Search for Neutrinoless Double Beta Decay of ^{76}Ge: latest results from GERDA and a novel detector design for GERDA & LEGEND

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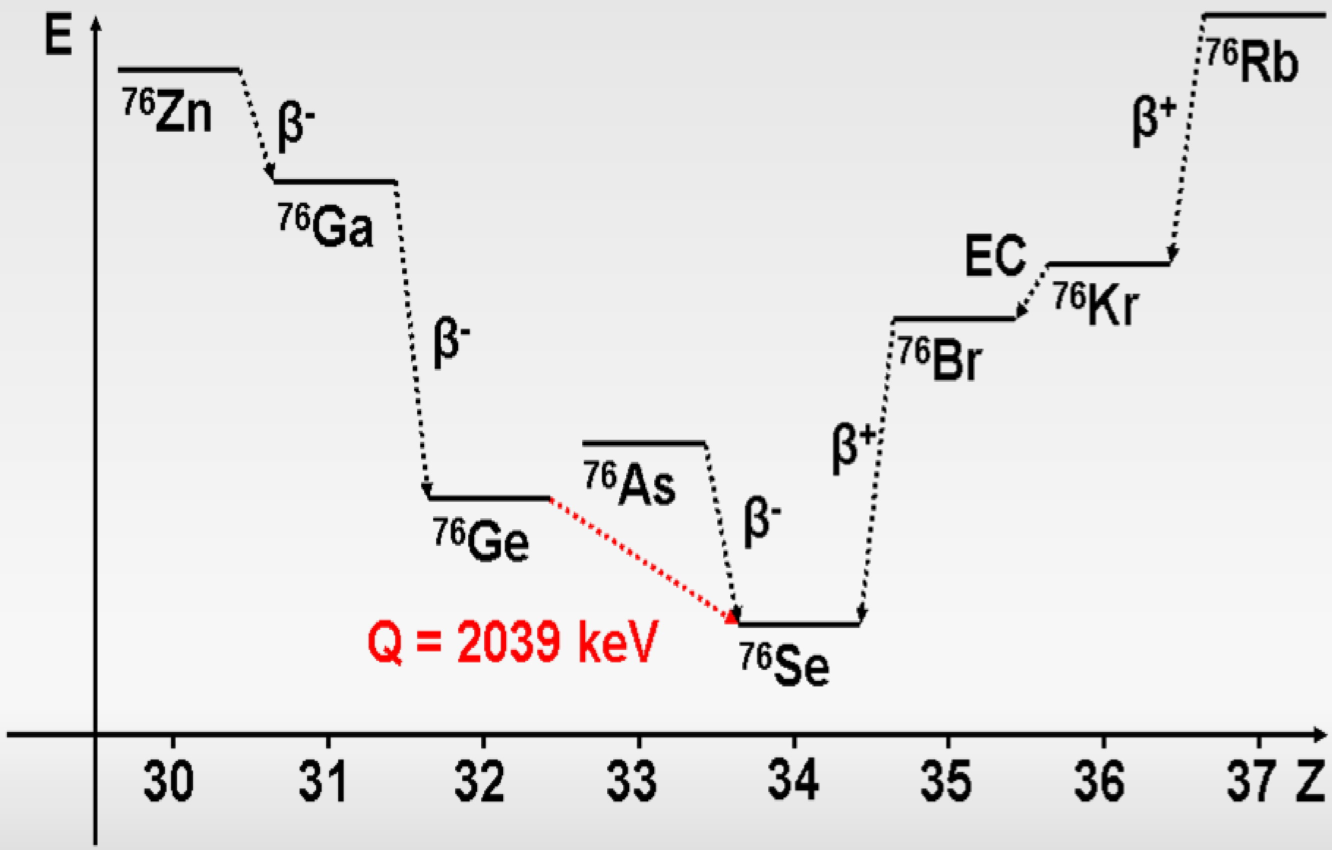
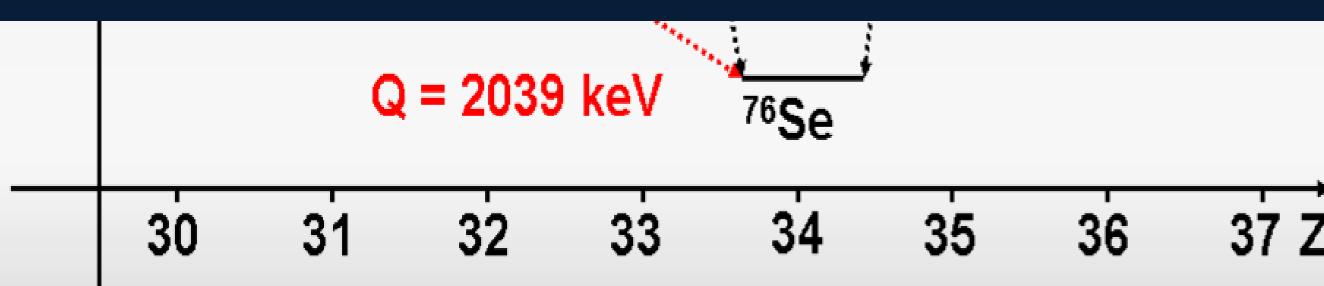


Search for Neutrinoless Double Beta Decay of ^{76}Ge: latest results from GERDA and a novel detector design for LEGEND

GERDA

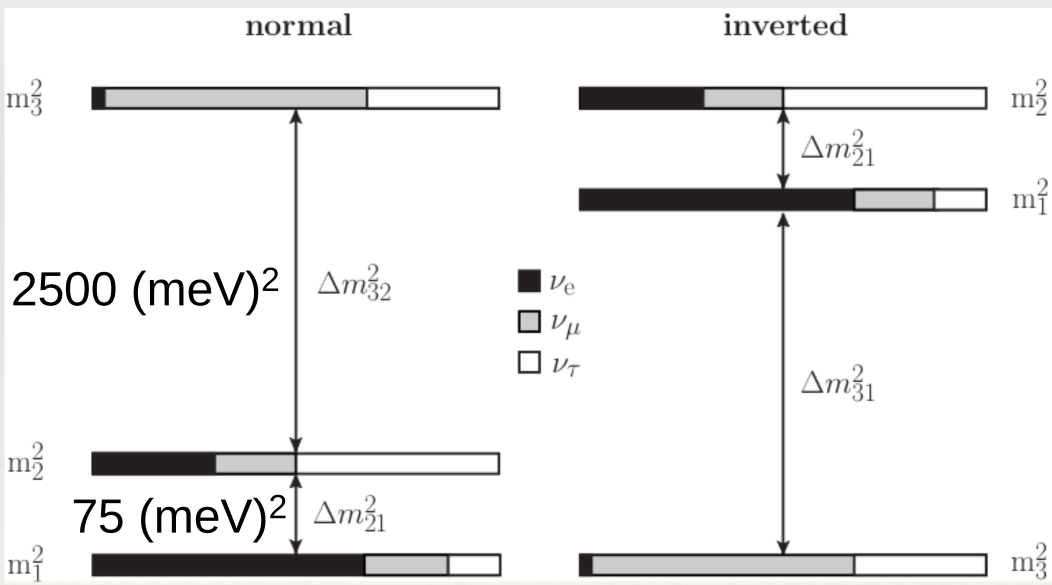
LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

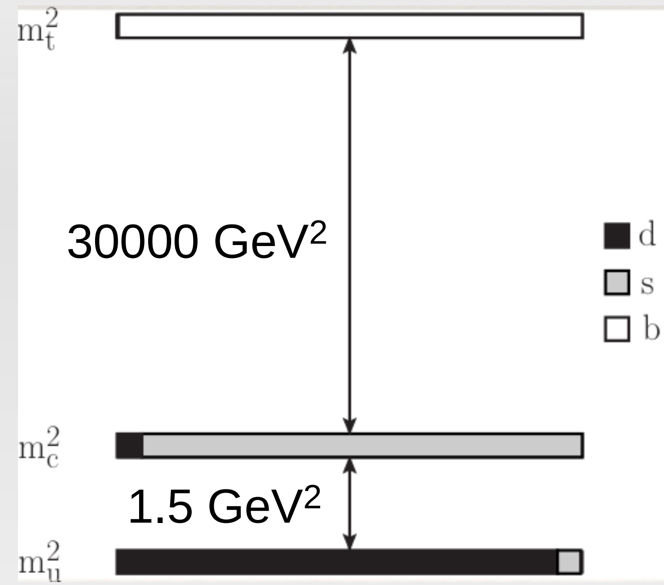


Neutrino physics

neutrinos: mass splitting and mixing



quarks



Neutrino flavor physics: underlying symmetry ?

- mixing matrix U and $|\Delta m^2|$, quite well known but: $\theta_{23} = 45^o$ or small deviation from 45^o ?
- sign of Δm_{31}^2 ?
- CP phase = $3\pi/2$? (likely not relevant for leptogenesis)
- absolute mass scale ?

major impact {

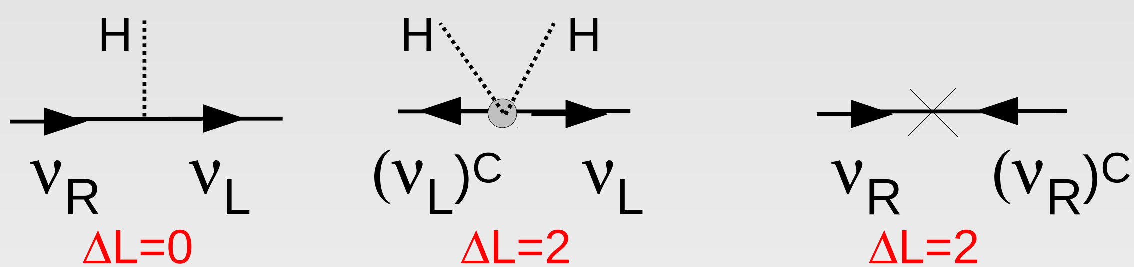
Is mixing matrix unitary (sterile neutrinos, ...)?

Are neutrinos Majorana or Dirac particles (lepton number violation)?

Neutrino mass: Lepton number violation?

possible neutrino mass terms (ν has no electric charge)

$$L_{Yuk} = m_D\, \bar{\nu}_L\, \nu_R + m_L\, \bar{\nu}_L\, (\nu_L)^C + m_R\, (\bar{\nu}_R)^C\, \nu_R + h.c.$$



ν_L couples to Standard Model W,Z bosons, ν_R does not (SM singlet)

m_D ~ normal Dirac mass term

m_L, m_R new physics

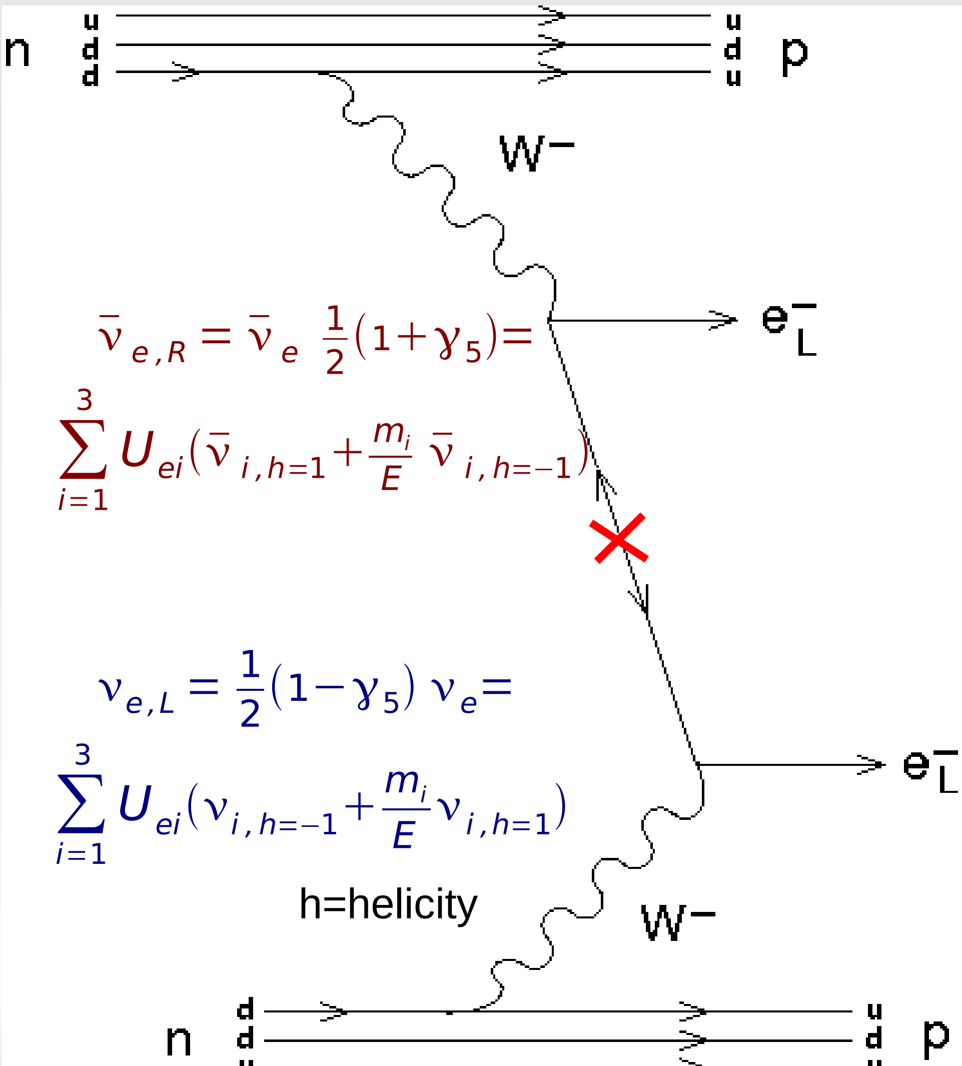
eigen vector $N \sim \nu_R + (\nu_R)^C$ $\nu \sim \nu_L + (\nu_L)^C$ Majorana particles

mass (m_L ~0) m_R m_D^2 / m_R

in general: expect ν to be Majorana particles → L violation

How to observe ΔL=2: 0νββ

Look for a process which can only occur if neutrino is Majorana particle



coupling strength ~ $m_{\beta\beta} = \sum_{i=1}^{3} U_{ei}^2 m_i$

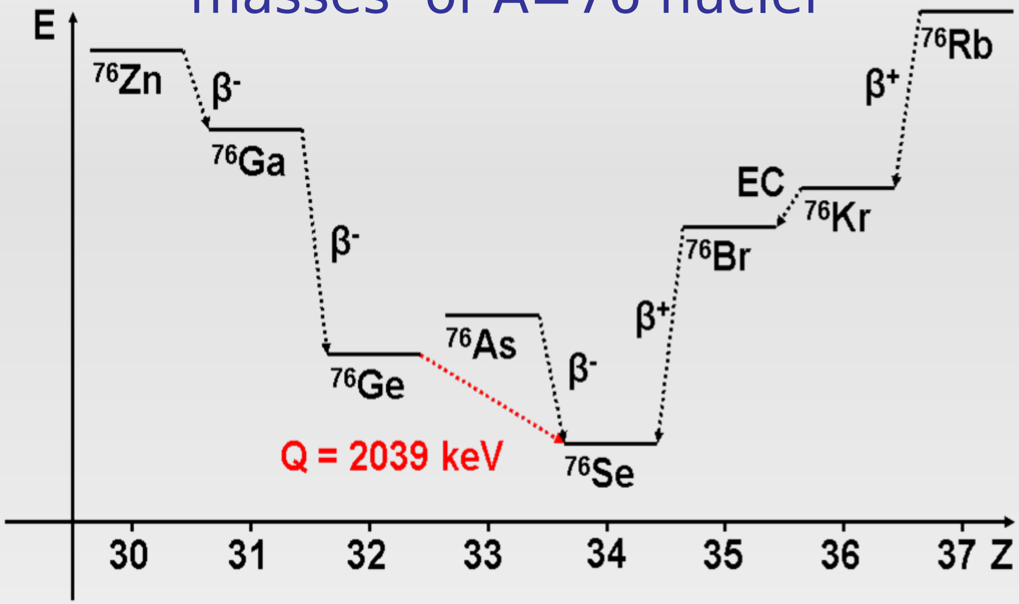
function of
- neutrino mixing parameters
- lightest neutrino mass
- 2 Majorana phases

also possible: heavy N exchange

→ coupling strength ~ $\sum_{i=1}^{3} V_{ei}^2 / M_i$

Neutrinoless double beta decay

masses of A=76 nuclei



"single" beta decay not allowed

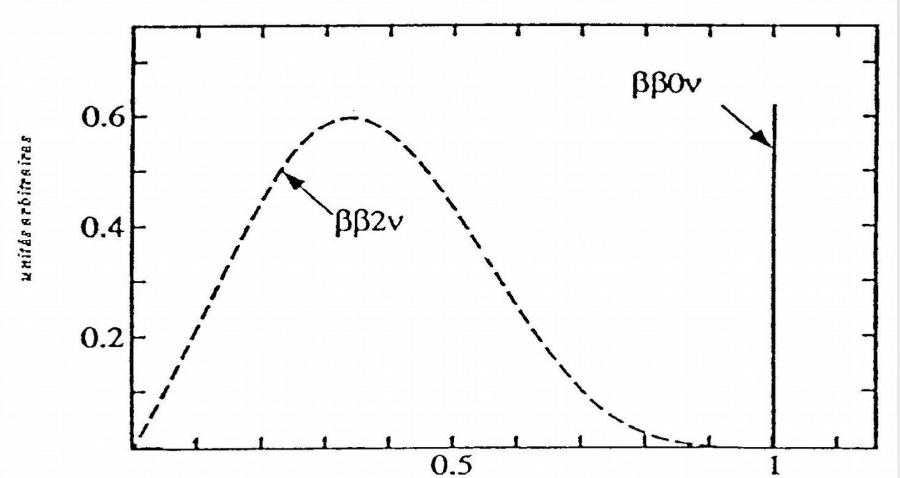
→ only "double beta decay"

$(A,Z) \rightarrow (A,Z+2) + 2\,e^- + 2\bar{\nu}$ $\Delta L=0$

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

0νββ: search for a line at Q value of decay

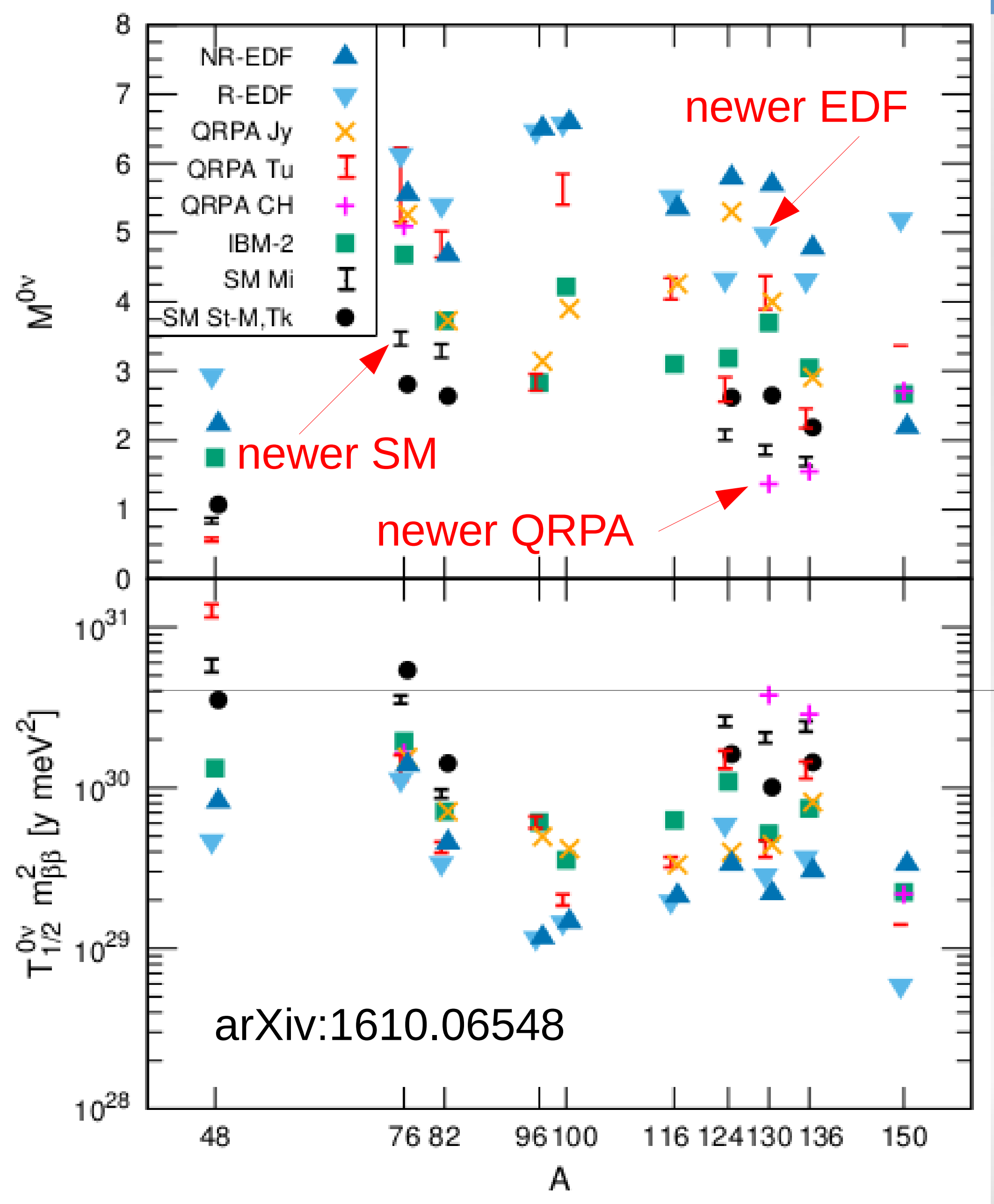
experimental signature for ββ



sum electron energies / $Q_{\beta\beta}$

Note: similar process in principle also observable at accelerator or reactor or ... but for light Majorana neutrino:
- background too high
- flux too low compared to Avogadro N_A

Expected $T_{1/2}$ for different matrix elements



$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu} \left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

$T^{0\nu}_{1/2}$ = measured experimentally

$G^{0\nu}$ = phase space factor ~ Q^5

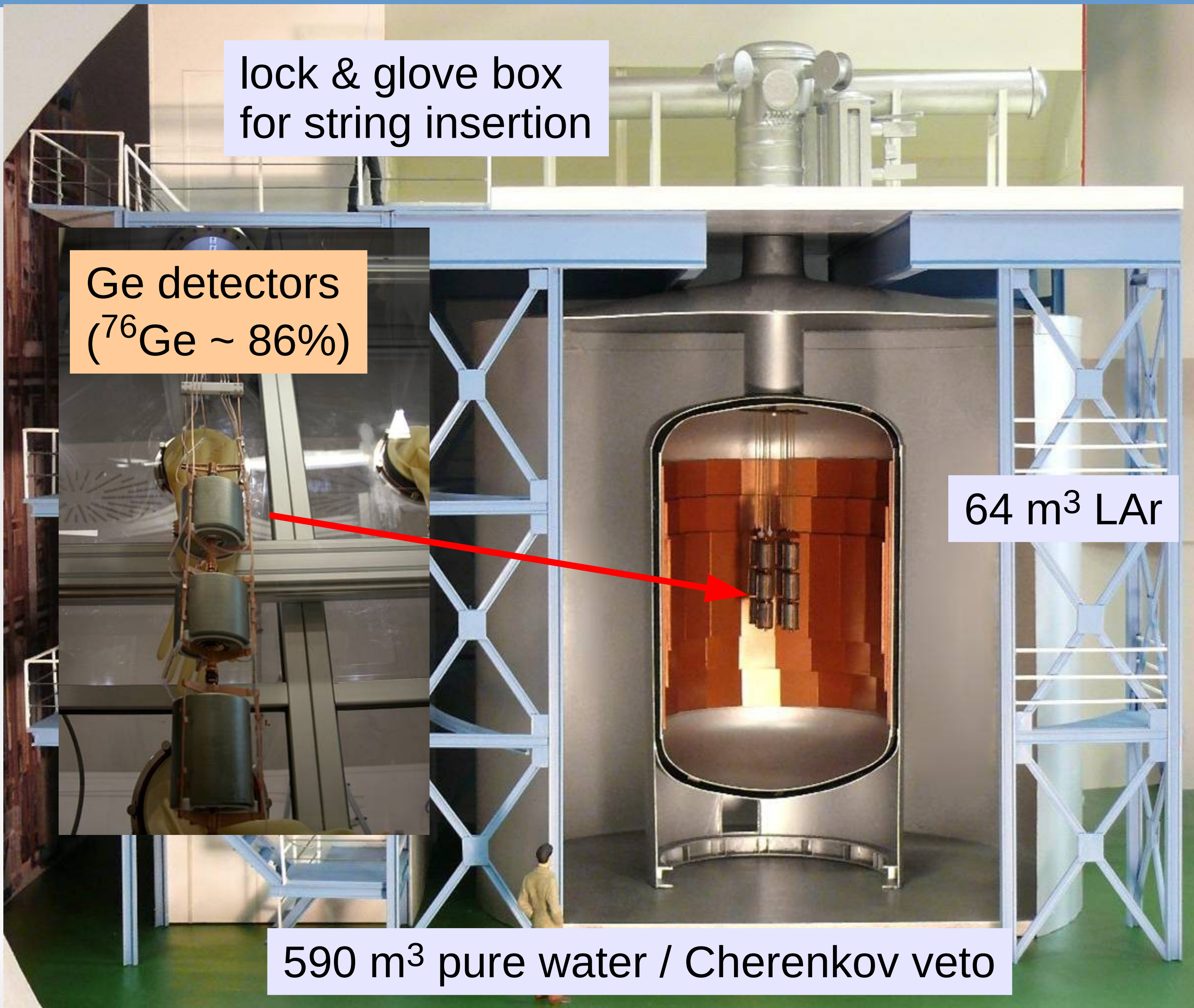
$M^{0\nu}$ = nuclear matrix element

m_e = electron mass

10^{28} yr for 20 meV effective mass
0.6 ^{76}Ge decays per t*yr exposure
0.3 ^{136}Xe decays per t*yr exposure
(before enrichment fraction & cuts)
→ background free conditions required

No favored isotope considering spread of nuclear matrix elements

GERDA: Ge in LAr @ Gran Sasso



EPJ C73 (2013) 2330

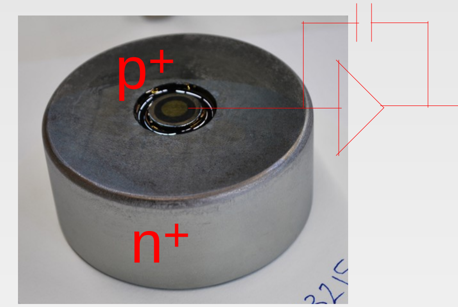
Phase I (2011-13):

$T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.)

^{76}Ge $0\nu\beta\beta$ decay, PRL 111 122503

Phase II:

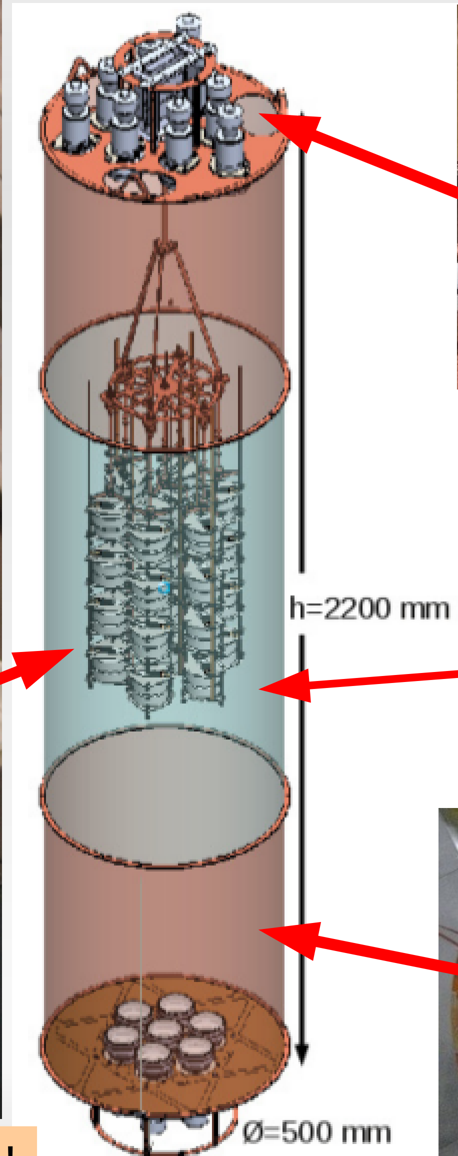
2x Ge mass (30 BEGe det.)

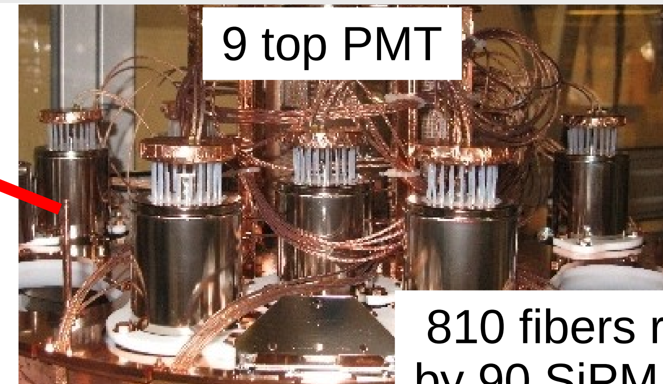


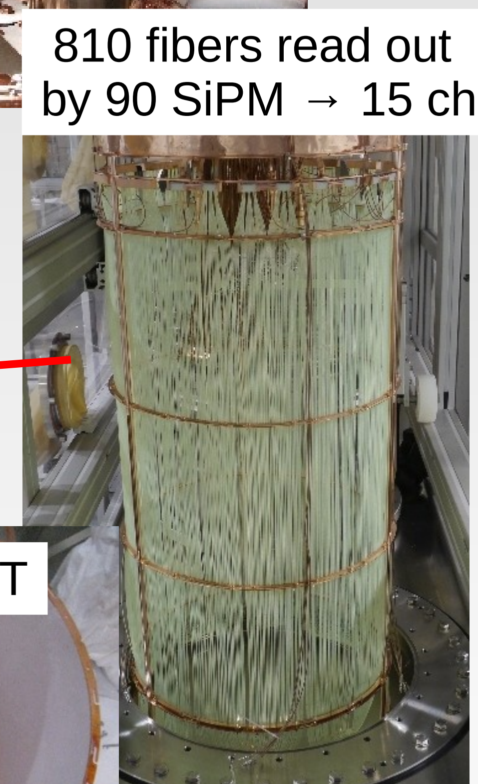
LAr scint. light readout

started end 2015

Phase II start December 2015

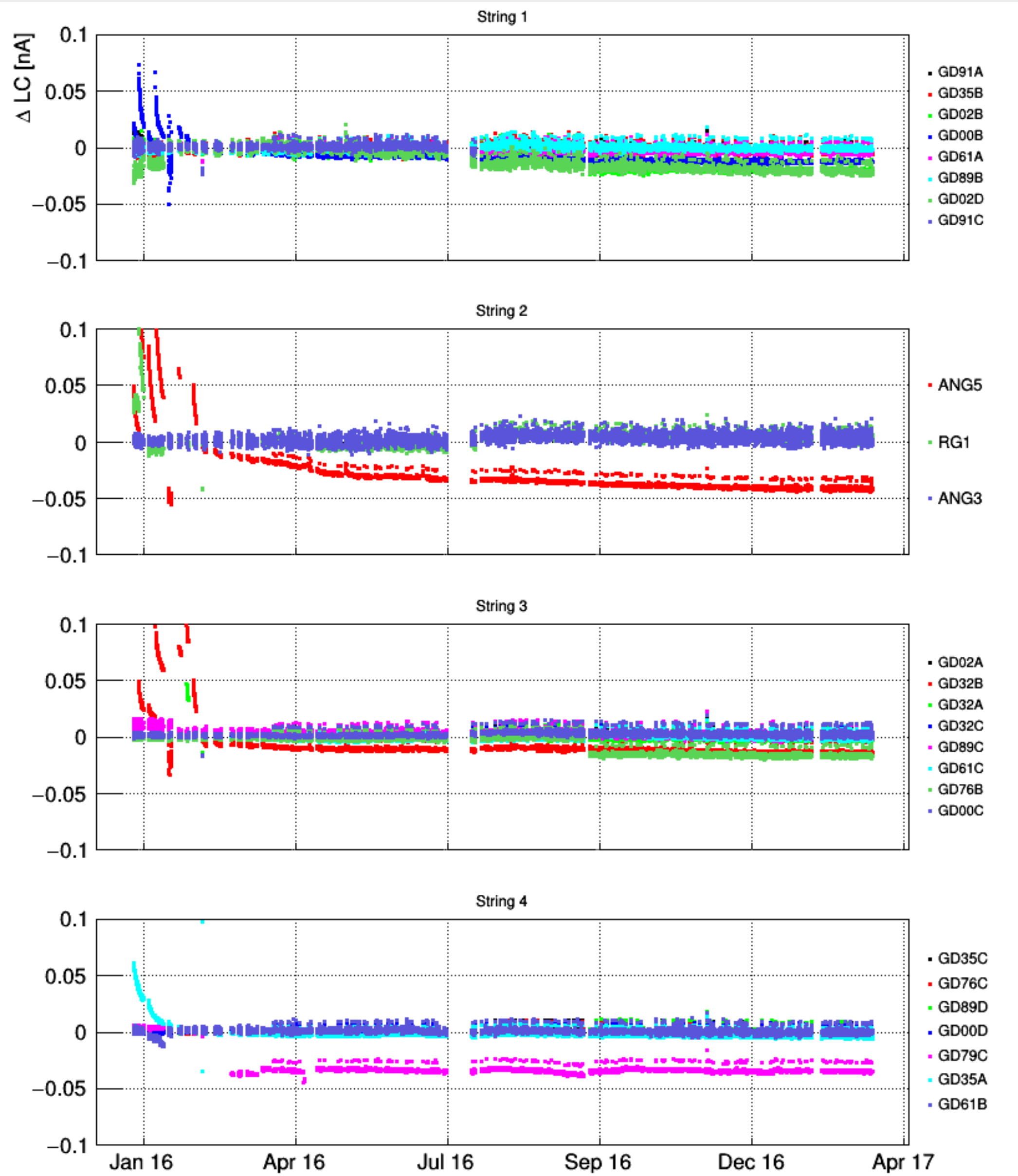


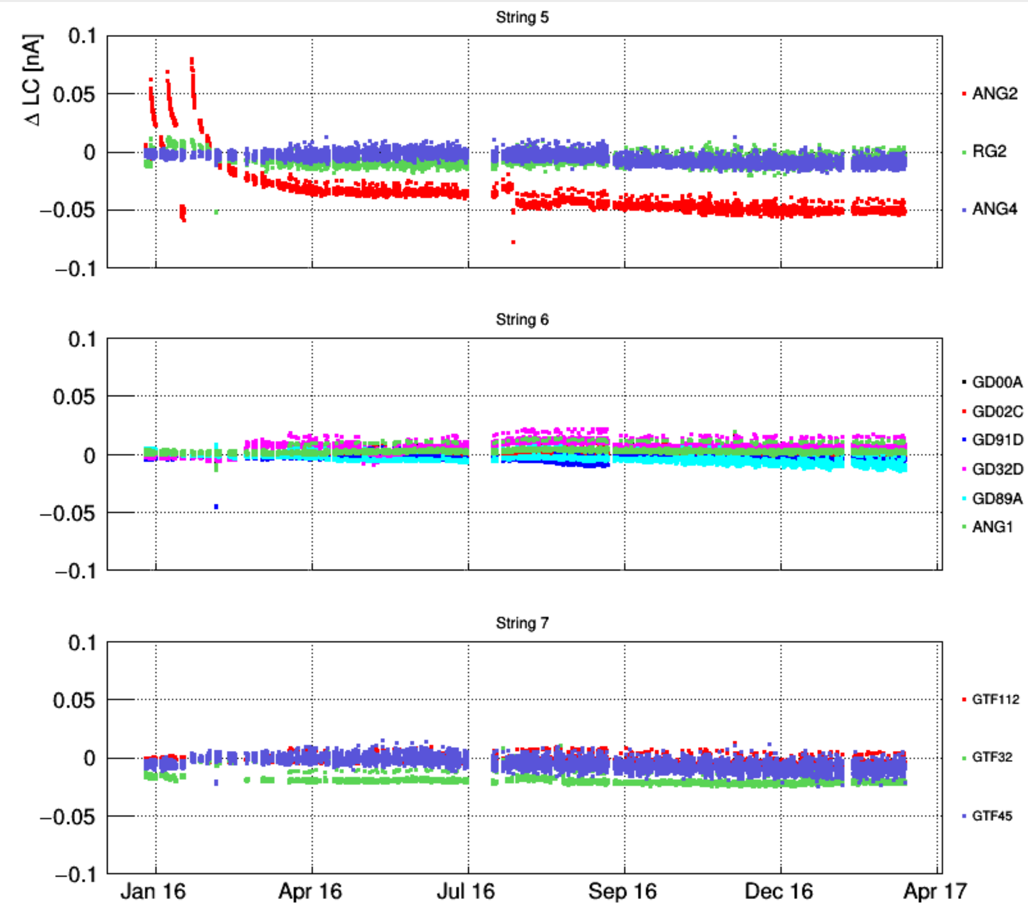




2015: all Ge + LAr veto ch. 'working' !!!

Stability Ge detector leakage current



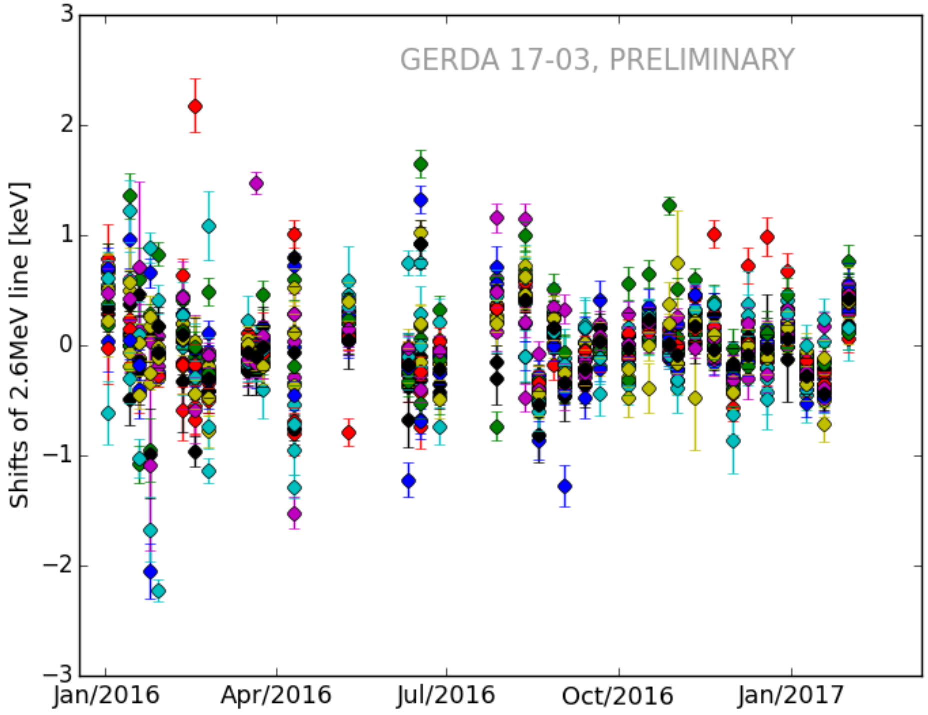


initially: some detector higher current after calibration,
very stable → operation in liquid Ar ok

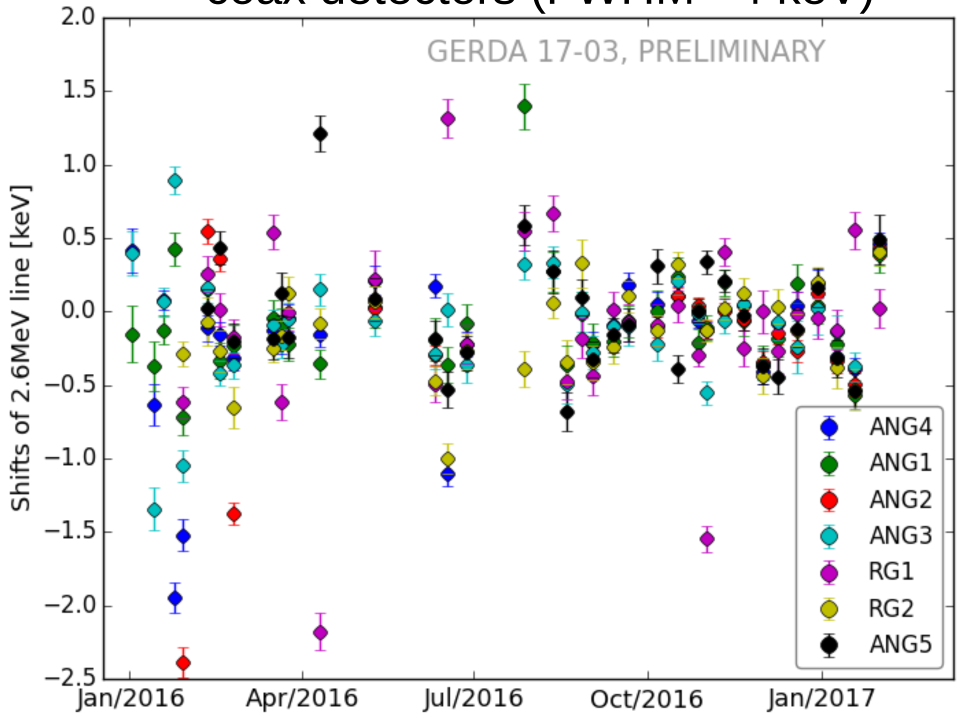
Stability Ge detector energy scale

Method: ^{228}Th calibration every ~10 days,
use calibration constant of previous calibration to reconstruct 2615 keV γ peak position,
→ shift of peak relative to previous calibration for every detector,
also: inject test charge at input of electronics every 20 s → stability between calibrations

BEGe detectors (FWHM ~ 3 keV)

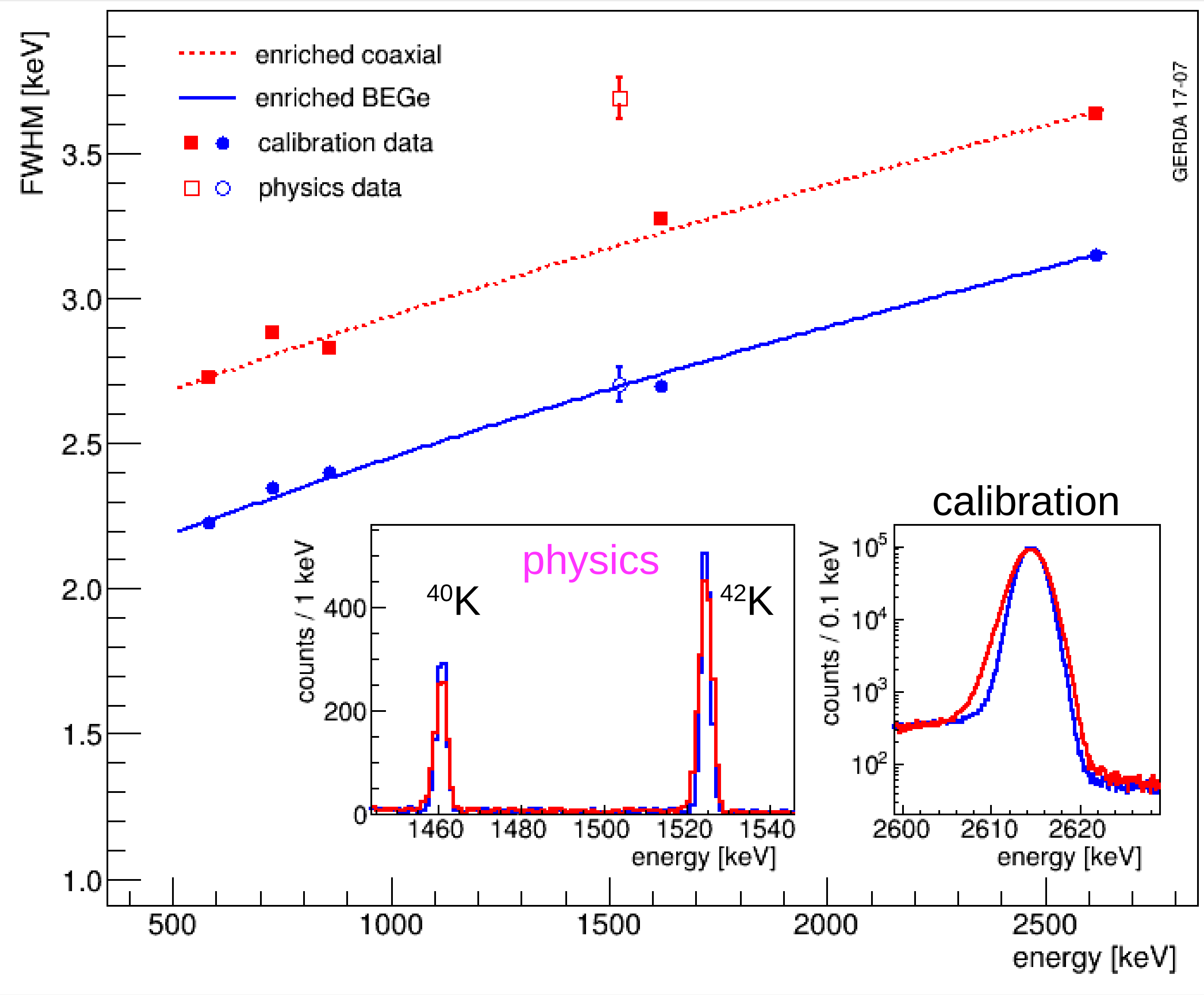


coax detectors (FWHM ~4 keV)



shifts typically < 1 keV → ok for 0νββ search to add entire period

Energy resolution: calibration + physics



physics data: 2 strong γ lines from ^{40}K and ^{42}K decays

→ compare expected resolution with physics data

→ add correction to expected resolution at $Q_{\beta\beta}$ = 2039 keV for 0νββ analysis (peak fit)

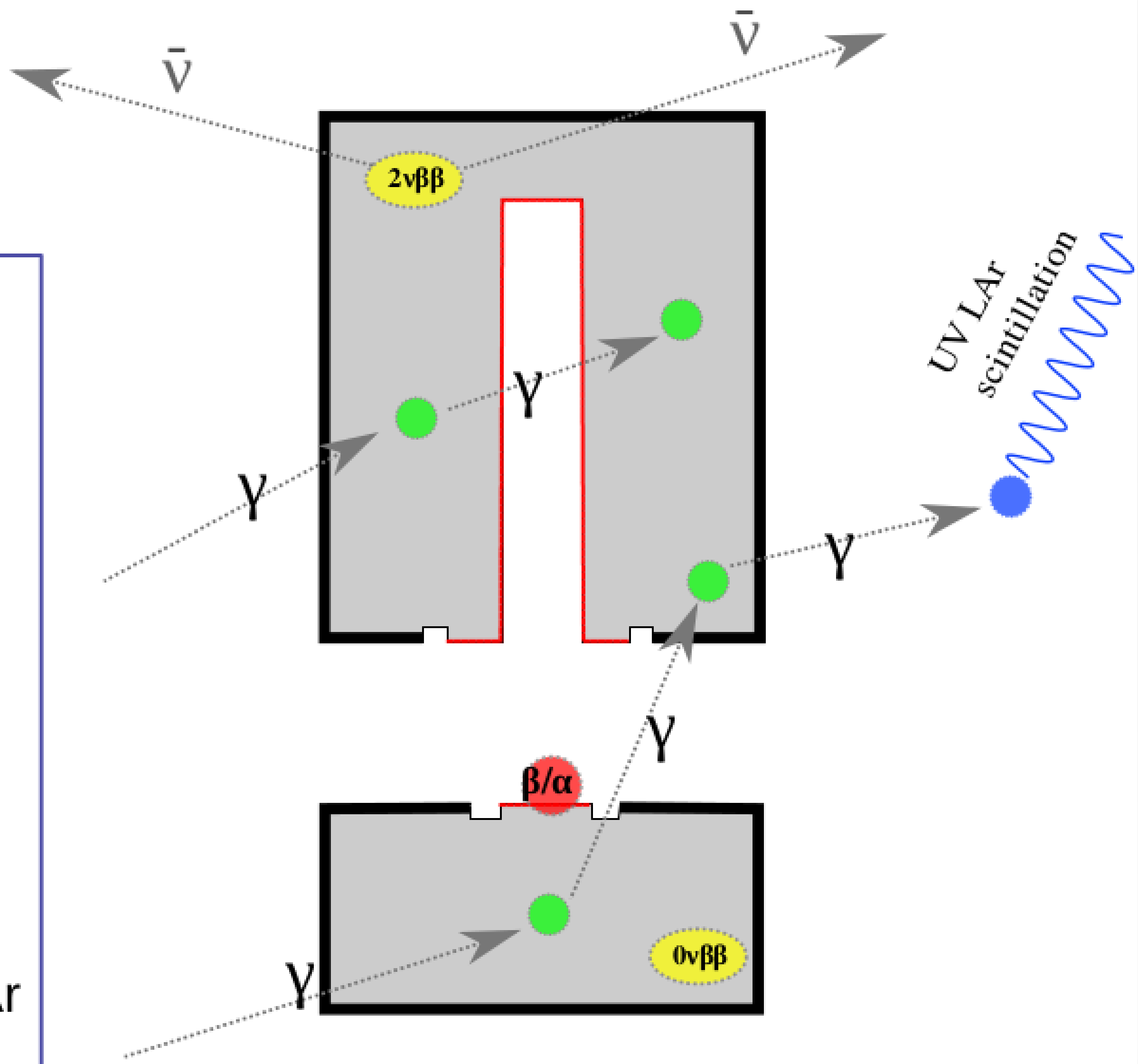
Background reduction techniques

ββ event

- local energy deposition (SSE) in single detector

background event

- energy deposition in multiple locations (MSE) in single detector or on detector surface (α/β)
  → **pulse shape discrimination**
- coincident energy deposition in more than one detector
  → **detector anti-coincindence**
- additional energy deposition in LAr
  → **LAr veto**



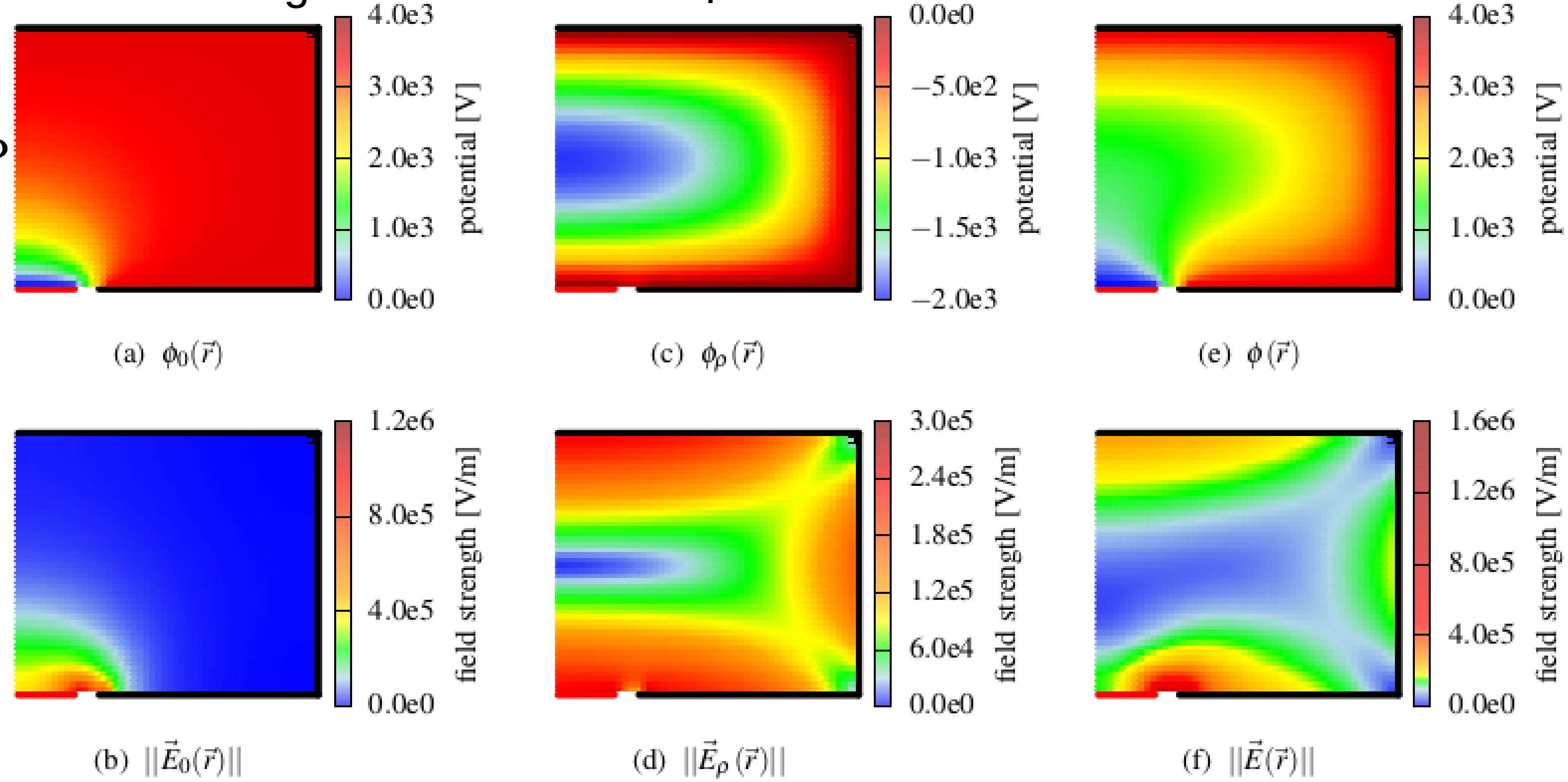
slide by Victoria Wagner

Pulse shape analysis BEGe: E field

external voltage | intrinsic impurities ~10^{10}/cm^3 | sum

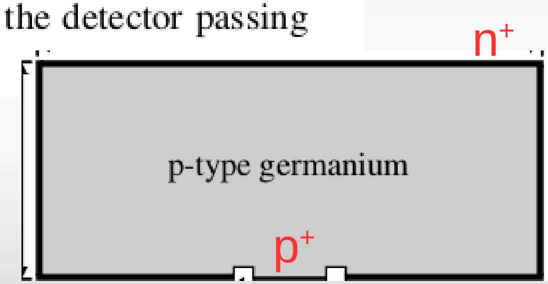
potential Φ

field strength E



from JINST 6 (2011) P03005

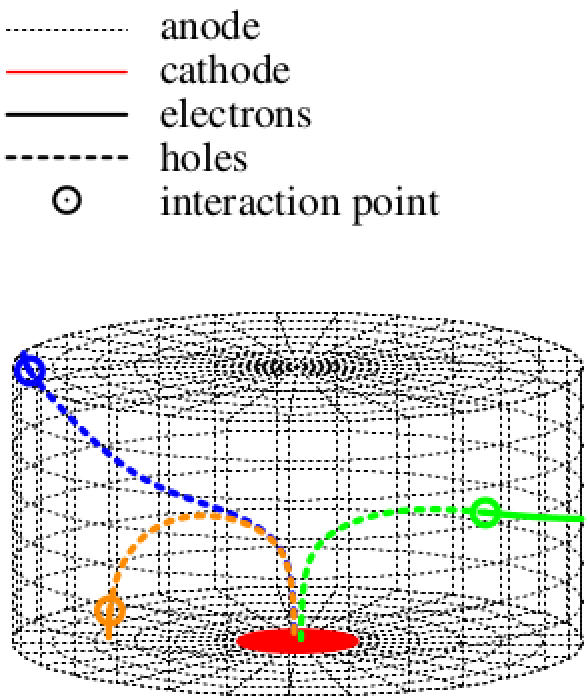
Figure 3. Simulated electric potential and electric field strength for different configurations of a BEGe detector. In (a) and (b) the electrode potential is considered, in (c) and (d) the charge distribution, and in (e) and (f) the sum of the two contributions. The plots show half of a vertical section of the detector passing through the symmetry axis. The cathode is drawn in red and the anode in black.

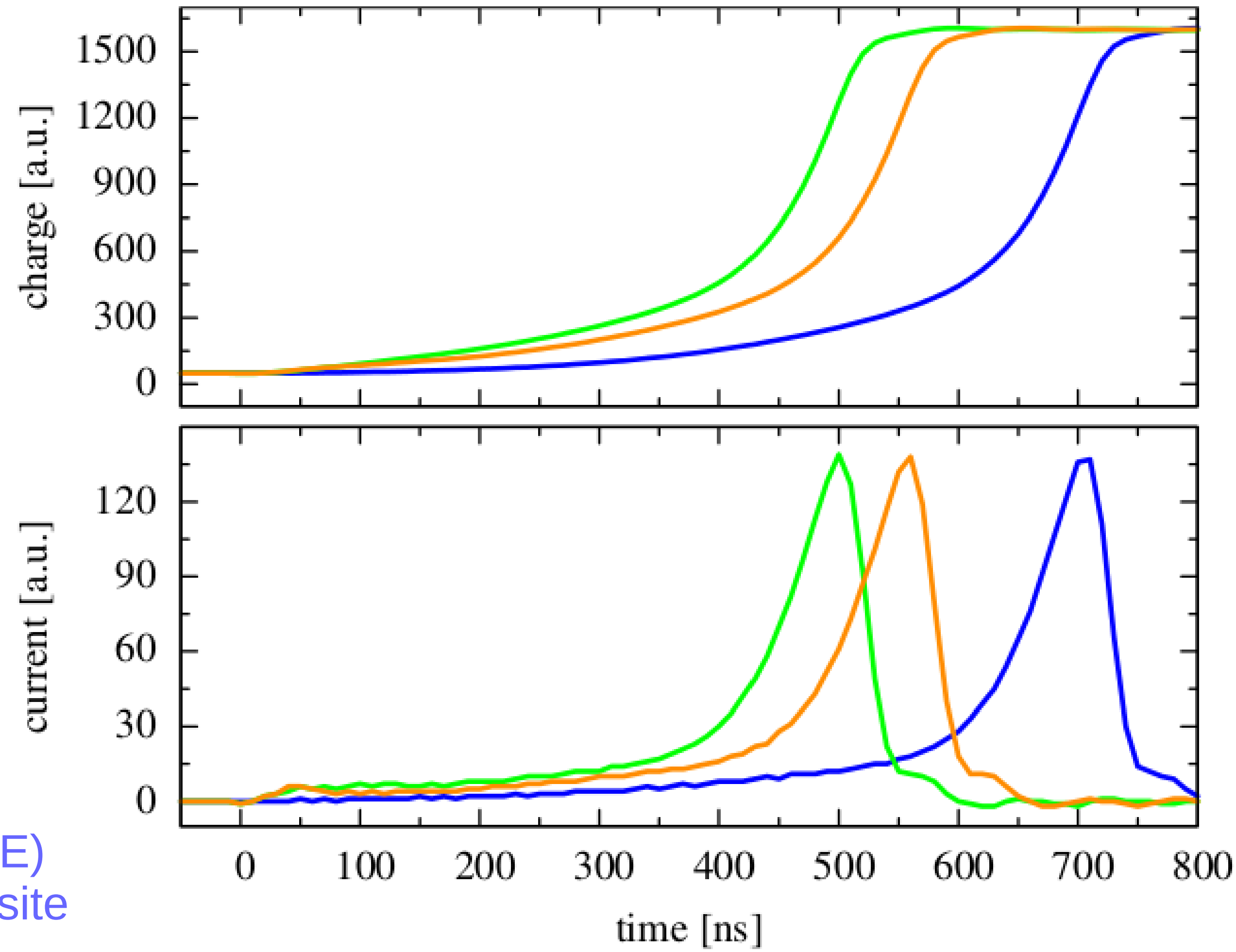


$\text{current signal} = q \cdot v \cdot \nabla \Phi$ depends on external potential (only)

q= charge, v = velocity
(Shockley-Ramo theorem)

Pulse shape analysis: charge drift





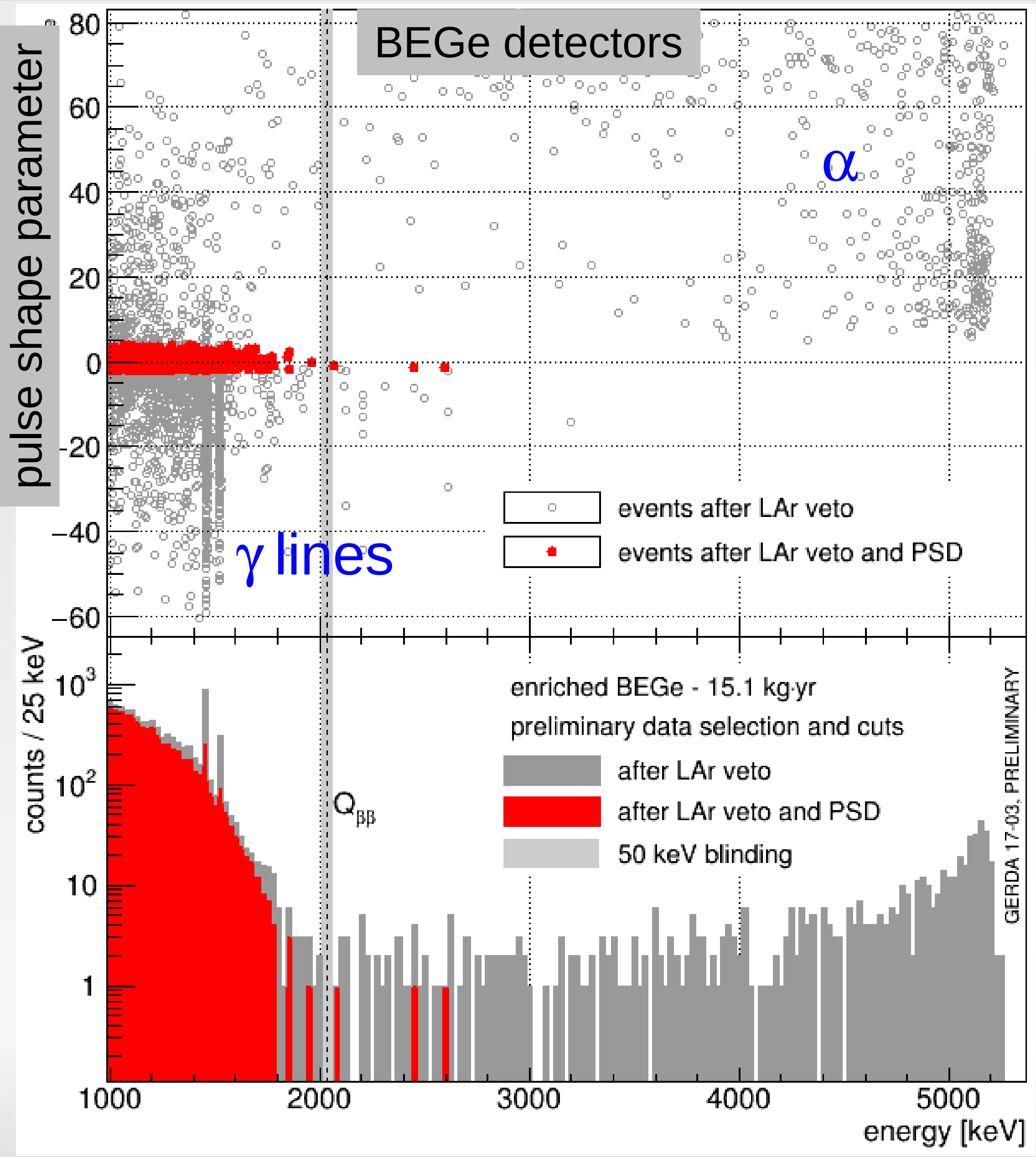
→ maximum current / energy (= A/E)
to discriminate multi-site vs single-site

Note: also good for α and β surface events!!!

p+: electron drift → larger drift v → larger A/E

n+: p-n contact region → electric field small → diffiusion → longer drift → A/E smaller

Pulse shape analysis: BEGe



0νββ proxies = 2νββ &

Double Escape Peak of 2615 keV γ

(γ + A→ e^+ e^- with 2x511 keV escape)

all α (surface) events removed

γ lines suppressed by factor ~6

0νββ signal efficiency 87±2 %

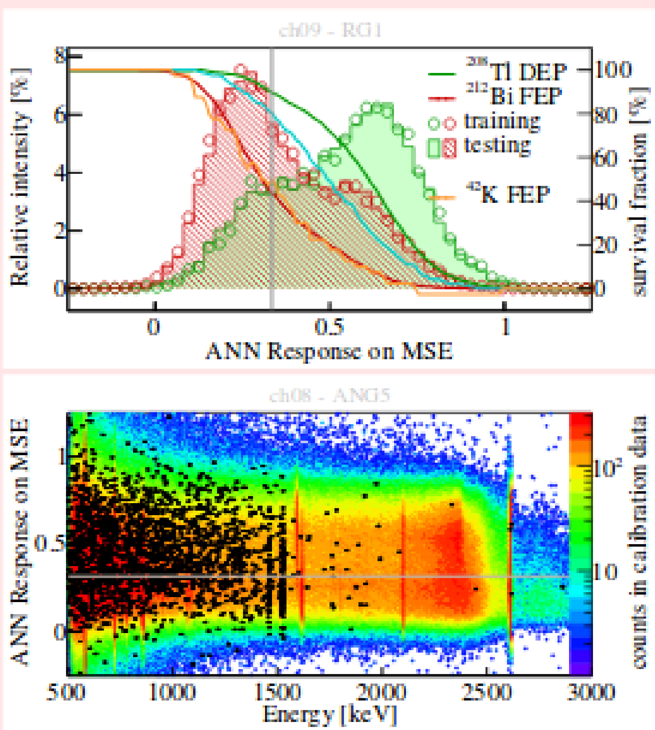
2νββ acceptance 85^{+2}_{-1} %

Pulse shape analysis: coax

Artificial Neural Network

- ROOT integrated TMVA toolkit (i.e. TMlpANN)
- 50 input variables: times where charge pulse is at $1\,\%$, $3\,\%$, ..., $99\,\%$ of maximum height

ANN on MSE



training / testing of supervised learning algorithm

^{228}Th calibration ←

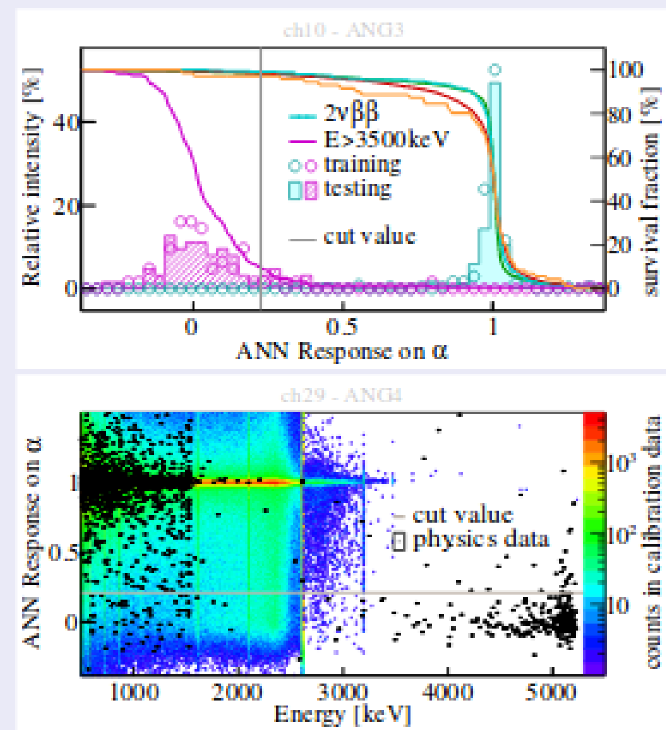
physics data →

adjust cut to survival fraction

$90\,\%$ @ DEP ←

$10\,\%$ @ $\gtrsim 3500\,$keV →

ANN on α

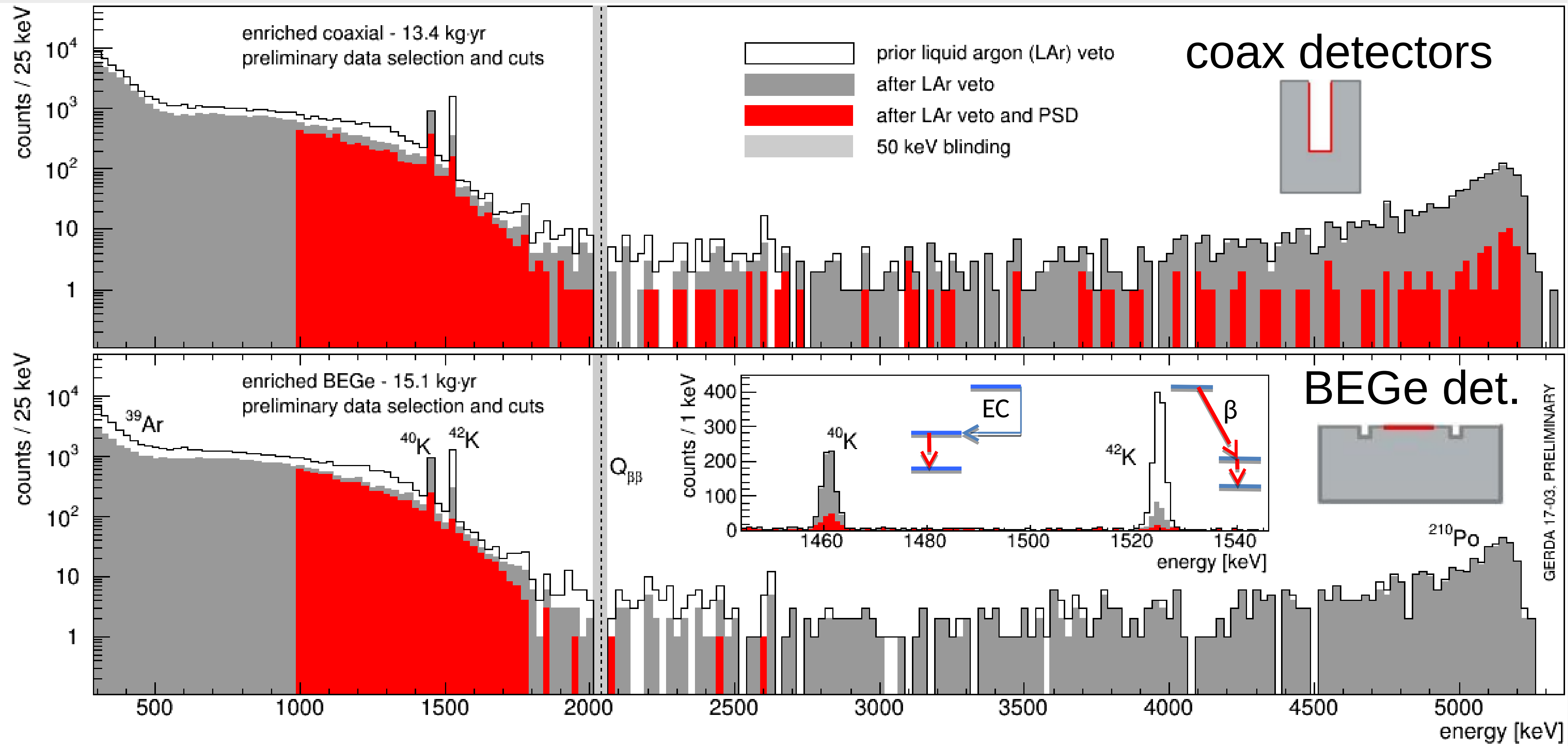


- signal efficiency determined by MC simulation: $\epsilon_{0\nu\beta\beta} = (79 \pm 5)\,\%$

slide by Andrea Kirsch

recognized recently: certain class of α events not cut by ANN → recent data not unblinded

Liquid Argon veto

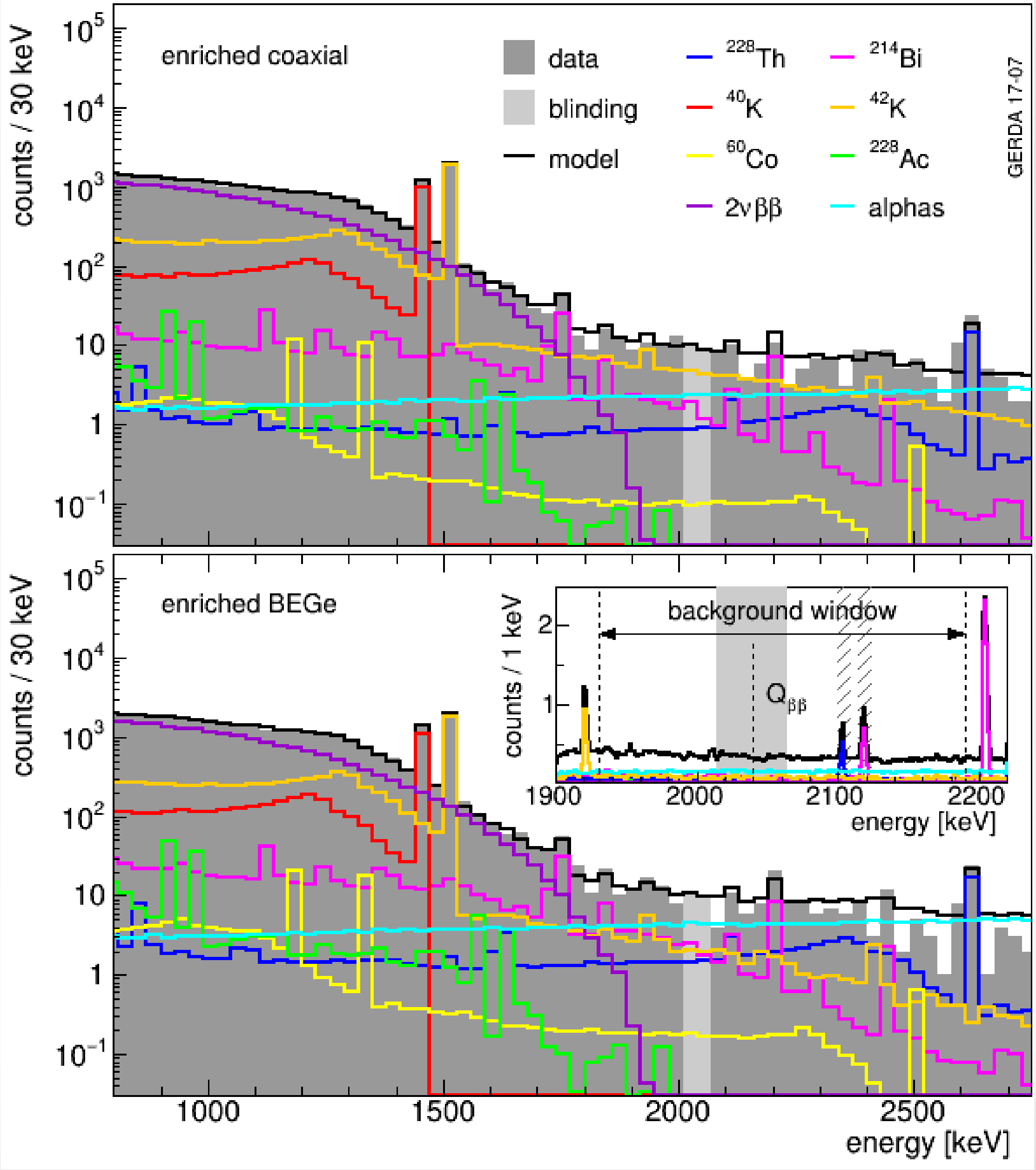


line at 1525 keV from ^{42}K: deposits up to 2 MeV in LAr → factor ~5 suppression by LAr veto

600-1300 keV: ~97% of events are $2\nu\beta\beta$ after LAr veto

at $Q_{\beta\beta}$ bkg reduced by factor ~20 (8) for BEGe (coaxial) detectors by LAr veto & PSD

Background model

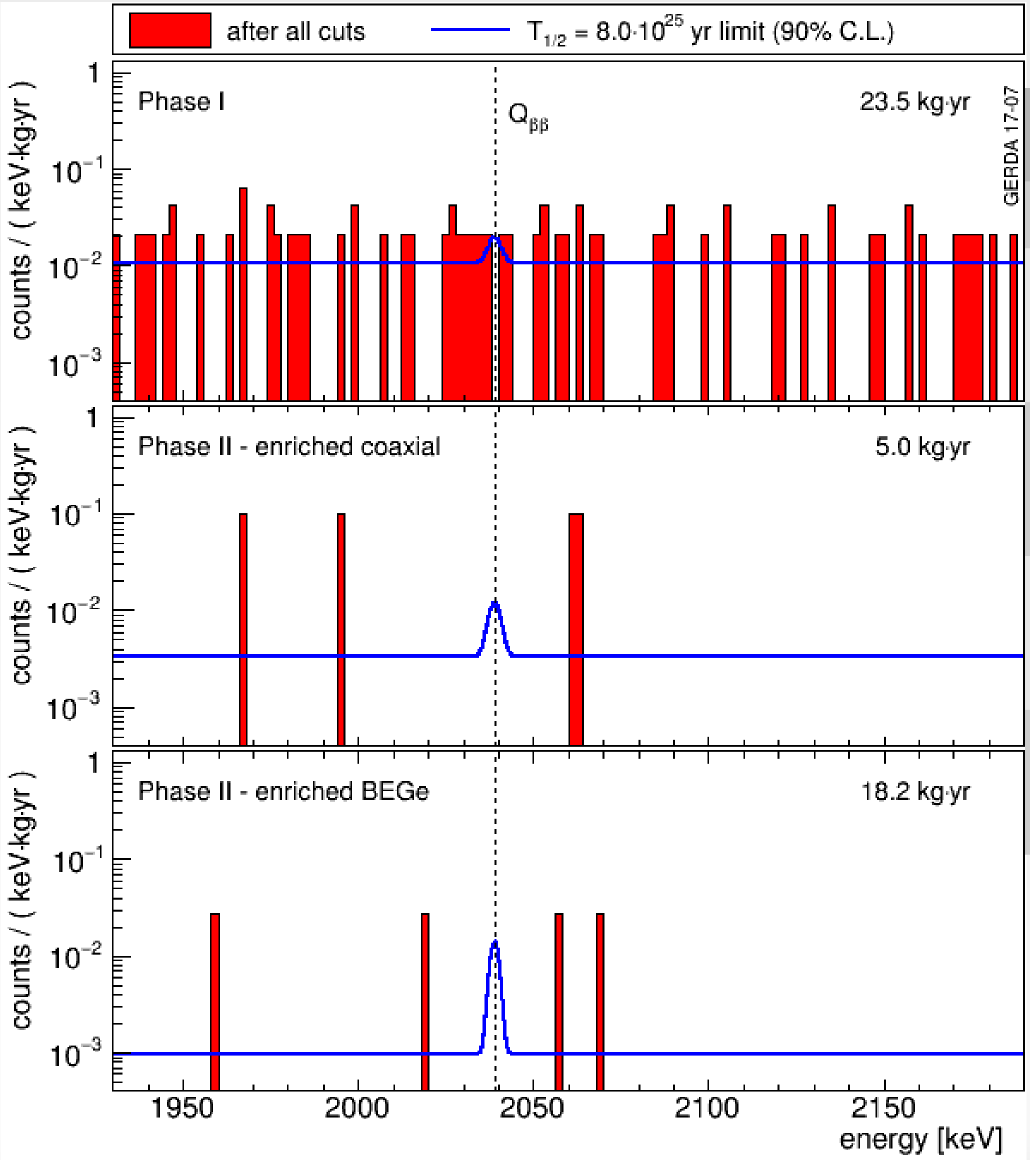


Spectra before pulse shape & LAr veto

fit to known background sources

at $Q_{\beta\beta}$: ~1/3 42K, 1/3 α, 1/3 γ from Tl/Bi

Results for 0νββ search (limits)



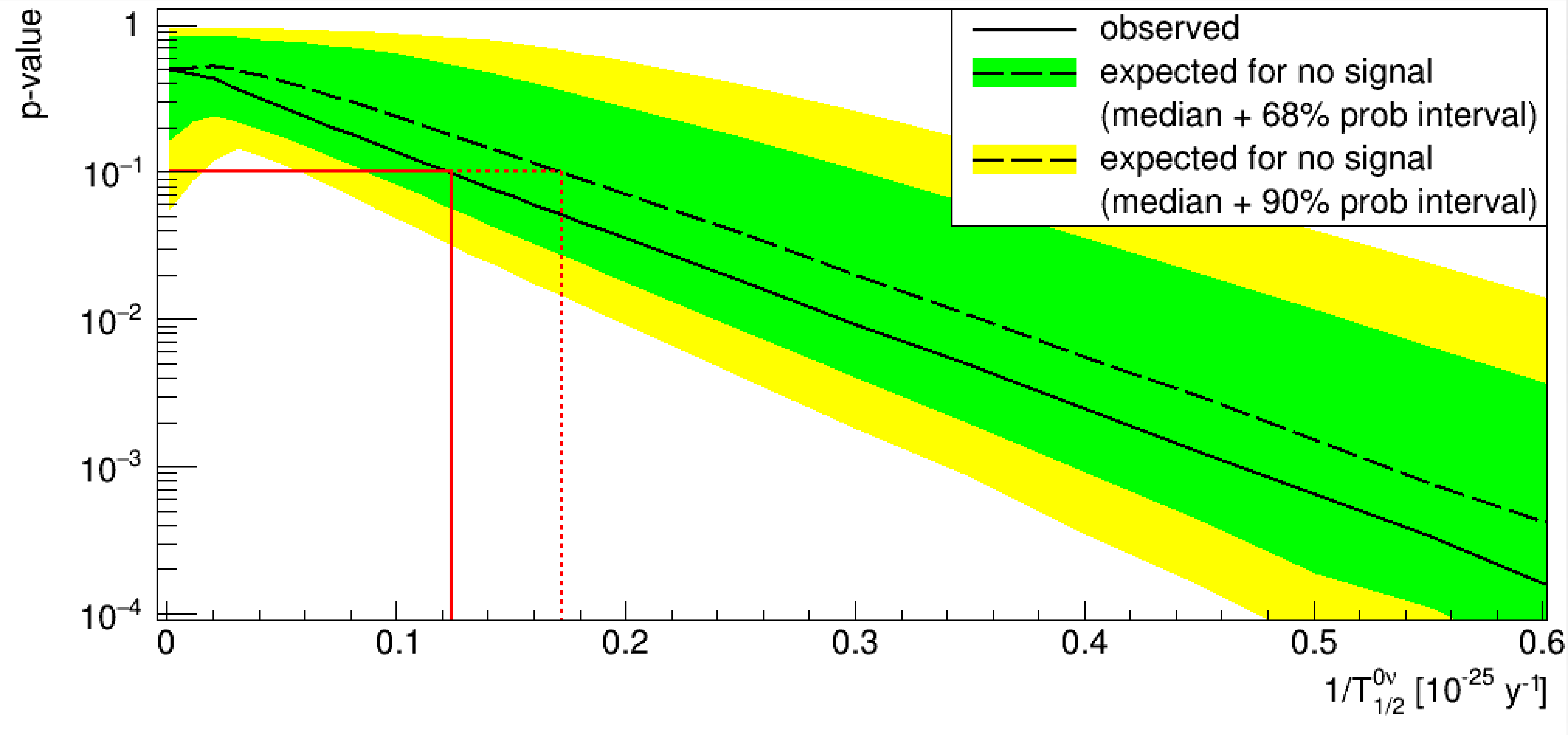
history of limits in 10^{25} yr

	PRL111 122503(2015)	Nature 554 47(2017)	TAUP2017 conference
	PI:6/2013	PII:6/2016	PII:7/2017
Frequentist limit	2.1	5.3	8.0
Frqquentist sensitivity	2.4	4.0	5.8
Bayesian limit	1.9	3.5	5.1
Bayesian sensitivity	2.0	3.1	4.5

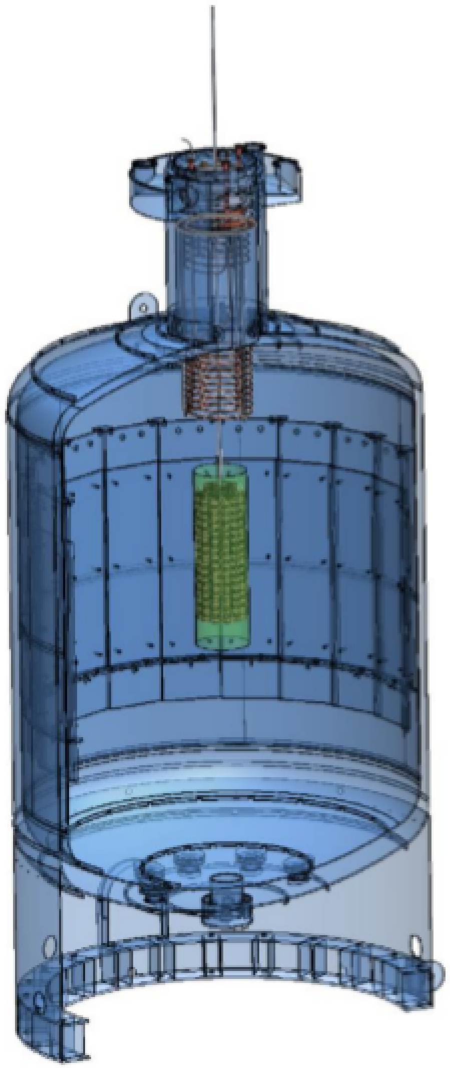
bkg BEGe Phase II: $1.0^{+0.6}_{-0.4} \cdot 10^{-3}$ cts/(keV kg yr)
for coax 2-3 higher due to poorer PSD rej.

for 100 kg yr exposure:
sensitivity > 10^{26} yr
expected bkg in FWHM < 1 → ‘background-free’

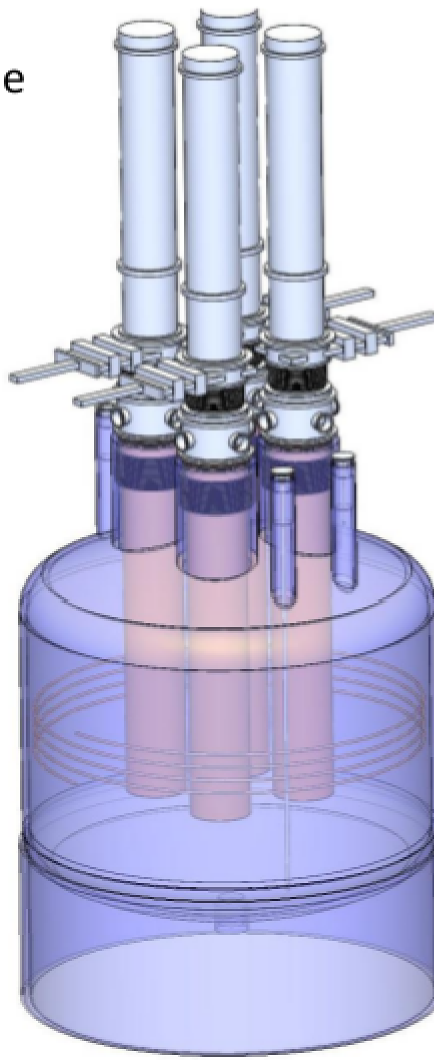
Result: p-value distribution for Frequentist



LEGEND: Large Enriched Ge Exp. for Neutrinoless ββ Decay



First stage:
- ✓ (up to) 200 kg in upgrade of existing GERDA infrastructure at LNGS
- ✓ bkg reduction by factor 3-5 w.r.t GERDA
- ✓ Sensitivity **10^{27}** yr



Subsequent stages:
- ✓ 1000 kg (staged)
- ✓ timeline connected to DOE down select process
- ✓ bkg factor 30 w.r.t GERDA
- ✓ Location tbd
- ✓ Sensitivity **10^{28}** yr

slide by Konstantin Gusev

founded October 2016, currently securing funding for LEGEND-200

Inverted-coax detectors

A novel HPGe detector for gamma-ray tracking and imaging

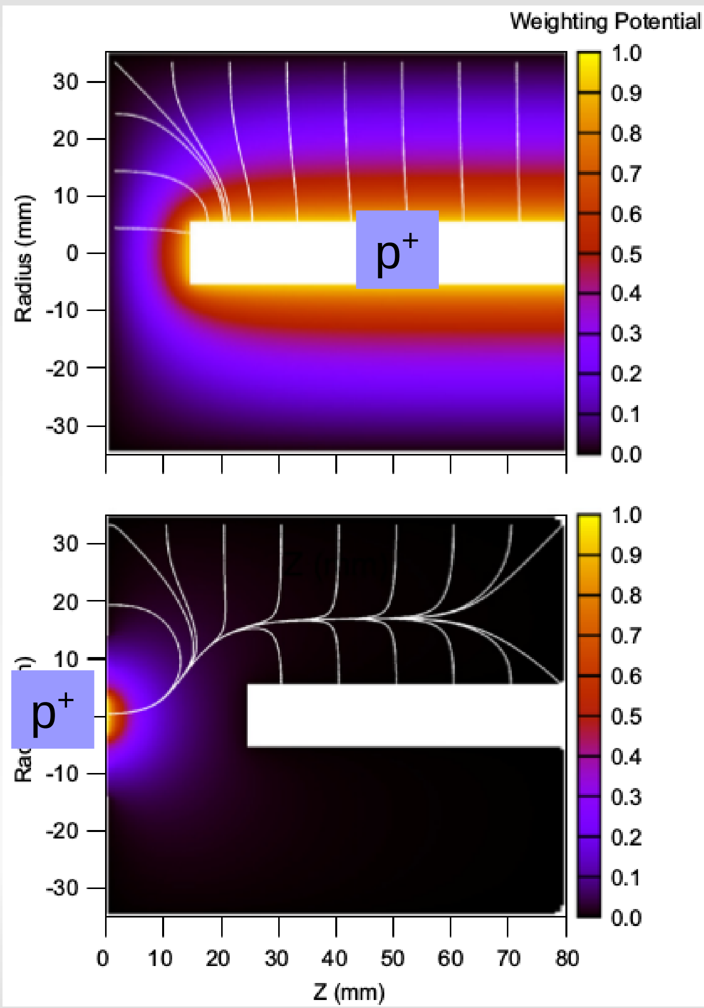
R.J. Cooper [a,*], D.C. Radford [b], P.A. Hausladen [c], K. Lagergren [a]

NIMA 665 (2011) 25

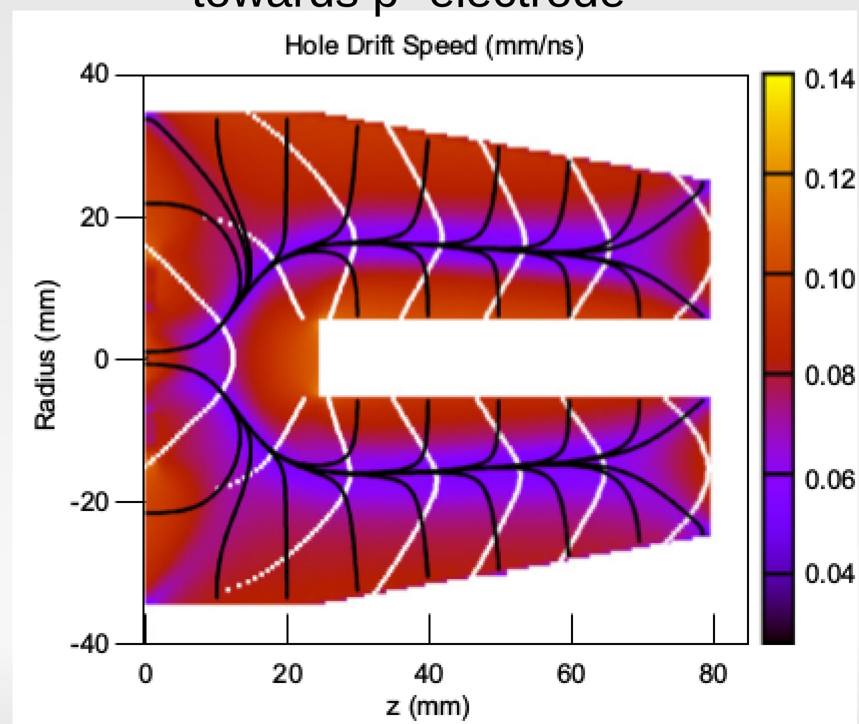
Motivation: 700 g / BEGe
→ 2-3 kg / inverted-coax
→ fewer cable / holder
→ lower background

normal coax

inverted coax

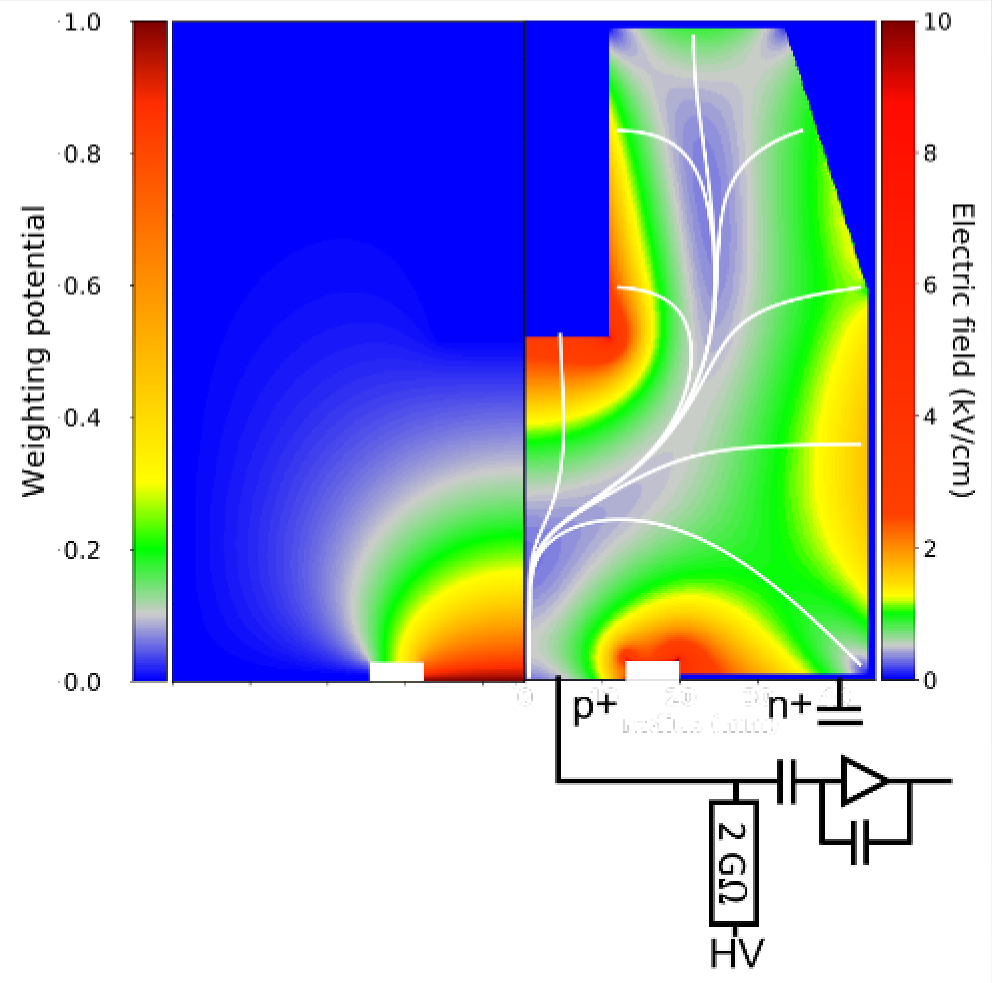


hole drift paths + velocity towards p+ electrode



Inverted-coax detectors available

Simulation 'HADES' detector



"Dresden":
- R = 3.6 cm
- H = 6.5 cm
- m = 1.4 kg

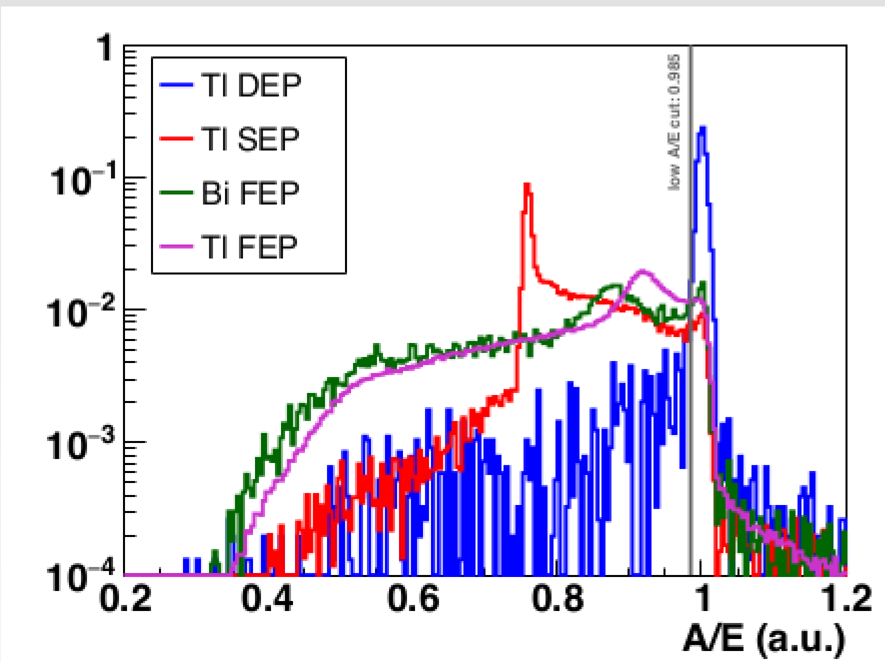
"HADES":
- R = 4.5 cm
- H = 8.5 cm
- m = 2.7 kg
- HV = 4000 V

"MPIK":
- R = 4.5 cm
- H = 9.0 cm
- m = 2.9 kg
- HV = 4500 V

commercial product by Canberra 'SAGe well'
large diameter hole for screening small samples

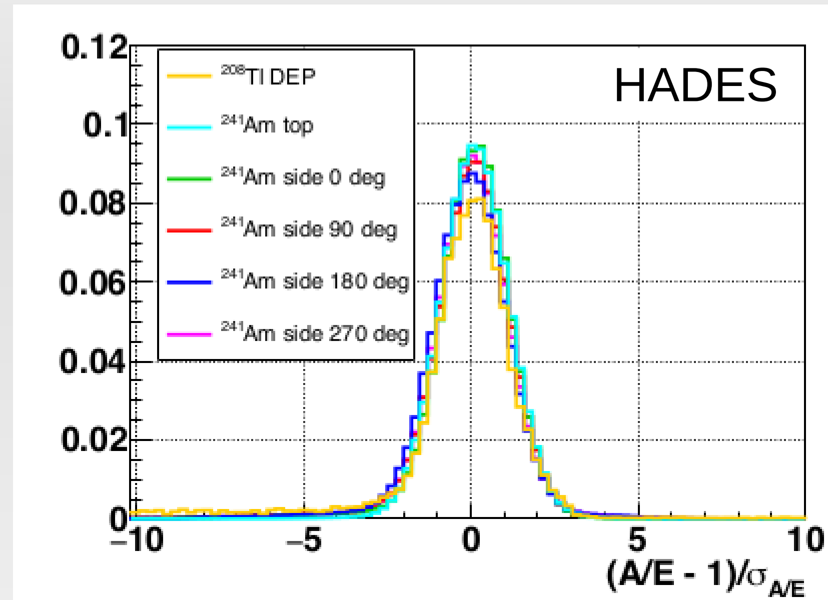
Inverted-coax A/E distribution

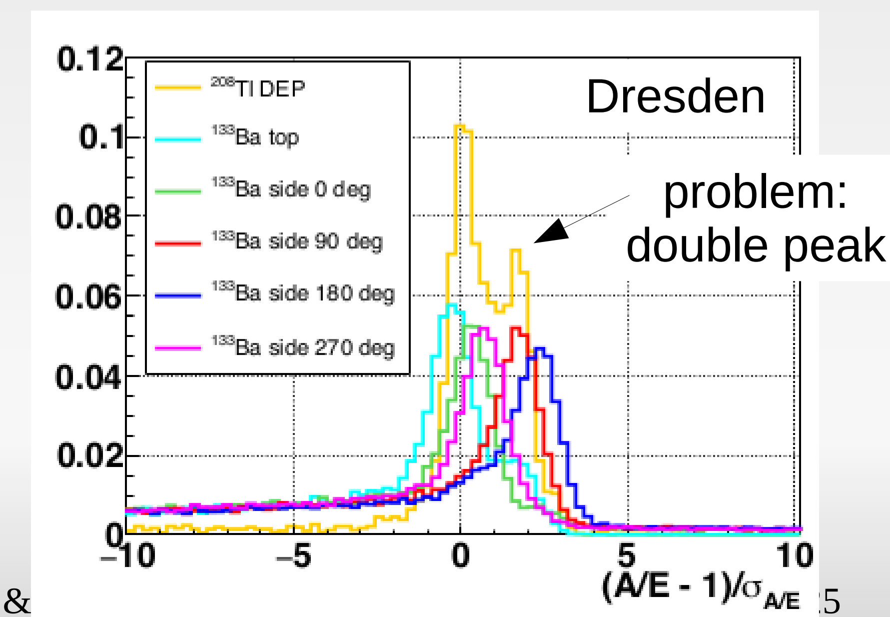
A/E distribution for several event classes from ^{228}Th calibration source measurements HADES detector



DEP = double escape peak = signal like
SEP = single escape peak = multi-site
Bi FEP = full energy γ at 1621 keV
Tl FEP = 2615 keV γ

surface scan with 59 keV γ from ^{241}Am





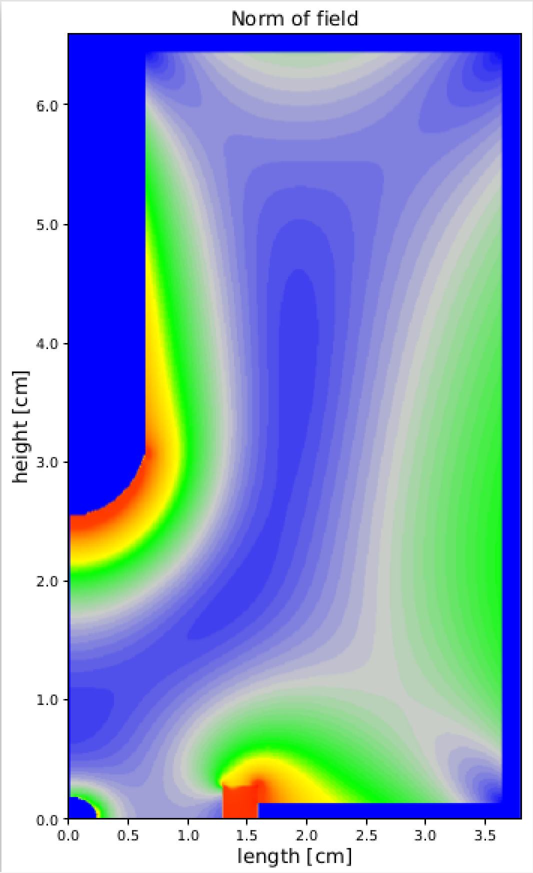
Results from 3 inverted-coax det

Resolution of pulse shape variable A/E and survival fractions for 3 inverted-coax and typical BEGe values

%	HADES	Dresden	MPIK	BEGe
$FWHM_{A/E}$	1.4	2.3	0.7	<1
DEP	89.8	90.2	90.0	90.0
SEP	6.2	5.5	5.4	~6
FEP Bi	9.6	8.4	9.2	~10
FEP Tl	8.6	8.0	10.3	~8

pulse shape discrimination similar to BEGe

we ordered prototypes from ORTEC & Baltic Scient Instr.



US groups ordered large detectors from different vendors

Summary

strong prejudice: $0\nu\beta\beta$ exists, $\Delta L=2$ process, possibly our only observable ΔL,
leptogenesis: mater-antimatter asymmetry linked to ΔL and $0\nu\beta\beta$

$T_{1/2}$ unknown (no real guidance from theory), discovery can be 'around the corner',

discovery would have a major impact on SM and cosmology

GERDA: ‘background-free’, newest limit $T^{0\nu}_{1/2} > 8.0 \cdot 10^{25}$ yr (90% C.L.)

GERDA and MajoranaDemonstrator will soon have half-life sensitivity $>10^{26}$ yr

Future = LEGEND
- first phase up to 200 kg at LNGS in existing GERDA infrastructure
- 1000 kg phase if successful at DOE down-select process
- new detector type with larger mass offers good PSD with lower background