Neutrinoless double beta decay with ^{76}Ge

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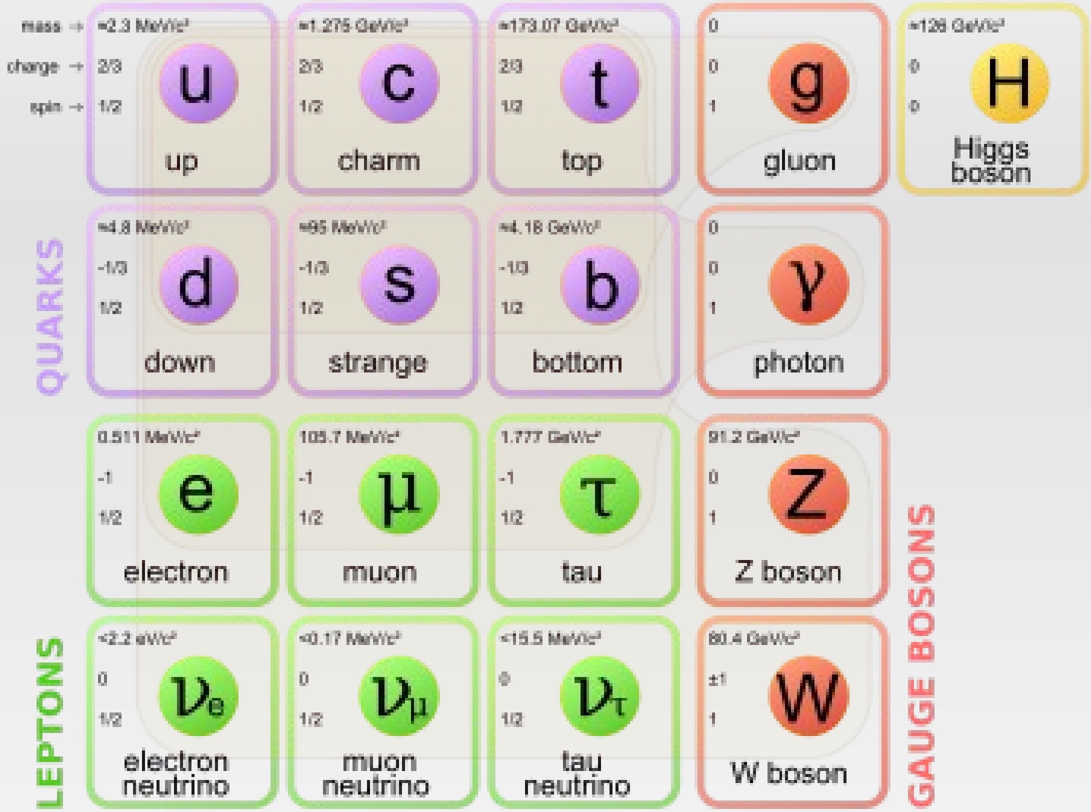
Standard Model

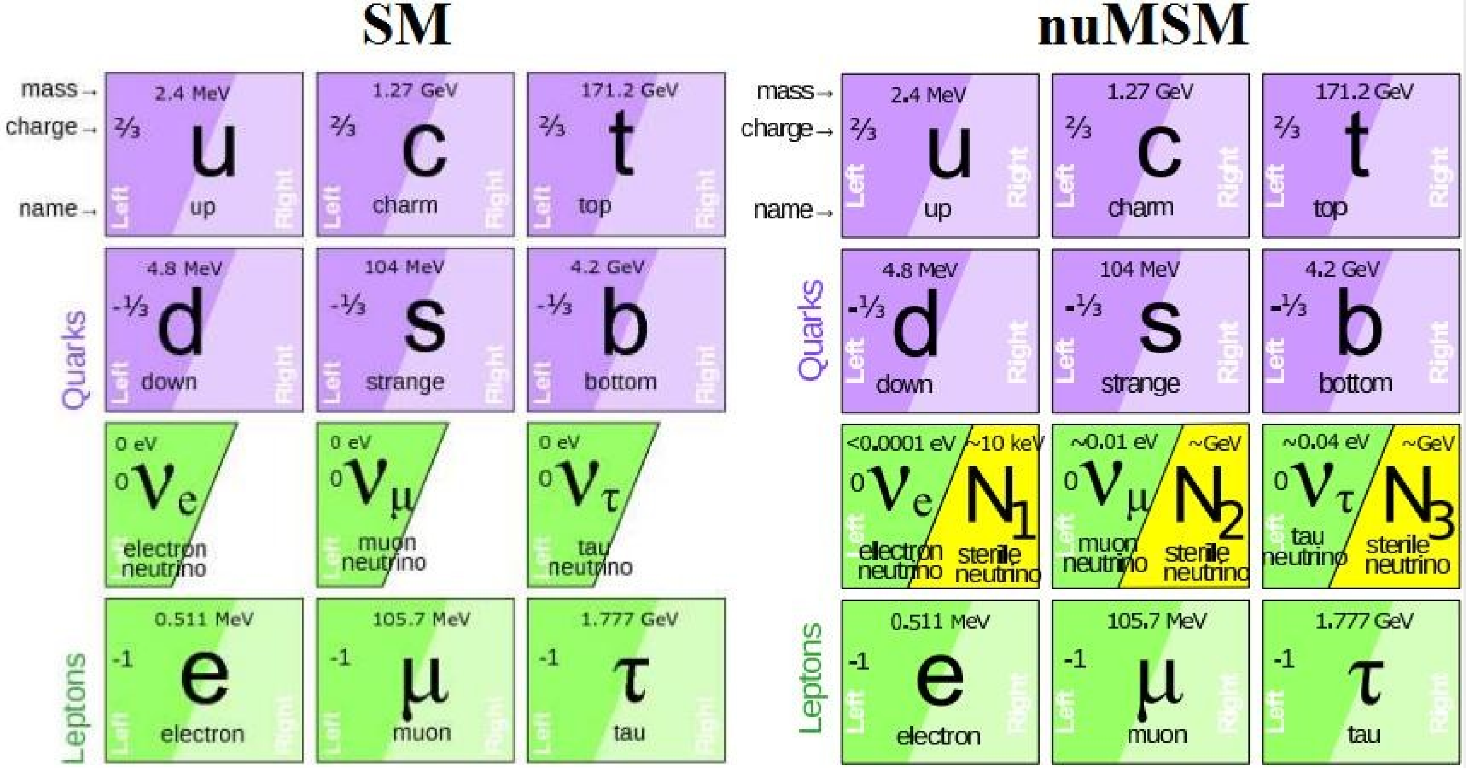


no new physics found at the LHC so far, SM could be valid up to Planck scale

BUT

- no dark matter candidate
- baryon asymmetry of the universe not explained
- dark energy not understood
- origin of (tiny) neutrino mass unknown

Neutrino mass: non-SM effect?



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

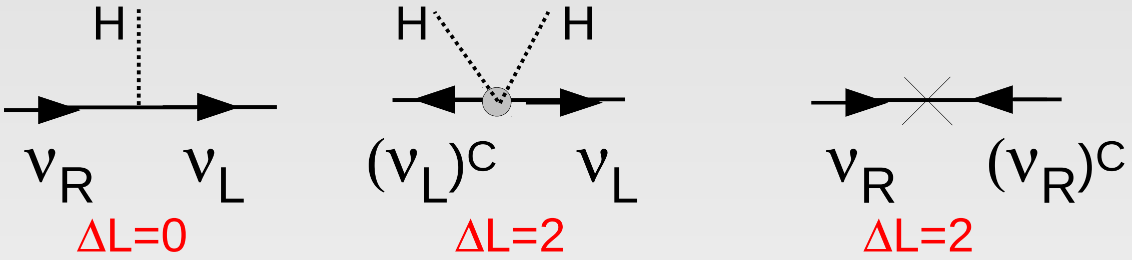
ν oscillations (Nobel prize 2015) → ν_L have (tiny) mass (< m_e / 10^6)

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 ~ 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 ~0)	m_R	m_D^2 / m_R	

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 ~ m_D^2 / M_R

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

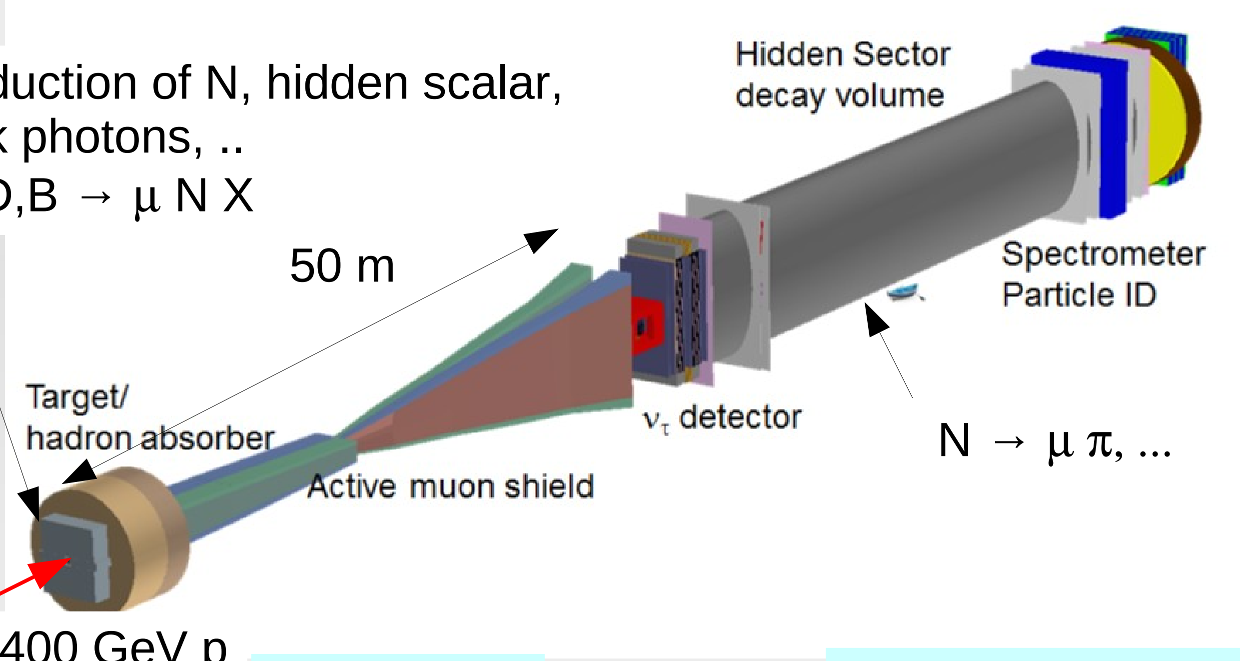
GeV: can explain baryon asymmetry
if <5 GeV observation e.g. $D \rightarrow N \mu X$ with $N \rightarrow \mu \pi$ by SHIP (200 MCHF)

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

eV range: LSND oscillation signal, reactor anomaly, … → SOX, Stereo, …
contribute to number of relativistic neutrinos measured by PLANCK

neutrino minimal SM (νMSM): 1x 10 keV N for DM and 2x ~GeV N for baryon asymmetry,
minimal extension of SM

SHIP proposal @ SPS



production of N, hidden scalar,
dark photons, ..
by D,B → μ N X

50 m

N → $\mu\ \pi$, ...

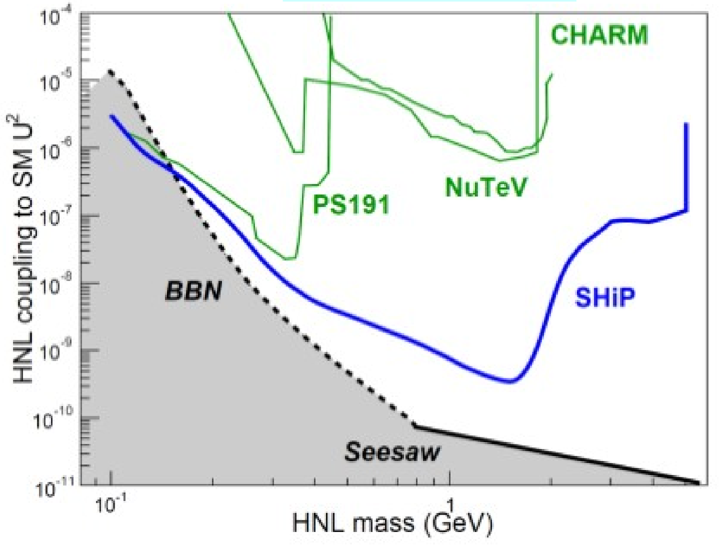
SPS 400 GeV p

arXiv:1504.04956
arXiv:1504.04855

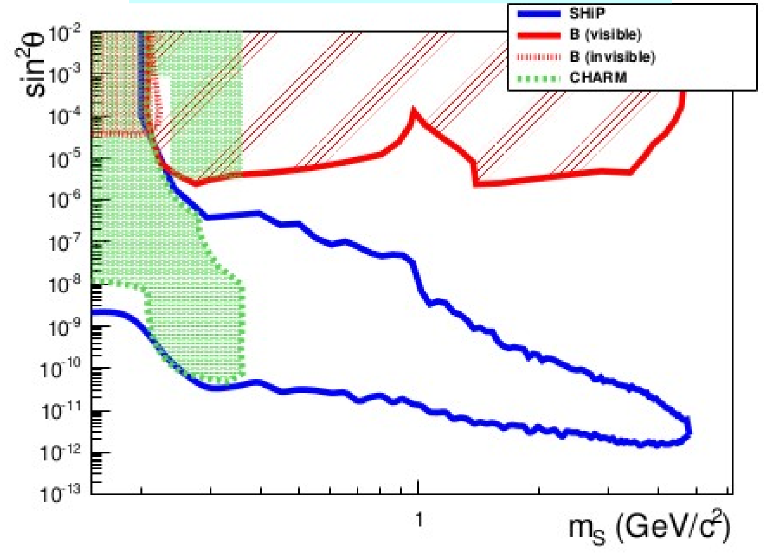
uses CNGS beam line,
total 2 10^{20} pot
~8 10^{17} D mesons

cost for beam+exp 200 MCHF

sensitivity N

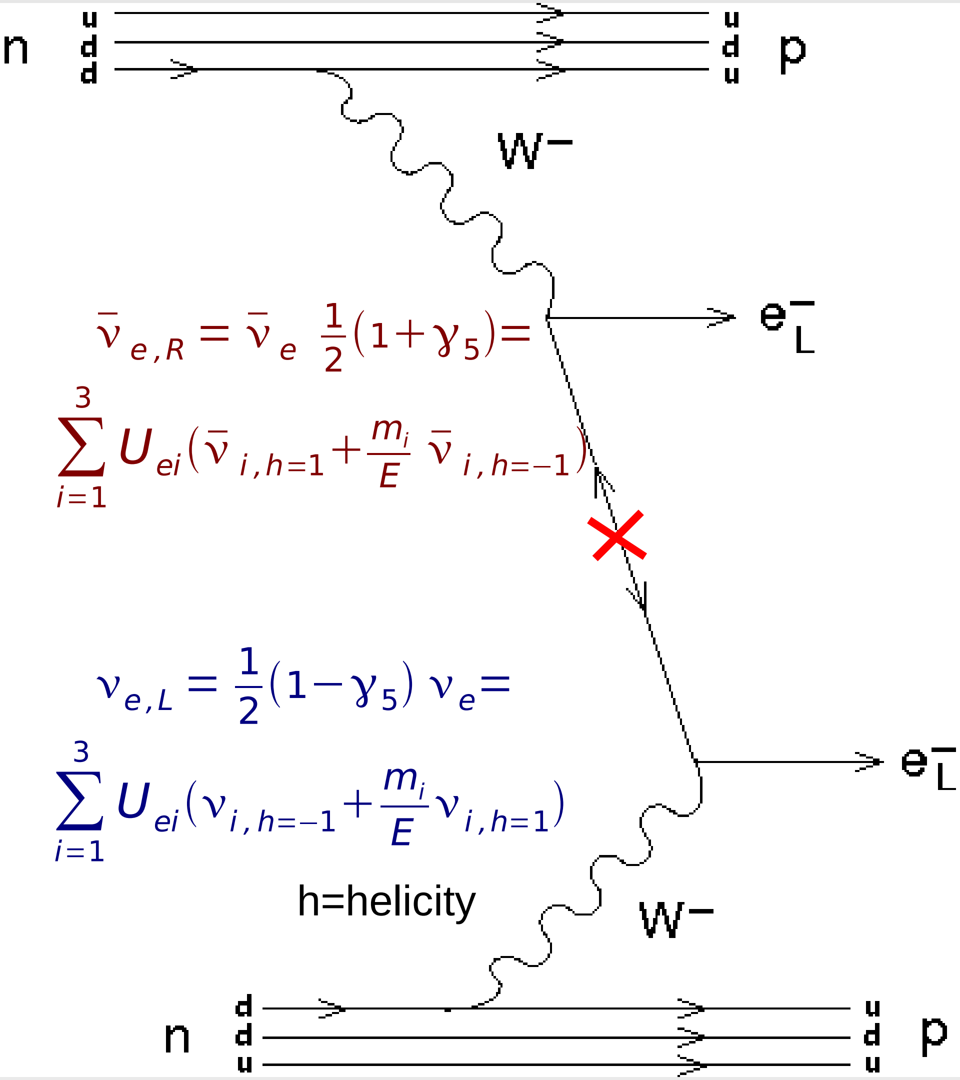


sensitivity hidden scalar



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

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



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

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

h=helicity

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

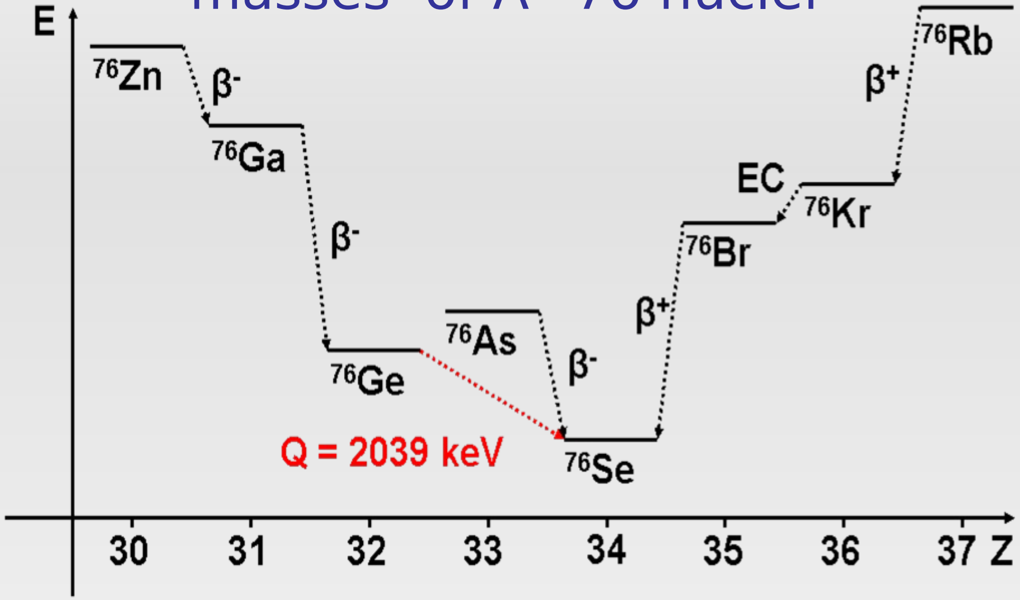
function of
- neutrino mixing parameters
- lightest neutrino mass
- 2 Majorana phases

also possible: heavy N exchange

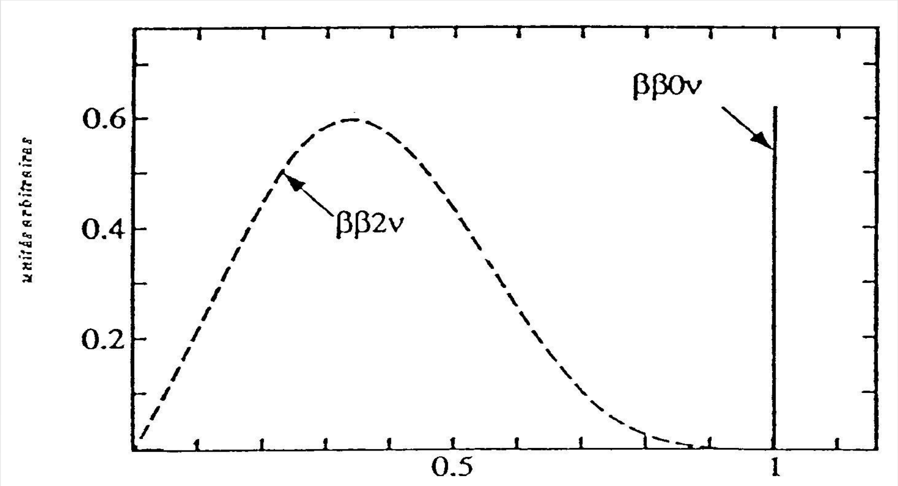
→ coupling strength ~ $\sum_{i=1}^{3} V_{ei}^2 / M_i$

Neutrinoless double beta decay

masses of A=76 nuclei



experimental signature for ββ



sum electron energies / $Q_{\beta\beta}$

”single” beta decay not allowed

$\longrightarrow$ only ”double beta decay”

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

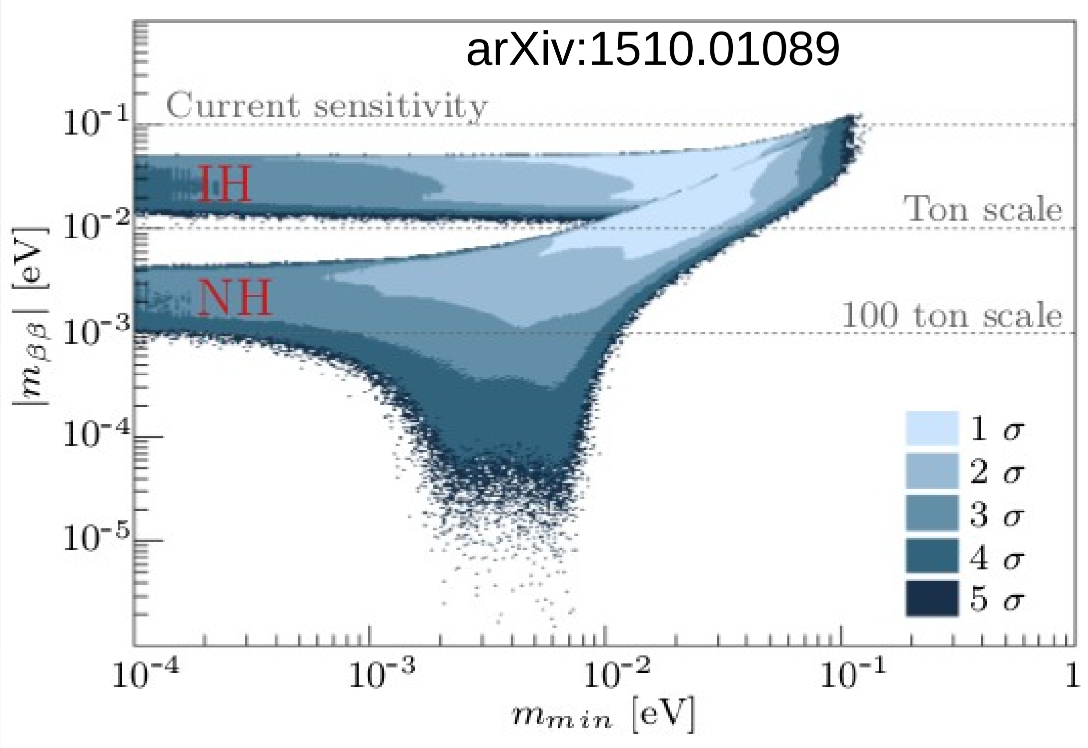
$(A,Z) \longrightarrow (A,Z+2) + 2\,e^-$ $\Delta L=2$

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

Light Majorana neutrino exchange

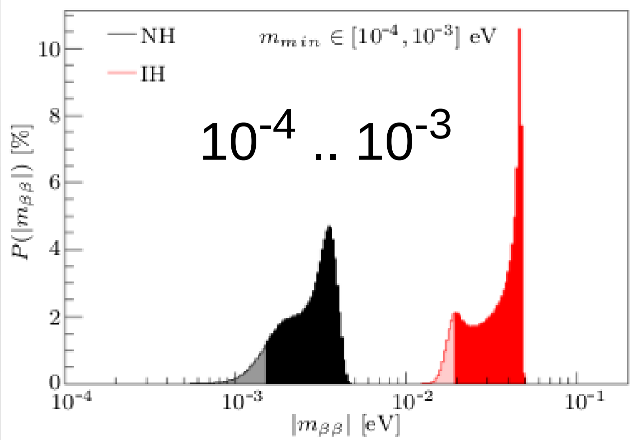
scan of $m_{\beta\beta}(\Delta m_{atm}^2, \Delta m_{sol}^2, m_{min}, \theta_{atm}, \theta_{sol}, \theta_{13}$, 2 Majorana $\Phi)$
according to measurements or random (2 Maj. phases)

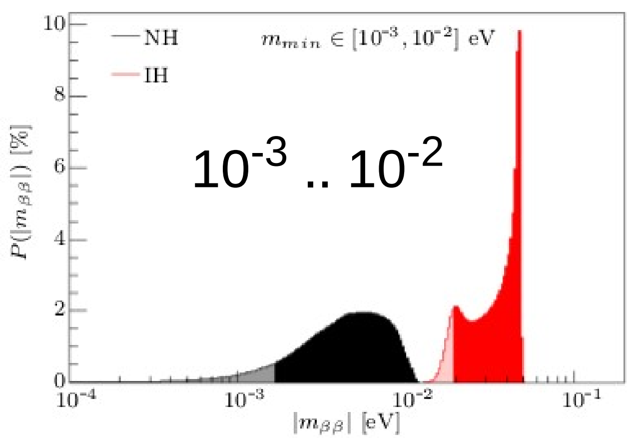

arXiv:1510.01089

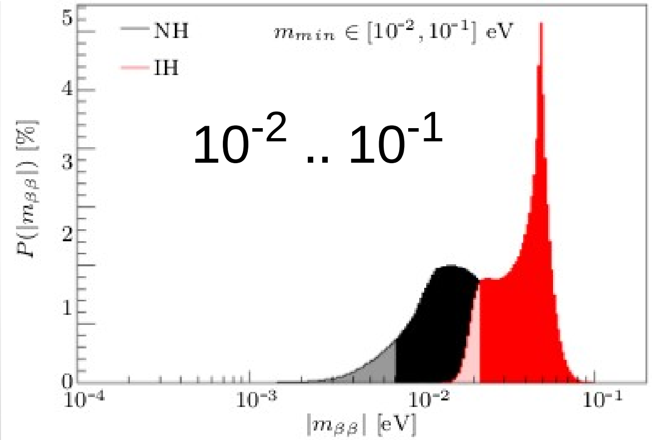
including cosmological bound $\Sigma = (22 \pm 62)$ meV[1]

[1] true for flat ΛCDM only

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


10^{-4} .. 10^{-3}

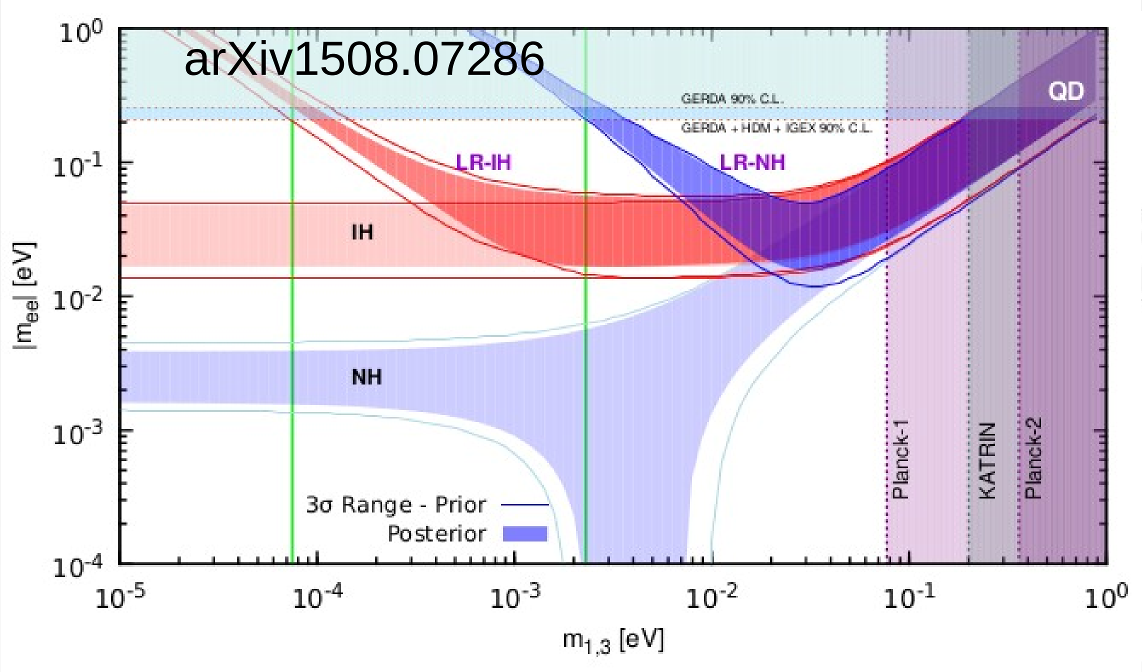

10^{-3} .. 10^{-2}

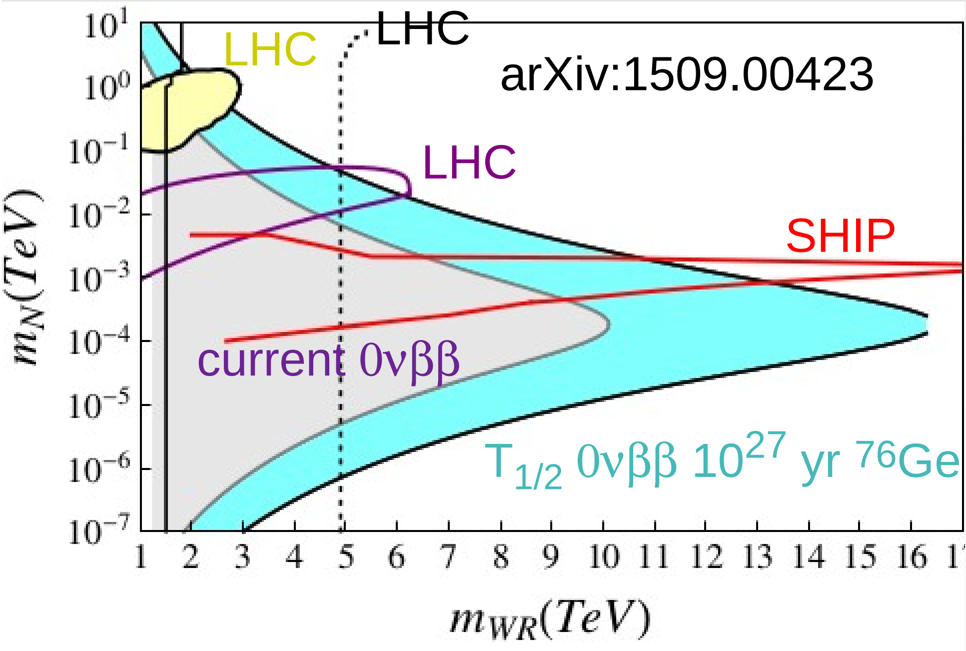

10^{-2} .. 10^{-1}

LHC vs 0νββ: other mechanisms

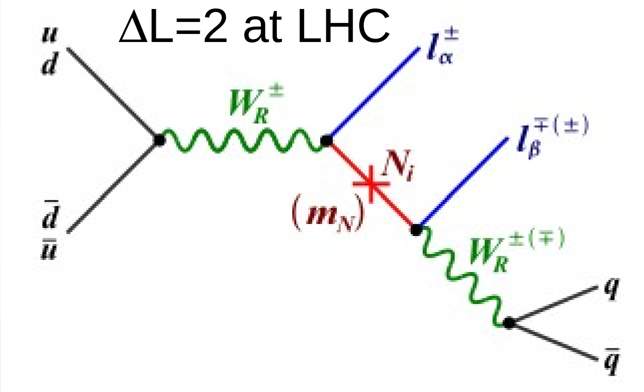
extensions of SM → other contributions to 0νββ possible, example LRSM

LHC might find W_R and/or ΔL=2 process


arXiv1508.07286

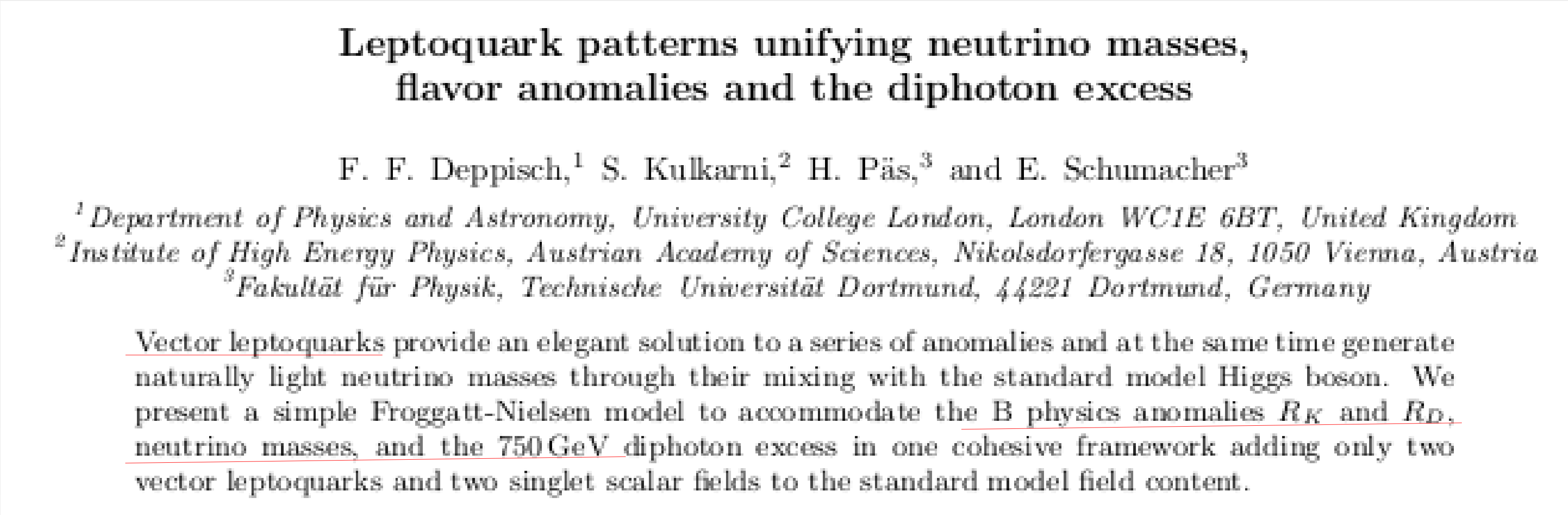

arXiv:1509.00423

ΔL=2 at LHC



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

LHC vs 0νββ: other mechanisms



Leptoquark patterns unifying neutrino masses, flavor anomalies and the diphoton excess

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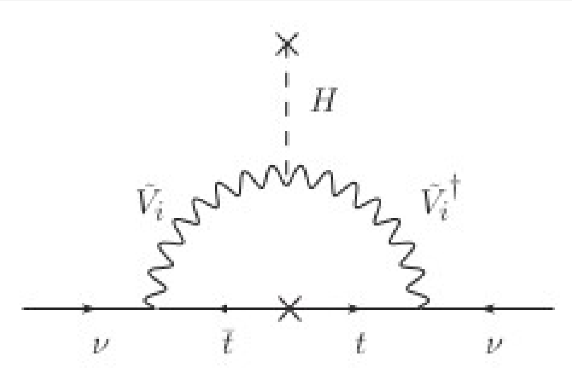
[2] *Institute of High Energy Physics, Austrian Academy of Sciences, Nikolsdorfergasse 18, 1050 Vienna, Austria*
[3] *Fakultät für Physik, Technische Universität Dortmund, 44221 Dortmund, Germany*

Vector leptoquarks provide an elegant solution to a series of anomalies and at the same time generate naturally light neutrino masses through their mixing with the standard model Higgs boson. We present a simple Froggatt-Nielsen model to accommodate the B physics anomalies R_K and R_D, neutrino masses, and the 750 GeV diphoton excess in one cohesive framework adding only two vector leptoquarks and two singlet scalar fields to the standard model field content.



ν Majorana mass term

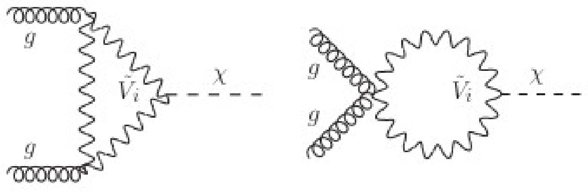


Figure 5: Dominating diagrams contributing to $\sigma(pp \to \chi)$.

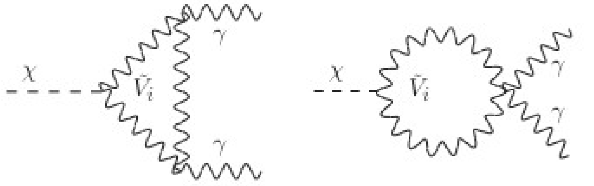


Figure 6: Diagrams contributing to $\Gamma(\chi \to \gamma\gamma)$.

preferential coupling
to gluon + photon
→ 750 GeV γγ @ LHC

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 $0\nu\beta\beta$ 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

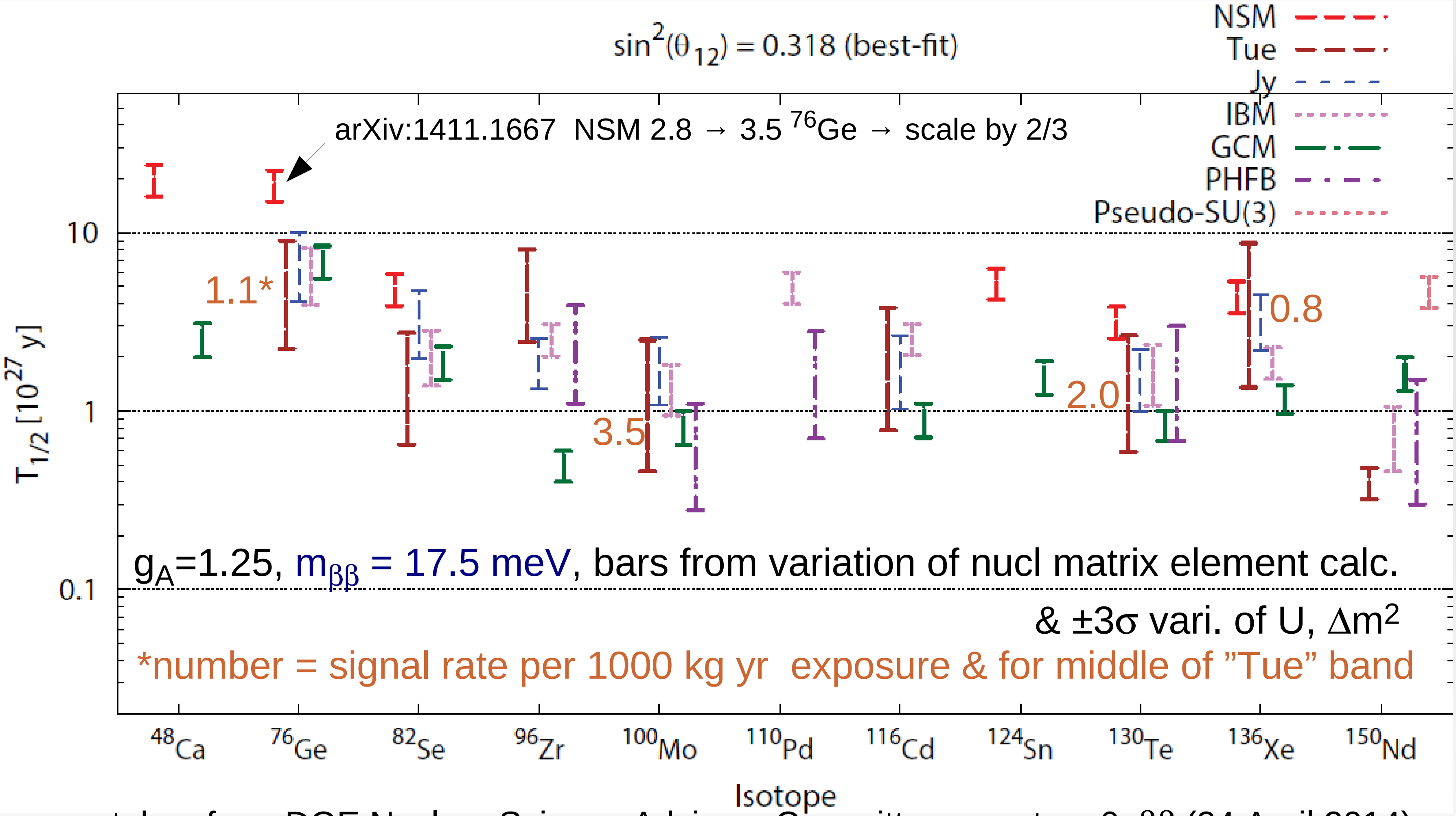
Experiment observes $N^{0\nu} = \ln 2 \frac{N_A}{A} \cdot a \cdot \epsilon \cdot M \cdot t \,/\, T_{1/2}$ and $N^{bkg} = M \cdot t \cdot B \cdot \Delta E$

Experimental sensitivity

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

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



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

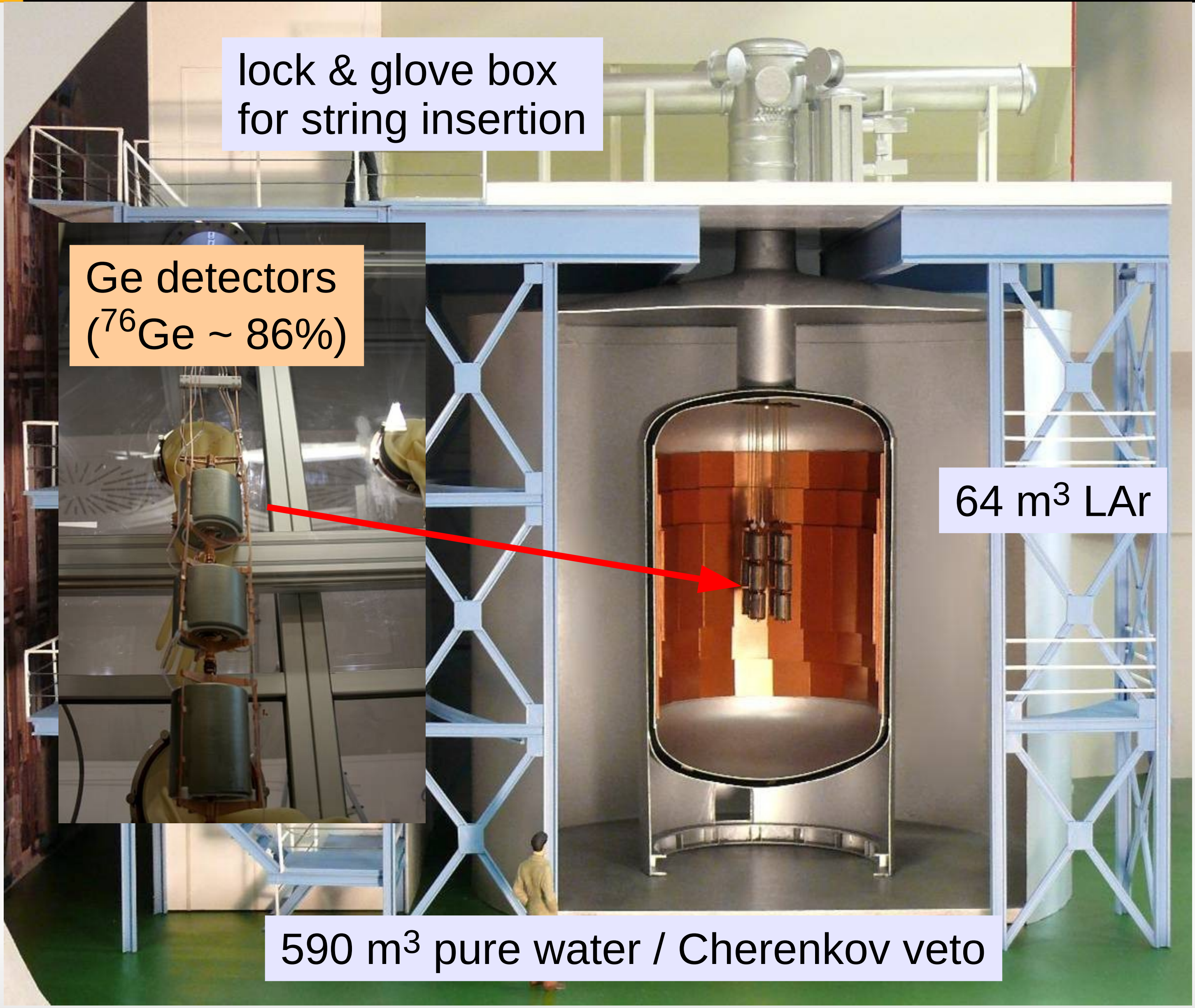
→ identify background events (multi-dim. selection) →

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



EPJ C73 (2013) 2330

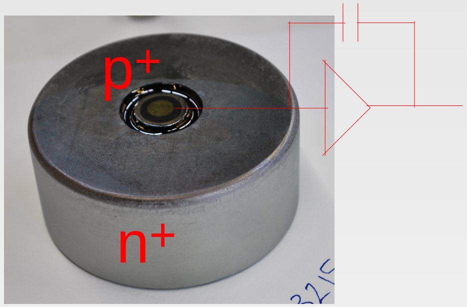
Phase I (2011-13):

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

^{76}Ge 0νββ decay, PRL 111 122503

Phase II:

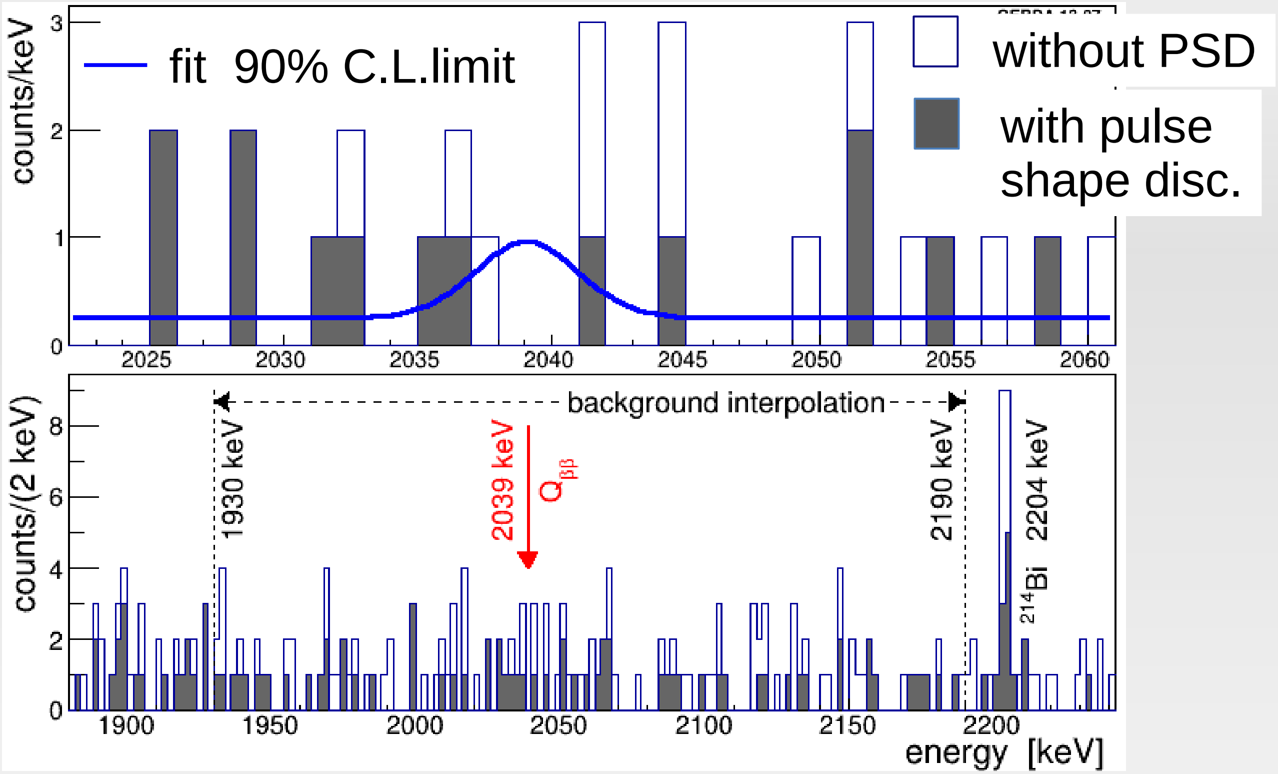
2x Ge mass (30 BEGe det.)



LAr scint. light readout

started end 2015

GERDA phase I results



events ±20 keV blinded

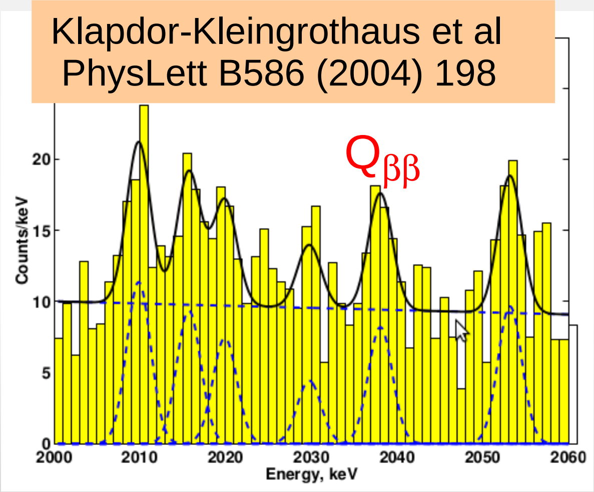
after calibration+selection finished
→ unblinding at meeting
in Dubna in June 2013

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

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

(sensitivity = 2.4 10^{25} yr)

PRL 111 (2013) 122503.



Klapdor-Kleingrothaus et al
PhysLett B586 (2004) 198

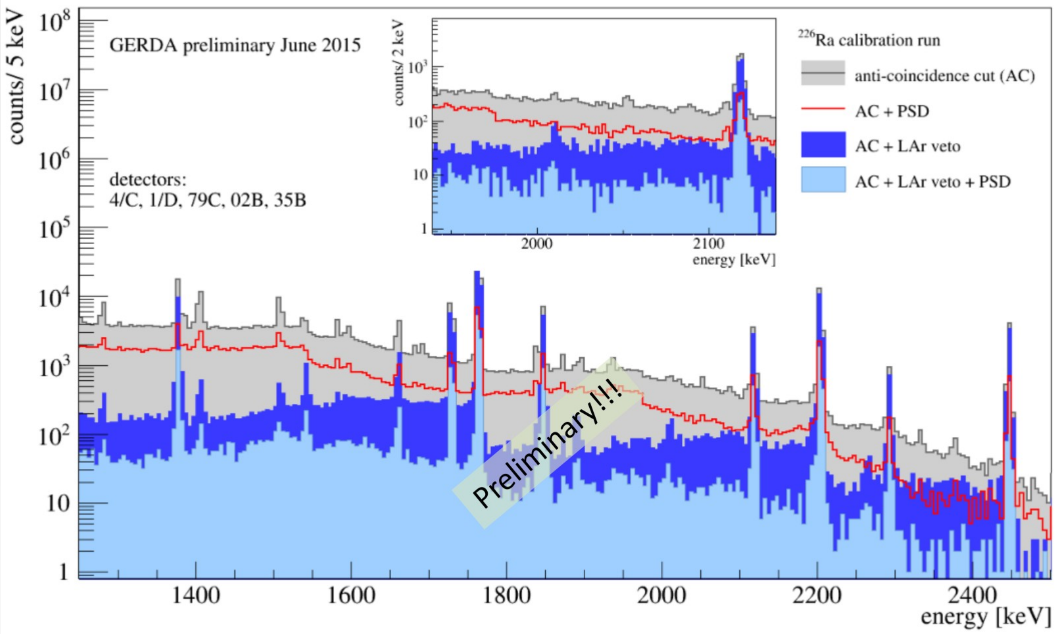
claimed signal: GERDA should see 5.9±1.4 0νββ events in ±2σ interval above background of 2.0±0.3

probability p($N^{0\nu}$=0 | H_1=signal+bkg) = 1%, claim ruled out @ 99%

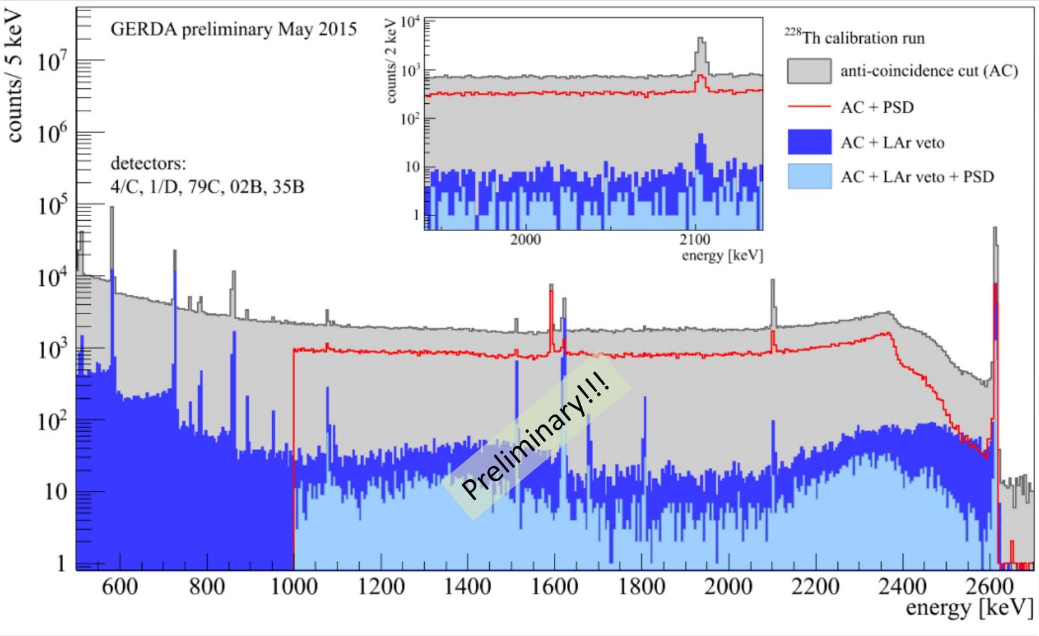
(GERDA best fit signal count $N^{0\nu}$ = 0)

Argon veto performance

^{226}Ra calibration source



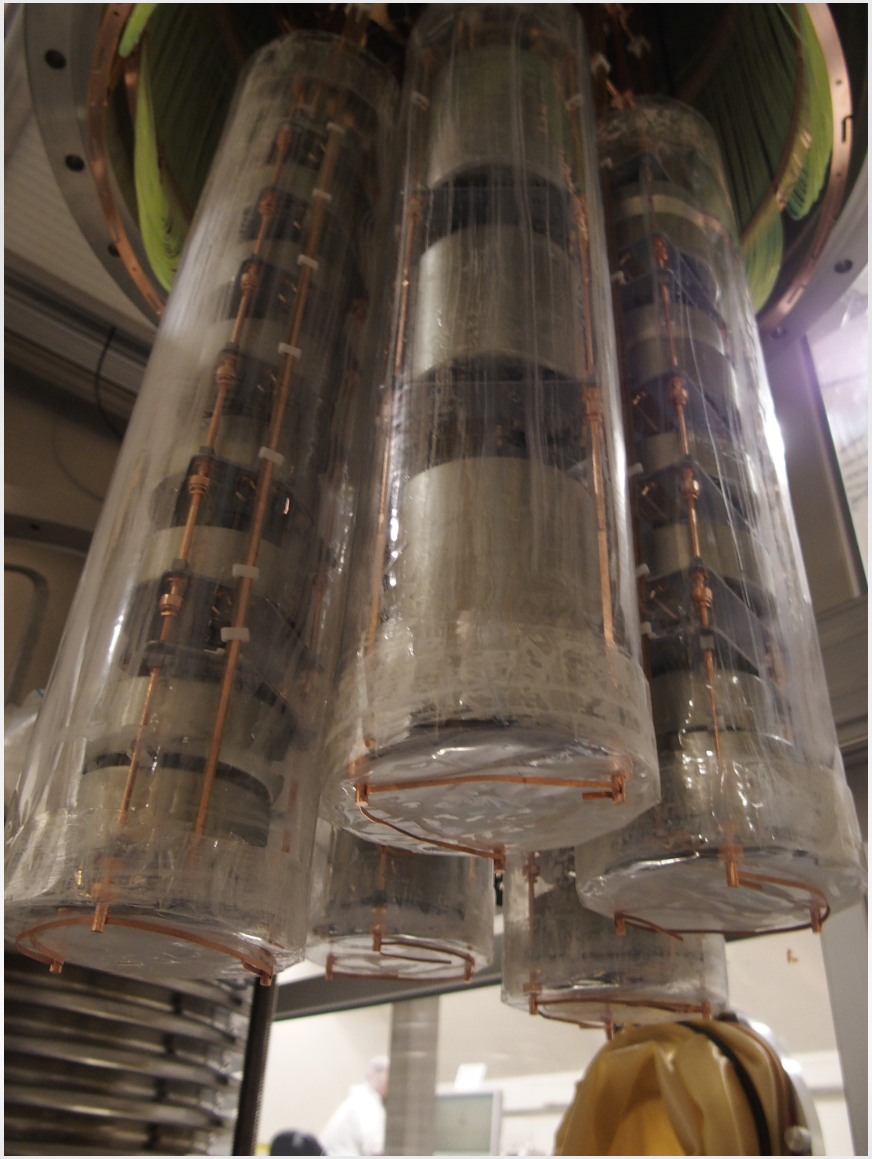
^{228}Th calibration source

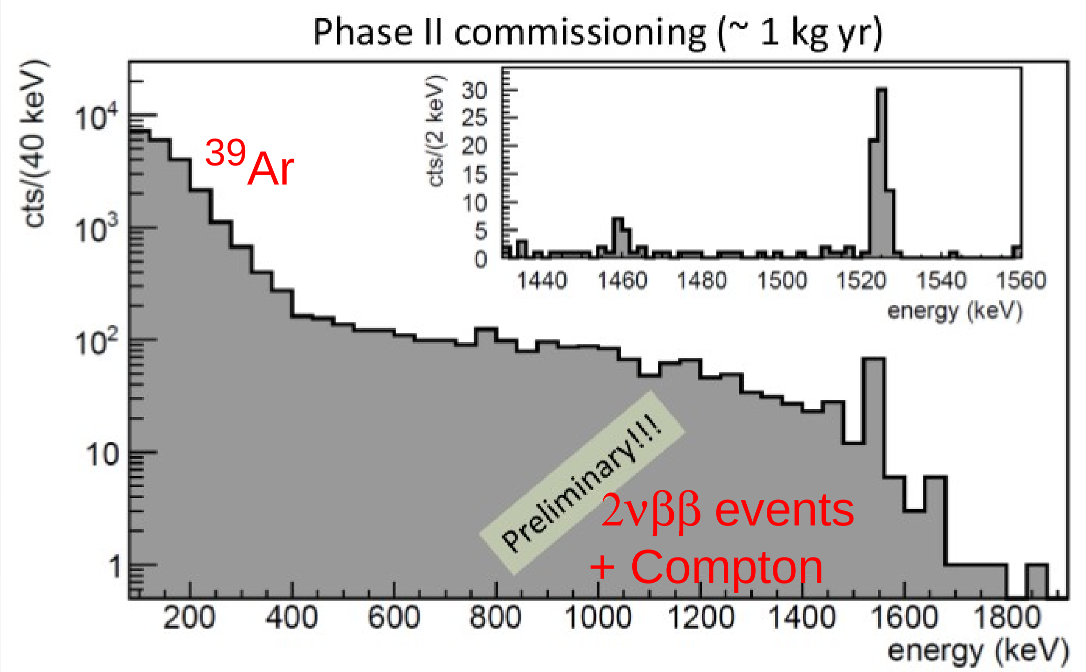


	^{226}Ra	^{228}Th
veto suppression factor	5.1±0.2	85±3
combined with pulse shape & anti-coincidence	25±2.2	390±28

>5 background suppression for ^{226}Ra & ^{228}Th by LAr veto

Phase II status





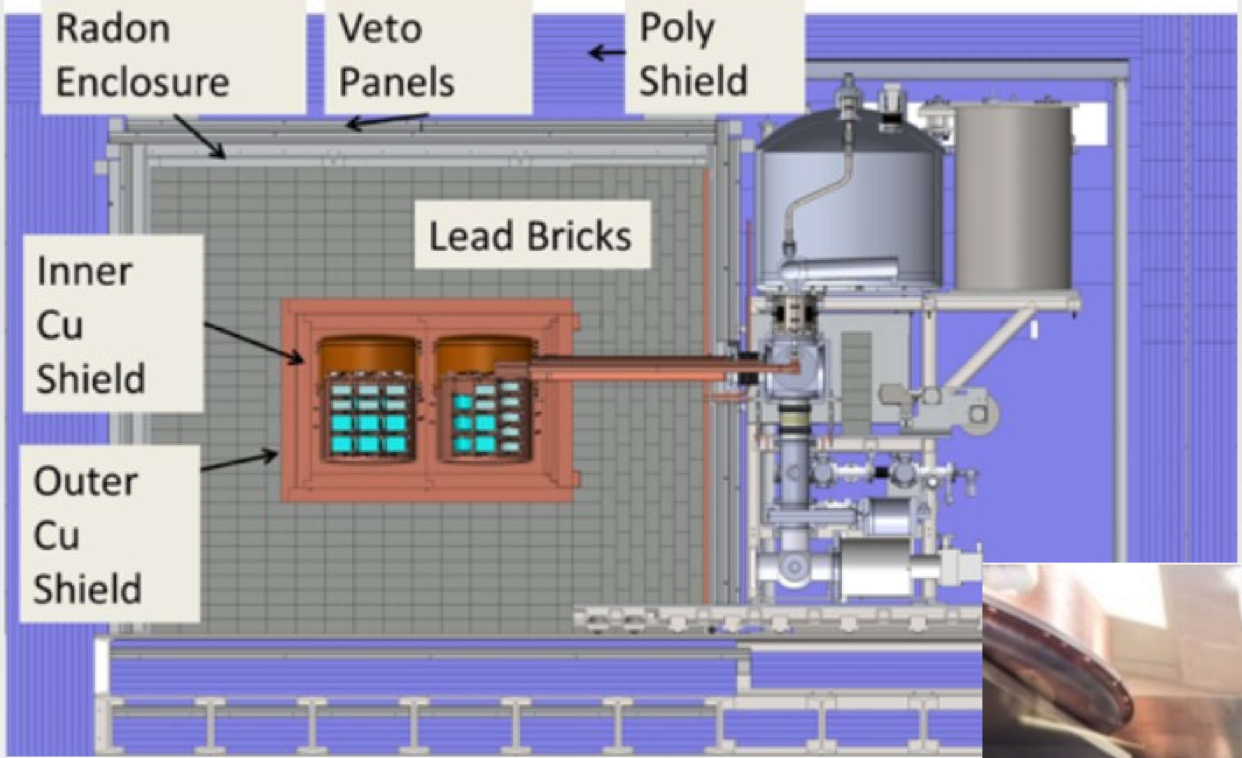
all detectors mounted & biased in Dec 2015
LAr veto working

Phase II data taking started

current sensitivity ~ 4.5 10^{25} yr (90% CL)

final ~1.5 10^{26} yr (90% CL)

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 + …

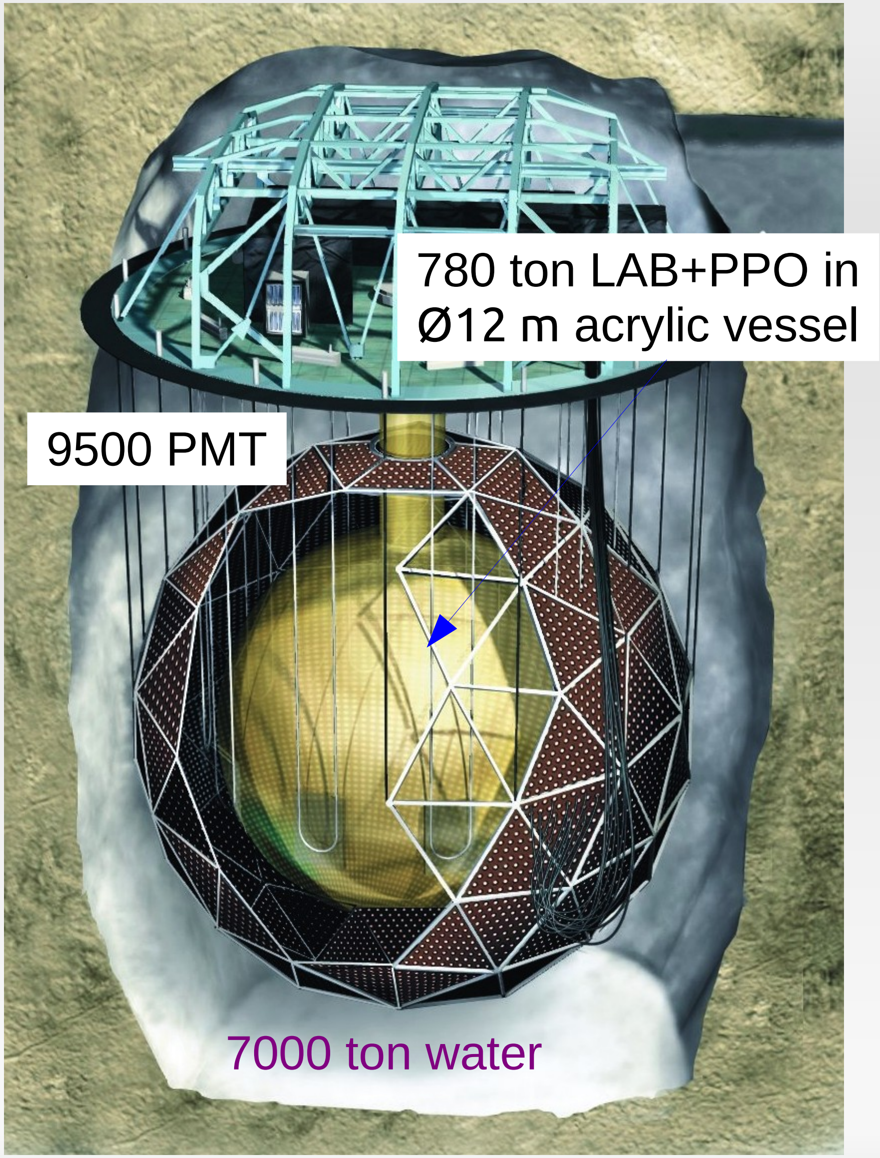
goal: prove design for ton scale

proto-type module:
10 detectors, 2014-2015

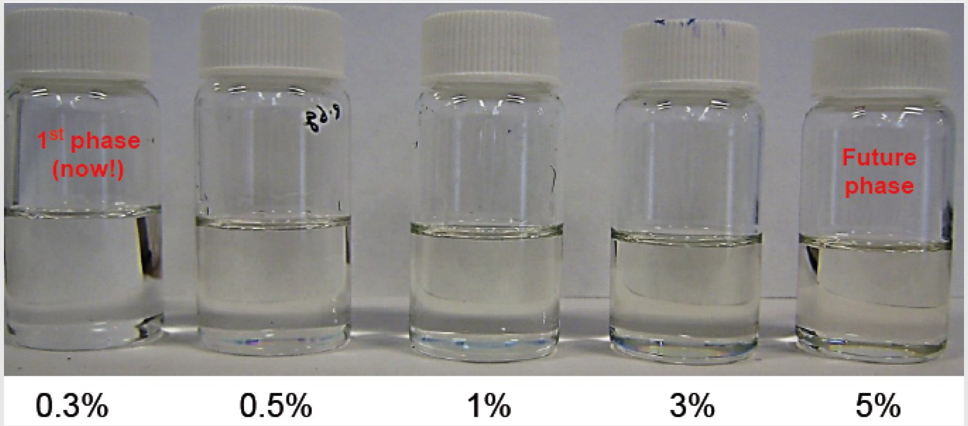
Module 1
29 detectors, 2015 first installation
running since Jan 2016

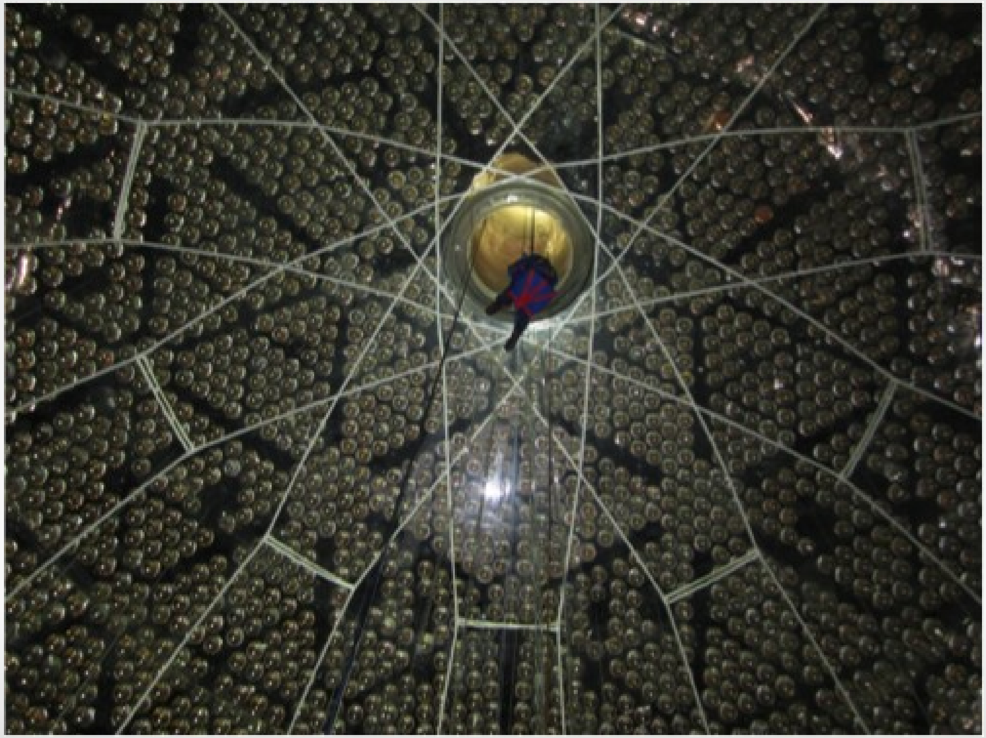
Module 2:
29 detectors, in few months complete

SNO+

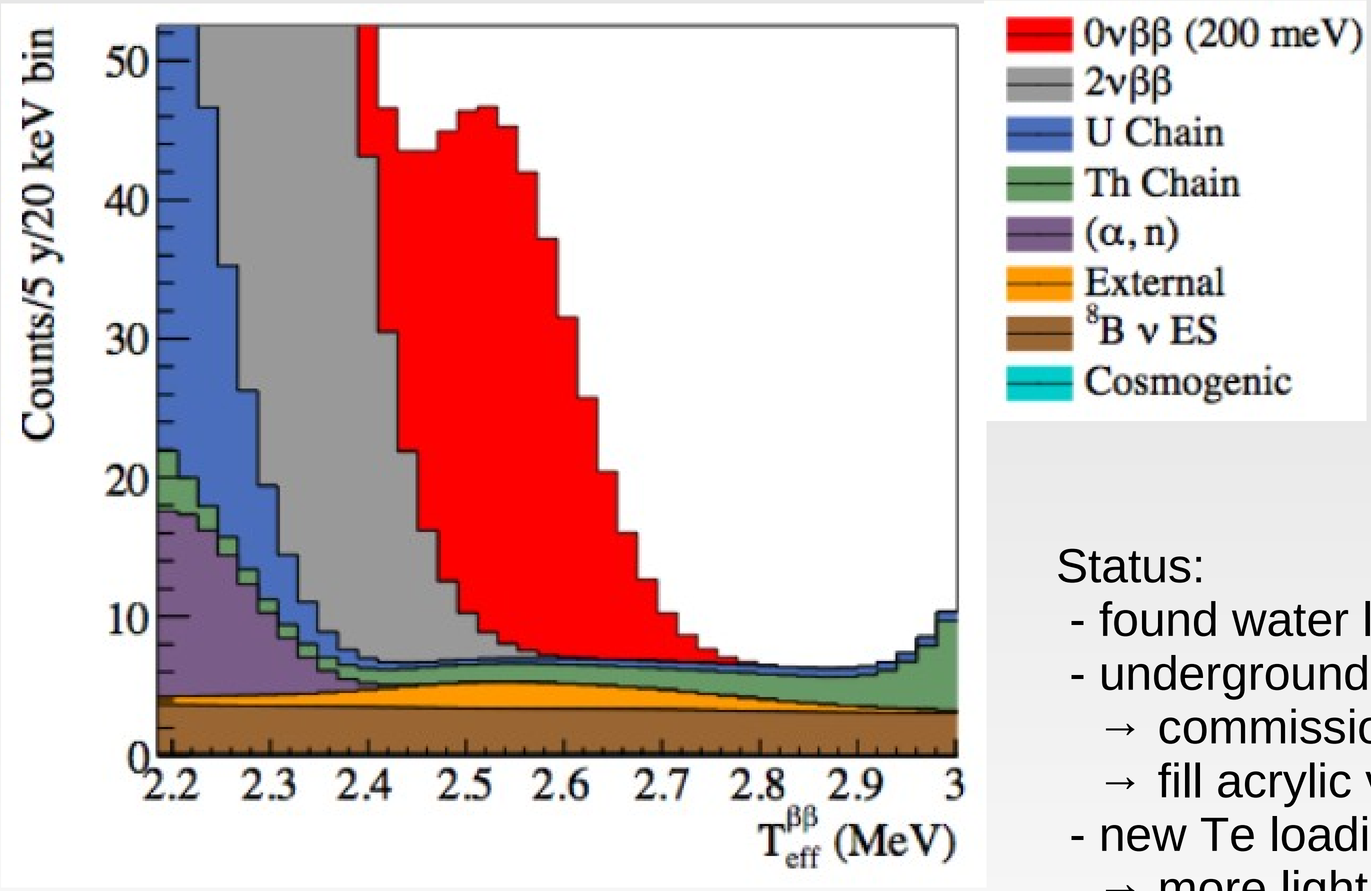


default: 0.5% loading → 3900 kg ^{nat}Te / 1300 kg ^{130}Te





SNO+



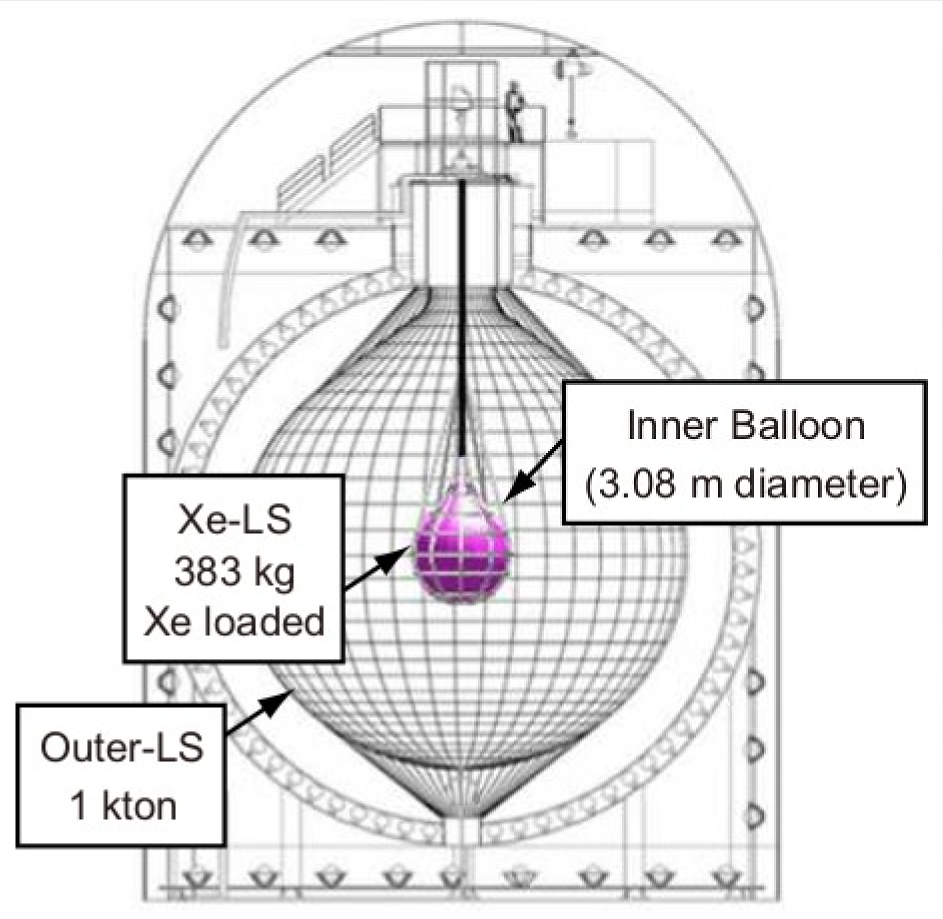
0.5% Te loading
FV: R<3.5 m (20% vol)
390 p.e./MeV light yield

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

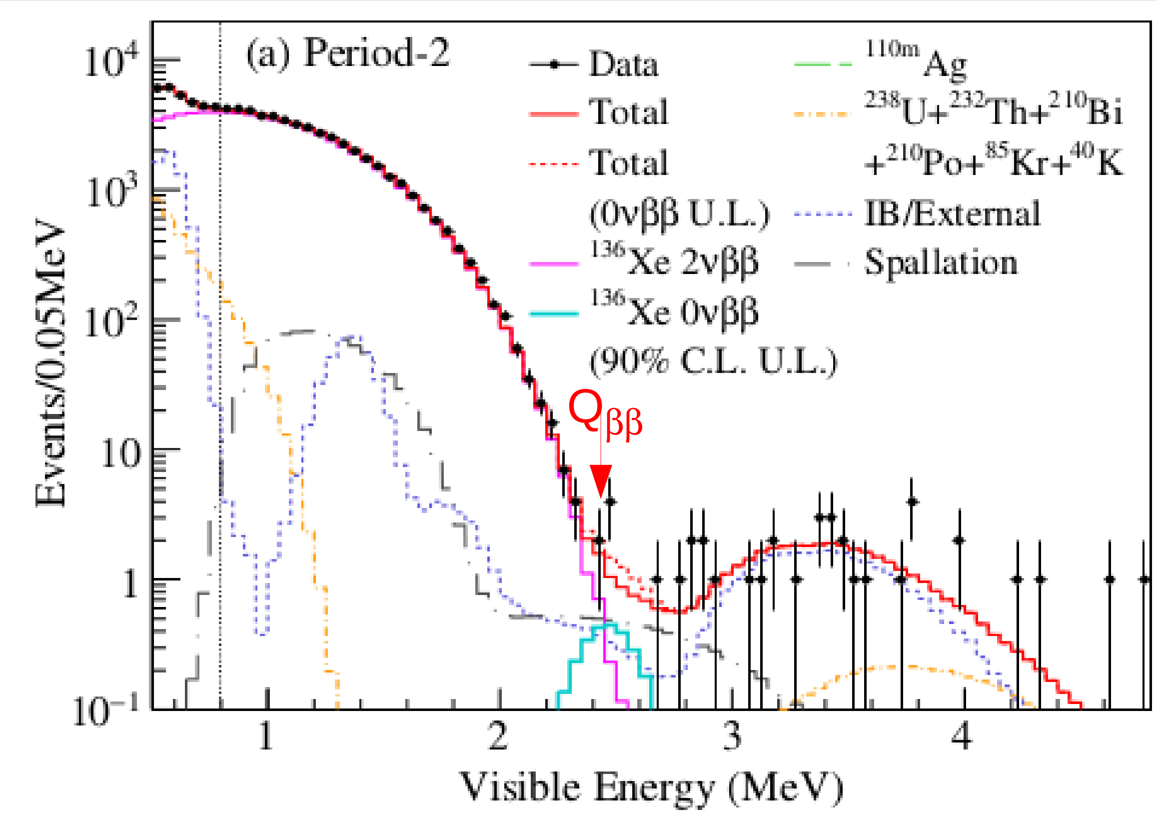
Status:

- 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

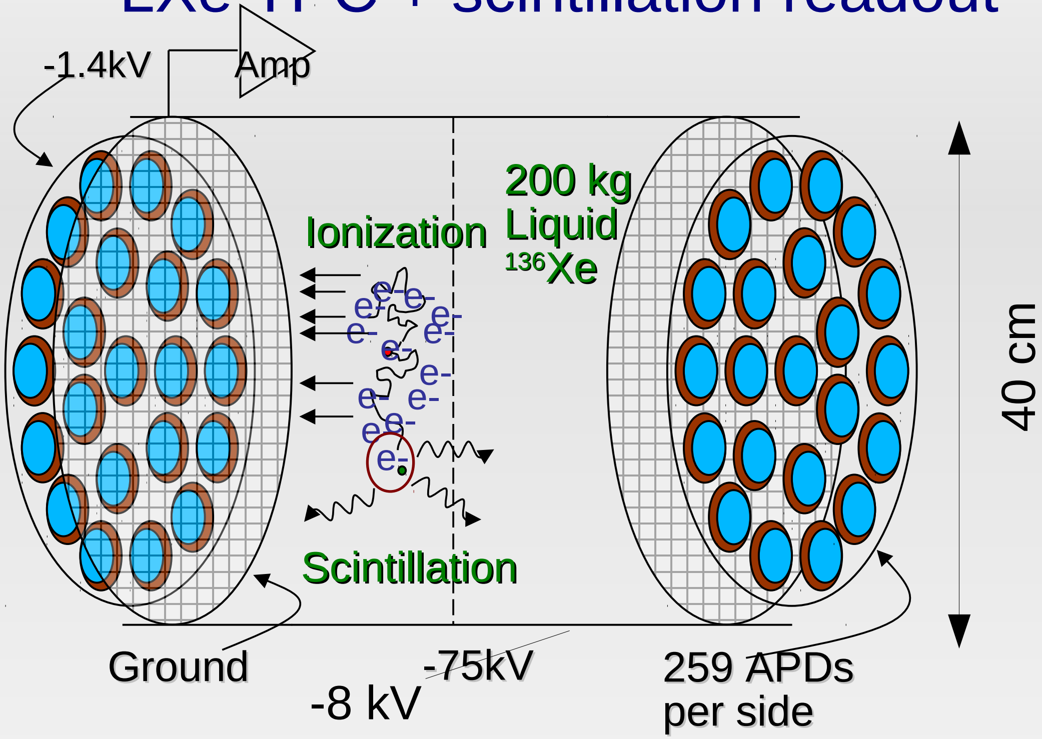


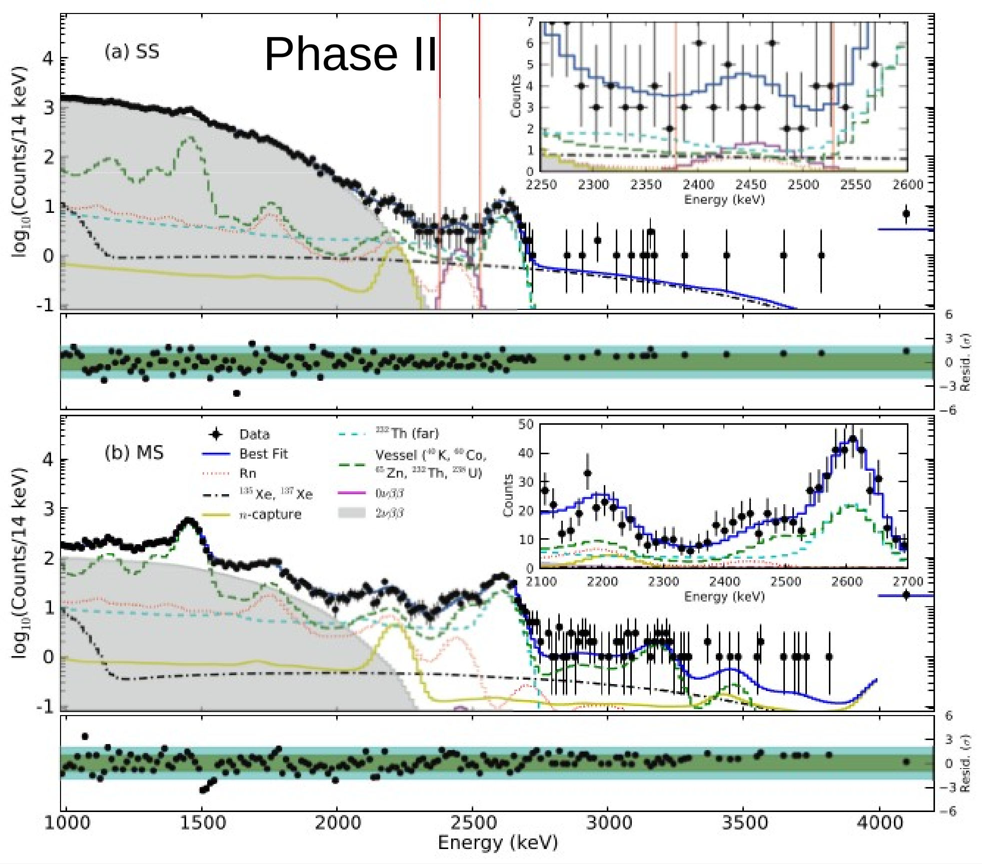
start 2011 (phase I): fall out of ^{110m}Ag from Fukushima on inner balloon
2012-13: purifications of scintillator and Xe
Dec 2013 – Oct 2015: phase II → ^{110m}Ag bkg factor 10 reduced, Xe loading 2.44% --> 2.96%
now: larger & cleaner balloon, loading 380 kg → 750 kg, restart now, sensitivity $T_{1/2} > 2\ 10^{26}$ yr

current limit for 0νββ of ^{136}Xe: $T^{0\nu}_{1/2} > 11 \cdot 10^{25}$ yr (90% C.L.) sensitivity ~5 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

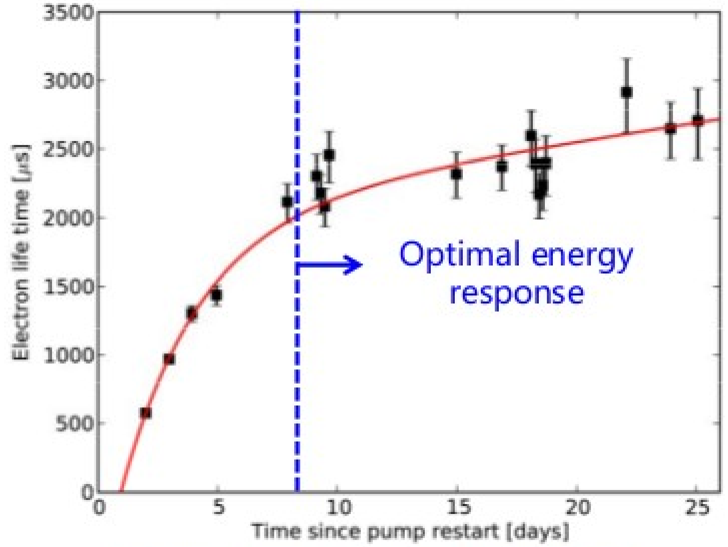
Phase II: Nature 510 (2014) 229-234

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

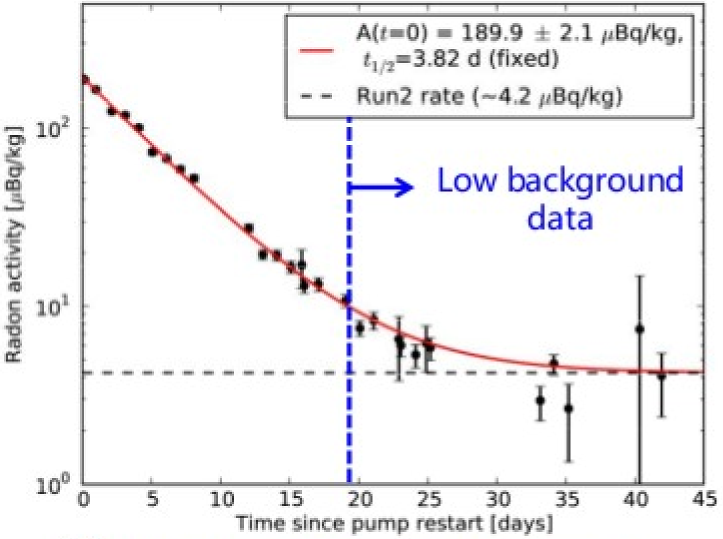
$$\boxed{T^{0\nu}_{1/2} > 1.1\cdot 10^{25}\ yr\,(@\ 90\ \ C.L.)}$$

(sensitivity 1.9 10^{25} yr)

EXO-200 restart



Xenon `purity' since January 31

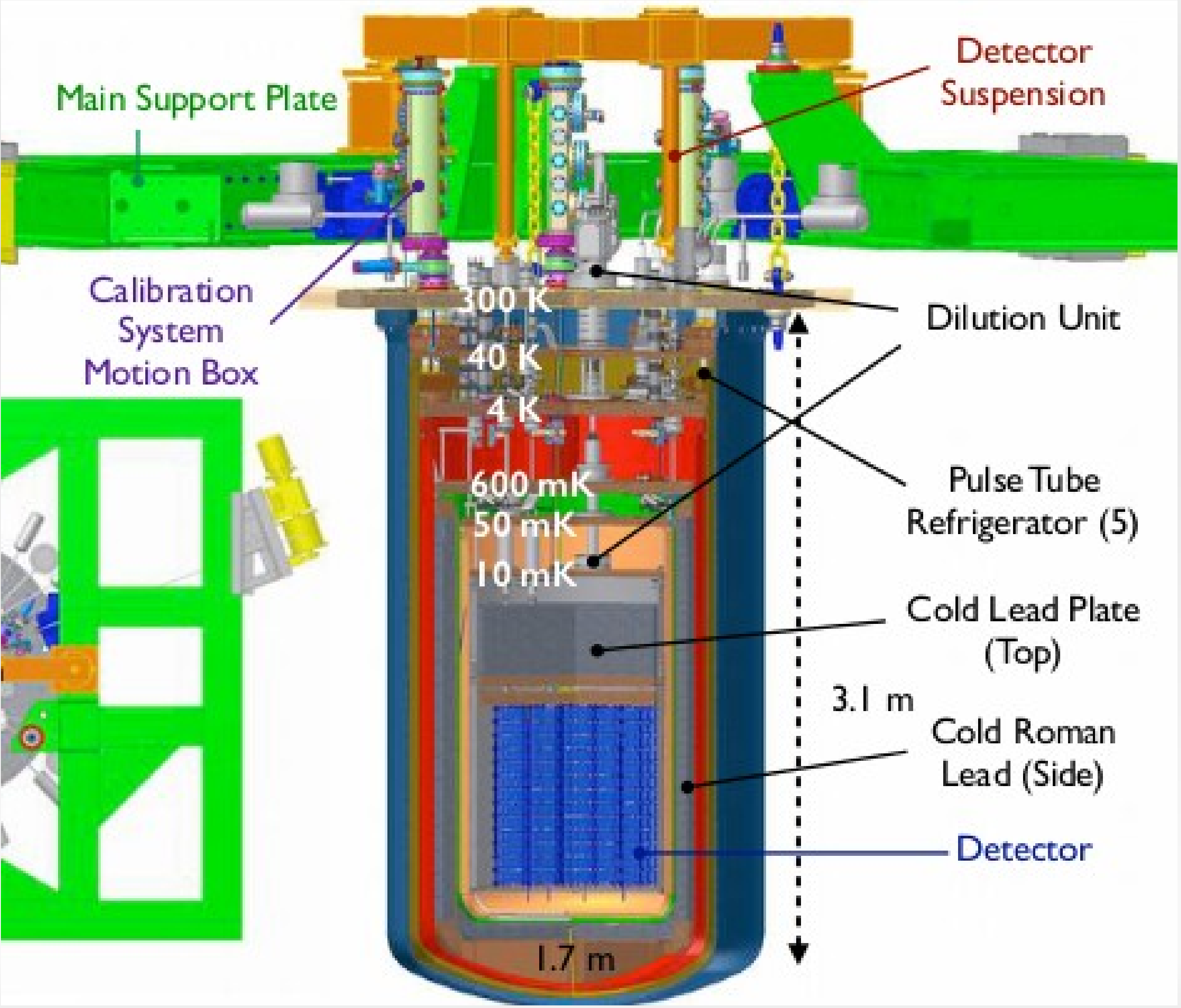


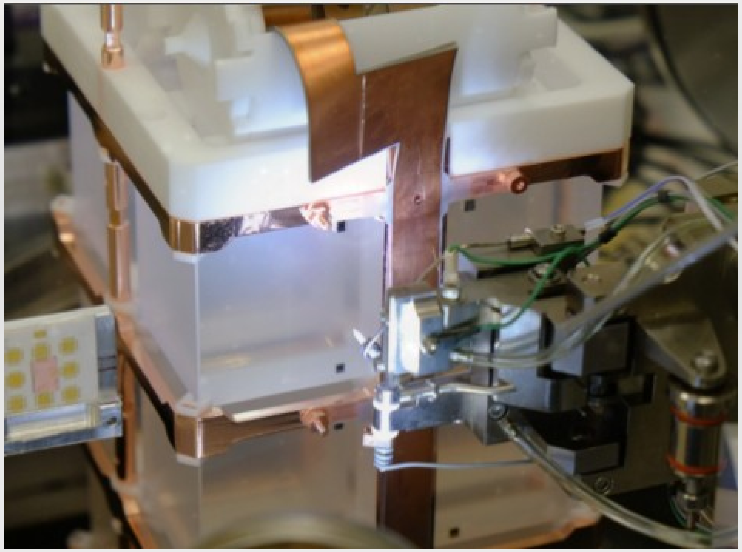
^{222}Rn level in TPC since January 31

lower noise electronics → FWHM improves to ~60 keV
lower Rn level → expect lower background

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

Cuore: ^{130}Te





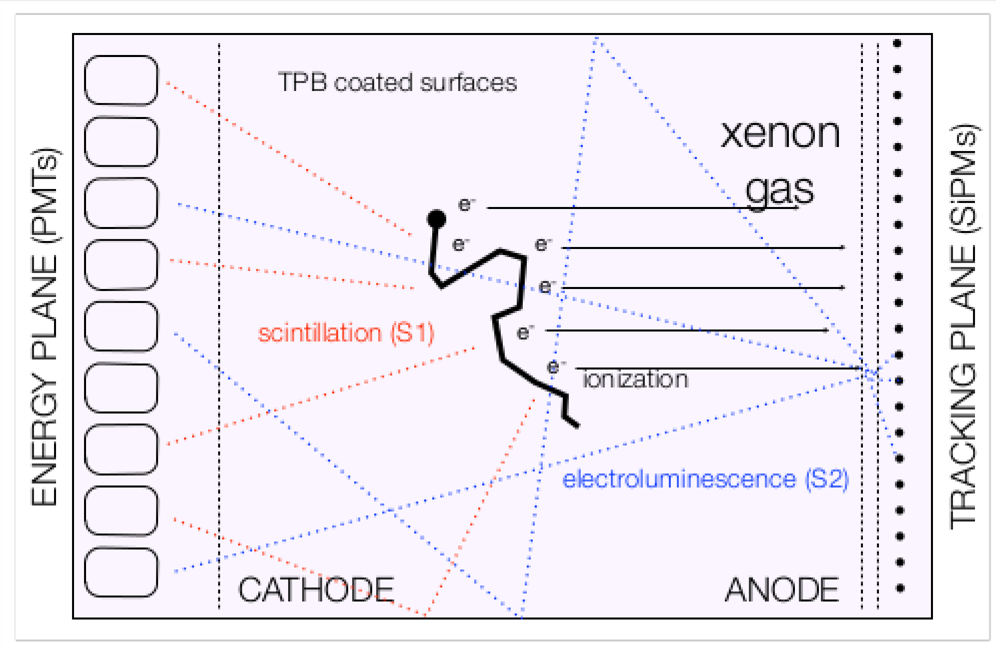
988 $^{nat}TeO_2$ crystals
206 kg ^{130}Te,

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

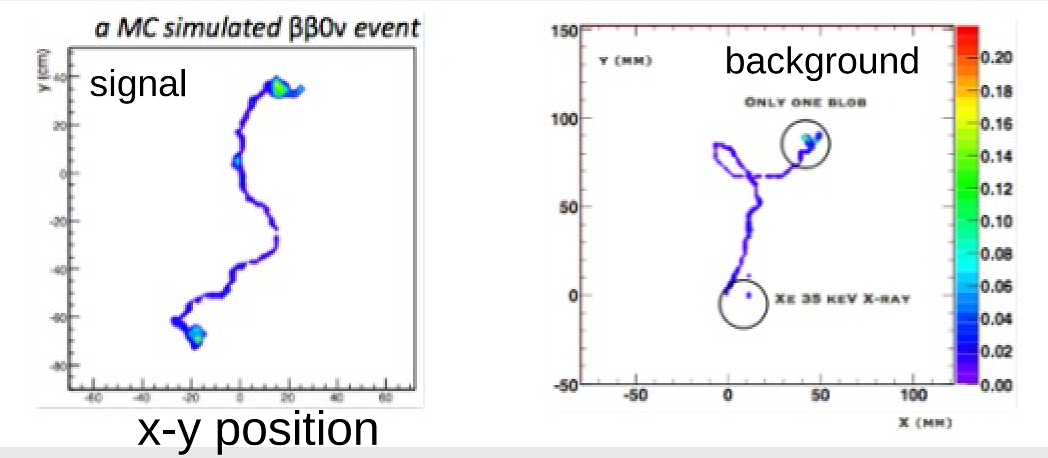
all towers are assembled!
test cool down of cryostat ok,
next: step mount towers + commissioning
physics run start end 2016,
sensitivity 90% limit ~ 1 10^{26} yr

NEXT @ Canfranc

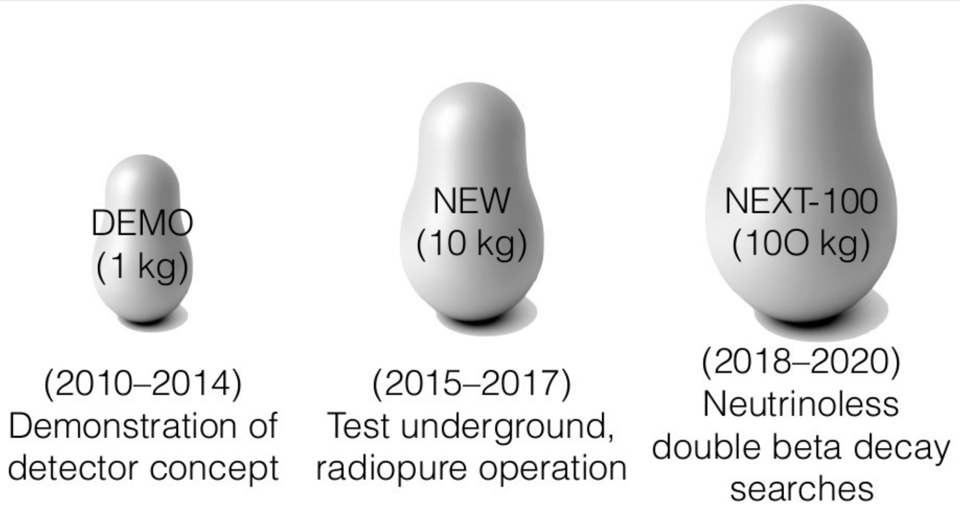
- 100 kg gas Xe TPC @ 15 bar
- measure scintillation light
- measure ionization w/ Electro Luminescence
- energy resolution FWHM <1% demonstrated
- reconstruction of event topology
  → background reduction



tracking of electrons



x-y position



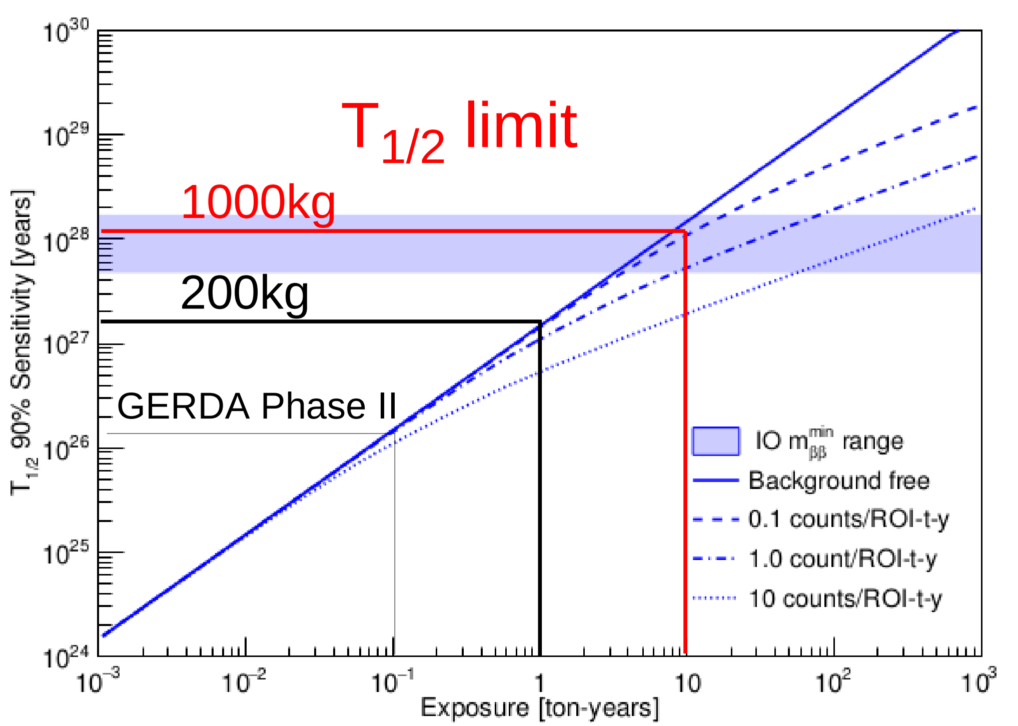
(2010–2014)
Demonstration of detector concept

(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

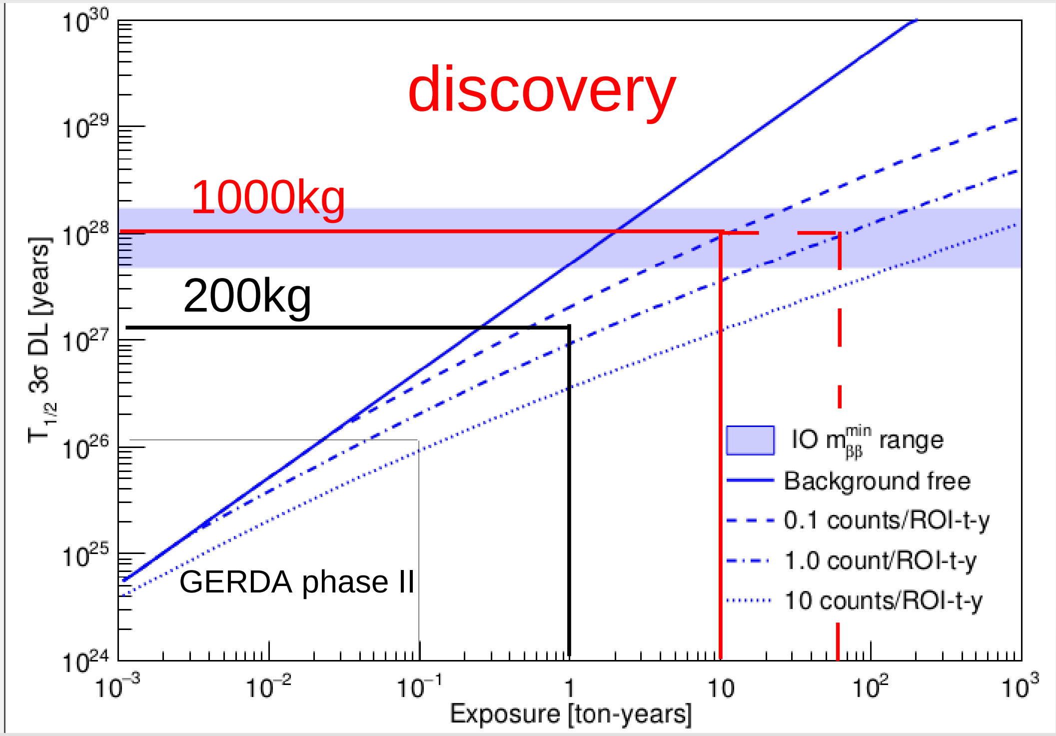
^{76}Ge sensitivity limit + discovery



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) - 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



for discovery:
factor 10 in background
→ 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 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,
I expect experiments meet 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