Search for Lepton Number Violation with Neutrinoless Double Beta Decay

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

GERDA

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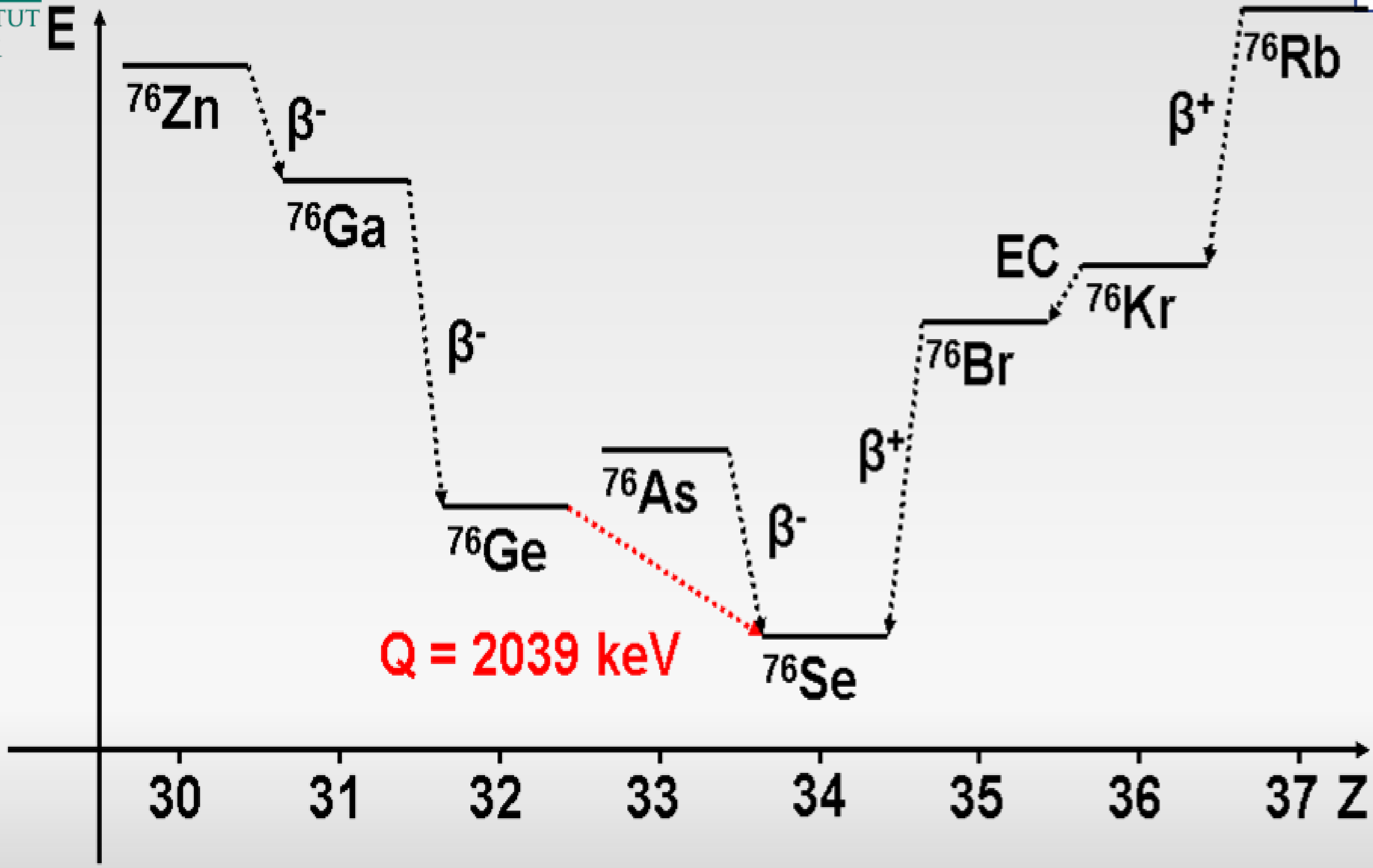
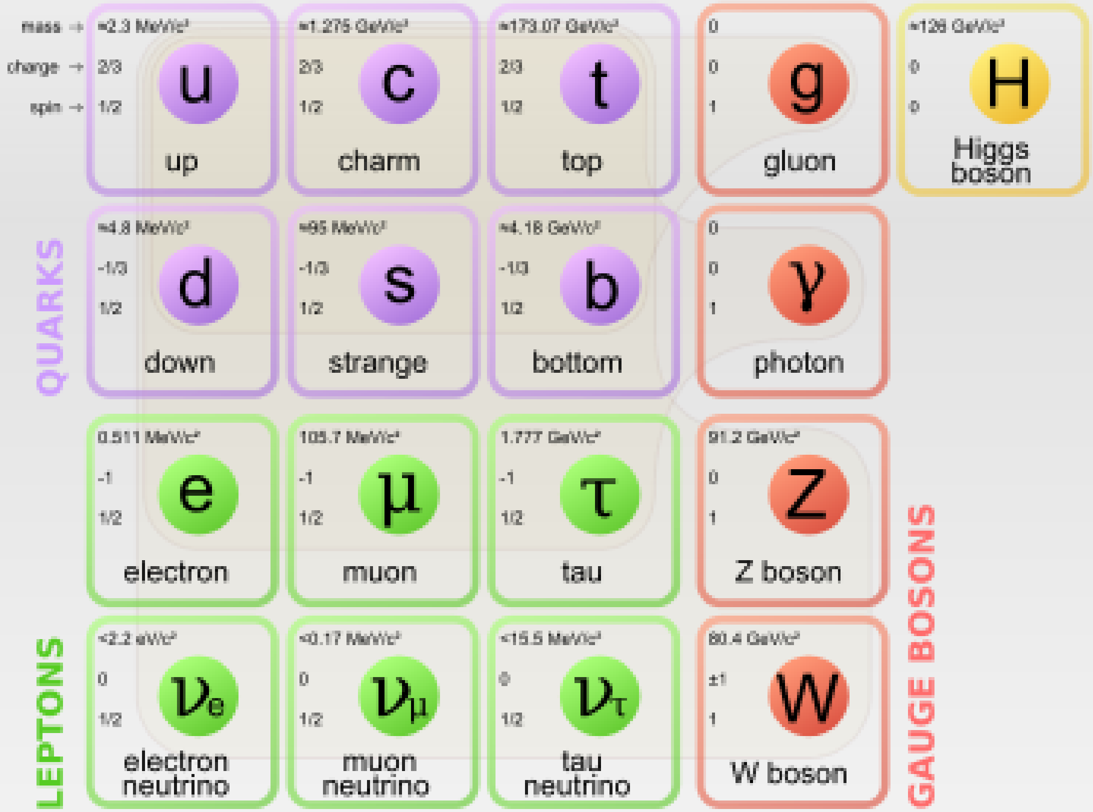


Standard Model



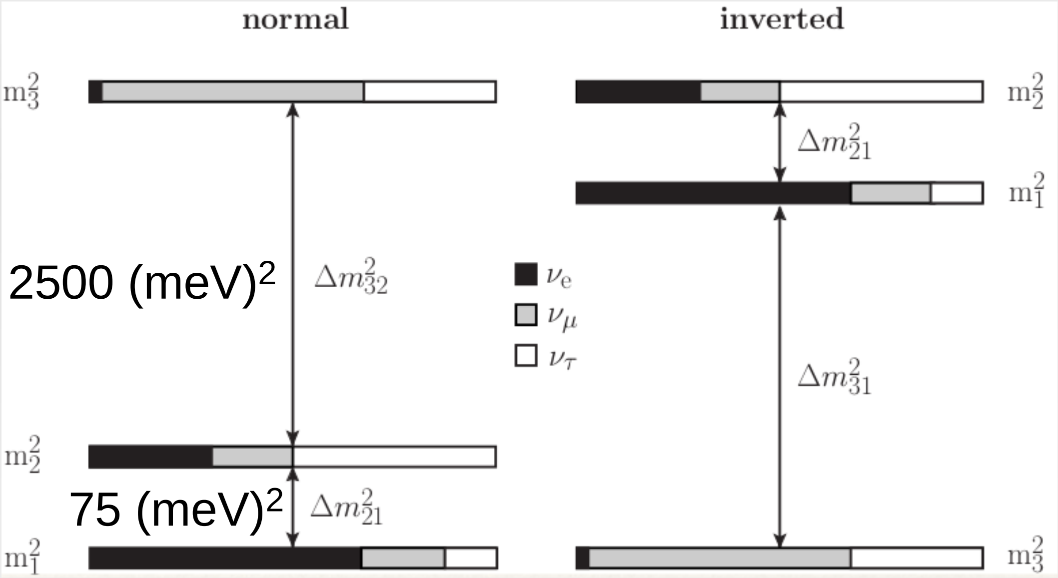
no new physics found at the LHC so far → SM could be valid up to Planck scale?

BUT

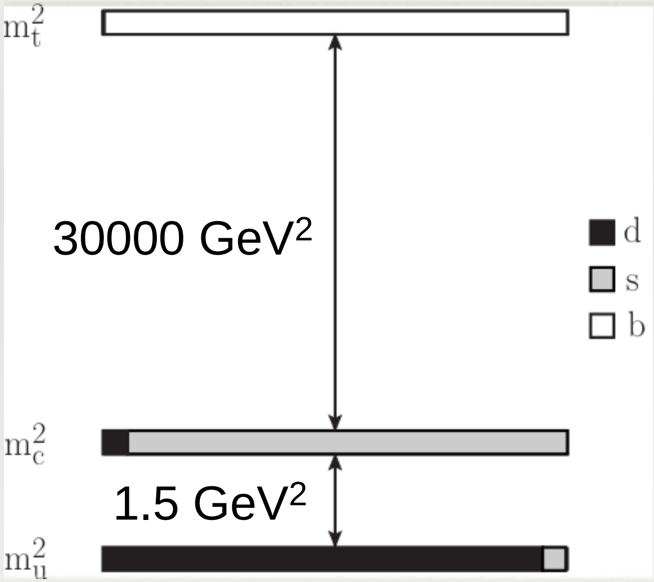
- no dark matter candidate
- baryon asymmetry of the universe not explained
- dark energy not understood
- origin of (tiny) neutrino mass unknown, Majorana particle?

Neutrino physics

neutrinos: mass splitting and mixing



quarks



Neutrino flavor physics: underlying symmetry ?

- mixing matrix U and $|\Delta m^2|$, quite well known but: $\theta_{23} = 45^o$ or small deviation from 45^o ?
- sign of $\Delta m_{31}{}^2$?
- CP phase = $3\pi/2$? (likely not relevant for leptogenesis)
- absolute mass scale ?

major impact

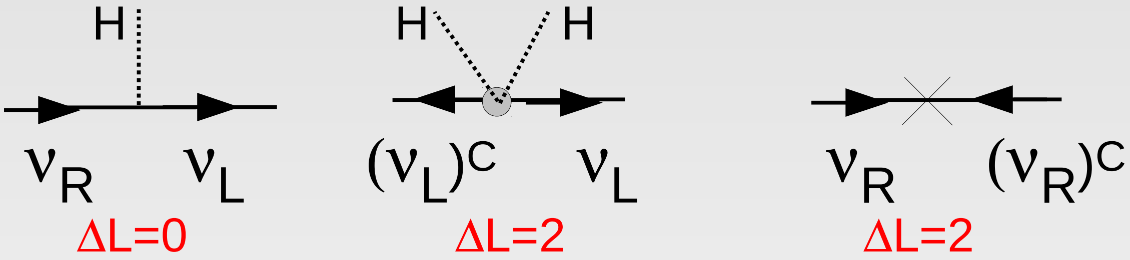
Is mixing matrix unitary (sterile neutrinos, ...)?

Are neutrinos Majorana or Dirac particles (lepton number violation)?

Neutrino mass: Lepton number violation?

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

in general: expect ν to be Majorana particles → L violation

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

~1 GeV: can explain baryon asymmetry
if <5 GeV observation e.g. $D \to N \mu X$ with $N \to \mu \pi$ by SHIP

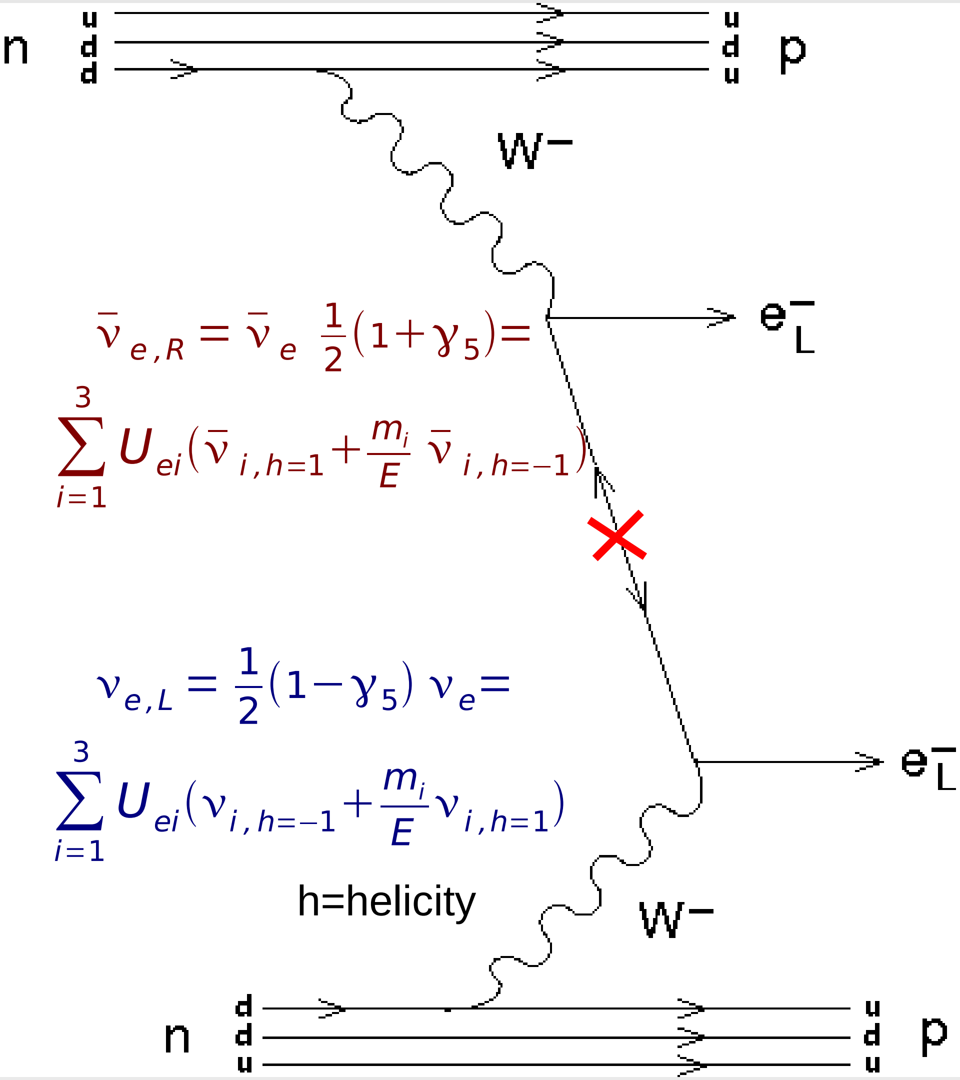
10 keV: (warm+cold) dark matter candidate, $N \to \gamma \nu$ decay ~ $U^2 m_R^5$

eV range: LSND oscillation signal, reactor anomaly, … → Stereo, SOX, …
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

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

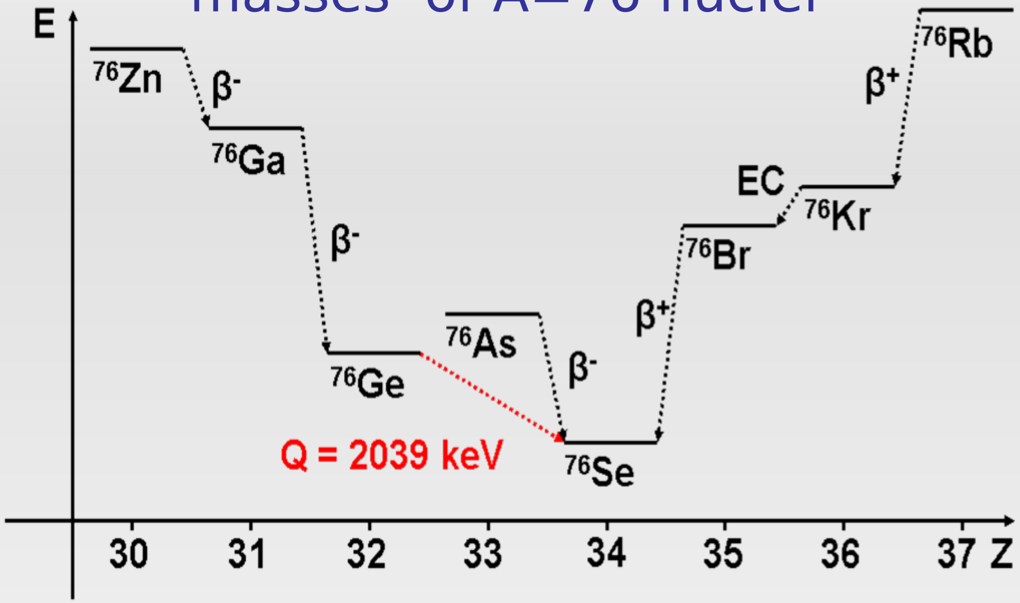
function of
- neutrino mixing parameters
- lightest neutrino mass
- 2 Majorana phases

also possible: heavy N exchange

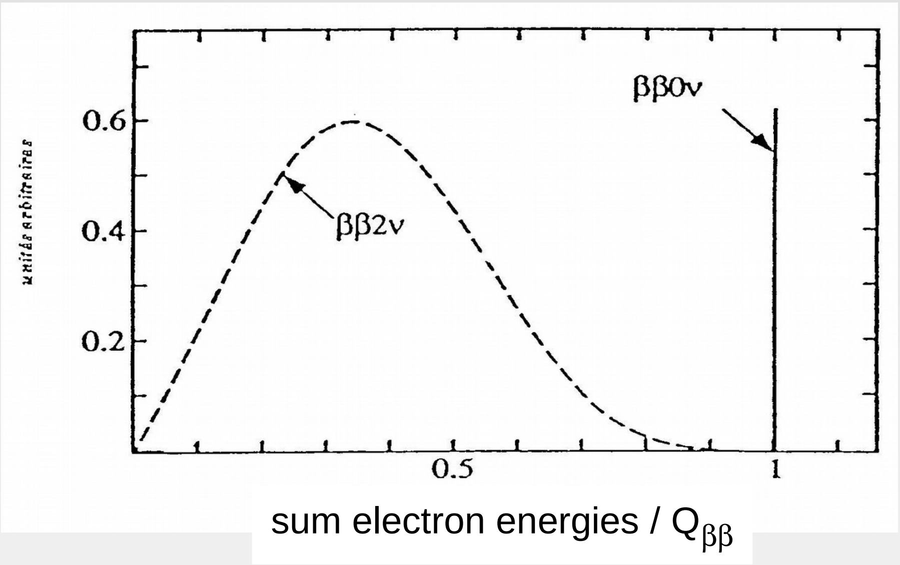
→ coupling strength ~ $\sum_{i=1}^{3} V_{ei}^2 / M_i$

Neutrinoless double beta decay

masses of A=76 nuclei



experimental signature for ββ



”single” beta decay not allowed

→ only ”double beta decay”

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

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

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

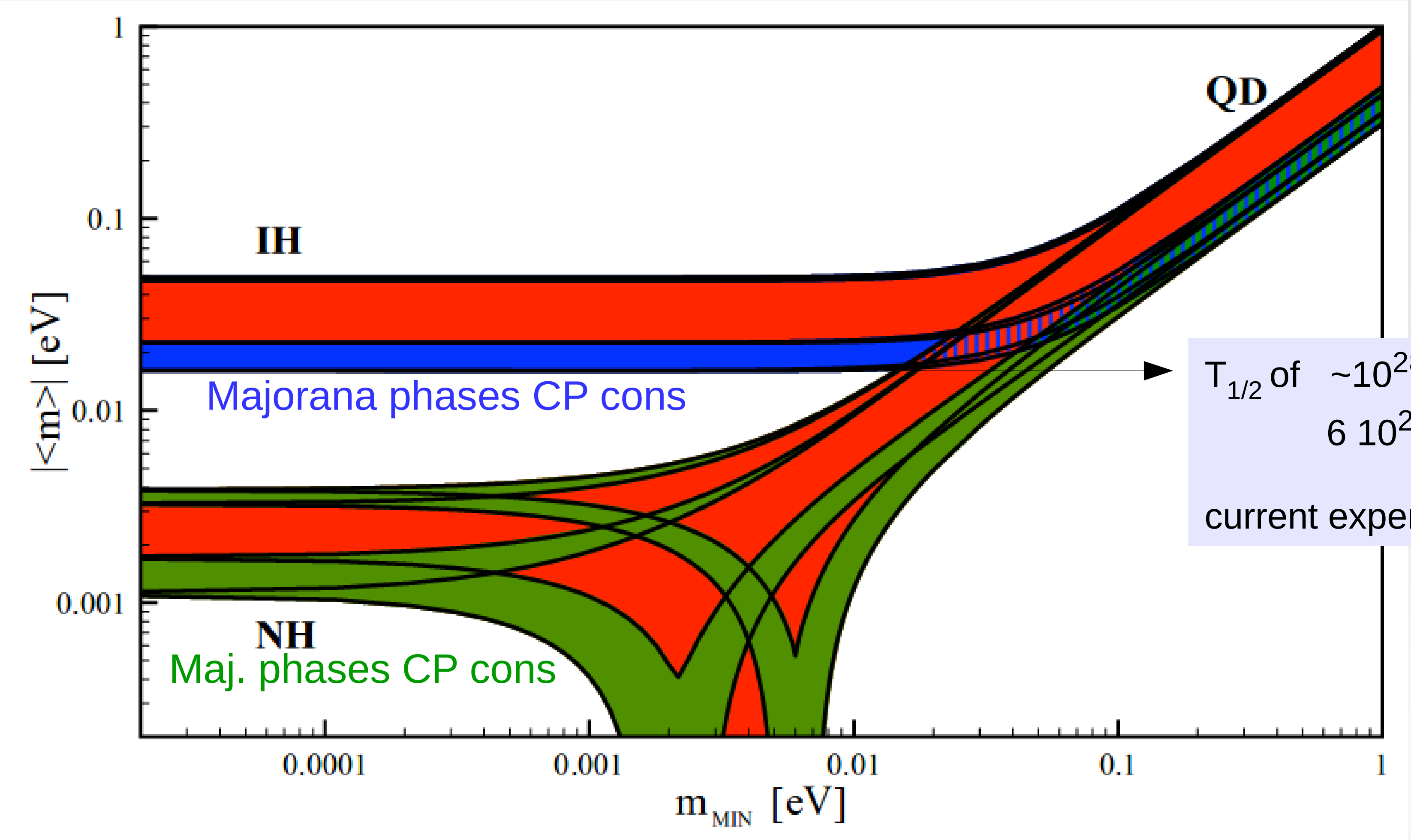
Note: similar process in principle also observable at accelerator or reactor or ... but for light Majorana neutrino:

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

Light Majorana neutrino exchange

scan of $m_{\beta\beta}$ (Δm_{atm}^2, Δm_{sol}^2, m_{min}, θ_{atm}, θ_{sol}, θ_{13}, 2 Majorana phases)

according to measurements (2 σ range) or random (2 Maj. phases)



$T_{1/2}$ of ~10^{28} yr for ^{76}Ge

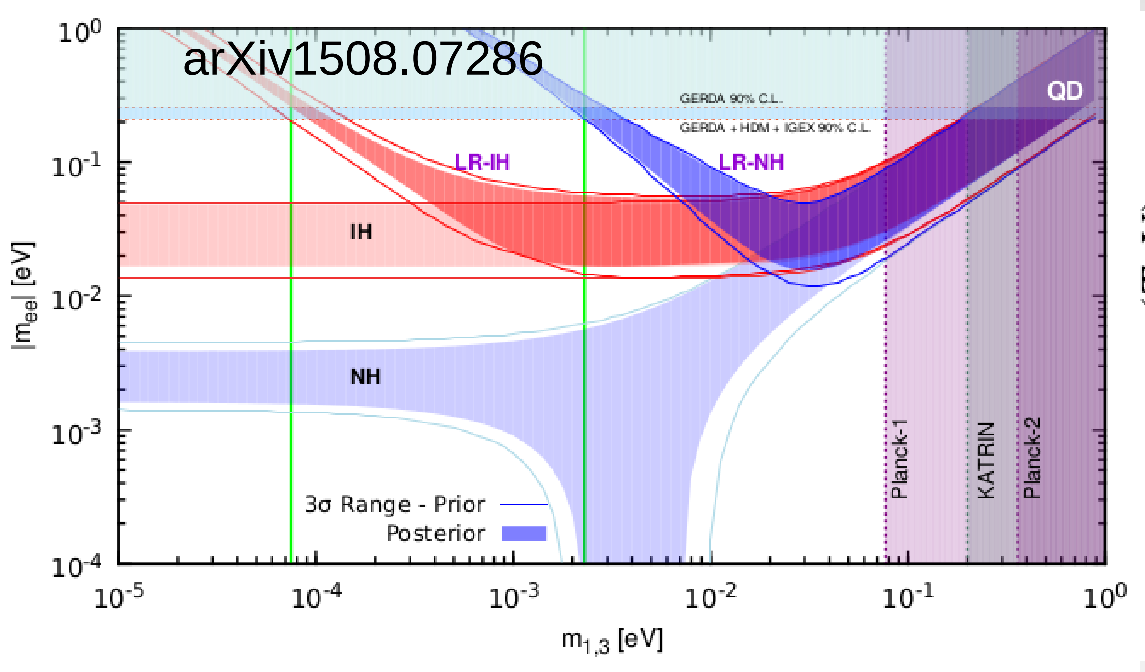
$6\ 10^{27}$ yr for ^{136}Xe

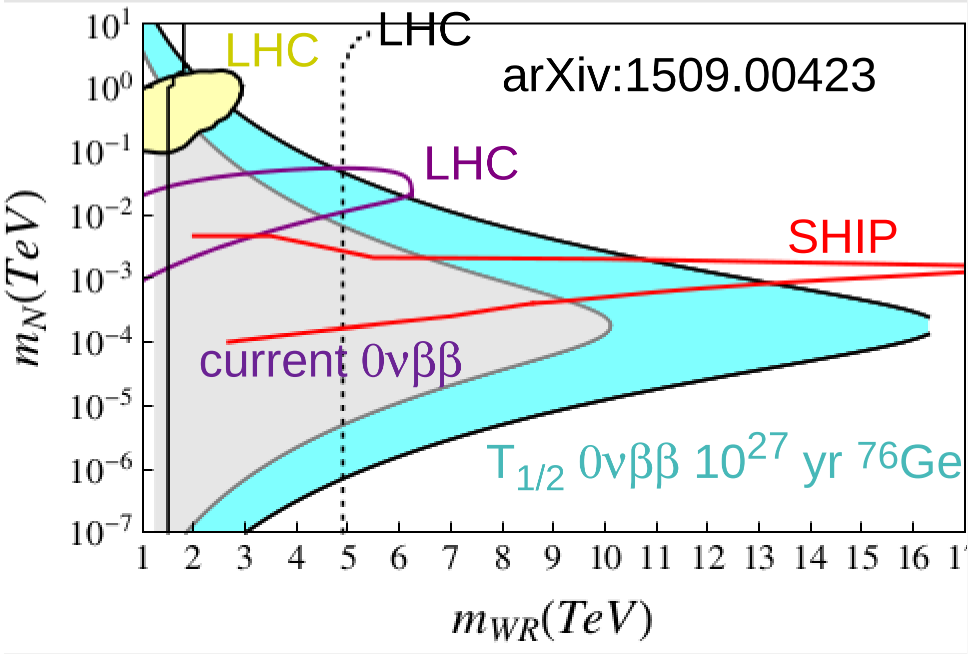
current experiments 10^{25} - 10^{26} yr

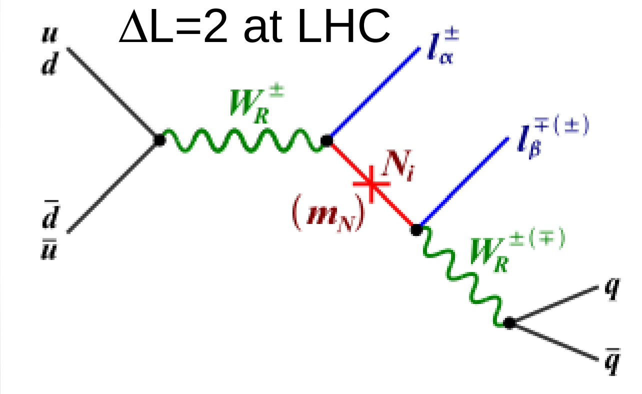
PDG 2016

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

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

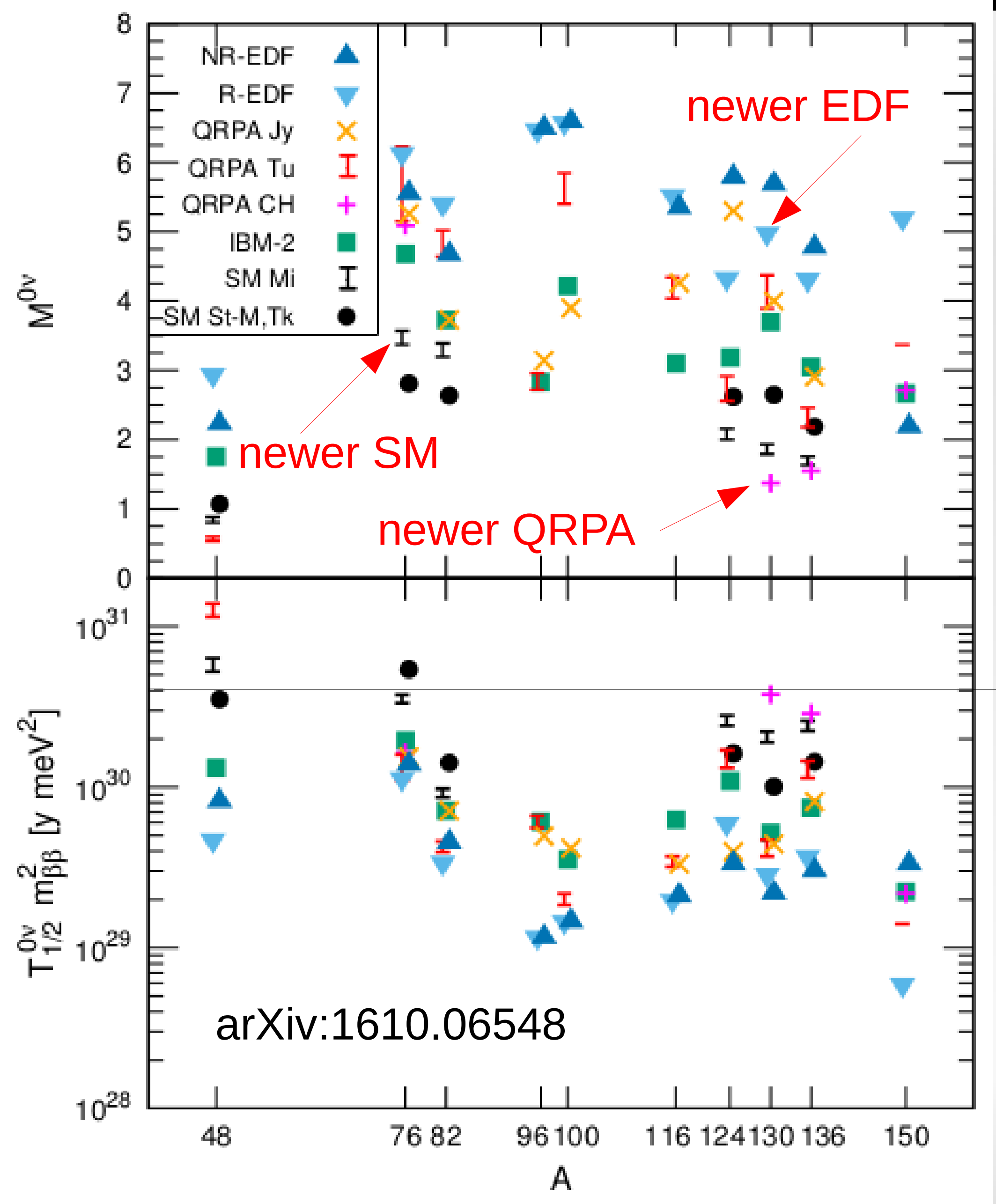
Experiment observes $N^{0\nu} = \ln 2 \frac{N_A}{A} \cdot a \cdot \epsilon \cdot M \cdot t \,/\, T_{1/2}$ and $N^{bkg} = M \cdot t \cdot B \cdot \Delta E$

Experimental sensitivity

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

M = mass of detector
t = measurement time
A = isotope mass per mole
N_A= Avogadro constant
a = fraction of 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



newer EDF

newer SM

newer QRPA

arXiv:1610.06548

10^{28} yr for 20 meV effective mass

0.6 ^{76}Ge decays per t*yr exposure

0.3 ^{136}Xe decays per t*yr exposure
(before enrichment fraction & cuts)

→ background free conditions required

No favored isotope considering spread of nuclear matrix elements

Experiments (status TAUP 2017)

	experiment	form	det.	shielding	bkg reduction	status
Ca	CANDLES	solid	light	Pb+B_4C+org scint	pulse shape	R&D, no enrichm.
Ge	GERDA	solid	ioniz.	water+liquid Ar	pulse s.+LAr veto	running since 2013
	Majorana D.	solid	ioniz.	Cu+Pb+PE	pulse shape	running since 2015
Se	CUPID0	solid	light+heat	Cu+Pb	light/heat	running since 2017
	SuperNemo	solid	track+cal		dE/dx,topology	start end 2017
Mo	AMoRE	solid	light+heat	Pb	light/heat	AMoRE I in 2018
	CUPID-Mo	solid	light+heat		light/heat	R&D
Te	CUORE	solid	heat	Cu+Pb		running since 2016
	SNO+	liquid	light	org. scintillator		start late 2018
Xe	EXO	liquid	light+ioniz	Pb	topology	running since 2011
	KamlandZen	liquid	light	org. scintillator		running since 2011
	NEXT	gas	light+ioniz	Cu+Pb	topology	start end 2018
	PandaX-III	gas	ionization	water	topology	first module in 2019
	AXEL	gas	light+ioniz		topology	R&D

new/first results at TAUP

How to reduce background

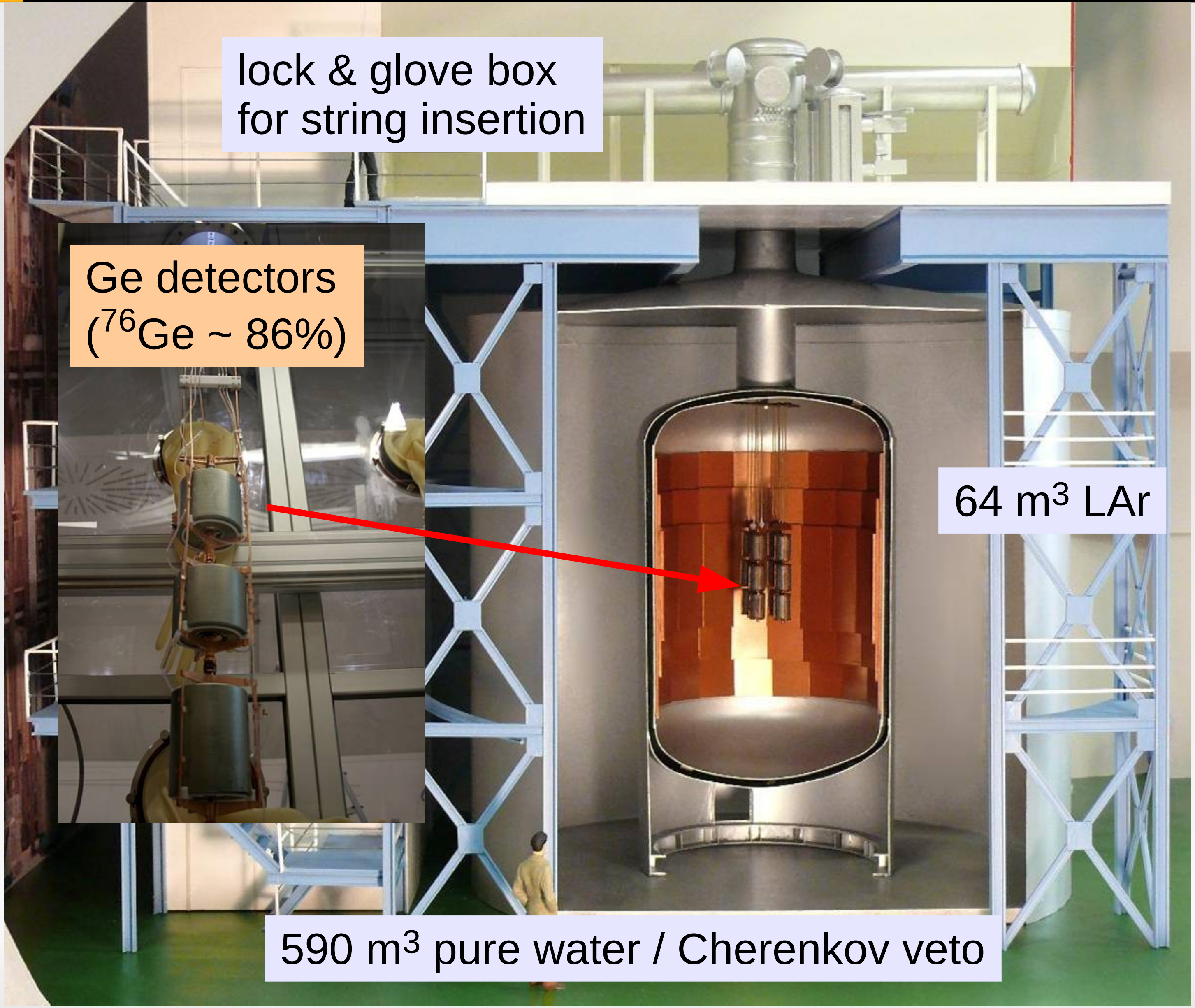
sources: cosmic rays (p,n,μ,γ) → underground like LNGS
neutrons from (α,n) and spallation induced by μ
α,β,γ from radioactive decay chains ^{238}U, ^{232}Th

→ 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

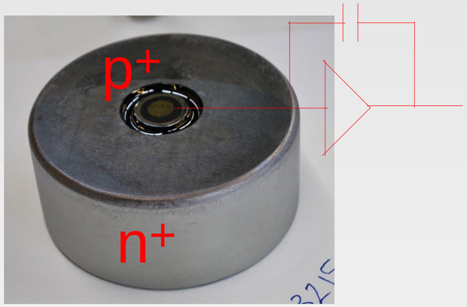
Phase I (2011-13):

$T^{0\nu}_{1/2} > 2.1\cdot10^{25}$ yr (90% C.L.)

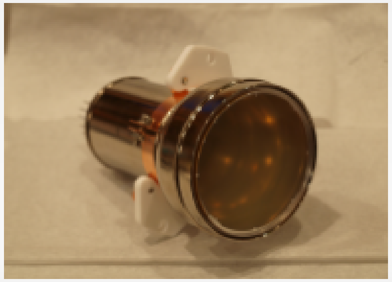
^{76}Ge 0νββ decay, PRL 111 122503

Phase II:

2x Ge mass (30 BEGe det.)

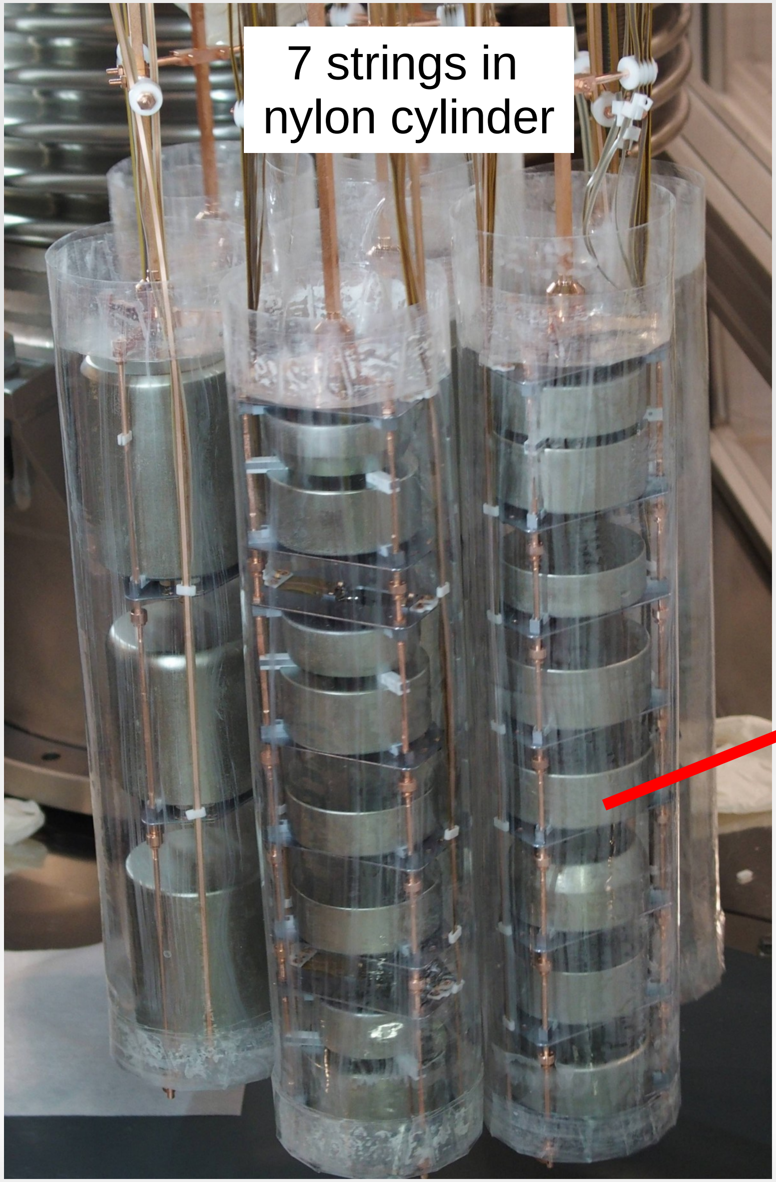


LAr scint. light readout

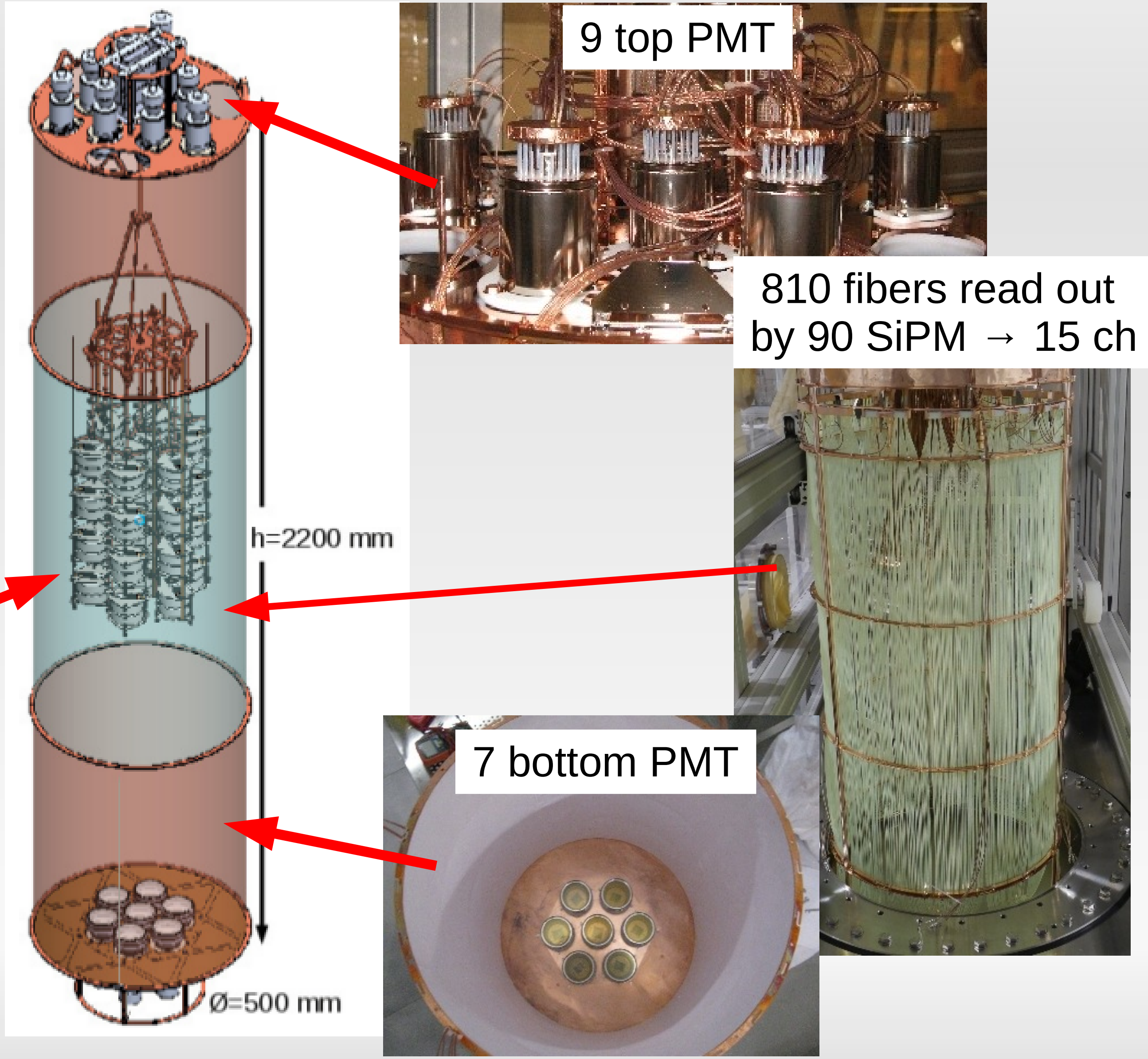


started end 2015

Phase II start December 2015



7 strings in nylon cylinder



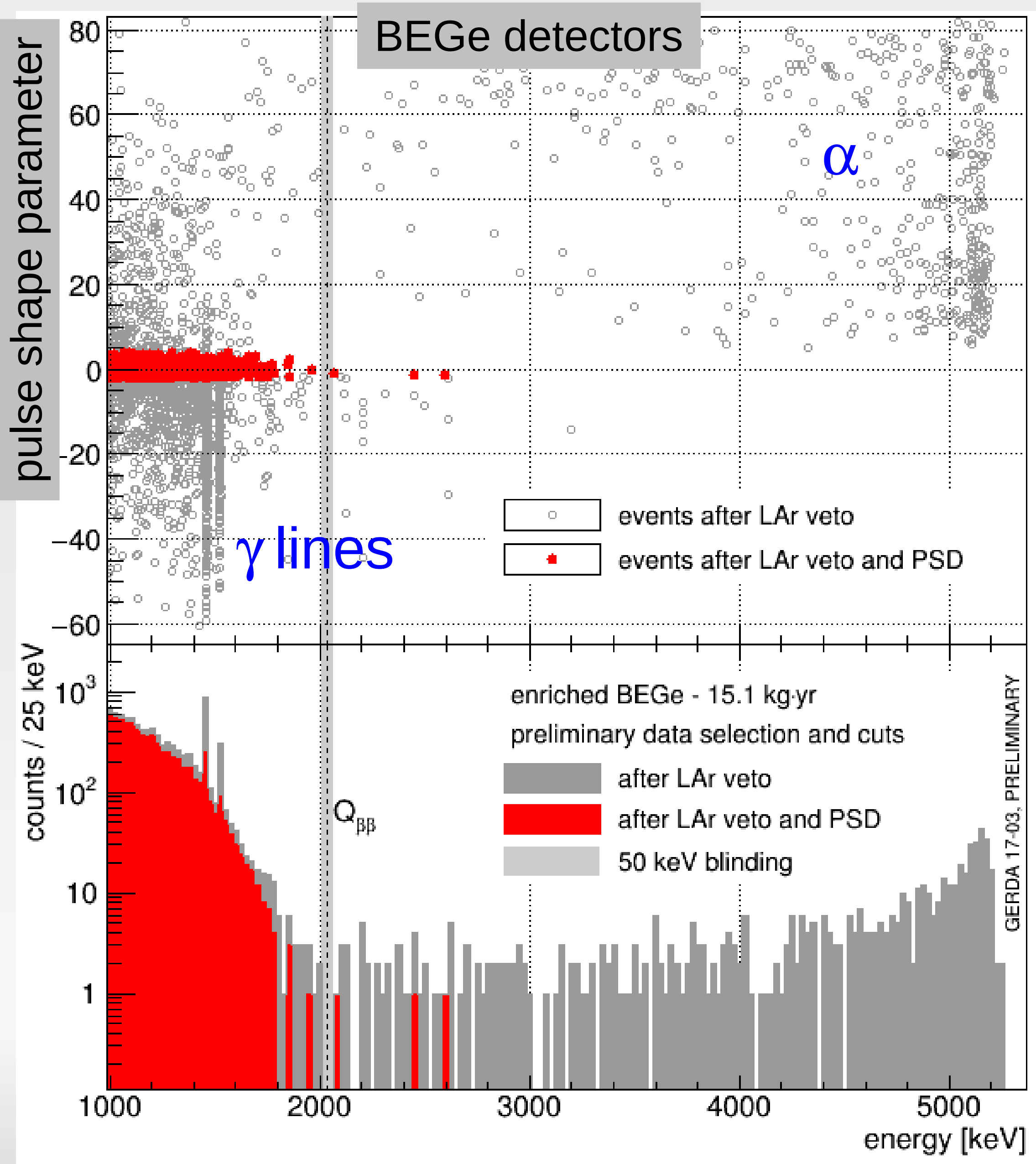
9 top PMT

810 fibers read out by 90 SiPM → 15 ch

7 bottom PMT

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

Background: pulse shape discrimination



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

energy resol FWHM ~ 3keV at $Q_{\beta\beta}$
(for MajoranaDemonstrator 2.4 keV)
→ Ge exp have superior resolution

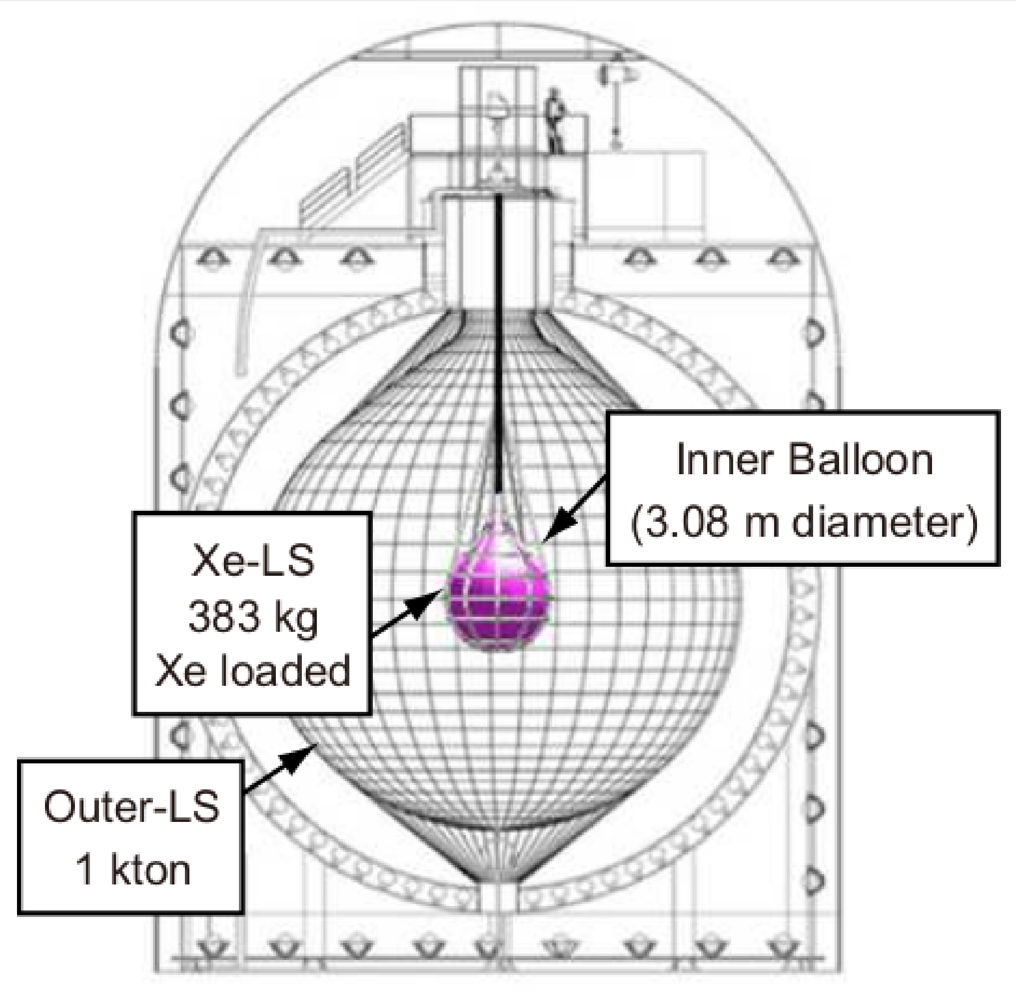
background ~3 cnt/(FWHM t yr)
→ Ge exp. have lowest background

after unblinding: no signal

$$\boxed{T^{0\nu}_{1/2} > 8.0 \cdot 10^{25}\,\mathrm{yr}\ (90\%\ \mathrm{C.L.})}$$

sensitivity = 5.8 10^{25} y
eventually >1 10^{26} yr

Kamland-Zen



^{136}Xe loaded in liquid scintillator in inner balloon

large mass, poor energy resolution ~250 keV

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

2012-13: purification of scintillator and Xe

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

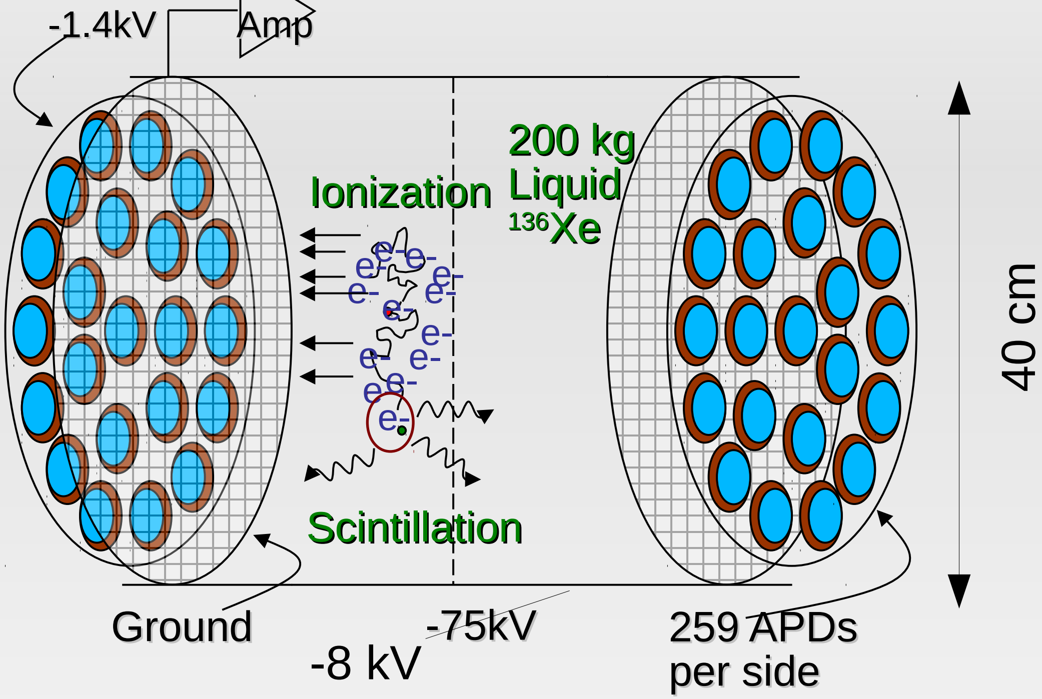
end 2017: larger & cleaner balloon,
loading 380 kg → 750 kg, restart end 2017,
sensitivity $T_{1/2} > 2\ 10^{26}$ yr

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

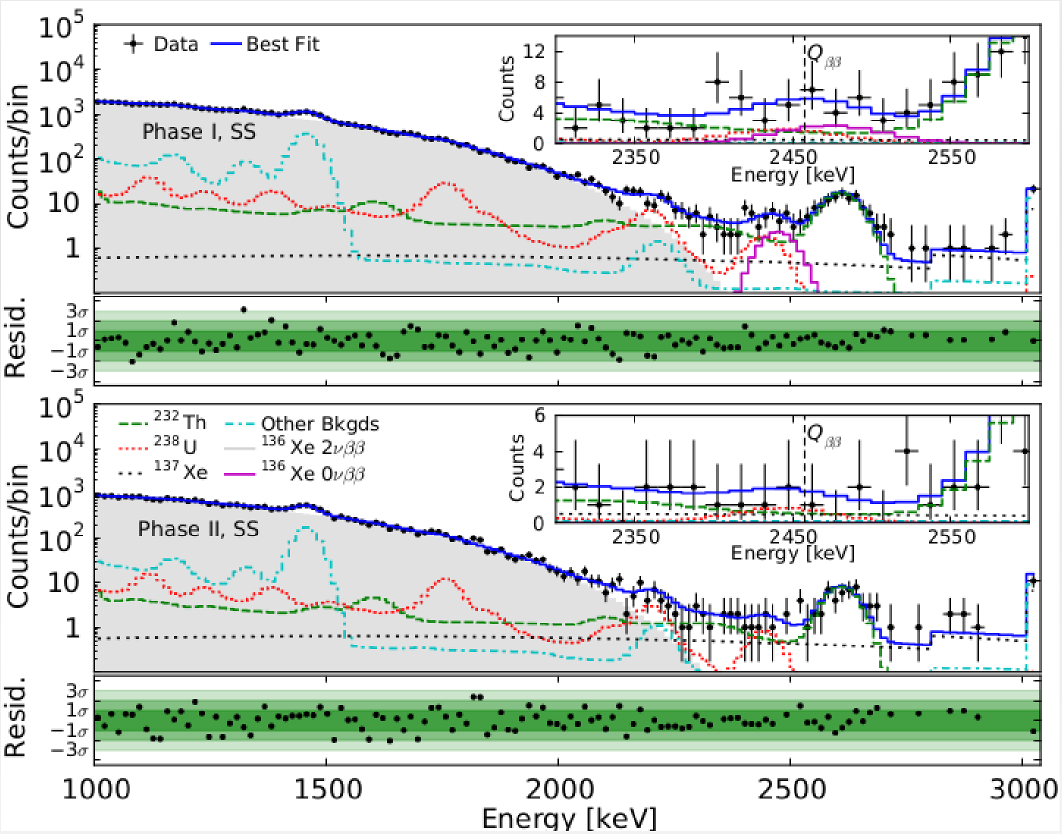
PRL 117 (2016) 082503

EXO-200 @ WIPP

LXe TPC + scintillation readout



light+ionization FWHM for 0νββ ~70 keV @ $Q_{\beta\beta}$



arXiv:1707.08707

$$\boxed{T^{0\nu}_{1/2} > 1.8\cdot 10^{25}\ yr\left(@\ 90\ \ C.L.\right)}$$

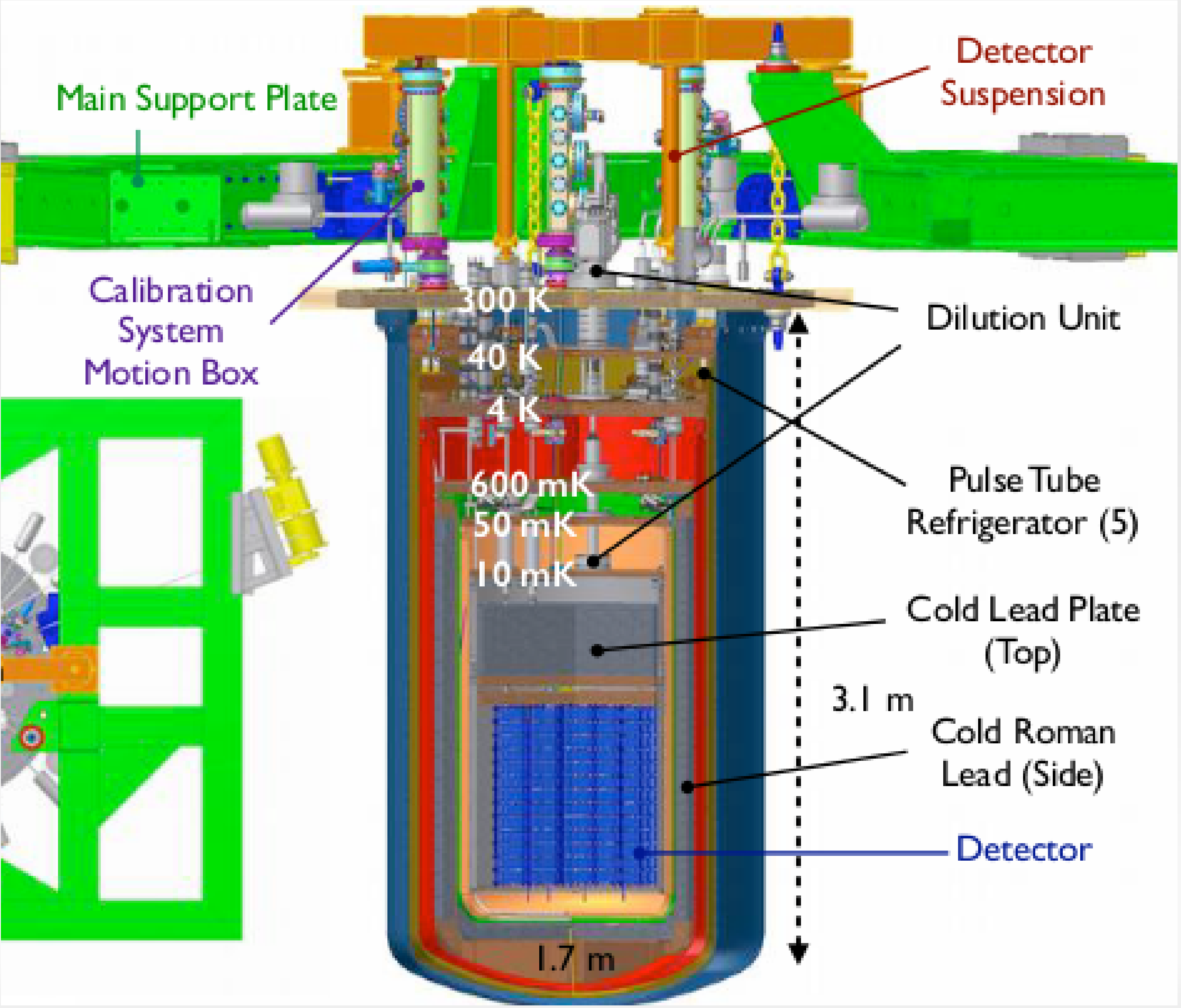
(sensitivity 3.7 10^{25} yr)

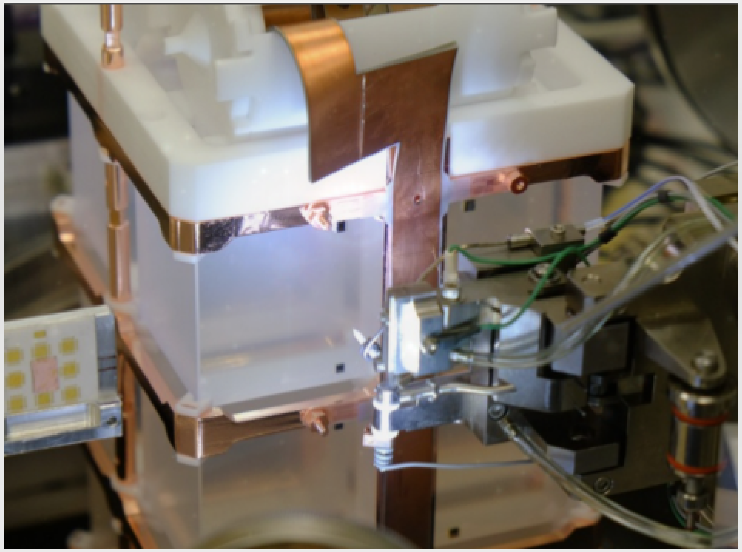
total/fiducial mass 160/100 kg, ^{136}Xe fraction 80.6%

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

now taking data, σ/Q improved to 1.23%
final sensitivity ~6 10^{25} yr (90% CL)

Cuore: ^{130}Te



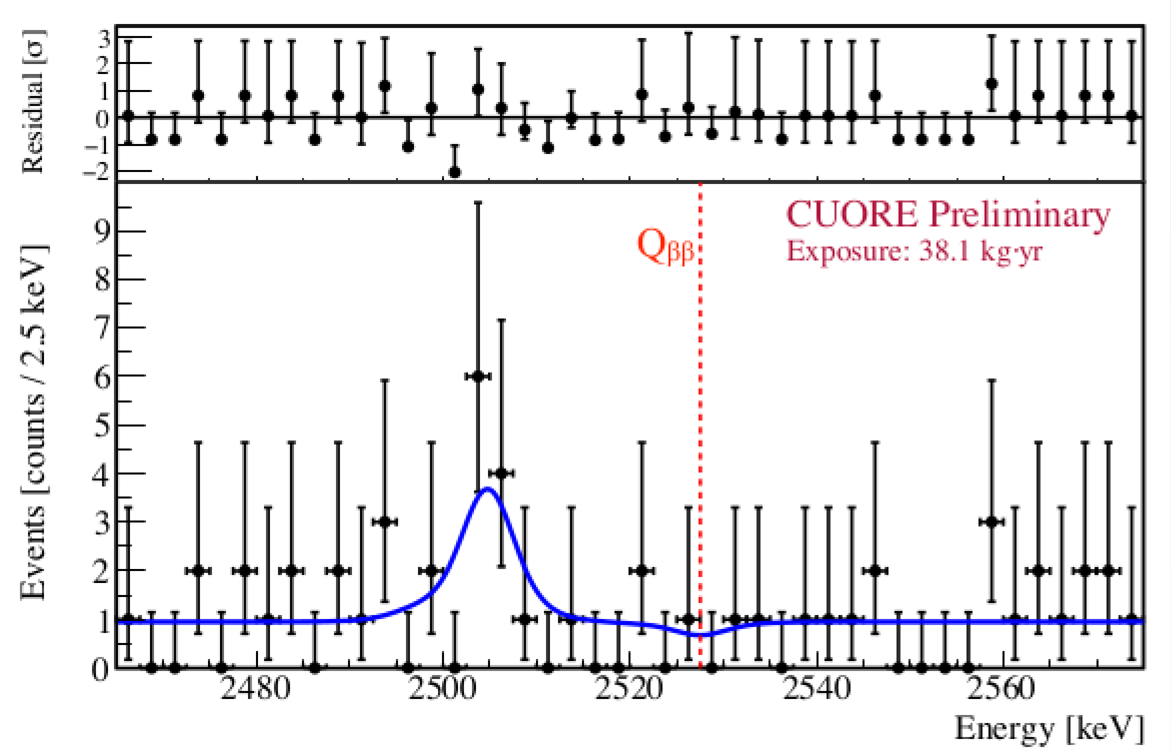


988 $^{nat}TeO_2$ crystals
206 kg ^{130}Te,

calorimeter with Ge NTD readout,
ΔT ~ 0.1 mK / MeV
final resolution ~ 5 keV FWHM

Cuore: ^{130}Te

new cryostat commissioned during last years
all detectors assembled, 984/988 channels working !!!
energy resolution currently ~ 8 keV FWHM at 2615 keV



first result for 2017 physics data:
(blind analysis)

background ~ 0.01 cnt/(keV kg yr)
→ meets design specification
bkg mainly degraded alpha

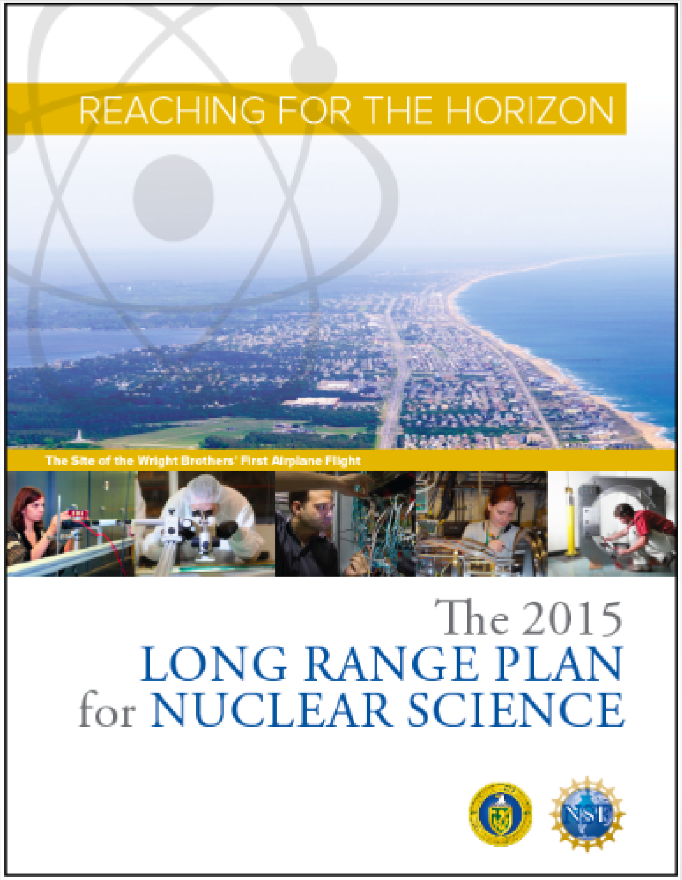
$T^{0\nu}_{1/2} > 4.5 \cdot 10^{24}\ yr\,(@\ 90\ C.L.)$
(sensitivity 3.6 10^{24} yr)

final sensitivity 10^{26} yr

future of 0νββ: personal thoughts

many ideas/proposals how to reach 10^{28} yr (discovery) $T_{1/2}$ sensitivity,
each cost 100 M$ (or more)

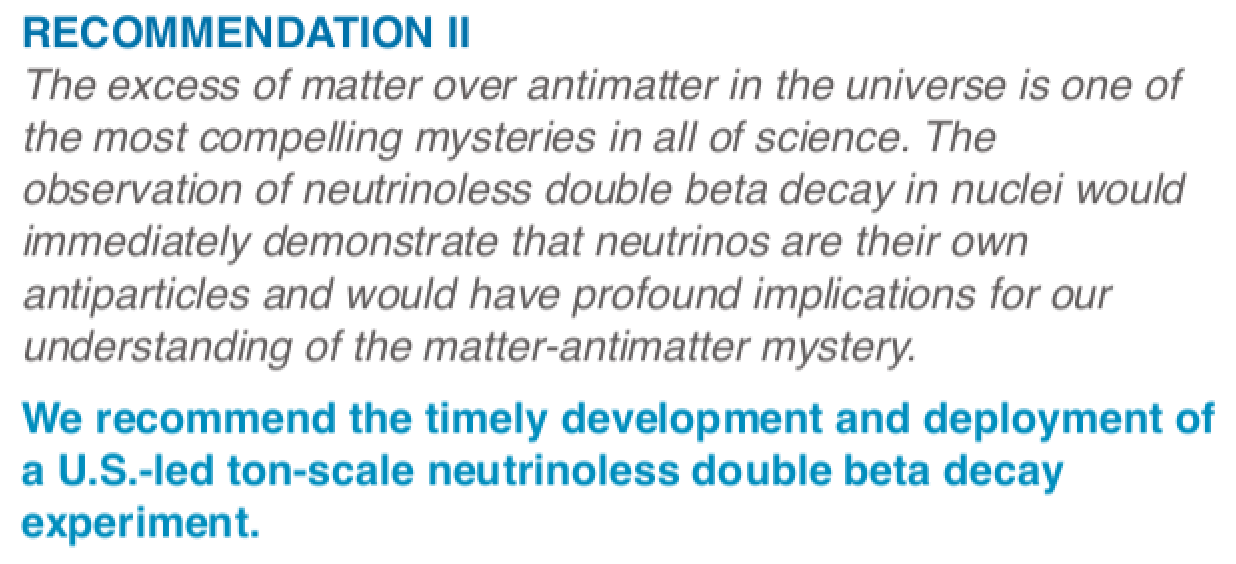
who will fund such experiment(s)?
answer might be here: https://science.energy.gov/np/nsac/



REACHING FOR THE HORIZON

The Site of the Wright Brothers' First Airplane Flight

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE



RECOMMENDATION II

The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

major funding from Europe, China, Japan, Canada, Korea?
US down-select in few years:
- nEXO (successor of EXO-200),
- LEGEND (successor of MajoranaDemonstrator+GERDA),
- + ?? will apply

comparison experiments

		mass [kg]* (total/FV)	FWHM [keV]	background[&] [cnt/t yr FWHM]	$T_{1/2}$ limit sensitivity [10^{25} yr] after 4 yr	worst m_{ee} limit [meV] (lowest NME, g_A unquenched)	
Gerda II	Ge	35/27	3	5	15	190	running
MajoranaD	Ge	30/24	2.4	7	15	190	
EXO-200	Xe	170/80	88	220	6	240	
Kamland-Z	Xe	383/88 750/??	250	90 ?	6 50	240 85	design
Cuore	Te	600/206	5	330	9	210	
NEXT-100	Xe	100/80	17	30	6	240	
SNO+	Te	2340/260	190	60	17	160	
nEXO	Xe	5000/4000	58	2	600	24	future
LEGEND-200	Ge	200/155	3	1	100	75	
LEGEND-1t	Ge	1000/780	3	0.2	1000	24	

* 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: 0νββ exists, ΔL=2 process, possibly our only observable ΔL,
leptogenesis: mater-antimatter asymmetry linked to ΔL and 0νββ

$T_{1/2}$ unknown (no real guidance from theory), discovery can be 'around the corner',

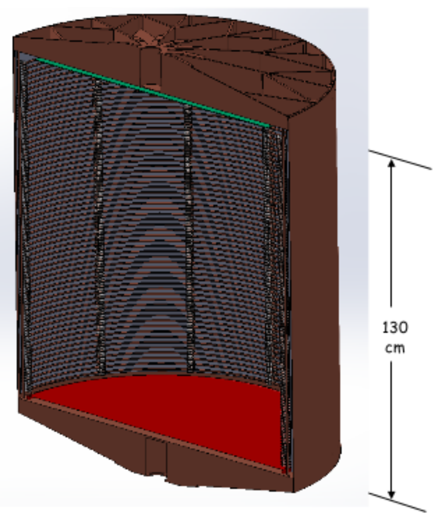
experimental input is desperately needed (0νββ, LFV, LHC, …),
discovery would have a major impact on SM and cosmology

current experiments have half-life sensitivity 10^{25} – 10^{26} yr (for different isotopes)

which technology best suited for future 10^{28} yr sensitivity experiment?

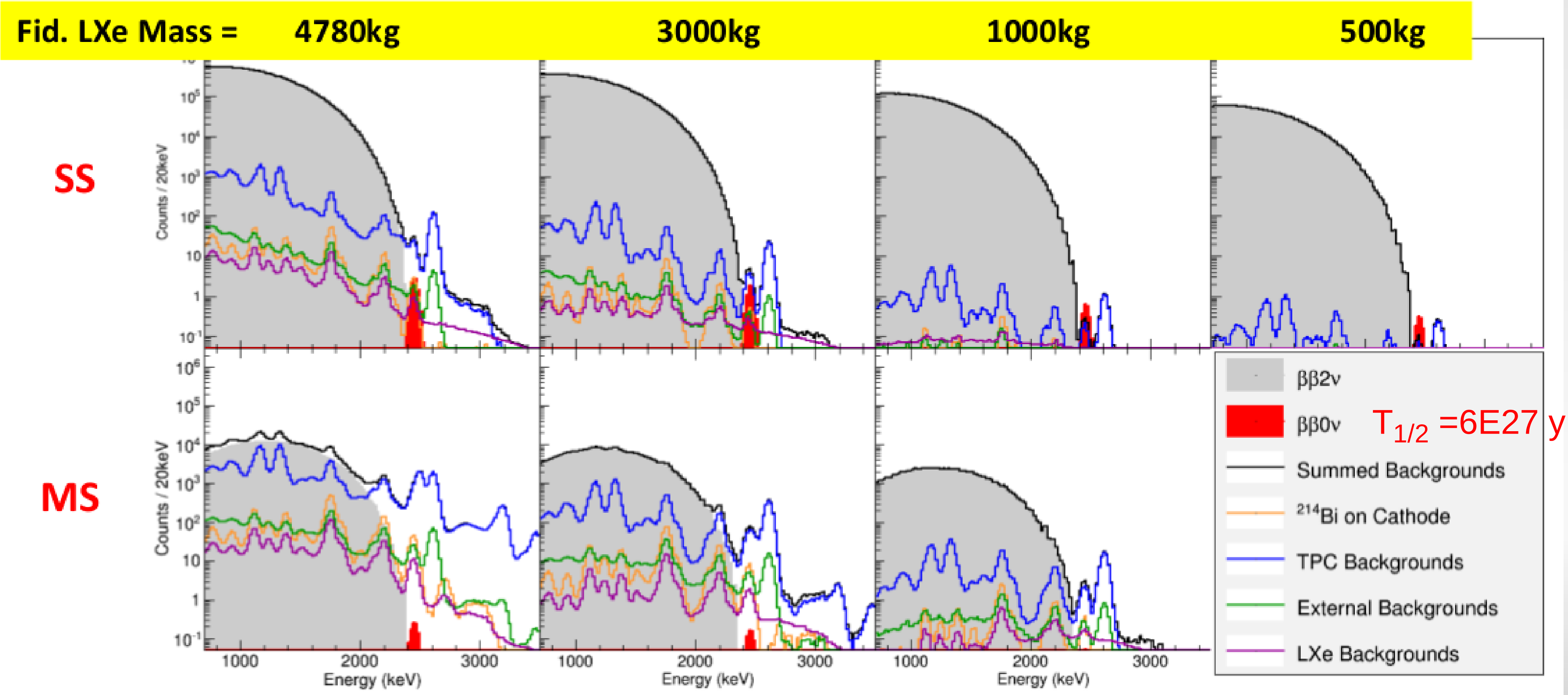
In US: 0νββ highest priority of any new projects for DOE nuclear physics

nEXO: 5 t liquid ^{136}Xe TPC



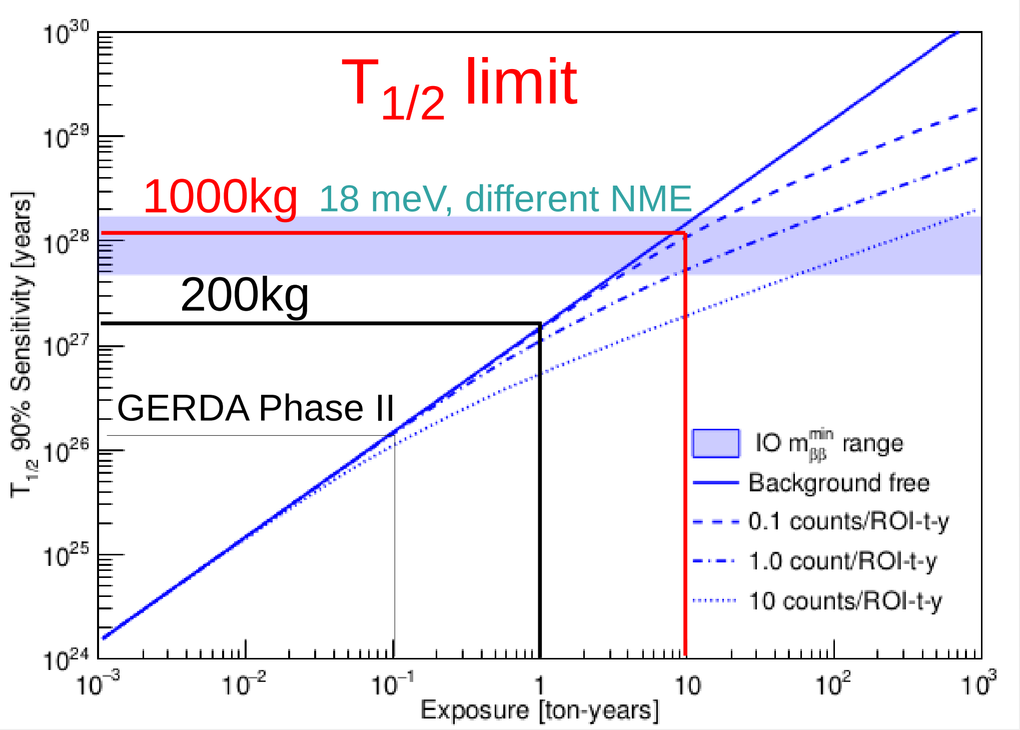
builds on EXO200 experience

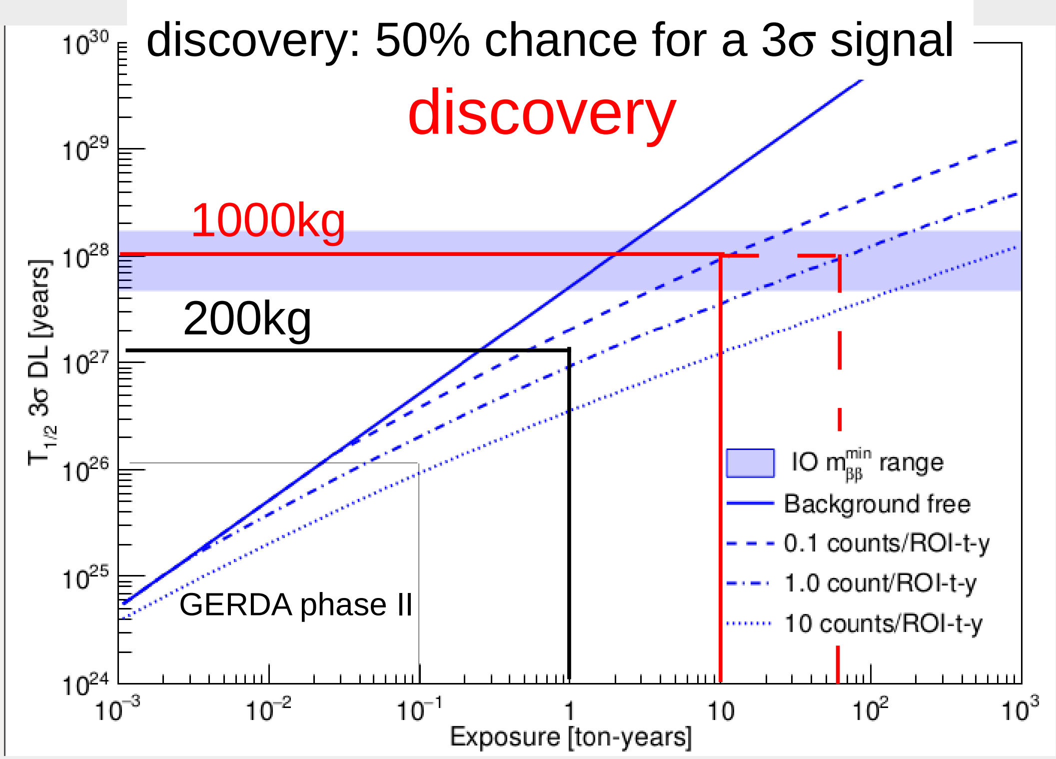
- R&D for cleaner material, full surface light readout, Ba tagging
- homogeneous detector
- enrichment much cheaper but factor 5 more material
- background can be reduced by lowering fiducial volume, but does not improve limit setting sensitivity
- ^{214}Bi line close to $Q_{\beta\beta}$



$T_{1/2}$ =6E27 yr

^{76}Ge sensitivity limit + discovery





discovery: 50% chance for a 3σ signal

- $T_{1/2}$ unknown, BSM → 'around corner'
  background reduction in steps → phased approach

- inputs: 60% efficiency (GERDA number)
  background GERDA ~ 3 cts/(FWHM t yr)
  200 kg ~ 0.6 cts/(FWHM t yr)
  1000 kg ~ 0.1 cts/(FWHM t yr)

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

”background-free” very important
(for all isotopes)