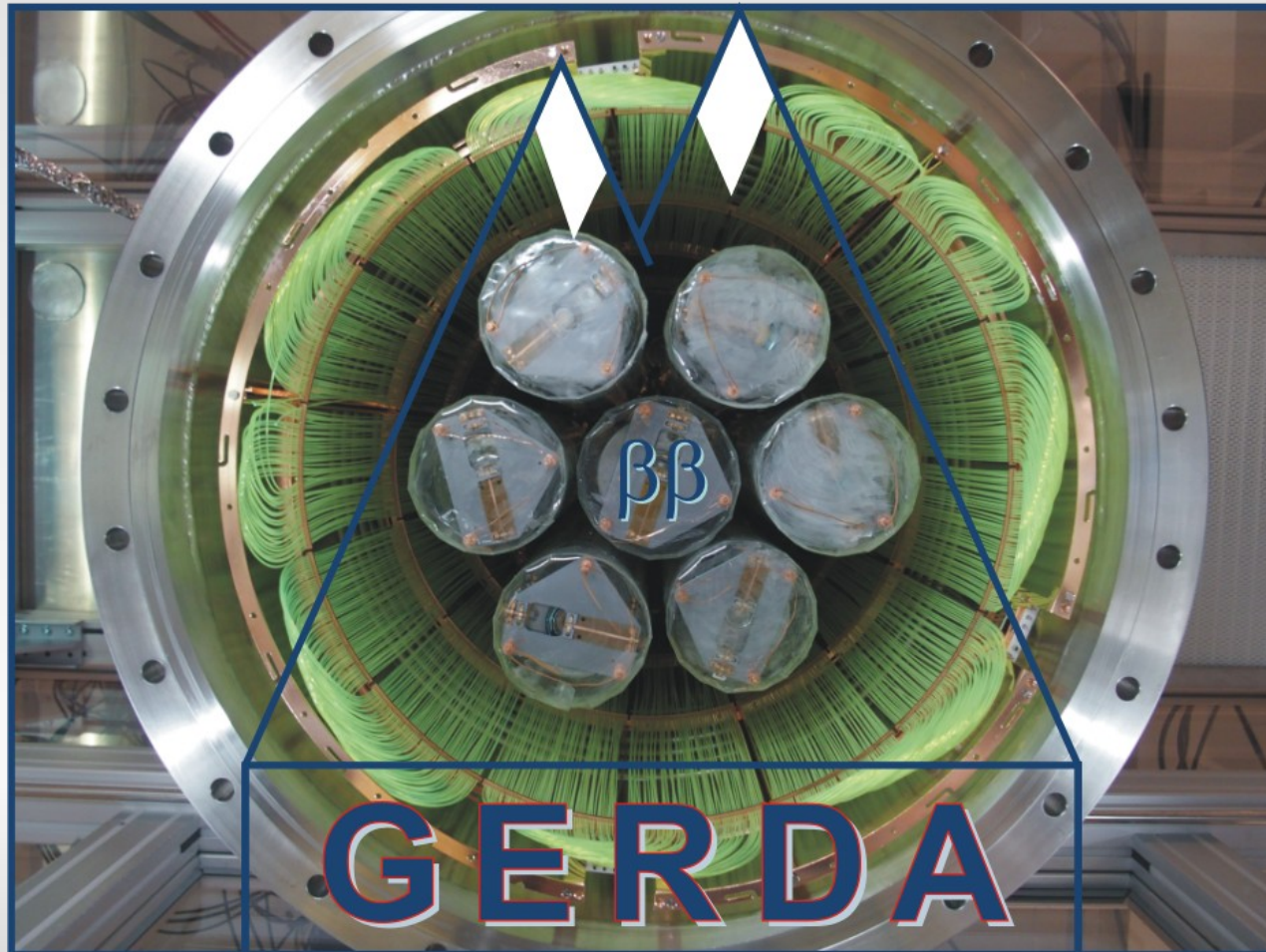


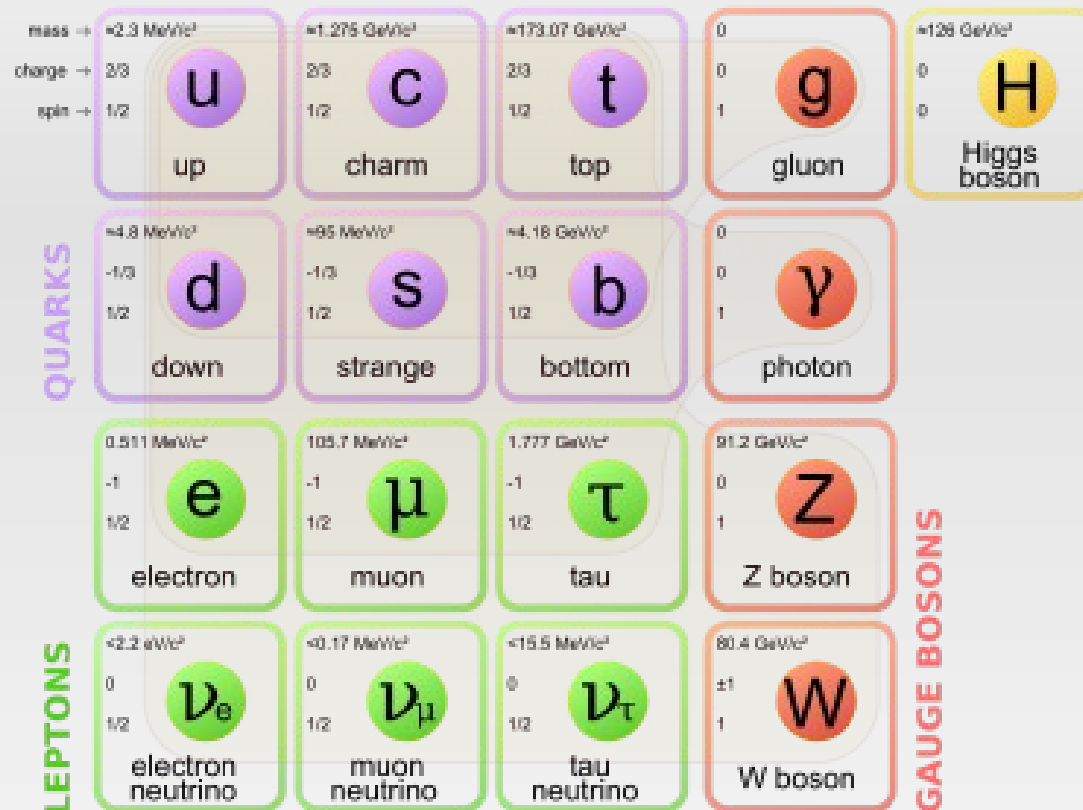
Neutrinoless double beta decay with ^{76}Ge



Bernhard Schwingenheuer
Max-Planck-Institut für Kernphysik, Heidelberg



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

Neutrino mass: non-SM effect?

	SM				nuMSM		
mass →	2.4 MeV	1.27 GeV	171.2 GeV	mass →	2.4 MeV	1.27 GeV	171.2 GeV
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
name →	u up	c charm	t top	name →	u up	c charm	t top
Quarks	4.8 MeV $-\frac{1}{3}$ d down	104 MeV $-\frac{1}{3}$ s strange	4.2 GeV $-\frac{1}{3}$ b bottom	Quarks	4.8 MeV $-\frac{1}{3}$ d down	104 MeV $-\frac{1}{3}$ s strange	4.2 GeV $-\frac{1}{3}$ b bottom
	0 eV 0 ν_e electron neutrino	0 eV 0 ν_μ muon neutrino	0 eV 0 ν_τ tau neutrino		<0.0001 eV 0 ν_e electron neutrino	~ 10 keV ~ 0.01 eV N ₁ sterile neutrino	$\sim \text{GeV}$ ~ 0.04 eV N ₂ sterile neutrino
	0.511 MeV -1 e electron	105.7 MeV -1 μ muon	1.777 GeV -1 τ tau		0.511 MeV -1 e electron	105.7 MeV -1 μ muon	1.777 GeV -1 τ tau
Leptons				Leptons			

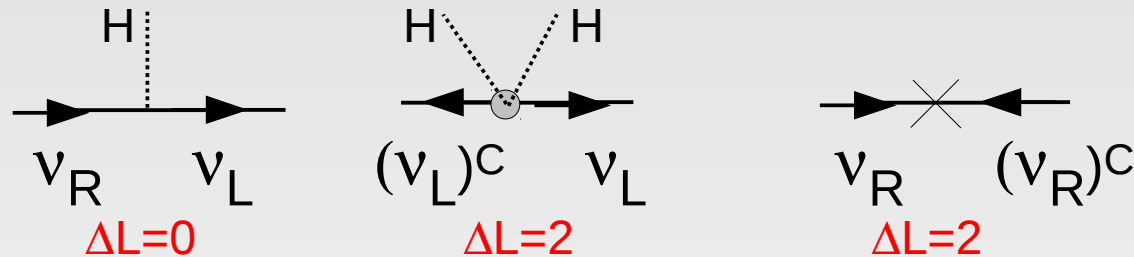
weak interactions: W/Z bosons couple only to **left**-handed fermions
 mass generation: Higgs couples to **left**- and **right**-handed fermions

ν oscillations (Nobel prize 2015) → ν_L have (**tiny**) mass ($< m_e / 10^6$)
same mass mechanism like for other fermions?

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)
 $m_D \sim$ normal Dirac mass term

m_L, m_R new physics

eigen vector $N \sim \nu_R + (\nu_R)^c$ $\nu \sim \nu_L + (\nu_L)^c$
 mass ($m_L \sim 0$) m_R m_D^2 / m_R

Majorana particles

N mass range

possible N mass ranges (**little guidance on scale available!**)

$10^9 - 10^{14}$ GeV: motivated by GUT, can explain baryon asymmetry (lepton asymmetry by CP violation converted via sphaleron to BAU),
see-saw: light neutrino mass $\sim m_D^2 / M_R$

0.1-few TeV: can explain baryon asymmetry, no hierarchy problem (see below),
accessible by LHC

GeV: can explain baryon asymmetry
if < 5 GeV observation e.g. $D \rightarrow N \mu X$ with $N \rightarrow \mu \pi$ by SHIP (**200 MCHF**)

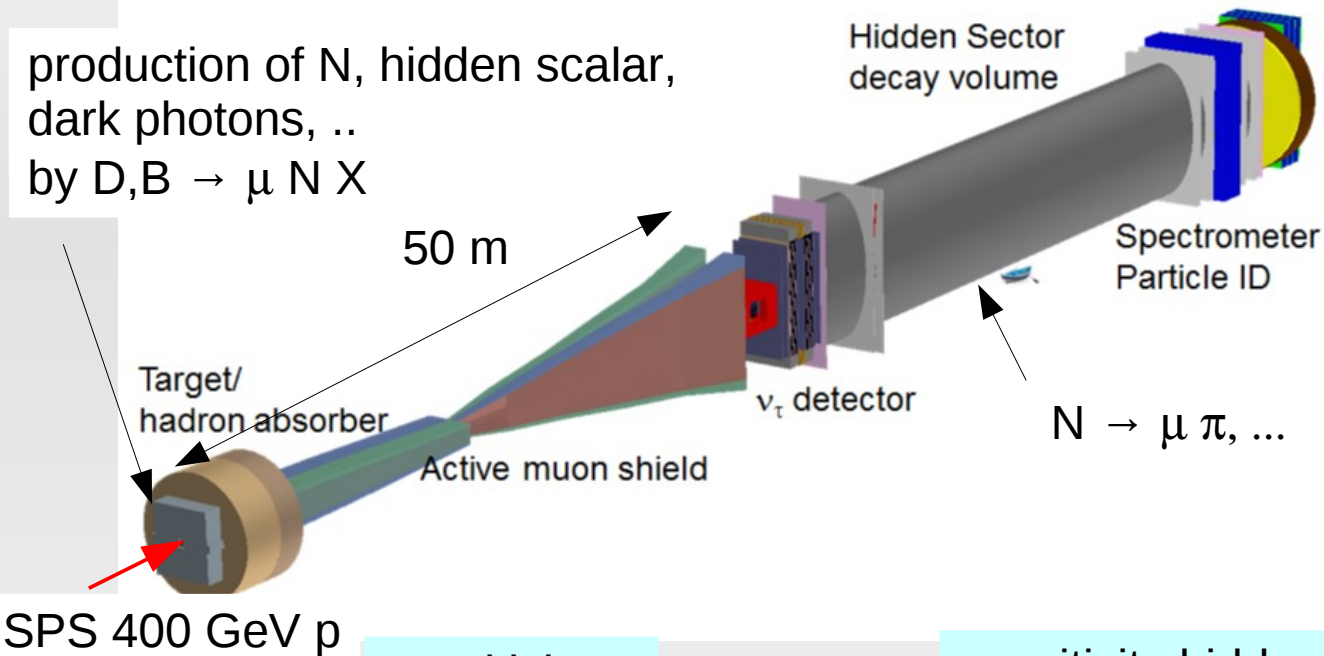
10 keV: (warm+cold) dark matter candidate, $N \rightarrow \gamma \nu$ decay $\sim U^2 m_R^5$
hint for 3.5 keV line ?? (arXiv:1402.2301, arXiv:1402.4119)

eV range: LSND oscillation signal, reactor anomaly, ... $\rightarrow$ SOX, Stereo, ...
contribute to number of relativistic neutrinos measured by PLANCK

neutrino minimal SM (ν MSM): 1×10 keV N for DM and $2 \times \sim$ GeV N for baryon asymmetry,
minimal extension of SM

SHIP proposal @ SPS

production of N , hidden scalar,
dark photons, ..
by $D, B \rightarrow \mu N X$



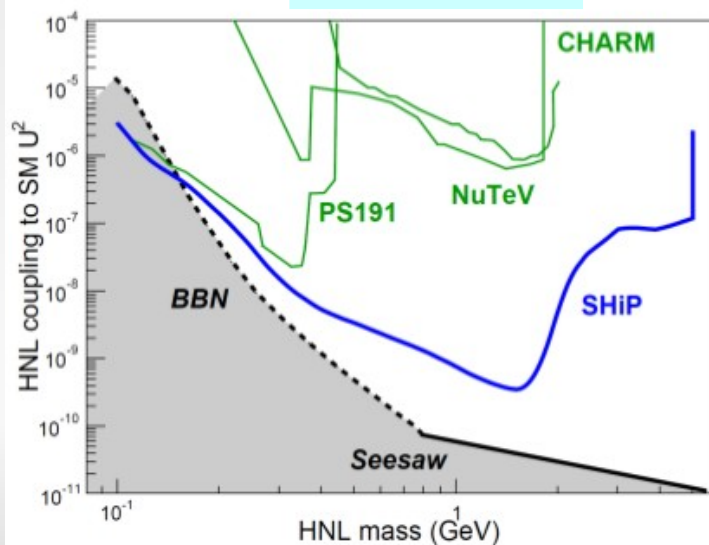
arXiv:1504.04956

arXiv:1504.04855

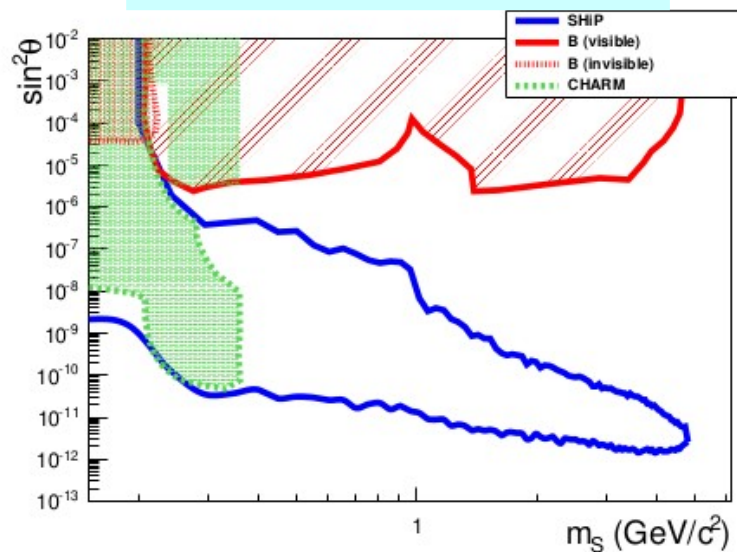
uses CNGS beam line,
total $2 \cdot 10^{20}$ pot
 $\sim 8 \cdot 10^{17}$ D mesons

cost for beam+exp 200 MCHF

sensitivity N

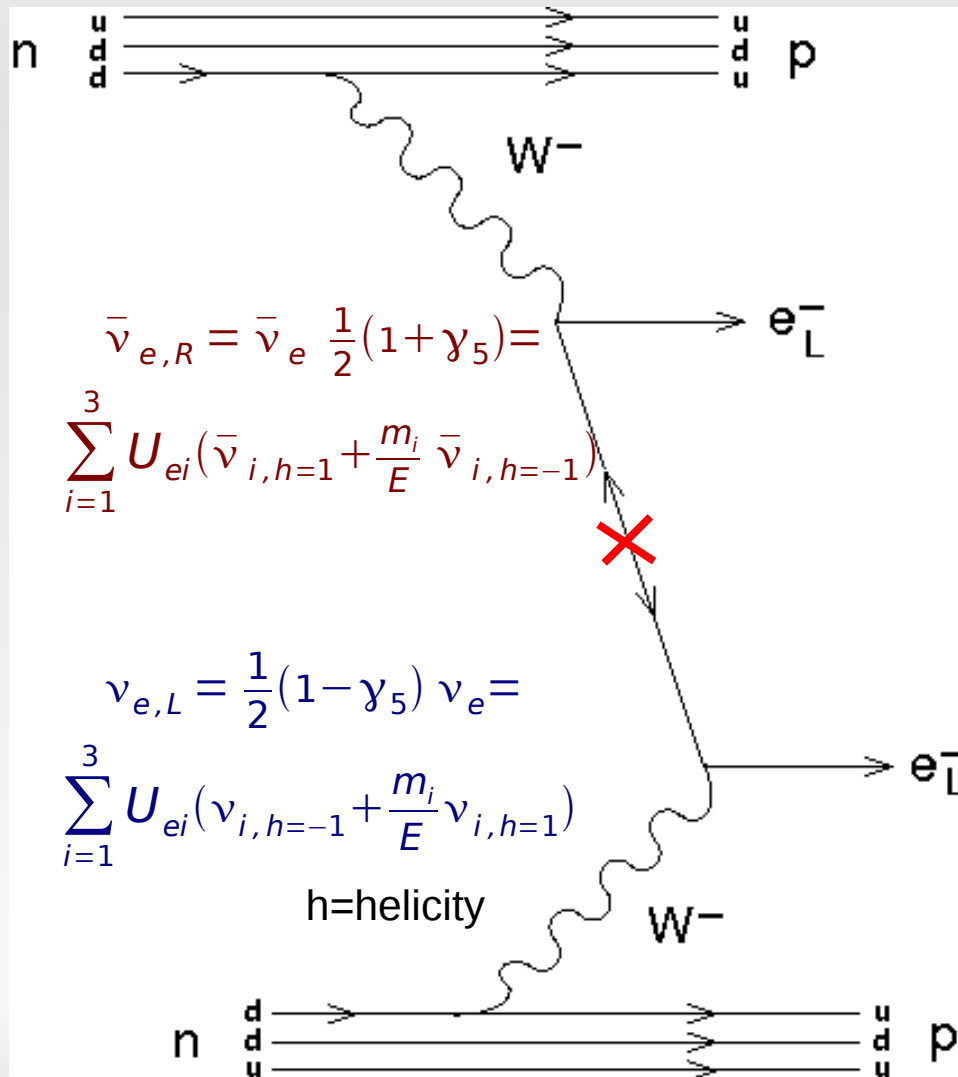


sensitivity hidden scalar



How to observe $\Delta L=2$: $0\nu\beta\beta$

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



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

function of

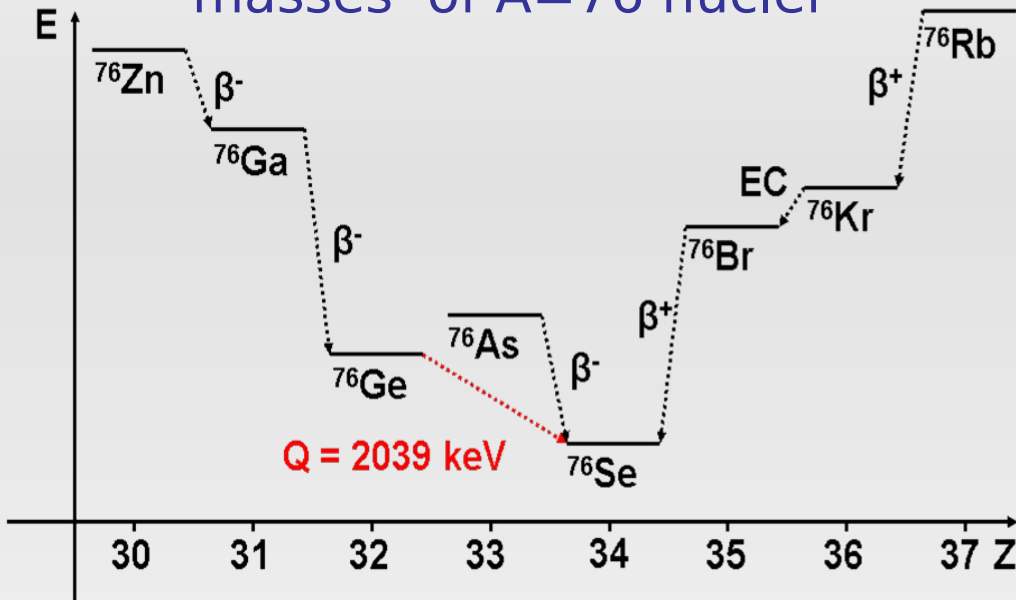
- neutrino mixing parameters
- lightest neutrino mass
- 2 Majorana phases

also possible: heavy N exchange

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

Neutrinoless double beta decay

masses of A=76 nuclei



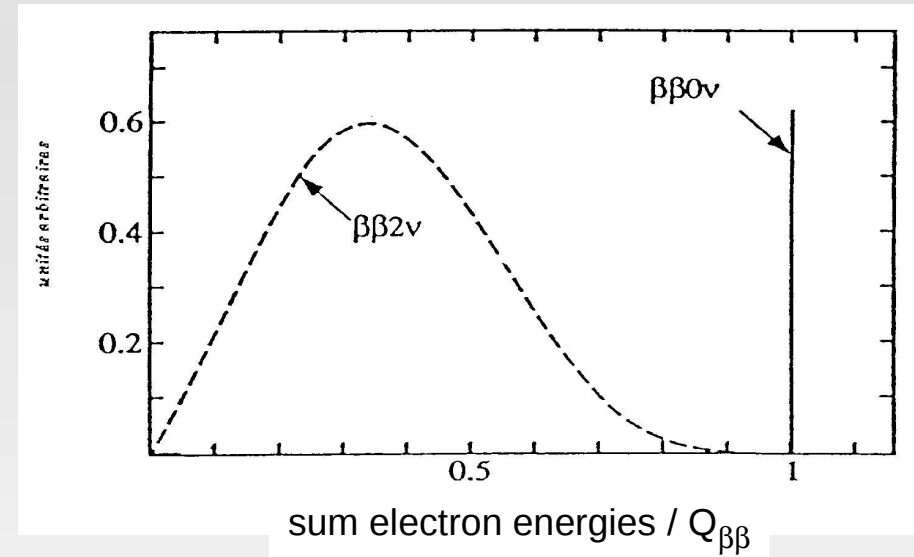
"single" beta decay not allowed
 → only "double beta decay"

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

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

$0\nu\beta\beta$: search for a line at Q value of decay

experimental signature for $\beta\beta$

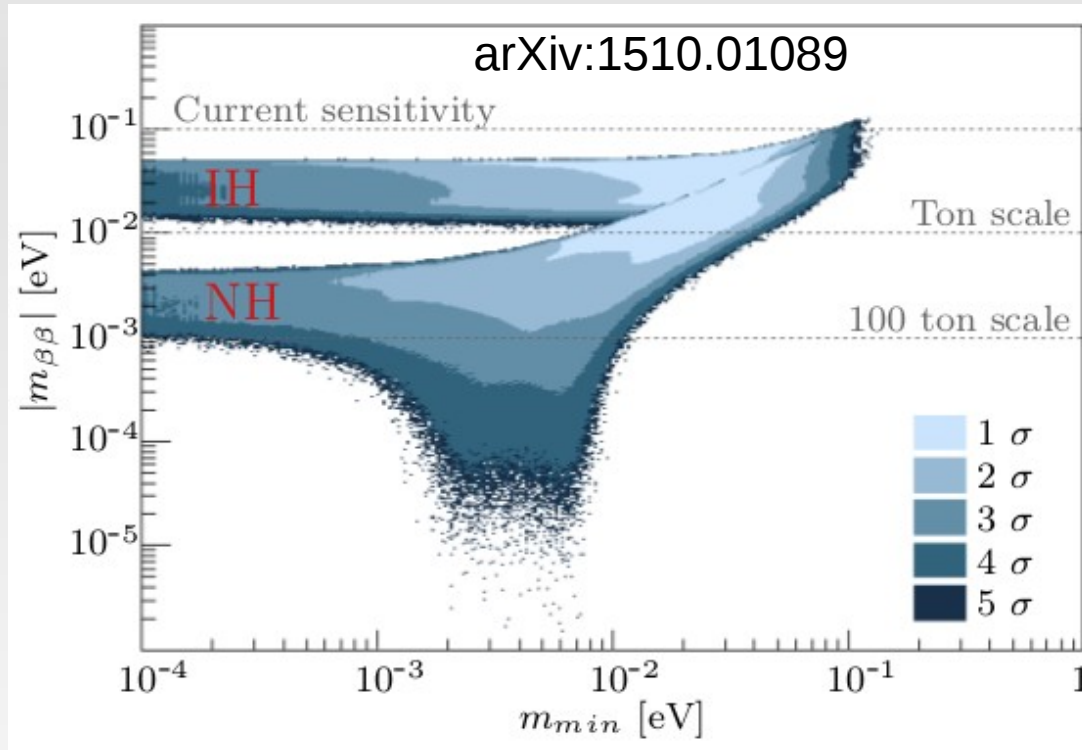


Note: similar process in principle also observable at accelerator or reactor or ... but for light Majorana neutrino:

- background too high
- flux too low compared to Avogadro N_A

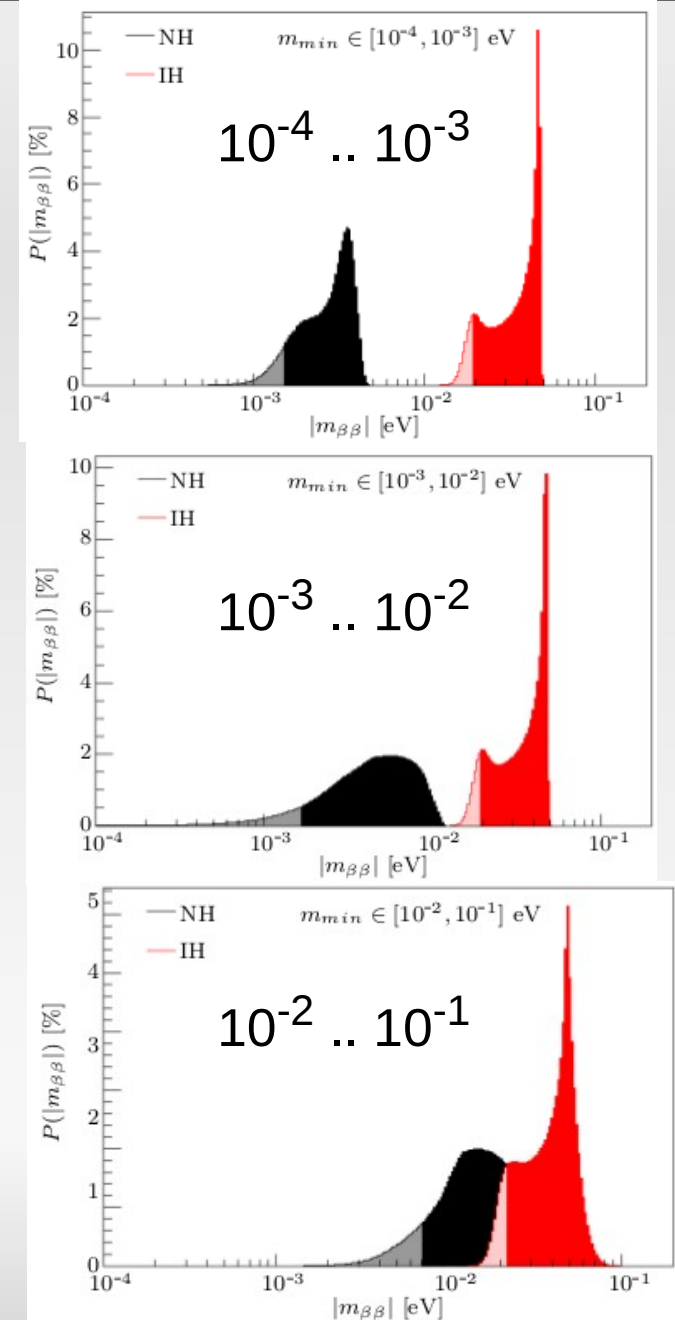
Light Majorana neutrino exchange

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



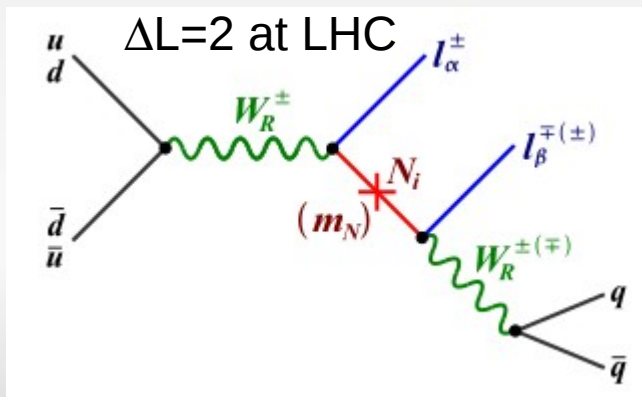
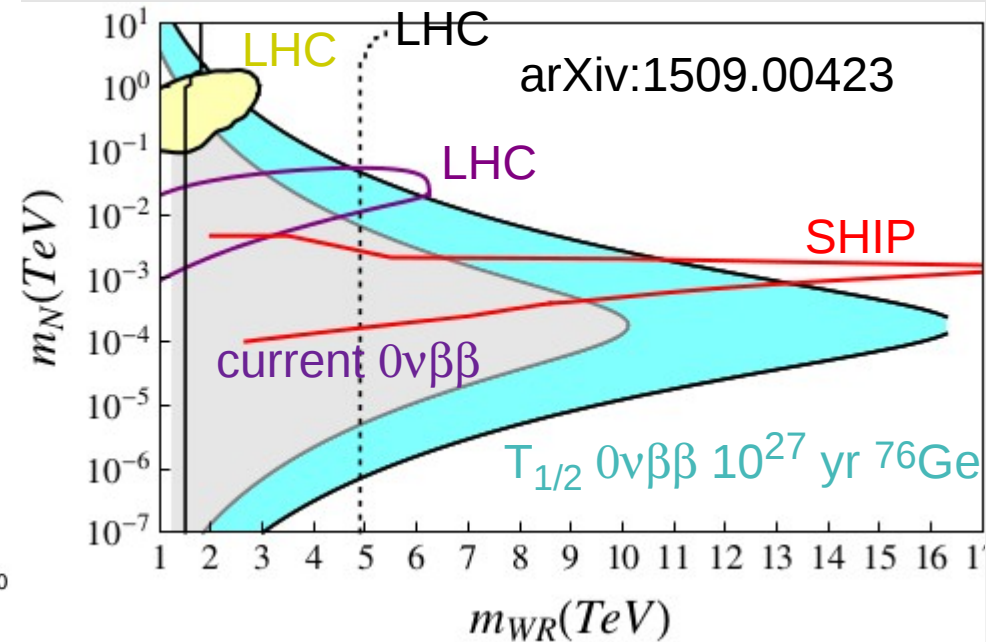
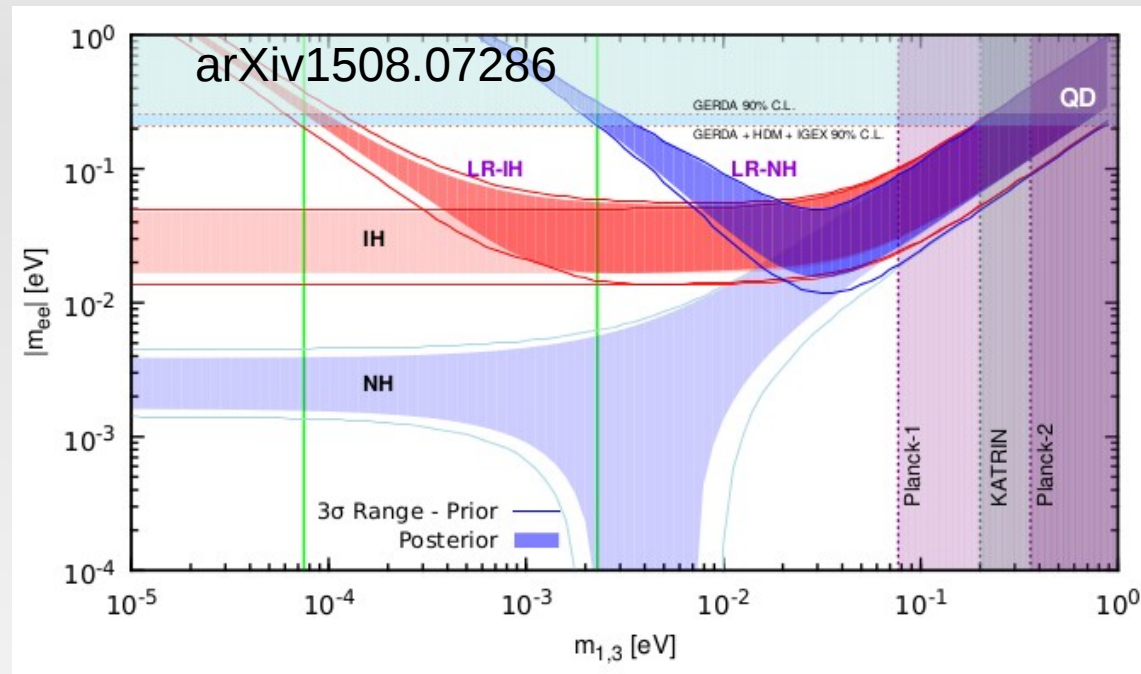
including cosmological bound $\Sigma = (22 \pm 62) \text{ meV}^1$
¹ true for flat Λ CDM only

unless Majorana phases are "aligned"
high $m_{\beta\beta}$ values are more likely to occur



LHC vs $0\nu\beta\beta$: other mechanisms

extensions of SM $\rightarrow$ other contributions to $0\nu\beta\beta$ possible, example LRSM
 LHC might find W_R and/or $\Delta L=2$ process



best case: find s.th. at LHC and $0\nu\beta\beta$ and
 lepton flavor violation $\mu \rightarrow e \gamma$

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

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

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

g_A = axial vector coupl. = 1.25

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

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

m_e = electron mass

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

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

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

selected $0\nu\beta\beta$ 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

M = mass of detector

t = measurement time

A = isotope mass per mole

N_A = Avogadro constant

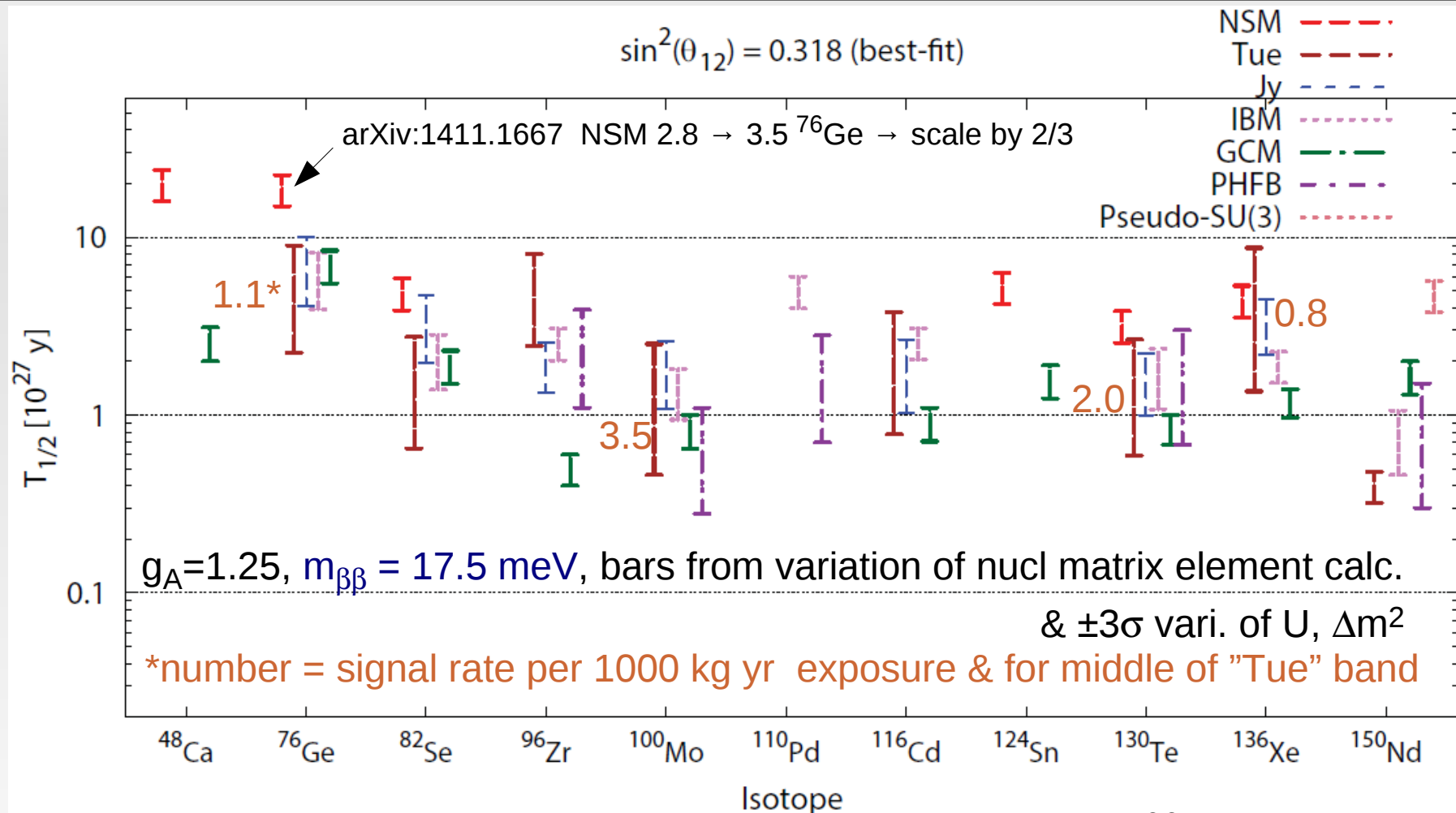
a = fraction of $0\nu\beta\beta$ isotope

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



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

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 [$\mu\text{Bq/kg}$]
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 m³ LAr

590 m³ pure water / Cherenkov veto

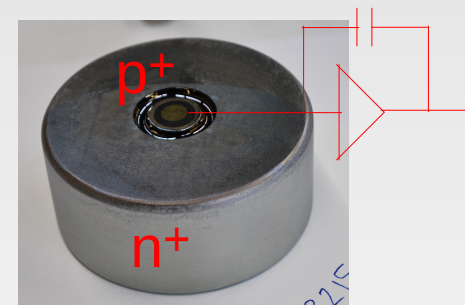
Phase I (2011-13):

$T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ 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



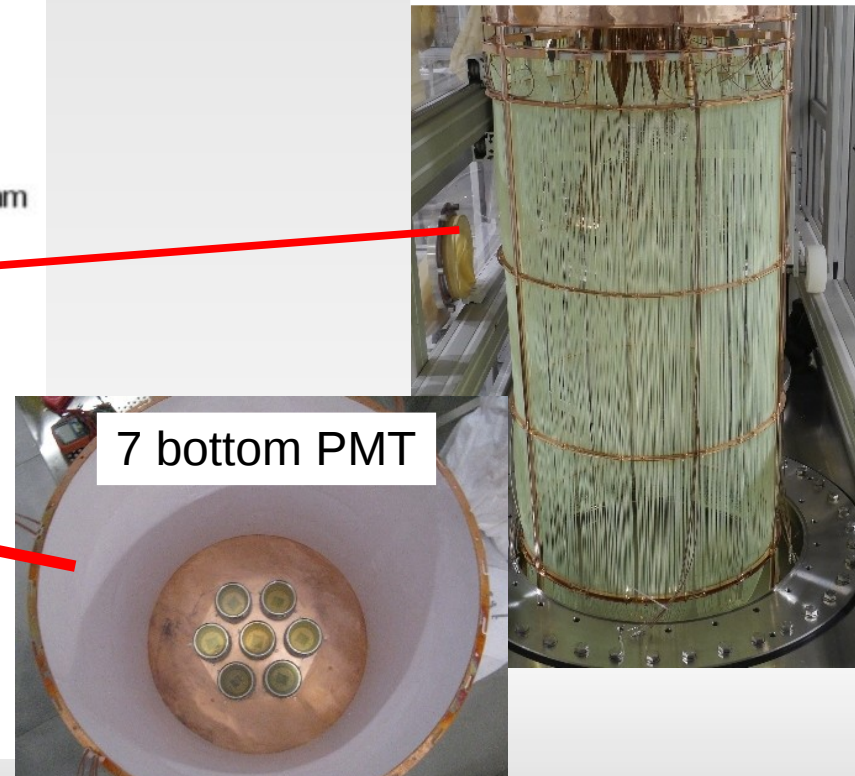
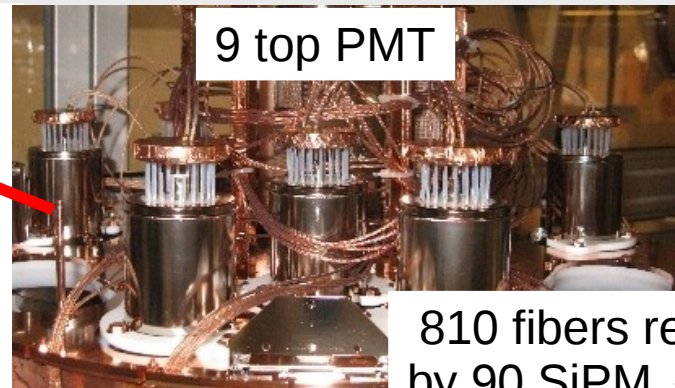
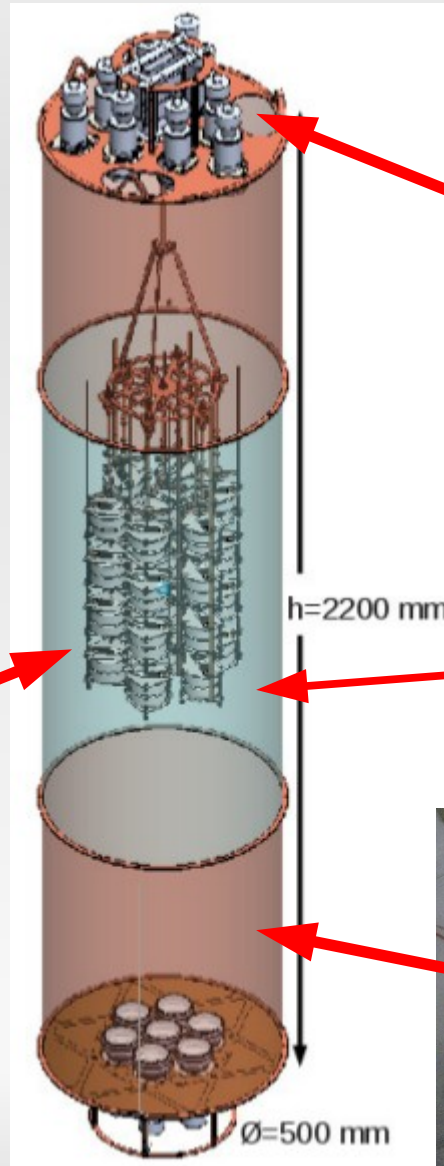
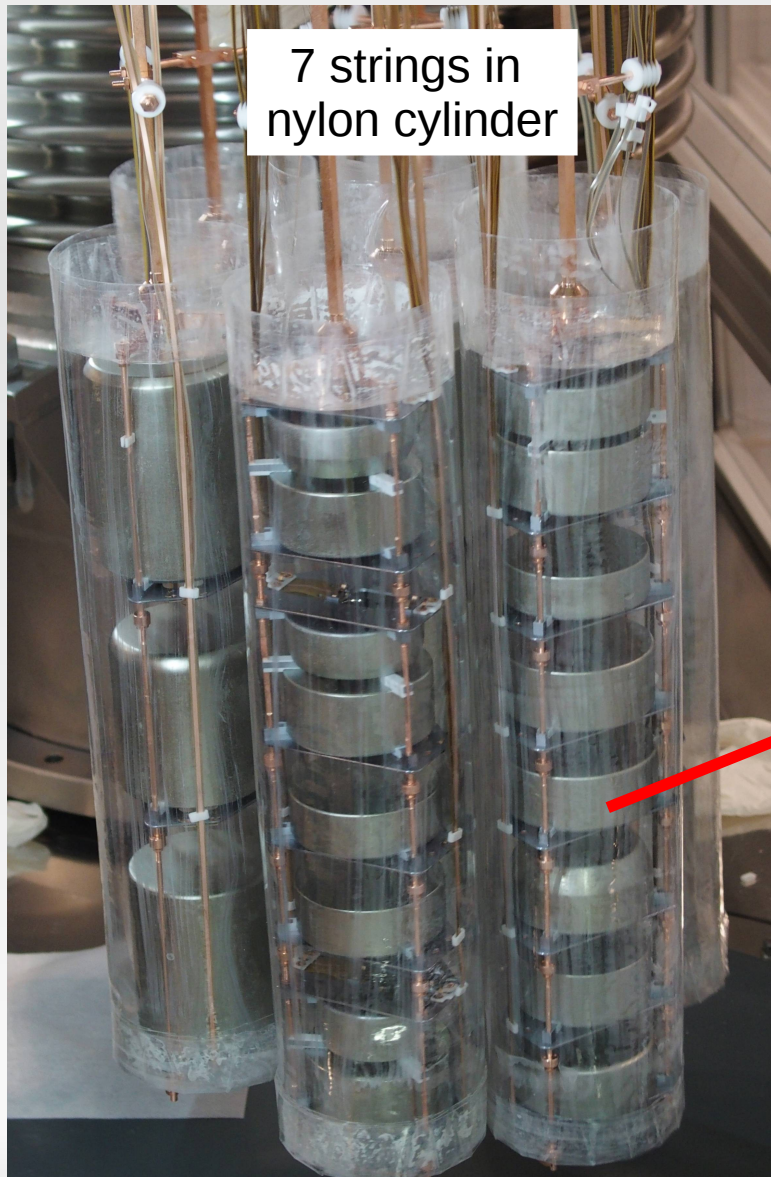
started end 2015

EPJ C73 (2013) 2330

Freiburg, 26 October 2016

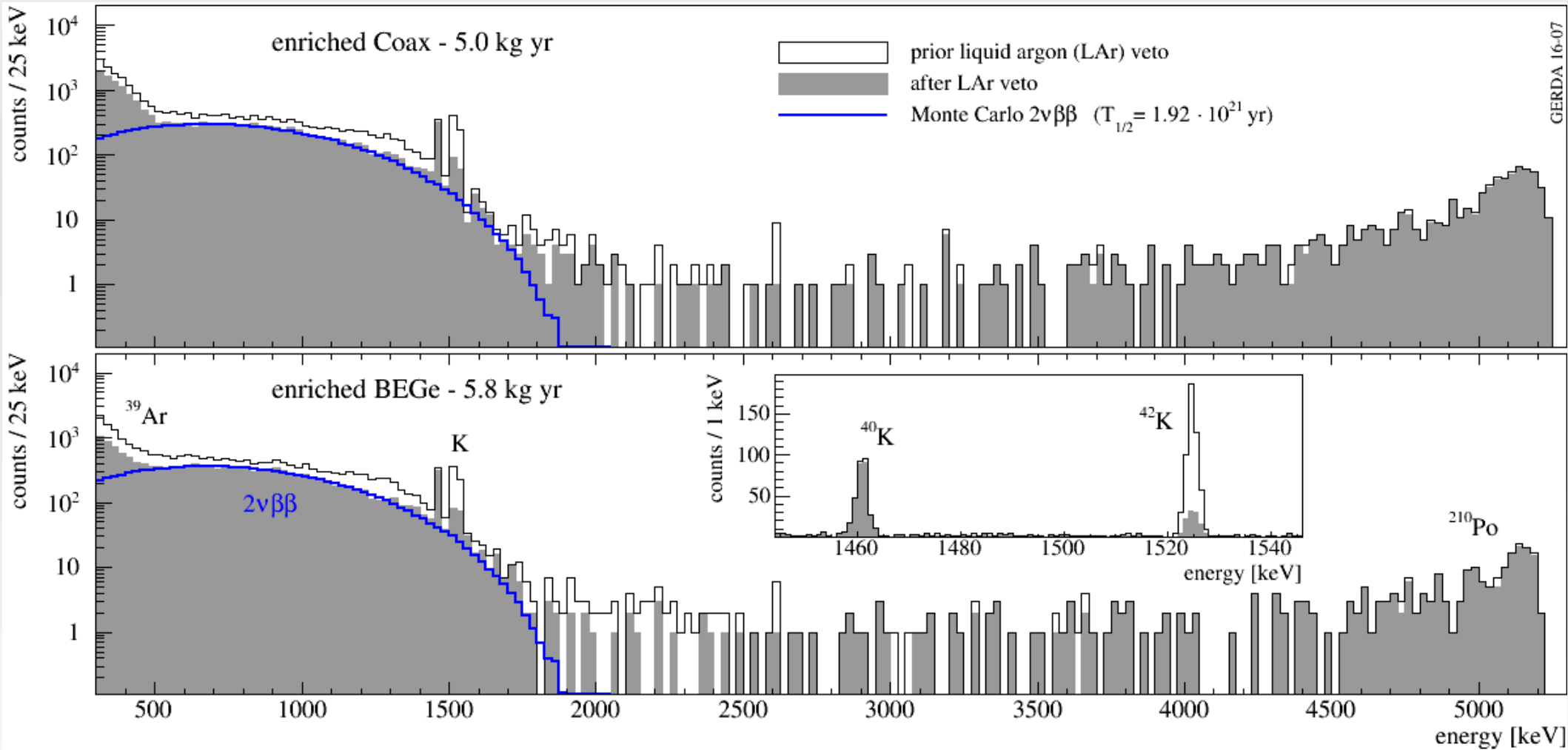
Schwingenheuer, $0\nu\beta\beta$ with ^{76}Ge

Phase II start December 2015



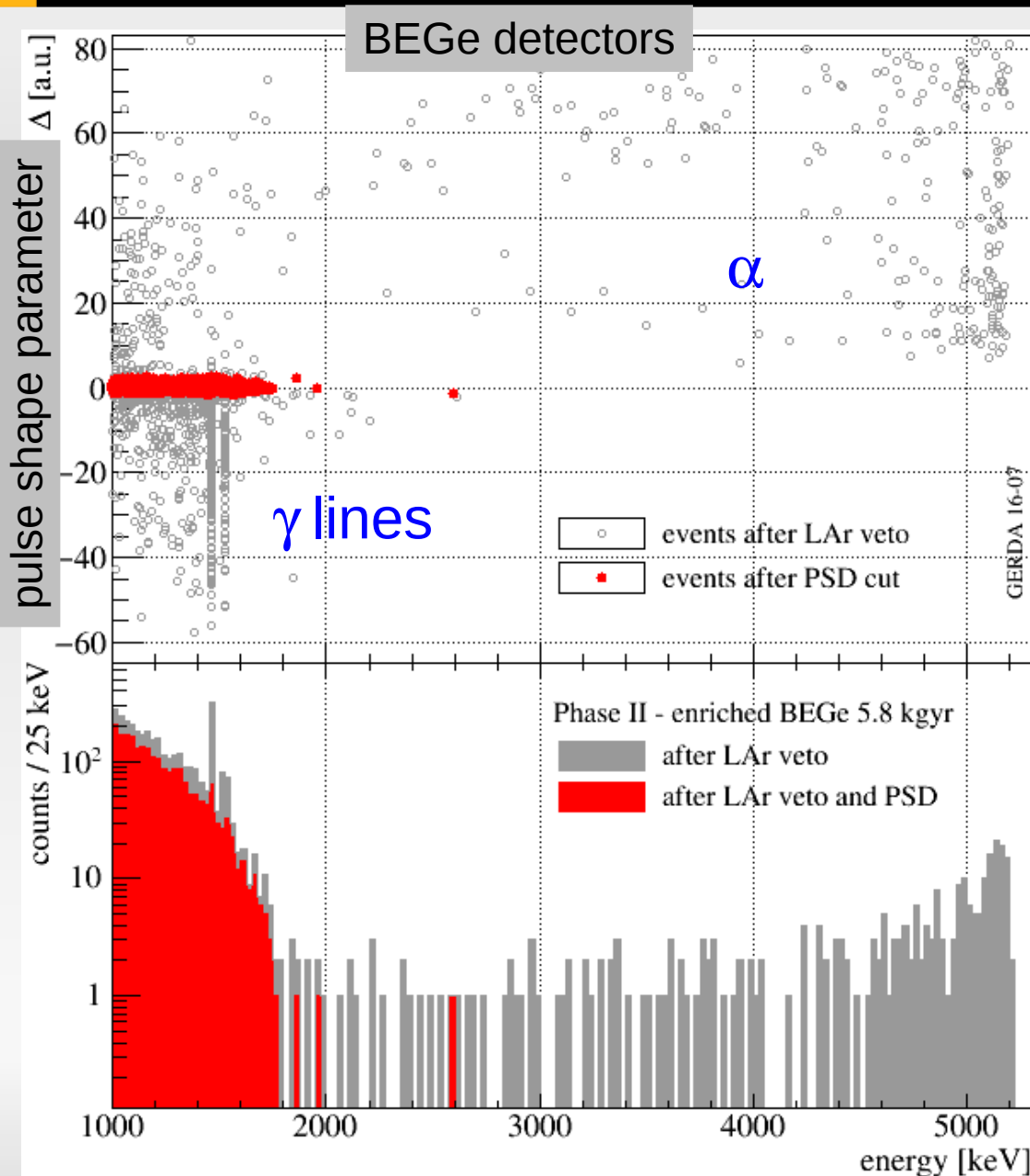
all Ge + LAr veto ch. 'working' !!!

Background reduction: argon veto



line at 1525 keV from 42K: deposits up to 2 MeV in LAr → factor ~5 suppression
600-1300 keV: ~97% of events are $2\nu\beta\beta$ 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 ($87.3 \pm 0.2 \pm 0.8$) %

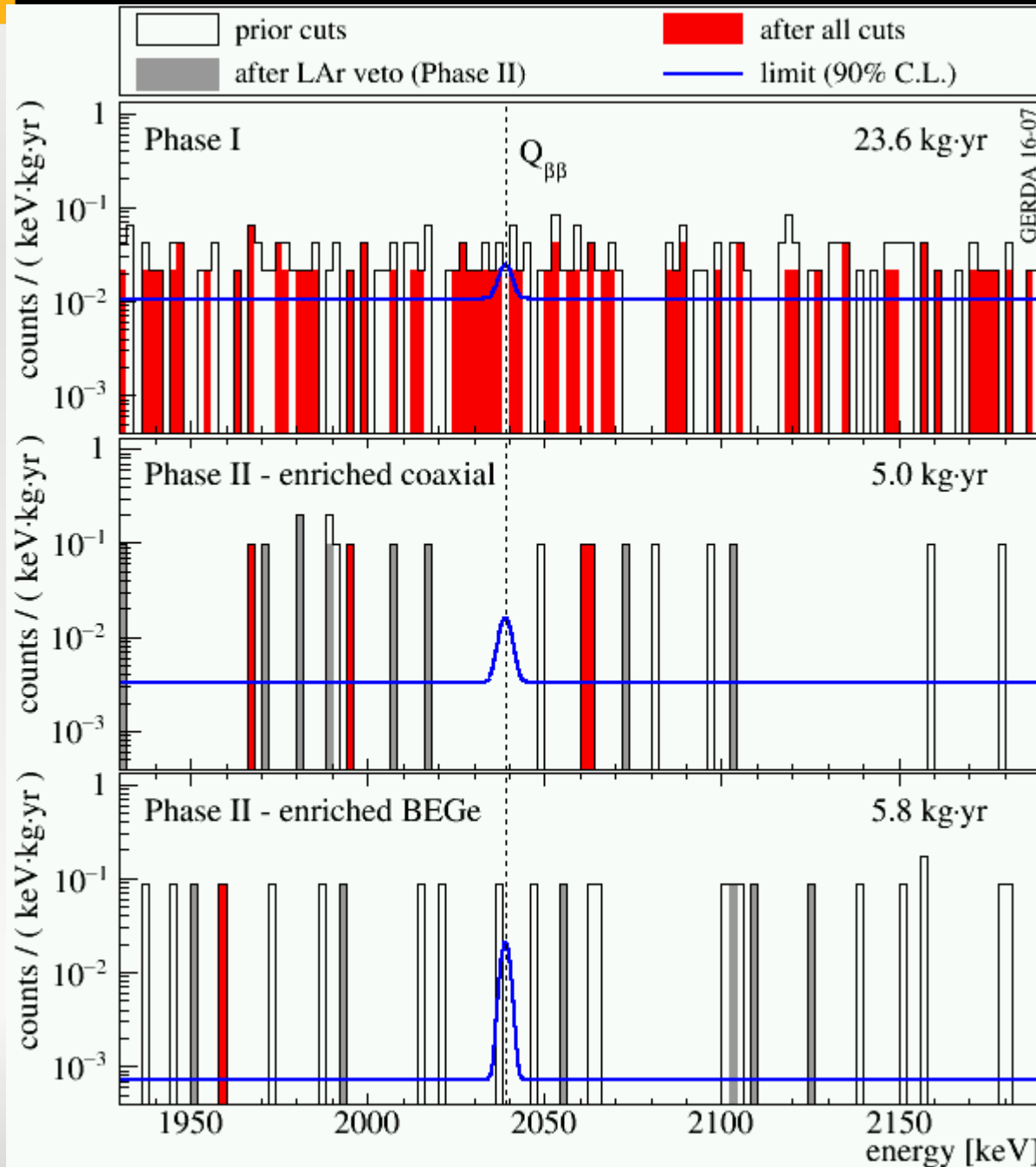
$2\nu\beta\beta$ ($85.4 \pm 0.8 \pm 1.7$) %

in fit energy window 1930-2190 keV:
 1 evt remains

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

$\sim 10\times$ lower than other exp.
 reach our background goal!

New limit (blind analysis)

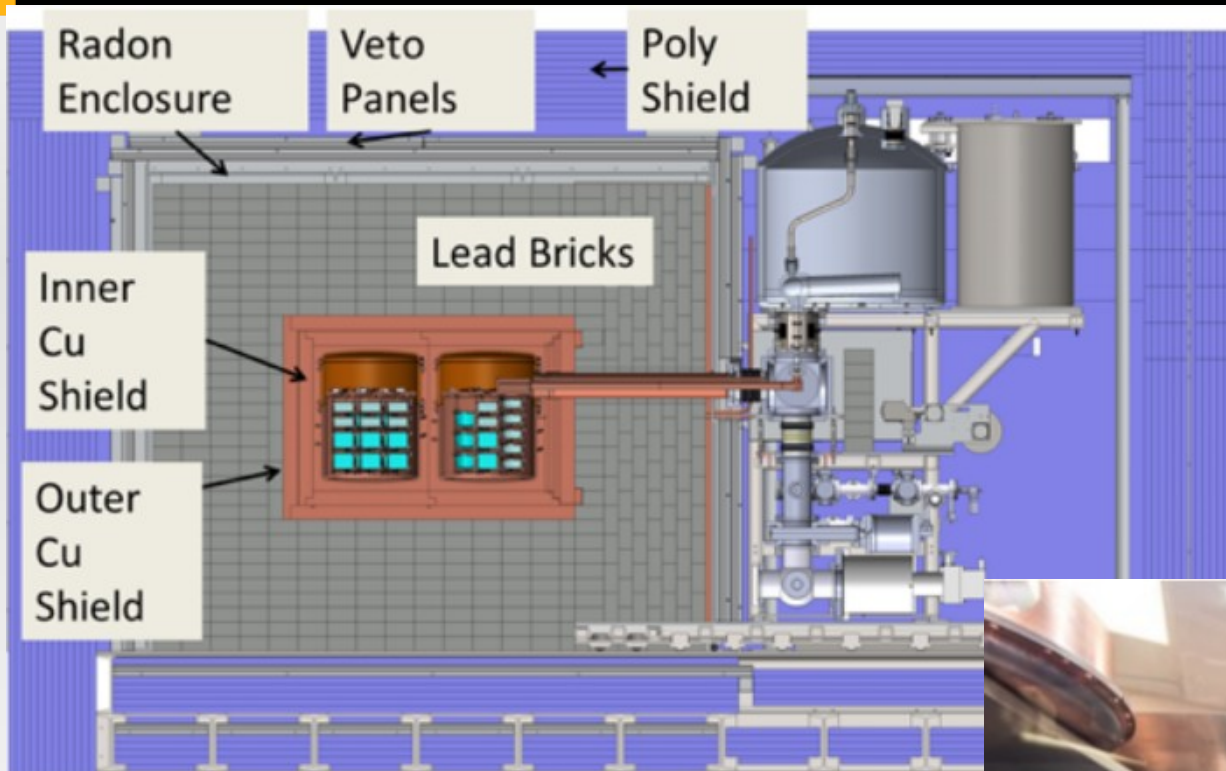


$$T_{1/2}^{0\nu} > 5.2 \cdot 10^{25} \text{ yr (90\% C.L.)}$$

sensitivity = $4.0 \cdot 10^{25} \text{ y}$
eventually $> 1 \cdot 10^{26} \text{ yr}$

first background-free experiment in field
(< 1 evt in FWHM until design exposure
for Phase II coaxial + BEGe detectors)

Majorana Demonstrator @ SURF



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

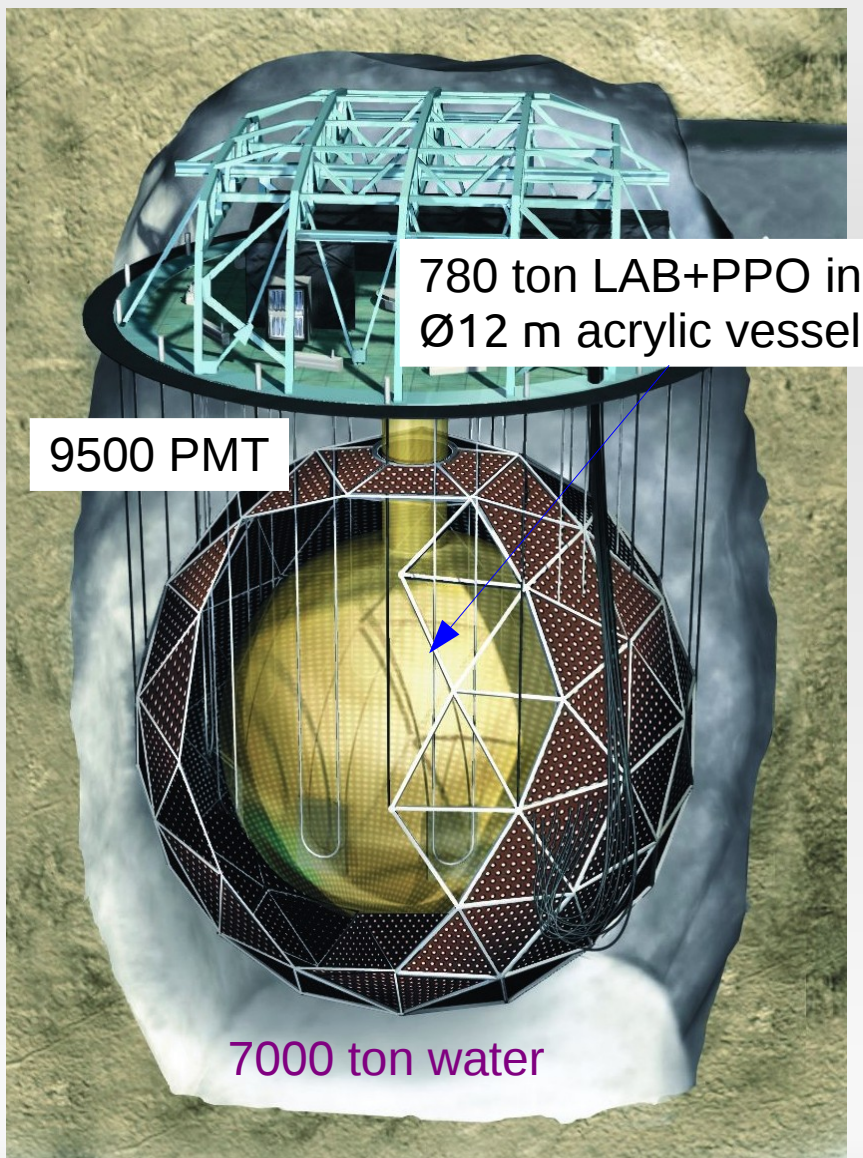
29 detectors, 2015 first installation running since Jan 2016

Module 2:

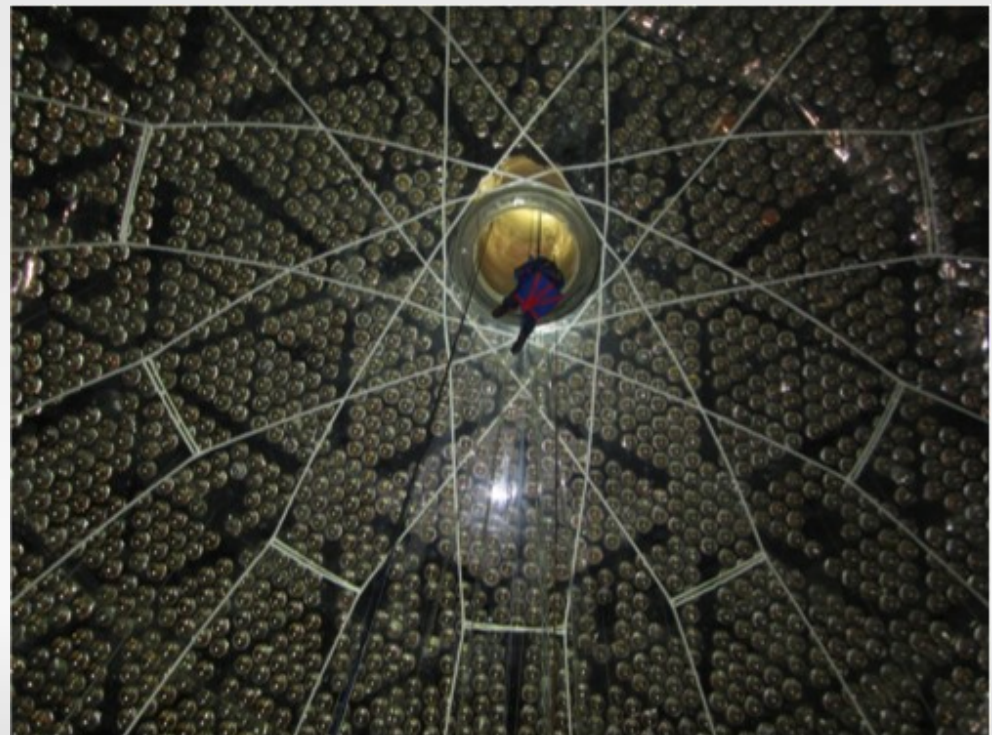
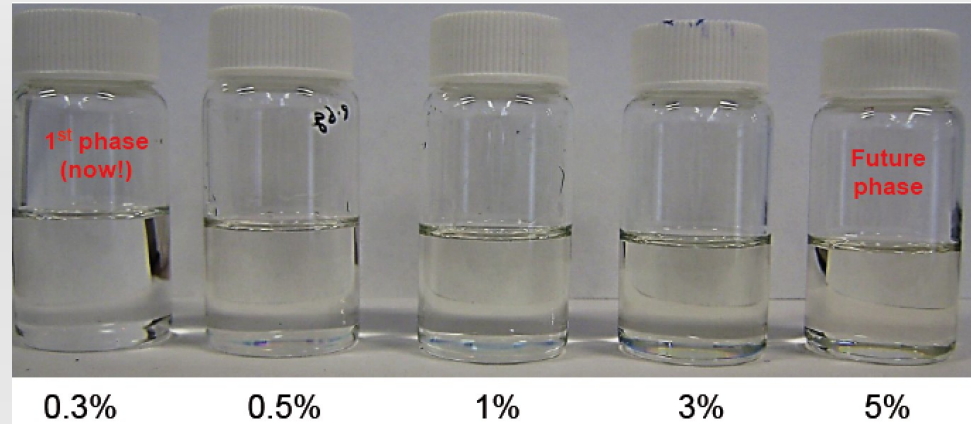
29 detectors, in few months complete

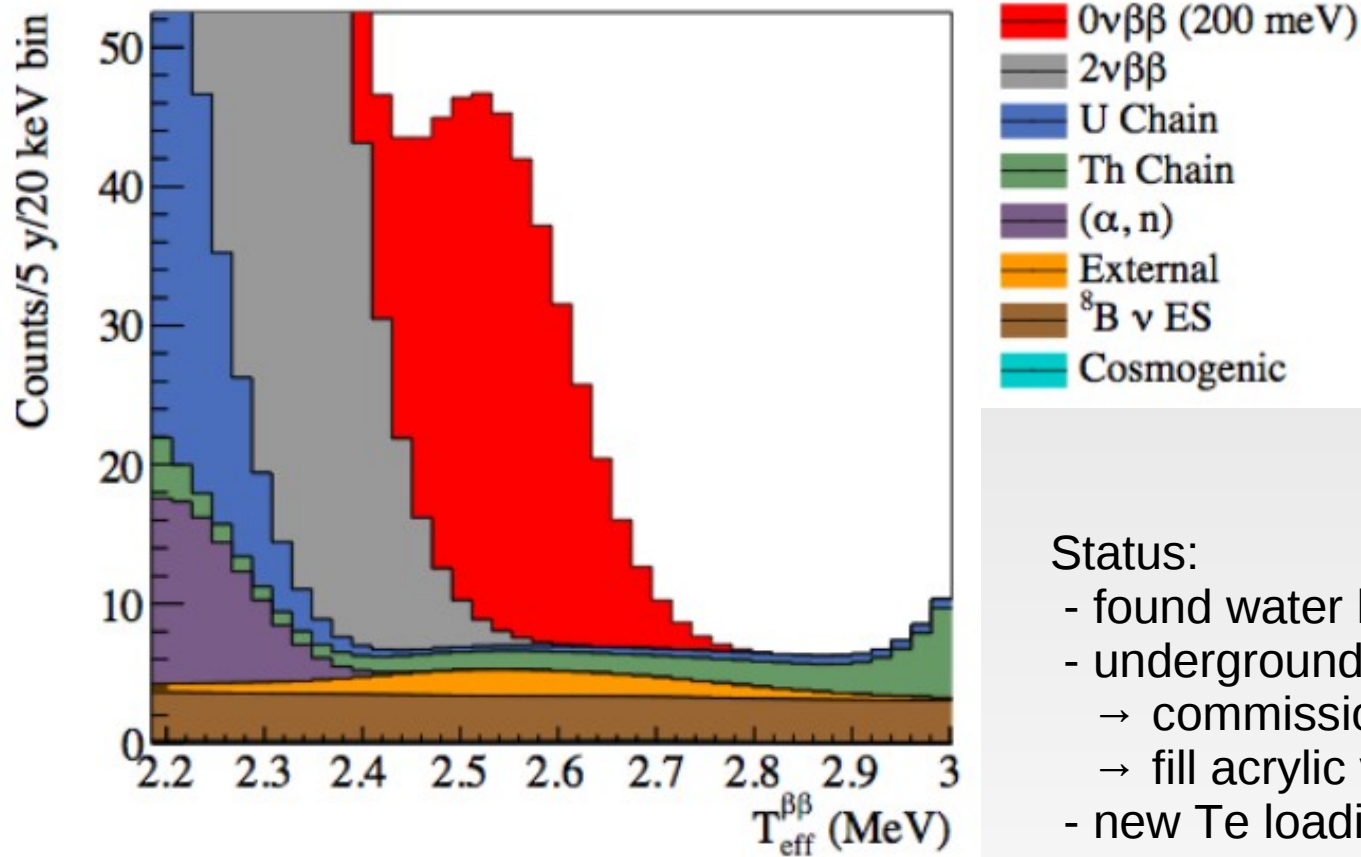


SNO+



default: 0.5% loading $\rightarrow$ 3900 kg $^{\text{nat}}\text{Te}$ / 1300 kg ^{130}Te





0.5% Te loading
FV: $R < 3.5$ m (20% vol)
390 p.e./MeV light yield

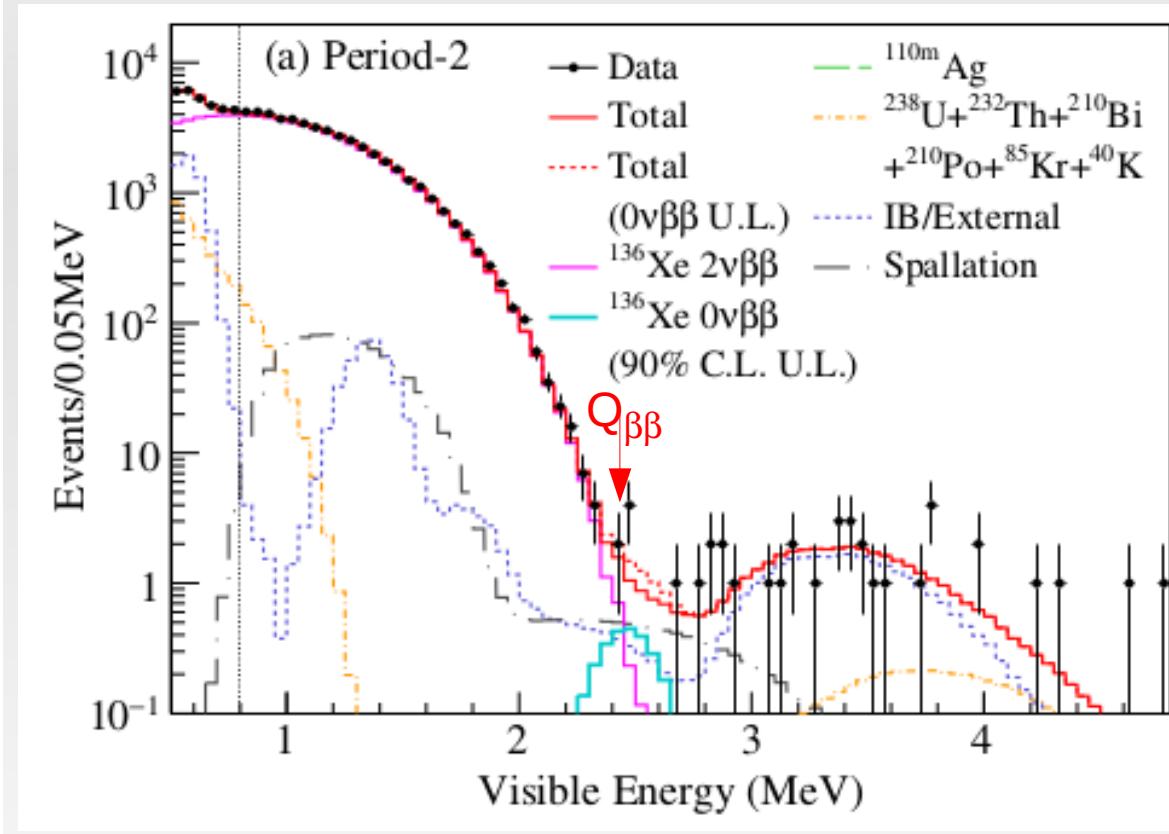
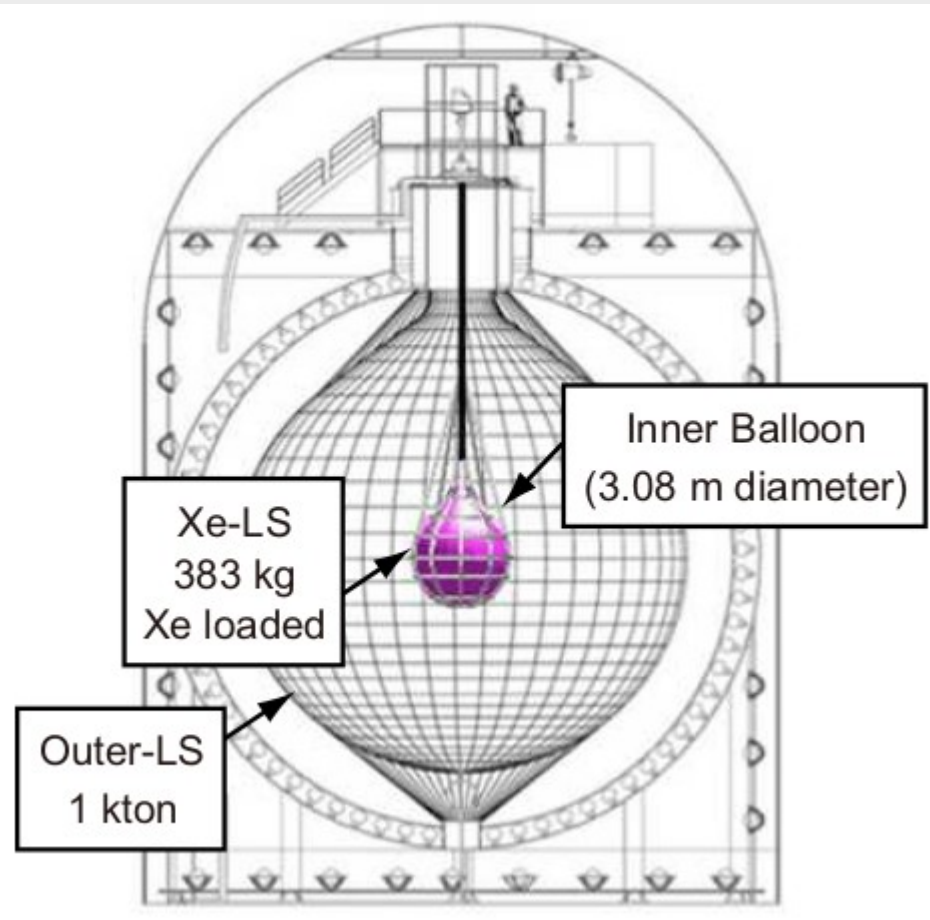
sensitivity 90% limit
 $T_{1/2} > 2 \cdot 10^{26}$ after 5 yr

Status:

- found water leak in cavity early 2016
- underground scintillator plant build
 - commissioning
 - fill acrylic vessel end of 2016
- new Te loading of scintillator
 - more light
- Te loading system design in 2016
- **loading Te end 2017**
 - start physics data taking

Kamland-Zen

arXiv:1605.02889



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

2012-13: purifications of scintillator and Xe

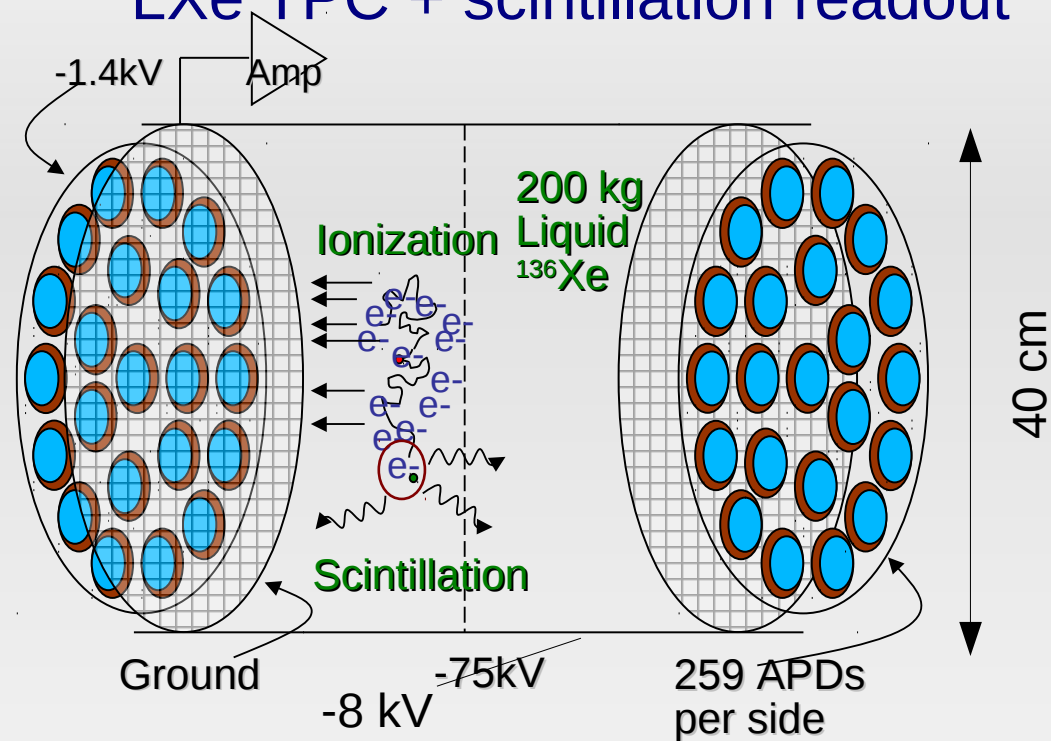
Dec 2013 – Oct 2015: phase II $\rightarrow$ $^{110\text{m}}\text{Ag}$ bkg factor 10 reduced, Xe loading 2.44% $\rightarrow$ 2.96%

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

current limit for $0\nu\beta\beta$ of ^{136}Xe : $T_{1/2}^{0\nu} > 10.7 \cdot 10^{25}$ yr (90% C.L.) sensitivity $\sim 5.6 \cdot 10^{25}$ yr

EXO-200 @ WIPP

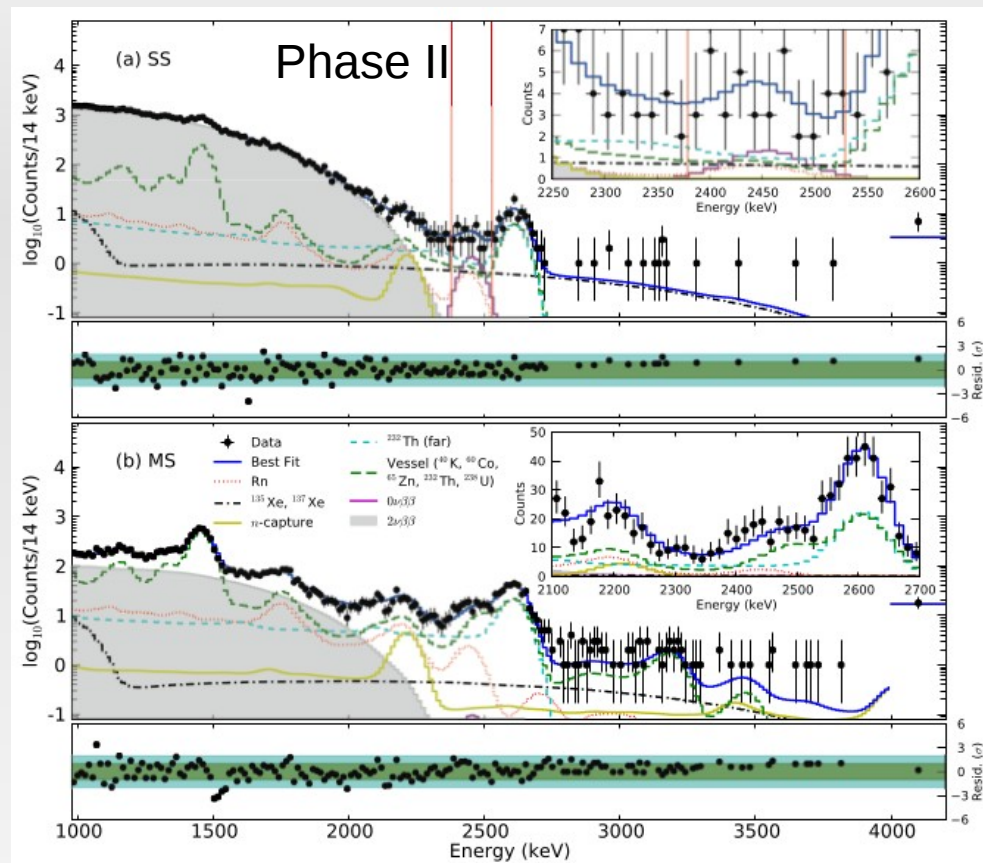
LXe TPC + scintillation readout



light+ionization FWHM for $0\nu\beta\beta$ ~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

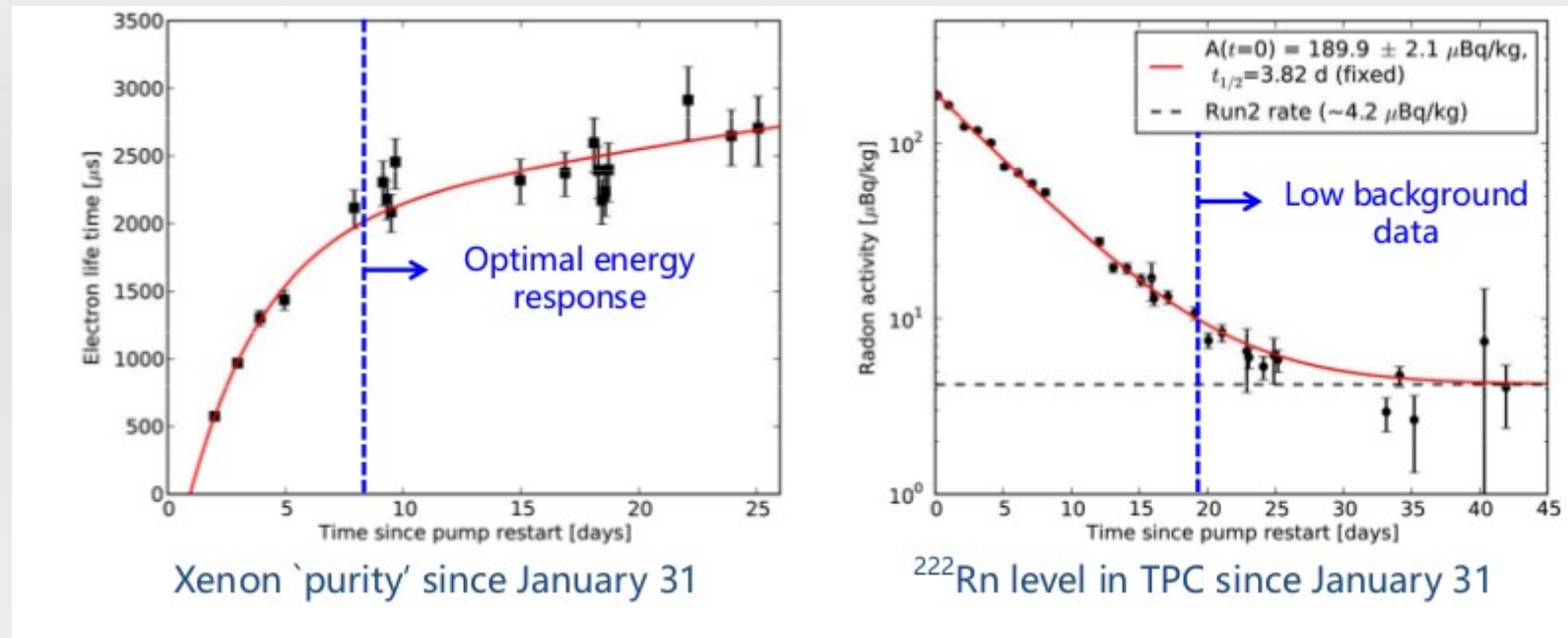


Phase II: Nature 510 (2014) 229-234
find/expect 39/31.1 evt @ $Q_{\beta\beta} \pm 2\sigma$

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

(sensitivity $1.9 \cdot 10^{25} \text{ yr}$)

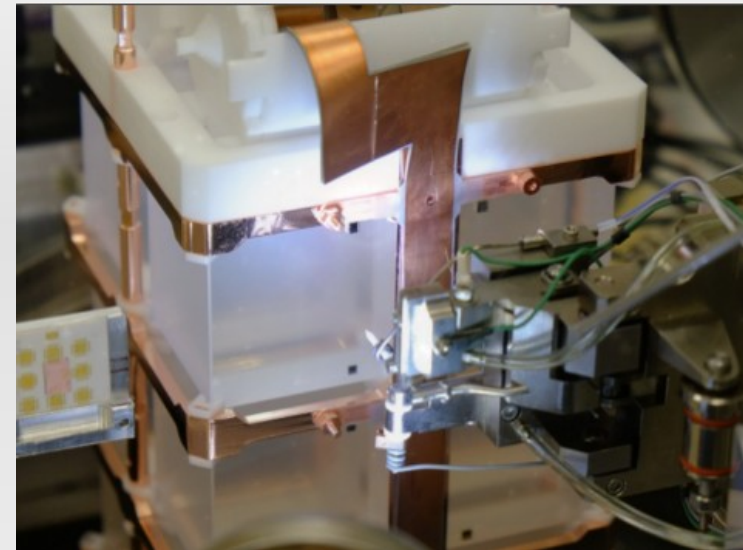
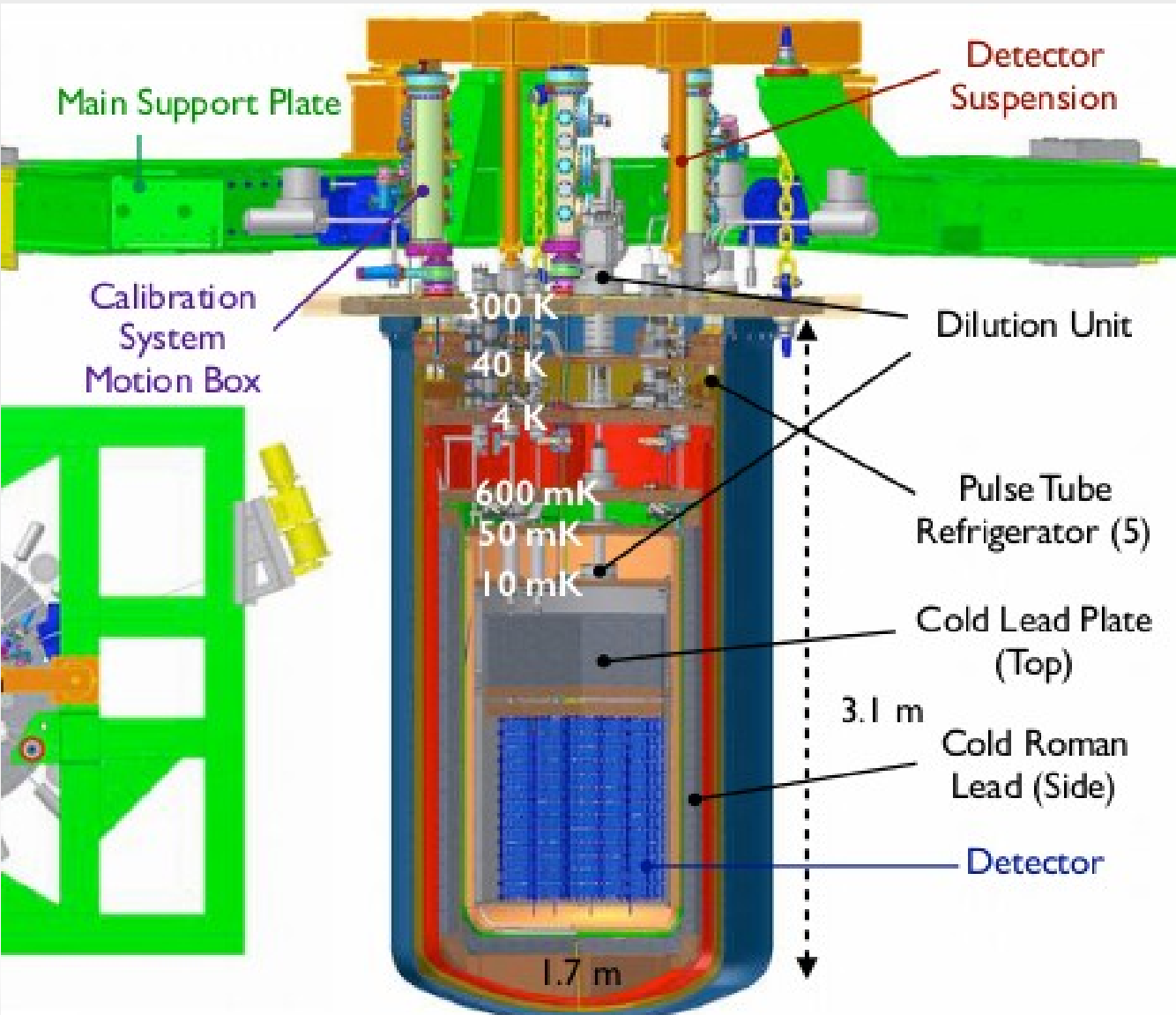
EXO-200 restart



lower noise electronics $\rightarrow$ FWHM improves to $\sim 60 \text{ keV}$
lower Rn level $\rightarrow$ expect lower background

after 3 yr running: sensitivity for 90% limit $T_{1/2} > 5.7 \cdot 10^{25} \text{ yr}$

Cuore: ^{130}Te



988 natTeO_2 crystals

206 kg ^{130}Te ,

calorimeter with Ge NTD readout,

$\Delta T \sim 0.1 \text{ mK} / \text{MeV}$

$\sim 5 \text{ keV FWHM}$

all towers are assembled!

test cool down of cryostat ok,

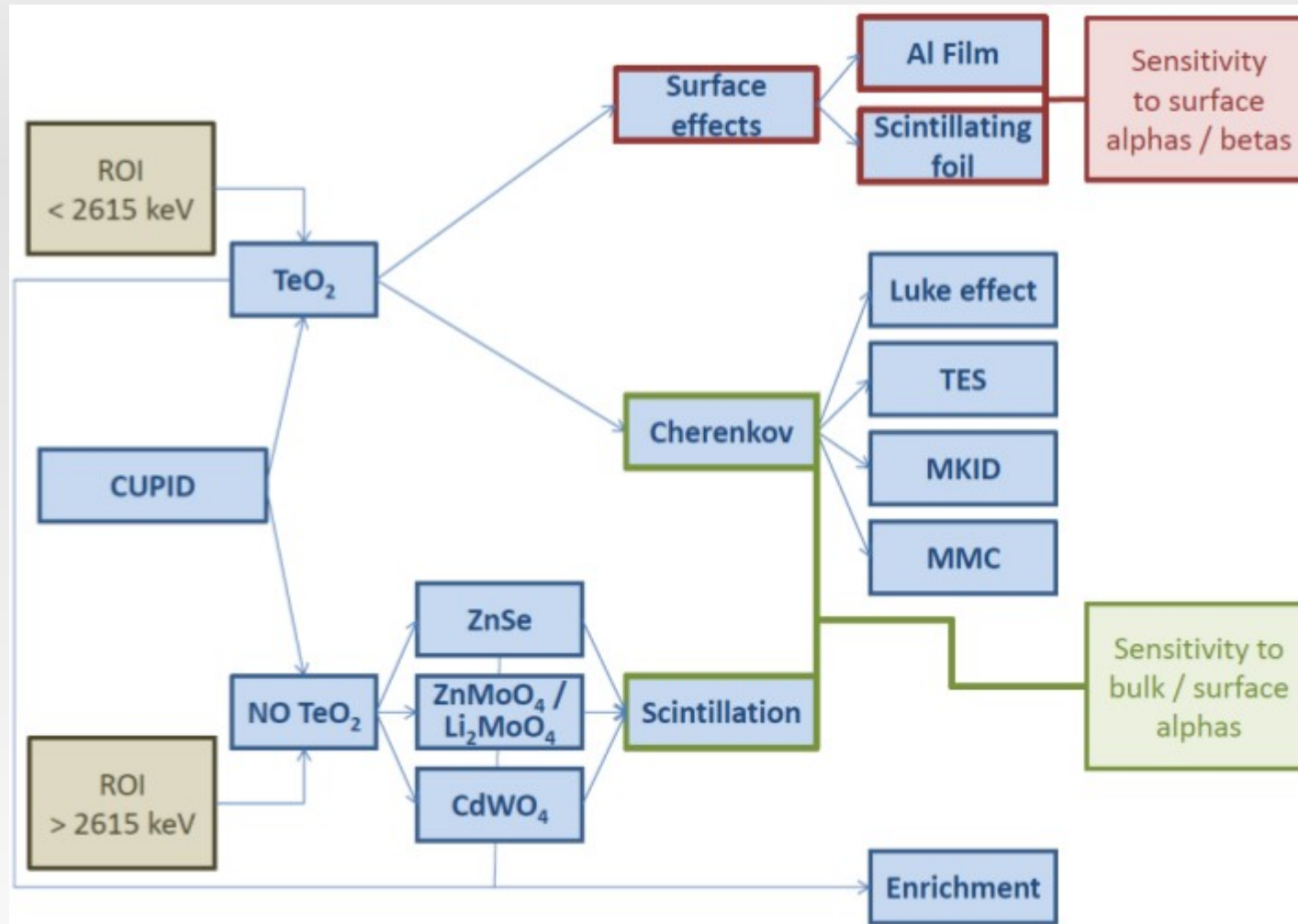
next: step mount towers +
commissioning

physics run start end 2016,

sensitivity 90% limit $\sim 1 \cdot 10^{26} \text{ yr}$

CUPID proposal

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

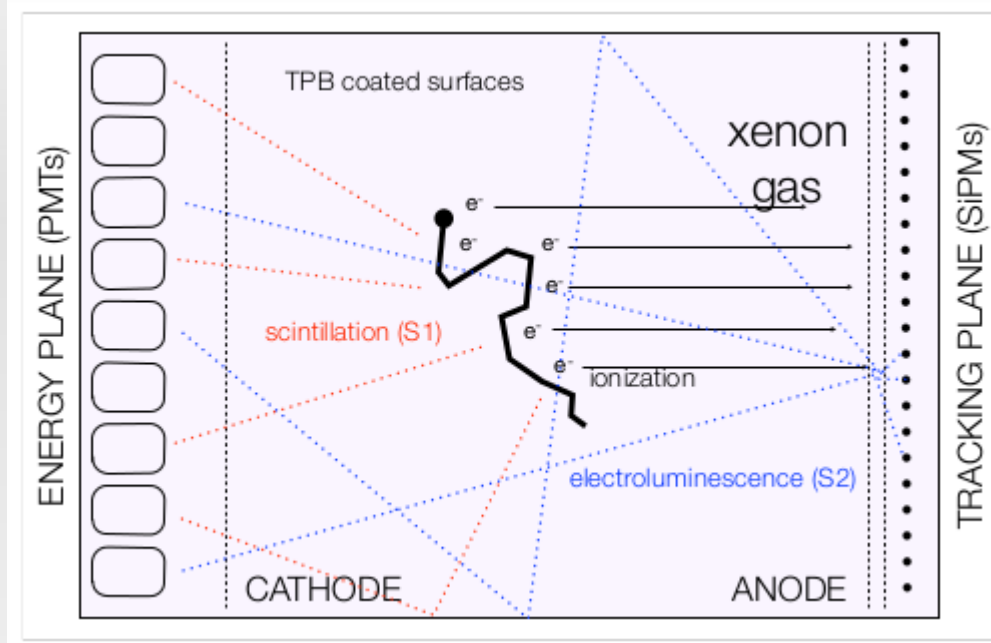


combination of all bolometer efforts and technologies, several R&D efforts, choose best technique in 2017-18

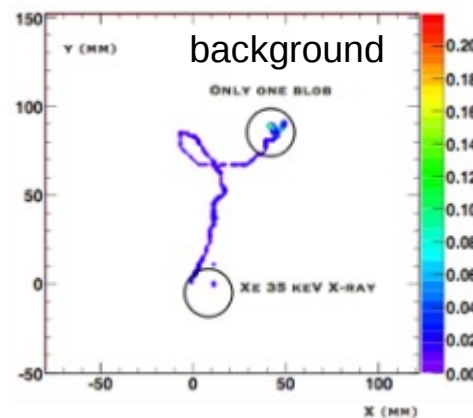
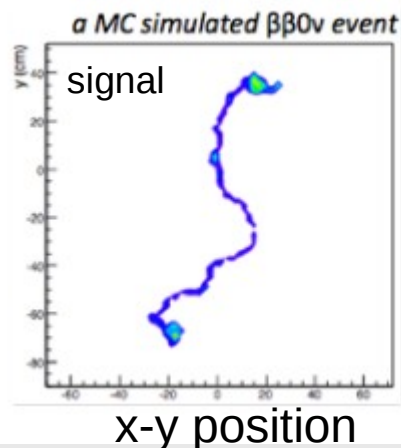
arXiv:1504.03612

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

NEXT @ Canfranc



tracking of electrons



- 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



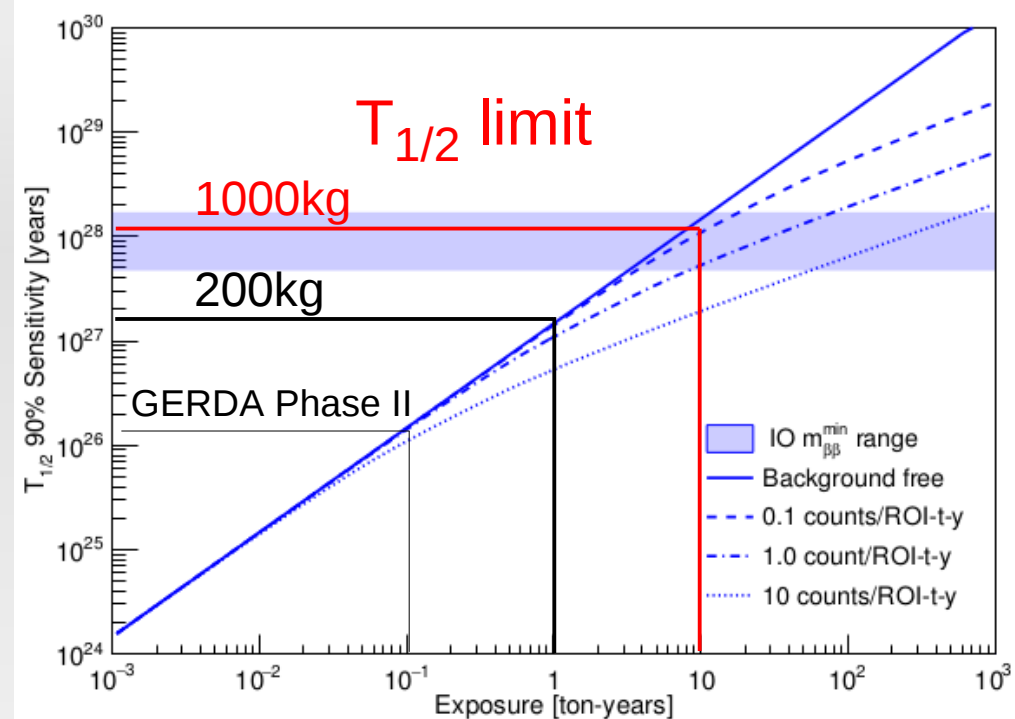
(2015–2017)
Test underground,
radiopure operation



(2018–2020)
Neutrinoless
double beta decay
searches

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

^{76}Ge sensitivity limit + discovery



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

"background free" very important
(for all isotopes)

plots by Jason Detwiler based on
 $m_{ee} = 18 \text{ meV}$, current matrix element calc.

GERDA numbers for efficiency & enrichment

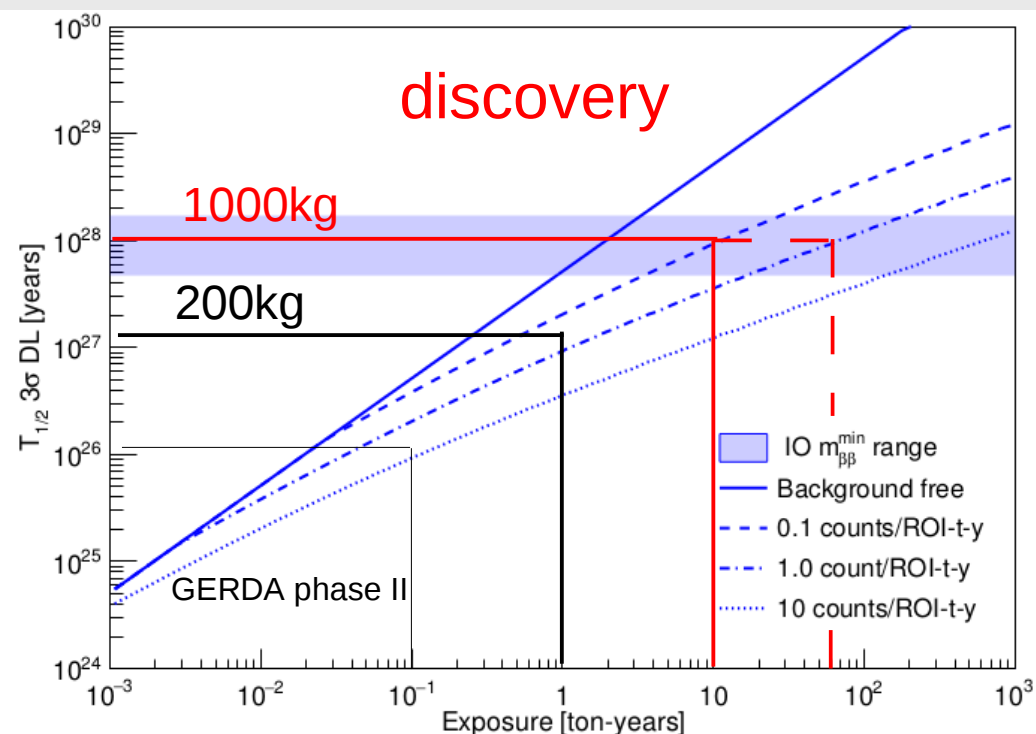
GERDA Phase I ~ 30 cnt/(ROI t yr) - achieved

Phase II ~ 3 cnt/(ROI t yr) - goal

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



200 kg in GERDA



- Cryostat large enough: current $\varnothing$ 500 can be enlarge to $\varnothing$ 630
- more cables and feedthroughs
- improve detection of LAr scintillation light
- bigger Ge detectors $\rightarrow$ few channel ?

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

- intrinsic bkg: Th/U not found in Ge detectors,
cosmogenic $^{68}\text{Ge}/^{60}\text{Co}$: limit time above GND, PSD $\rightarrow$ 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 ($\rightarrow$ dead time),
simulation $\rightarrow$ ok for 200 kg setup

cost $\sim 15\text{M}$ 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= $0\nu\beta\beta$ isotope mass in fiducial volume (incl enrichment fraction)
 & kg of $0\nu\beta\beta$ isotope in active volume and divided by $0\nu\beta\beta$ 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