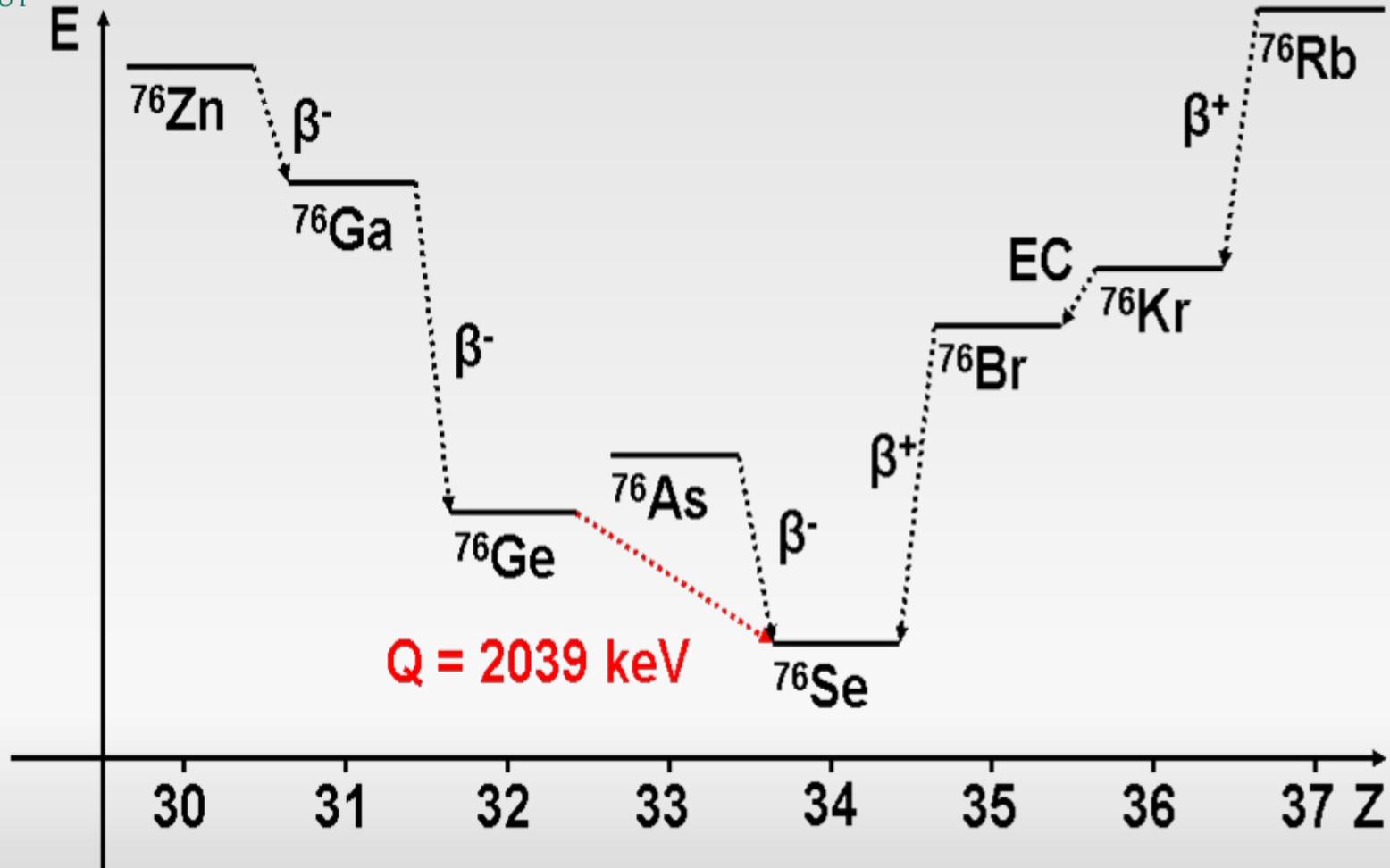


Double beta decay experiments

Bernhard Schwingenheuer
Max-Planck-Institut für Kernphysik, Heidelberg



Motivation for $0\nu\beta\beta$

Baryon number (B) & Lepton number (L) are accidentally conserved in Standard Model
B is violated (baryogenesis) → expect L violation

Most SM extensions predict $\nu = \bar{\nu} \rightarrow$

neutrinoless double beta decay $0\nu\beta\beta$ should exist: $(A,Z) \rightarrow (A,Z+2) + 2e$, $\Delta L=2$

other mechanisms (SUSY, W_R , ...) can cause $0\nu\beta\beta \rightarrow$ L violation at LHC, ...

(W. Rodejohann, Nucl. Phys. Proc. Suppl. 229-232 (2012) 113)

from DOE Nuclear Science Advisory Committee report on $0\nu\beta\beta$ (24 April 2014)

It is the assessment of this Subcommittee that the pursuit of neutrinoless double beta decay addresses urgent scientific questions of the highest importance, and that sufficiently sensitive second generation experiments would have excellent prospects for a major discovery.

Furthermore, we recommend that DOE and NSF support this subject at a level appropriate to ensure a leadership position for the US in this next phase of discovery-caliber research.

$$\frac{1}{T_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M^{'0\nu}|^2 \frac{\langle m_{ee} \rangle^2}{m_e^2}$$

g_A = axial coupling

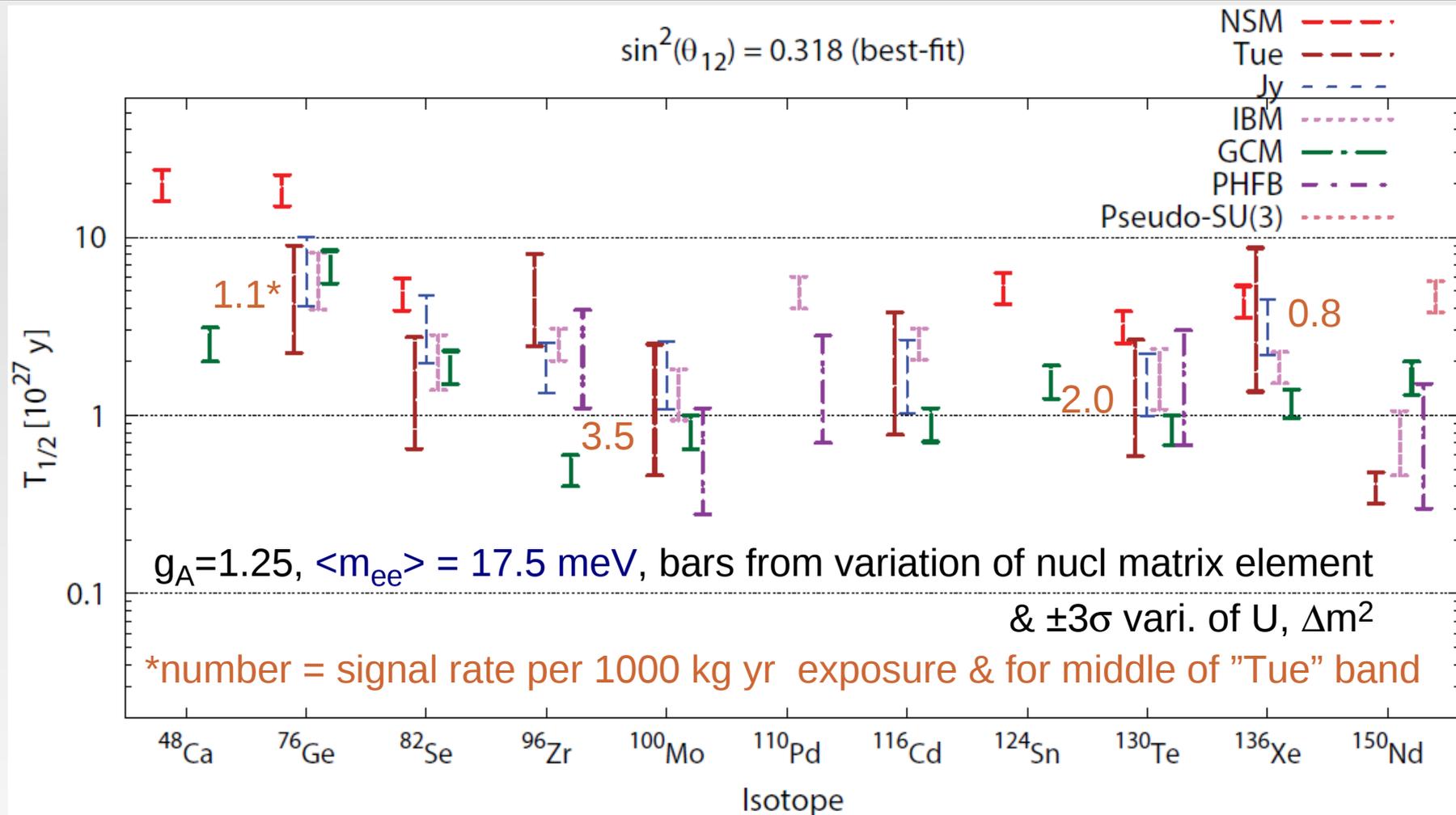
$G^{0\nu}$ = phase space factor

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

m_e = electron mass

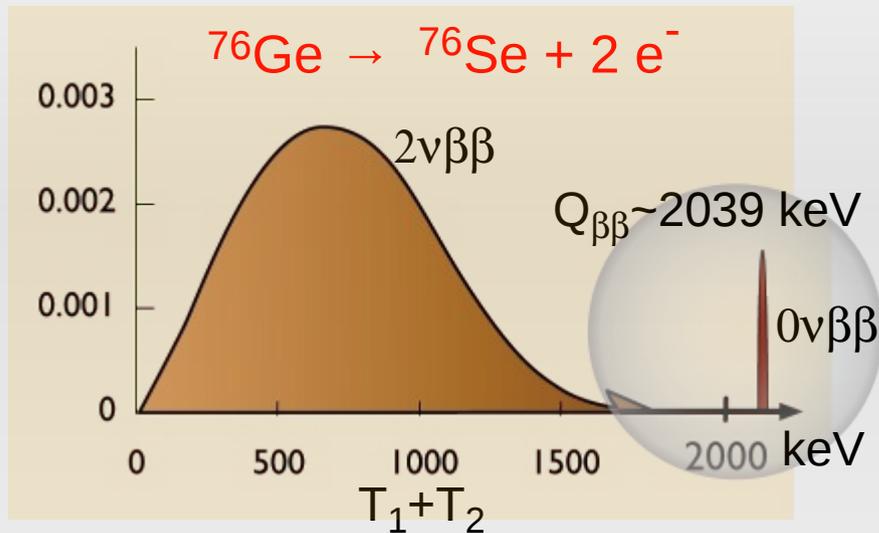
for inverted mass hierarchy $\langle m_{ee} \rangle \gtrsim 17 \text{ meV}$

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



taken from DOE Nuclear Science Advisory Committee report on $0\nu\beta\beta$ (24 April 2014)
 adopted from A. Dueck, W. Rodejohann and K. Zuber, Phys. Rev. D83 (2011) 113010

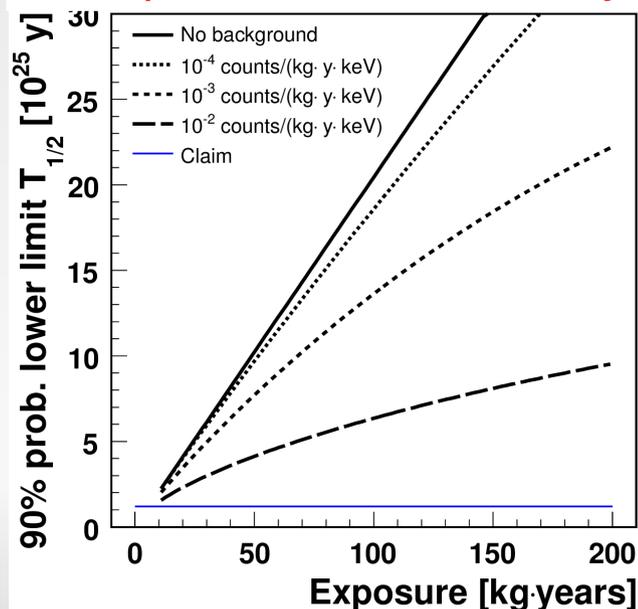
experimental considerations



How to measure energy?

- (Ge) diode (ionization): 0.1-0.2% FWHM
- bolometer (heat) 0.2% FWHM
 - NTD Ge resistor
 - TES
 - MMC
 } thermometer
- TPC (ionization + light), 3% liquid
 <1% gas FWHM
- solid or liquid scintillator, 5-10% FWHM

example: GERDA sensitivity



How to reduce background?

- radiopure materials: detector + support
- det. purification (for liquids + gases)
- clean shielding materials (water, liquids)
- high $Q_{\beta\beta}$ value
- active veto
- "particle identification" (tracking, pulse shape, light & heat, ...)
- good energy resolution

Overview experiments

Name	Nucleus	Mass	Method	Location	Time	D collaborators
Current experiments (under construction or running)						
GERDA I/II	^{76}Ge	15/35	ionization	LNGS	2011/15	++
Majorana Demonstrator	^{76}Ge	30	ionization	SURF	2015	
EXO200	^{136}Xe	170	liquid TPC	WIPP	2011	+
Cuore0/Cuore	^{130}Te	10/600	bolometer	LNGS	2013/15	
Kamland-Zen	^{136}Xe	400	liquid scint.	Kamioka	2011	
SNO+	^{130}Te	2340	liquid scint.	Sudbury	2015	+
NEXT	^{136}Xe	100	gas TPC	Canfranc	2015	
R&D, proto-typing phase						
Candles III	^{48}Ca	0.35	scint crystal	Oto Cosmo	2011	
DCBA	^{150}Nd	32	tracking			
Cobra	^{116}Cd		solid TPC	LNGS	2013	++
SuperNEMO	^{82}Se	7/100-200	track./calor.	Modane	2015/-	
Lucifer	^{82}Se		bolom+scint	LNGS		
AMoRE	^{100}Mo		bolom+scint	YangYang		+
LUMINEU	^{100}Mo		bolom+scint.			+

Overview experiments

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▶ Kamland-Zen	^{136}Xe	400	liquid scint.	Kamioka	2011	
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Lucifer	^{82}Se		bolom+scint	LNGS		
▶ AMoRE	^{100}Mo		bolom+scint	YangYang		+
▶ LUMINEU	^{100}Mo		bolom+scint.			+

Gerda

lock & glove box
for string insertion

64 m³ LAr

590 m³ pure water / Cherenkov veto

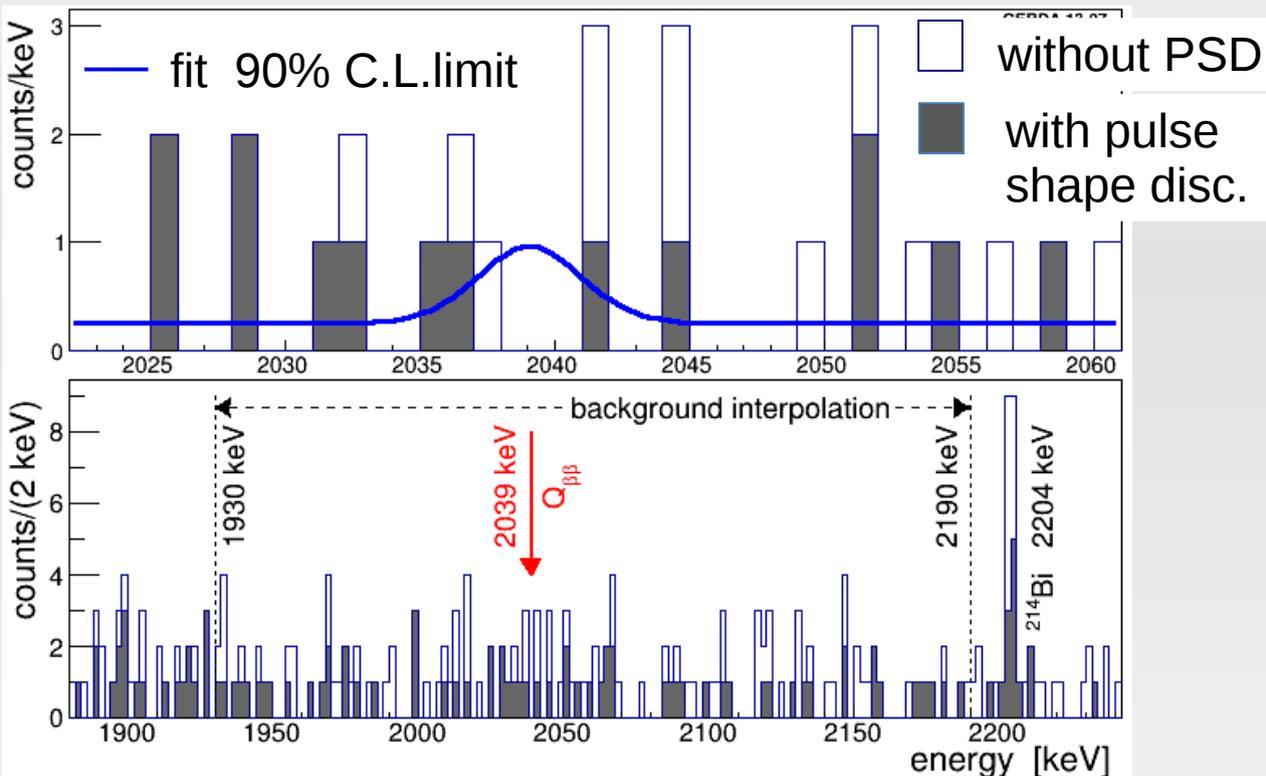
charge sens amp.
low radioactivity

string of 3 Ge detectors
low mass support
coaxial & BEGe det.

⁷⁶Ge fraction: 7% → 86%

physics data **Phase I 2011-13:**
coaxial (14.6 kg) & BEGe (3 kg) det
4.8 keV / 3.2 keV FWHM coax/BEGe
61.9% / 66.3% efficiency coax/BEGe
background 0.011 cnt/(keV kg yr) coax
0.005 cnt/(keV kg yr) BEGe

Gerda result Phase I



events ± 20 keV blinded

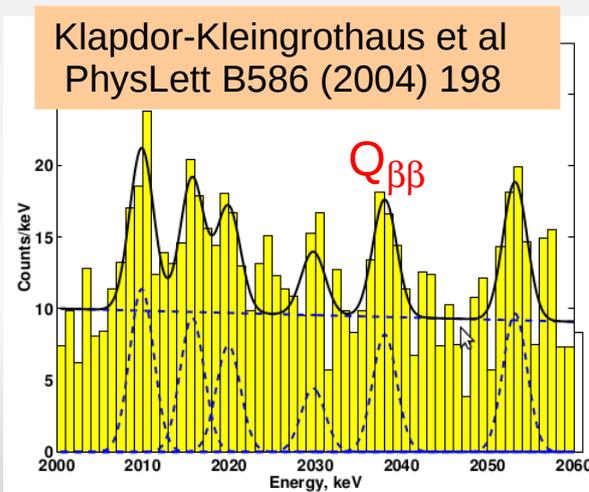
after calibration+selection finished
 → unblinding at meeting
 in Dubna in June 2013

exposure 21.6 kg yr
 backgr. 0.01 cnt/(keV kg yr)
 after pulse shape cut

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

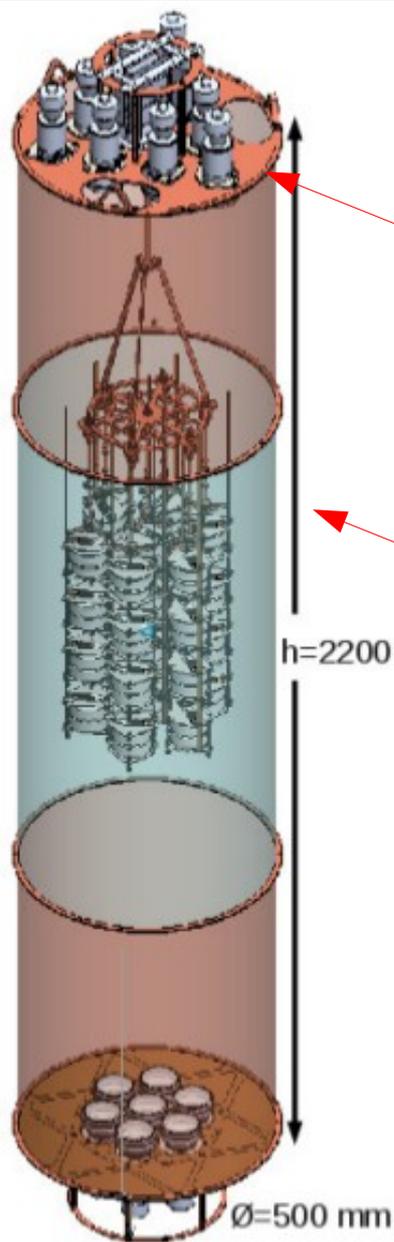
(sensitivity = $2.4 \cdot 10^{25}$ yr)

PRL 111 (2013) 122503.

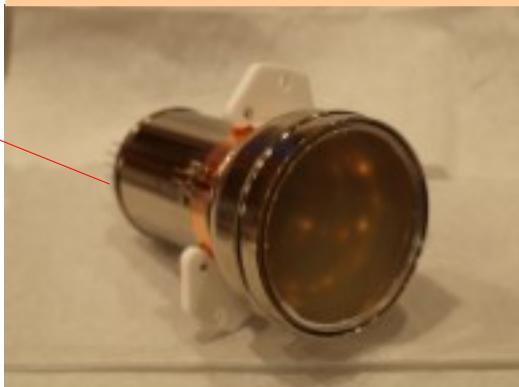


claimed signal: GERDA should see 5.9 ± 1.4 $0\nu\beta\beta$ events in
 $\pm 2\sigma$ interval above background of 2.0 ± 0.3
 probability $p(N^{0\nu}=0 | H_1=\text{signal}+\text{bkg}) = 1\%$, claim ruled out @ 99%
 (GERDA best fit signal count $N^{0\nu} = 0$)

Gerda Phase II

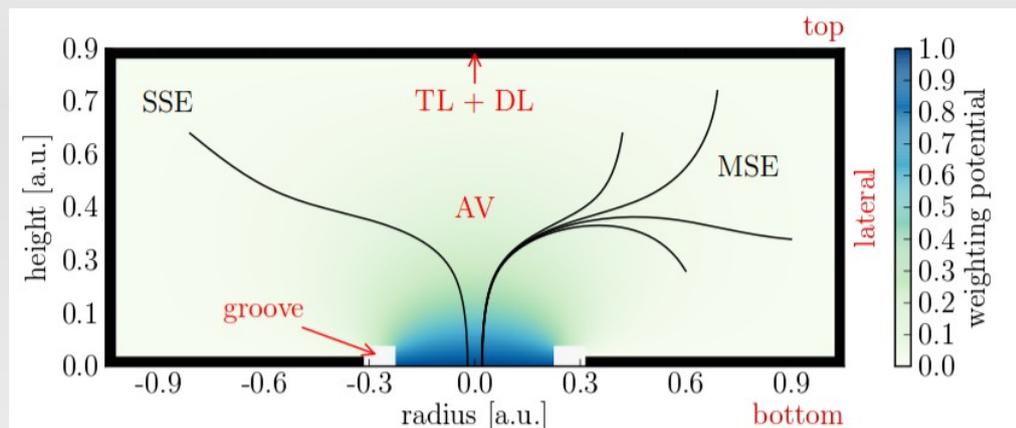


LAr scintillation veto

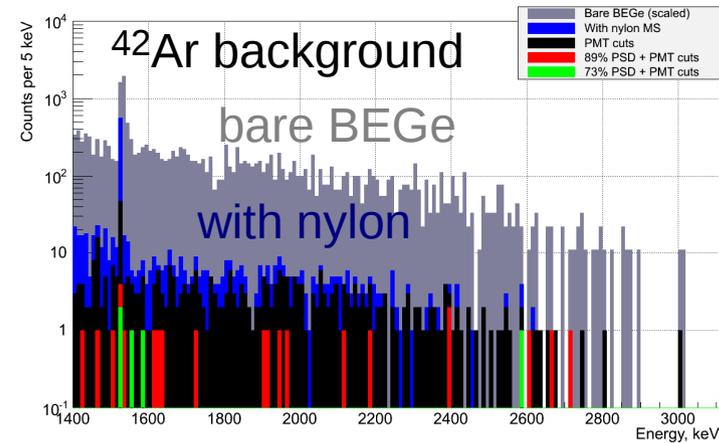


detector mass 2x
background 0.1x
start winter 2014/15

new detector type with better pulse shape discr.
detector support, electronics, contacting

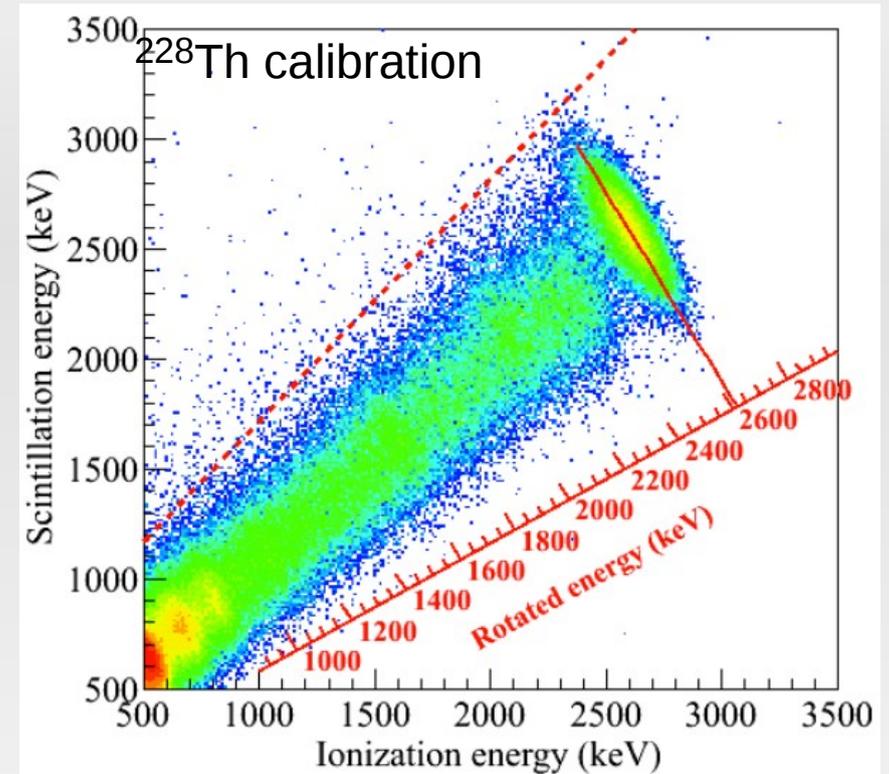
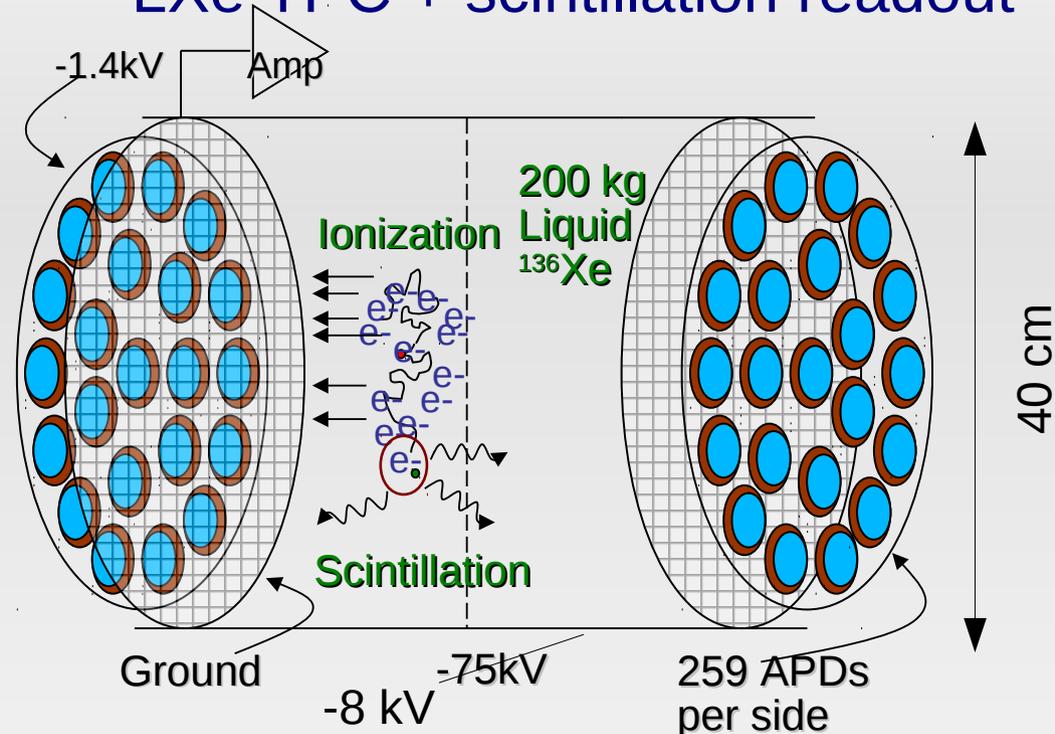


mitigation ^{42}Ar background:
nylon cylinder around detector string

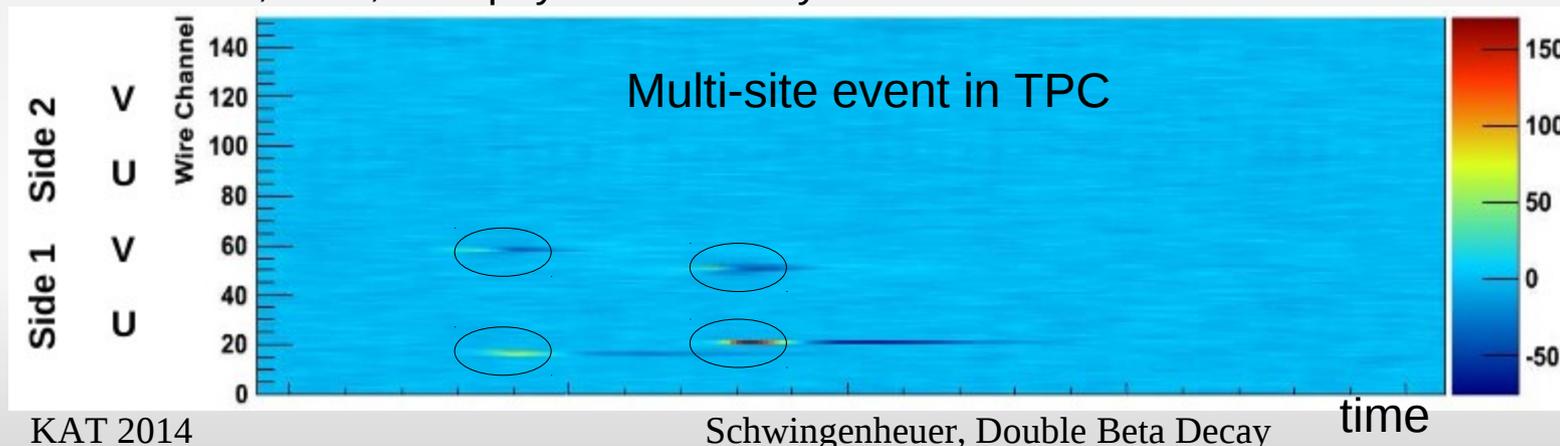


EXO-200

LXe TPC + scintillation readout

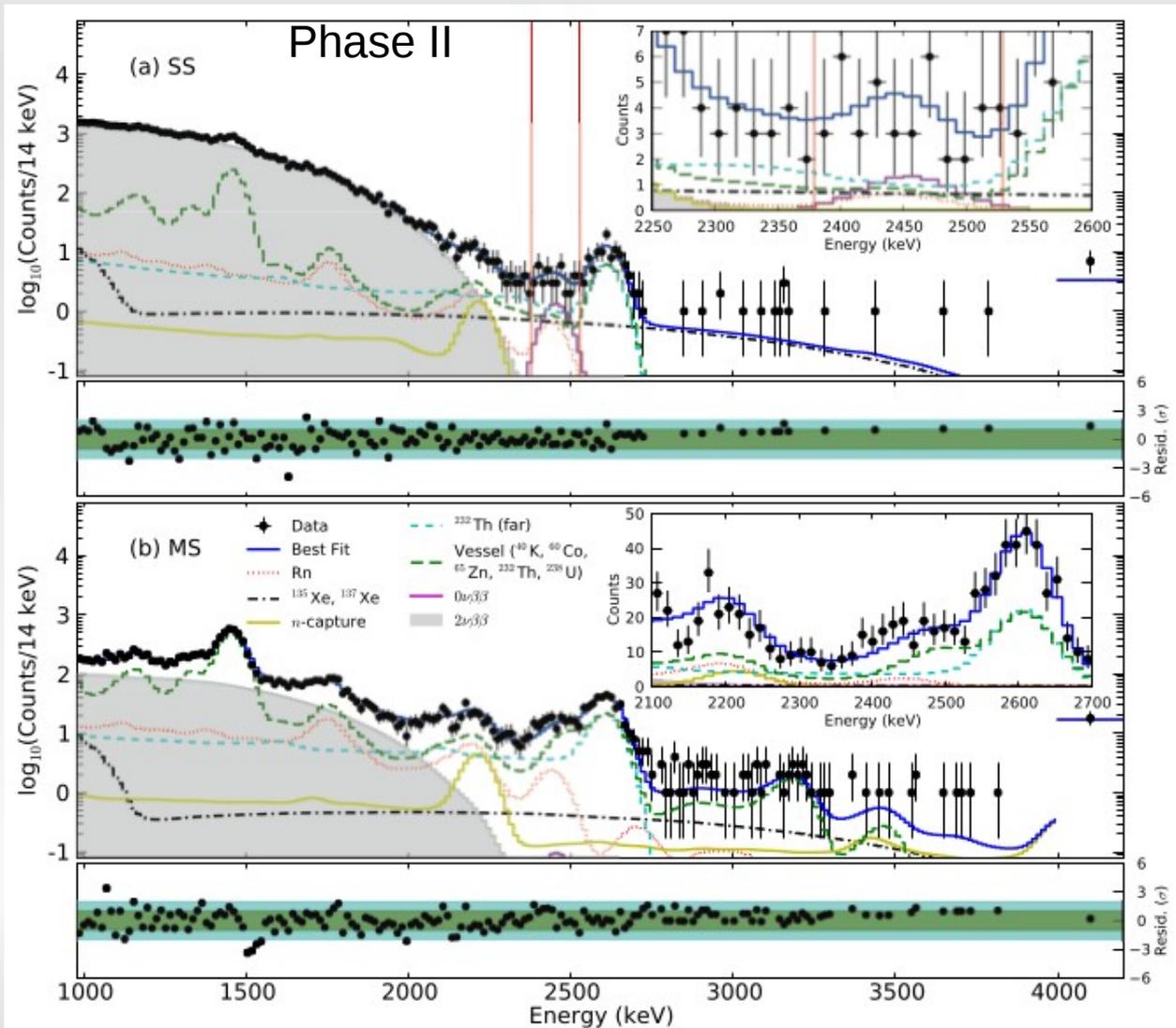


FWHM for $0\nu\beta\beta$ ~ 88 keV @ $Q_{\beta\beta}$



EXO-200

Phase I: 120.7 live days (58% live time), background 0.18 cnt / ((kg fiducial ^{136}Xe) yr FWHM)
 Phase II: 447.6 live days (84% live time), $0\nu\beta\beta$ efficiency 84.6%
 since Feb 2014: due to fire & airborne radiological event in WIPP stop of data taking



Phase I: PRL 109 (2012) 032505
 find/expect 1/4.1 evt @ $Q_{\beta\beta} \pm 1\sigma$

$$T_{1/2}^{0\nu} > 1.6 \cdot 10^{25} \text{ yr (@ 90 C.L.)}$$

(sensitivity 1.0 10^{25} yr)

Phase II: Nature 510 (2014) 229-234
 find/expect 39/31.1 evt @ $Q_{\beta\beta} \pm 2\sigma$

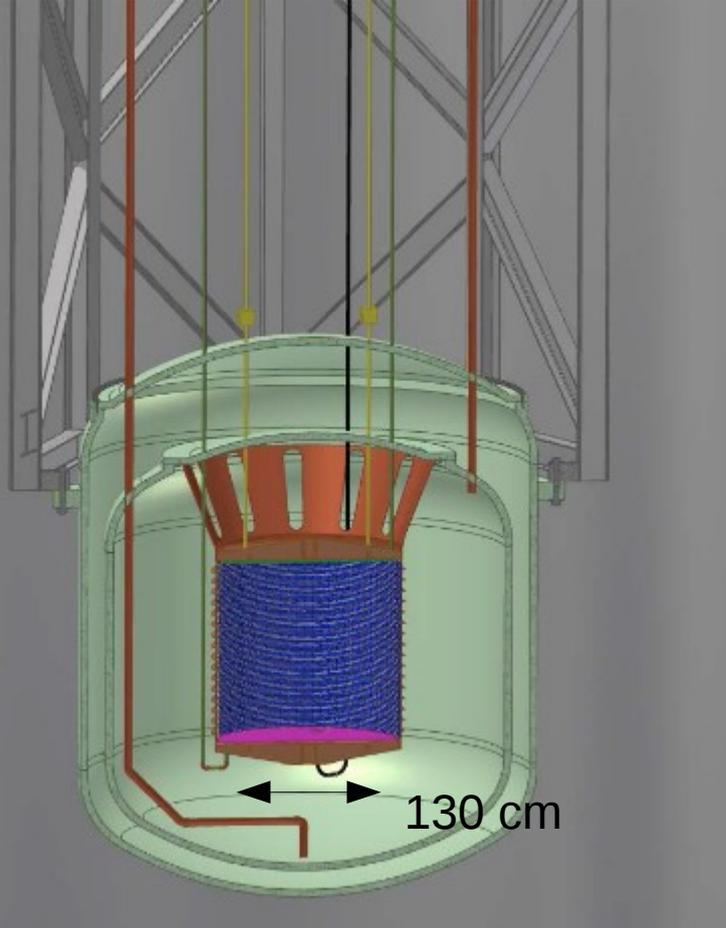
$$T_{1/2}^{0\nu} > 1.1 \cdot 10^{25} \text{ yr (@ 90 C.L.)}$$

(sensitivity 1.9 10^{25} yr)

sensitivity after 4 more years
 of live time ~ 6 10^{25} yr

nEXO proposal

LXe cryostat + TPC in water volume



n(ext)EXO: 5 t of liquid ^{enr}Xe TPC @ SNOLab

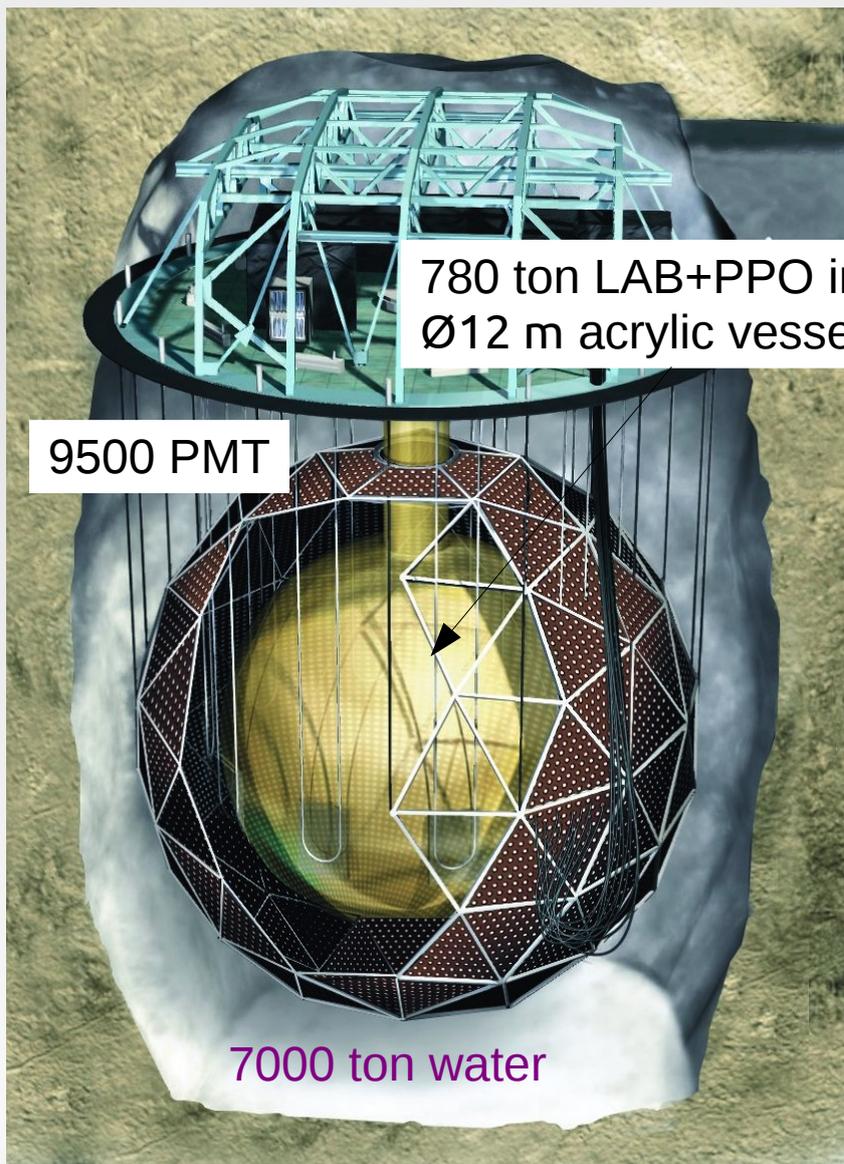
"LXe TPC as similar as possible to EXO-200"

	EXO-200	nEXO (5 yr)
fiducial mass [kg]	100	4780
enrichment	80%	90%
FWHM [keV]	88	58
background in [evt/(mol yr ROI)]	0.022	$6 \cdot 10^{-4}$
$T_{1/2}$ limit sens. (90% CL) [yr]	$6 \cdot 10^{25}$	$6 \cdot 10^{27}$

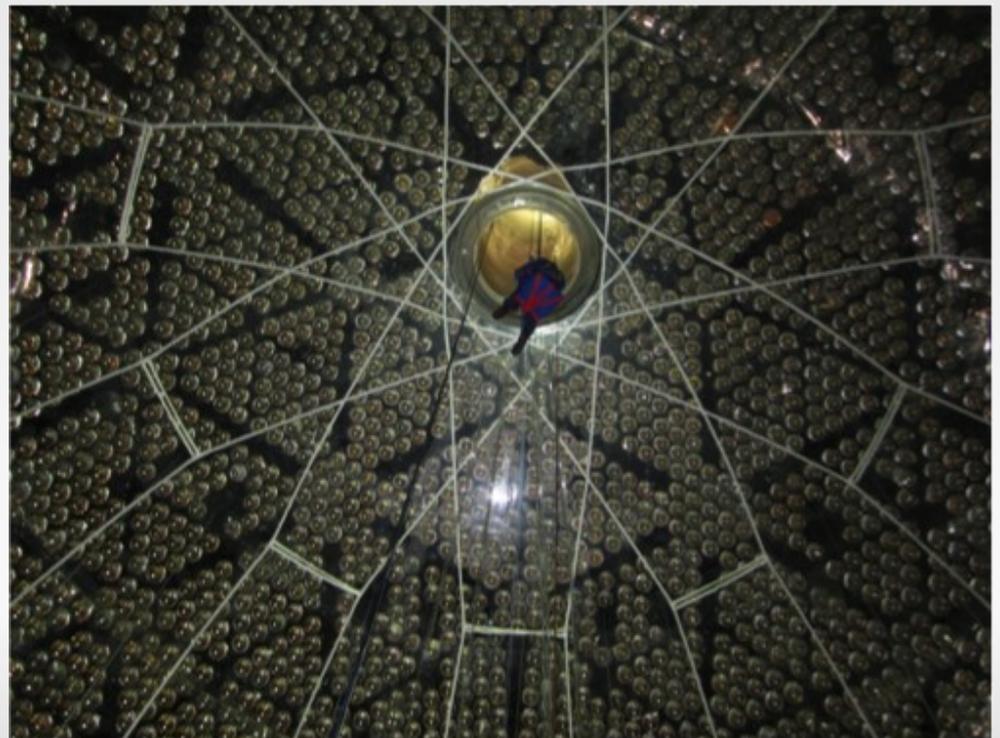
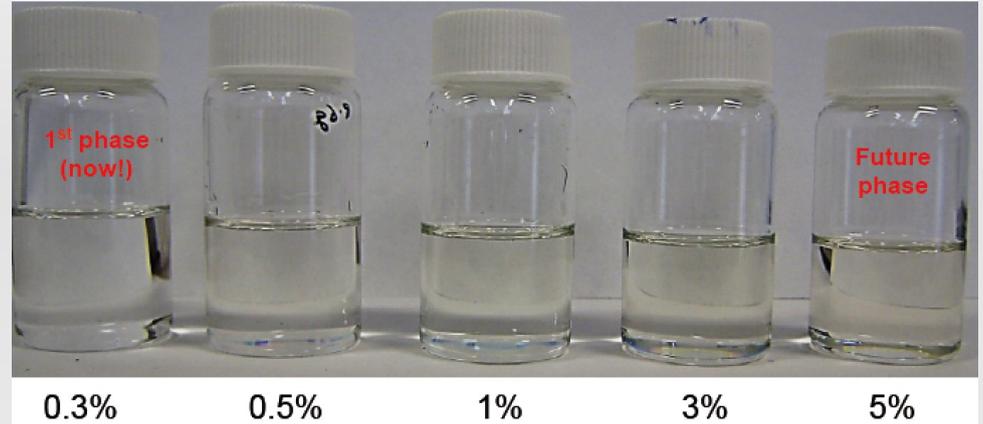
R&D ongoing to identify spectroscopically daughter nucleus of ^{136}Xe ("Ba tagging") \rightarrow only $2\nu\beta\beta$ bkg

$T_{1/2}$ limit sensitivity $3 \cdot 10^{28}$ yr after 10 yr (90% eff)

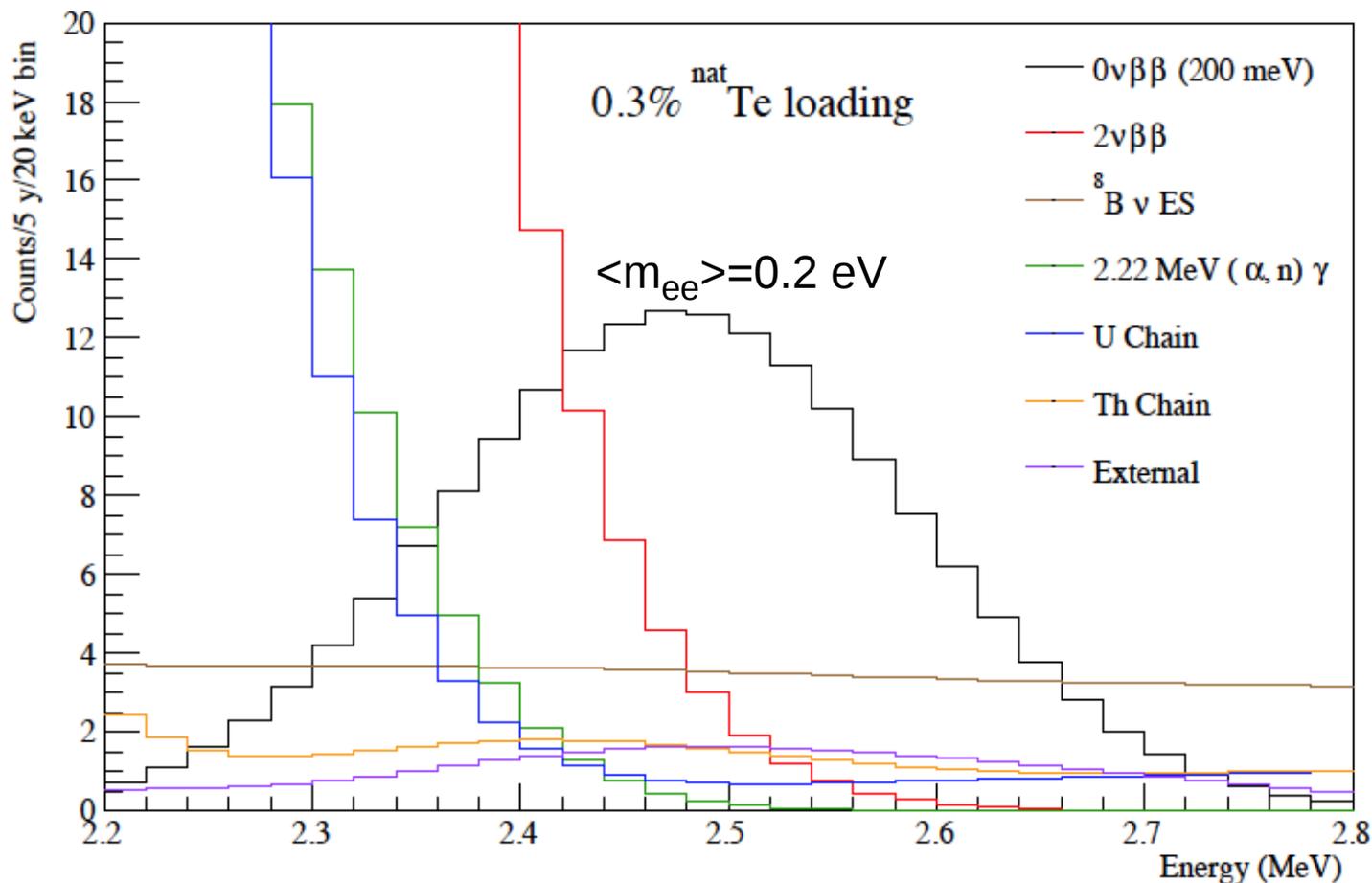
SNO+ with natTe



default: 0.3% loading \rightarrow 2340 kg natTe / 800 kg ^{130}Te



simulated spectrum after 5 yr



schedule:
soon water filling
scintillator filling 2015
physics run 2016

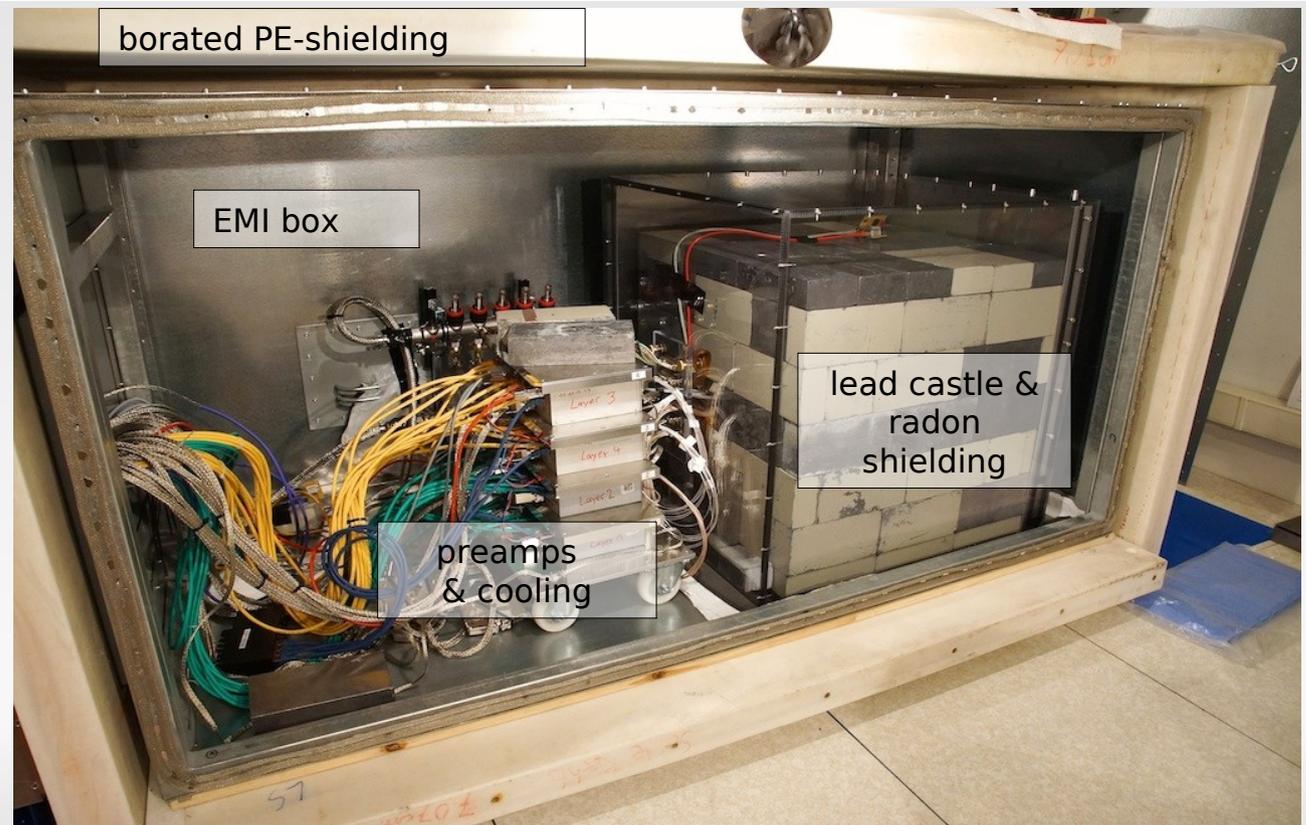
FWHM \sim 270 keV @ $Q_{\beta\beta}$, sensitivity 5 yr $T_{1/2} > 1.0 \cdot 10^{26}$ yr (90% CL)

Cobra

K. Zuber, Phys. Lett. B 519,1 (2001)

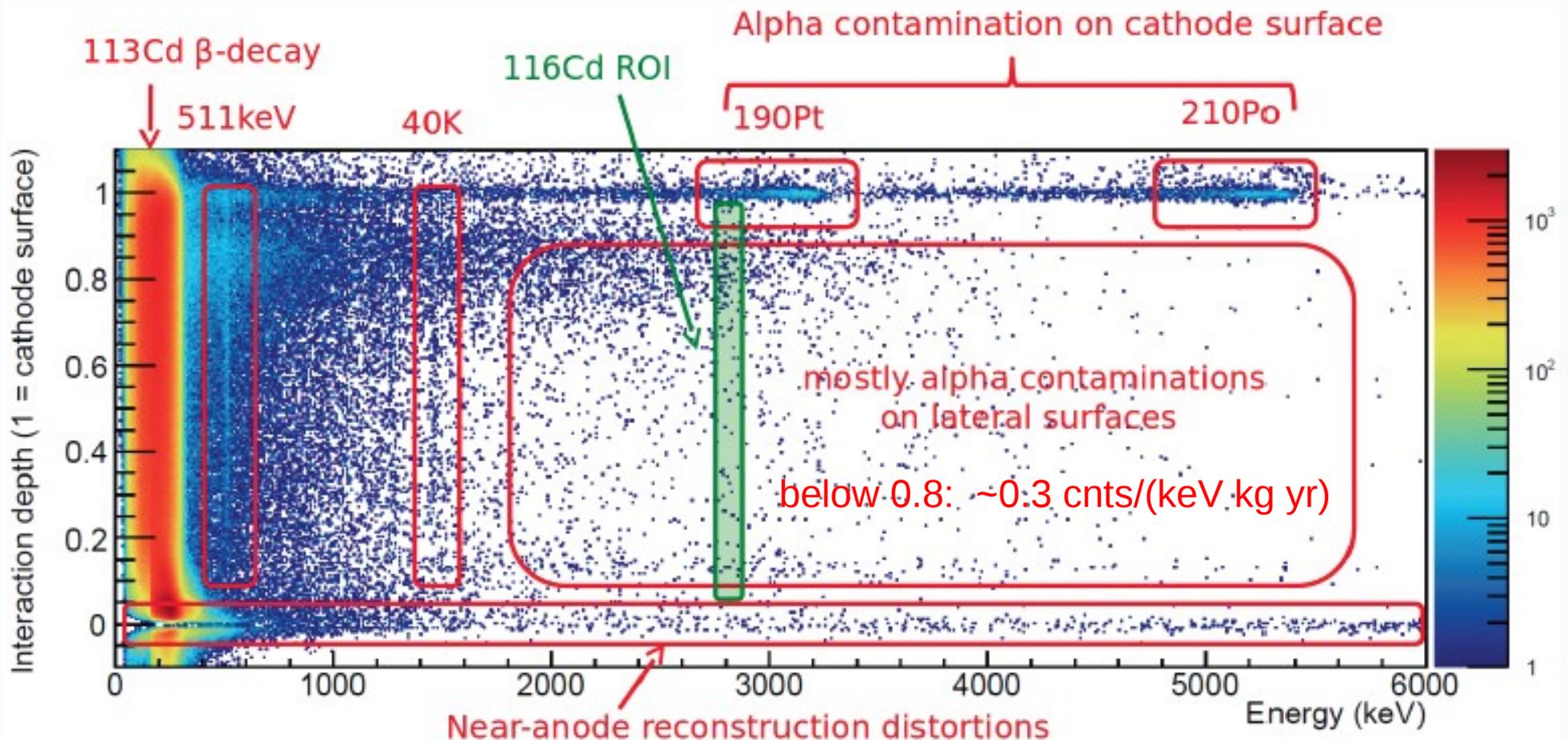
idea: Large array of $(^{116}\text{CdZnTe})$ semiconductor detectors:
 $Q_{\beta\beta} = 2.8 \text{ MeV}$, room temperature operation

64 det of 1 cm^3 @ LNGS since Nov 2013, $>0.7 \text{ kg yr}$ exposure



Cobra

pulse shape → interaction depth & multi site events, FWHM @ $Q_{\beta\beta} \sim 30$ keV



future: switching to 6x detector size

AMoRe and LUMINEU

^{100}Mo ($Q_{\beta\beta} = 3 \text{ MeV}$) scintil. crystal as bolometer & scintillation light readout
ratio photon energy / phonon energy different for α versus $e/\gamma \rightarrow$ background rejection

AMoRE

Advanced **Mo**-based **R**are process
Experiment

$^{40}\text{Ca}^{100}\text{MoO}_4$ scintillating crystals



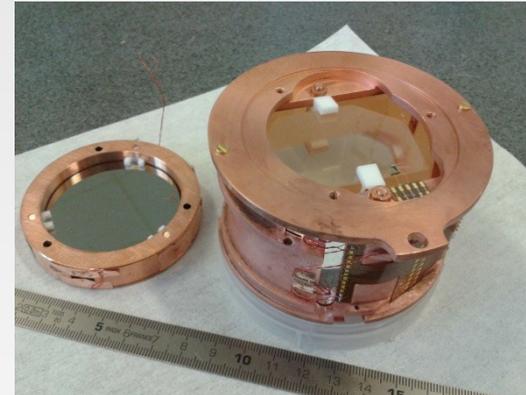
MMC for photon and phonon channel

Metallic **M**agnetic **C**alorimeter:
measure magnetization $M(T)$ with SQUID
developped at KIP, Universität Heidelberg
for X-ray detector, **EChO**, ...

LUMINEU

Luminescent **U**nderground
Molybdenum **I**nvestigation for
NEUtrino mass and nature

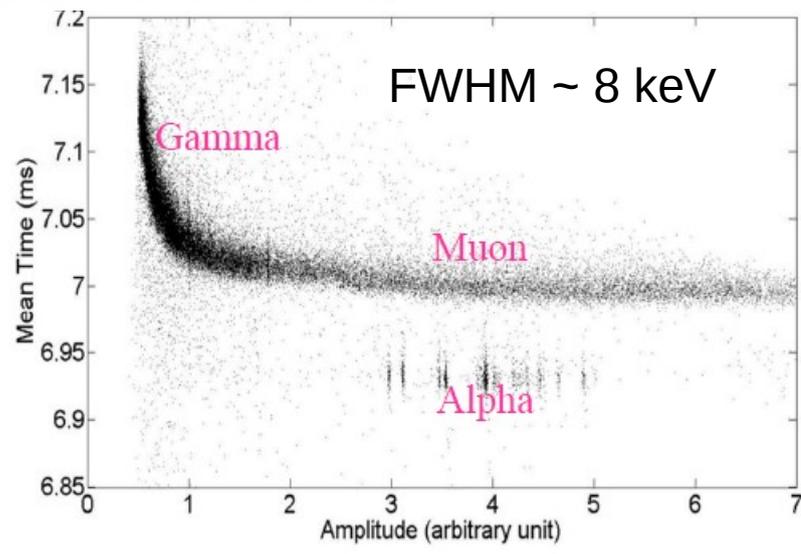
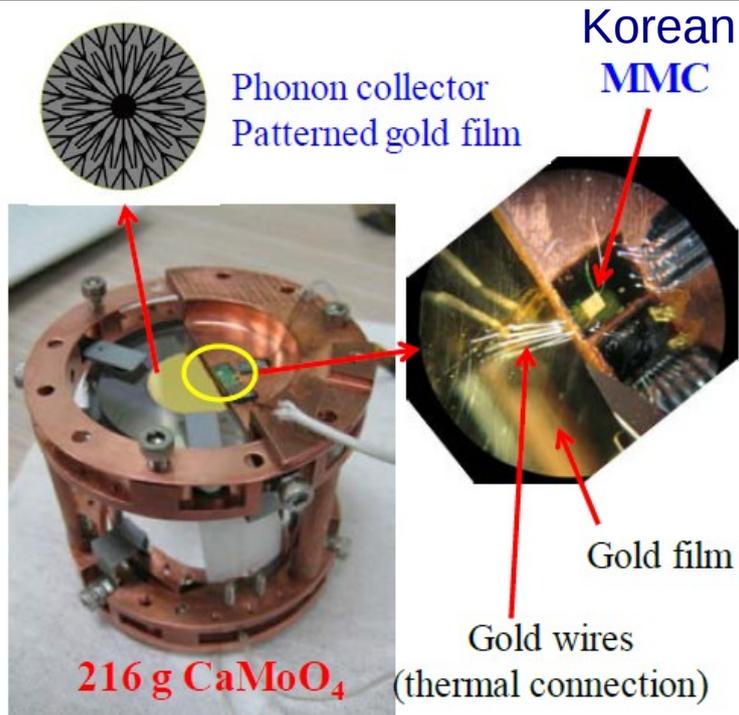
ZnMoO_4 scintillating crystals



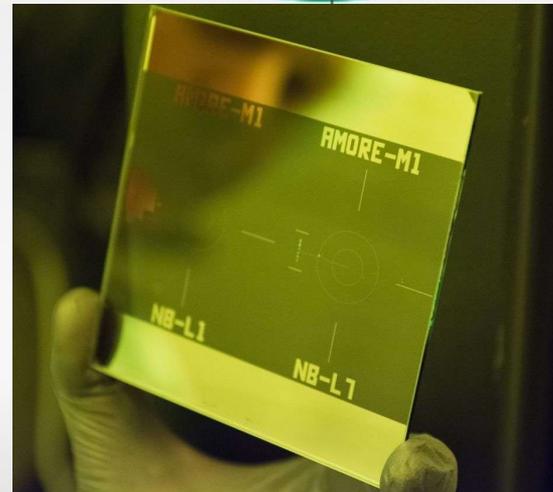
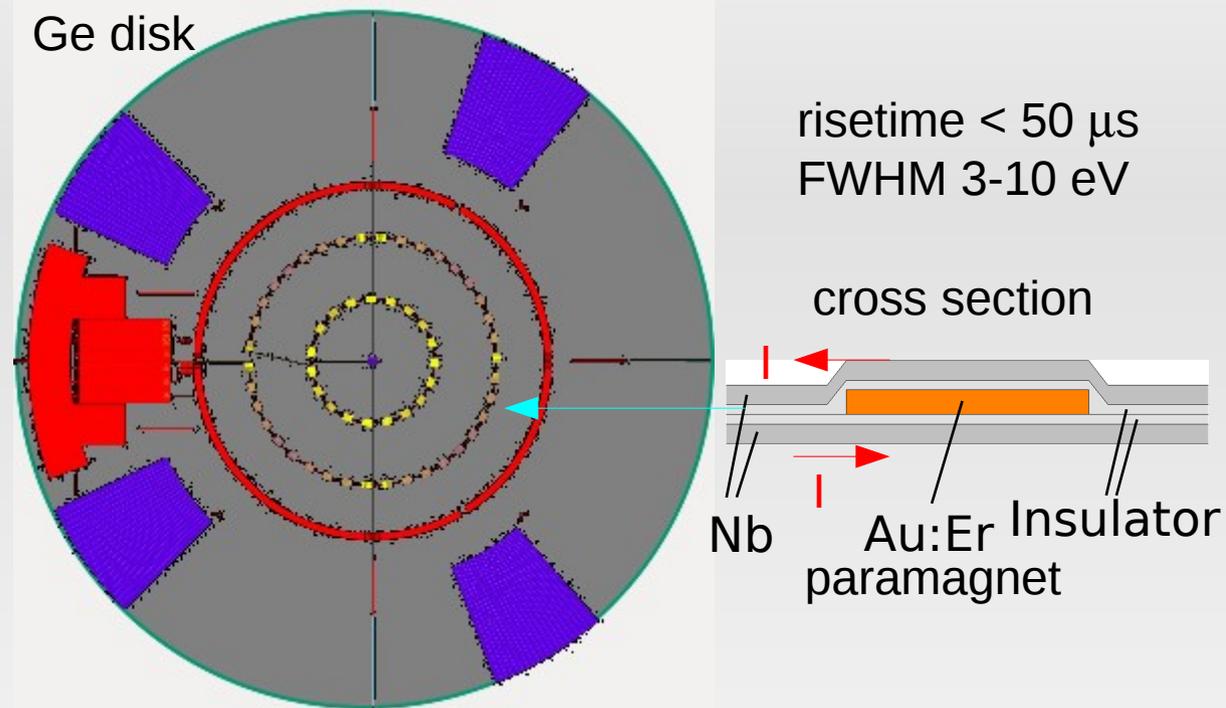
NTD-Ge baseline for photon and
phonon channel

MMC R&D for photon channel

MMC readout

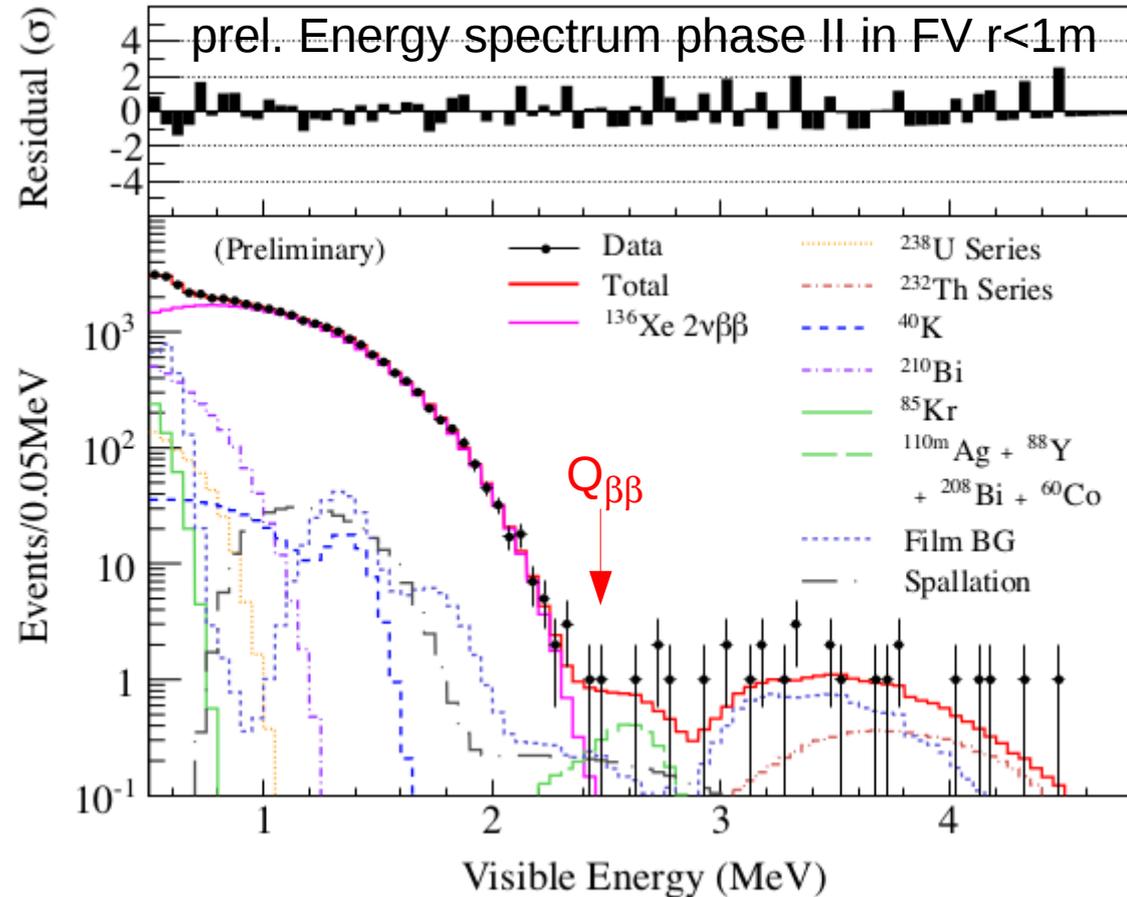
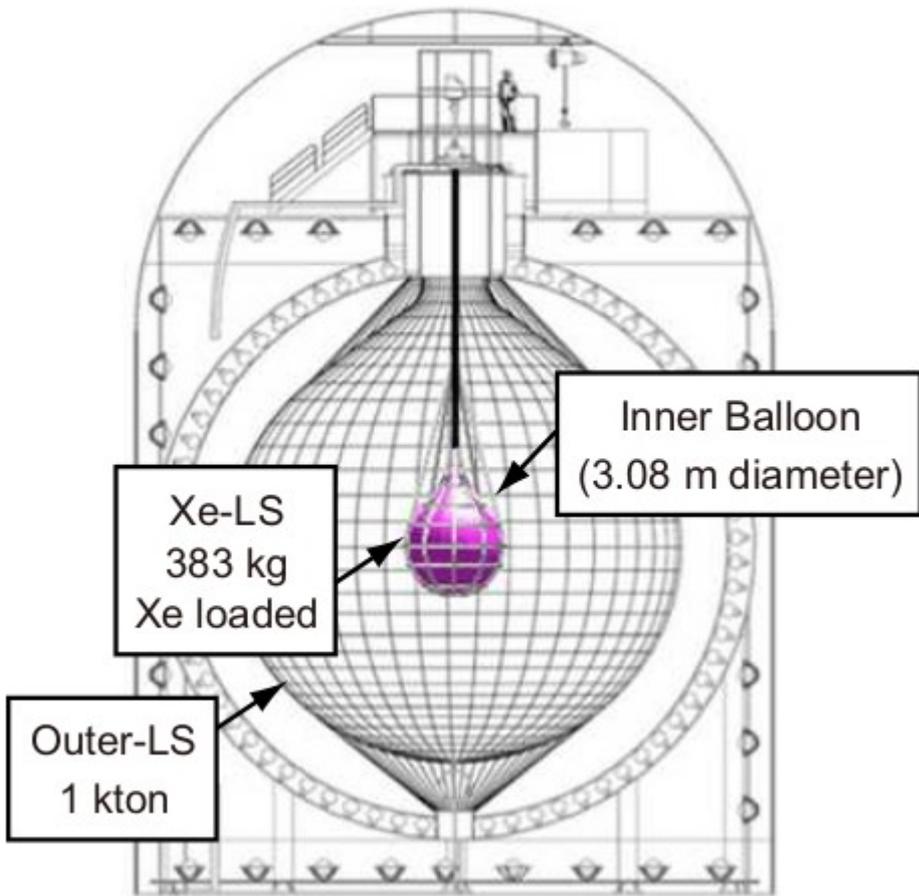


next generation **photon MMC** from KIP



currently first cool down

Kamland-Zen



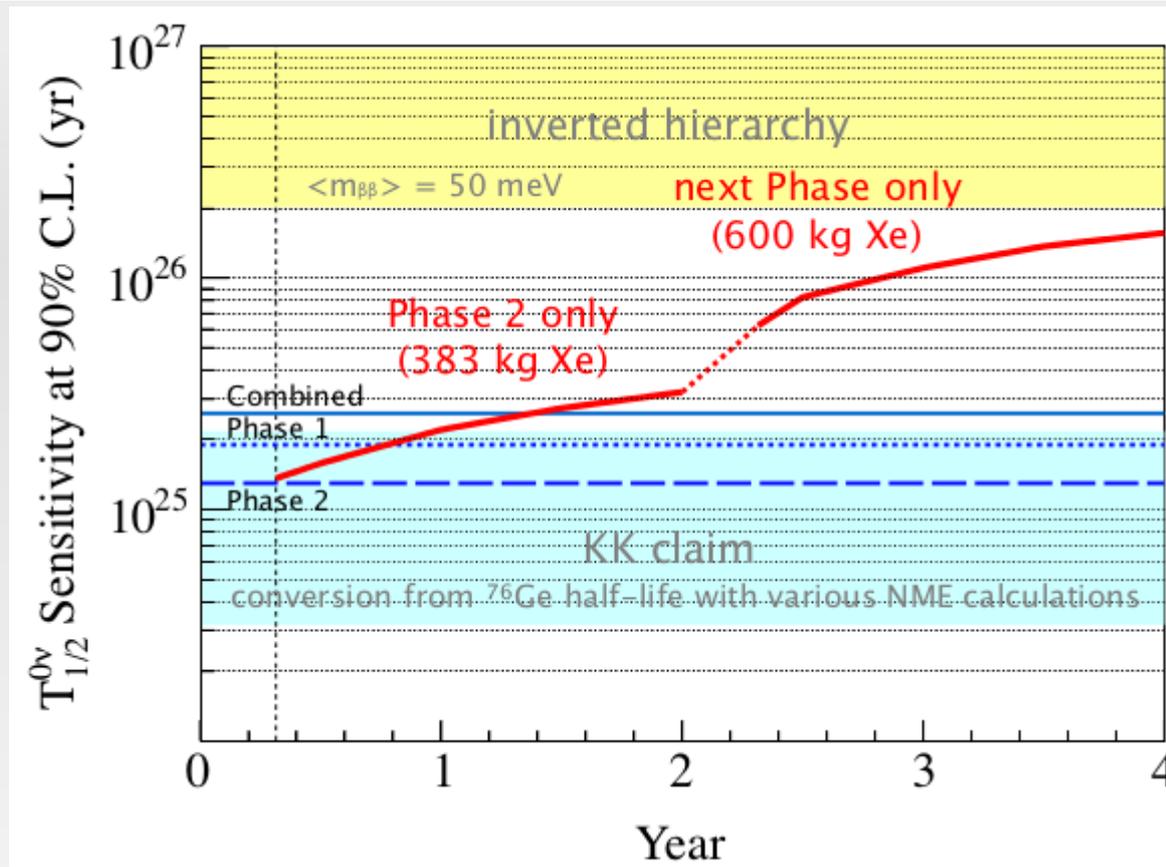
start 2011 (phase I): large background at $Q_{\beta\beta}$

most likely explanation: fall out of $^{110\text{m}}\text{Ag}$ from Fukushima on inner balloon

2012-13: purifications of scintillator and Xe

Dec 2013: start of phase II \rightarrow $^{110\text{m}}\text{Ar}$ background factor 10 reduced, Xe loading 2.44% \rightarrow 2.96%

Kamland-Zen



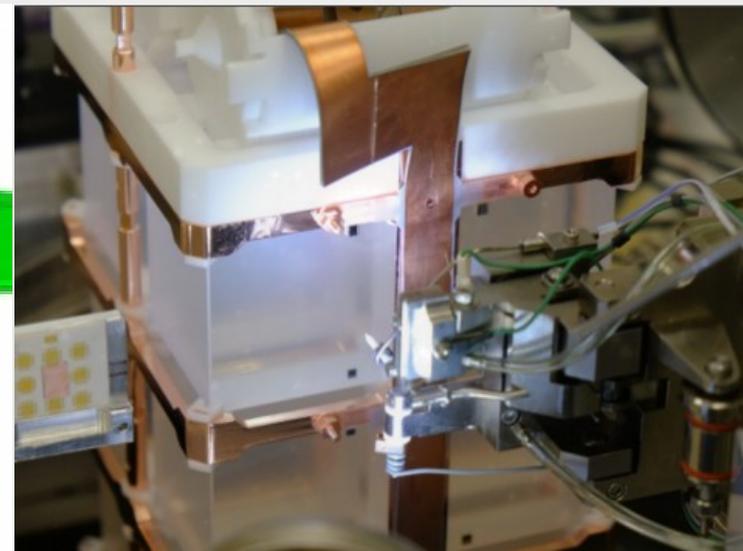
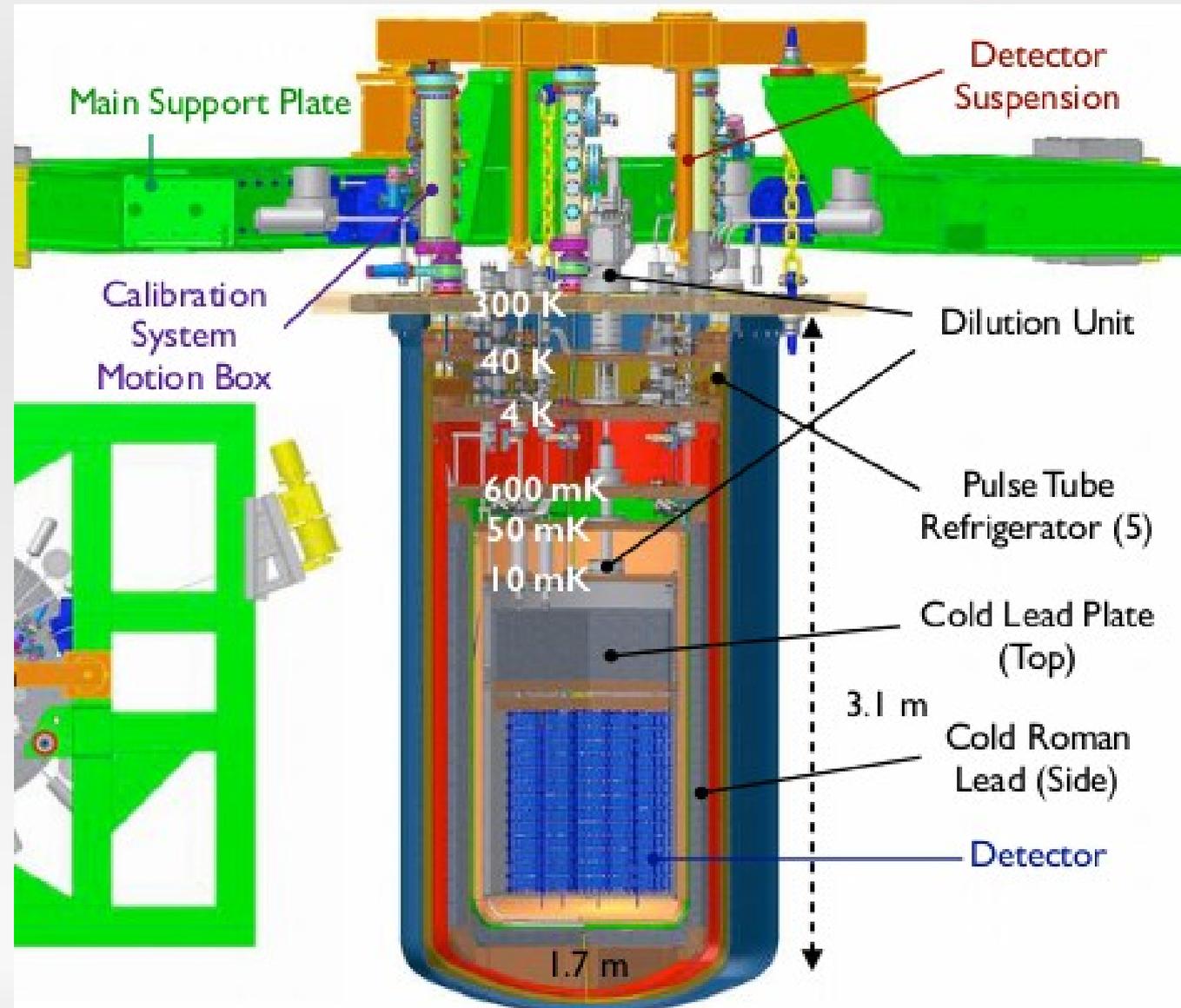
phase I: $T_{1/2} > 1.9 \cdot 10^{25}$ yr (90% CL), sensitivity $1.0 \cdot 10^{25}$ yr (PRL 110 (2013) 062502)

preliminary phase II (Dec 13- May 14): $T_{1/2} > 1.3 \cdot 10^{25}$ yr (90 % CL), sensitivity $1.3 \cdot 10^{25}$ yr
arXiv:1409.0077

next phase: rebuild mini-balloon, 600 kg ^{136}Xe

Kamland2-Zen: more light 5x, more than 1000 kg ^{136}Xe

Cuore

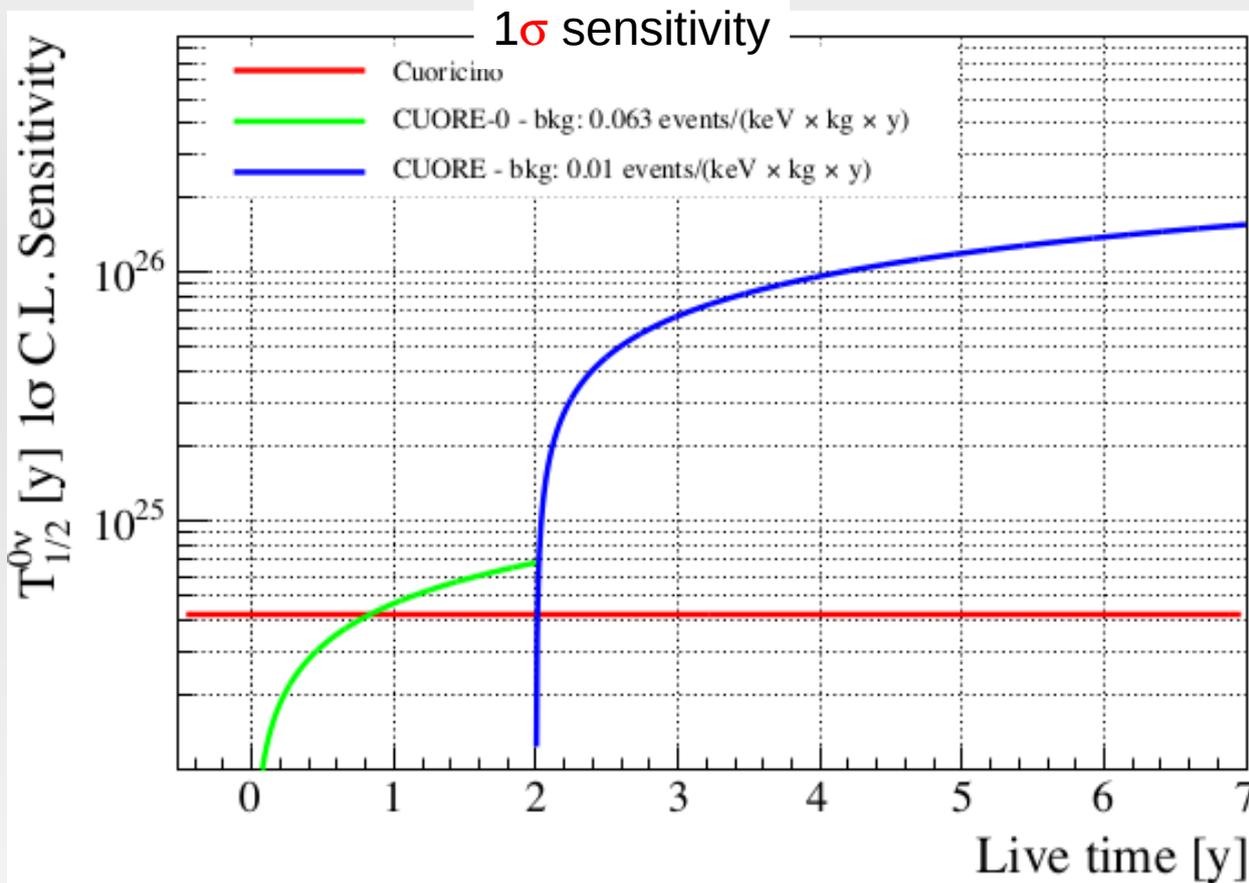


988 $^{nat}\text{TeO}_2$ crystals, 19 towers,
206 kg ^{130}Te ,
bolometer with Ge NTD readout

Cuore-0: 1 tower runs since 3/13
new cleaning \rightarrow α bkg factor 6
lower than Cuoricino

all towers assembled!
currently cool down of cryostat

Cuore



start in 2015

FWHM \sim 5 keV

background 0.01 cnt/(keV kg yr)

4 yr sensitivity 9.5 10^{25} yr (90% C.L.)

beyond CUORE:

- use of enriched Te
- Cherenkov light detection (arXiv:1407.6516) to reject α surface events

Comparison sensitivities

Current experiments and future experiments/proposals

		mass [kg]* (total/FV)	FWHM [keV]	background& [cnt/mol yr FWHM]	$T_{1/2}$ limit [10^{25} yr] after 4 yr	$\langle m_{ee} \rangle$ limit [meV]	date
Gerda II	Ge	35/27	3	0.0004	15	80-190	-2019
MajoranaD	Ge	30/24	3	0.0004	15	80-190	-2019
EXO-200	Xe	170/80	88	0.03	6	80-220	-2019
Kamland-Zen	Xe	383/88 (600/?)	250	0.03	20	44-120	-2018
Cuore	Te	600/206	5	0.02	9	50-200	-2019
SNO+	Te	2340/160	270	0.02	9	50-200	-2020
Kaml.2-Zen	Xe	1100/?	140	?	130	17-50	2019-24
nEXO	Xe	5000/4300	58	0.0007	600 (3000) ^{\$}	8-22 (4-10)	?

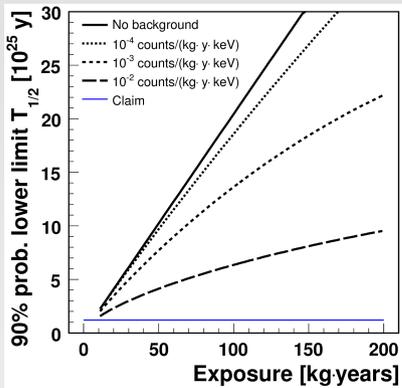
* total= element mass, FV= $0\nu\beta\beta$ isotope mass in fiducial volume (incl enrichment fraction)

& mol of $0\nu\beta\beta$ isotope in active volume and corrected for $0\nu\beta\beta$ efficiency

^{\$} assuming 10 years with 90% efficiency Ba tagging

Summary

claim of $0\nu\beta\beta$ signal by Klapdor-Kleingrothaus not confirmed by GERDA or Xe experiments (99% exclusion)



of current experiments only GERDA + MajoranaDemo.
plan to be "background free"
→ a 30 kg Ge experiment has similar sensitivity as others with >150 kg (total) mass

many experiments start next year → new results coming soon

many ideas for next generation exp. and new ideas constantly come up: liquid+gas Xe TPC, tonne-scale Ge, scintillating bolometers, liquid scint.