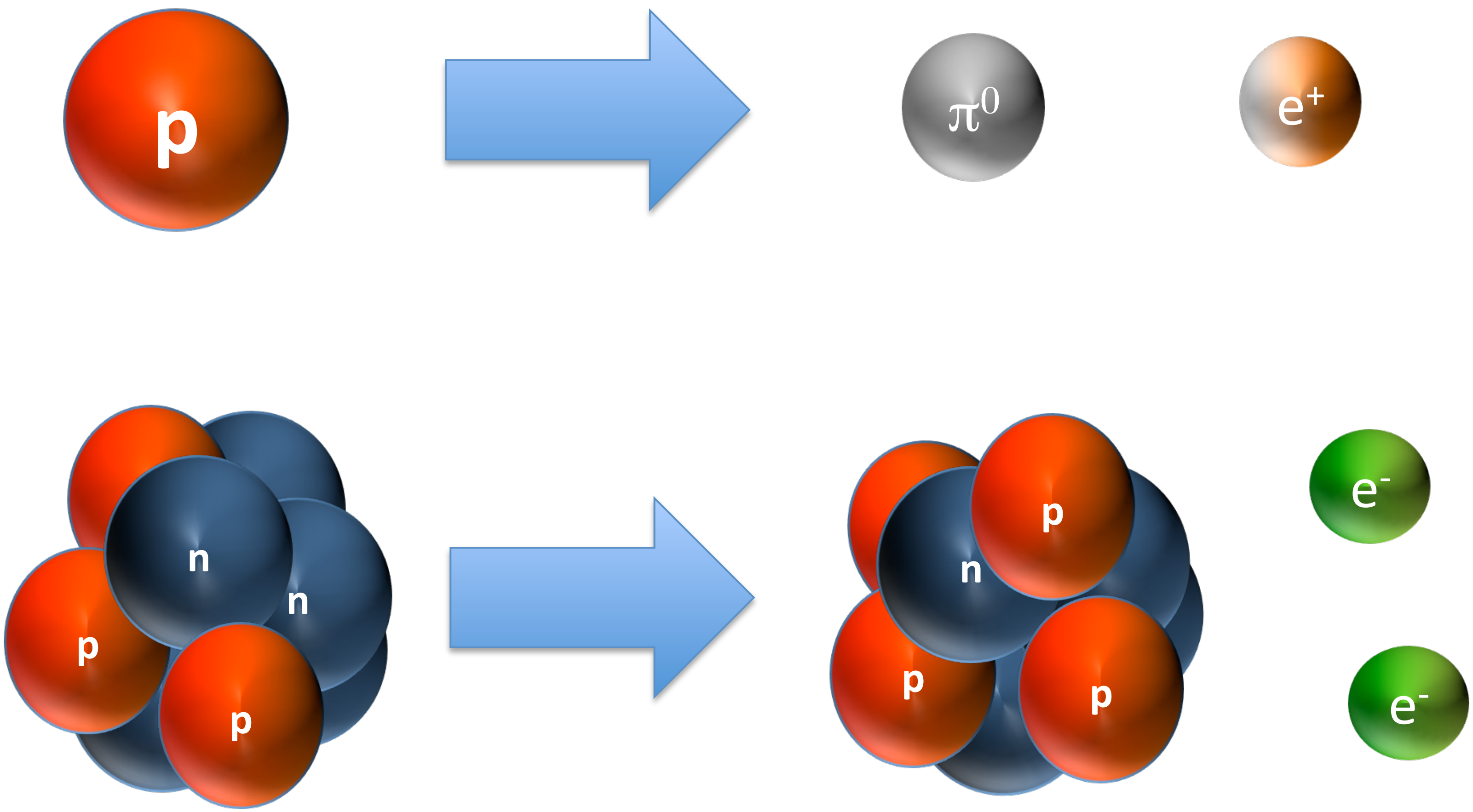
in *Standard model* we trust – or not?

SM ensures matter stability, but it has its own shortcomings

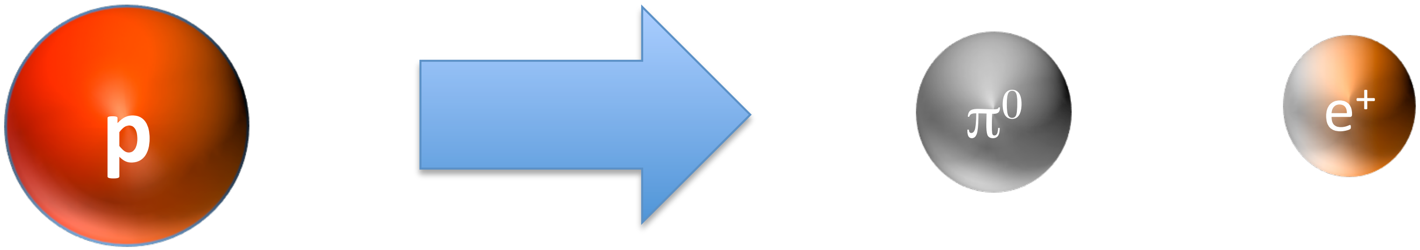
Matter stability is not for granted

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

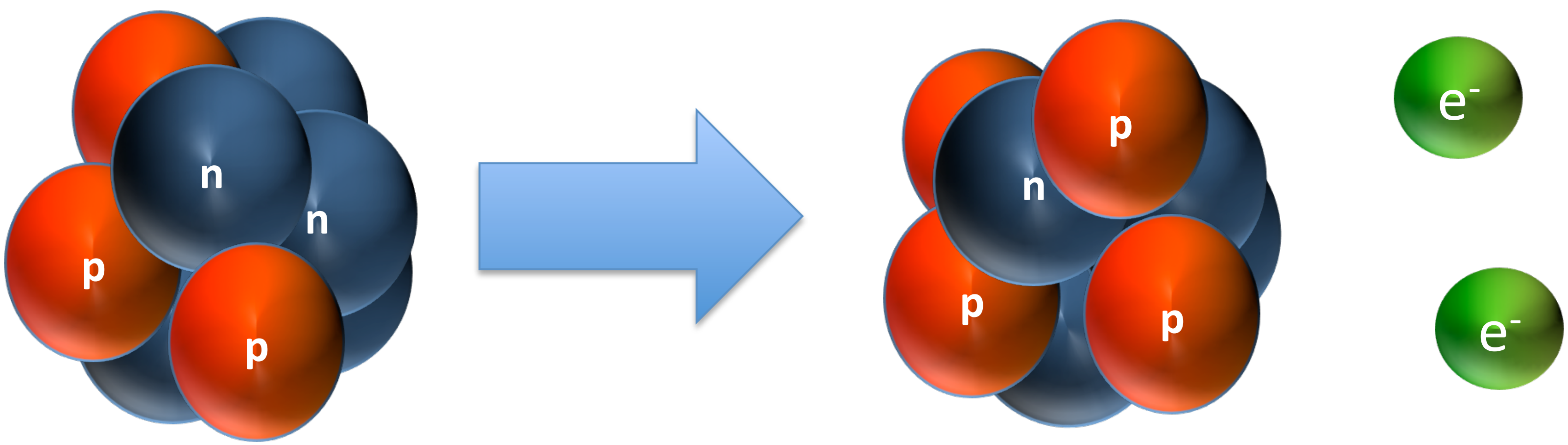
MAYBE MATTER IS NOT FOREVER



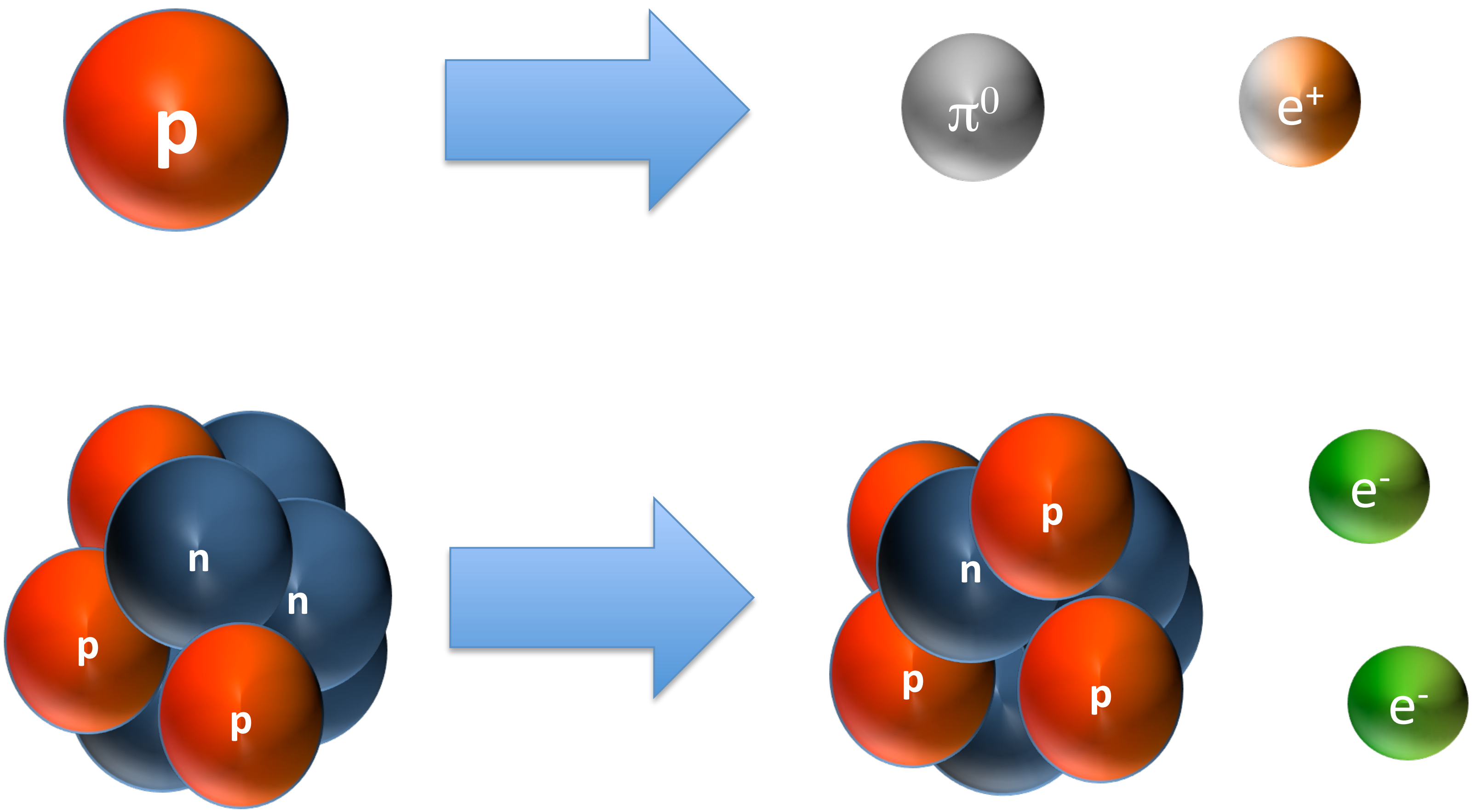
MAYBE MATTER IS NOT FOREVER



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

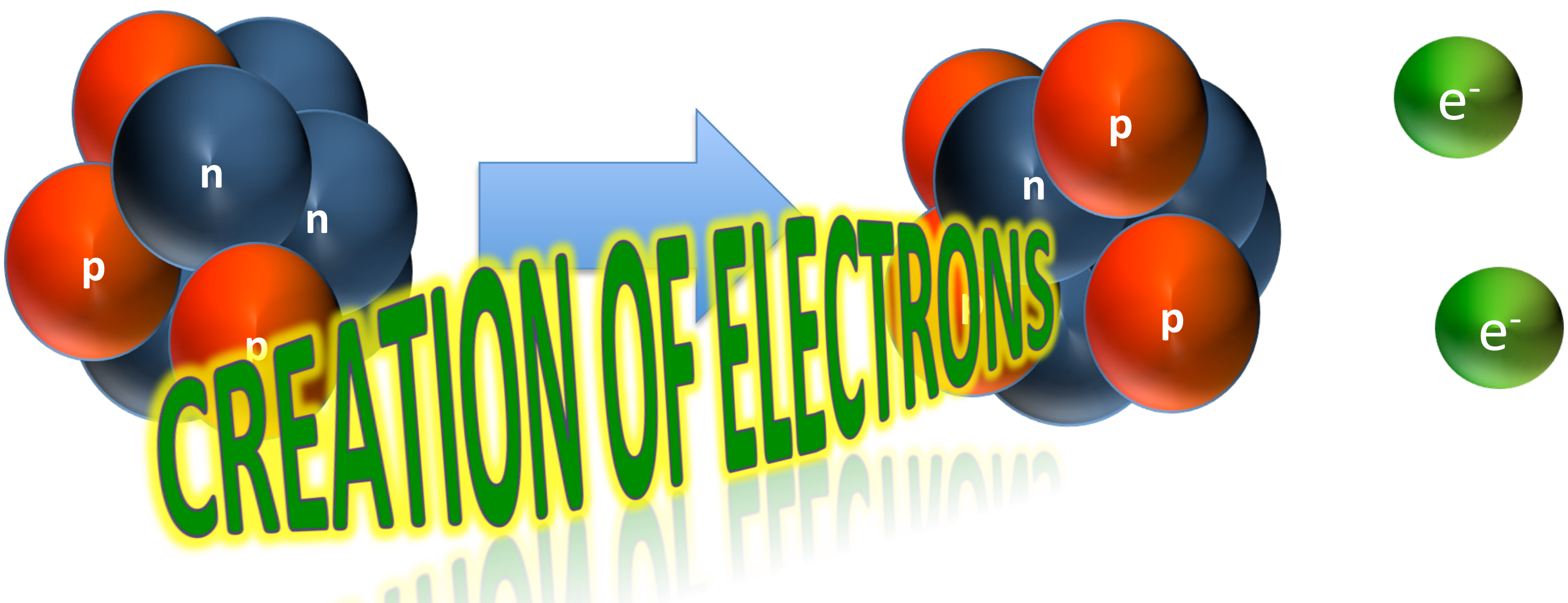


MAYBE MATTER IS NOT FOREVER

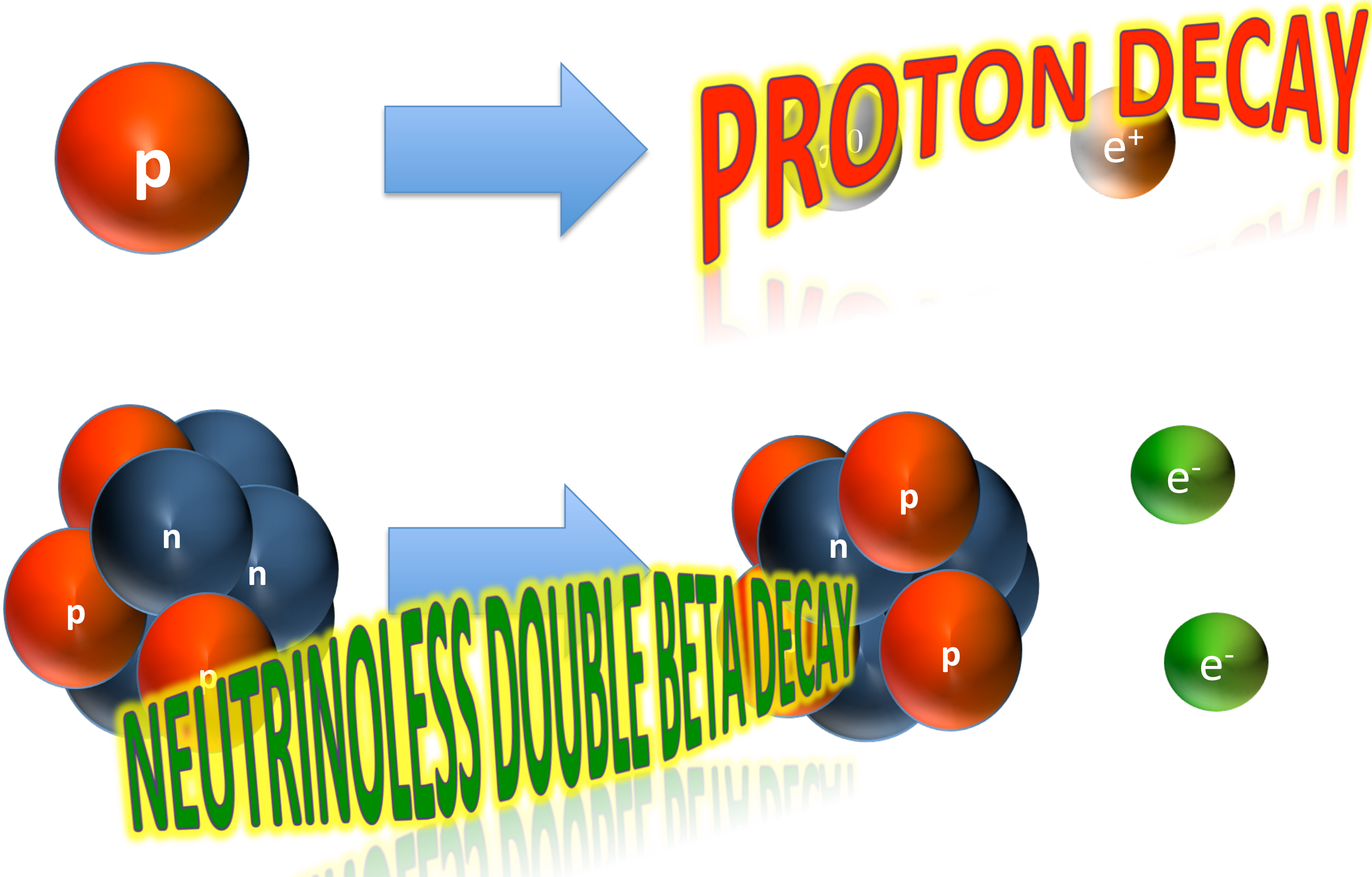


B=A , L=0 **B=A , L=2**

MAYBE MATTER IS NOT FOREVER

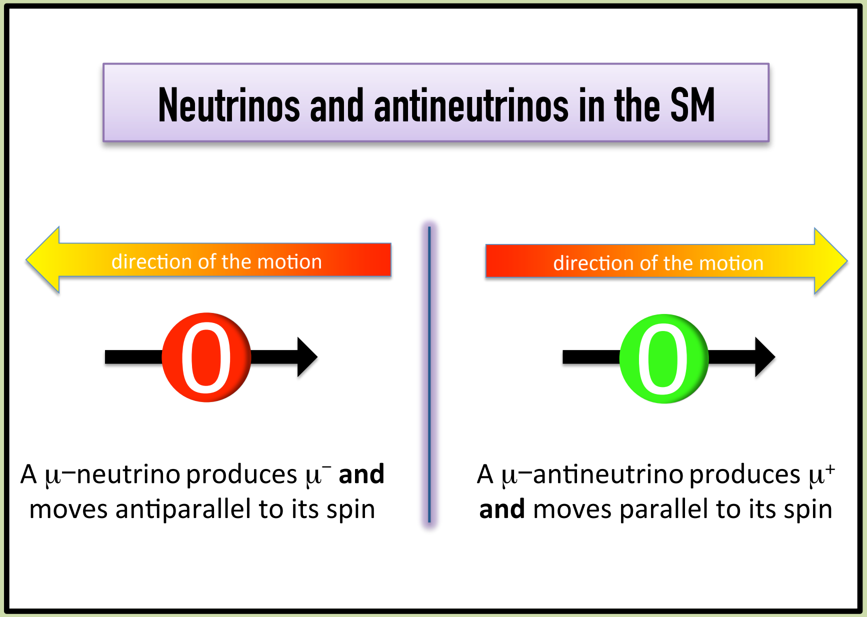


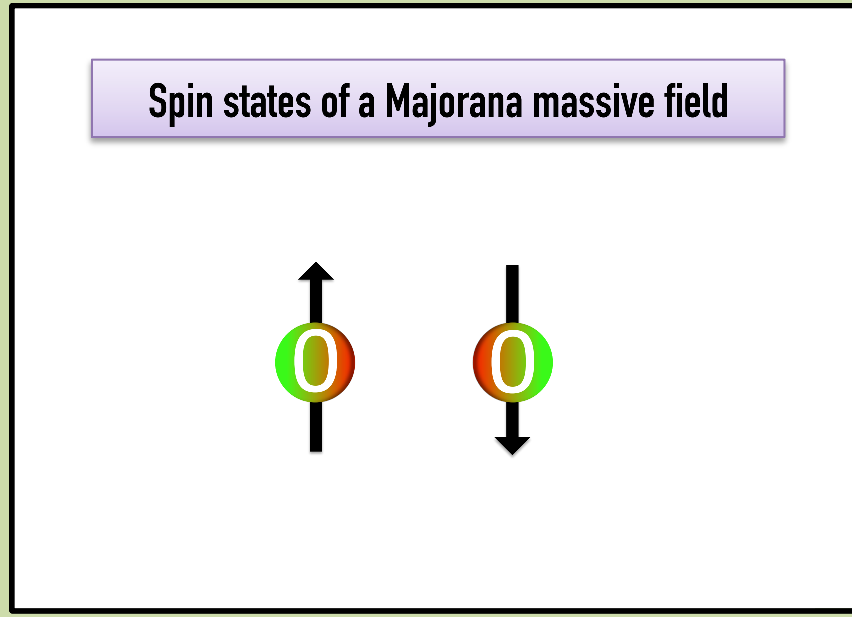
MAYBE MATTER IS NOT FOREVER



Majorana neutrino masses, new physics at very high energy, impact on the $0\nu2\beta$ decay process (or creation of electrons)

THE "NEUTRINIAN" CONNECTION


Neutrinos and antineutrinos in the SM
direction of the motion
direction of the motion
0
0
A μ−neutrino produces μ⁻ and moves antiparallel to its spin
A μ−antineutrino produces μ⁺ and moves parallel to its spin


Spin states of a Majorana massive field
0
0

SM upgrade with ν mass (dated 1937)

SM says: ν are exactly left-handed (anti-ν exactly right-handed).
We can tell matter from antimatter in ultrarelativistic conditions

Majorana says: ν & anti-ν are the same particle **in rest frame**;
they are matter & antimatter at once in that frame

(Note, difference between matter & antimatter
is not a Lorentz invariant concept)

SM upgrade with ν mass (dated 1937)

SM says: ν are exactly left-handed (anti-ν exactly right-handed).
We can tell matter from antimatter in ultrarelativistic conditions

Majorana says: ν & anti-ν are the same particle **in rest frame**;
they are matter & antimatter at once in that frame

(Note, difference between matter & antimatter is not a Lorentz invariant concept)

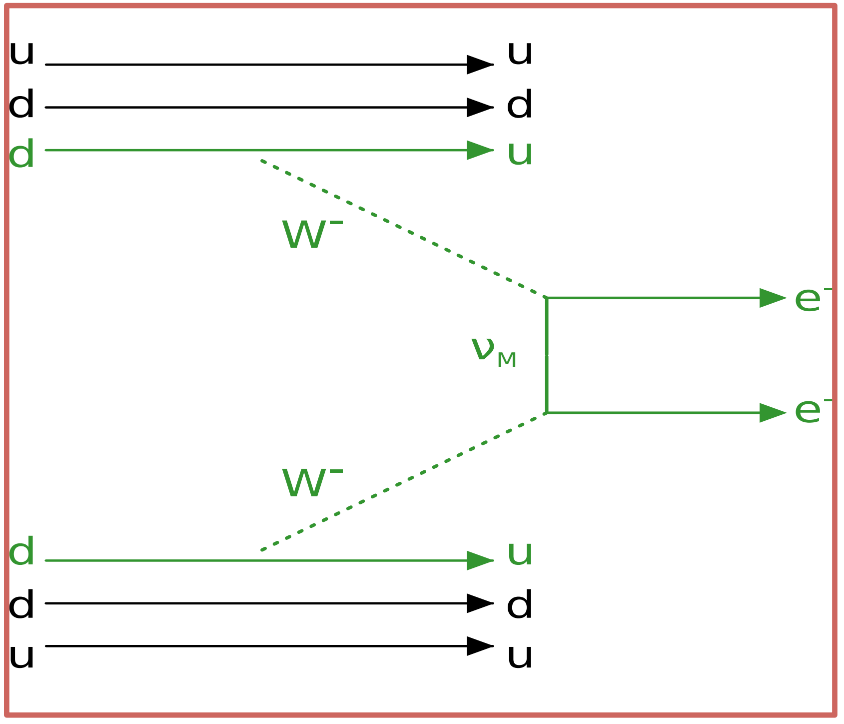
Usually $m_\nu << p_\nu$ and kinematical effects are tiny; however, the lepton number is violated as m_ν/p_ν

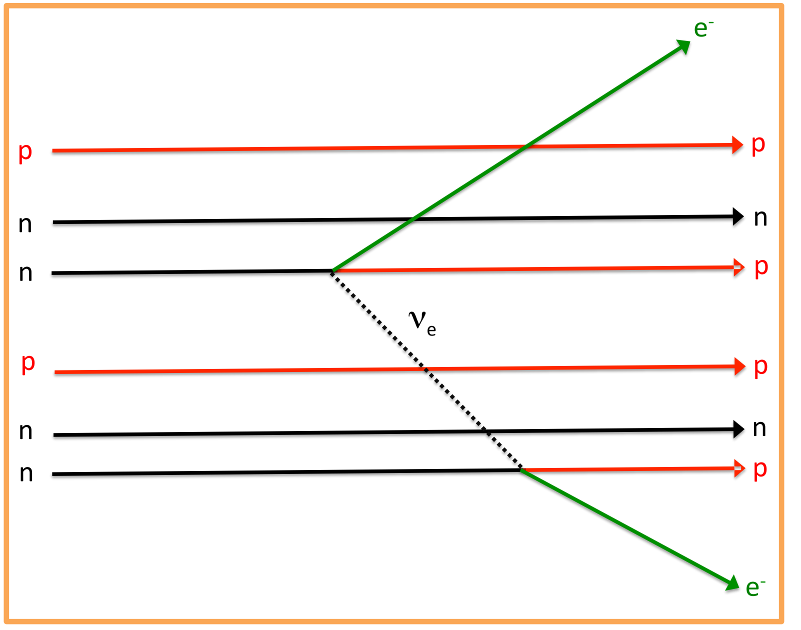
Glancing beyond SM

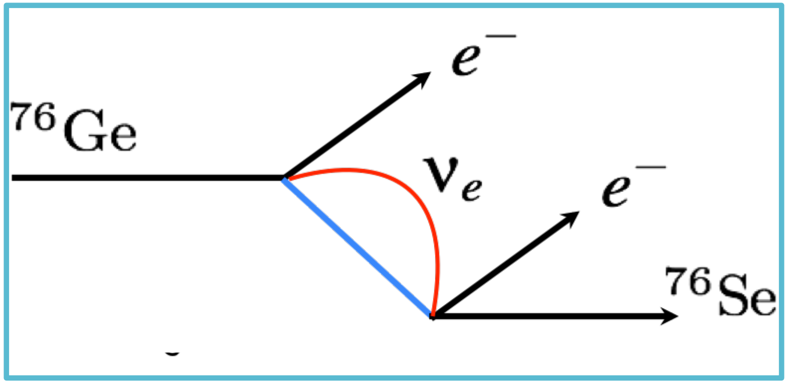
- High dim. operators, invariant under SM symmetry, summarize new physics at ultra-high scales, say, at GUT
- (They play exactly the same role of Fermi interactions)
- The one with dim.5 describes neutrino masses (Majorana's)
- A high mass scale matches well oscillations:

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

role of Majorana neutrinos for 0ν2β







The mass parameter that matters; implications of oscillations, cosmology and particle physics theory (or better, hypotheses/guesswork)

MAJORANA NEUTRINOS: IMPLICATIONS

the “electron neutrino” mass

If the mass of the light ν leads the transition, e.g. if new physics is at ultra-HE scale, the parameter that counts for 0ν2β is,

$$m_{\beta\beta} \equiv |(M_\nu)_{ee}| = \left| \sum_{i=1}^{3} |U_{ei}^2| \, e^{i\xi_i} \, m_i \right|$$

Symbols: first is the traditional one; second, ee-element of the ν mass matrix

The absolute mass scale and the (Majorana) **phases** ξ_i are not probed by oscillations: Only mass differences and electronic mixing $|U_{ei}^2|$ are measured.

what we know from neutrino oscillations

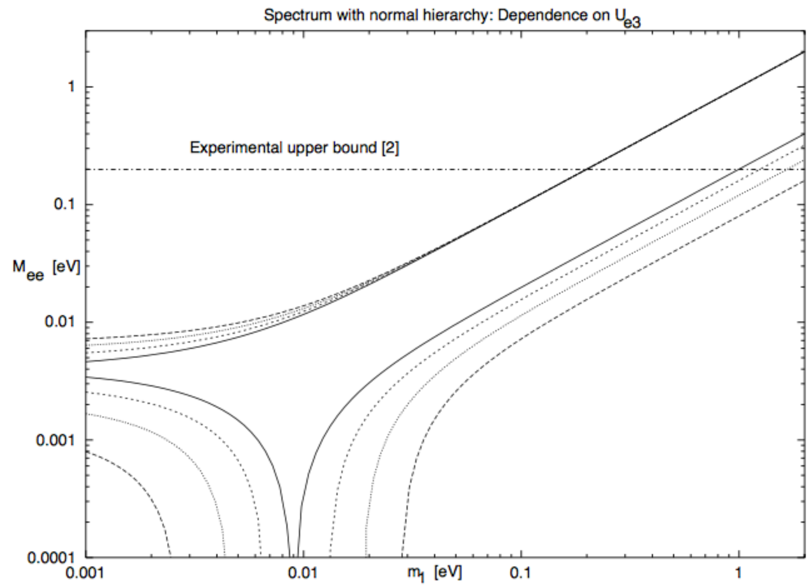
Signal of neutrinoless double beta decay, neutrino spectrum and oscillation scenarios

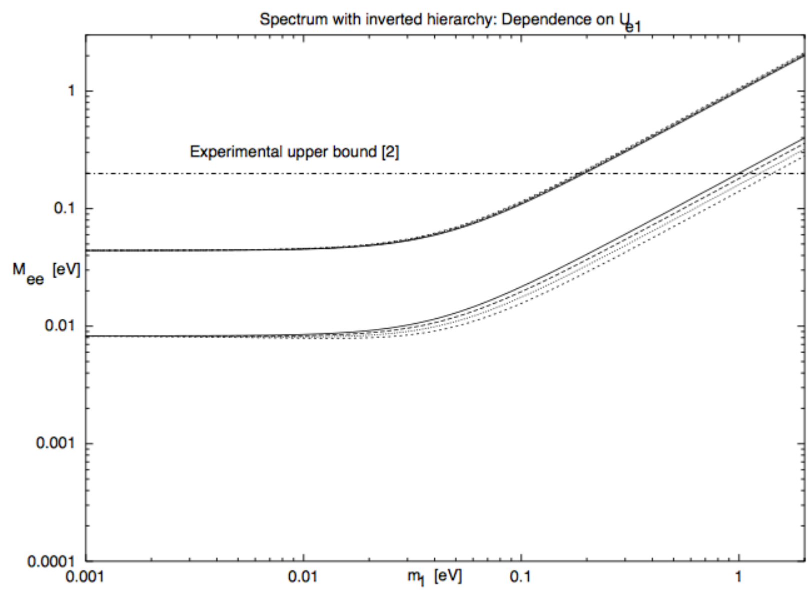
Francesco Vissani

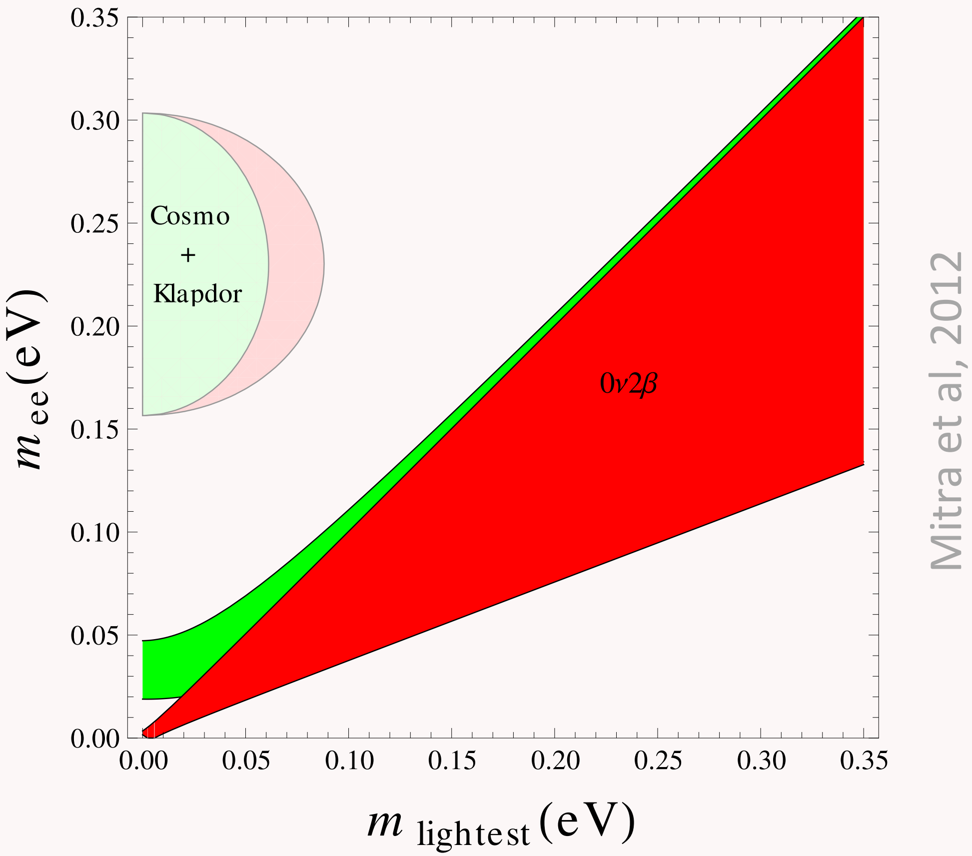
Deutsches Elektronen-Synchrotron, DESY
Notkestraße 85, D-22603 Hamburg, Germany, and
International Centre for Theoretical Physics, ICTP
Strada Costiera 11, 34100 Trieste, Italy
E-mail: `vissani@ictp.trieste.it`

Abstract: The lower and upper bounds on the neutrinoless double beta ($0\nu2\beta$) decay rate are obtained, as functions of the parameters of neutrino oscillations and of the lightest neutrino mass. The constraints on these parameters from the search for the $0\nu2\beta$ transition, as well as from the interpretation of solar and atmospheric neutrino data in terms of oscillations, can be conveniently represented in one unitarity triangle. This representation helps to clarify the cases when the $0\nu2\beta$ rate is small; the crucial dependence on the scenarios assumed for solar neutrino oscillations and on the neutrino spectrum is emphasized. We consider hierarchical and non-hierarchical neutrino spectra, and discuss their interest in view of future searches of the $0\nu2\beta$ decay.

Keywords: Neutrino Physics, Solar and Atmospheric Neutrinos.







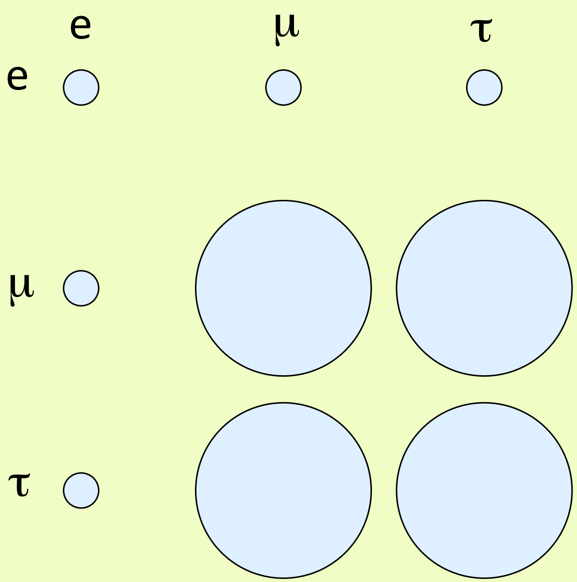
how to use the ($m_{lightest}$, $m_{\beta\beta}$)-plot

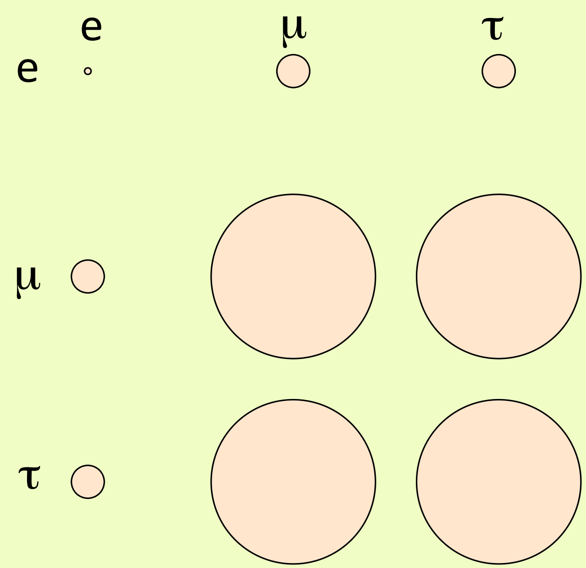
This drawing shows that Klapdor et al's result did not agree with light Majorana neutrino interpretation. A priori, a similar situation can signify that the findings are not reliable or that they hint at an alternative scenario; this could be very interesting ***if lepton number violation will be observed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

(extended dominant block)

(electronic selection rule)

HP. ON NEUTRINO MASS MATRIX,





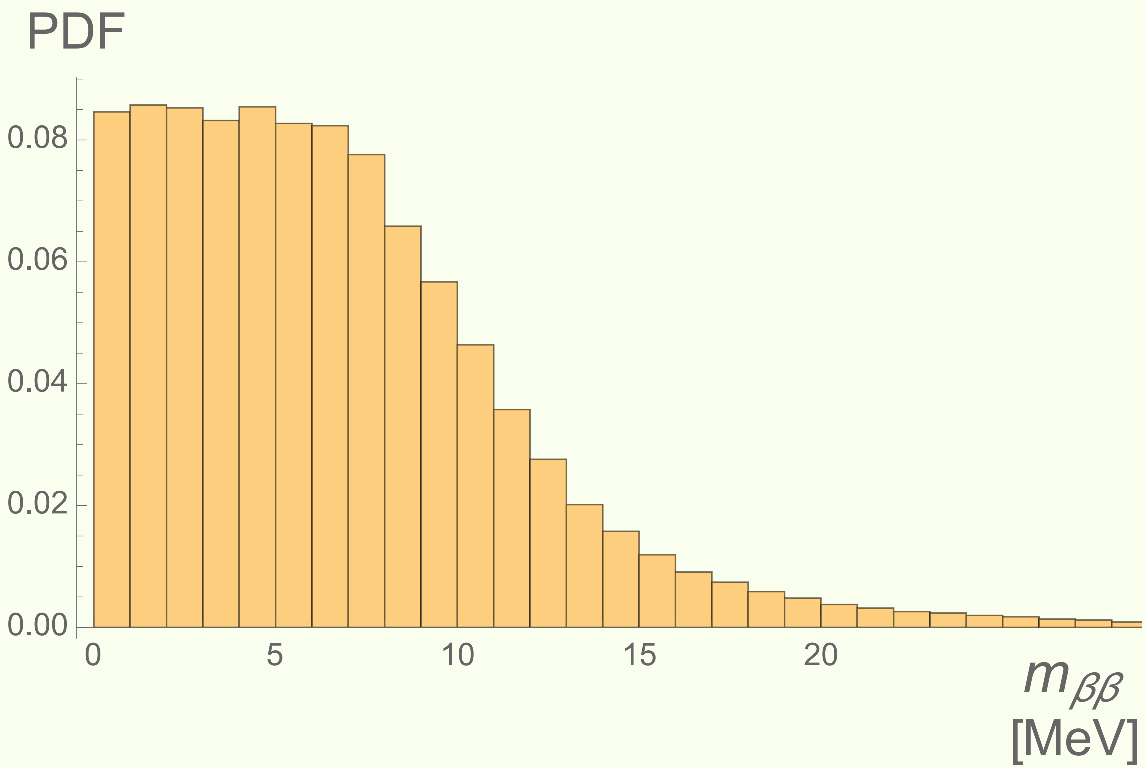
Vissani, 2001

Large atmospheric neutrino mixing suggests a matrix with a **dominant μ–τ block** (Berezhiani Rossi 96, Vissani 98).
The expectations can be explored with **random #** generators.
Since 2001, it is known that a "order parameter" θ_C=13° or $\sqrt{m_\mu/m_\tau}$=14° performs well: it agrees with LMA, it gives large θ_{13}, it has NH, etc. The second case has smaller $m_{\beta\beta} = |(M_\nu)_{ee}|$ but it is consistent with a U(1) selection rule

(extended dominant block)

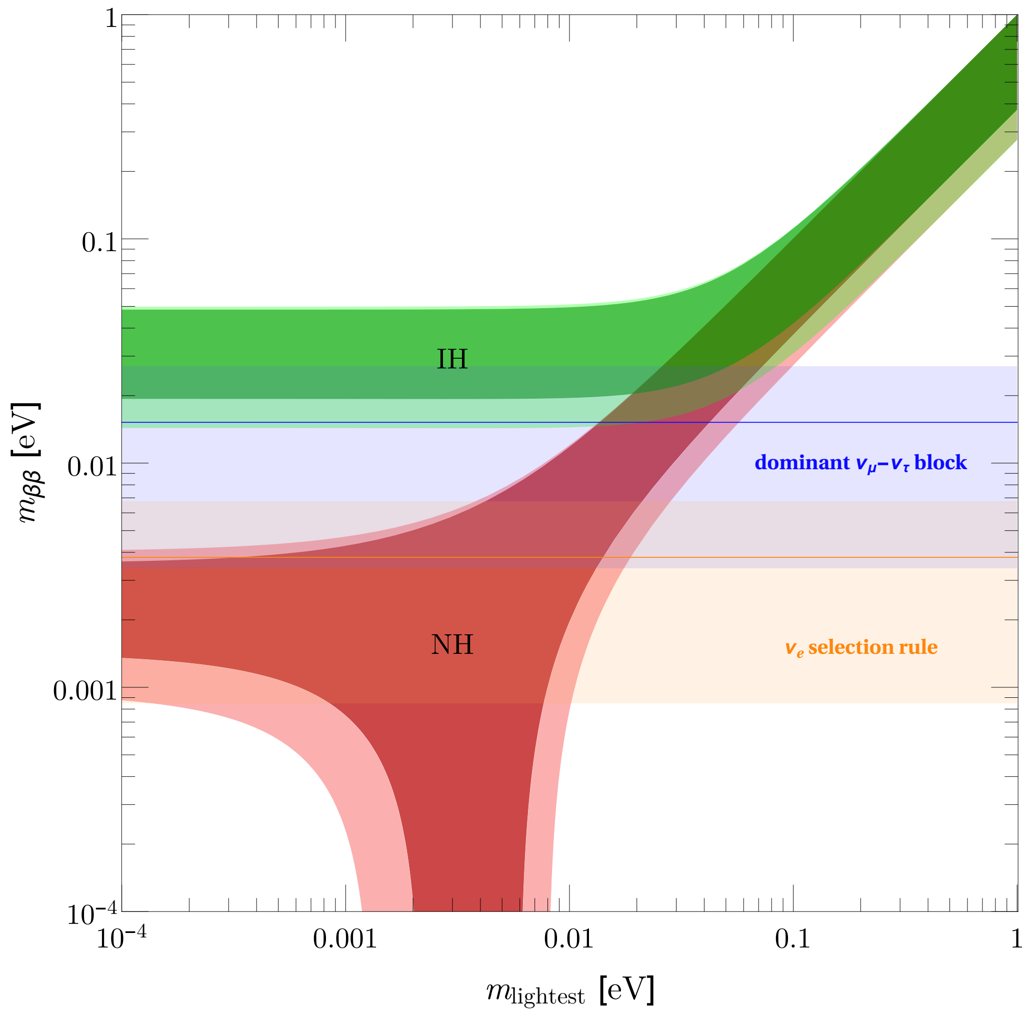
(electronic selection rule)

Expectations with the Extended Dominant Block



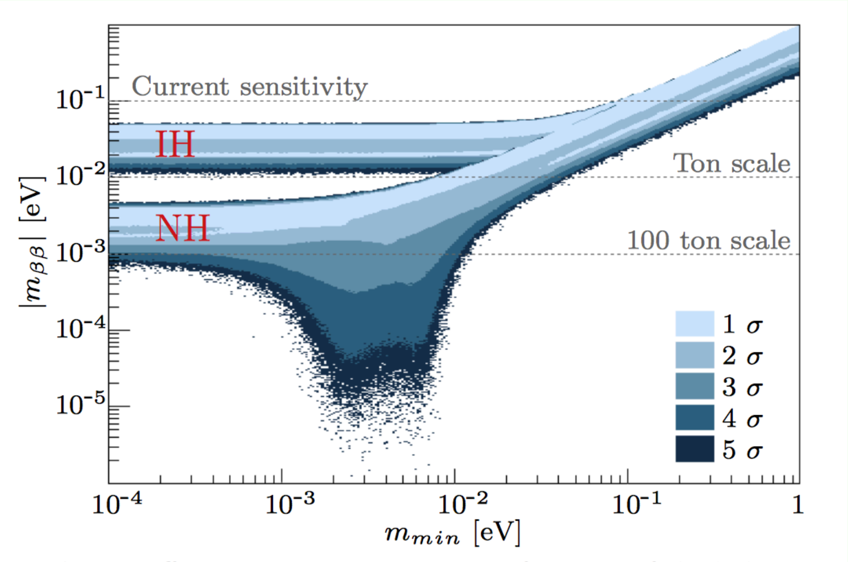
Output of the statistical exploration

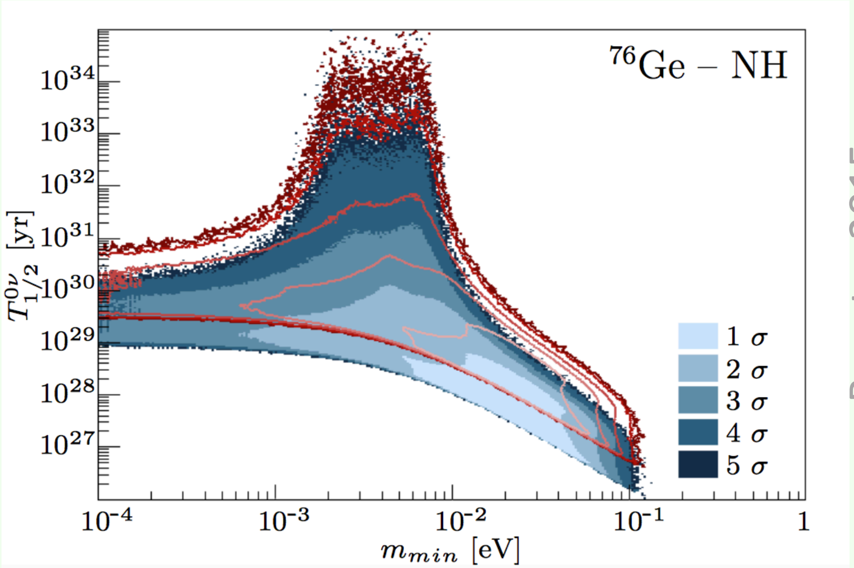
The expectation that $m_{\beta\beta}$ ~ 50 meV x θ_C ~ 10 meV is confimed by the Monte Carlo extraction. Here we use a very conservative assumption, that the unknown coefficients are complex random numbers in unit circle



The two strips on top of the "standard presentation" correspond to the values for $m_{\beta\beta}$ suggested by the previous sets of mass matrices. The case of normal hierarchy is favored and mass scale is within reach for cosmology and Project-8 phase IV.

alternative: try random phases

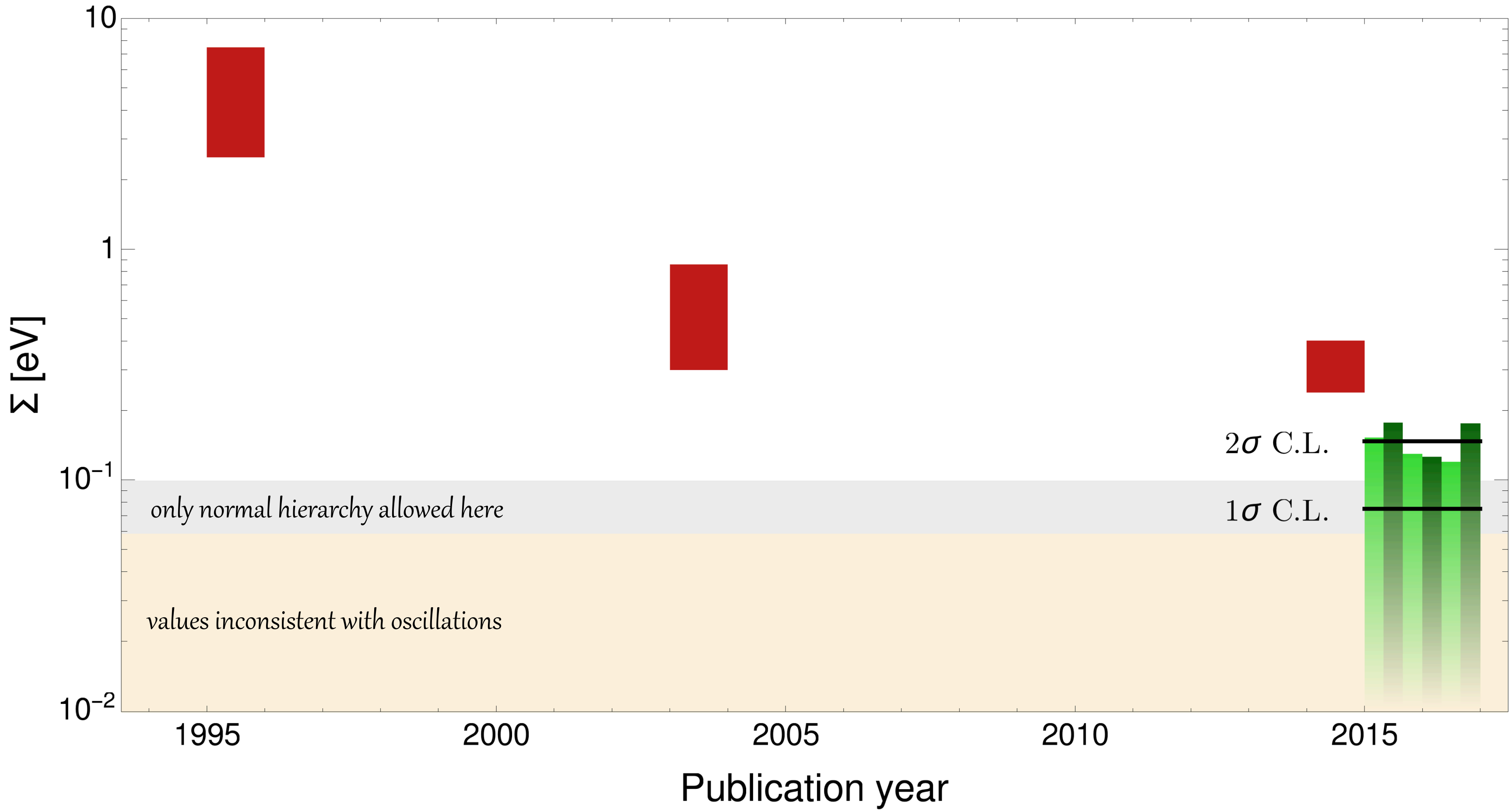




Benato, 2015

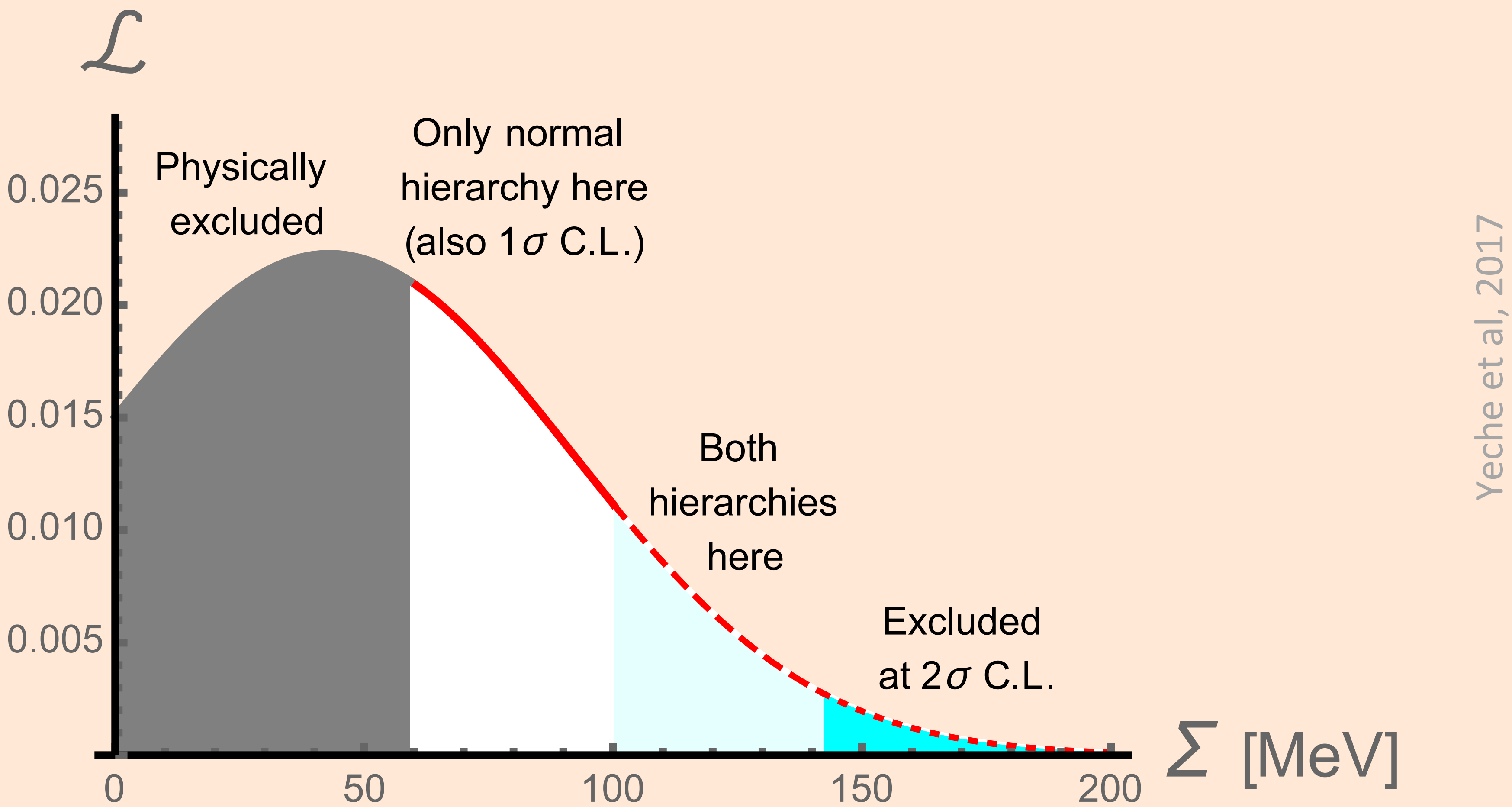
See also Caldwell, Merle, Schultz, Totzauer; Agostini, Benato, Detwiler 2017

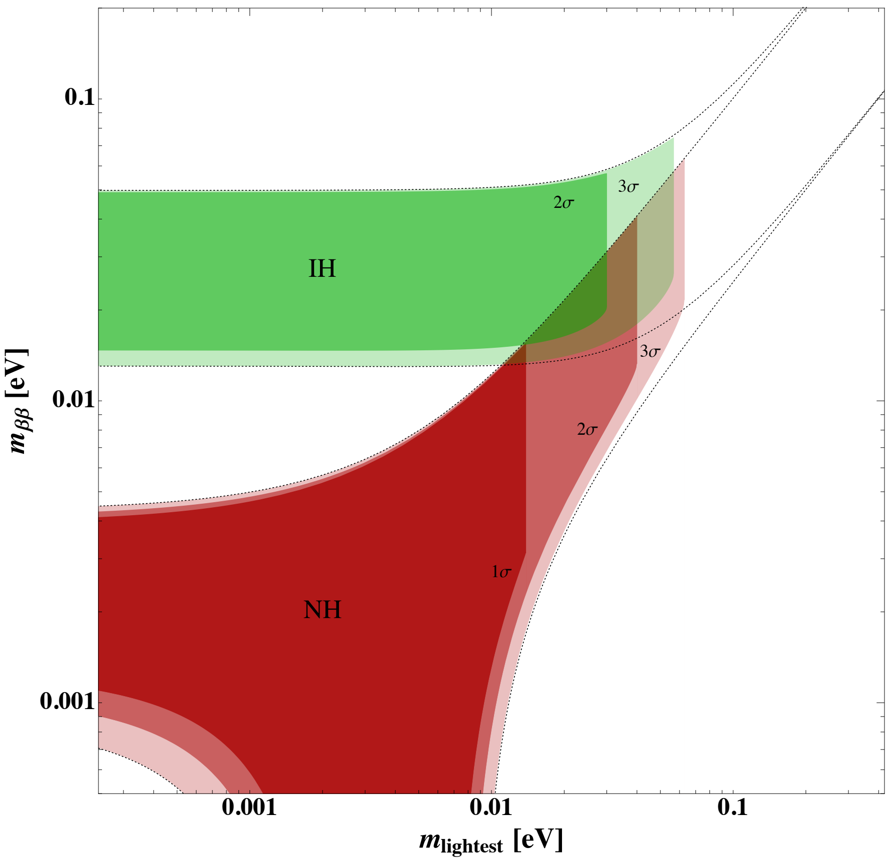
cosmology yields $\Sigma=m_1+m_2+m_3$



Dell'Oro et al, 2015

result confirmed & improved this year





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).

Nuclear matrix elements (NME), uncertainties from nuclear physics, the issue of axial coupling g_A

FROM MASS TO LIFETIME

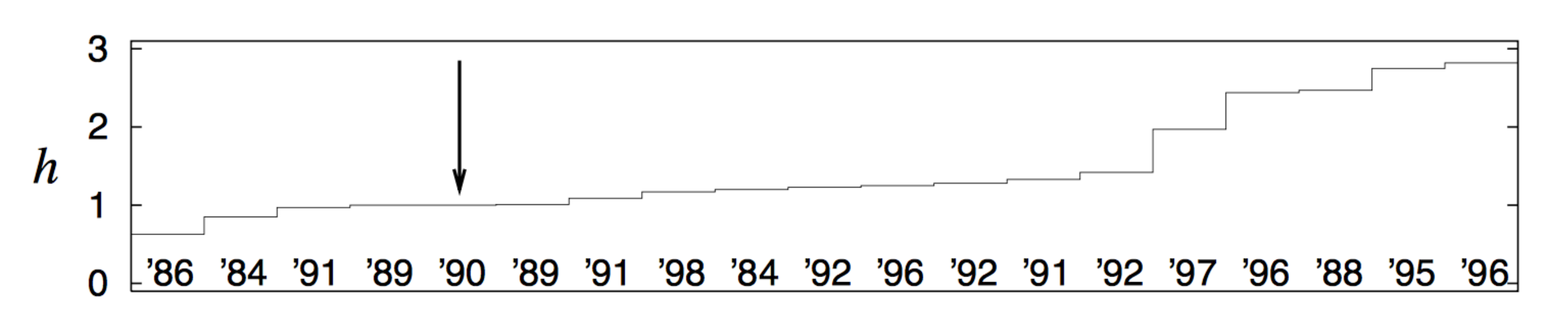
The $0\nu\beta\beta$ transition takes place in a nuclear medium.
Theory allows us to evaluate the amplitude.

$$[\, t^{1/2}_{0\nu} \,]^{-1} = G_{0\nu} \cdot |\, \mathcal{M}_{0\nu} \,|^2 \cdot |\, m_{\beta\beta}/m_e \,|^2$$

Momentum of virtual nucleon is large, O(100 MeV).
The axial coupling matters - a lot.

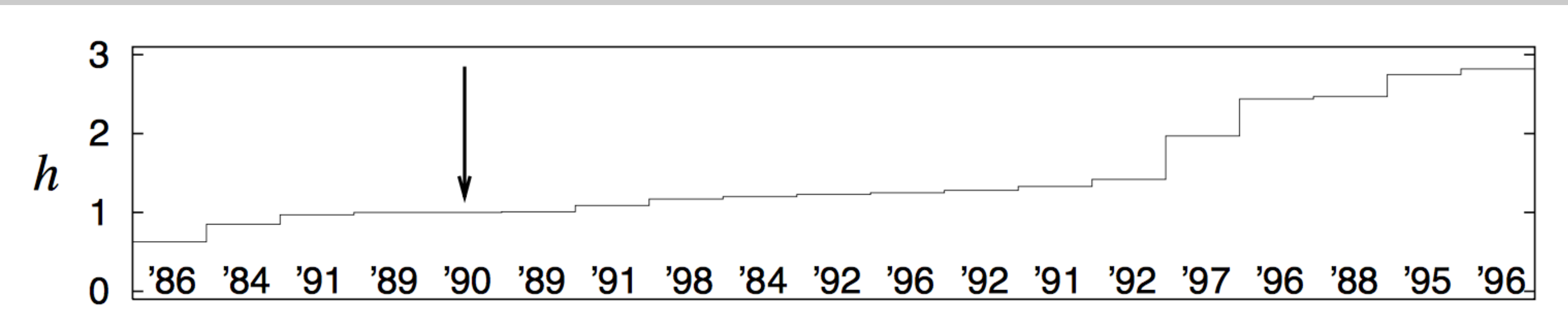
In the ideal case when the background=0, the bound improves with EXPOSURE $\times$ $(\mathcal{M}_{0\nu} \times m_{\beta\beta})^2$.

uncertainties 16 years ago:



Feruglio et al, 01

uncertainties 16 years ago:



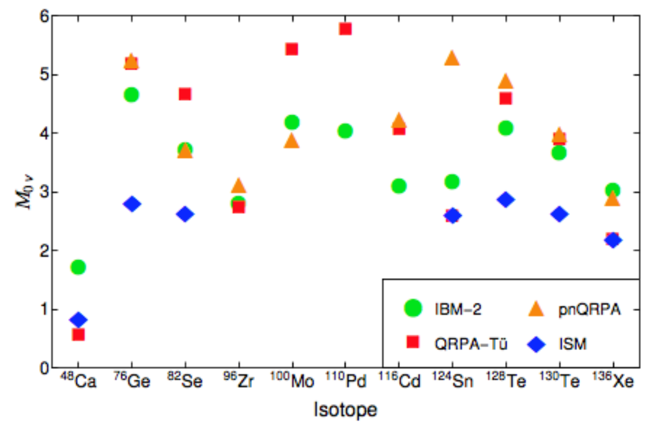
Feruglio et al, 01

and nowadays?

Models for the nuclear matrix elements

- Nucleus = p and n interacting, bound in a potential well
  - definition of the valence space
  - derivation of an effective Hamiltonian
  - ground state wave functions by solving the equations of motion
- different theoretical models
  - Quasiparticle Random Phase Approximation
  - Intermediate Boson Model
  - Interacting Shell Model
  - ...

QRPA / IBM-2 within ∼ 30%

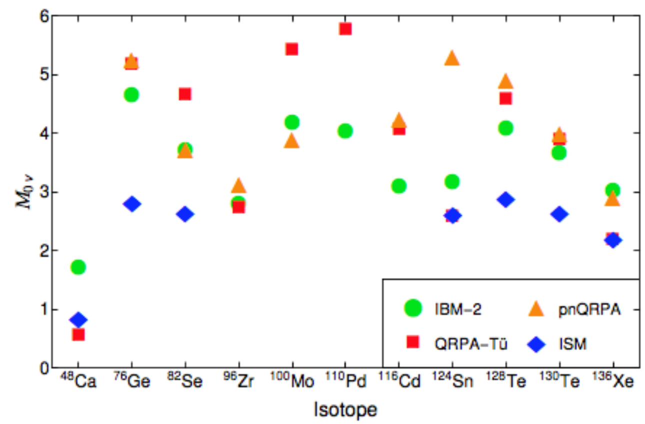


QRPA-Tü: F. Šimkovic *et al.*, **Phys. Rev. C 87, 045501 (2013)**
pnQRPA: J. Hyvärinen *et al.*, **Phys. Rev. C 91, 024613 (2015)**
IBM-2: J. Barea *et al.*, **Phys. Rev. C 91, 034304 (2015)**
ISM: J. Menéndez *et al.*, **Nucl. Phys. A 818, 139 (2009)**

Models for the nuclear matrix elements

- Nucleus = p and n interacting, bound in a potential well
  - definition of the valence space
  - derivation of an effective Hamiltonian
  - ground state wave functions by solving the equations of motion
- different theoretical models
  - Quasiparticle Random Phase Approximation
  - Intermediate Boson Model
  - Interacting Shell Model
  - ...

QRPA / IBM-2 within $\sim 30\%$



QRPA-Tü: F. Šimkovic *et al.*, **Phys. Rev. C 87, 045501 (2013)**
pnQRPA: J. Hyvärinen *et al.*, **Phys. Rev. C 91, 024613 (2015)**
IBM-2: J. Barea *et al.*, **Phys. Rev. C 91, 034304 (2015)**
ISM: J. Menéndez *et al.*, **Nucl. Phys. A 818, 139 (2009)**

J. BAREA, J. KOTILA, AND F. IACHELLO

Nucleus	$\tau_{1/2,\mathrm{exp}}(10^{18}$ yr) exp	$\tau_{1/2}$ (10^{18} yr) IBM-2	
		CA GT	*SSD GT*
^{48}Ca	44^{+6}_{-5}	2.30	
^{76}Ge	1500 ± 100	144	
^{82}Se	92 ± 7	7.68	
^{96}Zr	23 ± 2	5.31	0.187
^{100}Mo	7.1 ± 0.4	6.46	0.117
^{116}Cd	28 ± 2	14.5	0.306
^{128}Te	1900000 ± 400000	65600	1170
^{130}Te	680^{+120}_{-110}	15.5	
^{136}Xe	2110 ± 25	23.0	

But can we deem ≈30% a credible evaluation of the uncertainty?

Other methods of calculation as ISM suggest caution. Moreover, for the weak processes where we have data, as $2\nu2\beta$, IBM-2 (and QRPA) **overestimate** matrix elements much more than 30%. Maybe this indicates some systematics, i.e., a common cause of overestimation?

the hypothesis of g_A quenching

- Let us assume that the value of the axial coupling of the nucleon <u>in the nuclear medium</u> is not $g_A = 1.269$

- Let us assume that this is the reason why the calculated $2\nu 2\beta$ matrix elements are overestimated

- This gives the approximate scaling in **IBM-2**,

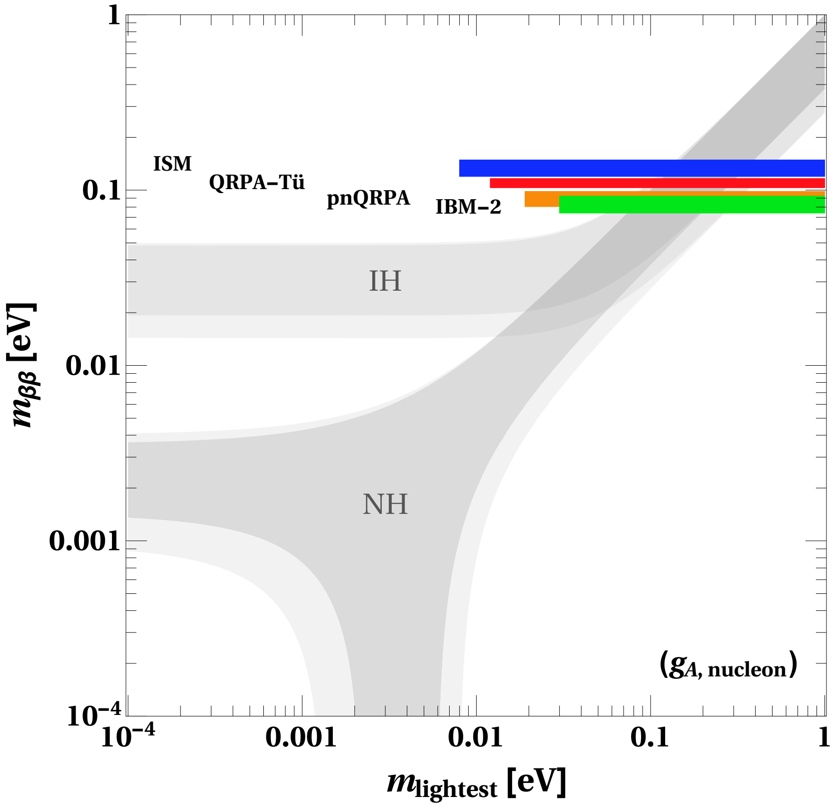
$$g_A = 1.269 \times A^{-0.18}$$

- Similar considerations apply to QRPA

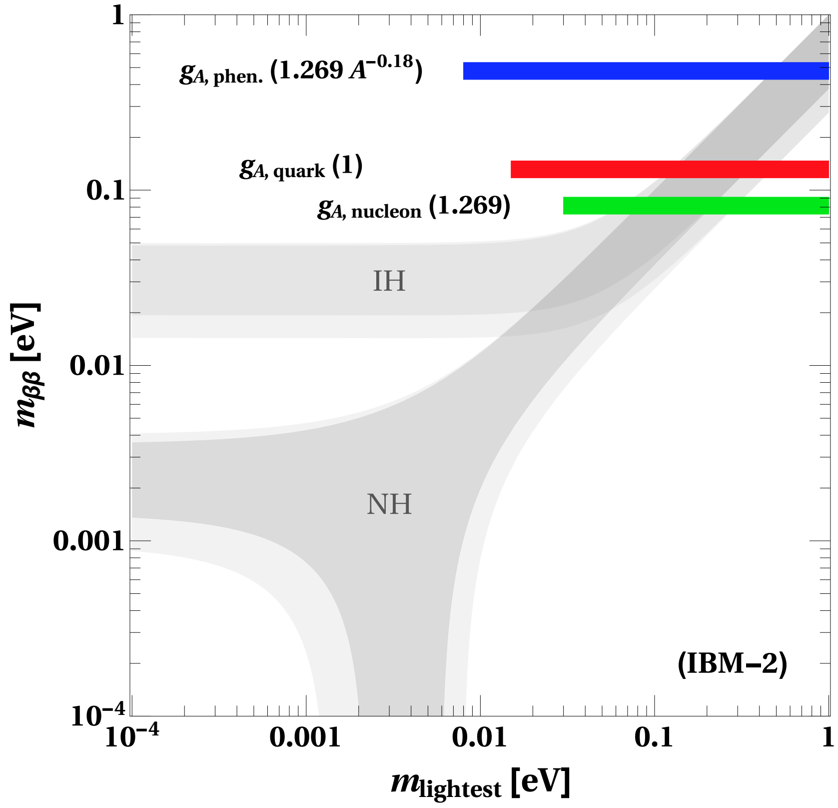
Barea, Kotila, Iachello, 2013

impact on Xe bound

Different NMEs, same g_A



Different g_A, same NME (IBM-2)



A CRITICAL ASSESSMENT

- To date, caution suggests to vary g_A in a wide range, to remind us that uncertainties are unlikely to be small

- The "quenching/renormalization" of g_A is not a theory; however, if it is there, it is likely to depend upon q^2

- Maybe the connection between $0\nu2\beta$ & $2\nu2\beta$ is not tight: the momentum of the virtual states q^2 is quite different

- For $0\nu2\beta$, q^2 is larger: maybe g_A is also larger, closer to the case of quark matter (g_A=1) or to the case of free nucleon [Menendez, Gazit, Schwenk 2011; Engel, Menendez 2016]

Hindawi

Advances in High Energy Physics

Advances in High Energy Physics
Volume 2016 (2016), Article ID 2162659, 37 pages
http://dx.doi.org/10.1155/2016/2162659

Review Article

Neutrinoless Double Beta Decay: 2015 Review

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

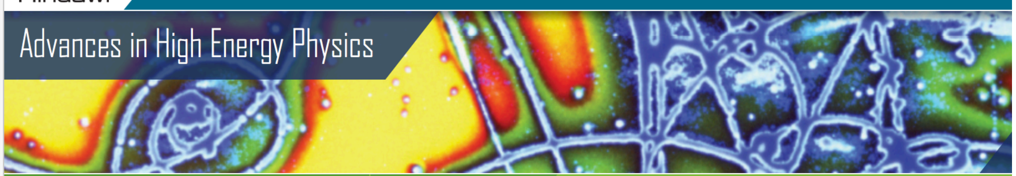
[1]INFN, Gran Sasso Science Institute, Viale F. Crispi 7, 67100 L'Aquila, Italy
[2]INAF, Osservatorio Astronomico di Trieste, Via G. B. Tiepolo 11, 34131 Trieste, Italy
[3]INFN, Sezione di Trieste, Via Valerio 2, 34127 Trieste, Italy
[4]INFN, Laboratori Nazionali del Gran Sasso, Via G. Acitelli 22, 67100 Assergi, Italy

TABLE 10: Sensitivity and exposure necessary to discriminate between $\mathcal{NH}$ and $\mathcal{IH}$: the go is $m_{\beta\beta}$ = 8 meV. e two cases refer to the unquenched value of $g_A = g_{\text{nucleon}}$ (mega) and $g_A = g_{\text{phen.}}$ (ultimate). The calculations are perfor *background* experiments with 100% detection efficiency and no fiducial volume cuts. The last column shows the maximum value of the product $B \cdot \Delta$ in order to actually comply with the zero background condition.

Experiment	Isotope	$S^{0\nu}_{0B}$ [yr]	Exposure (estimate)	
			$M \cdot T$ [ton·yr]	$B \cdot \Delta_{\text{(zero bkg)}}$ [counts kg^{-1} yr^{-1}]
mega Ge	^{76}Ge	$3.0 \cdot 10^{28}$	5.5	$1.8 \cdot 10^{-4}$
mega Te	^{130}Te	$8.1 \cdot 10^{27}$	2.5	$4.0 \cdot 10^{-4}$
mega Xe	^{136}Xe	$1.2 \cdot 10^{2}$[illegible]	3.8	$2.7 \cdot 10^{-4}$
ultimate Ge	^{76}Ge	$6.9 \cdot 10^{2}$[illegible]	125	$8.0 \cdot 10^{-6}$
ultimate Te	^{130}Te	$2.7 \cdot 10^{29}$	84	$1.2 \cdot 10^{-5}$
ultimate Xe	^{136}Xe	$4.0 \cdot 10^{29}$	130	$7.7 \cdot 10^{-6}$

Hindawi

Advances in High Energy Physics



About this Journal | Submit a Manuscript | Table of Contents

In Table 10 above: use IBM-2, show effect of g_A on *S=1, B<1*

pages

2015 Review

Viel,[2,3] and Francesco Vissani[1,4]

Crispi 7, 67100 L'Aquila, Italy

[2]INAF, Osservatorio Astronomico di Trieste, Via G. B. Tiepolo 11, 34131 Trieste, Italy

[3]INFN, Sezione di Trieste, Via Valerio 2, 34127 Trieste, Italy

[4]INFN, Laboratori Nazionali del Gran Sasso, Via G. Acitelli 22, 67100 Assergi, Italy

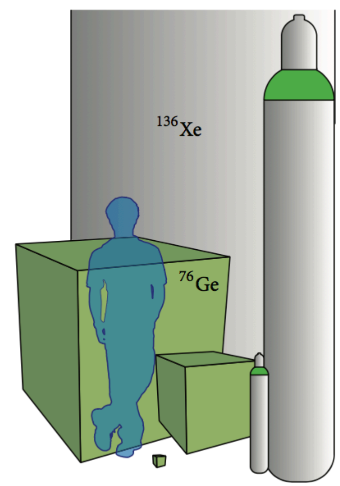


FIGURE 18: Masses corresponding to present, mega, and ultimate exposures, assuming zero background condition and 5 years of data acquisition. The cubes represent the amount of ^{76}Ge, the (150 bar = 15 MPa) bottles, and the one of ^{136}Xe. The smallest masses depict the present exposure, while the biggest bottle is out of scale.

Summary & Discussion

Motivations of $0\nu2\beta$ decay/electron creation/ are stronger than ever.

Particle physics theory helps for general considerations and/or for orientation (Majorana mass and SM; normal hierarchy, flavor structure).

Oscillations + cosmological measurements allowed us to progress a lot in the expectations.

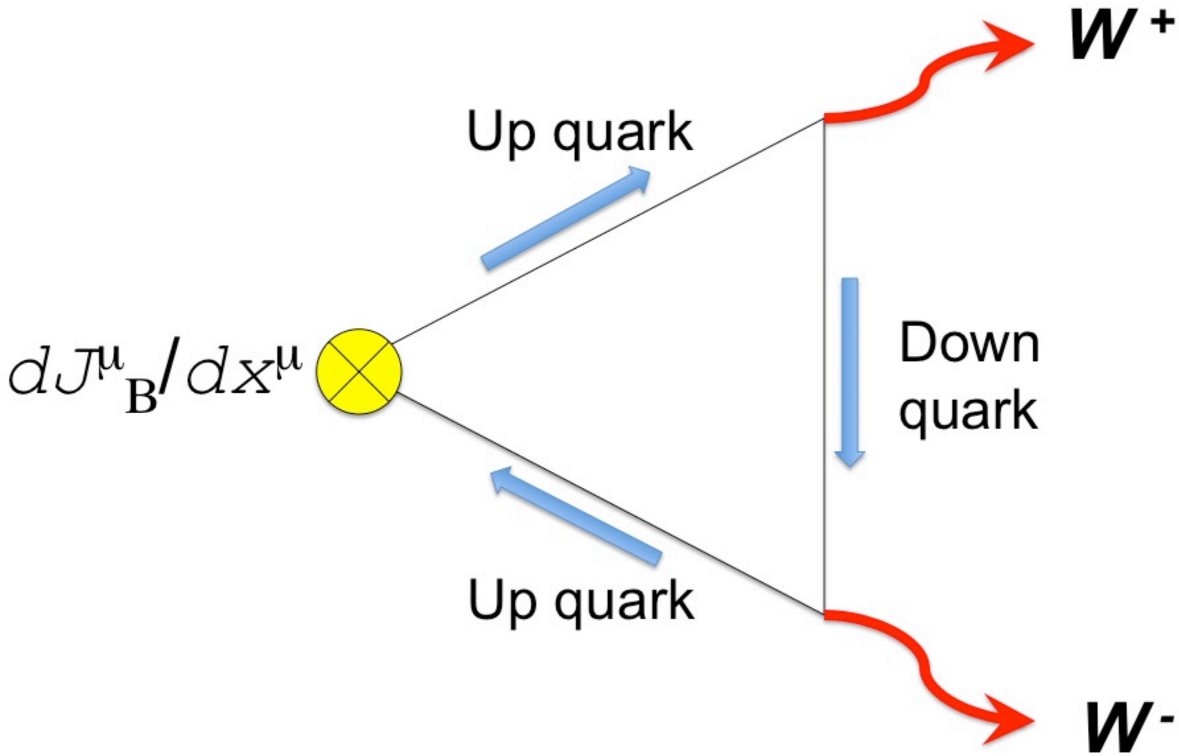
The tightest cosmological bounds imply that multi-ton detector mass will be needed, even if background events were absent.

Uncertainties on the rate are large, mostly due to particle physics, and partly due to nuclear physics but the situation seems to evolve.

Neutrino masses are very interesting but we measure lifetime: If new sources of lepton number violation at low energy (TeV?) exist, surprises may occur.

Thanks a lot for your attention!

The true global symmetry of SM is *B-L* --- not *B* and *L* alone



progresses of the last 20 years

Standard model gets heaps of confirmations

Oscillations due to massive neutrinos proved

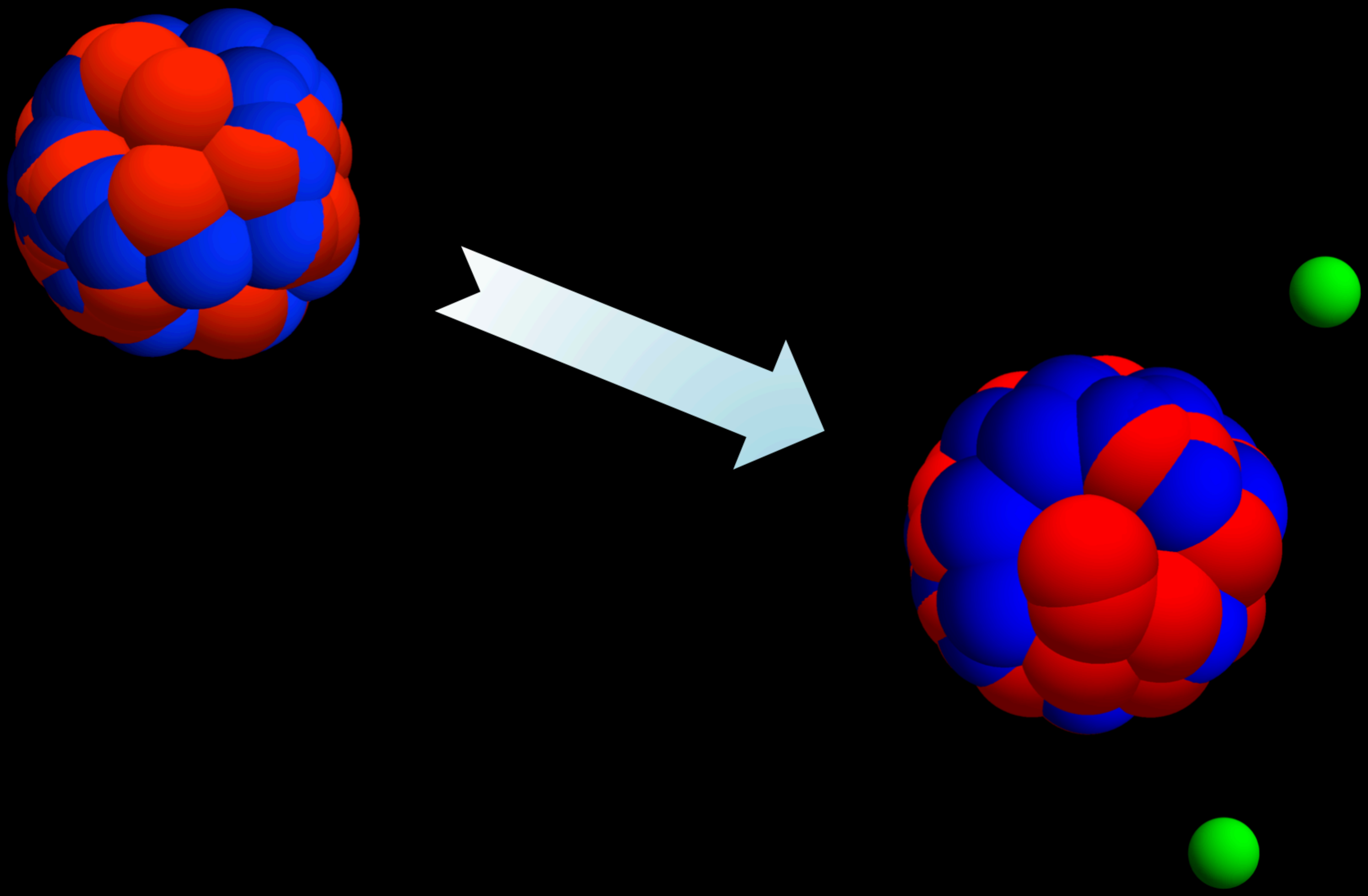
Cosmology (with ν-mass) enters precision era

Renewed interest in $0\nu2\beta$

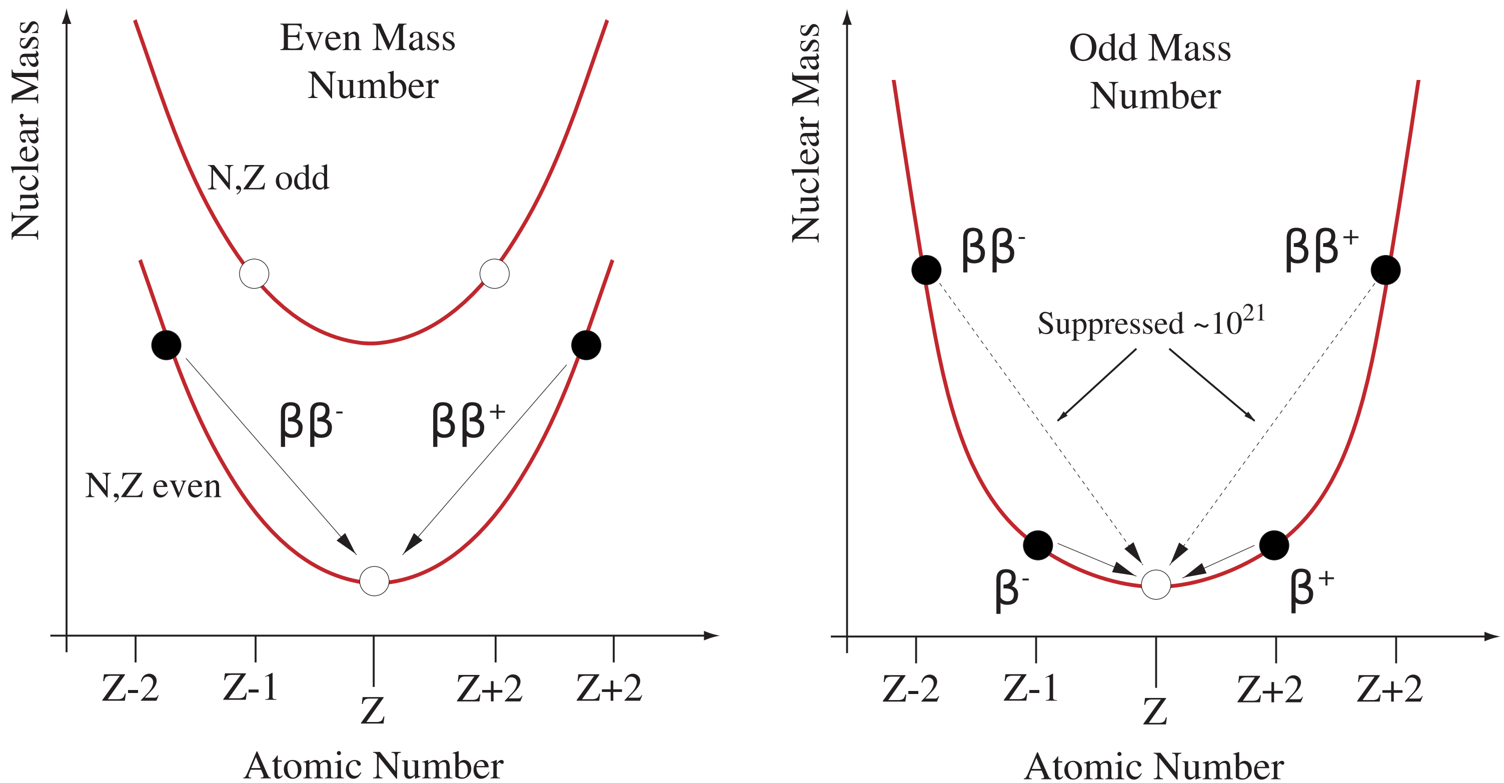
Many experimental progresses in $0\nu2\beta$

Many attempts of BSM - ν-mass and $0\nu2\beta$

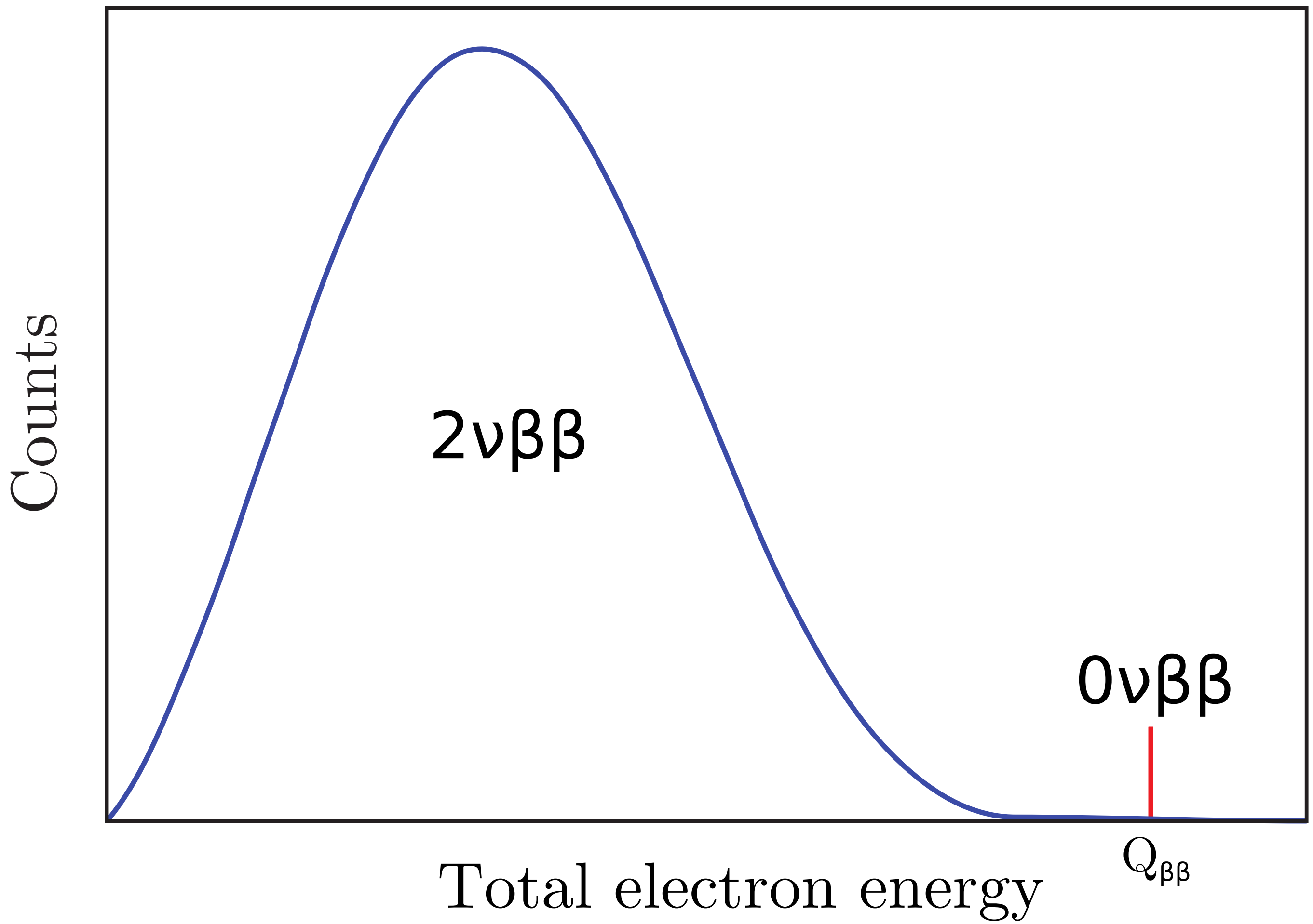
Discussion of nuclear uncertainties re-opened



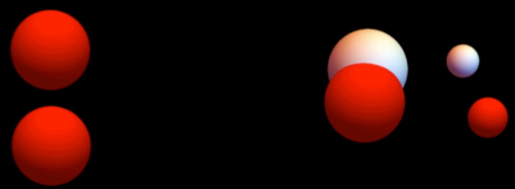
ββ-isotopes


Even Mass Number
Nuclear Mass
N,Z odd
N,Z even
ββ-
ββ+
Z-2
Z-1
Z
Z+2
Z+2
Atomic Number
Odd Mass Number
Nuclear Mass
ββ-
ββ+
Suppressed ~10^21
β-
β+
Z-2
Z-1
Z
Z+2
Z+2
Atomic Number

Main signature: absence of missing energy

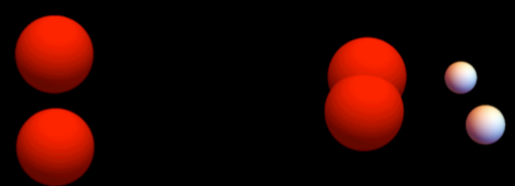


proton fusion: $p + p \rightarrow D + e^{+} + \nu$



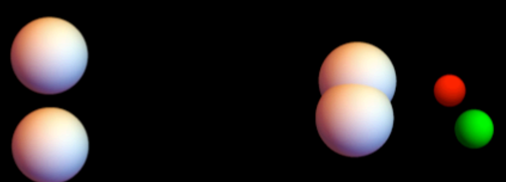
Electric charge is conserved:

$$1+1=1+1+0$$



Baryon number is conserved :

$$1+1=2+0+0$$



Lepton number is conserved:

$$0+0=0-1+1$$

Alternative designations for 0ν2β?

the suffix "-genesis" seems apt, but

"Electrogenesis" is already used in biochemistry

English [edit]

Etymology [edit]

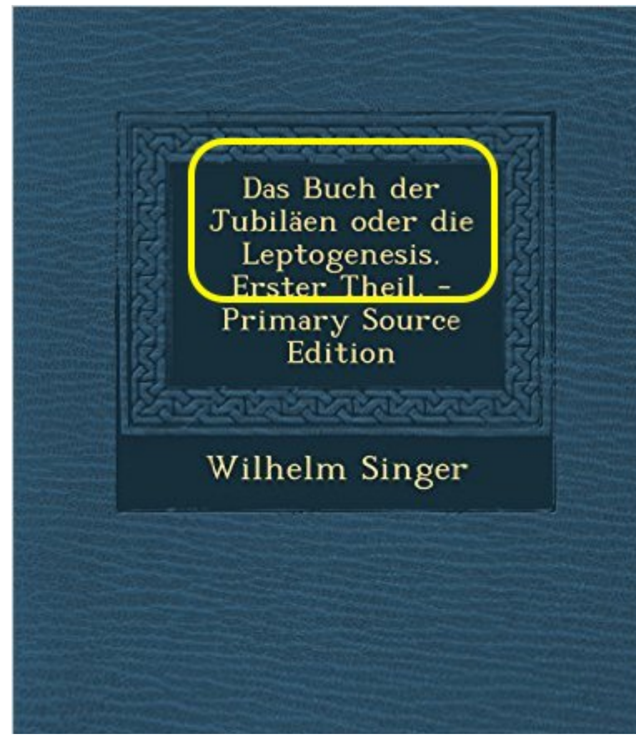
electro- + *-genesis*

Noun [edit]

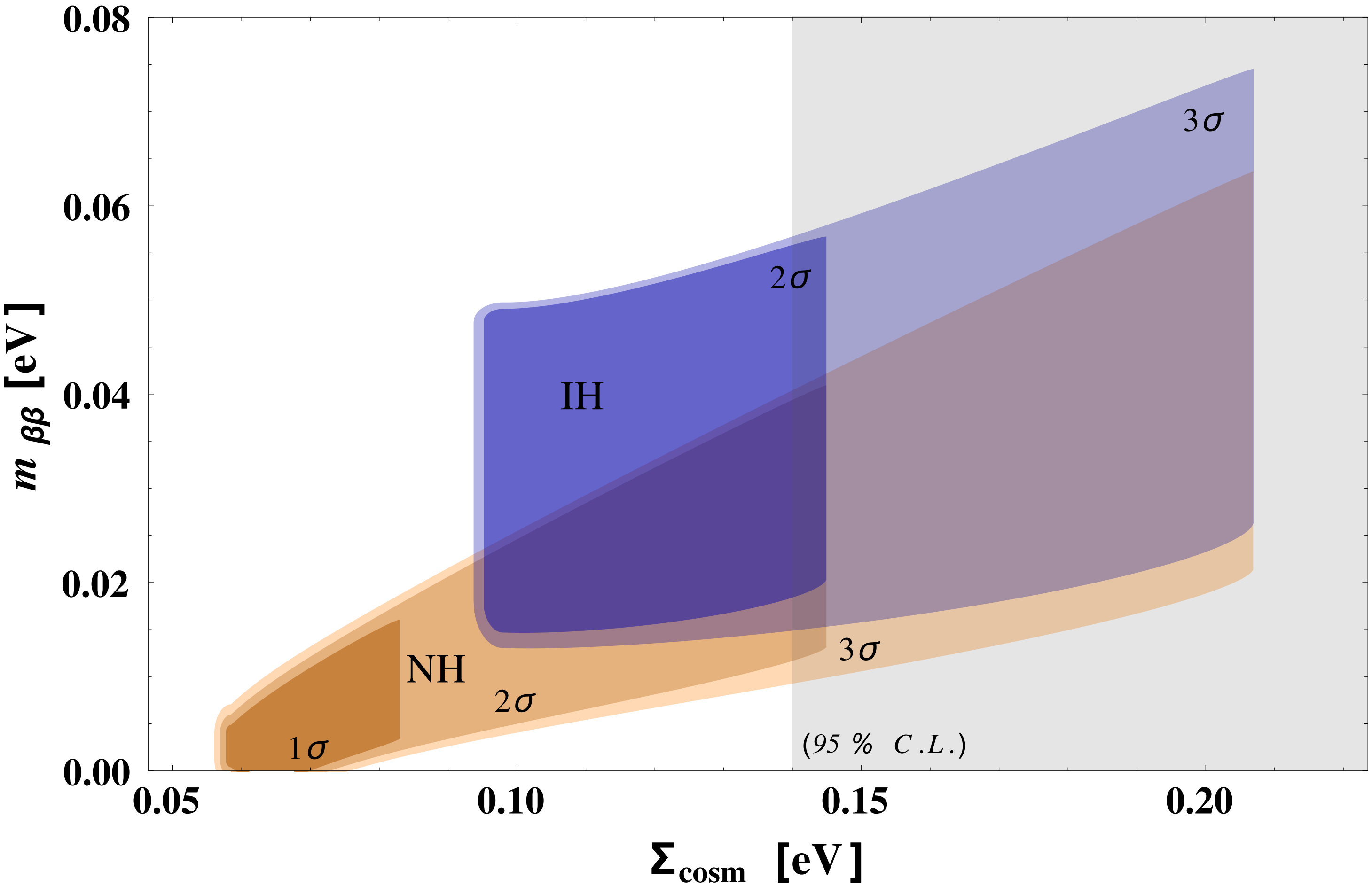
electrogenesis (*usuall* *uncountable*, *plural* **electrogeneses**)

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



(cosmology, illustrated using Bari's plot)



Dell'Oro et al, 2015

impact of $g_A \rightarrow g_A \times (1 - \delta)$

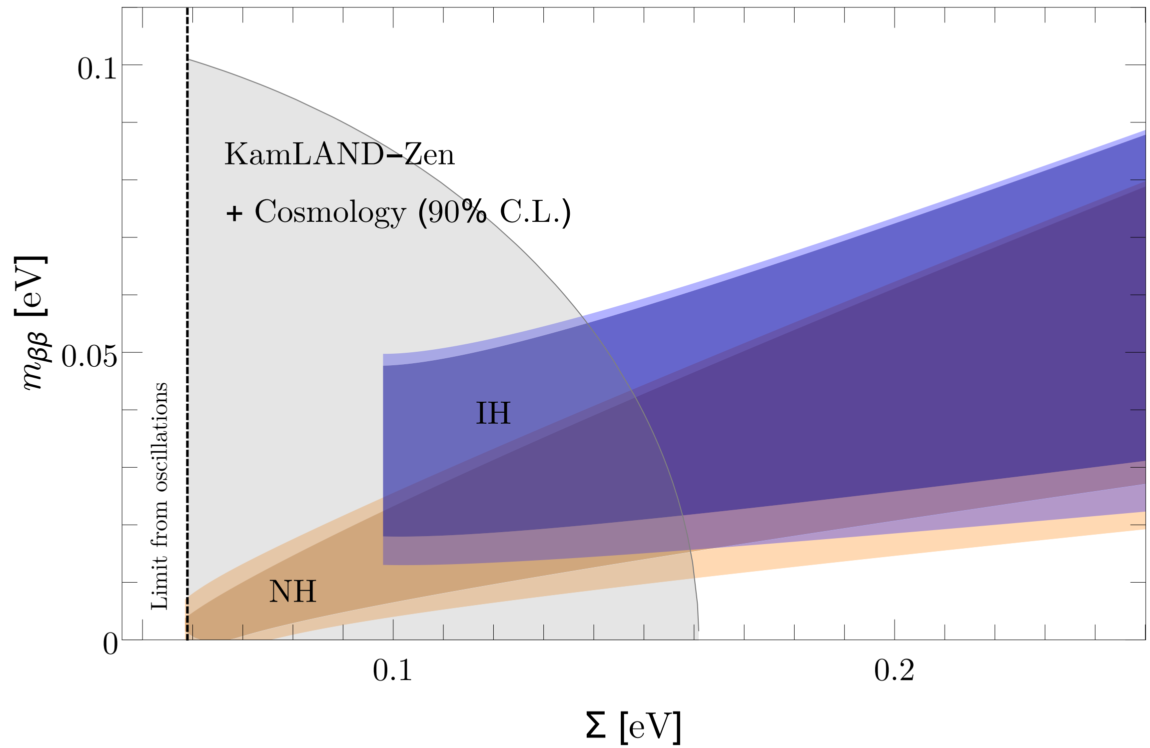
(even a small uncertainty *does* matter)

Amplitude scales roughly as g_A^2 for double β

Signal S scales as amplitude^2 and as mass × time

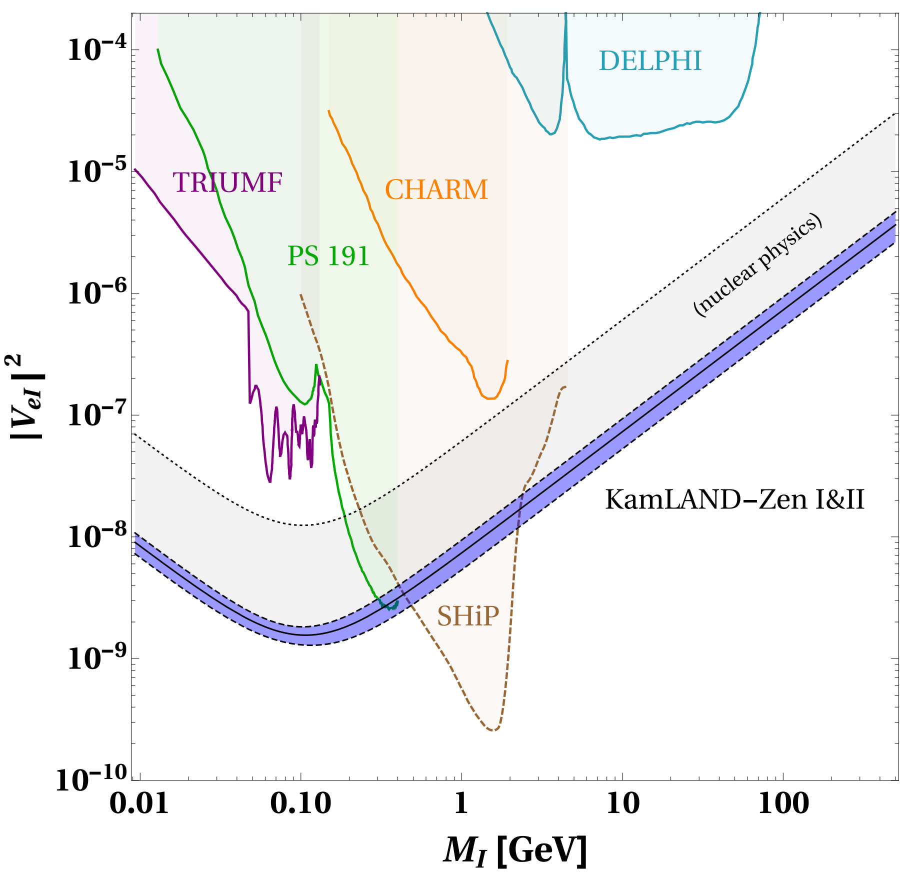
Significance $S/\sqrt{B}$ scales as $\sqrt{\text{mass} \times \text{time}}$

δ=10% (20%) uncertainty needs to be compensated with $1/(1-\delta)^8 = 2.3$ (6) more mass and/or time



It is possible to measure Majorana phases?

This is more than challenging with present systematic uncertainties; moreover, statistical errors are unlikely to be small (Dell'Oro et al 2014). For illustration, the figure compares current bound and predictions.



Effect of a "light" right-handed neutrino

A single (not-too) massive neutrino, coupled to the three usual ones, can saturate the present bound on 0β2β for suitable mixing angles and masses. The range of mass below 10 GeV is favored by theoretical considerations. Direct search at accelerators are relevant.