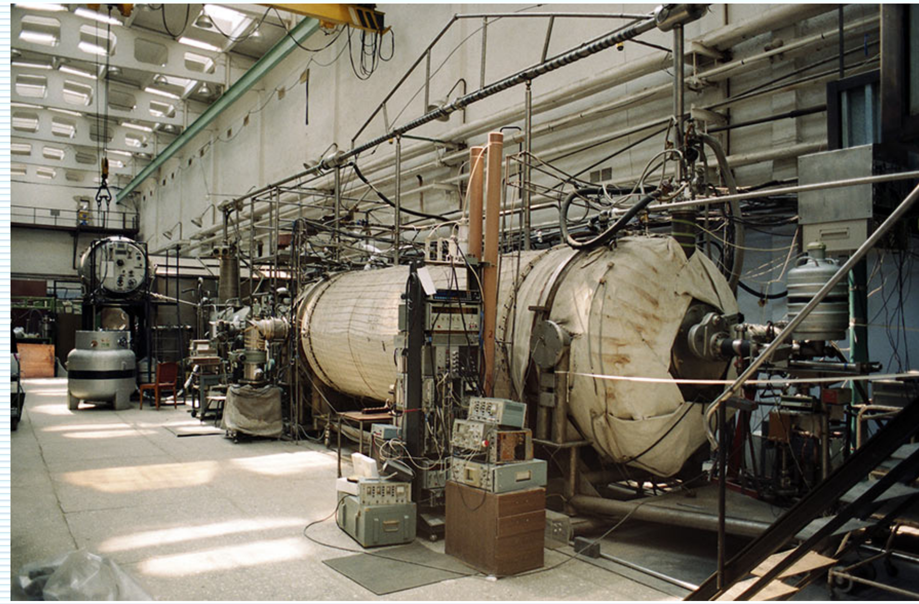
Юбилейнуя научная конференция
к 50-летию Институтфа ядерных исследований РАН,
3-4 декабря 2020 года (онлайн)

ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ РОССИЙСКОЙ АКАДЕМИИ НАУК



Лабораторные нейтринные эксперименты

Федор Шимкович (Fedor Šimkovic)

Дорогие друзья!

В этот день примите самые теплые поздравления

от словацких и чешских друзей

к 50-летию Института ядерных исследований РАН!

Желаем вам, чтобы ваш научный труд был всегда востребован и оценен по достоинству, чтобы он приносил вам удовлетворение и благополучие.

Новых научные достижения, крепкого здоровья жизненной энергии, счастья и благополучия!

OUTLINE

I. Introduction
(Majorana ν's)
II. Laboratory measurement of ν-mass
(history, Troitsk exp., KATRIN)
III. $0\nu\beta\beta$-decay experiments
(GERDA, LEGEND, AMoRE)
IV. $0\nu\beta\beta$-decay theory
(ν-mass mechanisms, non-standard ν-interactions, LR-symmetric models)
V. $0\nu\beta\beta$-decay NMEs
VI. $2\nu\beta\beta$-decay and quenching of g_A
(SSD/HSD, exotic contribution to $2\nu\beta\beta$-decay rate, etc)

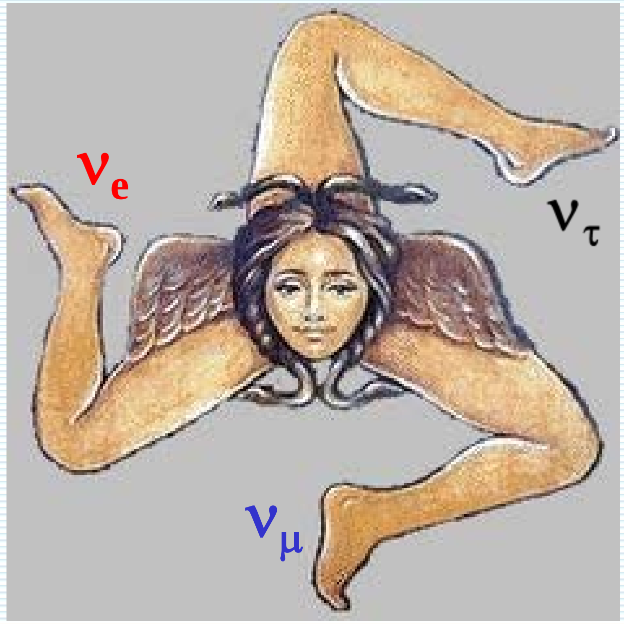
Acknowledgements: Sergey Troitsky, Igor Tkachev, Vladyslav Trotskyi, Albert Gangapshev, Vladimir Kazalov

After **90/64** years we know

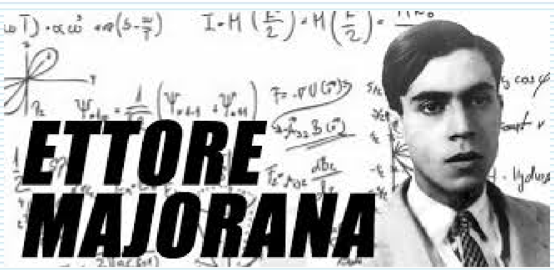
Fundamental ν properties

No answer yet

- 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)

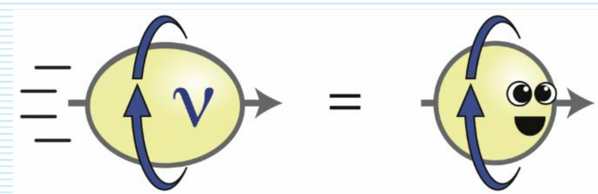


- Are ν Dirac or Majorana?
- Is there a CP violation in ν sector?
- Are neutrinos stable?
- What is the magnetic moment of ν?
- Sterile neutrinos?
- Statistical properties of ν? Fermionic or partly bosonic?



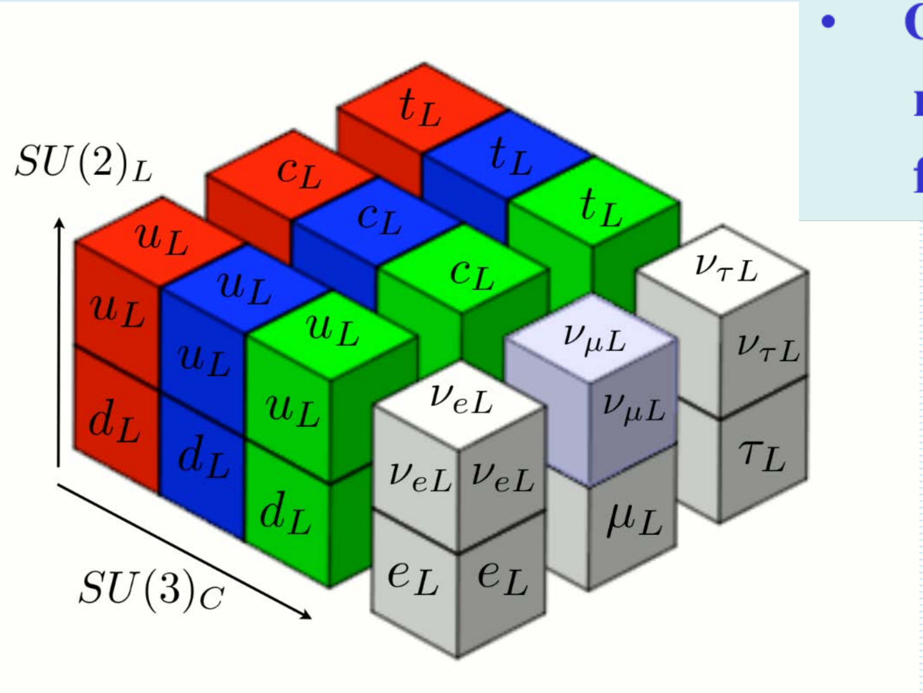
Currently main issue

Nature, Mass hierarchy,
CP-properties, sterile ν



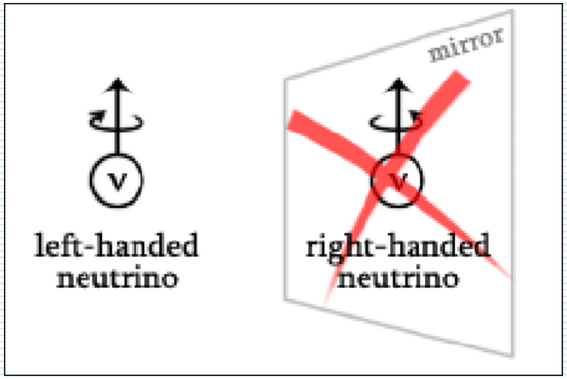
The observation of neutrino oscillations has opened a new excited era in neutrino physics and represents a big step forward in our knowledge of neutrino properties

Standard Model
(an astonishing successful theory, based on few principles)



Neutrino is a special particle in SM:

- **It is the only fermion that does not carry electric charge (like bosons γ, g, H^0) !**
- **In the SM, the only left-handed neutrinos ν_L appears in the theory.**
- **One cannot obtain a mass for ν_L with any renormalizable coupling with the Higgs fields through SSB.**



However, we know that ν's do have mass from the ν-oscillation experiments!
=> Thus the neutrino mass indicates that there is something new = BSM physics!

MESONIUM AND ANTIMESONIUM

B. PONTECORVO

Joint Institute for Nuclear Research

Submitted to JETP editor May 23, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 549-551 (August, 1957)

INVERSE BETA PROCESSES AND NONCONSERVATION OF LEPTON CHARGE

B. PONTECORVO

Joint Institute for Nuclear Research

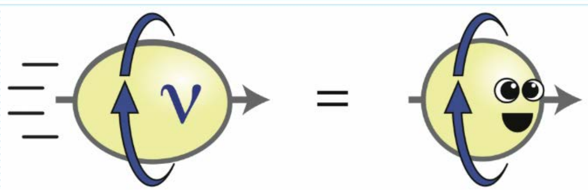
Submitted to JETP editor October 19, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) **34**, 247-249 (January, 1958)

$\nu \leftrightarrow \bar{\nu}$ oscillation

(neutrinos are Majorana particles)

It follows from the above assumptions that in vacuum a neutrino can be transformed into an antineutrino and vice versa. This means that the neutrino and antineutrino are "mixed" particles, i.e., a symmetric and antisymmetric combination of two truly neutral Majorana particles ν_1 and ν_2 of different combined parity.[5]



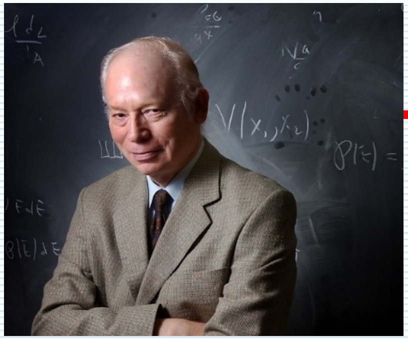
1968 Gribov, Pontecorvo [PLB 28(1969) 493]
oscillations of neutrinos - a solution
of deficit of solar neutrinos in Homestake exp.

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERN COURIER

VOLUME 57 NUMBER 9 NOVEMBER 2017

dimension-5 effective Weinberg operator (1979)



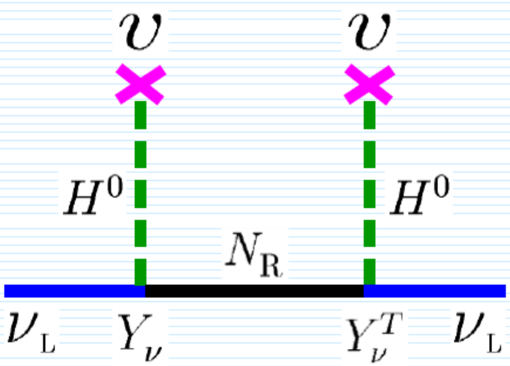
S. Weinberg

thought massless back in 1979. Weinberg does not take credit for predicting neutrino masses, but he thinks it's the right interpretation. What's more, he says, the non-renormalisable interaction that produces the neutrino masses is probably also accompanied with non-renormalisable interactions that produce proton decay and other things that haven't been observed, such as violation of baryon-number conservations. "We don't know anything about the details of those terms, but I'll swear they are there."

$$\mathcal{L}_5^{eff} = -\frac{1}{\Lambda}\sum_{l_1 l_2}\left(\overline{\Psi}^{lep}_{l_1 L}\tilde{\Phi}\right)\acute{Y}_{l_1 l_2}\left(\tilde{\Phi}^T(\Psi^{lep}_{l_2 L})^c\right)$$

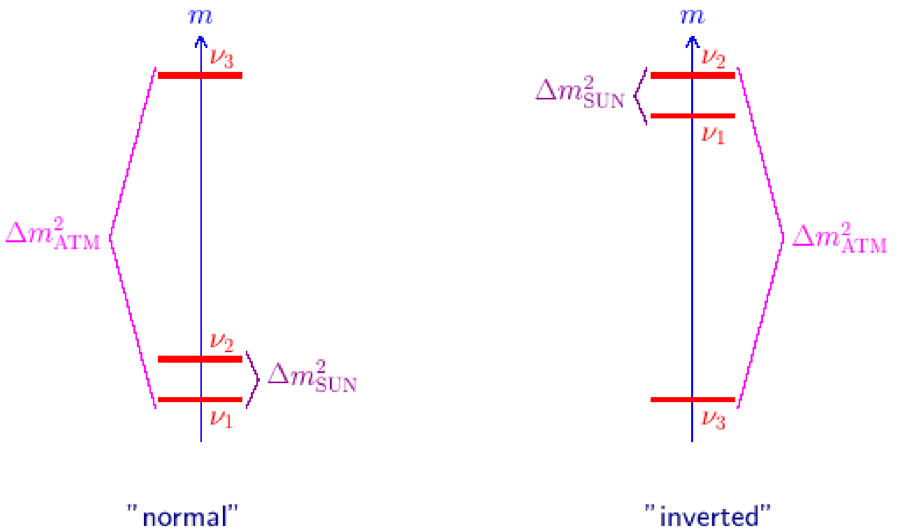
$$m_i = \frac{v}{\Lambda}\,(y_i v), \quad i = 1,2,3$$

$\Lambda \geq 10^{15}$ GeV



The three Majorana neutrino masses are suppressed by the ratio of the electroweak scale and a scale of a lepton-number violating (new) physics.

Neutrinos mass spectrum

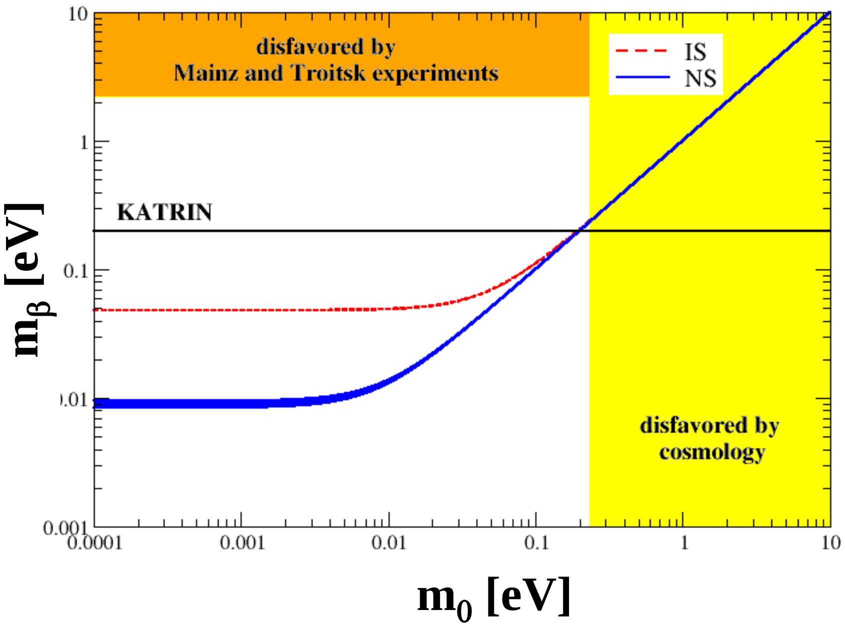


0νββ Measurements

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 e^{i\alpha_1} m_1 + c_{13}^2 s_{12}^2 e^{i\alpha_2} m_2 + s_{13}^2 m_3\right|$$

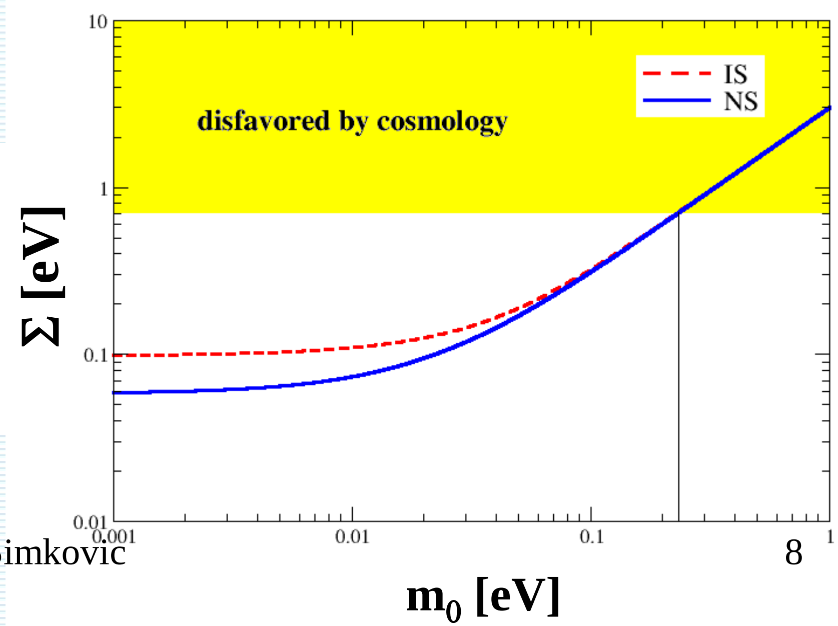
Beta Decay Measurements

$$m_\beta = \sqrt{c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2}$$



Cosmological Measurements

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



Laboratory measurement of ν-mass with beta decay

Beta decay (^{3}H, ^{187}Re, ^{115}In …)

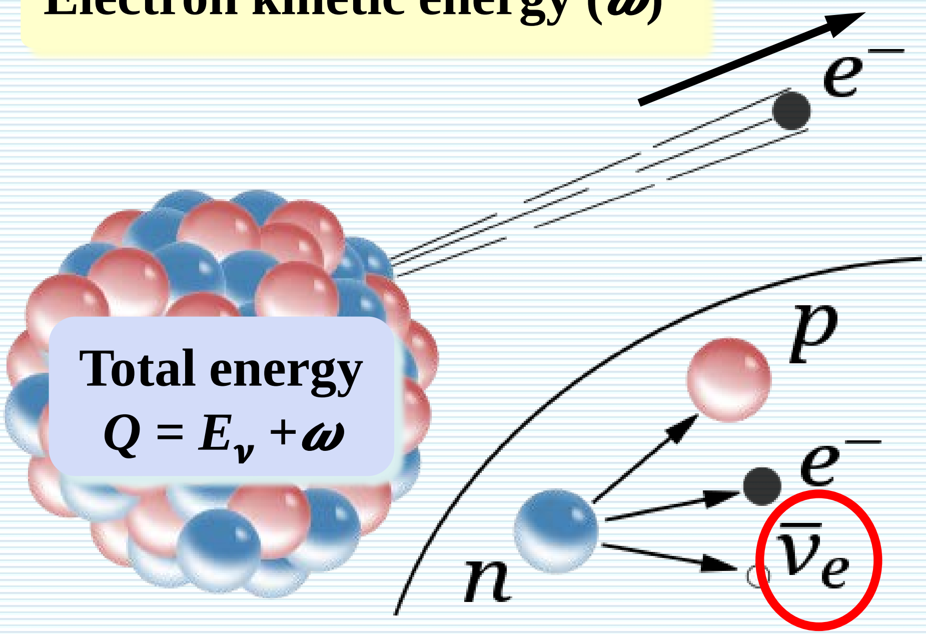
Exp: Troitsk, Mainz, Mare, Mibeta, KATRIN, Project8

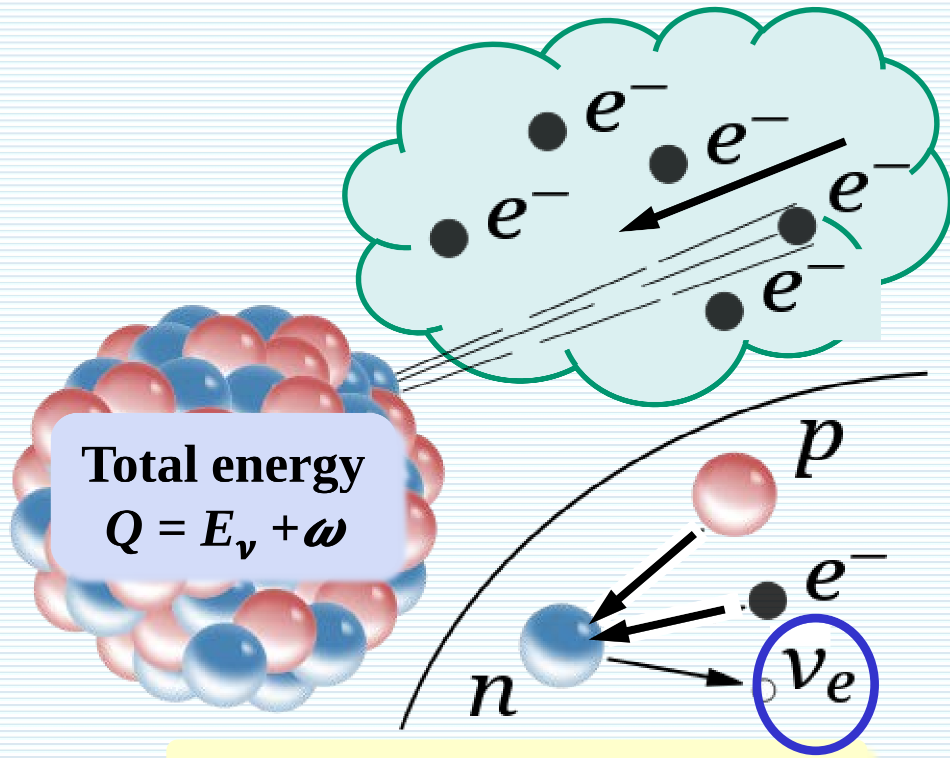
Electron capture (^{163}Ho)

Exp: ECHo, Holmes

Electronic excitations (ω)

Electron kinetic energy (ω)

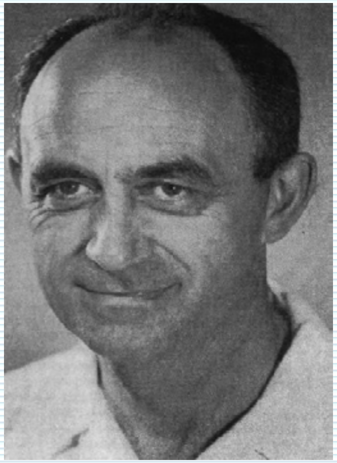




Neutrino kinetic energy (E_ν)

Neutrino kinetic energy (E_ν)

Fermi: Determine ν-mass from nuclear β-decay



Enrico Fermi,

Z. Physik 88 (1934)

7. Die Masse des Neutrinos.

Durch die Übergangswahrscheinlichkeit (32) ist die Form des kontinuierlichen β-Spektrums bestimmt. Wir wollen zuerst diskutieren, wie diese Form von der Ruhemasse μ des Neutrinos abhängt, um von einem Vergleich mit den empirischen Kurven diese Konstante zu bestimmen. Die Masse μ ist in dem Faktor p_σ^2/v_σ enthalten. Die Abhängigkeit der Form der Energieverteilungskurve von μ ist am meisten ausgeprägt in der Nähe des Endpunktes der Verteilungskurve. Ist E_0 die Grenzenergie der β-Strahlen, so sieht

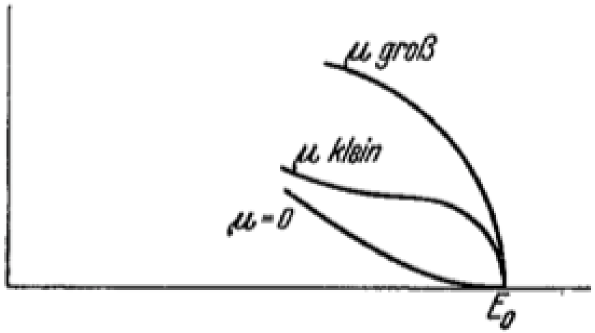
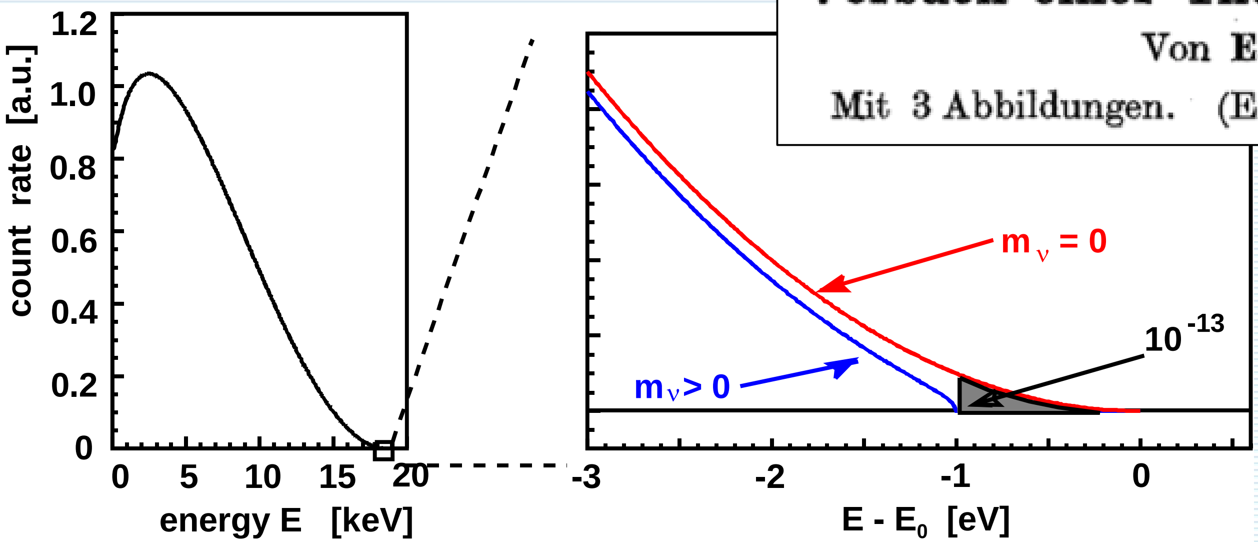


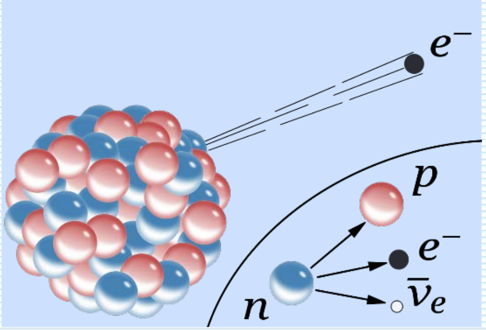
Fig. 1.

Versuch einer Theorie der β-Strahlen. I[1]).

Von **E. Fermi** in Rom.

Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

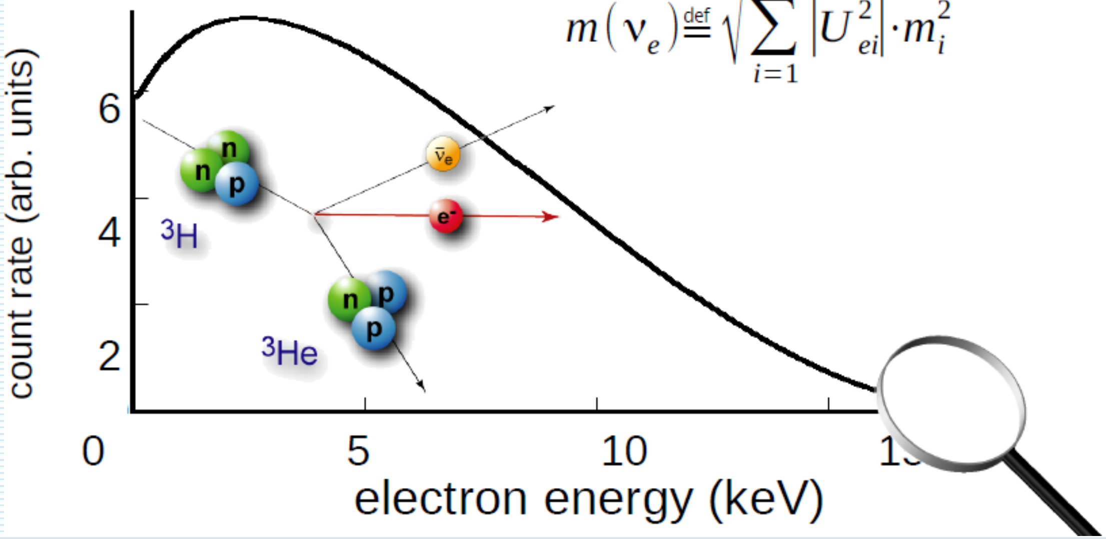


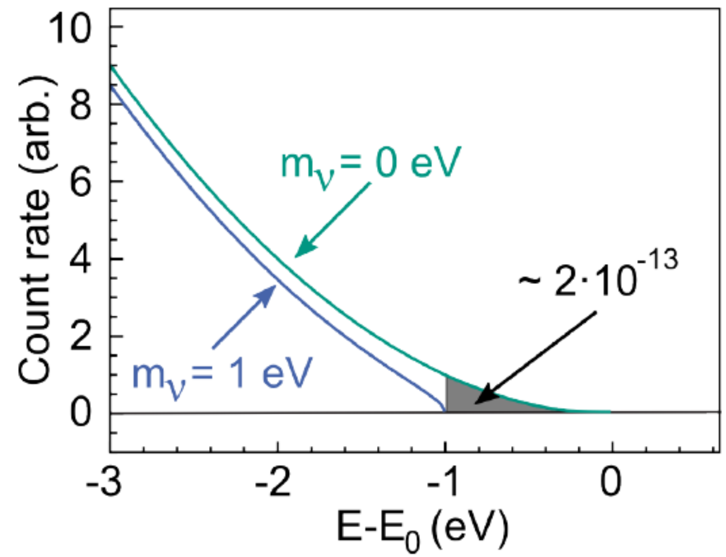


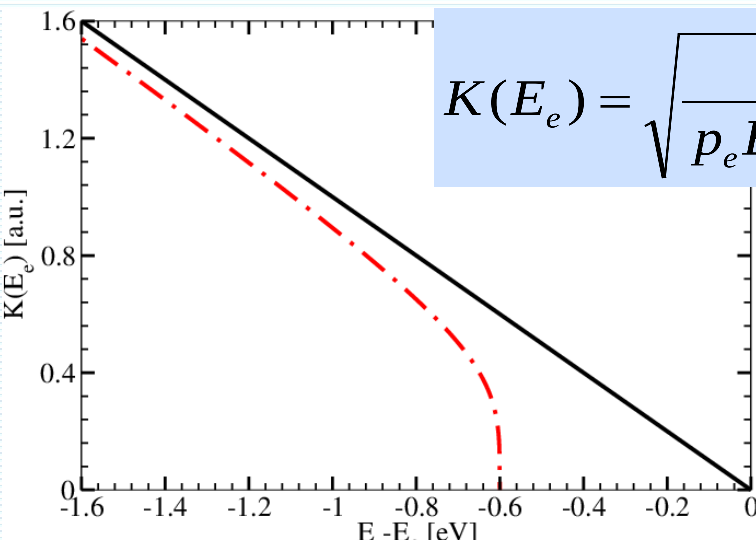
Spectrum shape at $m_\nu > 0$

$$\frac{d\Gamma}{dE} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sum_{i=1}^{3} \left|U_{ei}^2\right| \cdot \sqrt{(E_0 - E)^2 - m_{\nu_i}^2} \cdot F(E,Z) \cdot \theta(E_0 - E - m_{\nu_i})$$

$$m(\nu_e) \stackrel{\text{def}}{=} \sqrt{\sum_{i=1}^{3} \left|U_{ei}^2\right| \cdot m_i^2}$$

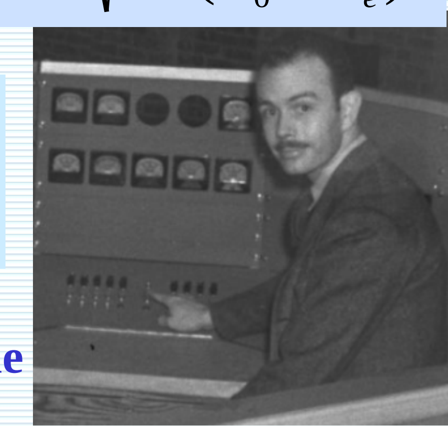






$$K(E_e) = \sqrt{\frac{d\Gamma/dE_e}{p_e E_e F_0(Z_f, E_e)}} = \frac{G_\beta g_A |M|}{\sqrt{2\pi^3}} (E_0 - E_e) \sqrt[4]{1 - \frac{m_\beta^2}{(E_0 - E_e)^2}}$$

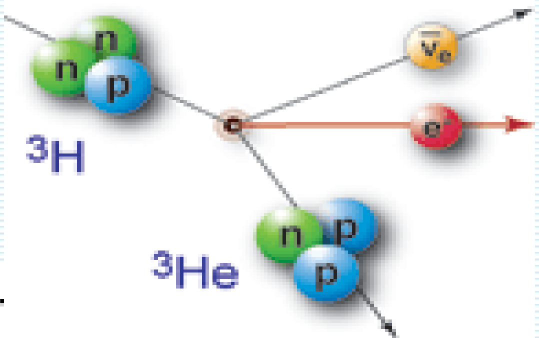
The advantage of Kurie plot is that non-linearity implies non-zero ν-mass.



Franz Newell Devereux Kurie

1948: First experiment with tritium

$T \rightarrow {}^3He + e^- + 18{,}6\ KeV$



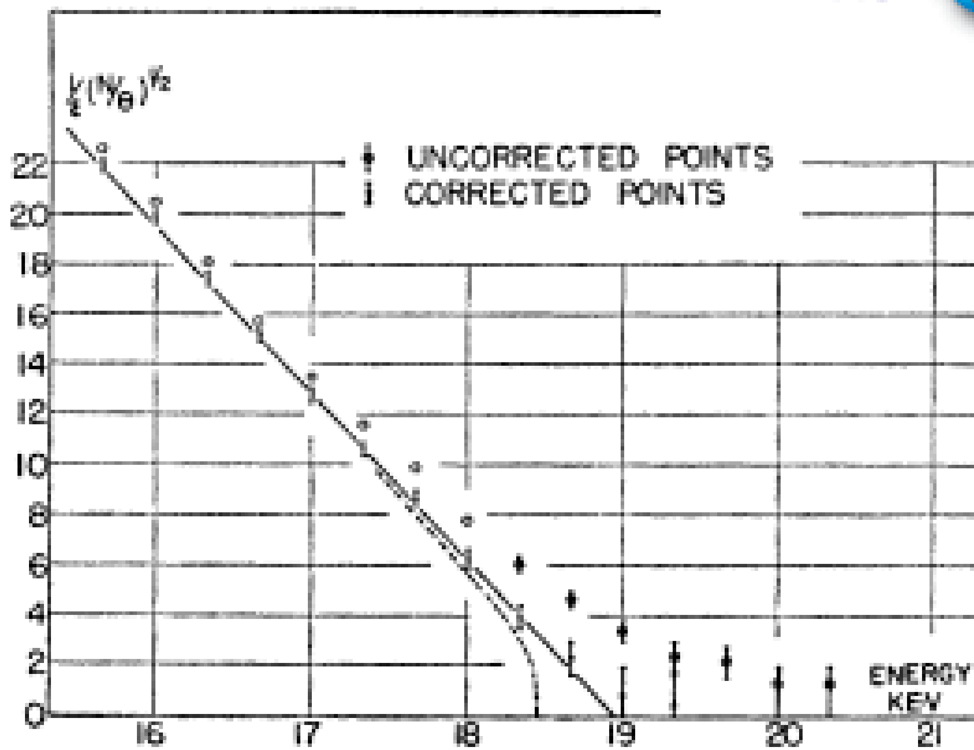


FIG. 2. "Kurie" plot of the end of the H³ spectrum. The theoretical curve (shown dotted) corresponding to a finite neutrino mass of 500 ev (or 1 kev —see text) has been included for comparison.

m_ν < 1 кэВ/c^2

Hanna G.C. and Pontecorvo B., Phys. Rev. 75 (1949) 983
Curran S C, Angus J, and Cockroft A, Phys. Rev. 76 (1949) 853

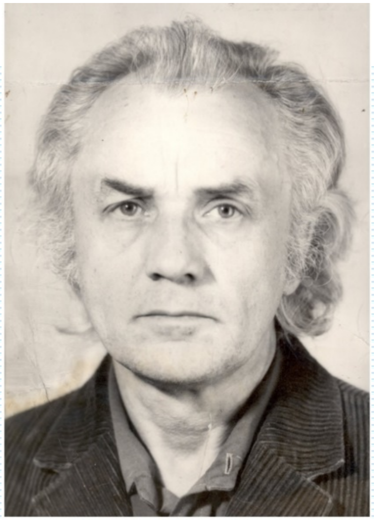
Estimation of the neutrino rest mass from measurements of the tritium β spectrum

V. A. Lyubimov, E. G. Novikov, V. Z. Nozik, E. F. Tret'yakov, V. S. Kozik, and N. F. Myasoedov

Institute of Theoretical and Experimental Physics
(Submitted 22 May 1981)
Zh. Eksp. Teor. Fiz. **81**, 1158–1181 (October 1981)

Е.Ф.Третьяков

В.А. Любимов



Toroidal spectrometer

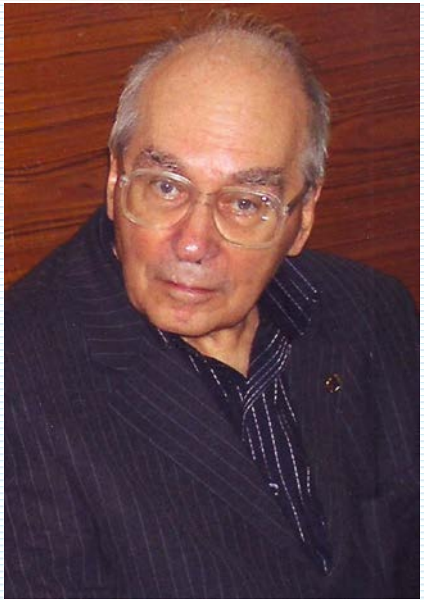
$14 < m_{\nu e} < 46$ eV
Closed Universe ?!

Peter Spivak

"Troitsk ν-mass" - Founders

Spectrometer resolution and Tritium source size became decoupled by an Electrostatic Spectrometer with Adiabatic Magnetic Collimation (MAC-E Filter)

V.M. Lobasev, P.E, Spivak,
Nucl. Instr. Meth. A240 (1985) 305



Vladimir Lobashev

High spectrometer resolution does ot depend on the size of the source

Установка «Троицк ν-масс»

Charged particle in a slowly varying magnetic field moves *adiabatically.*

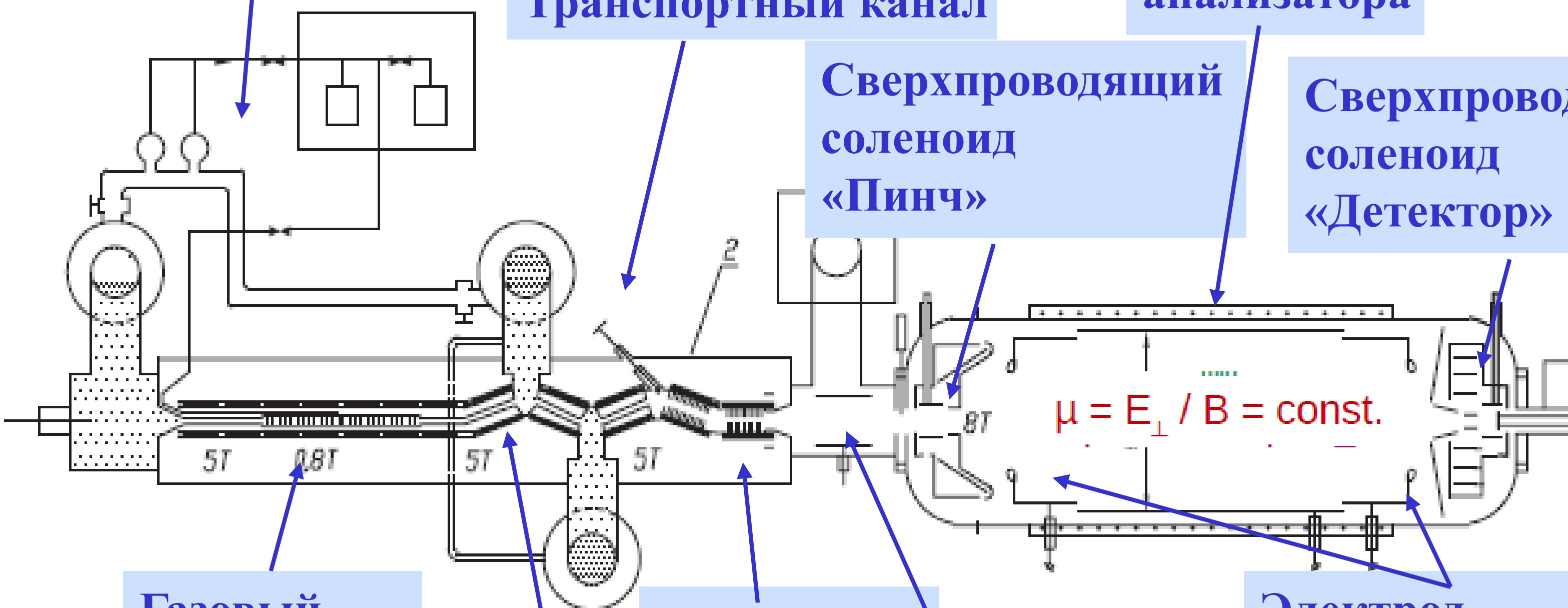
Система рециркуляции

Транспортный канал

Теплый соленоид анализатора

Сверхпроводящий соленоид «Пинч»

Сверхпроводящий соленоид «Детектор»



Газовый безоконный источник

Криогенная откачка

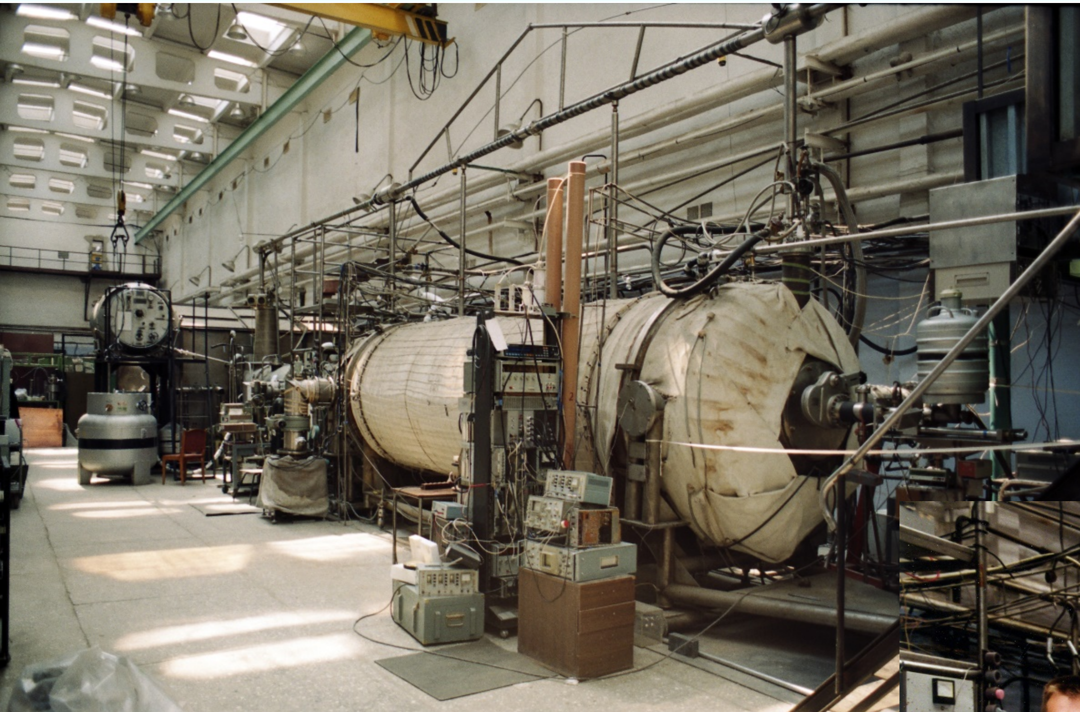
Предварительный спектрометр

Электрод электростатического анализатора

Дифференциальная откачка

In the transition into weaker magnetic field velocity vectors are aligned along the magnetic field direction.

Установка «Троицк ню-масс



Спектрометр
длина 6,5 м
диаметр электрода 1,2 м
разрешение 3,7 эВ
Диаметр источника 20 мм
толщина $1\cdot10^{17}$ мол/см^2,
активость 0,3 GBk (8 mCi)

Первые данные опубликованы в 1994 г:

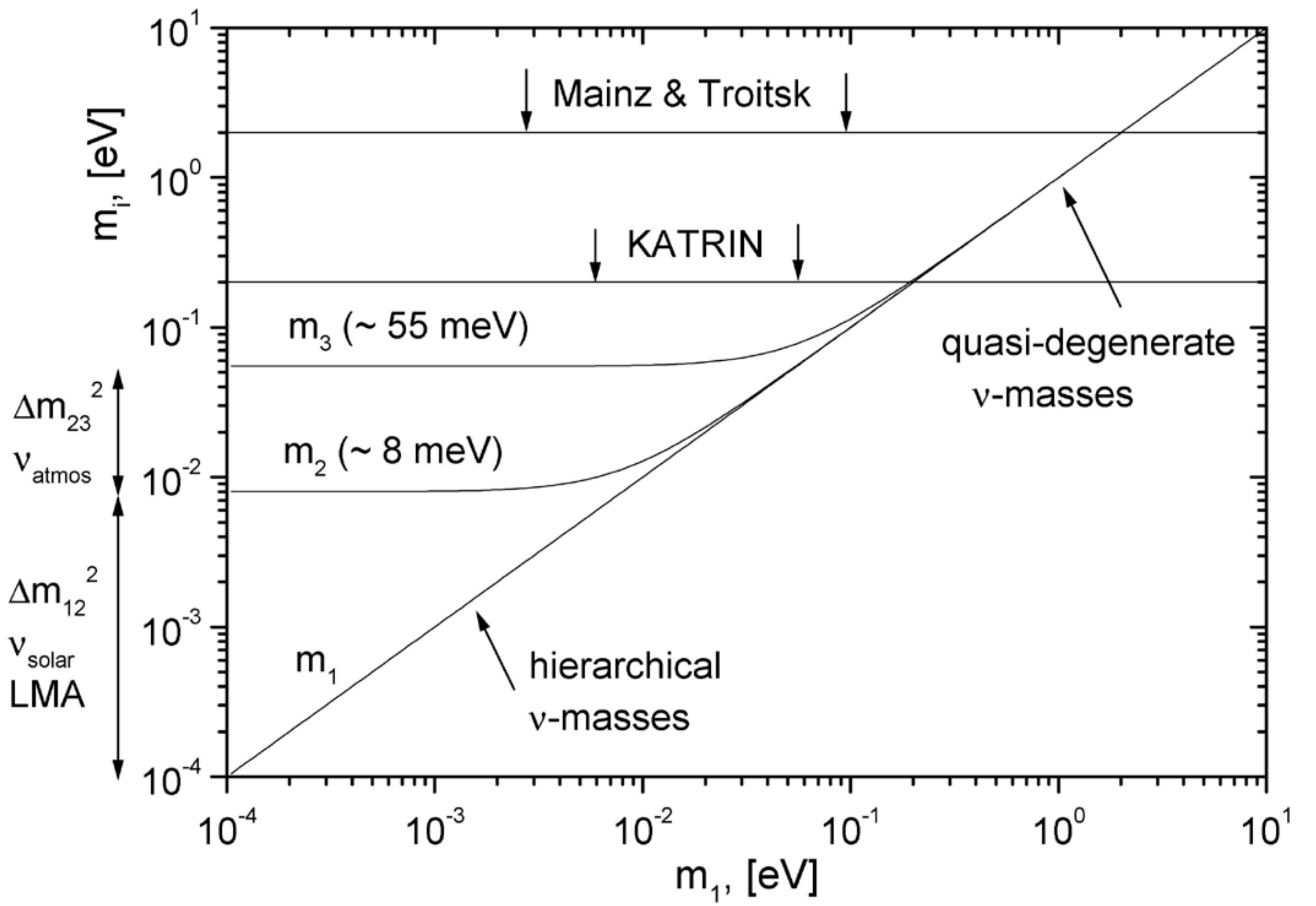
Paper presented at XXVII Int. Conf. on High Energy Physics. Glasgow, UK, 20–27 July 1994

Завершен набора данных в 2003г:
V.M.Lobashev Nucl.Phys. A719 (2003) 153e

$m_\nu < 2.05$ eV^2 (95% C.L.)

A new challenge ≈1998

Mainz and Troitsk reached their sensitivity limits but it is desirable and possible to improve neutrino mass limit by one more order of magnitude



Confirm or excludes quasi-degenerate mass regime

Test cosmological neutrino mass limit

KATRIN Collaboration

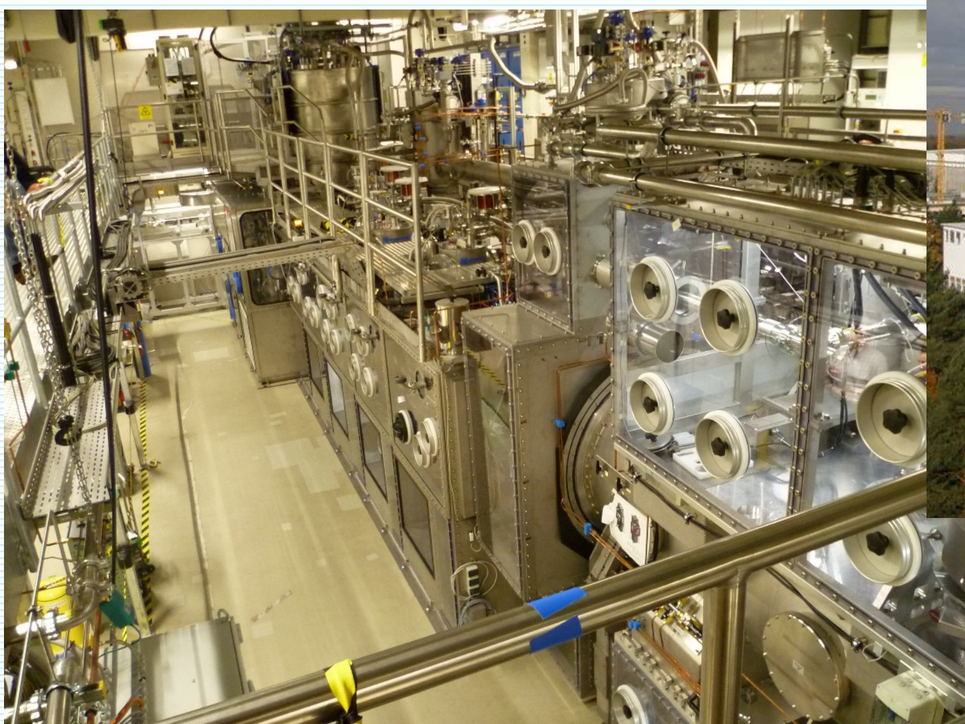
Institute for Nuclear Research of Russian Academy of Sciences Moscow, Russia

O. Kazachenko, V. M. Lobashev*, A. Lokhov, A. Skasyrskaya, N. Titov, I. Tkachev, S. Zadorozhny

Karlsruhe Institute for technology
(former Forschungszentrum Karlsruhe)

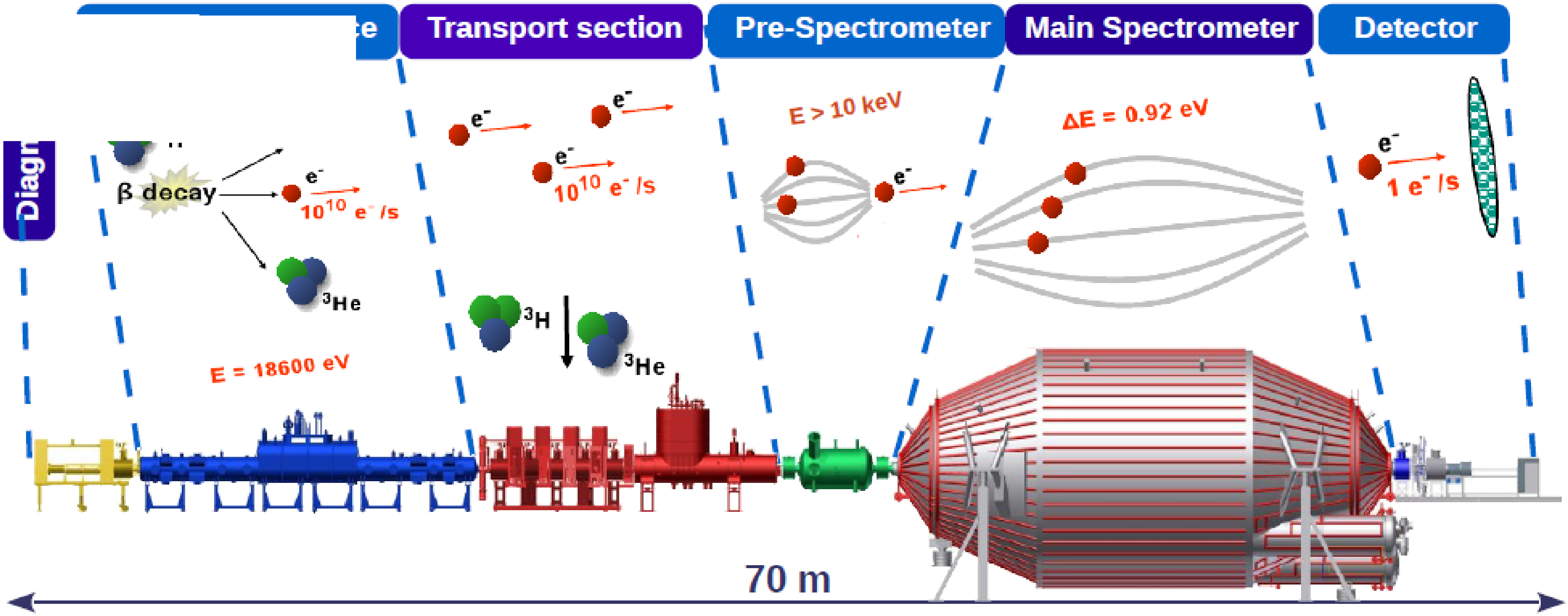
Tritium laboratory with license for 40g of Tritium
($3{,}6 \cdot 10^{14}$ Bq = 10 kCi)

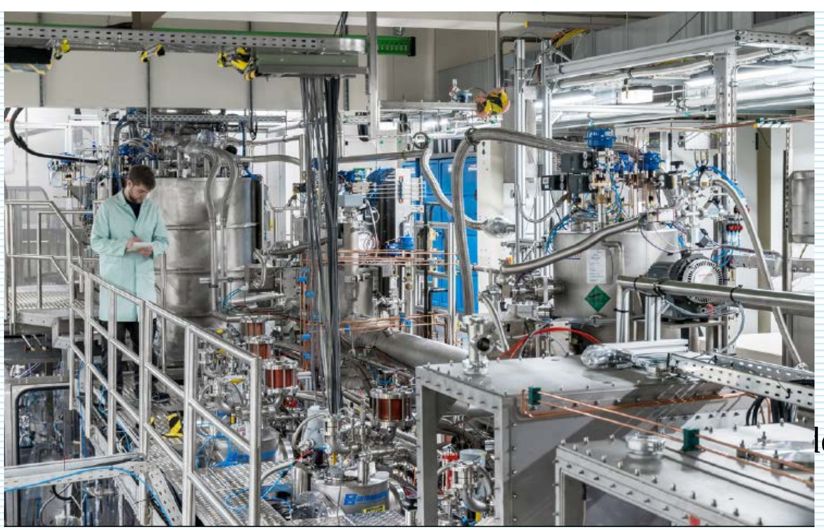
Project started at 2001



First Tritium in the set-up - 2018

The KATRIN experiment
at Karlsruhe Institute of Technology





lor Simkovic

Relativistic approach to ^{3}H 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) $\leftrightarrow$ (n,p)
- nuclear recoil of **3.4 eV** by E_e^{max}
- relevant only phase space

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

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

$$\begin{aligned}
y &= E_e^{max} - E_e \\
(m_{12})^2 &= M_i^2 - 2M_i E_e + m_e^2
\end{aligned}$$

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

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

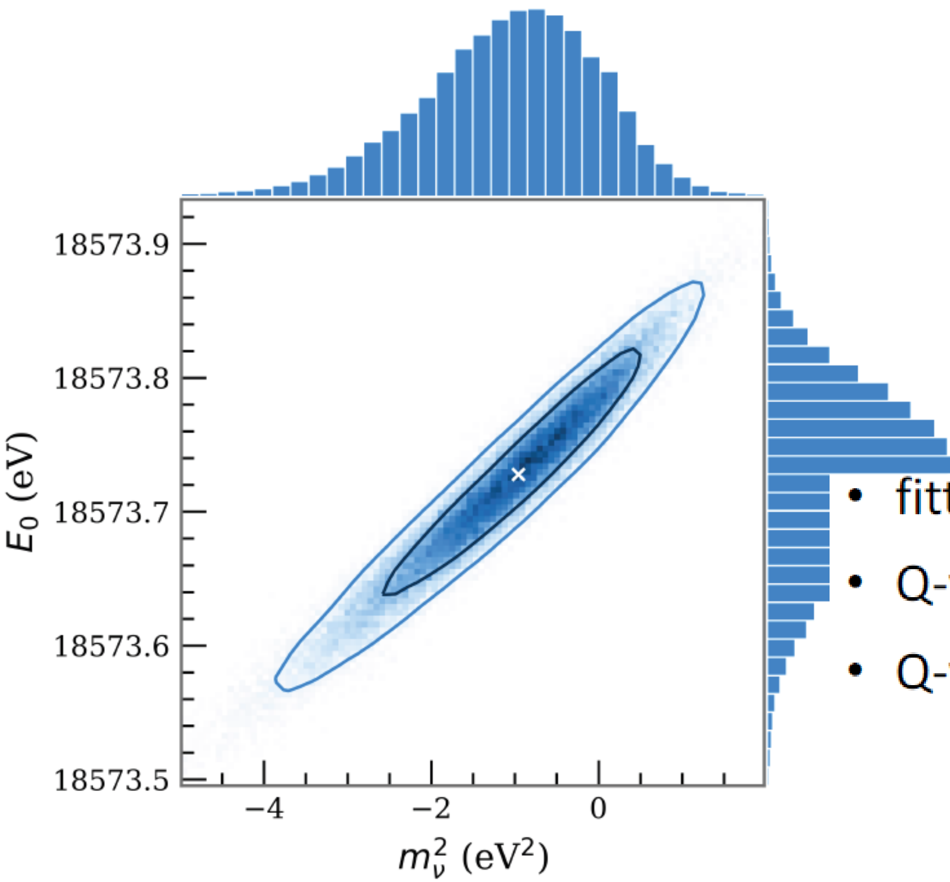
Katrin Results

M. Aker et al. (Katrin Collab.), PRL 123 (2019) 221802

$m^2(\nu_e) = -1.0\,^{+0.9}_{-1.1}\ \mathrm{eV}^2$ (90% C.L.)

$\rightarrow m(\nu_e) < 1.1$ eV at 90% CL (Lokhov-Tchakev)

$\rightarrow m(\nu_e) < 0.8$ eV (0.9 eV) at 90% (95%) CL (Feldman-Cousins)



Two independent analysis methods:

i) Covariance matrix

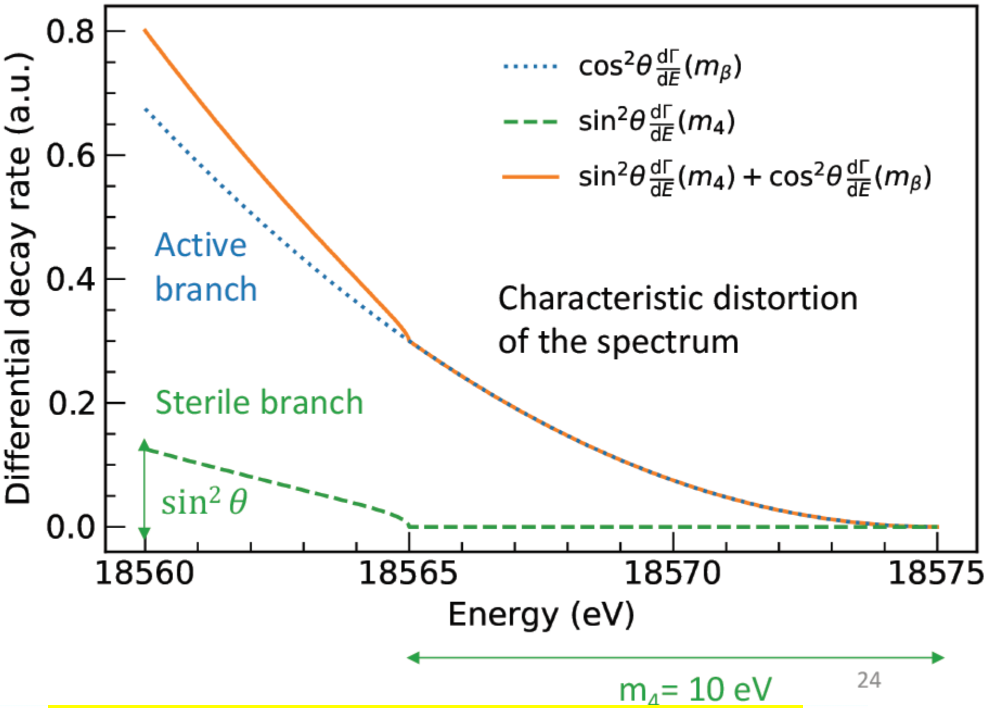
ii) Monte Carlo propagation

Both methods agree to a few percent

2million events in 90-eV wide interval

- fitted E_0 = 18573.7 ± 0.1 eV
- Q-value (KATRIN): 18575.2 ± 0.5 eV
- Q-value (literature): 18575.72 ± 0.07 eV

E.G. Myers et al. PRL 114 (2015) 013003 [$\Delta M(^3H, ^3He)$]



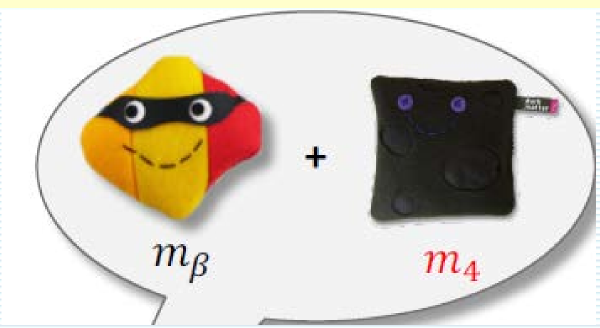
Multi-pixel Silicon Detector

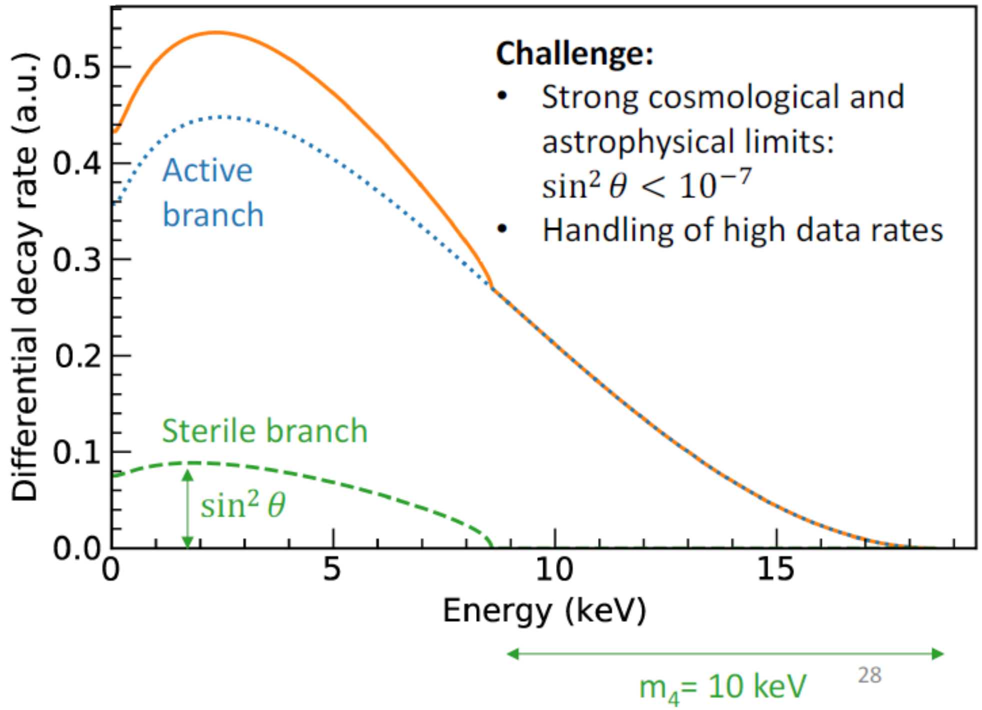
Sensitivity to $\sin^2\theta < 10^{-6}$

keV sterile neutrino search

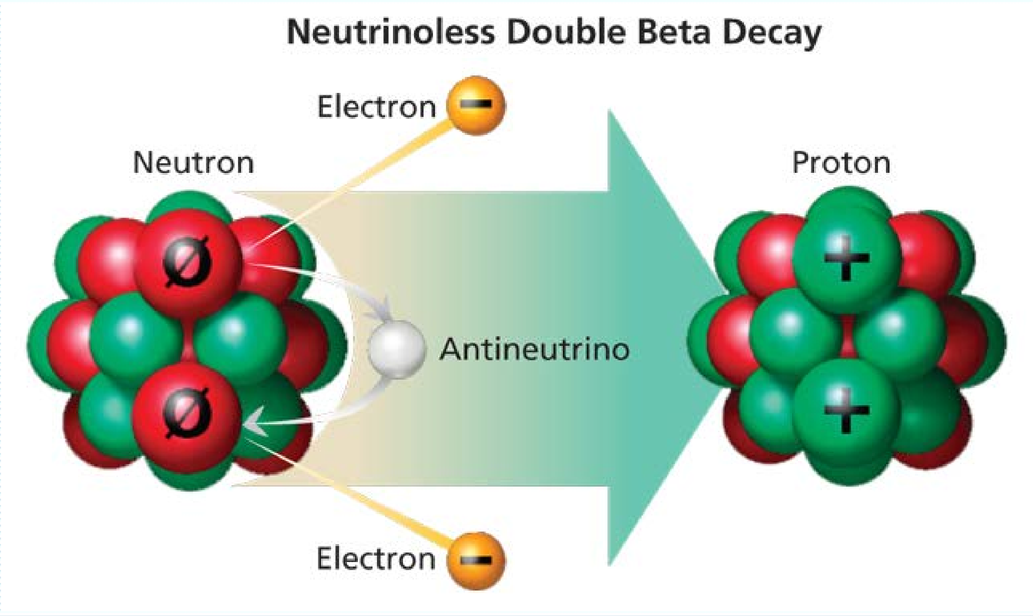
eV sterile neutrino search

Same set as for $m(\nu_e)$
3+1 sterile neutrino model
grid search in m_4, $|U_{e4}|^2$ plane






ARE NEUTRINOS THEIR OWN ANTIPARTICLES?


Neutrinoless Double Beta Decay
Electron
Neutron
Proton
Antineutrino
Electron

Majorana fermion

https://en.wikipedia.org/wiki/File:Ettore_Majorana.jpg

CNNP 2018, Catania, October 15-21, 2018

TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

Nota di Ettore Majorana

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

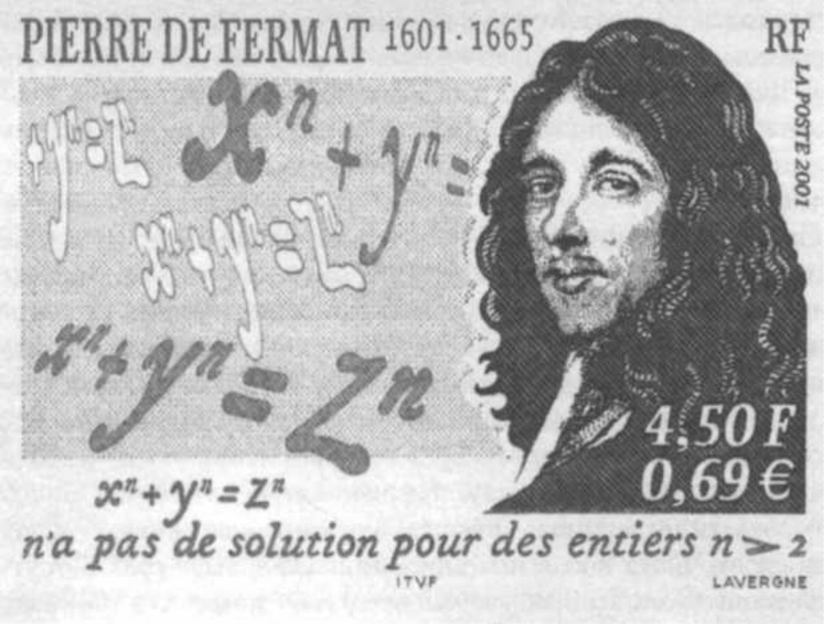
Sunto. - *Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di* Dirac *ne risulta alquanto modificato e non vi è più luogo a parlare di stati di energia negativa; nè a presumere per ogni altro tipo di particelle, particolarmente neutre, l'esistenza di « antiparticelle » corrispondenti ai « vuoti » di energia negativa.*

L'interpretazione dei cosidetti « stati di energia negativa » proposta da Dirac (¹) conduce, come è ben noto, a una descrizione sostanzialmente simmetrica degli elettroni e dei positroni. La sostanziale simmetria del formalismo consiste precisamente in questo, che fin dove è possibile applicare la teoria girando le difficoltà di convergenza, essa fornisce realmente risultati del tutto simmetrici. Tuttavia gli artifici suggeriti per dare alla teoria una forma simmetrica che si accord... isfacenti; sia perchè s... trica, sia perchè la si... iante tali procedimenti ... che possibilmente dov... uova via

che conduce più direttamente alla meta.

Per quanto riguarda gli elettroni e i positroni, da essa si può veramente attendere soltanto un progresso formale; ma ci sembra importante, per le possibili estensioni analogiche, che venga a cadere la nozione stessa di stato di energia negativa. Vedremo infatti che è perfettamente possibile costruire, nella maniera più naturale, una teoria delle particelle neutre elementari senza stati negativi.

(¹) P. A. M. Dirac, « Proc. Camb. Phil. Soc. », 30, 150, 1934. V. anche W. Heisenberg, « ZS. f. Phys. », 90, 209, 1934.



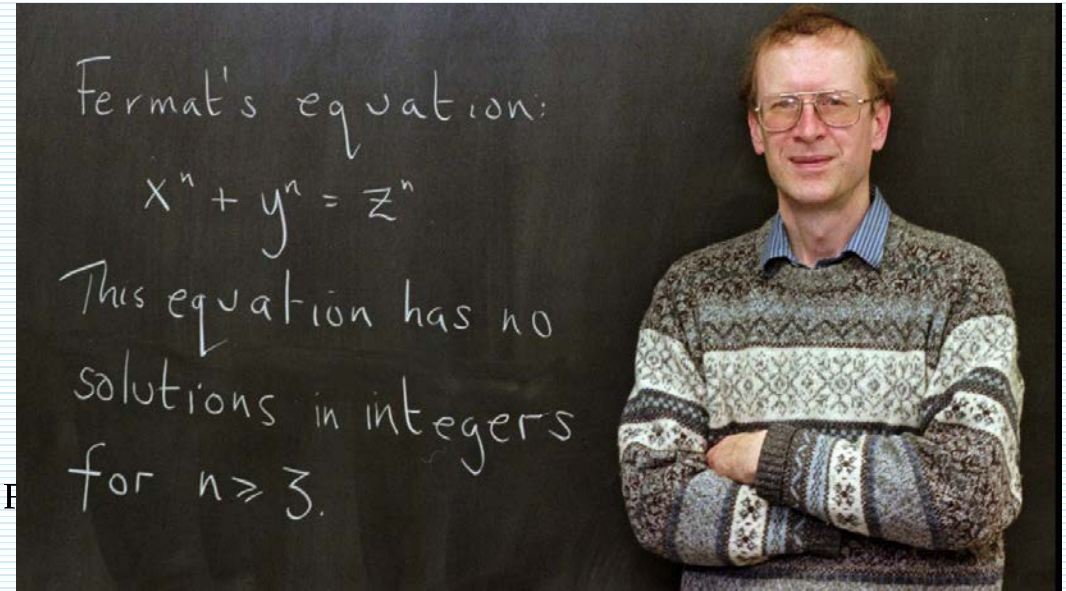
Around 1637, Fermat wrote in the margin of a book that the more general equation

$$a^n + b^n = c^n$$

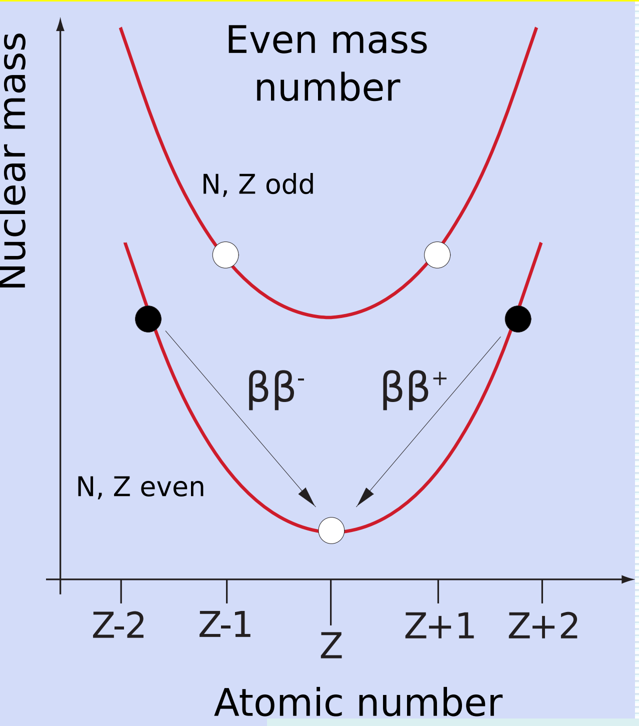
had no solutions in positive integers if *n* is an integer greater than 2.

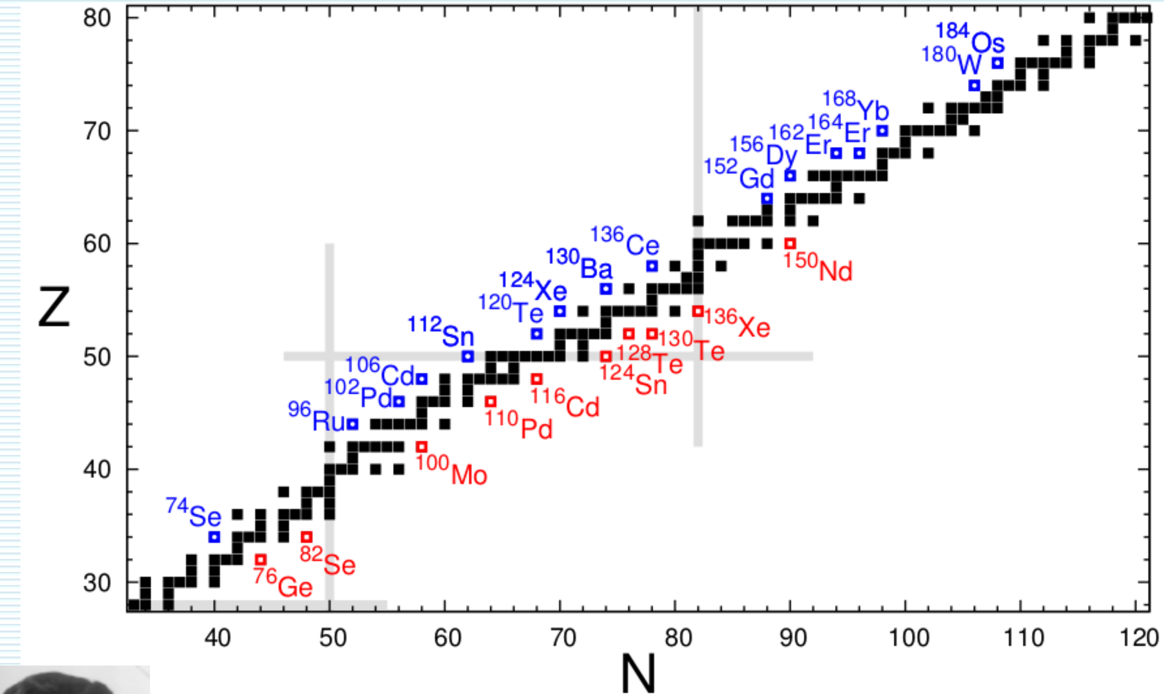
After 358 years

The corrected proof was published by Andrew Wiles in 1995.

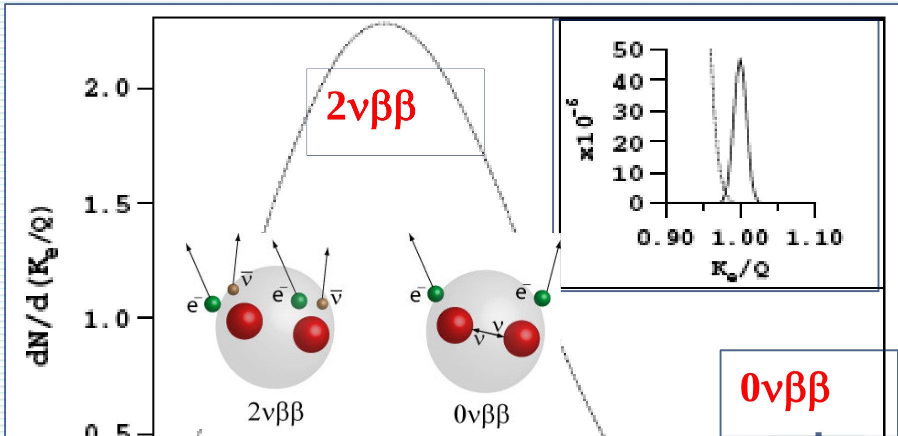


Nuclear double-β decay
(even-even nuclei, pairing int.)





Phys. Rev. 48, 512 (1935)



Two-neutrino double-β decay – LN conserved

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

Goepert-Mayer – 1935. 1st observation in 1987

Nuovo Cim. 14, 322 (1937)

Phys. Rev. 56, 1184 (1939)

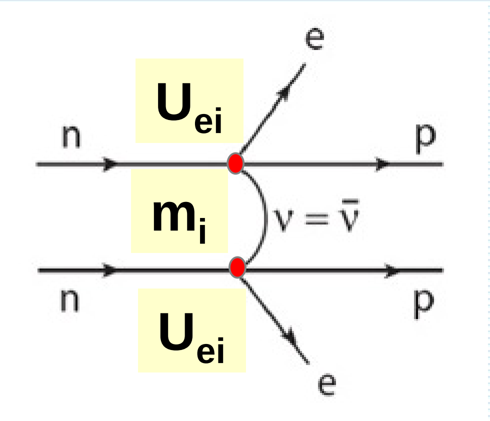
Neutrinoless double-β decay – LN violated

$$(A,Z) \rightarrow (A,Z+2) + e^- + e^- \quad \text{(Furry 1937)}$$

Not observed yet. Requires massive Majorana ν's

0νββ-decay *(traditional picture)*

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



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

?

Phase factor well understood

***NME** must be evaluated using tools of nuclear theory*

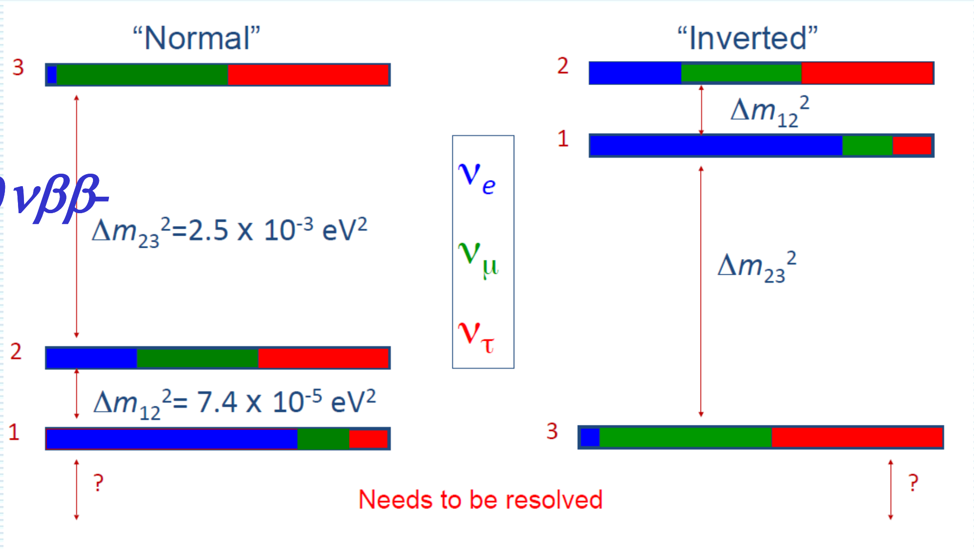
$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 e^{i\alpha_1} m_1 + c_{13}^2 s_{12}^2 e^{i\alpha_2} m_2 + s_{13}^2 m_3\right|$$

Effective Majorana mass can be evaluated. It depends on

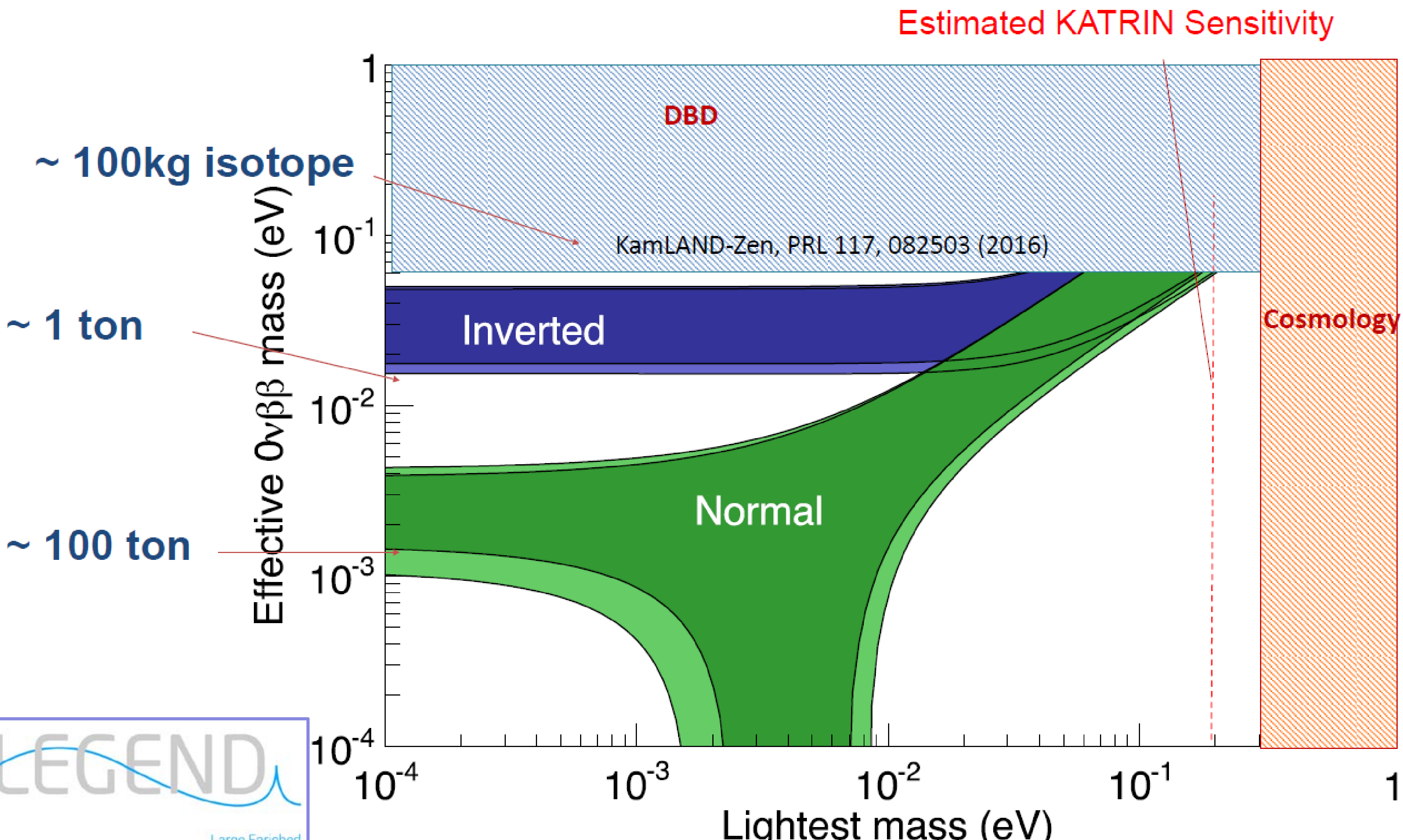
m_1, m_2, m_3, $\theta_{12}, \theta_{13}, \alpha_1, \alpha_2$

(3 unknown parameters: m_1/m_3, α_1, α_2)

0νββ-



$$U^{PMNS} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\ -c_{23}s_{12} - e^{i\delta}c_{12}s_{13}s_{23} & c_{12}c_{23} - e^{i\delta}s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23} - e^{i\delta}c_{12}c_{23}s_{13} & -e^{i\delta}c_{23}s_{12}s_{13} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

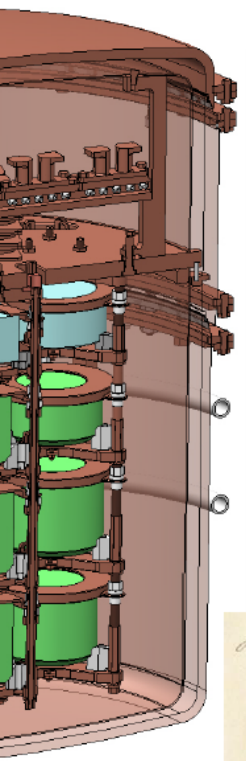
After 83 years …

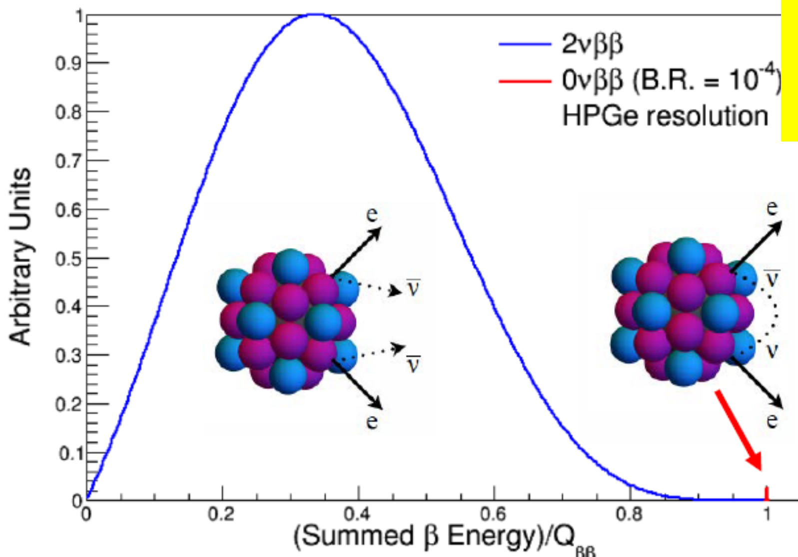
Collaboration	Isotope		mass ($0\nu\beta\beta$ isotope)	Status
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	~ ton	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Complete
GERDA II	Ge-76	Point contact Ge in LAr	31	Operating
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	25 kg	Operating
LEGEND	Ge-76	Point contact with active veto	**~ ton**	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
LUCIFER (CUPID)	Se-82	ZnSe scint. bolometer	18 kg	R&D
AMoRE	Mo-100	$CaMoO_4$ scint. bolometer	1.5 - 200 kg	R&D
LUMINEU (CUPID)	Mo-100	$ZnMoO_4$ / Li_2MoO_4 scint. bolometer	1.5 - 5 kg	R&D
COBRA	Cd-114,116	CdZnTe detectors	10 kg	R&D
CUORICINO, CUORE-0	Te-130	TeO_2 Bolometer	10 kg, 11 kg	Complete
CUORE	Te-130	TeO_2 Bolometer	**206 kg**	Operating
CUPID	Te-130	TeO_2 Bolometer & scint.	**~ ton**	R&D
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	**160 kg**	Construction
EXO200	Xe-136	Xe liquid TPC	79 kg	Operating
nEXO	Xe-136	Xe liquid TPC	**~ ton**	R&D
KamLAND-Zen (I, II)	Xe-136	2.7% in liquid scint.	**380 kg**	Complete
KamLAND2-Zen	Xe-136	2.7% in liquid scint.	**750 kg**	Upgrade
NEXT-NEW	Xe-136	High pressure Xe TPC	5 kg	Operating
NEXT-100	Xe-136	High pressure Xe TPC	100 kg - **ton**	R&D
PandaX - III	Xe-136	High pressure Xe TPC	~ ton	R&D
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D

Institute for Nuclear Research of Russian Academy of Sciences Moscow, Russia

I. Barabanov, S. Belogurov, L. Bezrukov, E. Doroshkevich, Gangapshev,V. Gurentsov, L.V. Inzhechik, V. Kazalov, V.N. Kornoukhov, B. Lubsandorzhiev, P. Moseev, O. Selivanenko, A. Veresnikova, E. Yanovich. Kazachenko, V. M. Lobashev*, A. Lokhov, A. Skasyrskaya, N. Titov, I. Tkachev, S. Zadorozhny

0νββ in ^{76}Ge



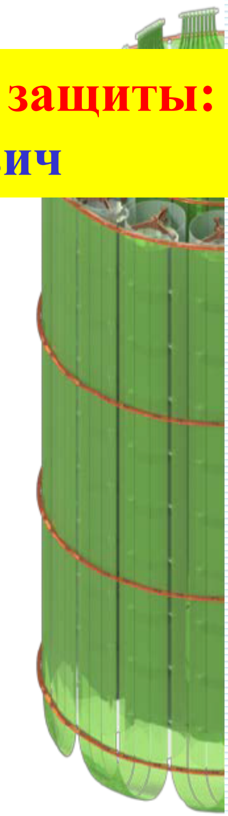


выбор медной внутренней защиты:
Гуренцов Валерий Иванович

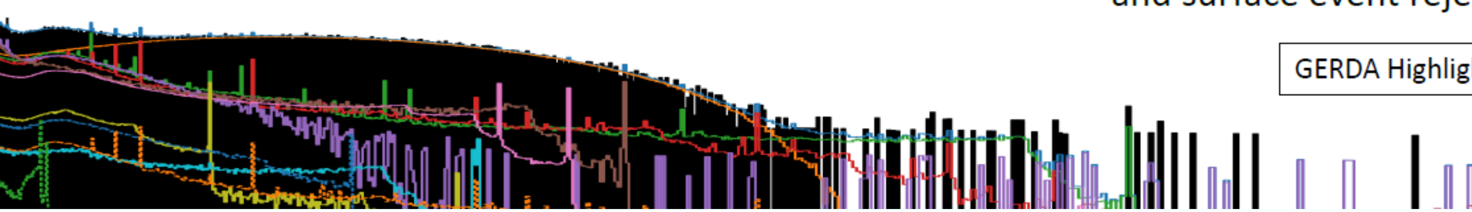
GERDA

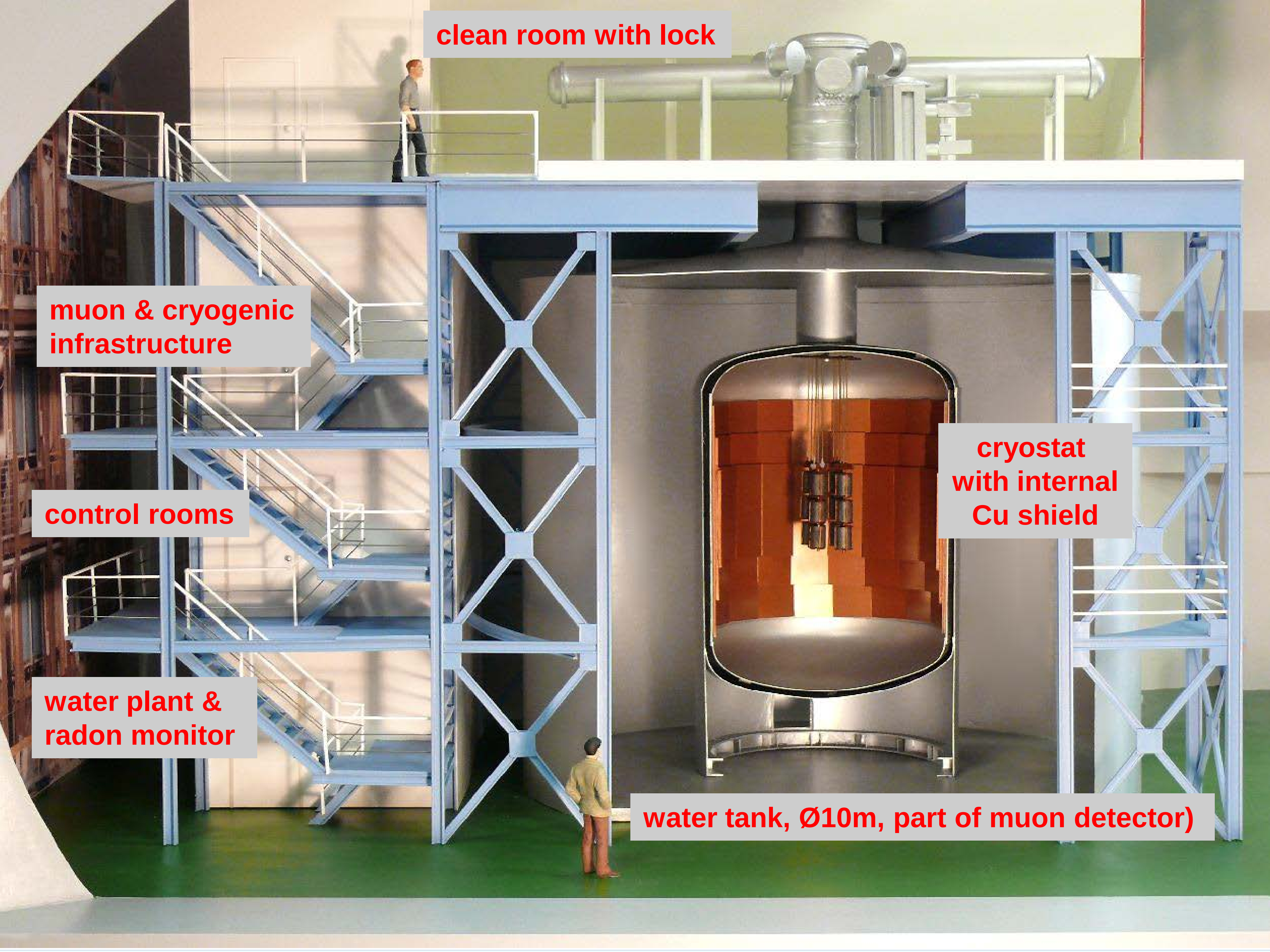
LEGEND

- efficiency
- Routinely enriched to 92%
- Excellent energy resolution: 2.5 keV FWHM at $Q_{\beta\beta}$ → 2νββ background suppressed
- Intrinsically radiopure → low background
- High density → 0νββ single-site (~1mm^3)
- Great multiplicity, timing, multi-site and surface event rejection



GERDA Highlights (25/02) *Luciano Pandola*




clean room with lock
muon & cryogenic infrastructure
control rooms
water plant & radon monitor
cryostat with internal Cu shield
water tank, Ø10m, part of muon detector)

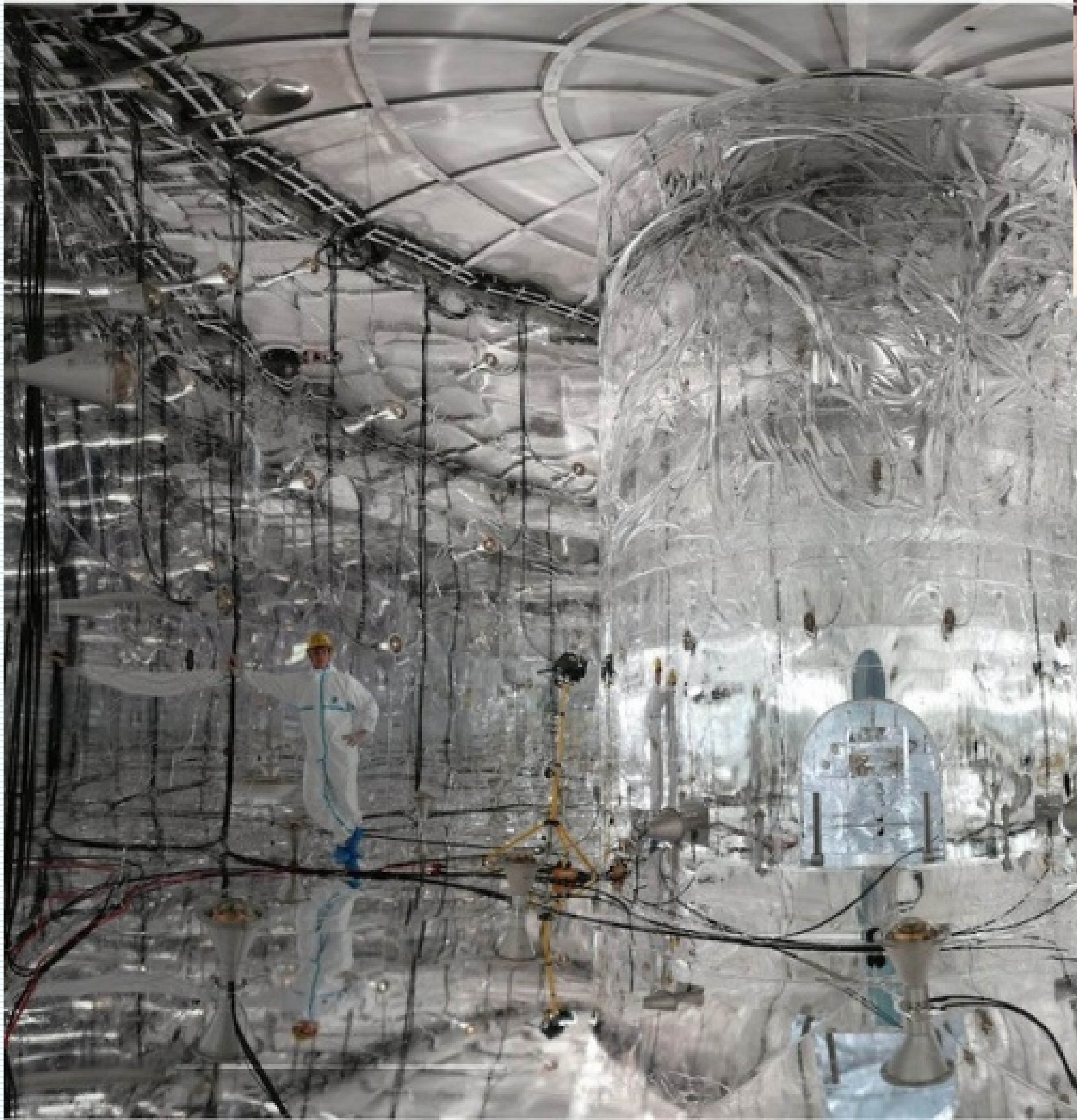
internal copper shield installation

13 mar 2008

конструкциа криогенного бака:
Барабанов Игорь Романович,
Безруков Леонид Борисович,
Гуренцов Валерий Иванович,
Корноухов Василий Николаевич

выбор медной внутренней защиты:
Гуренцов Валерий Иванович

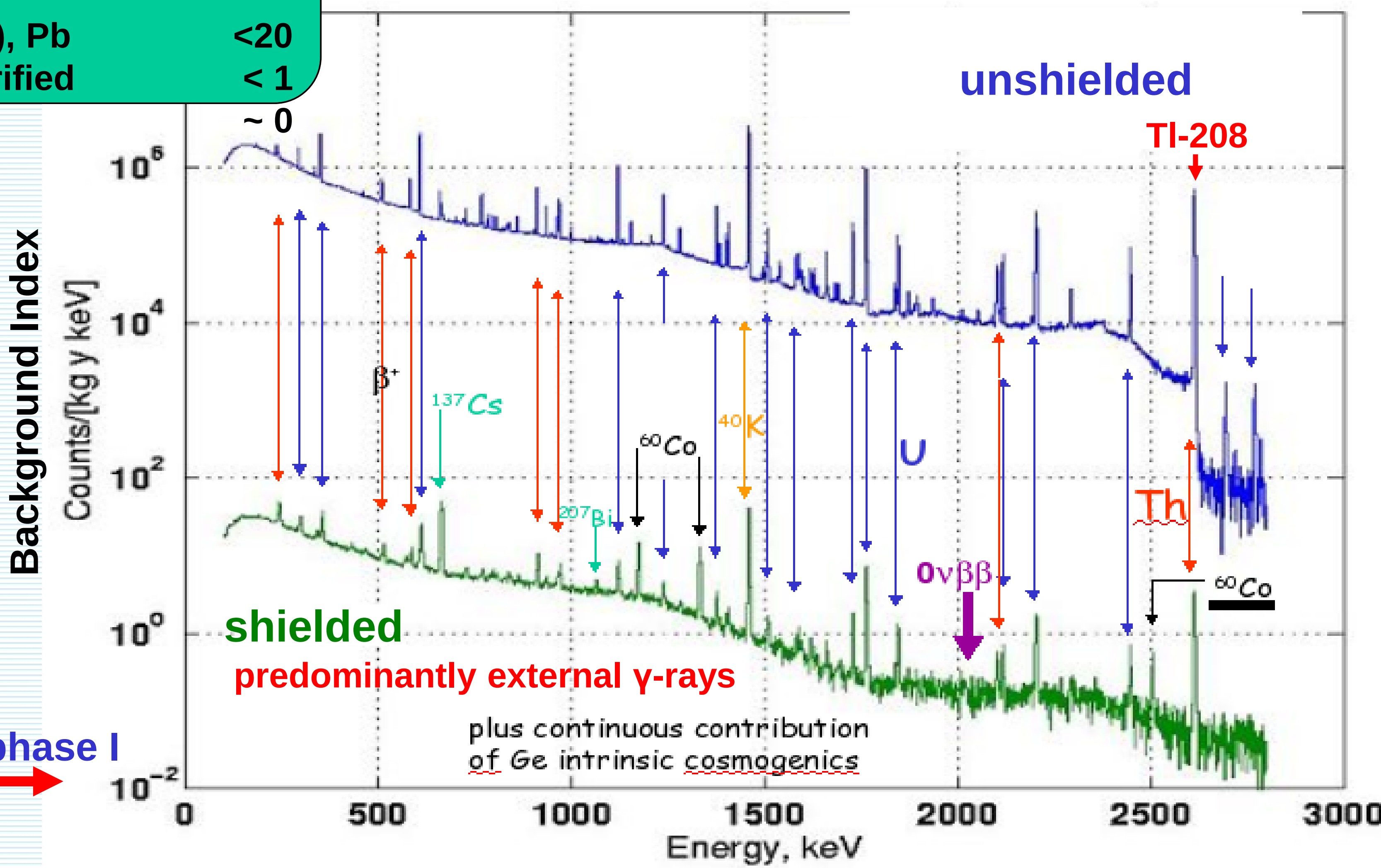
GERDA – muon veto tank



background spectra

Activity of Tl-208	(µBq/kg)
rock, concrete	3000000
stainless steel	~ 5000
Cu(NOSV), Pb	<20
water, purified	< 1
LN2, LAr	~ 0

spectra measured at LNGS with Ge diode



GERDA phase I

Enriched material for GERDA
Phase II: motivation

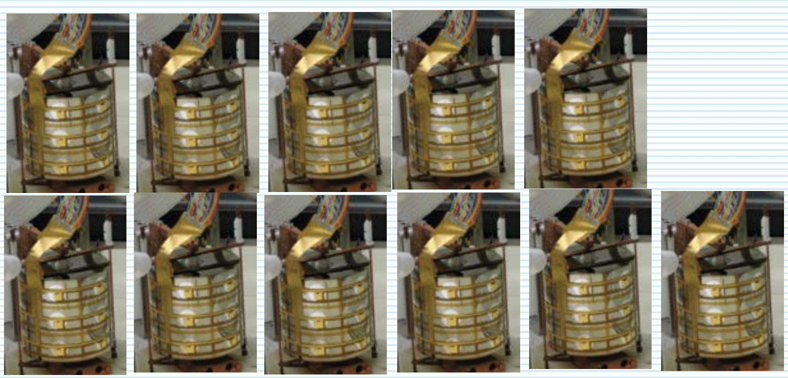
отбор изотопа Ge-76
Корноухов Василий Николаевич

One ^{enr}Ge diode
$\Rightarrow$ 11 ^{nat}Ge diodes

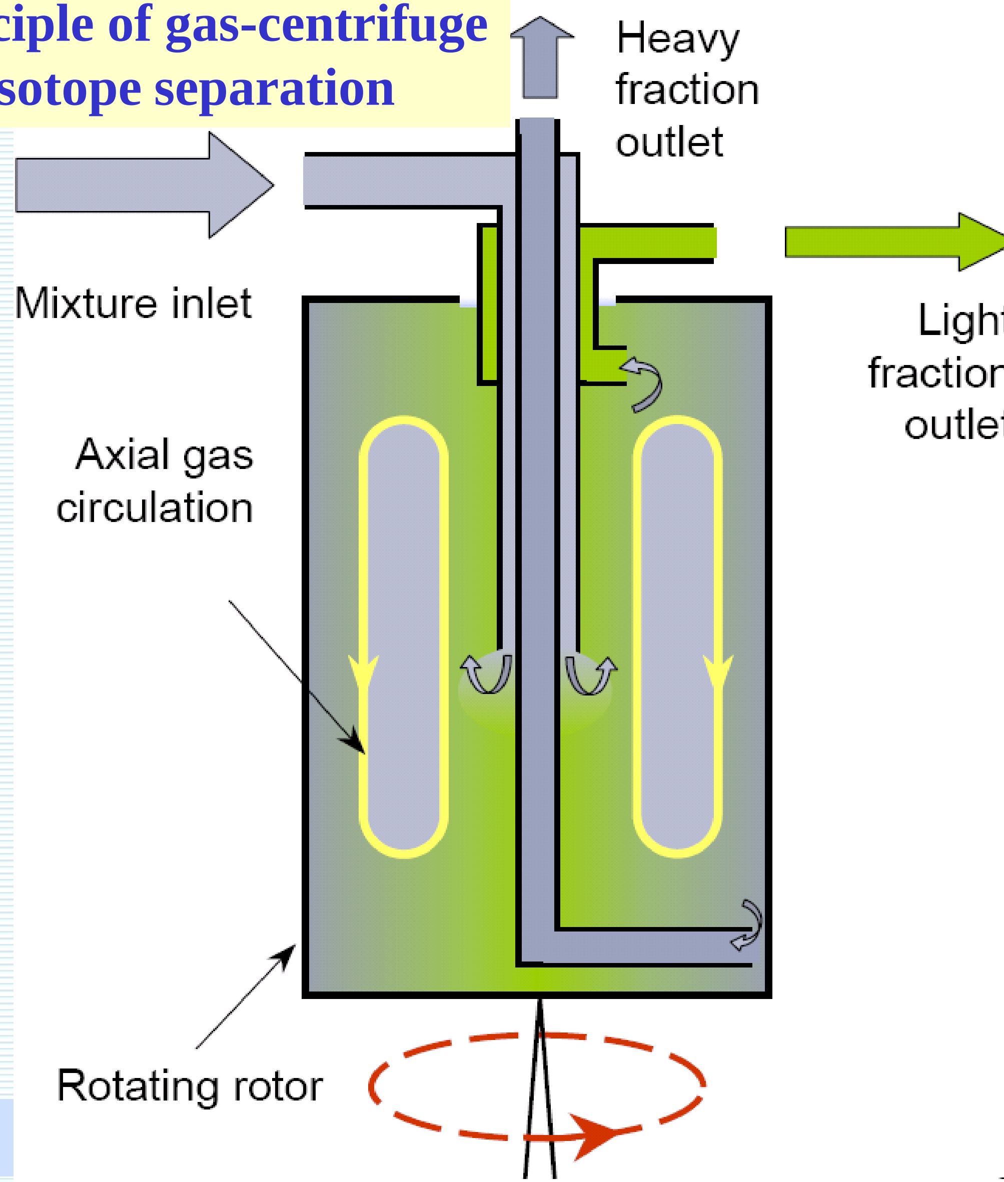
^{enr}Ge diode
(^{76}Ge = 86. %)

$\equiv$

^{nat}Ge diode
(^{76}Ge = 7.6 %)



Principle of gas-centrifuge isotope separation



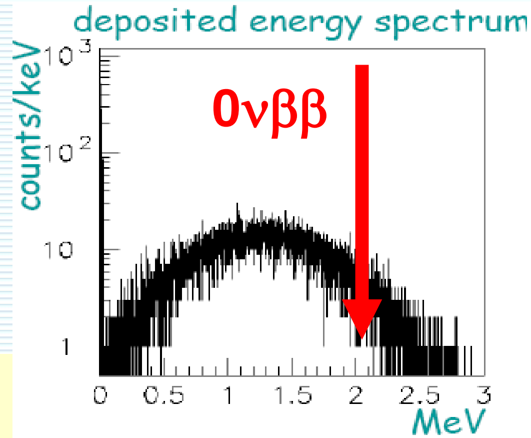
Centrifuge acceleration:

500 000 g, Rotation ~ 1500 s^{-1}

Operation life of centrifuge: 30 years

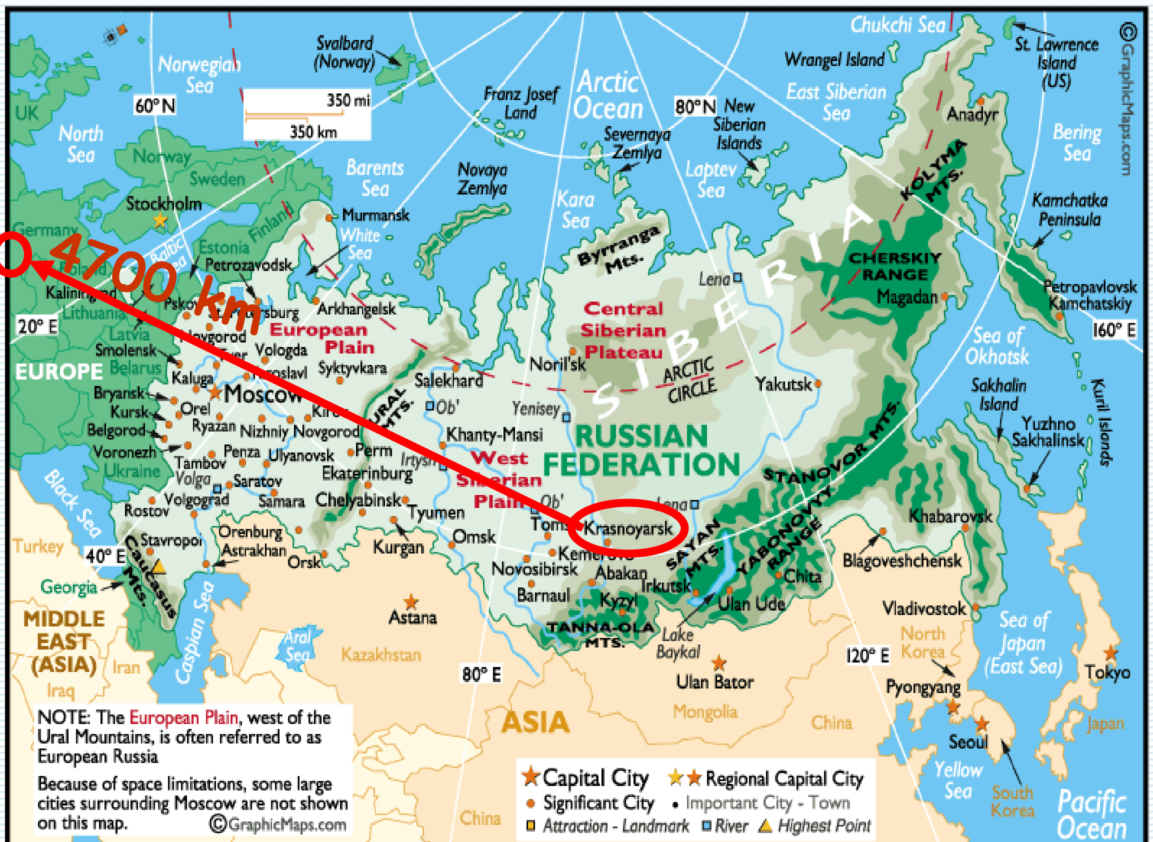
выбор материала и параметры транспортного контейнера
Барабанова Игоря Романович
+ Группа студентов

Cosmic ray activation at Earth surface



Transportation:
Zelenogorsk (Siberia) – Munich, 4700 km

Ge + N component → ^{60}Co and ^{68}Ge



Reduction of cosmic activation

K = 8 ↓ for ^{68}Ge

K = 13 ↓ for ^{60}Co

∅140 cm x 126.5 cm (H)

Weight is 15 tons

Institut für Kristallzüchtung (IKZ, Berlin): Crystal puller EKZ 2000

Crystal pulling (purity 99.9999999999 % Ge) some of the purest material in the world – impurities at the level of 10^{-12} /atom

Canberra-Lingolsheim for detector manufacture

LEGEND is building on the success of GERDA and Majorana

LEGEND-200 is well underway and construction set started in 2018

LEGEND-200 and 1000 backgrounds goals are based on a background free exposure

LEGEND-1000 R&D is ongoing

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

53 Institutions, 250+ scientists

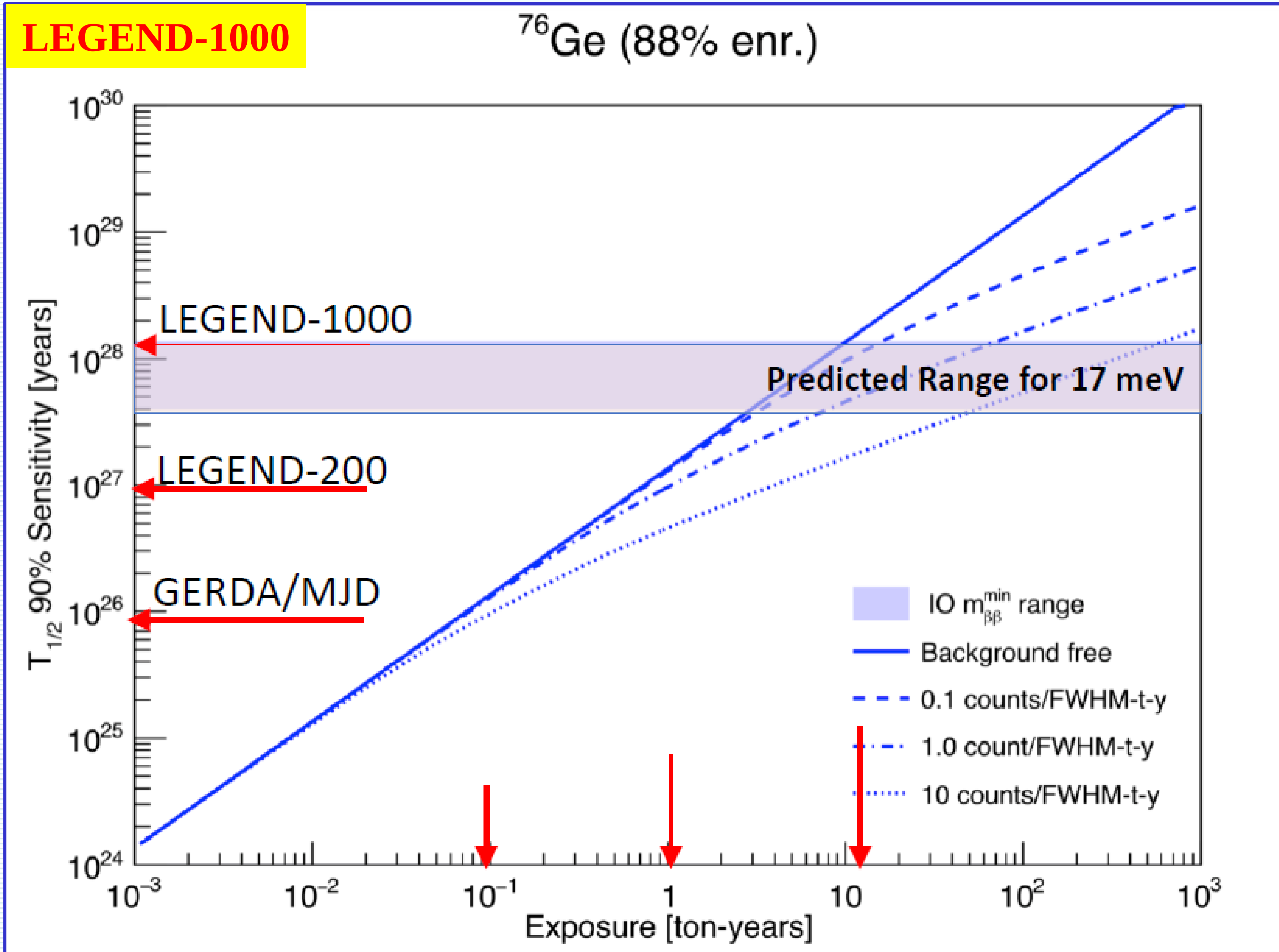
Czech Technical University Prague
North Carolina State University
South Dakota School Mines Tech.
University Washington
Academia Sinica
University Tübingen
University South Dakota
University Zurich

University of North Carolina
Sichuan University
University of South Carolina
Tennessee Tech University
Jagiellonian University
University of Dortmund
Technical University Dresden
Joint Inst. Nucl. Res.
Duke University

Triangle Univ. Nuclear. Lab.
Joint Research Centre, Geel
Max Planck Institute, Heidelberg
Queens University
University Tennessee
Lancaster University
University Liverpool
University College London
Los Alamos National Lab.

INFN Milano Bicocca
Milano University and Milano INFN
Institute Nuclear Research Russ. Acad. Sci.
National Research Center Kurchatov Inst.
Lab. Exper. Nucl. Phy. MEPhI
Max Planck Institute, Munich
Technical University Munich
Oak Ridge National Laboratory
Padova University
Padova INFN

Univ. New Mexico
L'Aquila University and INFN
Lab. Naz. Gran Sasso
University Texas, Austin
Tsinghua University
Lawrence Berkeley Natl. Lab.
University California, Berkeley
Leibniz Inst. Crystal Growth
Comenius University



>10^{28} yr or **$m_{\beta\beta}$=17 meV** for worst case NME and quenching of **g_A**

3 σ discovery level to cover inverted ordering, given NME uncertainty

ARTICLE

$T_{1/2}^{0\nu} > 5.3\ 10^{25}$ yr

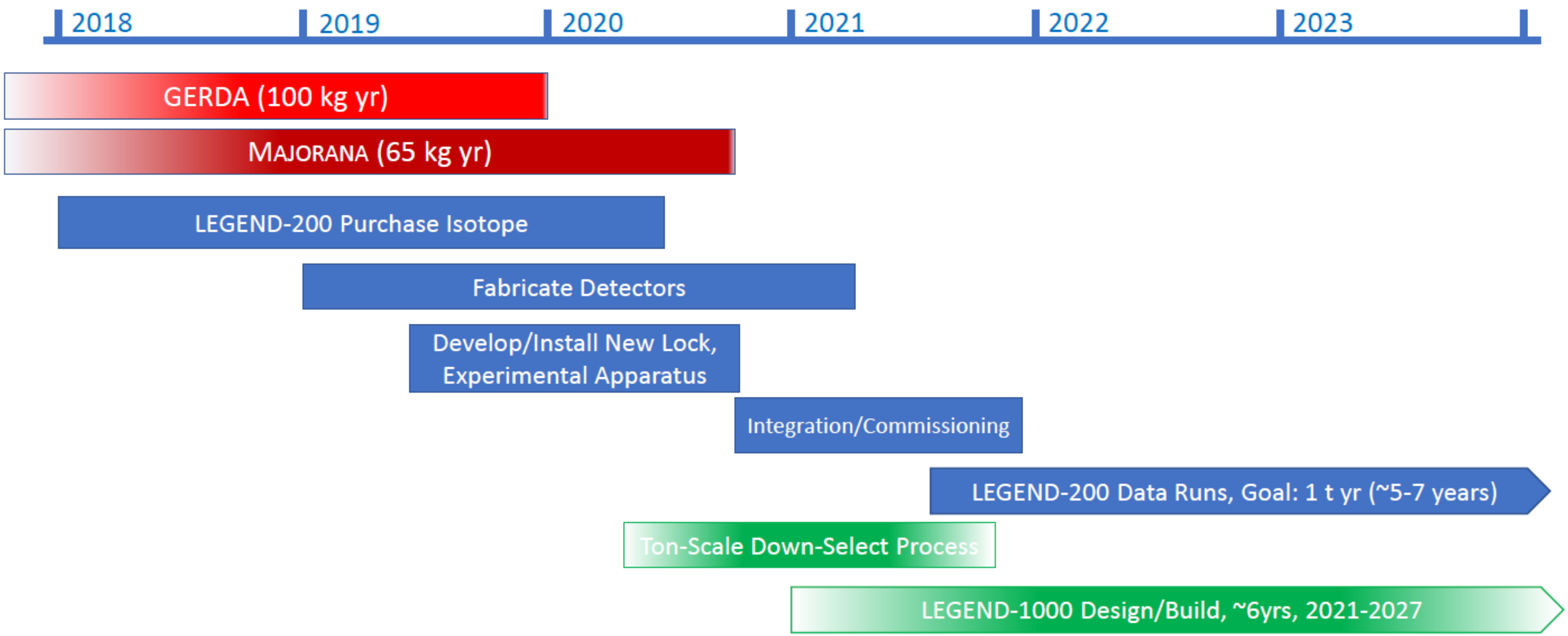
Schedule of Ge 0νββ-decay experiments

Background-free search for neutrinoless double-β decay of ^{76}Ge with GERDA

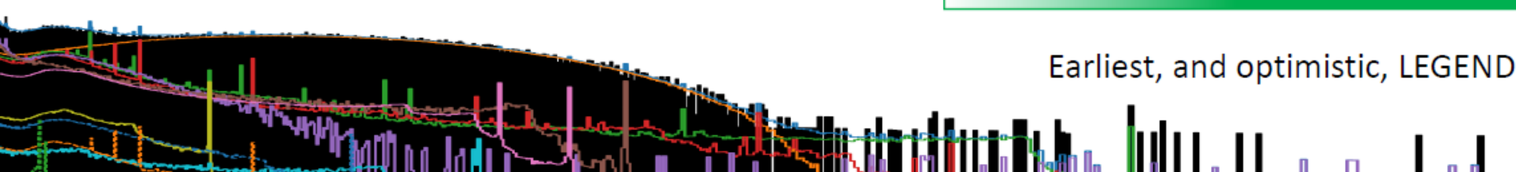
M. Agostini et al. (GERDA Coll.), *Nature* 544 (2017) 47

Schedule

LEGEND
Large Enriched Germanium Experiment for Neutrinoless ββ Decay



Earliest, and optimistic, LEGEND-1000 Data Start 2025/6



AMoRE (Advanced Mo-based Rare process Experiment)

Searching for neutrinoless double beta decay of ^{100}Mo using cryogenic $^{40}Ca^{100}MoO_4$ detectors

History of $^{40}Ca^{100}MoO_4$

2002: Idea and try to grow CMO in Korea

2003: Collaboration with V. N. Kornoukhov.
Received CMO (better)

2004: CMO test. Extended idea of XMoO4,
cryogenic detector of CMO

2005-7: Largw CMO with 1st ISTC project

2006: Collaboration with F. Danevich (CMO by Lviv))

2007: CMO R&D in cryogenic temperature started

2008: 2nd ICTC project: 1 kg of $^{40}Ca^{100}MoO_4$ crystal
growing

2009: AMORE Collaboration formed

2010-11: Characterization of $^{40}Ca^{100}MoO_4$ and
background study

2012: Russian group got funding for CMO
production line

2013: AMoRE project funded (Under IBS CUP)

Baksan Neutrino Observatory of Institute for Nuclear Research of Russian Academy of Sciences Moscow, Kabardino-Balkaria

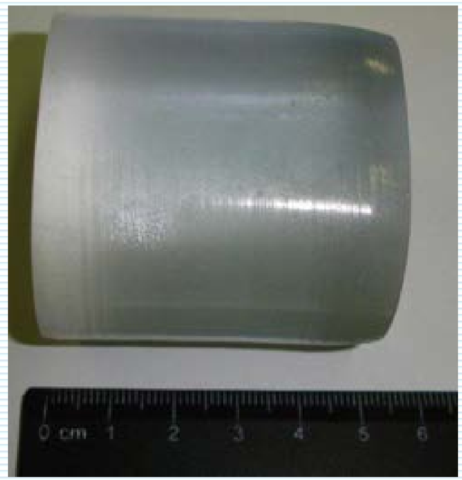
A. M. Gangapshev, Yu. M. Gavriljuk, A. M. Gezhaev, V. I. Gurentsov, V. V. Kazalov, V. N. Kornoukhov (MFTI),V. V. Kuzminov, S. I. Panasenko, S. S. Ratkevich

5 countries (Korea, Russia, Ukraine, China, Germany)
13 institutes, ~84 collaborators

$^{40}Ca^{100}MoO_4$ crystals

SB28
weight 196 g

SB29
weight 390 g



S35
weight ~300 g

Experimental Sensitivity of $T_{1/2}$ (0νββ)

Candidate	Q (MeV)	Abund. (%)
^{48}Ca	4.271	0.19
^{76}Ge	2.040	7.8
^{82}Se	2.995	8.7
^{100}Mo	3.034	9.7
^{130}Te	2.533	34.1
^{136}Xe	2.479	8.9
^{150}Nd	3.367	5.6

For sizeable background case

Isotopic Abundance

Detection Efficiency

Detector Mass

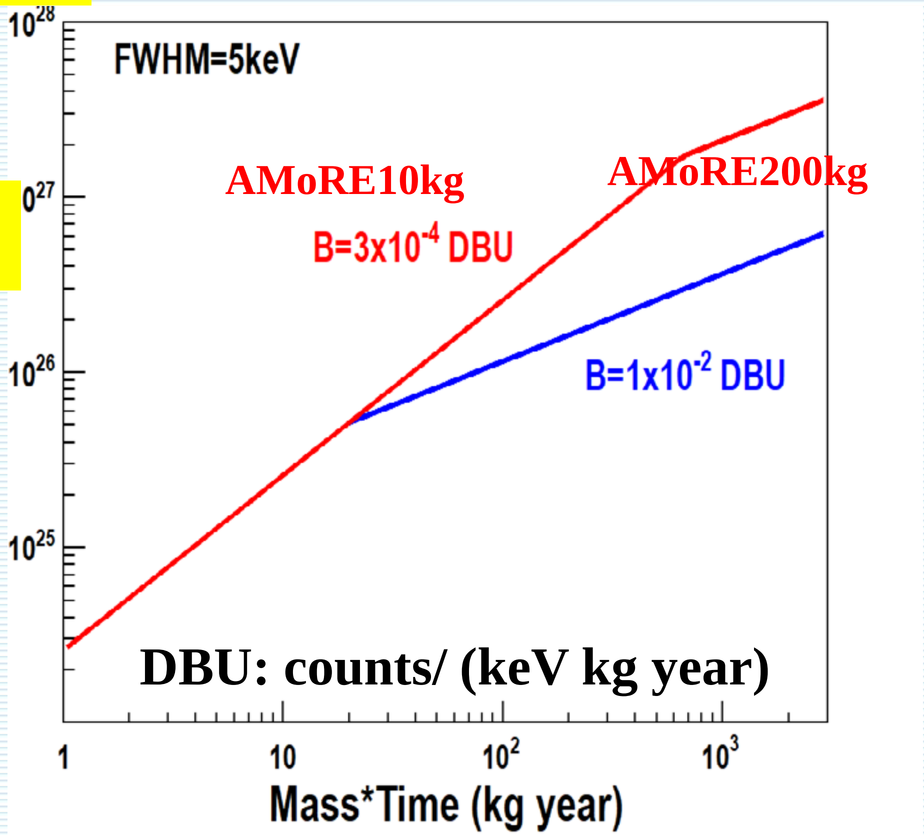
Time

$$T_{1/2}^{0\nu}(\exp) = (\ln 2) N_a \frac{a}{A} \varepsilon \sqrt{\frac{MT}{b\Delta E}}$$

Atomic mass

Background level (count/keV kg year)

Energy Resolution



For "zero" background case;
# of background events ~ 0 (1)

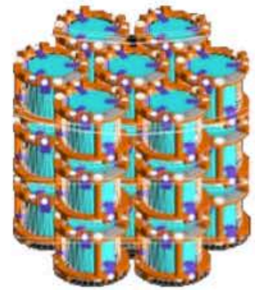
$$T_{1/2}^{0\nu}(\exp) = (\ln 2) N_a \frac{a}{A} \varepsilon \frac{MT}{n_{CL}}$$

Crystal: $^{40}Ca^{100}MoO_4$, doubly enriched scintillating crystals; MMC technology for heat and light measurement; Temperature: ~20 mK; Zero background measurement in ROI; Location: Y2L (till Phase I) and a new lab (after)

$^{40}Ca^{100}MoO_4$

~ 1.5 kg

AMoRE Pilot



$^{40}Ca^{100}MoO_4$

~ 5 kg

AMoRE-I

$X^{100}MoO_4$

200 kg

AMoRE-II

Summary of the AMoRE project

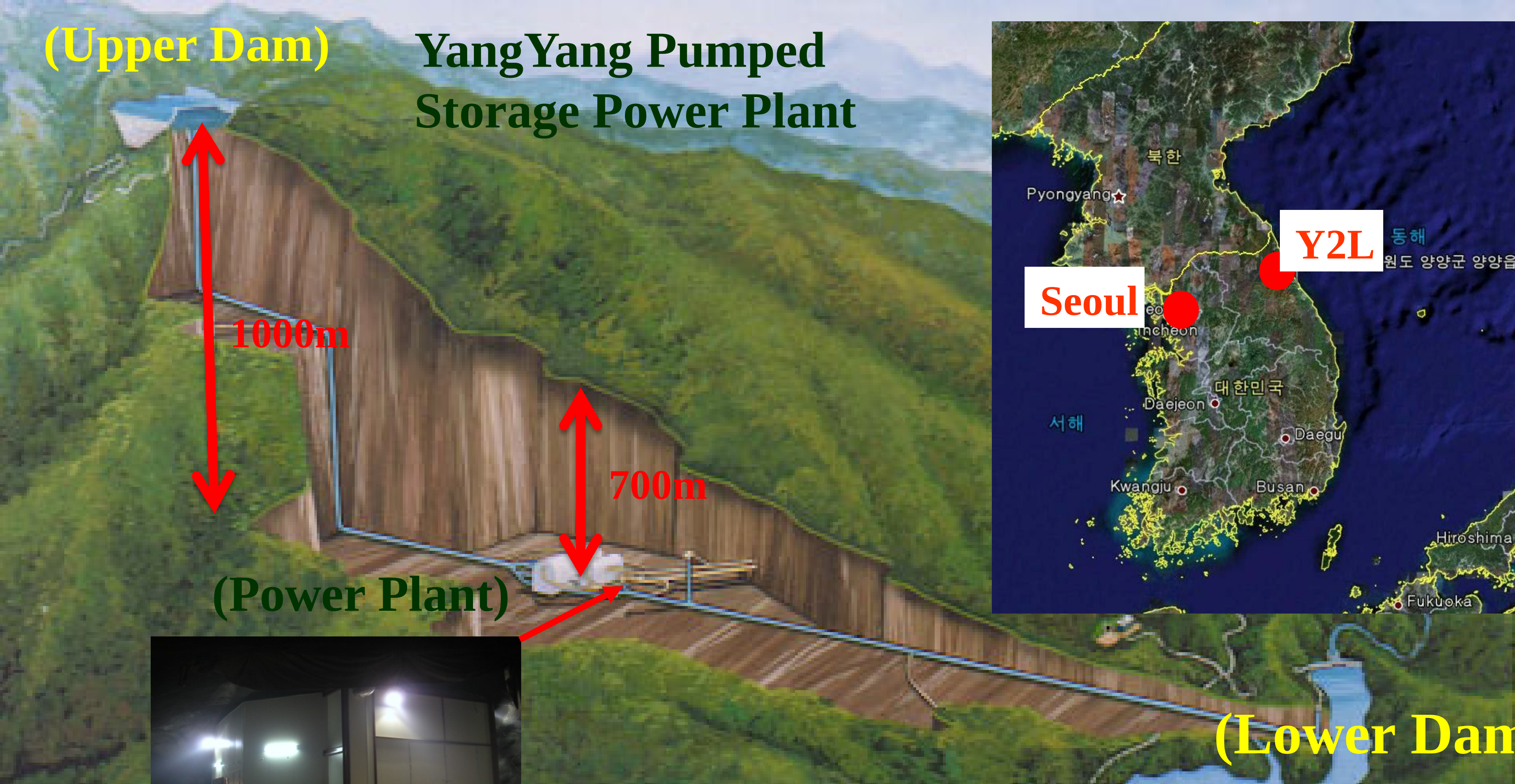
ckky : counts/ (keV kg year)

	AMoRE-Pilot	AMoRE-I	AMoRE-II
Crystal Mass (kg)	1.5	5	200
Backgrounds(ckky)	~ 10^{-2}	~ 10^{-3}	10^{-4}
$T_{1/2}$(year)	1.0×10^{24}	8.2×10^{24}	8.2×10^{26}
m_{bb} (meV)	380-719	130-250	13-25
Schedule	2017	2018	2020-2023

Fully funded for Pilot, Phase I and II

FIGURE 3. Phases of AMoRE Projectl. With 200 kg of Mo-100 crystals, we can reach 8.2×10^{26} years of sensitivity and 13-25 meV mass range.

YangYang(Y2L) Underground Laboratory



KIMS (Dark Matter Search)

AMoRE (Double Beta Decay Experiment)

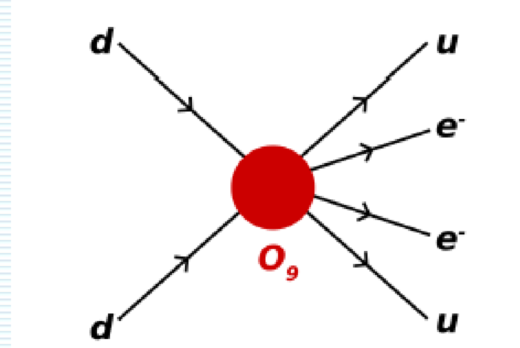
Minimum depth : 700 m / Access to the lab by car (~2km)

ν–mass $0\nu\beta\beta$-decay mechanisms

$$\mathcal{L} = \mathcal{L}_{SM}^{(4)} + \boxed{\frac{1}{\Lambda}\sum_i c_i^{(5)}\mathcal{O}_i^{(5)} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)}\mathcal{O}_i^{(6)} + O(\tfrac{1}{\Lambda^3})}$$

Beyond the SM physics

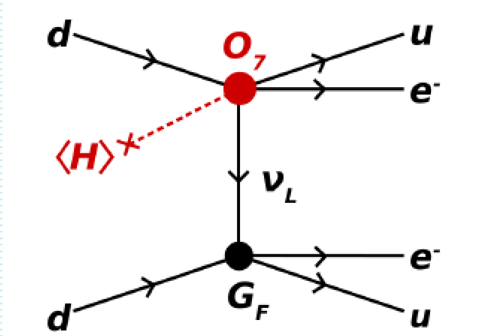
short range: d=9 (d=11)



+

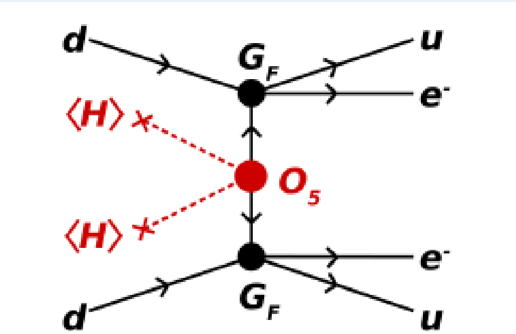
Amplitude for (A,Z)→(A,Z+2)+2e$^-$ can be divided into:

long range: d=7



mass mechanism: d=5

+



$$\mathcal{O}_W \propto \frac{c_{ij}}{\Lambda}(L_iH)(L_jH)$$

Weinberg, 1979

$$\mathcal{O}_2 \propto LLLe^cH$$
$$\mathcal{O}_3 \propto LLQd^cH$$
$$\mathcal{O}_4 \propto LL\bar{Q}\bar{u}^cH$$
$$\mathcal{O}_8 \propto L\bar{e}^c\bar{u}^cd^cH$$

Babu, Leung: 2001
de Gouvea, Jenkins: 2007

$$\mathcal{O}_5 \propto LLQd^cHHH^\dagger$$
$$\mathcal{O}_6 \propto LL\bar{Q}\bar{u}^cHH^\dagger H$$
$$\mathcal{O}_7 \propto LQ\bar{e}^c\bar{Q}HHH^\dagger$$
$$\mathcal{O}_9 \propto LLLe^cLe^c$$
$$\mathcal{O}_{10} \propto LLLe^cQd^c$$
$$\mathcal{O}_{11} \propto LLQd^cQd^c$$
$$\cdots\cdots$$

Valle

Quark Condensate Seesaw Mechanism for Neutrino Mass

A. Babič, S. Kovalenko, M.I. Krivoruchenko , F.Š., arXive:1911.12189, accepted in PRD

This operator contributes to the Majorana-neutrino mass matrix due to chiral symmetry breaking via the light-quark condensate.

The SM gauge-invariant effective operators

$$\mathcal{O}_7^{u,d} = \frac{\tilde{g}^{u,d}_{\alpha\beta}}{\Lambda^3}\, \overline{L^C_\alpha}\, L_\beta\, H \left\{ (\overline{Q}\, u_R),\ (\overline{d_R}\, Q) \right\}$$

After the EWSB and ChSB one arrives at the Majorana mass matrix of active neutrinos

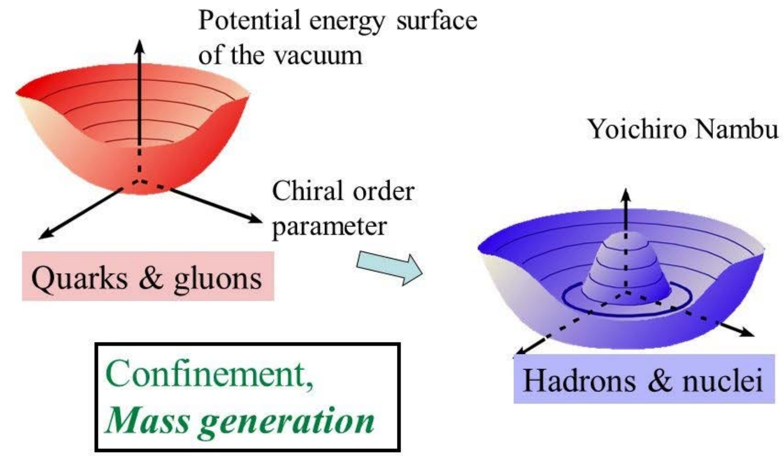
$$m_{\alpha\beta}{}^{\nu} = g_{\alpha\beta}\, v\, \frac{\langle \overline{q} q \rangle}{\Lambda^3} = g_{\alpha\beta}\, v \left(\frac{\omega}{\Lambda} \right)^3$$

$$g_{\alpha\beta} = g^u_{\alpha\beta} + g^d_{\alpha\beta}, \qquad v/\sqrt{2} = \langle H^0 \rangle$$

$$\omega = -\langle \overline{q} q \rangle^{1/3}, \qquad \langle \overline{q} q \rangle^{1/3} \approx -283\ \mathrm{MeV}$$

Spontaneous breaking of

chiral (χ) symmetry



Λ ~ a few TeV
we get the neutrino mass in the sub-eV ballpark

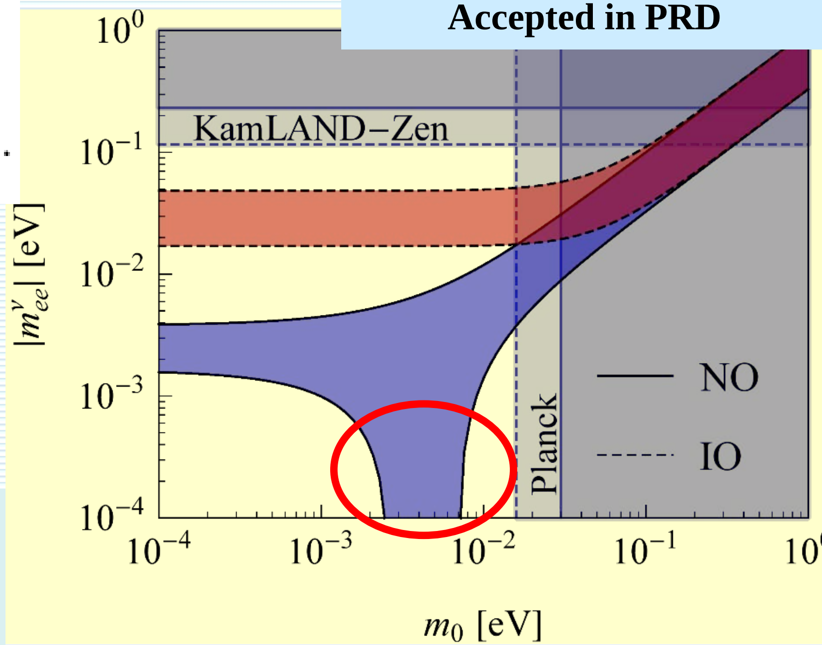
The genuine QCSS scenario with no fine-tuning

A. Babič, S. Kovalenko, M.I. Krivoruchenko , F.Š.,
arXiv: 1911.12189 [hep-ph], Accepted in PRD

$$\mathcal{L}_7 = \frac{G_F}{\sqrt{2}} \overline{e_L} \nu_L^C \left(\varepsilon^u{}_{ee} \overline{u_R} d_L - \varepsilon^d{}_{ee} \overline{u_L} d_R \right) + \frac{G_F}{\sqrt{2}} \overline{\nu_L^C} \nu_L \left(\varepsilon^u{}_{ee} \overline{u_L} u_R + \varepsilon^d{}_{ee} \overline{d_R} d_L \right) + \text{H.c.}$$

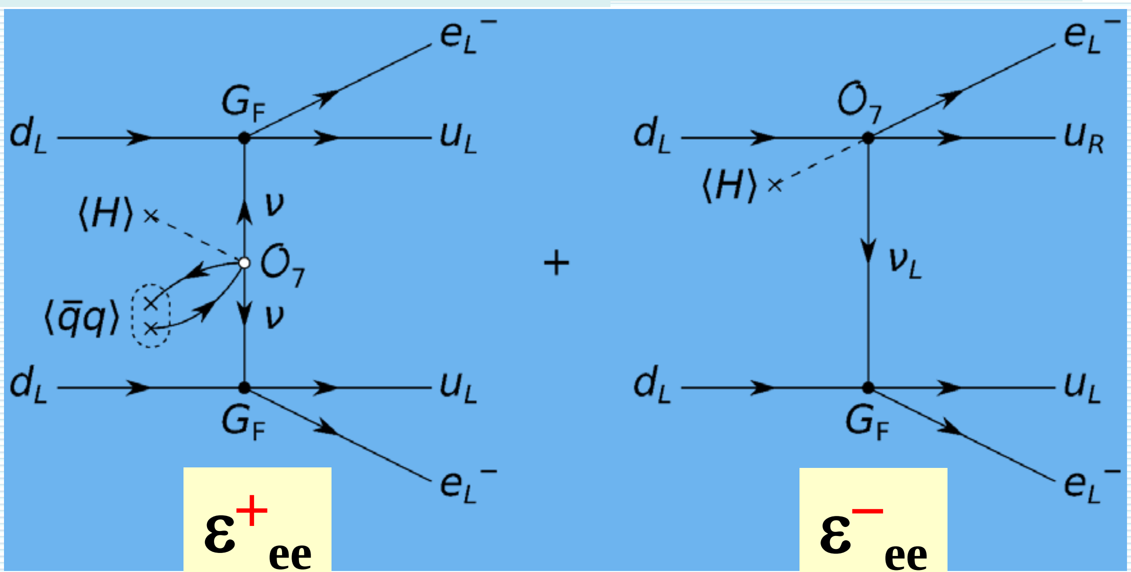
$$\varepsilon^{u,d}_{\alpha\beta} = \frac{g^{u,d}_{\alpha\beta} v/\Lambda^3}{G_F/\sqrt{2}}$$

$$\varepsilon^{\pm}_{\alpha\beta} = \varepsilon^u_{\alpha\beta} \pm \varepsilon^d_{\alpha\beta}$$



(a) discussed earlier in S.Kovalenko, M.I. Krivoruchenko, F.Š., PRL 112, 142503 (2014).

(b) discussed earlier in H. Päs, M. Hirsch, S. Kovalenko PLB 453, 194 (1999).



New features:

IH excluded, limits $\varepsilon < 10^{-8}$

2 meV < m_1 < 7 meV
9 meV < m_2 < 11 meV
50 meV < m_2 < 51 meV

Neutrino spectrum

Prediction for Kathrin

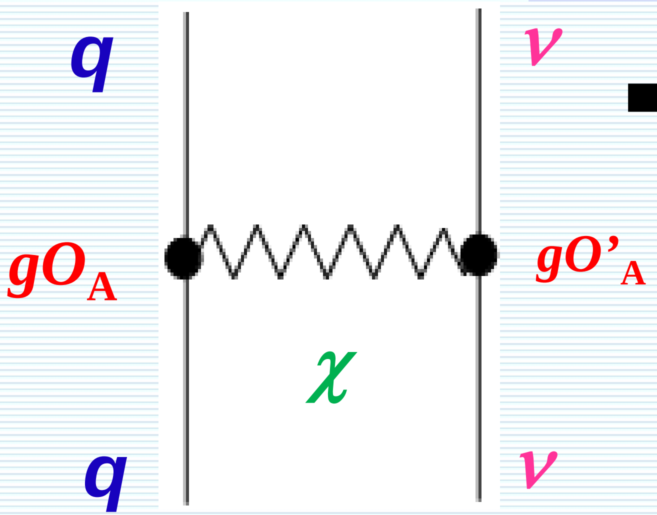
9 meV < m_β < 12 meV

Prediction for cosmology

62 meV < $m_1 + m_2 + m_3$ < 69 meV

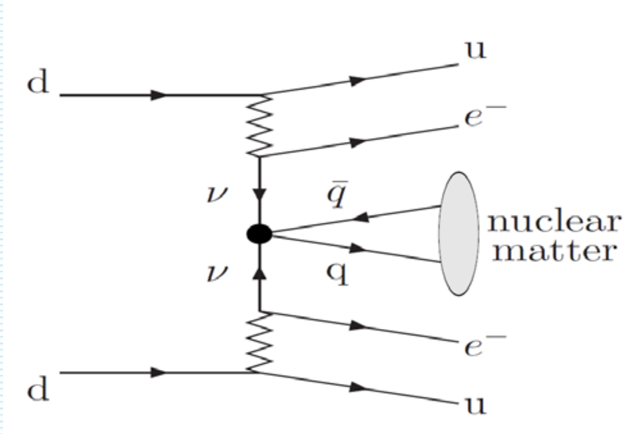
II.b Nuclear medium effect on the light neutrino mass exchange mechanism of the $0\nu\beta\beta$-decay

S.G. Kovalenko, M.I. Krivoruchenko, F. Š., Phys. Rev. Lett. 112 (2014) 142503



Low energy 4-fermion $\Delta L \neq 0$ Lagrangian

$$L_{\mathrm{eff}} = \frac{g^2}{m_\chi^2}\sum_A (\bar{q}O_A q)(\bar{\nu}O'_A\nu), \qquad m_\chi \gtrsim M_W .$$



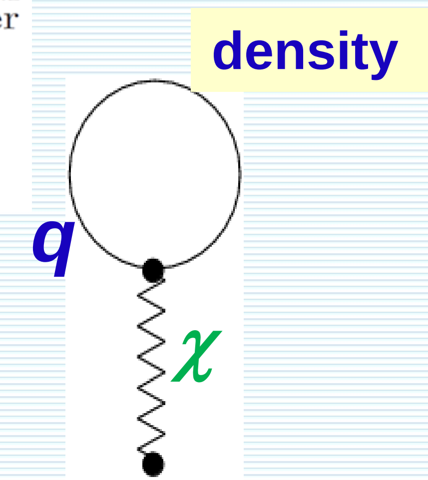
$0\nu\beta\beta$-decay

oscillation experiments, tritium β-decay

cosmology

$$\Sigma_\nu^{\mathrm{vac}} = \times \,, \;---$$

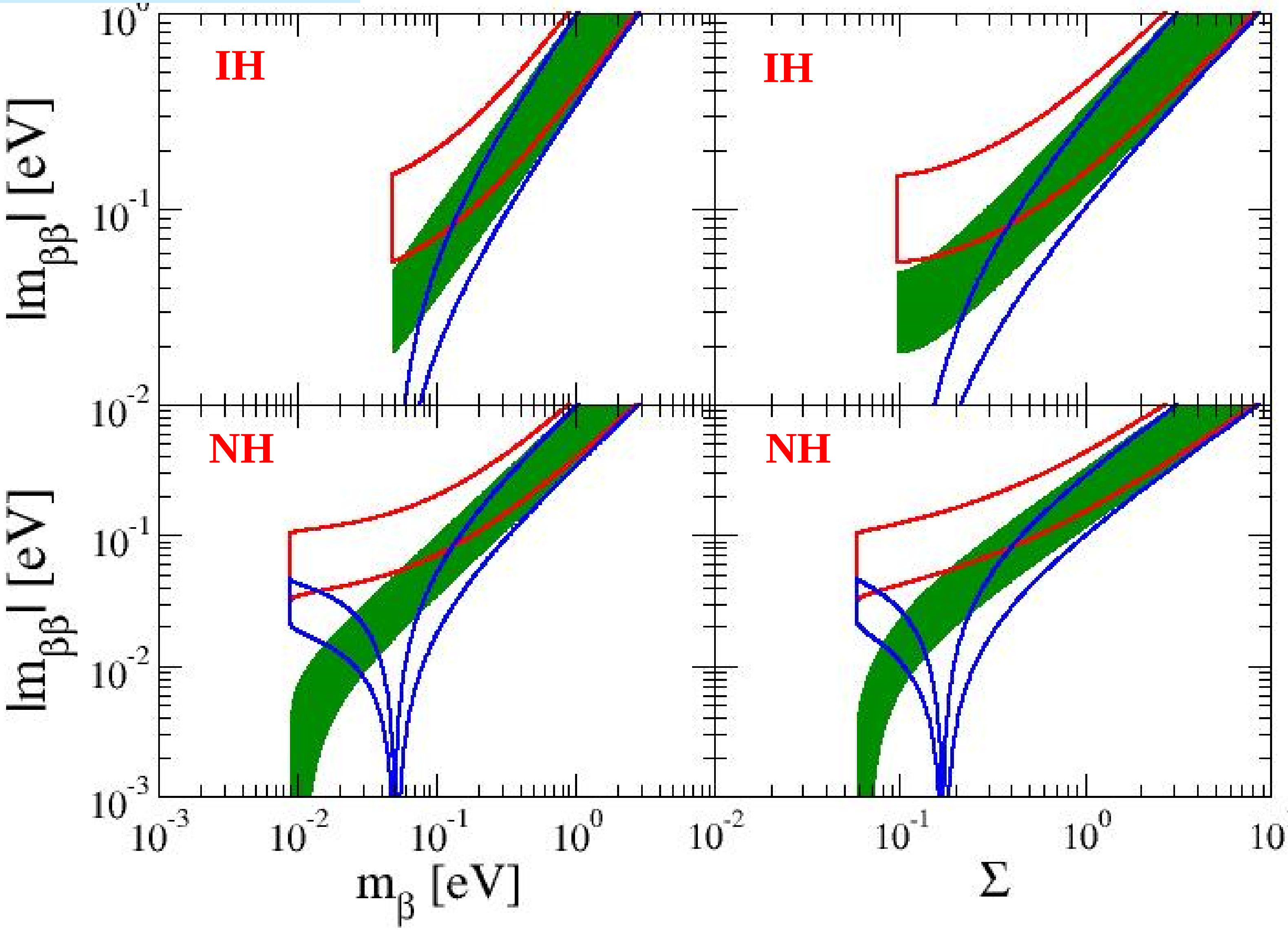
$$\Sigma_\nu^{\mathrm{medium}} = -\times- \;+$$



Area	$\langle\chi\rangle g_1$ [eV]
blue	-0.05
green	0
red	1

$$\langle\chi\rangle g^a_{ij} = -\frac{G_F}{\sqrt{2}}\langle\bar{q}q\rangle\varepsilon^a_{ij} \approx -25\,\varepsilon^a_{ij}\ \mathrm{eV}$$

$$\langle\chi\rangle = -\frac{g_\chi}{m_\chi^2}\langle\bar{q}q\rangle \qquad g^a_{ij} = \delta_{ij}g_a \qquad \varepsilon^a_{ij} = \delta_{ij}\varepsilon_a$$



Complementarity between β-decay, 0νββ –decay and cosmological measurements might be spoiled

The sterile ν mechanism of the 0νββ-decay
(D-M mass term, V-A,SM int.)
Interpolating formula

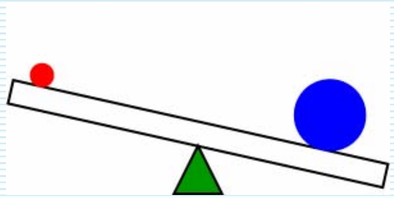
Dirac-Majorana mass term

$$N = \sum_{\alpha=s,e,\mu,\tau} U_{N\alpha}\, \nu_\alpha$$

Mixing of active-sterile neutrinos

small ν masses due to see-saw mechanism

$$\begin{pmatrix} 0 & m_D \\ m_D & m_{LNV} \end{pmatrix}$$



Light ν mass ≈ $(m_D/m_{LNV})\, m_D$
Heavy ν mass ≈ m_{LNV}

Neutrinos masses offer a great opportunity to jump beyond the EW framework via see-saw ...

Different motivations for the LNV scale Λ

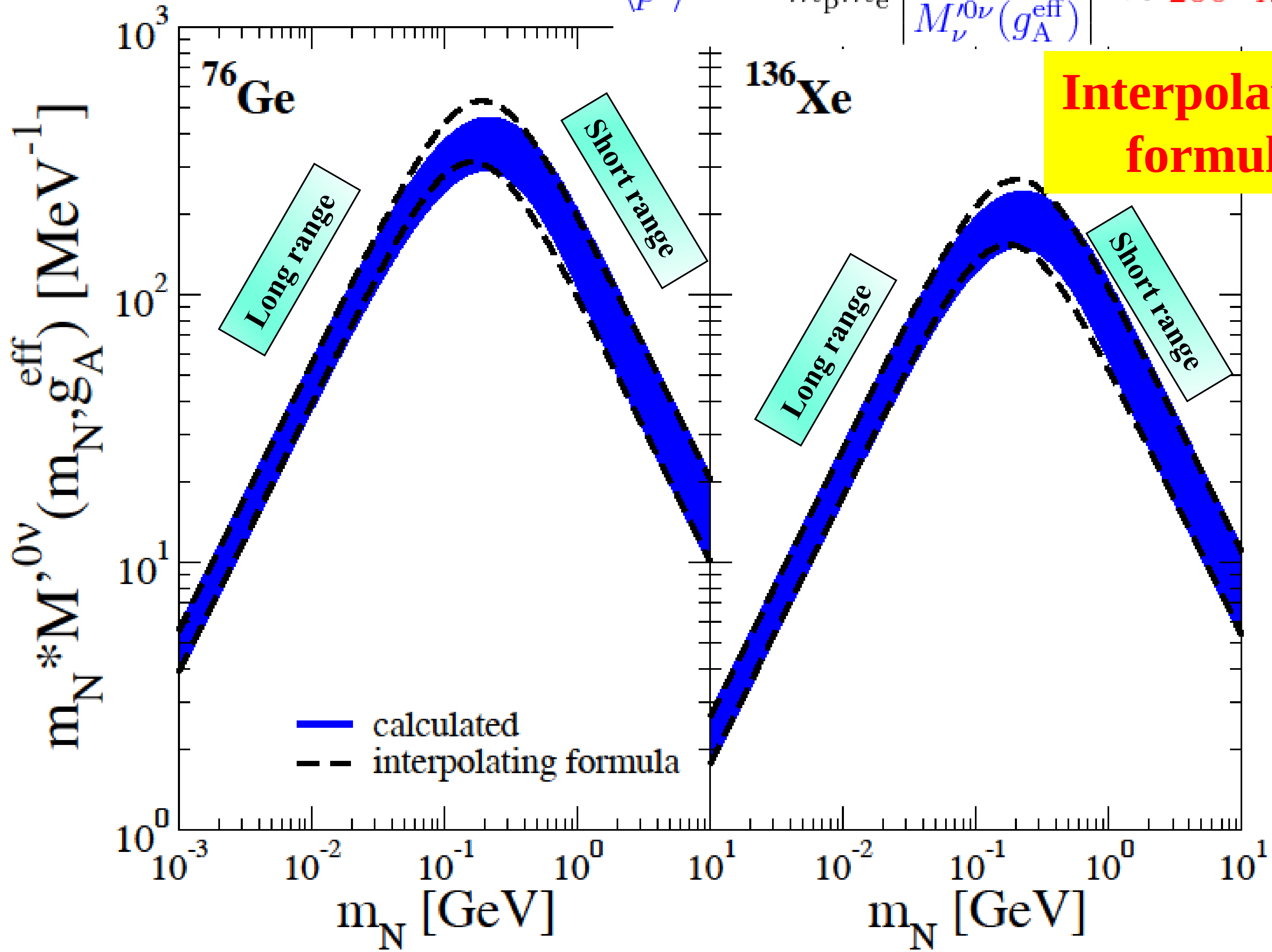
eV **light sterile ν** **10^{-6} GeV**	**keV** **hot DM** **10^{-6} GeV**	**Fermi** **10^{-6} GeV**	**TeV** **LHC** **10^{3} GeV**	**GUT** **10^{16} GeV**	**Planck** **10^{19} GeV**

$$[T^{0\nu}_{1/2}]^{-1} = \mathcal{A}\cdot \left| m_{\rm p} \sum_{\rm N} U^2_{e\rm N} \frac{m_{\rm N}}{\langle p^2\rangle + m_{\rm N}^2}\right|^2,$$

$$\mathcal{A} = G^{0\nu} g_{\rm A}^4 \left|M'^{0\nu}_{\rm N}(g_{\rm A}^{\rm eff})\right|^2,$$

$$\langle p^2\rangle = m_{\rm p} m_{\rm e} \left|\frac{M'^{0\nu}_{\rm N}(g_{\rm A}^{\rm eff})}{M'^{0\nu}_{\nu}(g_{\rm A}^{\rm eff})}\right| \approx 200 \ \ MeV$$

Interpolating formula

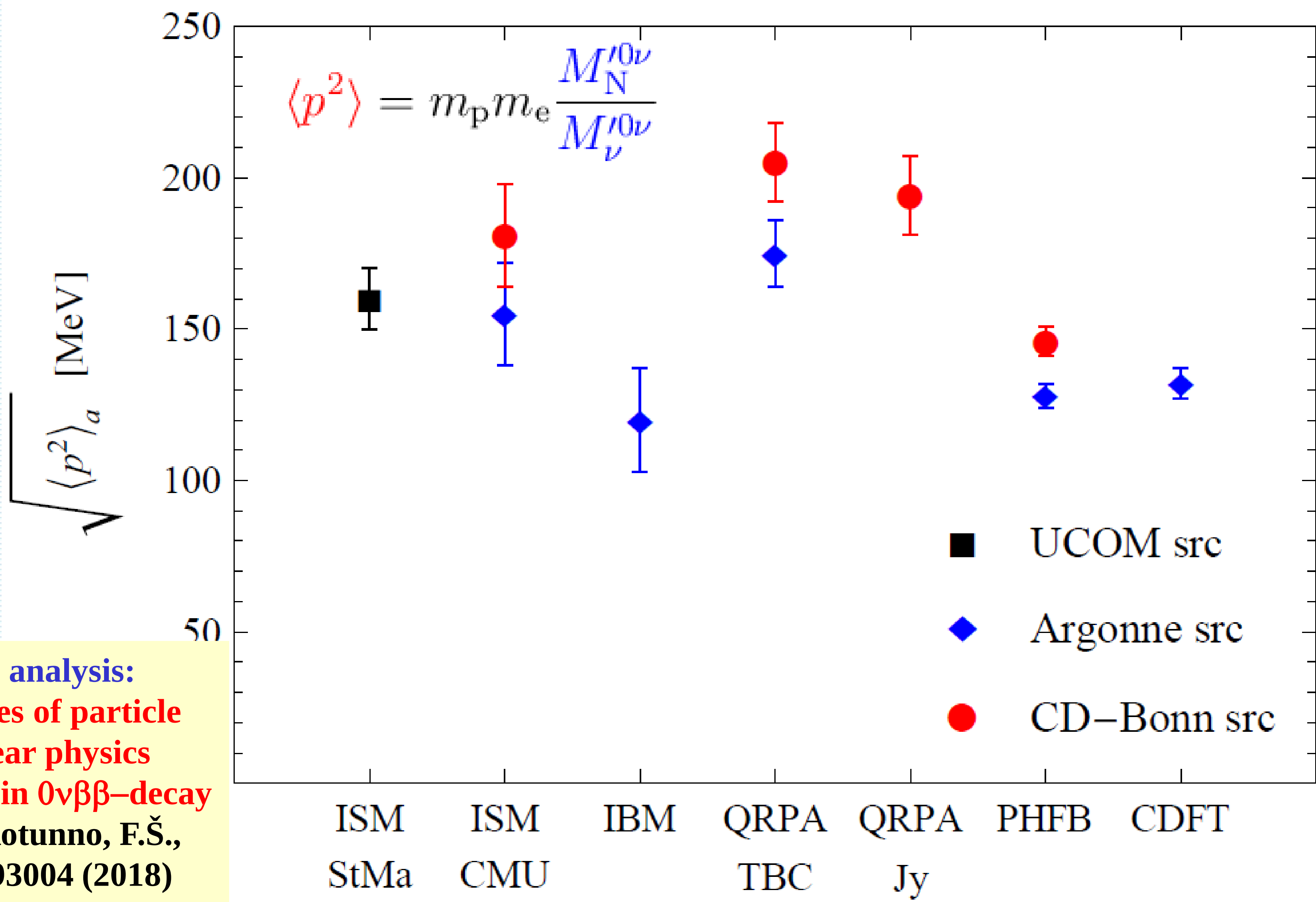


Faessler, Gonzales, Kovalenko, F. Š., PRD 90 (2014) 096010]

Interpolating formula is justified by practically no dependence <p^2> on A

A. Babič, S. Kovalenko, M.I. Krivoruchenko, F.Š., PRD 98, 015003 (2018)

$$[T^{0\nu}_{1/2}]^{-1} = \mathcal{A} \cdot \left| m_{\rm p} \sum_{\rm N} U^2_{e\rm N} \frac{m_{\rm N}}{\langle p^2 \rangle + m^2_{\rm N}} \right|^2 ,$$



Detailed analysis:

Degeneracies of particle and nuclear physics uncertainties in 0νββ–decay

E. Lisi, A. Rotunno, F.Š., PRD 92, 093004 (2018)

The $0\nu\beta\beta$-decay within L-R symmetric theories (interpolating formula)

(D-M mass term, see-saw, V-A and V+A int., exchange of heavy neutrinos)

A. Babič, S. Kovalenko, M.I. Krivoruchenko , F.Š., PRD 98, 015003 (2018)

$$[T^{0\nu}_{1/2}]^{-1} = \eta^2_{\nu N}\ C_{\nu N} \qquad C_{\nu N} = g^4_{\rm A}\ \left|M'^{0\nu}_{\nu}\right|^2\ G^{0\nu}$$

Mixing of light and heavy neutrinos

$$\mathcal{U} = \begin{pmatrix} U & S \\ T & V \end{pmatrix}$$

$$\nu_{eL} = \sum_{j=1}^{3}\left(U_{ej}\nu_{jL} + S_{ej}(N_{jR})^C\right),$$

$$\nu_{eR} = \sum_{j=1}^{3}\left(T^*_{ej}(\nu_{jL})^C + V^*_{ej}N_{jR}\right)$$

Effective LNV parameter within LRS model (due interpolating formula)

$$\langle p^2\rangle = m_{\rm p}m_{\rm e}\frac{M'^{0\nu}_{\rm N}}{M'^{0\nu}_{\nu}}$$

$$\eta^2_{\nu N} = \left|\sum_{j=1}^{3}\left(U^2_{ej}\ \frac{m_j}{m_e}\ +\ S^2_{ej}\ \frac{\langle p^2\rangle_a}{\langle p^2\rangle_a + M^2_j}\ \frac{M_j}{m_e}\right)\right|^2 + \lambda^2\left|\sum_{j=1}^{3}\left(T^2_{ej}\ \frac{m_j}{m_e}\ +\ V^2_{ej}\ \frac{\langle p^2\rangle_a}{\langle p^2\rangle_a + M^2_j}\ \frac{M_j}{m_e}\right)\right|^2$$

The dominance of light and heavy ν-mass contributions to 0nbb-decay rate can not be established by observing this process at different nuclei.

6x6 PMNS see-saw ν-mixing matrix

(the most economical one, prediction for mixing of heavy neutral leptons)

6x6 neutrino mass matrix

$$\mathcal{U} = \begin{pmatrix} U & S \\ T & V \end{pmatrix}$$

Basis $(\nu_L, (N_R)^c)^T$

$$\mathcal{M} = \begin{pmatrix} M_L & M_D \\ M_D & M_R \end{pmatrix}$$

6x6 matrix: 15 angles, 10+5 CP phases
3x3 matrix: 3 angles, 1+2 CP phases

3x3 block matrices U, S, T, V are generalization of PMNS matrix

Assumptions:
i) the see-saw structure
ii) mixing between different generations is neglected

$$\mathcal{U}_{\rm PMNS} = \begin{pmatrix} U_{\rm PMNS} & \zeta\,\mathbf{1} \\ -\zeta\,\mathbf{1} & U^{\dagger}_{\rm PMNS} \end{pmatrix}$$

$$\mathcal{U}_{\rm PMNS}\,\mathcal{U}^{\dagger}_{\rm PMNS} = \mathcal{U}^{\dagger}_{\rm PMNS}\,\mathcal{U}_{\rm PMNS} = \mathbf{1}$$

see-saw parameter

$$\zeta = \frac{m_{\rm D}}{m_{\rm LNV}}$$

6x6 matrix: 3 angles, 1+2 CP phases, 1 see-saw par.

A. Babič, S. Kovalenko, M.I. Krivoruchenko , F.Š., PRD 98, 015003 (2018)

6x6 PMNS see-saw ν-mixing matrix
(the most economical one)

$$\mathcal{U} = \begin{pmatrix} U_0 & \zeta\,1 \\ -\zeta\,1 & V_0 \end{pmatrix}$$

$$U_0 = U_{\rm PMNS}$$

A. Babič, S. Kovalenko, M.I. Krivoruchenko , F.Š., PRD 98, 015003 (2018)

$$V_0 = U^\dagger_{\rm PMNS} =$$

$$\begin{pmatrix} c_{12}\,c_{13}\,e^{-i\alpha_1} & \left(-s_{12}\,c_{23} - c_{12}\,s_{13}\,s_{23}\,e^{-i\delta}\right)e^{-i\alpha_1} & \left(s_{12}\,s_{23} - c_{12}\,s_{13}\,c_{23}\,e^{-i\delta}\right)e^{-i\alpha_1} \\ s_{12}\,c_{13}\,e^{-i\alpha_2} & \left(c_{12}\,c_{23} - s_{12}\,s_{13}\,s_{23}\,e^{-i\delta}\right)e^{-i\alpha_2} & \left(-c_{12}\,s_{23} - s_{12}\,s_{13}\,c_{23}\,e^{-i\delta}\right)e^{-i\alpha_2} \\ s_{13}\,e^{i\delta} & c_{13}\,s_{23} & c_{13}\,c_{23} \end{pmatrix}$$

Assumption about heavy neutrino masses M_i (by assuming see-saw)

Inverse proportional

$$m_i M_i \simeq m_D^2$$

$$M^{\rm R}_{\beta\beta} = \lambda\,\frac{\langle p^2\rangle_a}{m_D^2}\left|\sum_{j=1}^{3}(U_0^\dagger)^2_{ej}\,m_j\right|$$

Proportional

$$m_i \simeq \zeta^2 M_i$$

$$M^{\rm R}_{\beta\beta} = \lambda\,\zeta^2\left|\sum_{j=1}^{3}(U_0^\dagger)^2_{ej}\,\frac{\langle p^2\rangle_a}{m_j}\right|$$

$M^{R}_{\beta\beta}$ depends on "Dirac" CP phase δ unlike "Majorana" CP phases α_1 and α_2

Heavy Majorana mass $M^{R}_{\beta\beta}$ depends on the "Dirac" CP violating phase δ

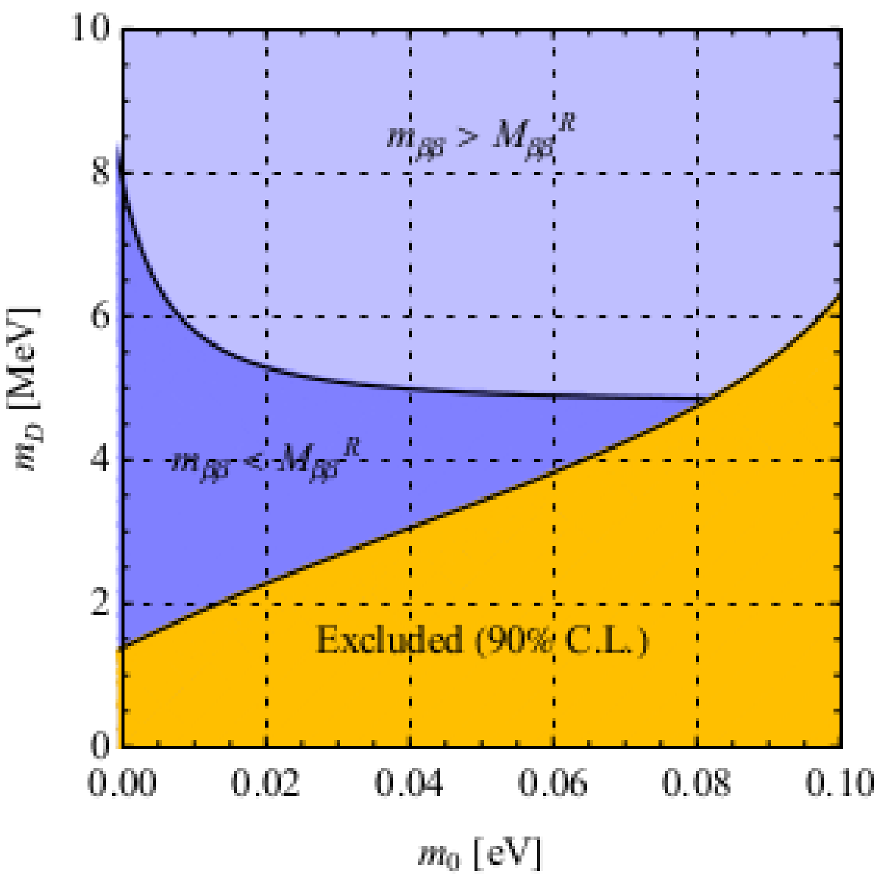
$$\eta_{\nu N}^2 = \frac{1}{m_e^2}\left(m_{\beta\beta}^2 + (M_{\beta\beta}^R)^2\right)$$

See-saw scenario

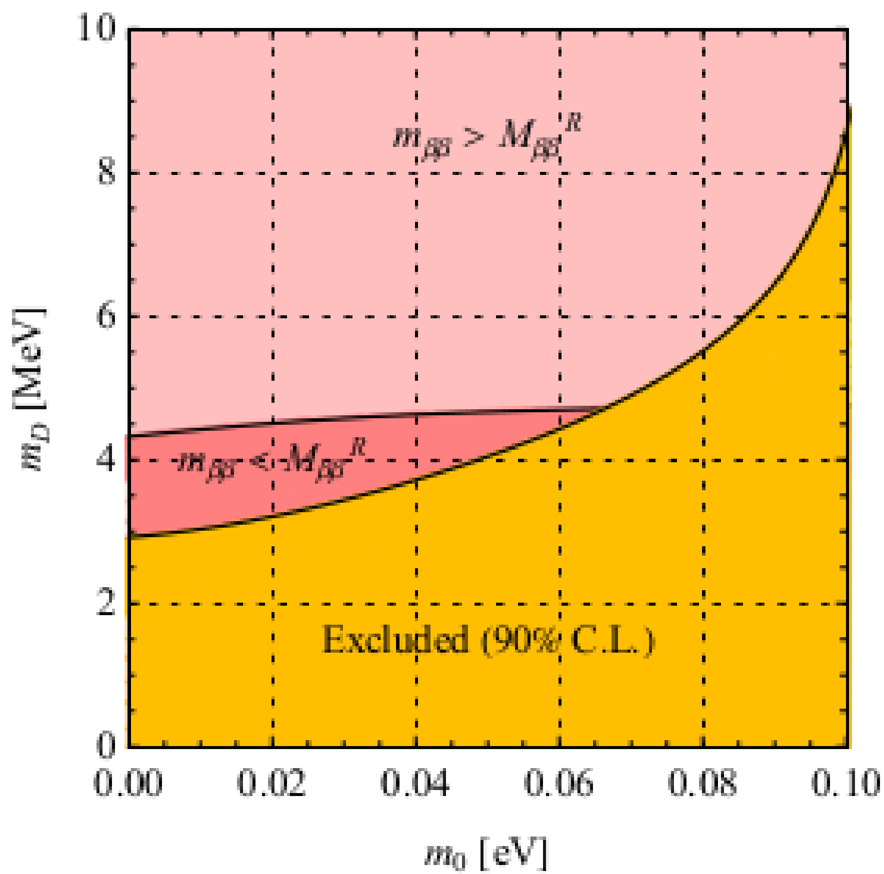
$$m_i M_i \simeq m_D^2$$

$$M_{\beta\beta}^{\mathrm{R}} = \lambda \frac{\langle p^2\rangle_a}{m_D^2} \left|\sum_{j=1}^{3} (U_0^\dagger)_{ej}^2 \, m_j\right|$$

Normal spectrum



Inverted spectrum



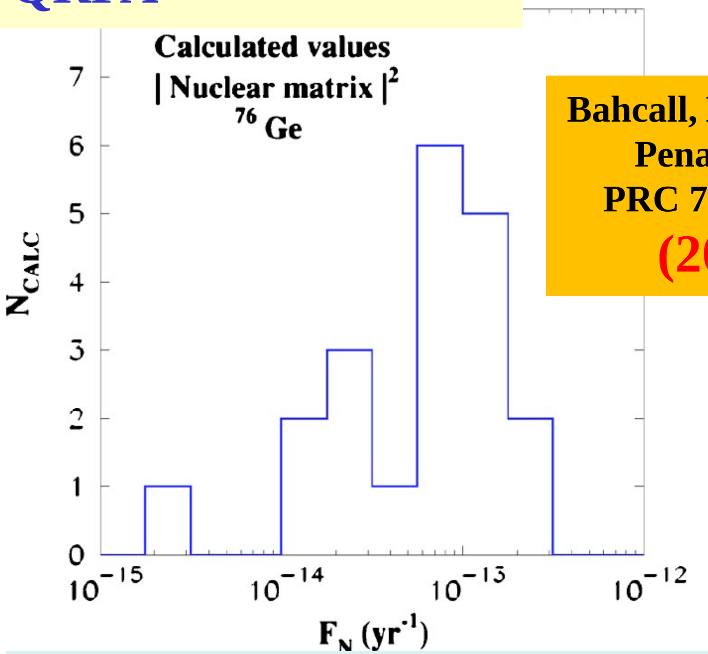
A. Babič, S. Kovalenko, M.I. Krivoruchenko , F.Š., PRD 98, 015003 (2018)

The $0\nu\beta\beta$-decay NMEs – current status

2004 (factor 10)
few groups, 2 nuclear structure methods:
Nuclear Shell Model, QRPA

$0\nu\beta\beta$ decay NMEs

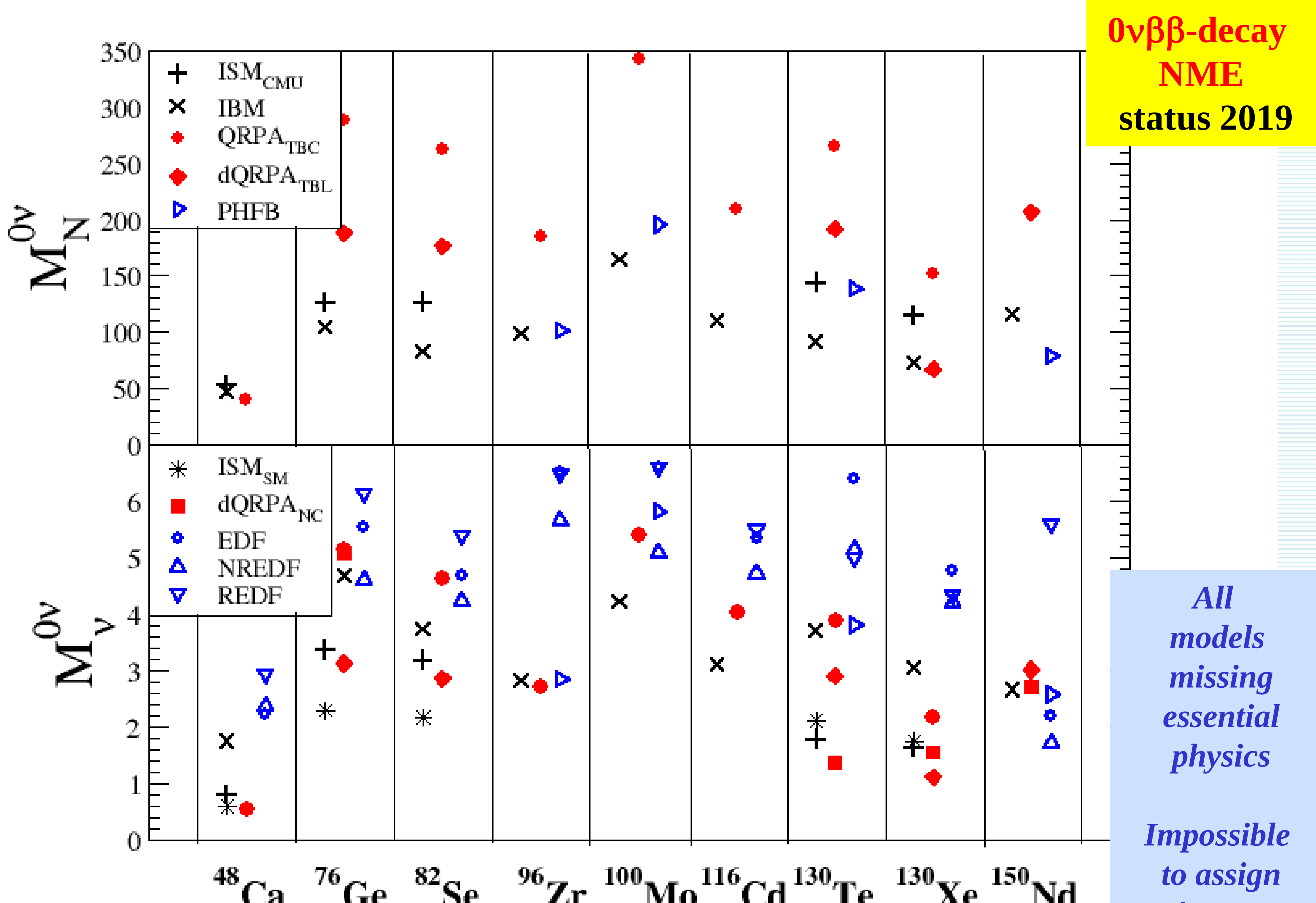
2019 (factor 2-3)
many groups, many nuclear structure methods:
Nuclear Shell Model, QRPA, Interacting Boson Model, Energy Density Functional



Bahcall, Maruyama, Pena-Garay, PRC 70, 033012 (2004)

Attempts (light nuclear systems):
Ab initio calculations by different approaches – No Core Shell Model, Green's Function Monte Carlo, Coupled Cluster Method, Lattice QCD

Nuclear Shell Model **(Madrid-Strasbourg, Michigan, Tokyo): Relatively small model space (1 shell), all correlations included, solved by direct diagonalization**
QRPA **(Tuebingen-Bratislava-Calltech, Jyvaskyla, Chapel Hill, Lanzhou, Prague): Several shells, only simple correlations included**
Interacting Boson Method **(Yale-Concepcion): Small space, important proton-neutron Pairing correlations missing**
Energy Density Functional theory **(Madrid, Beijing): >10 shells, important proton-neutron pairing missing**



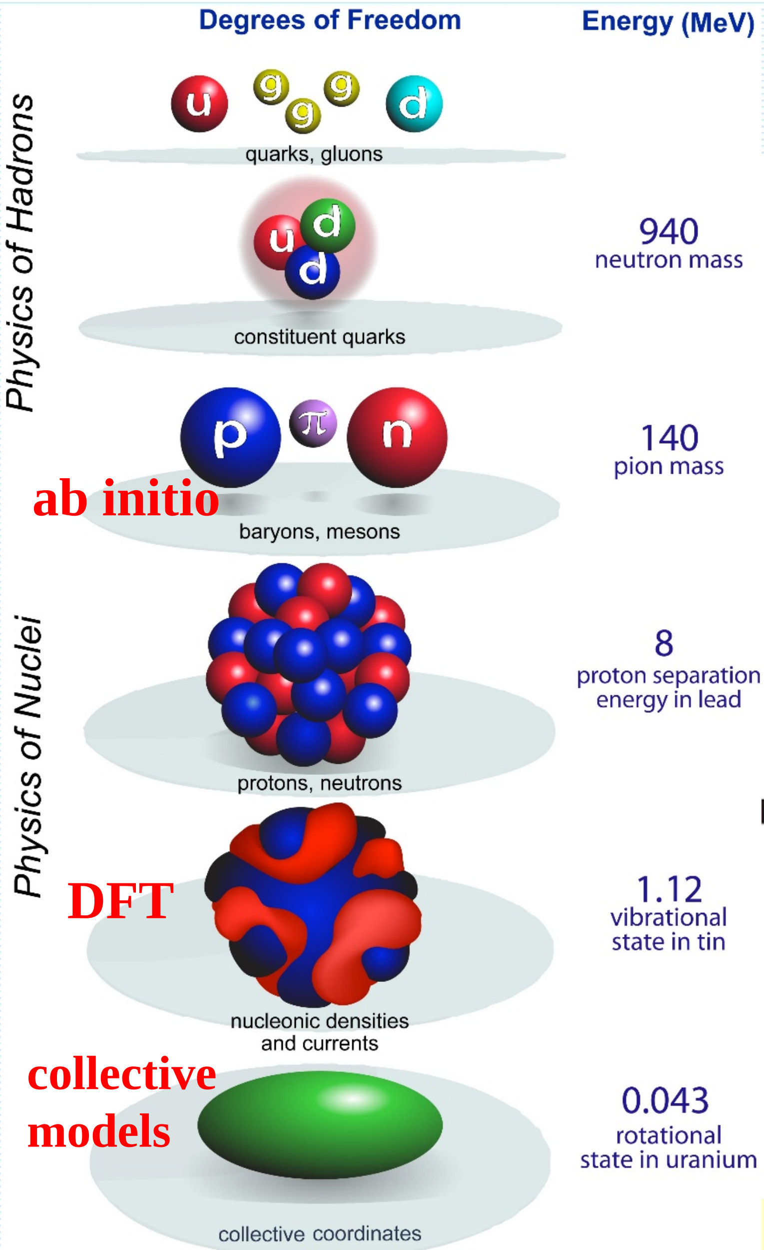
All models missing essential physics

Impossible to assign rigorous uncertainties

unquenched g_A

Ab Initio Nuclear Structure
(Often starts with chiral effective-field theory)

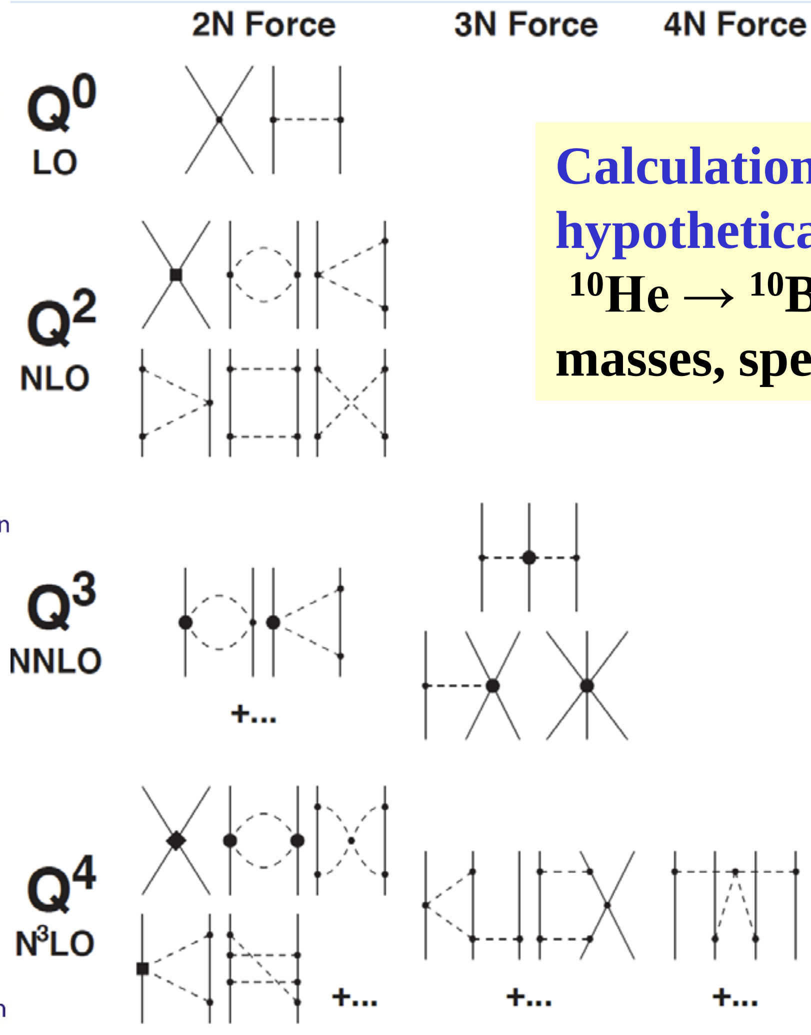
Nucleons, pions. Sufficient below chiral symmetry breaking scale. Expansion of operators in power of Q/Λ_χ. $Q=m_\pi$ or typical nucleon momentum.



ab initio

DFT

collective models



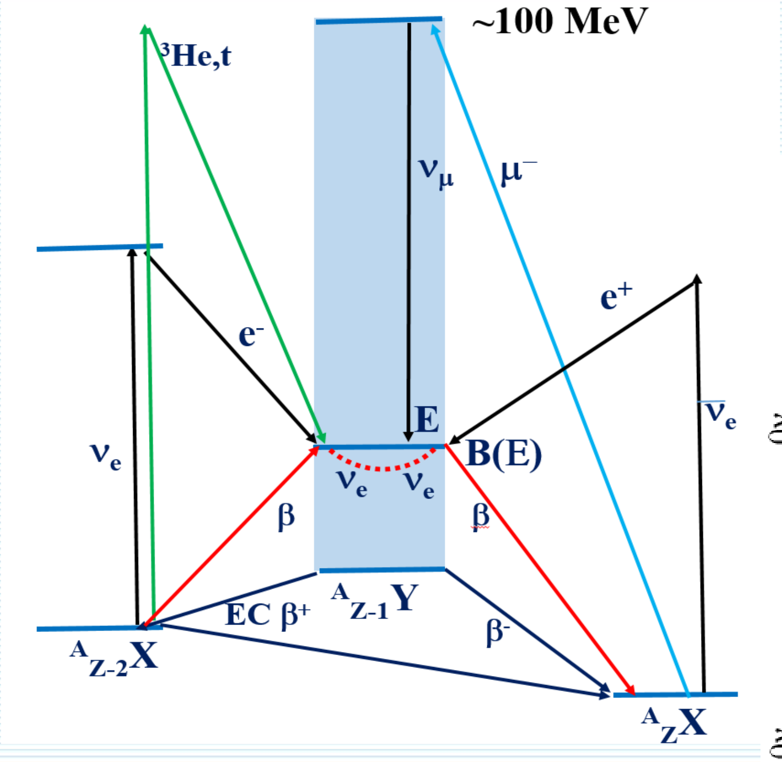
Calculation for the hypothetical 0νββ decay:
^{10}He → ^{10}Be + e$^-$ + e-
masses, spectra

A. Schwenk,
P. Navratil,
J. Engel,
J. Menendez

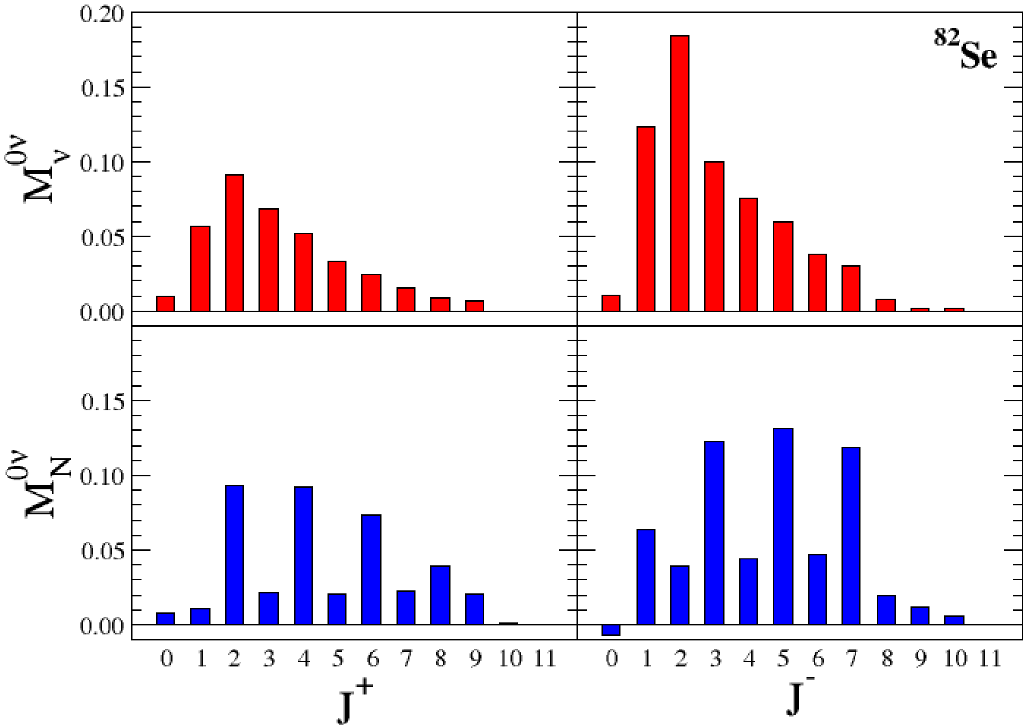
Moore's law: exponential growth in computing power

Supporting nuclear physics experiments

Exploiting charge-exchange reactions (^{3}He,t) and μ-capture to constrain 0νββ–decay NMEs



Multipole decomposition of light and heavy 0νββ-decay NMEs normalized to unity

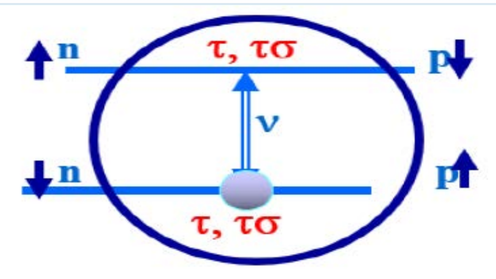


Higher multiploles are populated mostly due large ν-momenta transfer

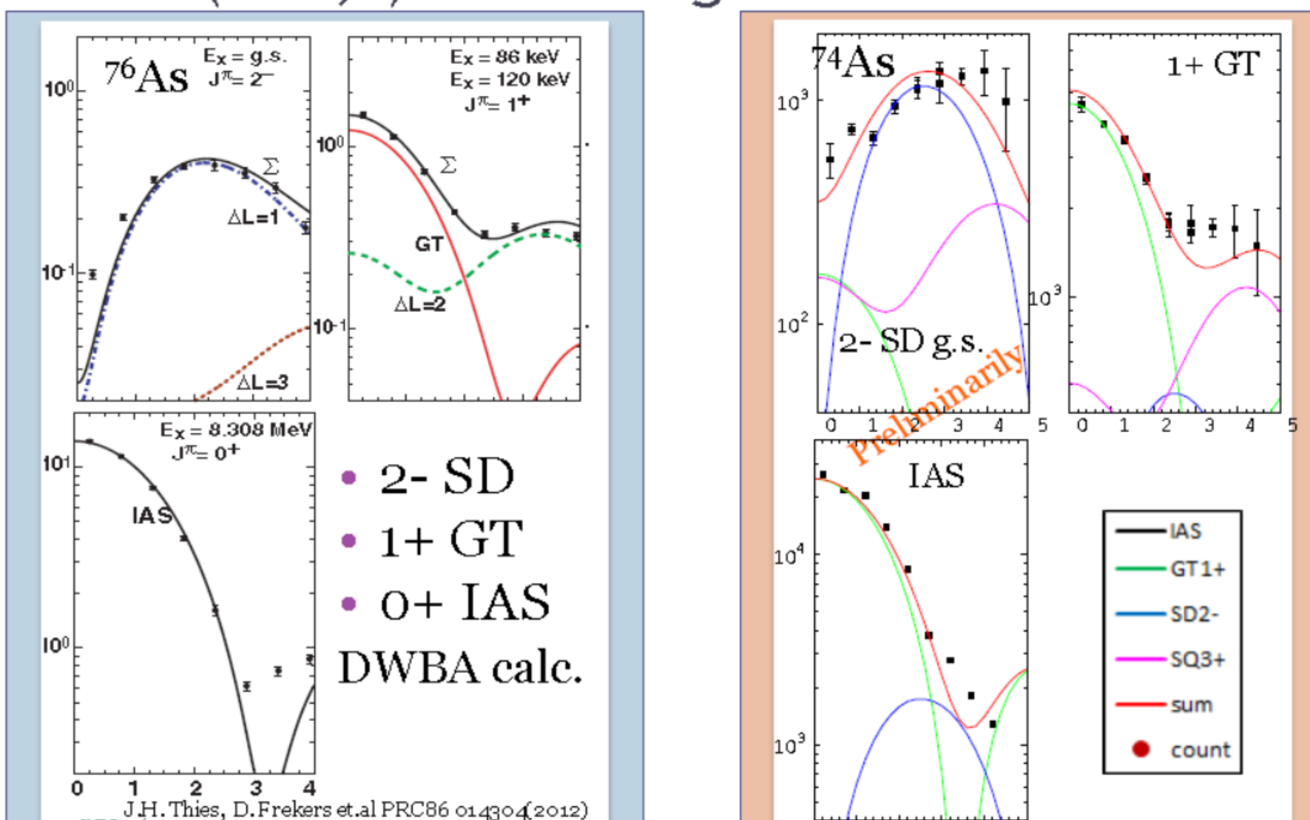
RCNP Osaka p,He

Measuring of GT-like (1^+, 2^-, 3^+) strengths distribution for ^{74,76}Ge → ^{74,76}As with (^{3}He,t) reactions

H. Akimune, H. Ejiri, RCNP, Catania, KVI , Munster・・

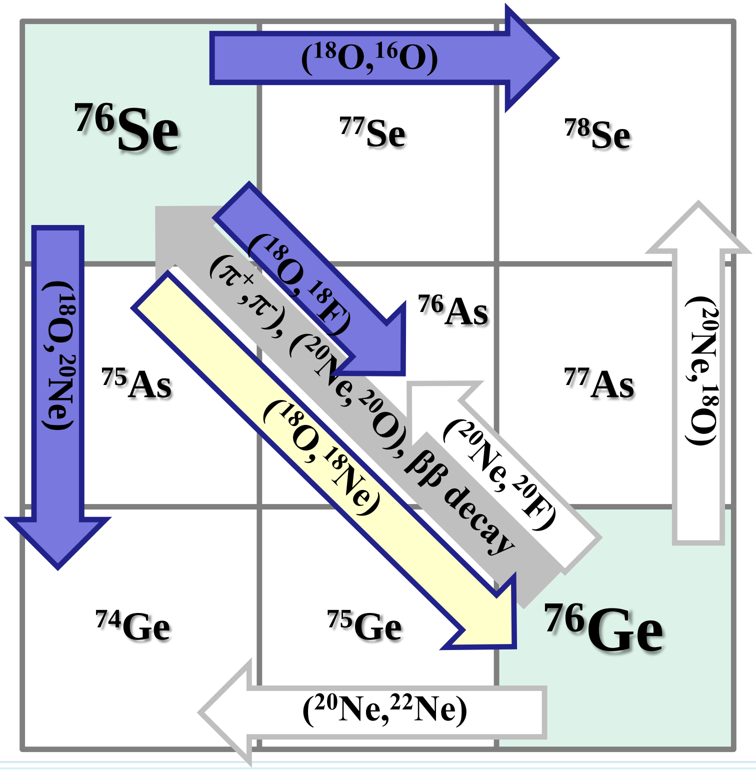


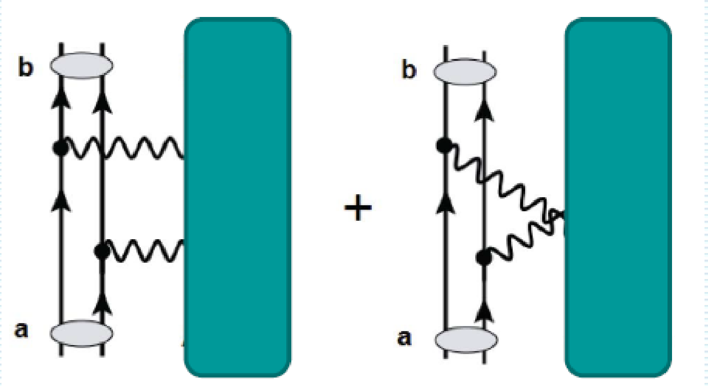
^{74,76}Ge (^{3}He,t)^{74,76}As Angular distribution



Supporting nuclear physics experiments

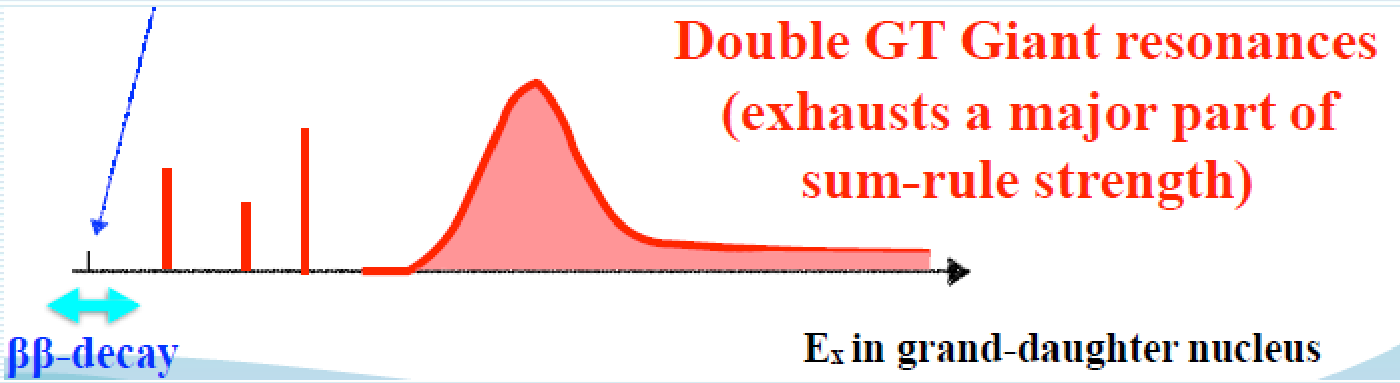
(2νββ-decay, μ-capture ChER, pion and heavy ion DCX, nucleon transfer reactions etc)



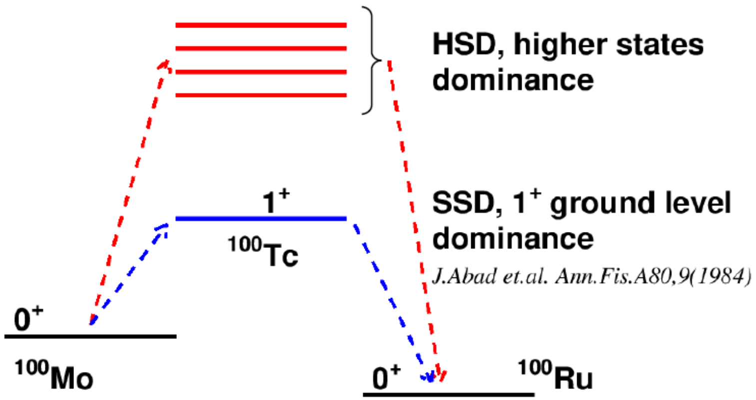


H. Lenske group
Theory of heavy ion DCX and connection to DBD NMEs

Heavy ion DCX: NUMEN (LNC-INFN), HIDCX (RCNP/RIKEN)



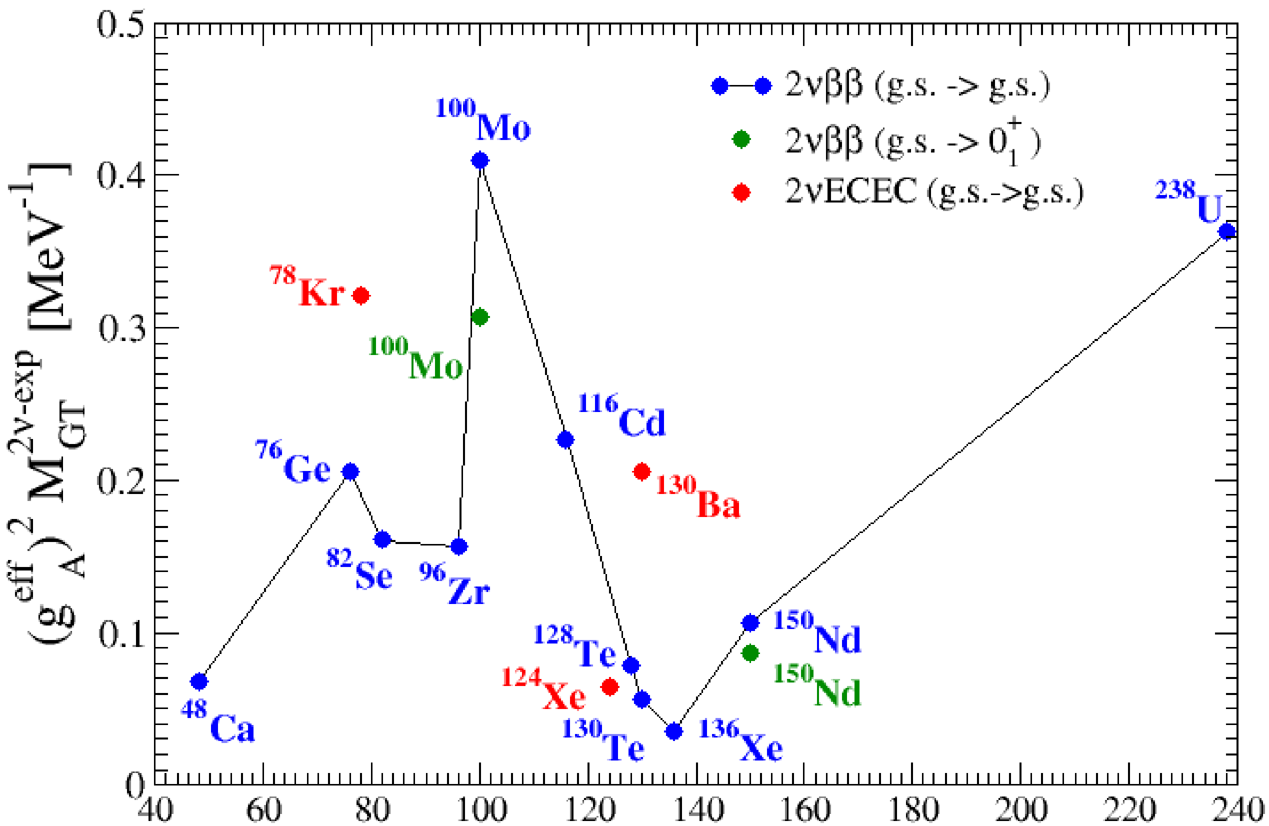
The 2νββ-decay



Understanding of the 2νββ-decay NMEs is of crucial importance for correct evaluation of the 0νββ-decay NMEs

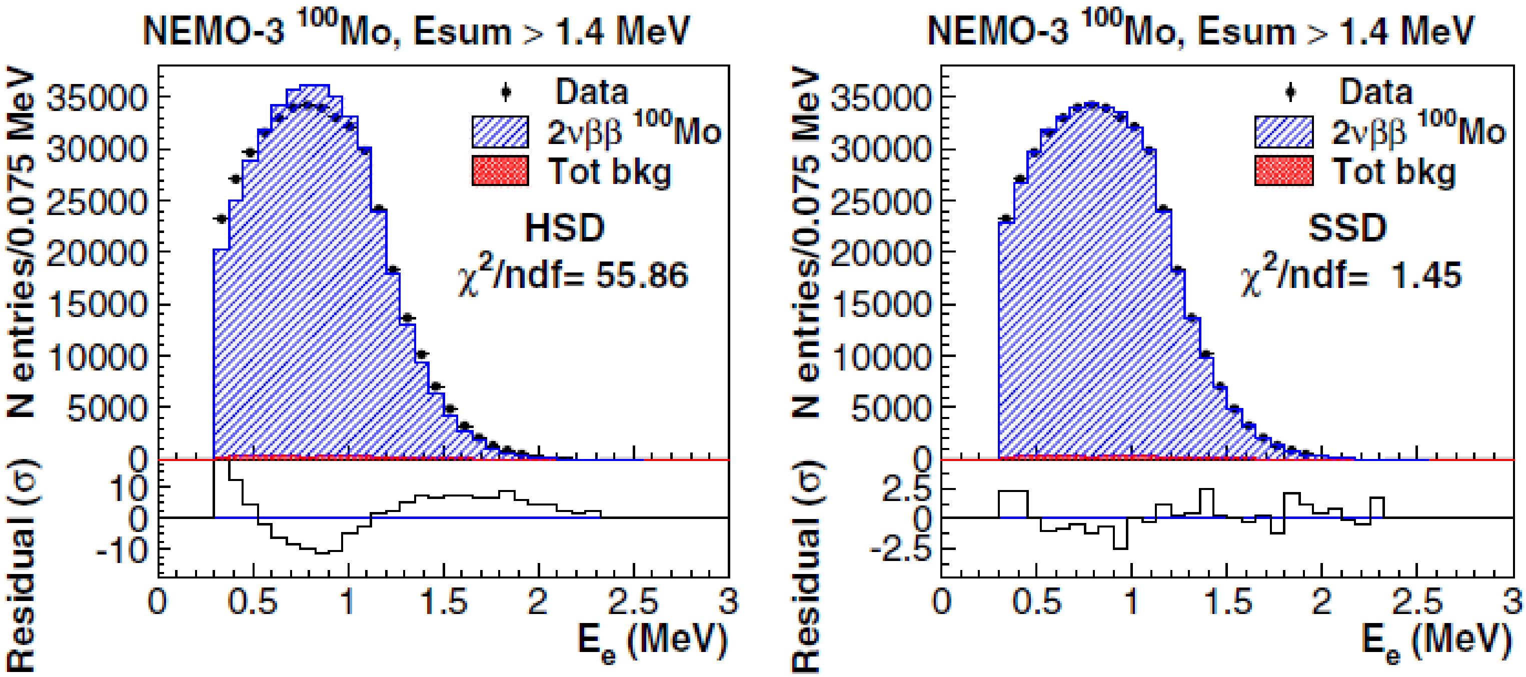
$$M^{2\nu}_{GT} = \sum_m \frac{< 0^+_f||\tau^+\sigma||1^+_m >< 1^+_m||\tau^+\sigma||0^+_i >}{E_m - E_i + \Delta}$$

There is no reliable calculation of the *2νββ-decay NMEs yet*



Both 2νββ and 0νββ operators connect the same states. Both change two neutrons into two protons. Explaining 2νββ-decay is necessary but not sufficient

Looking for SSD/HSD effect



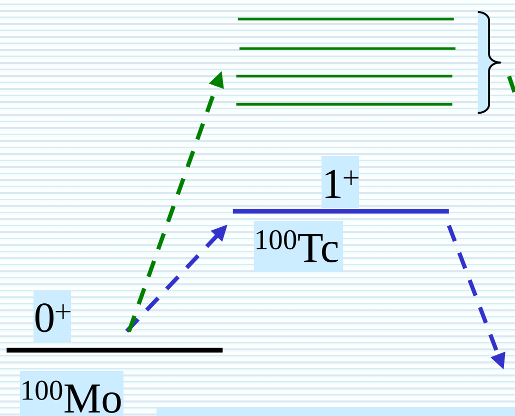
NEMO3 Collaboration, Eur. Phys. J. C79, 440 (2019)

SSD favored

$\Rightarrow$

Strong trans. through low lying states of (A,Z+1);

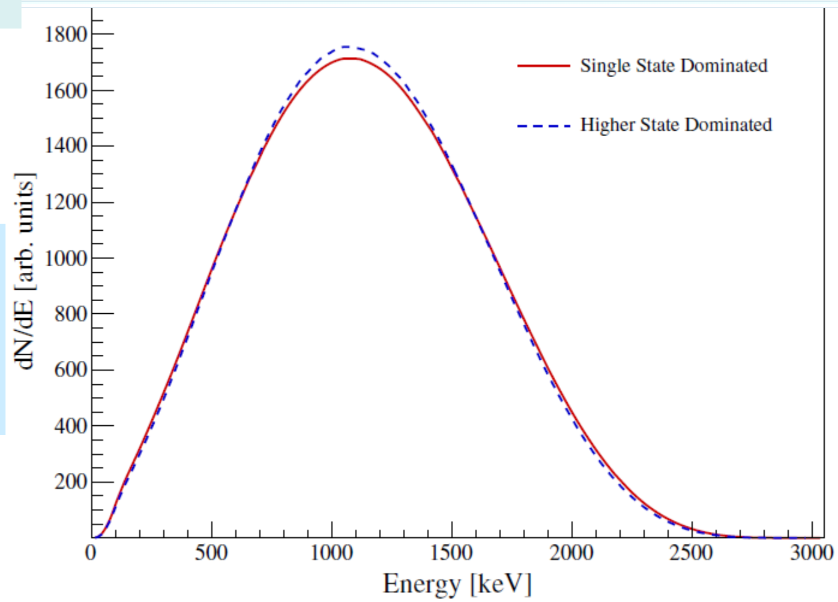
$M_F^{2\nu} \approx 0$



HSD, higher levels contribute to the decay

SSD, 1+ level dominates in the decay

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



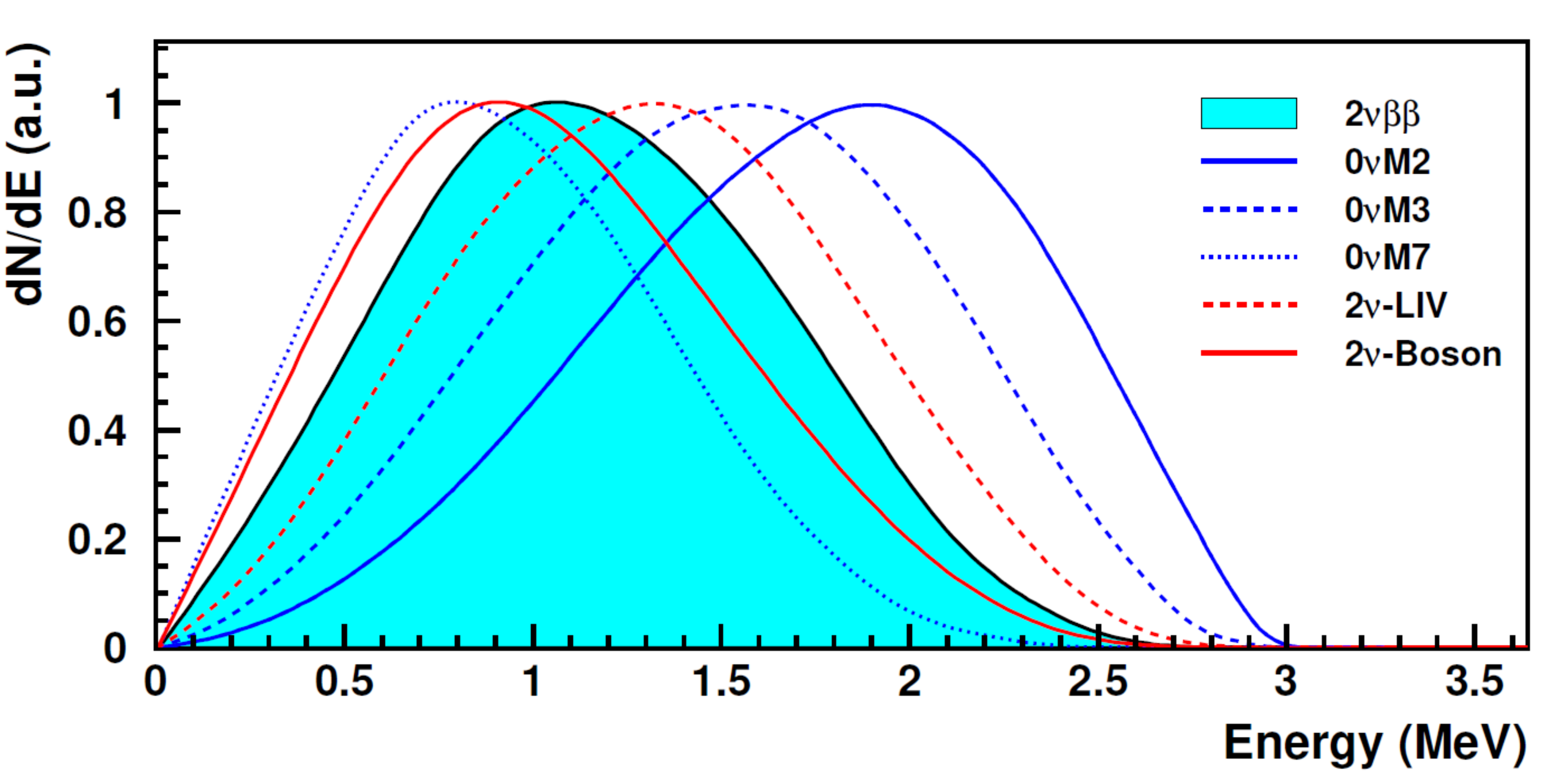
CUPID-0 Coll., PRL 123, 262501 (2019

Look at energy distributions

F. Š., Šmotlák, Semenov

J. Phys. G, 27, 2233, 2001

Looking for a new physics with differential characteristics



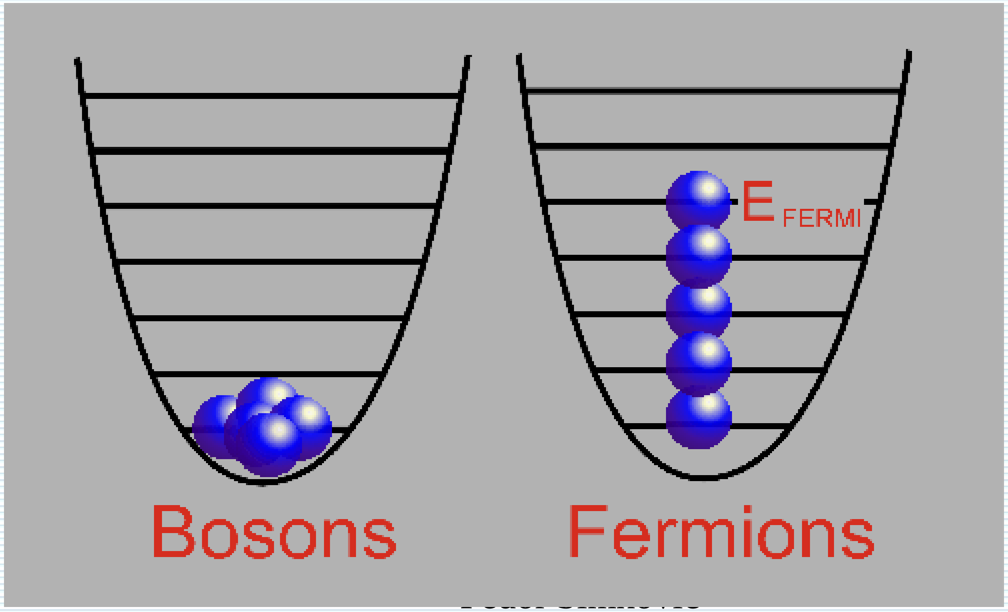
Spectral index n

$$\frac{d\Gamma}{d\varepsilon_1 d\varepsilon_2} = C(Q - \varepsilon_1 - \varepsilon_2)^n \; [p_1\varepsilon_1 F(\varepsilon_1)] \; [p_2\varepsilon_2 F(\varepsilon_2)]$$

(Partly)bosonic or fermionic neutrinos?

Bosons:
In the ground state (T=0) all bosons occupy lowest energy state.

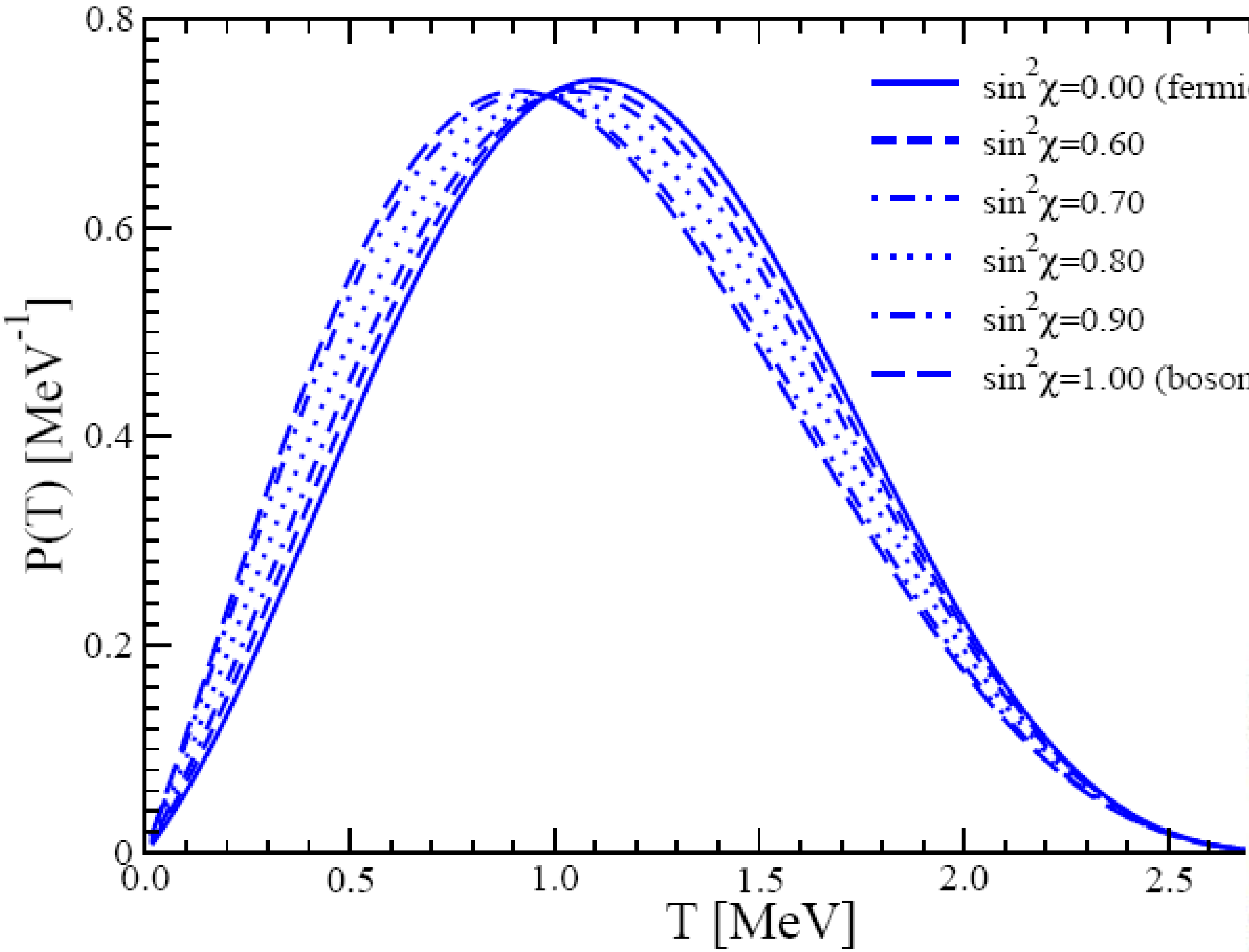
Fermions:
No two fermions can occupy the same state, so in the ground state (T=0), fermions stack from The lowest energy level to higher Energy levels, leaving no holes.

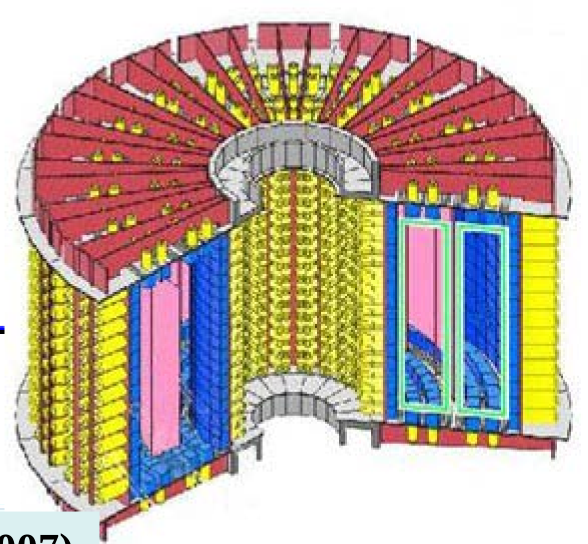


Mixed ν excluded for $\sin^2\chi < 0.6$ (NEMO3 data)

$$W^{2\nu} = \cos\chi^4\, W^f + \sin\chi^4\, W^b = (1-b^2)\, W^f + b^2\, W^b$$

$^{100}Mo \to {}^{100}Ru$ (SSD)



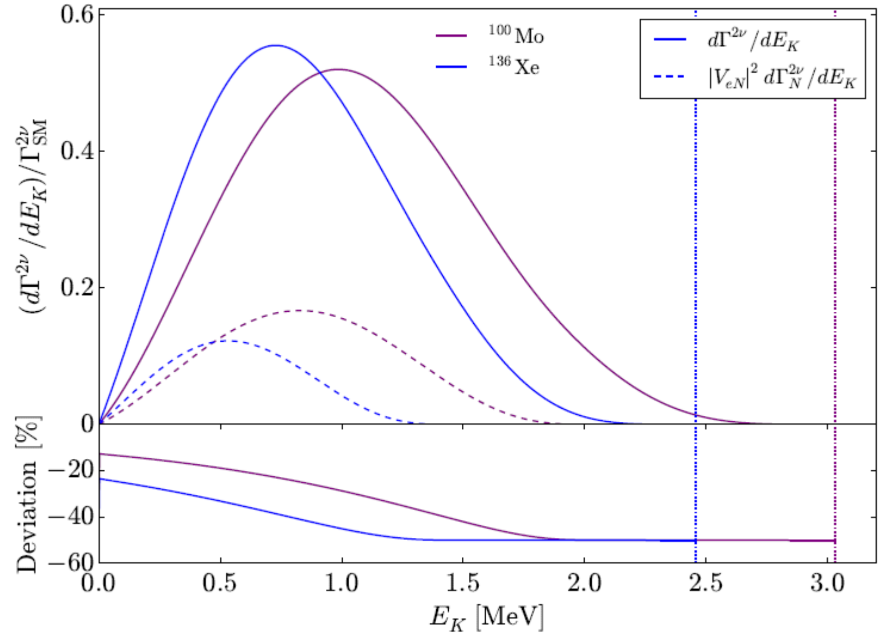


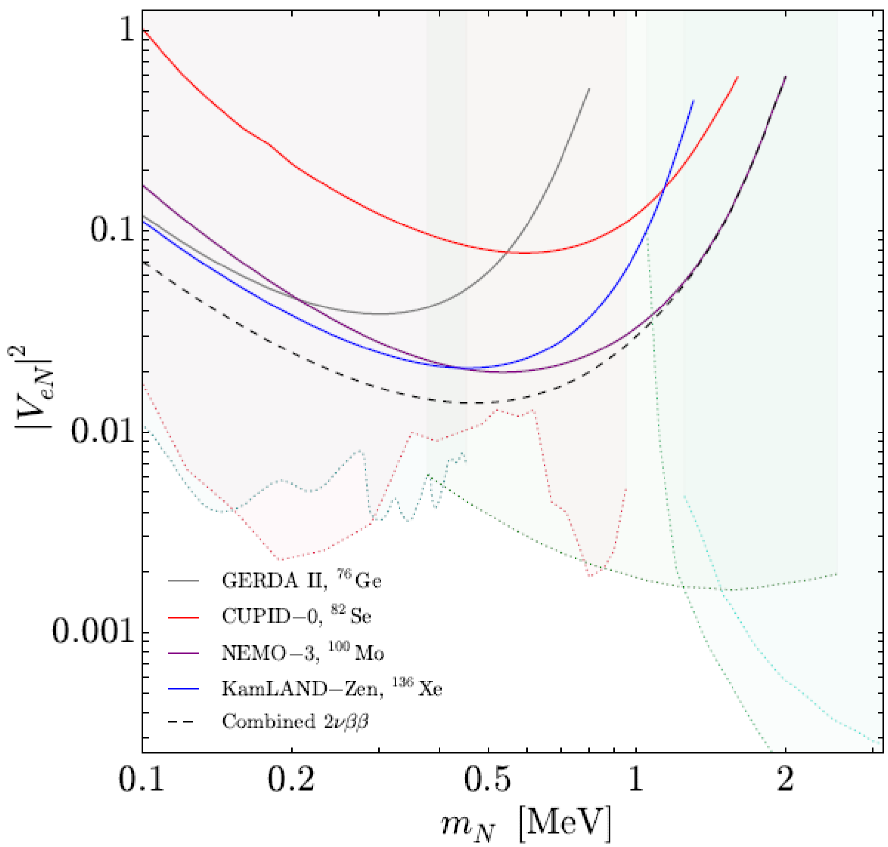
A. Barabash, A. Dolgov, Dvornický, F. Š., A. Smirnov NPB 783, 90 (2007)

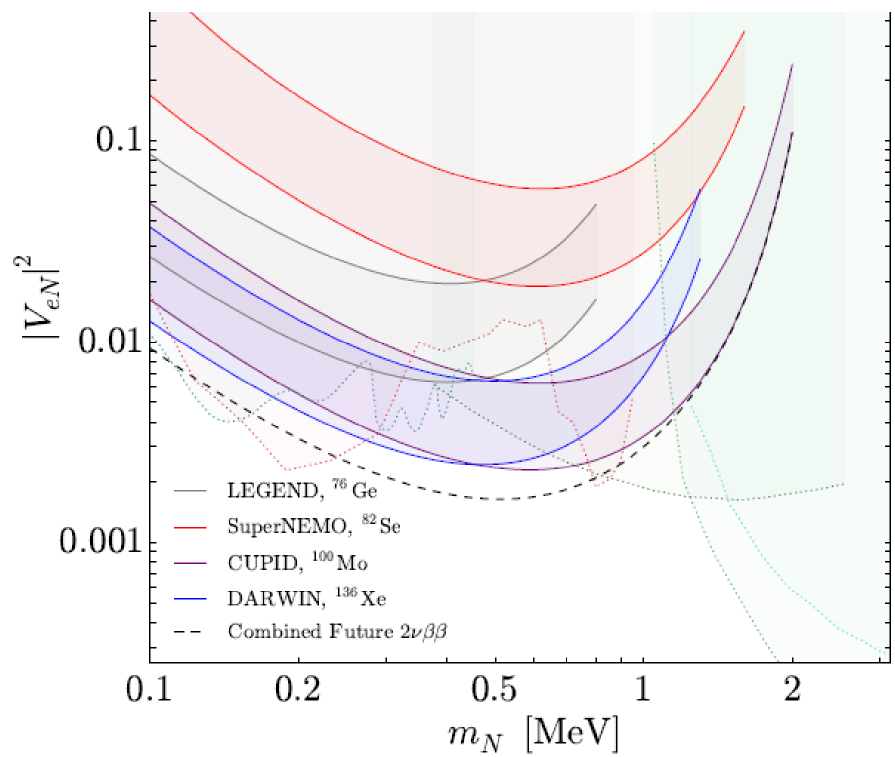
Two-neutrino Double Beta Decay with Sterile Neutrinos

P.D. Bolton, F.F. Depisch, L. Graf, F. Š., arXiv: 2011.13387 [hep-ph]

$$\mathcal{L} = \frac{G_F \cos\theta_C}{\sqrt{2}} \Big[(1+\delta_{\rm SM}) j_L^\mu J_{L\mu} + V_{eN} j_L^{N\mu} J_{L\mu} + \epsilon_{LR} j_R^{N\mu} J_{L\mu} + \epsilon_{RR} j_R^{N\mu} J_{R\mu} \Big] + \text{h.c.}$$



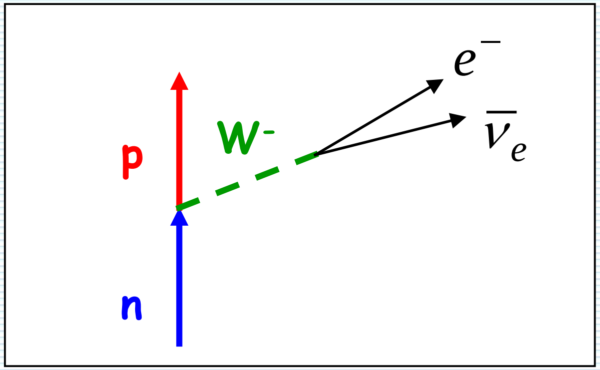




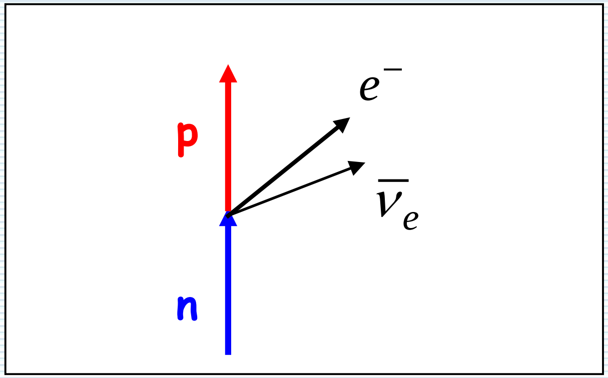
V. *Quenching of g_A ($q = g^{eff}_A / g^{free}_A$)*

Should g_A be quenched in medium?
Missing wave-function correlations
Renormalized operator?
Neglected two-body currents?
Model-space truncations?

Quenching in nuclear matter: $g^{eff}_A = q\, g^{free}_A$



$$\mathcal{L} = -\frac{G_\beta}{\sqrt{2}}\left[\overline{u}\gamma^\alpha(1-\gamma^5)d\right]\left[\overline{e}\gamma^\alpha(1-\gamma^5)\nu_e\right]$$



$$\mathcal{L} = -\frac{G_\beta}{\sqrt{2}}\left[\overline{p}\gamma^\alpha(g_V - g_A\gamma^5)n\right]\left[\overline{e}\gamma^\alpha(1-\gamma^5)\nu_e\right]$$

CVC hypothesis

g_V =1 at the quark level

g_V =1 at the nucleon level

g_V =1 inside nuclei

Quenching of g_A

g_A =1 at the quark level

g^{free}_A =1.27 at the nucleon level

g^{eff}_A = ? inside nuclei

ISM: $(g^{eff}_A)^4 \simeq 0.66$ (^{48}Ca), 0.66 (^{76}Ge), 0.30 (^{76}Se), 0.20 (^{130}Te) and 0.11 (^{136}Xe)

QRPA: $(g^{eff}_A)^4 = 0.30$ and 0.50 for ^{100}Mo and ^{116}Cd

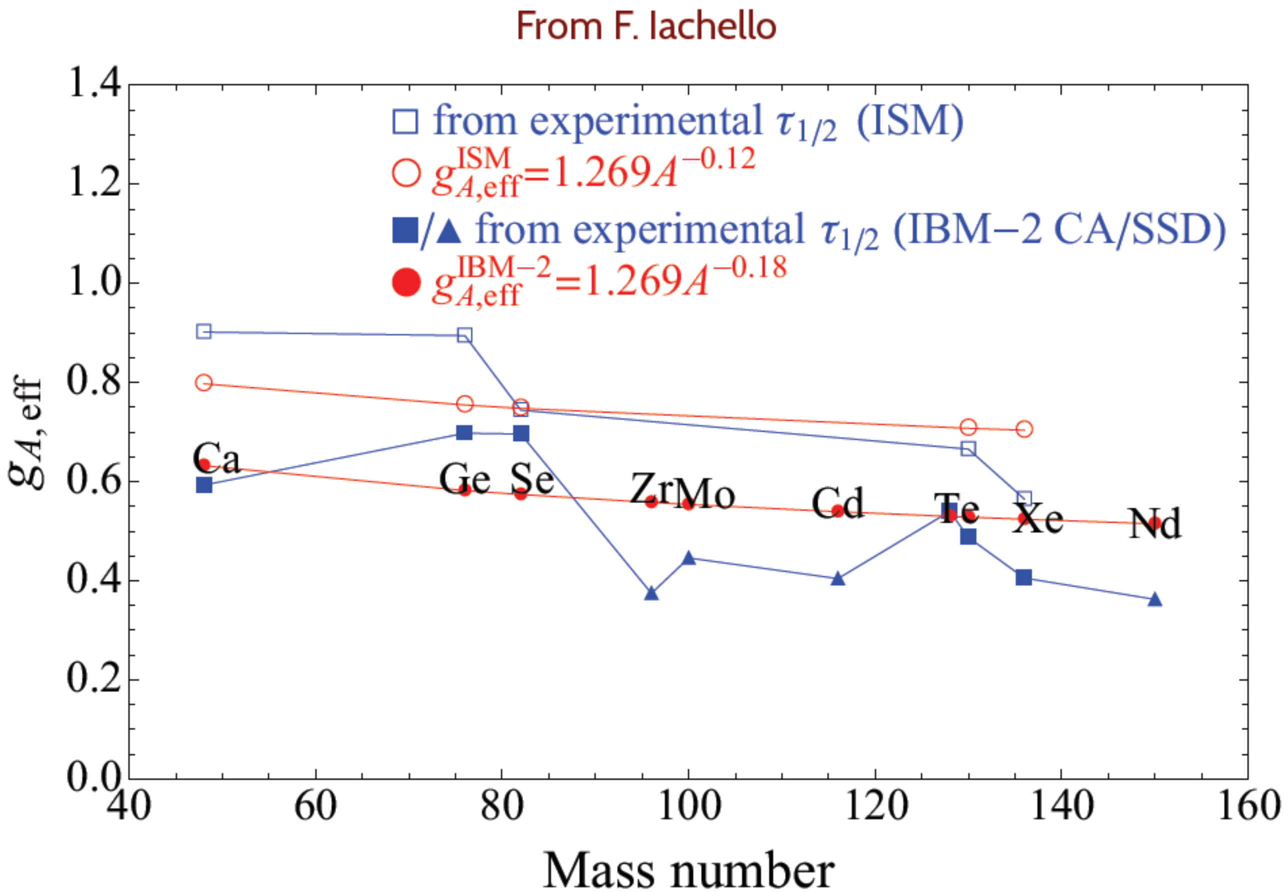
IBM: $(g^{eff}_A)^4 \simeq (1.269\, A^{-0.18})^4 = 0.063$

Faessler, Fogli, Lisi, Rodin, Rotunno, F. Š, J. Phys. G 35, 075104 (2008).

Quenching of g_A -IBM ($T_{1/2}^{0\nu}$ suppressed up to factor 50)

$(g^{eff}_A)^4 \simeq (1.269\ A^{-0.18})^4 = 0.063$ (The Interacting Boson Model). This is an incredible result. The quenching of the axial-vector coupling within the IBM-2 is more like 60%.

It has been determined by theoretical prediction for the 2νββ-decay half-lives, which were based on within closure approximation calculated Corresponding NMEs, with the measured half-lives.



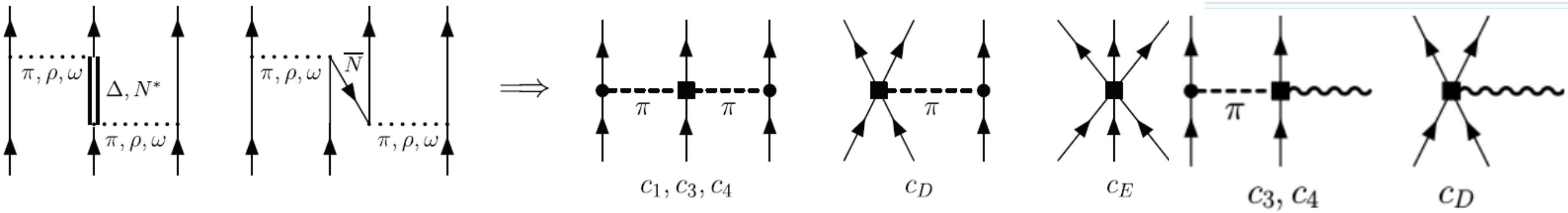
12/4/2020

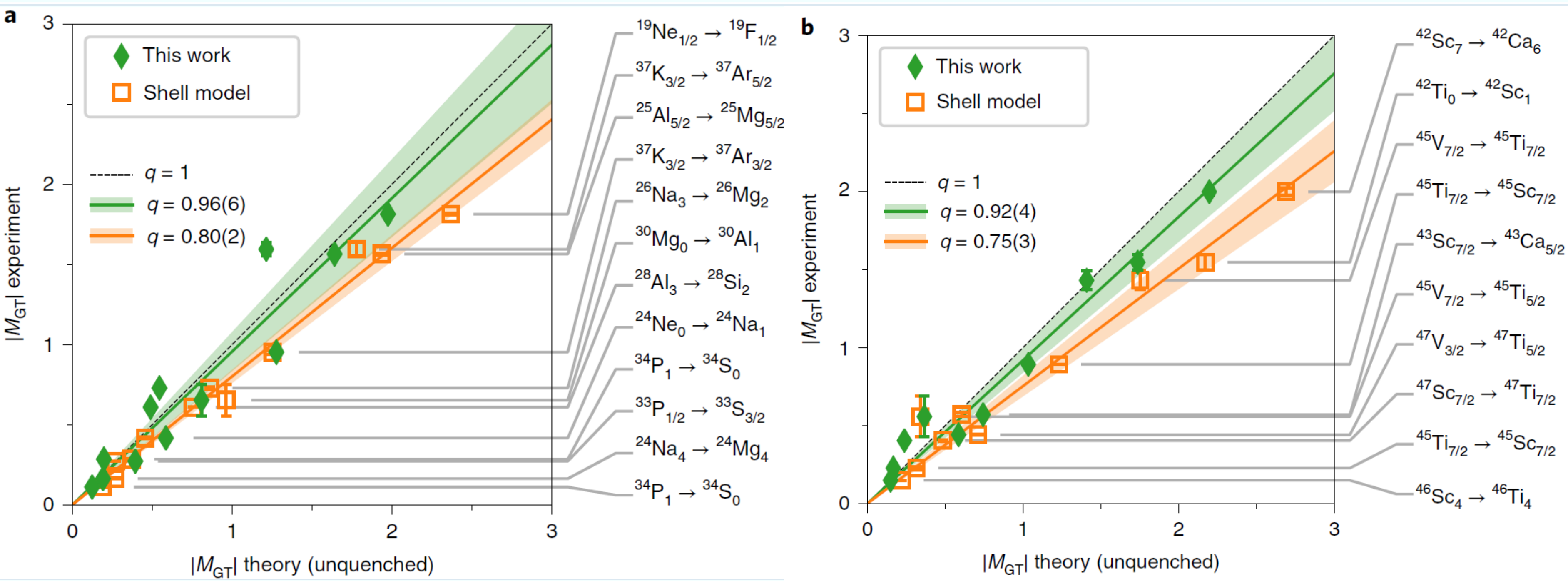
J. Barea, J. Kotila, F. Iachello, PRC 87, 014315 (2013).

LETTERS
https://doi.org/10.1038/s41567-019-0450-7
nature physics

Discrepancy between experimental and theoretical β-decay rates resolved from first principles

Ab initio calculations (light nuclear systems) including meson-exchange currents do not need any "quenching"





Improved description of the 0νββ–decay rate (and novel approach of fixing g_A^{eff})

F. Š, R. Dvornický, D. Štefánik, A. Faessler, PRC 97, 034315 (2018).

Let perform Taylor expansion

$$M_{GT}^{K,L} = m_e \sum_n M_n \frac{E_n - (E_i + E_f)/2}{[E_n - (E_i + E_f)/2]^2 - \varepsilon^2_{K,L}}$$

$$\frac{\varepsilon_{K,L}}{E_n - (E_i + E_f)/2}$$

$$\epsilon_K = (E_{e_2} + E_{\nu_2} - E_{e_1} - E_{\nu_1})/2$$
$$\epsilon_L = (E_{e_1} + E_{\nu_2} - E_{e_2} - E_{\nu_1})/2$$

$$\epsilon_{K,L} \in (-\frac{Q}{2}, \frac{Q}{2})$$

We get

$$\left[T^{2\nu\beta\beta}_{1/2}\right]^{-1} \simeq \left(g_A^{\text{eff}}\right)^4 \left|M^{2\nu}_{GT-3}\right|^2 \frac{1}{\left|\xi^{2\nu}_{13}\right|^2} \left(G^{2\nu}_0 + \xi^{2\nu}_{13} G^{2\nu}_2\right)$$

$$M^{2\nu}_{GT-1} = \sum_n M_n \frac{1}{(E_n - (E_i + E_f)/2}$$

$$M^{2\nu}_{GT-3} = \sum_n M_n \frac{4\, m_e^3}{(E_n - (E_i + E_f)/2)^3}$$

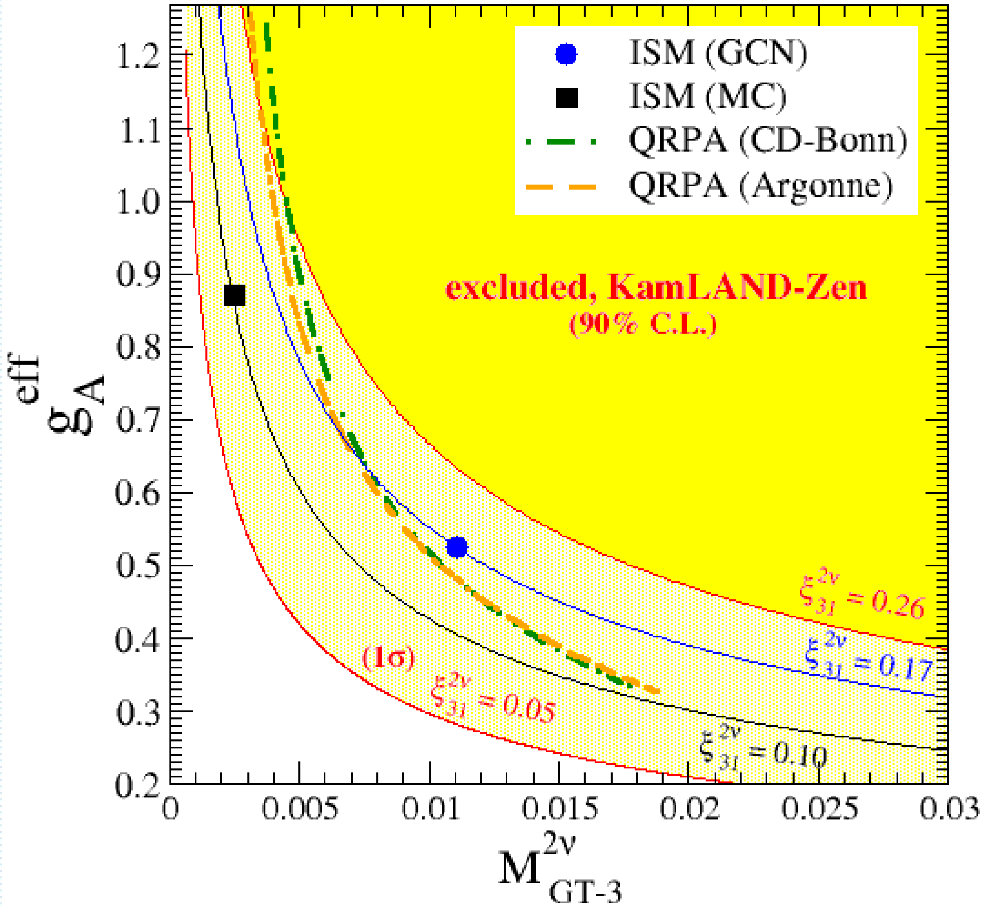
$$\xi^{2\nu}_{13} = \frac{M^{2\nu}_{GT-3}}{M^{2\nu}_{GT-1}}$$

The g_A^{eff} can be deterimed with measured half-life and ratio of NMEs and calculated NME dominated by transitions through low lying states of the intermediate nucleus (ISM)

The g_A^{eff} can be deterimed with measured half-life and ratio of NMEs ξ_{31} and calculated NME dominated by transitions through low lying states of the intermediate nucleus.

M_{GT-3} have to be calculated by nuclear theory - ISM

$$\left(g_A^{\text{eff}}\right)^2 = \frac{1}{\left|M^{2\nu}_{GT-3}\right|}\frac{\left|\xi^{2\nu}_{13}\right|}{\sqrt{T^{2\nu-exp}_{1/2}\left(G^{2\nu}_0 + \xi^{2\nu}_{13} G^{2\nu}_2\right)}}$$



$$M^{2\nu}_{GT-1} = \sum_n M_n \frac{1}{(E_n - (E_i + E_f)/2}$$

$$M^{2\nu}_{GT-3} = \sum_n M_n \frac{4\ m_e^3}{(E_n - (E_i + E_f)/2)^3}$$

$$\xi^{2\nu}_{13} = \frac{M^{2\nu}_{GT-3}}{M^{2\nu}_{GT-1}}$$

KamLAND-Zen Coll. (+J. Menendez, F.Š.), Phys.Rev.Lett. 122, 192501 (2019)

Measurement of GT strength via μ-capture

$\mu^-_b + (A,Z) \rightarrow (A,Z-1) + \nu_\mu$

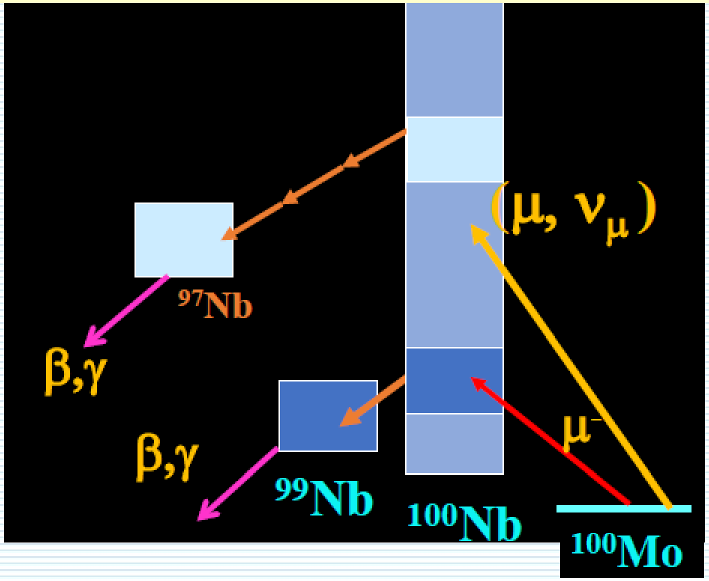
Contradicting results:

- **Strong quenching**

Jokiniemi, Suhonen, PRC 100, 014619 (2019)

- **Weak quenching**

Zinner, Langanke, Vogel PRC 74, 024326 (2006)
Marketin, Paar, Niksic, Vretenar PRC 79, 054323 (2009)

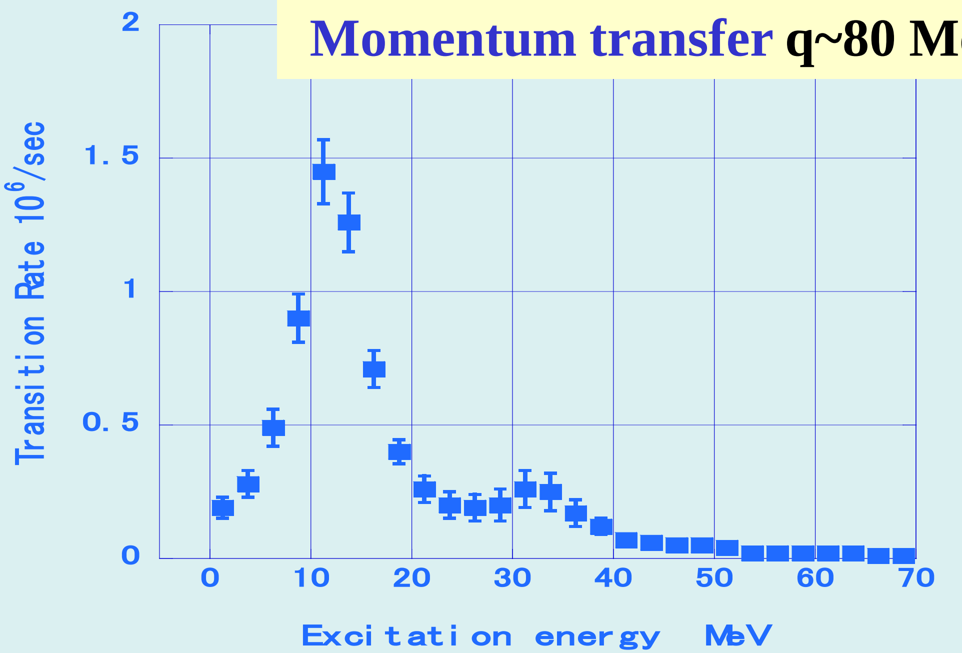


⇒ Small basis nuclear structure calculations (NSM, IBM) are disfavored. ⇒

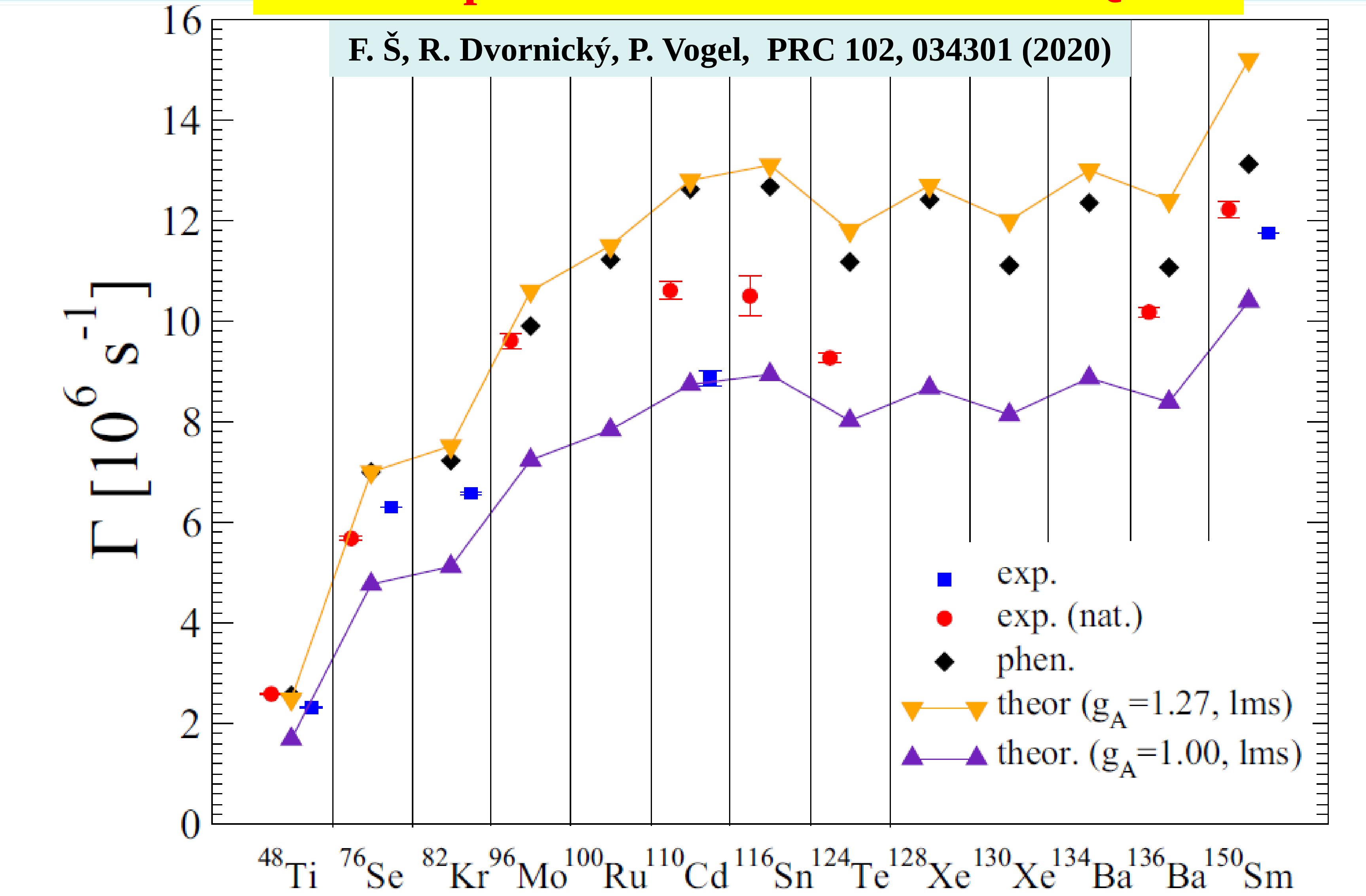
J-PARC 3-50 GeV p, ν, μ

I. Hashim H. Ejiri , MXG16, PR C 97 2018

Momentum transfer q~80 MeV



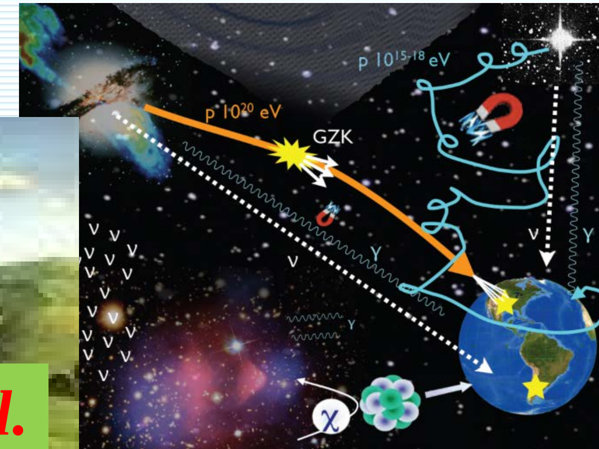
Muon capture rates evaluated within QRPA



In agreement with soft quenching **Zinner, Langanke, Vogel PRC 74, 024326 (2006); Marketin, Paar, Niksic, Vretenar PRC 79, 054323 (2009)**

Contradicting results: strong quenching **Jokiniemi, Suhonen, PRC 100, 014619 (2019)**

Thank You!



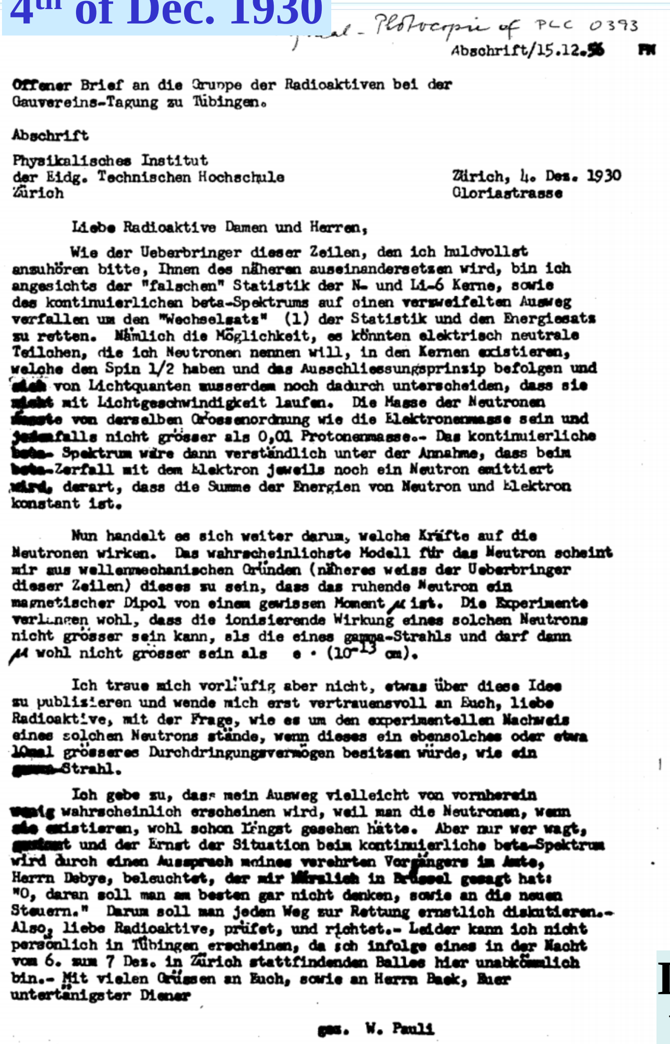
ν's, the Standard Model misfits

We are at the beginning of the Beyond Standard Model Road…

people often overestimate what will happen in the next two years and underestimate what will happen in ten (Bill Gates)

ν_e ν_μ ν_τ

4th of Dec. 1930



Original-Photocopie of PLC 0393
Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

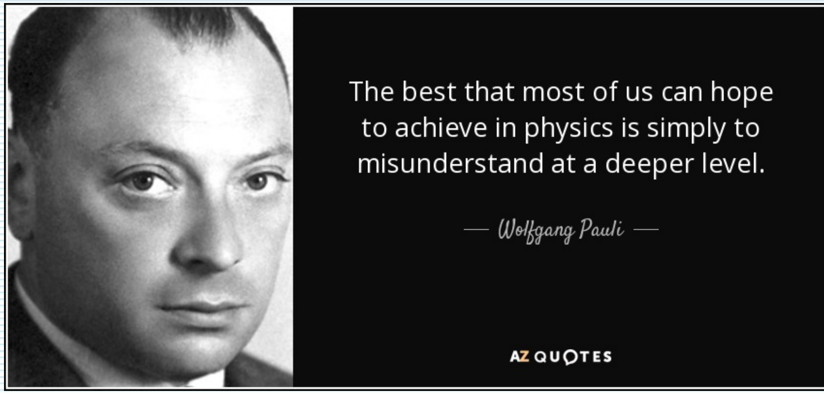
Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

90 years of ν-physics!



I have done a terrible thing. I invented a particle that cannot be detected. Wolfgang Pauli