The Search for Majorana Neutrinos in ^{76}Ge with GERDA

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GERDA Collaboration

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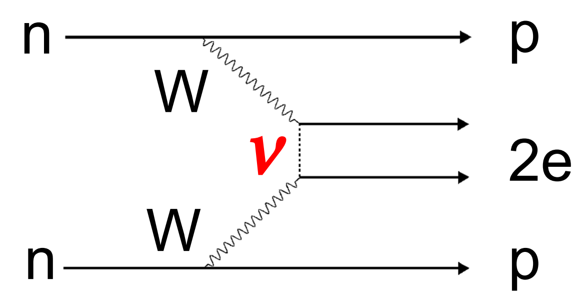
bmb+f - Förderschwerpunkt Astroteilchenphysik
Großgeräte der physikalischen Grundlagenforschung

Content

- neutrinoless double beta decay



Signature : peak @ $Q_{\beta\beta}$

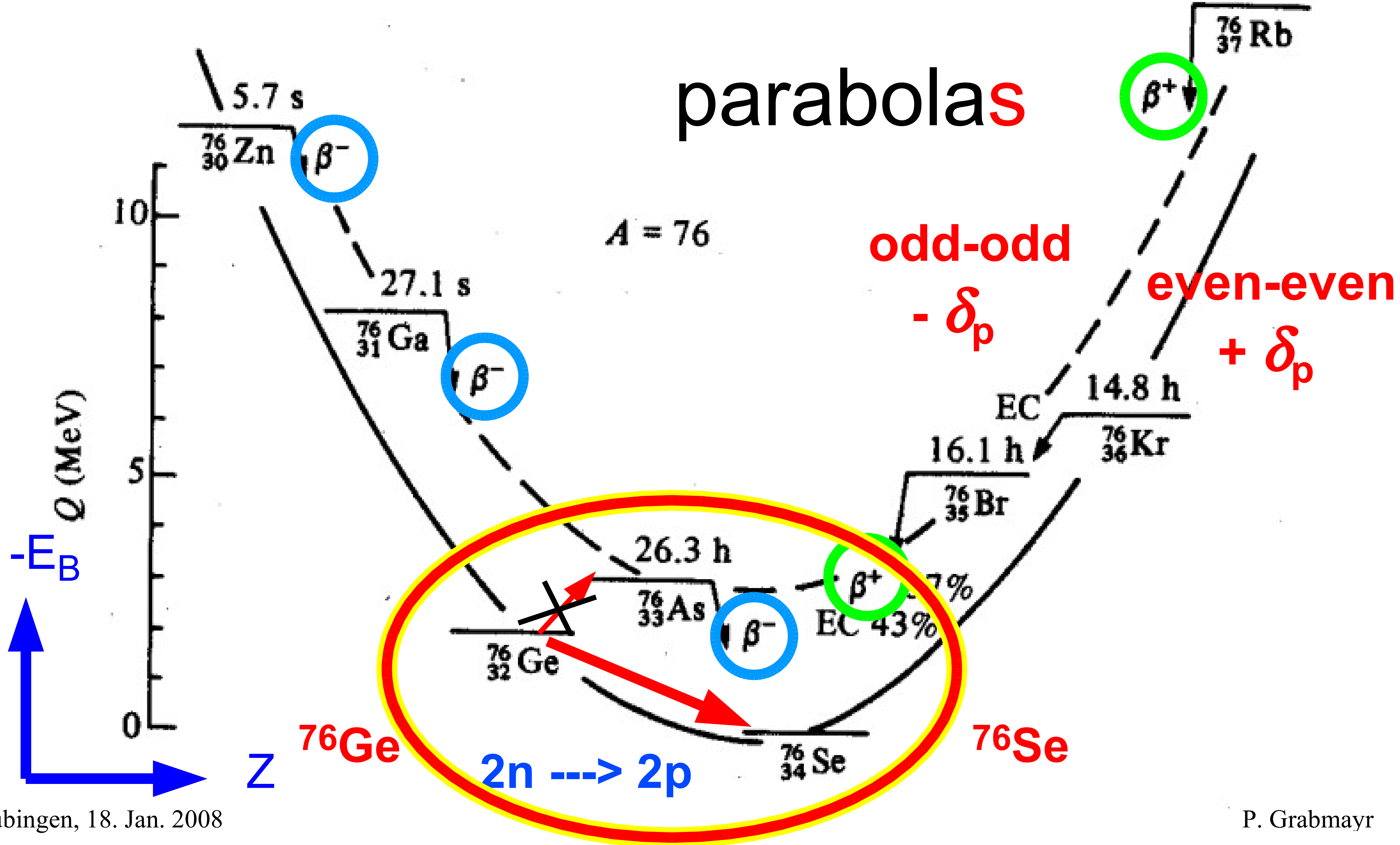
- experimental methods

  and setups

- ^{76}Ge experiments and GERDA
  - principle
  - background and sensitivity
  - setup and status
- Outlook

Weizsäcker mass formula

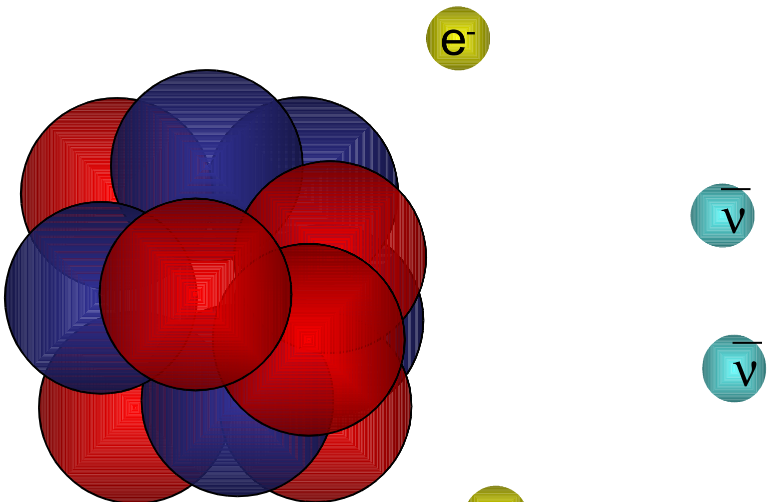
$$E_B = a_v A - a_s A^{2/3} - a_c Z(Z-1)A^{-1/3} - a_s A^{-1}(N-Z)^2 \ +/- \ \delta_p$$

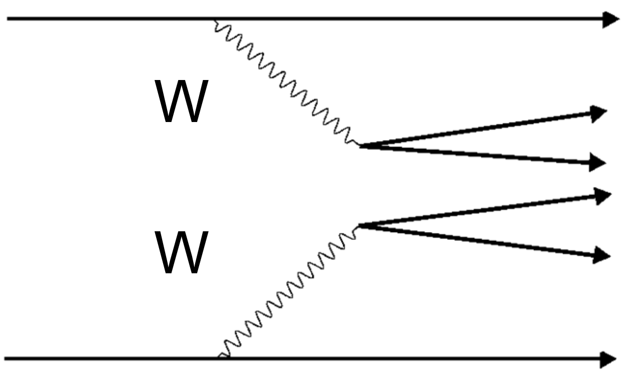


double beta decay

2^{nd} order allowed weak process

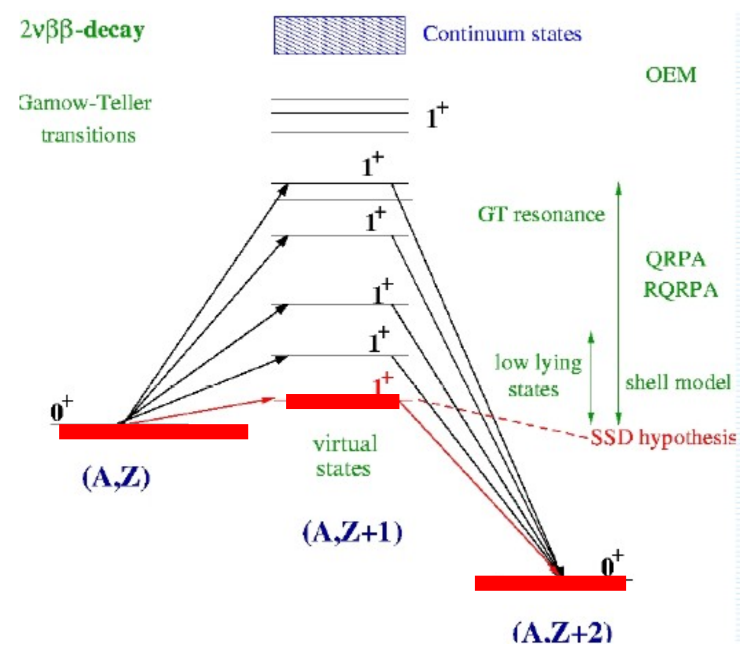
$$(A,Z) \rightarrow (A,Z+2) + 2\,e^- + 2\bar{\nu}_e \qquad (2\nu\beta\beta)$$





Gamow Teller only

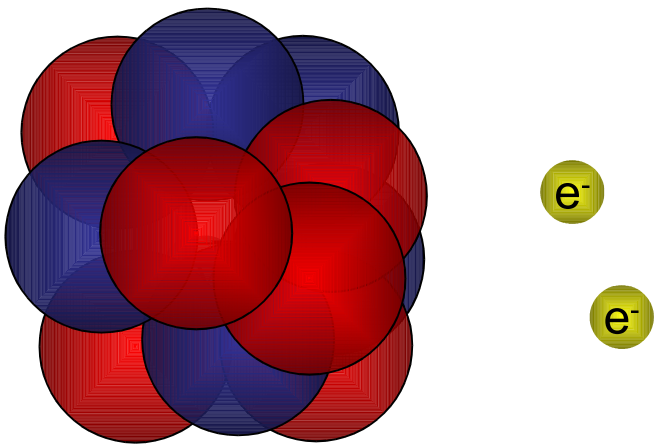
(p,n) (n,p)

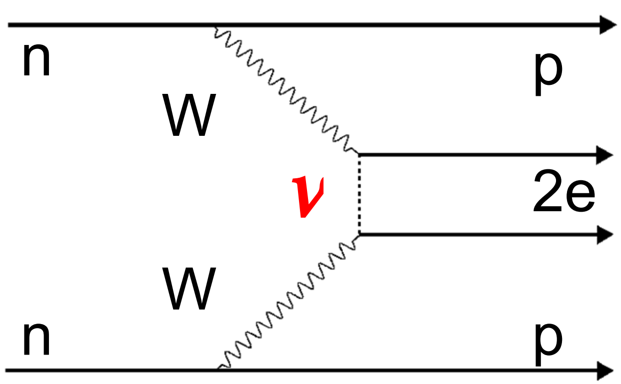


double beta decay

2nd order allowed weak process

$(A,Z) \rightarrow (A,Z+2) + 2\,e^-$ $(0\nu\beta\beta)$





Gamow-Teller and Fermi

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

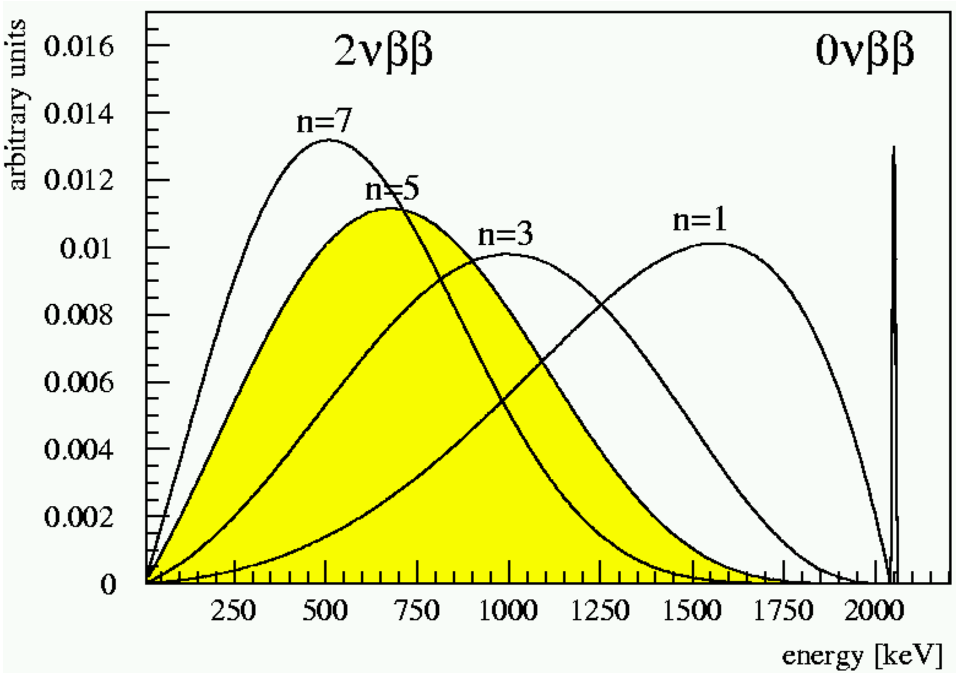
Neutrino = Anti-Neutrino
(Majorana type)

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

spectral shapes

sum energy spectrum of both electrons

$0\nu\beta\beta$: 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 !

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

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

^{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 ·10 ^{25} y (90%CL)

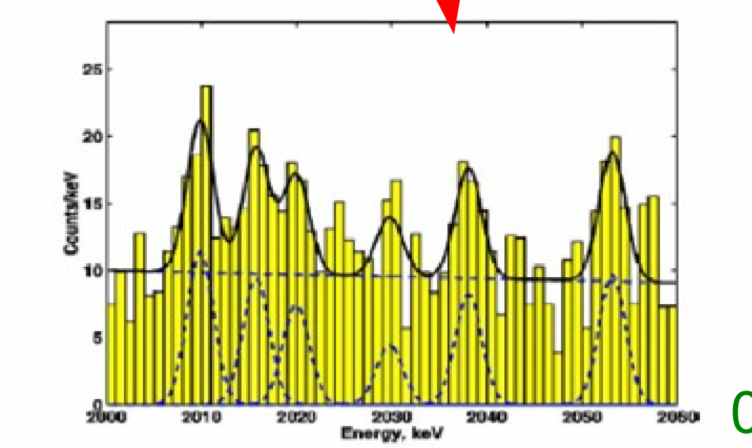
(0,69 - 4,18)

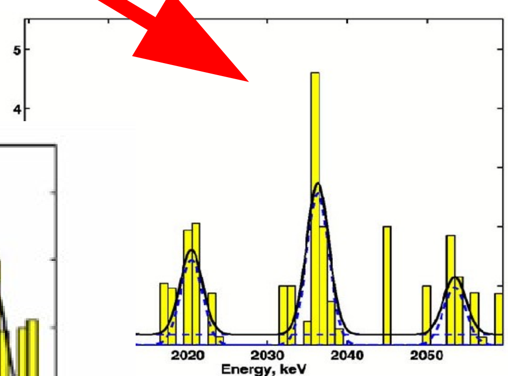
Aalseth et al.

Phys Rev D65 (2002) 092007

8,9 kg·y

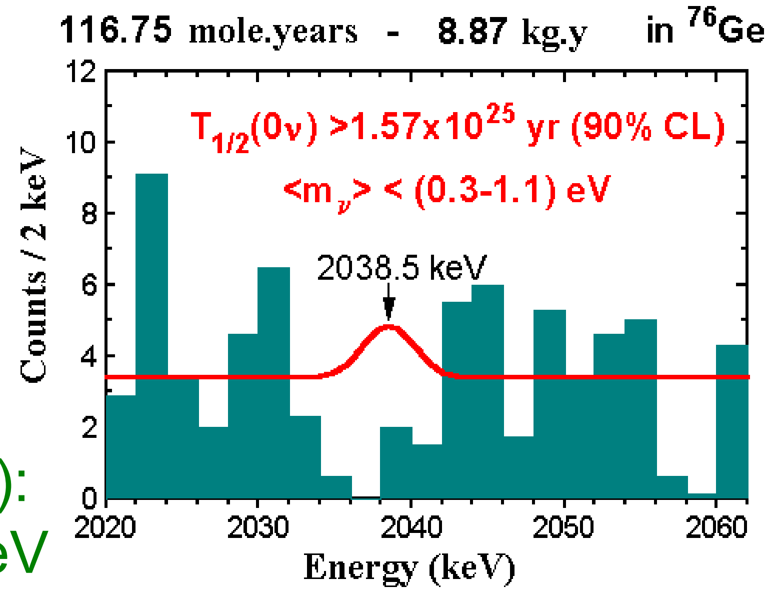
$T_{1/2}$> 1,6 ·10 ^{25} y (90%CL)





MPLA21 (2006):

0,27< $m_{\beta\beta}$ < 0,4 eV



mass of the neutrino I

Neutrino oscillations:

mass is finite

(Suzuki, INPC07)

$\Delta m^2_{solar} = 8{,}2\ 10^{-5}\ eV^2$

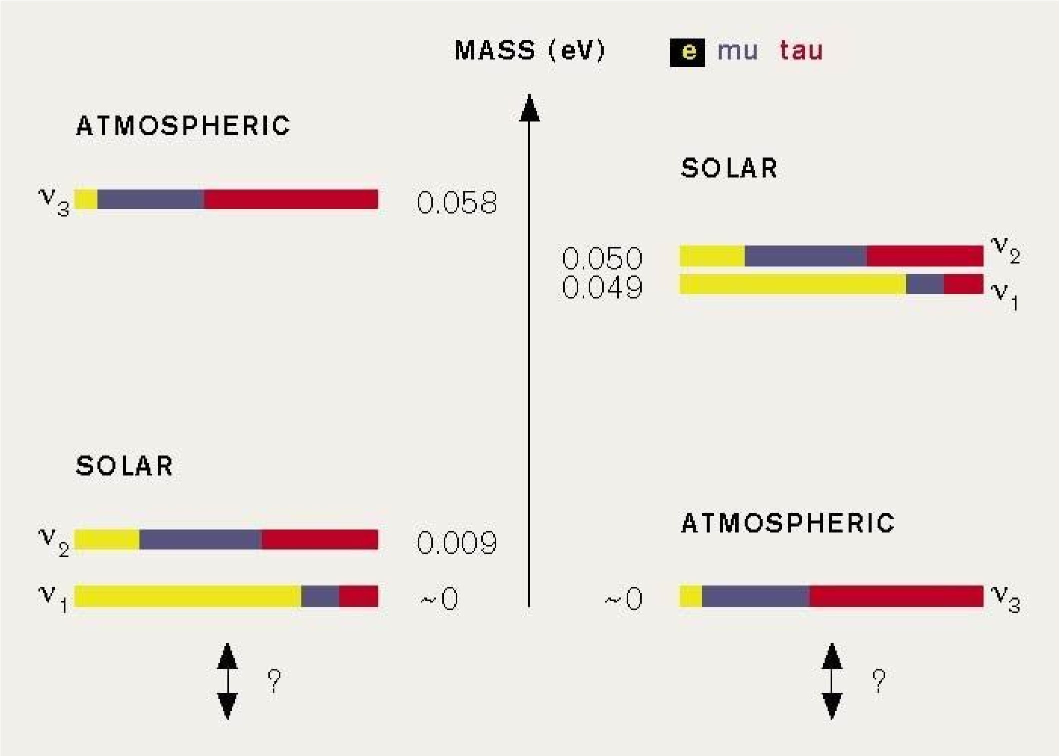
$\Delta m^2_{atm} = 2{,}7\ 10^{-3}\ eV^2$

still need:

- absolute mass scale
- hierachy

$\Delta m^2_{23} > 0$ normal

$\Delta m^2_{23} < 0$ inverted

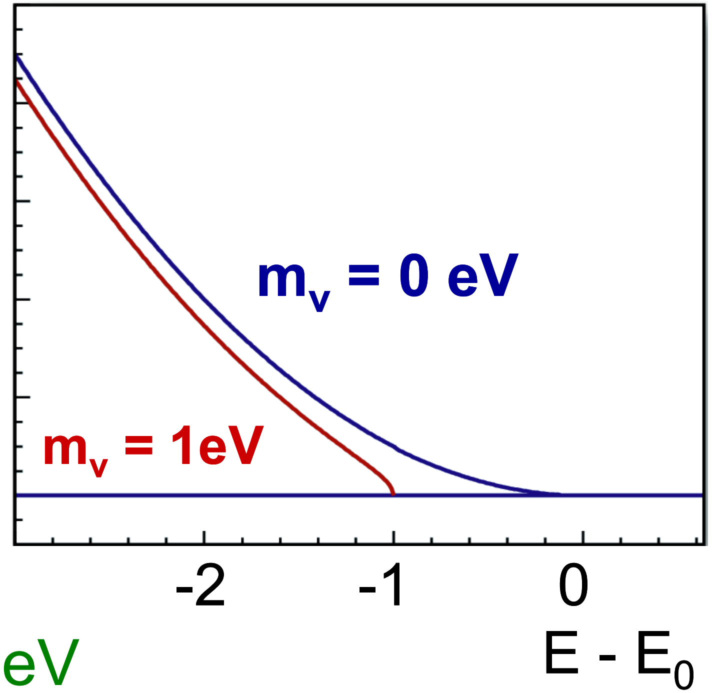


mass of the neutrino II

direct measurement of m_e :

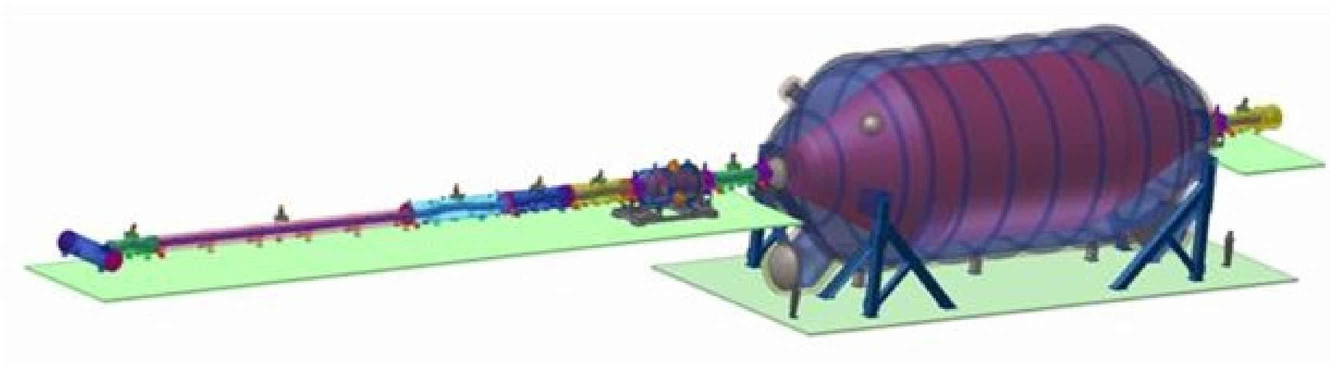
Tritium β decay

Mainz & Troitsk $m_e \sim 2{,}2$ eV



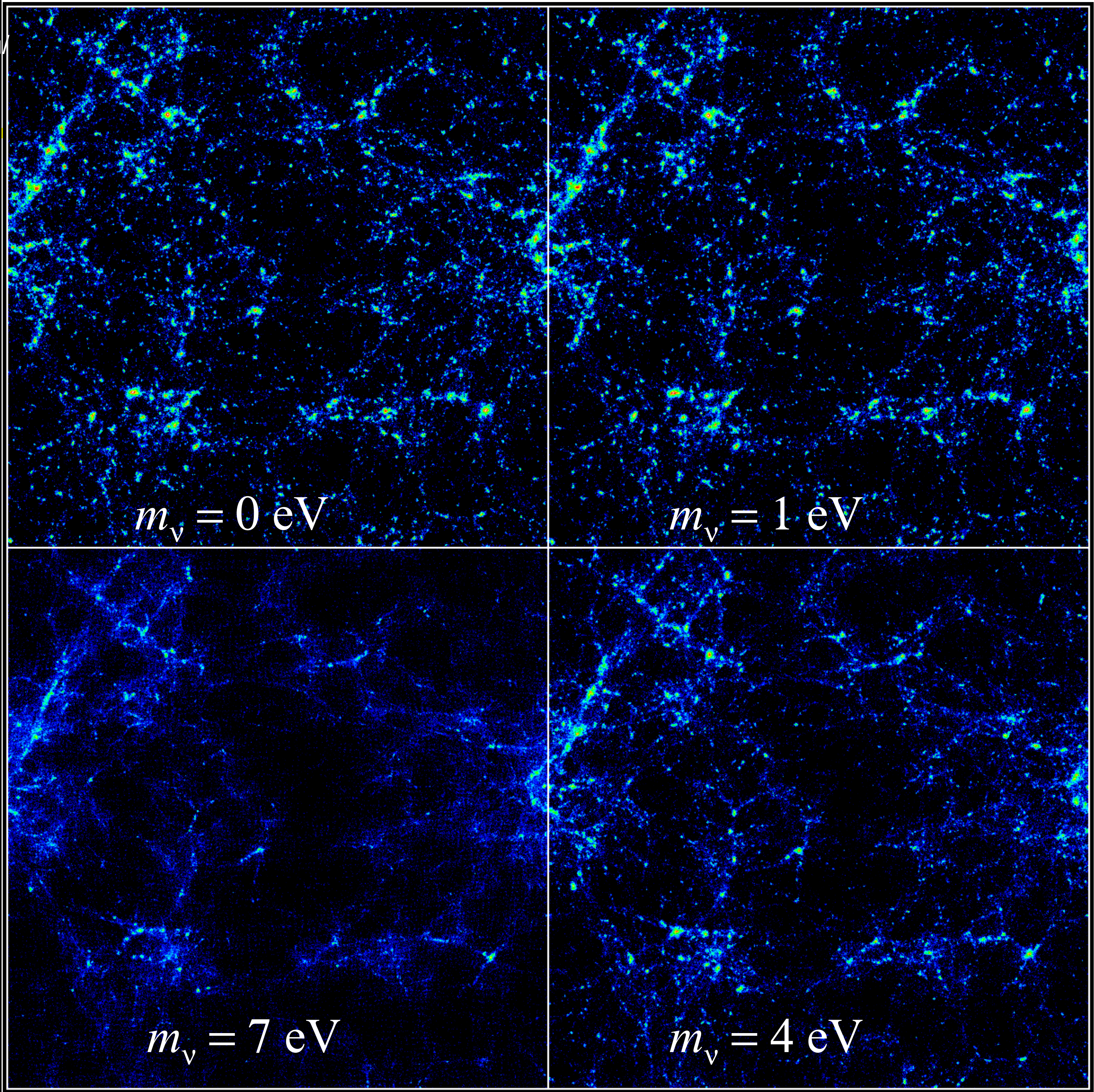
KATRIN (^{3}H, 18.9keV) $m_e \sim 0{,}2$ eV

MARE (^{187}Re, 2.9keV) $m_e \sim 0{,}2$ eV



http://cosmicweb.uchicago.edu/

Neutrinos speeds are larger than the escape velocity from the smaller structures
Moving from larger to smaller density regions neutrinos slow down the growth of structures smaller than a scale D_F inversely proportional to neutrino mass



http:

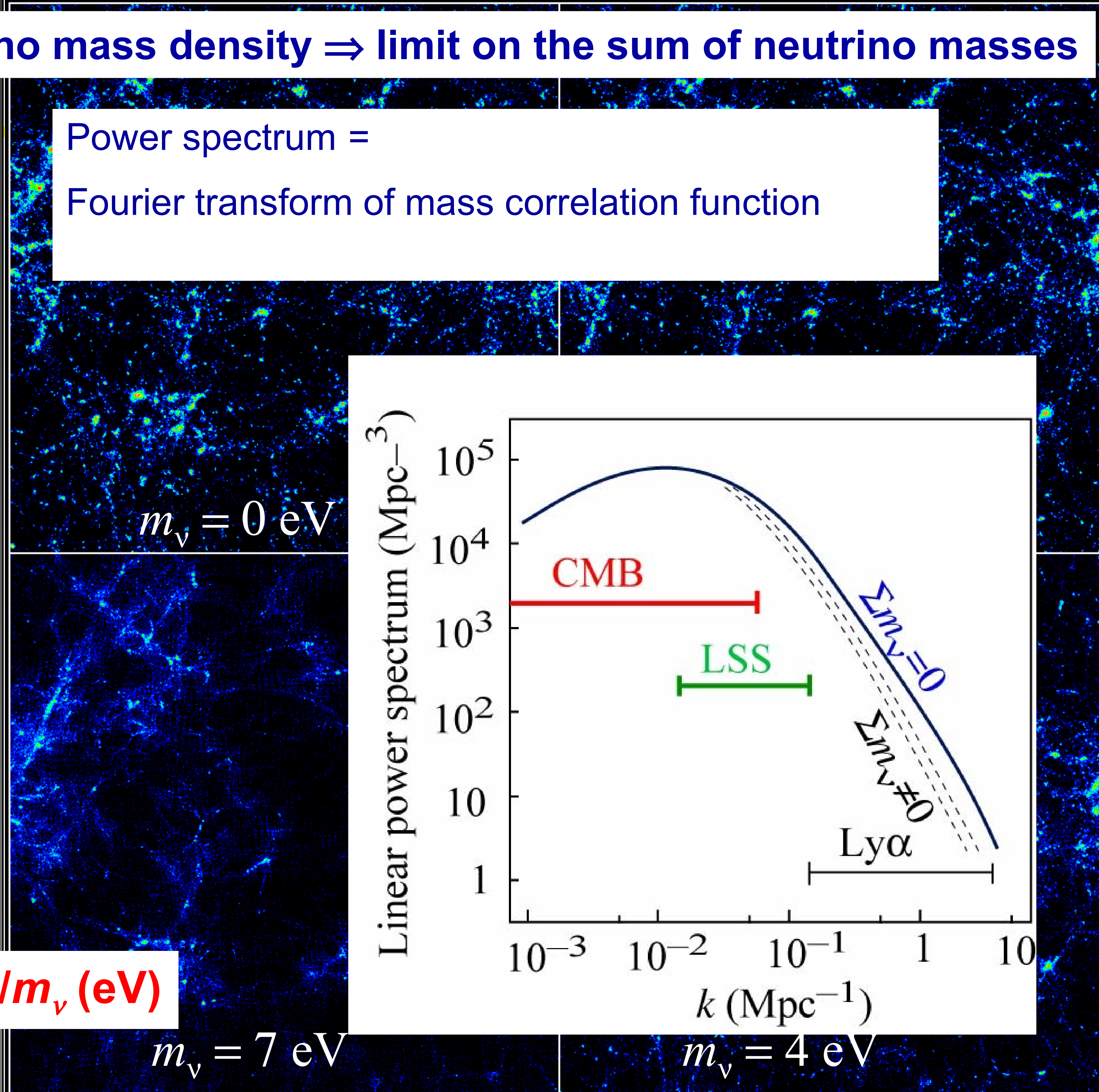
Limit on neutrino mass density ⇒ limit on the sum of neutrino masses

Power spectrum =

Fourier transform of mass correlation function

Neutrinos speeds are larger than the escape velocity from the smaller structures
Moving from larger to smaller density regions neutrinos slow down the growth of structures smaller than a scale D_F inversely proportional to neutrino mass

D_F (Mpc)≈ 1/m_ν (eV)



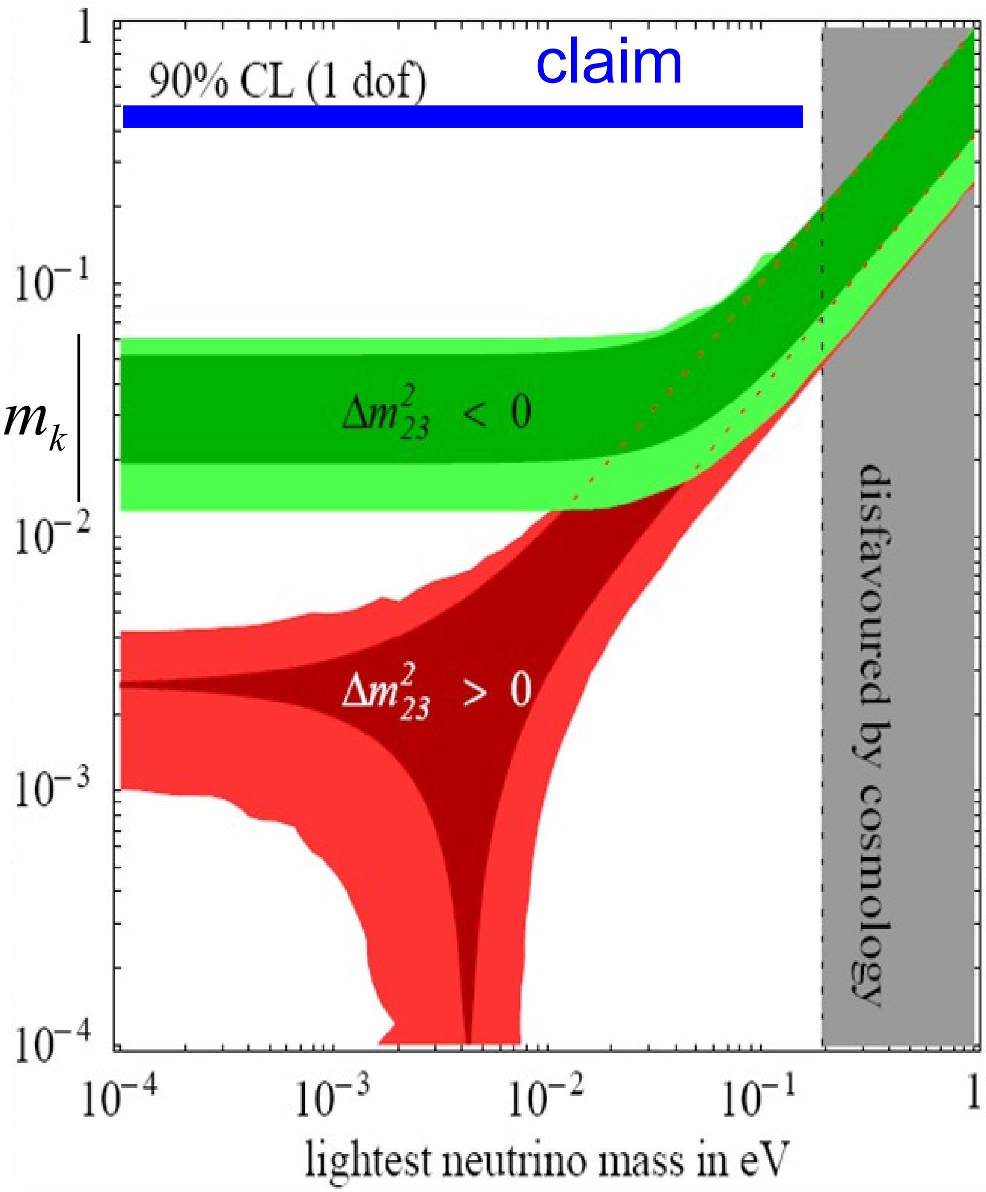
Hierarchy and limits

Tritium β decay : < 2,2 eV
Cosmology : < 1,0 eV
ββ decay : < 0,4 eV

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

PMNS - Matrix

ββ decay likely to give the most stringent limit on mass



history

1934: E. Fermi theory of weak interaction

1935: M. Goeppert-Mayer discussed $2\nu\beta\beta$

1938: E. Majorana two component neutrino

1939: W.H. Furry discussed $0\nu\beta\beta$

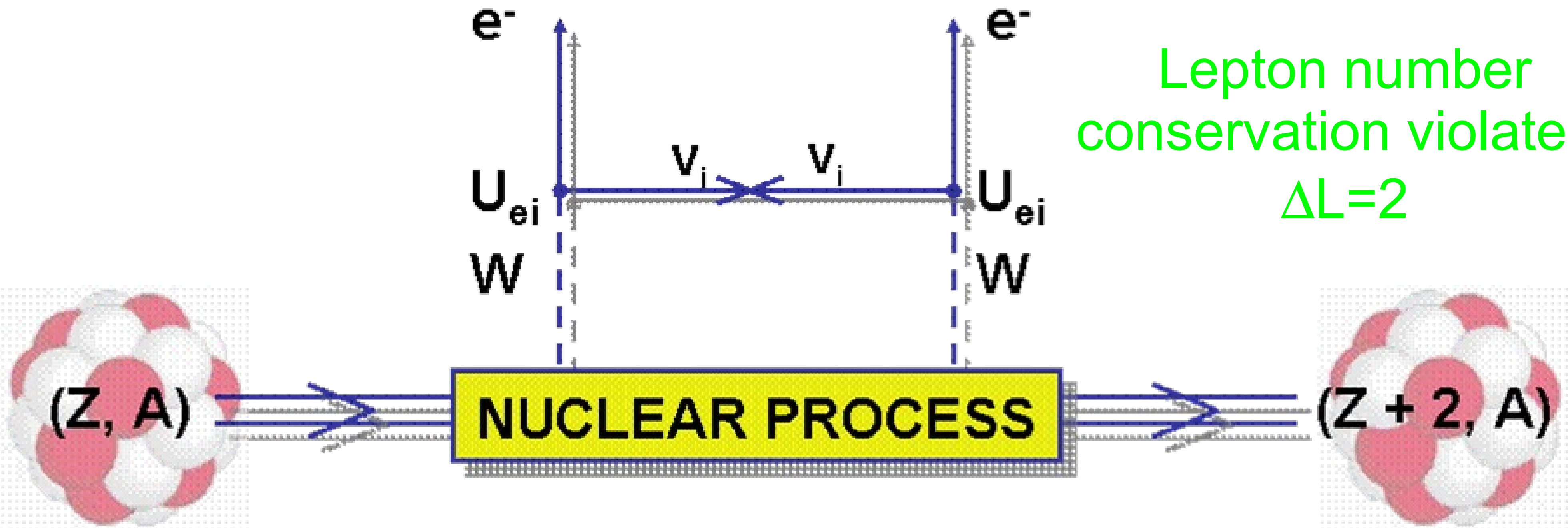
1949: First half-life limits (Fireman, Fremlin,...)

1967: First geochemical evidence for $2\nu\beta\beta$

1987: First laboratory evidence for $2\nu\beta\beta$

200x: First laboratory evidence for $0\nu\beta\beta$???

Neutrinoless 2β decay



Lepton number conservation violated: $\Delta L=2$

$0\nu2\beta$ process possible only if:

- Neutrino has finite mass
- Neutrino == Anti-Neutrino (Majorana type)

rate:

(exp.)

$$1/\tau = G(Q)\,\|M_{nucl}\|^2 <m_{ee}>^2$$

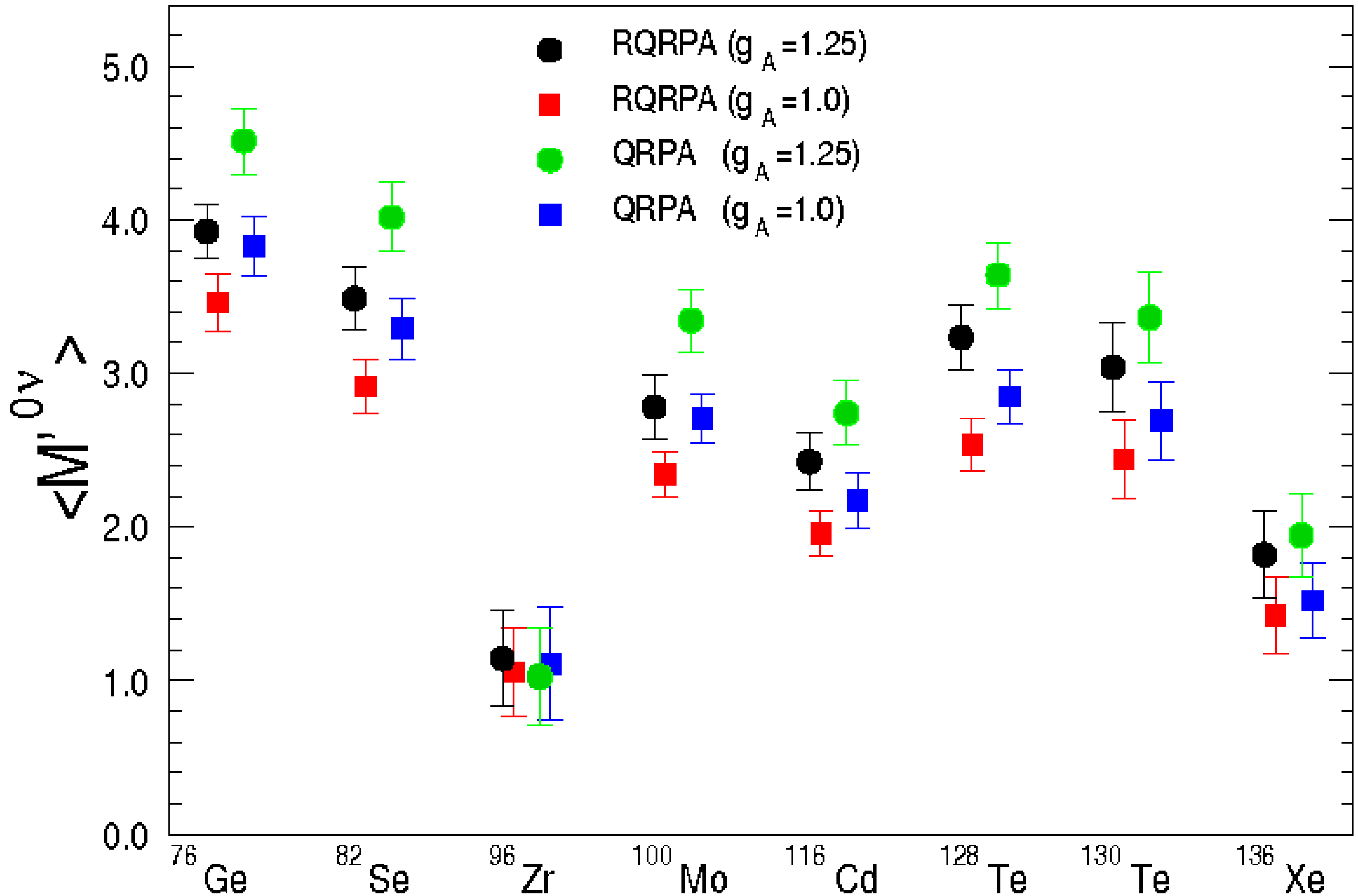
Phase space factor ($\sim Q^5$;choose (A,Z))

Nuclear matrix element (theory input)

Effective Majorana mass (hierachy)

Nuclear Matrix Elements

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



Shell Model: Strassbourg-Madrid; Caurier, Poves

phase space

$0\nu\beta\beta$ 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

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 ~1 kg

for ^{76}Ge : 1,8 kg

Now you only can loose:

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

Half - life estimate $0\nu\beta\beta$

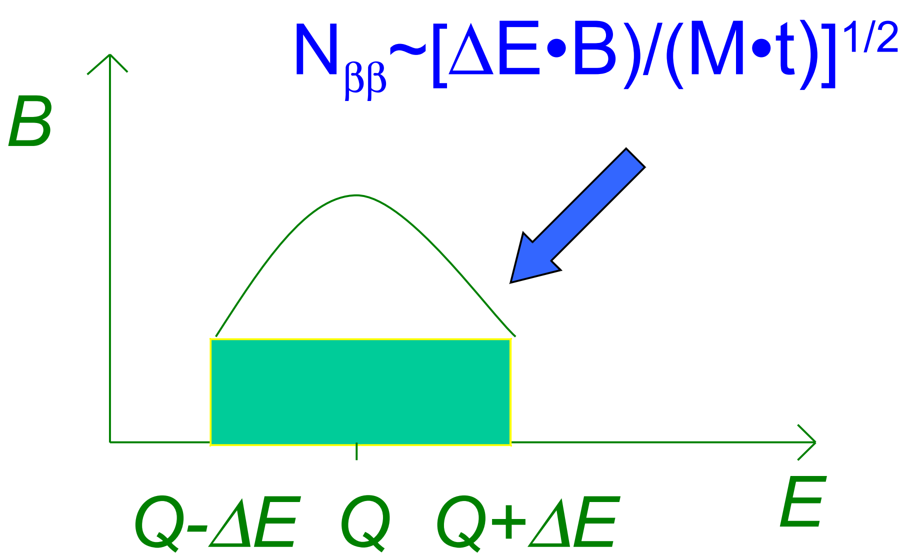
$$T_{1/2} = \ln 2 \cdot (N_A/A) \cdot M \cdot (N_{\beta\beta} / t)^{-1}$$

Signal sensitivity $\approx$ stat. precision of background $N_{obs} = \sqrt{N_{BG}}$

Background ~ detector mass

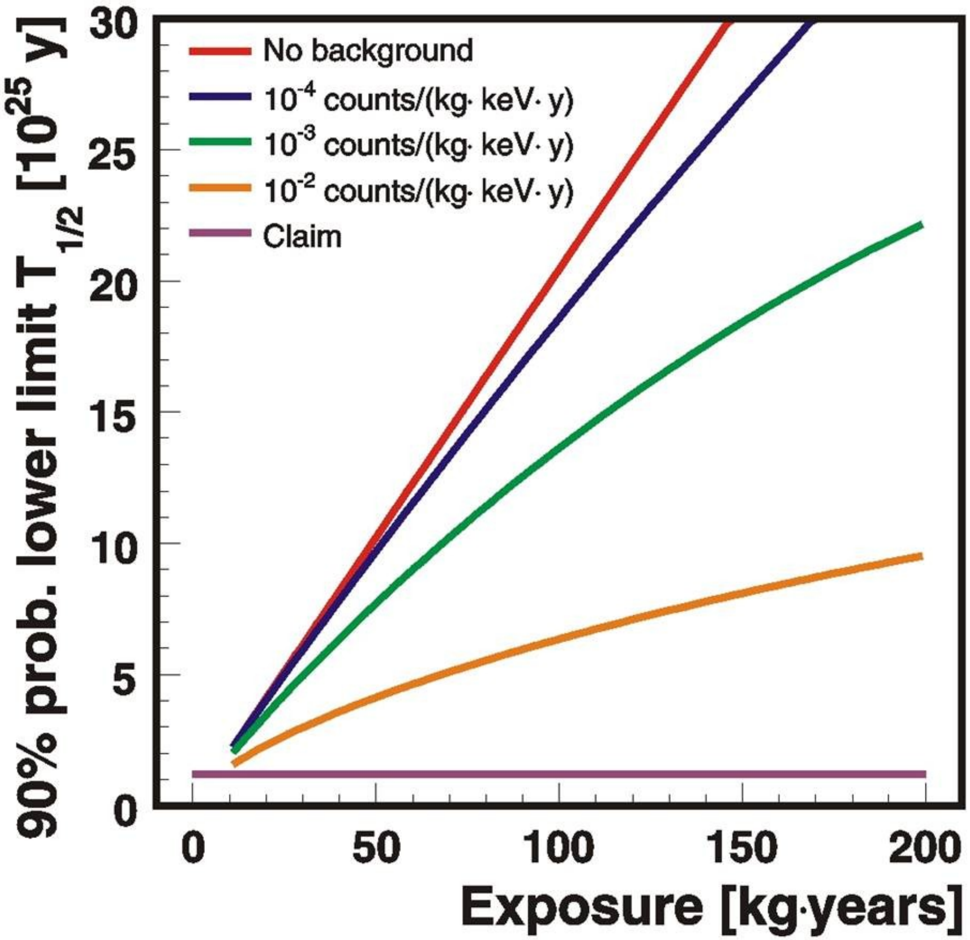
$$T_{1/2} \propto a \cdot \varepsilon \, [\, (M \cdot t) / \, (\Delta E \cdot B) \,]^{1/2}$$

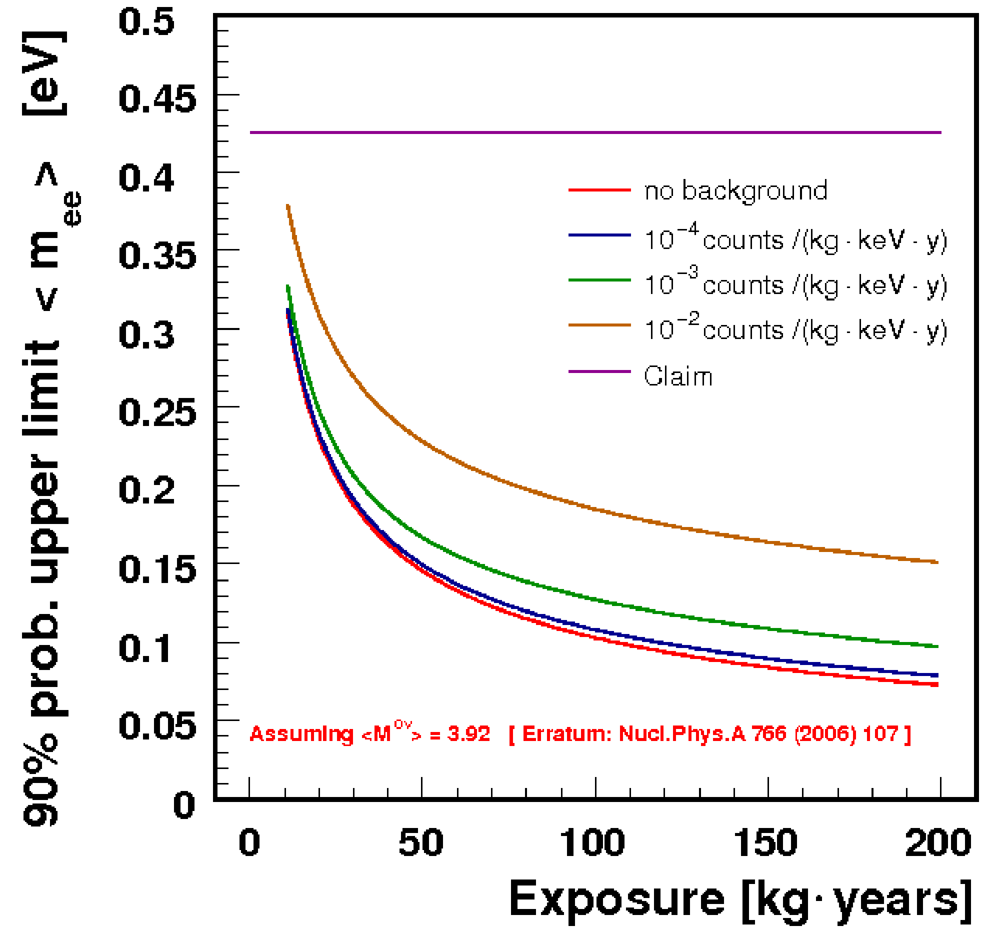
- a : isotopical abundance
- ε : detector efficiency
- M : mass
- t : measuring time
- ΔE : energy resolution
- B : background cts/(kg keV yr)



Region Of Interest

background



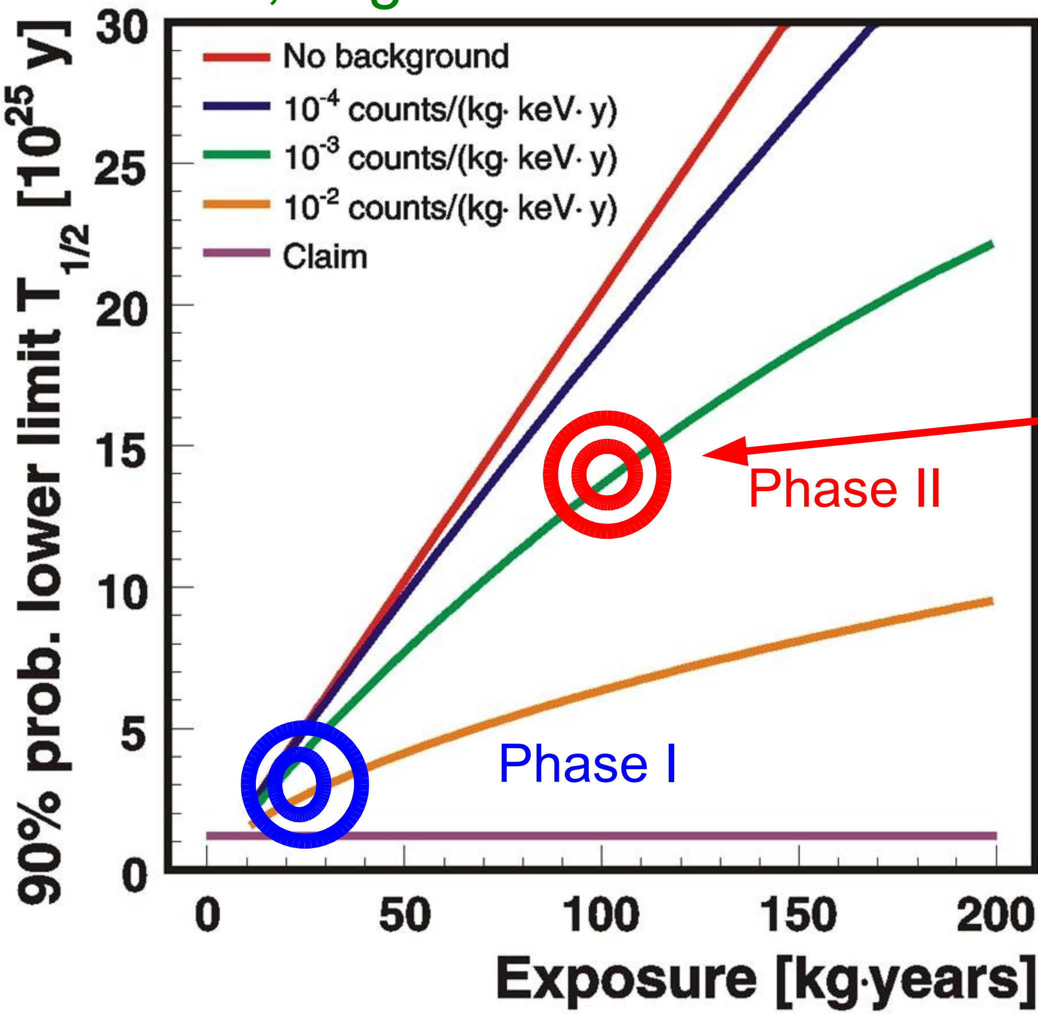


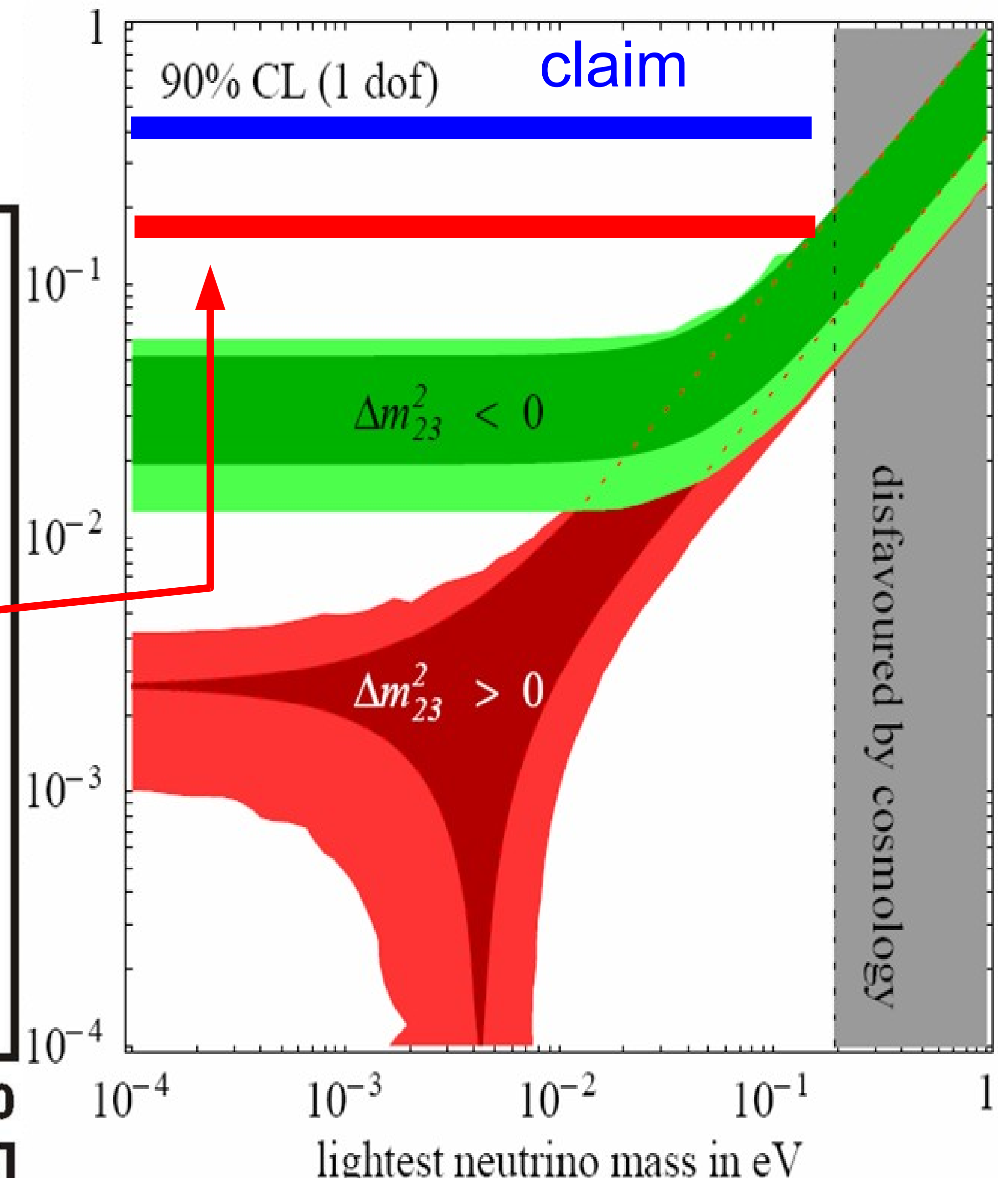
Background limits the discovery potential

absolute mass scale

Sensitivity of GERDA

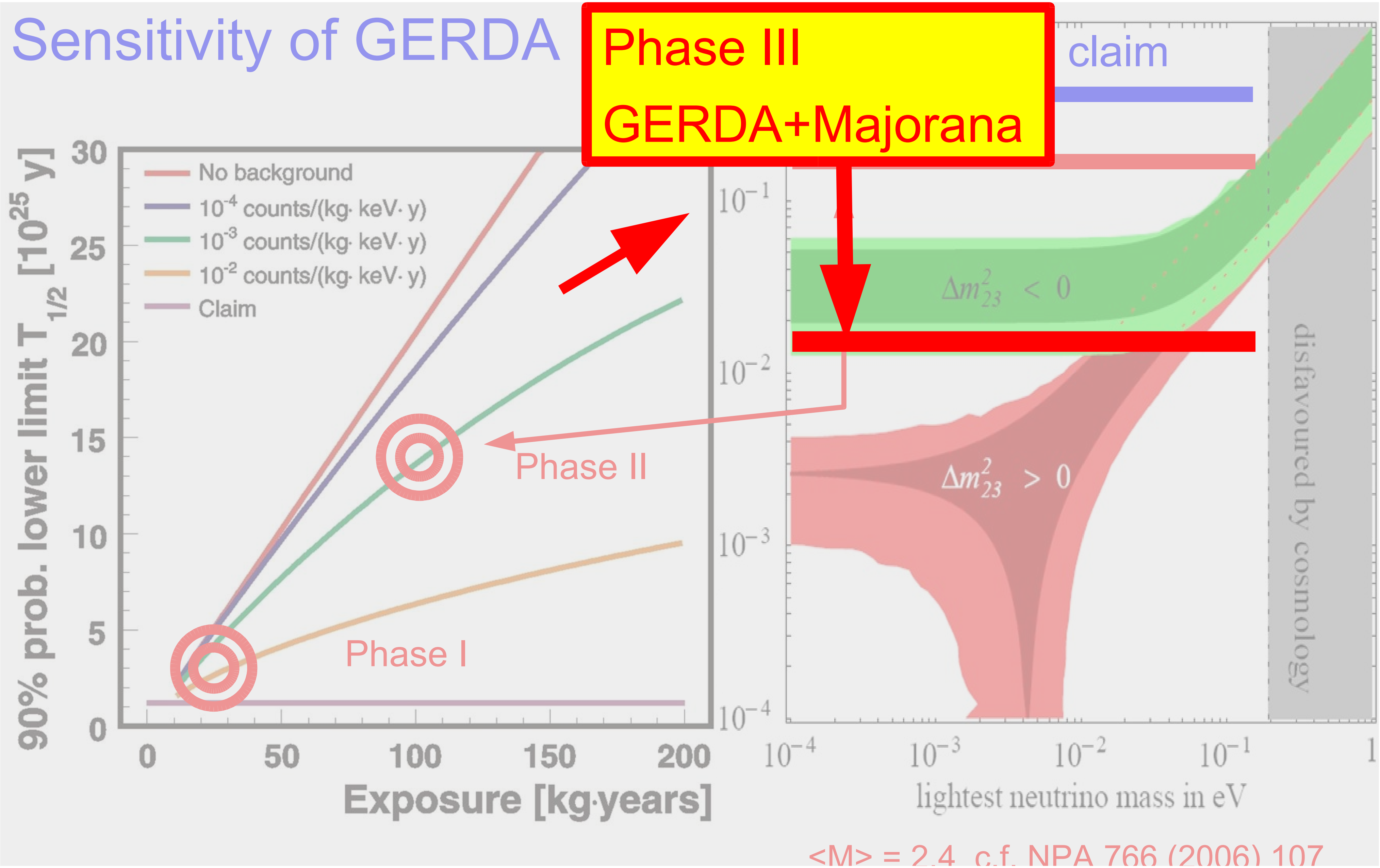
1,8 kg ~ 10^{25} Ge atoms





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

absolute mass scale



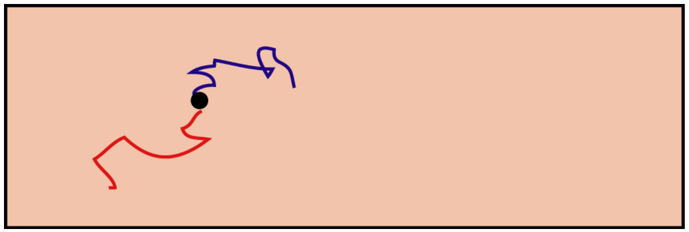
Methods and experiments

Methods

aim at 100 meV scale ⇒ B < 10^{-3}/(keV kg yr)

two orders of magnitude better than now

calorimetric:



Source = detector
Measure sum energy with calorimetric techniques
Ge semiconductor, bolometers

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

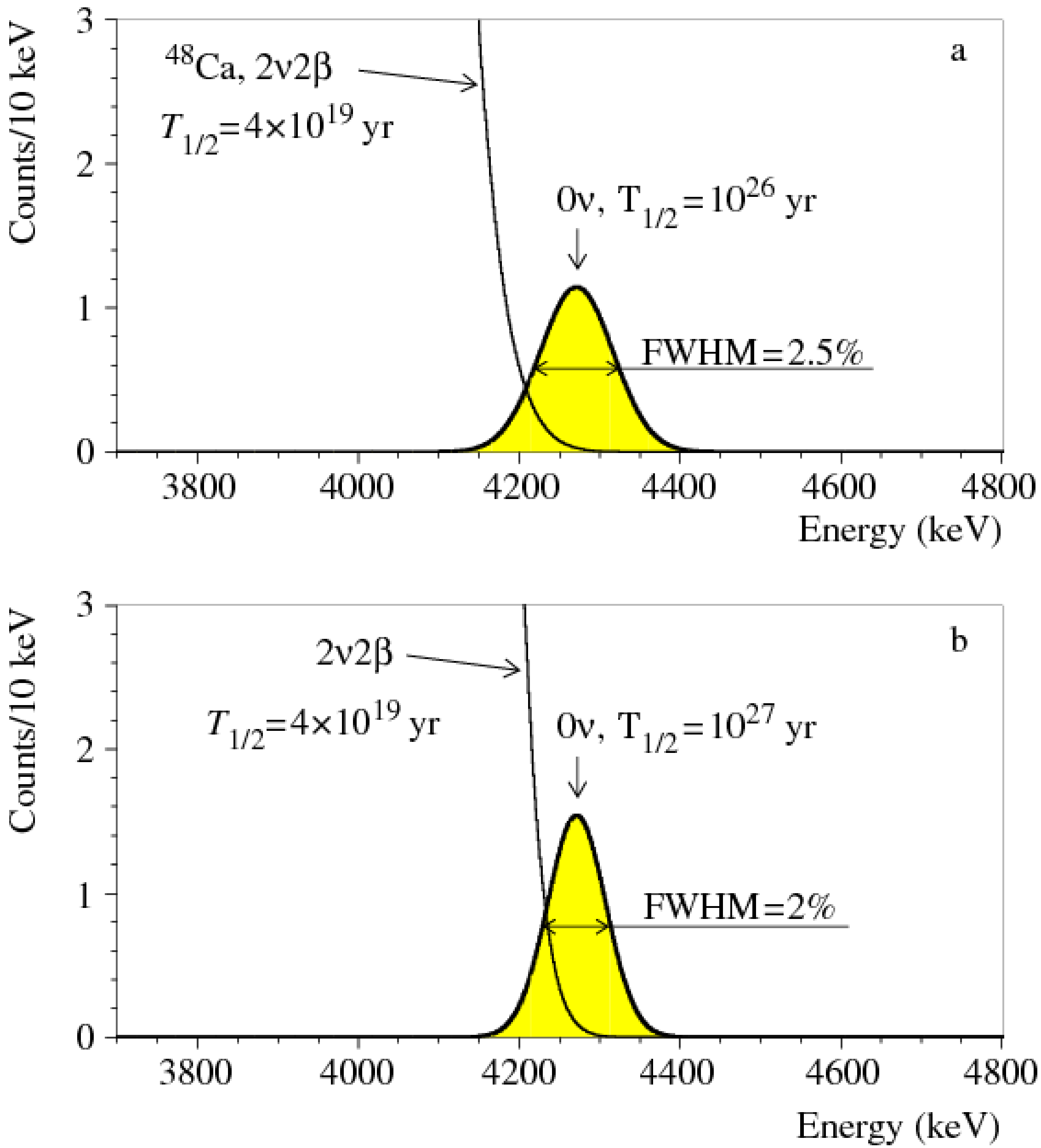
tracking:

Source ≠ detector

+ background suppression via event reconstruction, but $2\nu 2\beta$
– **energy resolution (to distinguish $2\nu 2\beta$)**
– “dilute” detectors, need large space
+ several nuclides possible (⇒ select high Q)
  NEMO3: tracking, calorimetry, **B**-field,
  ⇒ $T_{1/2}$ > 5.8 10^{23} y ⇒ M_{ee}< 0.4 - 1.4 meV
  ⇒ Future: SuperNEMO

Resolution

^{48}Ca



FWHM = 2,5 %

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

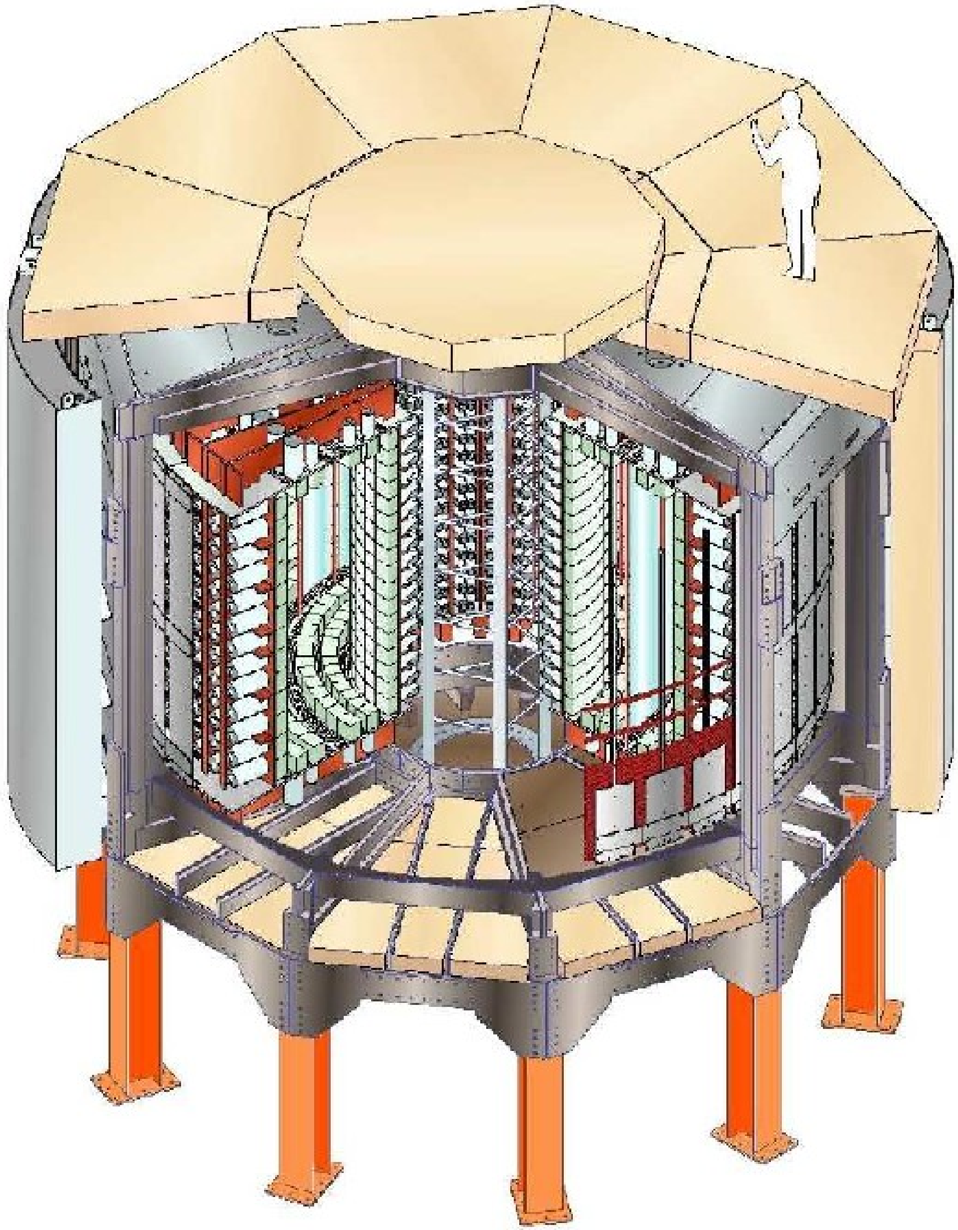
FWHM = 2,0 %

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

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?
EXO	^{136}Xe	TPC

NEMO



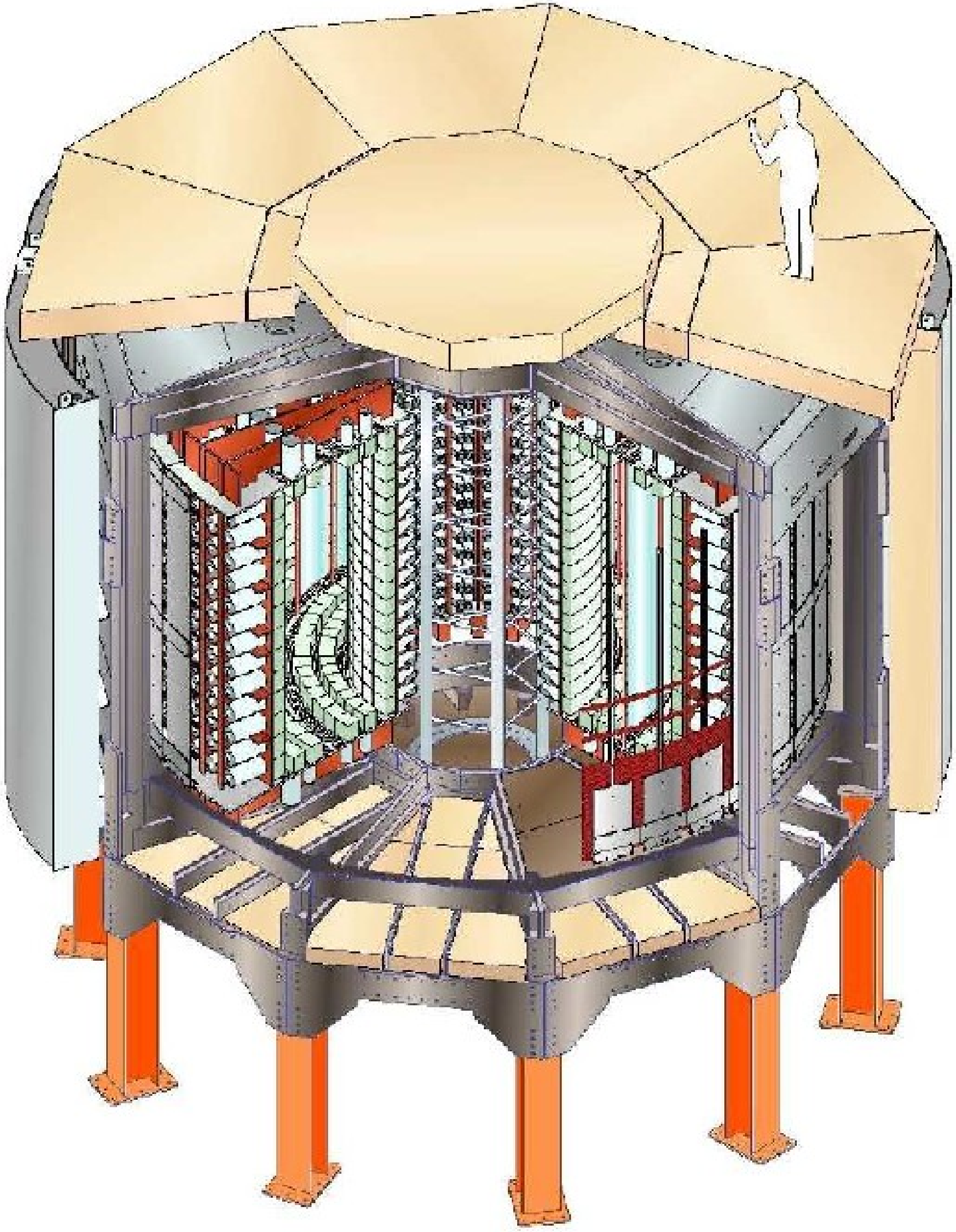
20 segments with thin foils
3D readout drift chambers
surrounding 1940 plastic szint.
B = 30G   (ε_{track} = 98%)

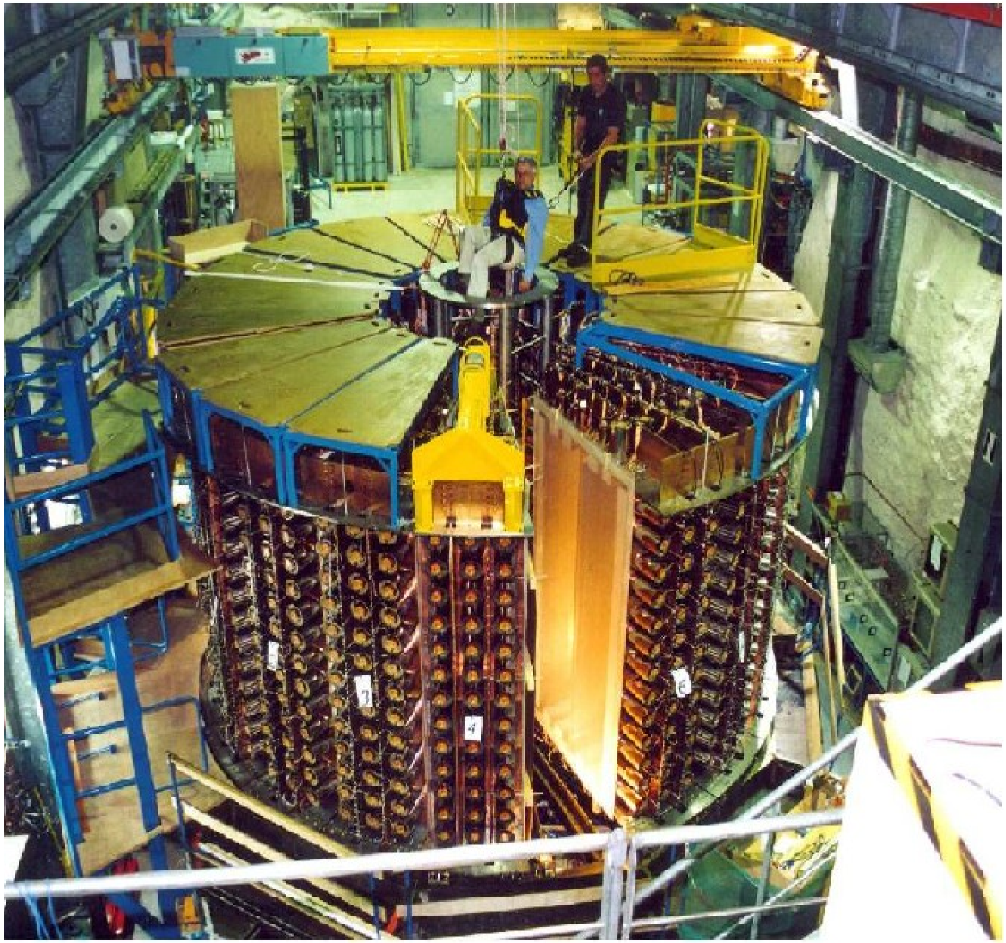
Mo (6,9kg), Se(0,9kg),Te(0,45kg)
Cd(0,40kg),Nd(36g)

Modane : 4800 mwe

ε = 50% @ 1 MeV
ΔE = 11-14% FWHM

NEMO



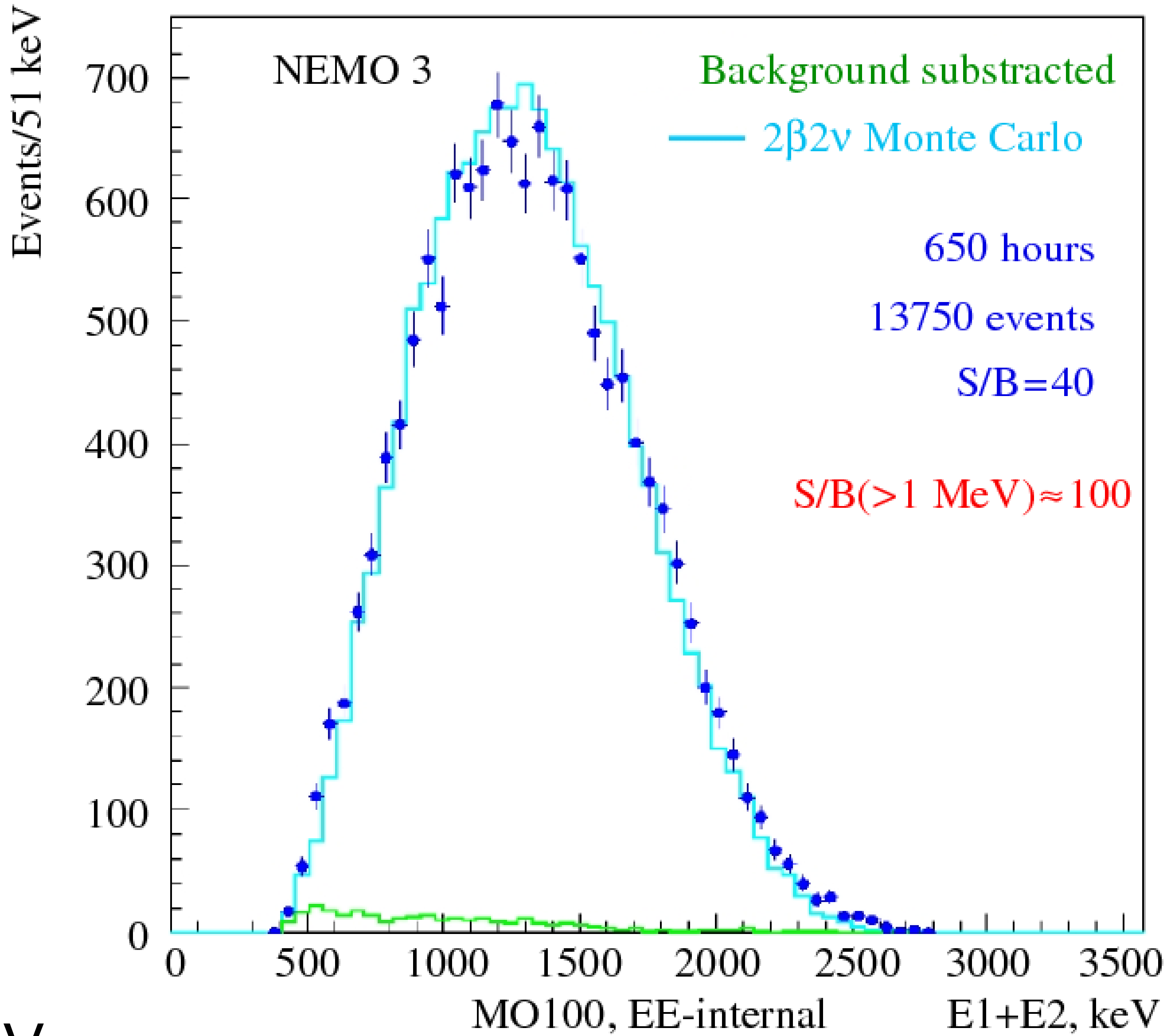


NEMO

^{100}Mo

Q = 3034 keV

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

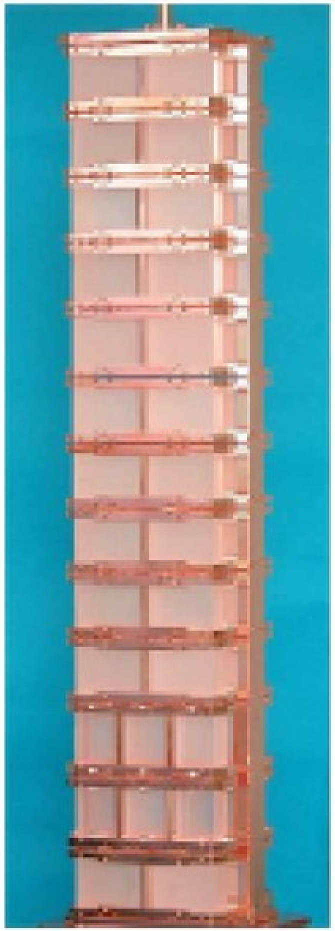


ΔE = 250 keV @ 3MeV

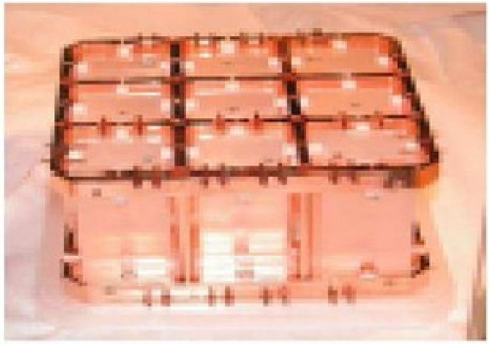
CUORICINO/CUORE

62 crystals in 13 planes

^{128}Te and ^{130}Te



5x5x5 cm^3



3x3x6 cm^3

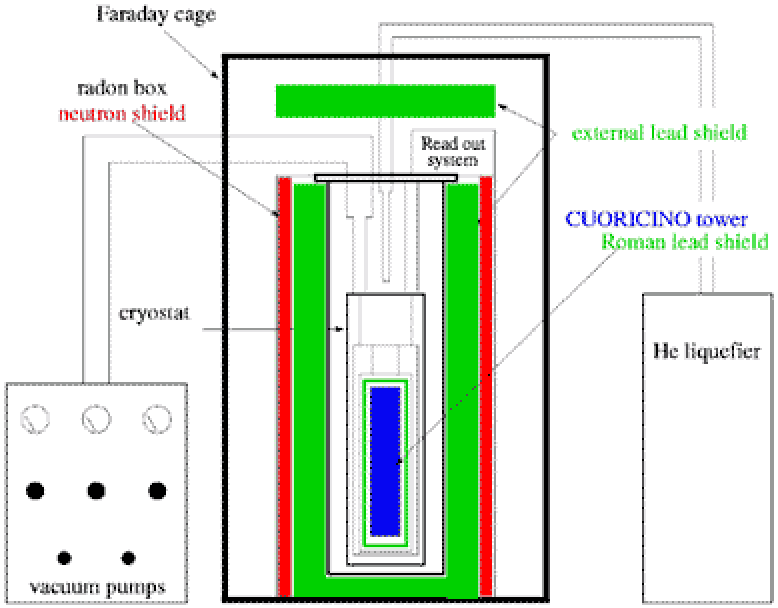
2 enriched

TeO_2 bolometers: M ~ 30kg

OFHC Copper & Teflon

T = 8 mK

b =0,2 cts/(kgkeVy)



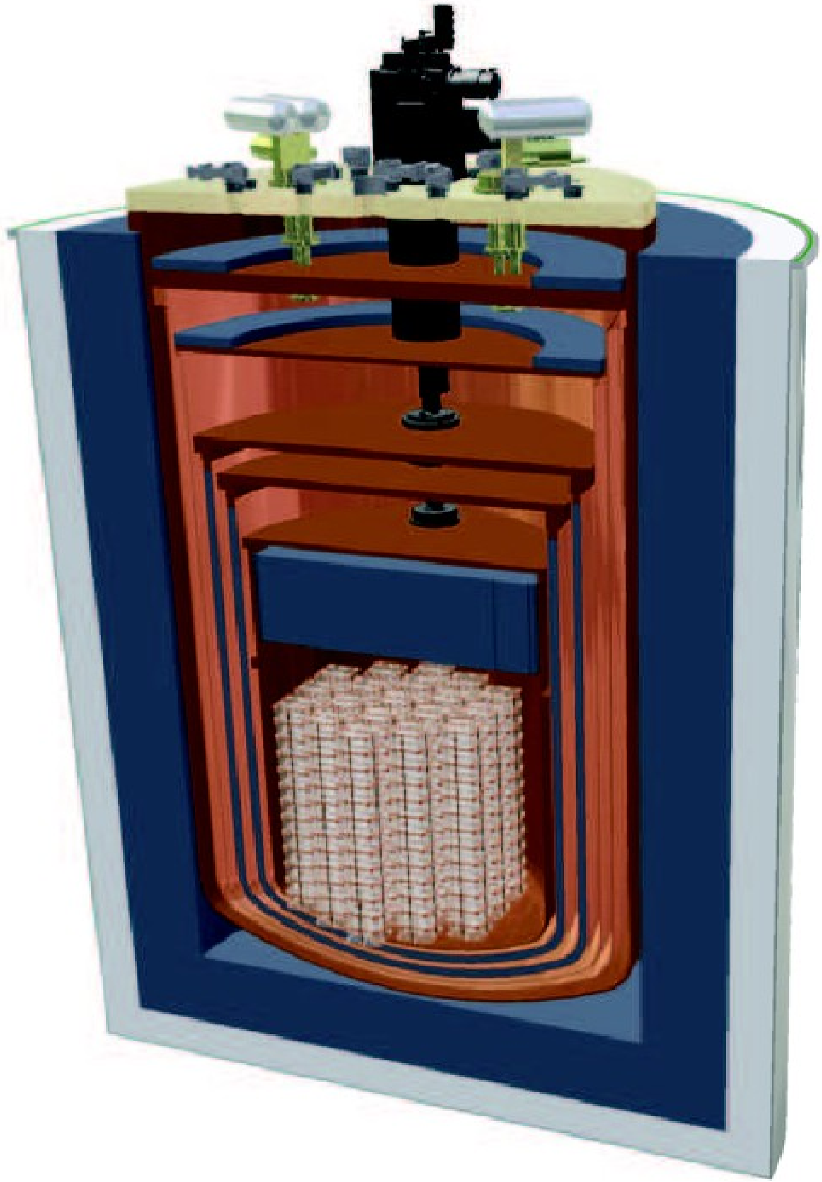
CUORICINO/CUORE

^{130}Te in CUORE

Q = 2530 keV

988 TeO_2 bolometers
in 19 towers

M = 750 kg



CUORICINO/CUORE

CUORE Site in Hall A at LNGS

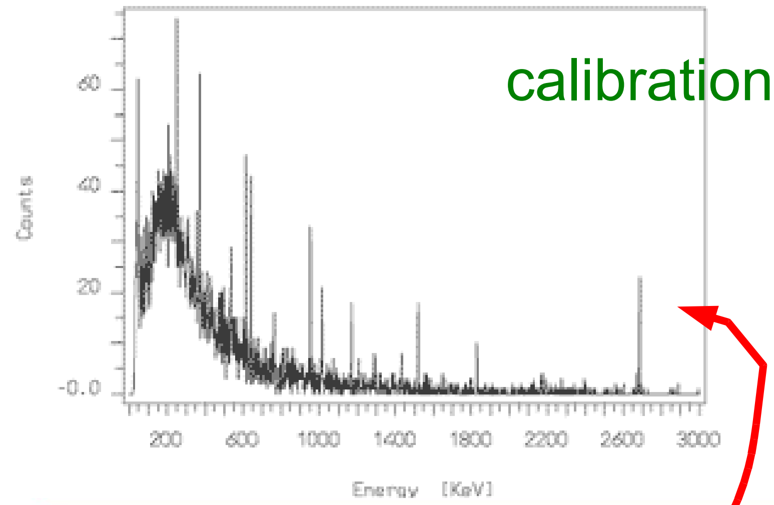
Neutrino 2006

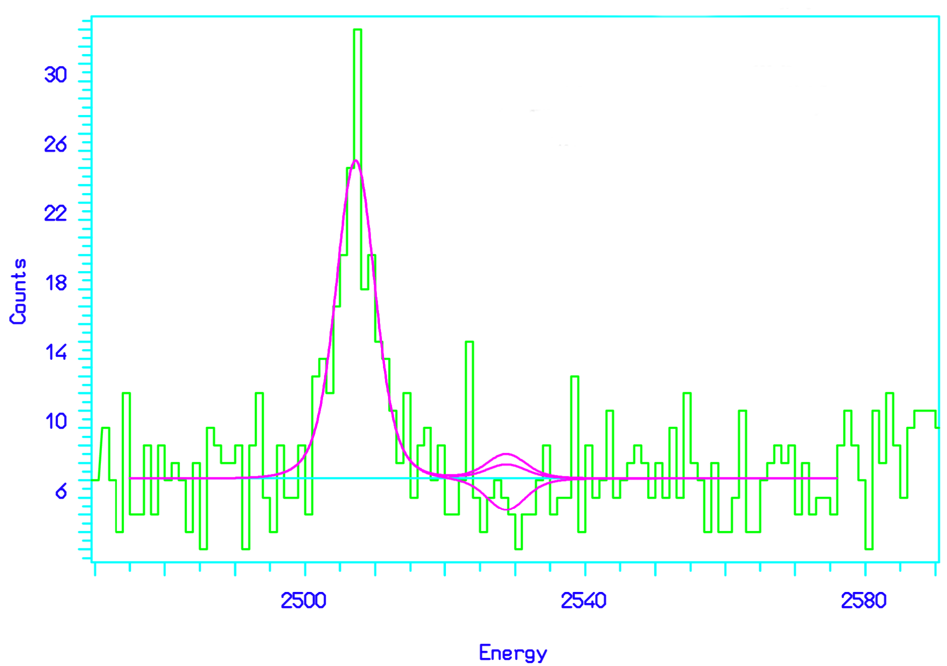
CUORICINO/CUORE

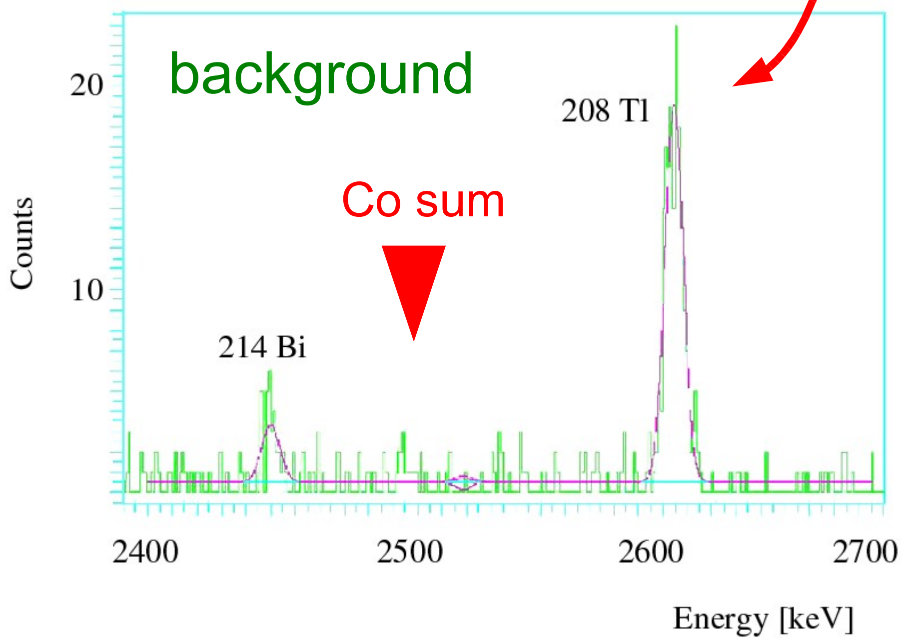
^{130}Te in CUORICINO

Q = 2530 keV

$T^{0\nu}_{1/2} > 3 \cdot 10^{24}$ y (11.8 kgy)







^{76}Ge experiments

^{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·keV·y)

passive : LNGS @ 3500 m.w.e. (reduce μ)

Watertank, LAr (avoid n,cosmogenic)

selection of material (reduce Th,U)

active : Muon veto

segmentation, anti-coincidence

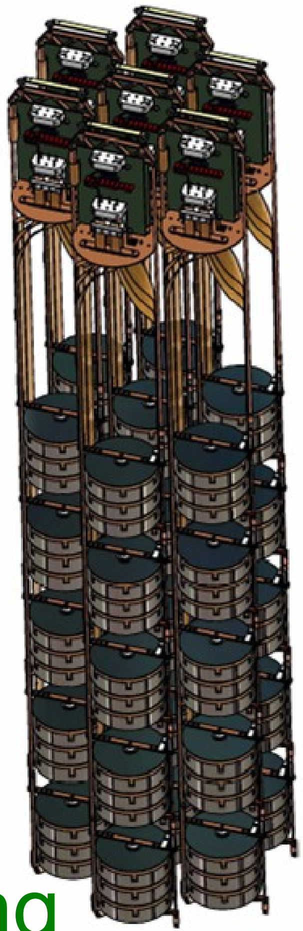
PSA

GERDA – the schema

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



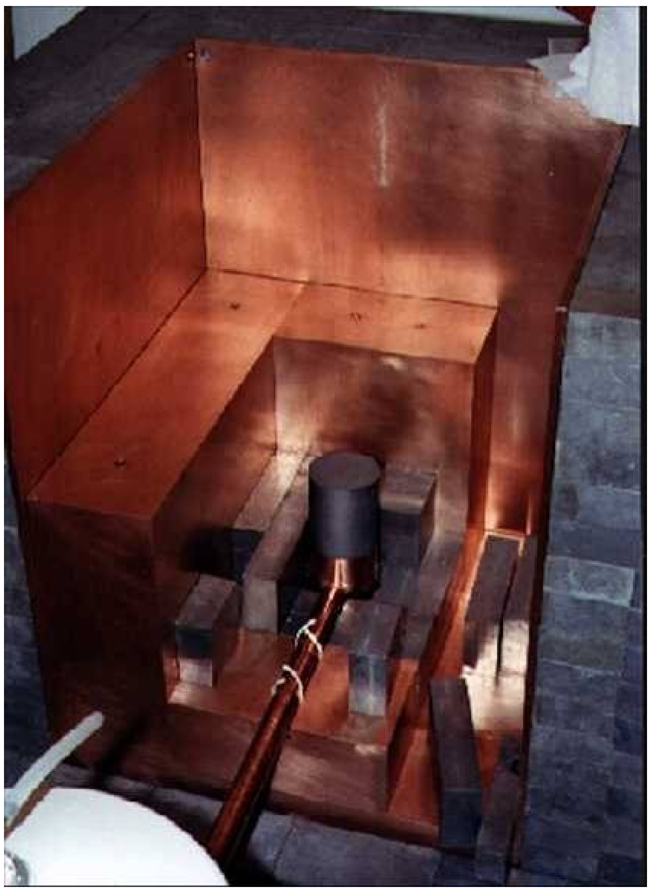
Ge diodes – enriched to 86%
liquid argon
stainless steel cryostat
water   to moderate neutrons and
         as muon veto (Cerenkov)

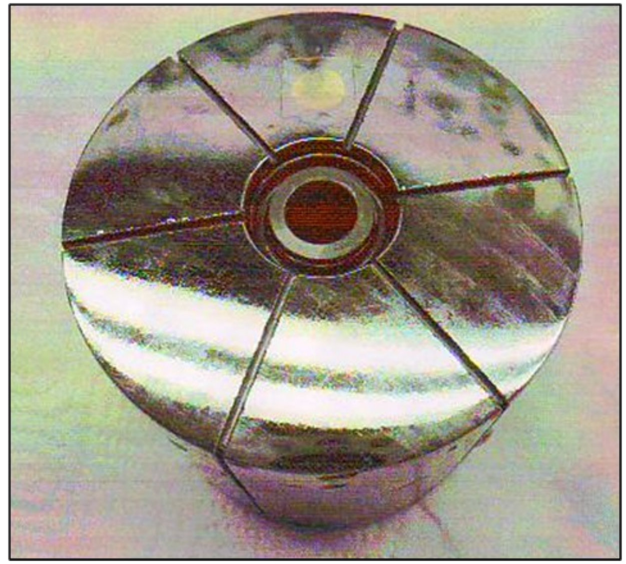
=>HdM, Majorana: closed compact shielding

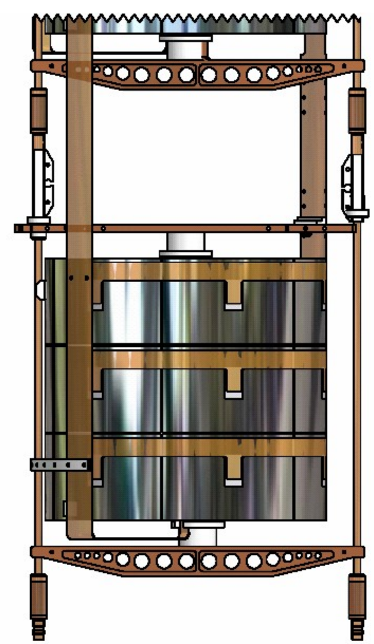
Setup: HdM versus GERDA

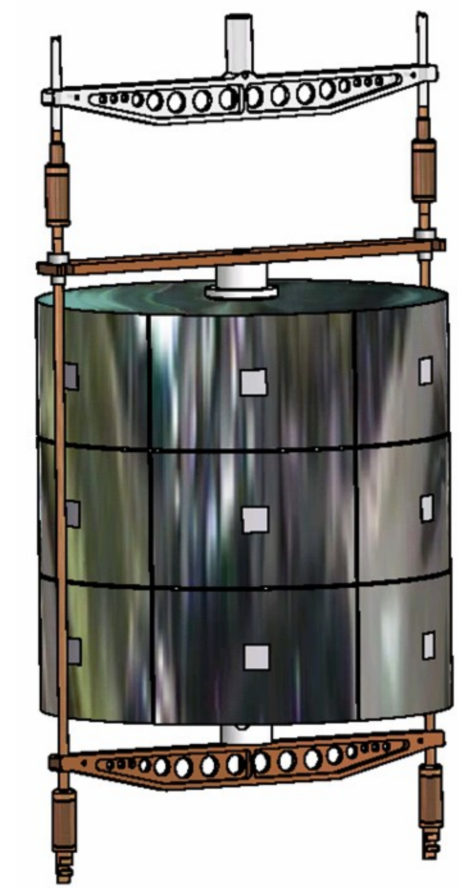
HdM

non-enriched prototype









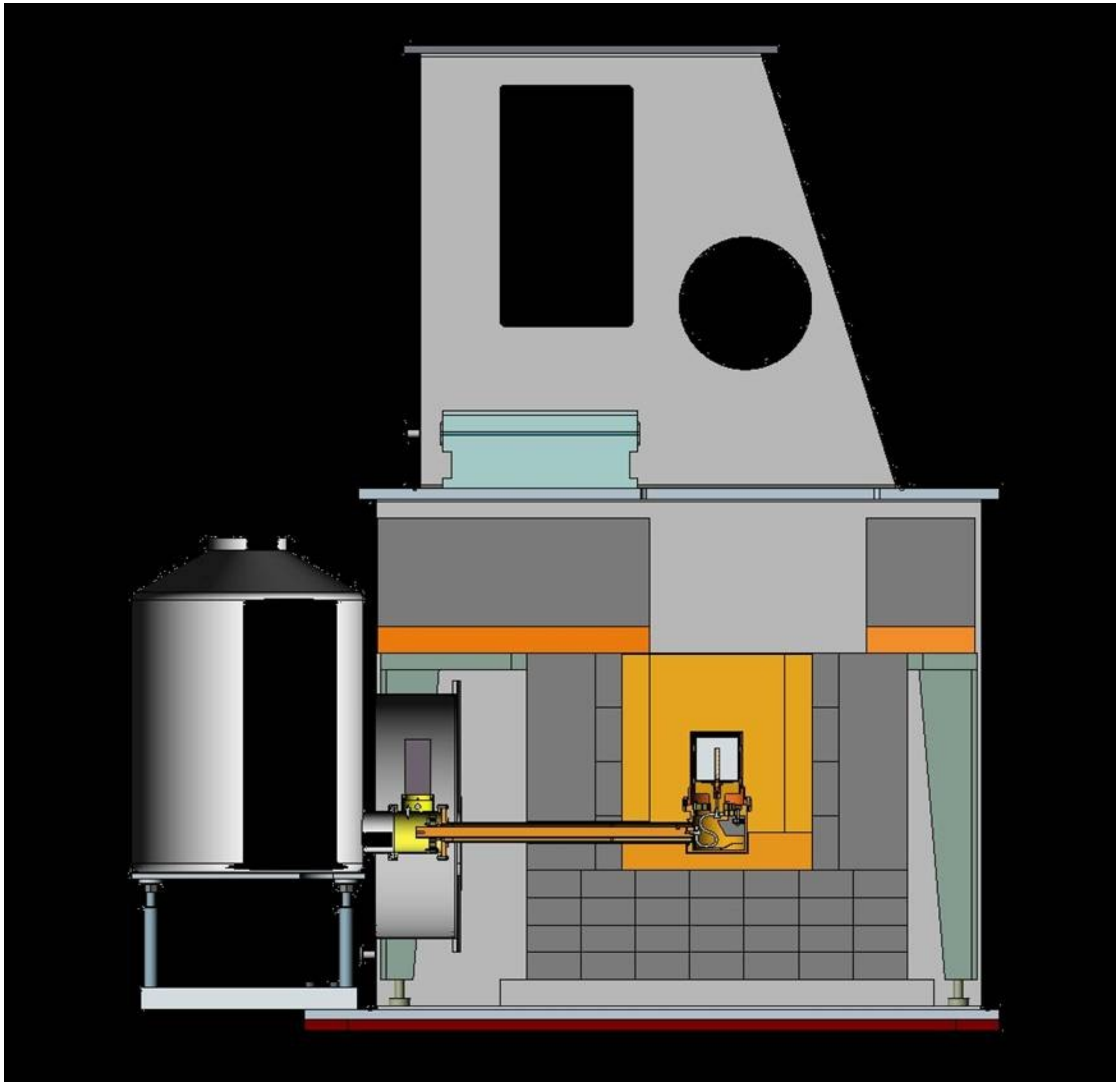
~ 12 g vs. ~ 2 kg

Material screening

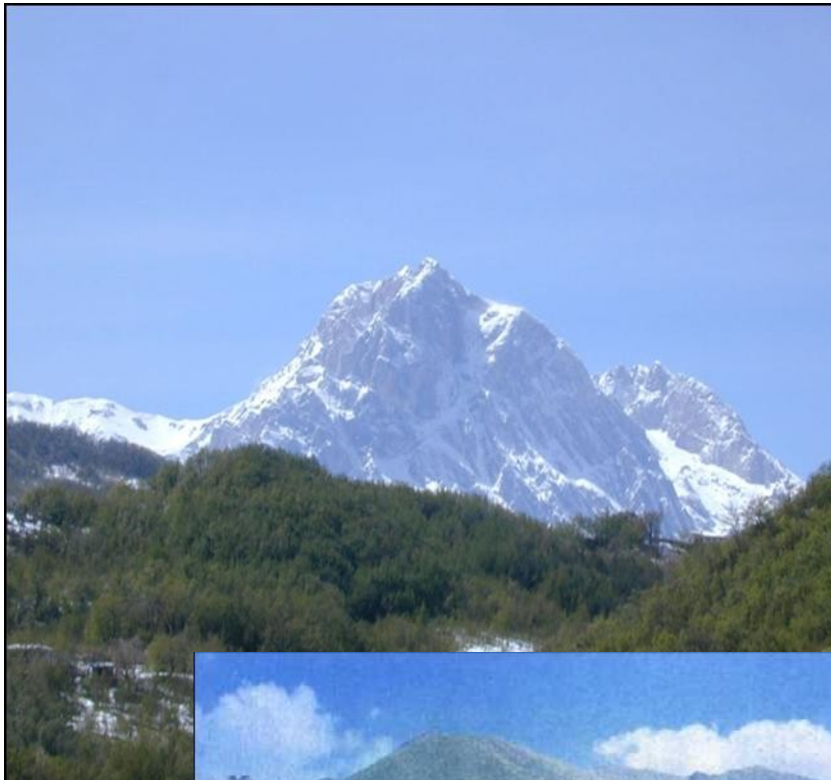
GeMPI
Corrado

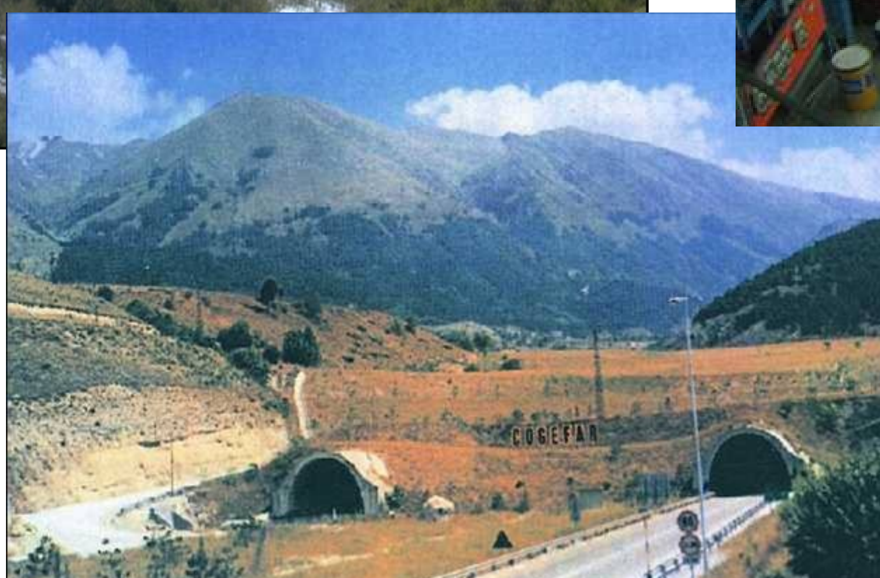
several systems
at LNGS & MPI

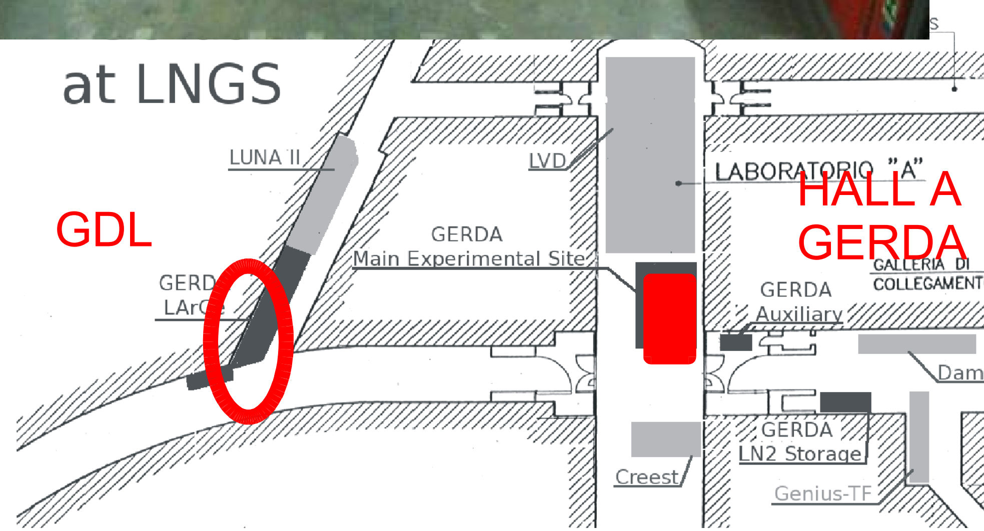
steel
Cuflon
preamps
O-rings



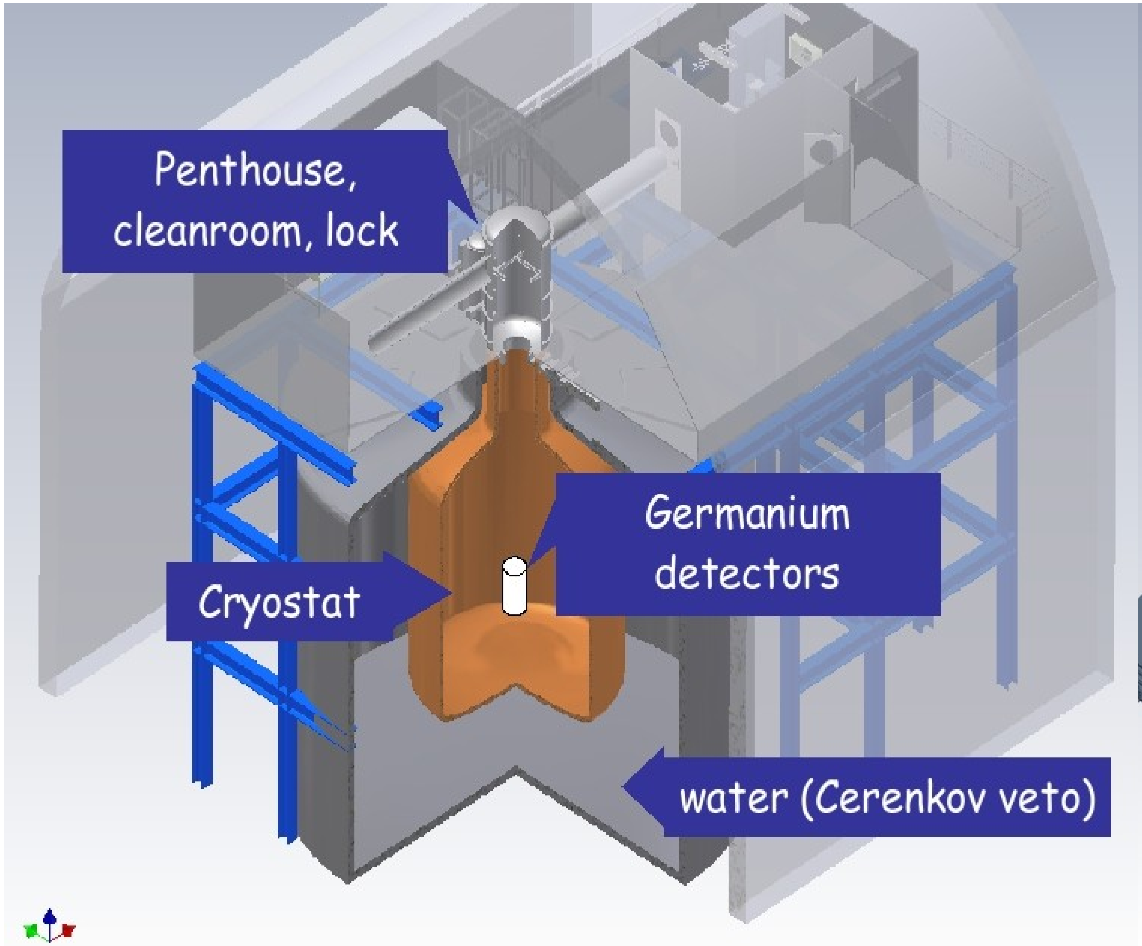
GERDA @ LNGS

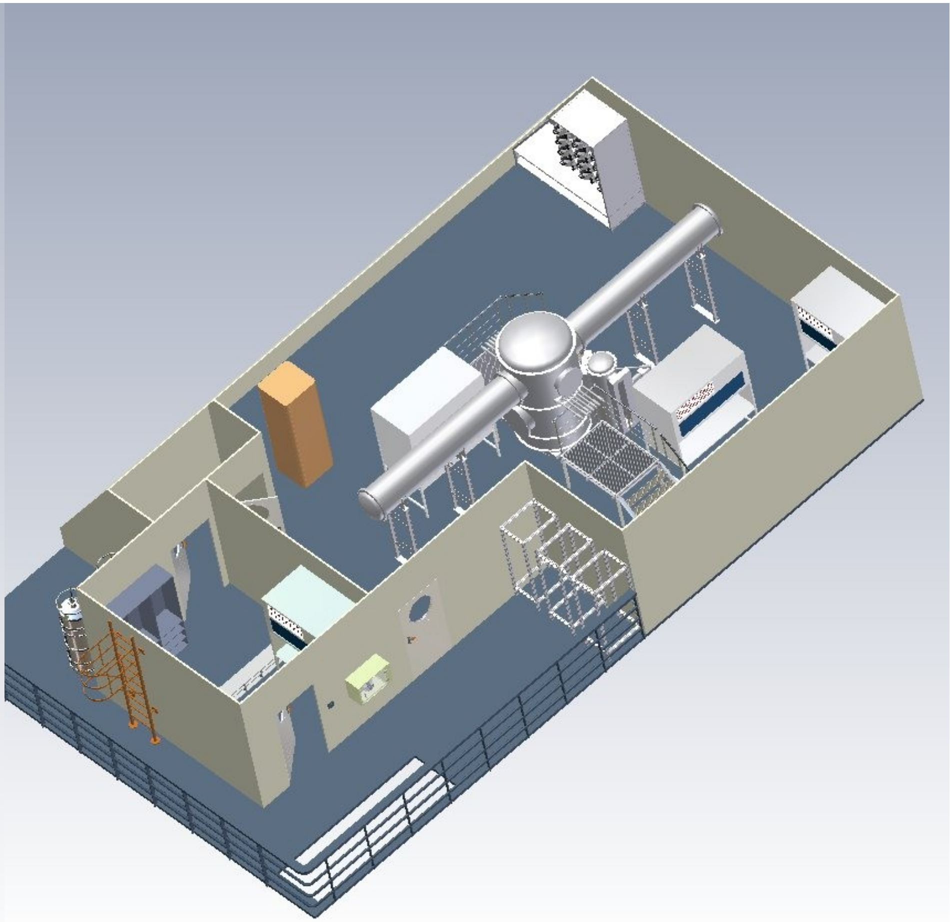





at LNGS
LUNA II
LVD
LABORATORIO "A"
HALL A
GERDA
GDL
GERDA
Main Experimental Site
GALLERIA DI
COLLEGAMENTO
GERDA
Auxiliary
Dama
GERDA
LN2 Storage
Creest
Genius-TF

Super-structure and Watertank



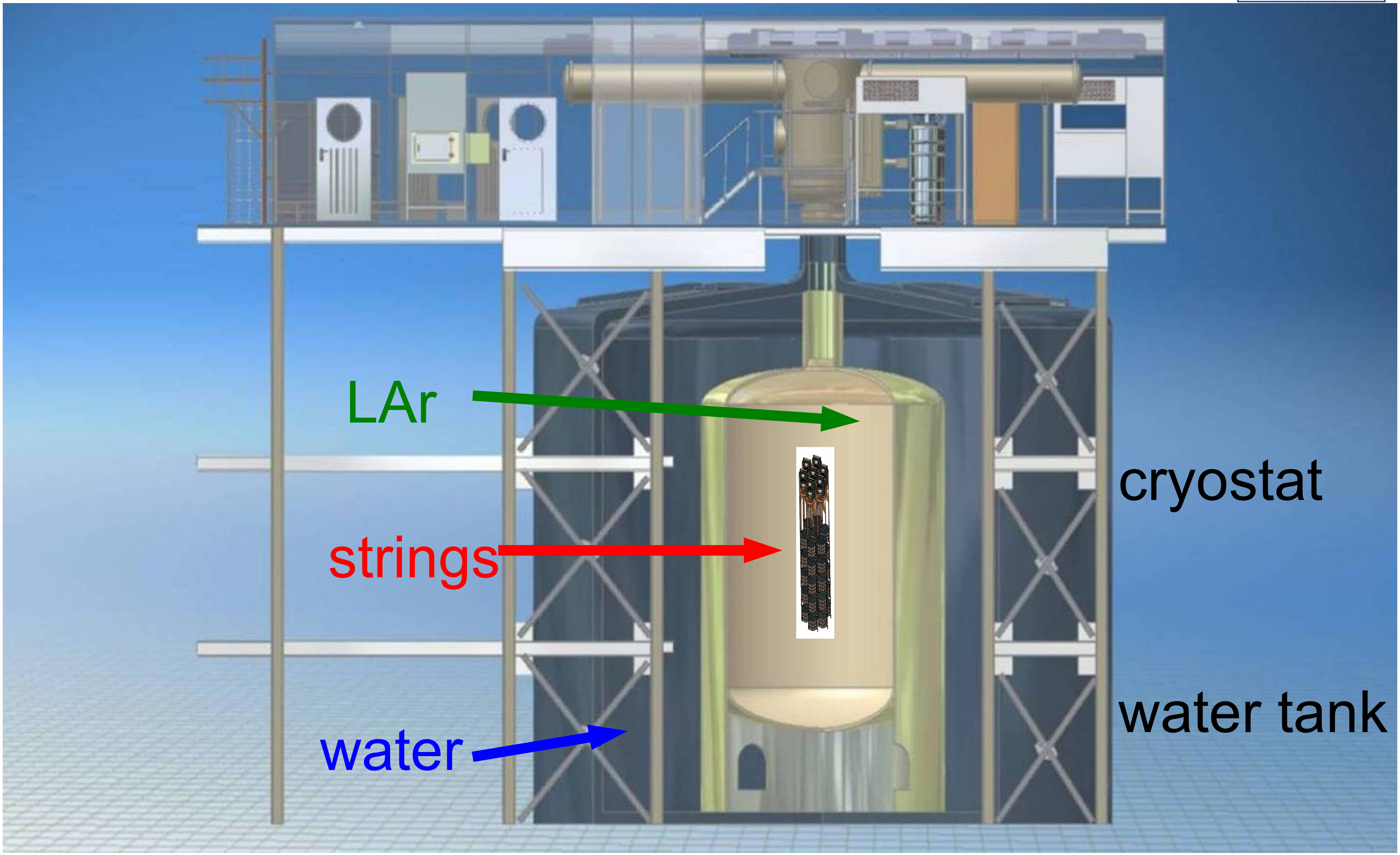


Hall A @ LNGS clean room on top

water tank as active muon veto (66 PMTs)

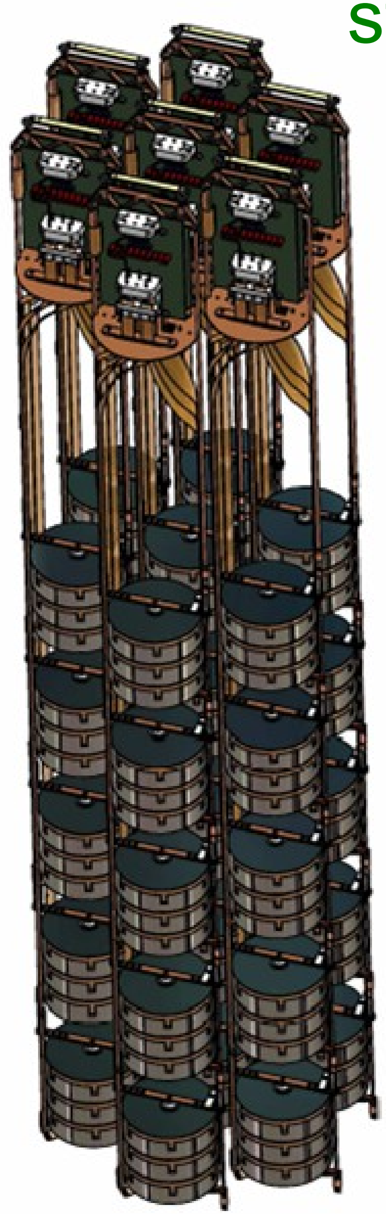
SS cryostat with copper shield, filled with LAr (~70m^3)

GERDA - experimental setup

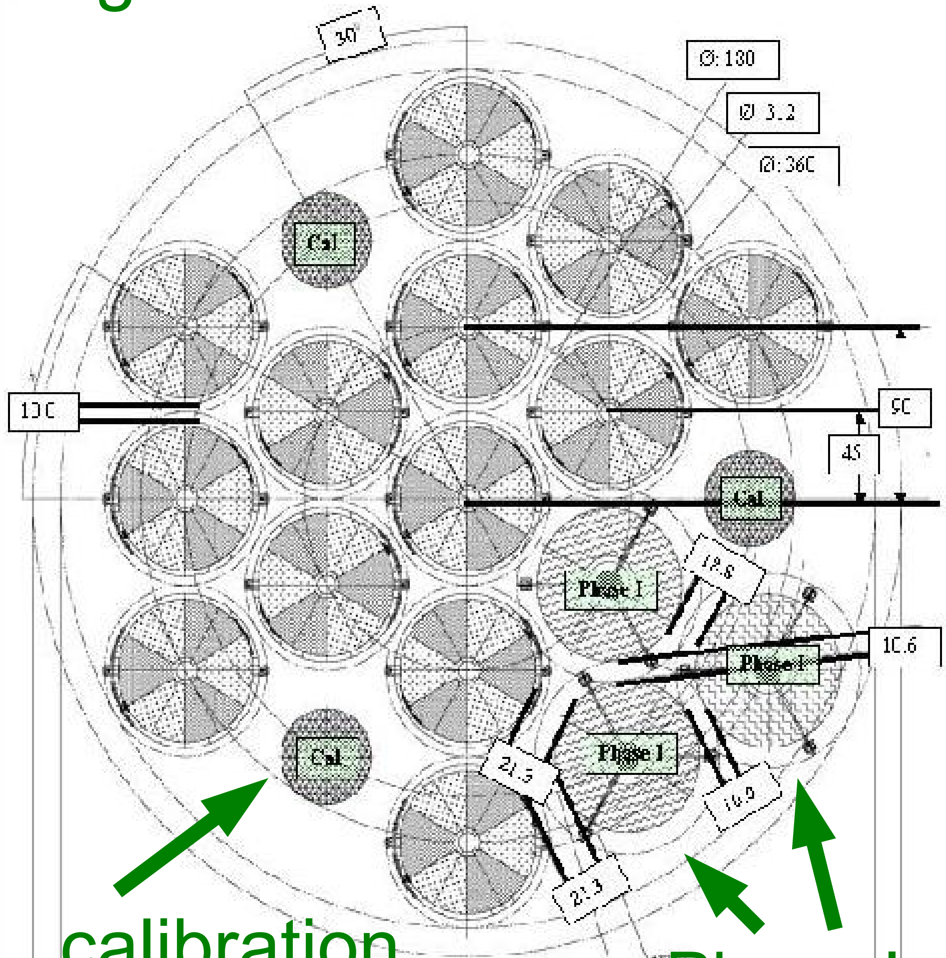


GERDA - detectors

strings

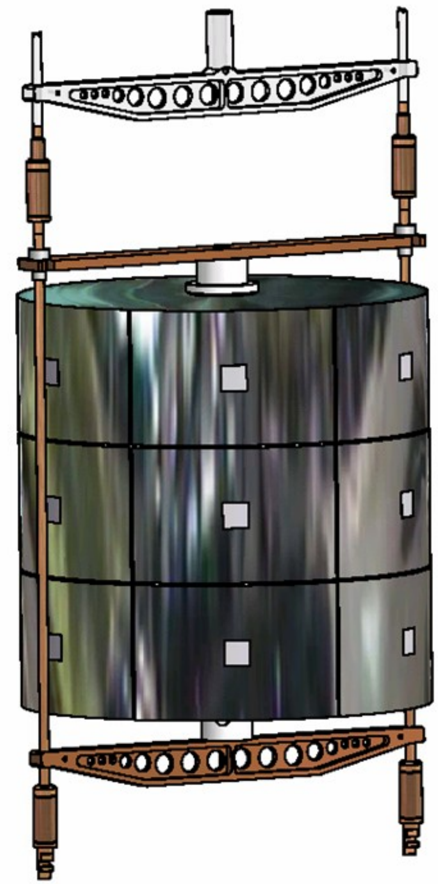


non-enriched prototype



calibration source

Phase I



~ 12 g vs. ~ 2 kg

GERDA – the collaboration

A.M. Bakalyarov[i], M. Balata[a], I. Barabanov[g], C. Bauer[c], E. Bellotti[f], S. Belogurov[g,h], S. T. Belyaev[i], M. Bernabe-Heider[c], A. Bettini[k], L. Bezrukov[g], V. Brudanin[b], D. Budjas[c], A. Caldwell[j], C. Cattadori[a,f], O. Chkvorets[c], E. V. Demidova[h], A. Di Vacri[a], V. Egorov[b], A. Gangapshev[g], J. Gasparro[m], P. Grabmayr[l], G. Y. Grigoriev[i], K. N. Gusev[i], V. Gurentsov[g], W. Hampel[c], M. Heisel[c], G. Heusser[c], W. Hofmann[c], M. Hult[m], L.V. Inzhechik[i], M. Jelen[j], J. Jochum[l], M. Junker[a], S. Katulina[b], J. Kiko[c], I.V. Kirpichnikov[h], A. Klimenko[b,g], M. Knapp[l], K.T. Knoepfle[c], O. Kochetov[b], V.N. Kornoukhov[g,h], K. Kroeninger[j], V. Kusminov[g], M. Laubenstein[a,f], V.I. Lebedev[i], M. Lindner[c], X. Liu[j], J. Liu[j], B. Majorovits[j], G. Marissens[m], I. Nemchenok[b], L. Niedermeier[l], J. Oehm[c], L. Pandola[a], P. Peiffer[c], A. Pullia[f], F. Ritter[l], C. Rossi Alvarez[k], V. Sandukovsky[b], S. Schoenert[c], J. Schreiner[c], U. Schwan[c], B. Schwingenheuer[c], M. Shirchenko[i], H. Simgen[c], N. Smale[c], A. Smolnikov[b,g], F. Stelzer[j], A.V. Tikhomirov[i], C. Tomei[a], U. Trunk[c], C.A. Ur[k], A.A. Vasenko[h], S.Vasiliev[b,g], M. Wojcik[e], E. Yanovich[g], J. Yurkowski[b], S.V. Zhukov[i], F. Zocca[f], G. Zuzel[c]

39 FTE

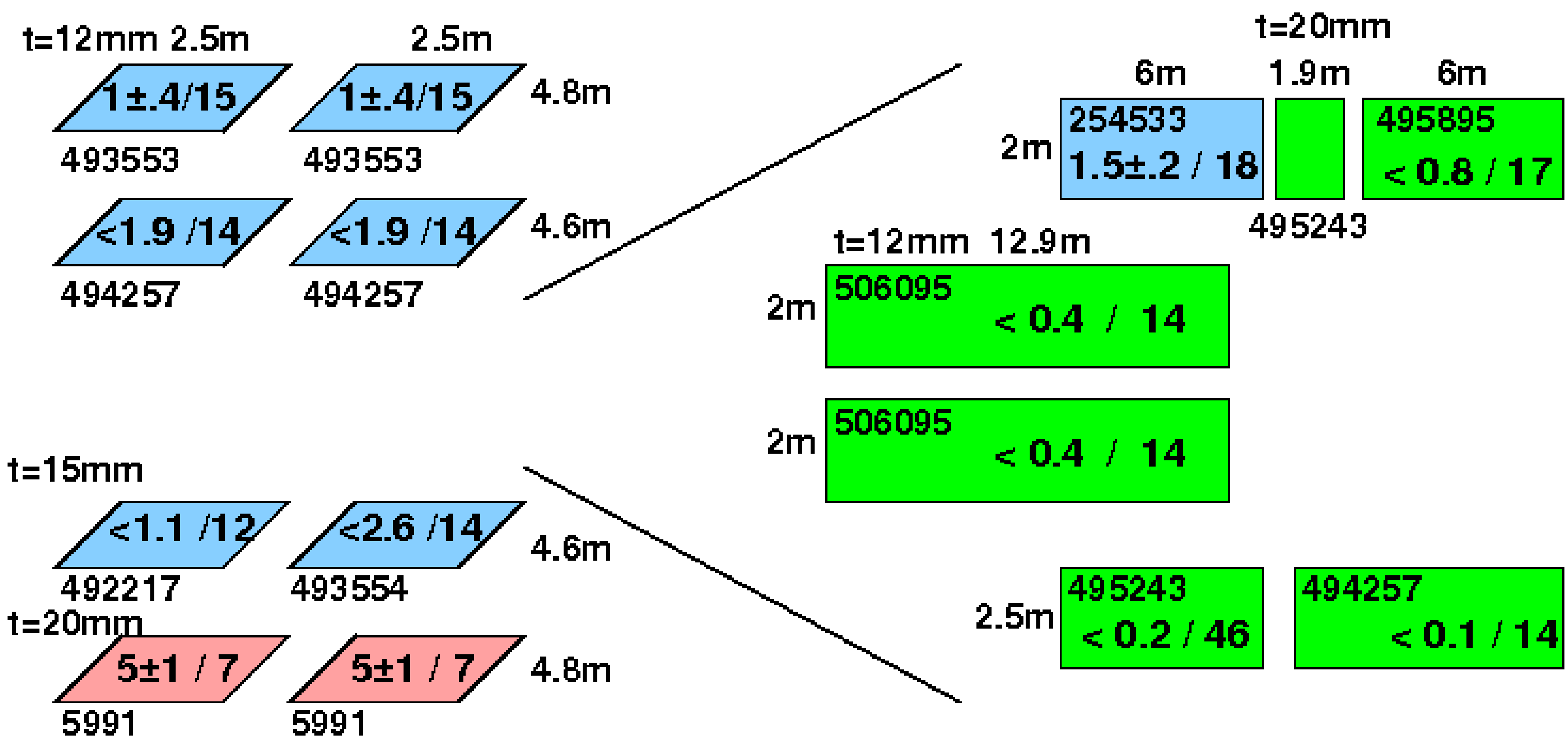
INFN LNGS, JINR Dubna, MPI Kernphysik Heidelberg, Jagellonian U. Cracow, U. Milano-Bicocca, INR Moscow, ITEP Moscow, Kurchatov Institute, MPI Physik München, U. Padova, U. Tübingen, IRMM Geel, TU Dresden, U.Zürich

Stainless Steel Cryostat

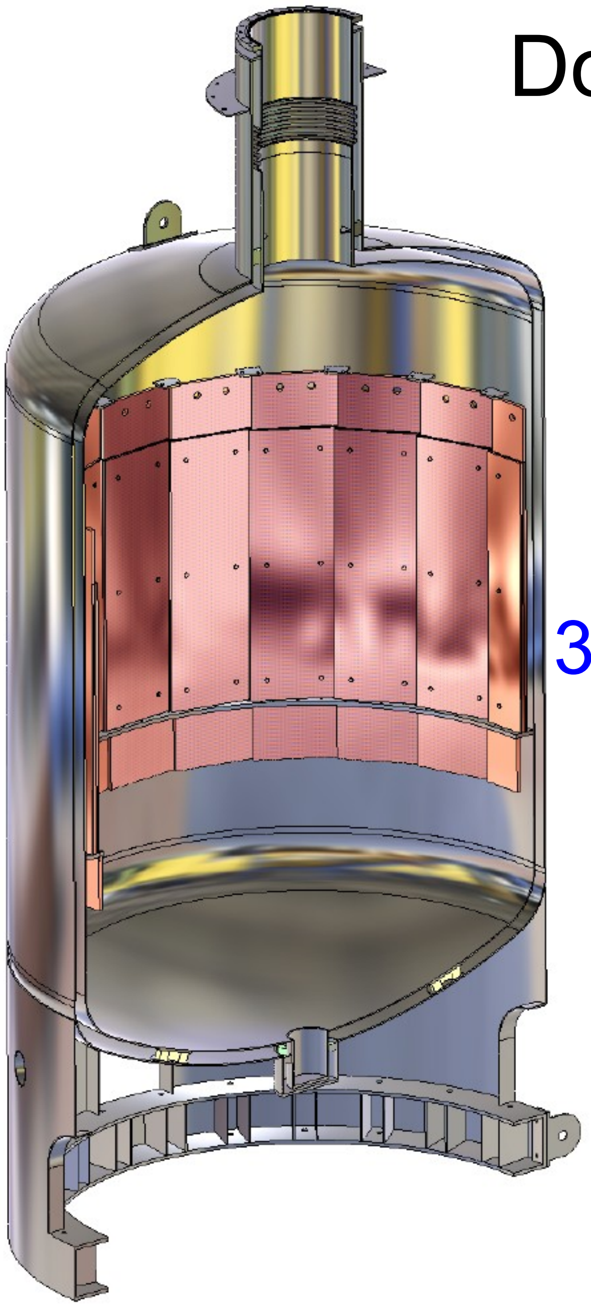
screening of SS sheets from different producers

(~ 27 tons of SS 1.4571)

units: mBq/kg for ^{228}Th and ^{60}Co



Stainless Steel Cryostat



Double walled SS container

reduce Cu shield from 40 to 16 t
(1t ~ 8000 €)

3 – 6cm Cu

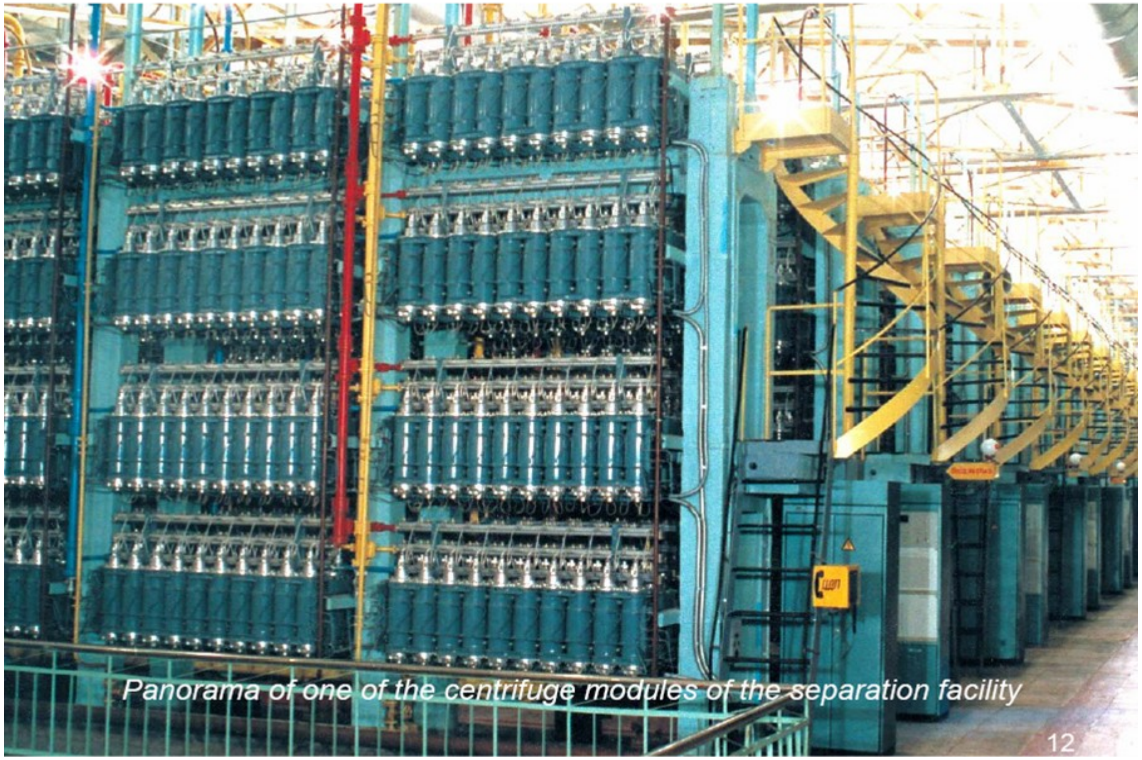
P. Grabmayr

MERRY CHRISTMAS and A HAPPY NEW YEAR

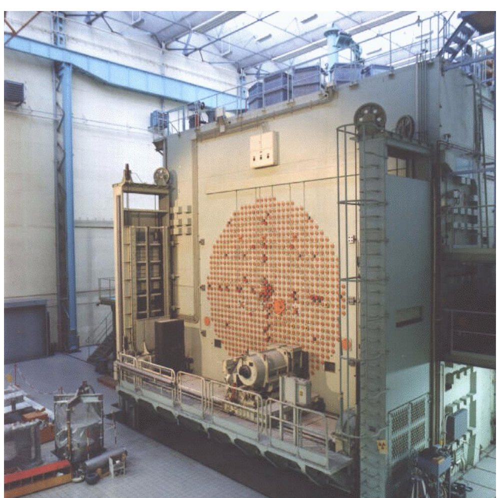
to all members of the GERDA collaboration
Tasso

Packaging is continuing but will be not ready for Xmas ...

Enrichment and Transport



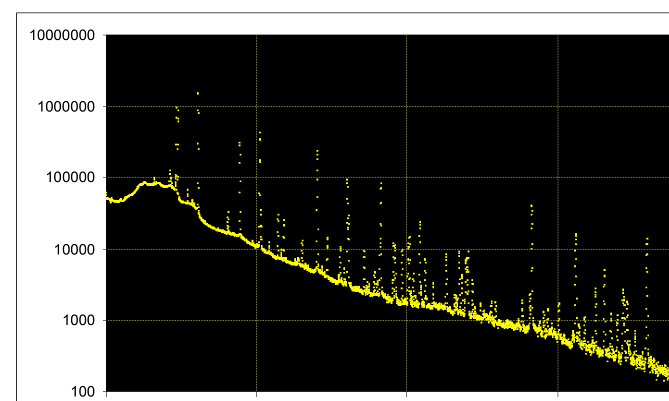
Krasnoyarsk (~Baykal)
37.5 kg enriched GeO_2



Geel, n activation

precise determination of abundance

zone refinement tested on depleted Ge

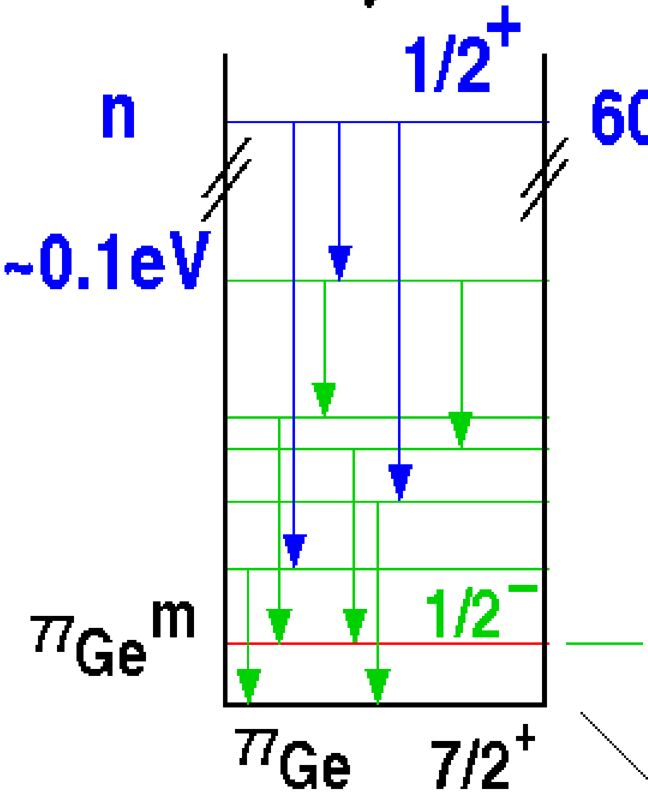


n-capture on ^{76}Ge @ FRM-II

$^{76}Ge(n,\gamma)\,^{77}Ge$

σ = 10/100/140 mb

E_γ=2037.76 keV



36% known
out off >200%

$Ge^{76}(n,\gamma)Ge^{77m} \xrightarrow[\text{54 sec}]{\beta} As^{77}$

I.T. 54 sec

$Ge^{76}(n,\gamma)Ge^{77} \xrightarrow[\text{11.3 hr}]{\beta^-} As^{77} \xrightarrow[\text{39 hr}]{\beta^-} Se^{77}$

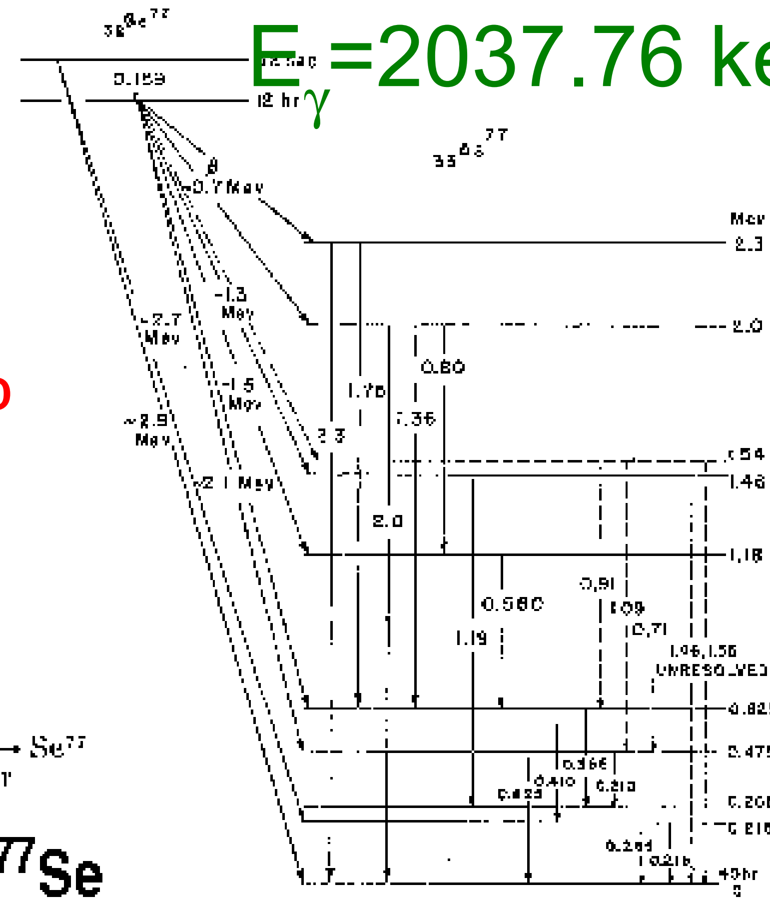


Fig. 6. Decay scheme of $_{32}Ge^{77}$.

$^{77}Ge \xrightarrow{\beta} {}^{77}As \xrightarrow{\beta} {}^{77}Se$

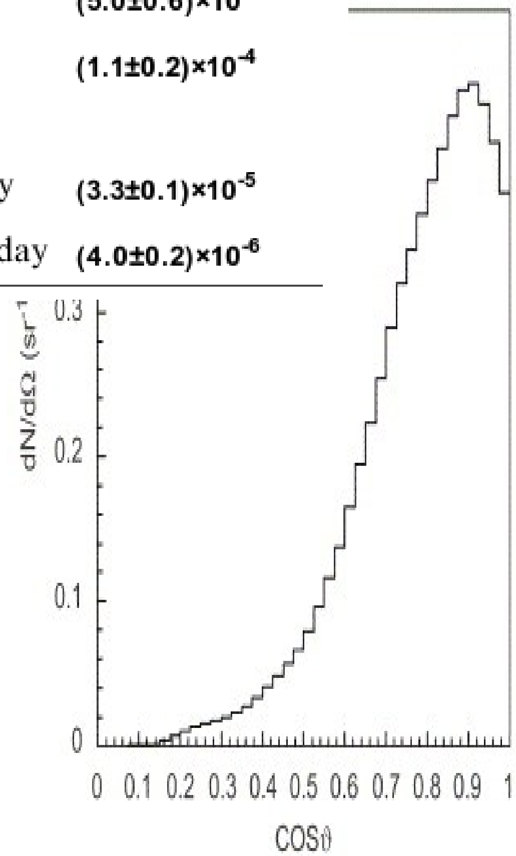
Q_β = 2703 690 keV

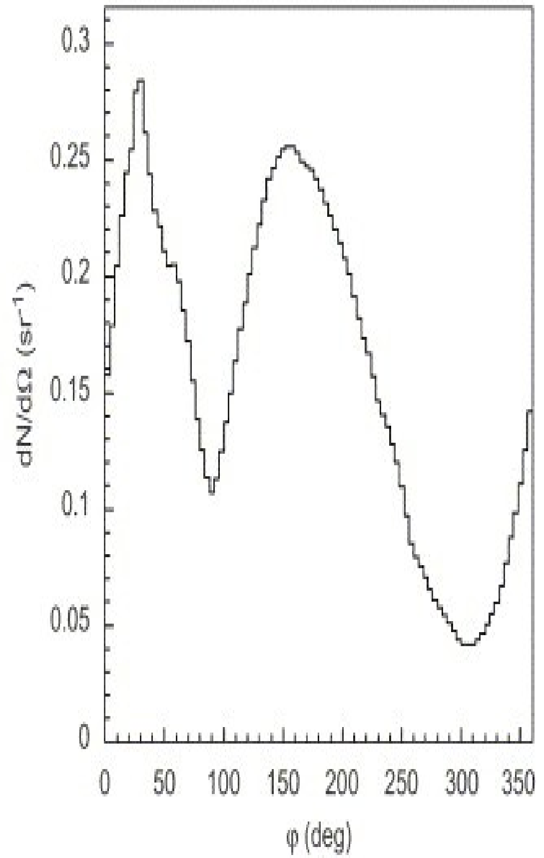
G. Meierhofer

Muon induced backgrond

Muon-induced isotope production

	Nitrogen		Argon	
	nuclei/(kg y)	counts/(kg keV y)	nuclei/(kg y)	counts/(kg keV y)
Isotopes produced in crystals				
^{74}Ga/^{75}Ga/^{76}Ga	<0.08	$<3\times10^{-5}$	<0.1	$<4\times10^{-5}$
^{68}Ge	0.07±0.03	$(4\pm2)\times10^{-6}$	0.08±0.03	$(5\pm2)\times10^{-6}$
^{69}Ge	0.38±0.08	$(1.0\pm0.2)\times10^{-6}$	1.8±0.2	$(5.0\pm0.6)\times10^{-6}$
^{77}Ge/^{77m}Ge	0.05±0.03	$(1.0\pm0.6)\times10^{-5}$	0.51±0.09	$(1.1\pm0.2)\times10^{-4}$
Isotopes produced in cryogenic liquid				
^{38}Cl	–	–	46 ± 1 nucl/day	$(3.3\pm0.1)\times10^{-5}$
^{40}Cl	–	–	2.7 ± 0.1 nucl/day	$(4.0\pm0.2)\times10^{-6}$

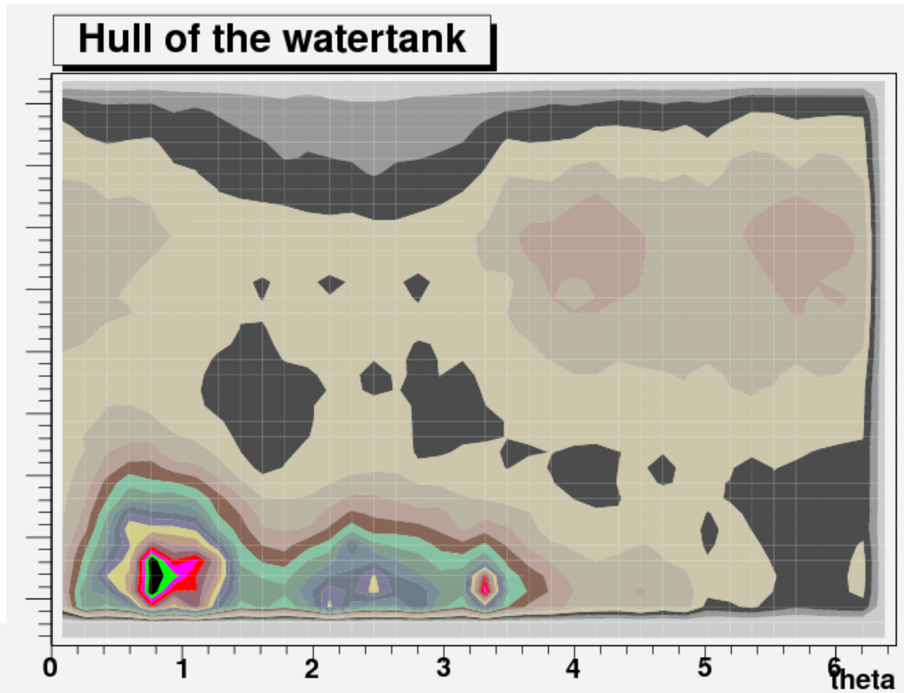


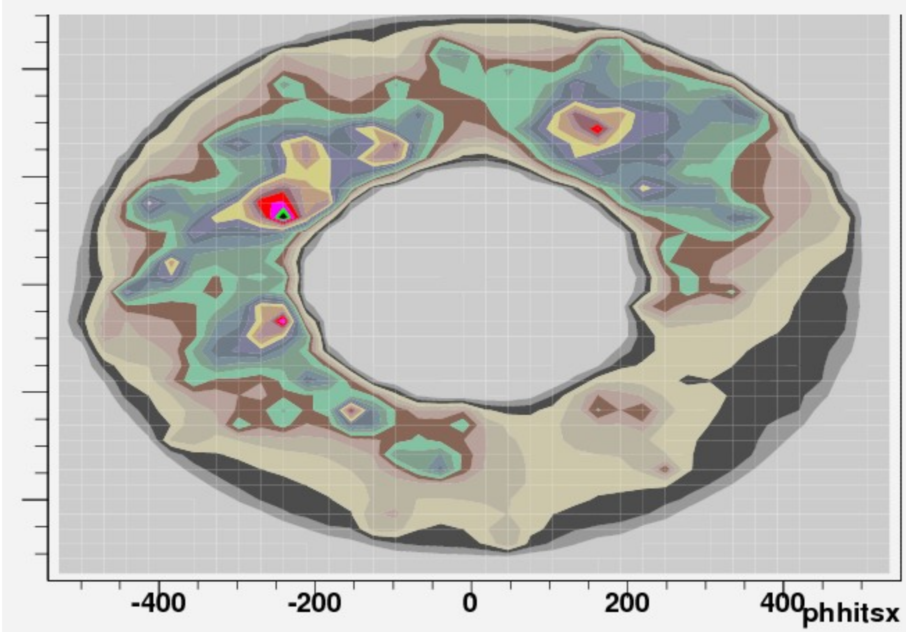


Muon veto necessary

$E_\mu \sim 250$ GeV

Water Cerenkov veto



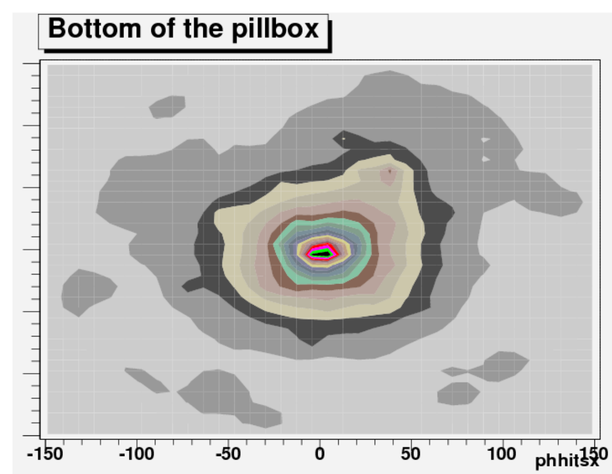


66 PMTs (ETL, 8")

VM2000

(3M,WLS+reflector)

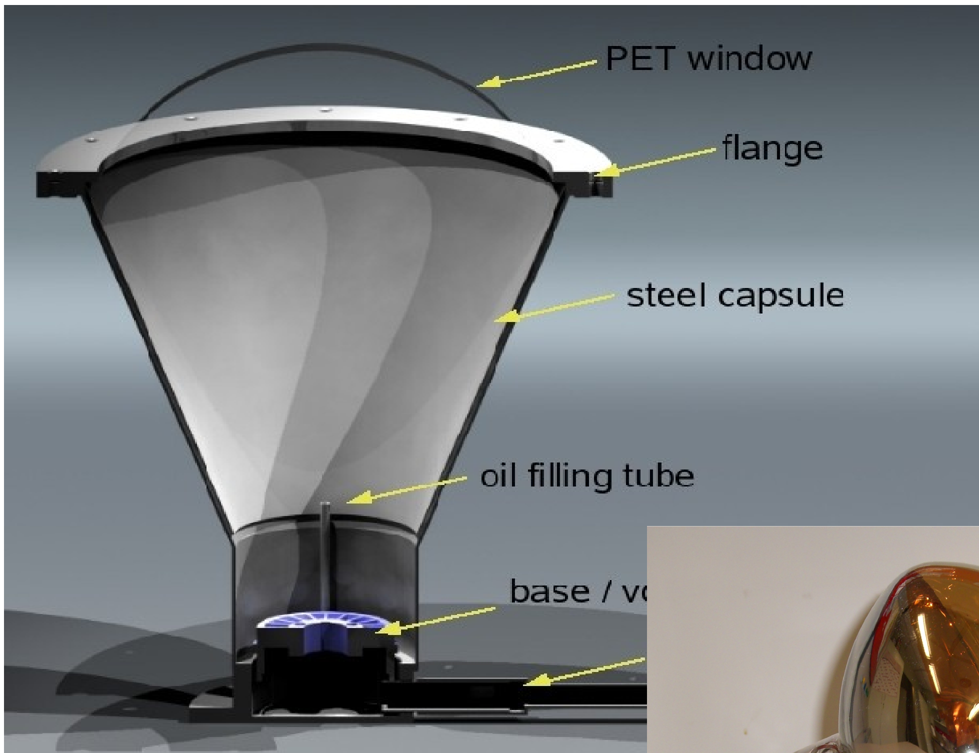
3PMT @ 0,5 pe ~99%



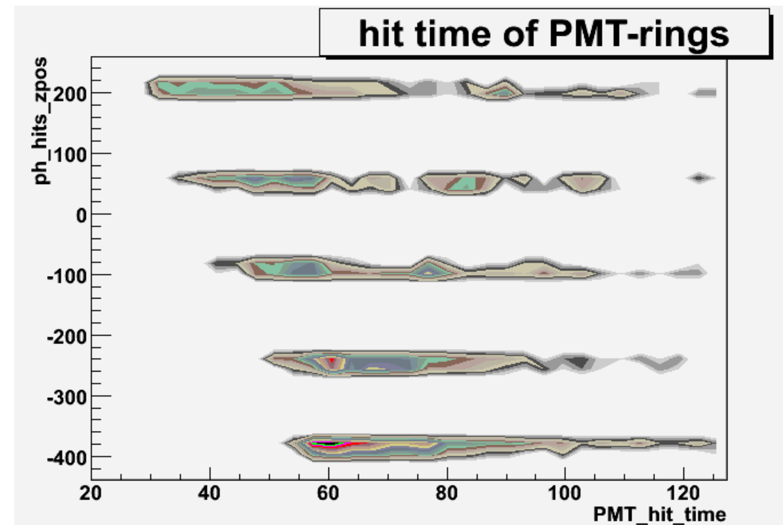
M. Knapp
F. Ritter

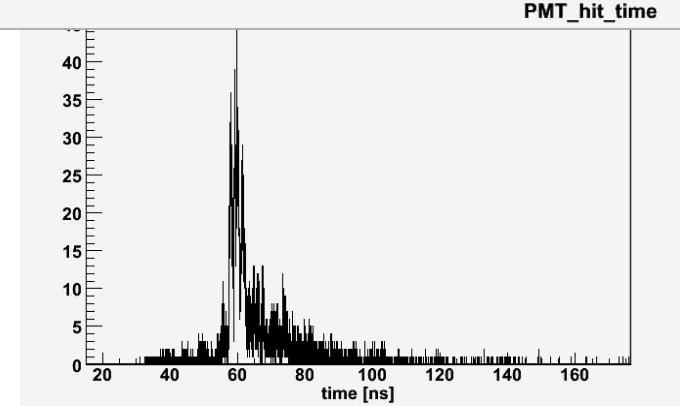
Cerenkov veto

ETL 8" inside capsule with oil



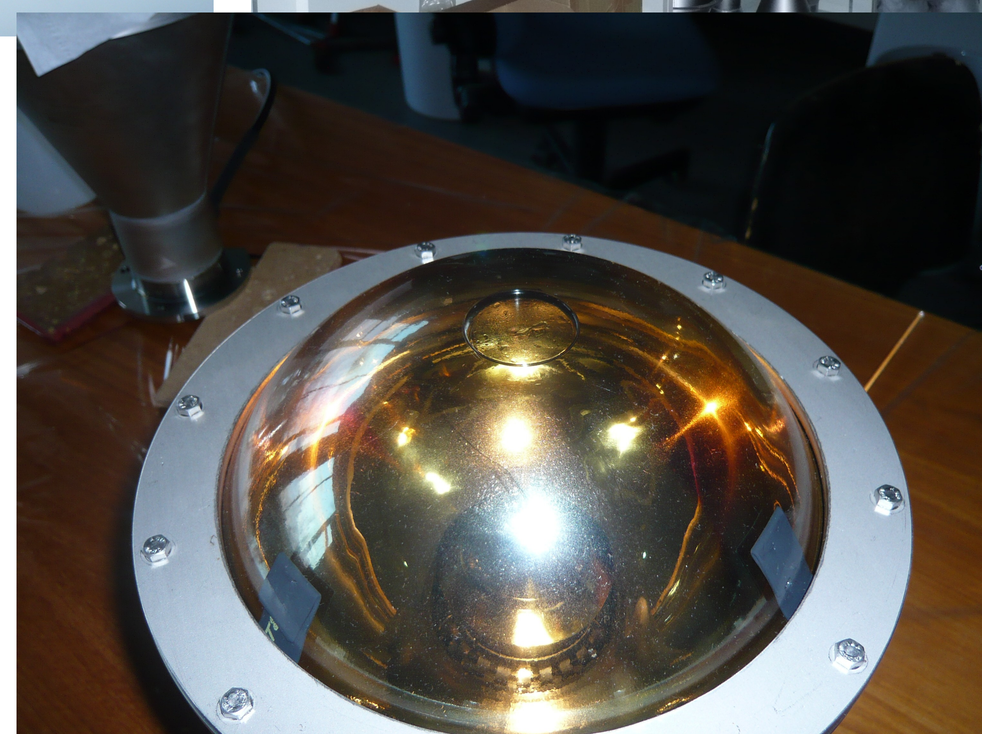
4 rings on wall
+ 2 rings on bottom
+ pillbox





+2mm μ metal-shield

production of ~70 PMT capsules



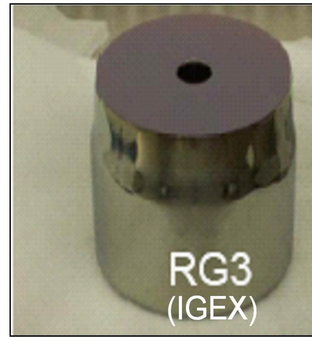
All HDM & IGEX detectors

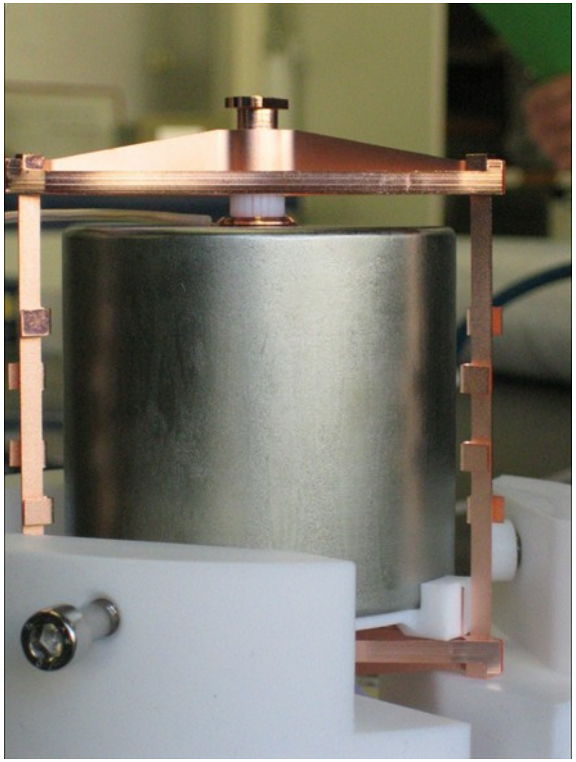
18.7 kg

86% ^{76}Ge

Refurbishing Ge diodes in GDL

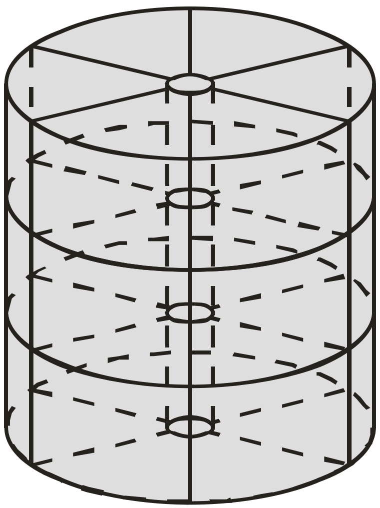
GDL: Installation of clean room
for diode preparation
and tests in LAr





segmentation

Discriminate e/γ by event type: single- or multi-site



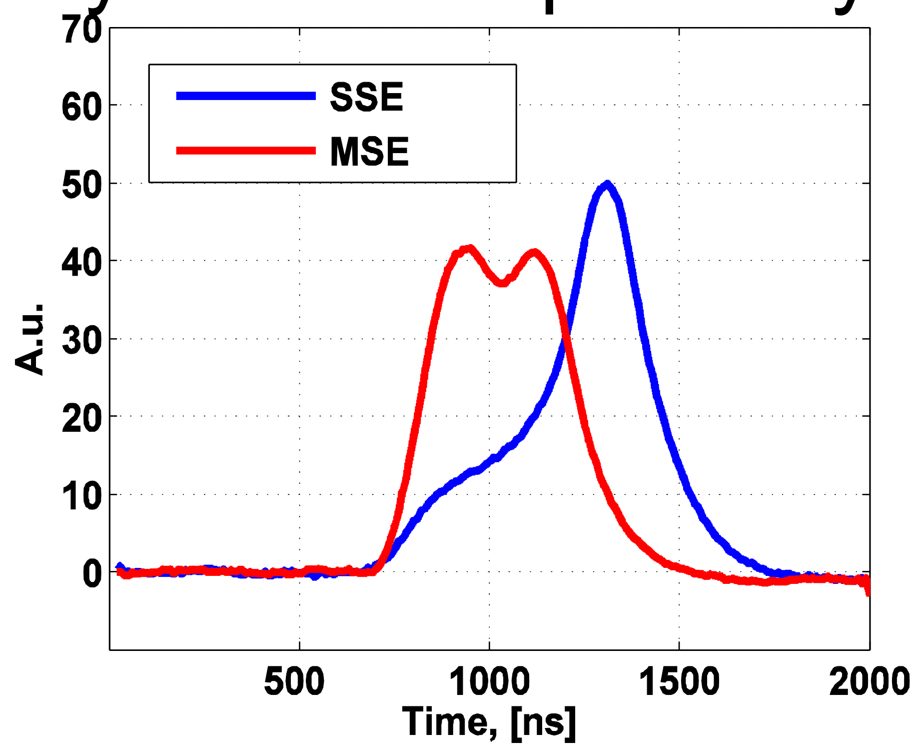
by anti-coincidence between diodes

Range of β ~ mm

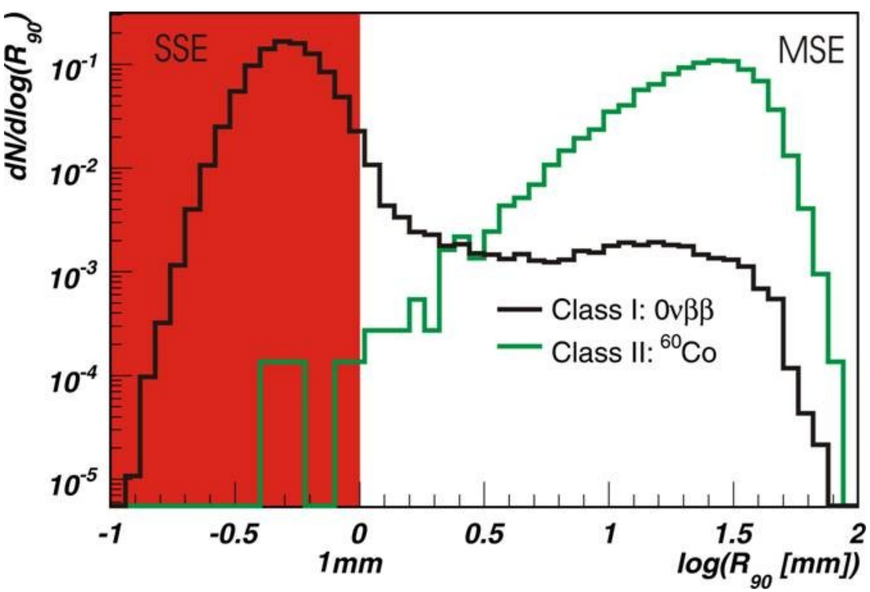
& segments

(6x3 fold)

by Pulse Shape Analysis

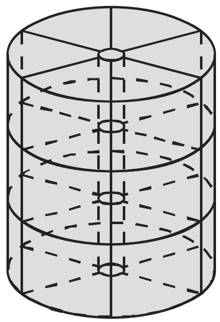


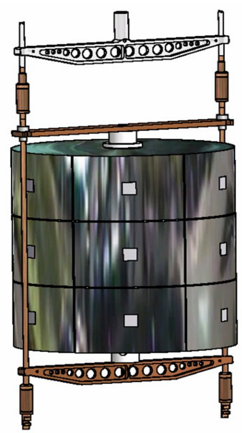
I.Abt et al., NIM A570 (2007) 479

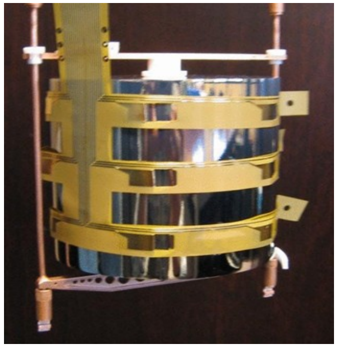


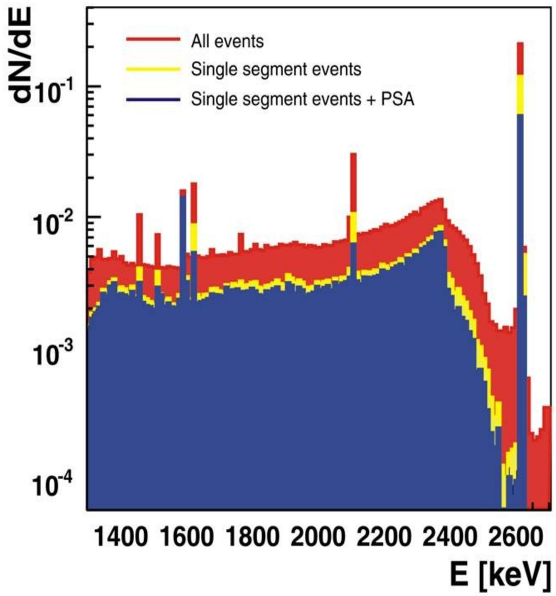
Segmentation

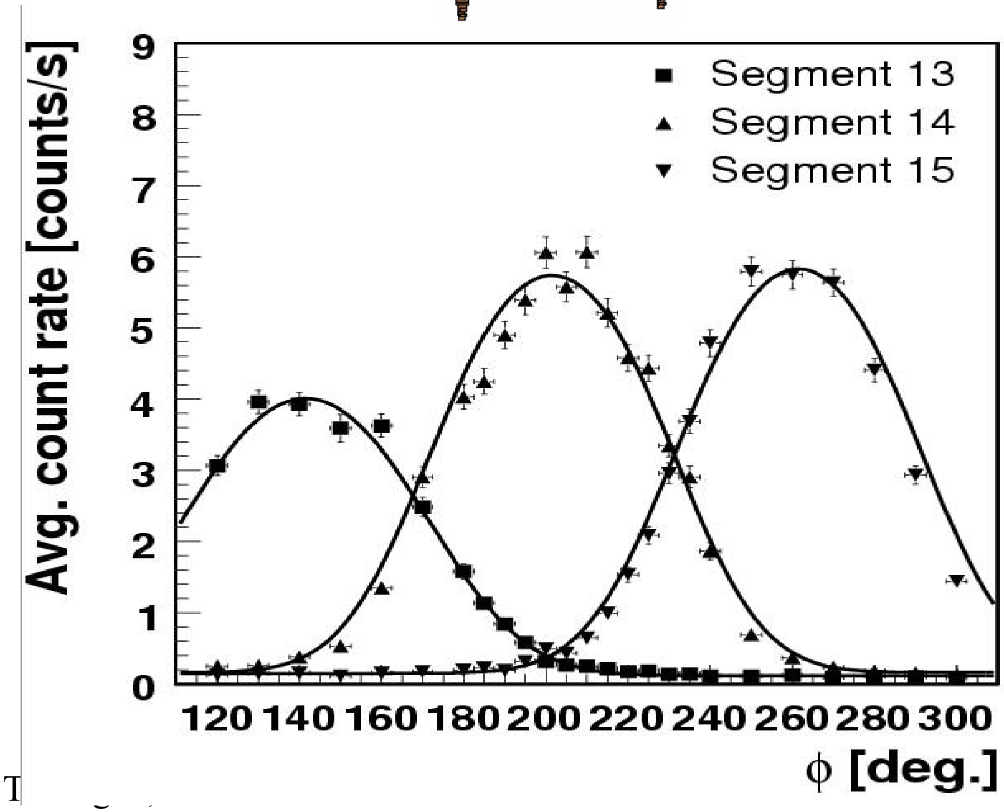
I. Abt et al., NIM A accepted

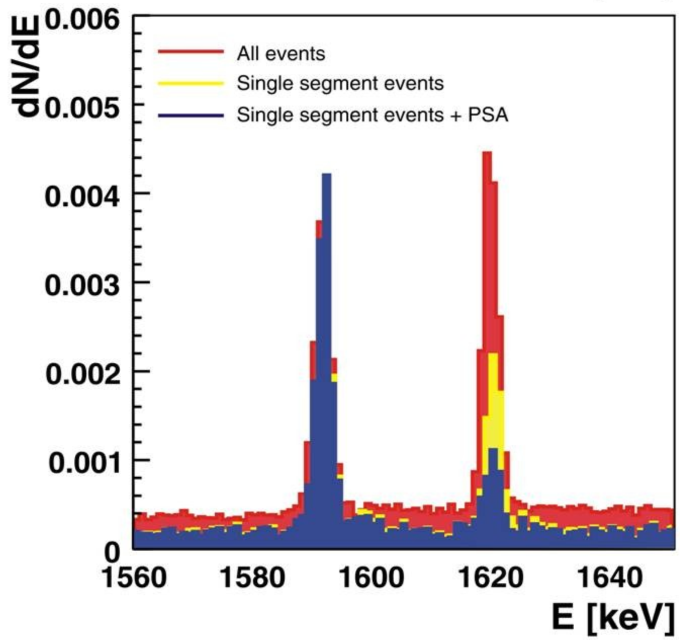










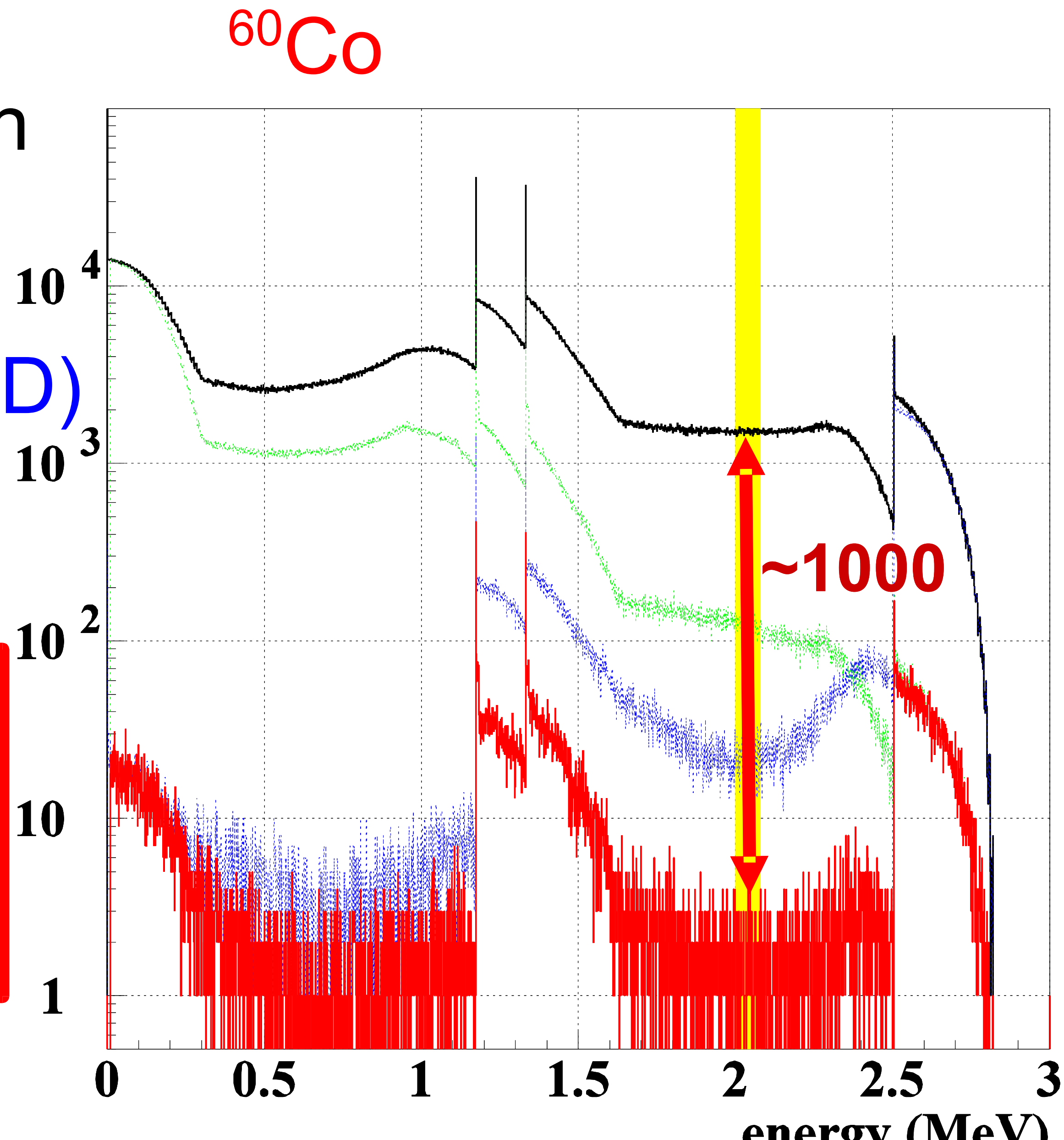


Veto through scintillation in LAr

MC simulation of background reduction through
segmentation and
scintillation in LAr (R&D)
and the combination of both methods.

factor 1000

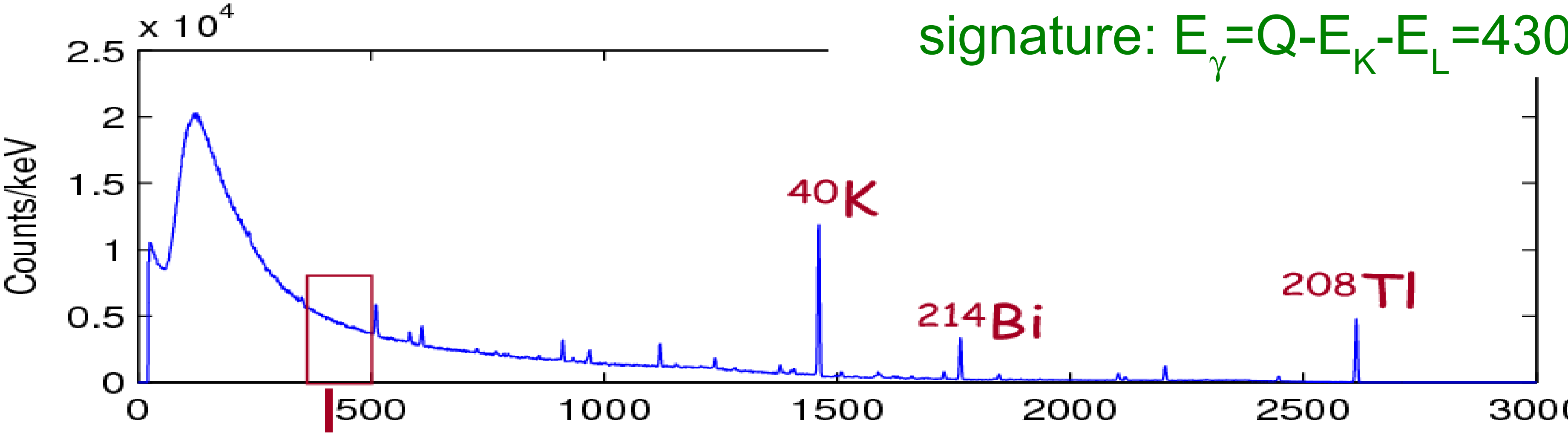
in ROI @ 2039 keV

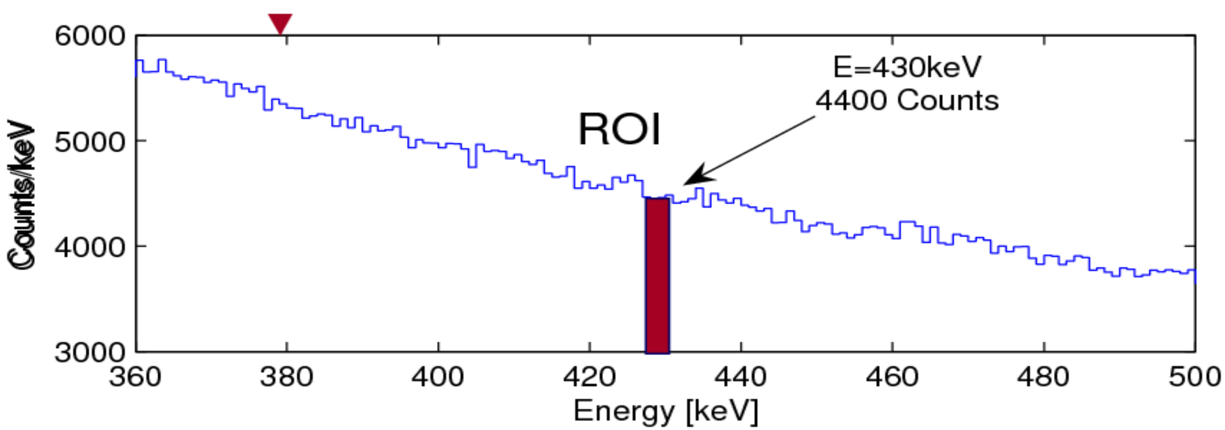


Physics results in GDL

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]

Schedule and Outlook

GERDA was constituted in 2004
~80 persons, 39 FTE in 17 institutions

Refurbishment of Hall A complete

Safety concept accepted by LNGS

Watertank & Cryostat ordered in 2006
installation by spring 2008
(to be) complete in early 2009

Muon Veto: PMT capsules being mass produced

Lock, clean room and infrastructure being tendered

Prototypes of preamps and cables
available for Phase I
prototyping for Phase II

DAQ & slow control

Schedule and Outlook

detectors:

Phase I

enriched detectors (HDM & IGEX)

presently being refurbished (18.7 kg)

15 kg non enriched detectors available

Phase II

37.5 kg enriched GeO_2 procured

segmented prototype successfully tested

zone refinement for first 'depleted detector'

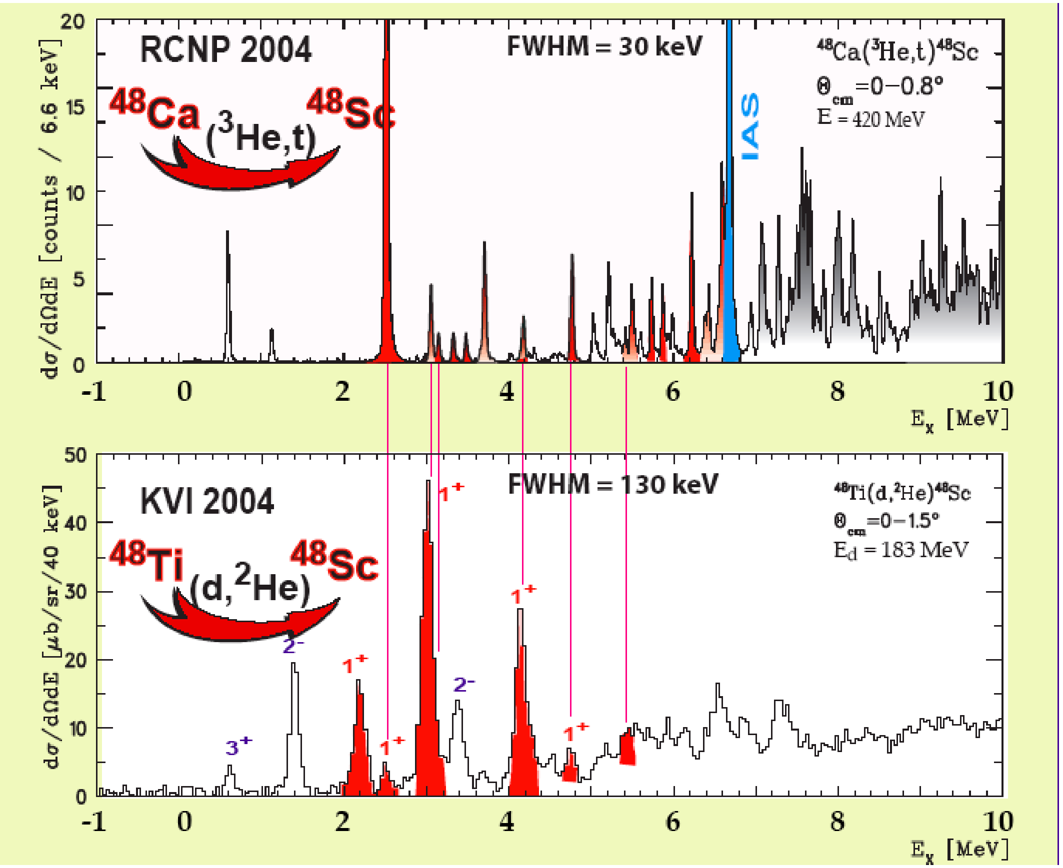
Charge exchange reactions

2νββ: Only intermediate 1^+ states contribute

Supportive measurements from accelerators

Done for ^{48}Ca and ^{116}Cd
more needed

D. Frekkers, K. Zuber



Currently: (d,^{2}He) and (^{3}He,t)

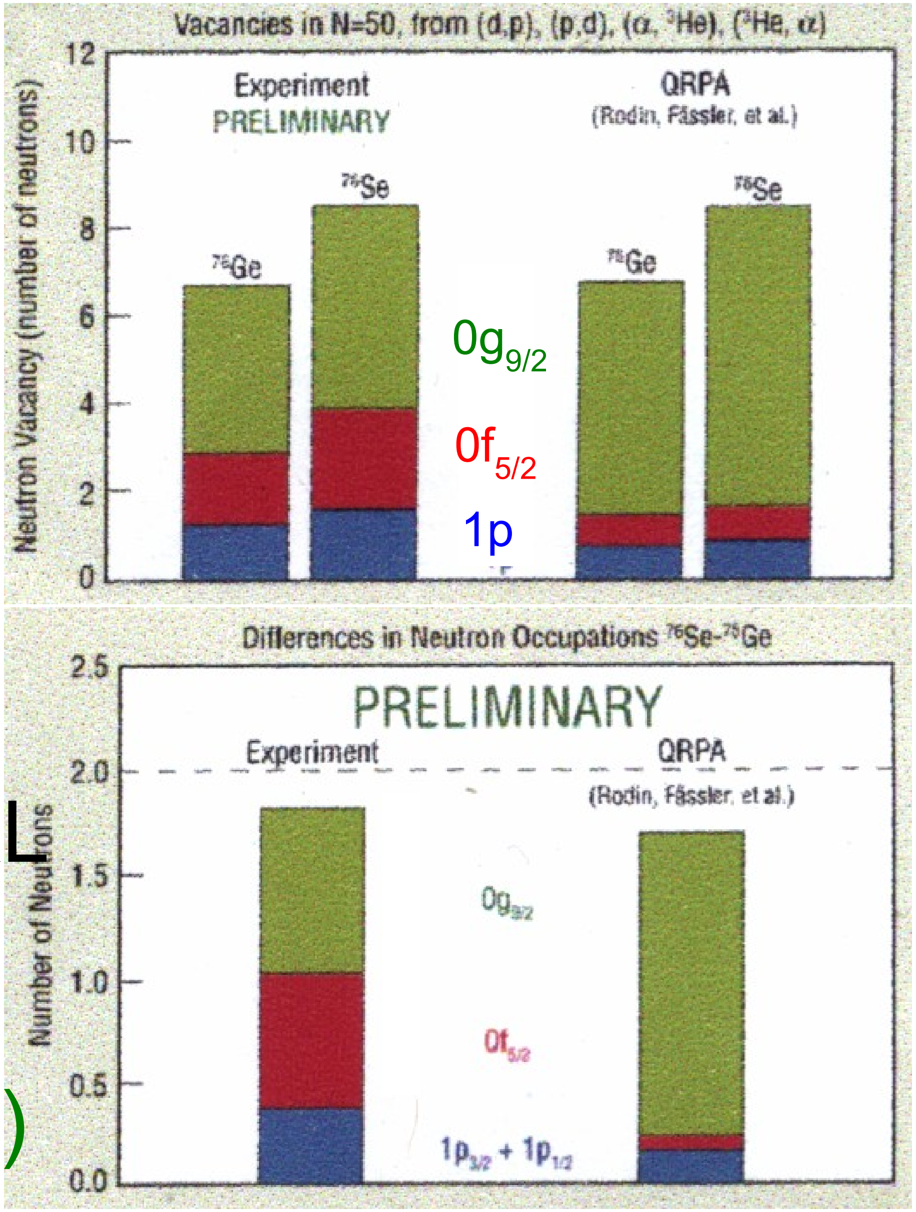
better resolution than (n,p) or (p,n)

Testing nuclear structure for 2β0ν

(d,p) & (p,d) reactions to measure neutron valence occupation and vacancy

$2J+1 = \Sigma^- C^2S^- + \Sigma^+ C^2S^+$

SM vacancy for valence:
6 & 8 for N=50
difference: ^{76}Ge – ^{76}Se = 2
exp.: J.P. Schiffer et al.,PRL
theo: V. Rodin et al.



measured (d,^{3}He) and (^{3}He,d) in Dec. 2007 @ RCNP

Outlook

Ge has $Q_{\beta\beta}$ < 2610 keV from ^{208}Tl

Ge expts. have lowest background

and highest resolution

GERDA and Cuoricino most advanced in setup

GERDA setup well under way

additional physics output

Majorana is planning a demonstrator for 1t

meanwhile: first limit for 0νECEC on ^{36}Ar

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

Outlook

Finish setup by end of 2008

verify background level of
$< 10^{-2}$ cts/(kg·y·keV)
for Phase I

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