

Neutrino mass measurements in the Americas

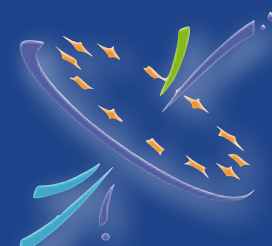
Nigel Smith

SNOLAB

... many thanks to contributors



Fermilab



APPEC

Scope of talk

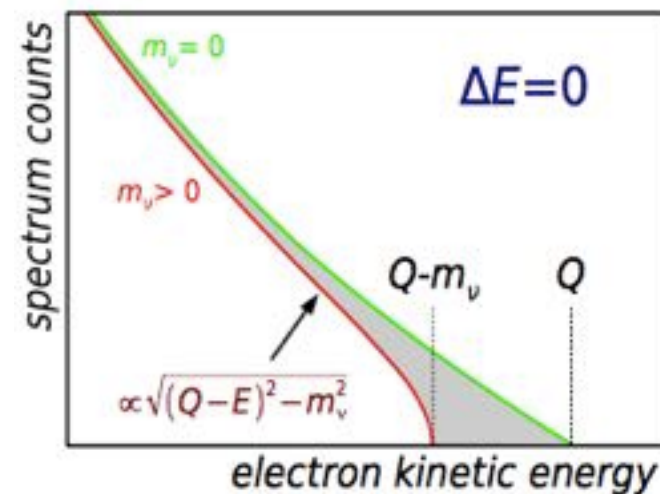


- Measurements of direct/effective neutrino mass using single/double beta process
- Single beta measurements
 - Calorimetric measurements
 - Frequency measurements
- Double beta decay experiments
 - Current project status and results
 - Background reduction techniques
 - Future projects and prospects
- International collaborations forming to build large scale detectors

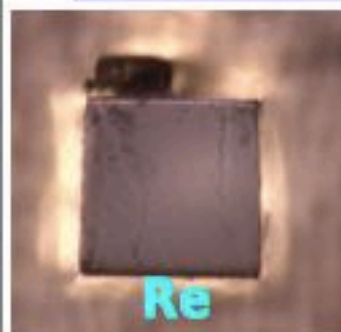
Direct single electron measurements



- Looking at the kinematics of β -decays
 - Looking for deviations at end-point
- Low Q isotopes (^3H , ^{187}Re , ^{163}Ho)
- Two approaches used
 - Spectroscopy (source \neq detector)
 - Calorimetry (source = detector)
- In calorimetry, full energy of decay measured, except for the hidden energy of the neutrino
 - can use electron capture process, similar deviations expected
 - no backscattering, energy loss in source, no solid state excitations
 - limited statistics, backgrounds pile-up, spectrum related systematics
- In spectroscopy measure energy (or cyclotron frequency of emitted electron)
 - high statistics, high energy resolution
 - high backgrounds, source effects




^{187}Re experiments: MANU-MIBETA ... MARE



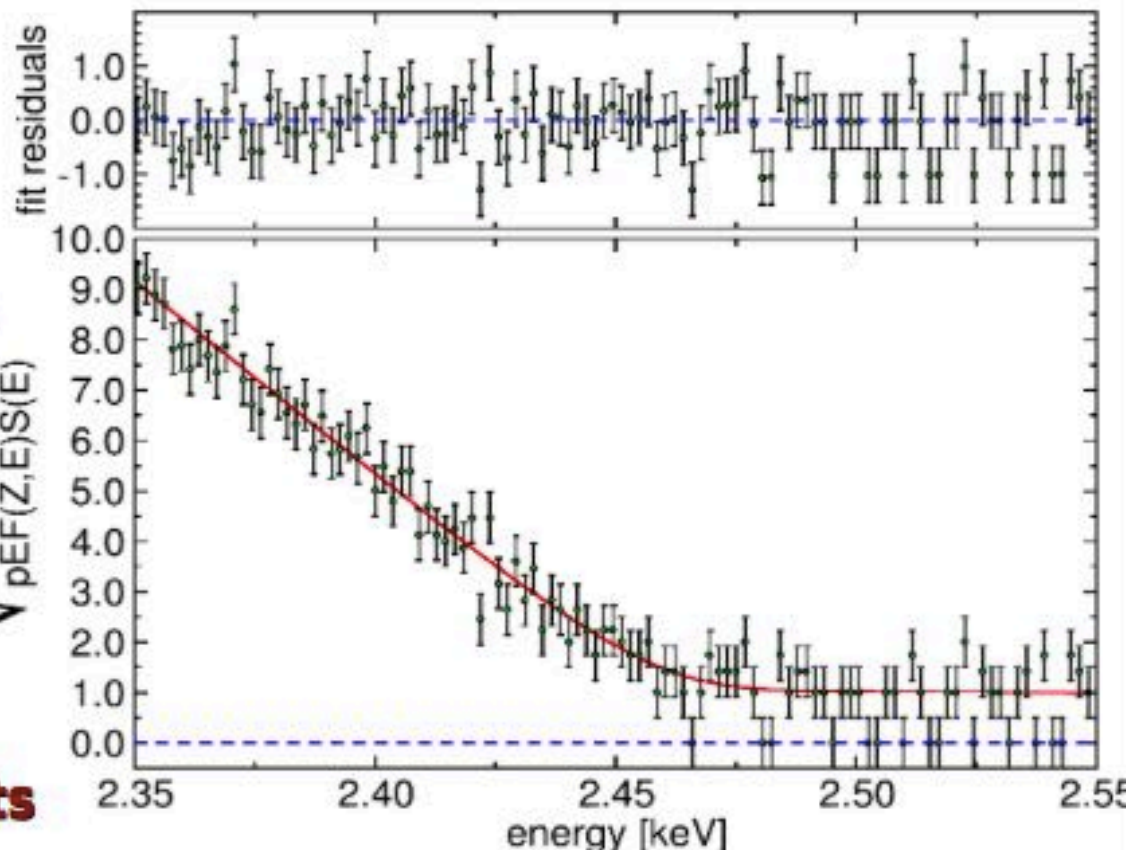
Re



AgReO₄

- proposed since 1985 by Genova group
- **MIBETA** @ MiB with AgReO₄
 - ▶ $m_\nu < 15$ eV 90% C.L. 
- **MANU** @ Ge with metallic Re
 - ▶ $m_\nu < 26$ eV 95% C.L.
- **first ^{187}Re experiments: $N_{\text{ev}} \sim 10^7$ events**

$N(E)$
 $\sqrt{\text{pEF}(Z,E)S(E)}$



MARE (Microcalorimeter arrays for a Rhenium Experiment)

- project for a sub-eV direct neutrino mass measurement
- wide international interest since Orlando (USA) meeting in 2007
- phased approach to optimize detectors technology

goal

- neutrino mass measurement: m_ν statistical sensitivity as low as 0.4 eV
- prove technique potential and scalability:
 - ▶ assess EC Q-value
 - ▶ assess systematic errors

baseline

- Transition Edge Sensors (TES) with ^{163}Ho implanted Au absorbers
 - ▶ 6.5×10^{13} nuclei per detector \rightarrow 300 dec/sec
 - ▶ $\Delta E \approx 1\text{eV}$ and $\tau_R \approx 1\mu\text{s}$
- 1000 channel array
 - ▶ 6.5×10^{16} ^{163}Ho nuclei $\rightarrow \approx 18\mu\text{g}$
 - ▶ 3×10^{13} events in 3 years

\rightarrow Project Start: 1 Feb 2014

^{163}Ho production and embedding

■ ^{163}Ho production by nuclear reaction

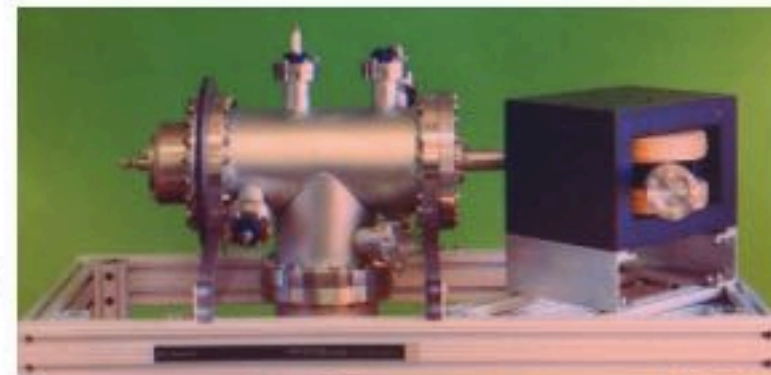
- ▶ high yield
- ▶ low by-products contaminations (in particular $^{166\text{m}}\text{Ho}$, β $\tau_{1/2}=1200\text{y}$)
- ▶ not all cross sections are well known
 - neutron activation of enriched ^{162}Er (nuclear reactor) → HOLMES baseline
 - $^{163}\text{Dy}(p,n)^{163}\text{Ho}$ $E_p > 10$ MeV (direct, low yield → PSI?)
 - $^{\text{nat}}\text{Dy}(\alpha,xn)^{163}\text{Er}$ and $^{159}\text{Tb}(^7\text{Li}, 3n)^{163}\text{Er}$

■ ^{163}Ho Separation from Dy, Er and more ...

- ▶ radiochemistry (before and/or after irradiation)
- ▶ magnetic mass separation
- ▶ resonance ionization laser ion source (RILIS)?

■ ^{163}Ho embedding in detector absorber

- ▶ implantation (+magnetic separation)
- ▶ Au film deposition for full containment



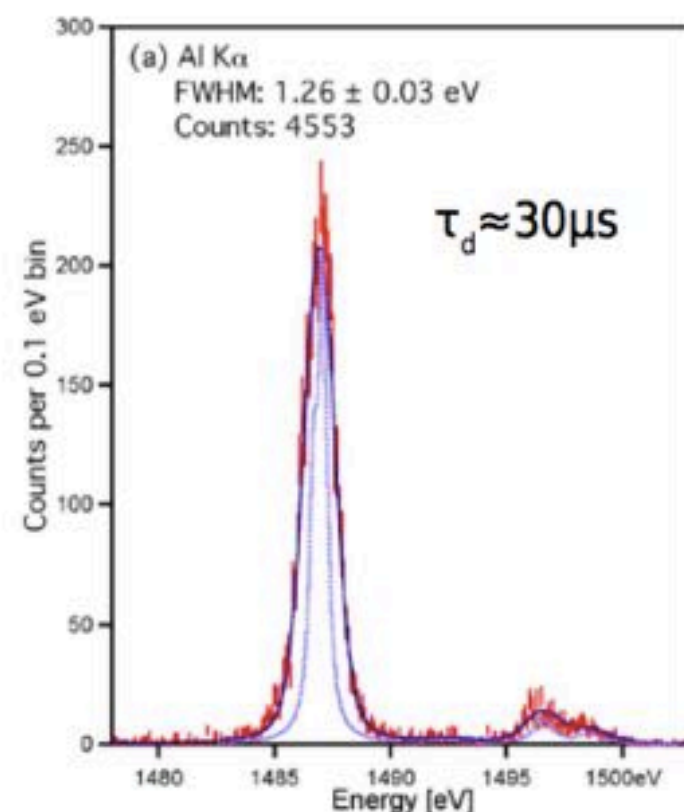
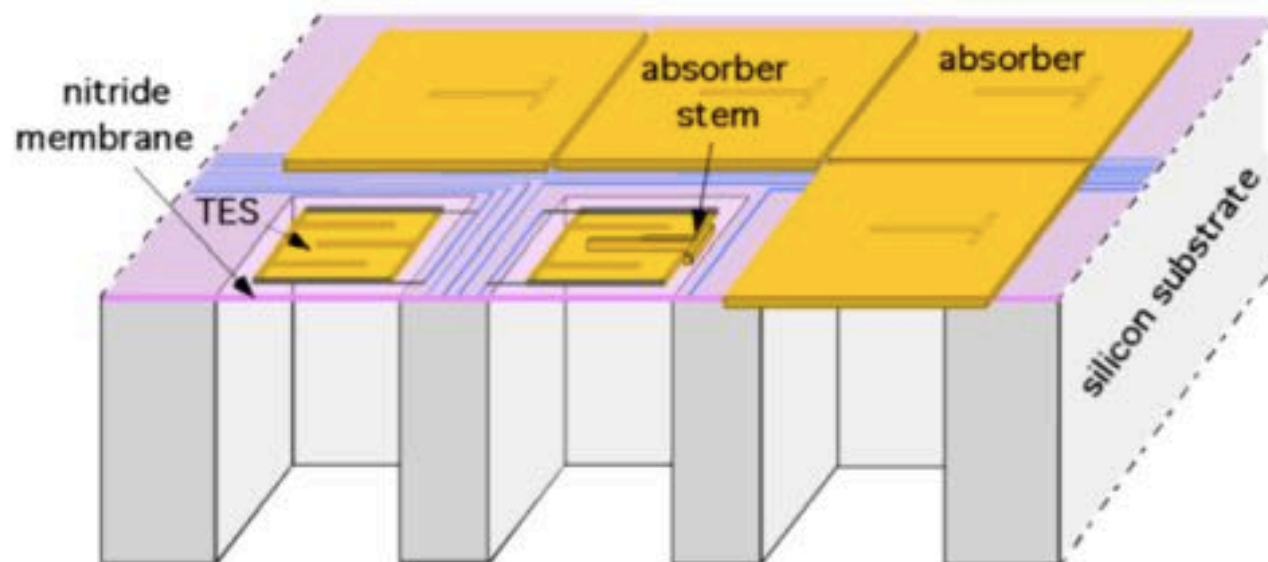
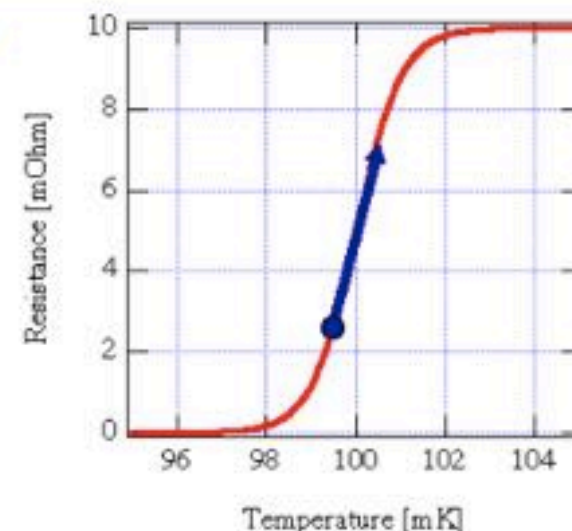
J.W. Engle et al., NIM B 311 (2013) 131-138

ECHO

particle	p	n 10^{14} n/cm ² /s	p 16 MeV 80 μA	p 24 MeV 240 μA	α 40 MeV 30 μA
target	W/Ta	^{162}Er (40%)	$^{\text{nat}}\text{Dy}$ 200mg/cm ²	$^{\text{nat}}\text{Dy}$ 20g	$^{\text{nat}}\text{Dy}$ "thick"
^{163}Ho prod rate [nuclei/h]	10^{14}	10^{13-15} / mg ^{162}Er	10^{14}	10^{15}	10^{13}

HOLMES detectors

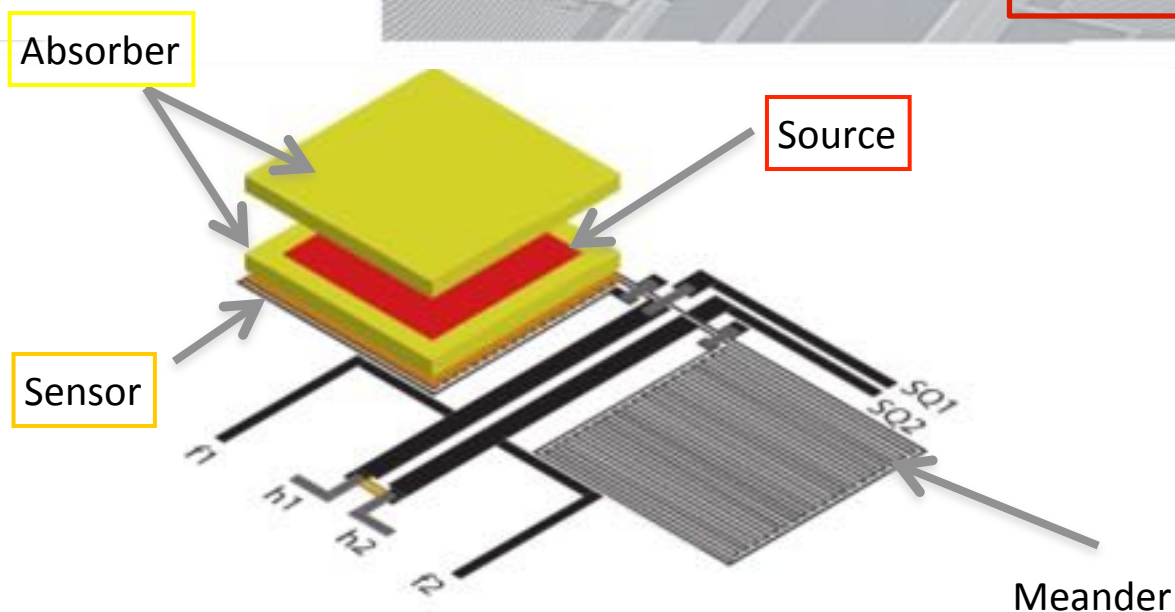
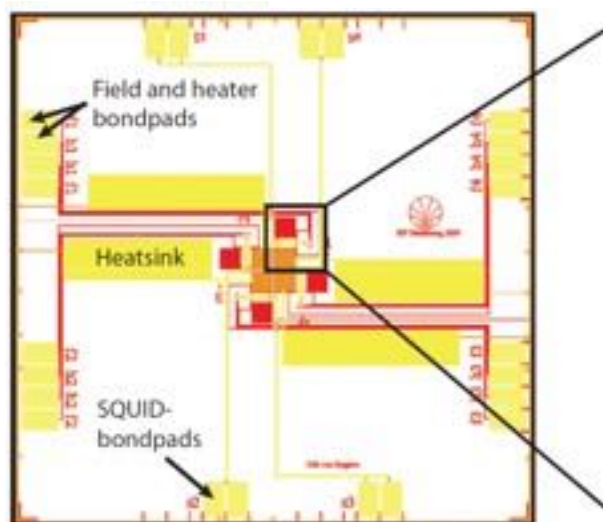
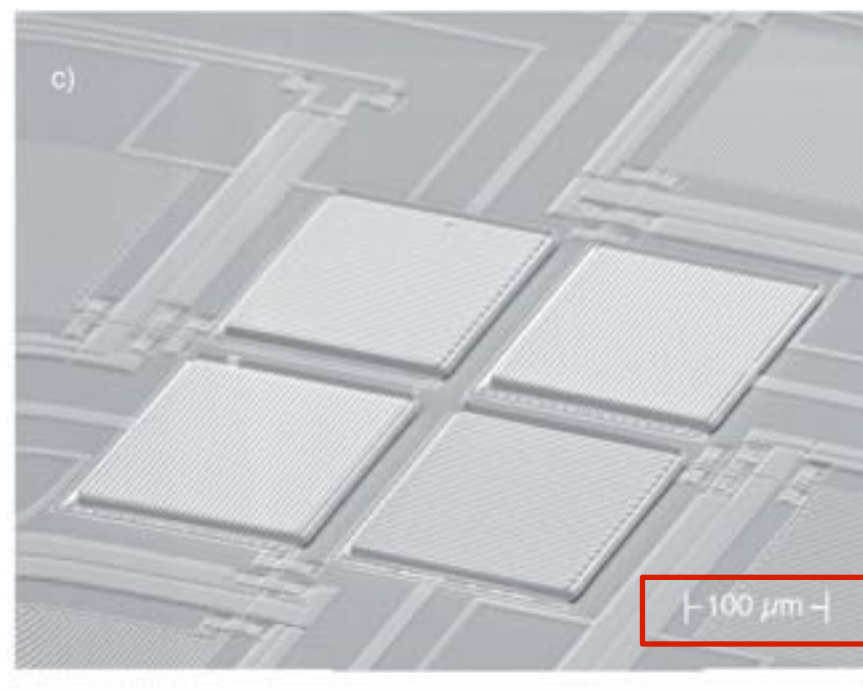
- Transition Edge Sensors (TES) with Au absorber
 - ▷ hot electron microcalorimeters with electro-thermal feedback
 - ▷ 2 μm thick electrodeposited Au for full absorption
- MoAu or MoCu proximity TES $\rightarrow T_c \approx 100\text{mK}$
- on Si_2N_3 membrane



NASA/GSFC

EC-Ho: first detector prototype

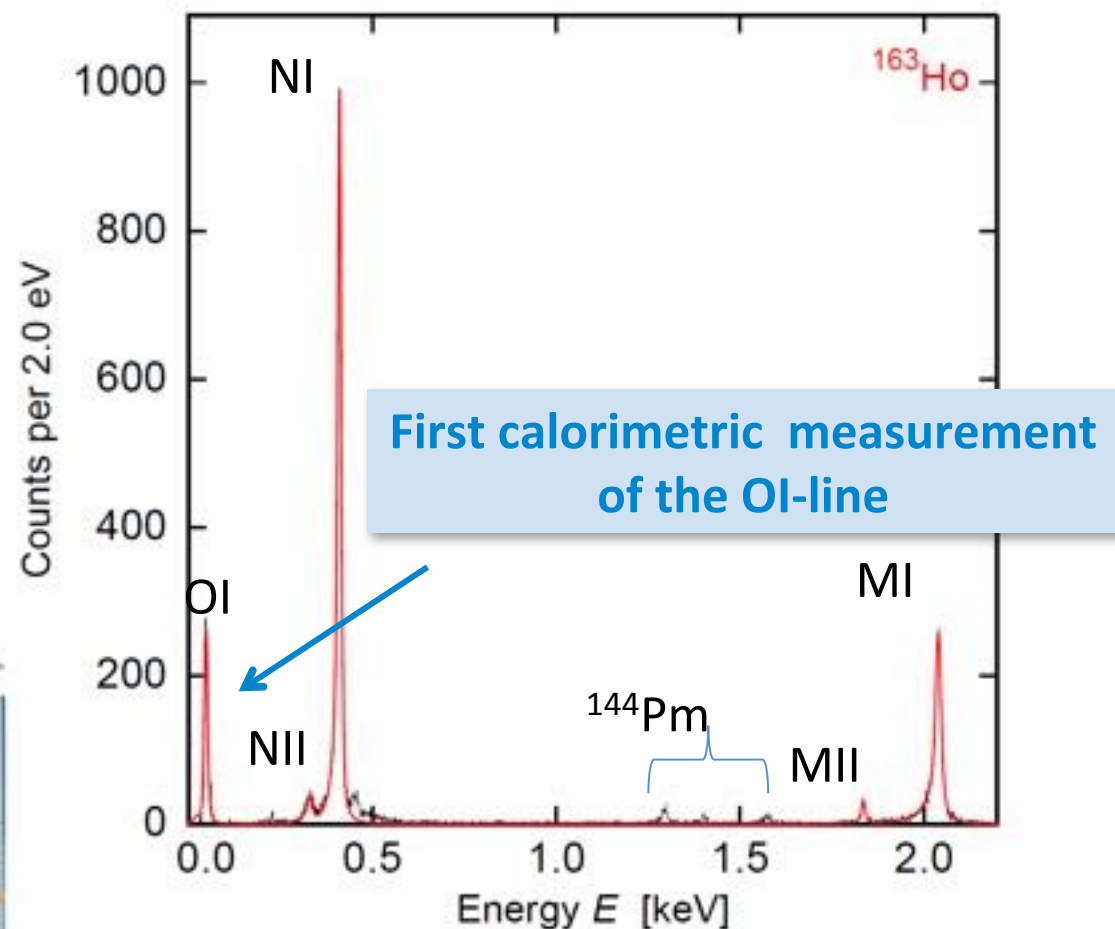
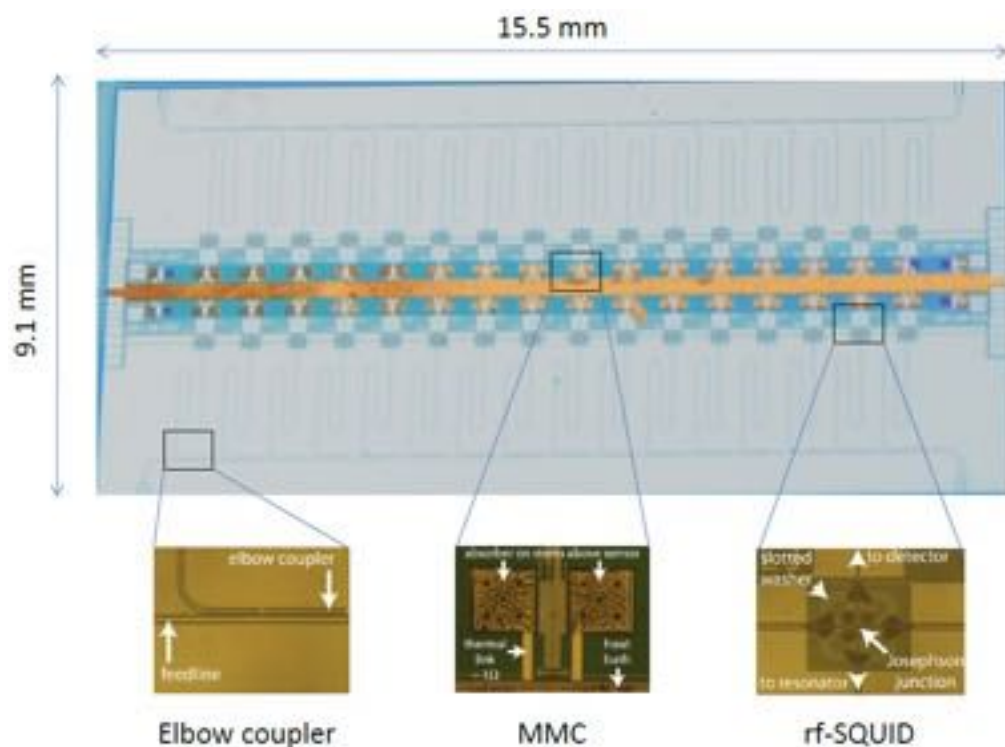
- Absorber for calorimetric measurement
→ ion implantation @ ISOLDE-CERN
- About 0.01 Bq per pixel
- Two pixels have been simultaneously measured



EC-Ho: measurement of the spectrum

Single pixels

- Rise Time ~ 130 ns
- $\Delta E_{\text{FWHM}} = 7.6$ eV @ 6 keV (2013)
 $\Delta E_{\text{FWHM}} = 2.4$ eV @ 0 keV (2014)
- Non-Linearity $< 1\%$ @ 6keV
- Presently most precise ^{163}Ho spectrum



Microwave multiplexing for large MMC arrays

- fabrication
- detection technique

EC^{Ho}: overview

- Prove **scalability** with medium large experiment **ECHo-1K**
 - $A \sim 1000 \text{ Bq}$ High purity ^{163}Ho source (produced at reactor)
 - $\Delta E_{\text{FWHM}} < 5 \text{ eV}$
 - $\tau_r < 1 \mu\text{s}$
 - multiplexed arrays \rightarrow microwave SQUID multiplexing
- 1 year measuring time $\rightarrow 10^{10}$ counts = Neutrino mass sensitivity $m_\nu < 10 \text{ eV}$

Just approved

Research Unit FOR 2202/1

„Neutrino Mass Determination by Electron Capture in Holmium-163 – ECHo“

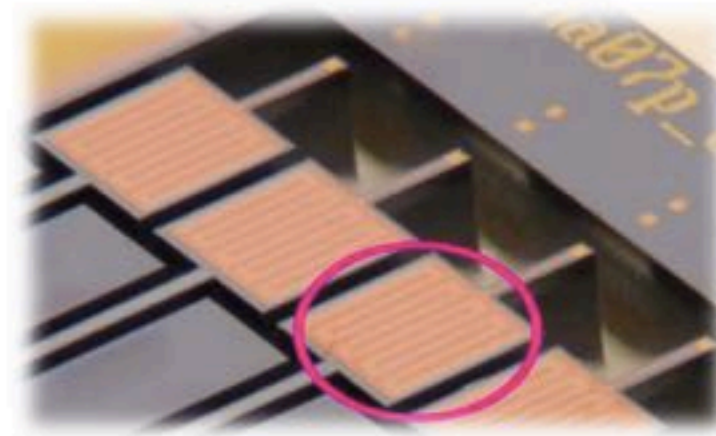
DFG Deutsche
Forschungsgemeinschaft

- **ECHo-1M** towards sub-eV sensitivity

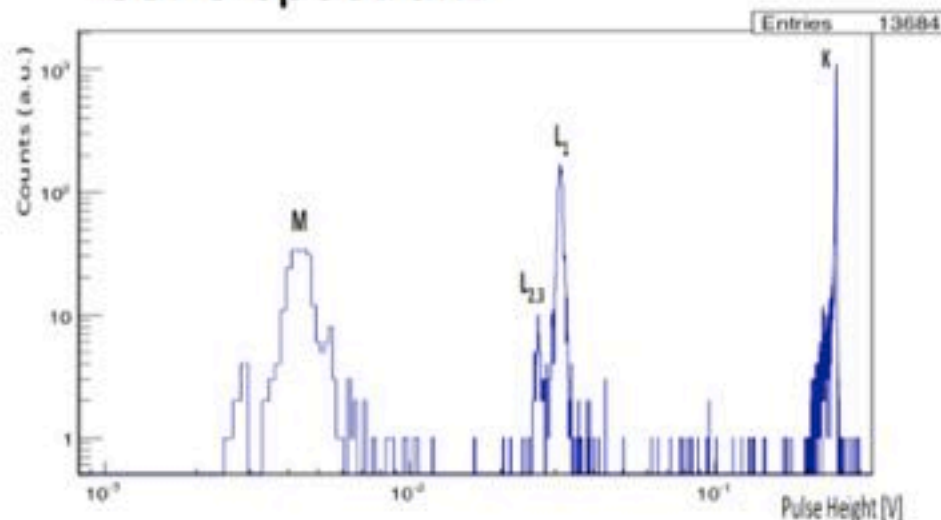
NuMECS (Ho EC detector)



- LANL, NIST, U.Madison
- Transition-Edge Sensors (TES)
- Good energy resolution (6 eV @ 6 keV with ^{55}Fe surrogate).
- Concentration on high purity ^{163}Ho production – proton activation of dysprosium
- Show scalability through a demonstrator experiment with 4×1024 TES array of Ho-implanted detectors with RF-SQUID multiplexing



^{55}Fe spectrum



Project 8

Coherent radiation emitted can be collected and used to measure the energy of the electron in a non-destructive manner.

PROJECT 8

Frequency Approach



I. I. Rabi



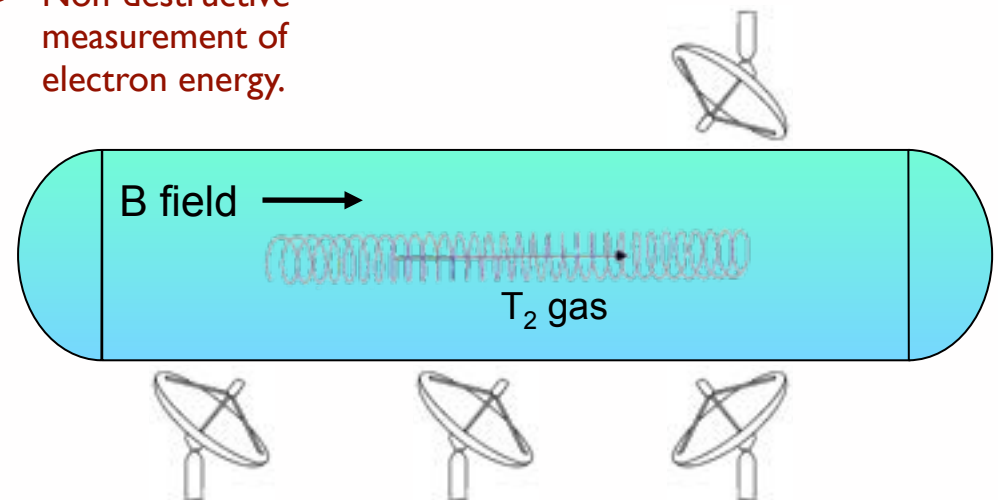
A. L. Schawlow

*“Never
measure
anything but
frequency.”*

- Use cyclotron frequency to extract electron energy.

$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

- Non-destructive measurement of electron energy.



The Apparatus

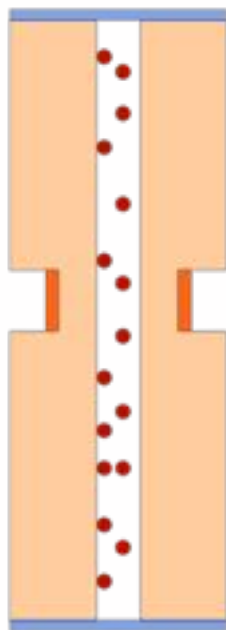
Copper waveguide

Kr gas lines

Magnetic bottle coil

Gas cell

Test signal injection port



Waveguide
Cut-away

B-Field trap profile

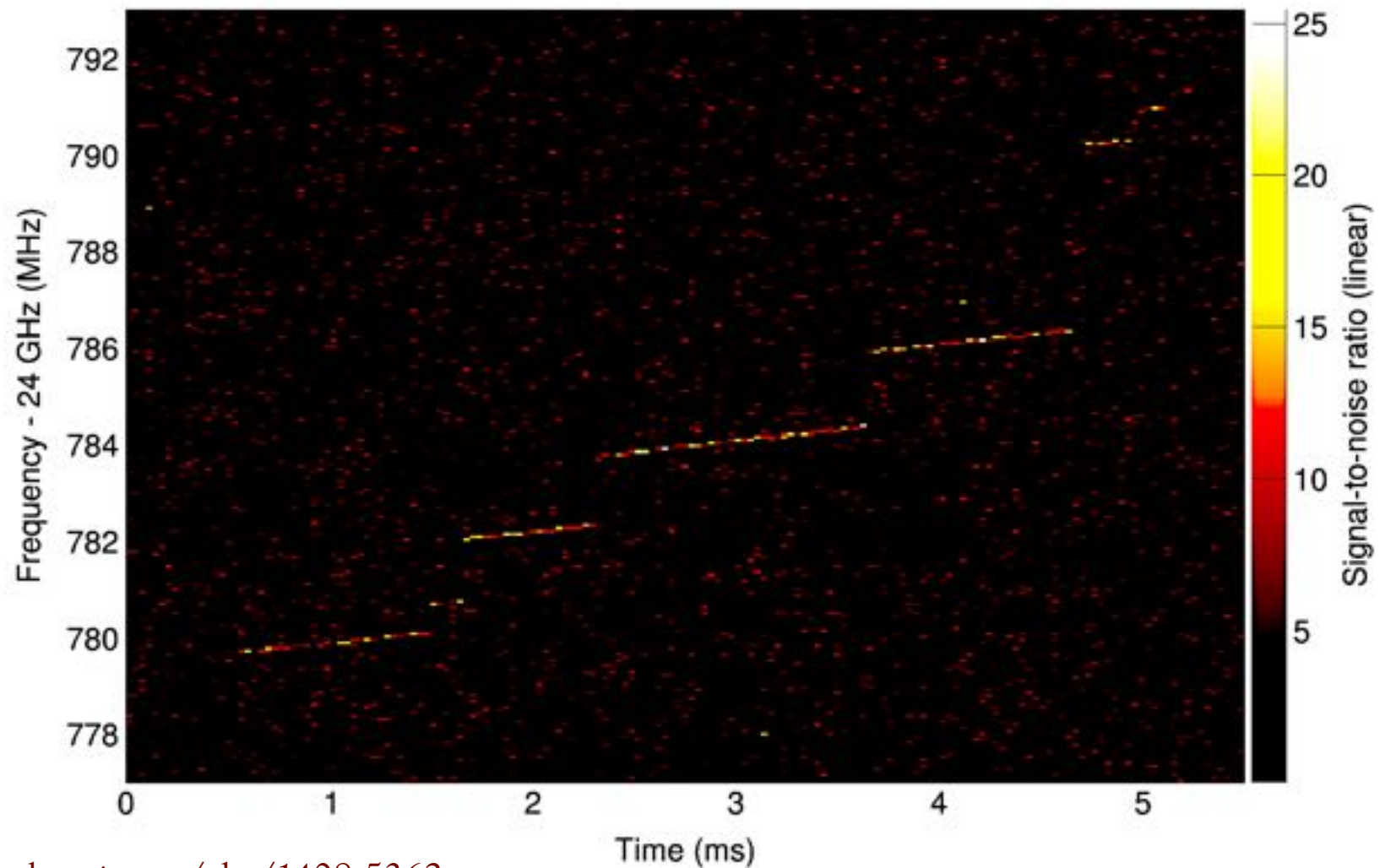


Photo of apparatus

Cyclotron frequency coupled directly to standard waveguide at 26 GHz, located inside bore of NMR 1 Tesla magnet.

Magnetic bottle allows for trapping of electron within cell for measurement.

Project 8 "Event Zero"

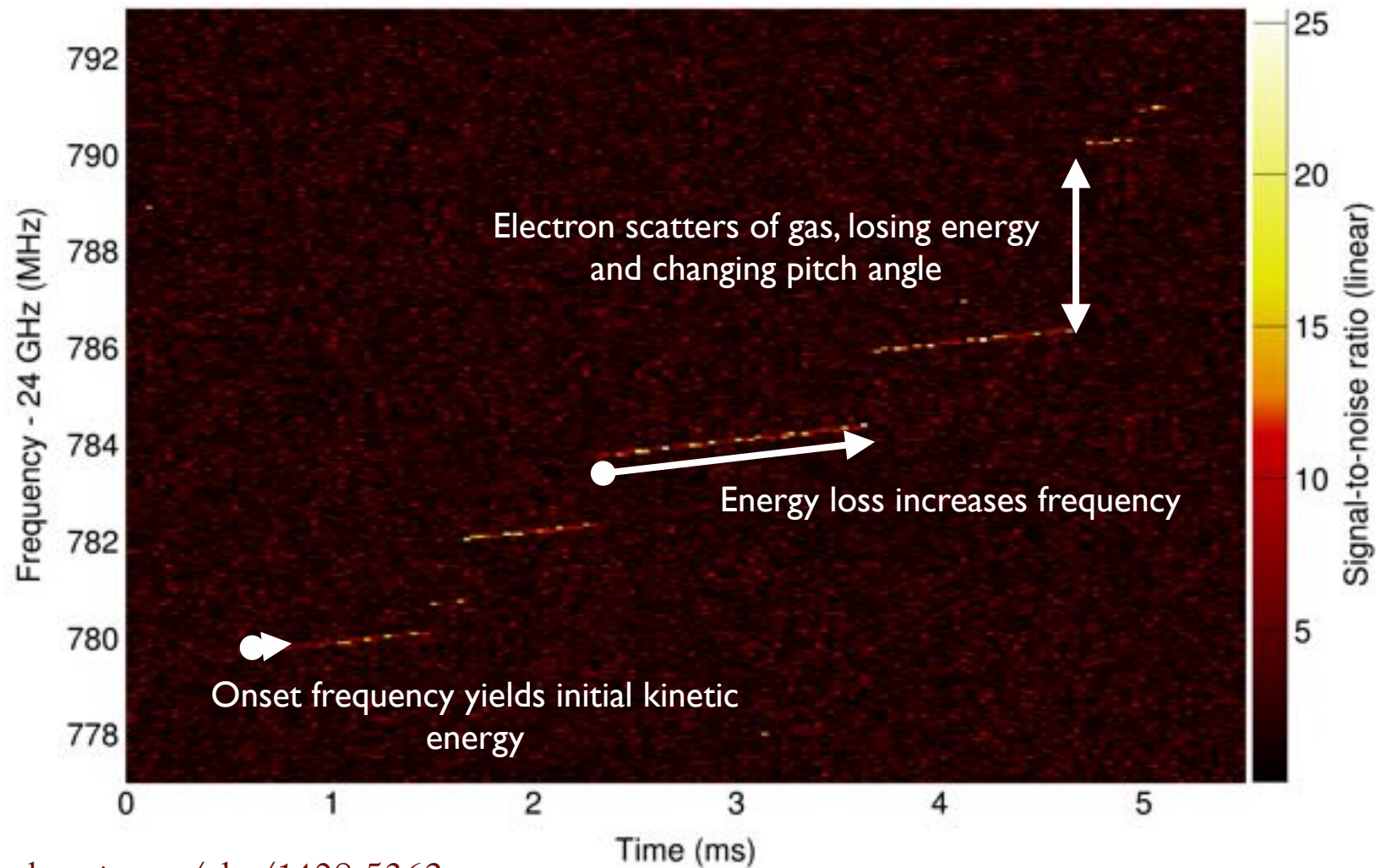


<http://lanl.arxiv.org/abs/1408.5362>

First detection of single-electron cyclotron radiation.

Data taking on June 6th, 2014 immediately shows trapped electrons.

Project 8 "Event Zero"

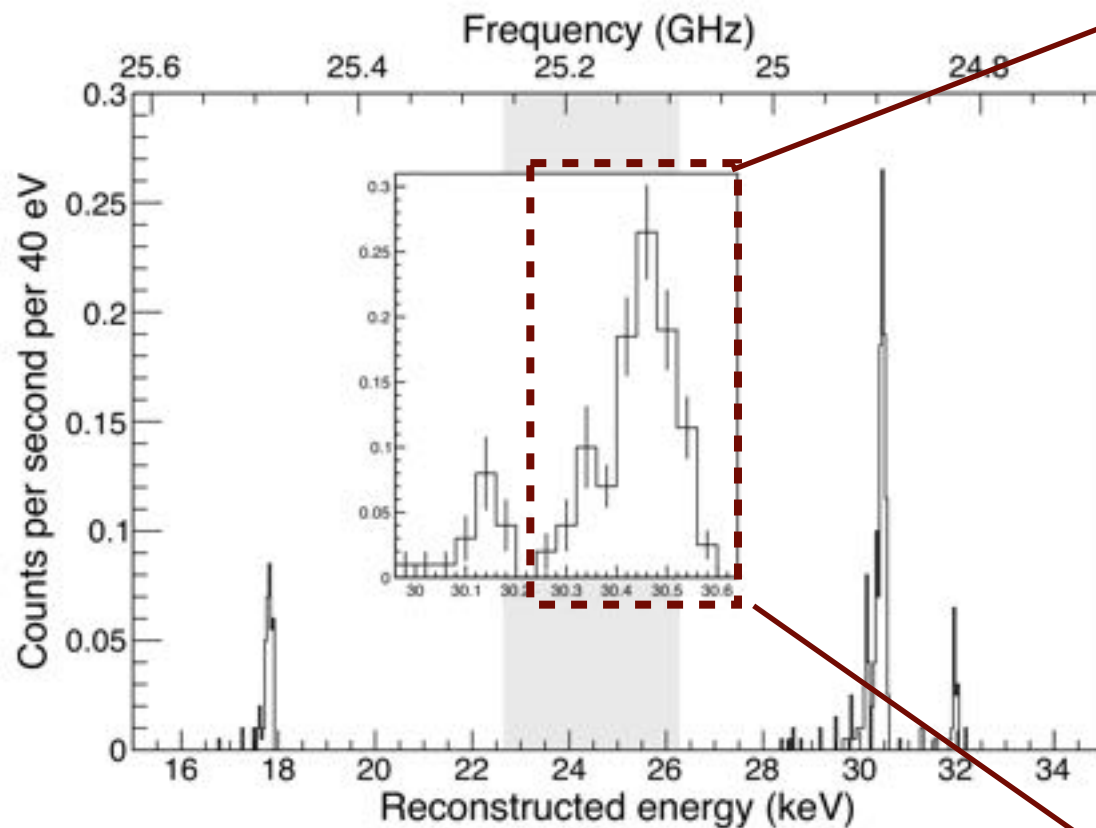


<http://lanl.arxiv.org/abs/1408.5362>

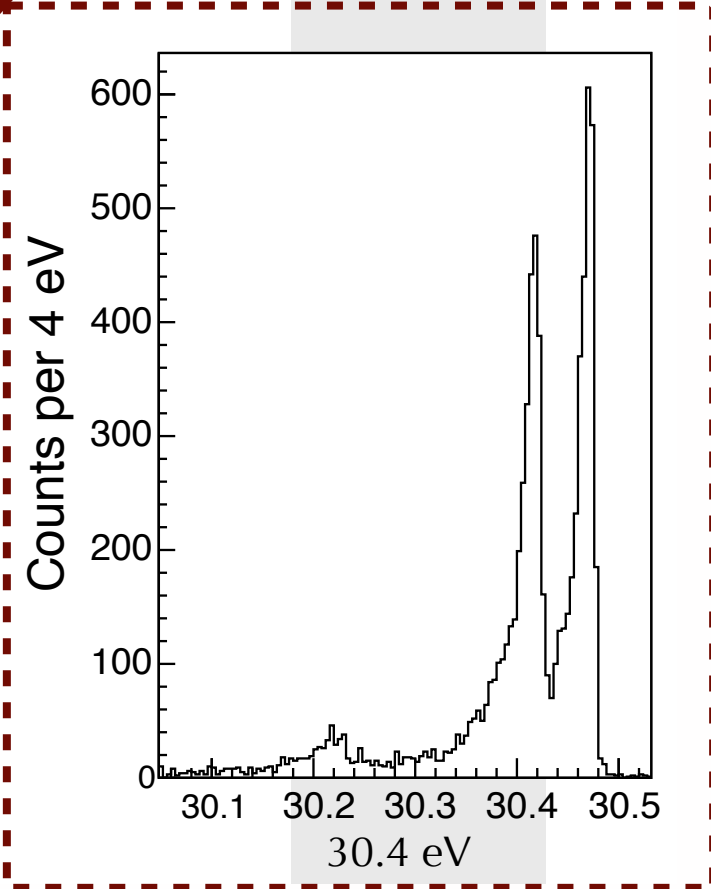
First detection of single-electron cyclotron radiation.

Data taking on June 6th, 2014 immediately shows trapped electrons.

Image Reconstruction & Energy Resolution



FWHM \sim 140 eV



Already improving...
(FWHM \sim 15 eV)

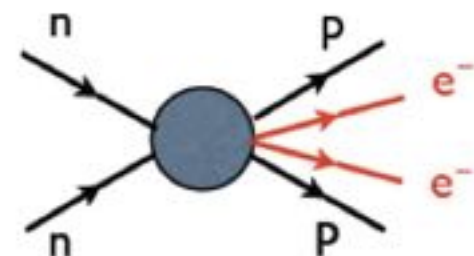
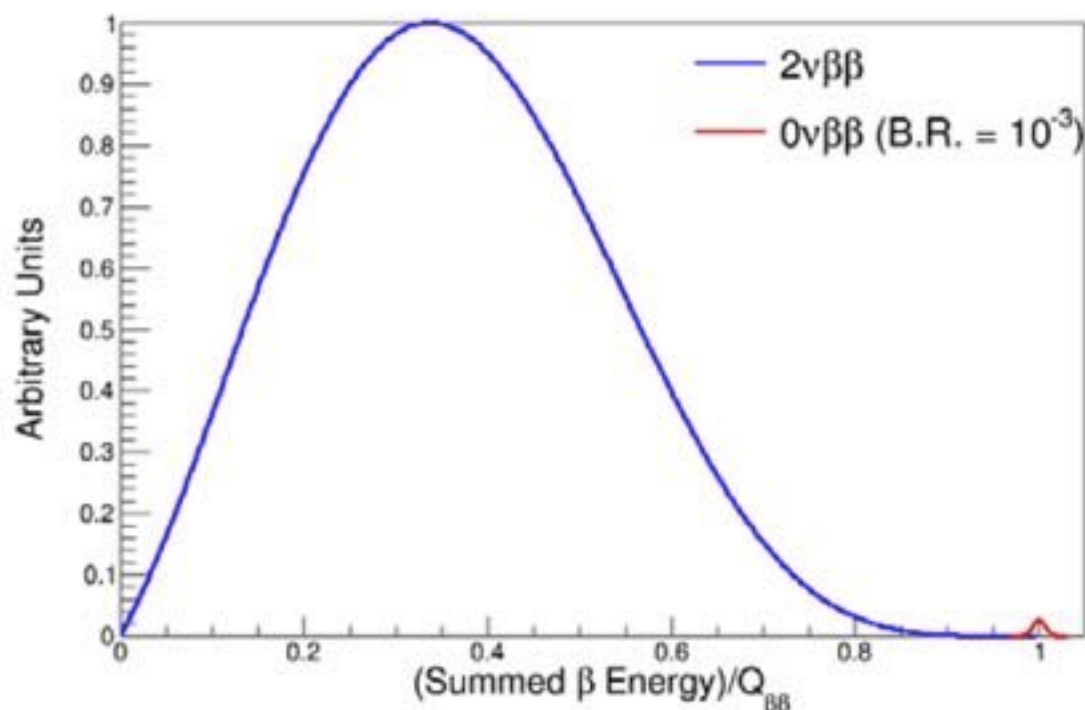
Event reconstruction from image reconstruction allows detailed analysis

(energy & scattering all extractable)

$0\nu\beta\beta$ Experimental challenge



- Looking for full energy peak of electrons at the tail of the (expected and irremovable) two-neutrino beta decay
 - $0\nu\beta\beta$ $T_{1/2} \sim 10^{27} - 10^{28}$ years
 - $2\nu\beta\beta$ $T_{1/2} \sim 10^{19} - 10^{21}$ years
- Tonne scale detectors required to reach higher half-life
- Need to remove/understand all backgrounds contributing to region of interest
 - including cosmogenic activation and c.r. by-products



$$\left| \sum_i m_i U_{ei}^2 \right| \equiv \langle m_{\beta\beta} \rangle$$

$$1 / T_{1/2} = PS * NME^2 * (\langle m_{\nu} \rangle / m_e)^2$$

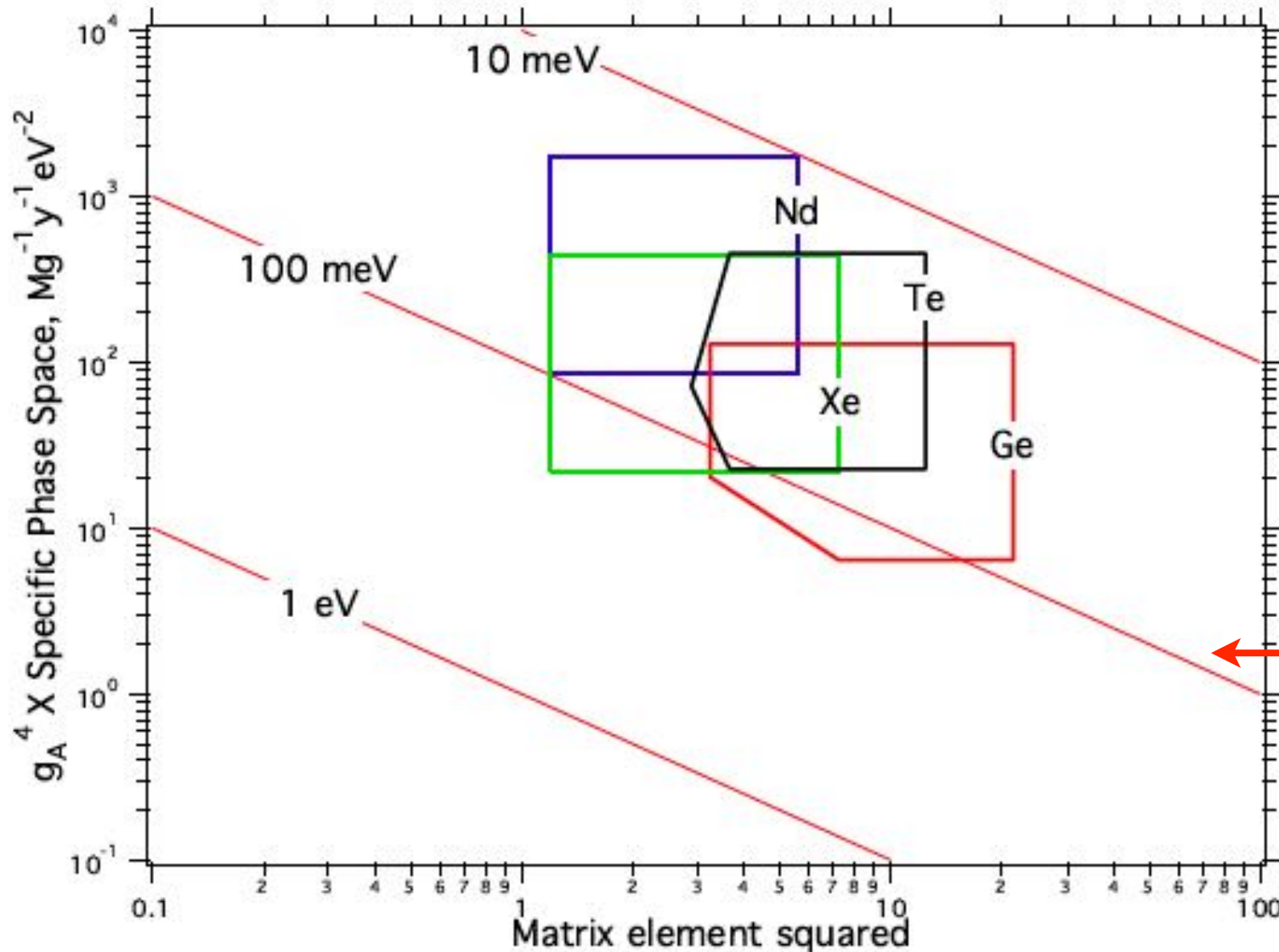
- Substantial progress over the last few years:
 - Multiple experiments have attained sensitivities of $T_{1/2} > 10^{25}$ years.
 - In the next few years expect to sensitivity exceeding $T_{1/2} > 10^{26}$ years.
 - Major advances in development of ultra-clean low activity materials and assay capabilities.
- Next generation detectors (tonne scale) are currently being developed by large international collaborations
 - Based on experience gained during the operation of current generation detectors
 - All aim for sensitivity and discovery levels at $T_{1/2} > 10^{27}$ years
 - An improvement of $\times 100$ over current results.

Sensitivity to $\langle m_{\beta\beta} \rangle$

R.G.H. Robertson, MPL A 28
(2013) 1350021
(arXiv 1301.1323)

For Ge, Te, Xe, Nd

← uncertainty
on NME^2 →

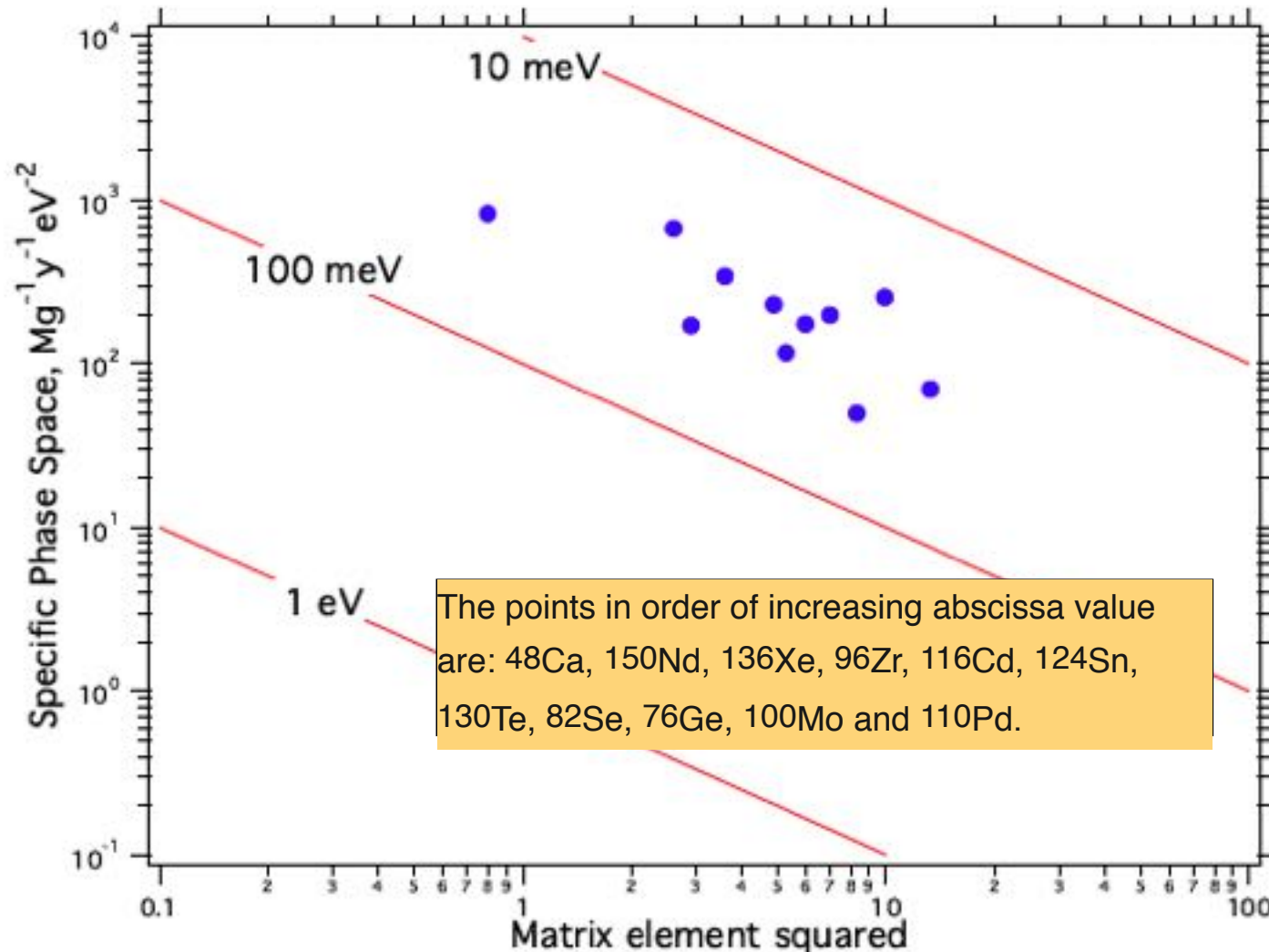


↑
uncertainty on
value of g_A^4
↓

Signal of
1 cnt/t-y for
corresponding
values of NME
and g_A

Sensitivity per unit mass of isotope

➡ Isotopes have comparable sensitivities in terms of rate per unit mass



R.G.H. Robertson, MPL
A **28** (2013) 1350021
(arXiv 1301.1323)

Inverse correlation
observed between phase
space and the square of the
nuclear matrix element .

geometric mean of the
squared matrix
element range limits & the
phase-space factor
evaluated at $g_A=1$

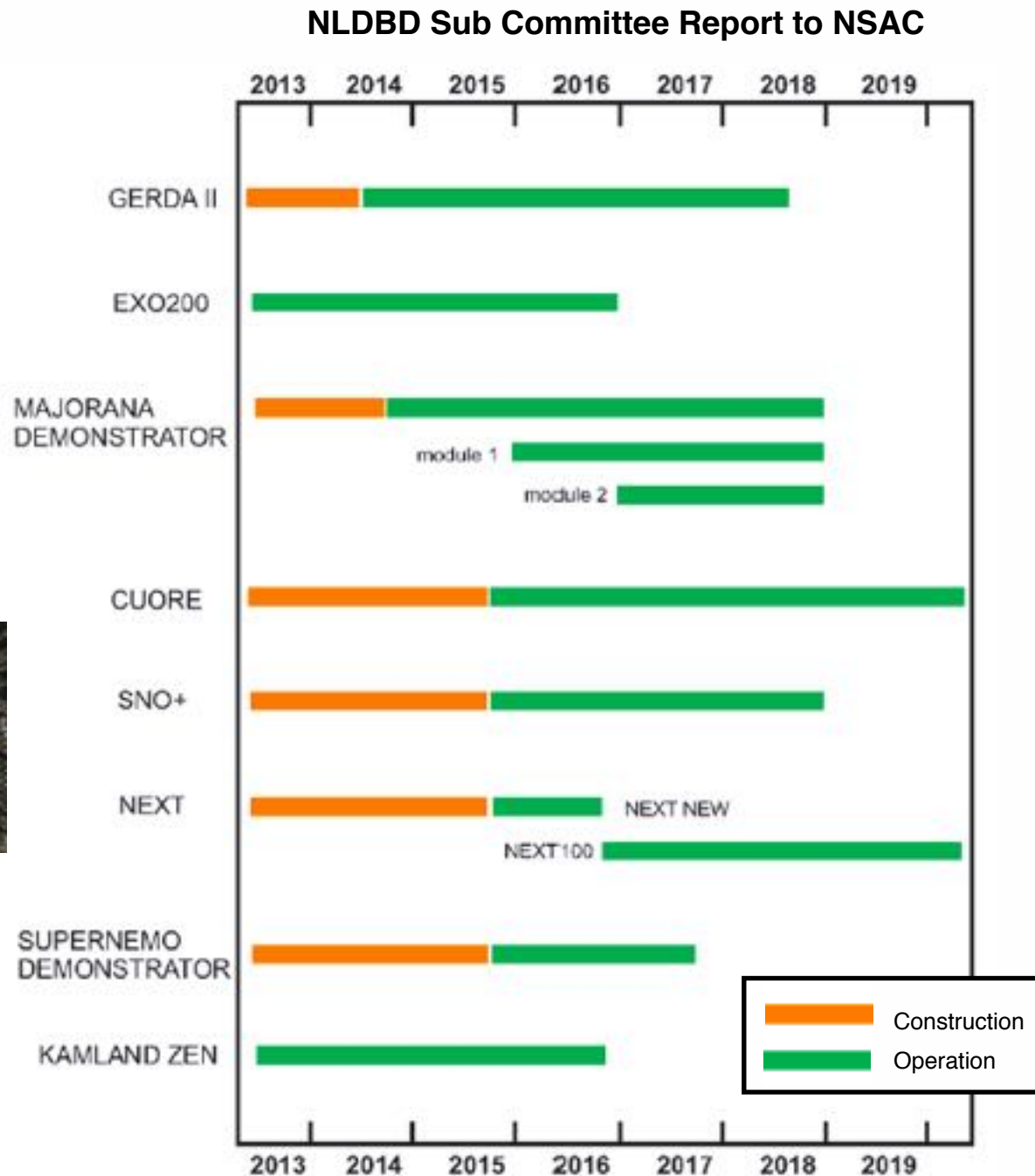
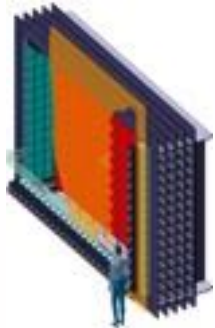
Reducing Backgrounds - Strategies

- Directly reduce intrinsic, extrinsic, & cosmogenic activities
 - Select and use ultra-pure materials
 - Minimize all non “source” materials
 - Clean (low-activity) shielding
 - Fabricate ultra-clean materials (underground fab in some cases)
 - Go deep — reduced μ 's & related induced activities
- Utilize background measurement & discrimination techniques

$0\nu\beta\beta$ is a localized phenomenon, many backgrounds have multiple site interactions or different energy loss interactions

- Energy resolution
- Active veto detector
- Tracking (topology)
- Particle ID, angular, spatial, & time correlations
- Fiducial Fits
- Granularity [multiple detectors]
- Pulse shape discrimination (PSD)
- Ion Identification

$0\nu\beta\beta$ decay Experiments - Efforts Underway



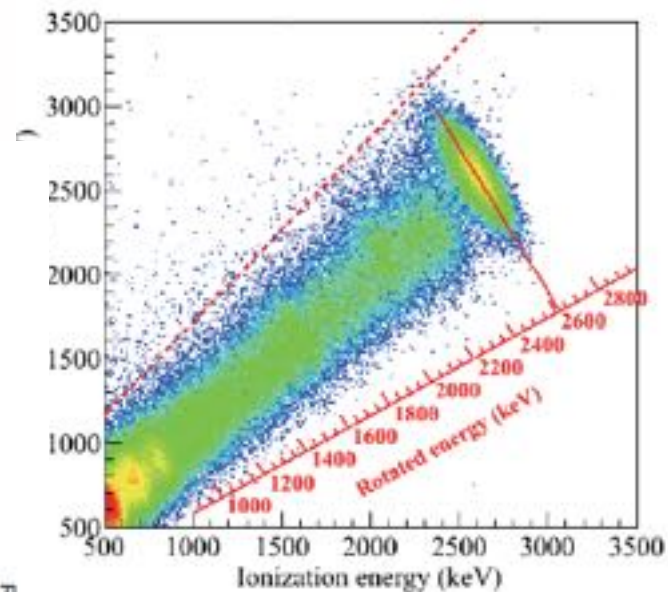
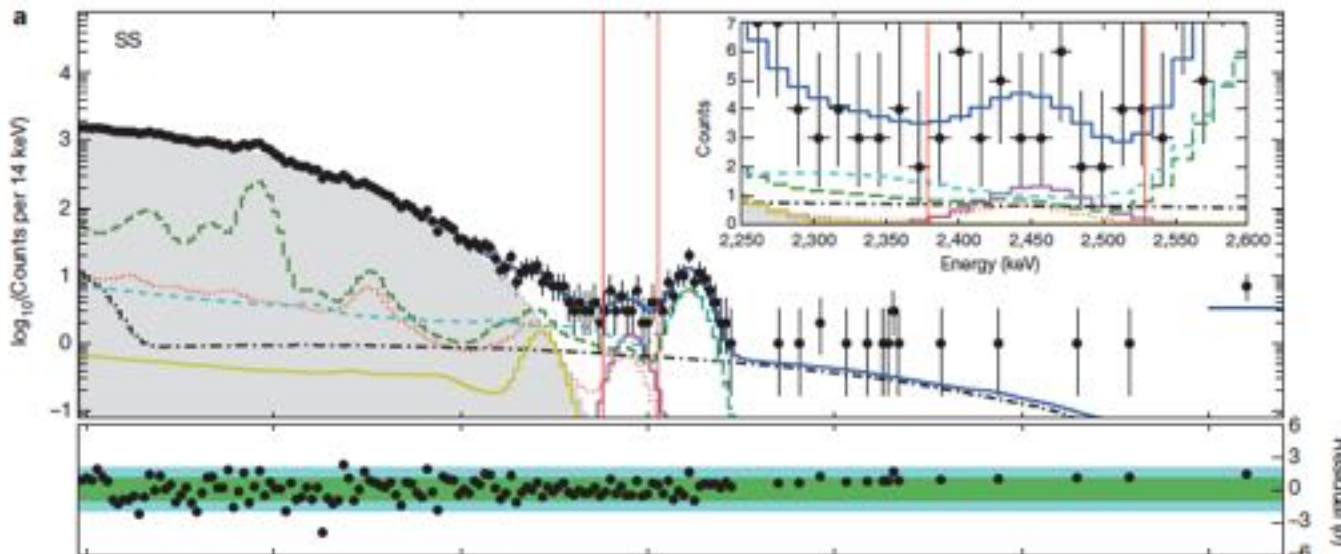
$0\nu\beta\beta$ Recent Highlights

From “*Fundamental symmetries, neutrinos, neutrons, and astrophysics: a White Paper on progress and prospects*”

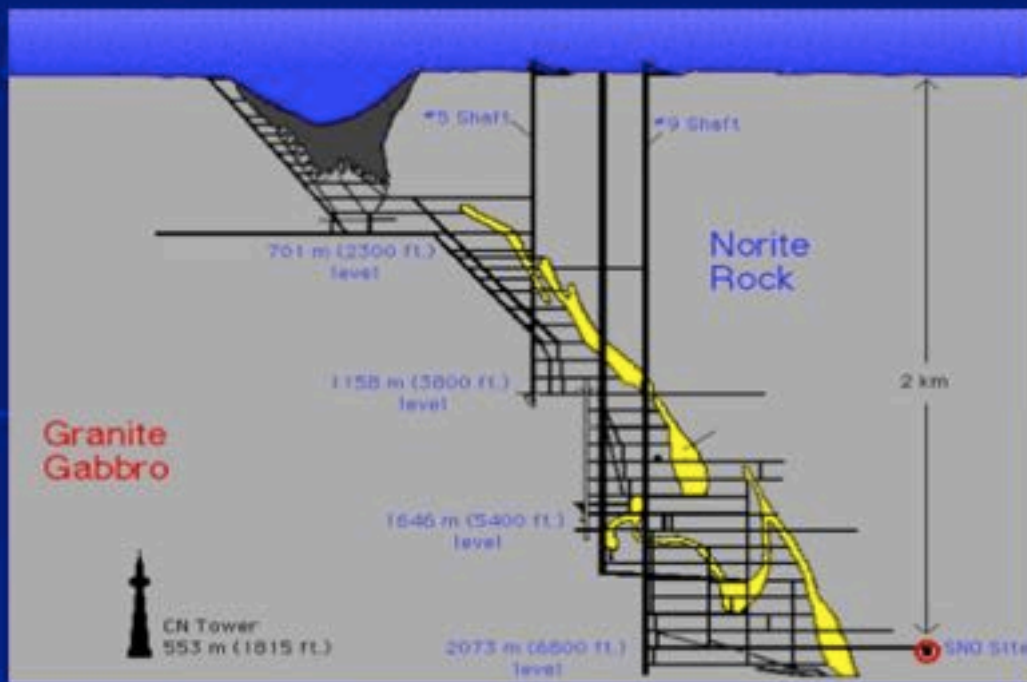
- The EXO, KamLAND-Zen, and GERDA double beta decay detectors have essentially ruled out a long-standing claim for observation of the neutrinoless decay mode in ^{76}Ge .
- The first measurement of the 2ν double beta decay of ^{136}Xe was made by the EXO Collaboration.
- The CUORE Collaboration has brought the world's largest-volume dilution refrigerator to base temperature, a major step towards a ton-scale bolometric experiment.
- The MAJORANA DEMONSTRATOR Collaboration has reported record Cu purity from its underground electroforming campaign, and expects to achieve the ultra-low backgrounds specified. Commissioning runs with more than 10 kg of highly enriched ^{76}Ge are beginning in the SURF laboratory.
- The SNO+ experiment has demonstrated the stable suspension of isotopes in the scintillator Linear Alkyl Benzene, another path toward a ton-scale experiment.

EXO-200 ^{136}Xe (2014)

- Enriched Liquid Xe in TPC
 - $Q_{\beta\beta}=2457.8$ keV
 - 200 kg of 80.6 % enriched ^{136}Xe
 - 75.6 kg fiducial mass,
 - 100 kg years exposure
 - Combine Scintillation-Ionization signal for improved resolution (88 keV FWHM @ $Q_{\beta\beta}$)
 - Single site - Multisite discrimination
- $T_{1/2} > 1.1 \times 10^{25}$ y (90% CL)**



EXO-200 Collaboration, Nature **510** 229 (2014)



~~1000 tonnes D_2O~~ → **780 tonnes liquid scintillator**

12 m diameter Acrylic Vessel

18 m diameter support structure; 9500 PMTs (~60% photocathode coverage)

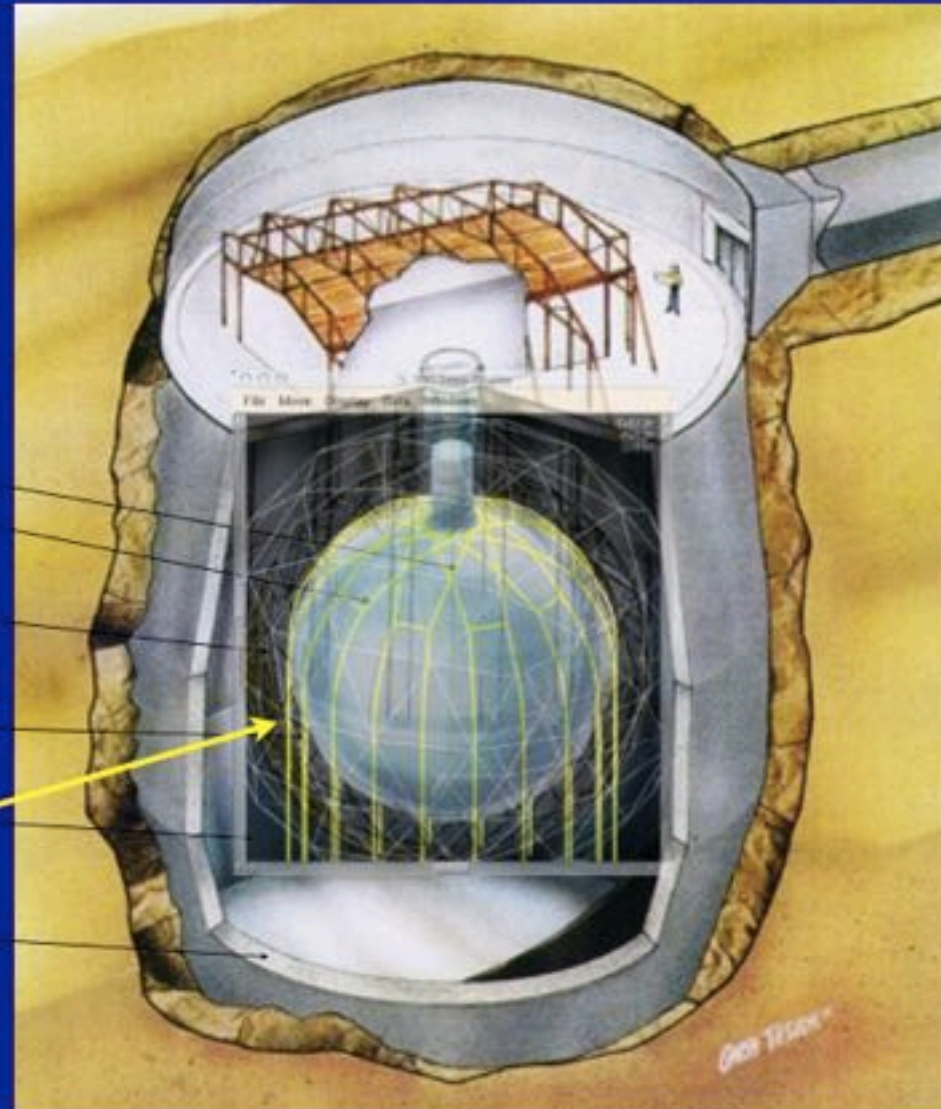
1700 tonnes inner shielding H_2O

5300 tonnes outer shielding H_2O

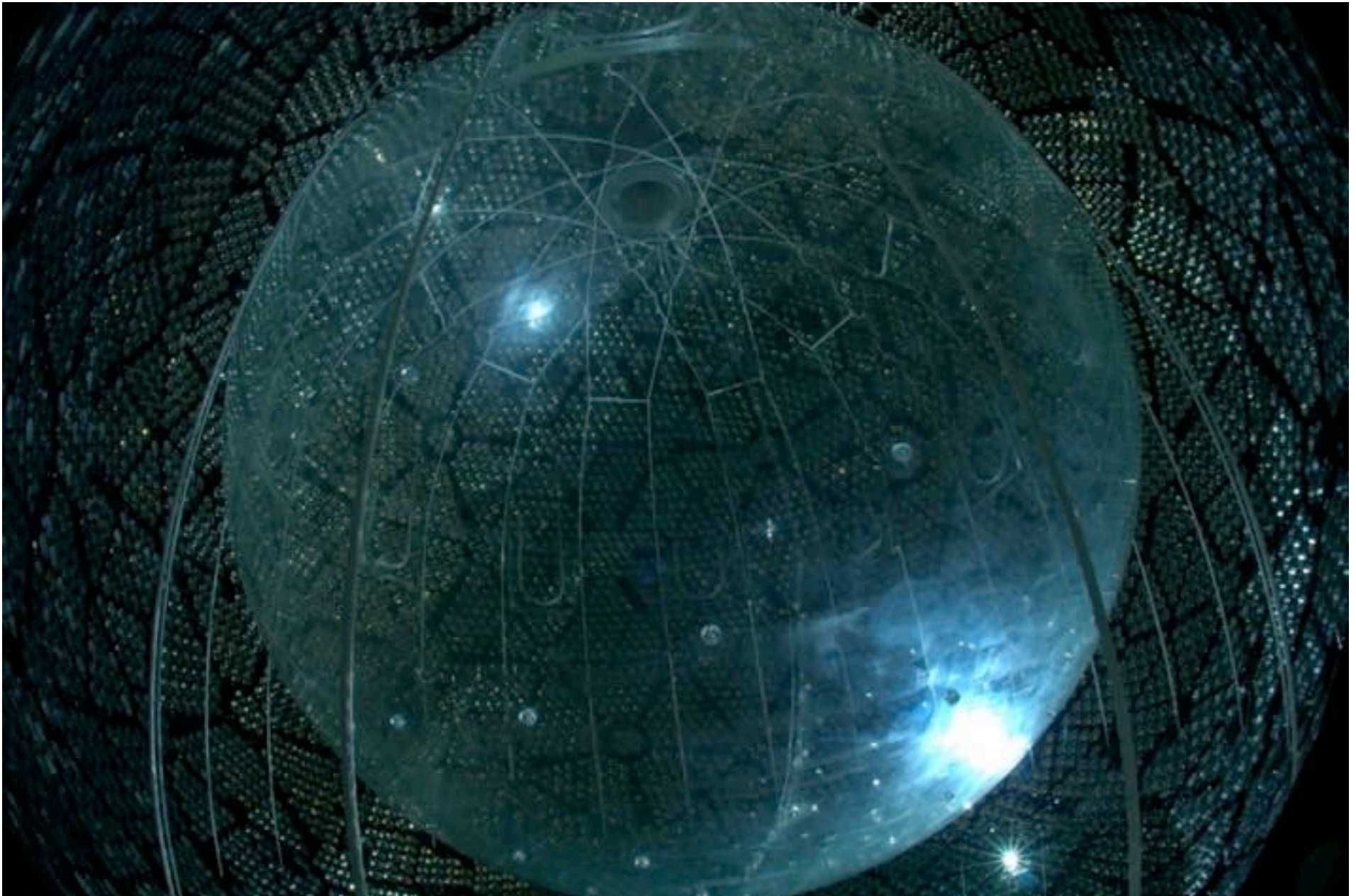
Urylon liner radon seal

hold-down rope net

depth: 2092 m (~6010 m.w.e.) ~70 muons/day

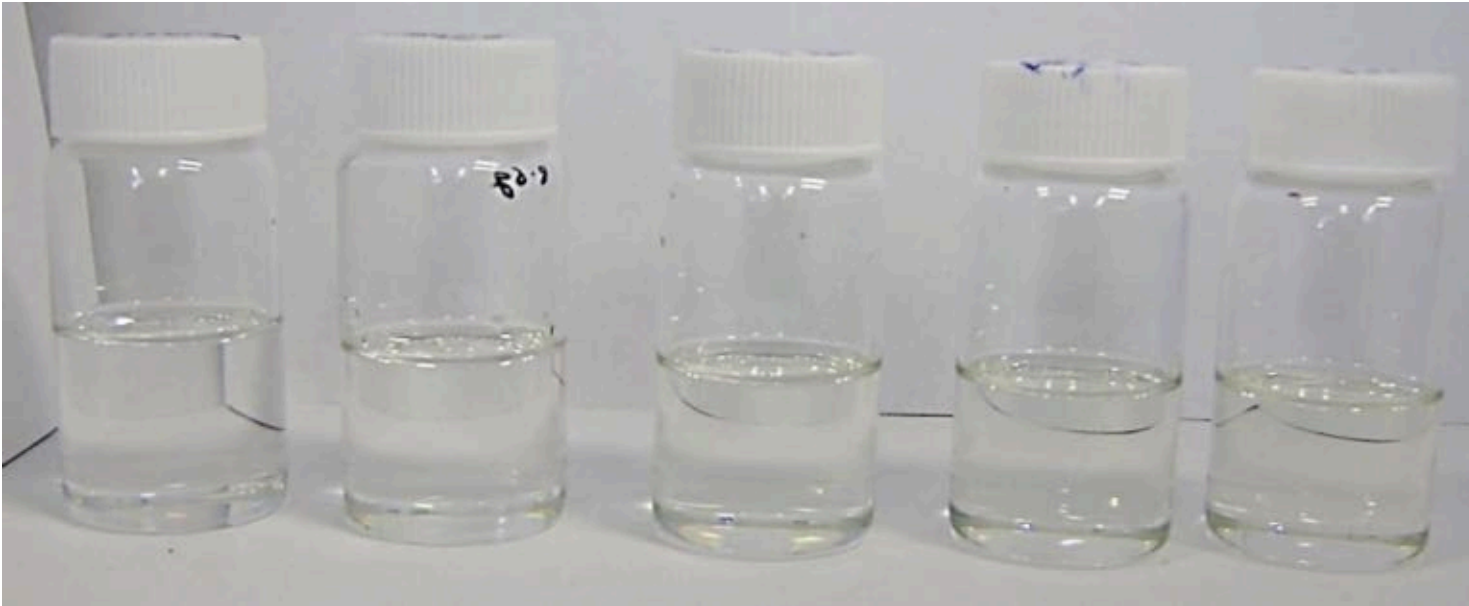


SNO+ Rope Net in place



Percent Loading of Tellurium is Feasible

- 0.3%, 0.5%, 1%, 3%, 5% (from left to right)



- 3% Te in SNO+ Phase II DBD corresponds to 8 tonnes of ^{130}Te *isotope* (cost for this much tellurium is only ~\$15M)

Ultraclean materials and Assay

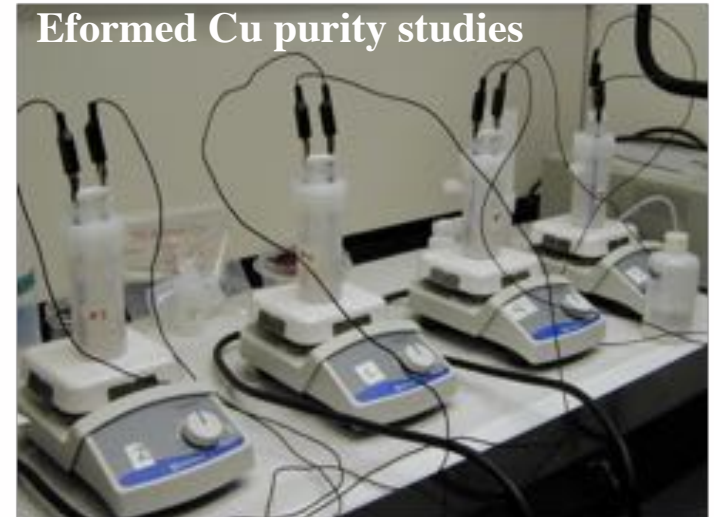


- Underground electroformed copper.
 - Th decay chain $0.06 \pm 0.02 \mu\text{Bq/kg}$ (0.15 counts in ROI)
 - U decay chain $0.17 \pm 0.03 \mu\text{Bq/kg}$ (0.08 counts in ROI)
- World's most sensitive ICP-MS based assay techniques for U and Th in Cu
 - U decay chain $<0.10 \mu\text{Bq } ^{238}\text{U/kg}$
 - Th decay chain $<0.06 \mu\text{Bq } ^{232}\text{Th/kg}$

Inspection of EF copper on mandrels



Eformed Cu purity studies



Backgrounds in experiments

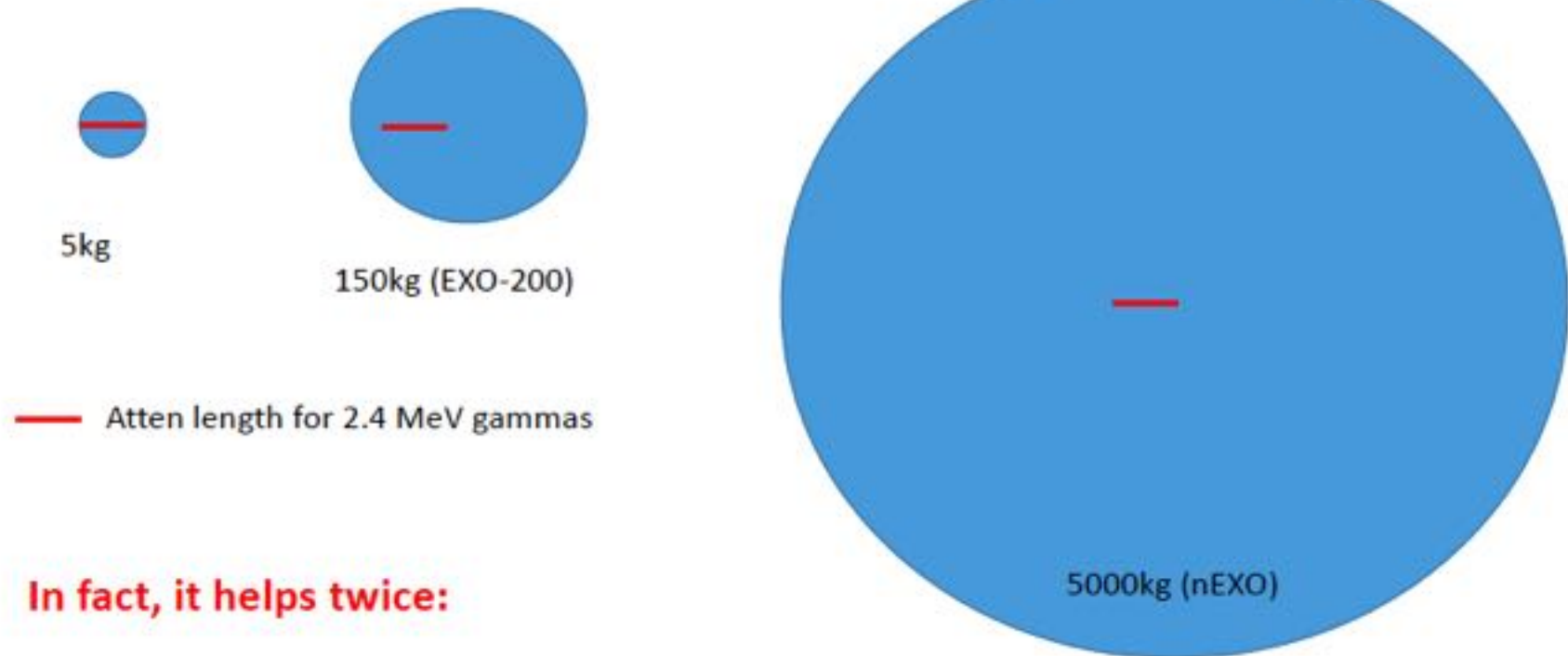
Experiment		Mass [kg] (total/FV*)	Bkg (cnts/ROI -t-y) [†]	Width (FWHM)	
CUORE0	^{130}Te	32/11	300	5.1 keV ROI	Measured
EXO-200	^{136}Xe	170/76	130	88 keV ROI	
GERDA I	^{76}Ge	16/13	40	4 keV ROI	
KamLAND-Zen (Phase 2)	^{136}Xe	383/88	210 per t(Xe)	400 keV ROI	
CUORE	^{130}Te	600/206	50	5 keV ROI	Projected
GERDA II	^{76}Ge	35/27	4	4 keV ROI	
MAJORANA DEMONSTRATOR	^{76}Ge	30/24	4	4 keV ROI	
NEXT 100	^{136}Xe	100/80	9	17 keV ROI	
SNO+	^{130}Te	2340/160	45 per t(Te)	240 keV ROI	

* FV = $0\nu\beta\beta$ isotope mass in fiducial volume (includes enrichment factor)

† Region of Interest (ROI) can be single or multidimensional (E, spatial, ...)

Scaling Example (nEXO)

Large scale helps



In fact, it helps twice:

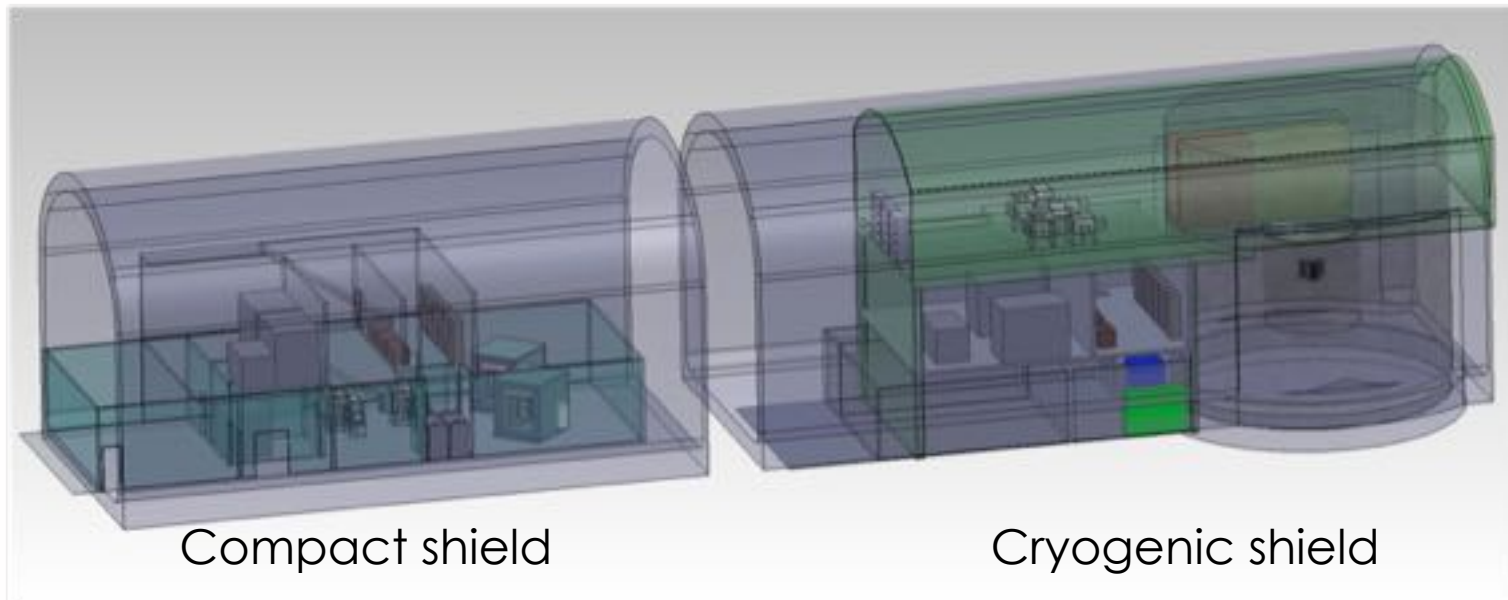
- 1) Self shielding becomes effective**
- 2) Compton tag efficiency greatly improves**

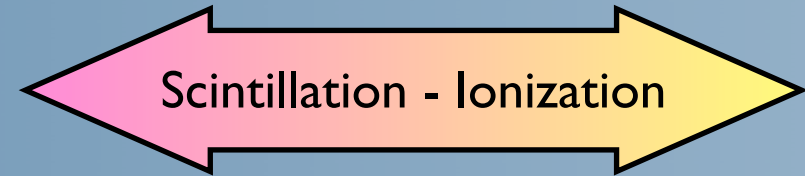
Next generation tonne scale experiments



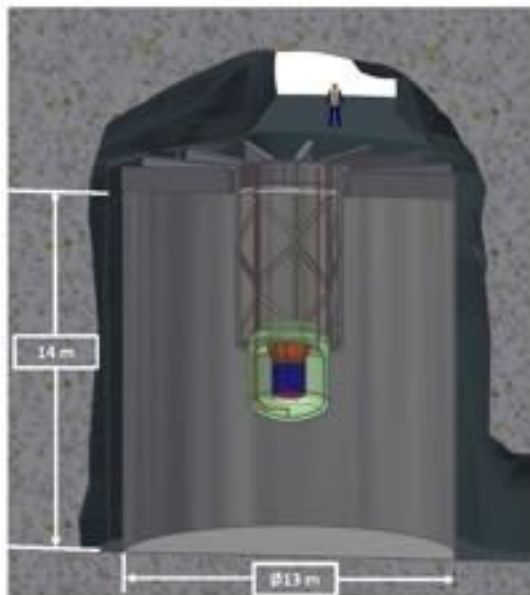
- For half-lives of 10^{27} years expect signals of ~ 1 count / tonne - year
- Aim for S:B of better than 1:1 in region of interest.
- Advances in development of ultra-clean materials and assay capabilities indicate one can achieve required backgrounds in next generation experiments.
 - Isotope enrichment requires time and \$s.
 - The field is rapidly approaching readiness to proceed with the construction of tonne scale experiments.
- Active international collaborations building on current efforts.
 - ^{76}Ge : Large Scale Ge, O(tonne) HPGE crystals (GERDA & Majorana)
 - ^{136}Xe : nEXO — Liquid TPC, 5 tonnes
 - ^{130}Te : SNO+ Phase II — ^{130}Te in scintillator
- Experiments can be done in a staged (phased) approach. Many are considering stepwise increments.
- Several potential underground lab sites
 - SNOLAB, JingPing, Gran Sasso, SURF, CanFranc, Frejus, Kamioka, ANDES, Y2L

- MAJORANA and GERDA are working towards the establishment of a single international ^{76}Ge $0\nu\beta\beta$ collaboration. (Name not set: GeIT, LSGe, ...)
- Envision a phased, stepwise implementation;
e.g. 250 \rightarrow 500 \rightarrow 1000 kg
5 yr 90% CL sensitivity: $T_{1/2} > 3.2 \cdot 10^{27}$ yr
10 yr 3σ discovery: $T_{1/2} \sim 3 \cdot 10^{27}$ yr
- Moving forward predicated on *demonstration* of projected backgrounds by MJD and/or GERDA
- Anticipate down-select of best technologies, based on results of the two experiments

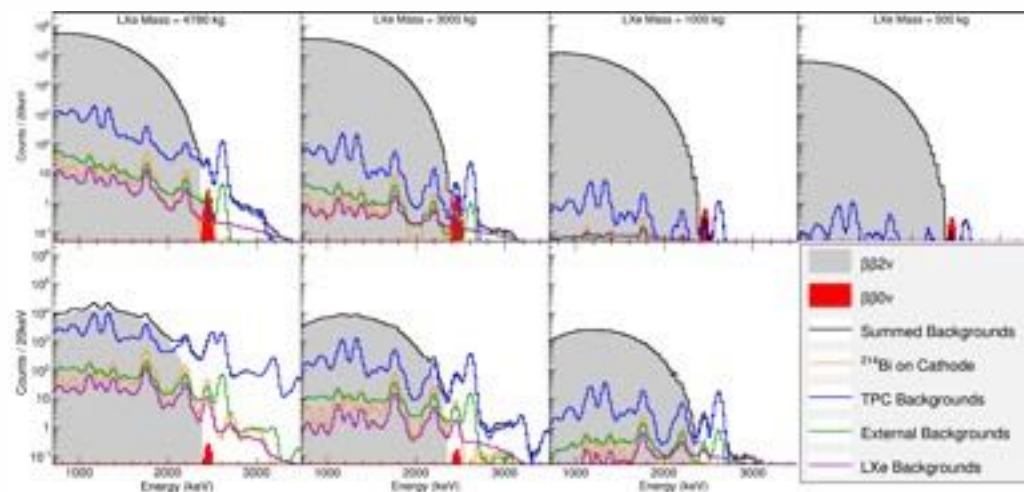




- 5 tonnes of $^{\text{enr}}\text{Xe}$
- nEXO 5 yr 90% CL sensitivity: $T_{1/2} > 6.6 \cdot 10^{27}$ yr
- LXe homogeneous imaging TPC similar to EXO-200:
 - baseline: install at SNOLAB (cosmogenic background reduced wrt EXO-200)
 - simultaneous measurement: energy, spatial extent, location, particle ID
 - Multi-parameter approach improves sensitivity: strengthens proof in case of discovery
 - inverted hierarchy covered with a well proven detector concept
 - possible later upgrade for Ba retrieval/tagging: start accessing normal hierarchy



Deeper into fiducial volume →



Single-site,
Mainly signal,
2v and 0v

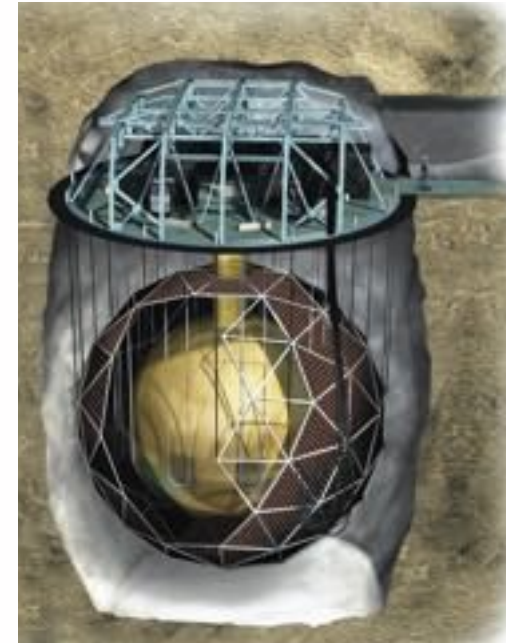
Multi-site,
Mainly
background

- 3% loading of Te already demonstrated
- Detector response model from Phase I predicts Phase II response

Plug-in replacement of SNO+ PMTs with R5912-HQEs
more than doubles light yield for Phase II

Additional wavelength-shifter R&D could further improve this

- Containment bag R&D necessary to achieve cleanliness
Can leverage KamLAND-Zen and BOREXINO knowledge

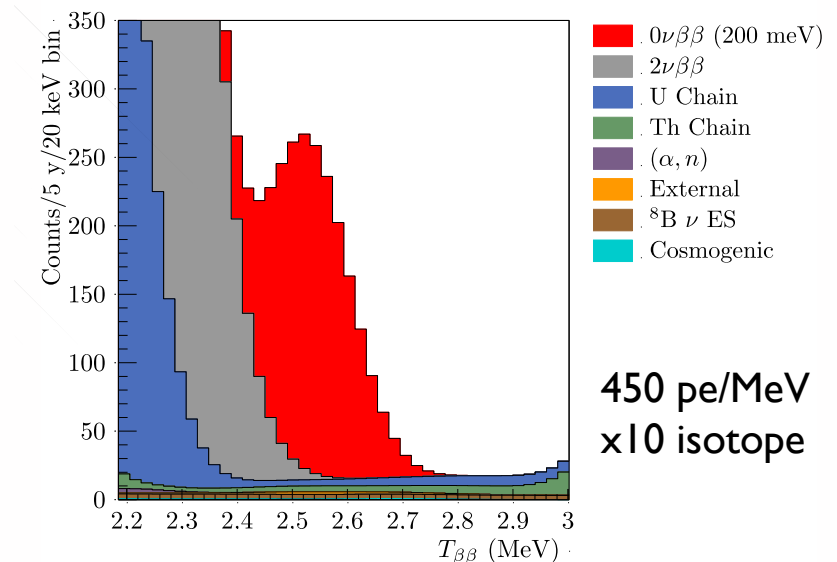


Phase II: $T_{1/2} > 7 \times 10^{26} \text{ y}$ (90% CL, natural)

$T_{1/2} > 10^{27} \text{ y}$ (90% CL, enriched)

$T_{1/2} > 4 \times 10^{26} \text{ y}$ (3σ , natural)

External γ and ^8B backgrounds are fixed
(but fewer in ROI because of increased light yield)



- New approaches to single beta decay measurements being developed
 - Aiming for direct measurements at sub-eV
- Substantial progress over the last few years:
 - Multiple experiments have attained sensitivities of $T_{1/2} > 10^{25}$ years.
 - In the next few years expect to sensitivity exceeding $T_{1/2} > 10^{26}$ years.
 - Major advances in development of ultra-clean low activity materials and assay capabilities.
- Next generation detectors (tonne scale) are currently being developed by large international collaborations
 - Based on experience gained during the operation of current generation detectors
 - All aim for sensitivity and discovery levels at $T_{1/2} > 10^{27}$ years
- Internationalisation of double-beta field occurring, both in creation of large scale collaborations, but also inter-collaboration connections forming