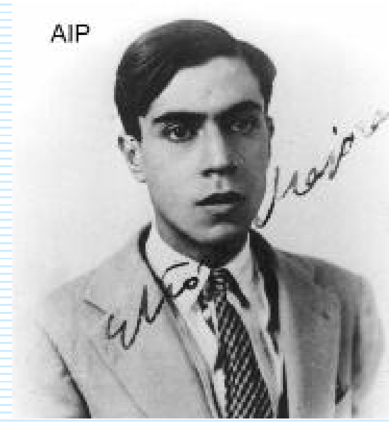
$0\nu\beta\beta$-decay:
To be, or not to be?



Double Beta Decay: History, Present and Future

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Comenius University, Bratislava

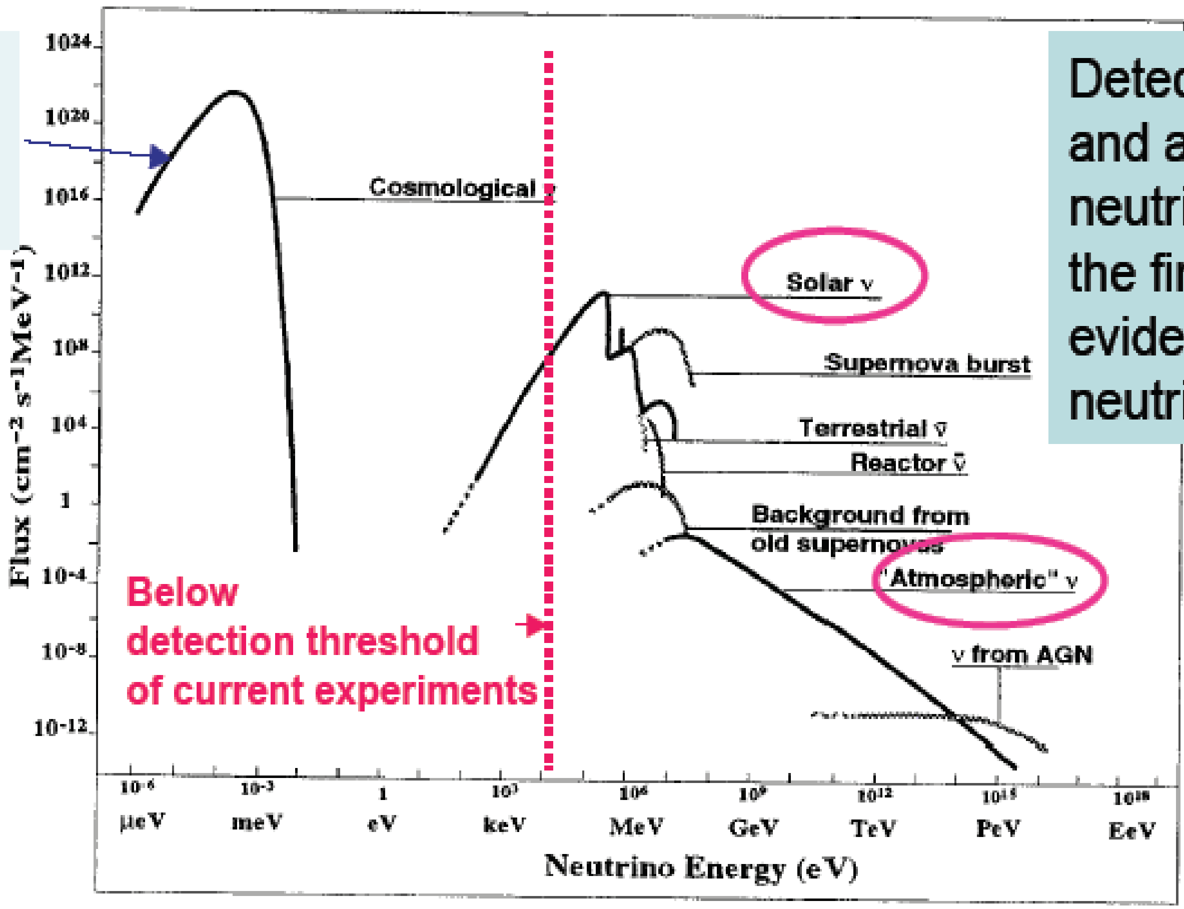
OUTLINE

- **Introduction (History and experimental status)**
- **The $0\nu\beta\beta$–decay in light of ν oscillations**
- **Mechanisms of the $0\nu\beta\beta$–decay (LR-symmetric models, R-parity breaking MSSM)**
- **The DBD NME**
- **Neutrinoless double electron capture (^{36}Ar)**
- **Bosonic neutrino and $2\nu\beta\beta$-decay (^{76}Ge)**
- **Conclusion and outlook**

Neutrinos are everywhere

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

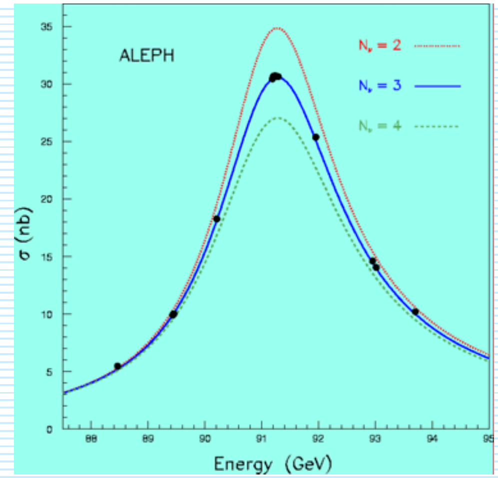
Abundant but challenging detection



Detection of solar and atmospheric neutrino has provided the first compelling evidence of neutrino oscillations

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

Neutrino properties
(60 years after discovery of ν)



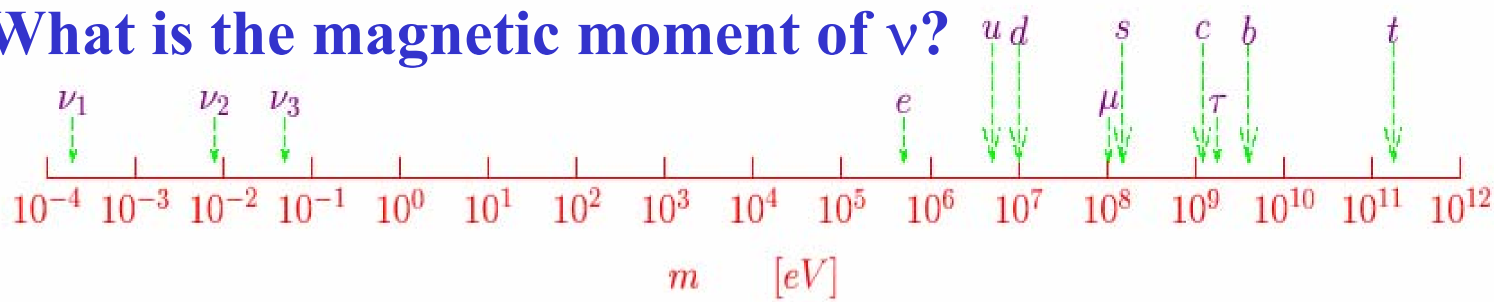
we know

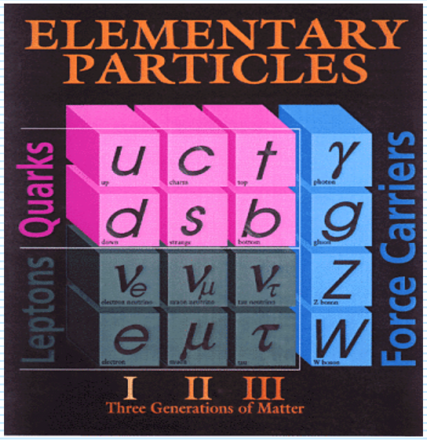
- **3 families of light (V-A) neutrinos:** ν_e, ν_μ, ν_τ
- **neutrinos are massive: we know mass squared differences**
- **relation between flavor eigenstates and mass eigenstates (neutrino mixing) only partially known**

we do not know

- **Absolute ν mass scale? (cosmolology, 0νββ-decay, ^{3}H, ^{187}Rh)**
- **Are ν their own antiparticle? (Majorana ν) or not (Dirac ν)**
- **Is there a CP violation in the neutrino sector? (leptogenesis)**
- **Are neutrinos stable?**
- **What is the magnetic moment of ν?**

??





Standard Model   Lepton Universality

Particle	*Symbol*	*Anti − p.*	*mass* [MeV]	L_e	L_μ	L_τ	*life − time* [s]
electron	e^-	e^+	0.511	1	0	0	*stable*
el.neutrino	ν_e	$\overline{\nu}_e$	$< 2.2\ 10^{-6}$	1	0	0	*stable*
muon	μ^-	μ^+	105.6	0	1	0	$2.2\ 10^{-6}$
muon neutr.	ν_μ	$\overline{\nu}_\mu$	< 0.19	0	1	0	*stable*
tau	τ^-	τ^+	1777.	0	0	1	$2.9\ 10^{-13}$
tau neutrino	ν_τ	$\overline{\nu}_\tau$	< 18.2	0	0	1	*stable*

Lepton Family Number Violation

NEW PHYSICS

massive neutrinos, SUSY...

Total Lepton Number Violation

$\nu_{e,\mu\tau} \leftrightarrow \nu_{e,\mu\tau}$, $\overline{\nu}_{e,\mu\tau} \leftrightarrow \overline{\nu}_{e,\mu\tau}$	*observed*
$\mu^+ \to e^+ + \gamma$	$R \leq 1.2 \times 10^{-11}$
$\mu^+ \to e^+ + e^- + e^+$	$R \leq 1.0 \times 10^{-12}$
$K^+ \to \pi^+ + e^- + \mu^+$	$R \leq 4.7 \times 10^{-12}$
$\tau^- \to e^- + \mu^+ + \mu^-$	$R \leq 1.8 \times 10^{-6}$
$Z^0 \to e^\pm + \mu^\mp$	$R \leq 1.7 \times 10^{-6}$
$\mu_b^- + (A,Z) \to (A,Z) + e^-$	$R \leq 1.2 \times 10^{-11}$

$\nu_{e,\mu\tau} \leftrightarrow \overline{\nu}_{e,\mu\tau}$	*not observed*
$K^+ \to \pi^- + e^+ + \mu^+$	$R \leq 5 \times 10^{-10}$
$\tau^- \to \pi^- + \pi^+ + e^+$	$R \leq 1.9 \times 10^{-6}$
$W^- + W^- \to e^- + e^-$	
$(A,Z) \to (A,Z+2) + e^- + e^-$	$T^{0\nu} \geq 1.9 \times 10^{-25}$
$\mu_b^- + (A,Z) \to (A,Z-2) + e^+$	$R \leq 3.6 \times 10^{-11}$
$e^- + e^- \to \pi^- + \pi^-$	?

1937 Beginning of Majorana neutrino physics

Ettore Majorana discoveres the possiility of existence of truly neutral fermions

Charged fermion (electron) + electromagnetic field

$$\left(i\gamma^{\mu}\partial_{\mu}-e\gamma^{\mu}A_{\mu}-m\right)\Psi=0$$

$$\left(i\gamma^{\mu}\partial_{\mu}+e\gamma^{\mu}A_{\mu}-m\right)\Psi^{c}=0$$

$\Psi^{c}=\Psi$ **forbidden**

Neutral fermion (neutrino) + electromagnetic field

$$\left(i\gamma^{\mu}\partial_{\mu}-m\right)\nu=0$$

$$\left(i\gamma^{\mu}\partial_{\mu}-m\right)\nu^{c}=0$$

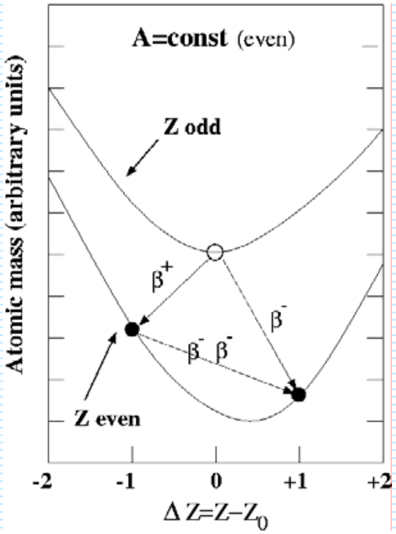
$\nu^{c}=\nu$ **allowed**

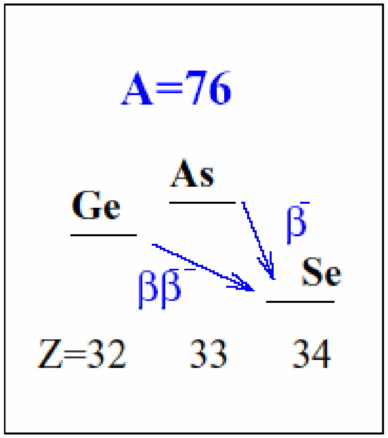
Majorana condition

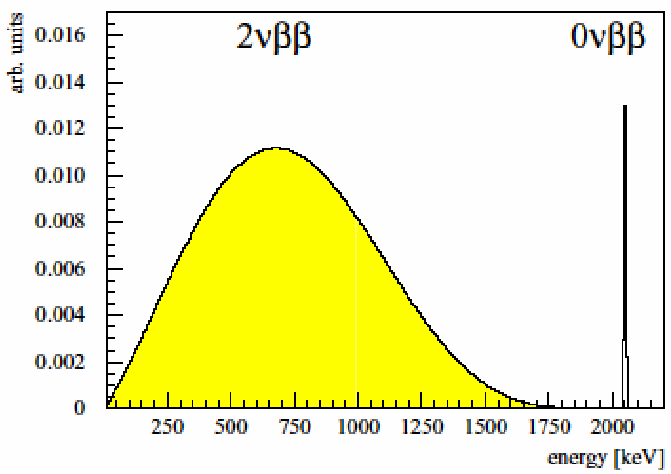
Symmetric Theory of Electron and Positron
Nuovo Cim. 14 (1937) 171

Here is the beginning of Nonstandard Neutrino Properties

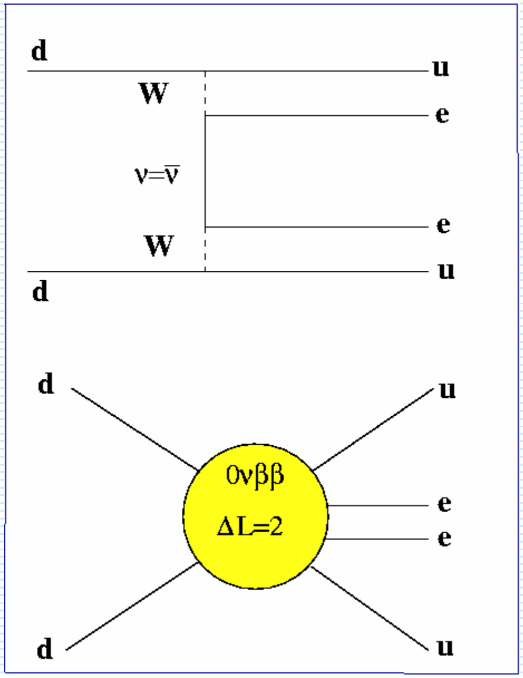
Double Beta Decay







$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\overline{\nu}_e$$

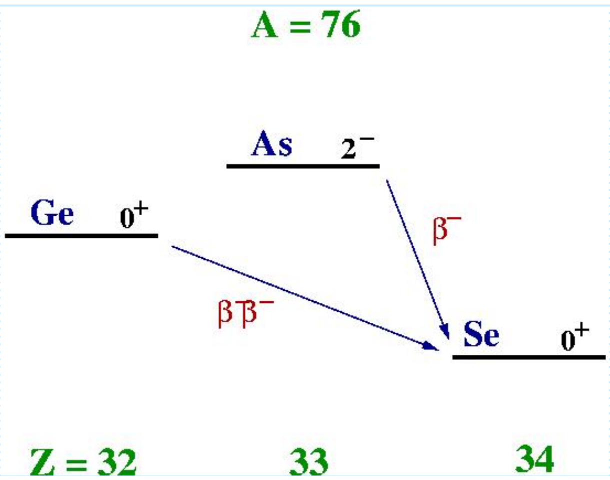


Observed for 10 isotopes: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo. ^{116}Cd. ^{128}Te, ^{130}Te, ^{150}Nd, ^{238}U, $T_{1/2} \approx 10^{18}$-10^{24} years

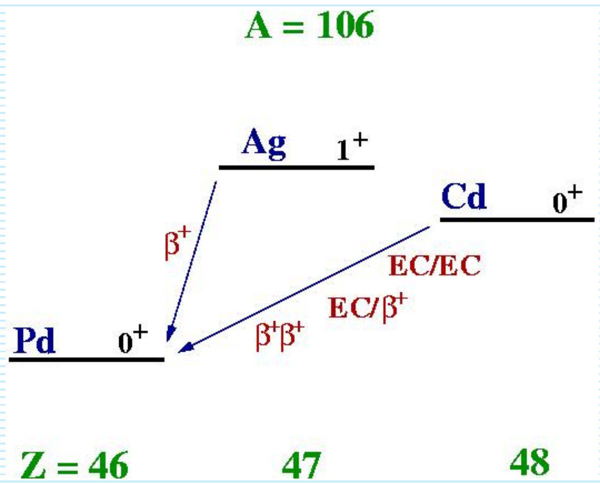
1967: ^{130}Te, Kirsten et al, Takaoka et al, (geochemical)
1987: ^{82}Se, Moe et al. (direct observation)
2006: ^{100}Mo, NEMO 3 coll. ~ 220 00 events

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

SM forbidden ,not observed yet: $T_{1/2}$ (^{76}Ge)>10^{25} years



Different types of Double Beta Decay



Emission of two e$^-$ ($\beta^-\beta^-$)

$$(Z-2,A) \rightarrow (Z,A) + 2e^- + (2\tilde{\nu}_e)$$

T(MeV): ^{76}Ge(2.045), ^{82}Se(3.005), ^{100}Mo(3.033), ^{130}Te(2.533), ^{150}Nd(3.367)

Capture of bound e$^-$ and emission of e$^+$ (EC/β^+)

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

T(MeV): ^{78}Kr(1.837), ^{106}Cd (1.724) ^{124}Xe(1.802), ^{130}Ba(1.515), ^{136}Ce(1.339)

Double capture of bound e$^-$ (EC/EC)

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

T(MeV): ^{78}Kr(2.841), ^{106}Cd (2.712) ^{124}Xe(2.782), ^{130}Ba(2.492), ^{136}Ce(2.313)

Emission of two e+ ($\beta^+\beta^+$)

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

T(MeV): ^{78}Kr(0.838), ^{106}Cd (0.738) ^{124}Xe(1.024), ^{130}Ba(0.534), ^{136}Ce(0.362)

⇑ Disfavored by Coulomb repulsion ⇑

Heidelberg-Moscow Experiment LNGS (completed 2003)

$T_{1/2}$ > 1.9 10^{25} years
<$m_{\beta\beta}$> < 0.34 eV

H-M collaborations,
PRL 83 (1999) 41

Technical parameters of the five enriched ^{76}Ge detectors

Detector number	Total mass (kg)	Active mass (kg)	Enrichment in ^{76}Ge(%)	PSA
No. 1	0.980	0.920	85.9 ± 1.3	No
No. 2	2.906	2.758	86.6 ± 2.5	Yes
No. 3	2.446	2.324	88.3 ± 2.6	Yes
No. 4	2.400	2.295	86.3 ± 1.3	Yes
No. 5	2.781	2.666	85.6 ± 1.3	Yes

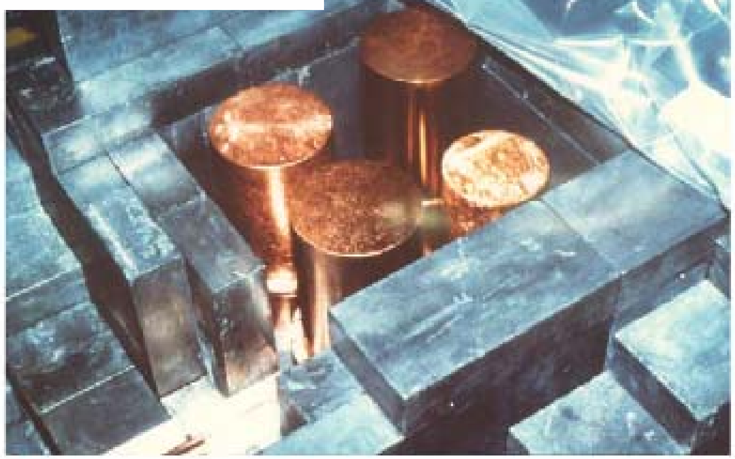


Fig. 1. The HEIDELBERG–MOSCOW $\beta\beta$-experiment in the Gran Sasso (top), and four of the enriched detectors during installation (bottom left). The fifth detector was installed in an extra shielding using electrolytic copper as inner shield (bottom right).

Heidelberg claim for evidence

Analysis of the ^{76}Ge experiment in Gran Sasso 1990-2003

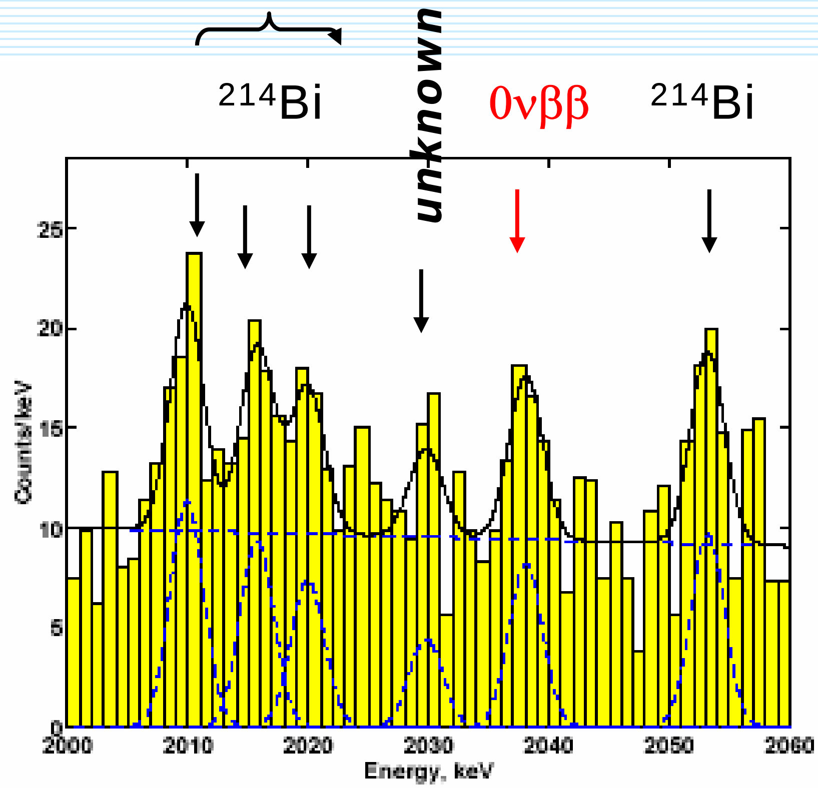
H.V. Klapdor-Kleingrothaus et al.,NIM A 522, 371 (2004); PLB 586, 198 (2004)

- Data reanalyzed with improved summing
- Peak visible
- Effect reclaimed with 4.2σ

- $T_{1/2}^{0\nu}$ = (0.69 - 4.18) 10^{25} years

- 0.23 eV ≤ $|m_{\beta\beta}|$ ≤ 0.57 eV

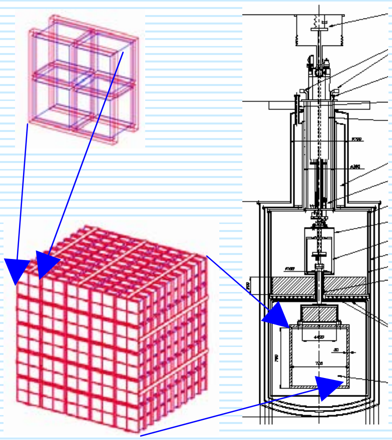
- Unknown peak at 2030 keV?



71.7 kg·yr

Running Double Beta Decay experiments

Gran Sasso



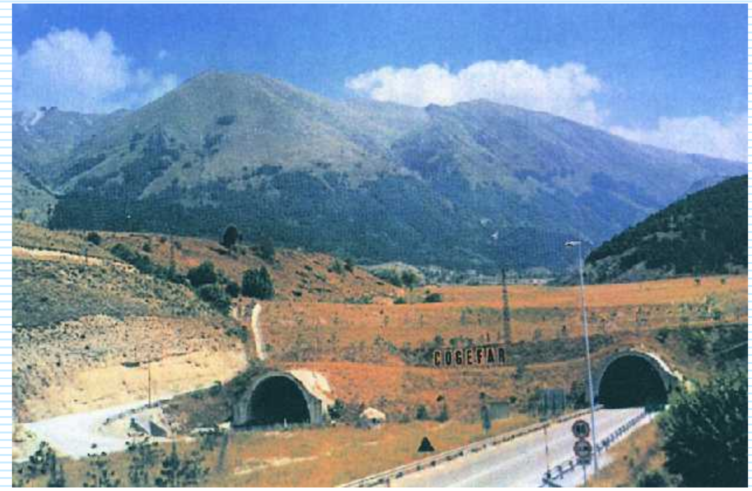
CUORICINO

^{130}Te 40.7 kg

$Q_{\beta\beta}$ = 2529 keV

$T_{1/2} > 3.0\ 10^{24}$ years

$|m_{\beta\beta}| < 0.42$ eV



NEMO 3

^{100}Mo (6.914 kg) $T_{1/2} > 5.8\ 10^{23}$ years

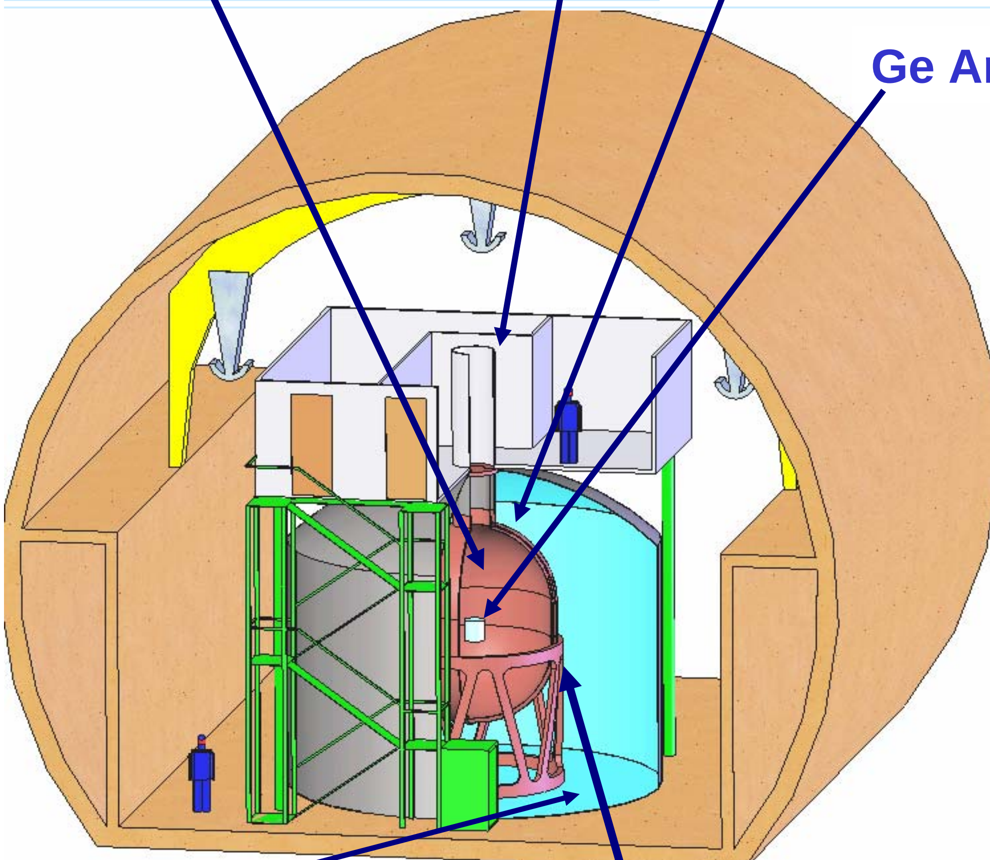
$Q_{\beta\beta}$ = 3034 keV $|m_{\beta\beta}| < 0.98$ eV

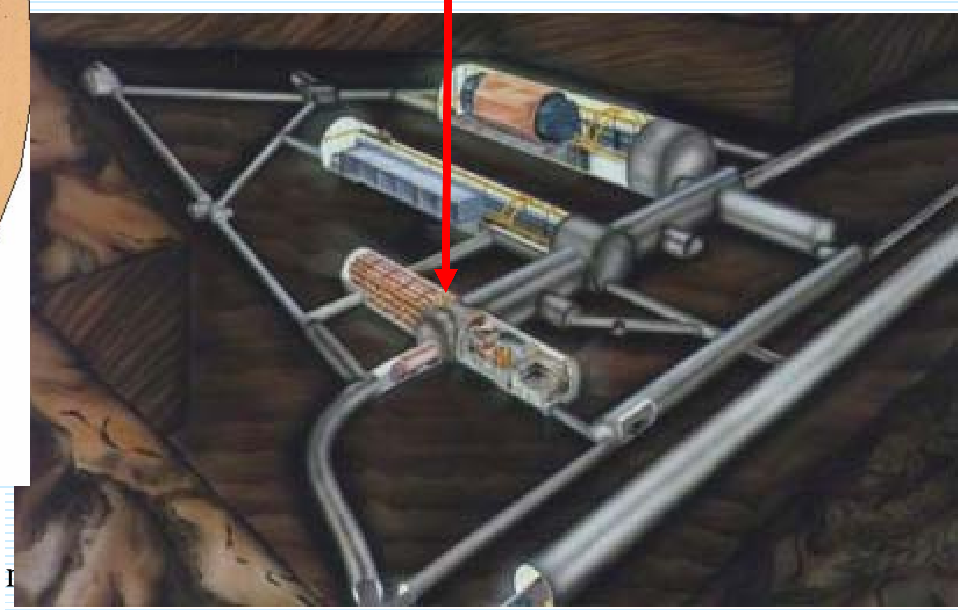
^{82}Se (0.932 kg) $T_{1/2} > 2.1\ 10^{23}$ years

$Q_{\beta\beta}$ = 2995 keV $|m_{\beta\beta}| < 1.7$ eV

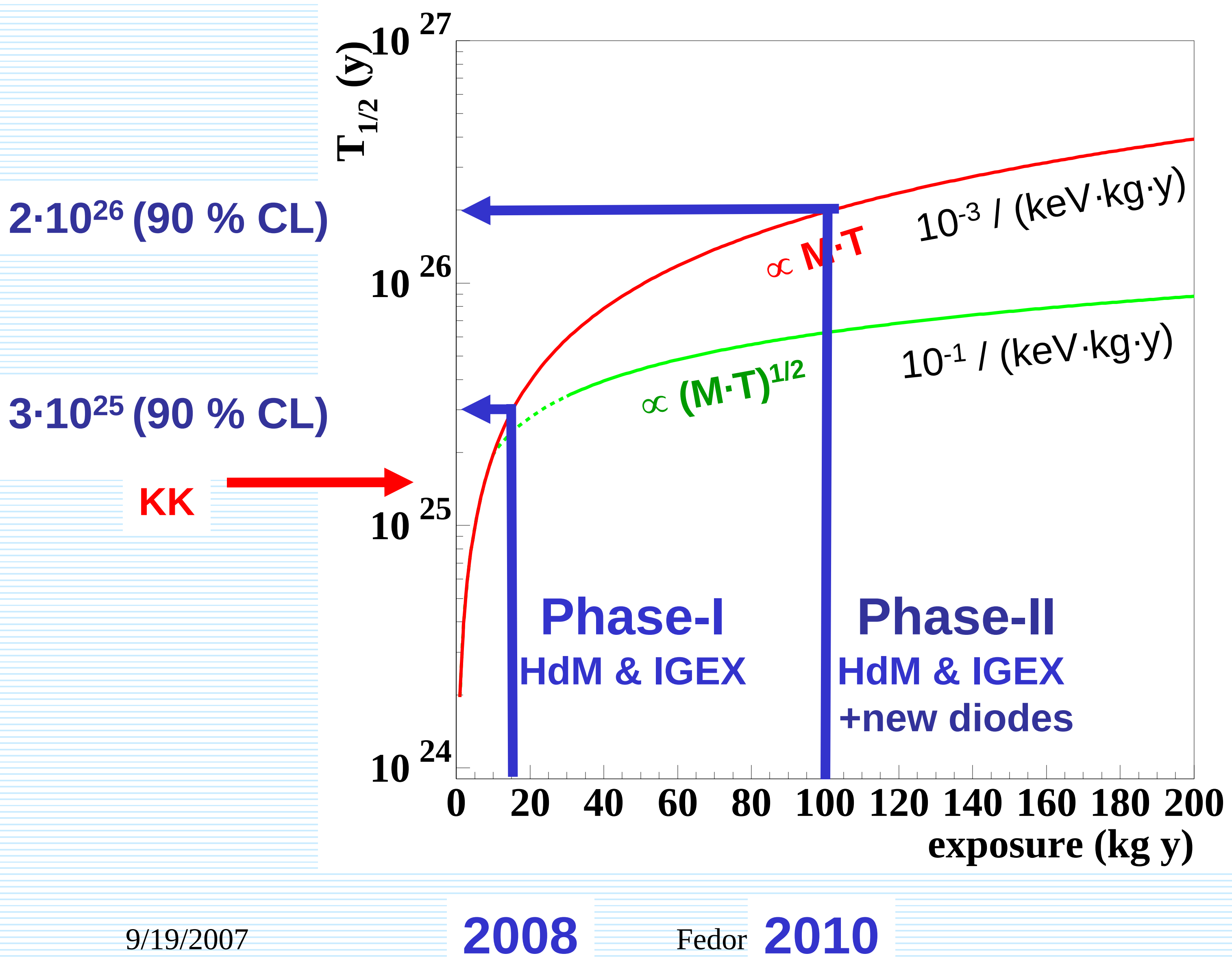
Fréjus Underground Laboratory : 4800 m.w.e.

GERDA at LNGS: GERmanium Detector Assembly for the search of neutrinoless ββ decays in Ge-76 at LNGS





Phases and physics reach of GERDA



History of Double Beta Decay I

The early period (1935-1957)

- **1935 Goepper-Mayer suggested the 2νββ-decay**
- **1937 Dirac $\nu \neq \overline{\nu}$ or Majorana $\nu \equiv \overline{\nu}$**
- **1939 Furry proposed the 0νββ-decay**
- **till 1957 Observation of 0νββ more favored (phase space)**

$$n \to p + e^- + \overline{\nu}_e \quad \nu_e + n \to p + e^-$$

Period of scepticism (1957-1970)

- **1957 Wu, weak interaction violates parity, Majorana or Dirac – open question**

$$n \to p + e^- + \overline{\nu}_e{}^{RH} \quad \nu_e{}^{LH} + n \to p + e^-$$

Declined interest to 0νββ-decay

- **1968 Pontecorvo proposed $\pi^- \to \pi^+ + 2e^-$, superweak int.**

Period of GUT (1970-1998)

- **1975 Primakoff and Rosen – Right handed current mech.**
- **1981 Doi, Kotani, Takasugi ν-mech. within gauge theories**
- **1981 Wolfenstein: cancellation mech. possible**

$$< m_\nu >= \sum_k |U_{ek}|^2 \; \eta_{CP} \; m_k, \quad \eta_{CP} = \pm i$$

History of Double Beta Decay II

- **1982** **Scheckter-Valle** **theorem** **The observation of 0νββ-decay implies the existence of Majorana mass term**
- **1986** **Vogel, Zirnbauer** **– quenching mech. of 2νββ-decay**
- **1987** **Elliott, Hahn, Moe** **-first detection of 2νββ-decay (^{82}Se)**
- **1987** **Mohapatra, Vergados, R-parity breaking SUSY mech.**
- **1997** **Feassler, Kovalenko, Simkovic, dominance of pion-exchange SUSY mech.**
- **1997** **Kovalenko, Hirsch, Klapdor,** **leptoquark mech.**

Period of massive ν (1998→20??)

- **1998- neutrino oscillations (SK, SNO, Kamland) convin. evid.**
- **2001** **Klapdor-Kleingrothaus, Dietz, Krivosheina, first claim for observation of the 0νββ-decay**
- **Many works on neutrino mass pattern, absolute mass scale, CP phases, extra dim. mech.**
- **Many works on future large (tons) 0νββ-decay experiments**

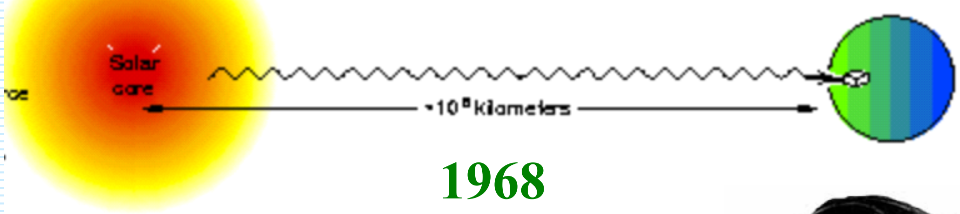
Quo vadis 0νββ-decay?

Majorana period (2???→)

- **2??? Observation of 0νββ-decay**
- **2??? …**

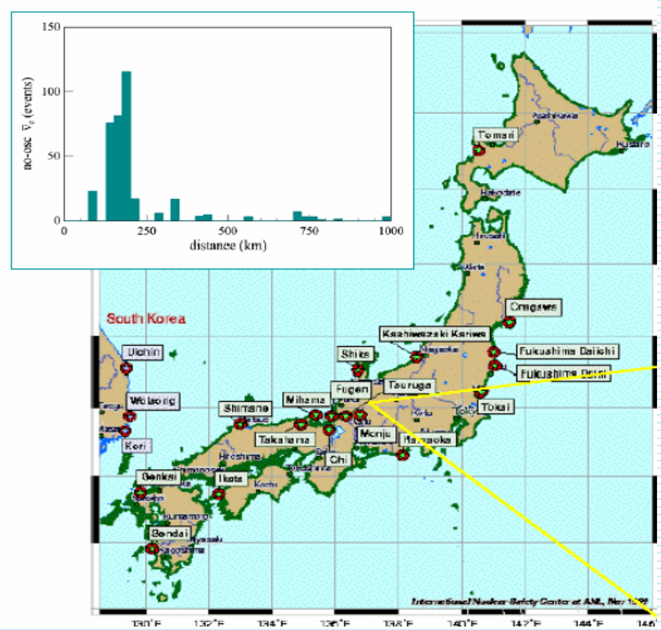
Neutrino oscillations ⇒ Massive neutrinos

Solar neutrinos



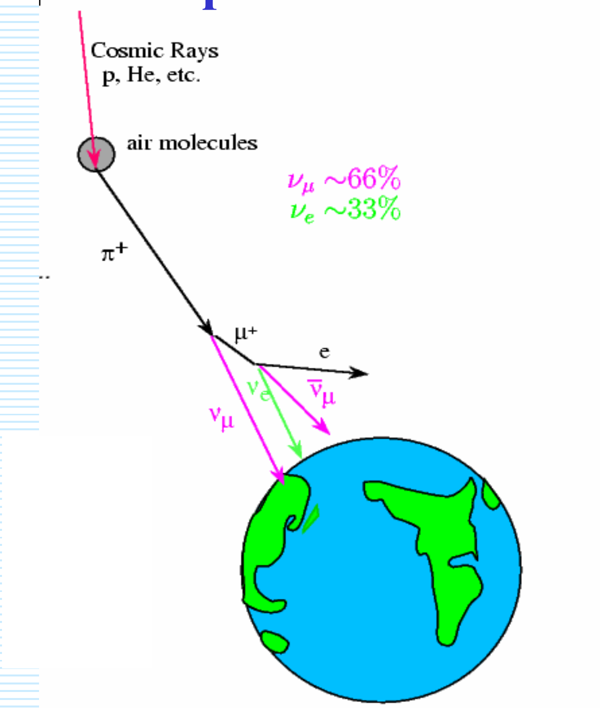
1968

Reactor neutrinos

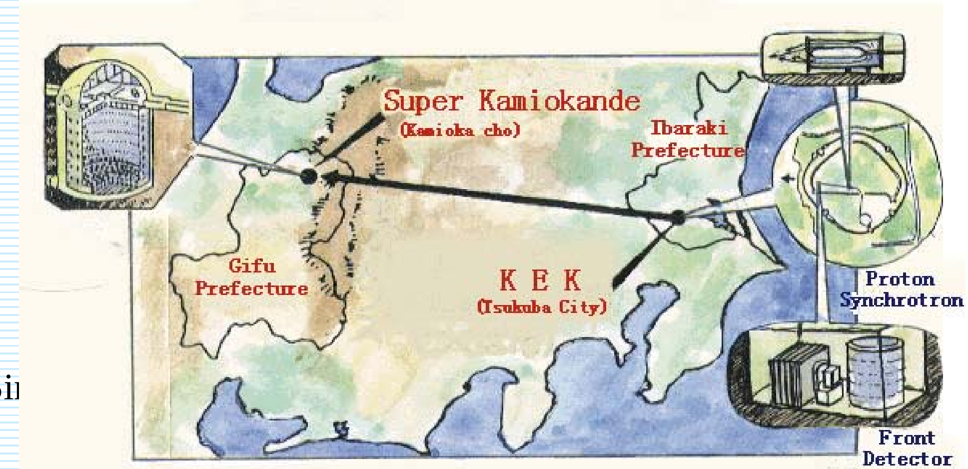


1957

Atmospheric neutrinos



Accelerator neutrinos

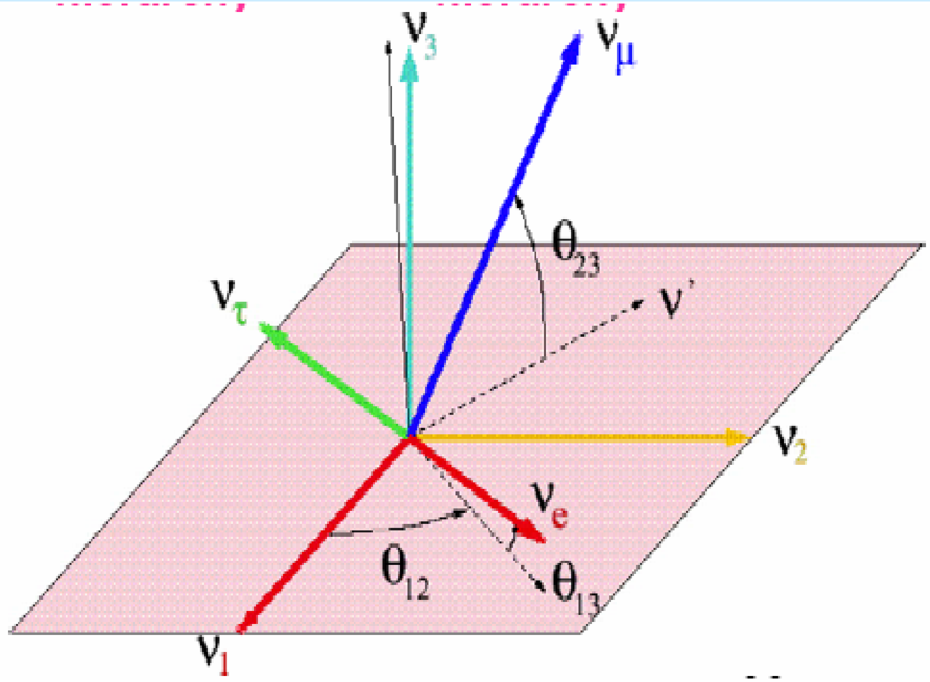


Mixing of 3 light Neutrinos

Pontecorvo -Maki-Nakagawa-Sakata matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor eigenstates **Mass eigenstates**



Mass matrix

$$\begin{pmatrix} M_{ee} & M_{e\mu} & M_{e\tau} \\ M_{\mu e} & M_{\mu\mu} & M_{\mu\tau} \\ M_{\tau e} & M_{\tau\mu} & M_{\tau\tau} \end{pmatrix}$$

$$m_{\beta\beta} = \Sigma\, U_{ei} U_{ei}\, m_i$$

Pontecorvo-Maki-Nakagawa-Sakata matrix

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

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

Quark mixing

$$U_{CKM} = \begin{pmatrix} 0.98 & 0.22 & 0.003 \\ -0.22 & 0.97 & 0.04 \\ 0.003 & -0.04 & 1.00 \end{pmatrix}$$

Neutrino mixing

$$U_{PMNS} = \begin{pmatrix} 0.83 & 0.55 & 0.05 \\ 0.34-0.45 & 0.56-0.62 & 0.70 \\ 0.34-0.45 & 0.55-0.62 & 0.70 \end{pmatrix}$$

Large off diagonal elements

! Instruction for an extension of SM? !

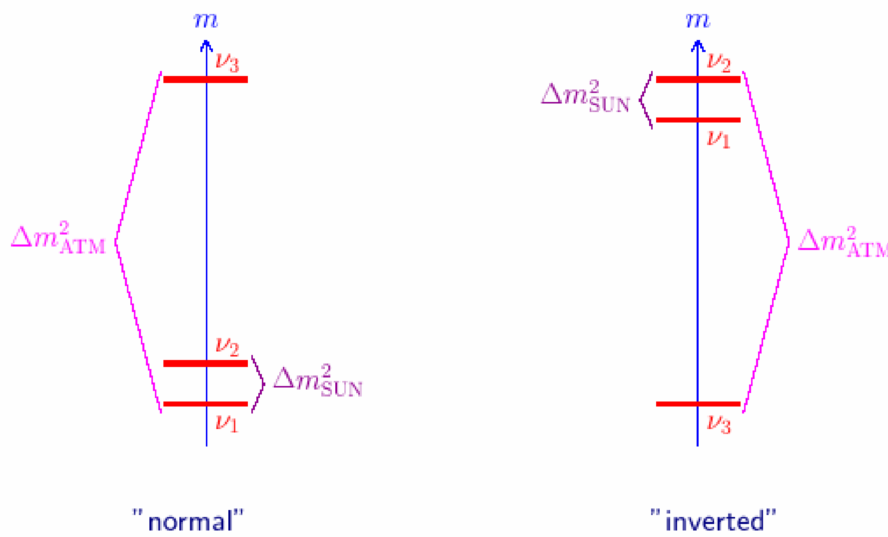
Disperity and challange for quark-lepton unified theories

Neutrinos mass spectrum

We need 3mass-eigenstates to explain 2 different Δm^2:

$$|m_2^2 - m_1^2| = \Delta m^2_{sol} \sim 3\ 10^{-5}\ eV^2$$

$$|m_3^2 - m_2^2| = \Delta m^2_{atm} \sim 2\ 10^{-3}\ eV^2$$

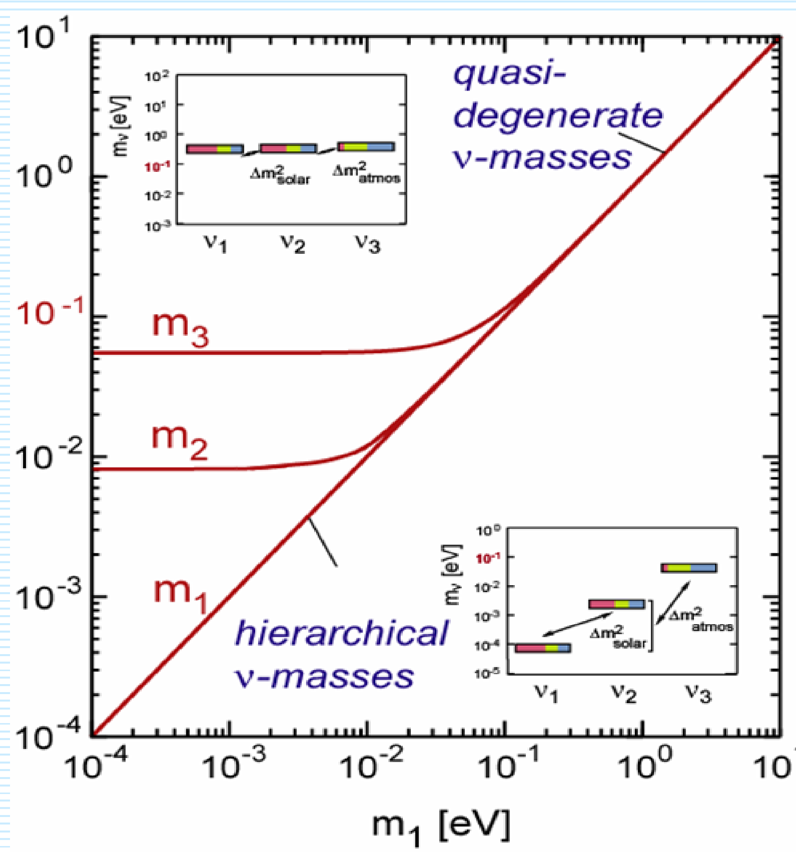


Absolute mass scale of neutrinos

0νββ-decay $m_{\beta\beta} = \sum_{i=1}^{3} U_{ei}^2\ m_i$

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

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



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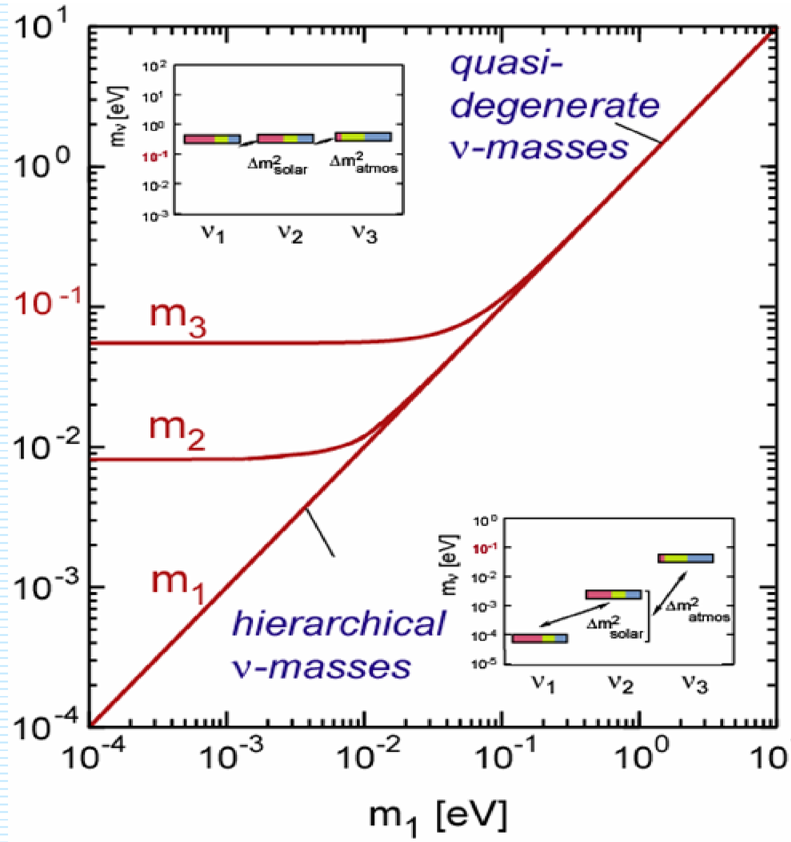


Absolute mass scale of neutrinos

0νββ-decay

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

Tritium decay

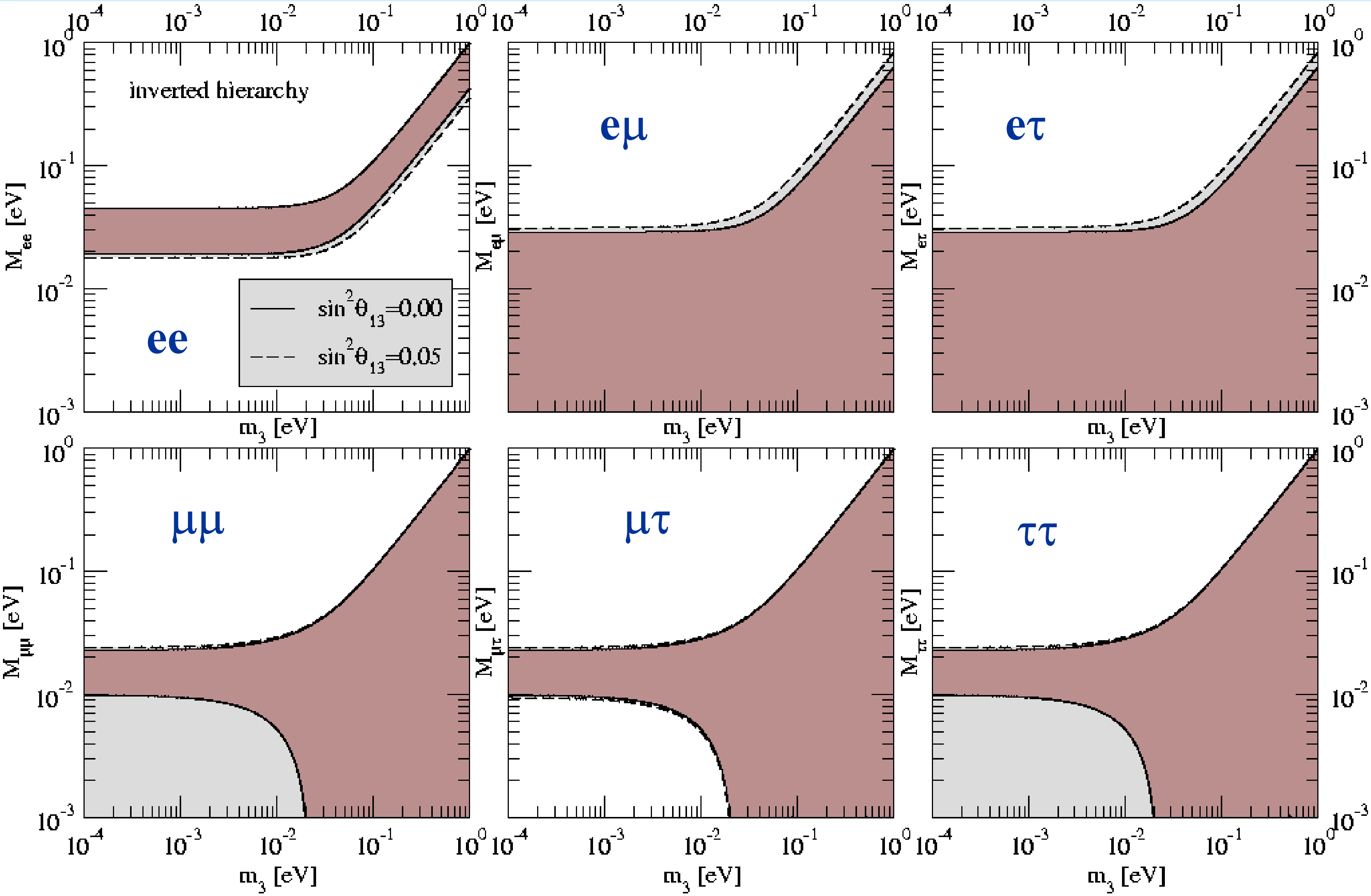
$$m_{\beta} = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2\ m_i^2}$$

Cosmology

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

ν-masses in flavor basis: Inverted hierarchy

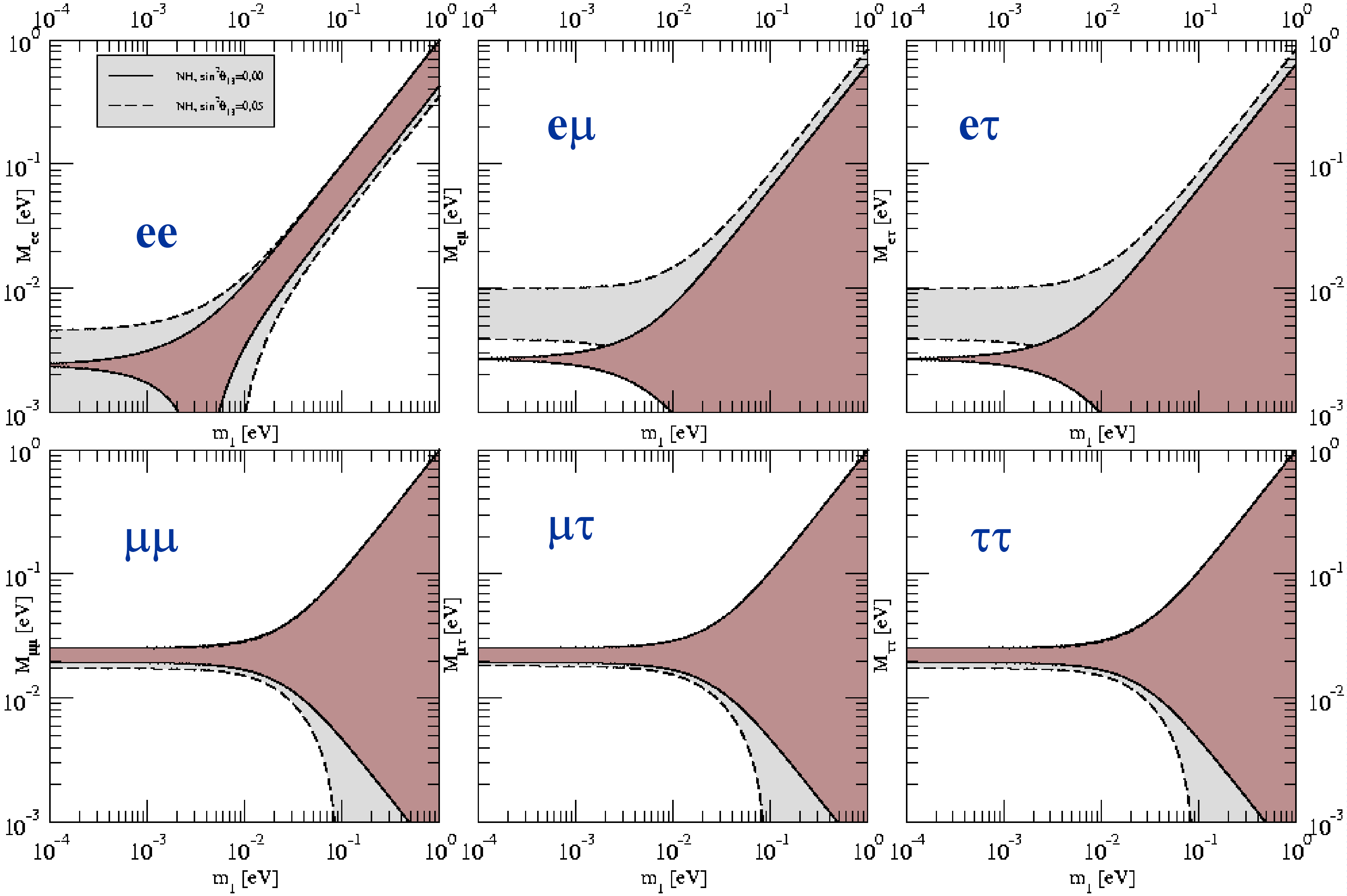
$$\begin{pmatrix} M_{ee} & M_{e\mu} & M_{e\tau} \\ M_{\mu e} & M_{\mu\mu} & M_{\mu\tau} \\ M_{\tau e} & M_{\tau\mu} & M_{\tau\tau} \end{pmatrix}$$



Gozdz,Kaminski, F.Š, Faessler, Acta Phys. Pol. 37 (2006) 2203

ν-masses in flavor basis: Normal hierarchy

$$\begin{pmatrix} M_{ee} & M_{e\mu} & M_{e\tau} \\ M_{\mu e} & M_{\mu\mu} & M_{\mu\tau} \\ M_{\tau e} & M_{\tau\mu} & M_{\tau\tau} \end{pmatrix}$$



Gozdz,Kaminski, F.Š, Faessler, Acta Phys. Pol. 37 (2006) 2203

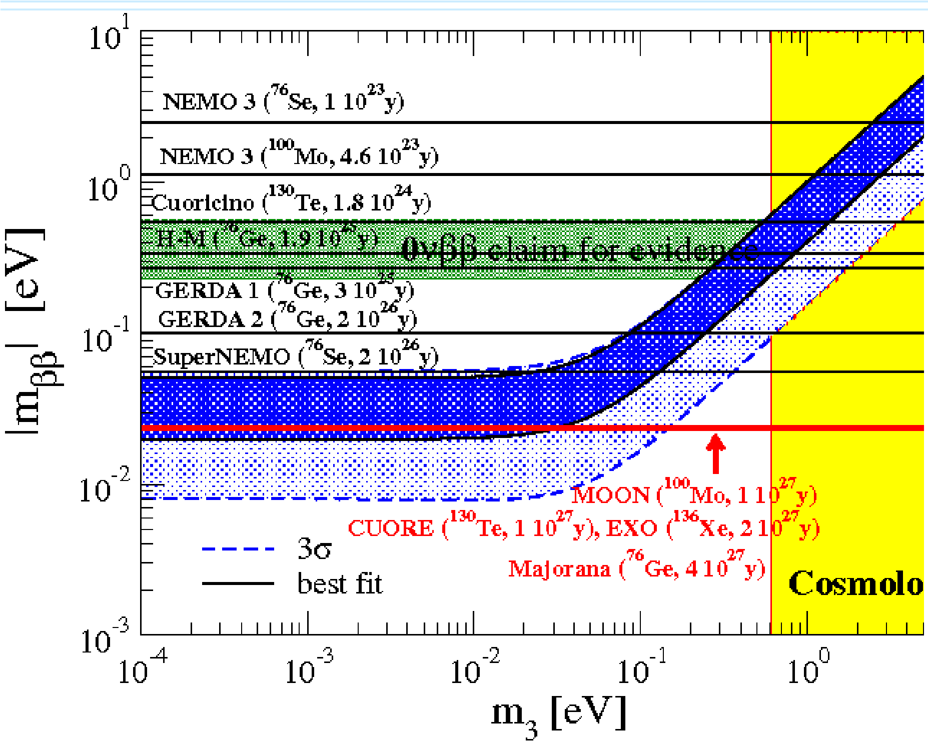
3 neutrino observables	Present knowledge	Near Future
$\theta_a \to \theta_{12}$	**45° ± 9°**	$P(\nu_\mu \to \nu_\mu)$ **MINOS , CNGS**
$\theta_s \to \theta_{23}$	**33° ± 3°**	$P(\nu_e \to \nu_e)$ **SNO**
$\theta_x \to \theta_{13}$	**≤ 9°**	$P(\bar{\nu}_e \to \bar{\nu}_e)$ Reactor, $P(\nu_\mu \to \nu_e)$ LBL
Δm_a^2	$(2.5^{+2}_{-1}) \times 10^{-3} \mathrm{eV}^2$	$P(\nu_\mu \to \nu_\mu)$ **MINOS , CNGS**
sign(Δm_a^2)	**unknown**	$P(\nu_\mu \to \nu_e)$, $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ **LBL**
Δm_s^2	$(7.\pm 2.) \times 10^{-5}\ \mathrm{eV}^2$	$P(\bar{\nu}_e \to \bar{\nu}_e)$ **KamLAND**
sign(Δm_s^2)	**+ (MSW)**	**done**
δ	**unknown**	$P(\nu_\mu \to \nu_e)$, $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ LBL
Majorana	**unknown**	**0νββ !**
α_{12}	**unknown**	**0νββ (if ≈ 0, π)**
α_{23}	**unknown**	**hopeless**
m_ν	$\Sigma m_\nu < 1$ eV	**cosmology, 0νββ, β-decay**

Neutrino mass spectrum
And perspectives of the 0νββ-decay search

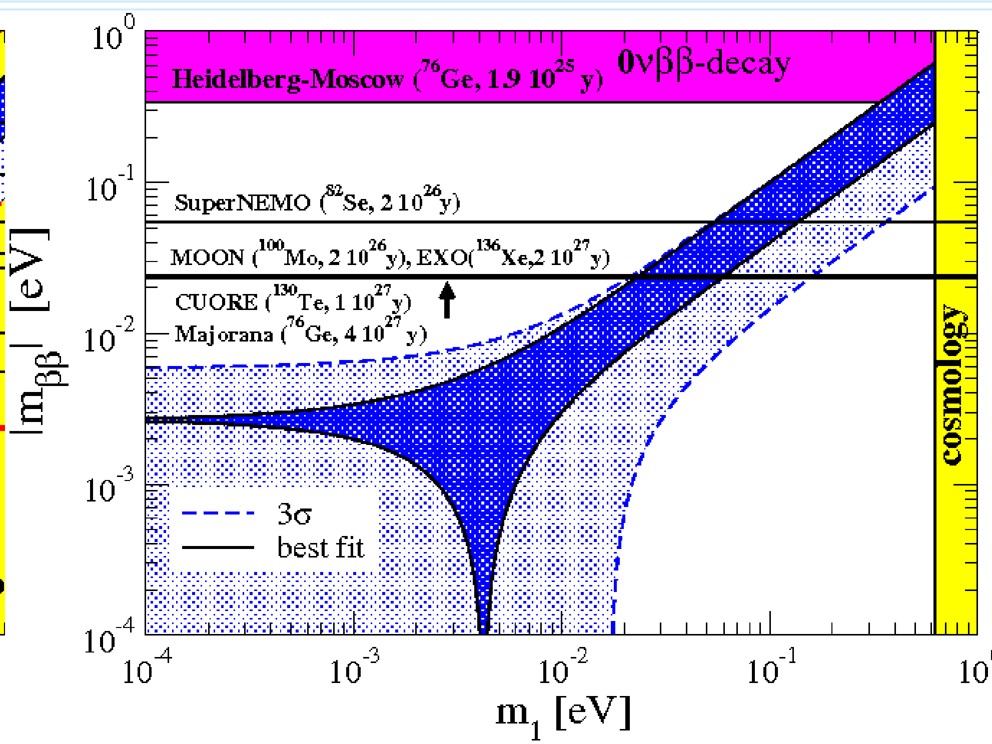
What is the absolute mass scale of neutrinos: Limits from cosmology, tritium beta decay, neutrinoless double beta decay

What are the Majorana CP phases? ...

Inverted hierarchy



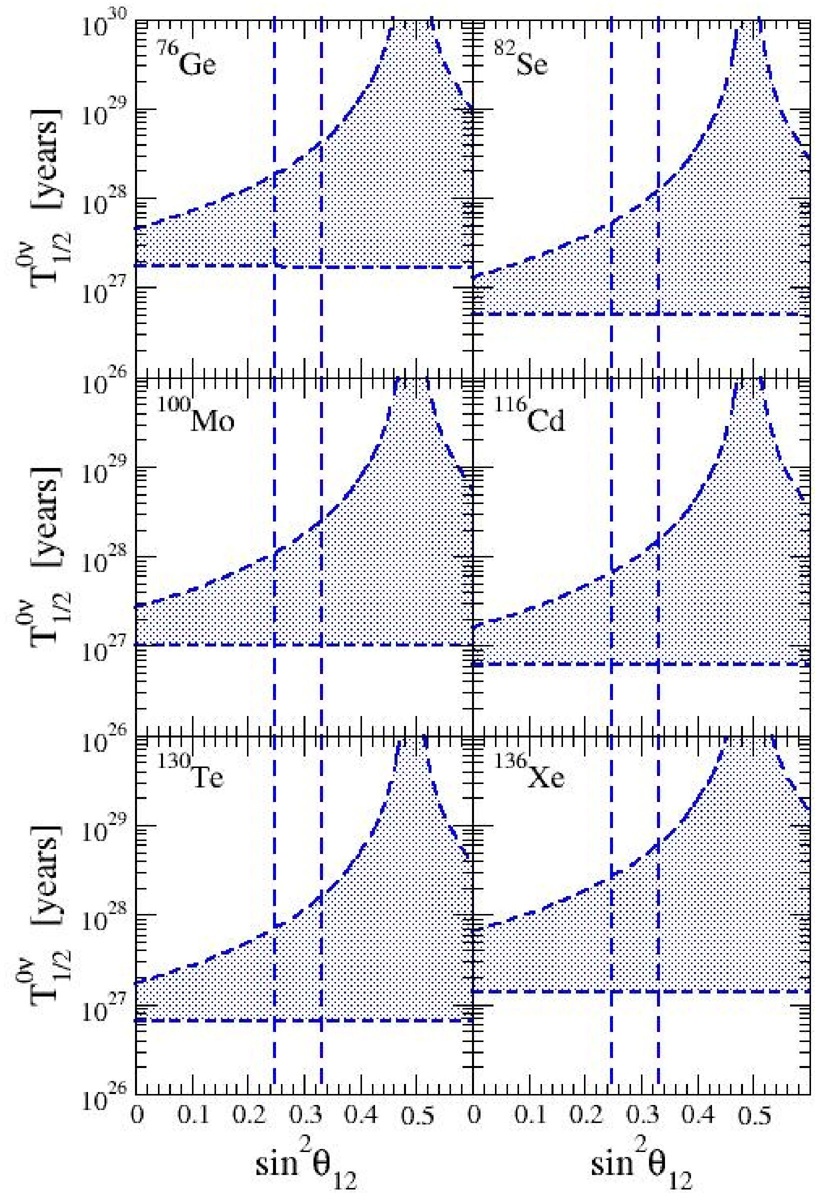
Normal hierarchy



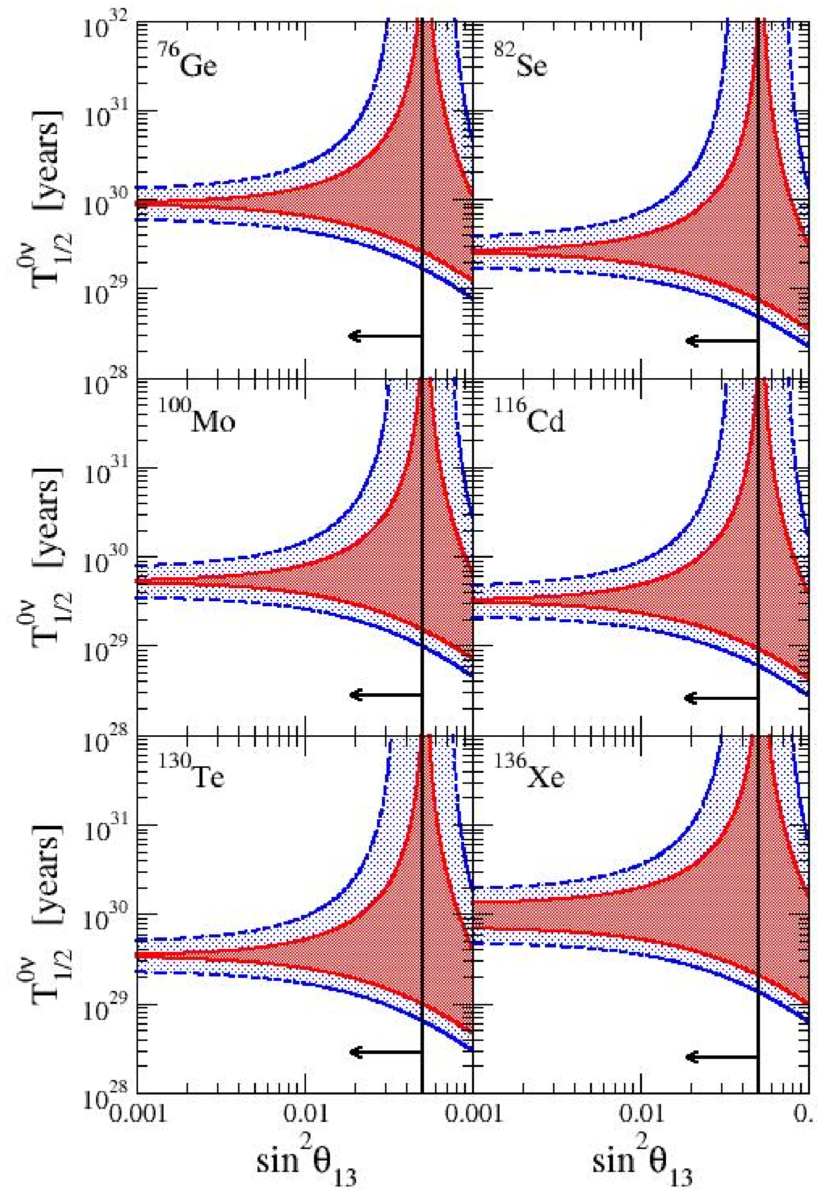
Bilenky, Faessler, Šimkovic, PRD 70 (2004) 033003

$$\sqrt{|\Delta m^2_{13}|}\cos 2\theta_{12} \le |m_{\beta\beta}| \le \sqrt{|\Delta m^2_{13}|}$$

$$|m_{\beta\beta}| \le \sin^2\theta_{12}\sqrt{\Delta m^2_{12}} + \sin^2_{13}\sqrt{\Delta m^2_{23}}$$



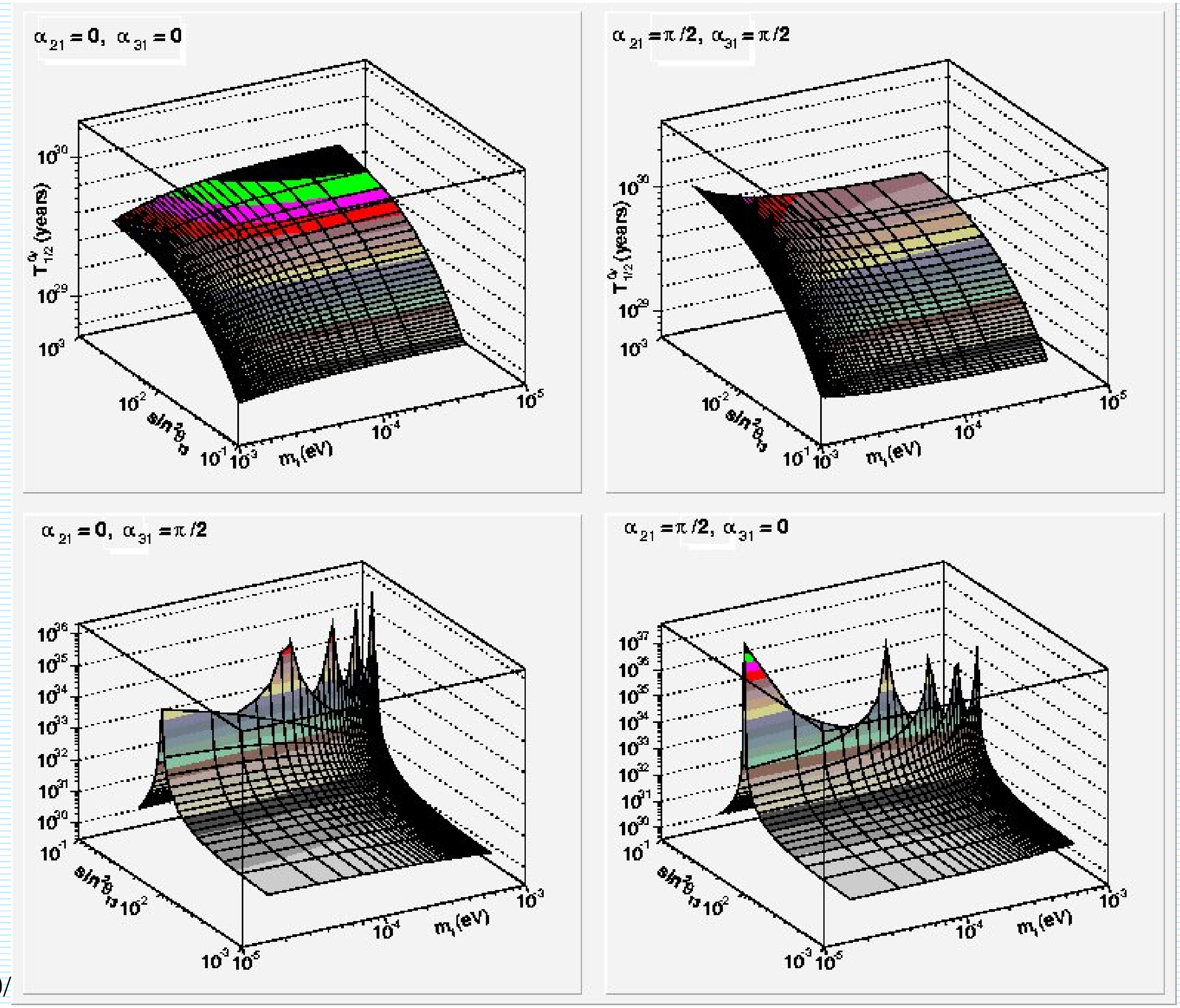
Inverted hierarchy



Normal hierarchy

10^{27}-10^{28}years **Bilenky,Faessler, Gutsche, F.Š., PRD 72 (2005) 053015** **10^{29}-10^{30}years**

θ_{13} and the cancellation



Bilenky,Faessler, Gutsche, F.Š., PRD 72, 053015 (2005)

Mechanisms of the 0νββ–decay

We know that ν are Massive particles

!!

- Neutrino mass mechanisms

  ν masses: see-saw – sterile ν

!

- R-parity breaking SUSY mechanisms

  ν masses: v.e.v + rad. cor.

SUSY particles are expected to be seen at LHC

- Leptoquark exchange mechanisms
- Extra dimensions
-
-
-

Light ν-exchange 0νββ–decay mechanism

S.M. Bilenky, S. Petcov, Rev. Mod. Phys. 59, 671 (1987)

Majorana condition

$$C\, \overline{\chi_k}^T(x) \;=\; \xi_k\, \chi_k(x)$$

Majorana particle propagator

$$\begin{aligned} < \chi_\alpha(x_1)\overline{\chi}_\beta(x_2) > \;&=\; \frac{-1}{(2\pi)^4}\int \left(\frac{1}{\gamma p - im}\right)_{\alpha\beta} e^{ip(x_1-x_2)}dp \\ &=\; S_{\alpha\beta}(x_1-x_2) \end{aligned}$$

$$\begin{aligned} < \chi(x_1)\chi^T(x_2) > \;&=\; -\xi S(x_1-x_2)C \\ < \overline{\chi}^T(x_1)\overline{\chi}(x_2) > \;&=\; \xi C^{-1} S(x_1-x_2) \end{aligned}$$

Weak β-decay Hamiltonian

$$\mathcal{H}^\beta_W = \frac{G_F}{\sqrt{2}}\, \overline{e}\gamma_\alpha(1+\gamma_5)\nu_e\; j_\alpha + h.c.$$

Neutrino mixing

$$\nu_{eL} \;=\; \sum_k\; U^L_{lk}\; \chi_{kL}$$

S-matrix term

$$S^{(2)} = -\frac{(-i)^2}{2} 4 \left(\frac{G_F}{\sqrt{2}}\right)^2 \int N \left[\overline{e_L}(x_1)\gamma_\alpha < \nu_{eL}(x_1)\nu^T_{eL}(x_2) > \gamma^T_\beta \overline{e_L}^T(x_2)\right] \times$$
$$T\left(j_\alpha(x_1) j_\beta(x_2) e^{-i\int \mathcal{H}_{str}(x)dx}\right) dx_1 dx_2$$

Contraction of ν-fields

$$< \nu_{eL}(x_1)\nu_{eL}{}^T(x_2) > = -\sum_k \left(U^L_{ek}\right)^2 \xi_k \frac{1+\gamma_5}{2} S_k(x_1 - x_2) \frac{1+\gamma_5}{2} C$$
$$= \frac{i}{(2\pi)^4} \sum_k \left(U^L_{ek}\right)^2 \xi_k m_k \int \frac{e^{iq(x_1-x_2)}dq}{q^2 + m_k^2} \frac{1+\gamma_5}{2} C$$

Effective mass of Majorana neutrinos

$$m_{\beta\beta} = \sum_k \left(U^L_{ek}\right)^2 \xi_k m_k$$

0νββ-decay matrix element

$$< f|S^{(2)}|i > = m_{\beta\beta}\left(\frac{G_F}{\sqrt{2}}\right)^2 N_{p_1}N_{p_2}\overline{u}(p_1)\gamma_\alpha(1+\gamma_5)\gamma_\beta C\overline{u}^T(p_2)\times$$
$$\int e^{-ip_1x_1}e^{-ip_2x_2}\frac{-i}{(2\pi)^4}\int\frac{e^{iq(x_1-x_2)}dq}{q^2}\times$$
$$< A'|T\left[J_\alpha(x_1)J_\beta(x_2)\right]|A > dx_1dx_2 - (p_1\leftrightarrow p_2)$$

Use of completeness 1=Σ_n|n><n|

$$< A'|J_\alpha(x_1)J_\beta(x_2)|A > = \sum_n < A'|J_\alpha(0,\vec{x}_1)|n >< n|J_\beta(0,\vec{x}_2)|A > \times$$
$$e^{-i(E'-E_n)x_{10}}e^{-i(E_n-E)x_{20}}$$

After integration over time variables

$$< f|S^{(2)}|i > = im_{\beta\beta}\left(\frac{G_F}{\sqrt{2}}\right)^2 N_{p_1}N_{p_2}\overline{u}(p_1)\gamma_\alpha(1+\gamma_5)\gamma_\beta C\overline{u}^T(p_2)$$
$$\times\int d\vec{x}_1d\vec{x}_2e^{-i\vec{p}_1\cdot\vec{x}_1}e^{-i\vec{p}_2\cdot\vec{x}_2}\frac{1}{(2\pi)^3}\int\frac{e^{i\vec{q}\cdot(\vec{x}_1-\vec{x}_2)}d\vec{q}}{\vec{q}^2}\times$$
$$\sum_n\left(\frac{< A'|J_\alpha(0,\vec{x}_1)|n >< n|J_\beta(0,\vec{x}_2)|A >}{E_n+q_0+p_{20}-E}+\frac{< A'|J_\beta(0,\vec{x}_1)|n >< n|J_\alpha(0,\vec{x}_2)|A >}{E_n+q_0+p_{10}-E}\right)$$
$$\times\ 2\pi\delta(E'+p_{10}+p_{20}-E)$$

Approximations and simplifications

1) Non-relativistic impulse approx. for nuclear current

2) Long-wave approximation for lepton wave functions

3) Closure approximation

$$J_\alpha(0,\vec{x}) = \sum_n \tau_n^+ (\delta_{\alpha 4} + i g_A (\vec{\sigma})_k \delta_{\alpha k}) \delta(\vec{x} - \vec{x}_n)$$

$$e^{-i\vec{p}_1\cdot\vec{x}_1 - i\vec{p}_2\cdot\vec{x}_2} \longrightarrow 1$$

$$E_n \rightarrow \; < E_n >$$

$$< f|S^{(2)}|i > = \overline{u}(p_1)\gamma_\alpha(1+\gamma_5)\gamma_\beta C\overline{u}^T(p_2) A_{\alpha\beta}, \quad A_{\alpha\beta} = A_{\beta\alpha}$$

Hadron part is symmetric

$$J_\alpha(0,\vec{x}_1) J_\beta(0,\vec{x}_2) = J_\beta(0,\vec{x}_2) J_\alpha(0,\vec{x}_1)$$

contribute

$$\gamma_\alpha\gamma_\beta = \delta_{\alpha\beta} + \frac{1}{2}(\gamma_\alpha\gamma_\beta - \gamma_\beta\gamma_\alpha)$$

0νββ-decay matrix element

$$\begin{aligned} < f|S^{(2)}|i > \; &= \; i\, m_{\beta\beta} \left(\frac{G_F}{\sqrt{2}}\right)^2 N_{p_1} N_{p_2} \overline{u}(p_1)(1-\gamma_5) C \overline{u}^T(p_2) \frac{1}{R} \\ &\times \left(M_F - g_A^2 M_{GT}\right) \delta(p_{10} + p_{20} + M' - M) \end{aligned}$$

Nuclear matrix elements

$$M_F = < A'| \sum_{n,m} \tau_n^+ \tau_m^+ h(|\vec{x}_n - \vec{x}_m|)|A >$$

$$M_F = < A'| \sum_{n,m} \tau_n^+ \tau_m^+ h(|\vec{x}_n - \vec{x}_m|)\vec{\sigma}_n \cdot \vec{\sigma}_m|A >$$

Neutrino exchange potential

$$h(|\vec{x}_n - \vec{x}_m|) = \frac{1}{2\pi^2} \int \frac{e^{i\vec{q}\cdot\vec{x}} d\vec{q}}{q_0(q_0 + < E_n > -(E+E')/2)} \approx \frac{1}{|\vec{x}|}$$

Differential 0νββ-decay rate

$$d\Gamma_{0\nu} = \frac{1}{2}\frac{G_F^4 m_e^5}{(2\pi)^5} |m_{\beta\beta}|^2 \frac{1}{R^2} |M_F - g_A^2 M_{GT}|^2 (1 - \cos\theta) F^2(Z)(\varepsilon_0 - \varepsilon + 1)^2(\varepsilon + 1) d\varepsilon \sin\theta d\theta$$

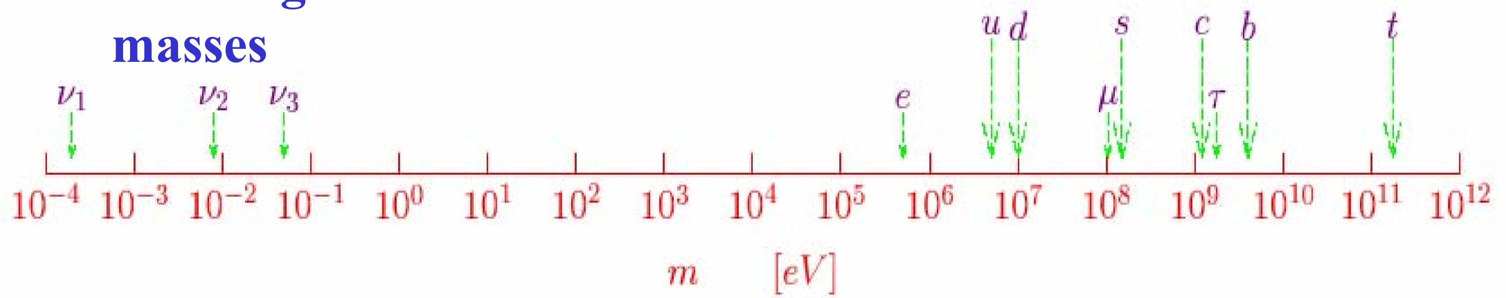
$$F(Z) = \frac{2\pi\alpha(Z+2)}{1 - exp[-2\pi\alpha(Z+2)]} \qquad \varepsilon_0 = \frac{1}{m_e}(M - M' - 2m_e)$$

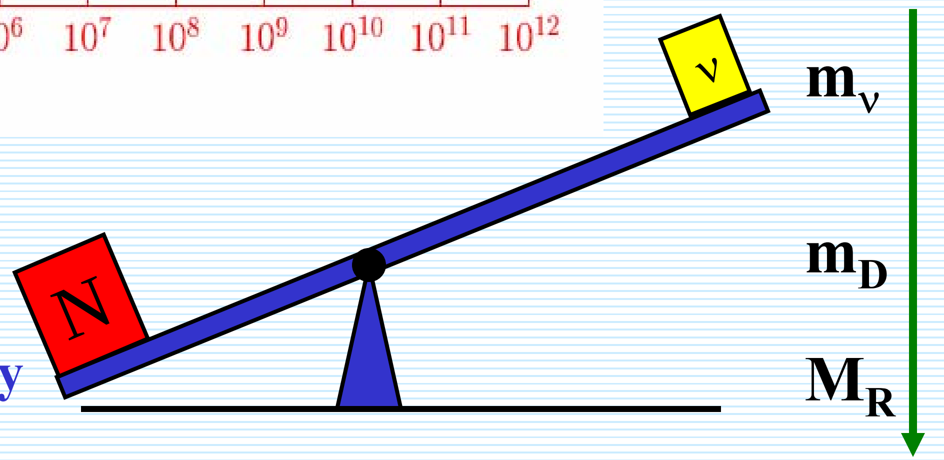
Full 0νββ-decay rate

$$\Gamma_{0\nu} = \frac{1}{2}\frac{G_F^4 m_e^5}{(2\pi)^5} |m_{\beta\beta}|^2 \frac{1}{R^2} |M_F - g_A^2 M_{GT}|^2 F^2(Z) \times \frac{1}{15}\left(\varepsilon_0^5 + 10\varepsilon_0^4 + 40\varepsilon_0^3 + 60\varepsilon_0^2 + 30\varepsilon_0\right)$$

Smallness of neutrino masses - Seesaw

Familiar light masses





Sterile neutrinos ν_R

- fully sterile feels no gauge interaction of any sort. Singlets of the SM symmetry group
- weakly sterile does not feel SM gauge interactions

Left-right symmetric models:

$SU(3)\otimes SU(2)_L\otimes SU(R)_R\otimes U(1)_{B-L}$

T. Yanagida, M. Gell-Mann, P. Ramond, R. Slansky

If ν_R exists $\Rightarrow$ then neutrino are naturaly massive $\Rightarrow$ mass is unprotected by symmetry, can be large at a scale of LNV

Assumption $M_R \gg m_D$

$$\begin{pmatrix} \overline{\nu}_L & \overline{(\nu_R)^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} (\nu_L)^c \\ \nu_R \end{pmatrix}$$

Eigenvalues and eigenvectors

$m_1 = m_D^2/M_R \ll m_D \quad m_2 \approx M_R$

$\nu_1 = \nu_L - m_D/M_R\, (\nu_R)^c \quad \nu_2 = \nu_R + m_D/M_R\, (\nu_L)^c$

Left-right symmetric models SO(10)

Two-charged vector bosons

$W_1^\pm = \cos\zeta\ W_L^\pm + \sin\zeta\ W_R^\pm$

$W_2^\pm = -\sin\zeta\ W_L^\pm + \cos\zeta\ W_R^\pm$

Parameters

$-2\ 10^{-4} \leq \zeta \leq 3.3\ 10^{-3}$ (superallowed β–decay)

$M_1 = 81$ GeV, $M_2 > 715$ GeV, $(M_1/M_2)^2 < 10^{-2}$

See-saw scenario

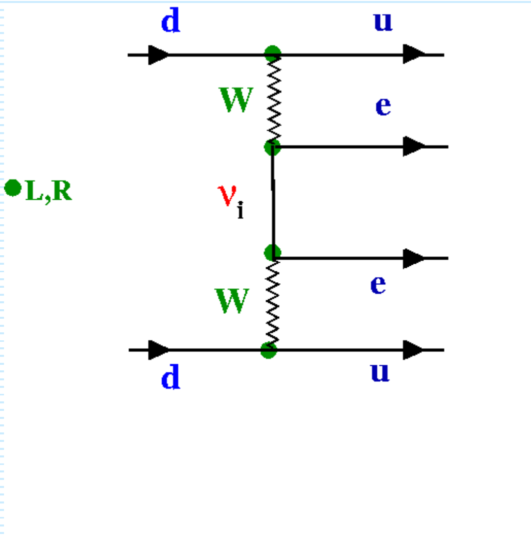
$$\nu_{eL} = \sum_{i=1}^{light} U_{ei}\chi_{iL} + \sum_{i=1}^{heavy} U_{ei} N_{iL}$$

$U_{ei}\chi_{iL}$: large; $U_{ei} N_{iL}$: small

$$(\nu_{eR})^c = \sum_{i=1}^{light} V_{ei}\chi_{iL} + \sum_{i=1}^{heavy} V_{ei} N_{iL}$$

$V_{ei}\chi_{iL}$: small; $V_{ei} N_{iL}$: large

quark level

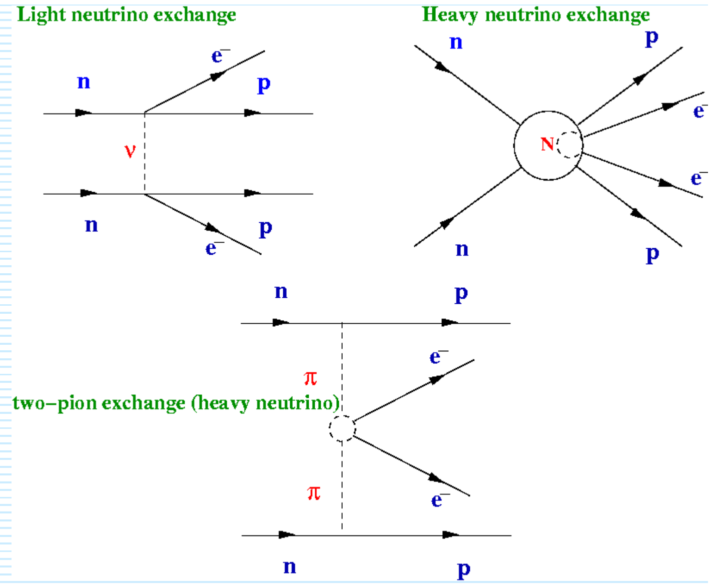


$$P_L \frac{\hat{q}+im}{q^2+m^2} P_L \quad \Rightarrow \quad \frac{im}{q^2}$$

$$P_L \frac{\hat{q}+im}{q^2+m^2} P_R \quad \Rightarrow \quad \frac{i\hat{q}}{q^2}$$

$$P_{L,R} \frac{\hat{q}+iM}{q^2+M^2} P_{L,R} \quad \Rightarrow \quad \frac{i}{M}$$

nucleon level

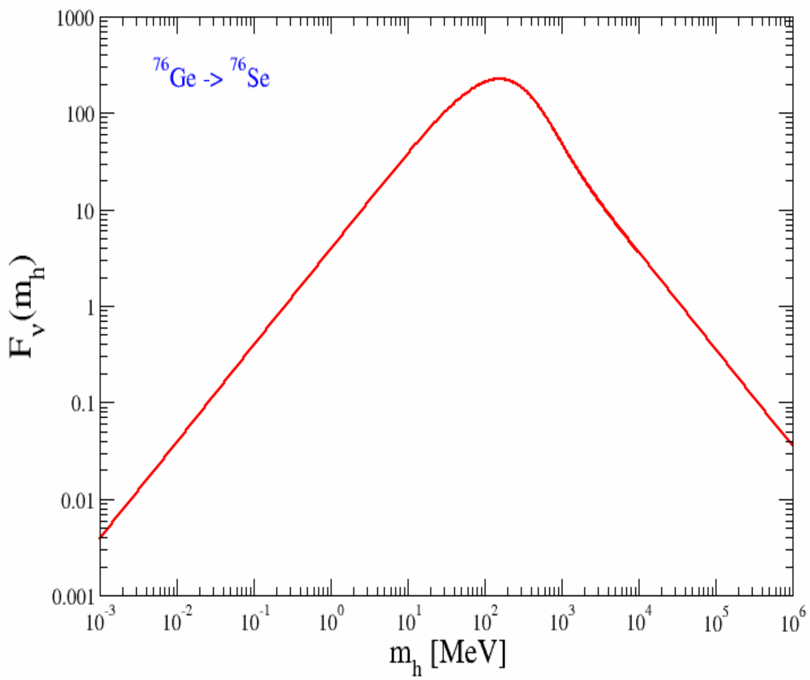


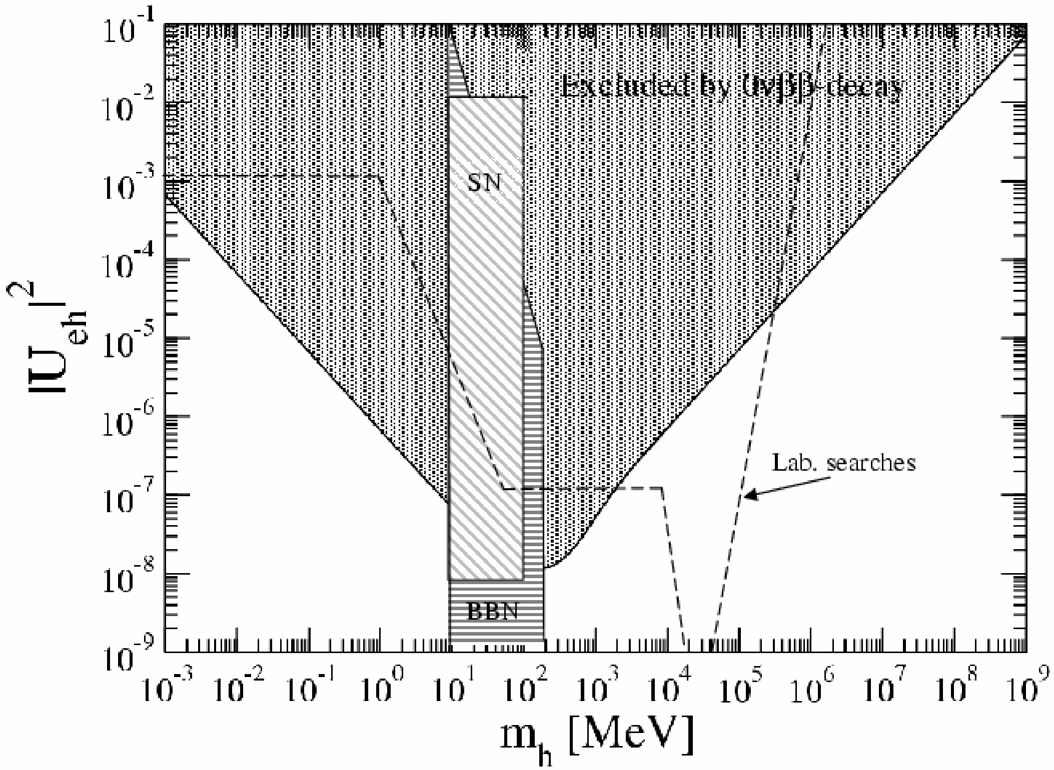
Mechanisms

neutrino	lept.v.	quarkv.	hadr.m.	supp.f.	LNVp.	limit
light	LL	LL	$2n$		$\sum^{light} UUm$	$m_{\beta\beta} \leq 0.5\ eV$
	LR	LR	$2n$	$(M_1/M_2)^2$	$\sum^{light} UV$	$<\lambda> \leq 7\ 10^{-7}$
	LR	LL	$2n$	$\tan\zeta$	$\sum^{light} UV$	$<\eta> \leq 4\ 10^{-9}$
heavy	LL	LL	$2n$	$-$	$\sum^{heavy} U\ U\ m_p/M$	$\eta_N \leq 8\ 10^{-8}$
	RR	RR	$2n$	$(M_1/M_2)^4$	$\sum^{heavy} V\ V\ m_p/M$	
	RR	LL	$2n$	$(\tan\zeta)^4$	$\sum^{heavy} V\ V\ m_p/M$	
	RR	RL	2π	$\tan\zeta\ (M_1/M_2)^2$	$\sum^{heavy} V\ V\ m_p/M$	

Sterile neutrino in 0νββ-decay

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





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

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

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

Analogues of neutrinoless double beta decay

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

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

$e^- + e^- \rightarrow W^- + W^-$

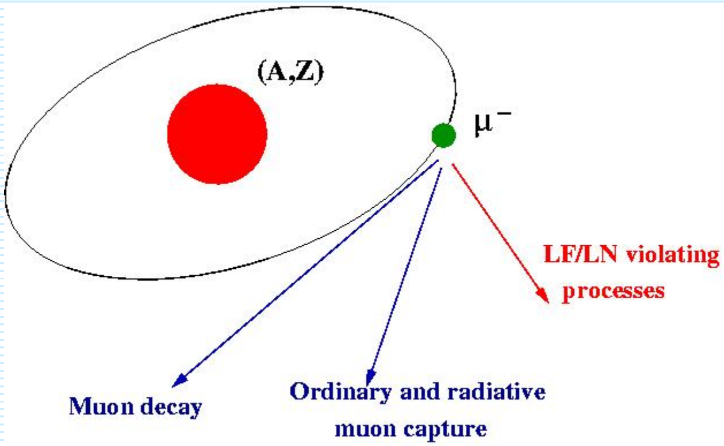
$K^+ \rightarrow \pi^- + \mu^+ + \mu^+$

$m_{\beta\beta}$ → M_{ee}

$$\begin{pmatrix} M_{ee} & M_{e\mu} & M_{e\tau} \\ M_{\mu e} & M_{\mu\mu} & M_{\mu\tau} \\ M_{\tau e} & M_{\tau\mu} & M_{\tau\tau} \end{pmatrix}$$

Muon-positron conversion

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

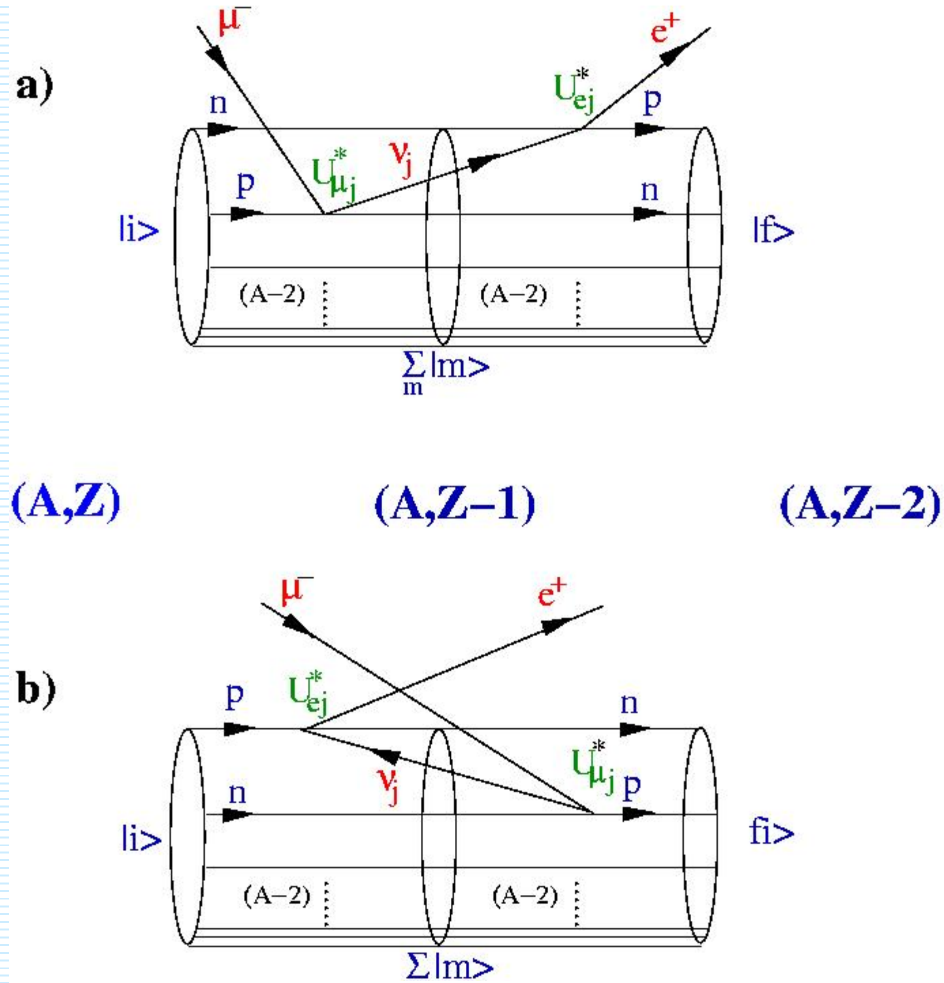


$$\frac{\Gamma_{\mu e^+}}{\Gamma_{\beta\beta}} = 176 \left| \frac{m_{\mu e}}{m_{\beta\beta}} \right|^2$$

$$\frac{\Gamma_{\mu e^+}}{\Gamma_{\mu}} = 1.3\ 10^{-25} \left| \frac{m_{\mu e}}{m_e} \right|^2$$

Domin, Kovalenko, Faessler, Šimkovic, PRD 70, 065501 (2004)

$$\sum_m \frac{|m><m|}{q - E_{\mu^-} + E_m - E_i + i\epsilon_m}$$

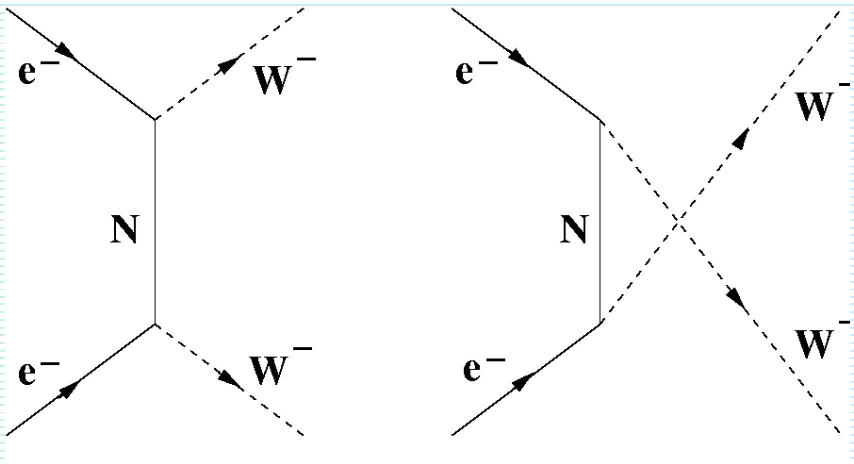


$$\sum_m \frac{|m><m|}{q + E_{e^+} + E_m - E_i + i\epsilon_m}$$

Inverse $0\nu\beta\beta$-decay: $e^- e^- \rightarrow W^- W^-$

$$\frac{d\sigma}{d\cos\theta} = \frac{g^4}{10024\pi M_W^4}[\sum_i M_i |U_{ei}|^2 \left(\frac{t}{(t-M_i^2)} + \frac{u}{(u-M_i^2)}\right)]^2$$

Belanger et al. PRD 53 (1996) 6292



The same LNV parameters as in $0\nu\beta\beta$–decay:

$|m_{\beta\beta}| < 0.55$ eV

$|\eta_N| < 10^{-7}$

Small neutrino masses

$$\frac{d\sigma}{d\cos\theta} = \frac{g^4}{256\pi M_W^4} |m_{\beta\beta}|^2 \leq 1.3 \times 10^{-17}\ fb$$

Not observable at any future collider

Heavy neutrino masses

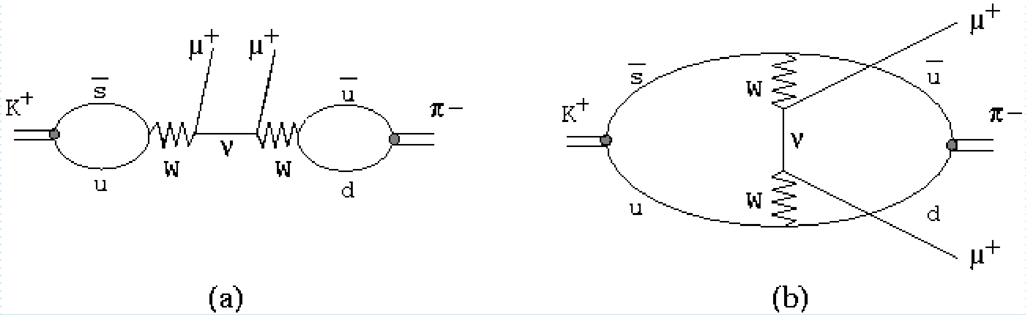
$$\frac{d\sigma}{d\cos\theta} = \frac{g^4}{1024\pi M_W^4} \frac{s^2}{m_p^2} |\eta_N|^2 \leq 4.9 \times 10^{-3}\ fb$$

The hoped-for luminosity at a $\sqrt{s}$=1 TeV NLC is 80 fb^{-1}

K-meson neutrinoless double muon decay

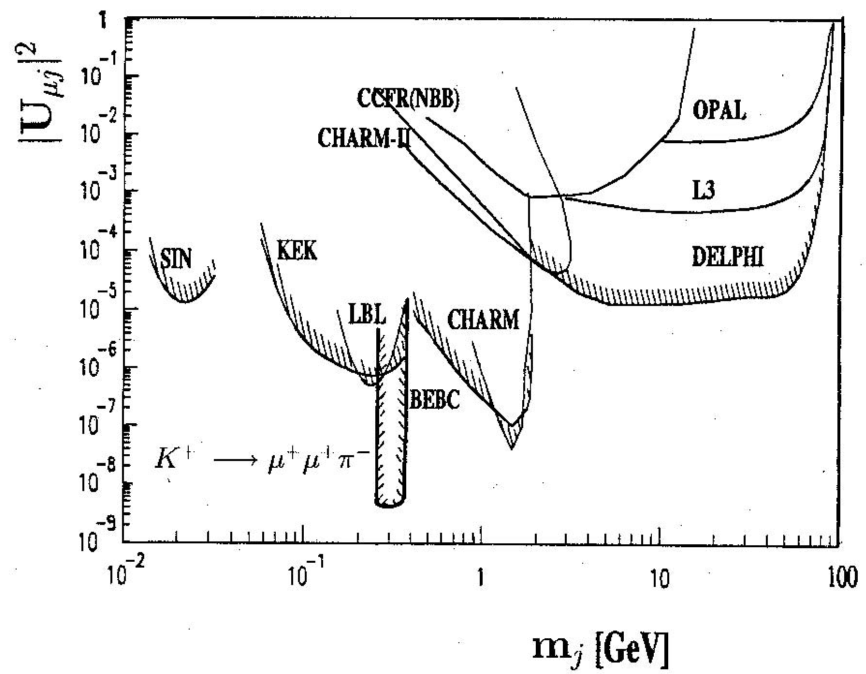
$K^+ \to \pi^- \mu^+ \mu^+$

Dib, Gribanov, Kovalenko, Schmidt, PLB 493 (2000) 82



E865 experiment at BNL:

R < 2.0 10^{-9}



The decay width of sterile neutrino play important role

$(m_j \to m_j + i\Gamma_{\nu\kappa}/2)$

$\nu_k \to e^+\pi^-, \mu^+\pi^- \ldots$

$$245\ MeV \leq m_{\nu_j} \leq 398\ MeV \Rightarrow |U_{\mu j}|^2 \leq (5.6 \pm 1) \times 10^{-9}$$

R-parity breaking mechanisms of the 0νββ-decay

massless ν

MSSM

GUT constrained MSSM (mSUGRA)

Neutralino is dark matter candidate

massive ν

R-parity breaking GUT constrained MSSM

0νββ–decay

Neutralino is not dark matter candidate

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_1^0	Higgs boson	$\tilde{H}_1^0$	Higgsino		
H_2^0	Higgs boson	$\tilde{H}_2^0$	Higgsino		
H_{31}^0	Higgs boson				

R=+1 R=–1

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

$$G_{SM} = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

Superfield	spin 1/2	spin 0	Y	T_3	Q
$\hat{Q}$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$	$+\frac{1}{6}$	$+\frac{1}{6}$ $-\frac{1}{2}$	$+\frac{2}{3}$ $-\frac{1}{3}$
$\hat{U}^c$	$\overline{u}_R$	$\tilde{u}_R^*$	$-\frac{2}{3}$	0	$-\frac{2}{3}$
$\hat{D}^c$	$\overline{d}_R$	$\tilde{d}_R^*$	$+\frac{1}{3}$	0	$+\frac{1}{3}$
$\hat{L}$	$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} \tilde{\nu}_L \\ \tilde{e}_L \end{pmatrix}$	$-\frac{1}{2}$	$+\frac{1}{2}$ $-\frac{1}{2}$	0 -1
$\hat{E}^c$	$\overline{e}_R$	$\tilde{e}_R^*$	$+1$	0	$+1$
$\hat{H}_u$	$\begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}$	$\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$	$+\frac{1}{2}$	$+\frac{1}{2}$ $-\frac{1}{2}$	$+1$ 0
$\hat{H}_d$	$\begin{pmatrix} \tilde{H}_d^+ \\ \tilde{H}_d^0 \end{pmatrix}$	$\begin{pmatrix} H_d^+ \\ H_d^0 \end{pmatrix}$	$-\frac{1}{2}$	$+\frac{1}{2}$ $-\frac{1}{2}$	0 -1

There is no right-handed neutrino superfield !

N	$\overline{\nu}_R$	$\tilde{\nu}_R^*$	0	0	0

MSSM

1973 SUSY introduced as a part of extension of the special relativity

The MSSM is the simplest extension of the SM

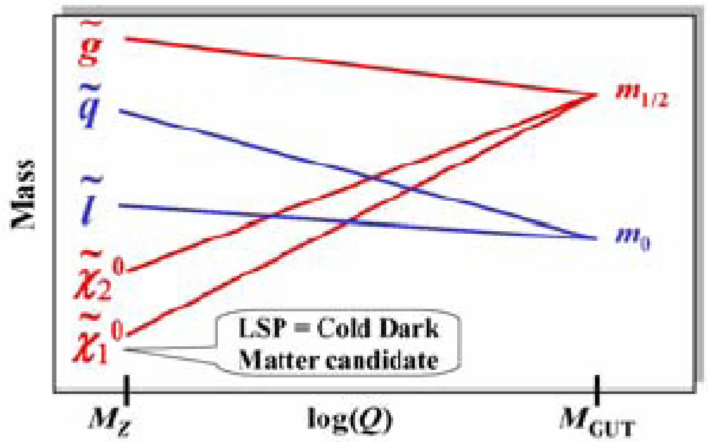
Minimal Supergravity Model (mSUGRA)

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 = Trilinear scalar coupling (A_b-bottom sector, A_t-top sector)

tan β = <H_1>/<H_2>

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

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

R-parity breaking terms In superpotential

$\lambda_{ij<k}$ LLE + λ'_{ijk} LQD + $\lambda''_{ij<k}$ UDD

9 + 27 + 9 = 45 coupling constants

$\lambda'_{11k} * \lambda''_{11k} < 10^{-22}$	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)

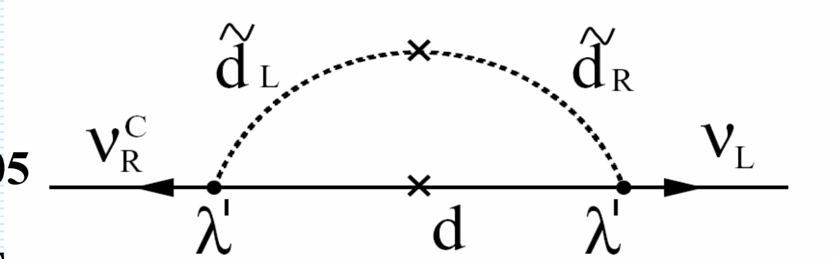
$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m \\ m^T & M_\chi \end{pmatrix}$$

$$\Psi'^T_{(0)} = (\nu_e, \nu_\mu, \nu_\tau, -i\lambda', -i\lambda_3, \tilde{H}^0_1, \tilde{H}^0_2),$$

Radiative corrections to neutrino mass

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

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



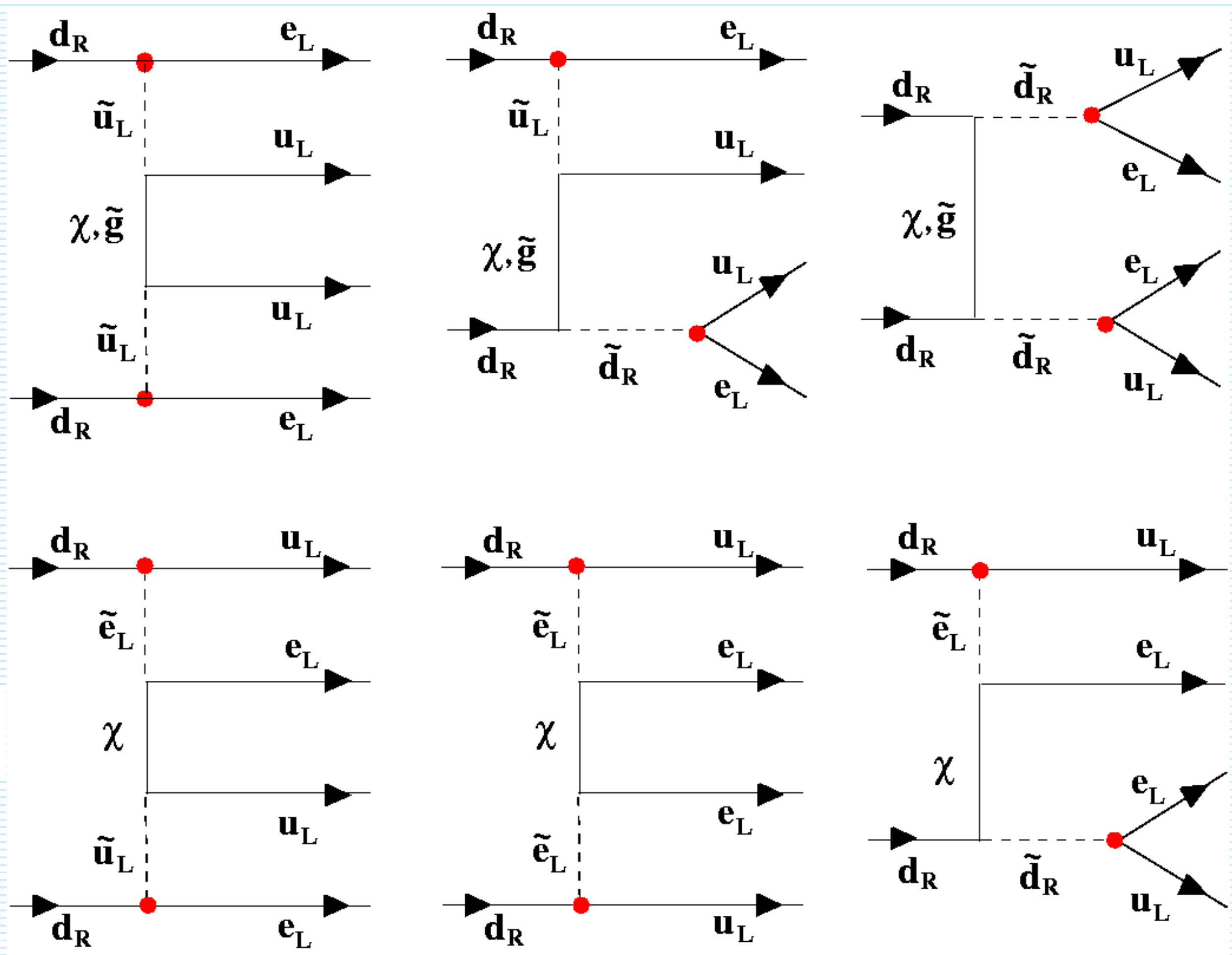
I. gluino/neutralino exchange R-parity breaking SUSY mechanism of the $0\nu\beta\beta$–decay

quark-level diagrams

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

exchange of squarks, neutralinos and gluinos

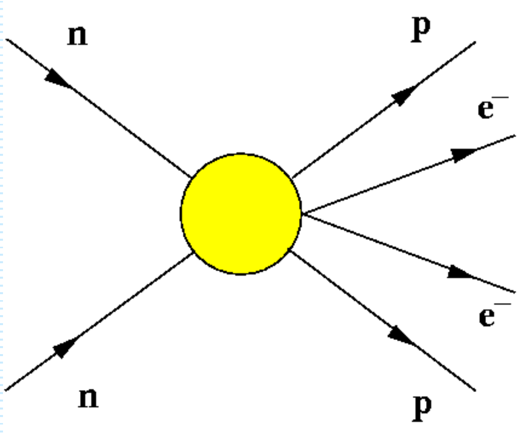
$(\lambda'_{111})^2$ mechanism



● R–parity violation

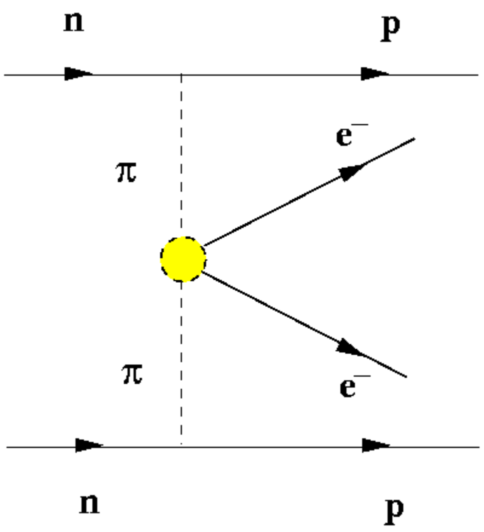
$$\mathcal{L}_{qe} = \frac{G_F^2}{2m_p}\, \bar{e}(1+\gamma_5)e^c \left[\eta^{PS}\; J_{PS} J_{PS} - \frac{1}{4}\eta^T\; J_T^{\mu\nu} J_{T\mu\nu} \right].$$

Two–nucleon mechanism



Can be neglected

Pion–exchange mechanism



The dominant contribution

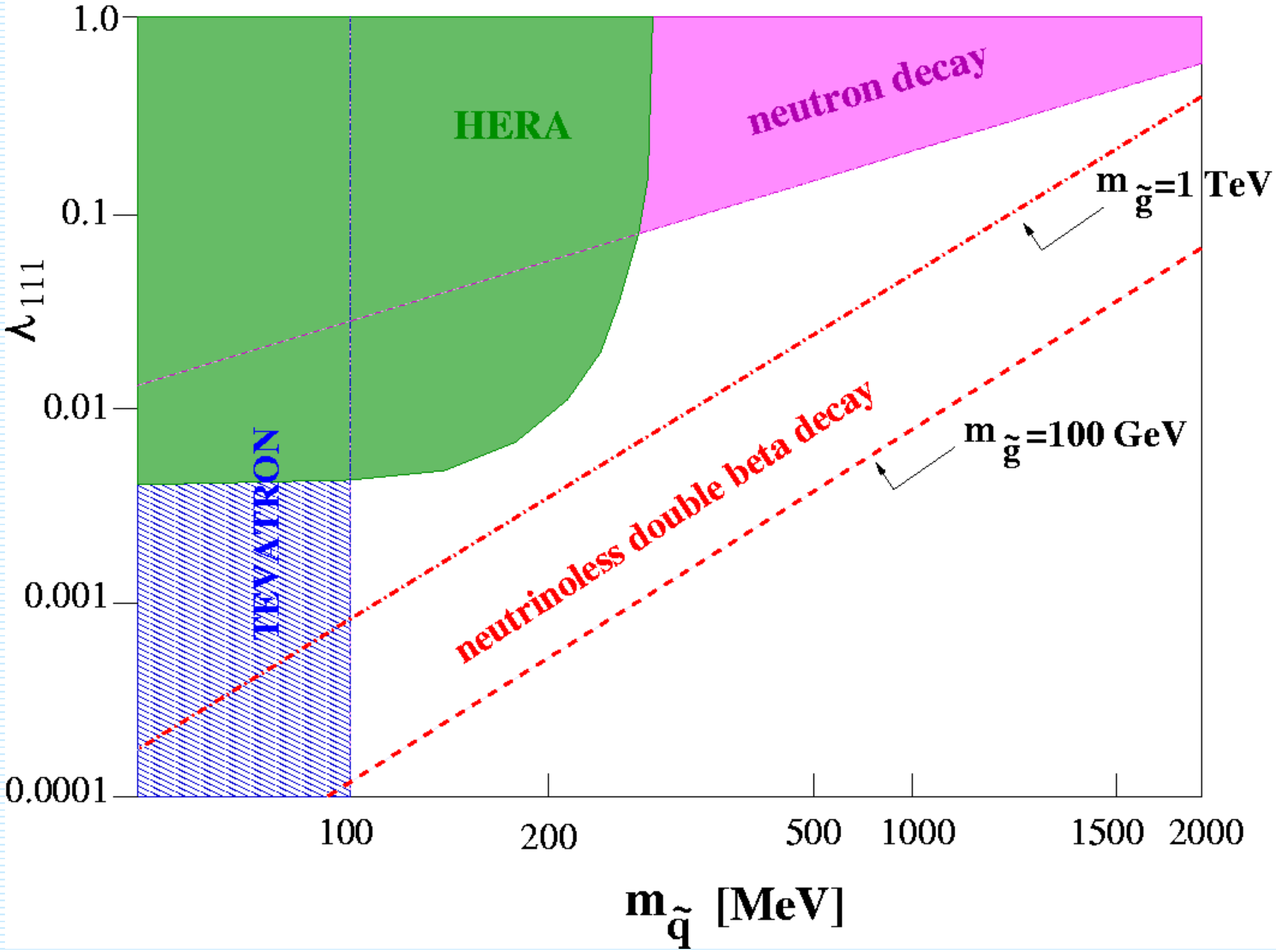
Hadron-level diagrams

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}



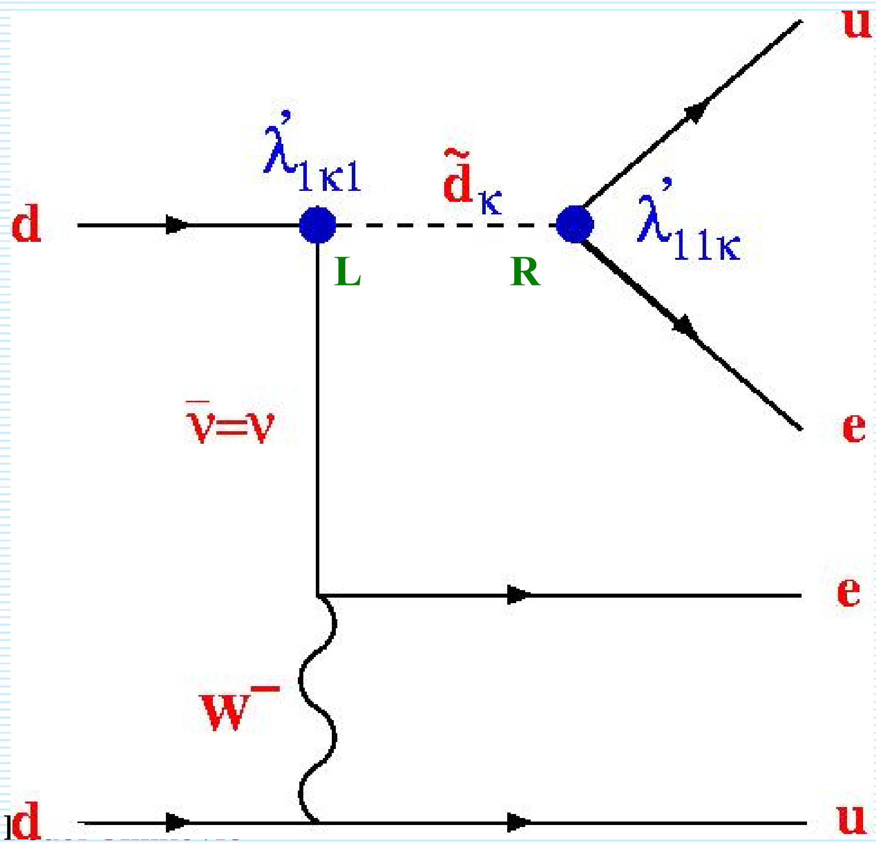
Faessler, F.Š , Kovalenko, PRD 58 (1998) 115004

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

II. Squark mixing SUSY mechanism

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

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



Effective SUSY ν-e Lagrangian

Neutrino vertex

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

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

R-parity violating SUSY vertex

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

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

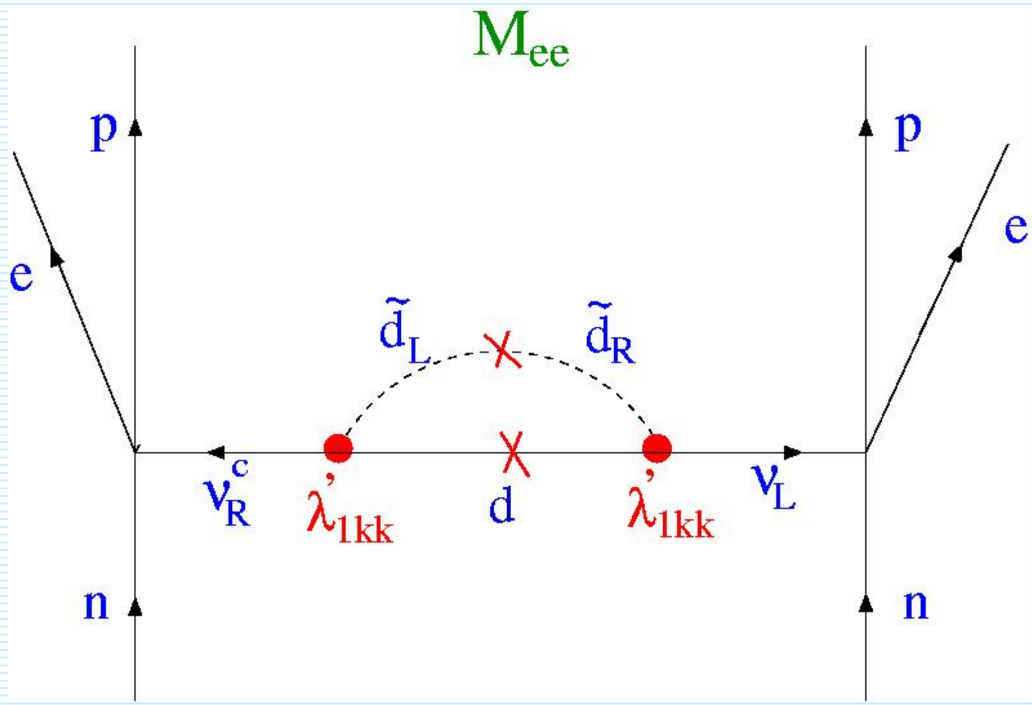
LN-violating parameter

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

III. Neutrino mass loop mechanism of the 0νββ-decay:

Half-life

$$\frac{1}{T^{0\nu}_{1/2}} = \left|\frac{\mathcal{M}^q_{ee}}{m_e}\right|^2 \; |M.E.|^2 \; G_{01}$$



Elements of neutrino mass matrix

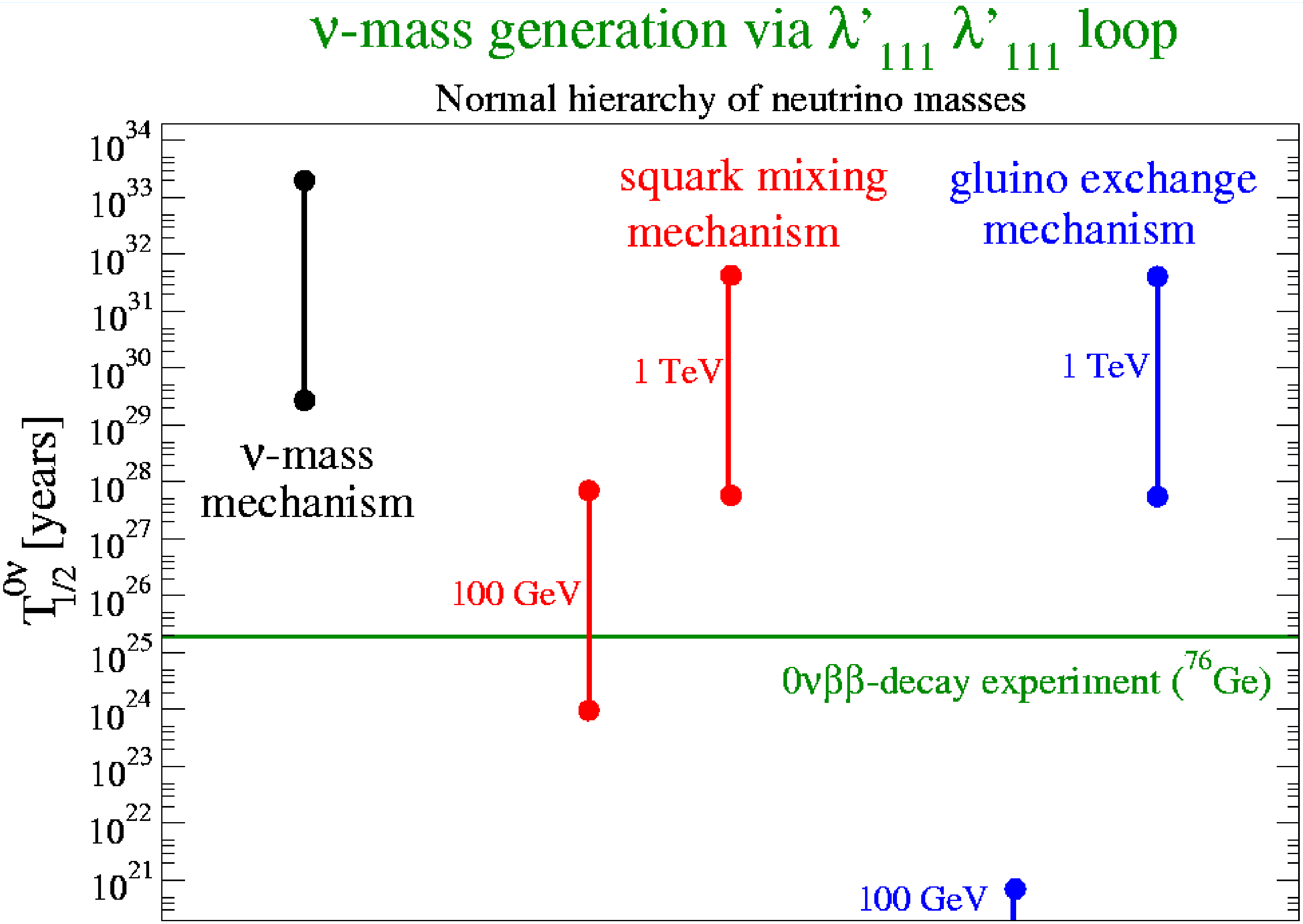
$$\mathcal{M}^q_{ii'} = \frac{3}{16\pi^2}\sum_{jkl}\left\{\left(\lambda'_{ijk}\lambda'_{i'kl}\sum_a V_{ja}V_{la}v^q_{ak}m_{d^a}\right) + \left(\lambda'_{ijk}\lambda'_{i'lj}\sum_a V_{ka}V_{la}v^q_{aj}m_{d^a}\right)\right\}.$$

Loop integrals

$$v^q_{jk} = \frac{\sin 2\theta^k}{2}\left(\frac{\ln x_2^{jk}}{1-x_2^{jk}} - \frac{\ln x_1^{jk}}{1-x_1^{jk}}\right)$$

$$x_1^{jk} \equiv m^2_{dj}/m^2_{\tilde{d}^k_1}, \qquad x_2^{jk} \equiv m^2_{dj}/m^2_{\tilde{d}^k_2}$$

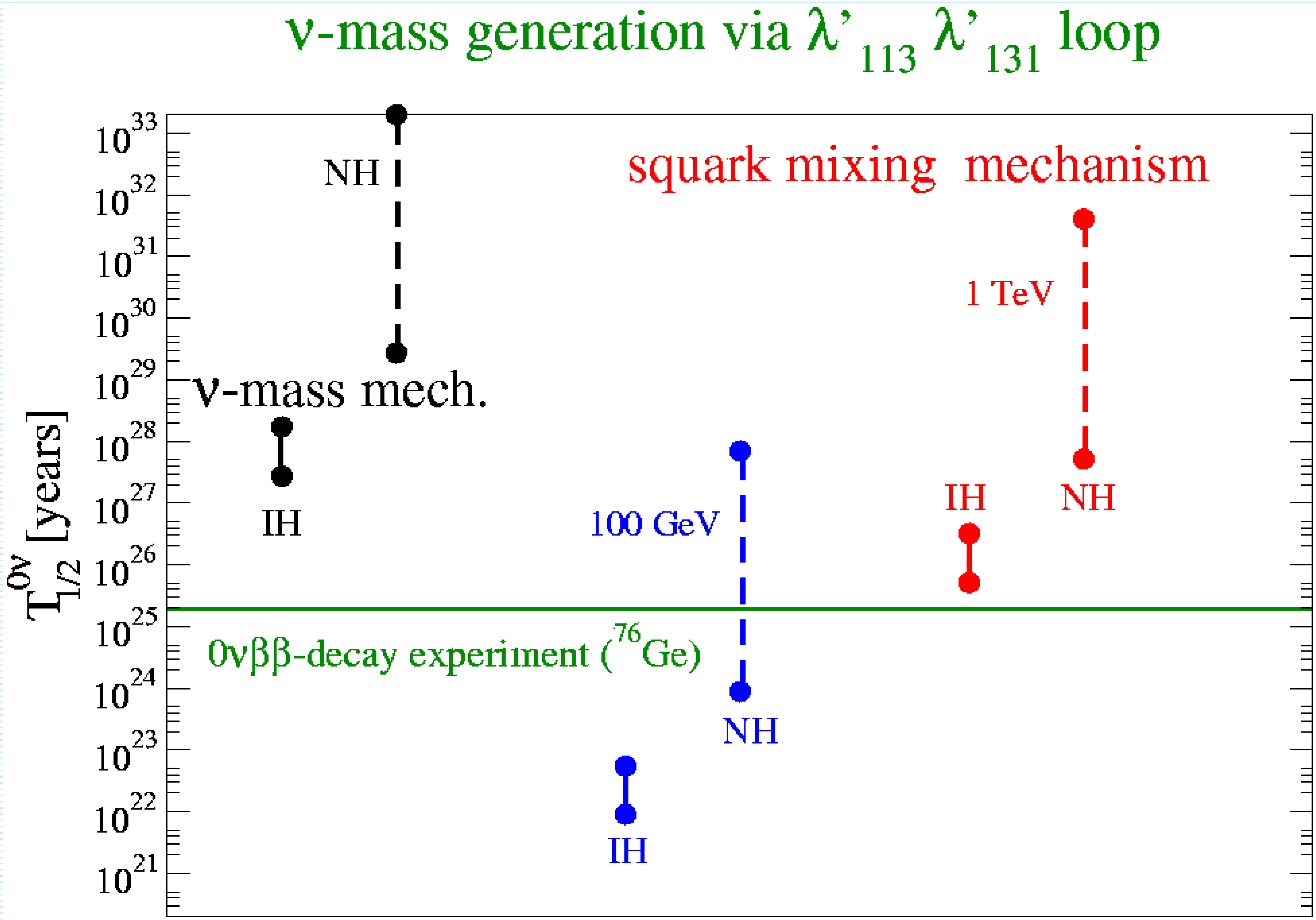
Gluino exchange (squark mixing mech.) are favored



Preliminary

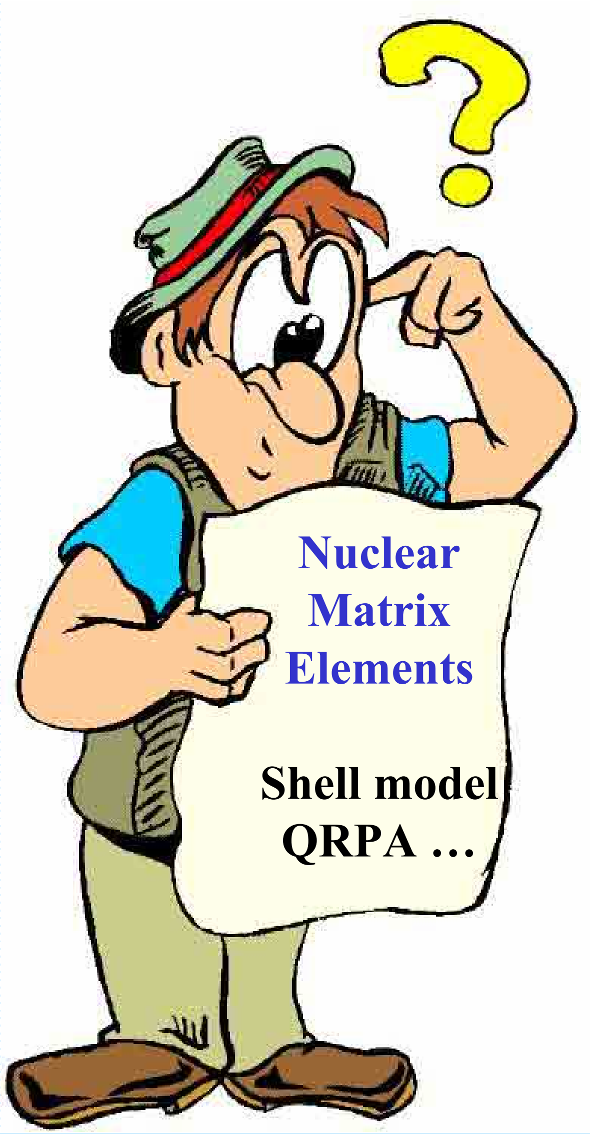
ν-mass generation via $\lambda'_{111}\lambda'_{111}$ loop practially excluded due to gluino exch. mech.

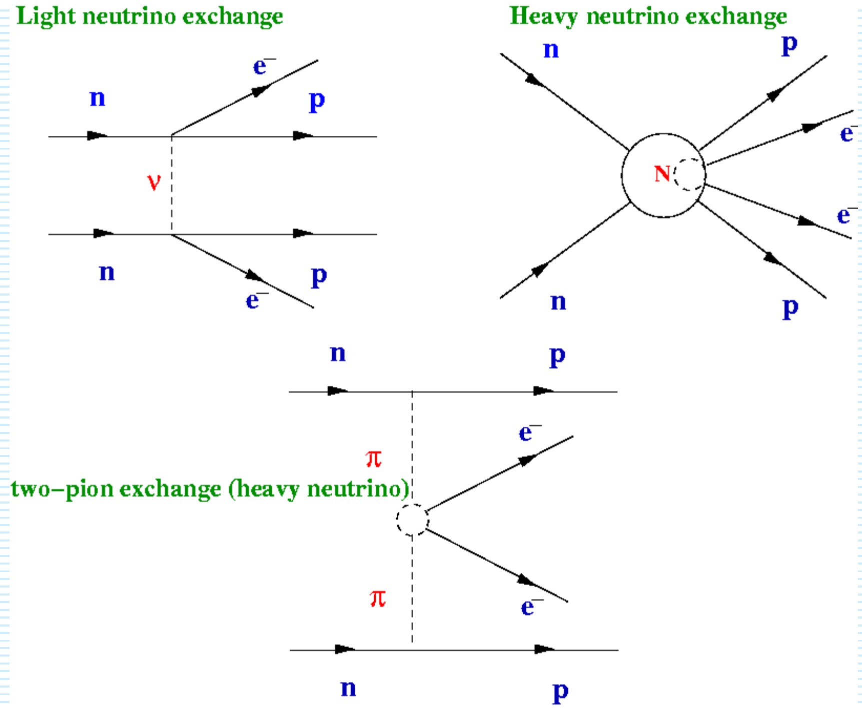
Squark mixing mech. is favored



Preliminary

$0\nu\beta\beta$–decay
Nuclear Matrix Elements





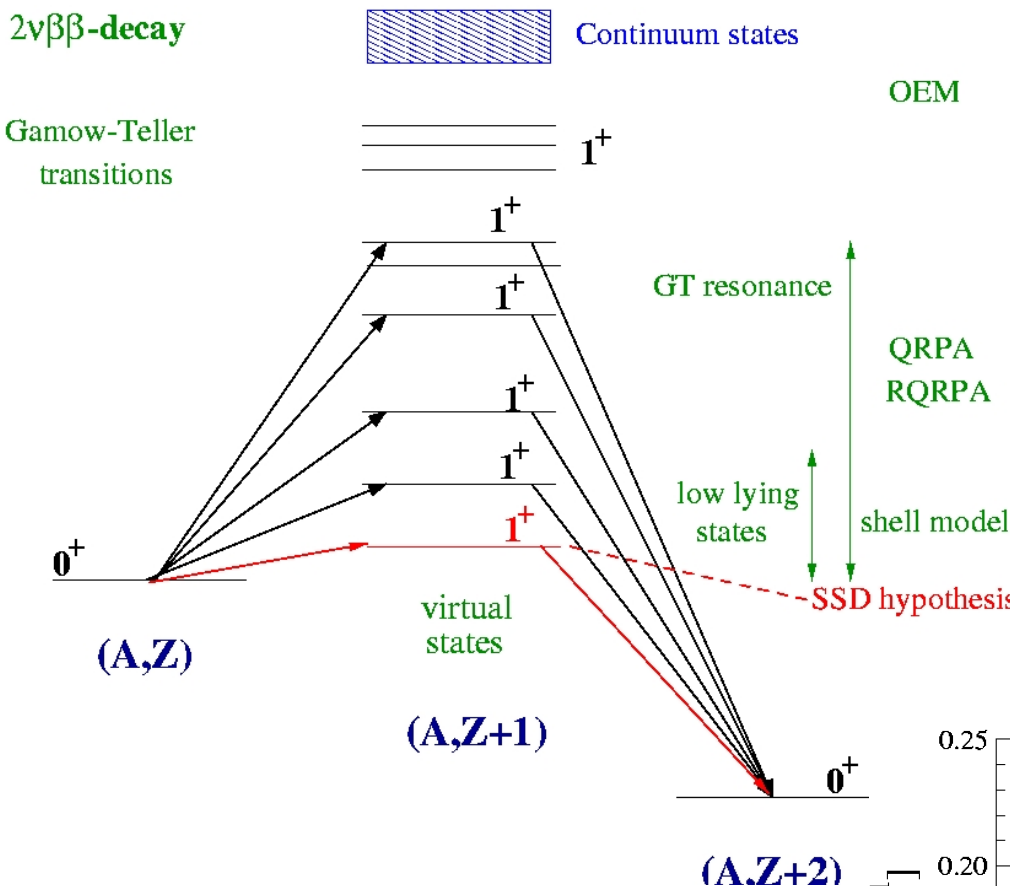
$$\left(T_{1/2}^{0\nu}\right)^{-1} = \eta^{LNV}\, G^{0\nu}\, \left|M^{0\nu}\right|^2$$

NME´s: which mechanism, which transition?

It is a complex task

- **Medium and heavy open shell nuclei with a complicated nuclear structure**
- **The construction of complete set of the states of the intermediate nucleus is needed**
- **Many-body problem $\Rightarrow$ approximations needed**
- **Nuclear structure input has to be fixed**

2νββ-decay nuclear matrix elements

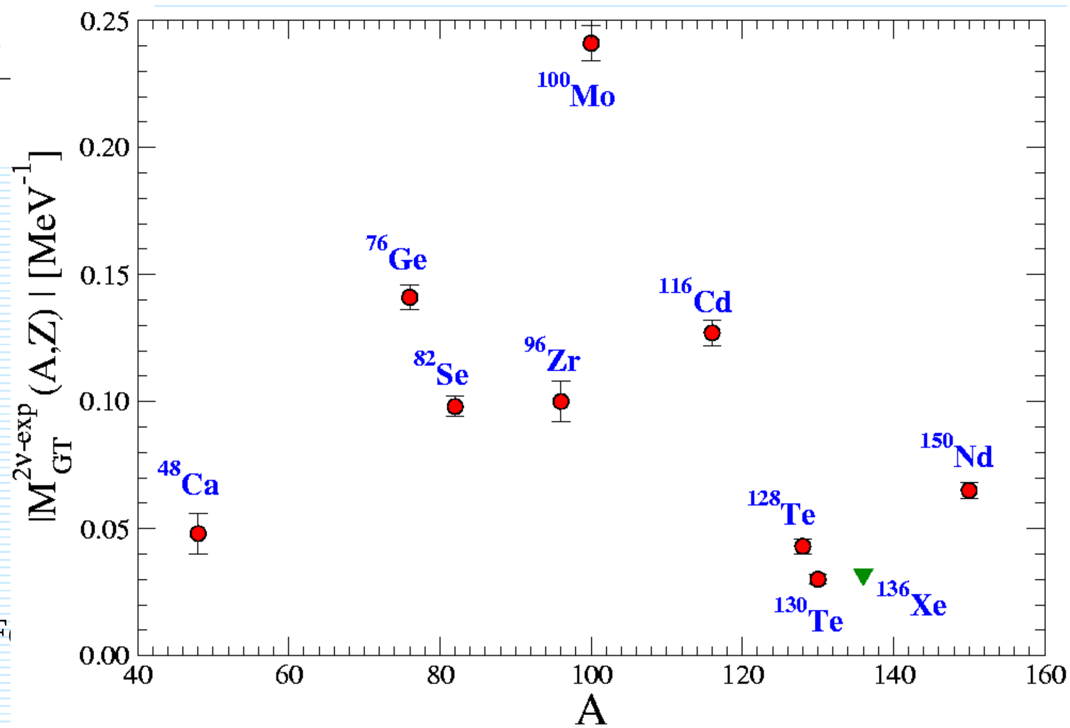


$$(T^{2\nu}_{1/2})^{-1} = G^{2\nu} |M^{2\nu}_{GT}|^2$$

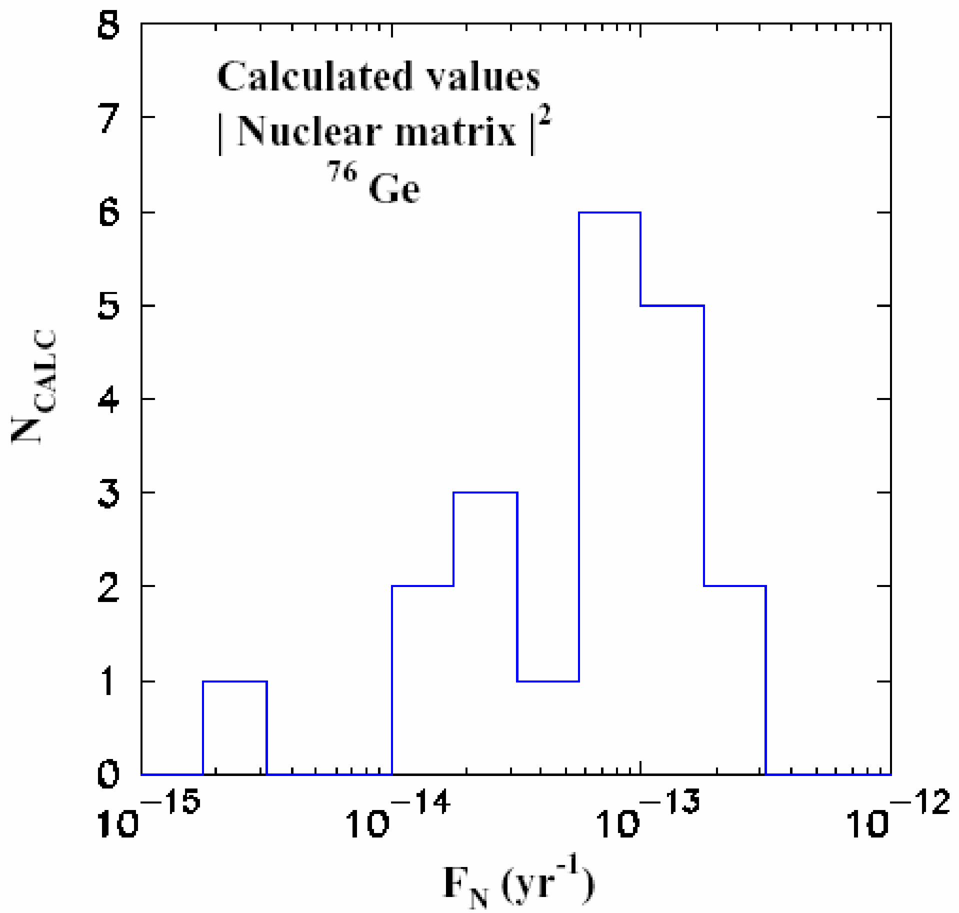
Deduced from measured $T_{1/2}^{2\nu}$

$$M^{2\nu}_{GT} = \sum_m \frac{< 0^+_f || \tau^+ \sigma || 1^+_m >< 1^+_m || \tau^+ \sigma || 0^+_i >}{E_m - E_i + \Delta}$$

difference: by factor ~ 10



Particle physicists are interested in NME´s



- absolute ν mass scale
- CP violating Majorana phases

Uncertainties in 0νββ–decay NME?

This suggest an uncertainty of NME as much as factor 5

Is it really so bad?!

Bahcall, Murayama, Pena-Garay,
Phys. Rev. D 70, 033012 (2004)

Nuclear structure approaches

$$H\,\Psi = E\,\Psi$$

We can not solve the full problem in the complete

Systematical study of the 0νββ-decay NME

Projected mean field (Vampir)

- **Tomoda, Faessler, Schmid, Grummer, PLB 157, 4 (1985)**

Shell model:
- **Haxton, Stephensson, Prog. Part. Nucl. Phys. 12, 409(1984)**
- **Caurier, Nowacki, Poves, Retamosa, PRL 77, 1954 (1996)**
- **E. Caurier, E. Martinez-Pinedo, F. Nowacki, A. Poves, A. Zuker, Rev. Mod. Phys. 77, 427 (2005).**

QRPA, RQRPA: About 10 papers 1987→ 2006

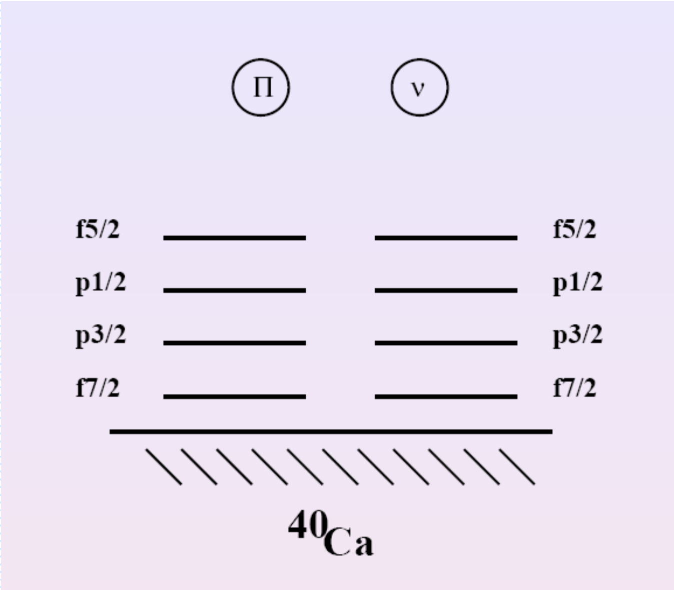
Other approaches:

Shell Model Monte Carlo (1996), Operator Expansion Method (1988-1994)...

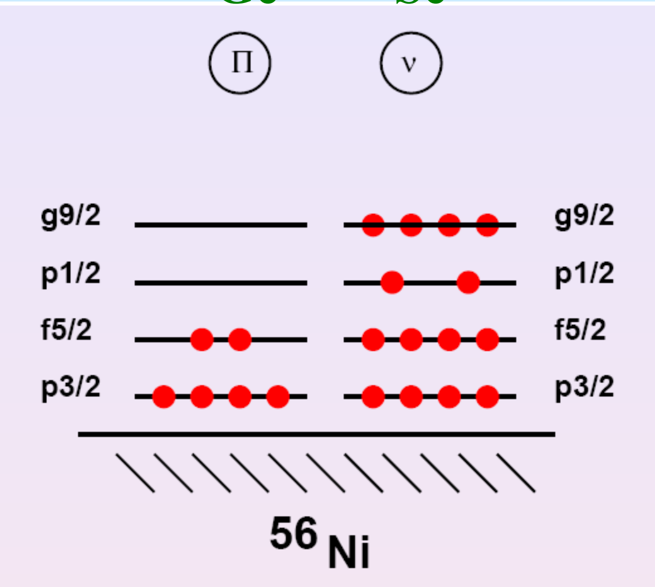
Shell Model

- Define a valence space
- Derive an effective interaction $H\,\Psi = E\,\Psi \rightarrow H_{eff}\,\Psi_{eff} = E\,\Psi_{eff}$
- Build and diagonalize Hamiltonian matrix (10^{10})
- Transition operator $<\Psi_{eff}\,|\,O_{eff}\,|\,\Psi_{eff}>$
- Some phenomenological input needed
  energy of states, systematics of B(E2) and GT transitions (quenching f.)

$^{48}Ca \rightarrow {}^{48}Ti$



$^{76}Ge \rightarrow {}^{76}Se$



Small calculations

$^{76}Se_{42}$ in the valence
6 protons and 14 neutrons

The 0νββ−decay NME within SRQRPA

Particle number condition

i) Uncorrelated BCS ground state

$Z=\langle BCS|Z|BCS\rangle$

$N=\langle BCS|N|BCS\rangle$

QRPA, RQRPA

ii) Correlated RPA ground state

$Z=\langle RPA|Z|RPA\rangle$

$N=\langle BCS|N|BCS\rangle$

SRQRPA

Complex numerical procedure

BCS and QRPA equations are coupled

Pauli exclusion principle

i) violated (QBA)

$[A,A^+] =\langle BCS|[A,A^+]|BCS\rangle$

QRPA

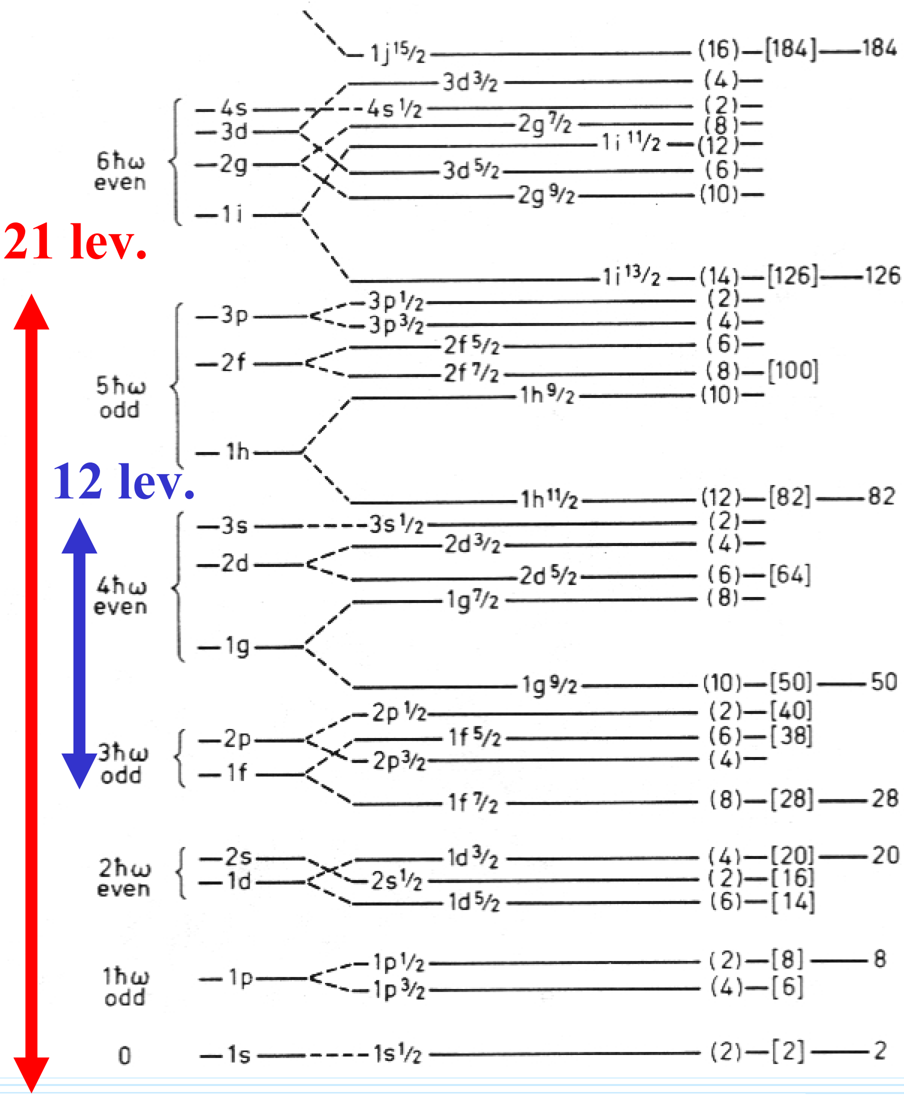
ii) Partially restored (RQBA)

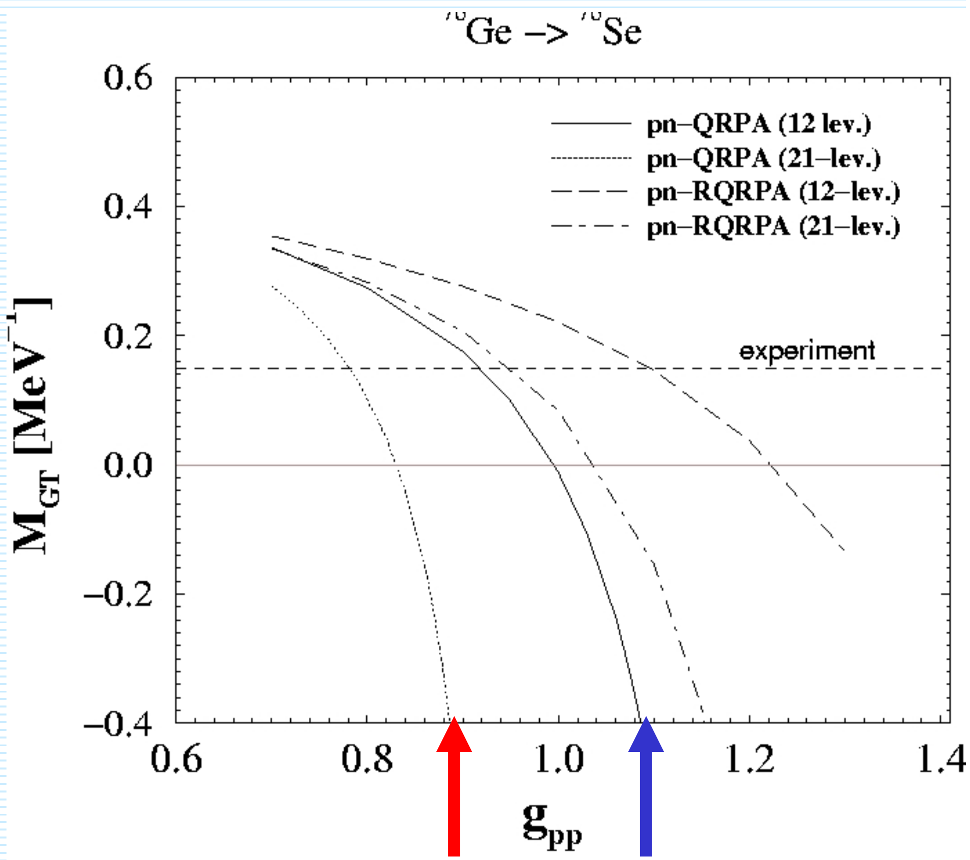
$[A,A^+] =\langle RPA|[A,A^+]|RPA\rangle$

RQRPA, SRQRPA

QRPA
2νββ-decay NME

$$H = H_0 + g_{ph}\, H_{ph} + g_{pp}\, H_{pp}$$





Collapse of the QRPA
21 l.m.s. 12 l.m.c

Only Bratislava-Tuebingen group

Fedor Simkovic

The 0νββ-decay NME (light ν exchange mech.)

The 0νββ-decay half-life

$$\frac{1}{T_{1/2}} = G^{0\nu}(E_0, Z)|M'^{0\nu}|^2|\langle m_{\beta\beta}\rangle|^2 ,$$

NME= sum of Fermi, Gamow-Teller and tensor contributions

$$M'^{0\nu} = \left(\frac{g_A}{1.25}\right)^2 \langle f| - \frac{M_F^{0\nu}}{g_A^2} + M_{GT}^{0\nu} + M_T^{0\nu}|i\rangle$$

Neutrino potential (about $1/r_{12}$)

$$H_K(r_{12}) = \frac{2}{\pi g_A^2} R \int_0^\infty f_K(qr_{12}) \frac{h_K(q^2) q dq}{q + E^m - (E_i + E_f)/2}$$

$$f_{F,GT}(qr_{12}) = j_0(qr_{12}), \qquad f_T(qr_{12}) = -j_2(qr_{12})$$

Form-factors:
finite nucleon size

$$h_F = g_V^2(q^2)$$

$$h_{GT} = g_A^2 \left[1 - \frac{2}{3}\frac{\vec{q}^2}{\vec{q}^2+m_\pi^2} + \frac{1}{3}\left(\frac{\vec{q}^2}{\vec{q}^2+m_\pi^2}\right)^2\right]$$

$$h_T = g_A^2 \left[\frac{2}{3}\frac{\vec{q}^2}{\vec{q}^2+m_\pi^2} - \frac{1}{3}\left(\frac{\vec{q}^2}{\vec{q}^2+m_\pi^2}\right)^2\right]$$

Induced pseudoscalar coupling (pion exchange)

$$M_{K=F,GT,T} = \sum_{J^\pi,k_i,k_f,\mathcal{J}} \sum_{pnp'n'} (-1)^{j_n+j_{p'}+J+\mathcal{J}} \sqrt{2\mathcal{J}+1} \begin{Bmatrix} j_p & j_n & J \\ j_{n'} & j_{p'} & \mathcal{J} \end{Bmatrix}$$

$$\langle p(1), p'(2); \mathcal{J} \parallel f(r_{12}) O_K f(r_{12}) \parallel n(1), n'(2); \mathcal{J}\rangle$$

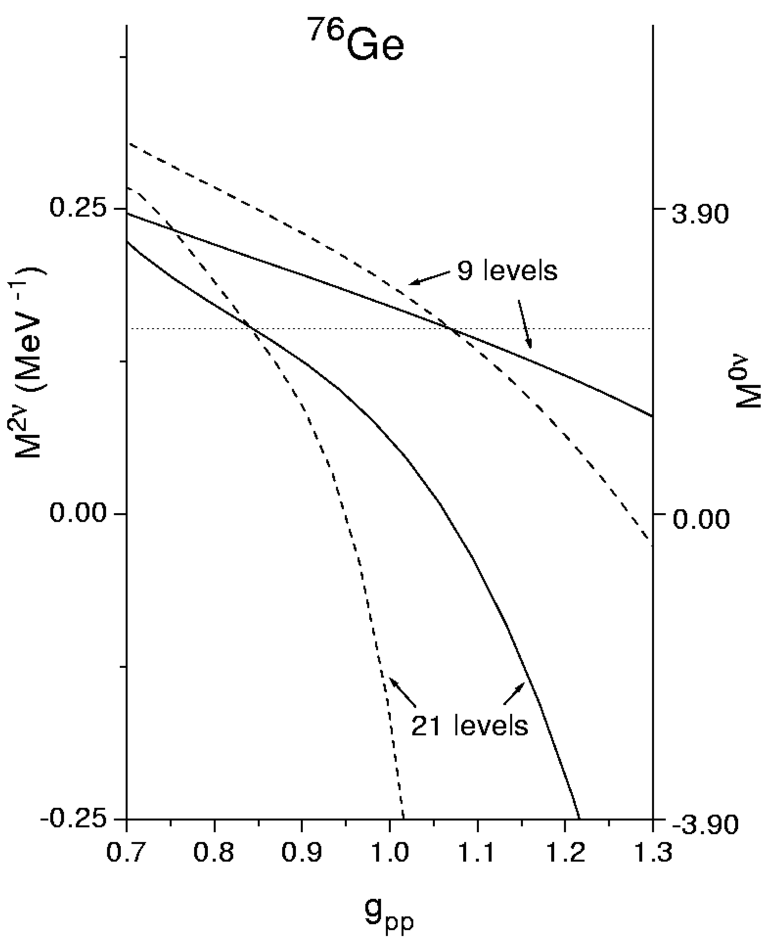
$$\times \langle 0_f^+ ||[c_{p'}^+ \tilde{c}_{n'}]_J|| J^\pi k_f\rangle\langle J^\pi k_f|J^\pi k_i\rangle\langle J^\pi k_f||[c_p^+ \tilde{c}_n]_J||0_i^+\rangle$$

Jastrow f. s.r.c.

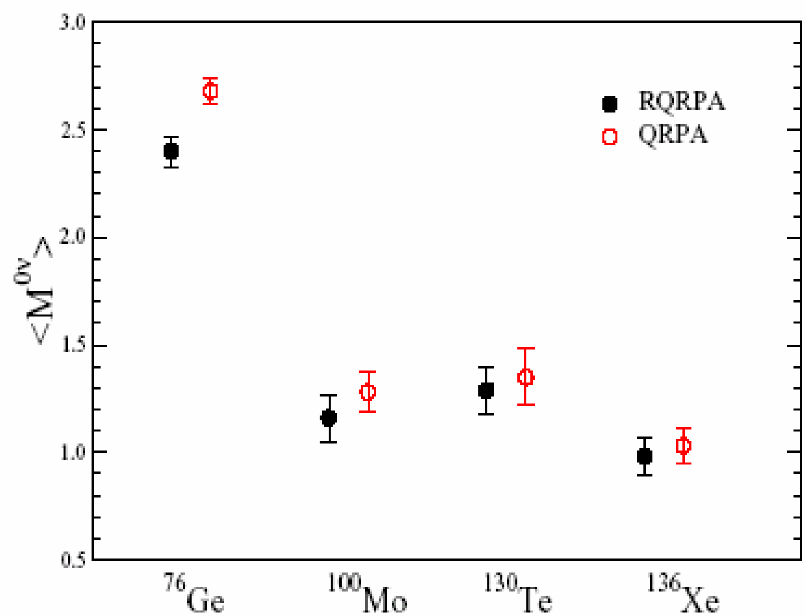
J^π = $0^+, 1^+, 2^+$... $0^-, 1^-, 2^-$...

The 0νββ-decay NME: g_{pp} fixed to 2νββ-decay

Each point: (3 basis sets) x (3 forces) = 9 values

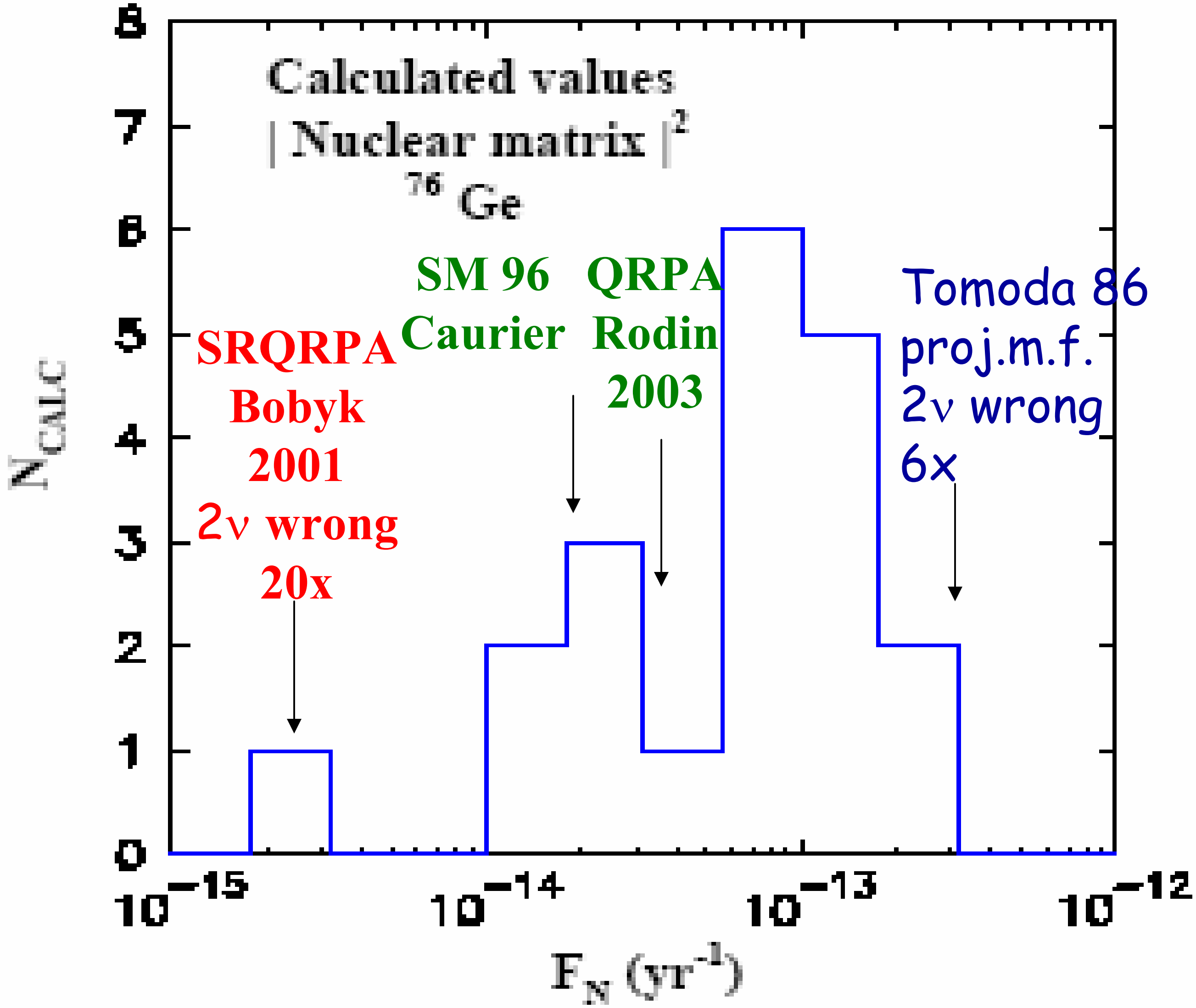


By adjusting of g_{pp} to 2νββ-decay half-life the dependence of the 0νββ-decay NME on other things that are not a priori fixed is essentially removed



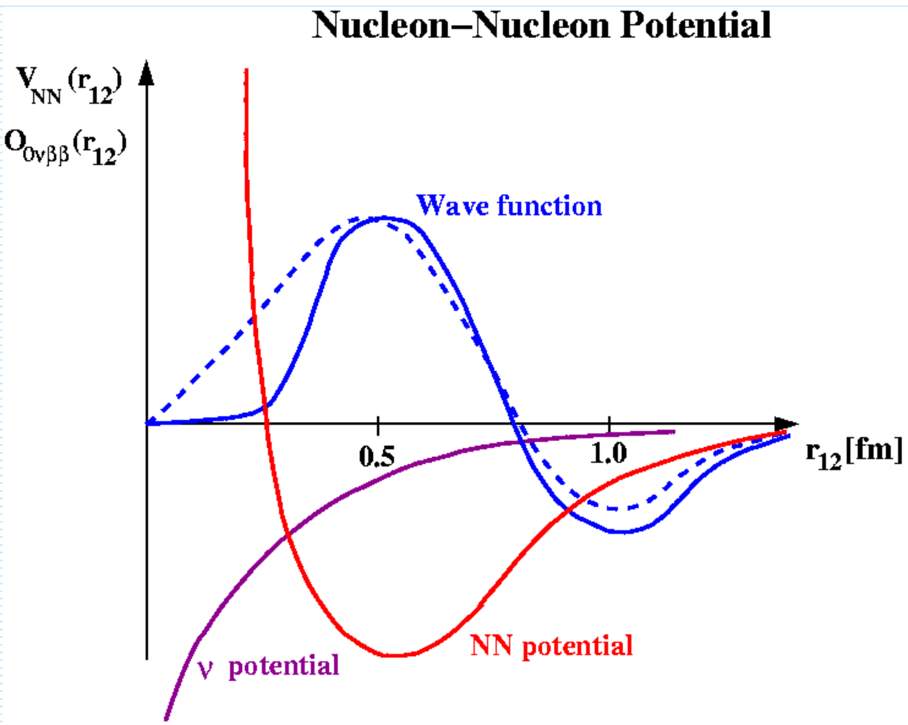
Rodin, Faessler, Šimkovic,Vogel,
Phys. Rev. C 68, 044302 (2003)

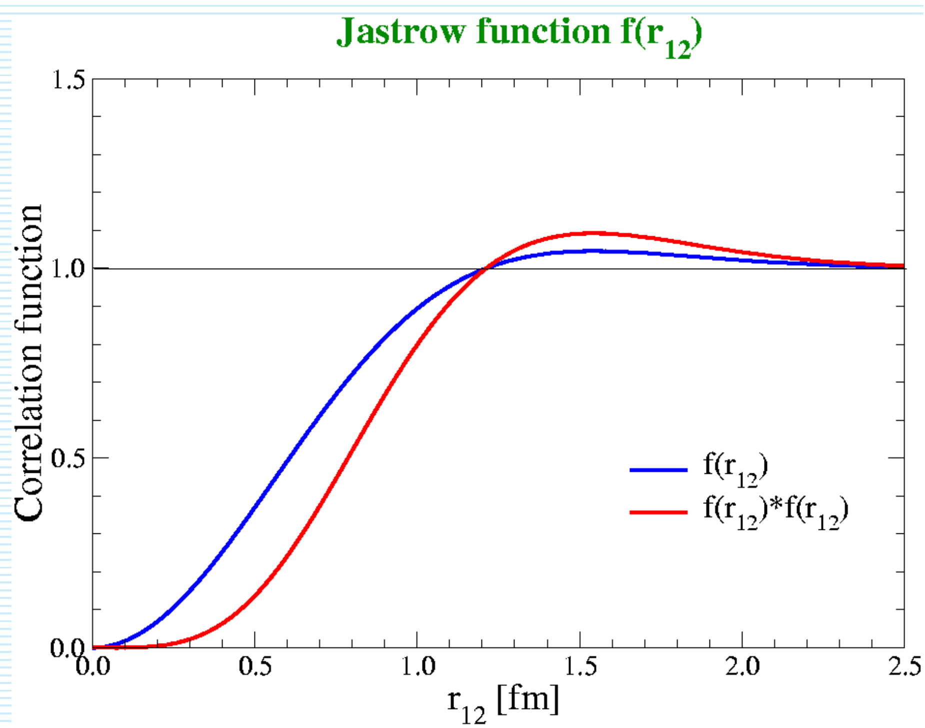
The outliers predict wrong $2\nu\beta\beta$ halflife. The matrix elements of SM and Rodin et al. are quite close.



Two-nucleon short range correlations: a question of physics

There is no double counting in QRPA
- QRPA violates Pauli exclusion principle
- 1/(0.2 fm) ~ 1 GeV

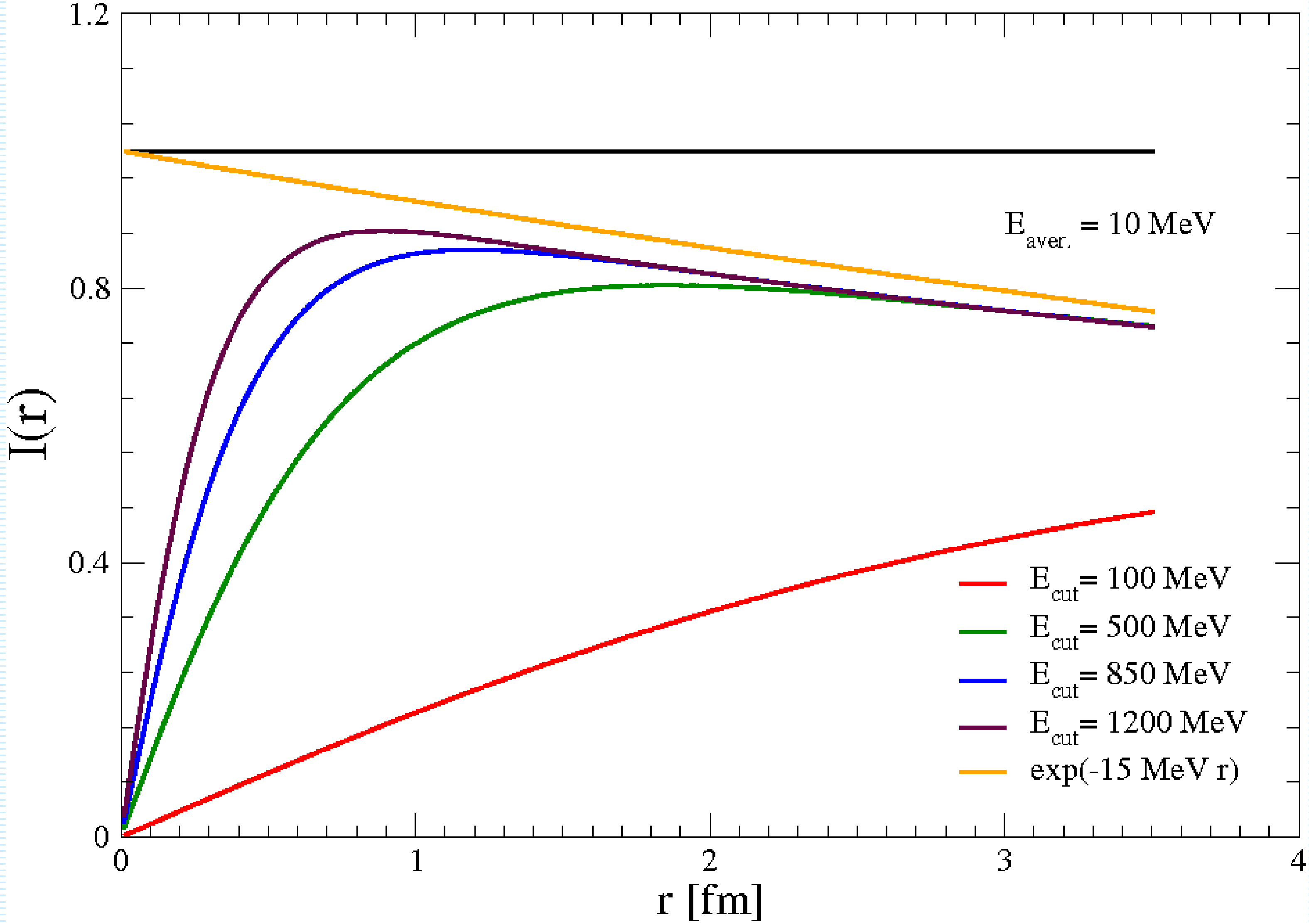


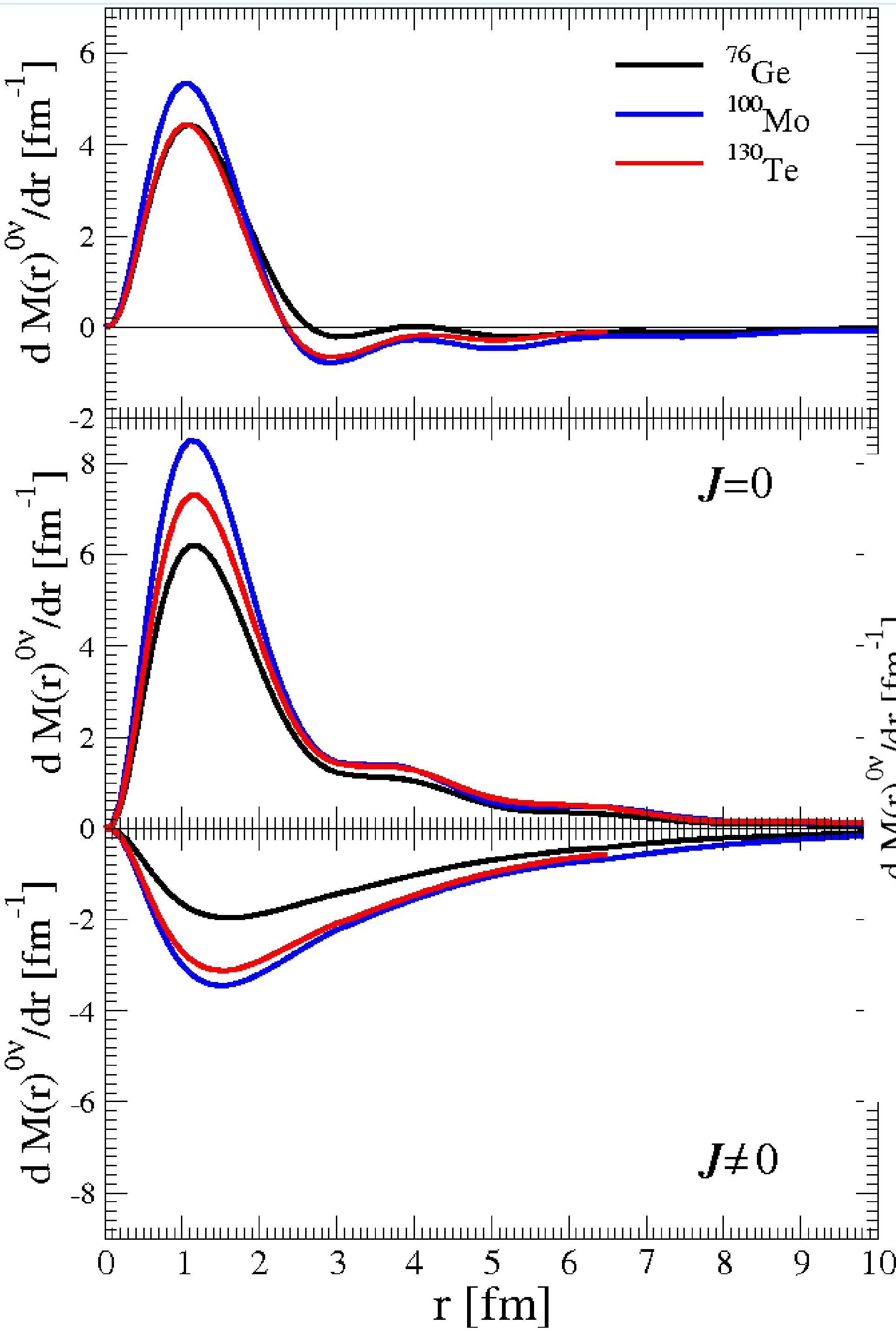


Finite nucleon size (formfactors) versus short range correlations.

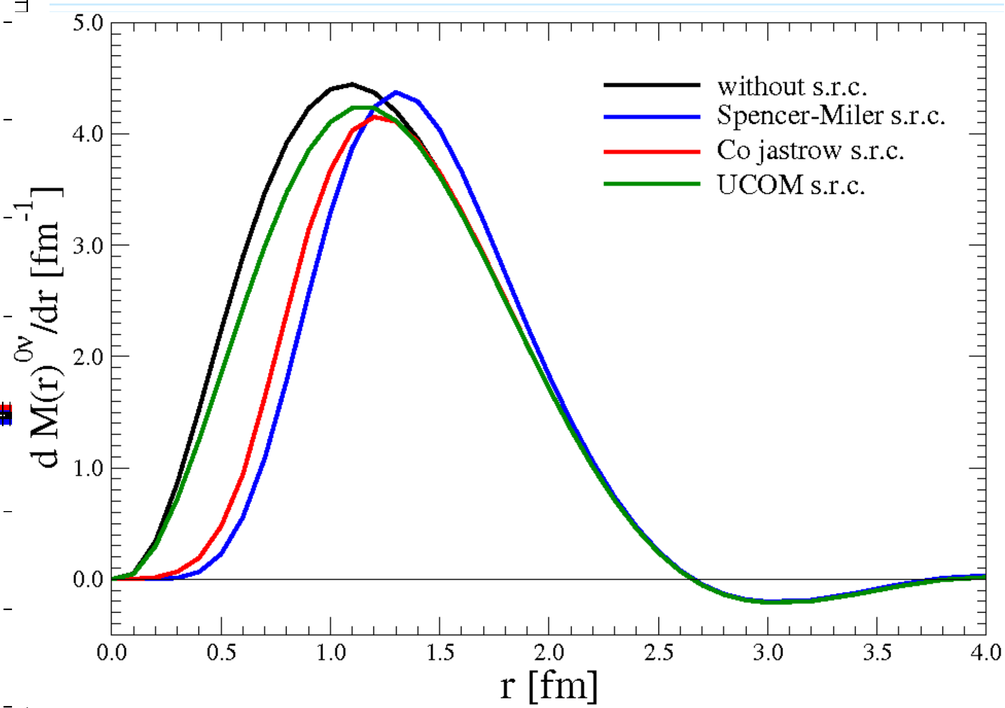
Neutrino potential: I(r)/r

$$I(r) = \frac{2}{\pi}\int_0^\infty \frac{\sin(qr)}{(q+E_{aver})}\frac{dq}{(1+q^2/E_{cut}^2)^4}$$



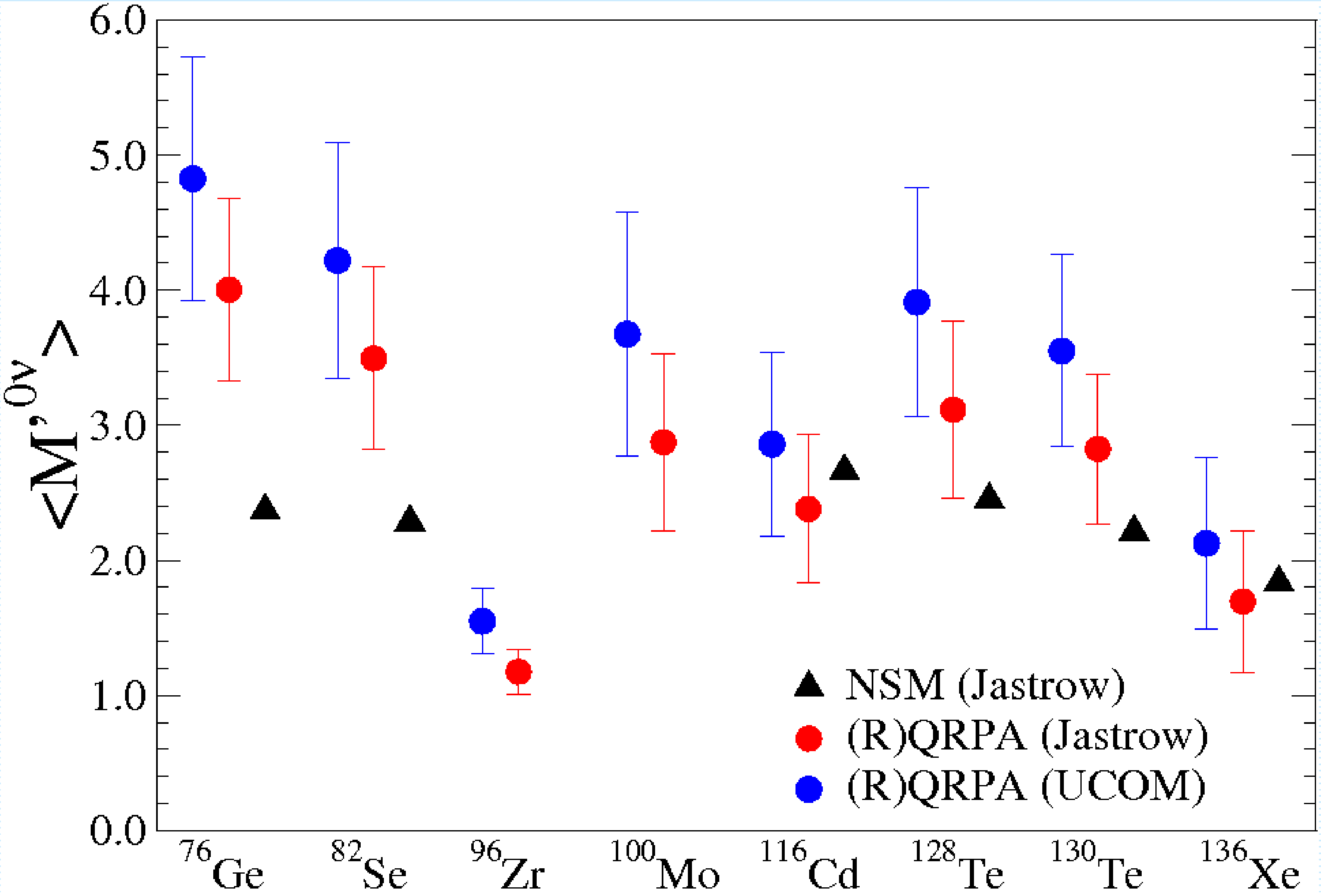


r-dependence of the 0νββ-decay NME



Neutrinoless Double Beta Decay Nuclear Matrix Elements

Light Majorana Neutrino Exchange Mechanism



Main uncetainty due to g_A

QRPA, RQRPA: **F.Š., A. Faessler, V. Rodin, P. Vogel, to be submitted**
shell model: **E. Caurier, E. Martinez-Pinedo, F. Nowacki, A. Poves, A. Zuker, Rev. Mod. Phys. 77, 427 (2005).**

Nuclear deformation

$$\beta = \sqrt{\frac{\pi}{5}} \frac{Q_p}{Z r_c^2}$$

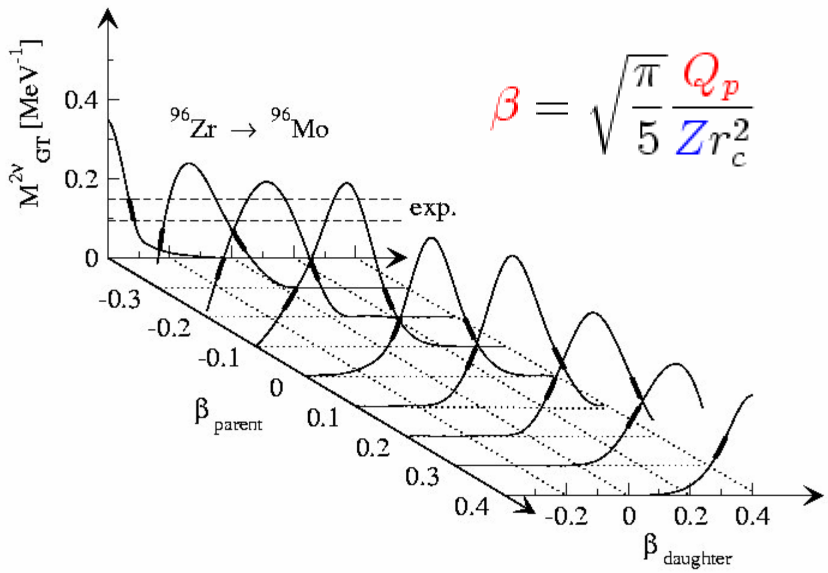
Exp. I (nuclear reorientation method)
Exp.II (based on measured E2 trans.)
Theor. I (Rel. mean field theory)
Theor. II (Microsc.-Macrosc. Model of Moeller and Nix)

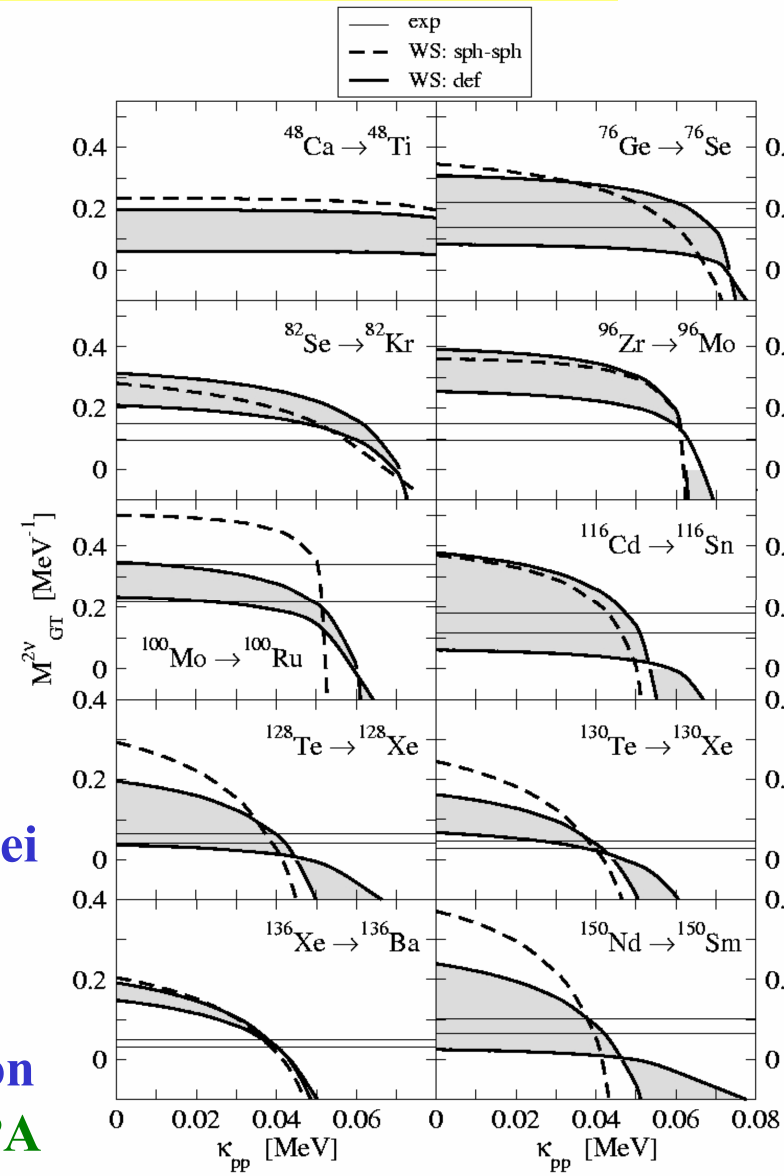
Till now, in the QRPA-like calculations of the 0νββ-decay NME spherical symetry was assumed

The effect of deformation on NME has to be considered

Nucl.	Exp. I	Exp. II	Theor. I	Theor. II
^{48}Ca	0.00	0.101	0.00	0.00
^{48}Ti	+0.17	0.269	-0.01	0.00
^{76}Ge	+0.09	0.26	0.16	0.14
^{76}Se	+0.16	0.31	-0.24	-0.24
^{82}Se	+0.10	0.19	0.13	0.15
^{82}Kr		0.20	0.12	0.07
^{96}Zr		0.081	0.22	0.22
^{96}Mo	+0.07	0.17	0.17	0.08
^{100}Mo	+0.14	0.23	0.25	0.24
^{100}Ru	+0.14	0.22	0.19	0.16
^{116}Cd	+0.11	0.19	-0.26	-0.24
^{116}Sn	+0.04	0.11	0.00	0.00
^{128}Te	+0.01	0.14	-0.00	0.00
^{128}Xe		0.18	0.16	0.14
^{130}Te	+0.03	0.12	0.03	0.00
^{130}Xe		0.17	0.13	-0.11
^{136}Xe		0.09	0.00	0.00
^{136}Ba		0.12	0.00	0.00
^{150}Nd	+0.37	0.28	0.22	0.24
^{150}Sm	+0.23	0.19	0.18	0.21

New Suppression Mechanism of the DBD NME





The suppression of the NME depends on relative deformation of initial and final nuclei

F.Š., Pacearescu, Faessler.
NPA 733 (2004) 321

Systematic study of the deformation effect on the 2νββ-decay NME within deformed QRPA

Alvarez,Sarriguren, Moya,Pacearescu, Faessler, F.Š.,
Phys. Rev. C 70 (2004) 321

Neutrinoless double electron capture

Modes of the 0νECEC-decay:

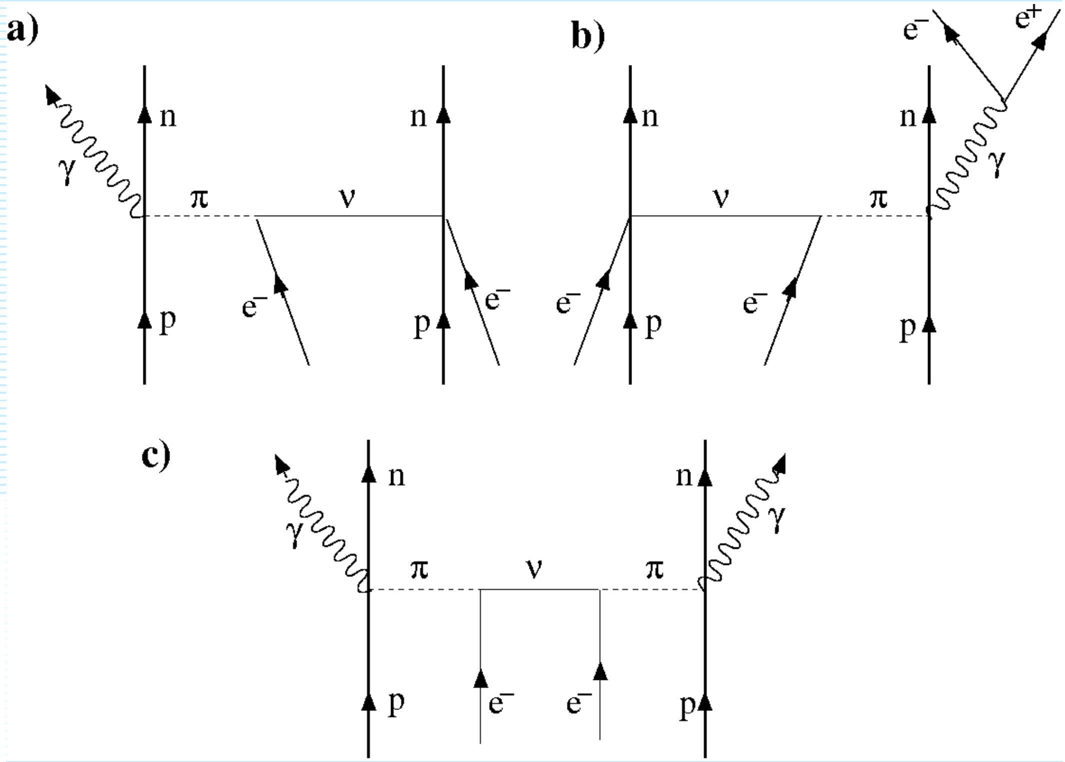
$e_b + e_b + (A,Z) \rightarrow (A,Z\text{-}2) + \gamma$

$+ \; 2\gamma$

$+ \; e^+e^-$

$+ \; M$

Nuclear physics mechanisms:
γ from the nucleus



Theoretically,
not well understood yet:

- **which mechanism is important?**
- **which transition is important?**

in comparison with the 0νββ-decay
disfavoured due:

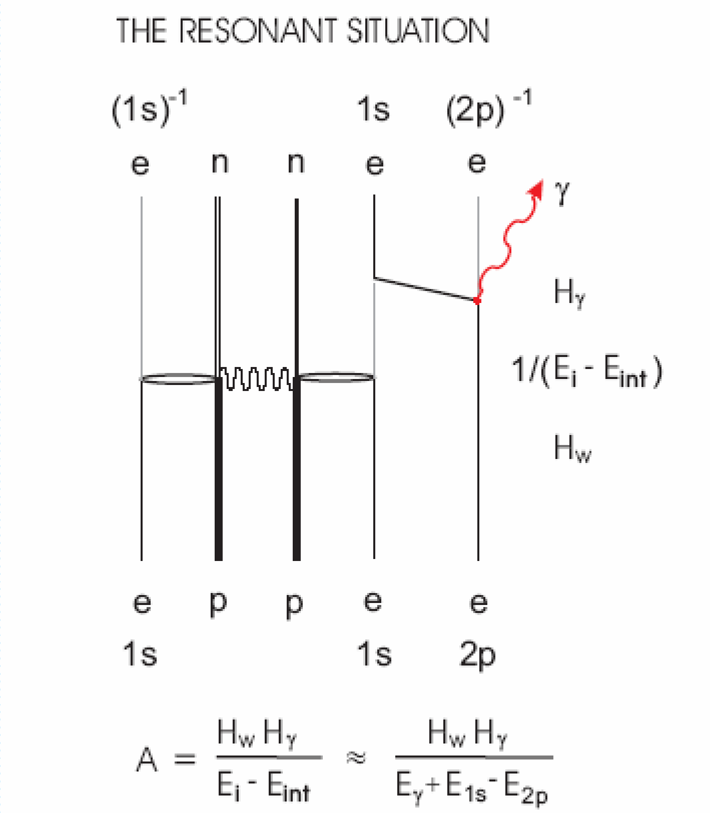
- **process in the 3-rd (4th) order in electroweak theory**
- **bound electron wave functions**

favoured due:?

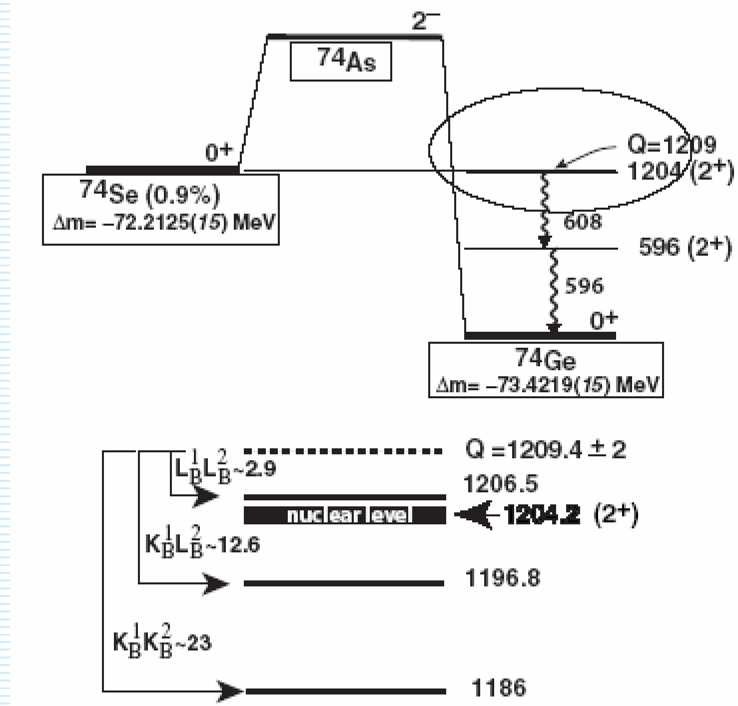
ECEC-γ decay

$e_b + e_b + (A,Z) \to (A,Z-2) + \gamma$

Sujkowski, Wycech, PRC 70, 052501 (2004)

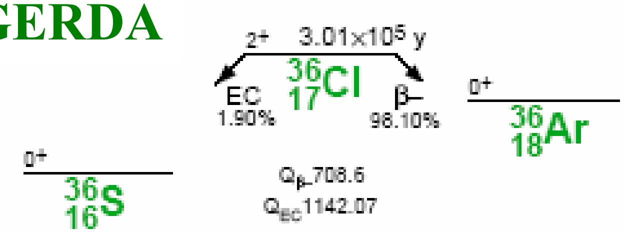


⇒



D.Frekers, hep-ex/0506002

GERDA



%: 0.337
Q=0.433 MeV
Γ^r=100 eV

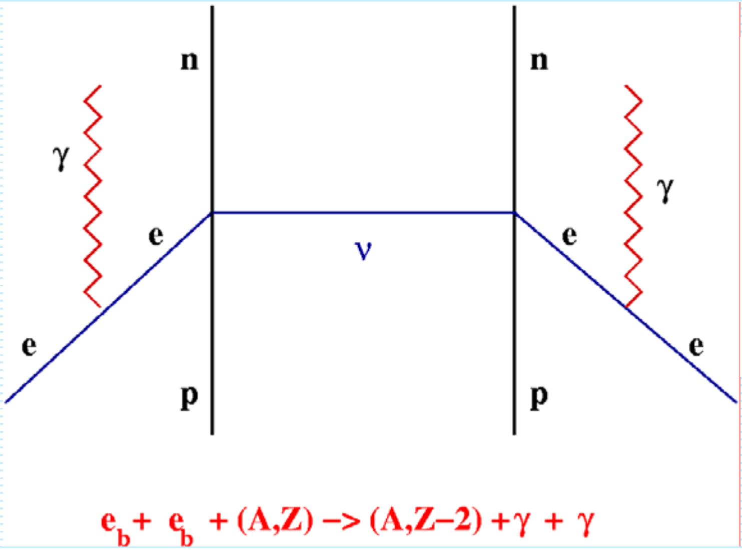
$$\Gamma^{0\nu\gamma} = \frac{\Gamma^r(2p \to 1s)}{[E_\gamma - Q_{res}]^2 + [\Gamma^r/2]^2} |R^{cc}_{0\nu}|^2$$

$$Q_{res} = E_{s_{1/2}} - E_{p_{1/2}}$$

$T_{1/2}^{0\nu\gamma}$ = 5 10^{34} years ($\langle m_{\beta\beta} \rangle$=1eV)

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

ECEC-γγ decay (preliminary)



Advanteges: - both e_b in $0s_{1/2}$ states (K-orbit)
- large Q values prefarable
- $1/(m_e(\varepsilon_{0s} + k_0))$ enhancement

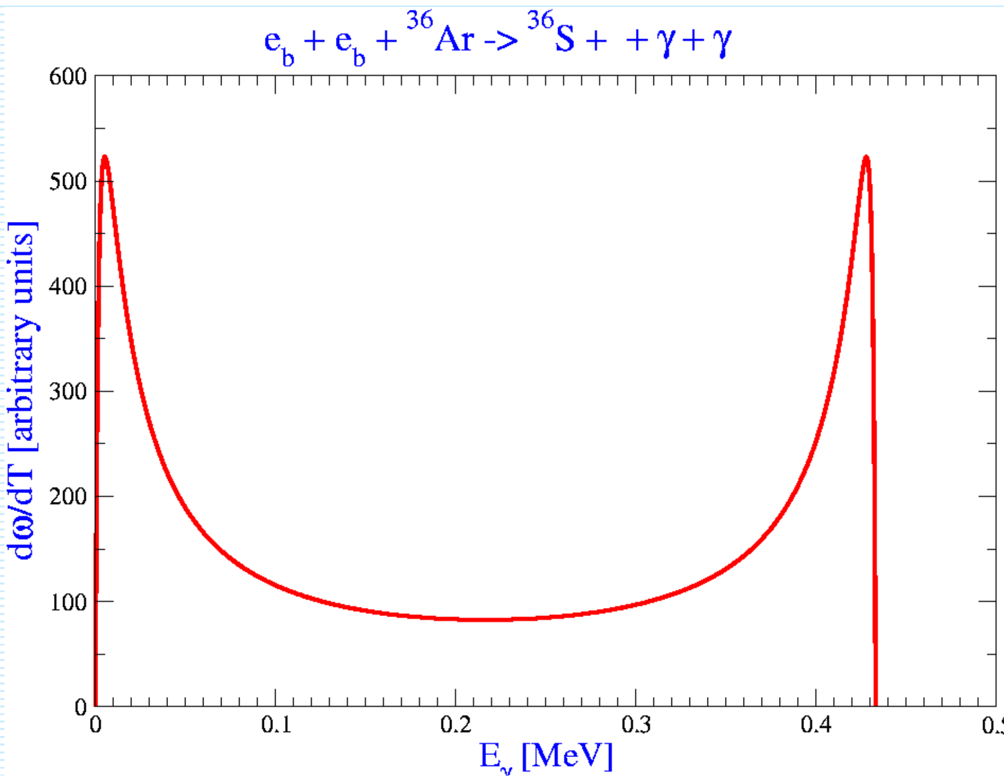
Disadvantages: - 2 γ´s in final state (phase space)
- additional el.-mag. interaction

$\langle m_{\beta\beta}\rangle$ = 1eV:

$T_{1/2}^{0\nu\gamma\gamma}$ (^{36}Ar) = 5 10^{34} years

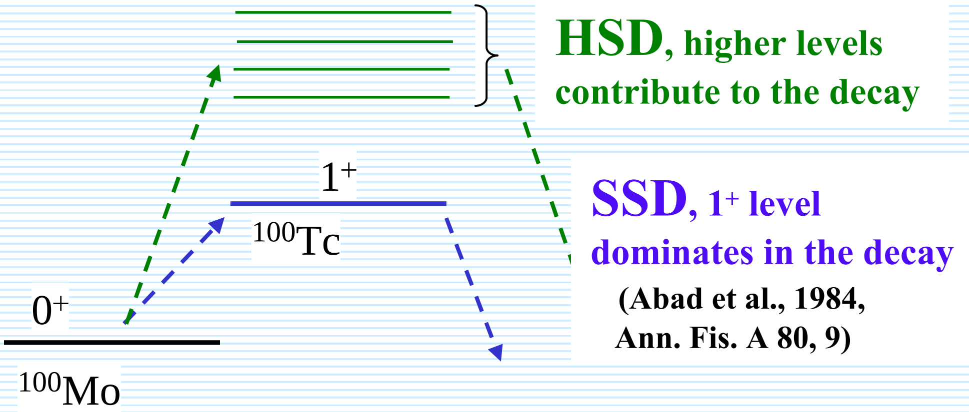
$T_{1/2}^{0\nu\gamma\gamma}$ (^{106}Cd) = 9 10^{32} years

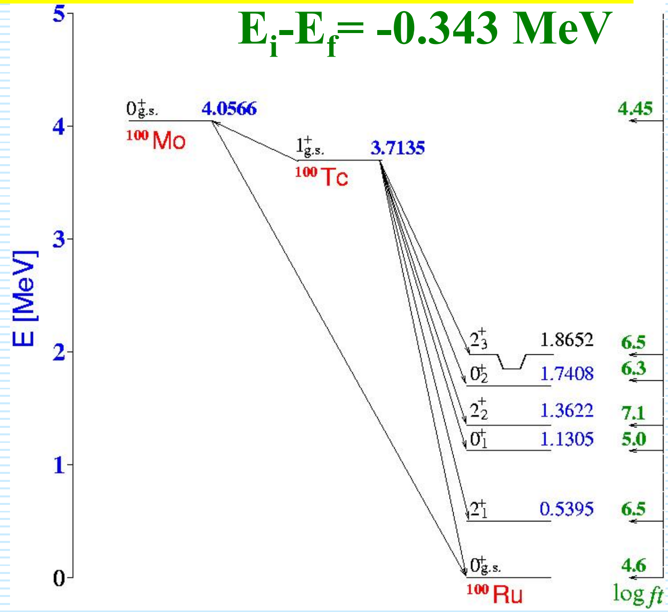
$T_{1/2}^{0\nu\gamma\gamma}$ (^{162}Er) = 7 10^{32} years

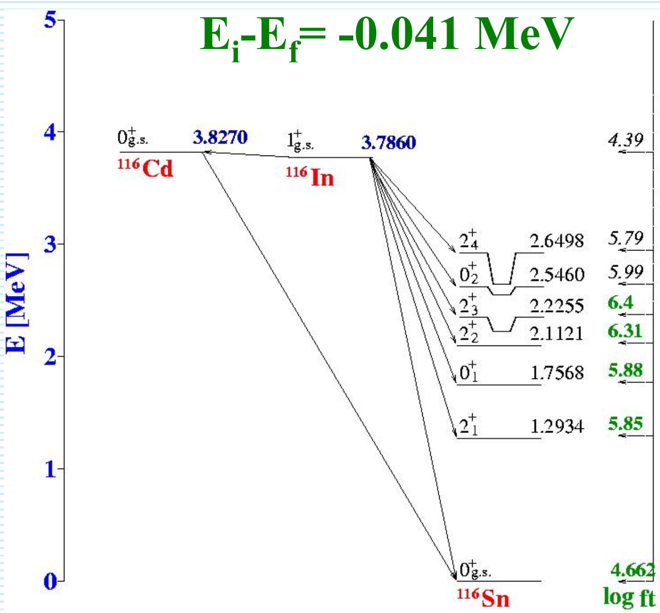


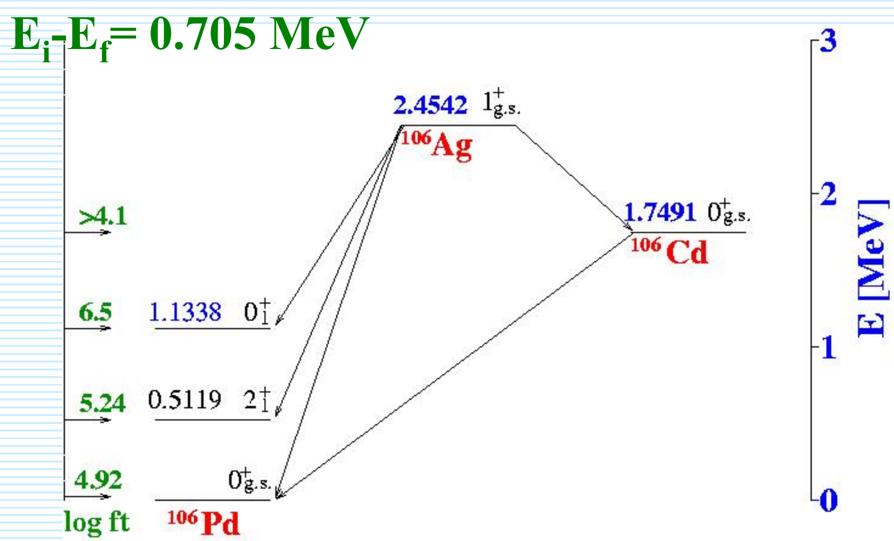
Carefull study study (Merle, Lindner, Beneš, F.Š) in progress

Single State Dominance (^{100}Mo, ^{106}Cd, ^{116}Cd, ^{128}Te …)



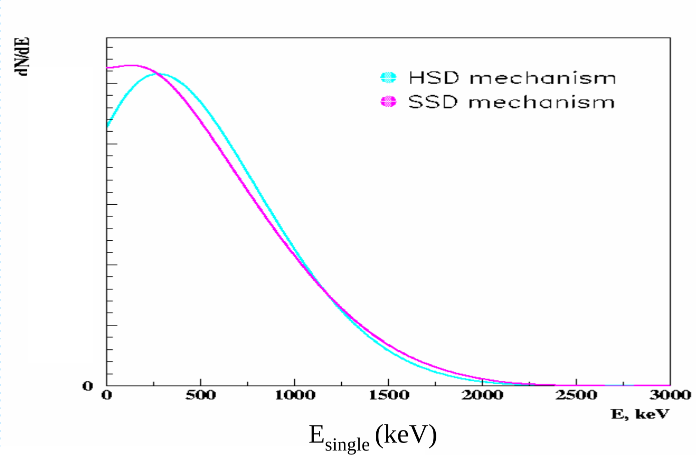






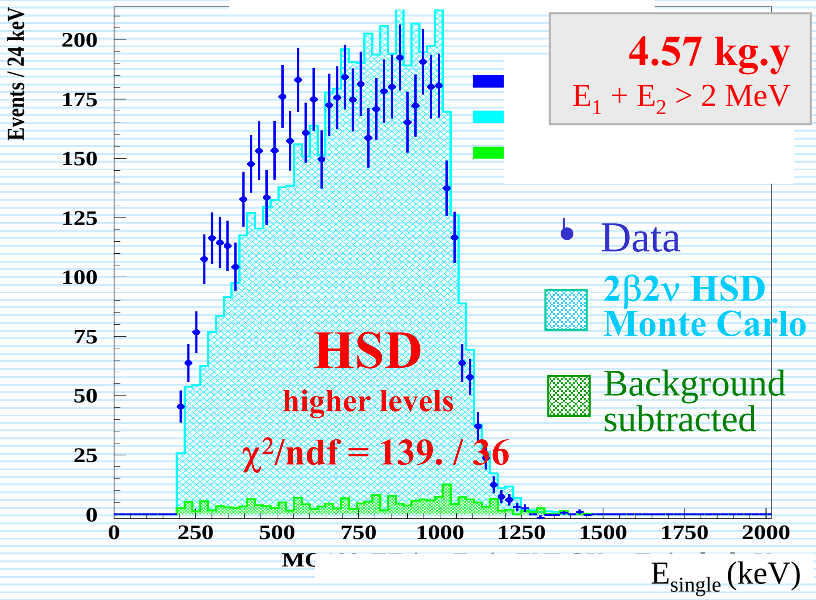
^{100}Mo 2β2ν: Experimental Study of SSD Hypothesis

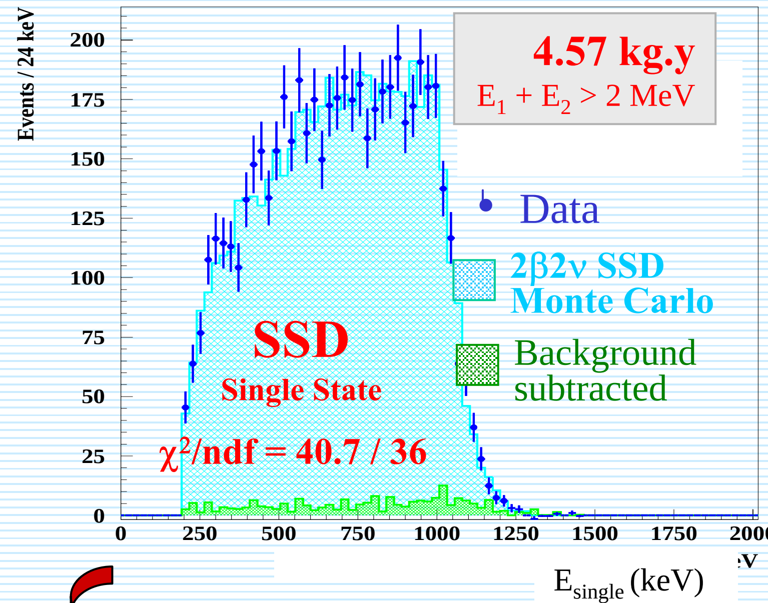
NEMO 3 exp.



Single electron spectrum different between SSD and HSD

F.Š., Šmotlák, Semenov
J. Phys. G, 27, 2233, 2001





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

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

^{100}Mo 2β2ν single energy distribution in favour of Single State Dominant (SSD) decay

2νββ-decay: fermionic (f) or bosonic (b) ν

$$|\nu_1\ \nu_2> \ = \ \hat{a}_1^\dagger\ \hat{a}_2^\dagger|0>$$

$$\{\hat{a}_i, \hat{a}_j^\dagger\}_+ \ = \ \delta_{i,j} \quad (fermionic\ \nu)$$
$$\left[\hat{a}_i, \hat{a}_j^\dagger\right]_- \ = \ \delta_{i,j} \quad (bosonic\ \nu)$$

$$dW^{f,b}(0^+ \to 0^+) \ \sim \ \left(3\left|\mathcal{M}^{f,b}{}_K + \mathcal{M}^{f,b}{}_L\right|^2 \ + \left|\mathcal{M}^{f,b}{}_K - \mathcal{M}^{f,b}{}_L\right|^2\right) \ d\vec{p_{e_1}}\, d\vec{p_{e_2}} d\vec{p_{\nu_1}}\, d\vec{p_{\nu_2}}$$
$$dW^{f,b}(0^+ \to 2^+) \ \sim \ \left|\mathcal{M}^{f,b}{}_K - \mathcal{M}^{f,b}{}_L\right|^2 \ d\vec{p_{e_1}}\, d\vec{p_{e_2}} d\vec{p_{\nu_1}}\, d\vec{p_{\nu_2}}$$

$$\mathcal{M}^{f,b}{}_K \ = \ \sum_m \left(\frac{M_m^I(1^+) M_m^F(1^+)}{E_m - E_i + e_1 + \nu_1} \ \pm \ \frac{M_m^I(1^+) M_m^F(1^+)}{E_m - E_i + e_2 + \nu_2}\right)$$

$$\mathcal{M}^{f,b}{}_K = \mathcal{M}^{f,b}{}_L(\nu_1 \leftrightarrow \nu_2)$$

Sign difference!!!
Lepton energies!!!

Dolgov, Smirnov, PLB 621, 1 (2005)

Higher states dominance (^{76}Ge, ^{82}Se, ^{130}Te, ^{136}Xe ....)

$$\left|\mathcal{M}^{f}{}_{K} + \mathcal{M}^{f}{}_{L}\right|^2 \simeq 16\left|M^{(1)}_{GT}\right|^2$$

$$\left|\mathcal{M}^{f}{}_{K} - \mathcal{M}^{f}{}_{L}\right|^2 \simeq \frac{4(e_1-e_2)^2(\nu_1-\nu_2)^2}{\Delta^4}\left|M^{(3)}_{GT}\right|^2$$

$$\left|\mathcal{M}^{b}{}_{K} + \mathcal{M}^{b}{}_{L}\right|^2 \simeq \frac{4(\nu_1-\nu_2)^2}{\Delta^2}\left|M^{(2)}_{GT}\right|^2$$

$$\left|\mathcal{M}^{b}{}_{K} - \mathcal{M}^{b}{}_{L}\right|^2 \simeq \frac{4(e_1-e_2)^2}{\Delta^2}\left|M^{(2)}_{GT}\right|^2$$

Approximation in energy denominators

$e_k + \nu_j \cong \Delta = (E_i - E_f)/2$

$$M^{(1)}_{GT} = \sum_m \frac{M^I_m(1^+)M^F_m(1^+)}{E_m - E_i + \Delta}$$ → **fermionic ν** 0^+

$$M^{(2)}_{GT} = \Delta \sum_m \frac{M^I_m(1^+)M^F_m(1^+)}{(E_m - E_i + \Delta)^2}$$ → **bosonic ν** 0^+, 2^+

$$M^{(3)}_{GT} = \Delta^2 \sum_m \frac{M^I_m(1^+)M^F_m(1^+)}{(E_m - E_i + \Delta)^3}$$ → **fermionic ν** 0^+, 2^+

$$M^{(3)}_{GT} \ll M^{(2)}_{GT} \ll M^{(1)}_{GT}$$

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

$$\frac{T_{1/2}^{2\nu-SSD}(2_f^+)}{T_{1/2}^{2\nu-SSD}(0_f^+)} = 2.41 \times 10^4 \quad \text{fermionic } \nu \qquad T_{1/2}^{2\nu}(2^+) = 1.73 \times 10^{23} years$$

$$= 403 \quad \text{bosonic } \nu \qquad = 2.74 \times 10^{21} years$$

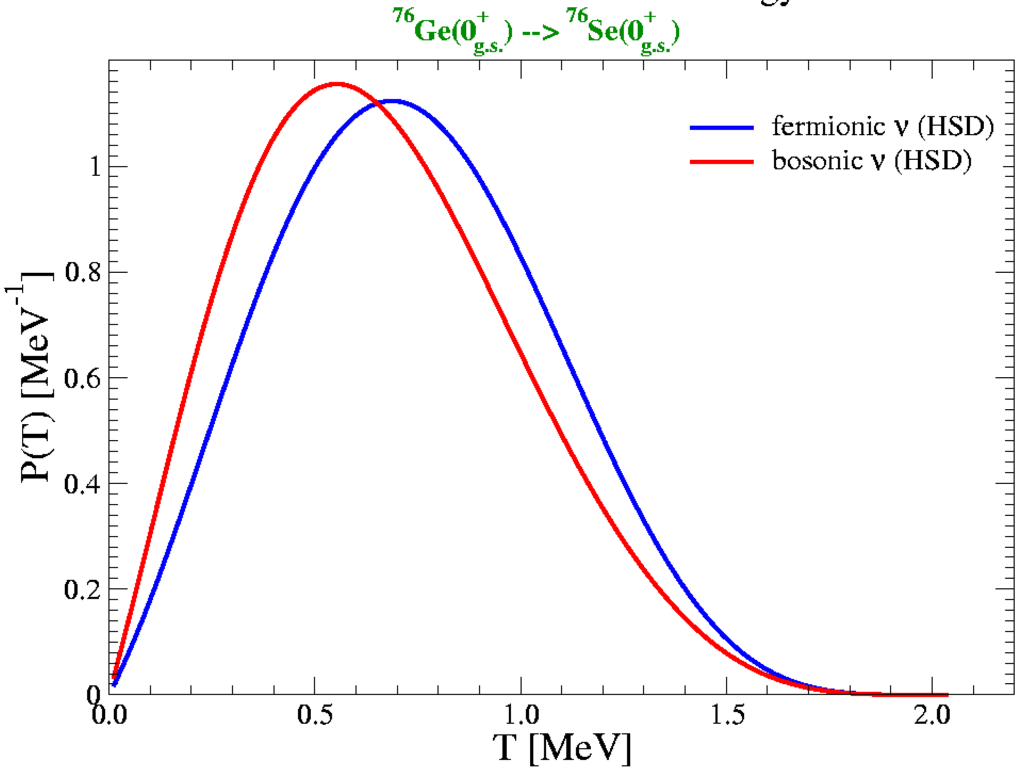
$$T_{1/2}^{2\nu-exp}(2^+) > 1.6 \times 10^{21} years$$

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)

The normalized distributions of the total energy of two electrons



2νββ-decay of ^{76}Ge

$0^+_{g.s.} \to 0^+_{g.s.}$

HSD

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

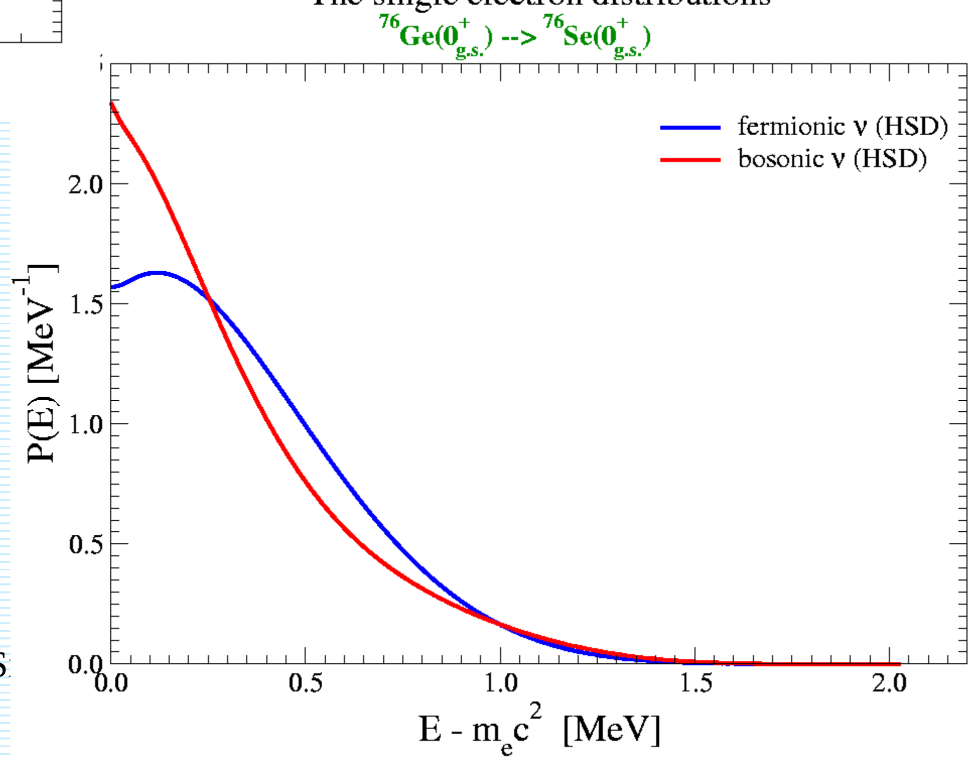
bosonic ↑ ↑ **fermionic**

$$P^{f,b}(T) = \frac{1}{W^{f,b}} \frac{dW^{f,b}}{dT}$$

$$P^{f,b}(E) = \frac{1}{W^{f,b}} \frac{dW^{f,b}}{dE}$$

Fedor S

The single electron distributions



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

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

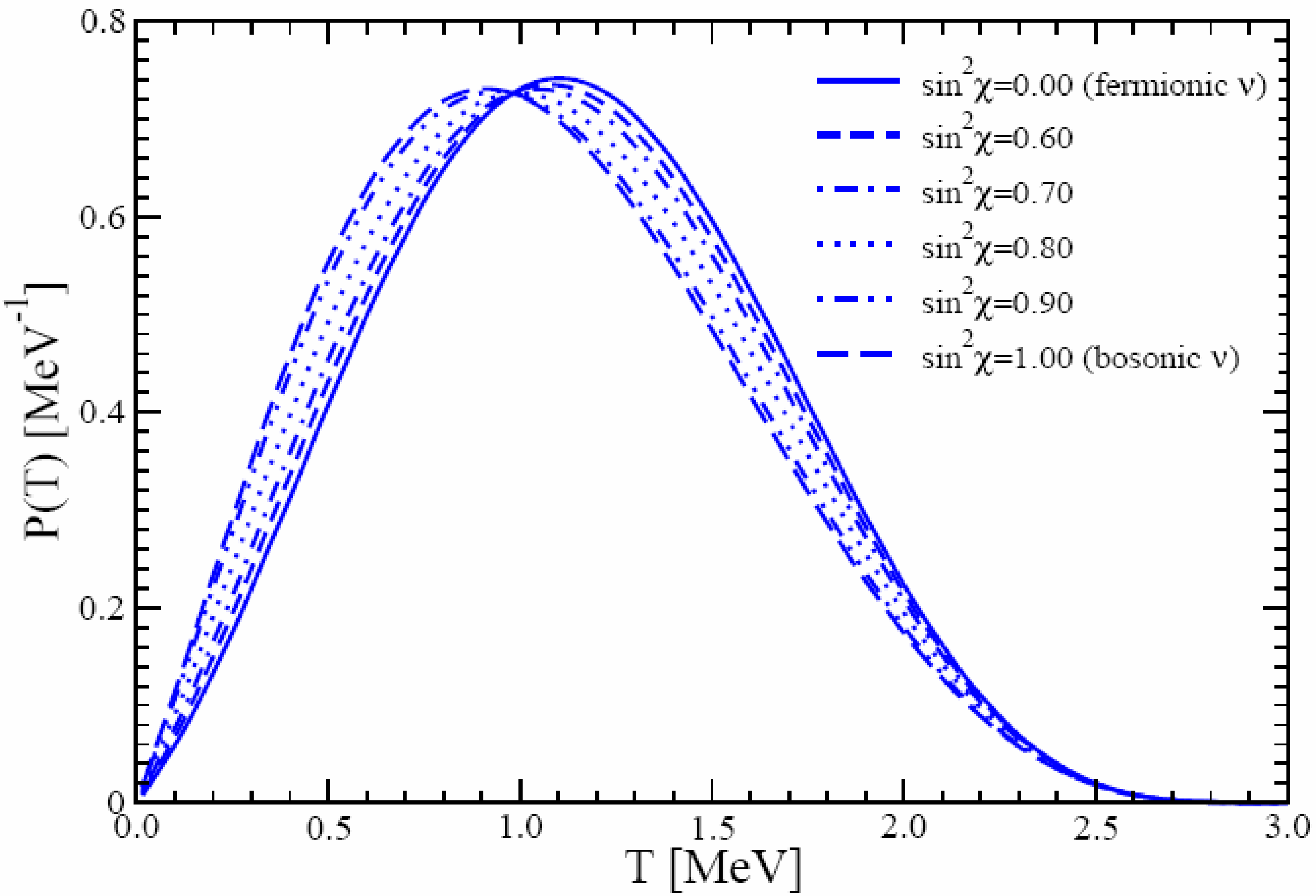
Decay rate

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

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

(calculations coming up soon)

Mixed ν excluded for $\sin^2\chi < 0.6$



Conclusions

- If the smallness of neutrino masses is explained with see-saw mechanism there are many possible mechanisms of the $0\nu\beta\beta$-decay.
- From the analysis of some of R-parity breaking SUSY mechanisms it follows that light neutrino mass mechanism has not be the dominant mechanism of the $0\nu\beta\beta$-decay
- Possibilities to distinguish between $0\nu\beta\beta$-decay mechanisms have to be studied. It should involve the most viable particle physics models and NME calculations

- There is a good agreement between the NSM and the QRPA NME. Why?
- The story about NME not finished yet. Study of further effects (deformation, overlap factor) and cross-check with other approaches required.

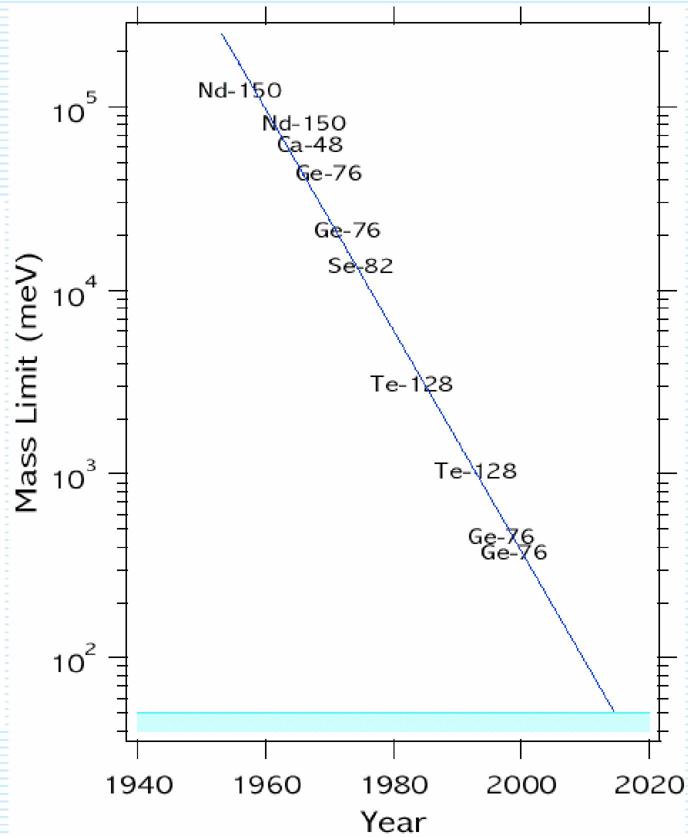
- Neutrinoless double electron capture is not well studied yet. Preliminary results for ^{36}Ar indicate strong suppression of this decay mode.

- $2\nu\beta\beta$-decay of ^{76}Ge allows to conclude whether neutrinos obey Bose-Einstein or Fermi-Dirac statistics

Outlook

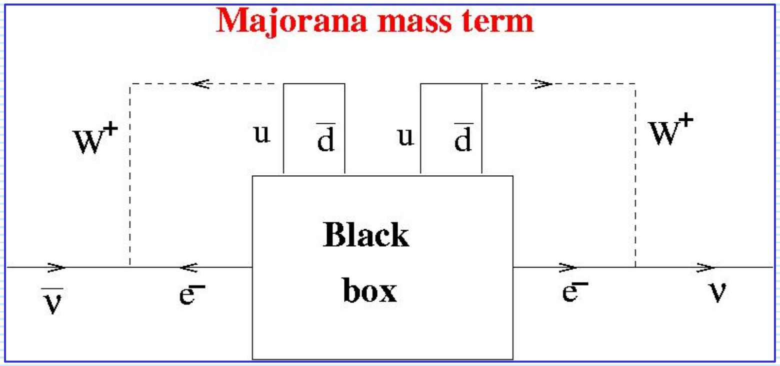
The 0νββ–decay will be observed (up to 2020)

- **Neutrino is Majorana particle (Schechter-Valle theorem)**
- **The dominant mechanism has to be determined, i.e., further study (differential characteristics, trans. to excited states, related phenomenology, NME, GUT models)**



The 0νββ–decay will be not observed (up to 2020)

- **Inverted hierarchy of neutrino masses excluded**
- **Stronger constraints on GUT, …**
- **A challenge for next generation?**
- **If mass spectrum already determined ⇒Dirac neutrino (why small mass?)**



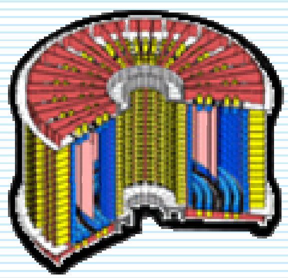
Schechter-Valle

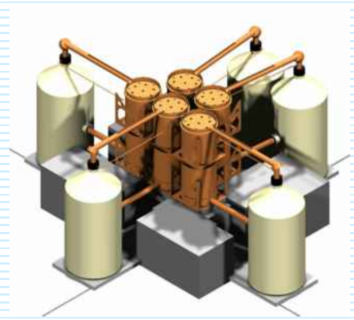
What is the nature of neutrinos?

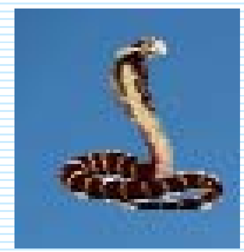
$\nu \Rightarrow$

theory

Only the 0νββ-decay can answer this fundamental question







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By product:

- **Absolute ν mass scale**
- **CP Majorana phases**