Neutrinoless double beta decay with ^{76}Ge

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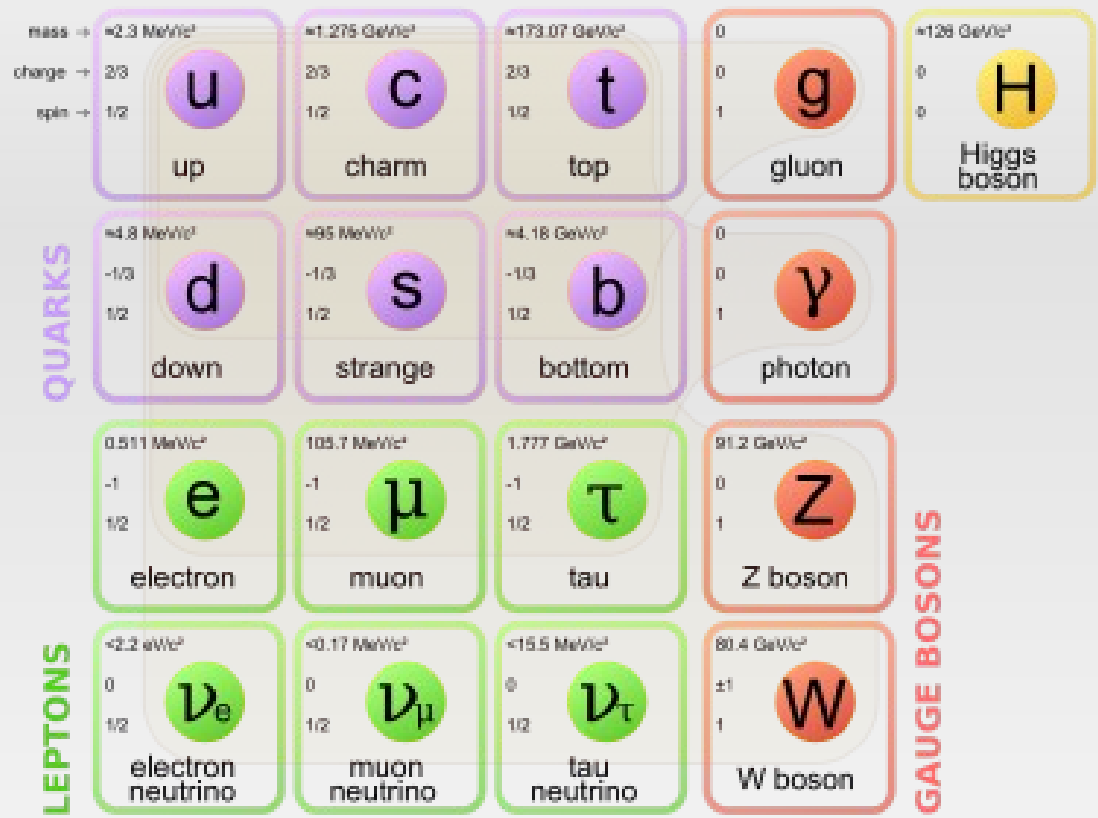
Standard Model

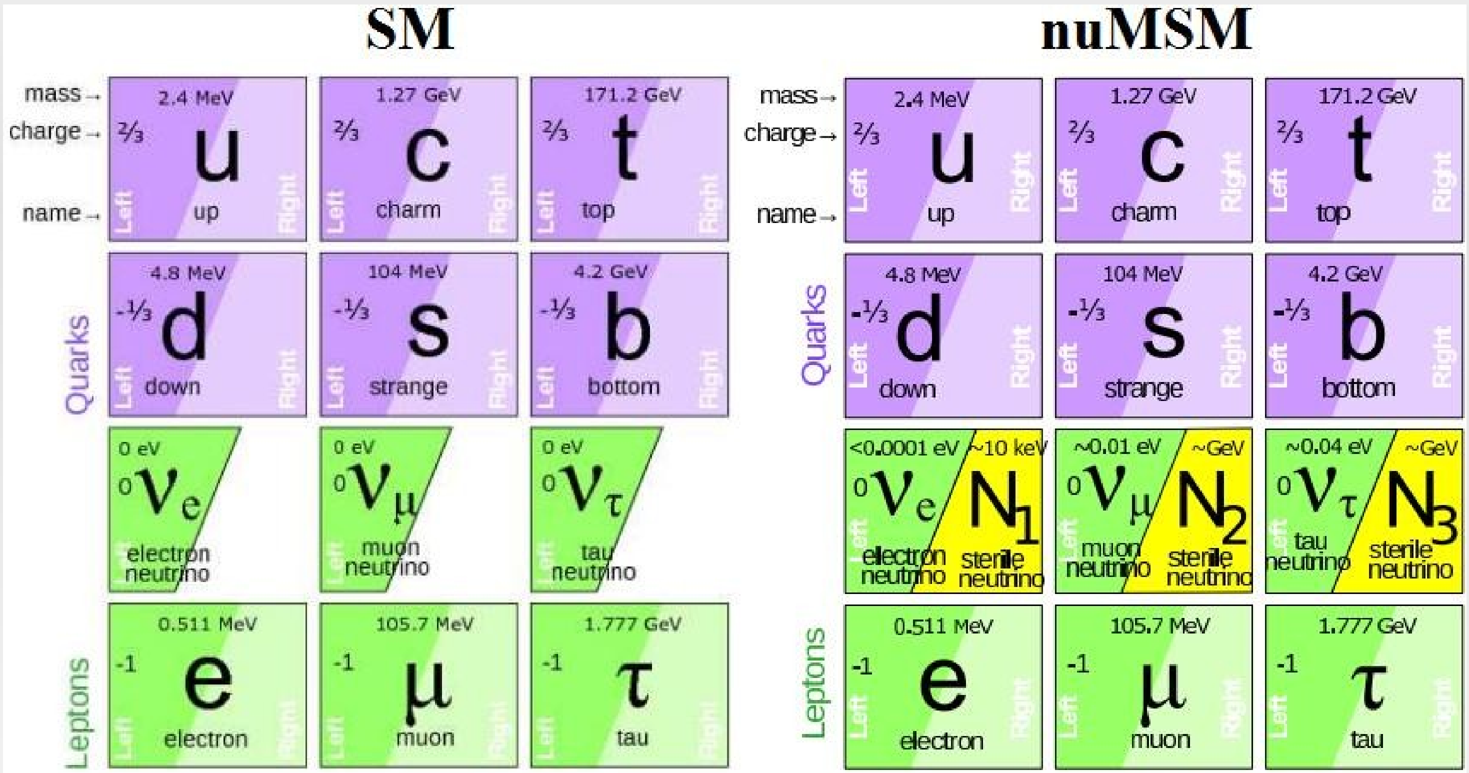


no new physics found at the LHC so far, SM could be valid up to Planck scale

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

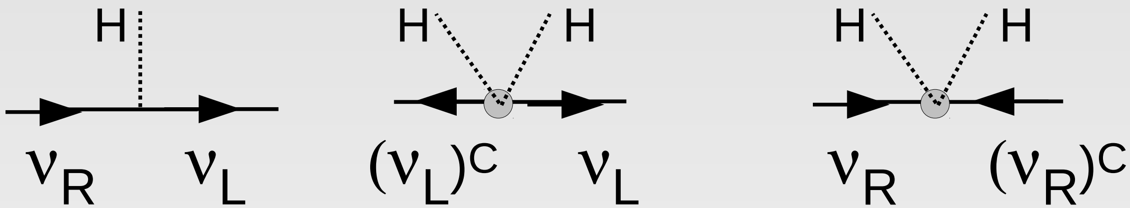
ν oscillations (Nobel prize 2015) → ν_L have (tiny) mass (< m_e / 10^6)

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 ($m_L \sim 0$) 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 → N μ X with N → μ π by SHIP (200 MCHF)

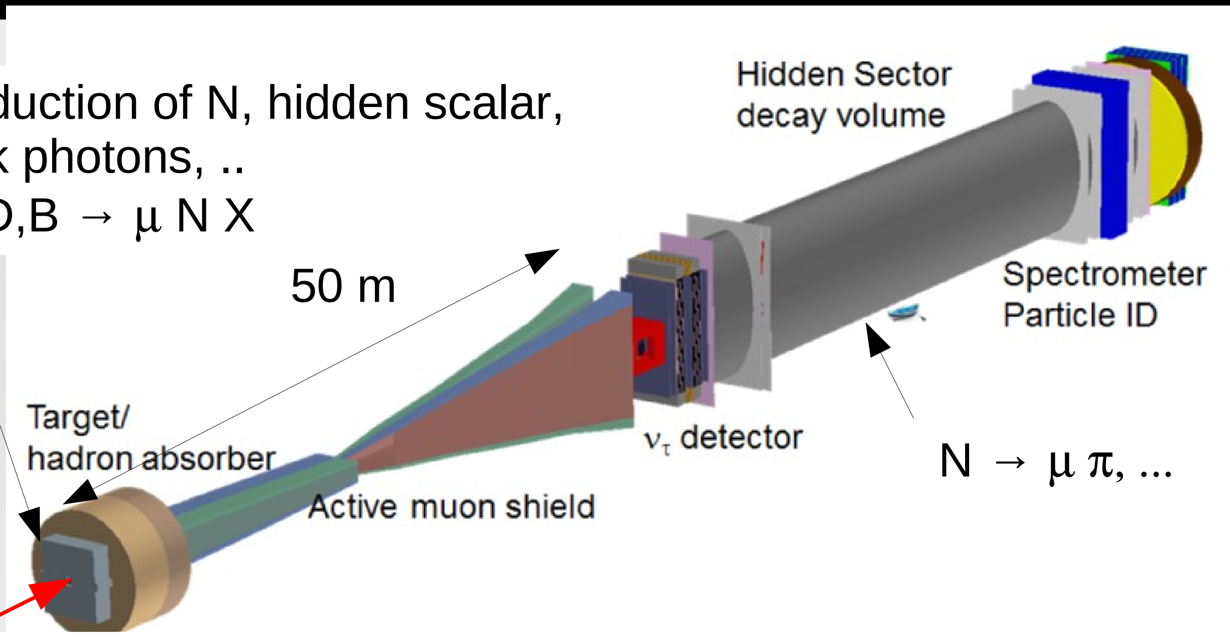
10 keV: (warm+cold) dark matter candidate, N → γ ν decay ~ $U^2\, m_R^5$
hint for 3.5 keV line ?? (arXiv:1402.2301, arXiv:1402.4119)

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



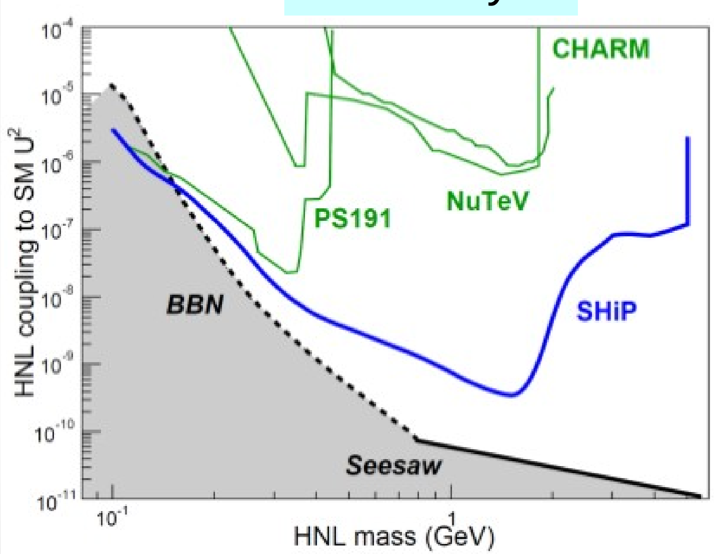
SPS 400 GeV p

arXiv:1504.04956
arXiv:1504.04855

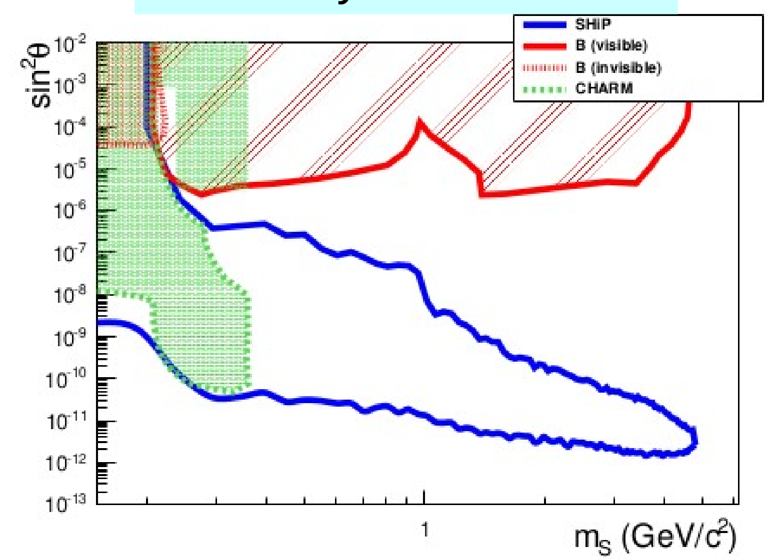
uses CNGS beam line,
total 2 10^{20} pot
~8 10^{17} D mesons

cost for beam+exp 200 MCHF

sensitivity N

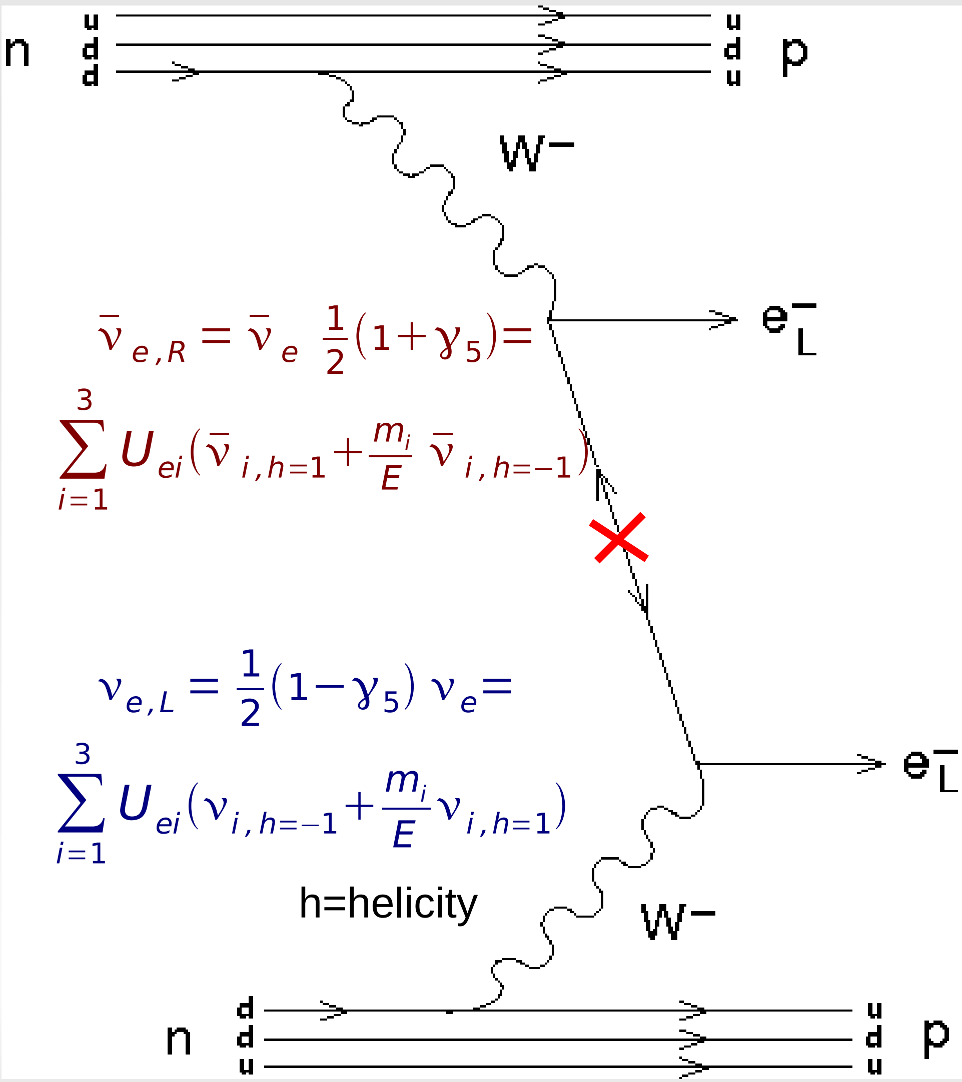


sensitivity hidden scalar



How to observe ΔL=2?

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



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

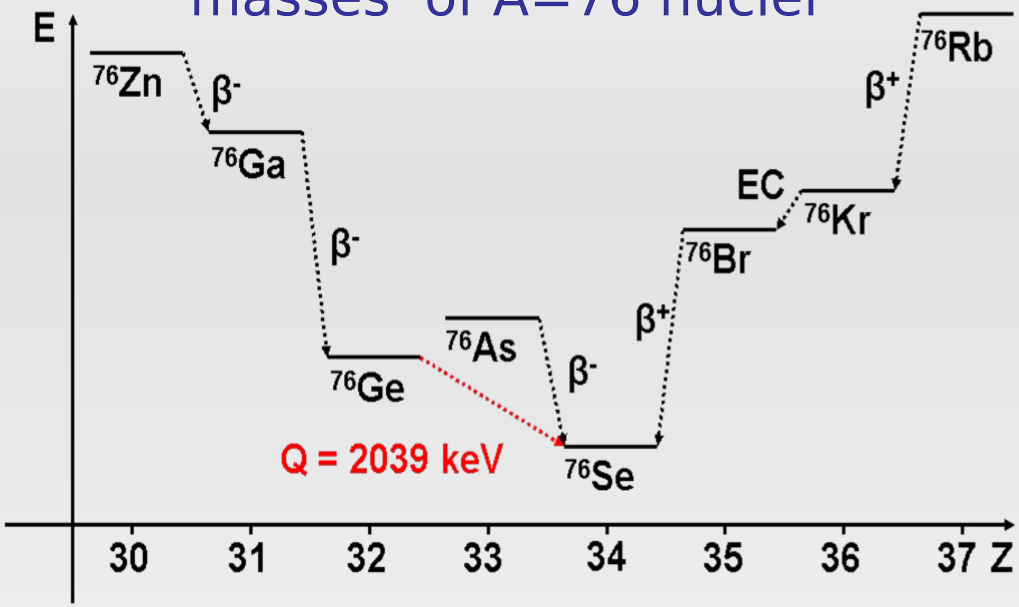
function of
- neutrino mixing parameters
- lightest neutrino mass
- 2 Majorana phases

also possible: heavy N exchange

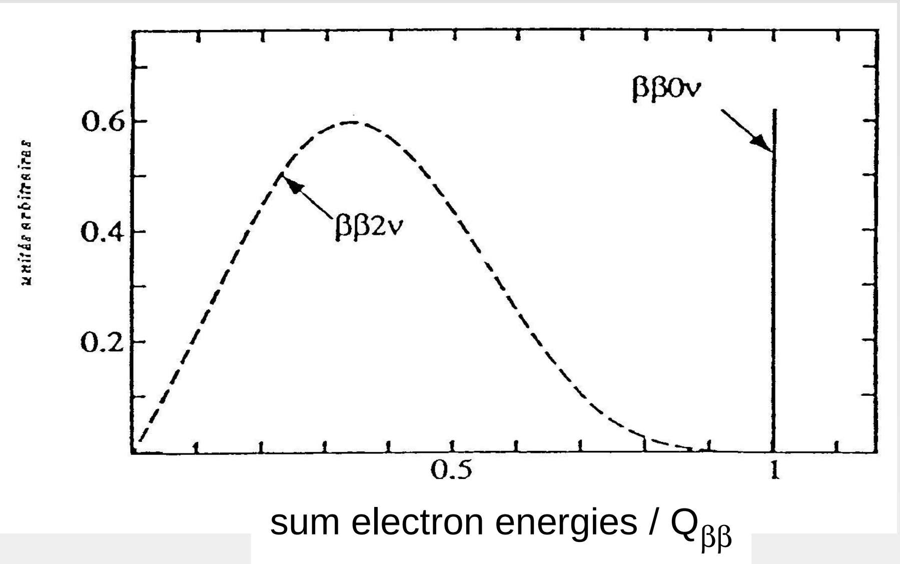
→ coupling strength ~ $\sum_{i=1}^{3} V_{ei}^2 / M_i$

How to observe ΔL=2?

masses of A=76 nuclei



experimental signature for ββ



”single” beta decay not allowed

→ only ”double beta decay”

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

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

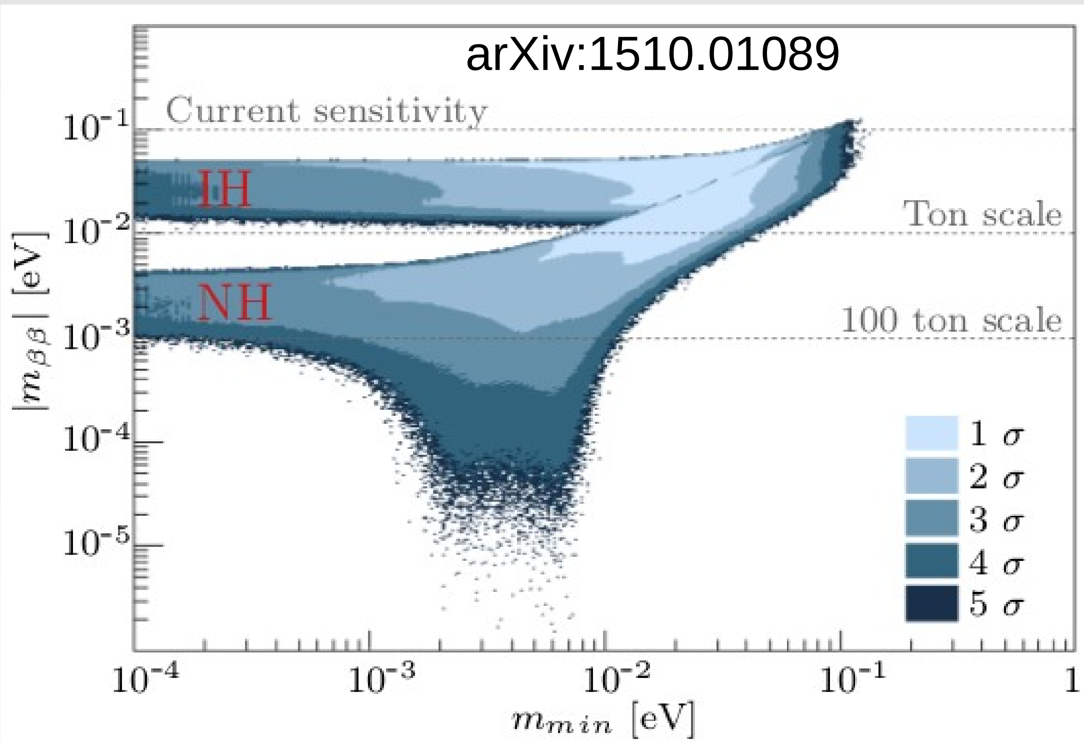
0νββ: search for a line at Q value of decay

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

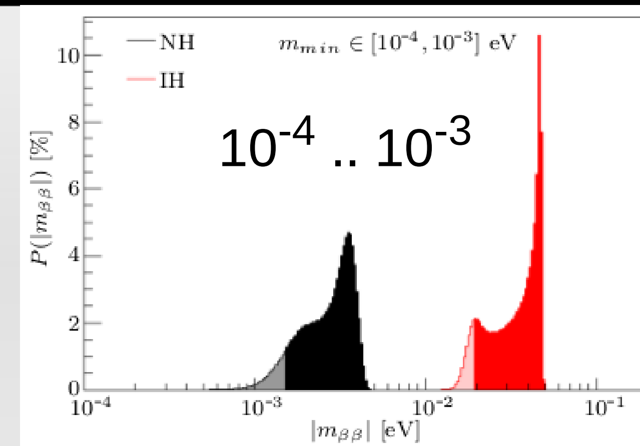
scan of $m_{\beta\beta}(\Delta m_{atm}^2, \Delta m_{sol}^2, m_{min}, \theta_{atm}, \theta_{sol}, \theta_{13}$, 2 Majorana Φ)
according to measurements or random (2 Maj. phases)

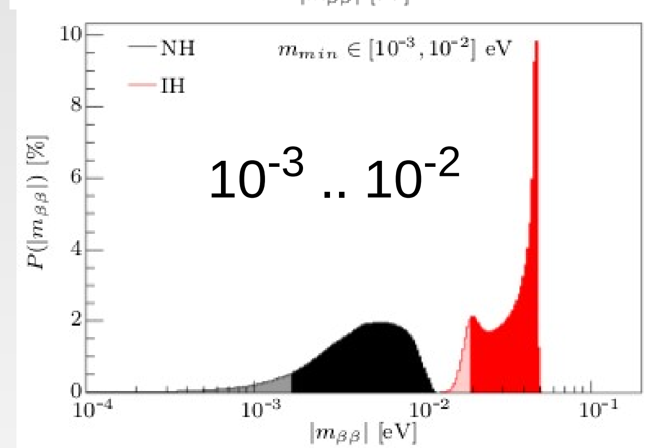


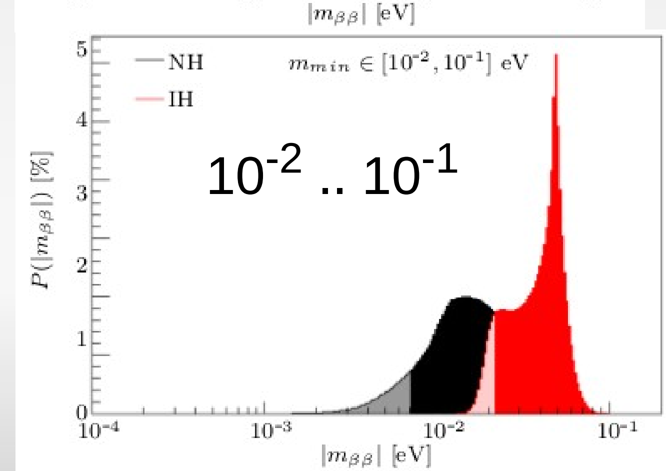
including cosmological bound Σ = (22±62) meV[1]

[1] true for flat ΛCDM only

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

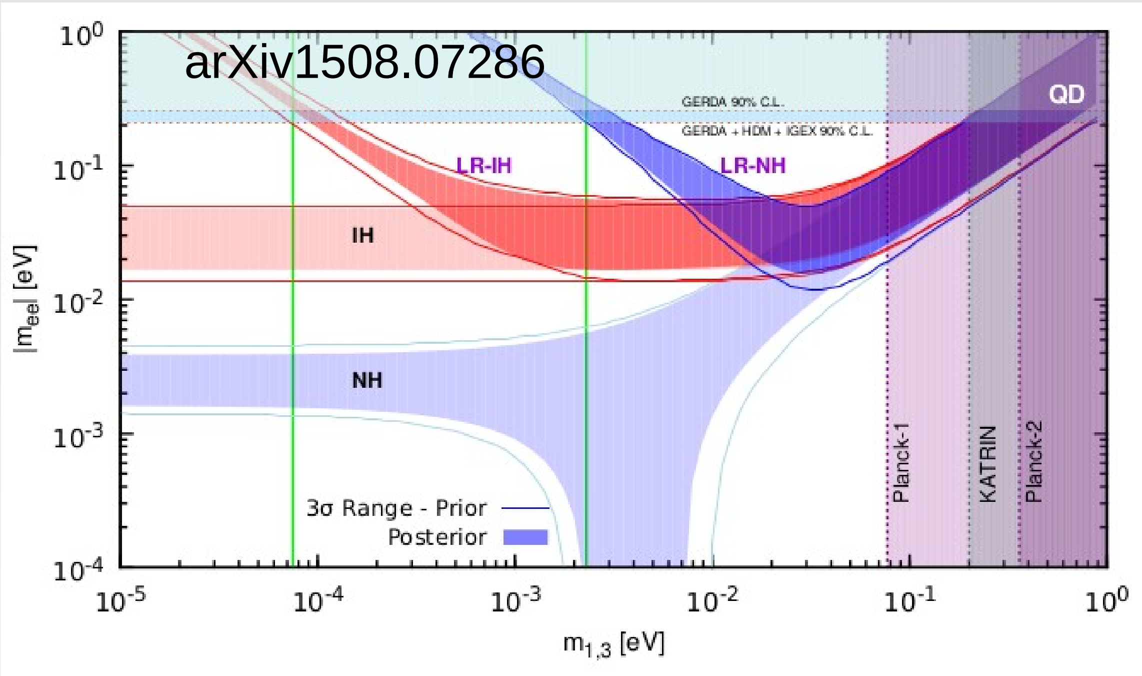


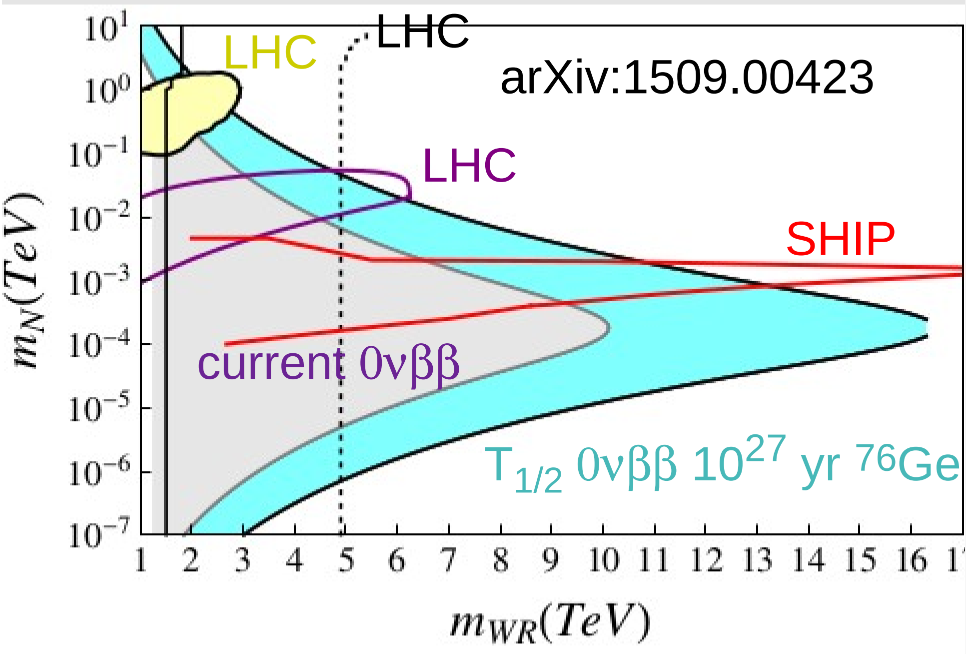


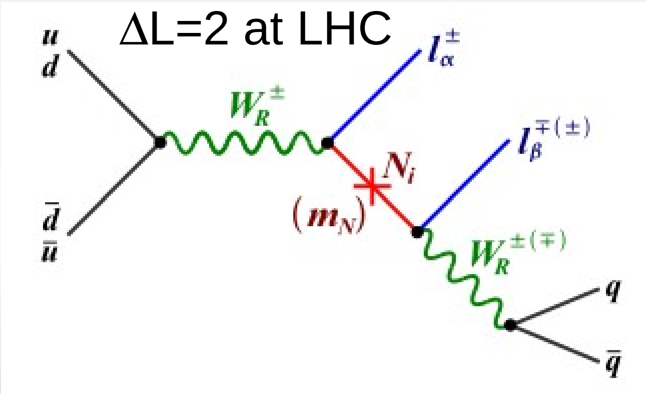


LHC vs 0νββ: other mechanics

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

LHC vs 0νββ: other mechanics

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

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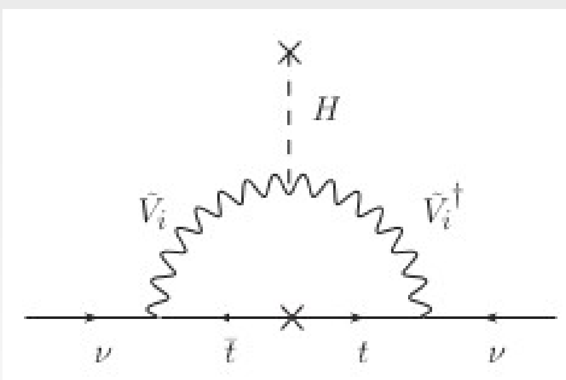
[2] *Institute of High Energy Physics, Austrian Academy of Sciences, Nikolsdorfergasse 18, 1050 Vienna, Austria*
[3] *Fakultät für Physik, Technische Universität Dortmund, 44221 Dortmund, Germany*

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

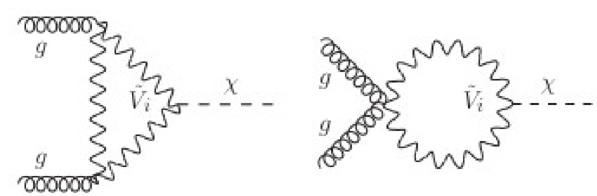


Figure 5: Dominating diagrams contributing to $\sigma(pp \to \chi)$.

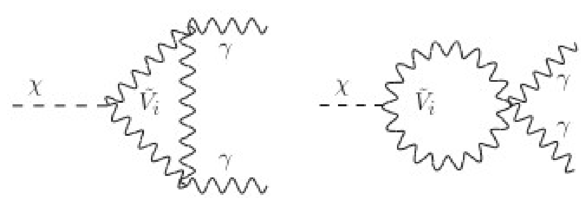


Figure 6: Diagrams contributing to $\Gamma(\chi \to \gamma\gamma)$.

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

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

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

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

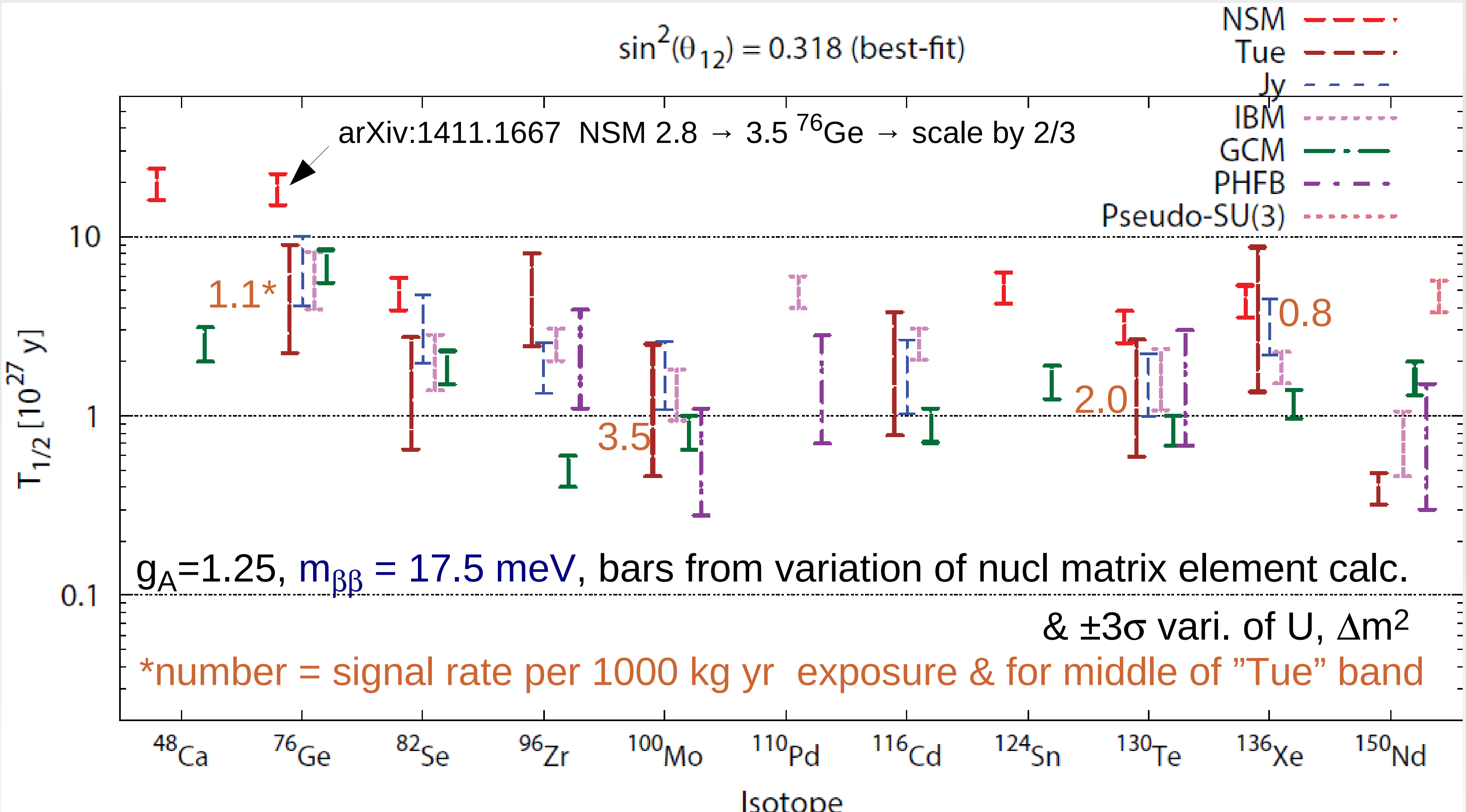
Experiment observes $N^{0\nu} = \ln 2 \frac{N_A}{A} \cdot a \cdot \epsilon \cdot M \cdot t \, / \, T_{1/2}$ and $N^{bkg} = M \cdot t \cdot B \cdot \Delta E$

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



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 favoured isotope if spread of NME considered
expect only ~1 event/year for 1000 kg isotope mass

How to reduce background

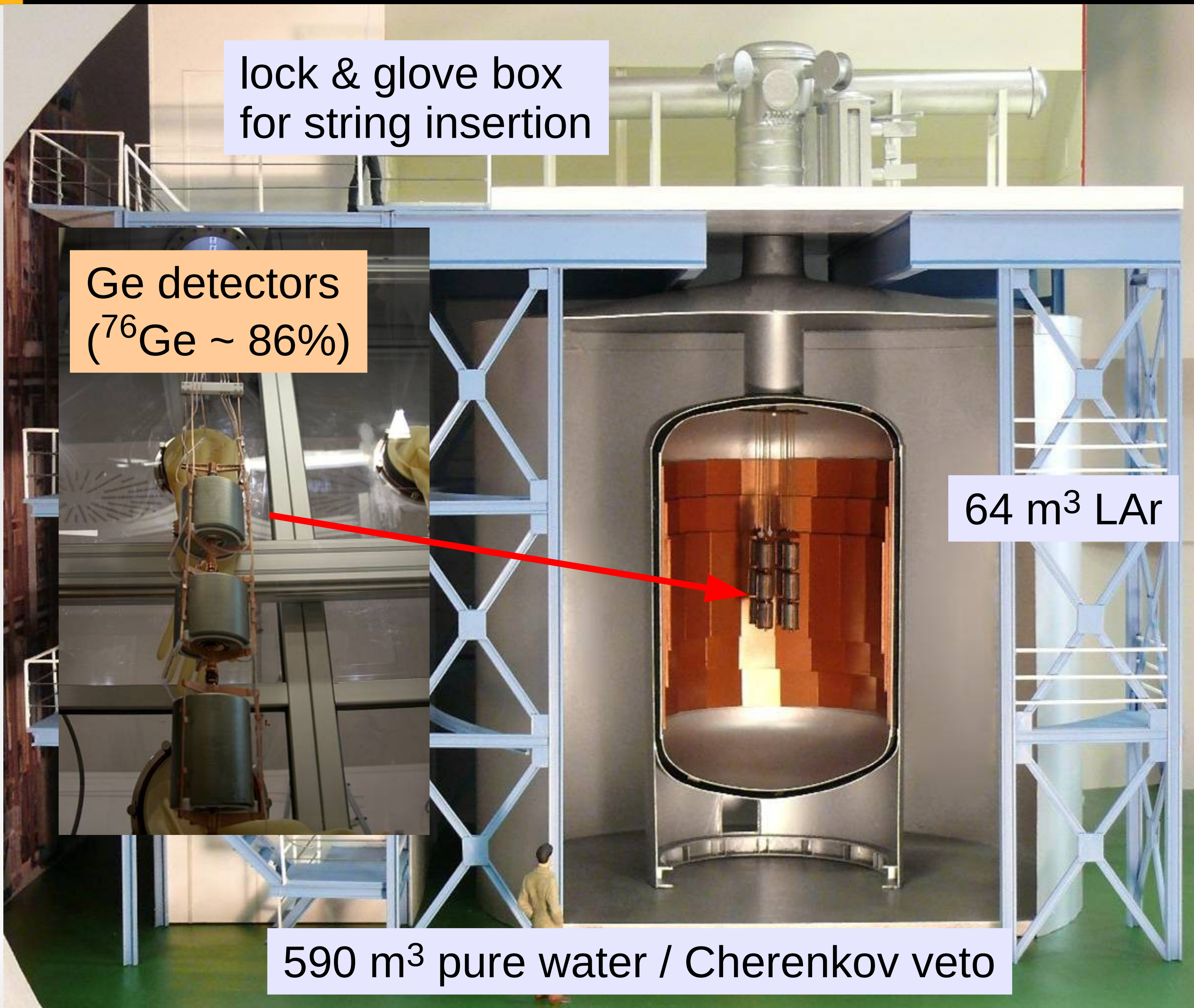
sources: cosmic rays (p,n,μ,γ) → underground like Homestake mine
neutrons from (α,n) and spallation induced by μ
α,β,γ from radioactive decay chains ^{238}U, ^{232}Th

→ 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

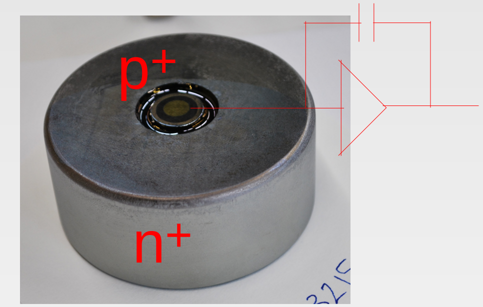
Phase I (2011-13):

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

^{76}Ge $0\nu\beta\beta$ decay, PRL 111 122503

Phase II:

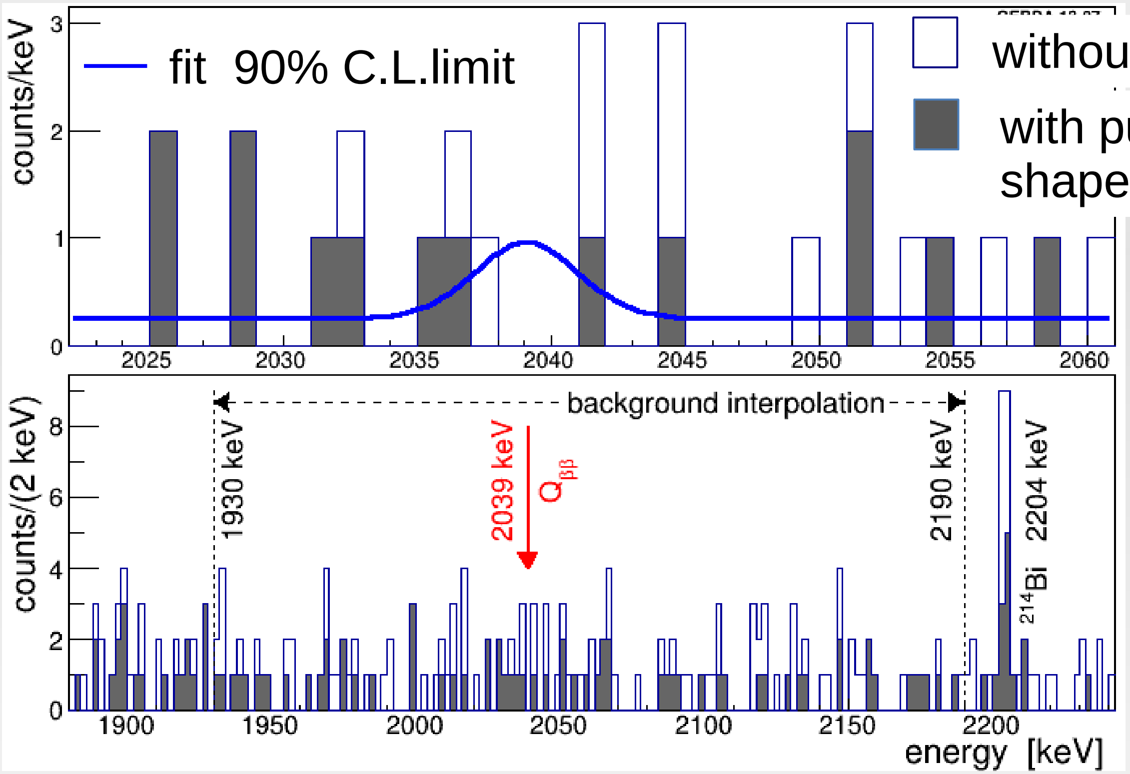
2x Ge mass (30 BEGe det.)



LAr scint. light readout

started end 2015

GERDA phase I results



events ±20 keV blinded

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

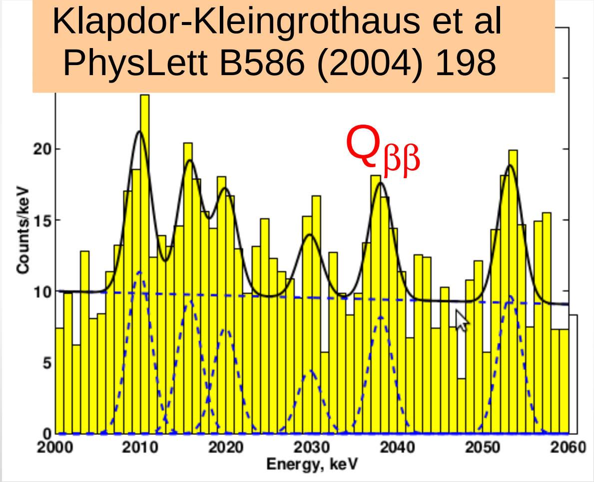
exposure 21.6 kg yr
backgr. 0.01 cnt/(keV kg yr)
after pulse shape cut

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

(sensitivity = 2.4 10^{25} yr)

PRL 111 (2013) 122503.

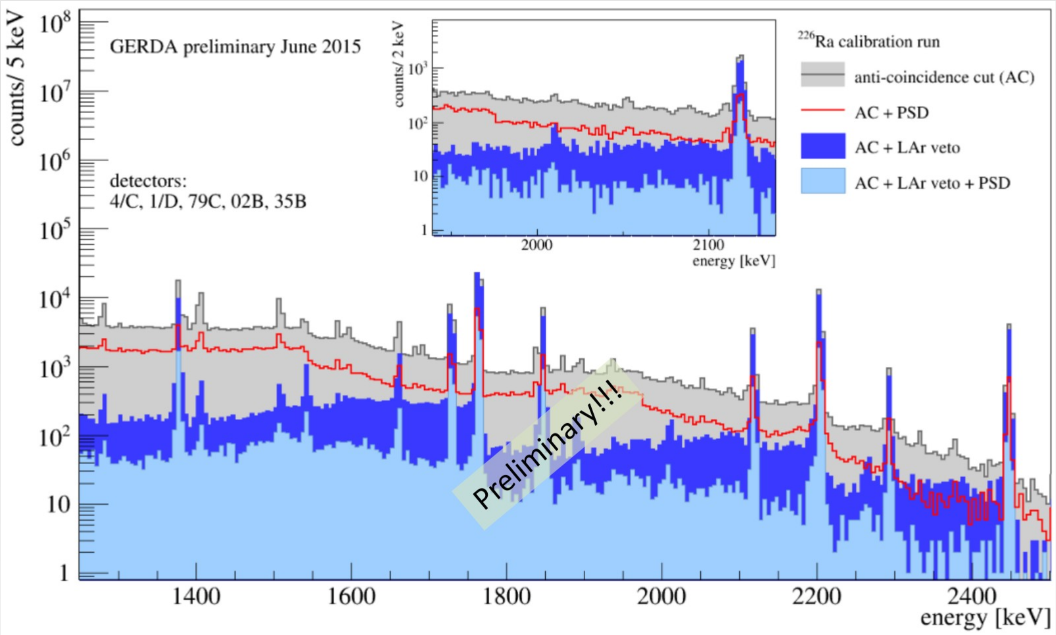
Klapdor-Kleingrothaus et al
PhysLett B586 (2004) 198



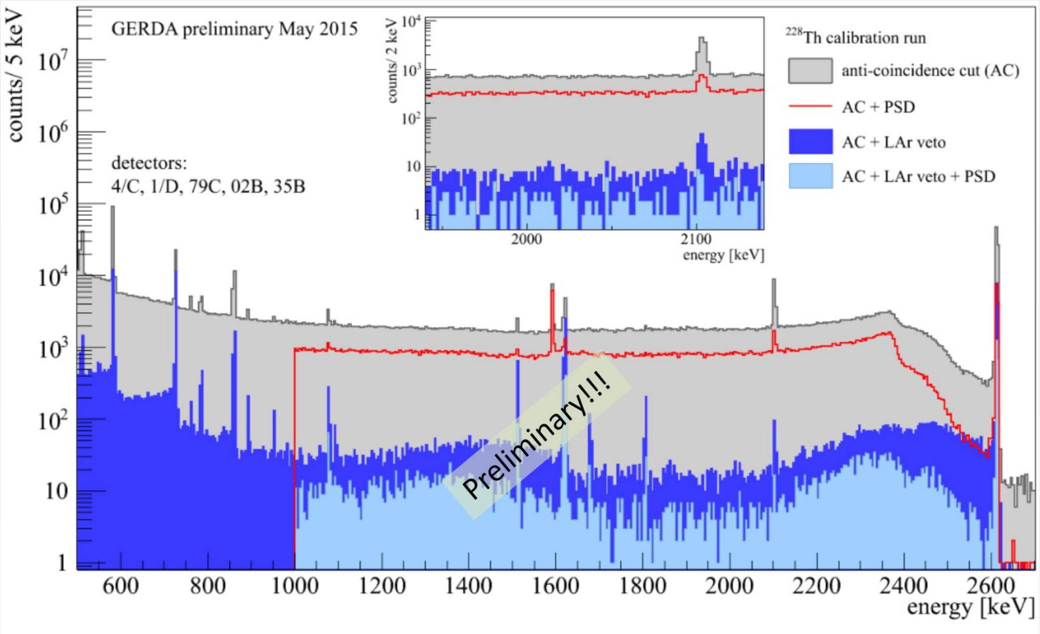
claimed signal: GERDA should see 5.9±1.4 $0\nu\beta\beta$ events in
±2σ interval above background of 2.0±0.3
probability p($N^{0\nu}$=0 | H_1=signal+bkg) = 1%, claim ruled out @ 99%
(GERDA best fit signal count $N^{0\nu}$ = 0)

Argon veto performance

^{226}Ra calibration source



^{228}Th calibration source

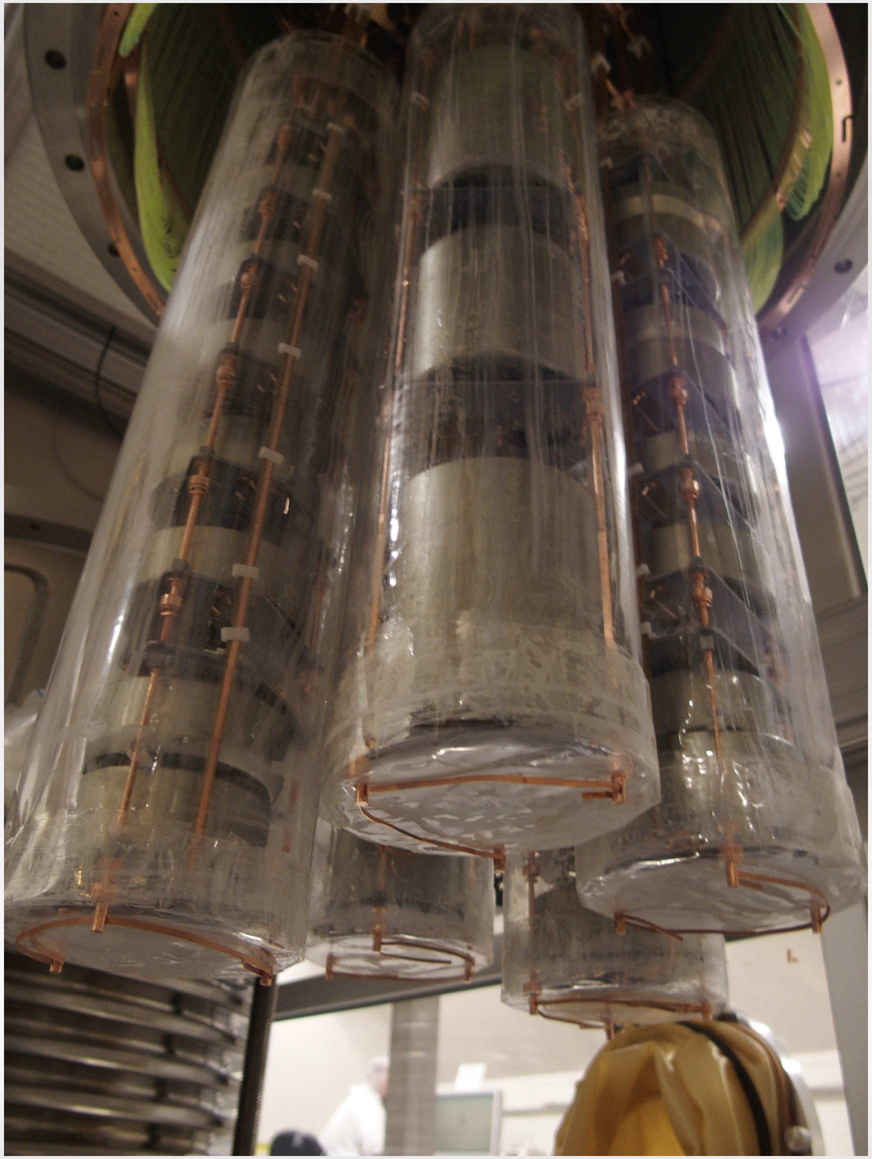


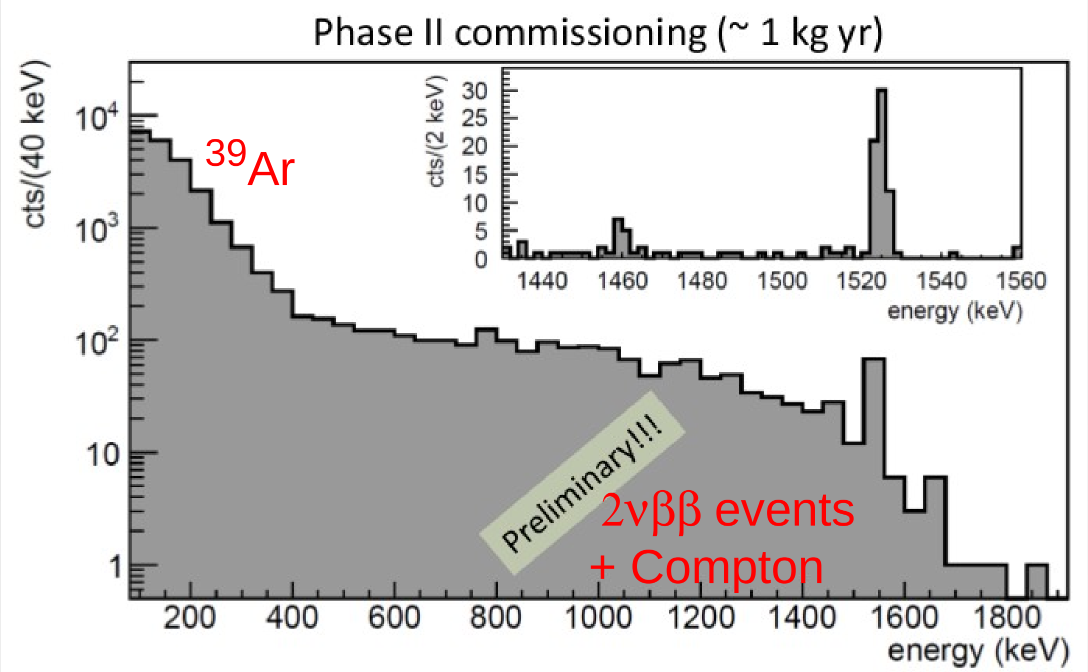
veto suppression factor 5.1±0.2
combined with pulse shape
& anti-coincidence 25±2.2

veto suppression factor 85±3
combined with pulse shape
& anti-coincidence 390±28

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

Phase II status

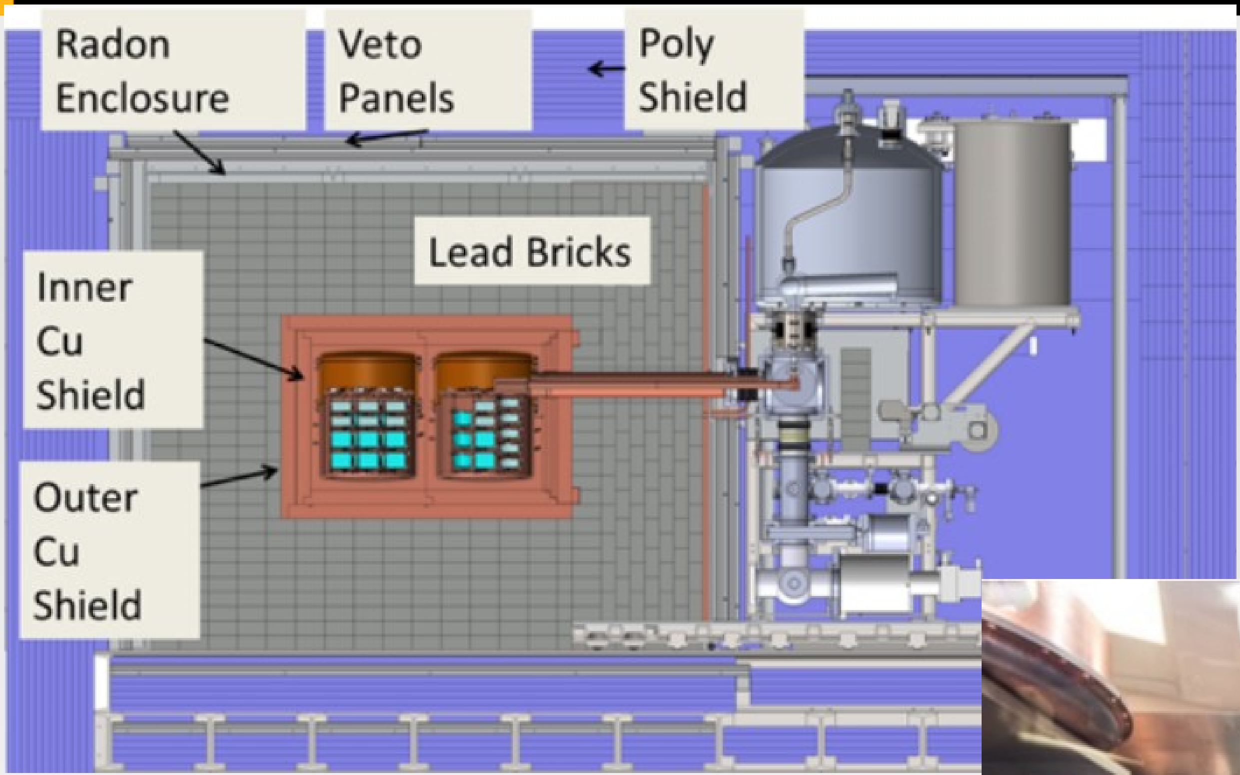




all detectors mounted & biased in Dec 2015
LAr veto working

Phase II data taking started

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 + …

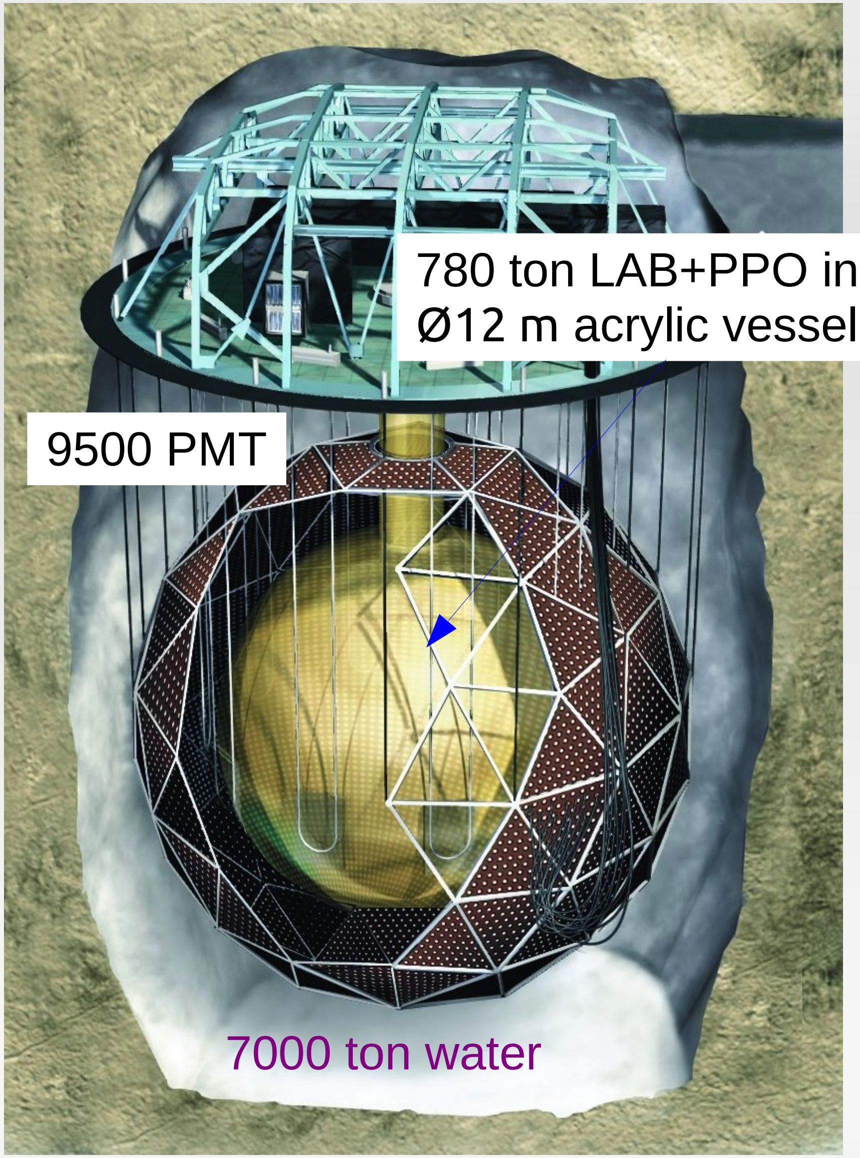
goal: prove design for ton scale

proto-type module:
10 detectors, 2014-2015

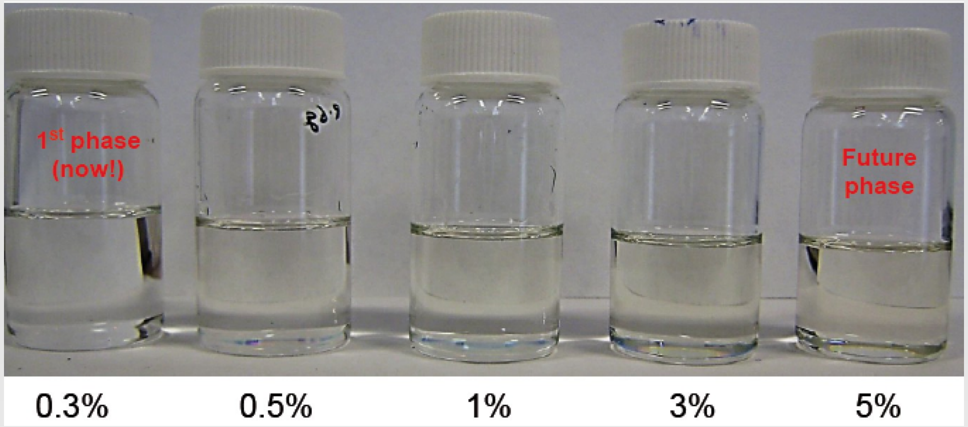
Module 1
29 detectors, 2015 first installation
running since Jan 2016

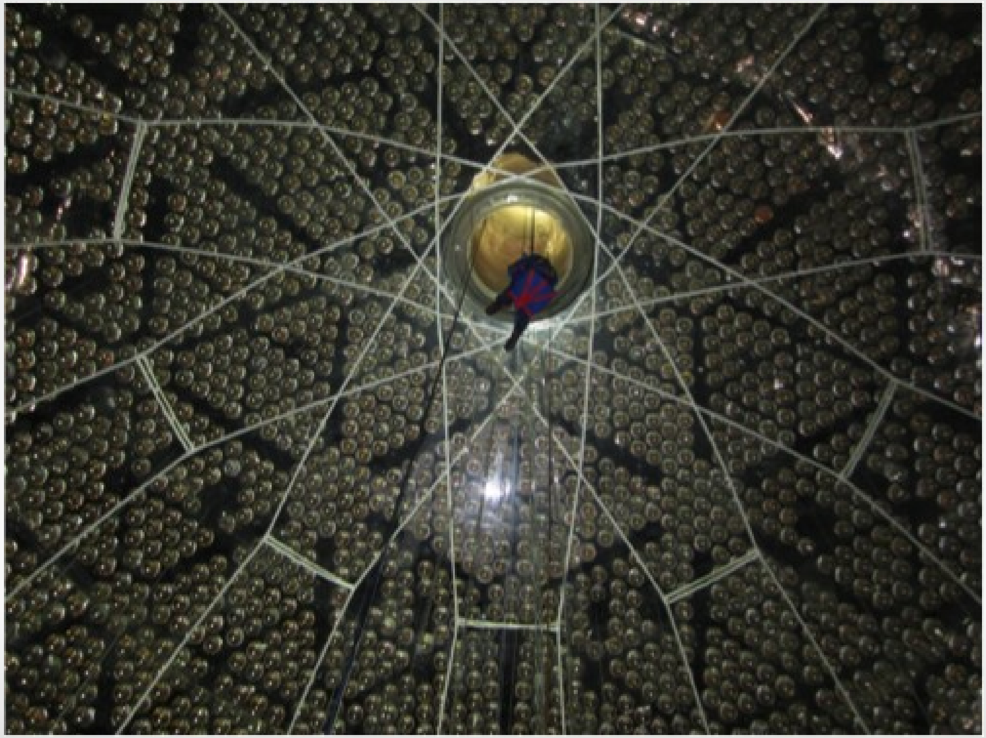
Module 2:
29 detectors, in few months complete

SNO+

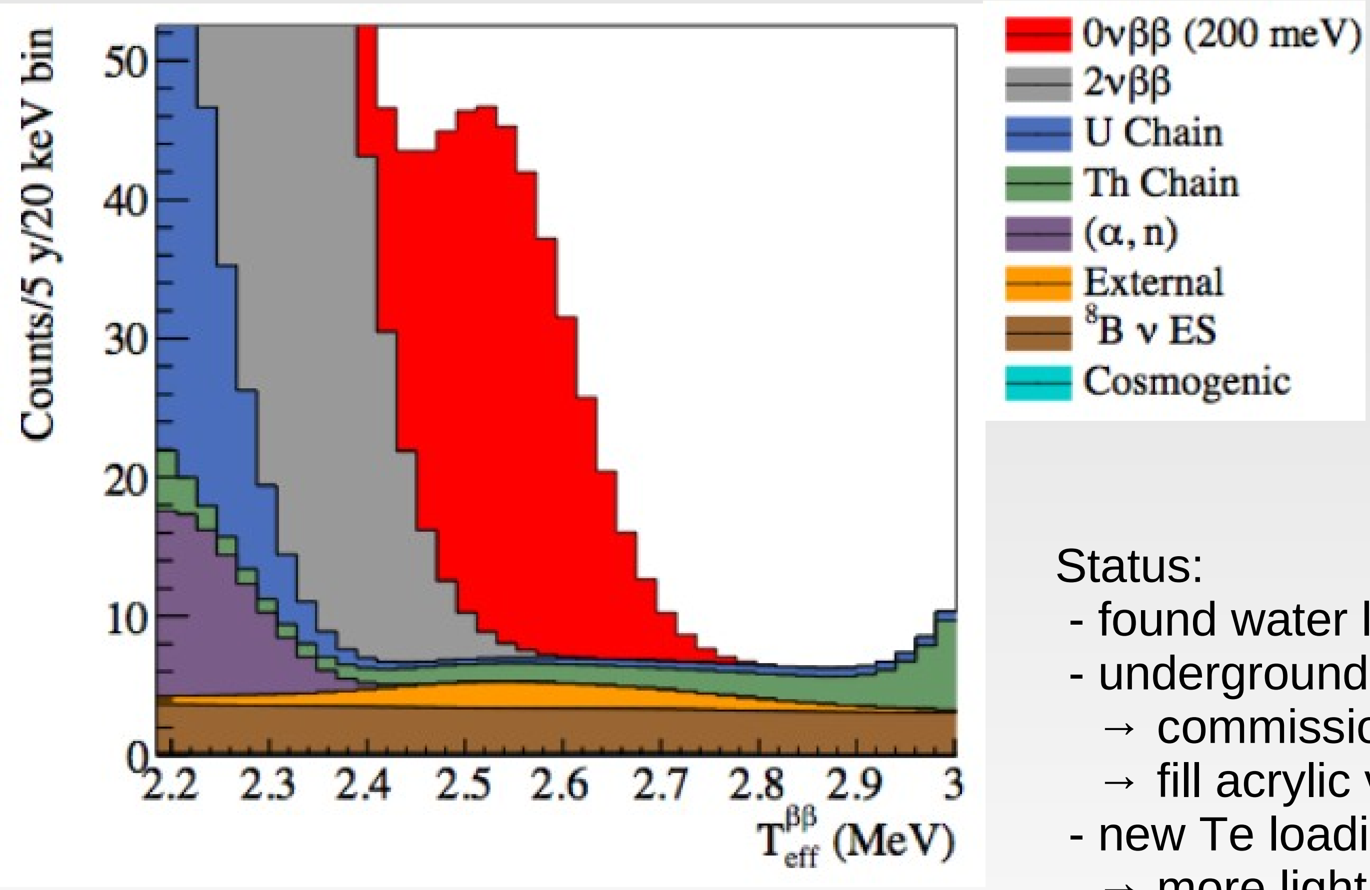


default: 0.5% loading → 3900 kg ^{nat}Te / 1300 kg ^{130}Te





SNO+

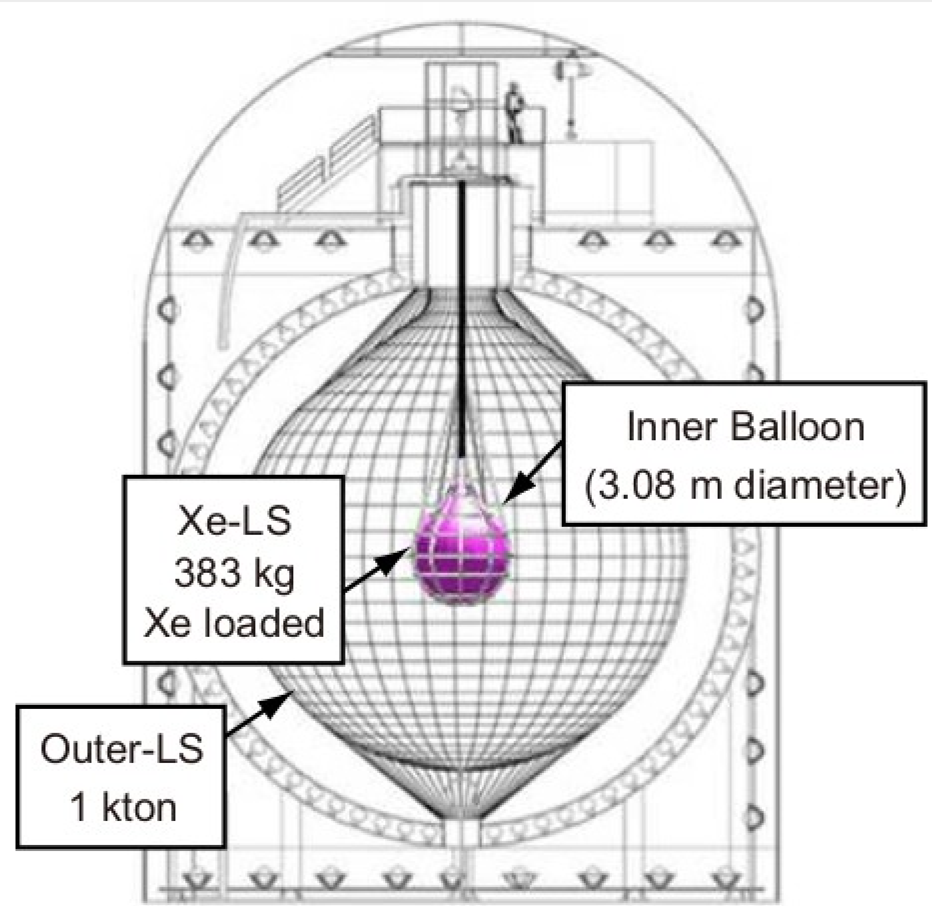


0.5% Te loading
FV: R<3.5 m (20% vol)
390 p.e./MeV light yield

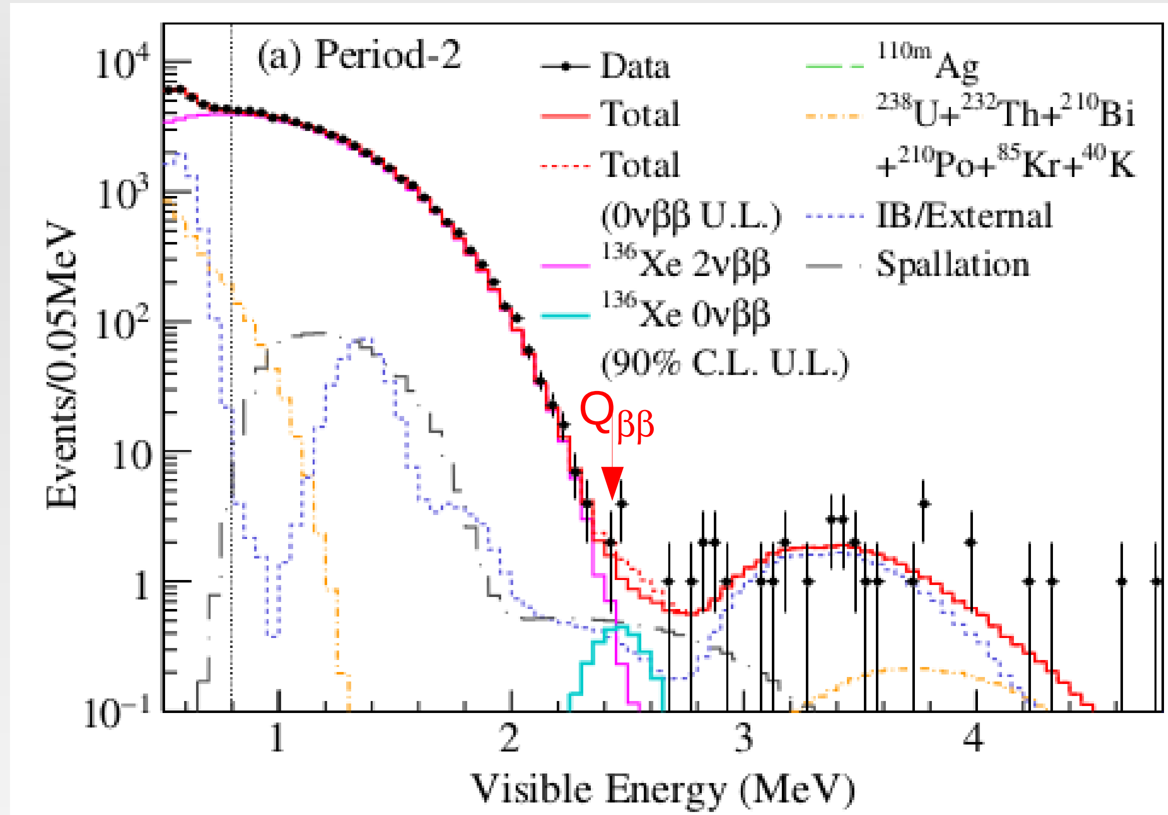
sensitivity 90% limit
$T_{1/2} > 2\ 10^{26}$ after 5 yr

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

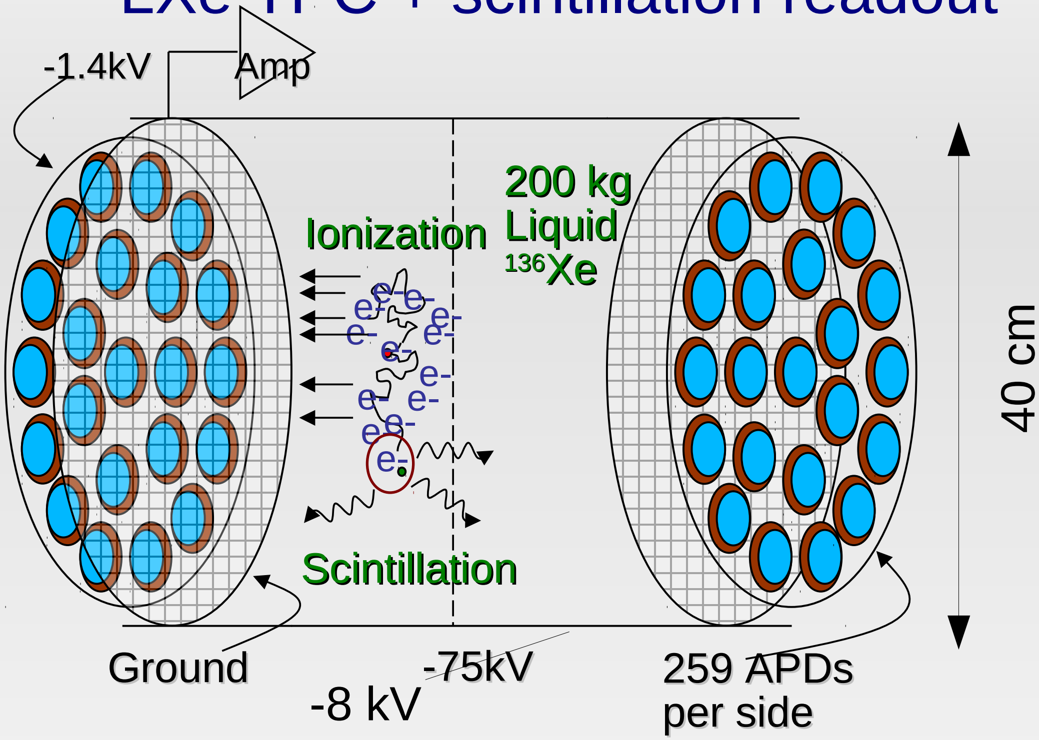


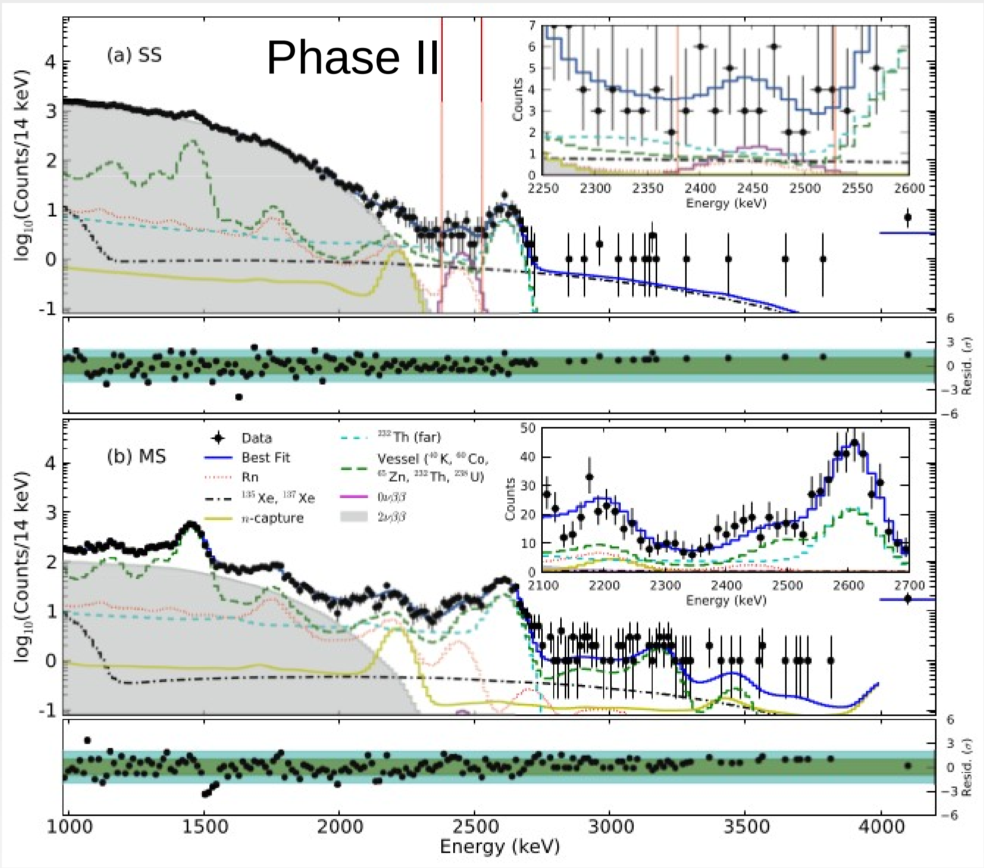
start 2011 (phase I): fall out of ^{110m}Ag from Fukushima on inner balloon
2012-13: purifications of scintillator and Xe
Dec 2013 – Oct 2015: phase II → ^{110m}Ar bkg factor 10 reduced, Xe loading 2.44% --> 2.96%
now: larger & cleaner balloon, loading 380 kg → 750 kg, restart now, sensitivity $T_{1/2}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

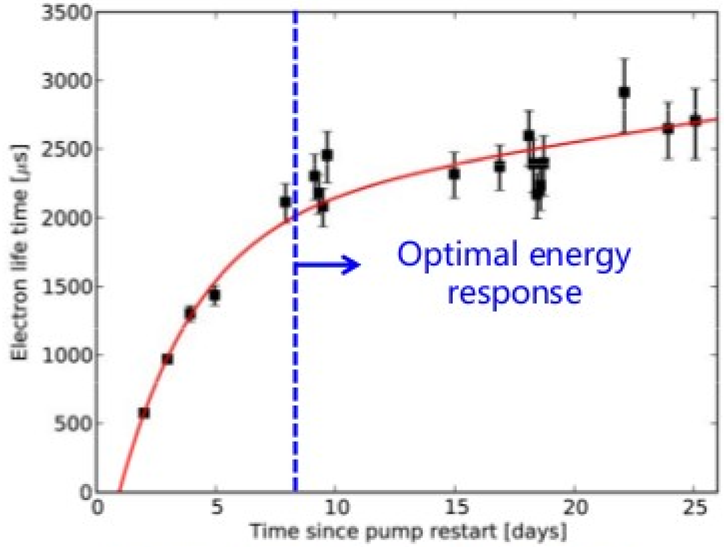
start physics data May 2011,
fire & radiation problem at WIPP → interrupt 2014-15

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

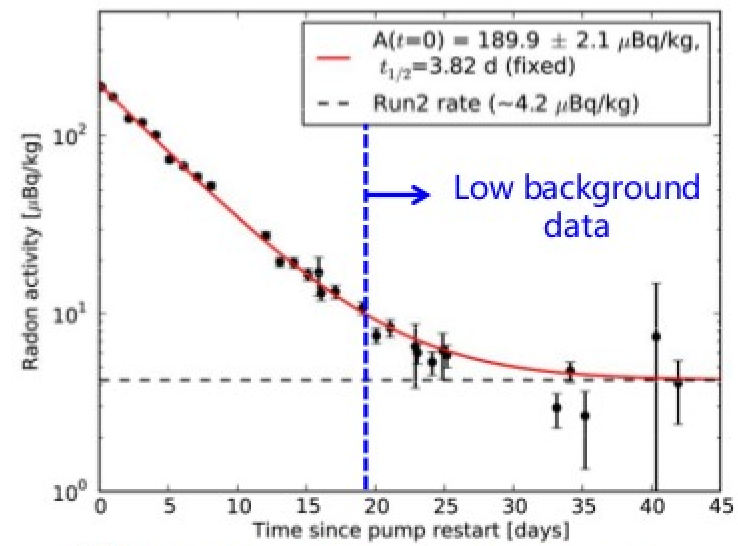
$$T^{0\nu}_{1/2} > 1.1\cdot 10^{25}\ yr\,(@\ 90\ \ C.L.)$$

(sensitivity 1.9 10^{25} yr)

EXO-200 restart



Xenon `purity' since January 31

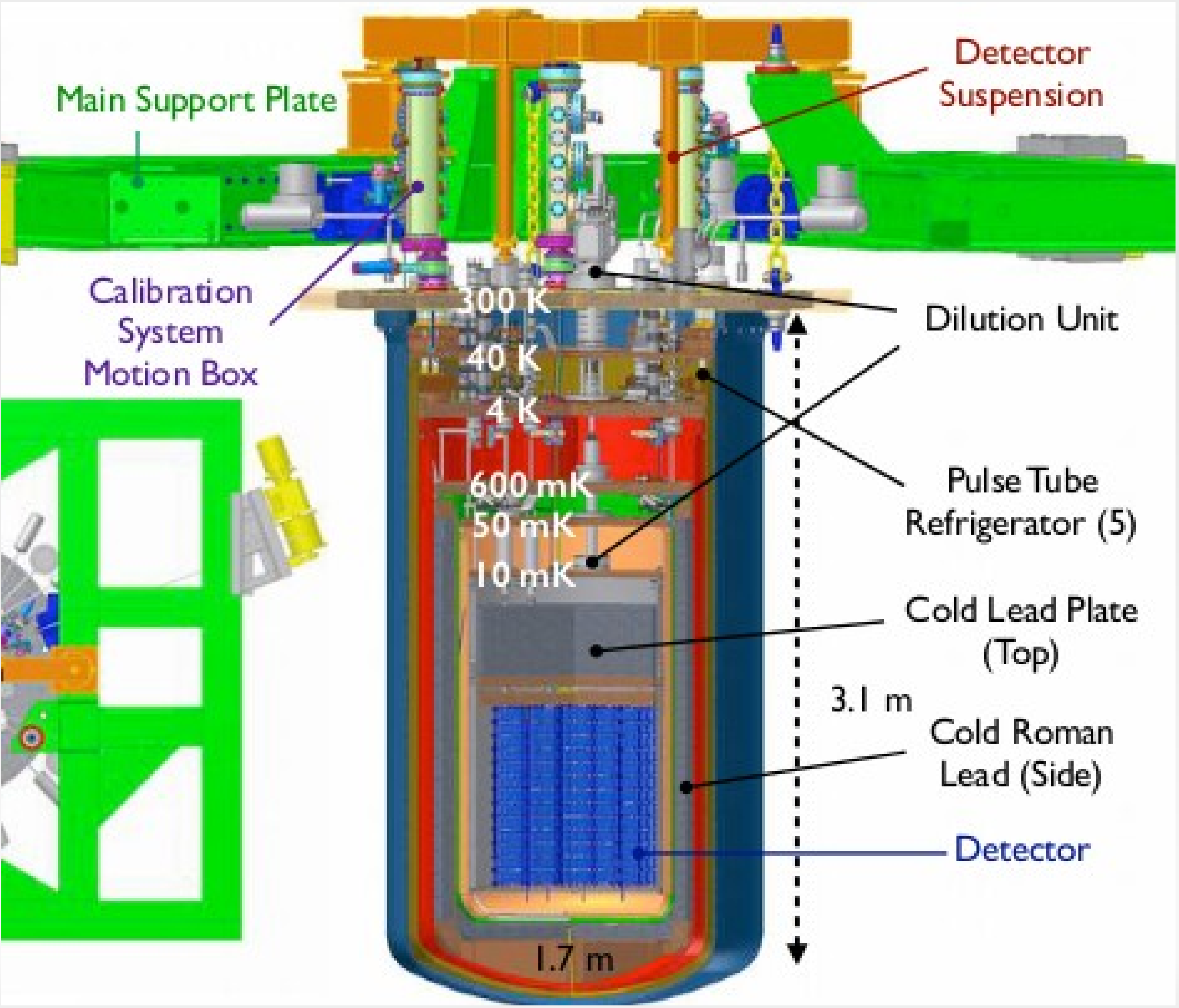


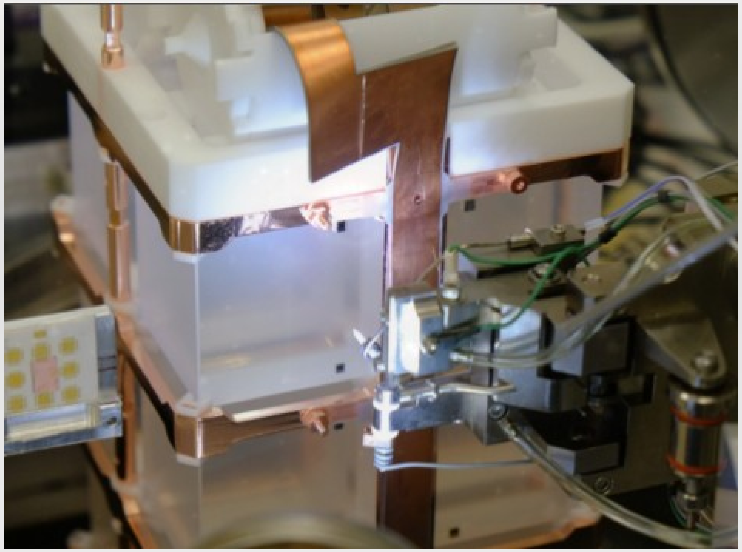
^{222}Rn level in TPC since January 31

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



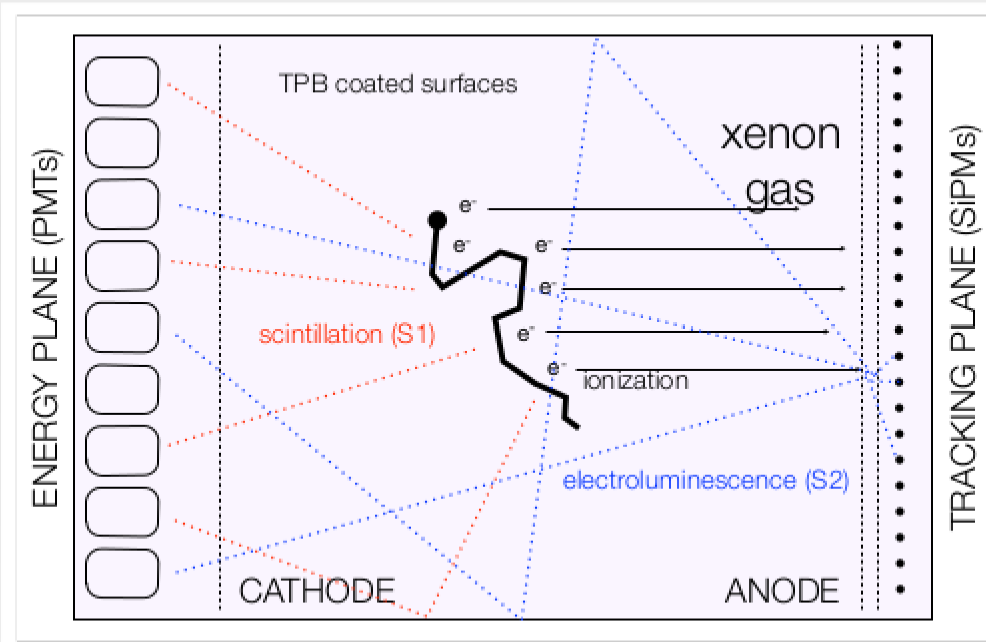


988 $^{nat}TeO_2$ crystals
206 kg ^{130}Te,

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

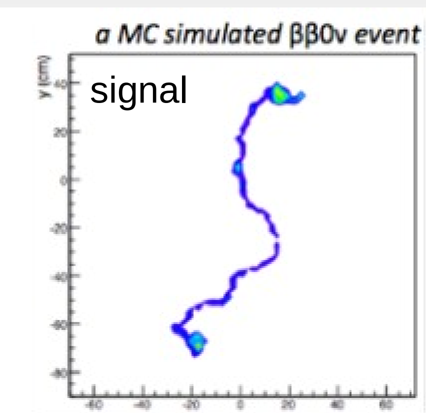
all towers are assembled!
test cool down of cryostat ok,
next: step mount towers + commissioning
physics run start end 2016,
sensitivity 90% limit ~ 1 10^{26} yr

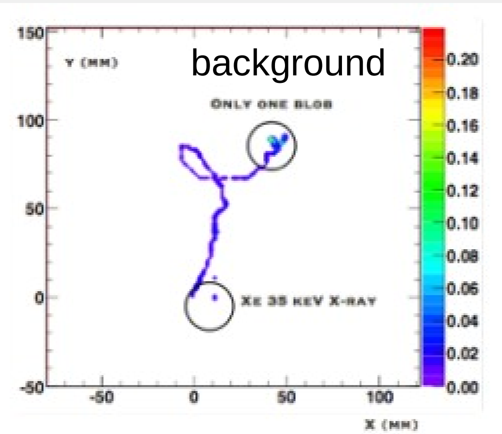
NEXT @ Canfranc



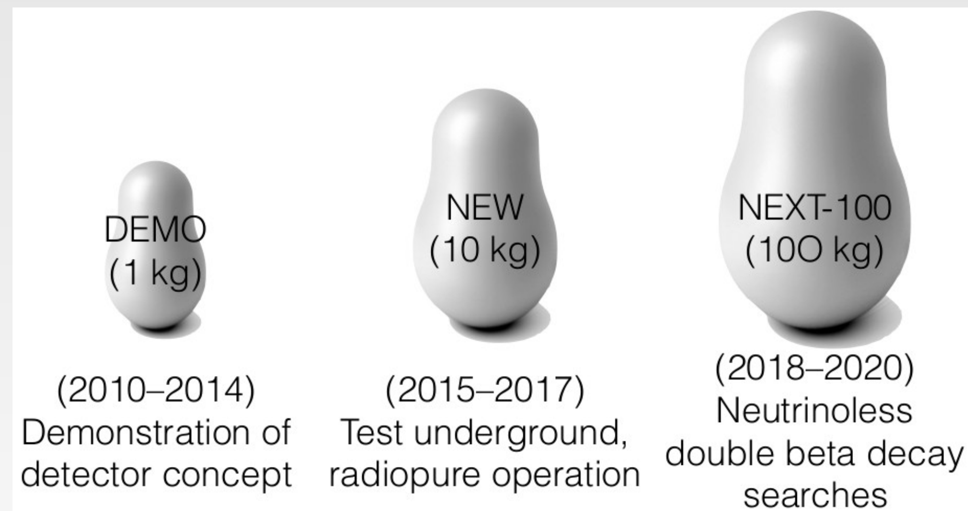
- 100 kg gas Xe TPC @ 15 bar
- measure scintillation light
- measure ionization w/ Electro Luminescence
- energy resolution FWHM <1% demonstrated
- reconstruction of event topology
  → background reduction

tracking of electrons



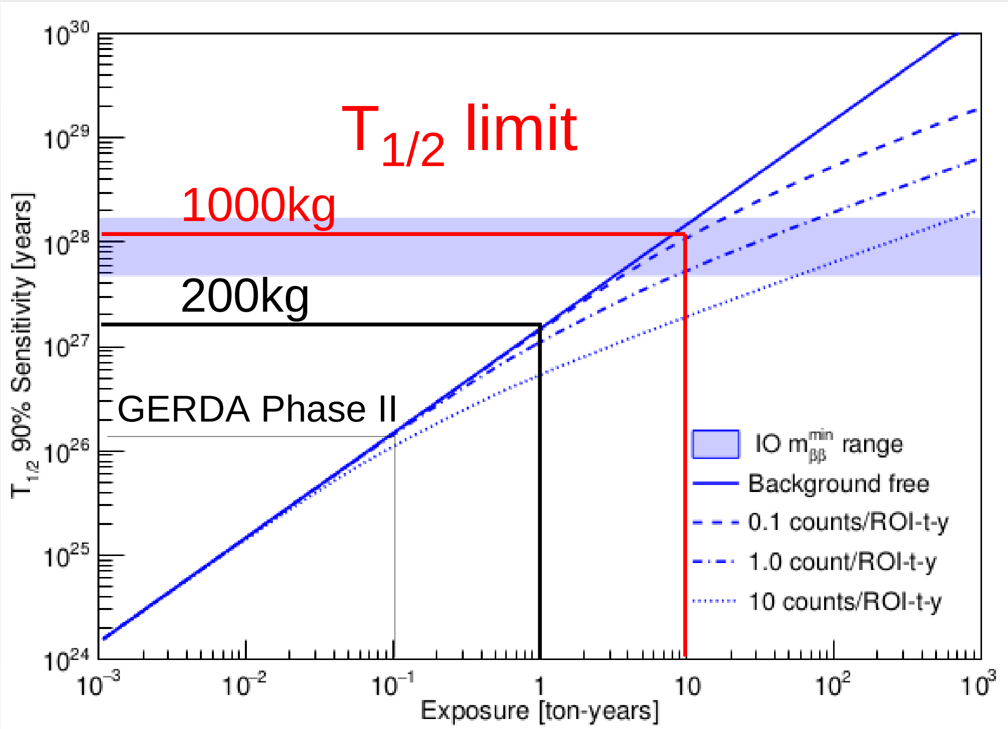


x-y position



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

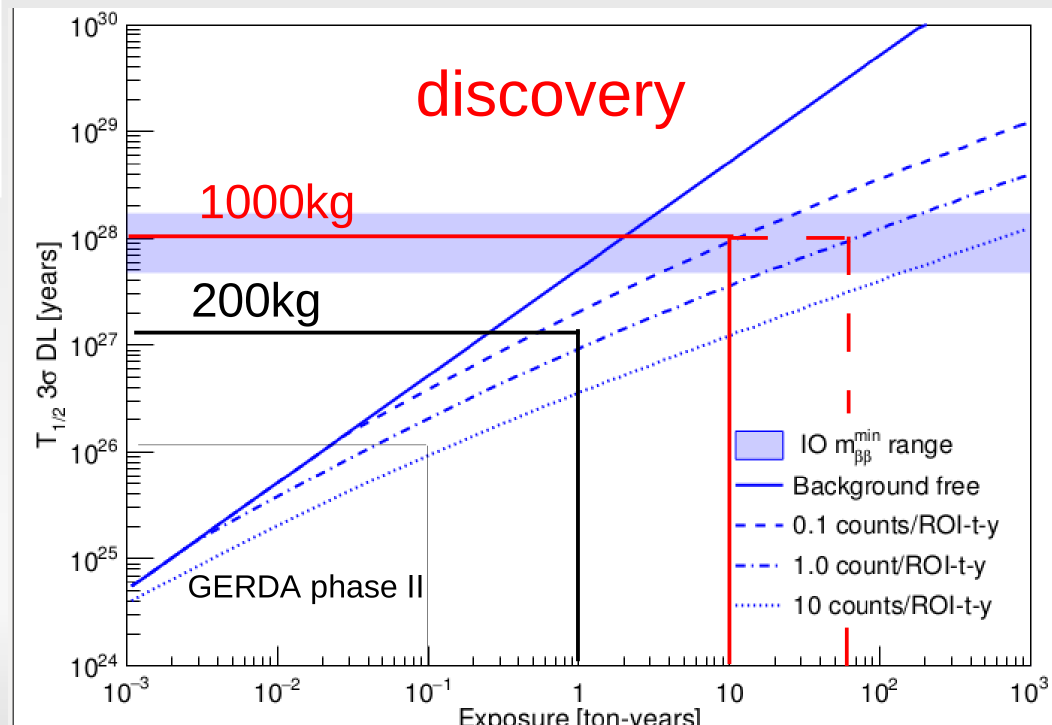
^{76}Ge sensitivity limit + discovery



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= $0\nu\beta\beta$ isotope mass in fiducial volume (incl enrichment fraction)

& mol of $0\nu\beta\beta$ isotope in active volume and divided by $0\nu\beta\beta$ 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

Why ^{76}Ge?

disadvantages:

- small phase space factor $G^{0\nu}$
- expensive (enrichment + diode production)
- scales not as easy as liquid/gas detectors

advantages:

- good energy resolution (currently best in the field)
  → small ROI & simple peak detection over smooth bkg
- lowest background if scaled by ROI
  → sensitivity comparable to experiments with much larger mass
- enrichment + diode production well established
  → no (little) R&D needed
- effective use of expensive material (not used for self-shielding)
- large annual Ge production
- 'relative' simple operation & background suppression