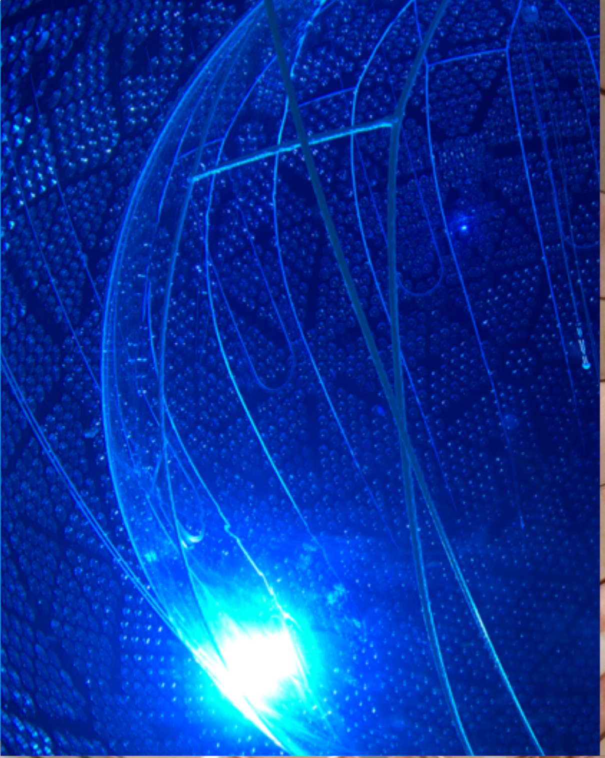
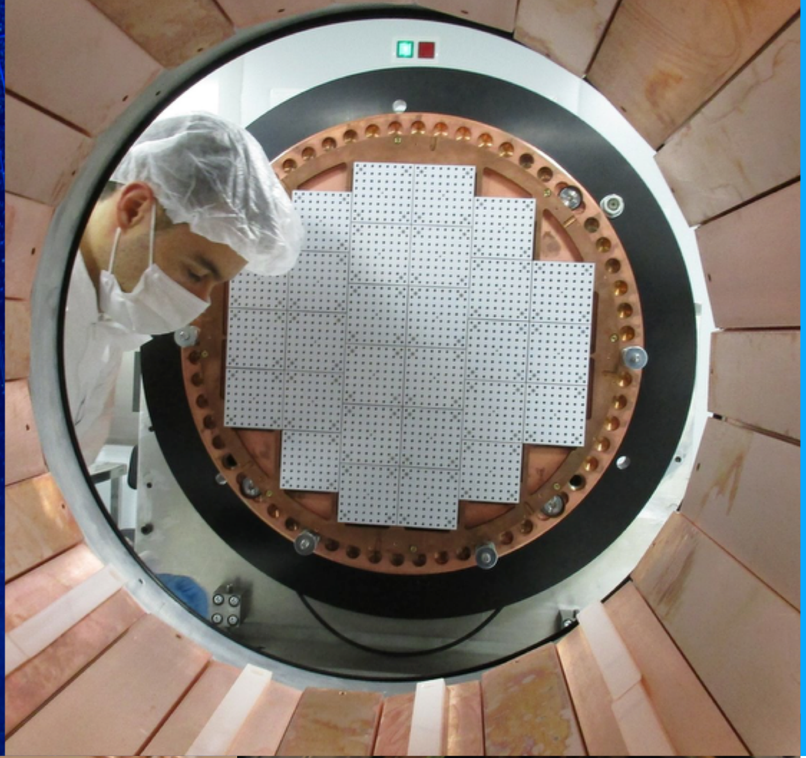
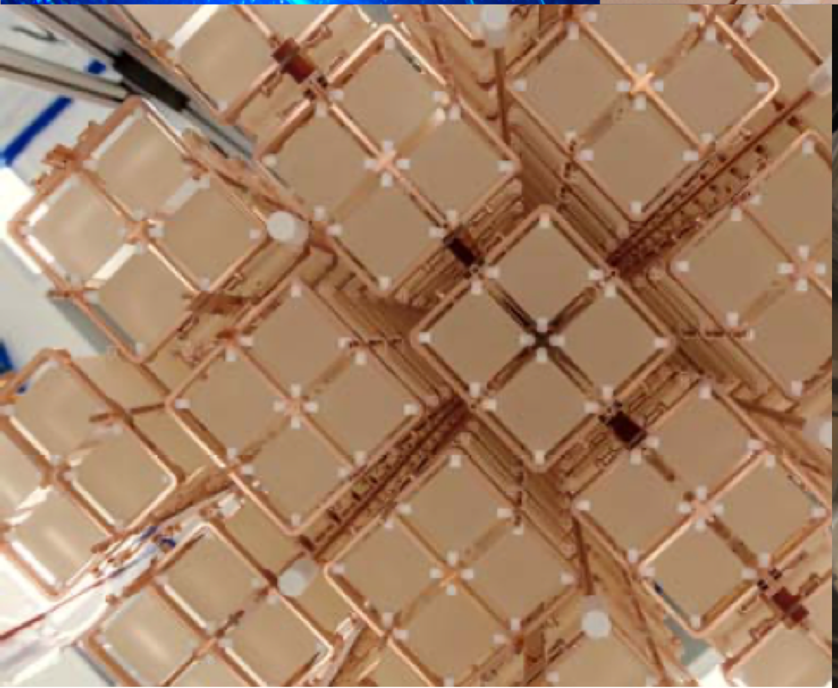
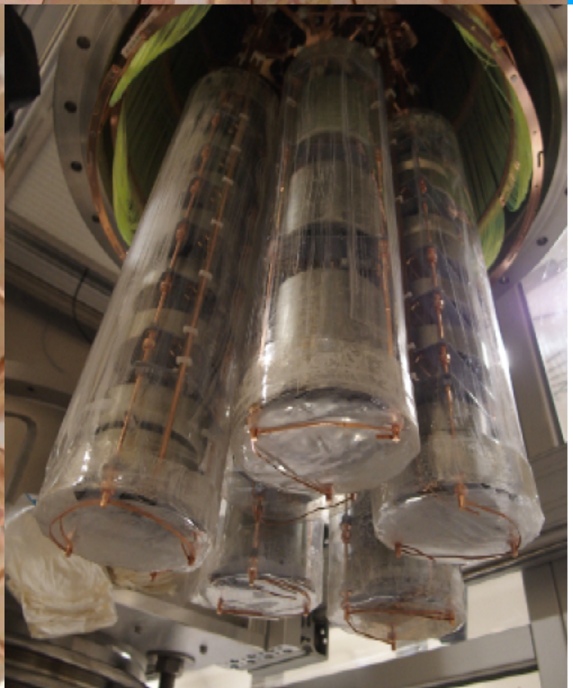



Experimental Prospects for 0νββ

Julieta Gruszko

UNC Chapel Hill/TUNL

NSF-DBD Project Scoping Workshop

January 31, 2022

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

Outline

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

- The state of experimental searches for $0\nu\beta\beta$
- Near-term prospects:
  - Final results from MJD and CUORE
  - KamLAND-Zen 800, SNO+, and LEGEND-200
- Ton-scale prospects and beyond:
  - DOE-NP and the “big 3”: CUPID, LEGEND-1000, and nEXO
  - Other large-scale efforts: NEXT, KamLAND2-Zen, SNO+/Theia

The State of $0\nu\beta\beta$ Searches

The State of 0νββ Searches

- Since 2014-2015, the P5 report and the DOE Long-Range Plan for Nuclear Science has listed development of a ton-scale 0νββ search as a top priority
- Many pathfinder/demonstrator experiments ran in the 2010's
  - 10's to 100's of kg of isotope
  - Half-life sensitivities up to 10^{26} years
  - Some still taking data or nearing release of final results
- Collaborations were preparing for a "technology down-select," which was switched to a "portfolio review" in 2020-2021.

Summer 2021 Portfolio Review

- CUPID, LEGEND, and nEXO were invited to participate in a DOE-NP portfolio review in Summer 2021
- Site decision will proceed separately
- All 3 collaborations presented baseline design, budget, and schedule information; all have publicly-available pre-Conceptual Design Reports on the arXiv
- Outcome of the portfolio review:
  - The DOE considers LEGEND and nEXO “large ton-scale projects,” CUPID is smaller in terms of both isotope mass and cost
  - The DOE is seeking international partners to support multiple ton-scale experiments
  - Collaborations have been encouraged to seek CD-1 approval in the next 6 months; early R&D funds available
  - Timeline depends on funding, but a technically-driven schedule would lead to early data in 2026 or 2027

A Rich Experimental Landscape

Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES	^{48}Ca	305 kg CaF_2 crystals - liq. scint	0.3 kg	Operating
CARVEL	^{48}Ca	$^{48}CaWO_4$ crystal scint.	16 kg	R&D
GERDA I	^{76}Ge	Ge diodes in LAr	15 kg	Complete
GERDA II	^{76}Ge	Point contact Ge in active LAr	44 kg	Complete
MAJORANA DEMONSTRATOR	^{76}Ge	Point contact Ge in Lead	30 kg	Operating
LEGEND 200	^{76}Ge	Point contact Ge in active LAr	200 kg	Construction
LEGEND 1000	^{76}Ge	Point contact Ge in active LAr	1 tonne	R&D
NEMO3	^{100}Mo/^{82}Se	Foils with tracking	6.9 kg/0.9 kg	Complete
SuperNEMO Demonstrator	^{82}Se	Foils with tracking	7 kg	Construction
SELENA	^{82}Se	Se CCDs	<1 kg	R&D
NvDEx	^{82}Se	SeF6 high pressure gas TPC	50 kg	R&D
AMoRE	^{100}Mo	CaMoO4 bolometers (+ scint.)	5 kg	Construction
CUPID	^{100}Mo	Scintillating Bolometers	250 kg	R&D
COBRA	^{116}Cd/^{130}Te	CdZnTe detectors	10 kg	Operating
CUORE-0	^{130}Te	TeO_2 Bolometer	11 kg	Complete
CUORE	^{130}Te	TeO_2 Bolometer	206 kg	Operating
SNO+	^{130}Te	0.3% ^{nat}Te in liquid scint.	800 kg	Construction
SNO+ Phase II	^{130}Te	3% ^{nat}Te in liquid scint.	8 tonnes	R&D
KamLAND-Zen 400	^{136}Xe	2.7% in liquid scint.	370 kg	Complete
KamLAND-Zen 800	^{136}Xe	2.7% in liquid scint.	750 kg	Operating
KamLAND2-ZEN	^{136}Xe	2.7% in liquid scint.	~tonne	R&D
EXO-200	^{136}Xe	Xe liquid TPC	160 kg	Complete
nEXO	^{136}Xe	Xe liquid TPC	5 tonnes	R&D
NEXT-WHITE	^{136}Xe	High pressure GXe TPC	~5 kg	Operating
NEXT-100	^{136}Xe	High pressure GXe TPC	100 kg	Construction
PandaX	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DARWIN	^{136}Xe	Xe liquid TPC	3.5 tonnes	R&D
AXEL	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DCBA	^{150}Nd	Nd foils & tracking chambers	30 kg	R&D

R&D | Construction | Operating | Complete

Completed enr. detector data-taking in 2020

CUPID-Mo also published results

Water phase results and LS characterization published, Te loading underway

Post-upgrade results expected soon

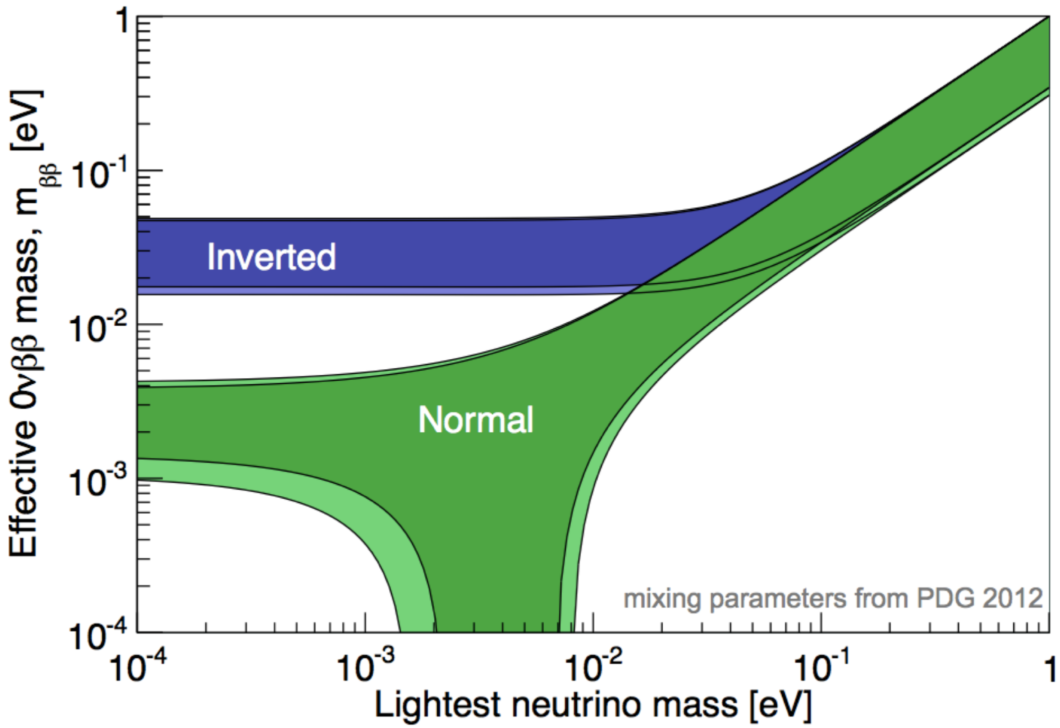
From J. Wilkerson

Interpretation of Half-Life Sensitivity

- Half-life limits are interpreted in the light Majorana neutrino exchange model

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}\, g_A^4 \left(M_{0\nu} + \frac{g_\nu^{NN} m_\pi^2}{g_A^2} M_{0\nu}^{cont} \right)^2 m_{\beta\beta}^2$$

$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$



NSAC recommendation: quote a range of $m_{\beta\beta}$ using the largest and smallest available NME from the 4 main calculation methods; g_A=1.27; no contribution from the contact term

Experiment	Isotope	Exposure [kg-yr]	$T^{0\nu}_{1/2}[10^{25}$ yr]	$m_{\beta\beta}$[meV]
GERDA [91]	^{76}Ge	127.2	18	79 – 180
MAJORANA [93]	^{76}Ge	26	2.7	200 – 433
KamLAND-Zen [95]	^{136}Xe	594	10.7	61 – 165
EXO-200 [94]	^{136}Xe	234.1	3.5	93 – 286
CUORE [97]	^{130}Te	1038.4	2.2	90 – 305

Defining the Goal of Ton-Scale Searches

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- Goals are defined in terms of discovery and exclusion sensitivities
- Discovery sensitivity: the smallest value of $m_{\beta\beta}$ for which an experiment has 50% probability of observing a signal at the 3σ (99.7%) confidence level
- Exclusion sensitivity: the median 90% confidence level upper limit that an experiment will set on $m_{\beta\beta}$ assuming that 0νββ is not observable
- Goal of ton-scale experiments: discovery sensitivity covering the IO region for all matrix elements
  - Using PDG neutrino oscillation results, $(m_{\beta\beta}^{min})_{\mathrm{IO}} = 18.4 \pm 1.3\,\mathrm{meV}$
  - Using latest NuFIT results, $(m_{\beta\beta}^{min})_{\mathrm{IO}} = 18.6 \pm 1.2\,\mathrm{meV}$
  - Corresponds to 10^{27}-10^{28} year half-life, depending on isotope

Discovery, Background, and Exposure

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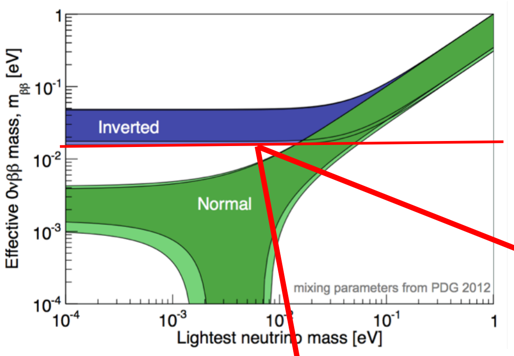
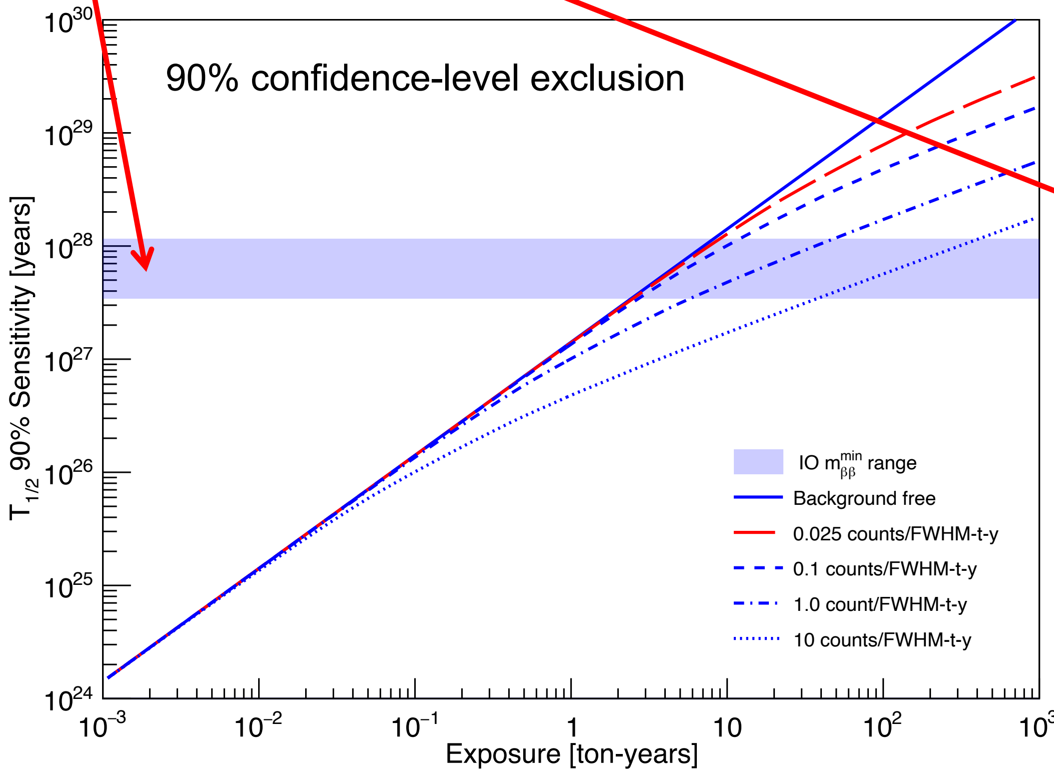
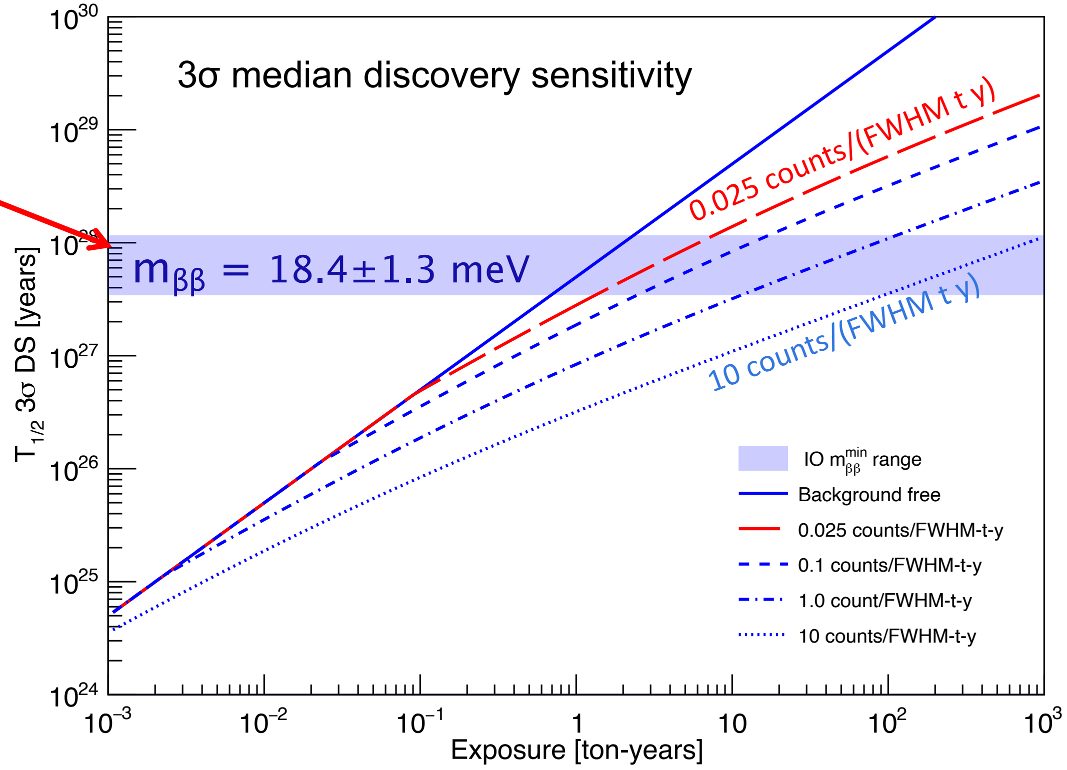
Setting a Limit

Discovery at 3σ

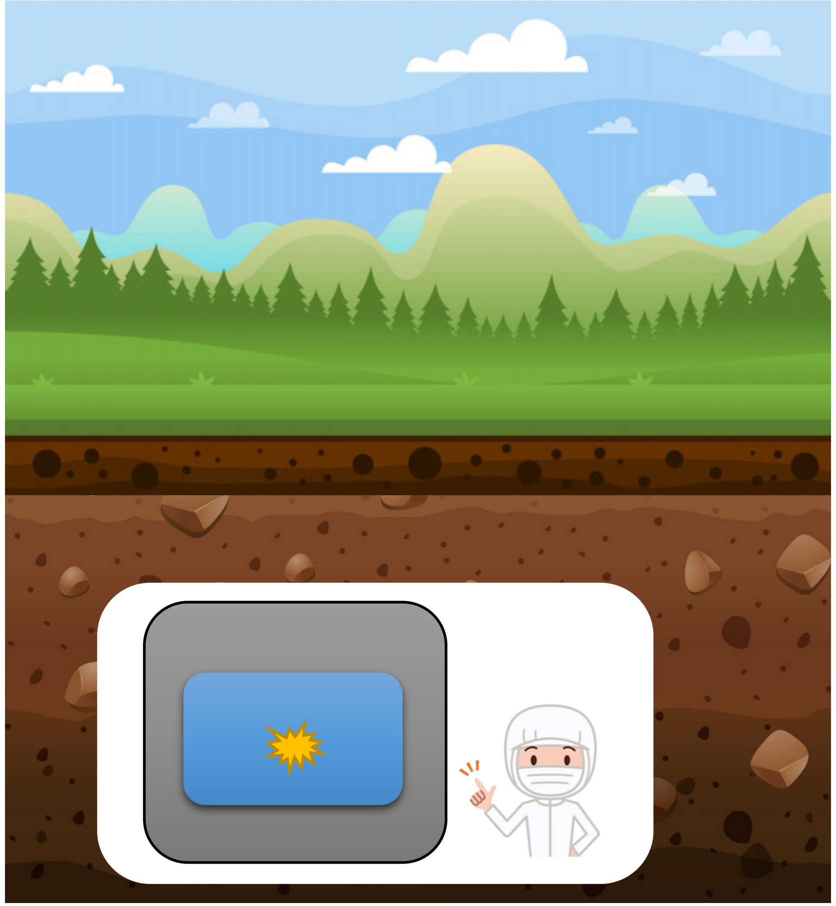




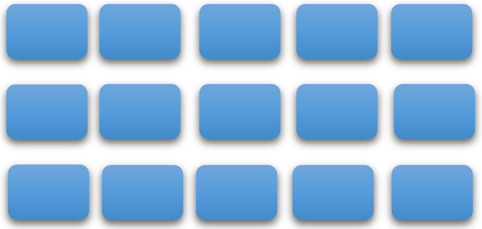


Experimental Techniques

Most Experiments



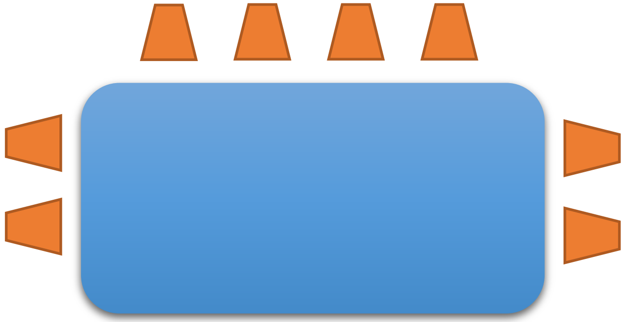
Granular Detectors



- Bolometers and semiconductors
- E.g. CUPID, LEGEND

Advantages:
- Energy resolution
- Staging

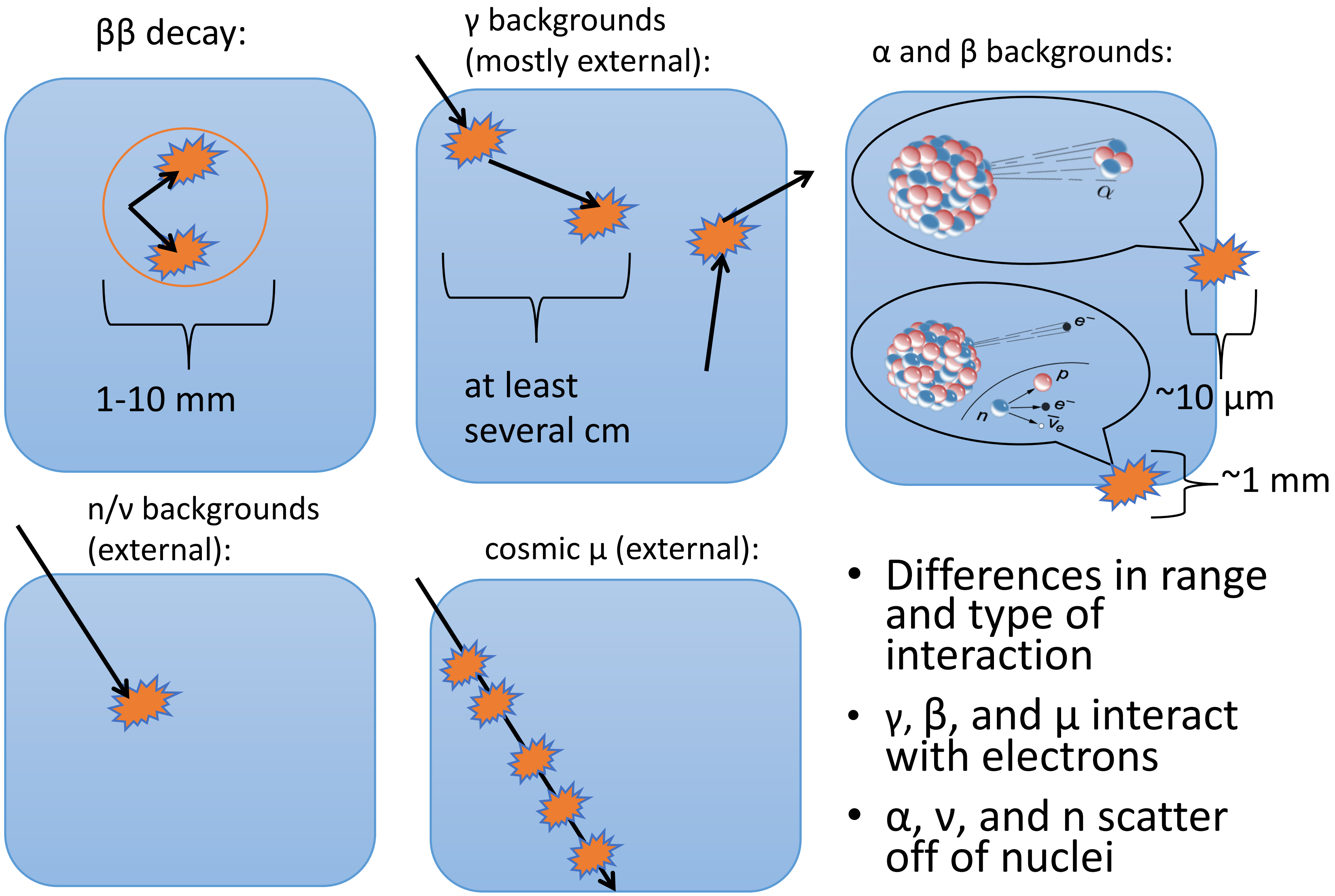
Monolithic Detectors



- Scintillators and TPCs
- E.g. KamLAND-Zen, SNO+, THEIA, nEXO, NEXT

Advantages:
- Self-shielding
- Scalability

$0\nu\beta\beta$ Signal and Backgrounds



- Differences in range and type of interaction
- γ, β, and µ interact with electrons
- α, ν, and n scatter off of nuclei

Techniques for background suppression:

- Event topology
- Time coincidence information
- Surface/bulk discrimination
- Veto systems
- Particle identification: distinguish nuclear and electron scatters, dE/dx, etc.
- Tag the daughter atom

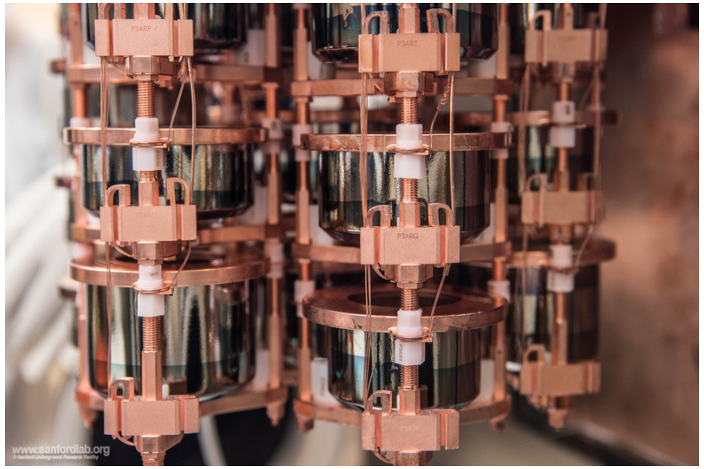
A Caveat

- I won't have time to go through all of the ongoing experiments, there are too many! I'll cover the largest efforts.
- The materials in these slides are courtesy of the various experimental collaborations

Near-Term Prospects

The MAJORANA DEMONSTRATOR

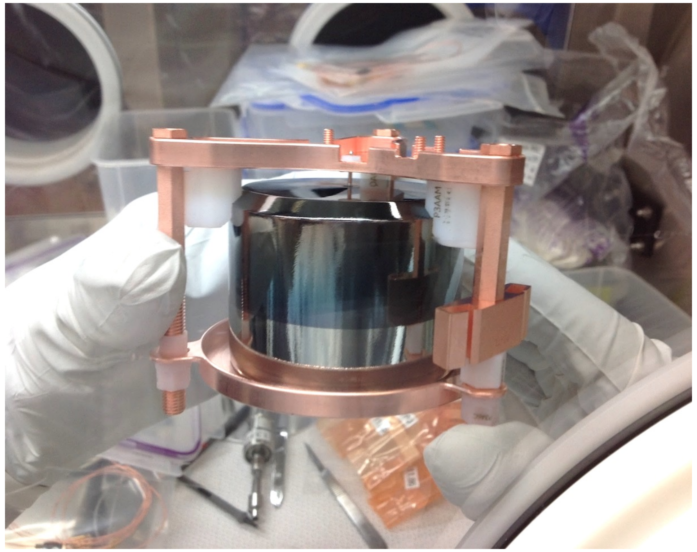
Searching for neutrinoless double-beta decay of ^{76}Ge in HPGe detectors and additional physics beyond the standard model



Source & Detector: Array of p-type, point contact (PPC) detectors
29.7 kg of 88% enriched ^{76}Ge crystals

Best Energy resolution: 2.5 keV FWHM @ 2039 keV

Low Background: 2 modules within a compact graded shield and active muon veto using ultra-clean materials like UGEFCu

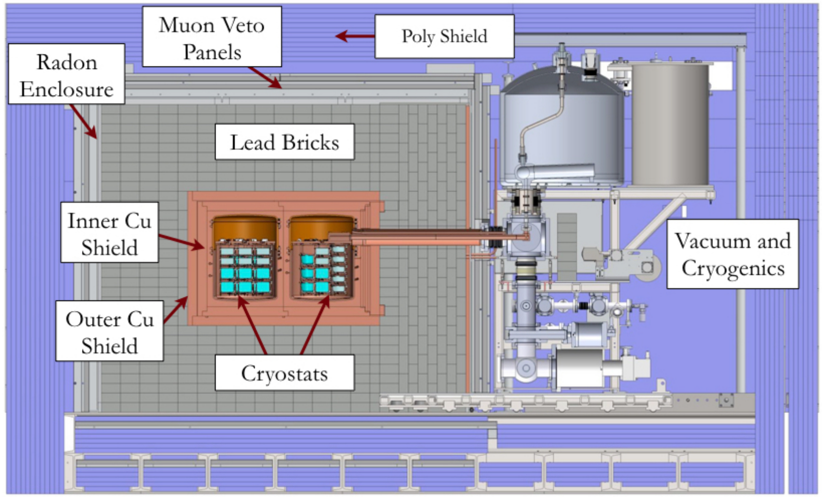


Full enriched data set results expected in Spring 2022: 65 kg yr exposure

Operating underground at the 4850' level of the Sanford Underground Research Facility since 2015

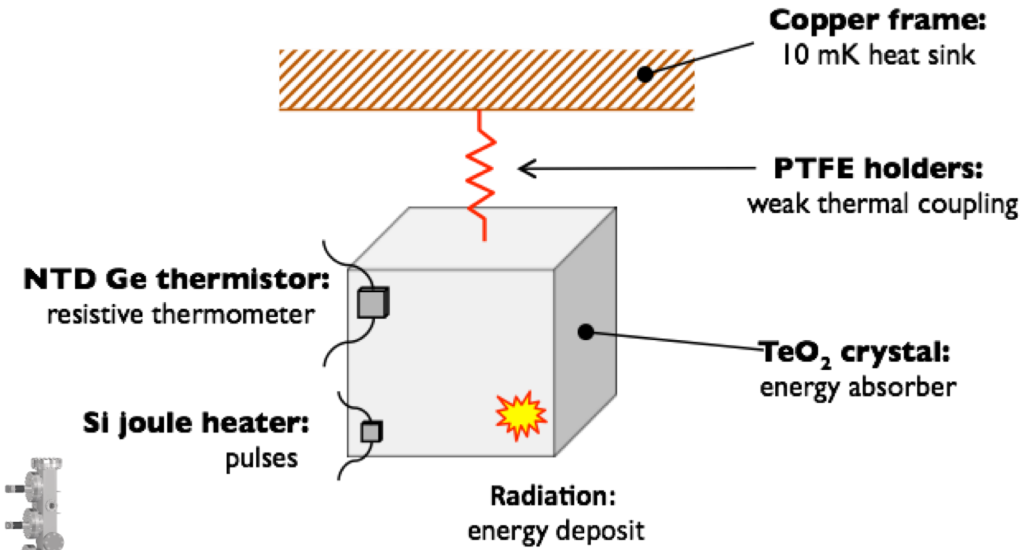
Sanford Underground Research Facility

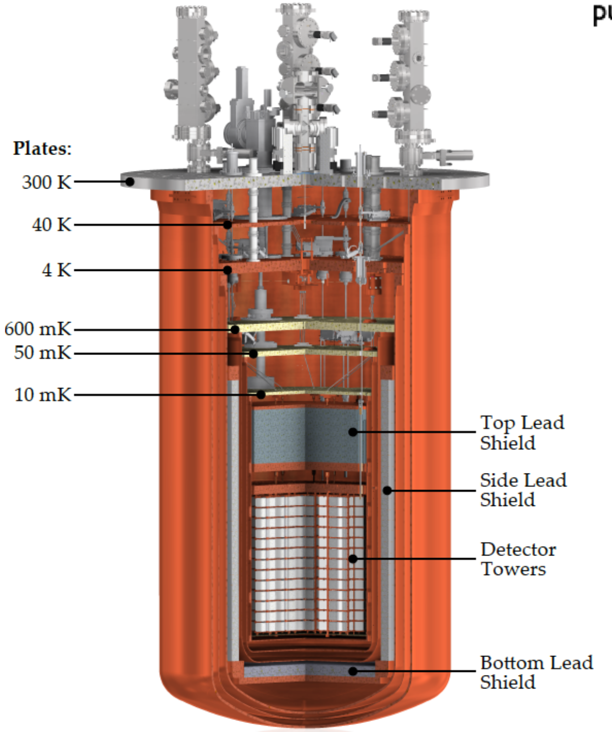
U.S. DEPARTMENT OF ENERGY | Office of Science

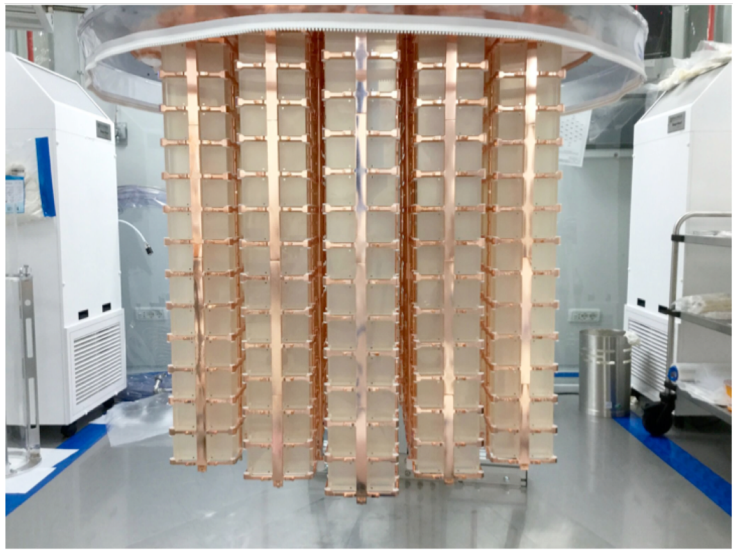


CUORE

- 988 natural-abundance TeO_2 crystals operated as bolometers
- 742 kg of detectors, 206 kg of ^{130}Te
- Taking data since 2017
- 90% of backgrounds from degraded α particles
- 2021 Results: $T_{1/2} > 2.2 \times 10^{25}$ yr, $m_{\beta\beta} > 90 – 305$ meV
- Will continue to take data until CUPID begins

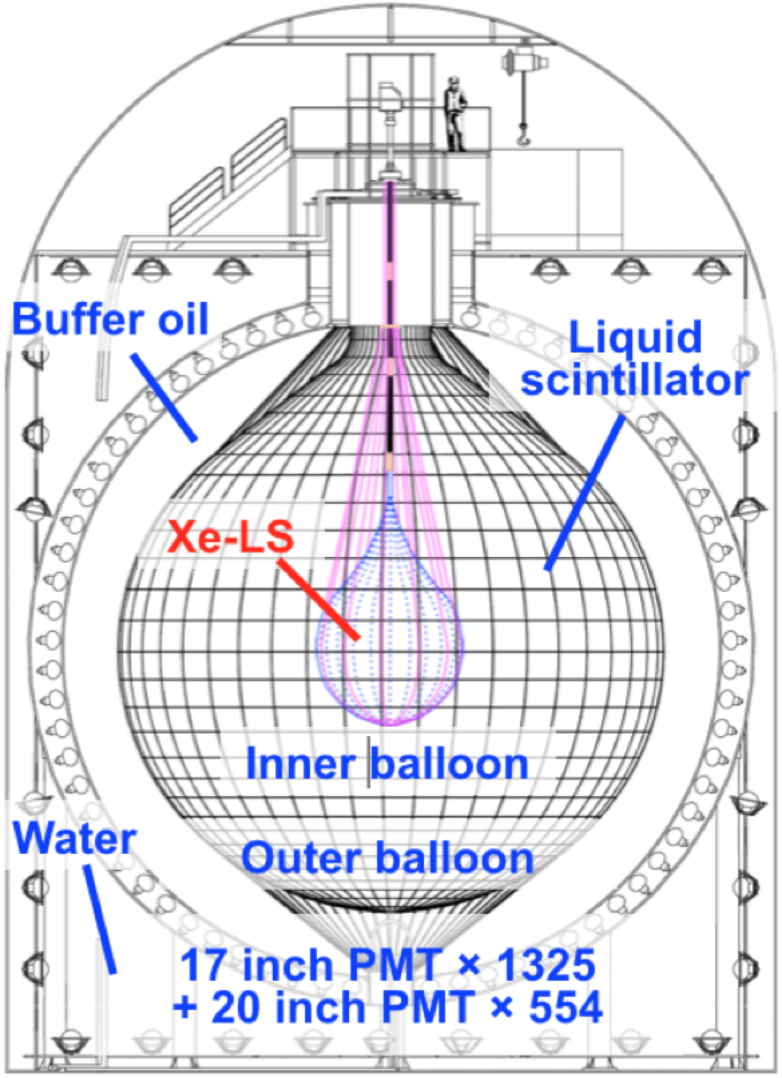






KamLAND-Zen 800

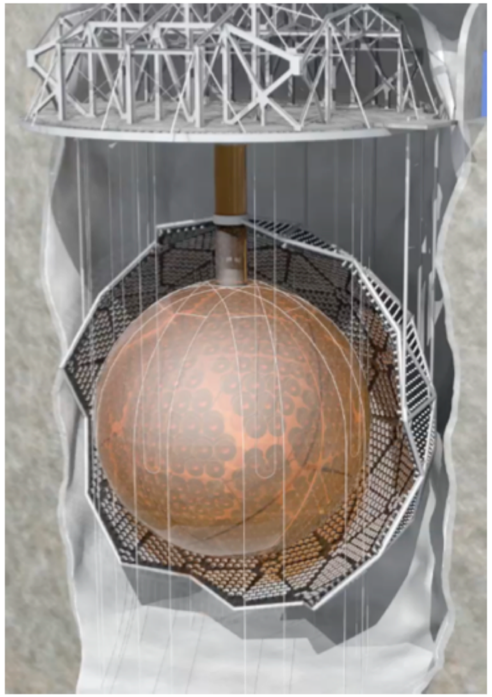
- KamLAND-Zen 400: 2011-2014
  - Phase I: 320 kg 90% enriched ^{136}Xe
  - Phase II: 380 kg
  - $T_{1/2} > 1.07 \times 10^{26}$ yr, $m_{\beta\beta} < 61\text{–}165$ meV
- KamLAND-Zen 800:
  - Data-taking began in January 2019
  - Scintillator purification campaign
  - Larger, cleaner inner balloon
  - 750 kg enriched ^{136}Xe
- First combined results expected in the next 1-2 months; should reach into IO band

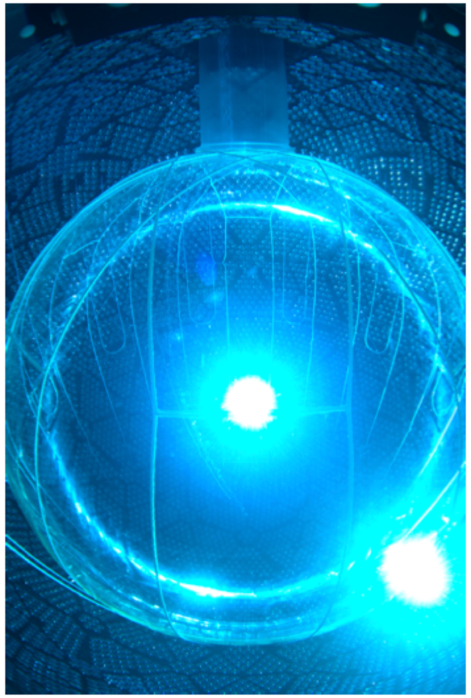


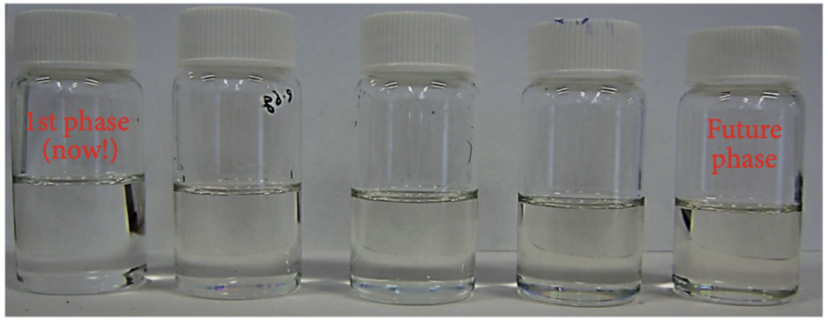
SNO+

- Ultra-pure water Cherenkov phase completed
  - Solar neutrino and BSM physics results released
- Unloaded liquid scintillator phase completed, scintillator characterized
- Tellurium loading underway @ 0.3%
  - Expected loading: 800 kg of ^{130}Te
- Expected 5 year sensitivity:

$T_{1/2} > 9 \times 10^{25}$ yrs , $m_{\beta\beta} < 55 - 133$ meV



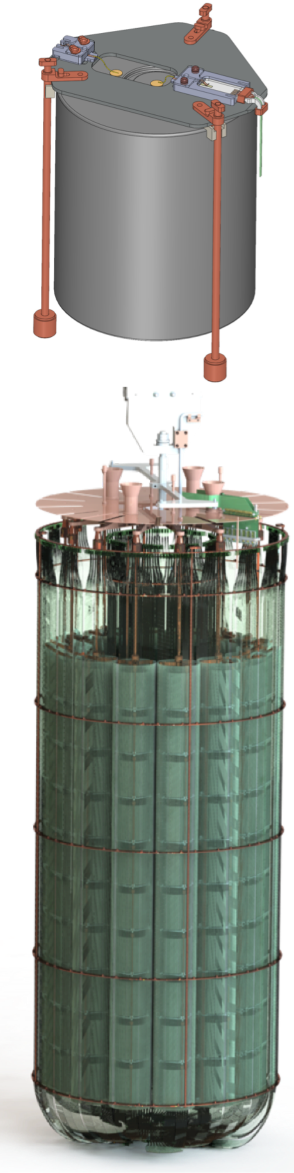


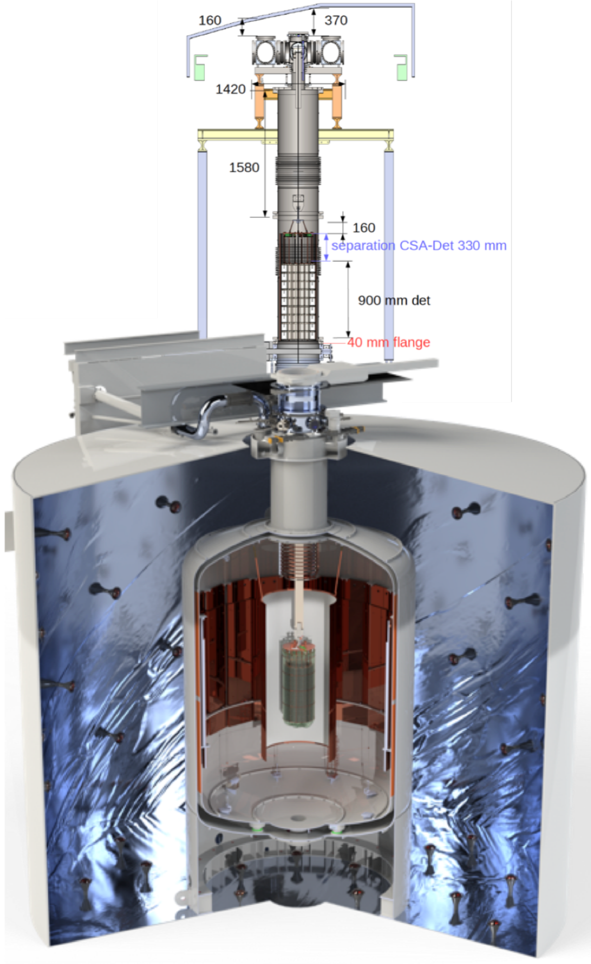


0.3% 0.5% 1% 3% 5%

LEGEND-200

- 200 kg of HPGe ICPC detectors enriched to 91% ^{76}Ge, operated in active LAr shield
- Upgrade of GERDA infrastructure
- >2.5x background reduction relative to GERDA expected
- Construction and commissioning underway, full detector deployment expected this year
- Final expected sensitivity: $T_{1/2} > 1 \times 10^{27}$ yrs

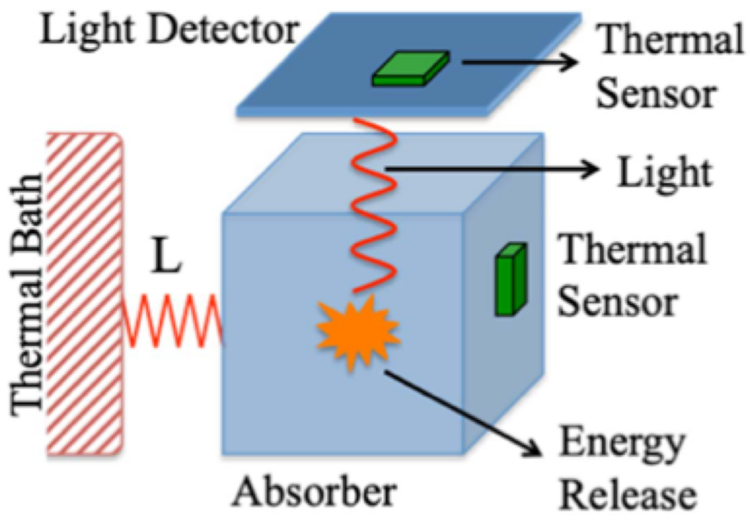




Ton-Scale Prospects

The CUPID Concept

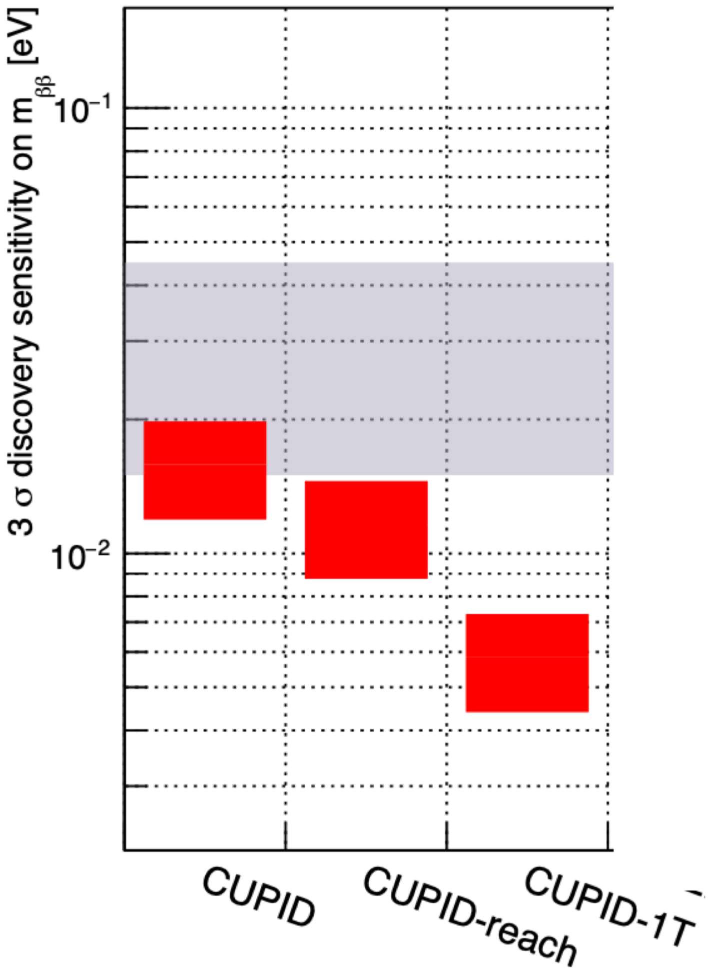
- Upgrade of CUORE cryostat with scintillating bolometer technique demonstrated in CUPID-Mo and other experiments
- Baseline crystal: Li_2MoO_4 with >95% enrichment in ^{100}Mo
- Scintillation light allows for α rejection
- ^{100}Mo 0νββ Q-value is higher in energy than most other backgrounds
- Other options for crystal/isotope: ZnSe (candidate ^{82}Se), $CdWO_4$ (candidate ^{116}Cd), and TeO_2 (candidate ^{130}Te)
- Projected discovery sensitivity: $T_{1/2}$ > 1.1 x 10^{27} yr, $m_{\beta\beta}$ > 12 – 20 meV



Parameter	Baseline
Crystal	Li_2MoO_4
Crystal size	∅50 mm× h50 mm
Crystal mass (g)	308
Number of crystals	1534
Number of light detectors	1652
Detector mass (kg)	472
^{100}Mo mass (kg)	253
Energy resolution FWHM (keV)	5
Background index (counts/(keV·kg·yr))	10^{-4}
Containment efficiency	79%
Selection efficiency	90%
Livetime	10 years
Half-life limit sensitivity (90%) C.L.	1.5×10^{27} y
Half-life discovery sensitivity (3σ)	1.1×10^{27} y
$m_{\beta\beta}$ limit sensitivity (90%) C.L.	10 – 17 meV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12 – 20 meV

Slides provided by CUORE, CUPID, CUPID-Mo, and CUPID-0 Collaborations

CUPID Improvements and Future Upgrades



Parameter	CUPID Baseline	CUPID-reach	CUPID-1T
Crystal	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$
Detector mass (kg)	472	472	1871
^{100}Mo mass (kg)	253	253	1000
Energy resolution FWHM (keV)	5	5	5
Background index (counts/(keV·kg·yr))	10^{-4}	2×10^{-5}	5×10^{-6}
Containment efficiency	79%	79%	79%
Selection efficiency	90%	90%	90%
Livetime (years)	10	10	10
Half-life exclusion sensitivity (90% C.L.)	1.5×10^{27} y	2.3×10^{27} y	9.2×10^{27} y
Half-life discovery sensitivity (3σ)	1.1×10^{27} y	2×10^{27} y	8×10^{27} y
$m_{\beta\beta}$ exclusion sensitivity (90% C.L.)	10–17 meV	8.2–14 meV	4.1–6.8 MeV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12–20 meV	8.8–15 meV	4.4–7.3 meV

CUPID pre-CDR: exactly what we could start building today: 10^{-4} counts/keV/kg/yr

CUPID reach: assume improvement at reach before construction: $2{\cdot}10^{-5}$ counts/keV/kg/yr

CUPID 1Ton: new, 4 times larger (in volume) cryostat, 1 ton 100Mo : $5{\cdot}10^{-6}$ counts/keV/kg/yr

The LEGEND-1000 Concept

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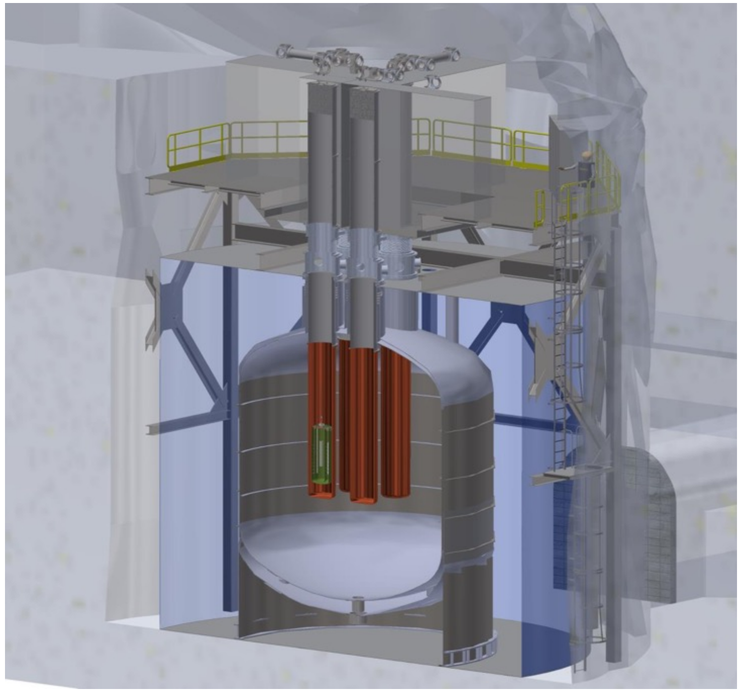
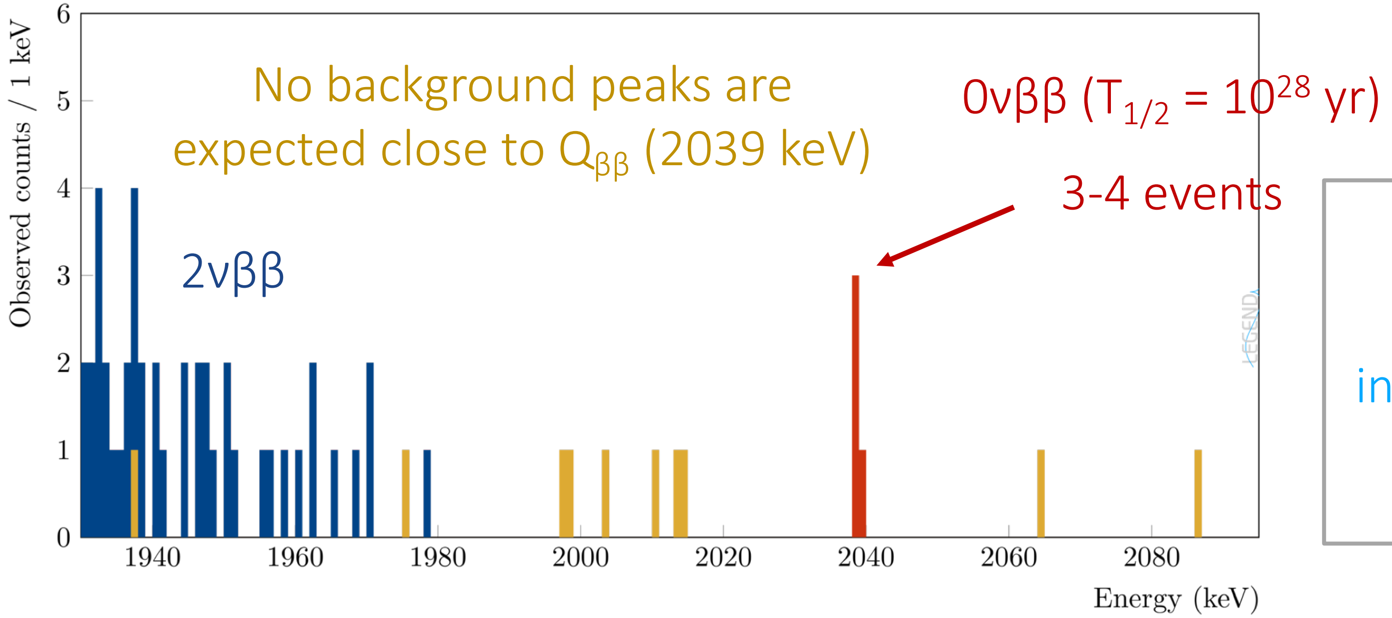
- New cryostat either at LNGS or SNOLAB; 4 independent payloads with depleted UAr in inner volumes
- 1000 kg of enriched Ge detectors: fabricate 870 kg of new detectors; use 130 kg from LEGEND-200; recycle 50 kg of small detectors
- Multi-dimensional analysis nearly eliminates γ, surface α and β backgrounds
- LEGEND goal: BI < 1×10^{-5} cnts/keV kg yr





Projected spectrum: even a signal at the bottom of the inverted ordering will be visible to the eye

LEGEND-1000 Discovery Sensitivity

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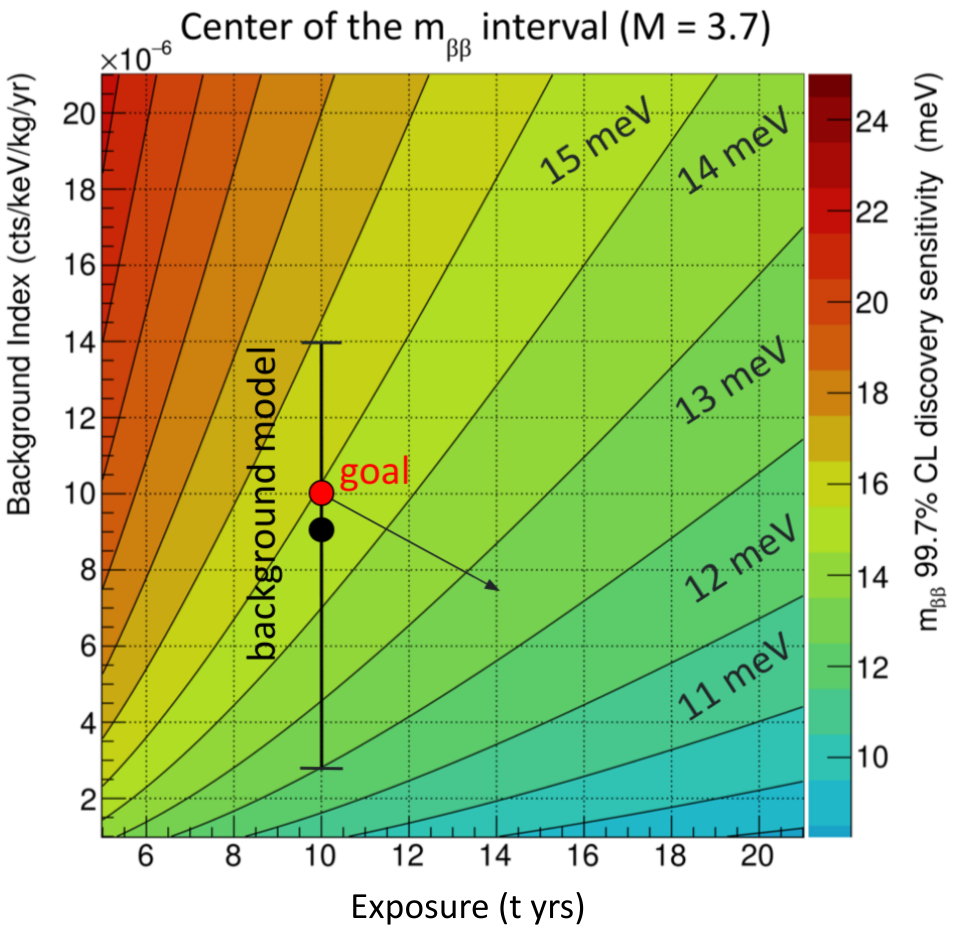
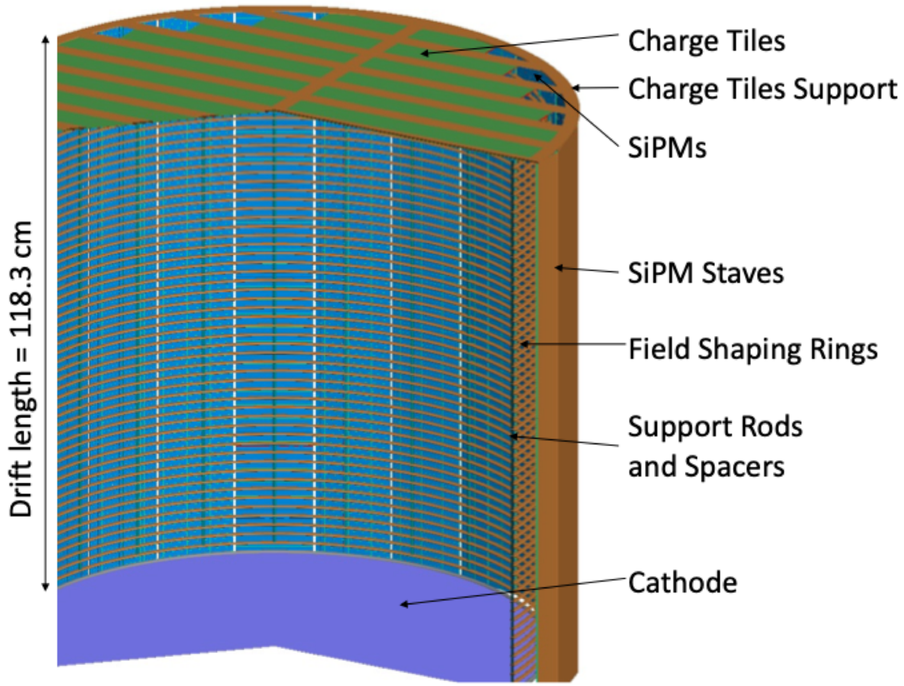


- Additional mass can be loaded in L-1000 cryostat
- Projected BI is upper limit

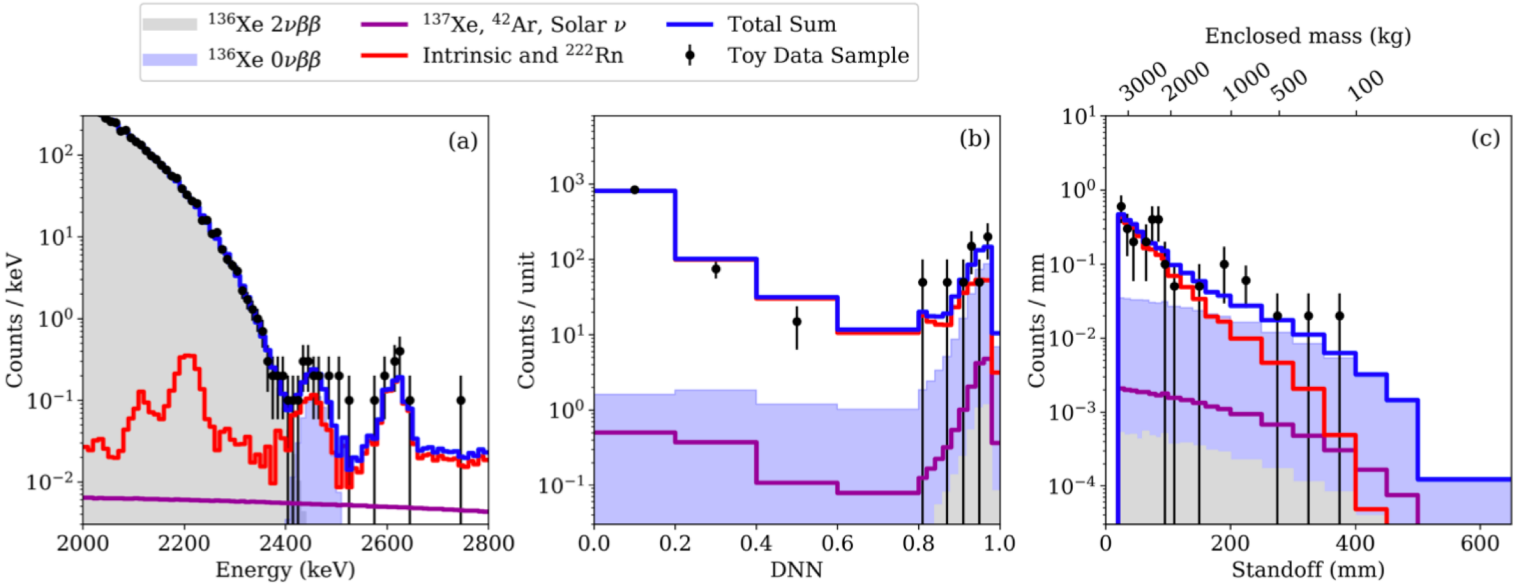
Parameter	Value
Performance Parameters	
$0\nu\beta\beta$ decay isotope	^{76}Ge
$Q_{\beta\beta}$	2039 keV
Total mass	1000 kg
Energy resolution at $Q_{\beta\beta}$	2.5 keV FWHM
Overall signal acceptance[a]	0.69
Live time goal	10 yr
Total exposure goal	10 t yr
Background goal	$< 1 \times 10^{-5}$ cts/(keV kg yr)
	< 0.025 cts/(FWHM t yr)
$T^{0\nu}_{1/2}$	1.3×10^{28} yr (99.7% CL discovery)
	1.6×10^{28} yr (90% CL sensitivity)
$m_{\beta\beta}$	9.4–21.4 meV (99.7% CL discovery)
	8.5–19.4 meV (90% CL sensitivity)
Physics Parameters	
$M_{0\nu}$	2.66–6.04 [28, 37]
$G_{0\nu}$	2.363×10^{-15} /yr [22]
g_A	1.2724

The nEXO Concept

nEXO Conceptual Design

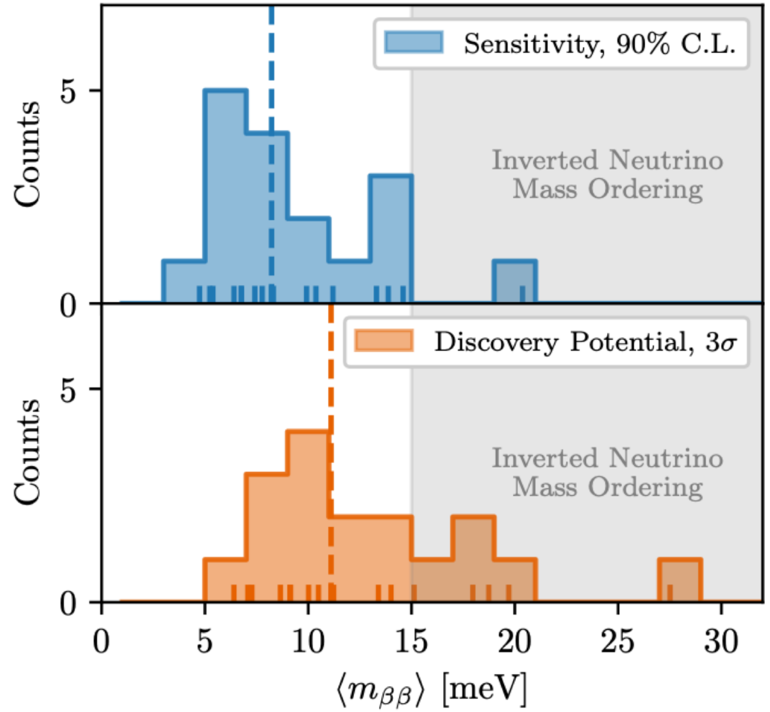


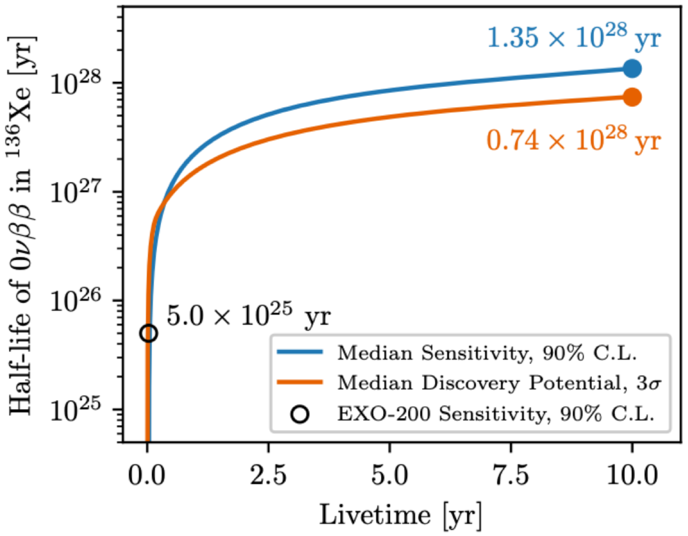
- Large single-phase LXe TPC: 4811 kg of enriched Xe
- Take advantage of self-shielding, (non-binary) fiducialization, and event topology information to reduce backgrounds



Slides provided by the EXO-200 and nEXO Collaborations, from D. Moore

nEXO Sensitivity Projection

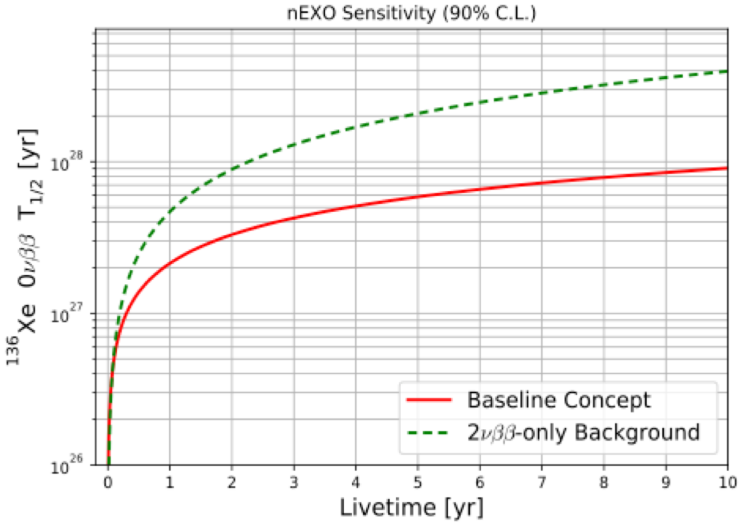




Potential future upgrade: Ba tagging

$$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}$$

In nEXO, eliminating other backgrounds could give up to 4x higher sensitivity



nEXO Collaboration, *Phys. Rev. C* **97**, 065503 (2018)

Discovery potential: $T_{1/2} > 0.74 \times 10^{28}$ yr , $m_{\beta\beta} < 6 - 27$ meV

Matrix Elements and the "Big 3"

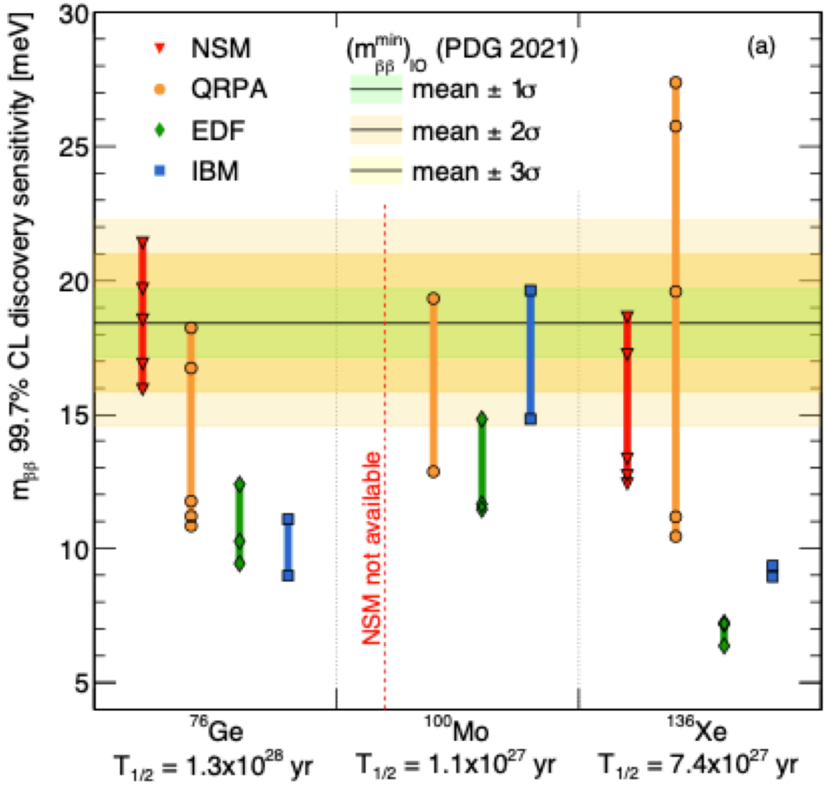
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

- All 3 experiments cover the IO for some matrix elements, and miss for others
- Larger background = more difference between discovery and exclusion

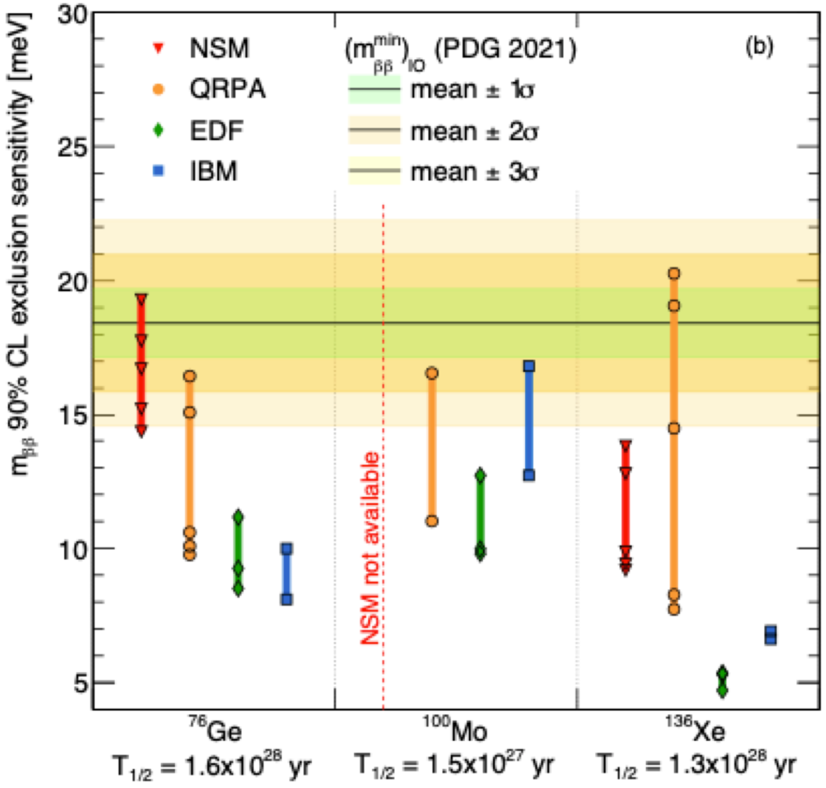
TABLE I. Nuclear matrix elements M for $0\nu\beta\beta$ decay mediated by light neutrinos, calculated with the NSM, QRPA, EDF, and IBM methods. The ranges correspond to the minimum and maximum values obtained with the same many-body method.

	Ref.	^{76}Ge	^{100}Mo	^{136}Xe
NSM	[35]	2.89, 3.07	–	2.28, 2.45
	[36]	3.37, 3.57	–	1.63, 1.76
	[37]	2.66	–	2.39
	All	2.66 - 3.57	–	1.63 - 2.45
QRPA	[38]	5.09	–	1.55
	[39]	5.26	3.90	2.91
	[40]	4.85	5.87	2.72
	[41]	3.12, 3.40	–	1.11, 1.18
	[42]	–	–	3.38
	All	3.12 - 5.26	3.90 - 5.87	1.11 - 3.38
EDF	[43]	4.60	5.08	4.20
	[44]	5.55	6.59	4.77
	[45]	6.04	6.48	4.24
	All	4.60 - 6.04	5.08 - 6.59	4.20 - 4.77
IBM	[46][a]	5.14	3.84	3.25
	[47]	6.34	5.08	3.40
	All	5.14 - 6.34	3.84 - 5.08	3.25 - 3.40

Discovery Sensitivity

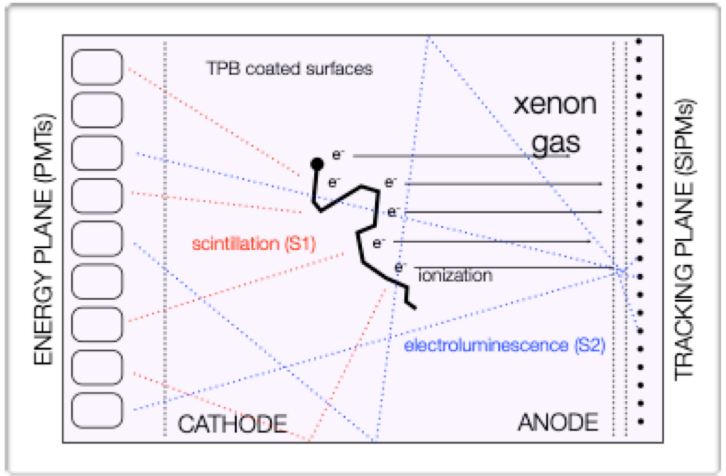


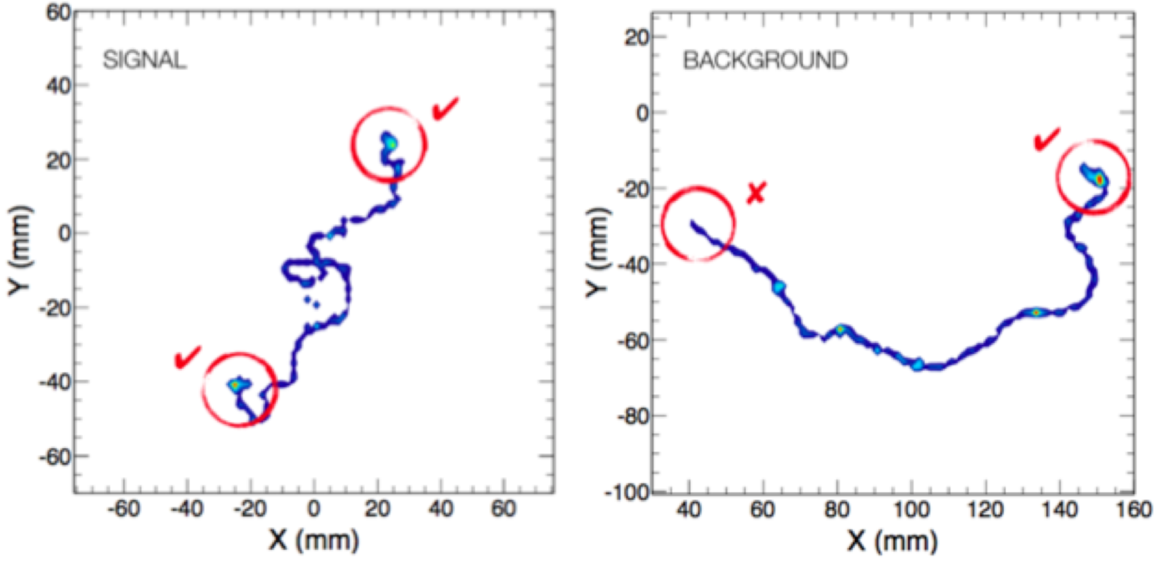
Exclusion Sensitivity



From Agostini et al., PRC **104**, L042501 (2021)

NEXT

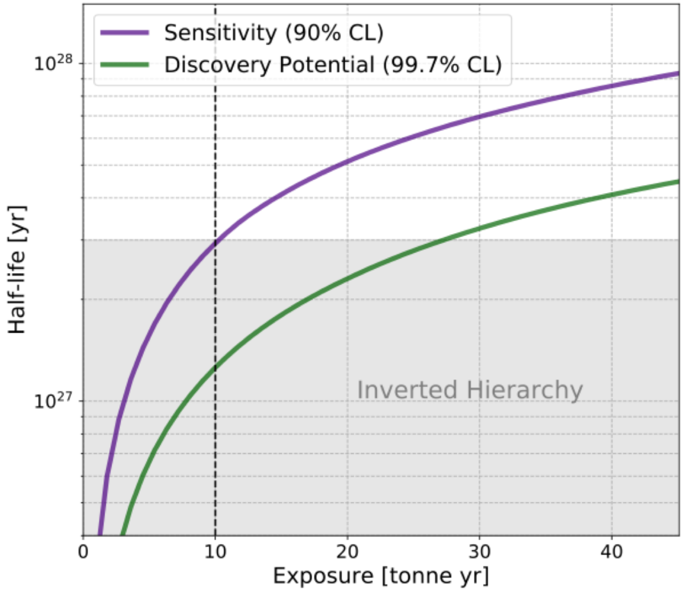




High-pressure gas Xenon time projection chamber:

- High pressure reduces volume for a given mass
- Energy resolution is intrinsically better in gas
- Extensive event topology information, fiducialization, and particle ID
- Ba tagging may be easier in gas

NEXT-100 expected to start operation in 2022



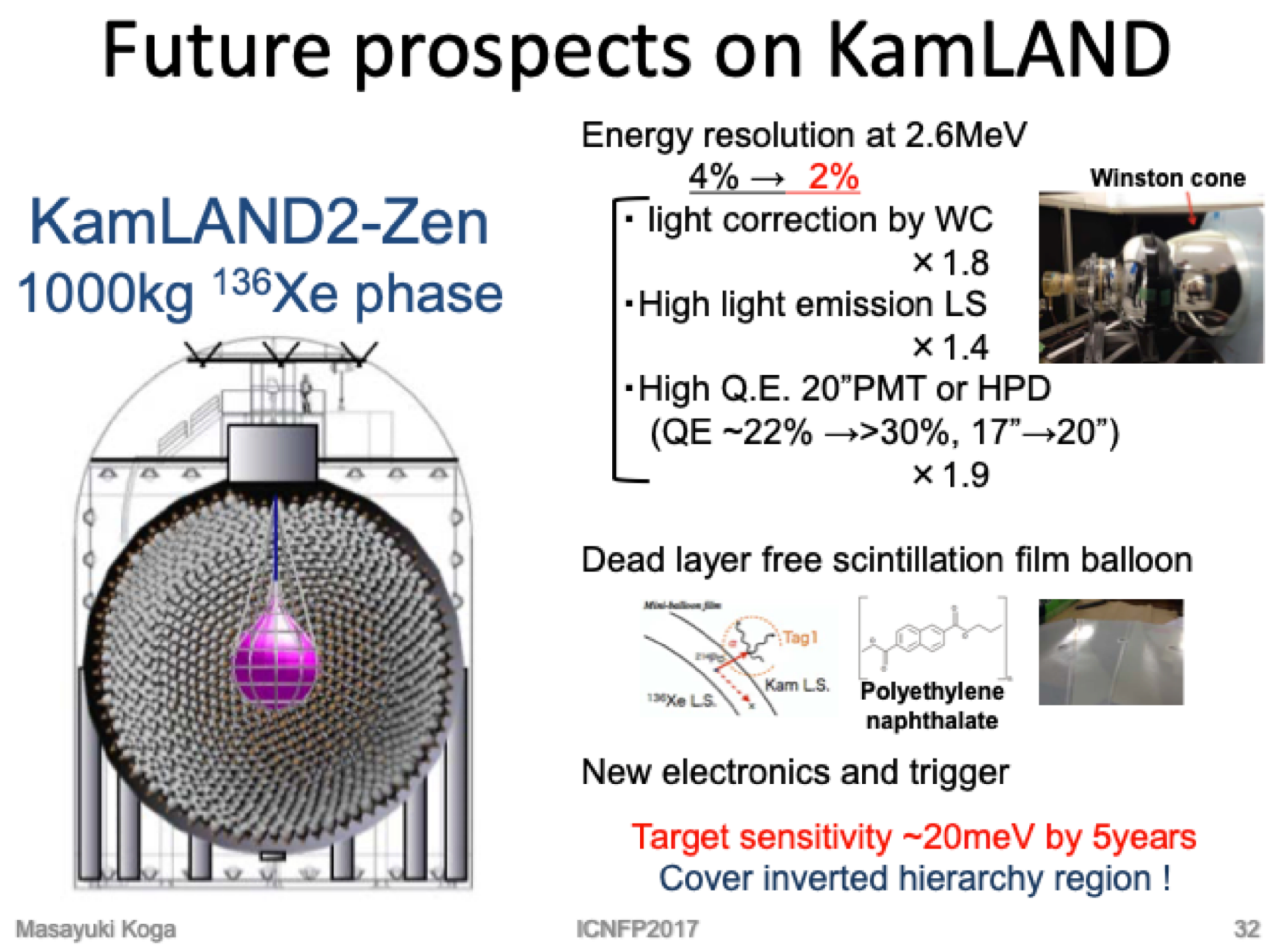
NEXT ton-scale proposal, using multiple modules

arXiv:2005.06467

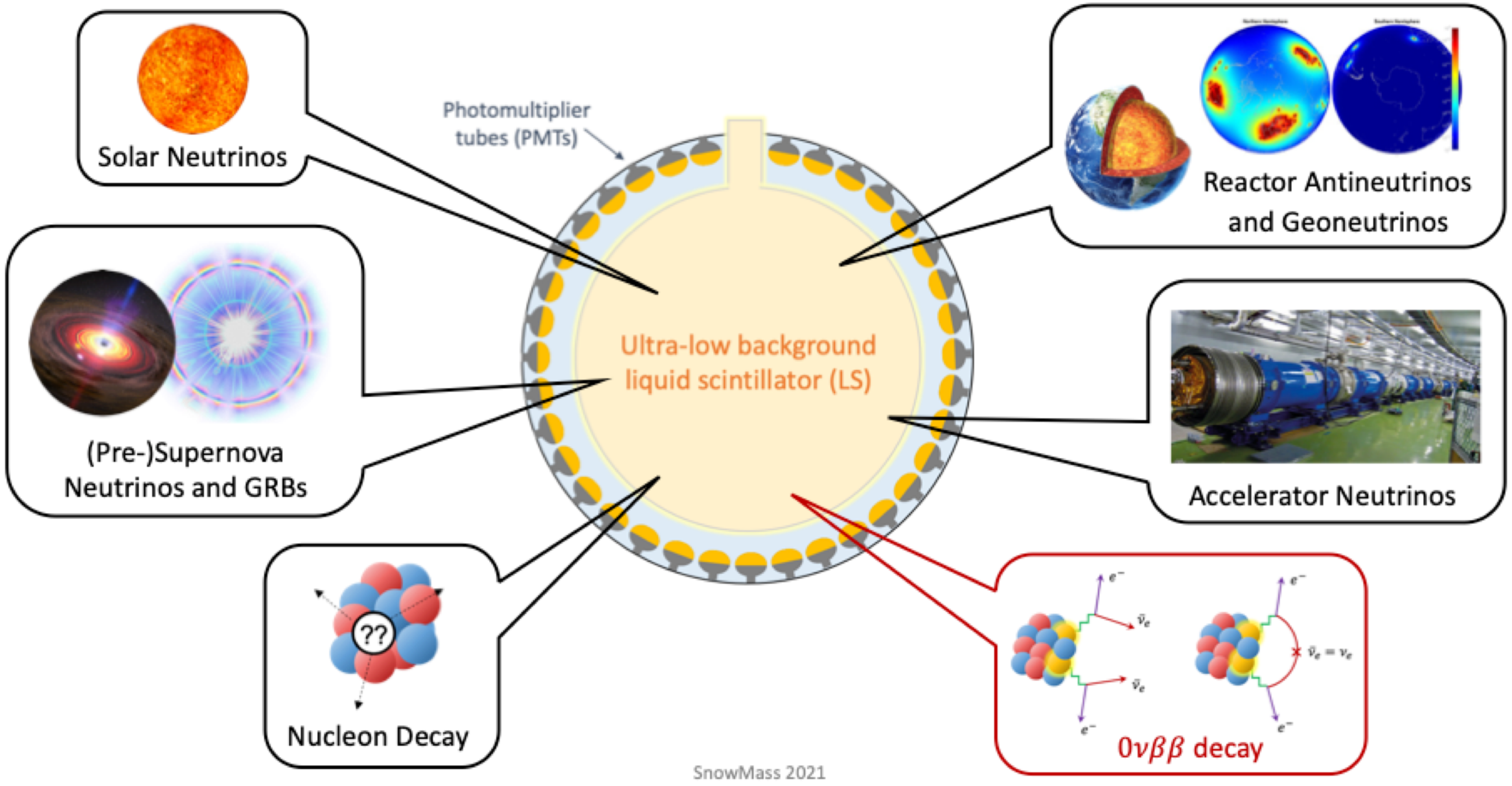
Slides courtesy of the NEXT Collaboration, from R. Guenette

KamLAND2-Zen

- New PMTs, brighter scintillator, and Winston cones
- New lower-noise electronics and trigger
- 5x increase in light collection: improves energy resolution by at least a factor of two
- Higher loading and scintillating balloon film
- Expected to cover the IO region



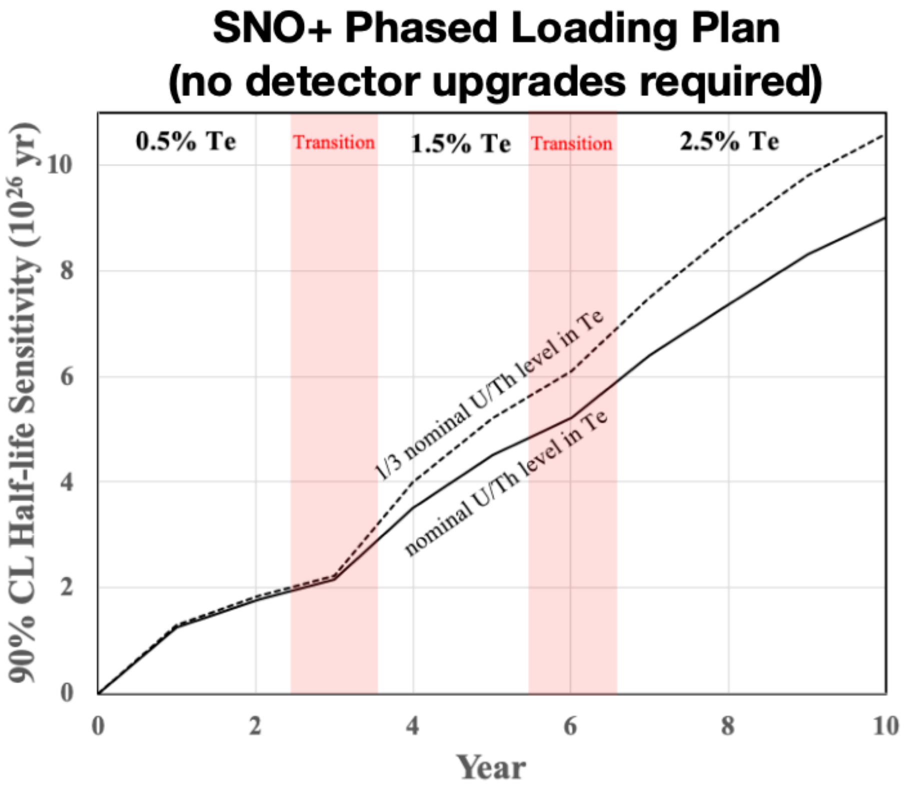
Theia Multi-Purpose Detector Concept

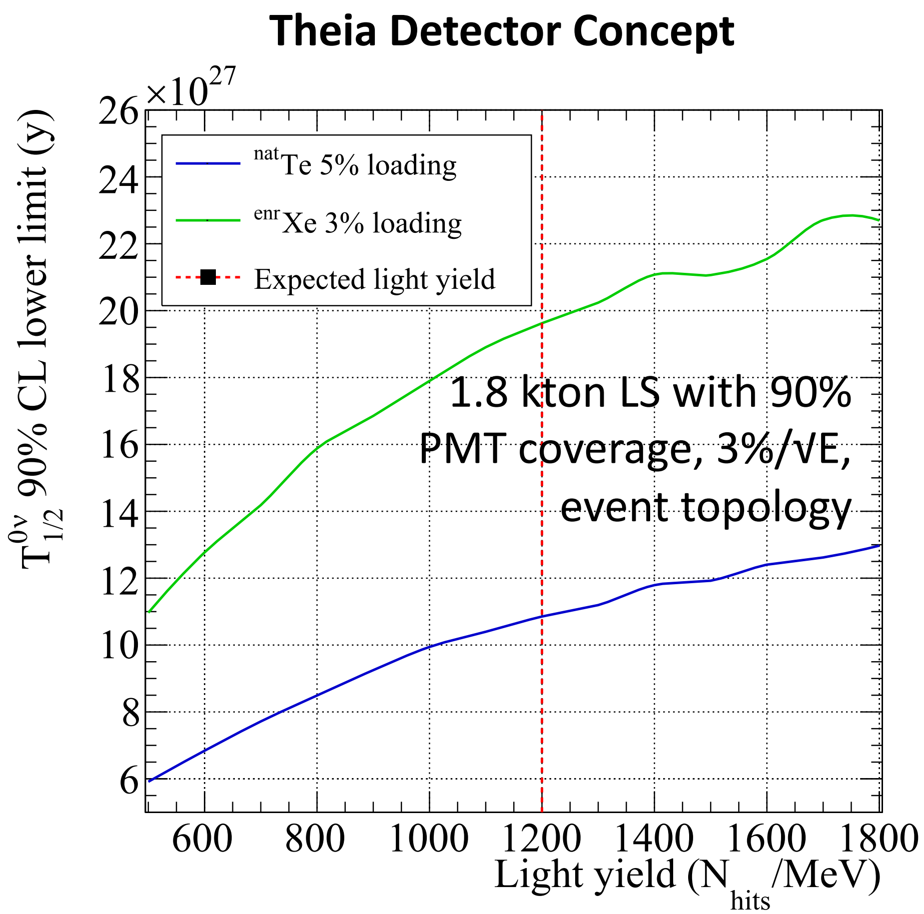


- Self-shielding, fiducialization
- Interior materials can be made extremely pure
- Pursuing R&D for additional event topology and particle ID
- Multi-purpose detector
- Measurement with and without isotope is possible

Slides courtesy of the SNO and Theia Collaborations, from C. Grant and R. Svoboda

SNO+ and Theia





Eur. Phys. J. C (2020) 80:416

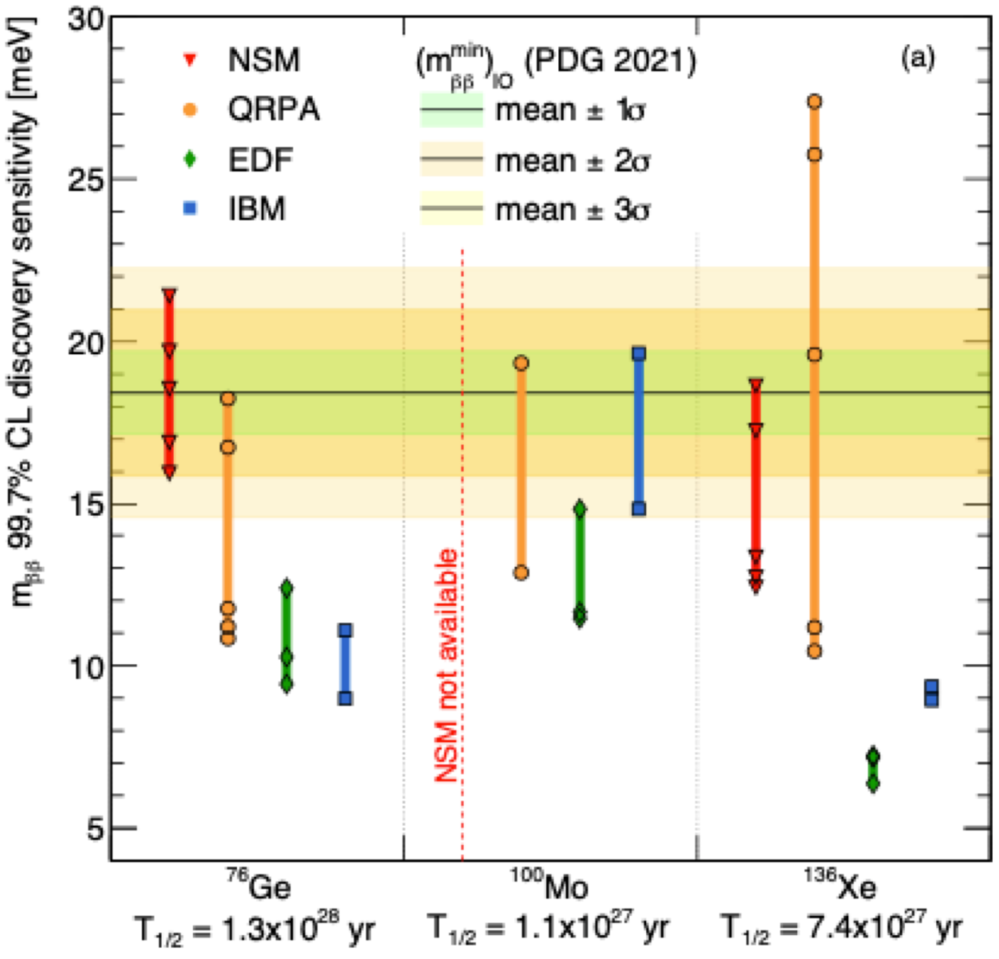
- Higher Te loadings planned for SNO+
- Theia is considering ^{enr}Xe or ^{nat}Te loading options:

$$\mathbf{Te}: \; T_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{28} \text{ y}, \; m_{\beta\beta} < 6.3 \text{ meV}$$

$$\mathbf{Xe}: \; T_{1/2}^{0\nu\beta\beta} > 2.0 \times 10^{28} \text{ y}, \; m_{\beta\beta} < 5.6 \text{ meV}$$

Conclusion

Discovery Sensitivity for the “Big 3”



- Near-term results will start to probe the IO region, and the coming generation of 0νββ experiments will fully explore it
- 2 to 3 ton-scale experiments are expected to begin construction in the coming years
- R&D is underway to reach smaller $m_{\beta\beta}$; Snowmass process will focus on these beyond-the-ton-scale efforts
- Discovery could come at any time!
- In the next decade, we may need to be able to meaningfully compare 0νββ signals between ^{100}Mo-, ^{136}Xe-, and ^{76}Ge-based experiments

Questions?