Beyond “Tonne Scale” Experiments

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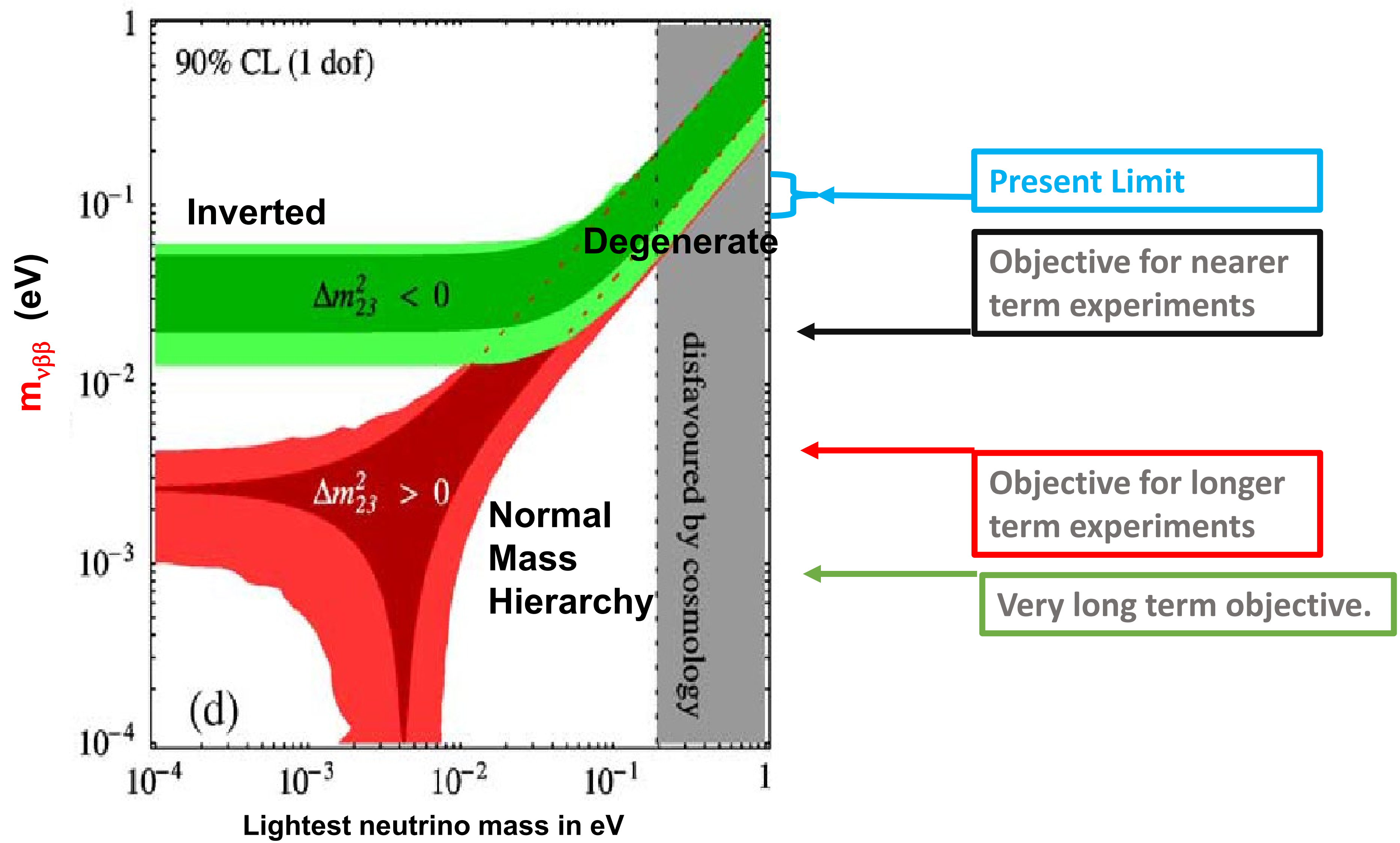
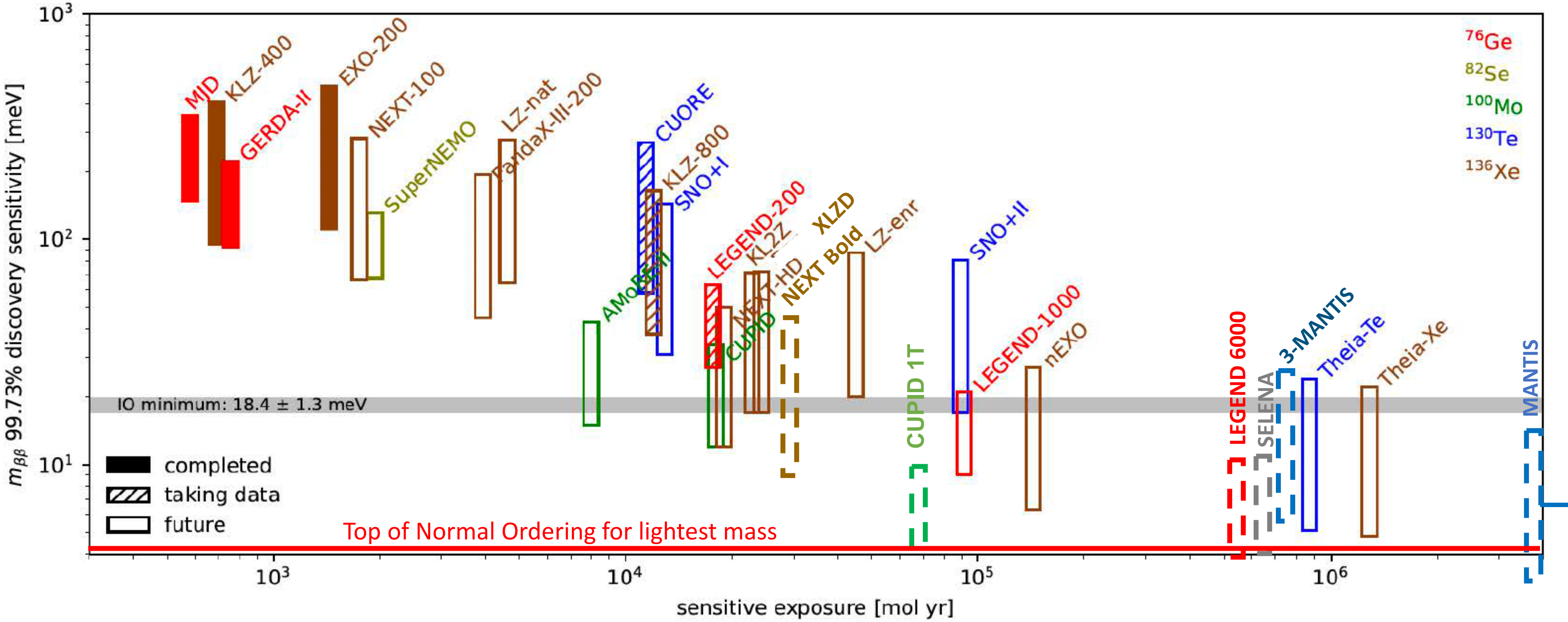
Kingston, Canada

Variation of $m_{\beta\beta}$ vs Lightest ν mass

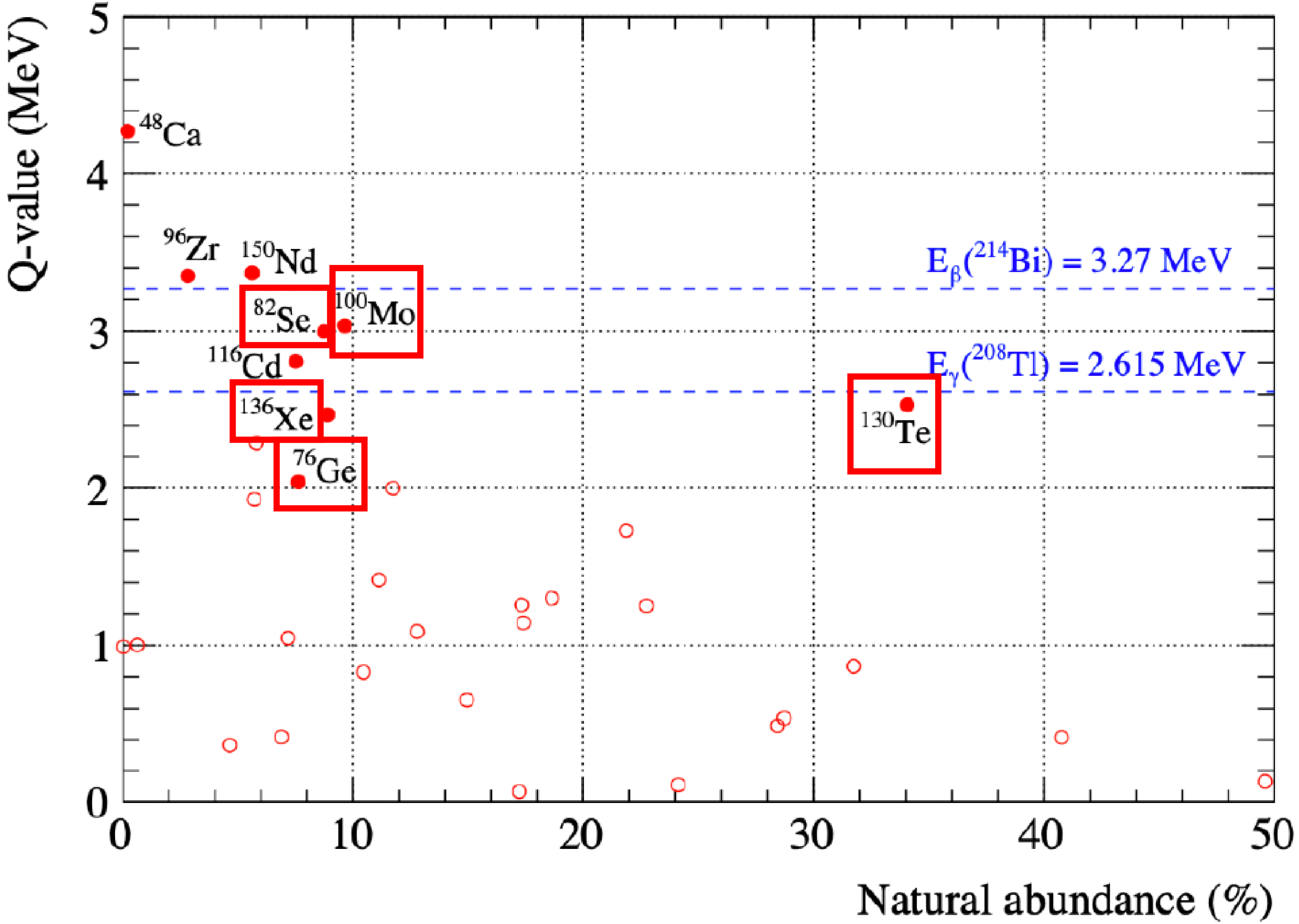


Summary plot from NSAC LRP White Paper (Augmented) (Values provided by experiments)

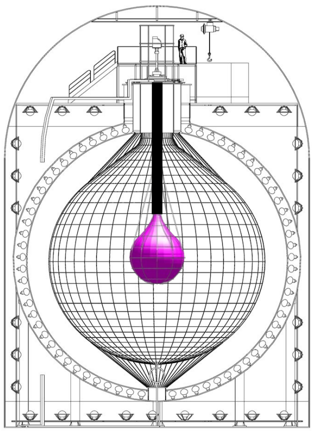


From: Fundamental Symmetries, Neutrons, and Neutrinos (FSNN): Whitepaper for the 2023 Nuclear Science Advisory Committee Long Range Plan: arXiv:2304.03451iv:2304.03451

Double Beta Decay Isotope Candidates



KamLAND-Zen 400

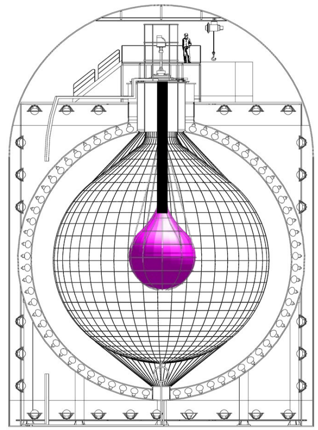


380kg deployed

$$T^{0\nu}_{1/2} > 1.07 \times 10^{26}\ \mathrm{yr}$$

PRL117, 082503 (2016)

KamLAND-Zen 800



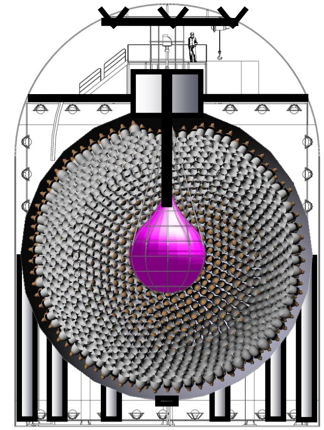
Now, 745kg deployed

$$> 2.3 \times 10^{26}\ \mathrm{yr}$$

PRL130, 051801 (2023)

Further improvements going on;
better neutron tagging
machine learning (ML) for long-lived tagging
ML for beta/gamma discrimination
muon-bundle tracking, and so on

KamLAND2-Zen



Mirror
HQE-PMT
new LS
} x5 p.e.
full volume effective
w/ scintillation film

1 ton planned (scalable)

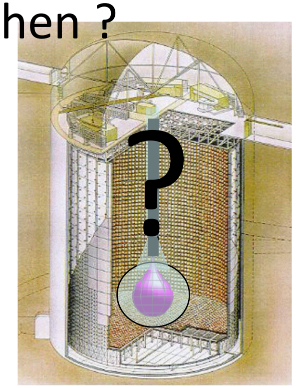
$$> 2 \times 10^{27}\ \mathrm{yr}$$ (target sensitivity)

$$< 12 \sim 53\ \mathrm{meV}$$ (corresponding mass limit)

3σ discovery potential is not studied, but ~1x10^{27} yr

Further technologies being developed
imaging sensor (1/10 reduction of long-lived BG)
high-p xenon deployment (2 times more xenon)

Then ?



It will not be a good choice for the single purpose, but this is multi-purpose detector.

$$> 2 \times 10^{28}\ \mathrm{yr}$$

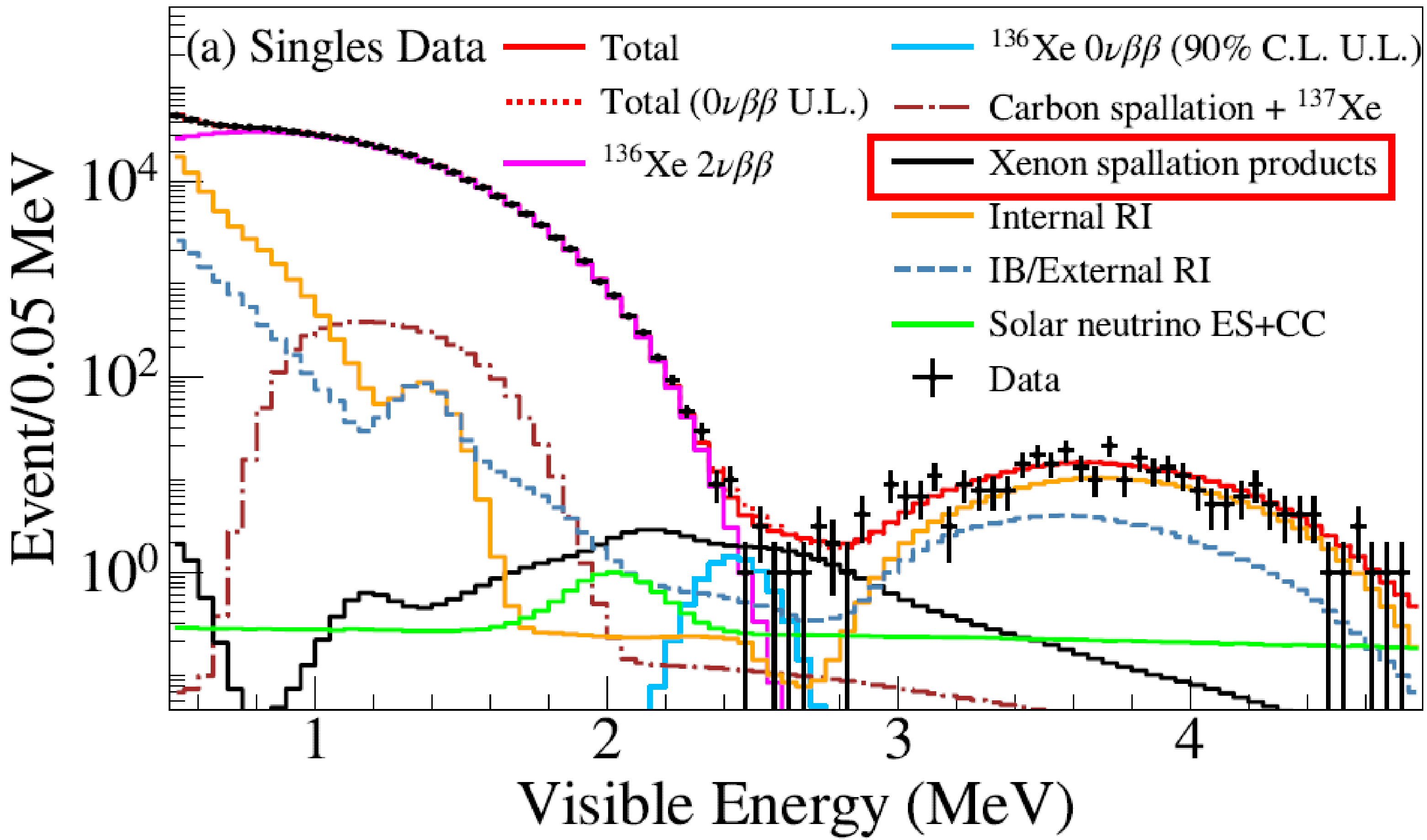
(guesstimated sensitivity)

w/ more than 20 ton xenon
imaging sensor
high-p xenon

For more xenon (possible source)
Extraction from nuclear spent fuel is considered.
More than 100 ton seems to be possible at 44% concentration of Xe-136 without centrifugal enrichment.

	36 months	atmospheric
$^{128}Xe/^{132}Xe$	$2.81 \cdot 10^{-3}$	$7.13 \cdot 10^{-2}$
$^{129}Xe/^{132}Xe$	$4.7 \cdot 10^{-6}$	0.9832
$^{130}Xe/^{132}Xe$	$3.32 \cdot 10^{-4}$	0.1518
$^{131}Xe/^{132}Xe$	0.3756	0.7876
$^{134}Xe/^{132}Xe$	1.3433	0.3883
$^{136}Xe/^{132}Xe$	2.1176 **44%**	0.3298 **8.9%**

Results from Kam-Zen 800 (arXiv 2203.02139) March 2022



$T^{1/2} > 2.3 \times 10^{26}$ yr (Combined Kam-Zen 400 and 800)

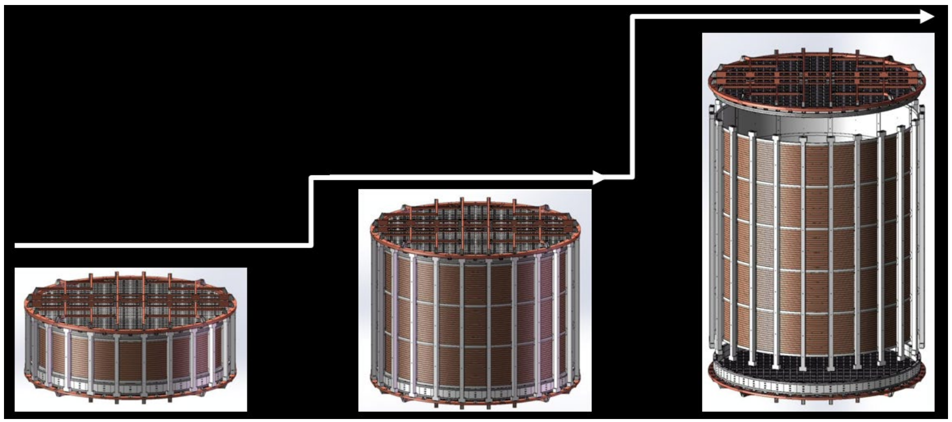
$\langle M_{\beta\beta} \rangle$ is < 36 – 156 meV

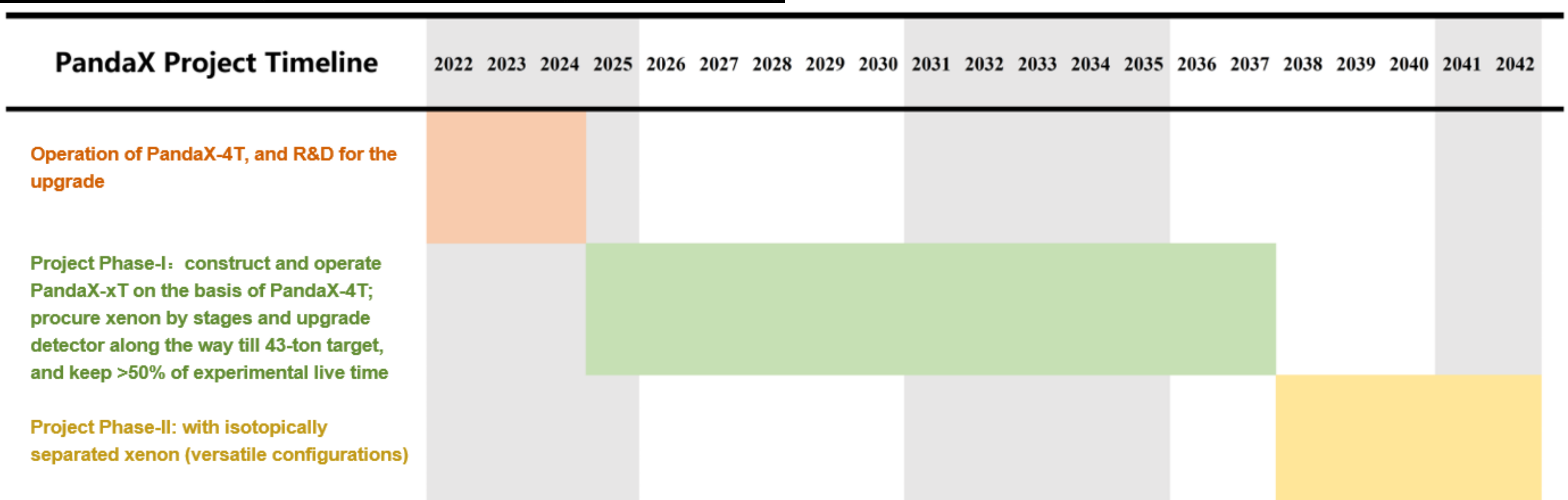
Future of PandaX: PandaX-xT

Now operating PandaX-4T (natural xenon)

Step-wise upgrade in the same experimental hall based on possessed xenon towards 43-ton (active), 47-ton (total) natural xenon

- Multiple physics topics (DM, 0vDBD, solar v, etc): no loss game
- Combines the advantage of CJPL, experience/team buildup of PandaX, and xenon resource in China
- Step-wise upgrade leverages technological challenges, and maintains continuous scientific output
- Versatile configuration with isotopic-separated ^{136}Xe in the next future





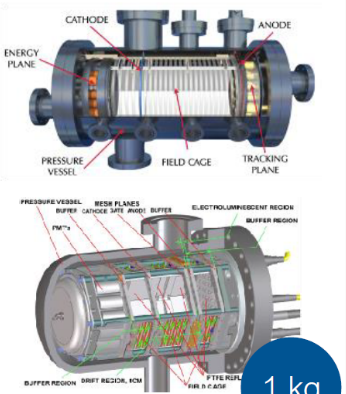
The NEXT program

At CanFranc Laboratory

Prototypes

2008-2015

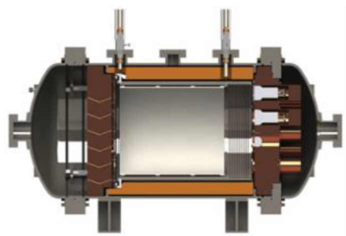
- Demonstration of detector concept



NEXT-White

2016-2021

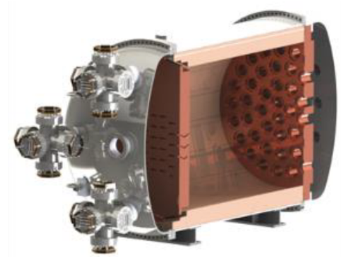
- Det. performance near $Q_{\beta\beta}$
- Background measurement
- $2\nu\beta\beta$ measurement



NEXT-100

2022-2025

- Background measurement
- $0\nu\beta\beta$ search



NEXT-HD

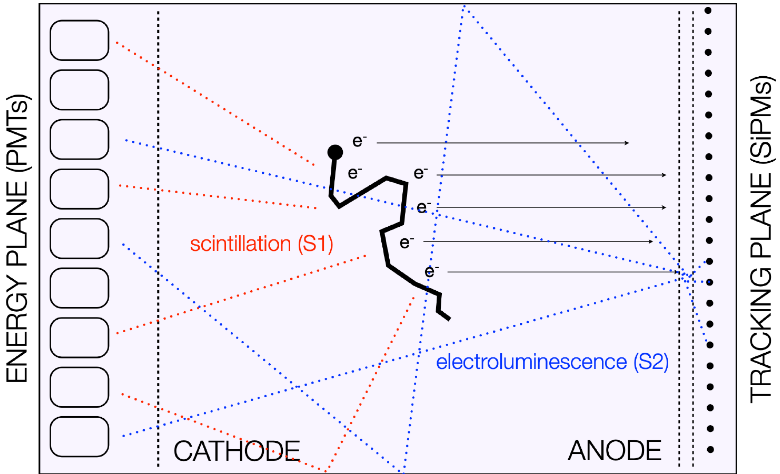
2026?

- $0\nu\beta\beta$ search through inverted ν mass ordering

NEXT-BOLD

- Barium tagging for bgr-free experiment

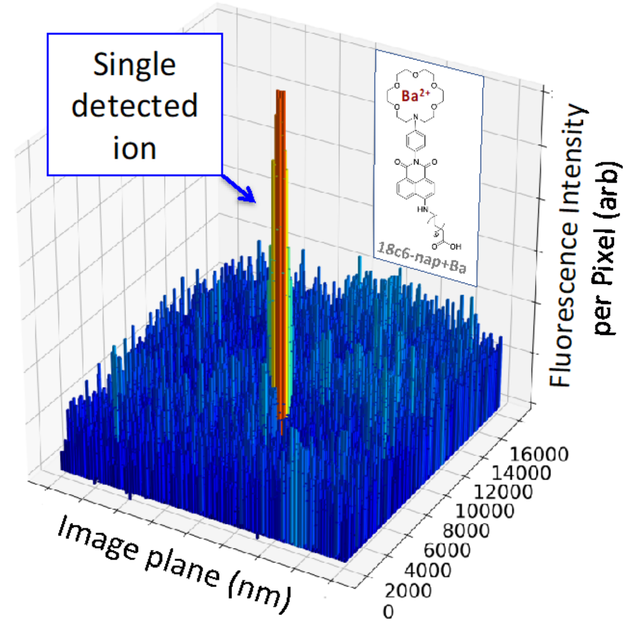
2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030

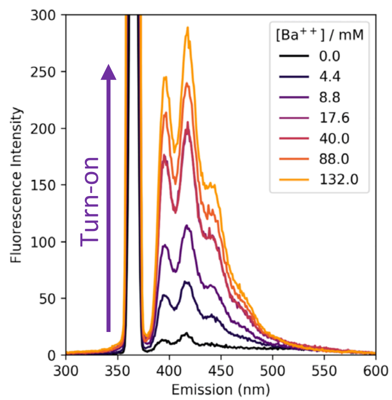


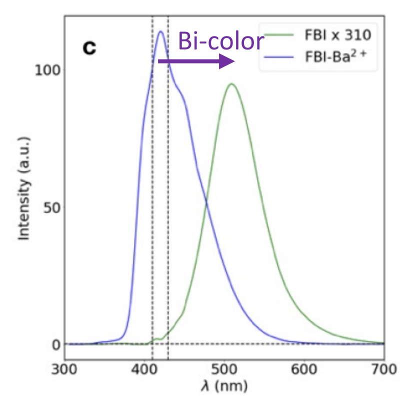
- **NEXT uses enriched ^{136}Xe gas at high pressure and provides tracks of individual electrons.**
- **There is also a program of extracting Ba^{+} through fluorescence in organic molecules aiming at NEXT-BOLD.**

Barium Tagging for NEXT

- NEXT aims to capture and image Ba^{2+} ions produced in double beta decay of ^{136}Xe.
- Single molecule fluorescence imaging (SMFI) employs molecular sensors undergoing photo-physical changes upon Ba^{2+} chelation.
- Signature of binding may be either:
  - **off->on:** Optically quiet molecule becomes bright
  - **Bi-color:** Fluorescent molecule changes emission spectrum
- Combined with 1% FWHM energy resolution available in Xe gas, Ba^{2+} tagging could enable a background free experiment at multi-ton scale.







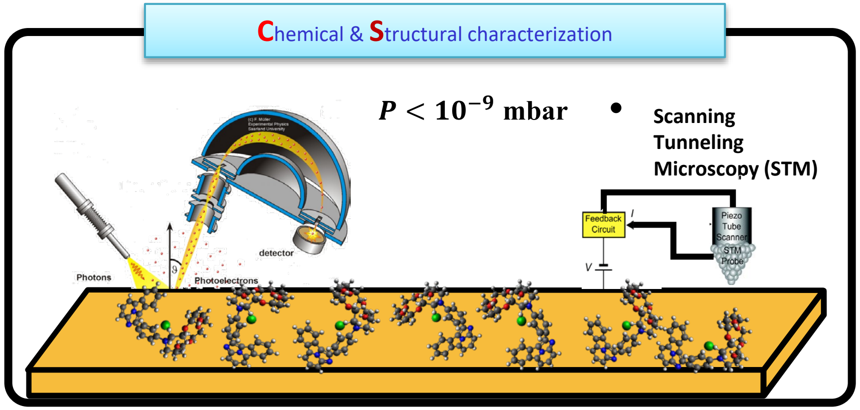
References:
J.Phys.Conf.Ser. 650 (2015) 1, 012002; JINST 11 (2016) 12, P12011; Phys. Rev. A 97, 062509 (2018); Phys. Rev. Lett. 120 (2018) 13, 132504; Sci.Rep. 9 (2019) 1, 15097; Nature 583 (2020) 7814, 48–54; ACS Sens. (2021) 6, 1, 192–202; NIMA. 1039, 167000 (2022); arXiv:2303.01522

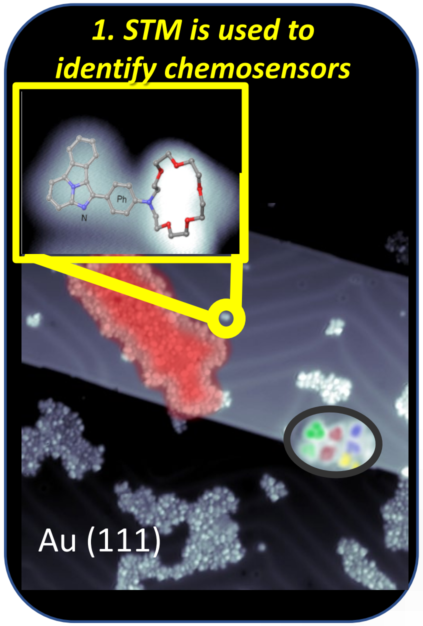
Dynamics of Ba^{2+} binding

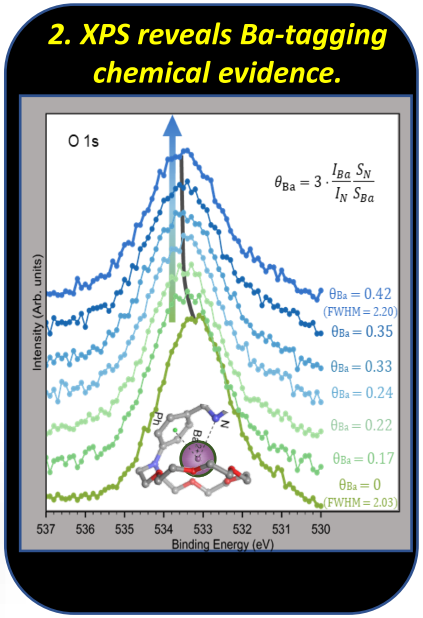
- Recent work has studied mechanisms of ion binding in NEXT barium sensing molecules.

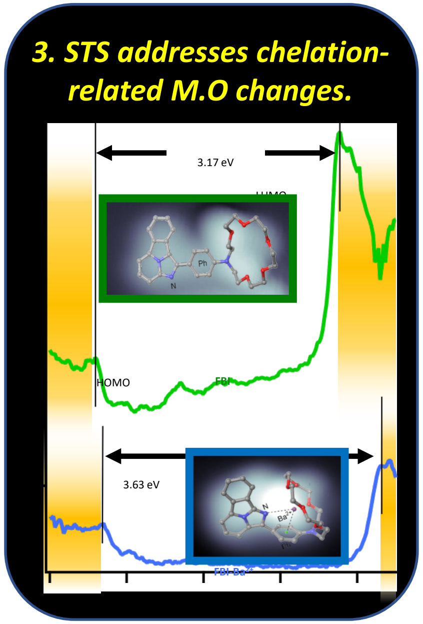
Nat.Comm.13, 7741 2023,

- Barium perchlorate evaporated in vacuum onto sub-monolayer of crown ether chemosensors.
- Molecules chemically react with the $Ba[ClO_4]_2$ to capture the Ba^{2+} into the receptor.
- Combination of STM, XPS and STS illuminates changes in electronic configuration, studying mechanism of the reaction at single molecule level.



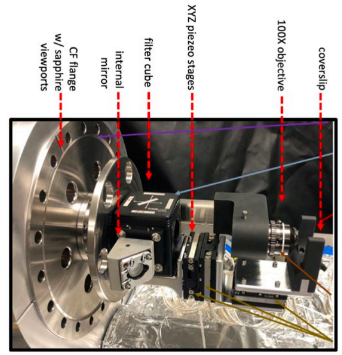


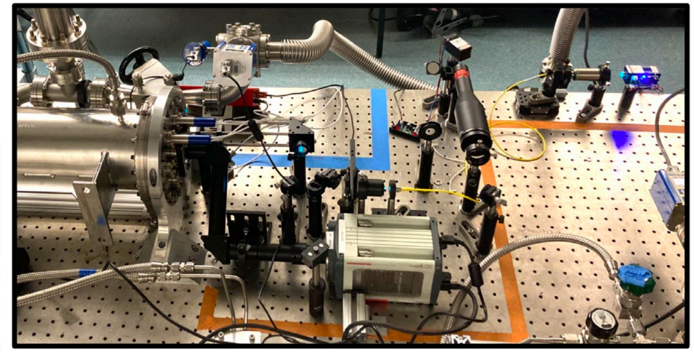


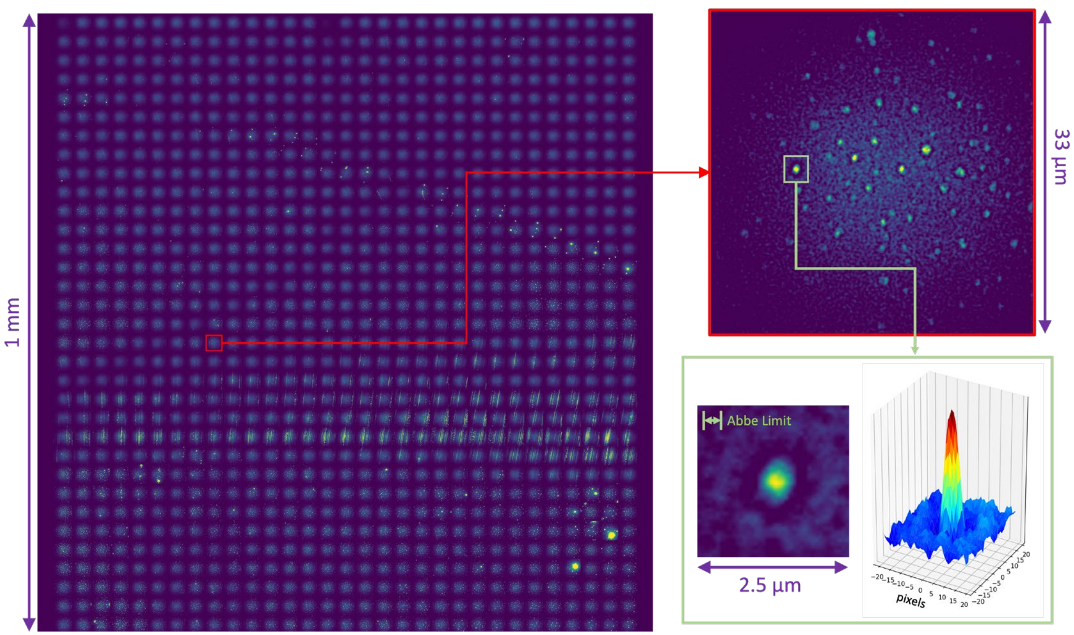


High pressure SMFI

- Novel fluorescence microscopes developed for operation over large surfaces in high pressure gases.







- Single molecule resolution achieved in high pressure xenon gas over 1x1 mm^2, working at at the Abbe diffraction limit.

- Single Ba^{2+} + chemosensor complexes imaged in Xe gas → first demonstration of single Ba^{2+} imaging in a working TPC medium.

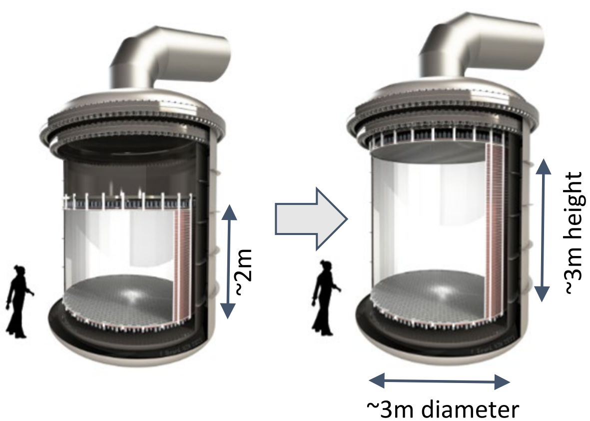
Paper in prep.

Sensitivity to 0$\nu\beta\beta$

TPC with large ^{nat}Xe target for direct dark matter search, offers position reconstruction, calorimetry and low background

⇒ **High sensitivity to 0νββ-decay**

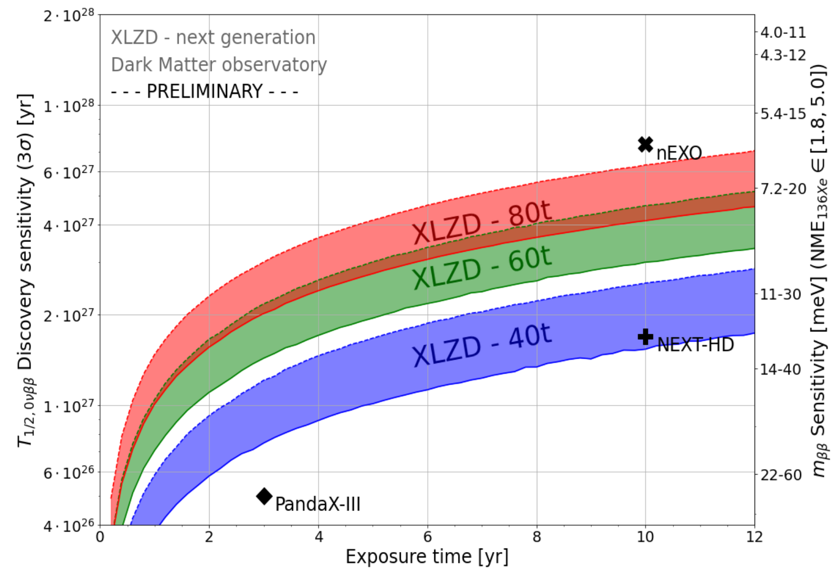
Xenon acquisition supports staged approach with



early science phase
40t TPC, < 5yr operation, shallow TPC design

main science phase
(60t TPC, > 10yr operation, optimized 1:1 aspect ratio)

+ 80t option in tall TPC, depending on Xe market

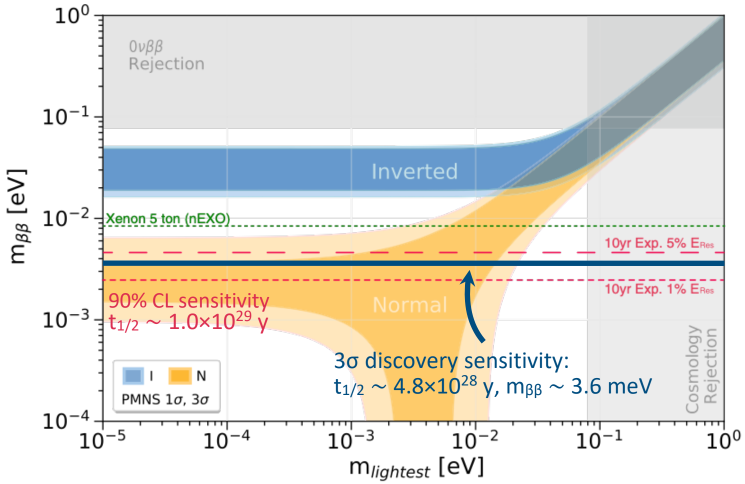


Projection bands cover a baseline scenario (lower bounds) based on state-of-the-art DM LXe-TPC performance to more progressive assumptions on backgrounds (upper bounds).

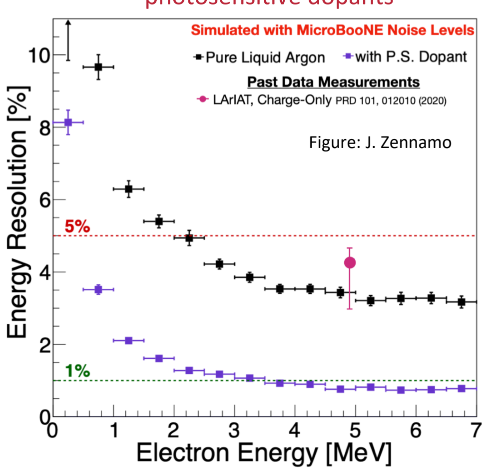
NLDBD with a Large Xe-loaded LArTPC

- Concept: Doping a DUNE-like underground detector with $\sim$2% ^{136}Xe for normal ordering NLDBD sensitivity
  - Recent work demonstrating MeV-scale signals in large LArTPCs: solar/SNe ν[1], BSM milli-charged particles[2], radioactive decays[3,4], DM ν[5], etc.
  - Discovery sensitivity $t_{1/2} \sim 4.8\times10^{28}$ years (3σ)
- Photosensitive dopants to convert UV scintillation light into ionization charge, improving energy resolution
- R&D challenges include large quantities of Xe & underground Ar, dopant optimization
- Simulation & bench-top studies are underway to test dopants and quantify the achievable energy resolution for MeV-scale electron signals:

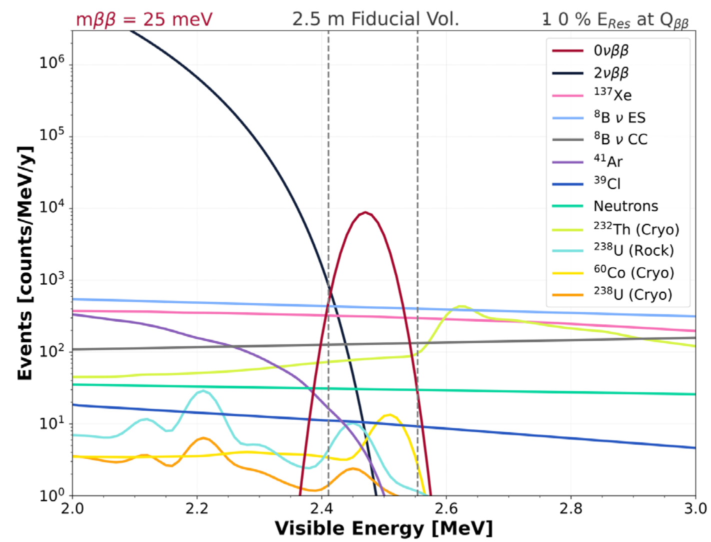
A. Mastbaum, F. Psihas and J. Zennamo, Phys. Rev. D 106 092002 (2022)



Resolution impact of photosensitive dopants



Fermilab TPC test stand development



[1]PRL 123, 131803 (2019); [2]PRL 124, 131801 (2020); [3]MICROBOONE-NOTE-1050-PUB; [4]JINST 17, P11022 (2022); [5]arxiv:2210.04920

New Technology Needed to Obtain ~ktonne of Xenon-136

M. Heffner LLNL

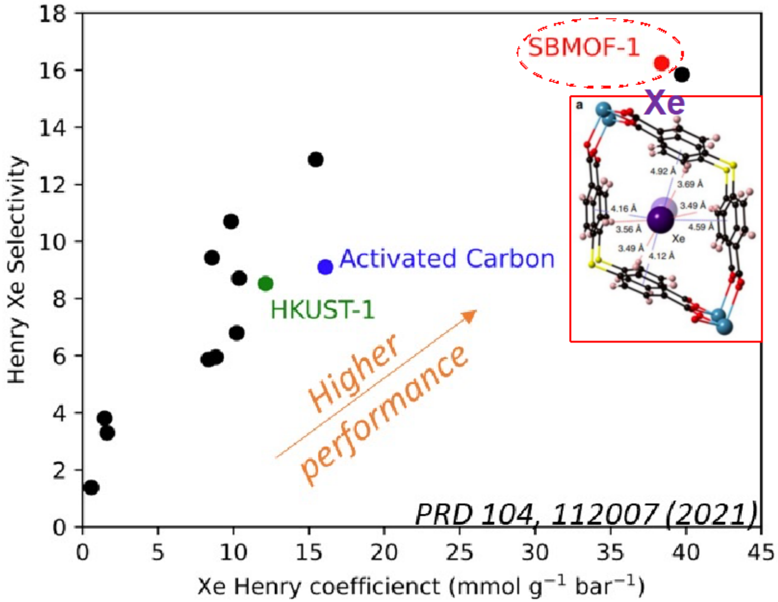
Challenge: Current xenon production worldwide is not sufficient, too expensive and cannot scale to ktonne

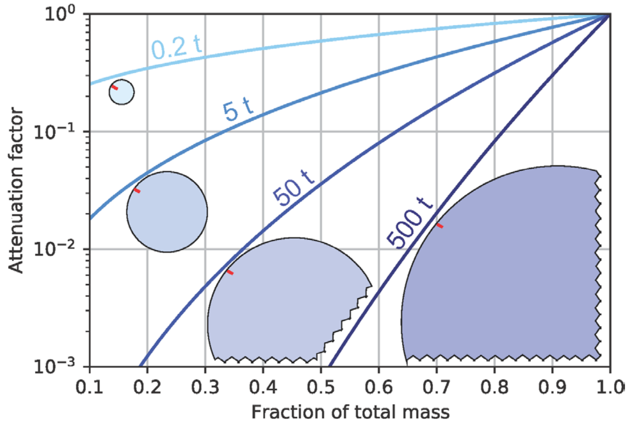
Solution: Develop new technology for Xe separation from air

- **Adsorption-based separation technology (Thermal)**
- **Metal-Organic-Frameworks (MOFs) materials can be engineered with desired characteristics**
- **Among these, a promising candidate SBMOF-1 has been identified**
- **Ongoing R&D focuses on:**
  1. **Scale up synthesis of SBMOF-1**
  2. **Optimized structured adsorbent beds to maximize the mass transfer to SBMOF-1 from the air**
  3. **Energy efficient process cycle**

- **Engagement from industry partners**
- **Funding-limited (slow) effort to date, but made significant progress on the 3 objectives**

Xenon selectivity vs adsorption coefficient for different materials



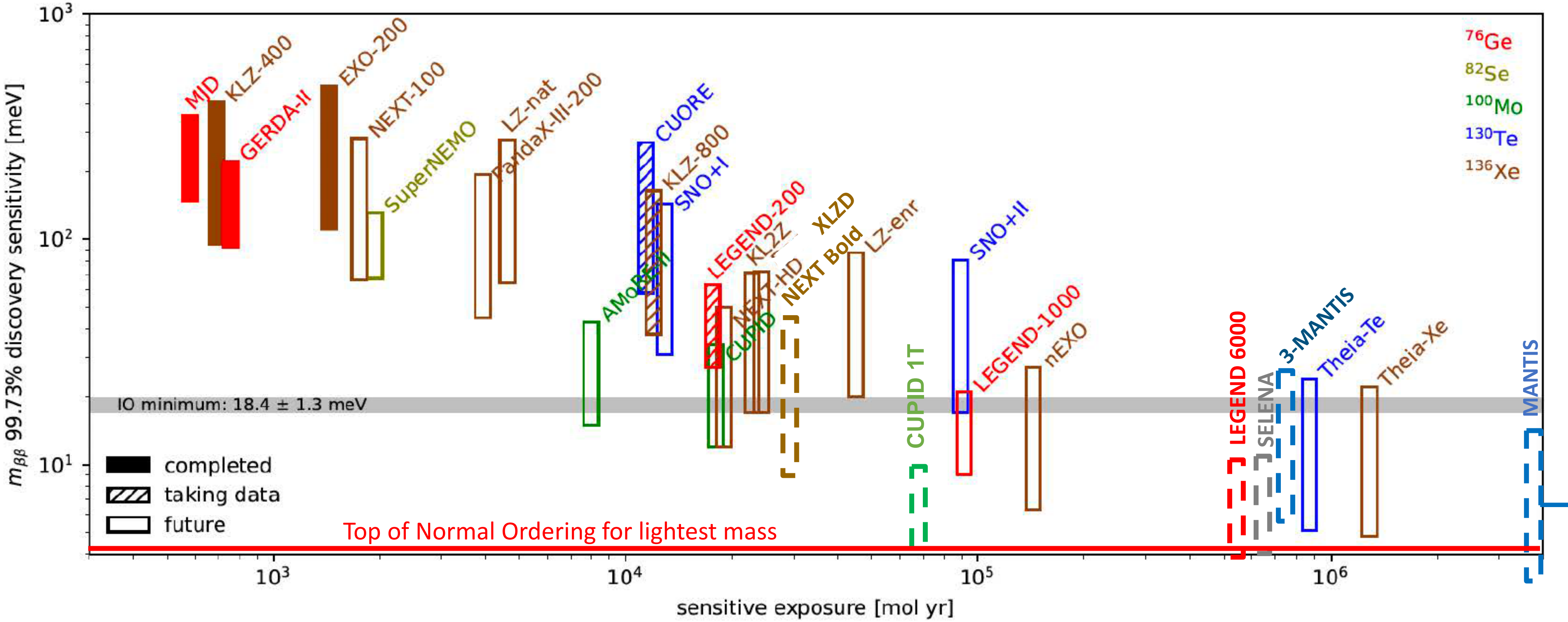


SBMOF-1 structured adsorbent bed prototype (LLNL)

200x scale up of SBMOF-1 synthesis

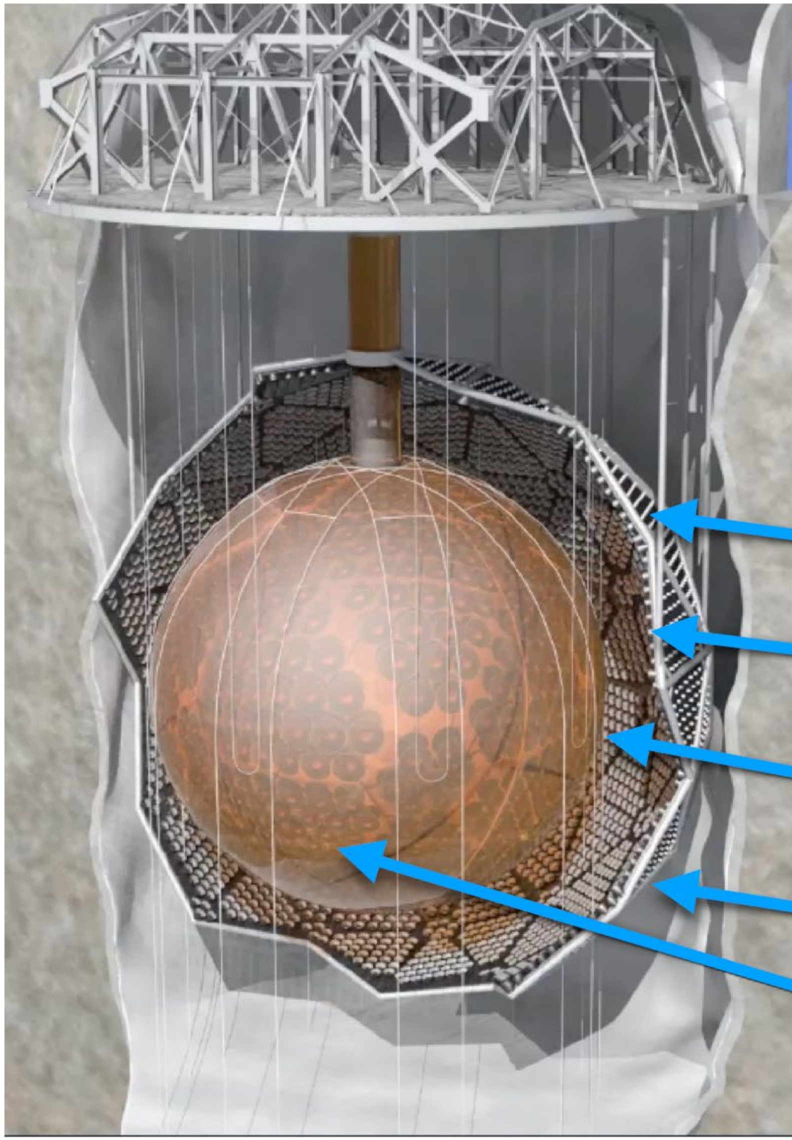
A. Avasthi et al., "Kiloton-scale xenon detectors for neutrinoless double beta decay and other new physics searches," Phys. Rev. D 104, 112007 (2021), arXiv:2110.01537

Summary plot from NSAC LRP White Paper (Augmented) (Values provided by experiments)



From: Fundamental Symmetries, Neutrons, and Neutrinos (FSNN): Whitepaper for the 2023 Nuclear Science Advisory Committee Long Range Plan: arXiv:2304.03451iv:2304.03451

The SNO+ Experiment



- **2km** underground in **SNOLAB**, Canada
- Infrastructure repurposed from **SNO**:
  - New calibration systems
  - Upgraded DAQ and electronics
  - New hold-down ropes
  - Scintillator Plant + Tellurium synthesis and purification

~9300 PMTs

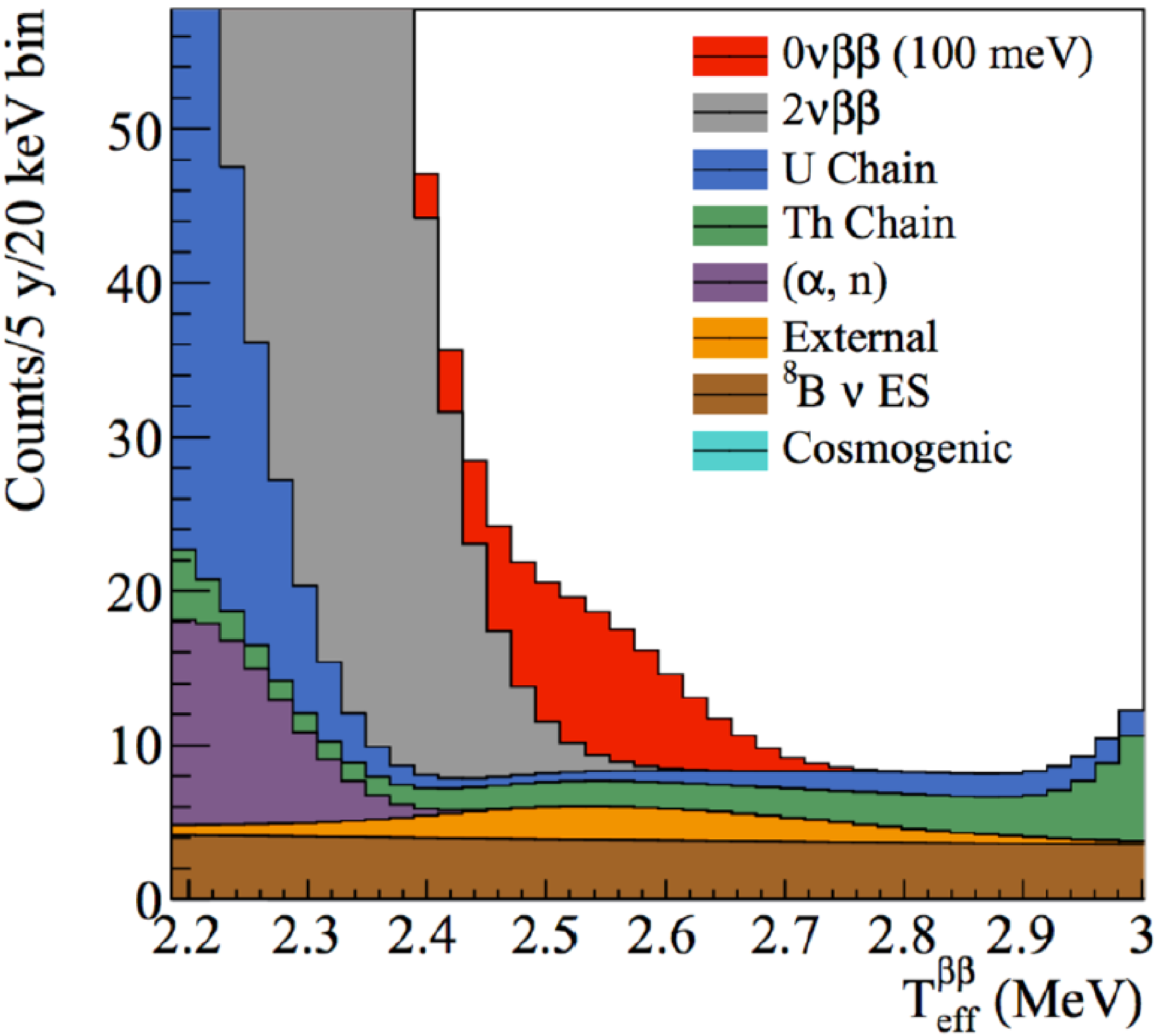
18m diameter PMT Support Structure

12m diameter Acrylic Vessel

7kt ultra pure water shielding

780t Liquid Scintillator to be loaded with 0.5% ^{130}Te initially

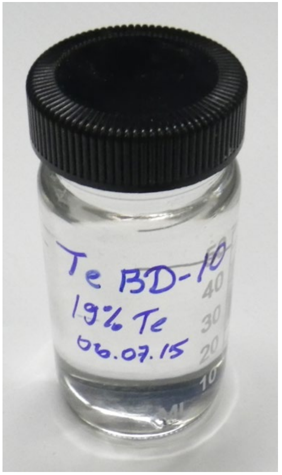
Increase to 3% planned for future



SNO+
5 years at 0.5% Te Loading: 1300 kg ^{130}Te

$m_{\beta\beta}$ < 30-130 meV (99.7% CL)

Phase II
3.0% ^{130}Te
$m_{\beta\beta}$ < 17-80 meV



Presently running with liquid scintillator for other physics and evaluating backgrounds. Te projected for early 2025.

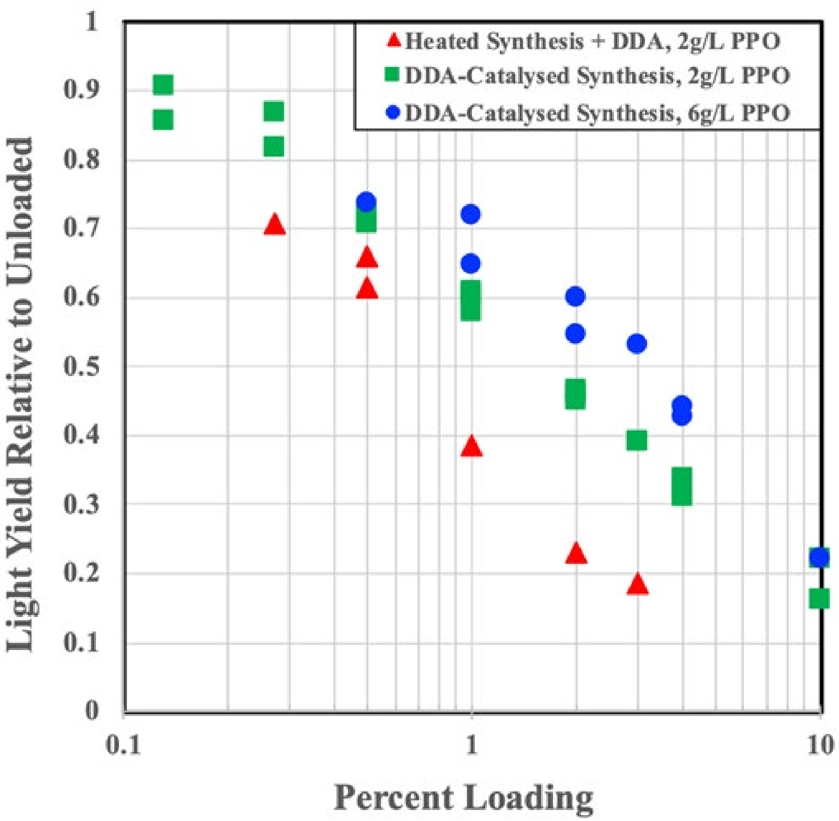
Te Organic Compounds (34% ^{130}Te)

Highly effective Te purification established

NIM 795 (2015) 132

Practical, stable Te loading established

NIM A 1051 (2023) 168204



- Relatively abundant & inexpensive (~$80/kg)
- The high natural abundance of ^{130}Te (~34%) means that ***enrichment*** (and its complications) ***is not necessary***
- LS provide a simple, scalable, low background technology
- Current cost of LS loading is less than $2M per tonne of isotope

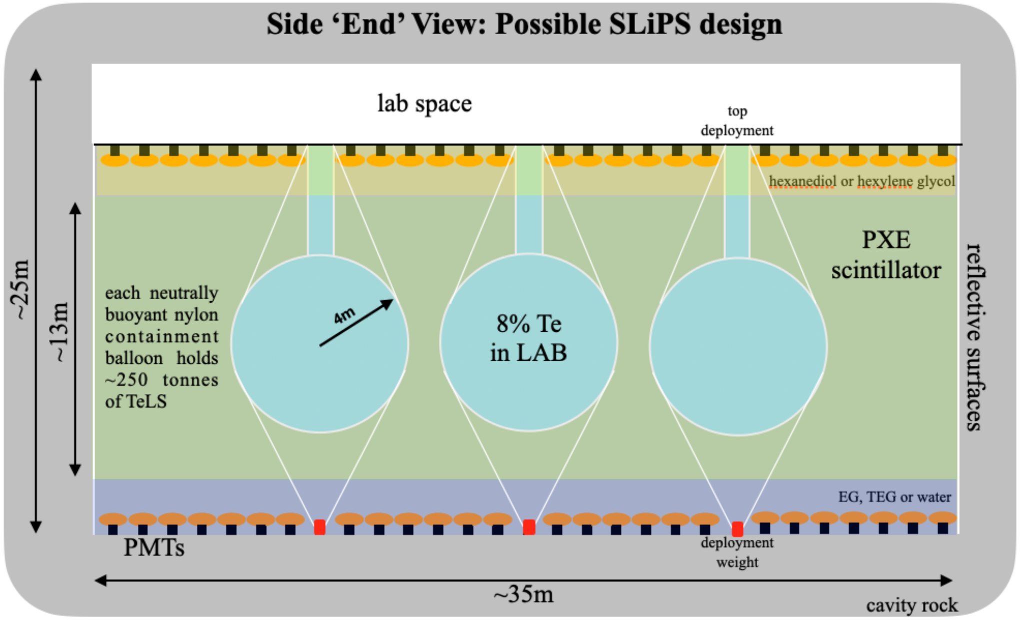
Ongoing Studies Include:

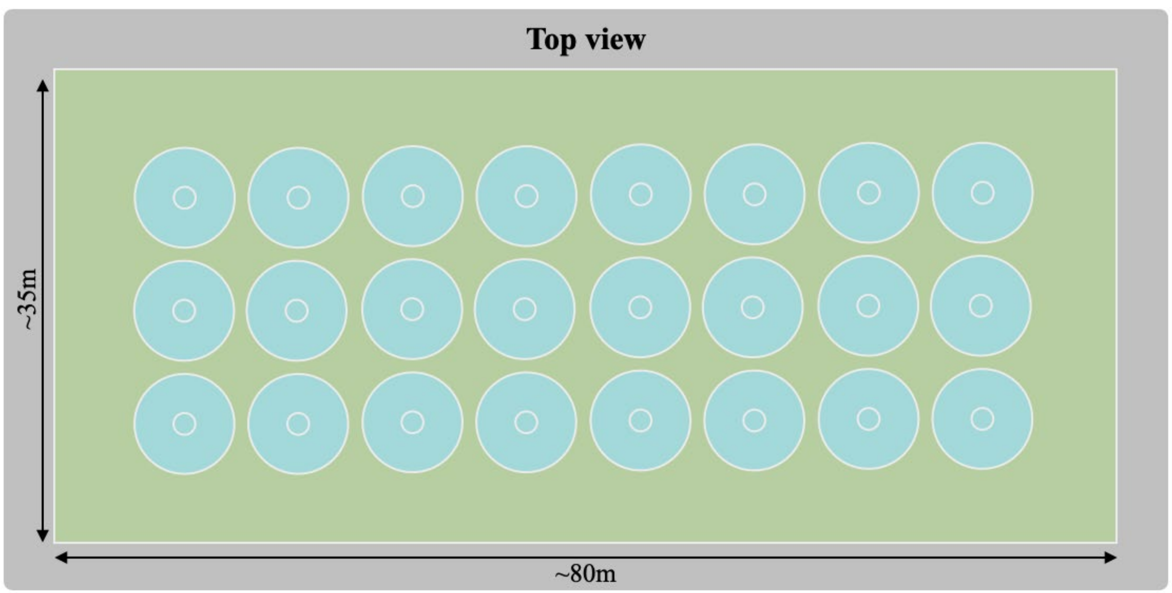
- Long term optical stability at higher loading levels
- Further light level improvements
- Improvements to purification and loading
- SNO+ as a technology demonstrator
- Practical designs for larger scale instruments

S. Biller et al: Sensitivity projections are possible based on realistic background models and reasonably modest extrapolations…

Straw-man for sensitivity estimates: modular deployment of 6kT

(MANTIS: Modular Approach for Nββ with Tellurium In Scintillator)





- Cost of Te loading per balloon: ~$15M
- Overall facility is JUNO-scale, with similar PMT coverage
- Each group of 3 balloons achieves a half-life sensitivity of ~1.1E28 yrs (90% CI) after 10 yrs running
- Staged balloon deployment over 10yrs plus an additional 10yrs running would yield a half-life sensitivity of ~4E28 yrs @90% CI (< 4meV for typical NME) or **2.2E28 @ 3σ : $m_{\beta\beta}$ < 5meV** for typical NME)
- Overall cost: **~$600M** (~half for facility & ~half for Te loading)
- The facility would also provide a ~30kT scintillator/Cherenkov detector for a wide range of other physics

Hybrid neutrino detection: THEIA

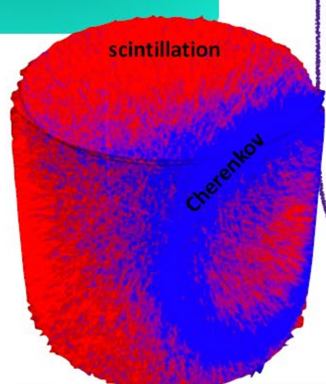
Combine Cherenkov + scintillation in a single, large detector

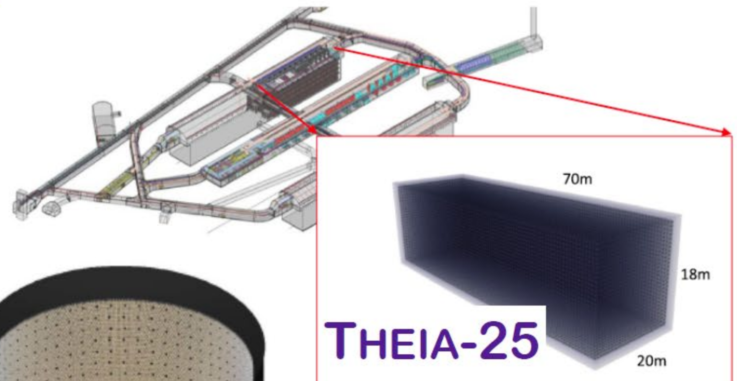
Directional information from Cherenkov topology + excellent resolution from high-yield scintillation

Can interrogate a uniquely broad program of physics, from sub-MeV to multi-GeV

Cutting-edge developments in target material and photon detection

Novel (Wb)LS
Fast photon detectors
LAPPDs
Spectral sorting





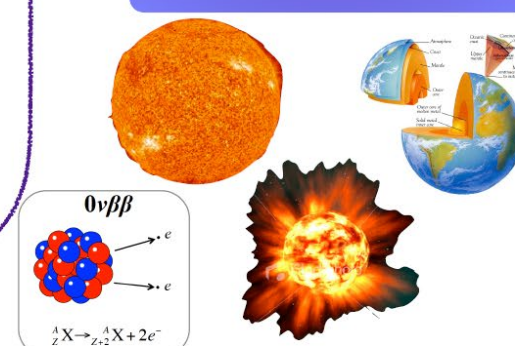
Large, multipurpose detector

- Baseline: 25ktonne (17kt FV)
- Ideal: 100 ktonne (70kt FV)

THEIA: An advanced optical neutrino detector
Eur. Phys. J. C 80, 416 (2020)

Broad physics program: Fundamental nature of matter *and* multi-messenger astrophysics

$0\nu\beta\beta$, CPV, solar, supernova, geo, nucleon decay

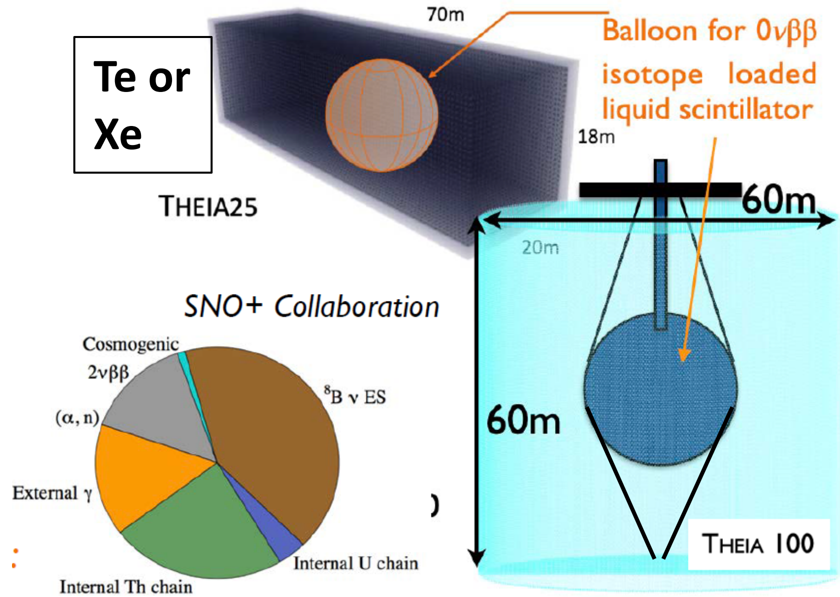


Part of DUNE Phase II Program

THEIA

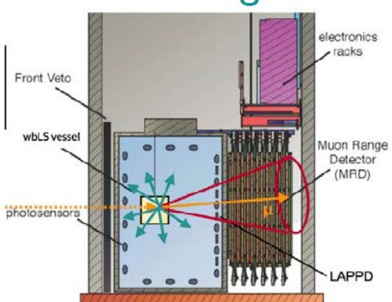
- Hybrid Cherenkov / scintillation detector improves background rejection via PID and event topology
- Scalable, ultra-clean liquid detector
- Potential to deploy a 25-kton THEIA module at LBNF, in a Module of Opportunity
- Mass sensitivity of ~4—22 meV
- Broad program of other physics

Background reduction via event imaging: PID, multi-site, directionality

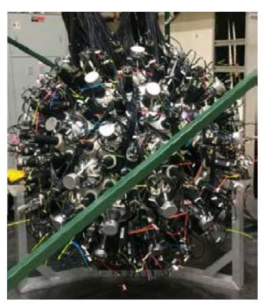


R&D into next-gen LS detectors

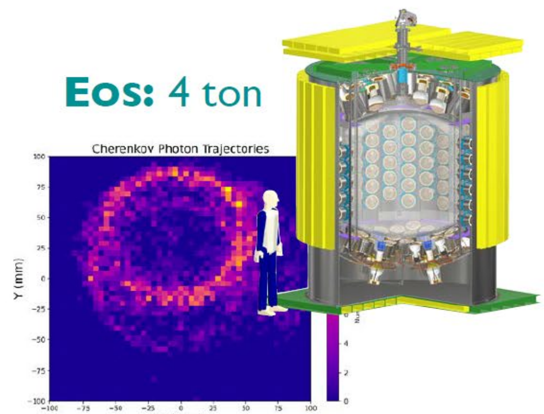
ANNIE: 365 kg



NuDot: 1 ton



Eos: 4 ton

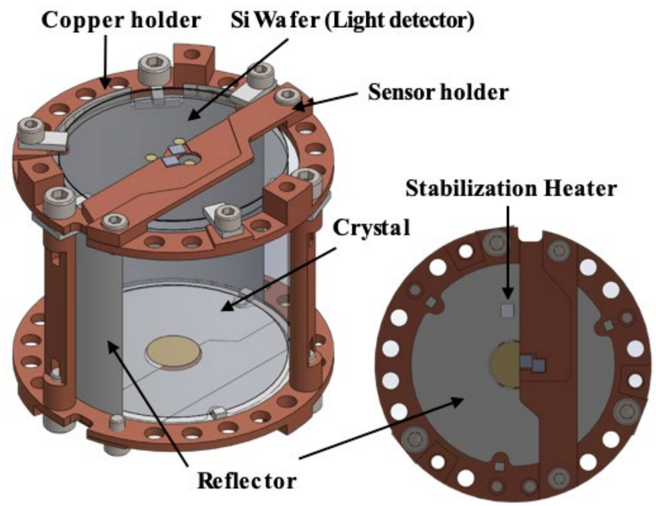


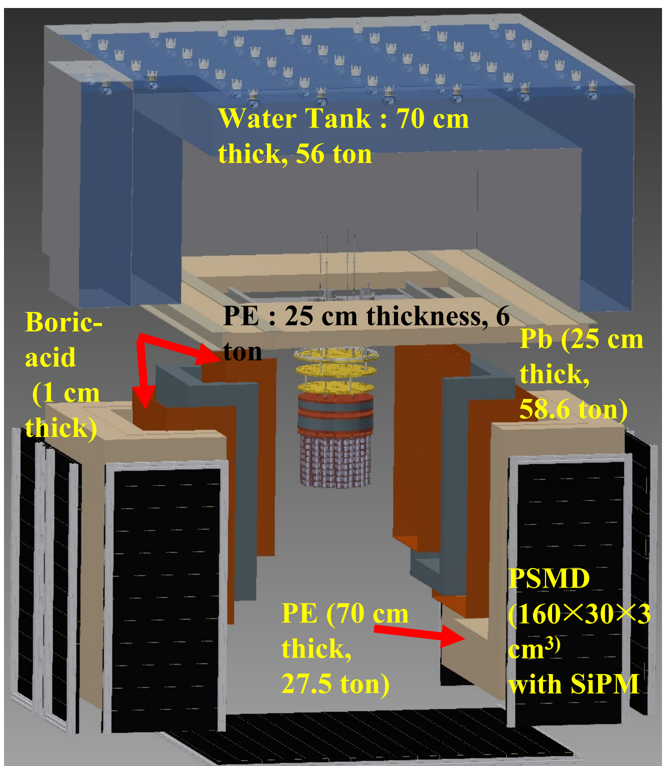
BNL: 1- and 30-ton

Builds on critical developments by KLZ & SNO+ collaborations

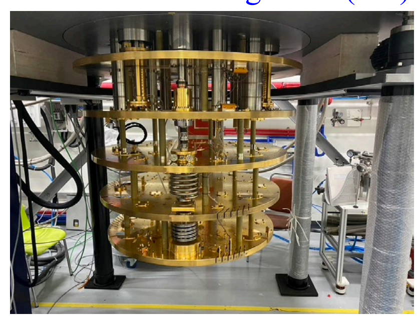
AMoRE-II experiment

- 100 kg of ^{100}Mo @ Yemilab for 5 years.
- $Li_2{}^{100}MoO_4$ crystals in 5 and 6 cm cylinder. (~ 400 crystals).
- Both phonons and photons are measured by MMC+SQUID sensors.
- DR inside shielding of 25cm Pb + 70cm of PE and water.
- Muon veto detectors installed.
- 90 crystal run begins in 2023 and full scale (100 kg of ^{100}Mo) run will begin early of 2025.



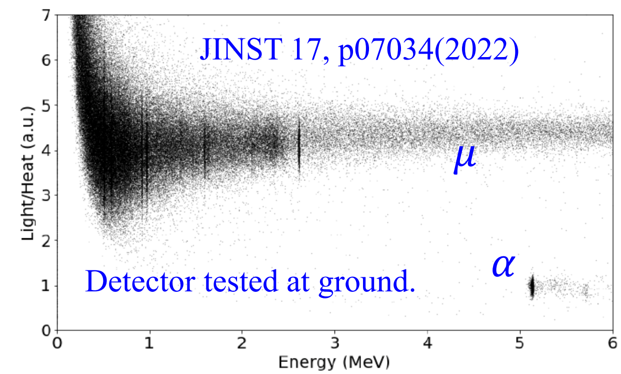


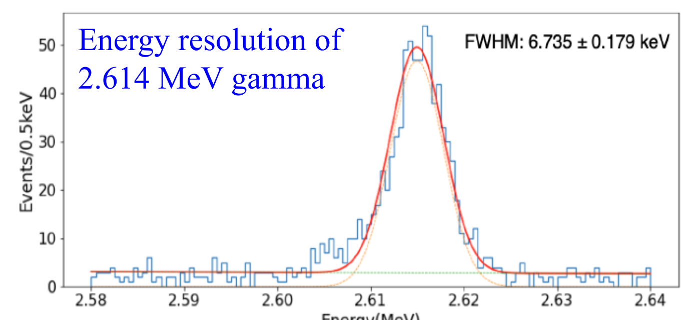
Dilution Refrigerator (DR)



Installed muon detectors

Recent progress in detector R&D

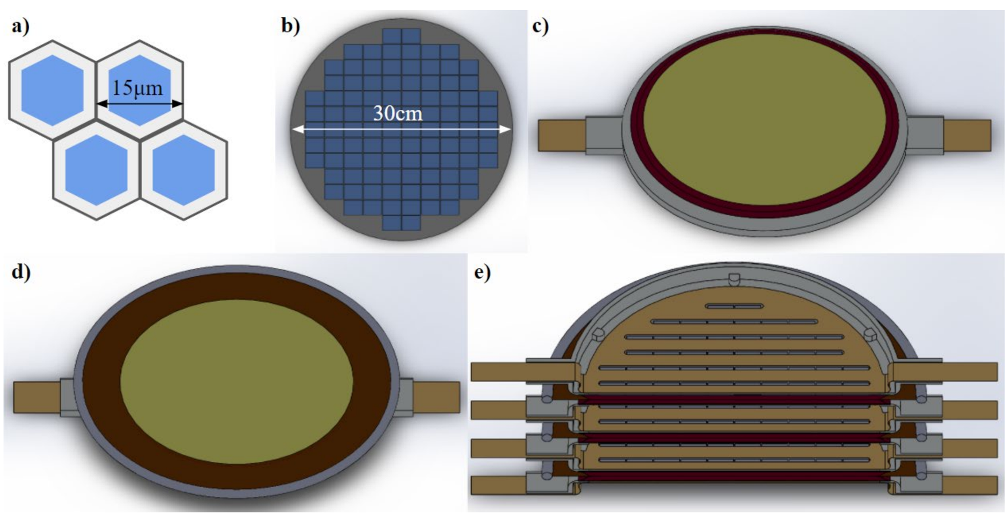


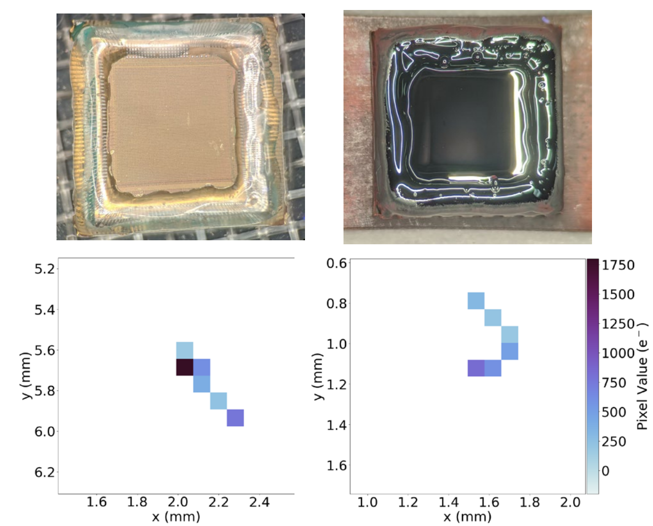


Selena

Snowmass White Paper: [arXiv:2203.08779]

- 10-ton ^{82}Se active target with exquisite spatial resolution for signal identification.
- Large-area hybrid CMOS imagers with ~5-mm thick layers of amorphous ^{82}Se.
- Leverages existing industrial capabilities for CMOS fabrication and aSe deposition for scalability.
- Neutrinoless $\beta\beta$ decay sensitivity of $\boldsymbol{m_{\beta\beta}}$ **= 4 to 8 meV** (3σ) in 100-ton year.
- Currently in R&D stage with small pixelated devices.





Demonstration of ~MeV electron tracks!

A. Chavarria

Selena $\beta\beta$

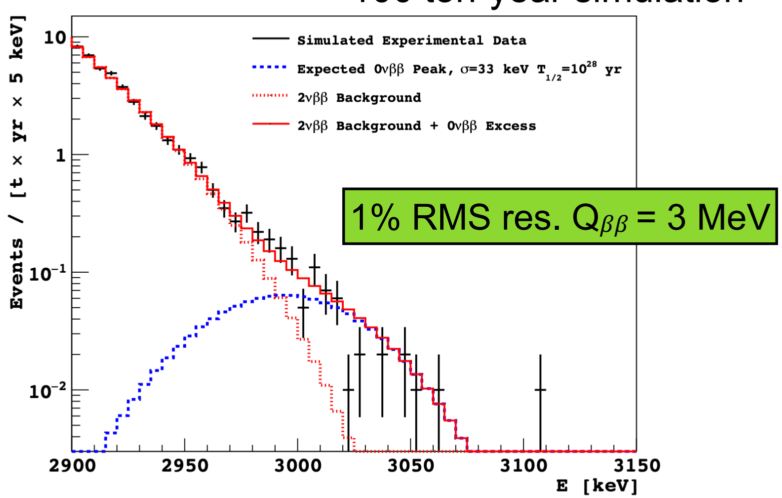
- By identification of Bragg peaks, can achieve 10^{-3} suppression of single-electron background, with 50% signal acceptance.
- Bulk backgrounds suppressed by α/β particle ID, spatial correlations.

Background rate <6 x 10^{-5} /keV/ton/year!

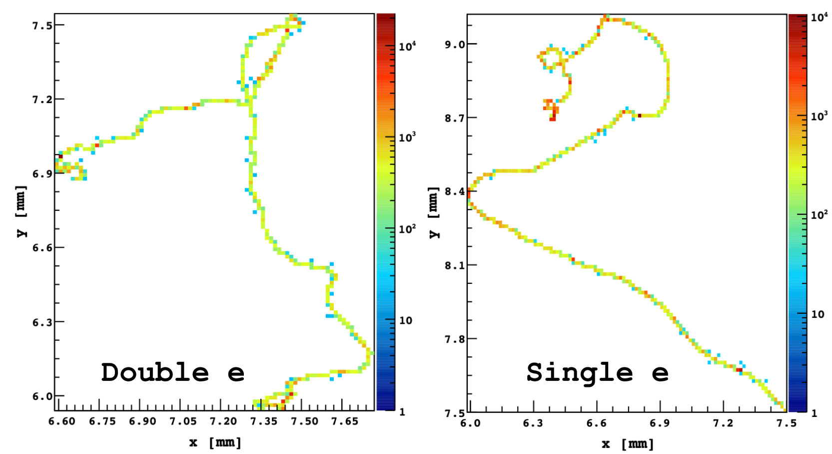
3σ discovery for $T_{1/2}$ = **2 x 10^{28} y** in ^{82}Se

Or study $0\nu\beta\beta$ mechanism after ton-scale discovery!

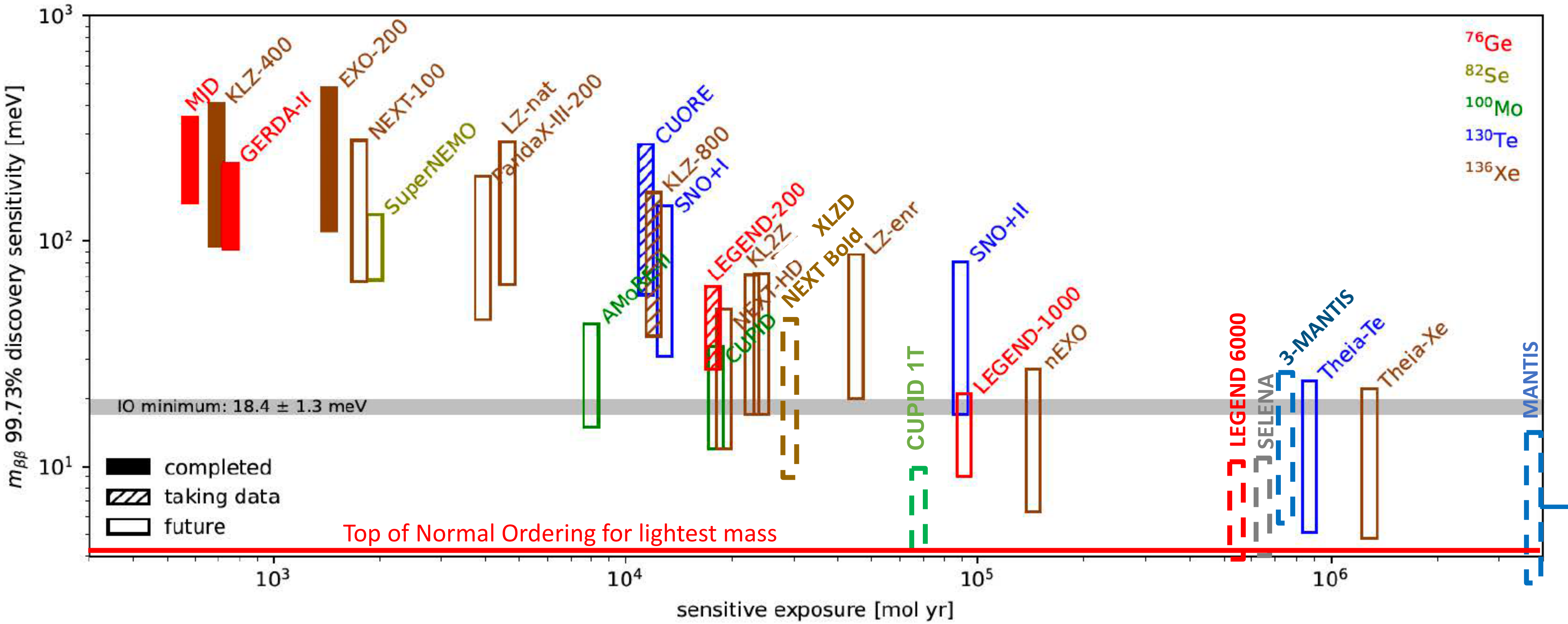
100 ton-year simulation



Simulation:



Summary plot from NSAC LRP White Paper (Augmented) (Values provided by experiments)



From: Fundamental Symmetries, Neutrons, and Neutrinos (FSNN): Whitepaper for the 2023 Nuclear Science Advisory Committee Long Range Plan: arXiv:2304.03451iv:2304.03451

SUMMARY

- Lots of potential for extensions beyond "Tonne Scale" experiments
- R&D focussed on
  - Background reduction
  - Efficiency for detection of light, charge, including light transmission
  - Loading of isotopes
  - Cheaper, more extensive production of elements
  - Sources and cost for isotope separation.
  - Better understanding of Nuclear Matrix Elements and quenching
- Neutrinos must be Majorana to define mass, so detection sensitivity is the important quantity.
- Next Generation beyond Tonne Scale could get below Inverted Hierarchy