Neutrinoless double beta decay

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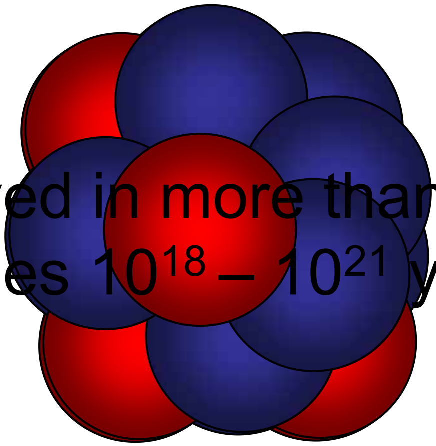
Rencontres de Moriond EW 2007
La Thuile, March 10-17, 2007

Outline

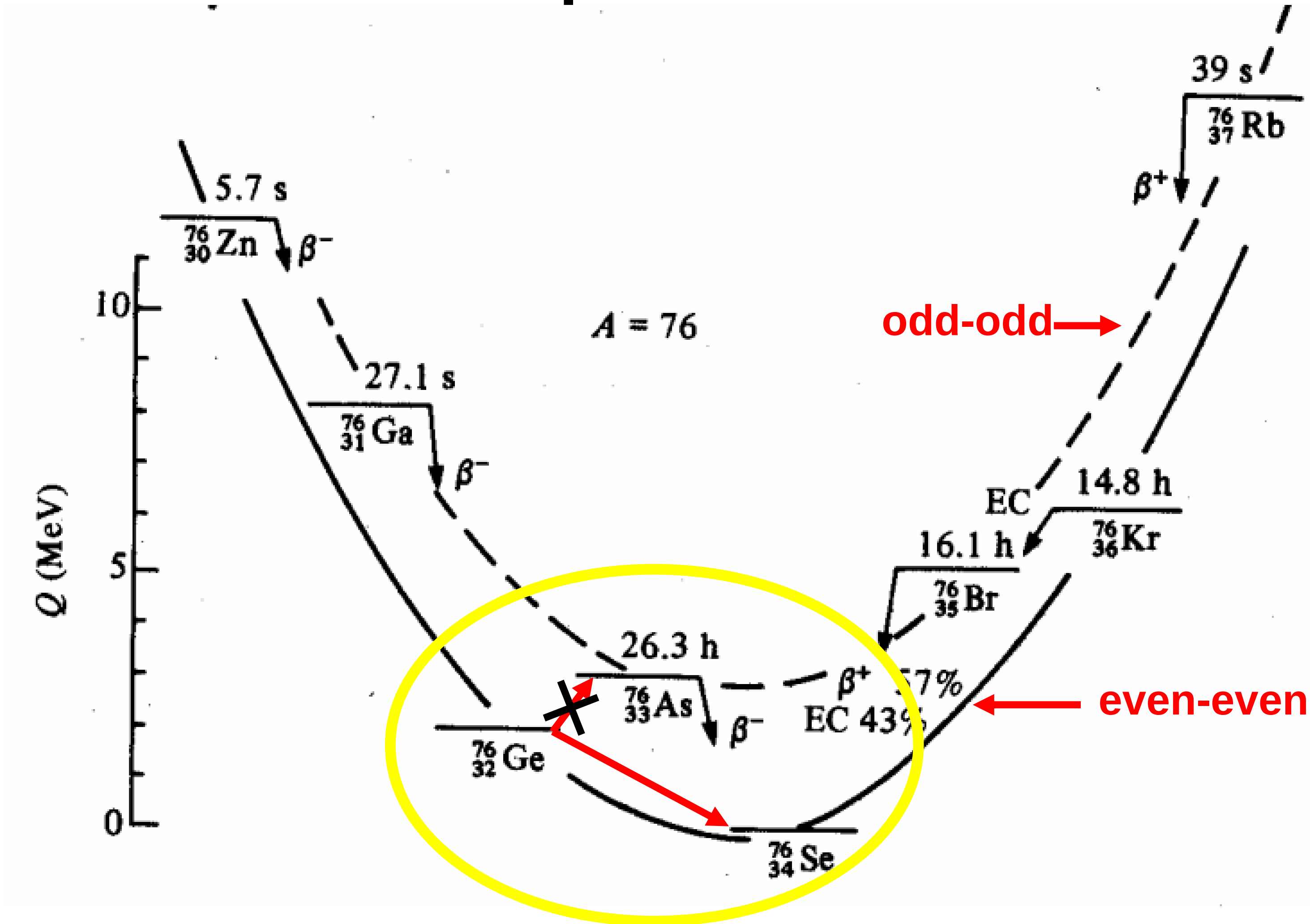
- Introduction DBD
  - Status NME
  - CP phases
- Experimental approaches
- Current experimental status
  - Claim for evidence
  - Running experiments
- Upcoming experiments
  - Overview
  - GERDA

2ν-ββ Decay



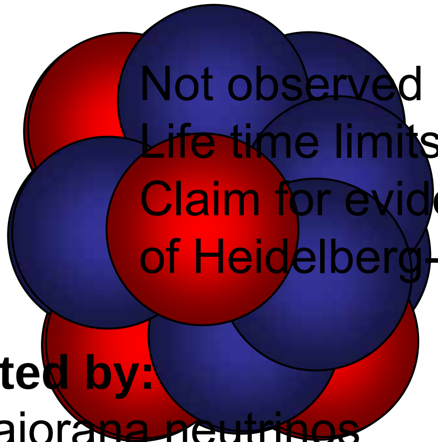
Observed in more than 10 isotopes
Life times $10^{18} - 10^{21}$ years

Mass parabolas



Ground states of even-even nuclei: 0^+

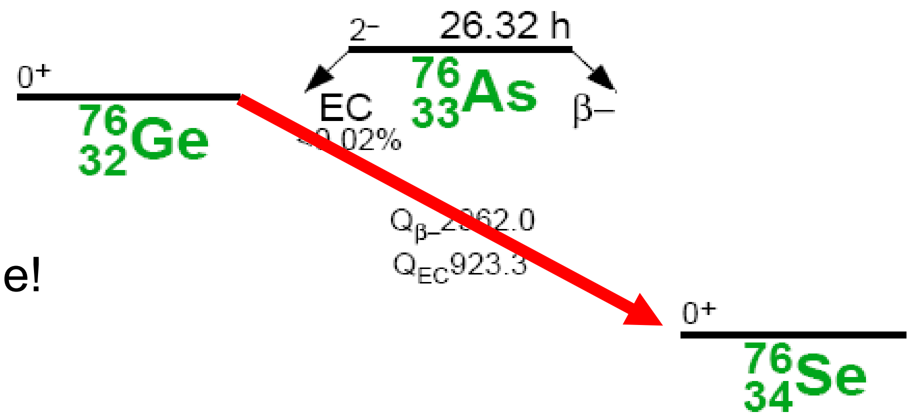
0ν-ββ Decay



Not observed yet;
Life time limits > $10^{24} – 10^{25}$ y;
Claim for evidence in Ge-76 by part of Heidelberg-Moscow Collab.

0νββ can be generated by:
- exchange of light Majorana neutrinos
- SUSY
- …..

Schechter & Valle:
if 0νββ observed ⇒ ν is Majorana particle!

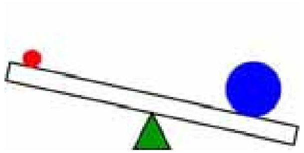


Physics motivations

1) Dirac vs. Majorana particle: (i.e. its own anti-particle)?

$0\nu\beta\beta \Rightarrow$ Majorana nature

Majorana $\Rightarrow$ See-Saw mechanism $m_\nu = \frac{m_D^2}{M_R} << m_D$



For $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim m_t$ ➔ $M_R \sim 10^{15}$GeV

Majorana $\Rightarrow$ CP violation in M_R → higgs + lepton $\Rightarrow$ Leptogenesis $\Rightarrow$ B asymmetry

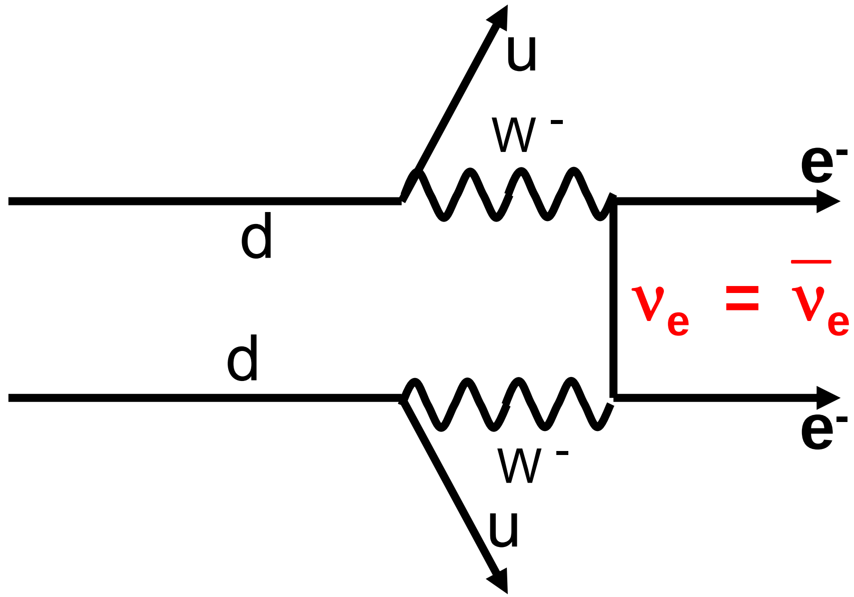
2) Absolute mass scale:

Hierarchy: degenerate, inverted or normal

(effective) neutrino mass

0ν-$\beta\beta$ Decay

$$(A,Z) \rightarrow (A,Z+2) + e_1^- + e_2^-$$



$\Delta L=2$

Assume leading term is exchange of light Majorana neutrinos

$$T_{1/2}(0\nu)^{-1} = G\, M^2\, m^2_{ee}$$

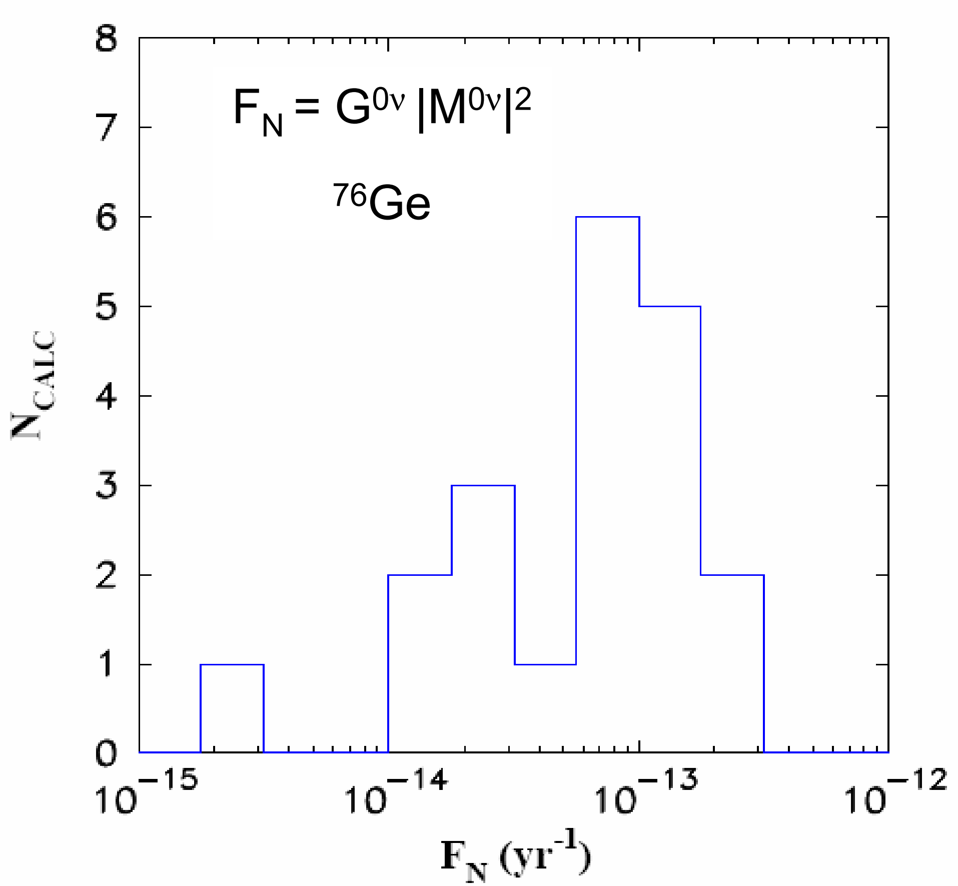
Effective neutrino mass

Phase space

Nuclear matrix element

Nuclear matrix elements

hep-ph/0403167 (Bahcall, Murayama, Pena-Garay)



Bahcall, Murayama, Pena-Garay (2004): "compilation 20 calculation range factor 100 for $|M^{0\nu}|^2$!!"

Paper triggered discussion on "democratic approach" (Faessler)

⇒Discussion in ILIAS/IDEA (shell models vs. QRPA; QRPA: g_{pp} fit to $2\nu\beta\beta$ or β, g_A, short range correlations, …)

⇒ Comprehensive analysis of differences of QRPA calculations (*V.A. Rodin et al. / Nuclear Physics A 766 (2006)*)

Convergence of QRPA results: "We show that in most, albeit not all, cases these differences can be understood"

NME: Shell model vs. QRPA

$M_{0\nu}$	LSSM	QRPA(1)	1+(hoc)	QRPA(hoc)(2)
^{76}Ge	2.58	3.60	2.80	2.40
^{82}Se	2.49	3.40	2.64	2.12
(^{116}Cd)	2.94	2.58	2.05	1.43
^{128}Te	2.67	2.96	2.17	1.60
^{130}Te	2.41	2.50	1.80	1.47
^{136}Xe	2.00	1.02	0.66	0.98

factor 2 or less difference

(hoc), including higher order corrections, their need is still under debate
(1) renormalized QRPA with the standard value of the strength of the particle-particle interaction. Simkovic, Pantis, Vergados, Faessler (1999)
(2) renormalized QRPA with the value of the strength of the particle-particle interaction adjusted to the 2ν lifetimes on a nucleus by nucleus basis (also under debate) Rodin, Faessler, Simkovic, Vogel (2006)

A. Poves, Ilias general meeting, Chambery 2007

Comparison of DBD Isotopes

$T_{1/2}(0\nu)^{-1} = G\,M^2\,m^2_{ee}$

$$N_{sig} = N_{Avg} \cdot \frac{mass \cdot t}{A} \cdot \ln 2 \cdot \Gamma \cdot M^2 \cdot \langle m_{ee} \rangle^2$$

isotope	$Q_{\beta\beta}$	nat. abund.	rel. A	rel Γ	rel. M^2	N_{sig}
$^{76}Ge \rightarrow ^{76}Se$	2039 keV	7.4%	1	1	1	2.4
$^{82}Se \rightarrow ^{82}Kr$	2995 keV	9.2%	0.93	4.4	0.71	7.0
$^{100}Mo \rightarrow ^{100}Ru$	3034 keV	9.6%	0.76	7.2	0.23	3.0
$^{130}Te \rightarrow ^{130}Xe$	2529 keV	34%	0.58	6.9	0.33	3.2
$^{136}Xe \rightarrow ^{136}Ba$	2479 keV	8.9%	0.56	7.4	0.15	1.5

for 1000 kg y, $\langle m_{ee} \rangle$ = 50 meV, M^2 from V.A.Rodin et al, Nucl. Phys. A766 (2006) 107.

GERDA, Majorana → ^{76}Ge

Super-Nemo → ^{82}Se

Nemo3 → ^{100}Mo

Cuoricino/Cuore → ^{130}Te

EXO → ^{136}Xe

Effective Majorana mass

$$m_{ee} = |\sum_i U_{ei}{}^2 \, m_i|$$

U_{ei} complex:

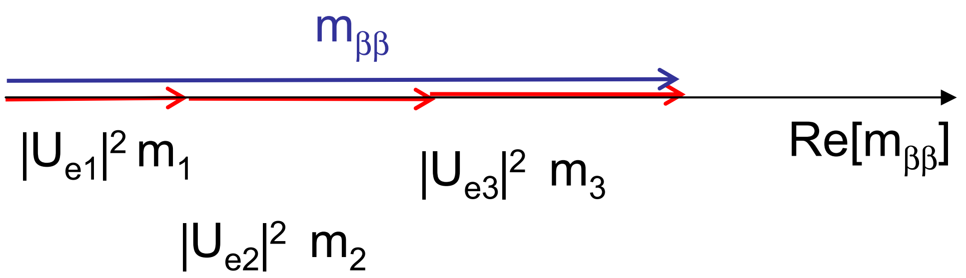
$\Rightarrow$ sensitive to CP phases (optimist☺)

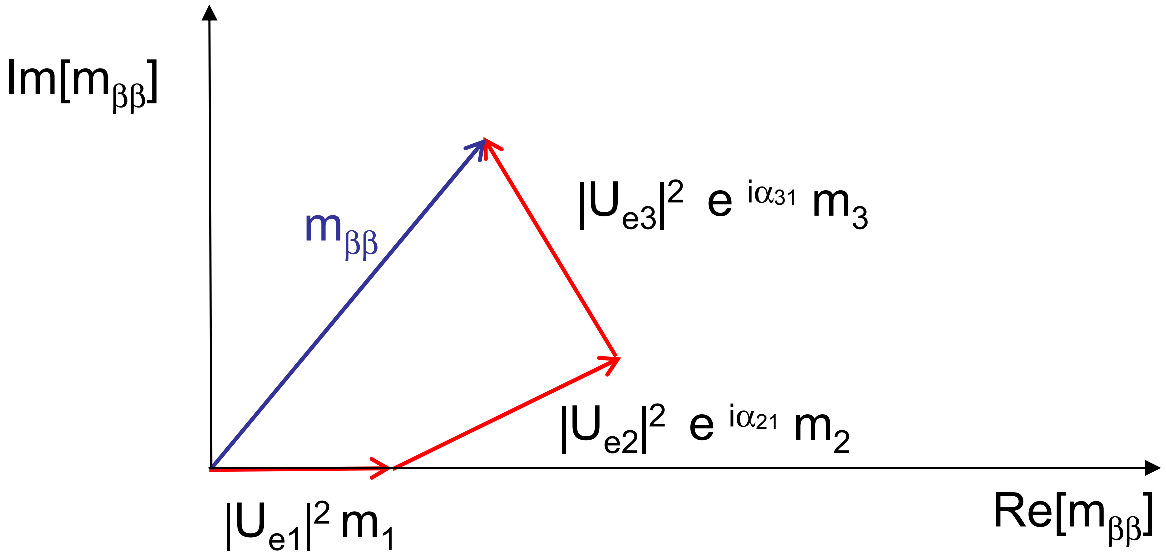
$\Rightarrow$ cancellation possible (pessimist)

NB: Beta-endpoint (Katrin)

$$m_{\nu_e} = (\sum_i |U_{ei}{}^2| \, m_i{}^2)^{1/2}$$

If CP is conserved:

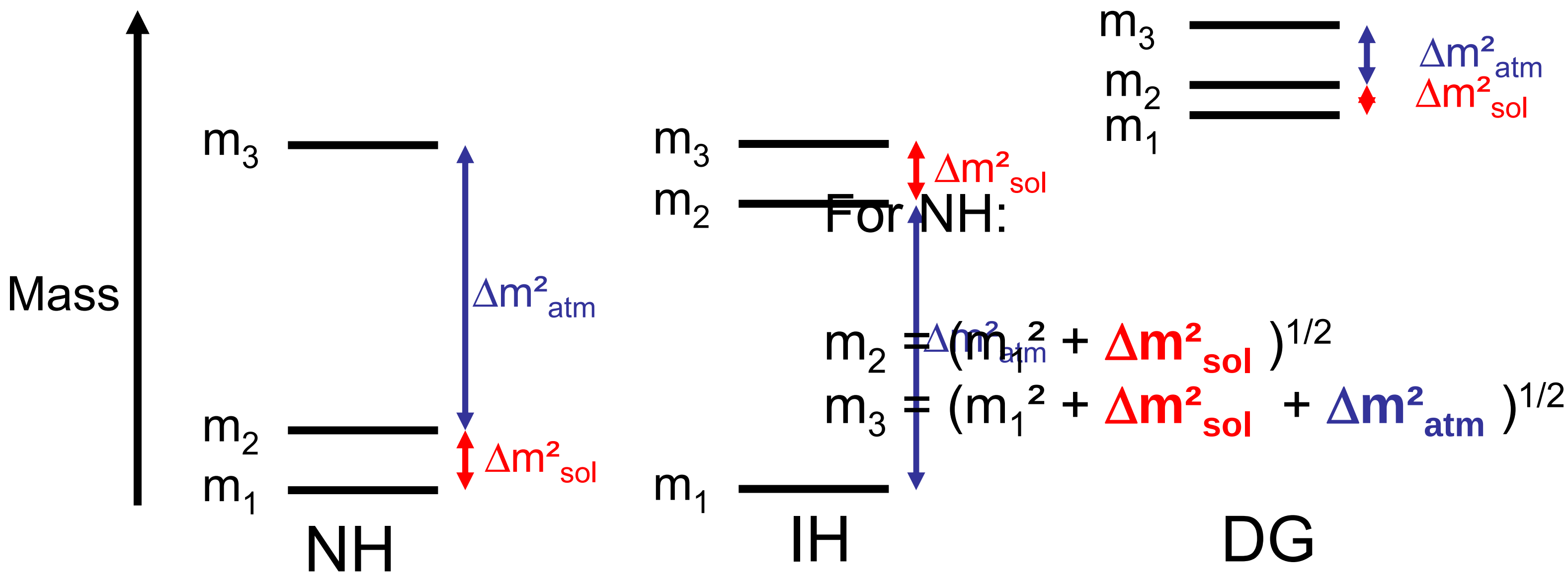




$Im[m_{\beta\beta}]$
$m_{\beta\beta}$
$|U_{e3}|^2\ e^{i\alpha_{31}}\ m_3$
$|U_{e2}|^2\ e^{i\alpha_{21}}\ m_2$
$|U_{e1}|^2\ m_1$
$Re[m_{\beta\beta}]$

Input for m_{ee} from ν-oscillations

Solar/Reactor -ν: θ_{12}, Δm^2_{sol} **Atmosph.-ν: Δm^2_{atm}** **Reaktor-ν: θ_{13}**



For NH:

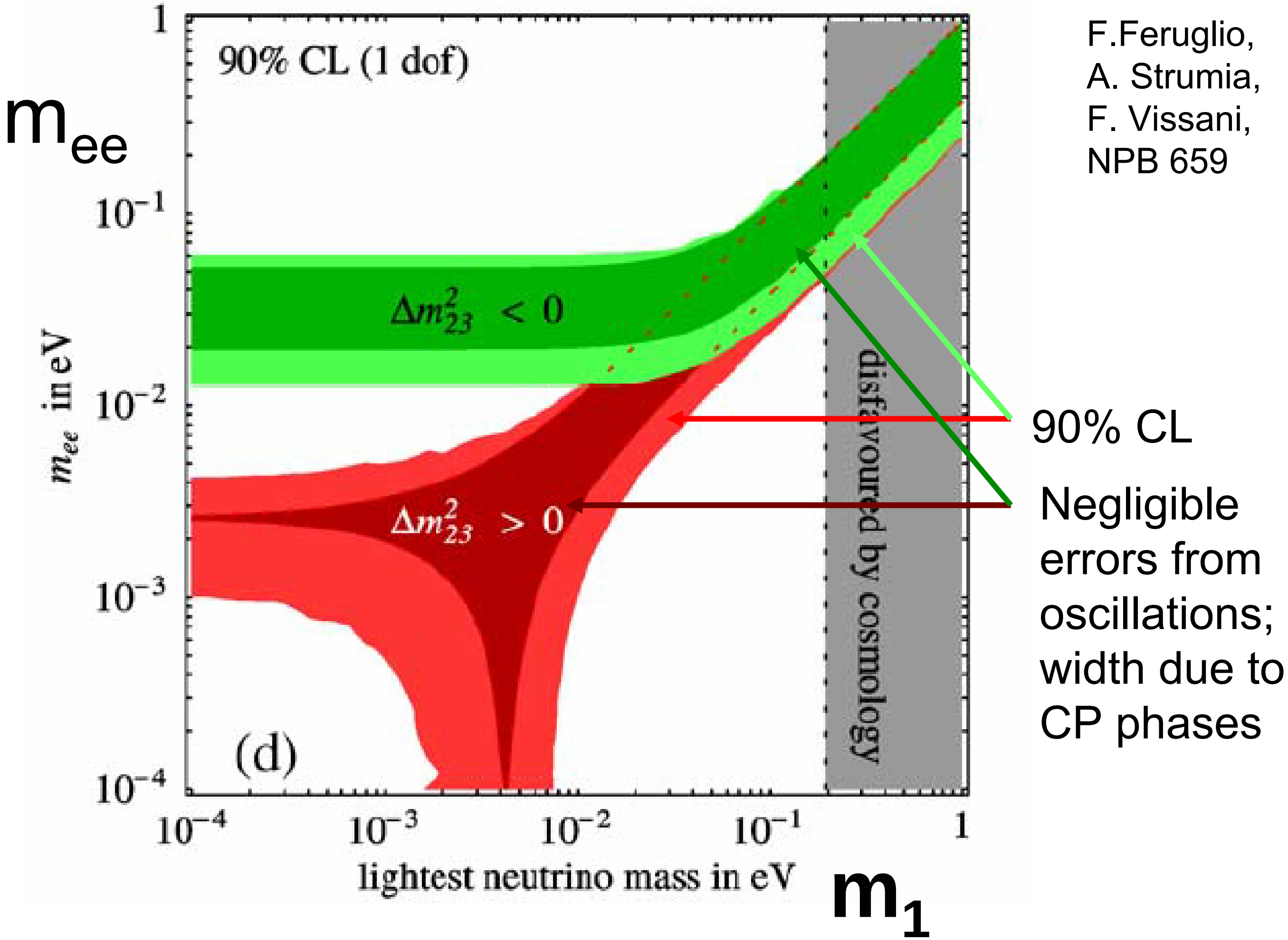
$$m_2 = (m_1^2 + \Delta m^2_{sol})^{1/2}$$

$$m_3 = (m_1^2 + \Delta m^2_{sol} + \Delta m^2_{atm})^{1/2}$$

$$m_{ee} = \left| \cos^2\theta_{13} (m_1 \cos^2\theta_{12} + m_2 e^{2i\alpha} \sin^2\theta_{12}) + m_3 e^{2i\beta} \sin^2\theta_{13} \right|$$

$$\Rightarrow m_{ee} = f(m_1, \Delta m^2_{sol}, \Delta m^2_{atm}, \theta_{12}, \theta_{13}, \alpha, \beta)$$

Predictions from oscillation experiments



F.Feruglio,
A. Strumia,
F. Vissani,
NPB 659

Experimental sensitivity

Without background: $$\langle m \rangle \leq \frac{\text{const}}{(M\,T)^{1/2}}$$ (M T: exposure [kg y])

With background: $$\langle m \rangle \leq \text{const.} \cdot \left(\frac{b\,\Delta E}{M\,T} \right)^{1/4}$$

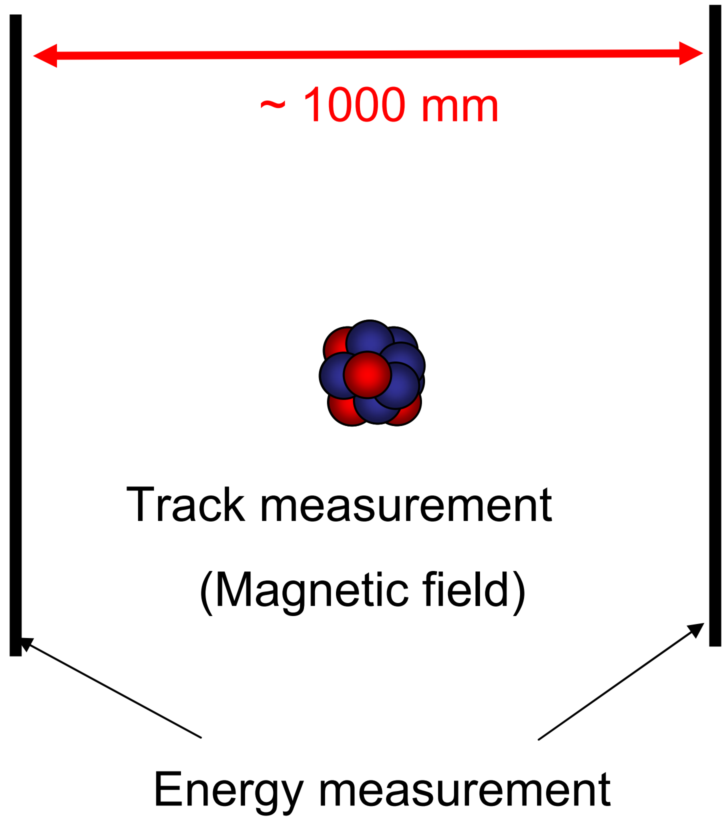
b: background rate at $Q_{\beta\beta}$ [cts/kg/keV/year]
ΔE: energy resolution

⇒ Maximize number of isotopes under observation
⇒Minimize background (radioactivity, cosmics) in energy window at $Q_{\beta\beta}$
Explore inverted hierarchy mass range completely
⇒ 1 ton of isotopes AND $b \cdot \Delta E \sim 10^{-3}$-$10^{-4}$/kg y

Two ways to measure 0ν-ββ decay

Source = Detector

Source ≠ Detector



Heidelberg-Moscow Experiment @ LNGS (completed 2003)

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

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

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

Data acquisition and analysis of the ^{76}Ge double beta experiment in Gran Sasso 1990–2003

H.V. Klapdor-Kleingrothaus*[,1], A. Dietz, I.V. Krivosheina[2], O. Chkvorets

NIM A 522 (2004)

Claim: Evidence for $\beta\beta(0\nu)$

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Data acquisition and analysis of the ^{76}Ge double beta experiment in Gran Sasso 1990–2003

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Abstract

Data acquisition in a long-running underground experiment has its specific experimental challenges, concerning data acquisition, stability of the experiment and background reduction. These problems are addressed here for the HEIDELBERG–MOSCOW experiment, which collected data in the period August 1990–May 2003. The measurement and the analysis of the data are presented. The duty cycle of the experiment was ~80%, and the collected statistics is 71.7 kg year. The background achieved in the energy region of the Q value for double beta decay is 0.11 events/kg year keV. The two-neutrino accompanied half-life is determined on the basis of more than 100 000 events. The confidence level for the neutrinoless signal has been improved to a 4σ level.

PACS: 14.60.Pq; 23.40.−s; 29.40.−n; 95.55.Vj

Keywords: Neutrino mass and mixing; Beta decay; Double beta decay; HEIDELBERG – MOSCOW experiment; High purity; Ge-detectors; Majorana neutrino

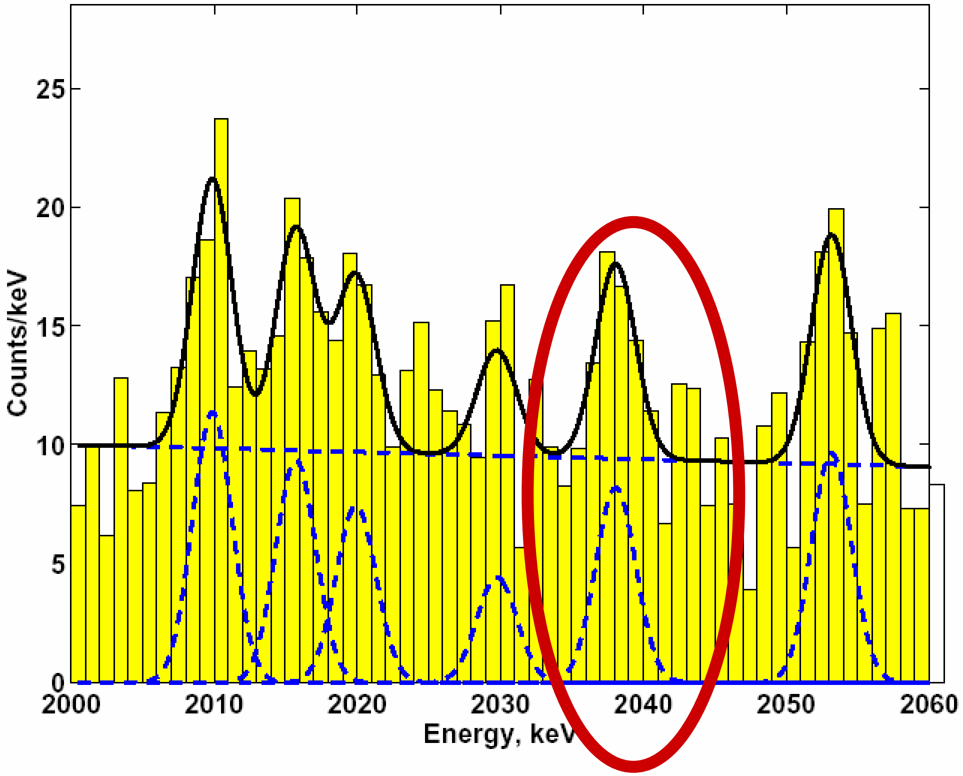


Fig. 17. The total sum spectrum of all five detectors (in total 10.96 kg enriched in ^{76}Ge), for the period November 1990–May 2003 (71.7 kg year) in the range 2000–2060 keV and its fit (see Section 3.2).

- Nov 1990- May 2003
- 71.7 kg year
- **Bgd 0.11 / kg y keV**
- 28.75 ± 6.87 events (bgd:~60)
- 4.2 sigma evidence for $0\nu\beta\beta$

- 0.34-2.03 $\times 10^{25}$ y (3 sigma)
- Best fit 1.19 $\times 10^{25}$ y

- m_{ee} = 0.1-0.9 eV
- best fit 0.44 eV

NB. Statistical significance depends on background model!

Compilation of running or proposed experiments

Name	Nucleus	Method	Location	European Members	Others
Running experiments					
CUORICINO	^{130}Te	bolometric	LNGS	IT, NL, ES	US
NEMO-3	^{100}Mo ^{82}Se	tracko-calo	LSM	FR, CZ, UK ES, FIN	US, RU, JP
Construction funding					
CUORE	^{130}Te	bolometric	LNGS	IT, NL, ES	US
GERDA	^{76}Ge	ionization	LNGS	DE,BE,IT,PO	RU
Substantial R&D funding					
EXO	^{136}Xe	tracking	WIPP	CH	US, RU, CAN
SuperNEMO	^{150}Nd or ^{82}Se	tracko-calo	LSC or LSM	FR,CZ,UK, SK, PL, ES, FIN	US,RU, JP UKR
R&D and/or conceptual design					
CANDLES	^{48}Ca	scintillation	Oto Lab	-	JP
CARVEL	^{48}Ca	scintillation	Solotvina	-	UKR, RU, US
COBRA	^{116}Cd, ^{130}Te	ionization	LNGS	UK, DE, IT, PO, SK	US
DCBA	^{150}Nd	tracking	t.b.d.	-	JP
MAJORANA	^{76}Ge	ionization	SNOLAB or DUSEL	-	US
MOON	^{100}Mo	tracking	t.b.d.	-	JP
SNO++	^{150}Nd	scintillation	SNOLAB	-	CAN, US + …
other decay modes					
TGV	^{106}Cd	el. capture, running	LSM	FR, CZ	RU

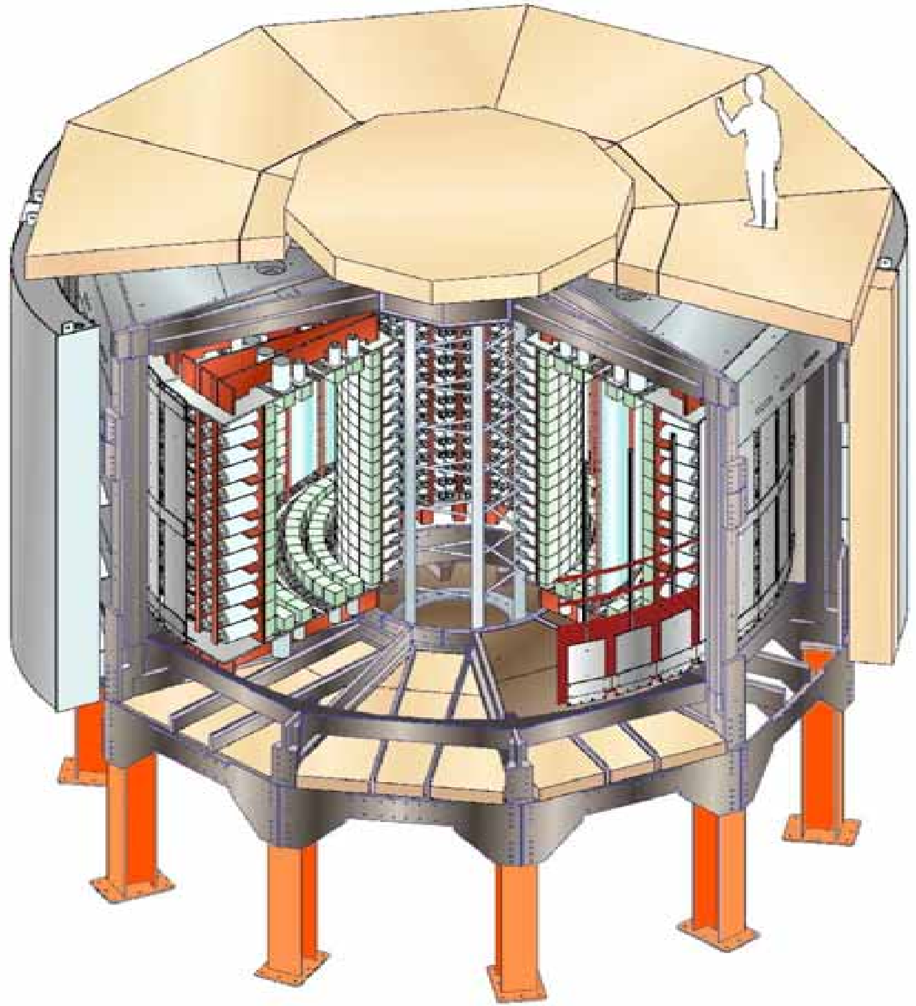
Silvia Capelli

this talk

Table from APPEC Roadmap draft

The NEMO3 detector

Fréjus Underground Laboratory : 4800 m.w.e.



Source: 10 kg of ββ isotopes
cylindrical, S = 20 m^2, e ~ 60 mg/cm^2

Tracking detector:
drift wire chamber operating in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

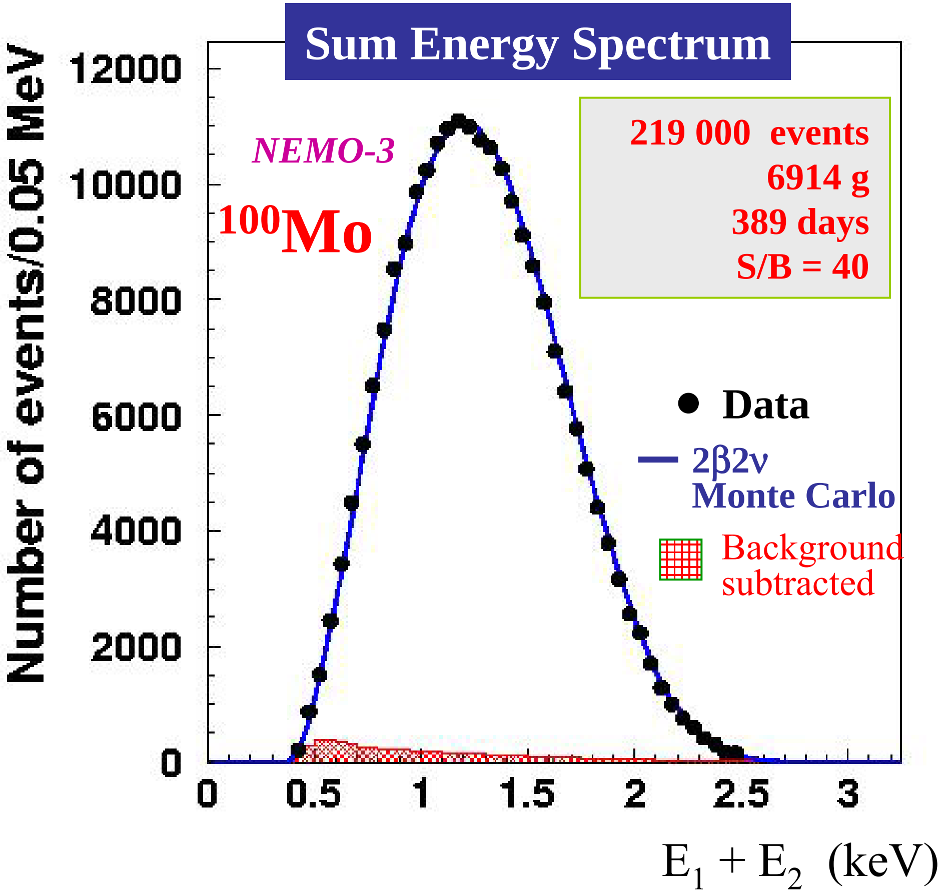
Calorimeter:
1940 plastic scintillators coupled to low radioactivity PMTs

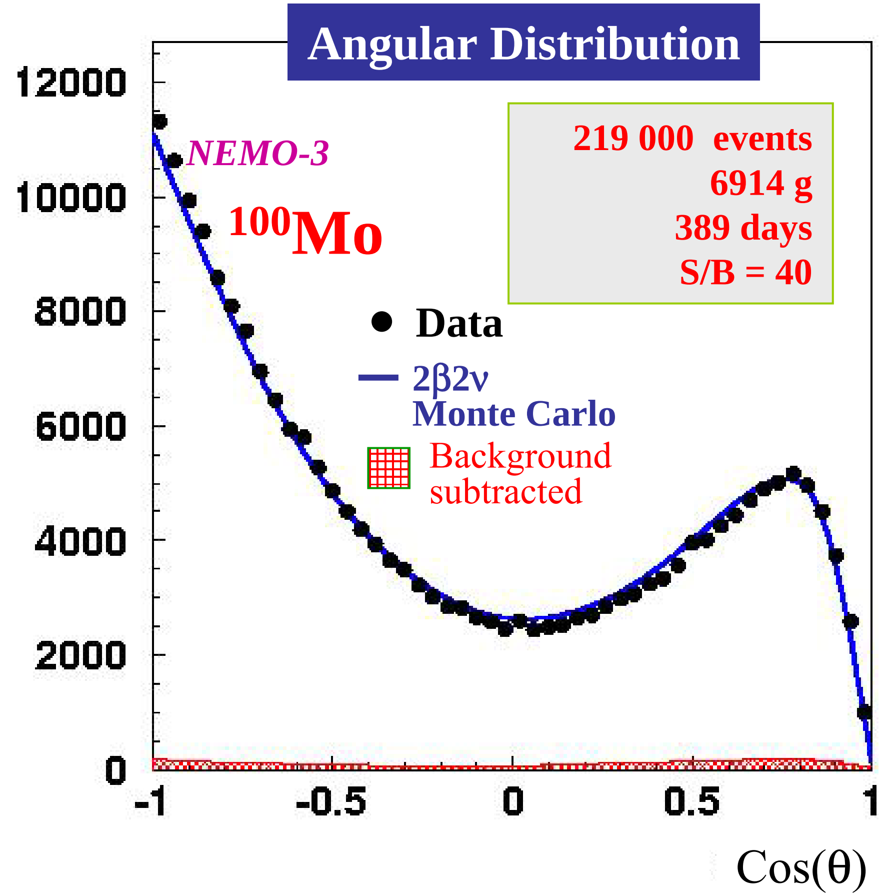
Magnetic field: 25 Gauss
Gamma shield: Pure Iron (e = 18 cm)
Neutron shield: 30 cm water (ext. wall)
40 cm wood (top and bottom)
(since march 2004: water + boron)

Able to identify e^-, e^+, γ and α

^{100}Mo 2β2ν preliminary results

(Data Feb. 2003 – Dec. 2004)





7.37 kg.y

$T_{1/2} = 7.11 \pm 0.02\ (stat) \pm 0.54\ (syst) \times 10^{18}$ y

Shitov, NANP05

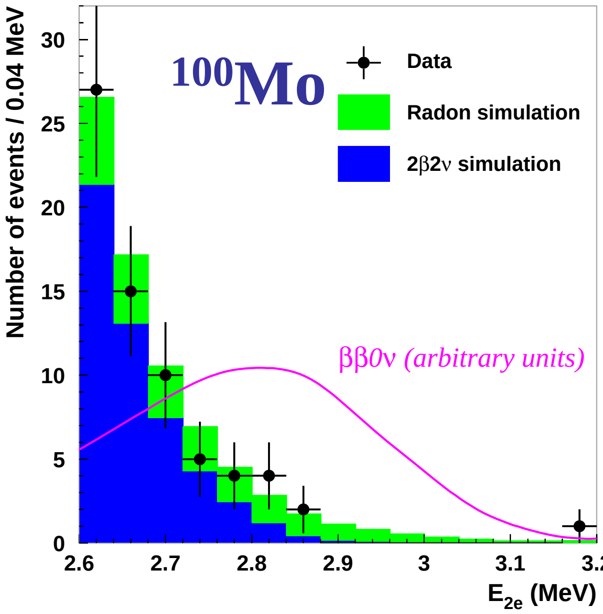
Limit on the effective mass of the Majorana neutrino

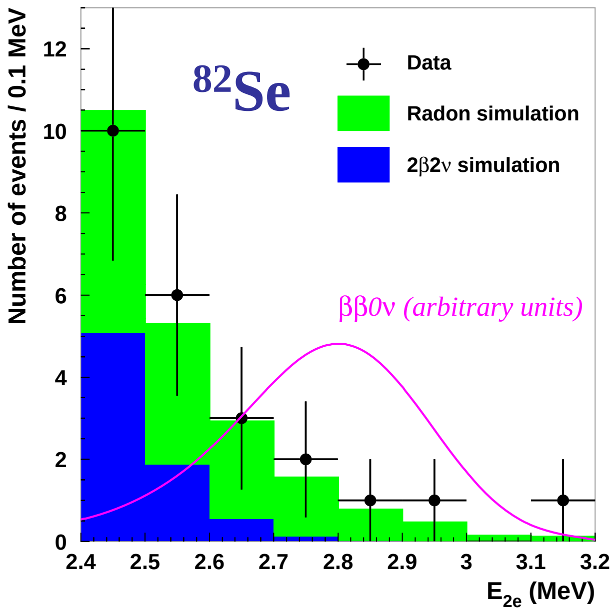
Phase 1 (Feb. 2003 – Sept. 2004: 1.08 y of data) with radon bkg (limits @ 90% CL)

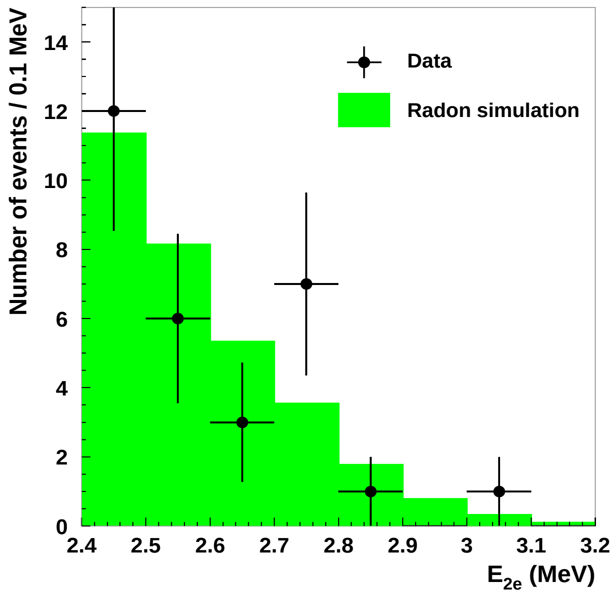
^{100}Mo (6.914 kg)
$T_{1/2}(\beta\beta0\nu) > 4.6\ 10^{23}$ y
$\langle m_\nu \rangle < 0.66 – 2.81$ eV

^{82}Se (0.932 kg)
$T_{1/2}(\beta\beta0\nu) > 1.0\ 10^{23}$ y
$\langle m_\nu \rangle < 1.75 – 4.86$ eV

Cu+^{nat}Te+^{130}Te
In agreement with only Radon bkg expected







[2.8-3.2] MeV: $\varepsilon(\beta\beta0\nu)$ = 8 %
Expected bkg = 8.1 ± 1.3
$N_{observed}$ = 7 events

[2.7-3.2] MeV: $\varepsilon(\beta\beta0\nu)$ = 13 %
Expected bkg = 3.1 ± 0.6
$N_{observed}$ = 5 events

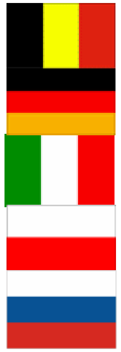
Previous limits: $T_{1/2}(\beta\beta0\nu) > 5.5\ 10^{22}$ y
Ejiri et al. (2001)

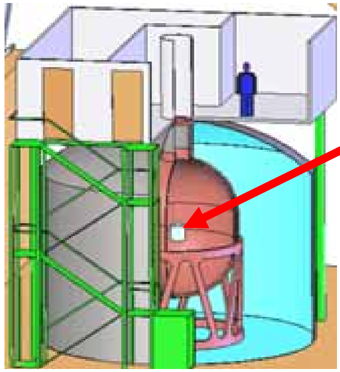
Previous limits: $T_{1/2}(\beta\beta0\nu) > 9.5\ 10^{21}$ y
Arnold et al. (1992)

Nuclear Matrice Elements Ref: Simkovic (1999), Stoica (2001), Suhonen (1998,2003), Rodin (2005), Caurier (1996)

Two new ^{76}Ge Projects:

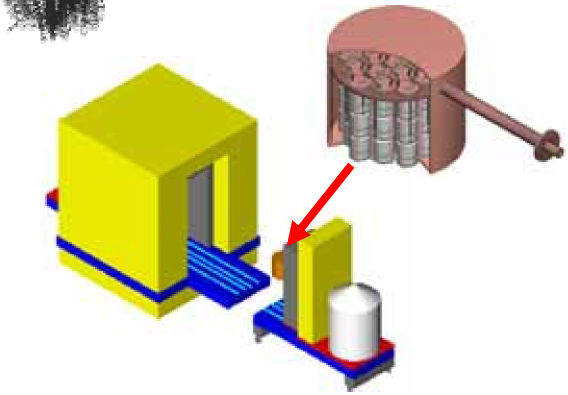
GERDA

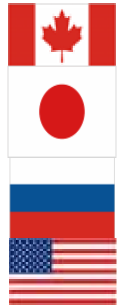




•'Bare' ^{enr}Ge array in liquid argon (nitrogen)
•Shield: high-purity liquid Argon (N) / H_2O
•Phase I: ~18 kg (HdM/IGEX diodes)
•Phase II: add ~20 kg new enr. Detectors; total ~40 kg

Majorana



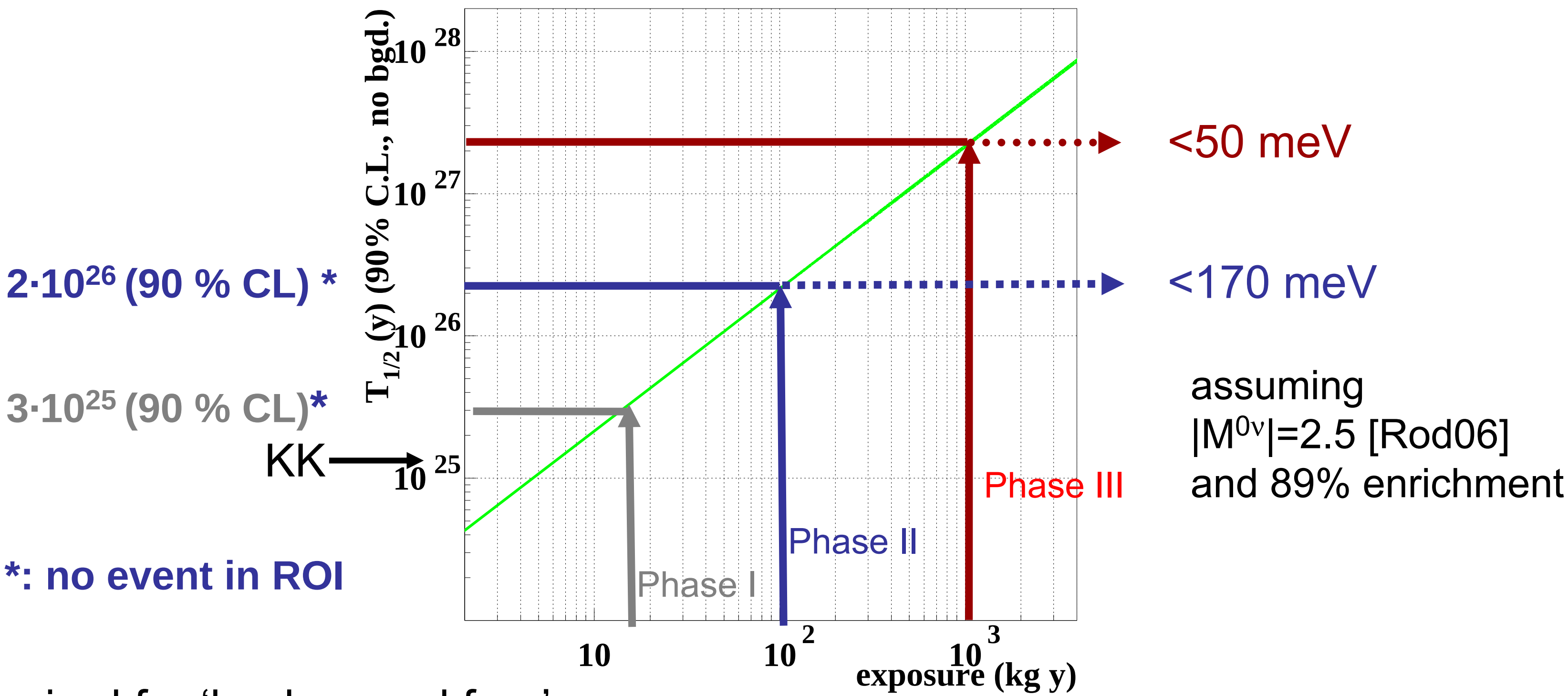


•Array(s) of ^{enr}Ge housed in high-purity electroformed copper cryostat
•Shield: electroformed copper / lead
•Staged approach based on 60 kg arrays (60/120/180 kg)

Physics goals: degenerate mass range
Technology: study of bgds. and exp. techniques

LoI
•open exchange of knowledge & technologies (e.g. MaGe MC)
•consider to merge for O(1 ton) exp. (inv. Hierarchy)

Phases and Physics reach of GERDA



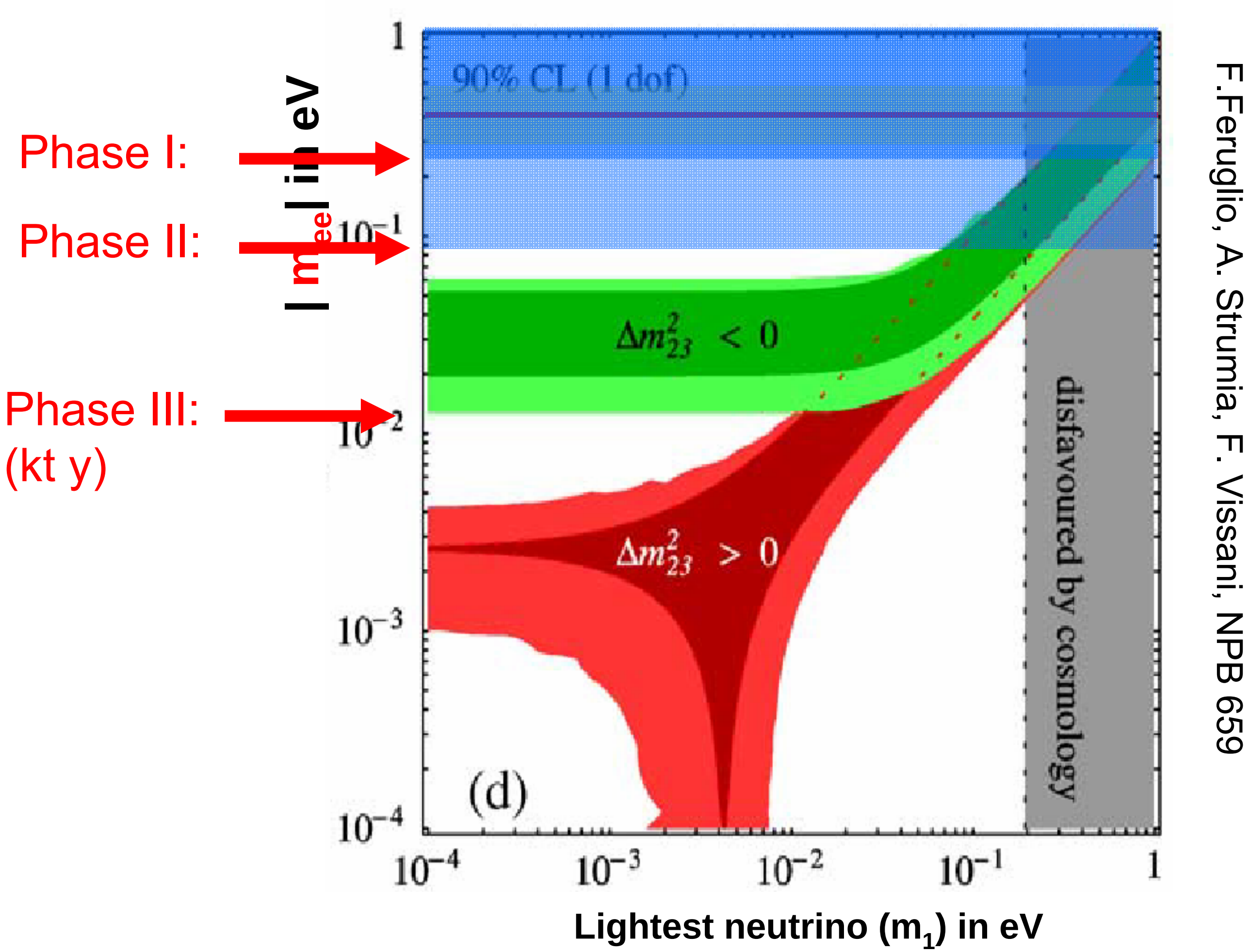
required for 'background free'
exp. with ΔE~3.3 keV (FWHM): **O(10^{-3})** **O(10^{-4})** counts/(kg·y·keV)

Background requirement for GERDA:

⇒Background reduction by factor **10^2 - 10^3** required w.r.t. to precursor exps.

⇒Degenerate mass scale **O(10^2 kg·y)** ⇒ Inverted mass scale **O(10^3 kg·y)**

Phases and Physics reach of GERDA



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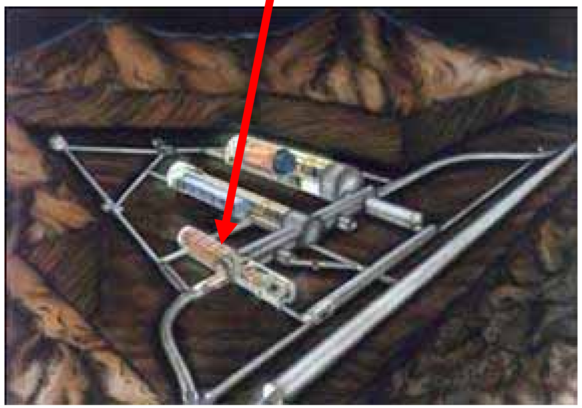
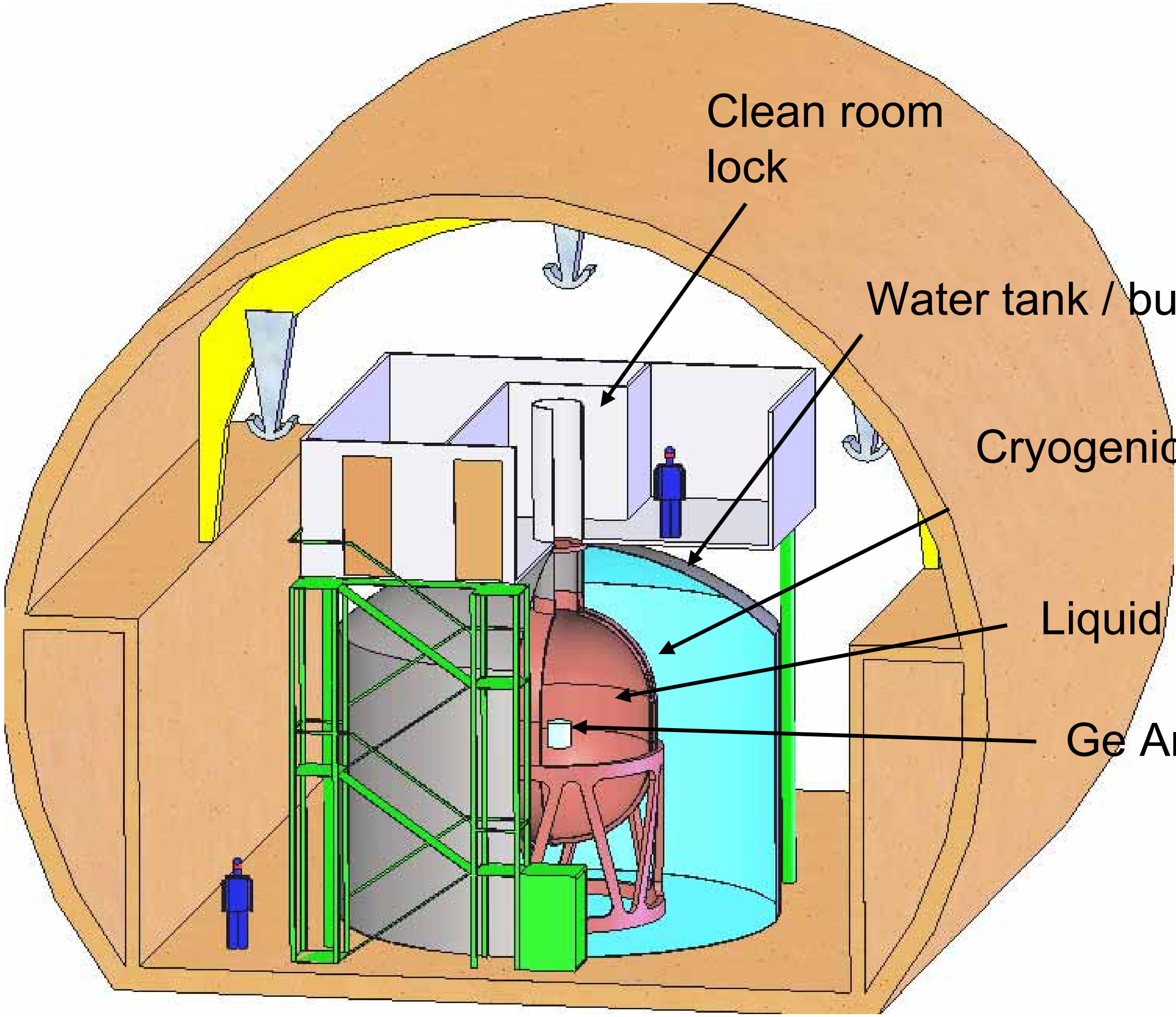
GERDA at LNGS



GERDA location:
hall A of LNGS

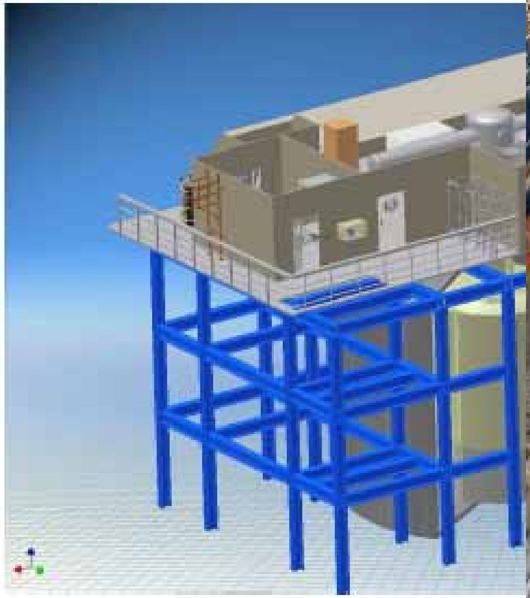
GERDA design



GERDA in hall A of LNGS

Lock with tubes for cabels

Clean room with lo



Rail system to
lower position
and lower
individual strings

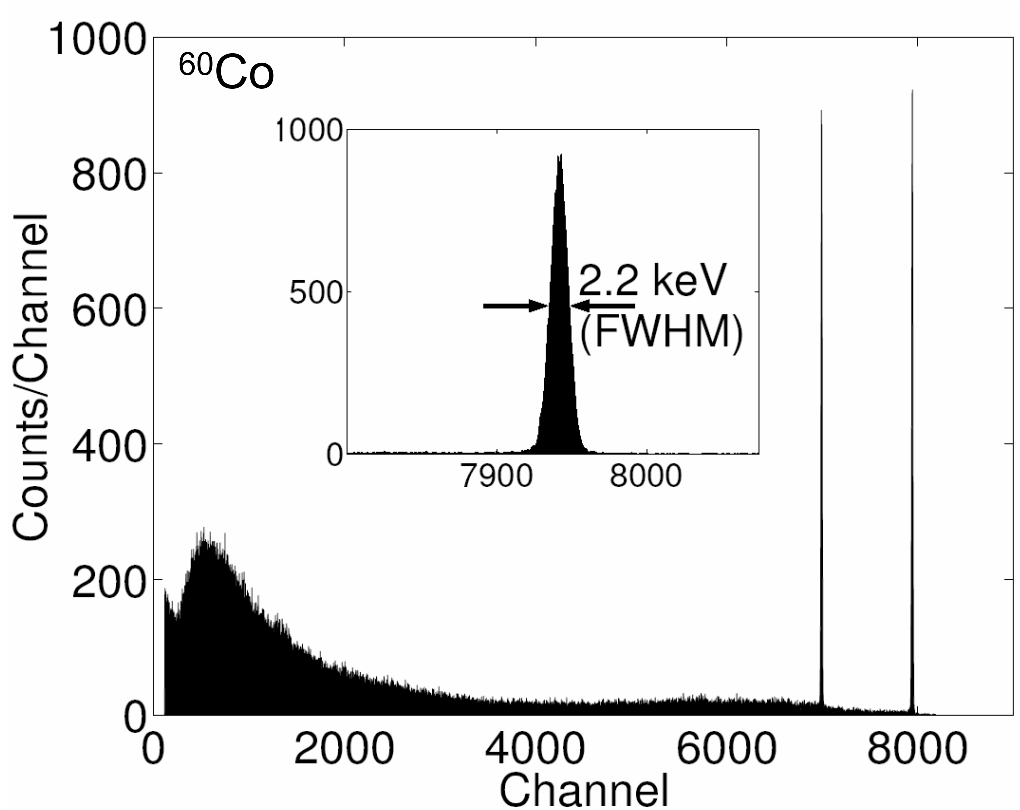
Phase I Detectors:

…intenance and Measurements in Undergrond detector laboratory (LArGe facility)

Since Nov. 2005: 17.9 kg of enriched Ge-detectors underground at LNGS; Characterization completed

Phase I Detectors:

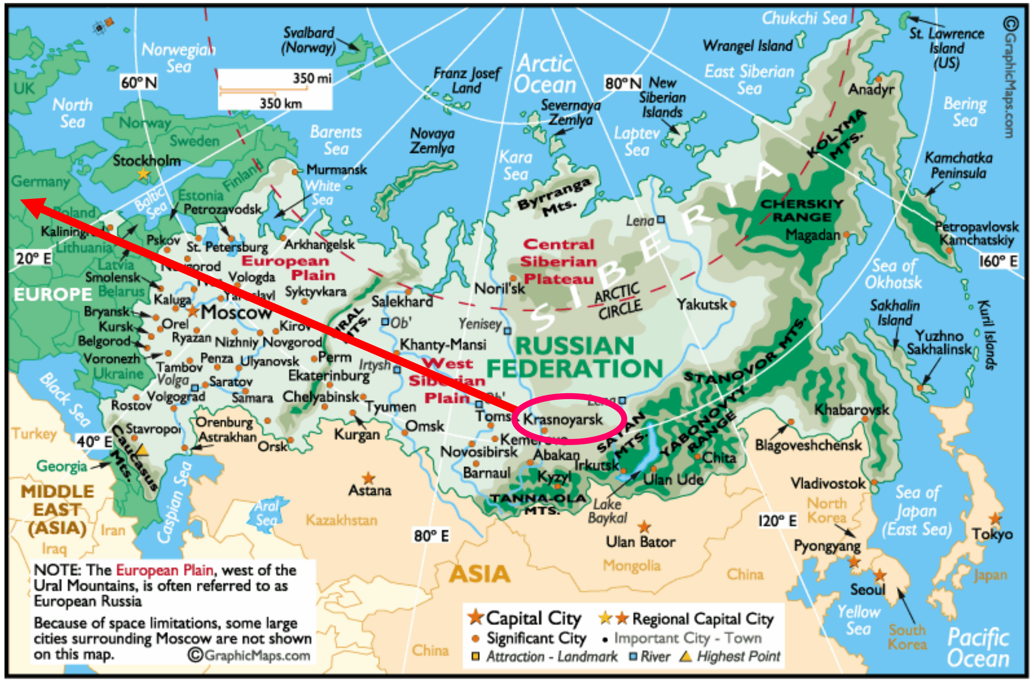
Prototype tests of (natural) low-mass detector assembly in liquid nitrogen



Enriched detectors are currently re-processed and prepared for testing

Phase II Detectors:

Procurement of enriched Ge

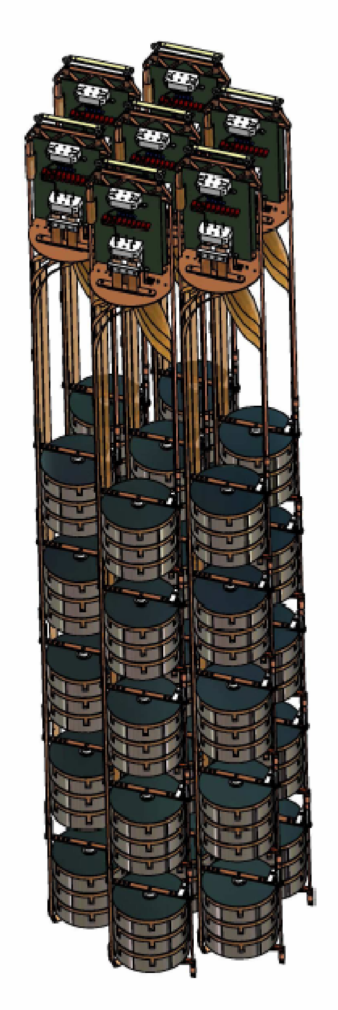


- •Enrichment of 37.5 kg Ge-76 completed in Sep.05
- •Transportation of Material to Europe by truck in spring for further processing
- •Specially designed protective steel container reduces activation by cosmic rays by factor 20

Test transportation March 05

Phase II Detectors:

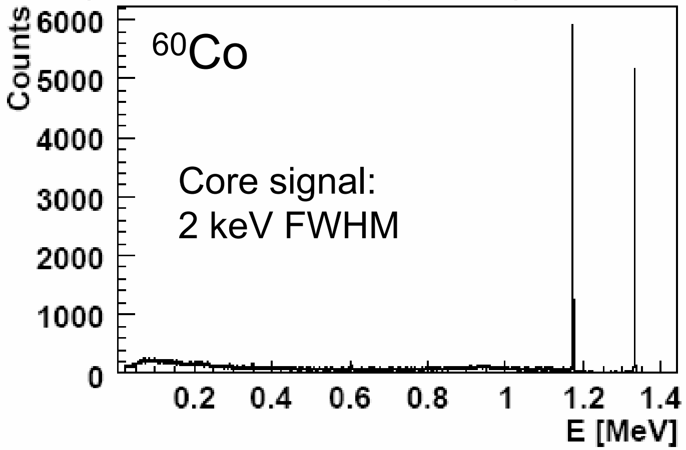
"True-coaxial" natural detectors

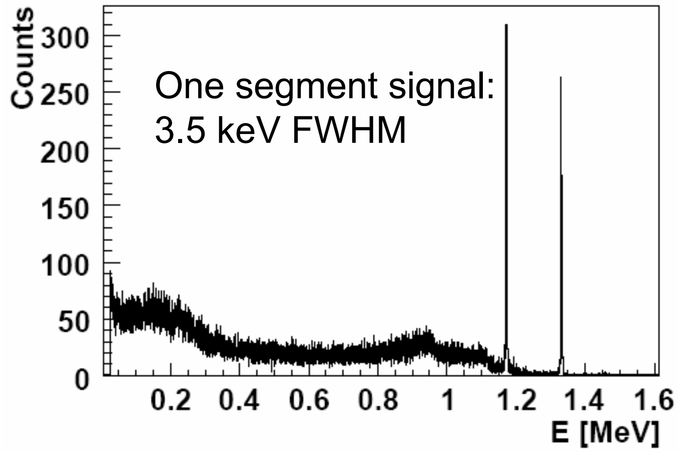


mock-up

18–fold (6-ϕ; 3-z) segmented n-type

18-fold segmented detector (in standard cryostat)





Backgrounds in GERDA

Source	B [10^{-3} cts/(keV kg y)]
Ext. γ from ^{208}Tl (^{232}Th)	<<1
Ext. neutrons	<0.05
Ext. muons (veto)	<0.03
Int. ^{68}Ge ($t_{1/2}$= 270 d)	**12**
Int. ^{60}Co ($t_{1/2}$= 5.27 y)	**2.5**
^{222}Rn in LN/LAr	<0.2
^{208}Tl, ^{238}U in holder	<1
Surface contam.	<0.6

derived from measurements and MC simulations

Muon veto

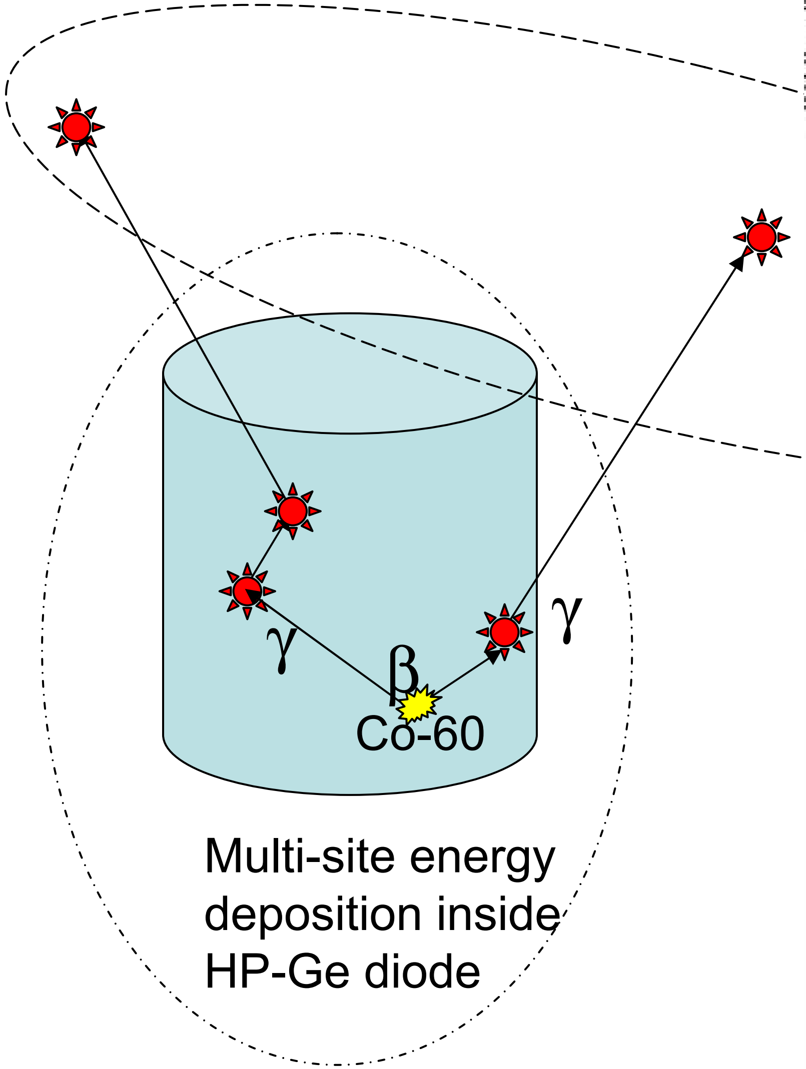
180 days exposure after enrichment + 180 days underground storage

30 days exposure after crystal growing

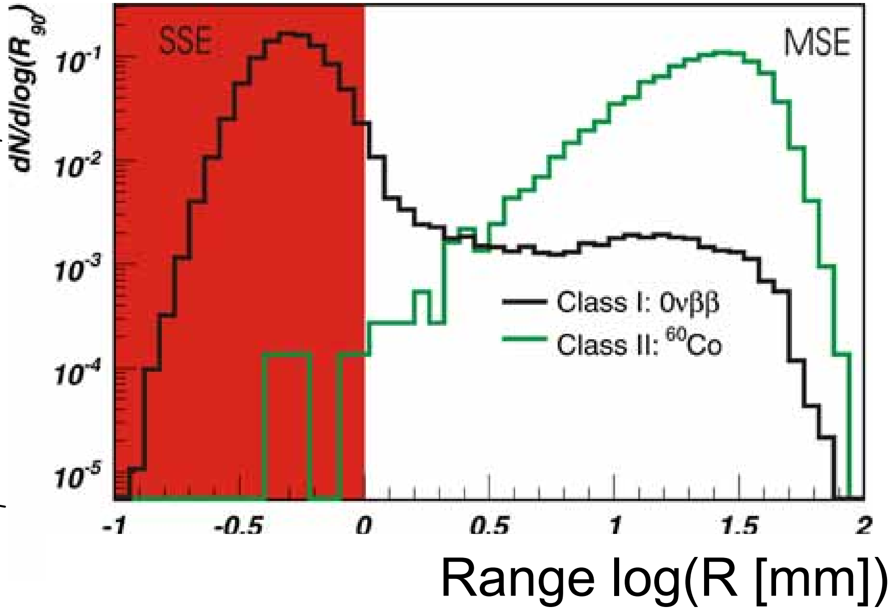
Target for phase II: Σ B $\leq$ 10^{-3} cts/(keV kg y)

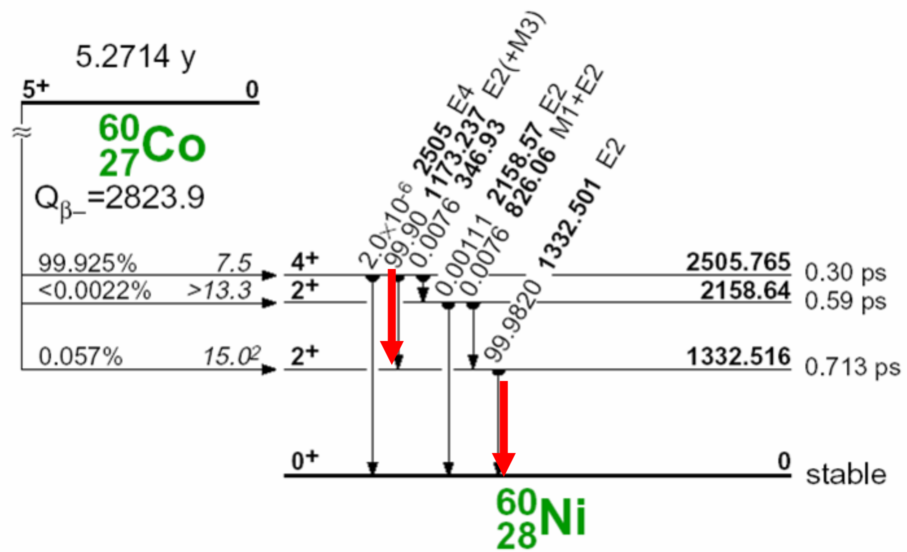
⇒ additional bgd. reduction techniques

Example of background topology



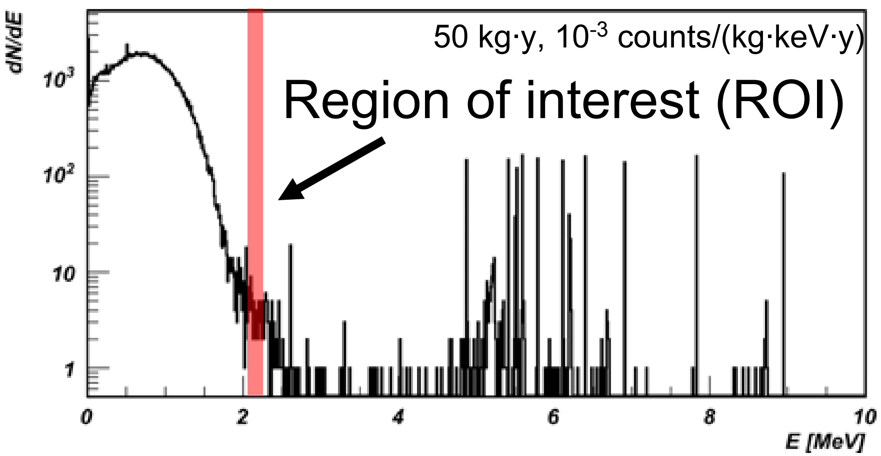
Multi-site energy deposition inside HP-Ge diode



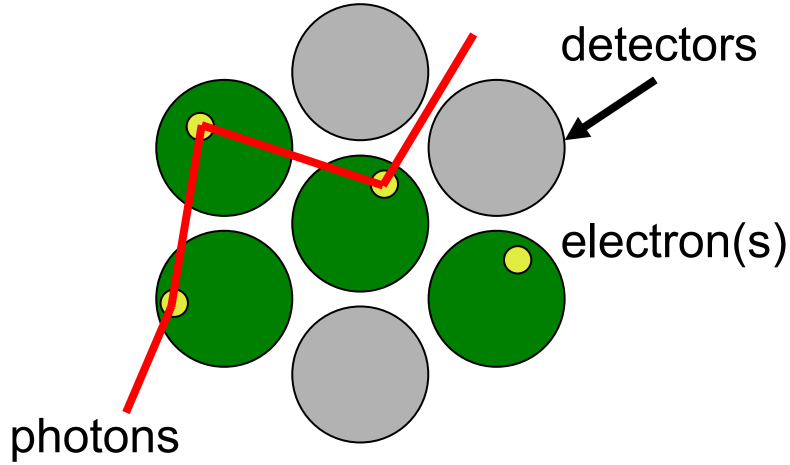


Analysis Chain: Electron / Photon Distinction

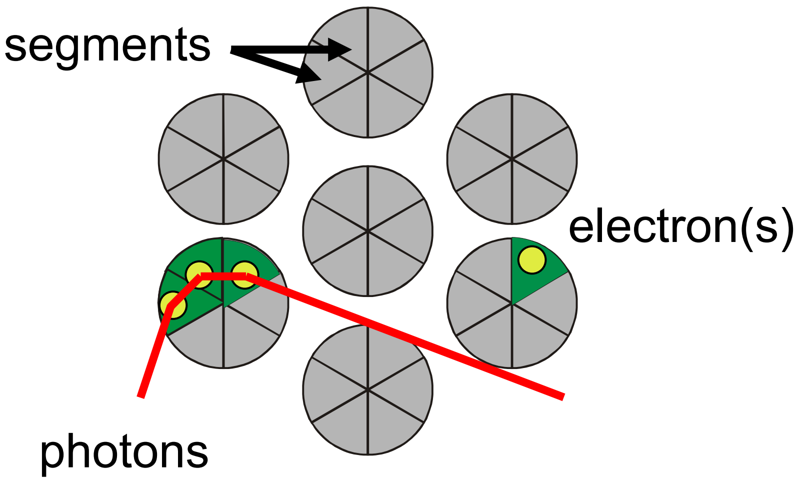
1. Energy cut



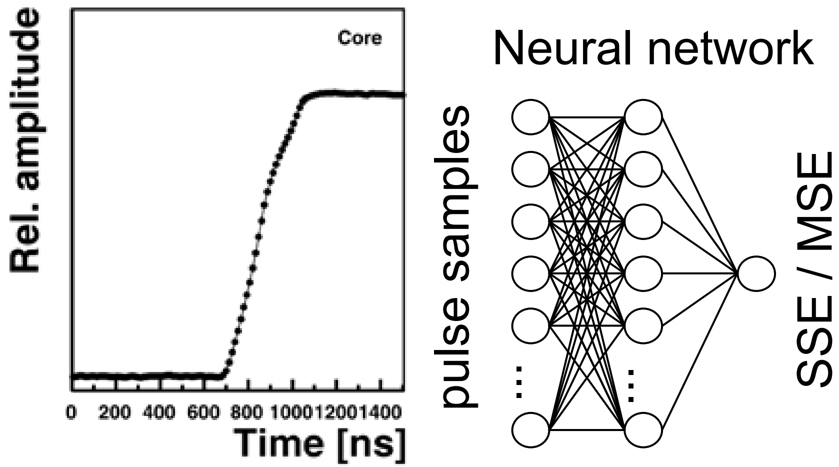
2. Crystal anti-coincidence



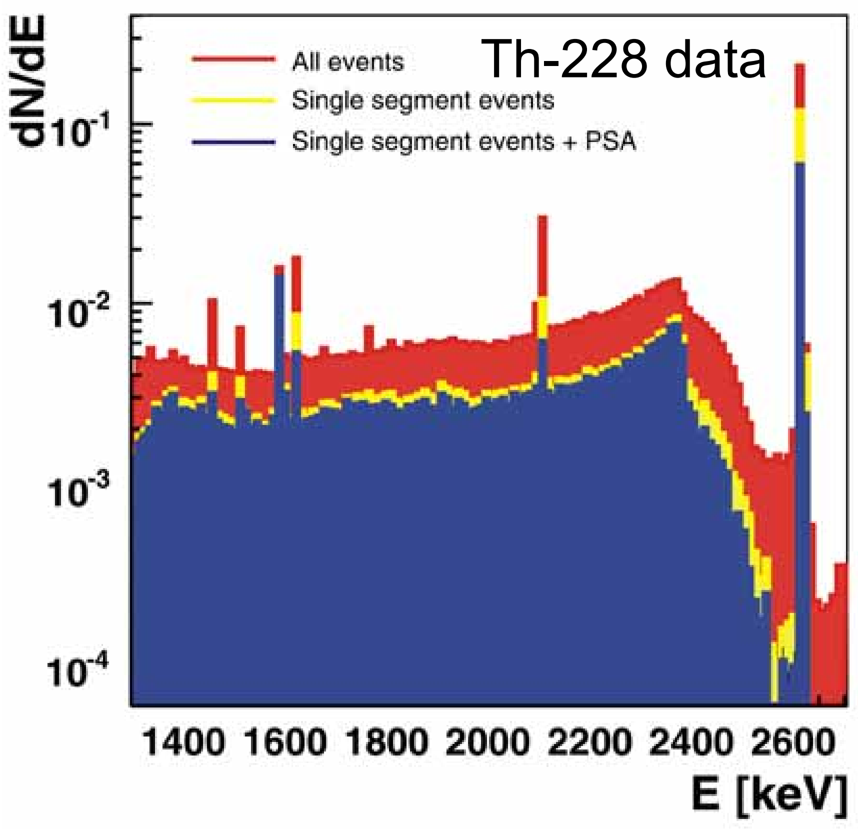
3. Segment anti-coincidence

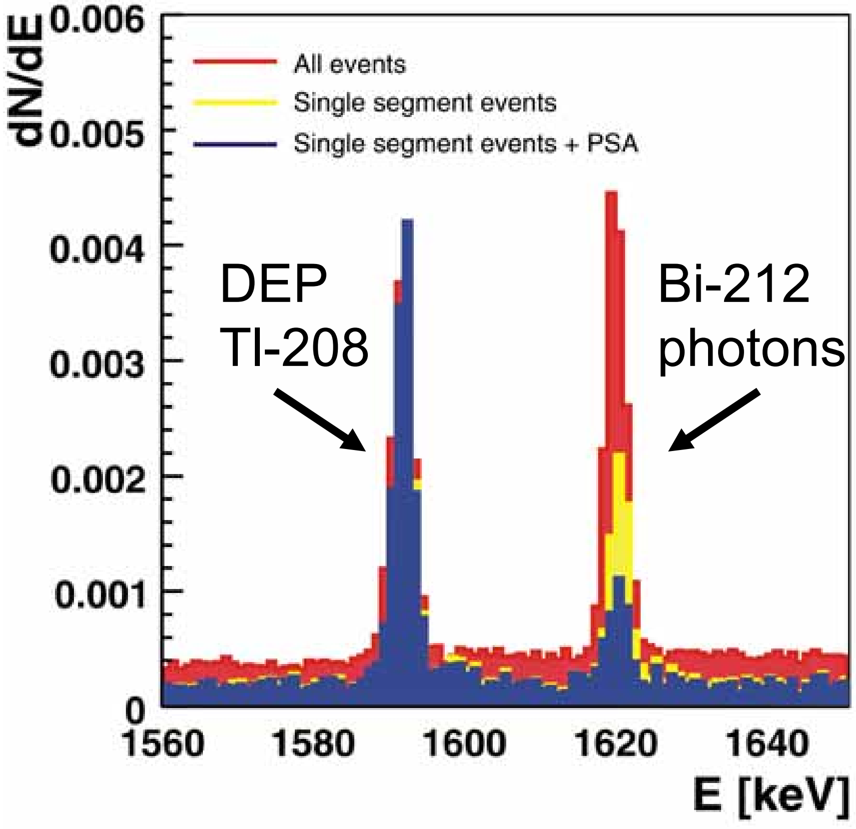


4. Pulse shape analysis



Photon discrimination with segmented detectors





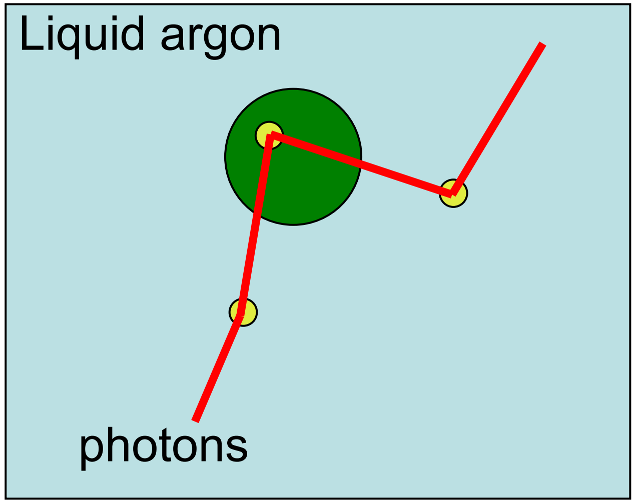
- Core energy spectrum
- **Segmentation reduces Compton-background in ROI**

- Correct identification of electrons and photons
- **PSA confirms signal**

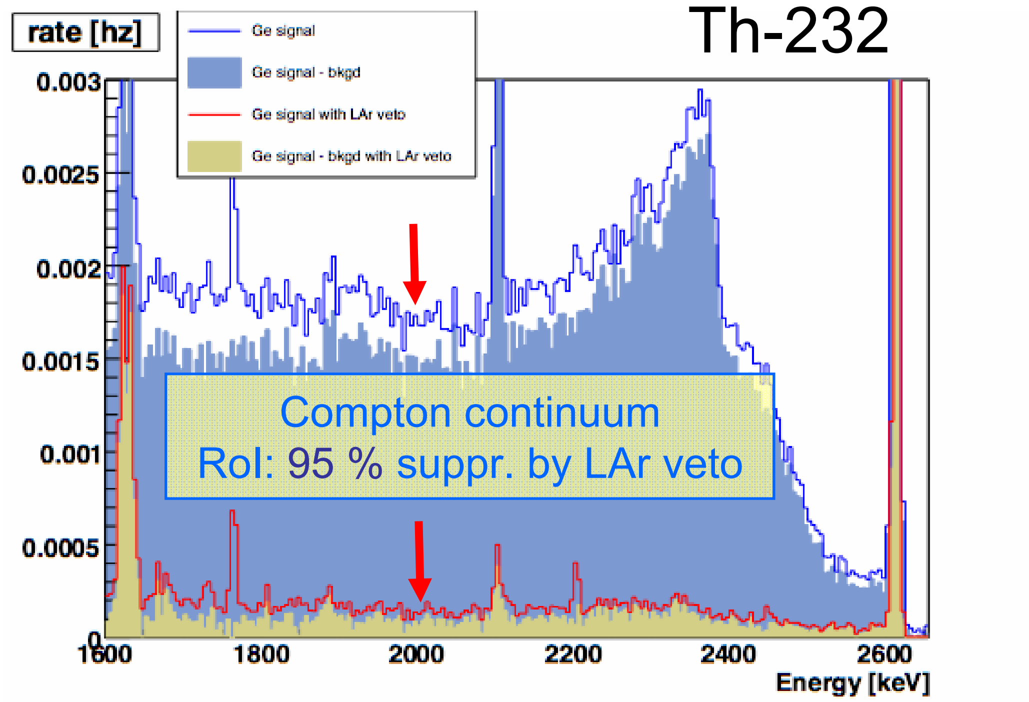
Kevin Kröninger, DPG Frühjahrstagung „Teilchenphysik“

R&D: LAr anti-coincidence

LAr anti-coincidence



Simultaneous detection of scintillation light



Suppression limited by size of Dewar (20 cm Ø)

Summary & Outlook

- Search for $0\nu\beta\beta$ rated at highest priorities
- Convergence of NME calculations – more efforts needed
- At least 3 different experiments (isotopes) required
- KK claim for evidence has many open questions, in particular PSA analysis
- Currently only two running experiments (Cuoricino, Nemo-3)
- New experiments under preparation
- GERDA: probe Majorana nature of neutrino with sensitivity down to inverse mass hierarchy scale

  phase I : background 0.01 cts / (kg·keV·y)

  ► scrutinize KKDC result within 1 year

  phase II : background 0.001 cts / (kg·keV·y)

  ► $T_{1/2} > 2 \cdot 10^{26}$ y , $\langle m_{ee} \rangle < 0.09 – 0.29$ eV

  phase III : world wide collaboration

  ► $T_{1/2} > \sim 10^{28}$ y , $\langle m_{ee} \rangle \sim 10$ meV
- 2007: Experimental installations (Cryotank, water tank, building etc.)
- End of 2008: target for detector readiness