Searching for Double Beta Decay with GERDA

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Les Rencontres de Physique de la Vallée d'Aoste
La Thuile, 26 February – 3 March, 2012

Outline

- Neutrinoless double beta decay ($0\nu\beta\beta$)
- The GERDA experiment
- First data
- Phase II preparations

Why do we search for 0νββ?

Unveil the nature of neutrinos:

Majorana

$\nu = \bar{\nu}$

or

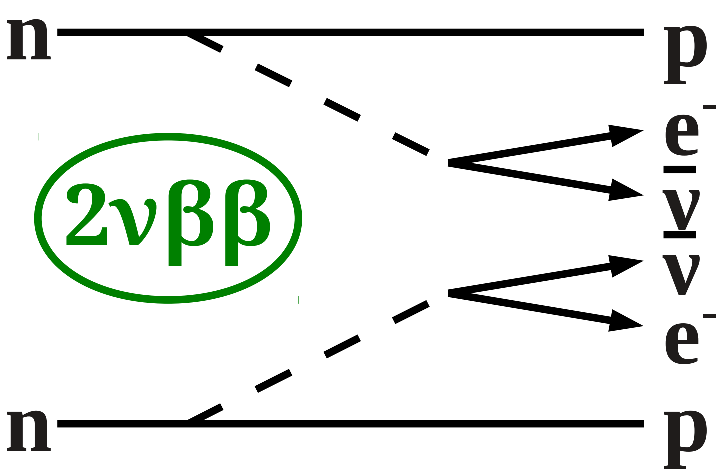
Dirac

$\nu \neq \bar{\nu}$

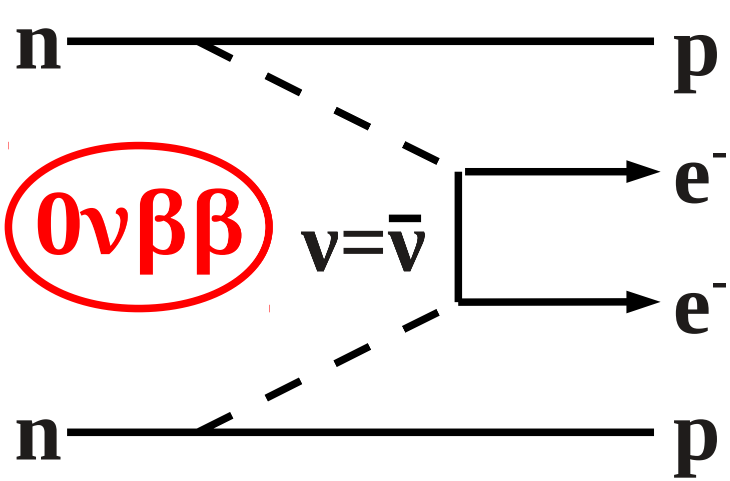
If 0νββ observed:

- Neutrino is a Majorana particle ($\nu = \bar{\nu}$)
- Lepton number violation $\Delta L = 2$
- Sheds light on absolute neutrino mass scale
- Sheds light on neutrino mass hierarchy

2νββ and 0νββ



- allowed by SM
- $\Delta L=0$
- observed in many isotopes
- $T_{1/2} \sim 10^{19}\text{-}10^{21}$ y



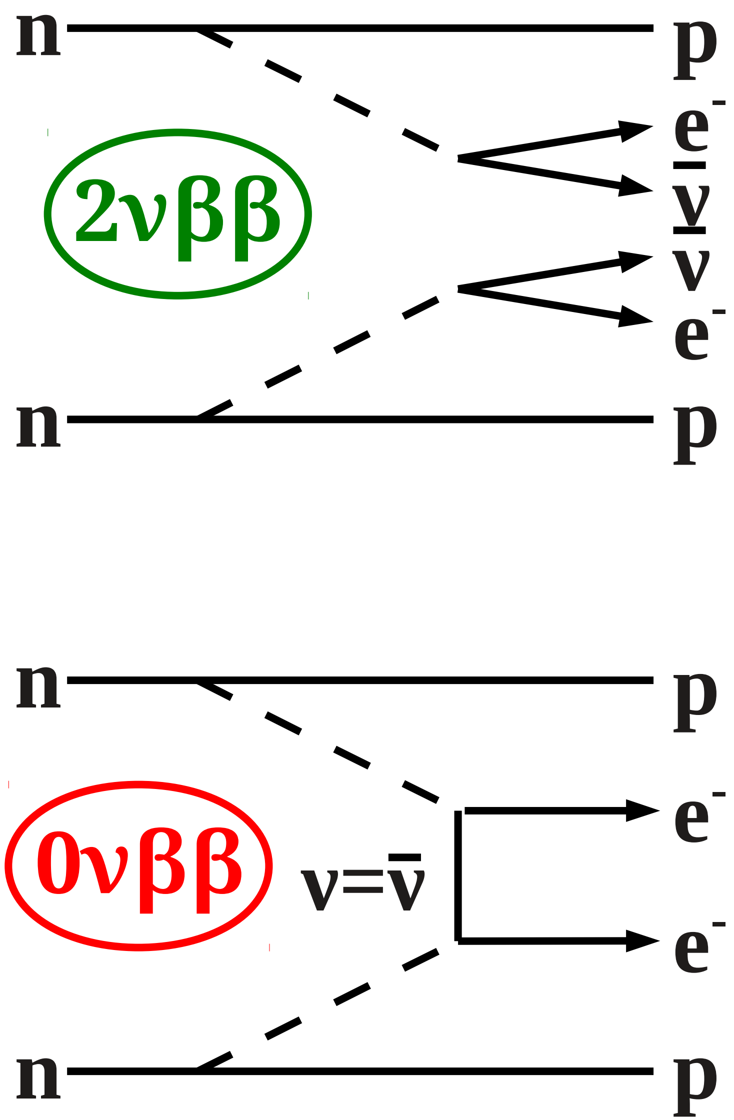
- Forbidden process in SM, needs Majorana neutrino
- $\Delta L=2$
- $(T_{1/2})^{-1} = G^{0\nu}(Q_{\beta\beta},Z)\cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta}\rangle^2$

$G^{0\nu}(Q_{\beta\beta},Z)$: Phase space ($\sim Q_{\beta\beta}^{5}$)

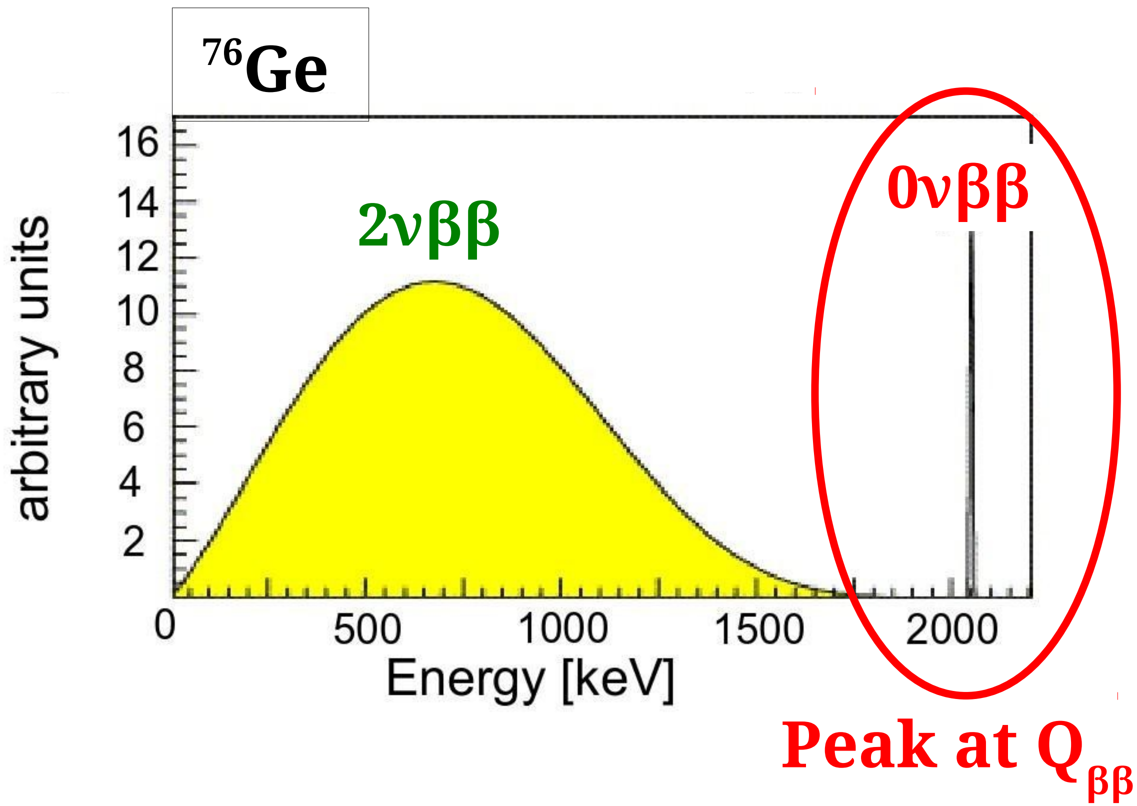
$|M^{0\nu}|^2$: nuclear matrix element

$\langle m_{\beta\beta}\rangle^2 = |\sum_i U_{ei}^2 m_i|^2$

2νββ and 0νββ



Experimental signature:

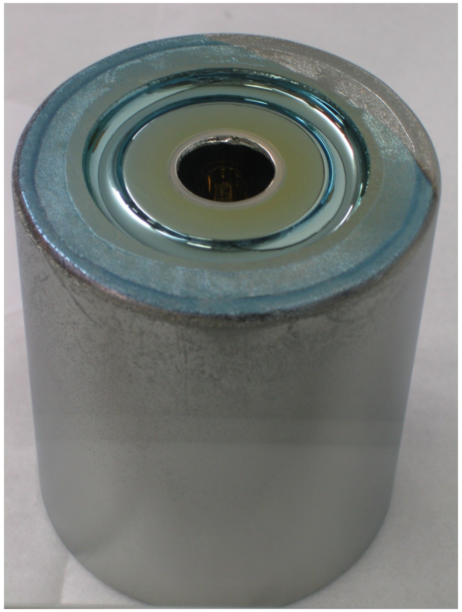


Searching in ^{76}Ge

$$S \sim \epsilon \cdot a \cdot \sqrt{\frac{M \cdot t}{b \Delta E}}$$

S: sensitivity
ε: efficiency
a: abundance of 2νββ isotope
M: detector mass

t: measured time
b: background index
ΔE: detector resolution



Germanium detector

Advantages of Germanium:

- **High ε**: Source = Detector
- **Small instrinsic b**: High purity Ge
- **Excellent ΔE**: FWHM ~ (0.1-0.2)%
- Well-established technology

Disadvantages of Germanium:

- **High external b:** $Q_{\beta\beta}$=2039keV
- **Small a of ^{76}Ge:** 7.8% → Enrichment needed!
- Limited sources of crystal & detector manufacturers

Previous ^{76}Ge experiments

	HdM	IGEX
Location	LNGS	Homestake, Baksan, Canfranc
Exposure [kg·y]	71.1	8.9
Bg [counts/keV·kg·y]	0.11	0.17
$T_{1/2}$ limit (90% CL) [y]	$1.9 \cdot 10^{25}$ [1]	$1.6 \cdot 10^{25}$ [2]

[1] *Eur. Phys. J. A12, 147-154 (2001)*
[2] *Phys. Rev. D 65, 092007 (2002)*

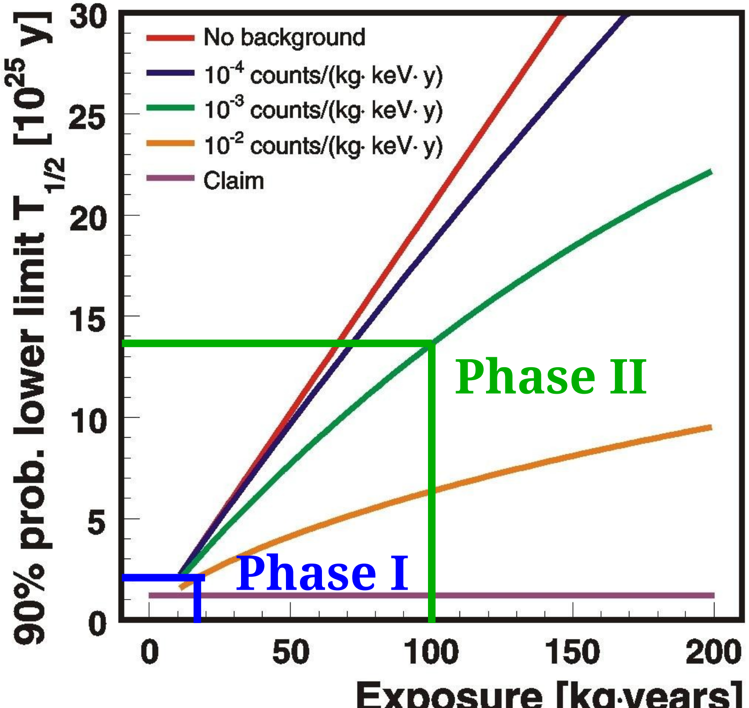
Claim of signal from parts of HdM:

$T_{1/2}$ (^{76}Ge) = $(0.69 – 4.18) \cdot 10^{25}$y (3σ) *(Phys. Lett. B 586, 198-212 (2004))*

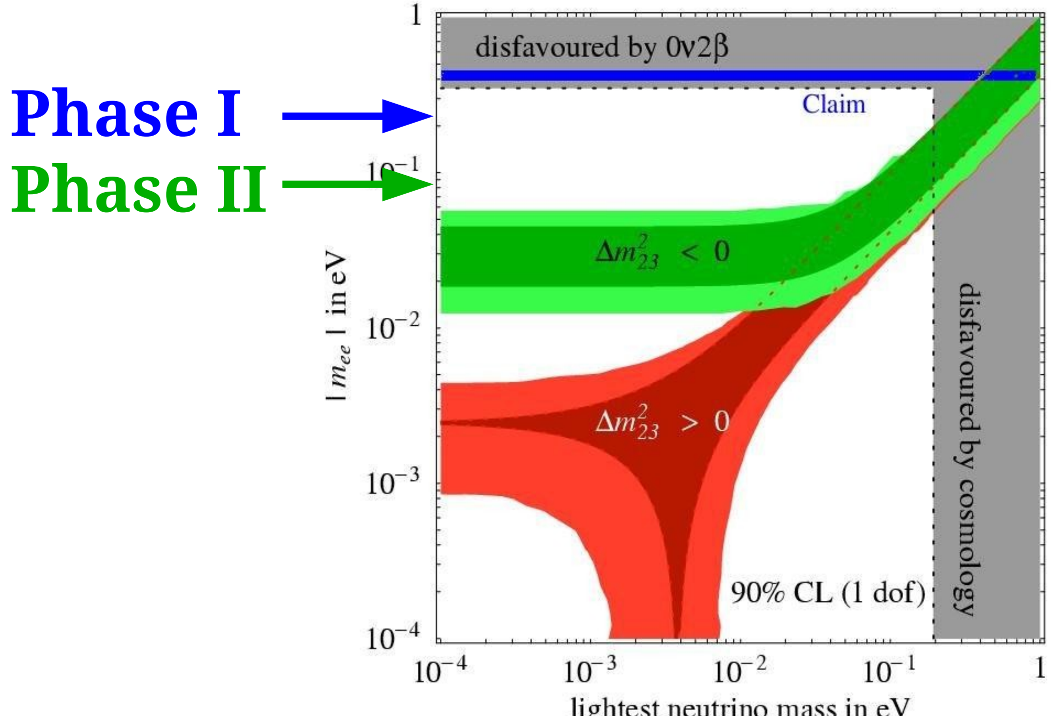
GERDA physics goal

Phase I:
- 18kg (HdM/IGEX) enriched (~86%) + 15kg natural
- reach background of **10^{-2} counts/(keV·kg·y)**
- Exposure of 15 kg·y → **check claim**
- $\langle m_{\beta\beta} \rangle \leq$ (0.23-0.39) eV *(Phys. Rev. C 81 (2010) 028502)*

Phase II:
- add ~20kg new enr. detectors
- reach background of **10^{-3} counts/(keV·kg·y)**
- Exposure of 100kg·y → $T_{1/2} > 1.5 \cdot 10^{26}$y
- $\langle m_{\beta\beta} \rangle \leq$ (0.09-0.15) eV *(Phys. Rev. C 81 (2010) 028502)*



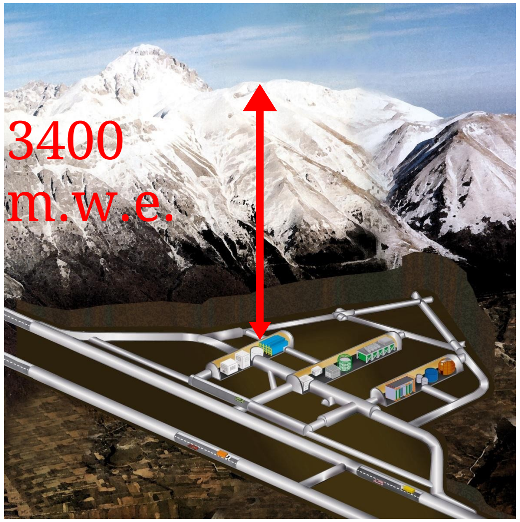
Phys. Rev. D 092003 (2006)

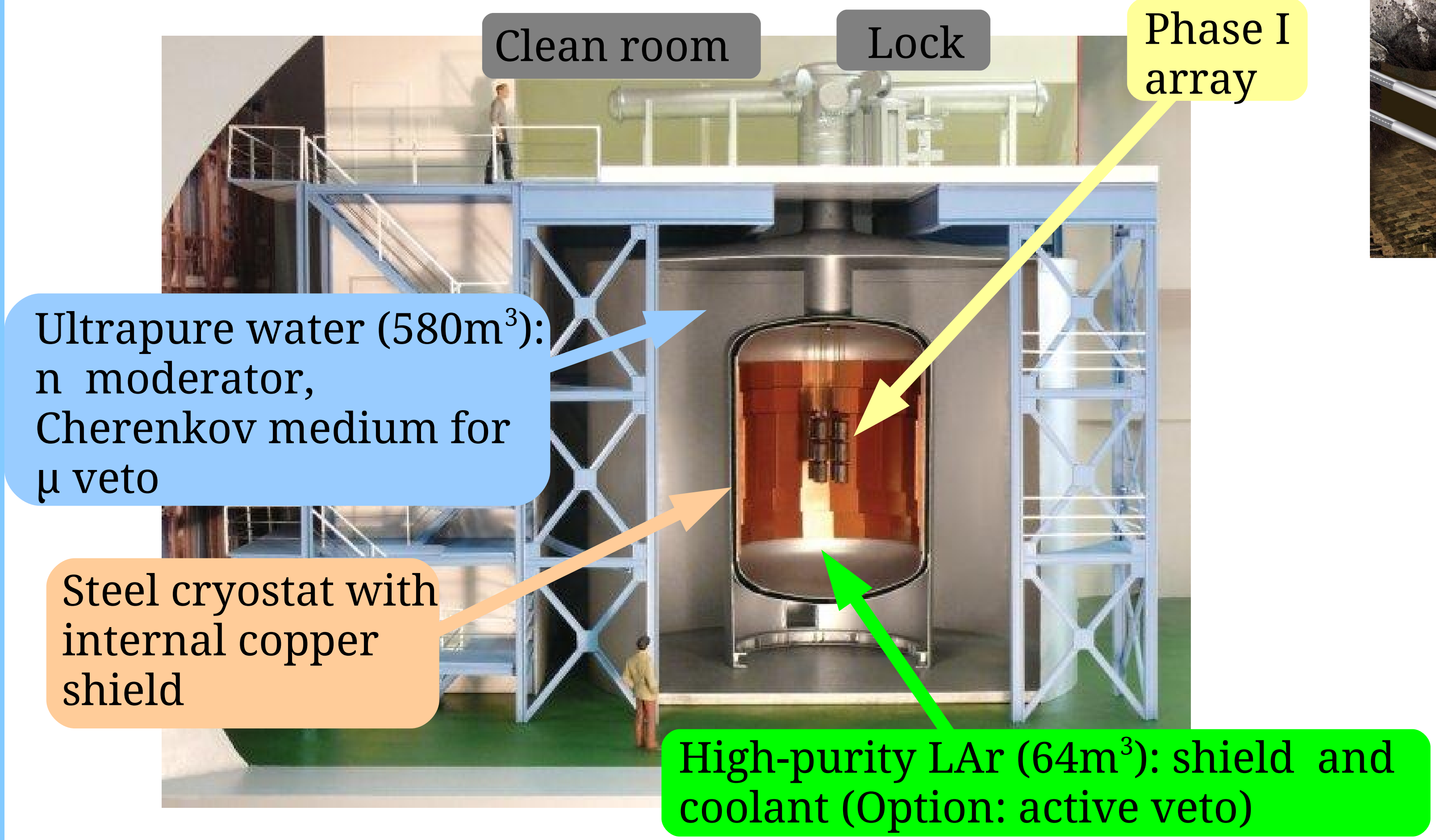


F. Feruglio, A. Strumia, F. Vissani, NPB 659

Background reduction

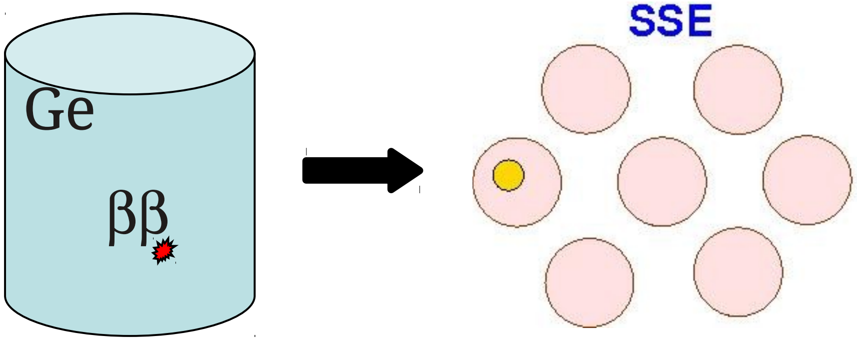
- GERDA situtated in LNGS underground laboratories: suppression of cosmic ray muons by factor 10^6 by overlaying rock
- Graded shielding against ambient radiation
- Rigorous material selection
- Avoid exposure above ground for detectors





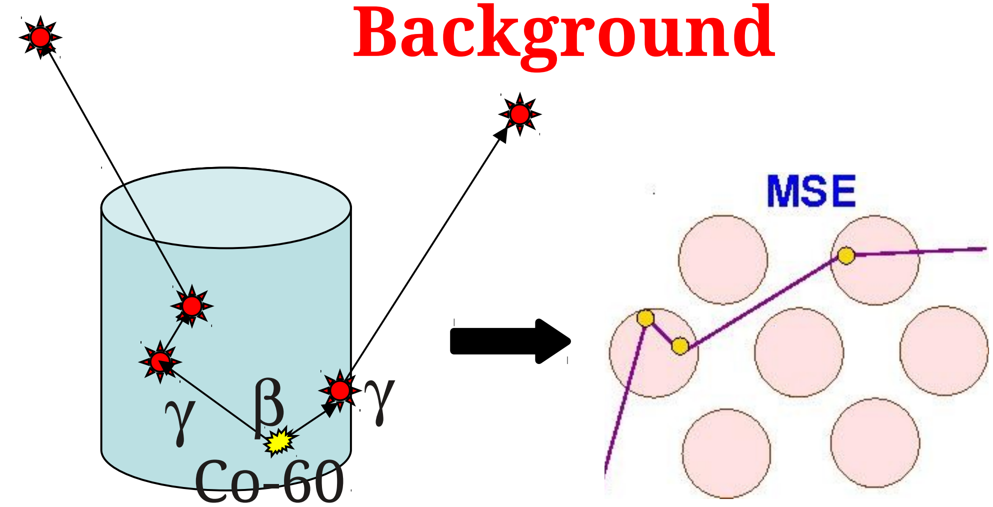
Background reduction

Signal



Point-like (single-site) energy deposition inside one HP-Ge diode (Range: ~ 1mm)

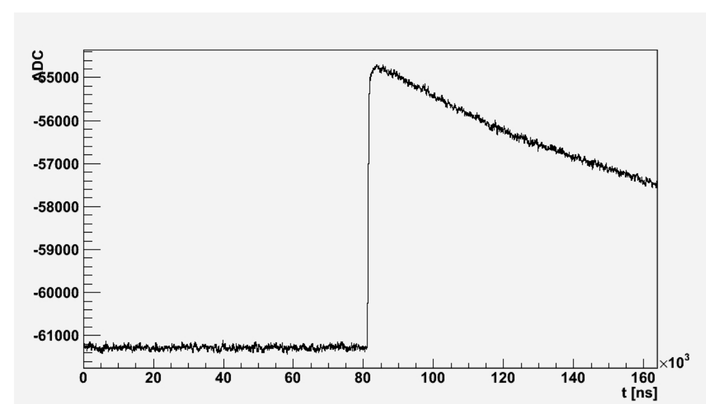
Background



Multi-site energy deposition inside HP-Ge diode (Compton scattering)

Signal analysis:

- anti-coincidence between detectors
- pulse shape analysis (PSA)

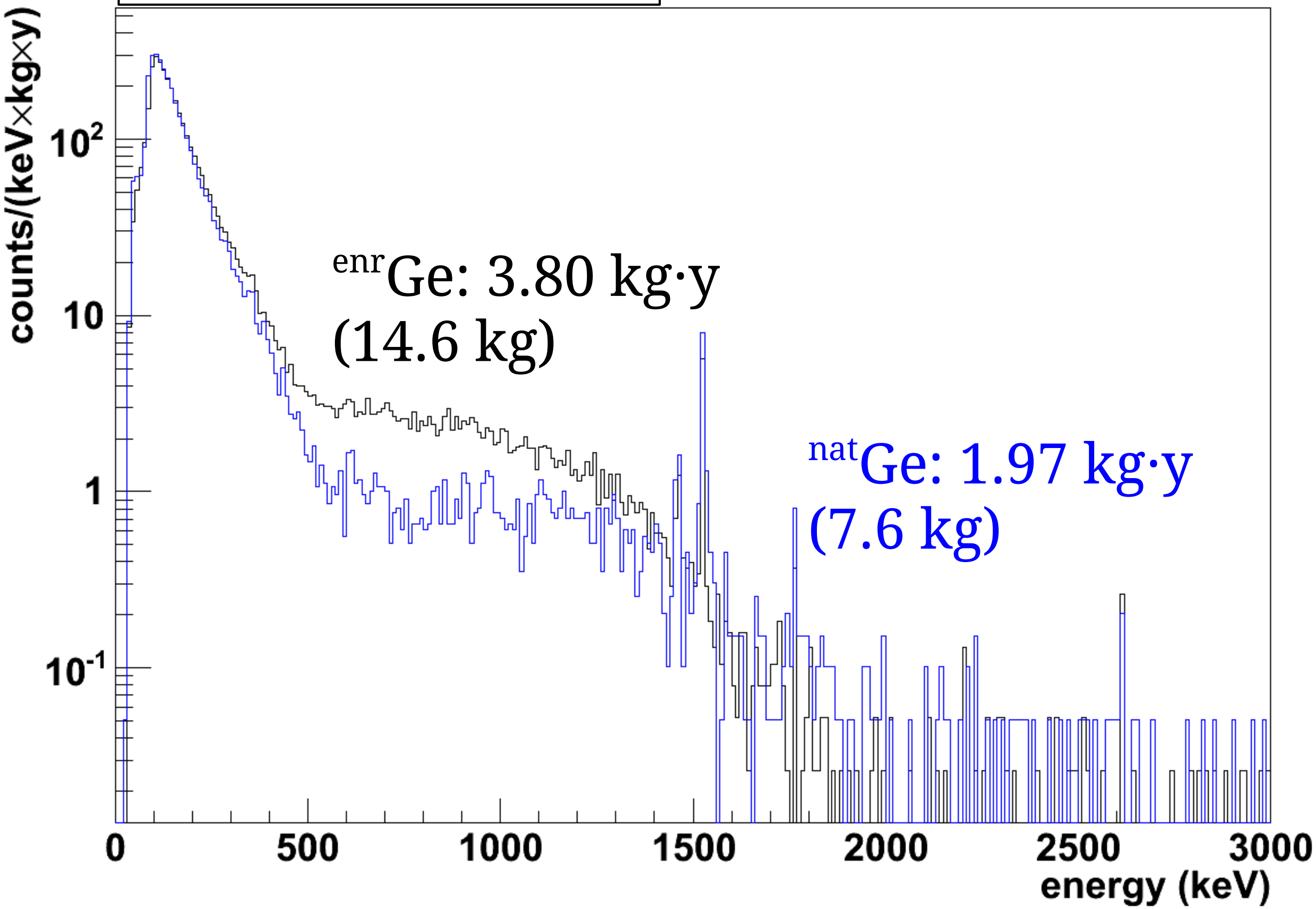


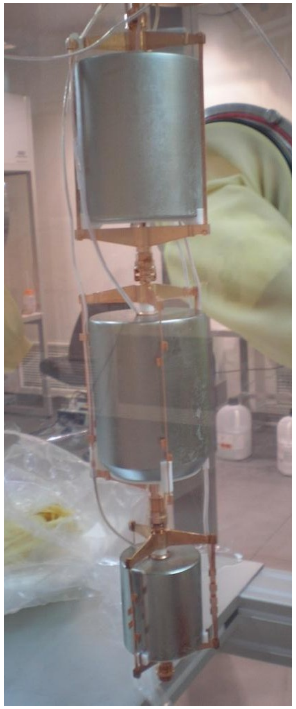
Start of Phase I

6 November 2011: Start of Phase I

All 8 ^{enr}Ge + 4 ^{nat}Ge detectors deployed in GERDA
(2 ^{enr}Ge detectors presently not used for analysis)

Energy spectrum

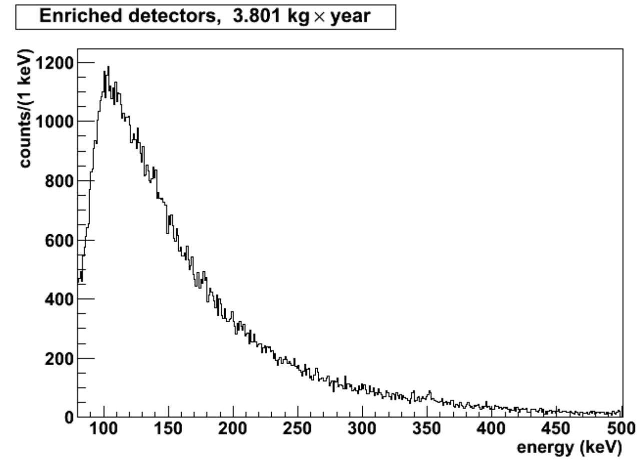




(Unexpected) Background from Argon

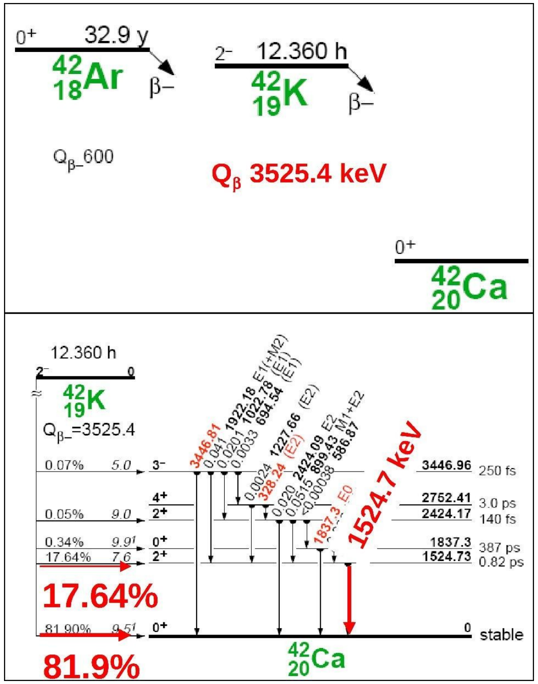
^{39}Ar

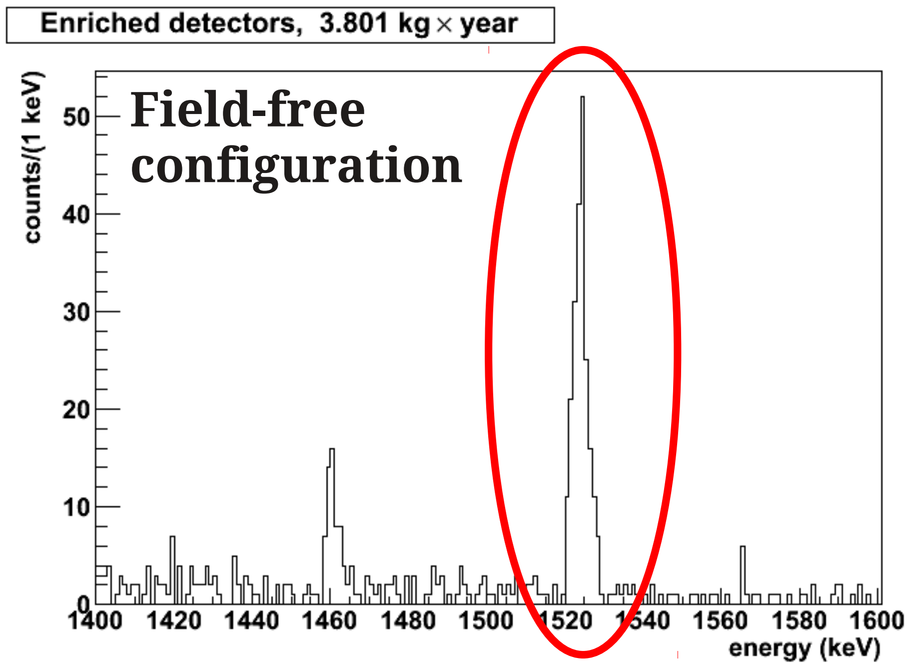
- 1.01 Bq/kg, $T_{1/2}$=269 y
- pure β emitter, Q-value=565keV
  → **below region of interest**



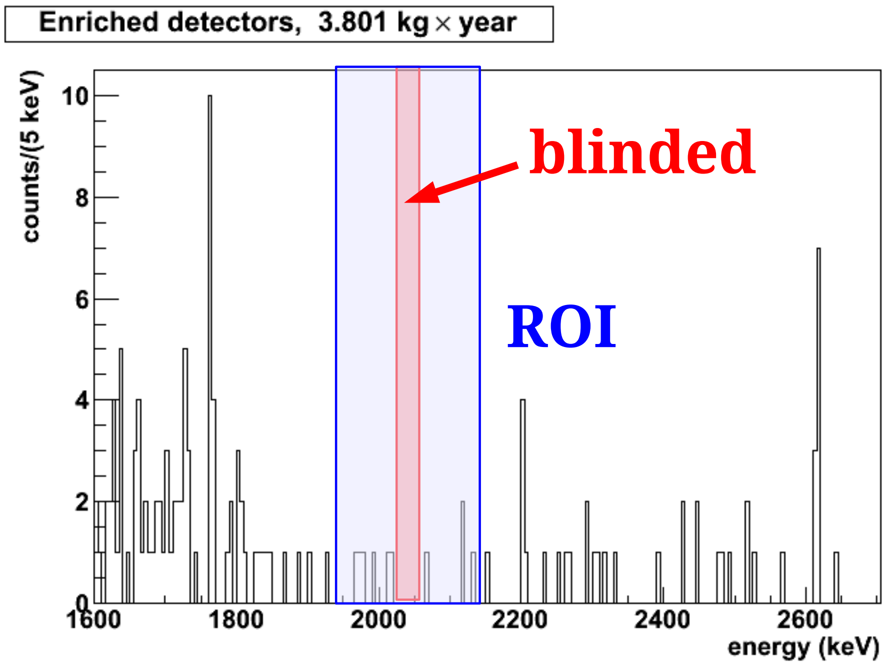
^{42}Ar

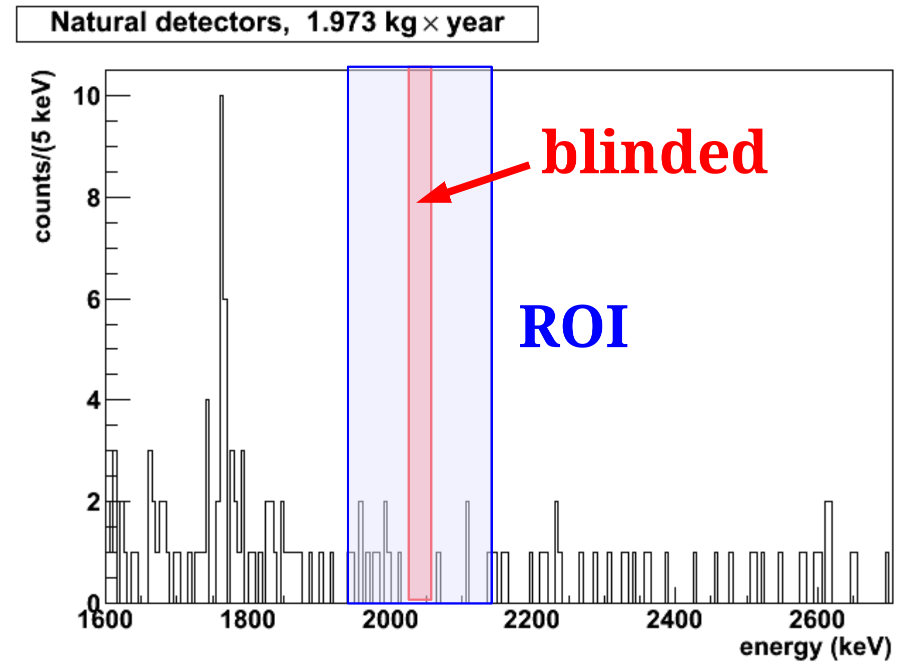
GERDA proposal: ^{42}Ar/^{nat}Ar < 3 x 10^{-21} (*Barabash et al. 2002)*
GERDA measurement: Count rate at 1525keV ~ 2 times expectation





Region of Interest





Background rate in ROI ($Q_{\beta\beta}$±100 keV, blinded window excluded):

^{enr}Ge: $0.017^{+0.009}_{-0.005}$ counts/(keV·kg·y)

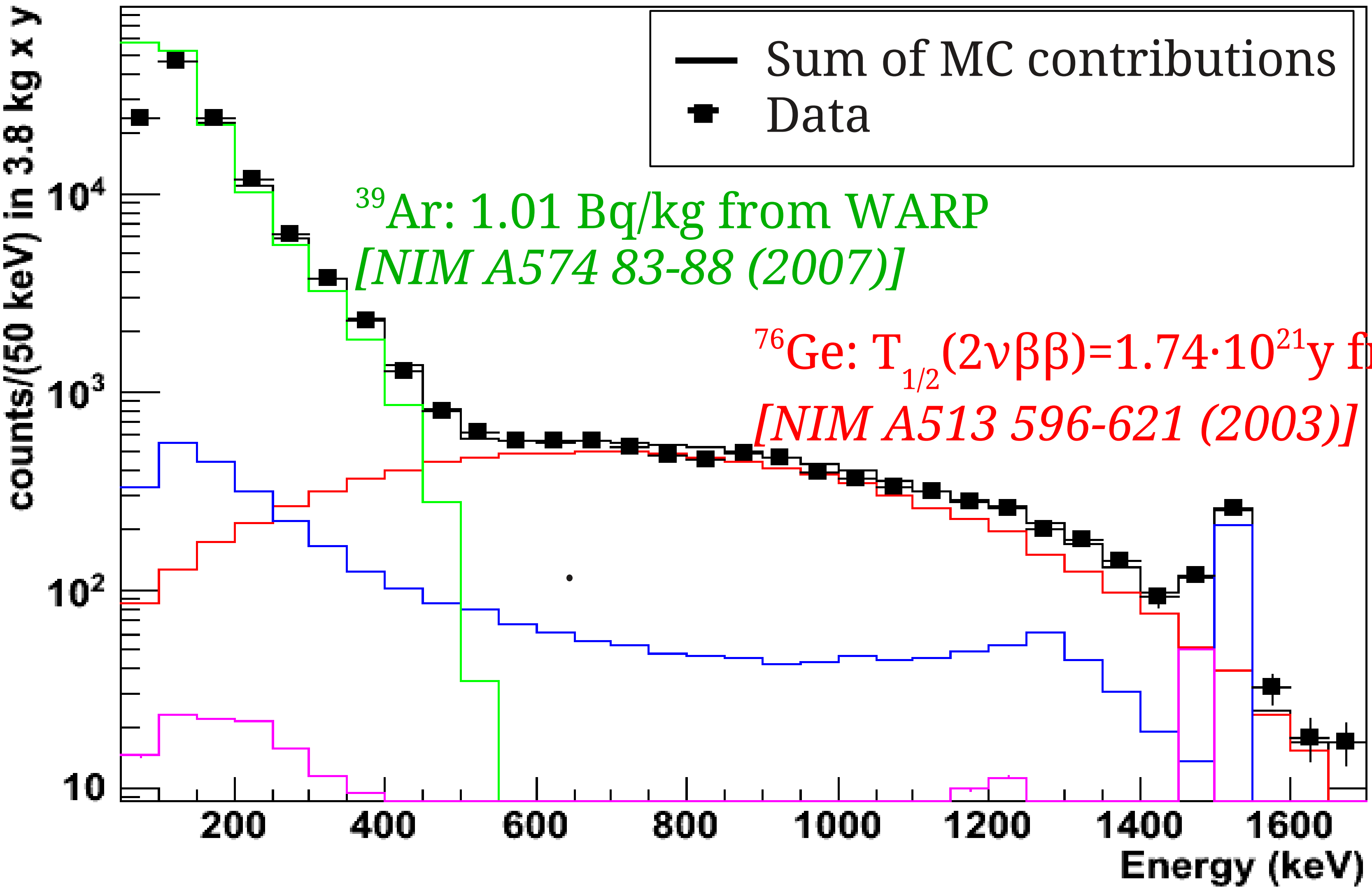
^{nat}Ge: $0.049^{+0.015}_{-0.013}$ counts/(keV·kg·y)

➔ most likely a combination of Th/U, ^{42}K, degraded α, cosmogenic isotopes

➔ factor ~10 lower than previous experiments (HdM, IGEX)

➔ no pulse shape analysis applied yet

2νββ



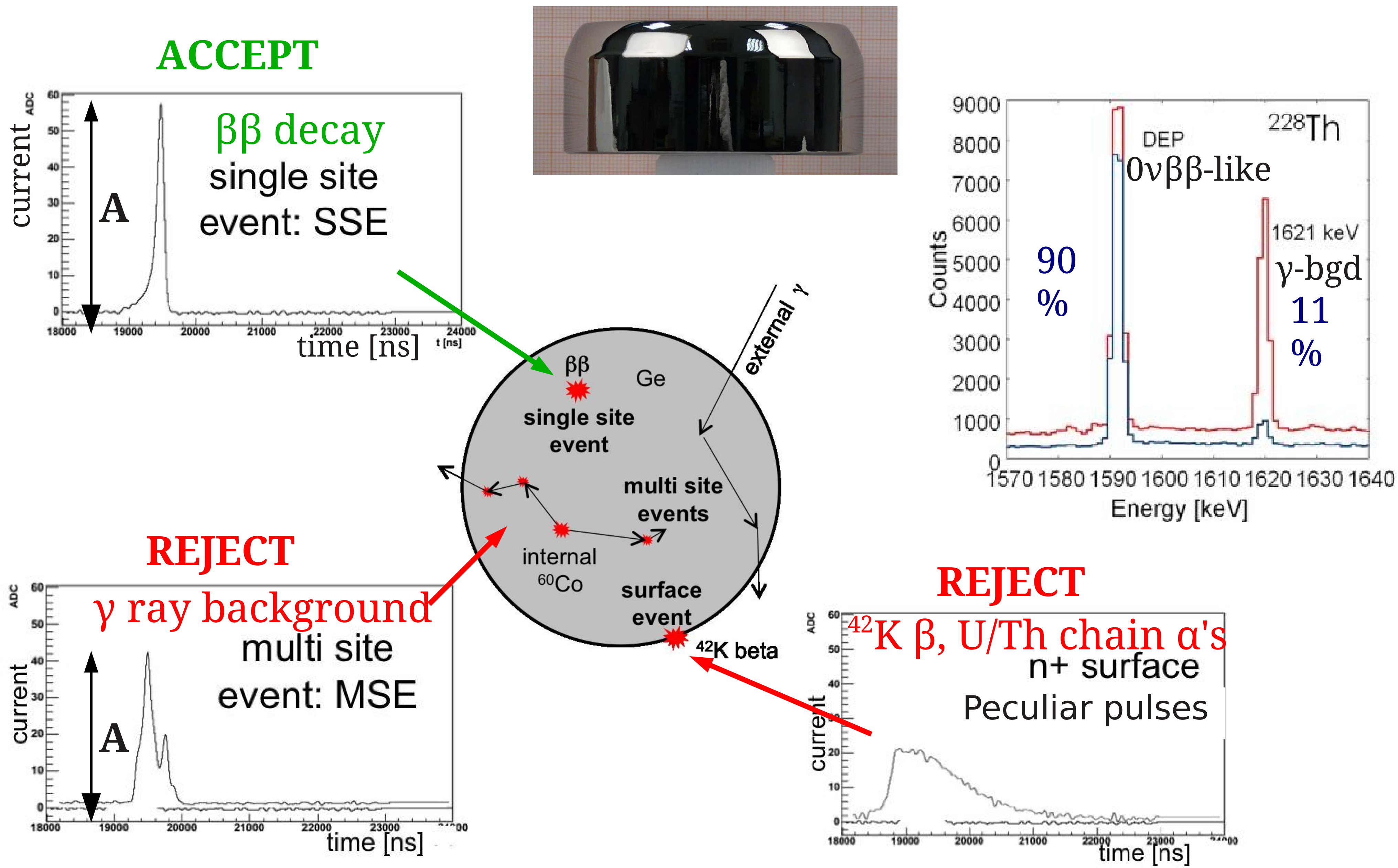
^{39}Ar: 1.01 Bq/kg from WARP
[NIM A574 83-88 (2007)]

^{76}Ge: $T_{1/2}(2\nu\beta\beta)=1.74\cdot10^{21}$y from HdM
[NIM A513 596-621 (2003)]

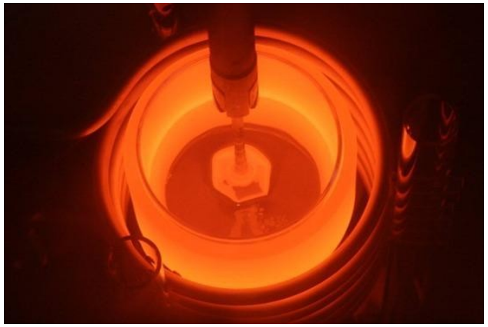
^{40}K: simulated decays in detector holders (normalized to peak)

^{42}K: homogeneously distributed decays in LAr (normalized to peak)

Phase II detectors

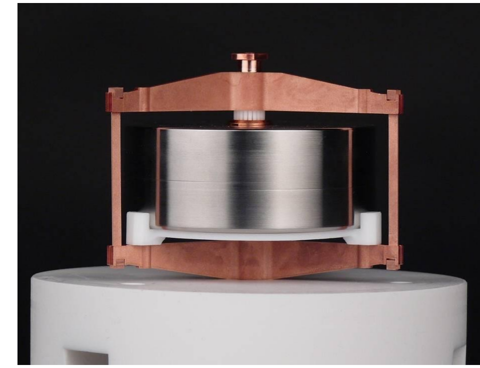


BEGe production



ONGOING

Crystal pulling at Canberra: Oakridge, TN, USA



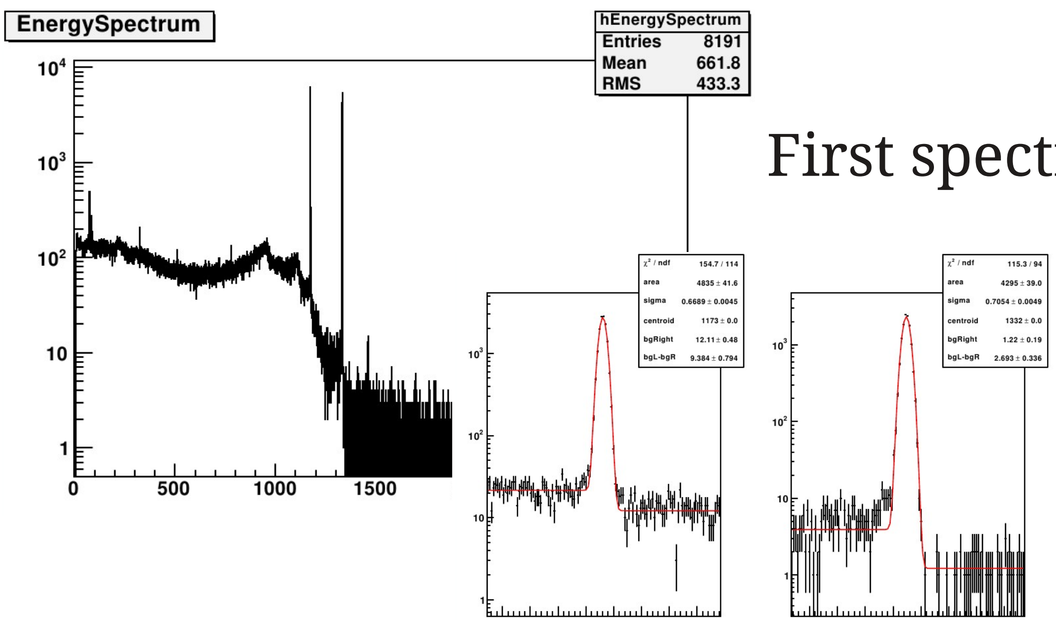
ONGOING

BEGe detector diode production: Olen, BE

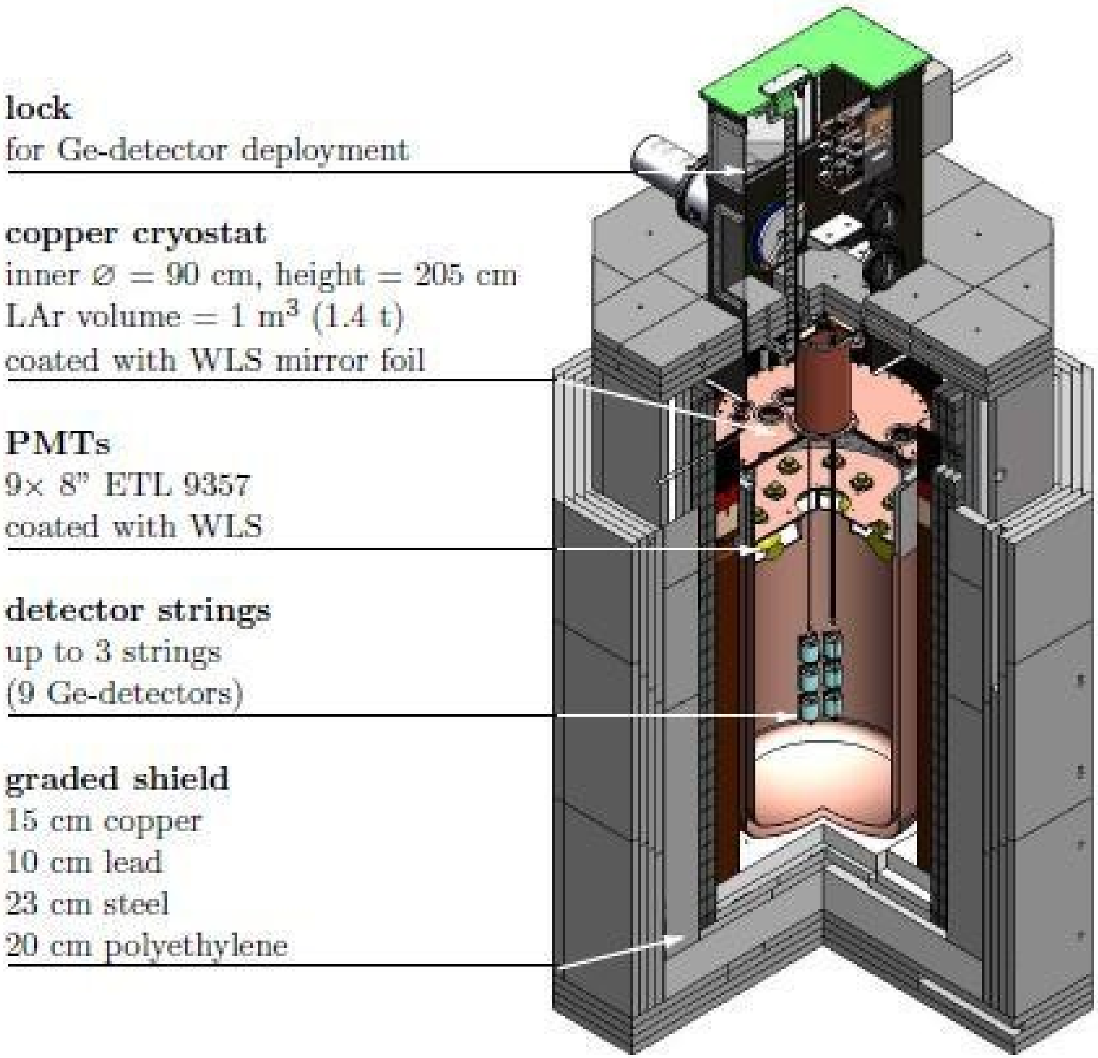
ONGOING

BEGe acceptance tests: Hades, BE

First spectra

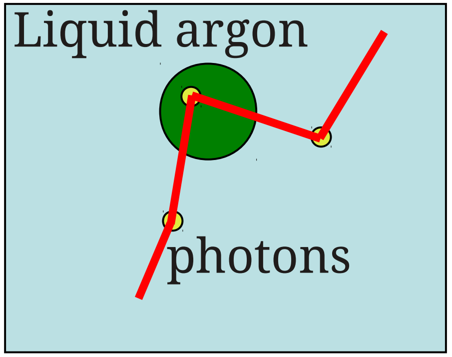


R&D liquid argon instrumentation



LarGe: Low-background test facility at LNGS

Detection of coincident liquid argon scintillation light to discriminate background



Combining **PSD of BEGe detector and LAr veto**:
Measured suppression factor for a ^{228}Th source at $Q_{\beta\beta}$: **~ 0.5·10^{4}**

Also other designs investigated → **avoid additional background!**

Summary

- GERDA Phase I started in November 2011
- Unexpectedly high contribution from ^{42}Ar decays
- Background in ROI lower than in previous experiments (~ factor 10), but slightly higher than design goal
- $2\nu\beta\beta$ spectrum well reproduced by MC (taking into account contributions from ^{39}Ar, ^{42}Ar, and ^{40}K)
- Phase II detector production and R&D on LAr scintillation light readout ongoing

The GERDA collaboration

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Backup:HdM claim

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

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

Phys. Lett. B 586, 198-212 (2004)

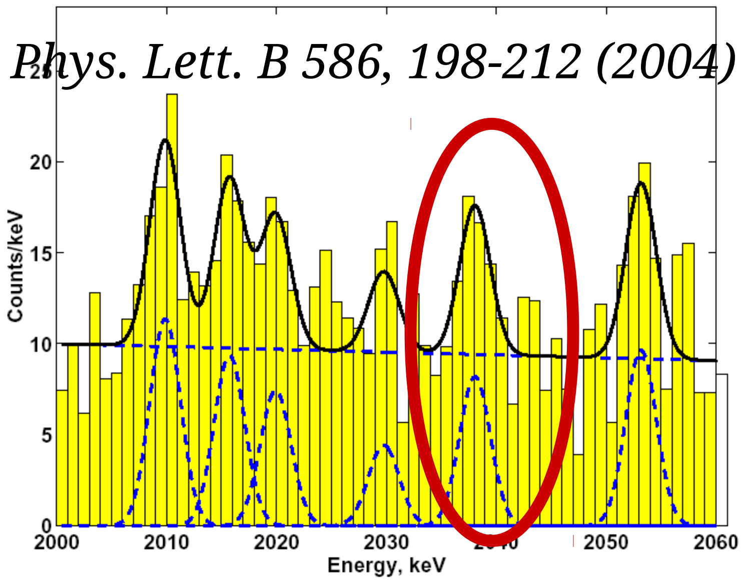


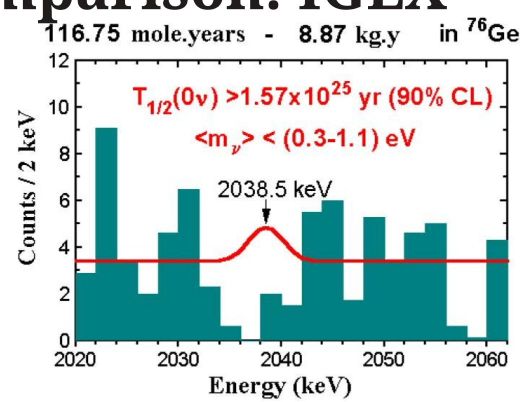
Fig. 17. The total sum spectrum of all five detectors (in total 10.96 kg enriched in ^{76}Ge), for the period November 1990–May 2003 (71.7 kg year) in the range 2000–2060 keV and its fit (see Section 3.2).

- Nov 1990 - May 2003
- 71.7 kg year
- **Bgd 0.11 counts / (keV·kg·y)**
- 28.75 ± 6.87 events (bgd:~60)
- 4.2σ evidence for 0νββ

- (0.69 – 4.18)·10^{25} y (3 σ)
- Best fit: 1.19·10^{25} y

- $m_{\beta\beta}$ = (0.24-0.58) eV
- best fit 0.44 eV

Comparison: IGEX

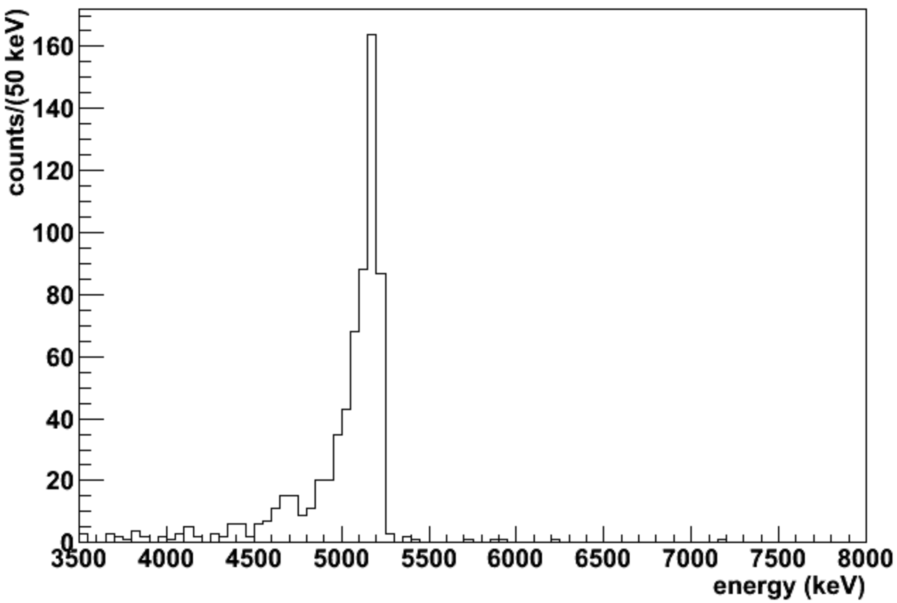


D. Gonzalez et al., NPB (Proc. Suppl.) 87 (2000) 278

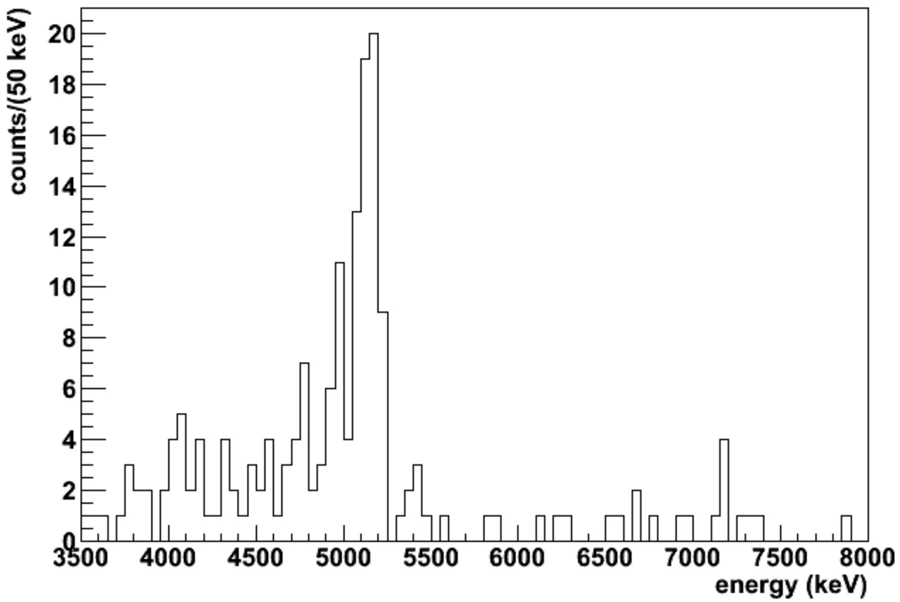
Note: statistical significance depends on background model!

Backup: α events

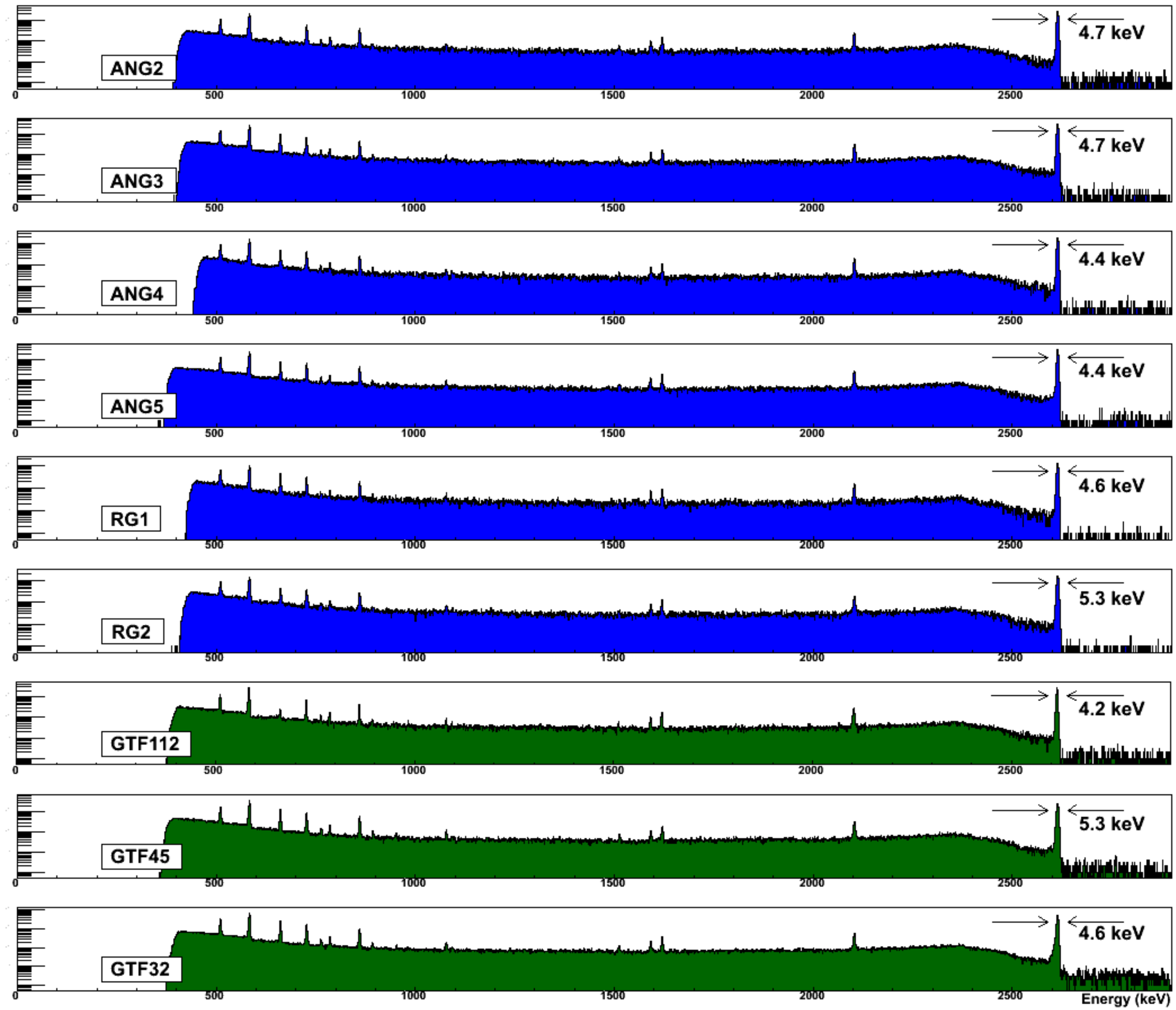
Enriched detectors, 3.801 kg × year



Natural detectors, 1.973 kg × year



Backup: calibration



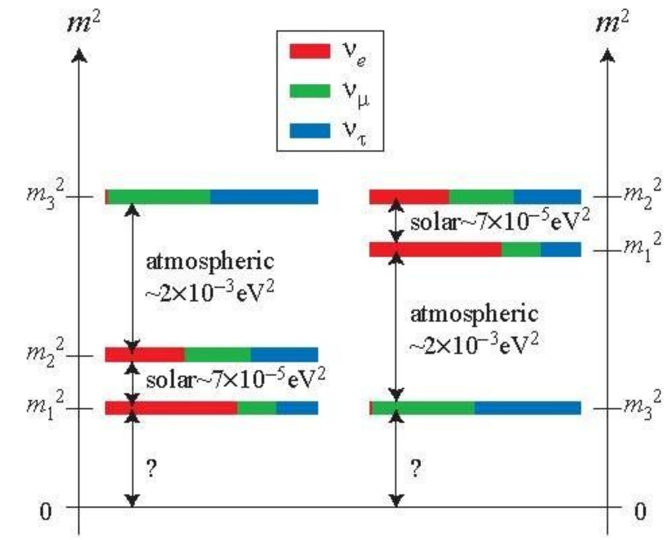
Backup:Neutrino properties

Neutrino Mixings

Weakly interacting and mass eigenstates are independant basis

$$\begin{bmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} |m_1\rangle \\ |m_2\rangle \\ |m_3\rangle \end{bmatrix}$$

$$U_{\nu i} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{bmatrix}$$



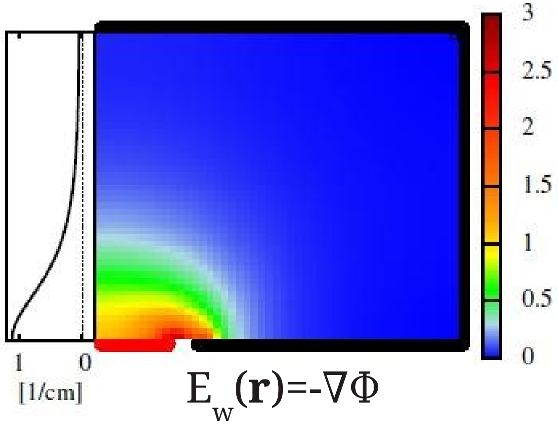
What we know:

- $m_2^2 - m_1^2 = \Delta m_{sun}^2$
- $m_2^2 - m_1^2 = \Delta m_{atm}^2$
- $\theta_{12} = \theta_{sun}$
- $\theta_{23} = \theta_{atm}$
- θ_{13}?

What we do not know:

- Absolute mass scale
- Mass hierarchy
- Phases (δ_{13}, α_{21}, α_{31})
- Nature of the neutrino mass (Dirac or Majorana)

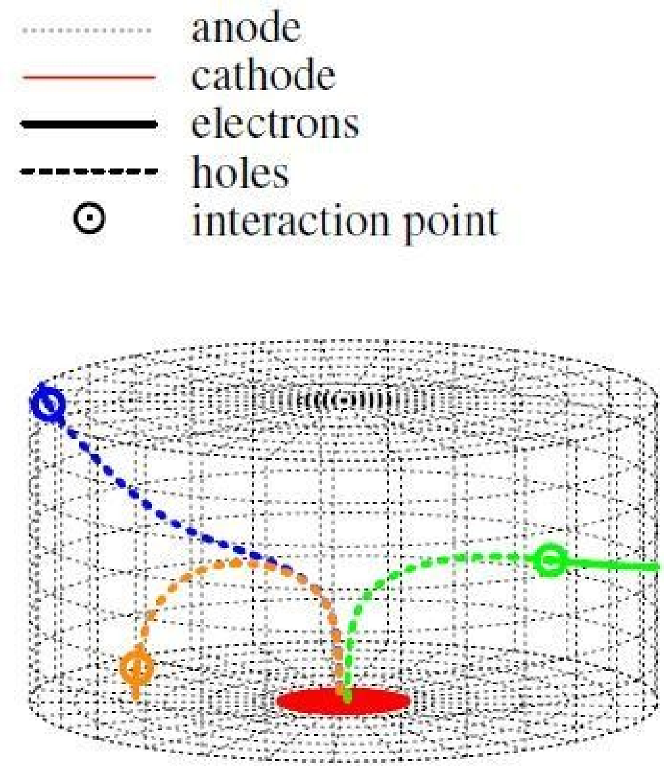
Backup:Phase II detectors

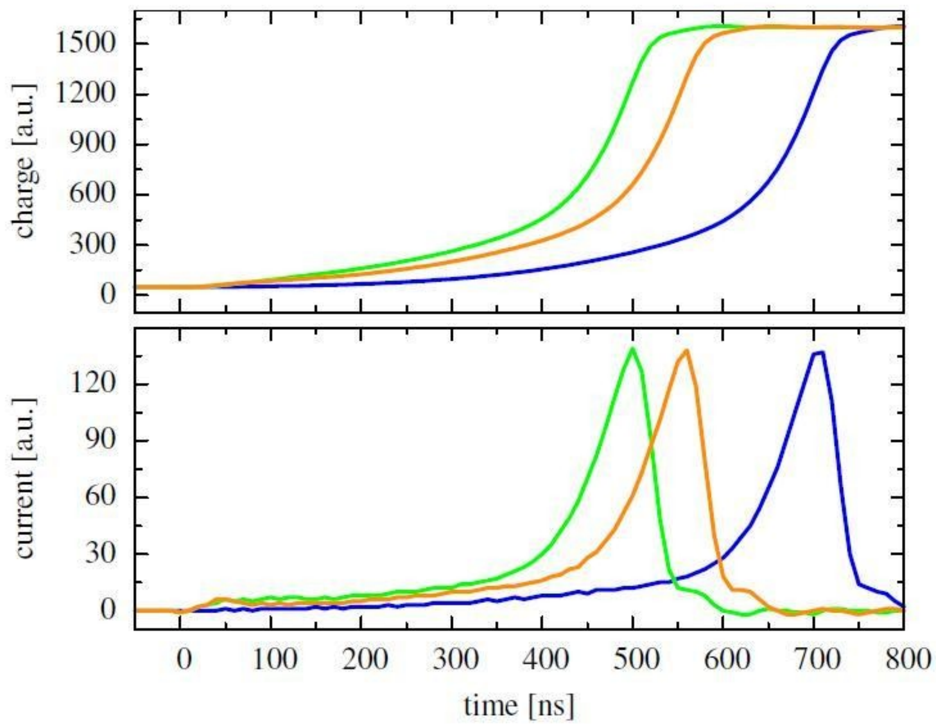


$E_w(\mathbf{r})=-\nabla\Phi$

Shockley-Ramo Theorem:

$Q(t)=-q\cdot\Phi_w(\mathbf{r}(t))$





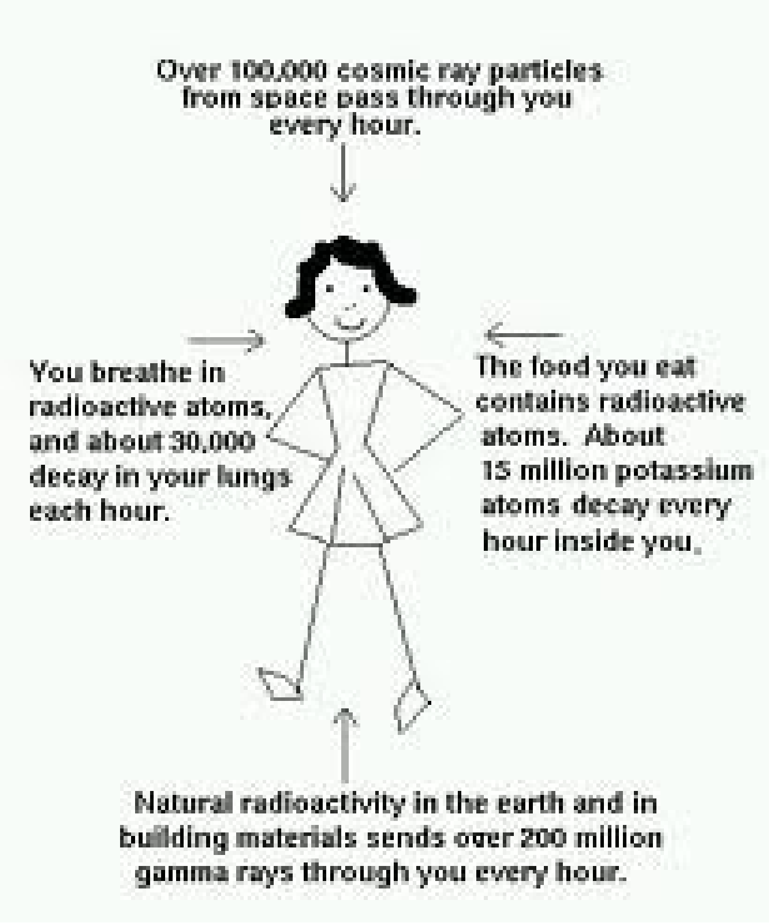
Backup: Background reduction

Key issue: Low background rate (Phase I: 1/10 HdM)

$$sensitivity \sim \epsilon \cdot a \cdot \sqrt{\frac{M \cdot t}{b \Delta E}}$$

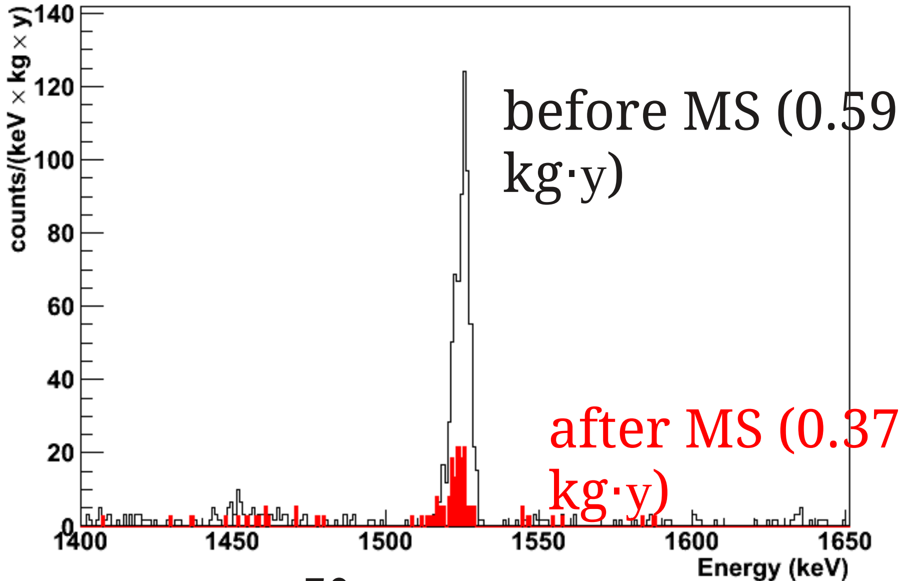
Possible backgrounds:

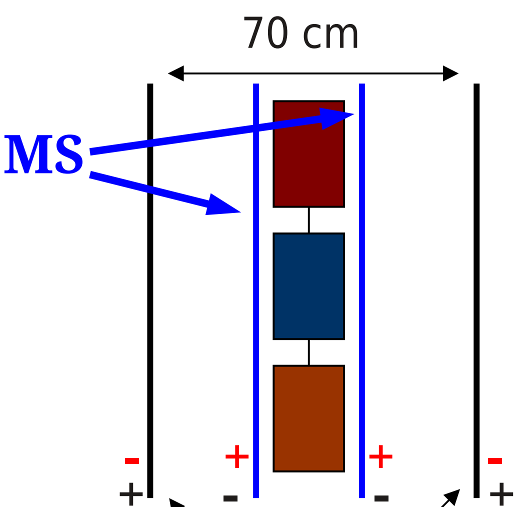
- External:
  - γ from Th and U chain
  - neutrons from spallation
  - μ from cosmic rays
- Internal:
  - cosmogenic ^{60}Co ($T_{1/2}$=5.3y)
  - cosmogenic ^{68}Ge ($T_{1/2}$=271d)
  - Radioactive surface contamination



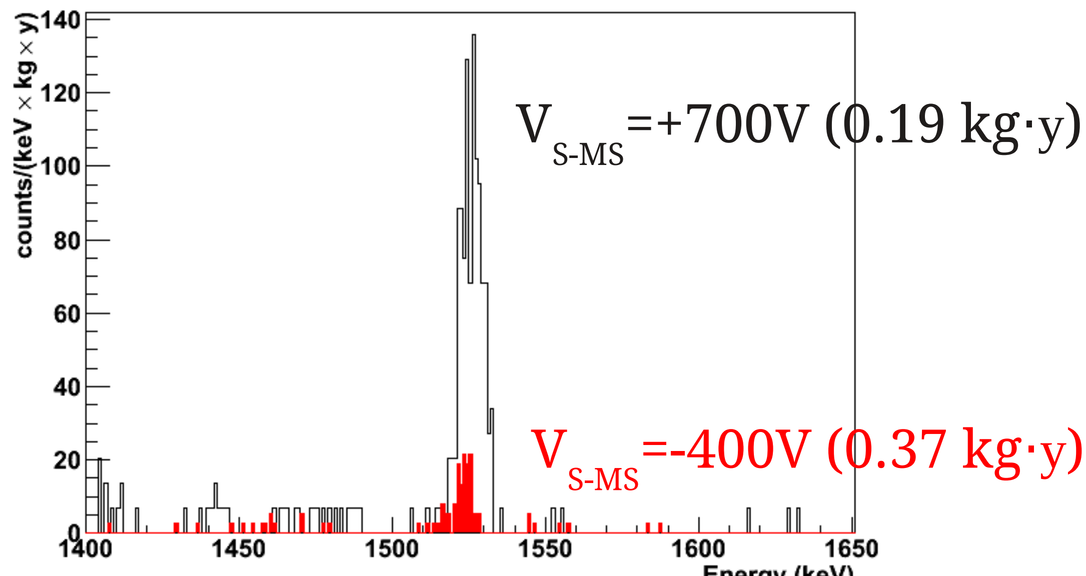
Backup: Play with the electric field

Add a mini-shroud (MS):



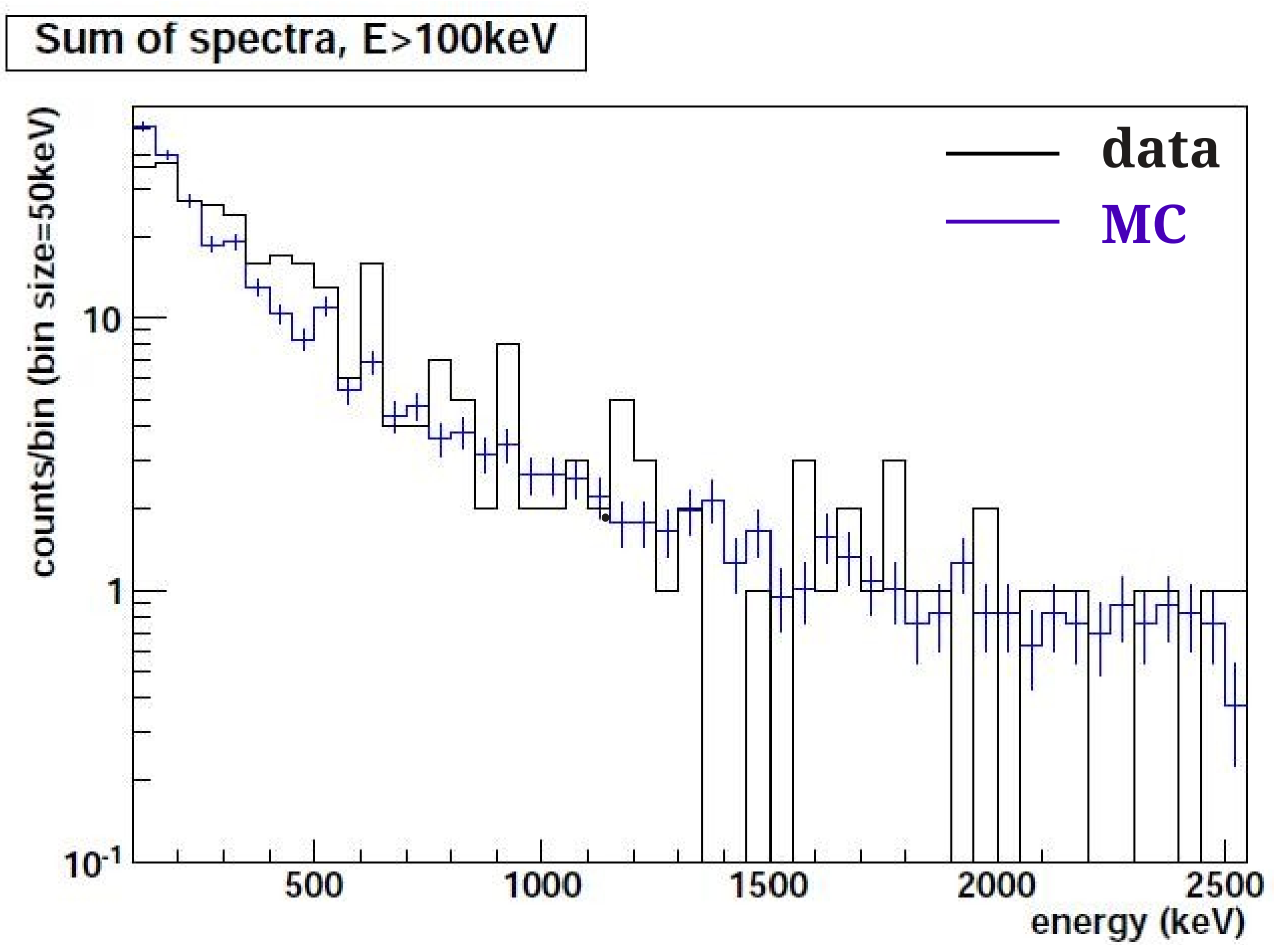


Shroud (already installed to prevent ^{222}Rn concentration)



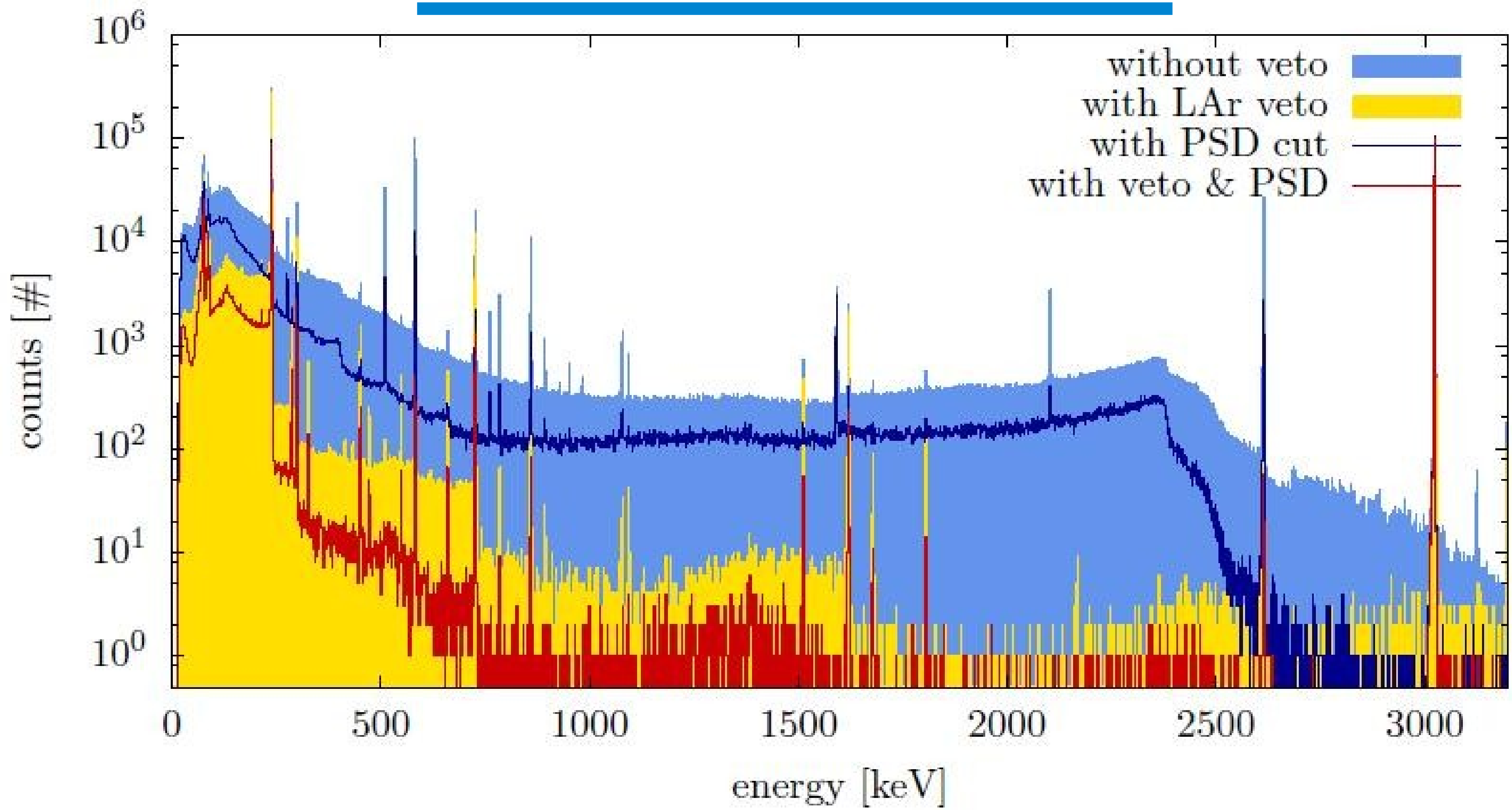
Backup: Muon induced events

Spectrum of muon-induced events in Germanium (2.09 kg·y during commissioning):



Estimate of muon veto efficiency for events causing a signal in Ge:
ε = 98.7%
Estimate of muon-induced background at $Q_{\beta\beta}$: $\mathbf{B_\mu < 2.0 \cdot 10^{-4}}$ **counts/keV·kg·y**

Backup: R&D liquid argon instrumentation



Operation of Phase II proto-type detector in LarGe:

Combining **PSD of BEGe detector and LAr veto**:

Measured suppression factor for a ^{228}Th source at $Q_{\beta\beta}$: **~ 0.5·10^4**

Also: successful read out scintillation light with fibers coupled to SiPMs