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

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

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.

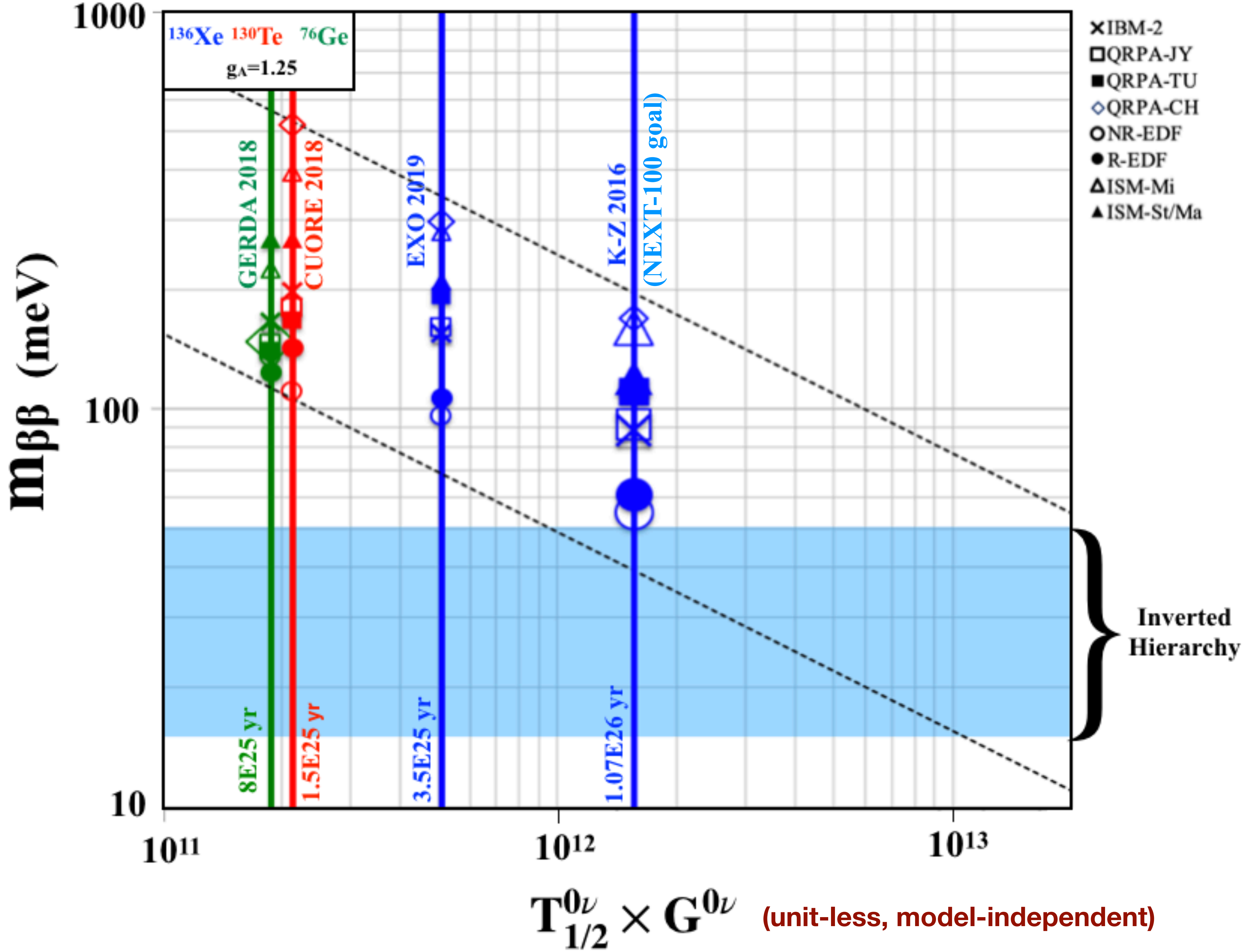
- To compare sensitivities appropriately across different (colour-coded) isotopes, the x-axis in the following plots gives the product of the projected half-life sensitivity times the isotopic phase space factor. The unit-less product is therefore effectively an indication of the relative sensitivity 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 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

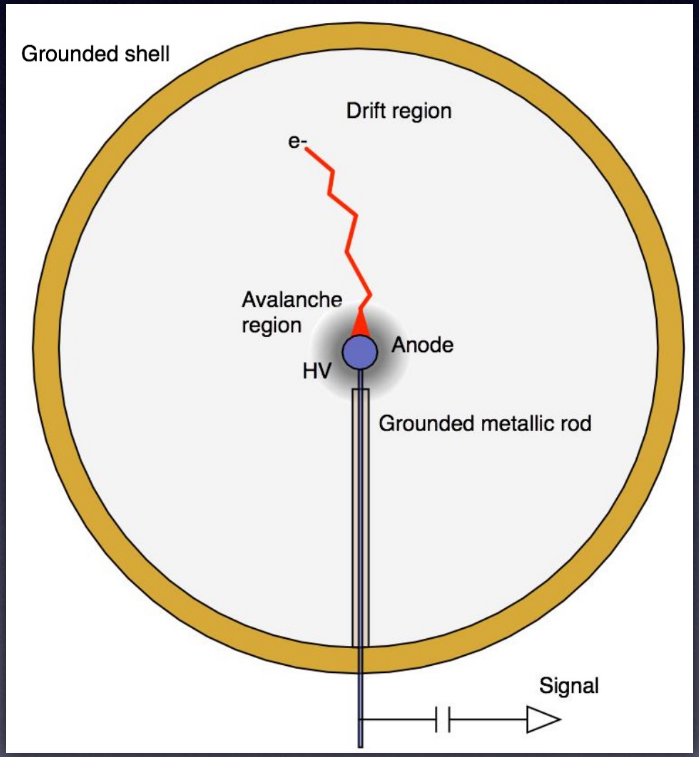
(slides from Anselmo Meregaglia)

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,[a] C. Cerna,[b] A. Dastgheibi-Fard,[c] C. Jollet,[b] S. Jullian,[f] I. Katsioulas,[d] I. Giomataris,[d] M. Gros,[d] P. Lautridou,[e] A. Meregaglia,[b] X. F. Navick,[d] F. Perrot,[b] F. Piquemal,[b,c] M. Zampaolo[c]

[a] *CPPM, Université d'Aix-Marseille, CNRS/IN2P3, F-13288 Marseille, France*
[b] *CENBG, Université de Bordeaux, CNRS/IN2P3, 33175 Gradignan, France*
[c] *LSM, CNRS/IN2P3, Université Grenoble-Alpes, Modane, France*
[d] *IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France*
[e] *SUBATECH, IMT-Atlantique, Université de Nantes, CNRS-IN2P3, France*
[f] *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

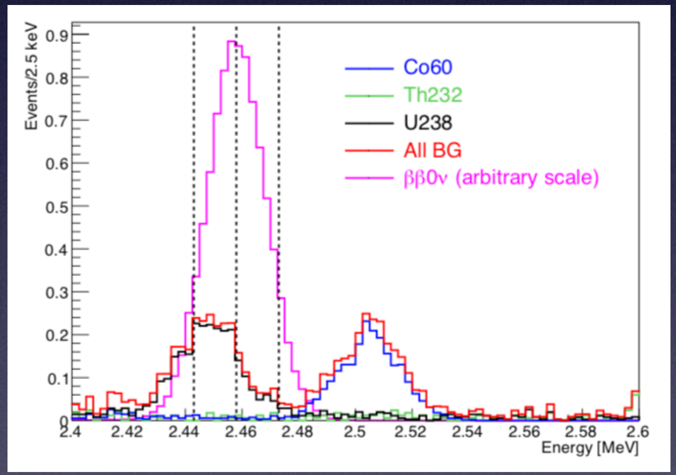
Up to 7.9 kg (40 bars) Xenon prototype (no low radioactivity) to demonstrate the detector capability in particular on the energy resolution

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



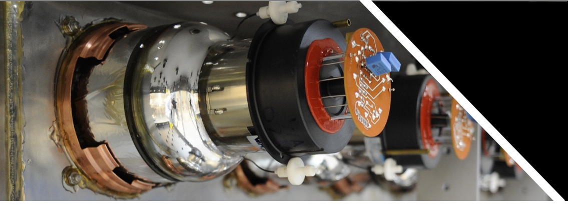
JINST 13 (2018) no.01, P01009

Depending on the results and fundings

Experiment

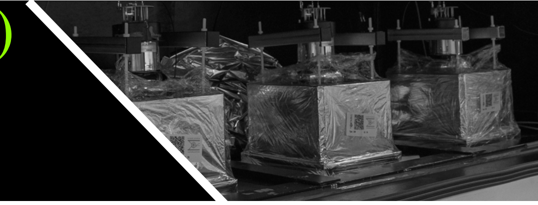
Going towards a 1 ton background free detector

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



(slides from Dave Waters)

SuperNEMO Overview



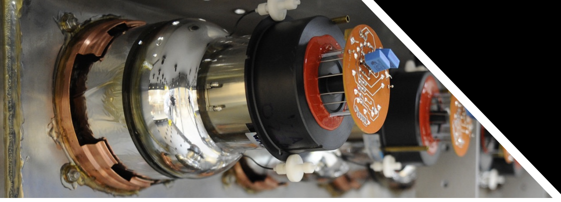
supernemo collaboration

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)

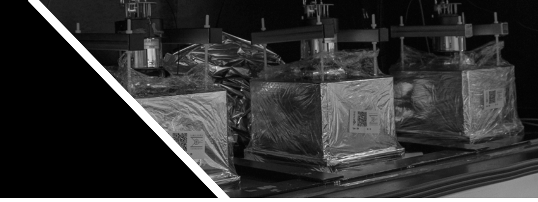
9 countries, 21 Laboratories

The goals of SuperNEMO :

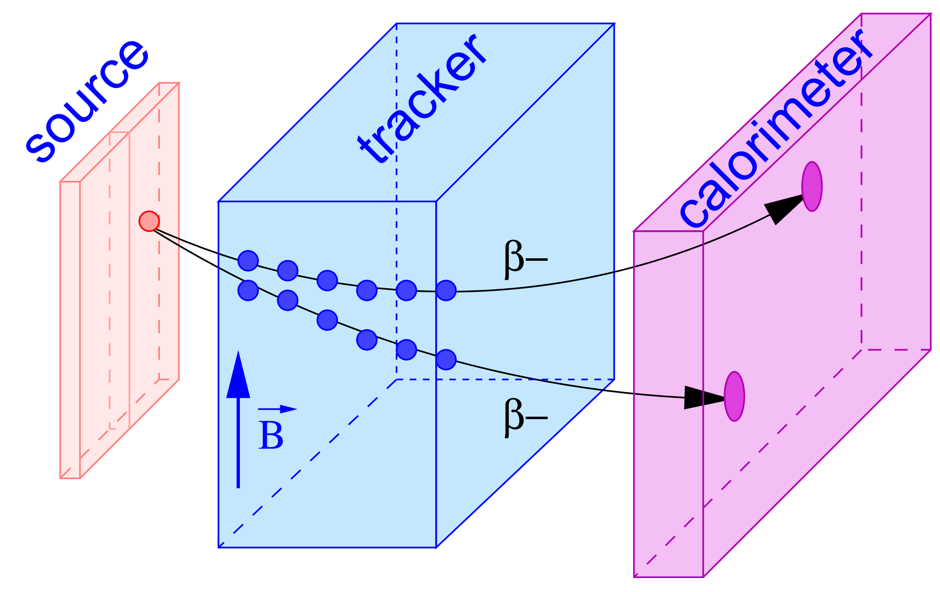
1. Build on the experience of the extremely successful NEMO-3 experiment.
2. Use the power of the tracking-calorimeter approach to identify and suppress backgrounds. This will yield a zero-background experiment in the first (Demonstrator Module) phase.
3. Prove that a 100 kg scale experiment can reach 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

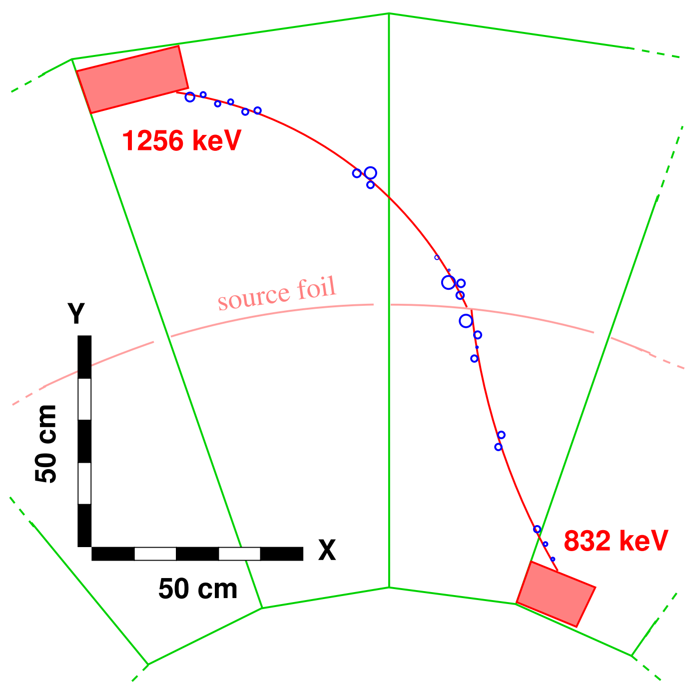


- Source separated from detector: (almost) any solid isotope can be hosted.
- Full topological event reconstruction including $e^{\pm}$, γ-ray and α-particle identification ➜ strong background control & mechanism probe.
- Successfully exploited by **NEMO-3** experiment: $0\nu\beta\beta$ limits and $2\nu\beta\beta$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



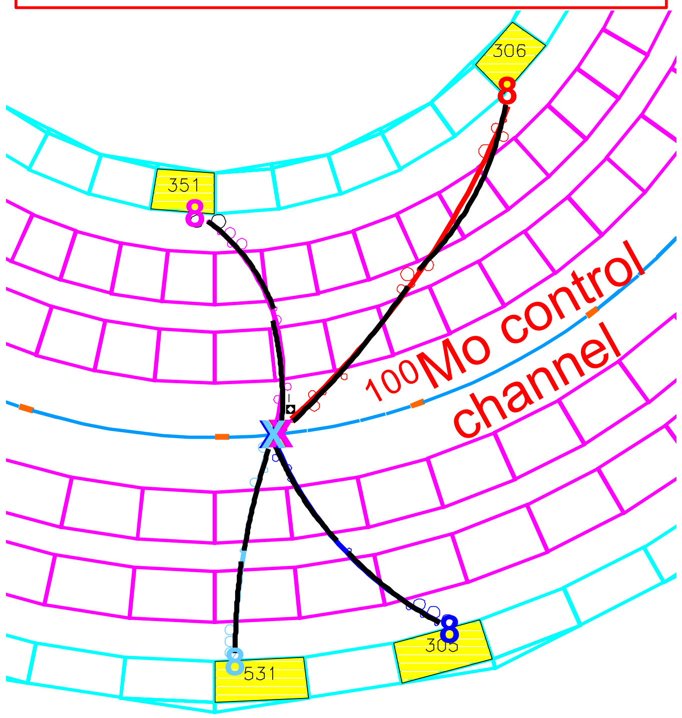
10^{24} year limit with just 7kg of ^{100}Mo

PRD 92, 072011 (2015)



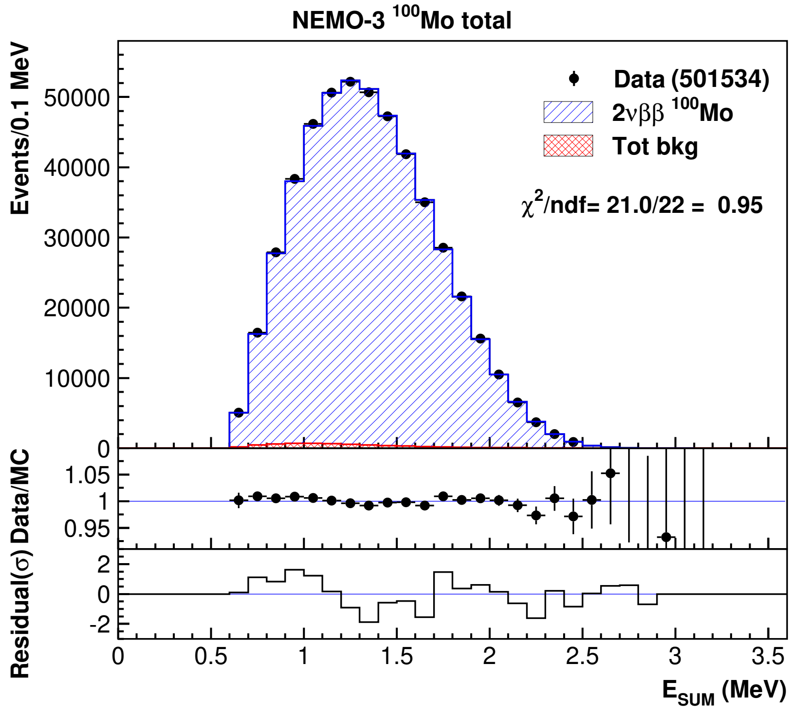
Access unique signatures, e.g. $0\nu4\beta$

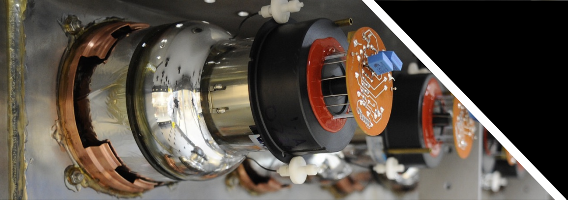
PRL 119, 041801 (2017)



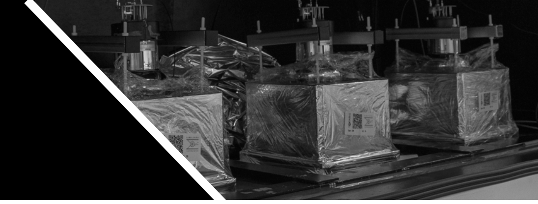
Kinematic probes of DBD mechanism (SSD/HSD)

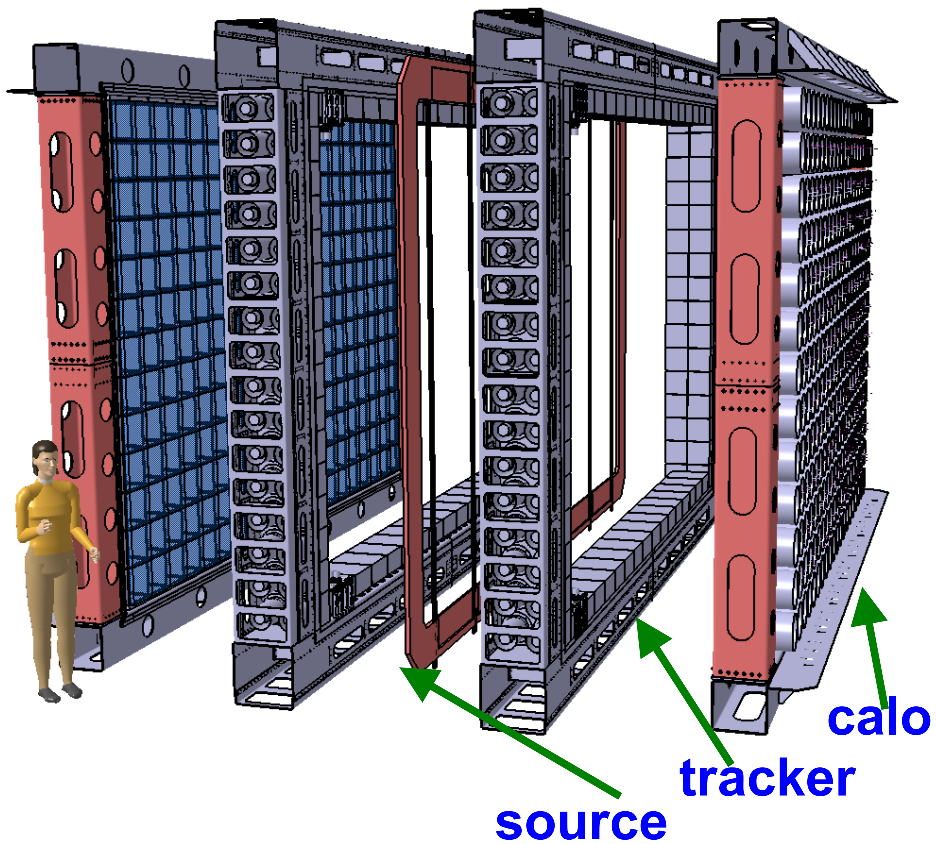
EPJ C79, 440 (2019)





SuperNEMO - demonstrator





Demonstrator Module (2.5 year run)

17.5 kg × yr initial exposure :

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

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

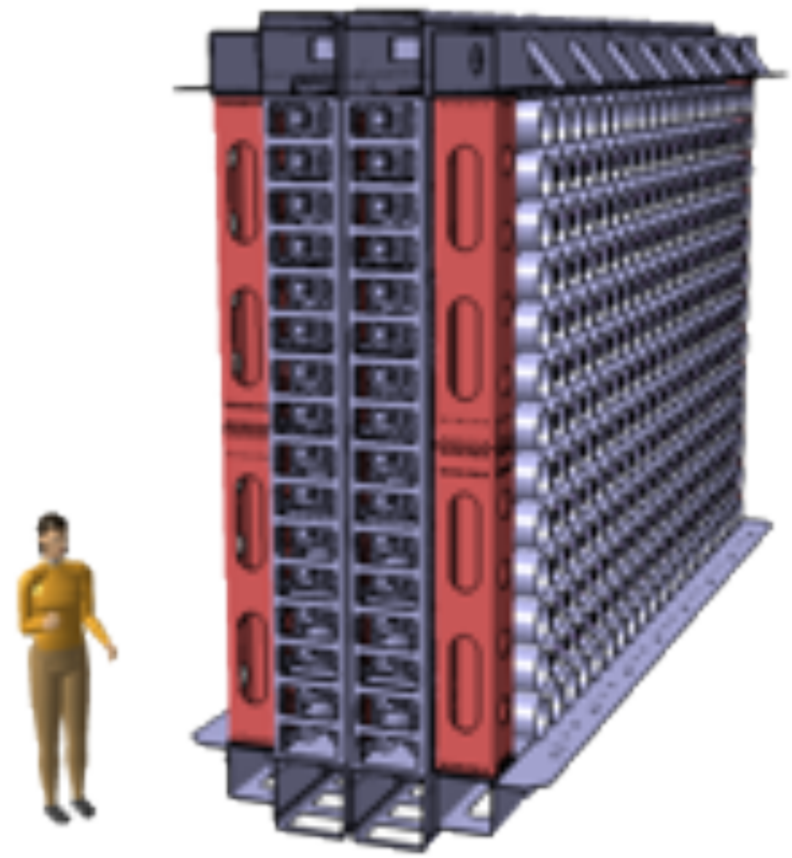
SuperNEMO Demonstrator Module :

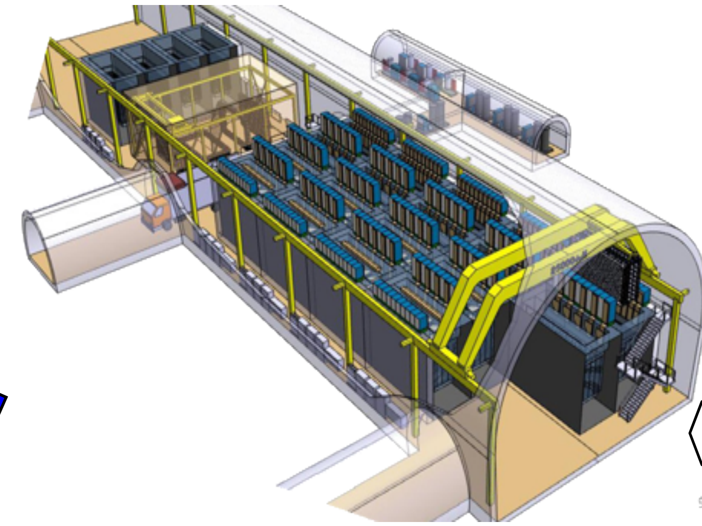
final commissioning

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



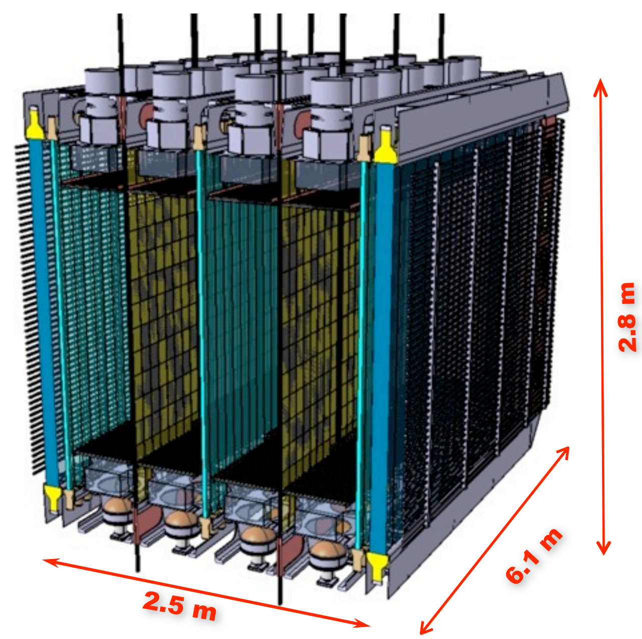


Full SuperNEMO

500 kg × yr :

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

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



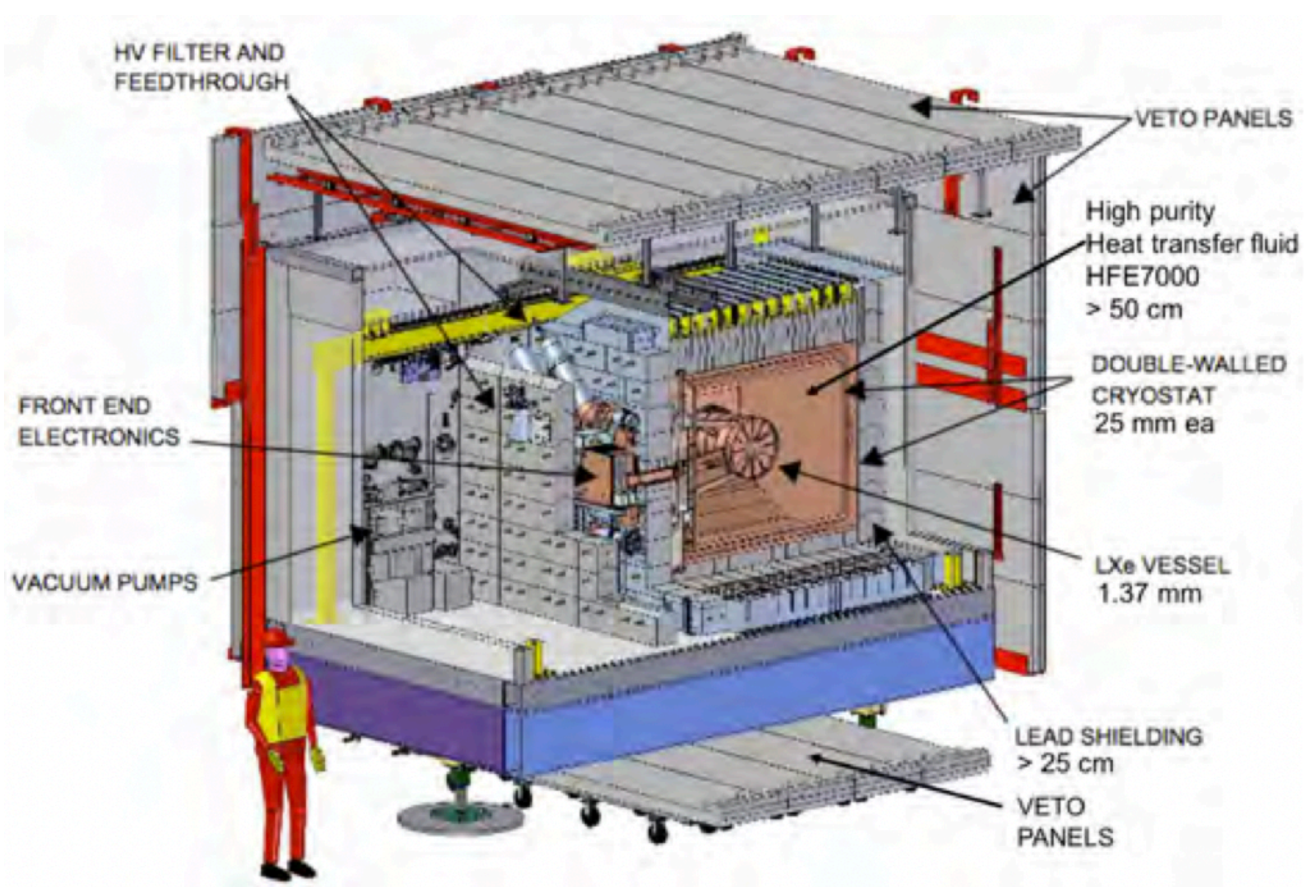
Alternative Designs

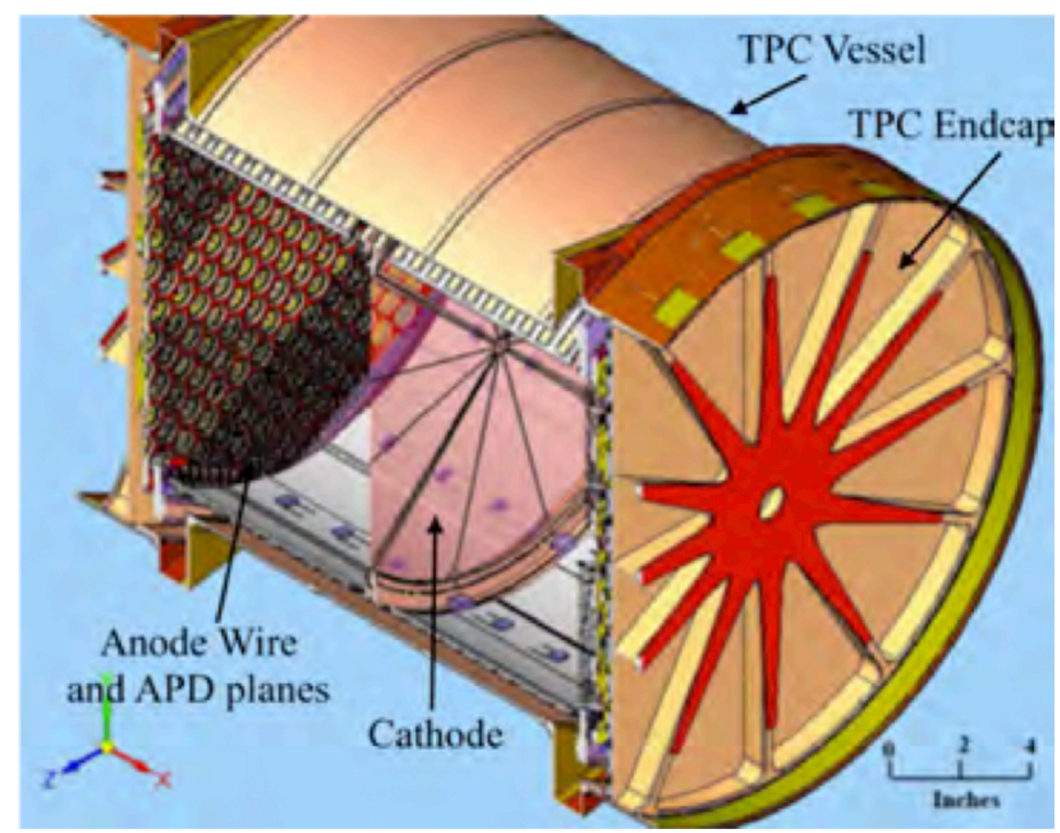
- A **unique approach** with access to fundamental nuclear physics.
- The best technique for **exploring a signal.**
- Europe-led.
- Continued support and R&D is essential.

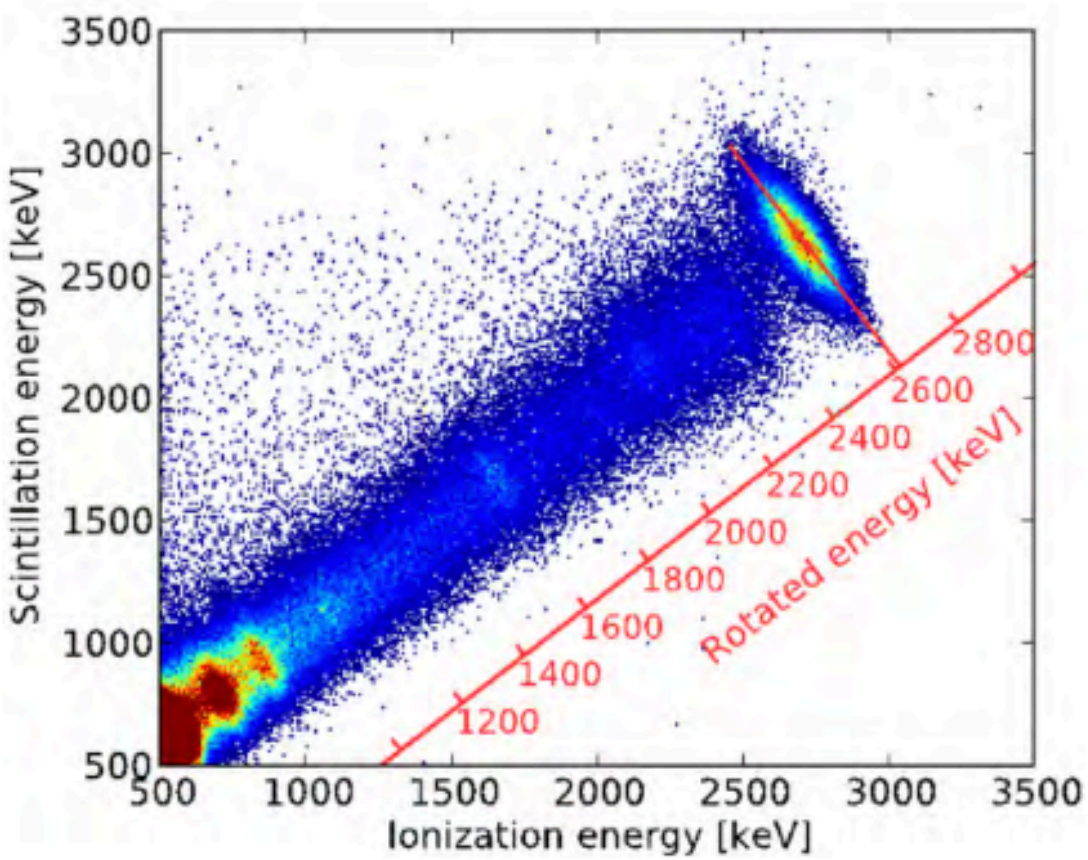
Major Projects With Future Plans Currently Not On EU Roadmap

(Andrea Pocar & nEXO pre-conceptual design report)

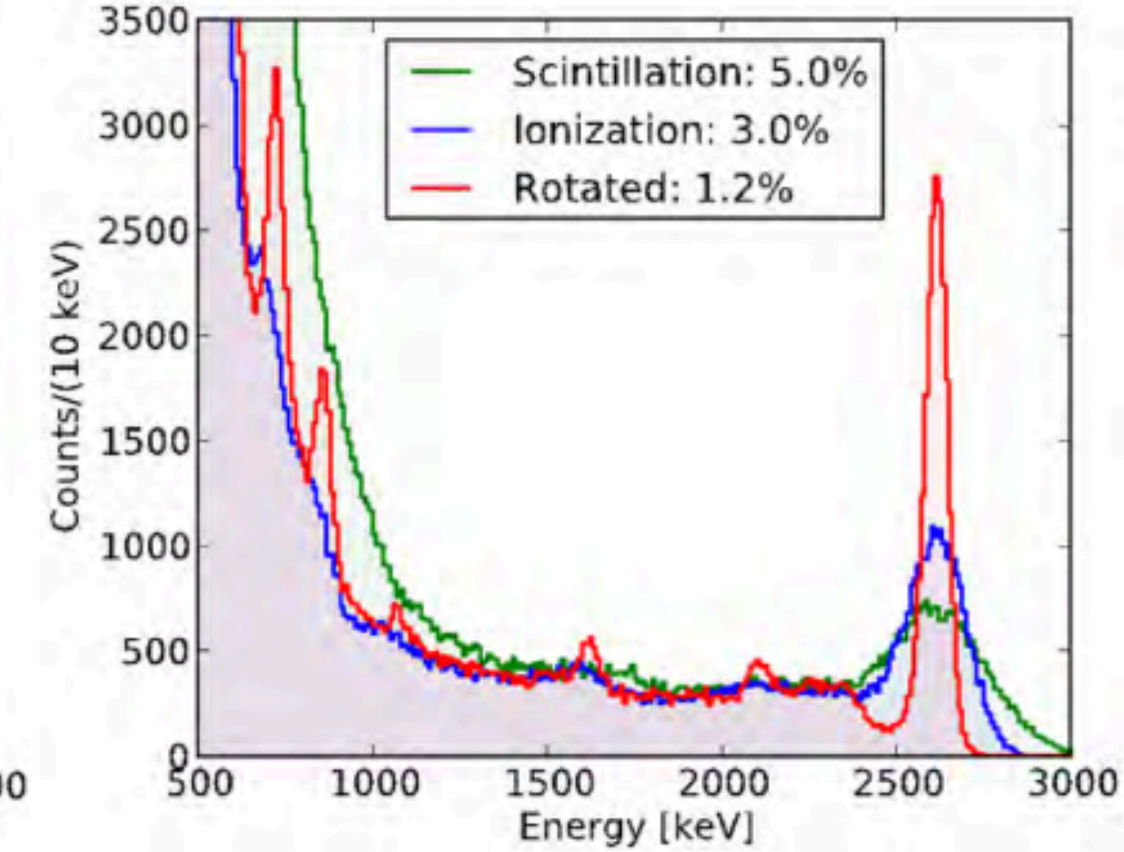
EXO-200



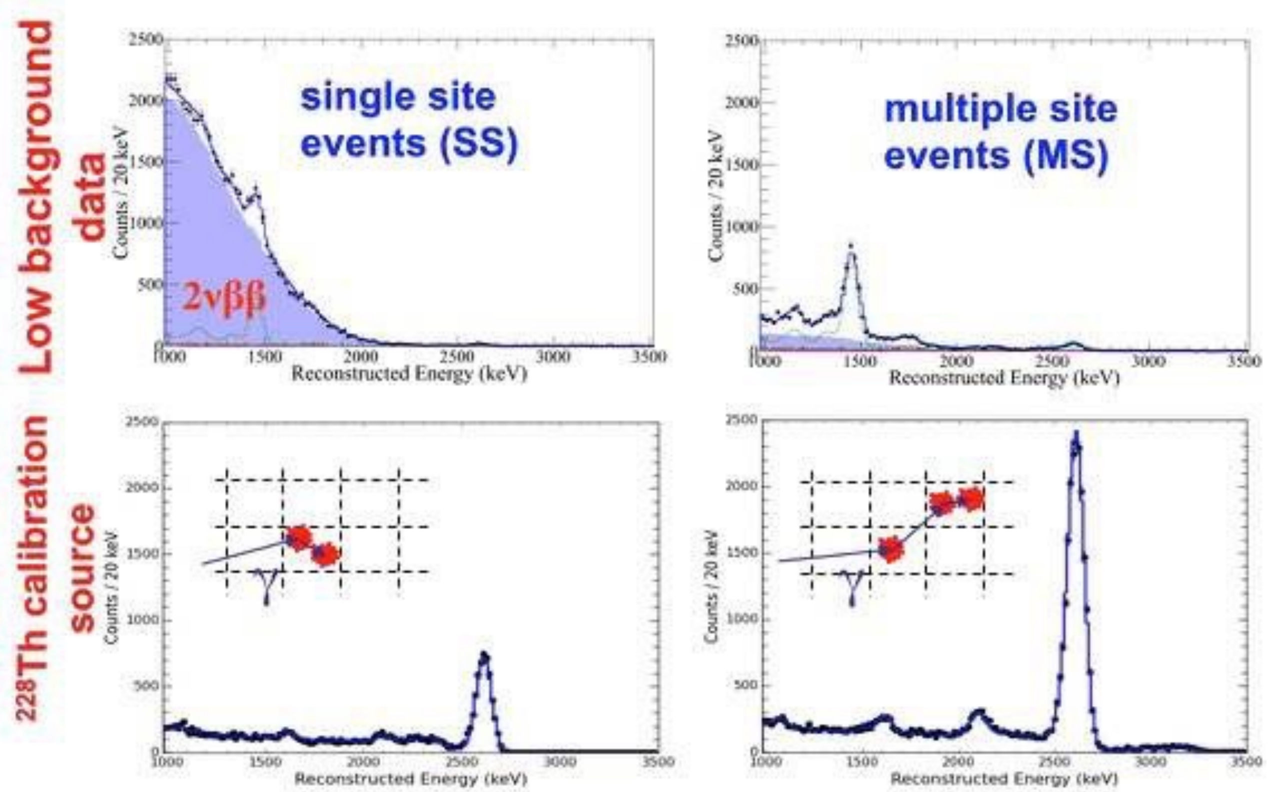




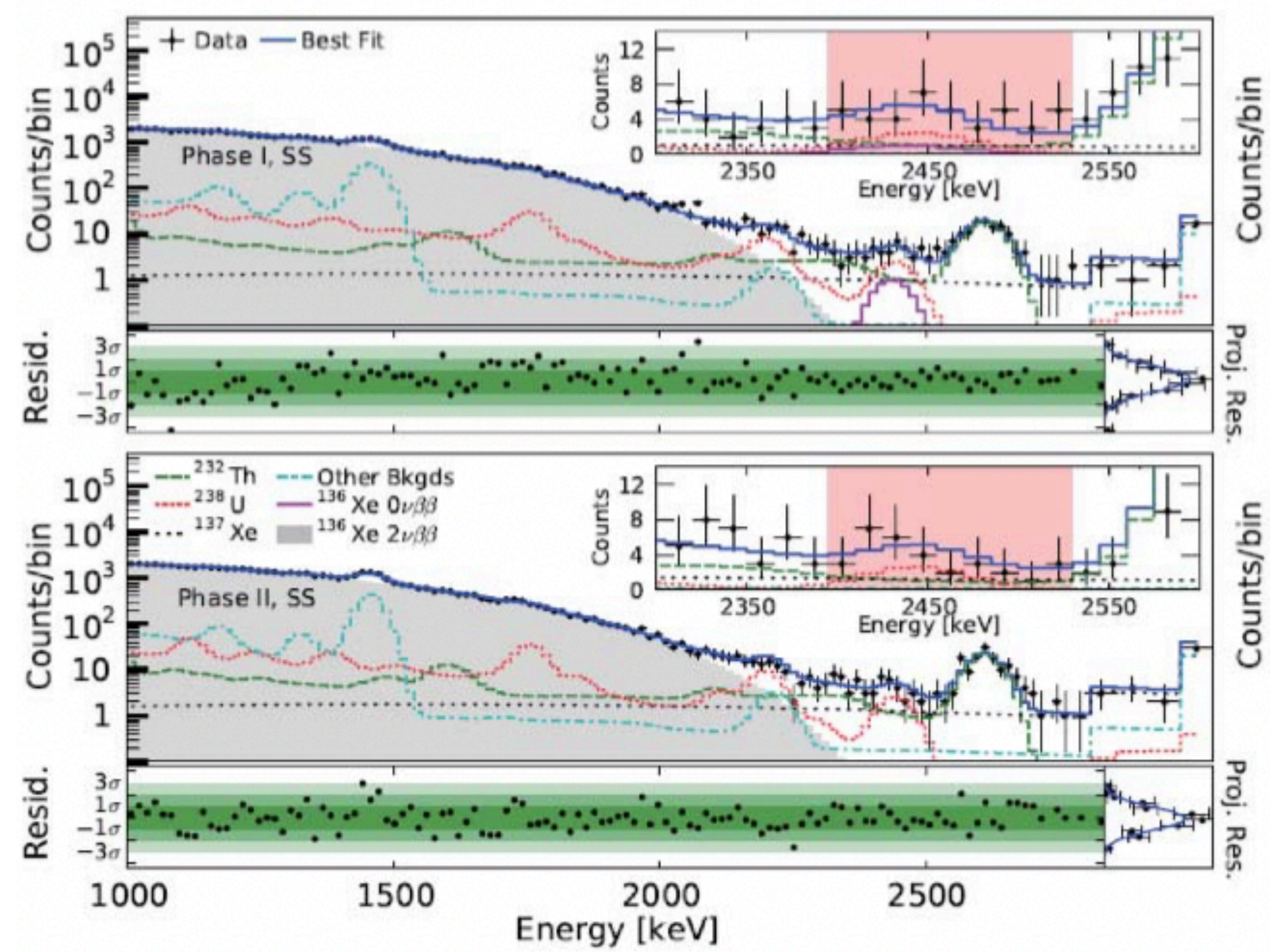
Scintillation energy [keV]
Ionization energy [keV]
Rotated energy [keV]
1200
1400
1600
1800
2000
2200
2400
2600
2800



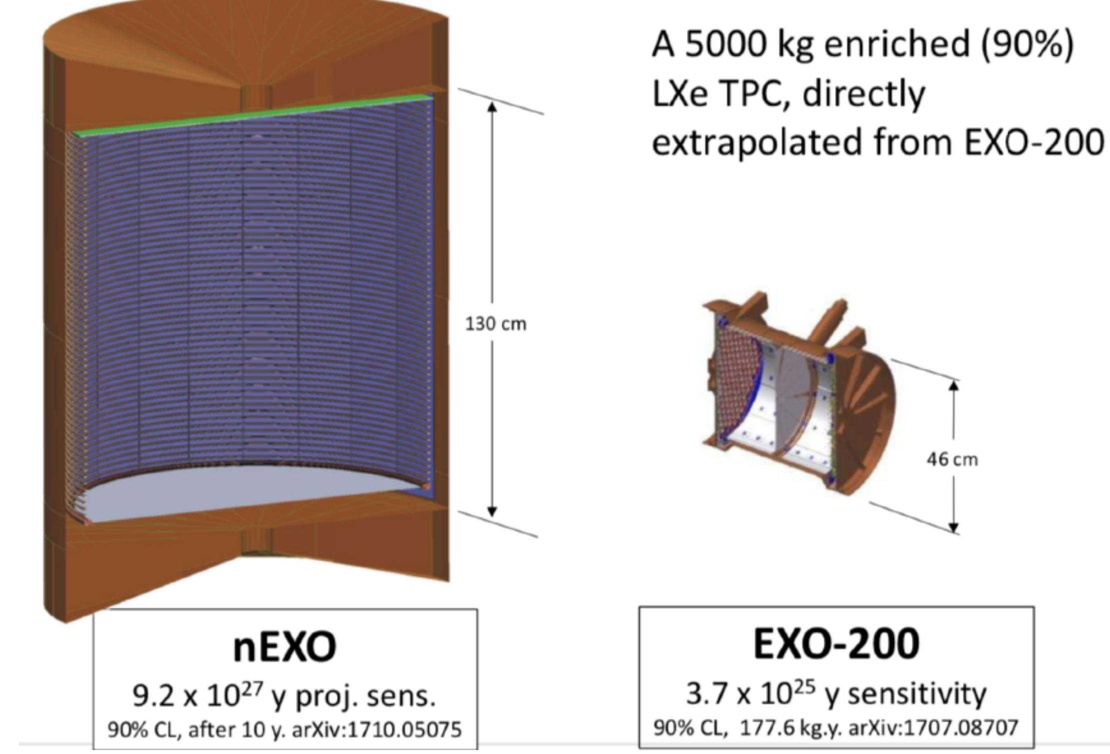
Scintillation: 5.0%
Ionization: 3.0%
Rotated: 1.2%
Counts/(10 keV)
Energy [keV]

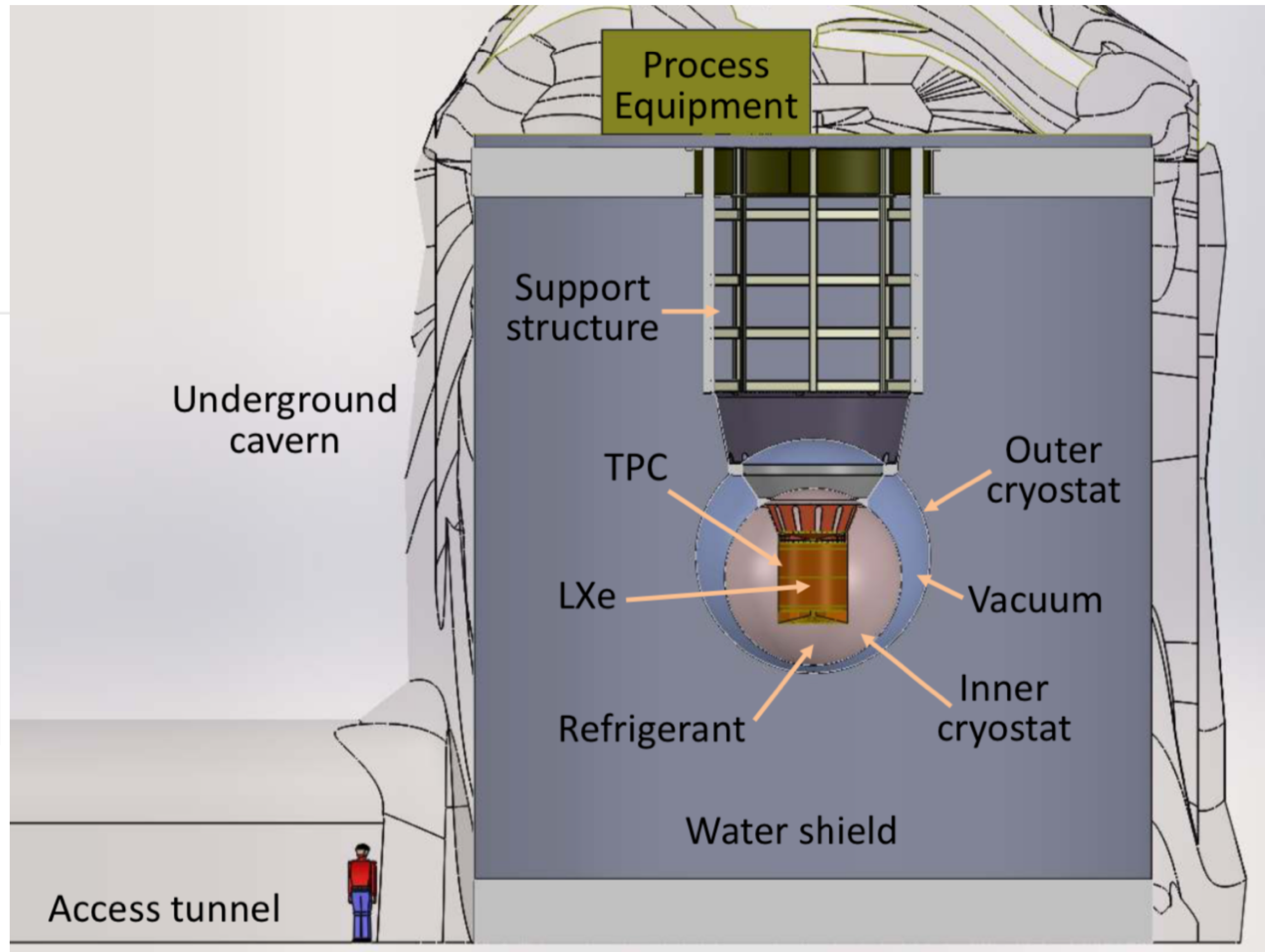


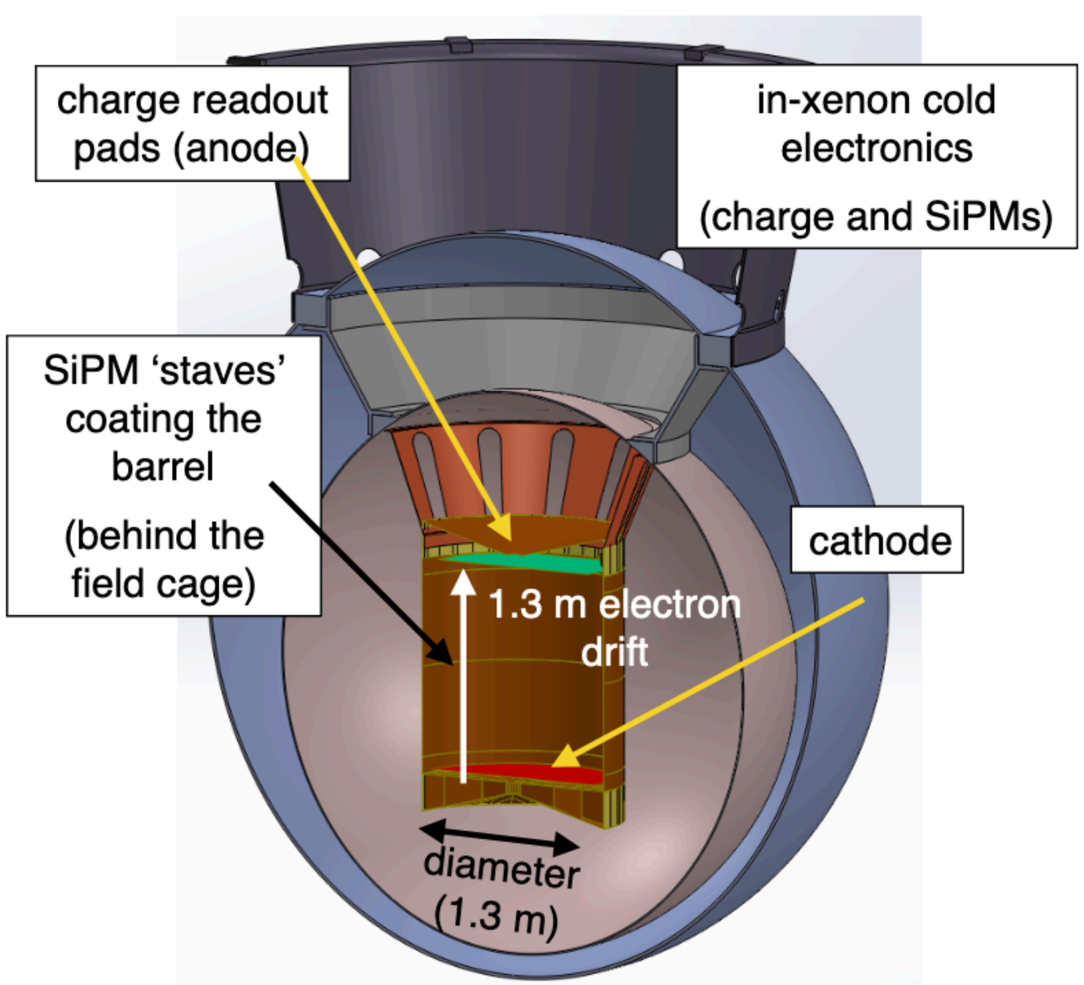
Low background data
single site events (SS)
multiple site events (MS)
2νββ
228Th calibration source
Reconstructed Energy (keV)
Counts / 20 keV



Data
Best Fit
Phase I, SS
Phase II, SS
Counts/bin
Counts
Energy [keV]
Resid.
Proj. Res.
232Th
238U
137Xe
Other Bkgds
136Xe 0νββ
136Xe 2νββ


A 5000 kg enriched (90%)
LXe TPC, directly
extrapolated from EXO-200
130 cm
46 cm
nEXO
9.2 x 10^27 y proj. sens.
90% CL, after 10 y. arXiv:1710.05075
EXO-200
3.7 x 10^25 y sensitivity
90% CL, 177.6 kg.y. arXiv:1707.08707

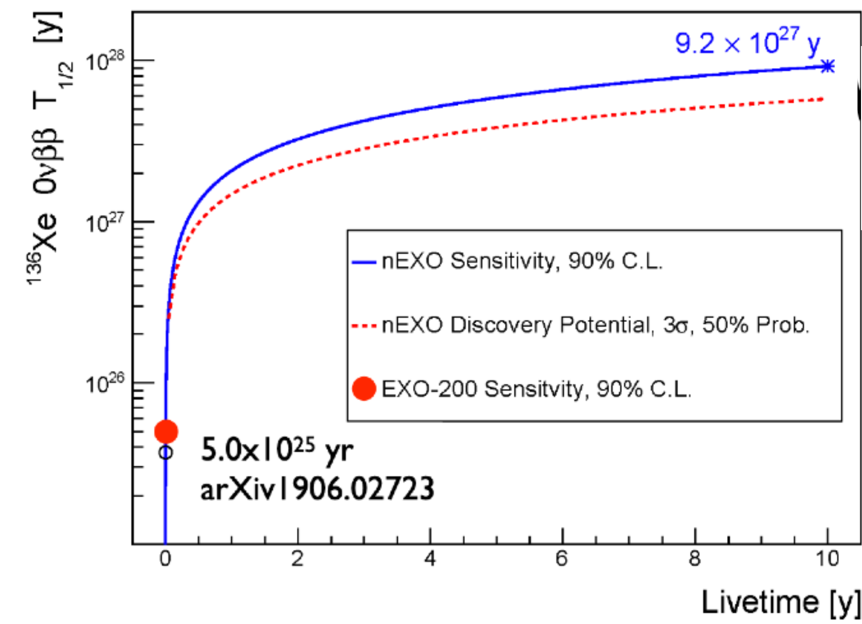

Process
Equipment
Support
structure
Underground
cavern
TPC
Outer
cryostat
LXe
Vacuum
Refrigerant
Inner
cryostat
Water shield
Access tunnel


charge readout
pads (anode)
in-xenon cold
electronics
(charge and SiPMs)
SiPM 'staves'
coating the
barrel
(behind the
field cage)
cathode
1.3 m electron
drift
diameter
(1.3 m)

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}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



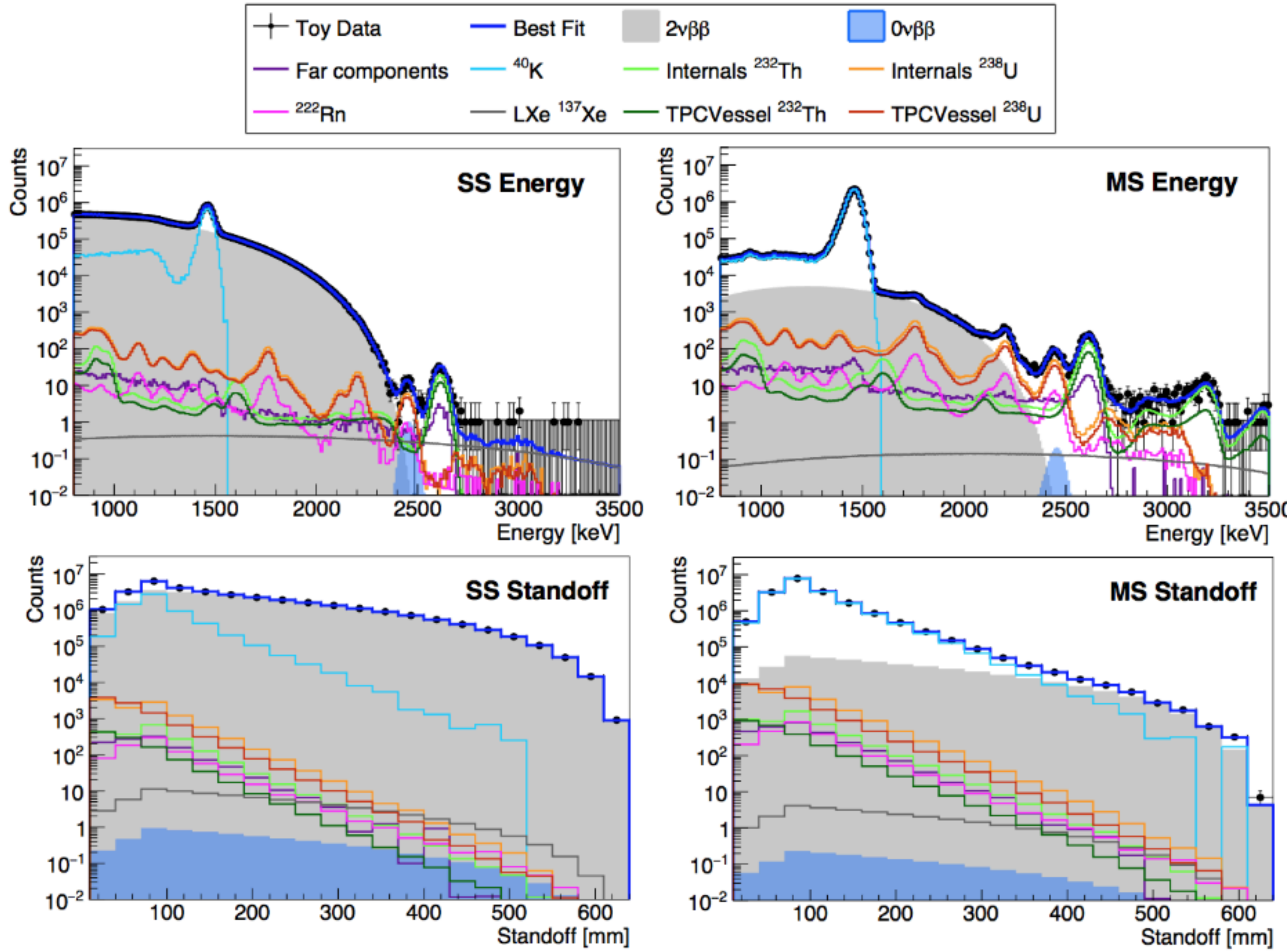


Figure 3.9: Result of the NLL fit to a representative nEXO toy dataset generated assuming a $0\nu\beta\beta$ signal corresponding to a half-life of 5.7×10^{27}y and 10 years of detector live time. The top plots are the energy distribution histograms while the bottom plots are the standoff distances;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

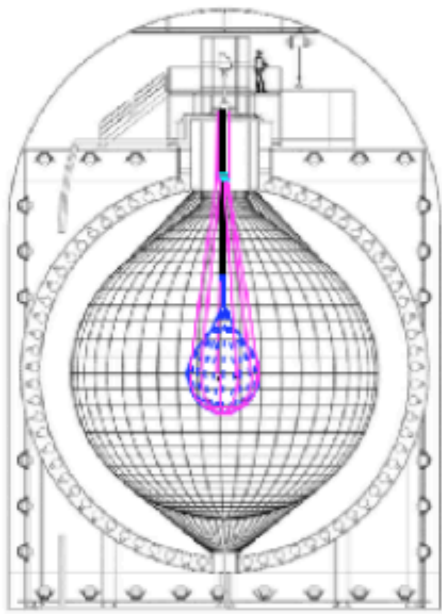
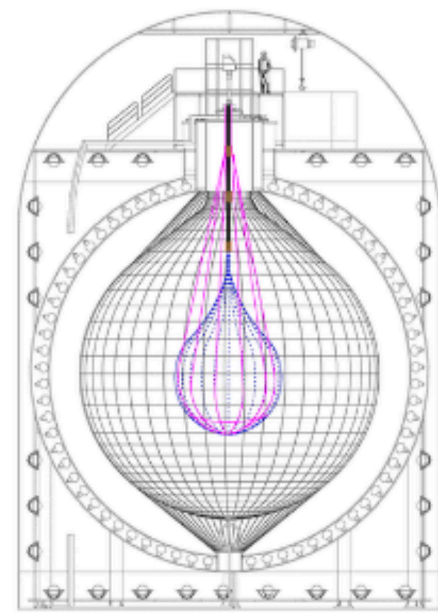
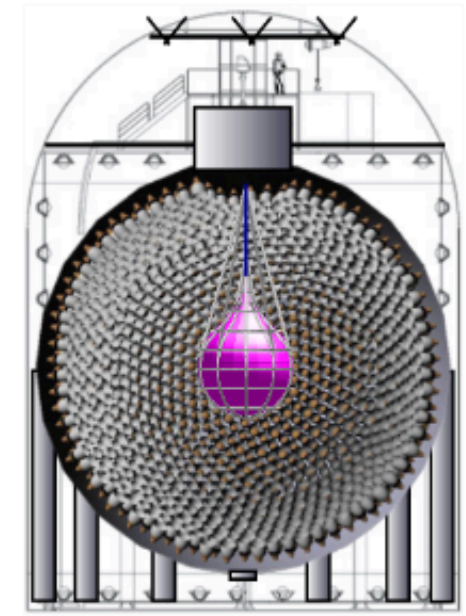
Abstract

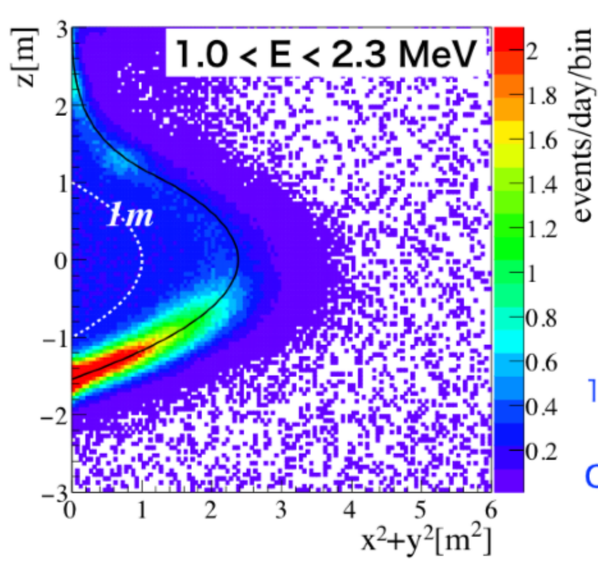
The projected performance and detector configuration of nEXO are described in this pre-Conceptual Design Report (pCDR). nEXO is a tonne-scale neutrinoless double beta ($0\nu\beta\beta$) decay search in ^{136}Xe, based on the ultra-low background liquid xenon technology validated by EXO-200. With ~ 5000 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 base 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.

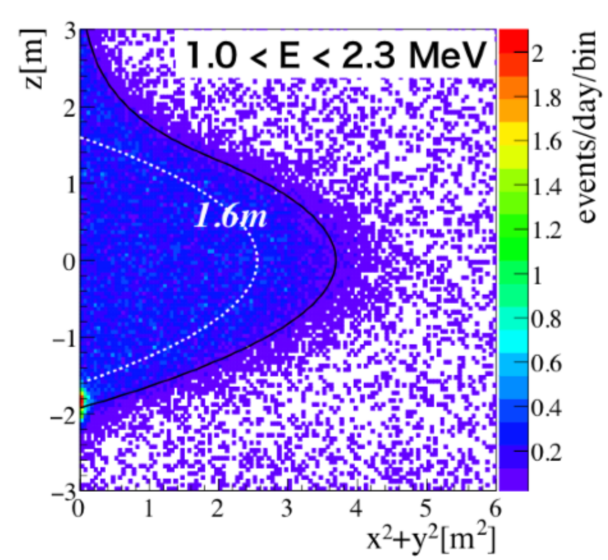
May 28, 2018

(Yoshihito Gando, TAUP 2019)

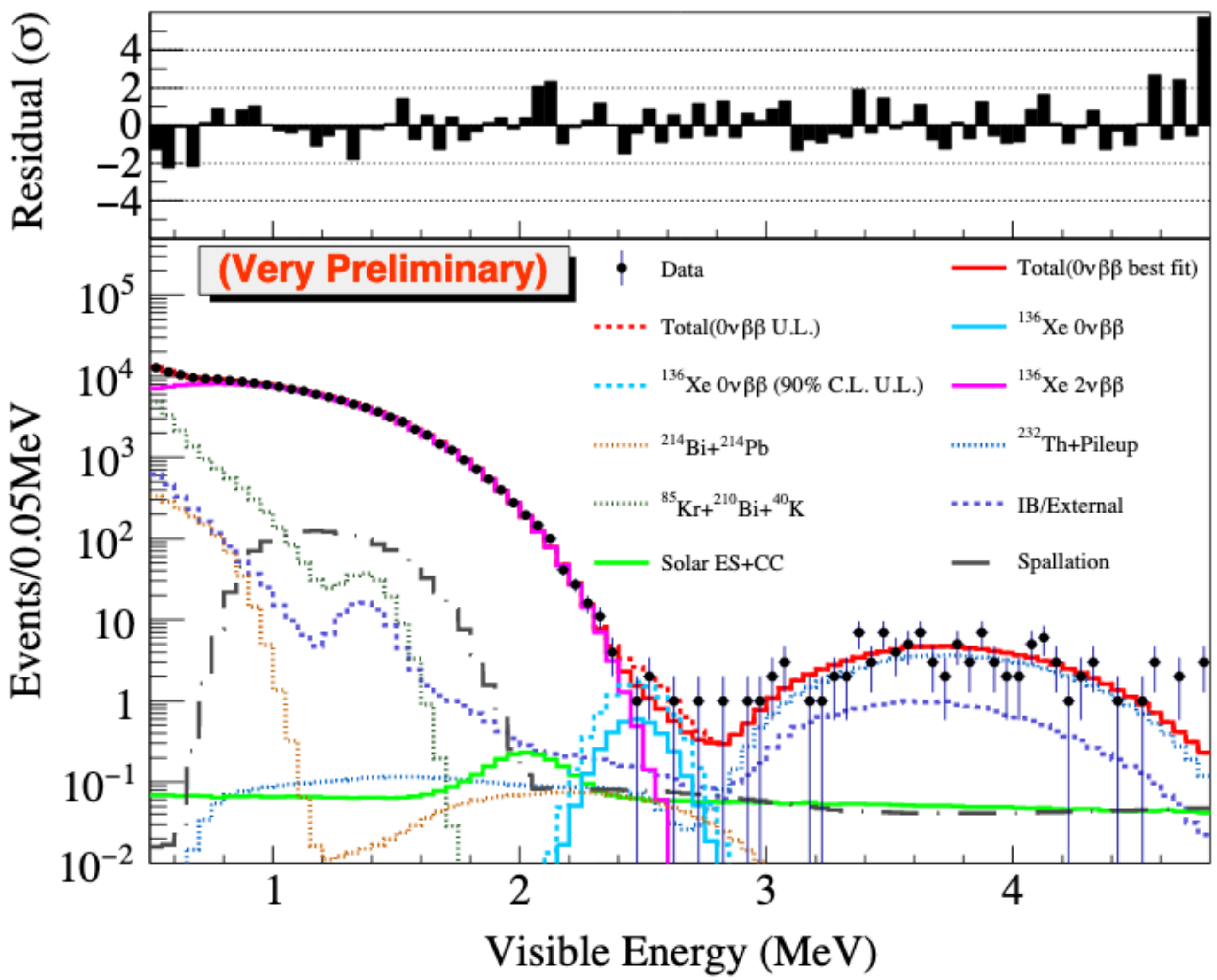
Past	Ongoing	Future
		
KamLAND-Zen 400	KamLAND-Zen 800	KamLAND2-Zen
R = 1.54m mini-balloon	R = 1.90m mini-balloon	
Xenon 320 ~ 380 kg	Xenon 745 kg	Xenon ~ 1 ton
2011 ~ 2015	Jan. 22, 2019 ~	



^{134}Cs, dust sank



$2\nu\beta\beta$ dominates in all volume



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

Best fit : 2.1 events/day/kton-XeLS

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

$T^{0\nu}_{1/2}$ > 4 × 10^{25} year (90% C.L.)

SNO+

$0\nu\beta\beta$

- Reactor neutrinos (will resolve Δm^2_{12} tension)
- Low energy solar neutrinos
- Geo neutrinos
- Supernova neutrinos
- Invisible modes of nucleon decay

^{130}Te-loaded scintillator
(Biller & Chen, 2012)

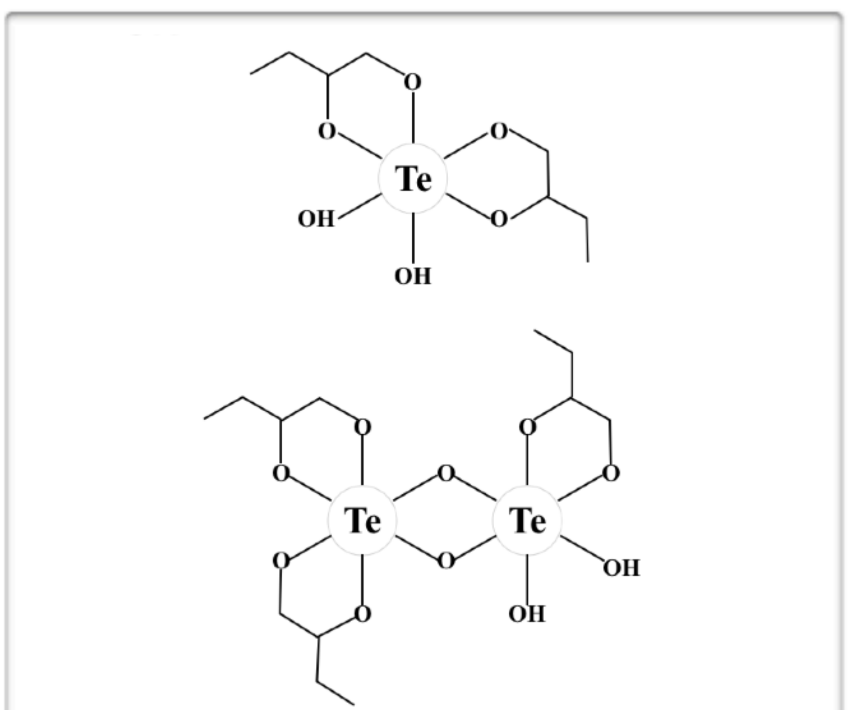
- ^{130}Te is the most cost effective isotope:

  Enriched ^{136}Xe ~ \$20,000 /kg of isotope
  Natural Te (34.5% ^{130}Te) ~ \$ 150 /kg of isotope

- ^{130}Te has good predicted matrix element values (better than ^{136}Xe) and a good phase space factor (comparable to ^{136}Xe and ~6 times better than ^{76}Ge)

- Liquid scintillator is the most cost effective and scalable 0νββ 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

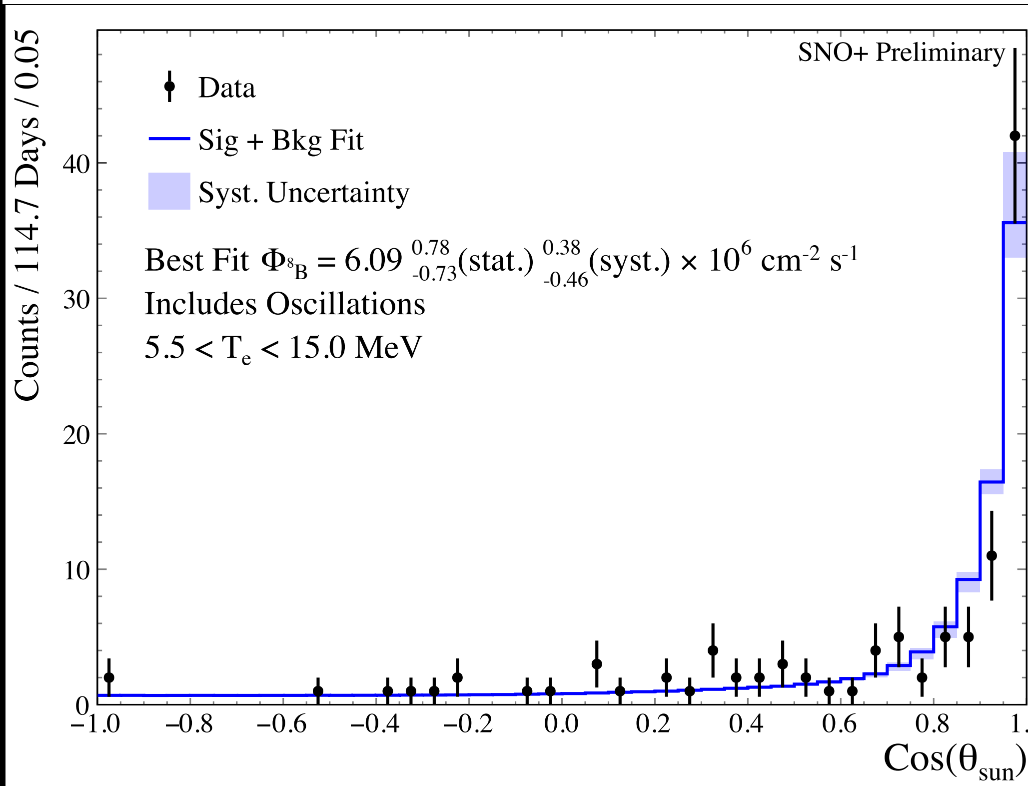

All of the Te needed for Phase I is now underground


Te purification and loading plants construction
finished (starting commissioning)
2018/03/29

Recent Water Results

PHYSICAL REVIEW D **99**, 012012 (2019)

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

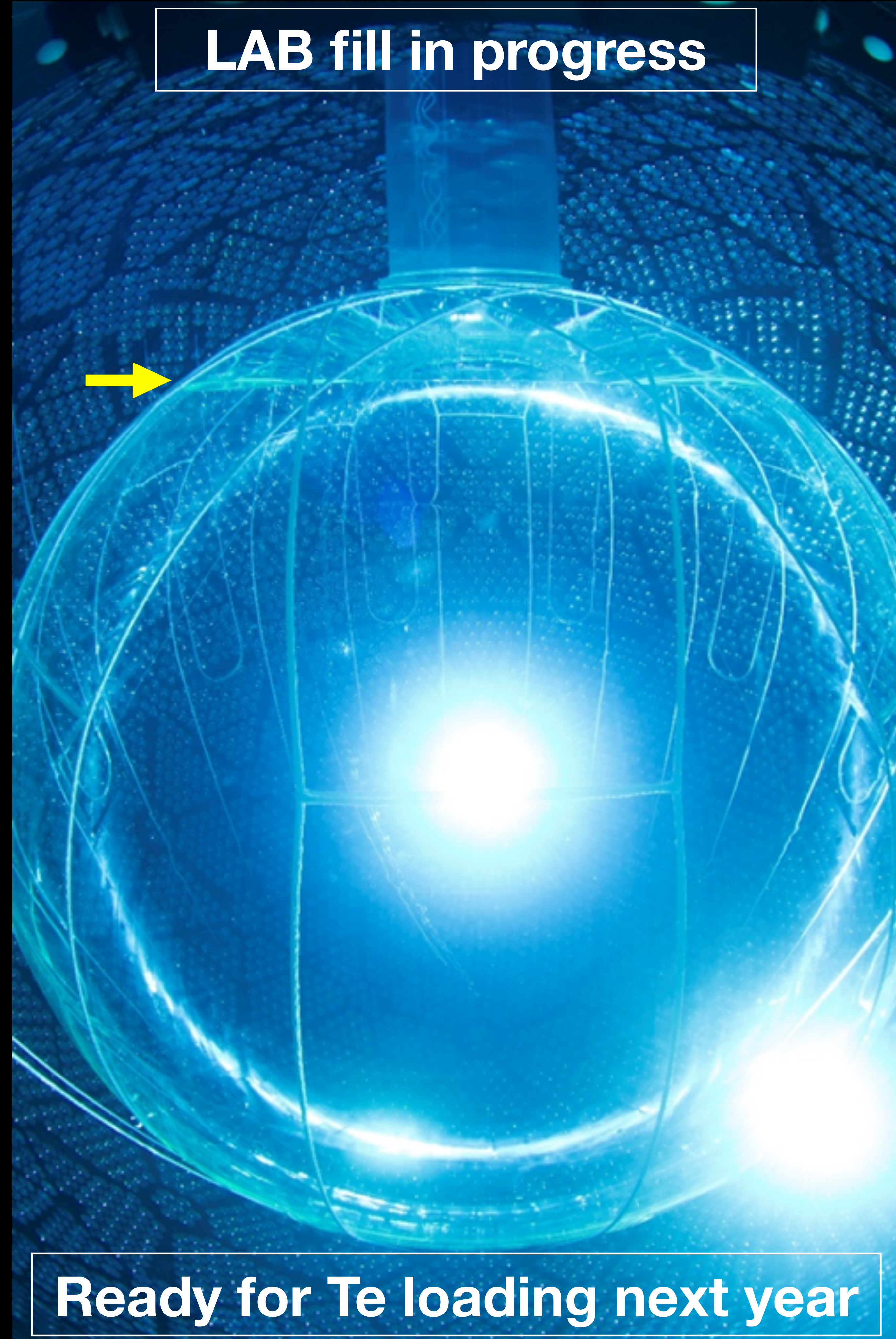


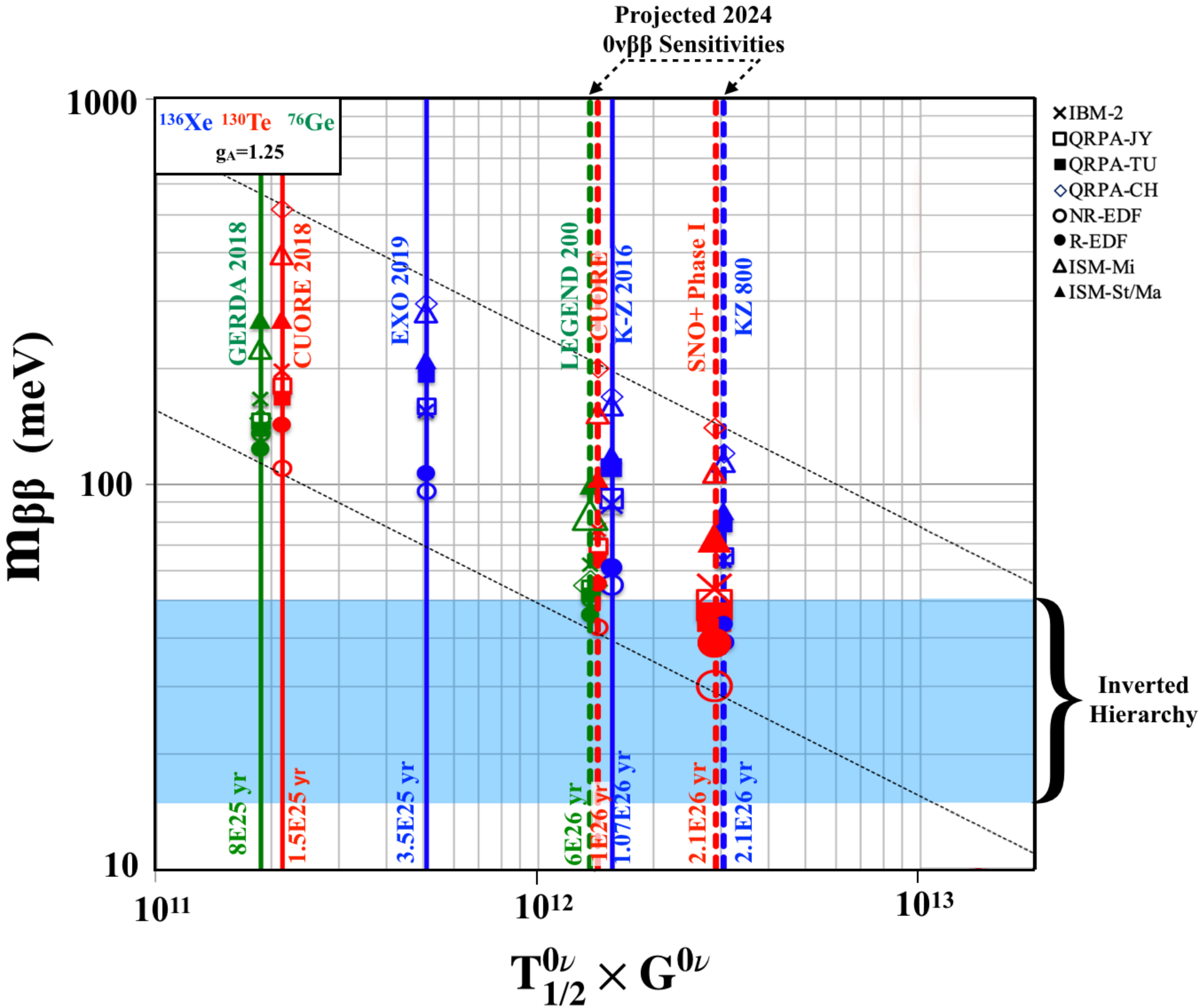
PHYSICAL REVIEW D **99**, 032008 (2019)

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

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

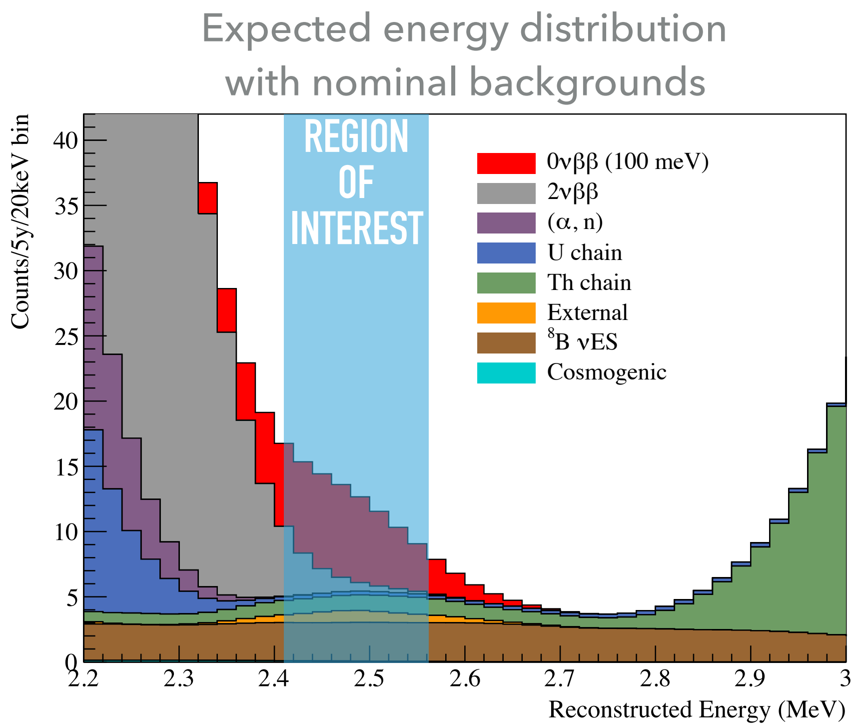
Several other papers in preparation



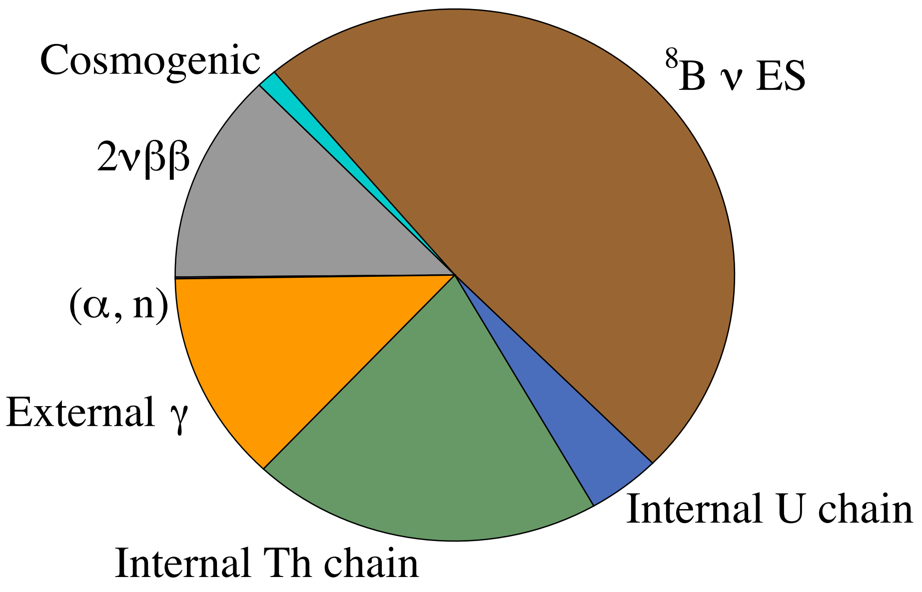


New Physics Sensitivity: Phase-Space Weighted Half-Life

Phase I:

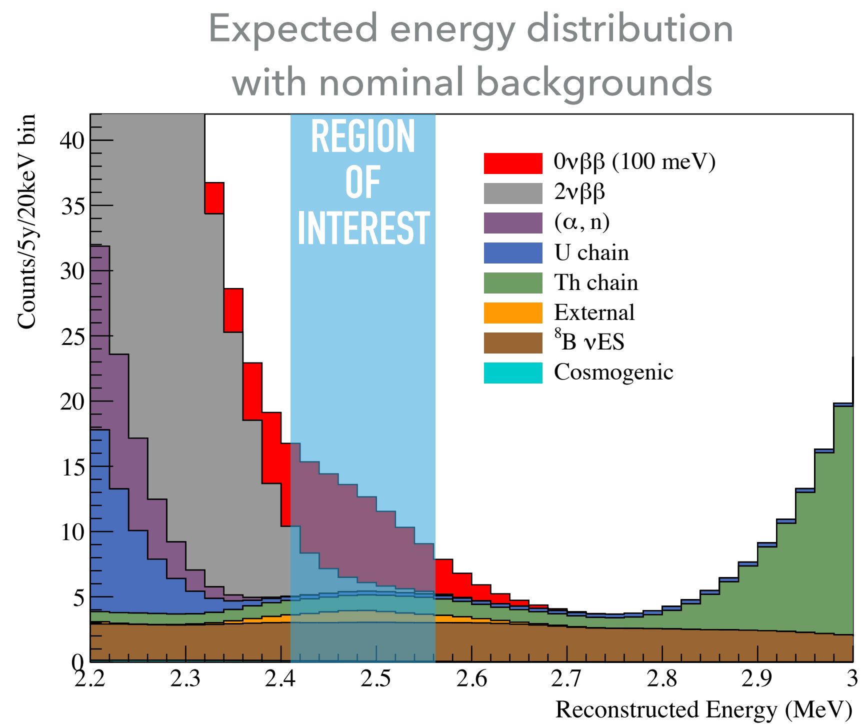


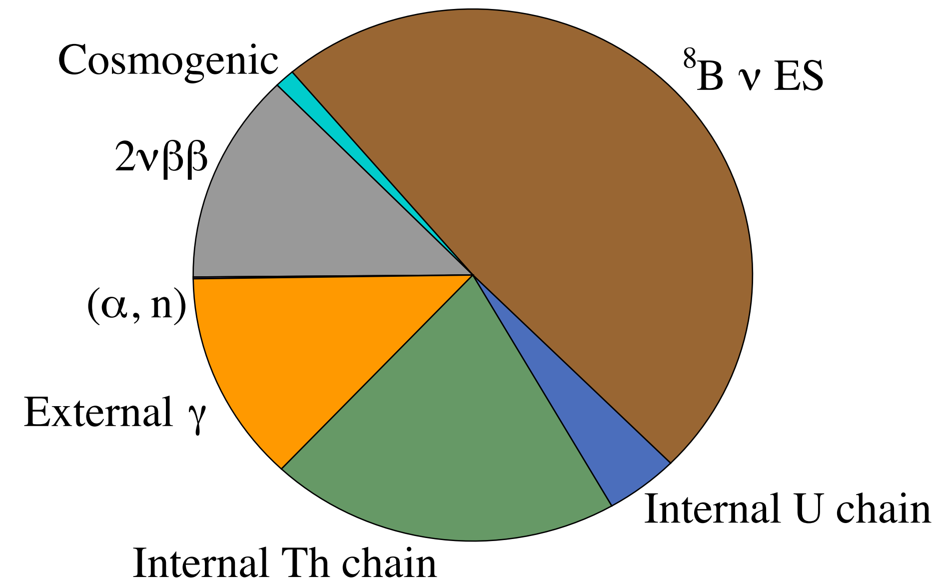
Expected energy distribution
with nominal backgrounds
REGION OF INTEREST
0νββ (100 meV)
2νββ
(α, n)
U chain
Th chain
External
8B νES
Cosmogenic
Counts/5y/20keV bin
Reconstructed Energy (MeV)



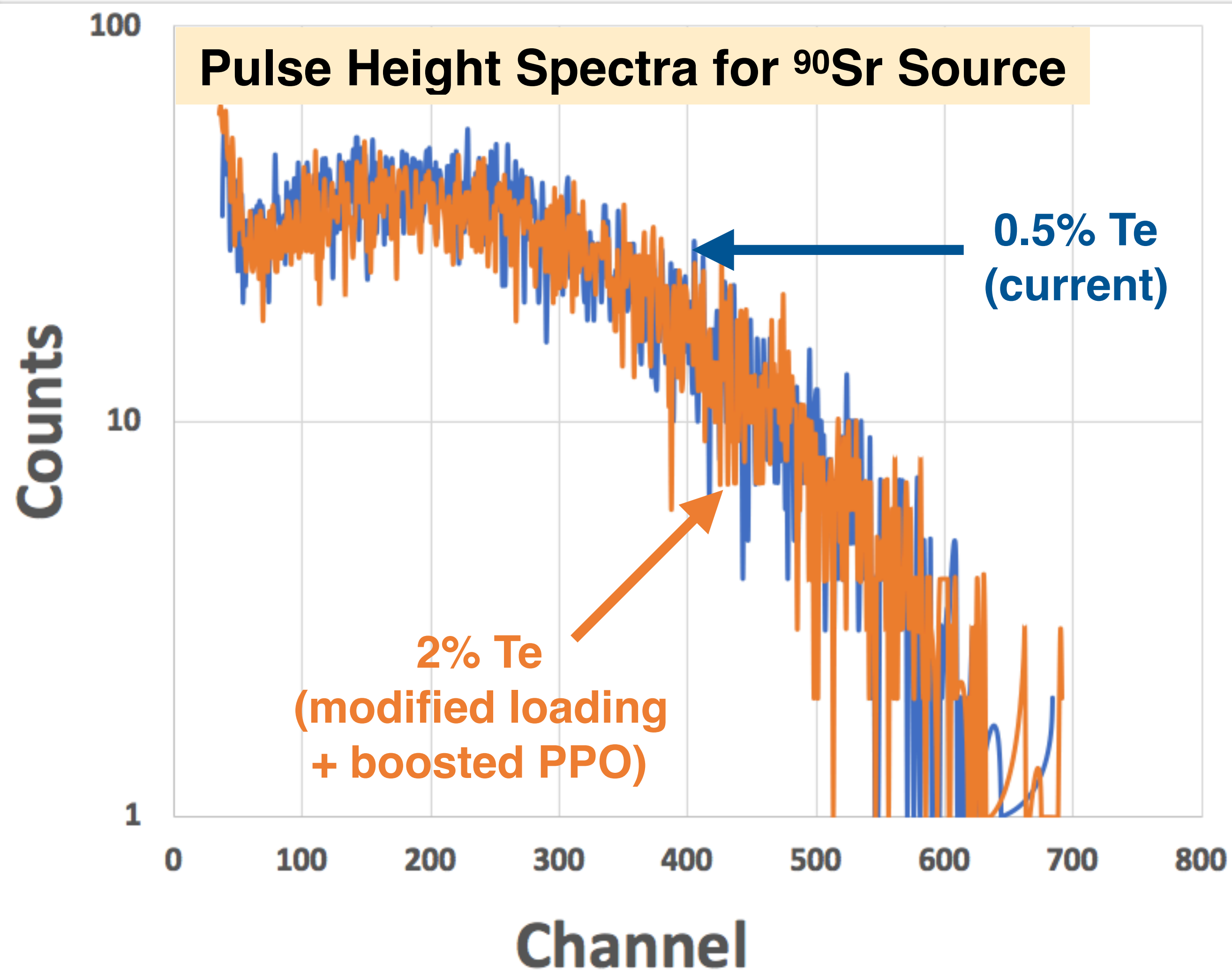
Cosmogenic
8B ν ES
2νββ
(α, n)
External γ
Internal U chain
Internal Th chain

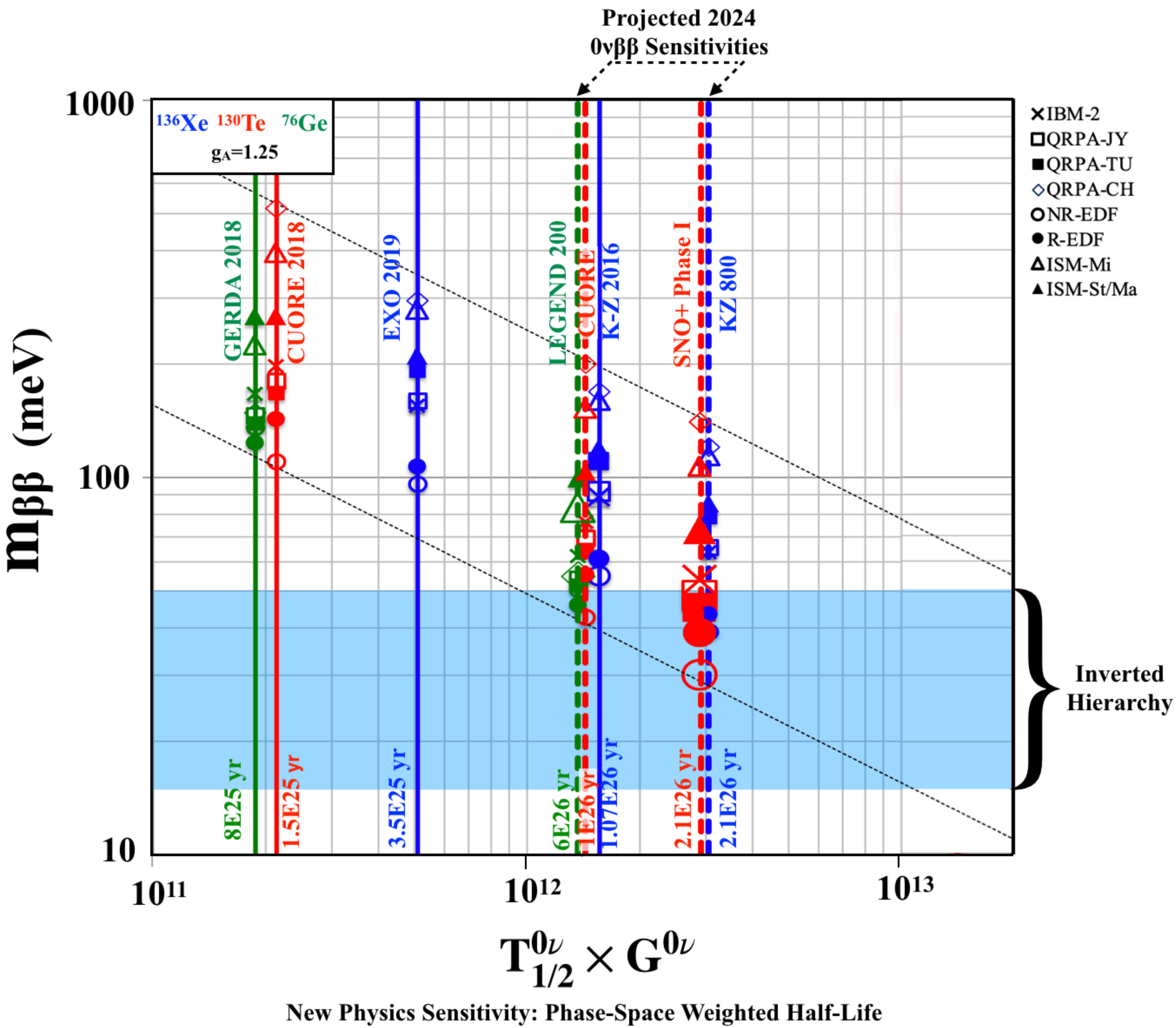
Phase I:



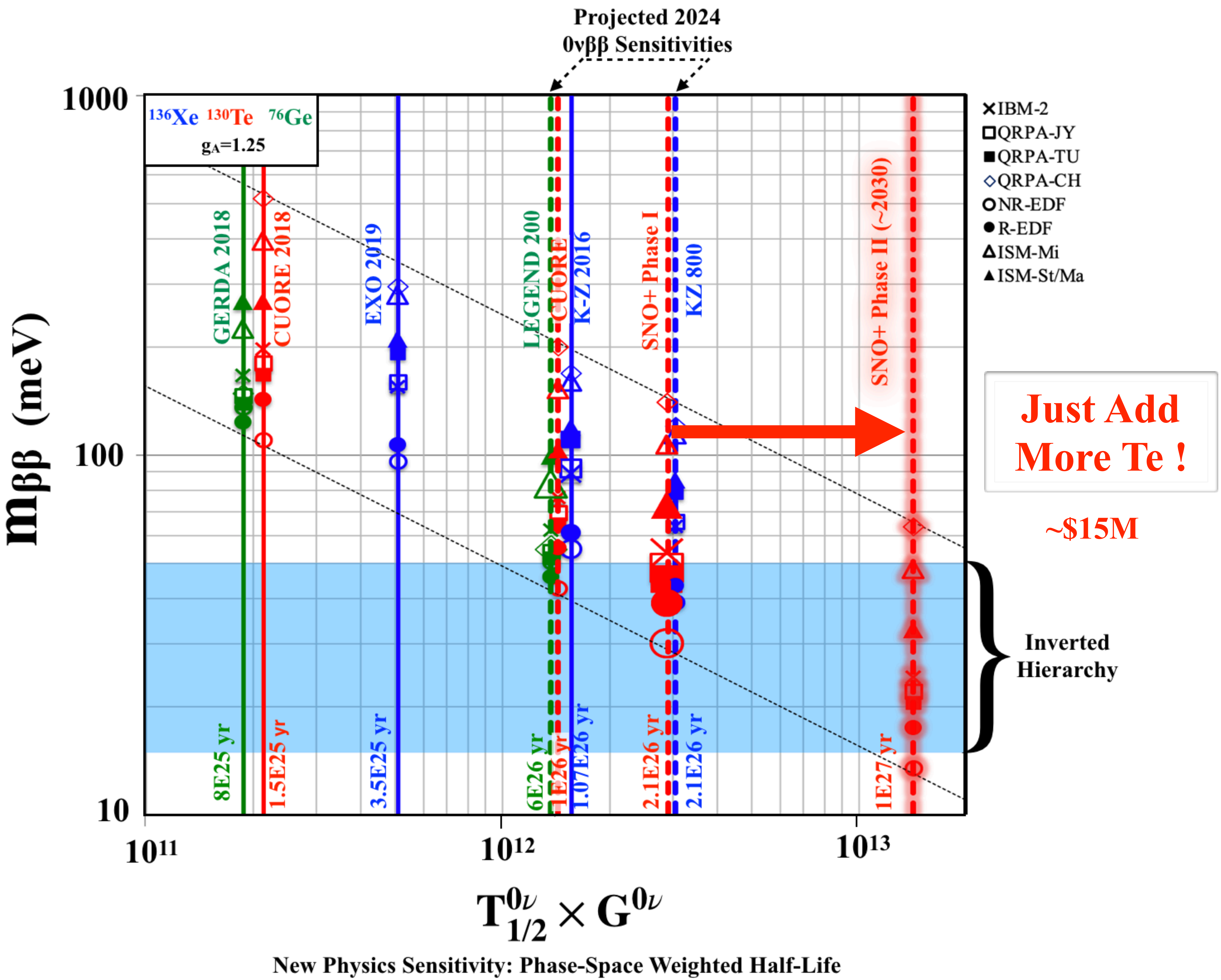


Improved Loading Protocol to Move Beyond Phase I





Projected 2024
0νββ Sensitivities
136Xe 130Te 76Ge
gA=1.25
GERDA 2018
CUORE 2018
EXO 2019
LEGEND 200
CUORE
K-Z 2016
SNO+ Phase I
KZ 800
8E25 yr
1.5E25 yr
3.5E25 yr
6E26 yr
1E26 yr
1.07E26 yr
2.1E26 yr
2.1E26 yr
IBM-2
QRPA-JY
QRPA-TU
QRPA-CH
NR-EDF
R-EDF
ISM-Mi
ISM-St/Ma
Inverted Hierarchy
1000
100
10
mββ (meV)
10^11
10^12
10^13
$T^{0\nu}_{1/2} \times G^{0\nu}$
New Physics Sensitivity: Phase-Space Weighted Half-Life



Projected 2024
0νββ Sensitivities
^{136}Xe ^{130}Te ^{76}Ge
g_A=1.25
GERDA 2018
CUORE 2018
EXO 2019
LEGEND 200
CUORE
K-Z 2016
SNO+ Phase I
KZ 800
SNO+ Phase II (~2030)
8E25 yr
1.5E25 yr
3.5E25 yr
6E26 yr
1E26 yr
1.07E26 yr
2.1E26 yr
2.1E26 yr
1E27 yr
IBM-2
QRPA-JY
QRPA-TU
QRPA-CH
NR-EDF
R-EDF
ISM-Mi
ISM-St/Ma
Just Add More Te !
~$15M
Inverted Hierarchy
$m_{\beta\beta}$ (meV)
1000
100
10
10^{11}
10^{12}
10^{13}
$T^{0\nu}_{1/2} \times G^{0\nu}$
New Physics Sensitivity: Phase-Space Weighted Half-Life

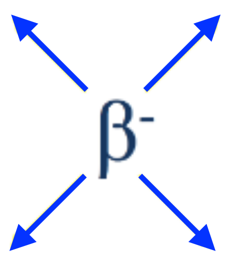
Other Recent Advances in the General Loaded Scintillator Approach

Multi-site event discrimination in large liquid scintillation detectors

Jack Dunger*, Steven D. Biller

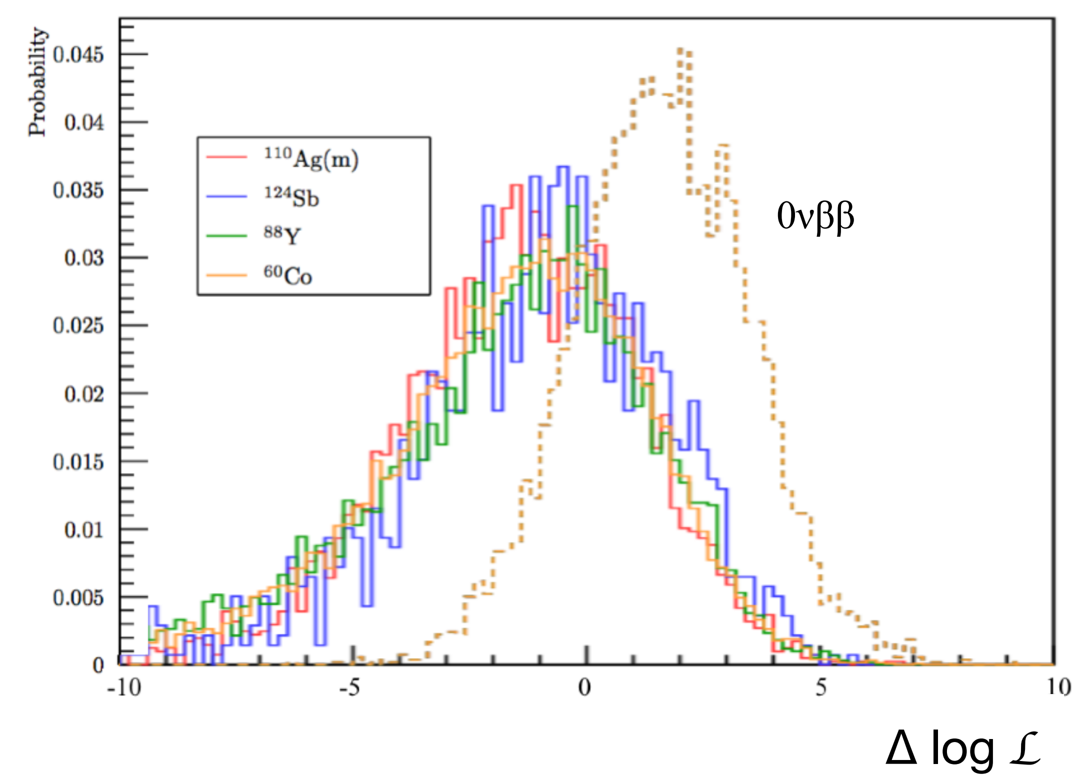
Department of Physics, Univeristy of Oxford, Oxford OX1 3RH, UK

(arXiv:1904.00440)



Compton length for 1 MeV γ in LAB ~20cm, vs vertex resolution of ~10cm

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



***In situ* calibration of technique**

multi-site events:

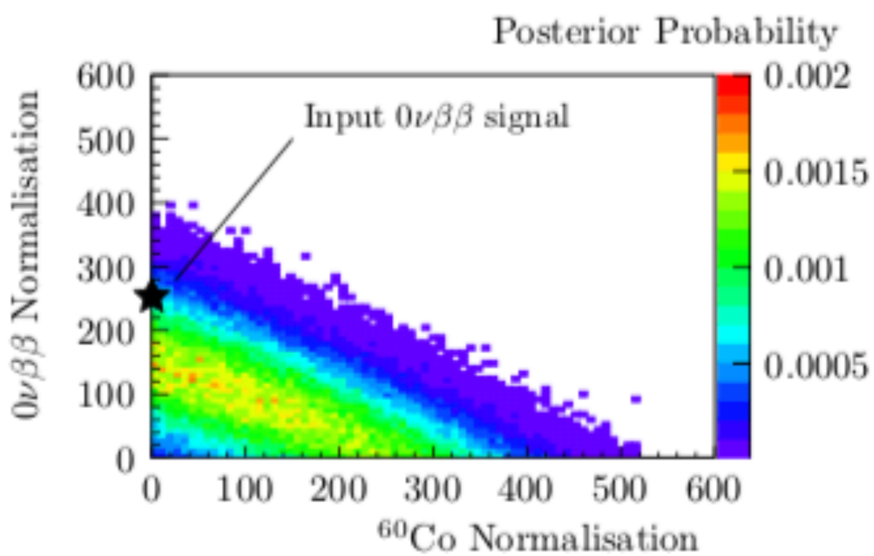
- α-tagged ^{214}Bi & ^{208}Tl decays
- external γ's (dominant at higher radius)

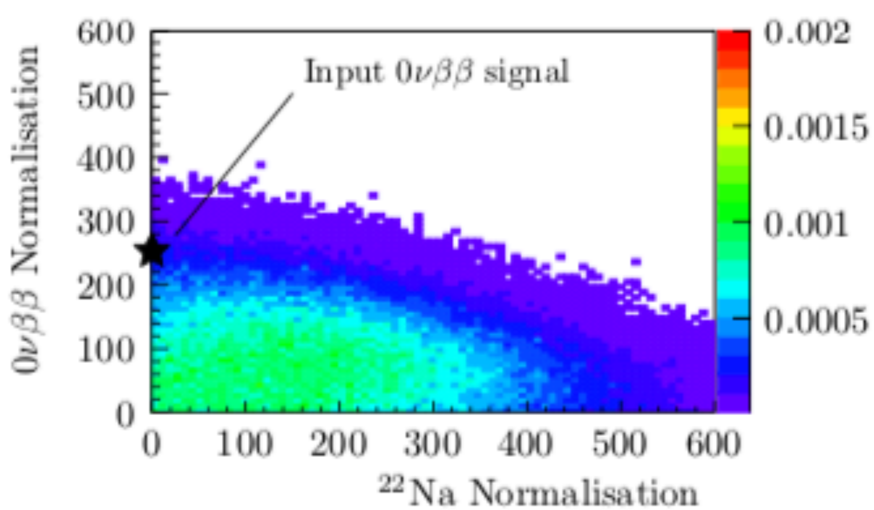
single-site events:

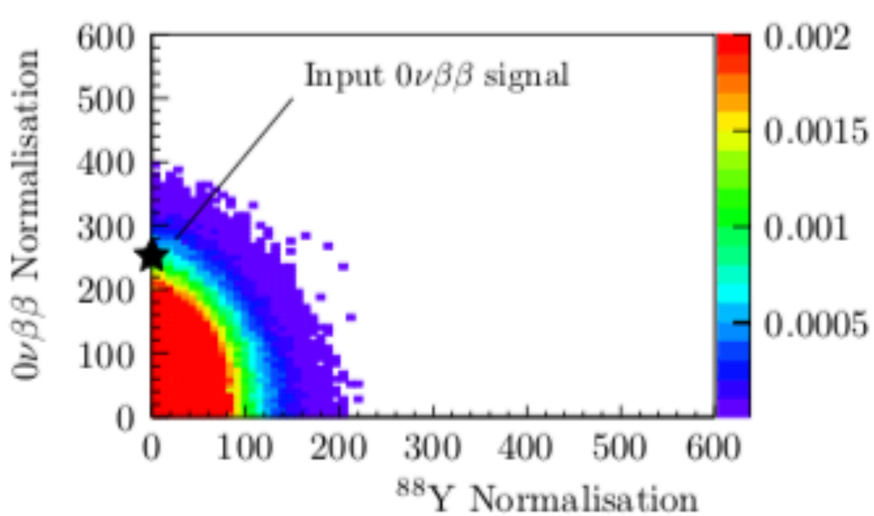
- 2νββ events (dominant at lower energy)
- ^{8}B solar ν (dominant at higher energies)

can also use deployed sources

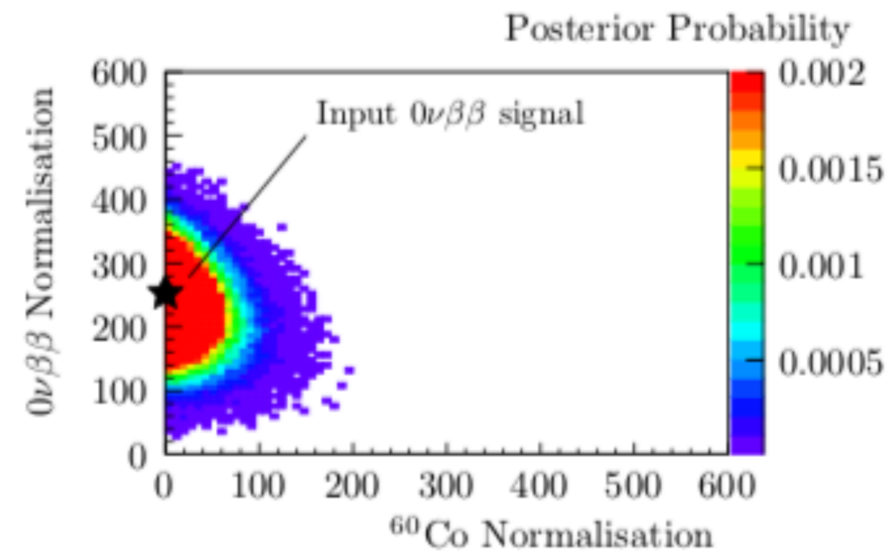
without multi-site parameter

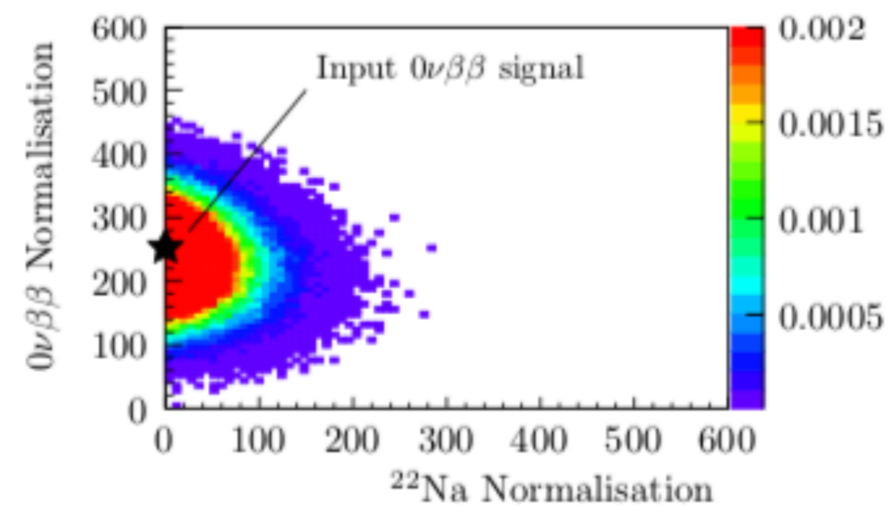


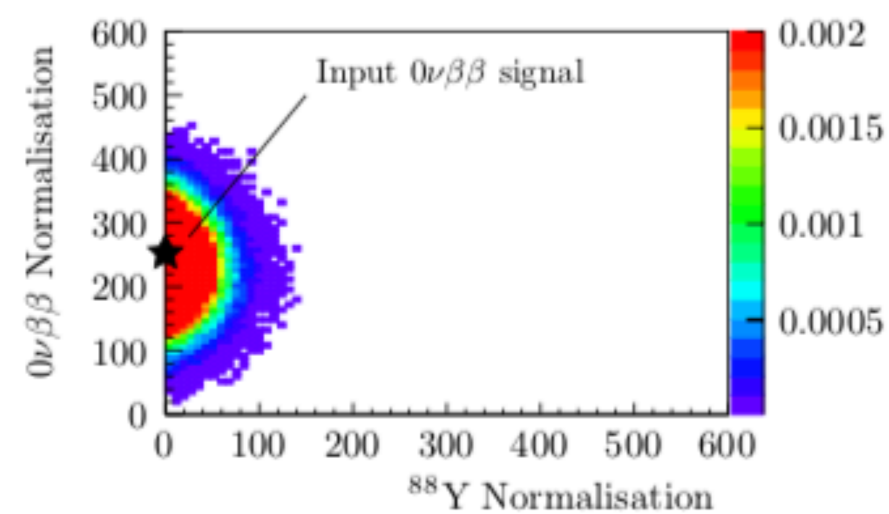




with multi-site parameter

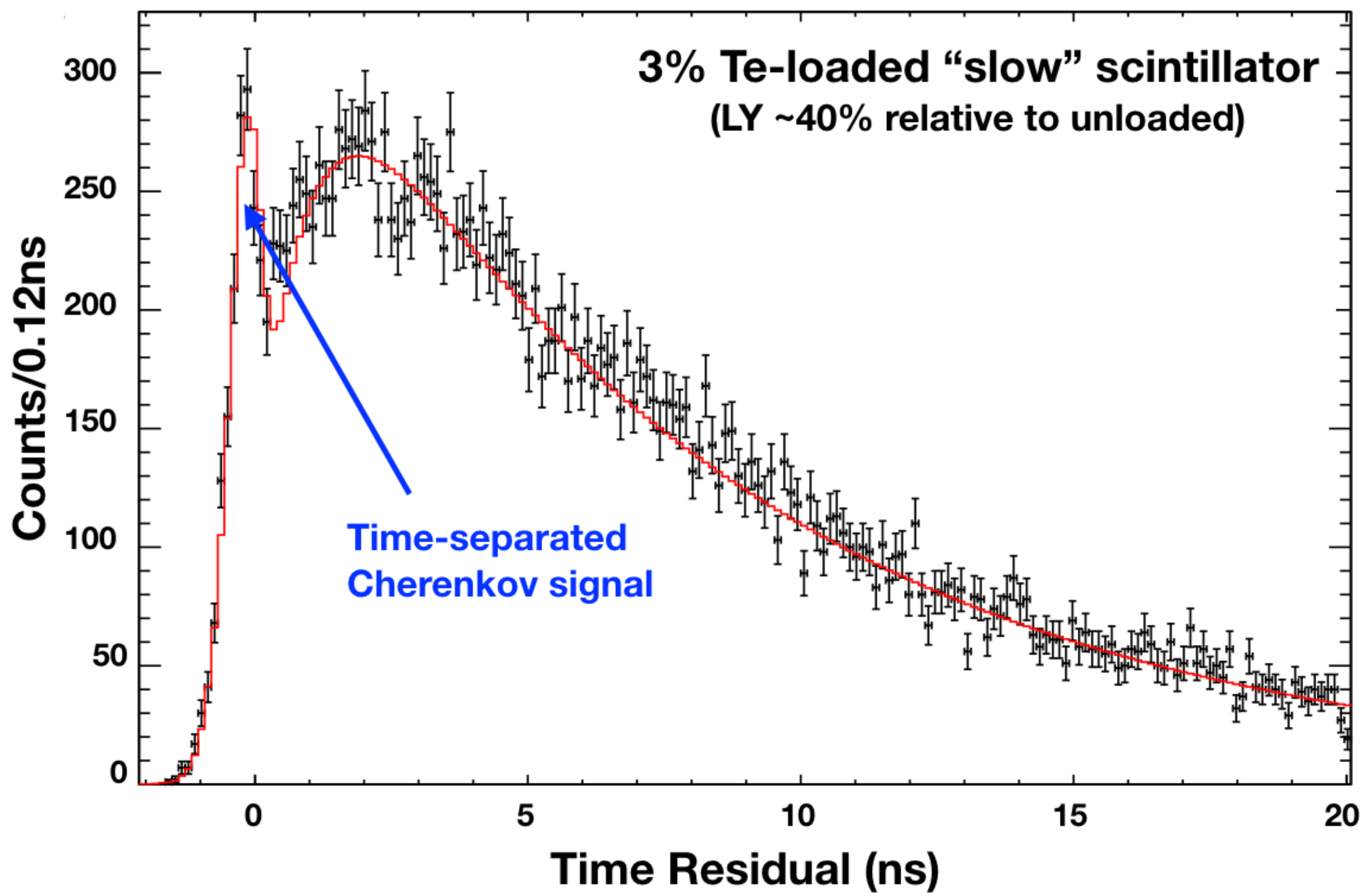






Cherenkov separation using slow fluors

(papers in progress)



Could allow suppression of ^{8}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?

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
^{48}Ca	4.27	0.19	0.16	2.4E8	24.81	1.5
^{76}Ge	2.04	7.8	1650	118	2.363	5.1
^{82}Se	3	9.2	174	2000	10.16	3.7
^{96}Zr	3.35	2.8	36	1.4E6	20.58	3.2
^{100}Mo	3.03	9.6	35	2.5E5	15.92	5.6
^{110}Pd	2.02	11.8	23000	200	4.815	6
^{116}Cd	2.82	7.6	2.8	2.2E4	16.7	4.3
^{124}Sn	2.29	5.6	30	2.5E5	9.04	3.2
^{130}Te	2.53	34.5	50	400	14.22	3.8
^{136}Xe	2.46	8.9	1000	50	14.58	2.6
^{150}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=2meV (10^{30}yr)	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})
^{48}Ca	4.27	0.19	0.16	2.4E8	24.81	1.5	1.17	134	70766	11.3	2689	0.55
^{76}Ge	2.04	7.8	1650	118	2.363	5.1	1.06	193	2479	4090.2	3867	18.08
^{82}Se	3	9.2	174	2000	10.16	3.7	0.47	92	1002	174.3	1844	2.05
^{96}Zr	3.35	2.8	36	1.4E6	20.58	3.2	0.31	71	2544	91.6	1425	0.76
^{100}Mo	3.03	9.6	35	2.5E5	15.92	5.6	0.13	31	326	11.4	626	0.53
^{110}Pd	2.02	11.8	23000	200	4.815	6	0.38	99	841	19341.2	1985	3.98
^{116}Cd	2.82	7.6	2.8	2.2E4	16.7	4.3	0.21	59	773	2.2	1175	1.32
^{124}Sn	2.29	5.6	30	2.5E5	9.04	3.2	0.71	209	3740	112.2	4189	14.18
^{130}Te	2.53	34.5	50	400	14.22	3.8	0.32	99	287	14.3	1980	25.79
^{136}Xe	2.46	8.9	1000	50	14.58	2.6	0.66	216	2424	2424.3	4315	32.61
^{150}Nd	3.37	5.6	42	1E4	63.03	2.8	0.13	47	848	35.6	949	0.69

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

Isotope	Q (MeV)	% nat. abund.	elem. cost $/kg	world prod. (tons/yr)	G^{0v} (10^{-15}/yr)	Median M^{0v} for g_A=1.25	$T_{1/2}^{0v}$ for m=2meV (10^{30}yr)	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})
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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

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=2meV (10^{30}yr)	Ton-yrs per event	equiv. nat. elem. Ton-yrs	nat. elem. cost ($M) @1ev/yr	cost ($M) if enriched @ $20/g	0ν/2ν rates (10^{-10})
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~~^{116}Cd~~	2.82	7.6	2.8	2.2E4	16.7	4.3	0.21	59	773	2.2	1175	1.32
^{124}Sn	2.29	5.6	30	2.5E5	9.04	3.2	0.71	209	3740	112.2	4189	14.18
^{130}Te	2.53	34.5	50	400	14.22	3.8	0.32	99	287	14.3	1980	25.79
~~^{136}Xe~~	2.46	8.9	1000	50	14.58	2.6	0.66	216	2424	2424.3	4315	32.61
~~^{150}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

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=2meV (10^{30}yr)	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})
~~^{48}Ca~~	4.27	0.19	0.16	2.4E8	24.81	1.5	1.17	134	70766	11.3	2689	0.55
~~^{76}Ge~~	2.04	7.8	1650	118	2.363	5.1	1.06	193	2479	4090.2	3867	18.08
~~^{82}Se~~	3	9.2	174	2000	10.16	3.7	0.47	92	1002	174.3	1844	2.05
~~^{96}Zr~~	3.35	2.8	36	1.4E6	20.58	3.2	0.31	71	2544	91.6	1425	0.76
~~^{100}Mo~~	3.03	9.6	35	2.5E5	15.92	5.6	0.13	31	326	11.4	626	0.53
~~^{110}Pd~~	2.02	11.8	23000	200	4.815	6	0.38	99	841	19341.2	1985	3.98
~~^{116}Cd~~	2.82	7.6	2.8	2.2E4	16.7	4.3	0.21	59	773	2.2	1175	1.32
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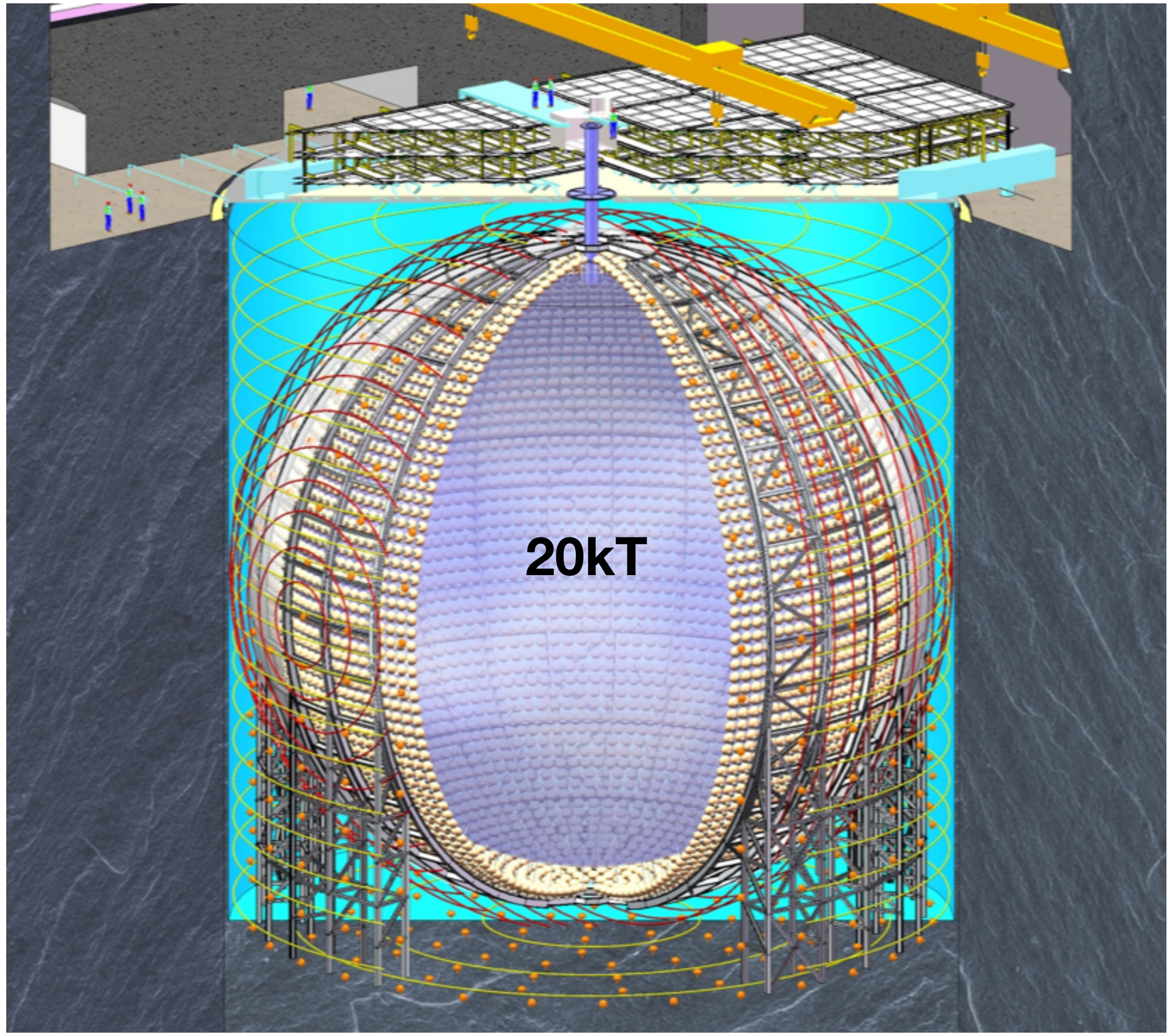
Possible Future of Loaded Scintillator:



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!

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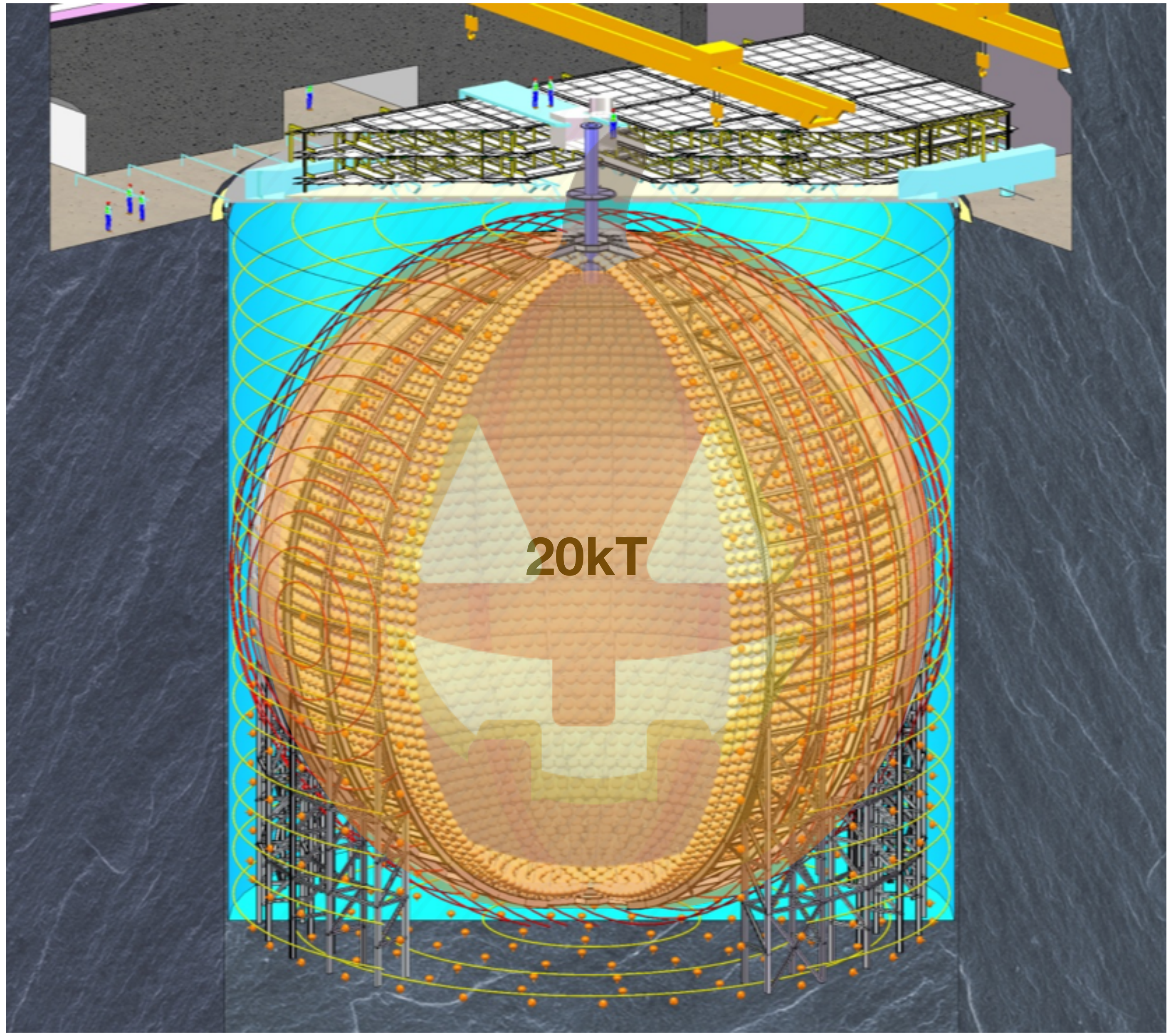

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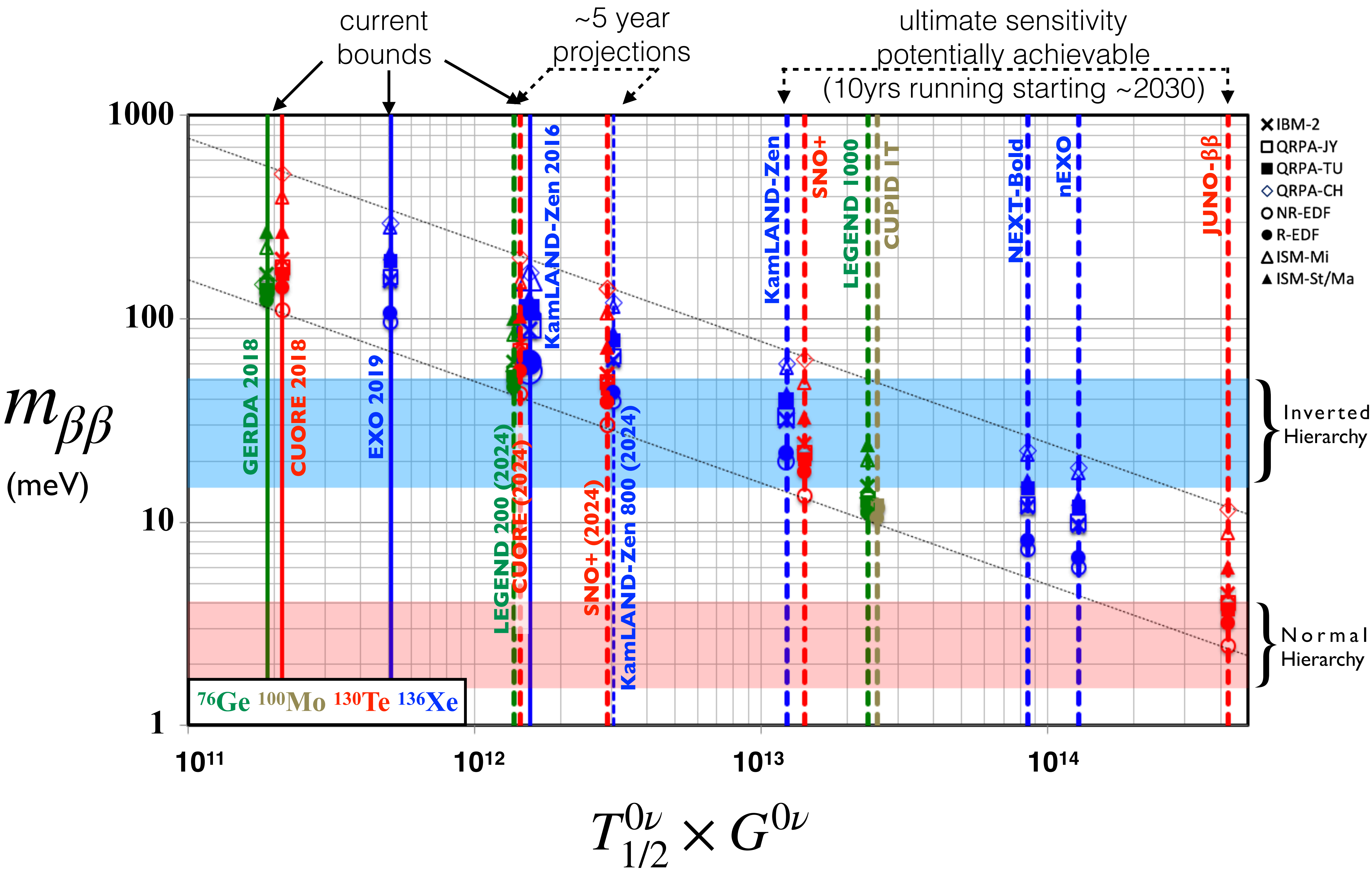

current bounds
~5 year projections
ultimate sensitivity potentially achievable (10yrs running starting ~2030)
1000
100
10
1
$m_{\beta\beta}$ (meV)
10^{11}
10^{12}
10^{13}
10^{14}
$T_{1/2}^{0\nu} \times G^{0\nu}$
GERDA 2018
CUORE 2018
EXO 2019
LEGEND 200 (2024)
CUORE (2024)
KamLAND-Zen 2016
SNO+ (2024)
KamLAND-Zen 800 (2024)
KamLAND-Zen
SNO+
LEGEND 1000
CUPID IT
NEXT-Bold
nEXO
JUNO-ββ
IBM-2
QRPA-JY
QRPA-TU
QRPA-CH
NR-EDF
R-EDF
ISM-Mi
ISM-St/Ma
Inverted Hierarchy
Normal Hierarchy
^{76}Ge ^{100}Mo ^{130}Te ^{136}Xe