Search for neutrinoless double beta decay of ^{76}Ge with the GERDA experiment

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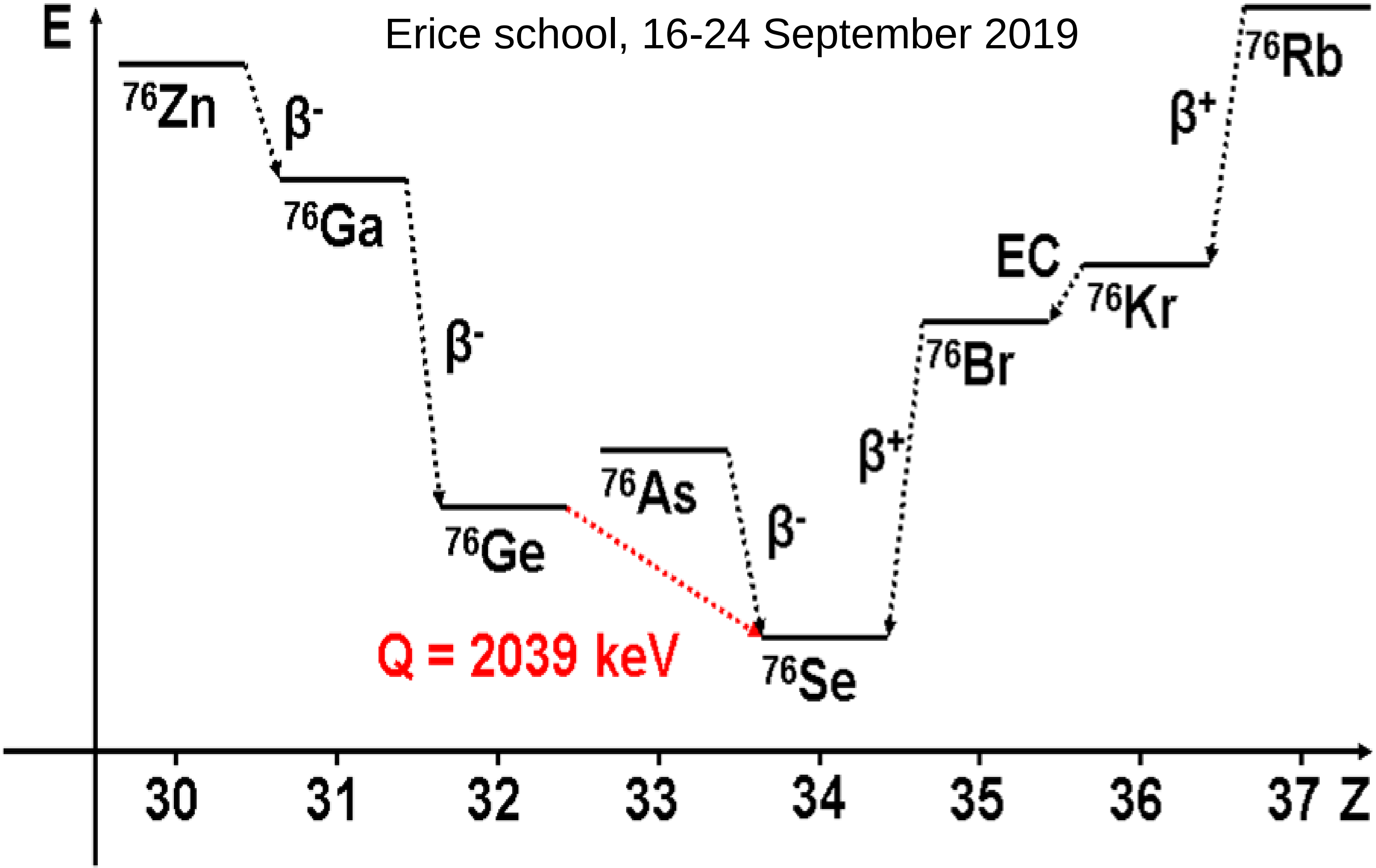
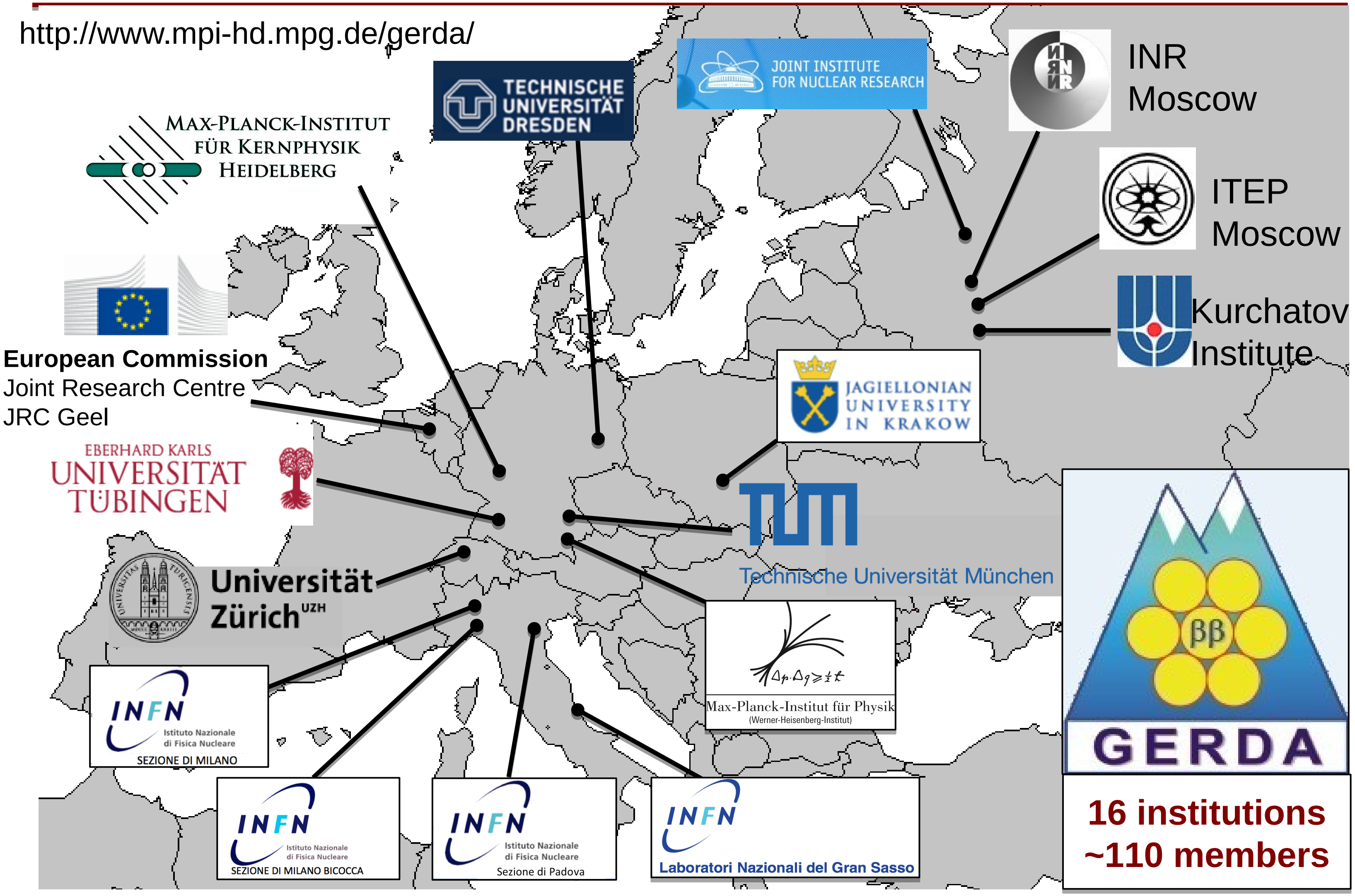
Erice school, 16-24 September 2019



GERDA collaboration

http://www.mpi-hd.mpg.de/gerda/



INR
Moscow

ITEP
Moscow

Kurchatov
Institute

European Commission
Joint Research Centre
JRC Geel

16 institutions
~110 members

Introduction $0\nu\beta\beta$ decay

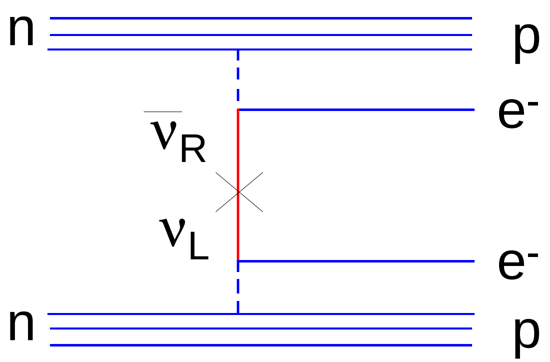
particle ↔ anti-particle have opposite electric charge, ν has no charge

lepton number only 'accidentally' conserved in Standard Model of particle physics

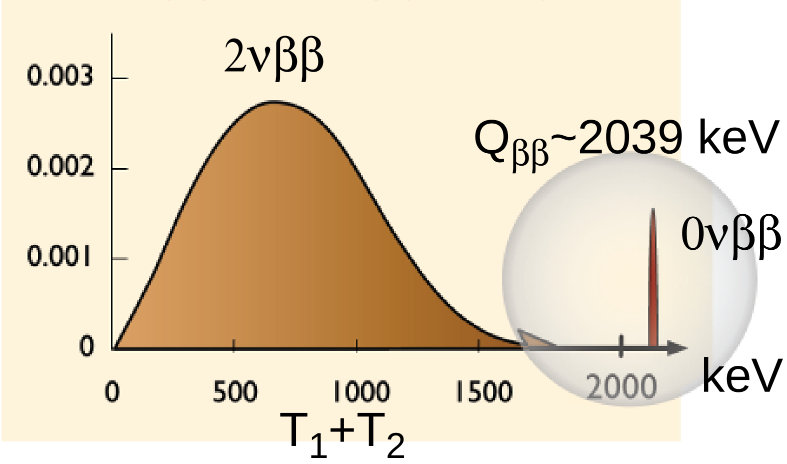
→ possible: neutrino = anti-neutrino (Majorana particle)

→ look for processes which can only occur if ν is Majorana
best chance: neutrinoless double beta decay

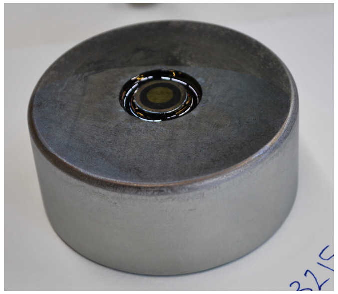
$0\nu\beta\beta$ decay, $\Delta L=2$



$^{76}Ge \rightarrow {}^{76}Se + 2e^-$



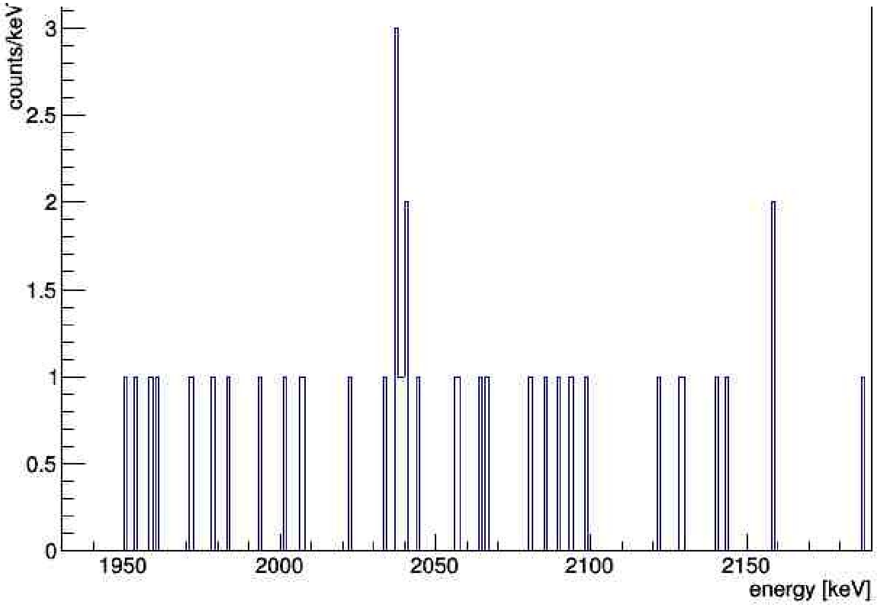
Ge detector



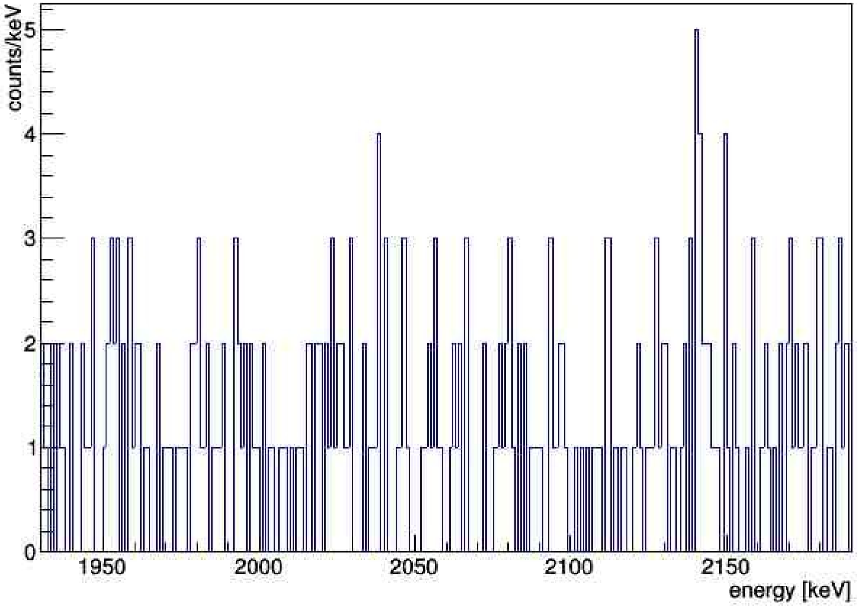
- ^{76}Ge 7.8% → 87% enr.
- best energy resolution in comparison

the starting idea: reduce background

MC spectrum with 6 signal evts, bkg 0.1/keV



MC spectrum with 6 signal evts, bkg 1/keV



$$N^{0\nu} = \ln 2 \frac{N_A}{A} \cdot a \cdot \epsilon \cdot M \cdot t \,/\, T_{1/2}$$

$$N^{bkg} = M \cdot t \cdot B \cdot \Delta E$$

M = mass of detector ~ 35 kg for GERDA
t = measurement time ~ 3 yr
A = isotope mass per mole = 75.6 g/mol
N_A= Avogadro constant
a = fraction of 0νββ isotope ~ 0.86
ε = detection efficiency ~ 0.7
B = background index in units cnt/(keV kg y) ~10^{-3}
ΔE = energy resolution = energy window size ~ 6 keV

Experimental sensitivity

$$T_{1/2}(90\%CL) > \begin{cases} \frac{\ln 2}{2.3} \frac{N_A}{A} a \cdot \epsilon \cdot M \cdot t & \text{for } N^{bkg} = 0 \\ \frac{\ln 2}{1.64} \frac{N_A}{A} a \cdot \epsilon \sqrt{\frac{M \cdot t}{B \cdot \Delta E}} & \text{for large } N^{bkg} \end{cases}$$

want to be “background free” $N^{bkg} < 1$ in ΔE
for the total exposure of experiment
→ GERDA bkg goal 0.001 cnt/(keV kg yr)

background sources

sources: a) cosmic rays (p,n,μ,γ) → underground like LNGS, …
different depth requirements (μ flux) for different experiments
b) neutrons from (α,n)&fission and spallation induced by μ
c) α,β,γ from radioactive decay chains ^{238}U, ^{232}Th

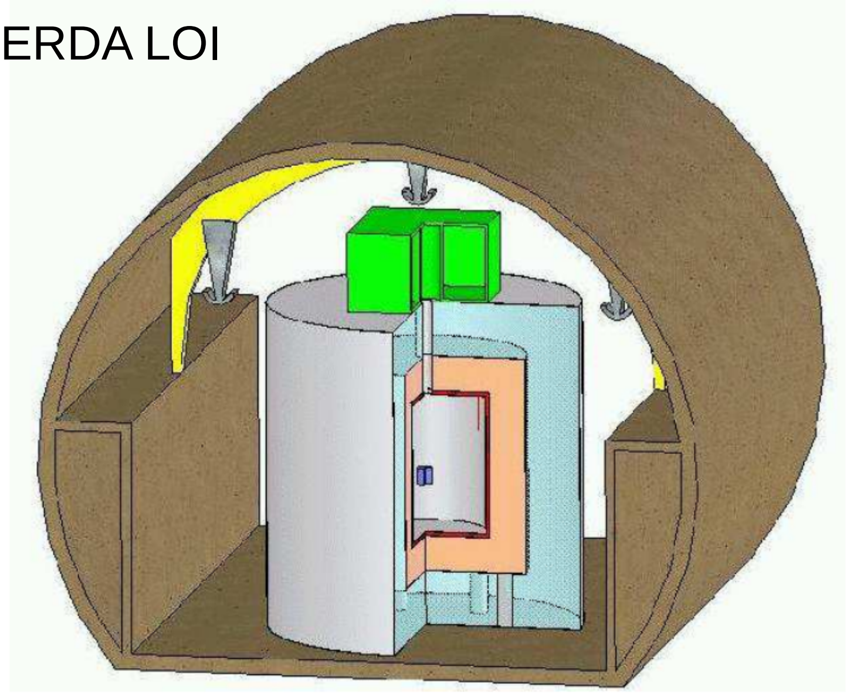
1. shield c) from the rock + concrete + steel = “external bkg”:
→ use clean materials, example of ^{232}Th activities [μBq/kg]:
1000 - steel, <1 - Cu, <1 - water, ~0 liquids like noble gases or organic scintillator
shield b) with a neutron moderator like water, borated PE

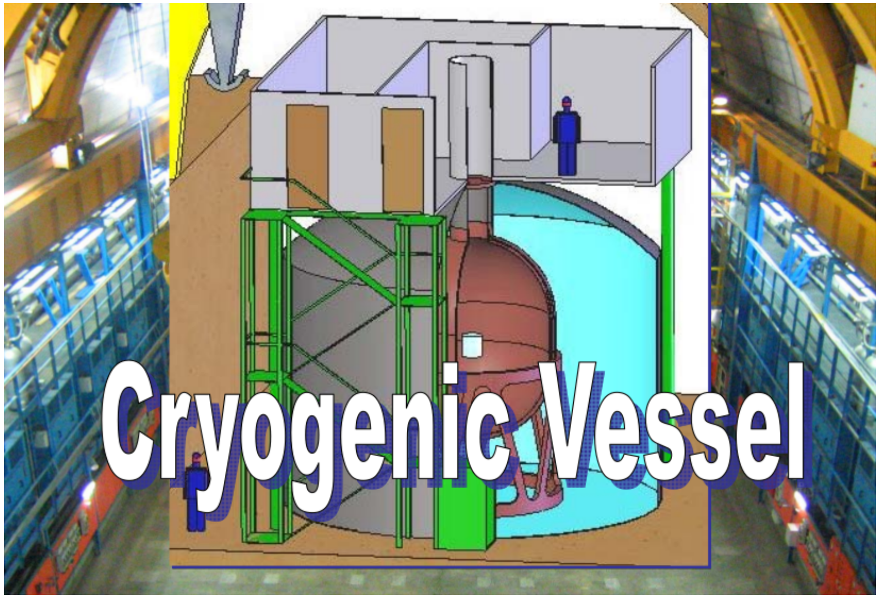
2. avoid contaminations in “close materials and intrinsic”
→ screen & select materials like cables, supports, …
big effort for many collaborations, shared knowledge about good materials,
select $0\nu\beta\beta$ candidate isotope with large Q value (above 2.6 MeV),
reduce time “above ground” for materials like Cu, Ge, ...

3. identify background events (multi-dim. selection) →
localize interactions (surface events, multiple interactions)
identify particle type (α versus β/γ)
'measure' all energy depositions (active veto)
...

liquid nitrogen/argon + water shield

GERDA LOI





basic idea of Gerd Heusser:
Ann. Rev. Nucl. Part. Sci. 45 (1995) 543.
use liquid nitrogen for shielding,
larger enough to shield ‘external bkg’
→ “bare” Ge detectors in liquid

GENIUS + GEM ideas around yr 2000

2004: GERDA LOI arXiv:hep-ex/0404039
use nitrogen or argon + water

2005: design for Cu cryostat in Hall A of LNGS
long and intense safety discussions

LN2 boiling
in water bath

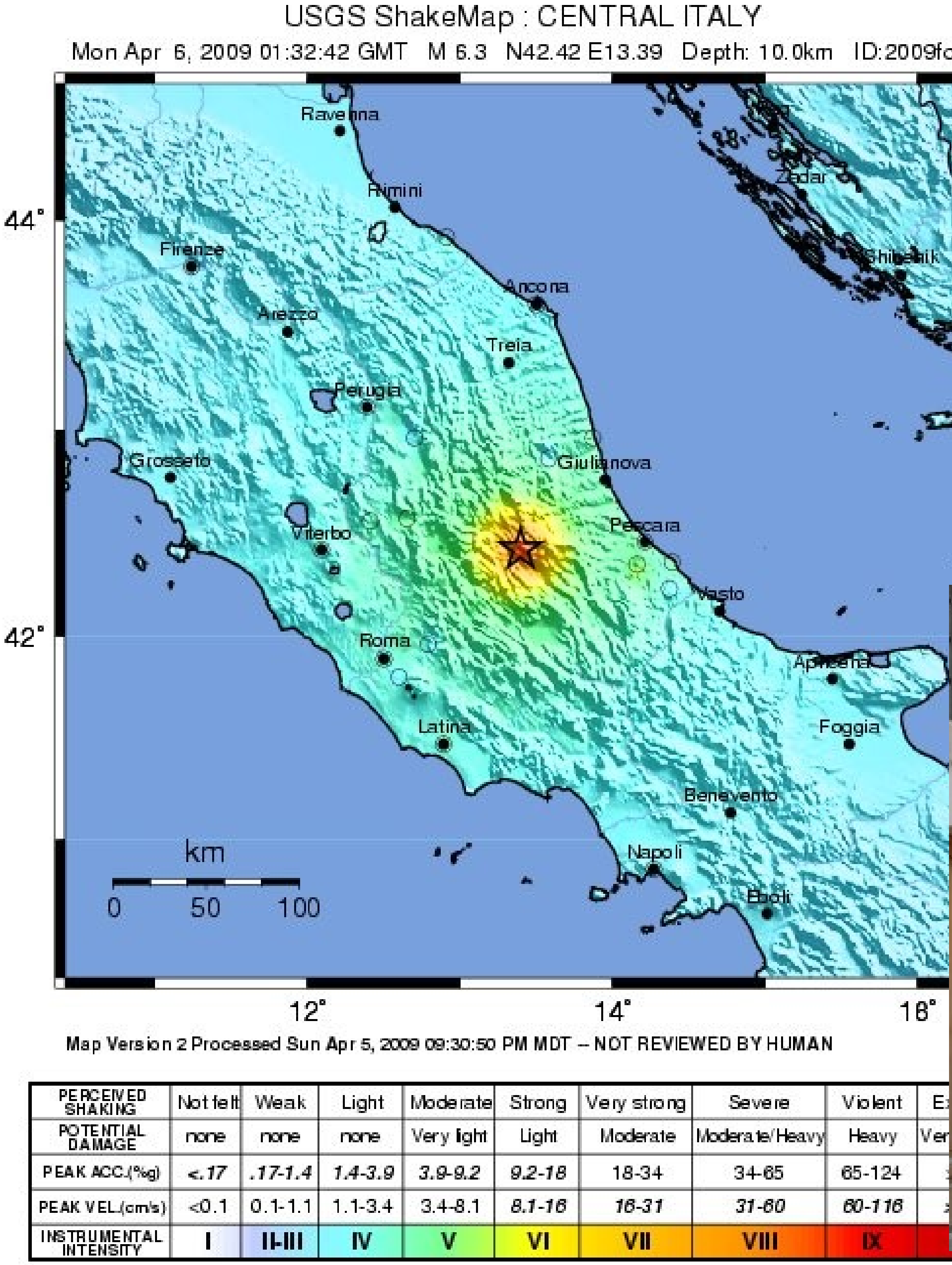
the steel cryostat

May 2006: steel + internal Cu shield: luckily Th contamination <10% of assumed value!

the steel cryostat

March 2008: cryostat arrives at LNGS (took 2 yr instead of 1 yr)
→ building water tank + clean room + … around it afterwards

6 April 2009



USGS ShakeMap : CENTRAL ITALY

Mon Apr 6, 2009 01:32:42 GMT M 6.3 N42.42 E13.39 Depth: 10.0km ID:2009fcaf

Map Version 2 Processed Sun Apr 5, 2009 09:30:50 PM MDT -- NOT REVIEWED BY HUMAN

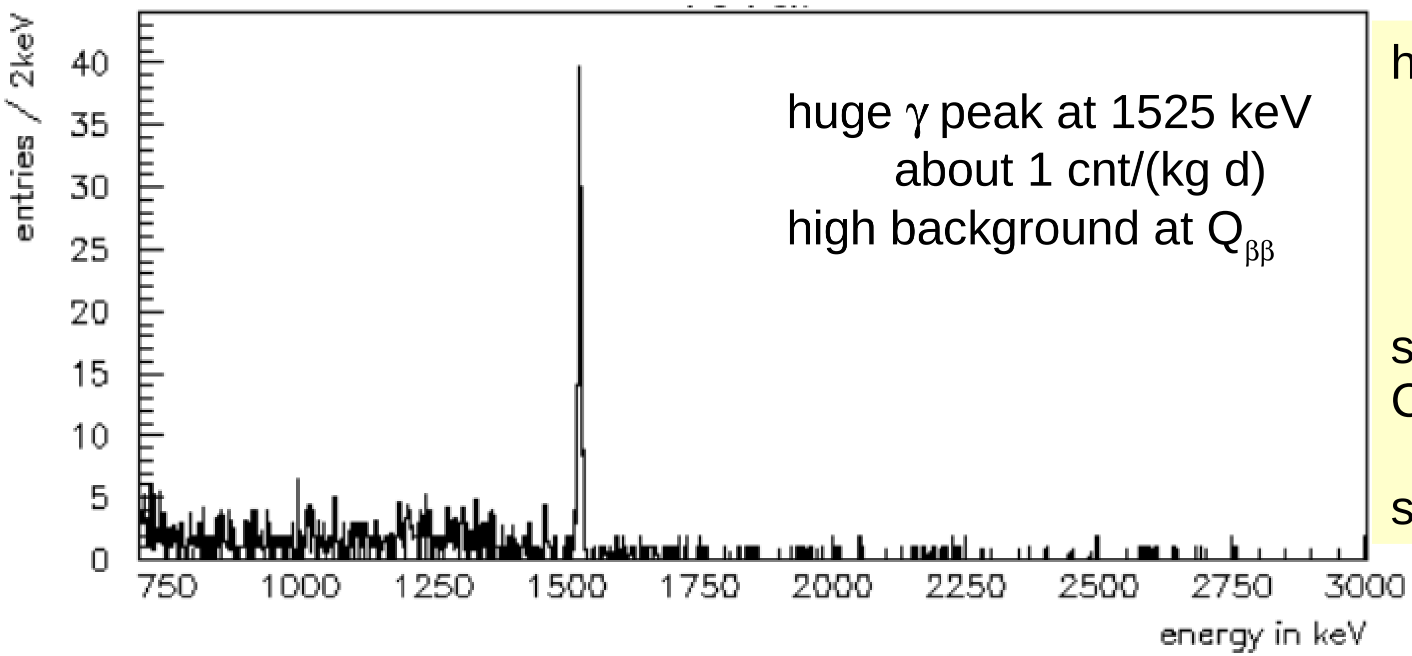
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Ex
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Ver
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	

the life of many people destroyed in a min

no damage in the underground LNGS lab
→ resumed work after few months

May 2010: first detectors in GERDA

first spectrum after a few days

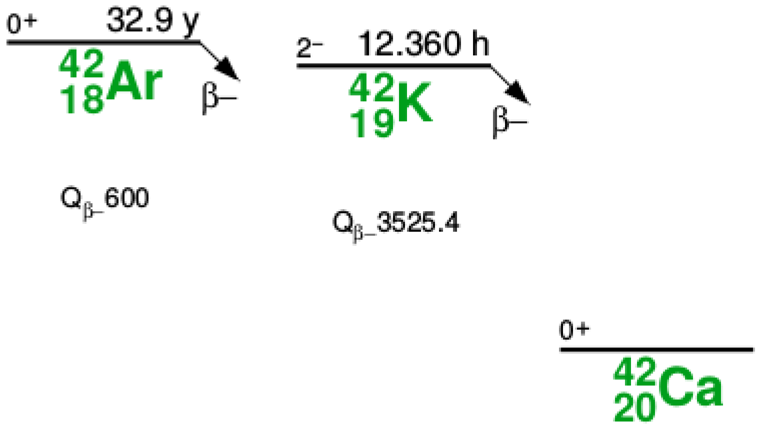


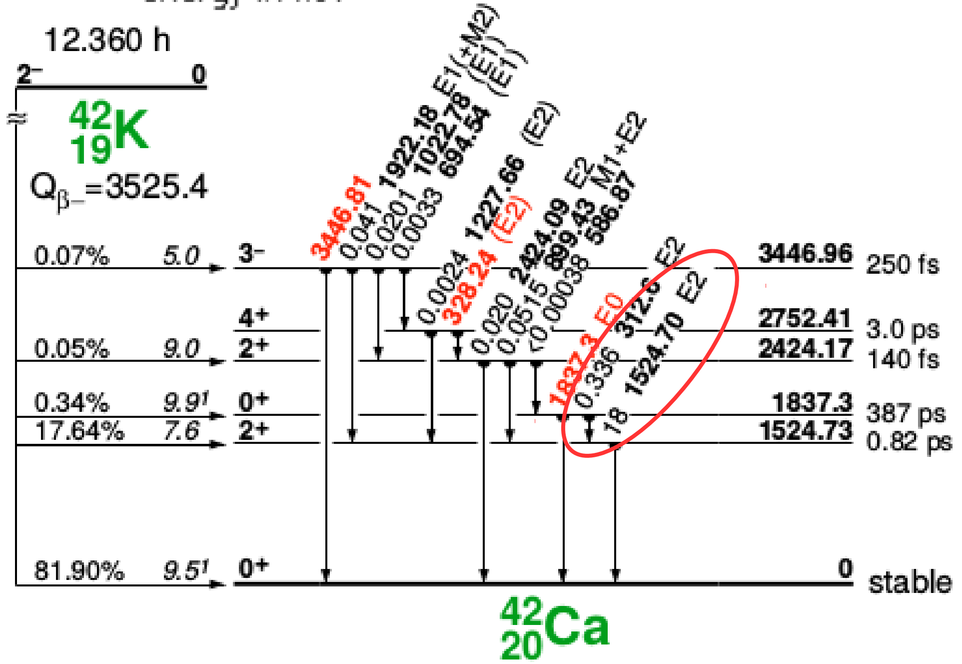
huge γ peak at 1525 keV
about 1 cnt/(kg d)
high background at $Q_{\beta\beta}$

had ignored β component of ^{42}K
& ^{42}K is charged
& ^{42}Ar content higher than in literature

solution: operate detectors in Cu foil containment / later nylon

start data taking Dec 2011





Ge detectors

- need enrichment in ^{76}Ge: $T_{1/2}$ sensitivity proportional to isotope fraction

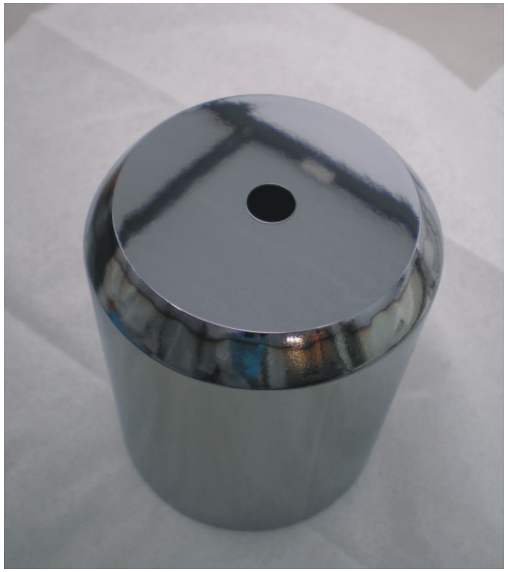
  GeF$_4$ in gas centrifuges is a standard process for enrichment,

  enriched in ^{72}Ge is used in semi-conductor industry,
  nowadays 2 suppliers, initially only ECP in Russia,
  typical enrichment from 7.8% → 86% or higher → sensitivity ~11x

- GERDA Phase I: 18 kg of existing detectors from pioneering experiments Heidelberg-Moscow and IGEX

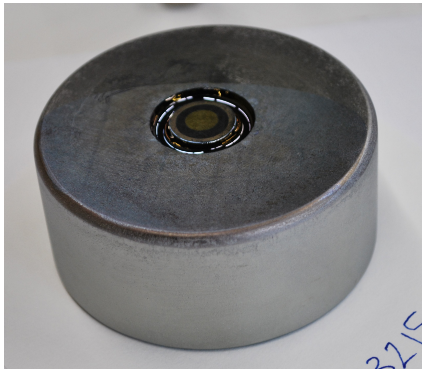
- Phase II: new detectors from newly purchased enriched Ge (bought 35 kg) But what type of detector?

coaxial detectors



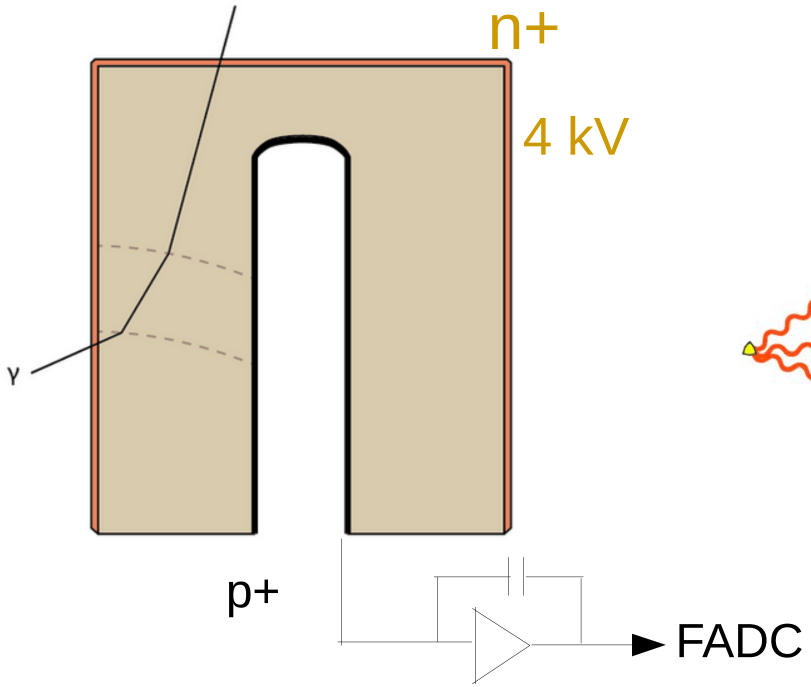
segmented detector

point contact detector

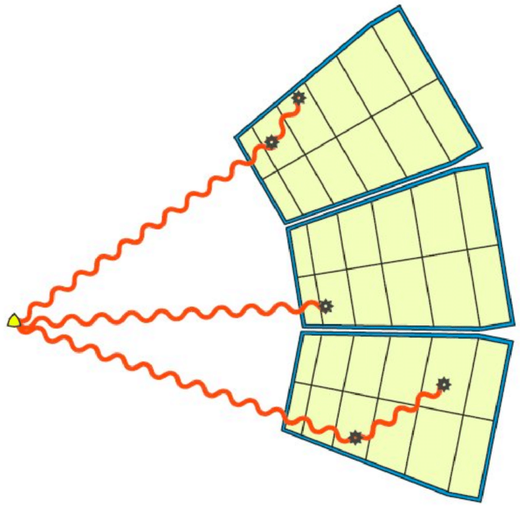


Phase II detector types

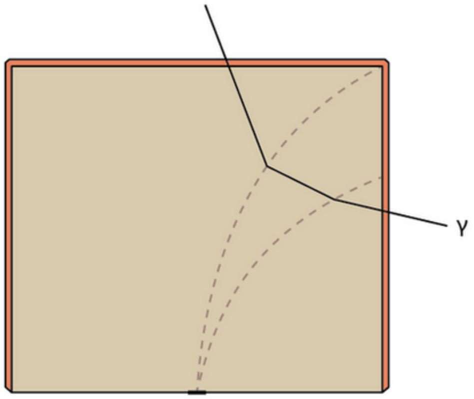
coaxial detectors



segmented detector



point contact detector



signal = 2 e$^-$ → localized energy deposition in bulk = single site event
background = multiple Compton scattered γ or α/β on detector surface

select detector type that can reject background due to the time profile of the signal

cost & ease of operation & background suppression
→ new detectors are point contact type = BEGe (broad energy germanium)

BEGe detector

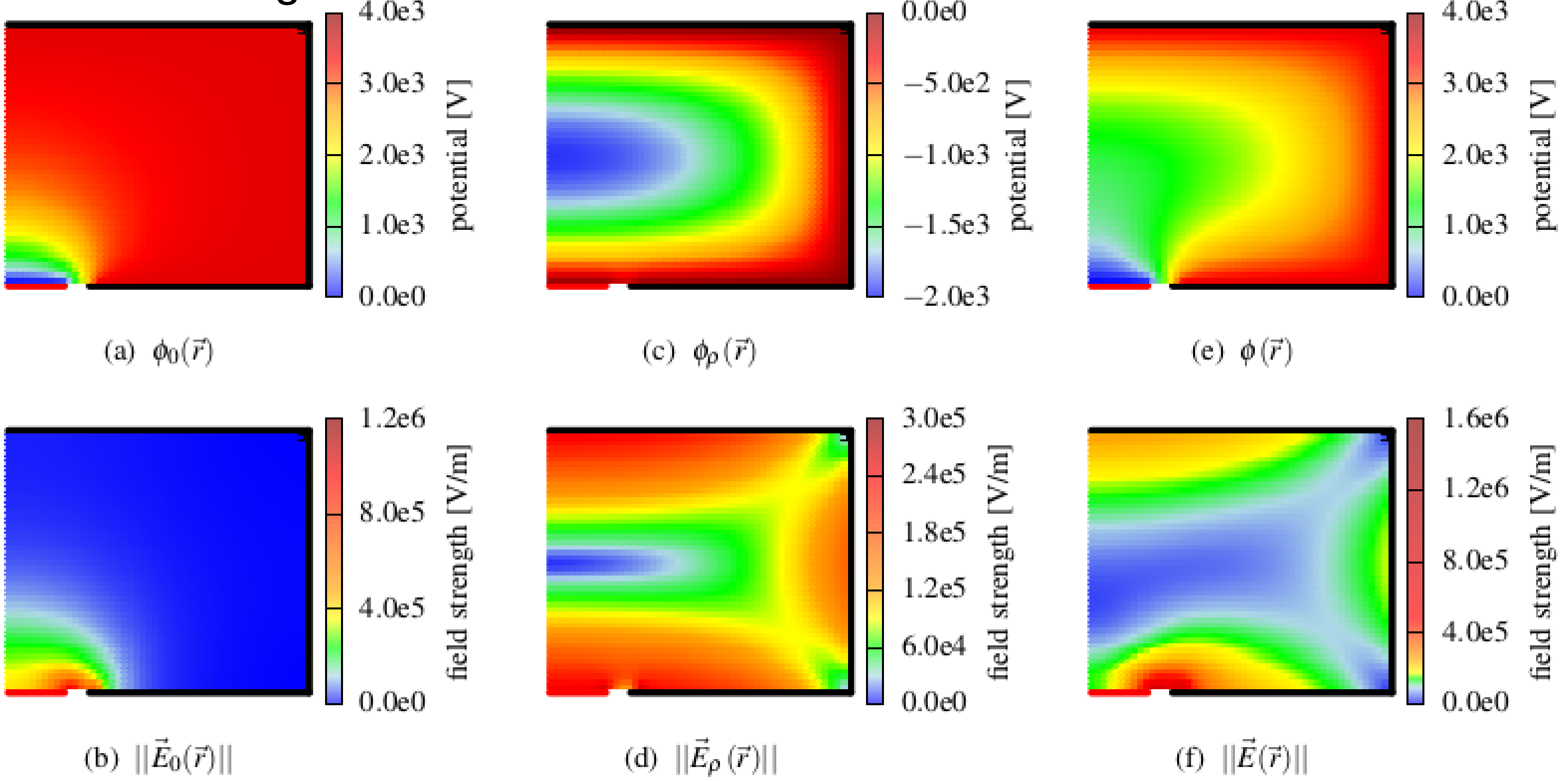
external voltage

intrinsic impurities ~10^{10}/cm^3

sum

potential Φ

field strength E



(a) $\phi_0(\vec{r})$ (c) $\phi_\rho(\vec{r})$ (e) $\phi(\vec{r})$

(b) $||\vec{E}_0(\vec{r})||$ (d) $||\vec{E}_\rho(\vec{r})||$ (f) $||\vec{E}(\vec{r})||$

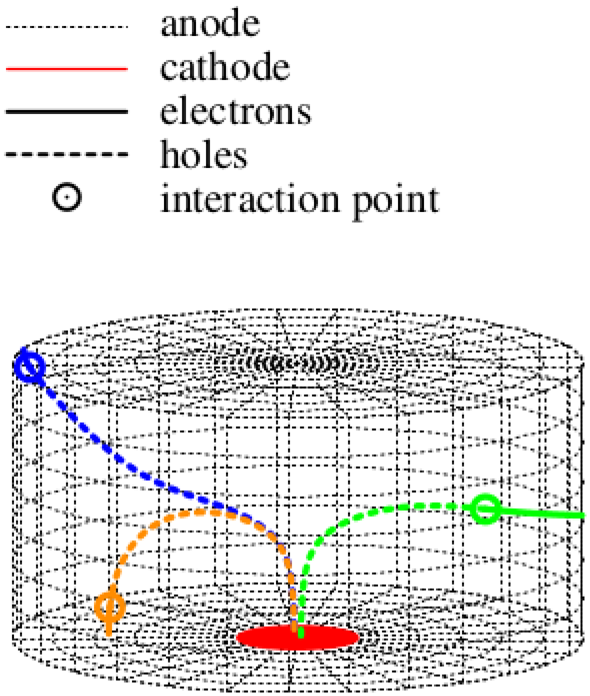
from JINST 6 (2011) P03005

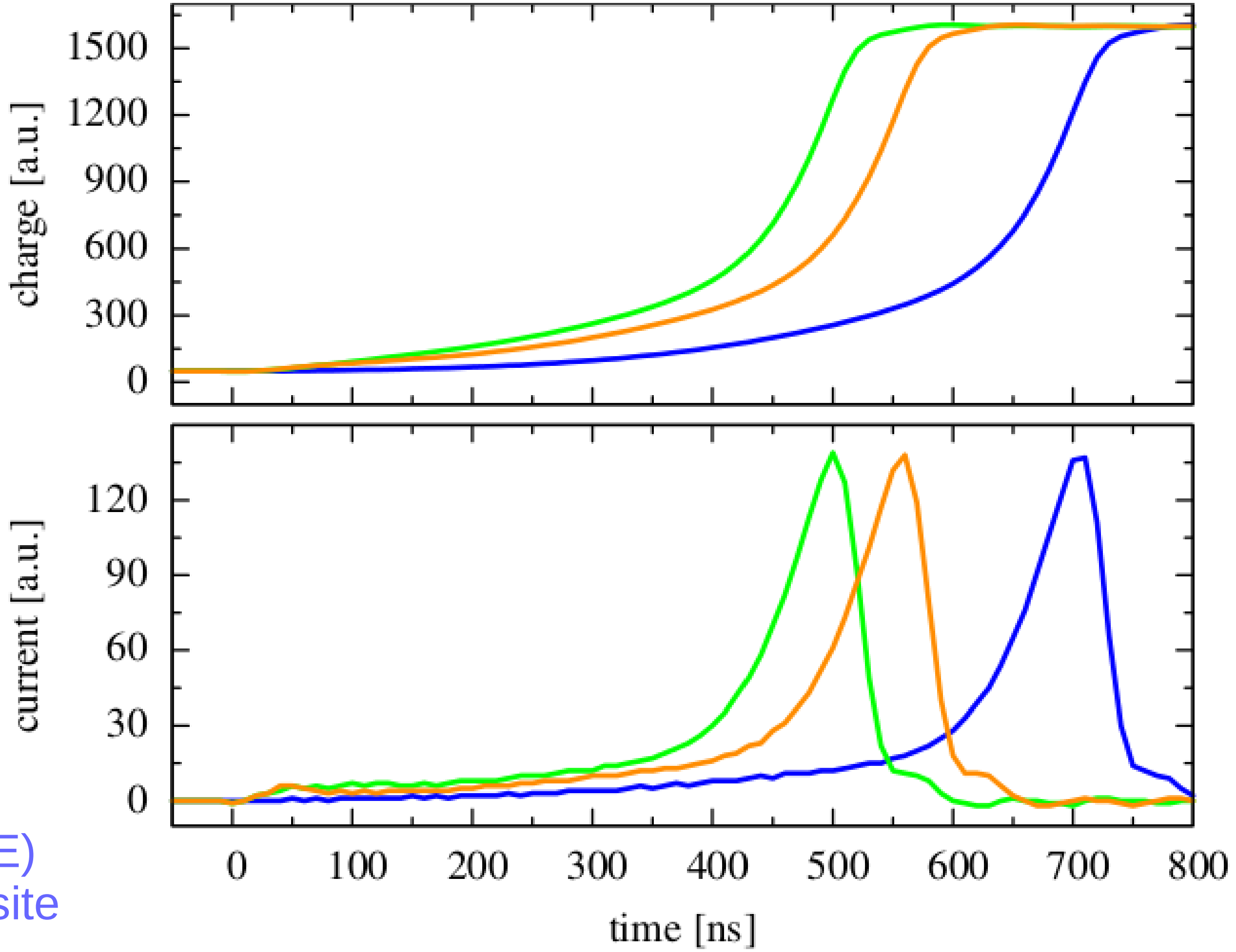
Figure 3. Simulated electric potential and electric field strength for different configurations of a BEGe detector. In (a) and (b) the electrode potential is considered, in (c) and (d) the charge distribution, and in (e) and (f) the sum of the two contributions. The plots show half of a vertical section 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 Φ (only)

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

BEGe pulse shape analysis





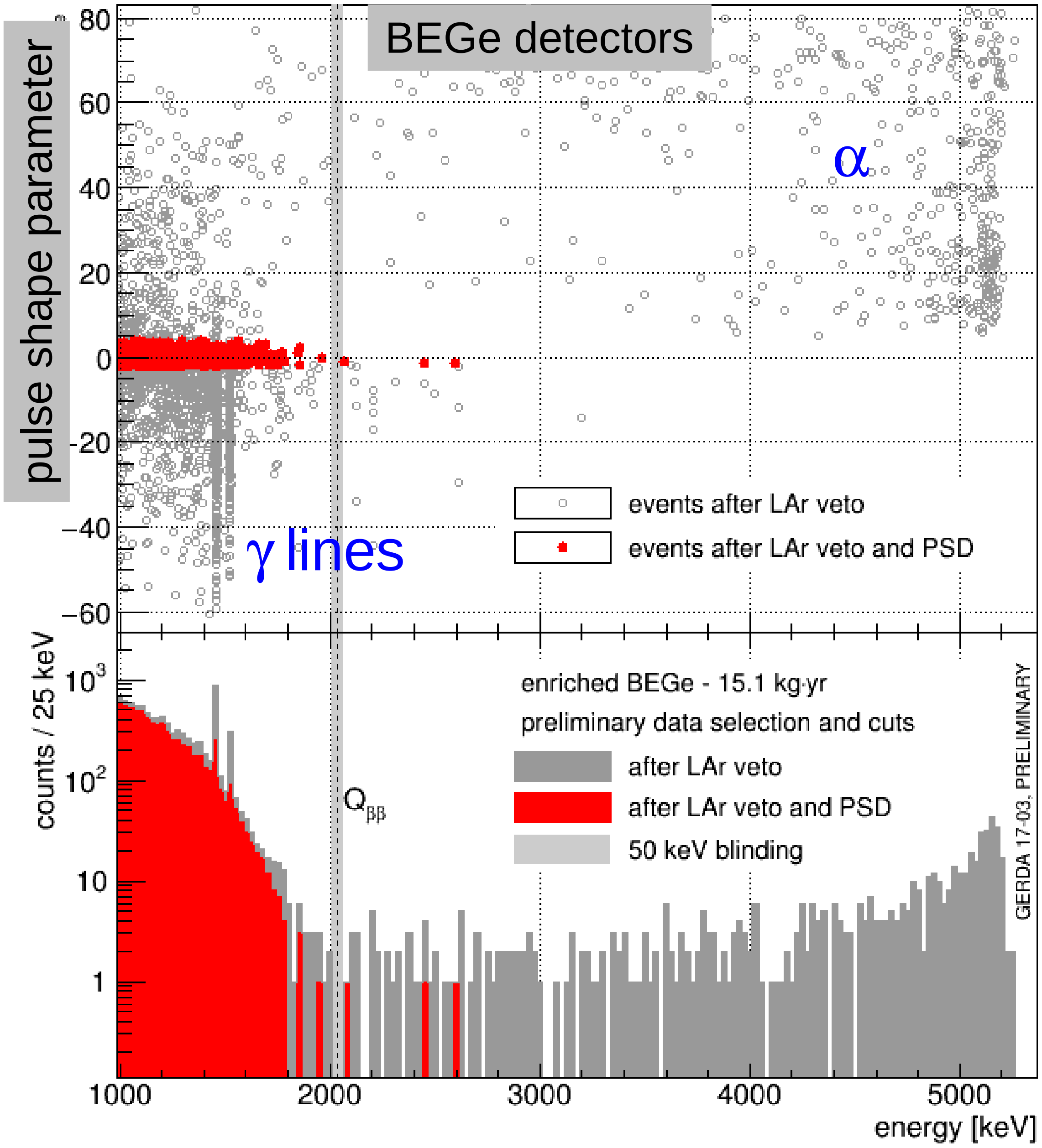
→ maximum current / energy (= A/E) to discriminate multi-site vs single-site

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 → diffusion → longer drift → A/E smaller

BEGe pulse shape performance



0νββ proxies = 2νββ &

Double Escape Peak of 2615 keV γ

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

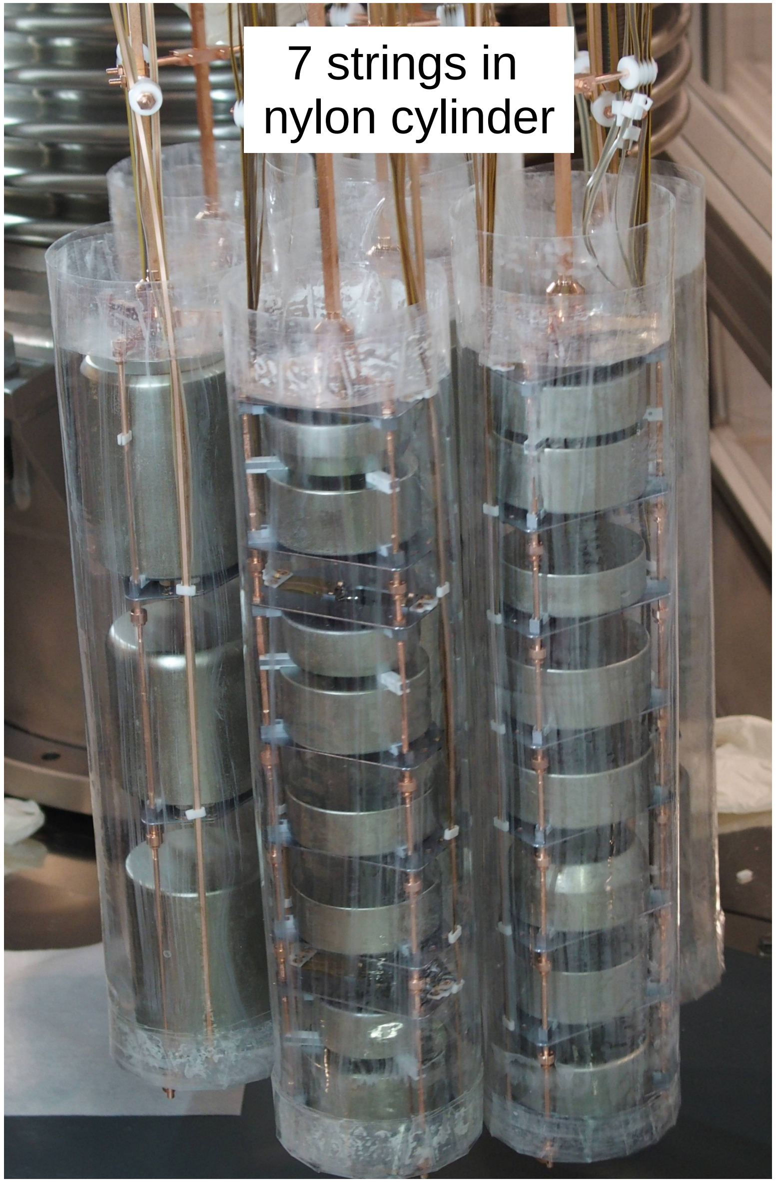
α (surface) events removed

γ lines suppressed by factor ~6

0νββ signal efficiency 87±2 %

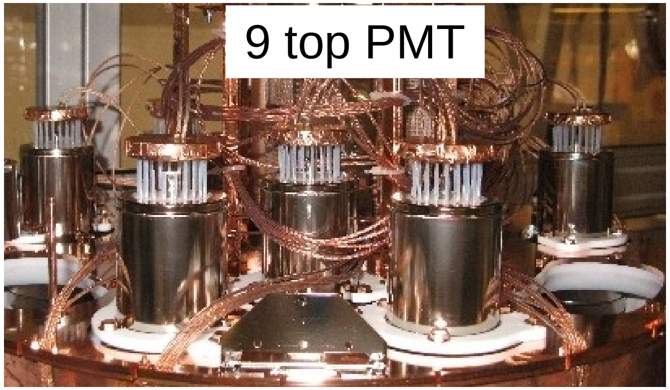
2νββ acceptance 85^{+2}_{-1} %

Phase II: LAr scintillation light readout



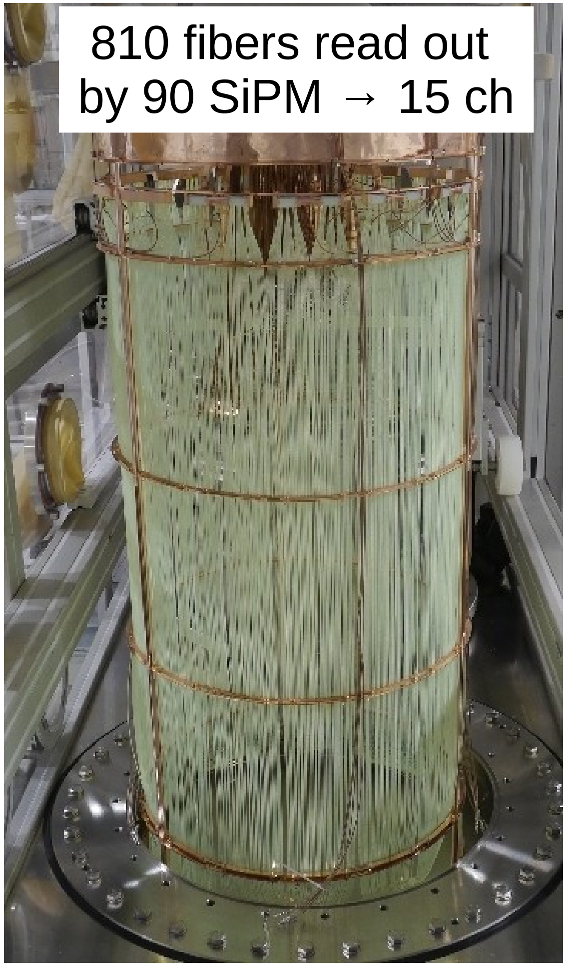
7 strings in nylon cylinder

start Phase II Dec 2015



9 top PMT

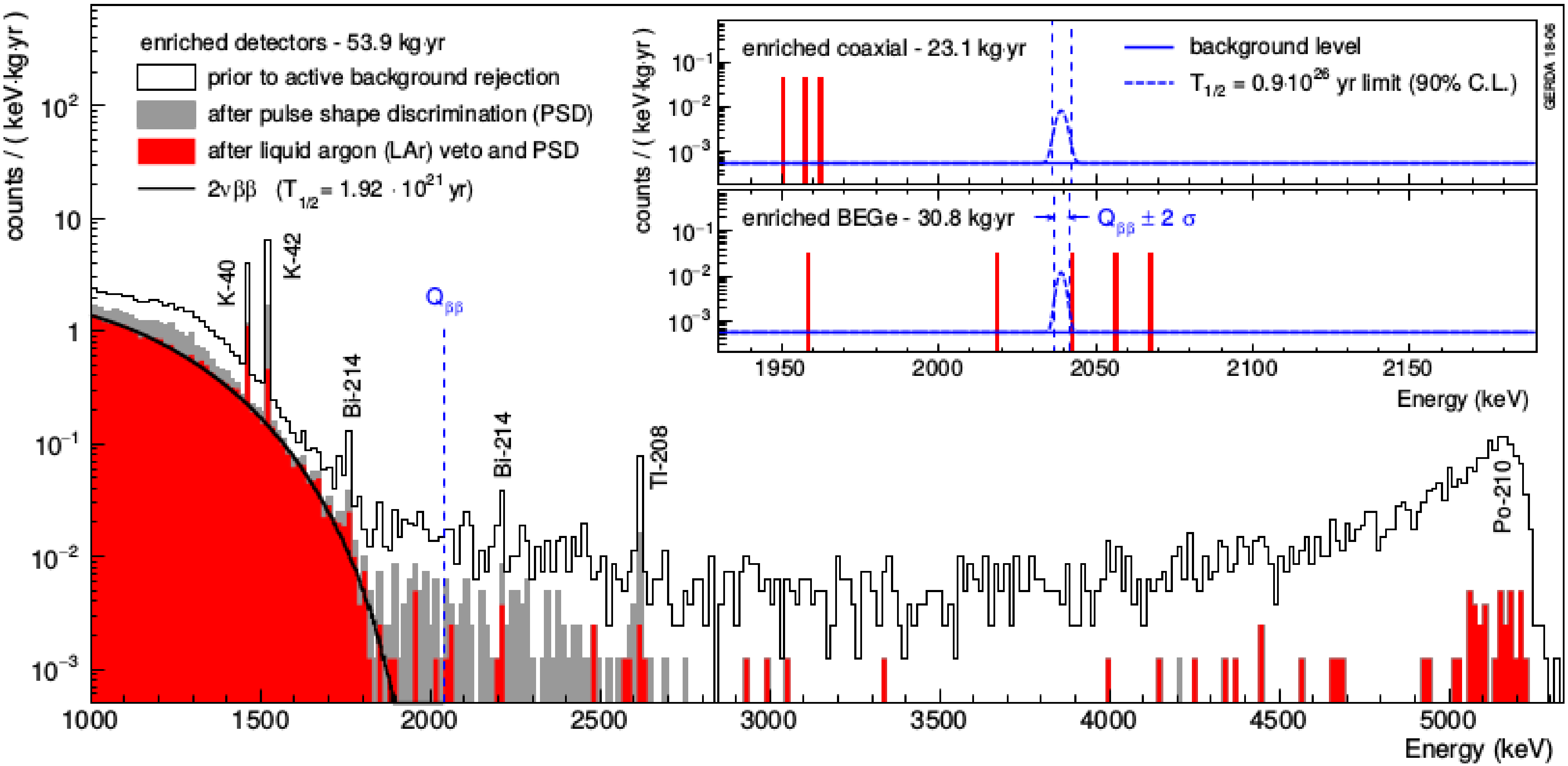
7 bottom PMT



810 fibers read out by 90 SiPM → 15 ch

background suppression

latest (2018) unblinded data set 54 kg yr Phase II exposure (coax + BEGe)

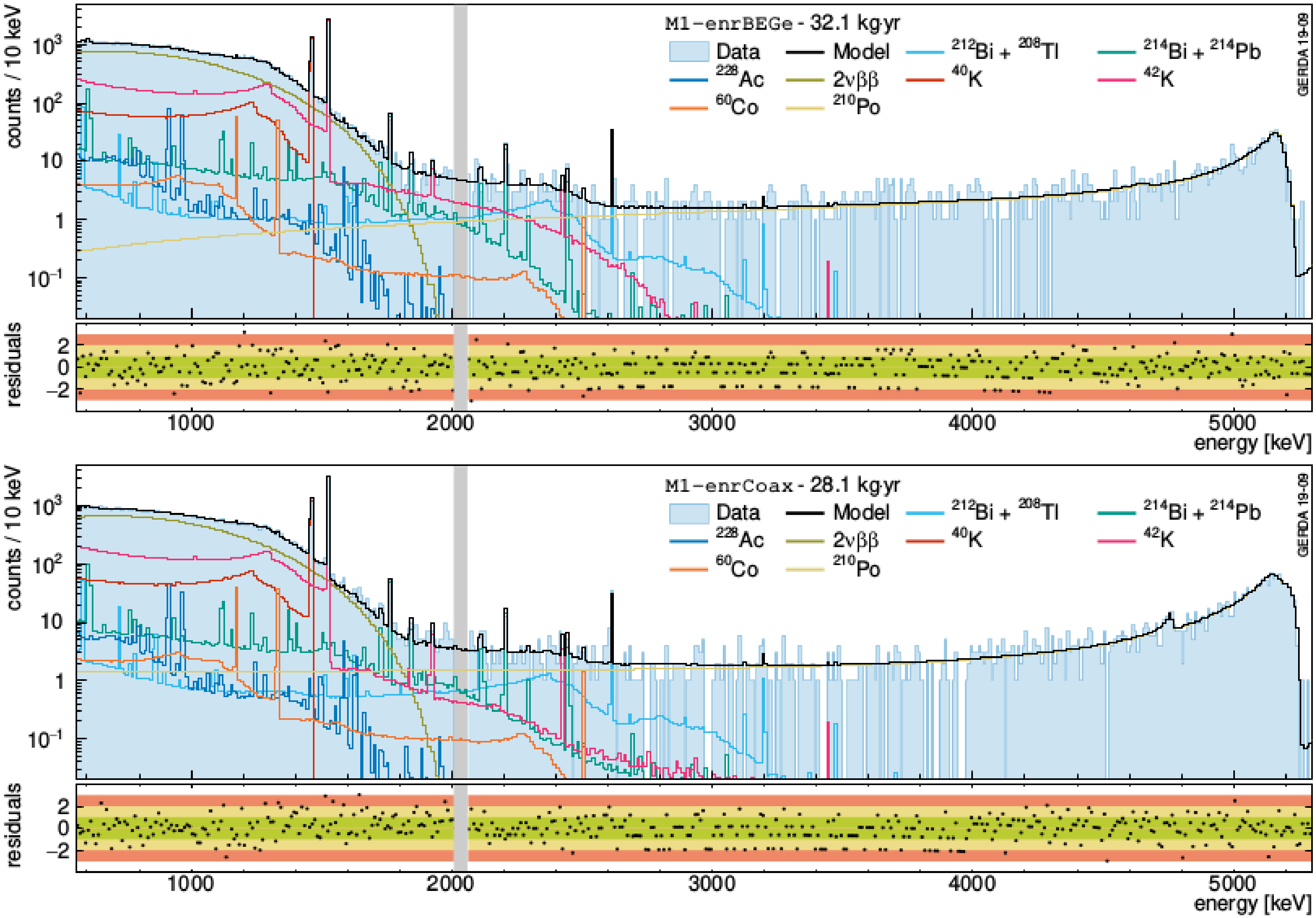


DOI:10.1126/science.aav8613

background level ~$6x10^{-4}$ cnt/(keV kg yr) for coax and BEGe detectors
reached goal of Phase II, “background-free” until design exposure of 100 kg yr, Nature 544(2017)47

blind analysis: - events within Q_{bb} ±25 keV are removed from normal data stream,
- fix all analysis cut
- then apply full analysis to possible events in the blinded window

background model arXiv:1909.02522



model ^{228}Th and ^{226}Ra background using screening results – works well

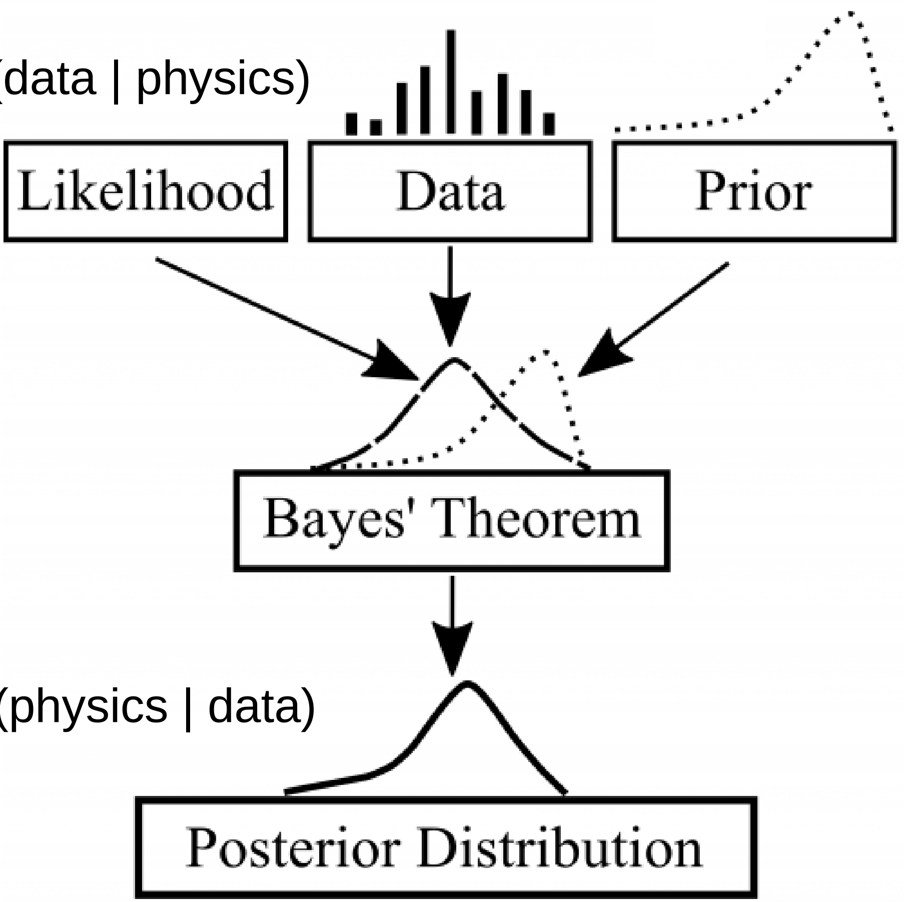
empirical model for α background and ^{42}K contribution, some addition ^{40}K needed

statistical analysis

Bayesian

L(data | physics)

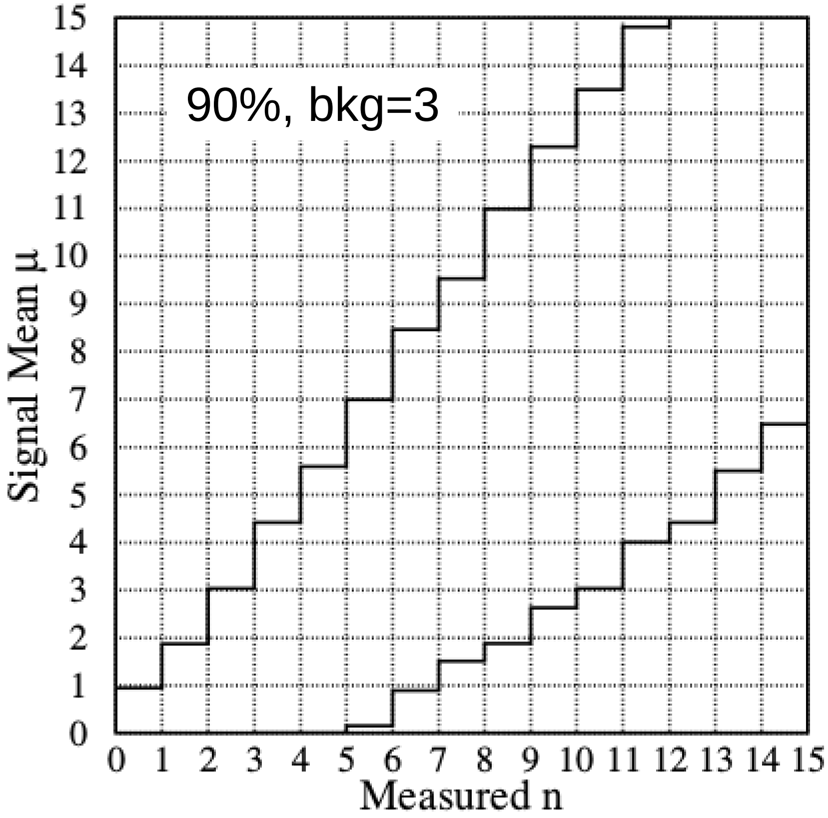
P(physics | data)



makes prob statement for physics quantity, but depends on prior → maybe strong effect

frequentist

likelihood → construct prob. intervals
Fedlman/Cousins Phys.Rev. D57 (1998)3873



makes NO statement about physics,
confidence interval: for $\mu_1 < \mu_{true} < \mu_2$
→ 90% of experiments measure “n”

frequentist analysis

1) Likelihood function (conceptual)

$L(E_i \mid \text{bkg}, T_{1/2}, \text{systematic}) = \prod_i$ “flat $(E_i \mid \text{bkg})$ + gauss$(E_i \mid T_{1/2})$” x gauss(systematic)

E_i = energy of event “i”

systematic = uncertainty of peak position, width, reconstruction efficiency

2) profile likelihood λ

$$\lambda(1/T^{0\nu}_{1/2}) = \frac{\max\limits_{b_k} L(b_k, 1/T^{0\nu}_{1/2})}{\max\limits_{\hat{b}_k, 1/\hat{T}^{0\nu}_{1/2}} L(\hat{b}_k, 1/\hat{T}^{0\nu}_{1/2})}$$

→ comparing 2 hypothesis

b_k = background & systematic

constrain to physical allowed range (signal>0, bkg > 0)

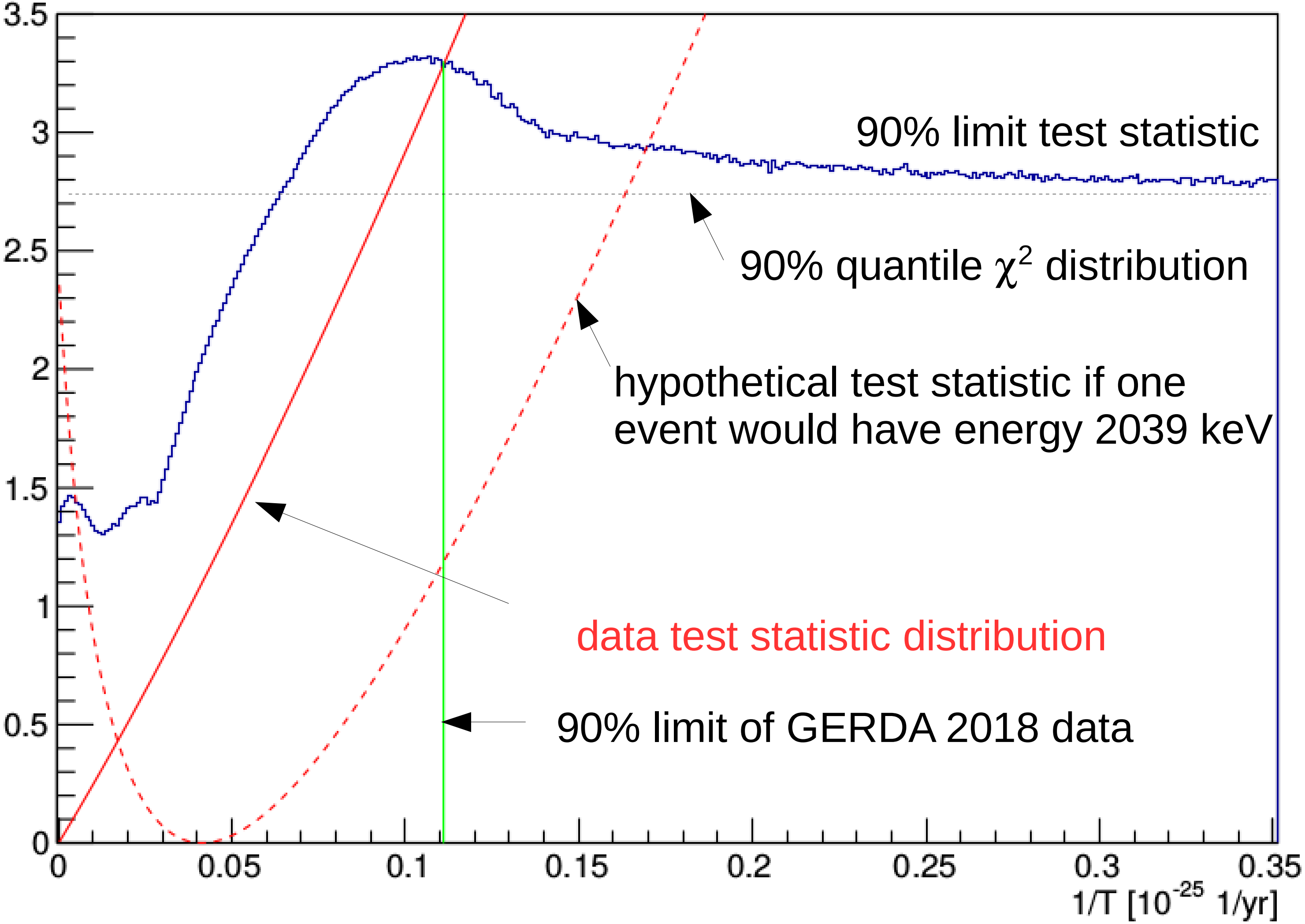
3) test statistic $t\,(1/T_{1/2}) = -2 \ln \lambda$

for large number of events t follows a χ^2 distribution for 1 degree of freedom (Wilks’ theorem), not for GERDA

4) construct confidence interval

generate toy MC spectra for every “true” $1/T_{1/2}$ and find the 90% interval $0 < t < t_{90}$

frequentist analysis (II)



90% limit test statistic

90% quantile χ^2 distribution

hypothetical test statistic if one event would have energy 2039 keV

data test statistic distribution

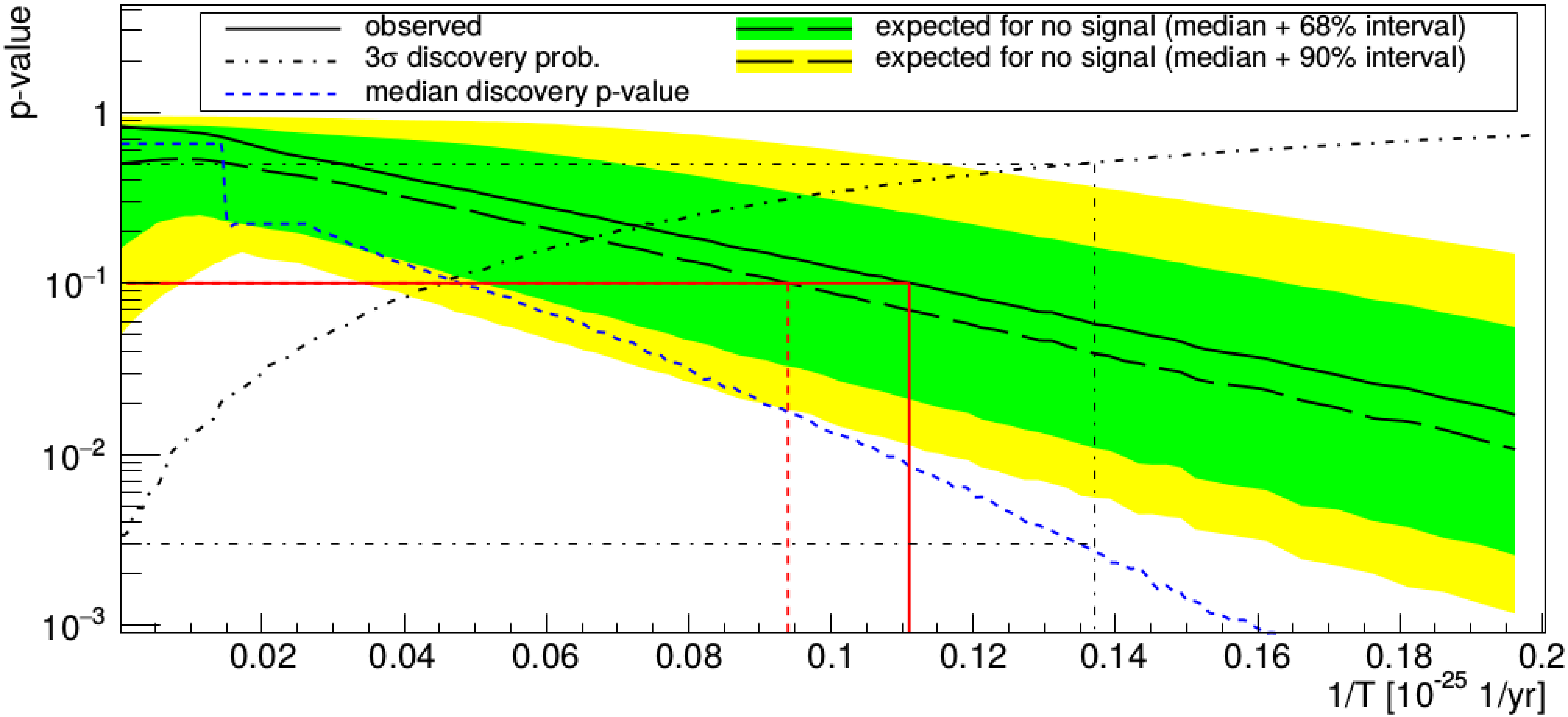
90% limit of GERDA 2018 data

for sensitivity: generate many toy MC spectra assuming NO signal
→ sensitivity = median of the 90% limits

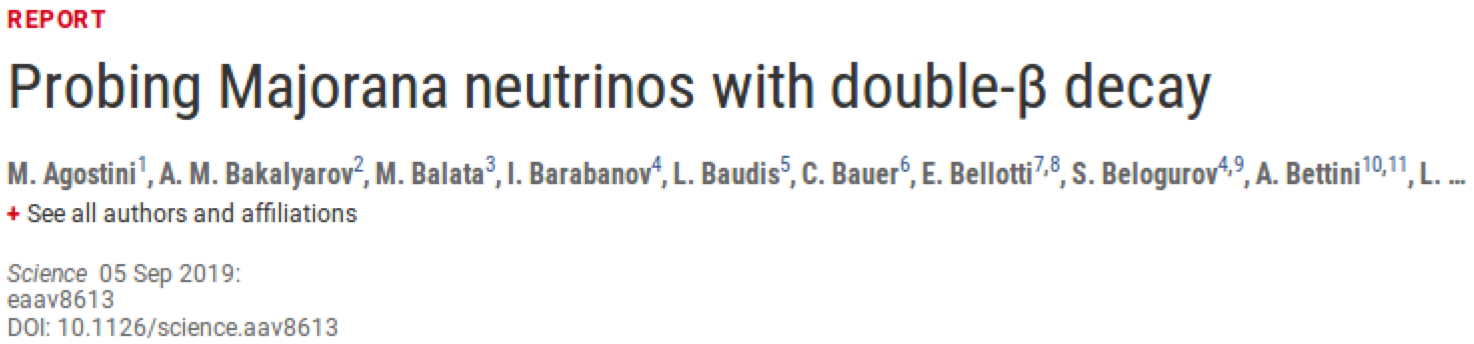
frequentist analysis (III)

alternative: for every t value of $1/T_{1/2}$ calculate p-value = quantile of test statistic distribution

sensitivity = median expected limit assuming NO signal



latest results (2018)



REPORT

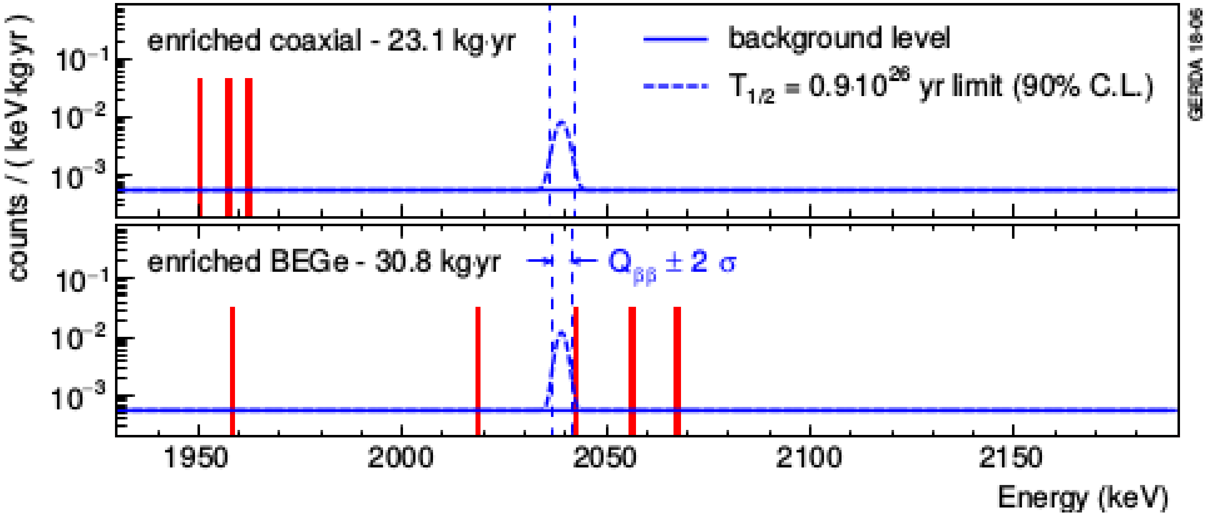
Probing Majorana neutrinos with double-β decay

M. Agostini[1], A. M. Bakalyarov[2], M. Balata[3], I. Barabanov[4], L. Baudis[5], C. Bauer[6], E. Bellotti[7,8], S. Belogurov[4,9], A. Bettini[10,11], L. ...

+ See all authors and affiliations

Science 05 Sep 2019:
eaav8613
DOI: 10.1126/science.aav8613

bkg goal 10^{-3} cnt/(keV kg yr) → “background-free” until 100 kg yr



no $0\nu\beta\beta$ signal

personal advice:
use frequentist sensitivity for $T_{1/2}$ “interpretation”

$T_{1/2}$ limits

	limit	sensitivity (no signal)
Bayesian 90% CI flat prior in 1/T	0.8 x 10^{26} yr	0.8 x 10^{26} yr
frequentist 90% CL	0.9 x 10^{26} yr	1.1 x 10^{26} yr

present

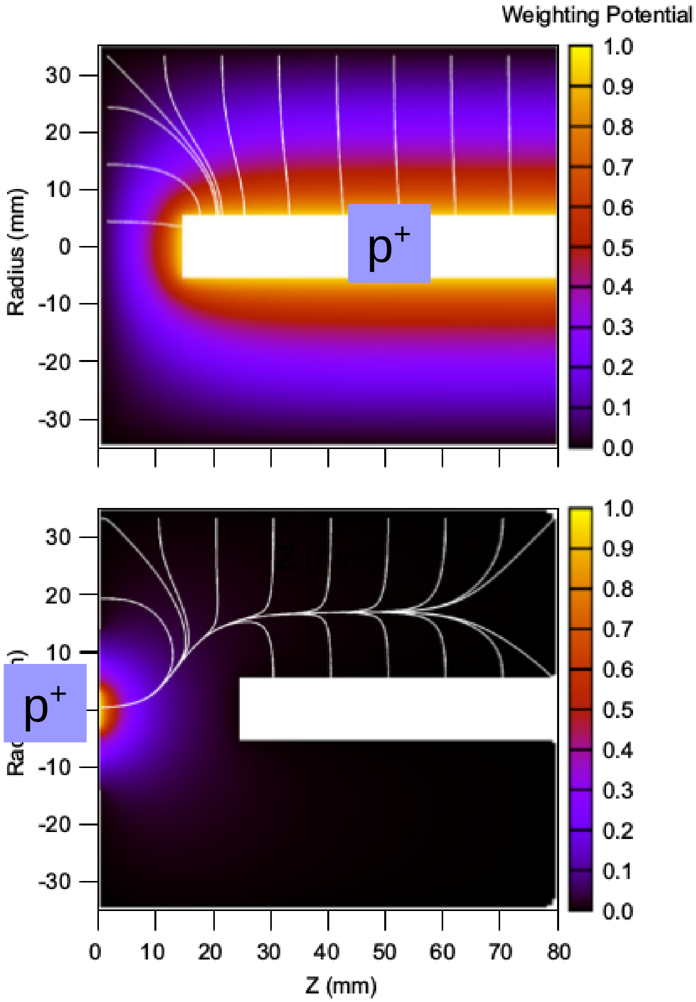
A novel HPGe detector for gamma-ray tracking and imaging

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

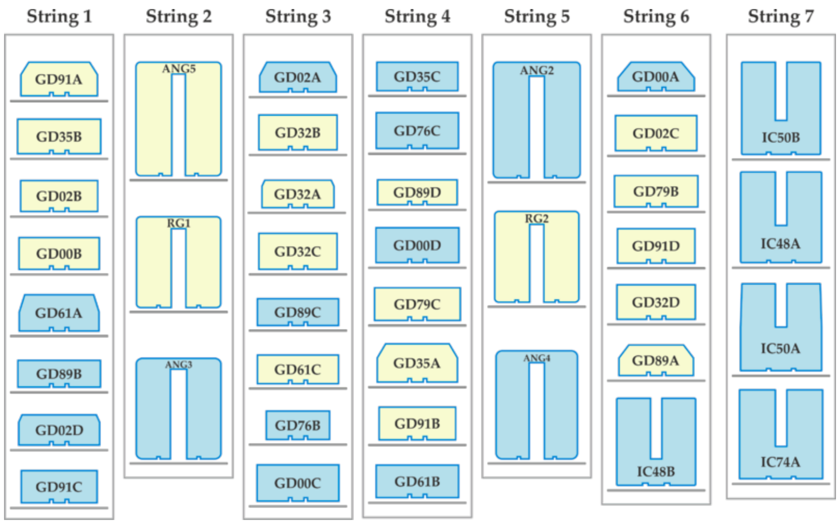
NIMA 665 (2011) 25

normal
coax

inverted
coax



current GERDA detector configuration



added 5 Inverted-Coax detectors in 2018
avg mass ~ 3 x BEGe
→ similar bkg & energy resolution as BEGe

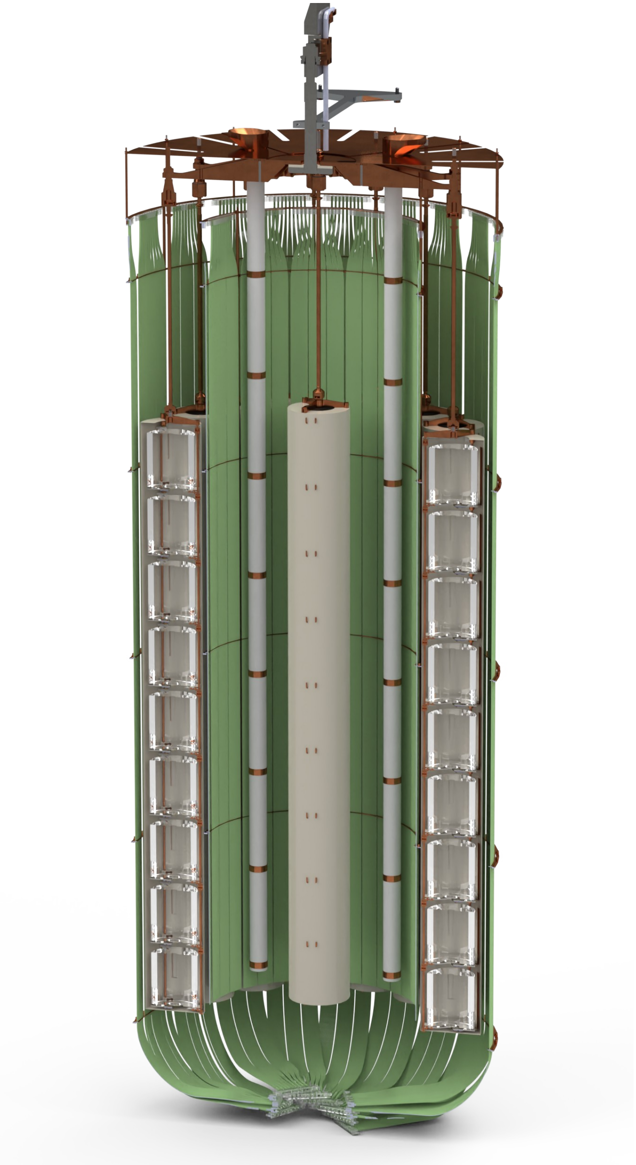
reach design exposure 100 kg yr end of 2019

future: LEGEND

“Large Enriched GErmanium Neutrinoless Double beta” collaboration formed in 2016

LEGEND-200: 200 kg in existing GERDA infrastructure at LNGS, ~ 10^{27} yr sensitivity

LEGEND-1000: 1000 kg experiment, realization depends on US-downselect, ~ 10^{28} yr



L200 design:
- 14 strings of inverted-coax det. in ring (+ 2 strings in center)
- surrounded by fibers+SiPM

approach:
- combine the best solutions of Majorana & GERDA & others
- minimize “dead” material: larger detectors
- better electronics
- more light

goal:
- background goal ~2 x 10^{-4} cnt/(keV kg yr) (1/3 current bkg)
- for 1000 kg yr exposure: $T_{1/2}$ sensitivity ~1 x 10^{27} yr

status:
- start data modification in 2020
- first data in 2021