Perspectives of future neutrinoless double beta decay experiments

Stefan Schönert | TU München

XXX International Conference on Neutrino Physics and Astrophysics

May 30 – June 4 2022

Virtual Seoul

Outline

17:00 (28+3m) **Overview of current experimental and theoretical status on 0nbb**
Speaker Fedor Šimkovic (Comenius University in Bratislava)

17:31 (15+2m) **KamLAND-Zen**
Speaker Azusa Gando (RCNS, Tohoku University)

17:48 (15+2m) **Updated results and progresses of the CUORE experiment**
Speaker Irene Nutini (INFN Milano Bicocca)

18:05 (24+2m) **CUPID and its demonstrators: scintillating bolometers for 0n2b search**
Speaker Zolotarova Anastasiia (IRFU, CEA, University of Paris-Saclay)

21:30 (15+2m) **AMoRE new results**
Speaker Yoomin Oh (IBS)

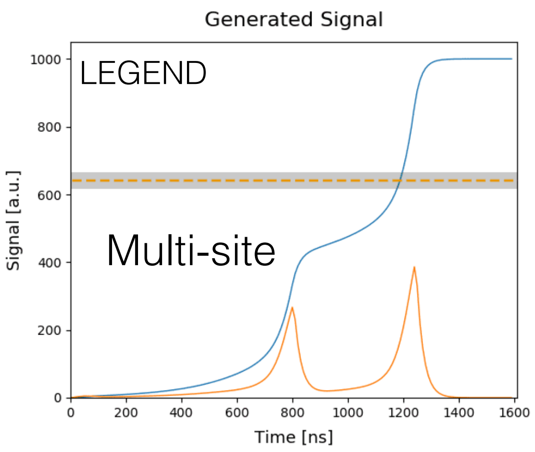
21:47 (15+2m) **NEXT (+ PandaX-III)**
Speaker Michel Sorel (IFIC,CSIC - University of Valencia)

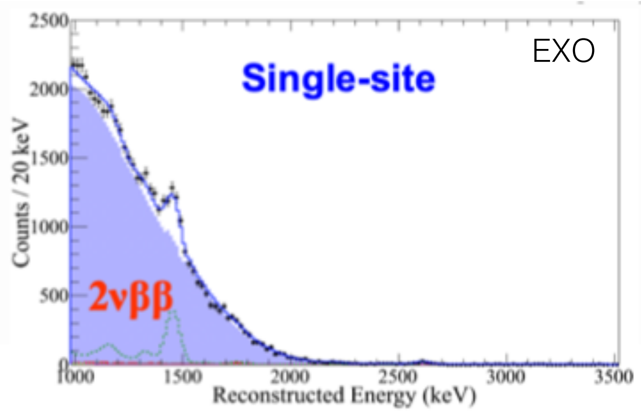
22:04 (25+2m) **0nbb search in Ge Detectors**
Speaker Julieta Gruszko (University of North Carolina at Chapel Hill)

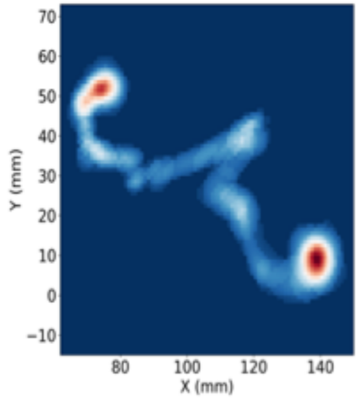
- Ton-scale experiments for discovery
- Isotope procurement as of today
- Discussion of selected projects or techniques
- Projected discovery sensitivities
- North-American -- European convergence
- Summary & Outlook

Ton-scale experiments for discovery

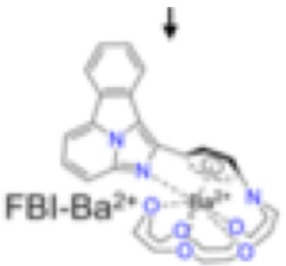
- Need to measure half-lives of up to 10^{28} years
- **One decay** per **ton-year** of material
- Need many **ton-years** of data
- Need extreme **low background rate** and best possible **energy resolution**
- Need to exploit **topology information** of signal and background
- And, if possible, identify **daughter nucleus**







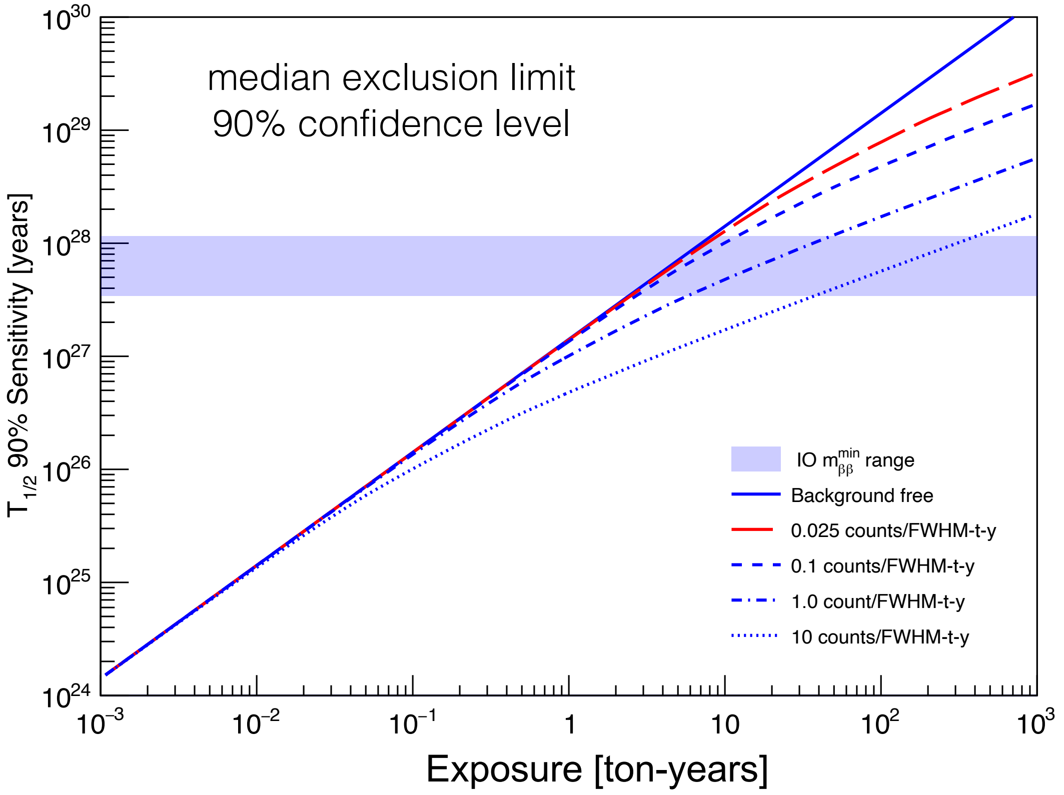
NEXT

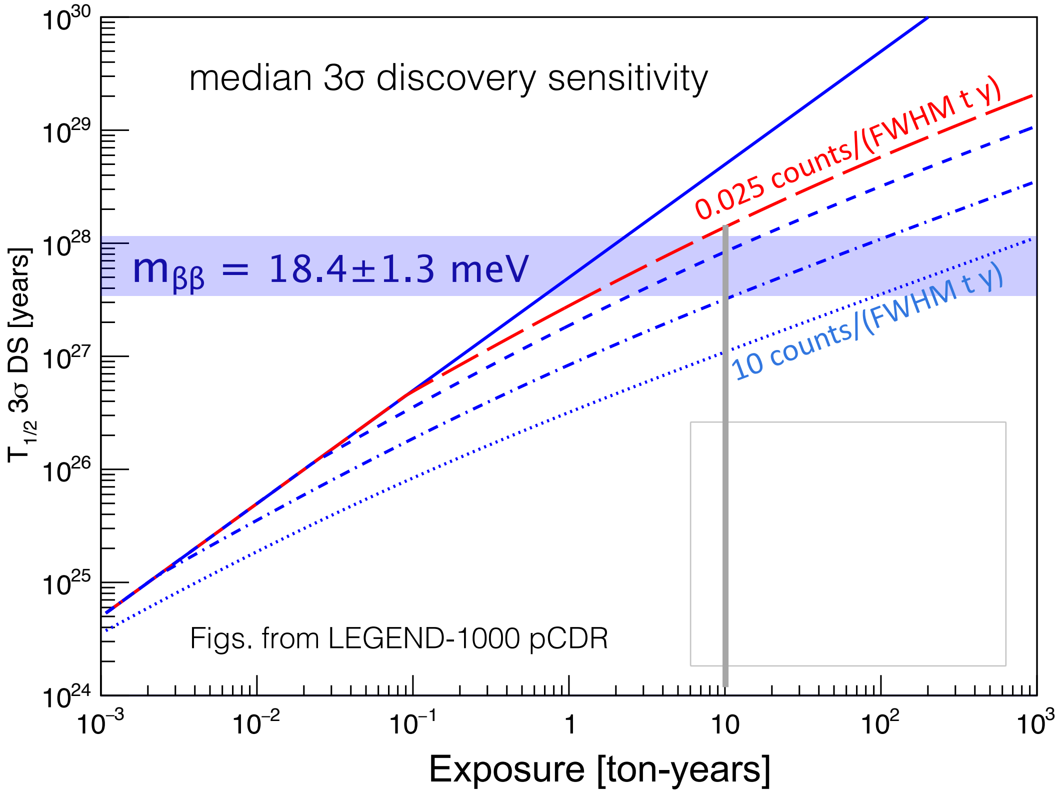


The Effect of Background: Discovery sensitivity vs. exclusion limit

- Ton-scale experiments aim for a **discovery**
- Background-free: Sensitivity rises **linearly with exposure**
- Background-limited: Sensitivity rises as the **square root of exposure**

=> **quasi-background-free**[1] operation makes most efficient use of valuable isotopes

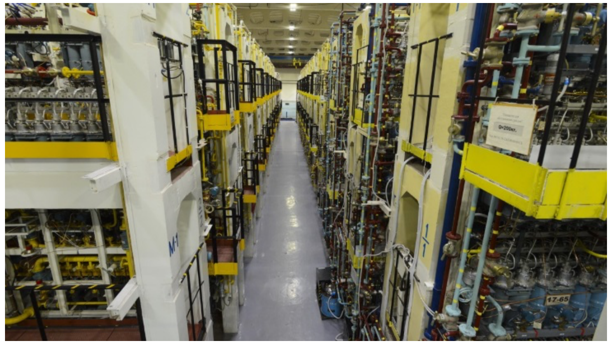




[1] Less than one background count expected in a 4σ Region of Interest (ROI) with 10 t y exposure

Double beta decay isotopes

An isotope production facility at ECP
(Image: TVEL)



Enrichment:

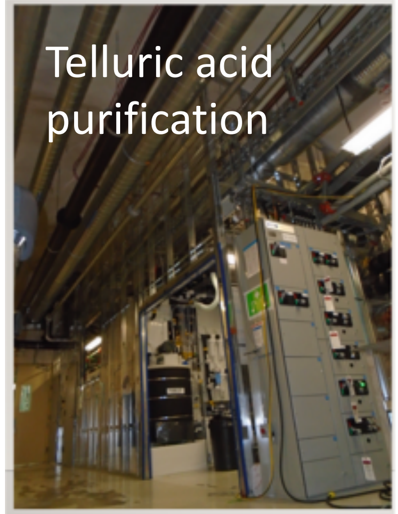
- Current experiments obtain $0\nu\beta\beta$ isotopes largely from **Russia**
- **Reliable** and high-quality supply chain
- Some $0\nu\beta\beta$ isotopes also procured from **European** producer
- Since the **war in Ukraine**, no procurement of $0\nu\beta\beta$ isotopes from Russia possible for **Western countries**
- European producer is **ramping up production capacities** to suffice demands and state that **sufficient capacities** will be available to fulfill demands by ton-scale experiments (^{76}Ge, ^{100}Mo, ^{136}Xe)
- Additional initiatives are being pursued: e.g. ^{136}Xe extraction from burned nuclear fuel elements
- Projects in China continue to procure $0\nu\beta\beta$ isotopes from Russia

Natural isotopic composition:

- Te (34% ^{130}Te): Cuore, SNO+, JUNO
- Xe (8.9 % ^{136}Xe): Darwin

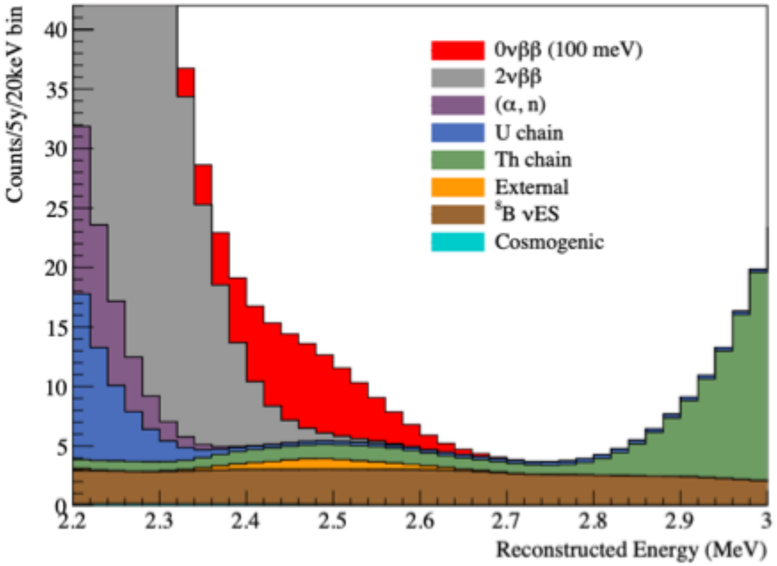
^{nat}Te-loaded liquid scintillator: SNO+

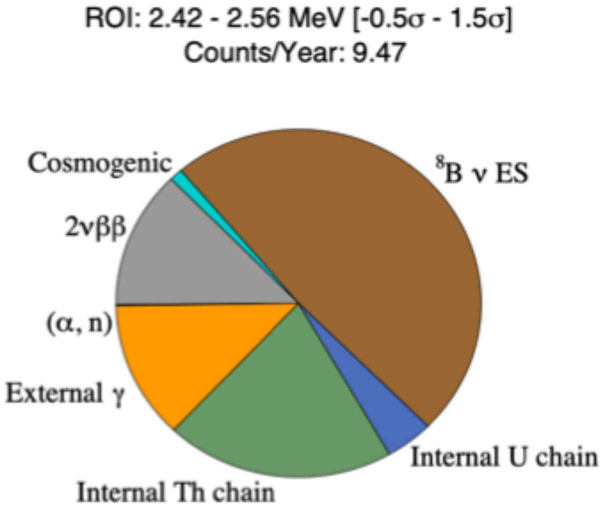
- 780t LS (2.2 g/L PPO in LAB)
- Currently data taking with unloaded LS
  - low energy ^{8}B solar-n, reactor & geo anti-ν_e, Δm^2_{12}, supernova-ν
- $0\nu\beta\beta$ phase: **natural Te** (34% ^{130}Te) loaded as metal organic complex (Te-diol)
- Te-systems ready for operations
- Full-scale Te-diol batches in 2022/23
- Following **demonstration of operations** and **approvals** by SNOLAB, begin **Te-loading in 2024**
- Original plan: load 0.5% (3.9t nat Te): $T_{1/2} > 2\times10^{26}$ yr
- R&D on higher (up to 3%) Te-loading ongoing
- **0.5%** loading phase critical to assess **performance** and Te-related **backgrounds**



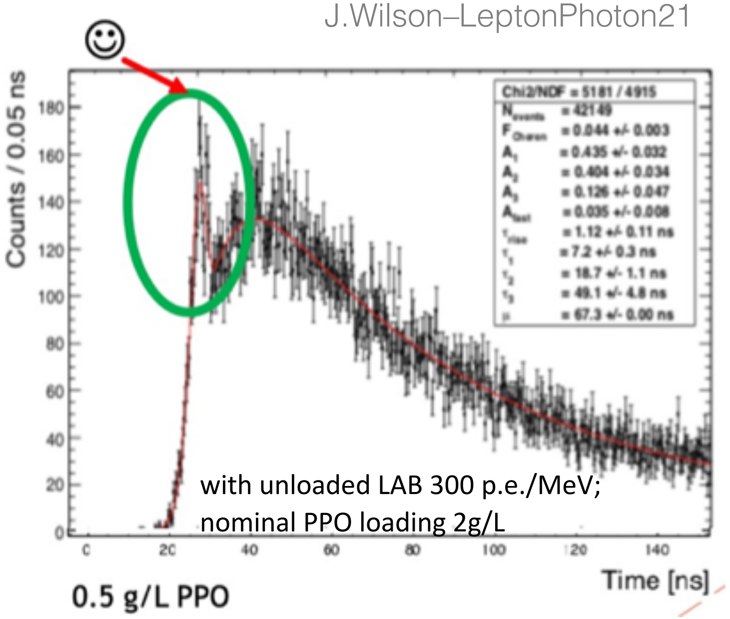
Courtesy M. Chen

^{nat}Te-loaded liquid scintillator: SNO+





J.Wilson–LeptonPhoton21

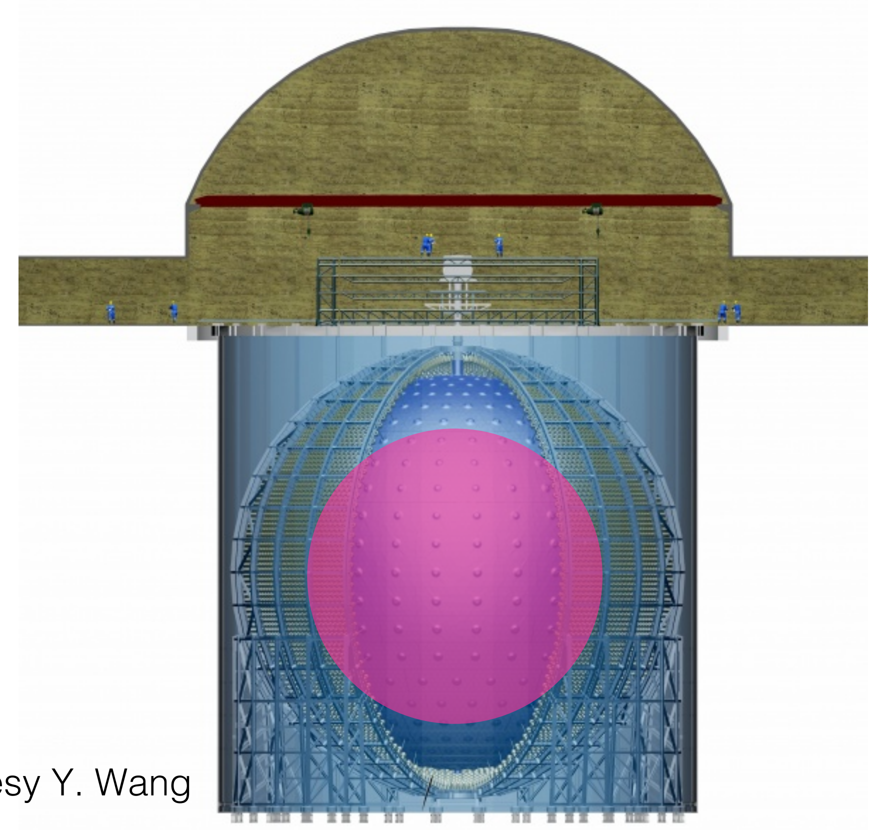


- **Pure scintillator** phase ”Te-out” measurement to test unexpected **backgrounds**
- **Staged Te-loading** to assess remaining Te-backgrounds
- Assess potential of suppression of **solar neutrinos** using **directionality information** arXiv:2001.10825

Courtesy M. Chen

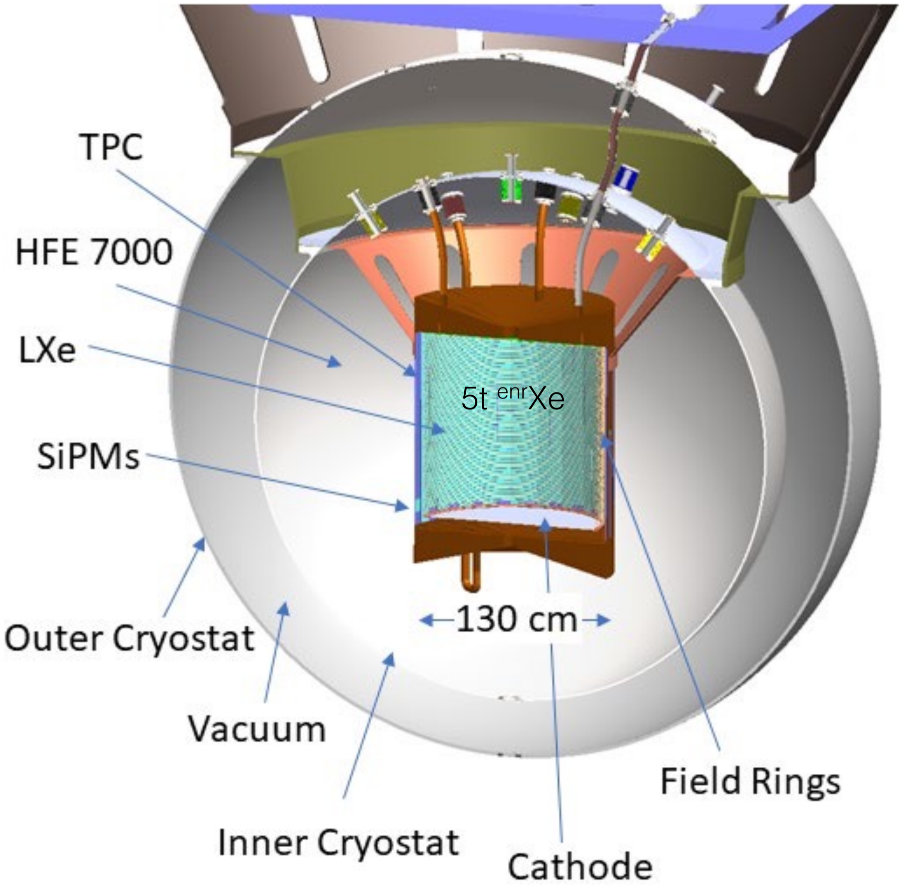
^{nat}Te-loaded liquid scintillator: JUNO

- 20 kt LS (LAB, 2.5 g/L PPO, 3 mg/L Bis-MSB)
- Main goals: **neutrino mass ordering** with reactor neutrinos, geo-, solar, atm-nu's
- After completion of mass ordering **(~2030)** upgrade for 0nbb search with ^{nat}Te or ^{136}Xe
- Huge target mass (100 t scale) and aspired low background
- High PMT coverage => 1200 p.e./MeV
- Reported R&D results on Te-diol based LS:
  - Best performance so far with 0.6% Te-loading
  - NO measurable difference compared to purified LAB (A.L. > 20m)
  - NO degradation after 6 months
  - Relative light output: 60%~70% w.r.t un-loaded LS
- Ambition: towards exploration of normal mass ordering

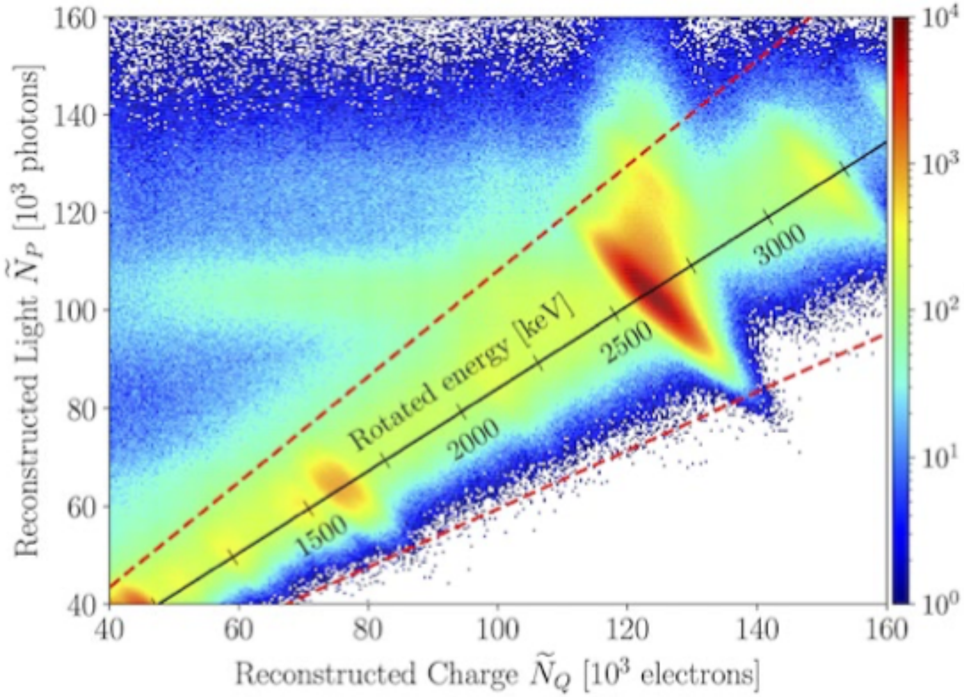


Courtesy Y. Wang

^{136}Xe: nEXO



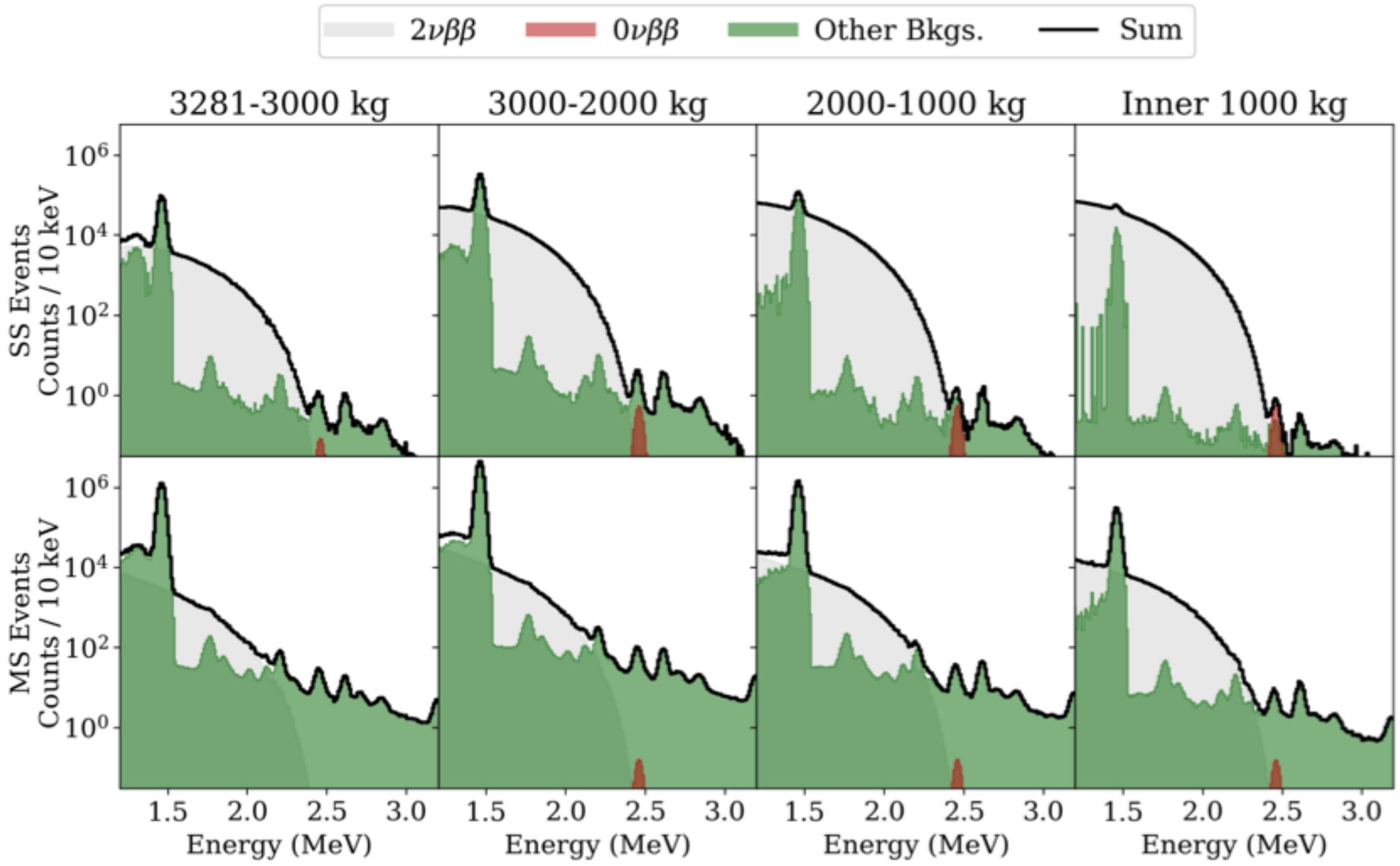
Charge & light readout: ^{232}Th source simulation



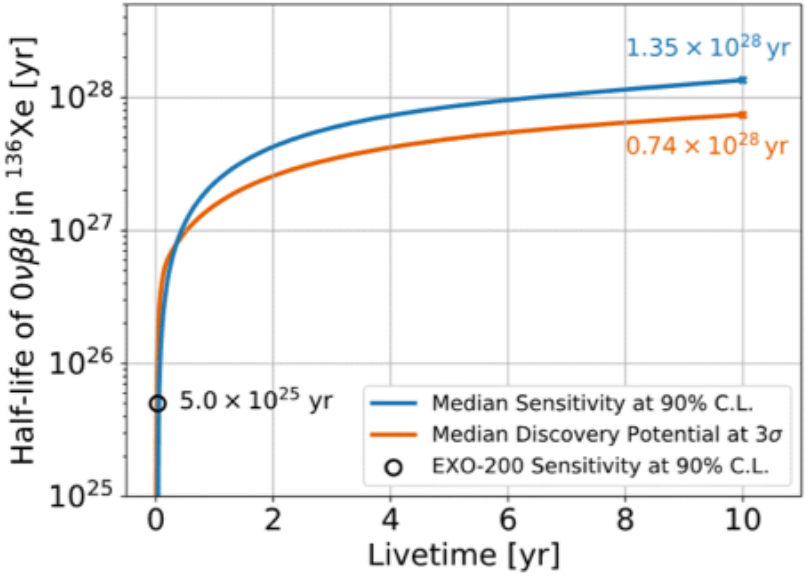
Energy resolution at $Q_{\beta\beta}$ (σ): 1.2% (req.), 0.8% (goal)

Courtesy G. Gratta

^{136}Xe: nEXO



- Advanced topological reconstruction
- γ background identification and rejection.
- Multi-parameter analysis

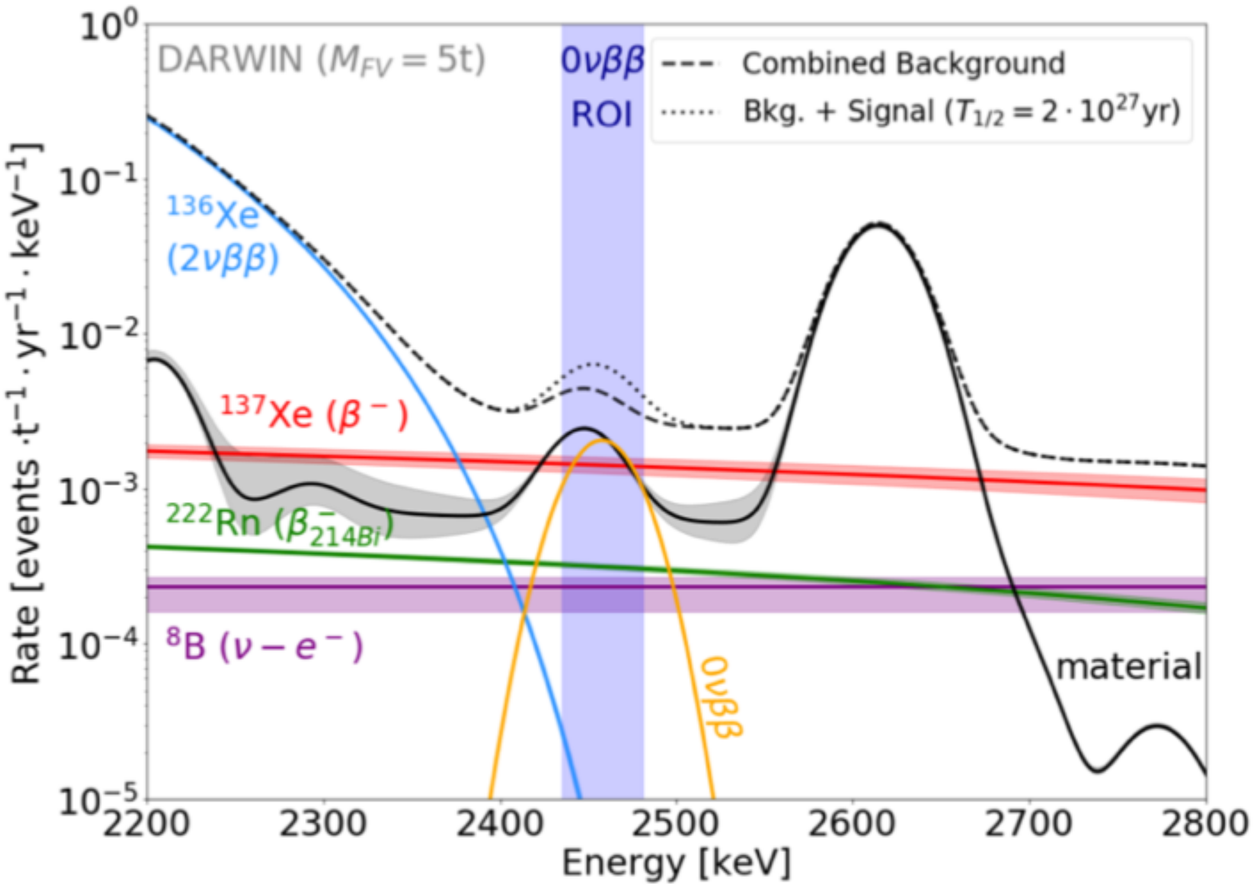


Courtesy G. Gratta

^{nat}Xe: Darwin

- Primary goal: direct dark search
- Large mass of a candidate isotope:
  3.5 t of ^{136}Xe in active target mass (8.9% abundance in natural xenon)
- Excellent energy resolution:
  expect ~0.8% σ at Q-value of 2.5 MeV as demonstrated by XENON1T (Eur. Phys. J. C 80, 785 (2020))
- Main potential backgrounds: ^{222}Rn, ^{8}B neutrinos, ^{137}Xe from cosmogenic activation, 2νββ decays

Signal: $T_{1/2} = 2 \times 10^{27}$ y



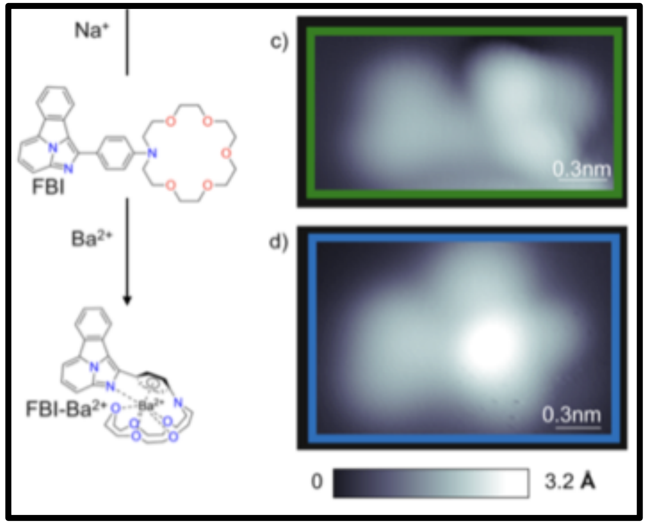
Courtesy K. Valerius

^{136}Xe: Barium tagging NEXT

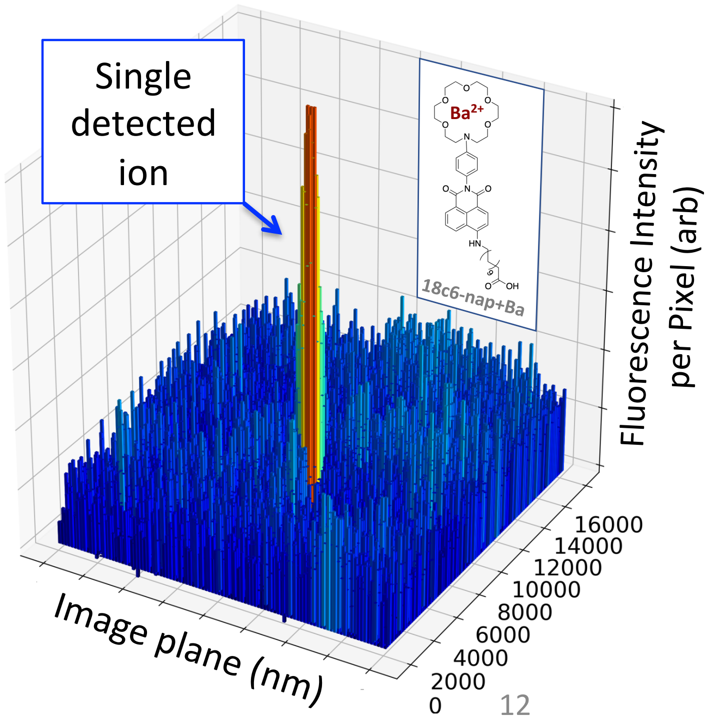
- Detection of single barium ion in coincidence with <1% FWHM energy resolution and event topology essential for background free $0\nu\beta\beta$ search in Xe (NEXT-BOLD)

- NEXT pursues single molecule fluorescent imaging (SMFI) based barium tagging sensors.
- R&D to date has realized molecular ion sensors that:
  - Exhibit barium chelation in vacuum &
  - Enable single ion sensing in xenon gas
  - ON/OFF and Bi-color approaches

STM shows barium location in molecule after chelation



SMFI + high pressure microscopy enables Ba2+ detection in Xe gas

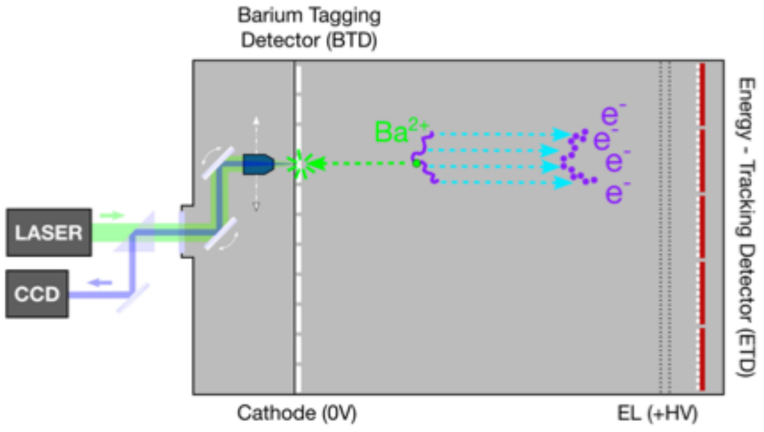


J.Phys.Conf.Ser. 650 (2015) 1, 012002; JINST 11 (2016) 12, P12011; Phys. Rev. Lett. 120 (2018) 13, 132504. Sci.Rep. 9 (2019) 1, 15097; Nature 583 (2020) 7814, 48–54; ACS Sens. (2021) 6, 1, 192–202; arXiv:2201.09099, arXiv:2109.05902

Courtesy M. Sorel, J. Gomez Cadenas

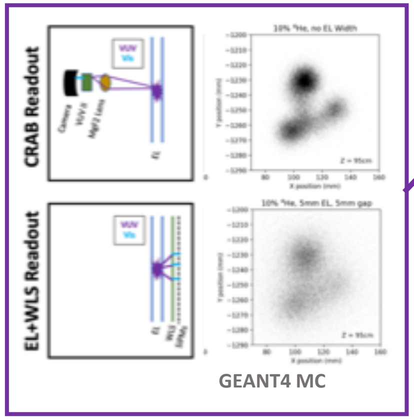
^{136}Xe: Barium tagging demonstrator phases

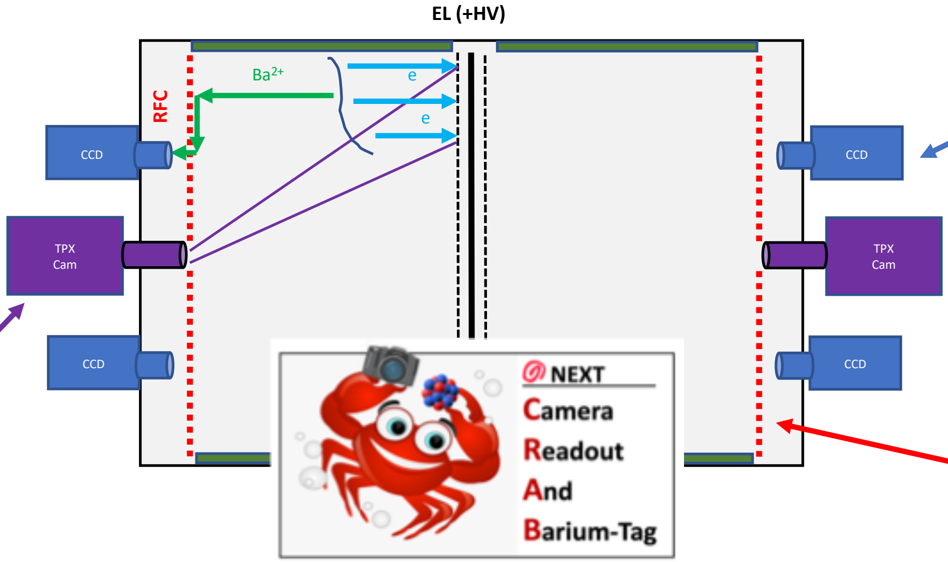
Sensor-to-ion concept (NEXT-BTD)



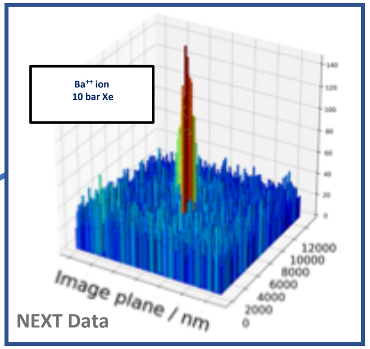
Ion-to-sensor concept (NEXT-CRAB)

1. Direct VUV camera tracking

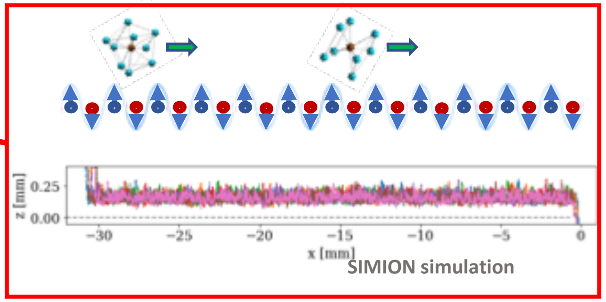




2. Single Ba^{2+} ion tagging w/SMFI



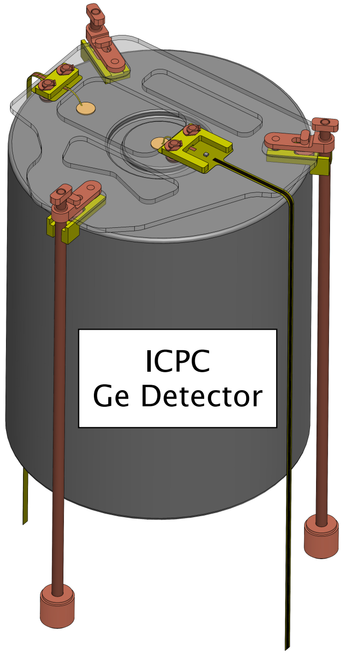
3. RF Carpet ion transport in xenon gas



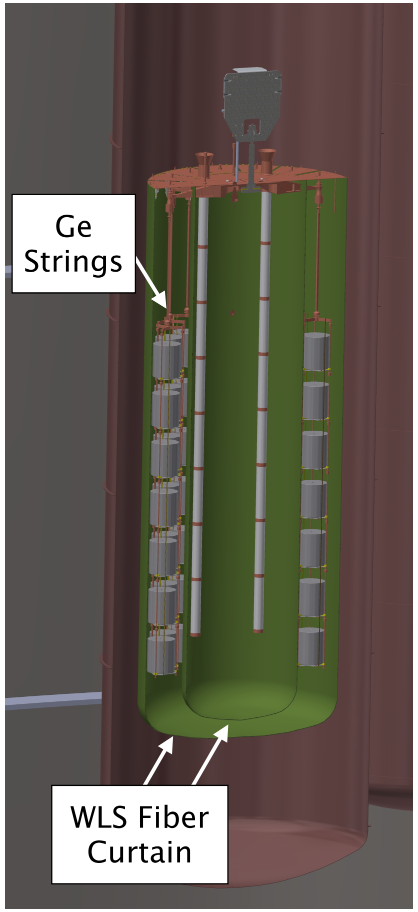
Courtesy M. Sorel, J. Gomez Cadenas

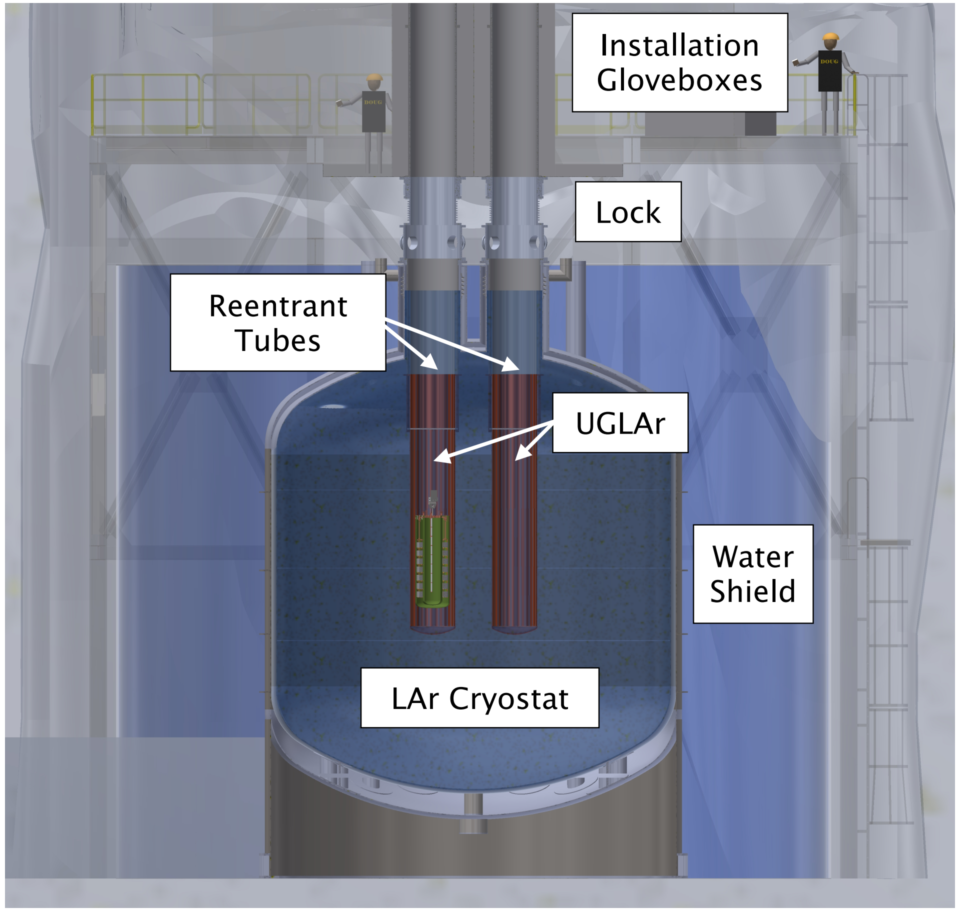
^{76}Ge: LEGEND-1000 - a discovery experiment for 0νββ of ^{76}Ge

Quasi-background-free[1] search for 0νββ decays of ^{76}Ge at $Q_{\beta\beta}$ = 2039.06 keV



ICPC: Inverted-Coaxial Point Contact
WLS: Wavelength-shifting
UGLAr: Underground Liquid Ar

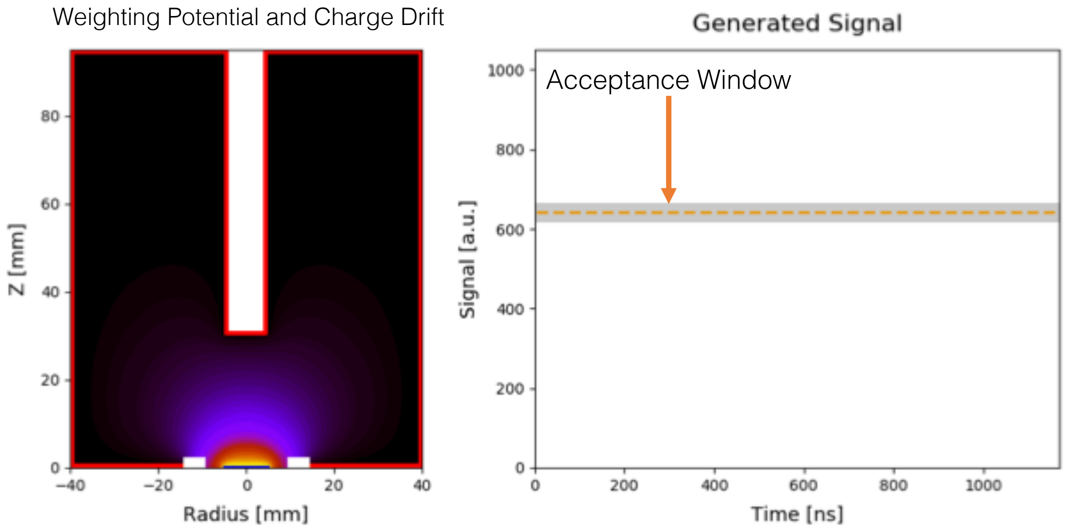




[1] Expected number of background counts is much lower than 1 in the FWHM at full exposure

^{76}Ge: LEGEND-1000 - Full event topology reconstruction in novel Ge detectors

0νββ signal candidate (single-site)

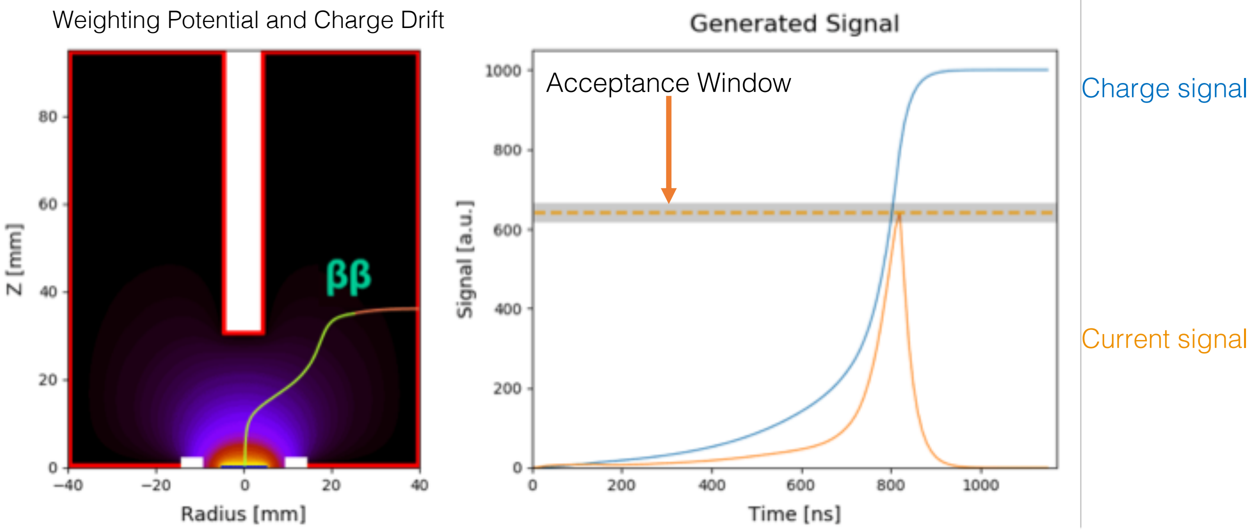


Charge signal

Current signal

N.B. animation only visible in pptx

$0\nu\beta\beta$ signal candidate (single-site)



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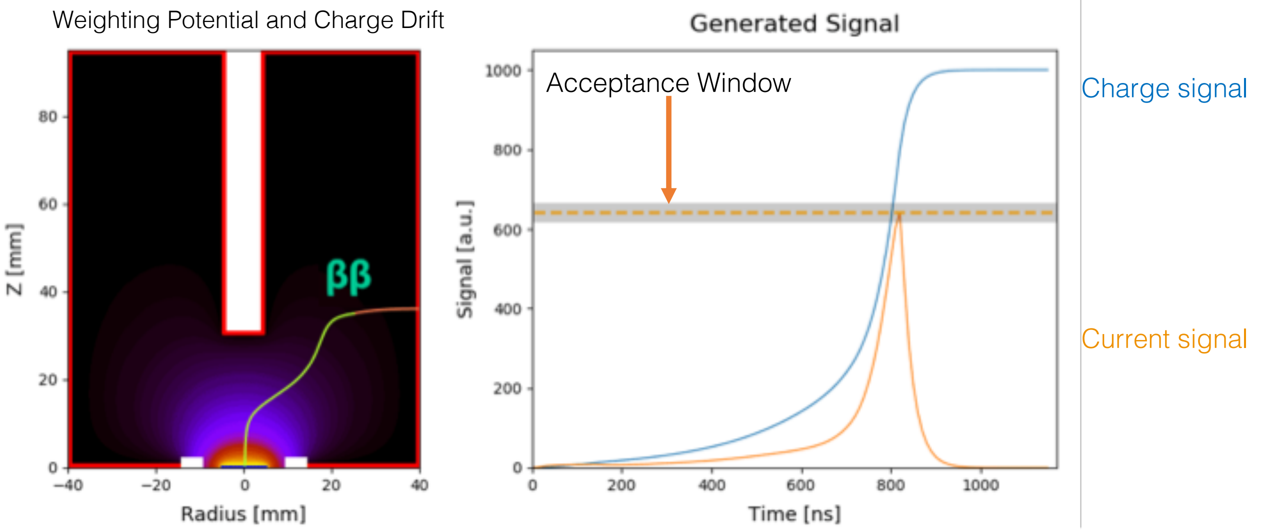
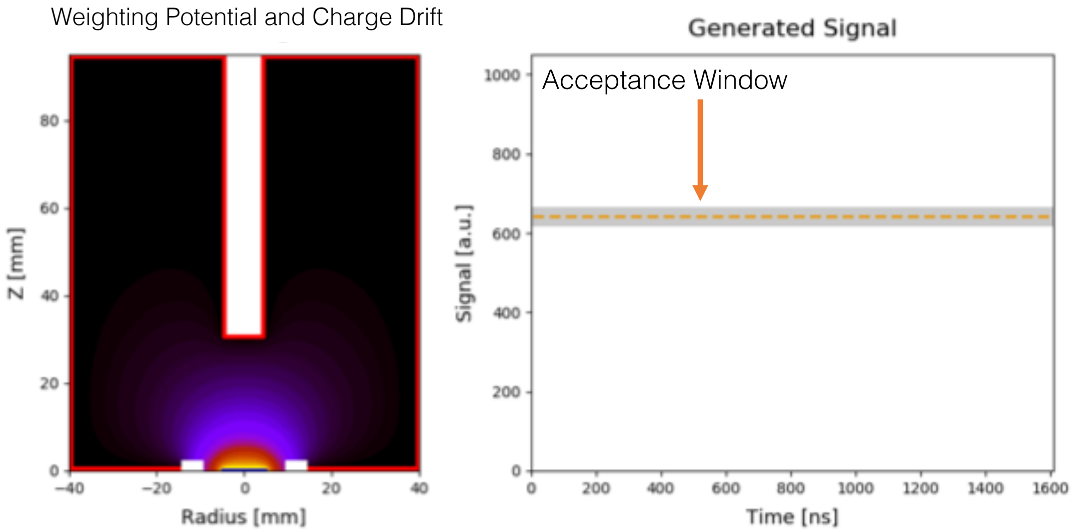


γ-background (multi-site)



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^{76}Ge: LEGEND-1000 - Full event topology reconstruction in novel Ge detectors

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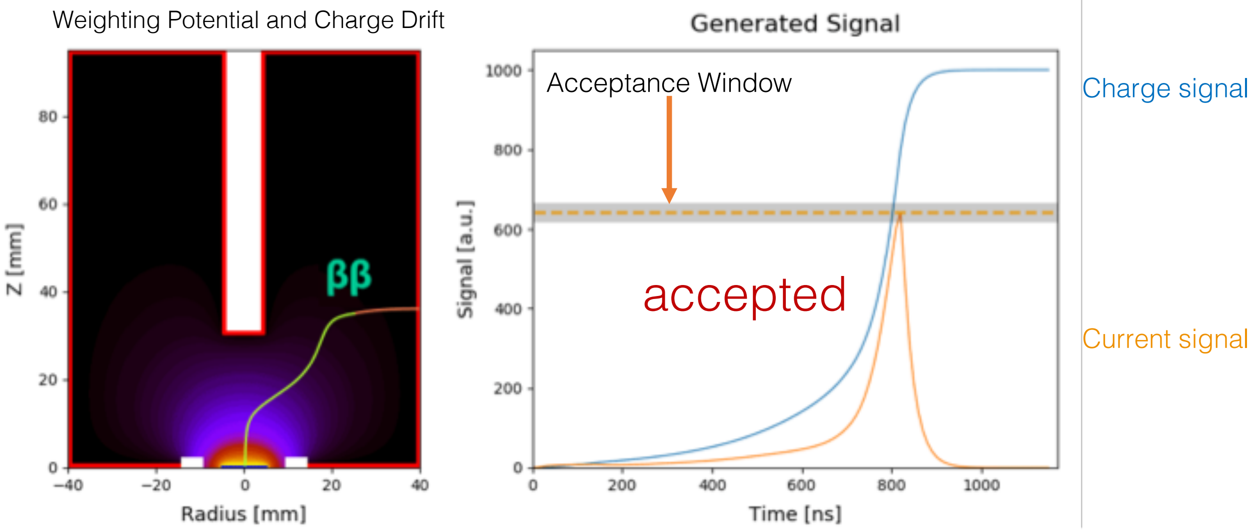
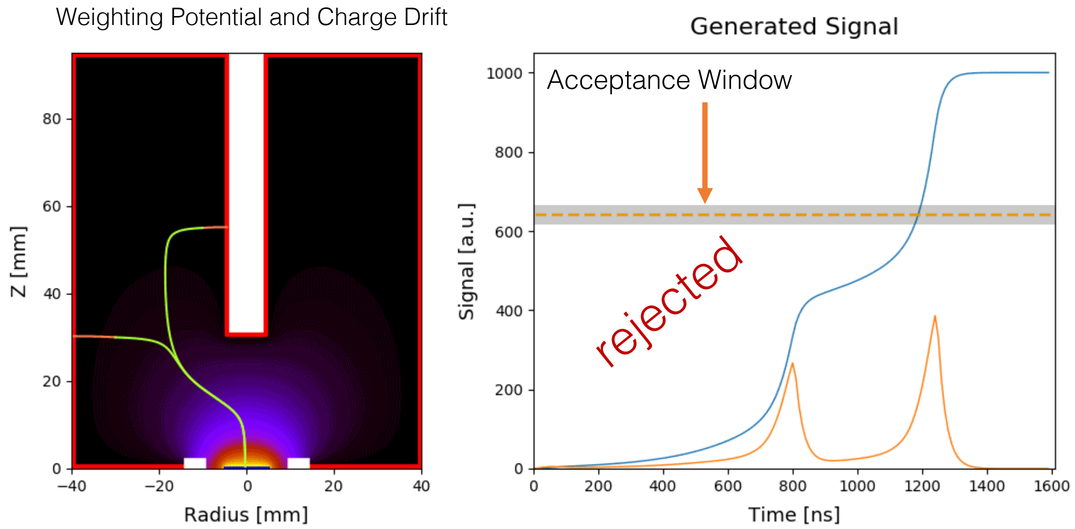


γ-background (multi-site)



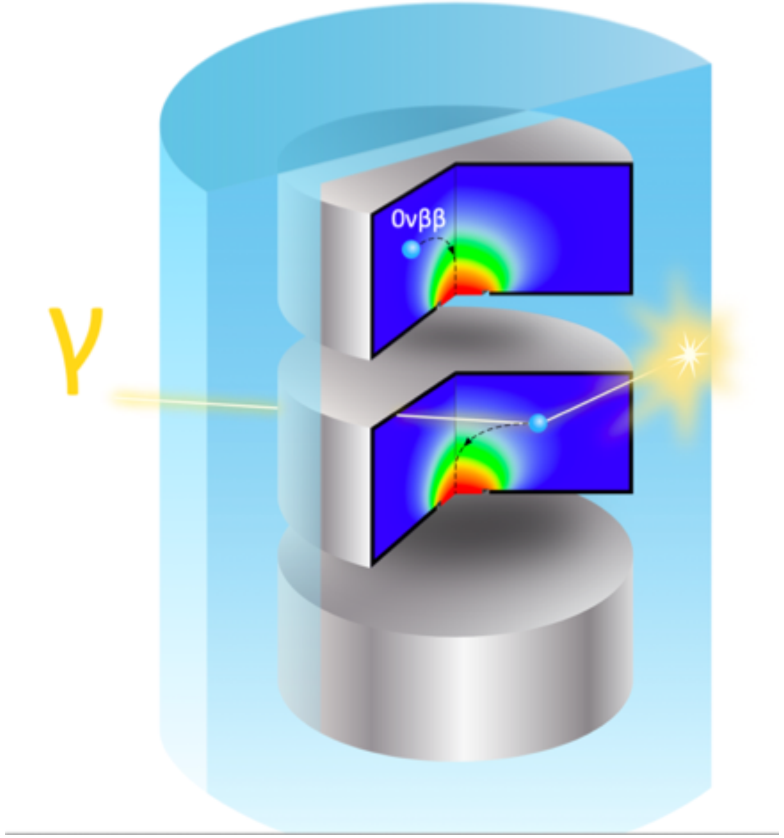
Also highly efficient suppression of surface events

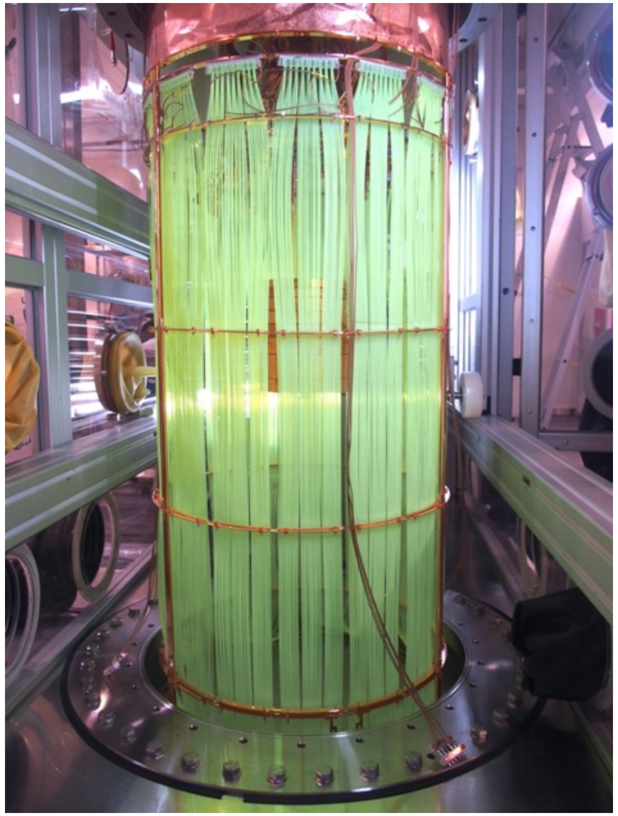
N.B. animation only visible in pptx

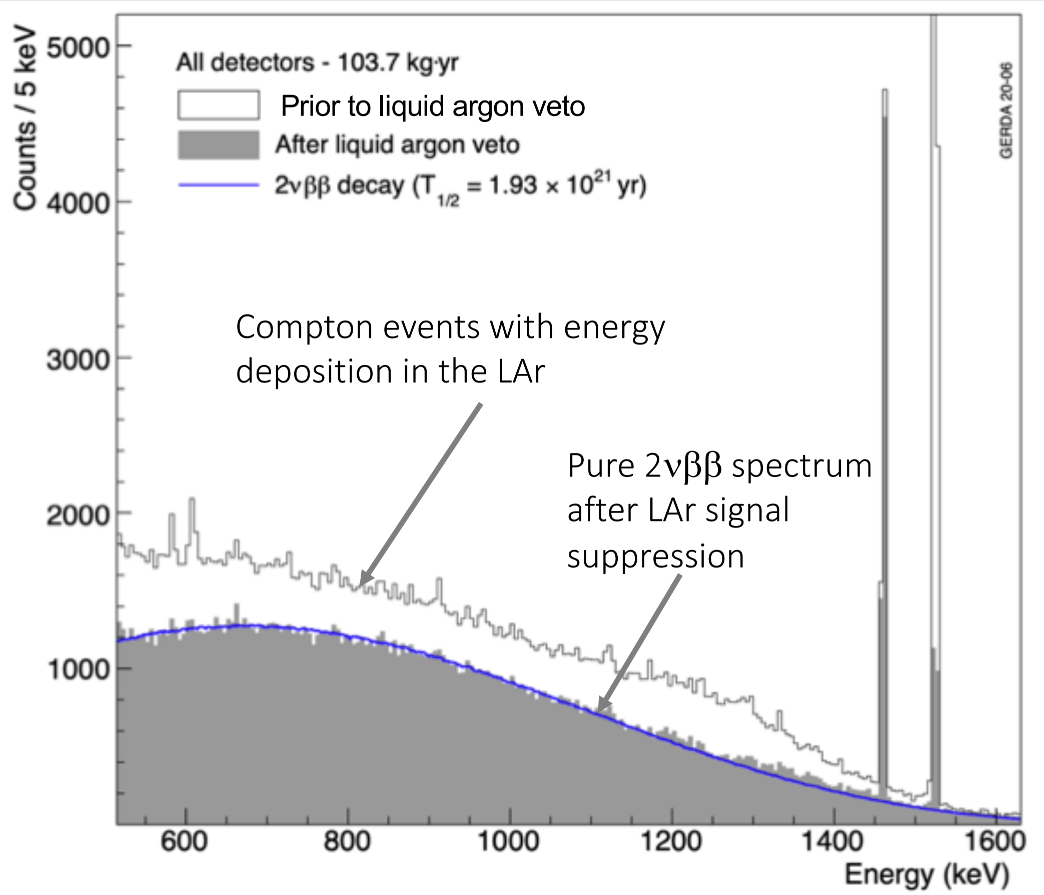
^{76}Ge: LEGEND-1000 - LAr Instrumentation

GERDA: Detection of liquid argon scintillation light

Low-background wavelength-shifting fibers and SiPM arrays for 128 nm single photon detection

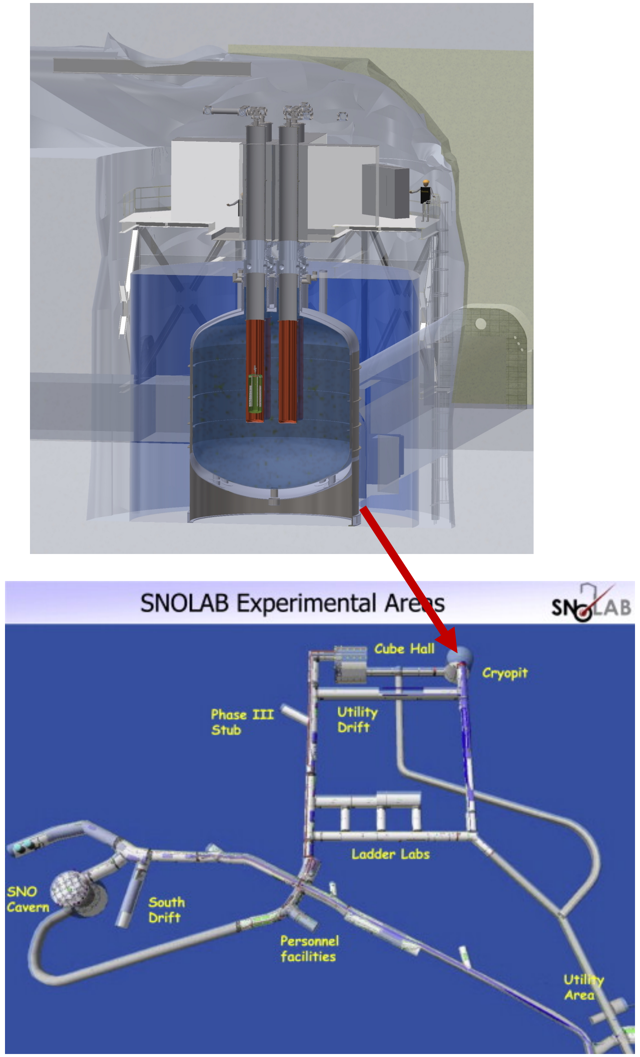




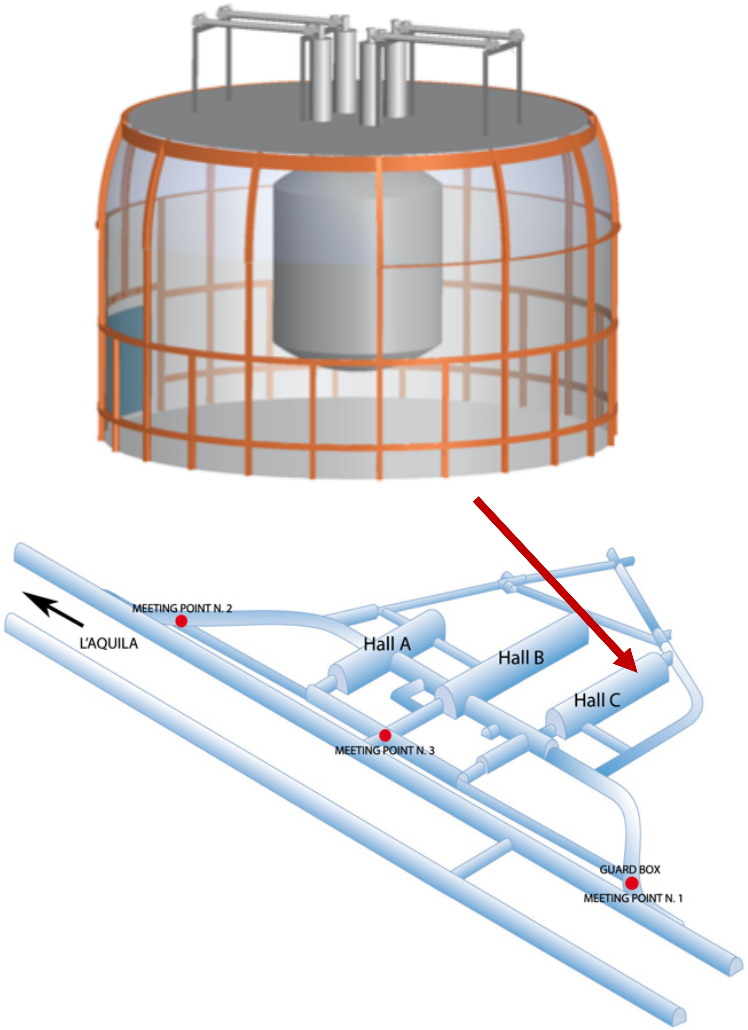


^{76}Ge: LEGEND-1000 underground sites

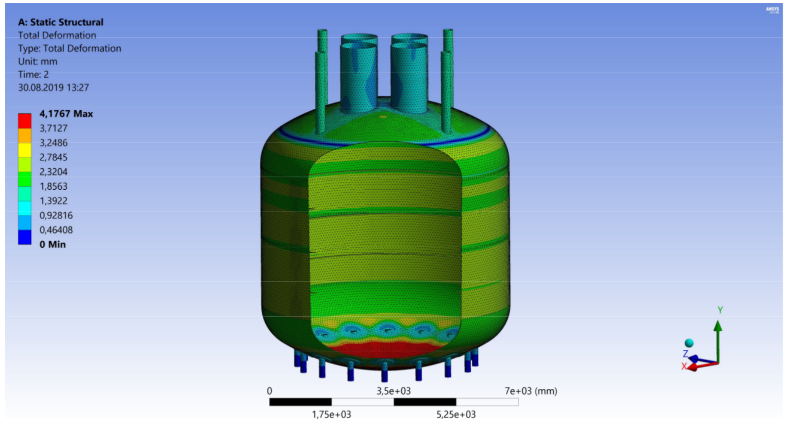
- SNOLAB **deeper** than LNGS;
- LNGS **depth sufficient** with tagging in-situ produced cosmogenic isotopes
- Repurposing of **BOREXINO** tank and infrastructures for LEGEND-1000 LNGS option



SNOLAB: cryopit committed for ton-scale 0nbb experiment

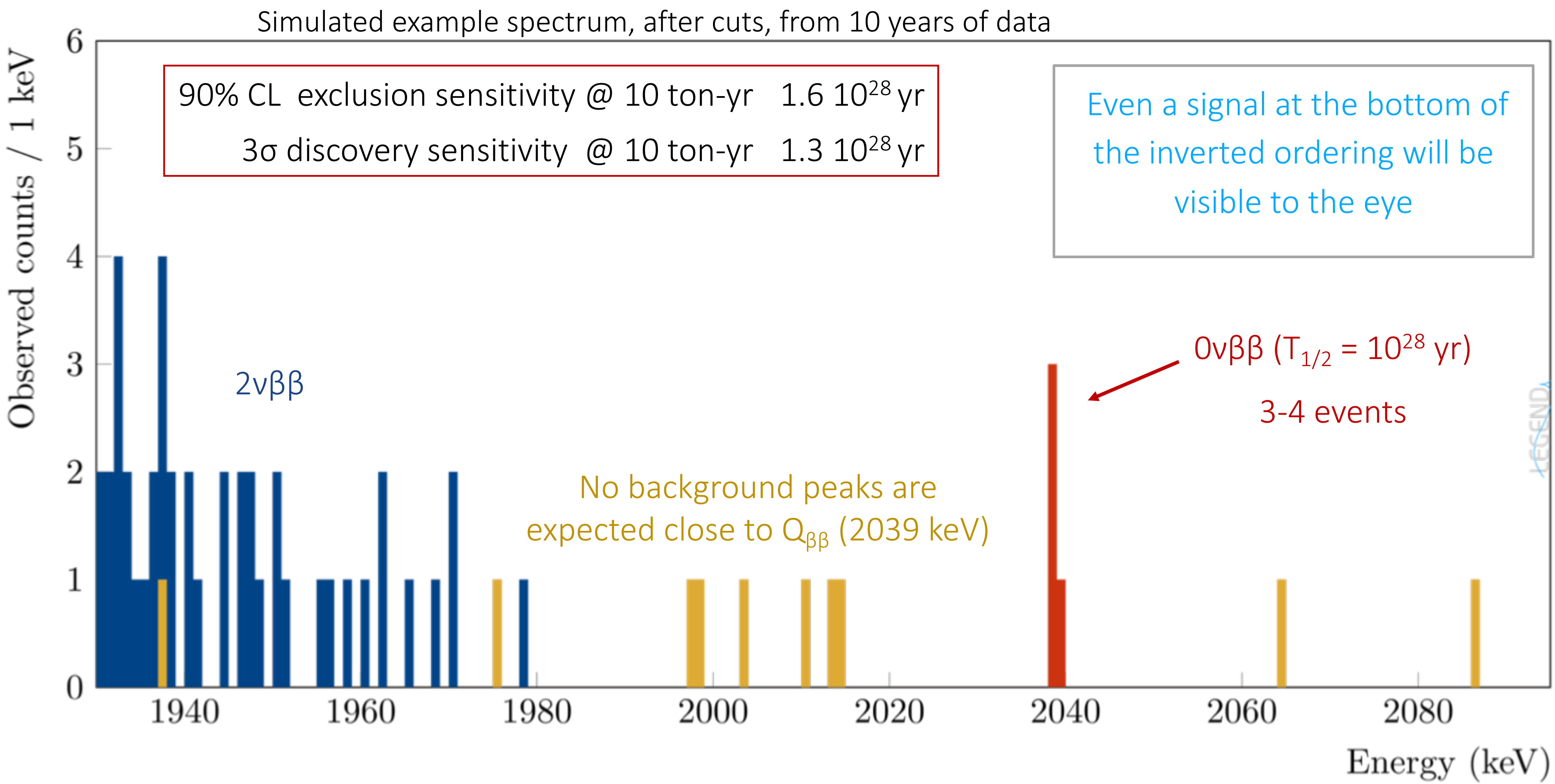


LNGS: Re-purpose BOREXINO tank and infrastructures



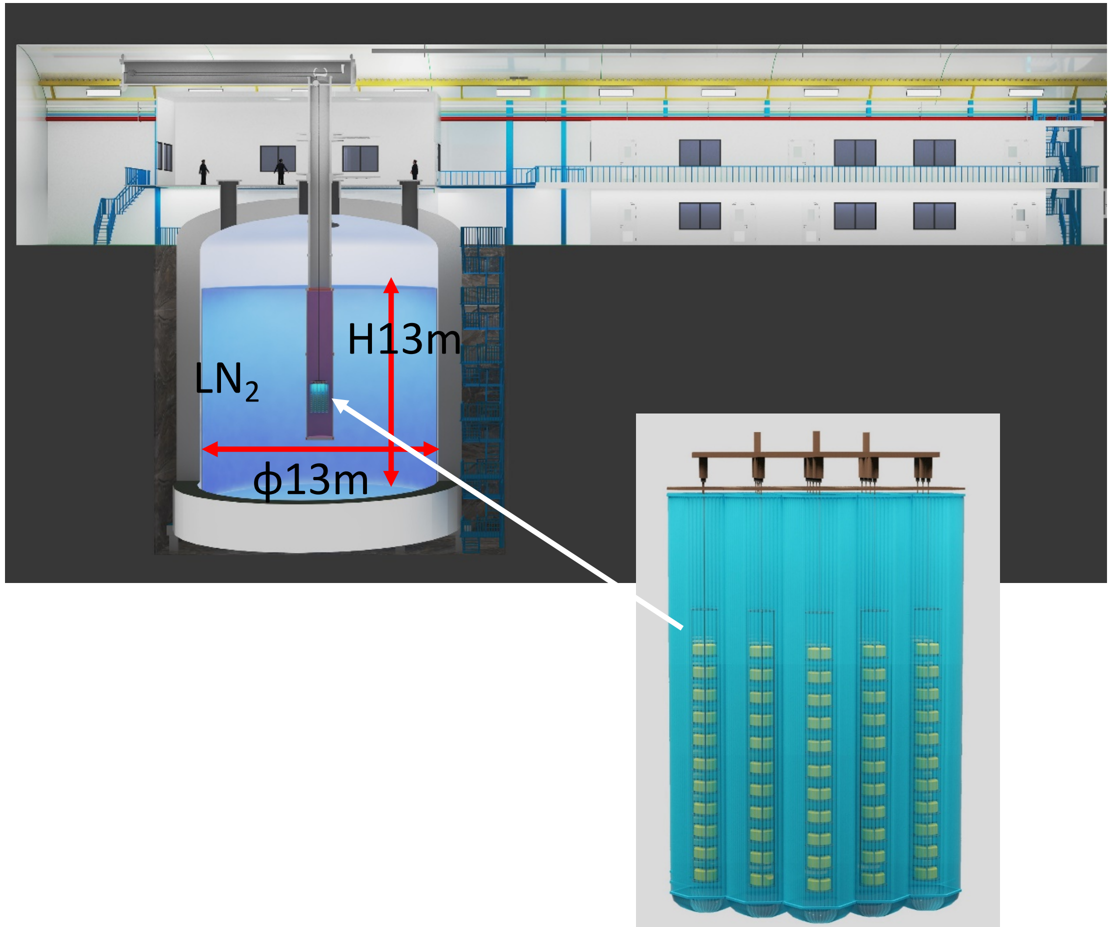
Deformation of cryostat for seismic event at LNGS

^{76}Ge: LEGEND-1000 designed for an unambiguous discovery



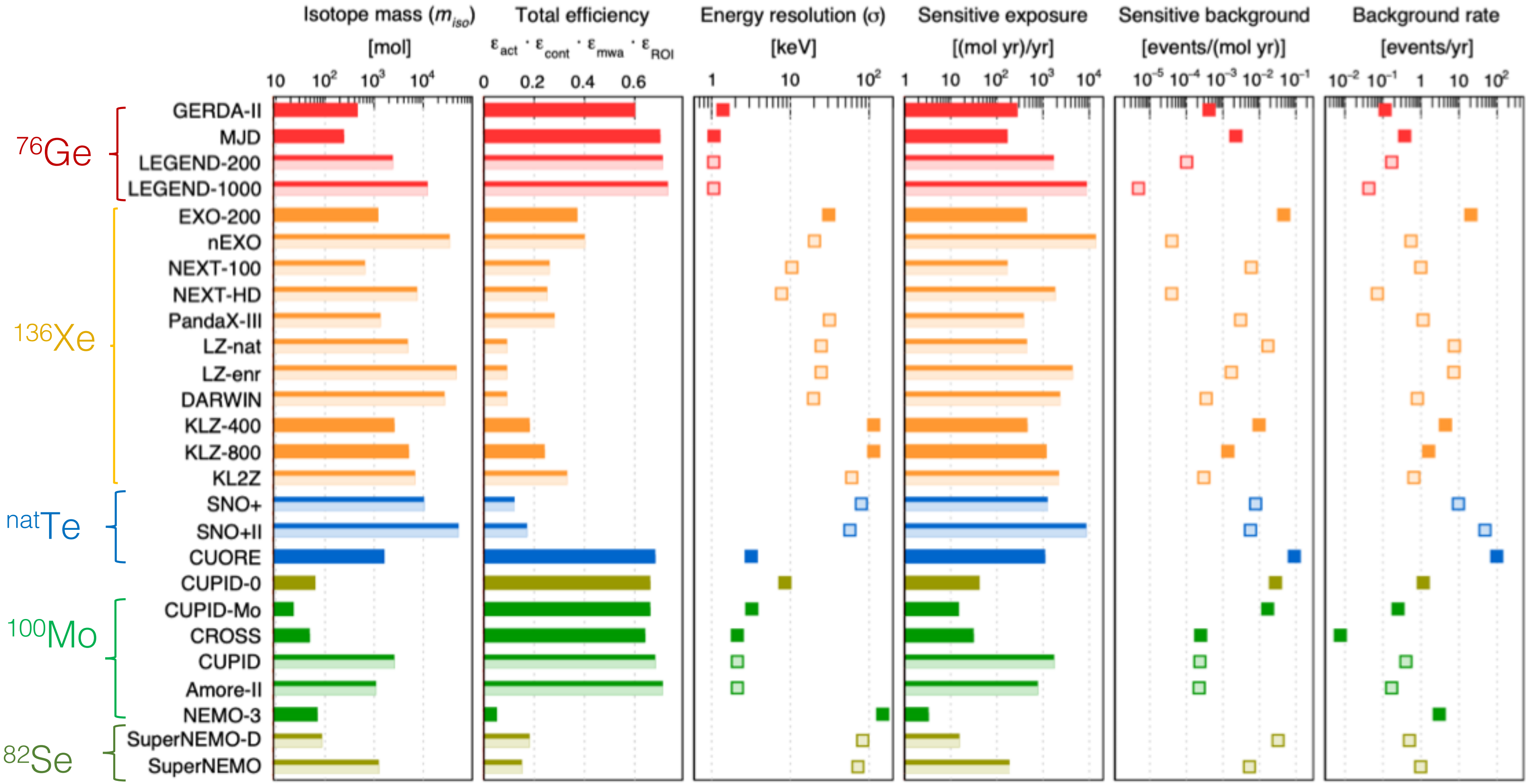
^{76}Ge: CDEX-300v @ CJPL

Adaptation of LEGEND concept



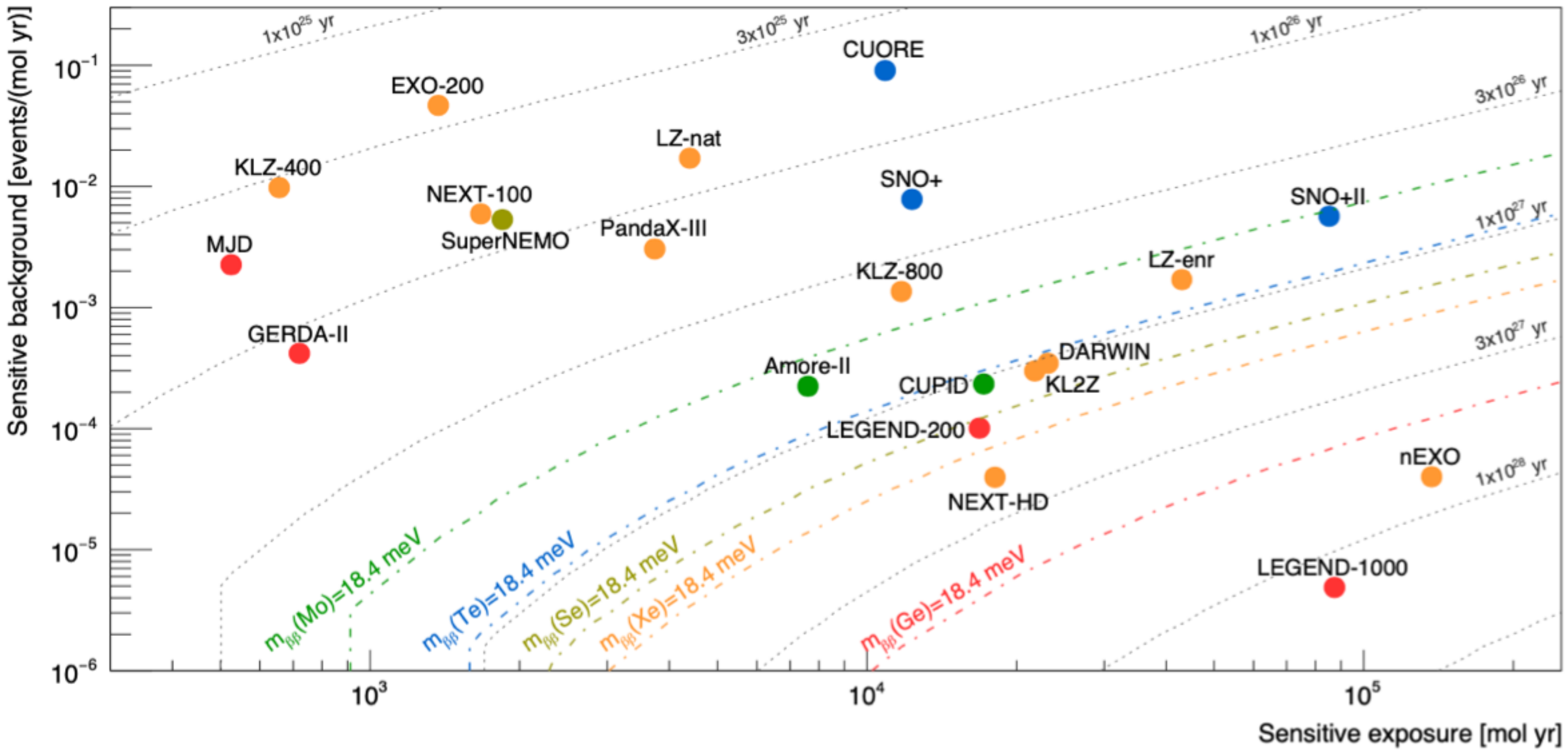
- 1725m^3 LN$_2$ for shielding and Cooling;
- Φ1.5m*8m copper tube filled with **LAr** and immersed into LN$_2$ for cooling;
- Enriched Ge array in LAr media for cooling and **active LAr shielding.**
- 1st 100kg >86% ^{76}GeO$_2$ in CJPL, 2nd 100kg ready in the first half of 2023; 3rd 100kg: under preparation;
- Enriched **BEGe** detectors: First batch (30-40 detectors) at CJPL in 2023

Isotope masses, efficiencies, sensitive background & exposure and backgrounds



Agostini, Benato, Detwiler, Menendez, Vissani, arXiv:2202.01787

Sensitive background and exposure for recent and future experiments

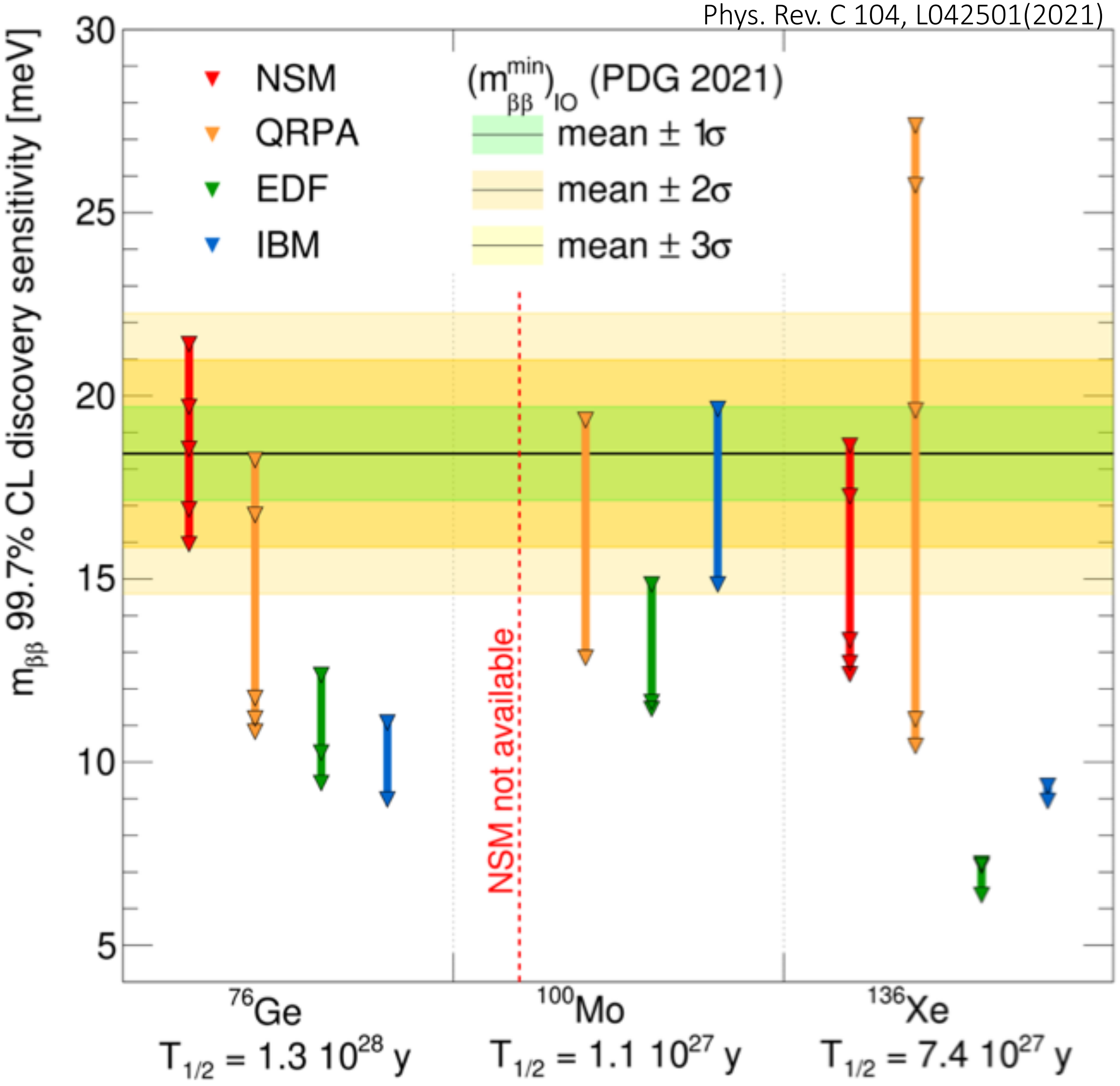


Agostini, Benato, Detwiler, Menendez, Vissani, arXiv:2202.01787

Comparison of $m_{\beta\beta}$ sensitivities

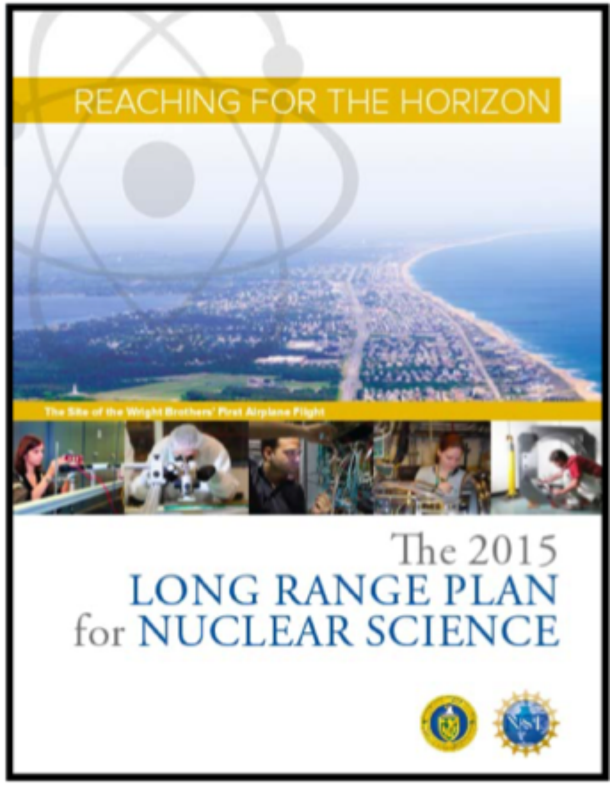
- Inverted ordering: $m_{\beta\beta}$ > 18.4 ± 1.3 meV
- M ➔ 4 many-body methods, each with specific systematics (soon also ab initio)
- Multiple, different set of calculations for each many-body method and isotope

Agostini, Detwiler, Benato, Menendez, Vissani
"Testing the Inverted Neutrino Mass Ordering with 0νββ Decay"
Phys. Rev. C 104, L042501(2021)



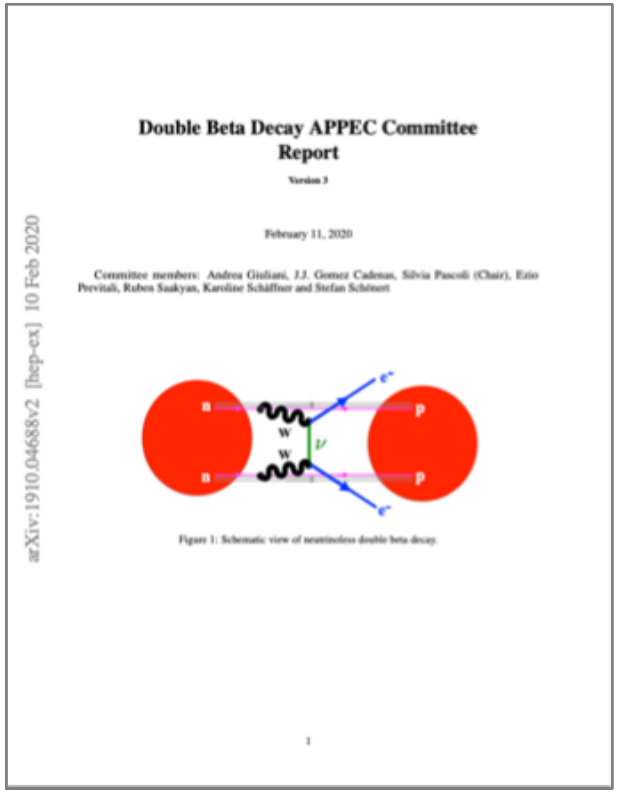
The European and North-American Process

https://science.osti.gov/np/nsac



"We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment."

https://arxiv.org/abs/1910.04688


arXiv:1910.04688v2 [hep-ex] 10 Feb 2020

Double Beta Decay APPEC Committee Report

Version 3

February 11, 2020

Committee members: Andrea Giuliani, J.J. Gomez Cadenas, Silvia Pascoli (Chair), Ezio Previtali, Ruben Saakyan, Karoline Schäffner and Stefan Schönert

Figure 1: Schematic view of neutrinoless double beta decay.

1

- Oct 2019: Roadmap document for the APPEC SAC on the future $0\nu\beta\beta$ decay experimental programme in Europe
- $0\nu\beta\beta$ town meeting London
- Roadmap update 2022, town meeting in Berlin, June 2022

DOE NP Portfolio Review
July 2021
CUPID
LEGEND-1000
nEXO

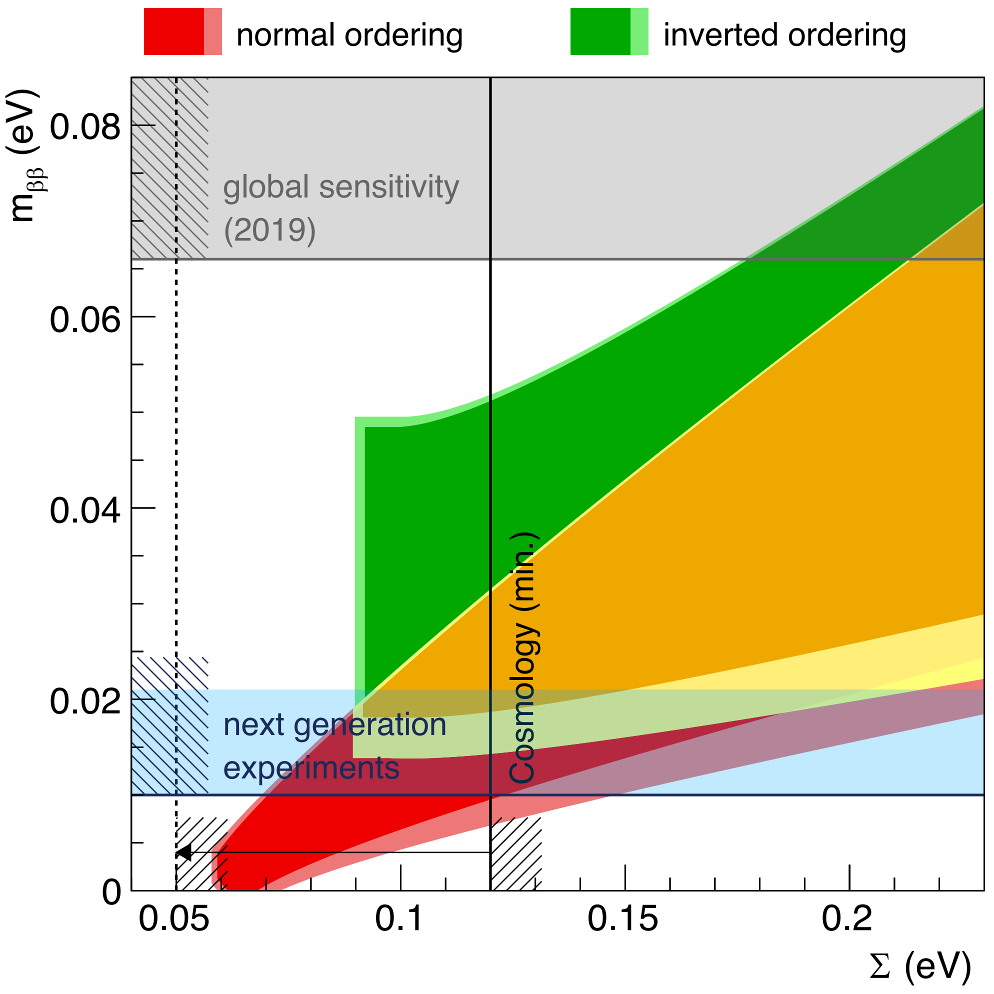
- Outcome: Realize international portfolio LEGEND-1000, nEXO and CUPID with European partners
- LEGEND-1000 was evaluated extremely positively at the Portfolio review. Now being funded by DOE to move to the next step, CD-1

https://agenda.infn.it/event/27143/

"The international stakeholders in neutrino-less double beta decay research do agree in principle that the best chance for success is an international campaign with more than one large ton-scale experiment implemented in the next decade, with one ton scale experiment in Europe and the other in North America. "

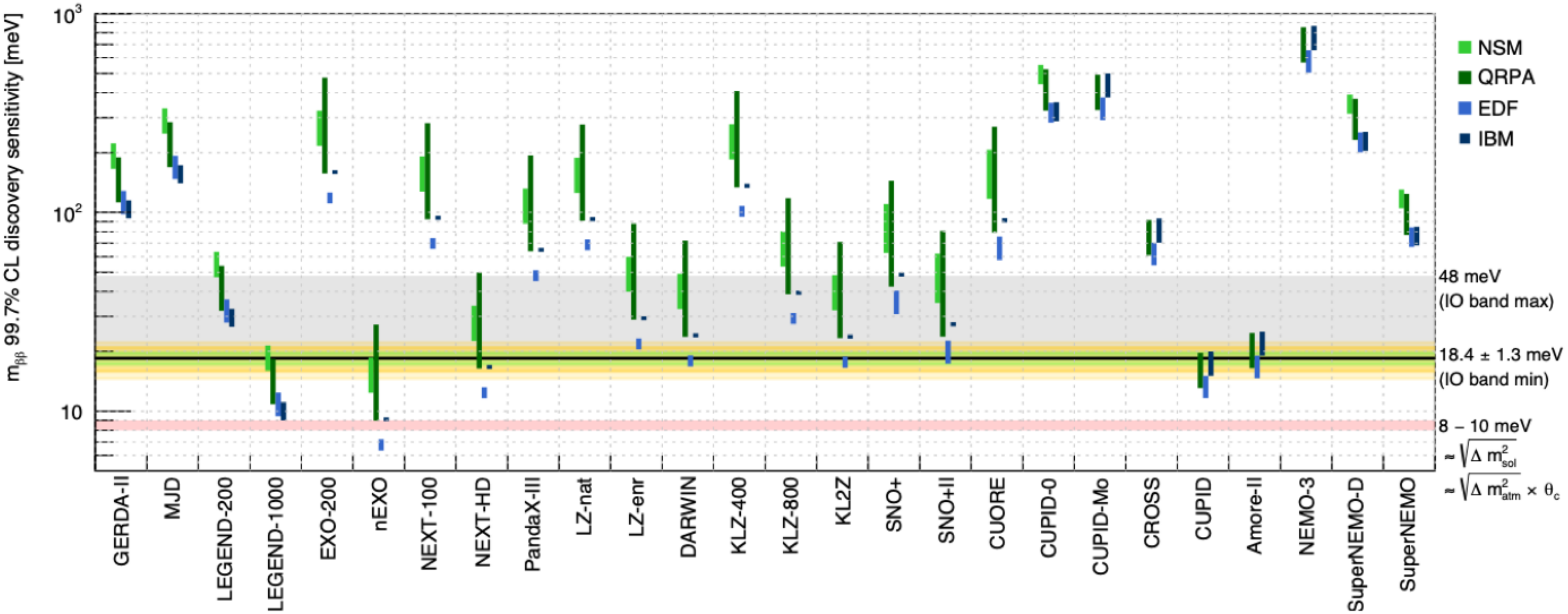
Summary & Outlook

- Major progress for preparation of **ton-scale** experiments over last two years
- Experiment design for **discovery** (not limit setting)
- Will fully explore **IO** and large part of **NO**
- Several DBD isotopes and techniques required, given **NME uncertainties**
- Formidable **experimental challenges** to acquire ton yr exposure quasi **background free – or compensate with huge mass (Te)**
- North-American – European **convergence on portfolio** of experiments contingent on funding: current front-runners are LEGEND-1000, nEXO and CUPID; breakthrough R&D on Ba-tagging
- Asia: KL2Z, Amore, PandaX, JUNO
- **Availability of DBD isotopes** from Western supplier
- How to go to **bottom of NO**? Assess **performance** of ton-scale experiments first. All have the potential to **increase exposure** and reduce further **backgrounds**



EXTRA slides

Discovery sensitivities of current- and next-generation 0νββ-decay experiments



Agostini, Benato, Detwiler, Menendez, Vissani, arXiv:2202.01787