Neutrino Physics and Dark Matter at IEAP CTU

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IEAP CTU was found in 2002 as a scientific and educational institute of the CTU in Prague, focusing on a research in the field of particle and subatomic physics performed in an international experiments (at present, 98 people)

1) Neutrino physics (ββ experiments SuperNEMO, TGV, excited states, LEGEND)

2) Dark matter (experiment PICO)

3) Ultra-low background techniques

Research activities of IEAP CTU:

(1) LHC at CERN – experiments ATLAS, MoEDAL (magnetic monopole)
(2) Neutrino physics – ββ decay of ^{106}Cd, ^{82}Se, ^{76}Ge (TGV, SuperNEMO, LEGEND), detection of atmospheric neutrinos (Baikal-GVD)
(3) Dark matter (neutralino) – experiment PICO in SNOLAB (Canada)
(4) Detection of cosmic rays – Timepix detectors on ISS, satellites Proba-V, RISESAT
(5) Structure of atomic nuclei and nuclear reactions
(6) Applications – pixel and strip detectors, imaging (X-rays and neutrons), biomedicine, study of material…..

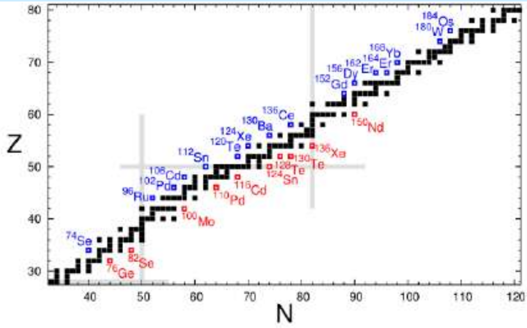
Nuclear double-β decay (even-even nuclei, pairing int.)

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



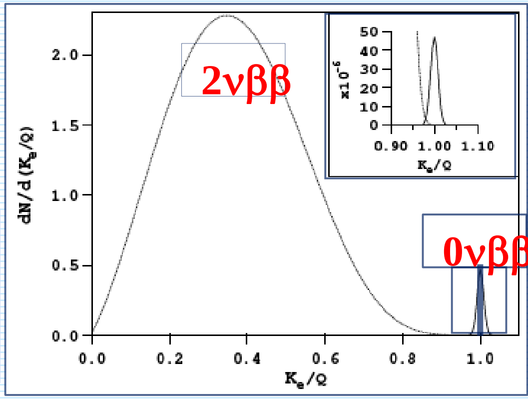
Nuovo Cim. 14, 322 (1937)

Phys. Rev. 56, 1184 (1939)

Neutrinoless double-β decay – LN violated

$(A,Z) \rightarrow (A,Z+2) + e^- + e^-$ **(Furry 1937)**

Not observed yet. Requires massive Majorana ν's



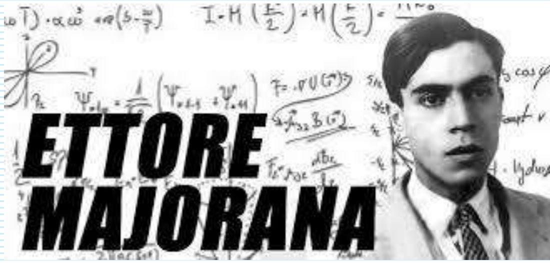
The observation of neutrino oscillations has opened a new excited era in neutrino physics and represents a big step forward in our knowledge of neutrino properties

After 90/64 years we know

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

No answer yet

- **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?**



Currently main issue

Nature, Mass hierarchy,

CP-properties, sterile ν

Two neutrino double beta decay (2νββ):

Direct measurement of NME values ⇒ nuclear theory

Very important to measure ββ decay for many nuclei, for different processes ($2\beta^-$, $2\beta^+$, EC/EC, excited states….)

2νββ process has been detected for 11 isotopes

Nucleus	Average value of $T_{1/2}$ [y]
^{48}Ca	$(5.3^{+1.2}_{-0.8}) \times 10^{19}$
^{76}Ge	$(1.88 \pm 0.08) \times 10^{21}$
^{82}Se	$0.87^{+0.02}_{-0.01} \times 10^{20}$
^{96}Zr	$(2.3 \pm 0.2) \times 10^{19}$
^{100}Mo	$7.06^{+0.15}_{-0.13} \times 10^{18}$
^{116}Cd	$(2.69 \pm 0.09) \times 10^{19}$
^{128}Te	$(2.25 \pm 0.09) \times 10^{24}$
^{130}Te	$(7.91 \pm 0{,}21) \times 10^{20}$
^{136}Xe	$(2.18 \pm 0{,}05) \times 10^{21}$
^{150}Nd	$(9.34 \pm 0{,}65) \times 10^{18}$
^{238}U	$(2.0 \pm 0.6) \times 10^{21}$ (radiochem.)
^{130}Ba (2νEC/EC)	$(2.2 \pm 0.5) \times 10^{21}$ (geochem.)

Nucleus	Average value of $T_{1/2}$ [y]
^{100}Mo–^{100}Ru (0^+_1)	$(6.7^{+0.5}_{-0.4}) \times 10^{20}$
^{150}Nd–^{150}Sm (0^+_1)	$(1.2^{+0.3}_{-0.2}) \times 10^{20}$
^{78}Kr 2K(2ν)	$(1.9^{+1.3}_{-0.8}) \times 10^{22}$
^{124}Xe 2K(2ν)	$(1.8 \pm 0.5) \times 10^{22}$

A.S. Barabash, **Precise Half-Life Values for Two-Neutrino Double-β Decay: 2020 review**. arXiv: 2009.14451v1

Experimental sensitivity and traditional picture of 0νββ

$$T_{1/2} = \frac{\varepsilon}{W} F_a \sqrt{\frac{M.t}{B.\Delta E}}$$

ε = detection efficiency
W = atomic mass
F_a = isotopical abundance
M = source mass
t = exposure time
B = background
ΔE = energy resolution

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

Candidates with $Q_{2\beta} > 2$ MeV
(natural γ rays < 2,615 MeV)
6 gold, 5 silver isotopes

Nuclei	$Q_{2\beta}$, keV	Abundance, %
1. ^{48}Ca	4272	0.187
2. ^{150}Nd	3371.4	5.6
3. ^{96}Zr	3350	2.8
4. ^{100}Mo	3034.4	9.63
5. ^{82}Se	2996	8.73
6. ^{116}Cd	2805	7.49
7. ^{130}Te	2527.5	34.08
8. ^{136}Xe	2458.7	8.87
9. ^{124}Sn	2287	5.79
10. ^{76}Ge	2039.0	7.61
11. ^{110}Pd	2000	11.72

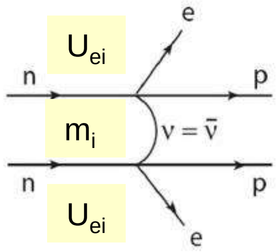
Phase factor well understood

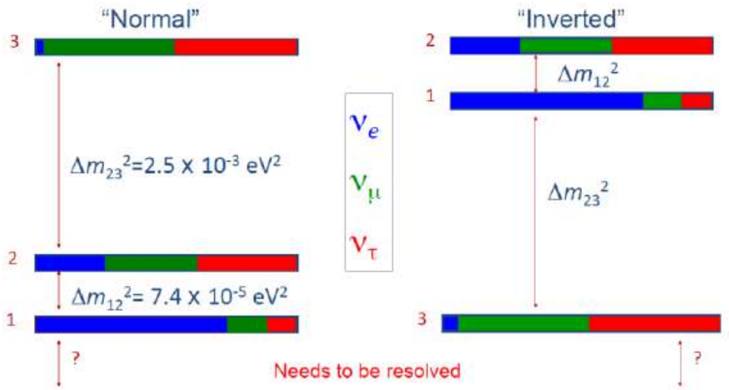
$$\left(T^{0\nu}_{1/2}\right)^{-1} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 g_A^4 \left|M^{0\nu}_{\nu}\right|^2 G^{0\nu}$$

?

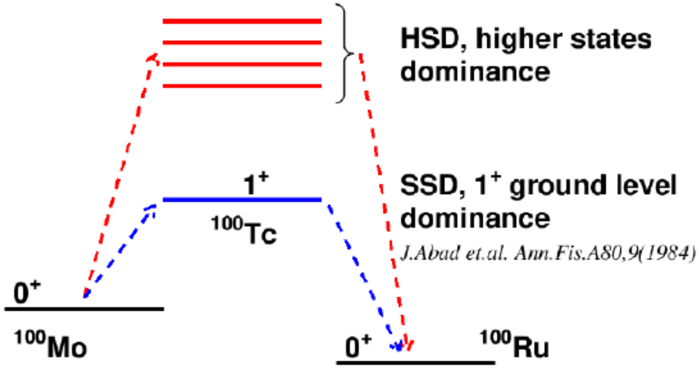
NME must be evaluated using tools of nuclear theory

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



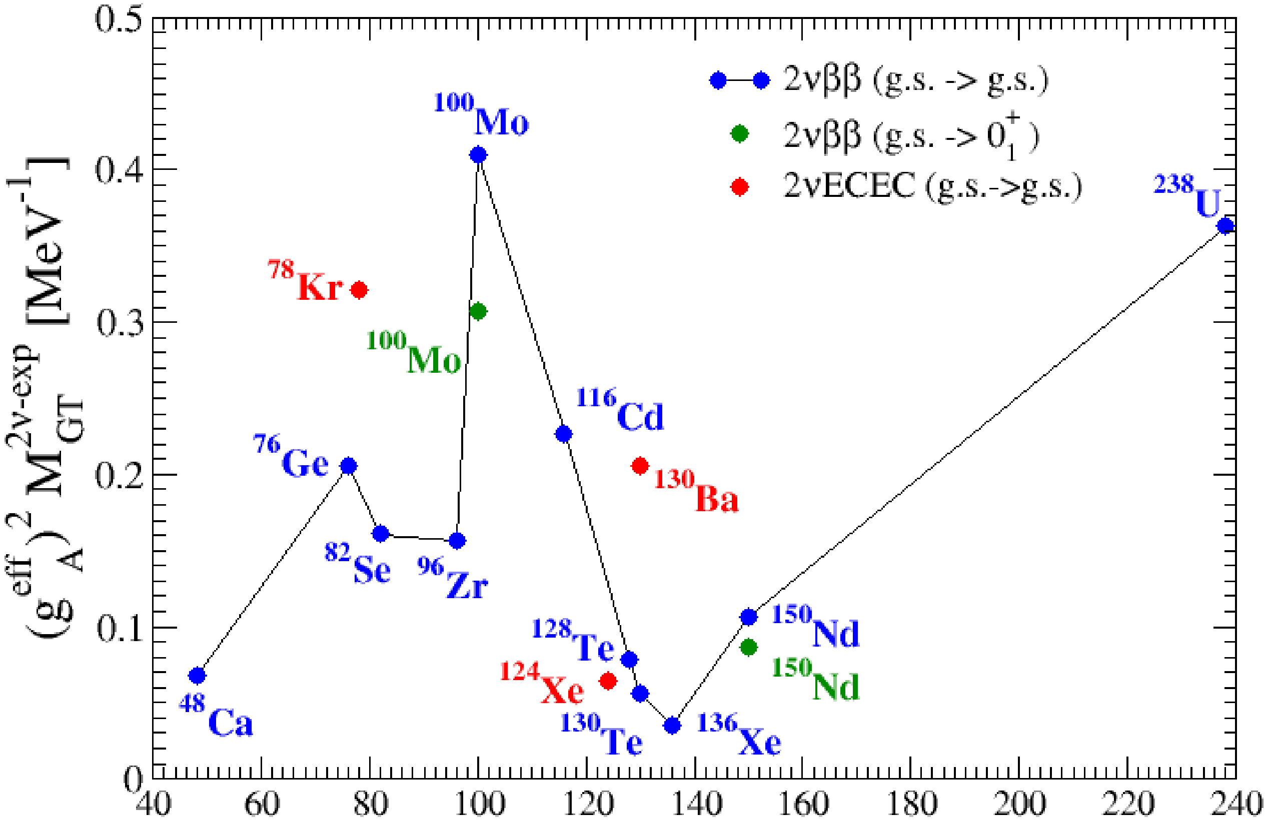


Understanding of the 2νββ-decay NMEs is of crucial importance for correct evaluation of the 0νββ-decay NMEs



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

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

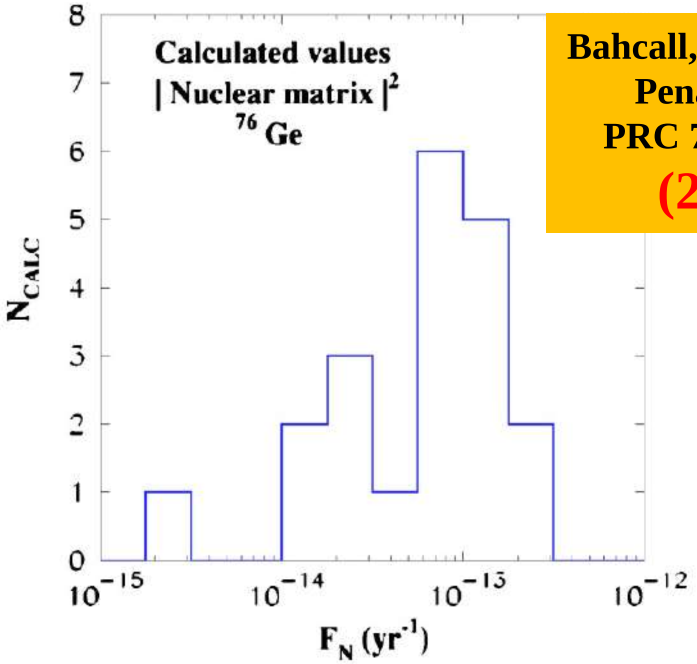


Both 2νββ and 0νββ operators connect the same states. Both change two neutrons into two protons. Explaining 2νββ-decay is necessary but not sufficient

0νββ decay NMEs

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

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): Calculations by different approaches – No Core Shell Model, Green's Function Monte Carlo, Coupled Cluster Method, Lattice QCD

Conference MEDEX (NME calculations) – every two years organized on CTU (J. Suhonen, O. Civitarese, I. Štekl, R. Hodák)

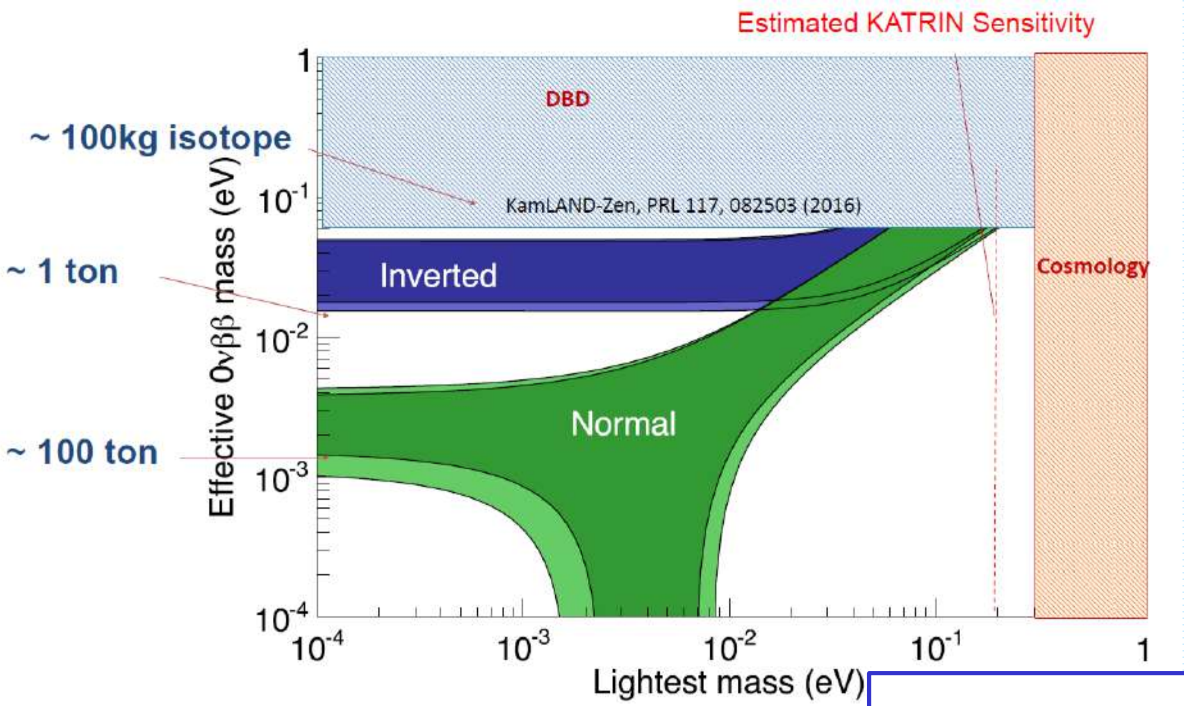
Nuclear Shell Model **(Madrid-Strasbourg, Michigan, Tokyo): Relatively small model space (1 shell), all correlations included, solved by direct diagonalization**

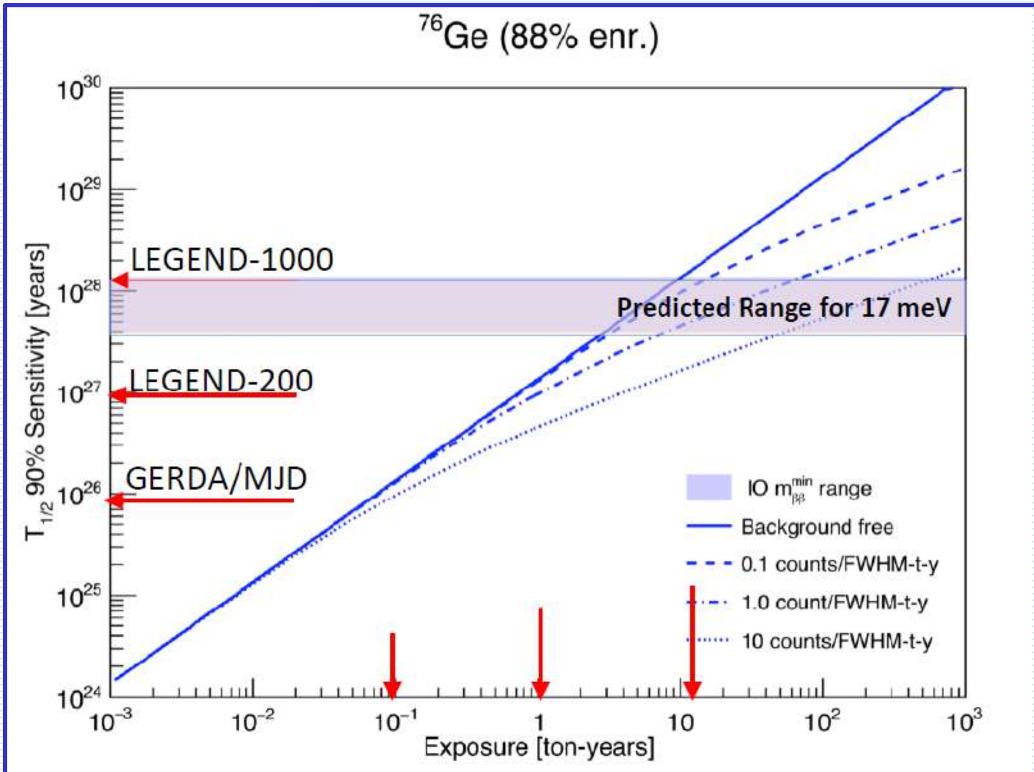
QRPA **(Tuebingen-Bratislava-Caltech, Jyvaskyla, Chapel Hill, Lanzhou, Prague): Several shells, only simple correlations included**

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**

Collaboration	Isotope	Technique	mass (0νββ 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





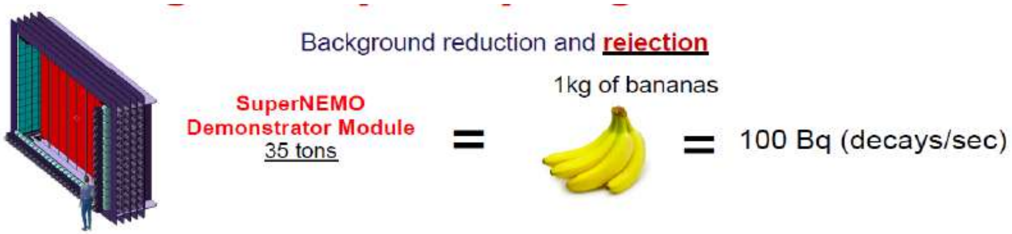
$>10^{28}$ yr or **$m_{\beta\beta}$=17 meV** for worst case NME and quenching of **g_A**

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

IEAP CTU in ββ experiments:

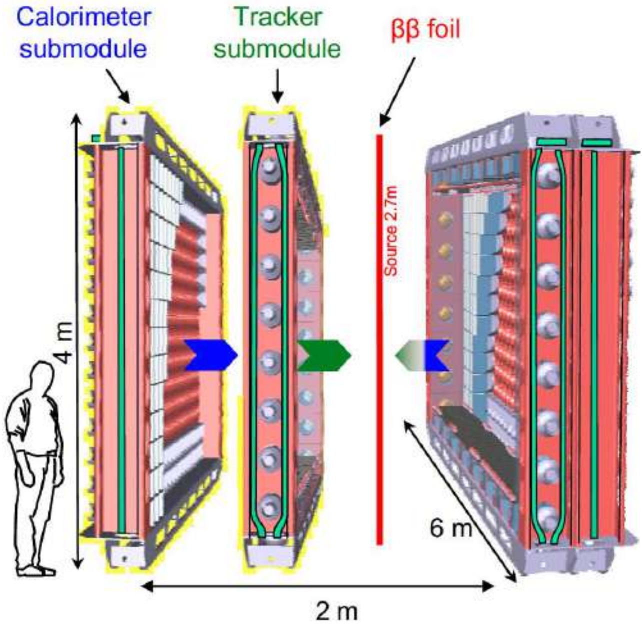
1) **NEMO3:** 10 kg of ββ isotopes, tracko-calo technique, headed by French institutions, in LSM
2) **SuperNEMO:** demonstrator (6,2 kg of ^{82}Se), expected start of running - mid 2022, in LSM
3) **TGV** : 2νEC/EC decay of ^{106}Cd (JINR/LSM/IEAP), in LSM
4) **LEGEND**: 0νββ of ^{76}Ge (broad international cooperation, USA, Germany…..)
5) **Excited states of ββ decay**: ultra-low background HPGe detectors, in LSM

Isotope	Half-life (10^{19} years)	S/B	Reference
^{82}Se	9.39 ± 0.08	4	Eur. Phys. J. C78, 821 (2018)
^{116}Cd	2.74 ± 0.18	12	Phys. Rev. D 95, 012007
^{150}Nd	0.93 ± 0.06	4	Phys. Rev. D 94, 072003
^{96}Zr	2.35 ± 0.21	1	Nucl.Phys.A 847(2010) 168
^{48}Ca	6.4 ± 1.2	3.9	Phys. Rev. D 93, 112008
^{100}Mo	0.68 ± 0.4	80	Eur.Phys. J. C79,440 (2019)
^{130}Te	70 ± 14	1/3	Phys. Rev. Lett. 107, 062504



Measurement of tracks and energies of both electrons (distinquishing of mass mechanism)

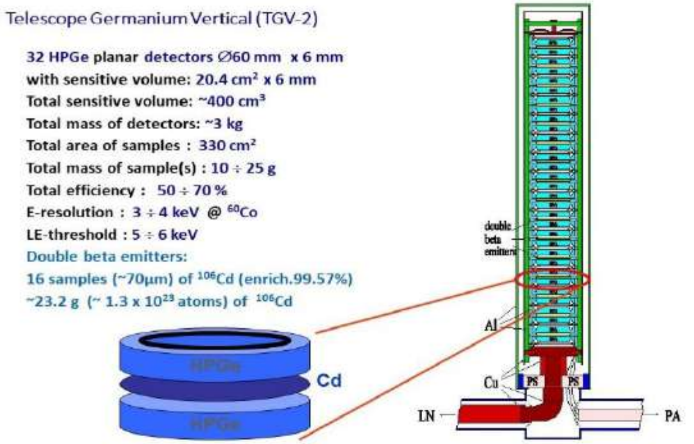
SuperNEMO
^{82}Se
100 - 200 kg
> 30 %
^{208}Tl ~ 2 μBq/kg ^{214}Bi < 10 μBq/kg Rn ≤ 0.2 mBq/kg
~ 8 % @ 1 MeV
$T_{1/2}(0\nu\beta\beta) > 1 \times 10^{26}$ y $\langle m_\nu \rangle < (0.04 - 0.11)$ eV



Experiment TGV – search for double beta decay of ^{106}Cd

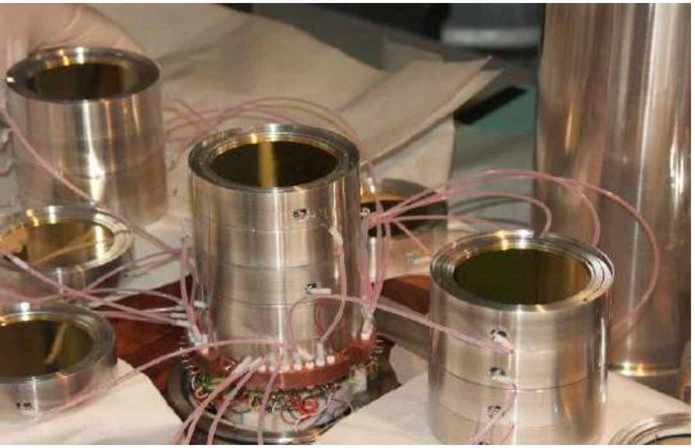
JINR Dubna, IEAP CTU, CU Bratislava, LSM

Phase III: ~ 23.2 g of ^{106}Cd (99.57%)
(~ 1.3 x 10^{23} atoms of ^{106}Cd)
(Feb.2014 – …..) in progress, T >40000 h



Telescope Germanium Vertical (TGV-2)

32 HPGe planar detectors ∅60 mm x 6 mm
with sensitive volume: 20.4 cm² x 6 mm
Total sensitive volume: ~400 cm³
Total mass of detectors: ~3 kg
Total area of samples : 330 cm²
Total mass of sample(s) : 10 ÷ 25 g
Total efficiency : 50 ÷ 70 %
E-resolution : 3 ÷ 4 keV @ ^{60}Co
LE-threshold : 5 ÷ 6 keV
Double beta emitters:
16 samples (~70μm) of ^{106}Cd (enrich.99.57%)
~23.2 g (~ 1.3 x 10^{23} atoms) of ^{106}Cd



EC/EC $2e_b^- + {}^{106}Cd \rightarrow {}^{106}Pd + (2\nu_e) + (\gamma)$

Observables: 2KXPd (+ γ for e.s.)

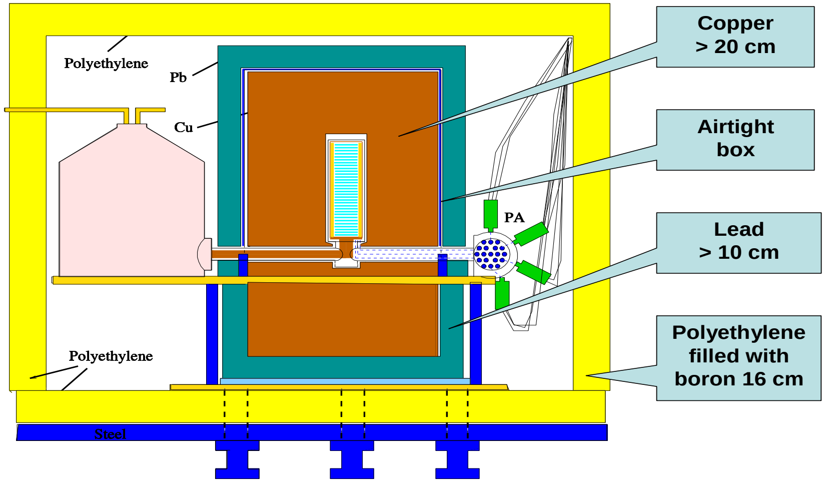
β⁺/EC $e_b^- + {}^{106}Cd \rightarrow {}^{106}Pd + e^+ + (2\nu_e) + (\gamma)$

Observables: KXPd + 2γ 511 (+ γ for e.s.)

β⁺β⁺ ${}^{106}Cd \rightarrow {}^{106}Pd + e^+ + e^+ + (2\nu_e) + (\gamma)$

Observables: 4γ 511 (+ γ for e.s.)

PASSIVE SHIELDING

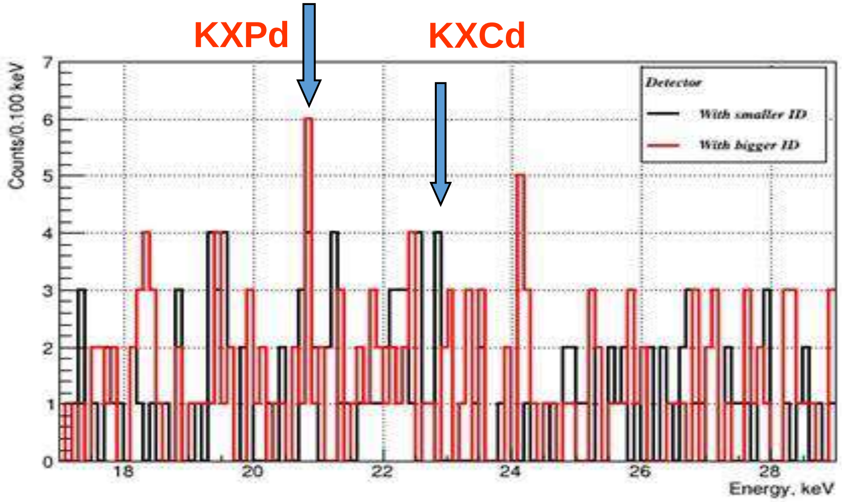


Copper > 20 cm

Airtight box

Lead > 10 cm

Polyethylene filled with boron 16 cm



Theoretical $T_{1/2}$ (2ν*EC/EC*) ~ 10^{20} – 10^{22} years

<u>Preliminary result for 2νEC/EC, 0^+g.s. (Phase III):</u>

$5.3\times10^{20} < T_{1/2} < 3.5\times10^{21}$ years

Detector “Obelix” (JINR/IEAP CTU/LSM) – excited states of 2νββ

P type coaxial HPGe detector (U-type ultra low background cryostat located at LSM (4800 m w.e.)

Sensitive volume 600 cm^3 Efficiency 162%

Energy resolution ~1.2 keV at 122 keV (^{57}Co), ~2 keV at 1332 keV (^{60}Co)

12 cm of arch. Pb, 20 cm of low active Pb, Radon free air

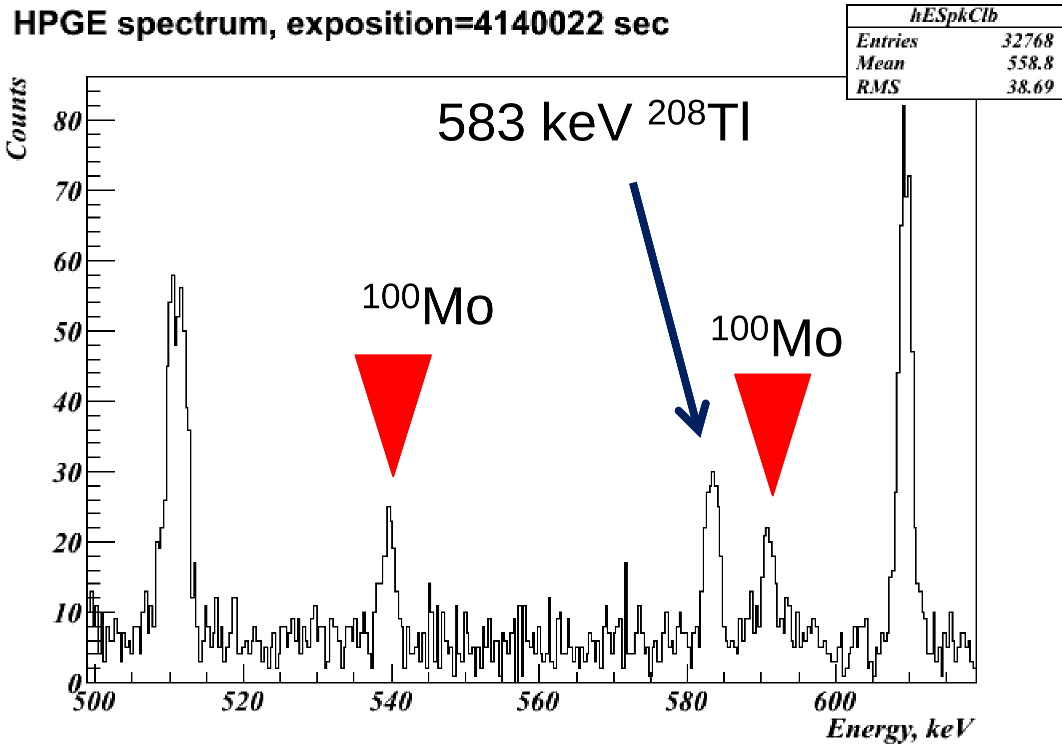
2νββ $^{100}Mo \rightarrow 0^+$, 1130 keV ^{100}Ru

590.8+539.5 keV*

Process	$T_{1/2}$ [years]
$2\nu2\beta^-$ decay to 0^+_1 [1130 keV]	7.5×10^{20}
$2\nu2\beta^-$ decay to 2^+_1 [540 keV]	$> 2.5 \times 10^{21}$

Mass of ^{100}Mo – 2517,15 g

Measurement time – 2288 h



Experiment LEGEND (47 institutions, ~ 240 scientists)

- next generation of ^{76}Ge-based double-beta decay experiment
- LEGEND-200 (200 kg of ^{76}Ge, (LNGS): discovery potential $T_{1/2}$ ~10^{27} years
- LEGEND-1000 (one-tonne of enriched germanium): discovery potential $T_{1/2}$ beyond 10^{28} years.

HPGe detectors (p-type, inverted-coaxial point contact, 80 detectors, 1.5-2kg) deployed in an active liquid argon shield at a deep underground location.

Why germanium detectors? High detection efficiency (source = detector); isotope enrichment from 7.7% to > 92%; excellent energy resolution at $Q_{\beta\beta}$-value (0.1% at 2039 keV, suppress 2νββcontinuum); high density material (ββ event point-like, backgrounds can be discriminated), stable long-term operation with minimal maintenance

LEGEND-200

- Existing GERDA infrastructure at LNGS
- Upgrade to 200 kg of germanium
- Background goal (reduction by factor >2 relative to GERDA/MAJORANA:

$< 2 \times 10^{-4}$cts/ (keV · kg ·yr)

< 0.6 cts/ (FWHM·t ·yr)

- Sensitivity goal:

$\boldsymbol{T_{1/2}0\nu > 10^{27}}$**yr**

- Start data taking in 2021

LEGEND-1000

- 1000 kg of germanium (staged)
- Background goal:

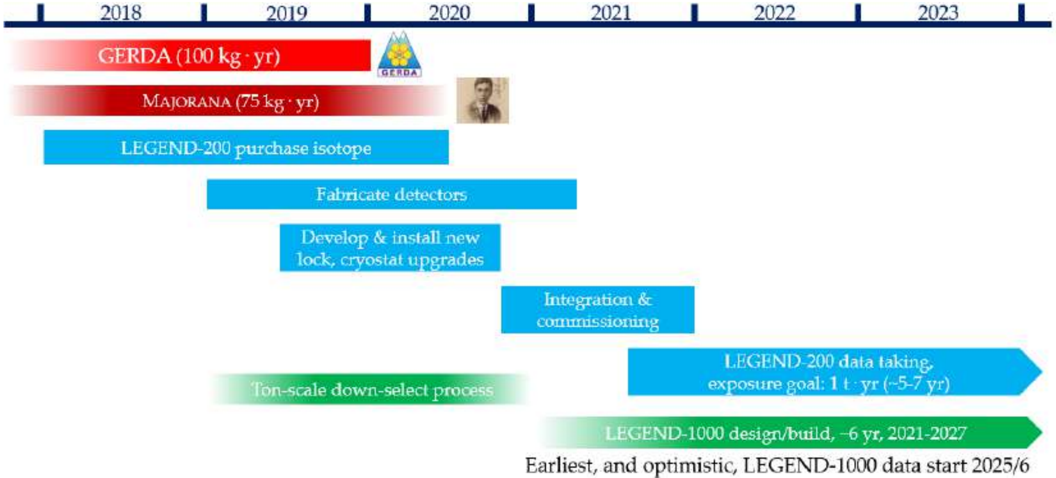
$<1 \times 10^{-5}$cts/ (keV · kg · yr)

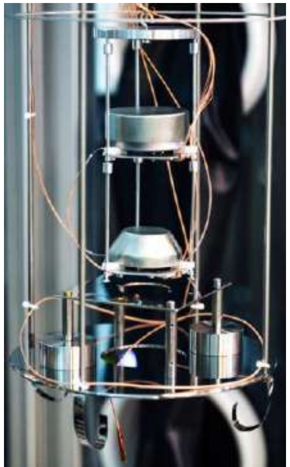
< 0.03 cts/ (FWHM·t·yr)

- Sensitivity goal:

$\boldsymbol{T_{1/2}0\nu > 10^{28}}$**yr**

- Location to be selected





PICO

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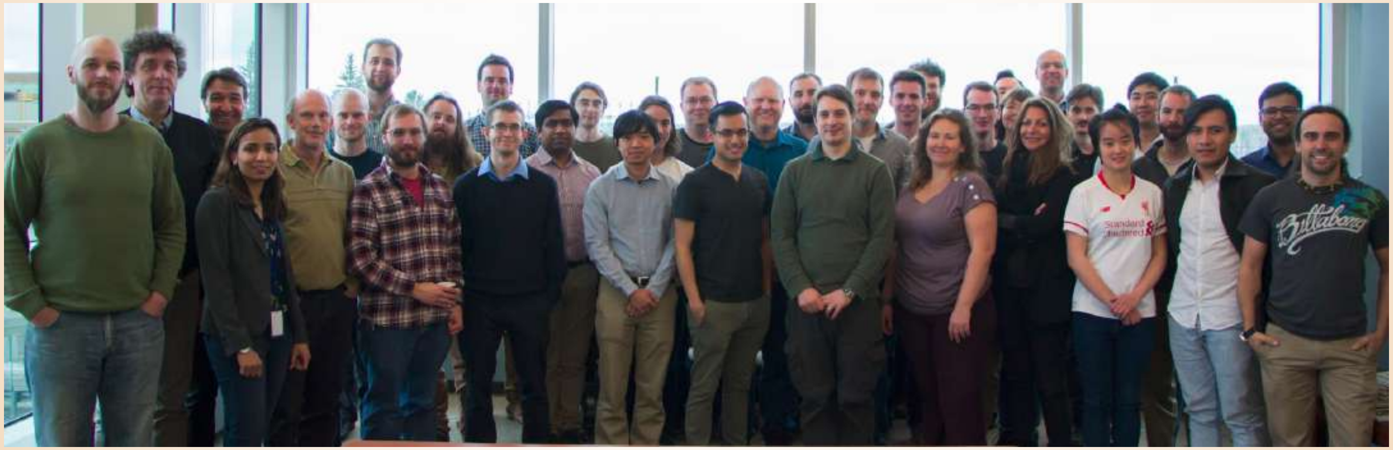

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What is Dark Matter (question from 1930 by astronomers, galaxies need invisible gravitational glue)?

Does not interact strongly (no classic atoms) or electromagnetically (dark), only weak and gravitational interaction
Different candidates: WIMP (proposed 1985, mass 1-1000 GeV), Axion (proposed 1977, tiny mass), Sterile neutrino (proposed late 1970s, mass ~ 1 GeV), SIMP (proposed 2014, mass 0,1 GeV) …….
In Supersymmetry WIMP = neutralino (majorana, massive, stable)

Detection: Indirect – neutrinos & gammas from WIMP annihilation
Direct – scattering of WIMPs off atomic nuclei within a detector

Different technologies:

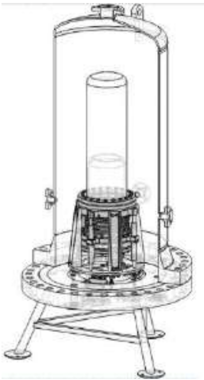
a) Cryogenic – T<100mK, detect heat produced when WIMP hits atom in crystal absorber (Ge)
b) Scintillation – detect scintillation light produced by WIMP collision in liquid noble gases (Xe, Ar)
c) Bubble detectors – detect phase transition in superheated liquids,

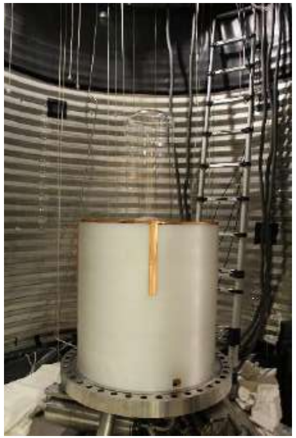
Different experiments: XENON1T, SuperCMDS, ADMX, PICO…..

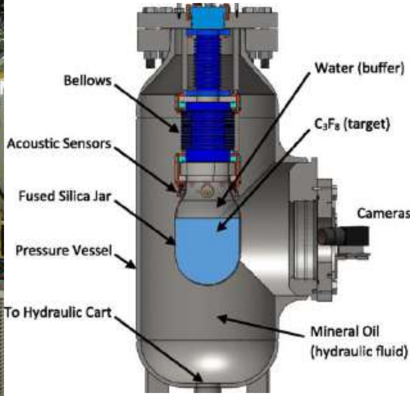
PICO: located at SNOLAB, series of experiment PICO 2L, PICO-60 (room temperature, cheap detection medium)
PICO 40L (technology demonstrator for PICO 500)

Advantages: insensitive to electron and gammas
easily scalable to large sizes at reasonable cost
excellent spin dependent sensitivity

Drawbacks: threshold detectors (lack of direct energy measurement)
sensitive to alpha radiation



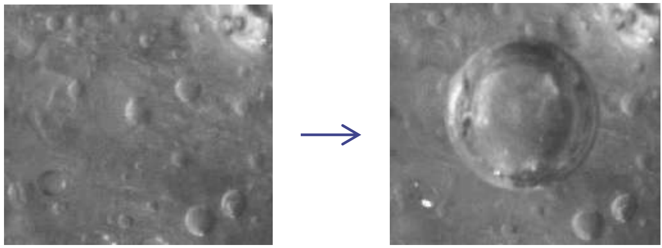


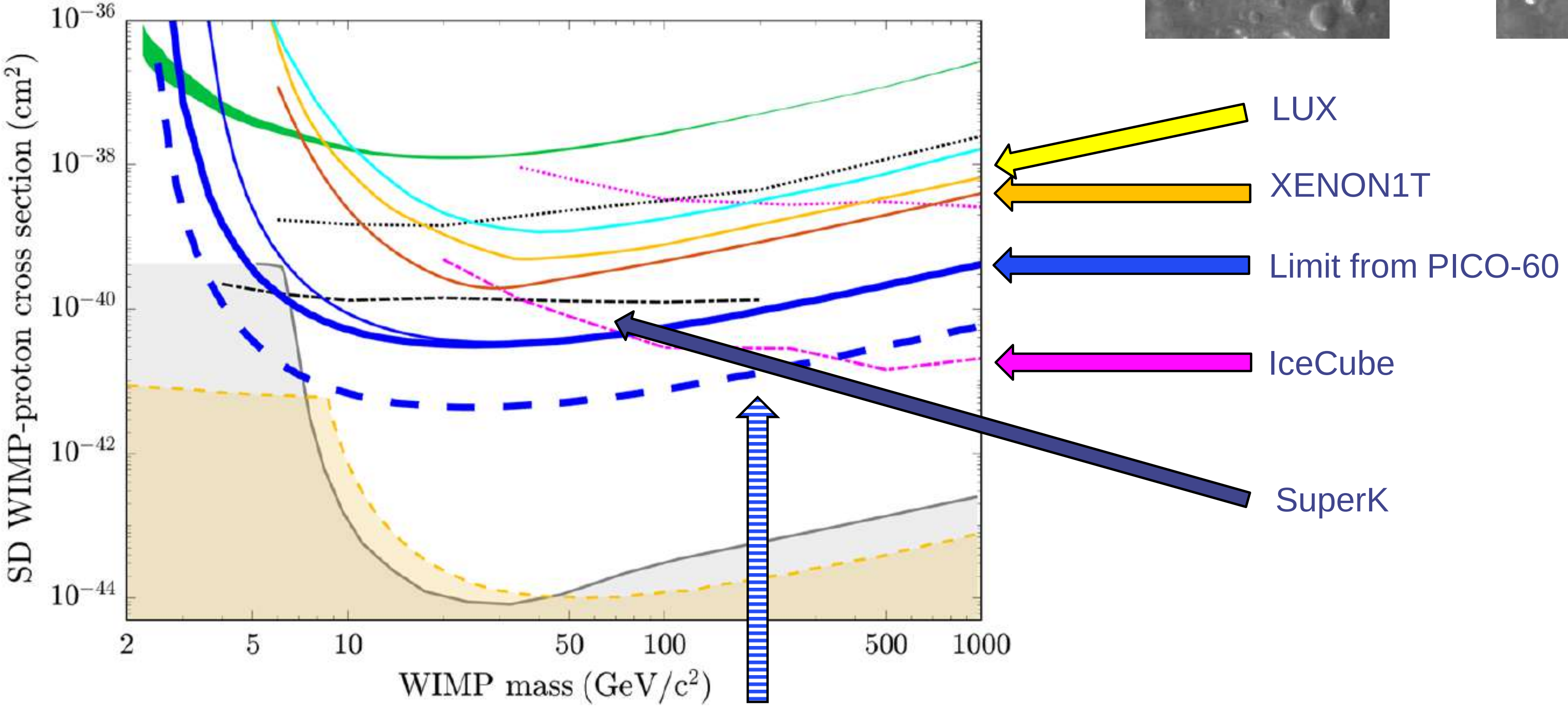


PICO

Operational Principle

- Superheated liquid detector based on bubble chamber (C_3F_8)
- If sufficient energy is deposited within minimal radius directly or via nuclear recoil:
- Phase transition occurs and a bubble is formed
- The explosion is measured acoustically or by camera
- Threshold detector, dependent on temperature





LUX

XENON1T

Limit from PICO-60

IceCube

SuperK

Projected 90% C.L. spin-dependent WIMP-proton exclusion for PICO-40L (2 expected backgr. events, 2.8 keV threshold with 1.64 x 10^4 kg.days exposure).

Limits: background from elastic solar neutrino-nucleus scattering

Selected low background technologies for detection of rare events

How to remove radon from air?

Radon trapping on charcoal => Radon decays during trapping :

reduction factor 100 => „retention time“ T = 606 hours (~ 25 days)

$$T\ (\text{hours}) = K\ (\text{m}^3/\text{kg}) * m\ (\text{kg}) / f\ (\text{m}^3/\text{hour})$$

T – retention time of Radon in charcoal
K – depends on charcoal type, temperature, pressure ....
m – mass of charcoal
f – flux of gas

Dependence of K on temperature (Jose Busto, CPPM):

t (°C)	20	0	-30	-40	-50	-60
K(m^3/kg)	4	12	53	78	152	272

Various charcoals	Sanders	SC44	Silcarbon C46	Silcarbon K48	Silcarbon K847
K [m^3/kg] at -40 °C	65	46	95	141	66

Free-Radon Air factory

A(^{222}Rn) in LSM ~ 10-15 Bq/m^3

Antiradon setup: starts running Oct. 2004

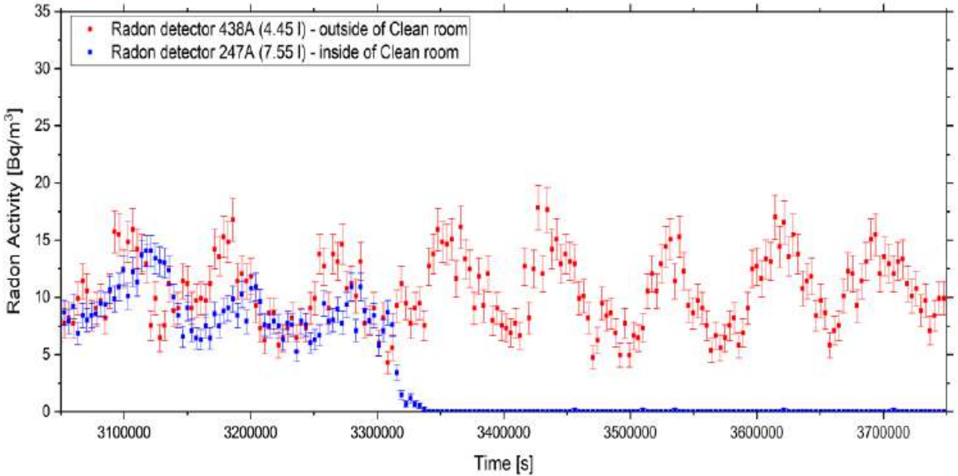
500 kg charcoal @ -50°C, 10 bars

Activity: A(^{222}Rn) < 10 mBq/m^3 !!!
Flux: 130 m^3/h (produced by ATEKO company, Czech Republic)
LNGS, Korea, Jin Ping, USA

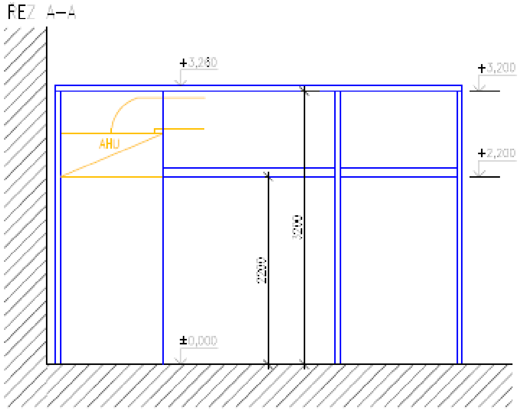
Air flow 20 - 300 m^3/h
Input radon concentration 20 - 100 Bq/m^3
Reduction of radon concentration 100 - 1000
Output air humidity -70°C

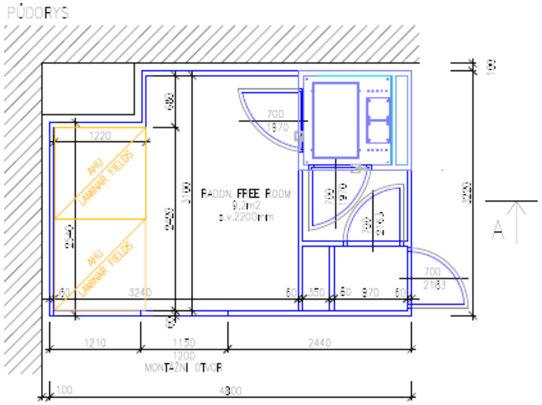
Low Rn clean room in LSM (ISO 5, zero-dose environment for biology):

- Clean room with highly suppressed radon was installed in LSM
- Suppression of all types of radioactivity (including Radon) for biological studies



Radon activities in LSM (red dots) and inside clean room with the source of radon-free air from anti-radon facility (blue dots). Average radon activity in LSM is around 12-13 Bq/m^3, while in low Rn clean room it is suppressed below the detection limit of used Rn detector (less than 20 mBq/m^3).





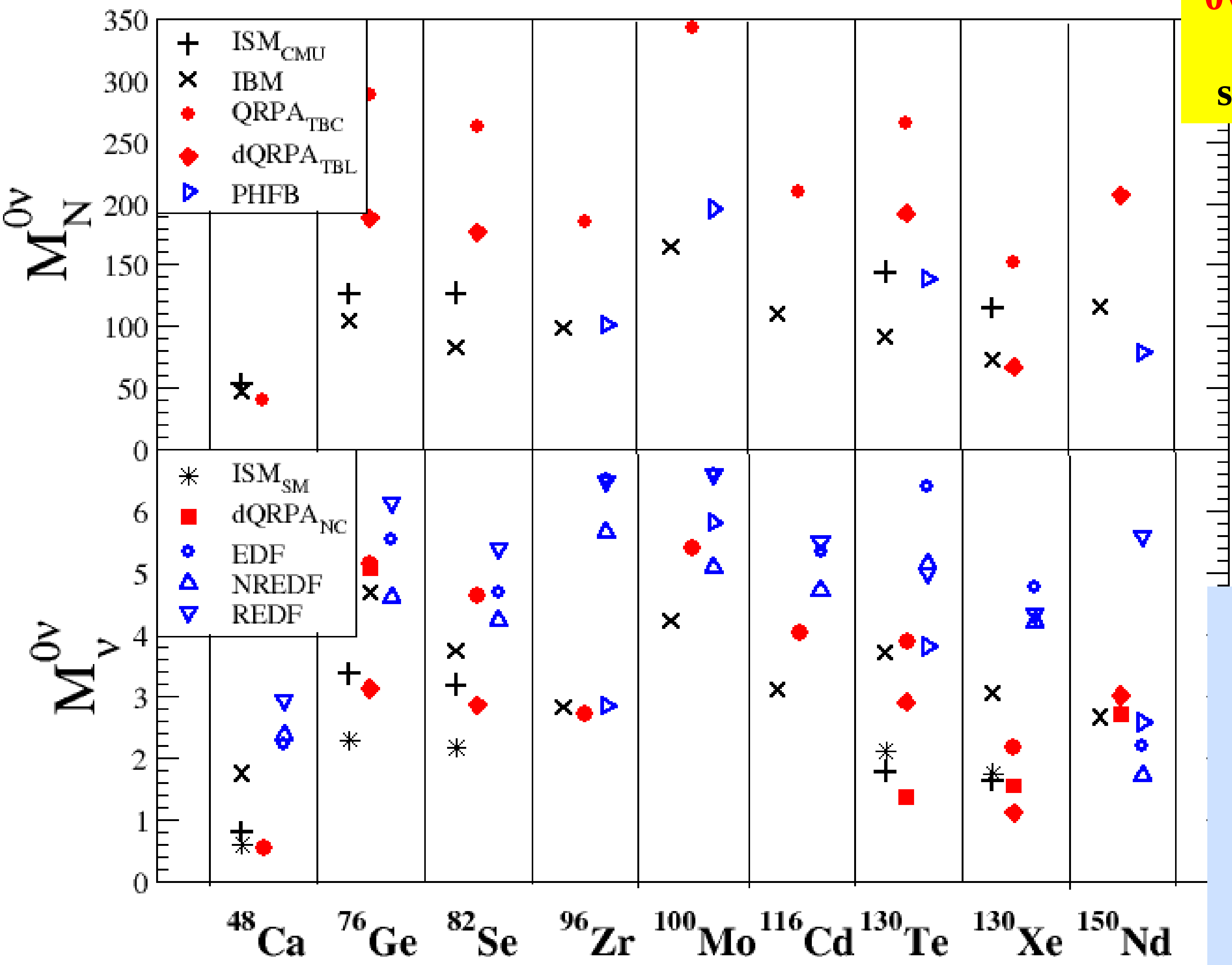
Thank You!

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

Thanks a lot for your attention

0νββ-decay NME

status 2019



All models missing essential physics

Impossible to assign rigorous uncertainties

unquenched g_A