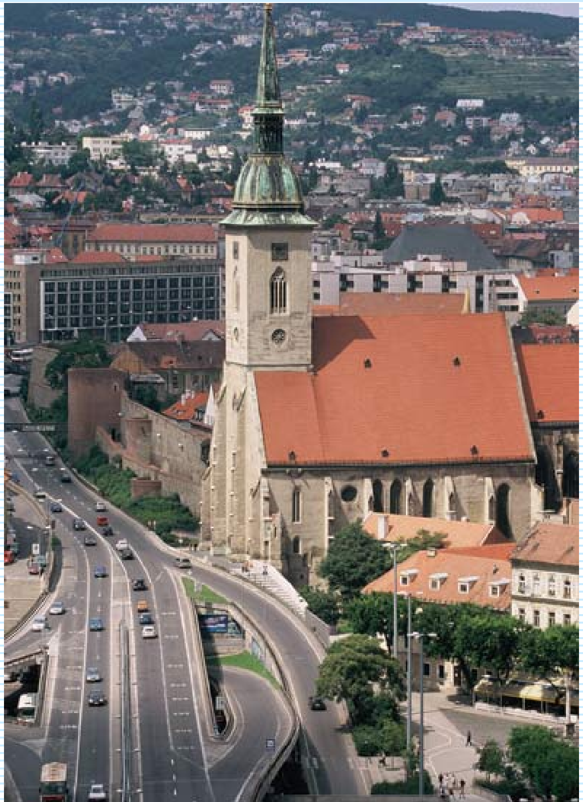
Workshop on future Dark Matter Experiments, Austrian Academy of Sciences, 15-16 october 2013

Theory astroparticle's activities in Bratislava

(Particle, Nuclear and Atomic Physics)

Fedor Šimkovic



Astroparticle (neutrino) Physicists in Slovakia

Department of Nuclear Physics and Biophysics
Comenius University, Bratislava

Participants (theory): F. Šimkovic, R. Dvornický, R. Hodák (UTEF Prague), D. Štefánik (PhD),

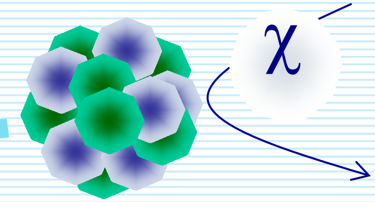
Participants (experiment): P. Povinec, K. Holý, I. Sýkora, J. Staníček, M. Pikna P. Valko, J. Szarka, J. Vanko, M. Mülerová, + PhD and diploma students

Experiments: **$0\nu\beta\beta$ (NEMO3, SuperNEMO , TGV, COBRA)**
$0\nu\varepsilon\varepsilon$ (on ^{74}Se in Bratislava, proposal for LSM Modane)
direct ν-mass measurements (ECHO collaboration)

OUTLINE

- ***Introduction***
- ***Dark matter search***
- ***0νββ-decay (theory+experiment)***
- ***0νεε-decay (theory+experiment)***
- ***2νββ-decay and bosonic neutrinos (theory)***
- ***Direct measurement of ν-mass (β-decay of ^{3}H, ^{187}Re, ^{163}Ho ...) (theory)***
- ***Lepton number non-conservation in white dwarfs***

Atomic Nucleus is a Laboratory

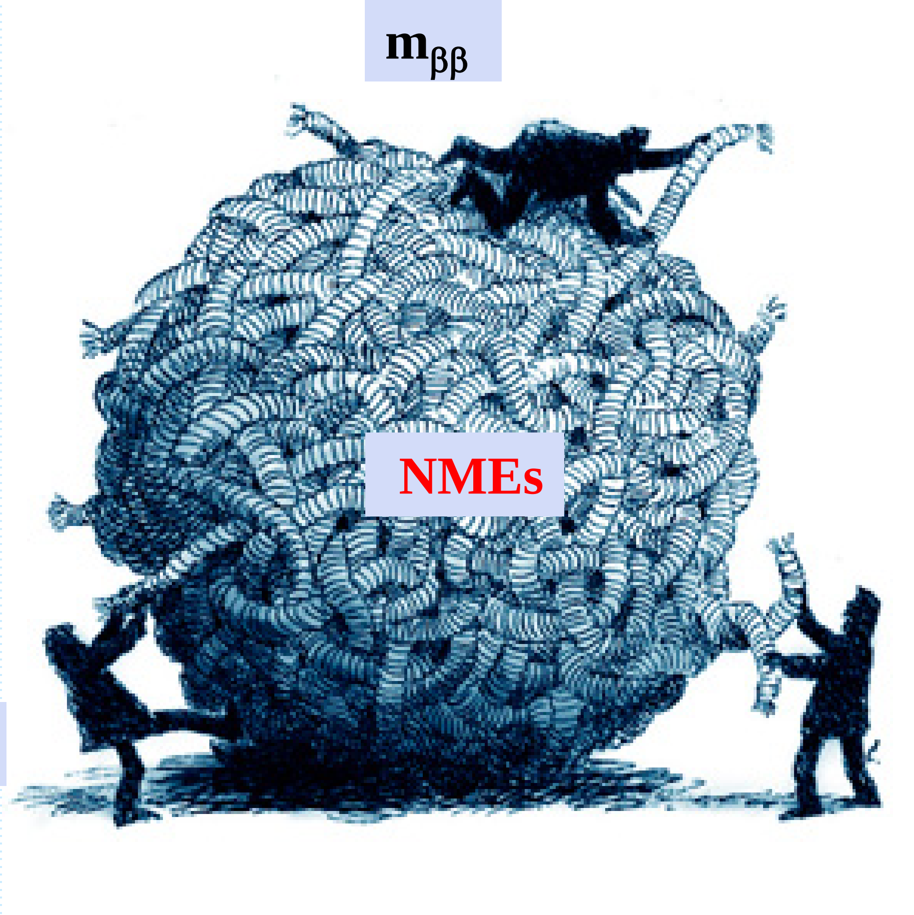


0νββ

0νεε

0νεβ

$m_{\beta\beta}$



NMEs

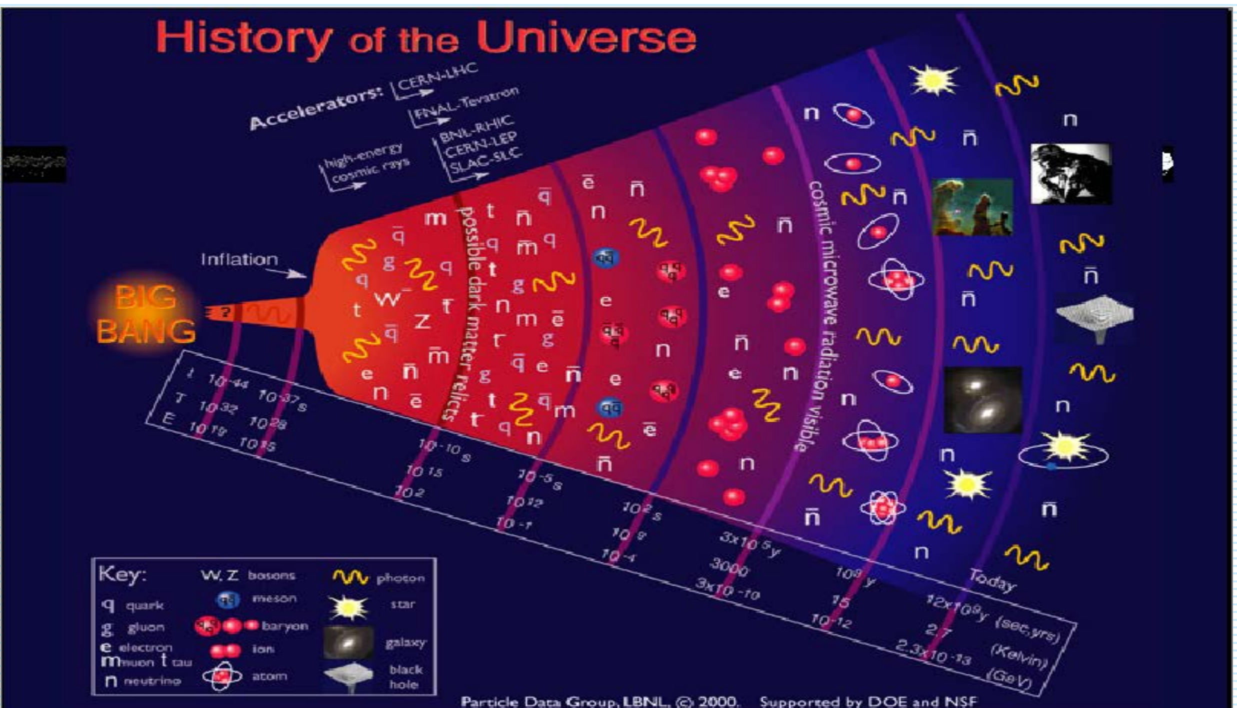
CP-phases

ν mass scale

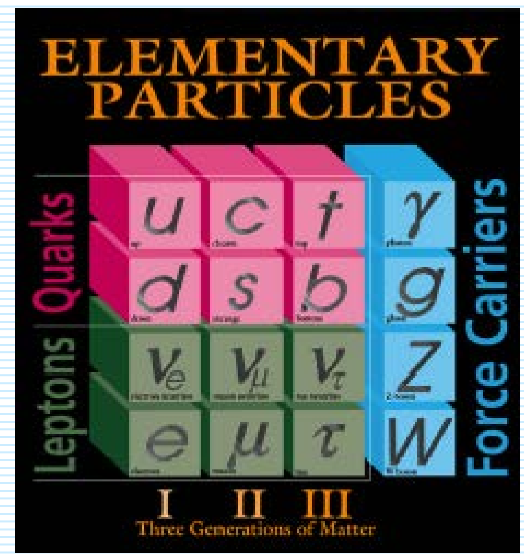
Physics where sun never shines

Many open problems of the present physics can be solved by use of technologies, which are able to separate a weak signal from the background

Understand the universe and its evolution



New physics beyond the Standard model

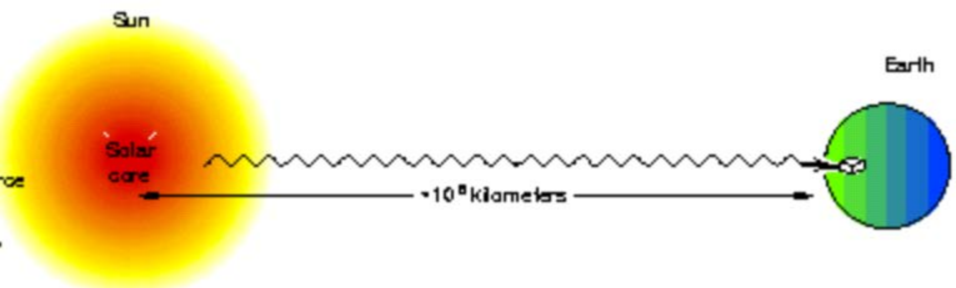


Two ways:

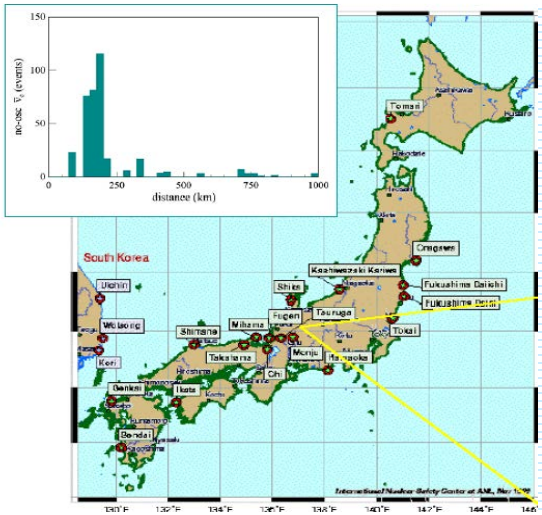
1) Go to high energies
2) Study rare, tiny effects

Underground Research has had Great Success

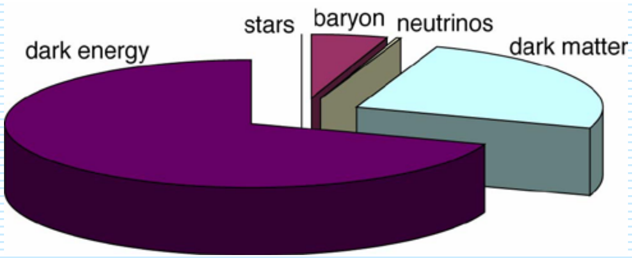
- The field has made recent fundamental discoveries
- These discoveries broadly impact physics, astronomy, cosmology
- A new laboratory would build on this success and open up the potential for next generation experiments and future discoveries

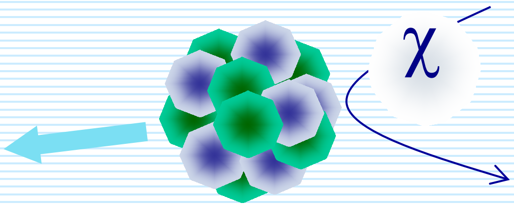


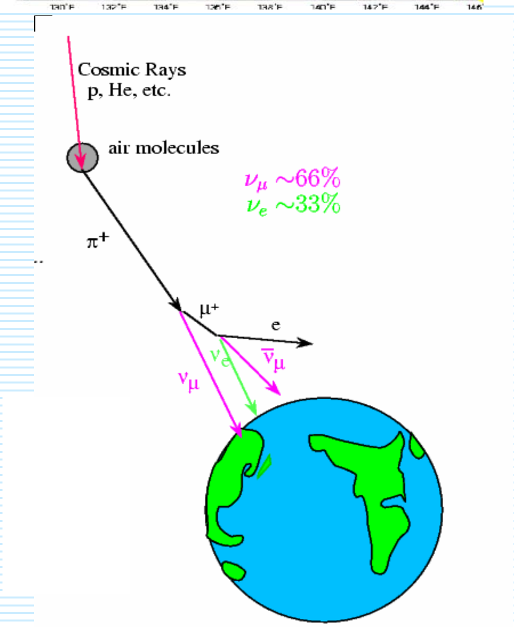
Physics at underground sites



- **neutrino oscillations** (solar, atmospheric, reactor)
- **Supernova neutrinos**
- **UHE neutrinos**
- **geo-neutrinos**
- **proton decay**
- **double beta decay**
- **dark matter search**
- **...**







First observation of new physics Beyond the SM

SN1987A

Candidate of dark matter

- **Neutrino (Not cold)**

  It might be hot or warm dark matter

- **Unknown stable particle**

  Relics in the early hot universe.

  WIMP (Weakly interacting massive particle) (Cold)

  SUSY particle, Kaluza-Klein particle, Wimpzilla,,,

  Axion (Cold)

Minimal Supersymmetric Standard Model

Normal particles / fields		Supersymmetric particles / fields			
		Interaction eigenstates		Mass eigenstates	
Symbol	Name	Symbol	Name	Symbol	Name
$q = d,c,b,u,s,t$	quark	$\tilde{q}_L, \tilde{q}_R$	squark	$\tilde{q}_1, \tilde{q}_2$	squark
$l = e, \mu, \tau$	lepton	$\tilde{l}_L, \tilde{l}_R$	slepton	$\tilde{l}_1, \tilde{l}_2$	slepton
$\nu = \nu_e, \nu_\mu, \nu_\tau$	neutrino	$\tilde{\nu}$	sneutrino	$\tilde{\nu}$	sneutrino
g	gluon	$\tilde{g}$	gluino	$\tilde{g}$	gluino
$W^\pm$	W-boson	$\tilde{W}^\pm$	wino	$\tilde{\chi}^\pm_{1,2}$	chargino
$H^\mp$	Higgs boson	$\tilde{H}^\mp_{1/2}$	Higgsino		
B	B-field	$\tilde{B}$	bino	$\tilde{\chi}^0_{1,2,3,4}$	neutralino
W^3	W^3-field	$\tilde{W}^3$	wino		
H^0_1	Higgs boson	$\tilde{H}^0_1$	Higgsino		
H^0_2	Higgs boson	$\tilde{H}^0_2$	Higgsino		
H^0_{31}	Higgs boson				

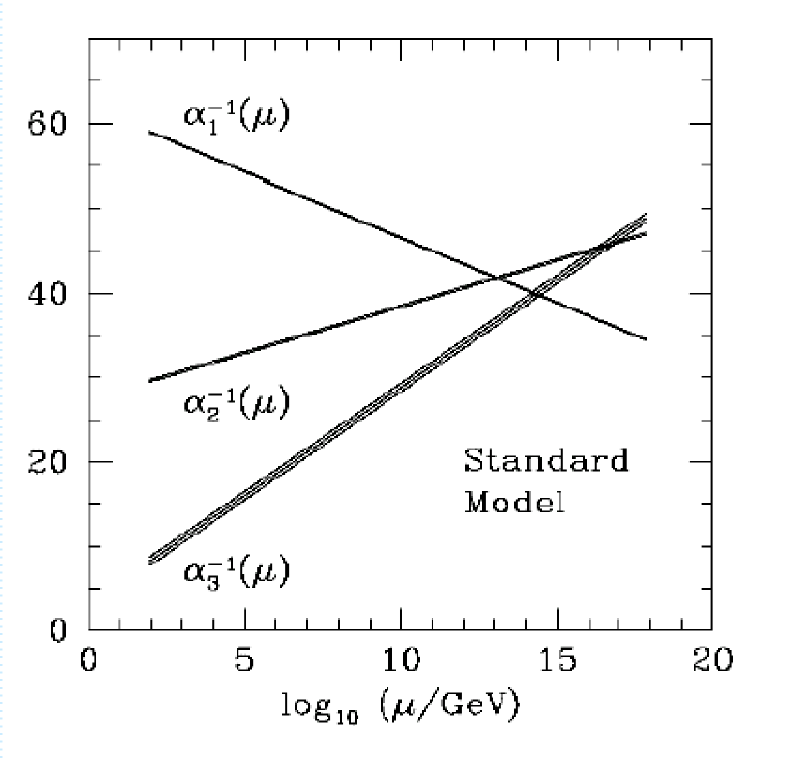
R=+1 R=–1

R-parity: $R=(-1)^{3B+L+2S}$

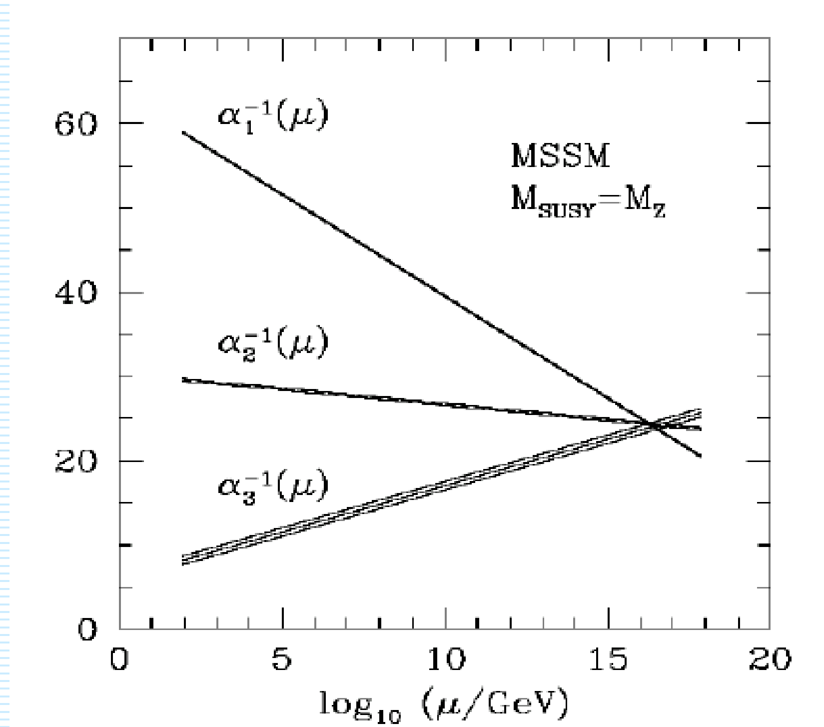
Evolution of gauge coupling

$$\underbrace{SU(3)}_{\alpha_s}\times\underbrace{SU(2)}_{\alpha_2}\times\underbrace{U(1)}_{\alpha_1}$$

$$\alpha_1 = \frac{5}{3}\frac{(g')^2}{4\pi} = \frac{5}{3}\frac{\alpha_{EM}}{\cos^2\theta_W}, \quad \alpha_2 = \frac{g^2}{4\pi} = \frac{\alpha_{EM}}{\sin^2\theta_W}, \quad \alpha_3 = \frac{g_s^2}{4\pi}$$



Standard Model



Supersymmetry

Gauge coupling unification works for SU(5) and SO(10) SUSY GUT

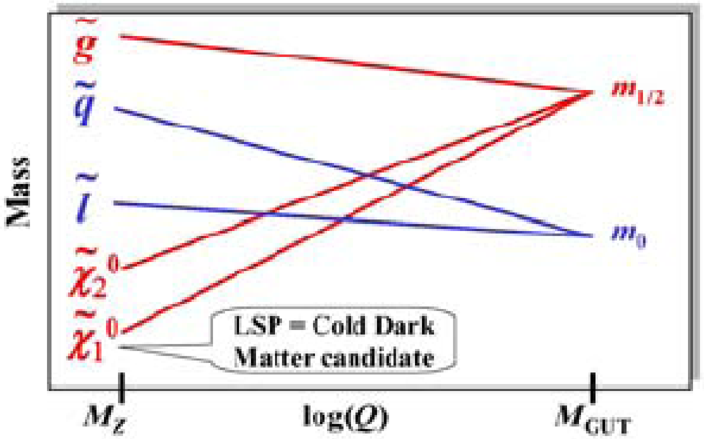
Minimal Supergravity Model (mSUGRA)

SUSY model with two Higgs fields in the framework of unification

All SUSY masses are unified at the grand unified scale

$m_{1/2}$ for gaugino masses

m_0 for squarks and sleptons



$m_{1/2}$ = gaugino mass parameter

$m_0(M_2)$ = scalar mass parameter for squarks and sleptons

A_0 = Common Yukawa coupling (A_b-bottom sector A_t-top sector)

tan β = $\langle H_1\rangle / \langle H_2\rangle$

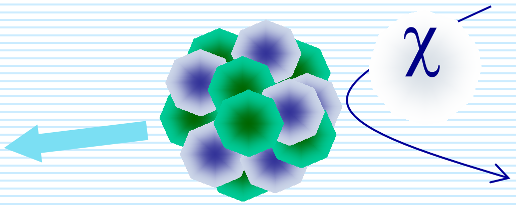
μ = Higgsino mass parameter

SUSY broken near GUT scale

Parameter	μ	M_2	tan β	m_A	m_0	A_b/m_0	A_t/m_0
Unit	GeV	GeV	1	GeV	GeV	1	1
Min	-50000	-50000	1	0	100	-3	-3
Max	+50000	+50000	60	10000	30000	3	3

WIMP Detection

- direct detection



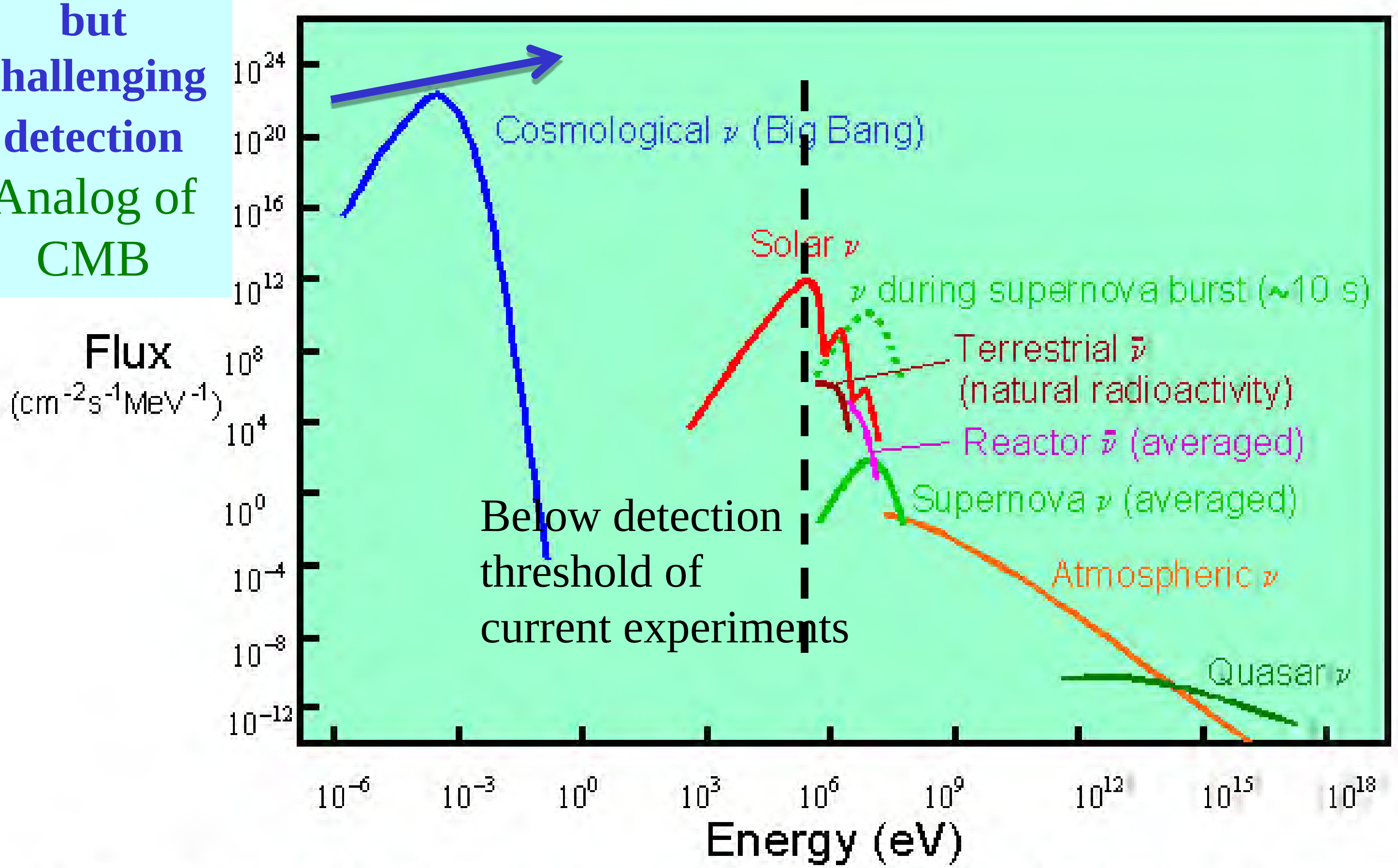
- Nuclear Spin Structure in Dark Matter Search: The Zero Momentum Transfer Limit
  V.A. Bednyakov, F. Š., Phys. Part. Nucl. 36, 131 (2006)
- Nuclear target effect on dark matter detection rate
  V.A. Bednyakov, F. Š., Phys. Rev. D 72, 035015 (2005)
- Nuclear Spin Structure in Dark Matter Search: The Finite Momentum Transfer Limit
  V.A. Bednyakov, F. Š., Phys. Part. Nucl. Suppl. 1, 37, S106 (2006)
- On the Importance of Nuclear Spin for Dark Matter Detection
  V.A. Bednyakov, M.A. Nazarenko, F. Š., FIZIKA B 17, 99 (2008)

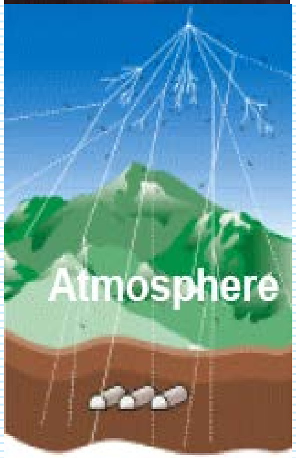
Sources of neutrinos

The Sun is the most intense detected source with a flux on Earth of 6 10^{10} $\nu/cm^2 s$

Abundant but challenging detection

Analog of CMB





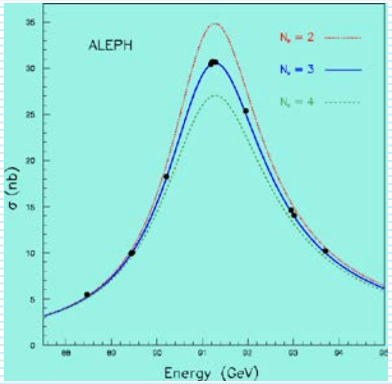
Flux on Earth of neutrinos from different sources as a function of energy

D. Vignaud and M. Spiro, Nucl. Phys.A 654 (1999) 350

Fundamental properties of neutrinos

After 57 years we know

- 3 families of light (V-A) neutrinos: ν_e, ν_μ, ν_τ
- ν are massive: we know mass squared differences
- relation between flavor states and mass states (neutrino mixing) only partially known



Claim for evidence of the $0\nu\beta\beta$-decay

H.V. Klapdor-Kleingrothaus et al.,NIM A 522, 371 (2004); PLB 586, 198 (2004)

- Absolute ν mass scale from the $0\nu\beta\beta$-decay. (cosmology, ^{3}H, ^{187}Rh ?)
- ν's are their own antiparticles – Majorana.

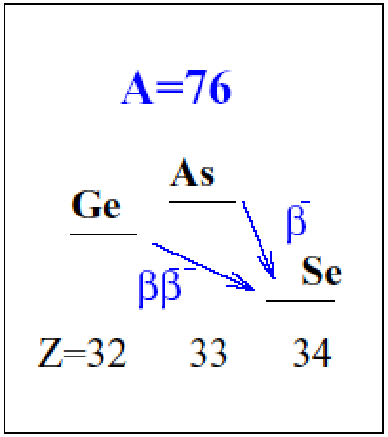
No answer yet

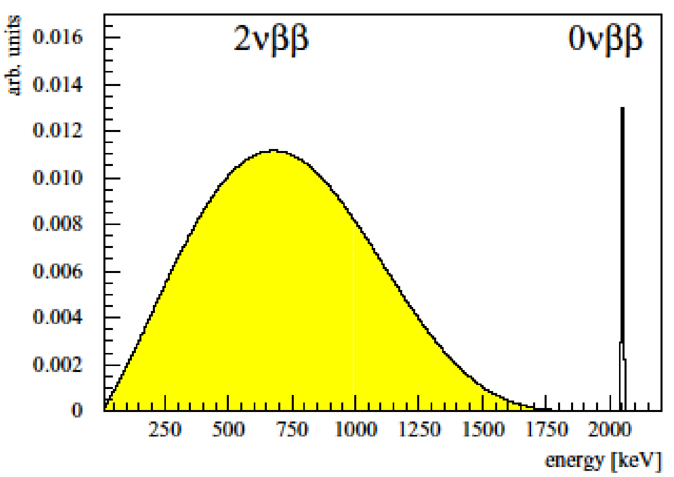
- Is there a CP violation in ν sector? (leptogenesis)
- Are neutrinos stable?
- What is the magnetic moment of ν?
- Sterile neutrinos?
- Statistical properties of ν? Fermionic or partly bosonic?

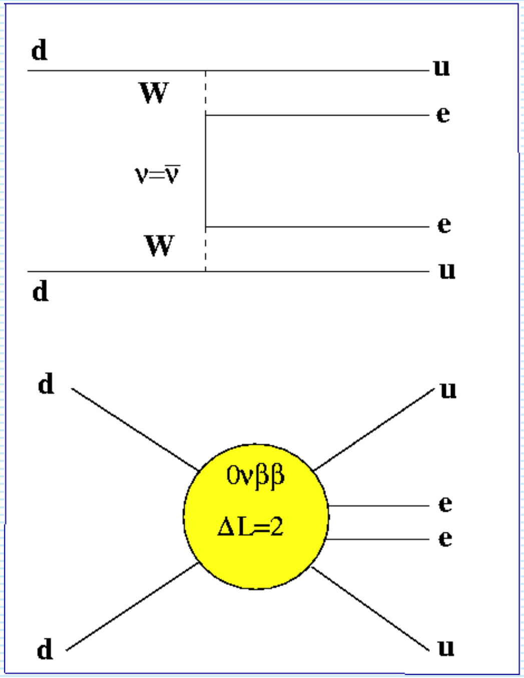
Neutrinoless Double-Beta Decay

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

Study of the 0νββ-decay is one of the highest priority issues in particle and nuclear physics





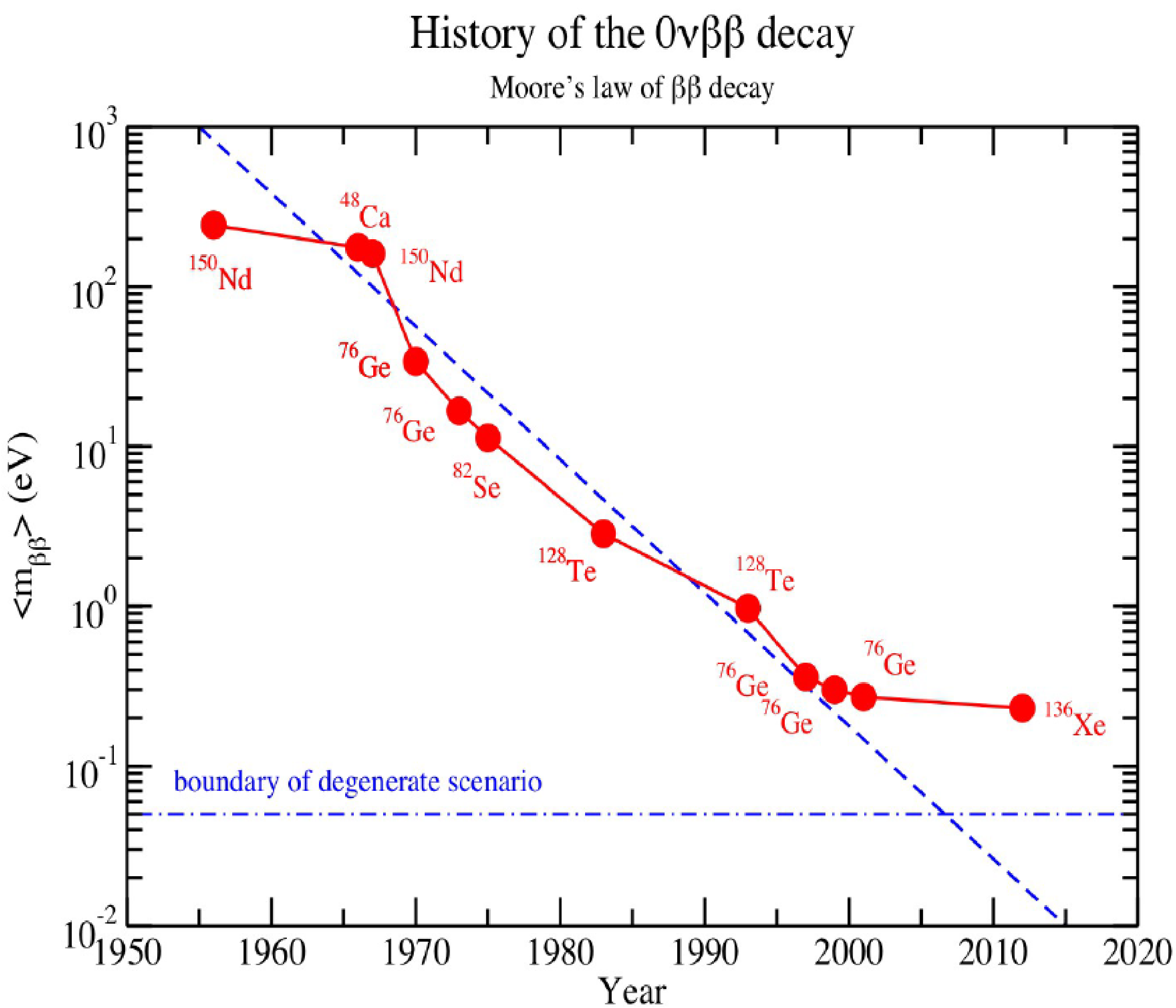


OUTLOOK

(slide of P. Vogel at Indian summer school, Prague, 2012)

Historically, there are > 100 experimental limits on $T_{1/2}$ of the $0\nu\beta\beta$ decay.

However, during the last decade the complexity and cost of such experiments increased dramatically. The constant slope is no longer maintained.



The answer to the question whether neutrinos are their own antiparticles is of central importance, not only to our understanding of neutrinos, but also to our understanding of the origin of mass.

What is the nature of neutrinos?

ν $\Rightarrow$

GUT's

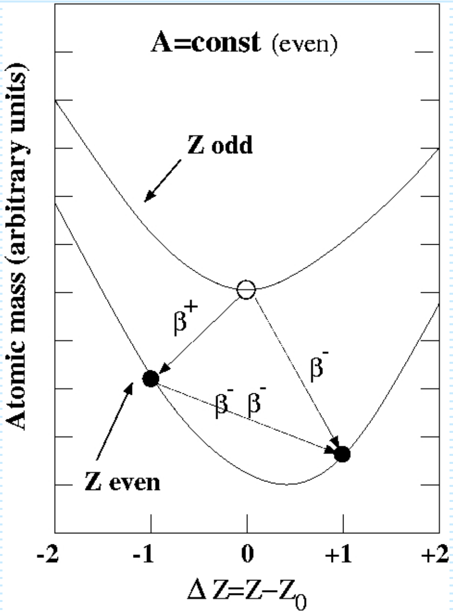
Only the 0νββ-decay can answer this fundamental question

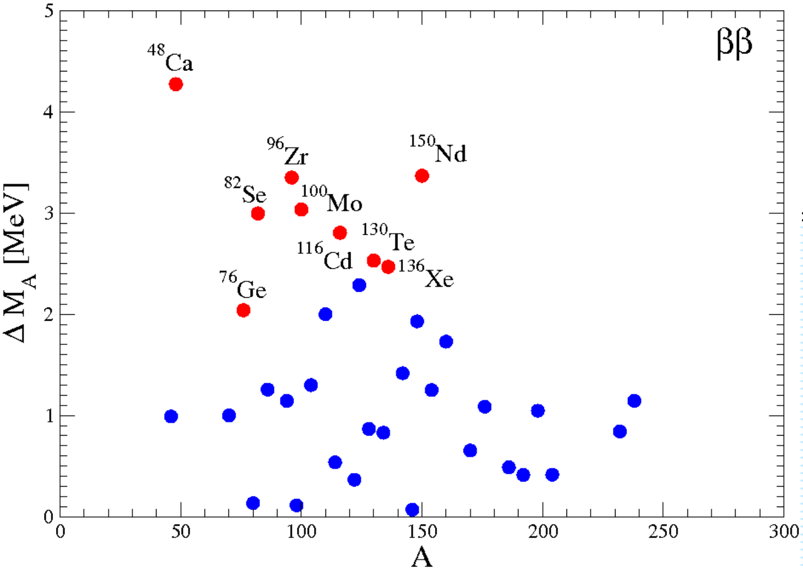
Analogy with kaons: K_0 and $\bar{K}_0$

Could we have both?
(light Dirac and heavy Majorana)

Analogy with π_0

The double beta decay process can be observed due to nuclear pairing interaction that favors energetically the even-even nuclei over the odd-odd nuclei





$$\left(T^{0\nu}_{1/2}\right)^{-1} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 g_A^4 \left|M^{0\nu}_{\nu}\right|^2 G^{0\nu}$$

transition	$G^{01}(E_0, Z)$ $\times 10^{14} y$	$Q_{\beta\beta}$ [MeV]	Abund. (%)	$\lvert M^{0\nu}\rvert^2$
$^{150}Nd \to {}^{150}Sm$	26.9	3.667	6	?
$^{48}Ca \to {}^{48}Ti$	8.04	4.271	0.2	?
$^{96}Zr \to {}^{96}Mo$	7.37	3.350	3	?
$^{116}Cd \to {}^{116}Sn$	6.24	2.802	7	?
$^{136}Xe \to {}^{136}Ba$	5.92	2.479	9	?
$^{100}Mo \to {}^{100}Ru$	5.74	3.034	10	?
$^{130}Te \to {}^{130}Xe$	5.55	2.533	34	?
$^{82}Se \to {}^{82}Kr$	3.53	2.995	9	?
$^{76}Ge \to {}^{76}Se$	0.79	2.040	8	?

The NMEs for 0νββ-decay must be evaluated using tools of nuclear theory

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 g_A^4 \left|M_\nu^{0\nu}\right|^2 G^{0\nu}$$

Absolute ν mass scale

Normal or inverted hierarchy of ν masses

CP-violating phases



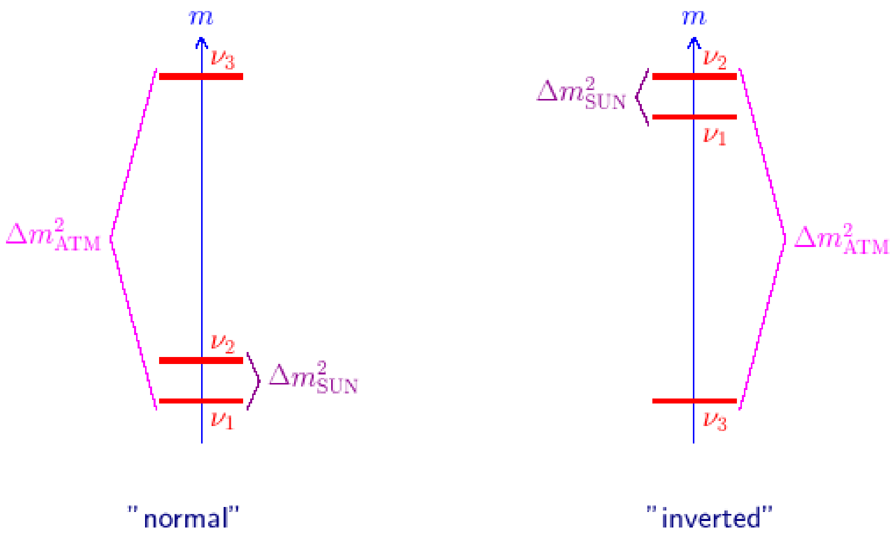
$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

An accurate knowledge of the nuclear matrix elements, which is not available at present, is however a pre-requisite for exploring neutrino properties.

Neutrinos mass spectrum

mass differences:
$|\Delta m^2_{sol}| = 7.65\ 10^{-5}\ eV^2$
$\Delta m^2_{atm} = 2.43\ 10^{-3}\ eV^2$

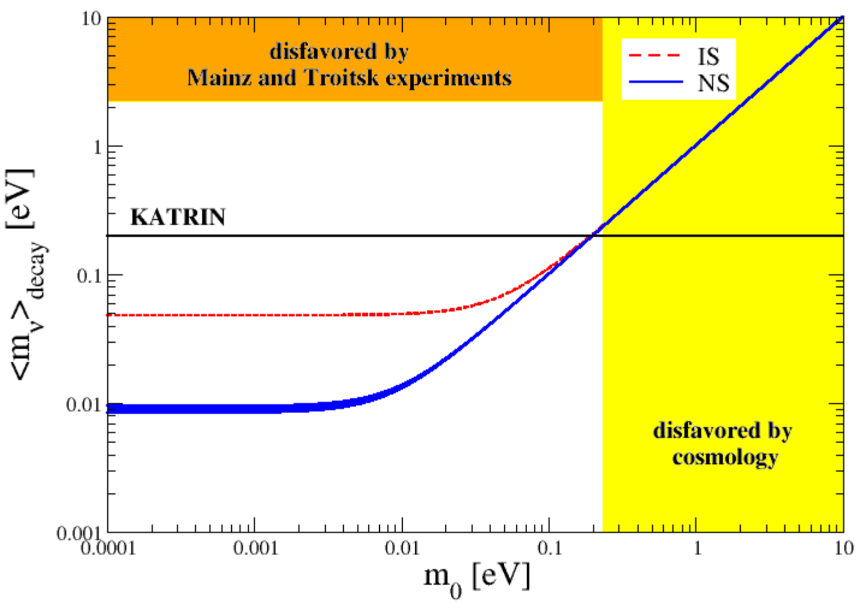


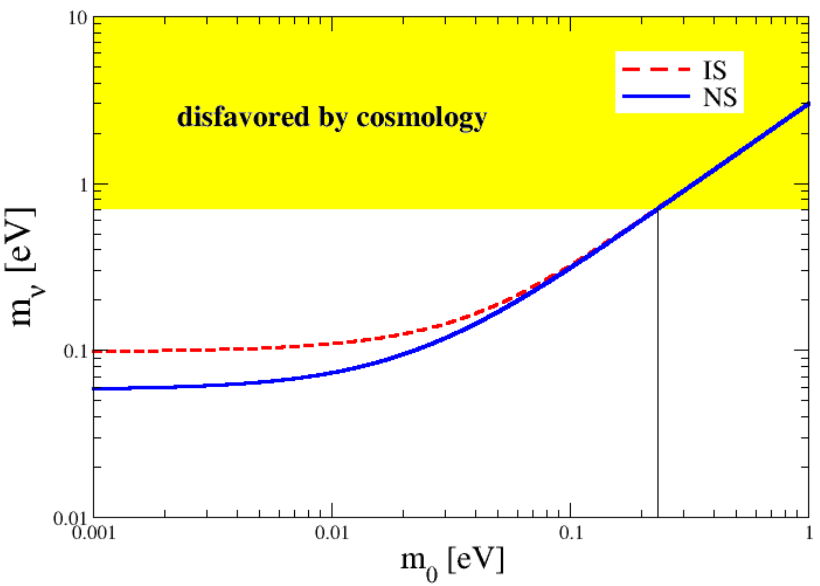
Tritium decay

$$m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2\ m_i^2}$$

Cosmology

$$\sum_{i=1}^{3} m_i$$

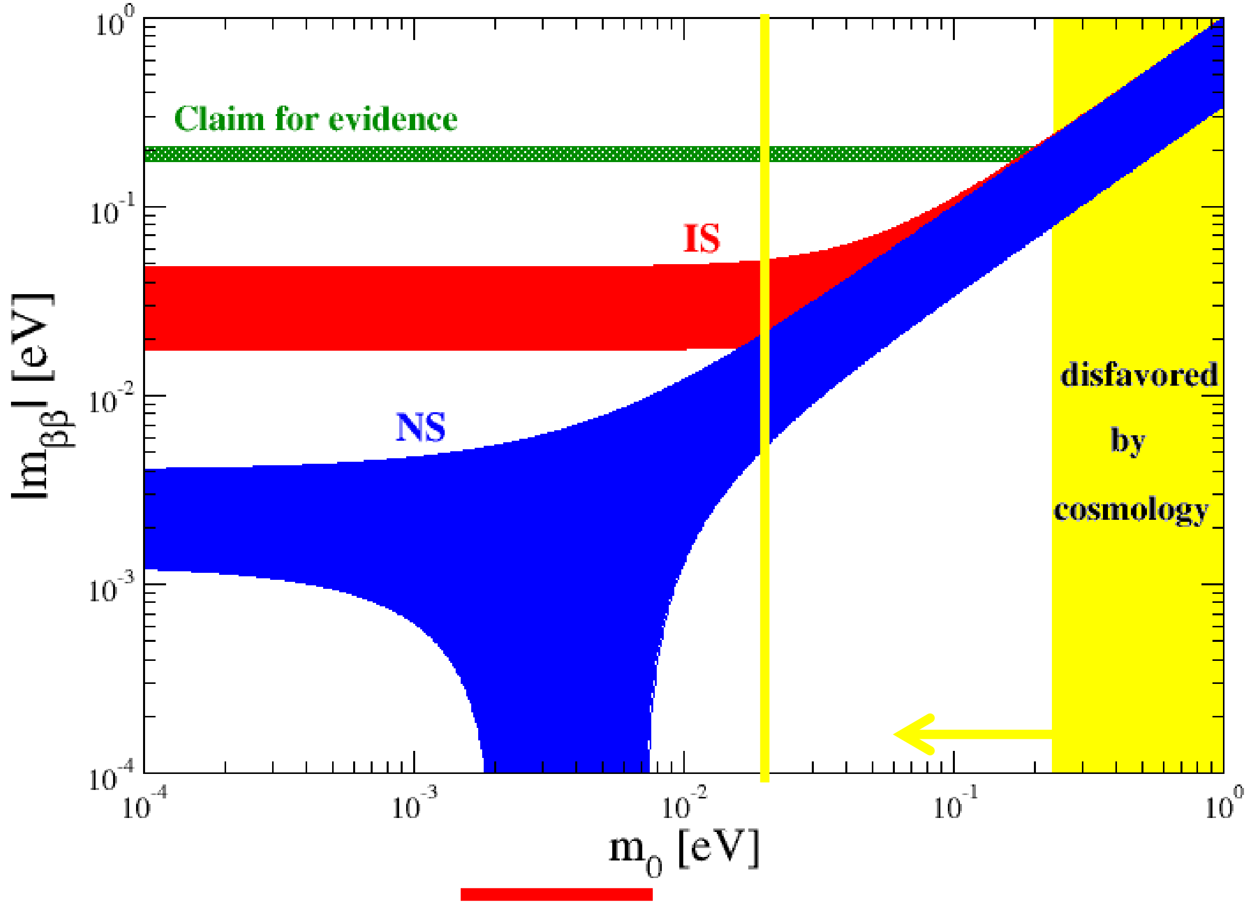


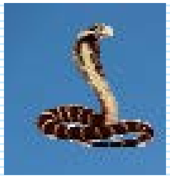


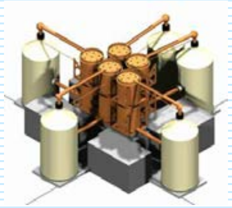
Daya Bay: $\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$ (March 2012)

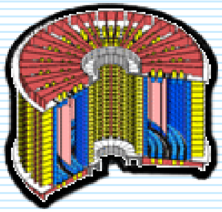
$$|m_{\beta\beta}{}^{(3\ \nu)}| = |c_{12}^2 c_{13}^2 e^{2i\alpha_1} m_1 + c_{13}^2 s_{12}^2 e^{2i\alpha_2} m_2 + s_{13}^2 m_3|$$

Issue: Lightest neutrino mass m_0

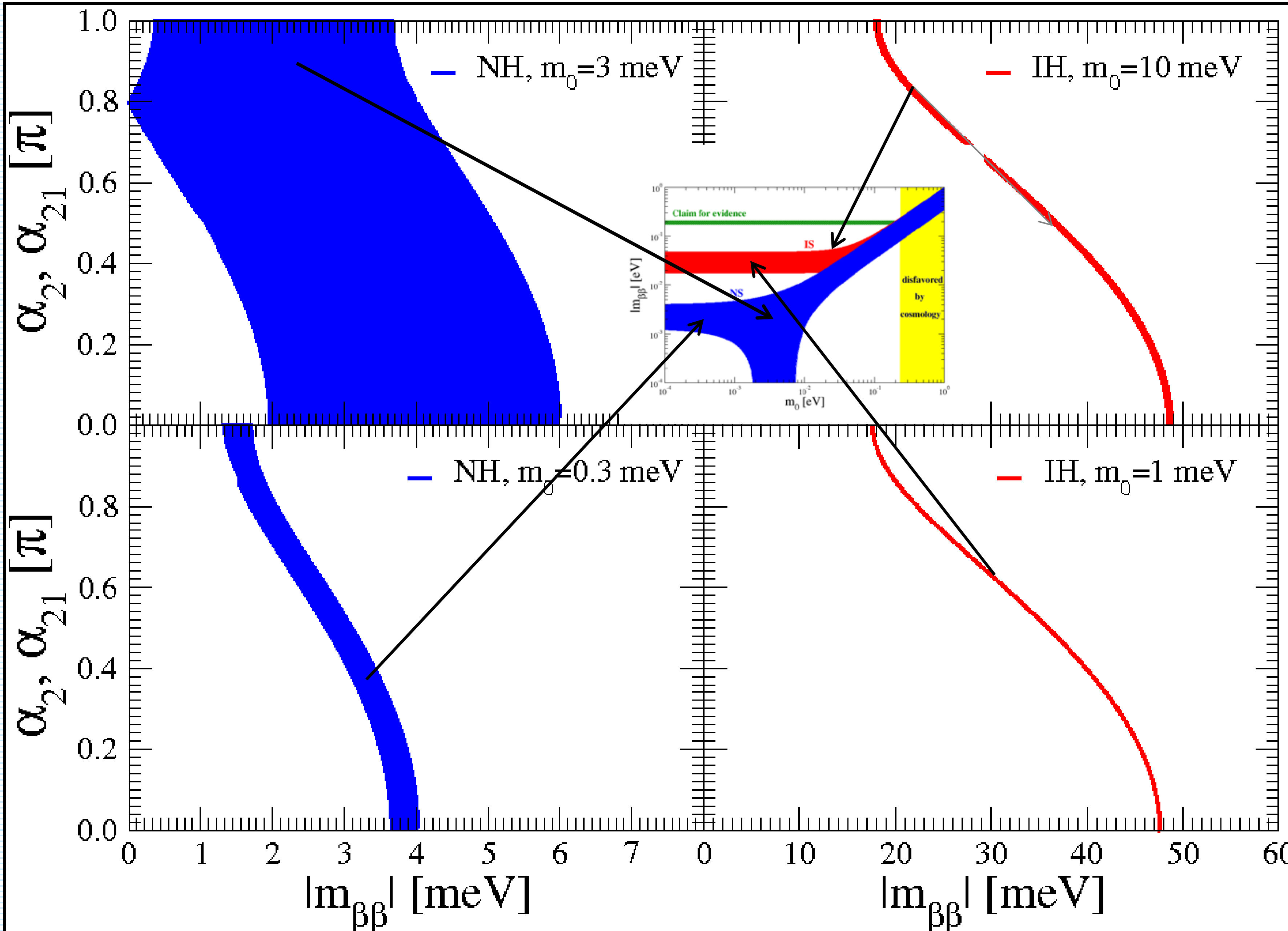






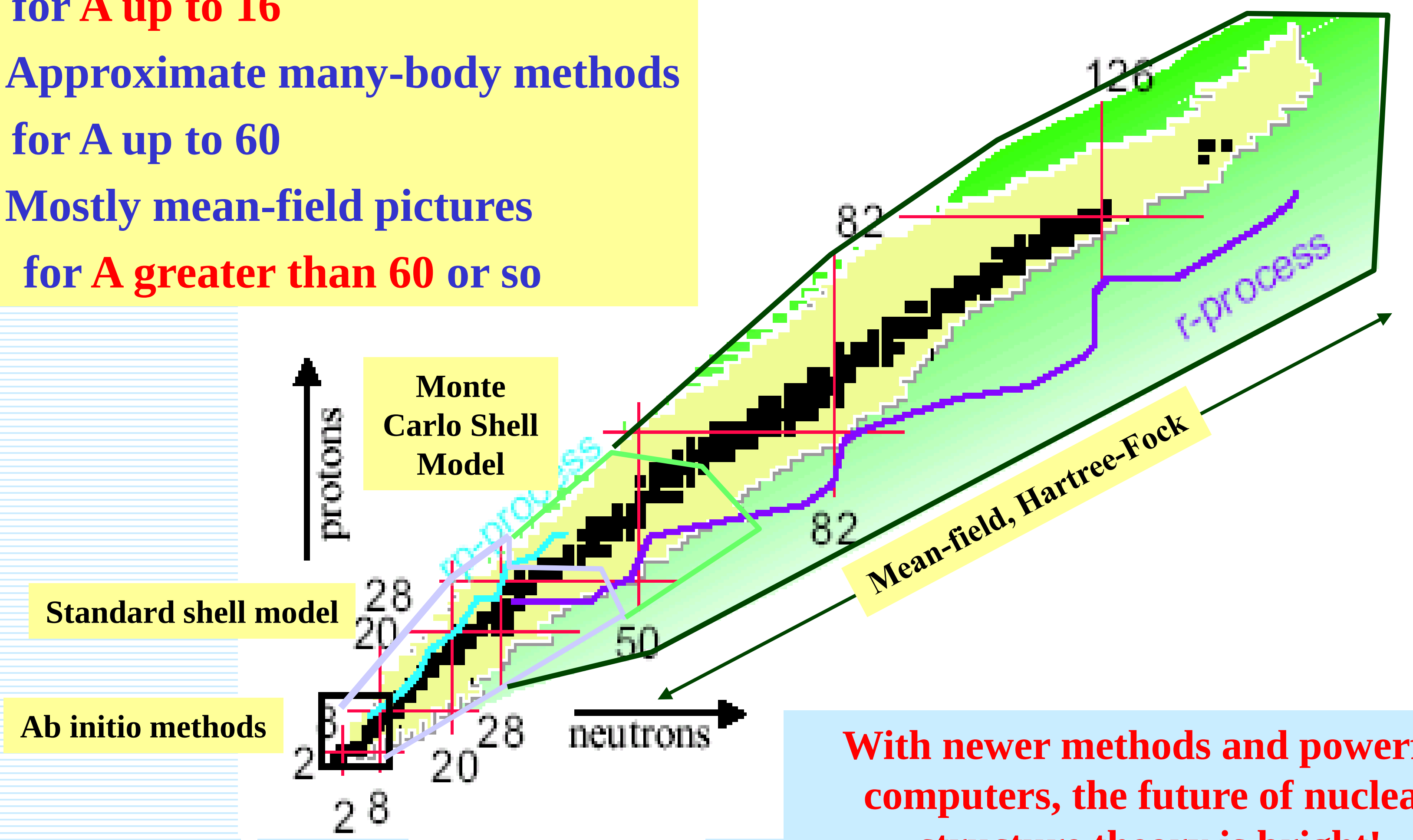


GUT's
(Rodejohann pres.)


NH, m0=3 meV
IH, m0=10 meV
NH, m0=0.3 meV
IH, m0=1 meV
α2, α21 [π]
|mββ| [meV]
Claim for evidence
IS
NS
disfavored by cosmology
|mββ| [eV]
m0 [eV]

Nuclear Structure

- Exact methods exist up to A=4
- Computationally exact methods for A up to 16
- Approximate many-body methods for A up to 60
- Mostly mean-field pictures for A greater than 60 or so



With newer methods and powerful computers, the future of nuclear structure theory is bright!

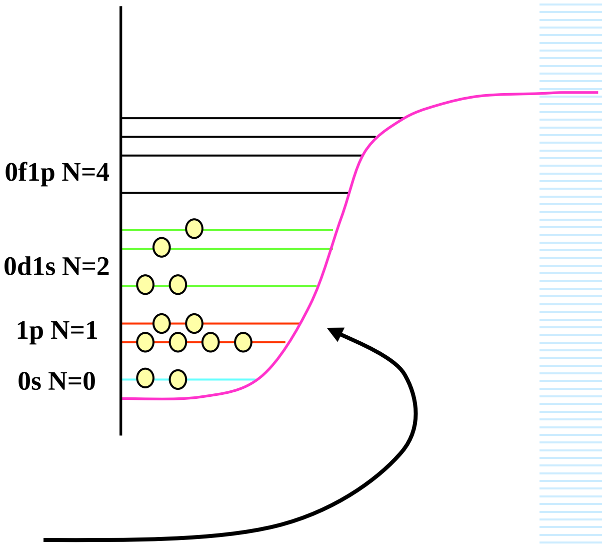
Many-body Hamiltonian

- Start with the many-body Hamiltonian

$$H = \sum_i \frac{\vec{p}_i^{\,2}}{2m} + \sum_{i<j} V_{NN}\left(\vec{r}_i - \vec{r}_j\right)$$

- Introduce a mean-field U to yield basis

$$H = \sum_i \left(\frac{\vec{p}_i^{\,2}}{2m} + U(r_i) \right) + \underbrace{\sum_{i<j} V_{NN}\left(\vec{r}_i - \vec{r}_j\right) - \sum_i U(r_i)}_{\text{Residual interaction}}$$



The success of any nuclear structure calculation depends on the choice of the mean-field basis and the residual interaction!

- The **mean field** determines the shell structure
- In effect, nuclear-structure calculations rely on **perturbation theory**

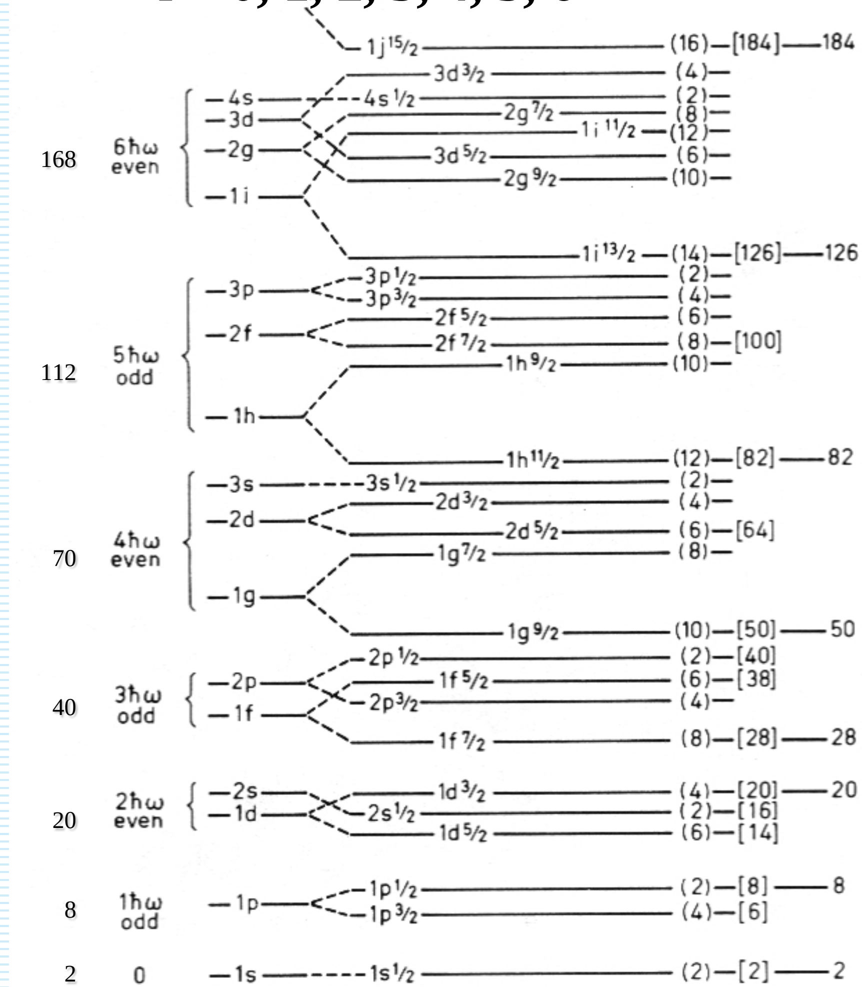
Goeppert-Mayer and Haxel, Jensen, and Suess proposed the independent-particle shell model to explain the magic numbers

2, 8, 20, 28, 50, 82, 126, 184

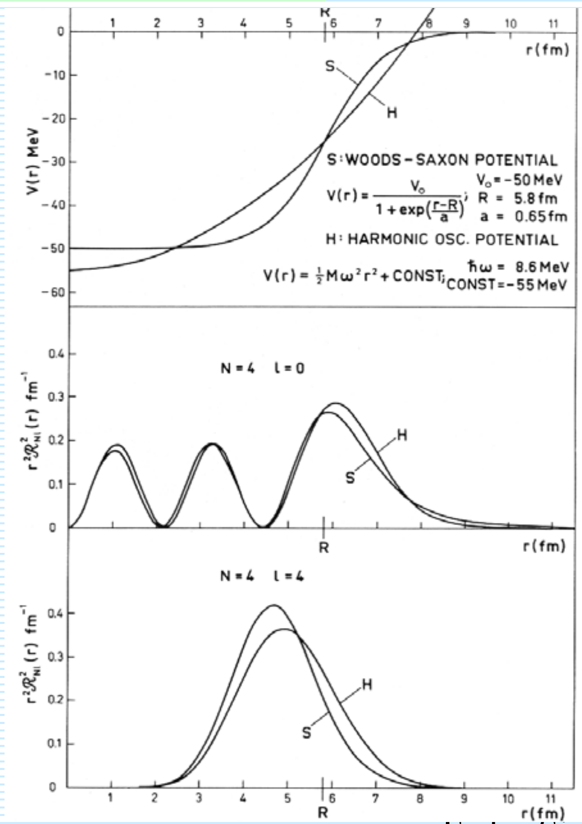
Shell structure of spherical nucleus

s, p, d, f, g, h, i

l = 0, 1, 2, 3, 4, 5, 6



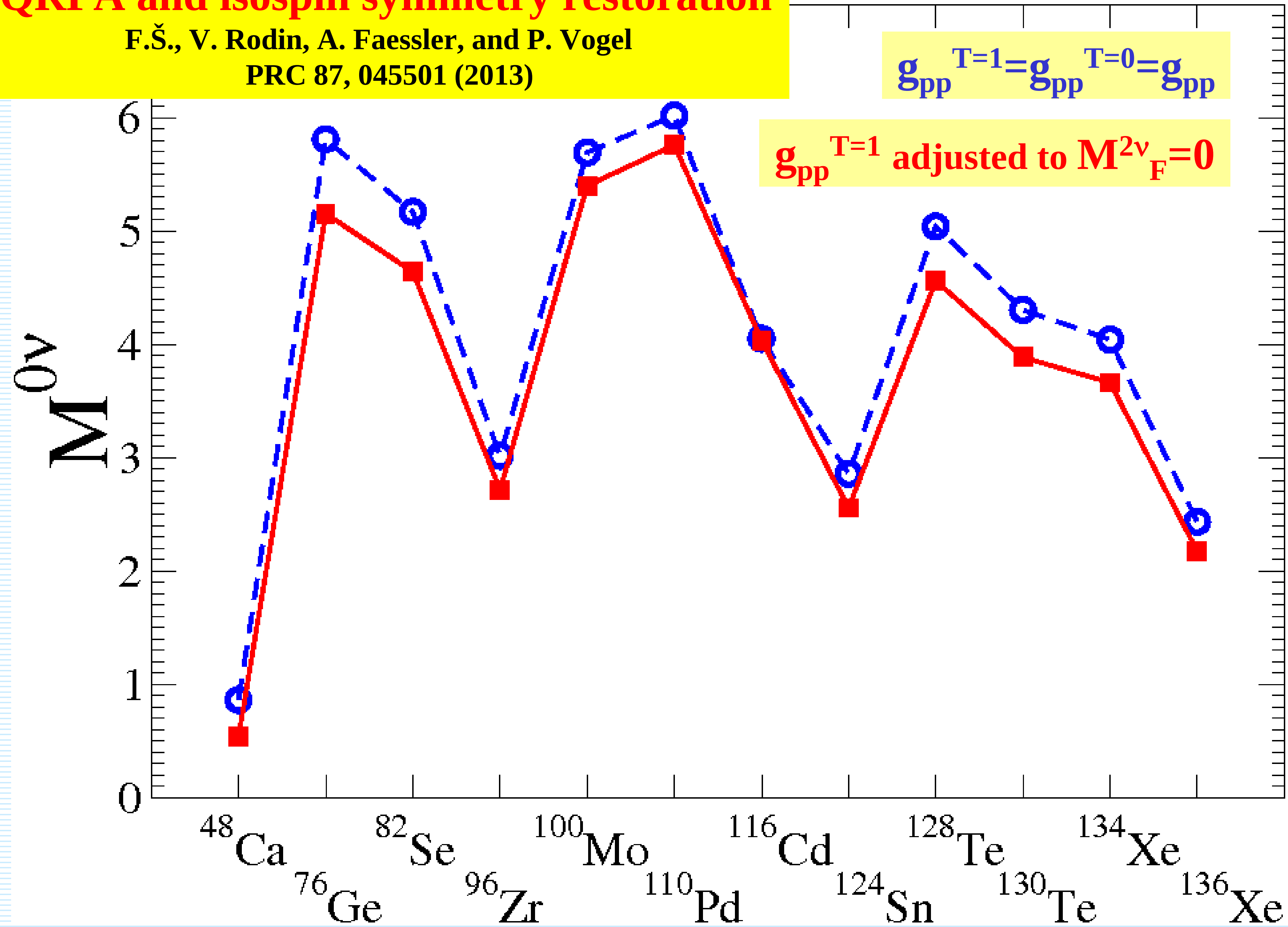
Harmonic oscillator with spin-orbit is a reasonable approximation to the nuclear mean field



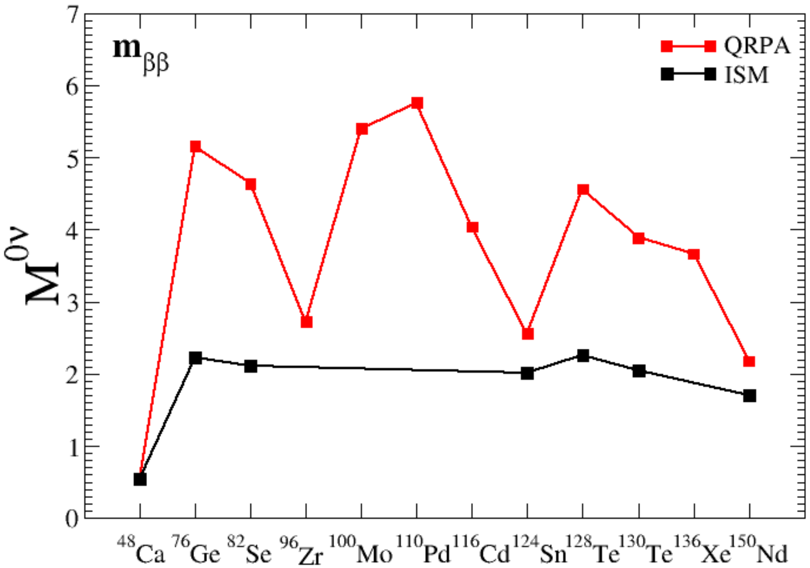
M.G. Mayer and J.H.D. Jensen, *Elementary Theory of Nuclear Shell Structure*, p. 58, Wiley, New York, 1955

QRPA and isospin symmetry restoration

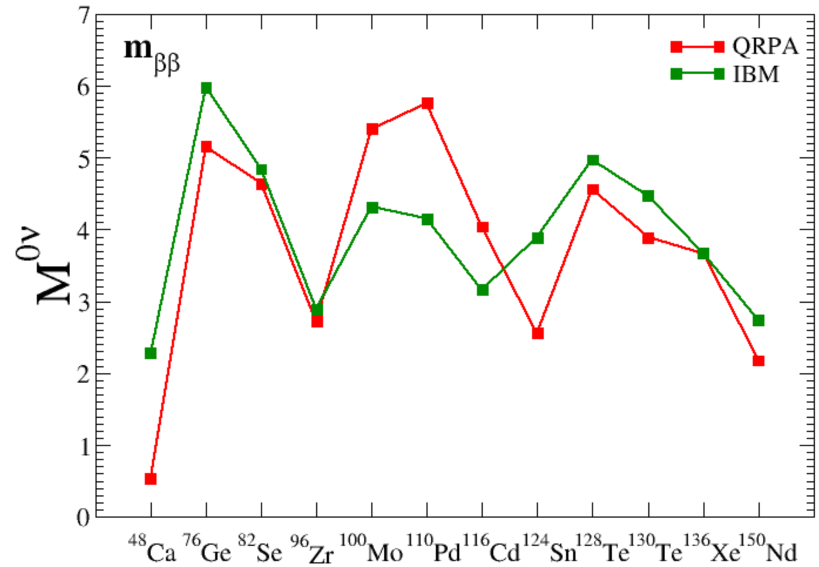
F.Š., V. Rodin, A. Faessler, and P. Vogel
PRC 87, 045501 (2013)



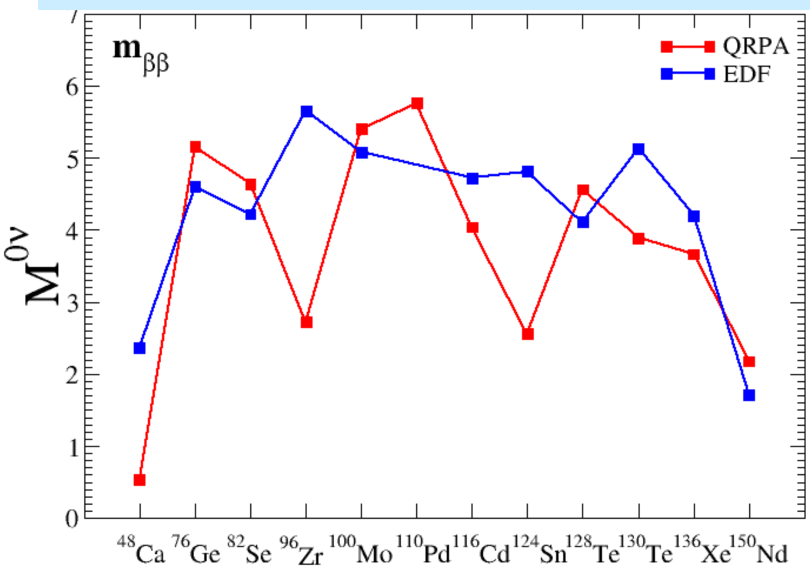
ISM: **Menendez et al. NPA 818 (2009) 139**



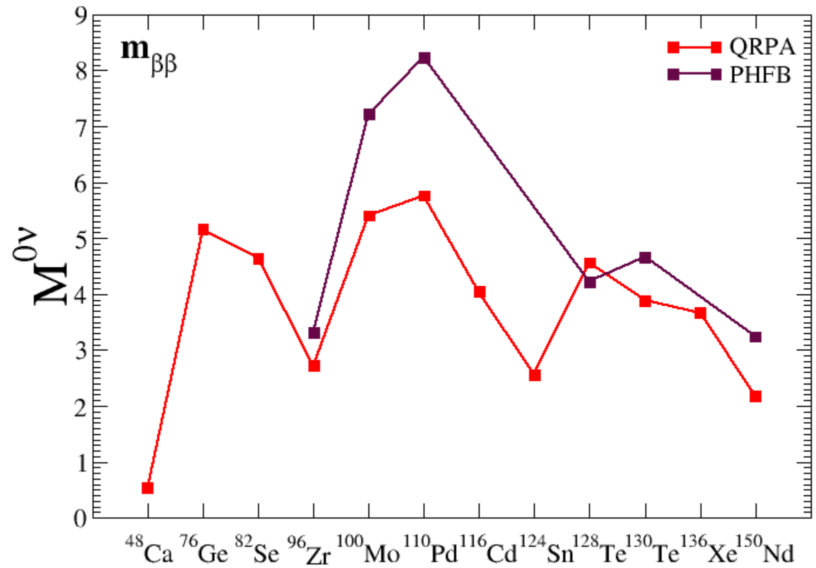
IBM: **Barea, Kotila, Iachello, PRC (2013) 014315**



EDF: **Rodrigez, Martinez-Pinedo, PRL (2010) 105**



PHFB: **K. Rath et al., PRC 85 (2012) 014308**



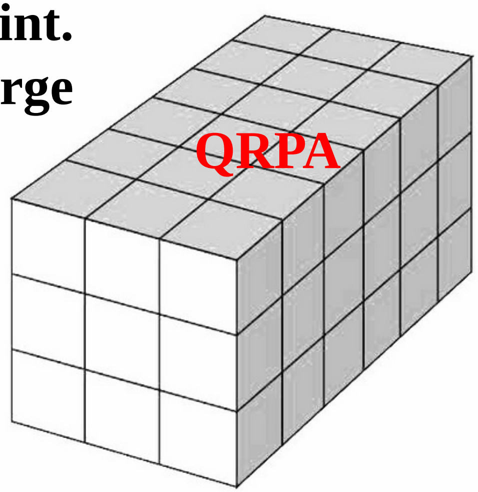
***Differences**: mean field; residual int.; size of the m.s.; many-body appr.*

QRPA uncertainties and their correlations in the analysis of $0\nu\beta\beta$ decay

A. Faessler, G.L. Fogli, E. Lisi, V. Rodin, A. M. Rotunno,F.Š.,

PRD 87, 053002 (2013)

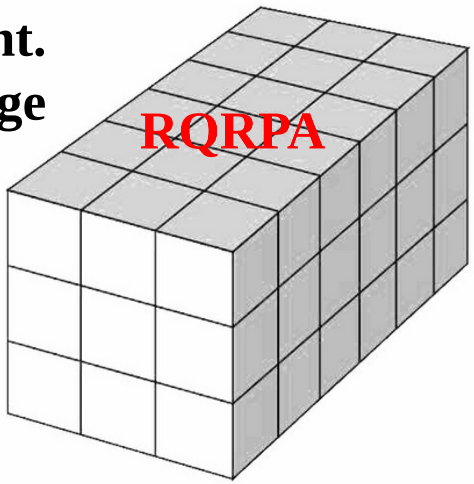
s.ms.: small, int., large



src: Argonne, CD-Bonn

g_A=1.0,1.25

s.ms.: small, int., large

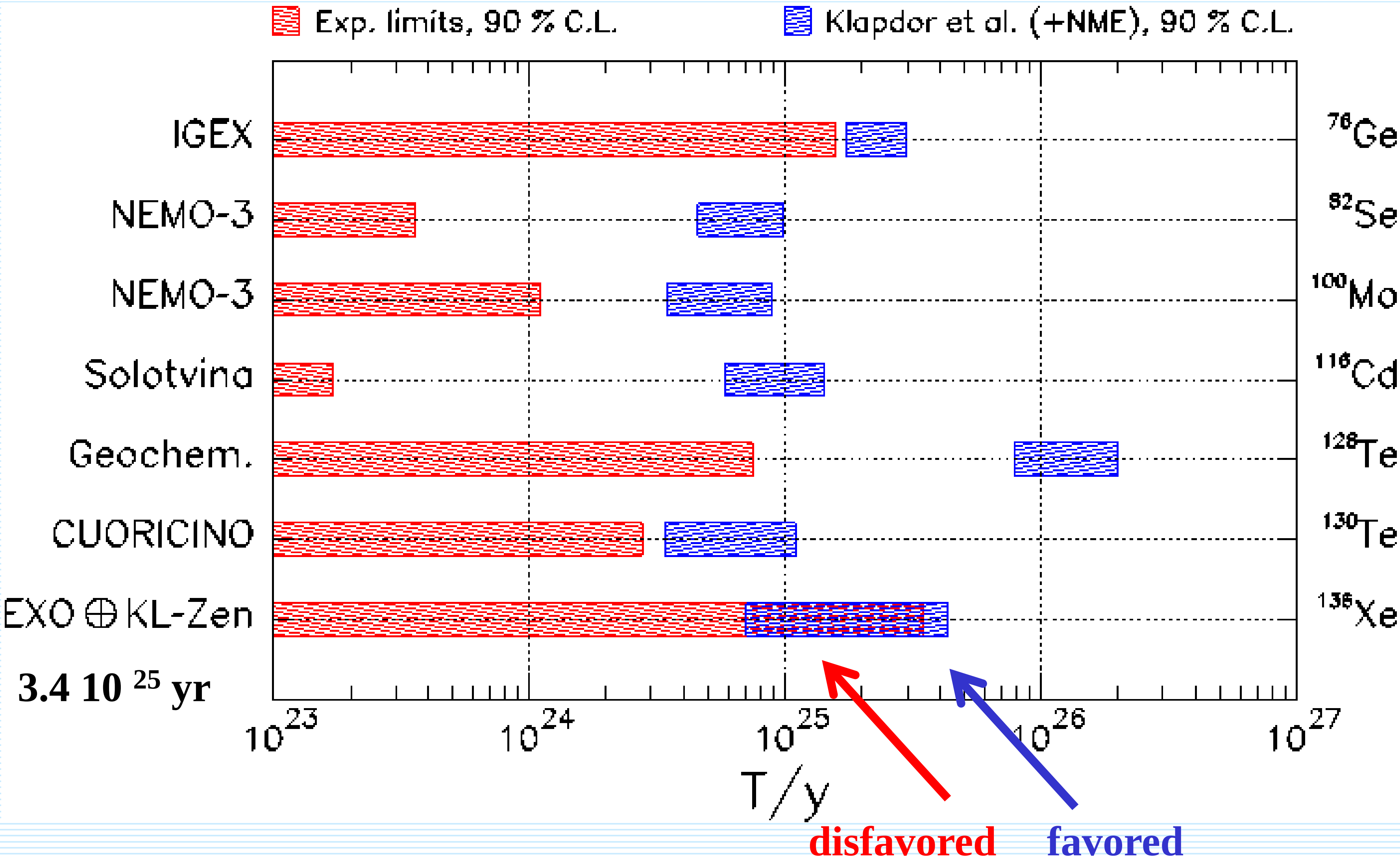


src: Argonne, CD-Bonn

g_A=1.0,1.25

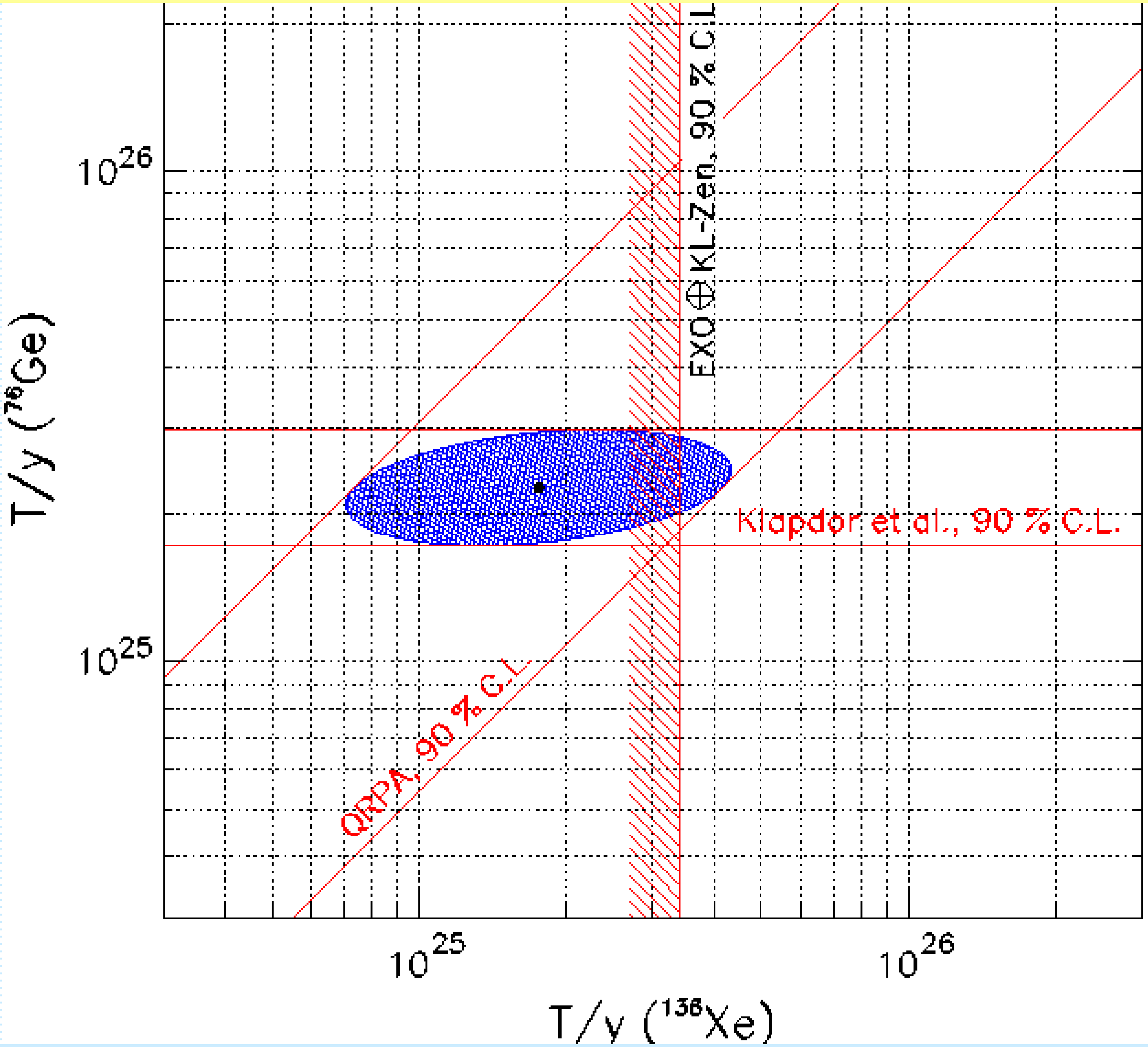
For each nucleus 2x2x2x3=24 NMEs

Range of half-lives preferred at 90% C.L. by the 0νββ claim of evidence compared with the 90% exclusion limits placed by other experiments.



The comparison involves the NME and their errors as well as their correlations

Theoretical and expperimental constraints in the plane charted by the 0νββ half-lives of ^{76}Ge and ^{136}Xe.



Horizontal band:range prefered by claim. Slanted band: constraint place by our QRPA estimates. The combination provides the shaded ellipse, whose projection on the abscissa gives the range preferred at 90% C.L. for the ^{136}Xe half-life.

Probing the see-saw I mechanism

Bilenky, Faessler, Potzel, F.Š, Eur. Phys. J. C 71 (2011) 1754

There exist heavy Majorana neutral leptons N_i (singlet of SU(2)xU(1) group)

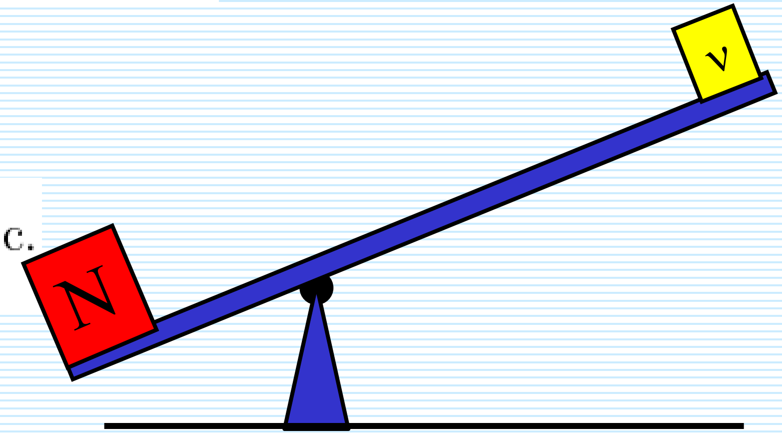
$$\mathcal{L} = -\sqrt{2}\sum_{i,l} Y_{li}\overline{L}_{lL}N_{iR}\tilde{H} + \mathrm{h.c.}.$$

$$L_{lL} = \begin{pmatrix} \nu_{lL} \\ l_L \end{pmatrix}$$

$$N_i = N_i^c = C\bar{N}_i^T$$

Effective interaction for processes with virtual N_i at electroweak scale

$$\mathcal{L}_{\mathrm{eff}} = -\frac{1}{\Lambda}\sum_{l',l,i}\overline{L_{l'L}}\tilde{H}\sum_i (Y_{l'i}\frac{\Lambda}{M_i}Y_{li})C\tilde{H}^T(\overline{L_{lL}})^T + \mathrm{h.c.}$$



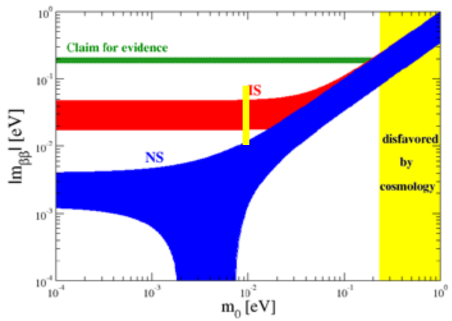
After spontaneous violation of the electroweak symmetry the left-handed Majorana mass term is generated

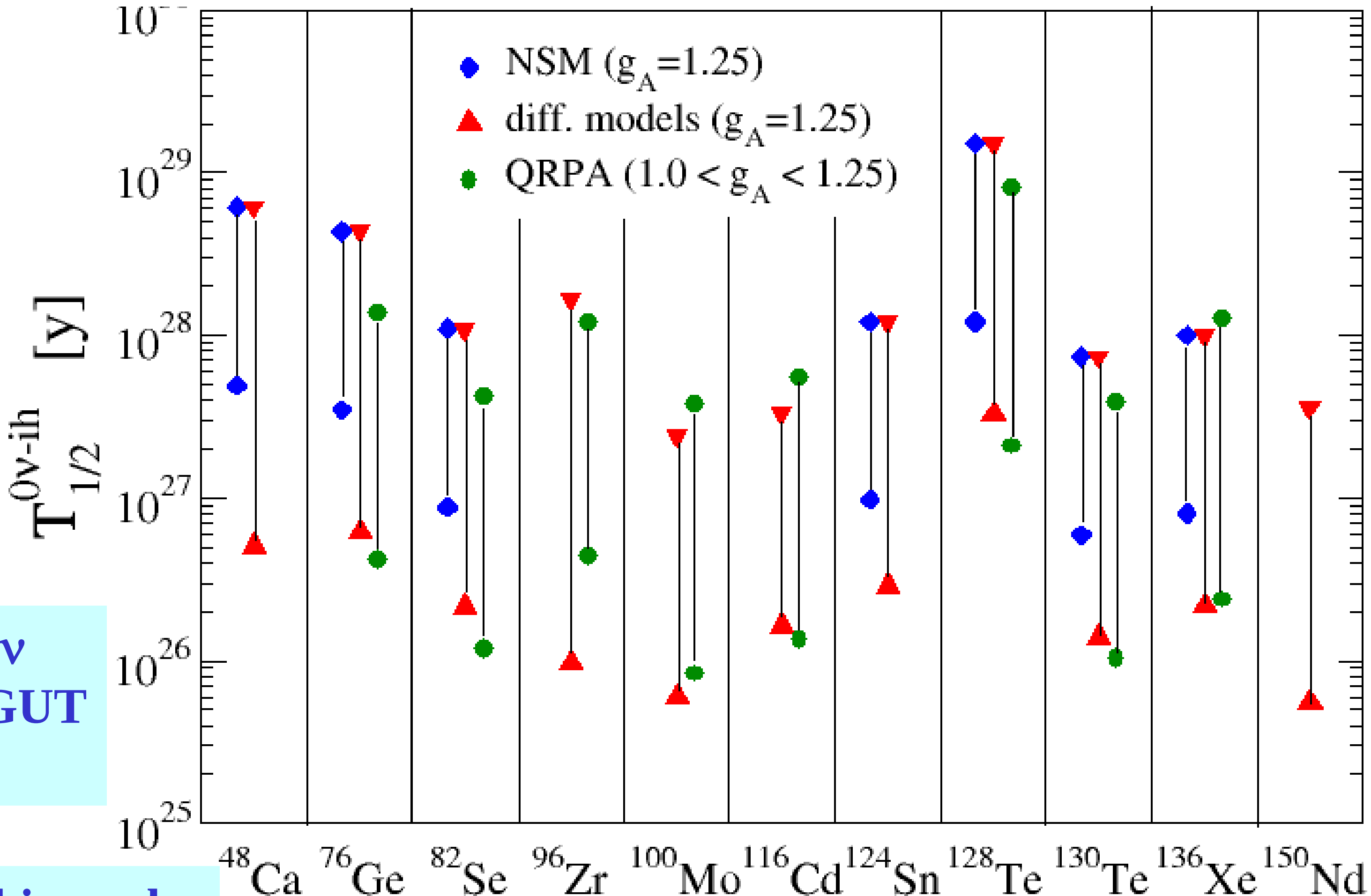
$$M^L = Y\frac{v^2}{M}Y^T = U\ m\ U^T$$

$$\mathcal{L}^{\mathrm{M}} = -\frac{1}{2}\sum_{l',l}\overline{\nu}_{l'L}\ M^L_{l'l}\ (\nu_{lL})^c + \mathrm{h.c.}$$

$$= -\frac{1}{2}\sum_i m_i\bar{\nu}_i\nu_i,$$

Probing the standard see-saw mechanism





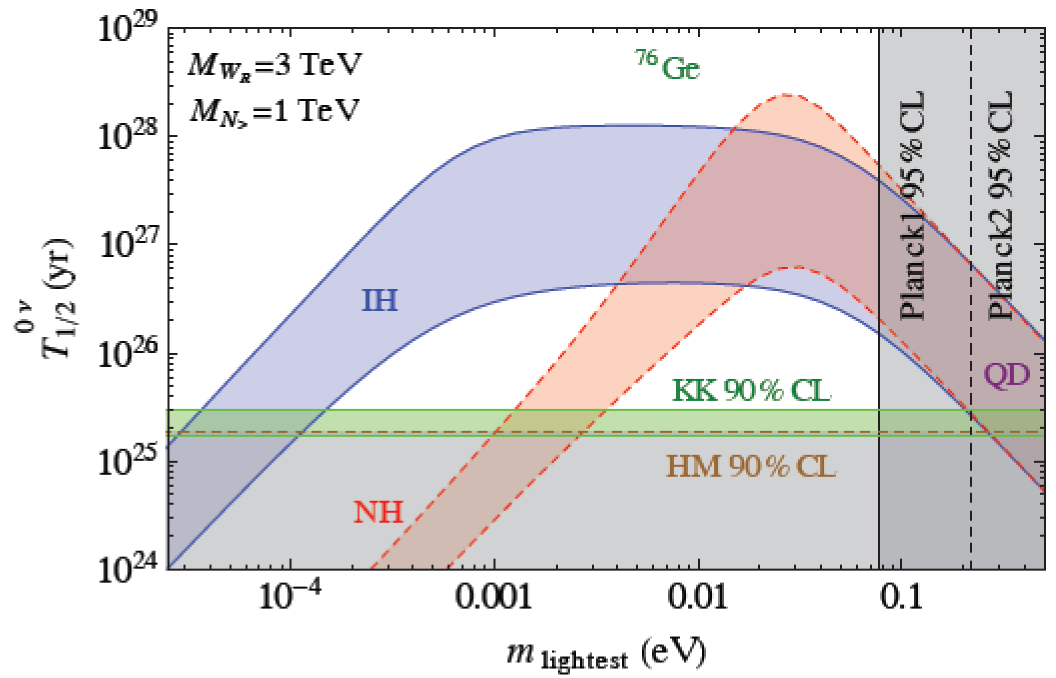
Heavy ν Mass at GUT scale

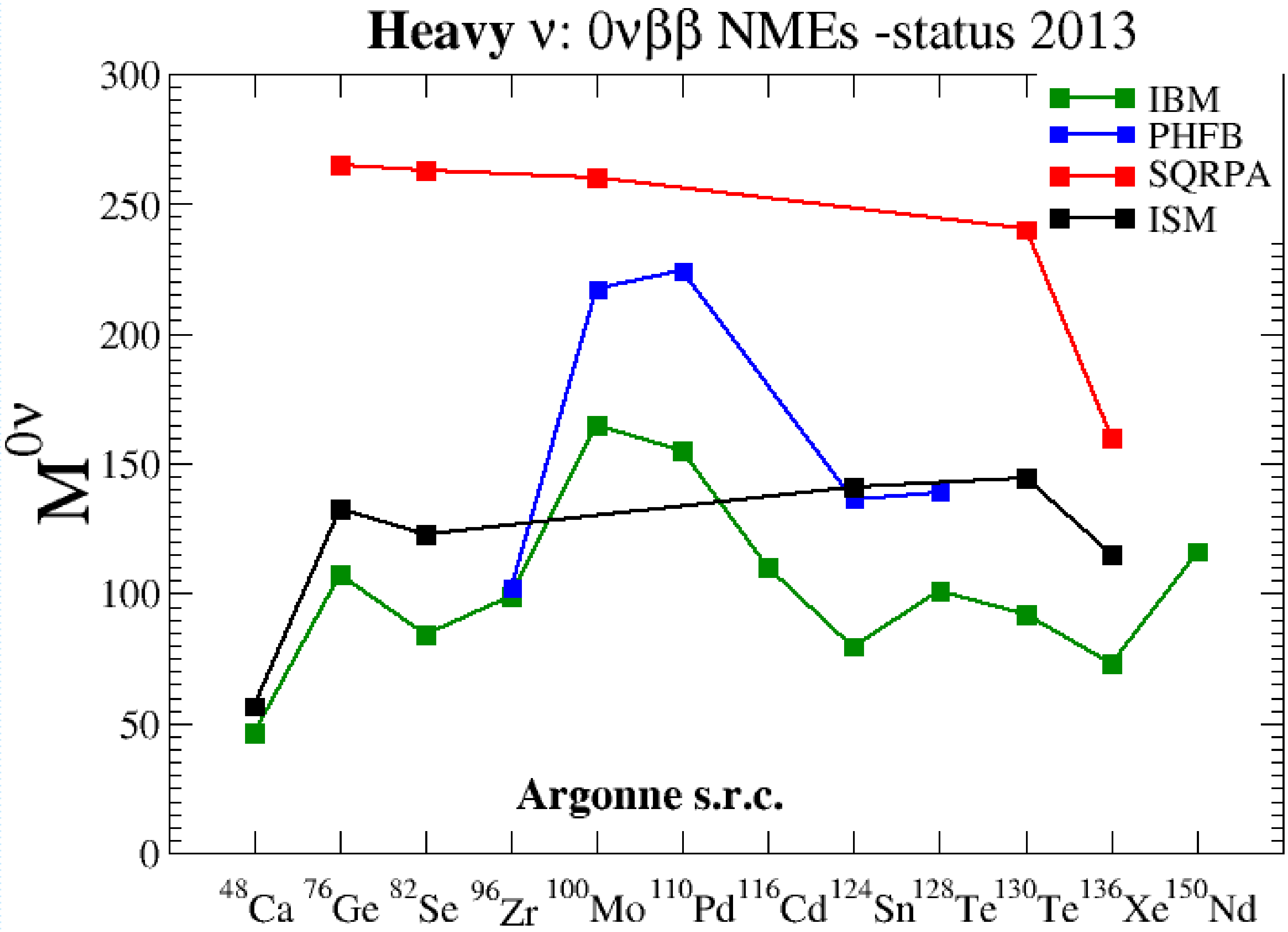
Inverted hierarchy

Heavy ν 0νββ-decay NMEs (type II see-saw)

LHC (scale!?) and L-R symmetric models

Discrete LR symmetry to parity (U=V)





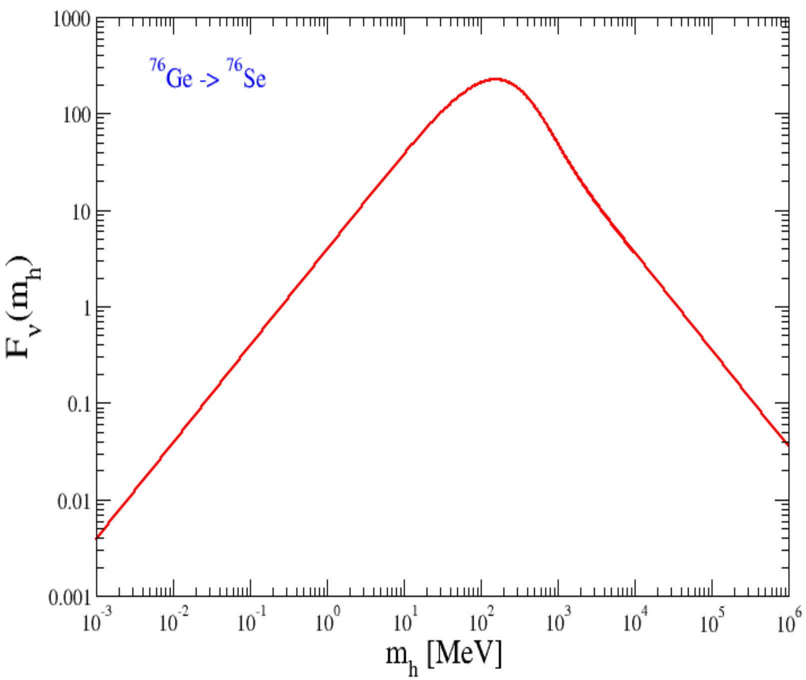
PHFB: K. Rath et al., PRC 85 (2012) 014308
IBM: Barea, Kotila, Iachello, PRC (2013) 014315

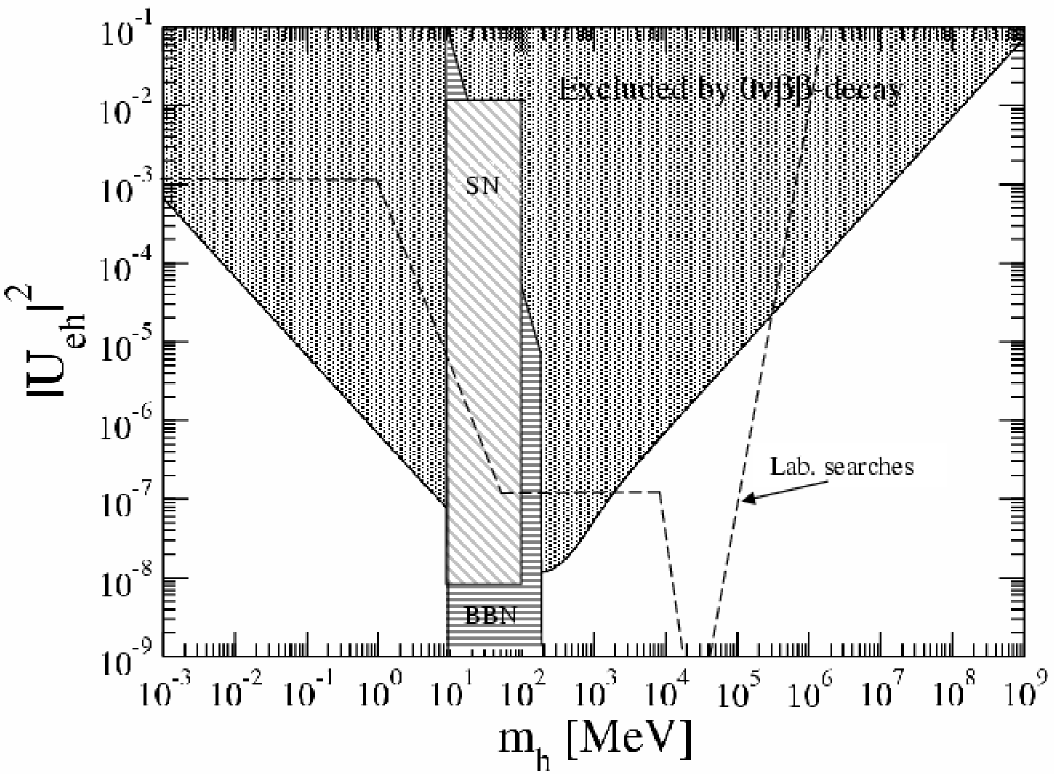
SQRPA: Vergados, Ejiri, F. Š., RPP 75 (2012) 106301
ISM: Menendez, privite communications

Sterile neutrino in 0νββ-decay

Matrix element depends on ν-mass

$$[T^{0\nu}_{1/2}]^{-1} = G_{01}\left|\frac{\langle m_\nu\rangle_{ee}}{m_e}M^{light}_\nu + U^2_{eh}\frac{m_h}{m_e}M^{0\nu}(m_h)\right|^2 .$$





$$F_\nu(m_h) = \frac{m_h}{m_e}M^{0\nu}(m_h)$$

$$|U_{eh}|^2 \le \frac{1}{|F_\nu(m_h)|}\frac{1}{\sqrt{T^{0\nu-exp}_{1/2}G_{01}}},$$

Beneš, Faesler, F.Š., Kovalenko, PRD 71 (2005) 077901

R-parity Breaking MSSM
(neutralino is not dark matter candidate)

$$\lambda_{i,j<k}\, LLE + \lambda'_{ijk}\, LQD + \lambda''_{i,j<k}\, UDD$$

$$9 \quad + \quad 27 \quad + \quad 9 \quad = \quad 45 \text{ coupling constants}$$

R-parity breaking terms
In superpotential

$\lambda'_{11k} * \lambda''_{11k} < 10^{-22}$	proton decay
$\lambda < 10^{-3}$ to 10^{-1}	with $\lambda_{133} < 0.003$ limit on ν_e mass
$\lambda' < 10^{-2}$ to 10^{-1}	with $\lambda'_{111} < 4.10^{-4}$ neutrinoless beta decay

Neutrino-Neutralino mixing matrix (see-saw structure)

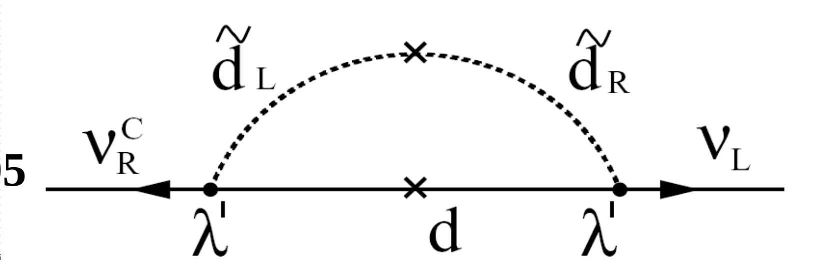
$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m \\ m^T & M_\chi \end{pmatrix}$$

$$\Psi'^{T}_{(0)} = \left(\nu_e, \nu_\mu, \nu_\tau, -i\lambda', -i\lambda_3, \tilde{H}_1^0, \tilde{H}_2^0\right),$$

Radiative corrections to neutrino mass

$$\mathcal{M}_\nu = \mathcal{M}^{tree} + \mathcal{M}^{l} + \mathcal{M}^{q}$$

Gozdz, Kaminski, Šimkovic, PRD 70 (2004) 095005



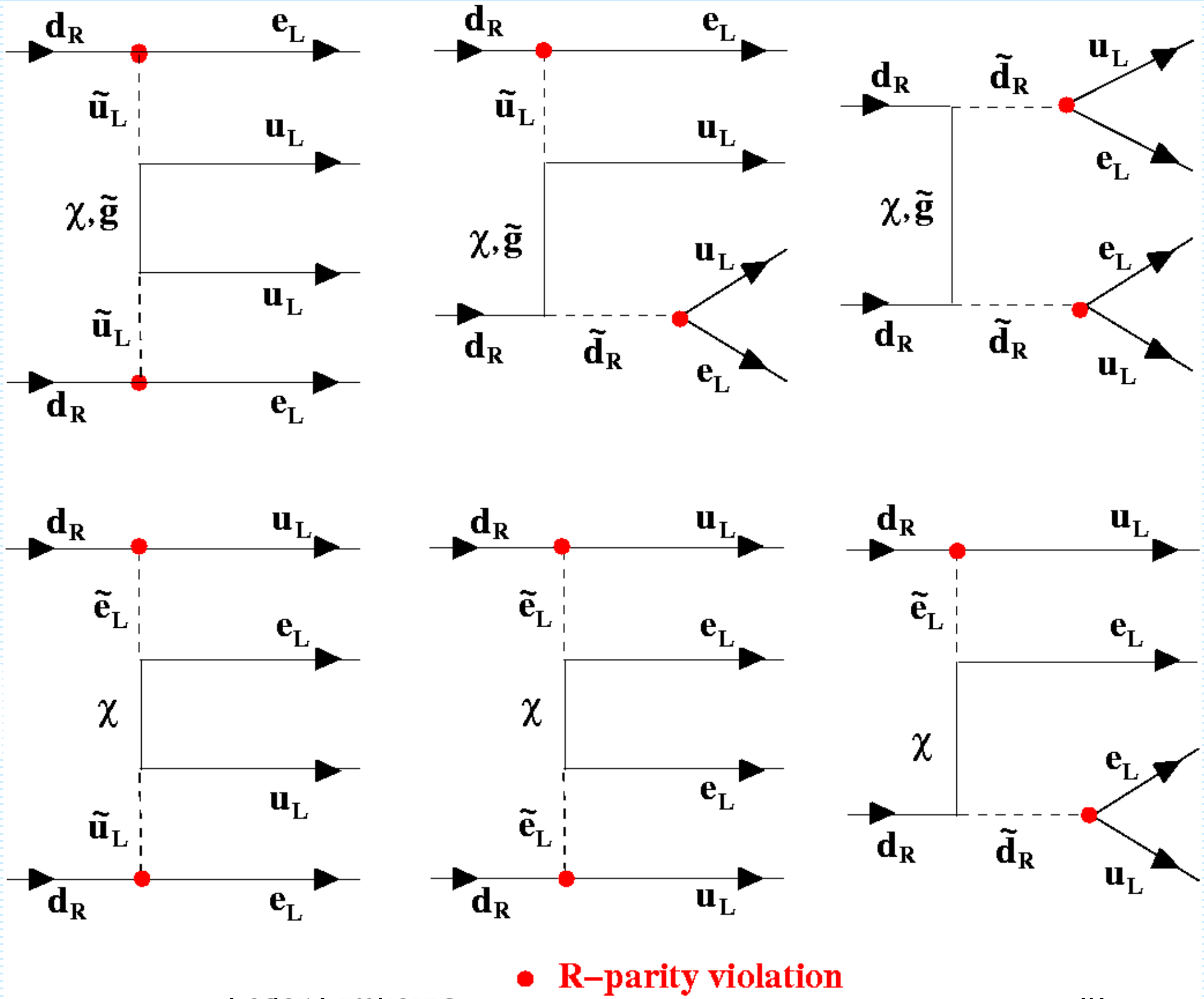
gluino/neutralino exchange R-parity breaking SUSY mechanism of the 0νββ–decay

$d + d \rightarrow u + u + e^- + e^-$

exchange of
squarks,
neutralinos
and
gluinos

$(\lambda'_{111})^2$ mechanism

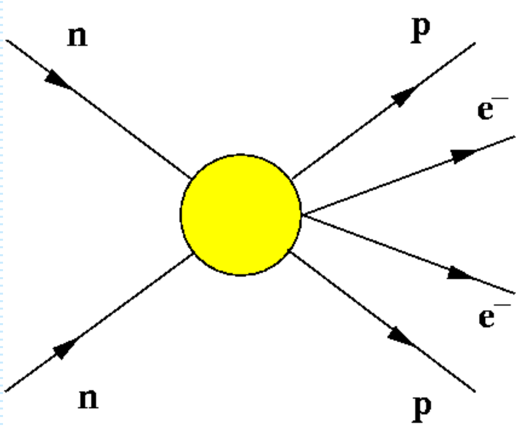
quark-level diagrams



1968 Pontecorvo proposed $\pi^- \rightarrow \pi^+ + 2e^-$, superweak int.
We identified with R-parity breaking SUSYmechanism

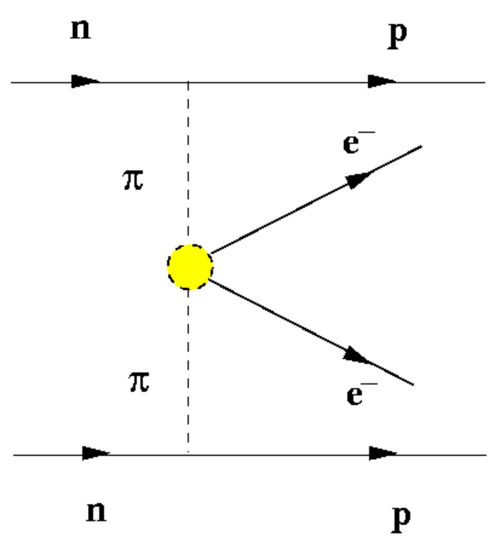
$$\mathcal{L}_{qe} = \frac{G_F^2}{2m_p} \bar{e}(1+\gamma_5)e^c \left[\eta^{PS} J_{PS} J_{PS} - \frac{1}{4} \eta^T J_T^{\mu\nu} J_{T\mu\nu} \right].$$

Two–nucleon mechanism



Can be neglected

Pion–exchange mechanism



The dominant contribution

Hadron-level diagrams

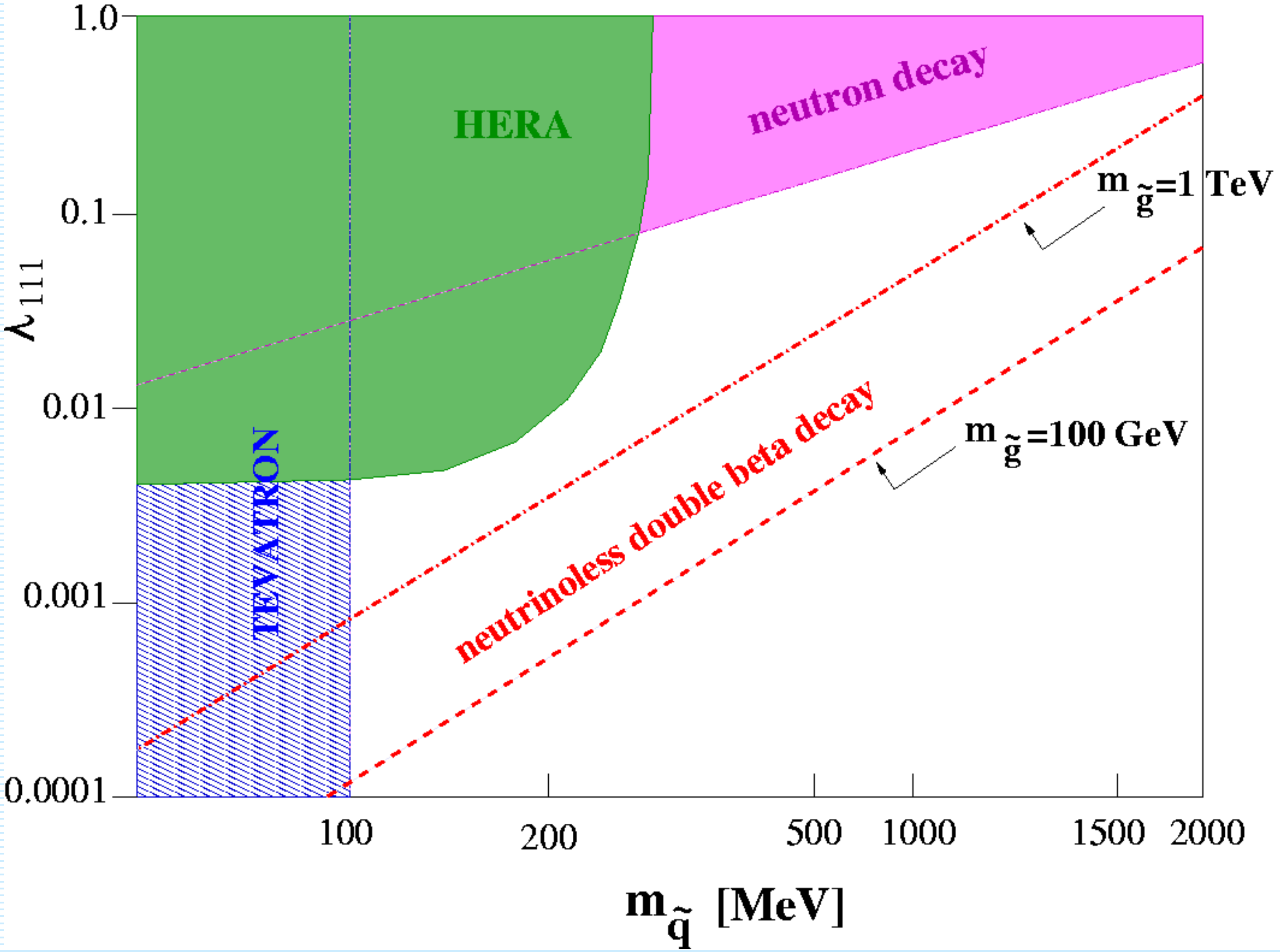
Faessler, Kovalenko, Šimkovic
PRL 78 (1998) 183
Wodecki, Kaminski, Šimkovic,
PRD 60 (1999) 11507

$$\langle 0|\bar{u}\gamma_5 d|\pi^-\rangle = i\sqrt{2} f_\pi \frac{m_\pi^2}{m_u + m_d}, \quad (m_\pi/(m_u+m_d) \approx 13)$$

$$\langle 0|\bar{u}\gamma_\alpha\gamma_5 d|\pi^-\rangle = i\sqrt{2} f_\pi k_\alpha$$

Limit on R-parity breaking parameter λ´$_{111}$

Faessler, F.Š , Kovalenko, PRD 58 (1998) 115004

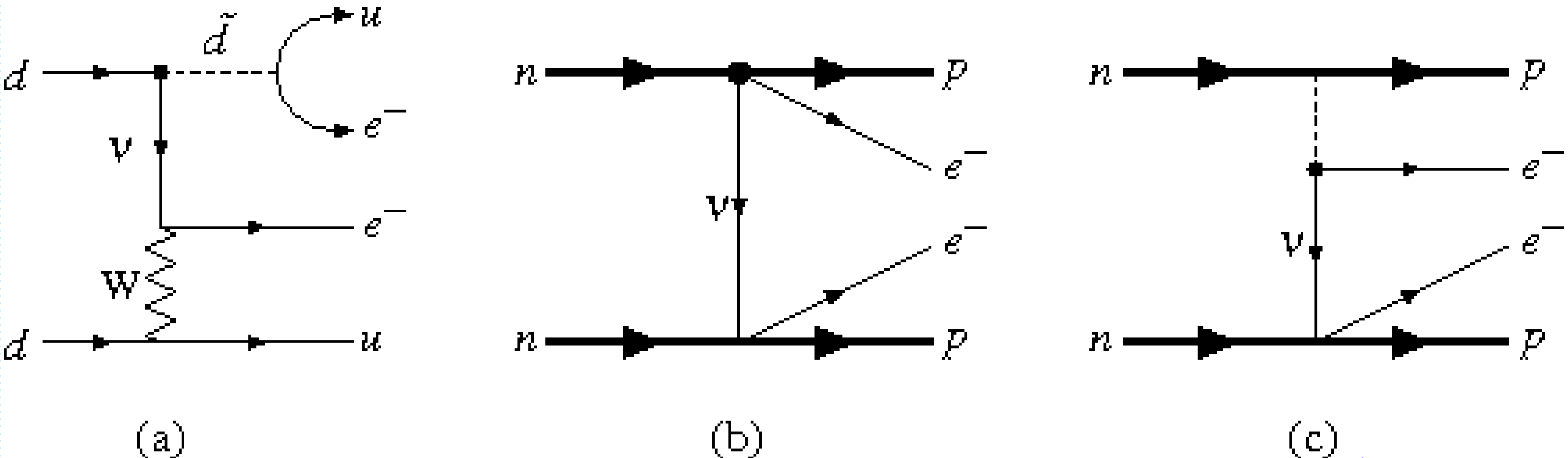


$$\acute{\lambda}_{111} = 1.3\ 10^{-4} \left(\frac{m_{\tilde{q}}}{100\ GeV}\right)^2 \left(\frac{m_{\tilde{g}}}{100\ GeV}\right)^{1/2}$$

Squark mixing SUSY mechanism

Mixing between scalar superpartners of the left- and right-handed fermions

$$M^2_{\tilde{d}^k} = \begin{pmatrix} m^2_{\tilde{d}^k_L} + m^2_{d^k} - \frac{1}{6}(2m^2_W + m^2_Z)\cos 2\beta & -m_{d^k}((\mathbf{A}_D)_{kk} + \mu \tan\beta) \\ -m_{d^k}((\mathbf{A}_D)_{kk} + \mu \tan\beta) & m^2_{\tilde{d}^k_R} + m^2_{d^k} + \frac{1}{3}(m^2_W - m^2_Z)\cos 2\beta \end{pmatrix}$$



Hirsch,
Klapdor-Kleingrothaus,
Kovalenko
PLB 372 (1996) 181

A. Faessler,
Th. Gutsche,
S. Kovalenko,
F.Š.,
PRD 77 (2008) 113012

Effective SUSY ν-e Lagrangian

Neutrino vertex

$$\mathcal{L}^{LH} = \frac{G_F}{\sqrt{2}} \sum_i U_{ei} \, (\bar{e}\gamma_\alpha(1-\gamma_5)\nu) \, (\bar{u}\gamma^\alpha(1-\gamma_5)d) + h.c. \quad (V-A)$$

R-parity violating SUSY vertex

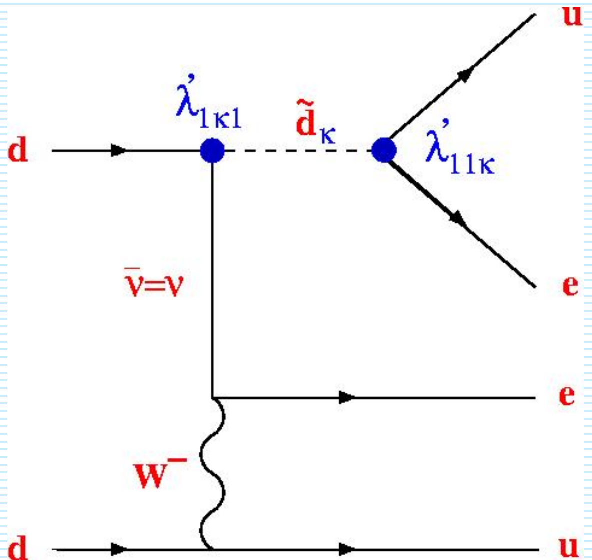
Hirsch, Klapdor-Kleingrothaus, Kovalenko
PLB 372 (1996) 181

$$\mathcal{L}^{eff}_{SUSY} = \frac{G_F}{\sqrt{2}} \left(\frac{1}{4}\eta_{(q)LR} \sum_i U^*_{ei} \, (\bar{\nu}(1+\gamma_5)e) \, (\bar{u}(1+\gamma_5)d) \quad (S,P) \right.$$
$$\left. + \frac{1}{8}\eta_{(q)LR} \sum_i U^*_{ei} \, (\bar{\nu}\sigma_{\alpha\beta}(1+\gamma_5)e) \, (\bar{u}\sigma^{\alpha\beta}(1+\gamma_5)d) + h.c. \right) \quad (Tensor)$$

Paes, Hirsch, Klapdor-Kleingrothaus,
PLB 459 (1999) 450

LN-violating parameter

$$\eta_{(q)LR} = \sum_k \frac{\lambda'_{11k}\lambda'_{1k1}}{8\sqrt{2}G_F} \sin 2\theta^d_{(k)} \left(\frac{1}{m^2_{\tilde{d}_1(k)}} - \frac{1}{m^2_{\tilde{d}_2(k)}} \right)$$



Limits on R-breaking parameters

TABLE II: Nuclear matrix elements (NMEs) of the squark-neutrino $R\!\!\!/_p$ SUSY mechanism of $0\nu\beta\beta$-decay. The NMEs of the 2N-mode are calculated for the two cases of the nucleon form factors: Quark Bag Model (QBM) and Non-Relativistic Quark Model (NRQM). The quantities M_{2N}, M_π are the 2N and pion mode nuclear matrix elements averaged over small, medium and large model spaces (see the text) with their variance σ given in parentheses.

	QBM				NRQM				
nucl.	$M^{\tilde{q}}_{VT}$	$M^{\tilde{q}}_{MT}$	$M^{\tilde{q}}_{AP}$	$M^{\tilde{q}}_{2N}$	$M^{\tilde{q}}_{VT}$	$M^{\tilde{q}}_{MT}$	$M^{\tilde{q}}_{AP}$	$M^{\tilde{q}}_{2N}$	$M^{\tilde{q}}_{\pi}$
^{76}Ge	-46.2	61.5	14.8	27.8 (4.6)	-25.5	64.6	15.6	52.4 (2.7)	302. (37)
^{100}Mo	-54.9	61.0	16.5	22.9 (1.8)	-30.3	64.1	17.4	51.0 (0.3)	297. (40)
^{130}Te	-44.9	51.6	14.2	19.3 (3.4)	-24.8	54.2	14.9	42.4 (2.6)	257. (16)

Pion mode

TABLE III: Upper bounds on the $R\!\!\!/_p$ SUSY parameter $\eta^{11}_{(q)LR}$ as well as on the related products of the trilinear $R\!\!\!/_p$-couplings $\lambda'_{11k}\lambda'_{1k1}$ (k=1,2,3) for $\Lambda_{SUSY} = 100$ GeV (see scaling law in Eq. (37)) deduced from the current lower bounds on the half-life of $0\nu\beta\beta$-decay for ^{76}Ge, ^{100}Mo and ^{130}Te.

nucl.	$T^{0\nu-exp}_{1/2}$ (years)	[Ref.]	$\eta^{11}_{(q)LR}$	$\lambda'_{111}\lambda'_{111}$	$\lambda'_{112}\lambda'_{121}$	$\lambda'_{113}\lambda'_{131}$
^{76}Ge	$\geq 1.9\ 10^{25}$	[2]	$8.5\ 10^{-9}$	$1.5\ 10^{-5}$	$8.0\ 10^{-7}$	$3.3\ 10^{-8}$
^{100}Mo	$\geq 5.8\ 10^{23}$	[4]	$1.8\ 10^{-8}$	$3.2\ 10^{-5}$	$1.7\ 10^{-6}$	$7.0\ 10^{-8}$
^{130}Te	$\geq 3.0\ 10^{24}$	[5]	$9.5\ 10^{-9}$	$1.7\ 10^{-5}$	$9.0\ 10^{-7}$	$3.7\ 10^{-8}$

A. Faessler,
Th. Gutsche,
S. Kovalenko,
F.Š.,
0710.3199 [hep-th]

Resonant Neutrinoless Double-Electron Capture

$$(A,Z) \rightarrow (A,Z-2)^{**}$$

Winter, Phys. Rev. 100 (1955) 142; Bernabeu, de Rujula, Jarlskog PRC 15 (1993) 223

Additional
modes of the 0νECEC-decay:

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

Resonance enhancement of neutrinoless double electron capture

M.I. Krivoruchenko, F. Šimkovic, D. Frekers, and A. Faessler,
Nucl. Phys. A 859, 140-171 (2011)

Oscillations of atoms

New $0\nu\varepsilon\varepsilon$ transitions with parity violation to ground and excited states of final atom/nucleus were found. Selection rules for the $0\nu\varepsilon\varepsilon$ transitions were established. The explicit form of corresponding NMEs was derived.

More accurate atomic mass measurements in the context of the $0\nu\varepsilon\varepsilon$ were initialized, which have been partially accomplished using the modern high-precision ion traps. In addition, new $0\nu\varepsilon\varepsilon$ experiments were initialized.

Available data of atomic masses, as well as nuclear and atomic excitations Were used to select the most likely candidates for resonant $0\nu\varepsilon\varepsilon$ transitions. Assuming an effective Majorana neutrino mass of 1 eV, some half-lives has been predicted to be as low as 10^{22} years in the unitary limit.

Nuclear matrix elements for $0\nu\varepsilon\varepsilon$

Ground state to ground state nuclear transitions

Initial (final)	β_{Q_p}	$\beta_{B(E2)}$	$\langle BCS_i \vert BCS_f \rangle$
^{152}Gd (^{152}Sm)	(+0.29)	0.212 (0.306)	0.44
^{164}Er (^{164}Dy)	0.36 (+0.32)	0.333 (0.348)	0.73
^{180}W (^{180}Hf)	0.27 (+0.27)	0.252 (0.273)	0.75

Deformed QRPA

Nucleus	$M^{2\nu}_{GT}$ $[MeV^{-1}]$	$M^{0\nu}$		
		sph. QRPA	def. QRPA ($\beta_2 = 0$)	def. QRPA
^{152}Gd	0.10	7.59	7.50	3.23
	0.00	7.21		2.67
^{164}Er	0.10	6.12	7.20	2.64
	0.00	5.94		2.27
^{180}W	0.10	5.79	6.22	2.05
	0.00	5.56		1.79

Fang et al., PRC 85, 035503 (2012)

EDF

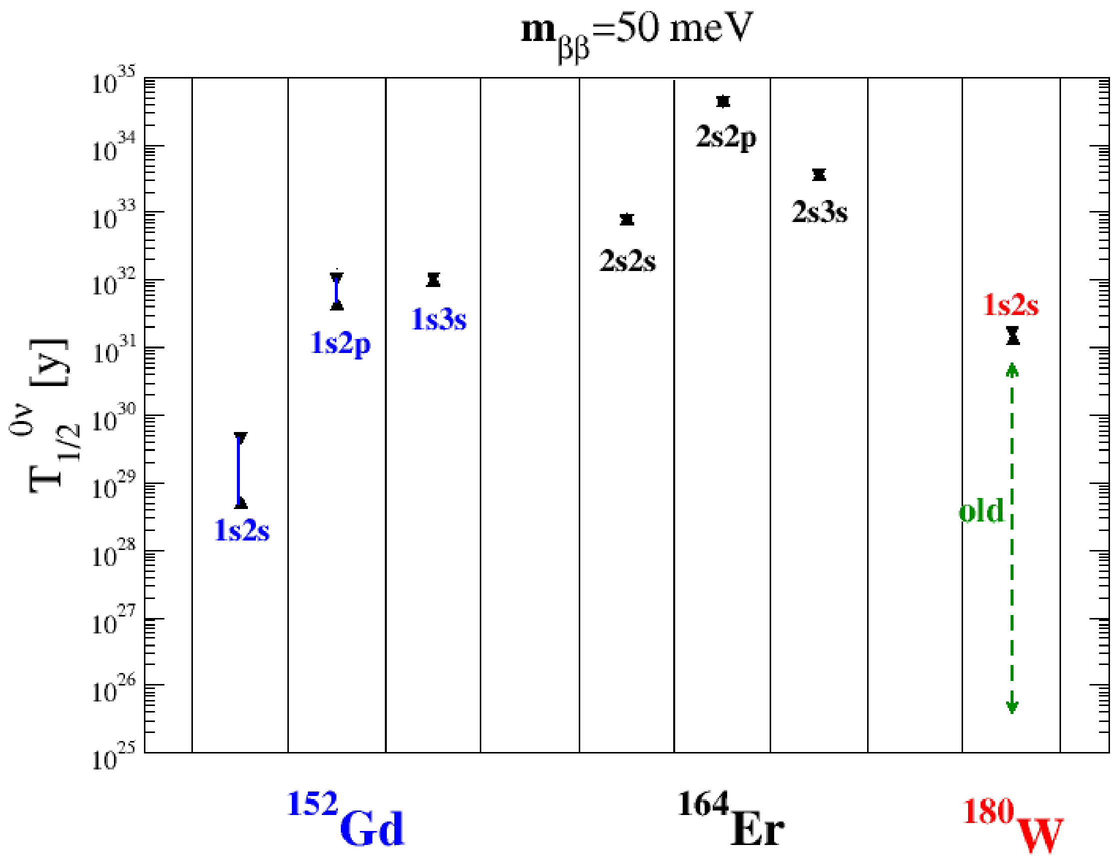
	$M^{0\nu}$
^{152}Gd	0.89, 1.07
^{164}Er	0.64, 0.50
^{180}W	0.58, 0.38

Rodrigez, Martinez-Pinedo, PRC 85, 044310 (2012)

Suppression of the NME depends not only on the relative deformation but also their absolute values

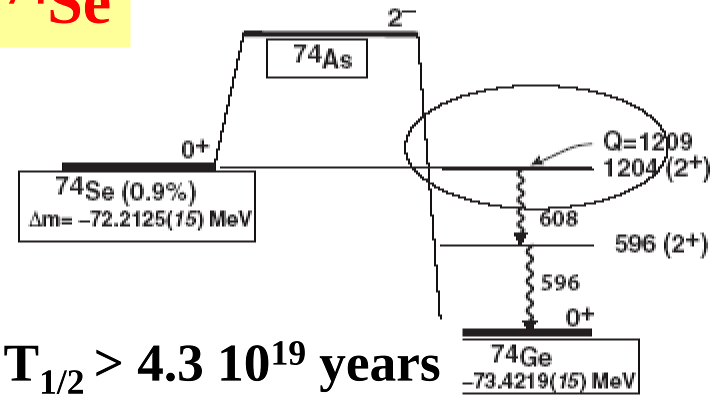
***0νεε* half-lives**

$m_{\beta\beta}$=50 meV

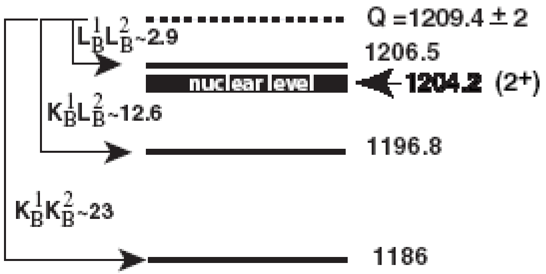


Nucleus	$(n2jl)_a$	$(n2jl)_b$	E_a	E_b	E_C	Γ_{ab} (keV)	Δ (keV)	$T^{min}_{1/2}$ (y)	$T^{max}_{1/2}$ (y)
^{152}Gd	110	210	46.83	7.74	0.34	2.3×10^{-2}	-0.83 ± 0.18	4.7×10^{28}	4.8×10^{29}
	110	211	46.83	7.31	0.32	2.3×10^{-2}	-1.27 ± 0.18	4.2×10^{31}	1.1×10^{32}
	110	310	46.83	1.72	0.11	3.2×10^{-2}	-7.07 ± 0.18	9.4×10^{31}	1.1×10^{32}
^{164}Er	210	210	9.05	9.05	0.22	8.6×10^{-3}	-6.82 ± 0.12	7.5×10^{32}	8.4×10^{32}
	210	211	9.05	8.58	0.23	8.3×10^{-3}	-7.28 ± 0.12	4.2×10^{34}	4.6×10^{34}
	210	310	9.05	2.05	0.11	1.8×10^{-2}	-13.92 ± 0.12	3.5×10^{33}	3.9×10^{33}
^{180}W	110	110	63.35	63.35	1.26	7.2×10^{-2}	-11.24 ± 0.27	1.3×10^{31}	1.8×10^{31}

^{74}Se

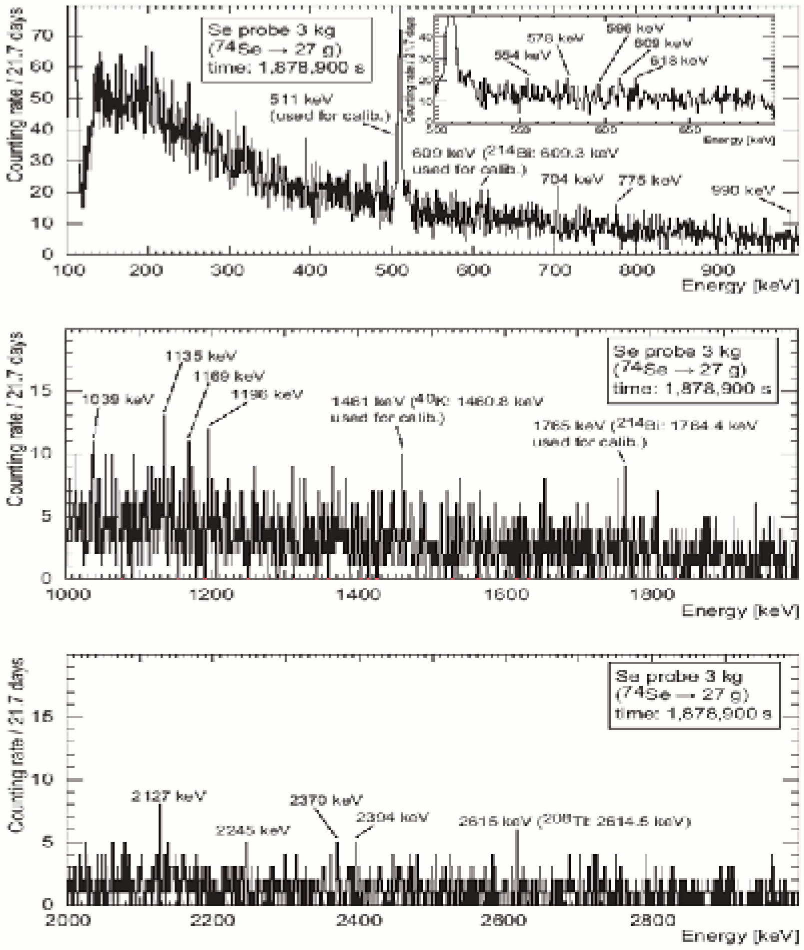


$T_{1/2} > 4.3\ 10^{19}$ years

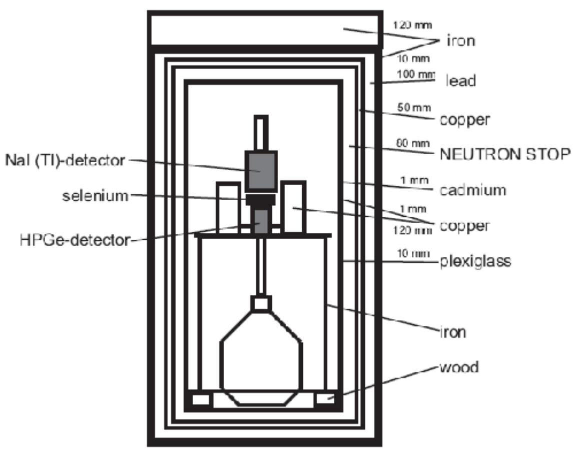


Experiment in Bratislava!

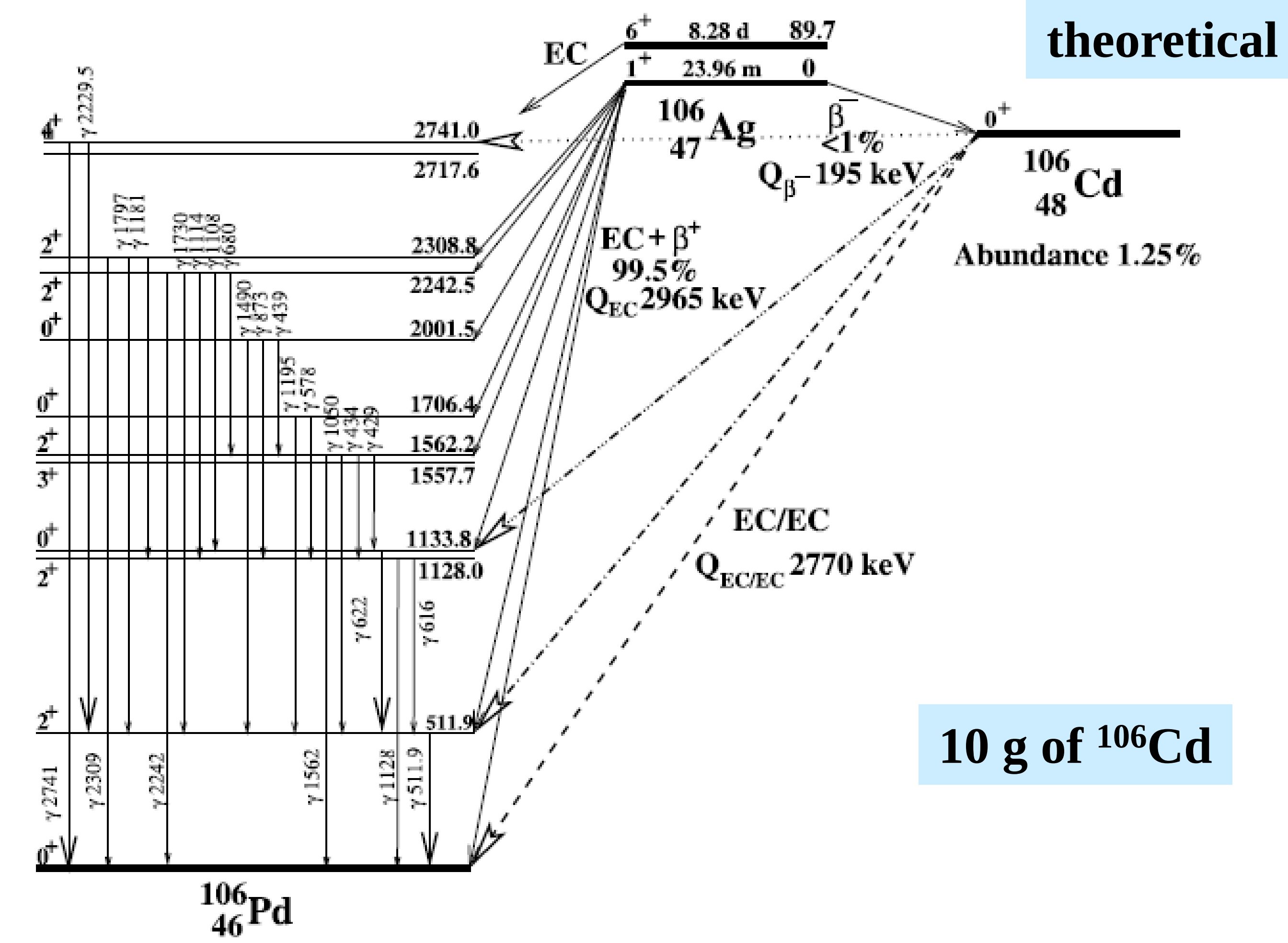
Muenster and Bratislava groups



Frekers, Puppe, Thies, Povinec, Šimkovic, Staníček, Sýkora, accepted in NPA



TGV experiment in Modane underground laboratory



theoretical support

10 g of ^{106}Cd

$T_{1/2}^{2\nu\varepsilon\varepsilon}$ (^{106}Cd) > 3.6 10^{20} y

$T_{1/2}^{0\nu\varepsilon\varepsilon}$ (^{106}Cd) > 1.1 10^{20} y

TGV Coll, Rukhadze et al., NPA 852, 197 (2011)

A comparison

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

Perturbation theory

$$\frac{1}{T^{0\nu}_{1/2}} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 G^{01}(E_0,Z)\left|M^{0\nu}\right|^2$$

- $2\nu\beta\beta$-decay background can be a problem
- Uncertainty in NMEs factor ~2, 3
- $0^+ \rightarrow 0^+, 2^+$ transitions
- Large Q-value
- ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe …
- Many exp. in construction, potential for observation in the case of inverted hierarchy (2020)

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

Breit-Wigner form

$$\Gamma^{0\nu ECEC}(J^\pi) = \frac{|V_{\alpha\beta}(J^\pi)|^2}{(M_i - M_f)^2 + \Gamma^2_{\alpha\beta}/4}\,\Gamma_{\alpha\beta}$$

- $2\nu\varepsilon\varepsilon$-decay strongly suppressed
- NMEs need to be calculated
- $0^+ \rightarrow 0^+, 0^-, 1^+, 1^-$ transitions
- Small Q-value
- Q-value needs to be measured at least with 100 eV accuracy
- ^{152}Gd, looking for additional
- small experiments yet

Two-neutrino Double-Beta Decay
and
statistical properties of ν

NEMO 3

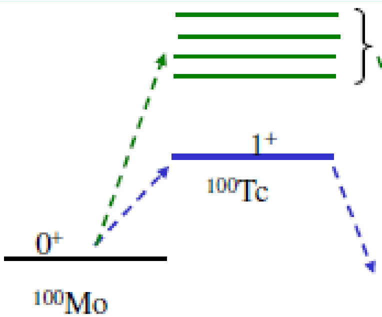
Fréjus Underground Laboratory: 4800 m.w.e.

^{100}Mo (6.914 kg) $T_{1/2}^{0\nu\beta\beta} > 4.6\ 10^{23}$ years

$Q_{\beta\beta}$ = 3034 keV $|m_{\beta\beta}| < 2.7$ eV

^{82}Se (0.932 kg) $T_{1/2}^{0\nu\beta\beta} > 1.0\ 10^{23}$ y

$Q_{\beta\beta}$ = 2995 keV $|m_{\beta\beta}| < 4.1$ eV

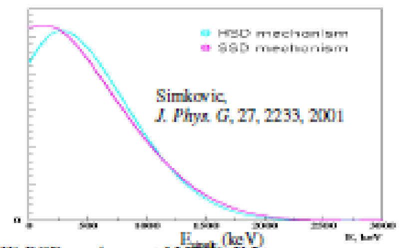


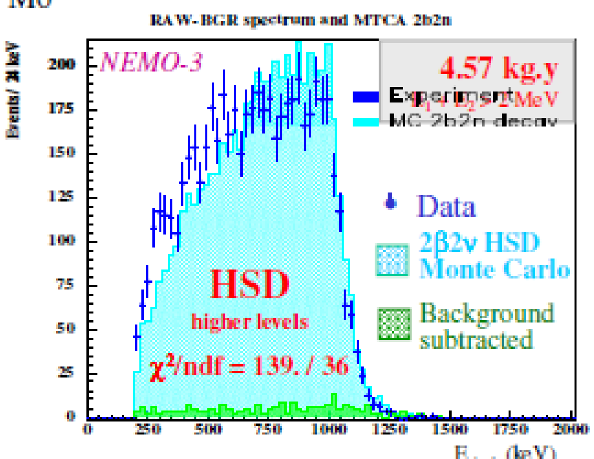
HSD, higher levels contribute to the decay

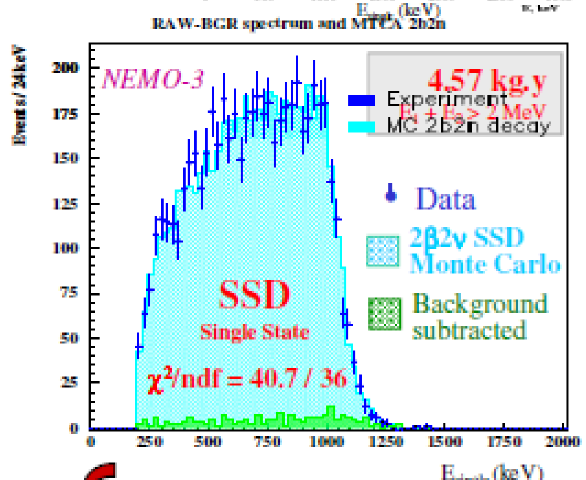
SSD, 1+ level dominates in the decay

(Abad et al., 1984, *Ann. Fis.* A 80, 9)

Single electron spectrum different between SSD and HSD







HSD: $T_{1/2} = 8.61 \pm 0.02\ (stat) \pm 0.60\ (syst) \times 10^{18}$ y

SSD: $T_{1/2} = 7.72 \pm 0.02\ (stat) \pm 0.54\ (syst) \times 10^{18}$ y

^{100}Mo $2\beta 2\nu$ single energy distribution in favour of Single State Dominant (SSD) decay

NEMO3 experiment

$2\nu\beta\beta$-decay
~10^6 events

Mixed statistics for neutrinos

Definnition of mixed state

$$\begin{aligned} |\nu> &= \hat{a}^\dagger|0> \\ &\equiv \cos\delta \;\; \hat{f}^\dagger|0> \;+\; \sin\delta \;\; \hat{b}^\dagger|0> \\ &= \cos\delta \;\; |f> \;+\; \sin\delta \;\; |b> \end{aligned}$$

with commutation Relations

$$\begin{aligned} \hat{f}\hat{b} &= e^{i\phi}\hat{b}\hat{f} \qquad \hat{f}^\dagger\hat{b}^\dagger = e^{i\phi}\hat{b}^\dagger\hat{f}^\dagger \\ \hat{f}\hat{b}^\dagger &= e^{-i\phi}\hat{b}^\dagger\hat{f} \qquad \hat{f}^\dagger\hat{b} = e^{-i\phi}\hat{b}\hat{f}^\dagger \end{aligned}$$

Amplitude for 2νββ

$$\begin{aligned} A^{2\nu} &= [\cos\delta^4 + \cos\delta^2\sin\delta^2(1-\cos\phi)]A^f \;+\; [\cos\delta^4 + \cos\delta^2\sin\delta^2(1+\cos\phi)]A^b \\ &= \cos\chi^2 A^f \;+\; \sin\chi^2 A^b \end{aligned}$$

Decay rate

$$\begin{aligned} W^{2\nu} &= \cos\chi^4 \; W^f \;+\; \sin\chi^4 \; W^b \\ &= (1-b^2)\; W^f \;+\; b^2 \; W^b \end{aligned}$$

Partly bosonic neutrino requires knowing NME or log ft values for HSD or SSD

(calculations coming up soon)

Looking for a signature of bosonic ν

2νββ–decay half-lives **($0^+ \to 0^+_{g.s.}$, $0^+ \to 0^+_1$, $0^+ \to 2^+_1$)**

- **HSD – NME needed**
- **SSD – log ft_{EC}, log ft_β needed**

$$\frac{T^{2\nu-SSD}_{1/2}(2^+_f)}{T^{2\nu-SSD}_{1/2}(0^+_f)} \begin{array}{ll} = 2.41 \times 10^4 & \text{fermionic } \nu \\ = 403 & \text{bosonic } \nu \end{array}$$

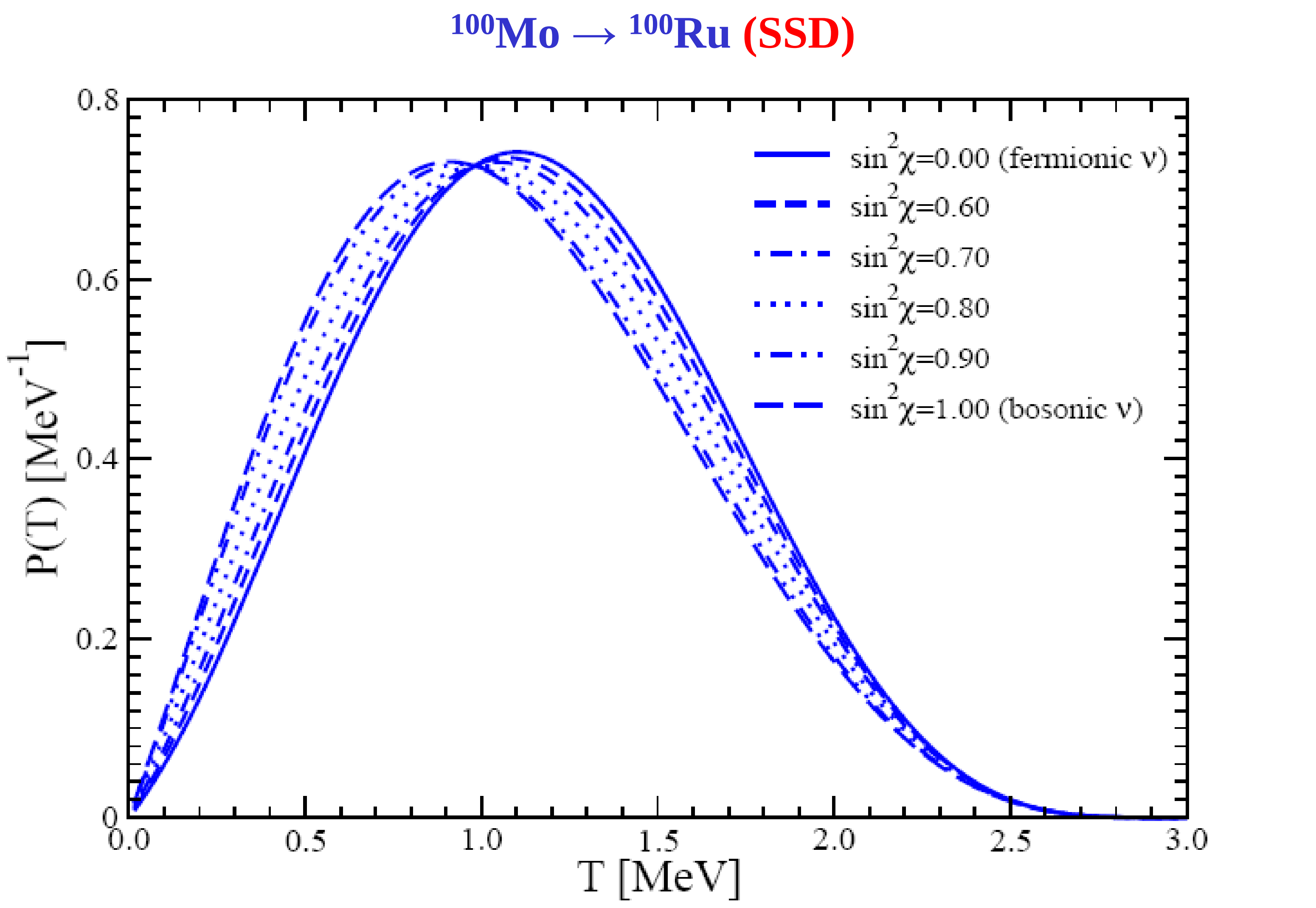
$$\begin{array}{rcl} T^{2\nu}_{1/2}(2^+) & = & 1.73 \times 10^{23} years \\ & = & 2.74 \times 10^{21} years \\ T^{2\nu-exp}_{1/2}(2^+) & > & 1.6 \times 10^{21} years \end{array}$$

Normalized differential characteristics

- **The single electron energy distribution**
- **The distribution of the total energy of two electrons**
- **Angular correlations of two electrons**

(free of NME and log ft)

Mixed ν excluded for $\sin^2\chi < 0.6$ (NEMO3 data)



Barabash, Dolgov, Dvornický, F. Š., Smirnov, NPB 783, 90 (2007)

Measuring mass of neutrinos with β-decays of ^{3}H, ^{187}Re, ^{115}In and electron capture of ^{163}Ho

Relativistic approach to ^3H decay
nuclear recoil (3.4 eV) taken into account

Standard approach

- **non-relativistic nuclear w.f.**
- **nuclear recoil neglected**
- **phase space analysis**

$$E_e^{max} = M_i - M_f - m_\nu$$

$$\frac{d\Gamma}{dT} = \frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E) pE (Q-T) \sqrt{(Q-T)^2 - m_{\nu_e}^2}$$

Relativistic EPT approach (Primakoff)

- **Analogy with n-decay**
  (^{3}H,^{3}He) ↔ (n,p)
- **nuclear recoil of 3.4 eV by E_e^{max}**
- **relevant only phase space**

$$E_e^{max} = \frac{1}{2M_f}\left[M_i^2 + m_e^2 - \left(M_f^2 - m_\nu^2\right)\right]$$

$$\begin{aligned}
\frac{d\Gamma}{dE_e} &= \frac{1}{(\pi)^3}(G_F\cos\theta_c)^2 F(Z,E_e)p_e \\
&\times \frac{M_i^2}{(m_{12})^2}\sqrt{y\left(y+2m_\nu\frac{M_f}{M_i}\right)} \\
&\times \Bigg[(g_V+g_A)^2 y\left(y+m_\nu\frac{M_f}{M_i}\right)\frac{M_i^2(E_e^2-m_e^2)}{3(m_{12})^4} \\
&\quad (g_V+g_A)^2(y+m_\nu\frac{M_f+m_\nu}{M_i})\frac{(M_iE_e-m_e^2)}{m_{12}^2} \\
&\quad \times (y+M_f\frac{M_f+m_\nu}{M_i})\frac{(M_i^2-M_iE_e)}{m_{12}^2} \\
&\quad -(g_V^2-g_A^2)M_f\left(y+m_\nu\frac{(M_f+M_\nu)}{M_i}\right) \\
&\quad \times \frac{(M_iE_e-m_e^2)}{(m_{12})^2} \\
&\quad +(g_V-g_A)^2E_e\left(y+m_\nu\frac{M_f}{M_i}\right)\Bigg]
\end{aligned}$$

$$y = E_e^{max} - E_e$$

$$(m_{12})^2 = M_i^2 - 2M_iE_e + m_e^2$$

Numerics:

Practically the same dependence of Kurie function on m_ν for $E_e \approx E_e^{max}$

lor Simkovic

F.Š., R. Dvornický, A. Faessler, PRC 77 (2008) 055502

Spectrum of emitted electrons in rhenium β-decay

Dvornický, F. Š., Muto, Faessler, PPNP (2009)

$$\frac{d\Gamma}{dE} = \frac{G_F^2 V_{ud}^2}{2\pi^3} |M|^2 \, pE(E_0 - E)\sqrt{(E_0-E)^2 - m_\nu^2}\, \frac{1}{3} R^2 \left(p^2 F_1(Z,E) + k^2 F_0(Z,E) \right)$$

$$k = \sqrt{(E_0 - E)^2 - m_\nu^2}$$

Electron $p_{3/2}$ decay channel clearly dominates

$$\Gamma_S / \Gamma_P = 1.011 \times 10^{-4}$$

In agreement with

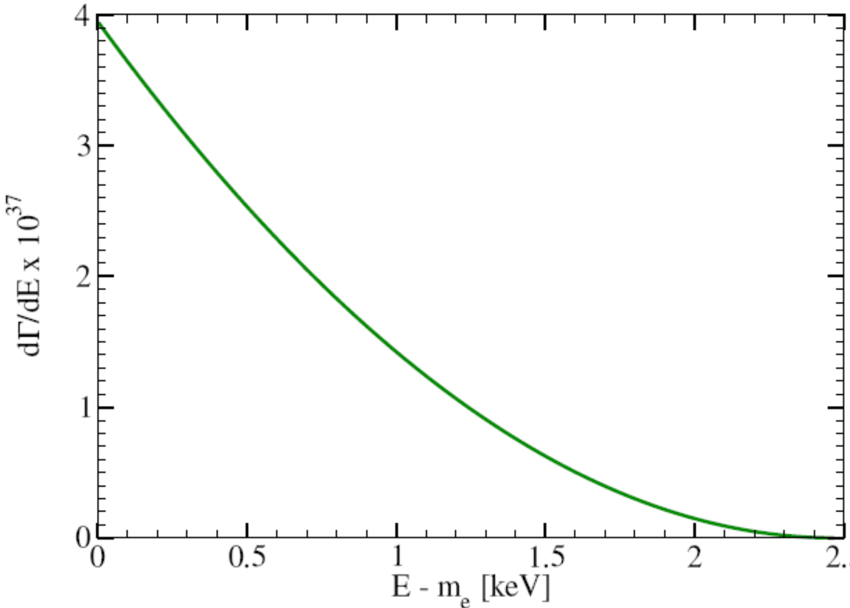
Arnaboldi et al.: PRL 96, 042503 (2006)

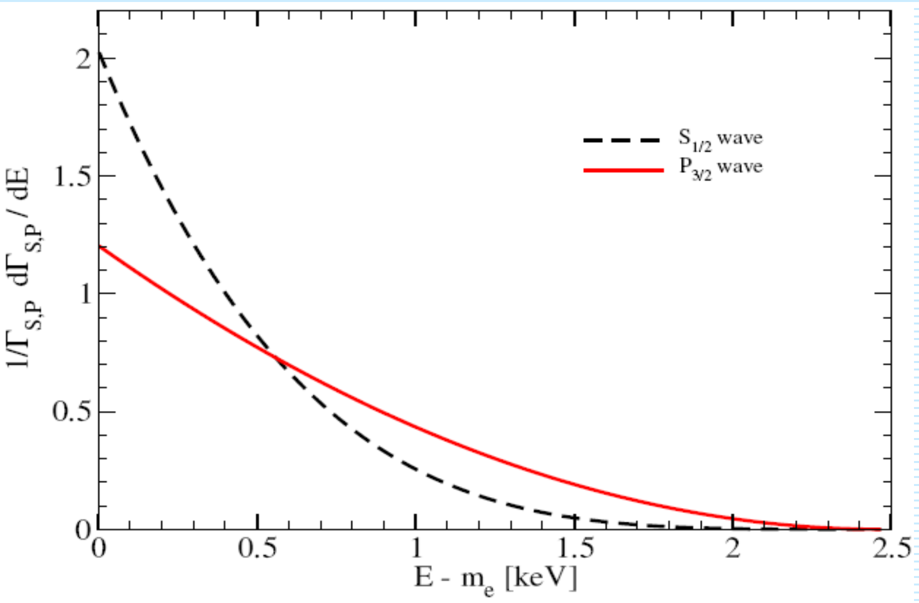
Electron in the $p_{3/2}$ state

$$p^{max} \cong 50 keV$$

Electron in the $s_{1/2}$ state

$$k^{max} = 2.47 keV$$





Kurie plots for rhenium (MARE) and tritium (KATRIN) β-decay

Rhenium

$$B_{\mathrm{Re}} = \frac{G_F V_{ud}}{\sqrt{2\pi^3}} \frac{g_A}{\sqrt{2J_i+1}} \left| \langle {}^{187}Os \| \sqrt{\frac{4\pi}{3}} \sum_n \tau_n^+ \frac{r_n}{R} \{\sigma_1 \otimes Y_1\}_2 \| {}^{187}Re \rangle \right| \times \sqrt{\frac{1}{3} R^2 p^2 \frac{F_1(Z,E)}{F_0(Z,E)}}$$

$$K(E_e)/B_{\mathrm{Re}} \cong (E_0 - E_e) \sqrt[4]{1 - \frac{m_\nu^2}{(E_0 - E_e)^2}}$$

Properly normalized Kurie functions are practically the same by the endpoint !

$$\mathbf{K(E)/B_{Re} \cong K(y)/B_T}$$

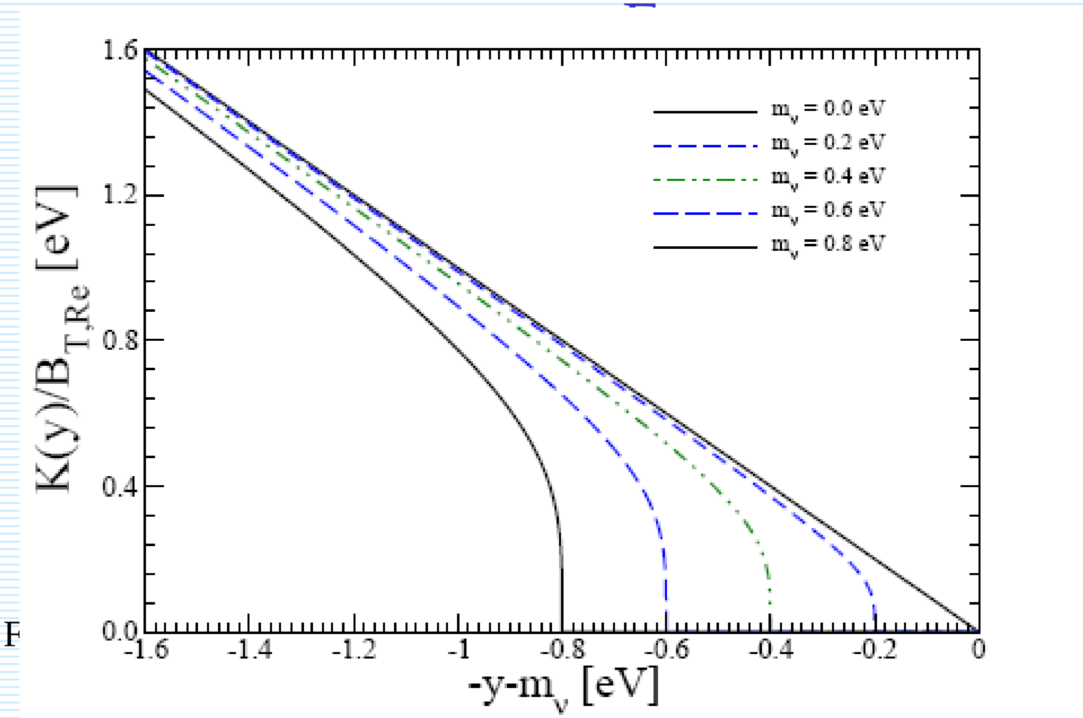
Dvornický, Muto, F.Š, Faessler, PRC 83, 045502 (2011)

Tritium

$$B_T = \frac{G_F V_{ud}}{\sqrt{2\pi^3}} \sqrt{g_V^2 + 3g_A^2}$$

$$K(y)/B_T = \left(\sqrt{y(y+2m_\nu)}(y+m_\nu)\right)^{1/2}$$

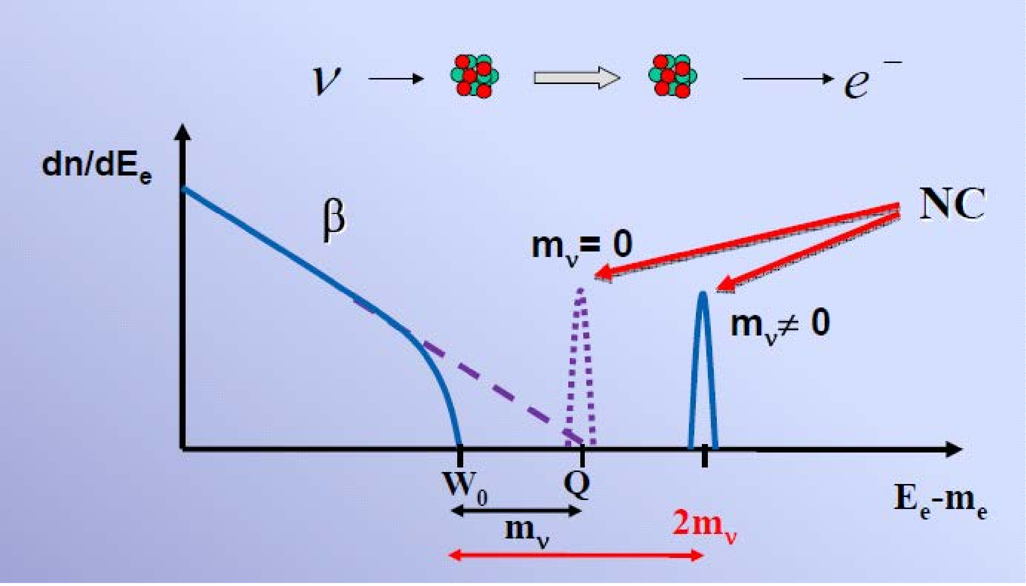
$y = E_e max-$



Detection of relic neutrinos by KATRIN experiment

$$\nu + {}^3H((1/2)^+) \rightarrow {}^3He((1/2)^+) + e^-$$

$$\Gamma^\nu({}^3H) = \frac{1}{\pi} G_\beta^2 \, F_0(2,p)\, p\, p_0 \, \left(|M_F|^2 + g_A^2 |M_{GT}|^2\right) \frac{\eta_\nu}{<\eta_\nu>} <\eta_\nu>$$



Assuming $M_F=1$, $M_{GT}=\sqrt{3}$ and $\eta_\nu=<\eta_\nu>$ the capture rate

$$\Gamma^\nu({}^3H) = 4.2 \;\, 10^{-25} \;\, y^{-1}$$

KATRIN will use ~50 μg of ^3H

Faessler, Hodák, Kovaenko, F.Š, arXiv: 1102.1799[hep-ph] accepted in J. Phys. G

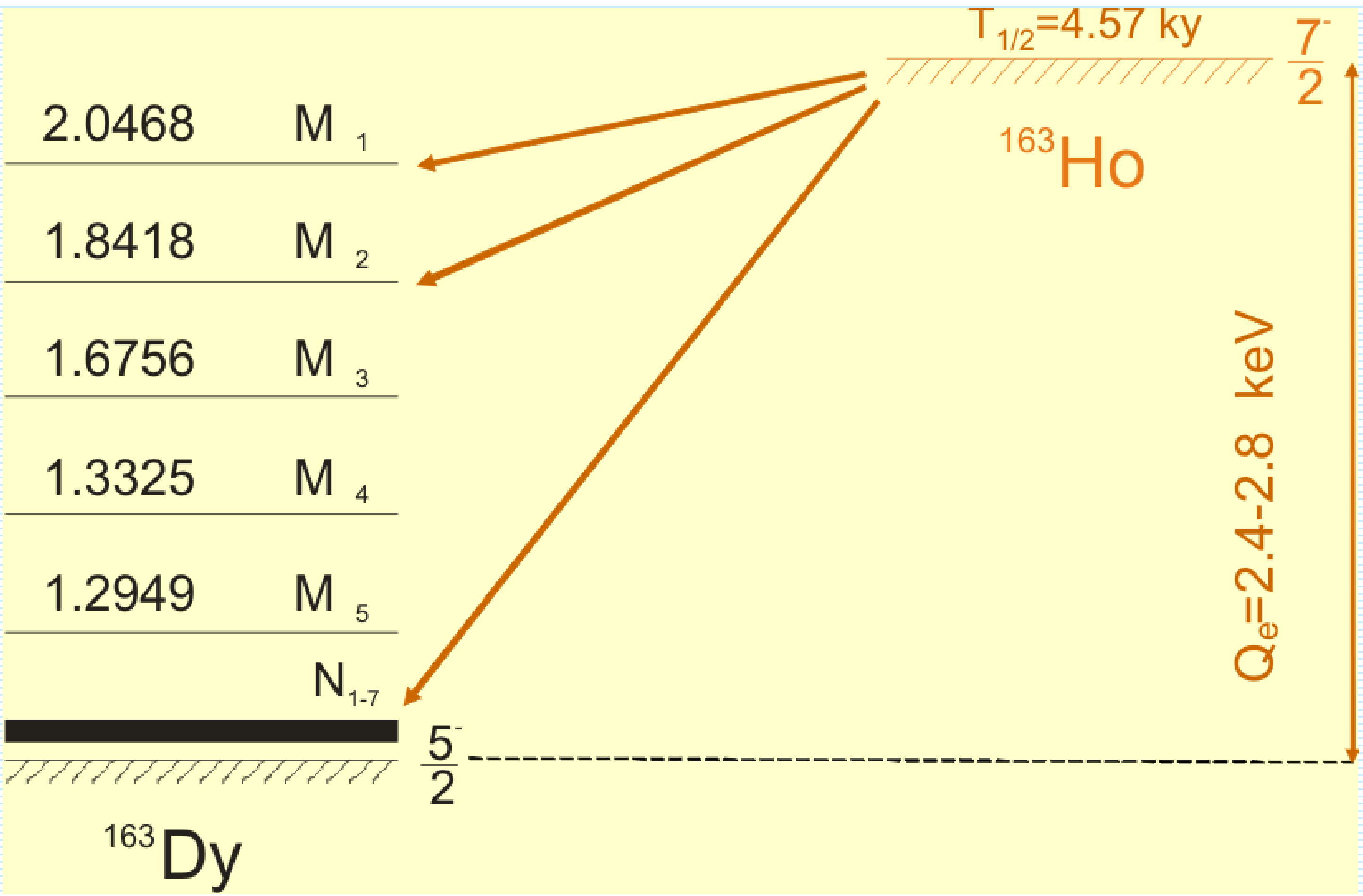
$$N^\nu_{capt}(KATRIN) \approx 4.2 \; 10^{-6} \, \frac{\eta_\nu}{<\eta_\nu>} \, y^{-1}$$

Even considering effect of clustering of ν, $\eta_\nu/<\eta_\nu> \sim 10^3$-$10^4$:
$N^\nu_{capt}(KATRIN) < 1 \; y^{-1}$

Mass of Neutrino: electron-capture in ^{163}Ho

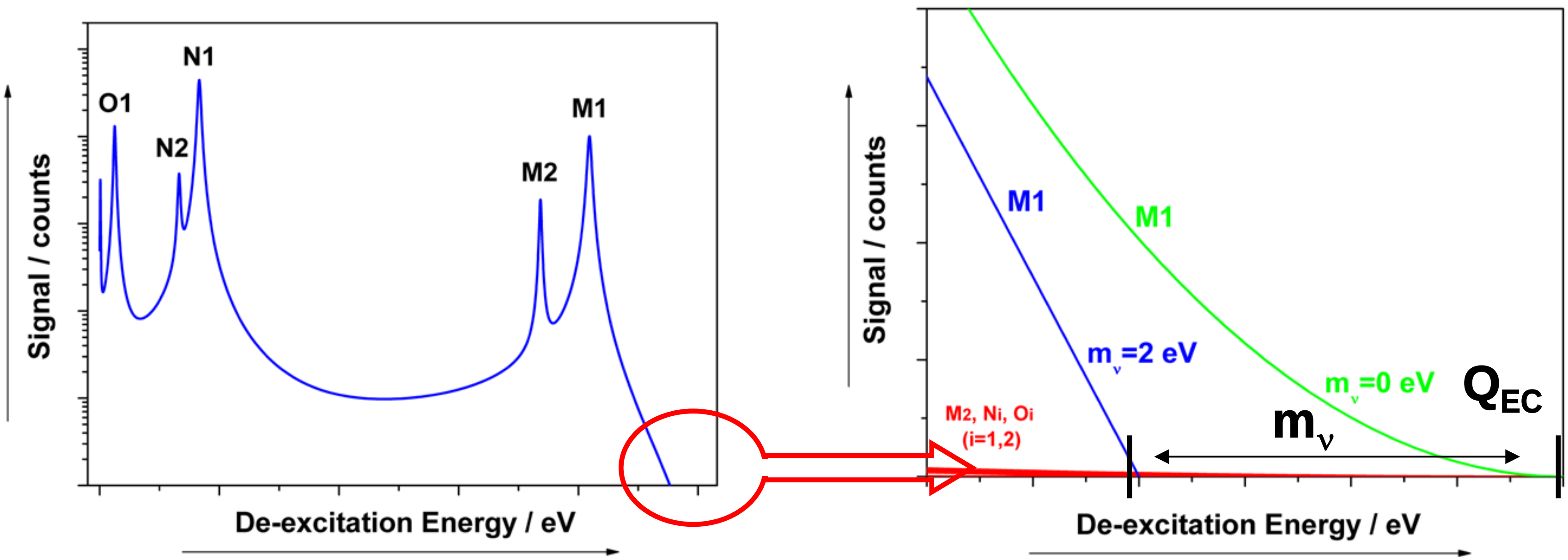
$$^{163}Ho \longrightarrow {}^{163}Dy^{*} + \nu_e\ (E_\nu)$$
$$\hookrightarrow {}^{163}Dy + E_c$$

analysis of calorimetric spectrum → m_ν



Mass of Neutrino: electron-capture in ^{163}Ho

Typical m-calorimetric de-excitation spectrum of EC in ^{163}Ho



Cryogenic m-calorimeters (Group of Prof. Enss, KIP, Uni Heidelberg)
end point with accuracy ~ 1 eV

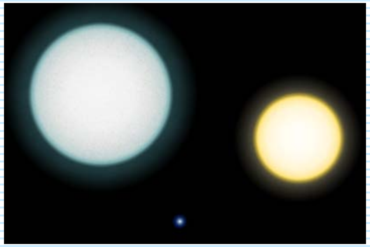
PENTATRAP (Group of Prof.K. Blaum, MPI-K, HD)
Q_{EC}-value with accuracy ~ 1 eV

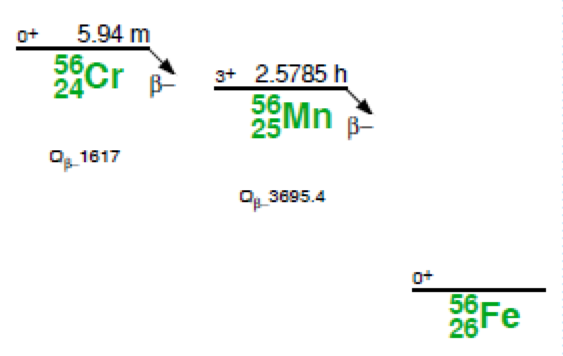
m_ν ~ 1 eV

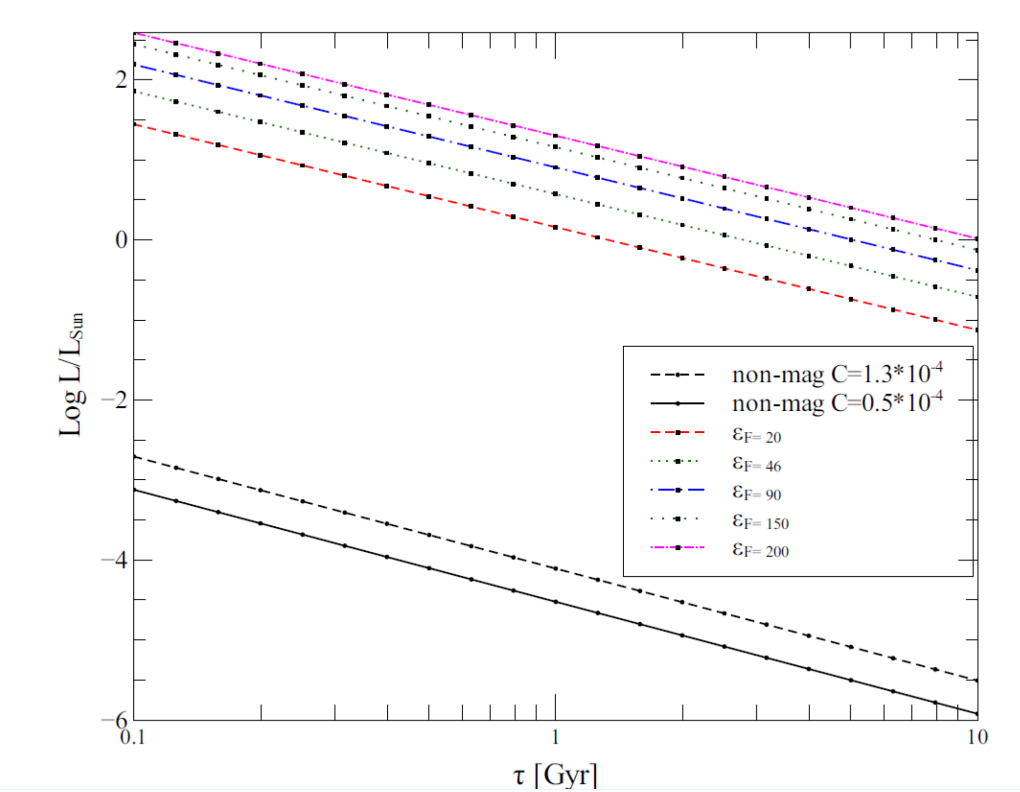
Universe as a laboratory to study LN violation

Belyaev, Ricci, Simkovic, Truhlik, arXiv: 1212.3155, Truhlik, MEDEX13 presentation

Cooling of strongly magnetized iron White dwarfs







$$e^- + {}^{56}Fe \rightarrow {}^{56}Cr + e^+$$

$$e^- + e^- + {}^{56}Fe \rightarrow {}^{56}Cr$$

Mathematics is Egyptian

Dark Matter (Neutrino) physics is Babylonian