DPG-Frühjahrstagung

Frankfurt, 17. - 21. März 2014

DPG-Frühjahrstagung mit den folgenden Fachverbänden

- Physik der Hadronen und Kerne
- Didaktik der Physik

Das GERDA Experiment zum neutrinolosen doppelten Betazerfall in ^{76}Ge

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Frankfurt, 19. März 2014

für die GERDA collaboration

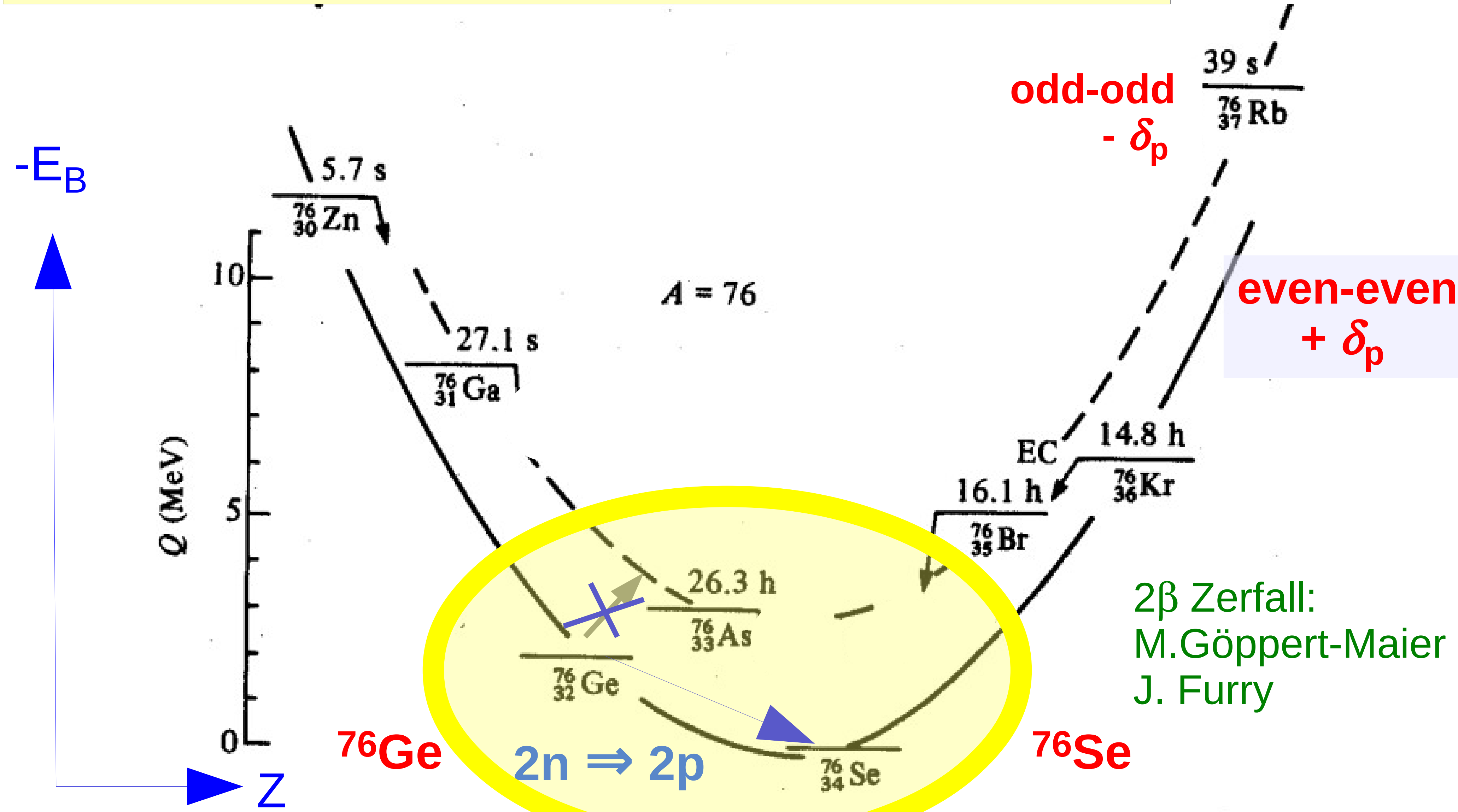
Kepler Center for Astro and Particle Physics

bmb+f - Förderschwerpunkt Astroteilchenphysik

Großgeräte der physikalischen Grundlagenforschung

Bethe-Weizsäcker Massenformel   für A = const. ⇨ Parabel

$$E_B = a_v A - a_s A^{2/3} - a_c Z(Z-1)/A^{1/3} - a_s (N-Z)^2 / A \pm \delta_p$$

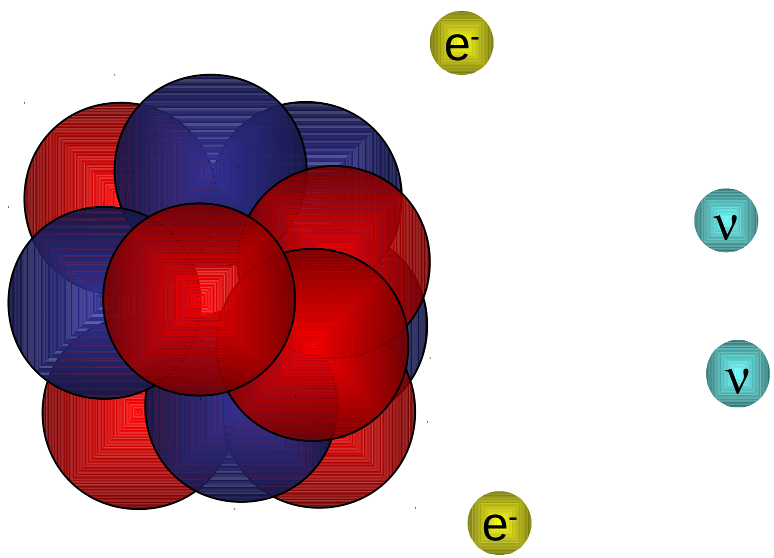


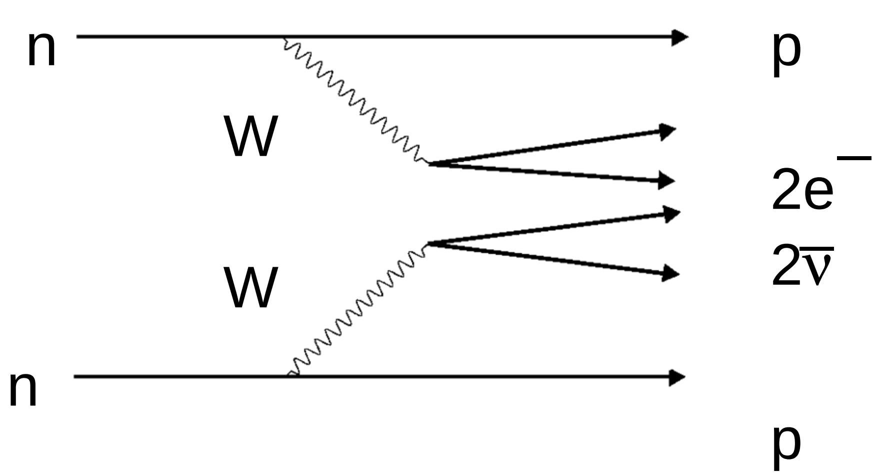
der doppelte Betazerfall

2nd order allowed weak process

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

(2νββ)

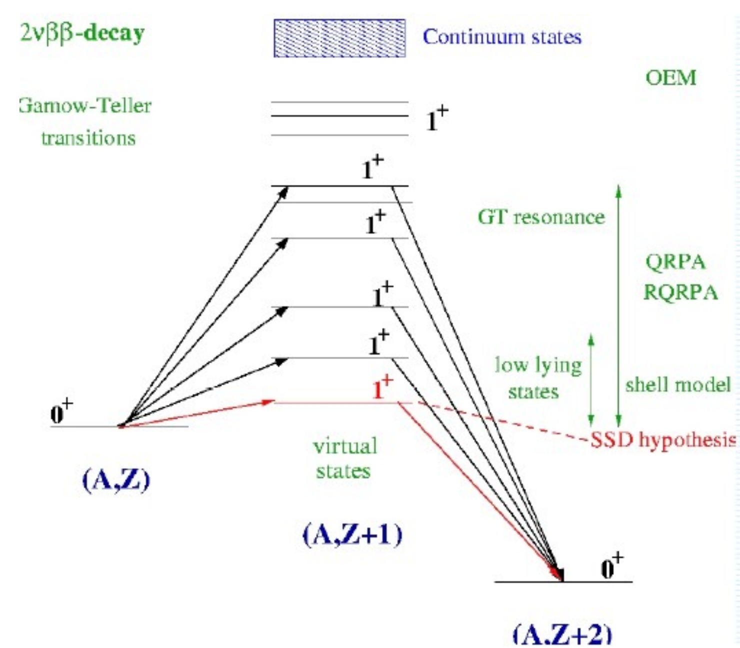




Gamow Teller

$$|\ M_{GT}\ |^2$$

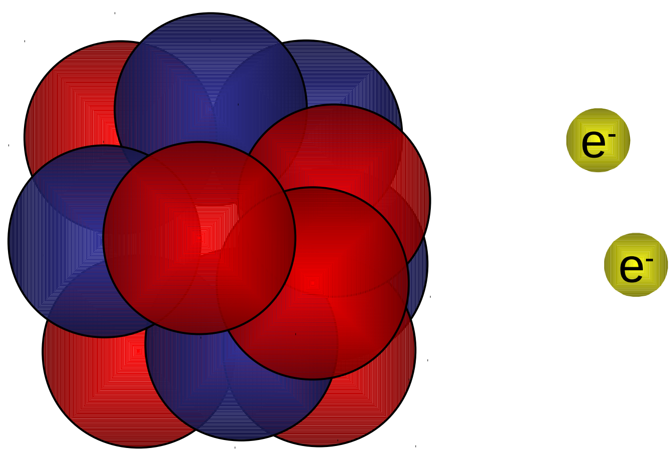
(p,n) (n,p)



der doppelte Betazerfall

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

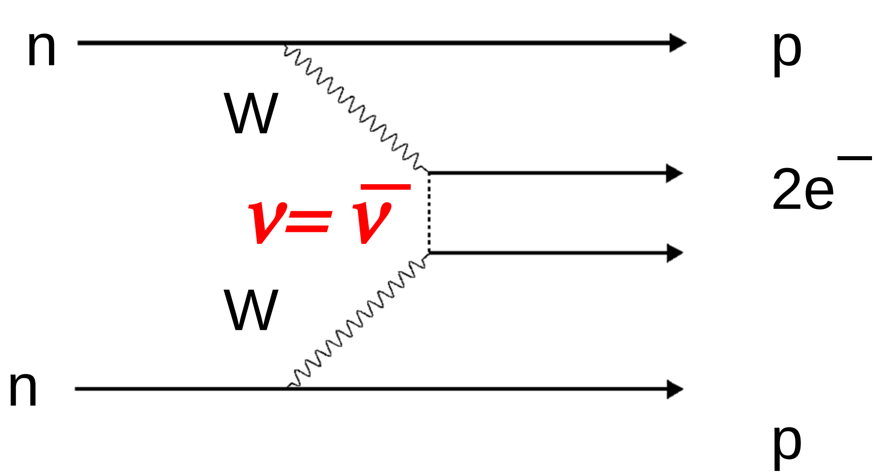
$(0\nu\beta\beta)$



Gamow-Teller and Fermi

$$\left| M_F - (g_a / g_v)^2 \, M_{GT} \right|^2$$

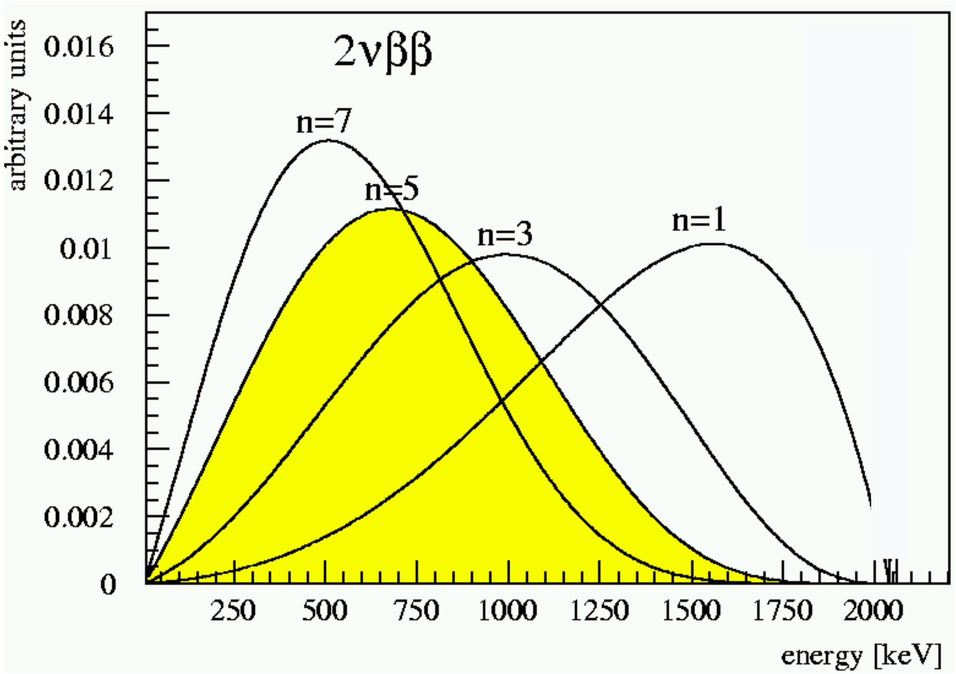
neutrino = anti-neutrino
(Majorana-Teilchen)

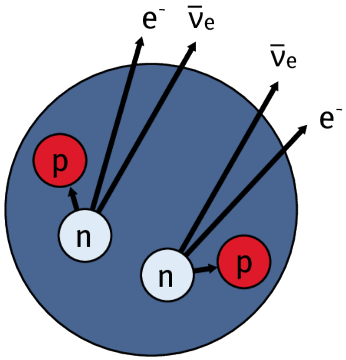


- endliche Masse (Osz.)
- Erhaltung der Leptonzahl verletzt: $\Delta L=2$

Spektrum: Summenenergie beider Elektronen

2νββ Spektrum





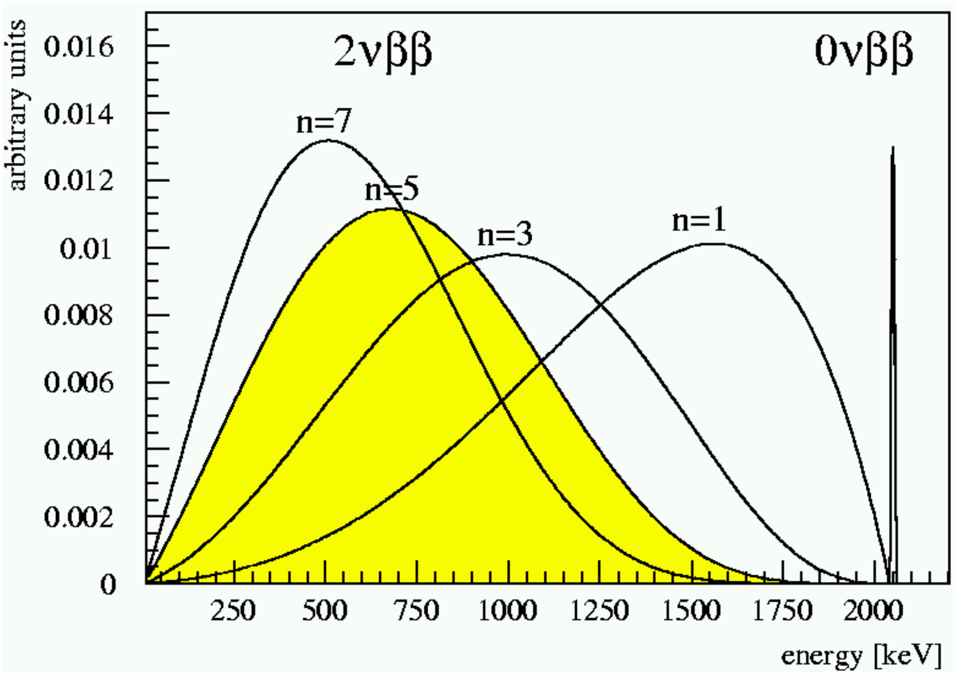
ν, Majoron,..

$$2\nu\beta\beta: \; T_{1/2} \sim 10^{\sim 21} \text{ yr}$$

$(10^{19} – 10^{24})$

Spektrum: Summenenergie beider Elektronen

0νββ Signal: Peak bei Q-Wert der Reaktion

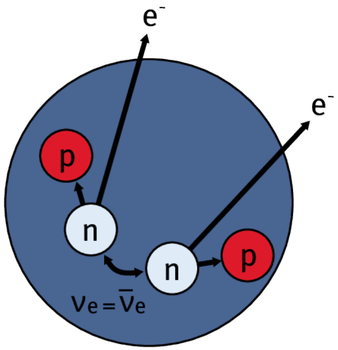


Peak vorhanden ?

Majorana - Natur

Messgröße: cts ⇒ Halbwertszeit

"Physik jenseits des SM"



ν, Majoron,..

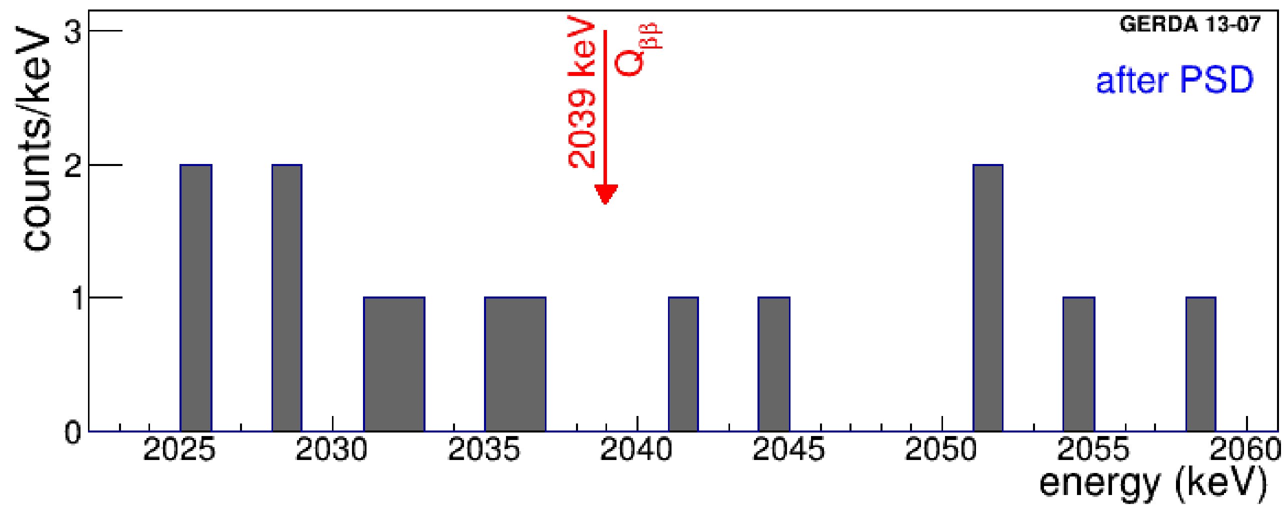
2νββ: $T_{1/2}$ ~ 10^{21} yr

0νββ: $T_{1/2}$ > 10^{25} yr

Erweiterungen des Standard Modells

Neutrinoloser doppelter Betazerfall

Summe der Elektronenenergien



2039 keV

$Q_{\beta\beta}$ of ^{76}Ge

GERDA Phase I

$\mathcal{E}$ = 21.6 kg yr

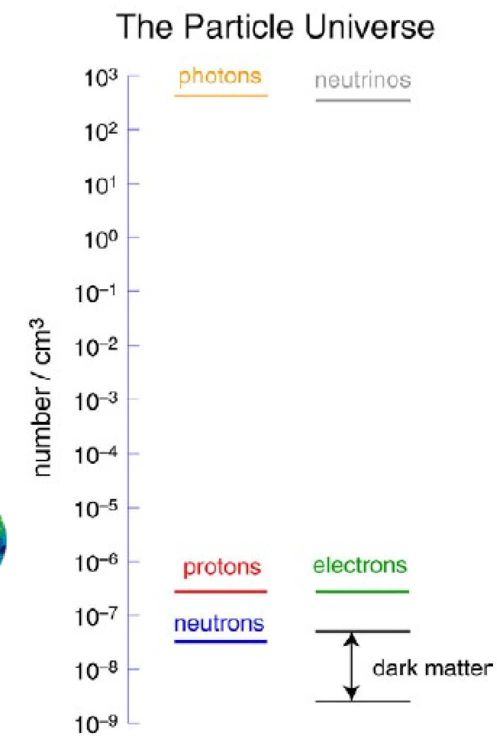
PRL111 (2013) 122503

Inhalt:

- Einleitung
- Neutrinos
- 0νββ Experimente
- GERDA Experiment
- GERDA Ergebnisse
- andere Experimente
- Ausblick

Neutrinos

Teilchen des Standard Models (mit $m_\nu = 0$, ν_L)



$N_\gamma, N_\nu \gg N_p$ $(\sim 10^{-9})$

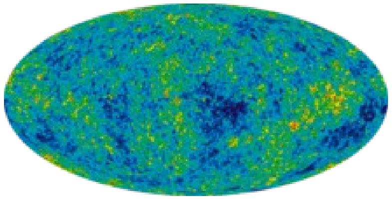
Baryon-Asymmetrie (Materie-Antimaterie)

Leptogenese, CPV auch im Leptonsektor?

kosm. Neutrino-Hintergrund

(relic neutrinos wie CMB)

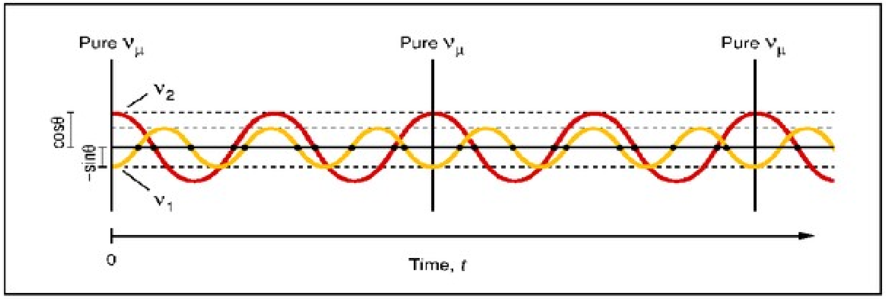
2 s ↔ 380.000 yr

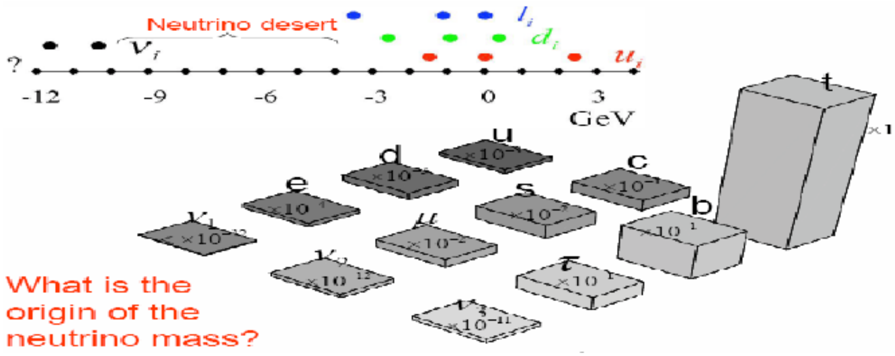


kosm. Strukturbildung, Multi-Messenger

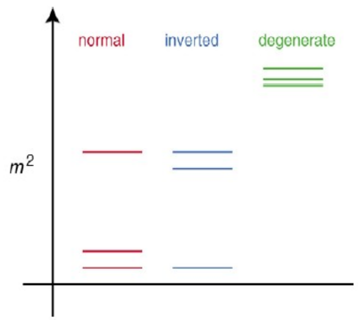
3 Flavor !? Sterile ν ?

ν : spin ½, keine Ladung, links-hand., $m \neq 0$, 3 Flavor





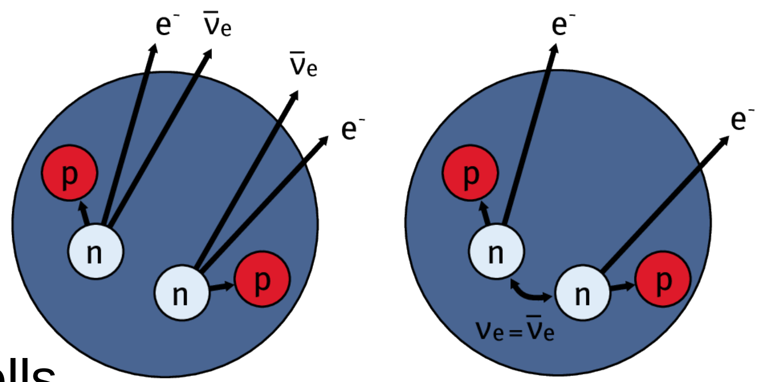
Verständnis der Eigenschaften von ν !



absolute Massenskala, Hierarchie (KATRIN,PINGU)

größtes Interesse: ist ν vom Typ Majorana ?

$$\nu \equiv \bar{\nu}$$



0νββ Zerfall

Verletzung der Leptonzahl durch 0νββ

Erweiterung des Standard Modells
(Baryonasymmetrie, Leptogenese, ...)
Massenerzeugung

Mechanismus

Austausch eines leichten ν, Hinweis auf m_ν, (mittels NME)
schwere ν in LR symm. Modell, R-hand W, see-saw, Majoron,
R-Parität verletzend SUSY,
MEG ($\mu \rightarrow e^- \gamma$, $\mu \rightarrow e^- e^+ e^-$)
leichter ν Austausch wahrscheinlich, falls LHC kein Signal findet

Notes from the Editors: Highlights of the Year 2013 (by APS)

Physics looks back at the standout stories of 2013. (http://physics.aps.org/articles/v6/139)

Majorana Fermions Annihilate in Nanowires

nanowires sind aber Quasi-Teilchen

Dark Matter is Still Obscure
Strangers from Beyond our Solar System
Light Stopped for One Minute
Four-Quark Matter
What's Inside a Black hole?

ν sind Elementar-teilchen

Methoden und Experimente: Nachweis der Elektronen

meist: kalorimetrisch (tracking bei NEMO)
(Ionisation,Szintillation,Wärme)

erwarten $T_{1/2} > 10^{25}$ yr

Annahme: 1 Zerfall pro Jahr : Rate $N_{\beta\beta} / t \sim 1$

$$T_{1/2} = \ln 2 \cdot (N_A/A) \cdot M \cdot (N_{\beta\beta} / t)^{-1}$$

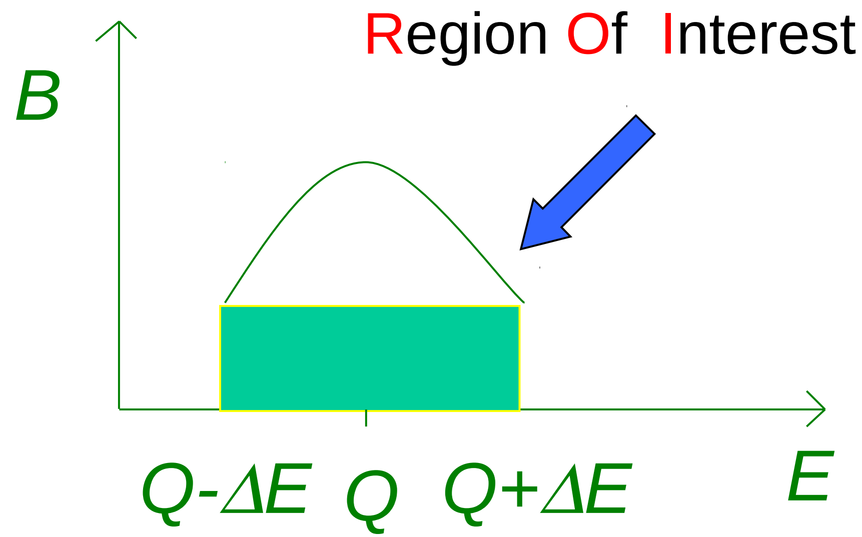
für ^{76}Ge : 2,1 kg @ 86% angereichert

Verluste: Effizienz, Untergrund...

Kosten: 1g $^{76}GeO_2$ für 60 €

Sensitivität $S_{1/2}$ für $0\nu\beta\beta$

$$T_{1/2} = \ln 2 \bullet (N_A/A) \bullet M \bullet (N_{\beta\beta} / t)^{-1}$$



$N_{obs} \sim M * t$ für $b = 0$

$N_{BG} \sim M * t * \delta E * b$

Sensitivität $\sim N_{obs} / \sqrt{N_{BG}}$

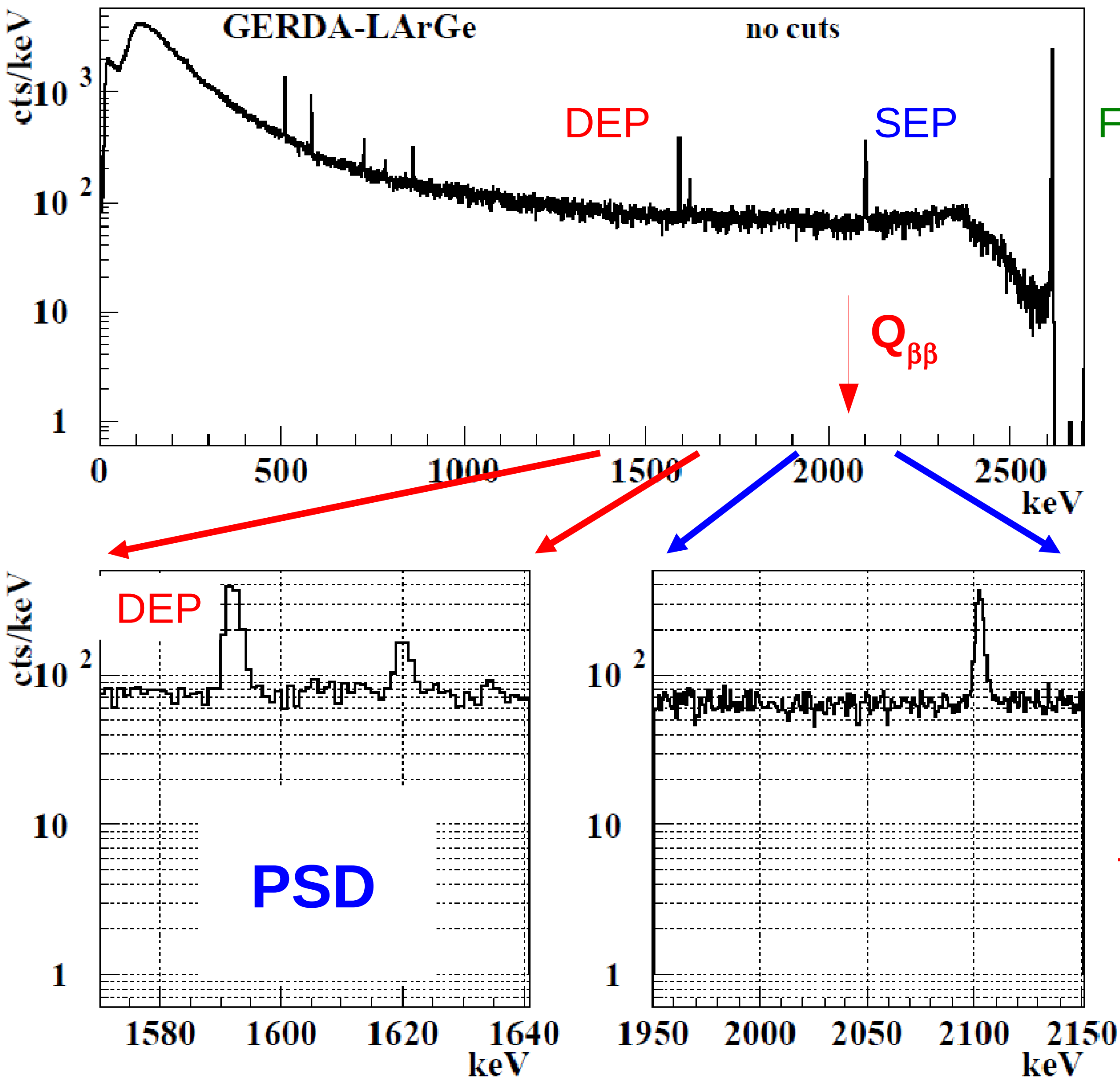
$$S_{1/2} \propto a * \varepsilon * \sqrt{\frac{M * t}{\delta E * b}}$$

relevante Einheiten: cts/(mol yr δE)

cts/(kg yr keV)

a : isotop. Anreicherungsgrad
ε : Nachweiseffizienz
M : Masse
t : Messzeit
δE : Energie auflösung
b : Untergrundrate

^{228}Th Spektrum



^{228}Th

2615 keV

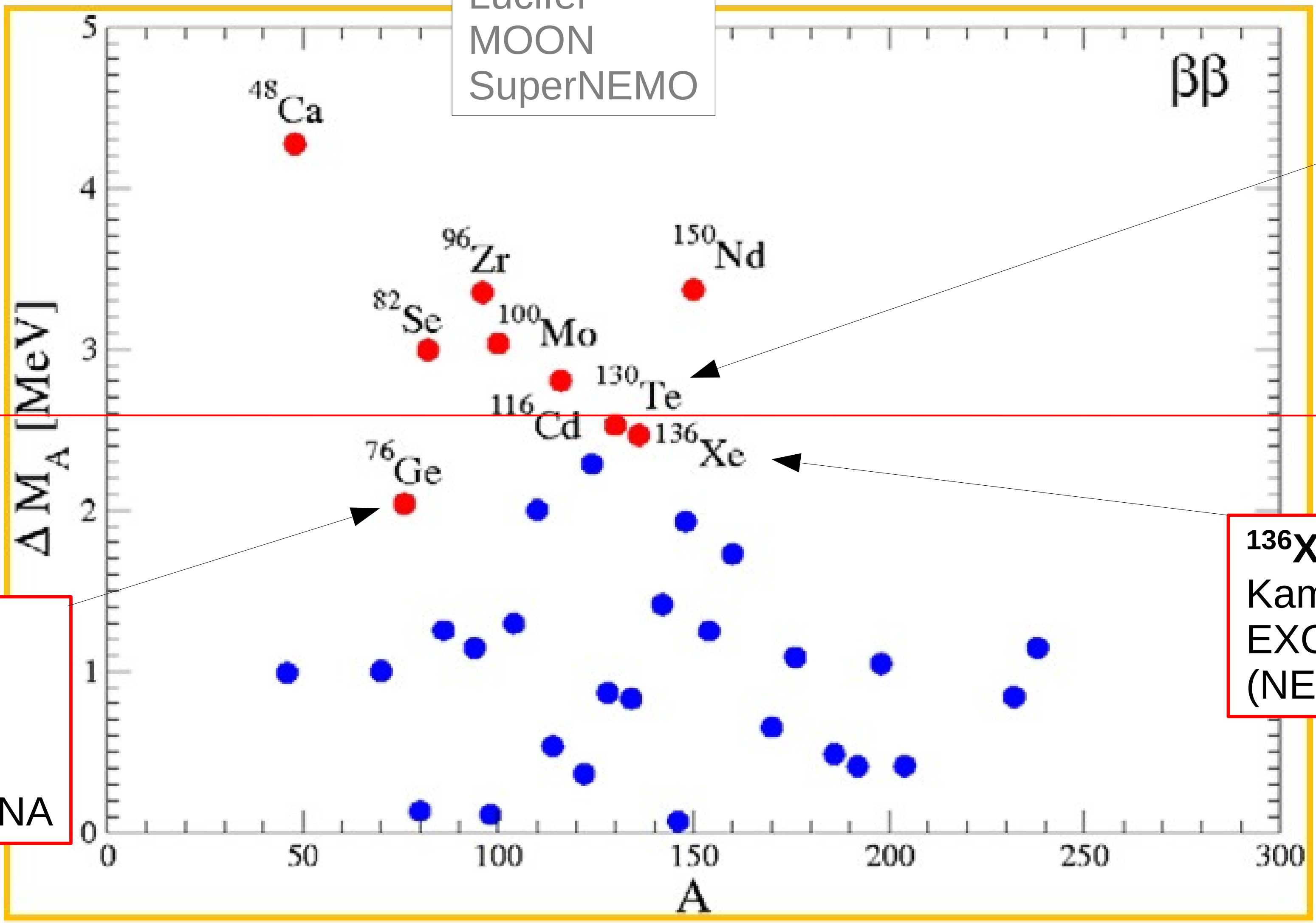
^{208}Tl

Untergrund durch natürliche Zerfallsreihen: U, Th

^{76}Ge: $Q_{\beta\beta}$ = 2039 keV

35 Kandidaten

Cd,Mo,Te
COBRA
Lucifer
MOON
SuperNEMO



^{130}**Te**
CUORE
SNO+

^{228}Th

^{136}**Xe**
KamLAND-Zen
EXO-200
(NEXT)

^{76}**Ge**
HdM
IGEX
GERDA
MAJORANA

^{76}Ge Heidelberg-Moskau & IGEX

HDM (5 Det.)

Klapdor-Kleingrothaus et al.

Phys Lett B586 (2004) 198

71.7 kg·yr

$T_{1/2}$ > 1,9 ·10 ^{25} yr (90%CL)

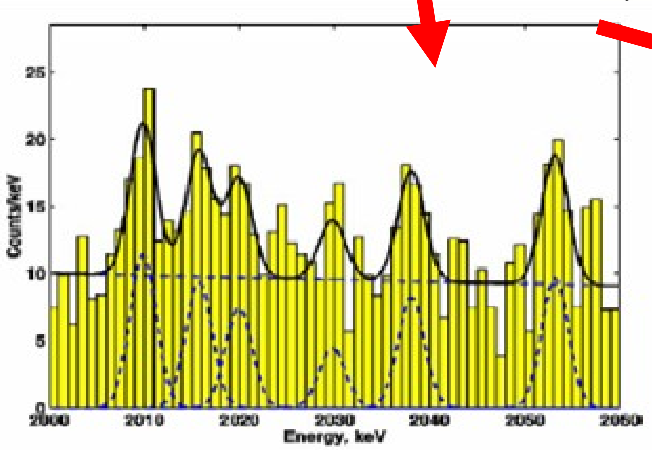
IGEX (3 Det.)

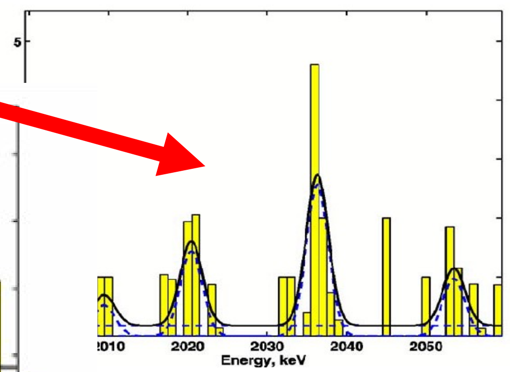
Aalseth et al.

Phys Rev D65 (2002) 092007

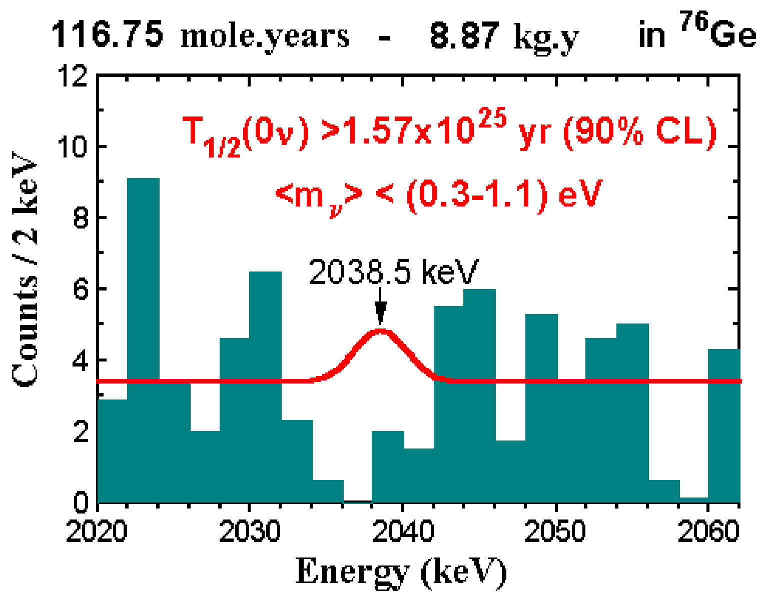
8.9 kg·yr

$T_{1/2}$ > 1,6 ·10 ^{25} yr (90%CL)





MPLA21 (2006)

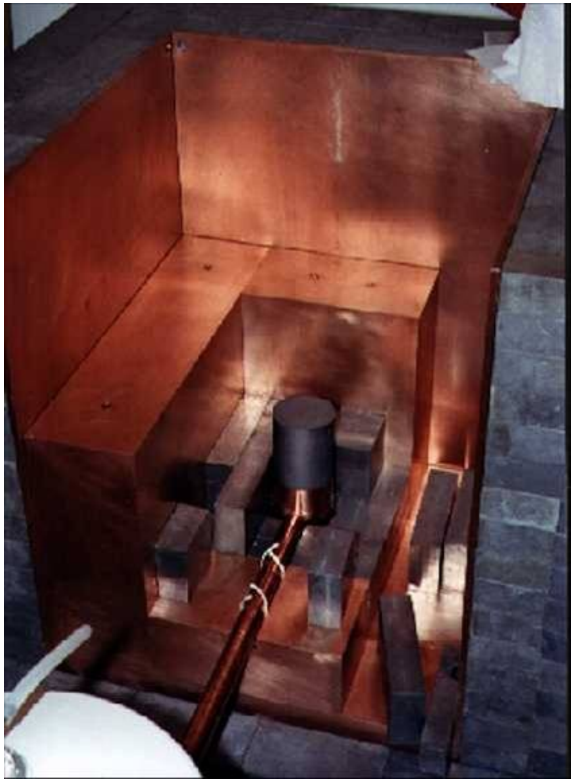


Kritik: B.SSchwingenheuer in Ann.Physik 525 (2013) 269

GERDA – die andere Idee

G. Heusser, Ann. Rev. Nucl. Part. Sci. 45 (1995) 543

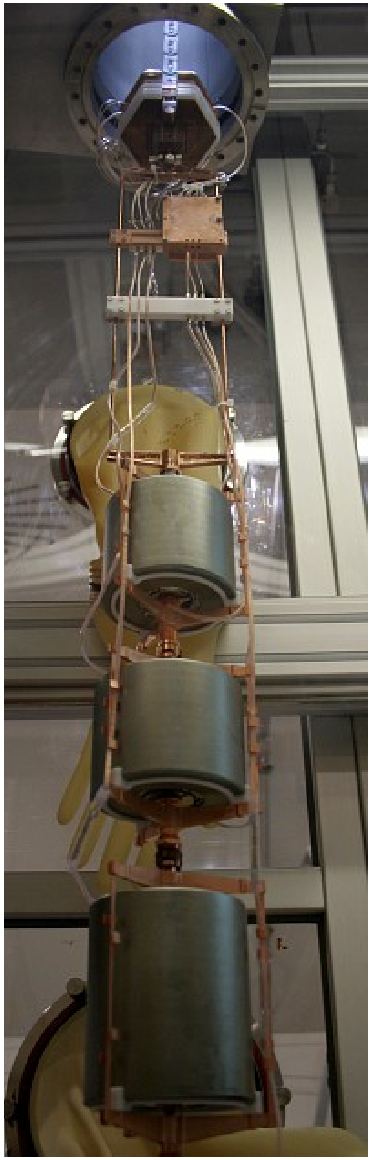
"... Material mit kleinem Z rund um Detektor..."
"...Ge Diodes direkt in Kühlflüssigkeit montieren"



Anreicherung an ^{76}Ge
Selektion der Materialien
kosm. Muon Unterdrückung
FE-Elektronik
Pulsform-Analyse

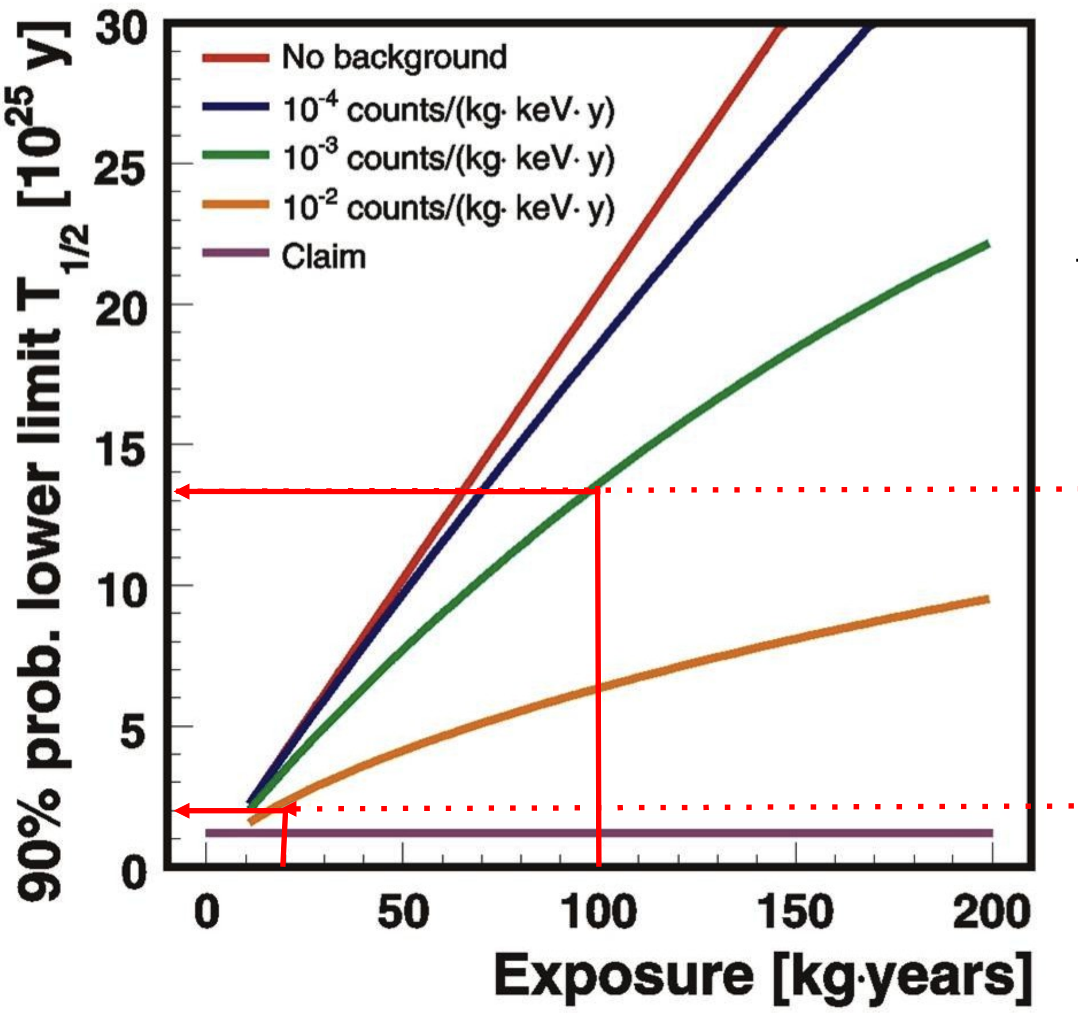
Phase I: Proof of Principle
FWHM < 5 keV & BI ~ 10^{-2} cts/(keV·kg·yr)

Phase II: verbesserter BI ↷ $T_{1/2}$
FWHM < 3 keV & BI ~ 10^{-3} cts/(keV·kg·yr)



→ HdM, Majorana: kompakte, klassische Abschirmung

Sensitivität

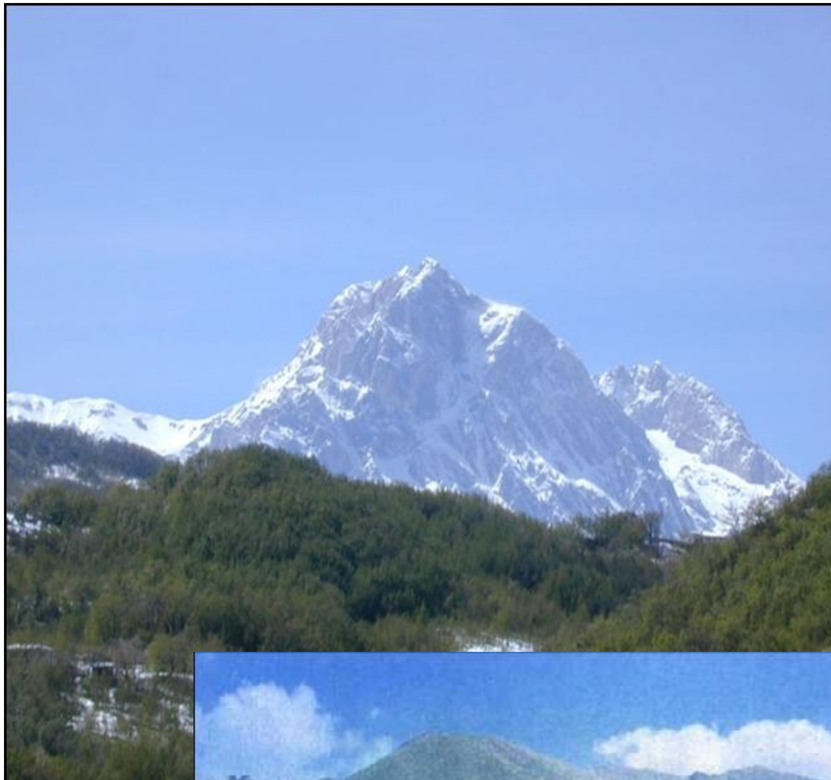


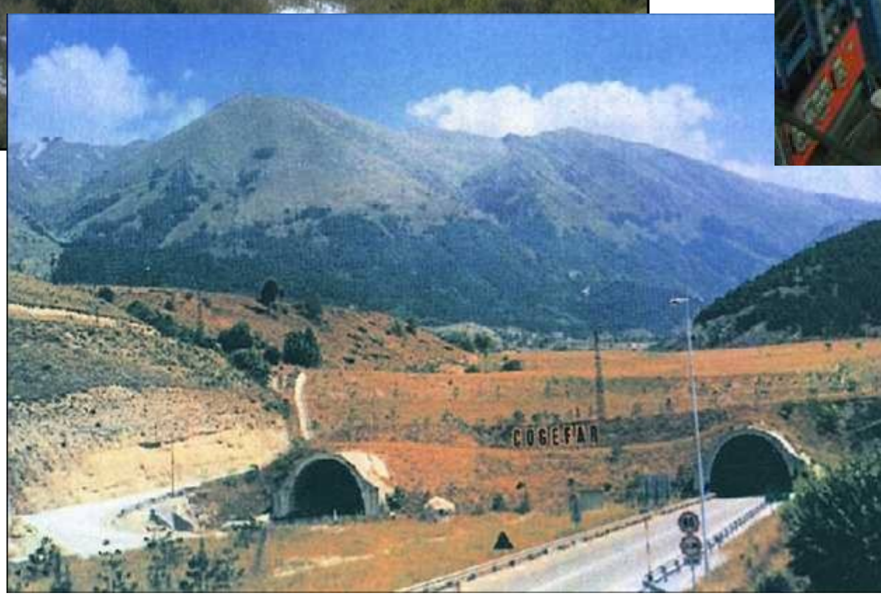
Phase II:
neue enr. BEGe Detektoren (20 kg)
BI ≈ 0.001 cts / (keV kg yr)
δE ~ 3 keV (FWHM)
Sensitivität nach 100 kg yr

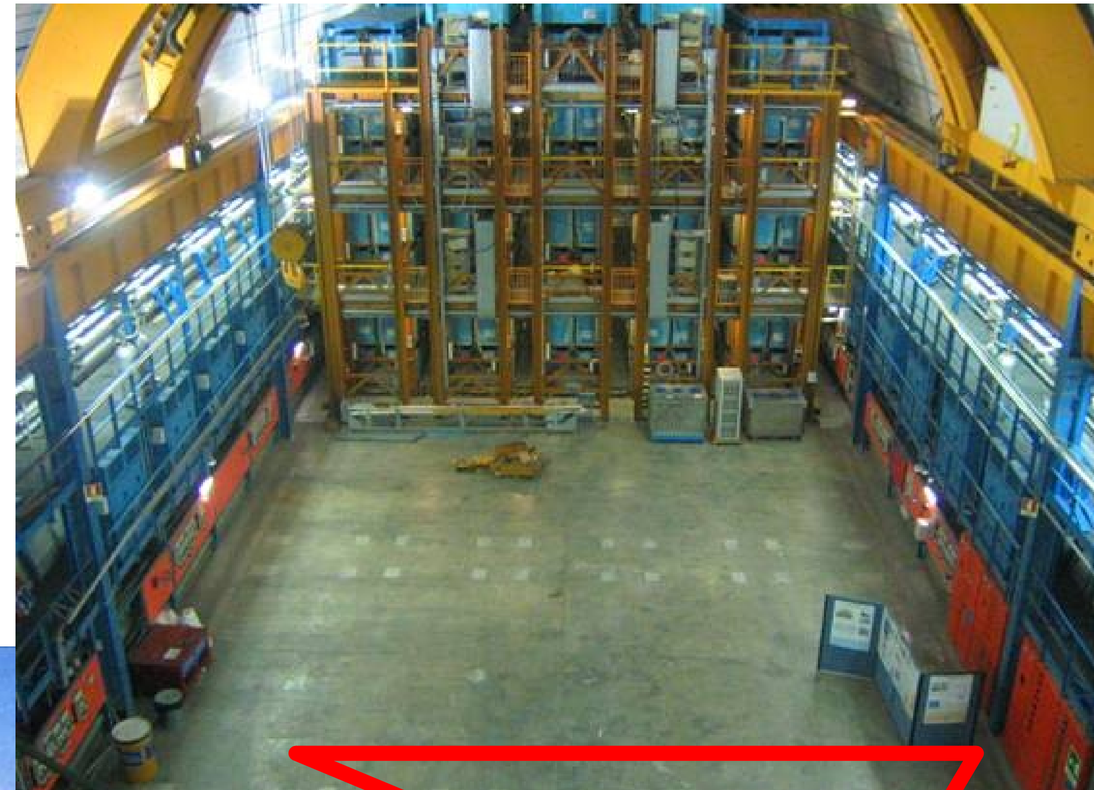
Phase I:
überarbeitete HdM & IGEX (18 kg)
BI ≈ 0.01 cts / (keV kg yr)
δE < 5 keV (FWHM)
Sensitivität nach 20 kg yr

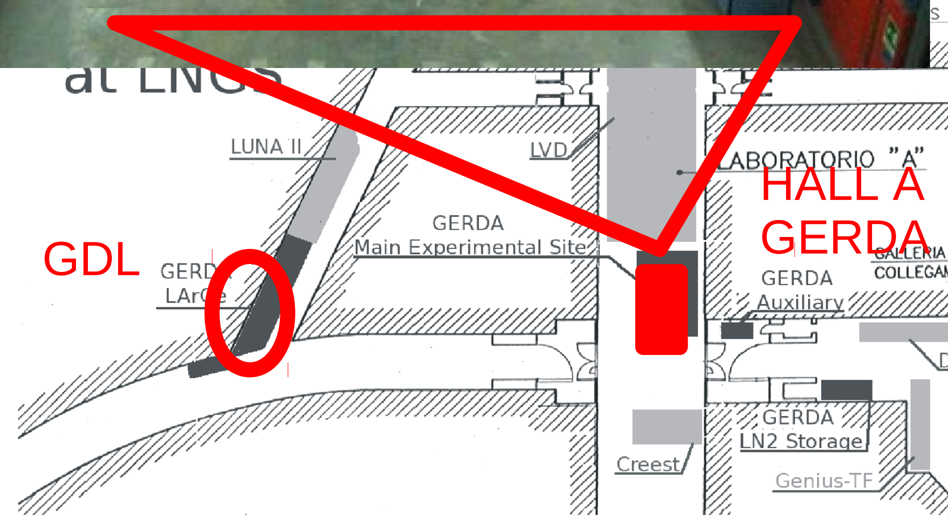
claim 2004

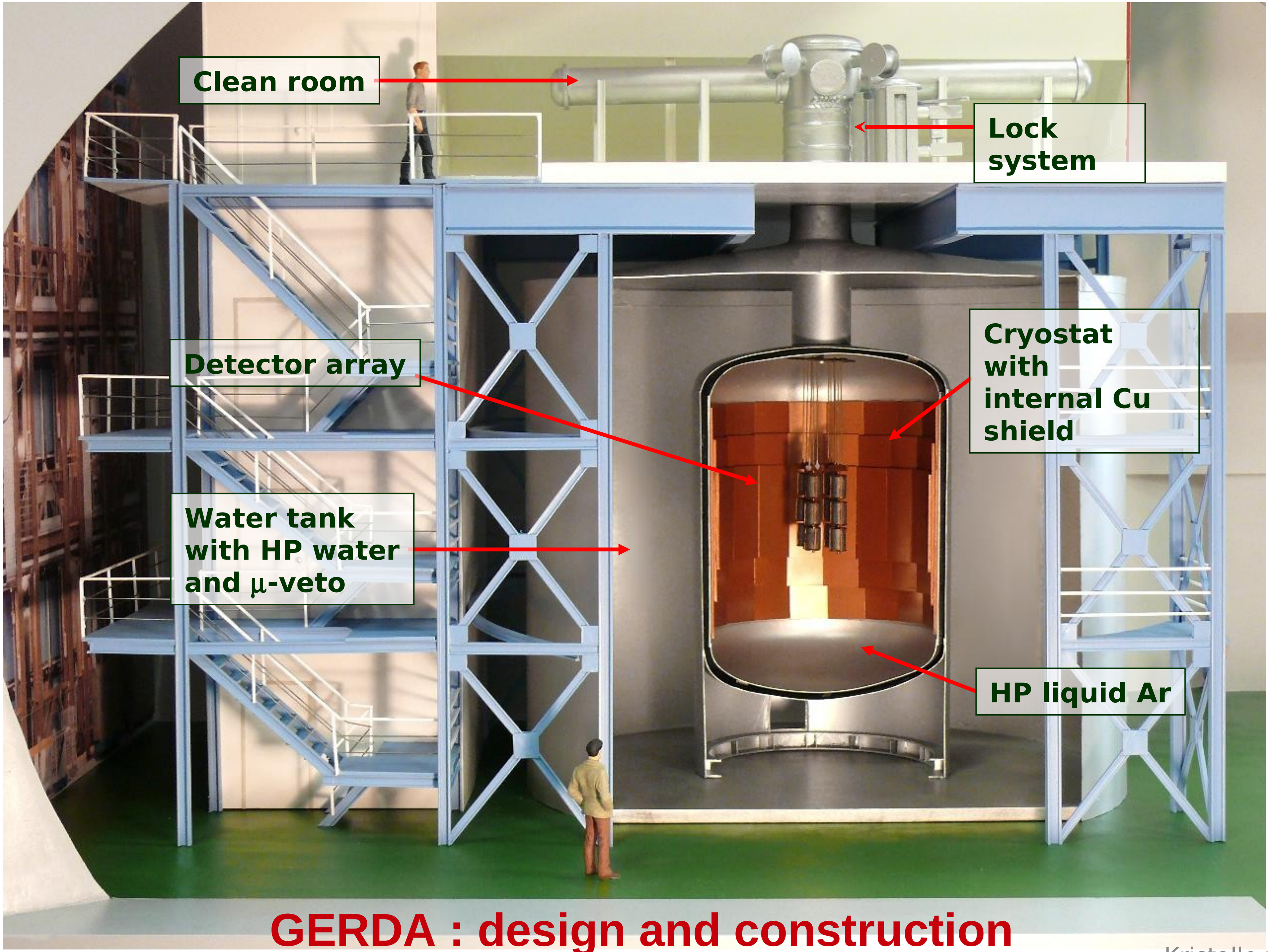
GERDA @ LNGS




COGEFAR




LUNA II
LVD
LABORATORIO "A"
HALL A
GERDA
GDL
GERDA
Main Experimental Site
GERDA
Auxiliary
GERDA
LN2 Storage
Creest
Genius-TF

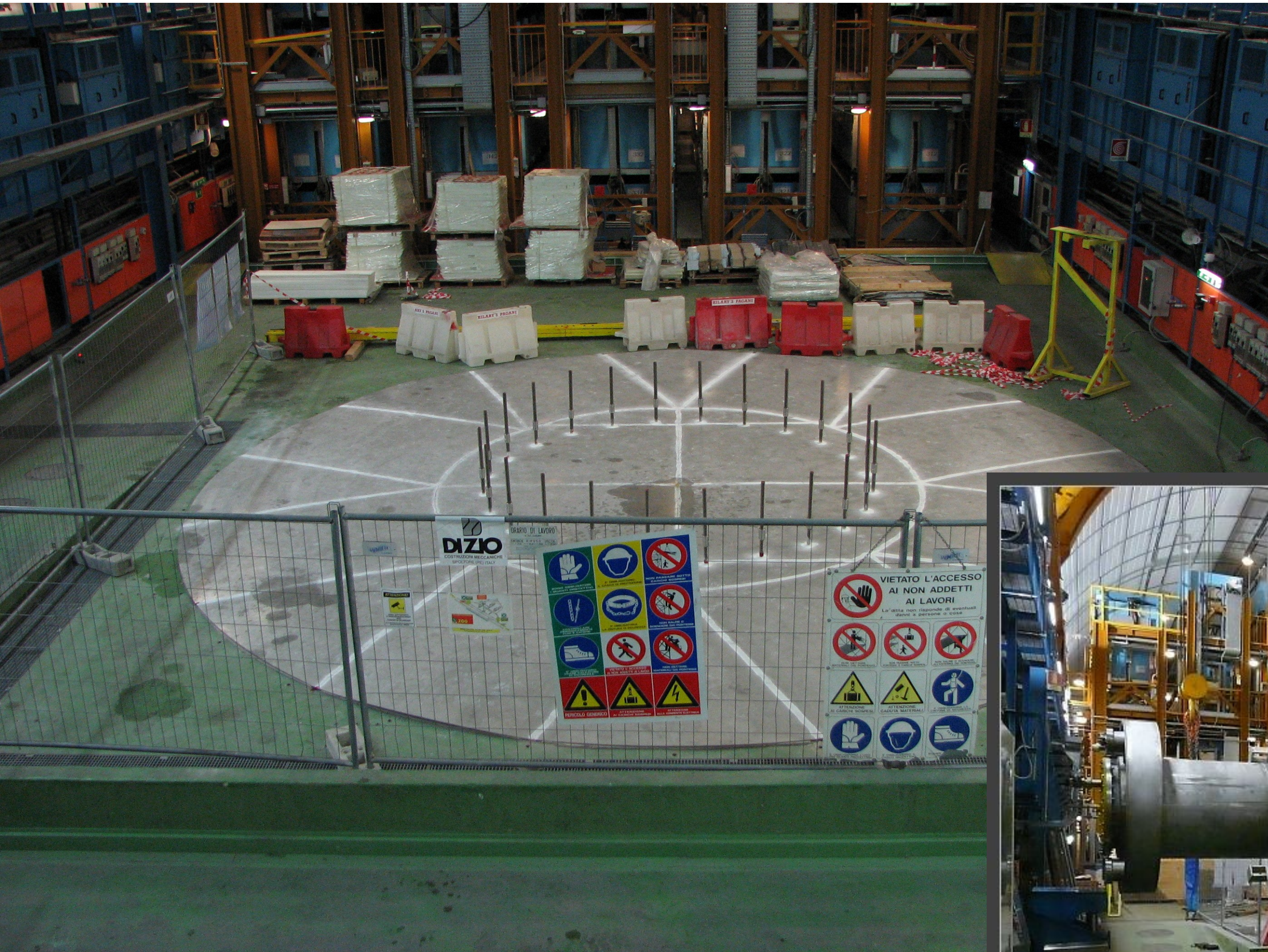


GERDA : design and construction

Kristalle vergrößert

proposal 2004

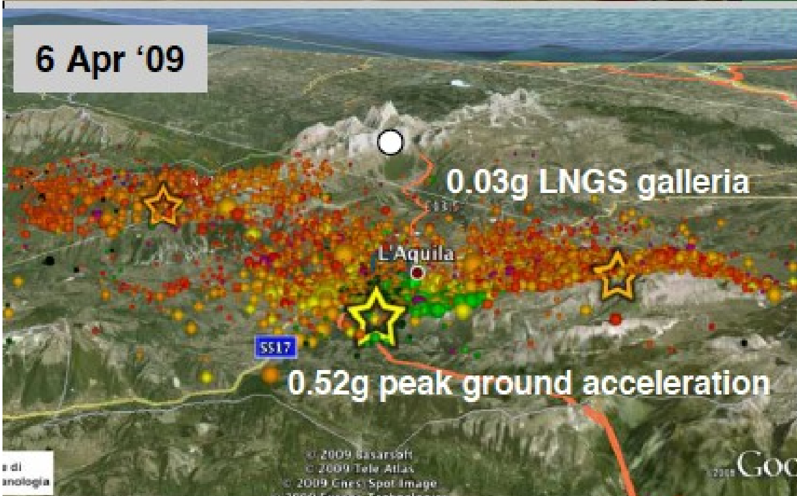
Aufbau @ LNGS

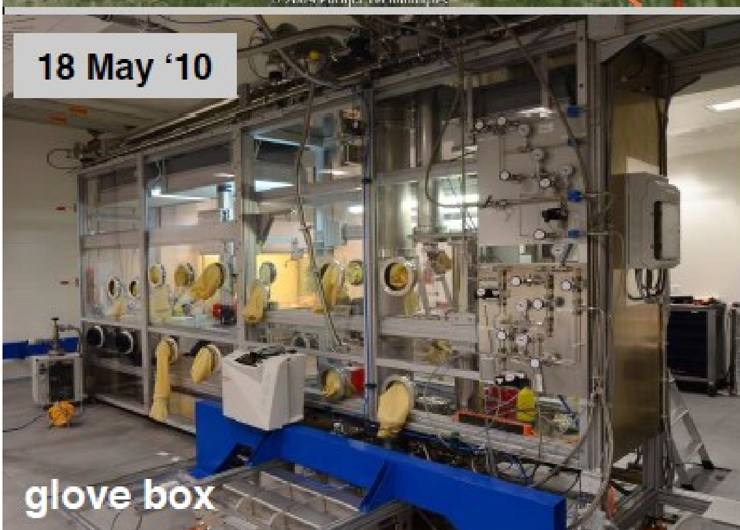


Februar 2008

März 2008

Der Aufbau von GERDA 2008-2010



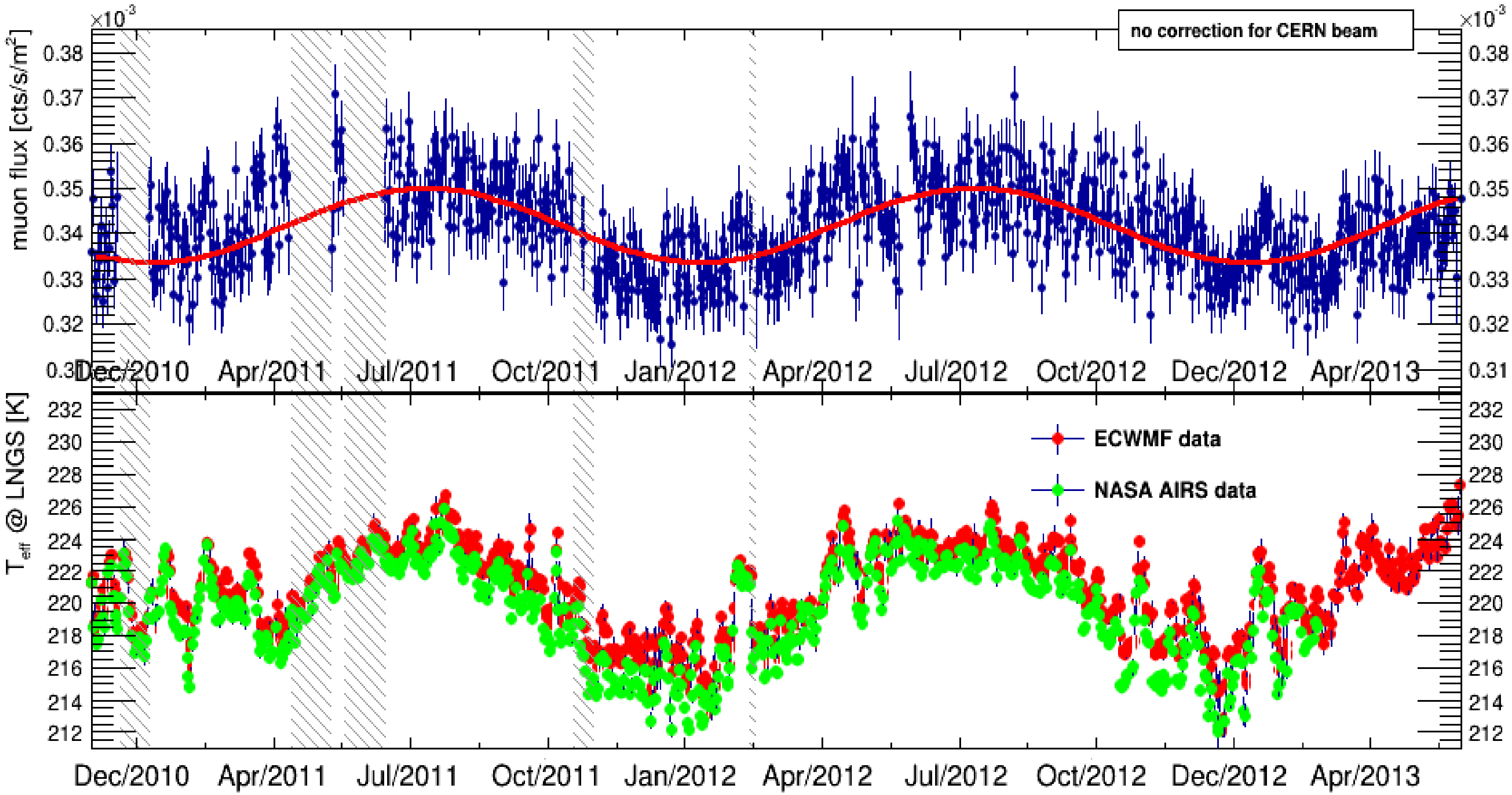


Cryostat filled since December 2009

Multiplizität der 66 Cherenkov PMT

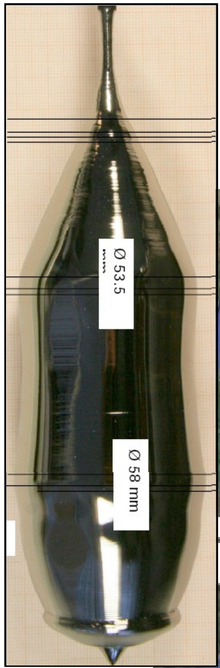
3 Ausfälle in 3 yr

muon rejection efficiency ε > 97 %



Path of new 37.5 kg of enrGe (86% enrichment in 76Ge):

from isotope separation to final Phase II detectors

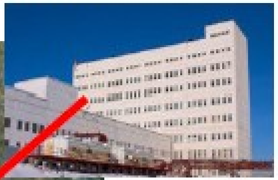


3) Crystal pulling at Oak Ridge (USA)

4) Detector production at Olen (Be)

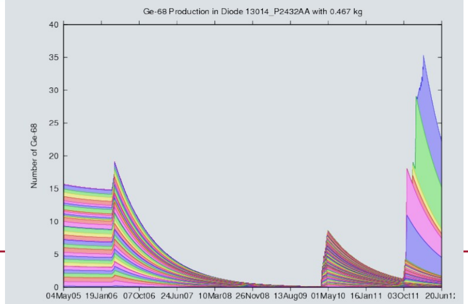
2) Reduction and zone refinment at Goettingen (Germany)

1) Isotope enrichement at ECP, Svetlana (Ru)



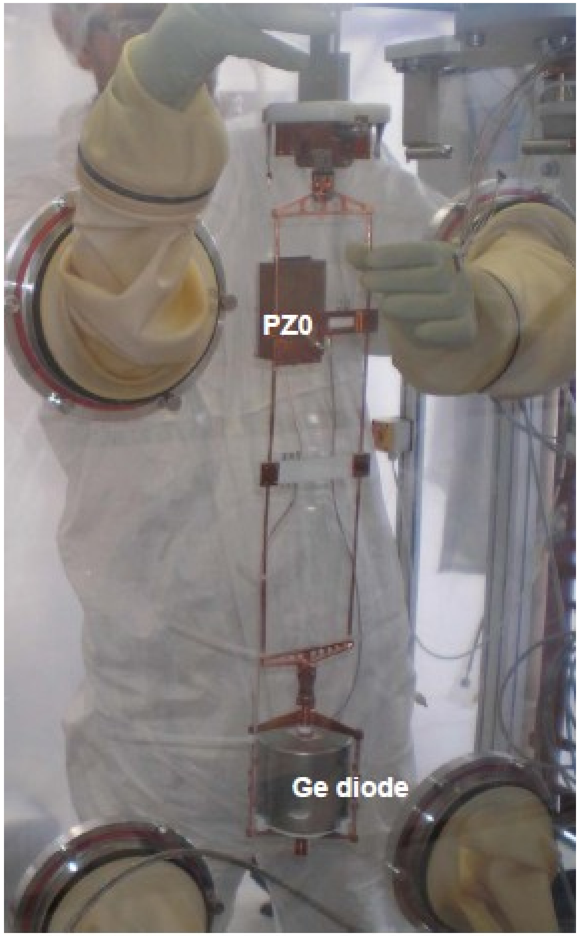
To minimize activation by cosmic ray:

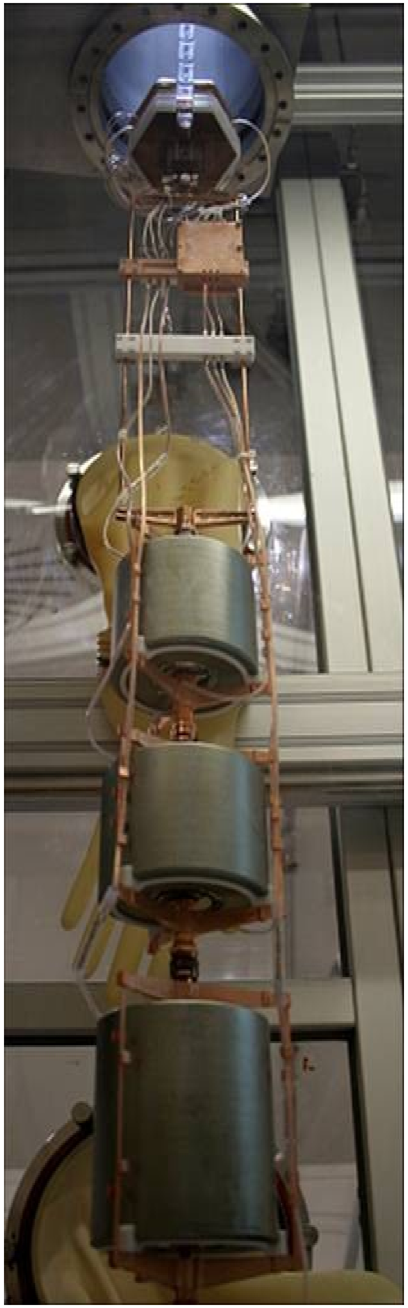
- Transportation by truck or ship in shielded containers
- deep underground storage



Montage der Ge Dioden

Tests in LArGe





Distanz zwischen Diode und FE-Vorverstärker

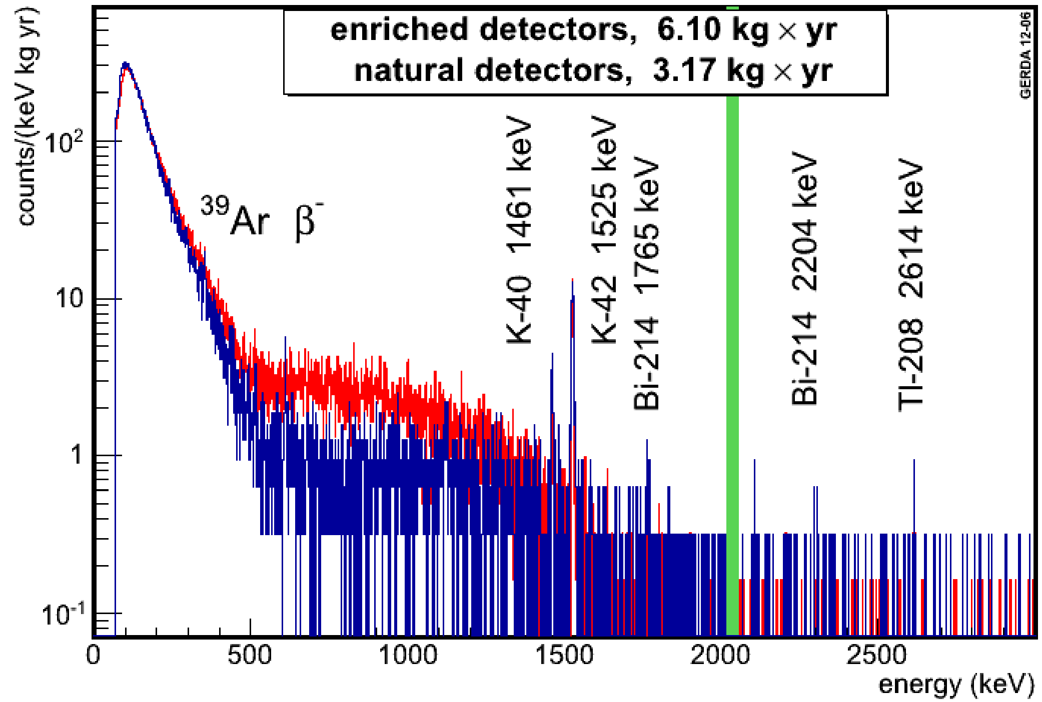
^{42}Ar Untergrund (β & γ)

GERDA proposal:

^{39}Ar: 1.01 Bq/kg (NIM A 574)

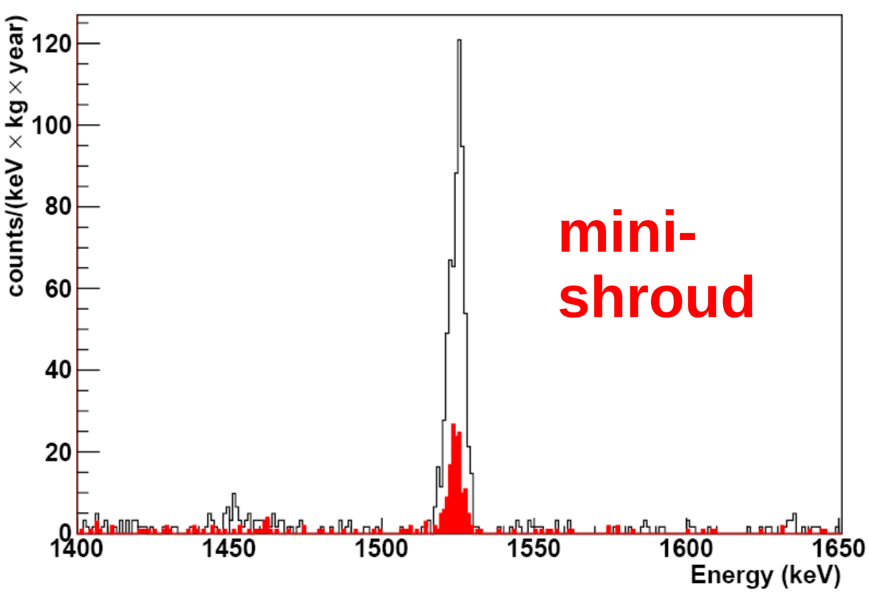
^{42}Ar/^{nat}Ar $< 3 \cdot 10^{-21}$ (90% C.L.)

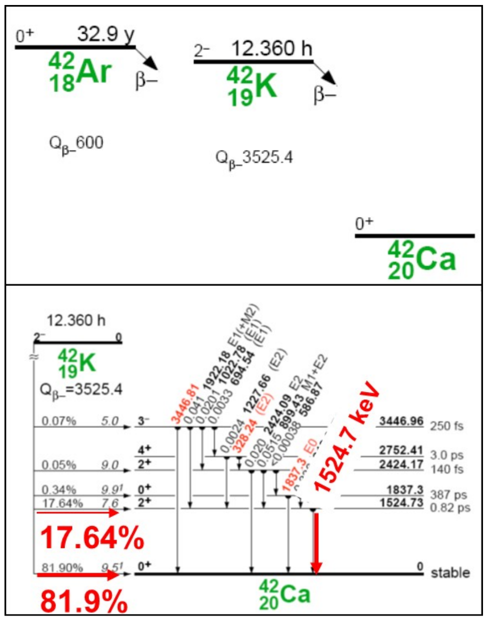
Barabash et al (2002)



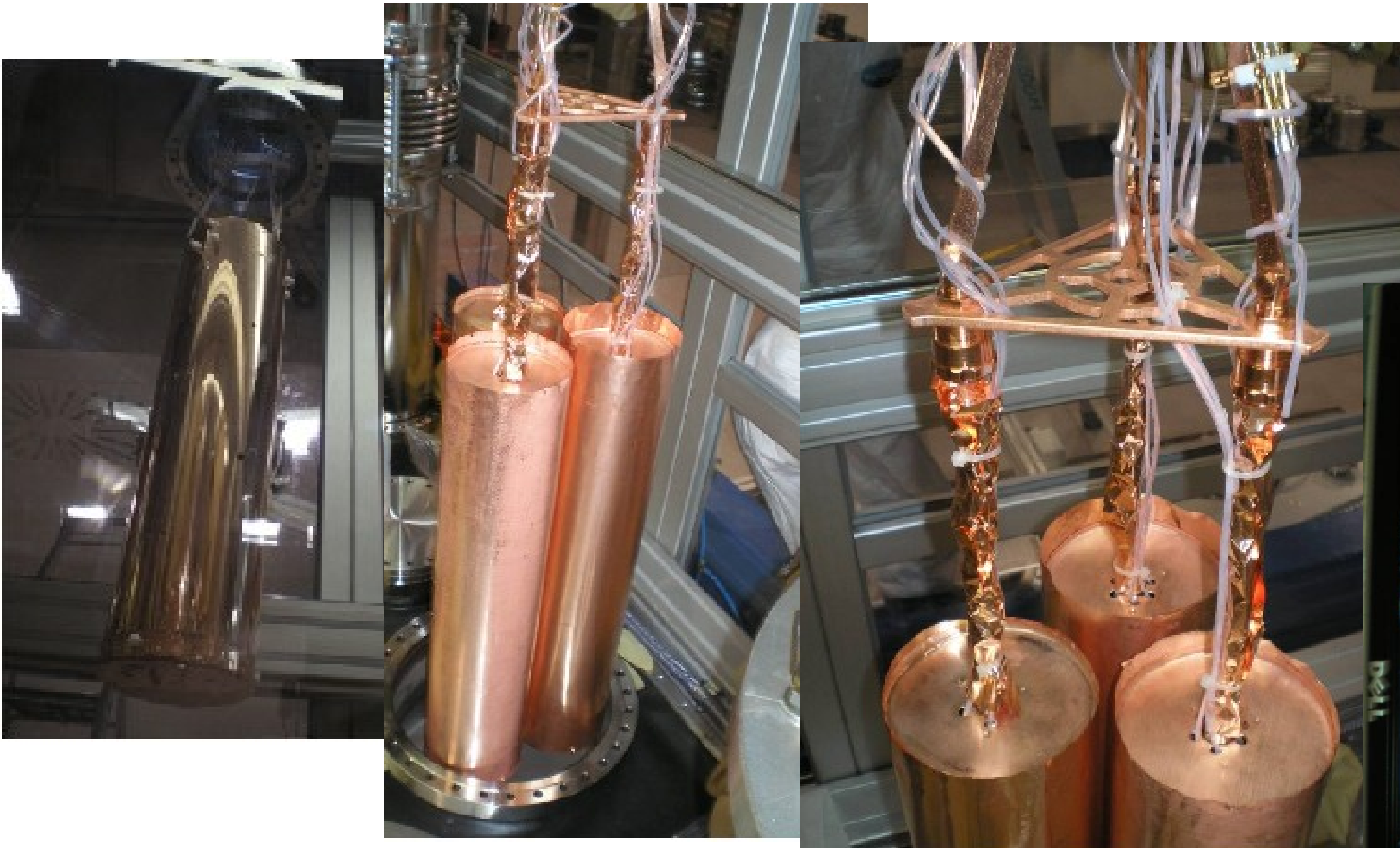
GERDA Daten:

^{42}Ar/^{nat}Ar $\sim 7 \cdot 10^{-21}$





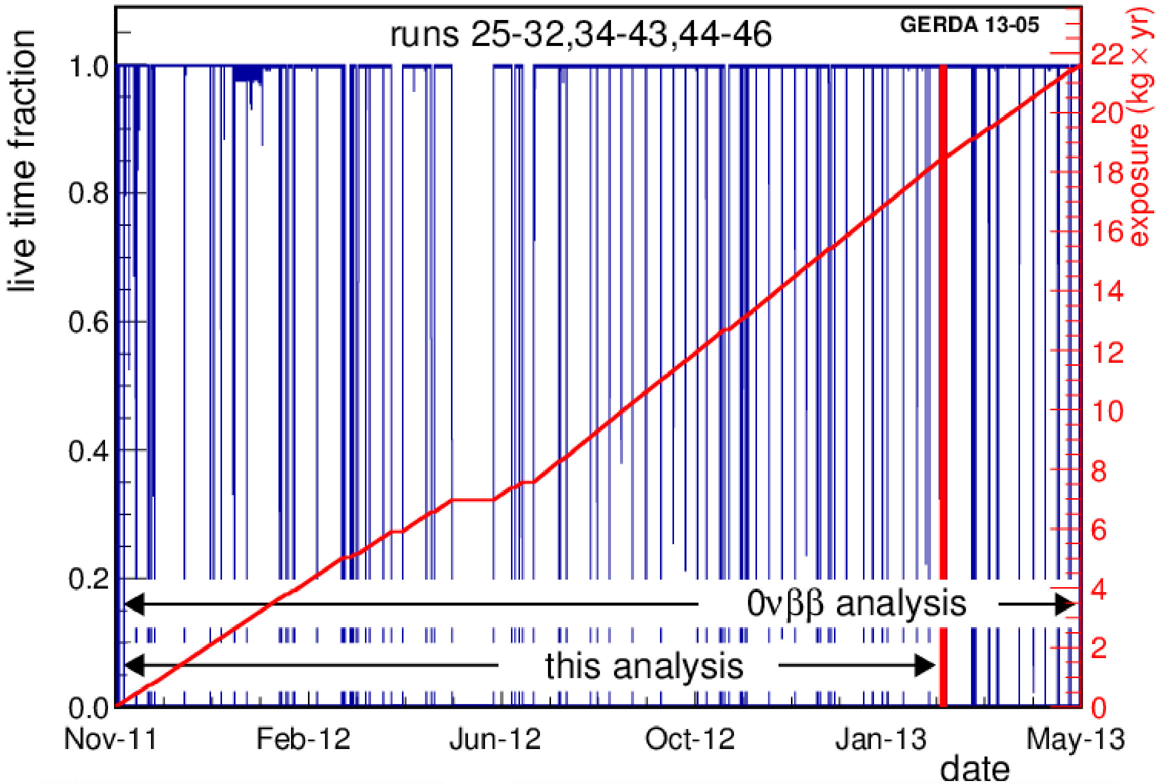
Einbringen von 11 Detektoren im Oktober 2011 (8 +3)

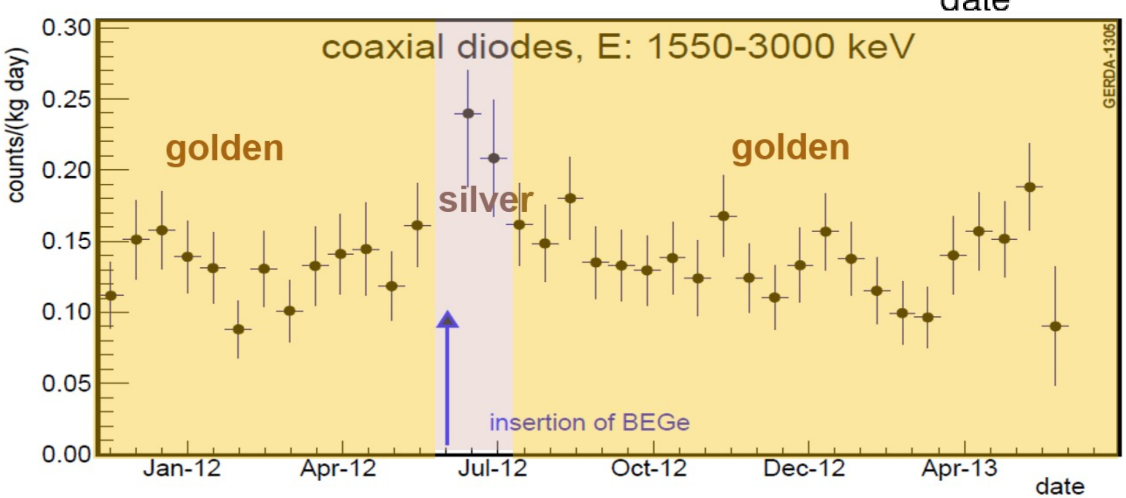


2 'angereicherte' Detektoren hatten sofort Probleme
(großer Leckstrom) kein Beitrag zur Analyse

6 'angereicherte' Detektoren mit 14.6 kg (totaler) Masse
3 'natürliche' Detektoren mit 7.6 kg (totaler) Masse

zusätzlich 5 BEGe Detektoren

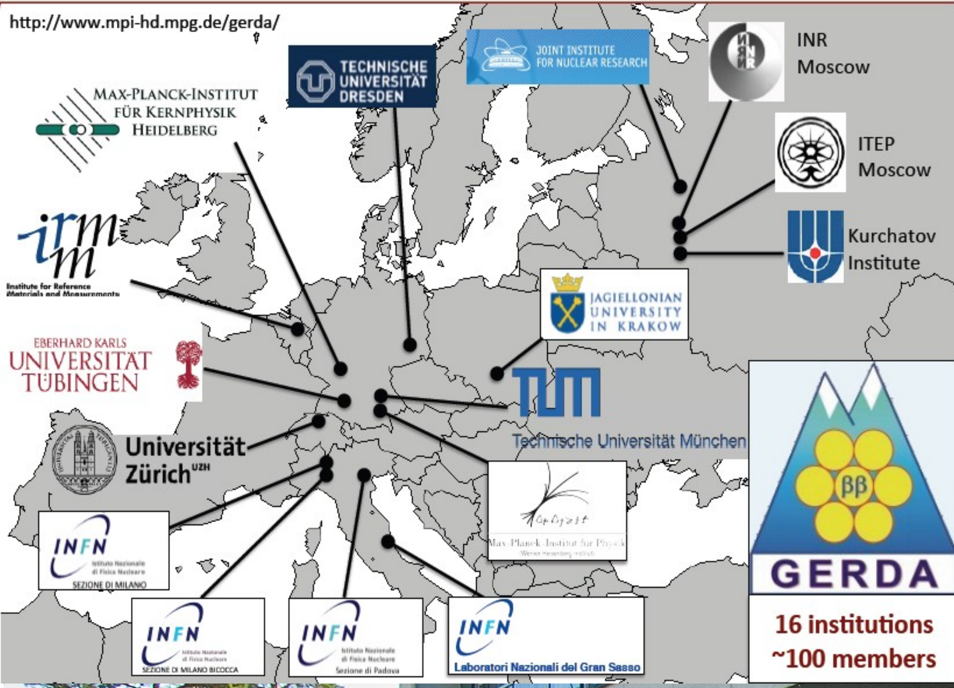




wöchentliche Kalibration mit ^{228}Th

duty 88%

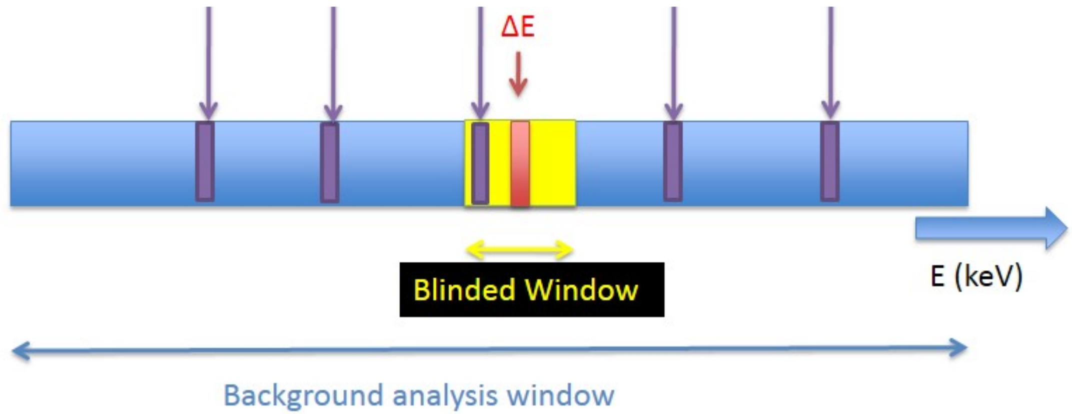
3 data sets:
- golden
- silver
- BEGe



Dubna, Juni 2013

Blind-Auswertung & Publikationen

blinding im Bereich $Q_{\beta\beta}$ ± 20 keV



EPJC 73 (2013) 2330 das GERDA Experiment (setup)

JPG 40 (2013) 035110 $T_{1/2}^{2\nu} = 1.84\,(^{+14}/_{-10}) \times 10^{21}$ yr

EPJC 74 (2014) Untergrund & Modelle arXiv:1306.5084

EPJC 73 (2013) 2583 PSD: pulse shape für coax & BEGe

Fixing der Parameter & Prozeduren @ Dubna meeting June 2013)

Spektren ohne / mit PSD geöffnet **@ Dubna** **(**rotes Fenster ΔE**)**

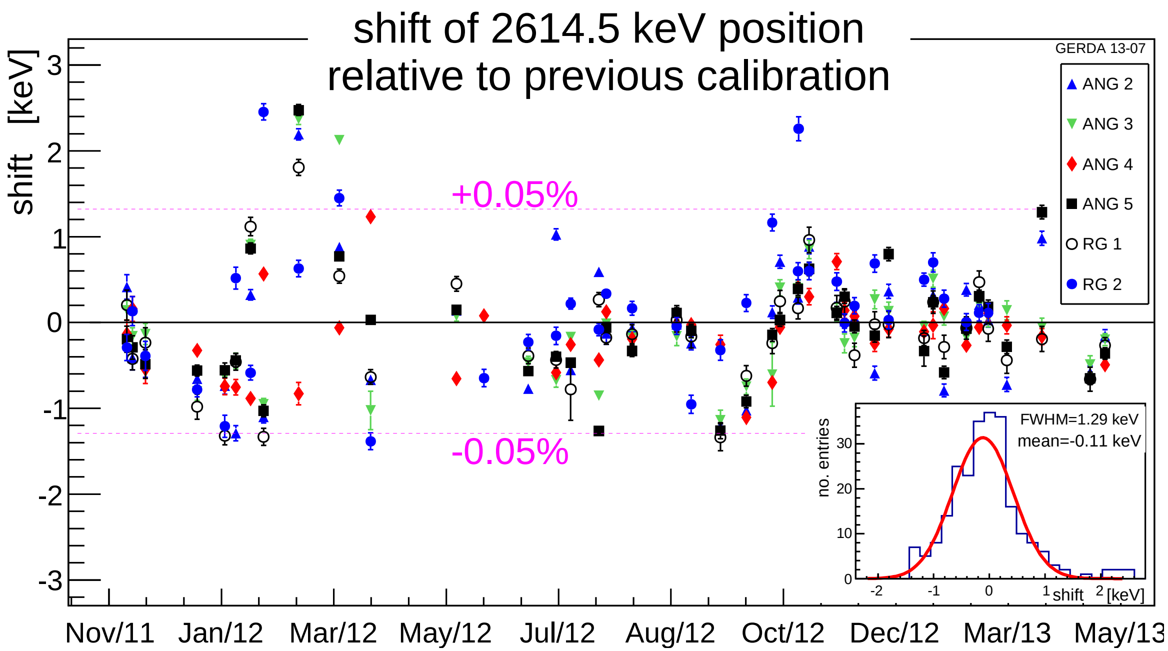
PRL 111 (2013) 122503 Limit for $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr (90% C.L. frequentist)

Kalibration & Analysekette

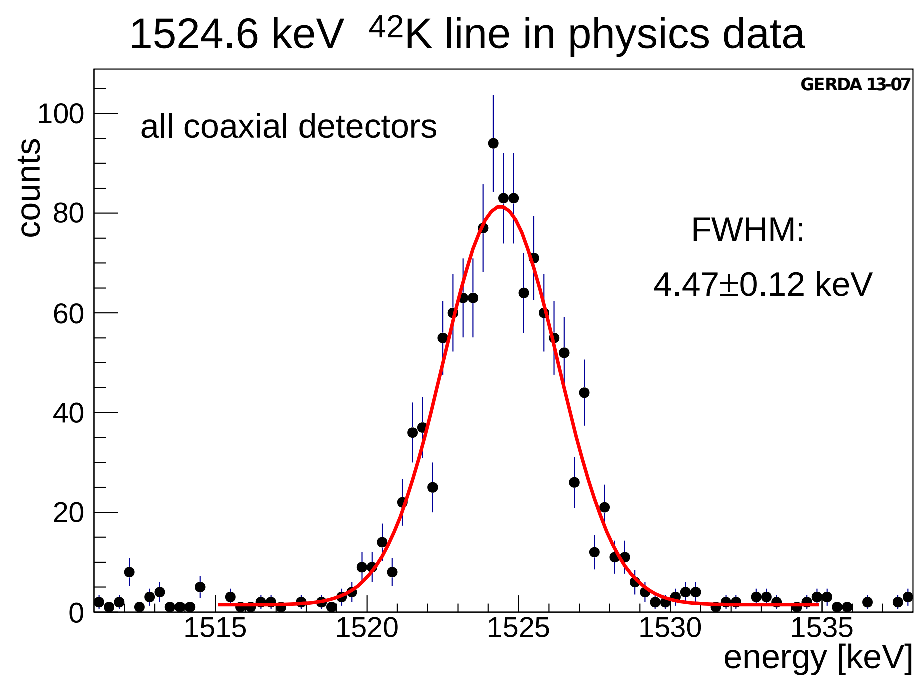
processing: diode → amplifier → FADC → filter → energy, rise time, PSD

selection: anti-coincidence muon / 2nd Ge (~20% rejected, @ $Q_{\beta\beta}$), quality cuts (~9% reject), pulse shape discrimination (~50% reject)

calibration: ^{228}Th (bi)weekly & pulser every 20 seconds for short term drifts

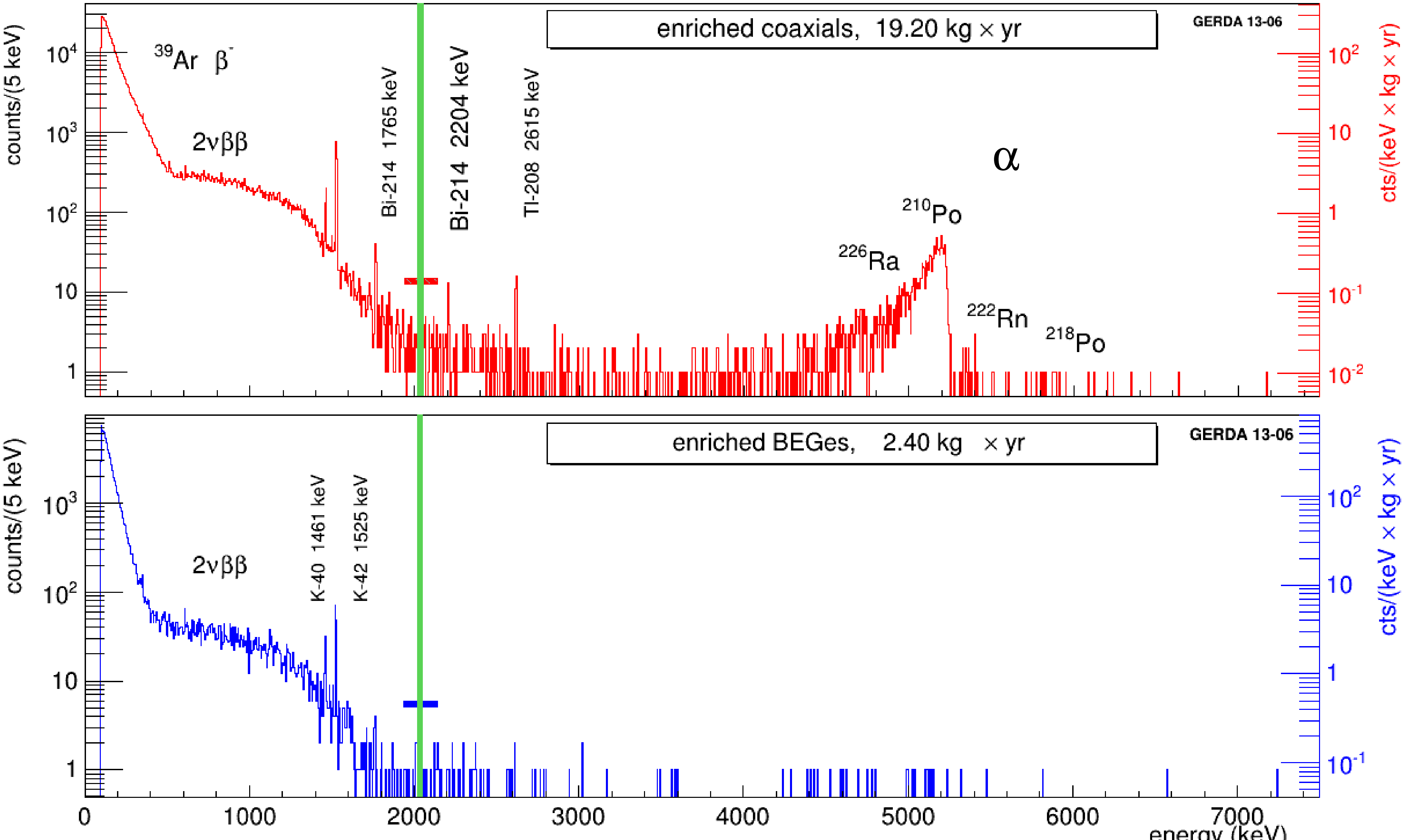


shifts are small compared to FWHM ~ 0.2% $Q_{\beta\beta}$



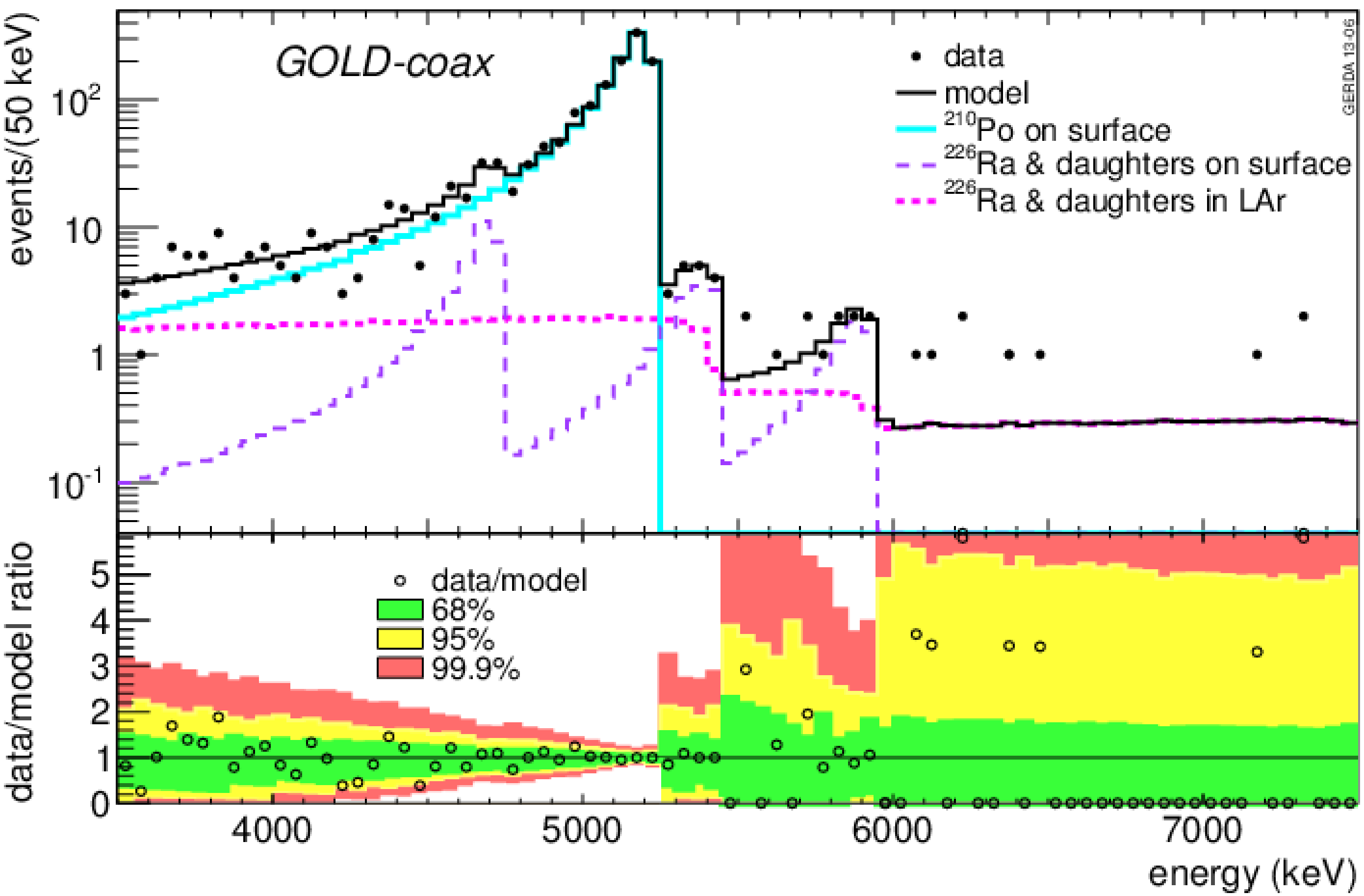
peak pos. within 0.3 keV at correct position
FWHM ~ 4% larger than expected
from calibration data

Spektren (Summen-Energie)

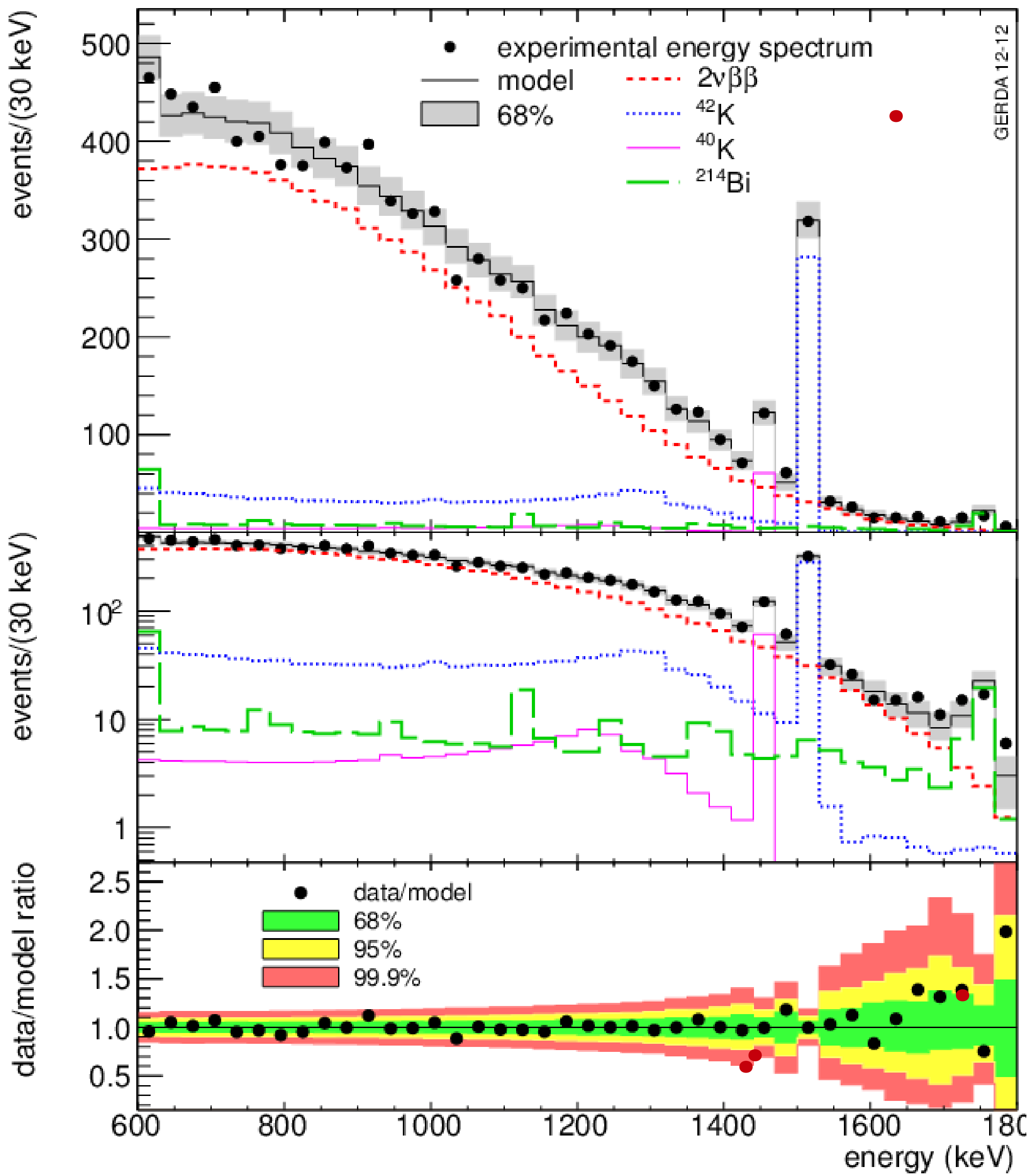


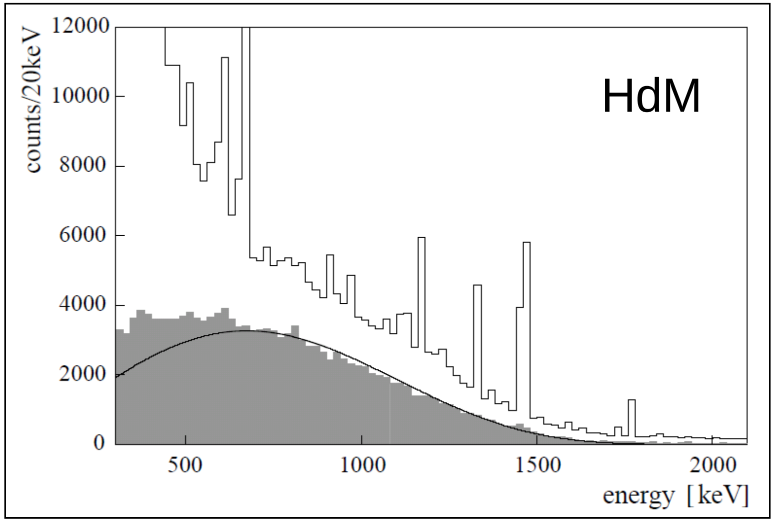
Untergrund: α & γ

isotope	energy [keV	^{enr}Ge (6.10 kg yr) tot/bck [cts]	^{enr}Ge (6.10 kg yr) rate [cts/(kg yr)]	HDM (71.7 kg yr) rate [cts/(kg yr)]
^{40}K	1460.8	125/42	$13.5^{+2.2}_{-2.1}$	181 ± 2
^{60}Co	1173.2	182/152	$4.8^{+2.8}_{-2.8}$	55 ± 1
	1332.3	93/101	<3.1	51 ± 1
^{137}Cs	661.6	335/348	<5.9	282 ± 2
^{228}Ac	910.8	294/303	<5.8	29.8 ± 1.6
	968.9	247/230	$2.7^{+2.8}_{-2.5}$	17.6 ± 1.1
			<7.6	36 ± 3
			$1.5^{+0.6}_{-0.5}$	16.5 ± 0.5
			$12.5^{+9.5}_{-7.7}$	138.7 ± 4.8
			$6.8^{+3.7}_{-4.1}$	105 ± 1
			<6.1	26.9 ± 1.2
			$3.6^{+0.9}_{-0.8}$	30.7 ± 0.7
			$0.4^{+0.4}_{-0.4}$	8.1 ± 0.5



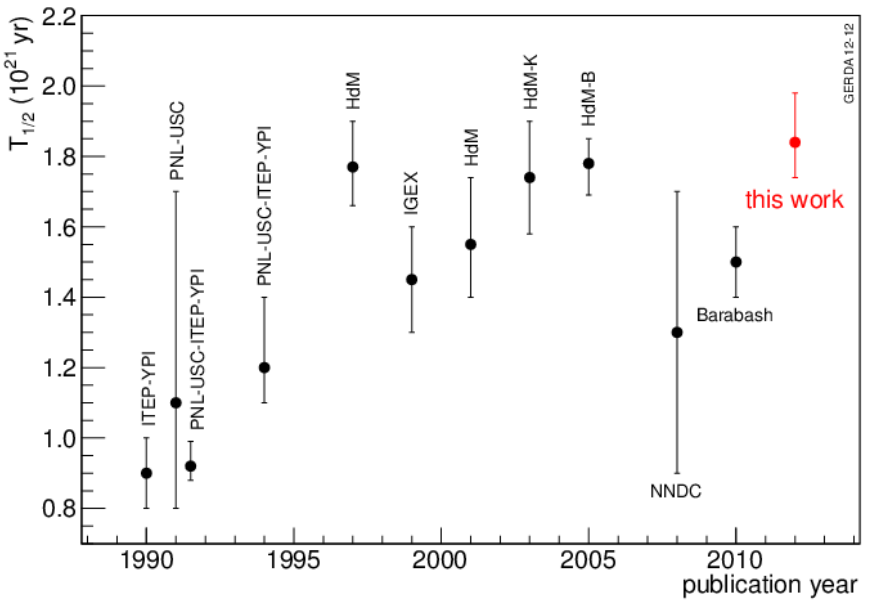
J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110





5.04 kg yr exposure

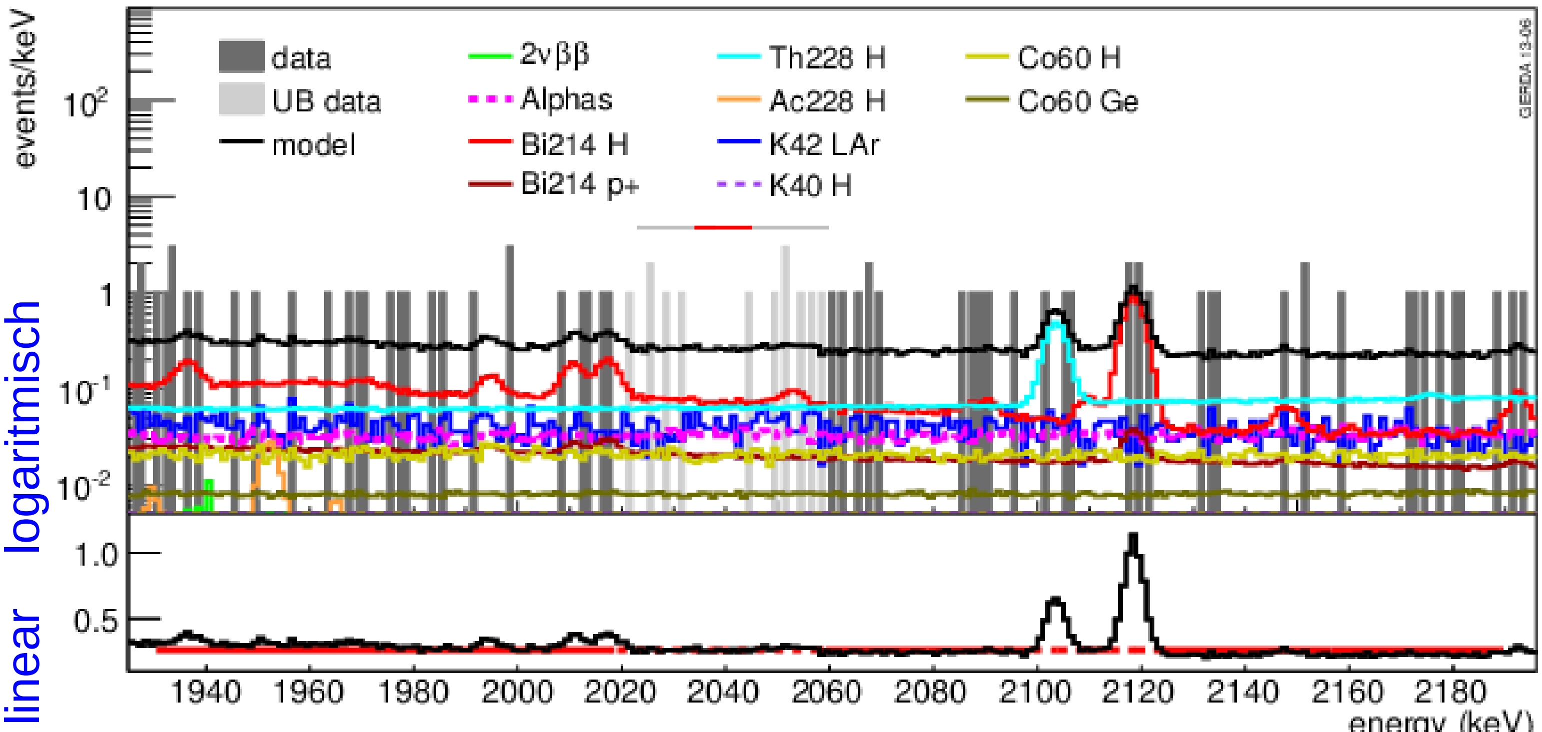
$T_{1/2}^{2\nu} = 1.84\ (^{+.14}/_{-.10}) \cdot 10^{21}$ yr



Untergrundmodel @ $Q_{\beta\beta}$

"minimal fit" (alle bekannte Beiträge)

blinded window (grau+rot)



Fit einer Konstanten an Modell außerhalb von $Q_{\beta\beta}$ ± 20 keV

Keine Linie in blinded window (rot) erwartet
(n,γ) gemessen

Untergrund flach in 1930-2190 keV
(ohne 2104±5 keV, ohne 2119±5 keV),

erwarten << 1 event in anderen Linien von ^{214}Bi
(e.g. 2017, 2053 keV)

partielles unblinding (graues Fenster) nach fixing der Kalibration, cuts & bkg Modell,
keine Linie in grauem Intervall gefunden
Modell: 8.6-10.3 events in grau & gefunden: 13 events

pulse shape discrimination (PSD)

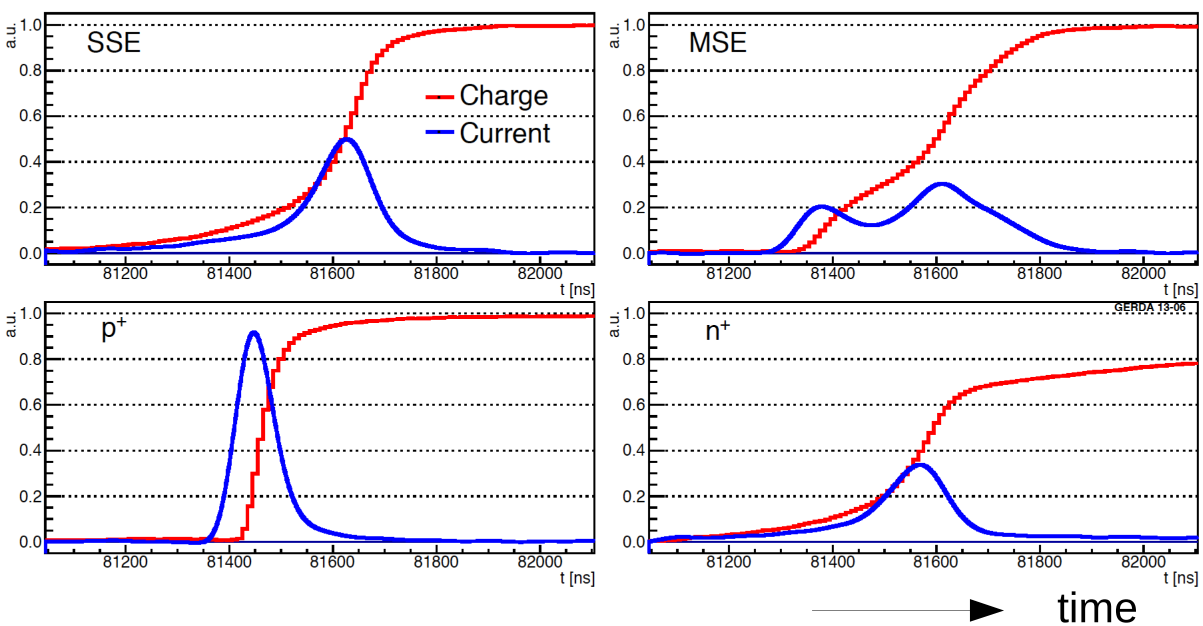
pulse shape discrimination to select $0\nu\beta\beta$ events

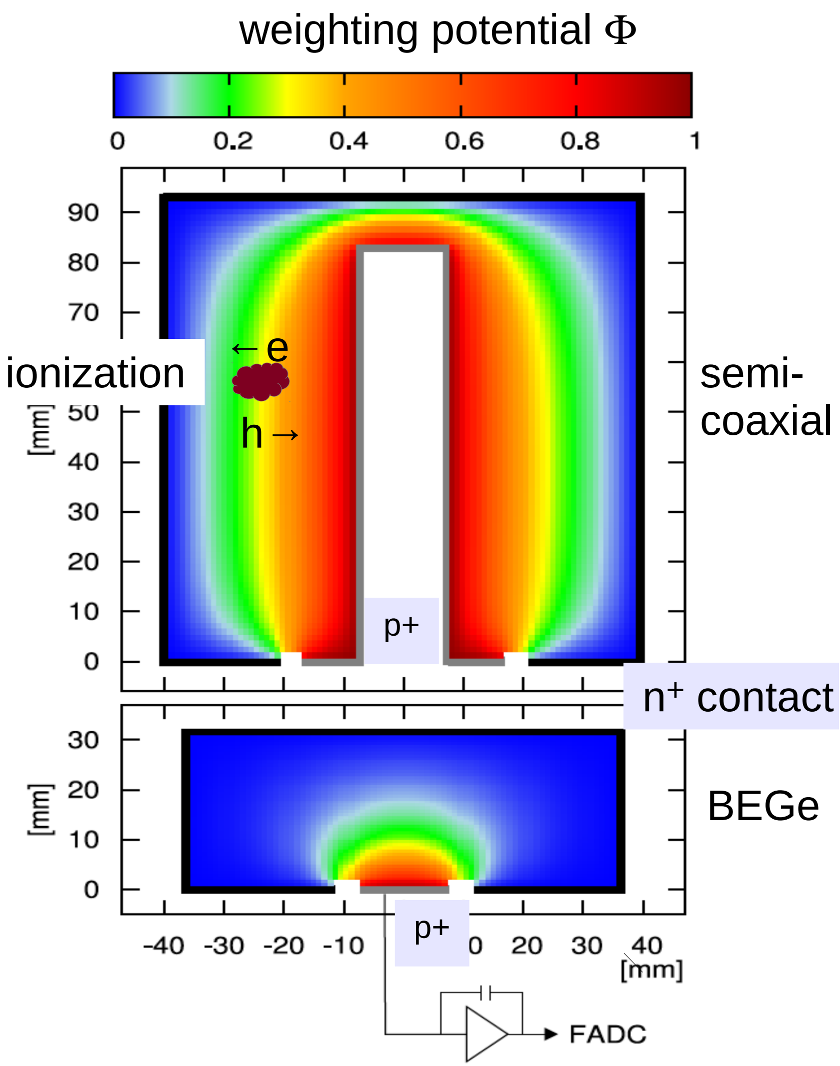
$0\nu\beta\beta$ events: range of 1 MeV electrons in Ge is ~1 mm
→ single drift of electrons & holes, single site event (SSE)

background from γ's: range of MeV γ in Ge >10x larger
→ often sum of several electron/hole drifts,
multi site events (MSE)

surface events: only electrons or holes drift

charge and current signal for BEGe detectors (data events)

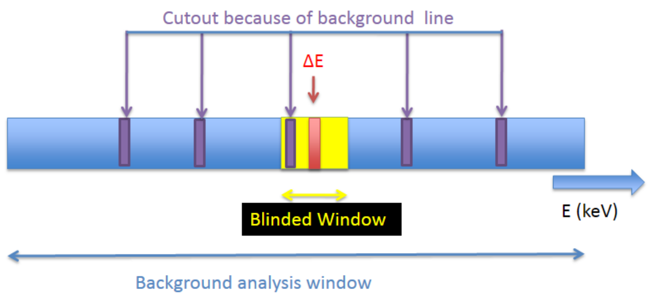




$$\text{current signal} = q \cdot v \cdot \nabla \Phi$$

(Shockley-Ramo theorem)

Ergebnisse der Untergrund-Analysen



Exposition of 21.6 kg yr von Nov. 2011 bis May 2013

3 data sets: golden, silver, BEGe

wöchentliche Kalibration mit ^{228}Th Quelle(n)

Auflösung (FWHM) @ 2 MeV: coax 4.8 keV, BEGe 3.2 keV FWHM (50 cm diode-CC2)

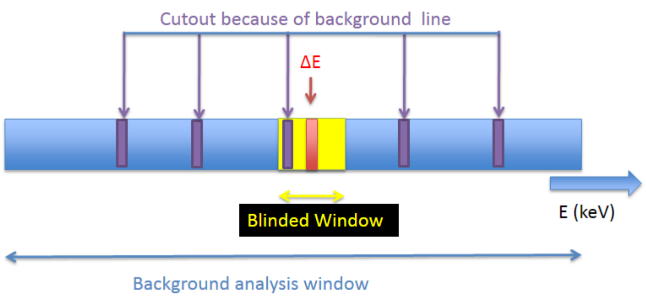
Elektronik/Verstärkung stabil innerhalb ±1.3 keV

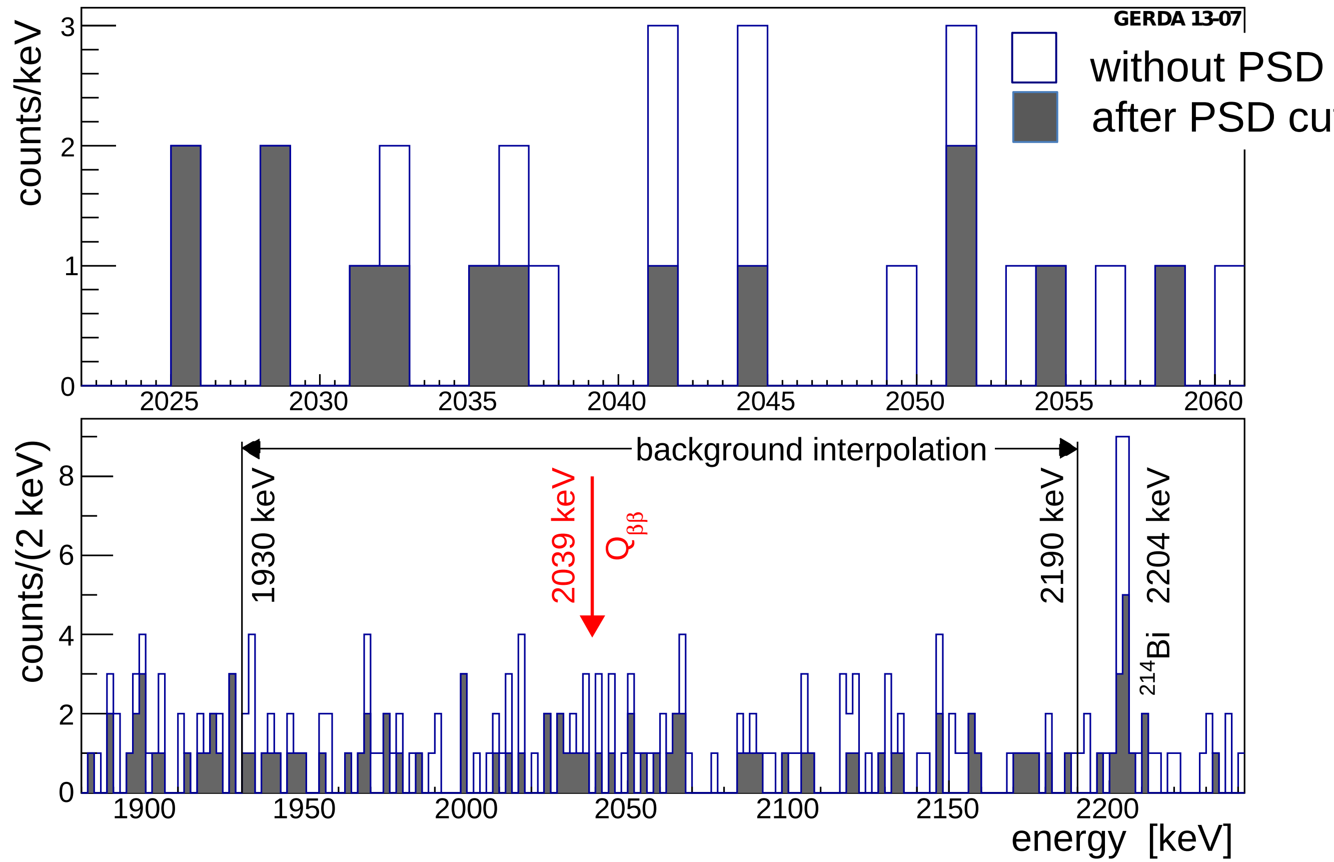
stärkste γ Linie ist: 1525 keV von ^{42}K

Spektrum dominiert von ^{214}Bi und ^{228}Th ↷ Untergrund verstanden

'nahe Quellen' (Det. Halter etc.) und Oberflächen-Kontamination

unblinding





11-14 Juni 2013

4 Tage Analyse & Diskussion
dann
unblinding der letzten ±5 keV

evt cts in ±5 keV	golden	silver	BEGe	total
erwart. w/o PSD	3.3	0.8	1.0	5.1
beob. w/o PSD	5	1	1	7
erwart. w/ PSD	2.0	0.4	0.1	2.5
beob w/ PSD	2	1	0	3

kein Peak im Spektrum bei $Q_{\beta\beta}$,

Zählung konsistent mit Bkg,
→ GERDA setzt ein Limit

Limit für Halbwertszeit im 0νββ Zerfall in ^{76}Ge

Proof of Principle OK, BI um Faktor 10 reduziert

$$T^{0\nu}_{1/2} = \frac{\ln 2 \cdot N_A}{m_{enr} \cdot N^{0\nu}} M \cdot t \cdot f_{76} \cdot f_{av} \cdot \epsilon_{fep} \cdot \epsilon_{psd}$$

exposure averaged efficiencies

data set	M*t	f_{76}	f_{av}	ε_{f}[illegible]	[illegible]
golden	17.9 kg yr	0.86	0.87	[illegible]	[illegible]0.90
silver	1.3 kg yr	0.86	[illegible]	[illegible]2	0.90
BEGe	2.4 kg yr	0[illegible]	[illegible]	0.90	0.92

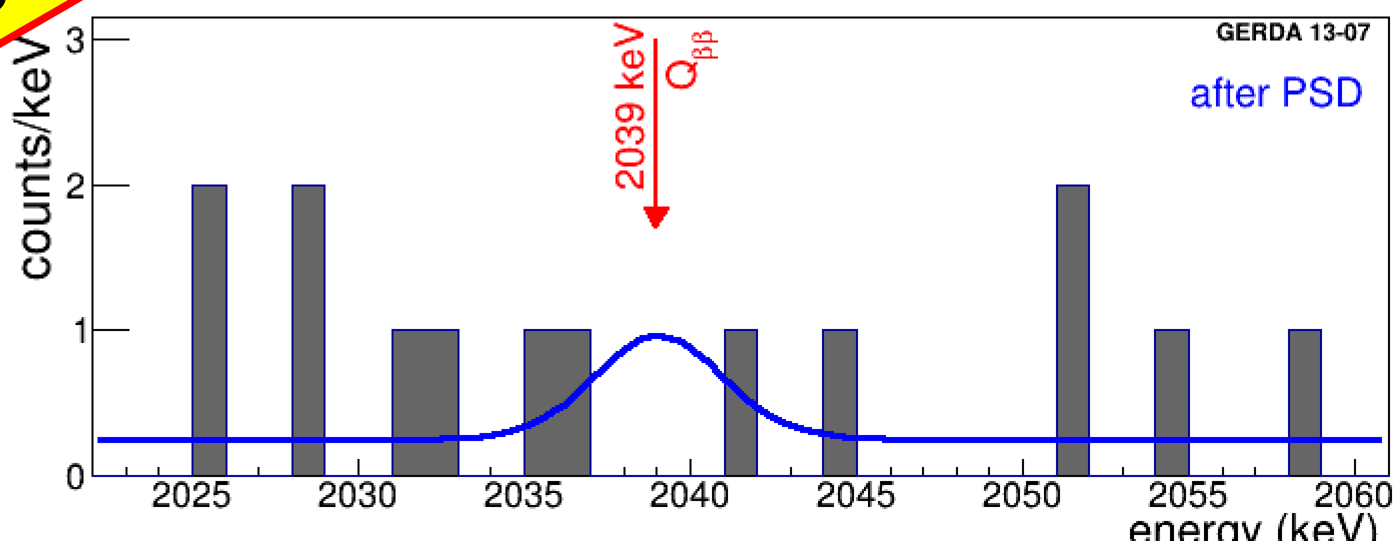
fit 3 data s[...]-2190 keV interval: const[...]g) + gauss (for signal),

[...]ters: 3x bkg level & $1/T^{0\nu}$ [...] > 0 constrain

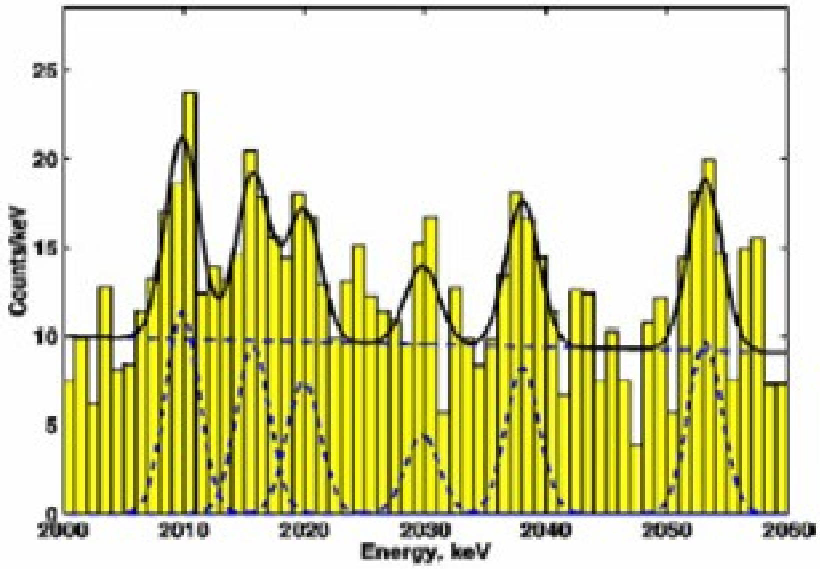
fix gaussian μ=(2039.06±0.2) keV, σ=(2.0±0.1)/(1.4±0.1) keV for coax/BEGe

systematic uncertainties on f, ε, μ, σ: Monte Carlo sampling & averaging

frequentist: [...]ood fit → best fit $N^{0\nu}$=0, $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.) (sensitivity = 2.4 10^{25} yr)



PRL111(2013) 122503

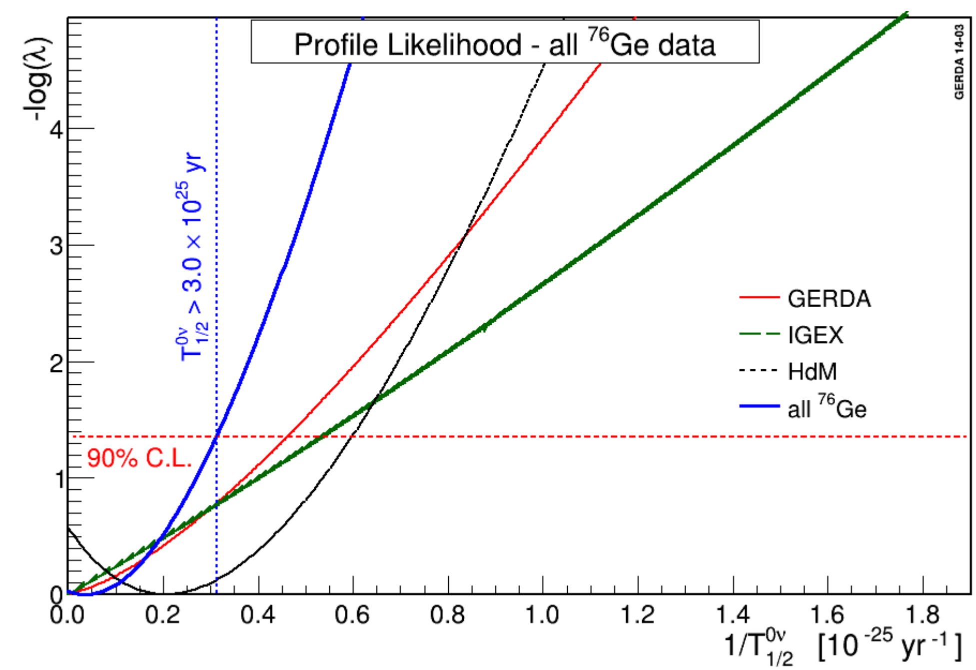


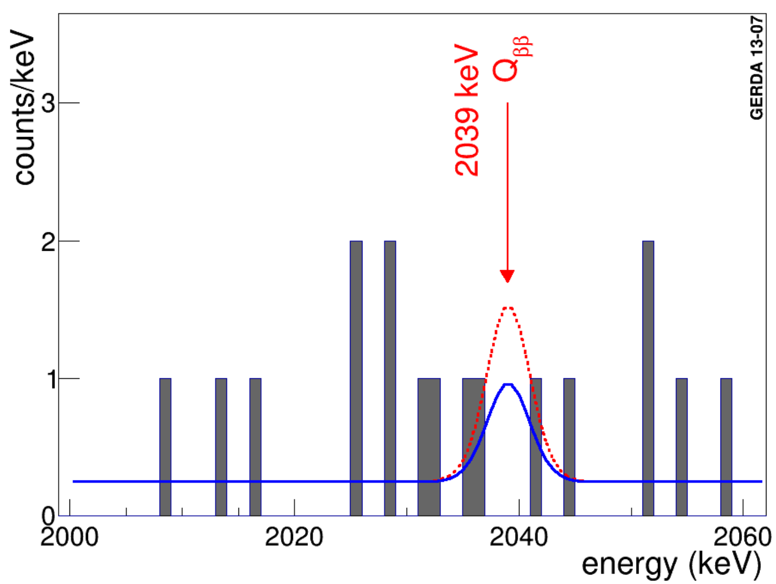
claim 2004

$\mathcal{E}$ = 71.7 kg yr

claim 2004:
Auschluss mit 99%
durch Hypothesentest
p = 0.01

p(N$^{0\nu}$=0 | H1=signal+bkg) = 0.01





GERDA Phase I

BI = 1.1 10^{-2} cts/(kg yr keV)
$\mathcal{E}$ = 21.6 kg yr
S ~ 0.006 cts/(mol yr δE)

MAJORANA

Sanford Underground Research Facility
SURF (1478 m) S Dakota, USA

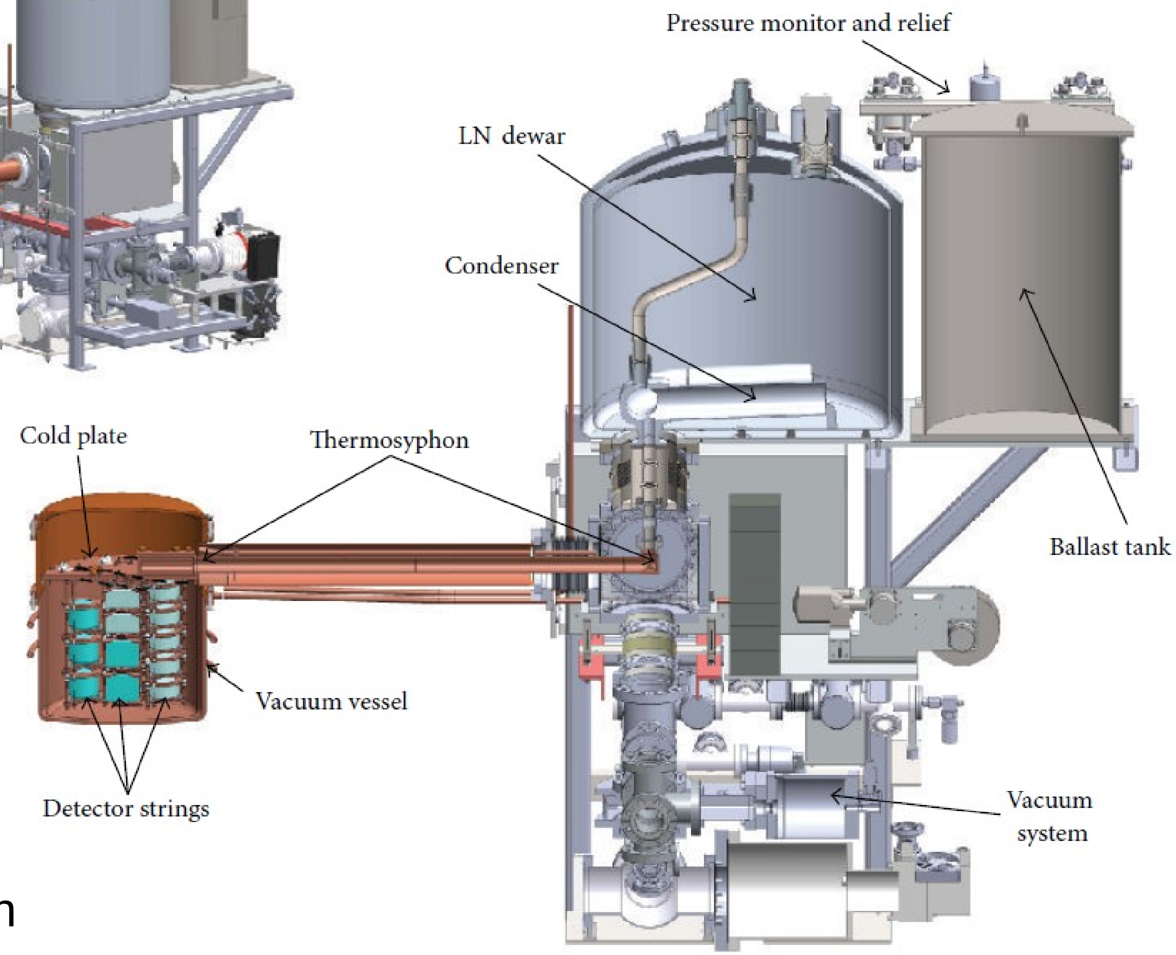
Ziel: BI <1 cts/ (t yr 4keV)
E_{th} ~ 0,5 keV

Kryostat: elektrolyth-Kupfer
OFHC Kupfer
Blei

20 kg Detektoren pro Kryostat

p-Typ point contact diodes (PPC)
87% angereichert in 76Ge

Demonstrator: 30 kg Ge vorhanden
2013 Prototyp Kryostat Komission
2013 Kryostat 1
2014 Kryostat 2
2015 volle Funktion für 100 kg yr



Advances in High Energy Physics (2014) ID365432

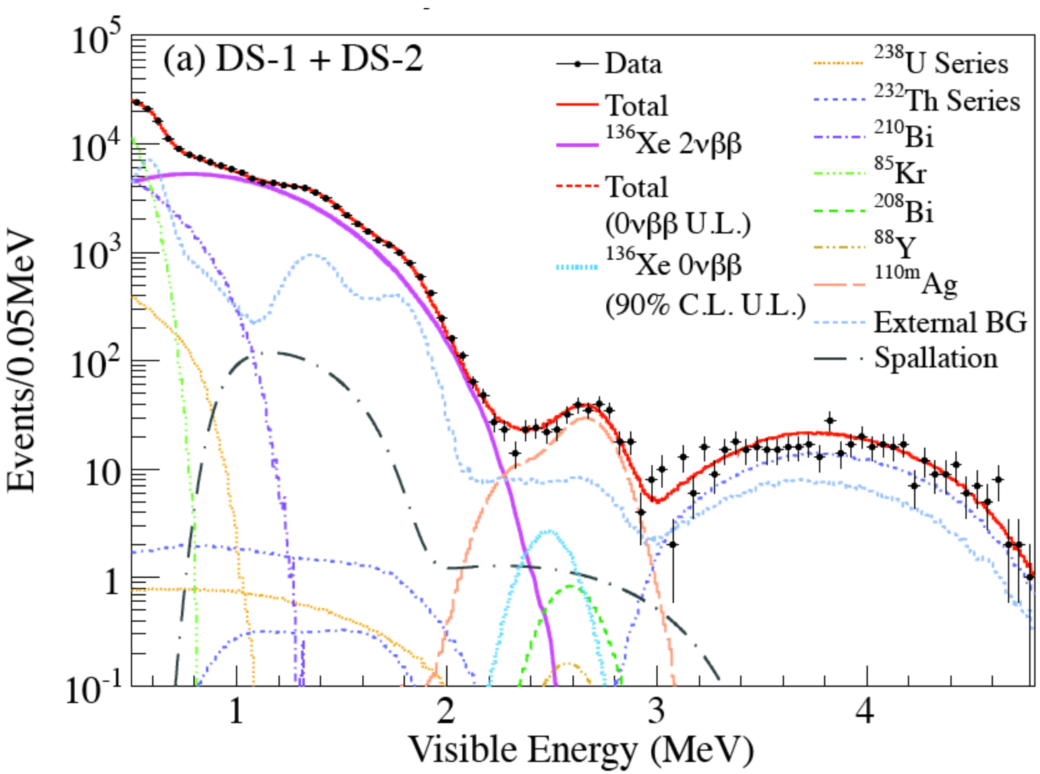
KamLAND-ZEN ^{136}Xe

PRL110 (2013) 062502 (89.5 kg yr)

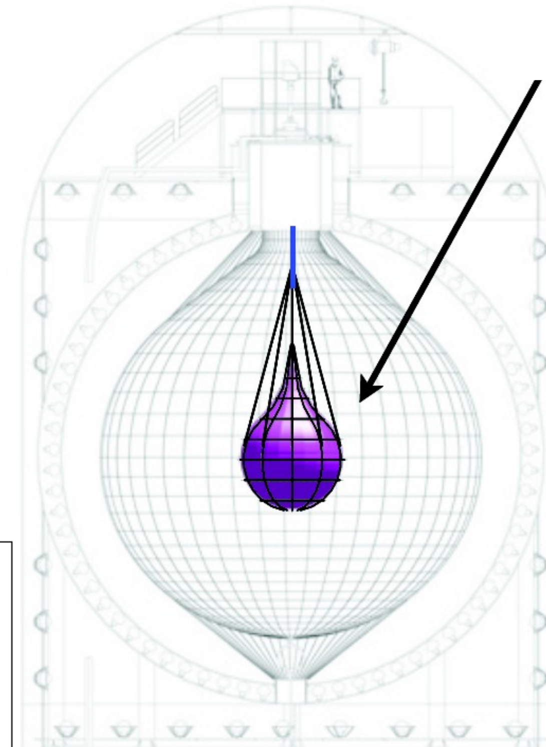
$$T_{1/2}^{2\nu} = 2.30 \pm 0.03\,(\mathrm{stat}) \pm 0.09\,(\mathrm{syst}) \times 10^{21}\ \mathrm{yr}$$

$$T_{1/2}^{0\nu} > 1.9 \times 10^{25}\ \mathrm{yr} \quad (90\%\ \mathrm{C.L})$$

Sensitivität: 1×10^{25} yr



13 t Szintillator mit ~300 kg ^{136}Xe

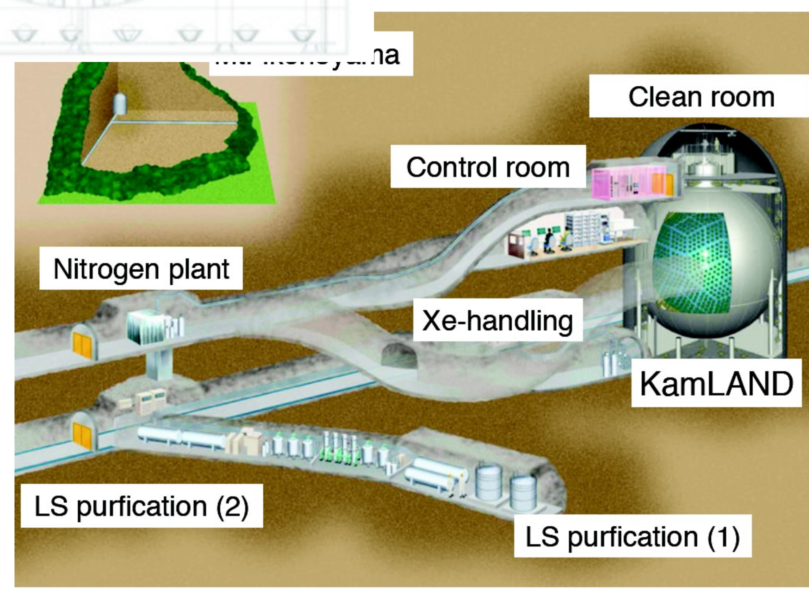


90% angereichert

$\Delta E \sim 6,6\%/\mathrm{sqrt}(E)$

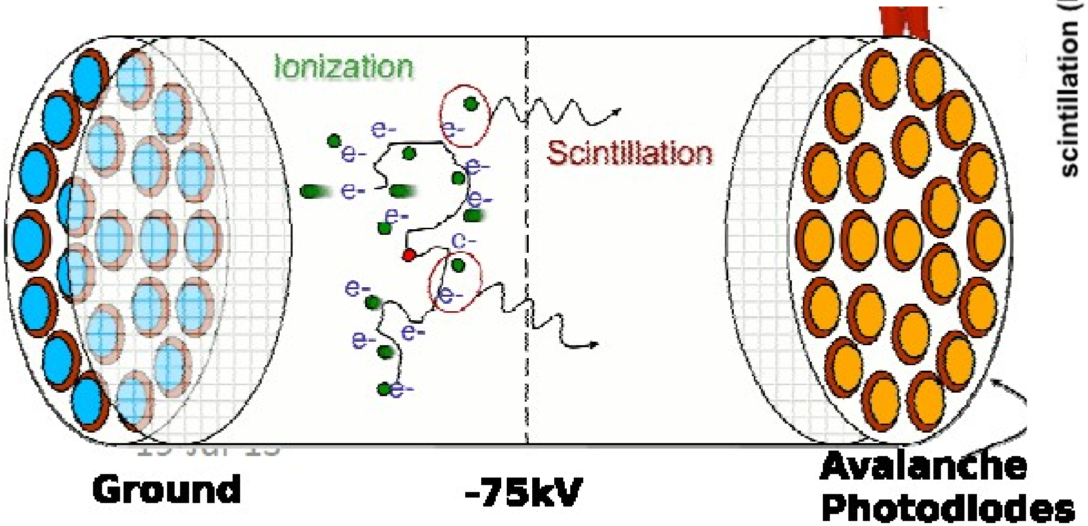
1000 t Szint. fiducial volume

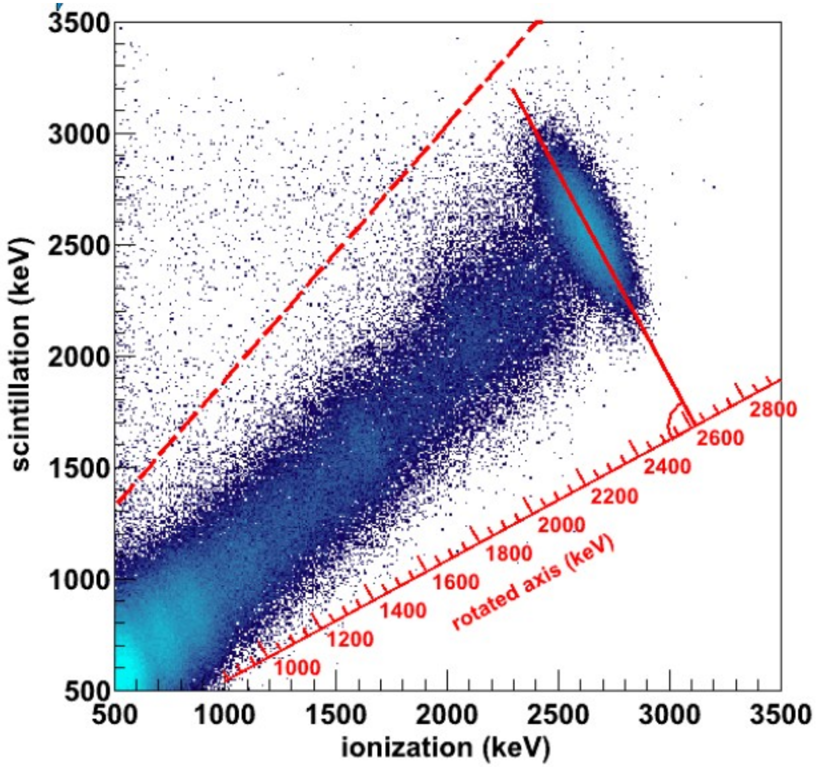
Spallation, fall-out(^{110m}Ag)

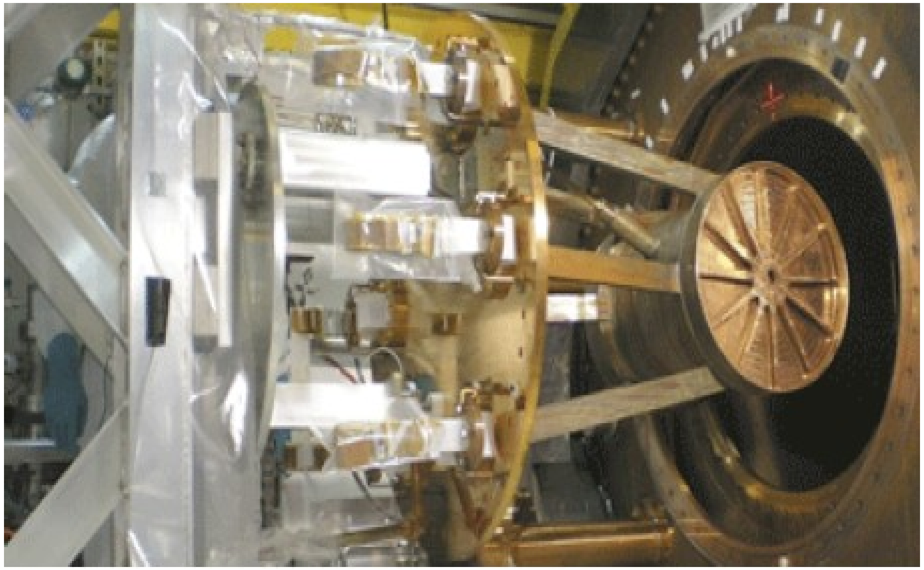


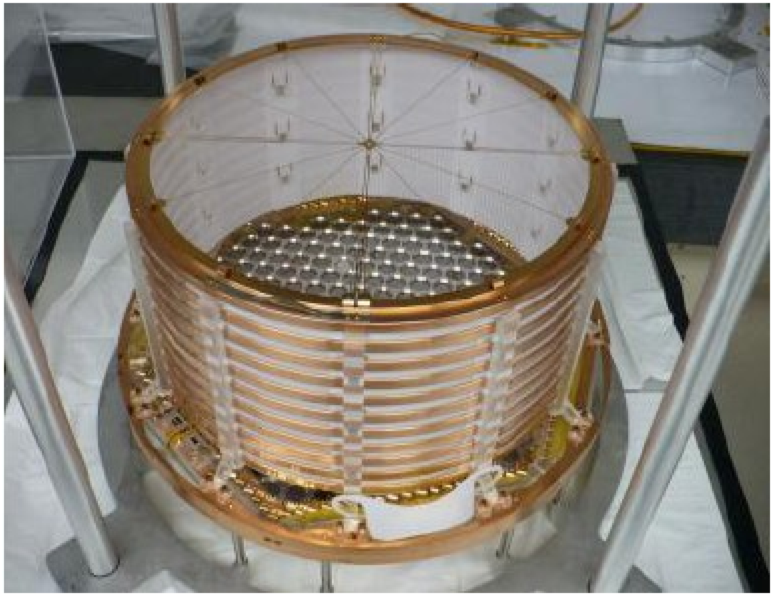
EXO200 (WIPP)

^{136}Xe $Q_{\beta\beta}$ = 2479 PRL109 (2012) 032505





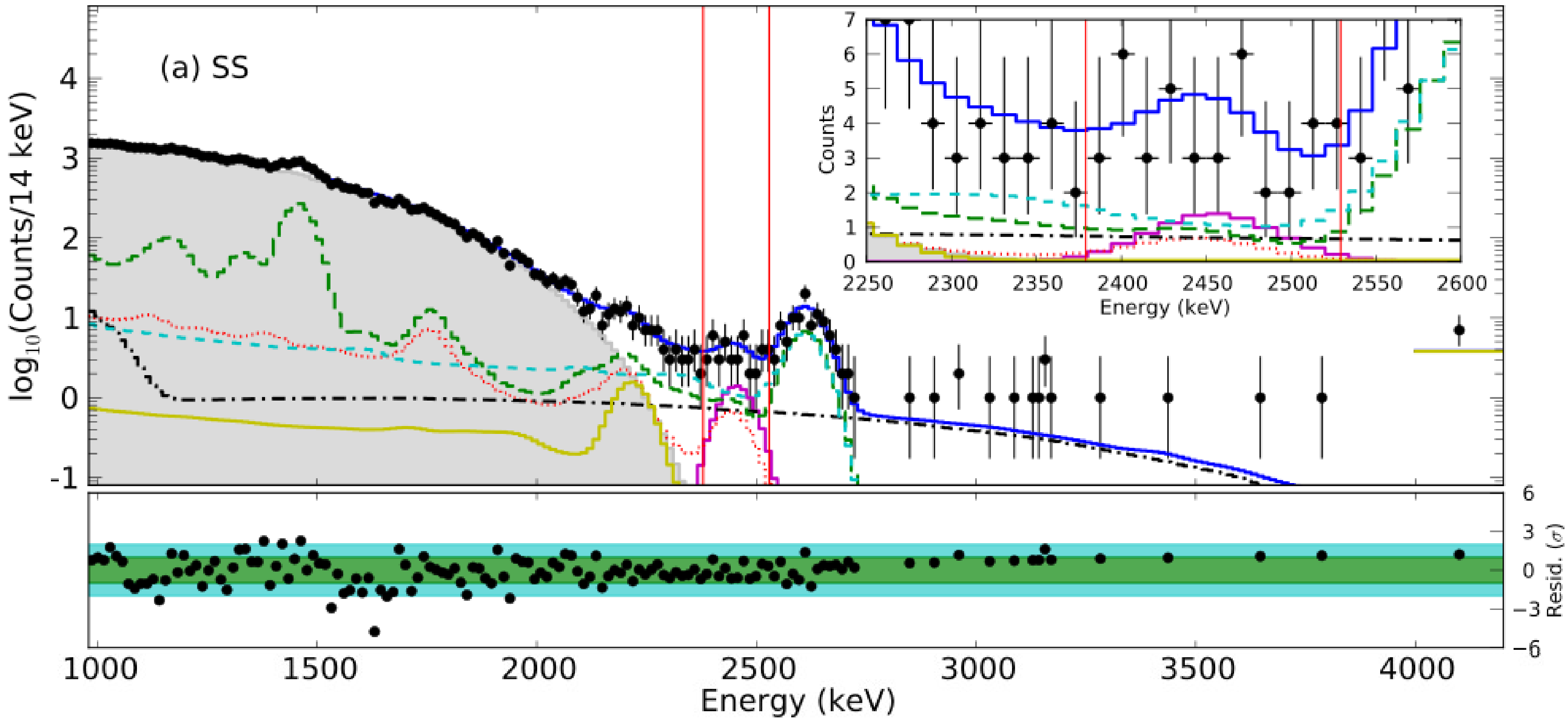




EXO 200

arXiv1402.6956

^{136}Xe



$\mathcal{E}$ = 99.8 kg yr

σ/E = 0.015 ±2σ = 150 keV

BI = 0.0017 cts/(kg yr keV)

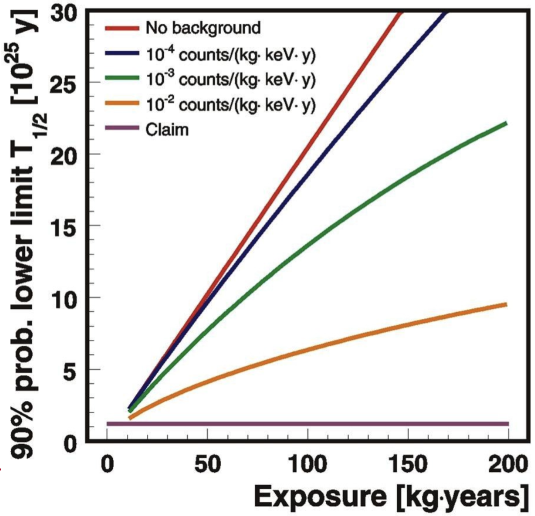
$T_{1/2}^{0\nu} > 1.1\ 10^{25}$ yr (90% C.L.)

Phys. Rev. C 89, 015502 (2014) $T_{1/2}^{2\nu}$ = 2.165 ± 0.016(stat) ± 0.059(syst) 10^{21} yr

Sensitivität für 0νββ Zerfall

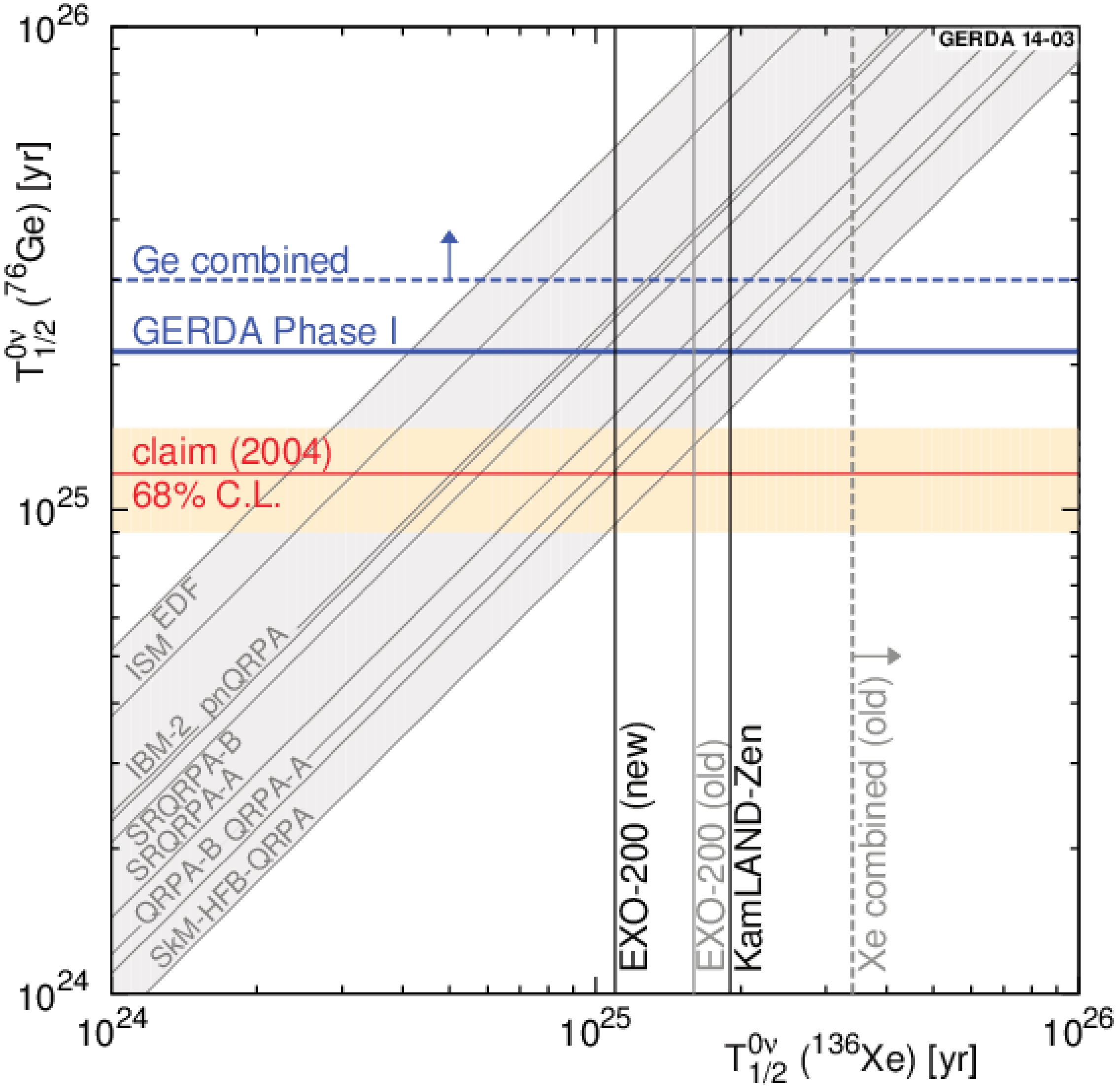
$$S_{1/2} \propto a * \varepsilon * \sqrt{\frac{M * t}{\delta E * b}}$$

Experiment	$\mathcal{E}$ kg yr	δE %	BI 10^{-3} cts/(kg yr keV)	S cts/(mol yr dE)	$T_{1/2} > x \bullet 10^{25}$ yr (90%CL)
KamLAND-Zen I	27.5	4.2%			> 0.5
KamLAND-Zen II	89.5	4.2%	41	0.19	> 1.9
EXO-200 1	32.5	1.67%	1.5 ± 0.1	0.044	> 1.6
EXO-200 2	99.8	1.53%	1.7 ± 0.2	0.053	> 1.1
GERDA Phase I	21.6	0.2%,	11 ± 2	0.006	> 2.1



Vergleich ^{76}Ge & ^{136}Xe

$$1/T_{1/2} = G^{0\nu} \, |M^{0\nu}|^2 \, m_{\beta\beta}^2$$



$G^{0\nu}$ Phasenraum

$m_{\beta\beta}$ effektive ν Masse

$M^{0\nu}$ nukl. Matrixelement (Kernstruktur)

Rodin, Faessler, Simkovic, Suhonen
Iachello, Poves,

aus Limit für $T_{1/2}$:

$m_{\beta\beta}$ < (0.2 – 0.4) eV (Ge comb.)

kleinstes Verhältnis $M^{0\nu}$ ^{136}Xe/^{76}Ge ~ 0.4

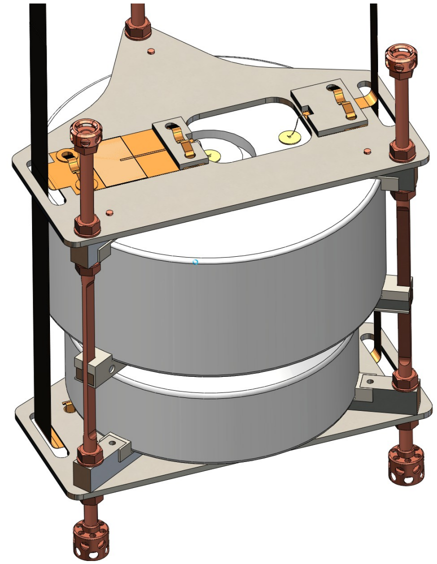
⇒ für claim günstigste Umrechnung
schwächster Ausschluss des claims

Bayes Faktor P(H1)/p(H0) = 0.0022

Phase II

1) zusätzliche BEGe 30 Detektoren:
+ 20 kg, bessere PSD

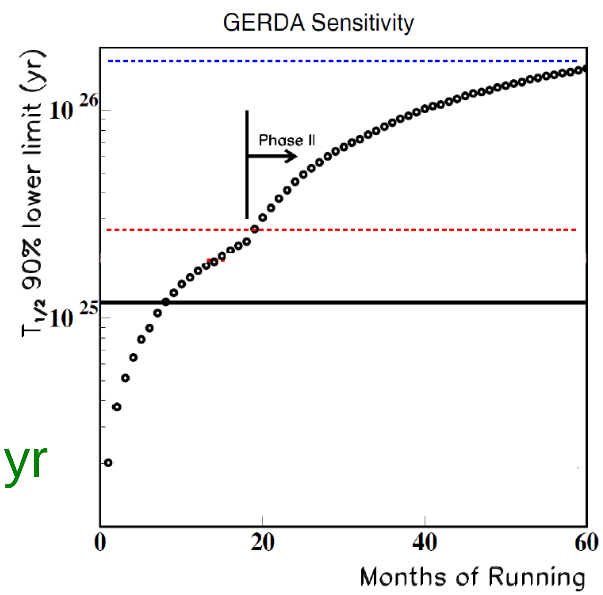
2) neue FE- Vorverstärker



3) Flüssig-Argon-Instrumentierung

Oberflächenkontaminationen & Comptonstreuung erzeugen Szinillationslicht (128nm) in LAr

Auslese mit
a) WLS-Fasern und SiPM
b) 3" PMT



Ziel : BI~10^{-3} cts/(keV·kg·yr)
$\mathcal{E}$ ~ 100 kg yr ↷ $T_{1/2}$ ~ 10^{26} yr

Zusammenfassung

neue Experimente zum $0\nu\beta\beta$ Zerfall:

Kamland-Zen,EXO, GERDA, Majorana

^{136}Xe, ^{76}Ge

Bedeutung von $0\nu\beta\beta$ für SM & Kosmologie

Majorana-Natur (Komponente)

GERDA für ^{76}Ge

Proof of Principle gezeigt: BI~10^{-2} cts/(keV·kg·yr)

$2\nu\beta\beta$: $T_{1/2}^{2\nu} = 1.84\ (^{+.14}/_{-.10}) \cdot 10^{21}$ yr

$0\nu\beta\beta$: $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr (90% C.L. frequentist)

Phase II mit ~ 35 kg Detektor & BI~10^{-3} cts/(keV·kg·yr) in Vorbereitung

Phase II notwendig, da

Zusammenfassung

neue Experimente zum $0\nu\beta\beta$ Zerfall:

Kamland-Zen,EXO, GERDA, Majorana

^{136}Xe, ^{76}Ge

Bedeutung von $0\nu\beta\beta$ für SM & Kosmologie

Majorana-Natur (Komponente)

GERDA für ^{76}Ge

Proof of Principle gezeigt: BI~10^{-2} cts/(keV·kg·yr)

$2\nu\beta\beta$: $T_{1/2}^{2\nu} = 1.84\ (^{+.14}/_{-.10}) \cdot 10^{21}$ yr

$0\nu\beta\beta$: $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr (90% C.L. frequentist)

Phase II mit ~ 35 kg Detektor & BI~10^{-3} cts/(keV·kg·yr) in Vorbereitung

Phase II notwendig, da wir immer noch nicht wirklich wissen

.... ob er recht hat