Search for Neutrinoless Double-Beta Decay

Werner Tornow

Duke University
&
Triangle Universities Nuclear Laboratory (TUNL)
&
Kavli-Tokyo Institute of the Physics and Mathematics of the Universe

On behalf of the KamLAND-Zen Collaboration

1. Introduction

2. Beta-and Double-Beta Decay

3. KamLAND-Zen

4. Look into the Future of $0\nu\beta\beta$ Searches

Neutrino Mass

- Compelling evidence for neutrino flavor oscillations

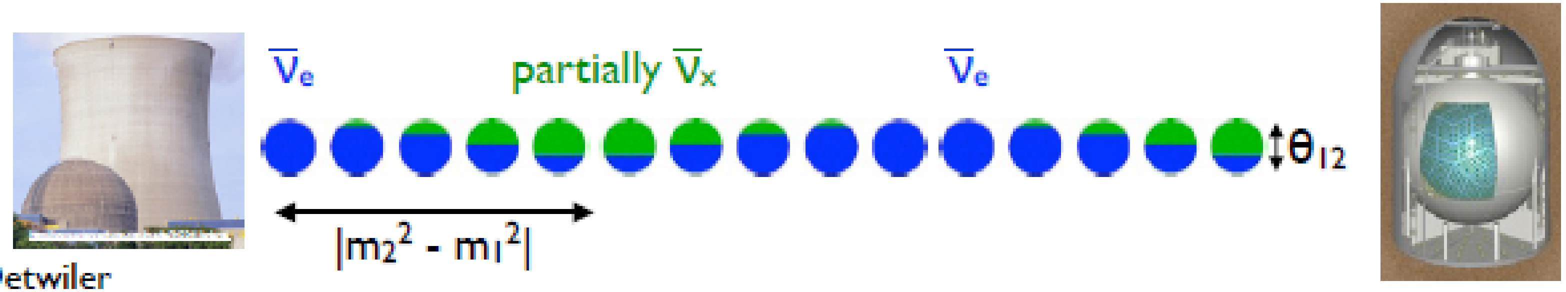


Figure credit: J. Detwiler

$$n \to p + e^- + \bar{\nu}_e \qquad\qquad \bar{\nu}_e + p \to n + e^+$$

$$\phi(L) \sim \sum_i U_{ei} e^{-im_i^2 L/2E} |\bar{\nu}_i\rangle$$

$$|\bar{\nu}_e\rangle = \sum_i U_{ei} |\bar{\nu}_i\rangle \qquad\qquad \langle\bar{\nu}_e| = \sum_i \langle\bar{\nu}_i| U_{ie}^*$$

weak-production — propagation distance = L → weak-detection

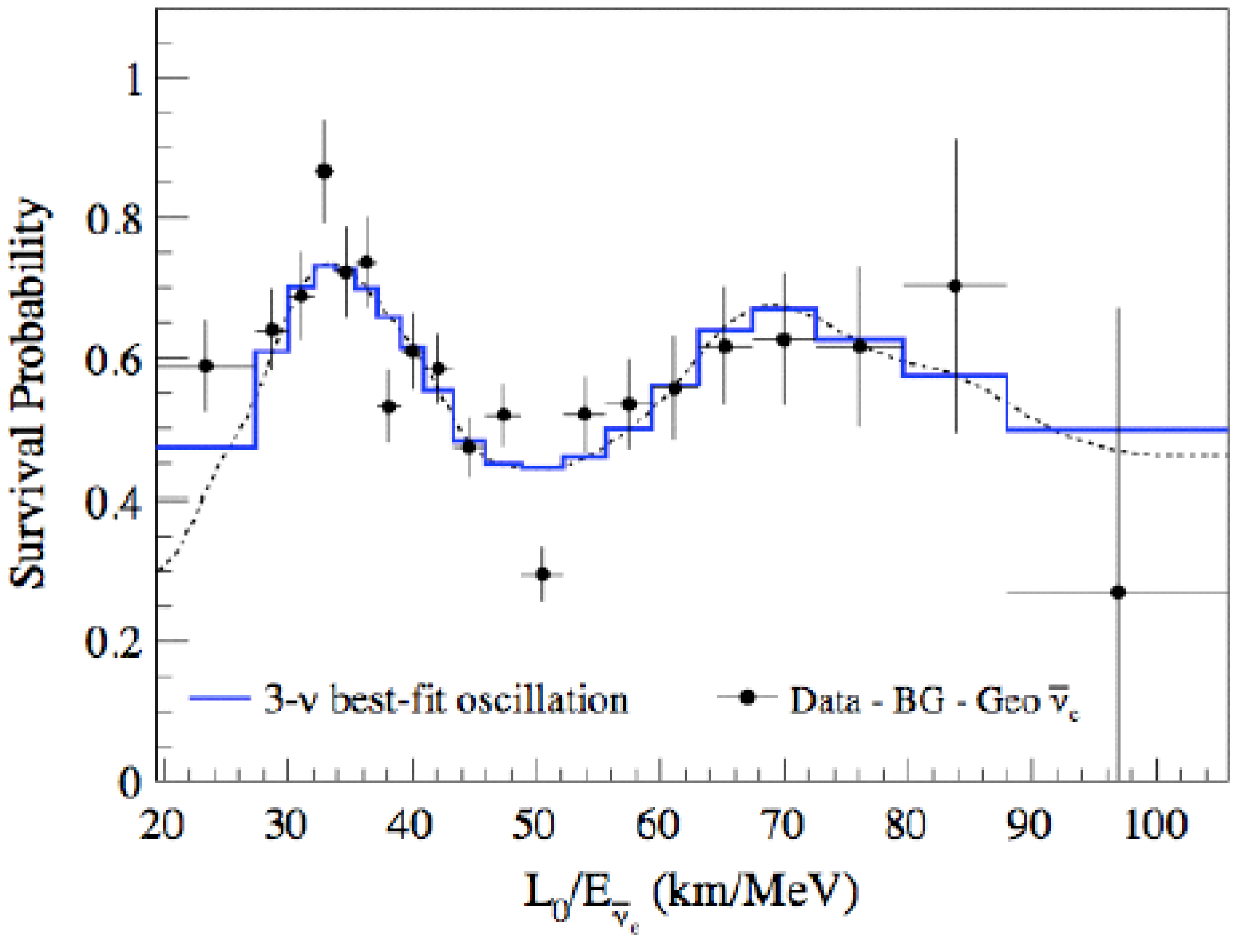
$$P(\bar{\nu}_e \to \bar{\nu}_e, L) = \left| \sum_i U_{ie}^* e^{-im_i^2 L/2E} U_{ei} \right|^2$$

T.O’Donnell

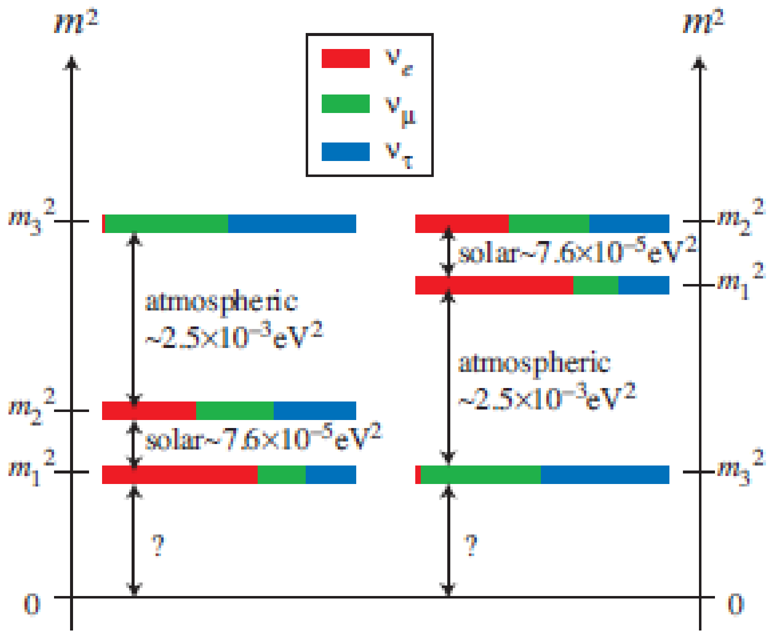
For a simple "2-flavor" world

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e, L, E) = 1 - \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2[\mathrm{eV}^2]\mathrm{L}[\mathrm{m}]}{E[\mathrm{MeV}]}.$$

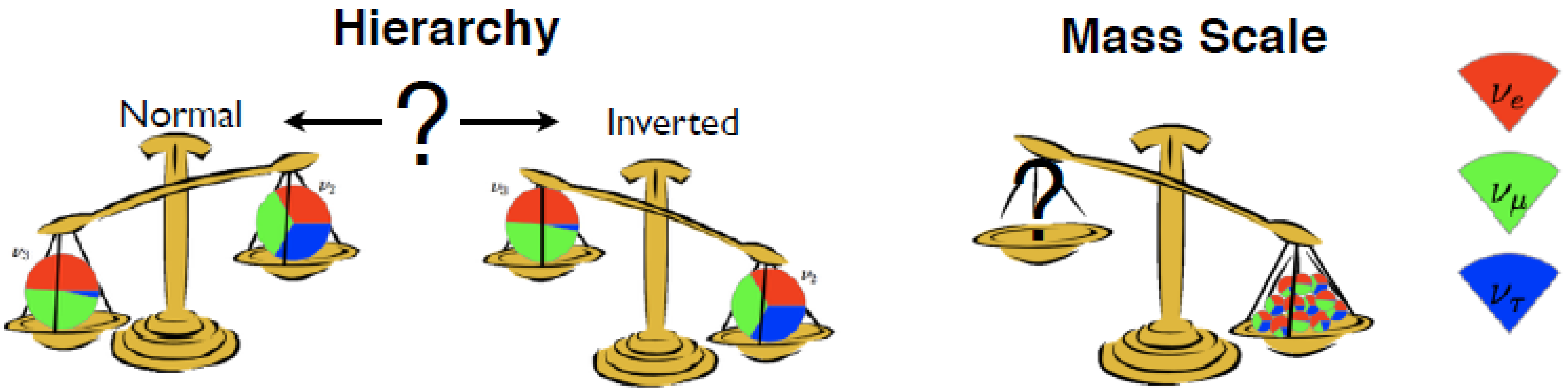


T.O'Donnell



Oscillation experiments provide the mass splittings

Solar matter effects provide the sign of dm^2_{21}



Don't know the sign of dm^2_{23}

Don't know the absolute mass scale

T.O'Donnell

Beta and Double-Beta Decay

Mass parabola for isobaric nuclei with even mass number (A)

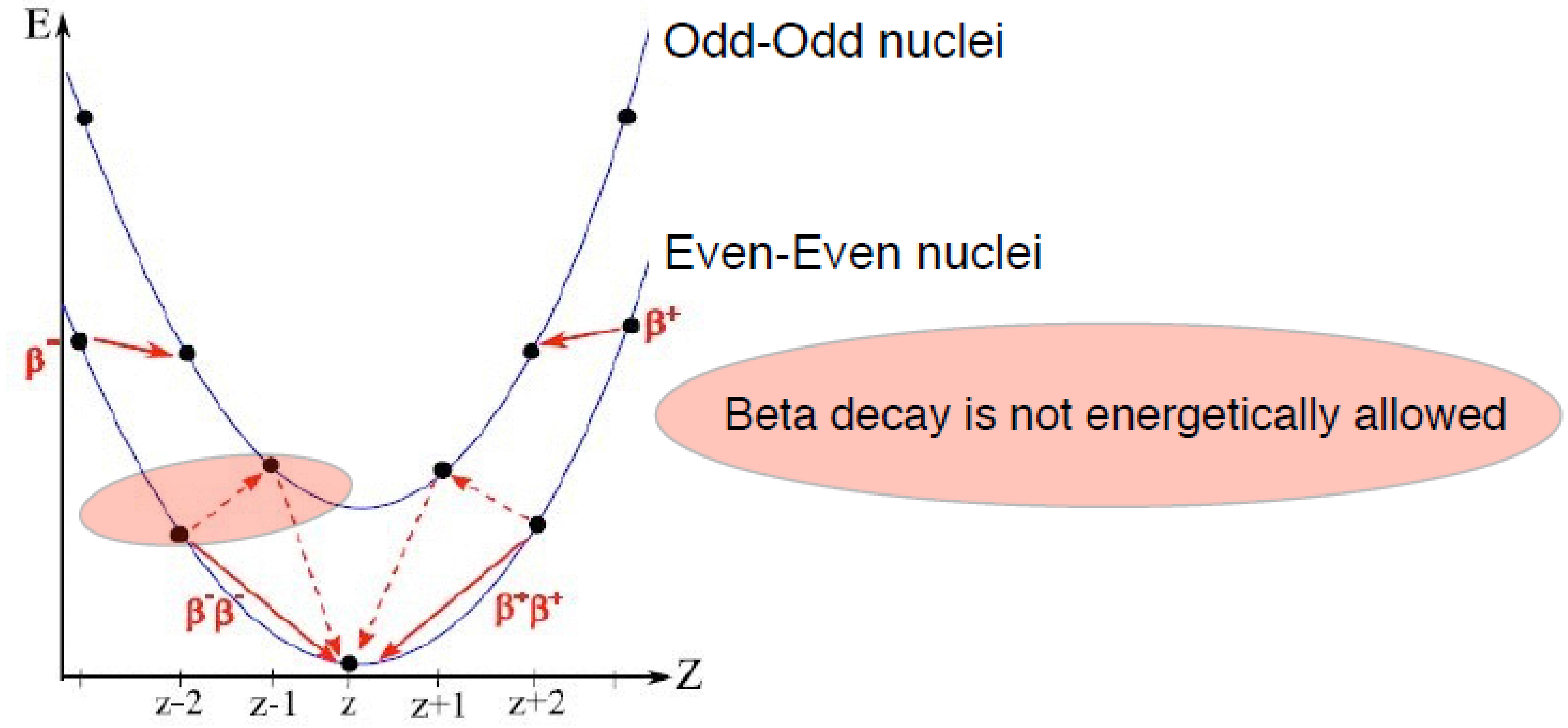
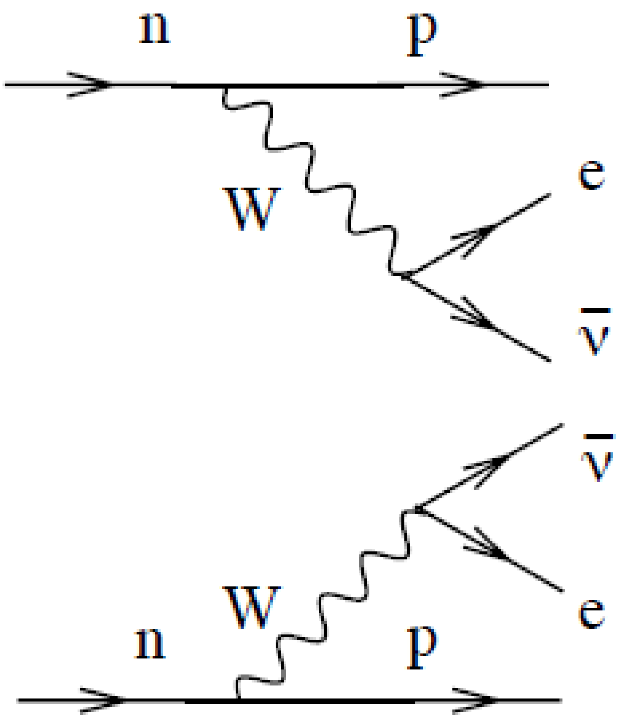


Figure adapted from: http://www.cobra-experiment.org/double_beta_decay/

Ordinary (2νββ) Double-Beta Decay



Phase space factor

$$\frac{1}{T_{1/2}^{2\nu}} = G^{2\nu}|M^{2\nu}|^2$$

Decay half-life

Nuclear matrix element

Simultaneous decay of 2 neutrons in a nucleus

Second-order weak process, allowed in SM

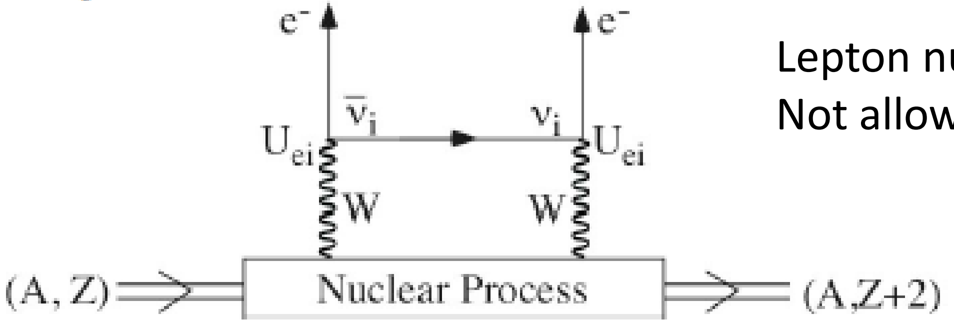
Observable only if ‘ordinary’ beta decay is inhibited

Directly observed in 12 nuclei, half lives ~10^{19}-10^{21} years !

Observed for ^{100}Mo and ^{150}Nd also to 1st excited 0^+ state of daughter nucleus

Neutrinoless ($0\nu\beta\beta$) Double-Beta Decay

Hypothetical $\beta\beta$ decay mode allowed if neutrinos are Majorana particles, i.e $\bar{\nu}_i \equiv \nu_i$



Lepton number violation
Not allowed in SM

Phase space factor

Nuclear matrix element

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

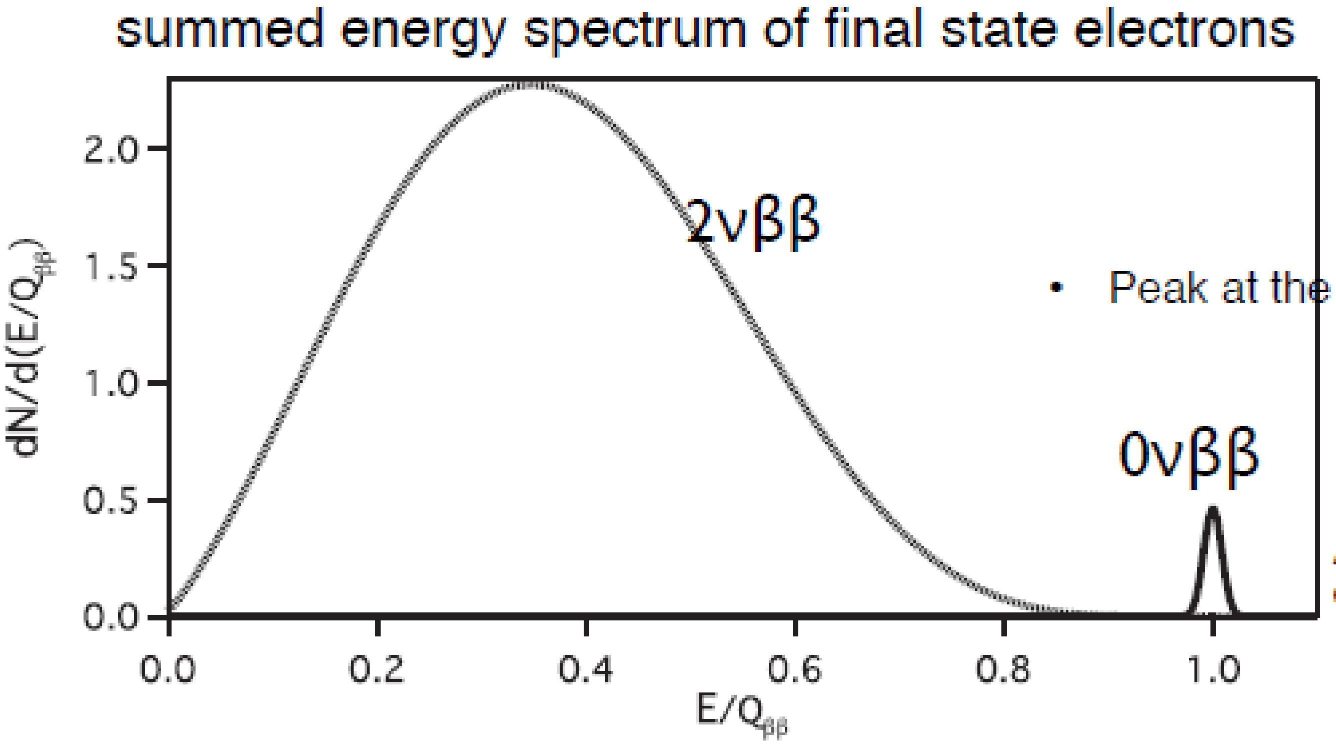
Decay half-life

Effective Majorana neutrino mass: $m_{\beta\beta} \equiv \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$

$M^{0\nu}$ is not known; estimates vary by factor of ~2 depending on method

For $m_{\beta\beta}$ = 50 meV estimated half lives 10^{25} - 10^{27} years ! depending on the nuclear system

T.O'Donnell



- Peak at the decay Q-value of the transition

Assumes BR 0ν/2ν = 1% and detector energy resolution is 2%

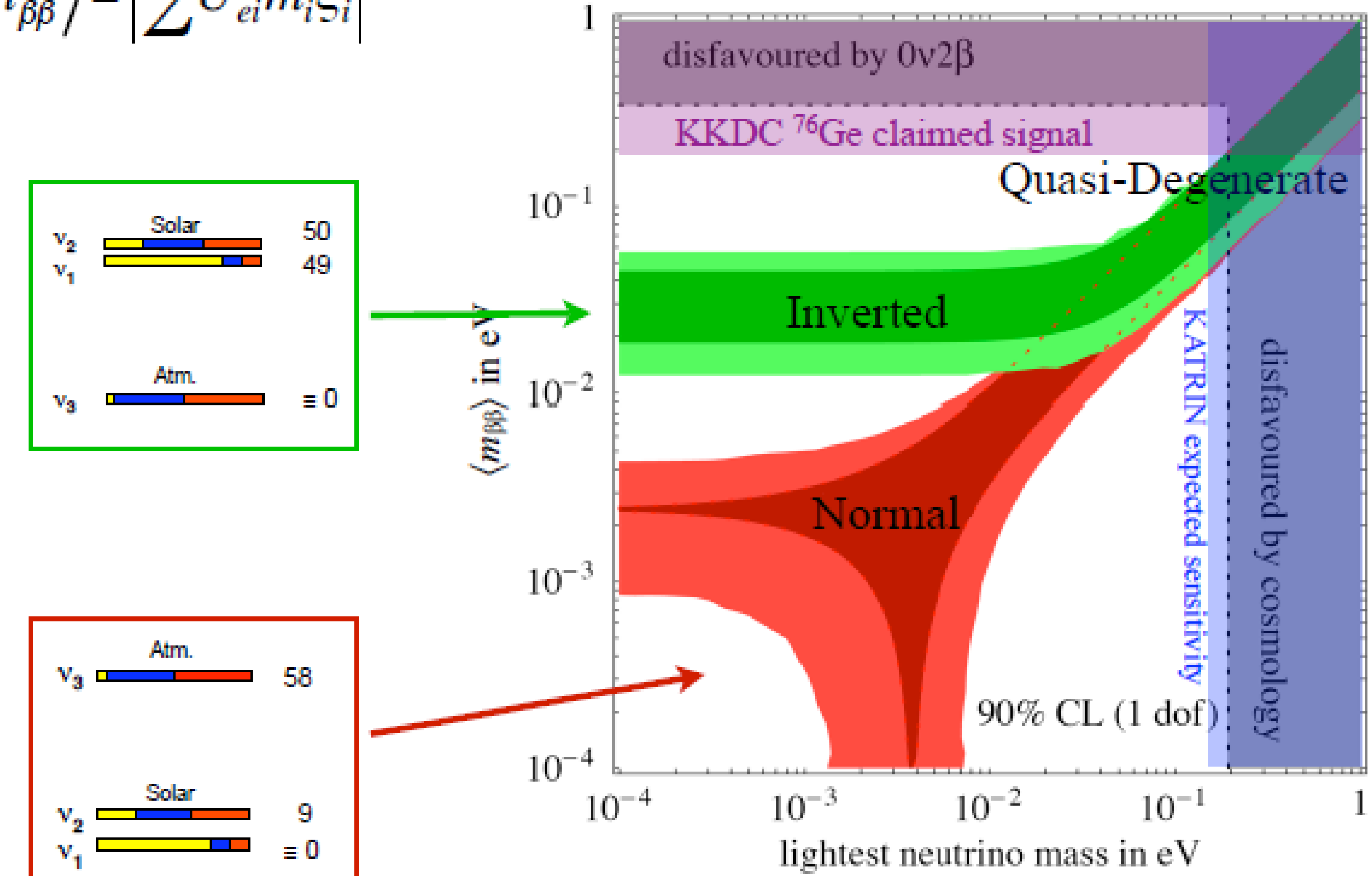
Rule of Thumb: Half-time sensitivity: $T_{1/2}(0\nu\beta\beta) \propto \sqrt{Nt/(B\Delta E)}$

N = Number of nuclei of the desired isotope
t = Measuring time
B = Number of background counts in the region of interest
ΔE= Energy resolution in the region of interest

0νββ Decay Sensitivity to <mββ>

0νββ limits for: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd

$$\langle m_{\beta\beta}\rangle = \left|\sum U_{ei}^2 m_i \xi_i\right|$$



F. Feruglio *et al.*, hep-ph/020191 (2002).

J.F. Wilkerson

$0\nu\beta\beta$ Experiments

Isotope	Experiment
^{48}Ca	Candles
^{76}Ge	Gerda, Majorana Demonstrator
^{82}Se	SuperNEMO
^{100}Mo	MOON
^{116}Cd	Cobra
^{130}Te	CUORE, Cobra, SNO+
^{136}Xe	EXO, NEXO, NEXT, KamLAND-Zen

Search for $0\nu\beta\beta$ of ^{136}Xe with KamLAND-Zen

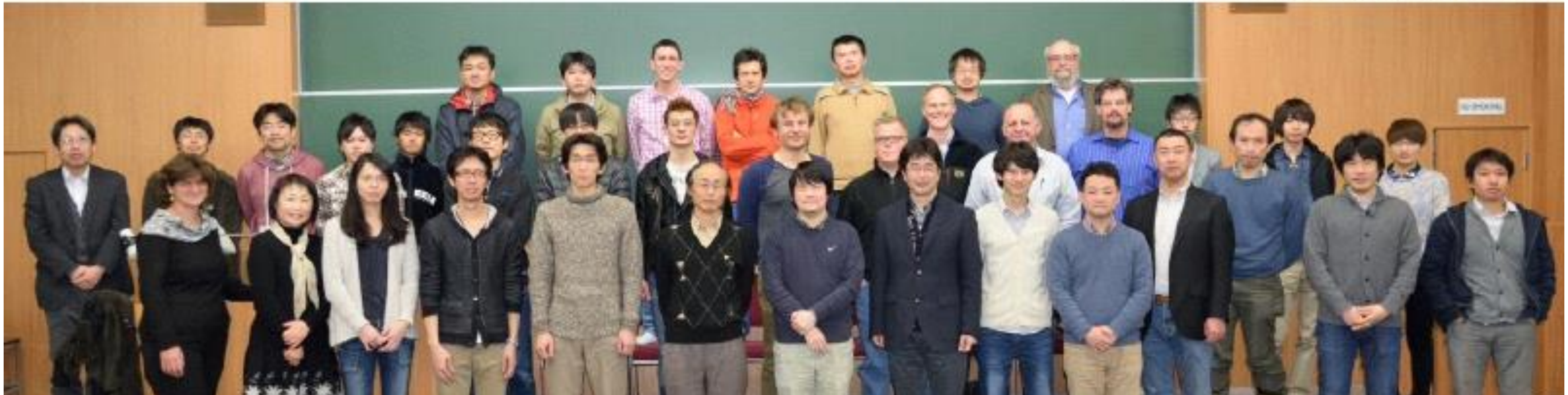
KamLAND-Zen Collaboration

K. Asakura,[1] A. Gando,[1] Y. Gando,[1] T. Hachiya,[1] S. Hayashida,[1] H. Ikeda,[1] K. Inoue,[1, 2] K. Ishidoshiro,[1] T. Ishikawa,[1] S. Ishio,[1] M. Koga,[1, 2] R. Matsuda,[1] S. Matsuda,[1] T. Mitsui,[1] D. Motoki,[1] K. Nakamura,[1, 2] S. Obara,[1] Y. Oki,[1] M. Otani,[1] T. Oura,[1] I. Shimizu,[1] Y. Shirahata,[1] J. Shirai,[1] A. Suzuki,[1] H. Tachibana,[1] K. Tamae,[1] K. Ueshima,[1] H. Watanabe,[1] B.D. Xu,[1] Y. Yamauchi,[1] H. Yoshida,[1] A. Kozlov,[2] Y. Takemoto,[2] S. Yoshida,[3] K. Fushimi,[4] T.I. Banks,[5] S.J. Freedman,[2, 5†] B.K. Fujikawa,[2, 5] T. O'Donnell,[5] L.A. Winslow,[6] B.E. Berger,[7] Y. Efremenko,[2, 8] H.J. Karwowski,[9] D.M. Markoff,[9] W. Tornow,[2, 9] J.A. Detwiler,[10] S. Enomoto,[2, 10] and M.P. Decowski[2, 11]

1Research Center for Neutrino Science, Tohoku University, Sendai 980-8578, Japan
2Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, Kashiwa, 277-8583, Japan
3Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan
4Faculty of Integrated Arts and Science, University of Tokushima, Tokushima, 770-8502, Japan
5Physics Department, University of California, Berkeley, and Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
6Department of Physics and Astronomy, University of California, Los Angels, Los Angels, California 90095, USA
7Department of Physics, Colorado State University, Fort Collins, Colorado 80523, USA
8Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA
9Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708, USA; Physics Departments at Duke University, Durham, North Carolina 27705, USA; North Carolina Central University, Durham, North Carolina 27701, USA and the University of North Carolina at Chapel Hill, Chapel Hill, North Carolina 27599, USA
10Center for Experimental Nuclear Physics and Astrophysics, University of Washington, Seattle, Washington 98195, USA
11Nikhef and the University of Amsterdam, Science Park, Amsterdam, the Netherlands

46 scientists form
11 institutions

Photo in the KamLAND collaboration meeting (Mar. 2014)

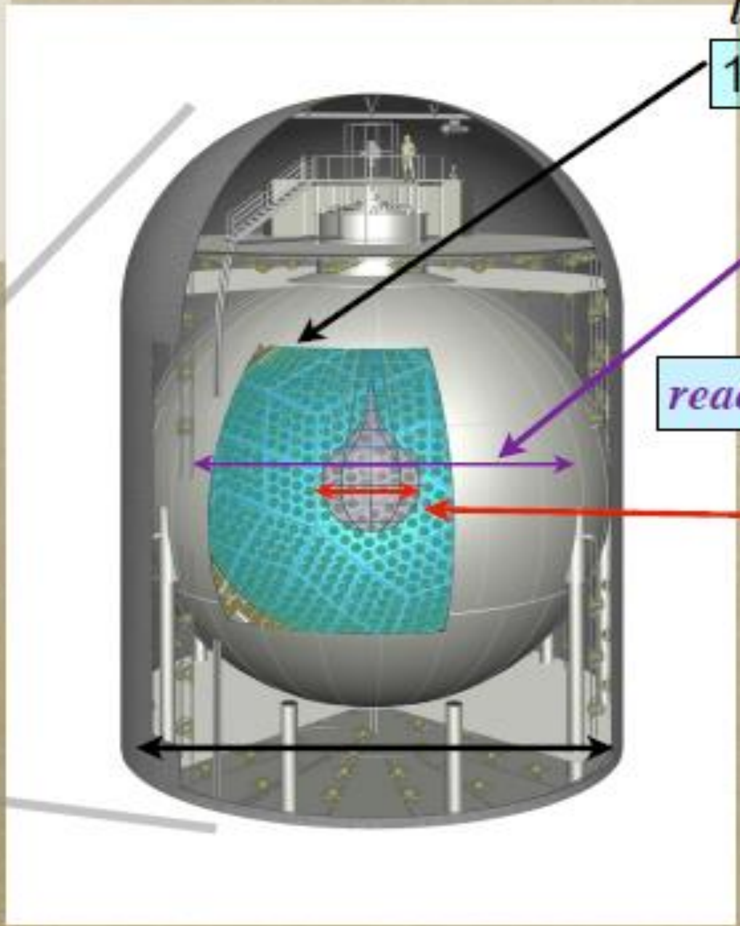


KamLAND

KamLAND

Kamioka **L**iquid Scintillator **A**nti-**N**eutrino **D**etector

1000m depth



inner detector

1,325 17inch + 554 20inch PMTs

* Photo coverage 34%

Balloon
φ13m,135μm thick.
1 kton LS

reactor ν, Geo-ν, Solar-ν, Supernova-ν

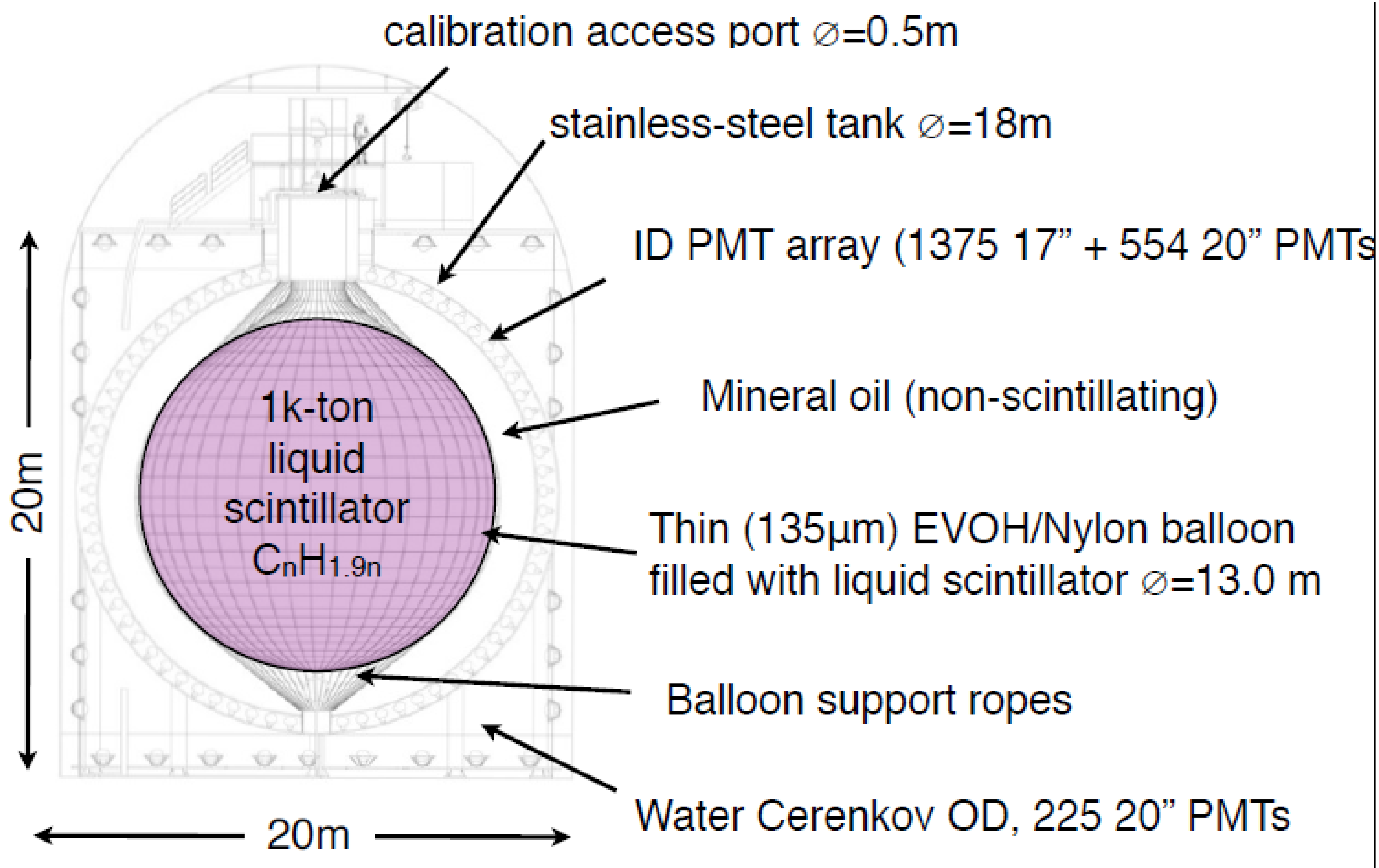
Mini-balloon
φ3.1m, 25μm thick.
Xe loaded LS

0ν2β search

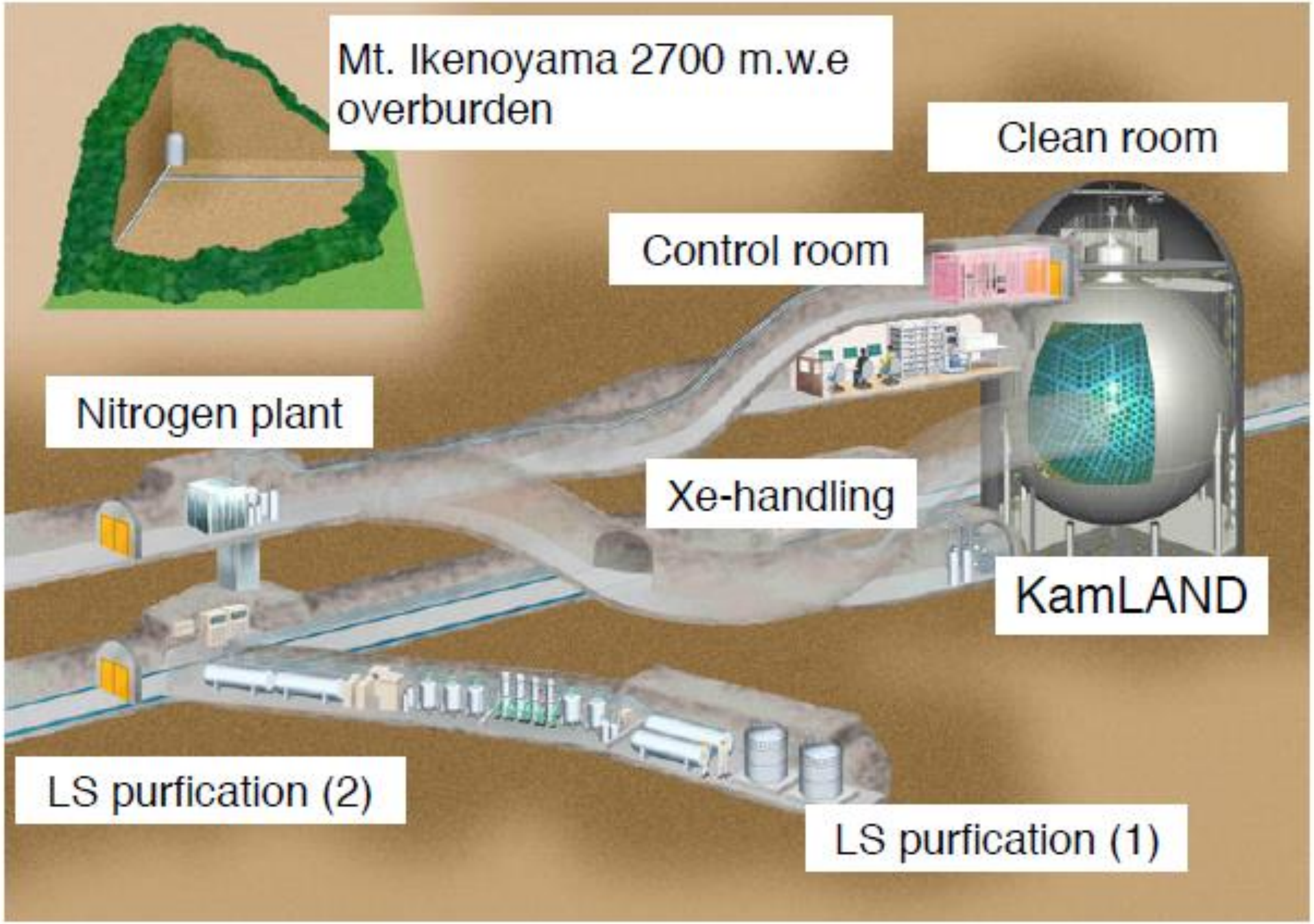
Water Cherenkov outer detector
φ18m, 3.2 kton pure water

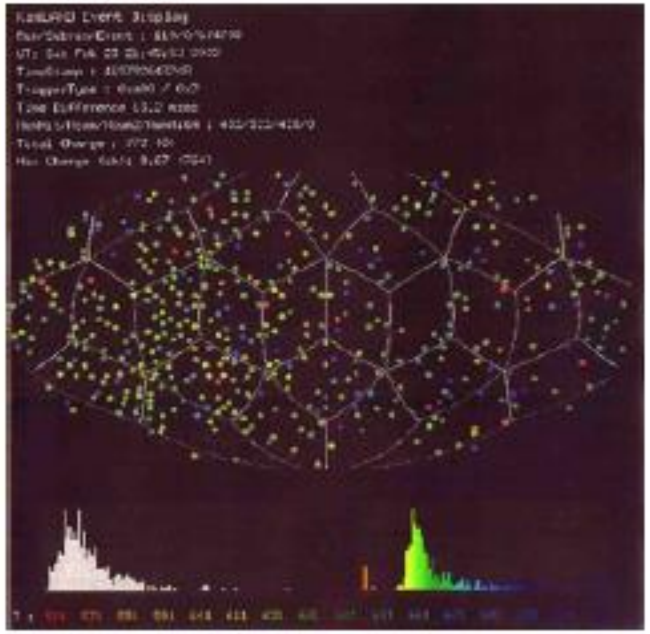
225 20inch PMTs

* Muon veto



LS: 82% Decane, 18% Pseudocumene, PPO 2.7 g/l


Mt. Ikenoyama 2700 m.w.e
overburden
Clean room
Control room
Nitrogen plant
Xe-handling
KamLAND
LS purfication (2)
LS purfication (1)



- Energy resolution: $\frac{\sigma_E}{E} = \frac{6.5\%}{\sqrt{E[MeV]}}$
- Position resolution: $\sigma_{\vec{R}} = \frac{12\,cm}{\sqrt{E[MeV]}}$

$$\frac{E_{vis}}{E_{\rm real}} = A \times \left(\frac{1}{1+R} \cdot \frac{1}{1+k_B(dE/dx)} + \frac{R}{1+R} \cdot \frac{dN_{\rm Ch}}{dE} \right)$$

Overall linear response of detector

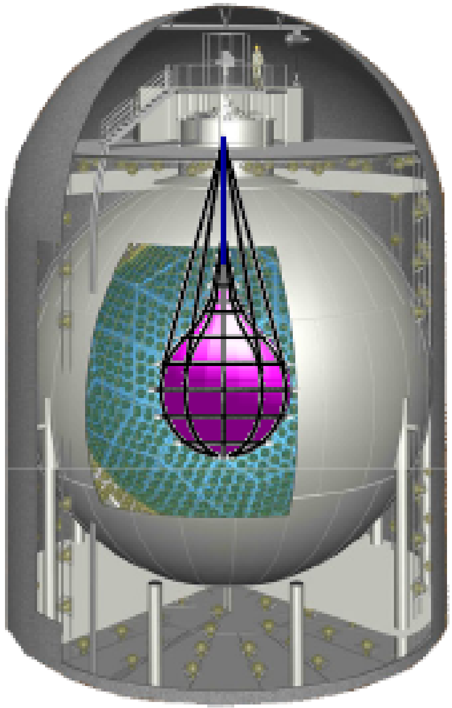
Scintillator nonlinearity from quenching

Fraction of visible energy from Cherenkov emission

0νββ search was envisioned already in the original U.S. KamLAND proposal to DOE (1999) as the end phase of KamLAND

Concrete plans were not developed before 2009

- Several advantages:
  - KamLAND-LS provides ultra-pure ***active*** shield
  - Mature detector, expertise and analysis tools
  - Potential to achieve large 0vBB target mass quickly
  - Possible to continue antineutrino program at KamLAND



Reactor, geoneutrinos and supernova watch

KamLAND-Zen only 1.4% of KamLAND liquid scintillator volume

New Approach to the Search for Neutrinoless Double Beta Decay

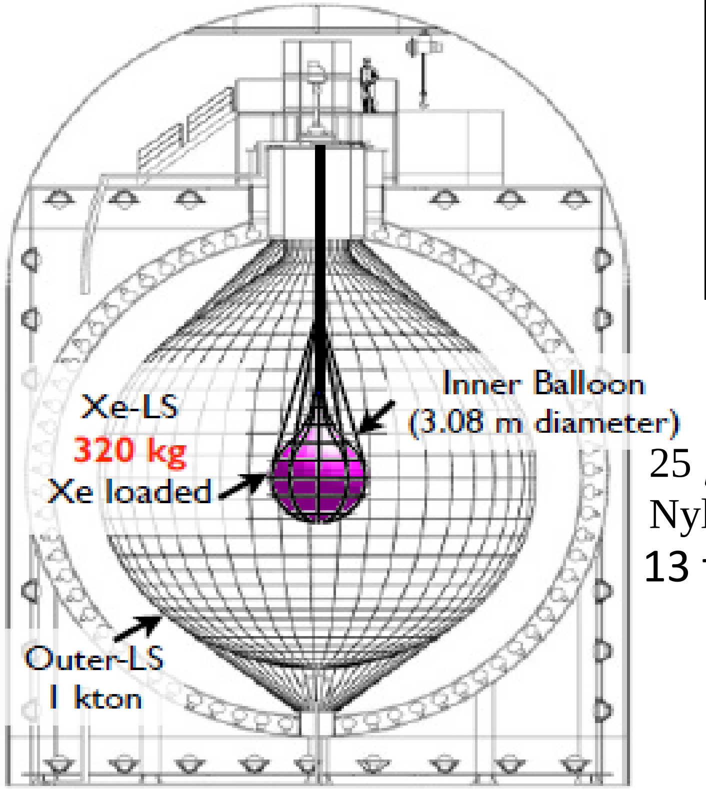
R. S. Raghavan
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
(Received 9 November 1993)

Sub-eV Majorana neutrino masses $\langle m_\nu \rangle$, can be explored by a new approach to neutrinoless double β decay using ^{136}Xe in a Xe gas-loaded, multiton liquid scintillator installed in a very low background detector such as the Kamiokande facility. With enriched ^{136}Xe, a readily implementable, 10 ton detector experiment can establish an $\langle m_\nu \rangle = 0.45$ eV at 3σ in 1 yr (or exclude an $\langle m_\nu \rangle < 0.23$ eV in 2 yr). A 100 ton detector can extend the limit to $\langle m_\nu \rangle < 0.1$ eV, compared with the present limit of $\langle m_\nu \rangle < 1.3$ eV.

KamLAND-Zen

Kamioka Liquid Scintillator Anti-Neutrino Detector
Zero Neutrino Double Beta

KamLAND-Zen Phase I



25 μm
Nylon film
13 ton LS

Xenon loaded LS (Xe-LS)	
decane	82%
pseudo-cumene	18%
PPO	2.7 g/liter
xenon	2.44 wt%

$\sigma_E(2.5\text{MeV}) = 4\%$

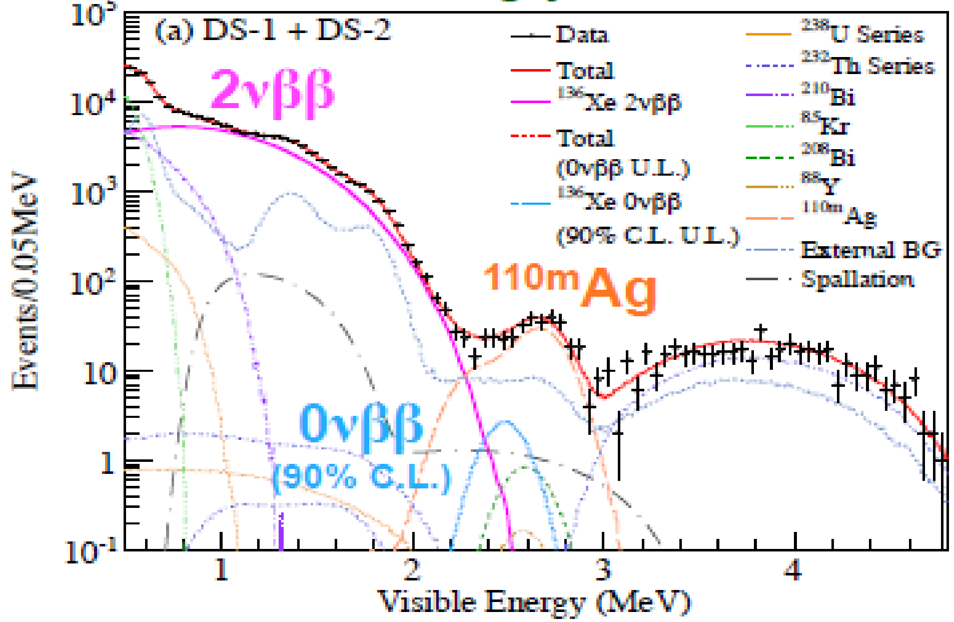
Advantage of KamLAND

- running detector : start quickly with relatively low cost
- big and pure : no BG from external gamma-rays
- purification of LS, replacement of mini-balloon are possible

→ **high scalability** (a few ton of Xe)

realize double beta-decay search with **low background**

Phase 1 89.5kg·yr PRL, 110, 062502 (2013)



2458 keV

$T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr (90% C.L.)

Improvement Efforts after Phase 1

1. Remove radioactive impurities by Xe-LS purification

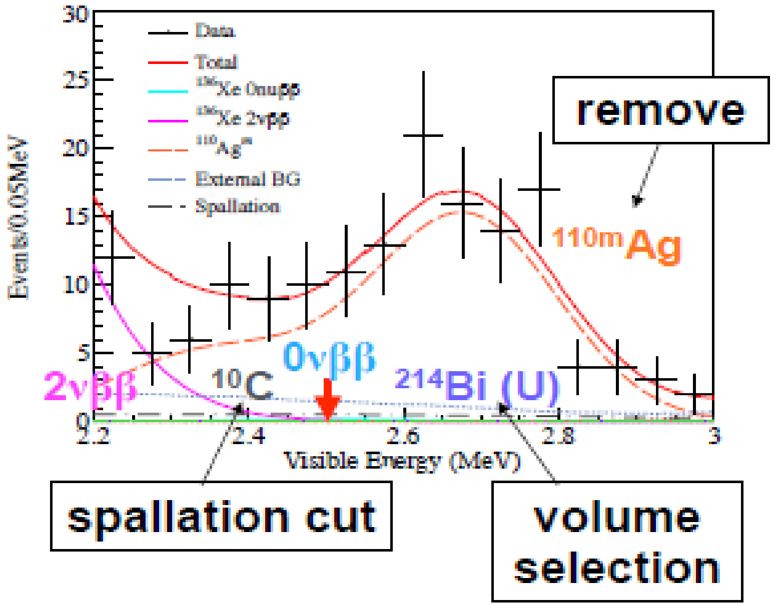
candidates of ~2.6 MeV peak

⟶ only 4 nuclei ^{110m}Ag (250 d), ^{208}Bi (3.68x10^{5} yr), ^{88}Y (107 d), ^{60}Co (5.27 yr)
lifetime longer than 30 days ↖ detected in Fukushima fallout

Two possibile sources:
(1) contamination by Fukushima-I reactor fallout
(2) cosmogenic Xe spallation while above ground

"primary" background source (^{110m}Ag)
can be removed by Xe-LS purification

Phase 1 (first 110.3 days)



2. Increase amount of Xenon

phase 1 phase 2
Xe concentration (2.44 ± 0.01) wt% ⟶ (2.96 ± 0.01) wt%

increase of S/N ~ 1.2 Xe-pressurized phase is a future option

3. Spallation cut after muon

muon-neutron-^{10}C (τ = 27.8 s) triple coincidence ⟶ ^{10}C background rejection

4. Optimization of volume selection

fiducial volume limitation by ^{214}Bi (U) on the balloon film ⟶ multi-volume selection

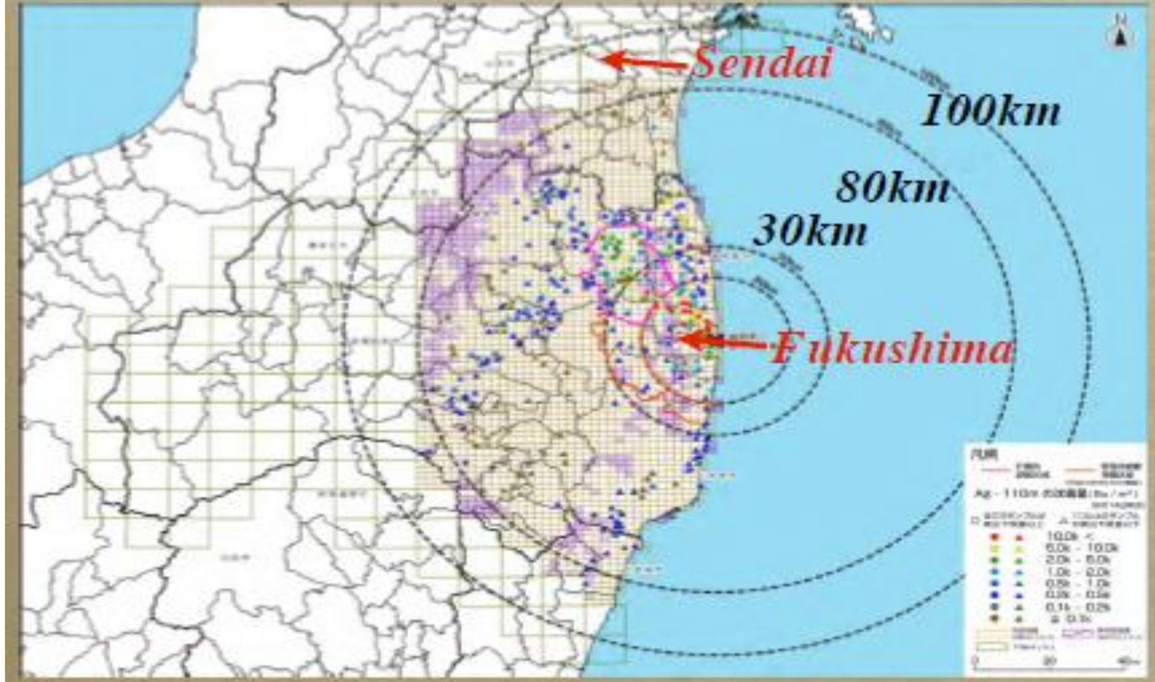
Fukushima reactor accident

BG origin

1, fall out from Fukushima.

^{134}Cs and ^{137}Cs were observed at KamLAND.
The ratio (^{134}Cs/^{137}Cs) is also same with soil samples.
^{110m}Ag also fall out from Fukushima reactor.

^{110m}Ag Concentration map in soil sample

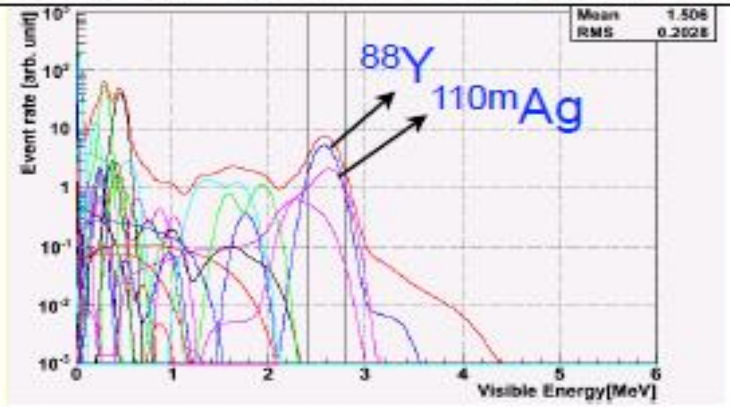


http://radioactivity.nsr.go.jp/ja/contents/6000/5050/24/5600_103120.pdf

2, Spallation products from ^{136}Xe

^{110m}Ag is also produced from ^{136}Xe by cosmic ray.
^{136}Xe was imported by air from Russia.

100 days on surface, 300 days in the mine

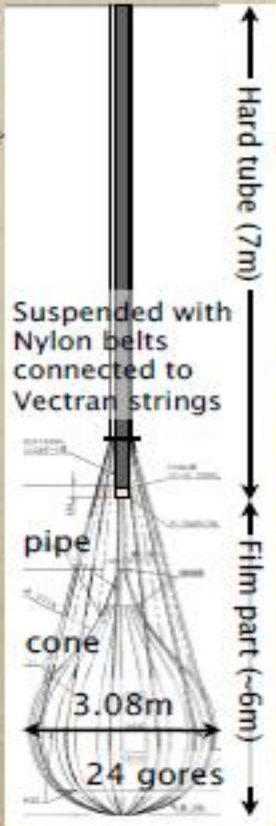


^{110m}Ag production :
accelerated ^{136}Xe on hydrogen target

Phys.Rev.C76,064609(2007)

Mini-balloon production and installation

at Sendai in June 2011



Mini-balloon was made in Sendai.
Deflated Mini-balloon was delivered to Kamioka.
After the Mini-balloon was installed in KamLAND, the Mini-balloon was inflated using normal LS.
Finally the normal LS was replace to the Xe loaded LS.

at Kamioka mine in Aug 2011

- Inner-balloon fabricated in class 1 cleanroom near Sendai Spring 2011
- Great Eastern Japan Earthquake occurred (3/11/11)

Test balloon at Kamioka

Practice installation at swimming pool

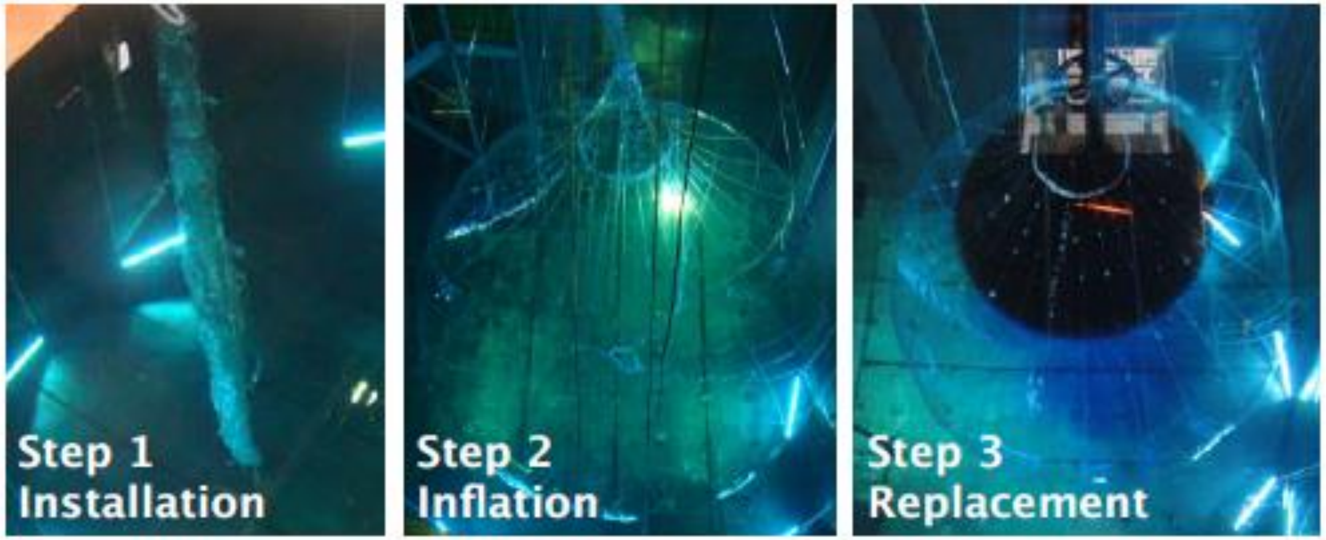
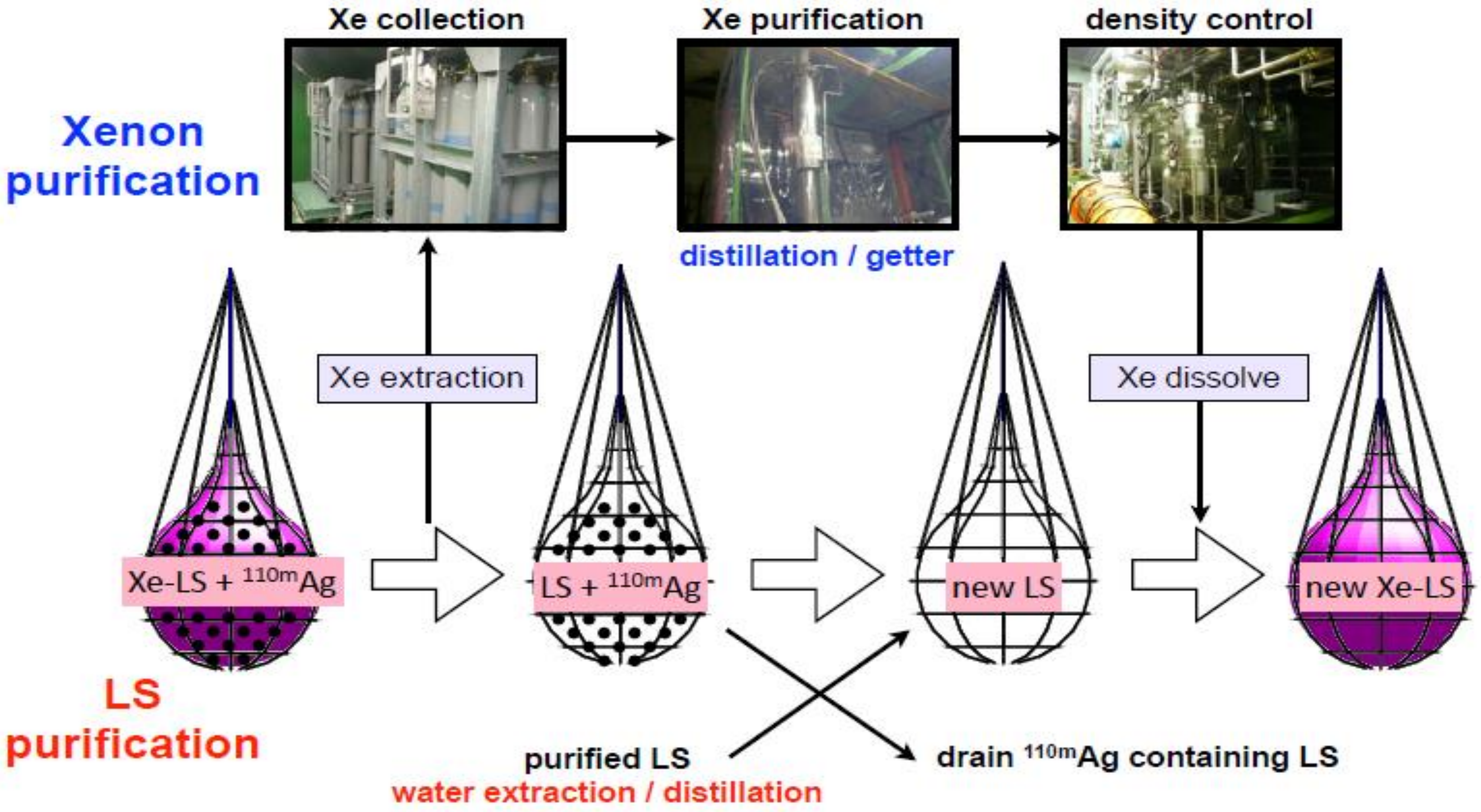


Figure courtesy of A. Gando 'First Results of Neutrinoless double beta decay Search with KamLAND-Zen', PhD Thesis, Tohoku University 2012

- Mini balloon was installed and filled in August 2011 - KamLAND-Zen began !

Purification Strategy



Xenon and LS purification to reduce radioactive impurities

Circulation of LS

Purification activity for 1.5 years

Jun. 2012 Xe extraction from Xe-LS
leakage trouble in diaphragm pump → increase of balloon film BG
→ confirm ^{110m}Ag remains in Xe-depleted LS

Jul. 2012 Xe purification by distillation and getter

Aug. 2012 Replacement by **new purified LS**
→ confirm ^{110m}Ag reduction to
1/3 - 1/4 **not enough …**

Nov. 2012 LS distillation in circulation mode (×**1**)
fire accident in the purified air system

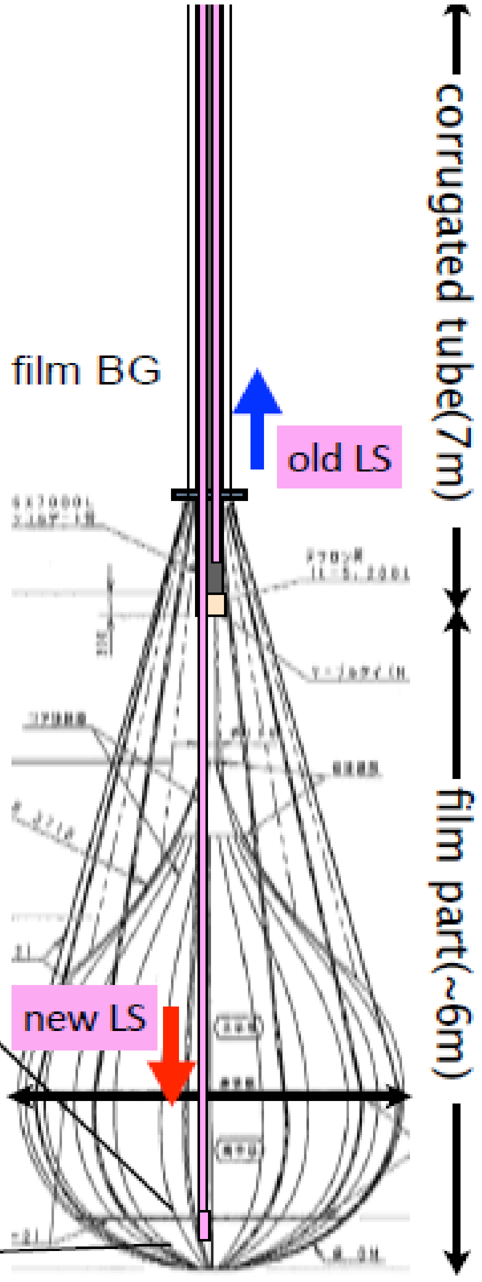
Jul. 2013 LS distillation in circulation mode (×**2**)

Oct. 2013 Replacement by **new purified LS**

Nov. 2013 Dissolving **purified Xe** into LS

Dec. 2013 Start phase 2 data-taking
→ confirm ^{110m}Ag reduction to
< 1/10 **including the decay**

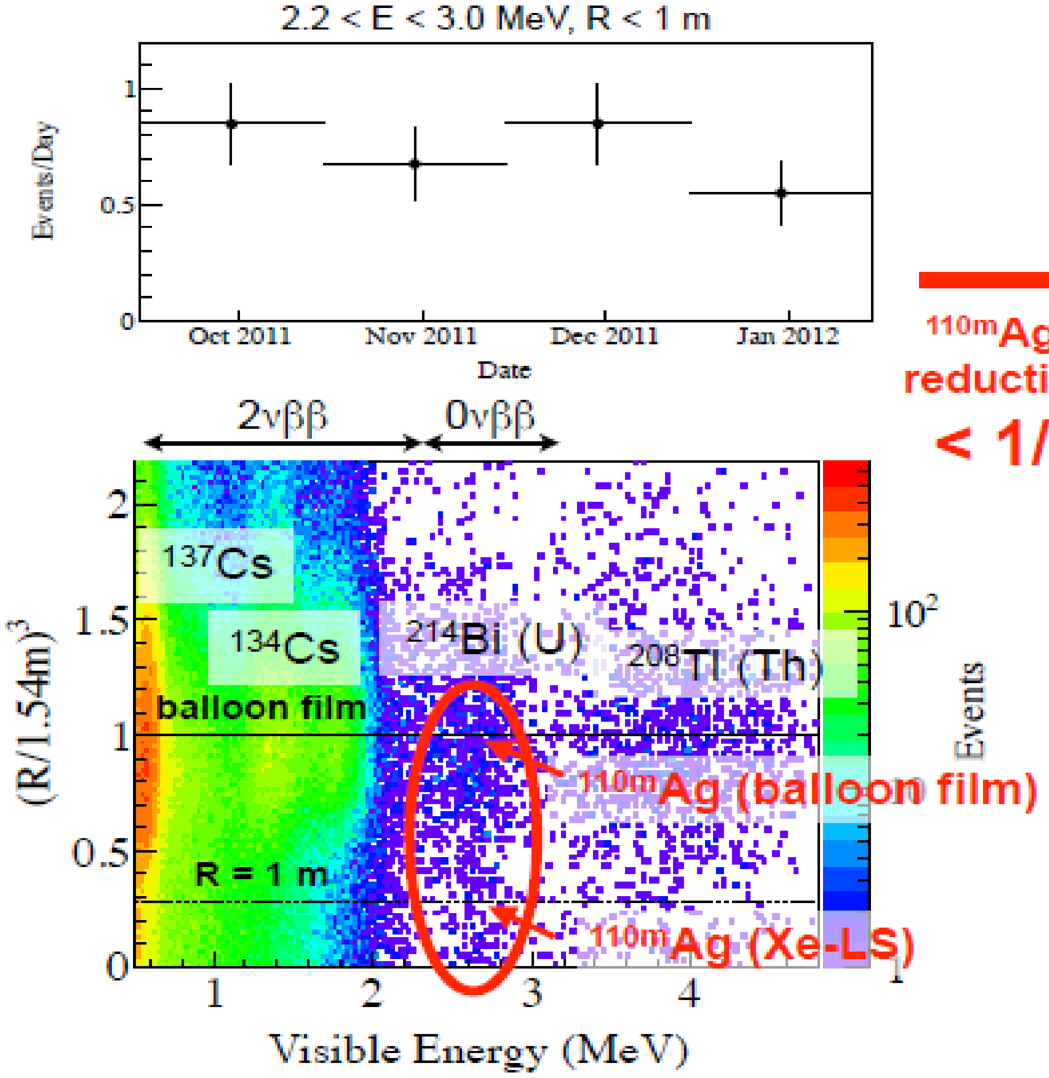
LS outlet



Phase 2 (low BG) data-taking started on Dec. 11, 2013

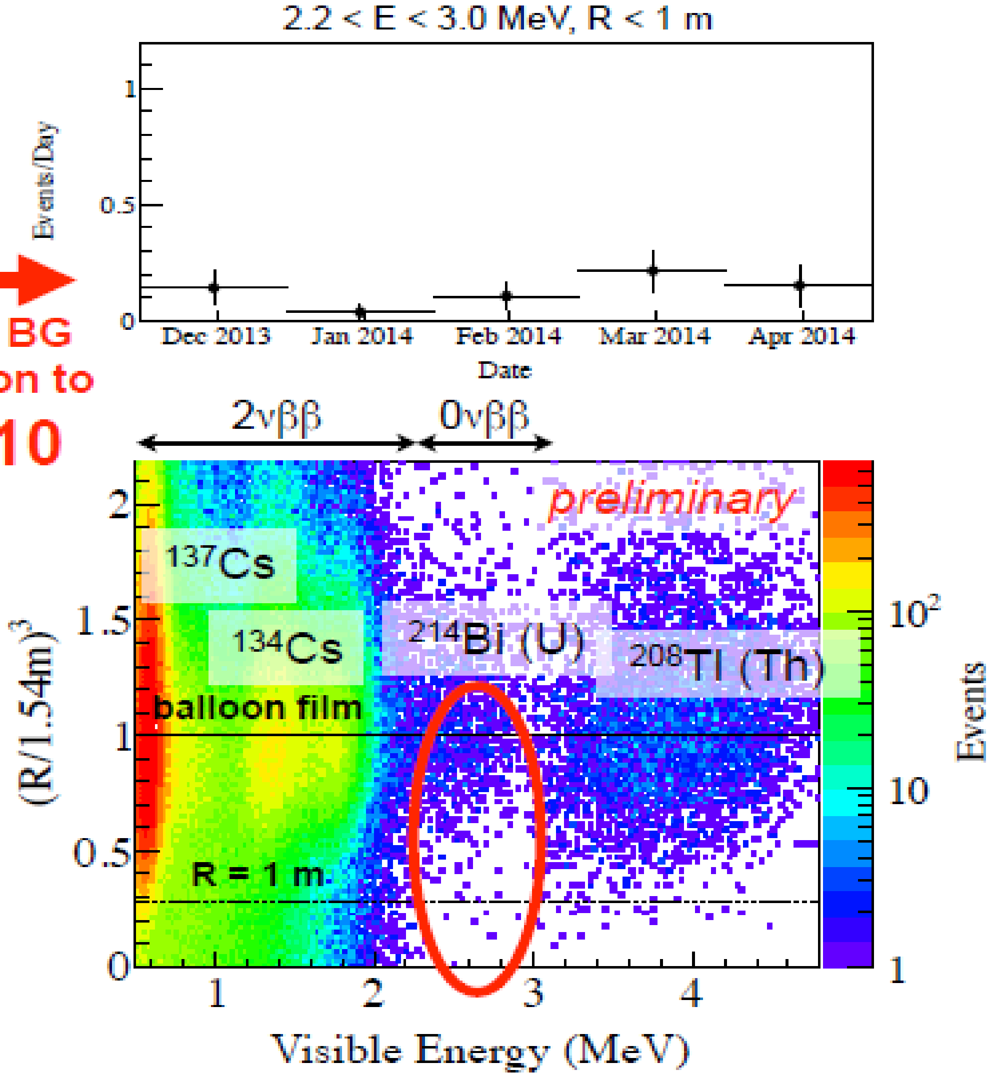
^{110m}Ag Background Reduction

Phase 1 (first 112.3 days)



^{110m}Ag BG reduction to < 1/10

Phase 2 (first 114.8 days)

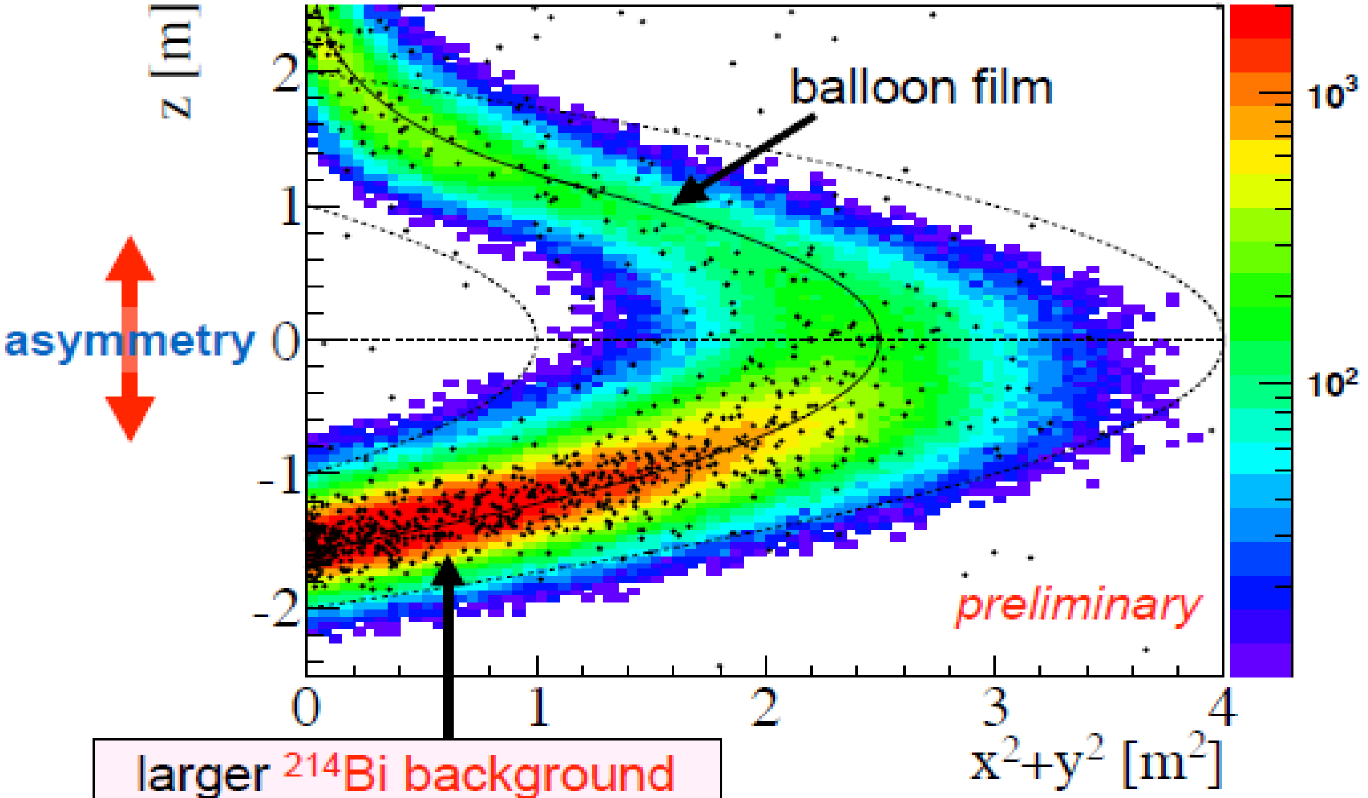


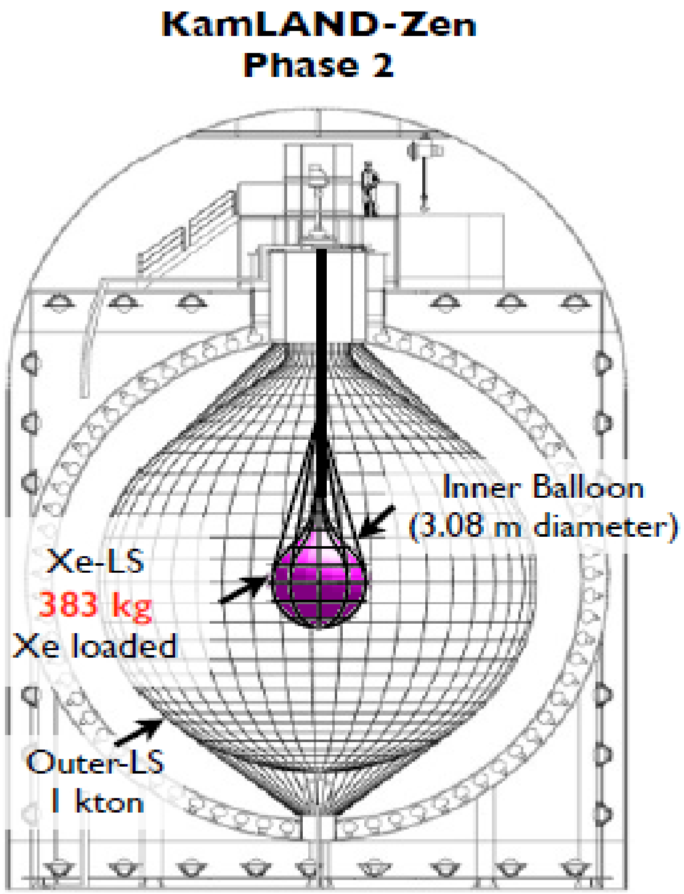
Primary BG : ^{214}Bi (U) at balloon / spallation ^{10}C / remaining ^{110m}Ag?

Optimization of Volume Selection

ROI : 2.3 < E < 2.7 MeV

candidate events (black points)
^{214}Bi MC simulation (color histogram)





larger ^{214}Bi background at balloon bottom
(due to leakage in diaphragm pump)

target volume for spectral fit : R < 2.0 m

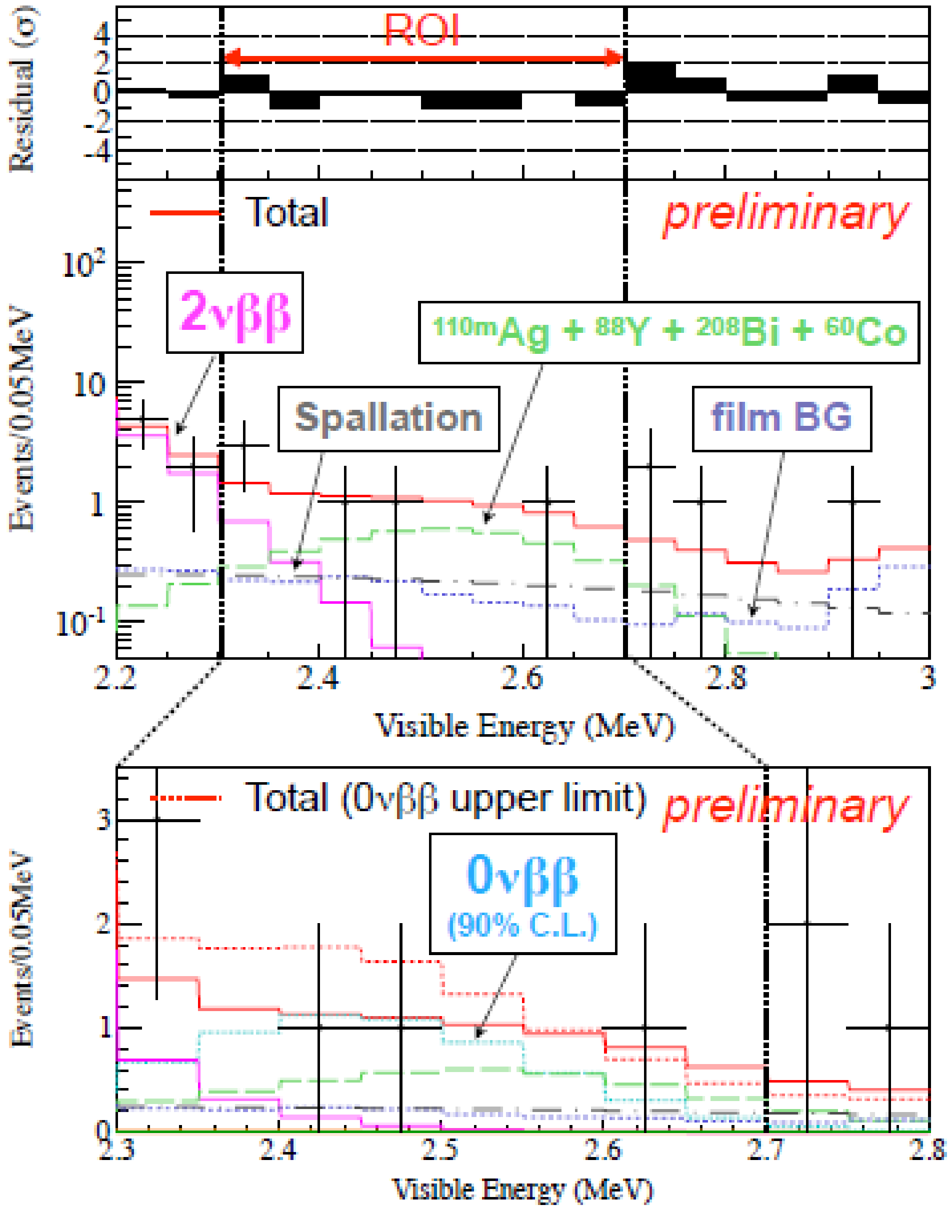
multi-volume selection for analysis optimization

↓

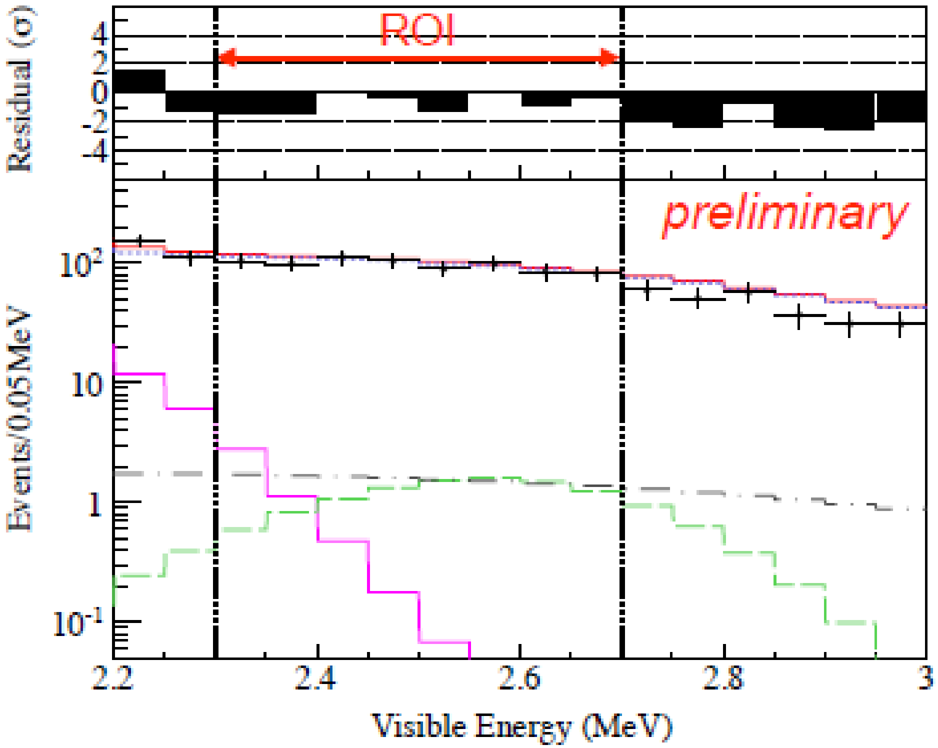
40 equal volume bins
(20 bins + 20 bins in upper / lower hemisphere)

Fit to Energy Spectra for 0νββ

Internal (R < 1.0 m)



External (1.0 < R < 2.0 m)



Fit to Energy-Volume 2D spectra

Limits on 0νββ at 90% C.L.

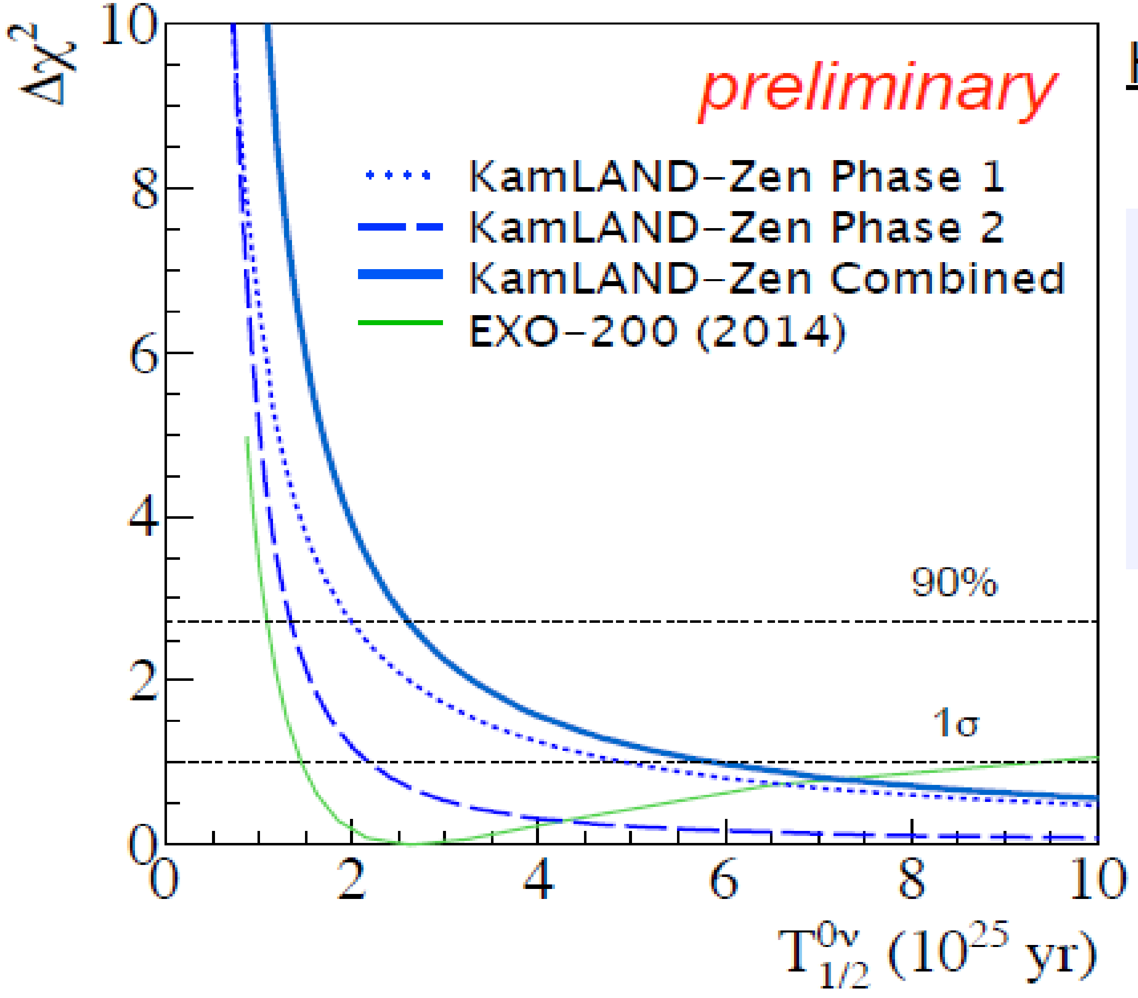
< 17.0 events/day/kton-LS

↓

$T^{0\nu}_{1/2} > 1.3 \times 10^{25}$ yr

^{136}Xe $0\nu\beta\beta$ Decay Half-life

combined result (Phase 1 + 2)



Half-life limit at 90% C.L.

KamLAND-Zen

Phase 1	$T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr
Phase 2	$T^{0\nu}_{1/2} > 1.3 \times 10^{25}$ yr
Combined	$T^{0\nu}_{1/2} > 2.6 \times 10^{25}$ yr

QRPA NME model
J. Phys. G 39 124006 (2012)

$\langle m_{\beta\beta} \rangle < 0.14\text{-}0.28$ eV

Neutrino2014 result

Limits on ^{136}Xe half-life and effective neutrino mass are improved

Half-Life Limits

EXO: $T_{1/2} > 1.1 \times 10^{25}$ yr (90% CL) ^{136}Xe WIPP

Nature, **510**, 229 (2014)

KamLAND-Zen: $T_{1/2} > 2.6 \times 10^{25}$ yr (90%CL) ^{136}Xe Kamioka

preliminary

GERDA: $T_{1/2} > 2.1 \times 10^{25}$yr (90% CL) ^{76}Ge LNGS

PRL, **111**, 122 (2013)

GERDA combined with HDM and IGEX: $T_{1/2} > 3.0 \times 10^{25}$ yr

H.V. Klapdor-Kleingrothaus *et al.*,
Eur. Phys. J. A **12**, 147 (2001)

C.E. Aalseth *et al.*,
Phys. Rev. D **65**, 092007 (2002)

H.V. Klapdor-Kleinkrothaus *et al.* $T_{1/2}=1.19 \times 10^{25}$ yr Phys. Lett. B **586**, 198 (2004)

Look into the Future

KamLAND-Zen

CUORE

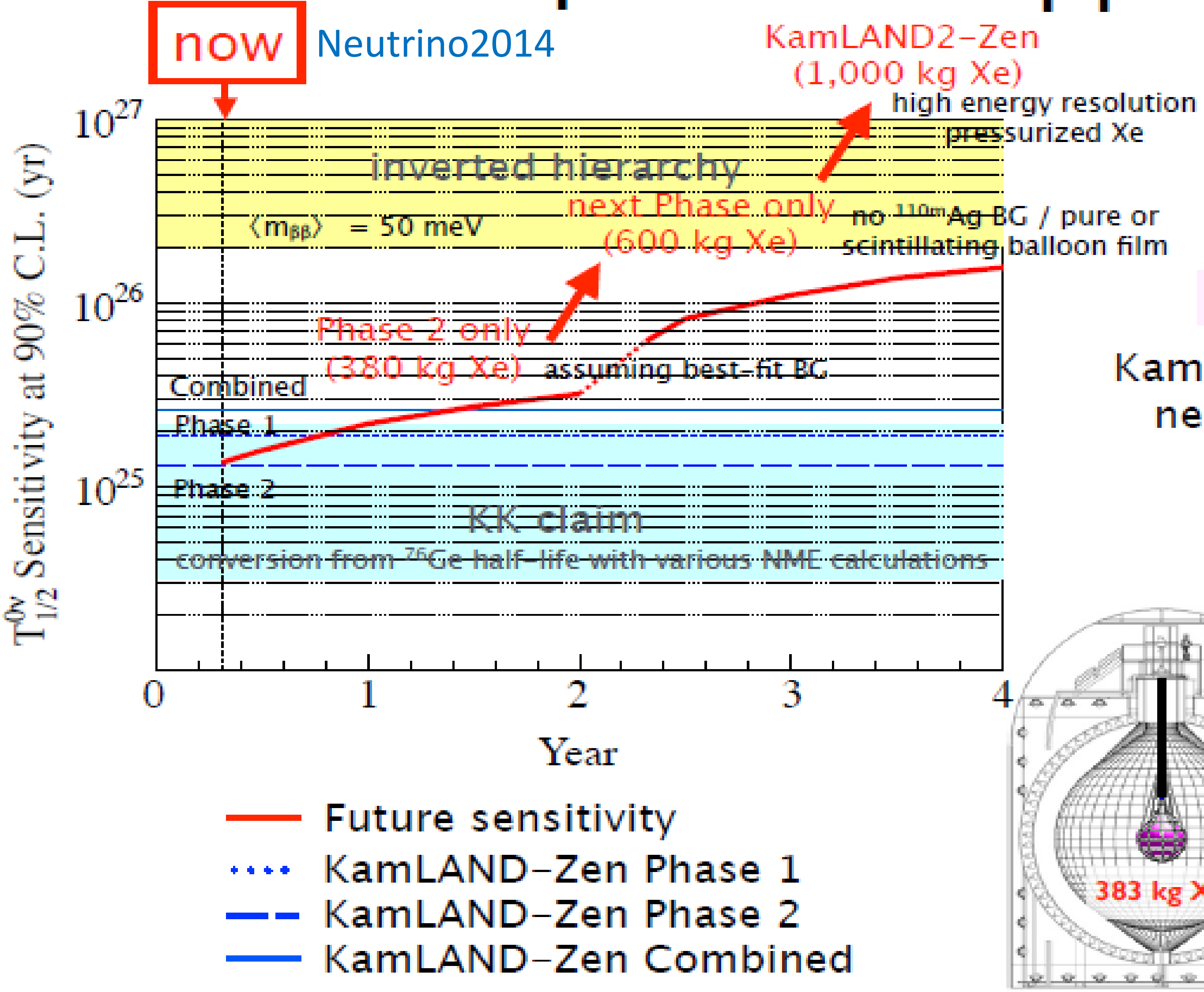
SuperNEMO

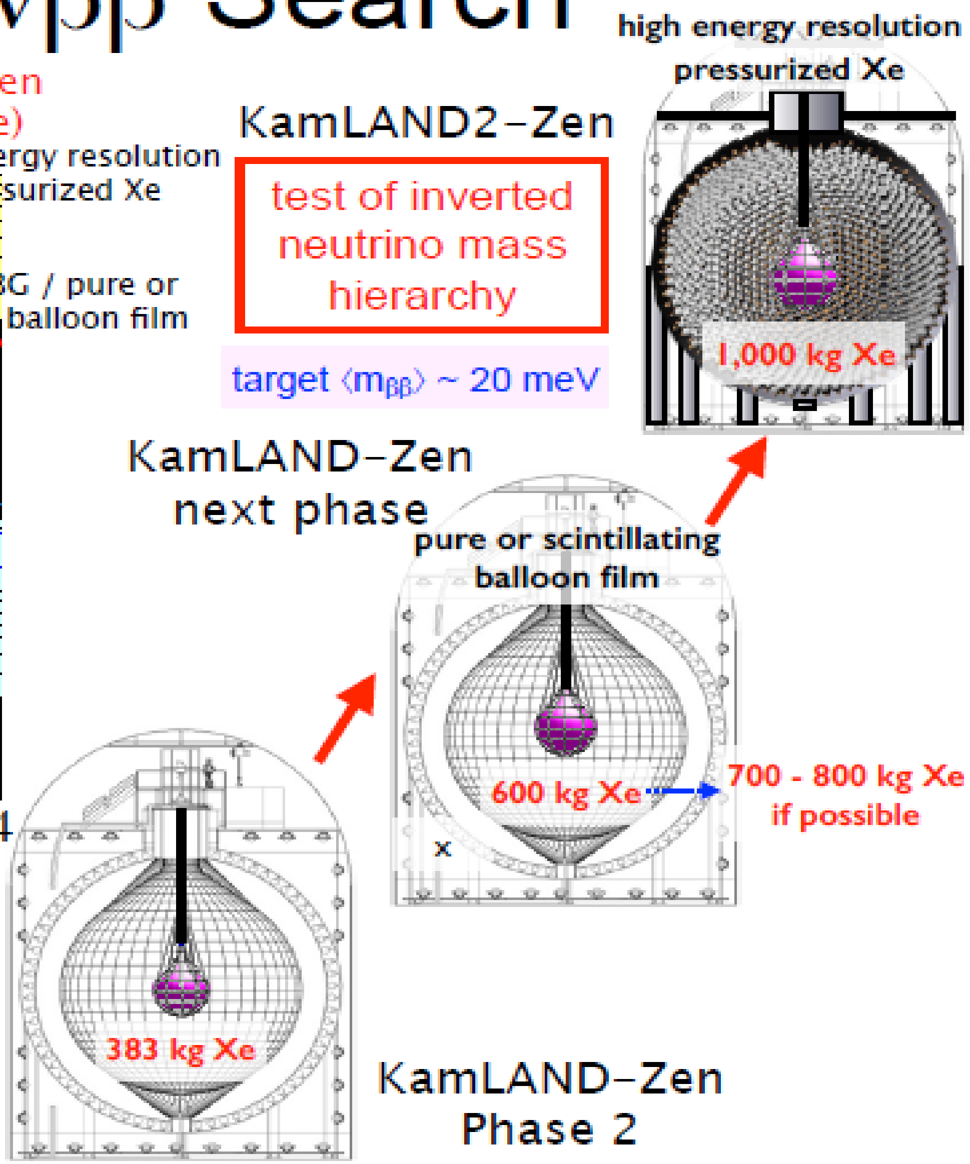
NEXO, NEXT

SNO+

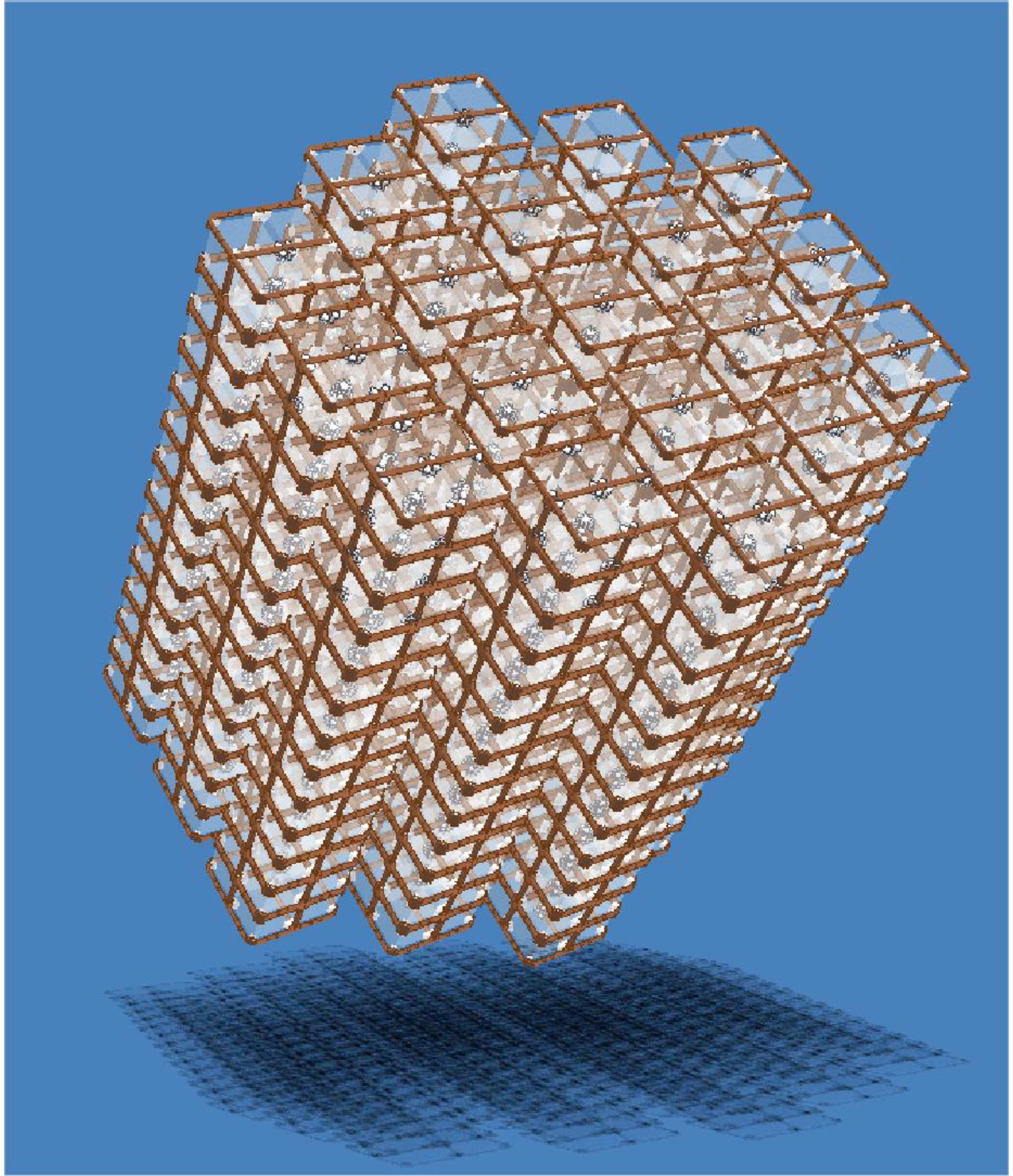
1-tonne ^{76}Ge Experiment

Prospect for 0νββ Search





Detector improvements are planned in the near future



CUORE

988 750 g TeO_2 bolometers

204 kg of ^{130}Te

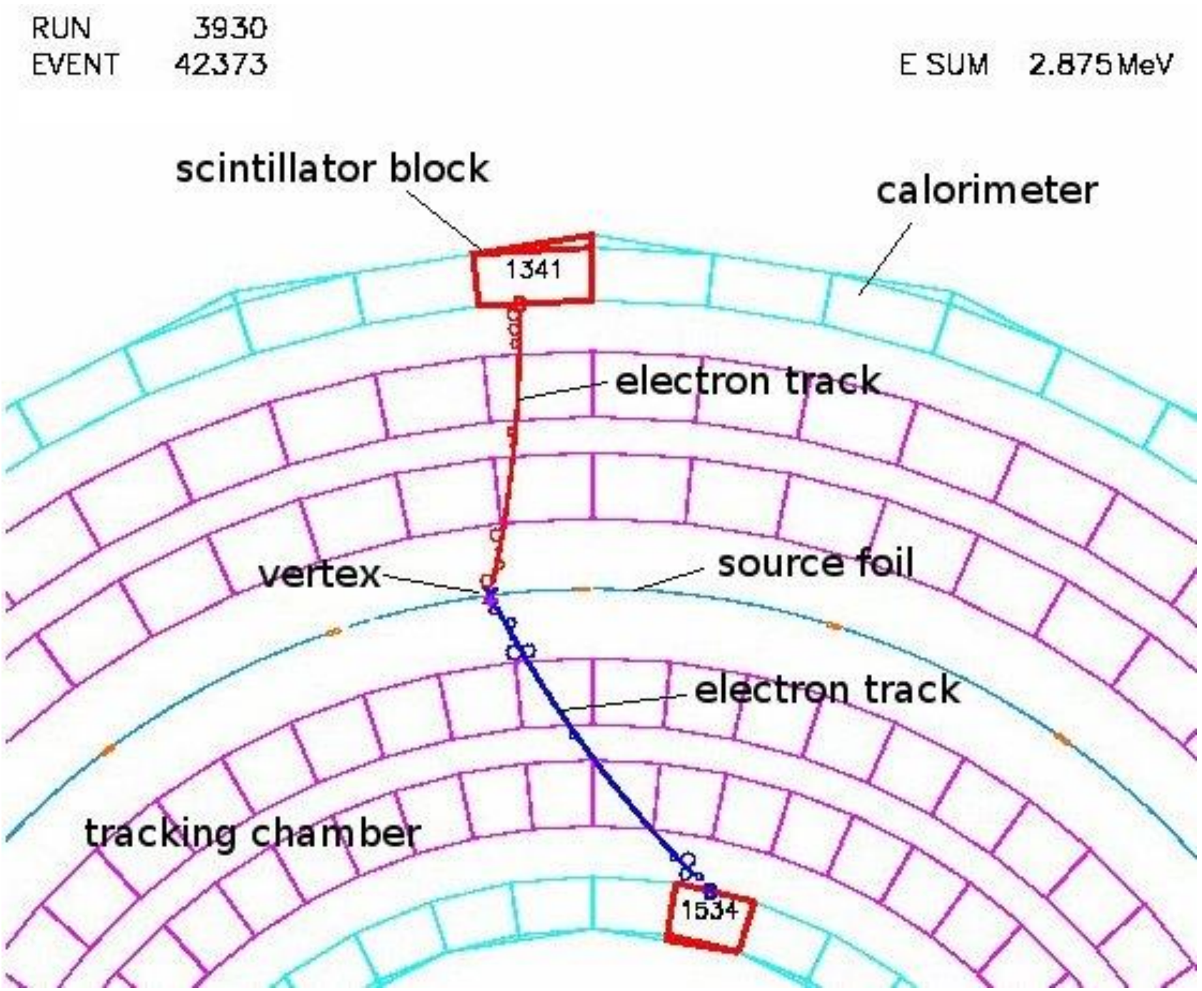
2.1×10^{26} yr

@LNGS

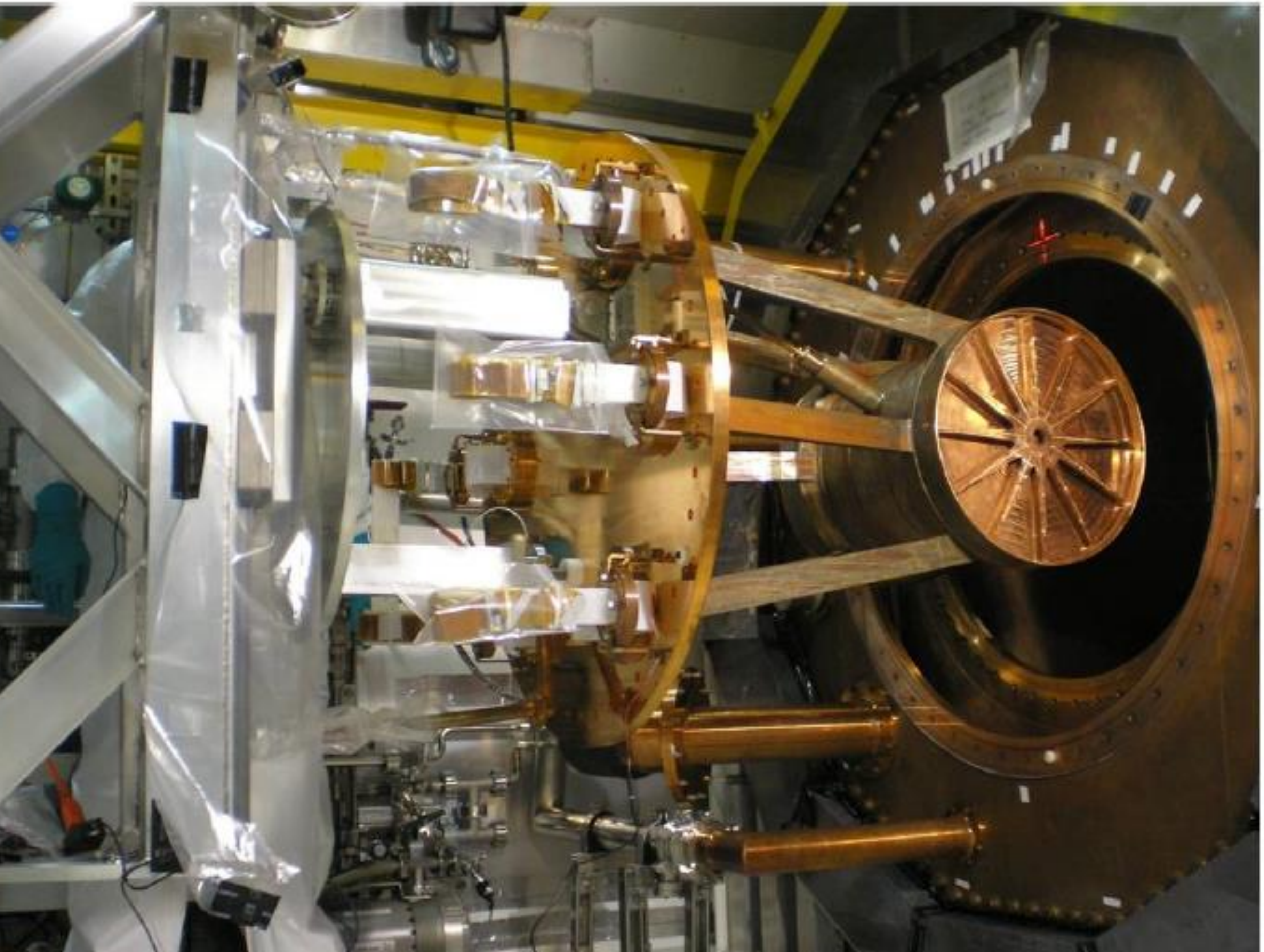
SuperNEMO

^{82}Se: Electron Tracking, 1 x 10^{26} yr

Frejus Underground Laboratory, France



NEMO 3



NEXO

Larger and improved version of EXO-200

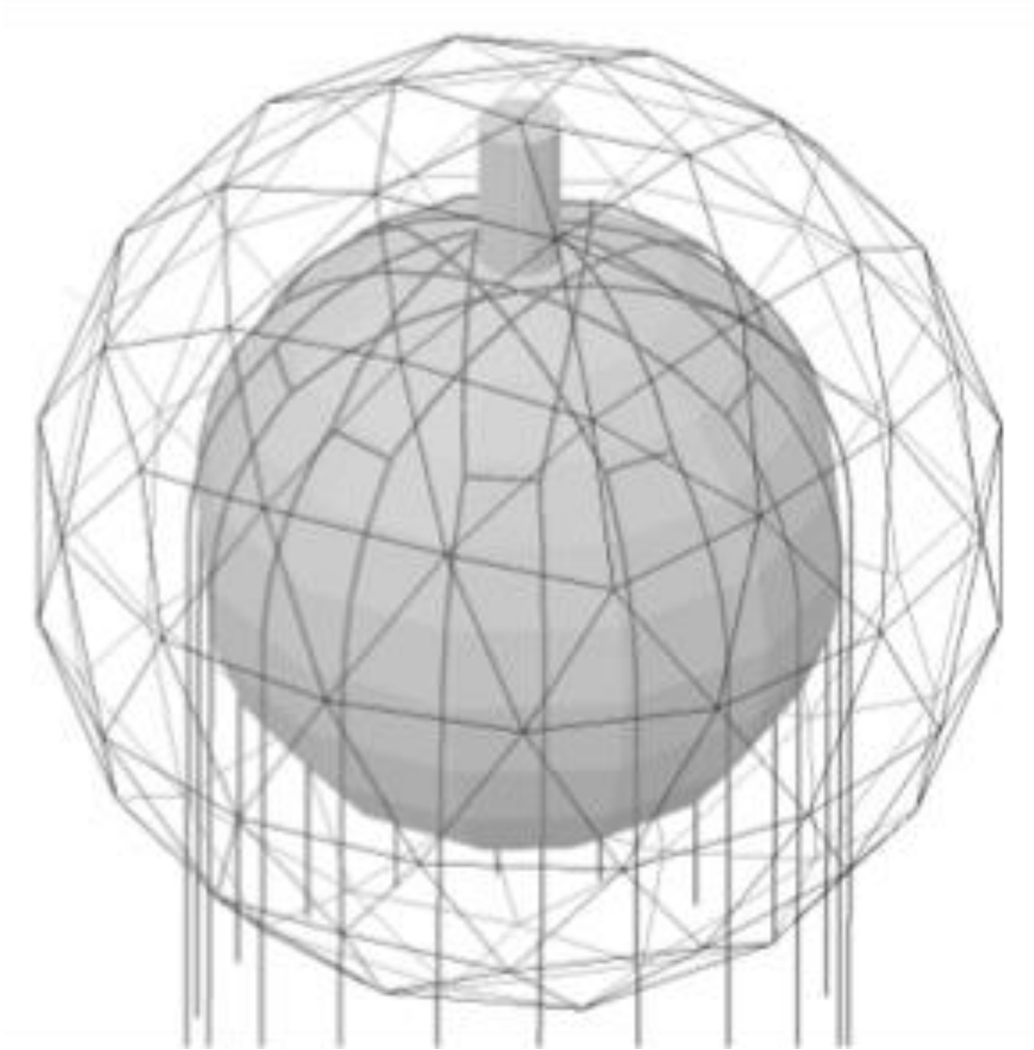
Xenon-based Time-Projection – Chamber

few 10^{26} yr

SNOLAB ?

Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM, USA

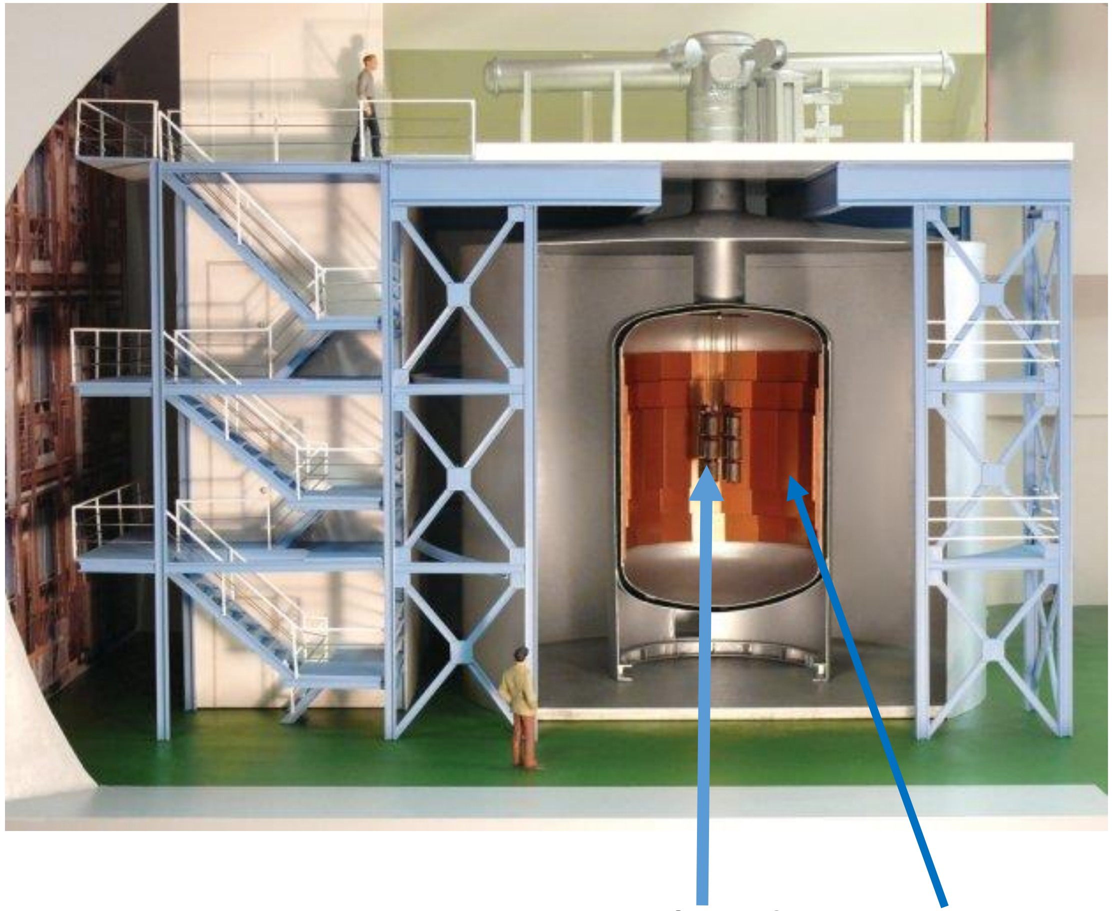
FV: 76.3 kg of ^{136}Xe

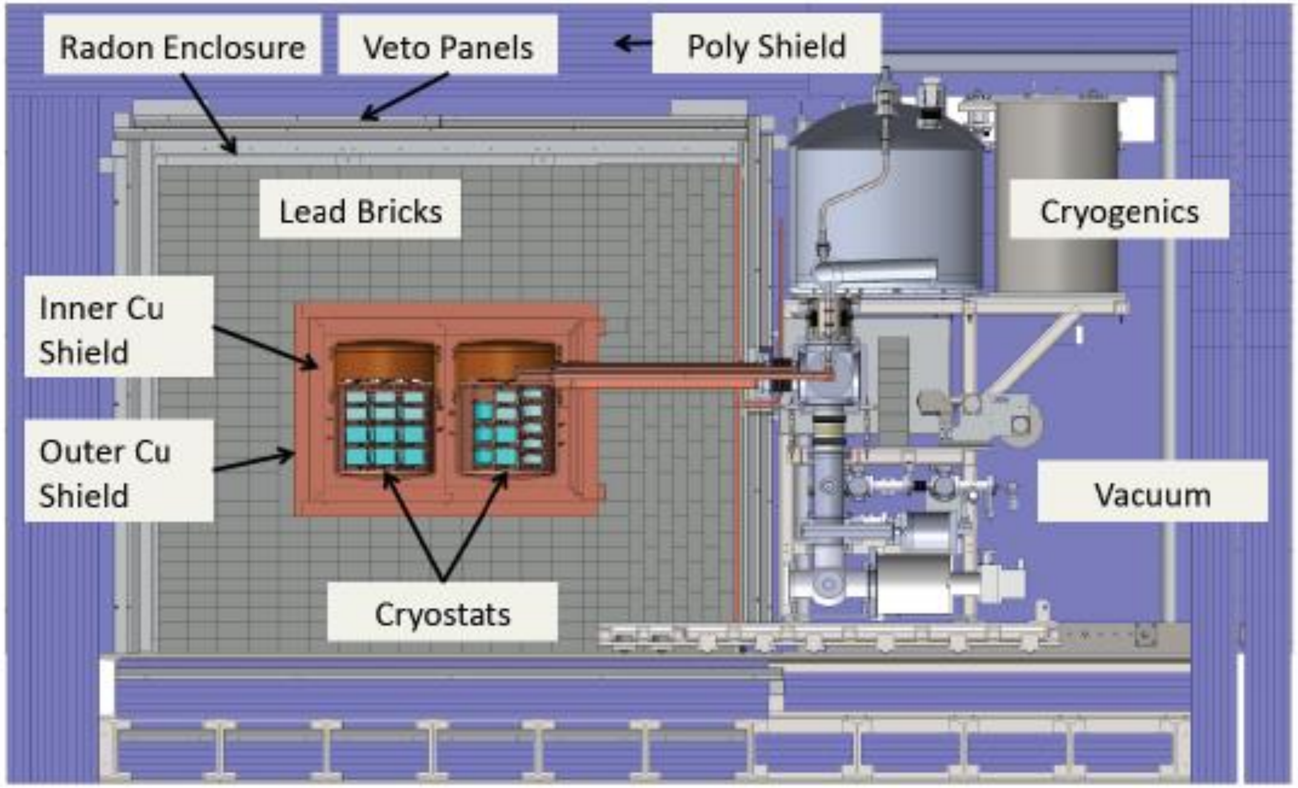


SNO+

Tellurium loaded
Liquid Scintillator

few 10^{26} yr





MAJORANA DEMONSTRATOR
@ SURF

GERDA:
GERmanium
Detector
Array @LNGS

Enriched
HPGe
Detectors

LAr

The two collaborations plan to join forces to build a 1-tonne ^{76}Ge based $0\nu\beta\beta$ experiment using the better of the two approaches: a few 10^{26} yr

Within the next 5 to 10 years : Several experiments will push the $T_{1/2}$ ($0\nu\beta\beta$) limit to $> 10^{26}$ yr

Effective neutrino mass range down to ~30 meV will be probed ("center" of inverted hierachy region)