Suche nach dem neutrinolosen doppelten Betazerfall

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Graduiertentag am 13. Mai 2011

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bmb+f - Förderschwerpunkt

Astroteilchenphysik

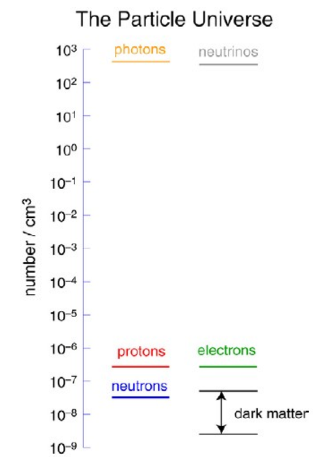
Großgeräte der physikalischen Grundlagenforschung

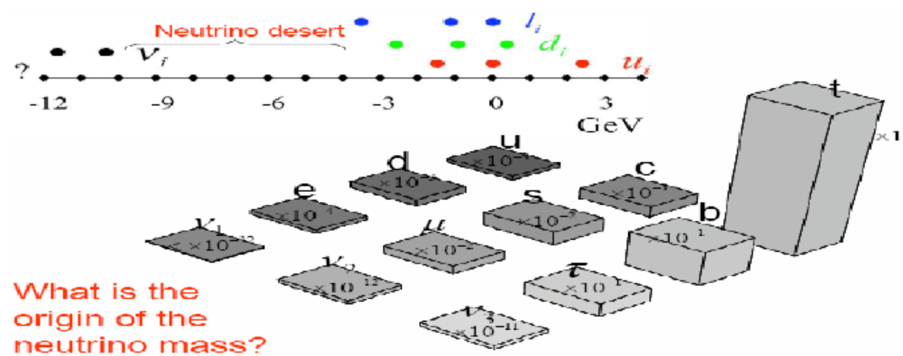
Neutrinos

Neutrinos and Photons are the most abundant particles

Standard Model of Particle Physics: very successful

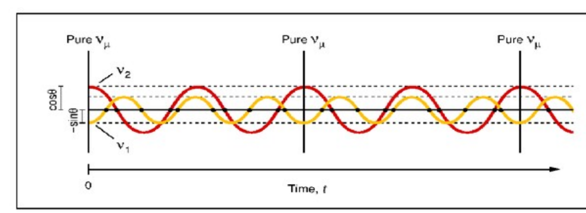
masses, Higgs, DM, SUSY





properties of ν are key

spin ½, no charge, left-handed



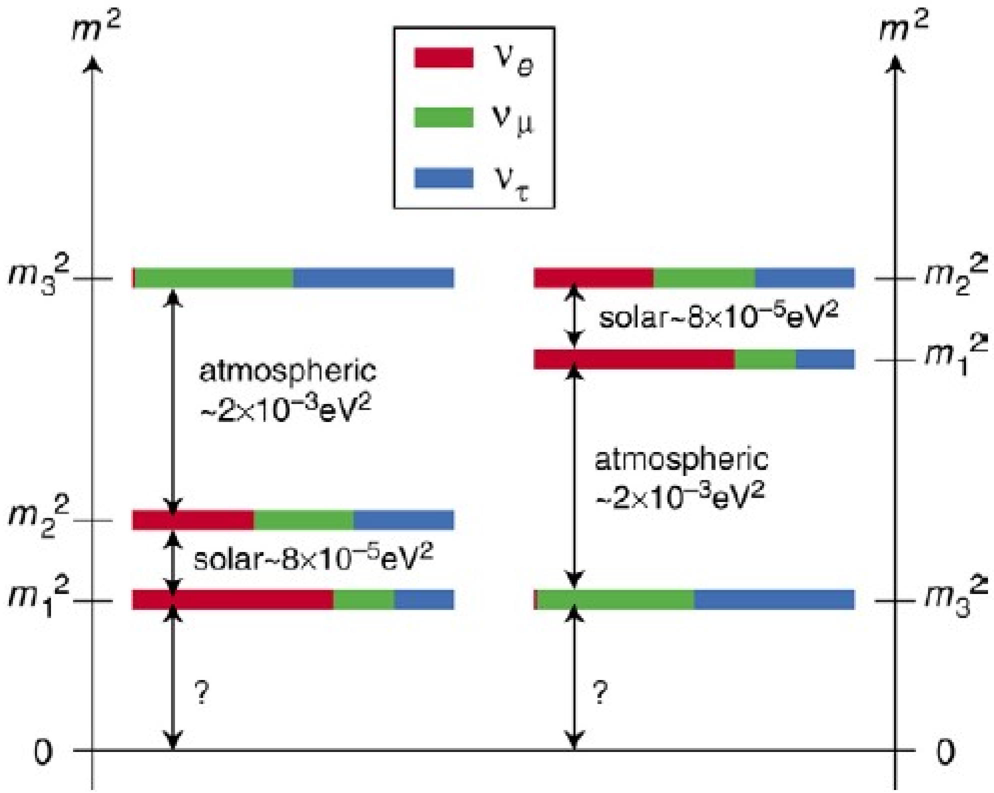
mass: yes (from oscillations), but value ?

Cosmology: flat ΛCDM $\Sigma\, m_\nu$

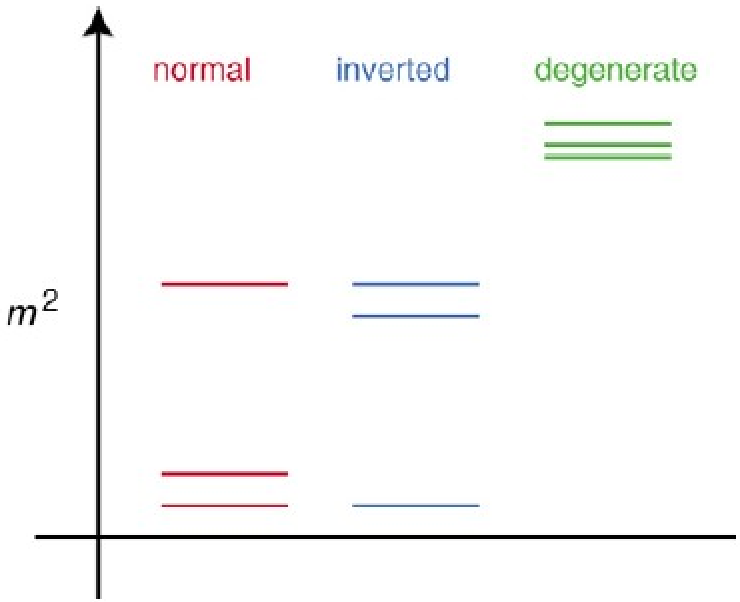
β-decay: Tritium $m_{\nu e} = \Sigma_i\, m_i \cdot |U_{ie}|^2 < 2{,}3$ eV

$0\nu2\beta$: eff. mass $m_{\beta\beta} = |\, \Sigma_i\, m_i \cdot U^2_{ie}\, | < 0{,}4$ eV

mass of ν



hierarchy



hierarchy and limits

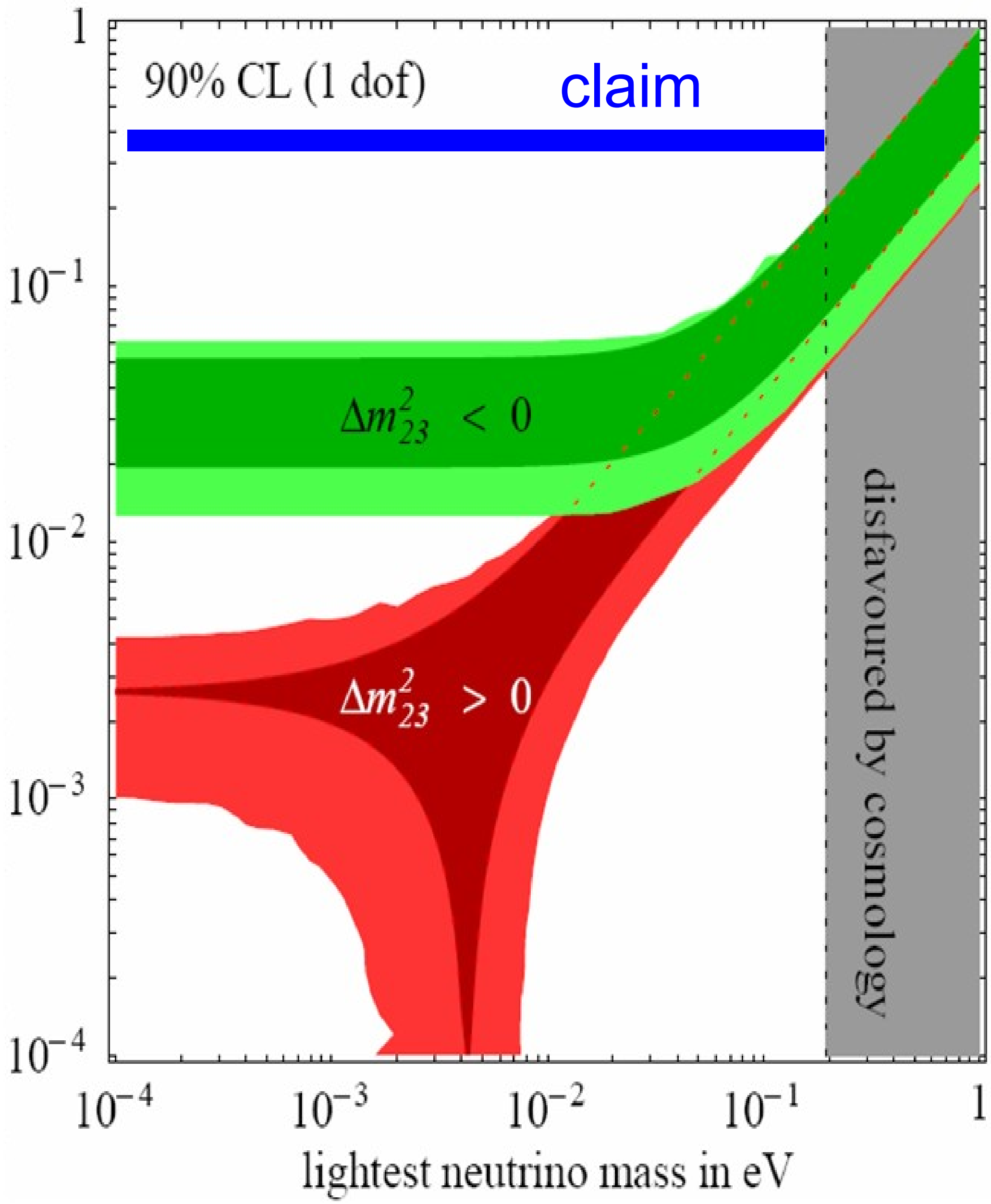
Tritium β decay : < 2,3 eV
Cosmology : < 0,28 eV
ββ decay : < 0,4 eV

$$\langle m_\nu \rangle \equiv m_{ee} = \left| \sum_k U_{ek}^2 m_k \right| = \left| \sum_k |U_{ek}|^2 e^{i\alpha_{ek}} m_k \right|$$

PMNS - Matrix

ββ decay likely to give the most stringent limit on mass

β decay : $m_\nu^2 = \sum_k |U_{ek}^2| m_k^2$



search for properties of ν !

absolute mass scale, hierarchy

most interesting: is ν of Majorana type?

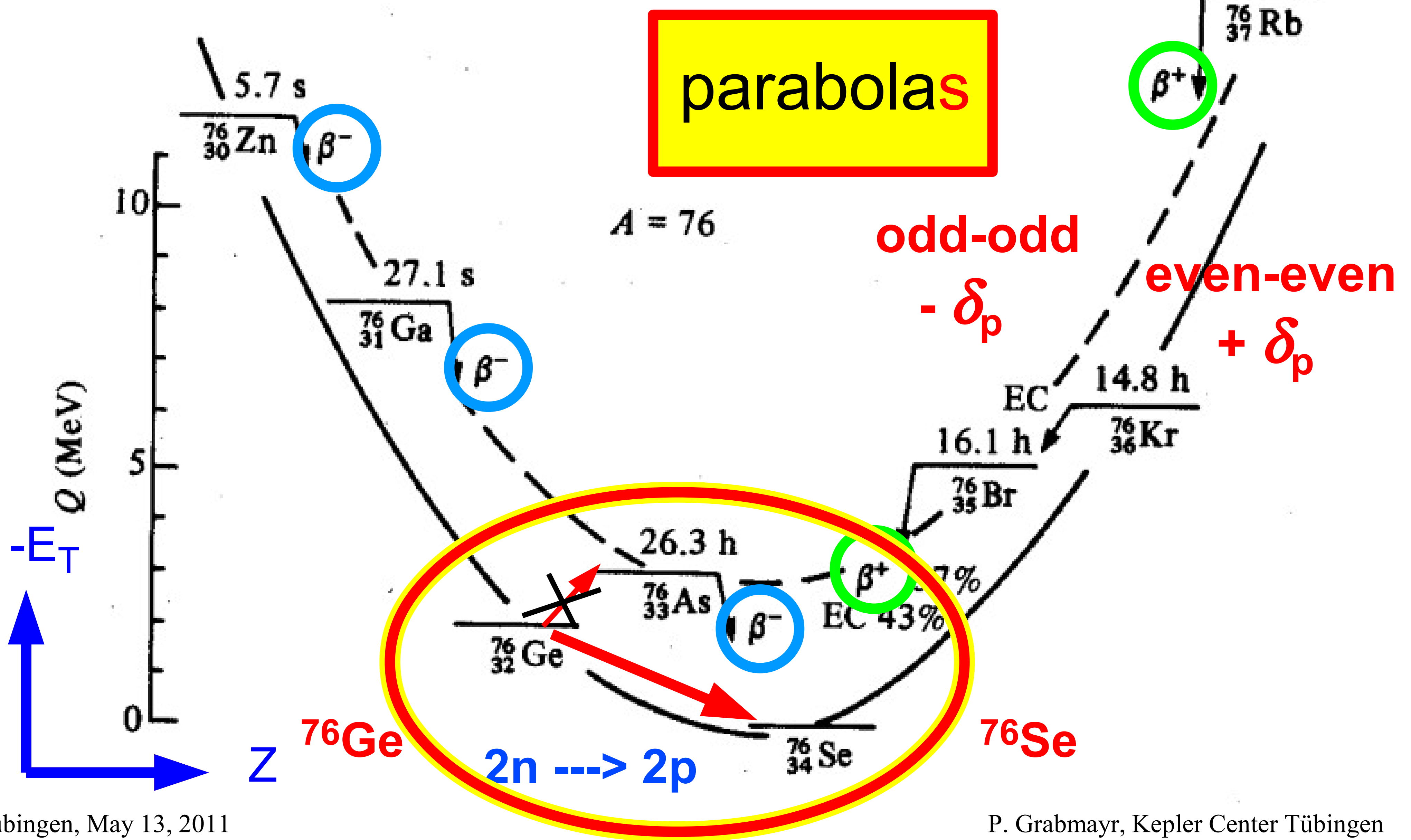
$$\nu \equiv \bar{\nu}$$

outline :

- $0\nu2\beta$ decay
- requirements
- methods and experiments
- GERDA
- conclusions

Weizsäcker mass formula

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

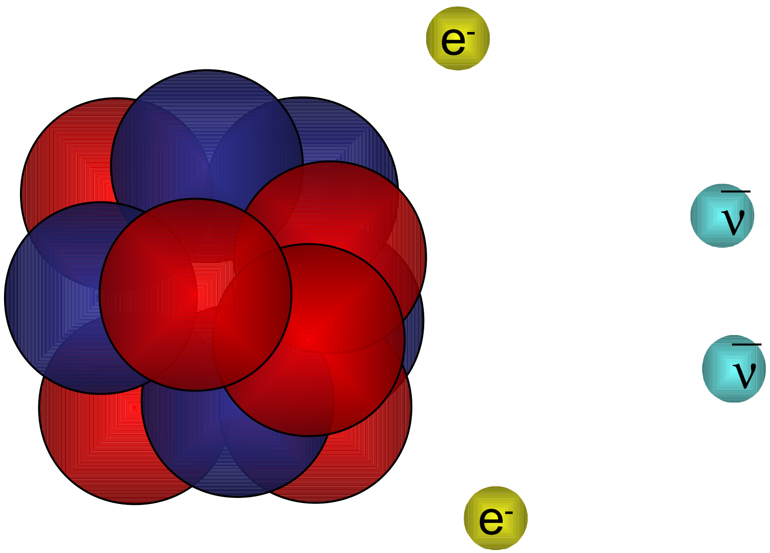


double beta decay

2nd order allowed weak process

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

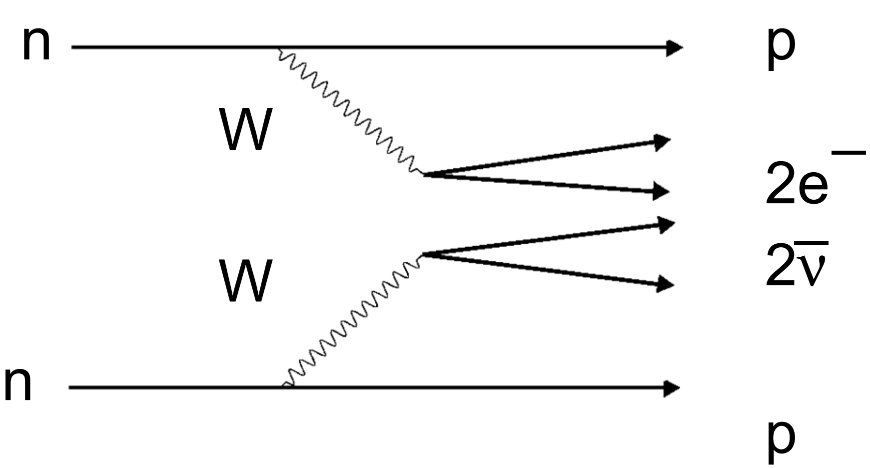
(2νββ)

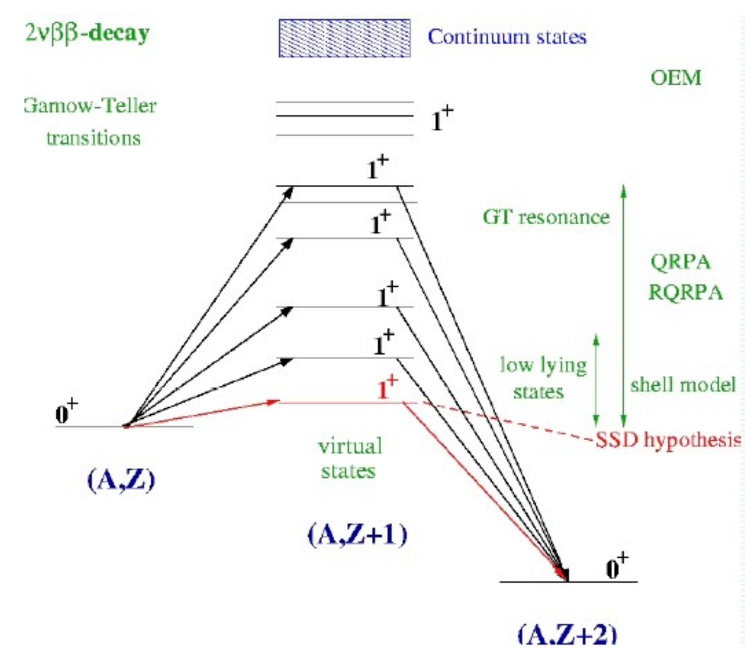


Gamow Teller only

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

(p,n) (n,p)



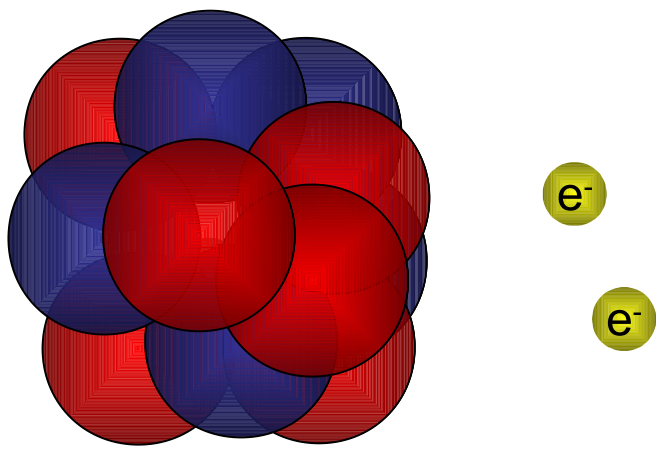


double beta decay

2nd order allowed weak process

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

$(0\nu\beta\beta)$

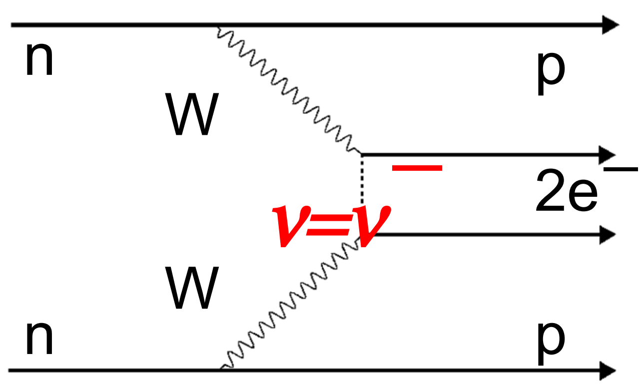


Gamow-Teller and Fermi

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

Neutrino = Anti-Neutrino
(Majorana type)

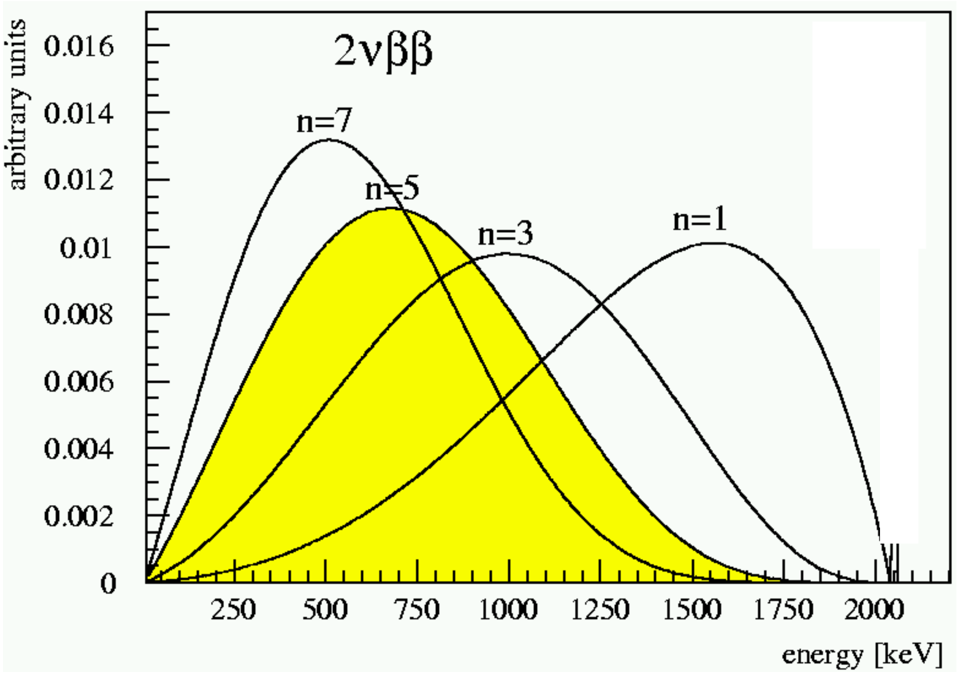
- must have finite mass
- violation of lepton number conservation $\Delta L=2$



spectral shapes

sum energy spectrum of both electrons

2νββ: spectrum

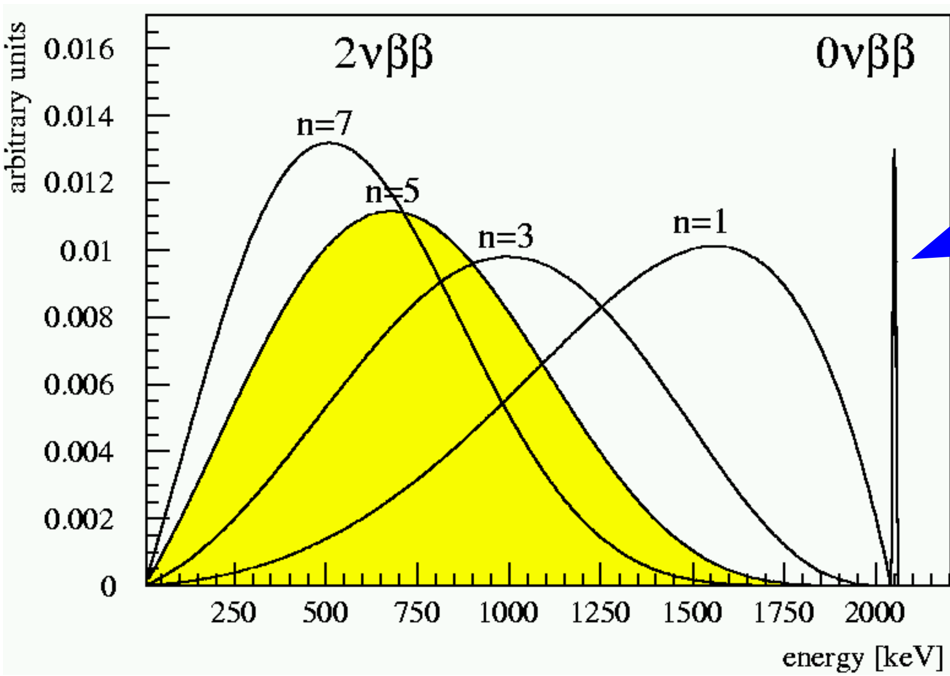


2β2ν: $T_{1/2} \sim 10^{(18\text{-}21)}$ y

spectral shapes

sum energy spectrum of both electrons

$0\nu\beta\beta$: peak at Q-value of nuclear transition



observation of peak ?

→ Majorana nature

measured quantity: half-life

link to eff. neutrino mass

$$1/T_{1/2} = PS * ME^2 * (m_\nu / m_e)^2$$

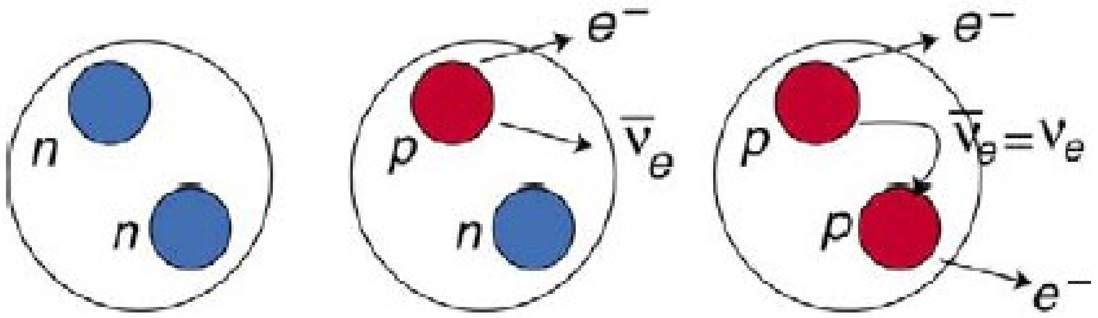
Nuclear physics input needed !

$2\beta2\nu$: $T_{1/2} \sim 10^{(18\text{-}21)}$ y

$2\beta0\nu$: $T_{1/2} > 10^{25}$ y

requirements

process:



$$R = 1/T_{1/2} = PS * ME^2 * (m_\nu / m_e)^2$$

- count rates
- backgrounds
- contaminations
- candidates (Q-value, nuclear matrix elements)
- detectors

back of the envelope

assume background free; $T_{1/2} \gg t$;

For half-lifes of $T_{1/2} = 10^{25}$ yrs

$N_{\beta\beta} / t = 1$ event/yr

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

This is about 10 moles of isotope, implying ~kg

for ^{76}Ge : 2,1 kg @ 86% enriched

Now you only can loose:

nat. abundance a, efficiency ε, background B, ...

1g $^{76}GeO_2$ for 50 €

halflife estimate for $0\nu\beta\beta$

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

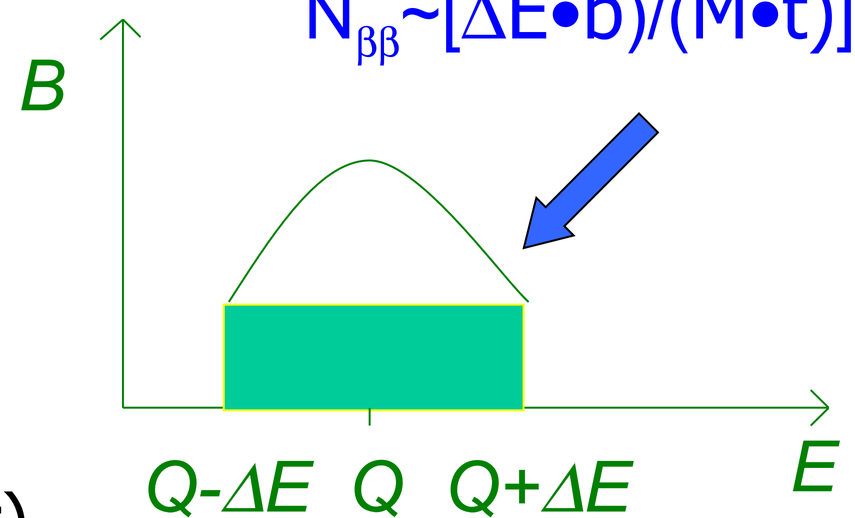
signal sensitivity ≈ stat. precision of background $N_{obs} = \sqrt{N_{BG}}$

background ~ detector mass

$$T_{1/2} \propto a \bullet \varepsilon \, [\, (M \bullet t) / (\Delta E \bullet b) \,]^{1/2}$$

- a : isotopical abundance
- ε : detector efficiency
- M : mass
- t : measuring time
- ΔE : energy resolution
- b : background cts/(keV kg yr)

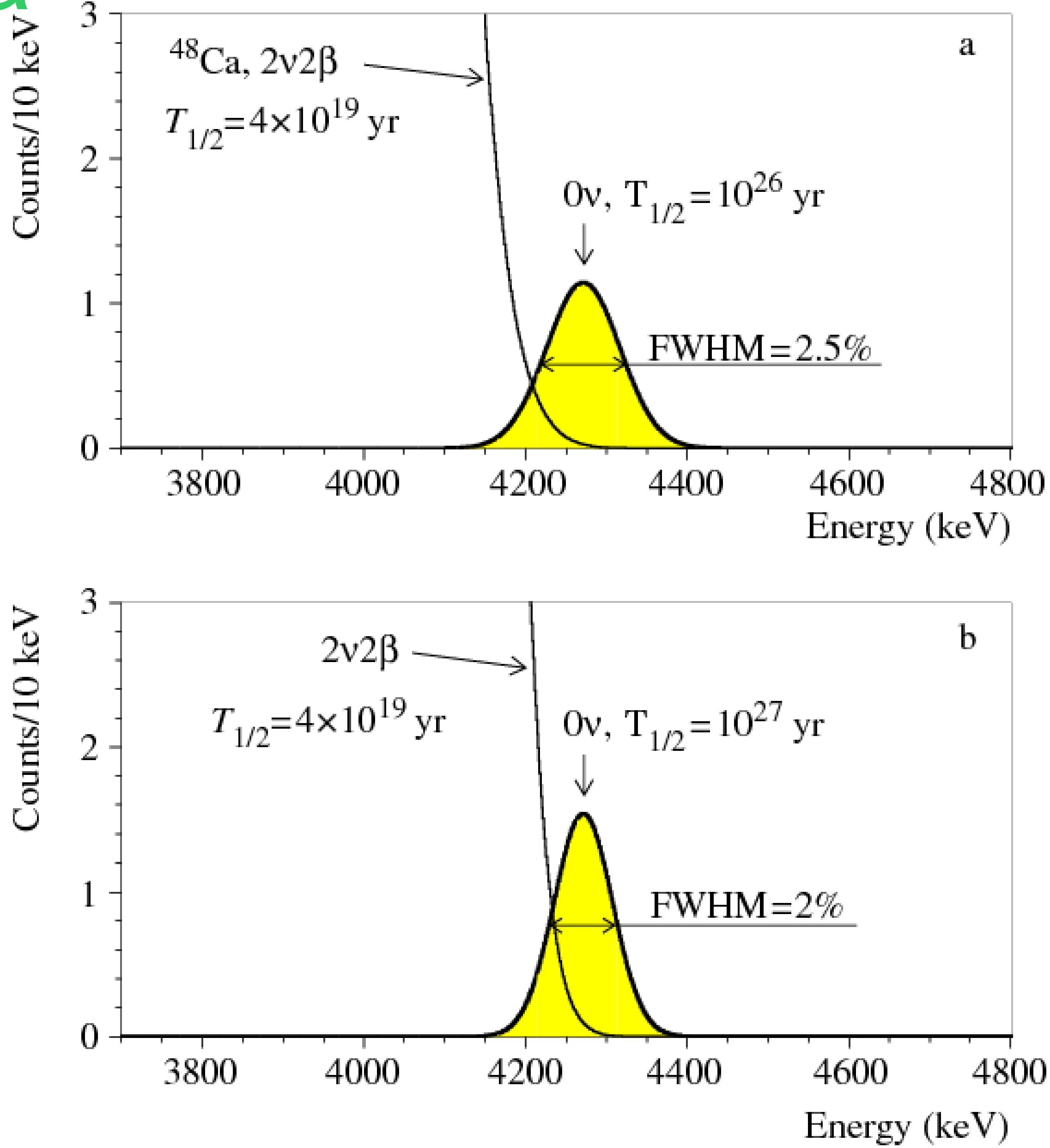
$N_{\beta\beta} \sim [\Delta E \bullet b)/(M \bullet t)]^{1/2}$



Region Of Interest

resolution

^{48}Ca



FWHM = 2,5 %

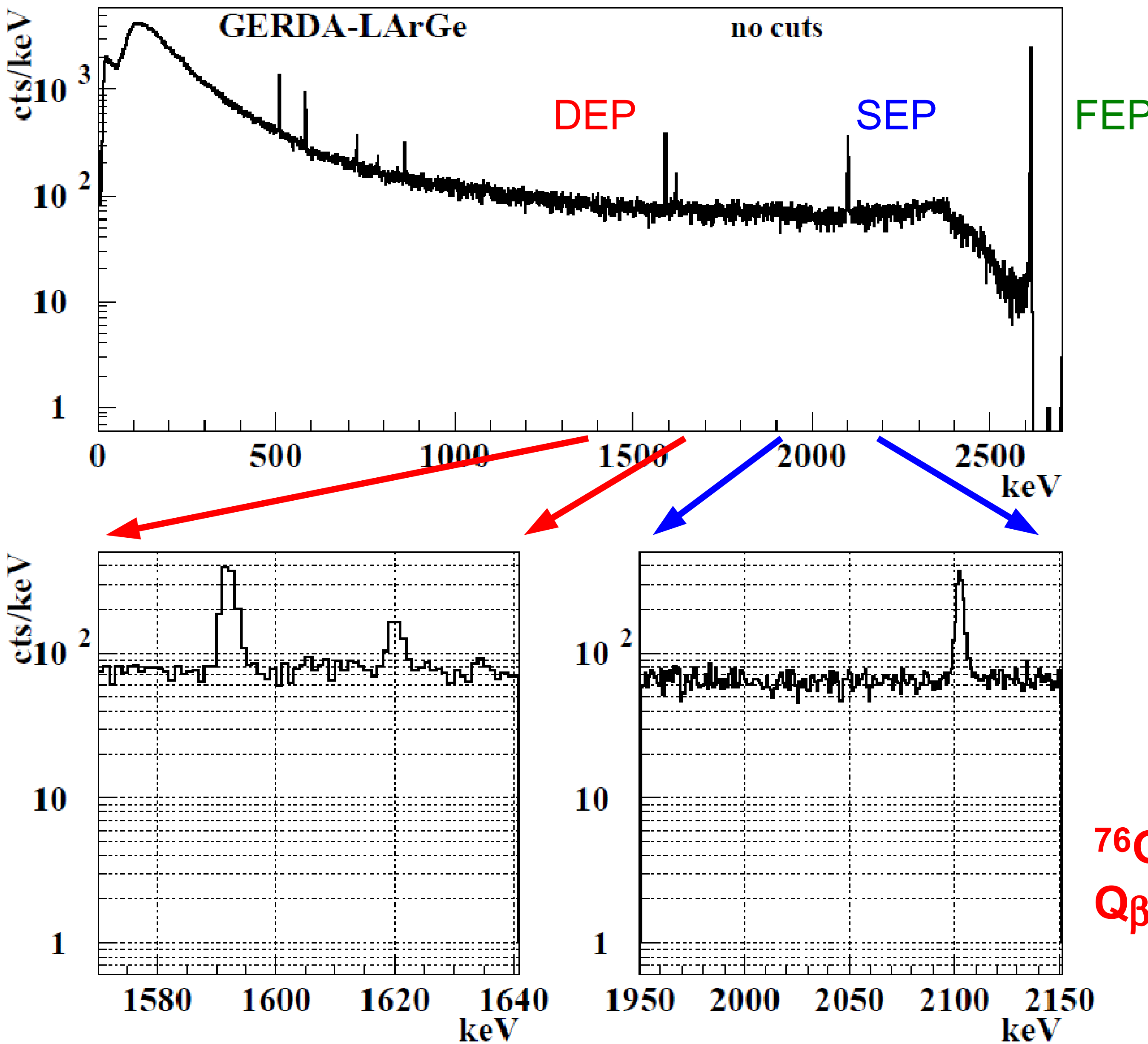
$T_{1/2} = 10^{26}$ yr

FWHM = 2,0 %

$T_{1/2} = 10^{27}$ yr

ratio 2ν/0ν !!!

^{228}Th spectrum



^{228}Th

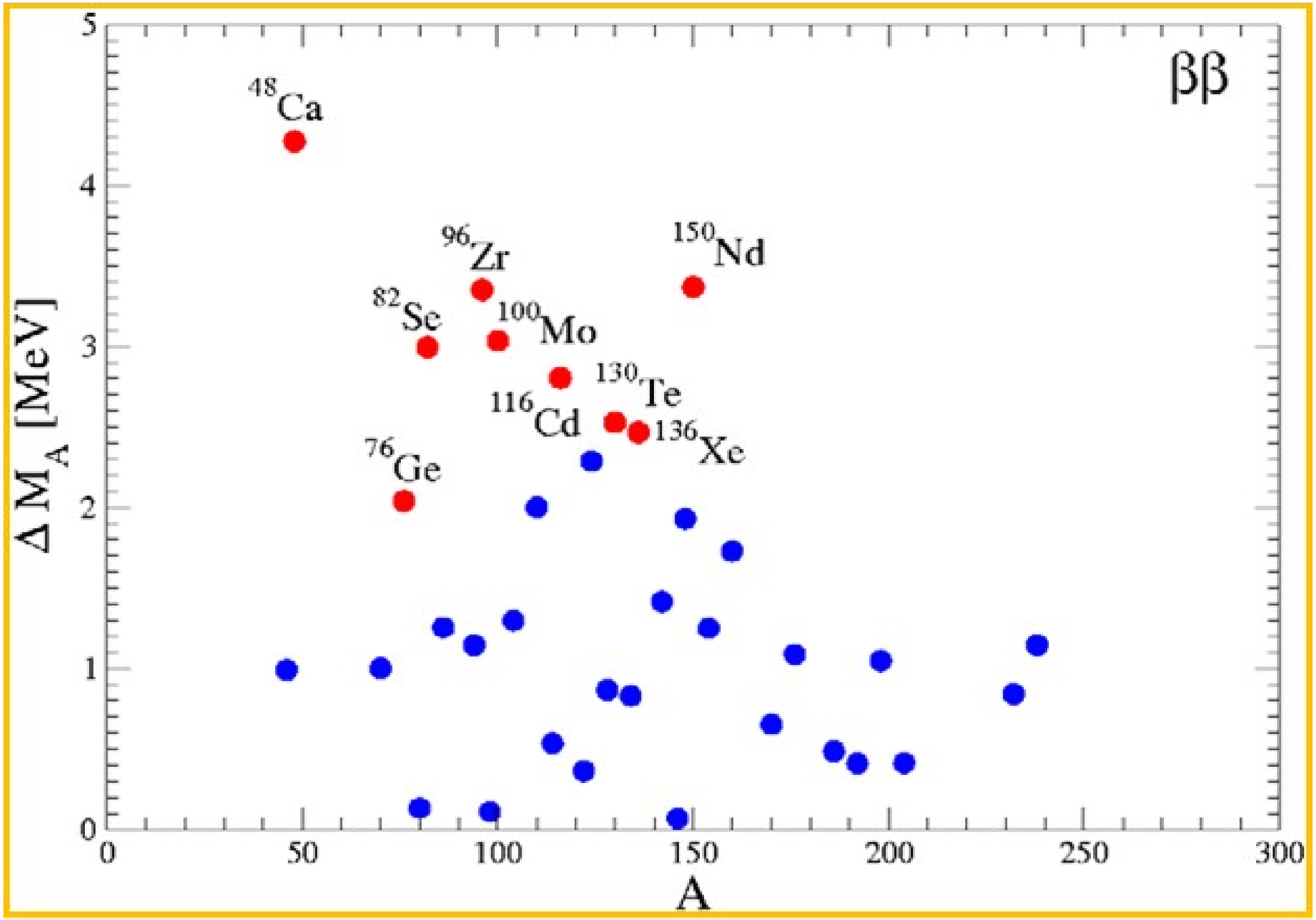
appears in natural decay chains

big source of backgound

radon

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

candidates



ββ
^{48}Ca
^{96}Zr
^{150}Nd
^{82}Se
^{100}Mo
^{130}Te
^{116}Cd
^{136}Xe
^{76}Ge
Δ M_A [MeV]
A
0
1
2
3
4
5
0
50
100
150
200
250
300

candidates

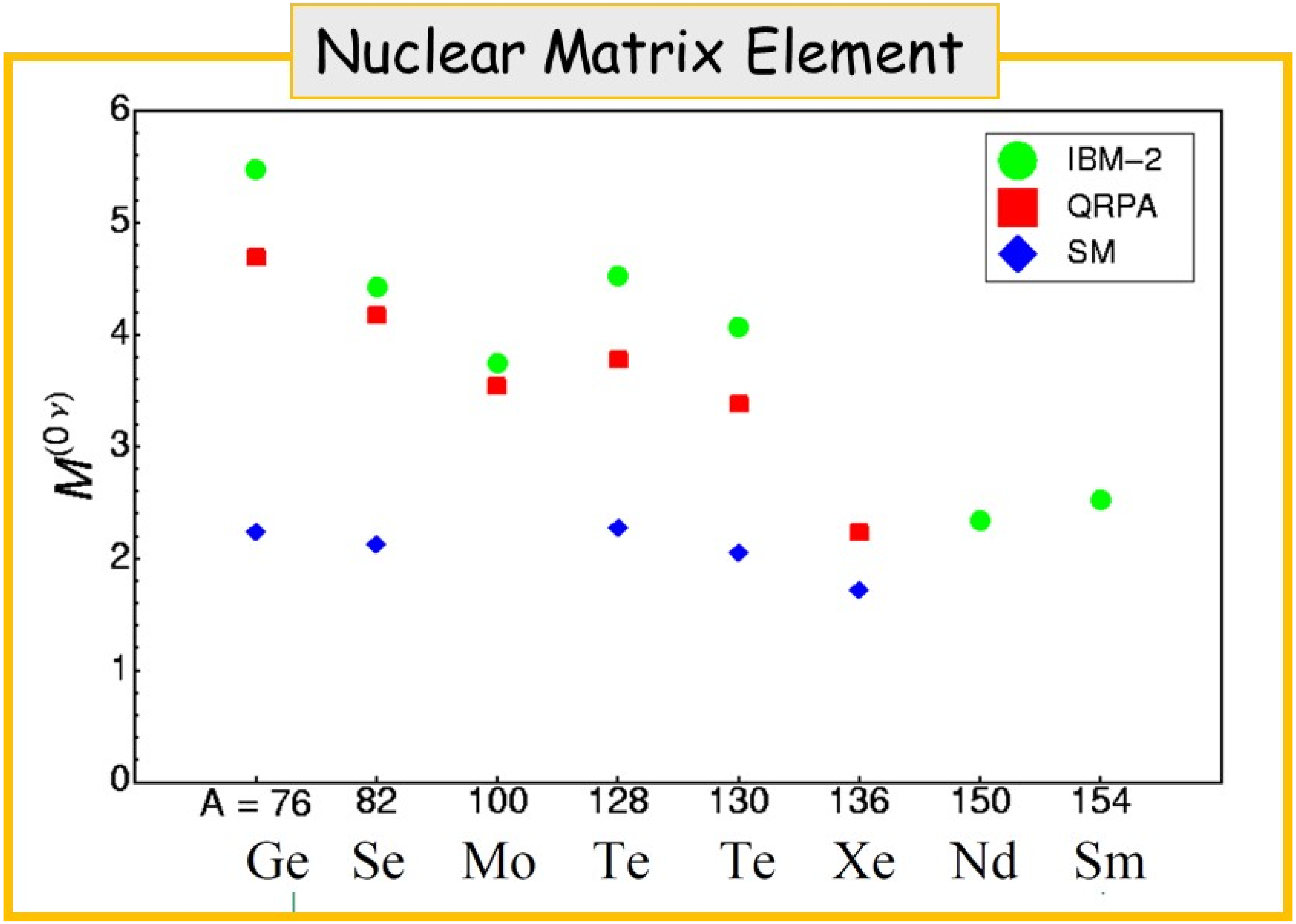
$0\nu\beta\beta$ decay rate scales with Q^5
$2\nu\beta\beta$ decay rate scales with Q^{11}

Isotope	Q-value (keV)	Nat. abund. (%)	$(PS\ 0\nu)^{-1}$ (yrs x eV^2)	$(PS\ 2\nu)^{-1}$ (yrs)
Ca 48	4271	0.187	4.10E24	2.52E16
Ge 76	2039	7.8	4.09E25	7.66E18
Se 82	2995	9.2	9.27E24	2.30E17
Zr 96	3350	2.8	4.46E24	5.19E16
Mo 100	3034	9.6	5.70E24	1.06E17
Pd 110	2013	11.8	1.86E25	2.51E18
Cd 116	2802	7.5	5.28E24	1.25E17
Sn 124	2288	5.64	9.48E24	5.93E17
Te 130	2529	34.5	5.89E24	2.08E17
Xe 136	2479	8.9	5.52E24	2.07E17
Nd 150	3367	5.6	1.25E24	8.41E15

natural α decay : 2615 keV

Nuclear Matrix Elements

QRPA: A. Faessler, F.Simkovic, V. Rodin NPA 766 (2006) 107 corr



Shell Model: Strassbourg-Madrid; Caurier, Poves

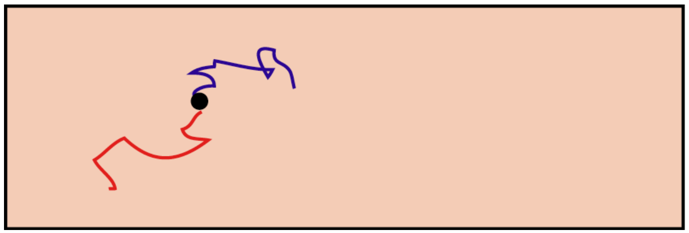
IBM: Barea,Iachello

methods and experiments

methods

aim at **100 meV scale** $\Rightarrow$ **B < 10^{-3}/(keV kg yr)**

calorimetric:



two orders of magnitude better than now

+ very clean materials
+ very large sensitive masses
  several 100 kg:
    CUORICINO/CUORE, bolometers
    GERDA, MAJORANA Ge diodes
+ per-mille energy resolution

source = detector

Measure sum energy with calorimetric techniques

Ge semiconductor, bolometers

tracking:

source ≠ detector

+ background suppression via event reconstruction,
  but $2\nu2\beta$

– **energy resolution (to distinguish $2\nu2\beta$)**

– “dilute” detectors, need large space

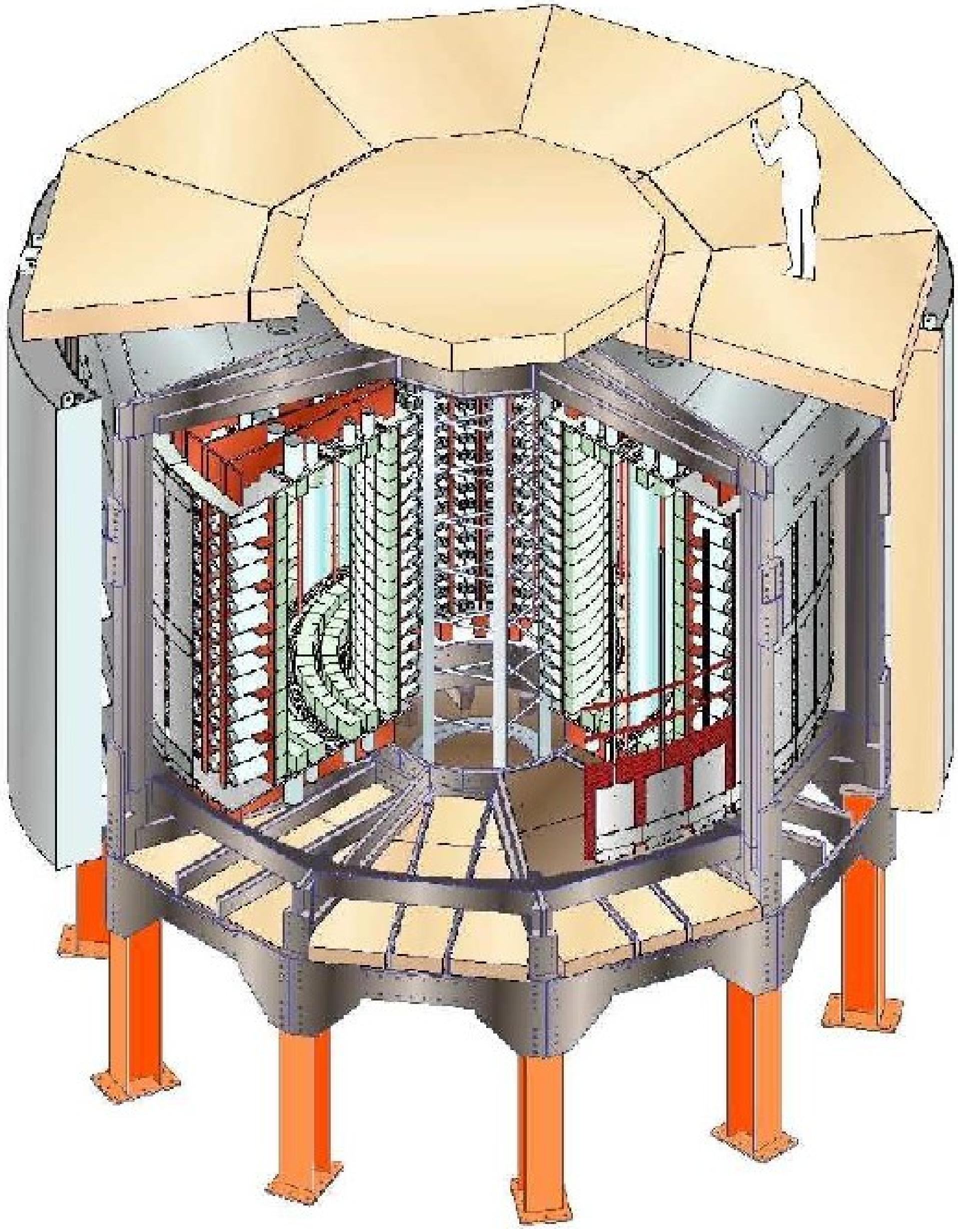
+ several nuclides possible ($\Rightarrow$ select high Q)
  NEMO3: tracking, calorimetry, **B**-field,
  $\Rightarrow$ **$T_{1/2}$ > 5.8 10^{23} y $\Rightarrow$ M_{ee} < 0.4 - 1.4 meV**
  $\Rightarrow$ **Future: SuperNEMO** , NEXT, COBRA

experiments

NEMO/SuperNEMO	^{100}Mo	DC tracking
cuoricino/cuore	^{130}Te	bolometer
Majorana/GERDA	^{76}Ge	ionisation

Candles	^{48}Ca	szintillation
SNOW++	^{150}Nd	szintillation
MOON	^{100}Mo	MWPC+PLfibres
COBRA	CdZnTe	ionisation+track?
LUCIFER	$CdWO_4$,	bolometer
EXO/NEXT	^{136}Xe	TPC

NEMO



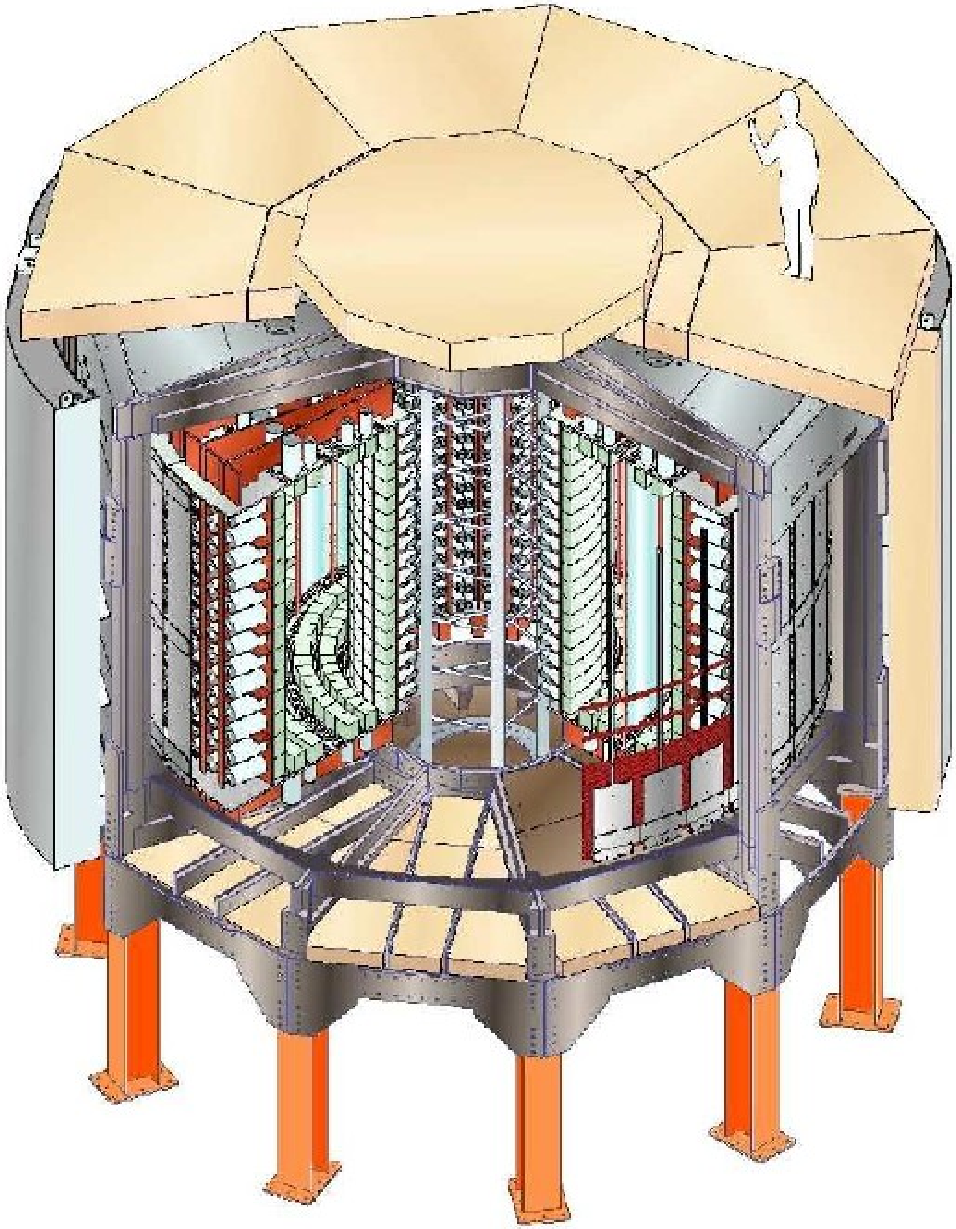
20 segments with thin foils
3D readout drift chambers
surrounding 1940 plastic szint.
B = 30G   (ε_{track} = 98%)

Mo (6,9kg), Se(0,9kg),Te(0,45kg)
Cd(0,40kg),Nd(36g)

Modane : 4800 mwe

$\boldsymbol{\varepsilon}$ = 50% @ 1 MeV
ΔE = 11-14% FWHM

NEMO

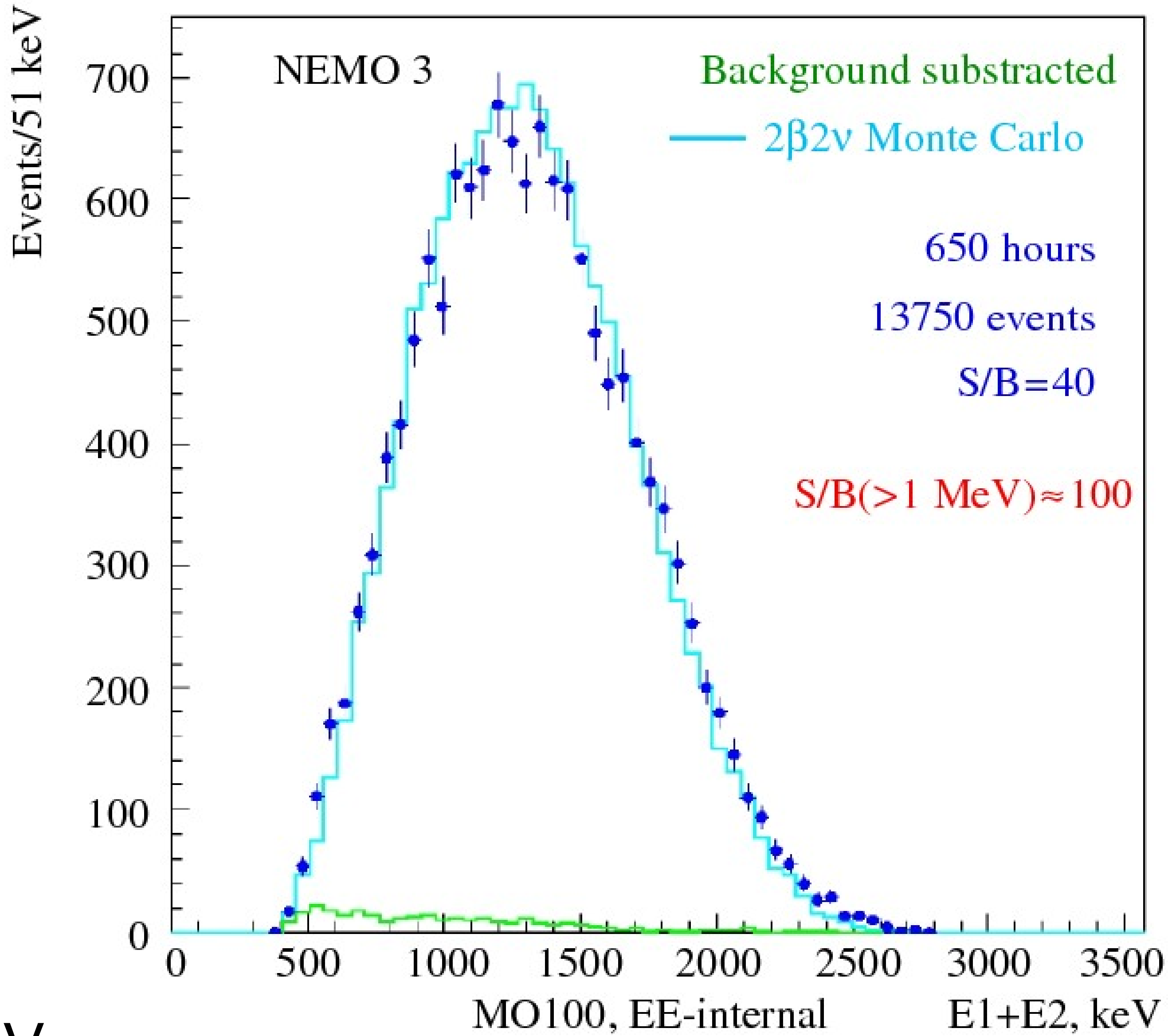


NEMO

^{100}Mo

Q = 3034 keV

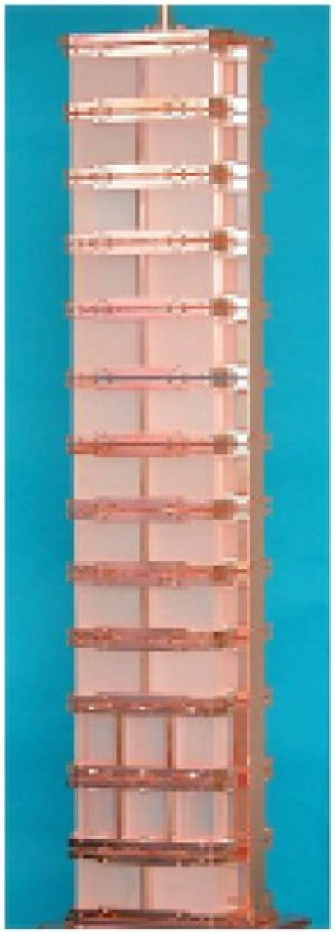
$T^{2\nu}_{1/2} = 7{,}8 \cdot 10^{18}$ y



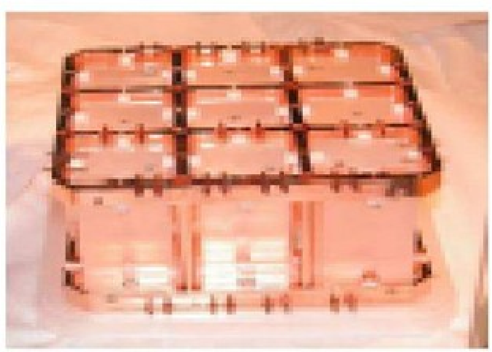
ΔE = 250 keV @ 3MeV

CUORICINO/CUORE

62 crystals in 13 planes



5x5x5 cm^3



3x3x6 cm^3

2 enriched

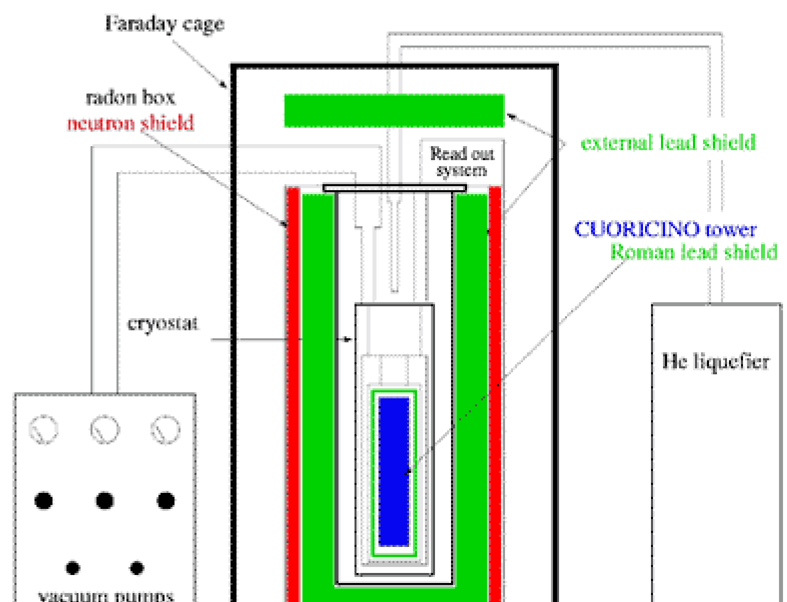
^{128}Te and ^{130}Te

TeO_2 bolometers: M ~ 30kg

OFHC Copper & Teflon

T = 8 mK

b =0,2 cts/(keVkgy)



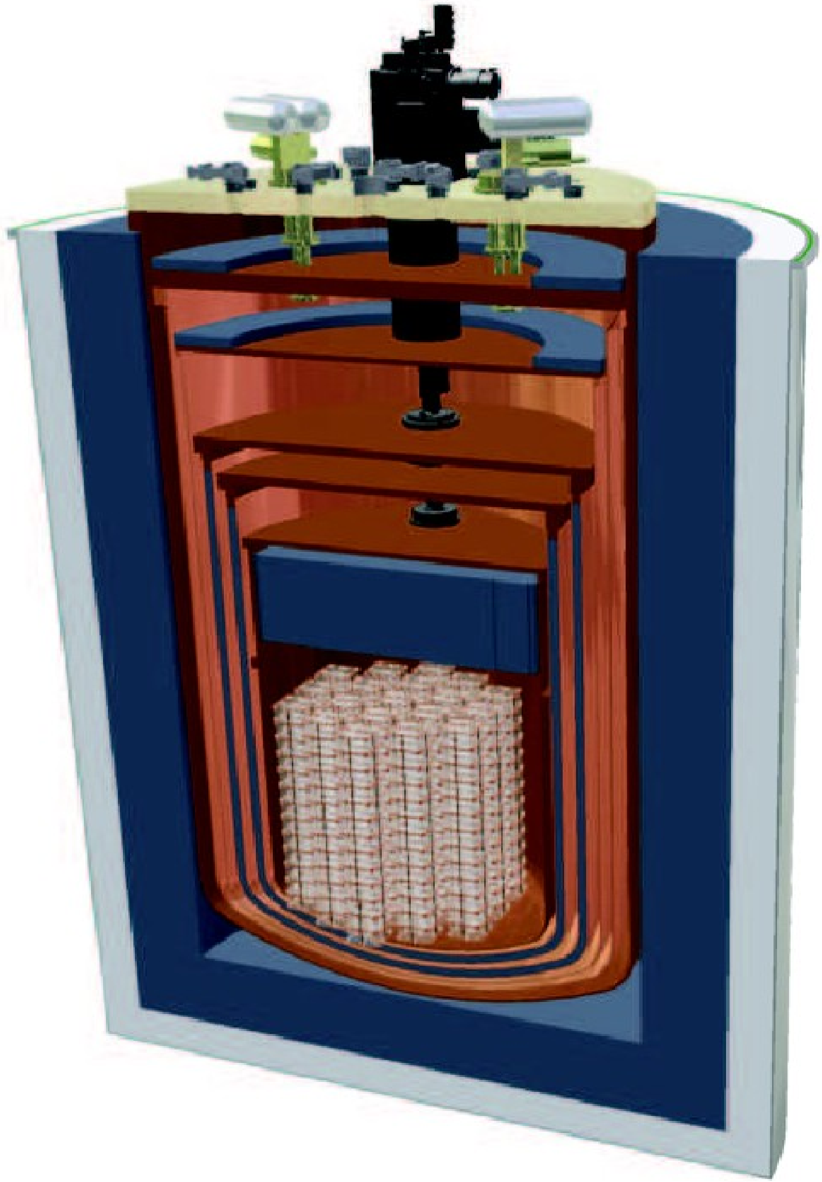
CUORICINO/CUORE

^{130}Te in CUORE

$Q_{\beta\beta}$ = 2530 keV

988 TeO_2 bolometers
in 19 towers

M = 750 kg

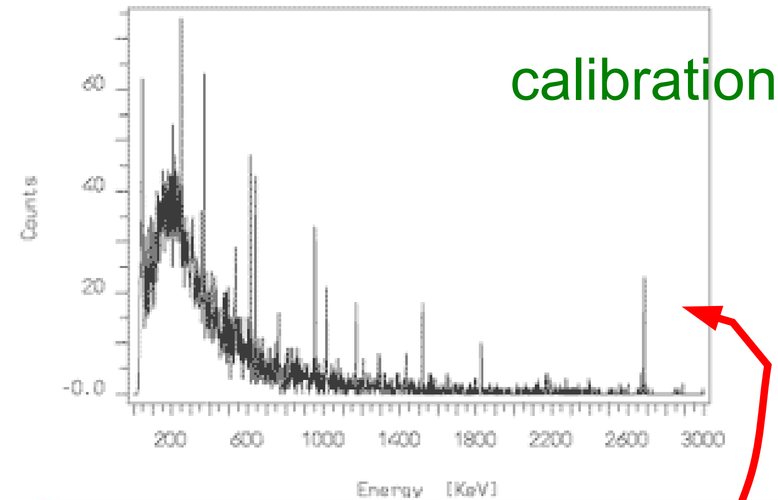


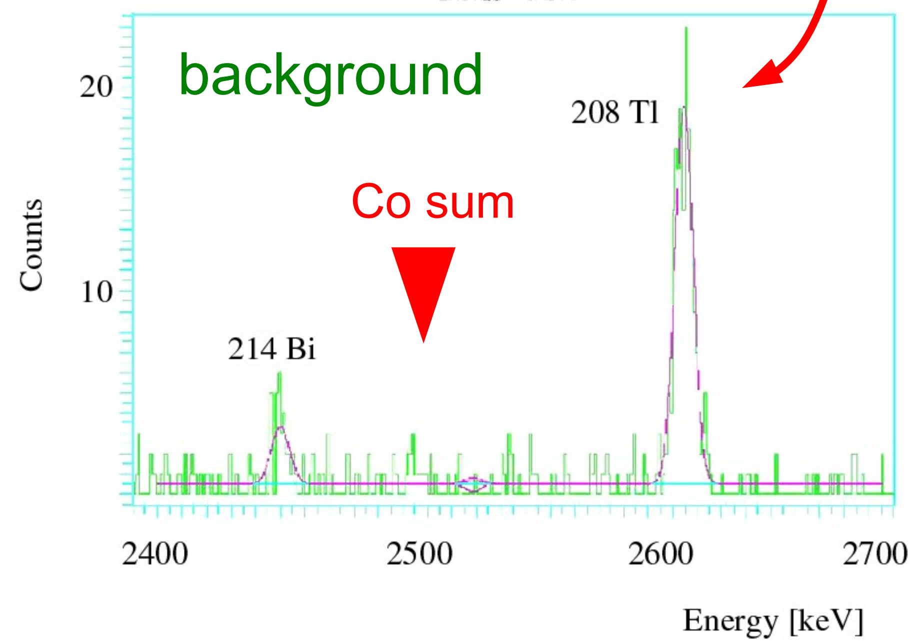
CUORICINO/CUORE

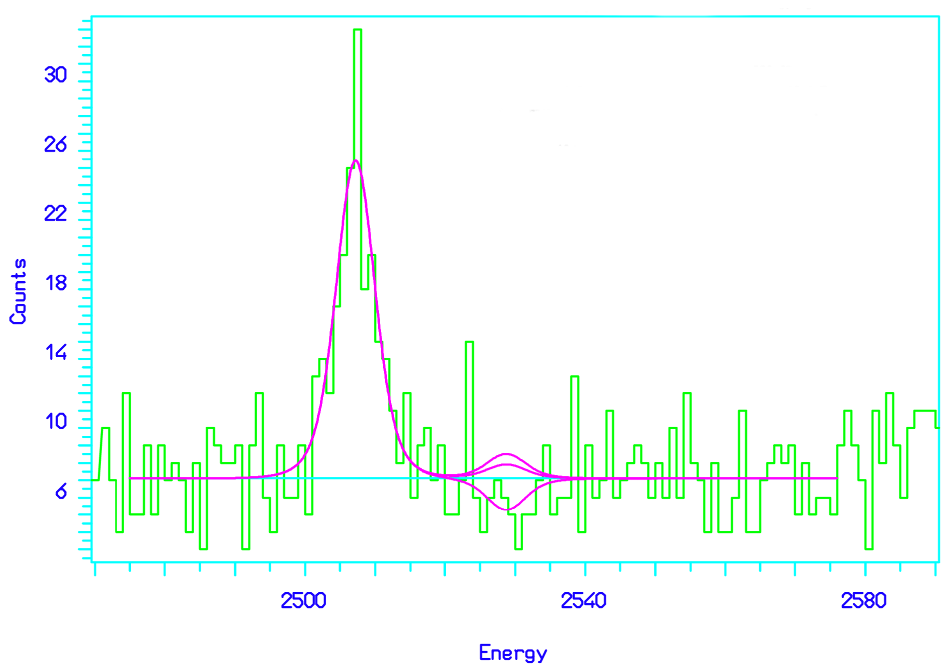
^{130}Te in CUORICINO

$Q_{\beta\beta}$ = 2530 keV

$T^{0\nu}_{1/2} > 3 \cdot 10^{24}$ y (11,8 kg·y)







^{76}Ge experiments

previous experiments: HDM (5 det) and IGEX (3 det)

Klapdor-Kleingrothaus et al.

Phys Lett B586 (2004) 198

71,7 kg·y

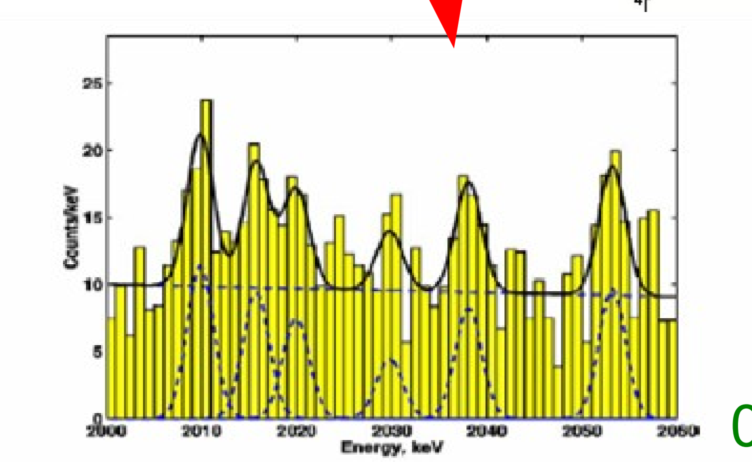
$T_{1/2} > 1,9 \cdot 10^{25}$ y (90%CL)

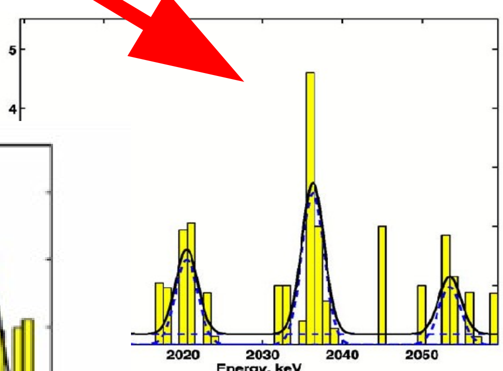
Aalseth et al.

Phys Rev D65 (2002) 092007

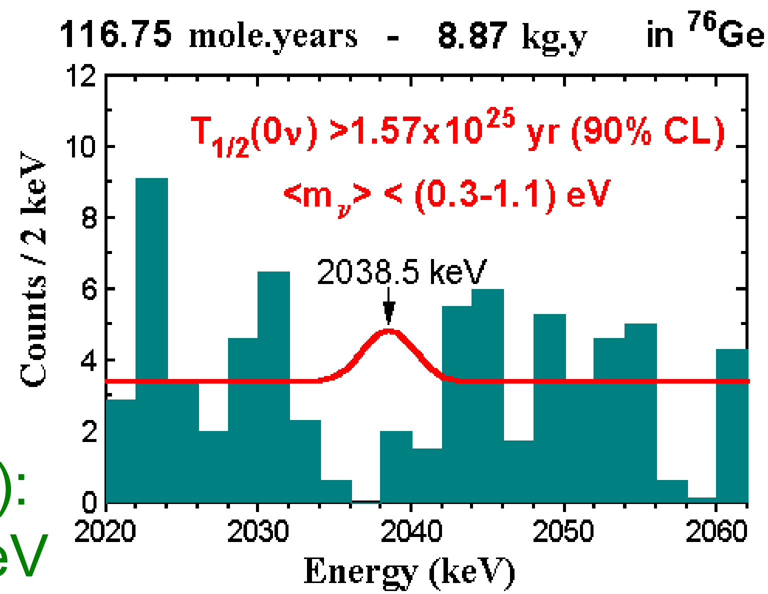
8,9 kg·y

$T_{1/2} > 1,6 \cdot 10^{25}$ y (90%CL)

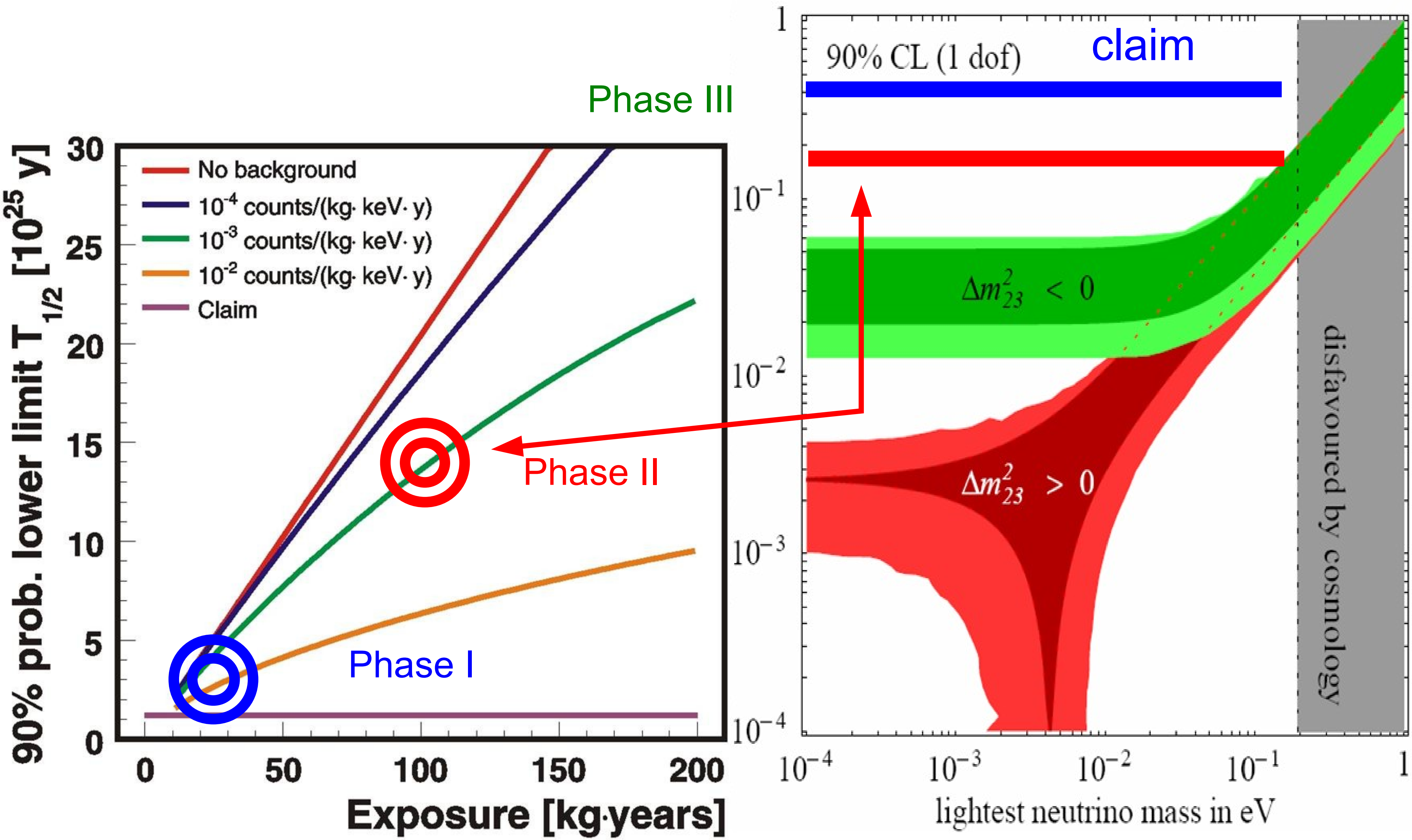




MPLA21 (2006):
$0,27 < m_{\beta\beta} < 0,4$ eV



sensitivity of GERDA

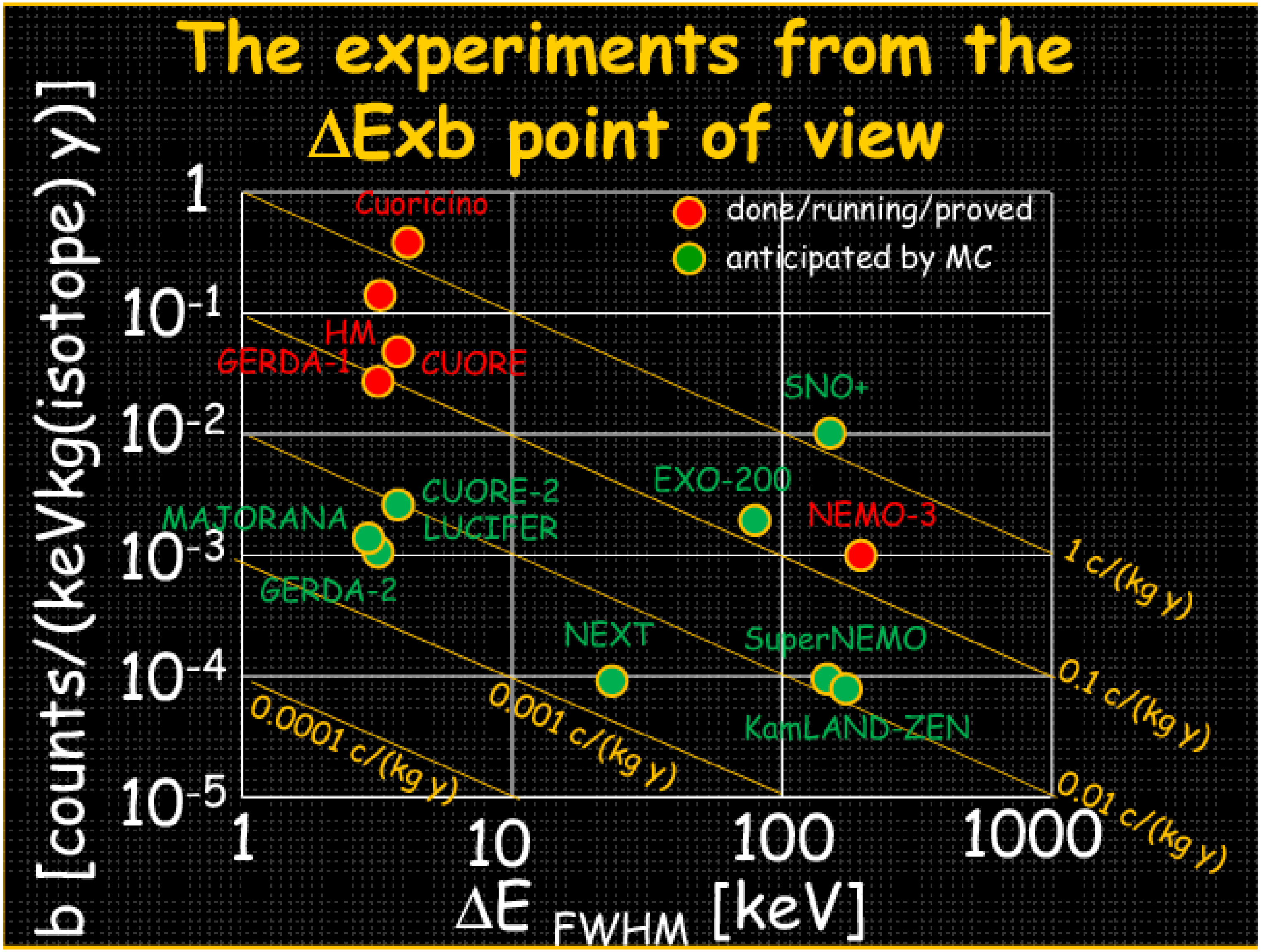


<M> = 2,4 c.f. NPA 766 (2006) 107

comparison

$T_{1/2} \propto a \bullet \varepsilon \, [\, (M \bullet t) \,/\, (\Delta E \bullet b) \,]^{1/2}$

M · t = money



A.Giuliani

strategy

Which choices should me make?

there is no super-DBD-isotope !

check on different isotopes for systematics

- detection techniques
- background contributions
- NME

GERDA – the collaboration

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~40 FTE

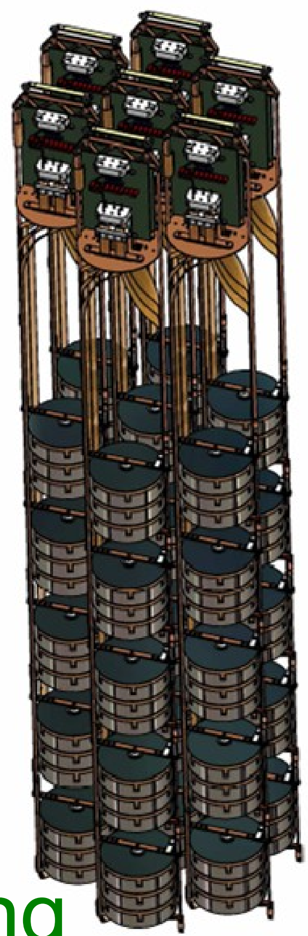
INFN LNGS, JINR Dubna, MPI Kernphysik Heidelberg, Jagellonian U. Cracow, U. Milano-Bicocca, INR Moscow, ITEP Moscow, Kurchatov Institute, MPI Physik München, U. Padova, U. Tübingen, TU Dresden,IRMM Geel, ETH Zurich

GERDA – the novel idea

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

"...low Z material around detector..."
"...mount the Ge diodes directly in cryo-liquid"

reduced radioactivity of environment
less muon-induced background



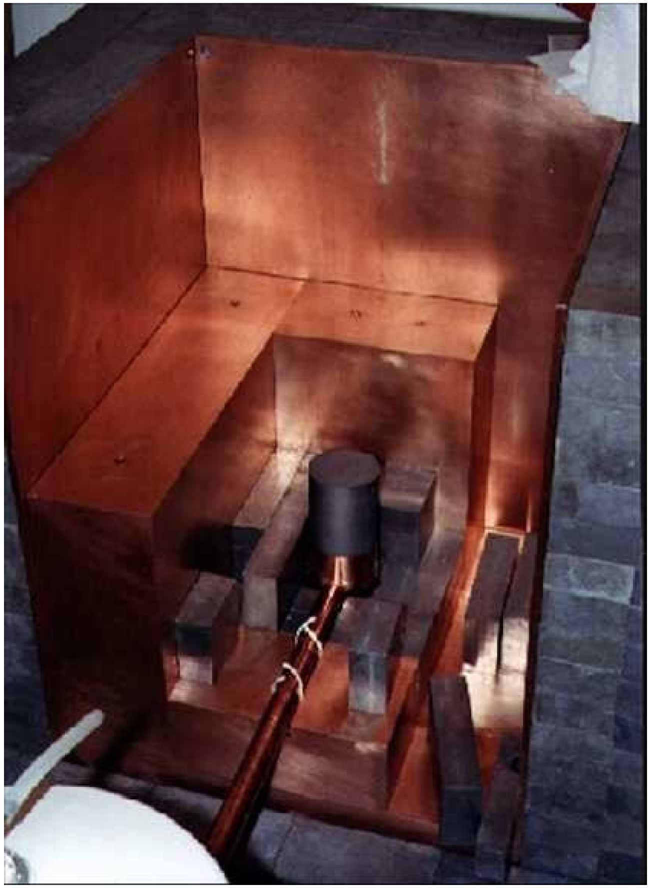
Ge diodes – enriched to 86%
liquid argon
stainless steel cryostat
water   to moderate neutrons and
as muon veto (Cerenkov)

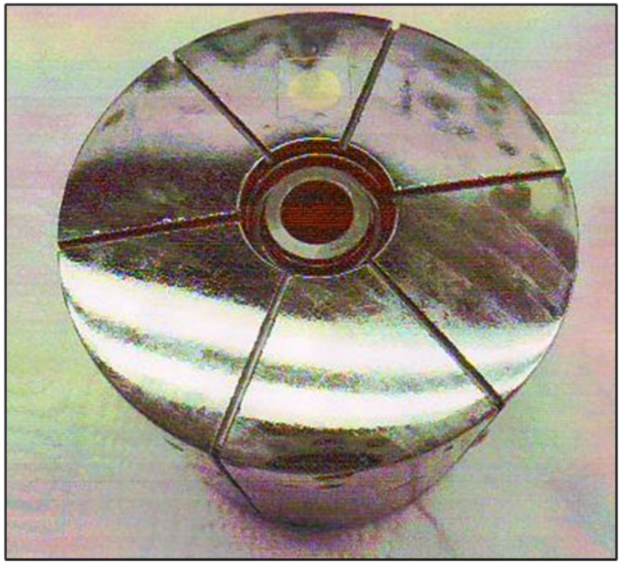
→ HdM, Majorana: closed compact shielding

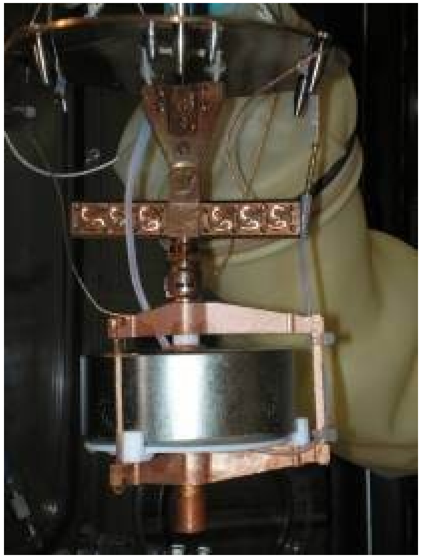
HdM/Majorana vs. GERDA

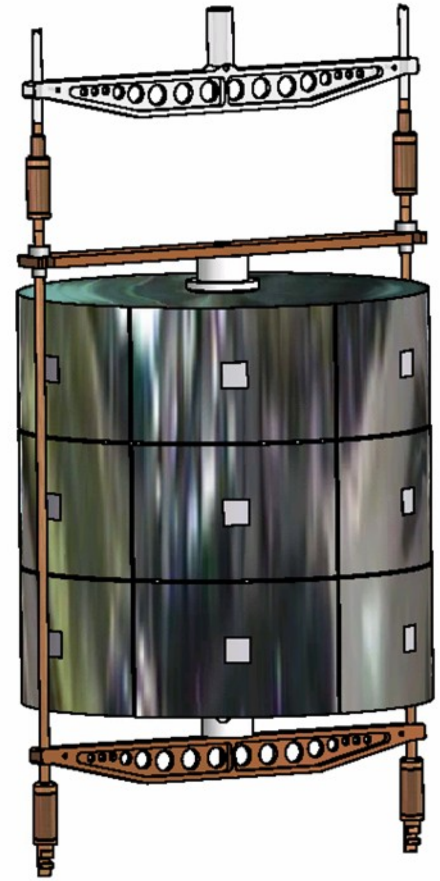
HdM

non-enriched prototype









BEGe

~ 12 g vs. ~ 2 kg

^{76}Ge experiment GERDA

^{76}Ge: Source == Detector

GERDA:

$Q_{\beta\beta}$ = 2039 keV

large mass of enriched material 7,44% → ~86%

high energy resolution <4 keV

separate $0\nu\beta\beta$ from $2\nu\beta\beta$

set smaller ROI

low background $<10^{-3}$ cts/(kg·y·keV)

passive : LNGS @ 3800 m.w.e. (reduce μ)

Watertank, LAr (avoid n,cosmogenic)

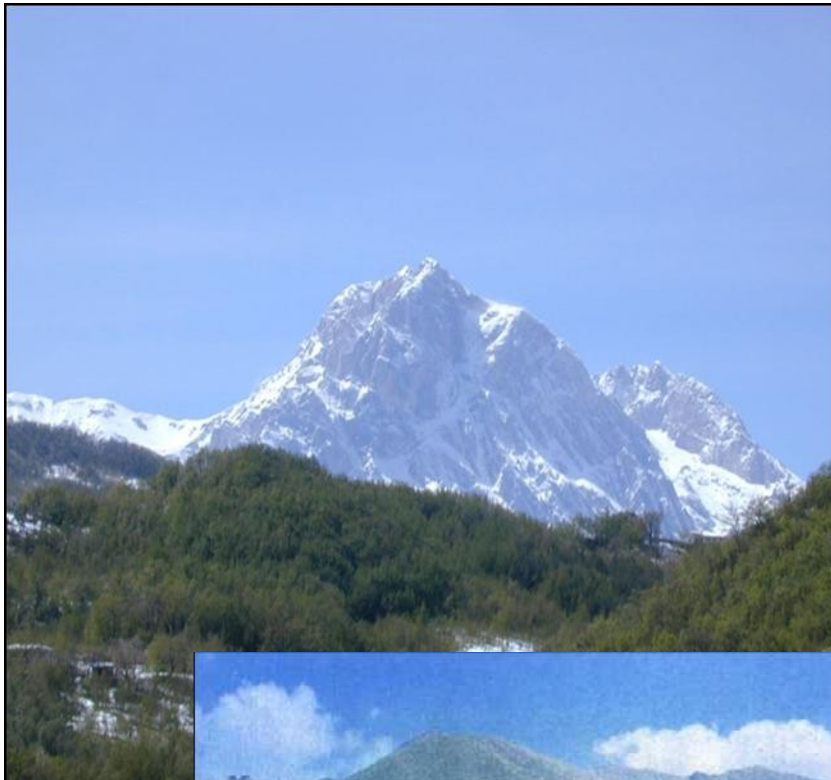
selection of material (reduce Th,U)

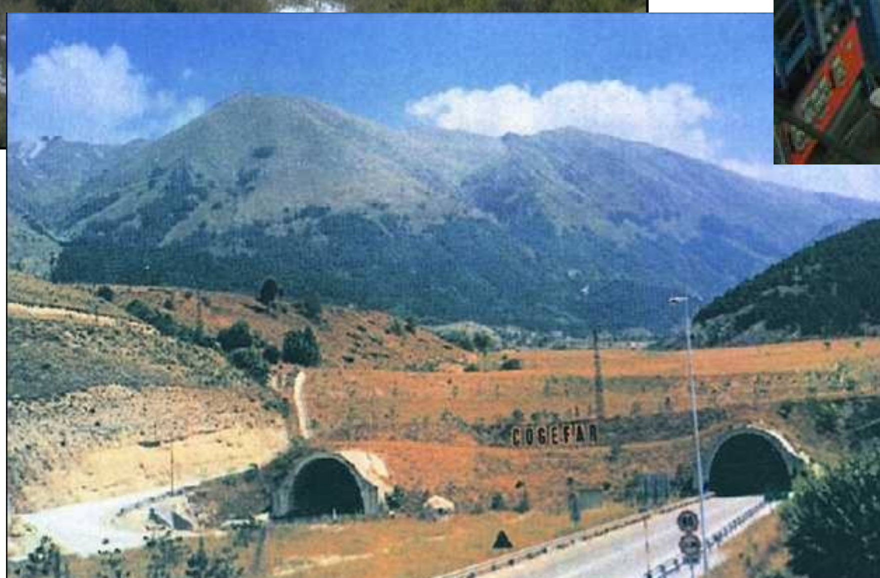
active : Muon veto

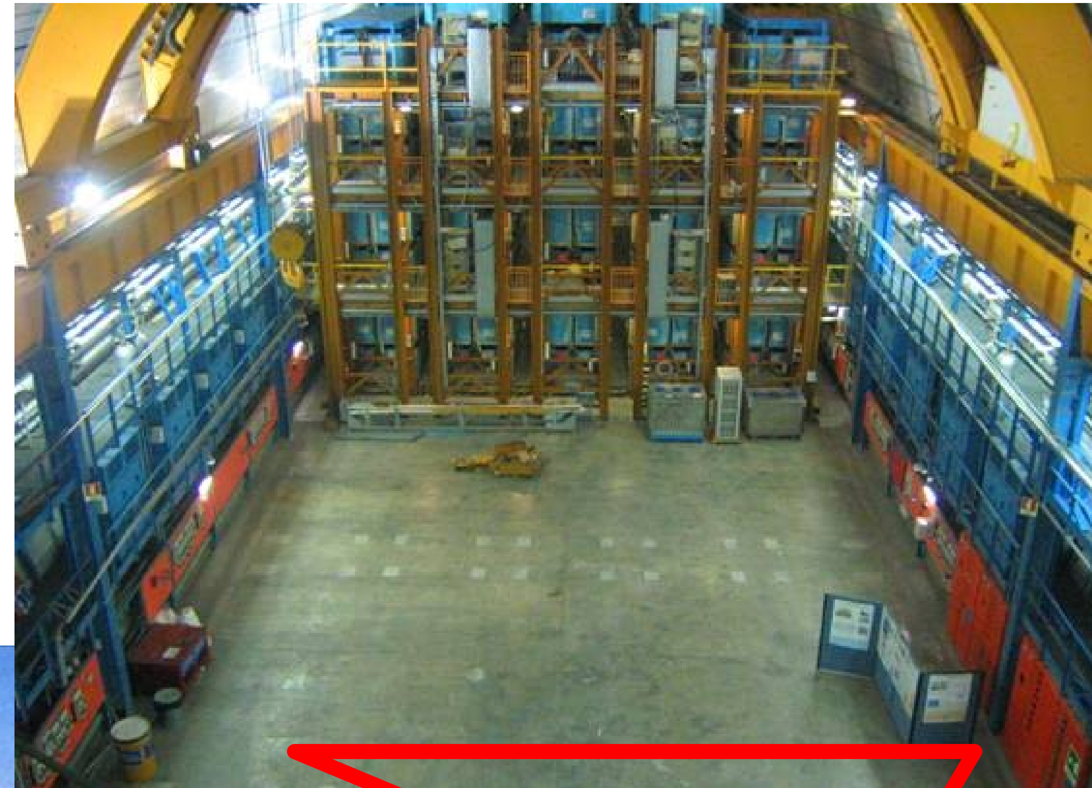
segmentation, anti-coincidence

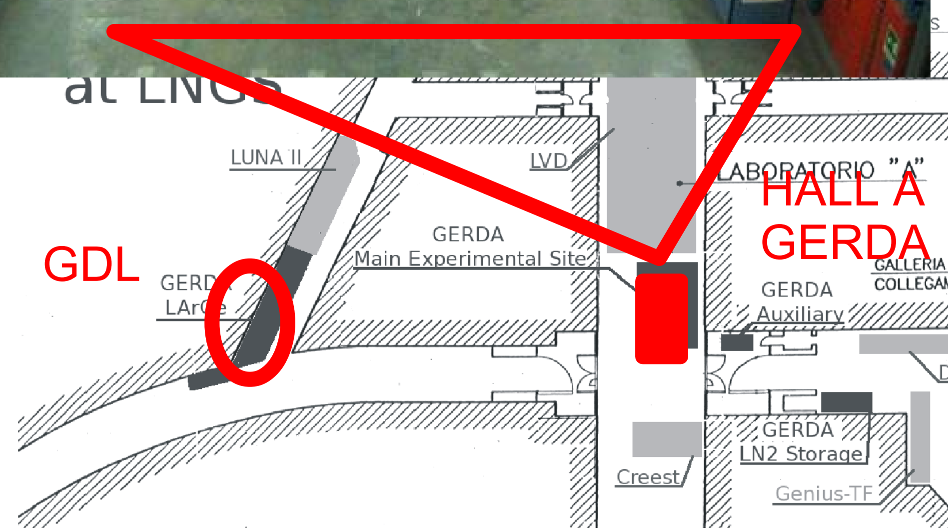
PSA

GERDA @ LNGS

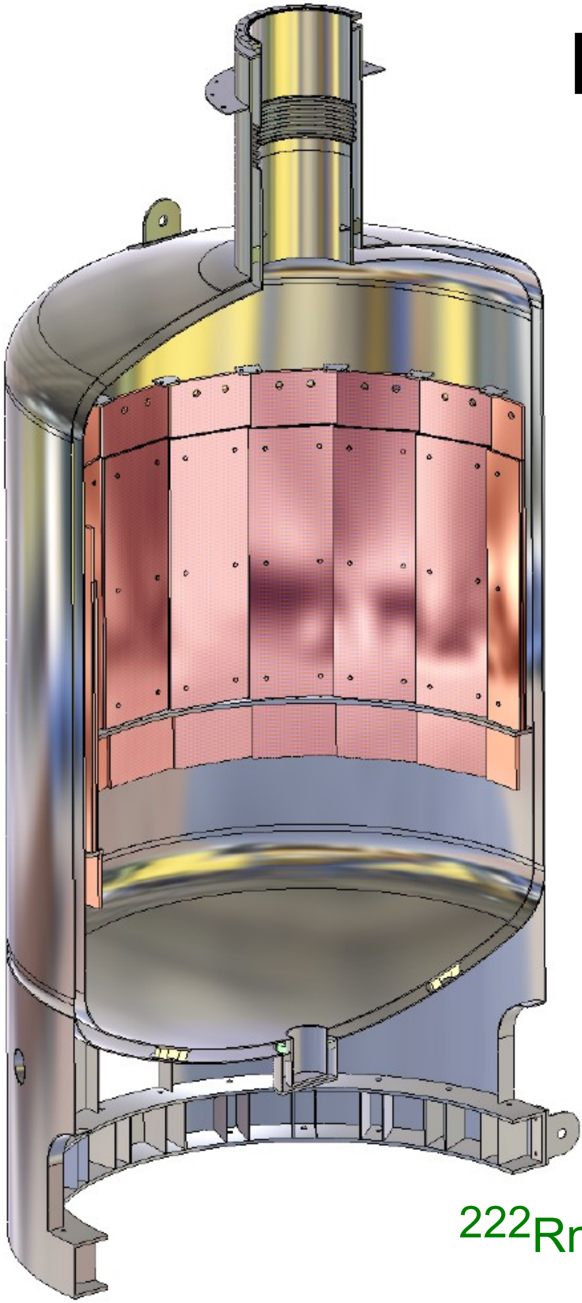







LUNA II
LVD
LABORATORIO "A"
HALL A
GERDA
GDL
GERDA
Main Experimental Site
GERDA
Auxiliary
GERDA
LN2 Storage
Creest
Genius-TF

Stainless Steel Cryostat



Double walled SS container

reduce Cu shield from 40 to 16 t

(1t ~ 8000 €)

LN_2 test

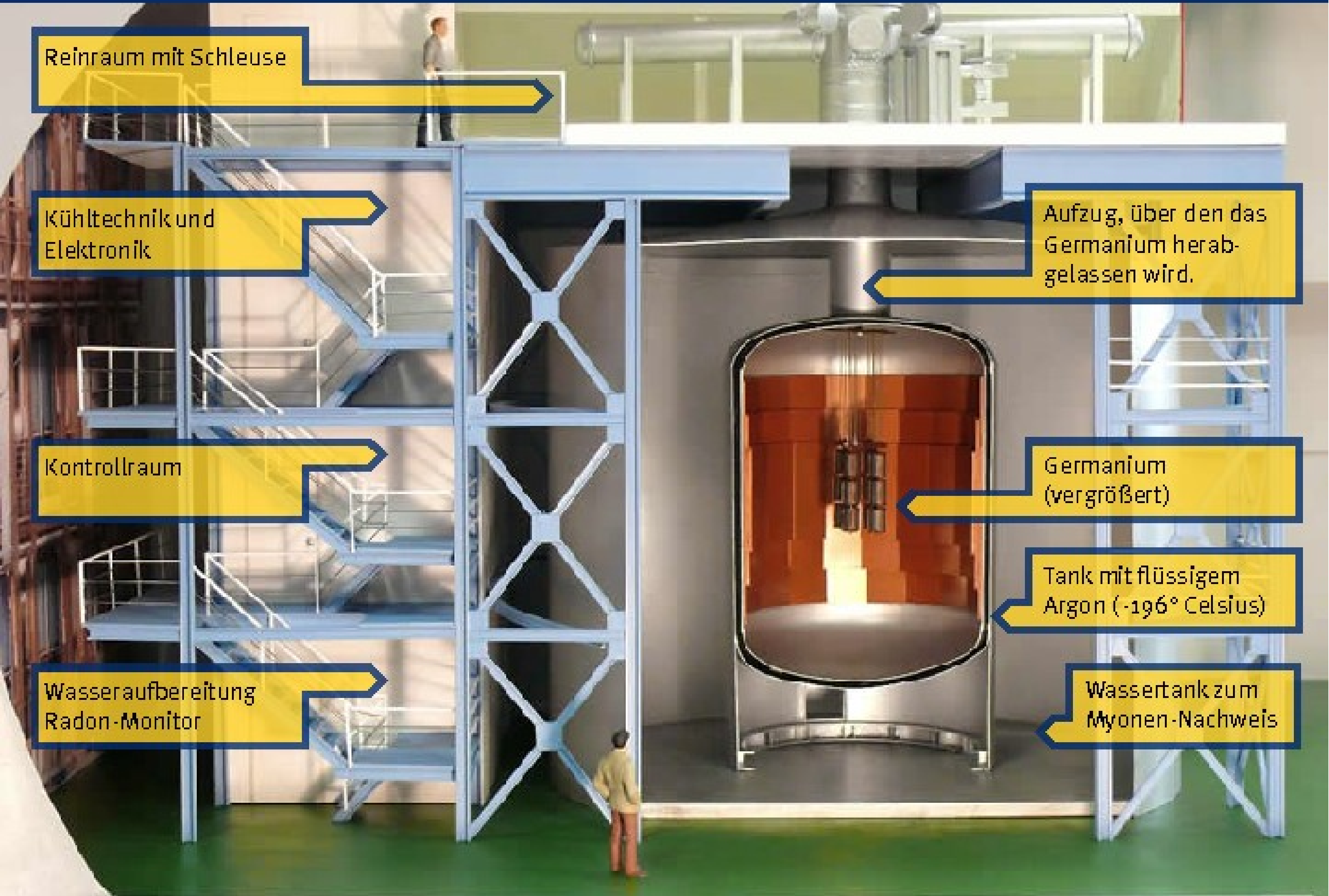
evaporation

< $4 Nm^3/h$

300 W

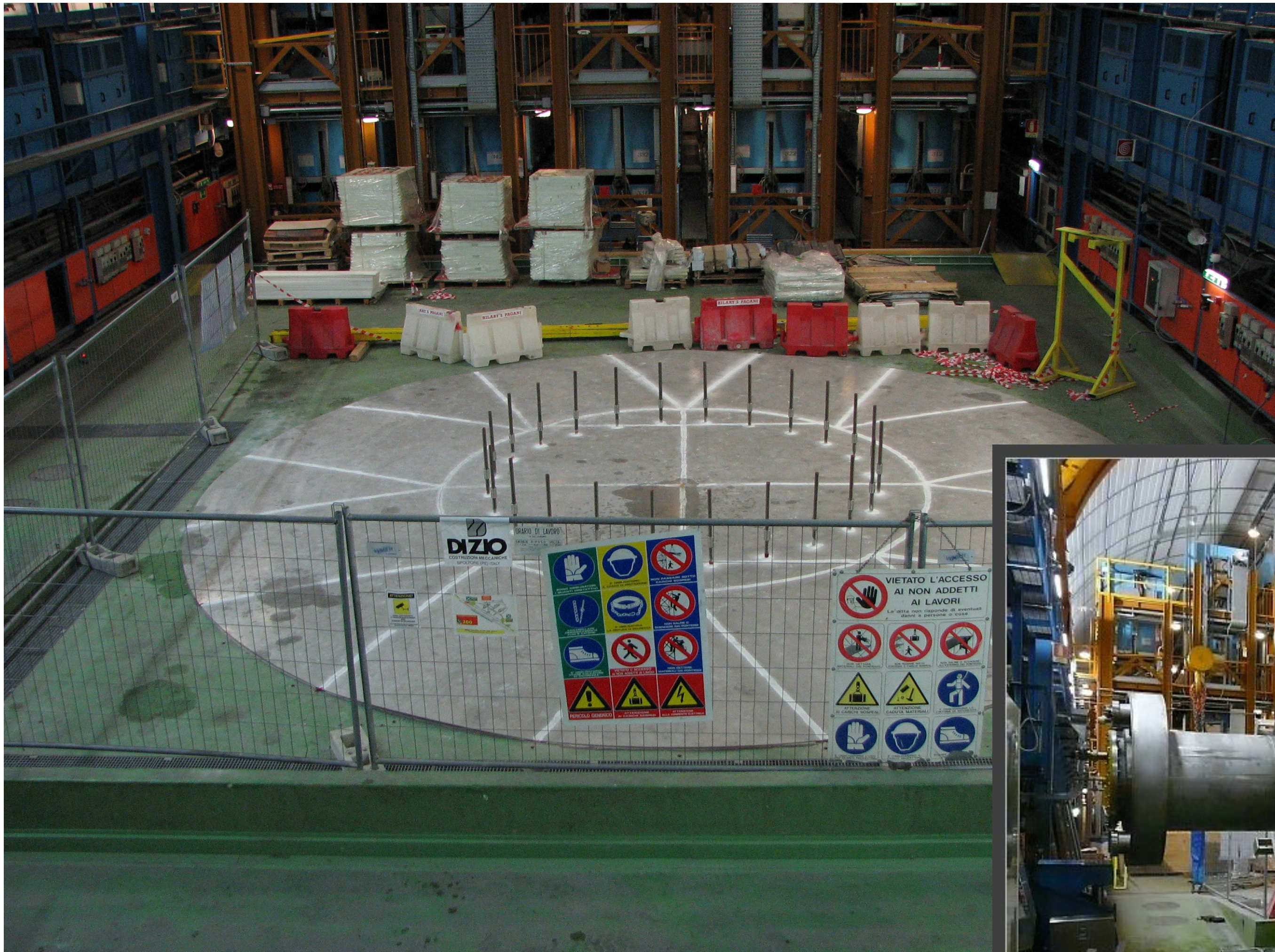
^{222}Rn: 14 → 30 mBq

GERDA-Experiment



construction @ LNGS

February 2008



March 2008

construction @ LNGS

March 2008

construction @ LNGS

May 2008

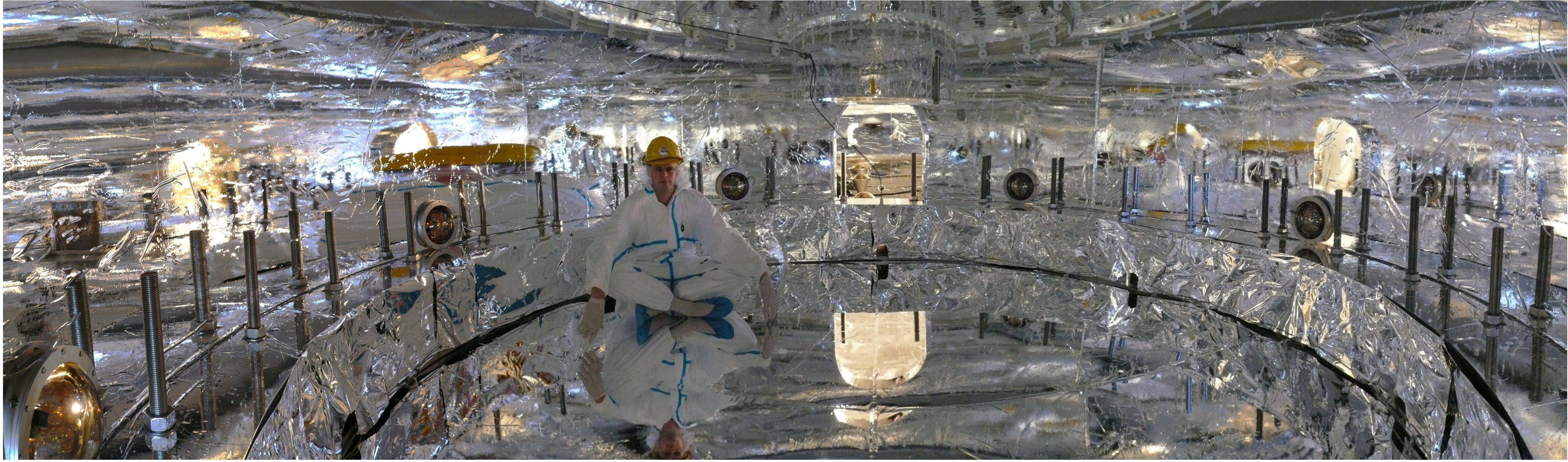
construction @ LNGS

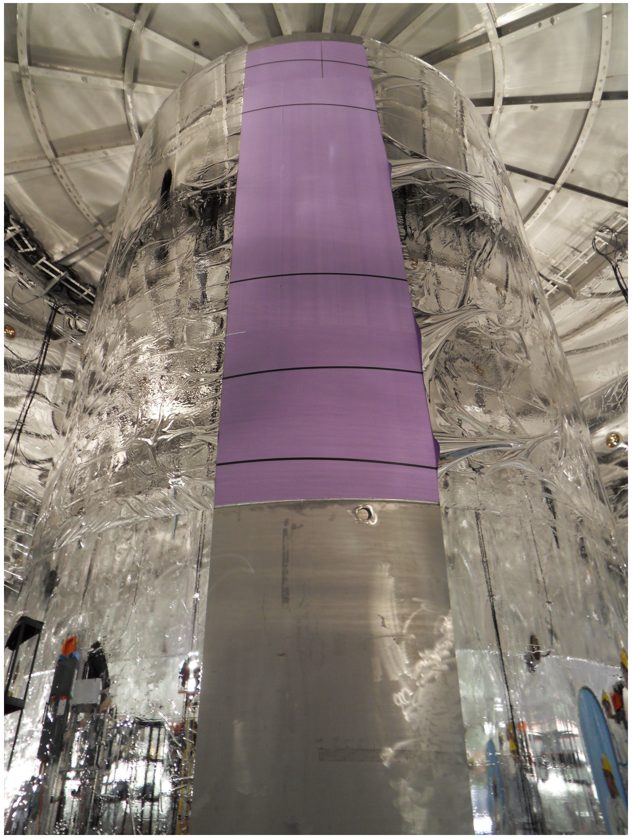
March 2009

Clean room, lock

cryogenic
infra structure

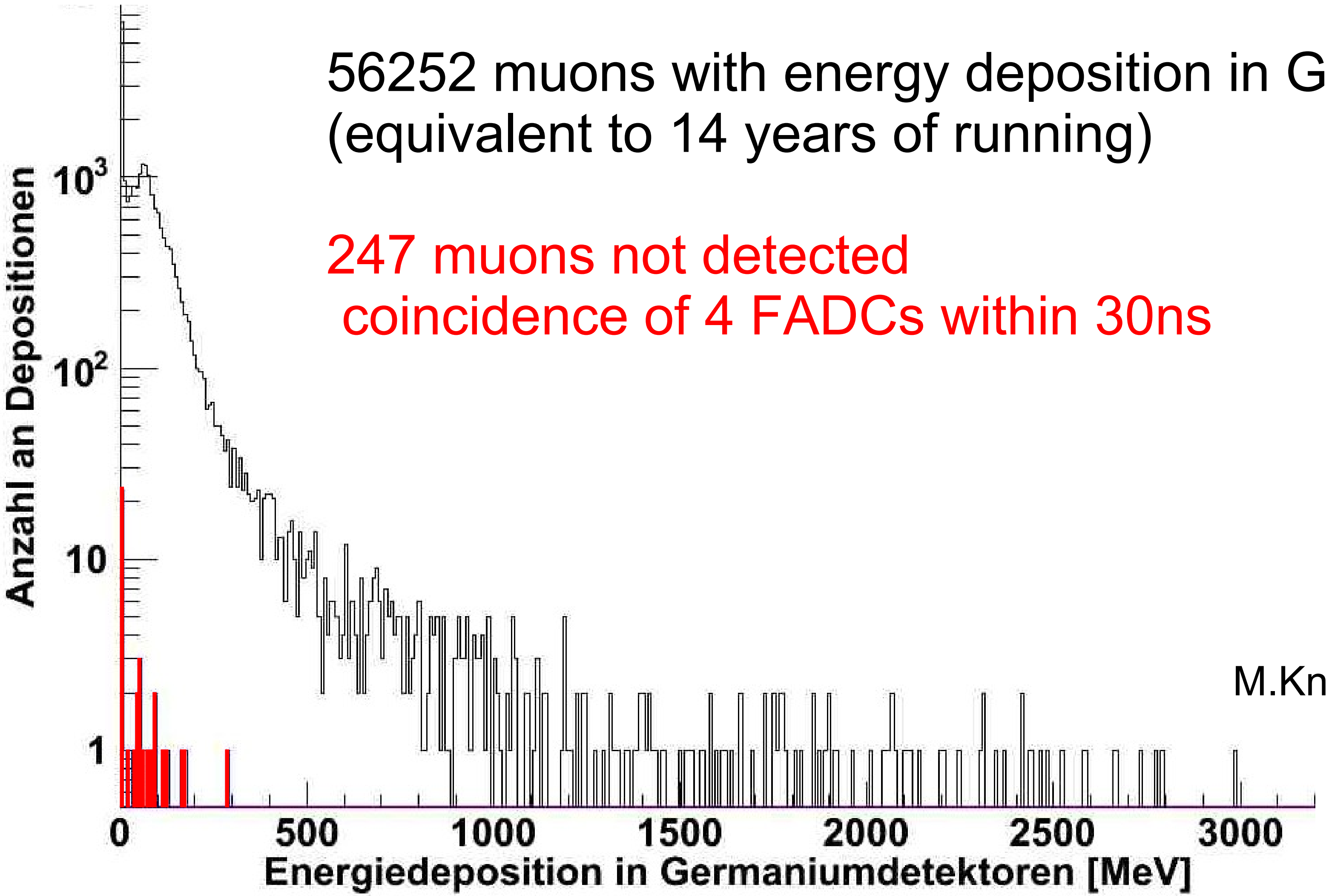
GERDA





M. Knapp, F. Ritter, K. Freund

Monte Carlo

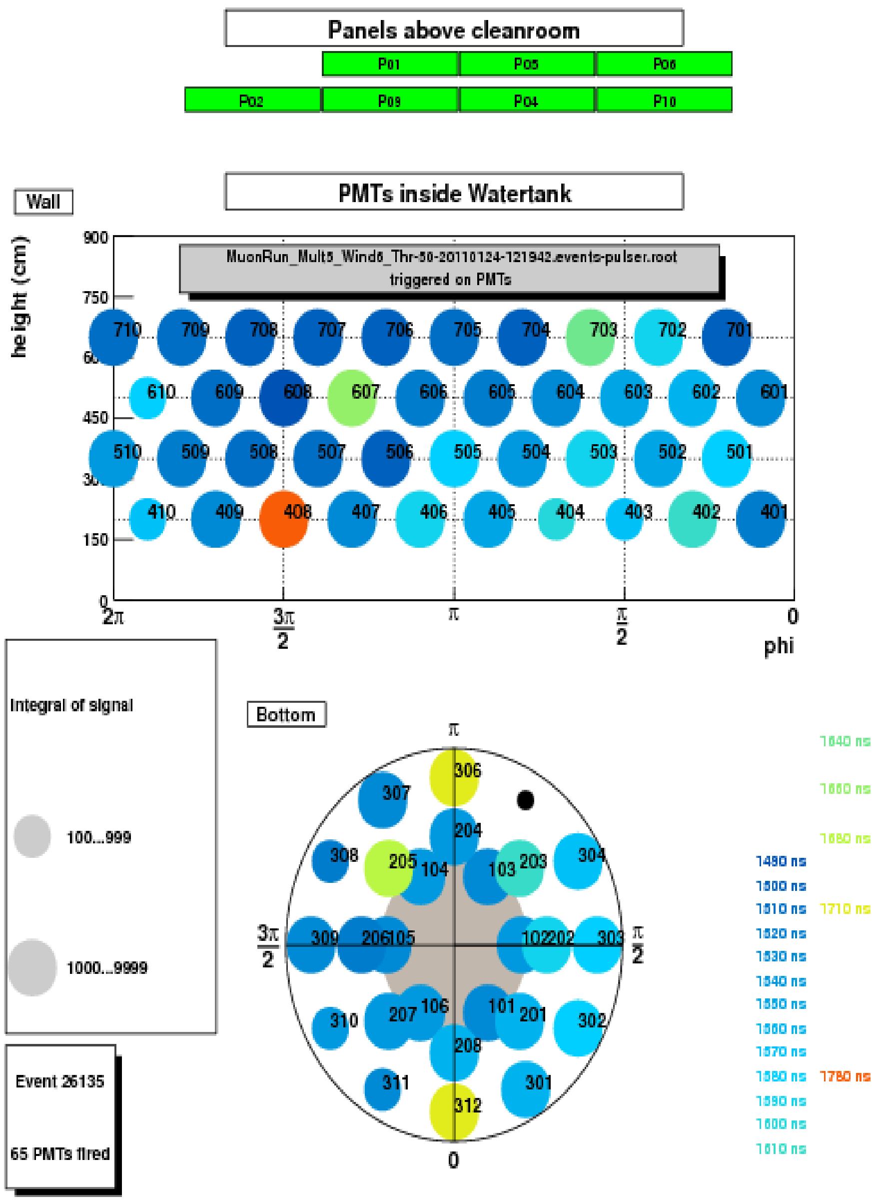


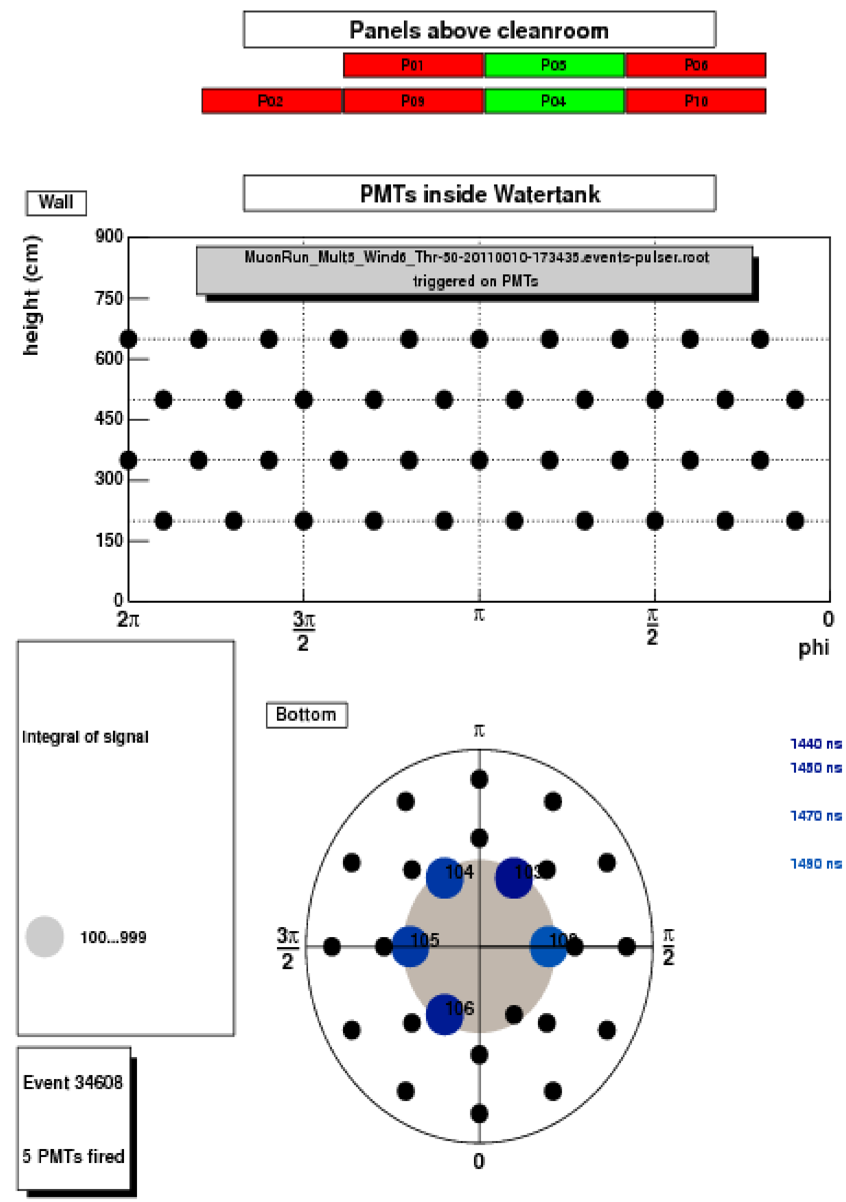
56252 muons with energy deposition in Ge
(equivalent to 14 years of running)

247 muons not detected
coincidence of 4 FADCs within 30ns

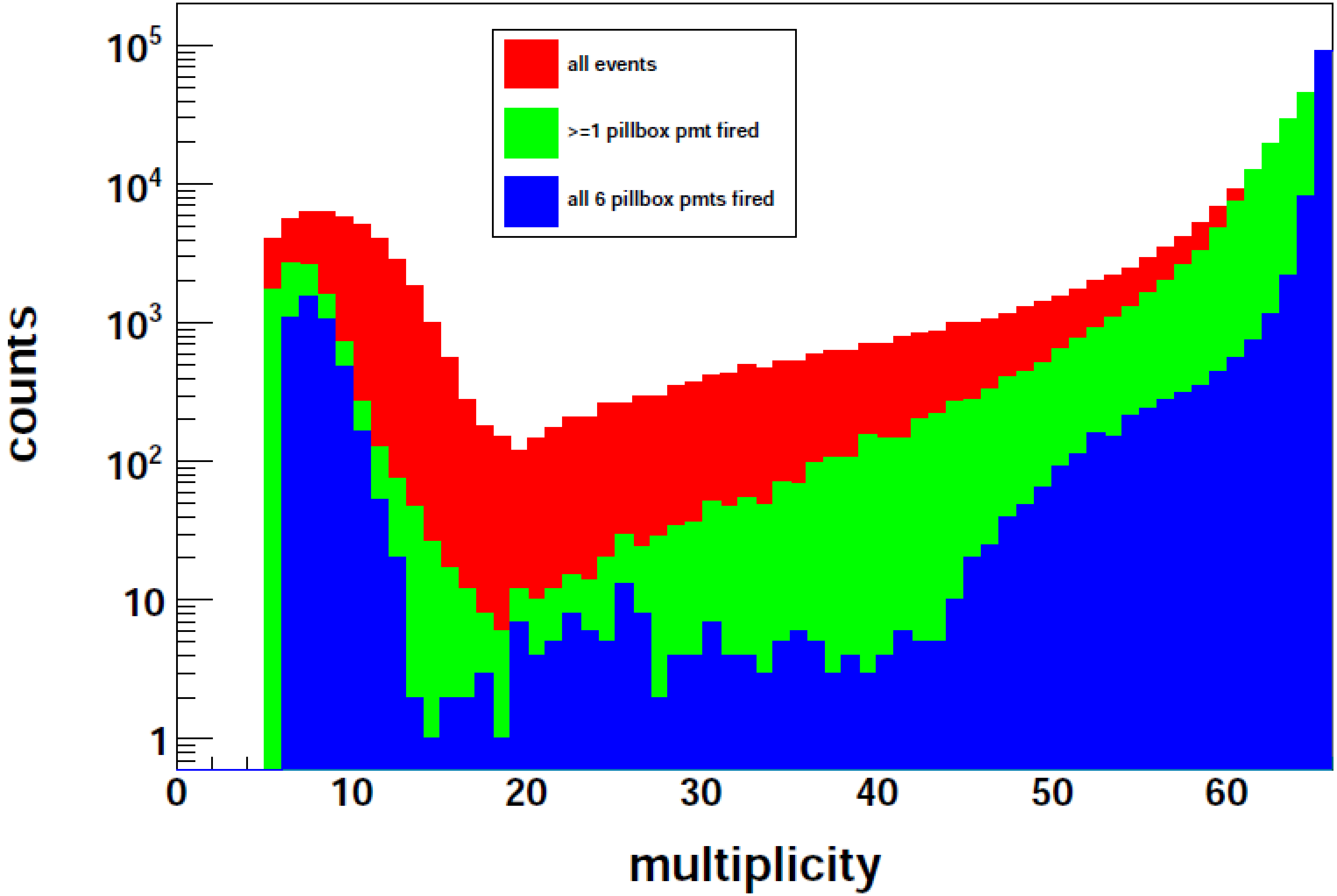
M.Knapp, PhD

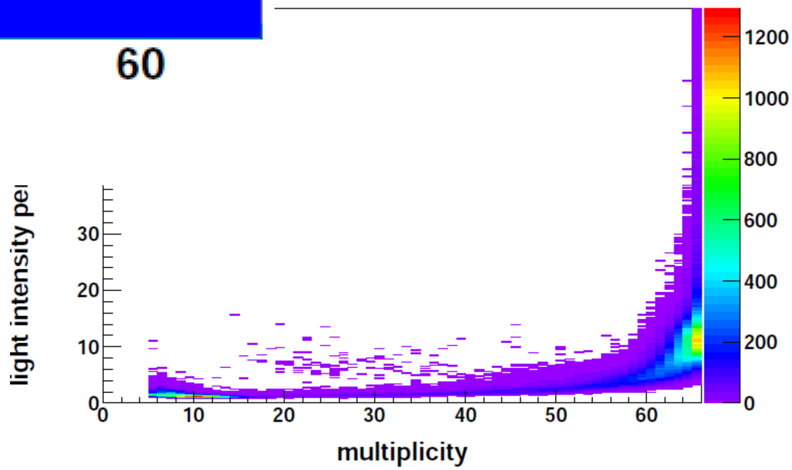
all PMT   only pillbox



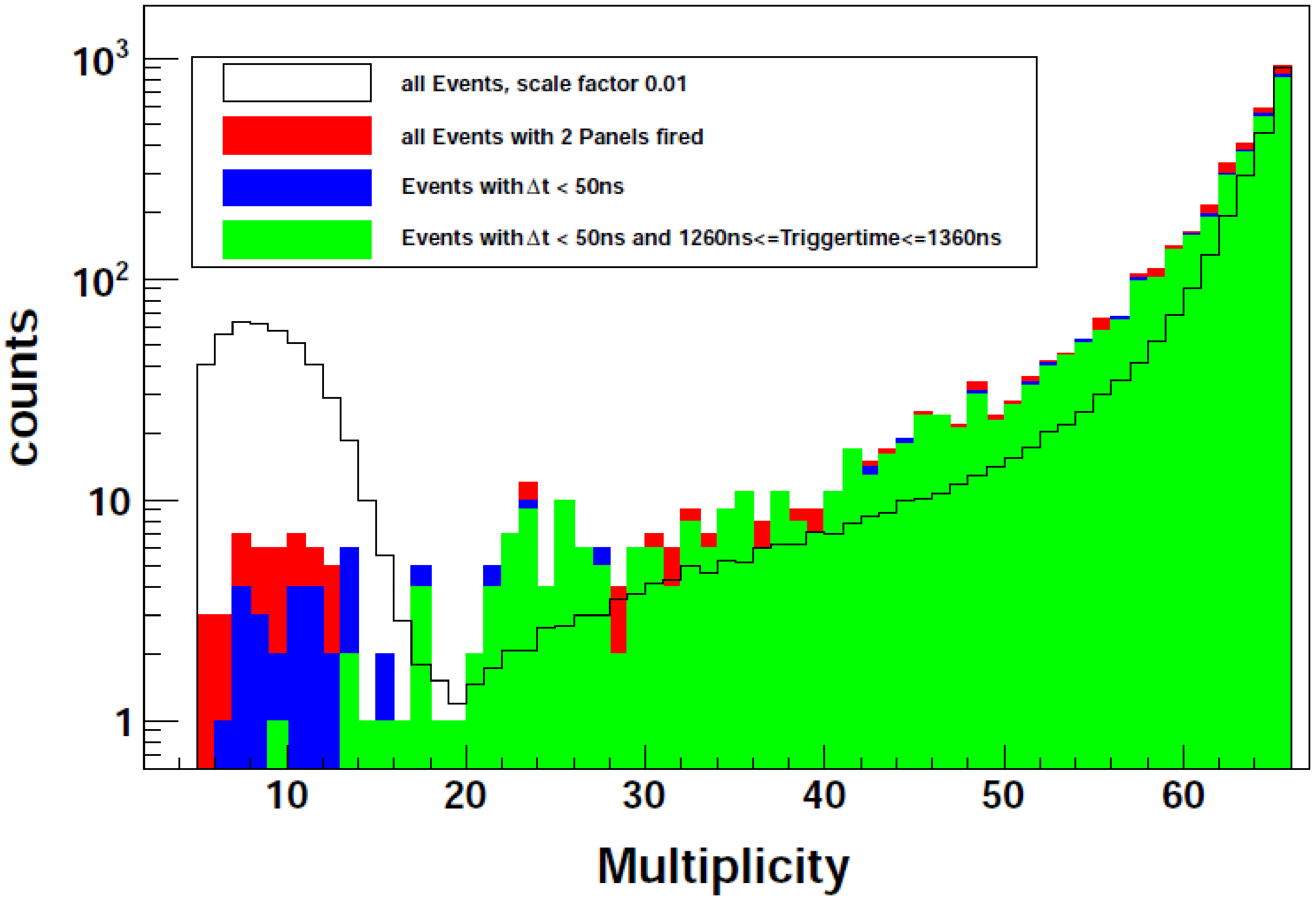


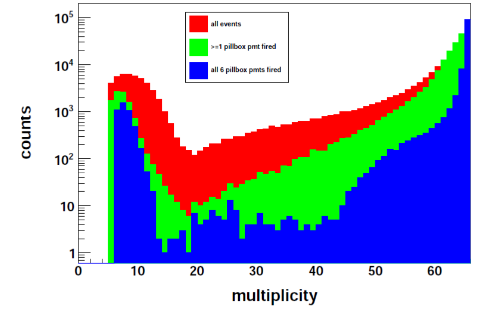
multiplicity



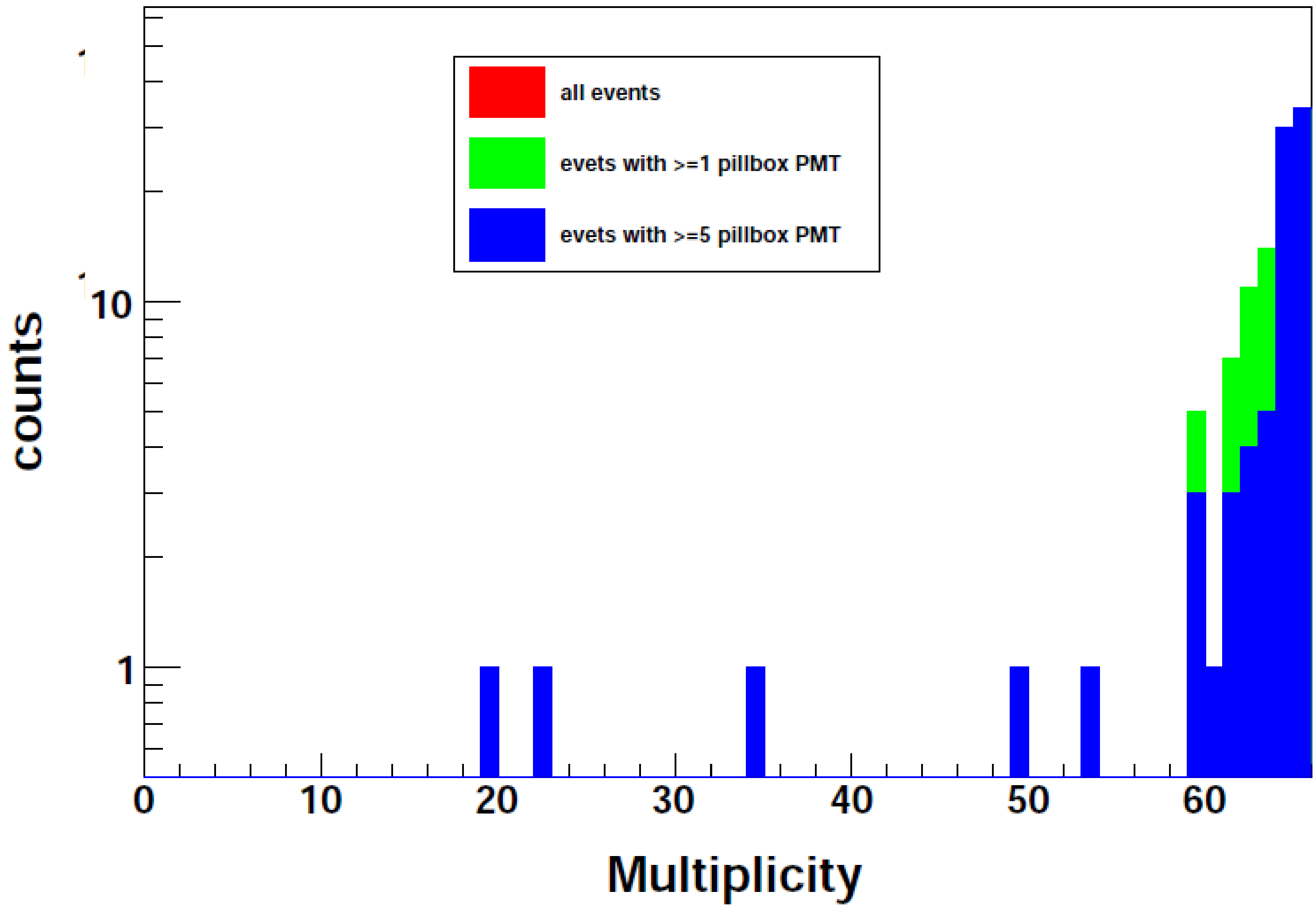


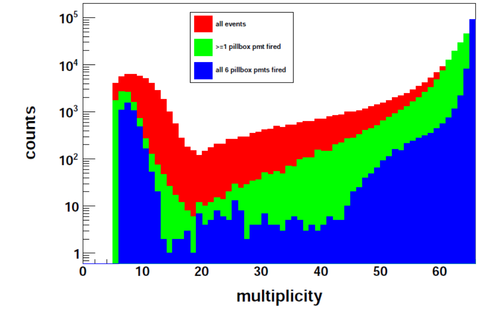
multiplicity

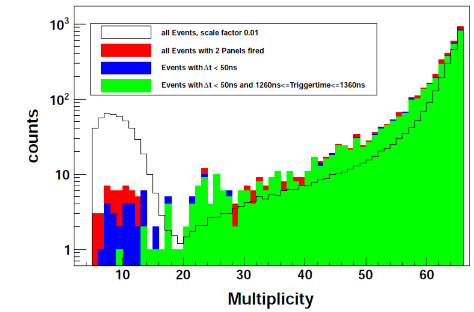




multiplicity





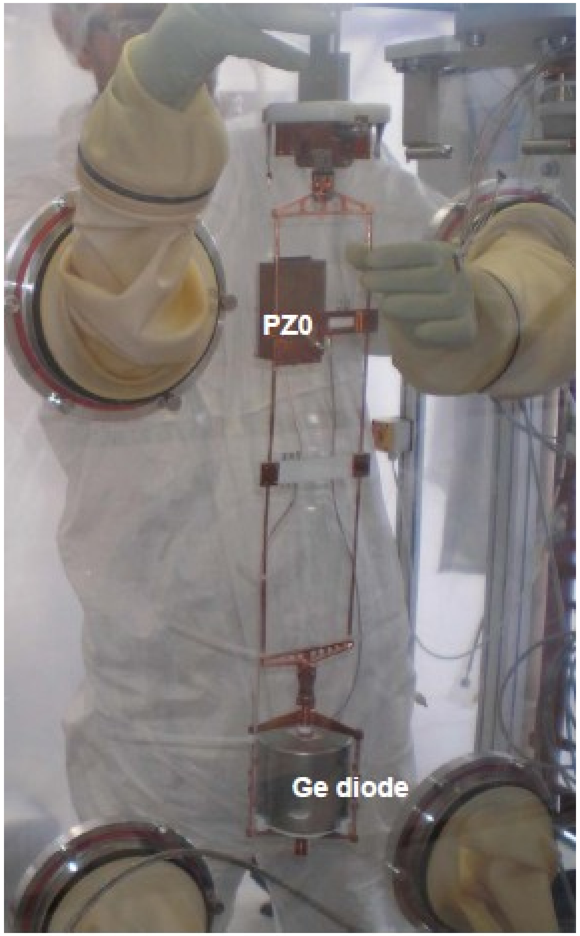


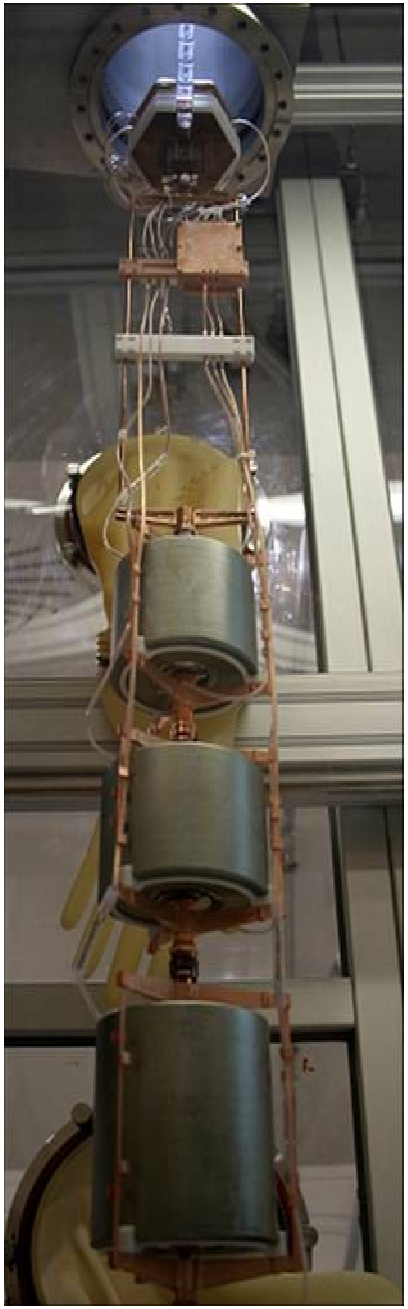
muon rejection efficiency $\varepsilon > 97$ %


construction of clean room
27 feb 09

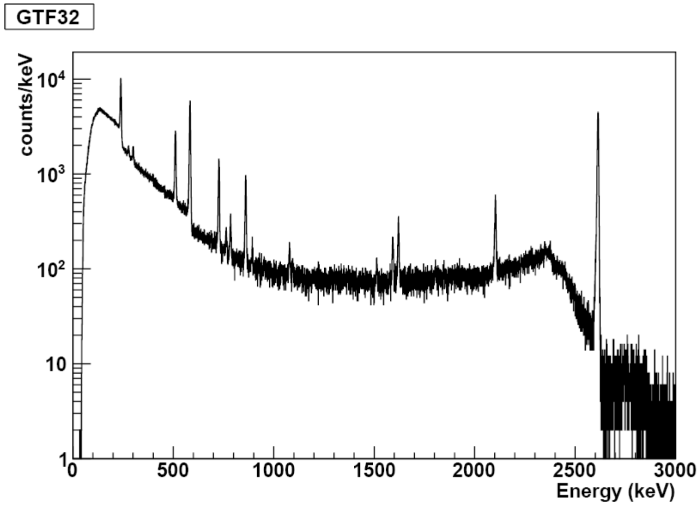
clean room, active cooling device getting prepared for installation

mounting diodes





energy calibration



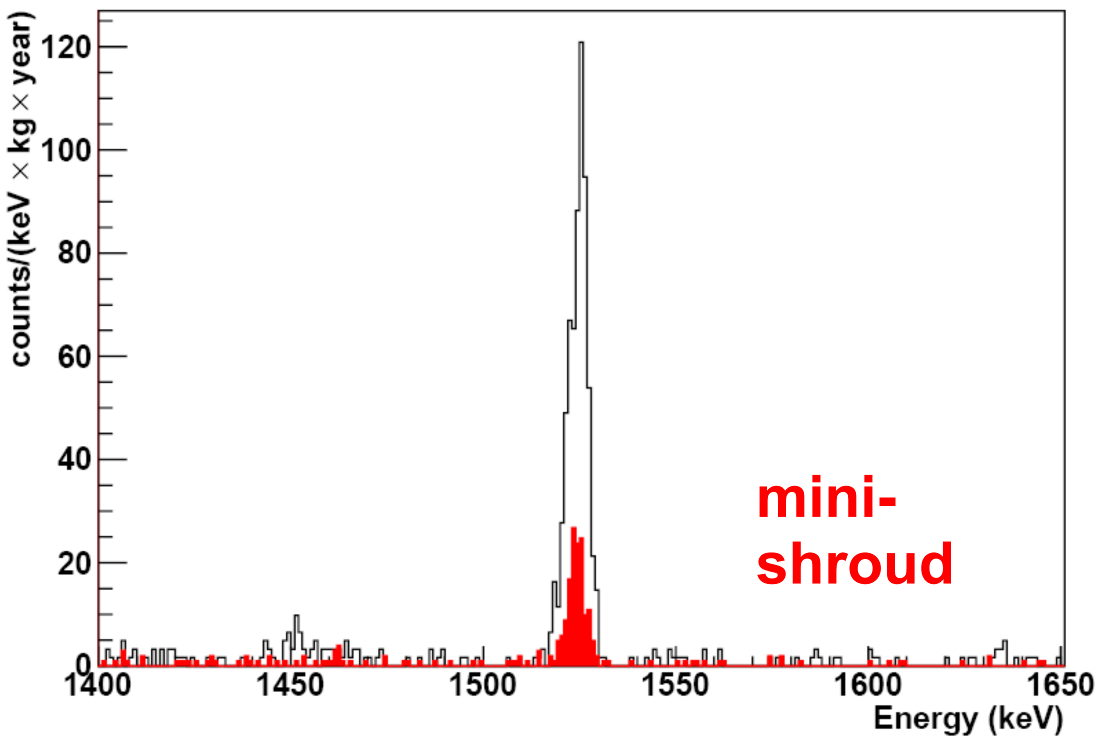
$\Delta E \sim 2{,}5$ keV

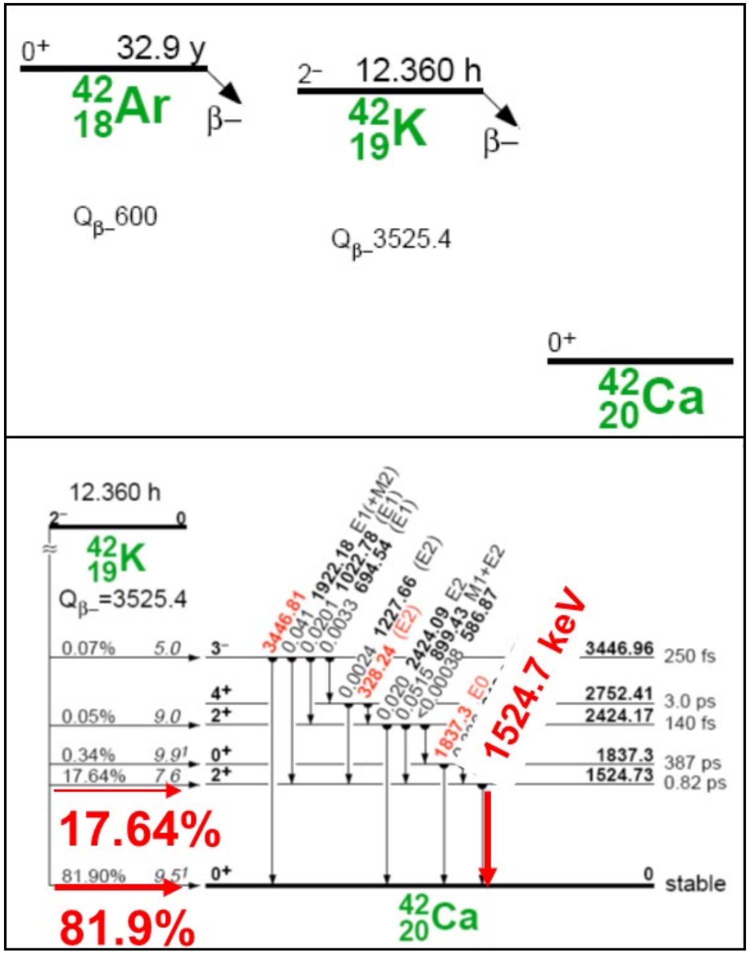
subtract lines at
811 & 1440 kev

^{42}Ar

GERDA proposal: ^{42}Ar/^{nat}Ar < 3 10^{-21}
Barabash et al (2002)

GERDA measurement

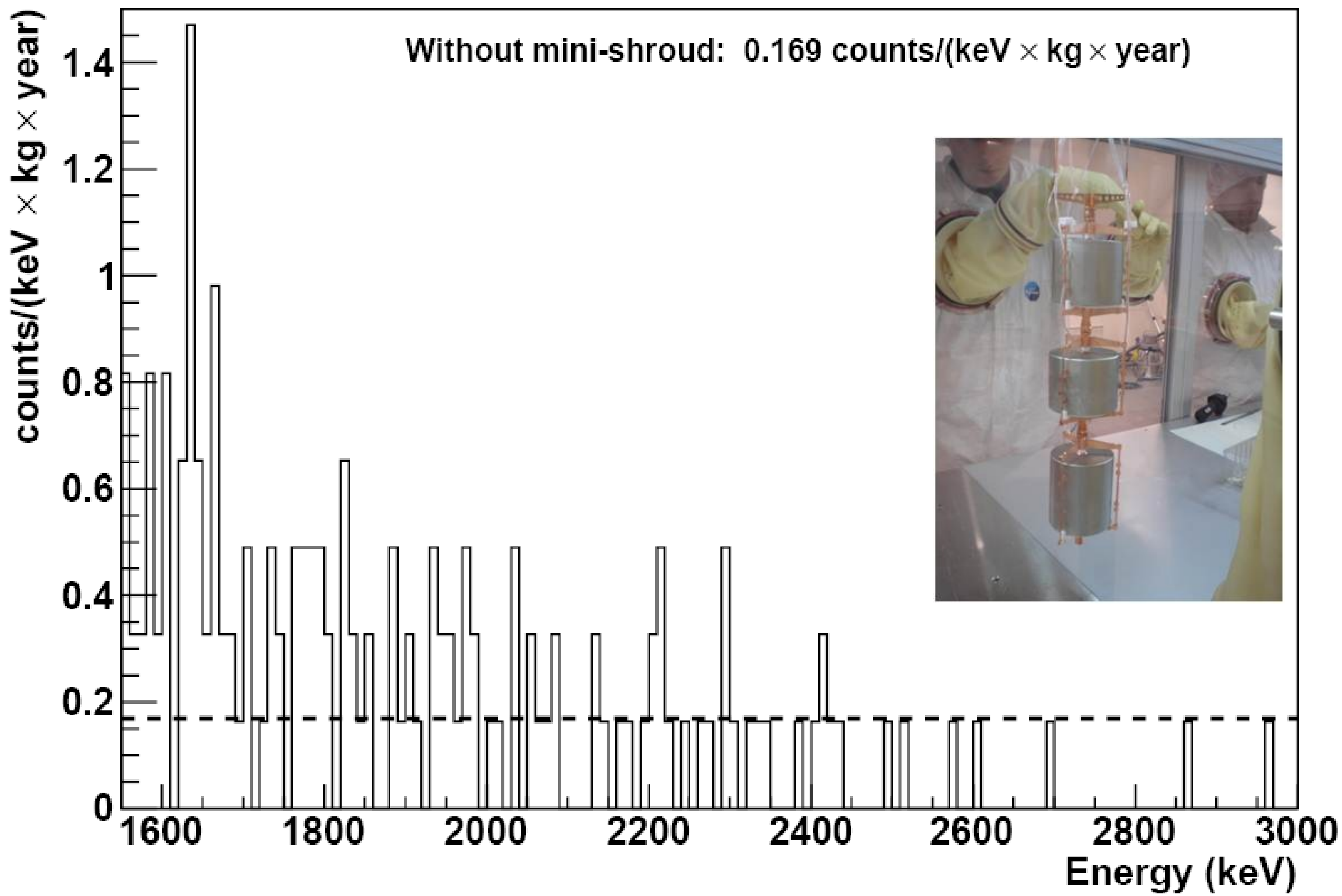




GERDA result:

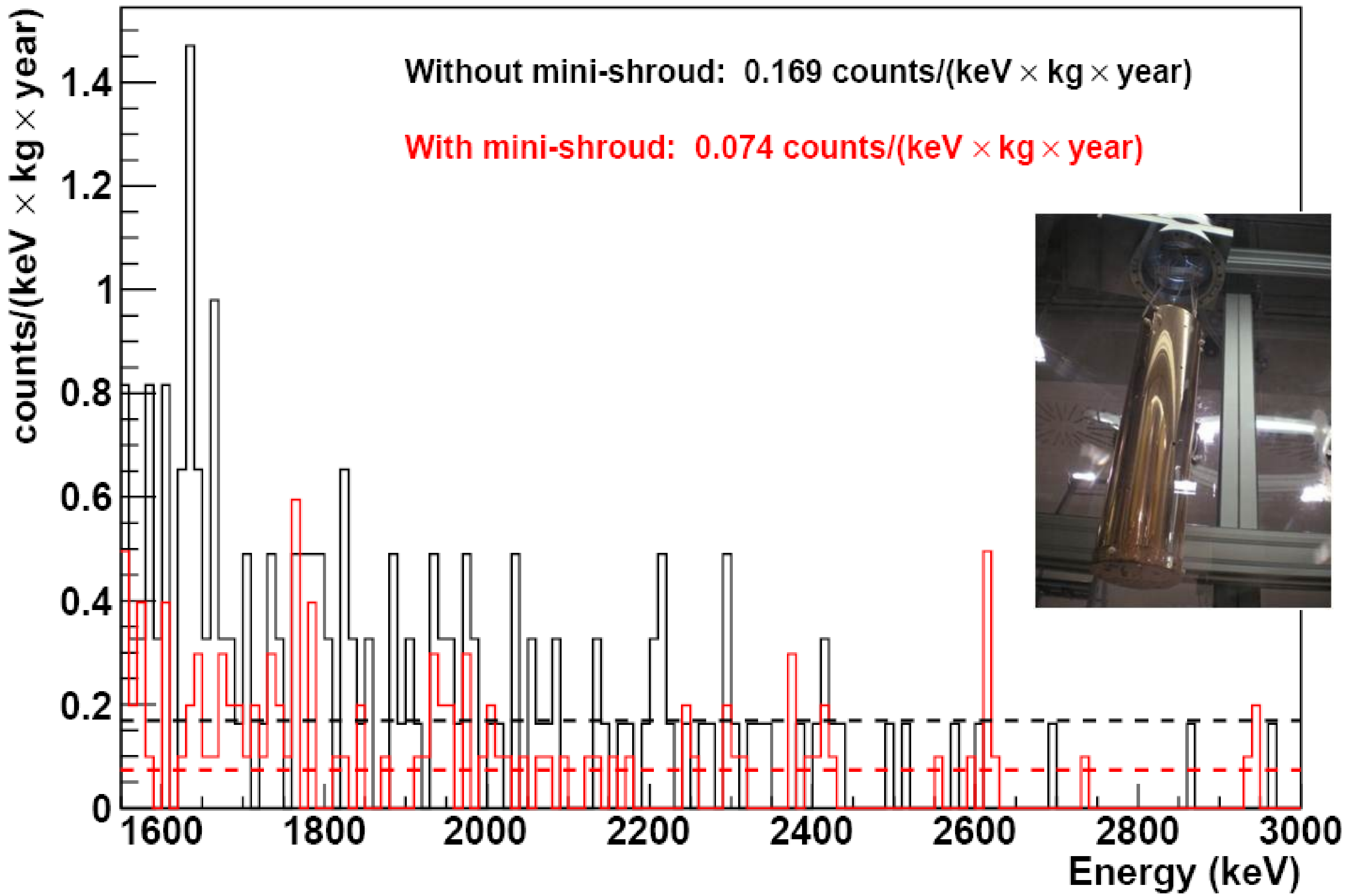
True value could 10 times higher

^{42}Ar

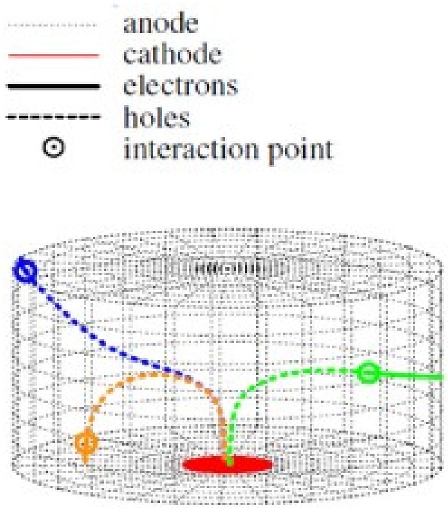


Without mini-shroud: 0.169 counts/(keV × kg × year)
counts/(keV × kg × year)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1600
1800
2000
2200
2400
2600
2800
3000
Energy (keV)

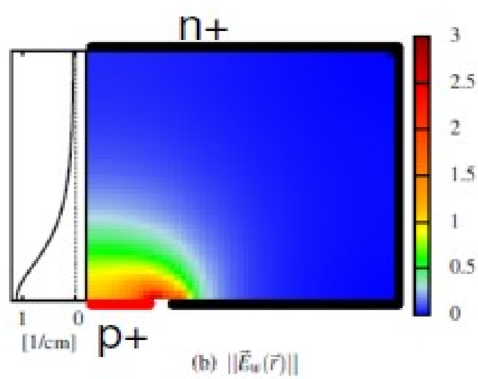
^{42}Ar


Without mini-shroud: 0.169 counts/(keV × kg × year)
With mini-shroud: 0.074 counts/(keV × kg × year)
counts/(keV × kg × year)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1600
1800
2000
2200
2400
2600
2800
3000
Energy (keV)

pulse shape analysis

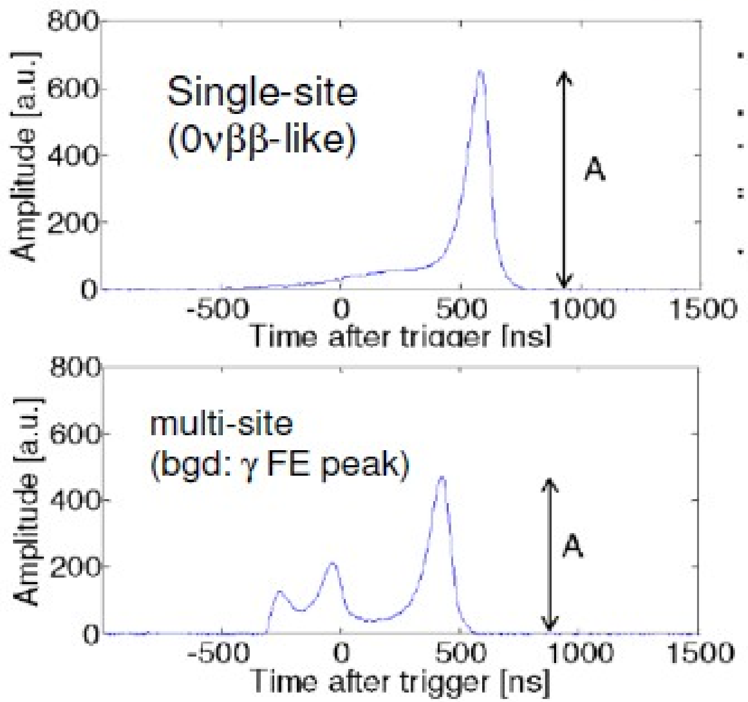


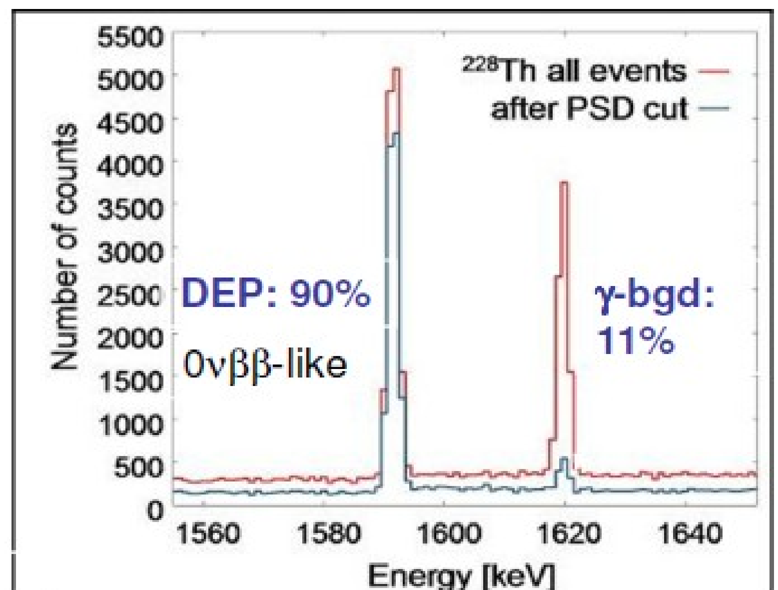
Phase II detectors



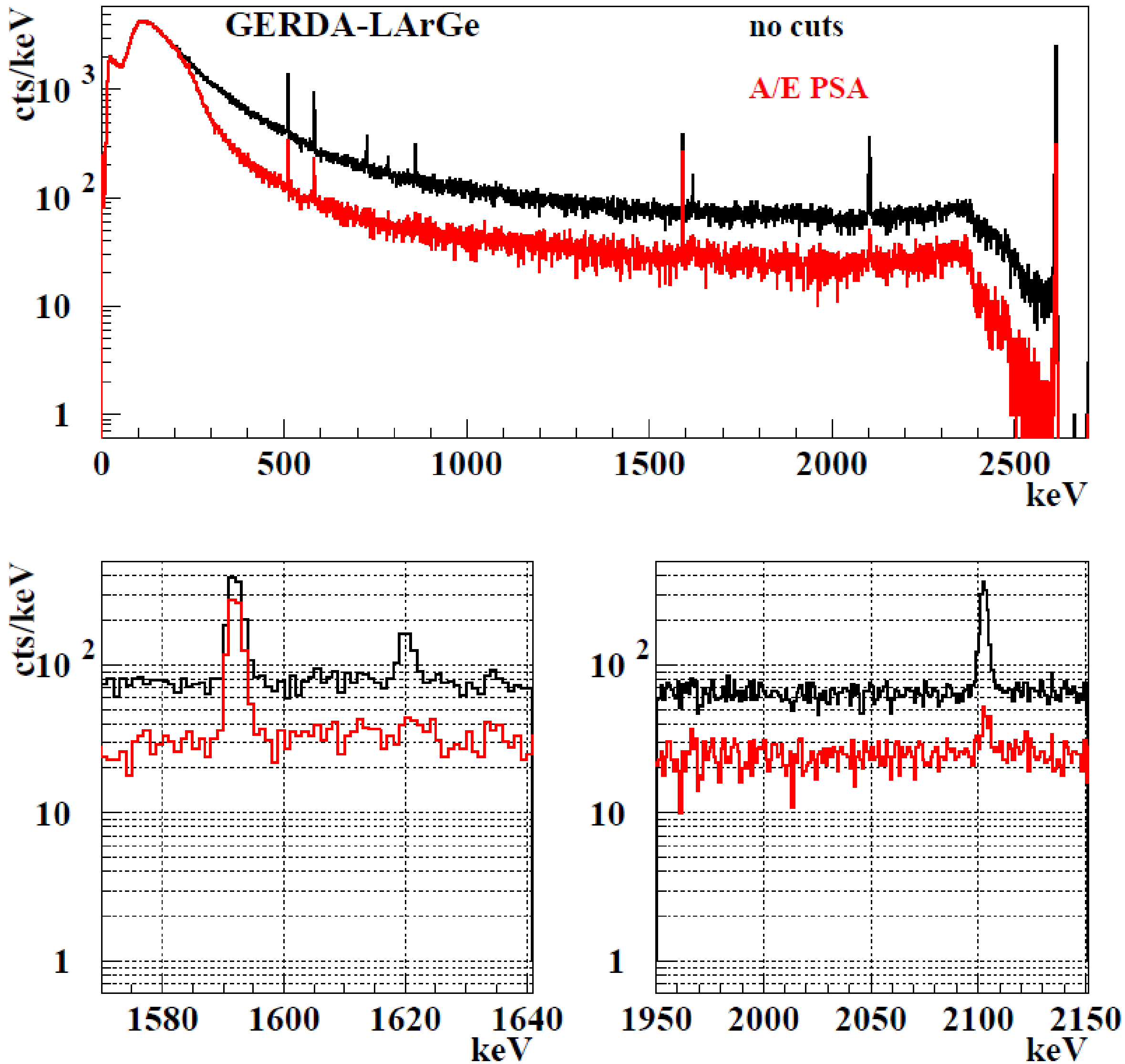
Signal shape provides clear topology for event-by-event signal ID / bgd discrimination:

- SSE/MSE discrimination
- Surface events:
  - n+ slow pulses
  - p+: 'amplified' current pulses



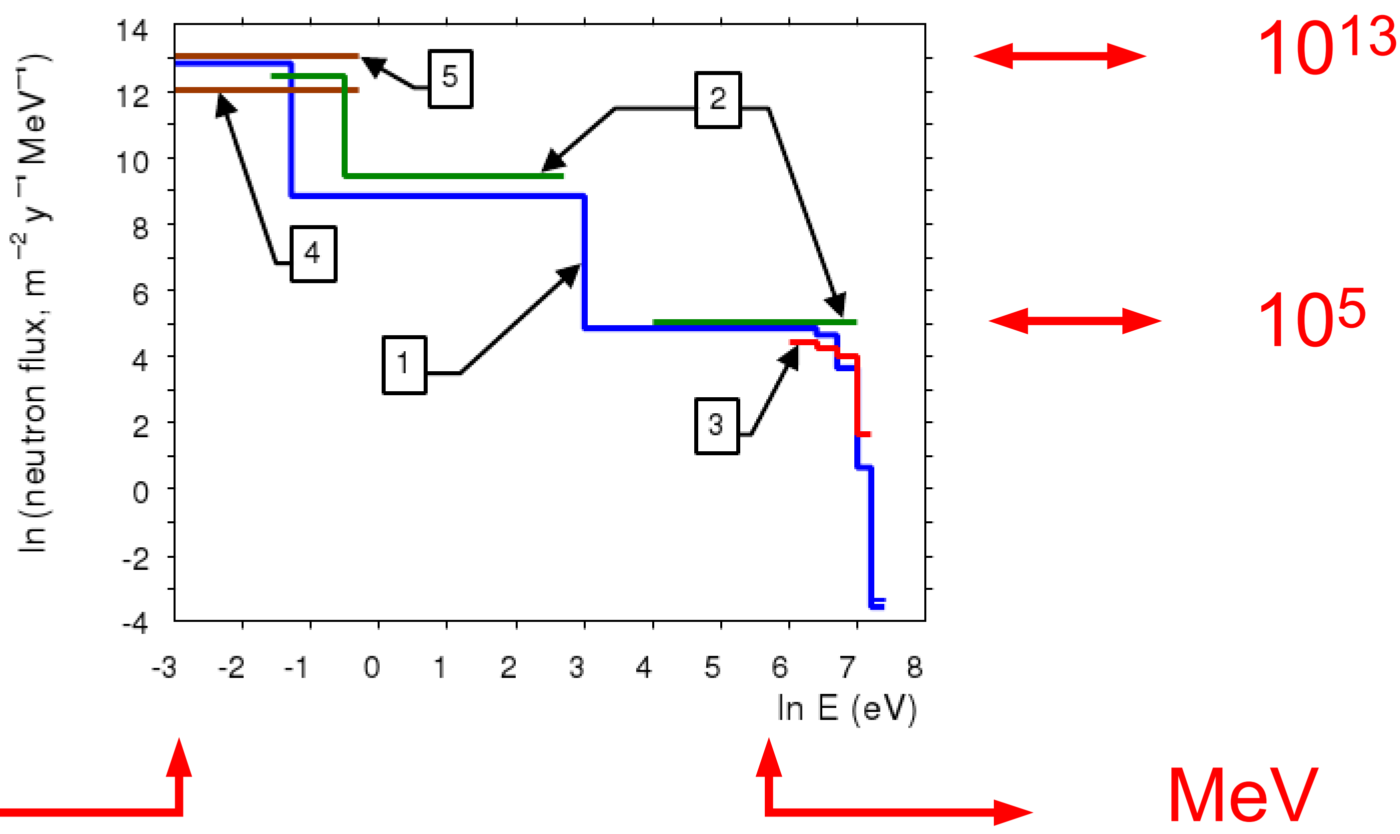


pulse shape analysis



neutron flux in underground labs

Measurements: difficult, selective, incomplete



Measured neutron flux in several underground laboratories.
1 LNGS, P. Belli et al. [5]; 2 LNGS, A. Rindi et al., [6] ;
3 LNGS, F. Arneodo et al., [7] ;4 Modane, V. Chazal et al., [11] ;
5 Broken Hill, S.R. Hashemi-Nezhad ad L.S: Pearl, [13]

calibrations

select source for

lines close to $Q_{\beta\beta}$ — ^{228}Th (^{56}Co, ^{238}U)

reasonable $T_{1/2}$ — 1,9 y

low α – energy — 7,7 MeV

select holder for

good shielding

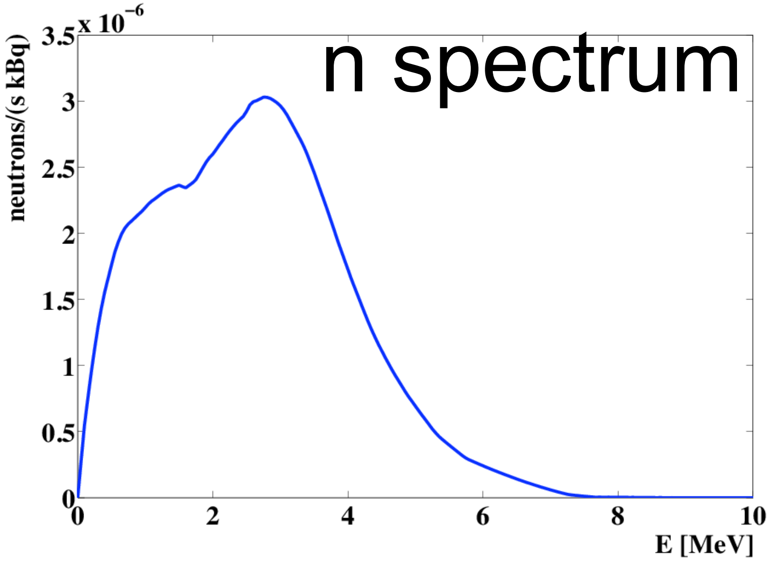
low emission prob.

select positions for optimal

parking

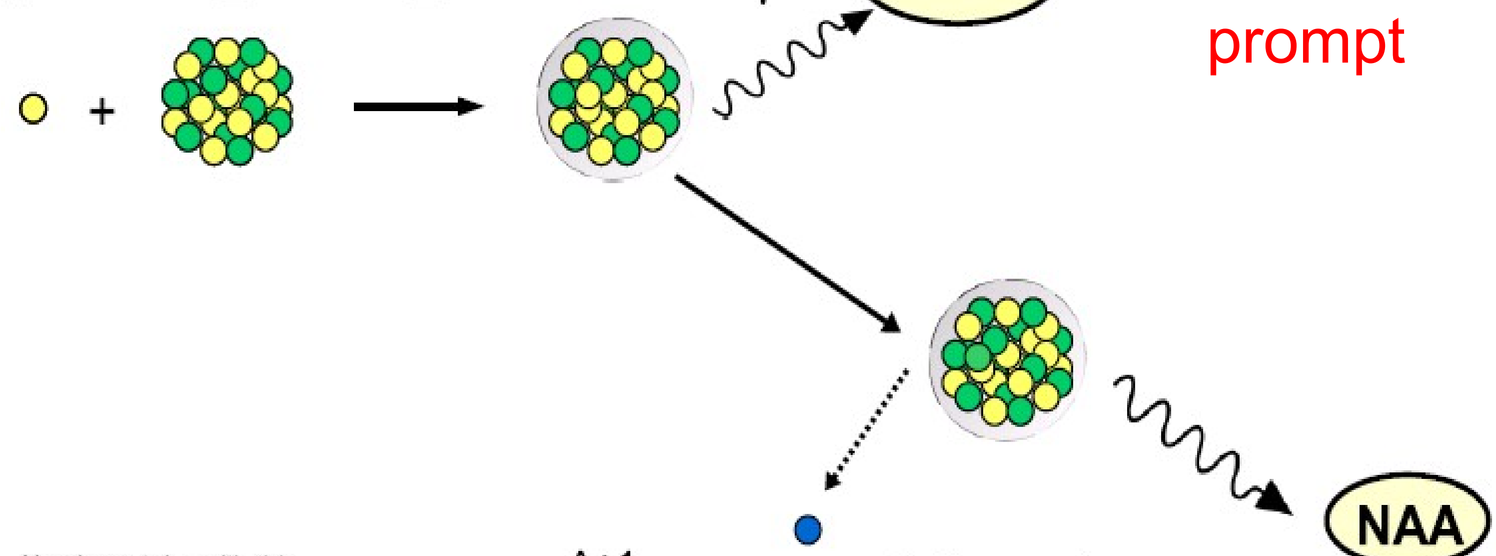
calibration

F.Froborg, NIMA/PhD thesis



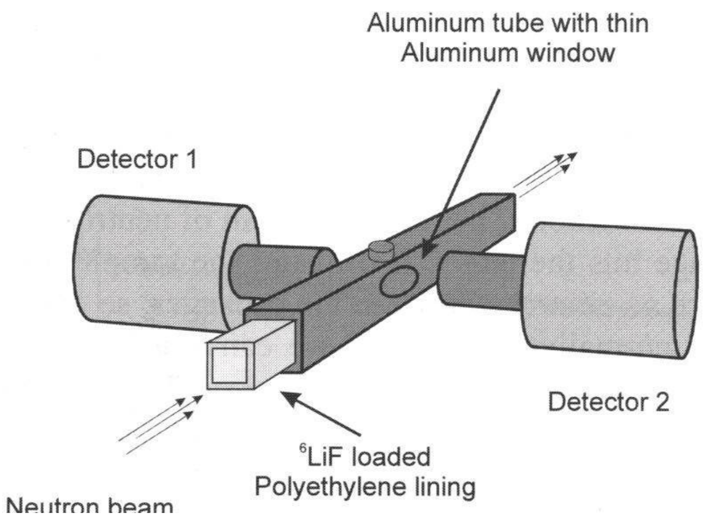
neutron capture

$$n + {}^{A}Z \rightarrow {}^{A+1}Z^{*} \rightarrow {}^{A+1}Z + \gamma$$



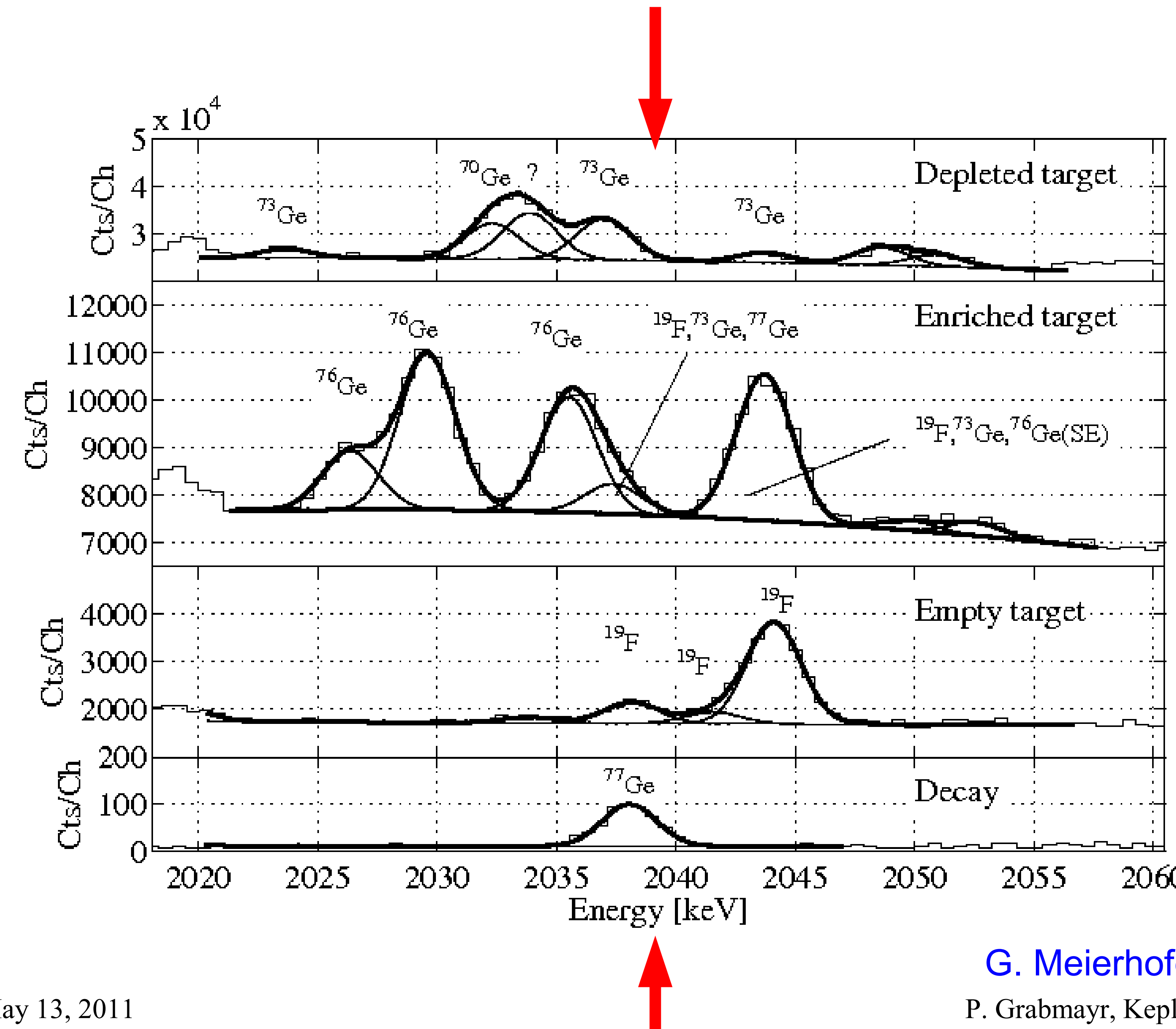
prompt

$${}^{A+1}Z \rightarrow \beta^{-} + {}^{A+1}(Z+1)^{*} \longrightarrow {}^{A+1}(Z+1) + \gamma$$



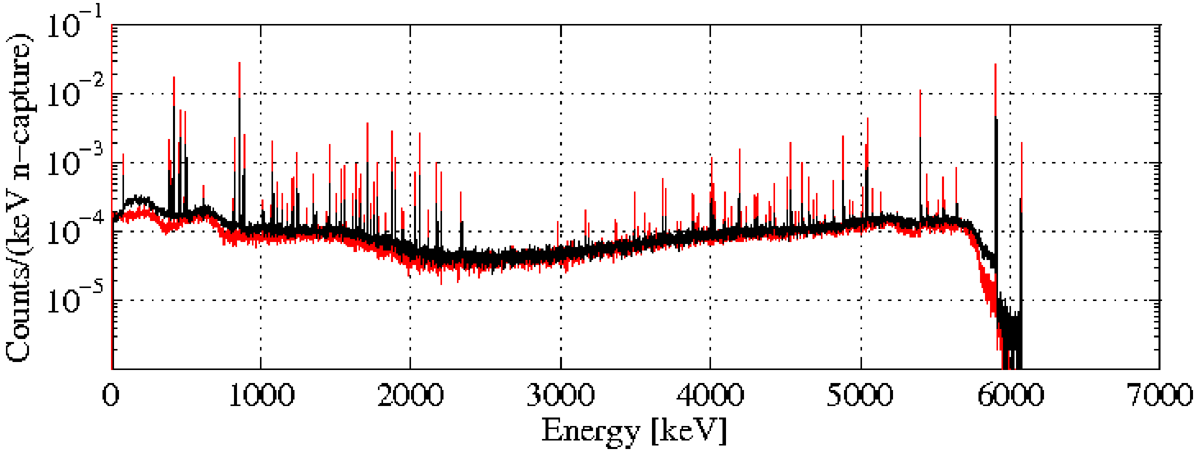
coincidence technique for
study of decay schema

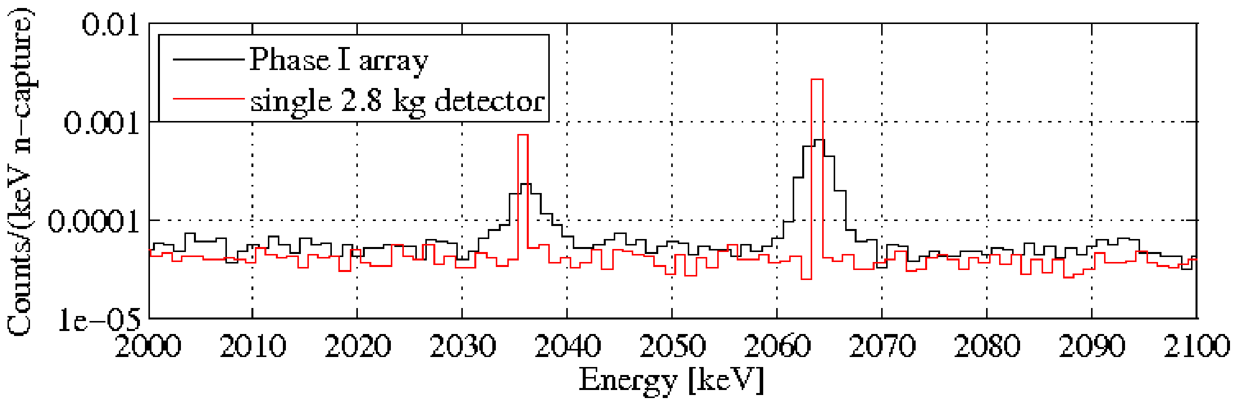
(n,γ) in the Qββ region



G. Meierhofer PhD2010

background contribution





MaGe MC Simulation
by L. Pandola

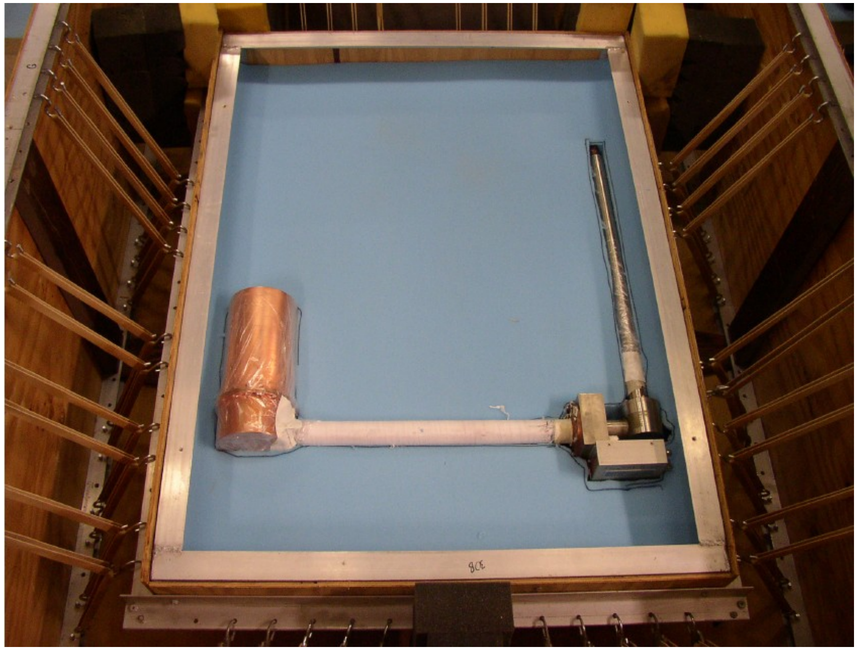
line 2035 keV:
1,5 x 10^{-4} counts/(capture)
1,7 x 10^{-4} counts/(capture)

Compton:
0,55 x 10^{-4} counts/(keV capture
0,44 x 10^{-4} counts/(keV capture

enriched GERDA detectors

Ge-Detectors from HdM and IGEX
(planned exposition = 18kg, 1 year)

Heidelberg-Moscow detectors before test in GDL

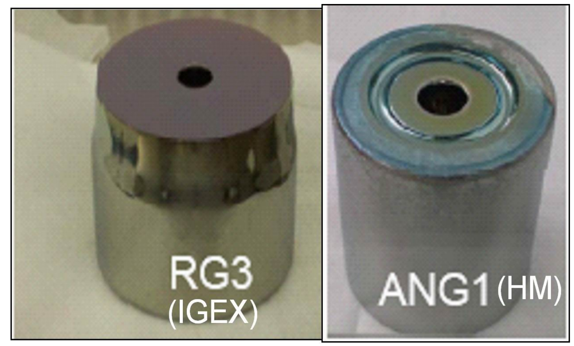


IGEX detector before transport to Gran Sasso

refurbishing Ge diodes in GDL

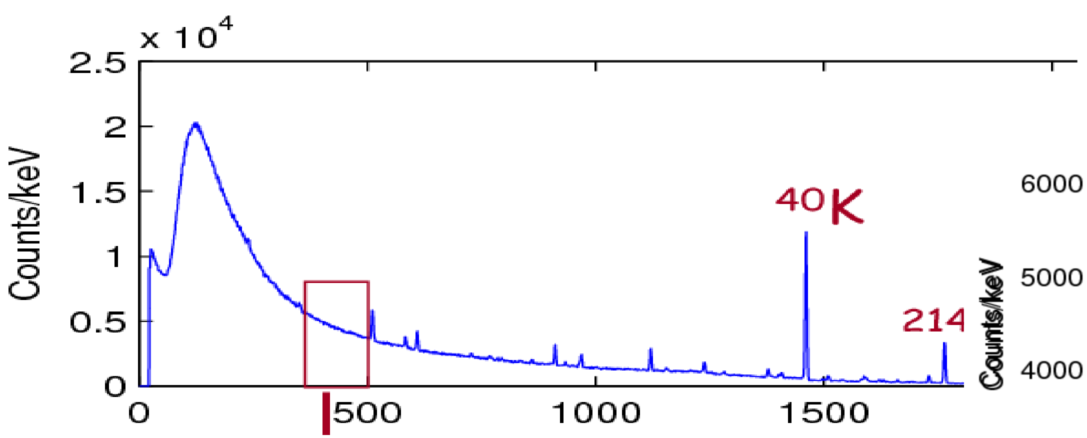
GDL:

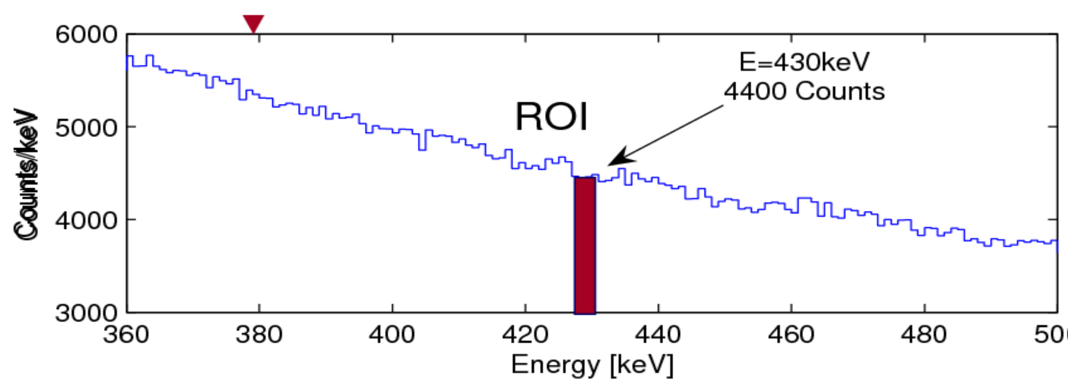
installation of clean room for diode preparation and tests in LAr



within 10 days a limit for 0νECEC on ^{36}Ar:

(liquid Ar contains 0,336% ^{36}Ar; signature: $E_\gamma = Q - E_K - E_L = 430$keV)





$T_{1/2} > 1{,}9 \cdot 10^{18}$ y (68% C.L.) [==> 10^{23} y]

summary

GERDA started commissioning
in summer 2010

verified background level of
$< 10^{-1}$ cts/(kg·y·keV)

will insert first enriched diode
in June 2011

wait one year with 17.9 kg ^{76}Ge
for first result on $0\nu\beta\beta$
.... if he is right