GERDA:
The GERmanium Detector Array for the search for neutrinoless ββ decays of ^{76}Ge

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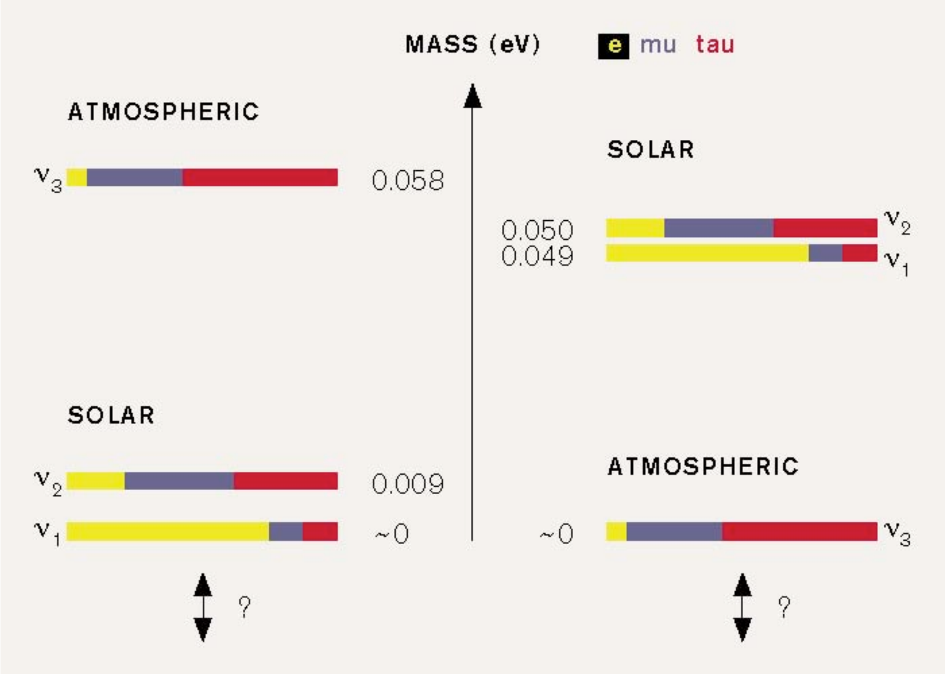
What we know

NORMAL INVERTED

Mass Scale



Δm_{12}^2 known

$|\Delta m_{13}^2|$ known

Mixing Matrix

U_{ij} can be characterized by three mixing angles, Θ_{12}, Θ_{23}, Θ_{13},
one Dirac CP phase, δ,
and two Majorana phases Φ_2, Φ_3

Θ_{12}, Θ_{23} measured, upper limit on Θ_{13}

Current (lack of) Understanding

What we do not know about neutrinos:

1. **absolute mass scale (offset)**
2. **mass hierarchy (1,2,3 or 3,1,2)**
3. **nature of neutrino (Majorana, Dirac particle)**
4. **value of third mixing angle (Θ_{13})**
5. **CP phases (δ, Φ_2, Φ_3)**

Double beta decay experiment can address 3, and, if neutrinos are Majorana particles, then also a combination of 1,2,5

Majorana vs Dirac

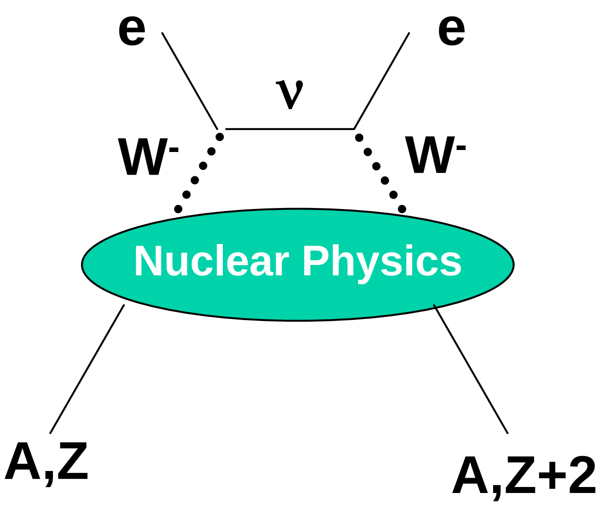
How can we test if neutrinos are Dirac or Majorana particles ?

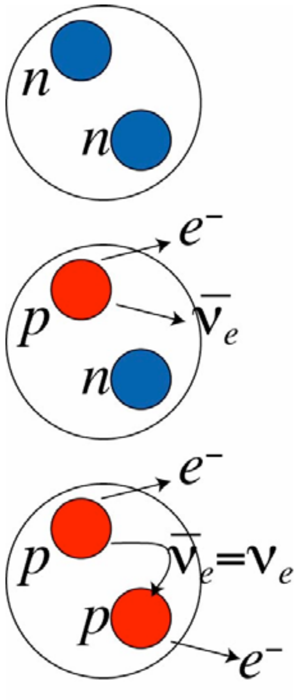
Experimental Problem:

$$P(\nu_L \rightarrow \nu_R) \propto \left(\frac{m_\nu}{E_\nu}\right)^2$$

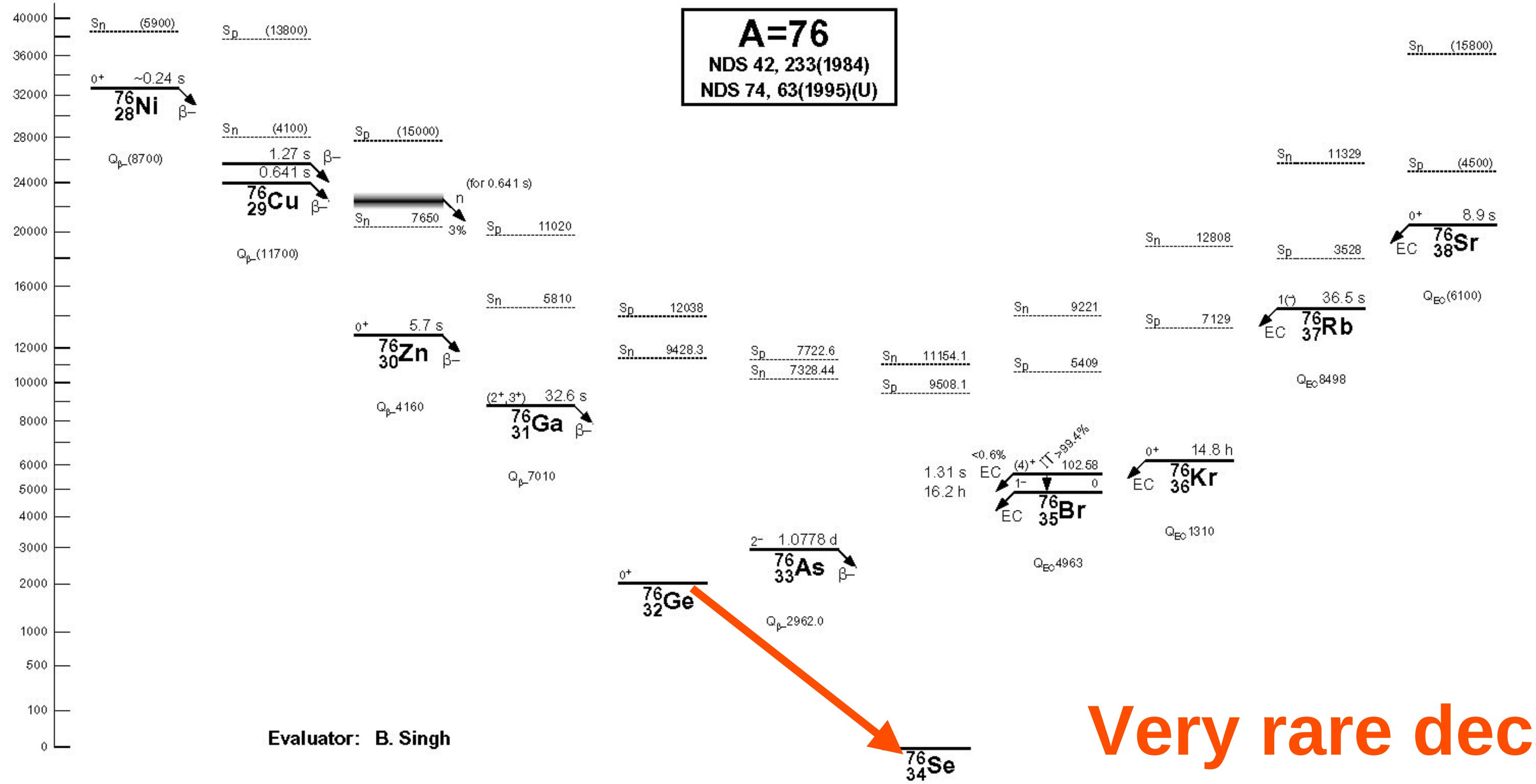
m ≤ eV, E MeV or more

Only known technique is neutrinoless double beta decay:





Double Beta Decay



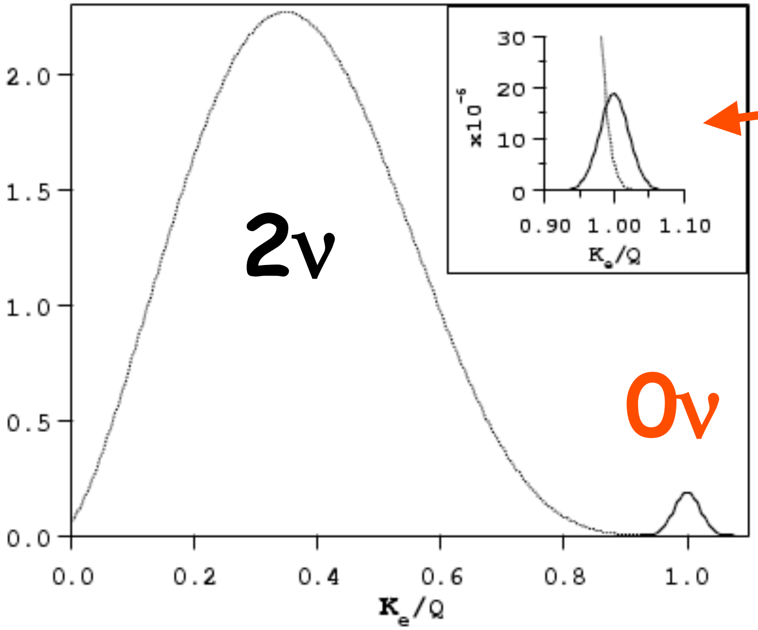
Very rare decay lifetimes $>10^{20}$ years !

$(A,Z) \rightarrow (A,Z+1)+e+\nu$ energetically forbidden
$(A,Z) \rightarrow (A,Z+2)+2e+2\nu$ is allowed.
Then, for Majorana particle $(A,Z) \rightarrow (A,Z+2)+2e$ possible

Note: process would violate lepton number conservation !

Decay Rate & Spectrum

Normalized energy spectrum



If resolution poor

If resolution good

0ν-DBD rate

Phase space $\propto Q^5$

Nuclear matrix element

Effective Majorana mass

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

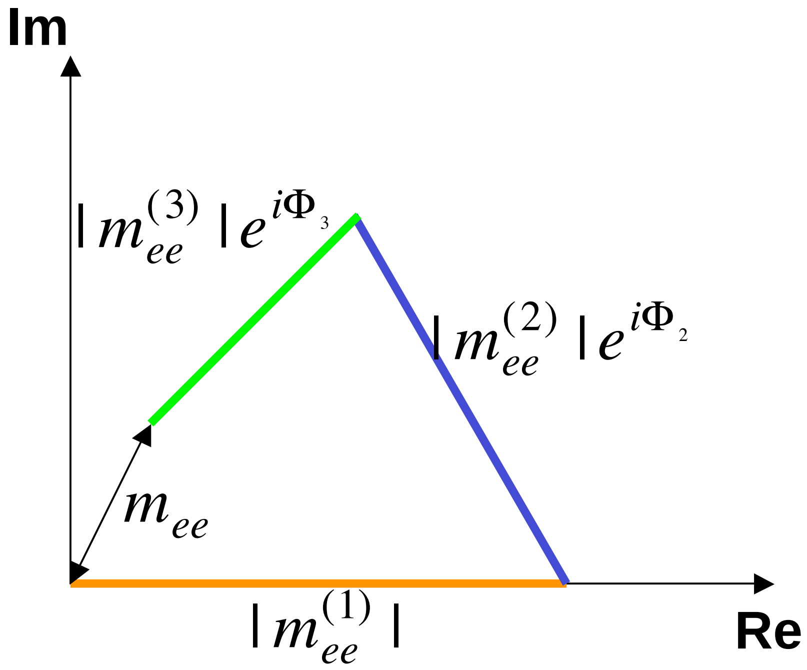
Effective Neutrino Mass

$$m_{ee} = |m_{ee}^{(1)}| + e^{i\Phi_2}\,|m_{ee}^{(2)}| + e^{i\Phi_3}\,|m_{ee}^{(3)}|$$

$$|m_{ee}^{(1)}| = |U_{e1}|^2\, m_1$$

$$|m_{ee}^{(2)}| = |U_{e2}|^2 \sqrt{m_1^2 + \Delta m_{21}^2}$$

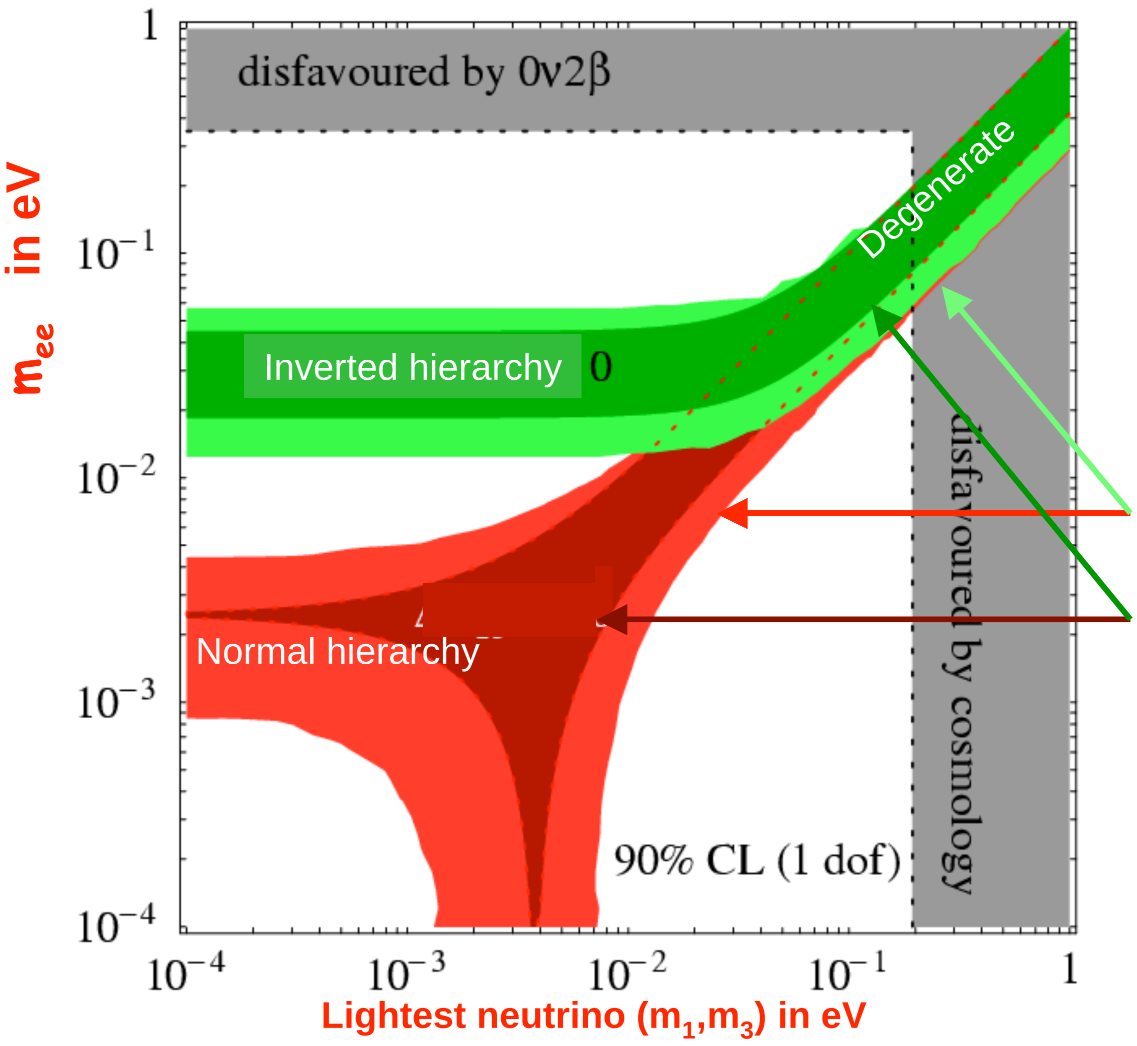
$$|m_{ee}^{(3)}| = |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2}$$



Complicated relationship between effective mass in neutrinoless double beta decay and neutrino masses, mixing angles and phases

Cancellation possible: m$_{ee}$ could be vanishingly small ☹

Effective Neutrino Mass

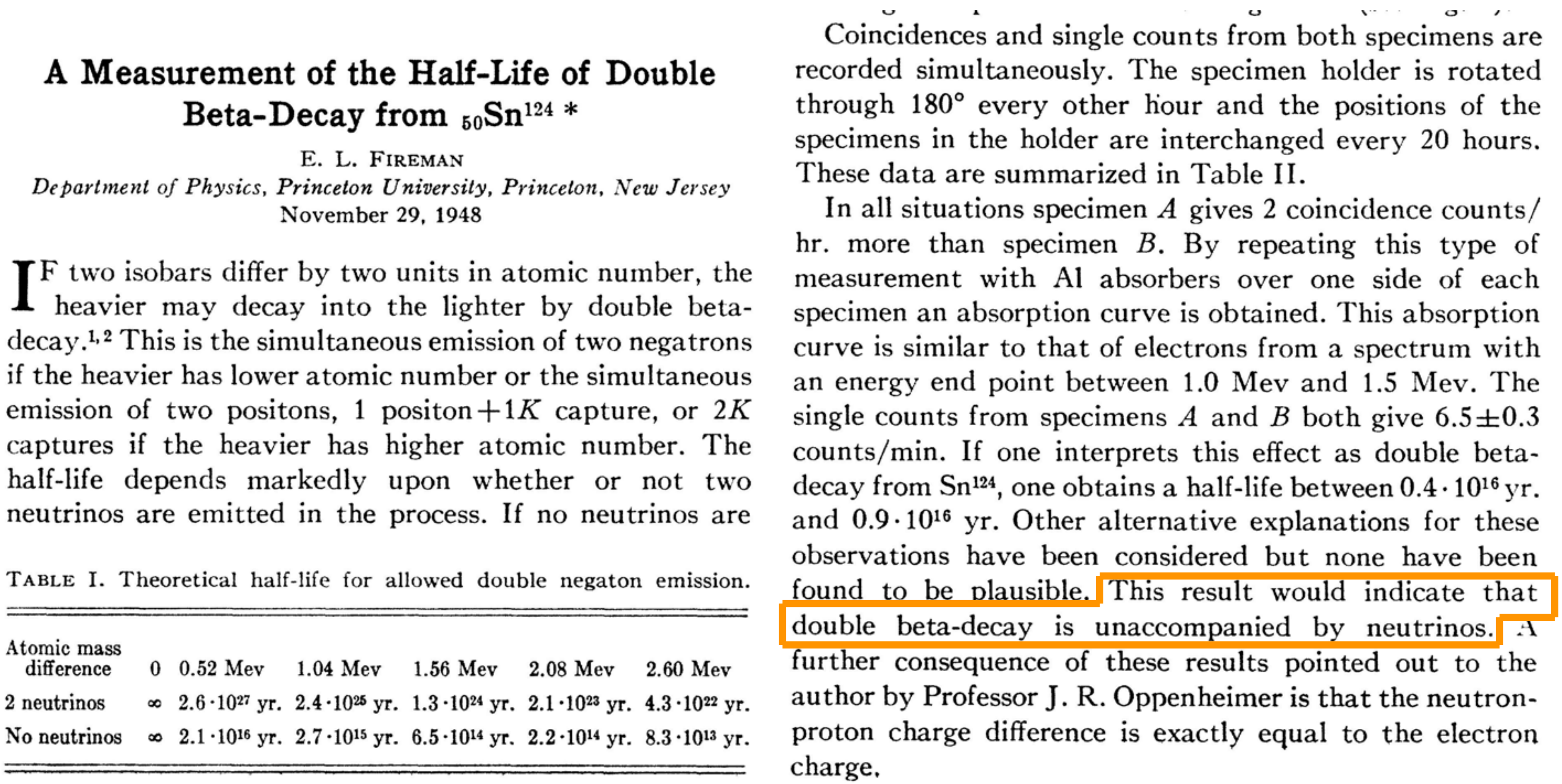


F.Feruglio,
A. Strumia,
F. Vissani,
NPB 637

90% CL

Negligible errors from oscillations; width due to CP phases

0ν DBD Claims



A Measurement of the Half-Life of Double Beta-Decay from $_{50}\mathrm{Sn}^{124}$ *

E. L. Fireman

Department of Physics, Princeton University, Princeton, New Jersey

November 29, 1948

IF two isobars differ by two units in atomic number, the heavier may decay into the lighter by double beta-decay.[1,2] This is the simultaneous emission of two negatrons if the heavier has lower atomic number or the simultaneous emission of two positons, 1 positon+1K capture, or 2K captures if the heavier has higher atomic number. The half-life depends markedly upon whether or not two neutrinos are emitted in the process. If no neutrinos are

Table I. Theoretical half-life for allowed double negaton emission.

Atomic mass difference	0	0.52 Mev	1.04 Mev	1.56 Mev	2.08 Mev	2.60 Mev
2 neutrinos	∞	$2.6\cdot10^{27}$ yr.	$2.4\cdot10^{25}$ yr.	$1.3\cdot10^{24}$ yr.	$2.1\cdot10^{23}$ yr.	$4.3\cdot10^{22}$ yr.
No neutrinos	∞	$2.1\cdot10^{16}$ yr.	$2.7\cdot10^{15}$ yr.	$6.5\cdot10^{14}$ yr.	$2.2\cdot10^{14}$ yr.	$8.3\cdot10^{13}$ yr.

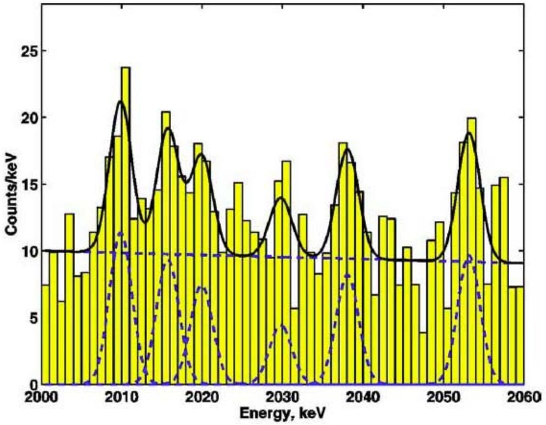
Coincidences and single counts from both specimens are recorded simultaneously. The specimen holder is rotated through 180° every other hour and the positions of the specimens in the holder are interchanged every 20 hours. These data are summarized in Table II.

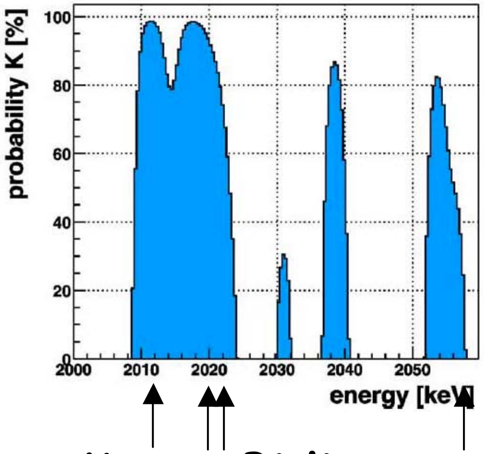
In all situations specimen A gives 2 coincidence counts/hr. more than specimen B. By repeating this type of measurement with Al absorbers over one side of each specimen an absorption curve is obtained. This absorption curve is similar to that of electrons from a spectrum with an energy end point between 1.0 Mev and 1.5 Mev. The single counts from specimens A and B both give 6.5 ± 0.3 counts/min. If one interprets this effect as double beta-decay from Sn^{124}, one obtains a half-life between $0.4\cdot10^{16}$ yr. and $0.9\cdot10^{16}$ yr. Other alternative explanations for these observations have been considered but none have been found to be plausible. This result would indicate that double beta-decay is unaccompanied by neutrinos. A further consequence of these results pointed out to the author by Professor J. R. Oppenheimer is that the neutron-proton charge difference is exactly equal to the electron charge.

Note: 0ν predicted to have shorter lifetime from phase space arguments

Positive result corresponds to $\langle m_{ee}\rangle \approx 30\ \mathrm{keV}$ **(my estimate)**

Heidelberg-Moscow Experiment





Known Bi lines

H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, A. Dietz, O. Chkvorets

Phys.Lett.B586:198-212,2004

- Experiment with Ge detectors enriched in ^{76}Ge
- Exposure 71.7 kg-yr
- Experiment carried out in Gran Sasso lab
- Background: 0.11/(keV kg yr)

Claim: 4.2σ signal

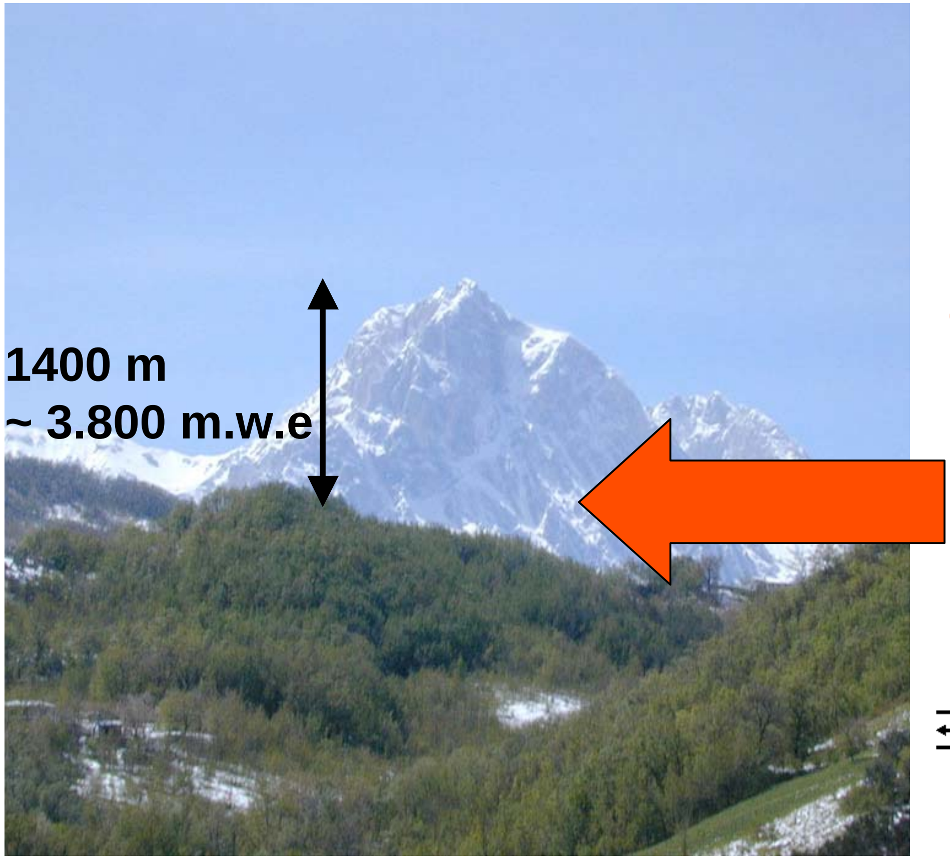
$T_{1/2}$=0.69-4.18 10^{25} yr

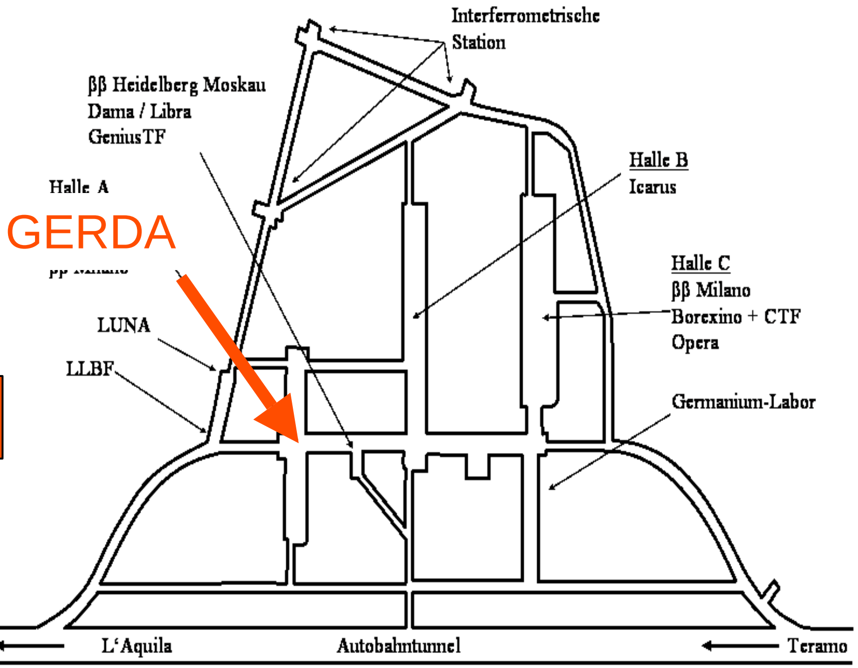
m_{ee}=440 meV (best fit) KK Matrix Element

m_{ee}≈700 meV Rodin et al. Matrix Element

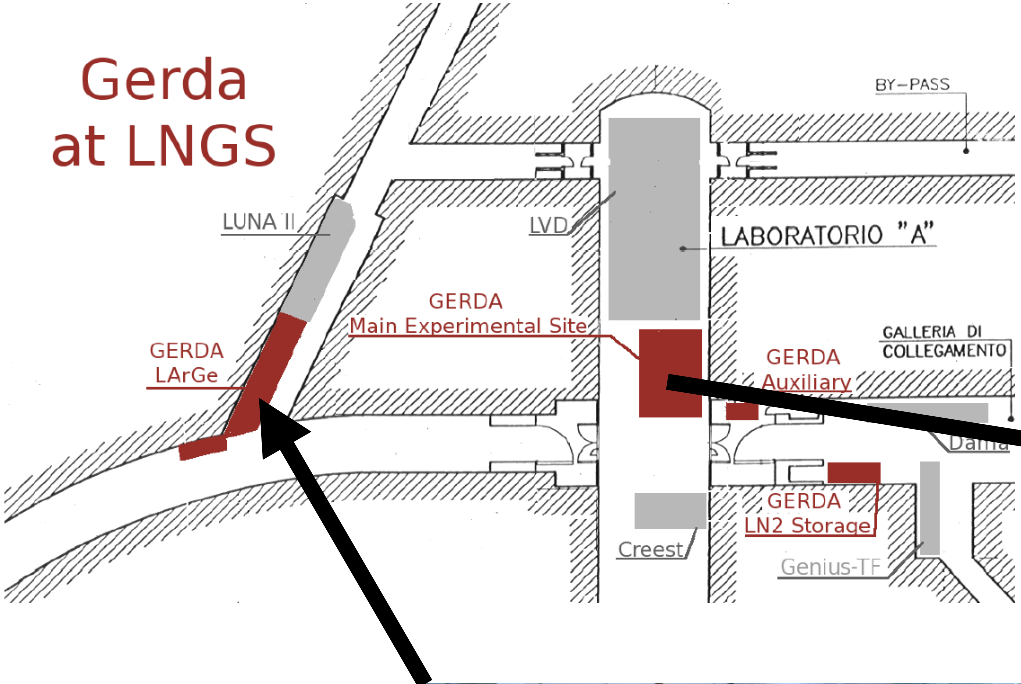
GERDA

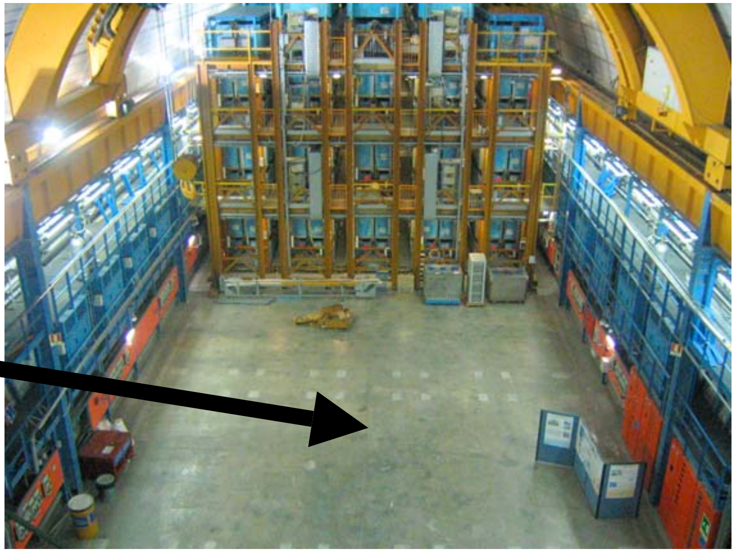
GERDA (GERmanium Detector Array) is a collaboration of 12 institutes, ca. 80 physicists, from Germany, Italy, Russia, Poland, Belgium.
The experiment has been approved by the LNGS (Gran Sasso)





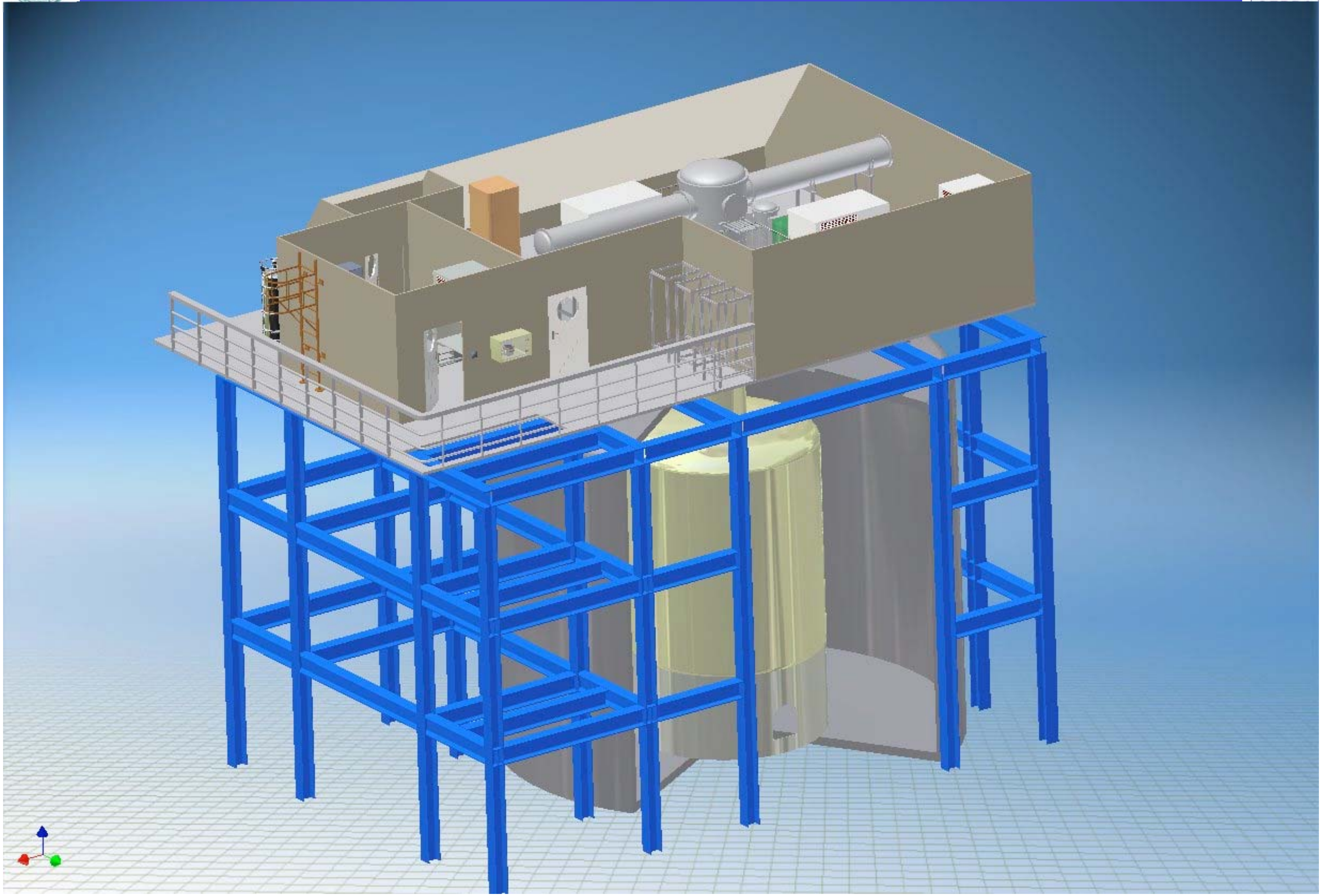
GERDA Locations





Underground detector laboratory (LArGe-facility)

GERDA



Proposed & Ongoing Experiments

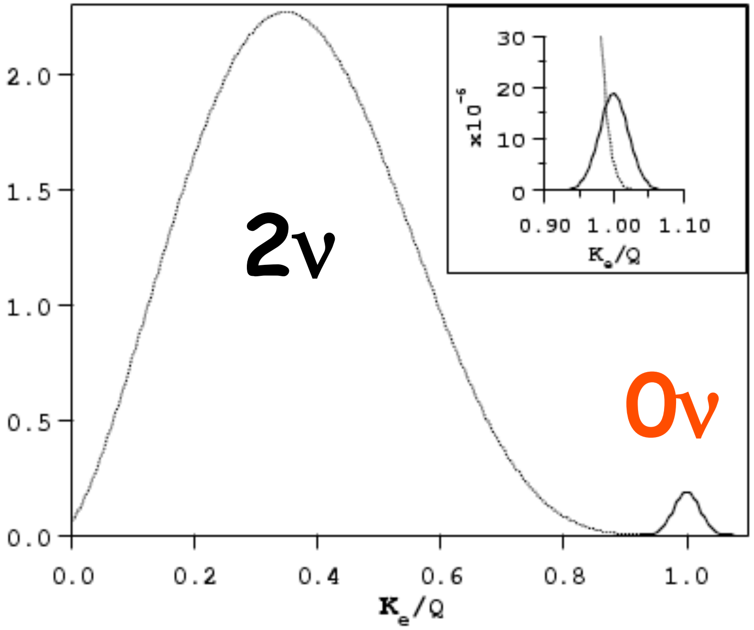
Some of the possible isotopes

Decay	Q(keV)	Nat. Abundance	Experiments
$^{48}\mathrm{Ca} \rightarrow {}^{48}\mathrm{Ti}$	4271	0.2%	CANDLES
$^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se}$	2039	7.4%	**GERDA,Majorana**
$^{82}\mathrm{Se} \rightarrow {}^{82}\mathrm{Kr}$	2995	8.4%	**NEMO**
$^{96}\mathrm{Zr} \rightarrow {}^{96}\mathrm{Mo}$	3350	2.8%	
$^{100}\mathrm{Mo} \rightarrow {}^{100}\mathrm{Ru}$	3034	9.6%	**NEMO,**MOON
$^{116}\mathrm{Cd} \rightarrow {}^{116}\mathrm{Sn}$	2802	7.5%	
$^{128}\mathrm{Te} \rightarrow {}^{128}\mathrm{Xe}$	867	32%	
$^{130}\mathrm{Te} \rightarrow {}^{130}\mathrm{Xe}$	2529	34%	COBRA,**CUORE**
$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba}$	2479	8.9%	**EXO,**XMASS
$^{150}\mathrm{Nd} \rightarrow {}^{150}\mathrm{Sm}$	3367	5.6%	

GERDA

We like Germanium because:

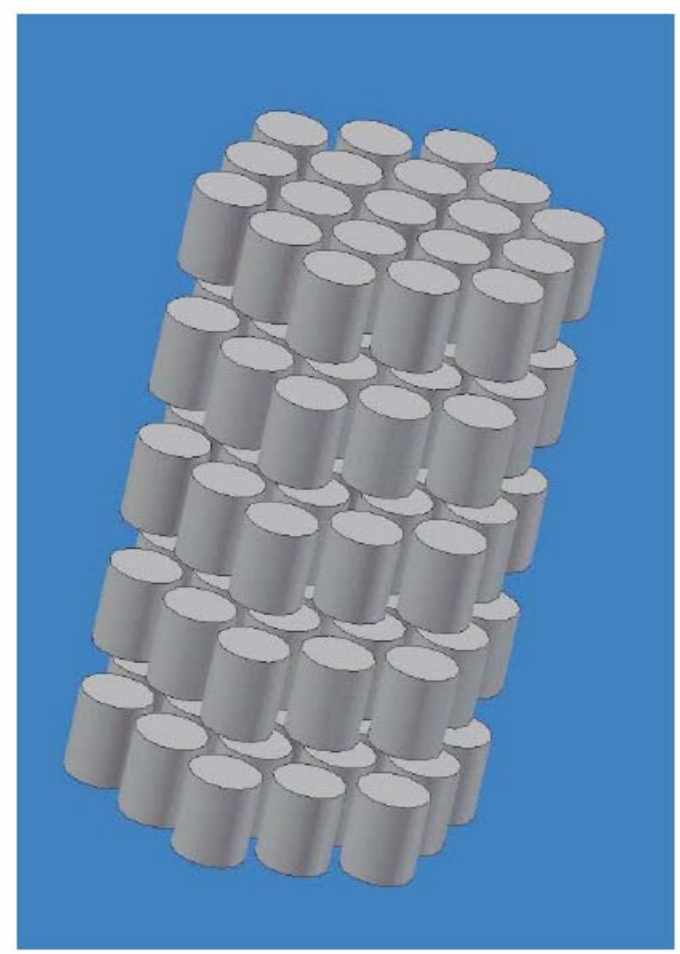
- **excellent energy resolution (3 keV @ 2 MeV)**
- **considerable experience built up over the years - best background levels, best limits to date !**
- **still improvements possible**



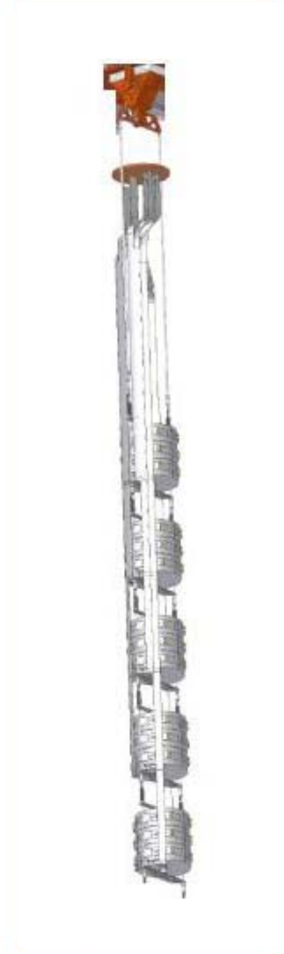
There are also some downsides:

- **Q=2039 keV in region of γ backgrounds**
- **Q=2039 keV not among the higher Q values (recall $\tau \propto 1/Q^5$)**
- **enrichment possible, but expensive !**
- **limited number of crystal growers, detector makers**

Detector Setup



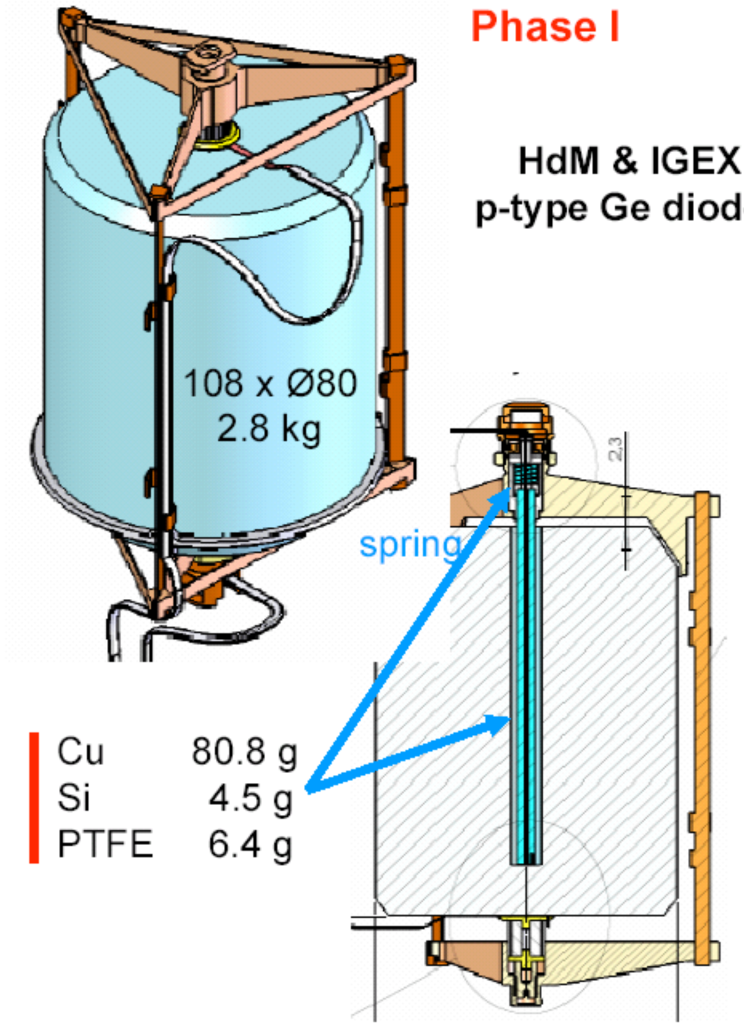
Maximum charge



Organized in strings

Phase I

HdM & IGEX
p-type Ge diodes

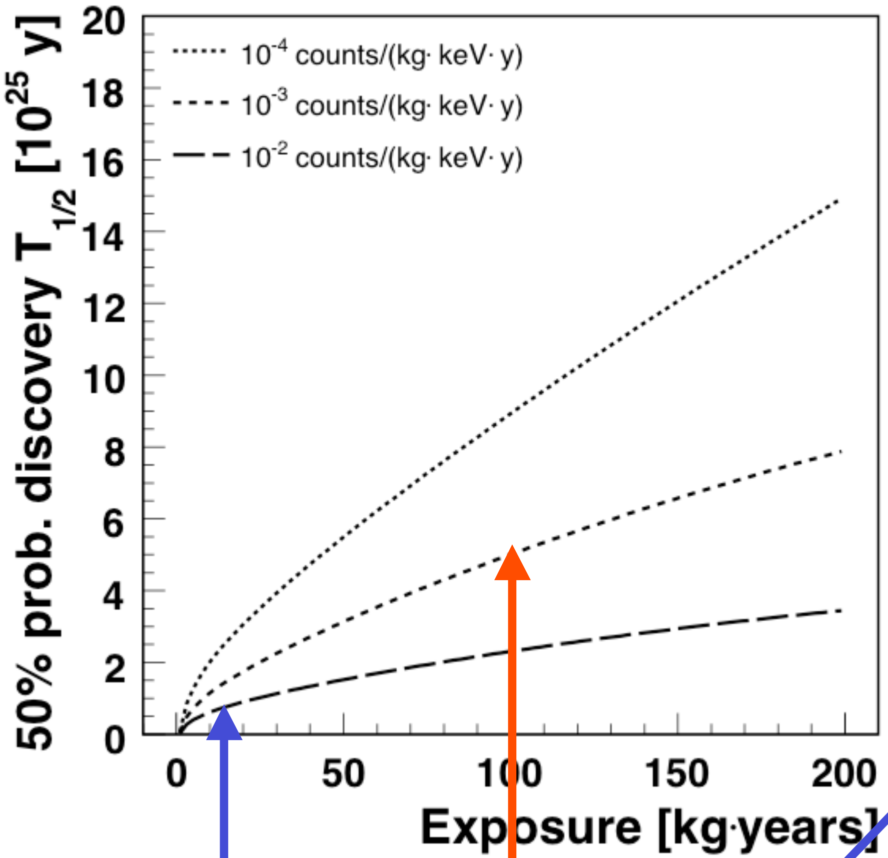


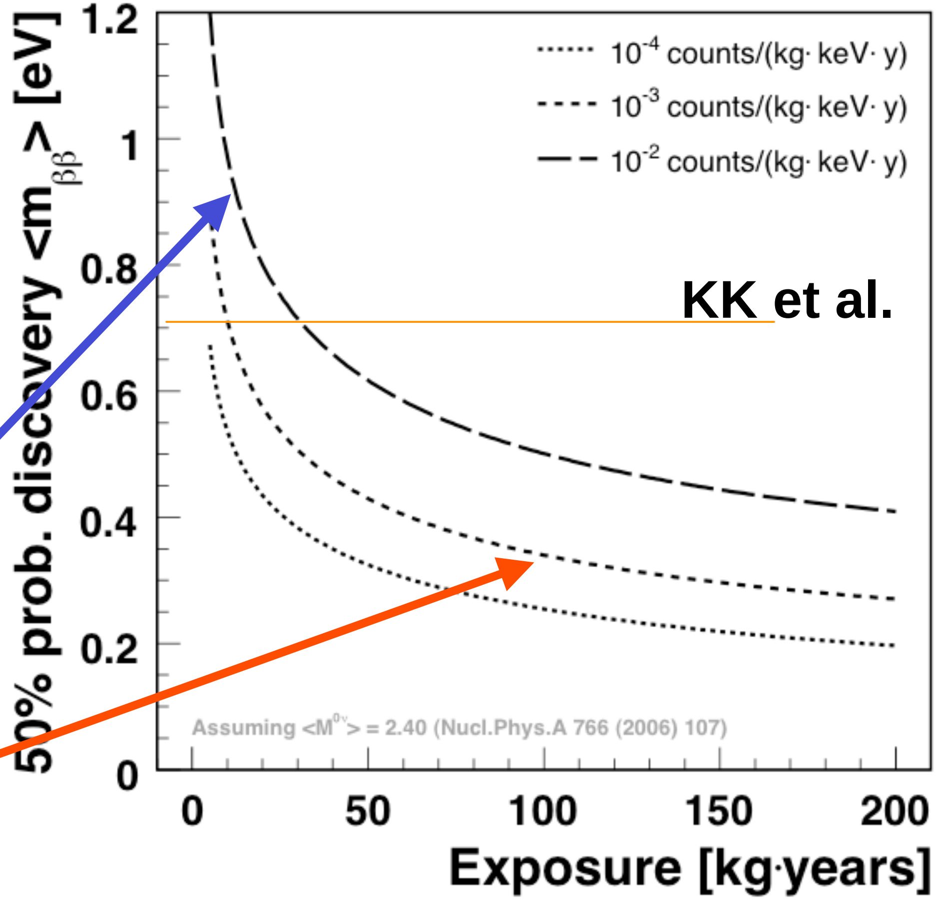
Cu	80.8 g
Si	4.5 g
PTFE	6.4 g

Start with existing detectors

Sensitivity

Bayesian analysis: discovery defined as P(background only|spectrum)<0.0001

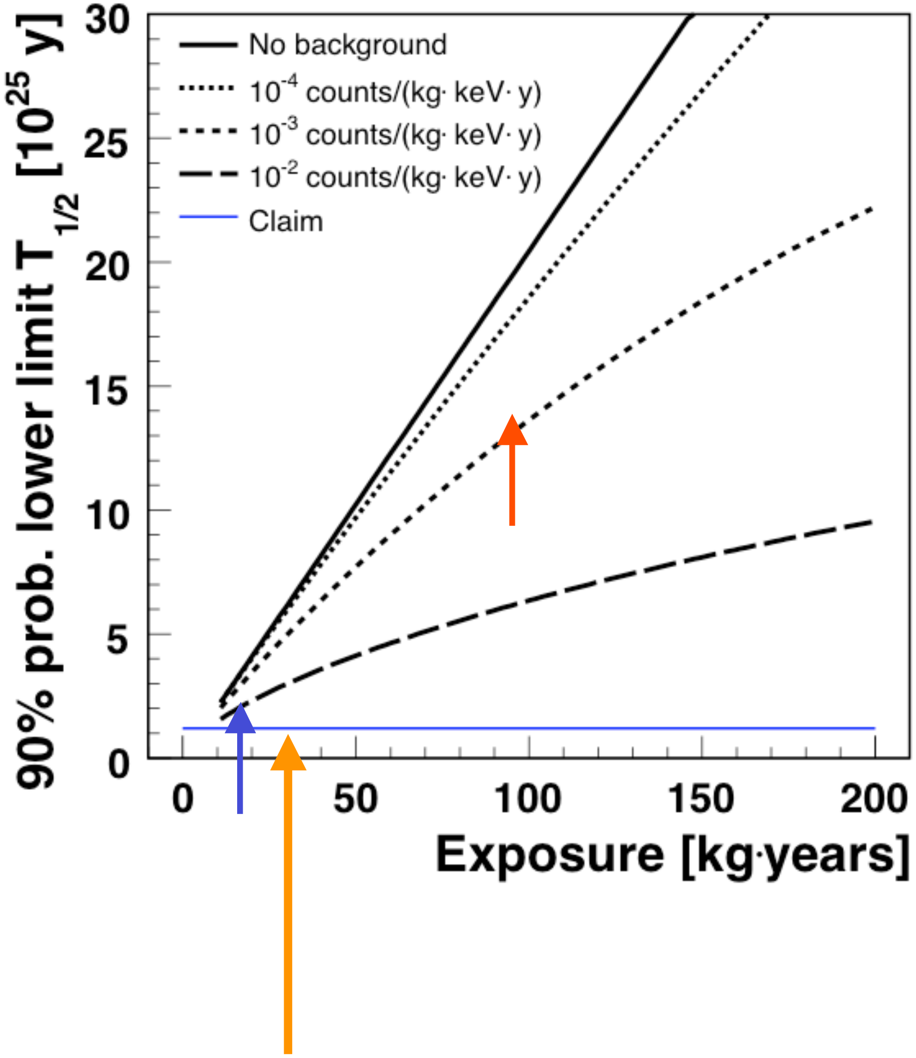




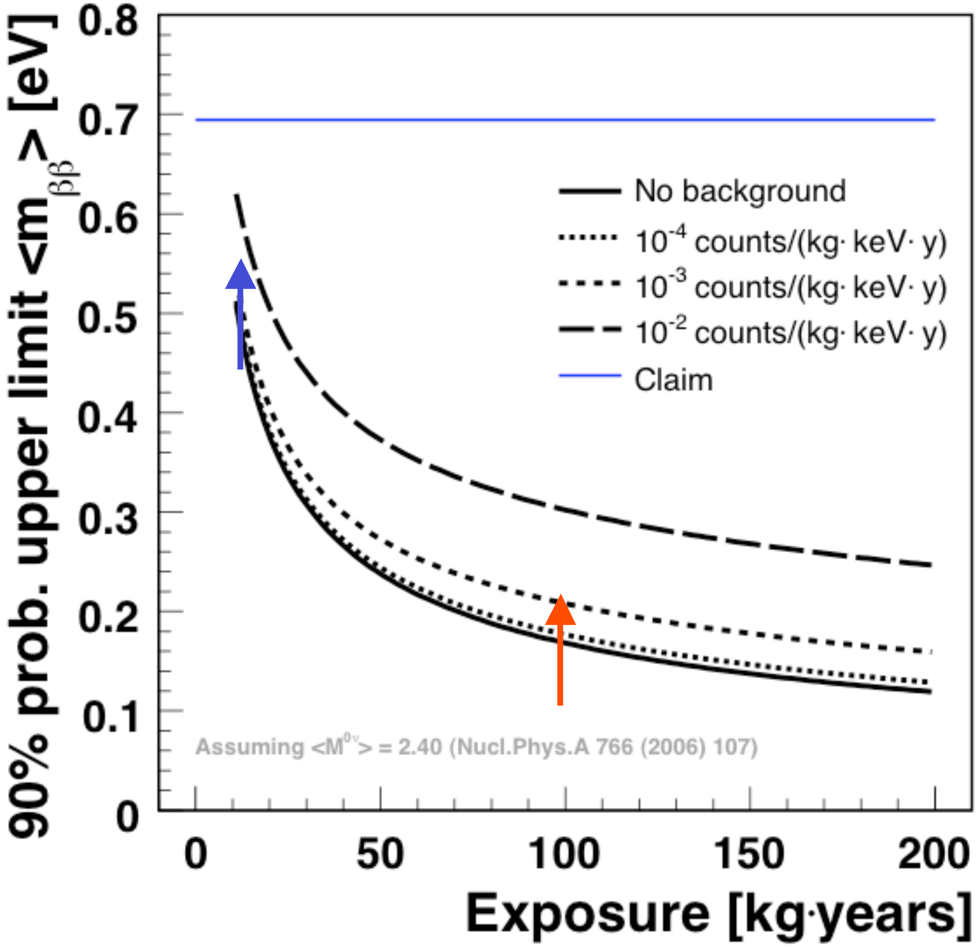
Phase I: 15 kg-yr, existing ^{enr}Ge crystals

Phase II: 100 kg-yr, new segmented ^{enr}Ge crystals

Sensitivity



Central value from KK et al.



Background Suppression

Source	Action
γ's external to crystals from ^{208}Tl(^{232}Th), ^{214}Bi(^{226}Ra), ^{60}Co,…	Shield: high-purity liquid argon shield. Minimize material close to detector.
Front-end electronics	Cold ASIC
μ Induced prompt signals	Underground location (LNGS - 3400 mwe); Water Cerenkov veto
μ Induced delayed signals (e.g. n+ ^{76}Ge→^{77}Ge→^{77}As)	Low-Z material shield (Ar)
Internal to crystal (cosmogenic)	Minimize time above ground after enrichment (^{68}Ge), crystal pulling (^{60}Co)

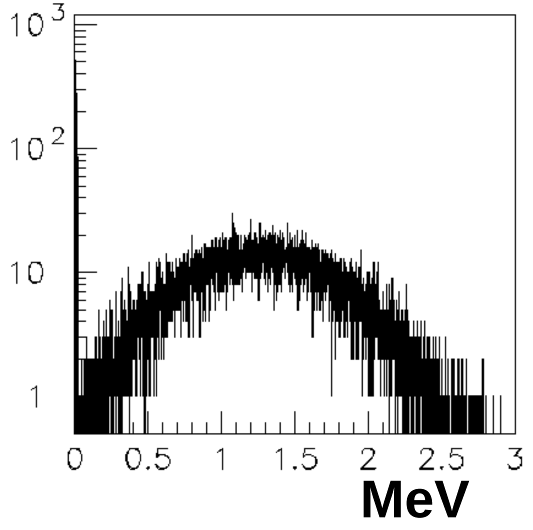
In addition: segmented detectors and pulse shape analysis (Phase II)

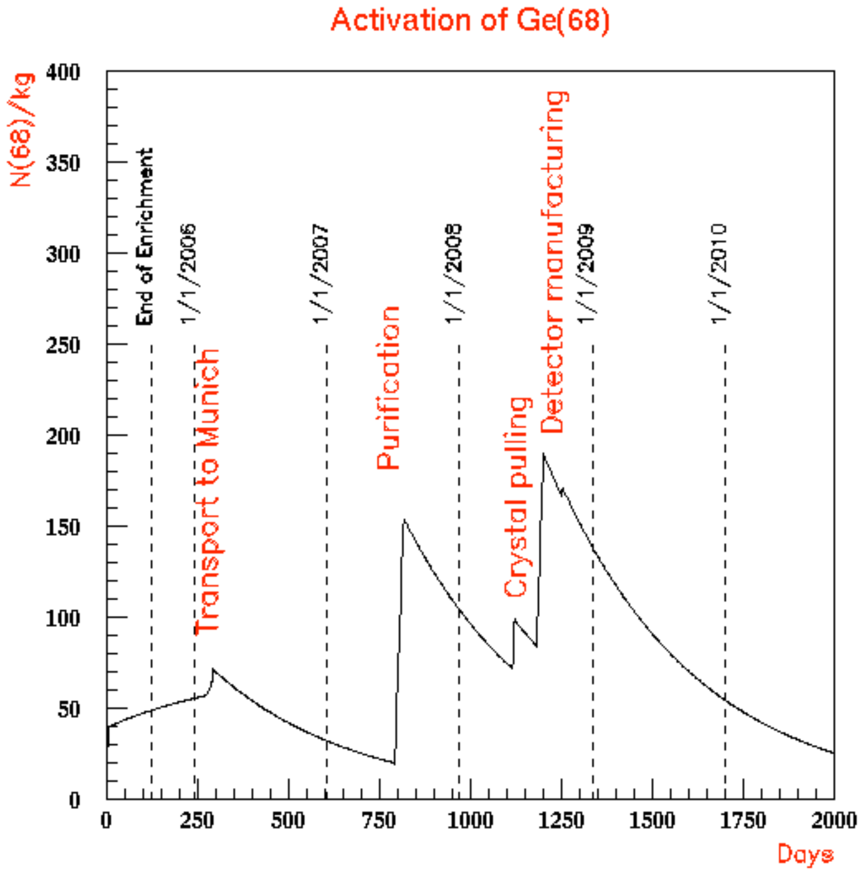
Backgrounds

The types of things we worry about:
e.g., cosmogenic activation of ^{68}Ge (about 6/(day kg) in enriched Ge)

$^{68}\text{Ge} \rightarrow {}^{68}\text{Ga}$ via EC (10.6 KeV X-ray)
τ=271 days

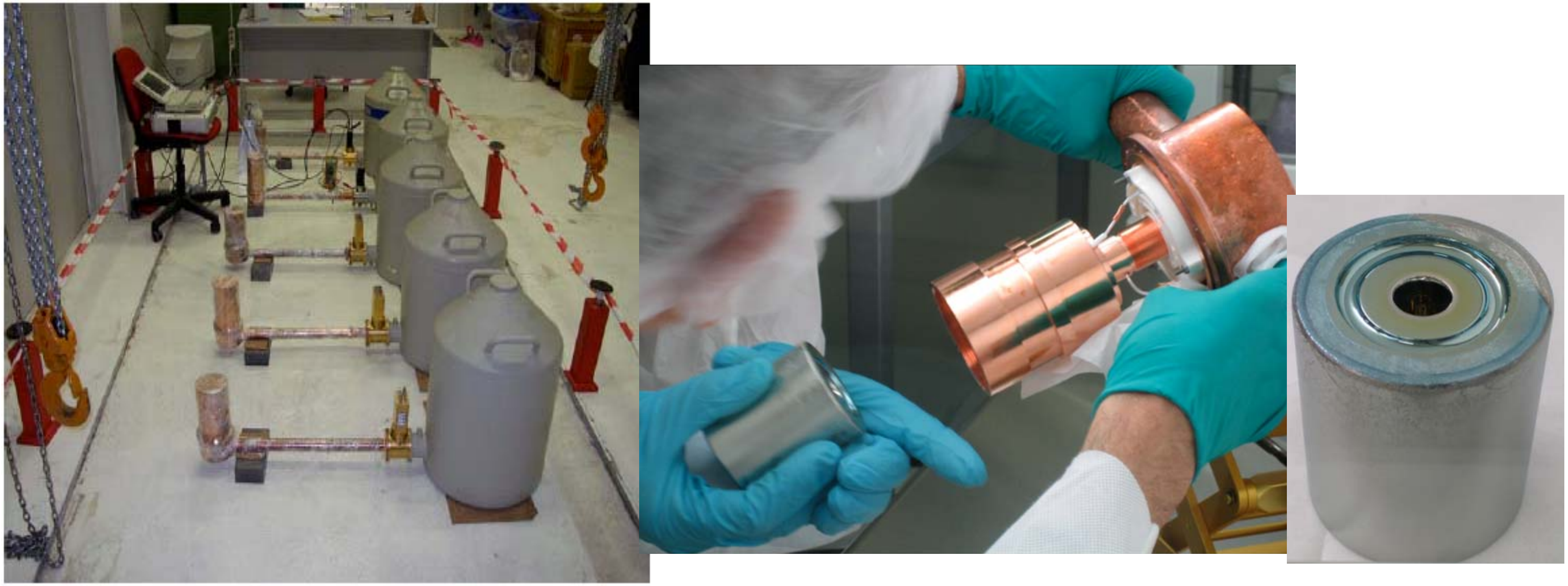
$^{68}\text{Ga} \rightarrow {}^{68}\text{Zn}$ via β^+ (90%, 1.9 MeV)
+ γ (0.511 MeV)
+ γ (0.511 MeV)
τ=68 minutes





Existing Detectors

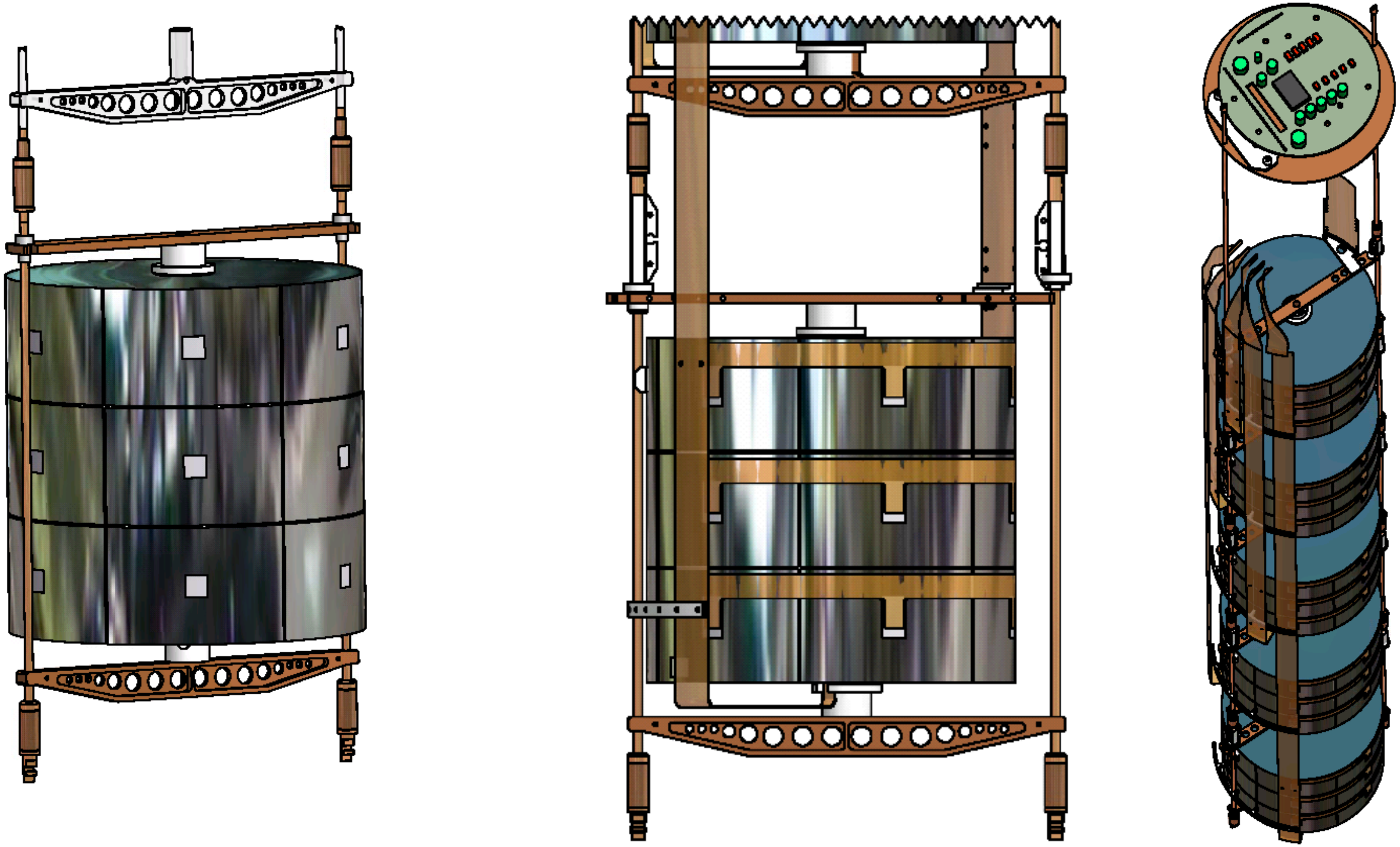
Heidelberg-Moscow detectors for Phase I of GERDA. In addition, three detectors from IGEX experiment. Total mass approx 18 kg. Detectors need to be refurbished to fit into GERDA scheme. This process is well underway.



	ANG1	ANG2	ANG3	ANG4	ANG5	RG1	RG2	RG3
FWHM [keV]	2.54	2.29	2.93	2.47	2.59	2.21	2.31	2.26
Mass [kg]	0.980	2.906	2.446	2.400	2.781	2.150	2.194	2.121

New Detectors

Phase II detectors 18-fold segmented detectors (true-coaxial, 3x6, n-type)



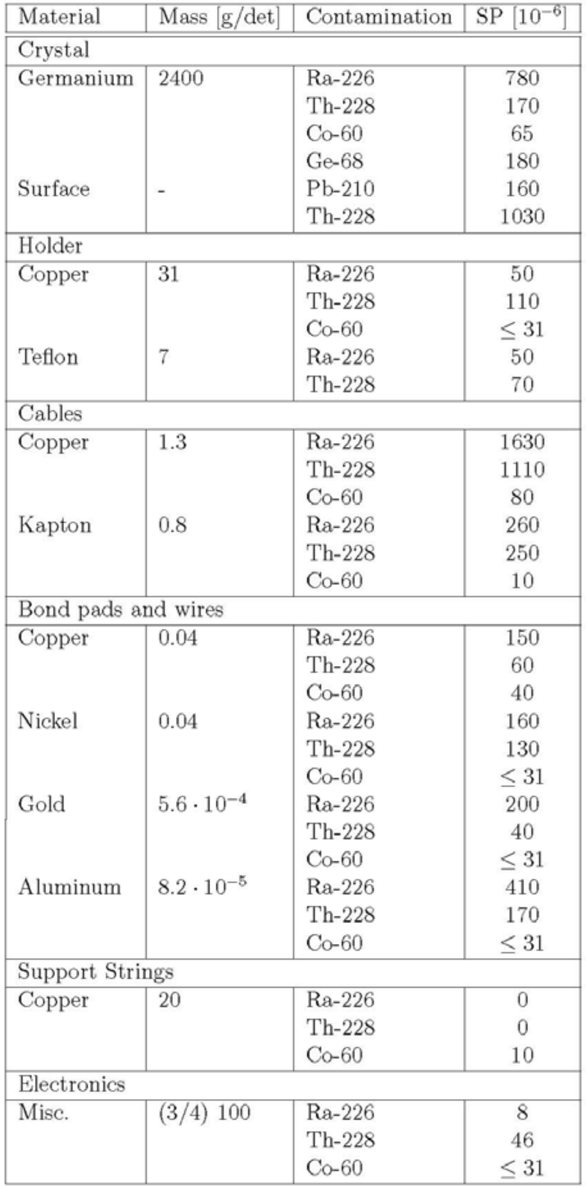
New Detectors

NOTE: The European Plain, west of the Ural Mountains, is often referred to as European Russia

Because of space limitations, some large cities surrounding Moscow are not shown on this map.

★ Capital City ★★ Regional Capital City
● Significant City • Important City - Town
□ Attraction - Landmark □ River ▲ Highest Point

Material Screening

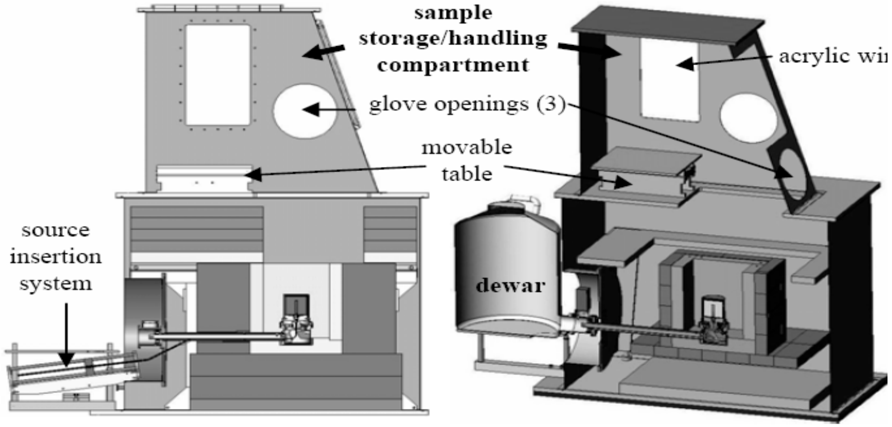


Material	Mass [g/det]	Contamination	SP $[10^{-6}]$
Crystal			
Germanium	2400	Ra-226	780
		Th-228	170
		Co-60	65
		Ge-68	180
Surface	-	Pb-210	160
		Th-228	1030
Holder			
Copper	31	Ra-226	50
		Th-228	110
		Co-60	≤ 31
Teflon	7	Ra-226	50
		Th-228	70
Cables			
Copper	1.3	Ra-226	1630
		Th-228	1110
		Co-60	80
Kapton	0.8	Ra-226	260
		Th-228	250
		Co-60	10
Bond pads and wires			
Copper	0.04	Ra-226	150
		Th-228	60
		Co-60	40
Nickel	0.04	Ra-226	160
		Th-228	130
		Co-60	≤ 31
Gold	$5.6 \cdot 10^{-4}$	Ra-226	200
		Th-228	40
		Co-60	≤ 31
Aluminum	$8.2 \cdot 10^{-5}$	Ra-226	410
		Th-228	170
		Co-60	≤ 31
Support Strings			
Copper	20	Ra-226	0
		Th-228	0
		Co-60	10
Electronics			
Misc.	(3/4) 100	Ra-226	8
		Th-228	46
		Co-60	≤ 31

Sample screening coordinated between:
MPIK, GEEL, Baksan, LNGS

All materials which can produce background are measured

GeMPI at LNGS:



Active Background Suppression

Background sources:

Cosmogenically produced ^{68}Ge and ^{60}Co

U/Th contamination, ^{210}Pb on surface

External gammas

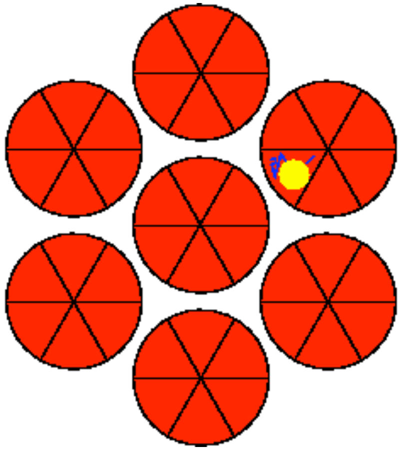
Signatures:

Signal has two electrons in final state → range ~mm

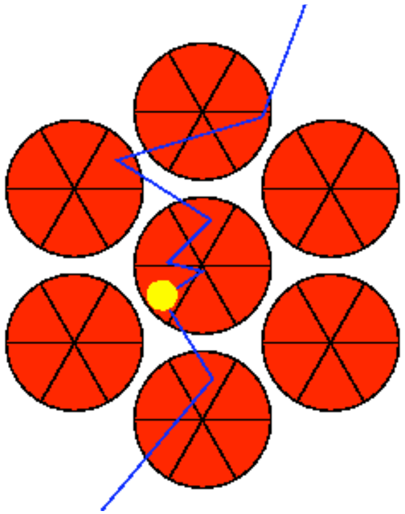
Background sources mostly γ with $E_\gamma > 2$ MeV

Compton scattering dominant interaction, range ~few cm

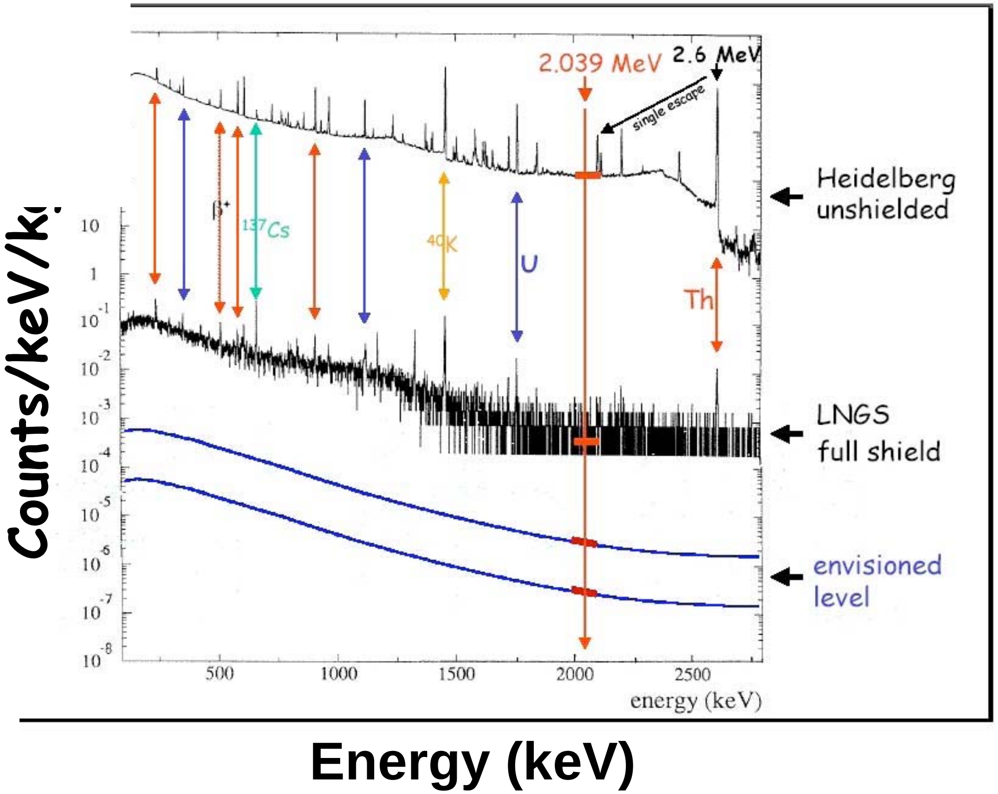
Signal:

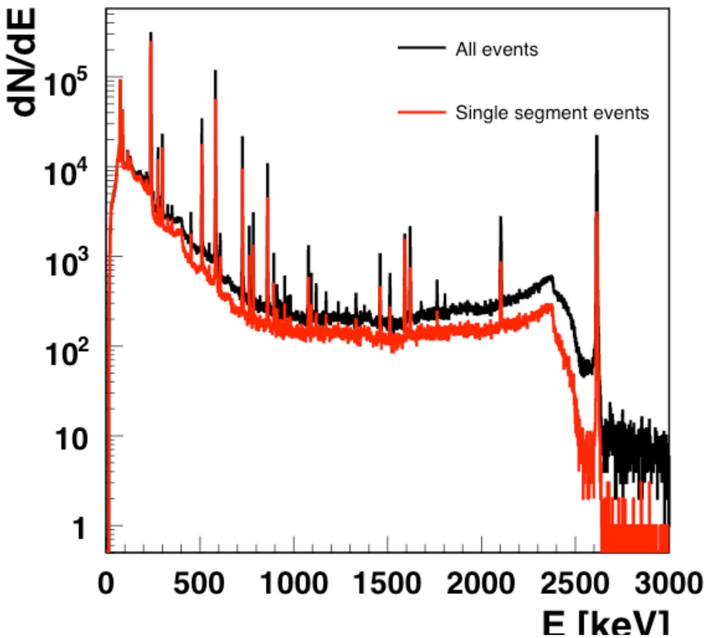


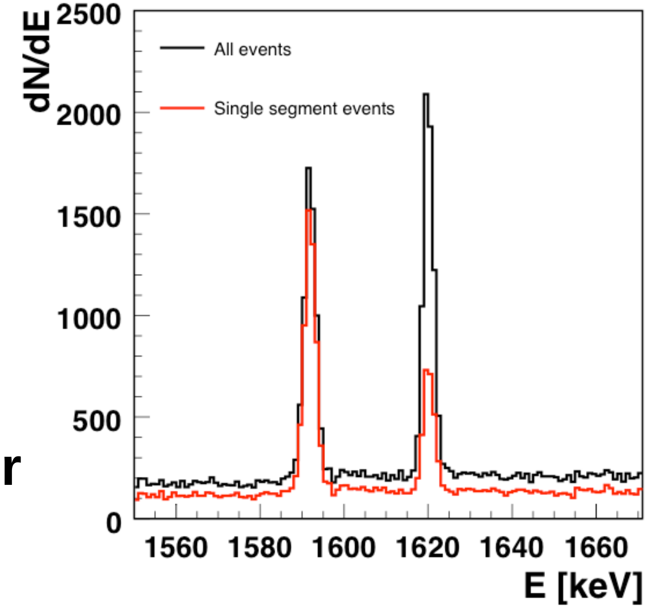
Background (^{60}Co):



Background Suppression

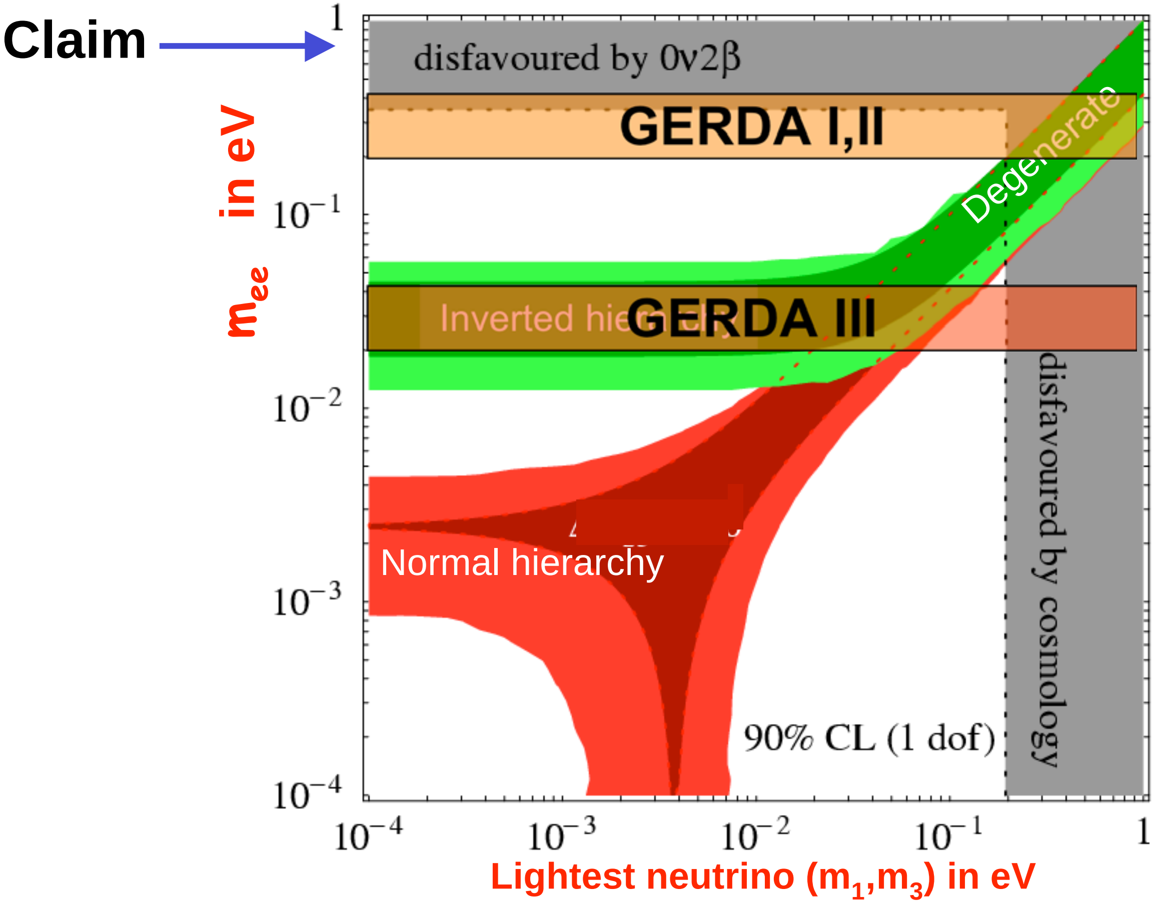


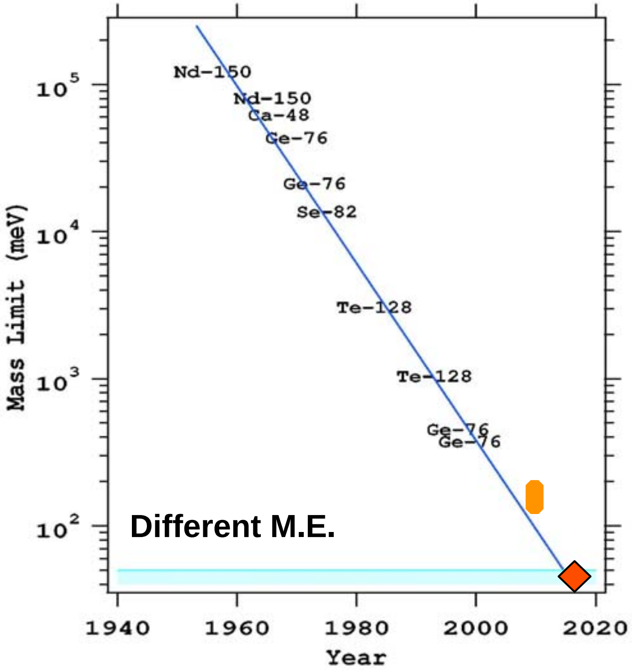




With prototype 18-fold segmented detector

Summary





1. **We will confirm or rule out the Klapdor-Kleingrothaus et al. claim**
2. **If not verified and background reduction to the level 10^{-3}/(kg yr keV) demonstrated, go for Phase III (ca. 1 ton, 20 meV level)**