Neutrinoless Double Beta Decay Summary

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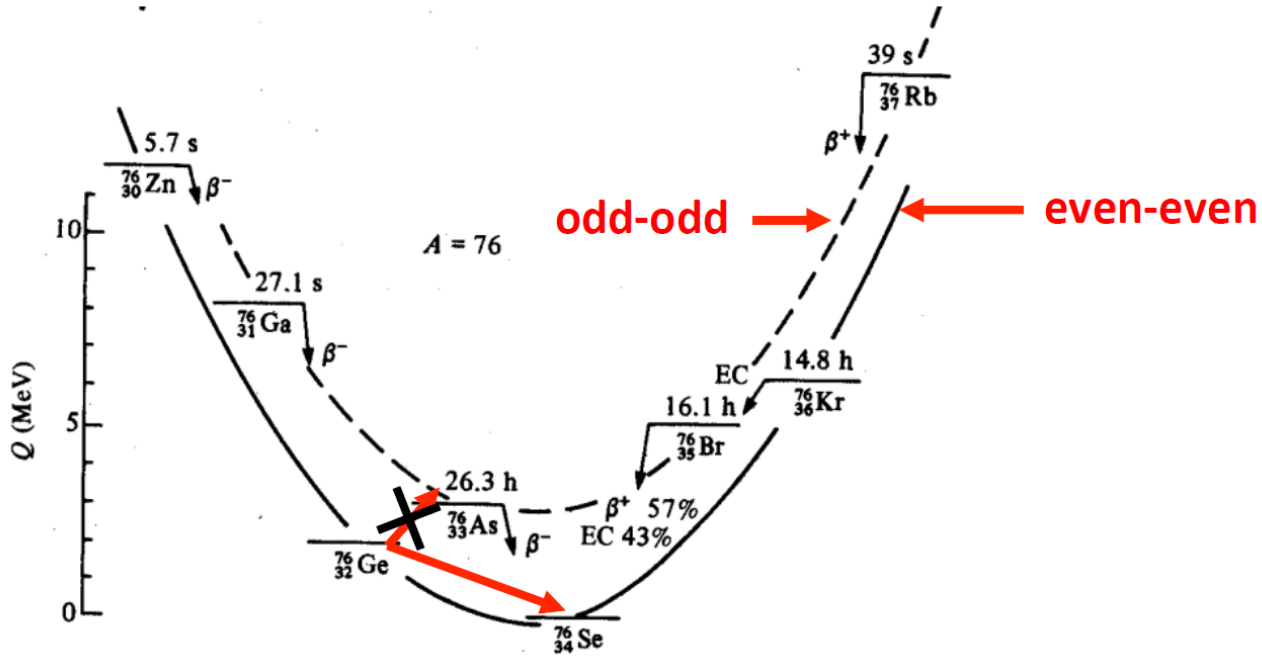
Queen's University, Kingston, Canada

Recent Developments in Neutrino Physics and Astrophysics;
BOREXINO 10th Anniversary, Gran Sasso, 2017



Double Beta Candidates

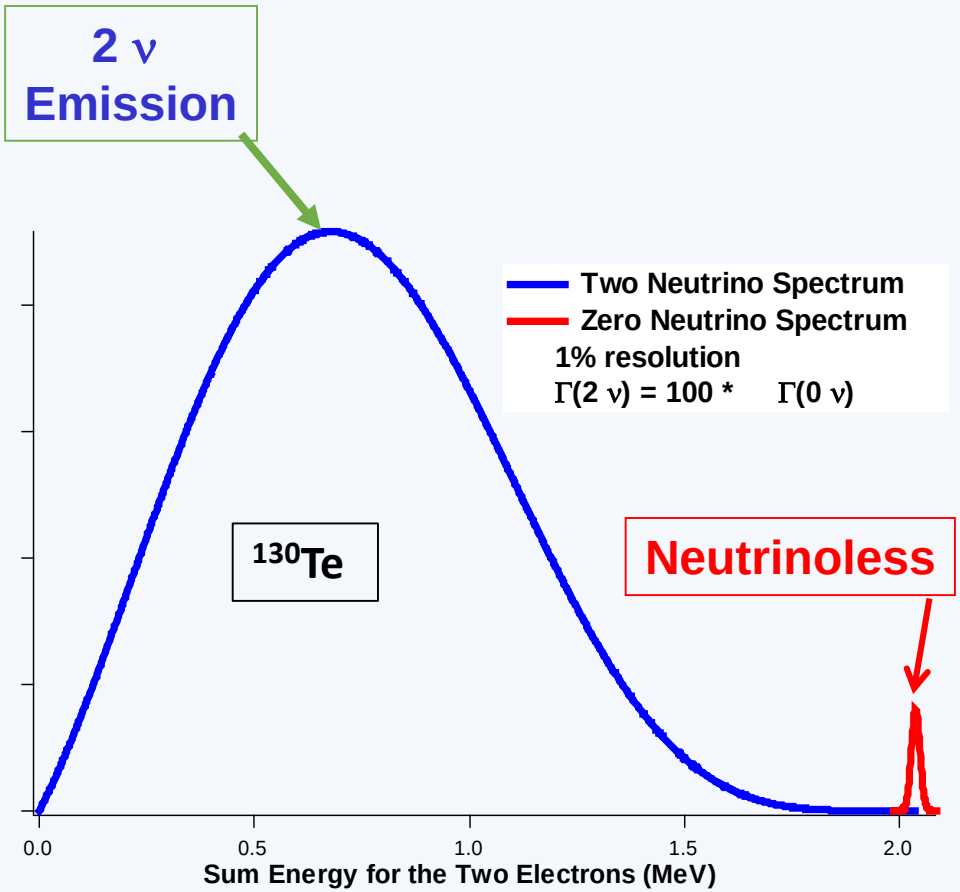
Isotope	Endpoint	Abundance
^{48}Ca	4.271 MeV	0.187%
^{150}Nd	3.367 MeV	5.6%
^{96}Zr	3.350 MeV	2.8%
^{100}Mo	3.034 MeV	9.6%
^{82}Se	2.995 MeV	9.2%
^{116}Cd	2.802 MeV	7.5%
^{130}Te	2.533 MeV	34.5%
^{136}Xe	2.479 MeV	8.9%
^{76}Ge	2.039 MeV	7.8%
^{128}Te	0.868 MeV	31.7%

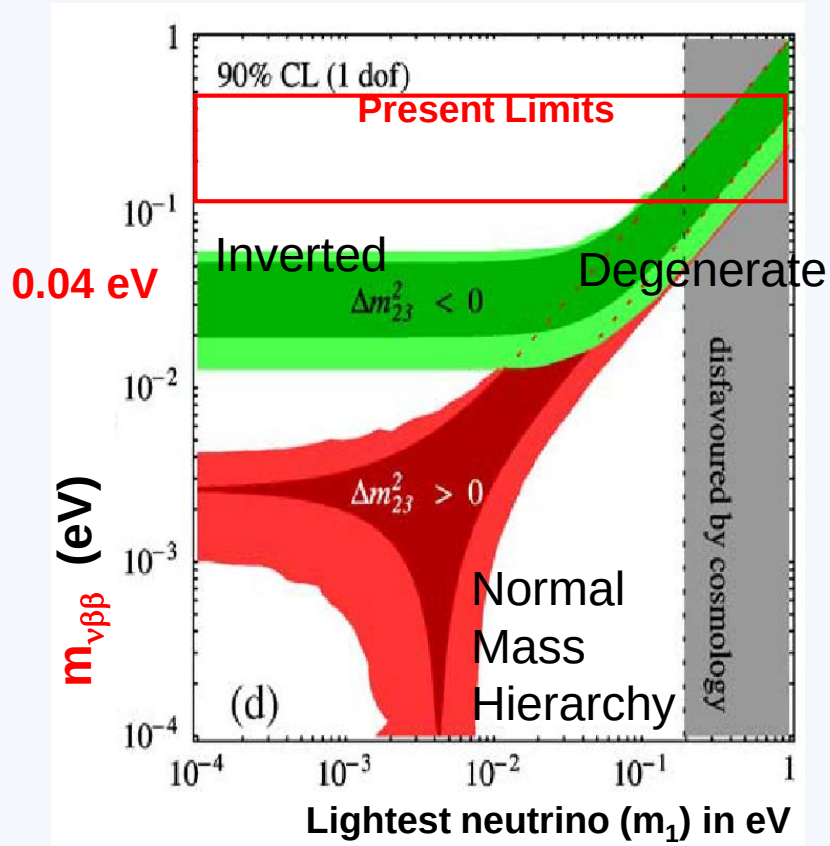
ν-less Double Beta Decay: Assuming a Light Majorana ν

$$(T_{1/2})^{-1} = G(Q_{\beta\beta},Z)\, g_A^4\, |M^{0\nu}|^2 \langle m_{\nu\beta\beta}\rangle^2$$

Additional phases

$$m_{\nu\beta\beta} = |m_1 \cos^2\theta_{13}\cos^2\theta_{12} + m_2\, e^{2i\alpha} \cos^2\theta_{13}\sin^2\theta_{12} + m_3\, e^{2i\beta} \sin^2\theta_{13}|$$





Requires: Neutrinos to be their own antiparticle (Majorana particles)

- **Finite ν mass: Lifetimes > ~10^{26} years imply ν mass < 0.1 eV**

As of today: Oscillation of 3 massive active neutrinos is clearly the dominant effect:

If neutrinos have mass: $$|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$$

For 3 Active neutrinos.

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata matrix

(Double β decay only)

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}$$

Atmospheric, Accel. | **CP Violating Phase** | **Reactor, Accel.** | **Solar,Reactor** | **Majorana CP Phases**

where $c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$

Range defined for Δm_{12}, Δm_{23}

For two neutrino oscillation in a vacuum: (a valid approximation in many cases)

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

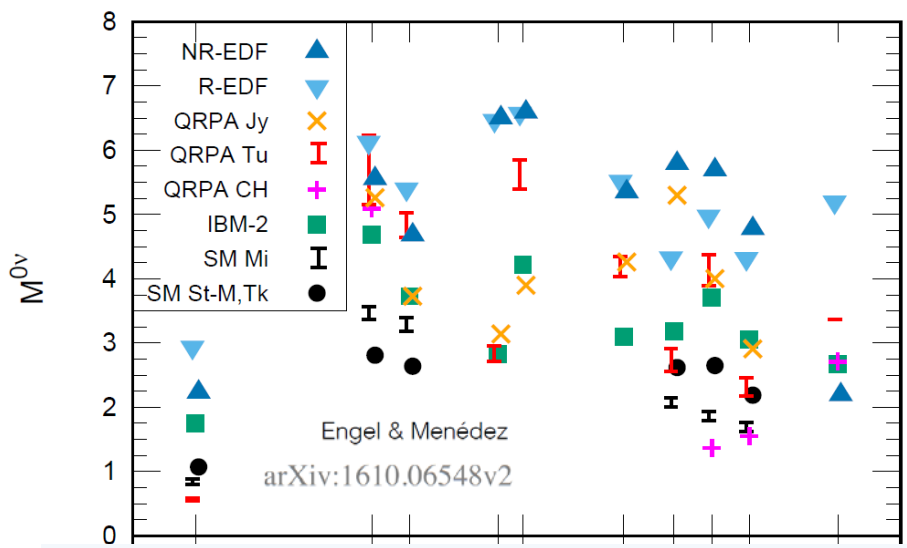
ν-less Double Beta Decay: Assuming a Light Majorana ν

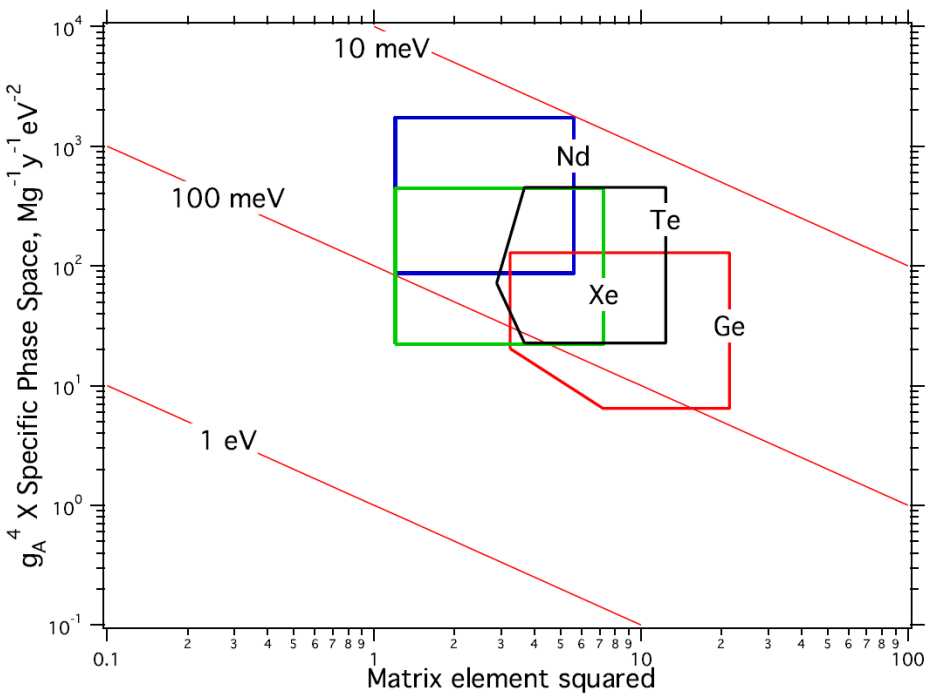
$$(T_{1/2})^{-1} = G(Q_{\beta\beta},Z)\, g_A^{\,4}\, |M^{0\nu}|^2 \langle m_{\nu\beta\beta}\rangle^2$$

Phase Space

Matrix Elements

R. G. H. Robertson, Mod. Phys. Lett. A 28, 1350021 (2013).





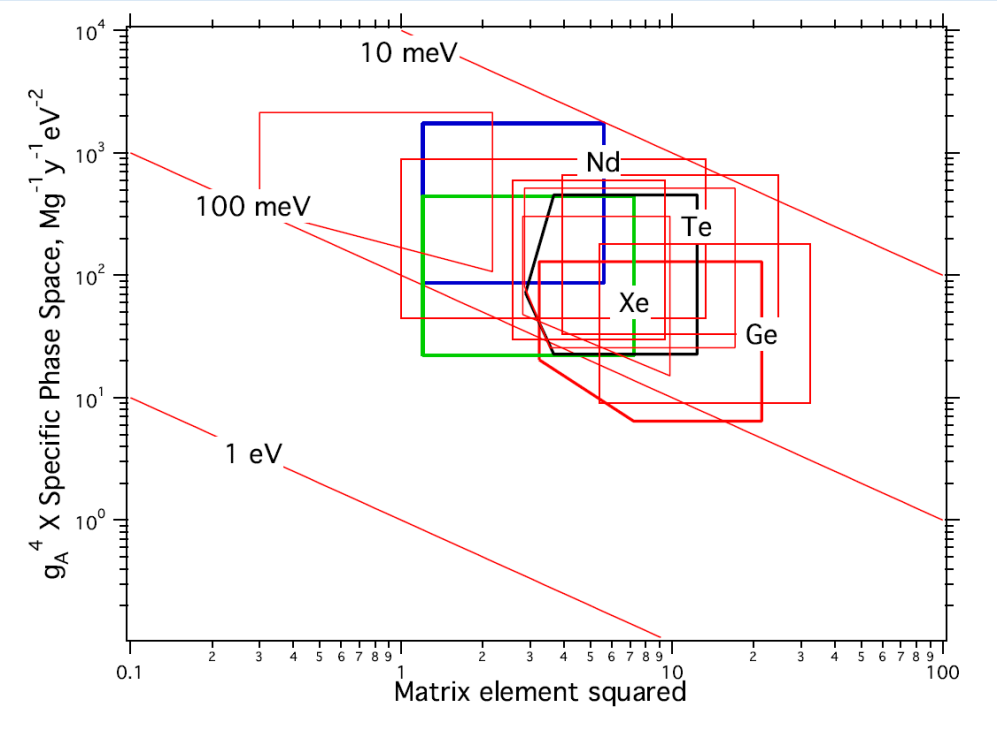
Combining this information on Phase Space and Matrix Elements, Robertson concludes that the sensitivity for observing an effective neutrino mass is quite similar for the various isotopes. The regions show the potential sensitivity for 1 event per tonne year. Note the uncertainty in g_A on the vertical axis from possible quenching.

$$(T_{1/2})^{-1} = G(Q_{\beta\beta},Z)\, g_A^4\, |M^{0\nu}|^2 \langle m_{\nu\beta\beta}\rangle^2$$

Theoretical Uncertainties

Same plot for all isotopes with Q greater than 2 MeV

R. G. H. Robertson, Mod. Phys. Lett. A 28, 1350021 (2013).



The plot illustrates the two major uncertainties in relating a measurement of half life to an effective neutrino mass.

- **The range of matrix element calculations squared is substantial**
- **The possibility of "quenching" of g_A is a topic of some controversy. It appears to occur for both single beta decay and for 2ν double beta decay. However, the components and phases are very different than for 0ν double beta decay.**

Fortunately, the nuclear physics theory community is taking on these questions as high priority and progress is being made on reducing the uncertainties.
See following talk by Javier Memendez

Limitations to Experimental Sensitivity

EXPERIMENTAL SENSITIVITY

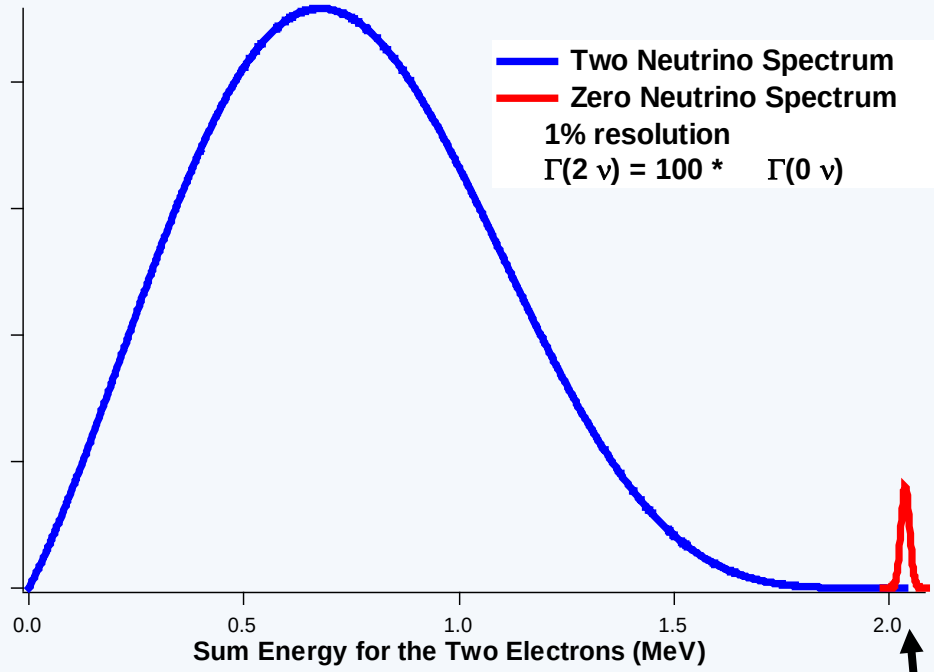
Lifetime corresponding to the minimum detectable number of events over background at a given C.L.:

$$S^{0\nu} \propto \epsilon\, i.a. \sqrt{\frac{MT}{b\Delta E}} \qquad b \neq 0$$

$$S^{0\nu} \propto \epsilon\, i.a.\, MT \qquad b = 0$$

- M: Total active mass in kg
- ϵ: Detector efficiency
- $i.a.$: Isotopic abundance
- b: Background in c/keV/kg/y
- ΔE: Detector resolution @ ROI in keV
- T: Exposure time in y

M. Martinez WIN 2017

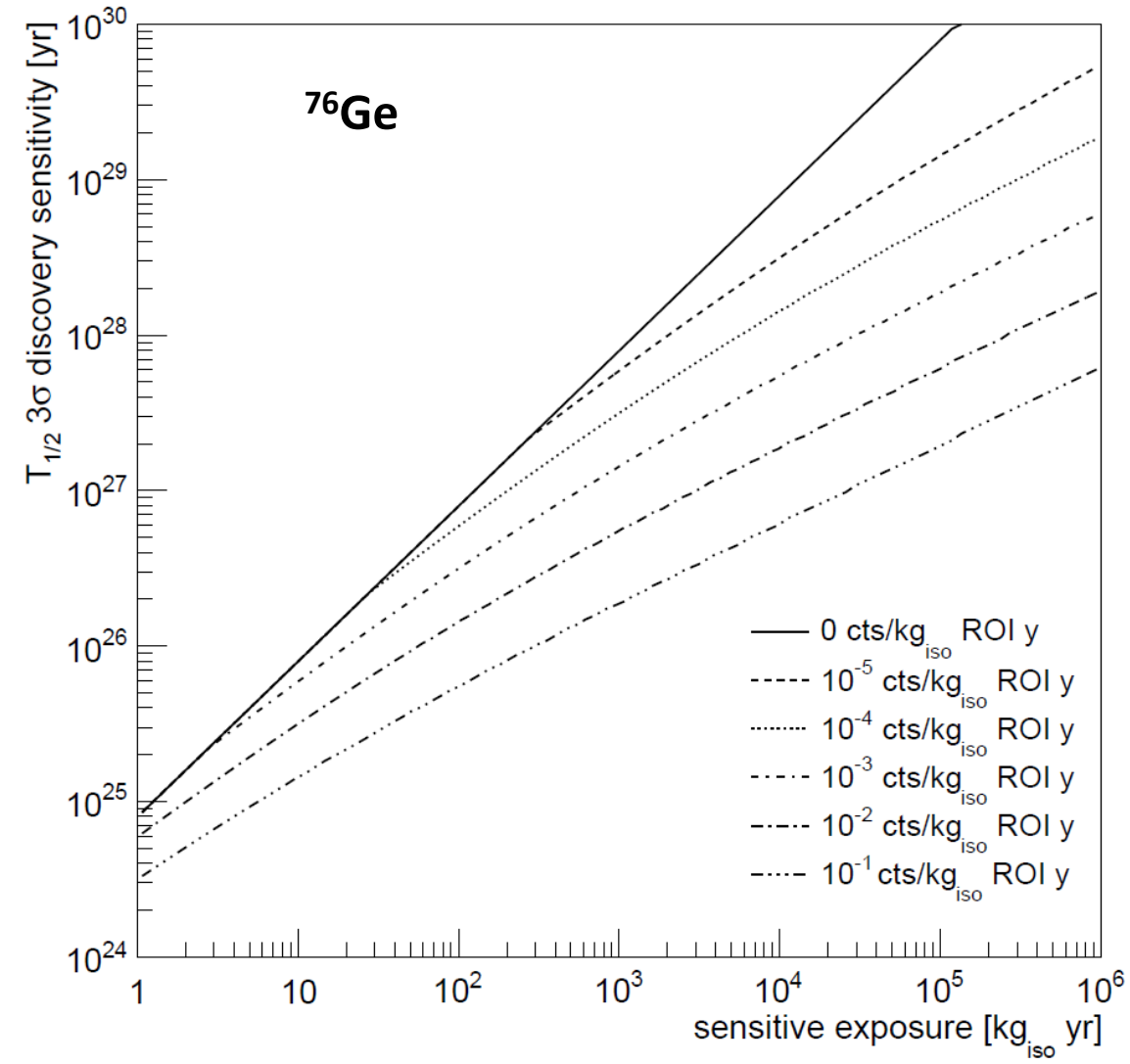


These Factors and Time are Universal

b ~ 2 ν Rate + Local background

Good resolution and Low background are the objectives to maximize sensitivity

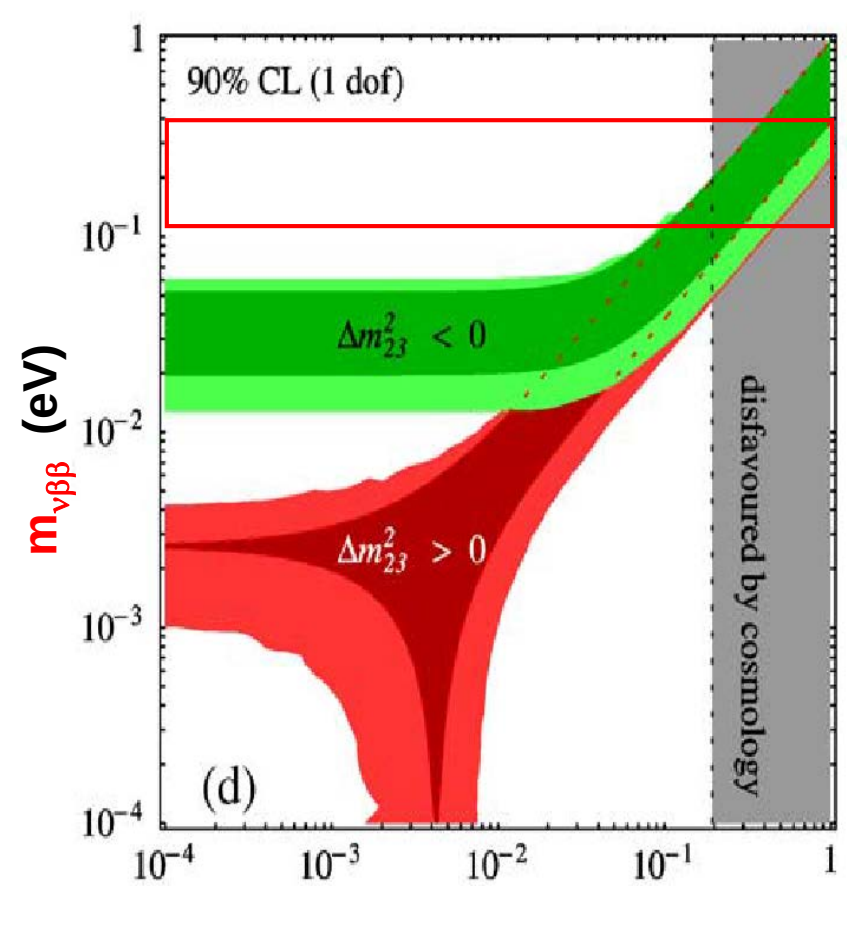
This translates into a sensitivity curve for a typical experiment where it is clear that background control and resolution are very important for discovery sensitivity.

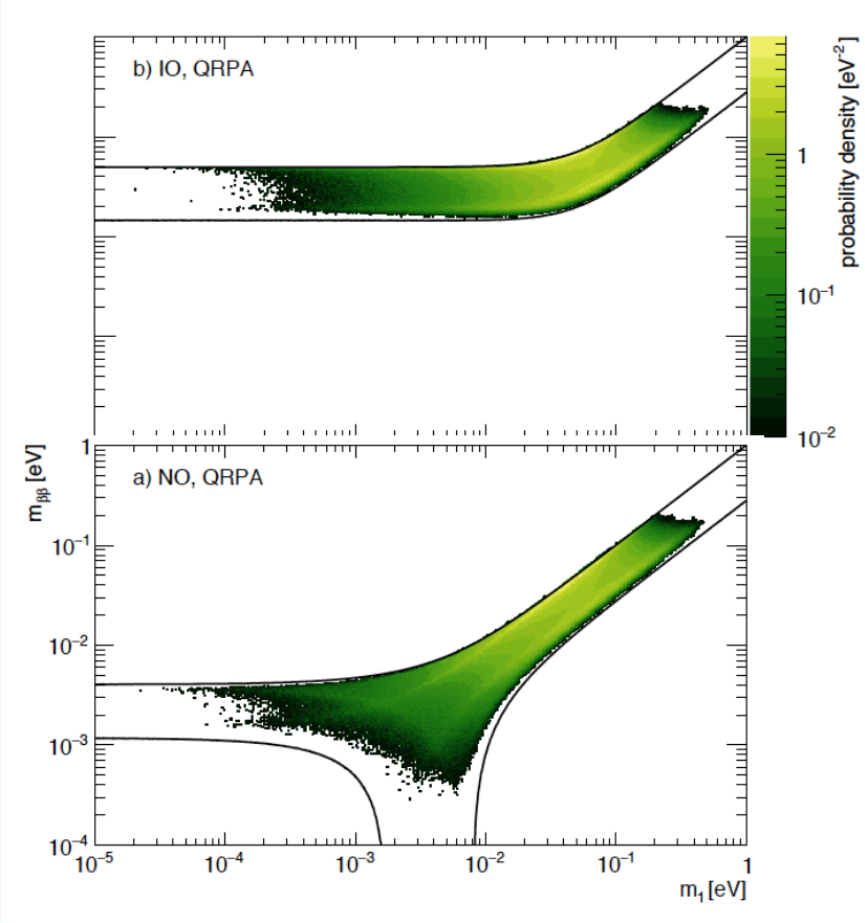


Agostini, Benato, Detwiler arXiv:1705.02996

Interesting Bayesian study of the probability of observation, assuming Majorana neutrinos and the known information about neutrino properties. Implies reasonable probabilities for regions accessible for next generation experiments. Note that this study and most experimental sensitivities do not include possible quenching effects on g_A in relating to the scale in eV.

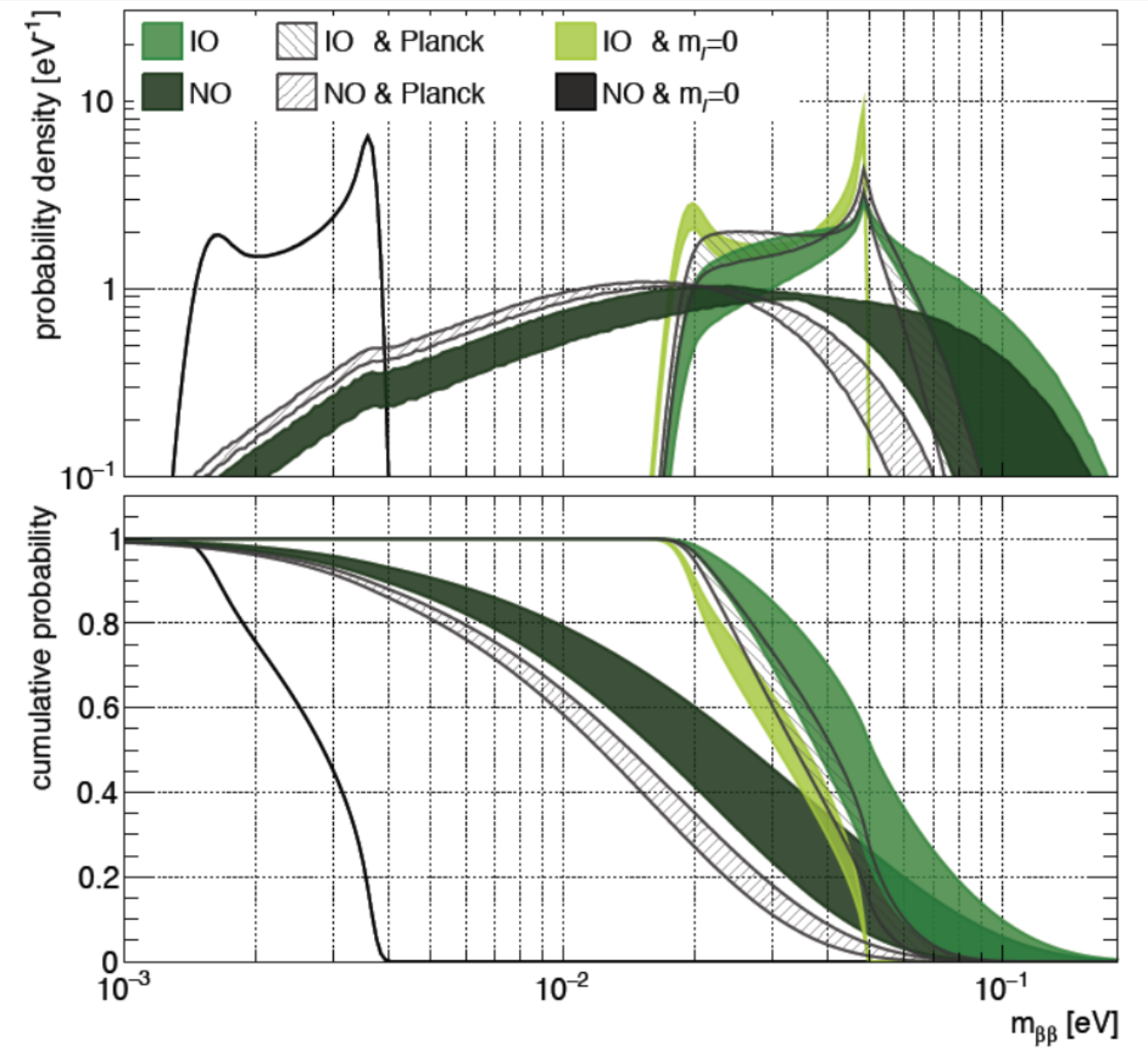
Agostini, Benato, Detwiler arXiv:1705.02996





Effects on Probabilities of including Cosmology or assuming m_l is zero

Agostini, Benato, Detwiler arXiv:1705.02996



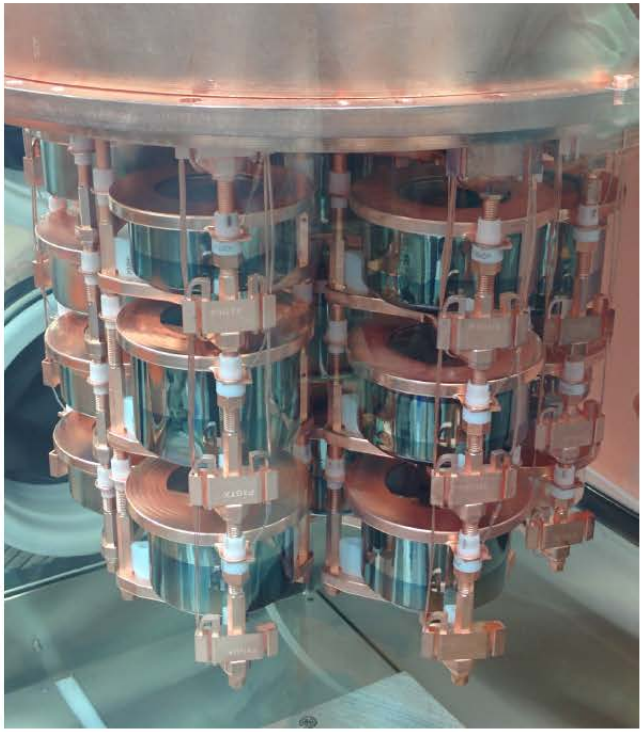
Status of Major International Experiments

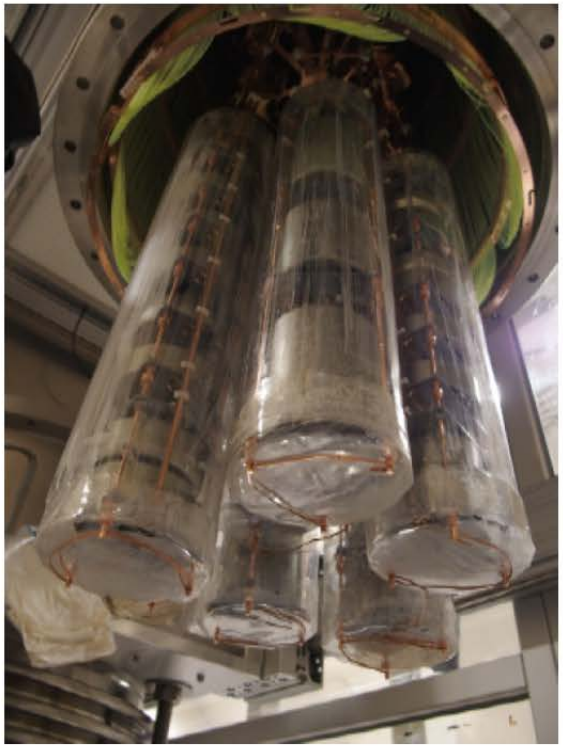
Isotope	Present with data	Future	Type
^{76}Ge	MAJORANA GERDA	 LEGEND	Semiconductor " "
^{82}Se	NEMO-3	SuperNEMO CUPID	Tracking Calorimeter Bolometer/Scintillator
^{100}Mo	AMoRE	 CUPID	Bolometer Bolometer/Scintillator
^{130}Te	CUORE	 SNO+	Bolometer Scintillator
^{136}Xe	EXO-200 KamLAND-Zen	 NEXO NEXT PANDA-X III	Liquid TPC Liquid TPC Scintillator Gas TPC Gas TPC

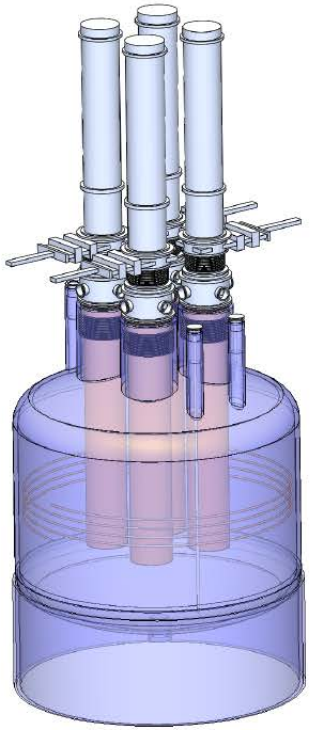
Plus other experiments in the R&D Phase: ^{48}Ca, ^{150}Nd…

^{76}Ge

MAJORANA AND GERDA → LEGEND







MAJORANA
Ultra Pure Copper cryostat

30 kg Enriched Ge

Background: 1.8 x 10^{-3} counts/(keV kg y)

GERDA
Ge crystals in liquid Ar

35 kg Enriched Ge

Background: 2.7 x 10^{-3} counts/(keV kg y)

LEGEND
Phase 1: Up to 200 kg Enr. Ge in GERDA cryostat

Phase 2: Up to 1000 kg Combined Technologies and Collaborations

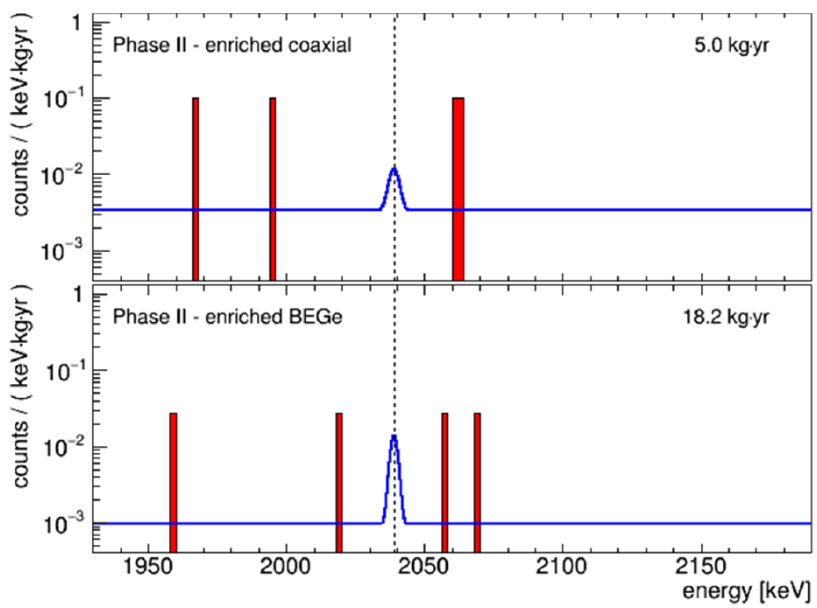
^{76}Ge

New GERDA Result: Caldwell, TAUP2017

Statistical analysis

	Exposure (kg·yr)	
Phase I (4 sets)	**23.5**	Same as Nature 544 (2017) 47
Phase II – coax	**5.0**	
Phase II – BeGe	**5.8+12.4 = 18.2**	

46.7 kg· yr



- Combined unbinned **maximum likelihood fit** of the six spectra
  - **Frequentist**: test statistics and method after Cowan et al., EPJC 71 (2011) 1554
  - **Bayesian**: flat prior on $1/T_{1/2}$ between 0 and 10^{-24} yr^{-1}
  - Systematic uncertainties folded as pull terms or by Monte Carlo

Preliminary

- Frequentist:

Best fit: $N^{0\nu} = 0$

$T_{1/2} > 8.0 \cdot 10^{25}$ yr @ 90% CL

It was $5.3 \cdot 10^{25}$ yr in Phasella

MC Median sensitivity (no signal):

$5.8 \cdot 10^{25}$ yr (for 90% C.L.)

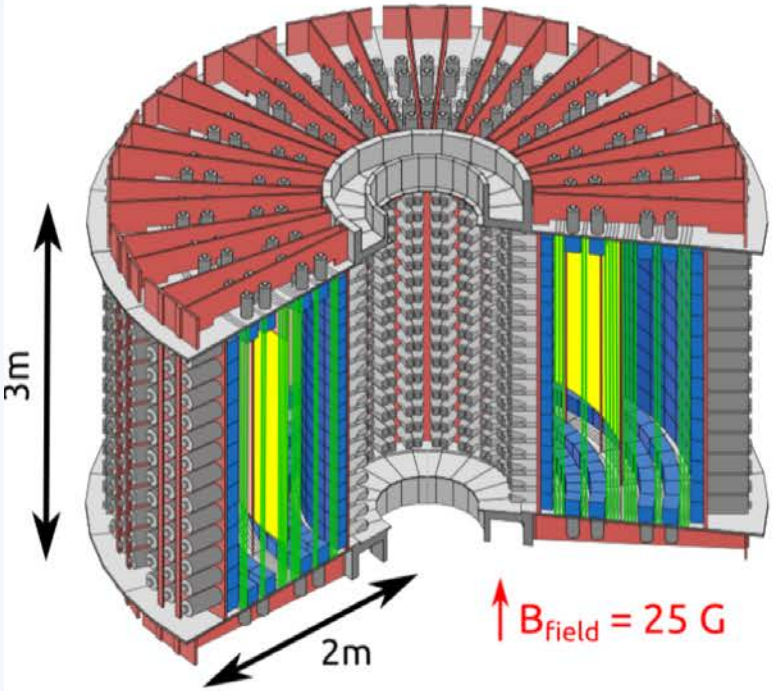
30% chance to have a better limit

- Bayesian:

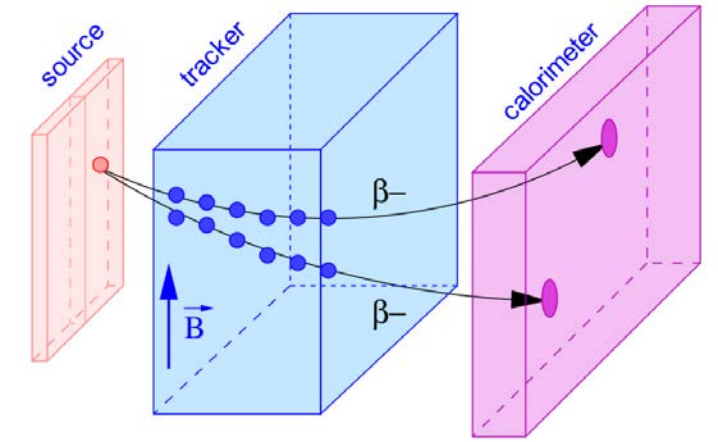
$T_{1/2} > 5.1 \cdot 10^{25}$ yr @ 90% CI

Median sensitivity $4.5 \cdot 10^{25}$ yr

NEMO-3



- ββ decay experiment which combines both tracker and calorimetric measurements
- Took data from February 2003 to January 2011
- Located in the Modane underground laboratory (LSM) at ~4800 m.w.e
- Investigated 7 different ββ isotopes
- Divided into 20 identical sectors



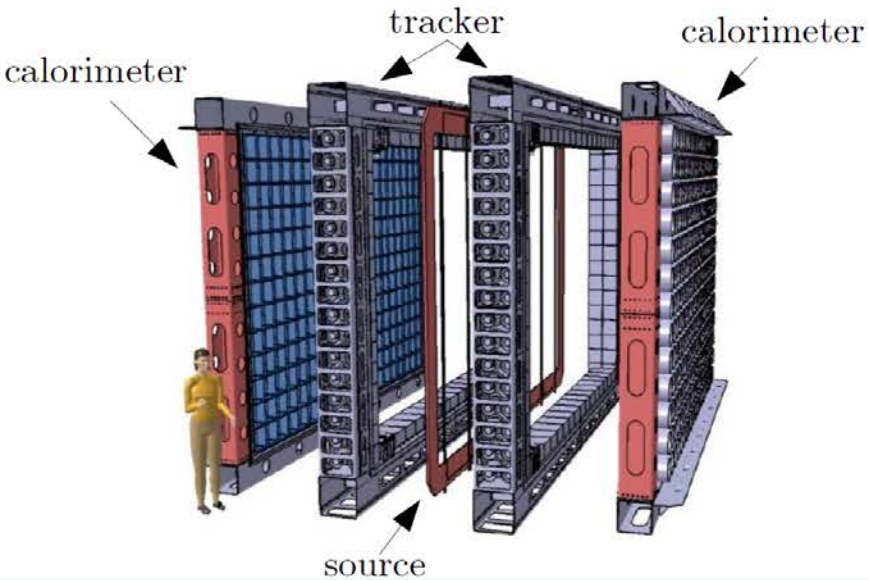
^{100}Mo (7 kg), ^{82}Se (1 kg), ^{130}Te, ^{116}Cd, ^{150}Nd, ^{96}Zr, ^{48}Ca

- **Provided the best value for the 2ν half life in these cases.**
- **Demonstrated the technology for the Super-NEMO detector**

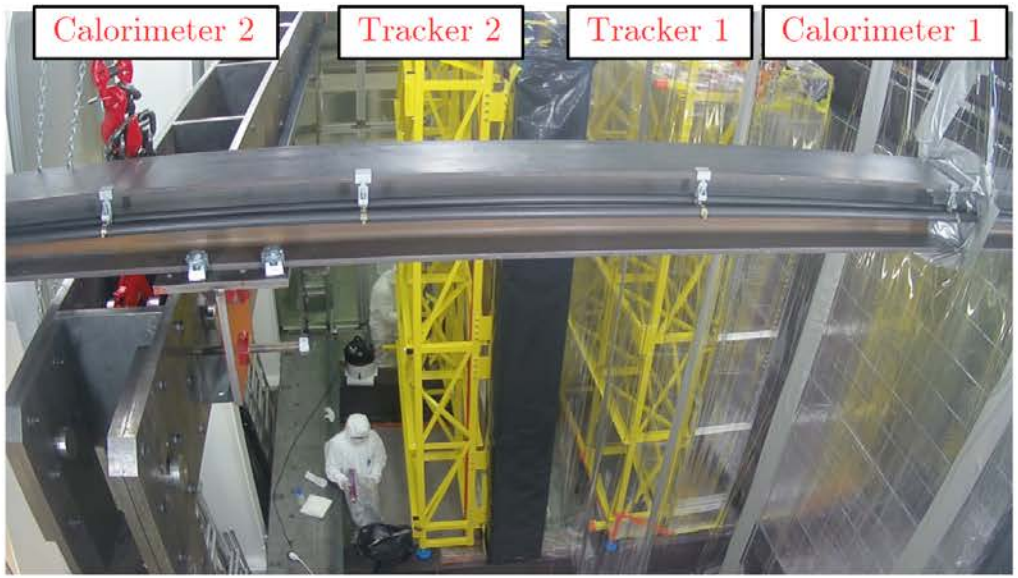
^{82}Se

Super – NEMO Demonstrator

- Goal of the demonstrator
  - Run for 2.5 y with 7 kg of ^{82}Se
    → $T_{1/2} > 6 \times 10^{24}$ y $m_{\beta\beta} < 0.2 - 0.55$ eV
  - Prove SuperNEMO module can be a background free experiment in the region of interest



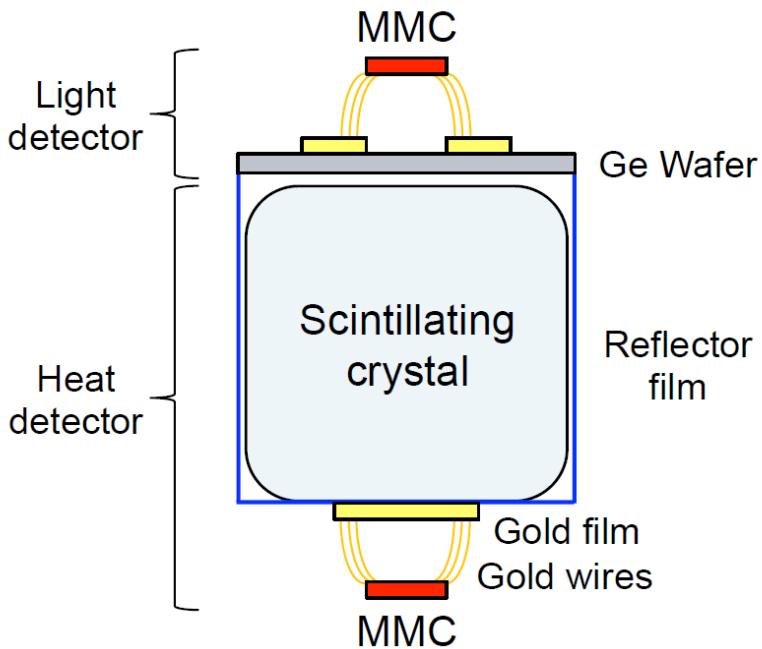
- The 2 calorimeter frames have been assembled and populated with the calorimeter blocks
- The tracker has been installed
- Installation of the source foil during fall 2017
- Demonstrator module starts data taking at end of 2017

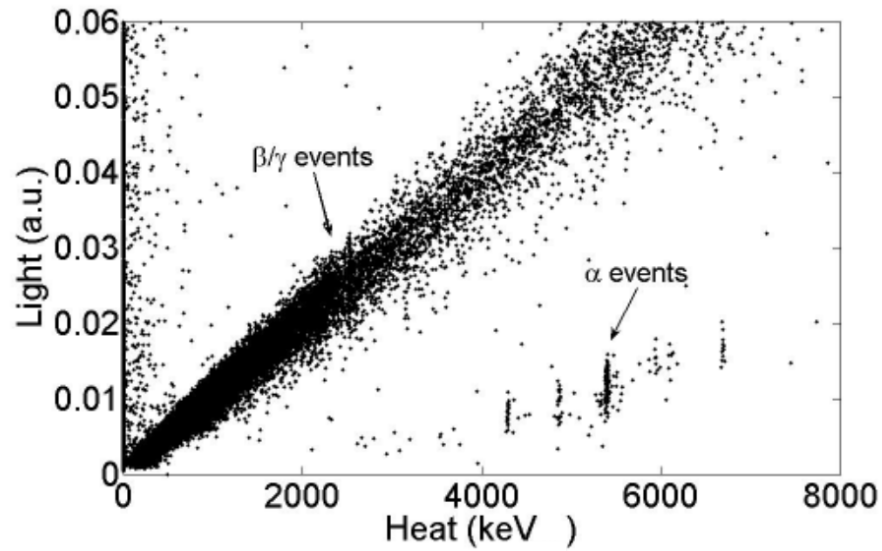


T. Le Noblet, TAUP 2017

AMoRE

$^{40}Ca^{100}MoO_4$ (enriched ^{100}Mo, depleted ^{48}Ca) or other Mo-based scintillating crystal used as source and detector
+ Metallic Magnetic Calorimeter (MMC, low temperature sensor)





"Source = detector" approach
- High detection efficiency
- High energy resolution

MMCs
- Fast response, high energy resolution, wide operating temperatures

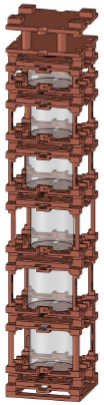
Simultaneous measurement of heat and light
- Particle discrimination for rejection of α-induced background

YangYang Lab, South Korea

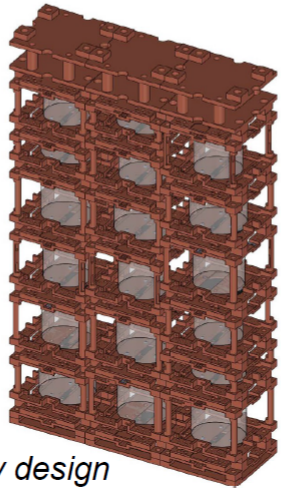
AMoRE

- AMoRE-I at Y2L (same cryostat as Pilot), with $CaMoO_4$ crystals + a few others (ZMO, LMO, …)
- AMoRE-II at a new, larger laboratory (ARF), $X^{100}MoO_4$ crystals (X = Li, Na, ^{40}Ca, Zn or other)

AMoRE-Pilot
~1.8 kg
2016-2017

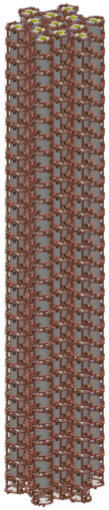


AMoRE-I
5~6 kg
2018~



Preliminary design

AMoRE-II
200 kg
2020~



Preliminary design

	Pilot	AMoRE-I	AMoRE-II
Mass	1.8 kg	~5 kg	~200 kg
Channels	12	36	1000
Background (counts/keV/kg/year)	0.01	0.001	0.0001
Sensitivity($T_{1/2}$) (year)	~10^{24}	~10^{25}	~5×10^{26}
Sensitivity(m_{ee}) (meV)	380-720	120-230	17-32
Location	Y2L	Y2L	ARF (new lab)
Schedule	2016-2017	2018-2019	2020-2022

^{130}Te

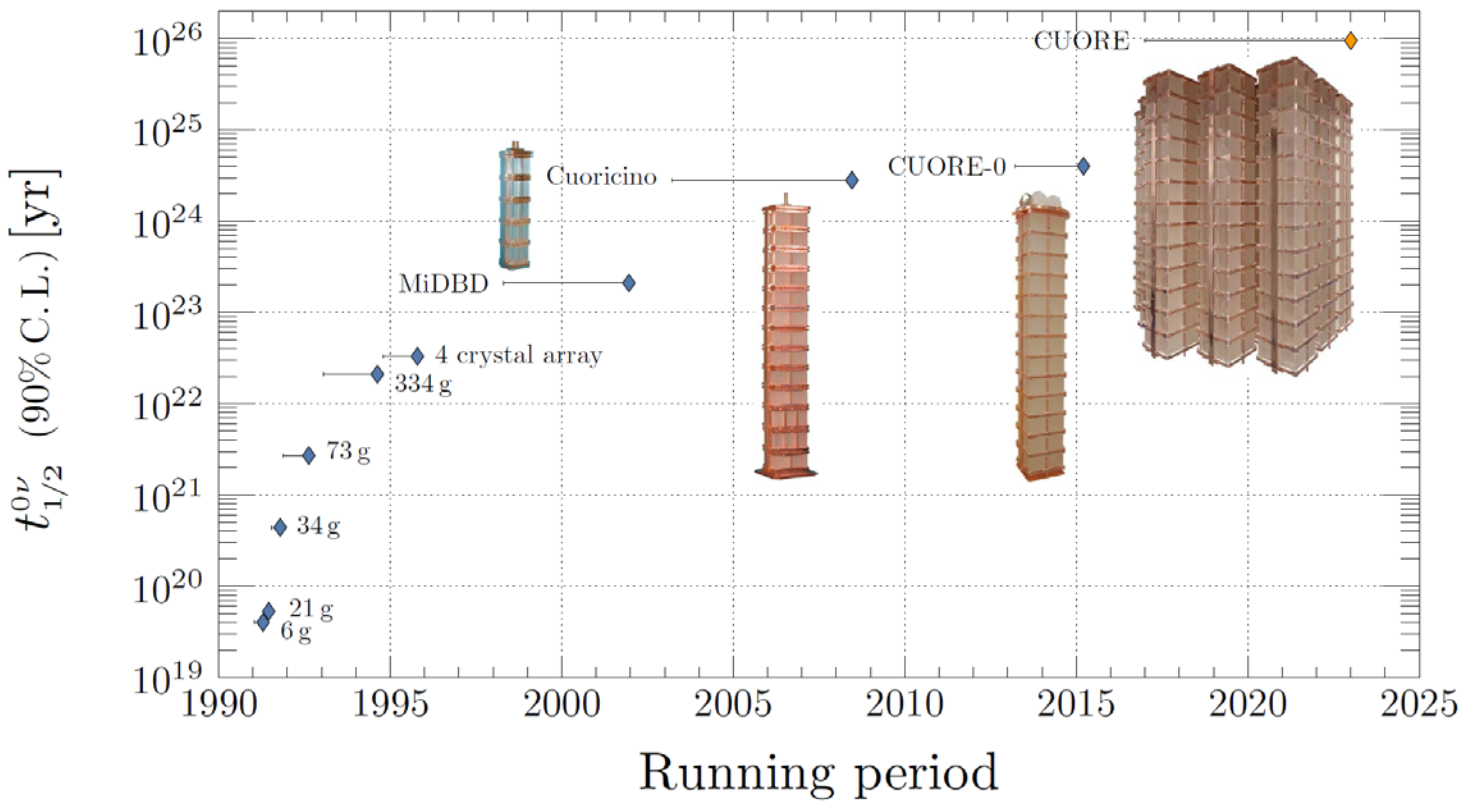
CUORE

First CUORE results

Oliviero Cremonesi
INFN - Sez. Milano Bicocca
on behalf of the CUORE Collaboration

TAUP 2017

TeO_2 arrays



CUORE is the latest evolution of a long series of TeO_2 detectors which included two large demonstrators:

- Cuoricino
- CUORE-0

^{130}Te

CUORE

The CUORE Collaboration

Congratulations to the CUORE Collaboration on their beautiful first results

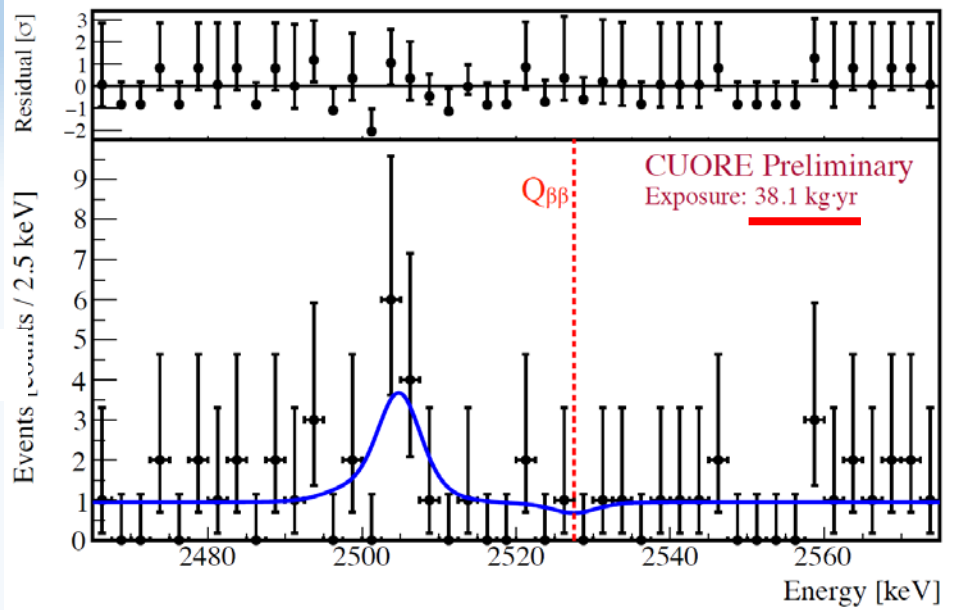
^{130}Te

First CUORE results

Oliviero Cremonesi
INFN - Sez. Milano Bicocca
on behalf of the CUORE Collaboration

TAUP 2017

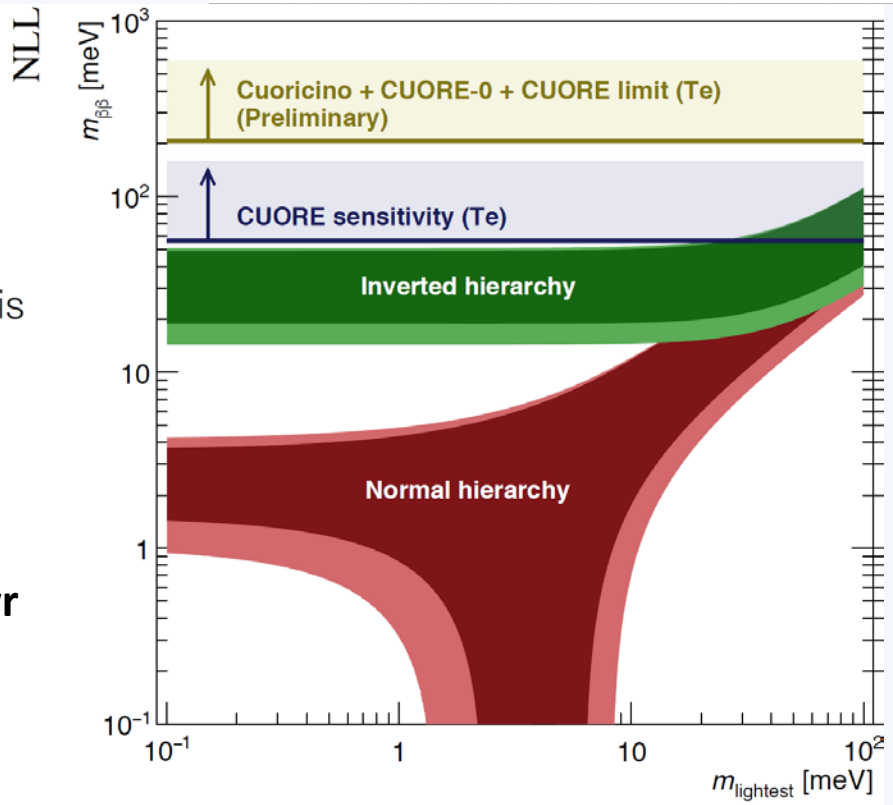
- Half-life limit (90% CL, including systematics): **4.5×10^{24} yr**



- We combined the CUORE result with the existing ^{130}Te
  - 19.75 kg·yr of Cuoricino
  - 9.8 kg·yr of CUORE-0
- The combined 90% C.L. limit is
  $T_{0\nu} > 6.6 \times 10^{24}$ yr

$m_{\beta\beta} <$ 210–590 meV

CUORE sensitivity:9 x 10^{25} yr

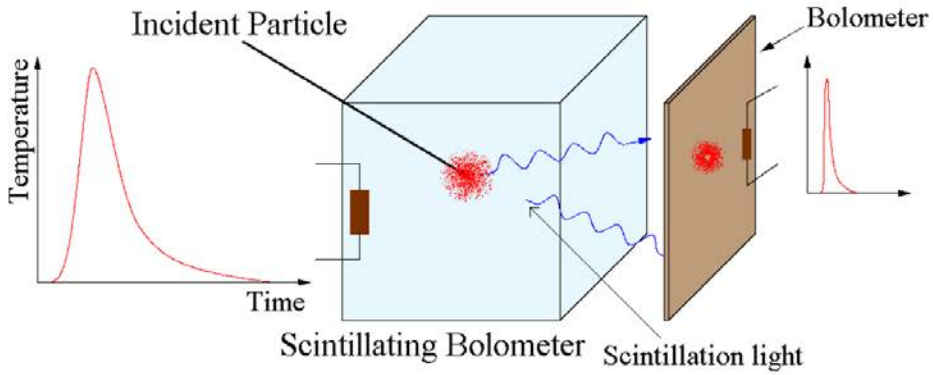


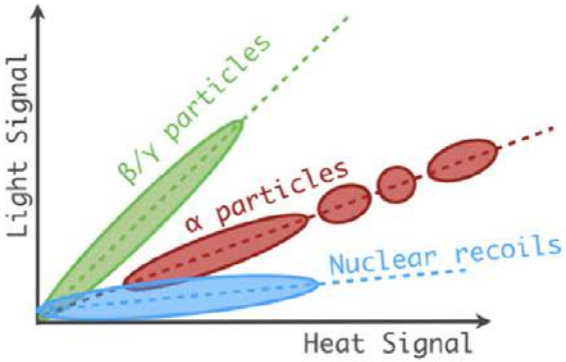
^{82}Se (^{100}Mo future)

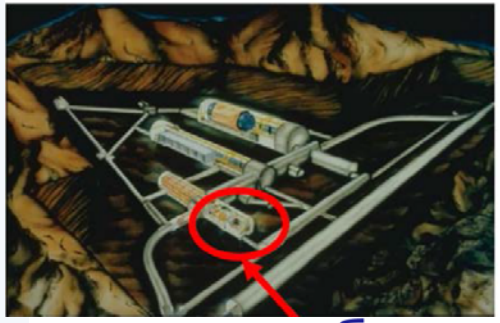
CUPID-0 (Formerly Lucifer)

Scintillating Bolometers: rudiments of operation

Operating Temperatures for *massive* detectors: 10÷30 mK







24 **Zn^{82}Se** bolometers, for a total mass ≈ **5.1 kg of ^{82}Se**
2 ZnSe bolometer ≈400 g each, not enriched in ^{82}Se
$Q_{\beta\beta}$(^{82}Se) = 2998 keV
Light detectors high purity Ge wafers with antireflecting coating
Thermal sensors made with NTD thermistors
Detector assembled in 5 towers in Cuoricino/CUORE-0 cryostat
Total active **mass of the detector ~10.5 kg**

Science Run 0 (17 March – 15 May)
- 0.89 kg x y exposure of ZnSe
- **0.47 kg x y** exposure of ^{82}Se

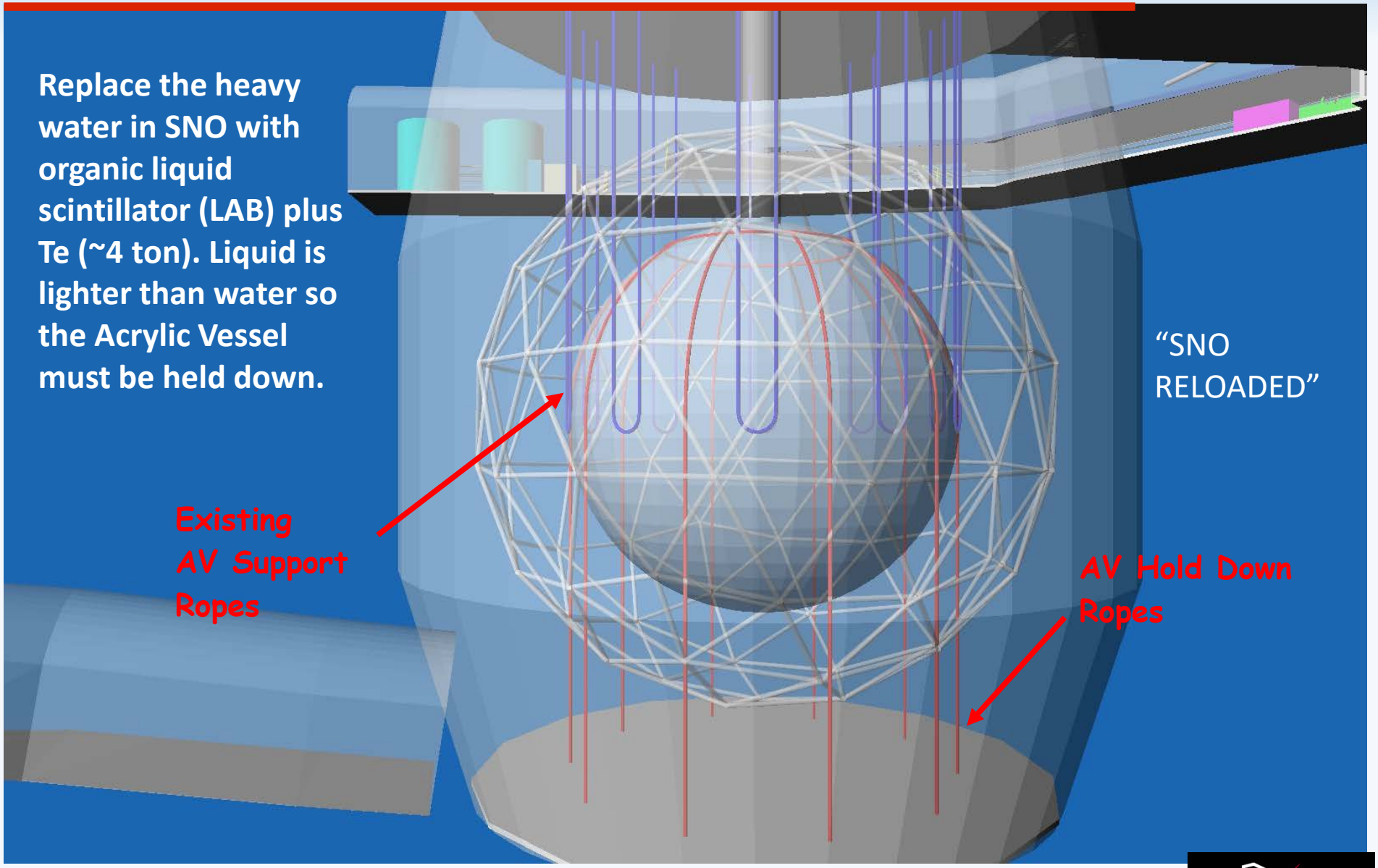
The **SR-1** started 3 June 2017

S. Pirro TAUP 2017

^{130}Te

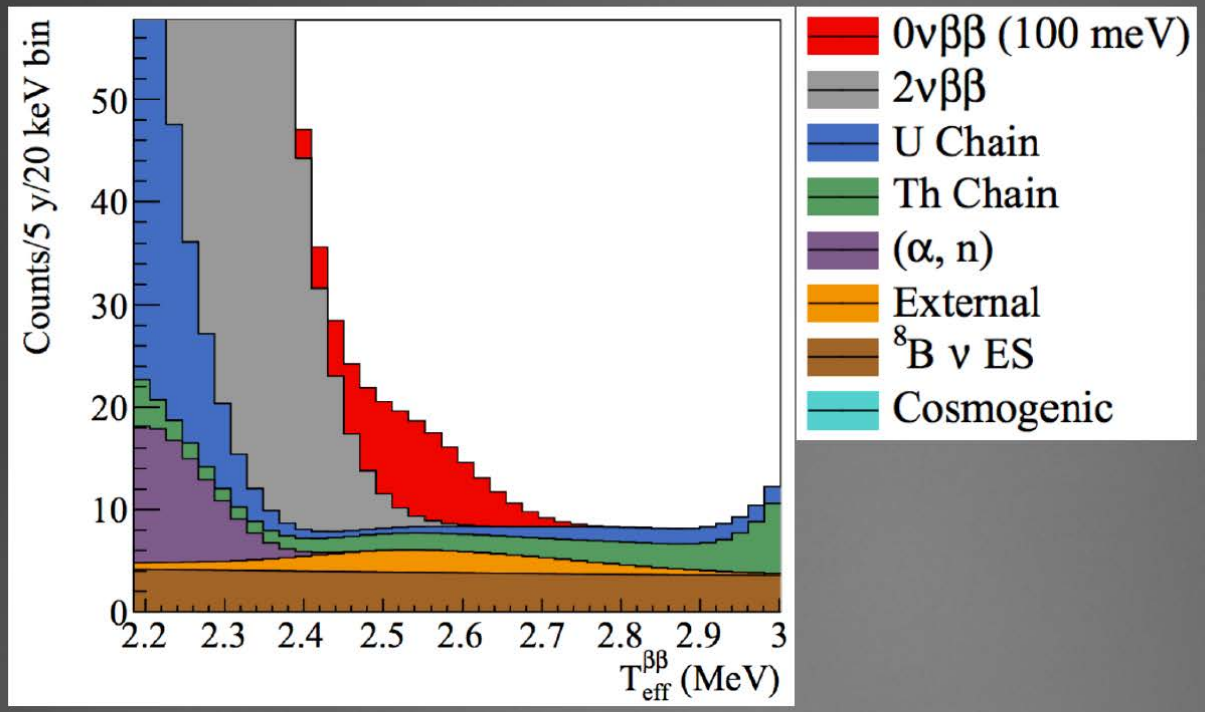
SNO+

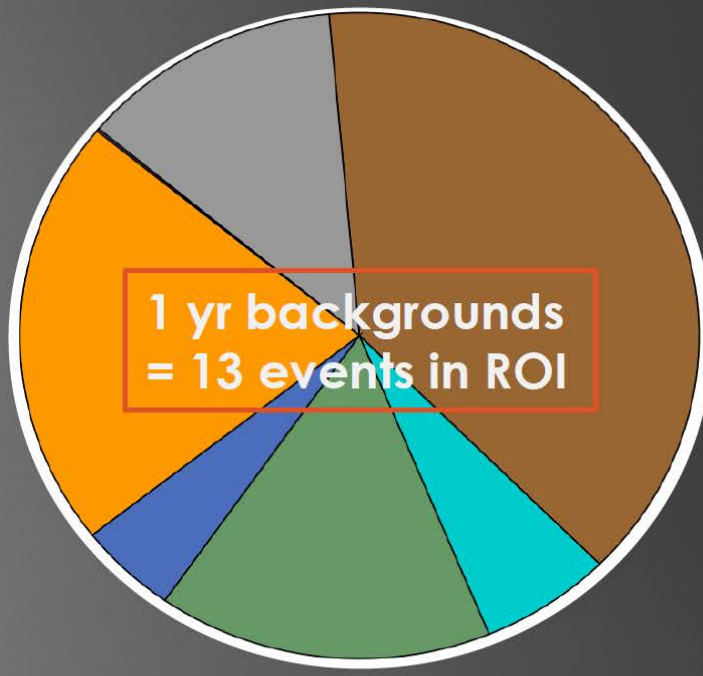
Replace the heavy water in SNO with organic liquid scintillator (LAB) plus Te (~4 ton). Liquid is lighter than water so the Acrylic Vessel must be held down.



Hold-down ropes installed, now full with pure water, running. LAB installation 2018, Te installation early 2019.

SNO+ Sensitivity





- LAB + PPO (2g/L) + bisMSB (15mg/L)
- 0.5% nat. Te (1330 kg ^{130}Te)
- FV = 3.5 m (20%)
- > 99.99% rejection ^{214}BiPo
- 98% rejection ^{212}BiPo
- 390 hits/MeV
- $m_{\beta\beta}$ =100 meV

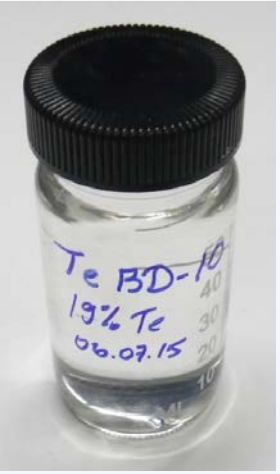
After 5 yrs, 0.5% loading:
$T_{1/2} > 2 \times 10^{26}$ y, 90% CL
$m_{\beta\beta} \approx 40 - 90$ meV

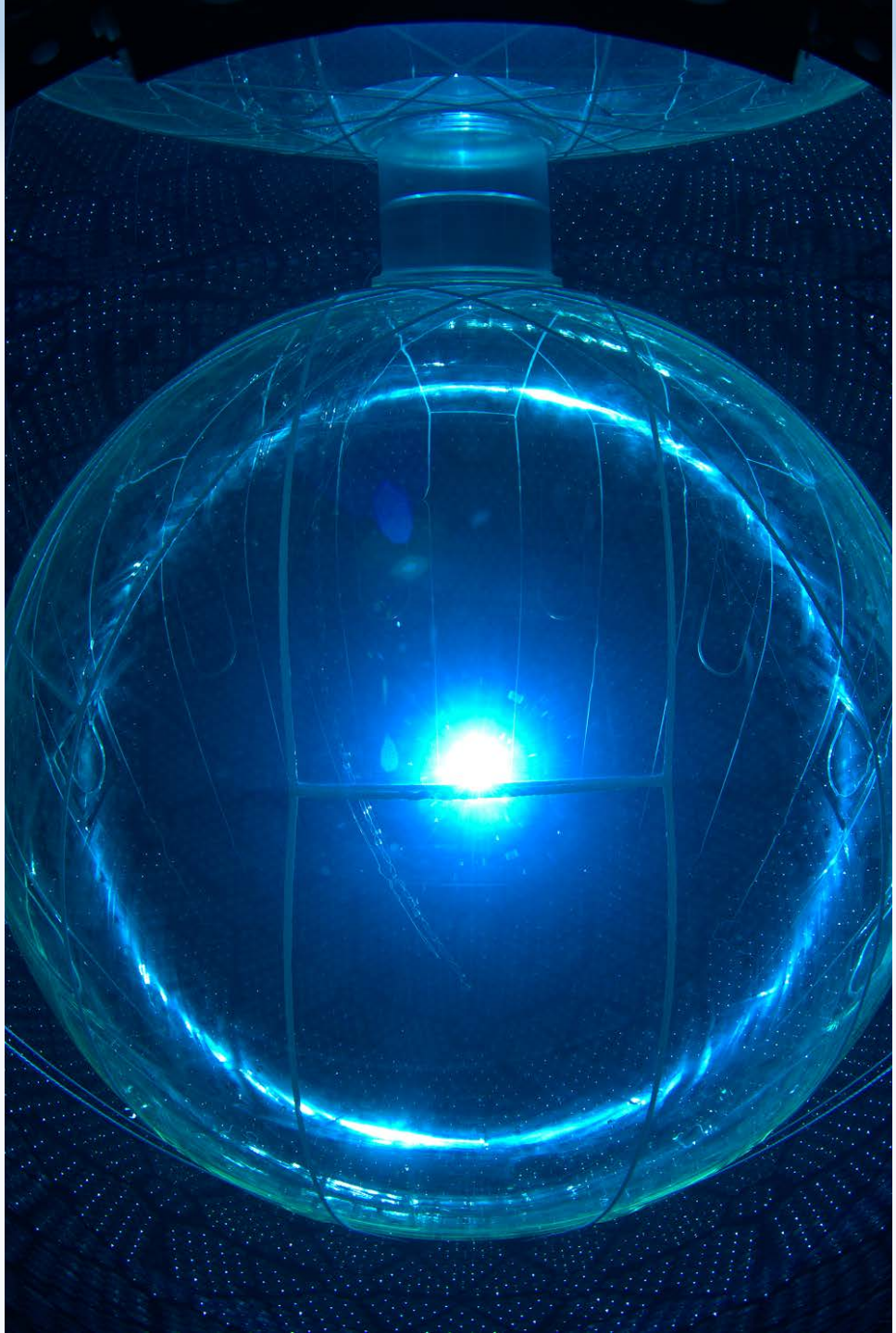
^{130}Te

Possible Phase II:

5% Te Loading

PMT's replaced with High Quantum Efficiency



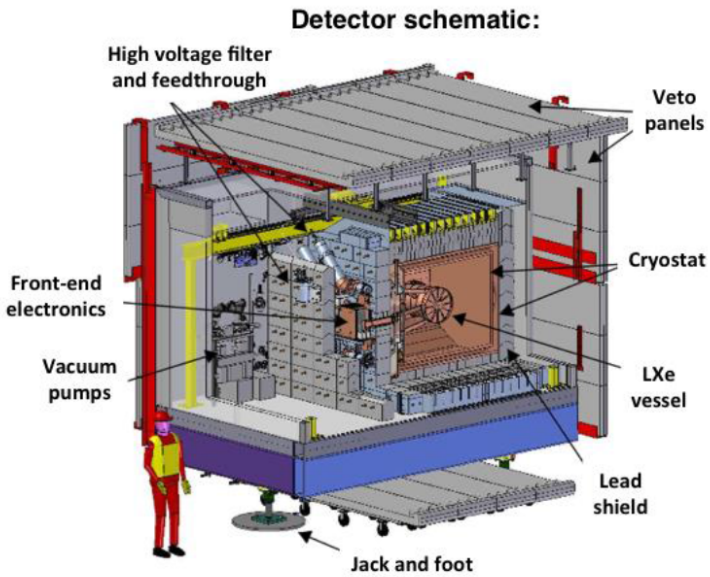


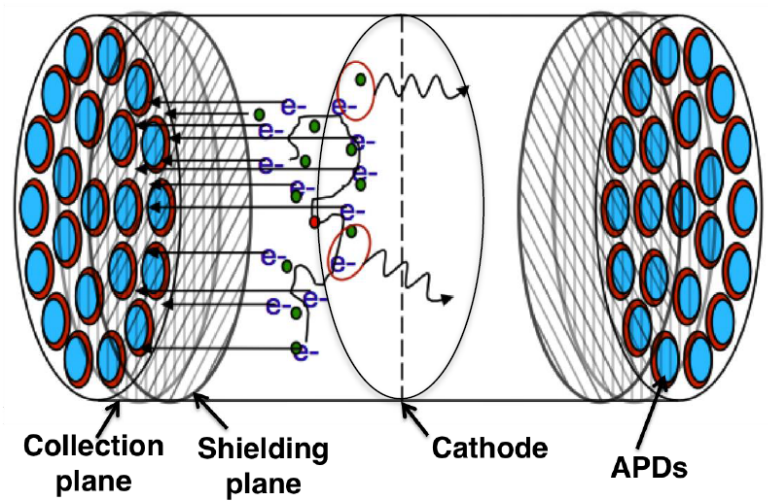
SNO+ Picture From Internal Camera

^{136}Xe

EXO-200: New Results

- EXO-200 consists of a radiopure TPC filled with enriched LXe (80.6%)
- Located at Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM, USA
- High-voltage applied between cathode and anodes (opposite ends)
- Two measurements of energy deposited in event
  - Scintillation light (178 nm), by large avalanche photo-diodes (APDs)
  - Ionization charge, by 2 wire grids (induction and collection)





^{136}Xe

EXO-200: New Results

- Combined analysis:
  - Total exposure = 177.6 kg.yr

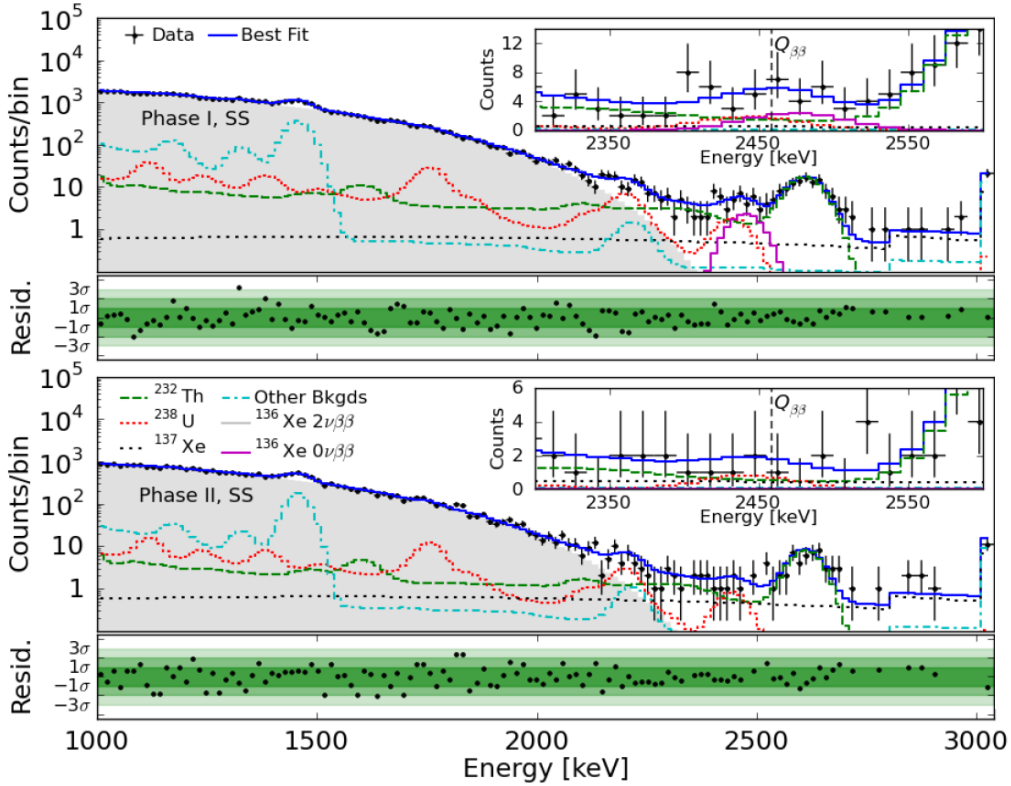
Sensitivity of 3.7x10^{25} yr (90% CL)

$T_{1/2}^{0\nu\beta\beta} > 1.8 \times 10^{25}$ yr

$\langle m_{\beta\beta} \rangle < 147 - 398$ meV

(90% C.L.)

arXiv: 1707.08707



- No statistically significant excess: combined p-value ~1.5σ

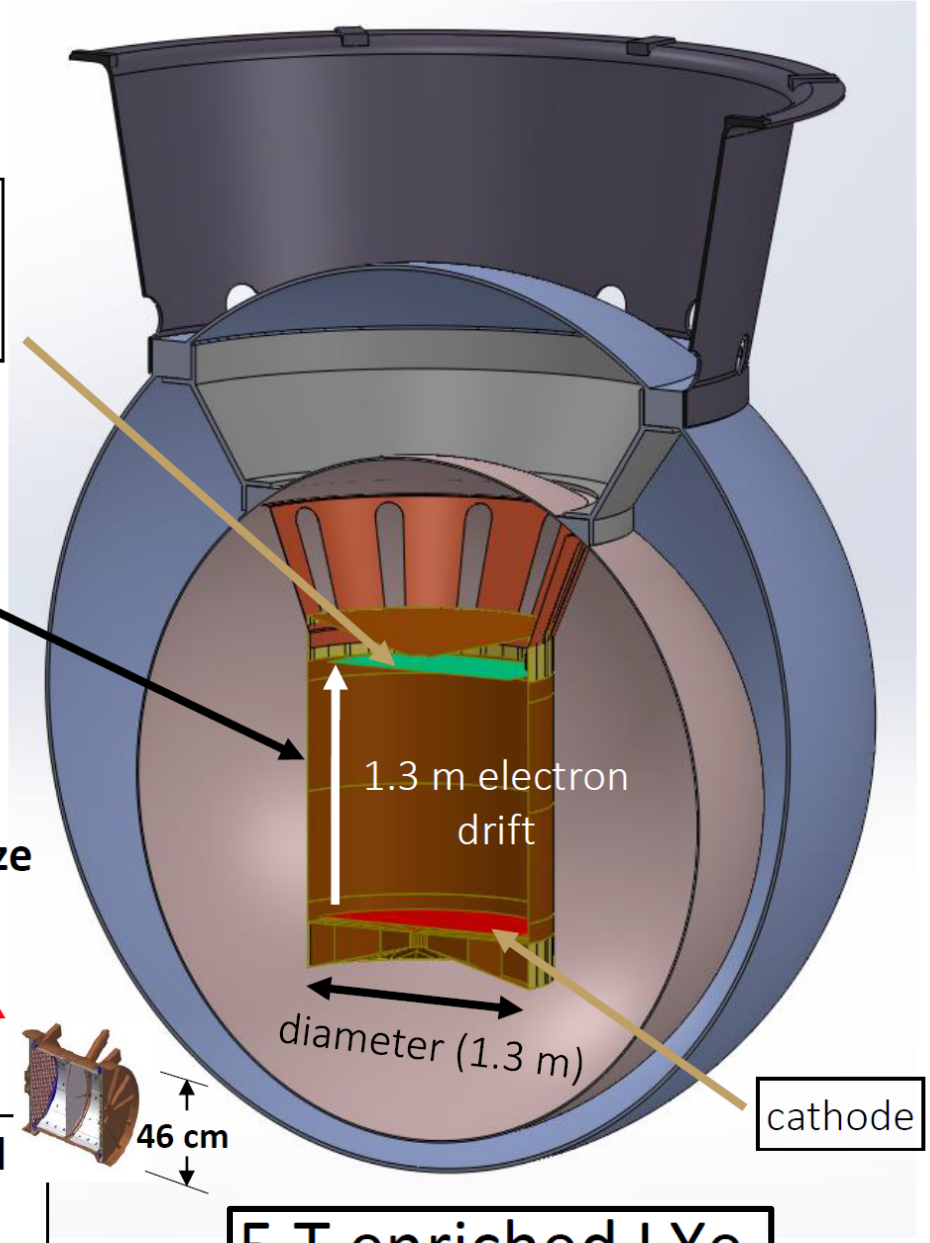
The nEXO TPC

Long, single drift
- HV
- Xe purity (low outgassing)

Novel charge tiles
- very low noise
- modularity
- self-supporting

SiPMs on the barrel
- optically open, reflective field cage
- no HV required
- Robust
- larger gain
- large scale production

In-Xe electronics
- radioactivity



R. MacLellan TAUP2017

^{136}Xe

nEXO

Discovery sensitivity (3σ, 50%) after 10 yr
$T_{1/2}^{0\nu\beta\beta} = 5.5 \times 10^{27}$ yr

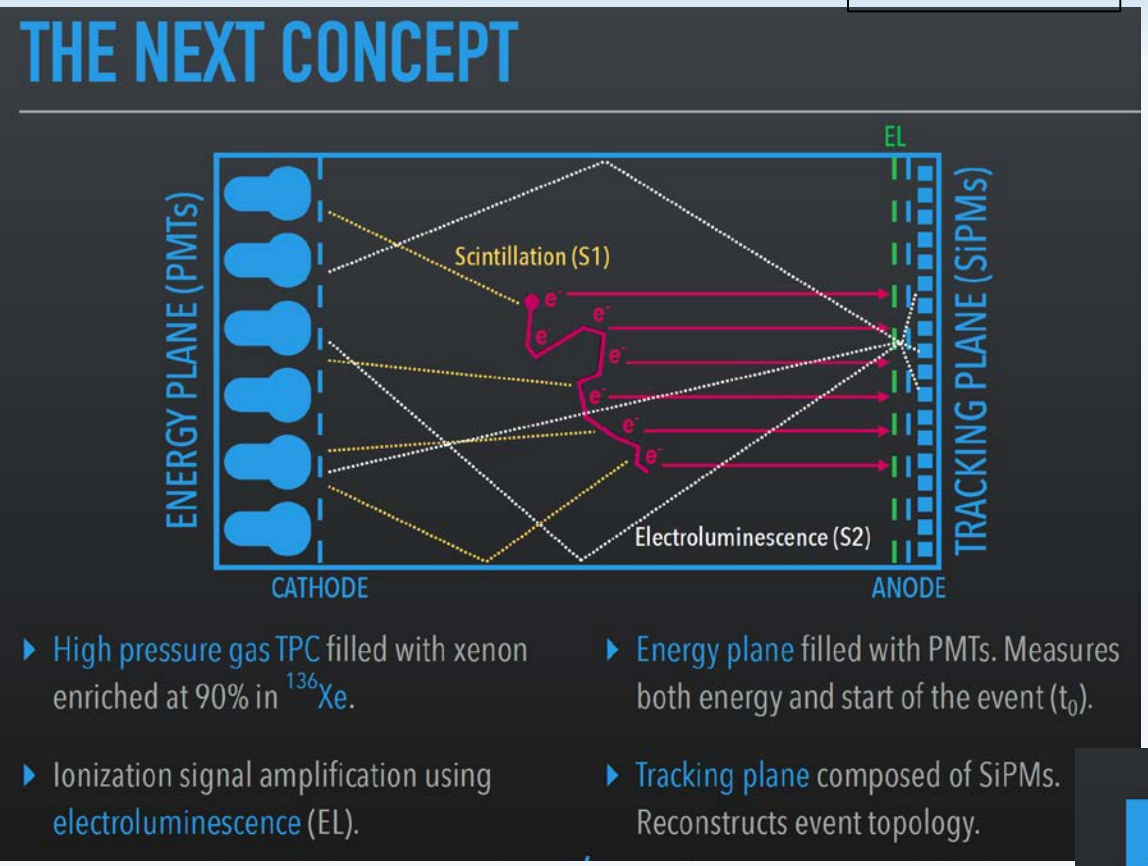
If ^{136}Ba-tagging can be implemented:
$T_{1/2}^{0\nu\beta\beta} = 1.6 \times 10^{28}$ yr

Ba-Tagging research ongoing:

- Electrically Biased probe with Resonance Ionization Spectroscopy
  - Stanford University
- Extraction to Gas Phase with Ion Trapping
  - Carleton and McGill Universities and TRIUMF
- Electrically Biased probe with Thermal Desorption
  - University of Illinois Urbana-Champaign
- Cryogenic probe with Fluorescence Spectroscopy
  - Colorado State University

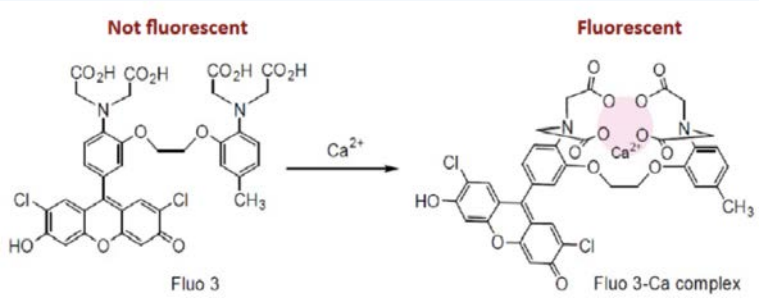
^{136}Xe

NEXT

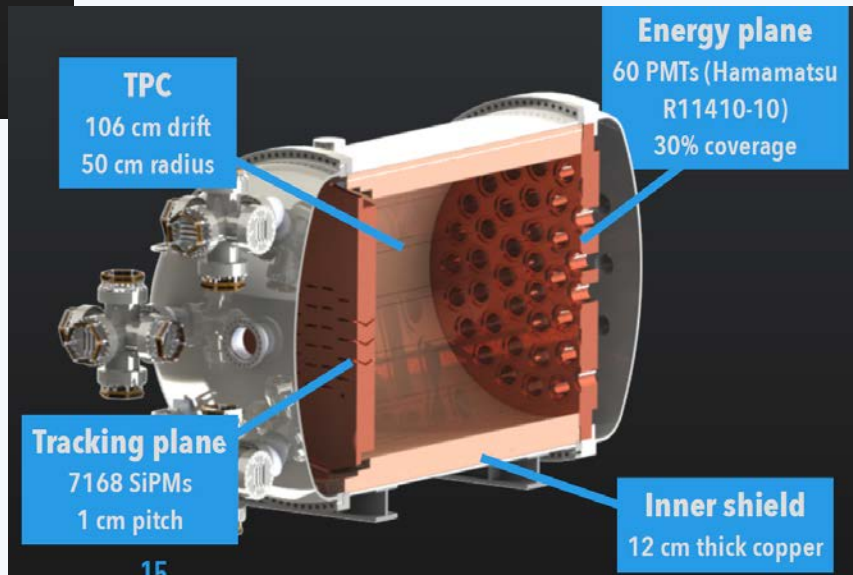


- 5 kg of Ar has been running at CanFranc since Oct 2016.
- NEXT-100: 100 kg of Ar will be running by the end of 2018

Fluorescence of organic molecules being studied for Ba-tagging.

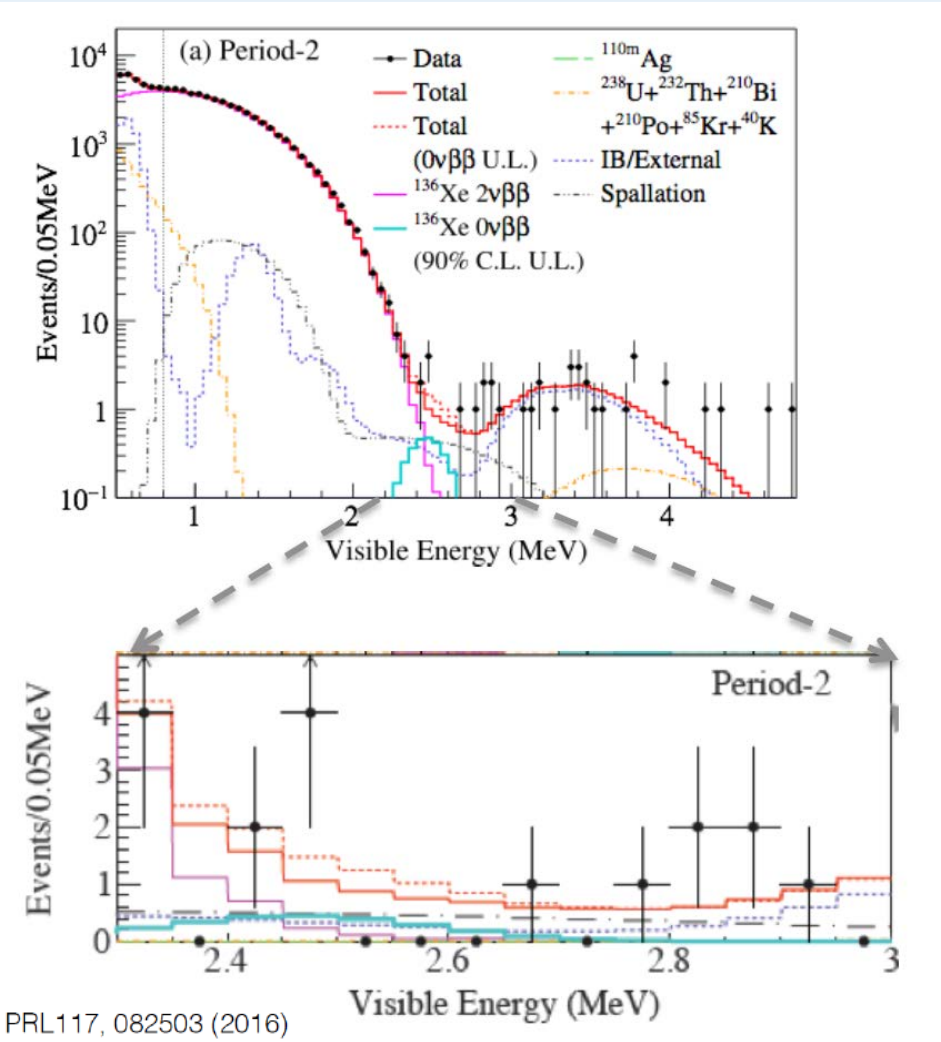


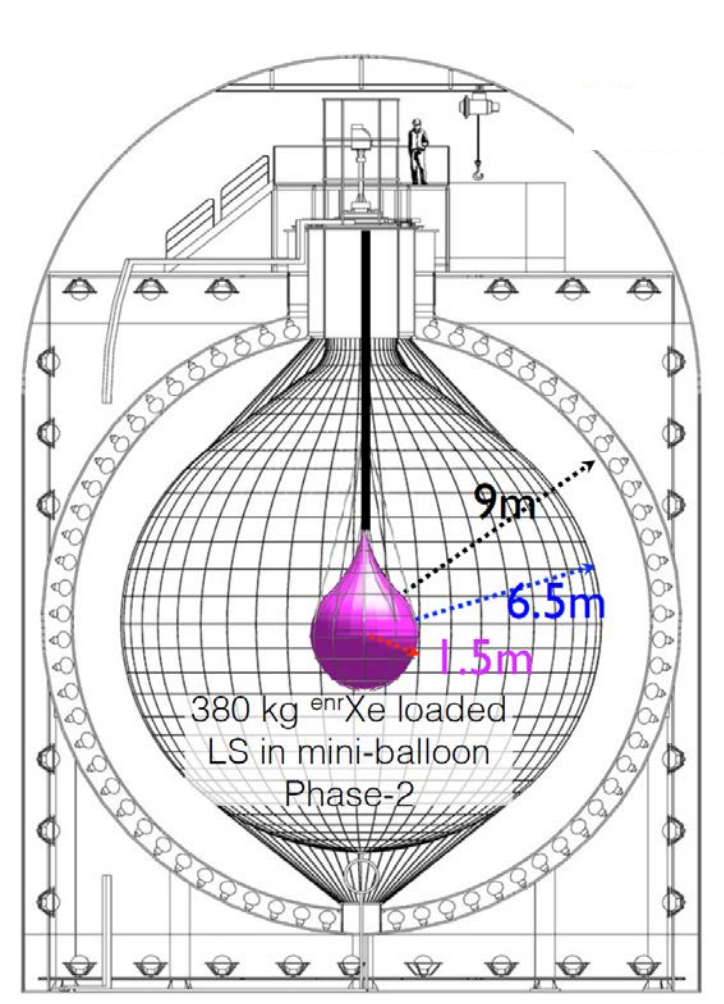
NEXT-100



^{136}Xe

KamLAND-Zen



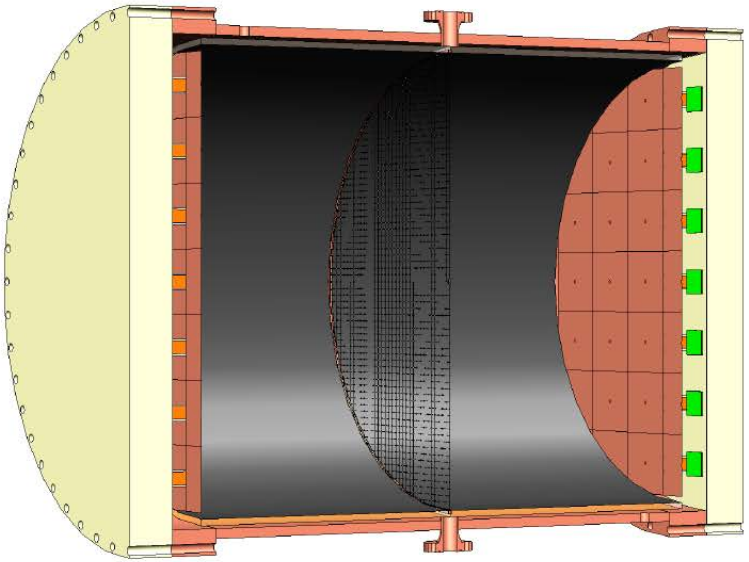


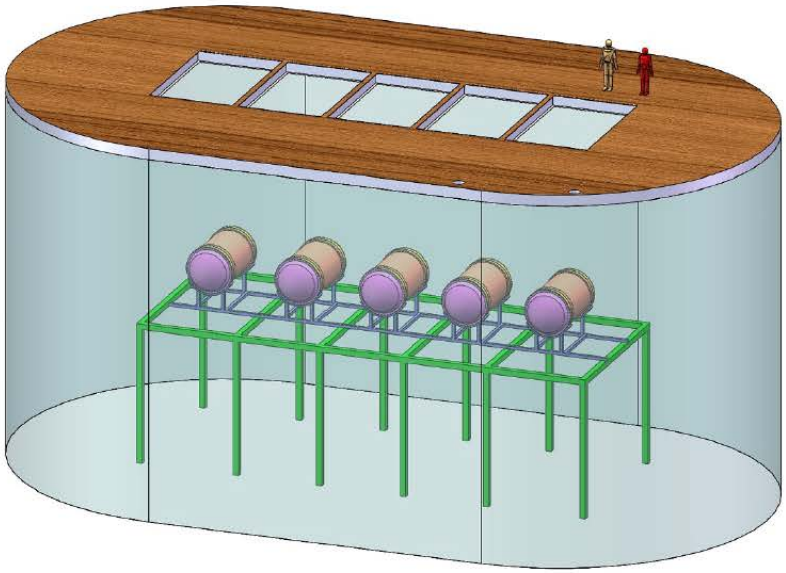
Phase I + II (504 kg-yr): $t_{½} < 1.07 \times 10^{26}$ yrs
Now running with New Balloon and 750 kgs
Future: 1000 kg

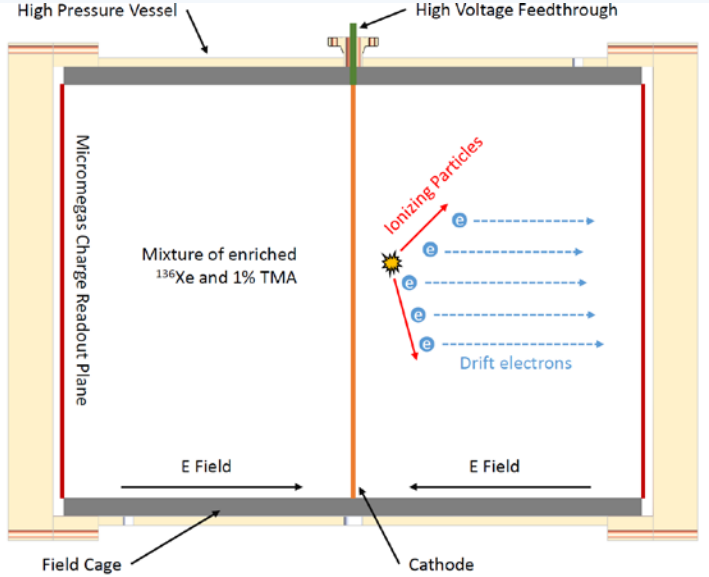
^{136}Xe

PandaX-III

10 Bar Gas TPC:



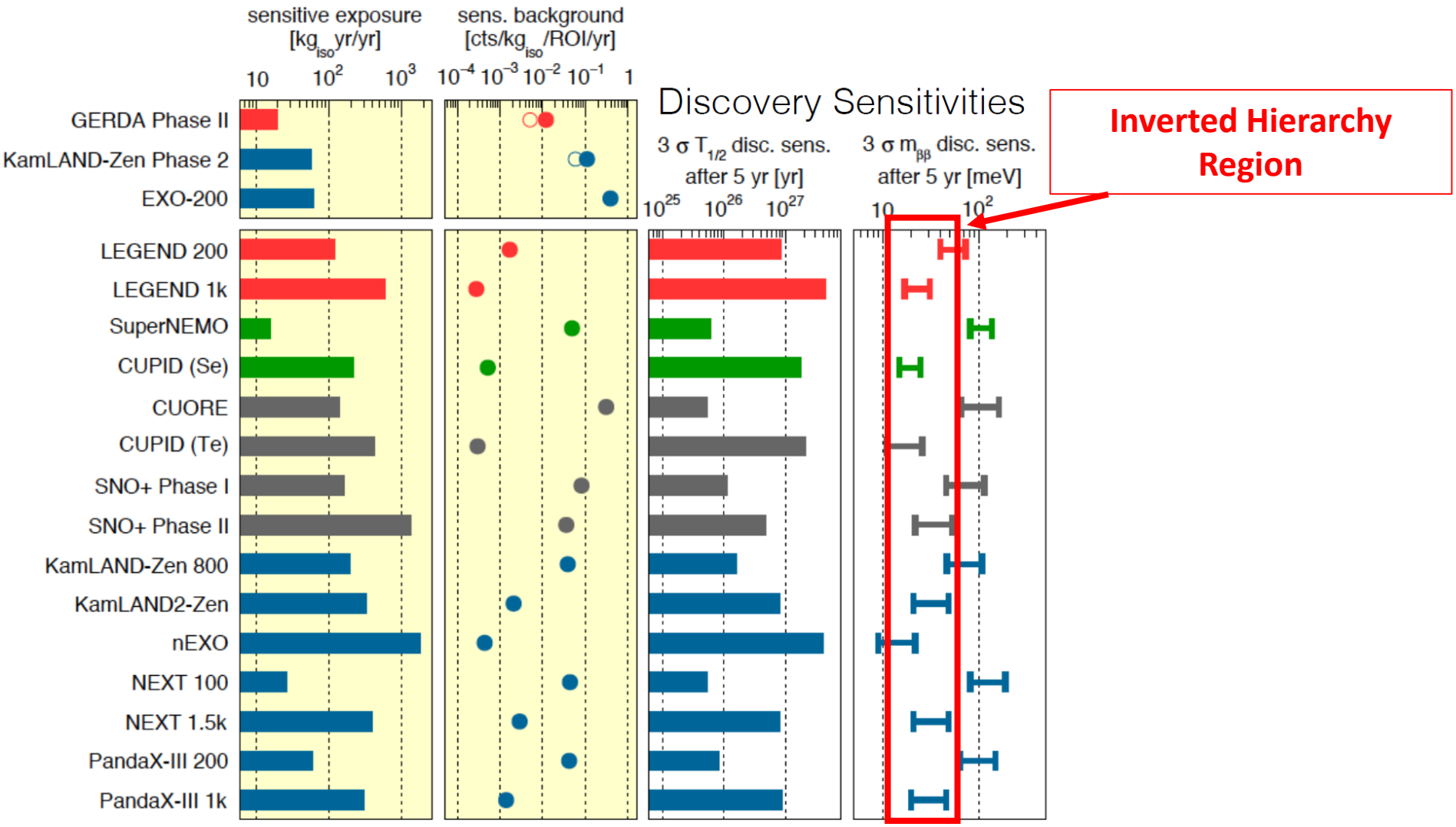




Full Project: 5 x 200 kg Modules in water shield in Jing Ping Laboratory

Presently one prototype module with Micromegas readout.

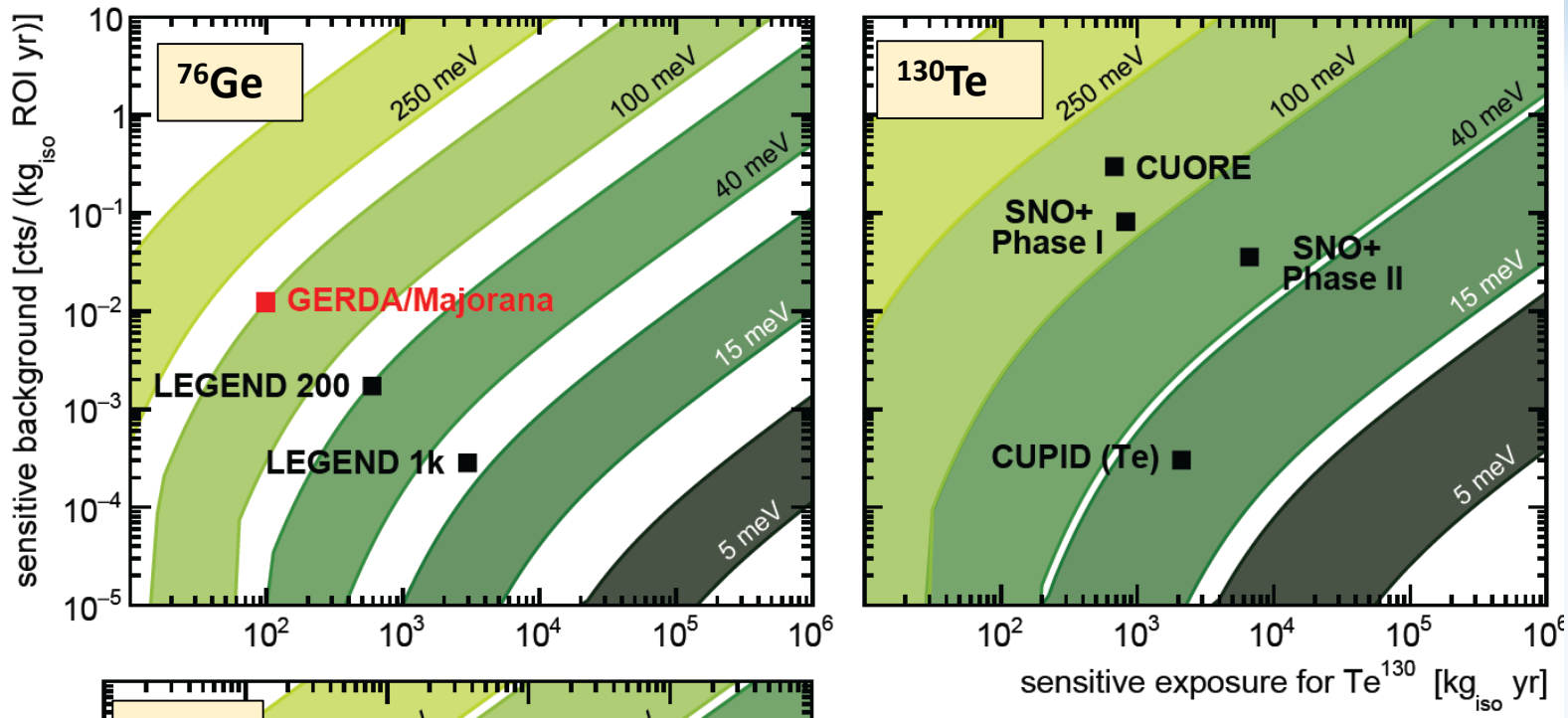
Comparison of Experiments

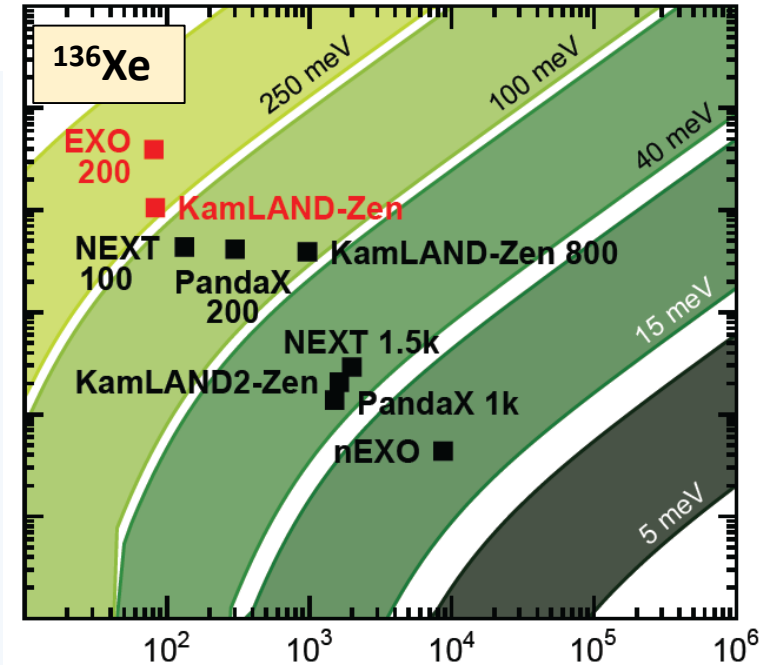


Adopted from Agostini, Benato, Detwiler arXiv:1705.02996

Discovery Potential (5 year running)

Agostini, Benato, Detwiler arXiv:1705.02996





Contours in $m_{\beta\beta}$ cover the range of Nuclear Matrix Elements (but not possible g_A quenching)

Summary and Future Outlook

- **Several experiments are prepared to dip into the Inverted Hierarchy region in the full operation of their present configuration.**

- **There are future prospects for sensitivity that will extend at least to the bottom of the IH region.**

- **Considerable work continues to be needed on control of backgrounds to attain adequate sensitivity in finite time.**

- **Analysis by Agostini et al suggests optimism for the possibility for discovery within the potentially accessible regions if neutrinos are Majorana particles.**

- **Further theoretical work is very important to improve the uncertainty in nuclear matrix elements and g_A quenching.**