Neutrinoless double beta decay with ^{76}Ge

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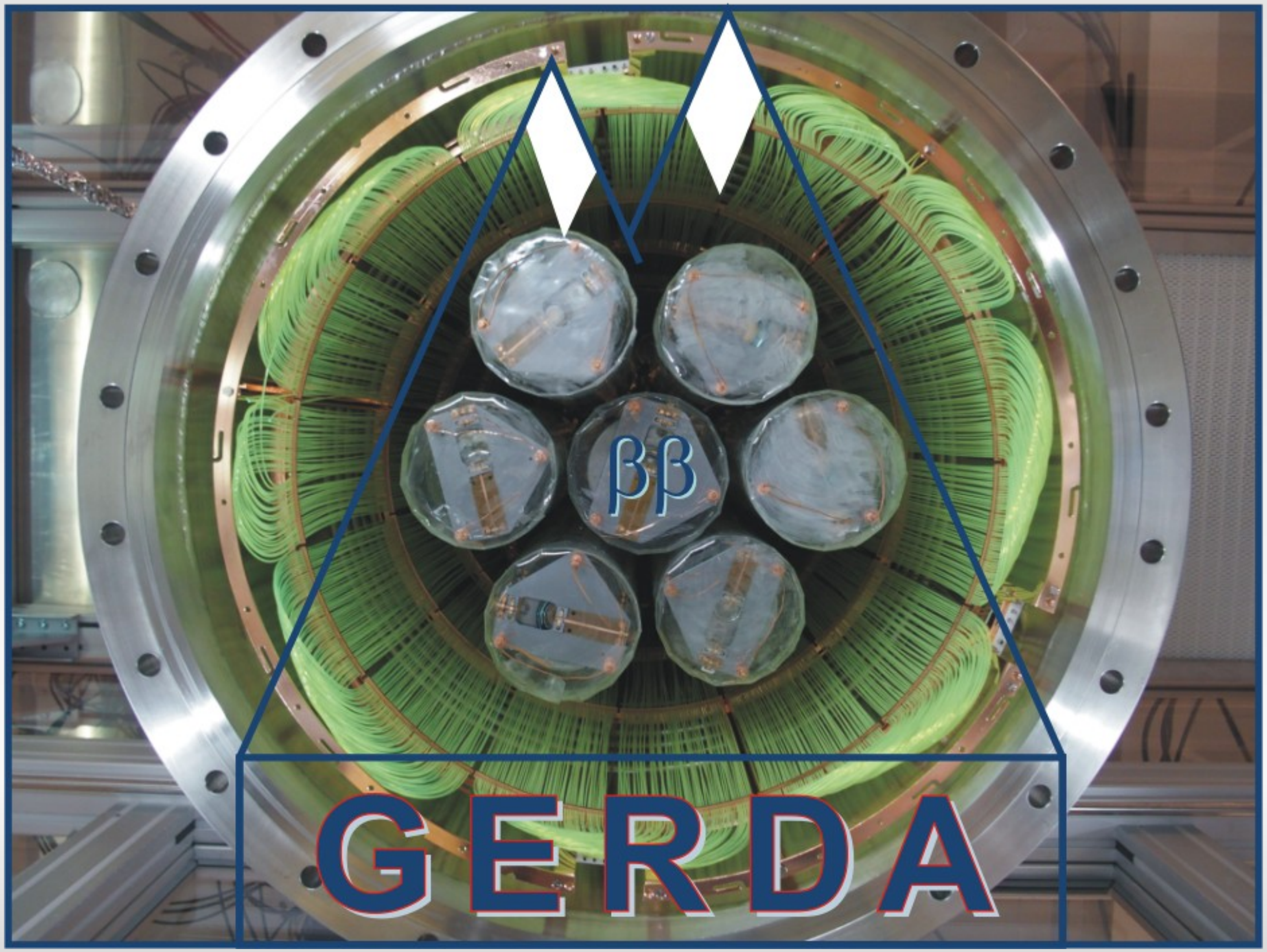
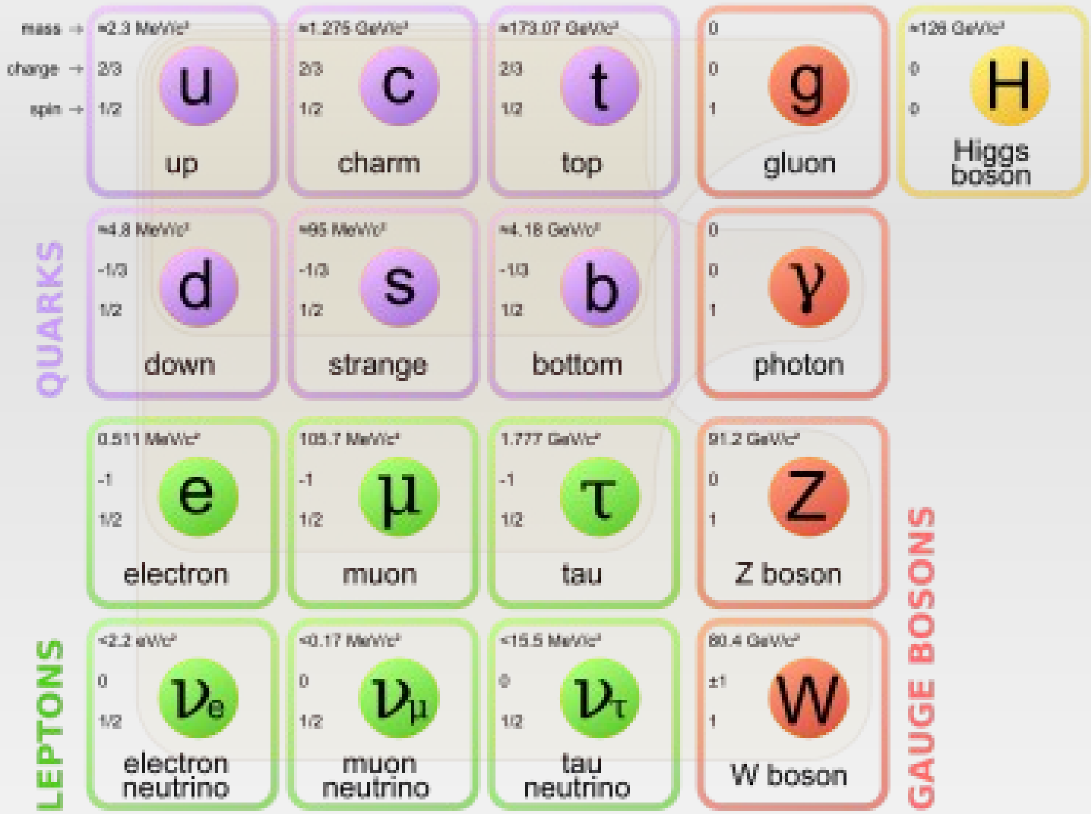


Standard Model



no new physics found at the LHC so far, SM could be valid up to Planck scale

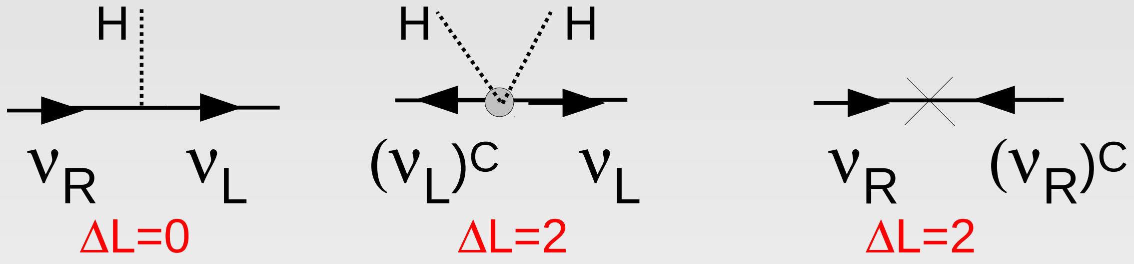
BUT

- no dark matter candidate
- baryon asymmetry of the universe not explained
- dark energy not understood
- origin of (tiny) neutrino mass unknown, $m_\nu < 10^{-6}\ m_e$

Neutrino mass: non-SM effect?

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)

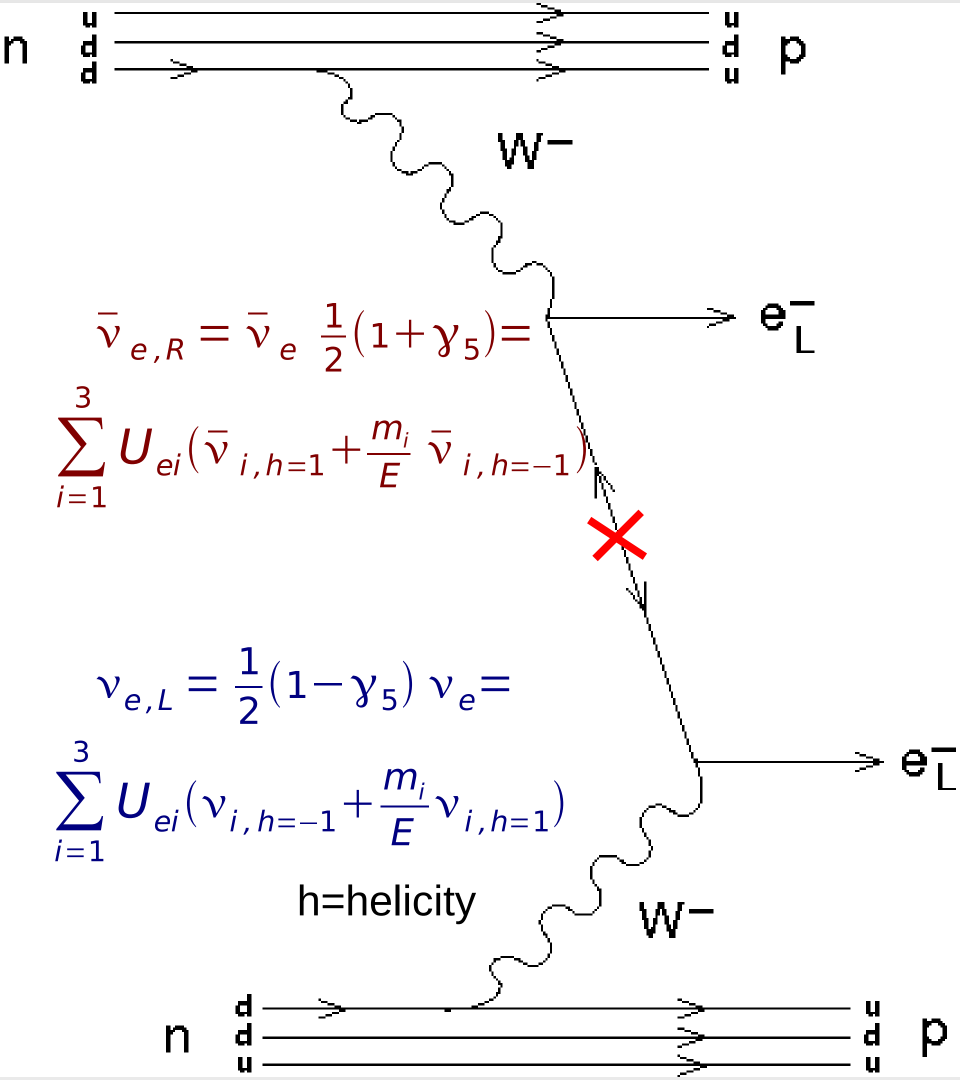
m_D ~ normal Dirac mass term

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 ($m_L \sim 0$)	m_R	m_D^2 / m_R	

How to observe ΔL=2: 0νββ

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



$$\bar{\nu}_{e,R} = \bar{\nu}_e\,\frac{1}{2}(1+\gamma_5) = \sum_{i=1}^{3} U_{ei}\left(\bar{\nu}_{i,h=1} + \frac{m_i}{E}\,\bar{\nu}_{i,h=-1}\right)$$

$$\nu_{e,L} = \frac{1}{2}(1-\gamma_5)\,\nu_e = \sum_{i=1}^{3} U_{ei}\left(\nu_{i,h=-1} + \frac{m_i}{E}\nu_{i,h=1}\right)$$

h=helicity

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

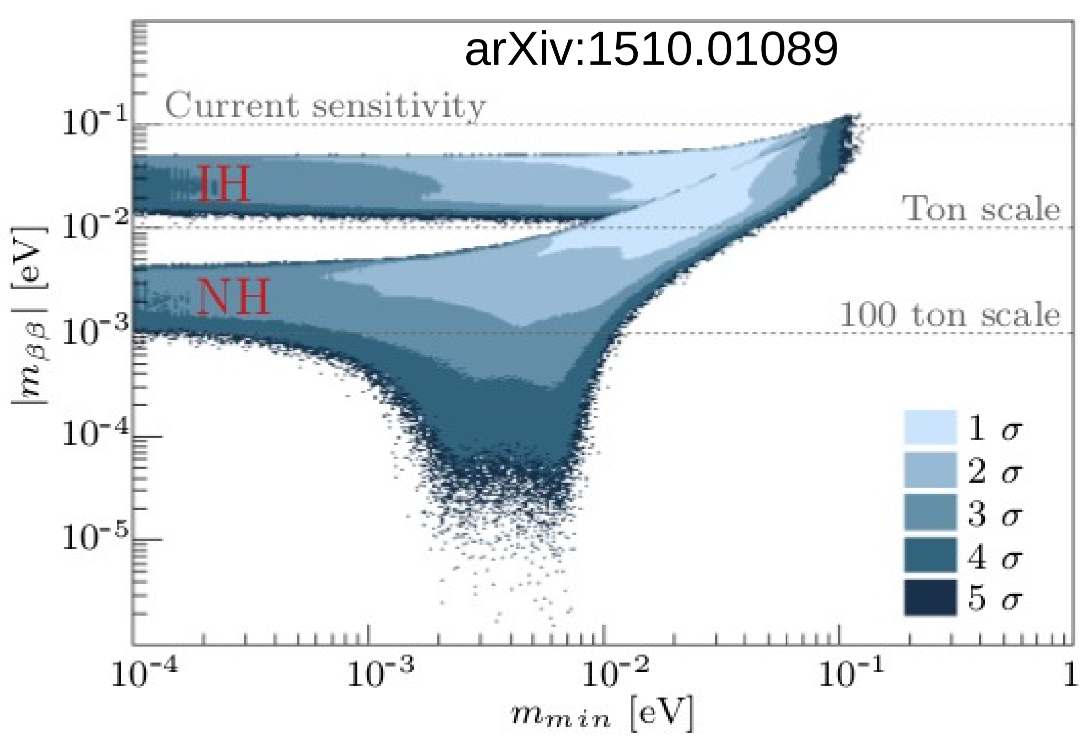
function of
- neutrino mixing parameters
- lightest neutrino mass
- 2 Majorana phases

also possible: heavy N exchange

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

Light Majorana neutrino exchange

scan of $m_{\beta\beta}(\Delta m_{atm}^2, \Delta m_{sol}^2, m_{min}, \theta_{atm}, \theta_{sol}, \theta_{13}$, 2 Majorana $\Phi)$
according to measurements or random (2 Maj. phases)



arXiv:1510.01089

unless Majorana phases ”aligned”
high $m_{\beta\beta}$ values are more likely

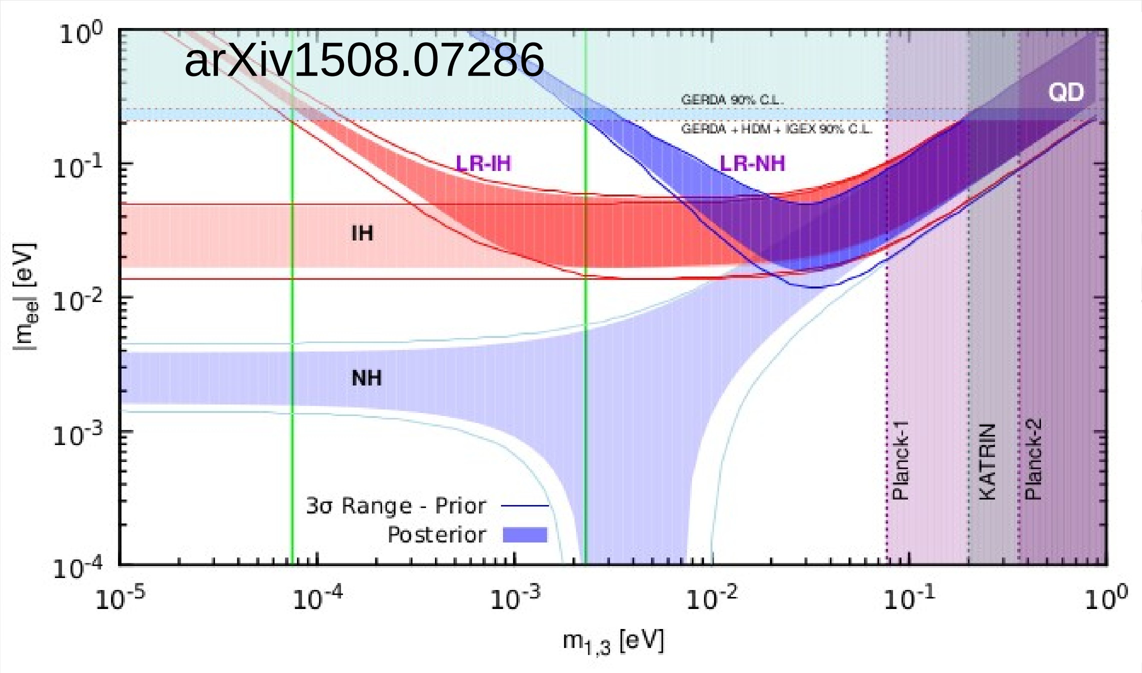
including cosmological bound Σ = (22±62) meV[1]

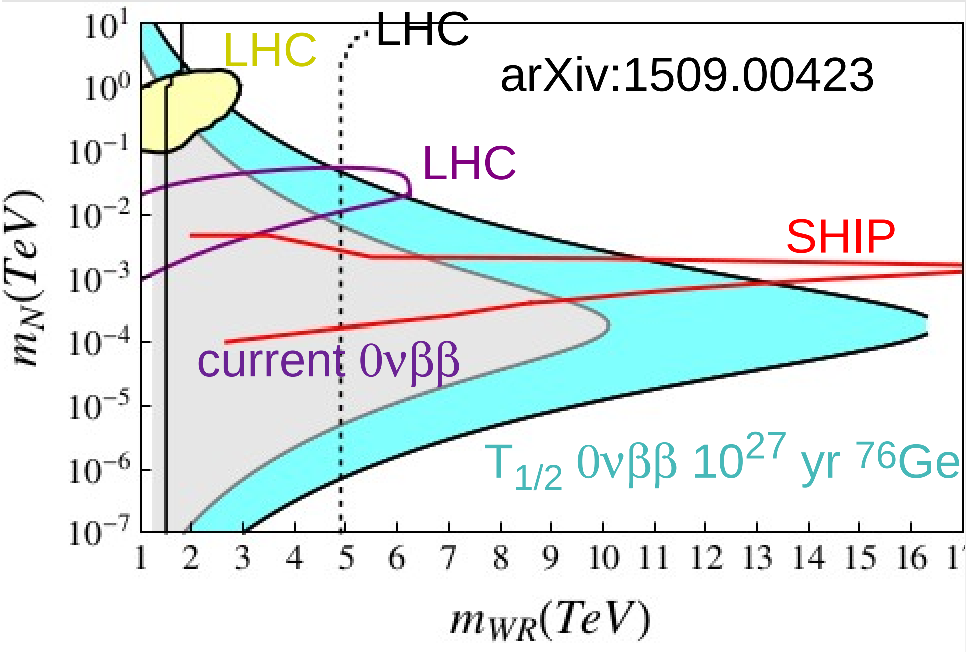
[1] true for flat ΛCDM only

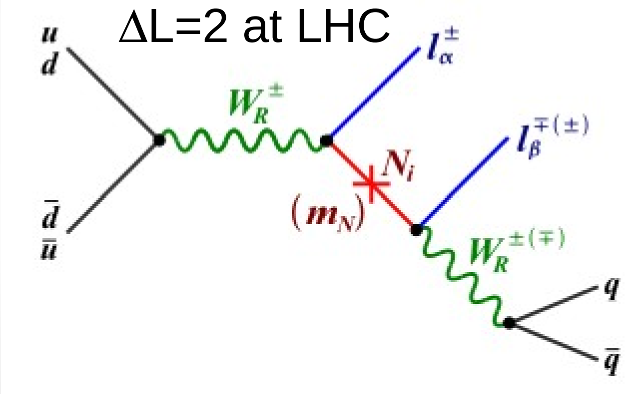
LHC vs 0νββ: other mechanisms

extensions of SM → other contributions to 0νββ possible, example LRSM

LHC might find W_R and/or ΔL=2 process

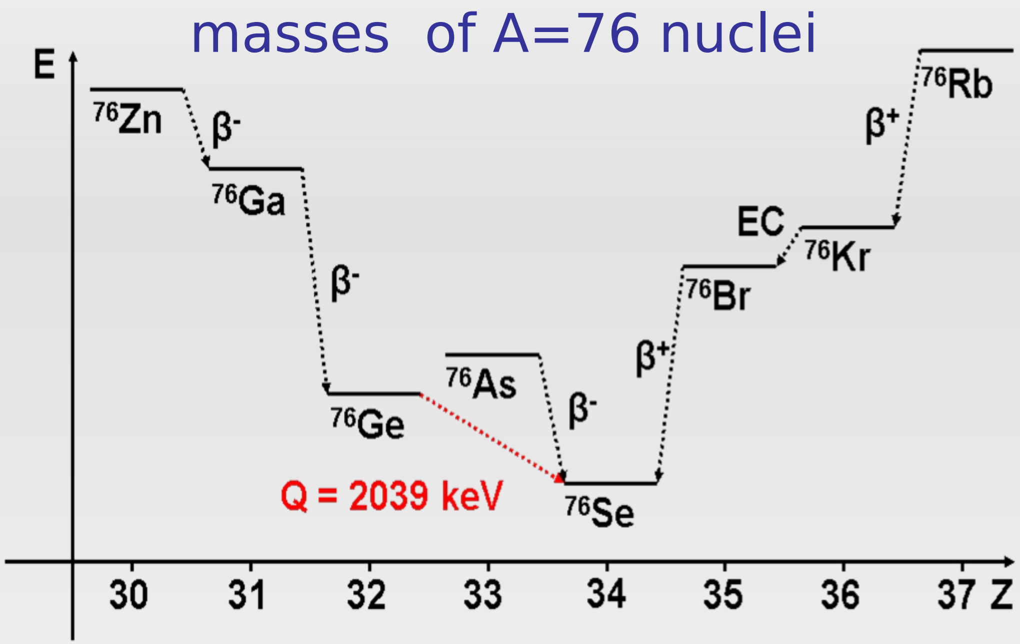




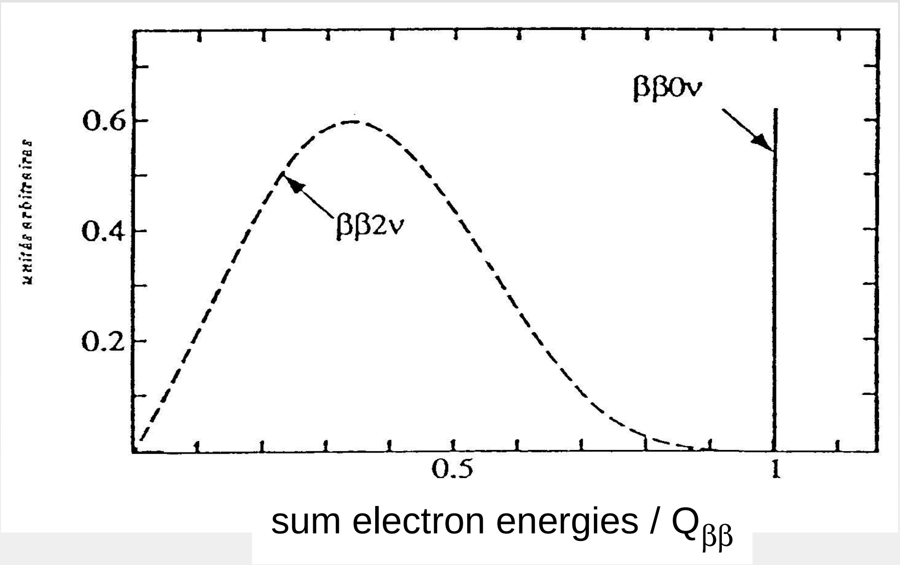


best case: find s.th. at LHC and 0νββ and lepton flavor violation μ → e γ

Neutrinoless double beta decay


masses of A=76 nuclei

experimental signature for ββ



"single" beta decay not allowed

$\longrightarrow$ only "double beta decay"

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

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

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

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

From $T_{1/2}$ to $m_{\beta\beta}$

$$\frac{1}{T^{0\nu}_{1/2}} = g_A^4 G^{0\nu} \left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

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

g_A = axial vector coupl. = 1.25

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

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

m_e = electron mass

need $M^{0\nu}$ to understand physics mechanism

selected 0νββ isotopes from PRD 83 (2011) 113010

Isotope	$G^{0\nu}$ [10^{-14}y]	Q[keV]	nat. abund.[%]
^{48}Ca	2.5	4273.7	0.187
^{76}Ge	0.23	2039.1	7.8
^{82}Se	1.0	2995.5	9.2
^{100}Mo	1.6	3035.0	9.6
^{130}Te	1.4	2530.3	34.5
^{136}Xe	1.5	2461.9	8.9
^{150}Nd	6.6	3367.3	5.6

enrichment required except for ^{130}Te, not (yet) possible for all, costs differ

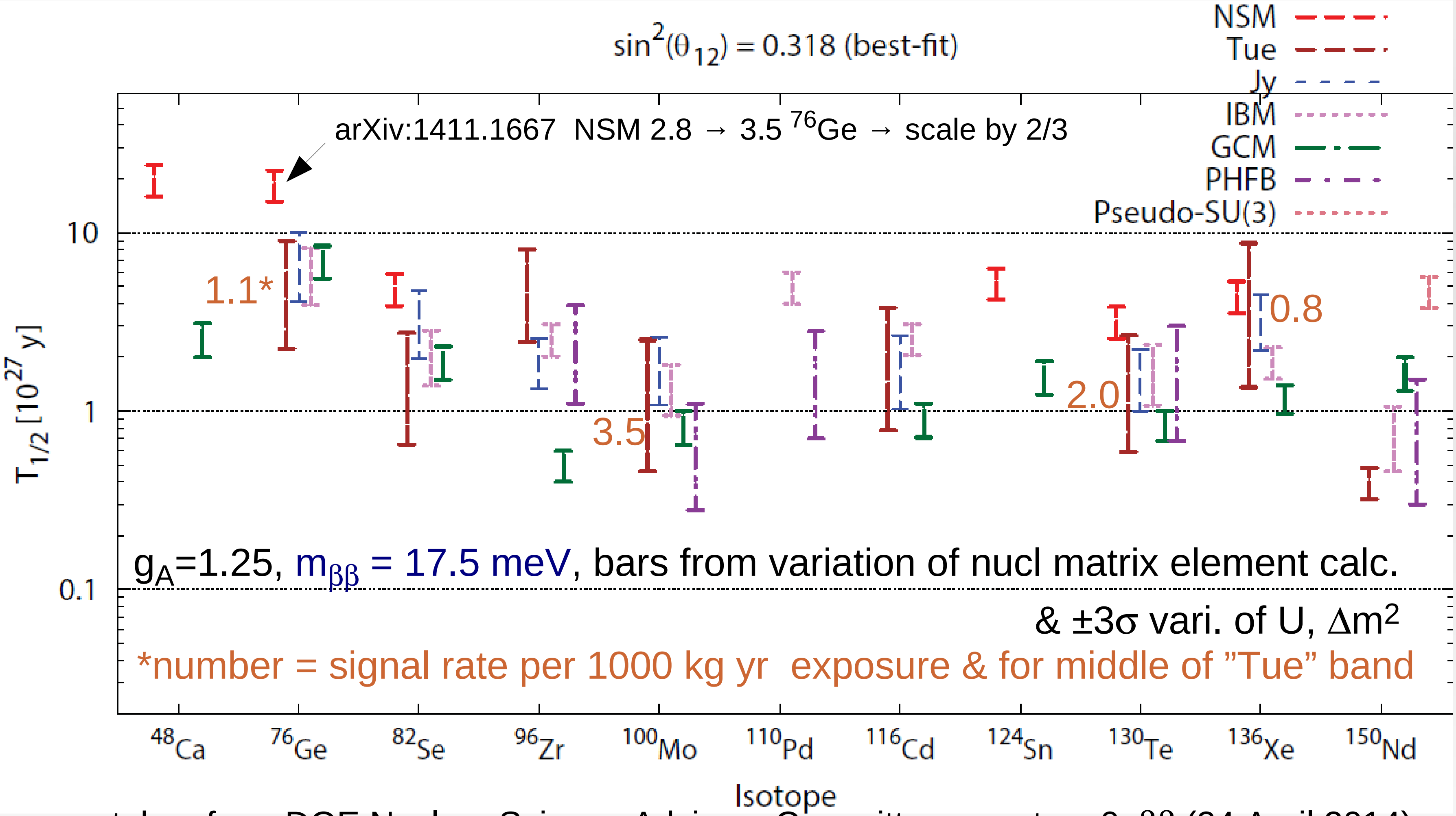
Experiment observes $N^{0\nu} = \ln 2 \frac{N_A}{A} \cdot a \cdot \epsilon \cdot M \cdot t \,/\, T_{1/2}$ and $N^{bkg} = M \cdot t \cdot B \cdot \Delta E$

Experimental sensitivity

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

M = mass of detector
t = measurement time
A = isotope mass per mole
N_A= Avogadro constant
a = fraction of 0νββ isotope
ε = detection efficiency
B = background index in units cnt/(keV kg y)
ΔE = energy resolution = energy window size

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



arXiv:1411.1667 NSM 2.8 → 3.5 ^{76}Ge → scale by 2/3

g_A=1.25, $m_{\beta\beta}$ = 17.5 meV, bars from variation of nucl matrix element calc.

& ±3σ vari. of U, Δm^2

*number = signal rate per 1000 kg yr exposure & for middle of ”Tue” band

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

No clearly favored isotope if spread of NME considered
expect only ~1 event/year for 1000 kg isotope mass

How to reduce background

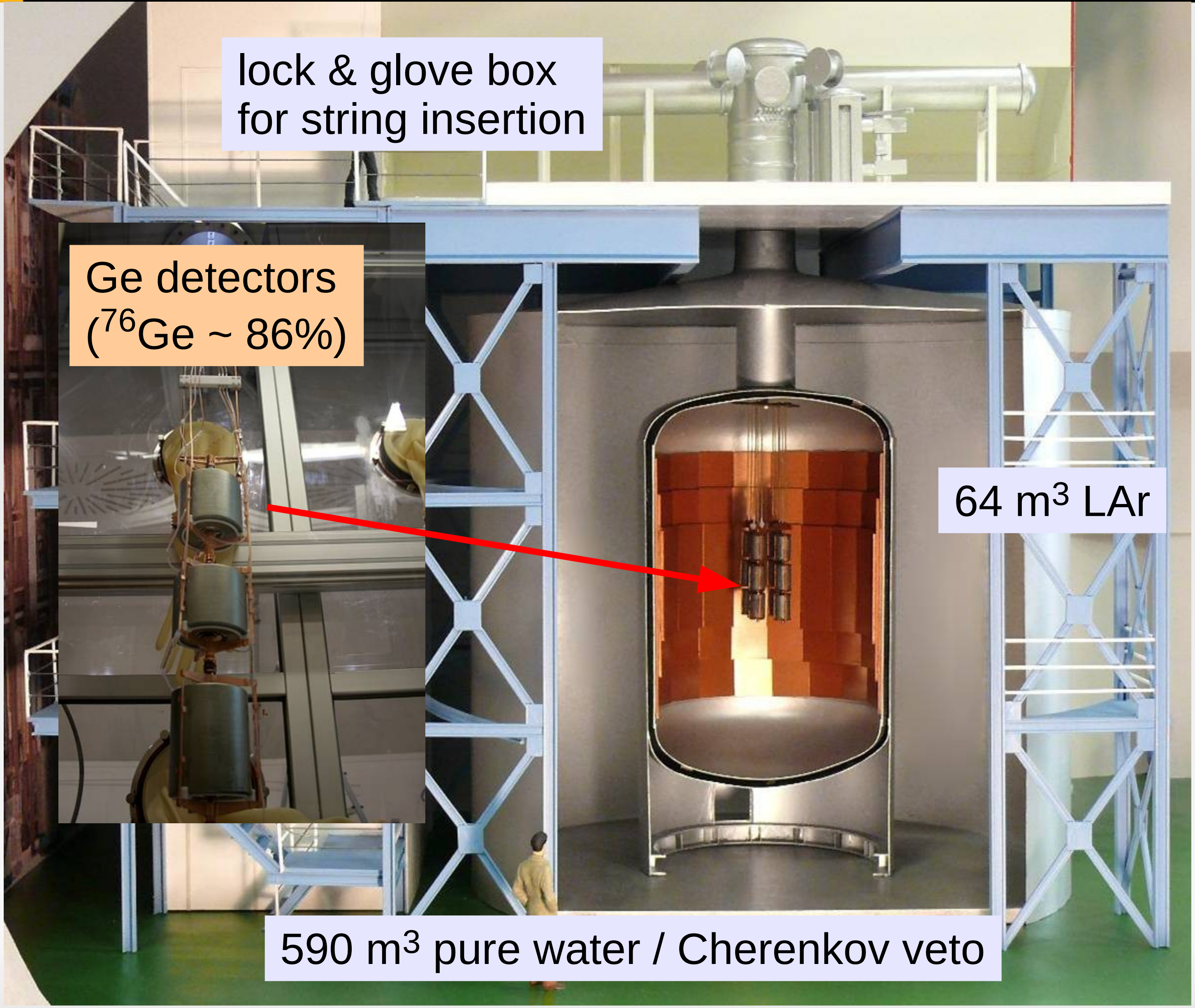
sources: cosmic rays (p,n,μ,γ) → underground like LNGS
neutrons from (α,n) and spallation induced by μ
α,β,γ from radioactive decay chains ^{238}U, ^{232}Th

→ avoid contamination → screen & select materials like cables, holders

→ shield (external) radioactivity → example ^{232}Th activities [μBq/kg]
1000 - steel, <1 - Cu, <1 - water, ~0 liquid argon / org. scintillator

→ 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)

GERDA: Ge in LAr @ Gran Sasso



lock & glove box
for string insertion

Ge detectors
(^{76}Ge ~ 86%)

64 m^3 LAr

590 m^3 pure water / Cherenkov veto

EPJ C73 (2013) 2330

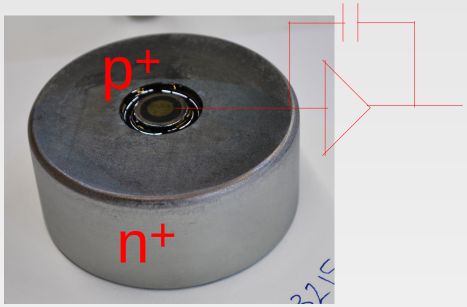
Phase I (2011-13):

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

^{76}Ge 0νββ decay, PRL 111 122503

Phase II:

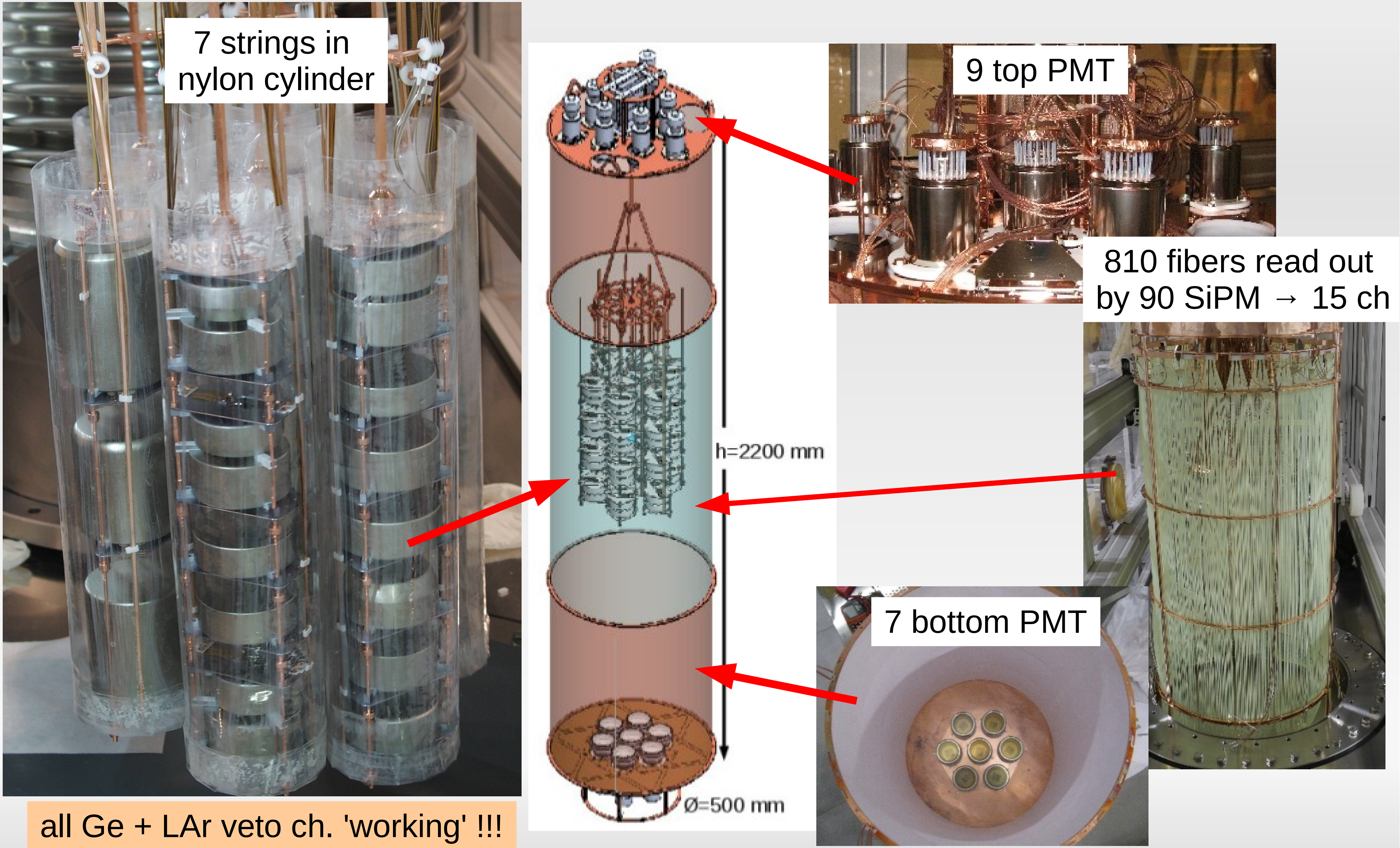
2x Ge mass (30 BEGe det.)



LAr scint. light readout

started end 2015

Phase II start December 2015



7 strings in nylon cylinder

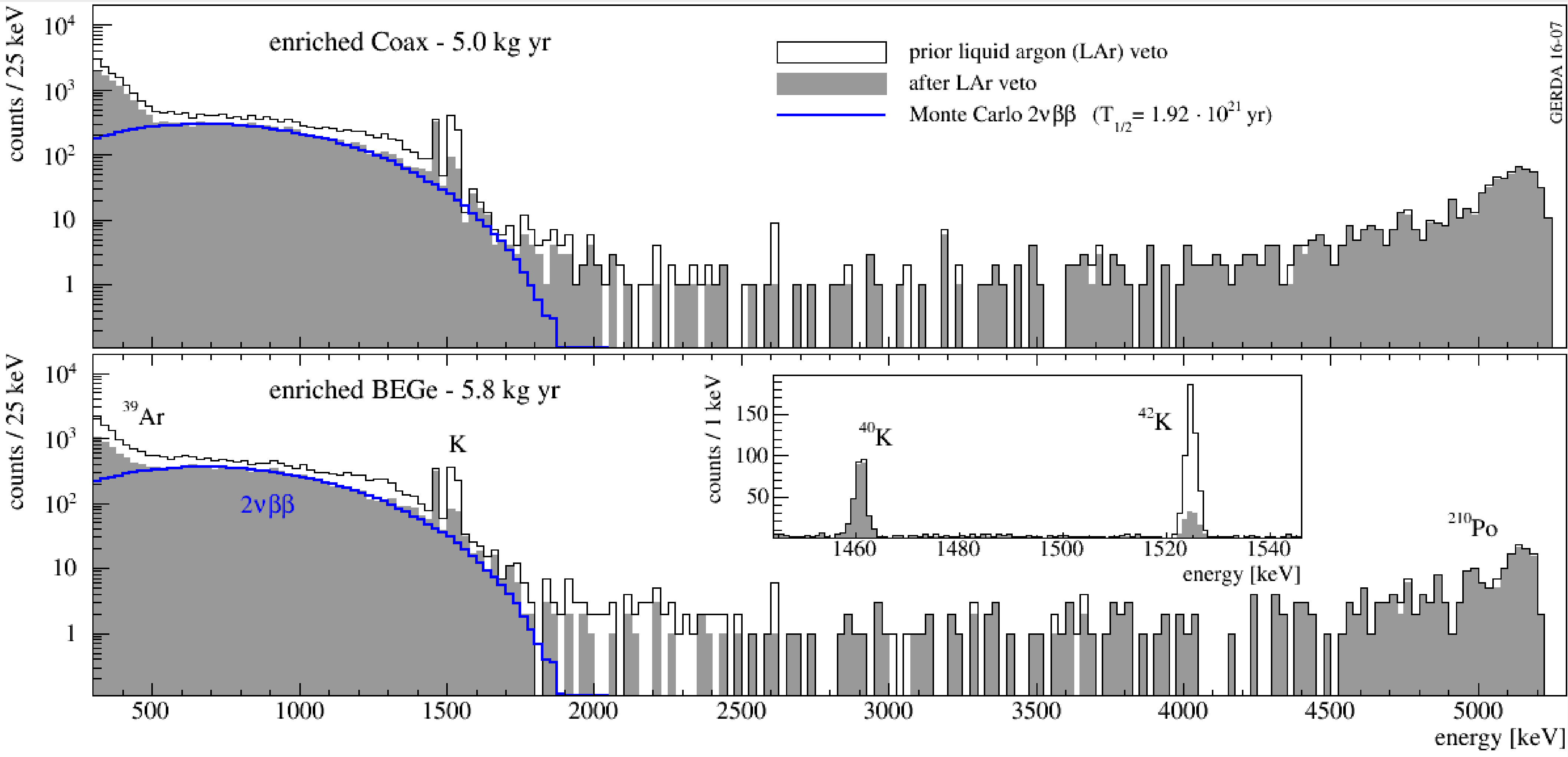
9 top PMT

810 fibers read out by 90 SiPM → 15 ch

7 bottom PMT

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

Background reduction: argon veto

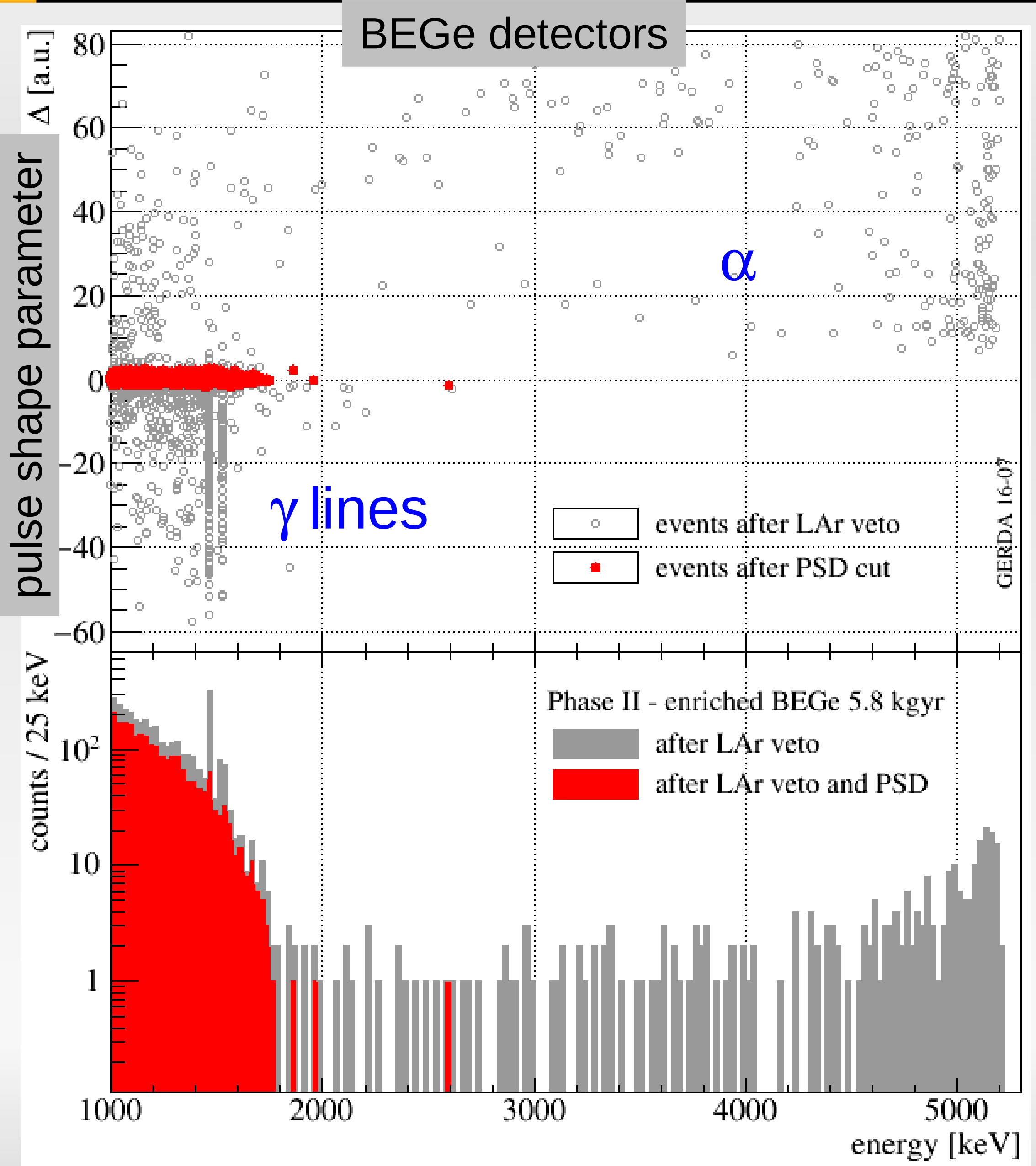


line at 1525 keV from 42K: deposits up to 2 MeV in LAr → factor ~5 suppression

600-1300 keV: ~95% of events are 2νββ after LAr veto → almost clean sample

at $Q_{\beta\beta}$ ~ factor ~2 background reduction (depends on bkg composition, location, ...)

Background red.: det. pulse shape



use time profile of detector signal to

→ identify signal-like evt, proxies = $2\nu\beta\beta$ & Double Escape Peak of 2615 keV γ ($\gamma + A \rightarrow e^+ e^-$ with 2x511 keV escape)

all α (surface) events removed

γ lines suppressed by factor ~6

efficiency

DEP (87.3±0.2±0.8) %

$2\nu\beta\beta$ (85.4±0.8±1.7) %

in fit energy window 1930-2190 keV:

1 evt remains

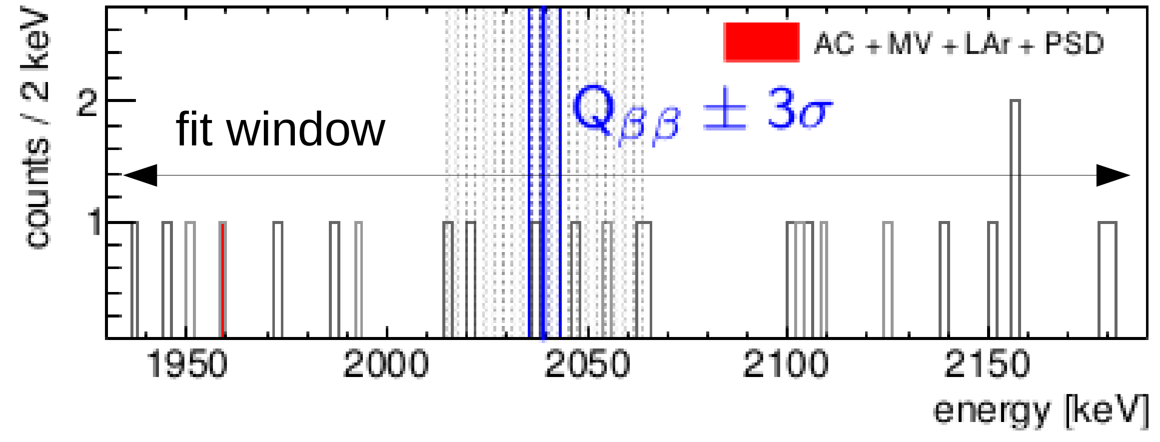
bkg ~ $0.7^{+1.2}_{-0.5}$ x 10^{-3} cnt/(keV kg yr)

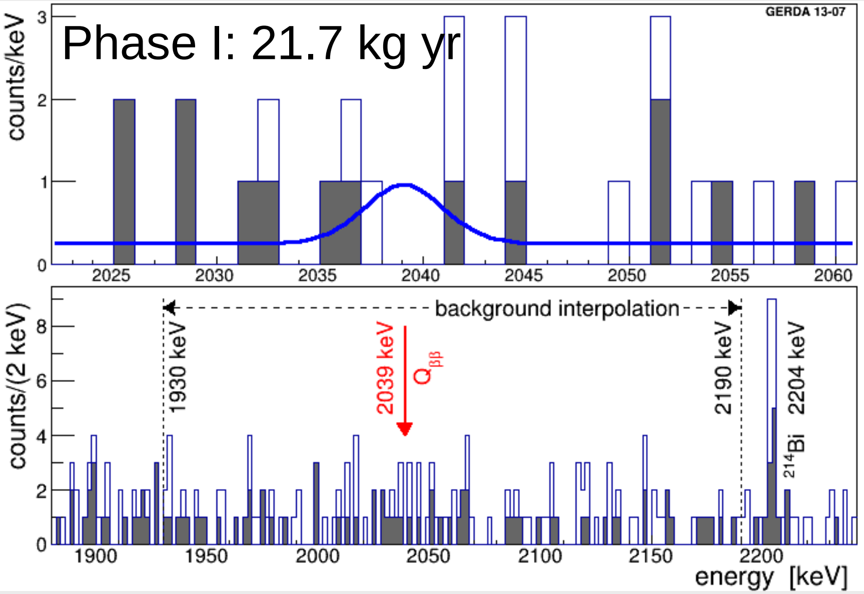
~10x lower than other exp.

reach our background goal!

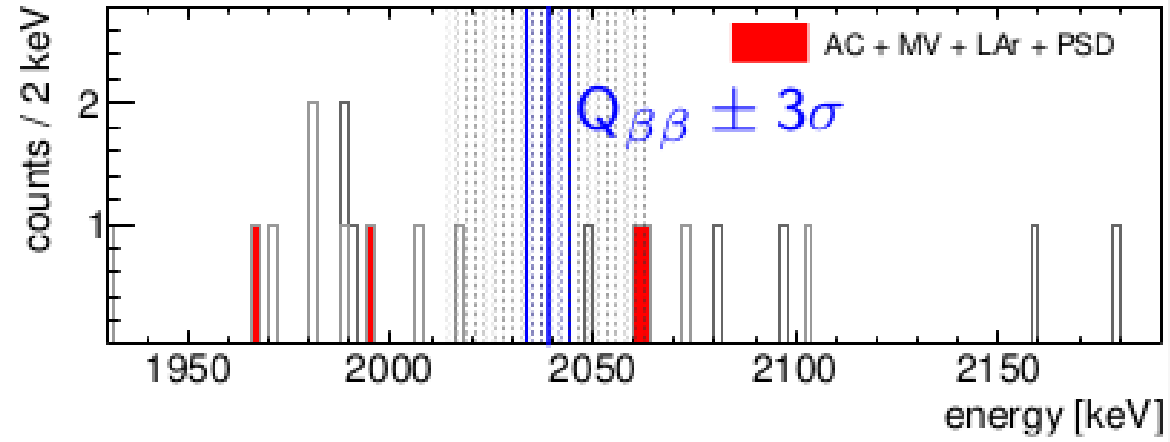
New limit

Phase II BEGe 5.8 kg yr





Phase II coax 5.0 kg yr



$$T^{0\nu}_{1/2} > 5.2 \cdot 10^{25} \text{ yr (90\% C.L.)}$$

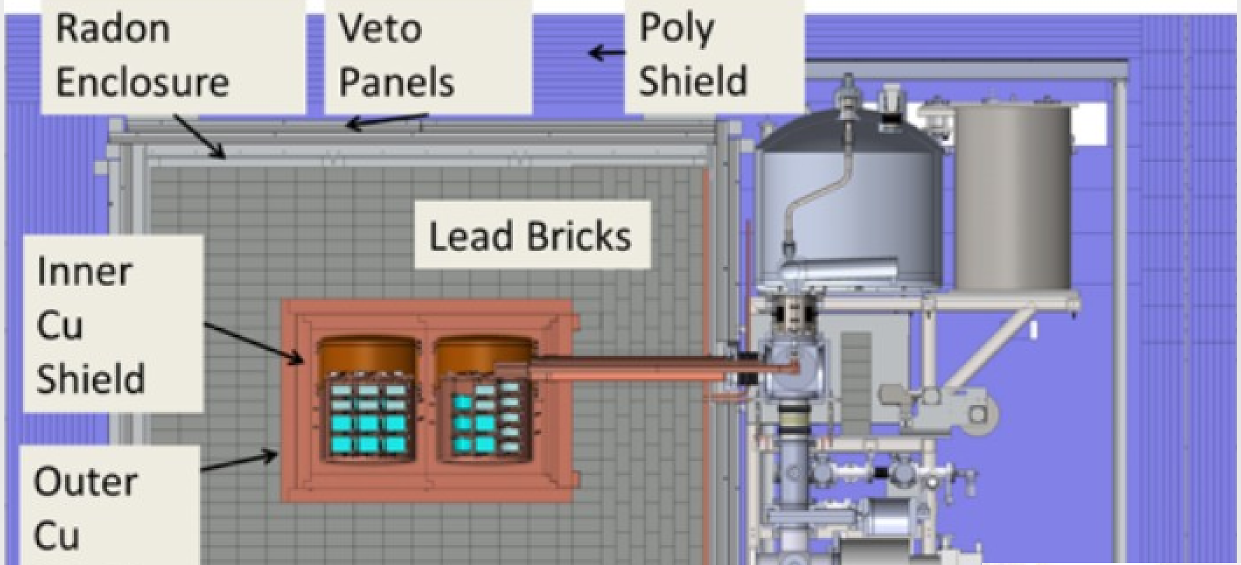
sensitivity = 4.0 10^{25} y

eventually >1 10^{26} yr

first background-free experiment in field
(<1 evt in FWHM until design exposure)

for details see talk of Andrey CHERNOGOROV today at 18.00

Majorana Demonstrator @ SURF



29 kg ^{76}Ge detectors (87% enr) in conventional copper/lead shield (+15 kg ^{nat}Ge detectors)

point-contact detectors →
rejection surface evt + multiple int.

ultra-clean copper (”home made”) + cables + …

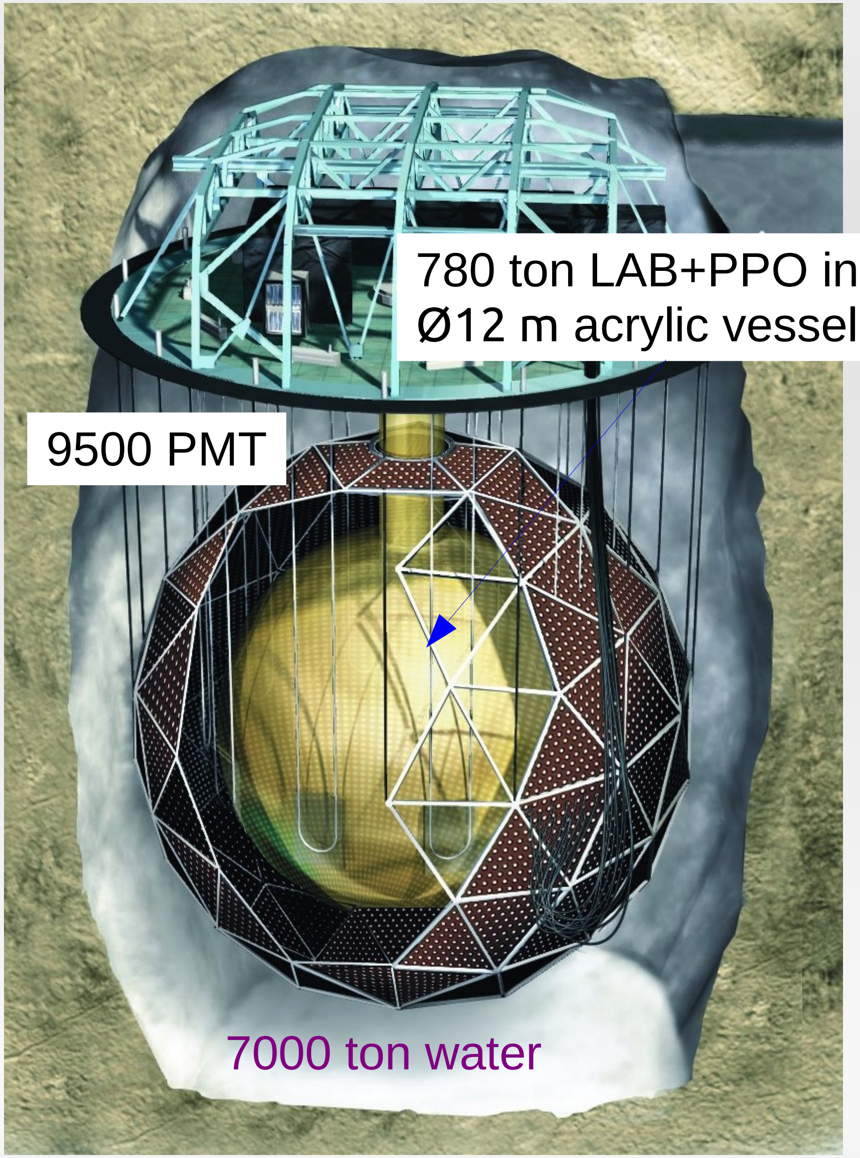
goal: prove design for ton scale

proto-type module:
10 detectors, 2014-2015

Module 1
29 detectors, 2015 first installation
running since Jan 2016

Module 2:
29 detectors, taking data since Aug

SNO+

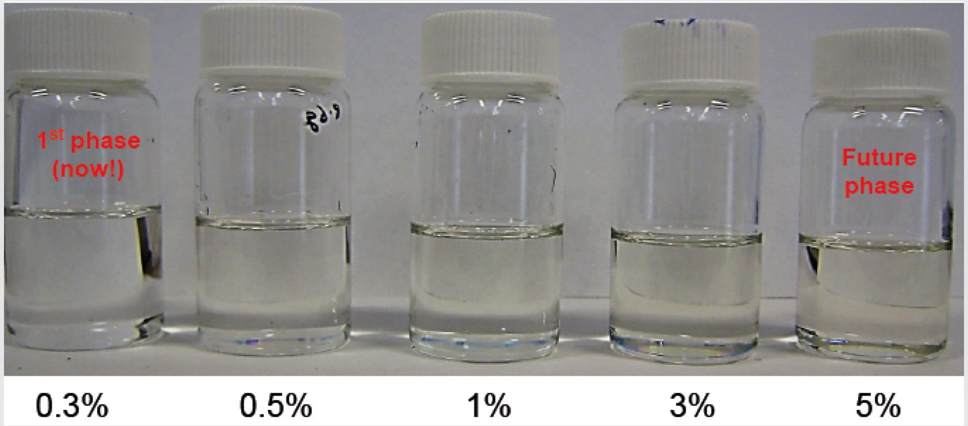


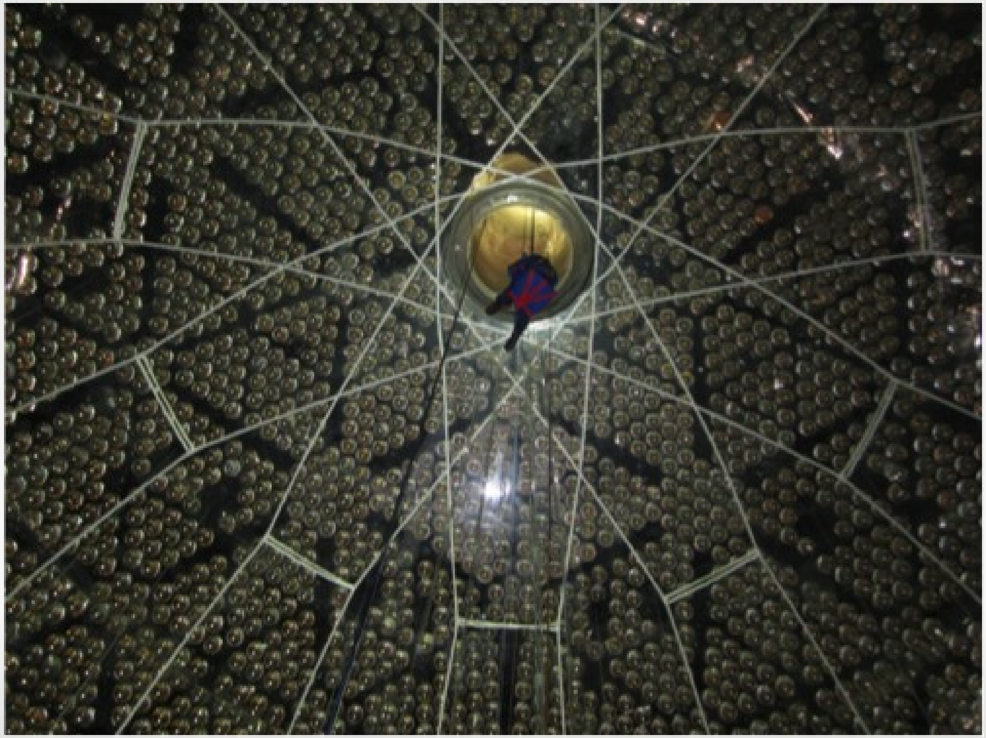
780 ton LAB+PPO in Ø12 m acrylic vessel

9500 PMT

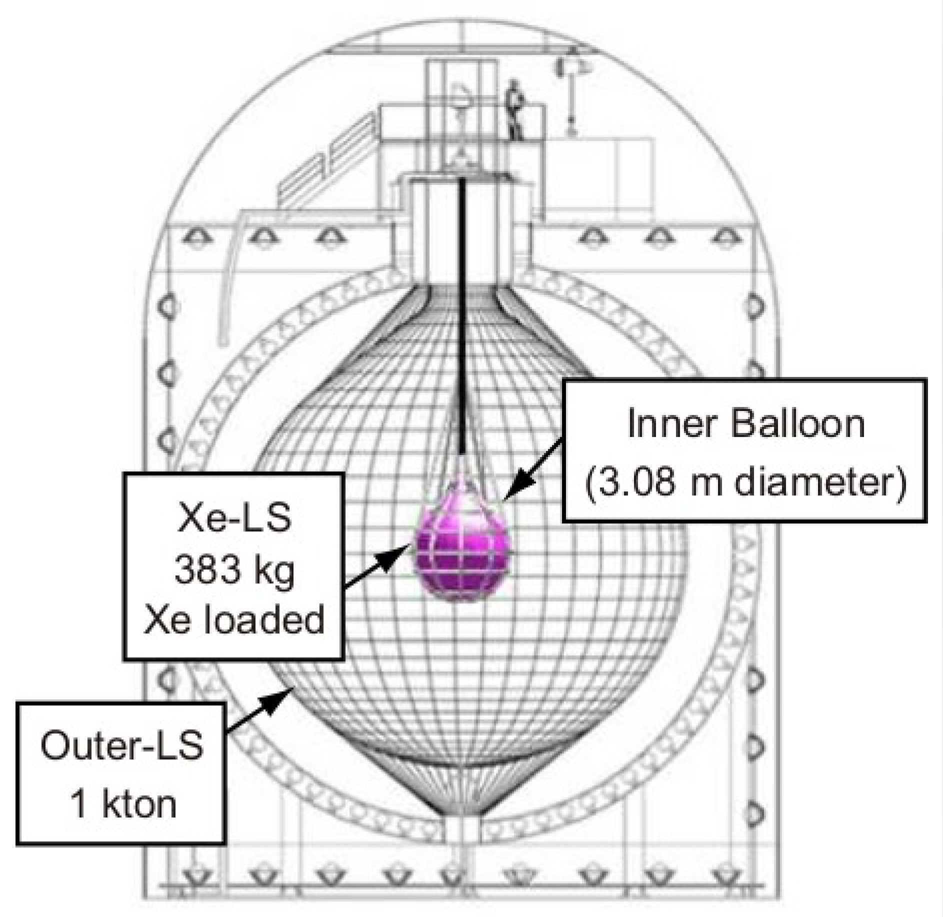
7000 ton water

default: 0.5% loading → 3900 kg ^{nat}Te / 1300 kg ^{130}Te

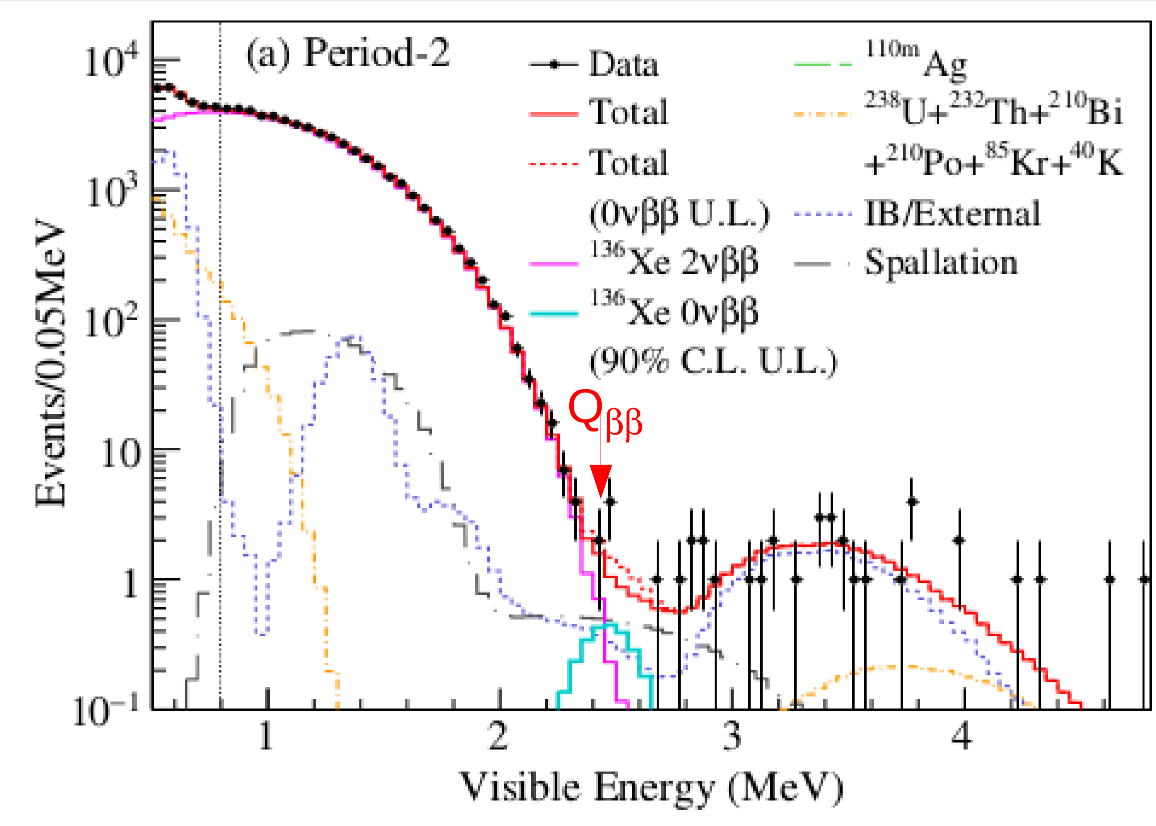




Kamland-Zen



arXiv:1605.02889



start 2011 (phase I): fall out of ^{110m}Ag from Fukushima on inner balloon

2012-13: purifications of scintillator and Xe

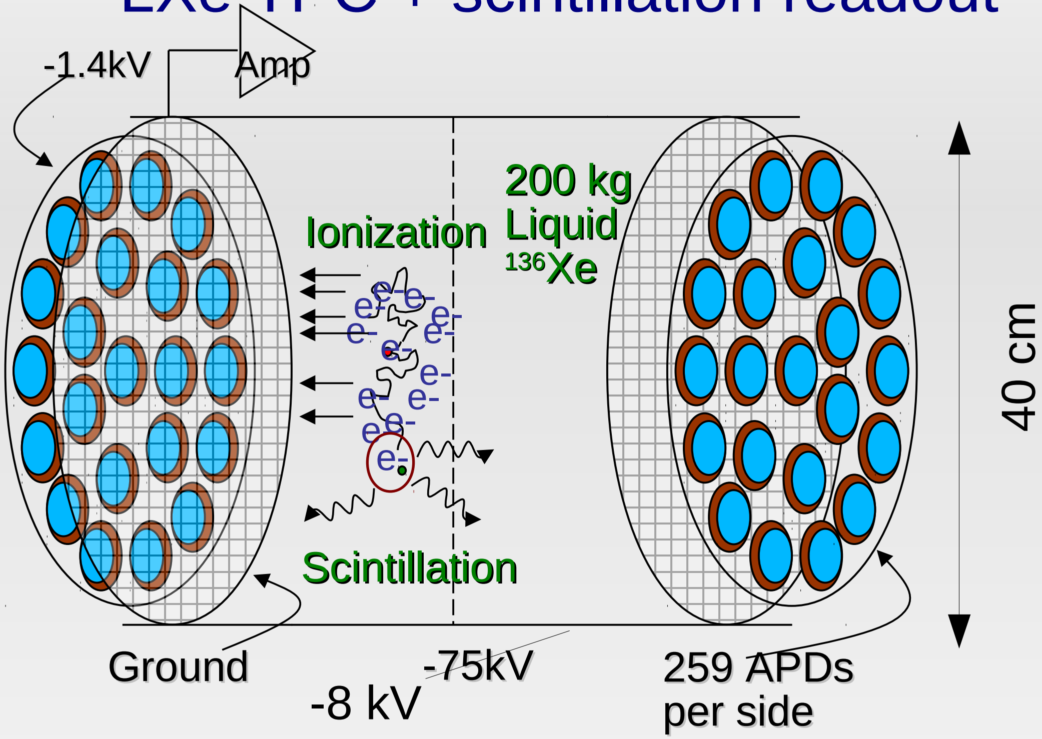
Dec 2013 – Oct 2015: phase II → ^{110m}Ag bkg factor 10 reduced, Xe loading 2.44% --> 2.96%

now: larger & cleaner balloon, loading 380 kg → 750 kg, restart soon, sensitivity $T_{1/2} > 2\ 10^{26}$ yr

current limit for 0νββ of ^{136}Xe: $T^{0\nu}_{1/2} > 10.7\cdot10^{25}$ yr (90% C.L.) sensitivity ~5.6 10^{25} yr

EXO-200 @ WIPP

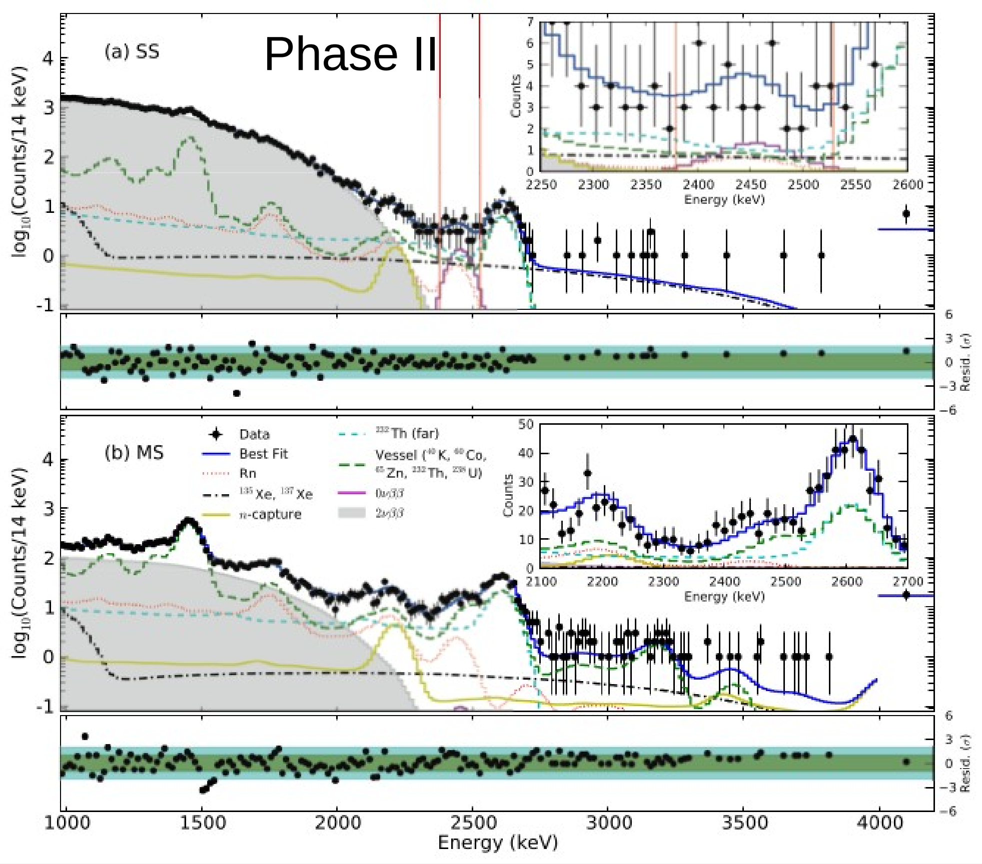
LXe TPC + scintillation readout



light+ionization FWHM for 0νββ ~88 keV @ $Q_{\beta\beta}$

total/fiducial mass 160/100 kg, ^{136}Xe fraction 80.6%

start physics data May 2011,
fire & radiation problem at WIPP → interrupt 2014-15



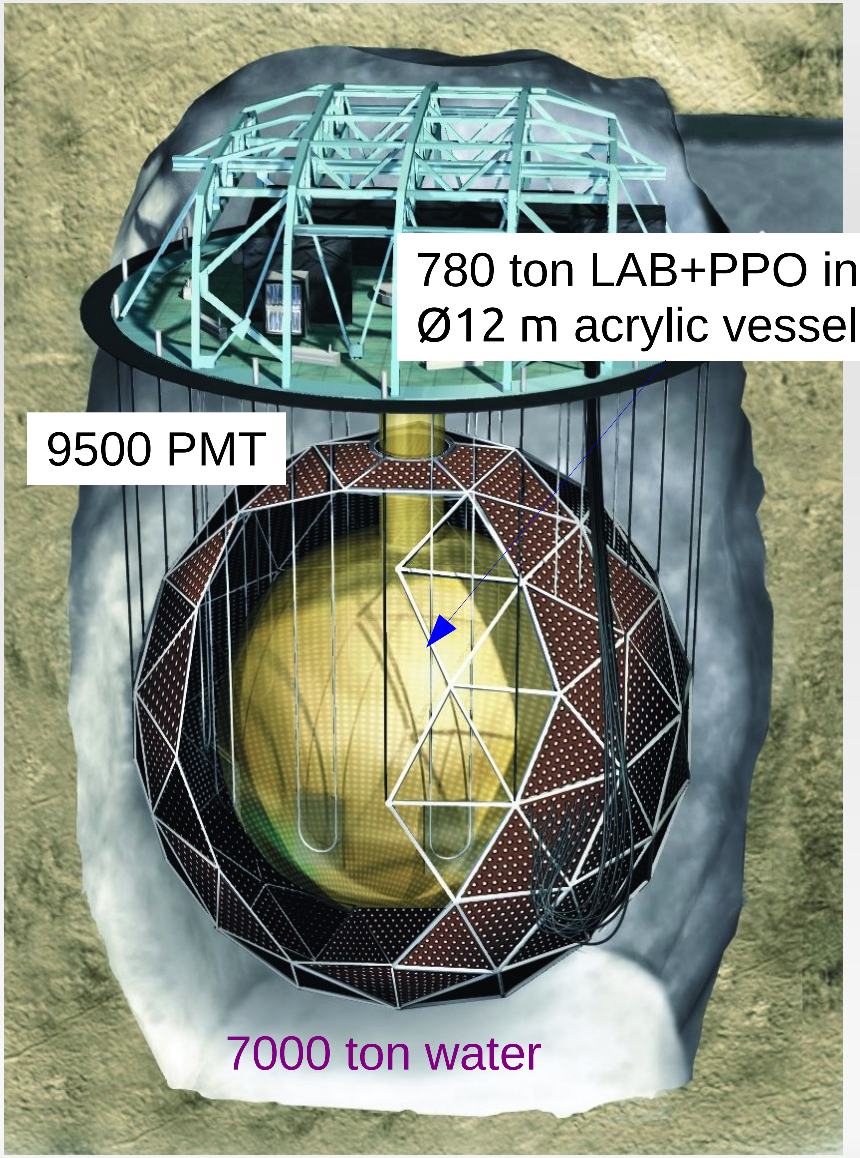
Phase II: Nature 510 (2014) 229-234

find/expect 39/31.1 evt @ $Q_{\beta\beta}$ ±2σ

$$\boxed{T^{0\nu}_{1/2} > 1.1\cdot 10^{25}\ yr\left(@\ 90\ C.L.\right)}$$

(sensitivity 1.9 10^{25} yr)

SNO+

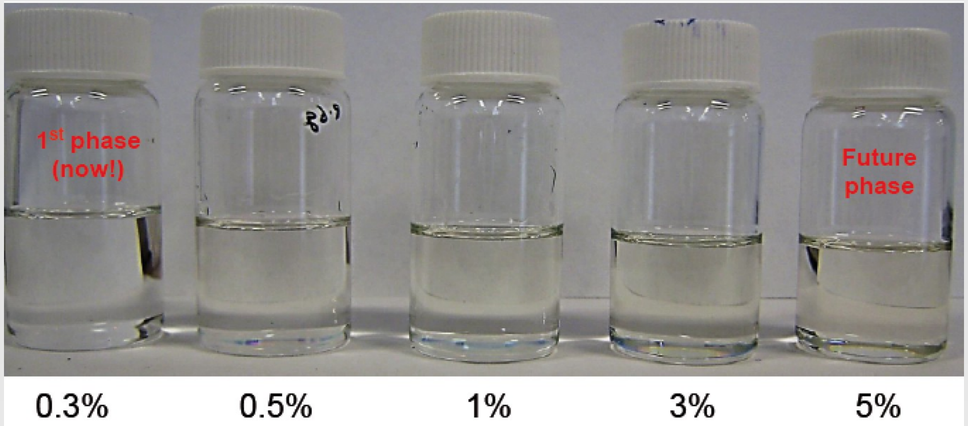


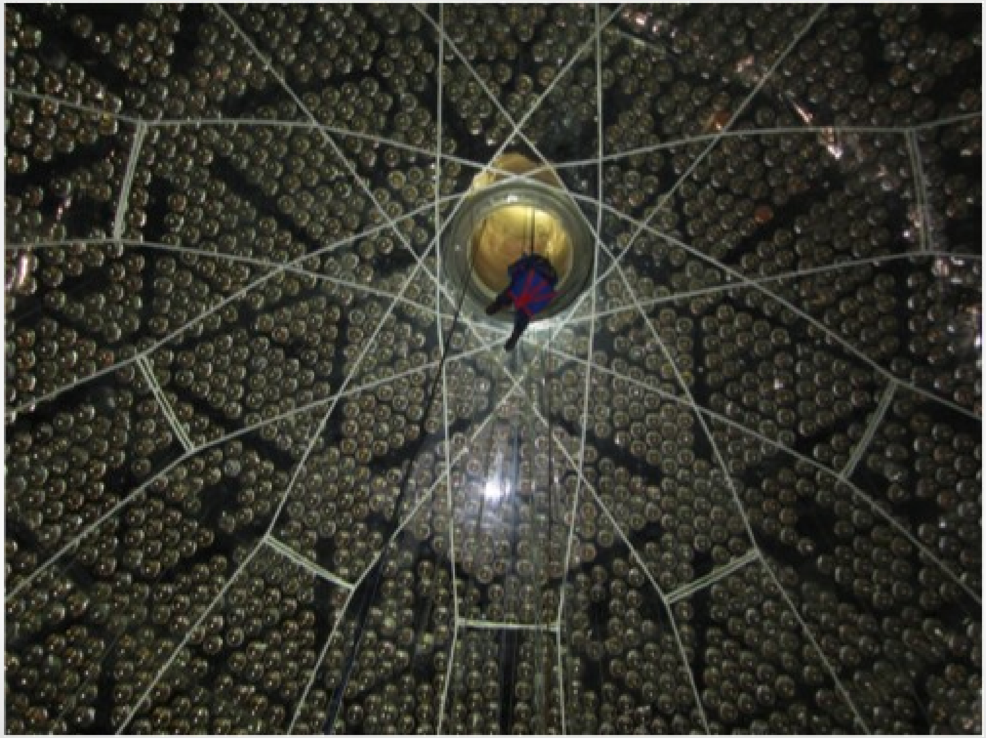
780 ton LAB+PPO in Ø12 m acrylic vessel

9500 PMT

7000 ton water

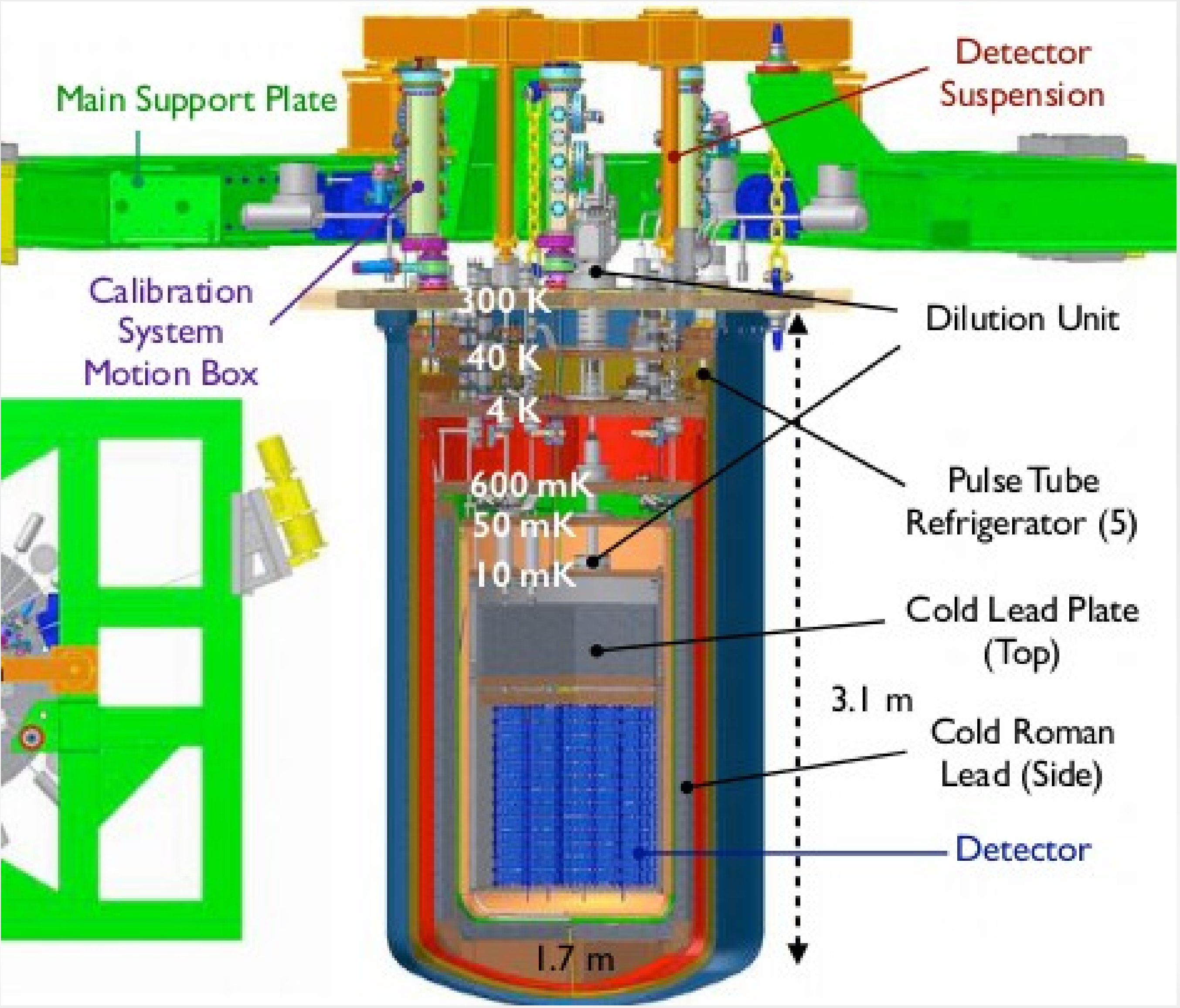
default: 0.5% loading → 3900 kg ^{nat}Te / 1300 kg ^{130}Te

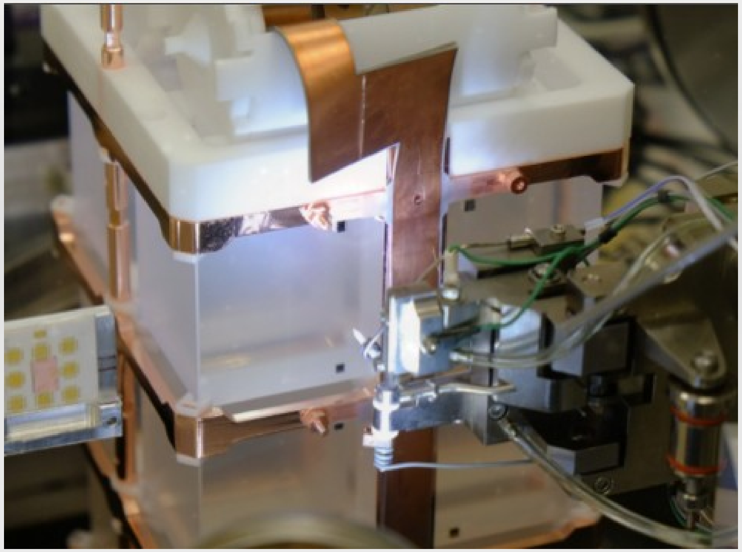




start ~ 2018, sensitivity ~ 2 10^{26} yr (5 yr)

Cuore: ^{130}Te





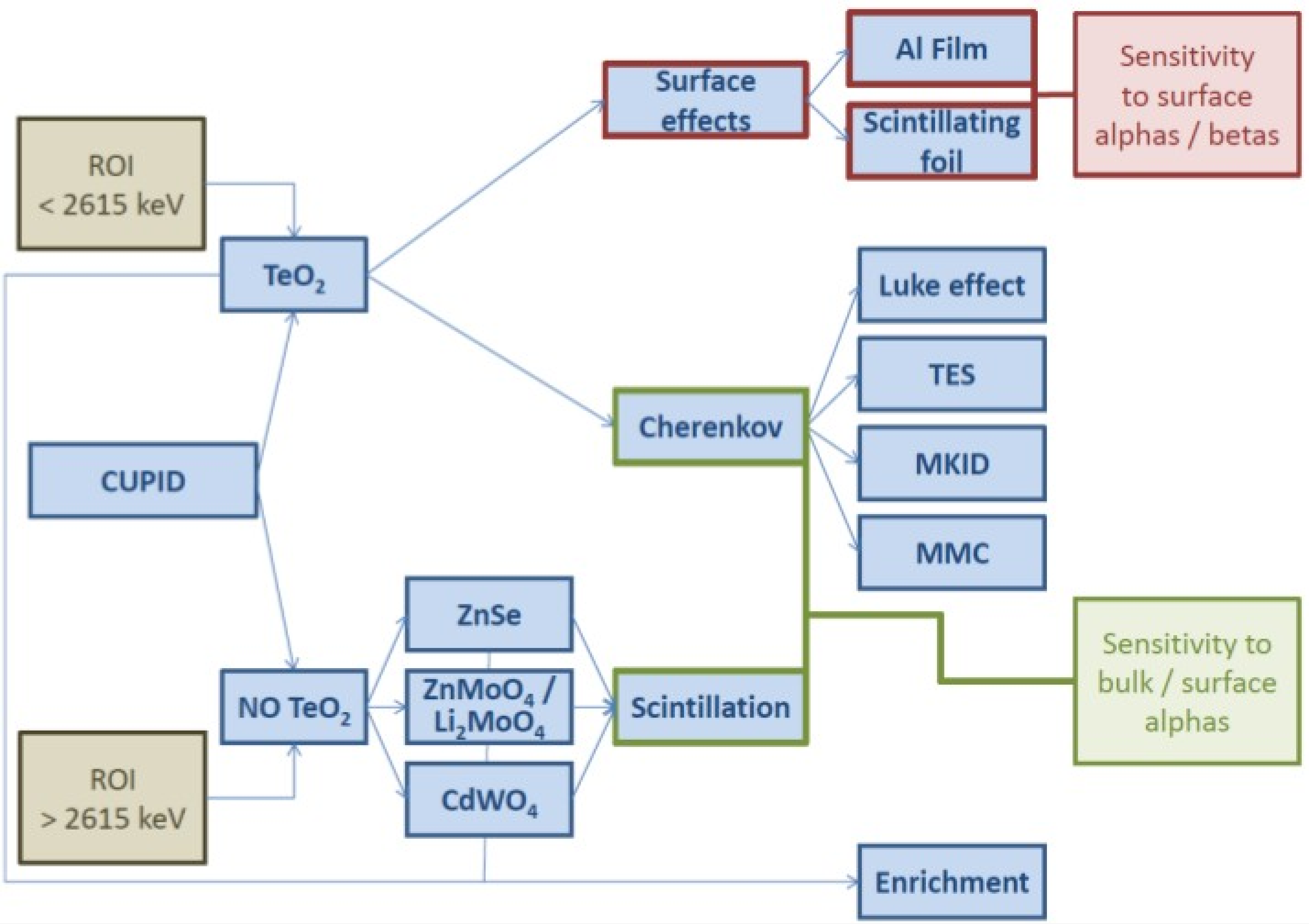
988 $^{nat}TeO_2$ crystals
206 kg ^{130}Te,

calorimeter with Ge NTD readout,
$\Delta T \sim 0.1$ mK / MeV
~ 5 keV FWHM

all towers are assembled!
test cool down of cryostat ok,
next: step mount towers + commissioning
physics run start end 2016,
sensitivity 90% limit ~ 1 10^{26} yr

CUPID proposal

idea: use CUORE cryostat, enriched isotopes and light + phonon detection for surface bkg rej.

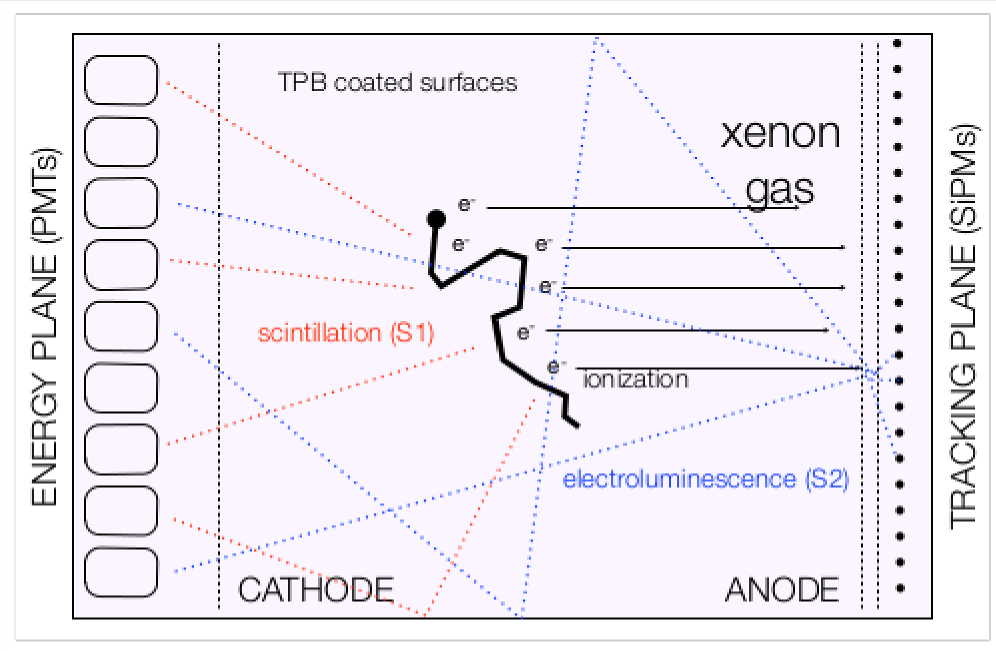


combination of all bolometer efforts and technologies,
several R&D efforts,
choose best technique in 2017-18

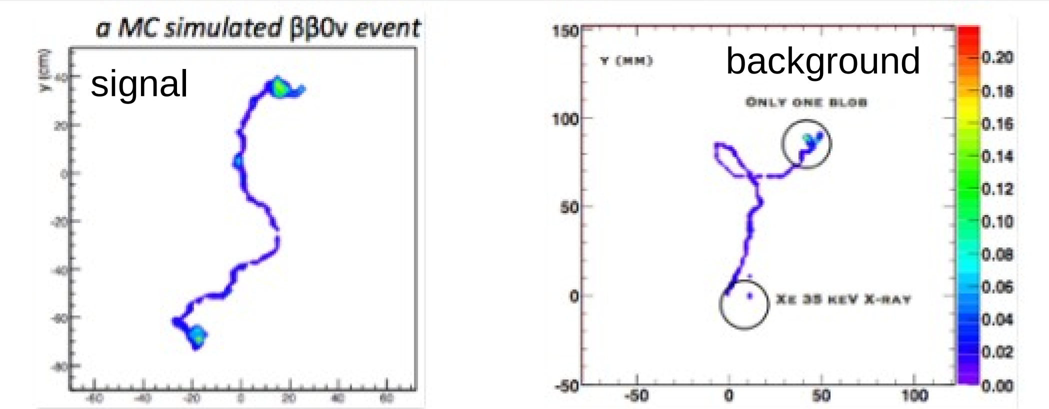
arXiv:1504.03612

goal: bkg < 0.1 cnt/(ROI kg yr), tonne scale mass → $T_{1/2} > \sim 5\ 10^{27}$ yr

NEXT @ Canfranc

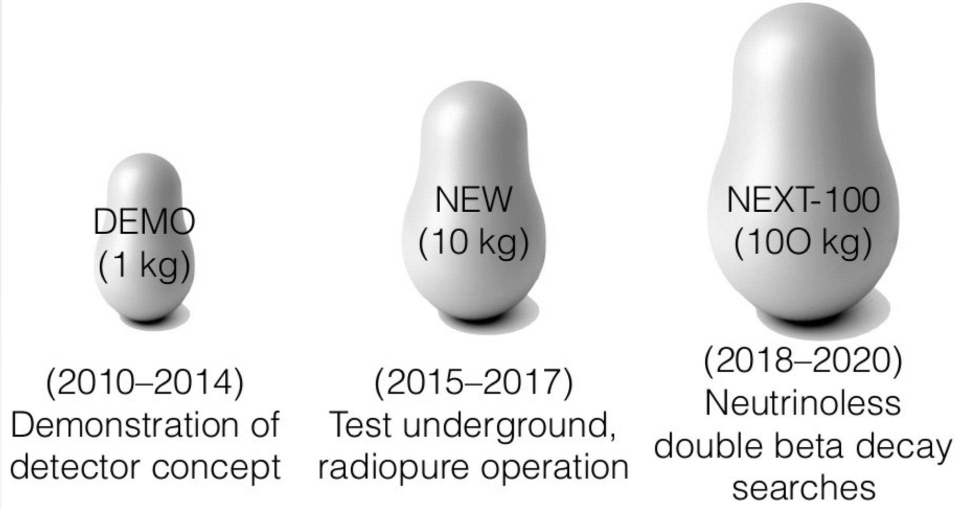


tracking of electrons



x-y position

- 100 kg gas Xe TPC @ 15 bar
- measure scintillation light
- measure ionization w/ Electro Luminescence
- energy resolution FWHM <1% demonstrated
- reconstruction of event topology
  → background reduction



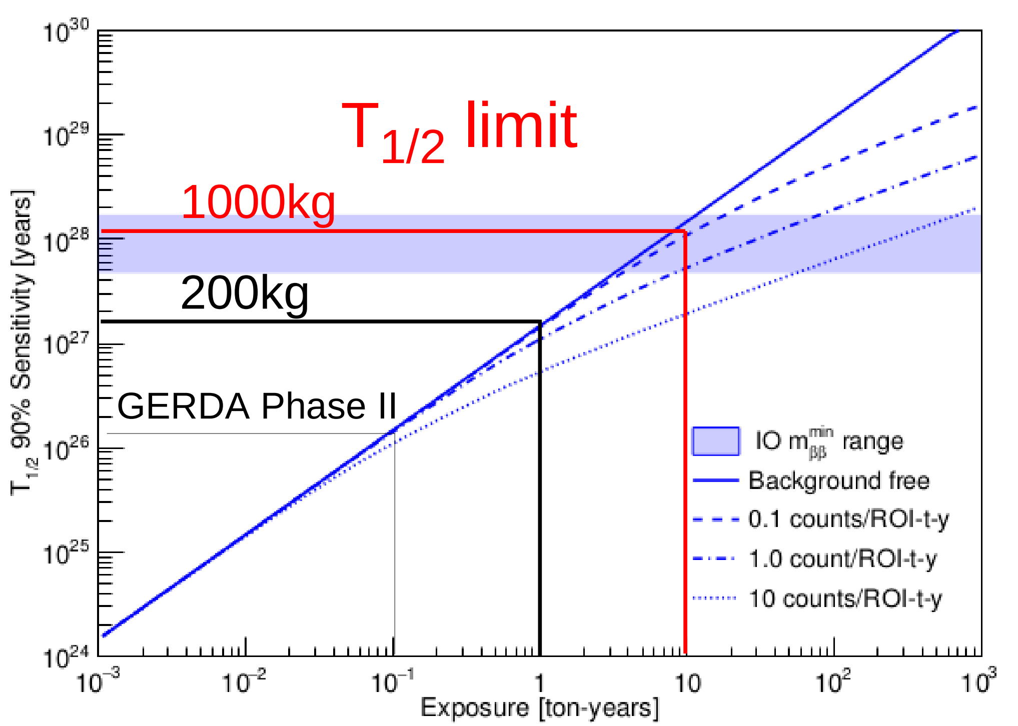
(2010–2014)
Demonstration of detector concept

(2015–2017)
Test underground, radiopure operation

(2018–2020)
Neutrinoless double beta decay searches

sensitivity for 90% limit $T_{1/2} > 5\ 10^{25}$ in 3 yr

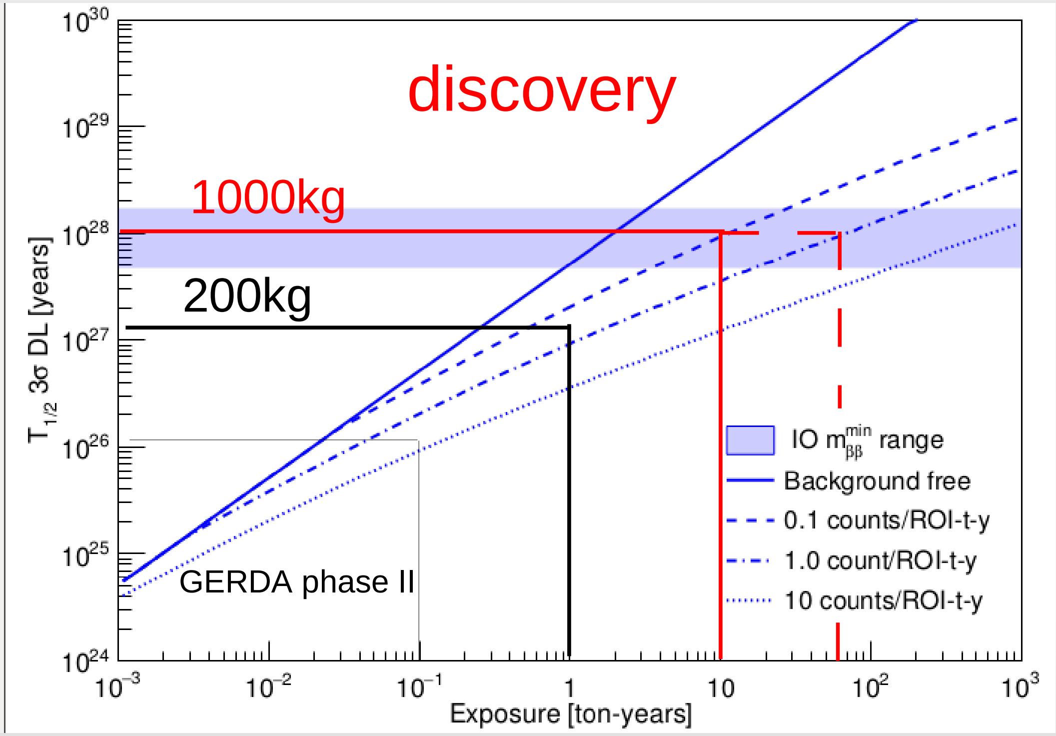
^{76}Ge sensitivity limit + discovery



plots by Jason Detwiler based on
m_{ee} = 18 meV, current matrix element calc.
GERDA numbers for efficiency & enrichment

GERDA Phase I ~ 30 cnt/(ROI t yr) - achieved
Phase II ~ 3 cnt/(ROI t yr) - achieved
future ”200 kg” ~ 0.5 cnt/(ROI t yr)
”1000 kg” ~ 0.1 cnt/(ROI t yr)

discovery: 50% chance for a 3σ signal discovery



for discovery:
factor 10 worse in background
→ need factor ~6 in exposure

”background free” very important
(for all isotopes)

200 kg in GERDA

- Cryostat large enough: current Ø 500 can be enlarge to Ø 630

- more cables and feedthroughs

- improve detection of LAr scintillation light

- bigger Ge detectors → few channel ?

Background reduction by ~5 relative to Phase II should be possible:

- intrinsic bkg: Th/U not found in Ge detectors,
  cosmogenic ^{68}Ge/^{60}Co: limit time above GND, PSD → ok

- external Th/U: cleaner materials (levels like for Majorana are ok),
  LAr veto powerful (>90% rejection in comb. w/ PSD)

- surface events: alpha on p^+ contact rejected by PSD
  beta from ^{42}K most critical, on n^+ contact

- muon induced: prompt events rejected by muon veto
  delayed by decay chain (→ dead time),
  simulation → ok for 200 kg setup

cost ~ 15M Euro – mainly depending on price for enrichment

comparison experiments

		mass [kg]* (total/FV)	FWHM [keV]	background[&] [cnt/t yr FWHM]	$T_{1/2}$ limit [10^{25} yr] after 4 yr	m_{ee} limit [meV]
Gerda II	Ge	35/27	3	5	15	80-190
MajoranaD	Ge	30/24	3	5	15	80-190
EXO-200	Xe	170/80	88	220	6	80-220
Kamland-Z	Xe	383/88 750/??	250	40 ?	20	44-120
Cuore	Te	600/206	5	300	9	50-200
NEXT-100	Xe	100/80	17	30	6	80-220
SNO+	Te	2340/260	190	60	17	36-150
nEXO	Xe	5000/4300	58	5	600	8-22
Ge-200	Ge	200/155	3	1	100	35-75
Ge-1000	Ge	1000/780	3	0.2	1000	10-23

* total= element mass, FV= 0νββ isotope mass in fiducial volume (incl enrichment fraction)

[&] kg of 0νββ isotope in active volume and divided by 0νββ efficiency

Note: values are design numbers except for GERDA, EXO-200 and Kamland-Zen

Summary

strong prejudice: $0\nu\beta\beta$ exists, $\Delta L=2$ process, possibly our only observable ΔL,
(reminder: from cosmology we know B is violated)
$T_{1/2}$ unknown (no real guidance from theory), discovery can be around the corner,
experimental input is desperately needed ($0\nu\beta\beta$, LFV, LHC, …)
4 Nobel Prices in last 30 years for neutrino physics, I expect more to come

^{76}Ge detector features:

- well known technology (enrichment + diode production)
- best energy resolution
- lowest bkg in ROI
- flat background at Q value

→ all are important features for discovery

GERDA Phase II & Majorana Demonstrator are taking first data,
GERDA meets specifications
→ next step new collaboration for "200 kg" and "1000 kg" Ge

In US: $0\nu\beta\beta$ highest priority of any new projects for DOE nuclear physics