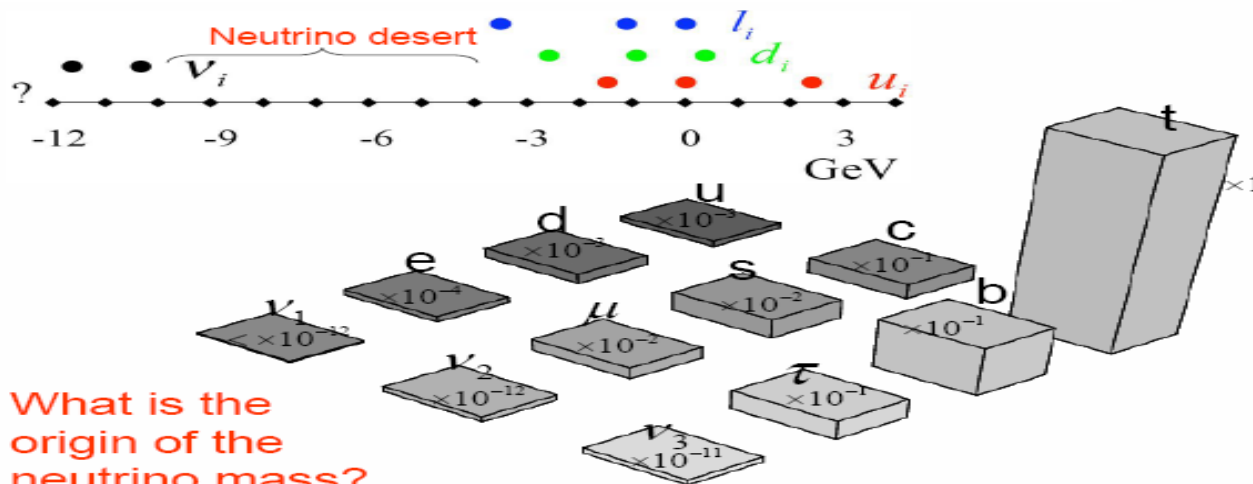


Double Beta Decay, the Neutrino Mass and Physics beyond the Standard Model

Amand Faessler ,
Vadim Rodin,
Mohamed Saleh Yousef,
Fedor Simkovic and Petr Vogel

- Why is the Neutrino Mass so small ?
- What is the Origin of the Neutrino Mass?
- ν Masses(KATRIN; $0\nu\beta\beta$ matrix elements)?
- Neutrino Mixing Matrix $U_{\alpha j}$
- Majorana or Dirac Neutrinos?
- Dirac and Majorana Phases; PC-Invariance?
- Neutrino Oscillations
- Physics at Neutrino Factories.

■ Quark and lepton masses



Tuebingen, February first. 2008.

Neutrino Masses

- Single Beta Decay (Mainz, Troisk; Weinheimer)

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2 \right]^{\frac{1}{2}} < 2.2 \text{ [eV]}$$

- Double Beta Decay Majorana Mass (Tübingen):

$$m_{\beta\beta} = \left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right| < 0.27 \text{ [eV]}$$

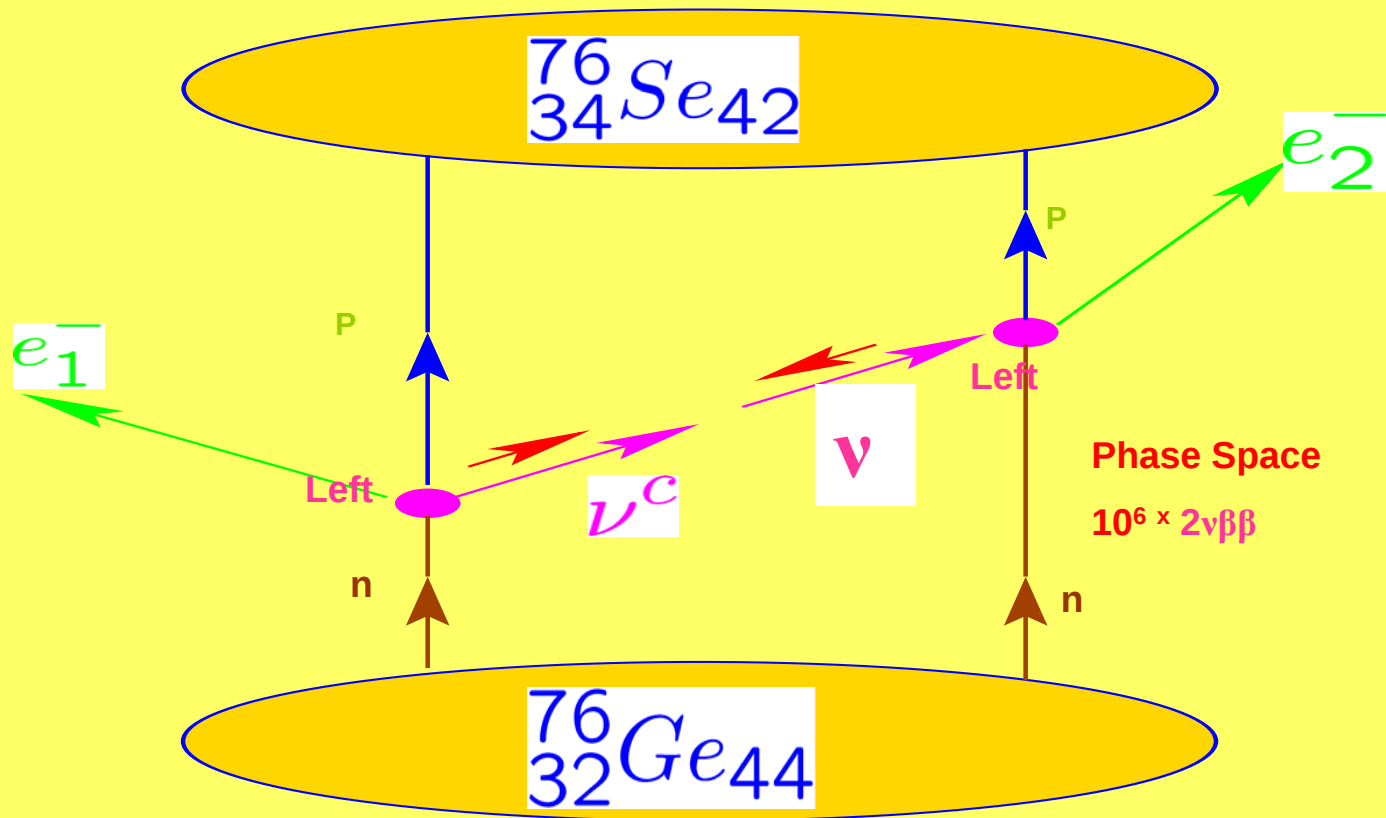
- Astrophysics: $\Sigma = m_1 + m_2 + m_3 < 0.17 \text{ to } 2.0 \text{ [eV]}$

Depends on Cosmological models (Hannestad)

- The neutrinoless Double Beta Decay forbidden in the Standard Model allows to determine the mass of massive Majorana Neutrinos, (if it yields the biggest term).
- Practically all Grand Unified Theories and Supersymmetry request massive Majorana Neutrinos

$$\nu = \bar{\nu}; \quad m_\nu > 0$$

$0\nu\beta\beta$ -Decay (forbidden in Standard Model)



only for massive Majorana Neutrinos

$$\nu = \bar{\nu}$$

GRAND UNIFICATION

Left-right Symmetric Models SO(10)

$$W_L^\pm; W_R^\pm;$$

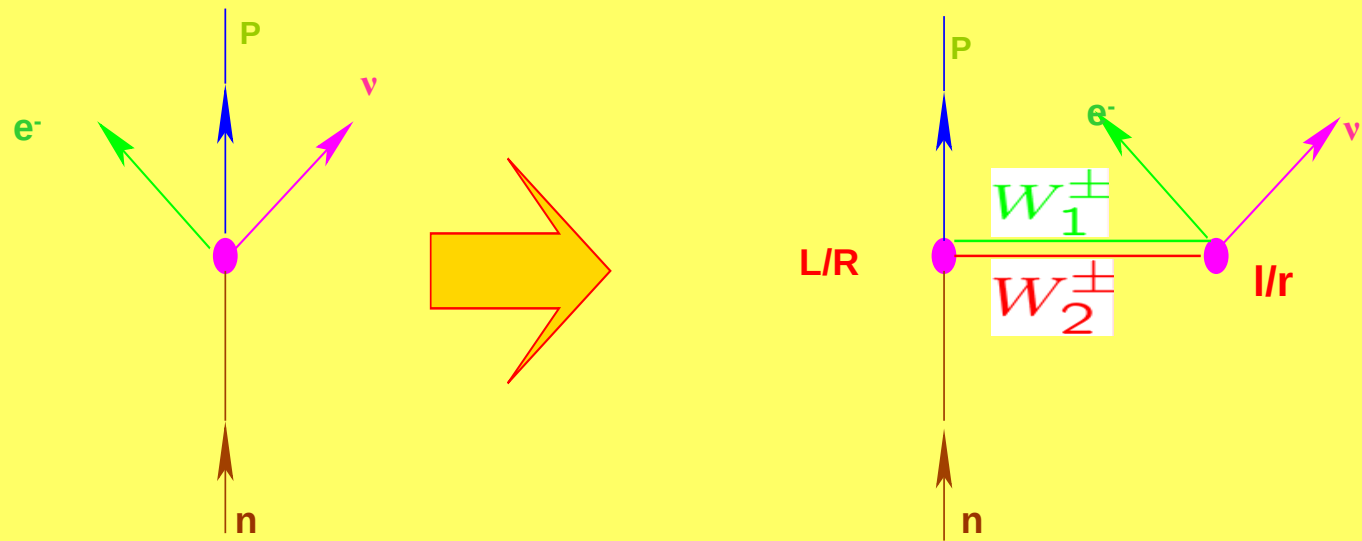
$$\nu = \nu^c$$

Majorana Mass:

$$\mathcal{L} = \dots + m_\nu \bar{\nu}^c \nu + m_\nu^* \bar{\nu} \nu^c$$

$$W_1^\pm(81\text{GeV}) = \cos\vartheta W_L^\pm + \sin\vartheta W_R^\pm$$

$$W_2^\pm(? \text{GeV}) = -\sin\vartheta W_L^\pm + \cos\vartheta W_R^\pm$$



$$l/r = \bar{e} \gamma^\mu (1 \mp \gamma^5) \nu$$

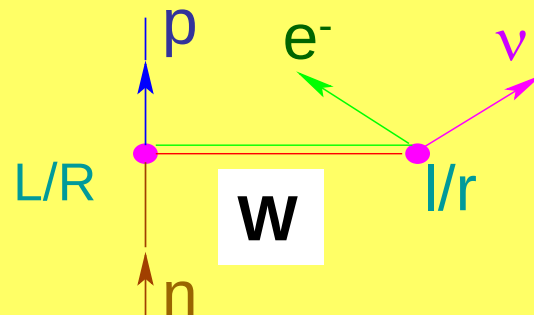
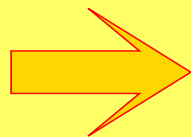
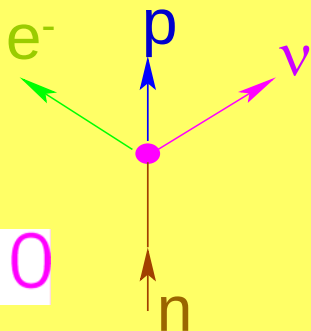
$$L/R = p^\dagger (g_V \mp g_A \vec{\sigma}) n$$

$$g_V = 1;$$

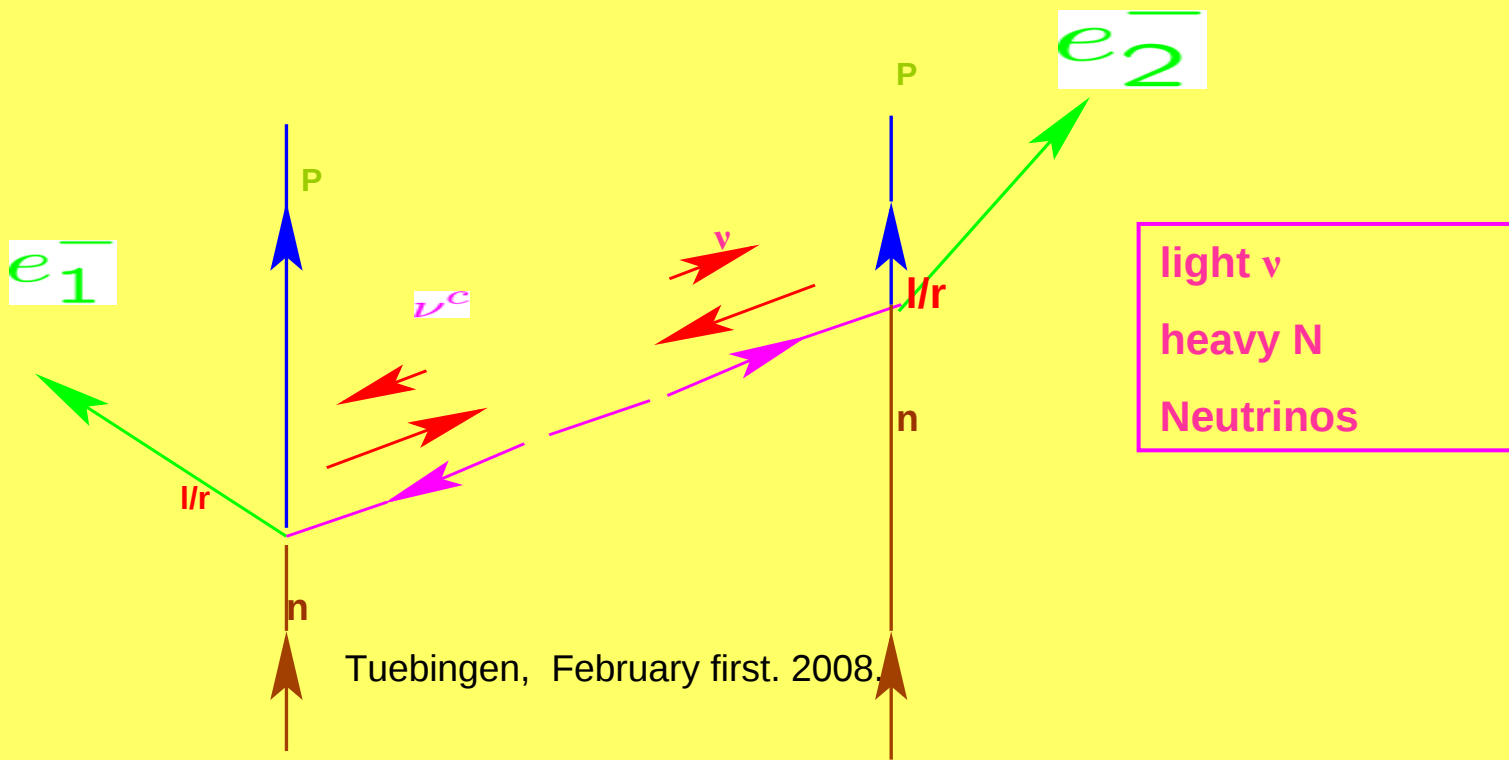
$$g_A = 1.25$$

$$\hat{H}_{weak} =$$

$$m_\nu \neq 0$$

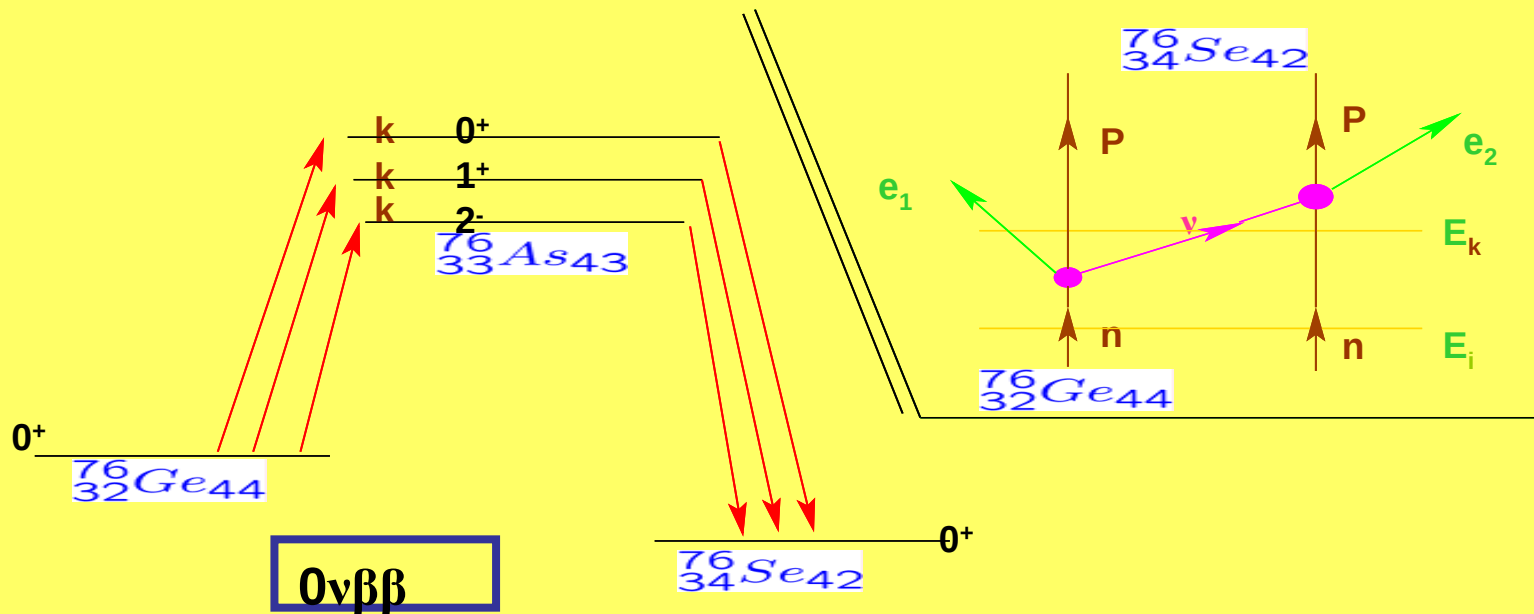


$$\hat{H}_{Weak}^{GUT} = \frac{G_F \cos \vartheta_c}{\sqrt{2}} [1 \cdot l \cdot L + \text{tg} \vartheta r \cdot L + \text{tg} \vartheta l \cdot R + \frac{M_1^2}{M_2^2} r \cdot R + \dots]$$



Theoretical Description of Nuclei:

Vadim Rodin, Fedor Simkovic,
Amand Faessler, Saleh Yousef



The best choice: Quasi-Particle Random Phase Approximation (QRPA) and Shell Model

QRPA starts with Pairing:

$$a_i^+ = u_i c_i^+ - v_i c_{\bar{i}}$$

$$A_\alpha^+ = [a_i^+ a_k^+] J_\alpha$$

$$Q_m^+ = \sum_\alpha [X_\alpha^m A_\alpha^+ - Y_\alpha^m A_\alpha]$$

$$|m\rangle = Q_m^+ |g\rangle$$

$$[A_\alpha, A_\beta^+] = \delta_{\alpha,\beta} + \hat{X}$$

$$\hat{H} Q_m^+ |g\rangle = E_m Q_m^+ |g\rangle$$

$$\hookrightarrow X_m^\alpha; Y_m^\alpha; E_m$$

Neutrinoless Double Beta- Decay Probability

$$T = \int dE_k(\nu) \sum_k \frac{\langle f | \hat{H}_W | k \rangle \langle k | \hat{H}_W | i \rangle}{E_0(^{76}\text{Ge}) - [E_k(e_1^-) + E_k(\nu) + E_{\text{Kern}}(^{76}\text{As}; k)]}$$

$$T = M_m \langle m_\nu \rangle + M_\theta \langle \text{tg}\vartheta \rangle + M_{WR} \left\langle \left(\frac{M_1}{M_2} \right)^2 \right\rangle$$

$$+ M_{SUSY} \lambda_{111}'^2 + M_{VR} \left\langle \frac{m_p}{M_{VR}} \right\rangle + \dots$$

$$w = \frac{2\pi}{\hbar} |T|^2 \rho_f \leq 4.4 \cdot 10^{-33} [\text{sec}^{-1}] \quad {}^{128}\text{Te}$$

Effective Majorana Neutrino-Mass

Single Beta Decay

Electron Capture

$$m^2(\nu_e) = \sum_{i=1,2,3} |U_{ei}|^2 m_i^2$$

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

$$\begin{aligned} | \langle m_{\beta\beta} \rangle | &= | m_1 |U_{e1}|^2 \\ &+ m_2 |U_{e2}|^2 e^{i\alpha_{21}} + m_3 |U_{e3}|^2 e^{i\alpha_{31}} | \\ &= | m_1 |U_{e1}|^2 \pm m_2 |U_{e2}|^2 \pm m_3 |U_{e3}|^2 | \end{aligned}$$

CP



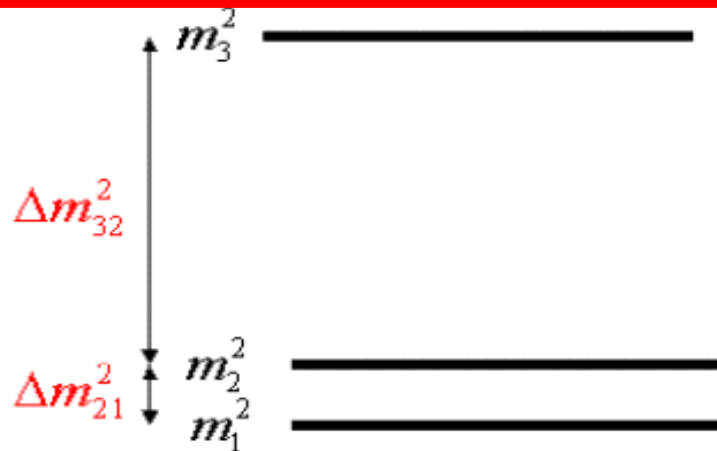
Time reversal

CPT

Results from Oscillations:

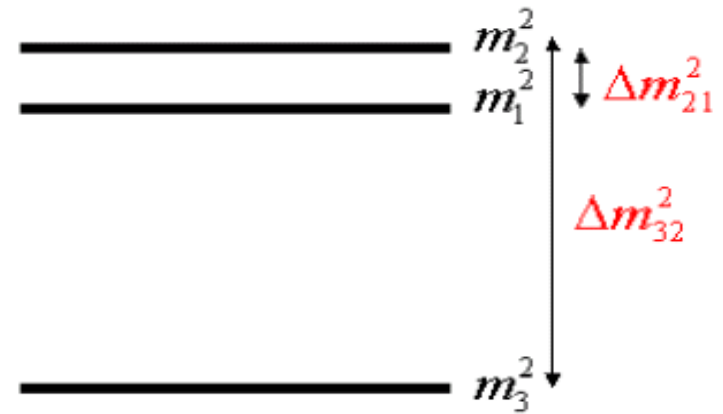
No Hierarchy, no absolute Mass Scale

Fogli, Lisi, Marrone, Palazzo: Prog. Part. Nucl. Phys. 57(2006)742



“Normal”

$$\Delta m_{32}^2 > 0$$



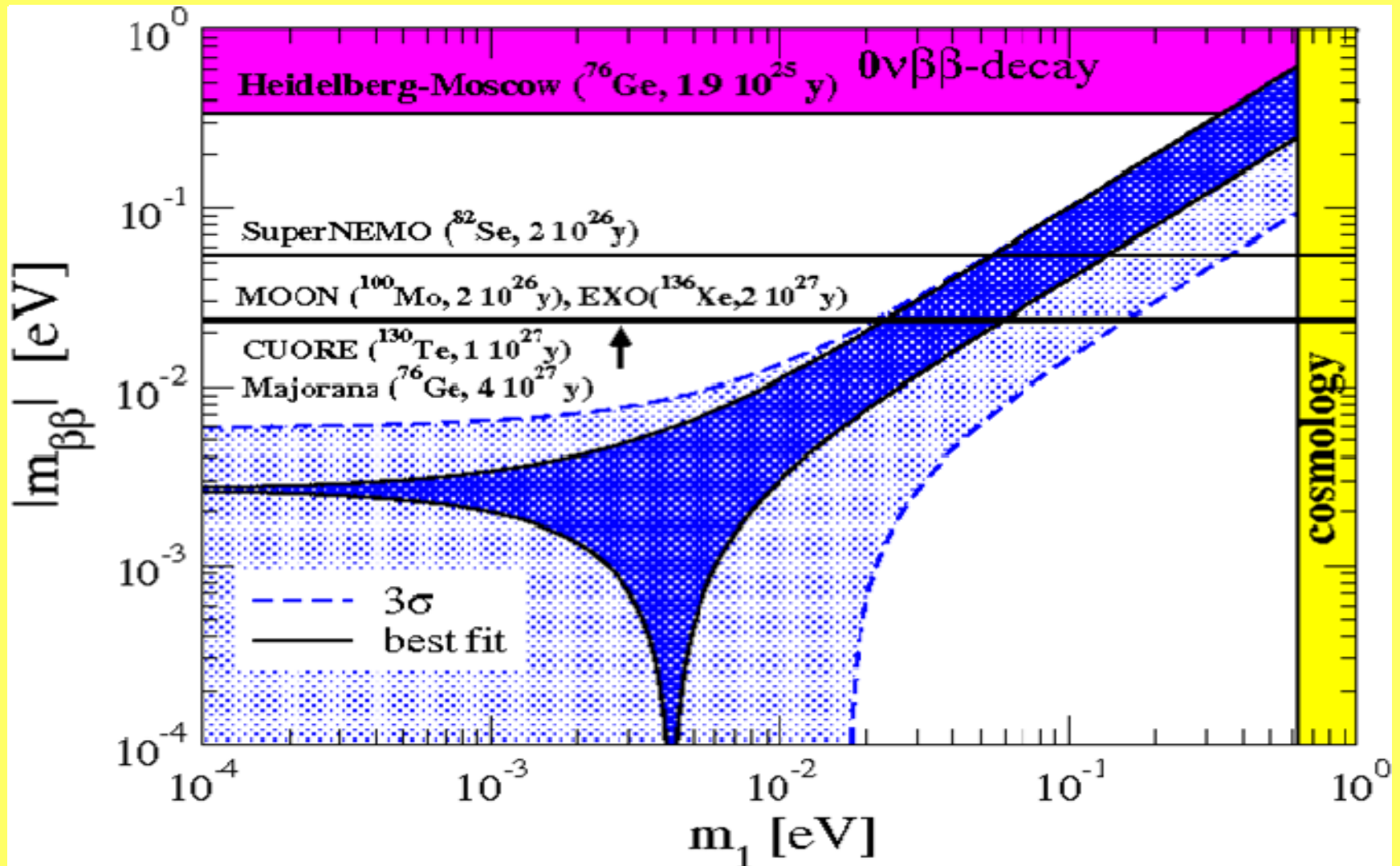
“Inverted”

$$\Delta m_{32}^2 < 0$$

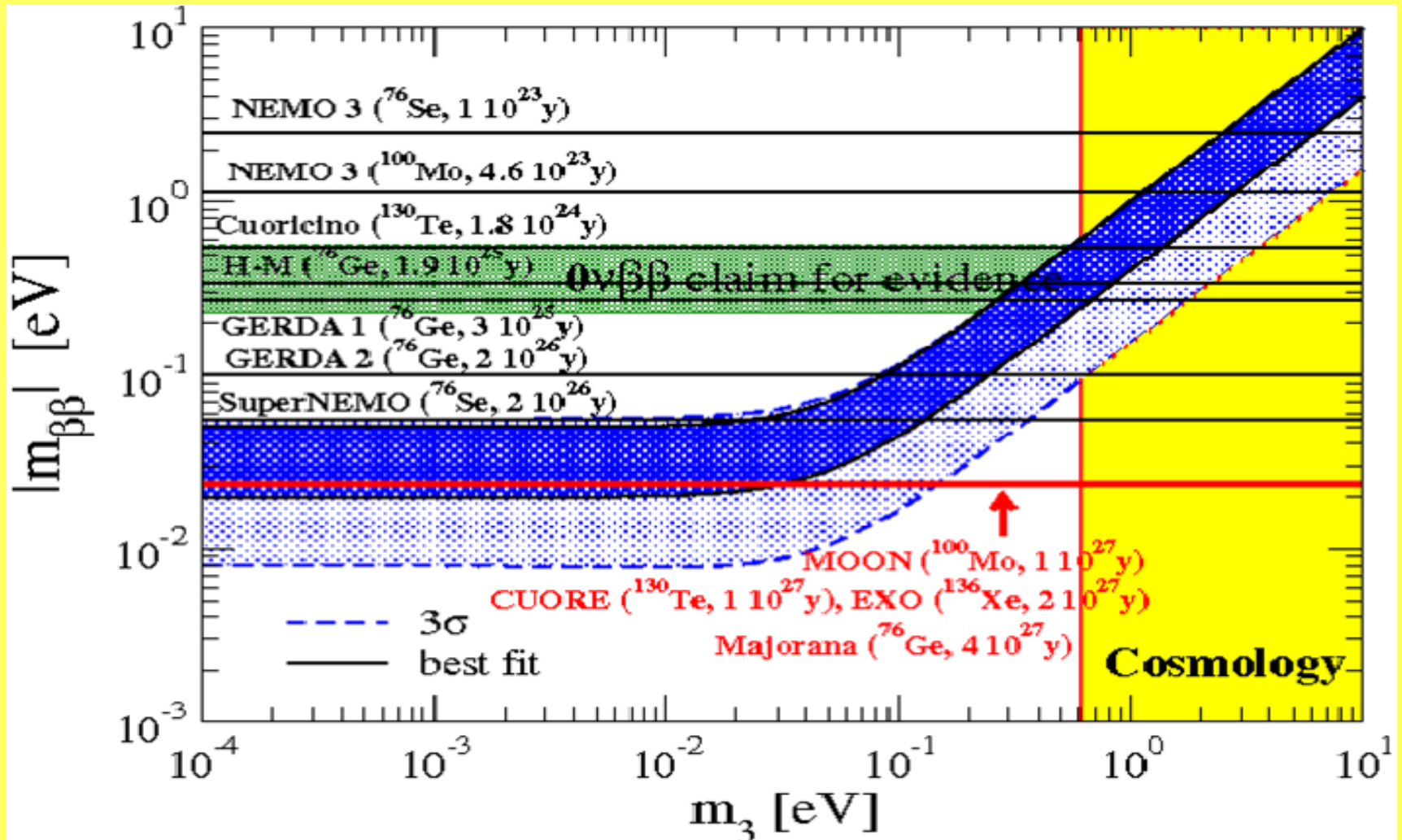
$$\Delta m_{21}^2 = 7.92 \cdot 10^{-5} [eV^2]; \Delta m_{32}^2 = 2.4 \cdot 10^{-3} [eV^2]$$

$$\vartheta_{23} \approx 41.6^\circ, \vartheta_{12} \approx 34.1^\circ, |\vartheta_{13}| \leq 9^\circ$$

Normal Hierarchy: Double Beta Decay Majorana Mass $m_{\beta\beta}$ versus lowest mass m_1

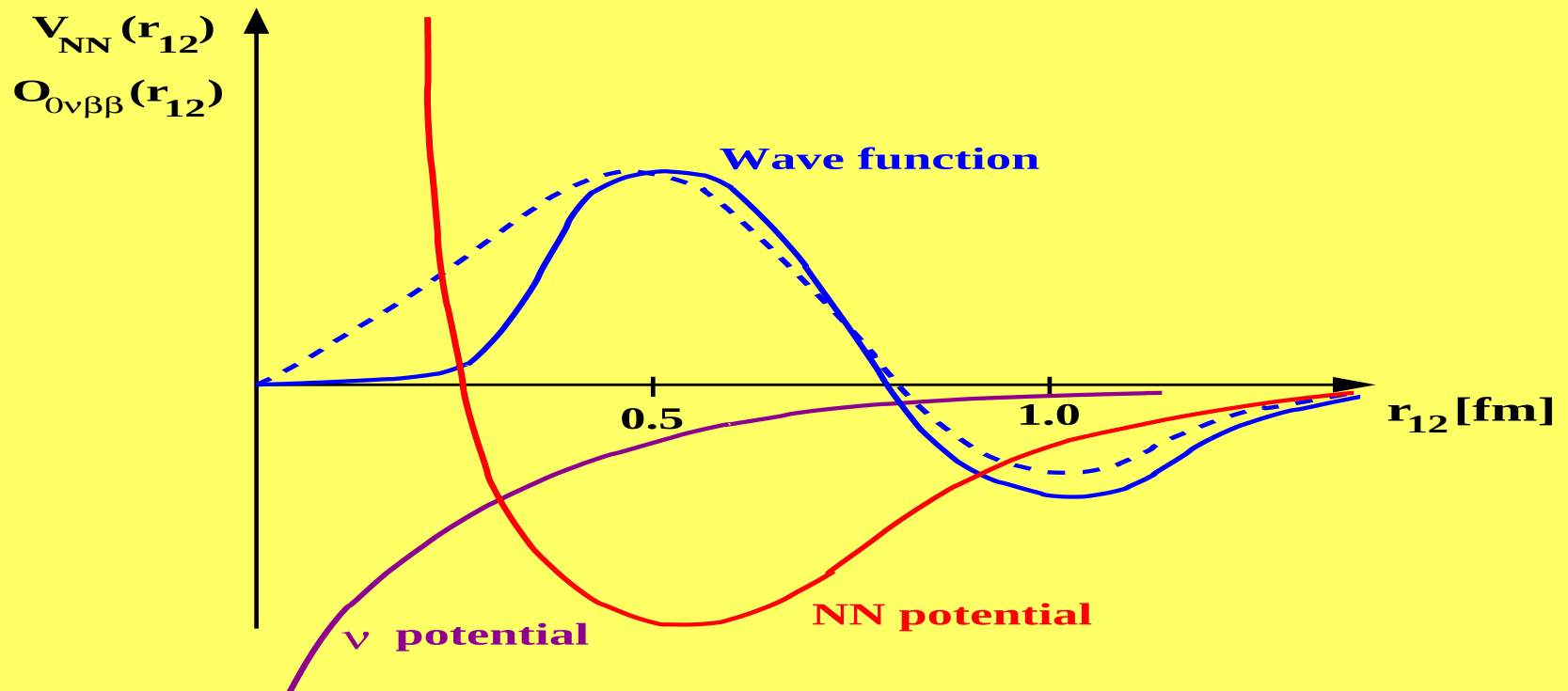


Inverted Hierarchy: Double Beta Decay Majorana Mass $m_{\beta\beta}$ versus lowest mass m_3



Uncorrelated and Correlated Relative N-N- (two neutrons $\rightarrow$ two protons) Wavefunction in the N-N-Potential

Nucleon–Nucleon Potential

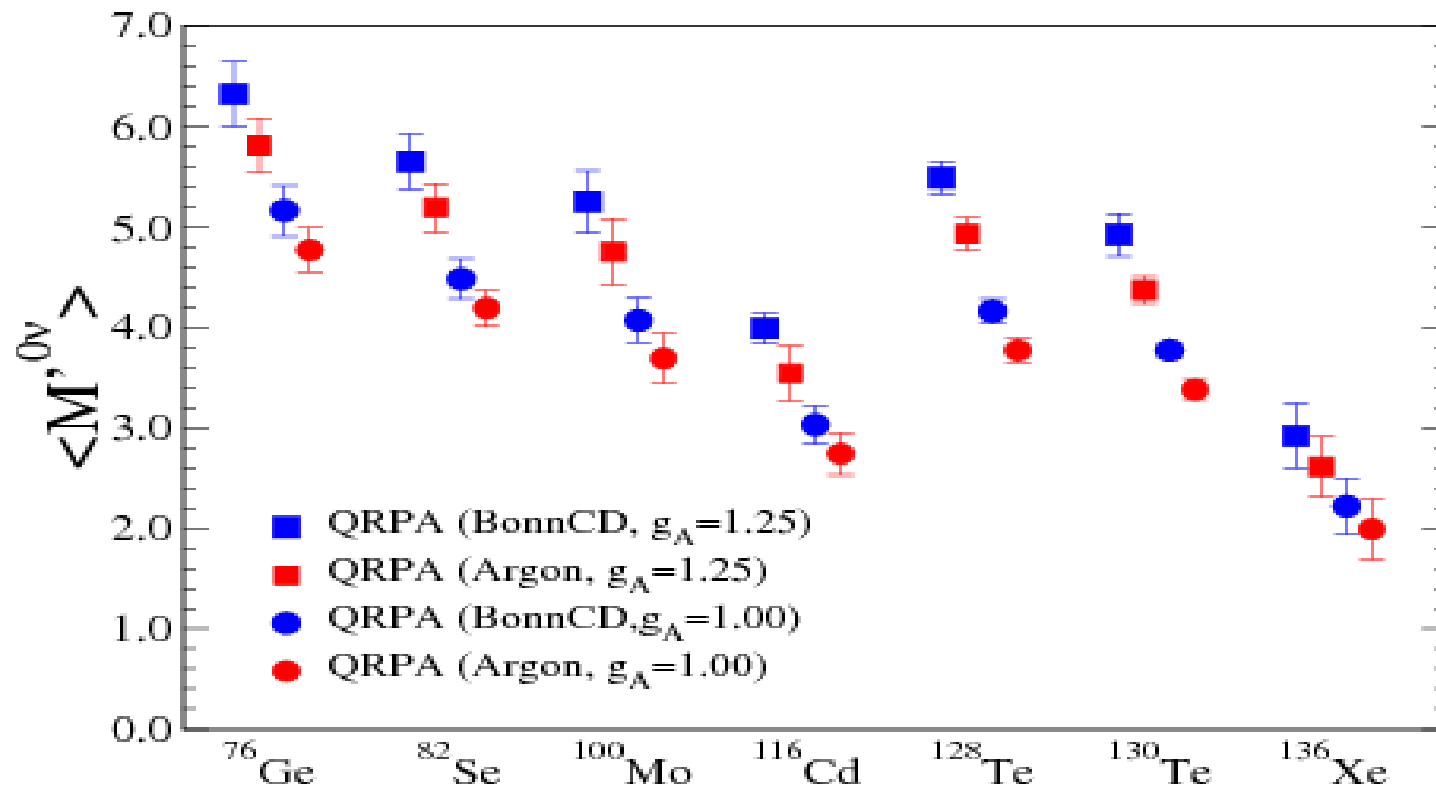


Short Range Correlations

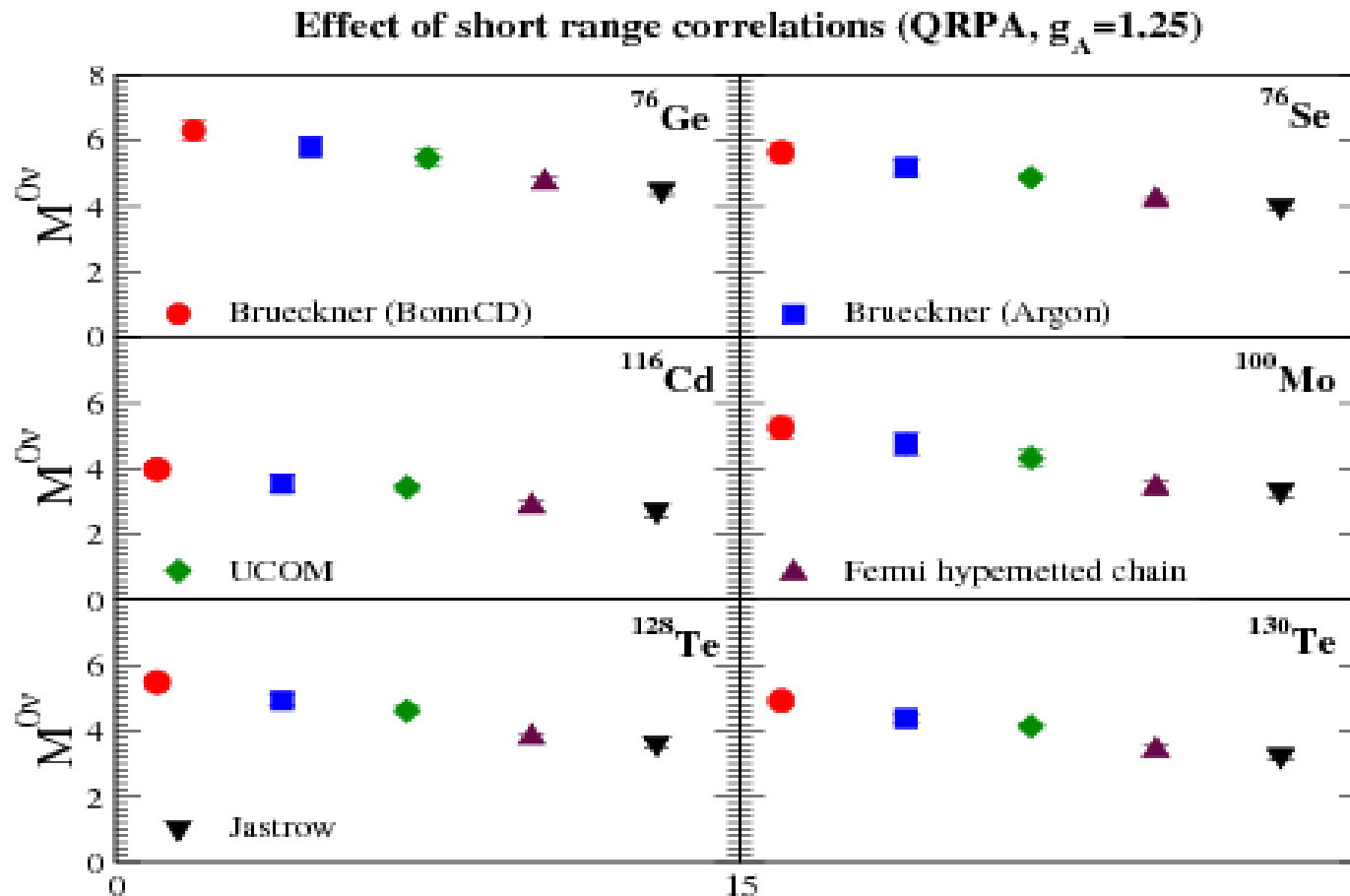
Tuebingen, February first. 2008.

First consistent treatment of pairing, nucleon-nucleon G-matrix, nuclear structure and short range correlation by the same realistic force by Brückner theory (Relativist. BG-eq.)

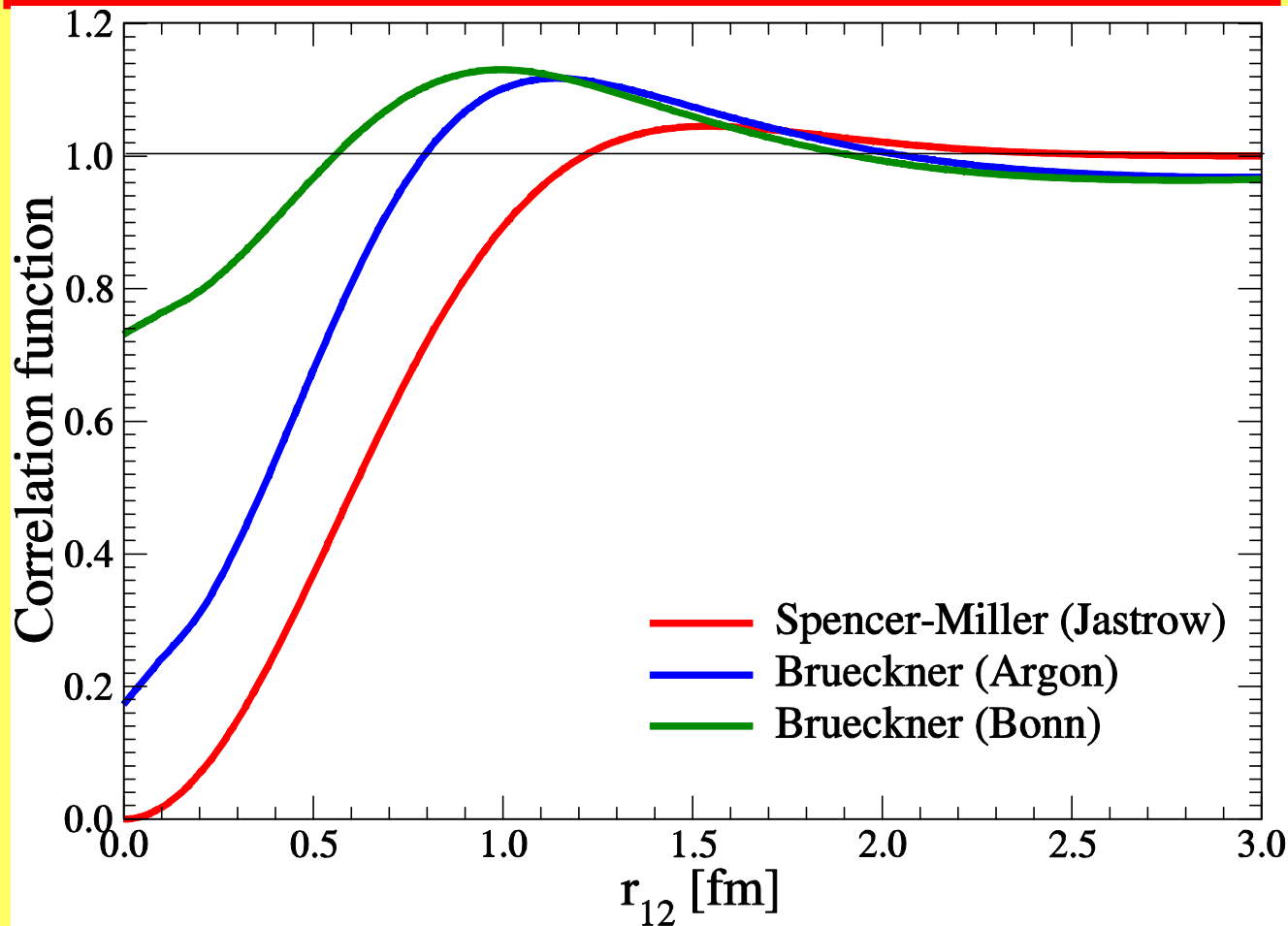
Rodin, Simkovic, Stauf, Muether and Faessler.



Different treatments of short range correlations: Brückner Bonn CD; Brückner Argonne; UCOM; Hypernetted chain; Jastrow

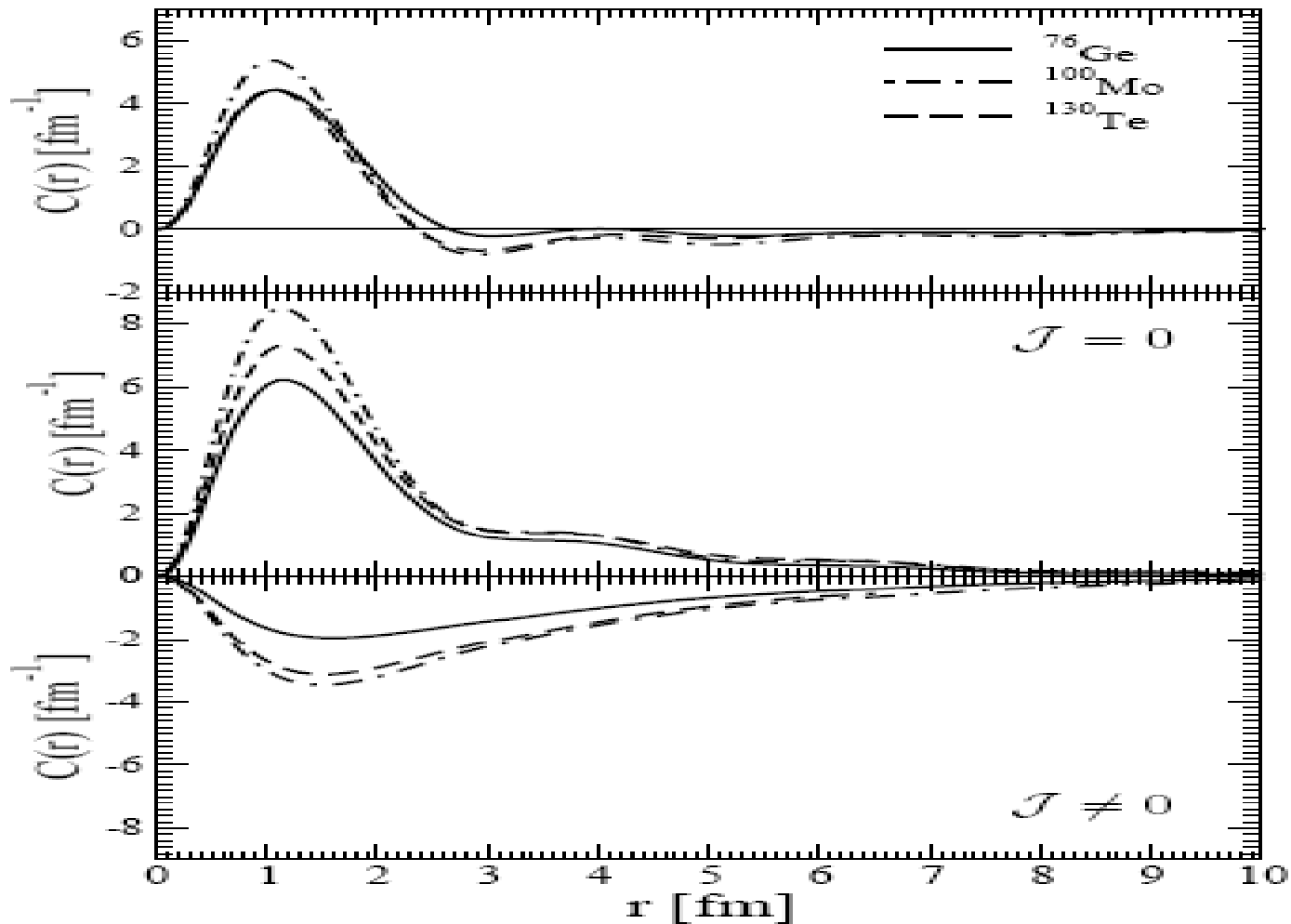


Different Short Range Correlations



Tuebingen, February first. 2008.

Radial Contributions to the $0\nu\beta\beta$ Matrix Element

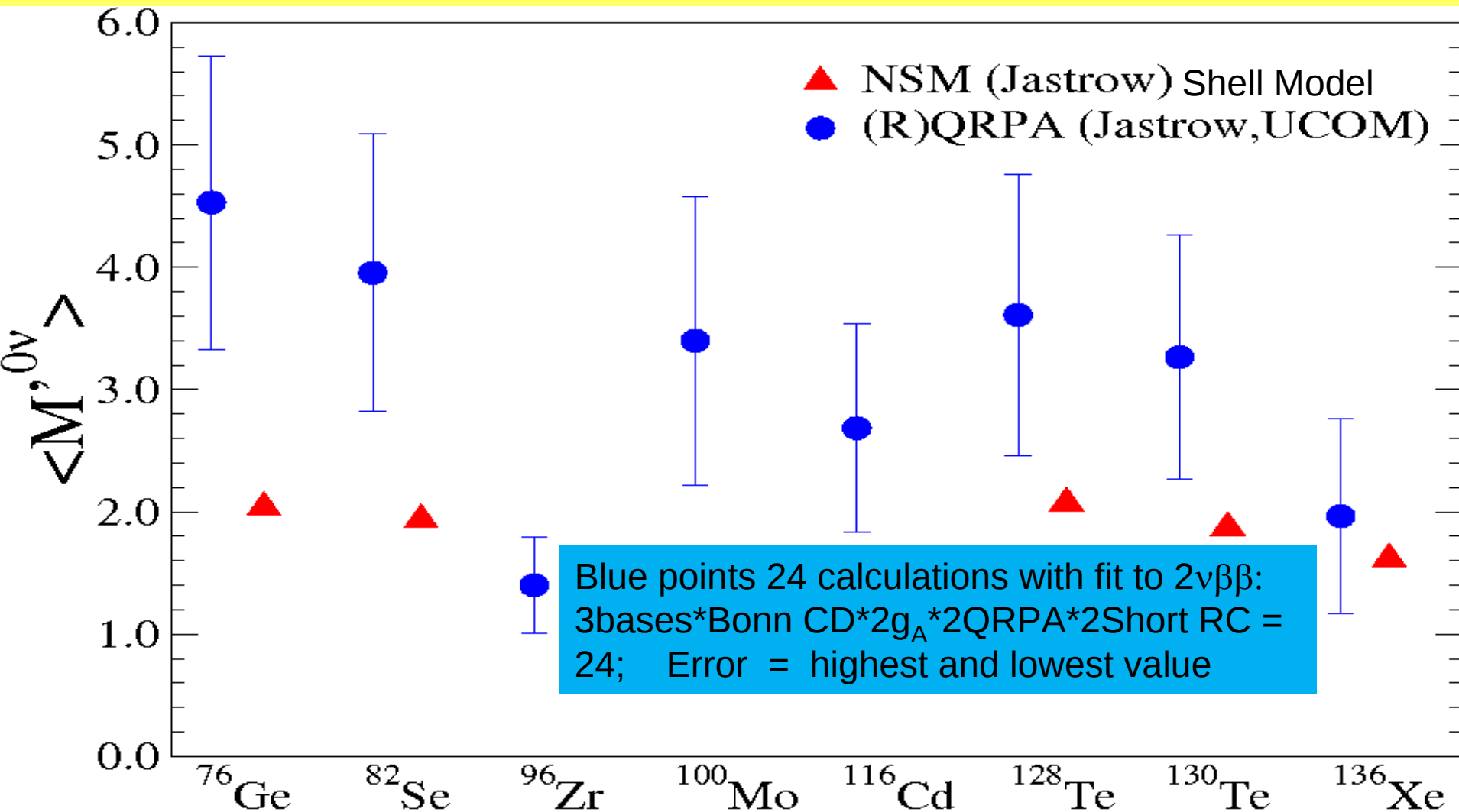


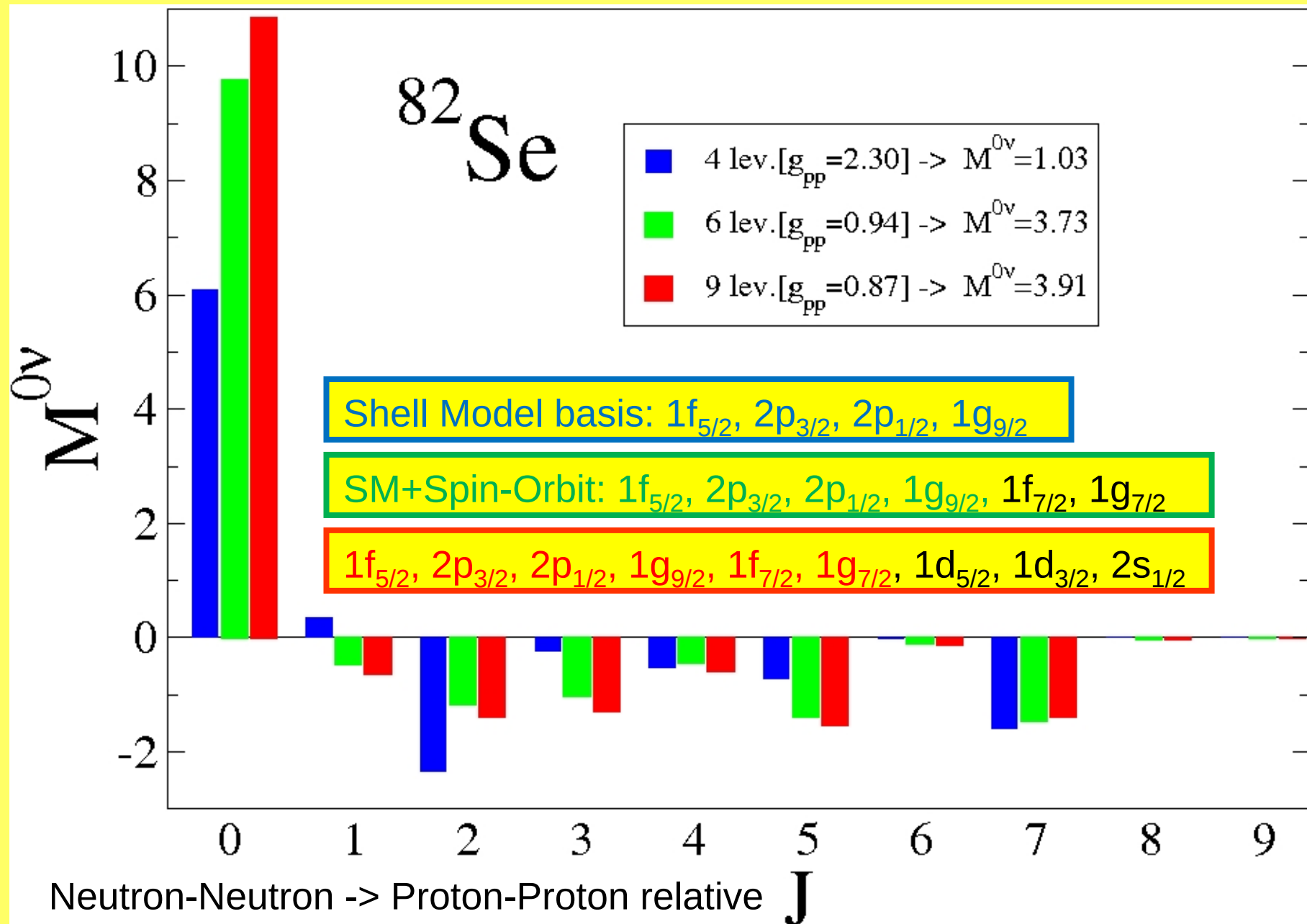
Tuebingen, February first. 2008.

Different treatment of Short Range Correlations (SRC)

- Brückner Correlations: The same realistic force for Pairing, G-matrix elements, for the solution of the Many Body Problem and Short Range Correlations. All as solutions of the same relativistic Bethe-Goldstone Eq.. **First fully consistent calculation.**
- UCOM: Different forces and treatment for Nuclear Structure and SRC. SRC (AV18) fitted to an analytic function with about 3(plus) parameters to the Deuteron and suppression of the Long Range Changes.
- Fermi Hypernetted chain: SRC parametrized by 3(plus) parameters fixed by the many body variational approach (Argonne).
- Jastrow: Fit of Gerry Miller and Spencer to Brückner results with two parameters to S-waves.

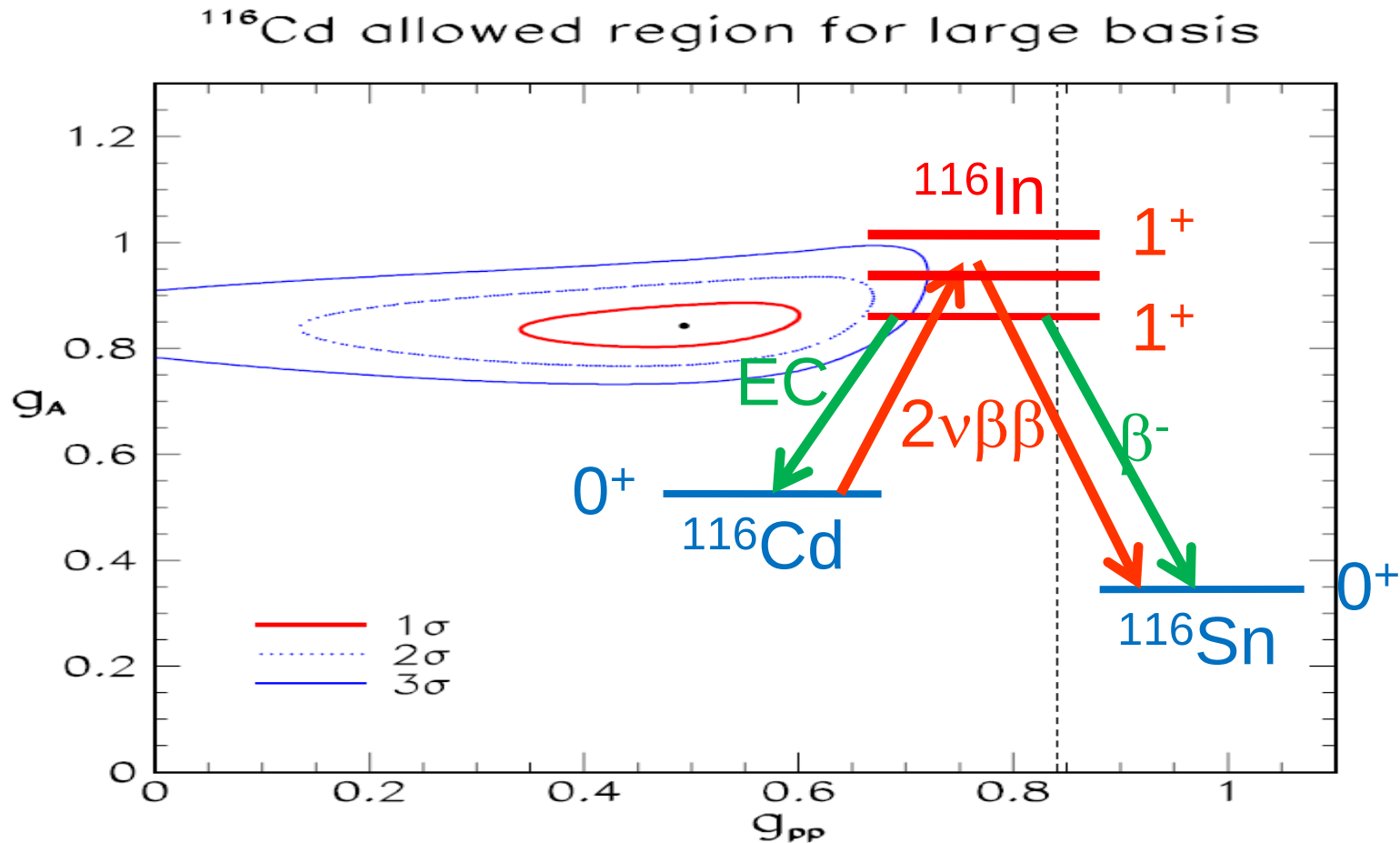
QRPA and RQRPA with errors from Basis Size, exp.
 2-Neutrino Decay, axial Coupling Constant $g_A = 1.25$ and
 1.00 and Short Range Correlations (UCOM + Jastrow)





Overconstraining the $0\nu\beta\beta$ Matrix Element

Faessler, Rodin, Fogli, Lisi, Rodin Rotunno,
Simkovic; ArXiv: 0711.3996[nucl-th];
 ^{116}Cd , ^{100}Mo , ^{128}Te



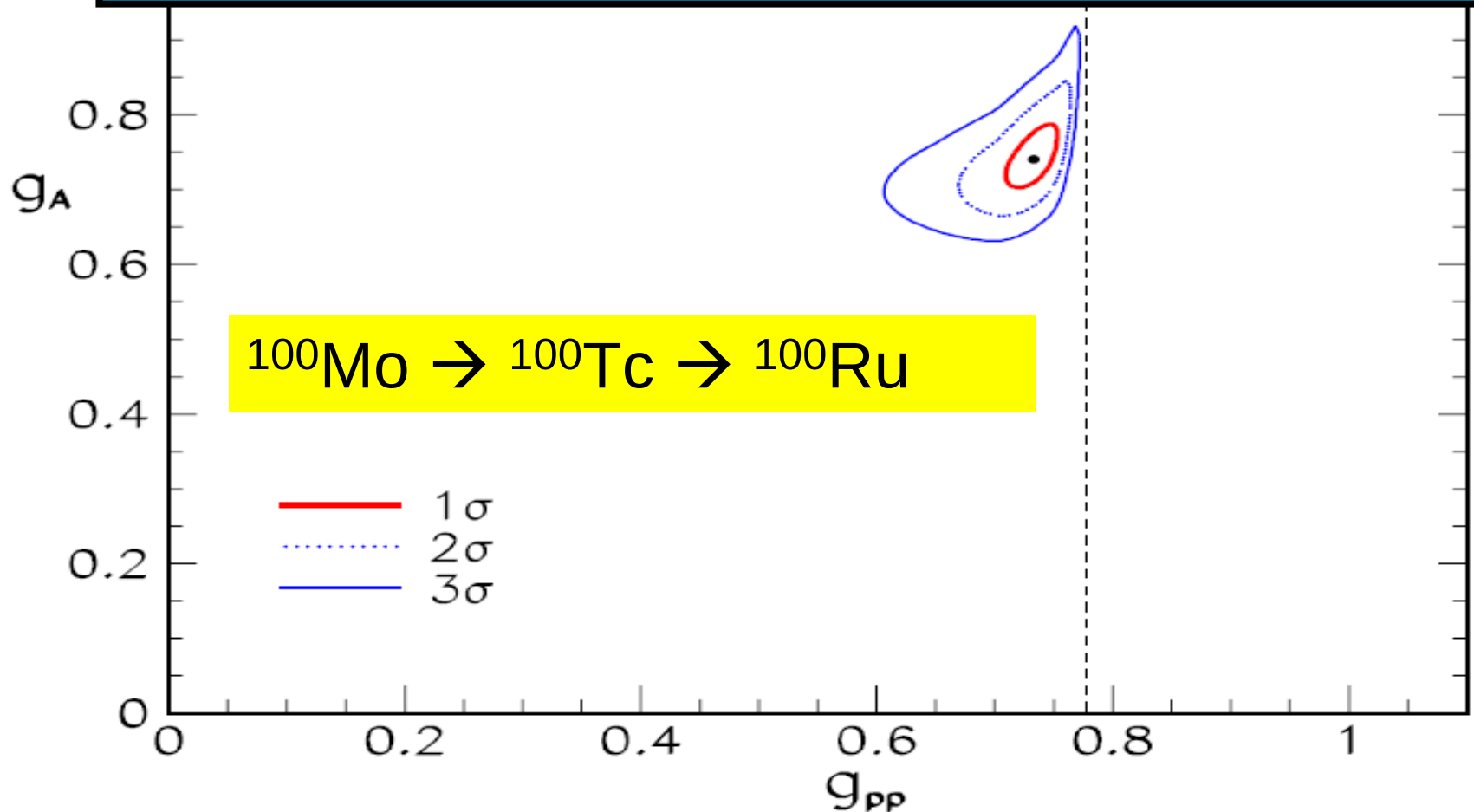
^{100}Mo allowed region for large basis

Overconstraining the $0\nu\beta\beta$ Matrix Element

Faessler, Rodin, Fogli, Lisi, Rodin Rotunno, Simkovic;

ArXiv: 0711.3996[nucl-th];

^{116}Cd , ^{100}Mo , ^{128}Te



Quenched Axial Charges g_A in Medium Mass Nuclei

Skouras, Manakos; J. Phys. G 19(1993) 731

^{98}Cd , ^{94}Ru : $g_A = 0.47 \rightarrow 0.62$

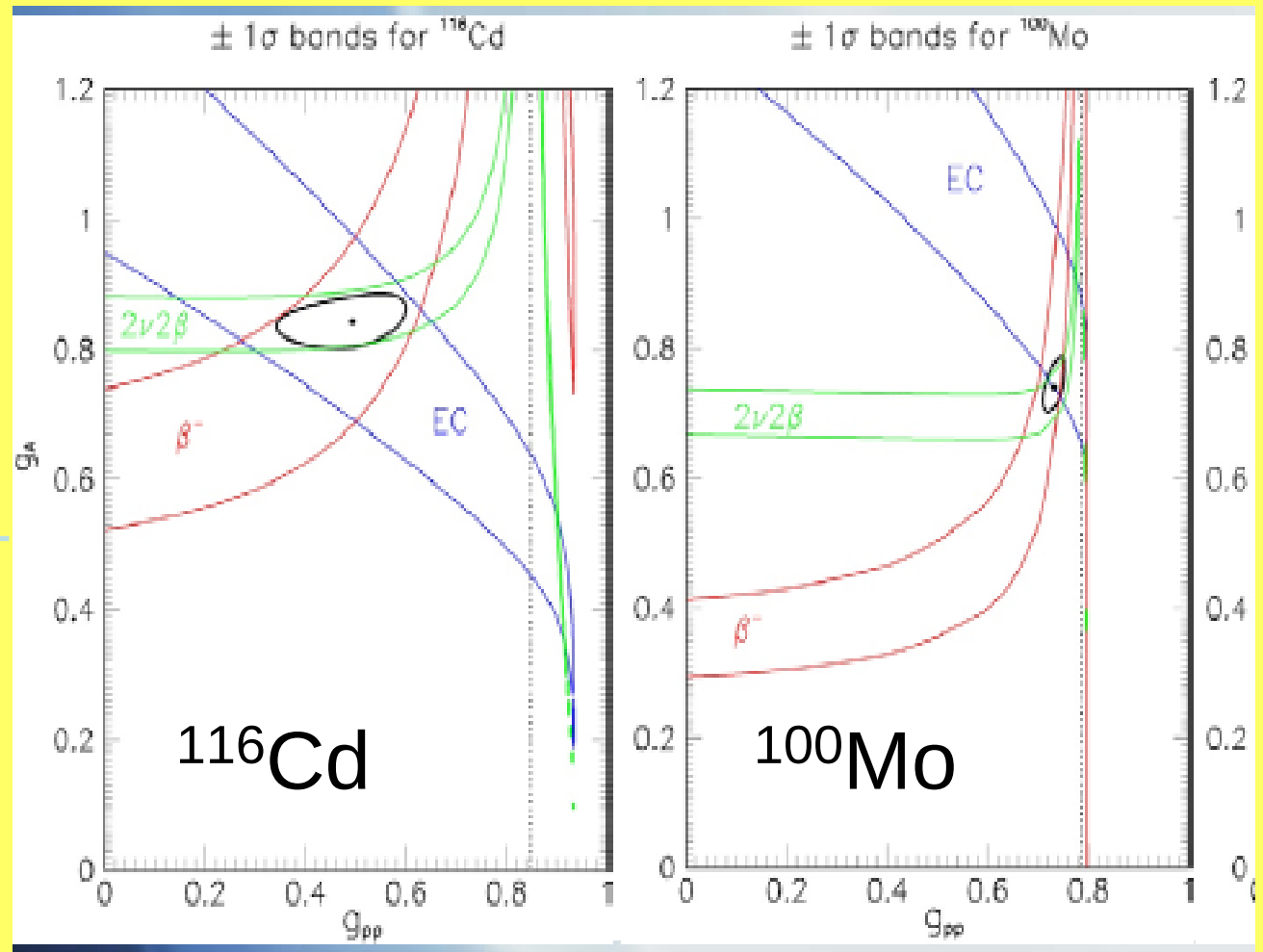
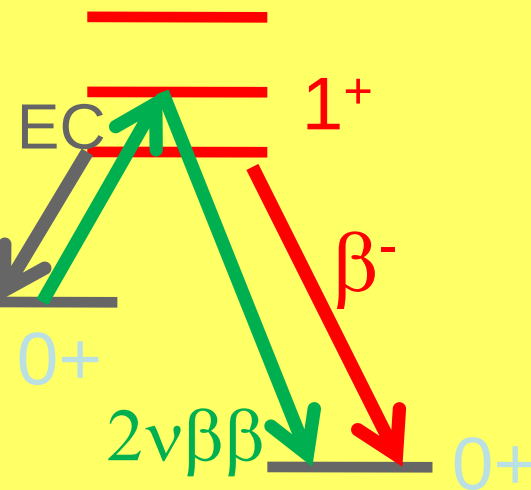
Brown, Rykaczewsky; Phys. Rev. C 50(1994)R2270

$\sim^{100}\text{Sn}$: $g_A = 0.64$

Juodagalvis, Dean; Phys. Rev. C 72(2005)024306

$A = 90 \rightarrow 97$: $g_A = 0.62$

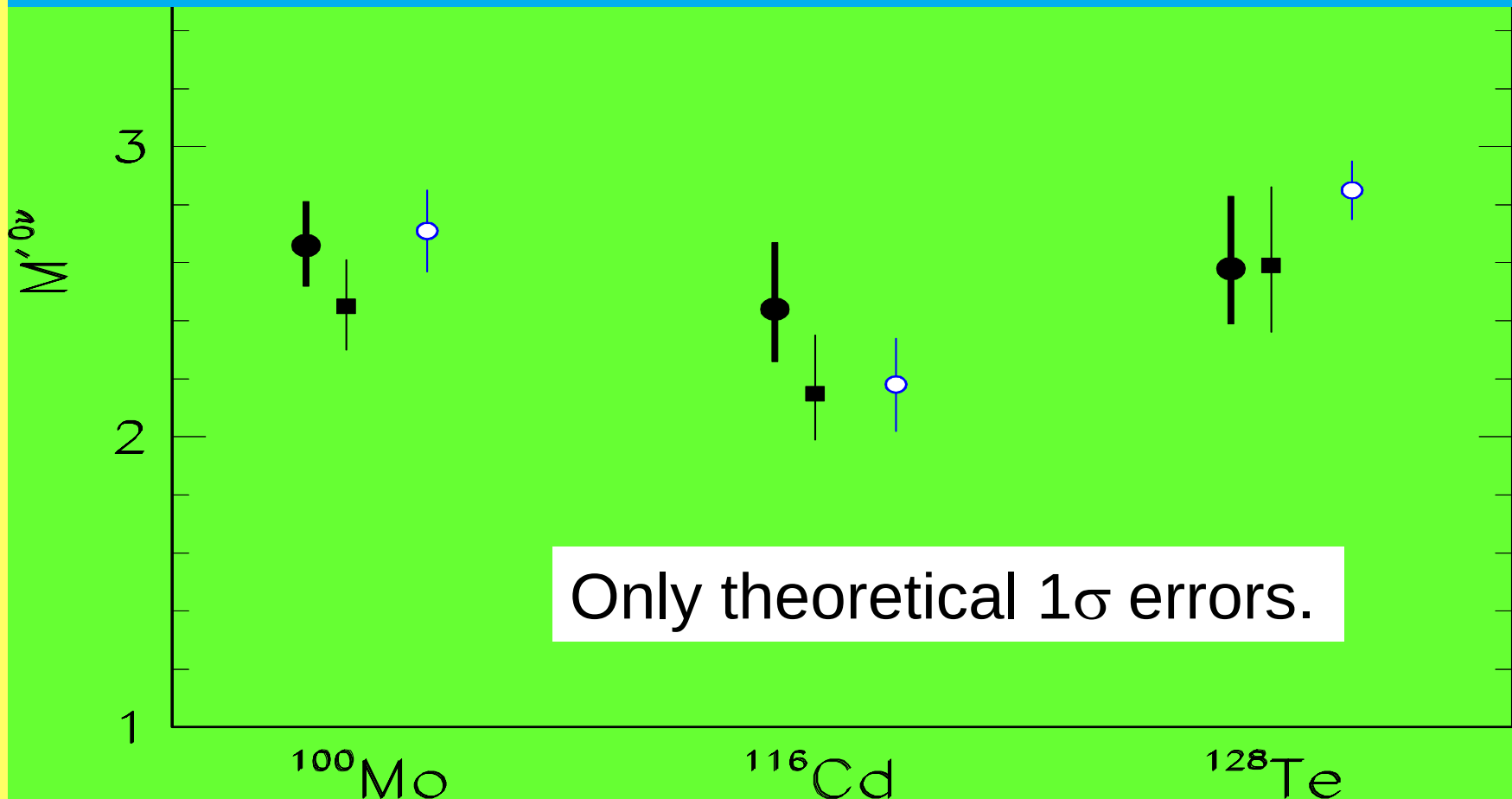
Overconstraining the $2\nu\beta\beta$ by adjusting g_{pp} and g_A to β^- , EC and $2\nu\beta\beta$ for ^{116}Cd and ^{100}Mo (Bari+Tuebingen)



Tuebingen, February first. 2008.

$0\nu 2\beta$ matrix elements (1σ ranges)

Solid points: Overconstrained results small and large basis.
Open circle QRPA 3 bases and $g_A = 1.00$.



HD claim for Detection of 0ν DBD

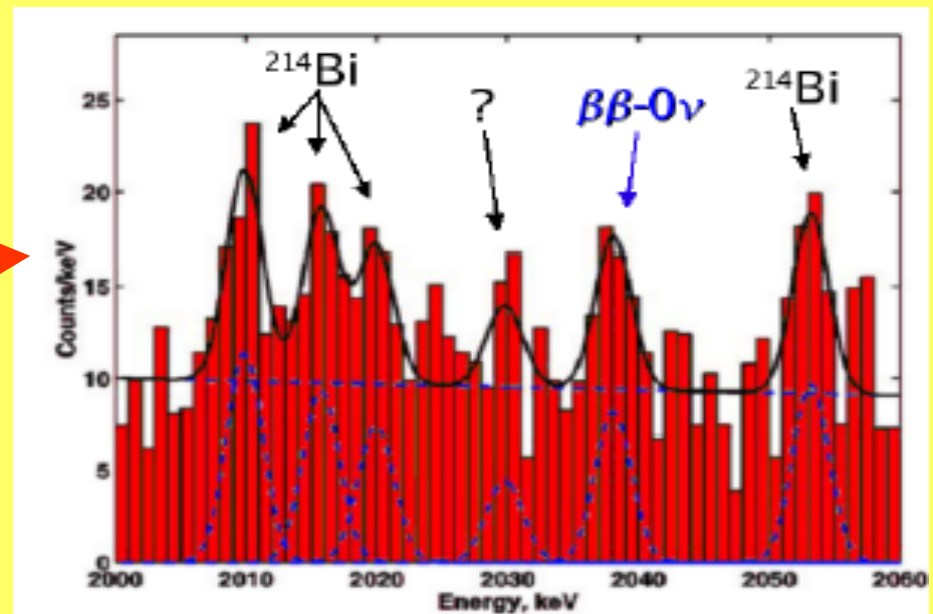
hep-ph/0512263 HM collaboration claim the 0ν DBD of ^{76}Ge

Source = Detector

- 10.9 kg - (86% from 8% nat.) ^{76}Ge
- Gran Sasso Laboratory (Italy)



Spectrum with 71.7 kg•y →



Tuebingen, February first. 2008.

Summary: Neutrino Mass from $0\nu\beta\beta$

Theory with R-QRPA and $g_A = 1.25$

Exp. Klapdor et al. Mod. Phys. Lett. A21,1547(2006) ; ^{76}Ge

$T(1/2; 0\nu\beta\beta) = (2.23 +0.44 -0.31) \times 10^{25} \text{ years}; 6\sigma$

- $\langle m(\nu) \rangle = 0.24 \text{ [eV]} (\text{exp} \pm 0.02; \text{theor} \pm 0.01) \text{ [eV]}$
Bonn CD, no short range correlations

- $\langle m(\nu) \rangle = 0.22 \text{ [eV]} (\text{exp} \pm 0.02; \text{theor} \pm 0.01) \text{ [eV]}$
Bonn CD, Consistent Brückner Correlations

- $\langle m(\nu) \rangle = 0.24 \text{ [eV]} (\text{exp} \pm 0.02; \text{theor} \pm 0.01)$
Argonne, Consistent Brückner Correlations

THE END

- $\langle m(\nu) \rangle = 0.30 \text{ [eV]} (\text{exp} \pm 0.03; \text{theor} \pm 0.01) \text{ [eV]}$
Bonn CD, Fermi Hypernetted Chain (Argonne in nuclei)

- $\langle m(\nu) \rangle = 0.26 \text{ [eV]} (\text{exp} \pm 0.02; \text{thero} \pm 0.01) \text{ [eV]}$ Bonn CD, UCOM (AV18 in D)

- $\langle m(\nu) \rangle = 0.31 \text{ [eV]} (\text{exp} \pm 0.03; \text{theor} \pm 0.02) \text{ [eV]}$ Bonn CD, Jastrow