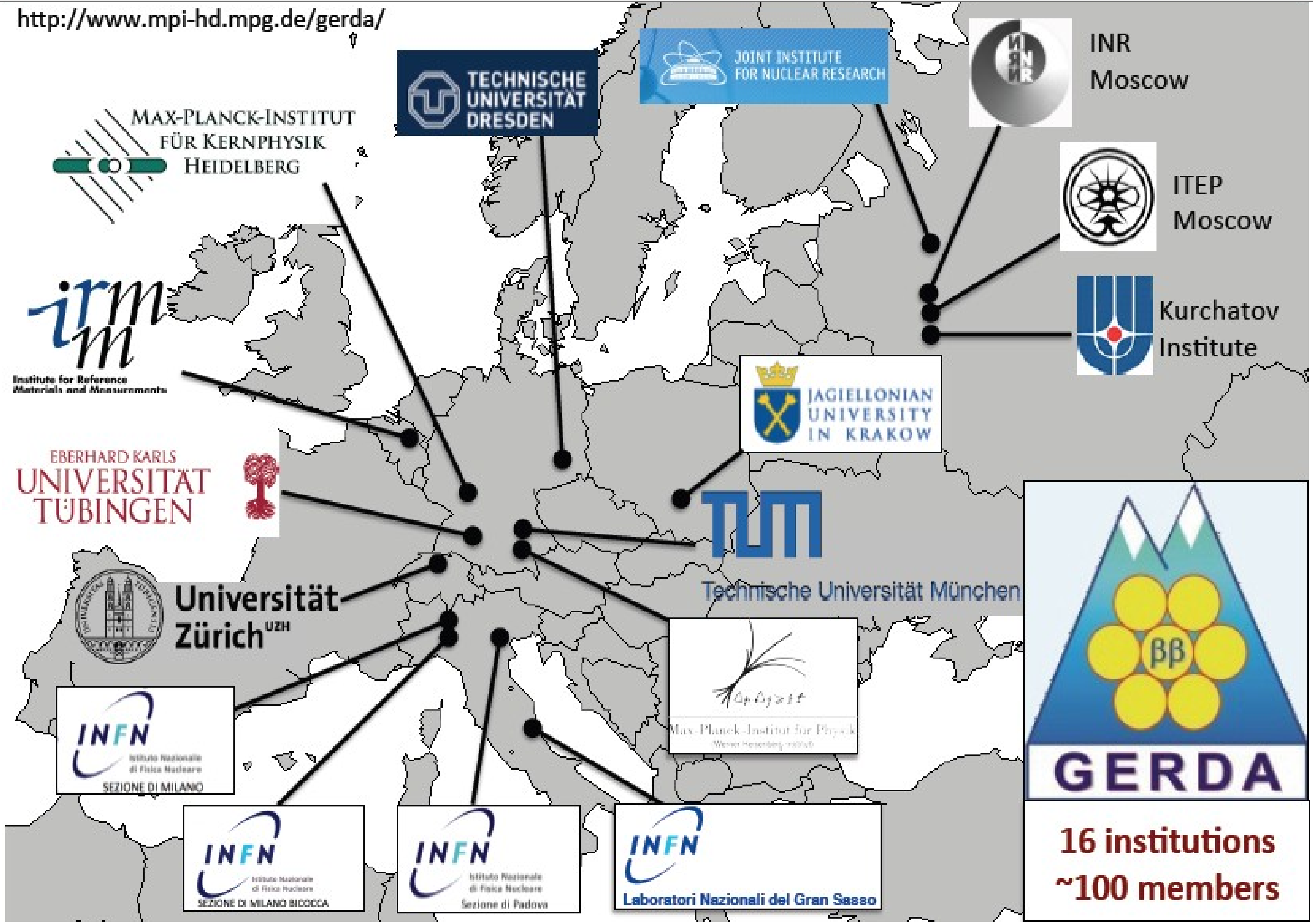
GERmanium **D**etector **A**rray "**GERDA**",

Phase II - Upgrade

József, Janicskó Csáthy for the GERDA collaboration

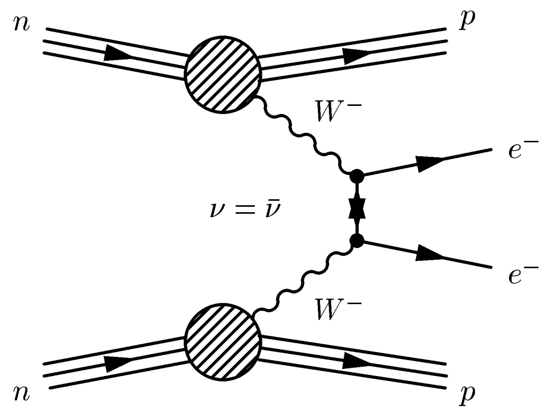
GERDA

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

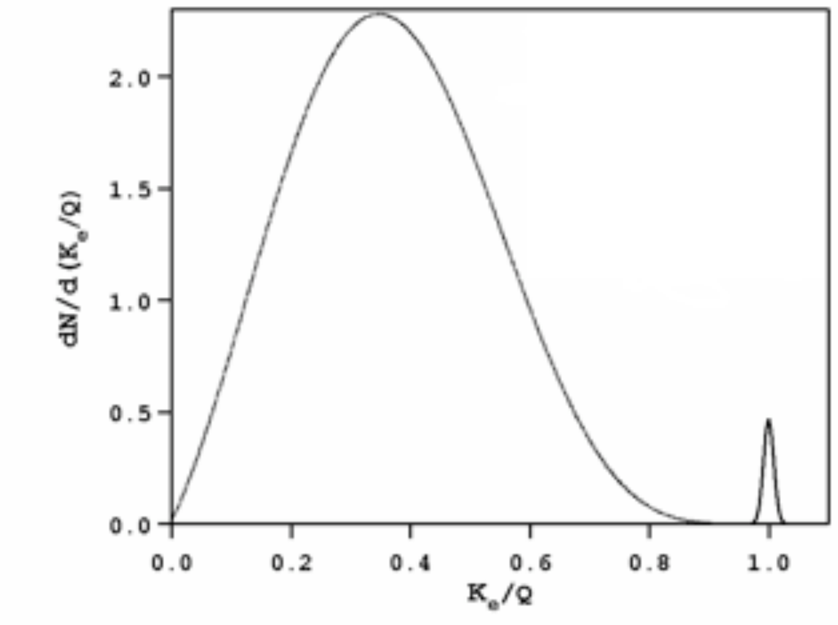


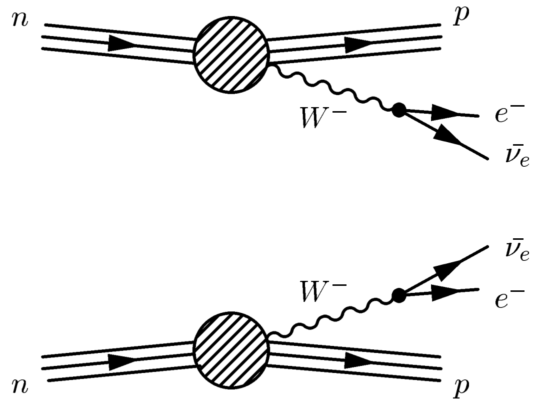
16 institutions
~100 members

0νββ decay



2β decay with 2 neutrinos





2β decay with 0 neutrinos

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

allowed and observed

(A,Z)→(A,Z+2) + $2e^-$

violates lepton number conservation

$$\left(T^{0\nu}_{1/2}\right)^{-1} = F^{0\nu}\cdot\left|\mathcal{M}^{0\nu}\right|^2\cdot m^2_{\beta\beta}$$

$$\langle m_{\beta\beta}\rangle^2 = \left|\sum_i U^2_{ei} m_{\nu i}\right|^2$$

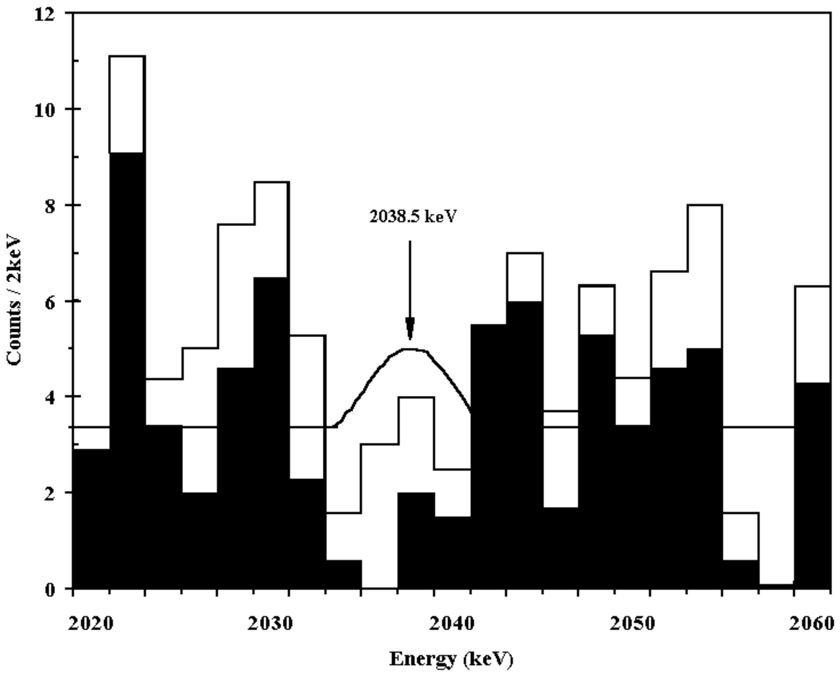
$M^{0\nu}$ - nuclear matrix element

$F^{0\nu}$ - phase space integral depends on the Q value

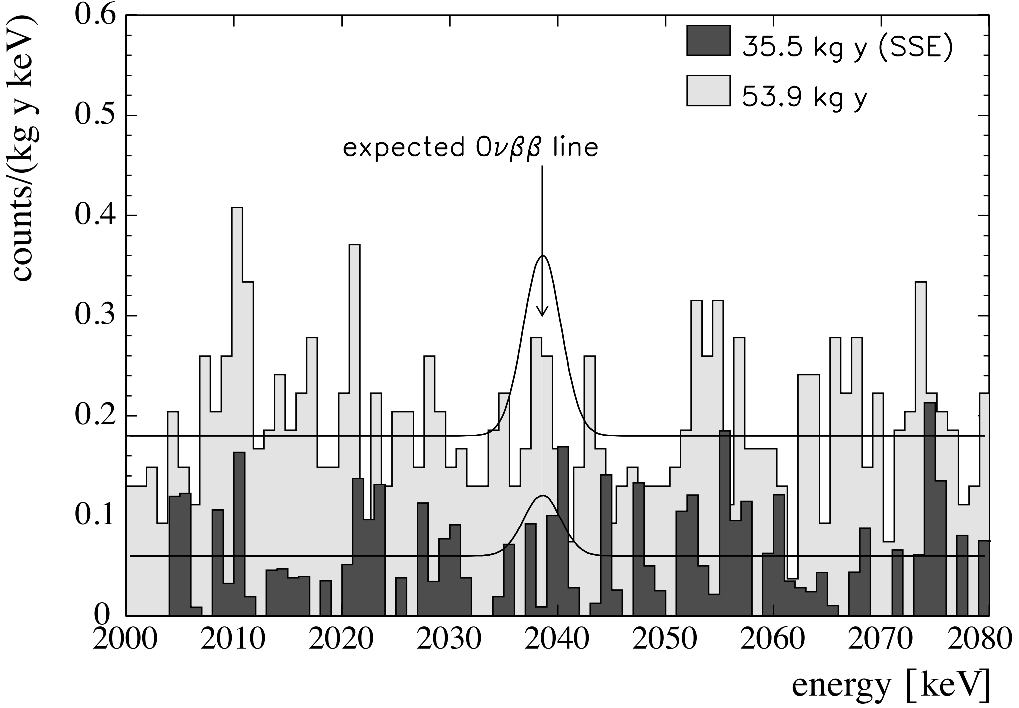
$\langle m_{\beta\beta}\rangle$ - effective neutrino mass

$0\nu\beta\beta$ in ^{76}Ge

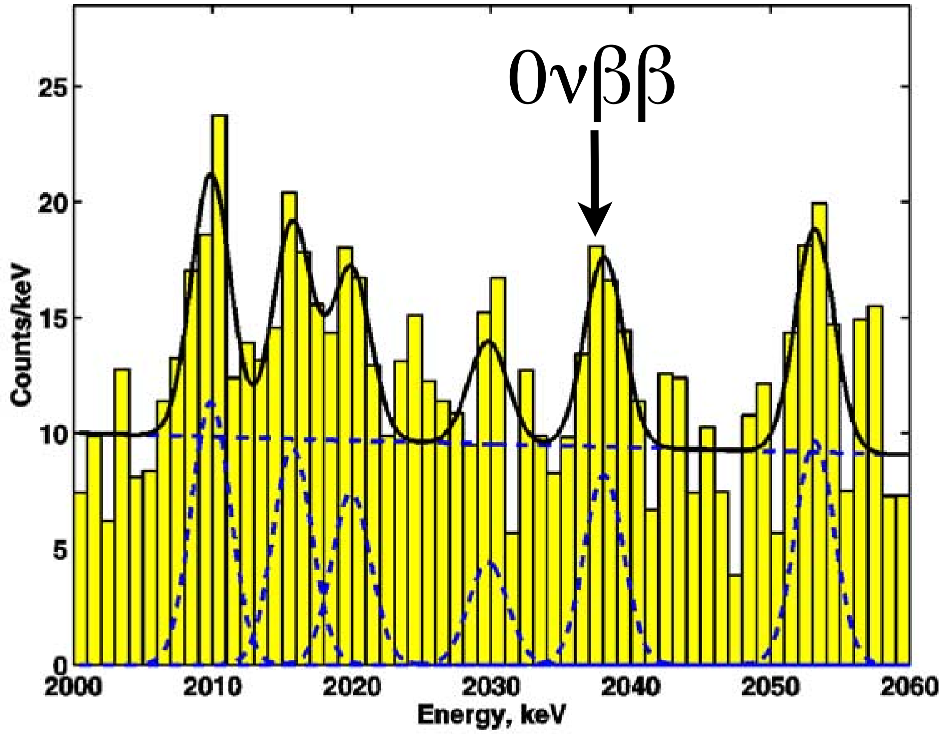
PHYSICAL REVIEW D, VOLUME 65, 092007



Eur. Phys. J. A 12, 147–154 (2001)

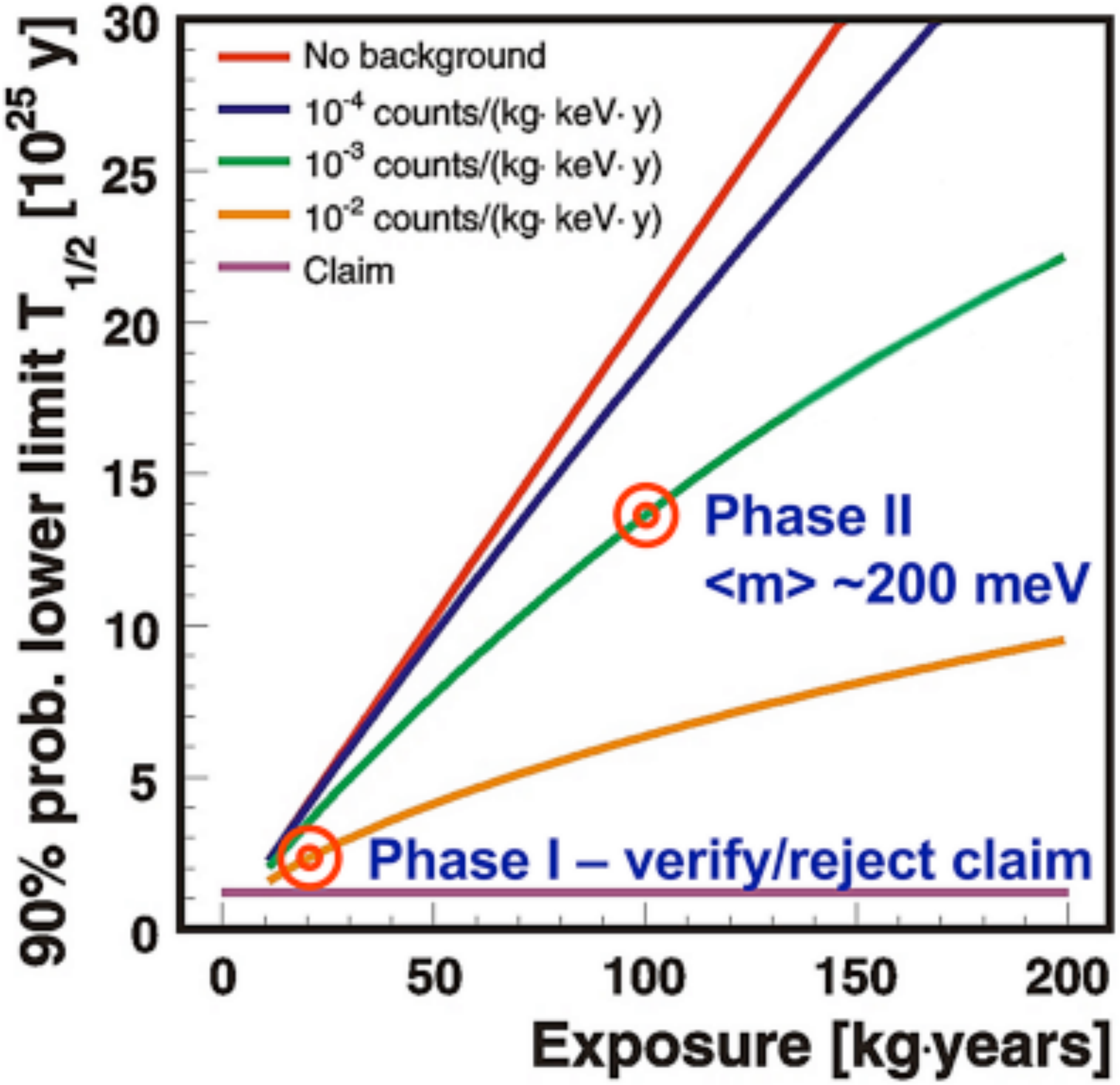


H.V. Klapdor-Kleingrothaus et al. / Physics Letters B 586 (2004)



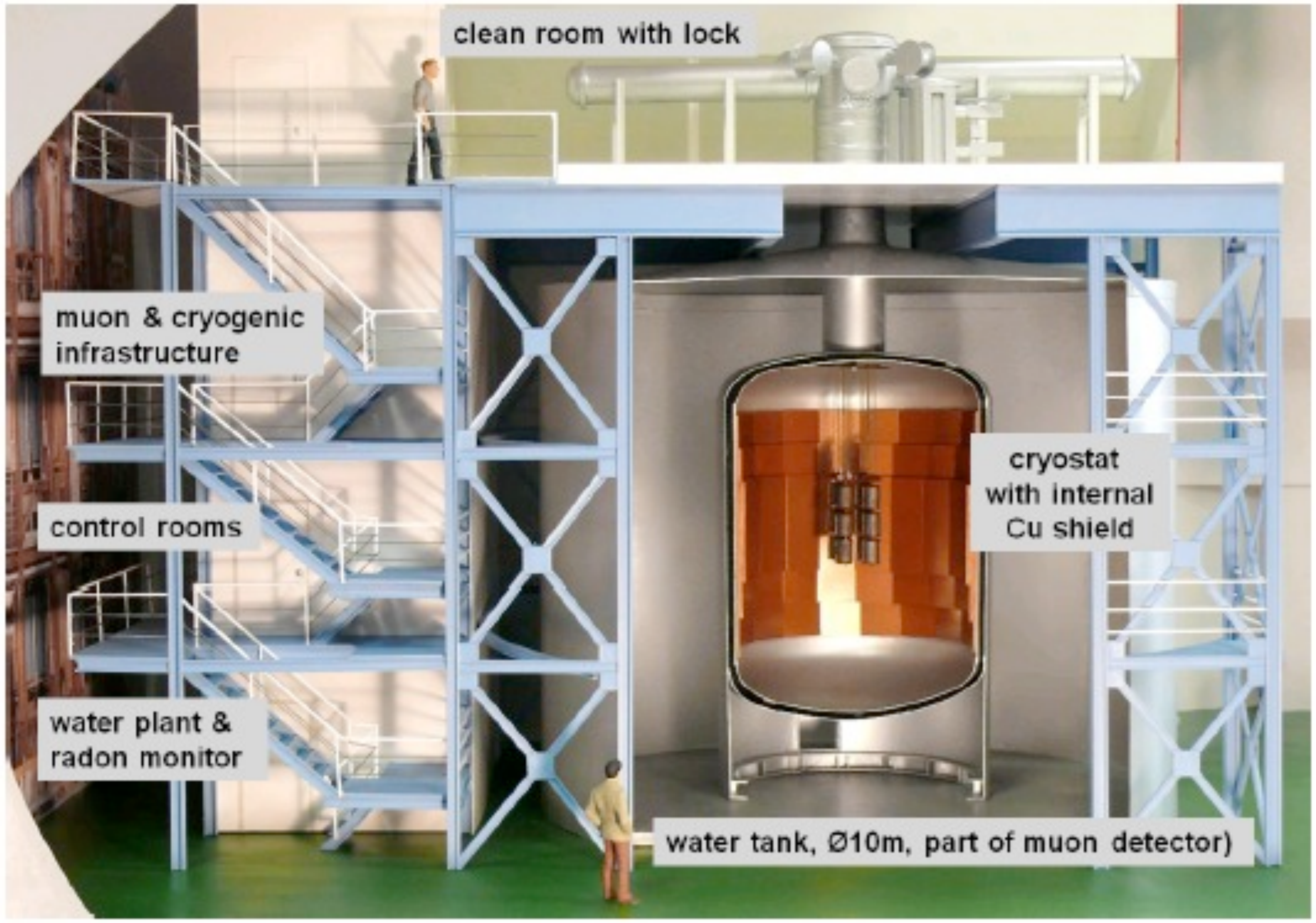
- IGEX no signal $T_{1/2} > 1.6\text{x}10^{25}$ yr
- HdM no signal $T_{1/2} \geq 1.9\times10^{25}$ yr
- Klapdor-Kleingrothaus *et alii* claim of evidence: $T_{1/2} = 1.9\times10^{25}$ yr

GERDA status



- *Goal of Phase I*: Re-deploy HdM and IGEX detectors (18 kg) in LAr with a background of 0.01 cts/(keV kg yr), scrutinize the claim
- *Status of Phase I*: data taking ended with 21.6 kg · y exposure: from Nov. 2011 to May 2013
- *Goal of Phase II*: background level of 0.001 cts/(keV kg yr) and 100 kg yr exposure
- *Status of Phase II*: under construction: 30 new HPGe detectors (~20 kg) are ready to be deployed

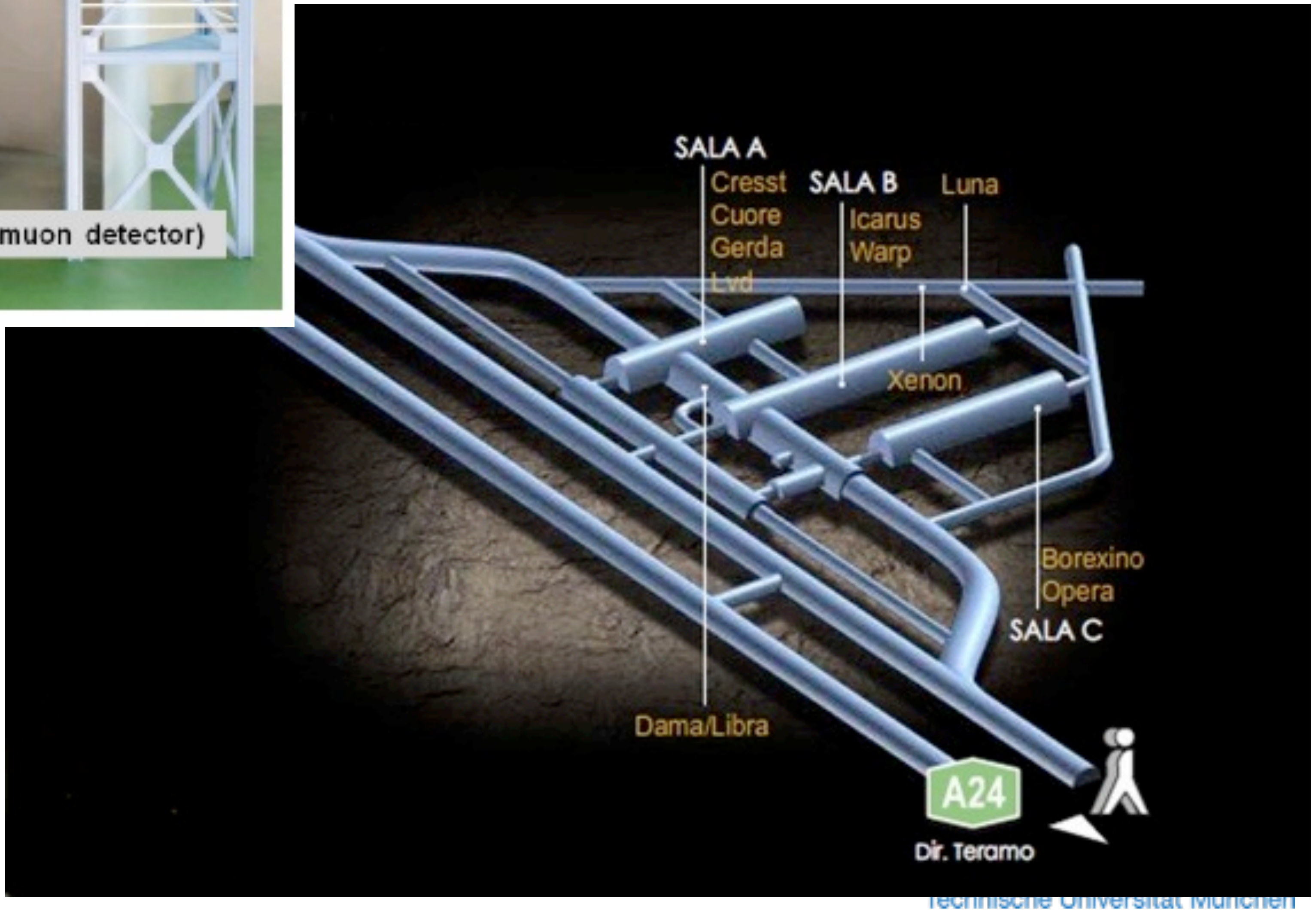
GERDA at Gran Sasso



Under a 3000 m high mountain,

inside 650 m^3 water tank,

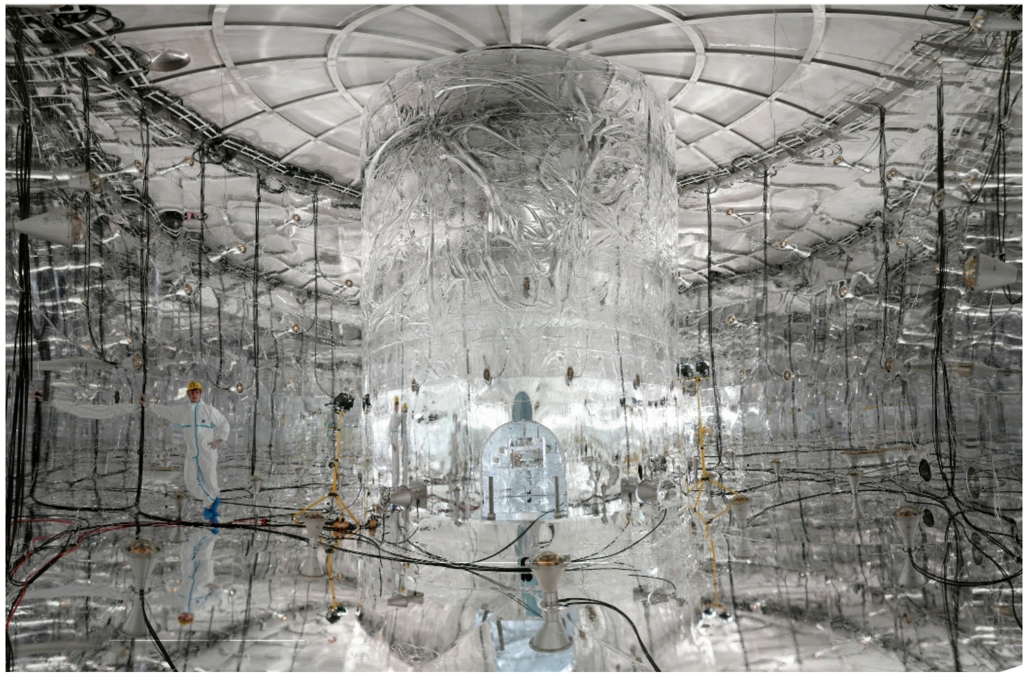
in a 66 m^3 LAr cryostat ...



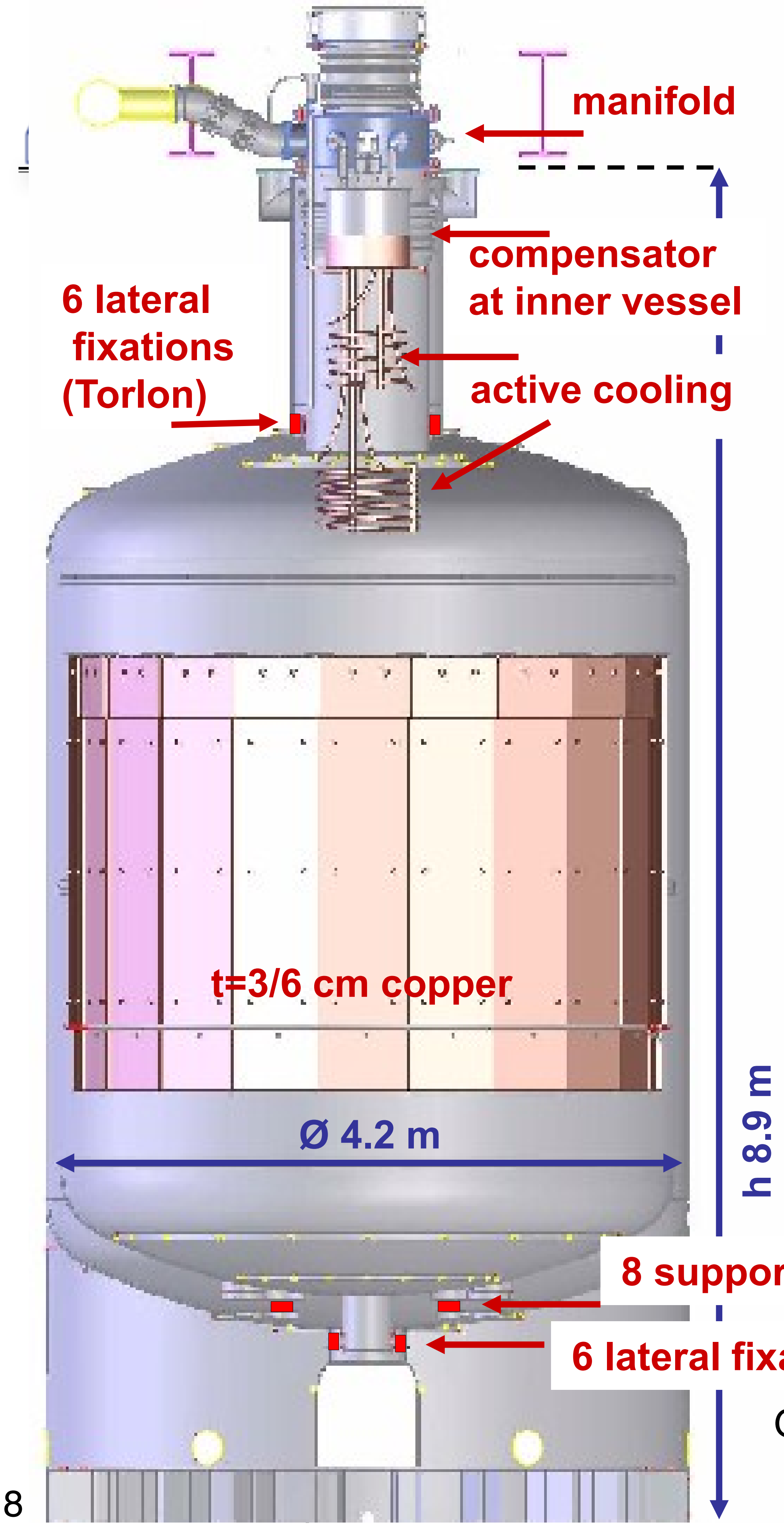
... there are some germanium detectors

GERDA milestones

- Construction started in 2008
- Cryostat, water tank, clean room ready in 2009
- Dec. 2009 cryostat filled with LAr
- Water-Cerenkov veto completed in 2010



adopted design



Stainless steel cryostat with vacuum superinsulation

double-walled X6 CrNiMoTi 17-12-2

64 m^3 volume for LN2/LAr
design pressure -1/1.5 barg
operating pressure 0.2 barg
AD2000 design
immersed in water of 8m height
no penetration below water level

200W measured thermal loss

active cooling with LN2
no refill since January 2010

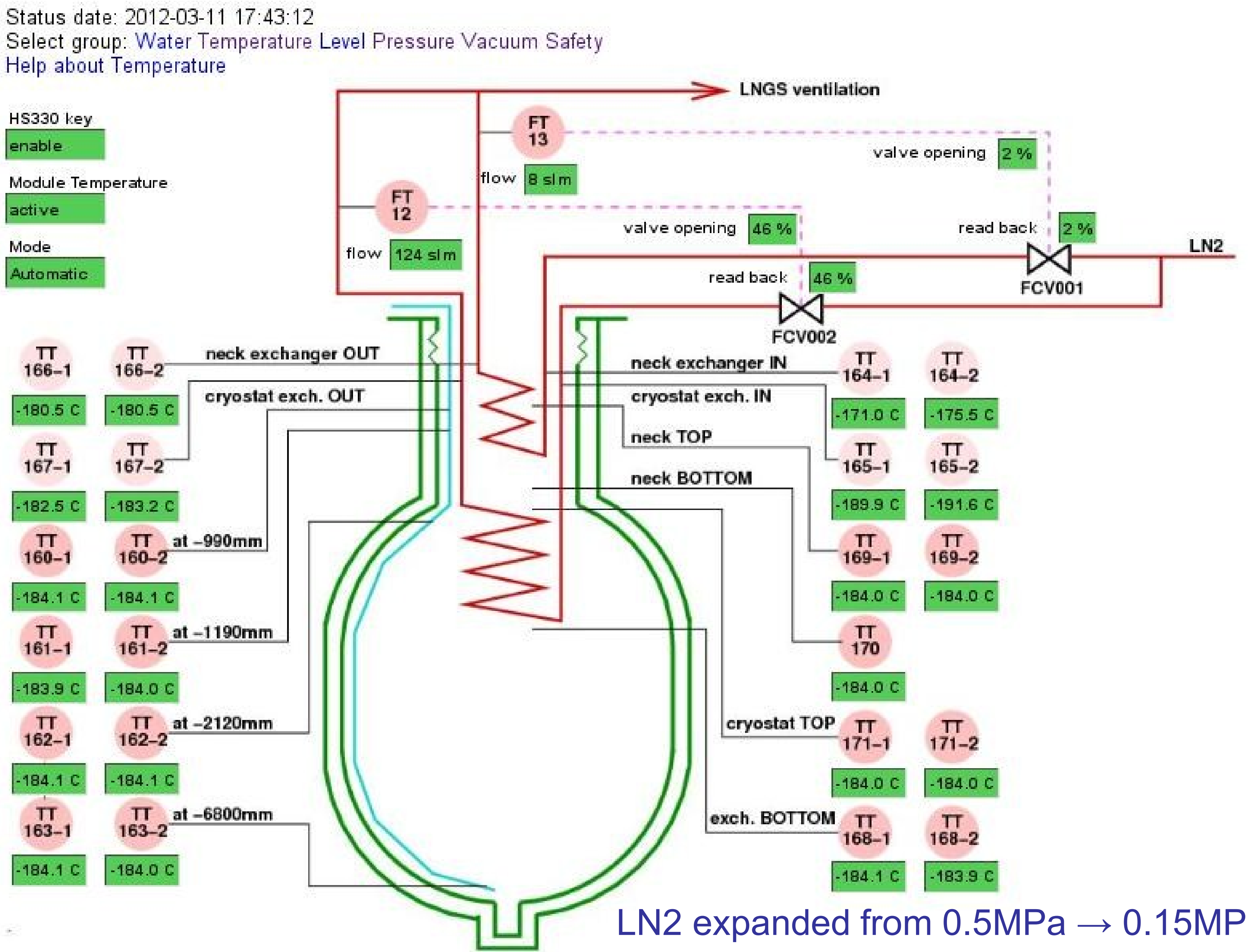
internal copper shield (16 tons)

hi-rel design
detailed risk analysis of cryostat in ‘water bath’

infrastructure active cooling of LAr

two LN2 evaporators, one in main LAr volume, one in neck

test installation at MPI-K



Status date: 2012-03-11 17:43:12
Select group: Water Temperature Level Pressure Vacuum Safety
Help about Temperature

HS330 key: enable
Module Temperature: active
Mode: Automatic

FT 13 flow: 8 slm
valve opening: 2 %
read back: 2 %
FT 12 flow: 124 slm
valve opening: 46 %
read back: 46 %

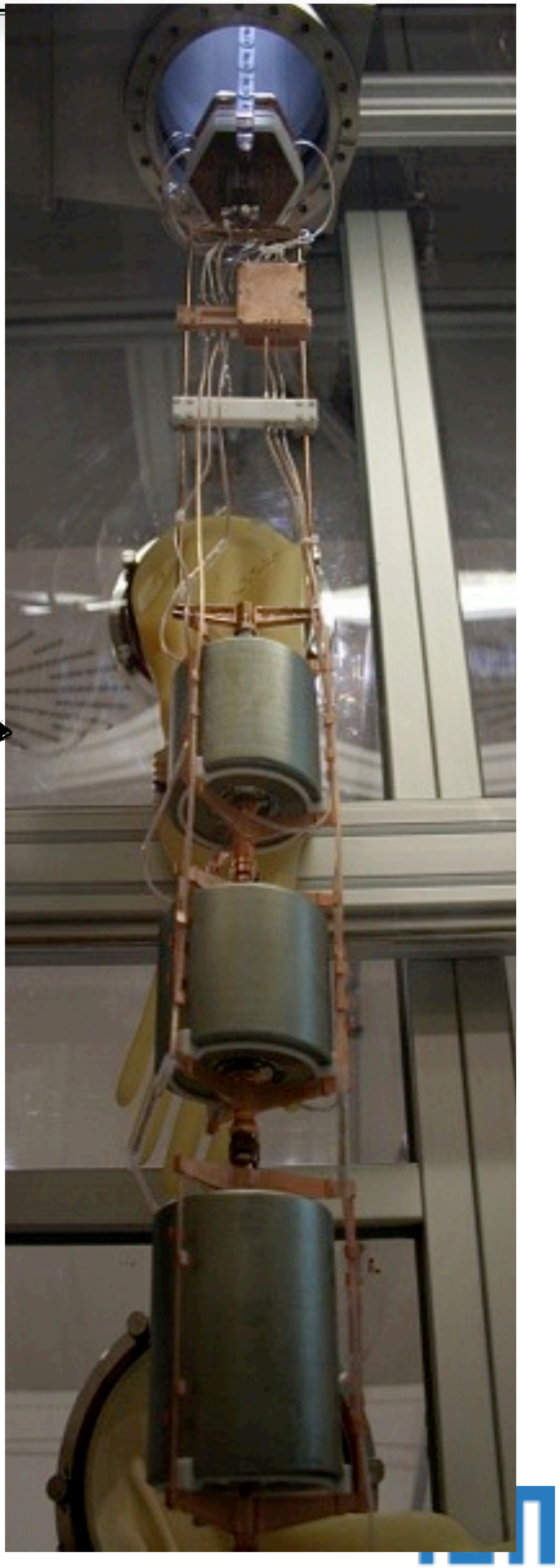
TT 166-1: -180.5 C
TT 166-2: -180.5 C
TT 167-1: -182.5 C
TT 167-2: -183.2 C
TT 160-1: -184.1 C
TT 160-2: -184.1 C
TT 161-1: -183.9 C
TT 161-2: -184.0 C
TT 162-1: -184.1 C
TT 162-2: -184.1 C
TT 163-1: -184.1 C
TT 163-2: -184.0 C
TT 164-1: -171.0 C
TT 164-2: -175.5 C
TT 165-1: -189.9 C
TT 165-2: -191.6 C
TT 169-1: -184.0 C
TT 169-2: -184.0 C
TT 170: -184.0 C
TT 171-1: -184.0 C
TT 171-2: -184.0 C
TT 168-1: -184.1 C
TT 168-2: -183.9 C

LN2 expanded from 0.5MPa → 0.15MPa
- ► large vapour fraction at inlet
- ► nitrogen will be completely evaporated
- ► acceptable level of microphony

C.Haberstroh, AIP Conf Proc 985 (2008) 1201

GERDA milestones

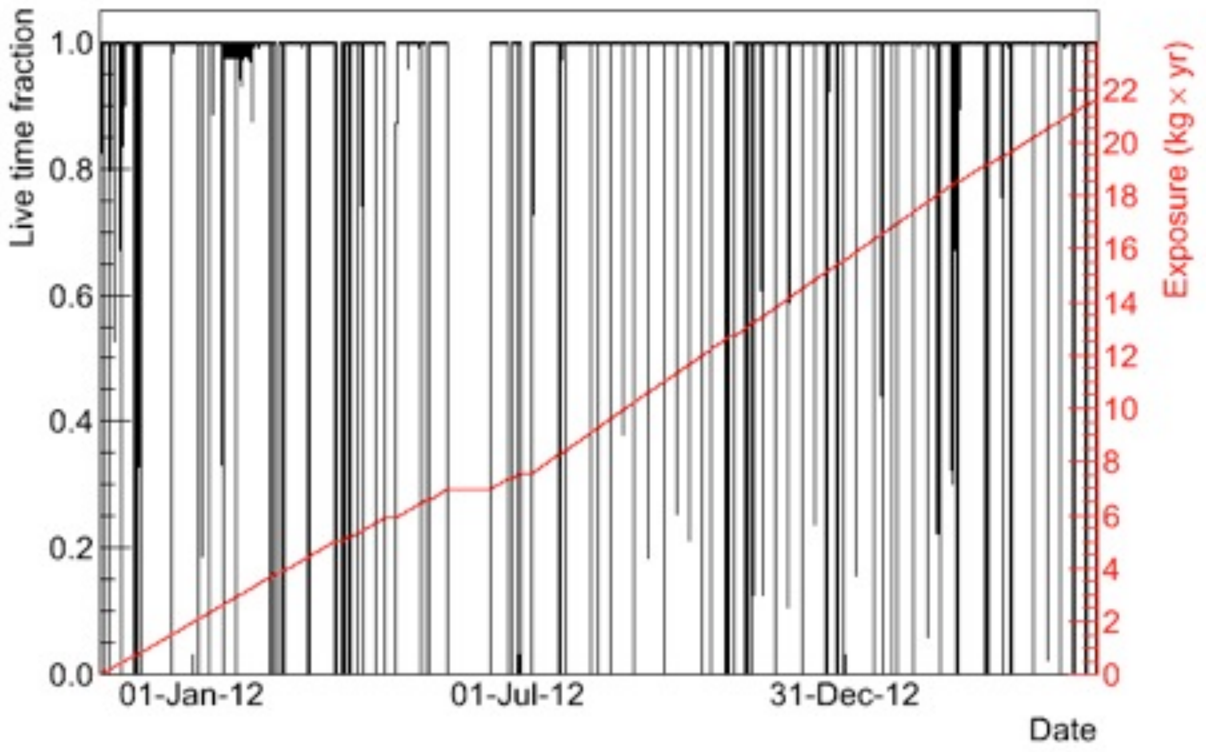
- HdM and IGEX detectors refurbished at Canberra
- Mounted in low-mass holders and deployed in LAr

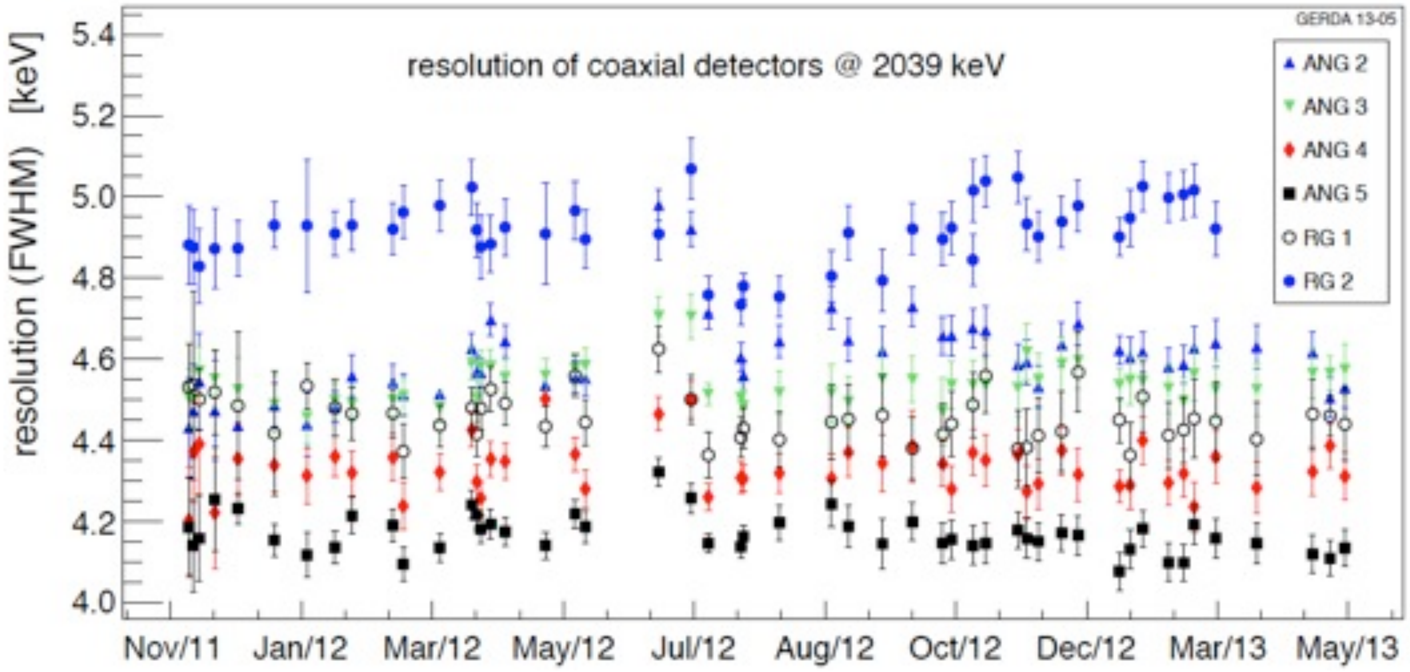


- Commissioning runs: 2010 - 2011
- Physics run with 9 detectors: from 2011 Nov. (+5 BEGe in July 2012)

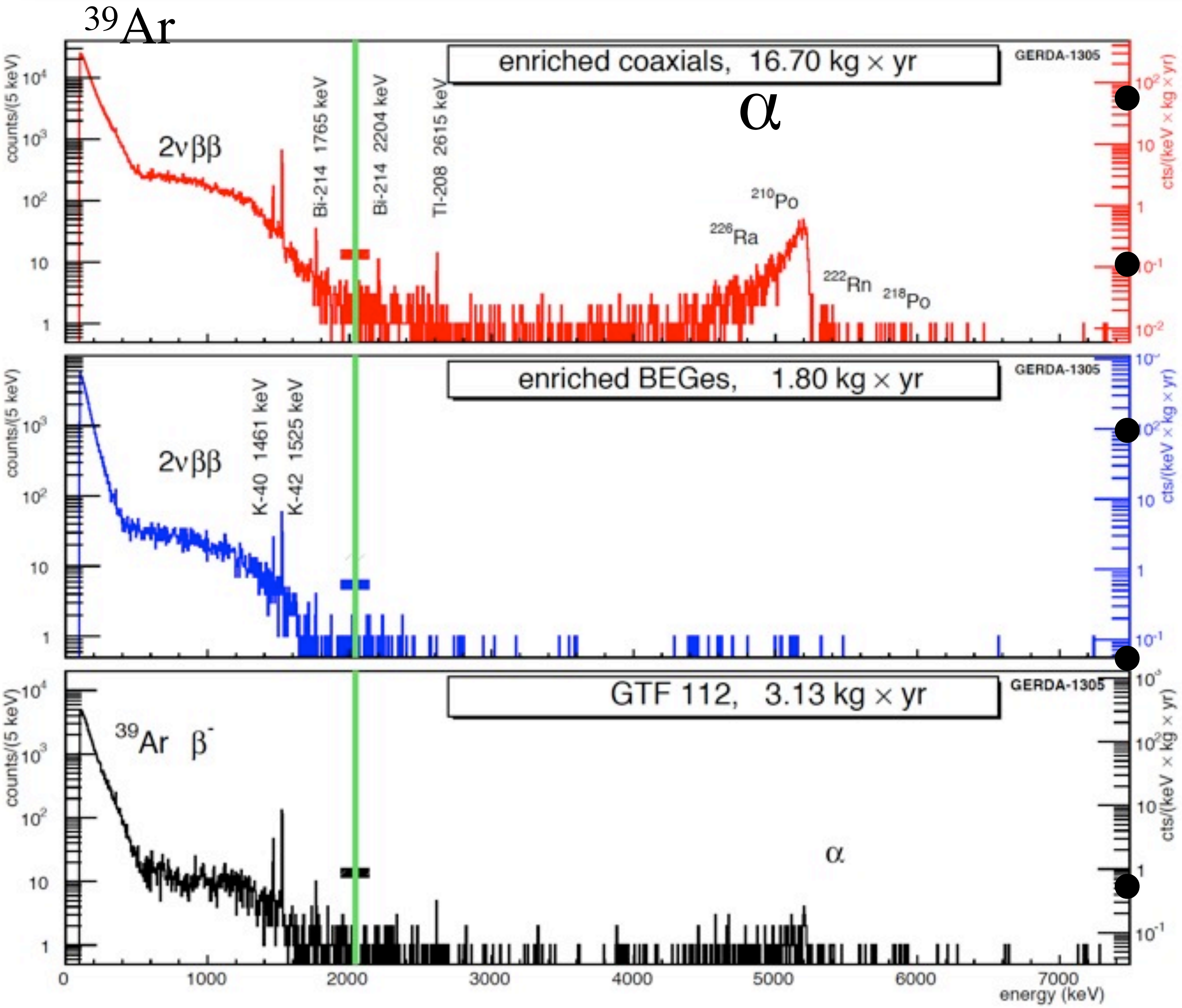
Run history

- Total exposure of 21.6 kg yr between Nov. 2011 and May 2013
- 8 coax detectors + 5 BEGe detectors added in June 2012
- Weekly callibration runs with ^{228}Th source
- Mean resolution at 2 MeV: coax 4.8 keV, BEGe 3.2 keV FWHM





Full Spectrum



- Blind analysis, 40 keV blinded window
- Background model developed before unblinding
- PSA cuts defined before unblinding, PSA methods compared
- Background rate golden coax: $1.8\text{x}10^{-2}$ cts/(keV kg yr)
- Background 10x smaller than in HdM experiment

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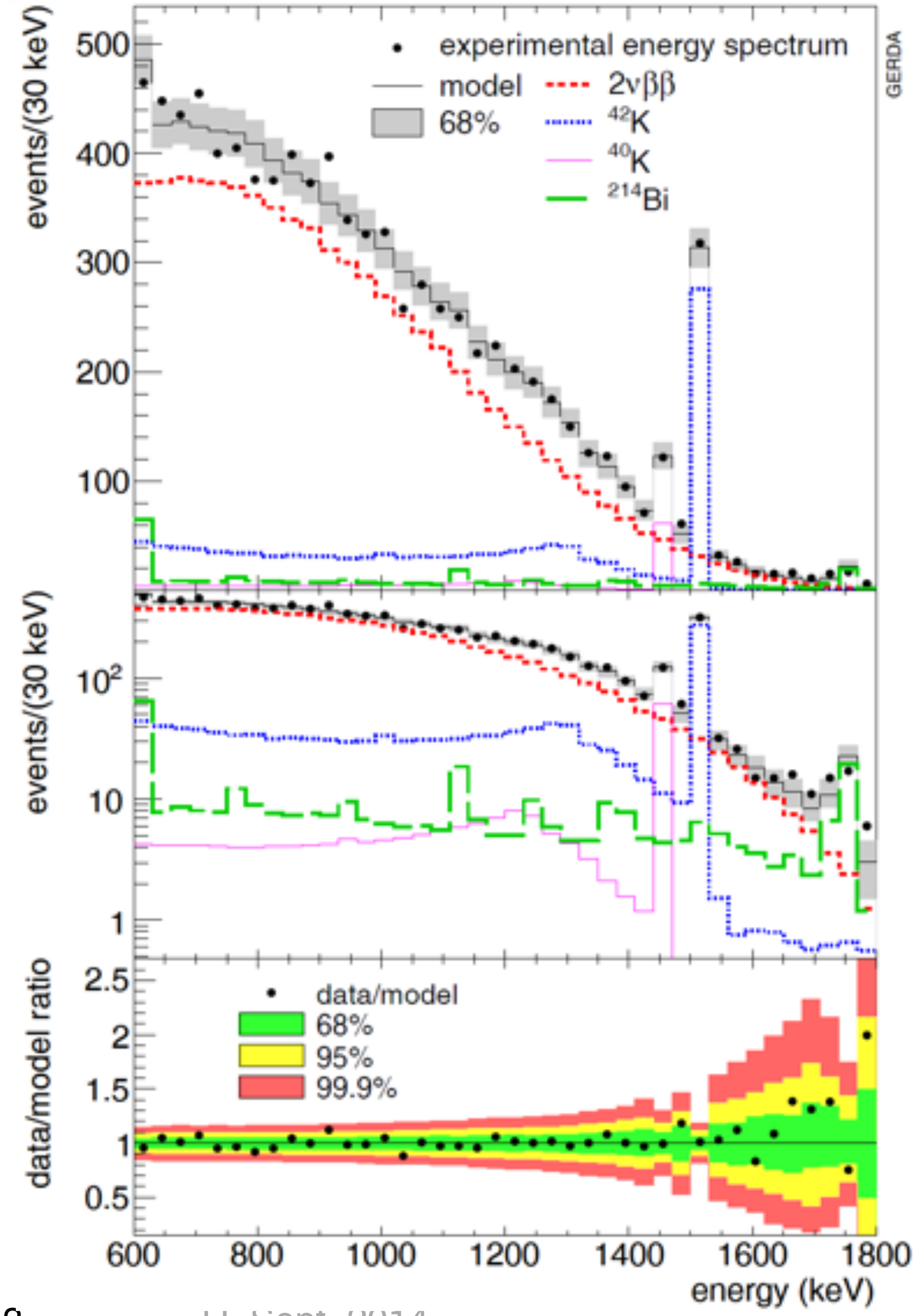
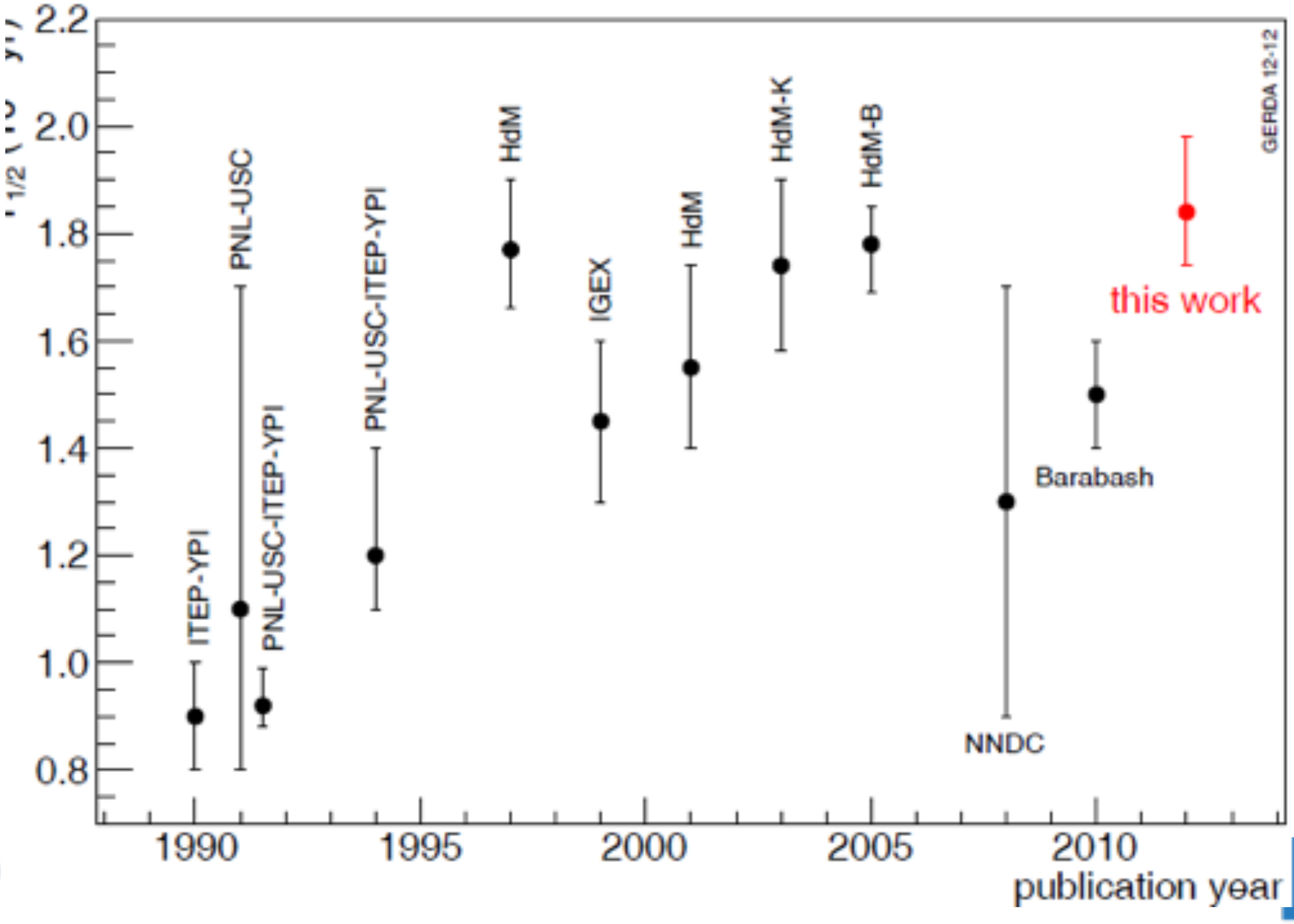
$2\nu\beta\beta$ - $T_{1/2}$



- With only 5.04 kg yr exposure the $2\nu\beta\beta$ $T_{1/2}$ could be already measured

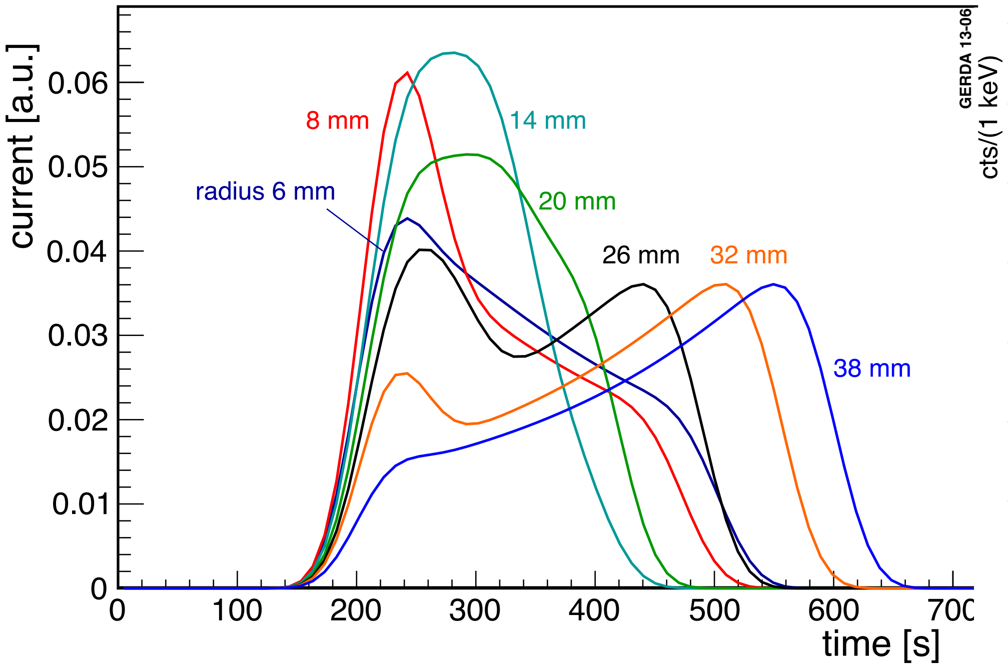
$$T^{2\nu}_{1/2}(^{76}\text{Ge}) = 1.84 \times 10^{21}\ \text{yr}$$

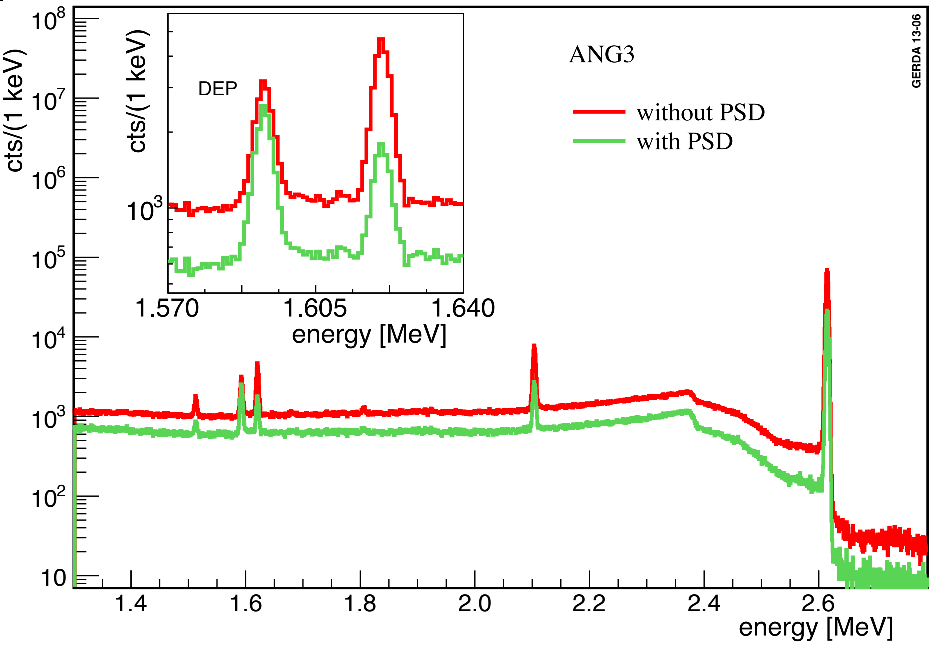
J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110 (13pp)

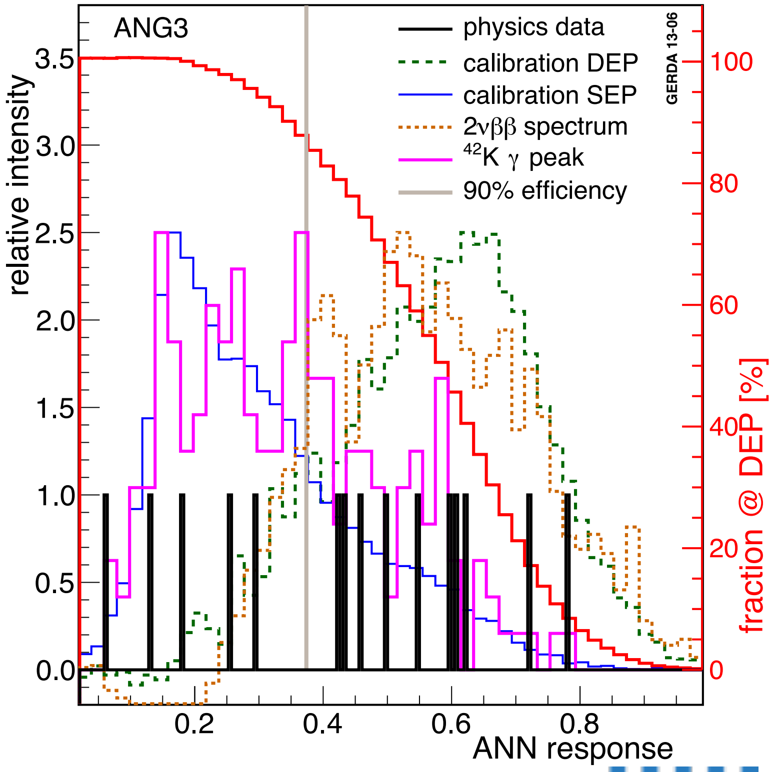


Pulse-shape analysis

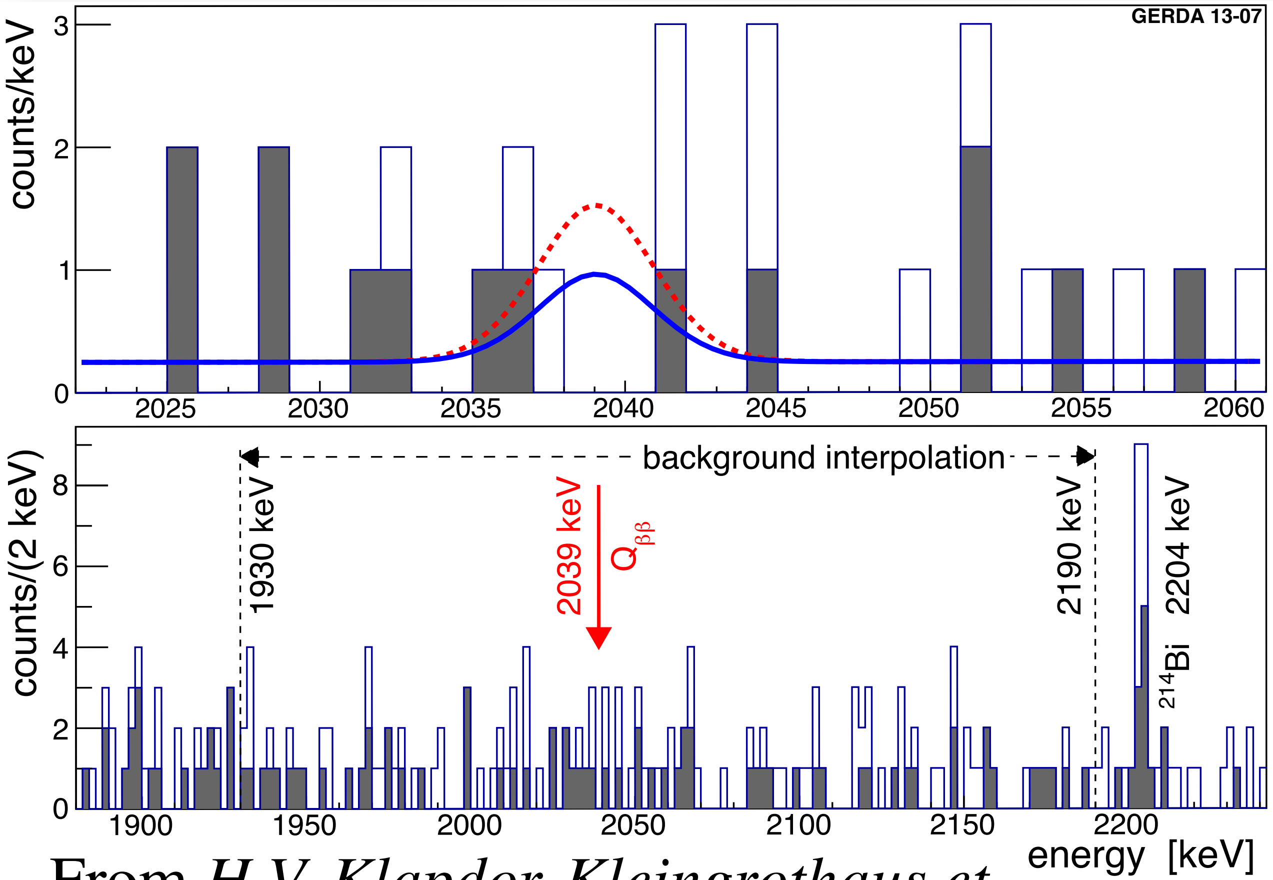
- PSA has to be tuned for each detector, for each run period.
- PSA is tuned to retain 90% of the DEP of the ^{228}Th 2.6 MeV line. (90% signal efficiency)
- Typical background survival prob. ~60%
- 3 different methods used: ANN, likelihood analysis, pulse-asymmetry cut.
- From the events rejected by one method 90% are rejected by the other methods as well.







GERDA results

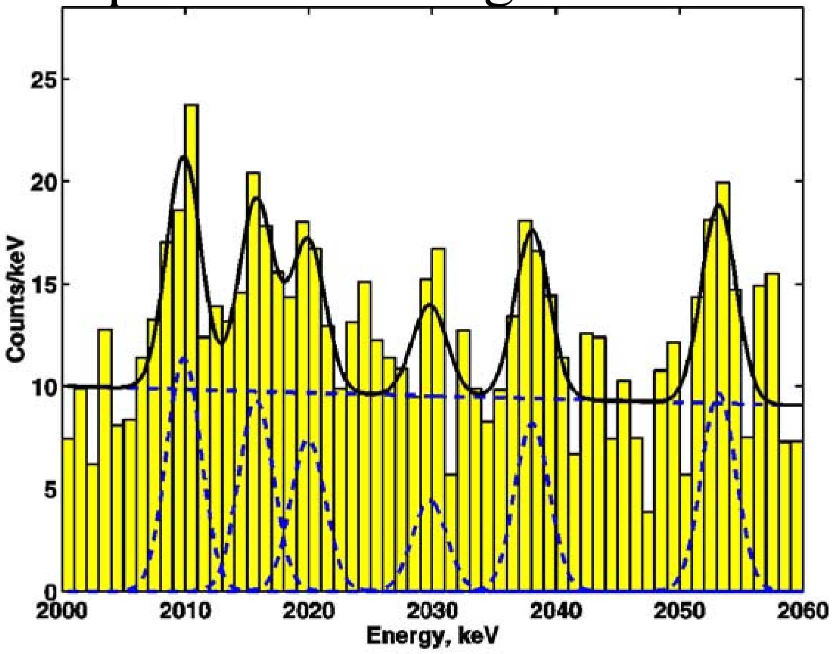


In 2039 ±5 keV we see 7 counts, after PSD only 3 remain:

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

Phys. Rev. Lett. **111**, 122503 (2013)

From *H.V. Klapdor-Kleingrothaus et al. / Physics Letters B 586 (2004)* we expect to see 6 signal events



data set	$\mathcal{E}$[kg·yr]	$\langle\epsilon\rangle$	bkg	BI †)	cts
without PSD					
golden	17.9	0.688 ± 0.031	76	18 ± 2	5
silver	1.3	0.688 ± 0.031	19	63^{+16}_{-14}	1
BEGe	2.4	0.720 ± 0.018	23	42^{+10}_{-8}	1
with PSD					
golden	17.9	$0.619^{+0.044}_{-0.070}$	45	11 ± 2	2
silver	1.3	$0.619^{+0.044}_{-0.070}$	9	30^{+11}_{-9}	1
BEGe	2.4	0.663 ± 0.022	3	5^{+4}_{-3}	0

†) in units of 10^{-3} cts/(keV·kg·yr).

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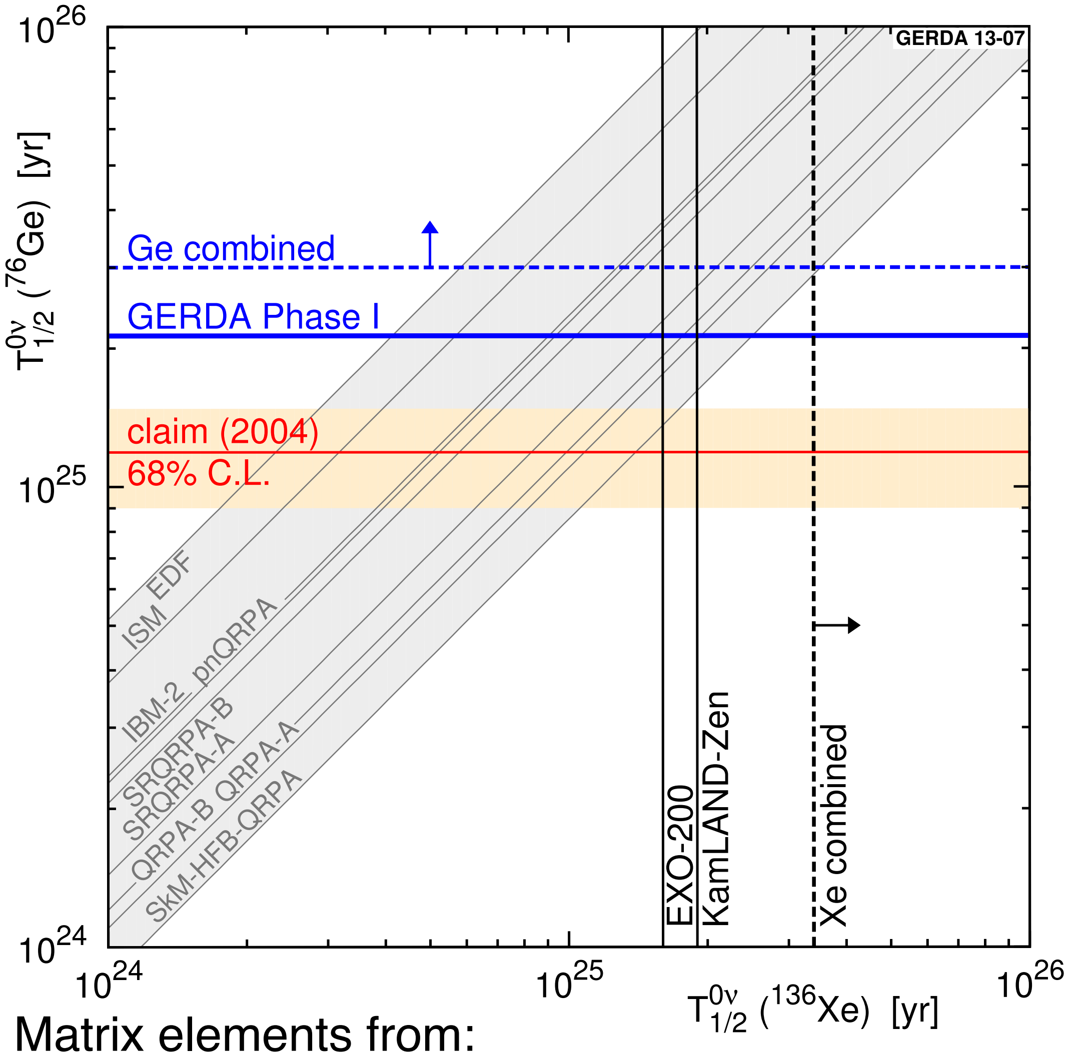
Combined results

- All ^{76}Ge experiments combined give: $T_{1/2} > 3.0 \times 10^{25}$ yr
- The claim is disfavored also by the ^{136}Xe experiments

H1: signal with $T_{1/2}^{0\nu} = 1.19 \times 10^{25}$ yr
H0: background only

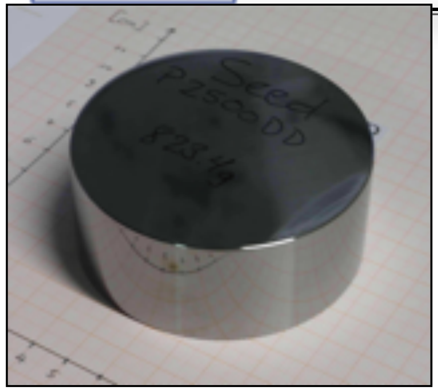
	Isotope	$P(H_1)/P(H_0)$	Comment
GERDA	^{76}Ge	0.024	Model independent
GERDA+HdM +IGEX	^{76}Ge	0.0002	Model independent
KamLAND-Zen*	^{136}Xe	0.40	Model dependent: NME, leading term
EXO-200*	^{136}Xe	0.23	Model dependent: NME, leading term
GERDA+KLZ* +EXO*	^{76}Ge + ^{136}Xe	0.002	Model dependent: NME, leading term



Matrix elements from:

P. S. Bhupal Dev *et al.*, (2013), arXiv:1305.0056

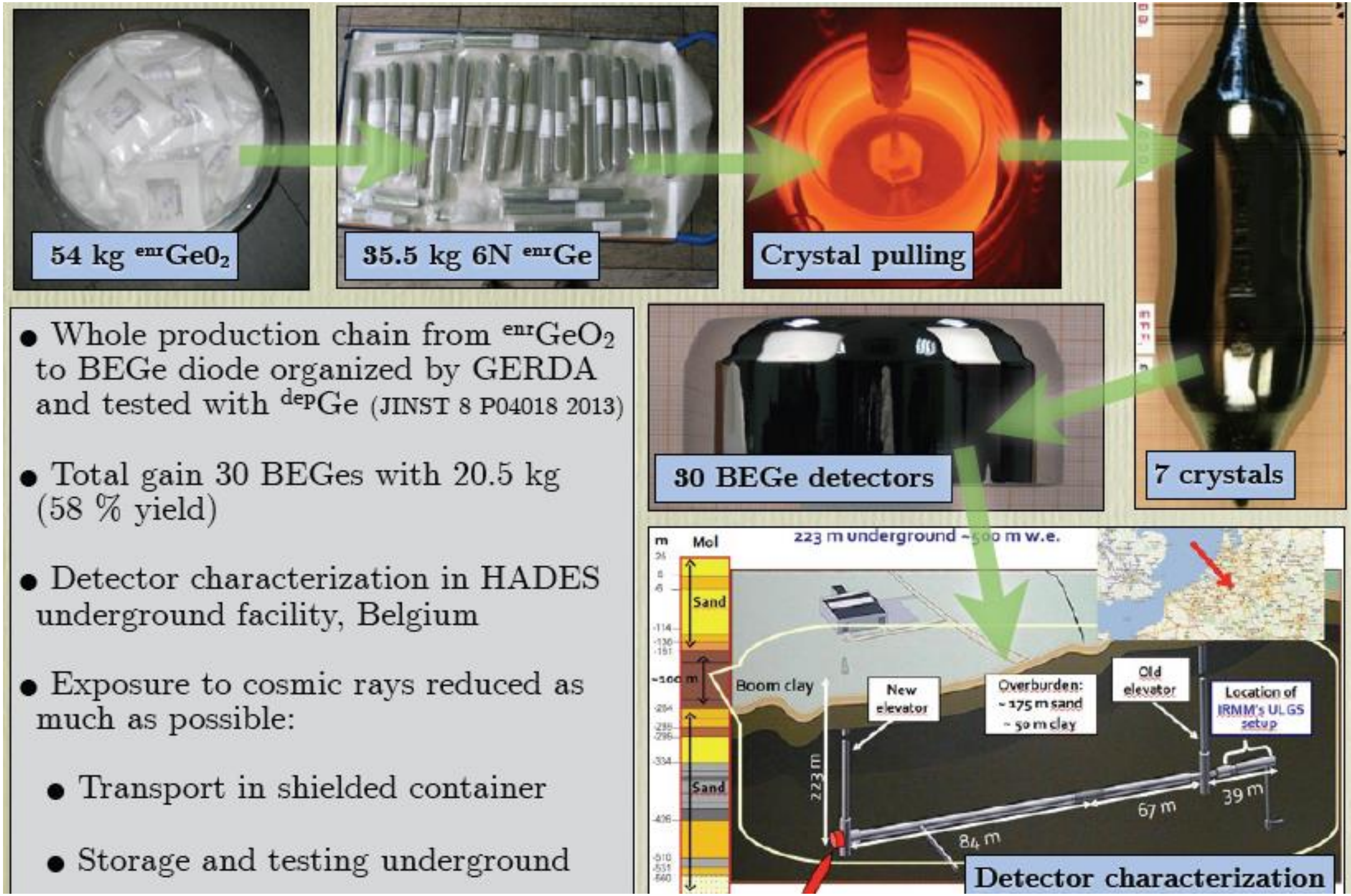
Phase II = Upgrade



$$T^{0\nu}_{1/2} \sim \sqrt{\frac{M \cdot t}{B \cdot \Delta E}} \; [y]$$

- ***More mass:*** From the available 37.5 kg enriched germanium 30 new detectors were produced (~20 kg)
  - 5 of the new BEGe detectors already deployed in Phase I.
- ***Lower background:*** the goal is 10x lower background
  - New detector holders and new FE electronics
  - 'BEGe' detectors for better Pulse Shape Analysis
  - New lock was built to accommodate the LAr veto with PMTs and WLS fibers

Phase II (and Phase I-b) detectors - BEGe



- Whole production chain from $^{\mathrm{enr}}\mathrm{GeO}_2$ to BEGe diode organized by GERDA and tested with $^{\mathrm{dep}}\mathrm{Ge}$ (JINST 8 P04018 2013)
- Total gain 30 BEGes with 20.5 kg (58 % yield)
- Detector characterization in HADES underground facility, Belgium
- Exposure to cosmic rays reduced as much as possible:
  - Transport in shielded container
  - Storage and testing underground

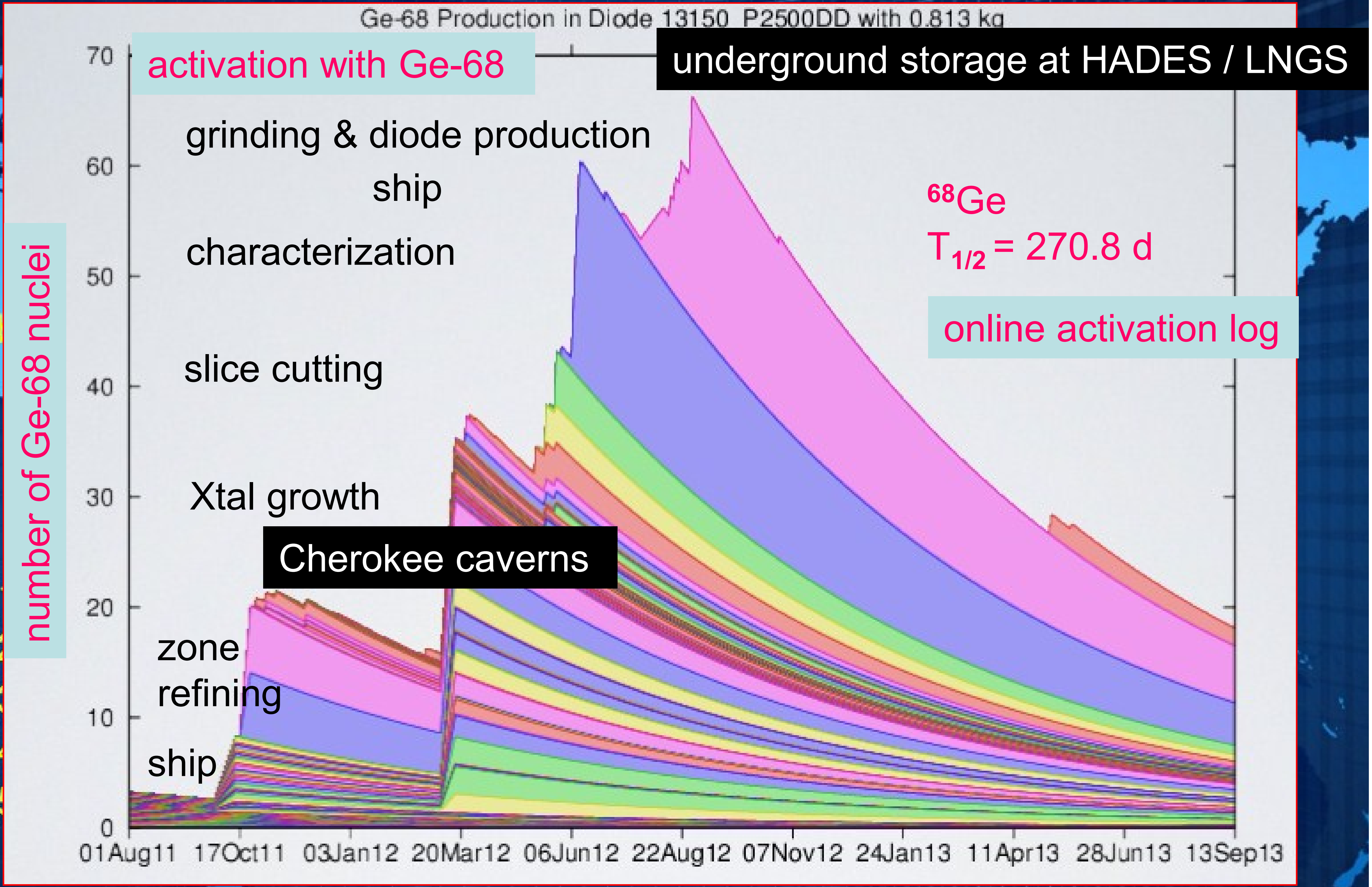
Adopted from: B.Lehnert., Talk at RICAP 13 conf., Rome, 23 May 2013

From raw germanium material to diode production

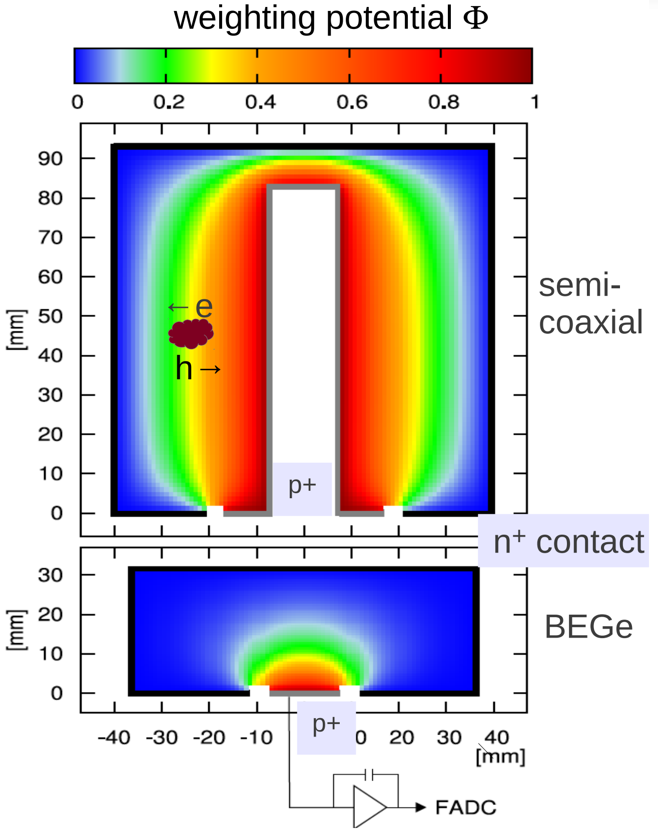
[1] Germanium enrichment, ECP, Zelenogorsk, Russia	53.3 kg $^{enr}GeO_2$, 88% Ge76
[2] Metal reduction and purification, PPM, Langelsheim, Germany	35.5 kg ^{enr}Ge, 6N
[3] Xtal pulling/Zone refinement, Canberra, Oak Ridge, USA	9 Xtals → 30 slices
[4] Diode production, Canberra, Olen, Belgium	30 ^{enr}Ge diodes (20kg)
[5] Diode storage and characterization, HADES, Mol, Belgium	

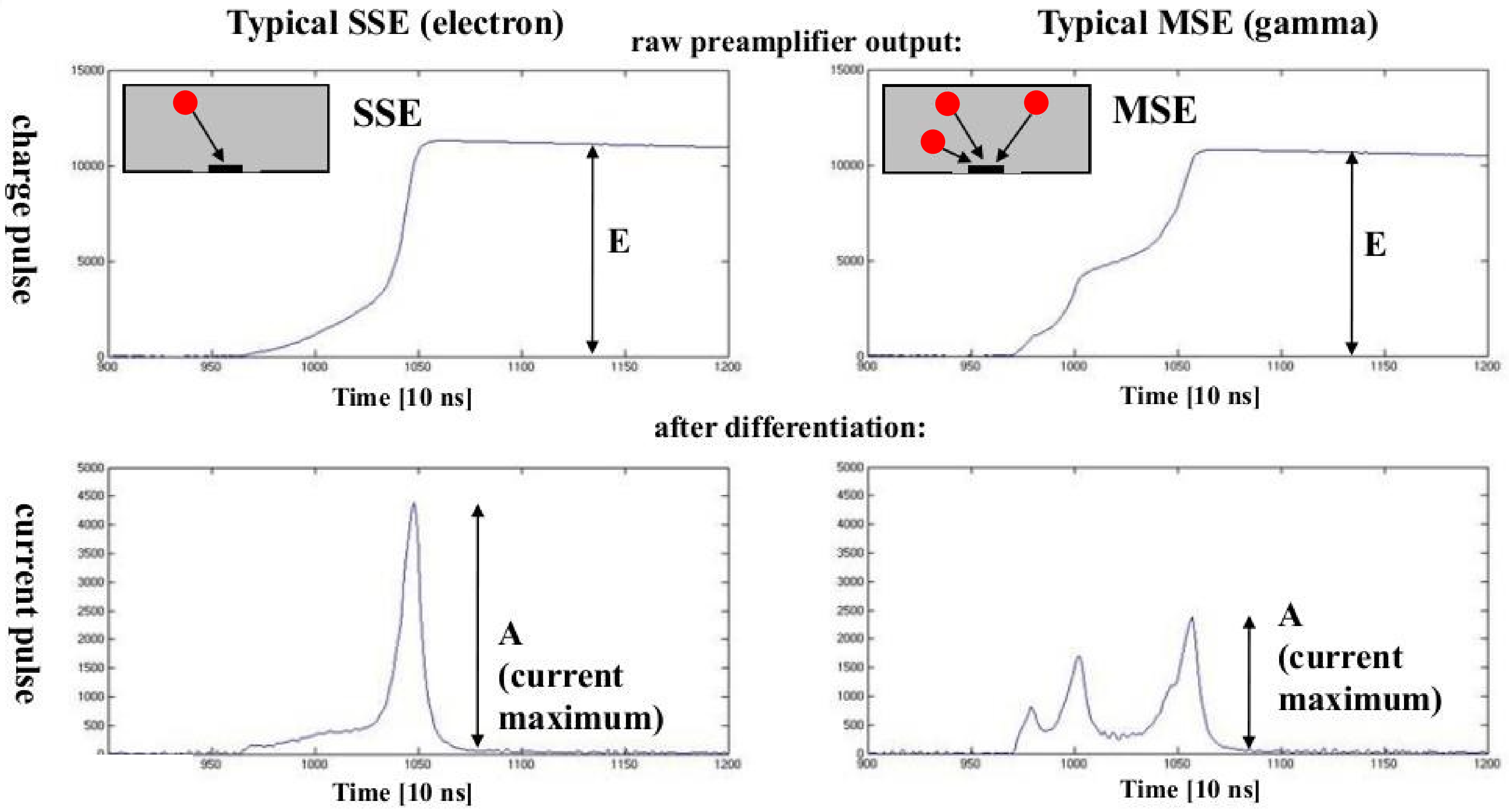
From raw germanium material to diode production

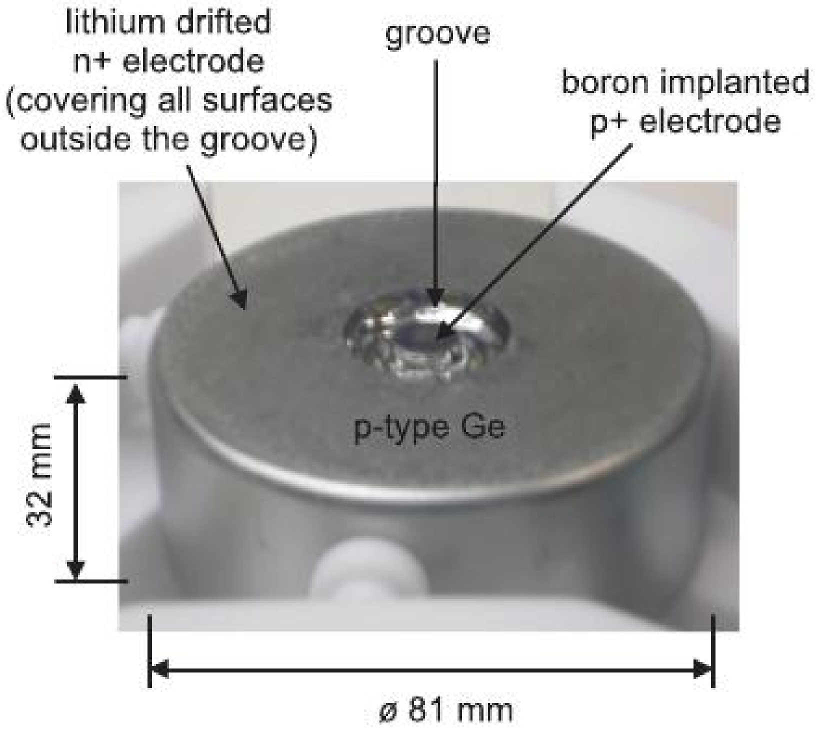
[3] Can



Pulse Shape Discrimination







A/E ≡ 1

A/E < 1

SSE accepted for 0.965 < A/E < 1.07:
0νββ efficiency = 92 ± 2 %
2νββ efficiency = 91 ± 5 %
80% of background events rejected

EPJ C73 (2013) 2583

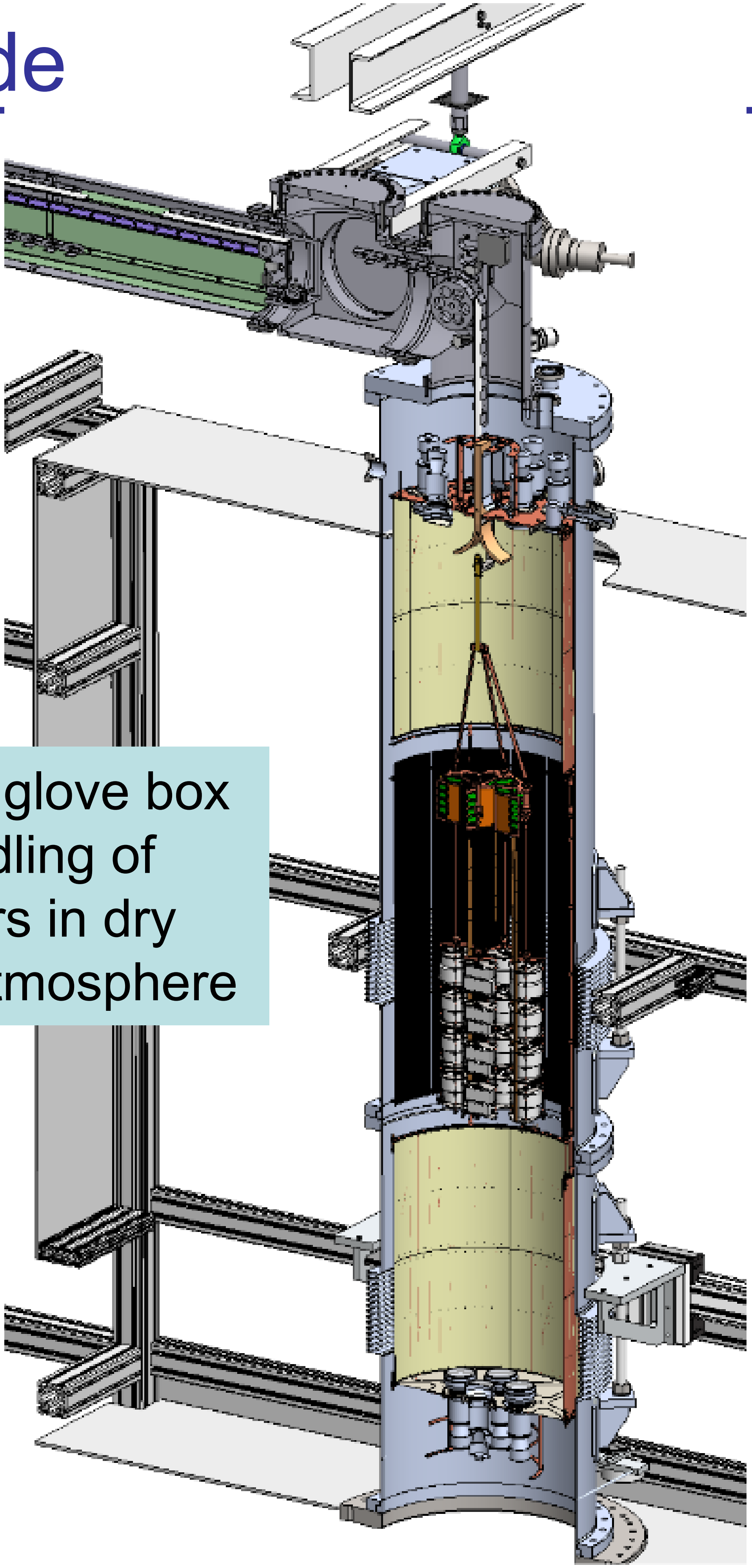
upgrade

new lock

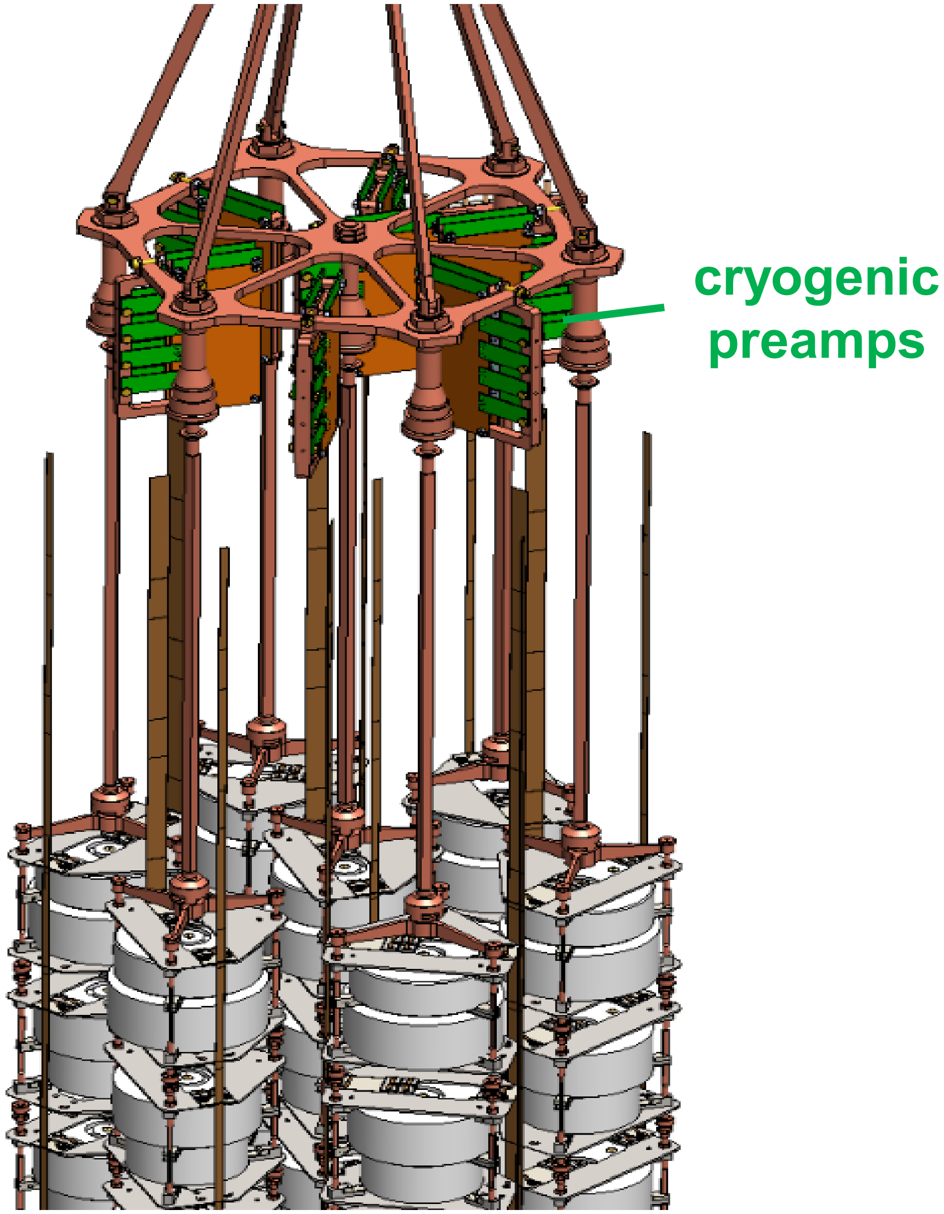
in cleanroom on top of cryostat:
replaces Phase I twin lock

- larger Ø 0.49 m, h = 2.8 m

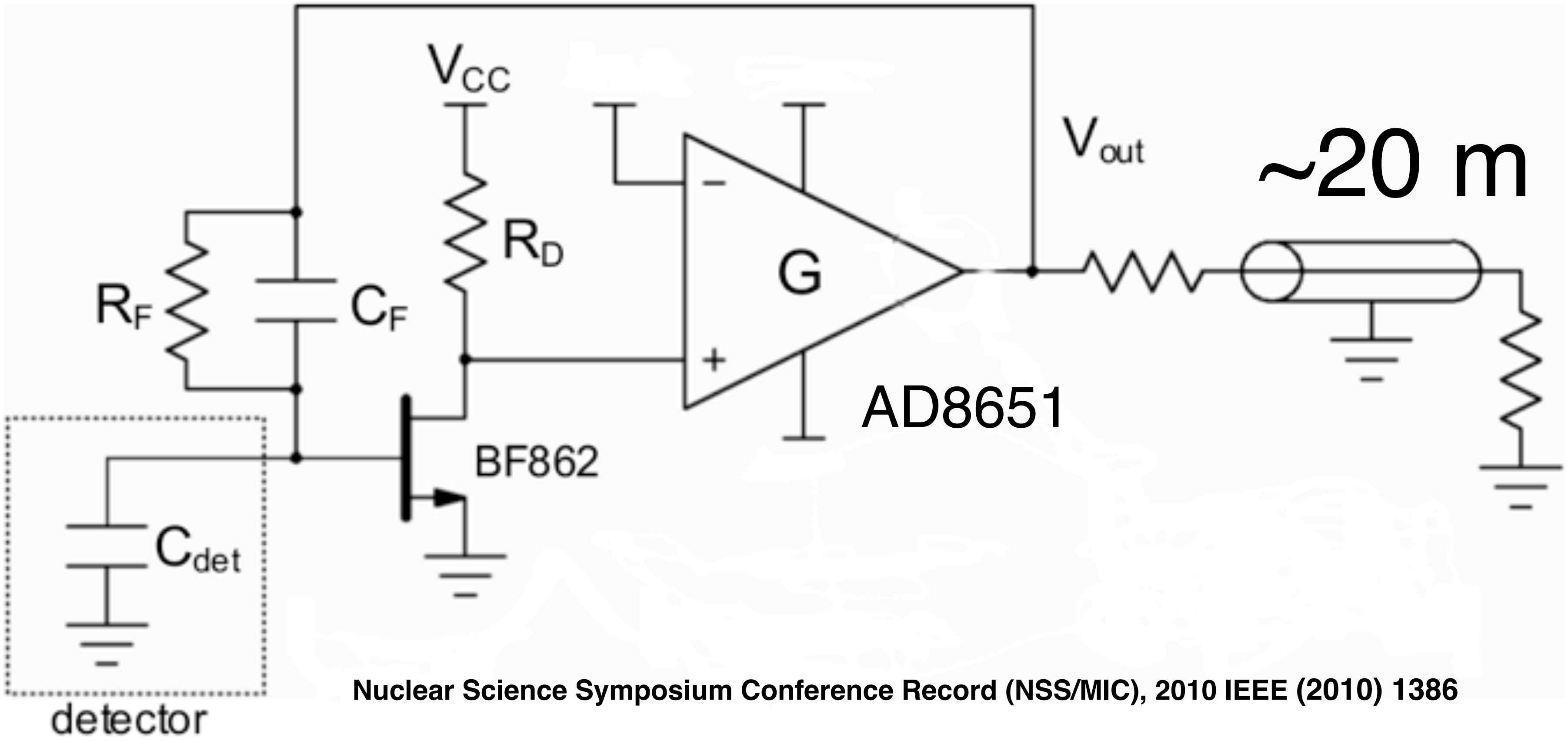
► space for 7 string array



lock within glove box for handling of detectors in dry nitrogen atmosphere

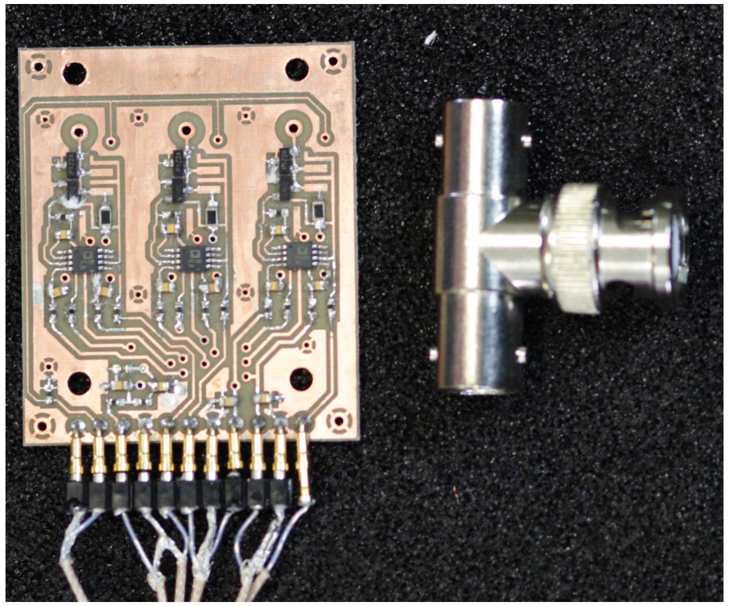


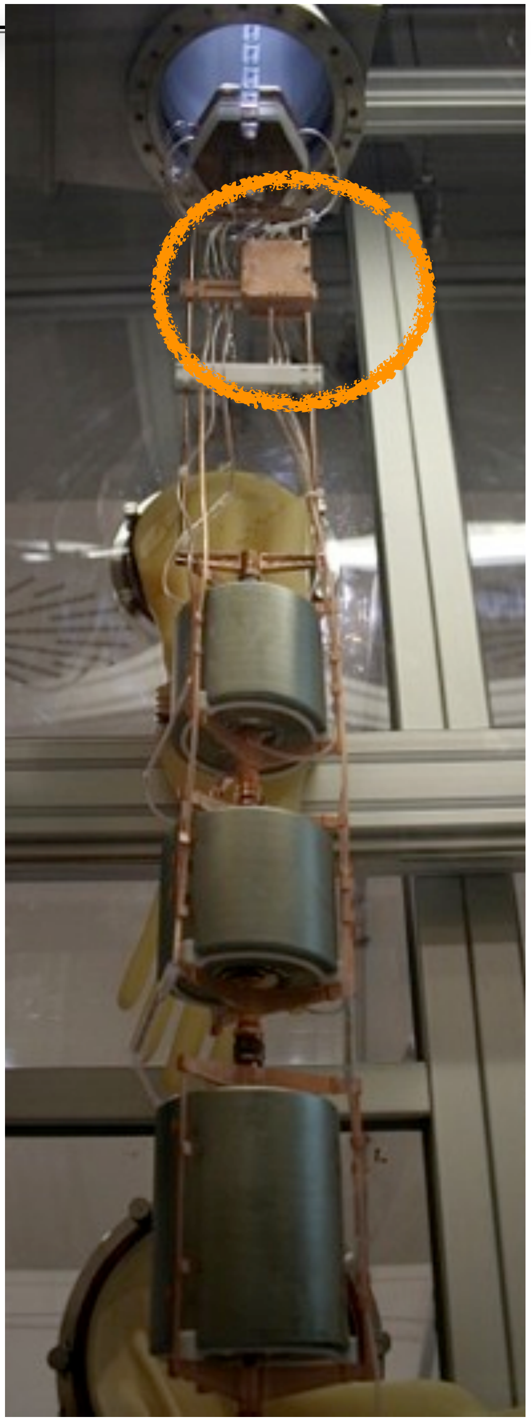
Phase I Front-End



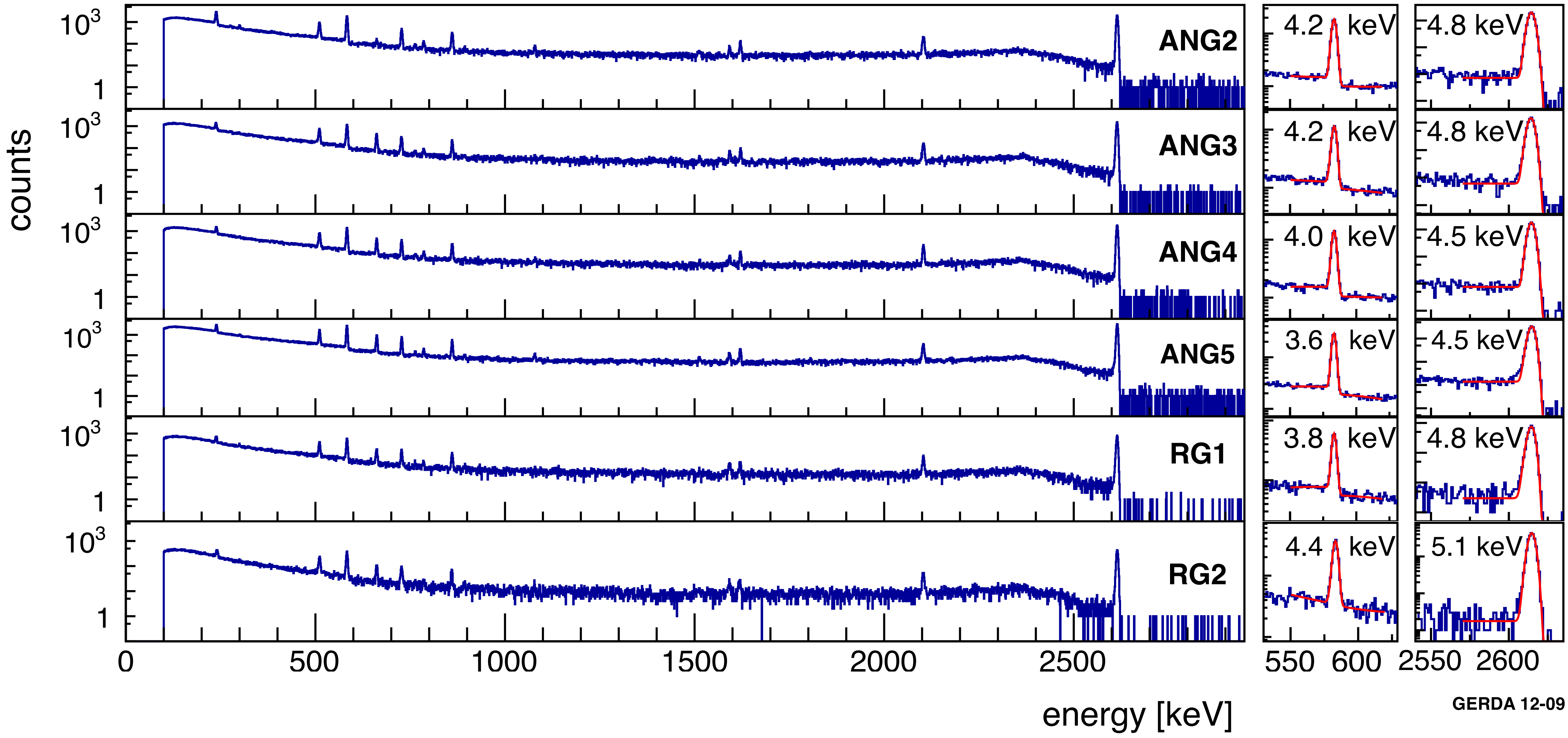
Nuclear Science Symposium Conference Record (NSS/MIC), 2010 IEEE (2010) 1386

- Based on commercial CMOS OpAmp & JFET
- Works at LN temperature
- Good spectroscopic performance





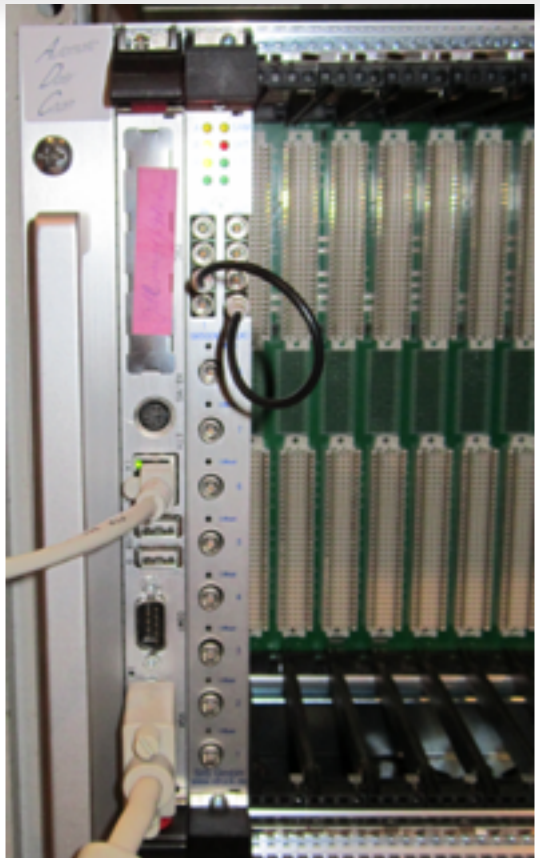
Detector calibration (Th-228)



Energy resolution at $Q_{\beta\beta}$ (FWHM, mass weighted average):

- ~ 4.5 keV for coaxials
- ~ 3 keV for BEGes

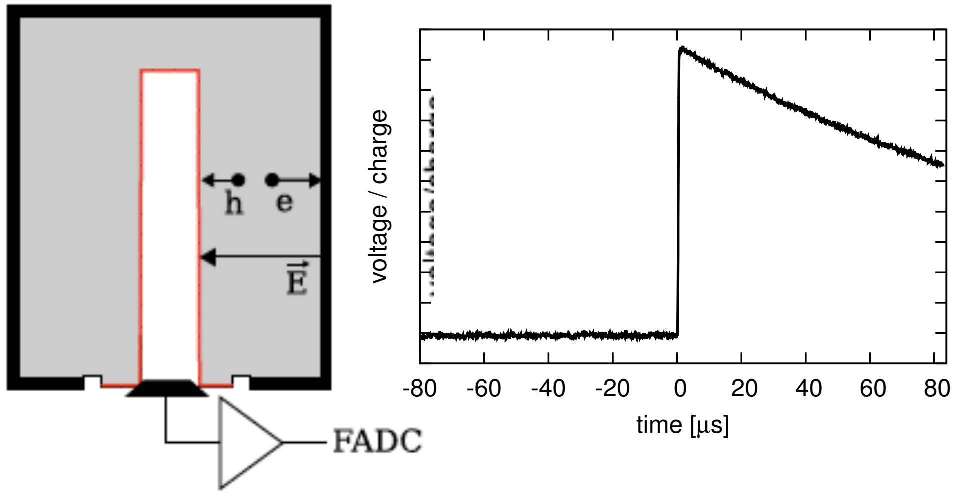
Phase I DAQ



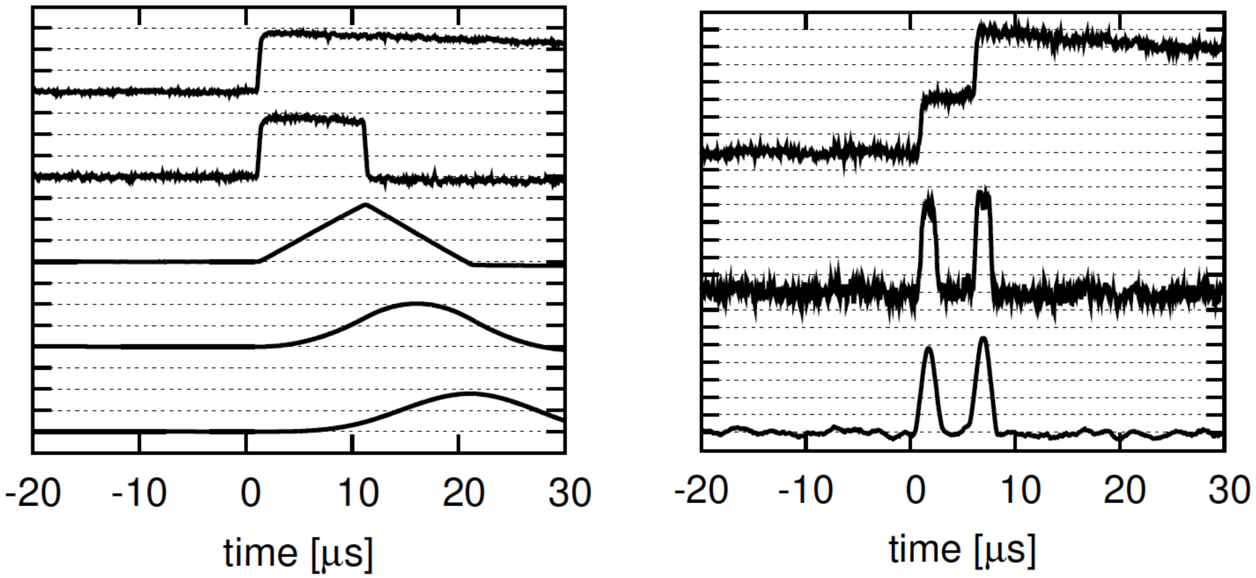
- Struck SIS3301 14 bit FADC
- Pulse shapes recorded for off-line analysis
- processed off-line: energy, PSD

Eur. Phys. J. C (2013) 73:2330
[arXiv:1212.4067](https://arxiv.org/abs/1212.4067)

Read-out and signal structure

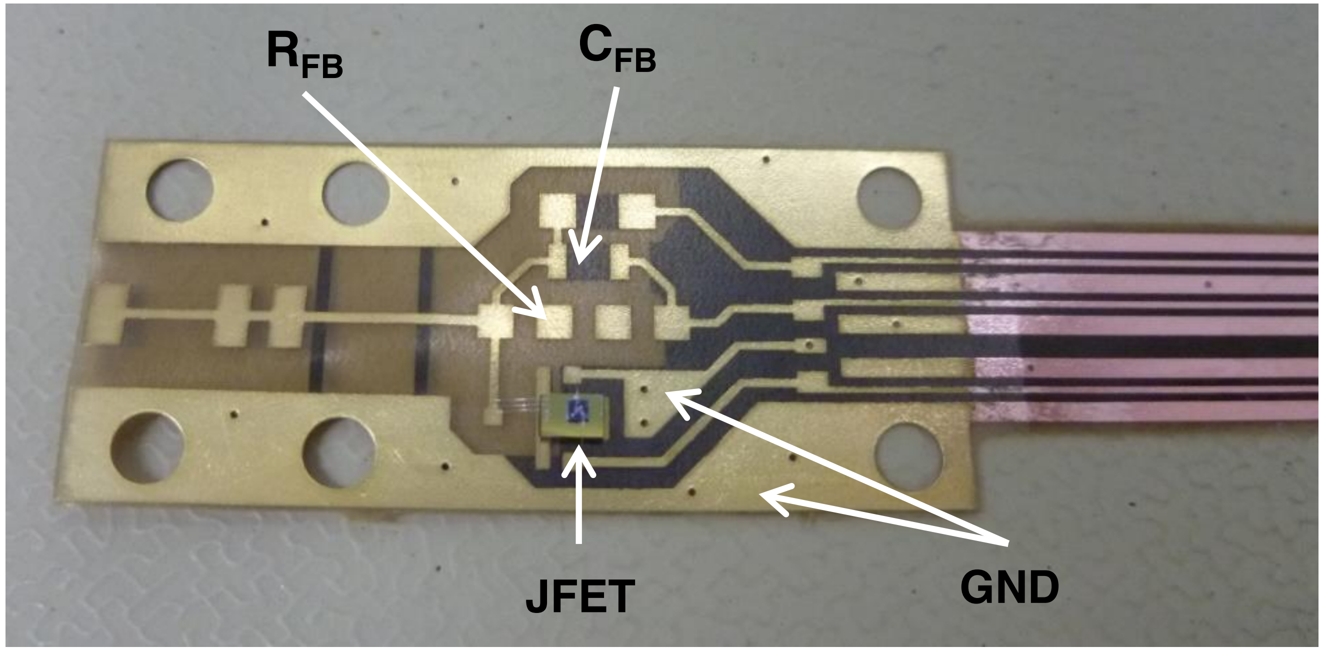


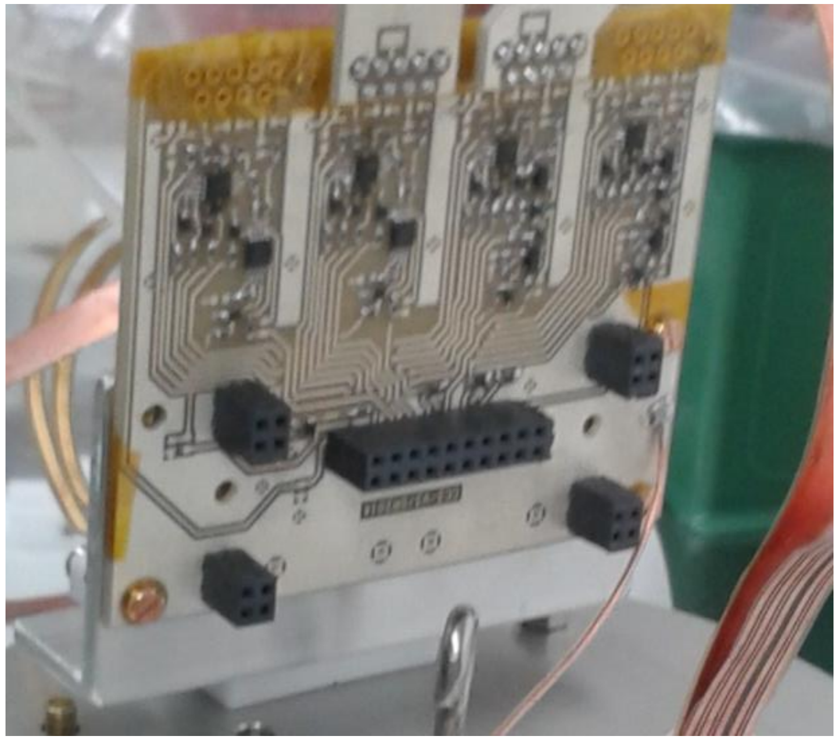
Digital signal processing to extract amplitude, rise time, etc.



Phase II Front-End electronics

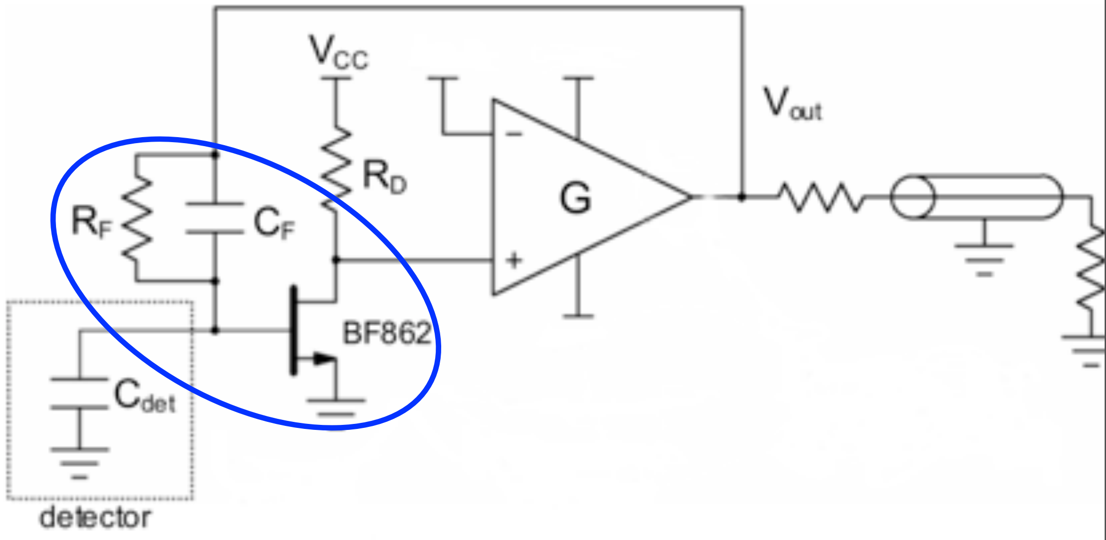
Resistive feedback circuit of FE electronics (Very front-end VFE)





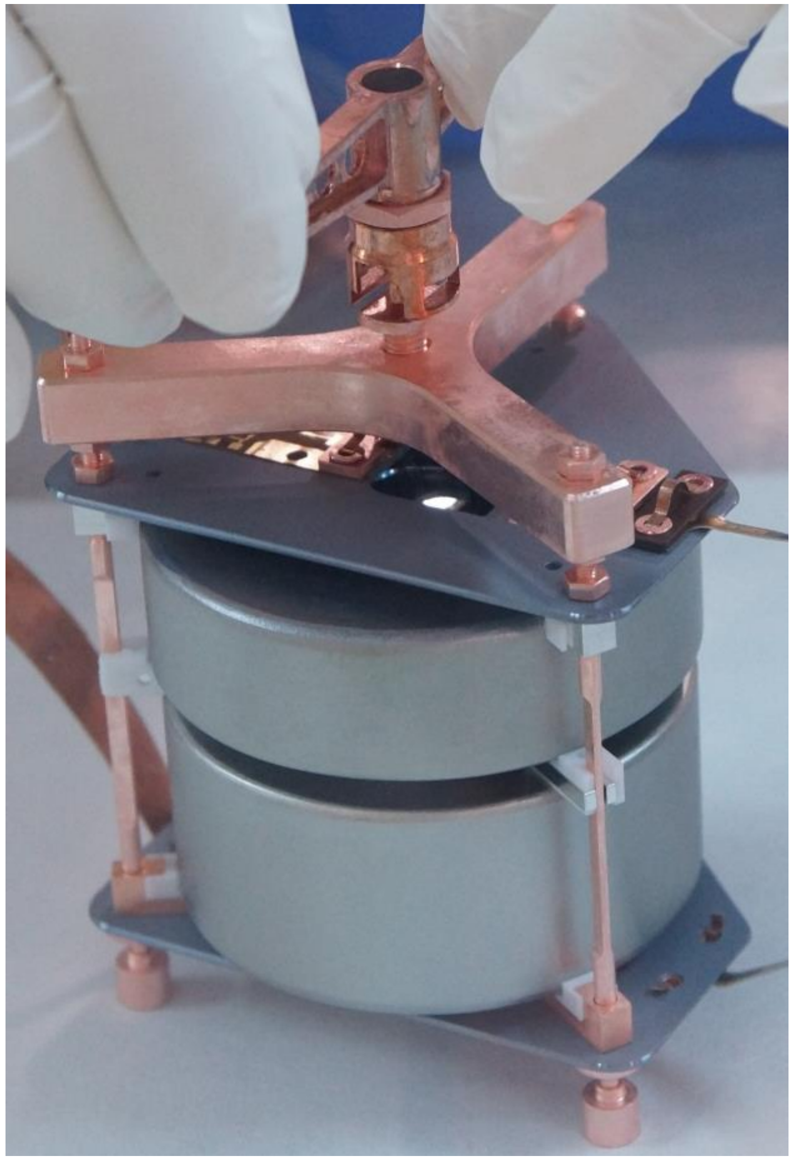
2nd stage (CC3) for 4 channels

- Seperation of Very Front-End and second stage of FE charge sensitive amplifier (CC3)
- Advantages
  - Minimal mass and radiopure components for VFE possible
  - More radioactive & complex 2nd stage further (~50 cm) from detectors



The Phase II detector mount

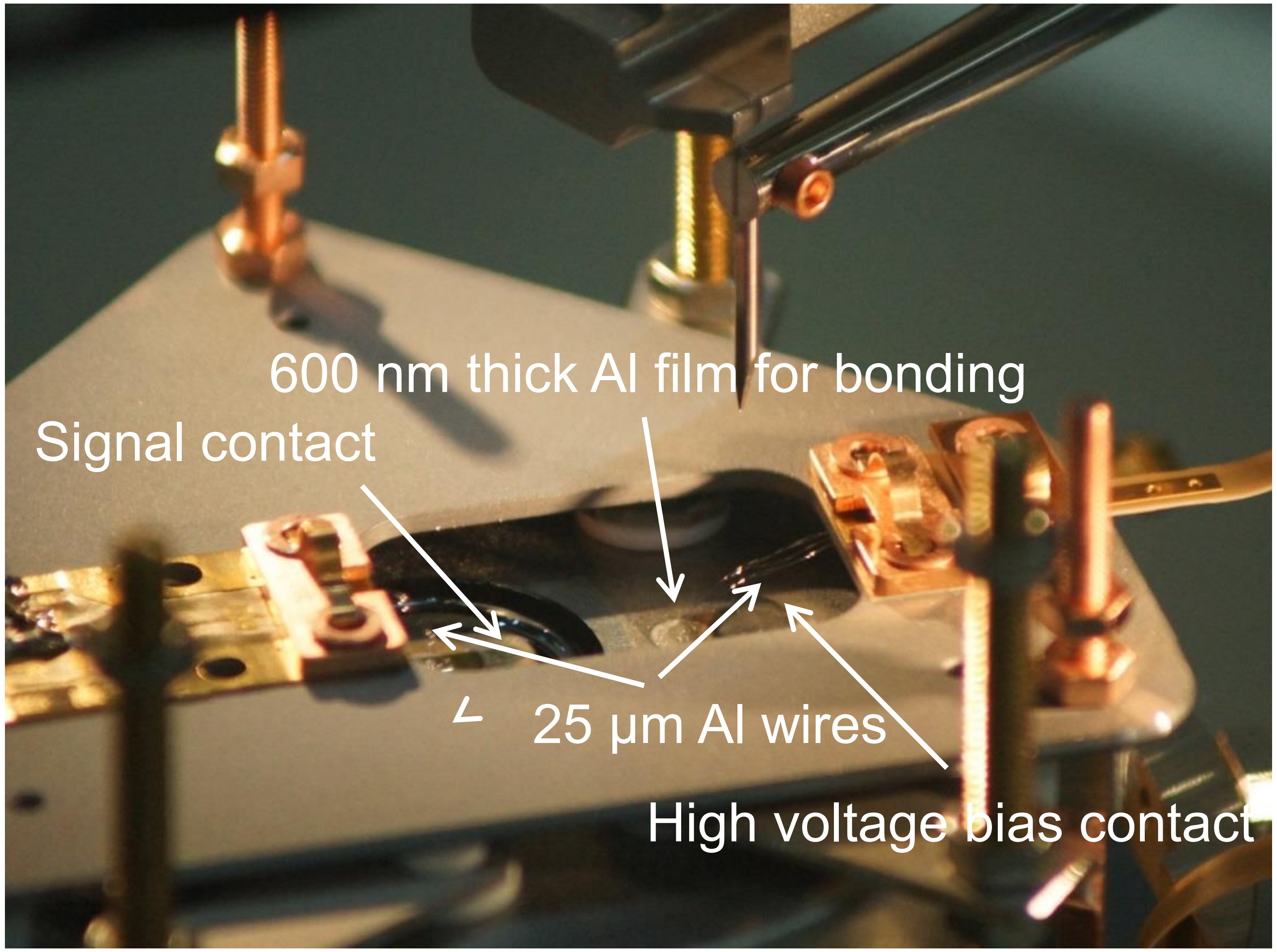
- Material in vicinity of detectors to be reduced
  - Detector mount & Front-end electronics
- Reduction of holder mass per kg detector mass necessary (BEGe smaller than semi-coax!)
- Replace as much copper as possible with intrinsically pure mono crystalline silicon
- Design achieves factor ~1.5 reduction copper & PTFE mass per kg detector mass
- New contacting scheme (wire bonding) allows holder with reduced mass & material strength i.e. Si



Material	Phase I holder		Phase II holder	
	[g]	[uBq]	[g]	[uBq]
Cu	80	<1.6	26	<0.5
Si	1	-	40	-
PTFE	7	0.3	2	~0.1
Bronze	-	-	1	<0.02

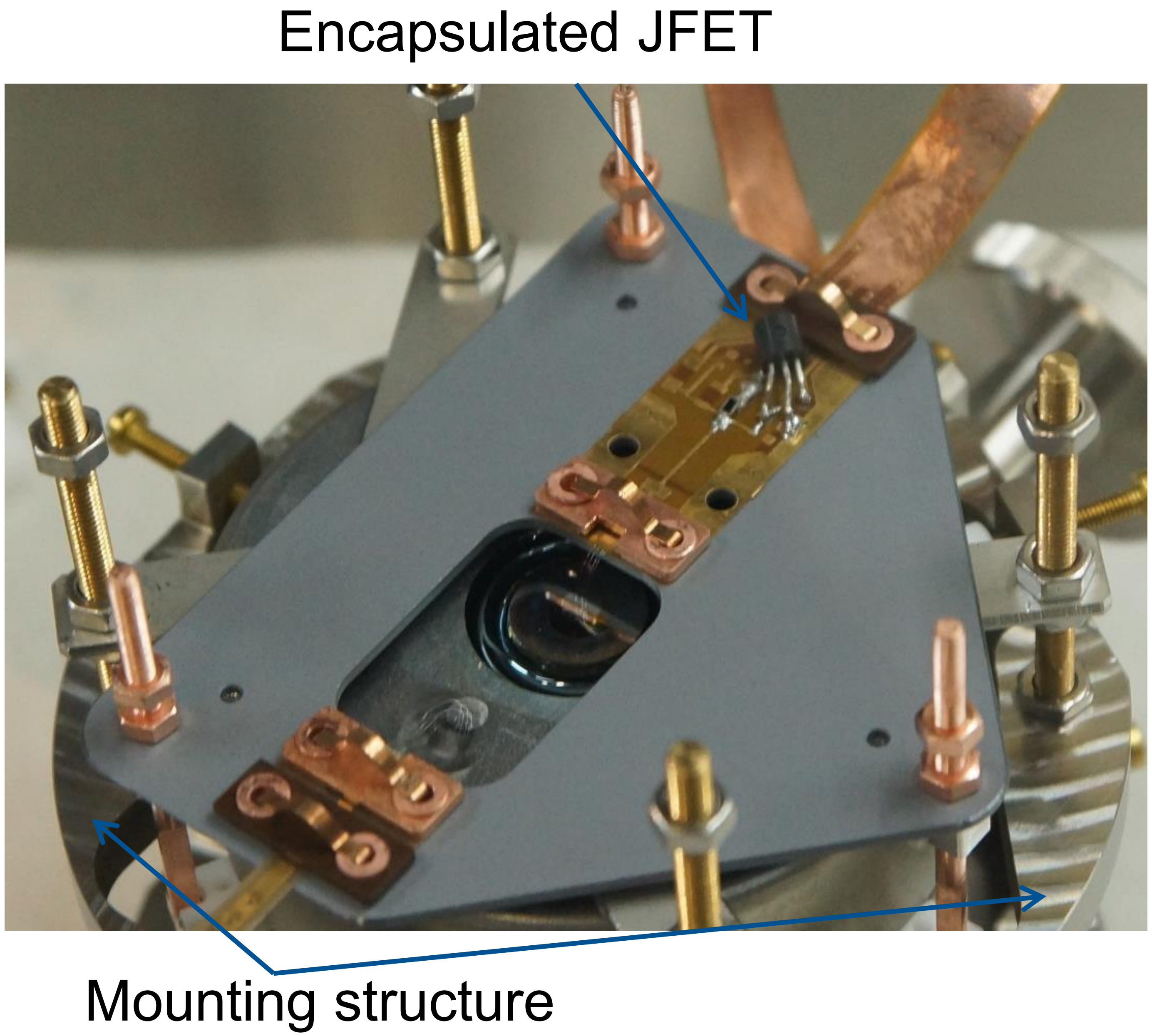
The Phase II detector mount - contacting

- Ultrasonic wire bonding identified as a low-mass, reliable electrical contact between detector, amplifying electronics and HV supply
- First time large volume Germanium diode detectors contacted with wire bonding
- Deposition of Al thin film on germanium diodes to allow bonding at manufacturer's site
- All 30 BEGe's from enriched Ge modified

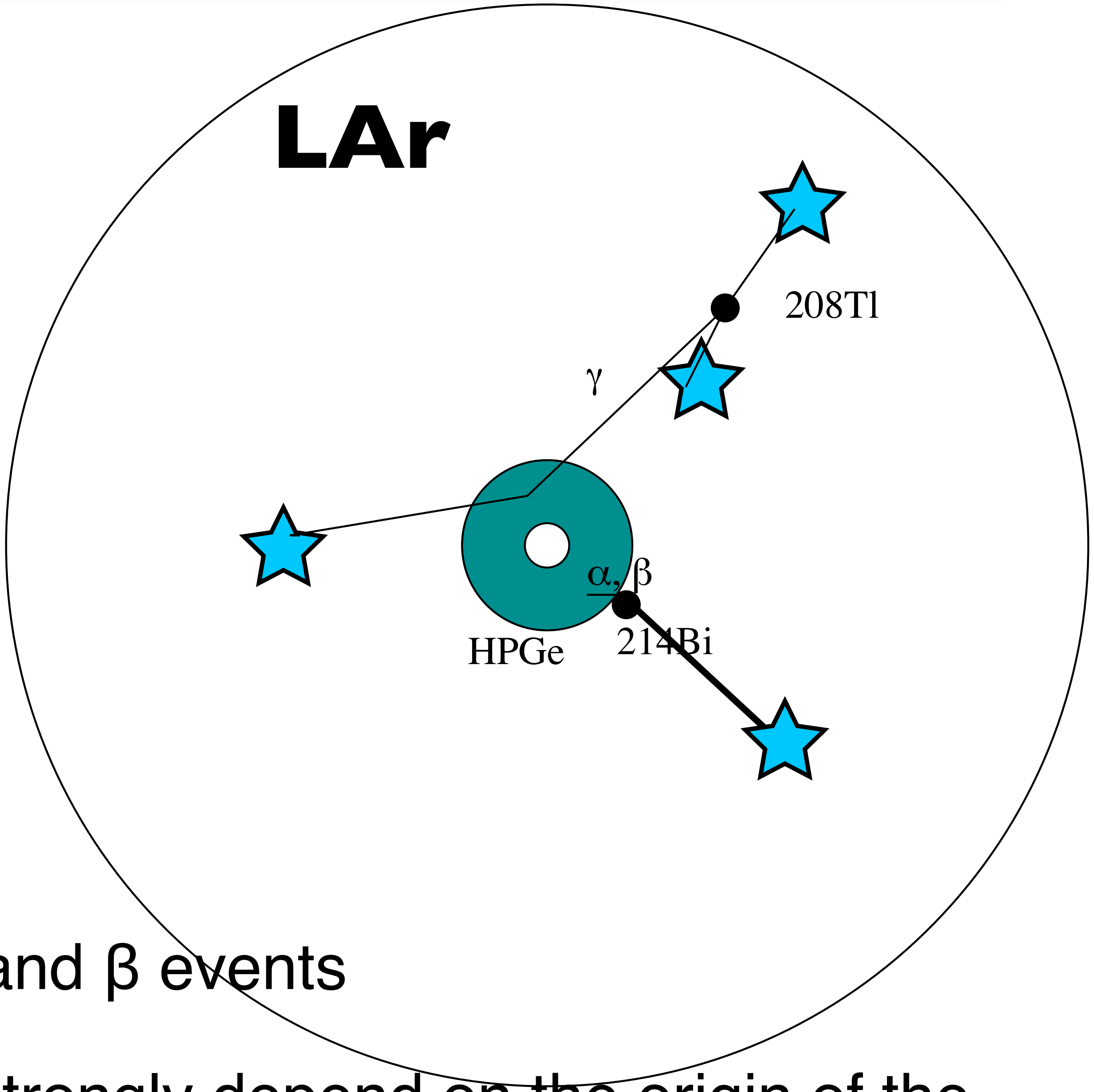


Tests of integrated detector pair

- Two test detectors with Al films mounted in Phase II holder
- Bonded to make electrical contact
- Tests of newly designed Phase II electronics; also with JFET in-die
- Test of assembly in liquid argon cryostat (Noise, microphonics, handling in glove box, stability)
- No principal issues with designs of holder, contacts & electronics found
- Th-228 calibrations taken like in GERDA



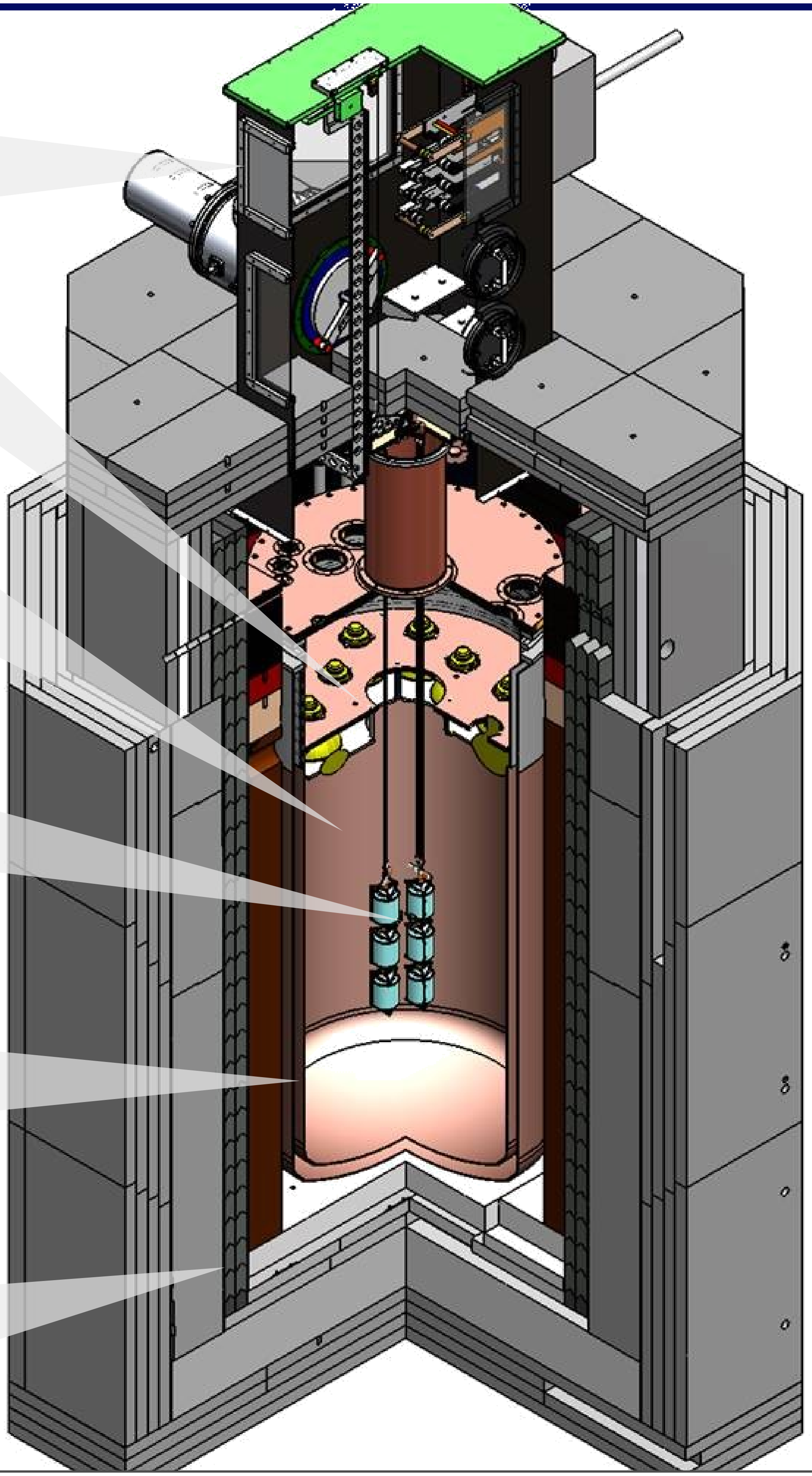
LAr veto - The concept



In the Region of Interest
around 2040 keV

- Nearby ^{208}Tl events can be easily vetoed with very high efficiency
- ^{214}Bi is less effective
- Does not work well for surface α and β events
    - Veto efficiency in GERDA will strongly depend on the origin of the background

LArGe test facility



lock system

9x 8“ PMTs

reflector foil
& wavelength shifter

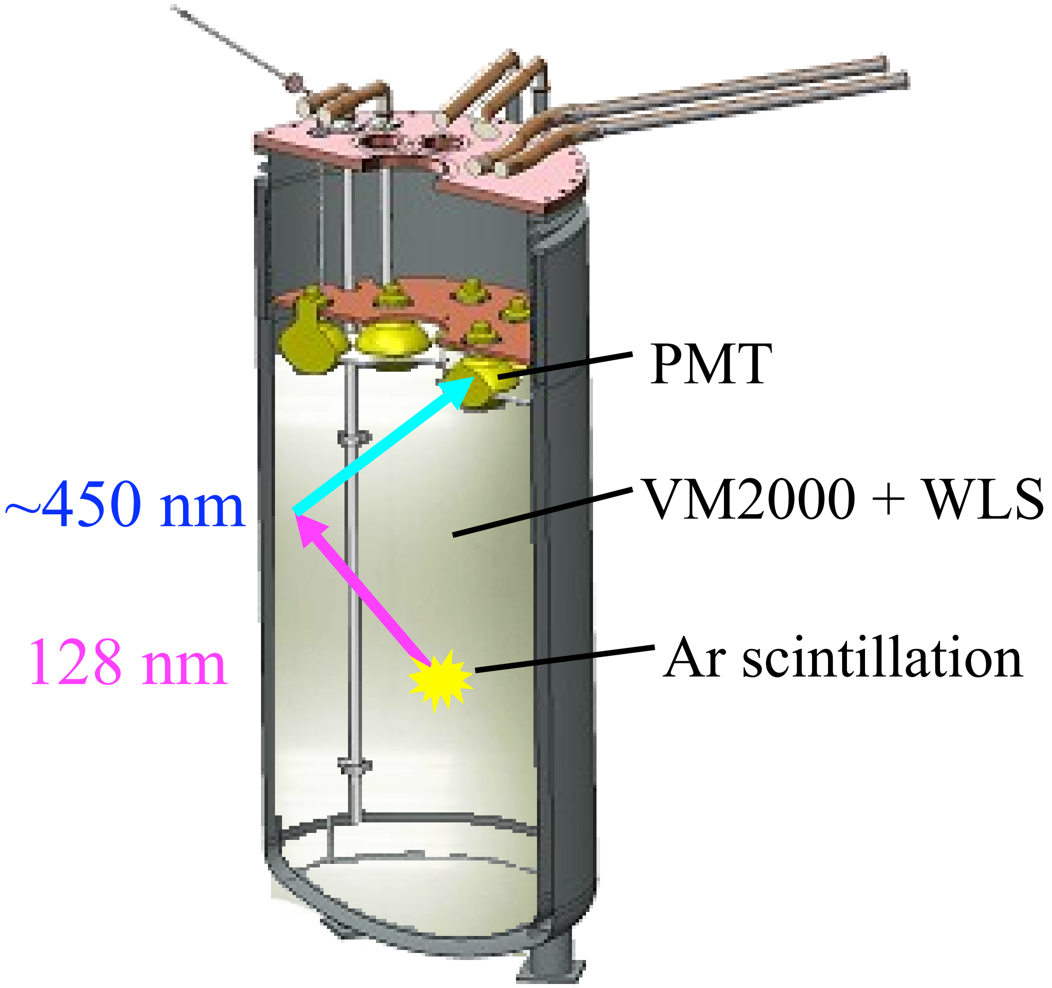
bare Ge-detector

cryostat with LAr
volume 1000 l

Shield (unfinished)
Cu 15 cm, Pb 10 cm,
Steel 23 cm, PE 20 cm

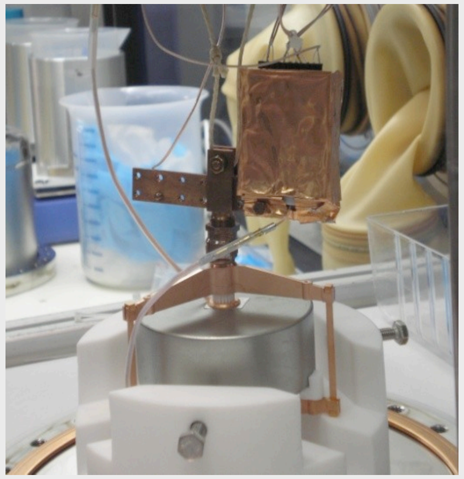
Location:
Germanium detector lab
LNGS @ 3800 m w.e.

Ref:arXiv:0701001, TAUP2011 proc.



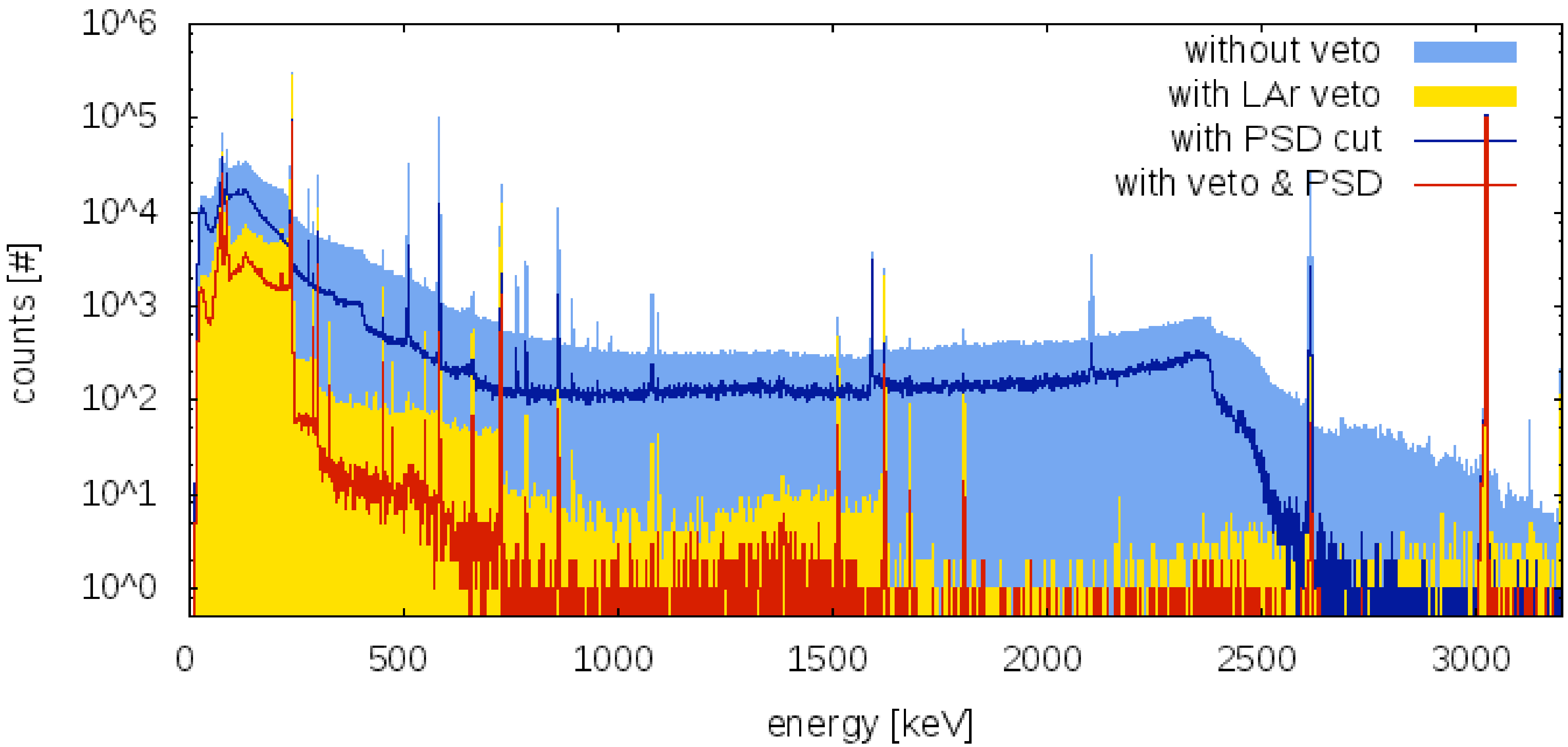
LArGe test facility

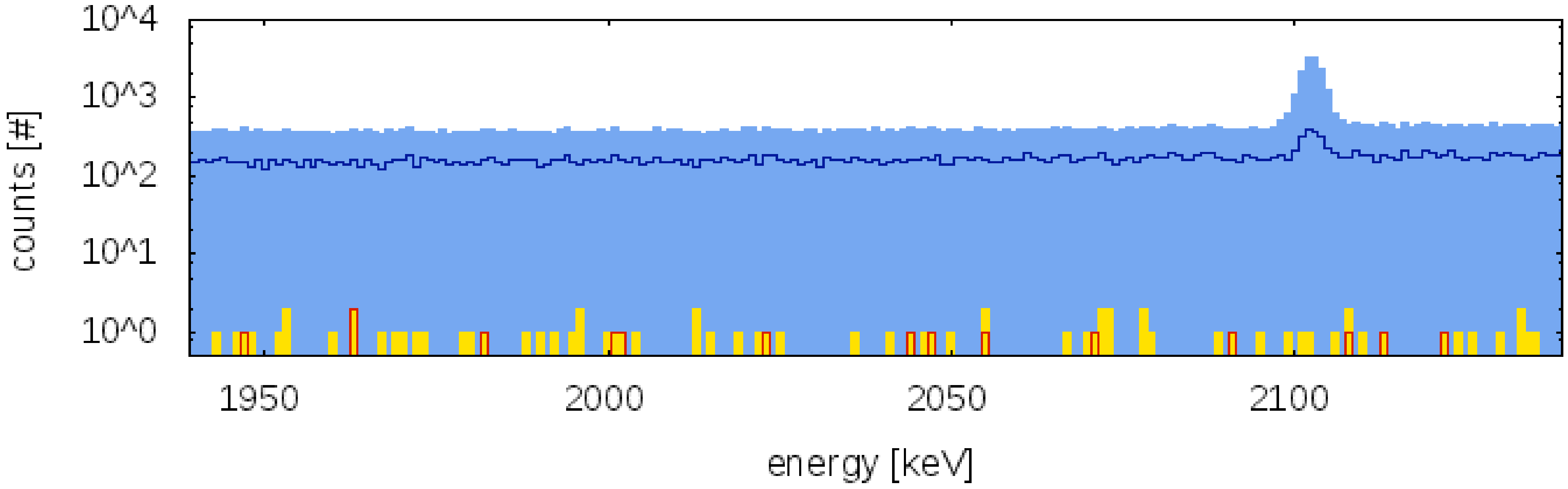
- detector: BEGe



- ^{228}Th source

  distance ~7 cm
- DAQ via FADC

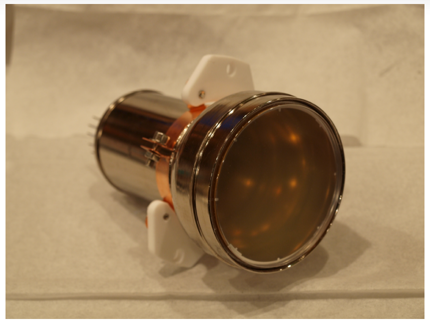




Suppression factors at $Q_{\beta\beta}$ ± 35 keV:

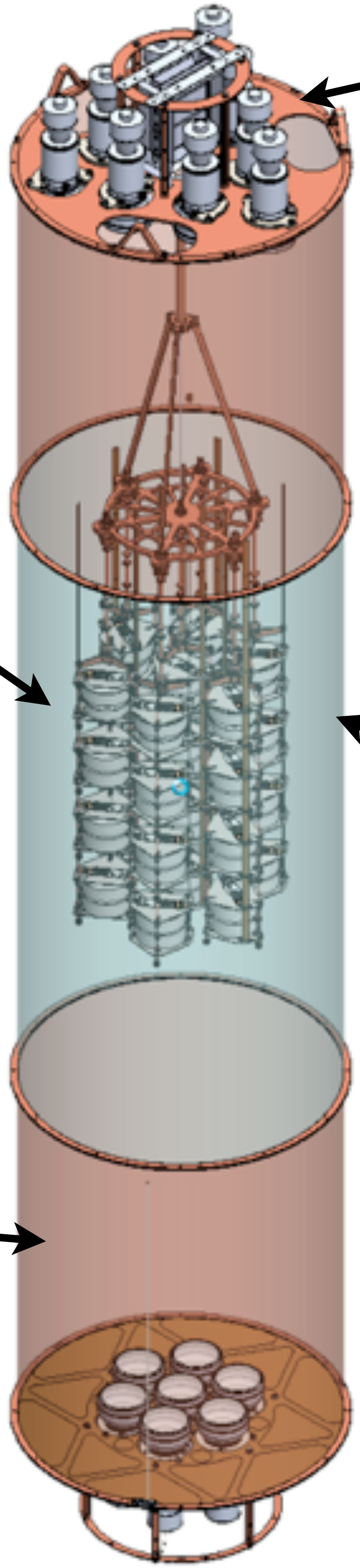
LAr veto	~1200
PSD	~2.4
veto+PSD	~5200

LAr - veto

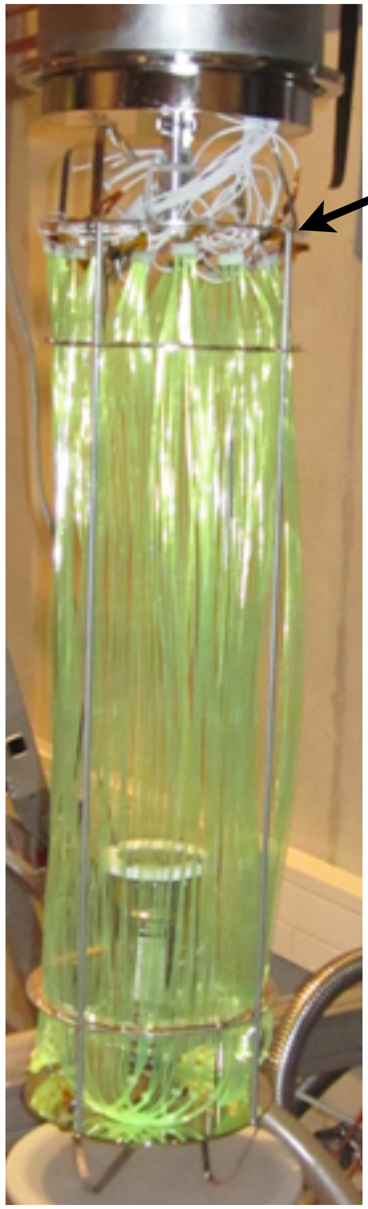


3” low-background PMT
Hamamatsu R11065-xx

HPGe detector array

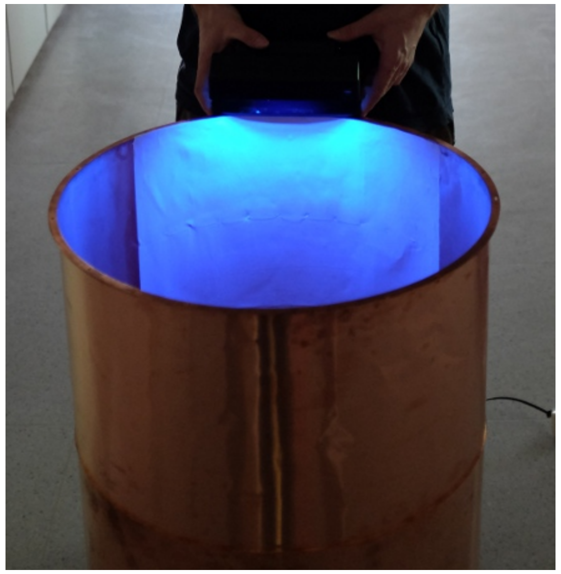


SiPMs



Fiber “shroud”
1000 m WLS
fiber coated
with TPB

Copper “shroud” with
Tetratex reflector
coated with TPB



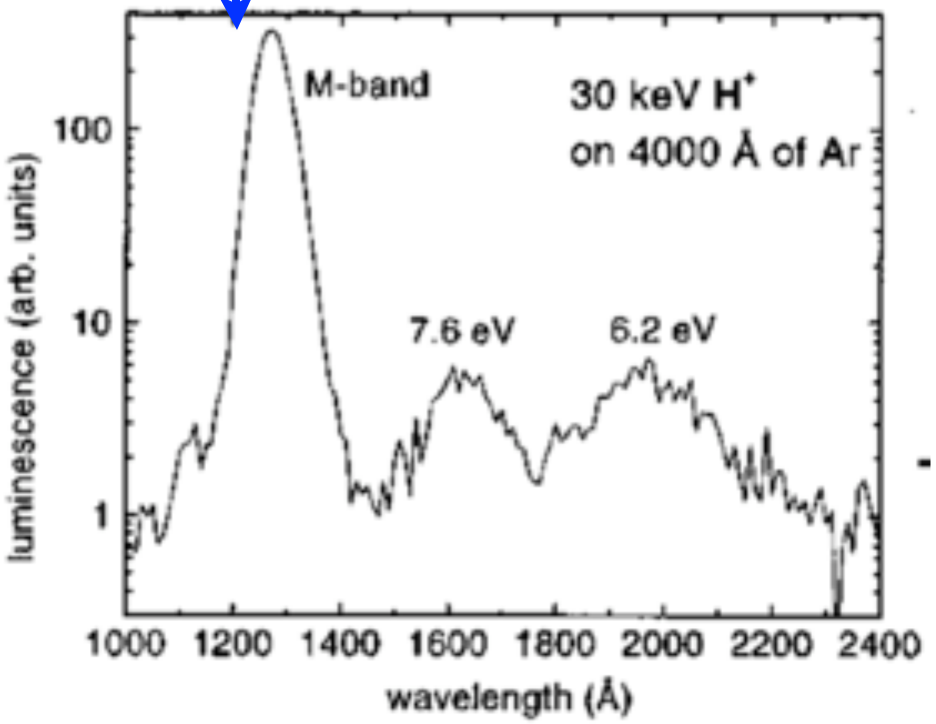
The Wavelength shifter

Tetra-Phenyl-Butadiene (TPB)

128 nm (VUV) → 430 nm → Detected with PMT

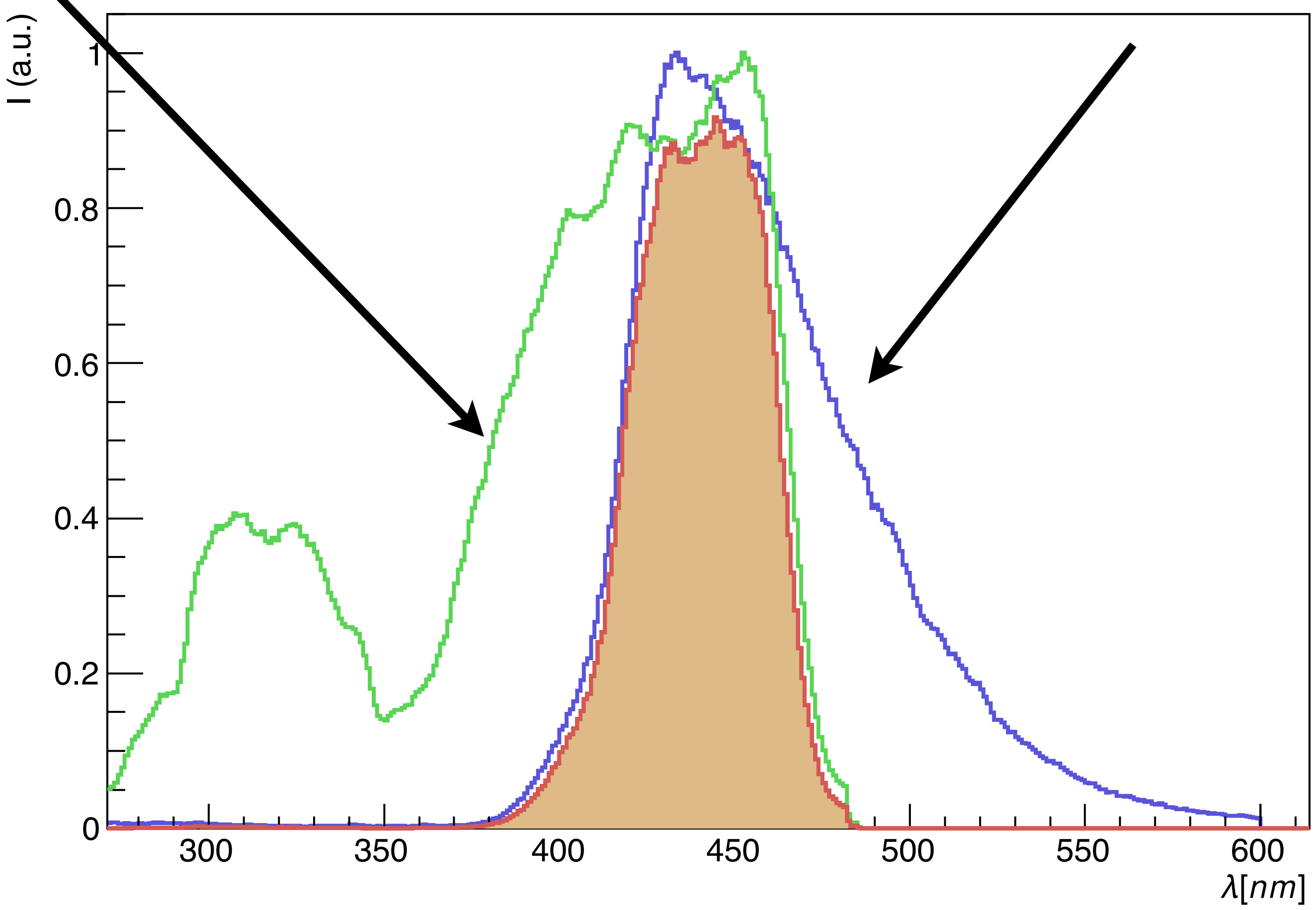
430 nm → Collected with WLS fiber

Emitted by Ar



BCF-91A absorption

TPB - emission spectrum



Inefficient (~60%), but it works

Induced background

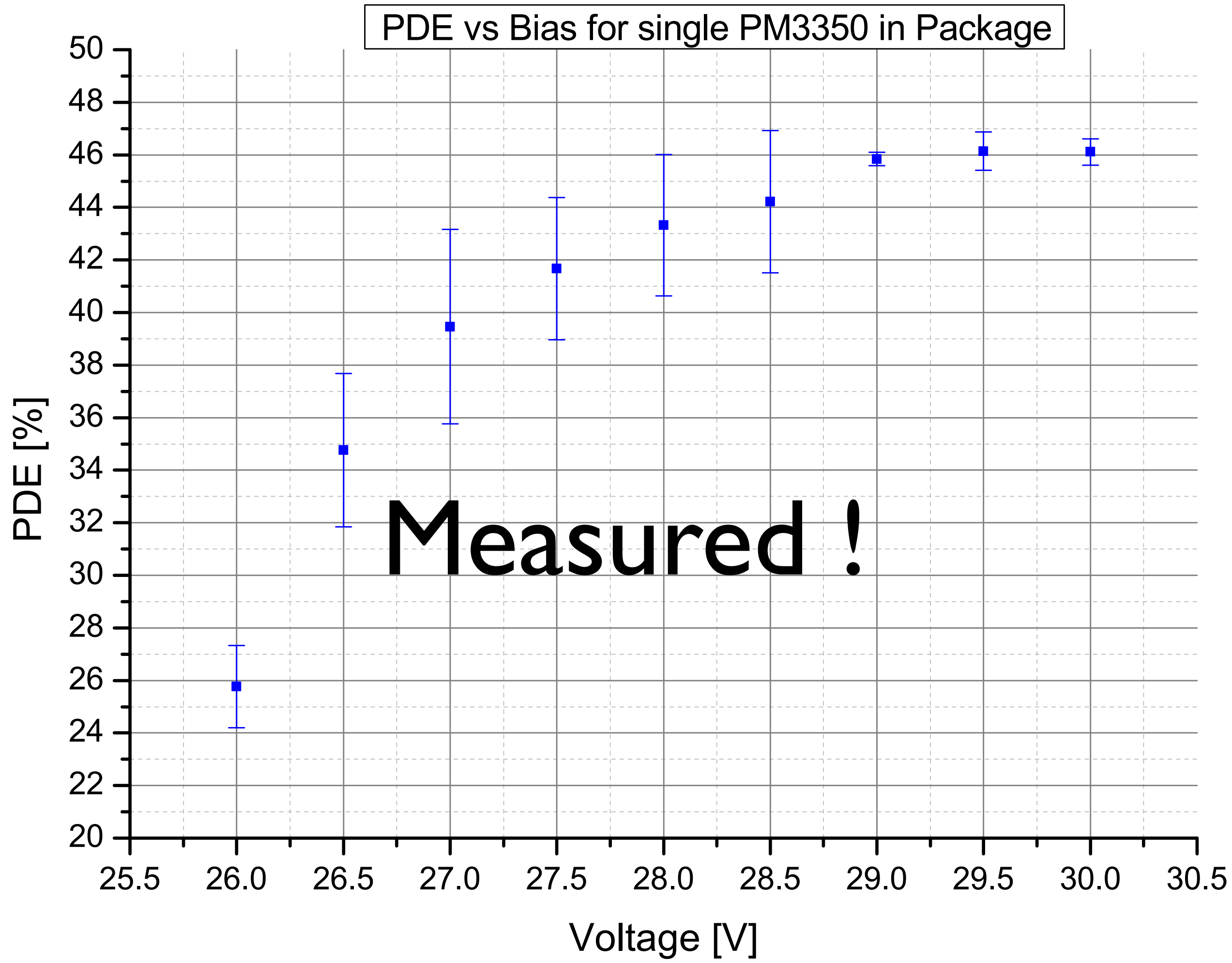
ICPMS results: WLS fiber measured at LNGS

Element	Conc.	Activity Bq/kg	Background cts/(keV kg Year)
K	15 ppb	4.6×10^{-4}	-
Th	14.3 ppt	5.8×10^{-5}	3.4×10^{-4}
U	3.4 ppt	4.2×10^{-5}	2.3×10^{-5}

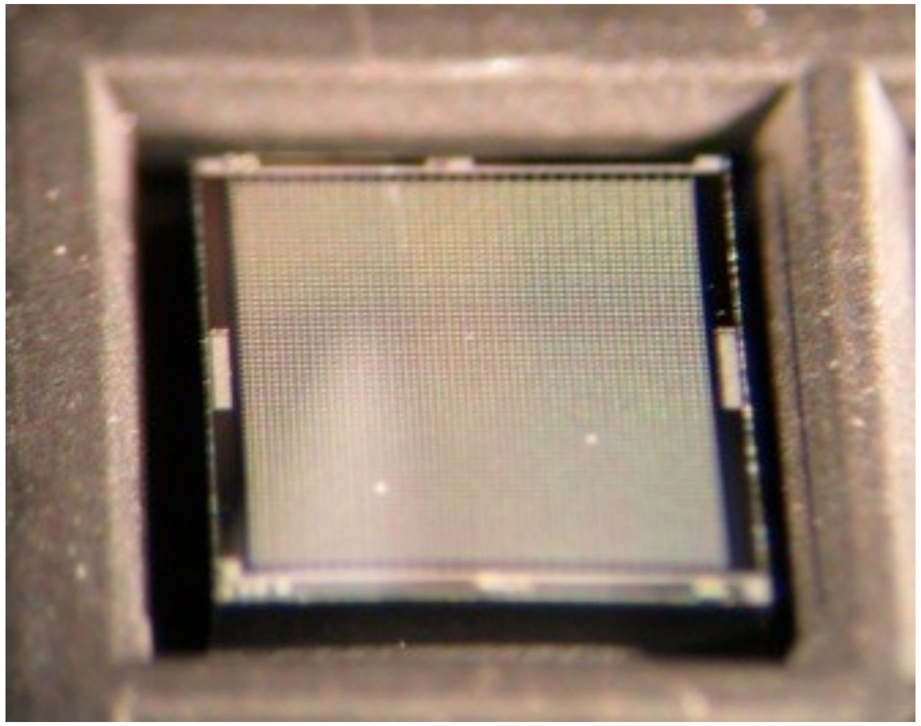
- The whole setup consists of about 1 kg fiber (4 m^2 photon detector)
- Relevant activity: O(>100 µBq)
- Compatible with the background goal of GERDA Phase II (10^{-3} cts/(keV kg yr))

Why SiPMs ?

- Good mach for the size of the WLS fiber
- Small & Silicon = Low background
- High QE
- Works in LN
- Inexpensive

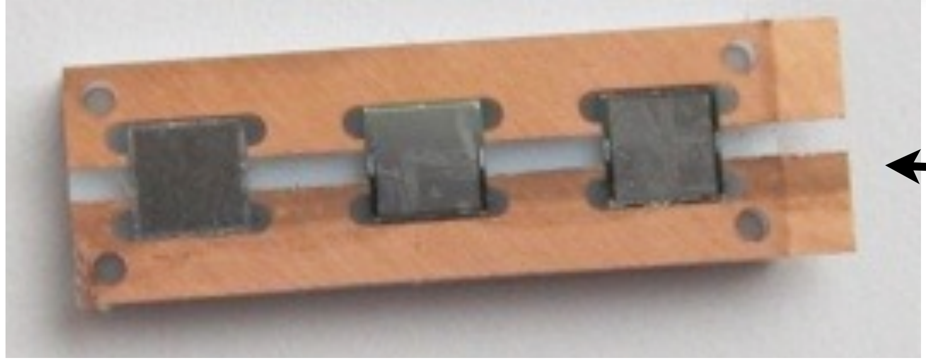


Measured !

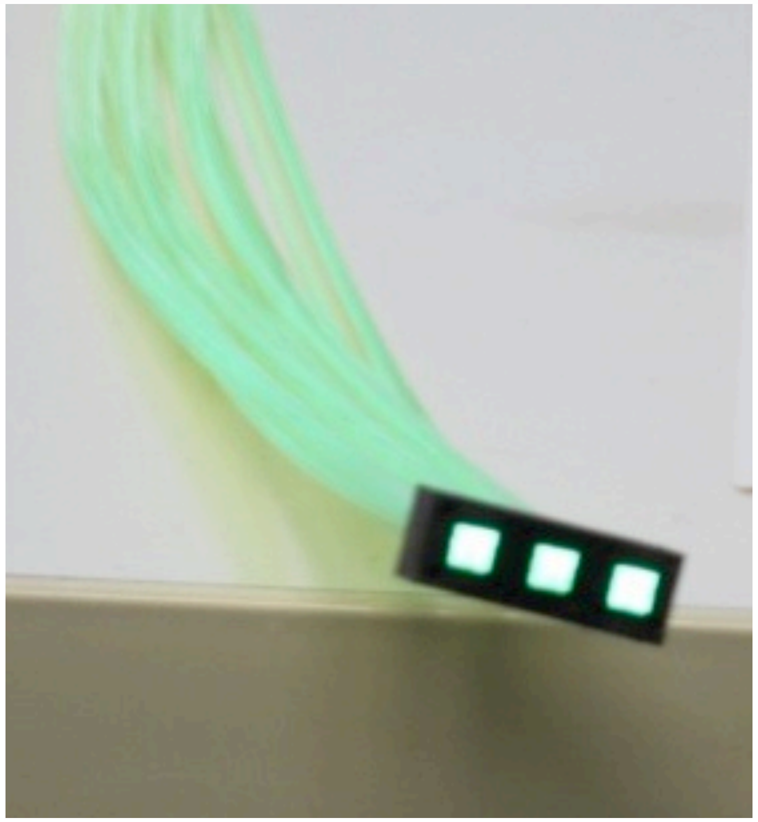


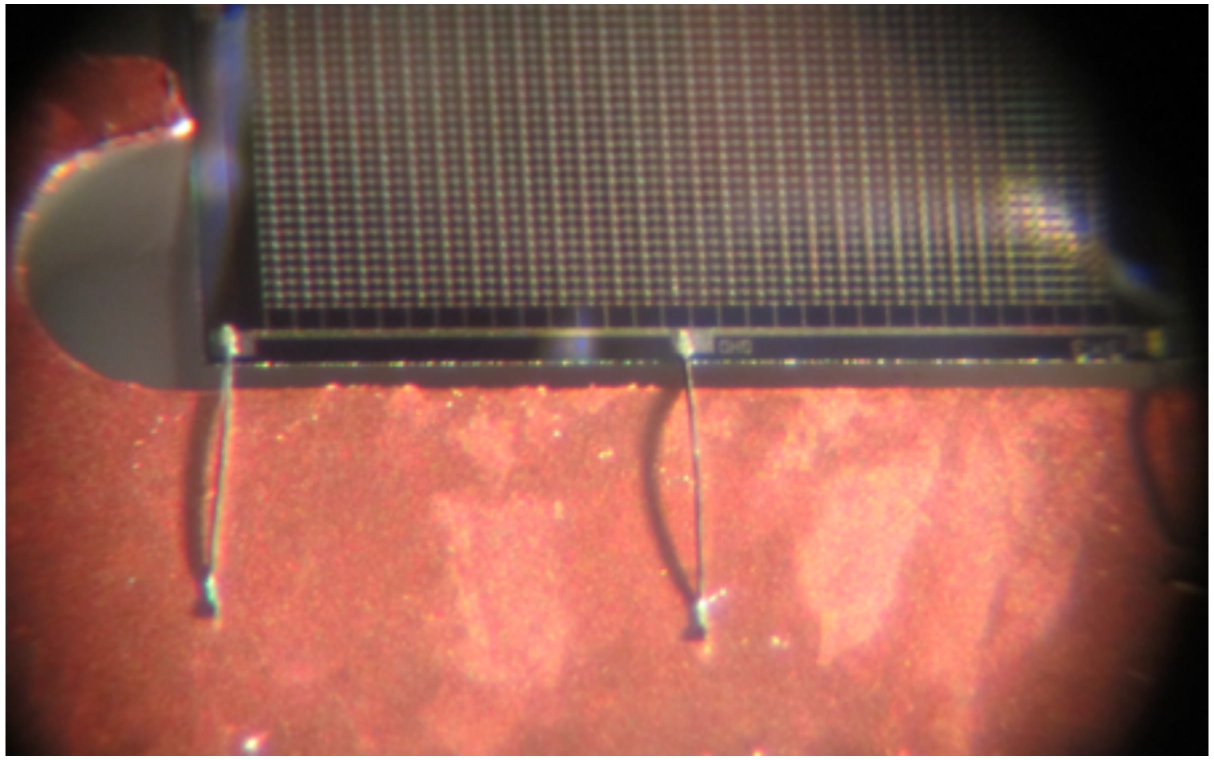
Ketek SiPM purchased in die (3x3 mm 50µm)

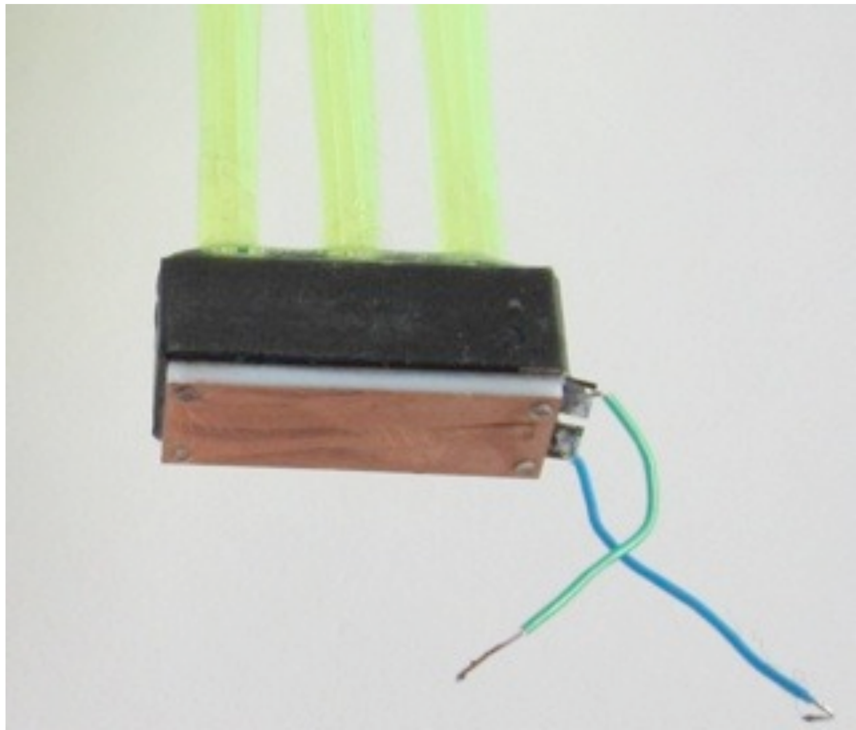
SiPM holder, coupling



Cuflon PCB



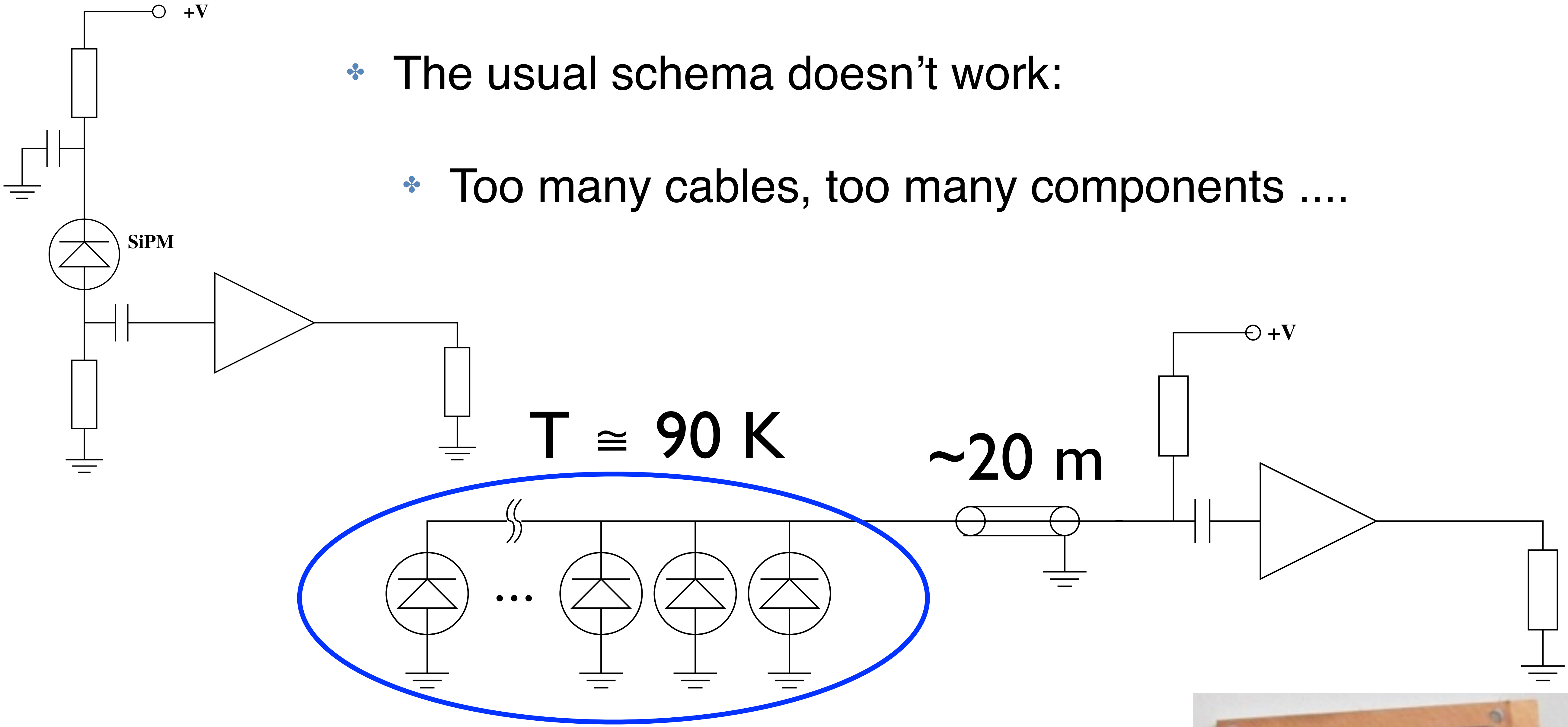


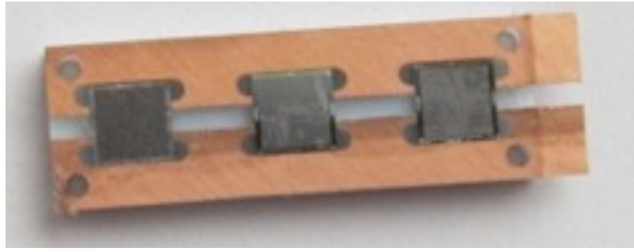


- SiPM delivered in ‘die’, low background packaging is developed
- 9 fiber coupled to 1 SiPM

SiPM read-out

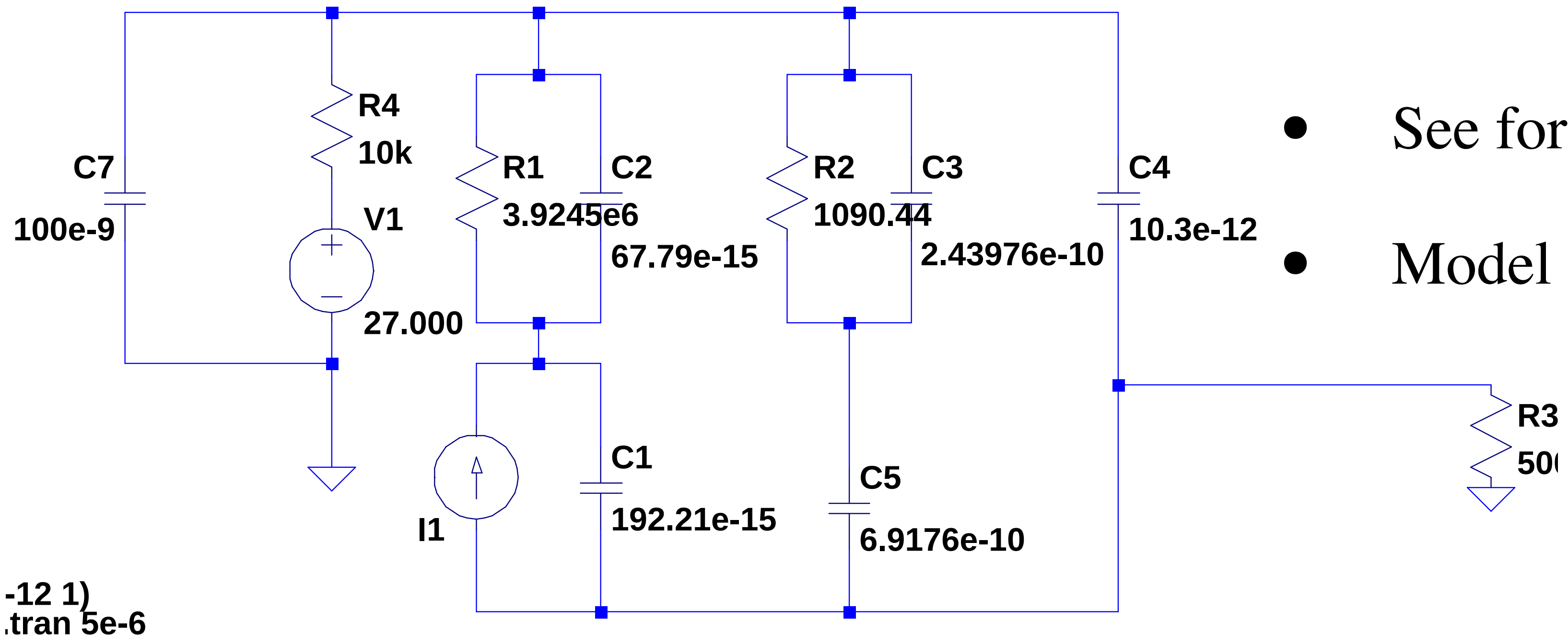
- The usual schema doesn't work:
  - Too many cables, too many components ....



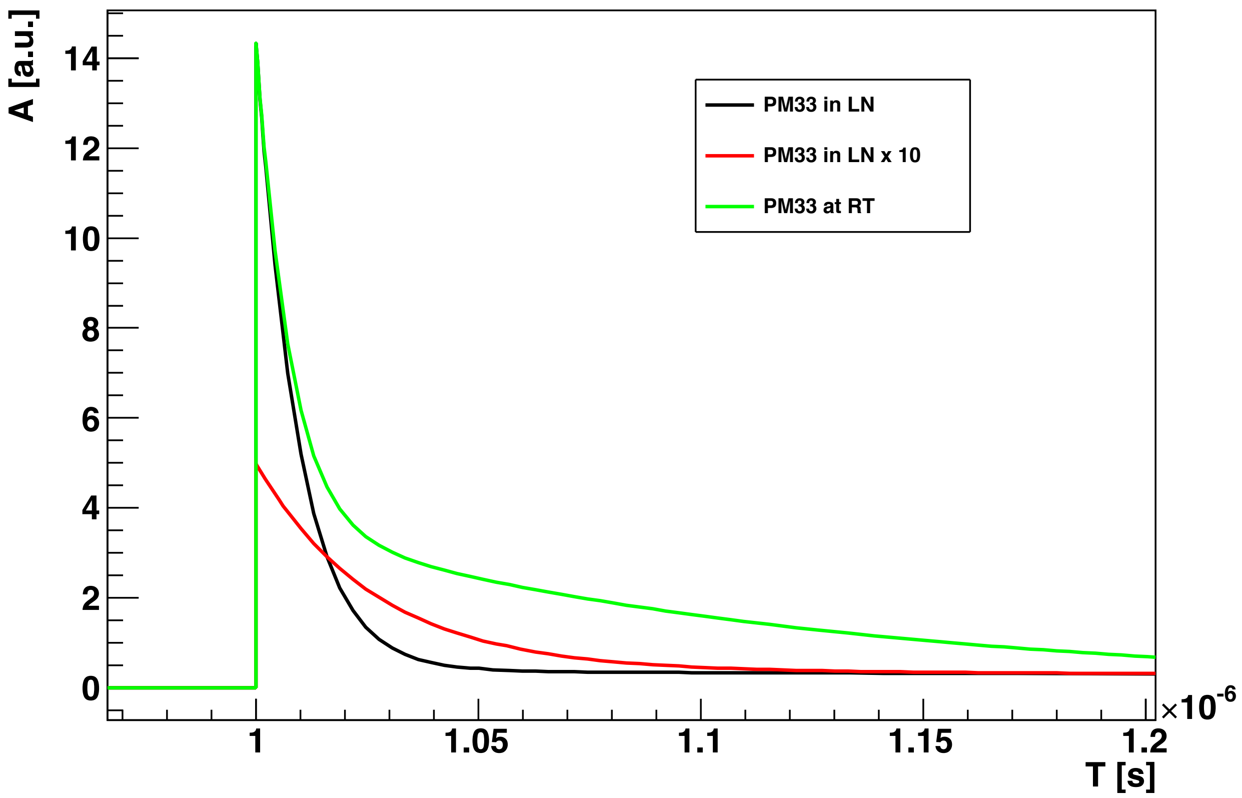


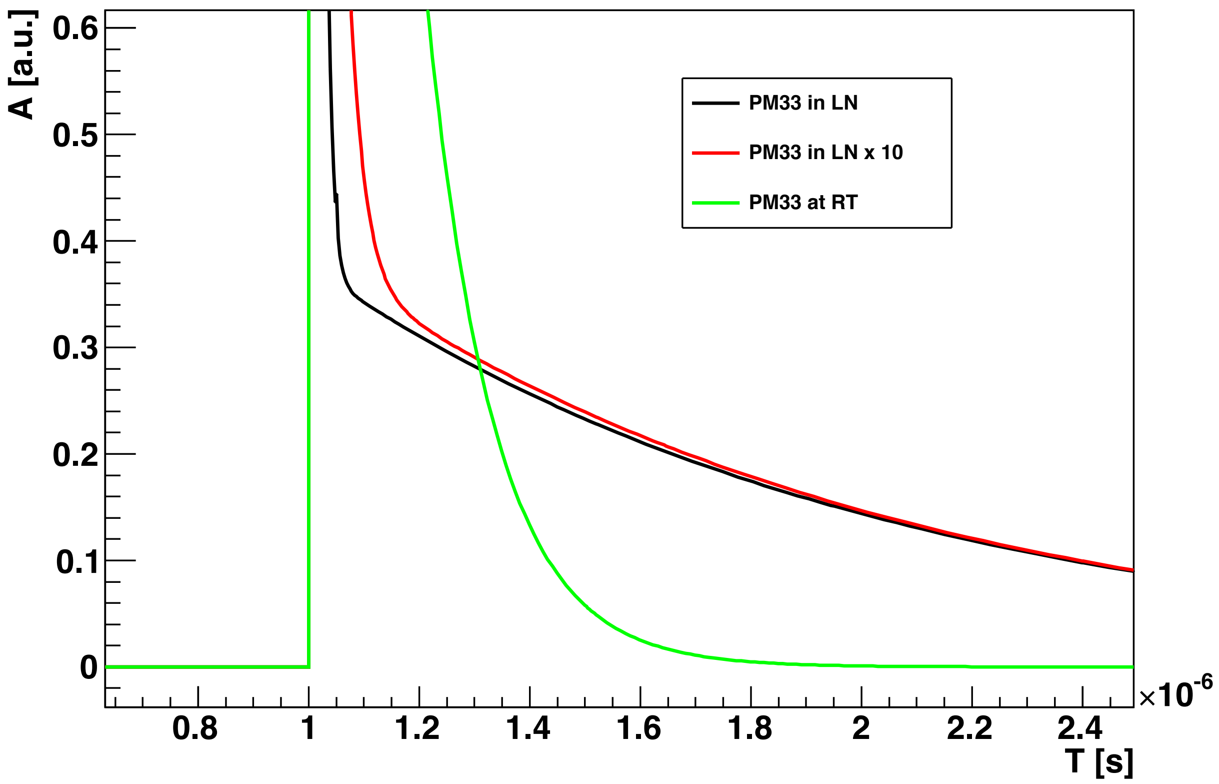
- How many SiPMs can be connected in parallel ?
  - Not limited by the Dark Rate
- Single p.e. preserved?

Spice model of the SiPM



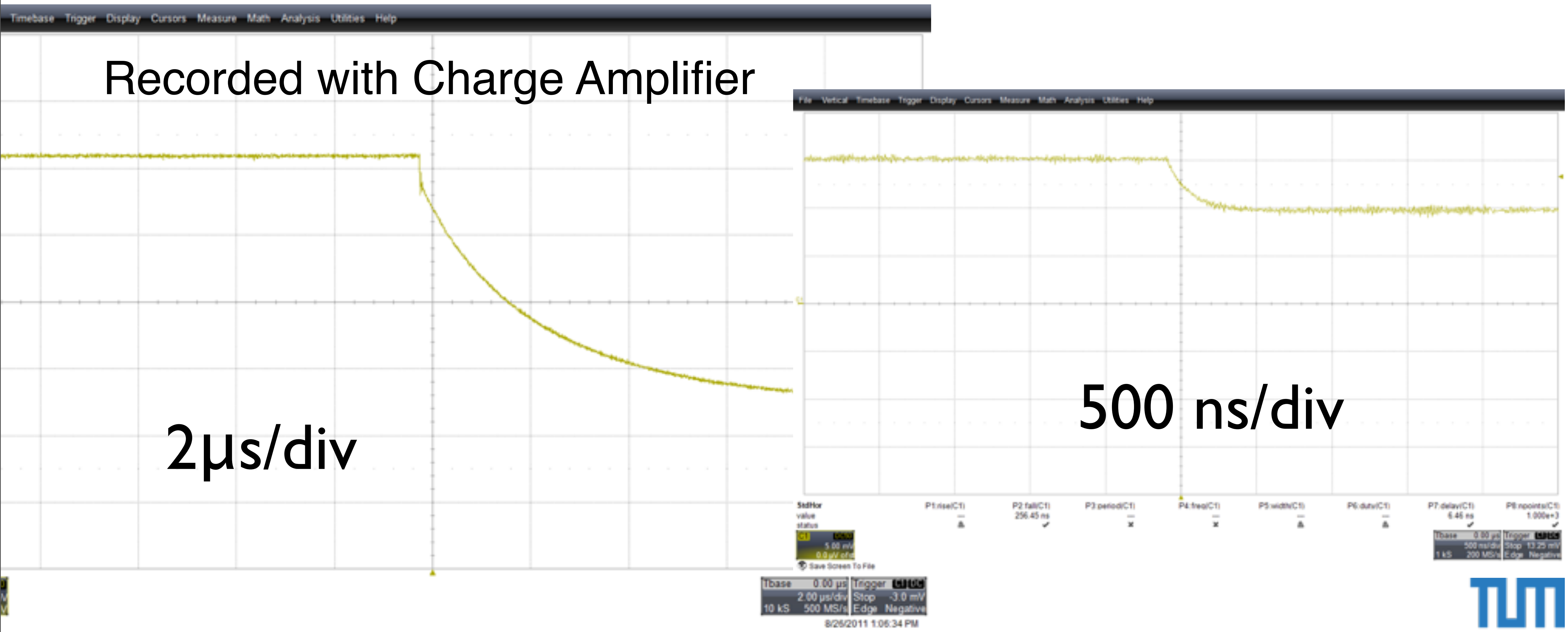
- See for example: NIM A 572 (2007) 416–418
- Model tuned for Ketek SiPMs in LN





Pulse Shapes

Specifications	Ketek PM 33	Ketek PM 33 OTI	Hamamatsu
Pixel capacity	192 fF	118 fF	92 fF
R_q (room temp.)	359 kΩ	918 kΩ	156 kΩ
R_q (in LN)	3.92 MΩ	8.02 MΩ	1.81 MΩ
Gain at 1 V OV*3	$1.20 \cdot 10^6$	$0.74 \cdot 10^6$	$0.58 \cdot 10^6$
Max. gain (in LN)*5	$7.68 \cdot 10^6$	$2.02 \cdot 10^6$	$1.56 \cdot 10^6$
Max. gain (room temp.)*5	$3.18 \cdot 10^6$	$3.90 \cdot 10^6$	$1.09 \cdot 10^6$
OV*3 range (room temp.)	≈ 2.7 V	≈ 5.3 V	≈ 1.9 V
OV*3 range (in LN)	≈ 6.4 V	≈ 2.7 V	≈ 2.7 V



Recorded with Charge Amplifier

2µs/div

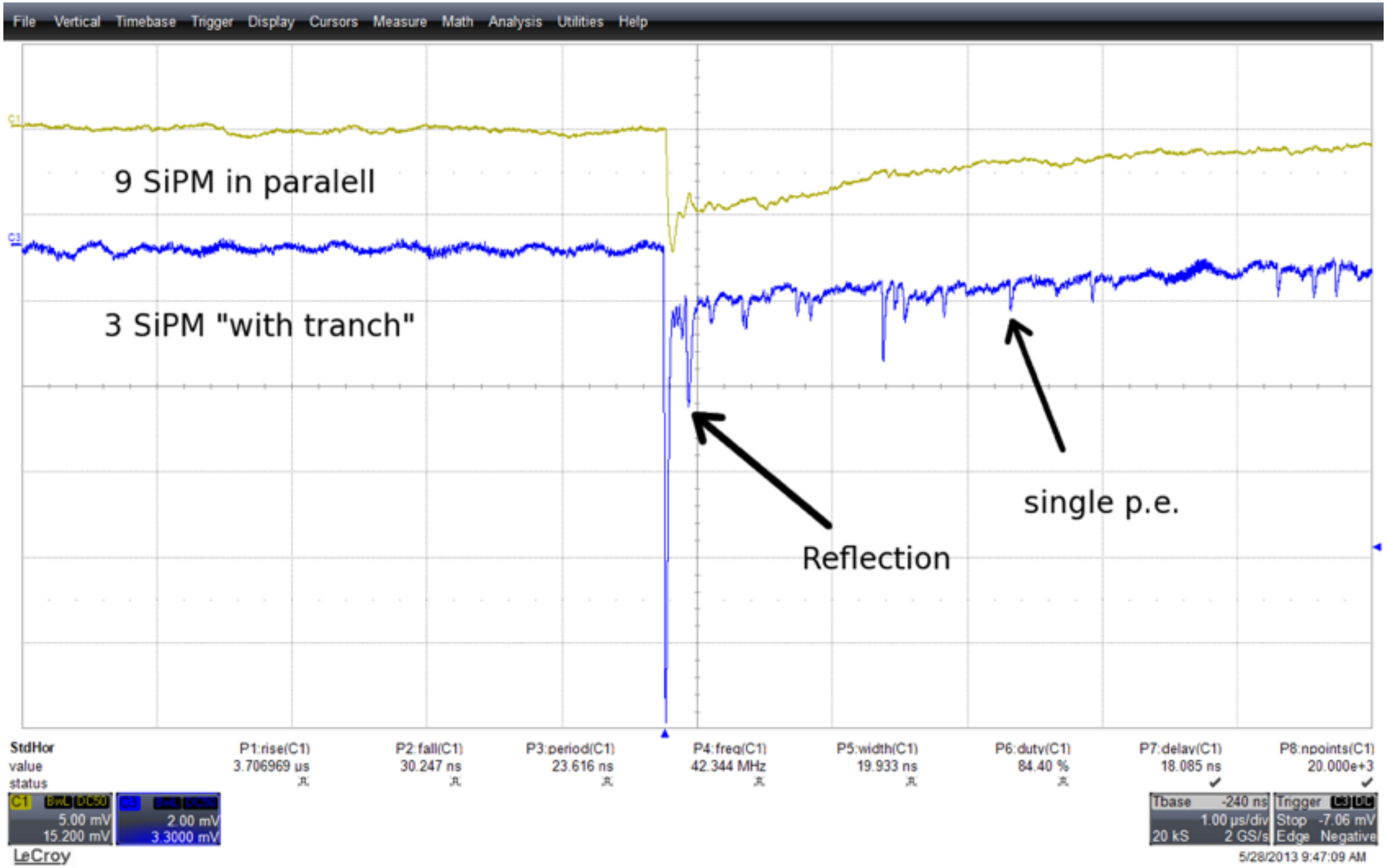
500 ns/div

P2:fall(C1) 256.45 ns
P7:delay(C1) 6.46 ns
P8:npoints(C1) 1.000e+3

Tbase 0.00 µs, 500 ns/div, 1 kS 200 MS/s
Trigger C1 DC, Stop 13.25 mV, Edge Negative

Tbase 0.00 µs, 2.00 µs/div, 10 kS 500 MS/s
Trigger C1 DC, Stop -3.0 mV, Edge Negative
8/26/2011 1:06:34 PM

Scintillation light signal



9 SiPM in paralell

3 SiPM "with tranch"

Reflection

single p.e.

StdHor	P1:rise(C1)	P2:fall(C1)	P3:period(C1)	P4:freq(C1)	P5:width(C1)	P6:duty(C1)	P7:delay(C1)	P8:npoints(C1)
value	3.706969 µs	30.247 ns	23.616 ns	42.344 MHz	19.933 ns	84.40 %	18.085 ns	20.000e+3
status							✓	✓

C1 BwL DC50
5.00 mV
15.200 mV

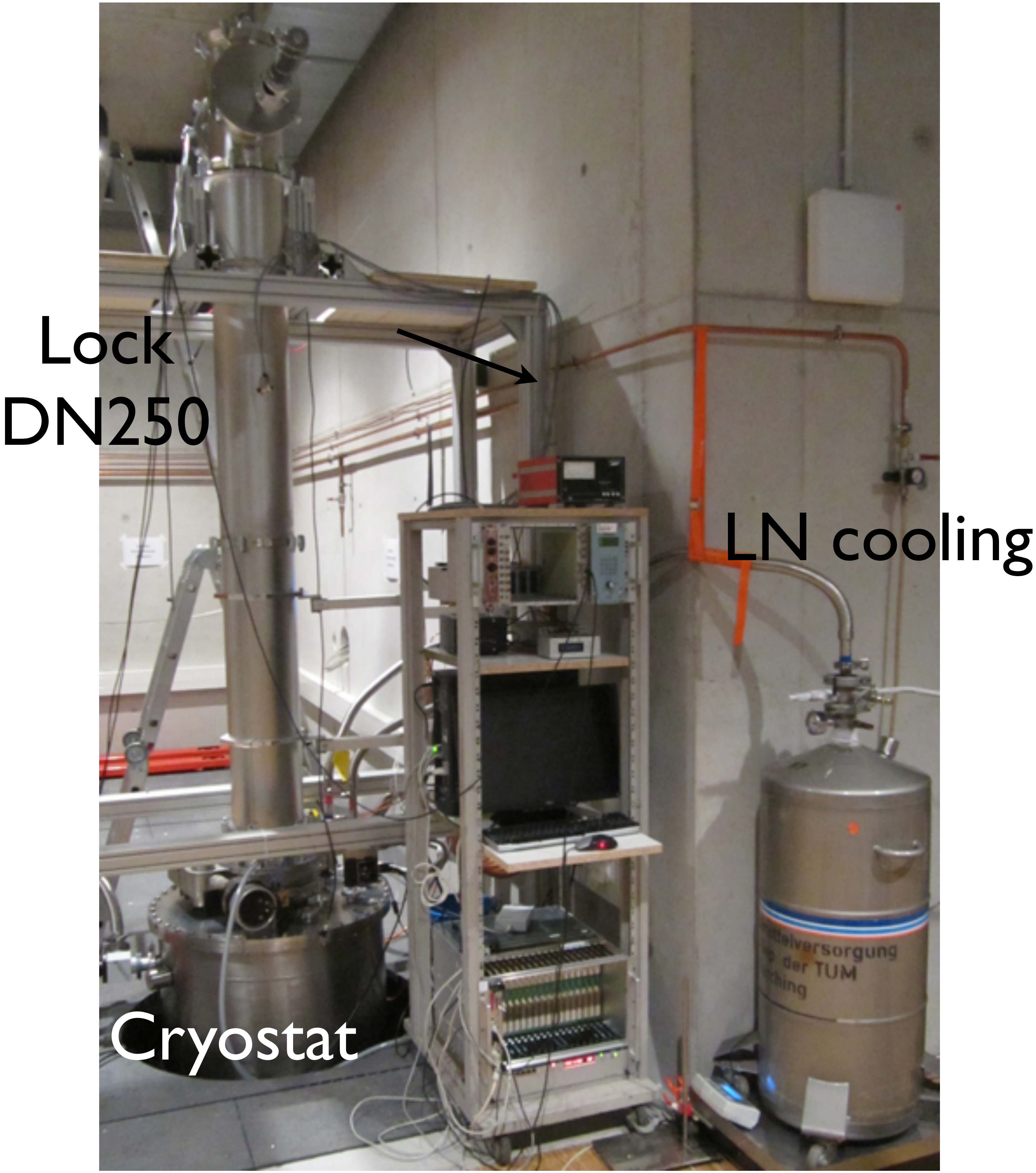
C3 BwL DC50
2.00 mV
3.3000 mV

Tbase -240 ns
1.00 µs/div
20 kS 2 GS/s

Trigger C3 DC
Stop -7.06 mV
Edge Negative

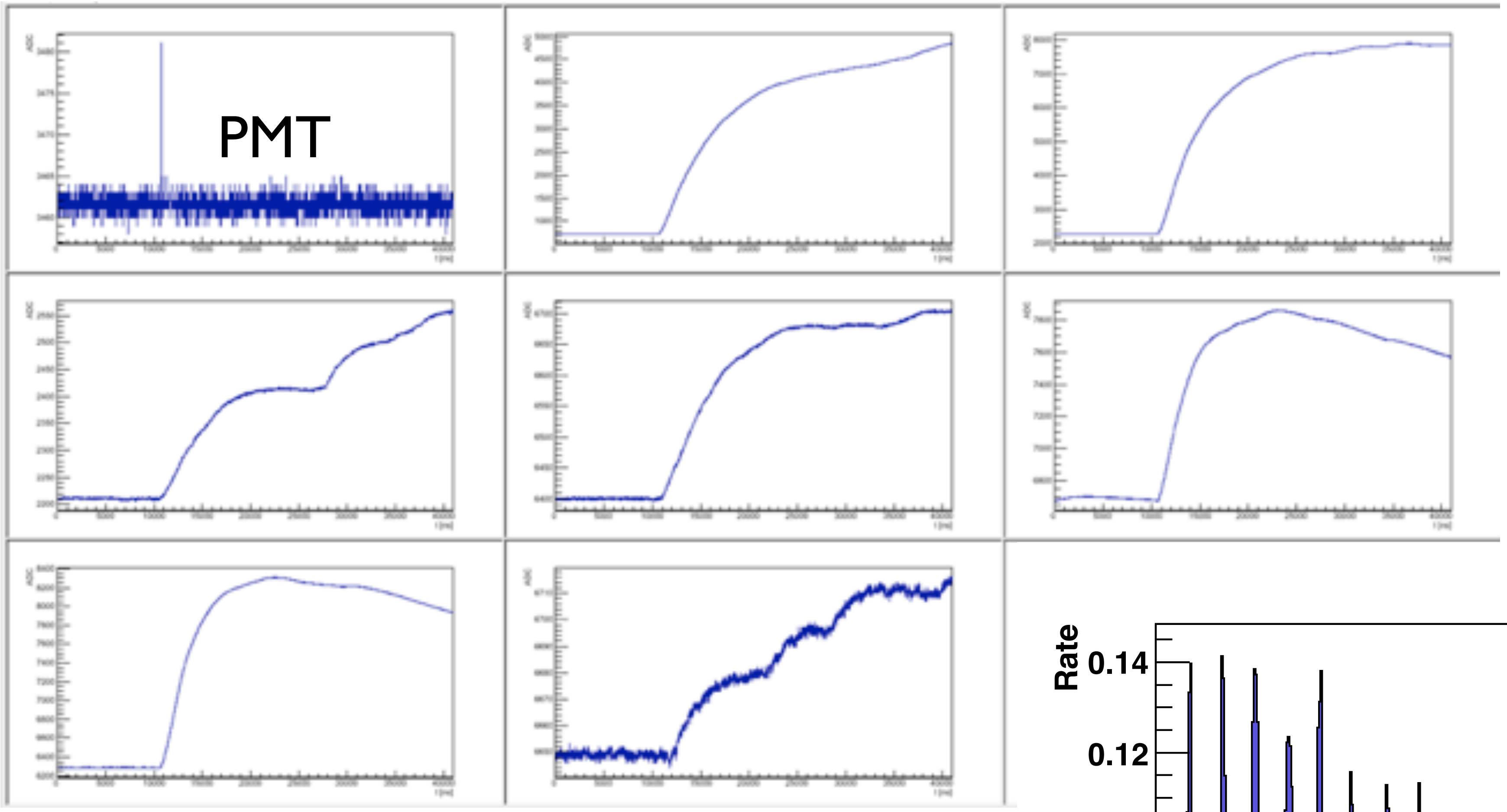
5/28/2013 9:47:09 AM

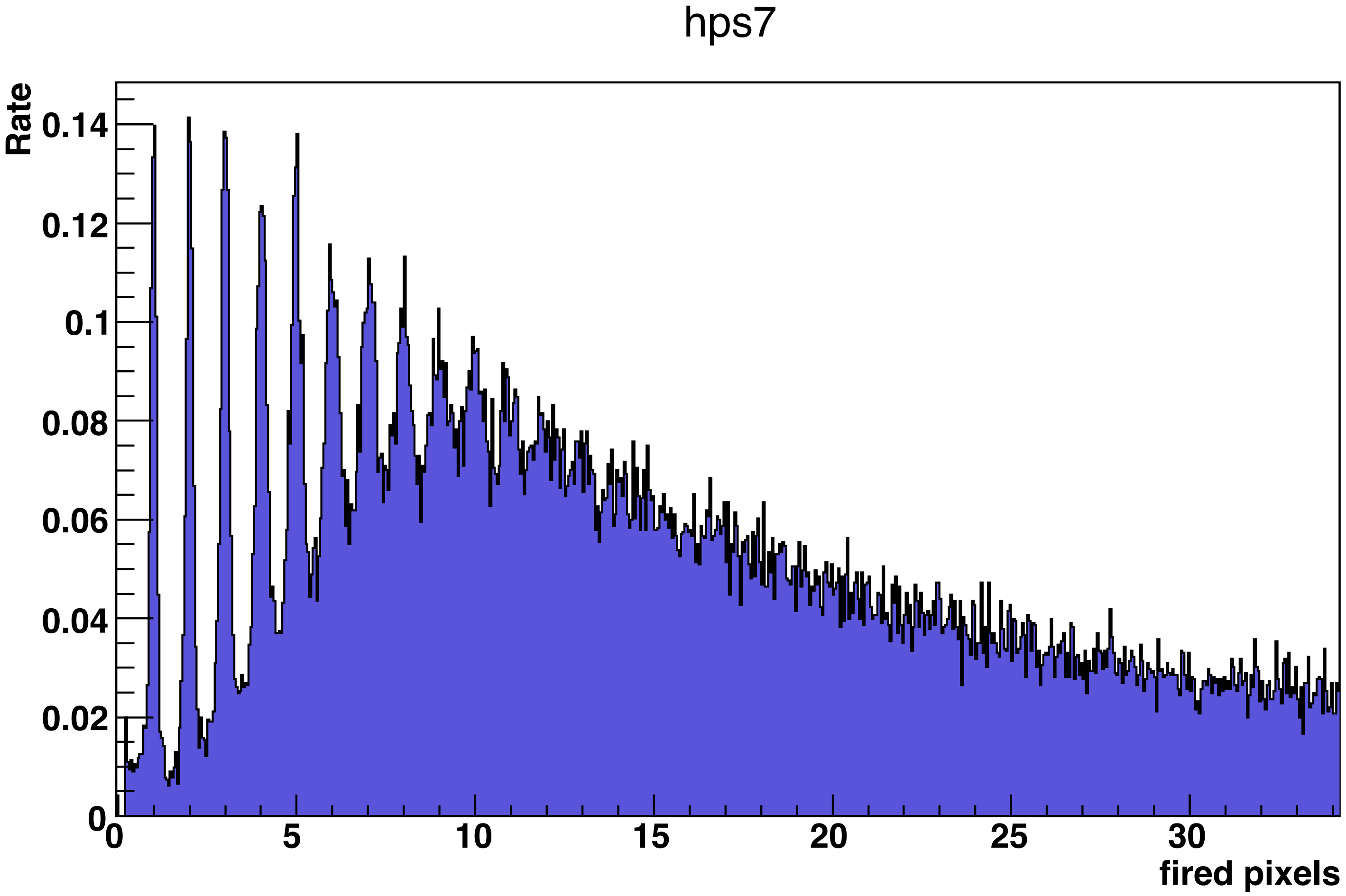
TUM -UGL test stand



DN250 setup

8 channels = 42 SiPM + PMT





Real data:
LAr scintillation light

Conclusion

- The Phase I of GERDA was ended after 21.6 kg yr exposure.
  - Background goal of 0.01 cts/(keV kg yr) was achieved
  - No indication of $0\nu\beta\beta$ signal ⇒ $T_{1/2} > 2.1 \times 10^{25}$ yr
- Phase II construction started:
  - BEGe (point contact like) detectors
  - New Front-End was developed
  - LAr veto is under construction