

# Tales of Other neutrinoless double beta decay efforts in Europe



...and worldwide  
...and R&D for the future (!!)

A frightening task taken on by S. Biller (Oxford)

# A Brief Word On Sensitivity Comparisons

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} \left| M^{0\nu} \right|^2 \left( \frac{m_{\beta\beta}}{m_e} \right)^2$$

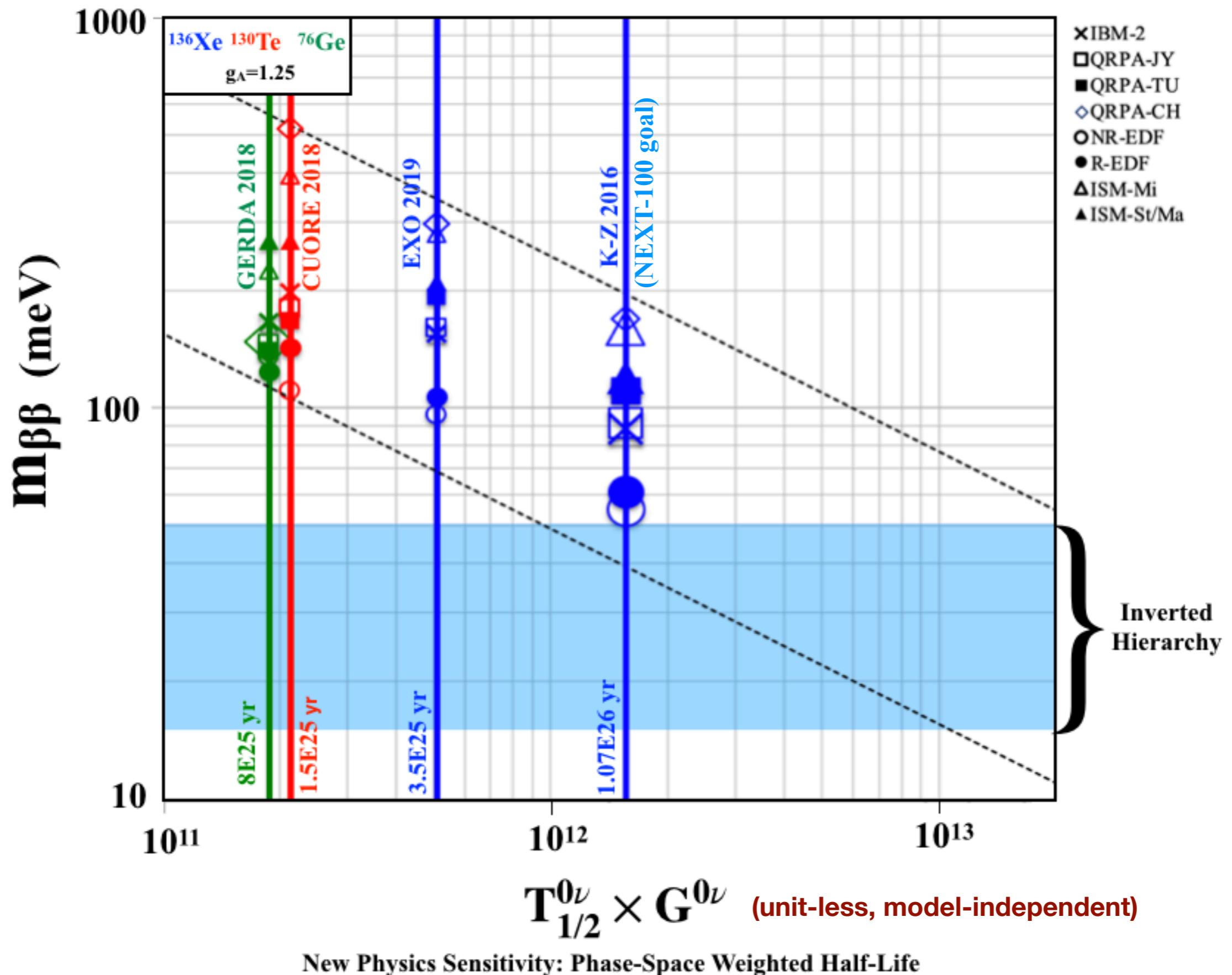
**Exactly calculable, model-independent** phase space factor accounting for different momentum distributions corresponding to different isotope endpoints and the impact of the nuclear charge on the produced electrons.

**Not so exactly calculable, model-dependent** matrix element for the transition. Many different approaches to estimations, even for the “standard mechanism.” Proportional to  $g_A^2$  (factored from  $G^{0\nu}$ ), which might entail an effective “quenching.”

Want to represent results so as to fairly compare across different isotopes and make the nature of model dependencies transparent

- The expression is first divided into model-independent and model-dependent pieces.
- To compare sensitivities appropriately across different (colour-coded) isotopes, the x-axis in the following plots gives the product of the projected half-life sensitivity times the isotopic phase space factor. The unit-less product is therefore effectively an indication of the relative sensitivity to  $0\nu\beta\beta$  if the impact of uncertain matrix elements were ignored (*e.g.* if the mechanism is not known).
- For the standard light neutrino exchange mass mechanism, different matrix element models are represented by the different symbols indicated, each allowing a model-dependent translation to an effective neutrino mass on the y-axis, here assuming  $g_A=1.25$ . Note that if the value of  $g_A$  is instead taken to be 1.0, the position of these symbols would be shifted upwards in mass by about 50%. This representation allows for the comparison of relative experimental sensitivities model-by-model.
- Larger symbols indicate the experiment for which the projected sensitivity is anticipated to provide the best constraint for that particular model.
- The region approximately corresponding to the inverted neutrino mass hierarchy (which also includes part of the normal mass hierarchy for degenerate neutrinos) is indicated by the horizontal blue band.

# Current Leading Bounds



R&D Currently Not  
Associated With A  
Major Future Project

# The R2D2 project

- R2D2 (Rare Decays with Radial Detector) is an R&D program aiming at the development of a zero background ton scale detector to search for the neutrinoless double beta decay.
- We aim at developing a detector which meets all the main requirements at the same time i.e. an excellent energy resolution, a low (potentially zero) background and large masses of isotopes.
- The idea is to use a **spherical Xenon gas TPC at high pressure** (i.e. 40 bars).
- The development include a multichannel central anode for PID and coarse tracking (common R&D with NEWS-G).

J. Busto,<sup>a</sup> C. Cerna,<sup>b</sup> A. Dastgheibi-Fard,<sup>c</sup> C. Jollet,<sup>b</sup> S. Jullian,<sup>f</sup> I. Katsioulas,<sup>d</sup> I. Giomataris,<sup>d</sup> M. Gros,<sup>d</sup> P. Lautridou,<sup>e</sup> A. Meregaglia,<sup>b</sup> X. F. Navick,<sup>d</sup> F. Perrot,<sup>b</sup> F. Piquemal,<sup>b,c</sup> M. Zampaolo<sup>c</sup>

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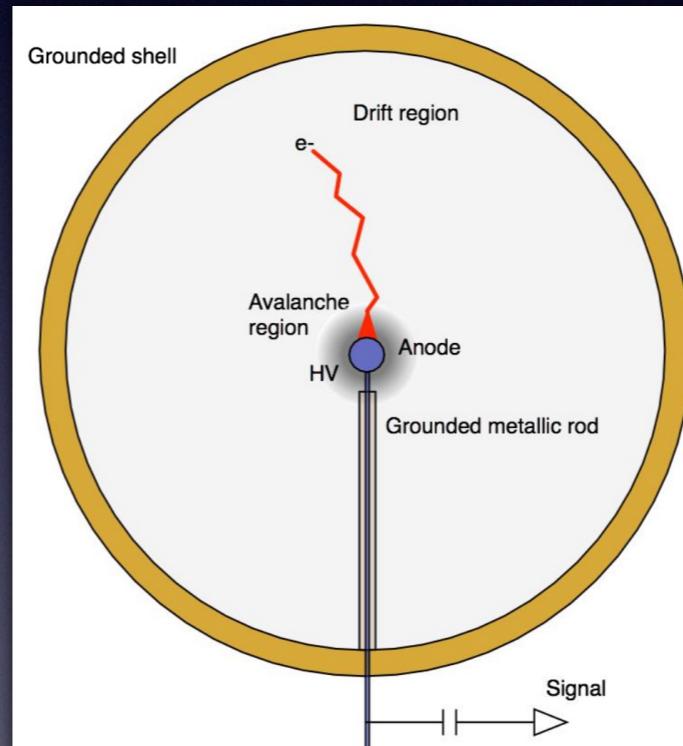
<sup>b</sup>CENBG, Université de Bordeaux, CNRS/IN2P3, 33175 Gradignan, France

<sup>c</sup>LSM, CNRS/IN2P3, Université Grenoble-Alpes, Modane, France

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<sup>e</sup>SUBATECH, IMT-Atlantique, Université de Nantes, CNRS-IN2P3, France

<sup>f</sup>LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, F-91405 Orsay, France



## 3 key requirements for $0\nu\beta\beta$

- Energy resolution → To be validated
- Low background → Low material budget
- Large masses of isotopes → Easily scalable (1ton = 1m radius)  
or multiple spheres

# The R2D2 Roadmap

Prototype 1

Tests ongoing - Funded by IN2P3 R&D

Up to 7.9 kg (40 bars) Xenon prototype (no low radioactivity) to demonstrate the detector capability in particular on the energy resolution

↓ If prototype 1 successful  
and prototype 2 funded

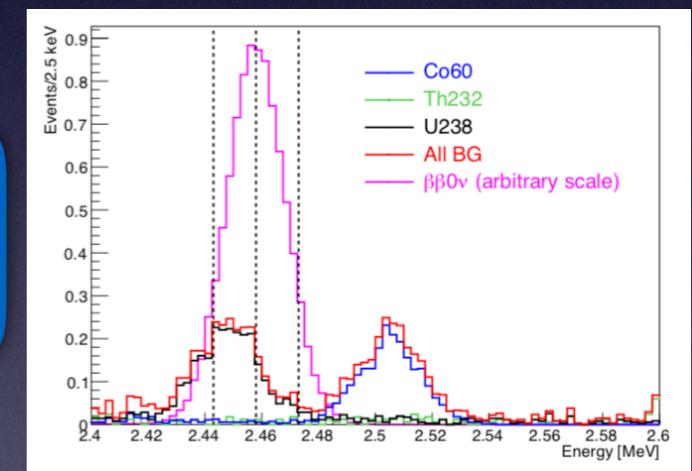


Prototype 2

Sensitivity studies carried out

50 kg Xenon detector (low radioactivity) with LS veto for first physics results to demonstrate the almost zero background

Depending on the results  
and fundings



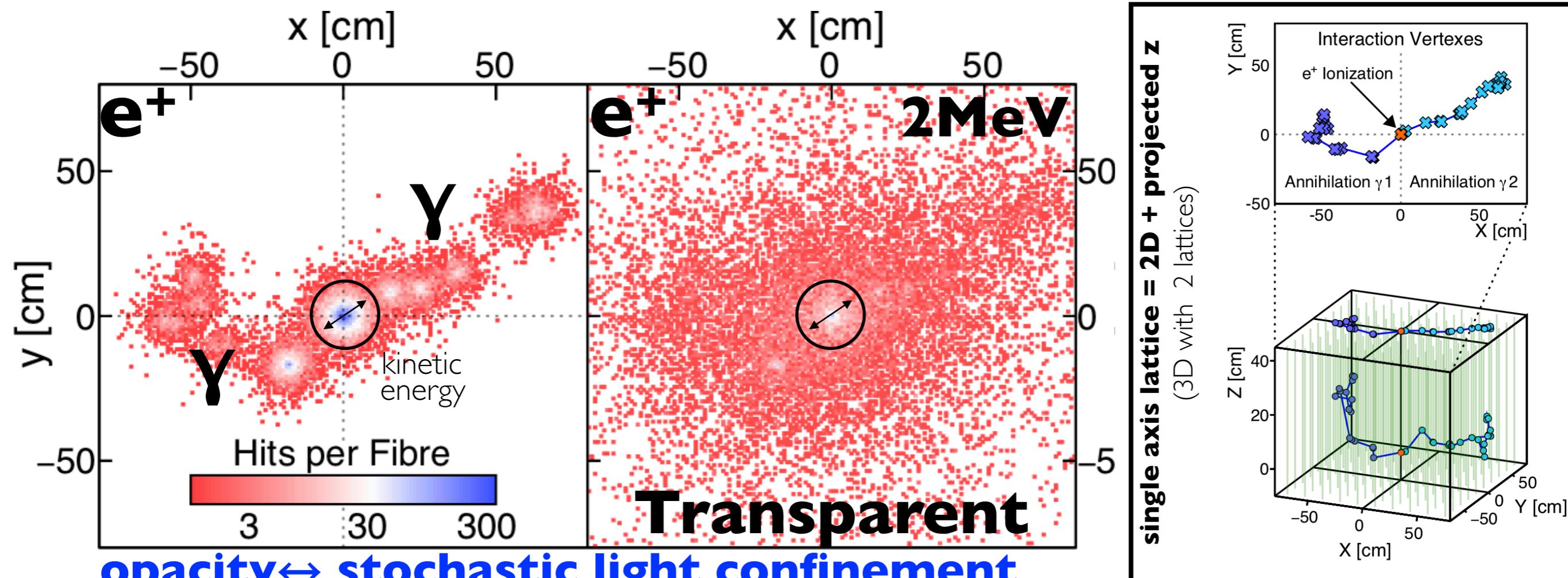
JINST 13 (2018) no.01, P01009

Experiment

Going towards a 1 ton  
background free detector

Exploit the detector with other gases to cross check the background and possibly obtain interesting results selecting higher Q $\beta\beta$ , as well as the possibility to do tracking

# novel opaque-liquid-scintillator technology



**LiquidO**  $\approx$  PID  $\oplus$  (high) Doping

( $\beta\beta$ : less background)

( $\beta\beta$ : large isotopic mass **R&D**)

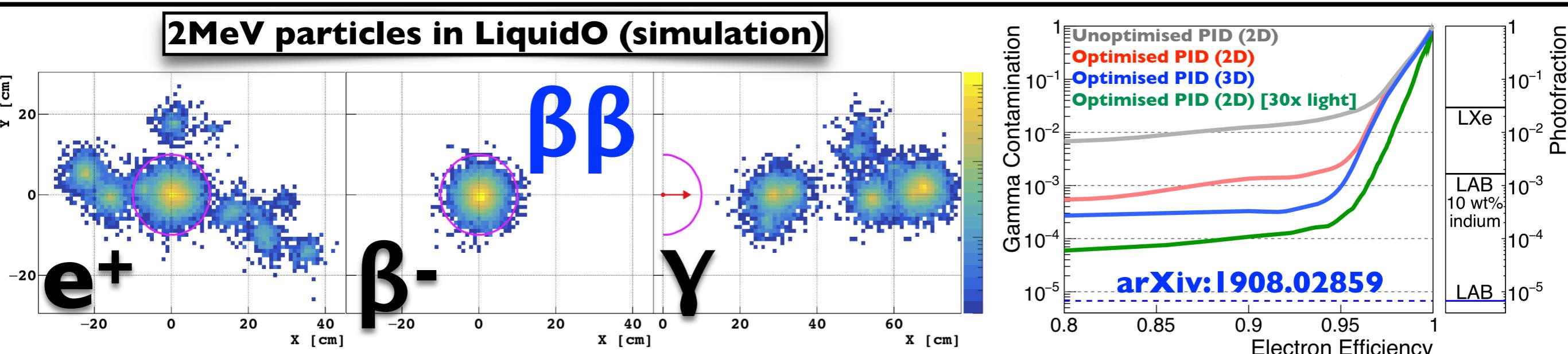
# LiquidO...

Release @CERN: <https://indico.cern.ch/event/823865>

Publication: arXiv:1908.02859

# unique event-wise sub-atomic MeV imaging

- $\beta\beta$ : • **≥ 10 tons** loading (no-enrichment): **Te/Nd/Mo [R&D: ≥ 10% loading]**  
• **BG-Index  $\leq 10^{-4}/(\text{keV} \cdot \text{kg} \cdot \text{year})$**  via **active PID [R&D: fibres & cosmogenic]**  
•  **$\sigma_E \geq 3.6\%$  @ Q-value** [R&D: higher light level via new scintillators?]



## R&D



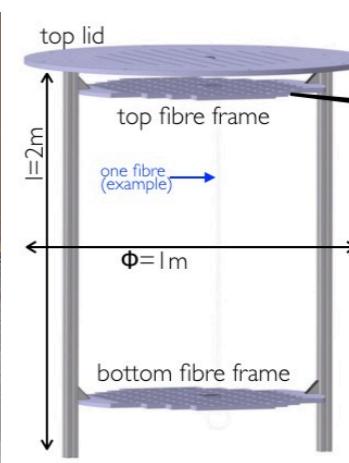
opaque scintillator



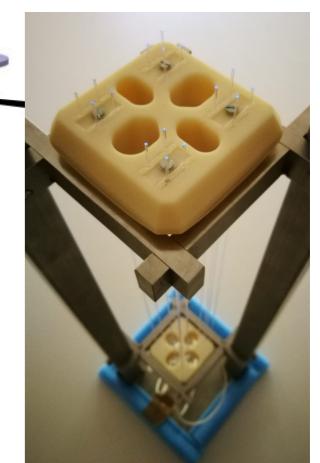
new readout



experimental validation prototype



mechanical design & prototype



# LiquidO...

**Collaborators<sup>⊕</sup>Cooperators**  
(Brasil, Canada, Chile, France, Germany, Italy, Japan, Spain, UK, USA)  
contact: [anatael@in2p3.fr](mailto:anatael@in2p3.fr) & [suekane@awa.tohoku.ac.jp](mailto:suekane@awa.tohoku.ac.jp)

R&D with  
Supporting Physics  
Programme

# SuperNEMO Overview



CENBG (Bordeaux), CPPM (Marseille), Charles U. (Prague), Comenius U. (Bratislava), CTU (Prague), INL (Idaho Falls), Imperial College (London), ITEP (Moscow), JINR (Dubna), LSM (Modane), LPC (Caen), LAL (Orsay), LAPP (Annecy), INR (Kiev), Osaka U. (Osaka), Manchester U. (Manchester), Texas U. (Austin), UCL (London), Jyväskylä U. (Jyväskylä), Warwick U. (Warwick), Werc (Fukui)

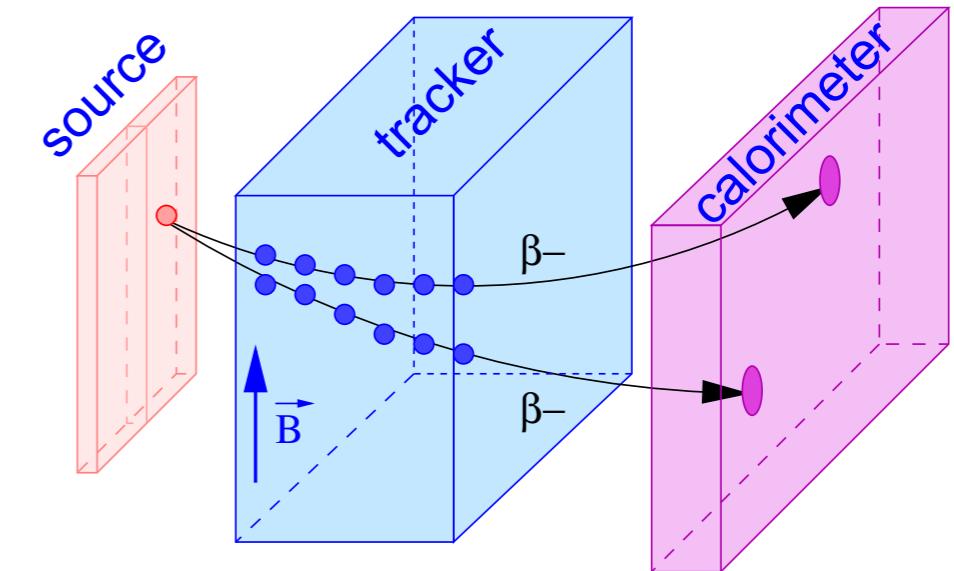
**9 countries, 21 Laboratories**

## The goals of SuperNEMO :

1. Build on the experience of the extremely successful **NEMO-3** experiment.
2. Use the power of the tracking-calorimeter approach to identify and suppress backgrounds.  
This will yield a **zero-background** experiment in the first (**Demonstrator Module**) phase.
3. Prove that a 100 kg scale experiment can reach the **inverted mass hierarchy** (~50 meV) domain.
4. In the event of a discovery by any of the next-generation experiments, demonstrate that the tracking-calorimeter approach is by far the best one for **characterising** the mechanism of  $0\nu\beta\beta$  decay.

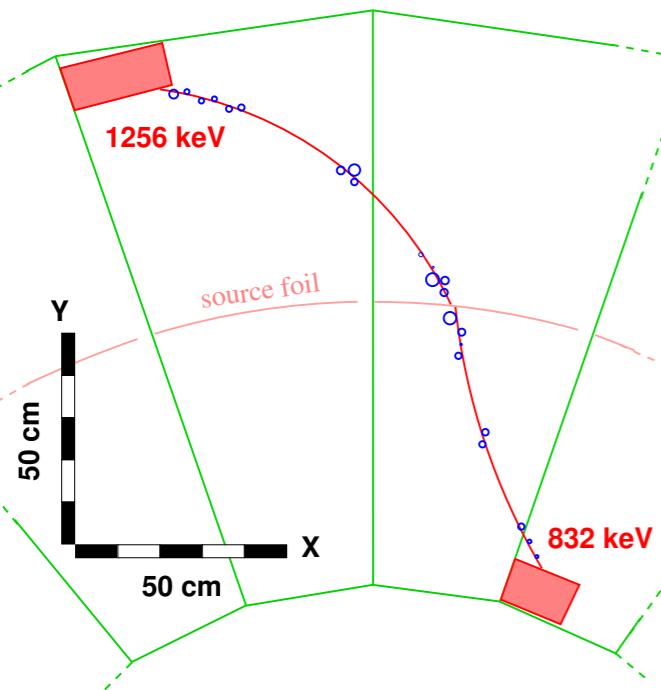
# The Tracker-Calorimeter Technique

- Source separated from detector: (almost) any solid isotope can be hosted.
- Full topological event reconstruction including  $e^\pm$ ,  $\gamma$ -ray and  $\alpha$ -particle identification → strong background control & mechanism probe.
- Successfully exploited by **NEMO-3** experiment:  $0\nu\beta\beta$  limits and  $2\nu\beta\beta$   $T_{1/2}$  for several isotopes.



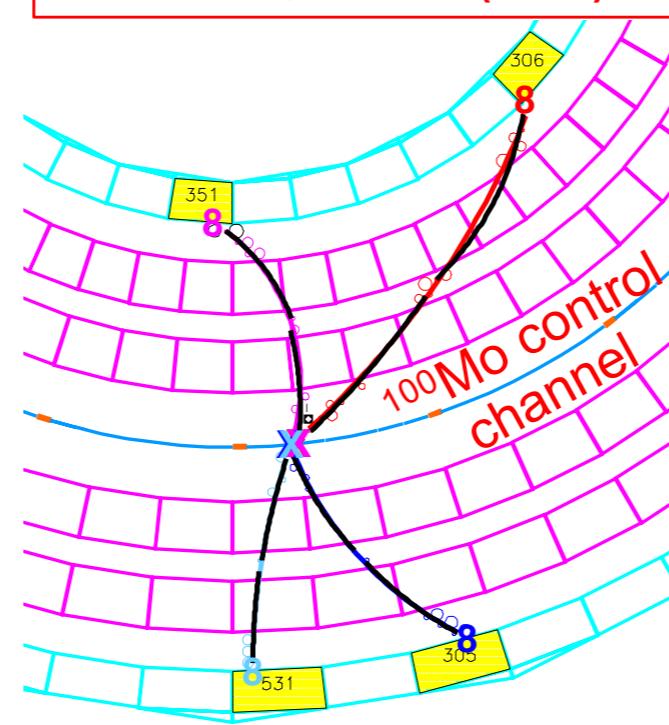
$10^{24}$  year limit with just  
7kg of  $^{100}\text{Mo}$

PRD 92, 072011 (2015)



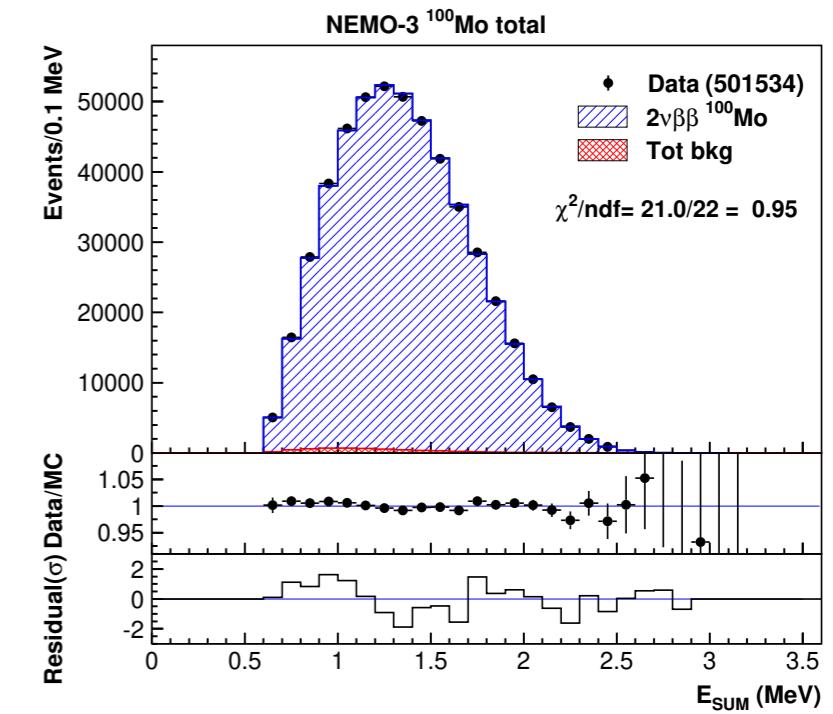
Access unique  
signatures, e.g.  $0\nu4\beta$

PRL 119, 041801 (2017)

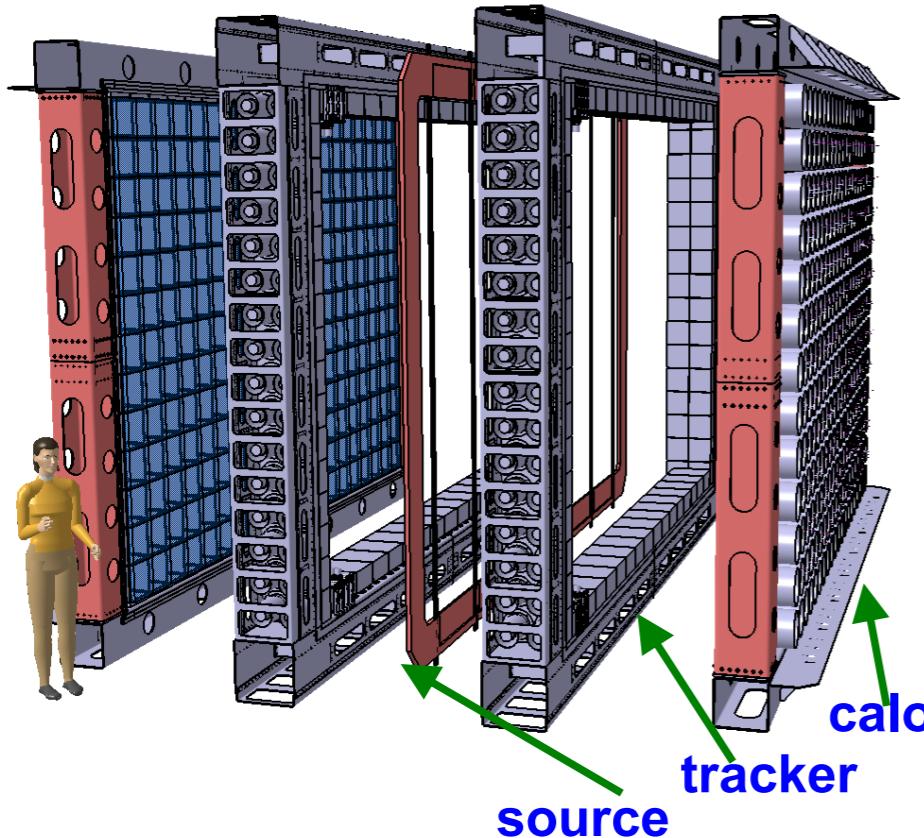


Kinematic probes of DBD  
mechanism (SSD/HSD)

EPJ C79, 440 (2019)



# SuperNEMO - demonstrator



## Demonstrator Module (2.5 year run)

17.5 kg × yr initial exposure :

$$T_{1/2}^{0\nu} > 6.5 \times 10^{24} \text{ yr}$$

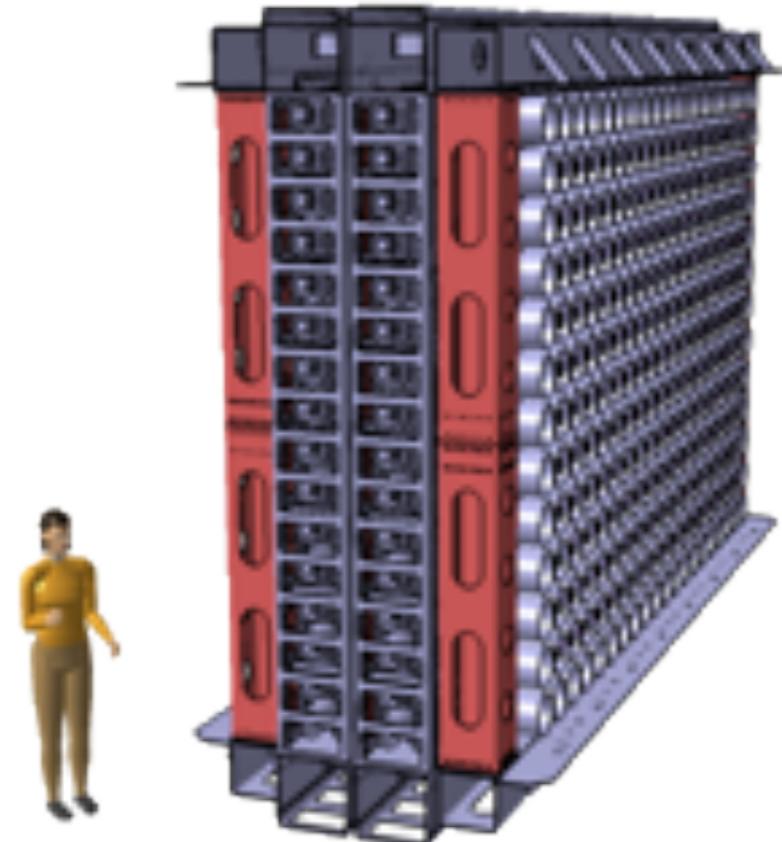
$$\langle m_\nu \rangle < 0.20 - 0.40 \text{ eV}$$



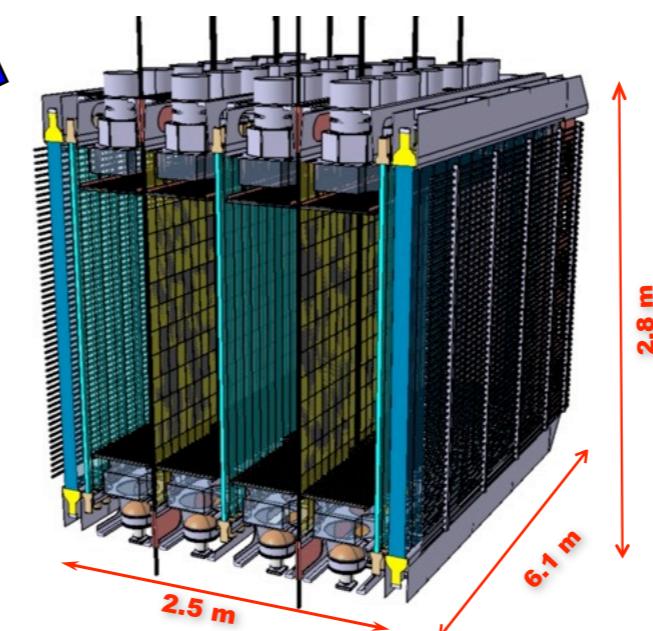
**SuperNEMO  
Demonstrator  
Module :**  
final  
commissioning  
in progress

- Experience from the Demonstrator Module suggests a 100 kg,  $10^{26}$  yr class experiment ("full SuperNEMO") would be possible.
- Full event reconstruction of  $2\nu\beta\beta$  **gives unique precision measurements** and access to nuclear physics :  $g_A$  analysis in preparation.
- Can the technique be extended to **confirm a signal anywhere in the IH region ? R&D and isotope developments** can point the way.

# SuperNEMO Future Directions



- A **unique approach** with access to fundamental nuclear physics.
- The best technique for **exploring a signal**.
- Europe-led.
- Continued support and R&D is essential.



Full SuperNEMO

500 kg × yr :

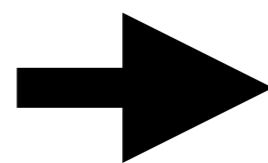
$$T_{1/2}^{0\nu} > 10^{26} \text{ yr}$$

$$\langle m_\nu \rangle < 50 - 100 \text{ meV}$$

Alternative Designs



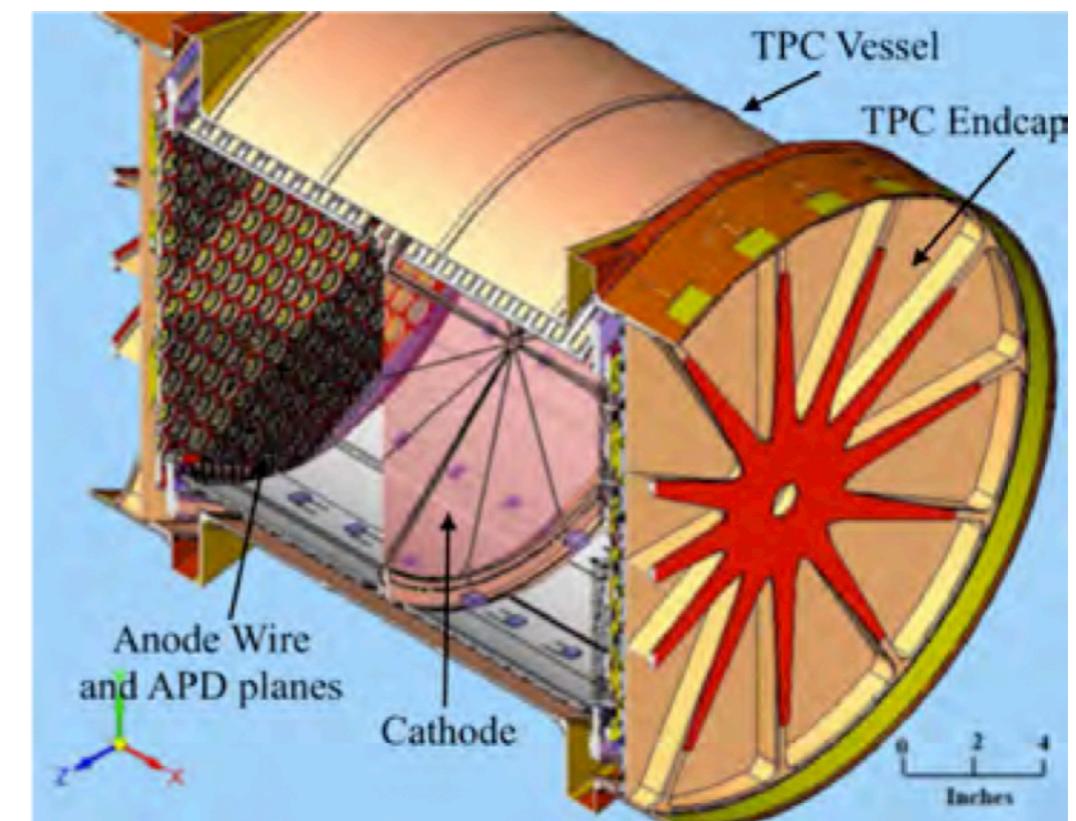
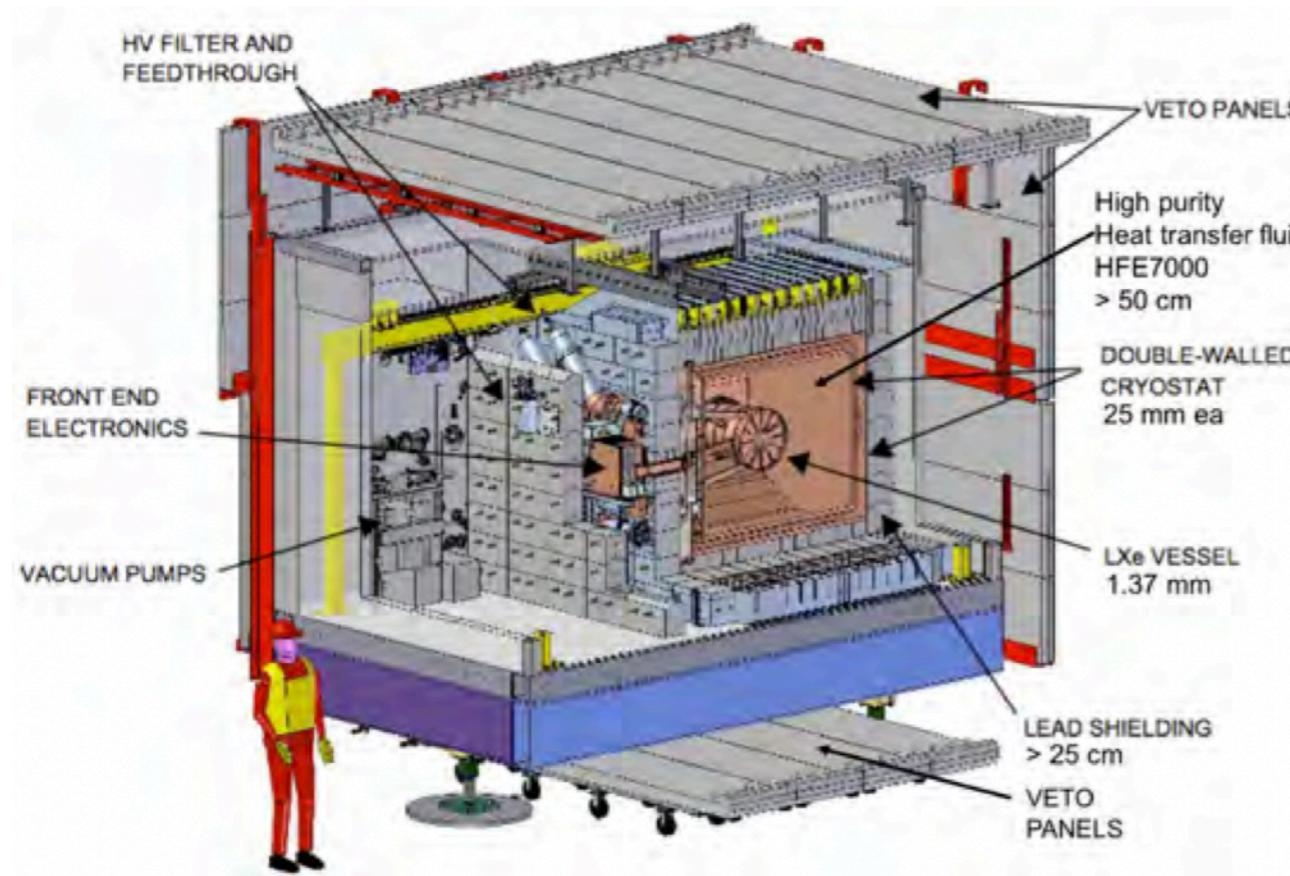
# Major Projects With Future Plans Currently Not On EU Roadmap

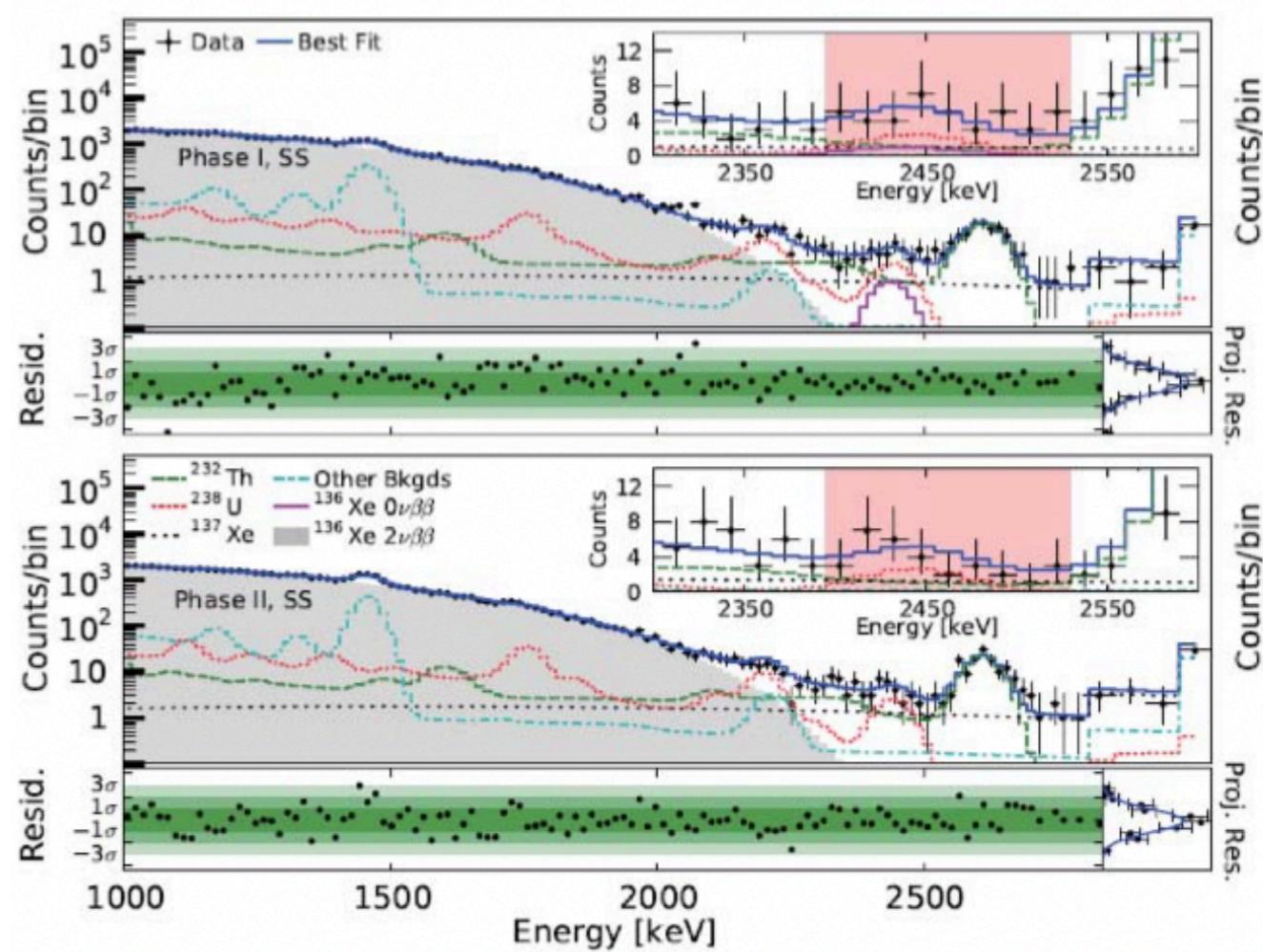
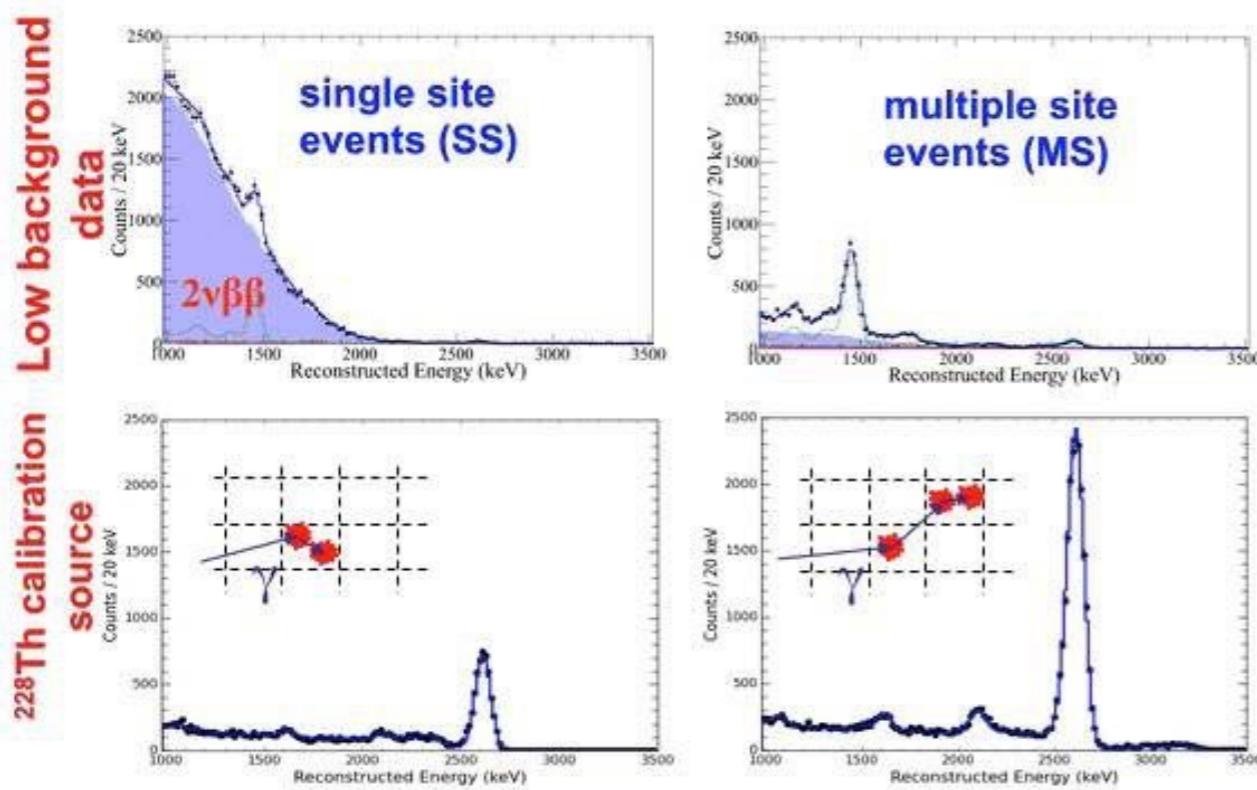
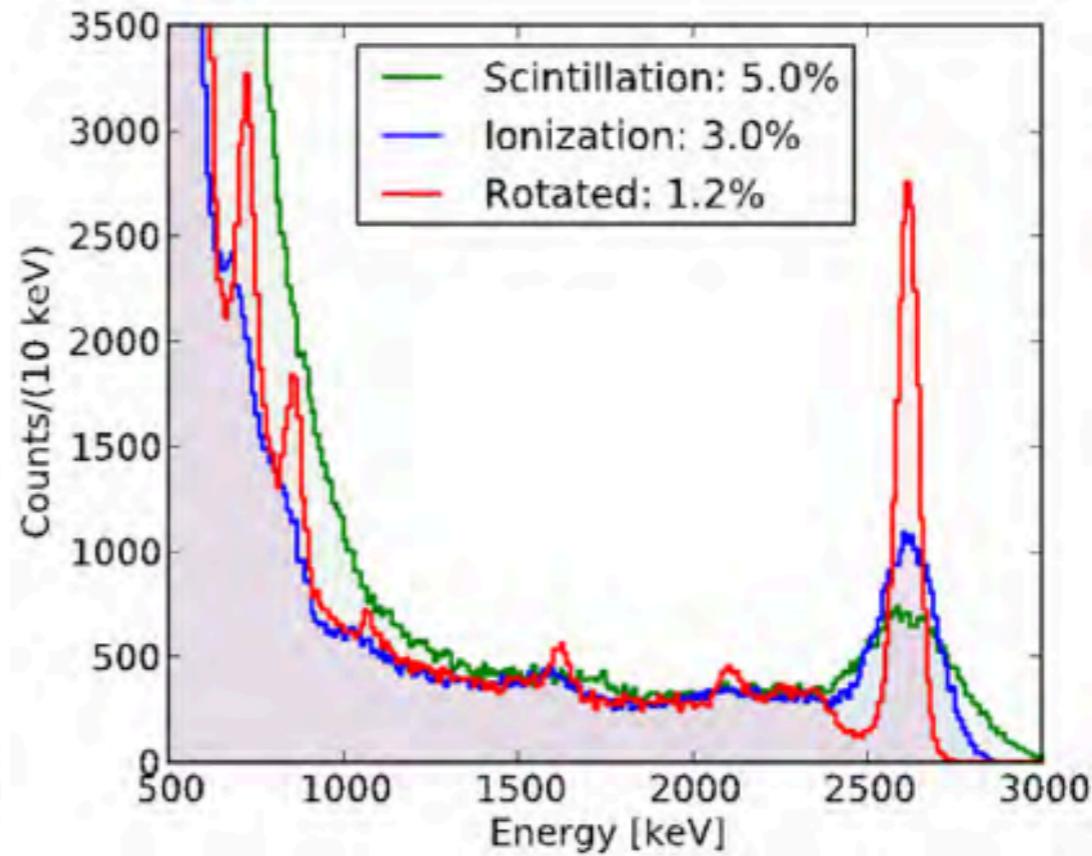
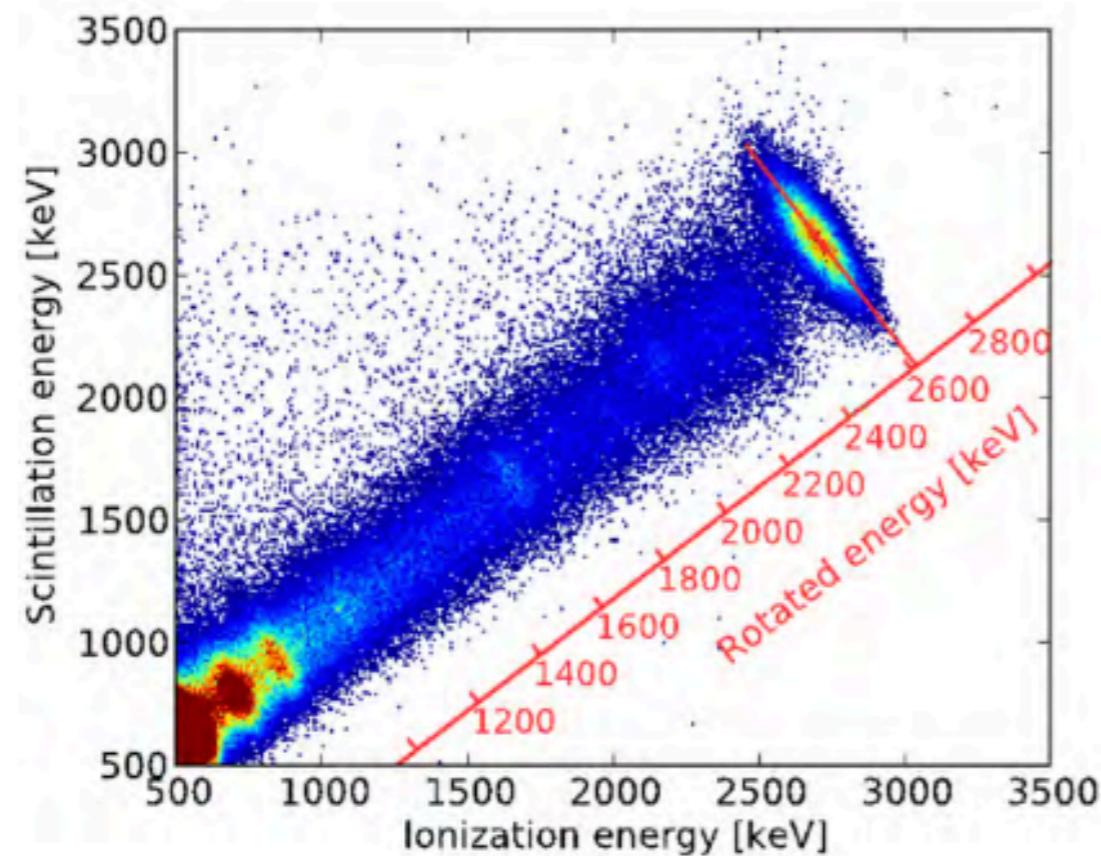


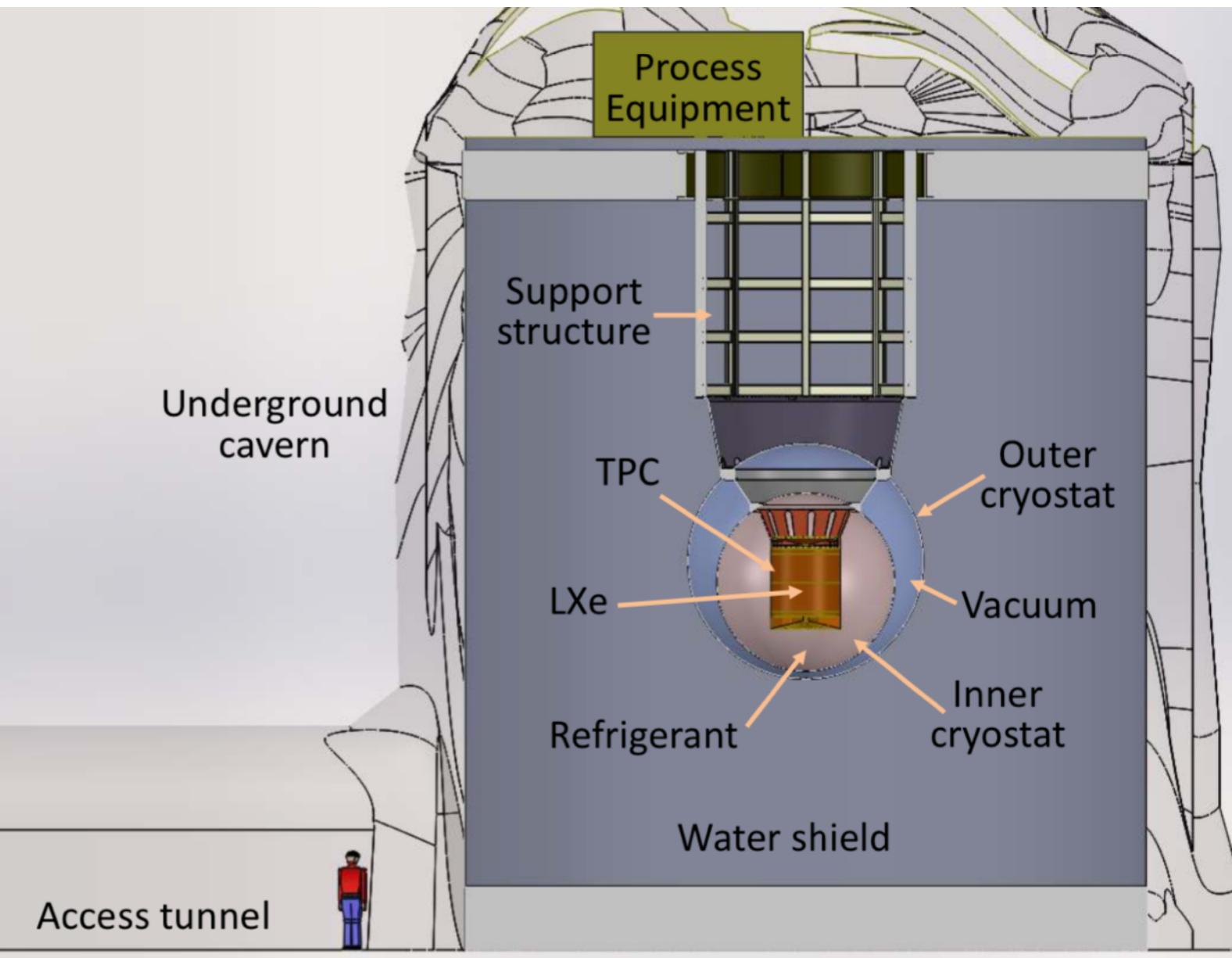
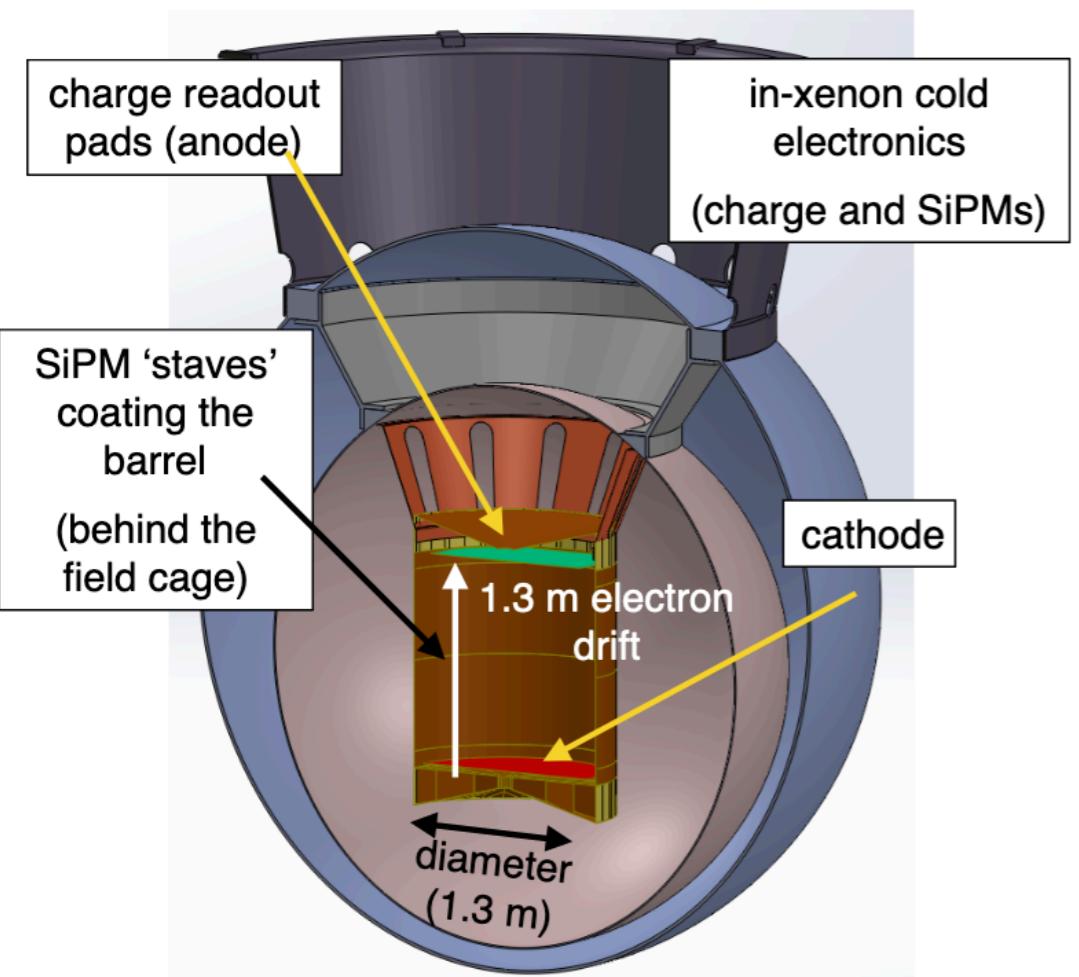
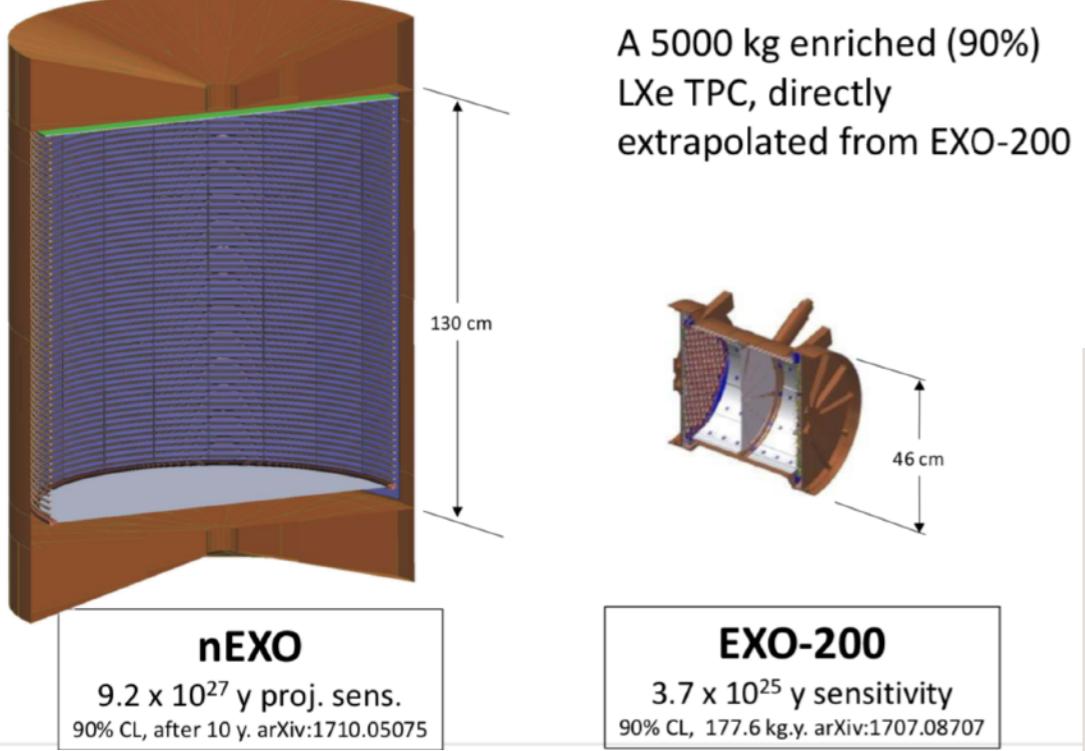
# nEXO

(Andrea Pocar, TAUP 2019 &  
nEXO pre-conceptual design report)

**EXO-200**



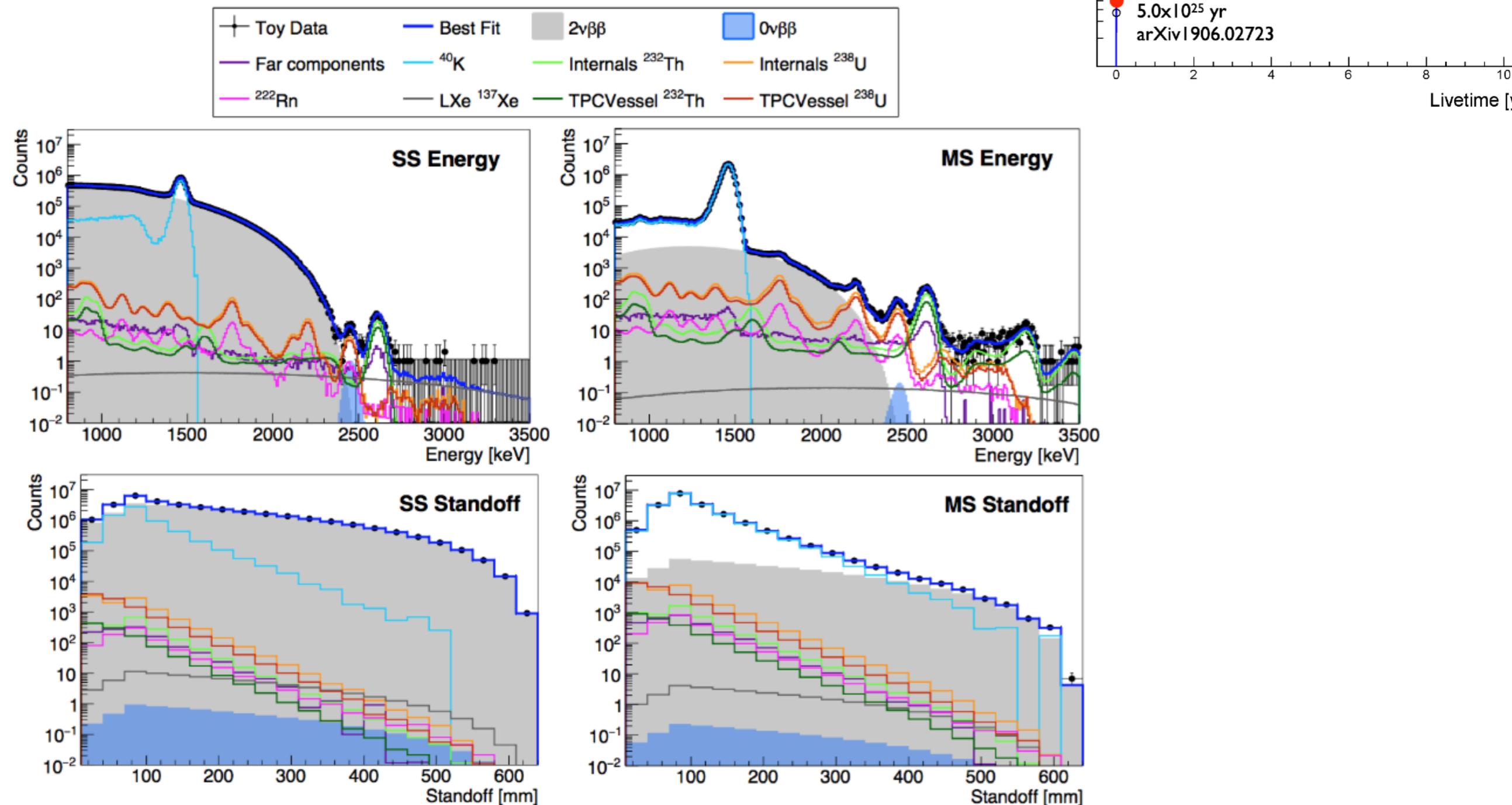




# from EXO-200 to nEXO

What	Why
~30x volume/mass	To give sensitivity to the inverted hierarchy
No cathode in the middle	Larger low background volume/no $^{214}\text{Bi}$ in the middle
6x HV for the same field	Larger detector and one drift cell
>3x electron lifetime	Larger detector and one drift cell
Better photodetector coverage	Energy resolution, lower scintillation threshold
SiPM instead of APDs	Higher gain, lower bias, lighter, E resolution, lower scintillation threshold
In LXe electronics	Lower noise, more stable, fewer cables/feedthroughs, E resolution, lower threshold for Compton ID
Lower outgassing components	Longer electron lifetime
Different calibration methods	Very “deep” detector (by design)
Deeper site	Less cosmogenic activation
Larger vessels	5 ton detector and more shielding

# Multi-Parameter Fit



**Figure 3.9:** Result of the NLL fit to a representative nEXO toy dataset generated assuming a  $0\nu\beta\beta$  signal corresponding to a half-life of  $5.7 \times 10^{27} \text{ y}$  and 10 years of detector live time. The top plots are the energy distribution histograms while the bottom plots are the standoff distances; left (right) spectra are for SS (MS)

# nEXO publications: detector, sensitivity, R&D

- "Simulation of charge readout with segmented tiles in nEXO"  
arXiv:1907.07512
- "Characterization of the Hamamatsu VUV4 MPPCs for nEXO"  
arXiv:1903.03663, Nucl Inst Meth A 940 371 (2019)
- "Imaging individual Ba atoms in solid xenon for barium tagging in nEXO" Nature 569 (2019) 203 \*
- "Study of Silicon Photomultiplier Performance in External Electric Fields" JINST 13 (2018) T09006
- "VUV-sensitive Silicon Photomultipliers for Xe Scintillation Light Detection in nEXO" IEEE Trans NS 65 (2018) 2823
- "nEXO pCDR" arXiv:1805.11142 (2018)
- "Sensitivity and Discovery Potential of nEXO to  $0\nu\beta\beta$  decay"  
Phys. Rev. C 97 065503 (2018)
- "Characterization of an Ionization Readout Tile for nEXO"  
J.Inst. 13 P01006 (2018)
- "Characterization of Silicon Photomultipliers for nEXO"  
IEEE Trans. NS 62 1825 (2015)

\* Not nEXO baseline

nEXO Pre-Conceptual Design Report



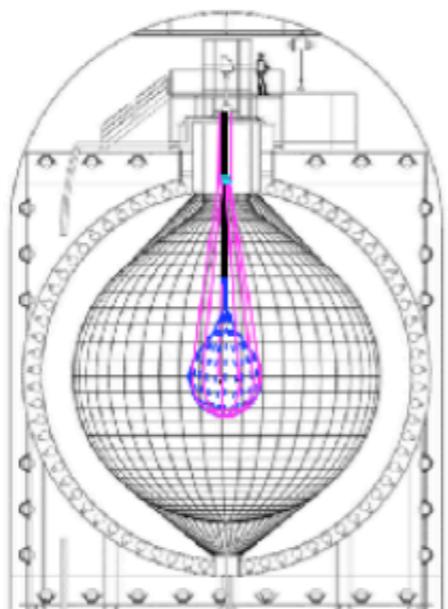
## Abstract

The projected performance and detector configuration of nEXO are described in this pre-Conceptual Design Report (pCDR). nEXO is a tonne-scale neutrinoless double beta ( $0\nu\beta\beta$ ) decay search in  $^{136}\text{Xe}$ , based on the ultra-low background liquid xenon technology validated by EXO-200. With  $\sim 5000$  kg of xenon enriched to 90% in the isotope 136, nEXO has a projected half-life sensitivity of approximately  $10^{28}$  years. This represents an improvement in sensitivity of about two orders of magnitude with respect to current results. Based on the experience gained from EXO-200 and the effectiveness of xenon purification techniques, we expect the background to be dominated by external sources of radiation. The sensitivity increase is, therefore, entirely derived from the increase of active mass in a monolithic and homogeneous detector, along with some technical advances perfected in the course of a dedicated R&D program. Hence the risk which is inherent to the construction of a large, ultra-low background detector is reduced, as the intrinsic radioactive contamination requirements are generally not beyond those demonstrated with the present generation  $0\nu\beta\beta$  decay experiments. Indeed, most of the required materials have been already assayed or reasonable estimates of their properties are at hand. The details described herein represent the basic design of the detector configuration as of early 2018. Where potential design improvements are possible, alternatives are discussed.

This design for nEXO presents a compelling path towards a next generation search for  $0\nu\beta\beta$ , with a substantial possibility to discover physics beyond the Standard Model.

May 28, 2018

arXiv:1805.11142 [physics.ins-det] 28 May 2018

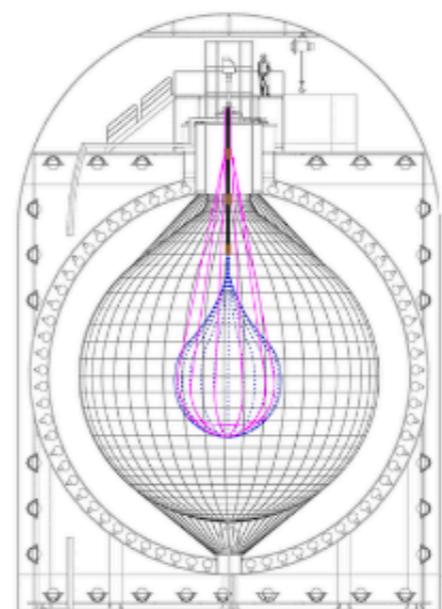
Past

KamLAND-Zen 400

R = 1.54m mini-balloon

Xenon 320 ~ 380 kg

2011 ~ 2015

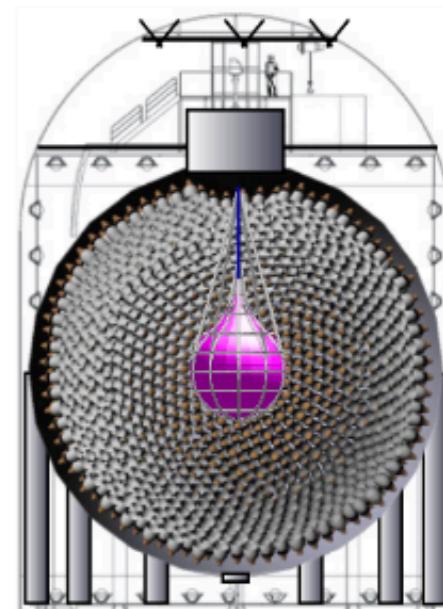
Ongoing

KamLAND-Zen 800

R = 1.90m mini-balloon

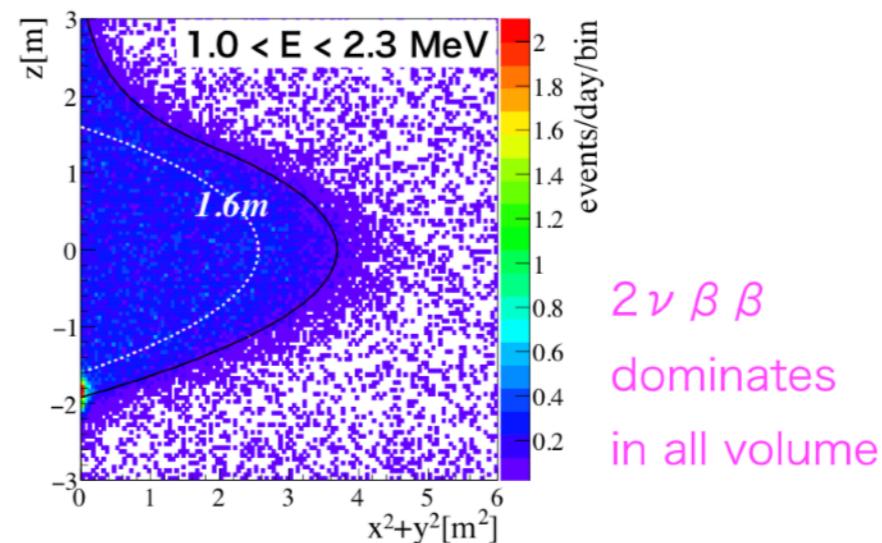
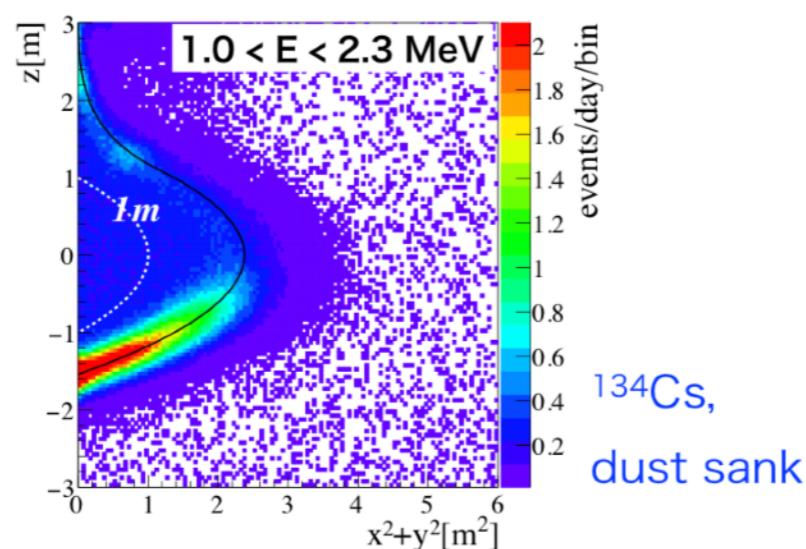
Xenon 745 kg

Jan. 22, 2019 ~

Future

KamLAND2-Zen

Xenon ~ 1 ton

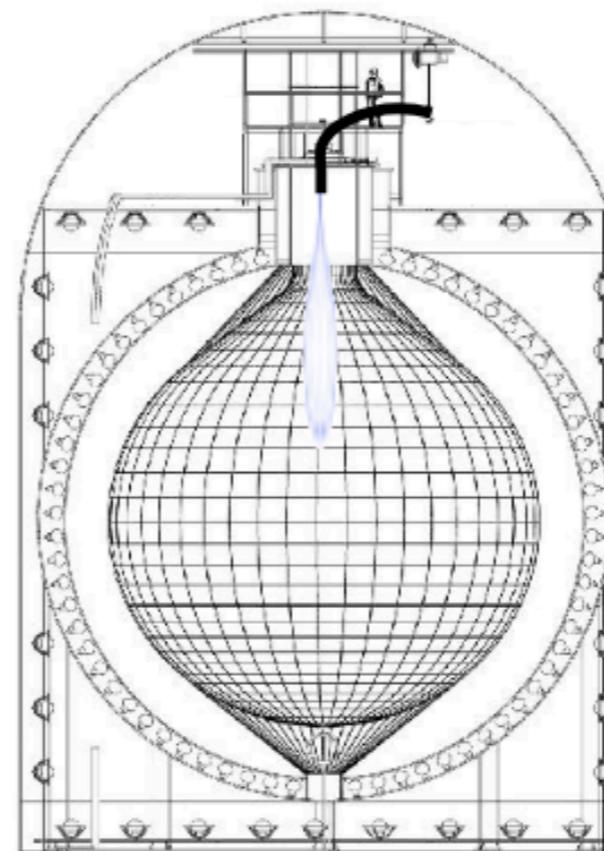


# Mini-balloon installation

May 10, 2018



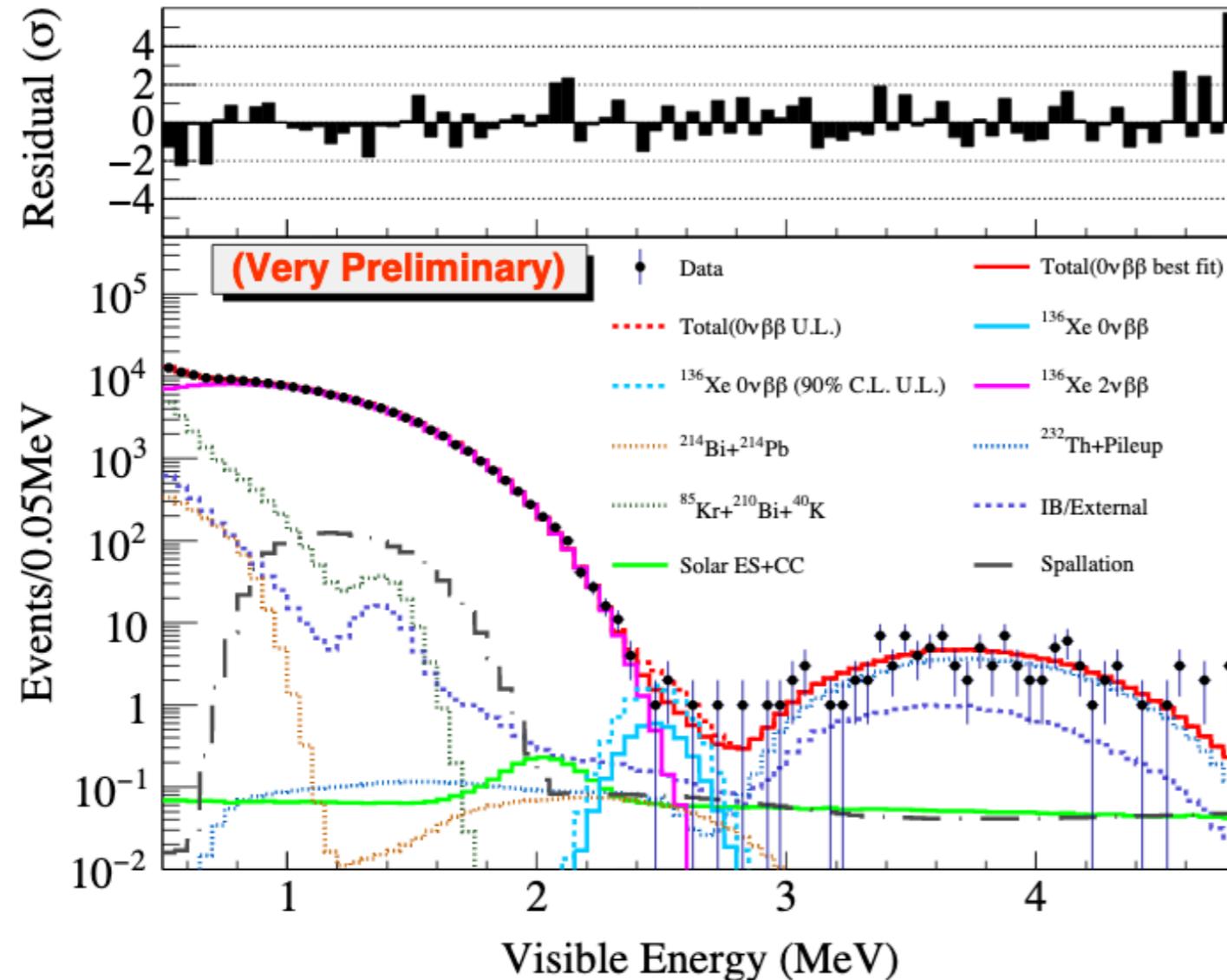
50cm width for detector access



Mini-balloon installation  
with LS of +0.4% weight  
compared with  
KamLAND LS

Expansion with +0.025%  
weight non-xenon LS





Best fit : 2.1 events/day/kton-XeLS

90% Upper limit : < 6.0 events/day/kton-XeLS

$T_{1/2}^{0\nu} > 4 \times 10^{25} \text{ year}$  (90% C.L.)

Observed events	8
Best-fit total events	10.7
$0\nu\beta\beta$	2.8
$2\nu\beta\beta$	5.1
$^{214}\text{Bi}$ in LS	0.4
$^{212}\text{Bi}-^{212}\text{Po}$ pile-up	0.4
Film BG ( $^{214}\text{Bi}$ )	0.9
Spallation ( $^{10}\text{C}$ )	0.2
Spallation ( $^{137}\text{Xe}$ )	0.1
Spallation (short-lived)	0.2
Solar $^8\text{B}$ $\nu$	0.4



$0\nu\beta\beta$

- Reactor neutrinos (will resolve  $\Delta m_{12}^2$  tension)
- Low energy solar neutrinos
- Geo neutrinos
- Supernova neutrinos
- Invisible modes of nucleon decay
- 
- 
-

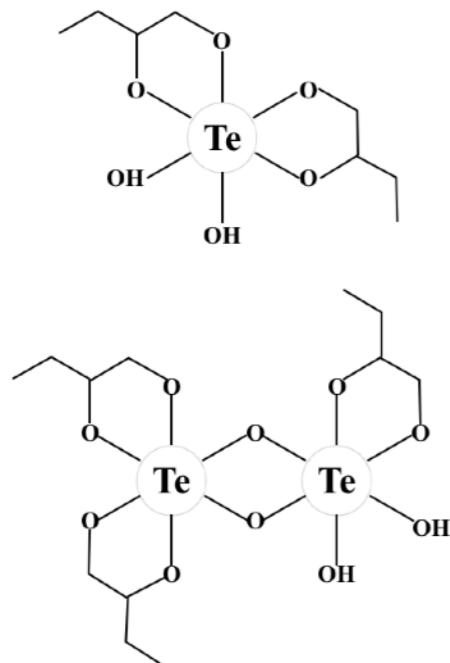
# $^{130}\text{Te}$ -loaded scintillator

- $^{130}\text{Te}$  is the most cost effective isotope:  
Enriched  $^{136}\text{Xe}$  ~ \$20,000 /kg of isotope  
Natural Te (34.5%  $^{130}\text{Te}$ ) ~ \$ 150 /kg of isotope
- $^{130}\text{Te}$  has good predicted matrix element values (better than  $^{136}\text{Xe}$ ) and a good phase space factor (comparable to  $^{136}\text{Xe}$  and ~6 times better than  $^{76}\text{Ge}$ )
- Liquid scintillator is the most cost effective and scalable  $0\nu\beta\beta$  detection technology

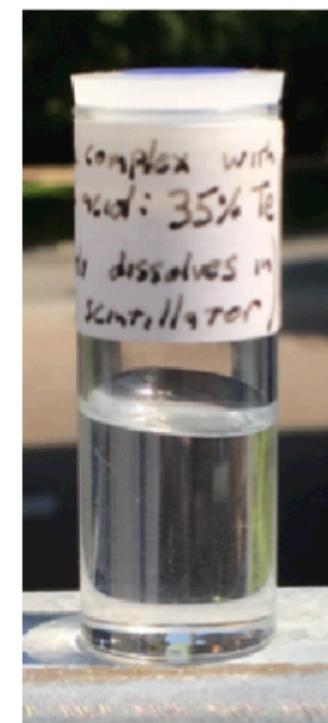
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- Liquid scintillator is the most cost effective and scalable  $0\nu\beta\beta$  detection technology

## New loading method (developed in UK): Te-diol complex



- Simple synthesis
- Single safe, distillable chemical
- Low radioactivity levels
- Minimal optical absorption
- High light levels at 0.5% Te Loading



**LAB arrival at site**



**Scintillator purification system operational**



**All of the Te needed for Phase I is now underground**



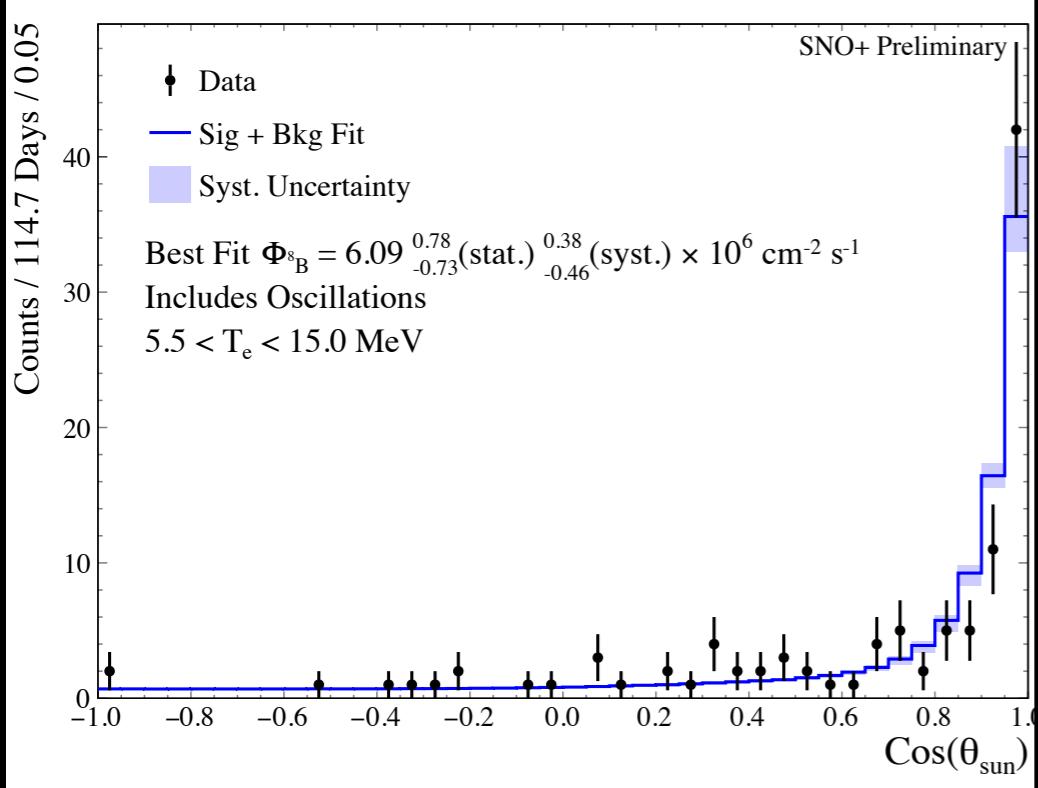
**Te purification and loading plants construction finished (starting commissioning)**



# Recent Water Results

PHYSICAL REVIEW D 99, 012012 (2019)

## Measurement of the ${}^8\text{B}$ solar neutrino flux in SNO+ with very low backgrounds

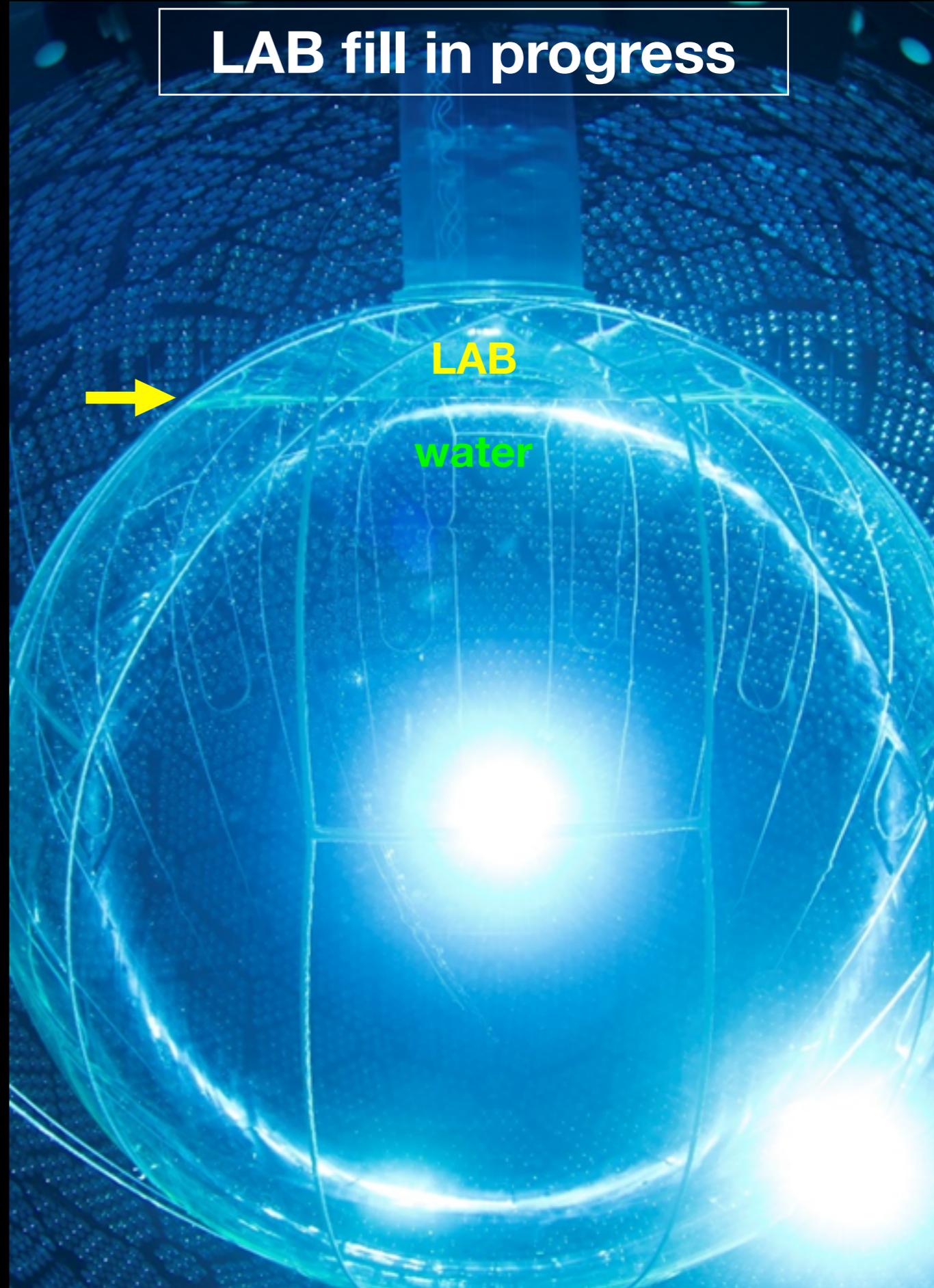


PHYSICAL REVIEW D 99, 032008 (2019)

## Search for invisible modes of nucleon decay in water with the SNO+ detector

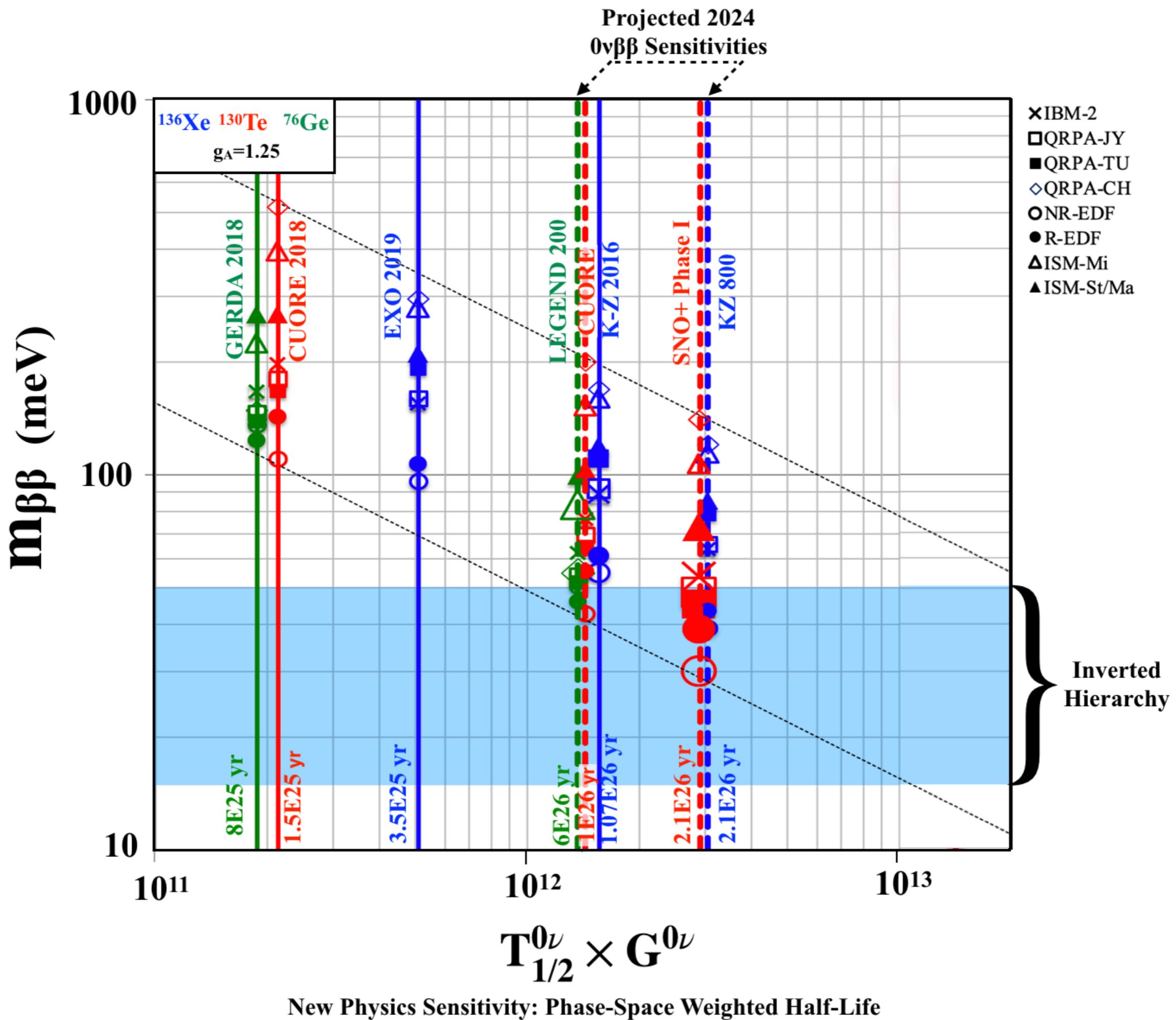
	Spectral analysis	Counting analysis	Existing limits
$n$	$2.5 \times 10^{29} \text{ y}$	$2.6 \times 10^{29} \text{ y}$	$5.8 \times 10^{29} \text{ y}$ [9]
$p$	$3.6 \times 10^{29} \text{ y}$	$3.4 \times 10^{29} \text{ y}$	$2.1 \times 10^{29} \text{ y}$ [10]
$pp$	$4.7 \times 10^{28} \text{ y}$	$4.1 \times 10^{28} \text{ y}$	$5.0 \times 10^{25} \text{ y}$ [11]
$pn$	$2.6 \times 10^{28} \text{ y}$	$2.3 \times 10^{28} \text{ y}$	$2.1 \times 10^{25} \text{ y}$ [13]
$nn$	$1.3 \times 10^{28} \text{ y}$	$0.6 \times 10^{28} \text{ y}$	$1.4 \times 10^{30} \text{ y}$ [9]

LAB fill in progress



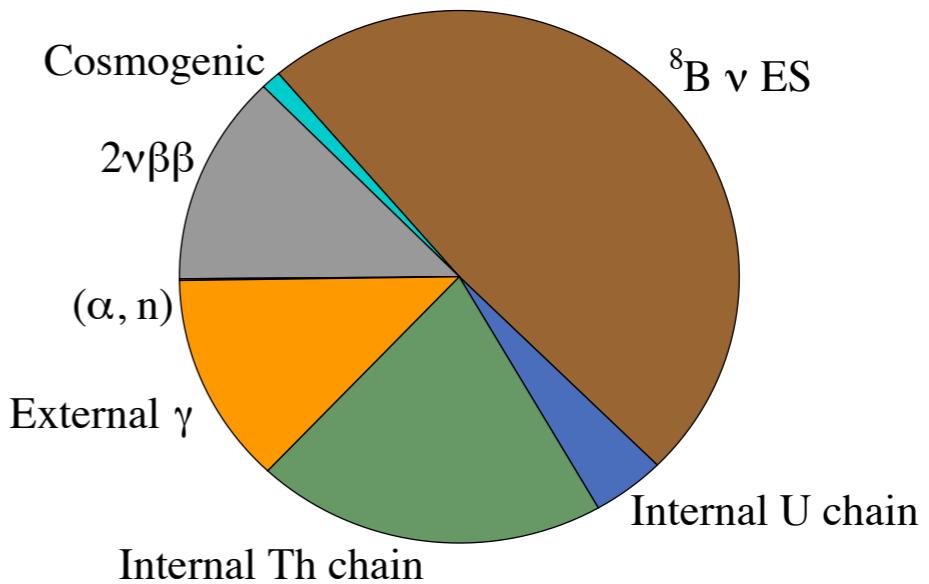
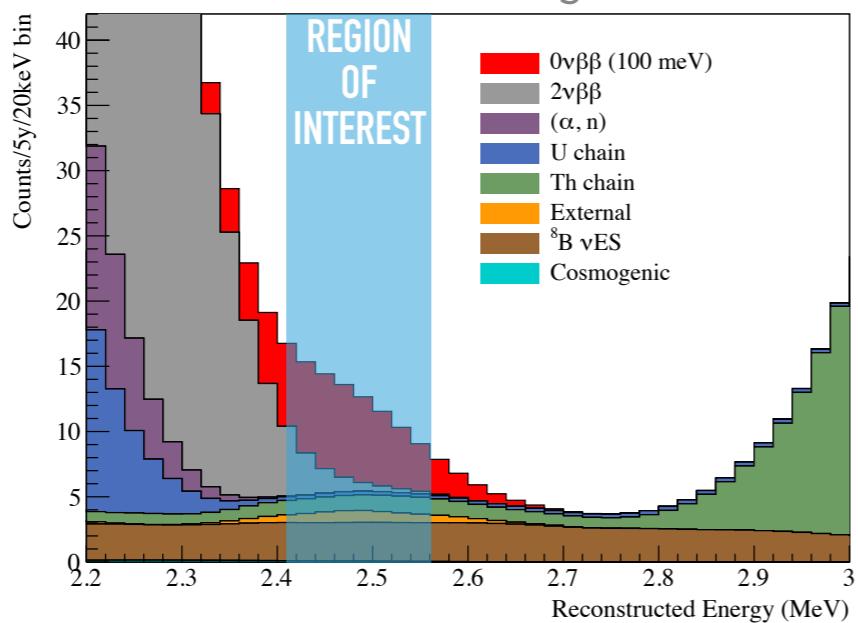
Several other papers in preparation

Ready for Te loading next year

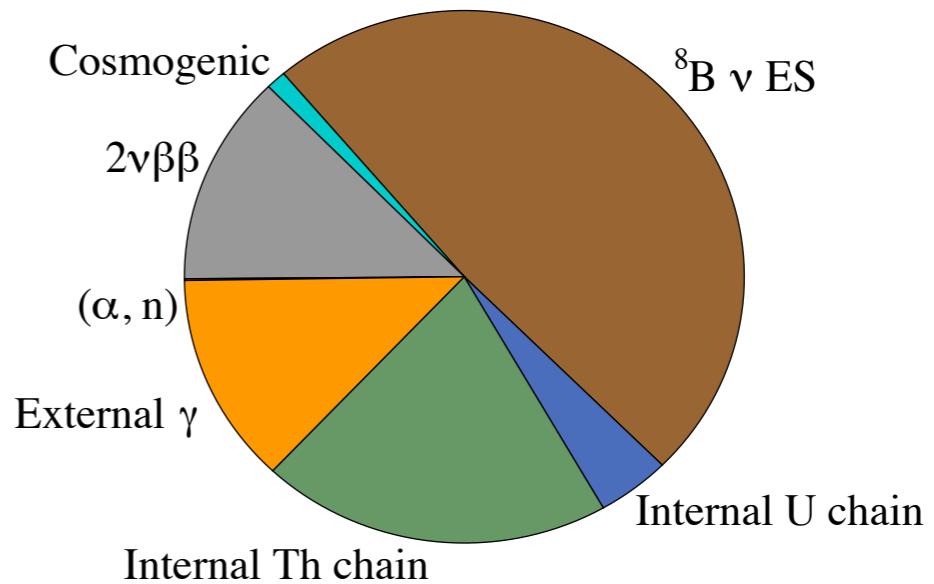
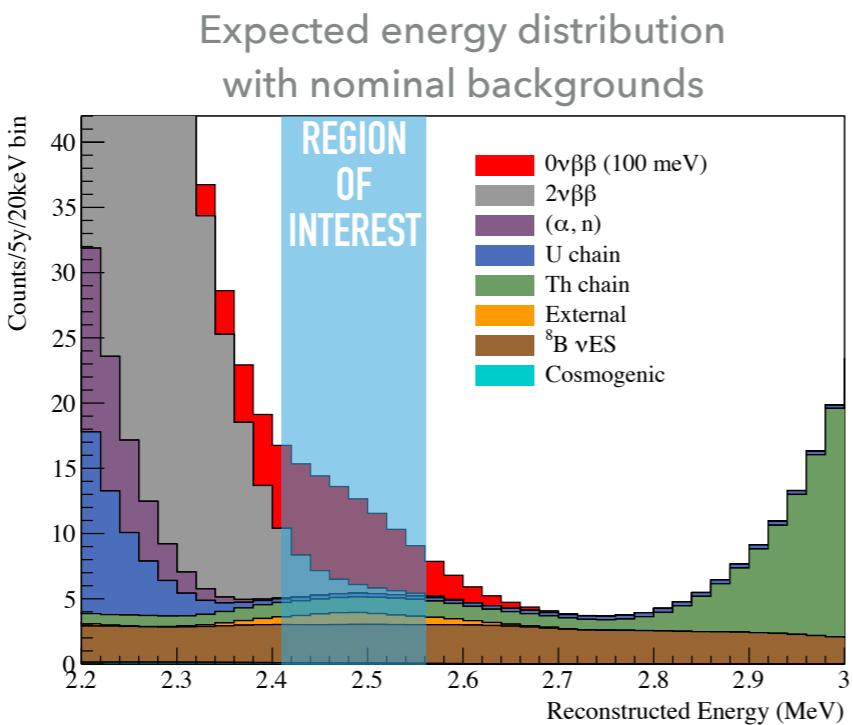


## Phase I:

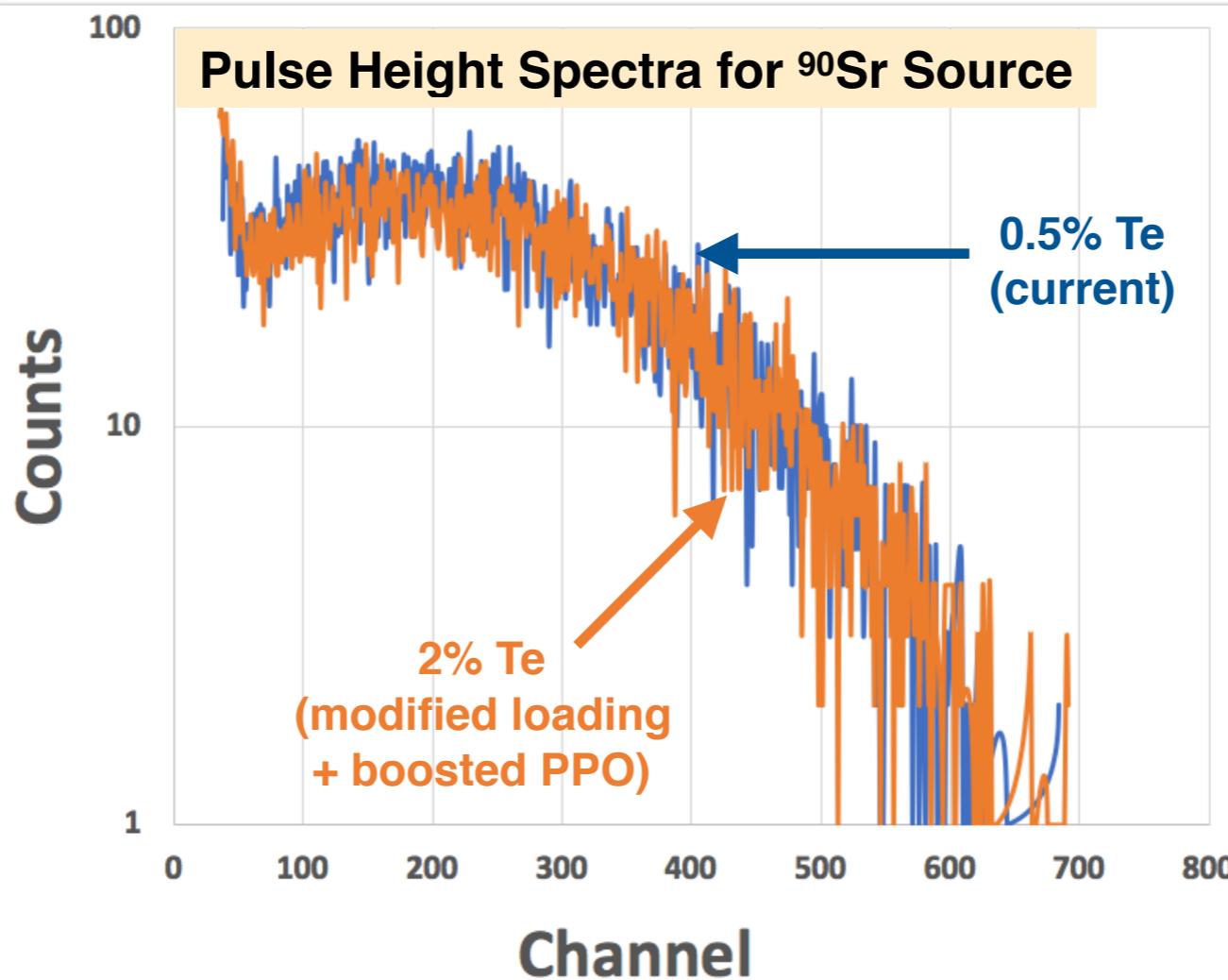
Expected energy distribution  
with nominal backgrounds

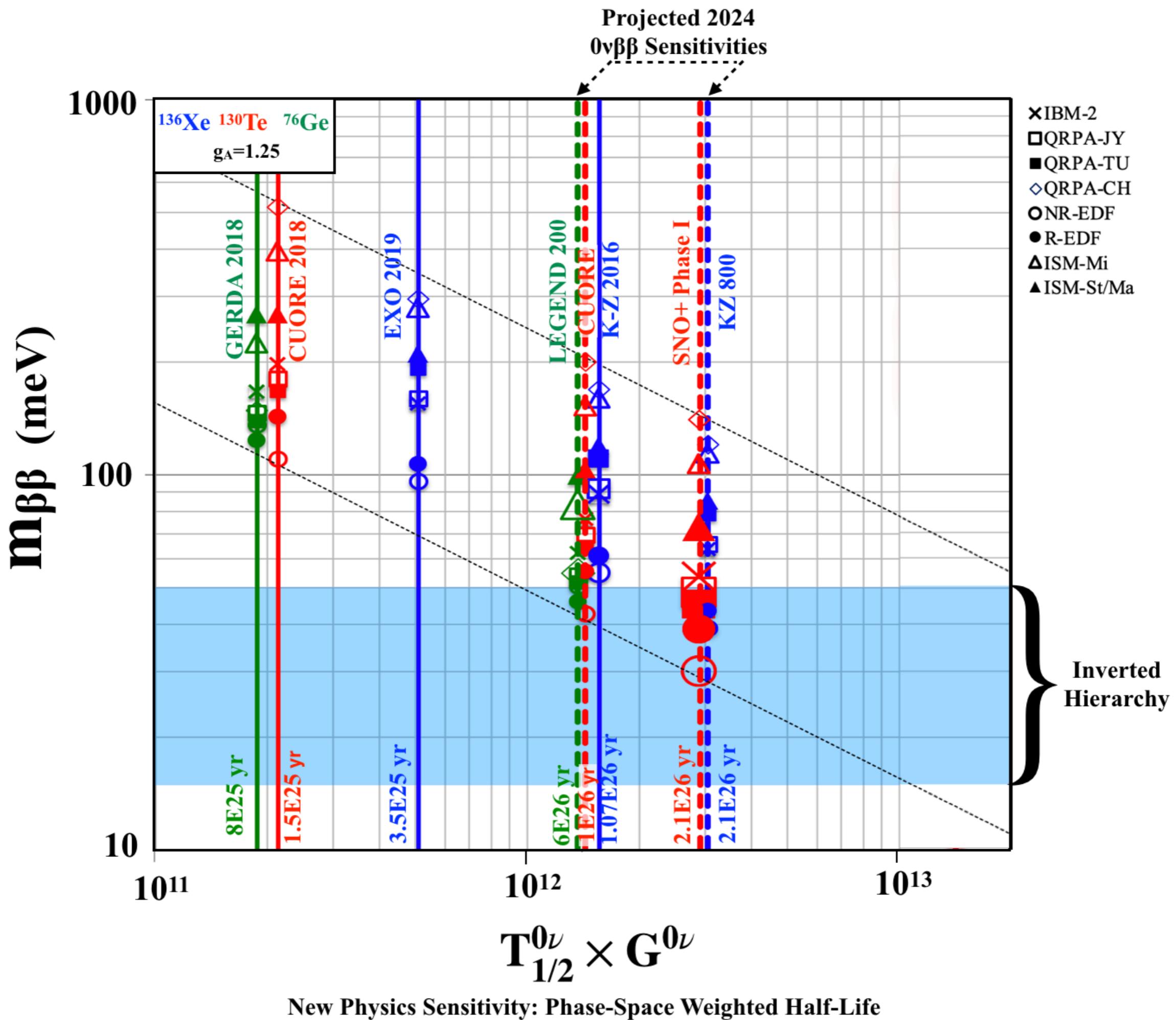


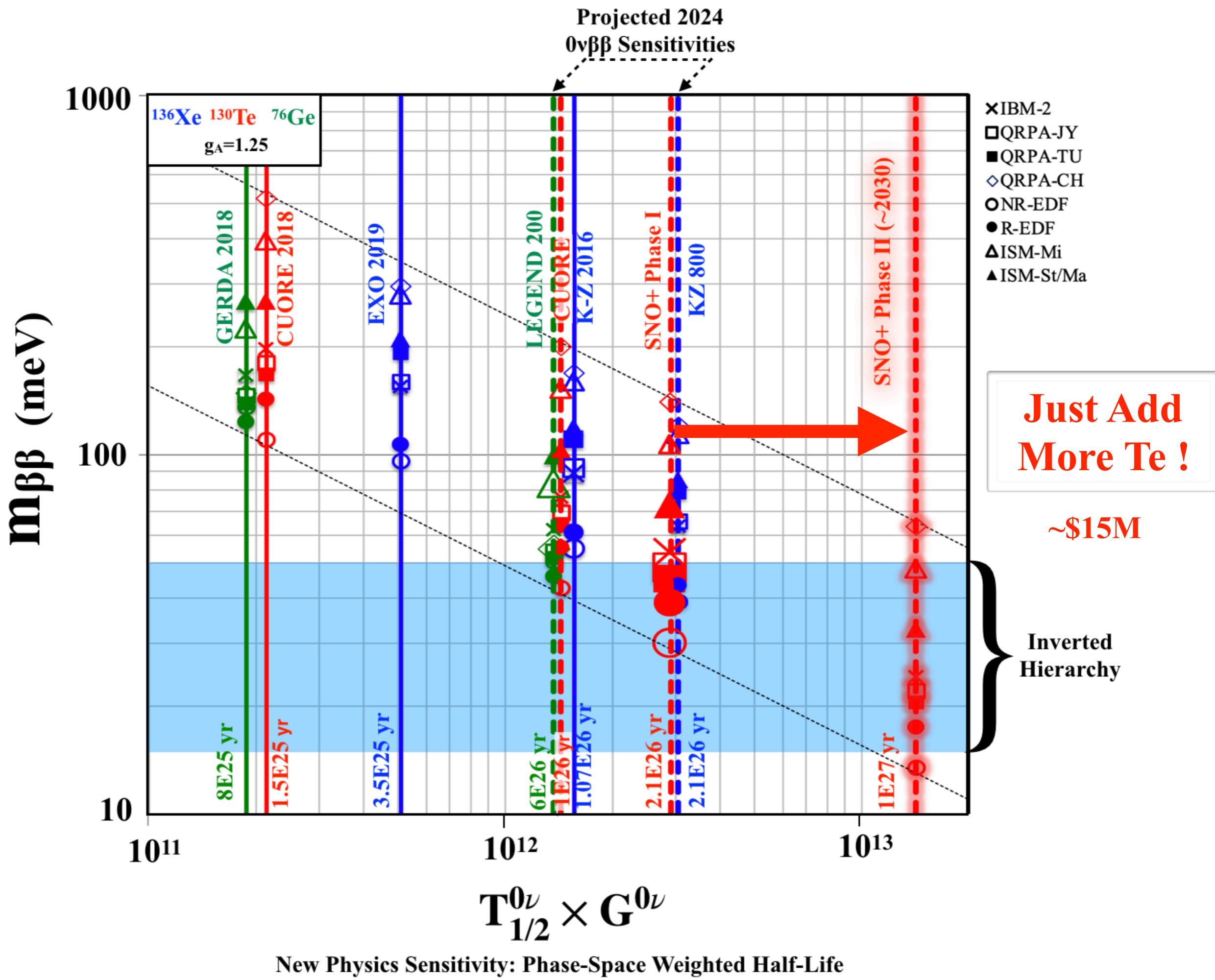
## Phase I:



### Improved Loading Protocol to Move Beyond Phase I







# Other Recent Advances in the General Loaded Scintillator Approach

# Multi-site event discrimination in large liquid scintillation detectors

(Dunger and Biller, NIM, 943, 162420, 1 November 2019, arXiv:1904.00440)



Compton length for 1 MeV  
 $\gamma$  in LAB  $\sim 20\text{cm}$ , vs vertex  
resolution of  $\sim 10\text{cm}$

**use time residuals  
from vertex fit to form  
PDFs for a likelihood  
discriminant**

## In situ calibration of technique

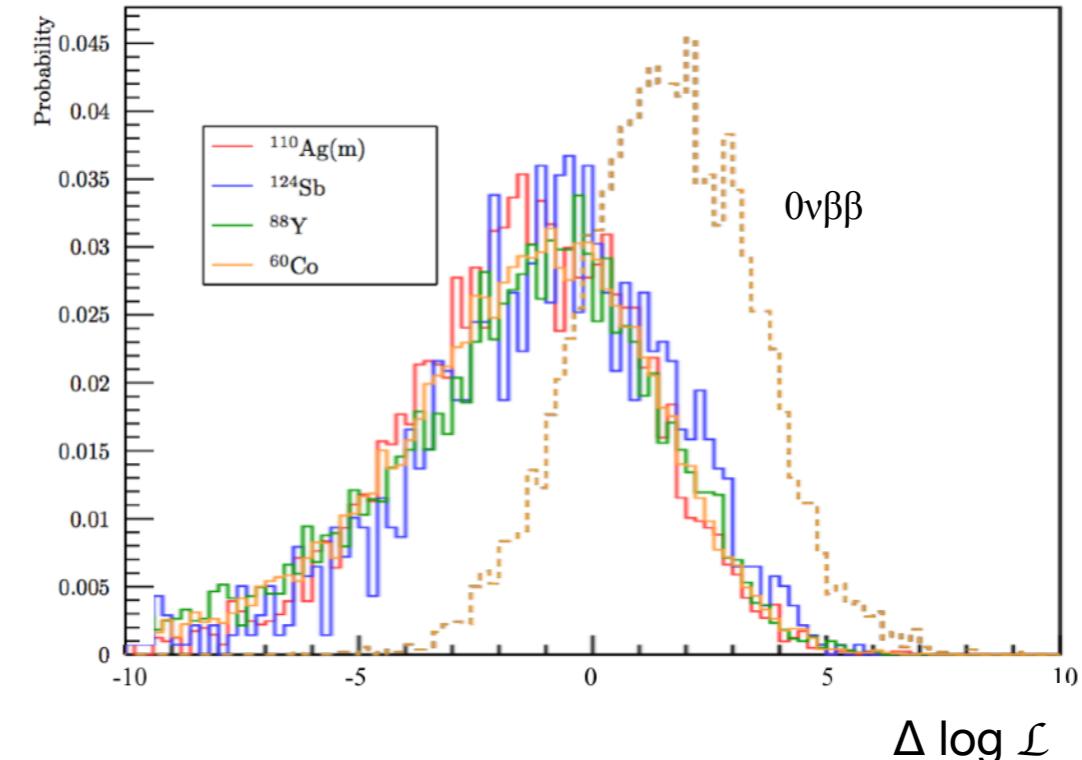
multi-site events:

- $\alpha$ -tagged  $^{214}\text{Bi}$  &  $^{208}\text{Tl}$  decays
- external  $\gamma$ 's (dominant at higher radius)

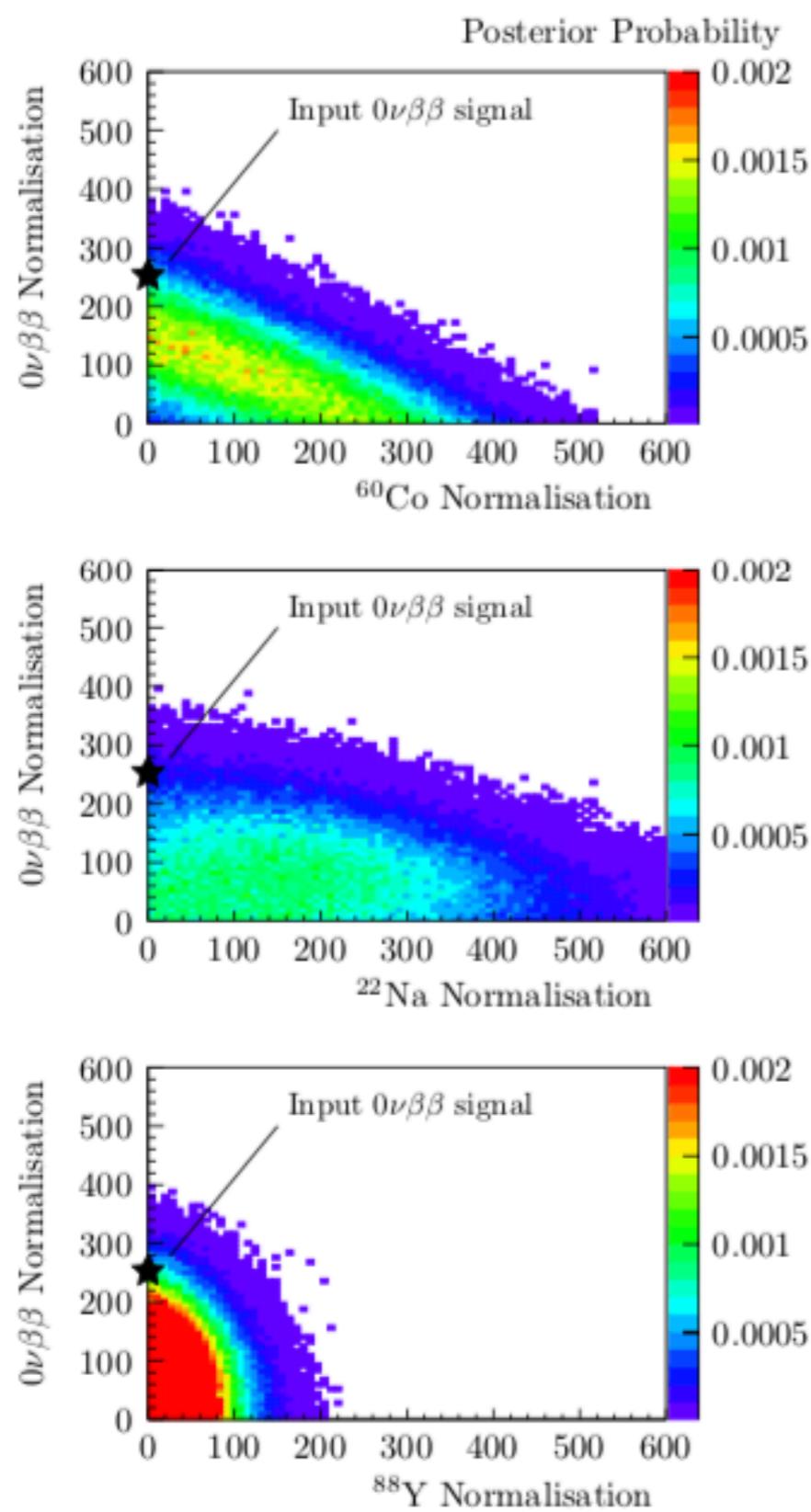
single-site events:

- $2\nu\beta\beta$  events (dominant at lower energy)
- $^8\text{B}$  solar  $\nu$  (dominant at higher energies)

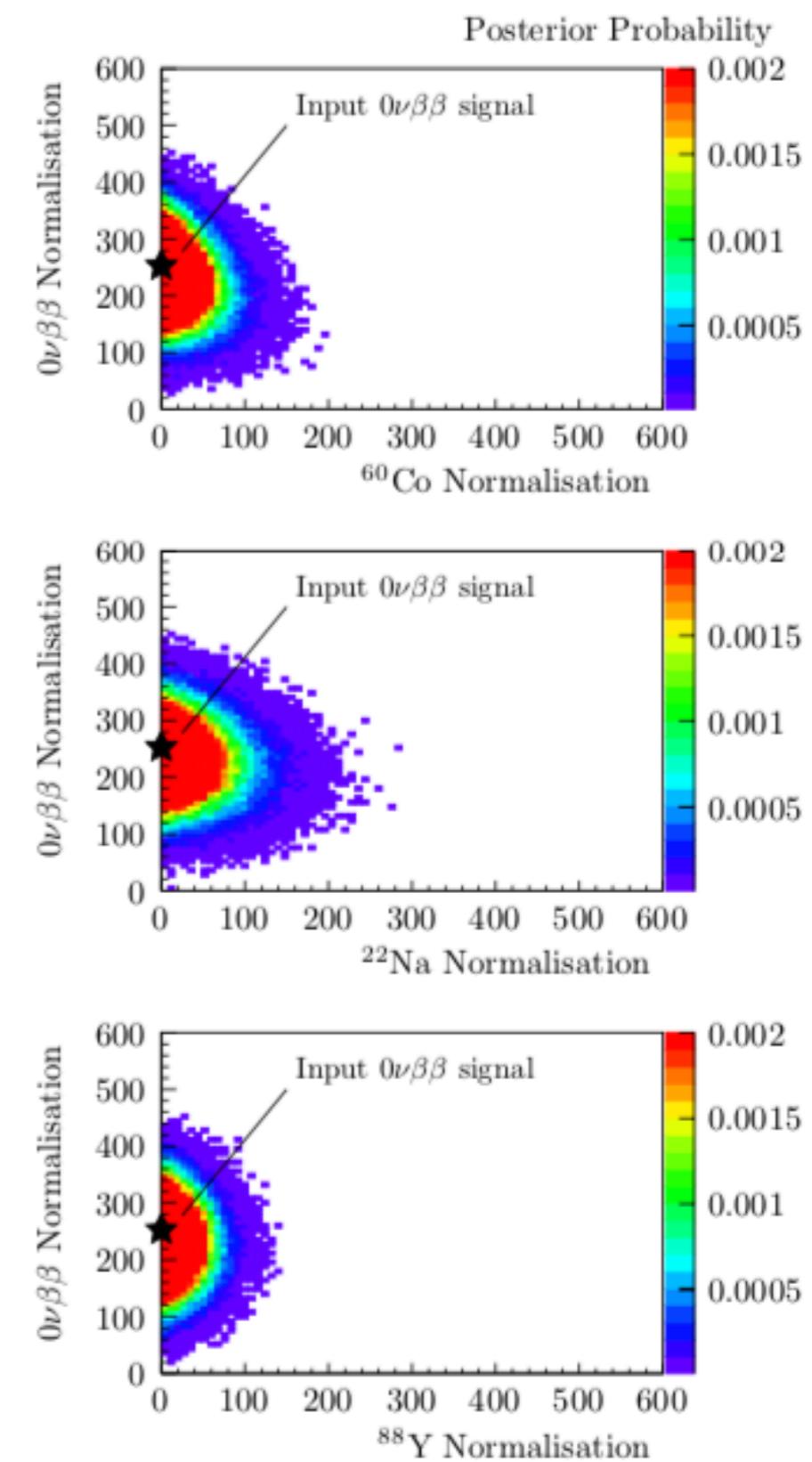
can also use deployed sources



**without multi-site parameter**

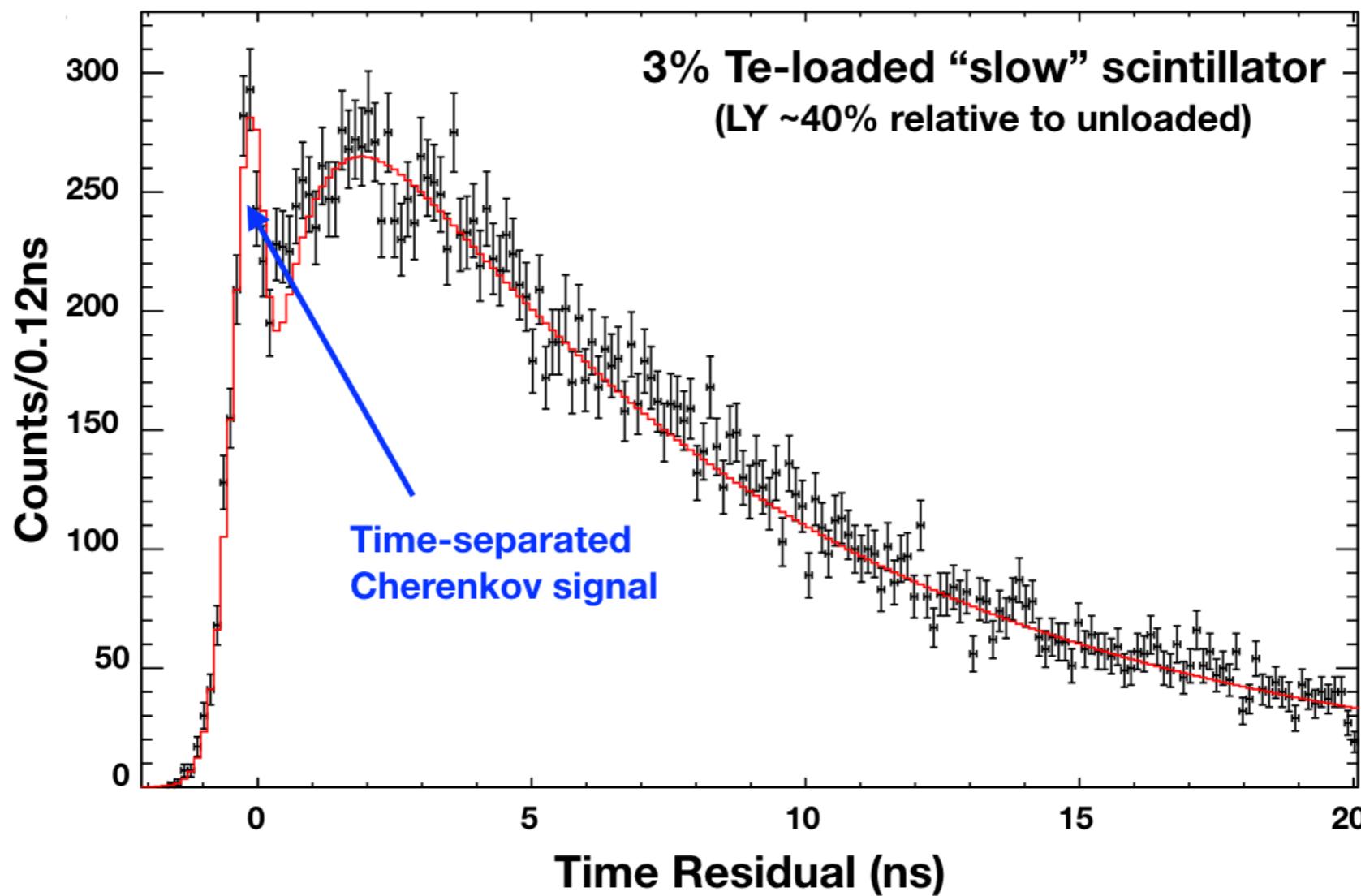


**with multi-site parameter**



## Cherenkov separation using slow fluors

(papers in progress)



Could allow suppression of  ${}^8\text{B}$  background and potentially provide topological information to test  $0\nu\beta\beta$  mechanism



Is there a practical approach that could  
ever let us explore the non-degenerate  
Normal Neutrino Mass Hierarchy?

<b>Isotope</b>	<b>Q (MeV)</b>	<b>% nat. abund.</b>	<b>elem. cost \$/kg</b>	<b>world prod. (tons/yr)</b>	<b>G<sup>0v</sup> (10<sup>-15</sup>/yr)</b>	<b>Median M<sup>0v</sup> for g<sub>A</sub>=1.25</b>
<sup>48</sup> Ca	4.27	0.19	0.16	2.4E8	24.81	1.5
<sup>76</sup> Ge	2.04	7.8	1650	118	2.363	5.1
<sup>82</sup> Se	3	9.2	174	2000	10.16	3.7
<sup>96</sup> Zr	3.35	2.8	36	1.4E6	20.58	3.2
<sup>100</sup> Mo	3.03	9.6	35	2.5E5	15.92	5.6
<sup>110</sup> Pd	2.02	11.8	23000	200	4.815	6
<sup>116</sup> Cd	2.82	7.6	2.8	2.2E4	16.7	4.3
<sup>124</sup> Sn	2.29	5.6	30	2.5E5	9.04	3.2
<sup>130</sup> Te	2.53	34.5	50	400	14.22	3.8
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<sup>150</sup> Nd	3.37	5.6	42	1E4	63.03	2.8

Isotope	Q (MeV)	% nat. abund.	elem. cost \$/kg	world prod. (tons/yr)	$G^{0\nu}$ ( $10^{-15}$ /yr)	Median $M^{0\nu}$ for $g_A=1.25$	$T_{1/2}^{0\nu}$ for $m=2\text{ meV}$	Ton-yrs per event	equiv. nat. elem. Ton-yrs	nat. elem. cost (\$M) @ 1ev/yr	cost (\$M) if enriched @ \$20/g	0v/2v rates ( $10^{-10}$ )
							$(10^{30}\text{ yr})$					
<sup>48</sup> Ca	4.27	0.19	0.16	2.4E8	24.81	1.5	1.17	134	70766	11.3	2689	0.55
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<sup>136</sup> Xe	2.46	8.9	1000	50	14.58	2.6	0.66	216	2424	2424.3	4315	32.61
<sup>150</sup> Nd	3.37	5.6	42	1E4	63.03	2.8	0.13	47	848	35.6	949	0.69

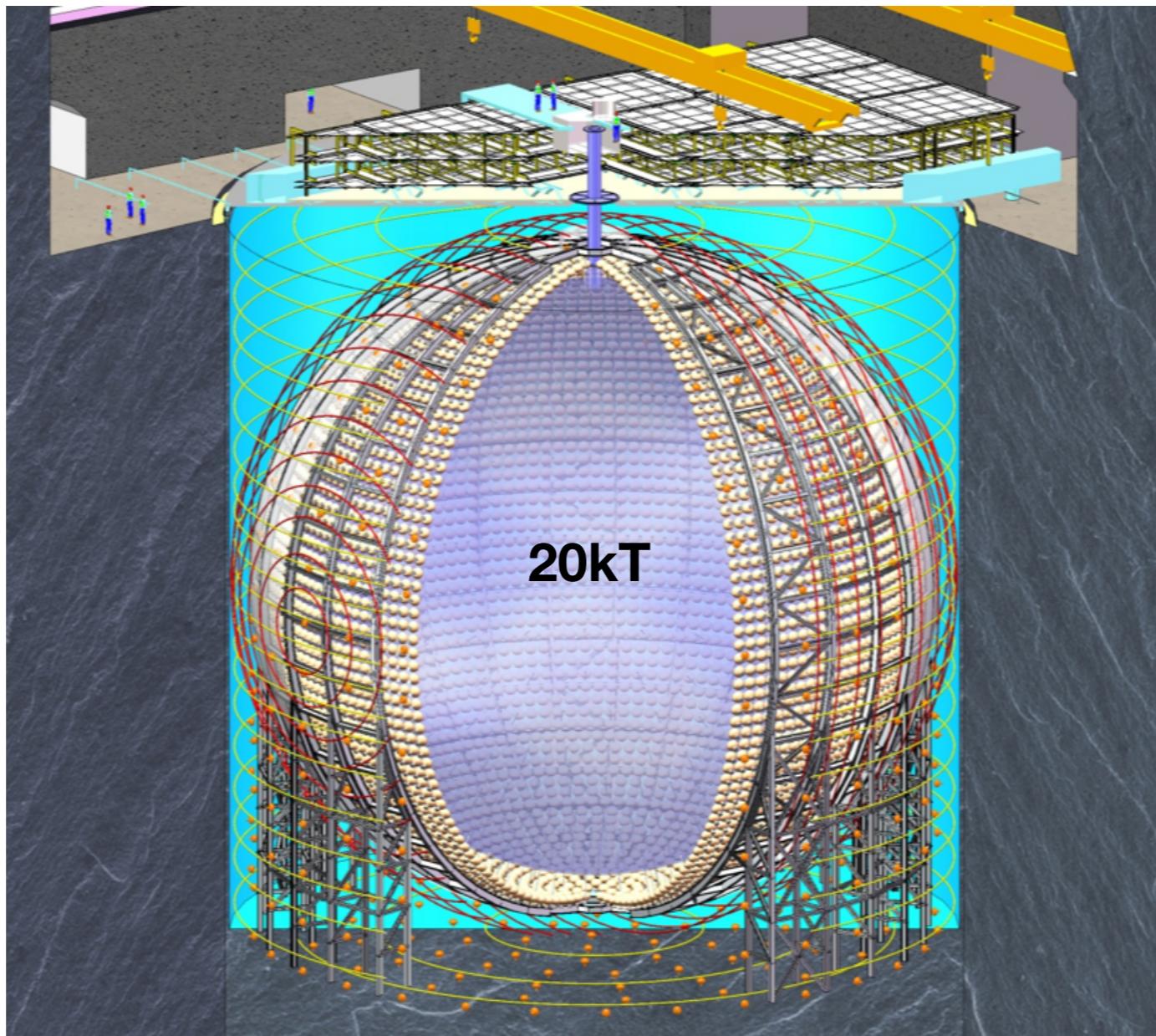


**Loaded scintillator**  
currently the only practical approach that might be able to deal with several hundreds of tonnes



**Forget enrichment**  
especially since actual costs are likely several times higher than this for most isotopes

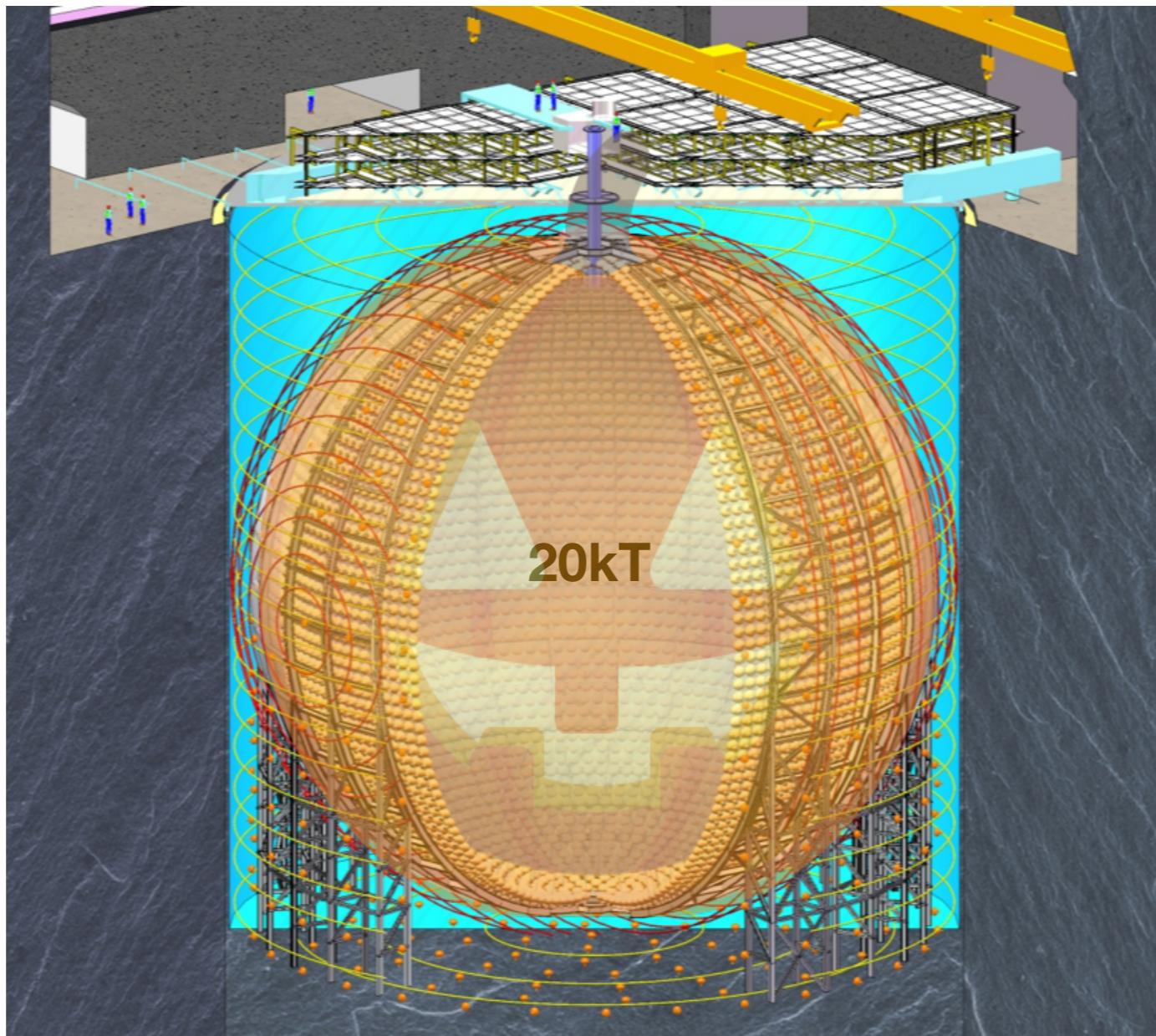
## Possible Future of Loaded Scintillator:



**In discussions with group about possible future deployment of Te in JUNO**

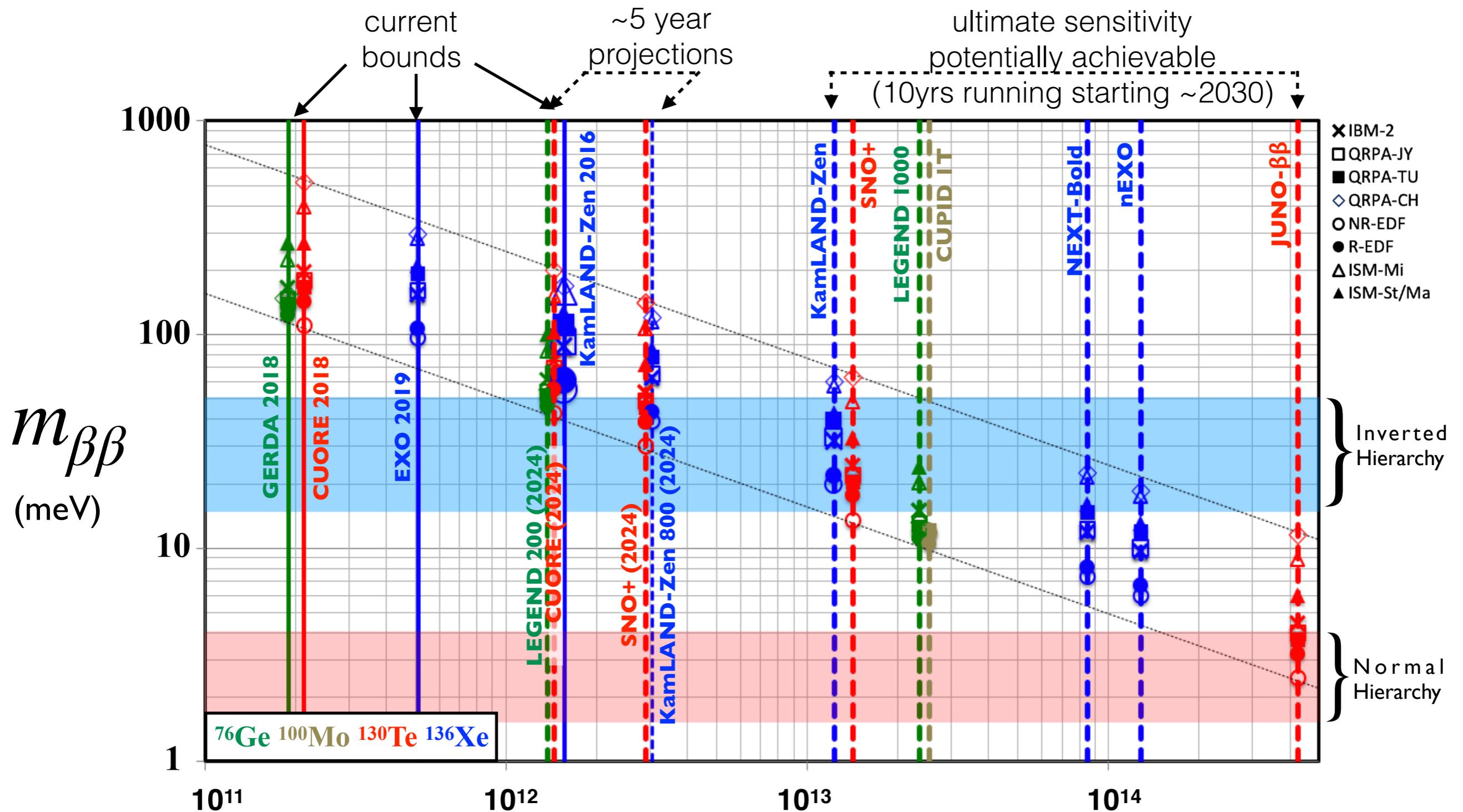
**Potential to have greatest reach of any experiment and begin to probe non-degenerate normal hierarchy!**

## Possible Future of Loaded Scintillator:



**In discussions with group about possible future deployment of Te in JUNO**

**Potential to have greatest reach of any experiment and begin to probe non-degenerate normal hierarchy!**



$$T_{1/2}^{0\nu} \times G^{0\nu}$$