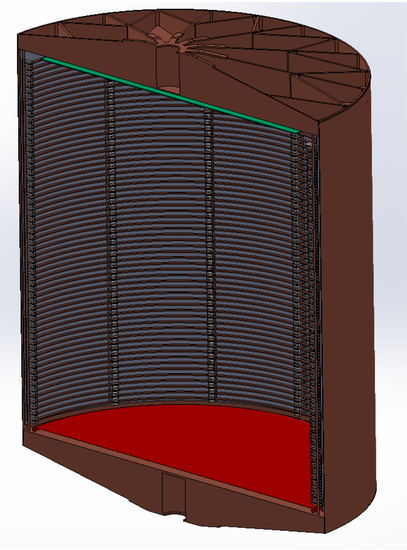
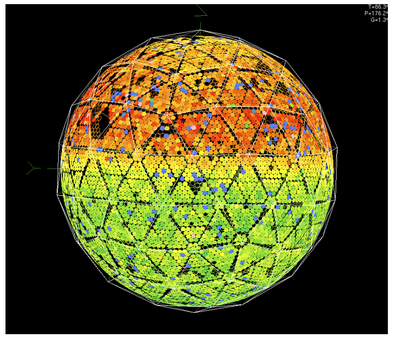
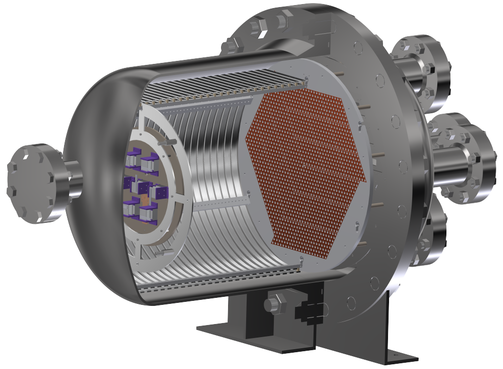
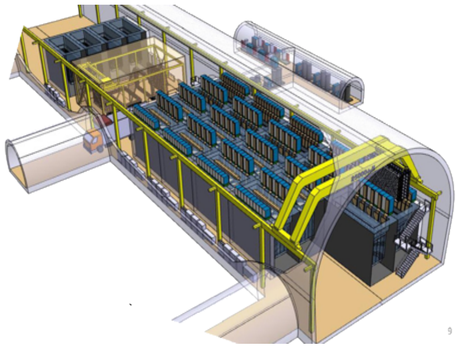
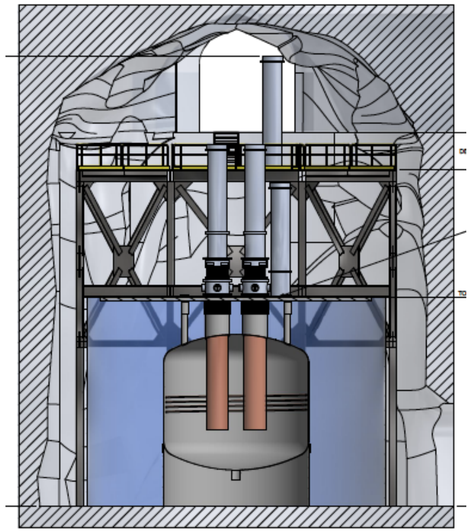
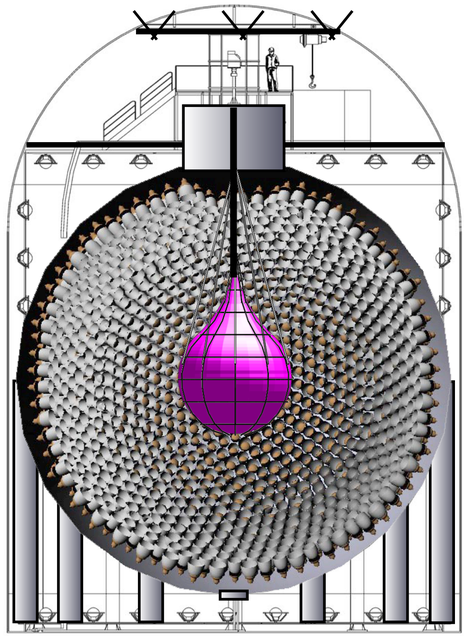
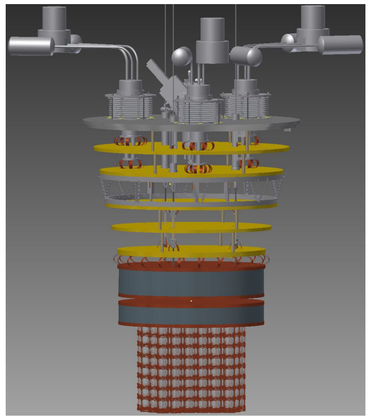
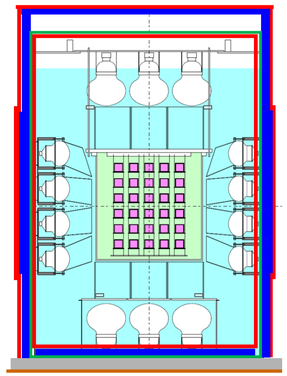
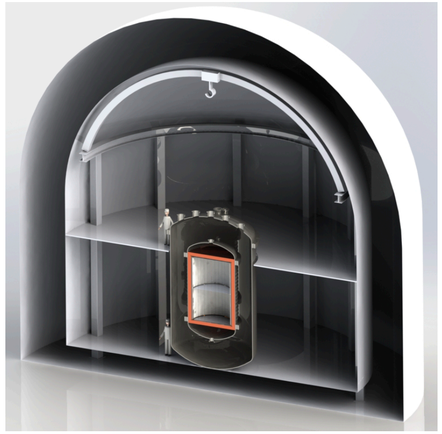
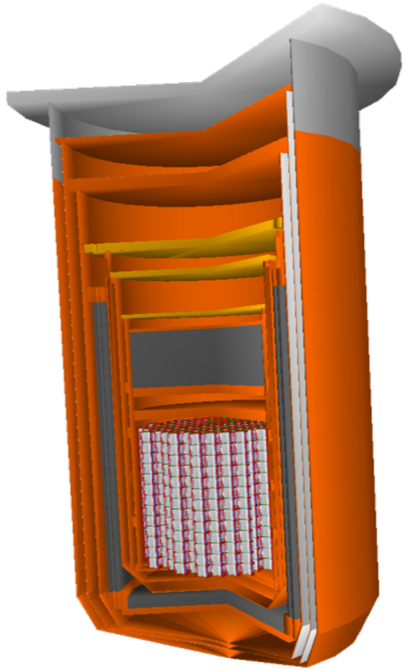






Future Neutrinoless Double-Beta Decay Experiments

Jason Detwiler, University of Washington

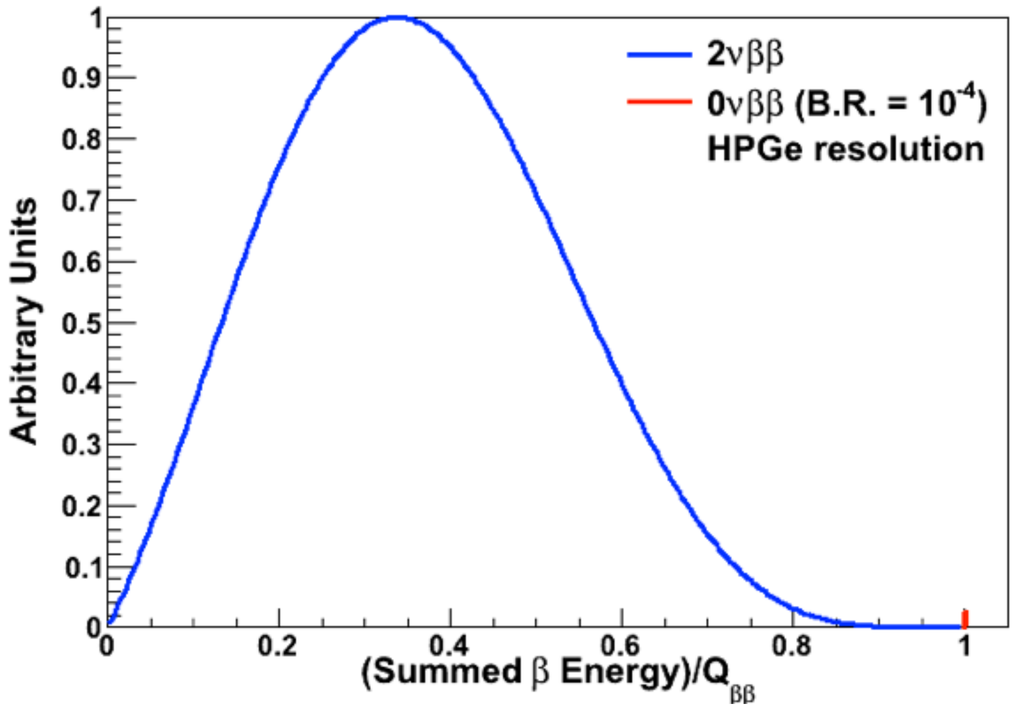
Neutrino 2020 - Virtual Meeting

1 July 2020

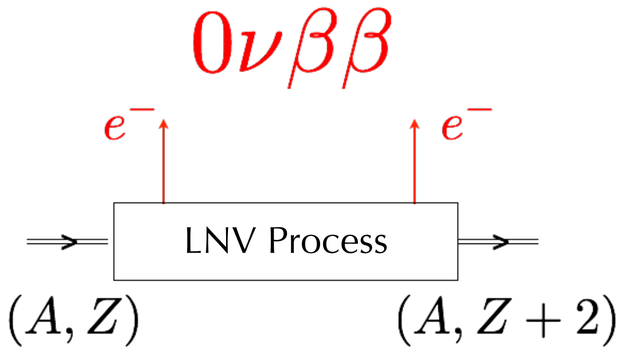






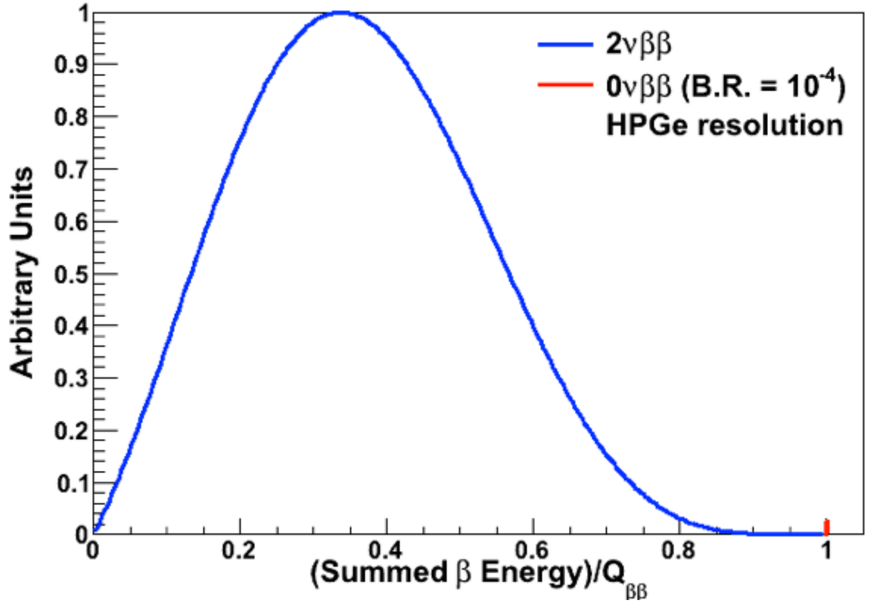
Outline

- Introduction
- Experiments
  - Bolometers
  - External Trackers
  - Scintillators
  - Semiconductors
  - TPCs
- Experimental summary



Neutrinoless Double-Beta Decay



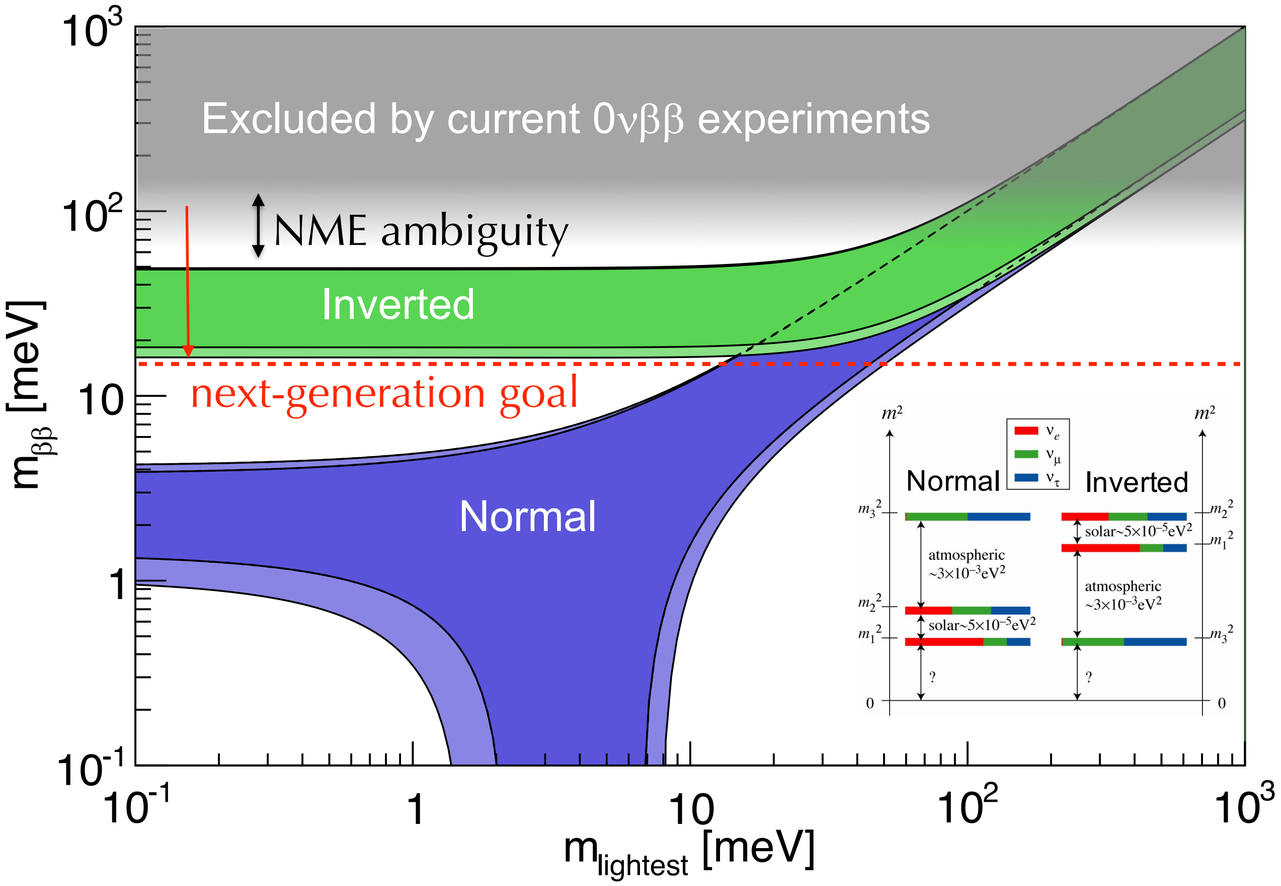


- Matter creation process! (irrespective of mechanism)
- *Must* measure summed electron kinetic energy to distinguish from Standard-Model 2ν process: ionization, scintillation, and/or heat
- Some experiments can also measure electron momenta (tracking), provides a handle on the LNV process
- Additional experimental handles (position, pulse shape / topology, daughter nucleus ID...) reject background
- The peak in the plot exceeds current limits by ~1 order of magnitude

Current Limits and Future Goals

- Present best limits:
  - ^{136}Xe (KamLAND-Zen): $T_{1/2} > 10^{26}$ yrs
  - ^{76}Ge (GERDA): $T_{1/2} > 10^{26}$ yrs
  - ^{130}Te (CUORE): $T_{1/2} > 3\text{x}10^{25}$ yrs
- Future goal:
  ~2 OoM improvement in $T_{1/2}$
  - Covers IO
  - Up to 50% of NO
  - Factor of ~few in Λ
  - An aggressive experimental goal

$$\frac{1}{T_{1/2}} = G_{01}\, g_A^4 \left(M^{0\nu} + \frac{g_\nu^{\mathrm{NN}}\, m_\pi^2}{g_A^2} M^{0\nu}_{\mathrm{cont}} \right)^2 \frac{m_{\beta\beta}^2}{m_e^2}$$



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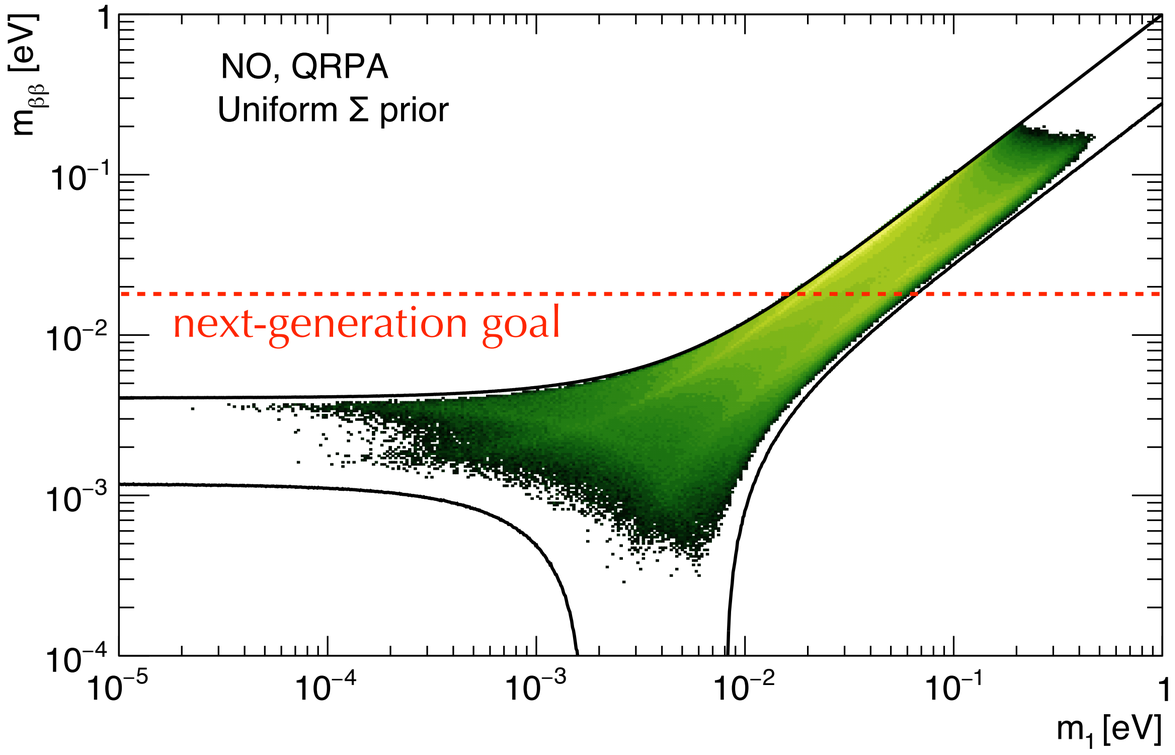

PRD **96**, 053001 (2017)

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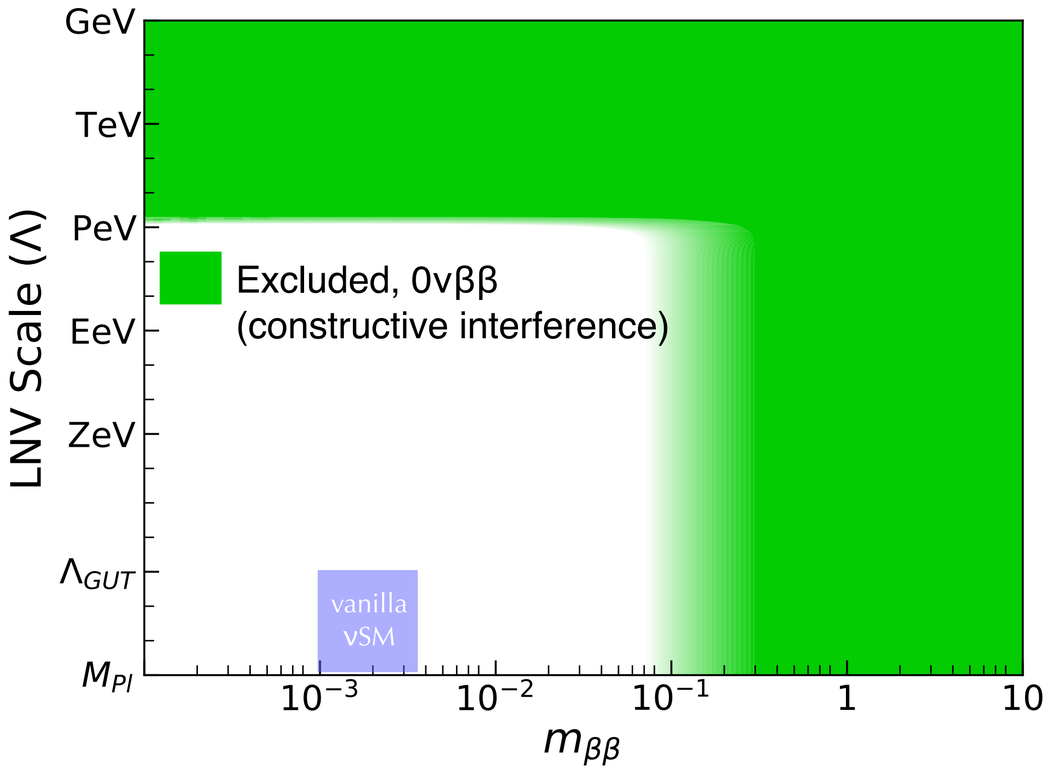

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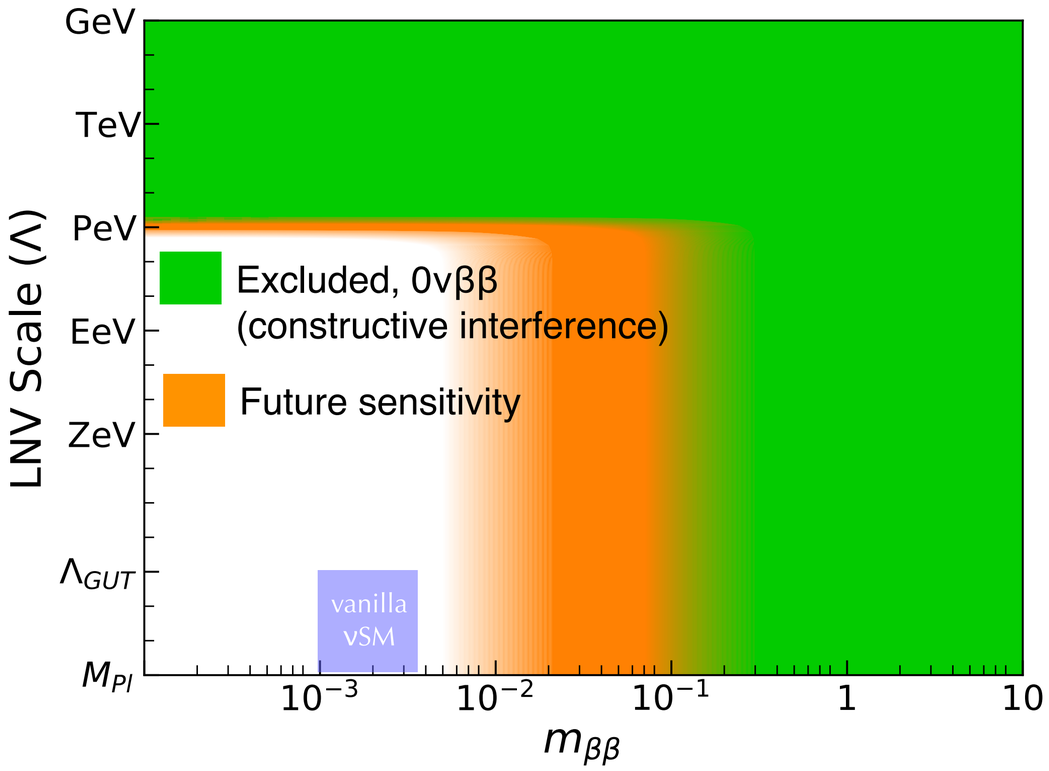


Experimental Focus: Discovery

- Energy is the only observable that is both necessary and sufficient for discovery of 0νββ decay: effectively a Poisson counting experiment

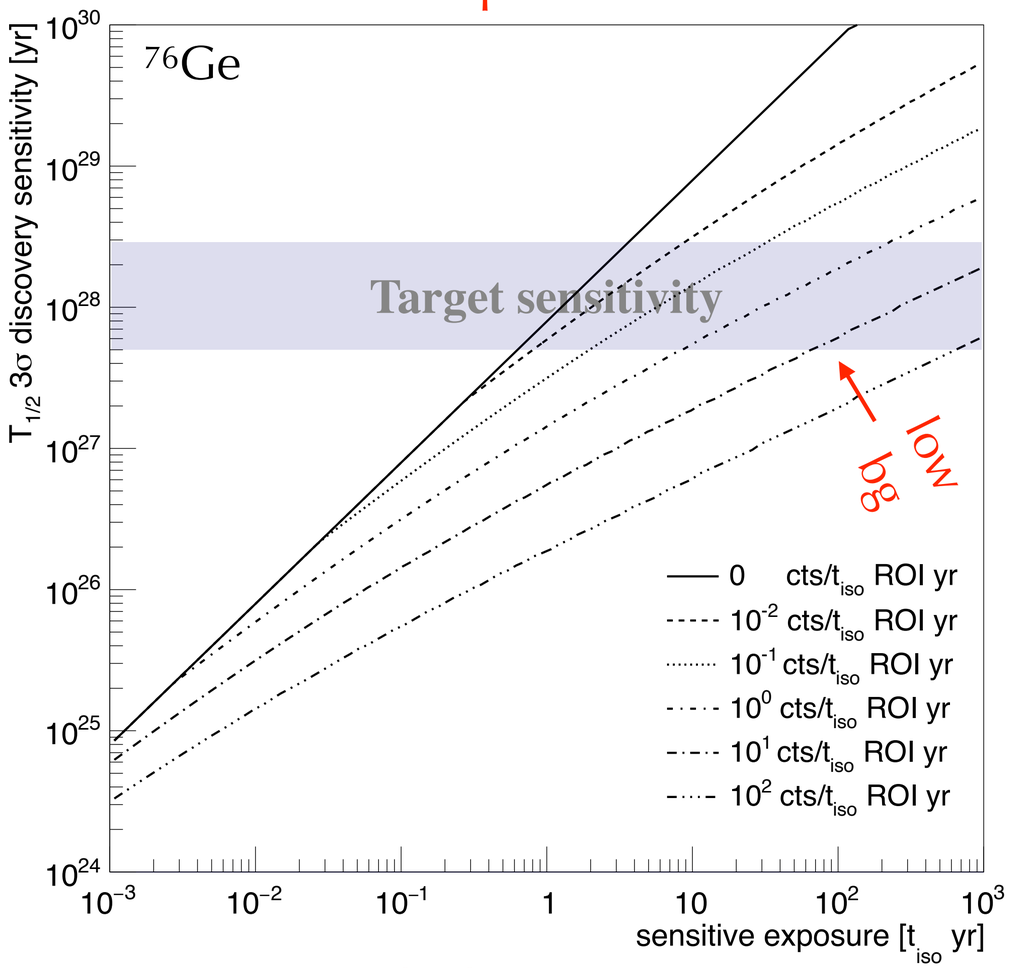
- Relevant parameters: sensitive exposure and sensitive background

$$\mathcal{E} = \epsilon\, m_{iso}^{FV}\, t \qquad \mathcal{B} = N_{bg}/\mathcal{E}$$

- Discovery sensitivity: the value of $T_{1/2}$ for which an experiment has a 50% chance to observe a signal above background with 3σ significance:

$$T_{1/2}^{3\sigma} = \ln 2 \frac{N_A \mathcal{E}}{m_a S_{3\sigma}(\mathcal{B}\mathcal{E})}$$

Requirements:



high exposure →

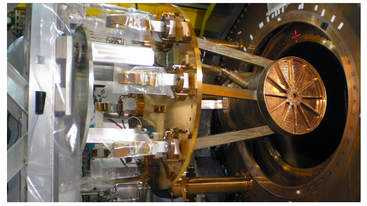
PRD **96**, 053001 (2017)

Experimental Techniques

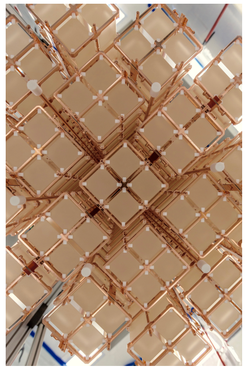
- Bolometers (CUPID, AMoRE, CANDLES IV)
  - Measure *E* (σ ~ 0.1-0.3%) from phonons; granularity gives position info
  - Instrumenting with photon detectors for background rejection
- External trackers (SuperNEMO)
  - Trackers + calorimeters, measure *E* (σ ~ 3-10%) + tracks / positions + PID
- Scintillators (KamLAND2-Zen, SNO+, Theia, ZICOS)
  - Measure *E* (σ ~ 3-10%) + position from scintillation light; some PID
- Semiconductors (LEGEND, SELENA)
  - Measure *E* (σ ~ 0.05-0.3%) from ionization; some tracking / position sensitivity
- TPCs (nEXO, NEXT, PandaX, AXEL, NvDEx, DARWIN, LZ)
  - Collect scintillation + ionization: measure *E* (σ ~0.4-3%) + tracks / position + PID

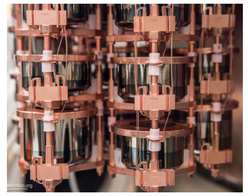

KamLAND-Zen

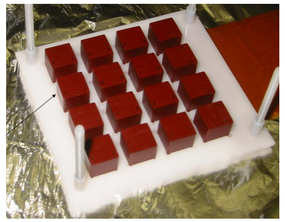

CANDLES

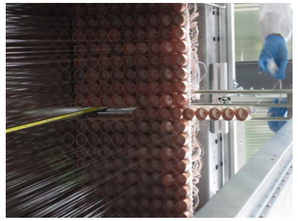

EXO-200


NEXT-100


CUORE


MAJORANA


COBRA


SuperNEMO


NEMO3

Experiments

Collaboration	Isotope	Technique	mass (0νββ isotope)	Status
CANDLES-III	^{48}Ca	305 kg CaF_2 crystals in liquid scintillator	0.3 kg	Operating
CANDLES-IV	^{48}Ca	CaF_2 scintillating bolometers	TBD	R&D
GERDA	^{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
SuperNEMO Demonstrator	^{82}Se	Foils with tracking	7 kg	Construction
SELENA	^{82}Se	Se CCDs	<1 kg	R&D
NvDEx	^{82}Se	SeF_6 high pressure gas TPC	50 kg	R&D
ZICOS	^{96}Zr	10% ^{nat}Zr in liquid scintillator	45 kg	R&D
AMoRE-I	^{100}Mo	$^{40}CaMoO_4$ scintillating bolometers	6 kg	Construction
AMoRE-II	^{100}Mo	Li_2MoO_4 scintillating bolometers	100 kg	Construction
CUPID	^{100}Mo	Li_2MoO_4 scintillating bolometers	250 kg	R&D
COBRA	$^{116}Cd/^{130}Te$	CdZnTe detectors	10 kg	Operating
CUORE	^{130}Te	TeO_2 Bolometer	206 kg	Operating
SNO+	^{130}Te	0.5% ^{nat}Te in liquid scintillator	1300 kg	Construction
SNO+ Phase II	^{130}Te	2.5% ^{nat}Te in liquid scintillator	8 tonnes	R&D
Theia-Te	^{130}Te	5% ^{nat}Te in liquid scintillator	31 tonnes	R&D
KamLAND-Zen 400	^{136}Xe	2.7% in liquid scintillator	370 kg	Complete
KamLAND-Zen 800	^{136}Xe	2.7% in liquid scintillator	750 kg	Operating
KamLAND2-Zen	^{136}Xe	2.7% in liquid scintillator	~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
AXEL	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DARWIN	^{136}Xe	^{nat}Xe liquid TPC	3.5 tonnes	R&D
LZ	^{136}Xe	^{nat}Xe liquid TPC		R&D
Theia-Xe	^{136}Xe	3% in liquid scintillator	50 tonnes	R&D

R&D | Construction | Operating | Complete

J. Detwiler

Updated from J. Wilkerson

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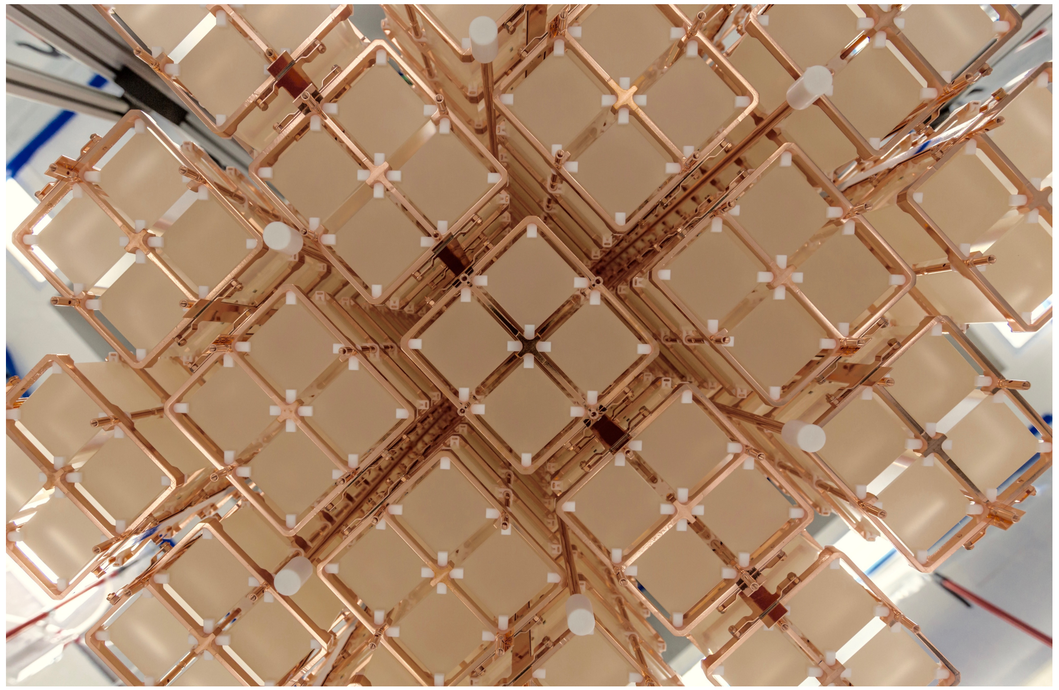
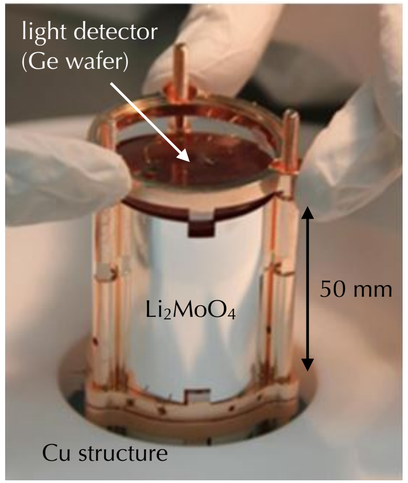


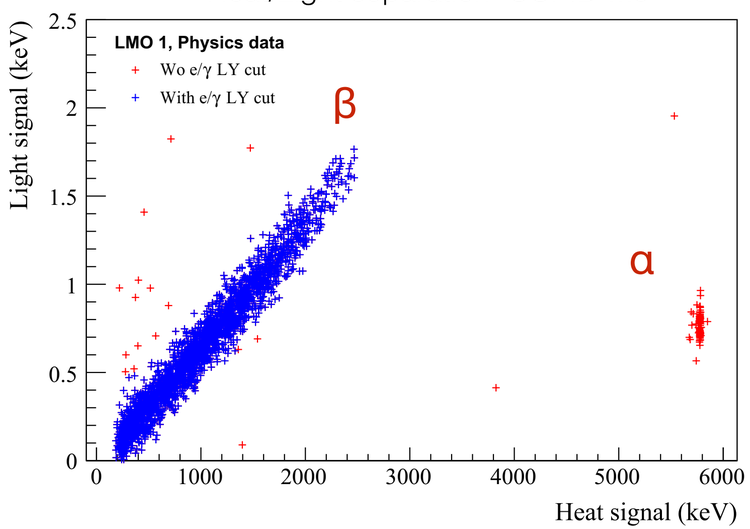
CUORE

Bolometers: CUPID

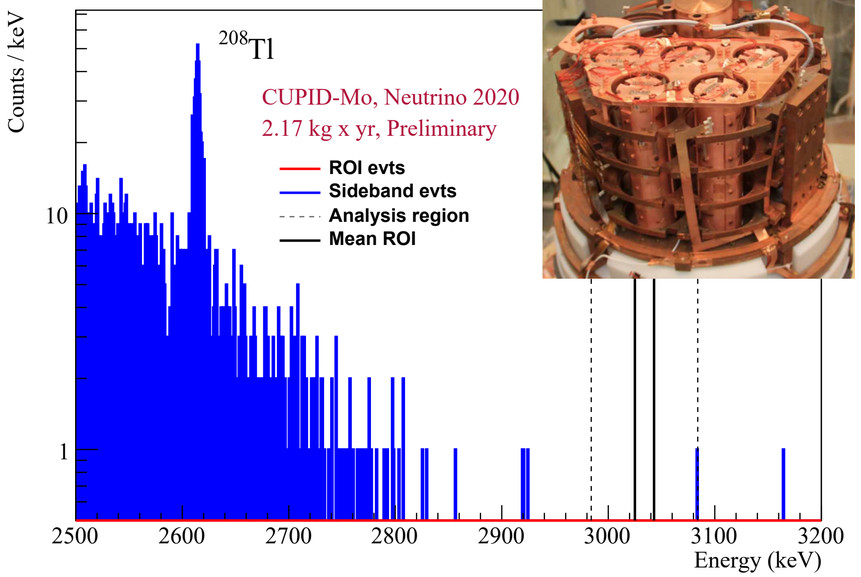
- 250 kg of ^{100}Mo in 1500 Li_2MoO_4 crystals (>95% enrichment) in CUORE cryostat
  - Good *E* resolution from phonons: ~5 keV FWHM at $Q_{\beta\beta}$
  - Scintillation readout rejects background
- Particle ID technique robustly demonstrated by CUPID-0 and CUPID-Mo
  - >99.9% α rejection, >99.9% β/γ acceptance
  - No further R&D needed
- Background goal: 0.5 c/(FWHM t y) dominated by 2νββ pile-up and U/Th γ summing
- Discovery sensitivity (10 years): $T_{1/2} > 1.1 \times 10^{27}$ yr
- PreCDR online, planning for TDR in 2021, followed by 5 years construction at LNGS. 1 ton experiment under consideration
- See posters 111, 374, 382, 404, 418, 419, 448, 525

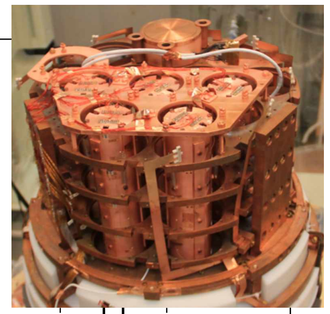


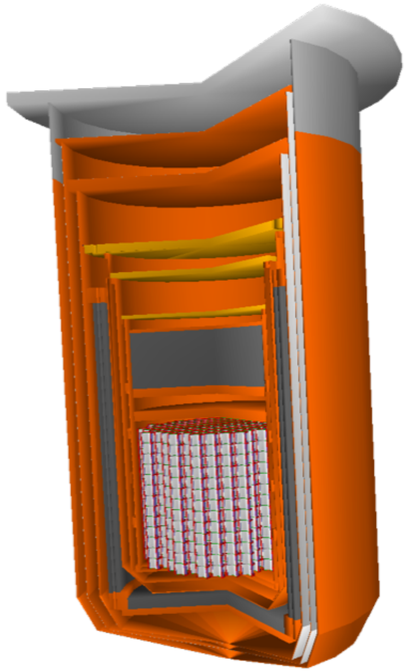
Heat/Light separation -CUPID-Mo



CUPID-Mo



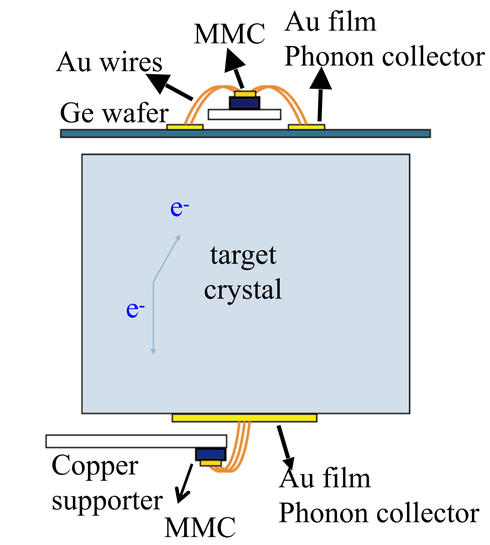




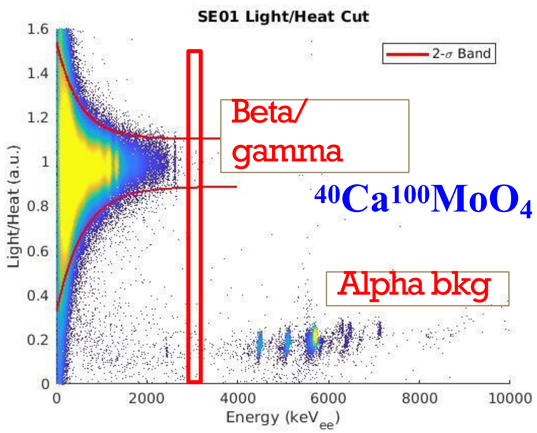
Eur. Phys. J. C 78, 734 (2018), arXiv:1907.09376, and A. Giuliani

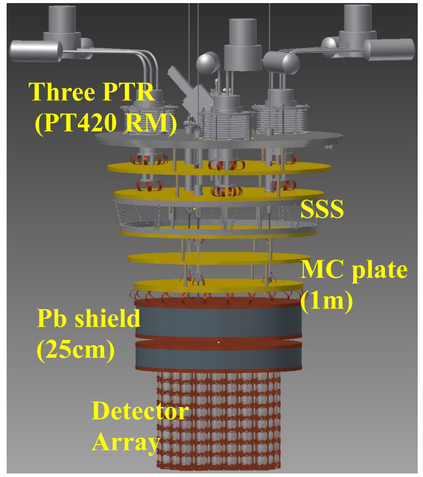
Bolometers: AMoRE

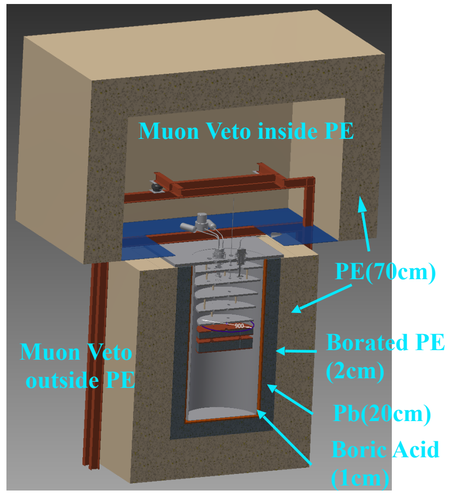
- 100 kg of ^{100}Mo in >95% enriched $Li_2^{enr}MoO_4$ crystals
  - Good *E* resolution from phonons
  - Scintillation readout rejects background
- Scaling up from AMoRE-pilot
  - Demonstrated MMC + SQUID readout
  - Switching from $^{40}Ca^{100}MoO4$ crystals
- Background goal: <0.05 c/(keV t y) dominated by 2νββ pile-up
- Limit sensitivity (5 years): $T_{1/2} > 8 \times 10^{26}$ yr
- AMoRE-I with 13 $CaMoO_4$ + 5 Li_2MoO_4 (6 kg) starts Aug 2020 at Y2L. BG goal: <1.5 c/(keV t y). Full-scale AMoRE-II starts 2022 in YemiLab
- See poster 571



(Metallic Magnetic Calorimeter)



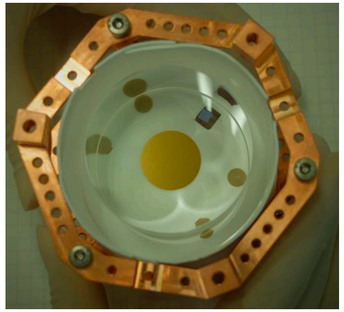




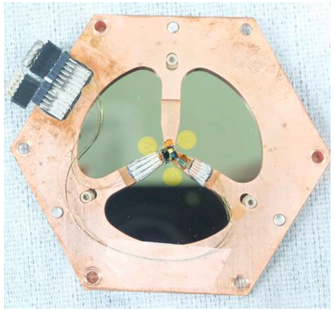
AMoRE-I

Bolometers: CANDLES

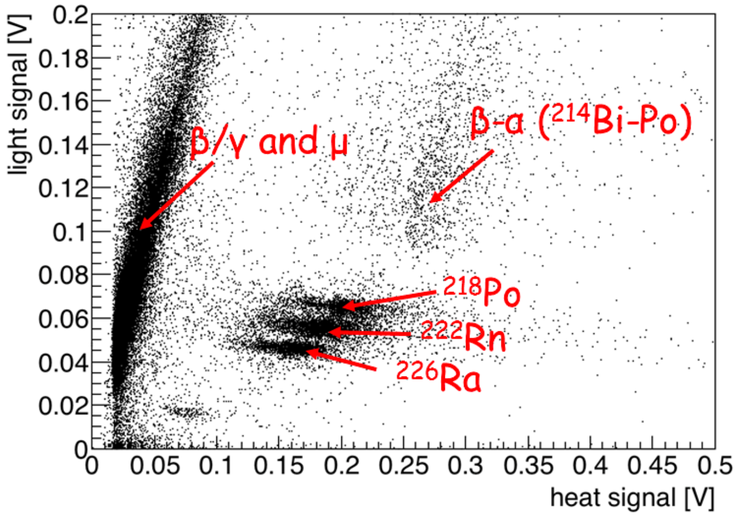
- CaF_2 scintillating crystals
  - Take advantage of ^{48}Ca's high $Q_{\beta\beta}$, "easy" NME
    - But: very low natural abundance (0.19%)
  - CANDLES-III: immerse in RT liquid scintillator (TAUP 2019: $T_{1/2} > 6\times10^{22}$ y)
  - Next system: operate as scintillating bolometers with MMC phonon readout and Ge wafer for photons
- Crystal performance measurements
  - Good α discrimination
  - E resolution $\sigma = 2\%$ at $Q_{\beta\beta}$ (position uniformity)
  - Purity improved x~10
- ^{48}Ca enrichment: laser isotope separation
  - Proof-of-priniciple complete
  - Scaling up for mass-production
- See poster 446

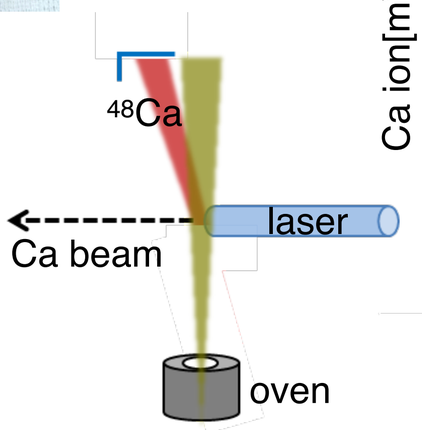


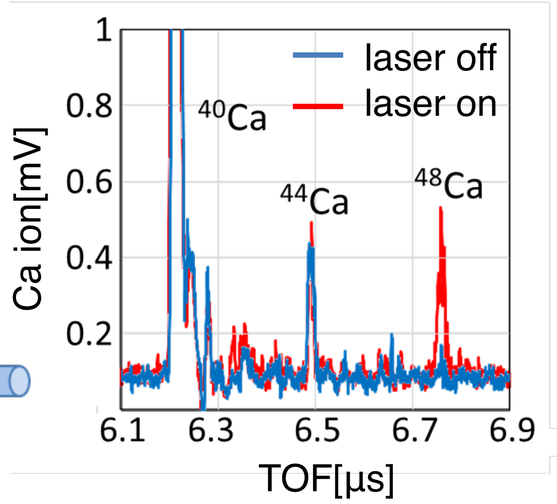
CaF_2 crystal



Ge wafer



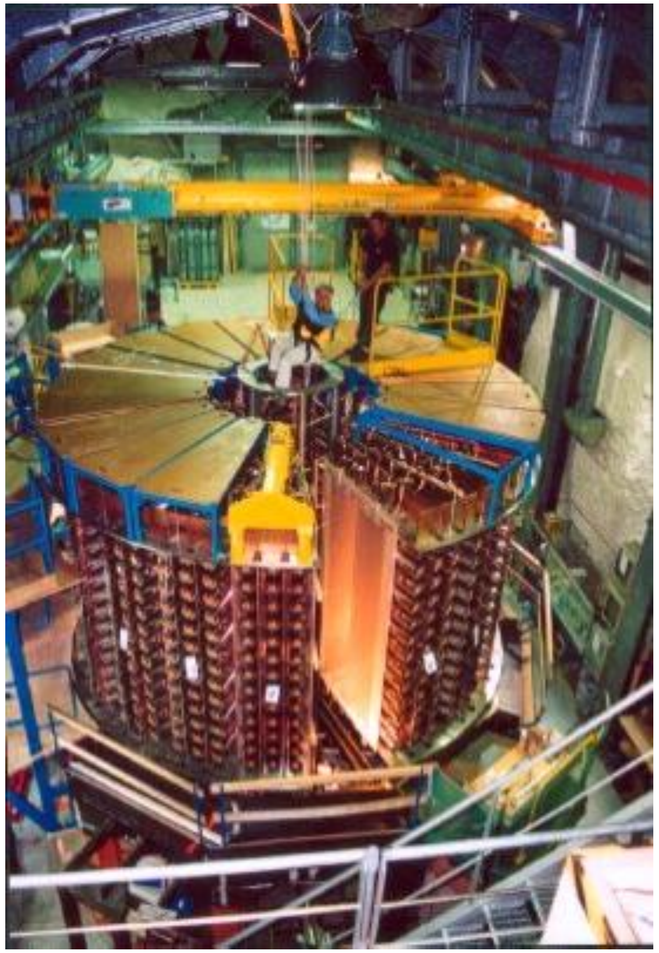




From T. Kishimoto

Outline

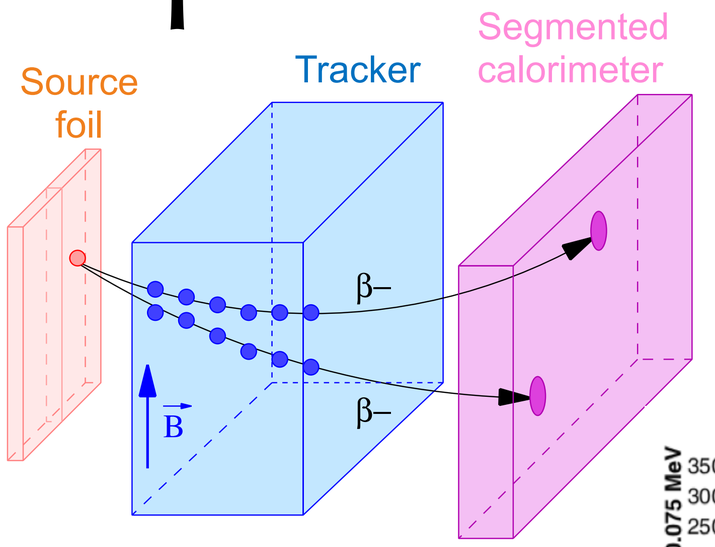
- Introduction
- Experiments
  - Bolometers
  - External Trackers
  - Scintillators
  - Semiconductors
  - TPCs
- Experimental summary

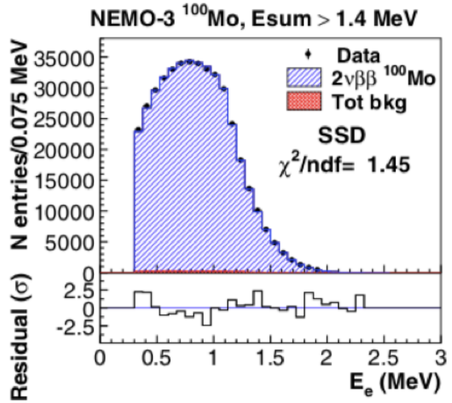


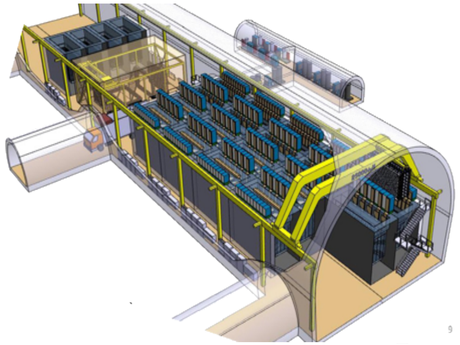
NEMO3

External Trackers: SuperNEMO

- Foils of isotope viewed by tracker, calorimeter
  - Foils can be made of any ββ isotope (SuperNEMO now ^{82}Se)
  - Full PID(*e*-, *e*+, *γ* and *α*), ββ kinematics, and topology: E_{single}, E_{sum}, *x*, *y*, *z*, *t*, cosθ: can be used to probe exchange mechanism
- Builds off of NEMO success: most precise 2νββ measurement for several isotopes
- SuperNEMO Demonstrator with 6.3 kg ^{82}Se under commissioning at LSM
- Scaling up to 500 kg would provide half-life sensitivity beyond 10^{26} years
- See posters 310, 457







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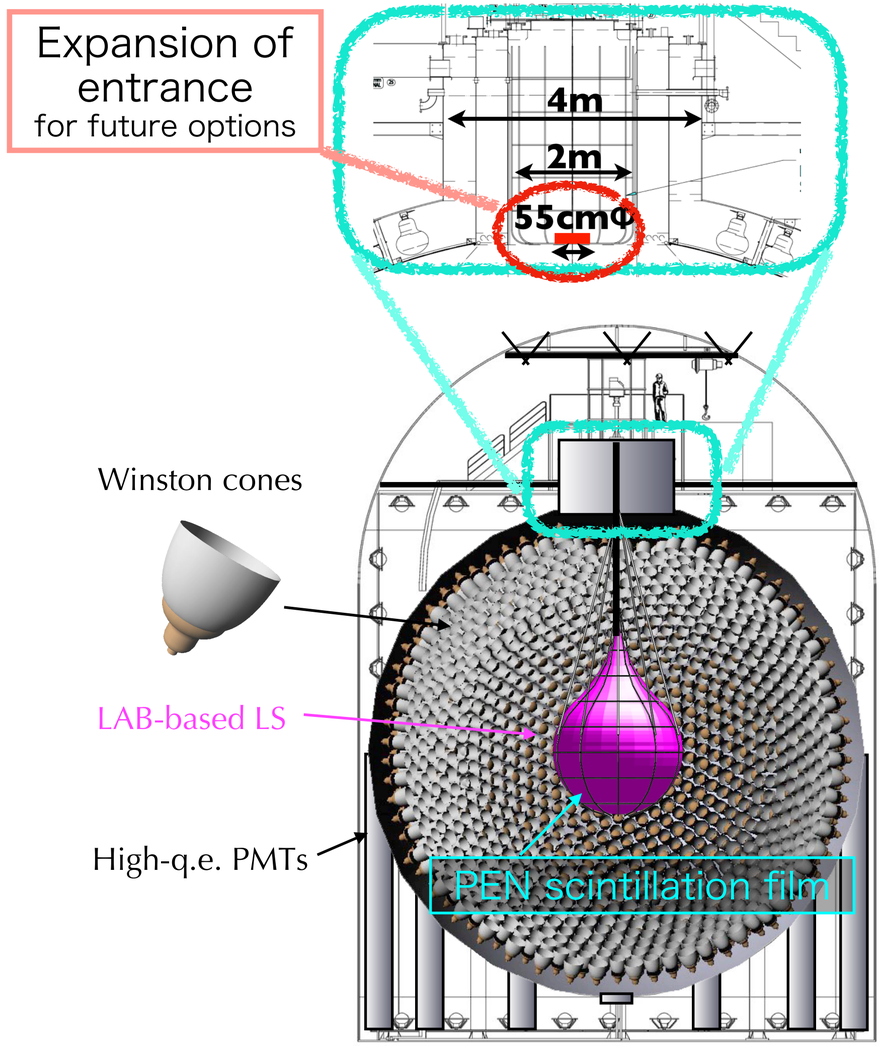
KamLAND

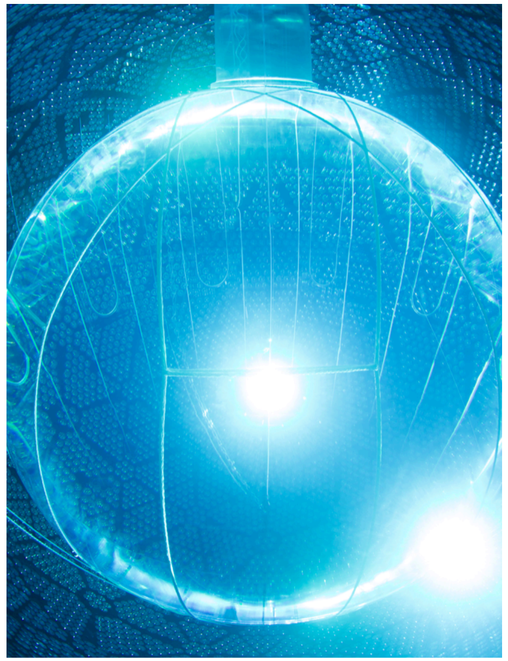
Scintillators: KamLAND2-Zen

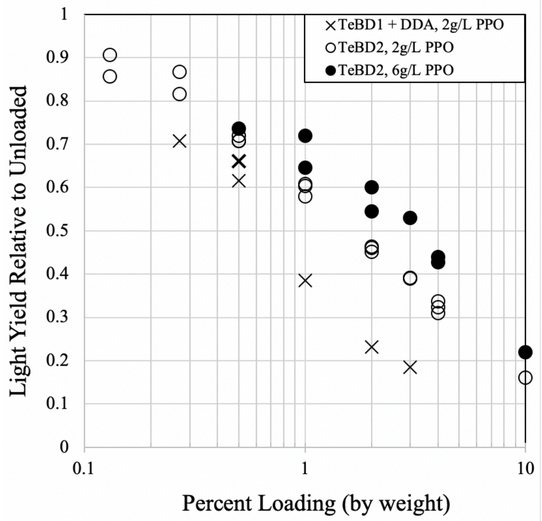
- 1000+ kg 90% enriched ^{136}Xe loaded in liquid scintillator (2.7% wt)
  - High exposure, good self-shielding
  - Energy and position reconstructed from number and timing of photons
- Upgrade of successful KamLAND-Zen detector
  - x2 improved resolution: Winston cones, high-q.e. PMTs, LAB LS
  - PEN balloon for active veto of balloon backgrounds
  - Improved electronics, background tagging, PID, possibly pressurized LS
- Background ~2 c/(FWHM t y)
  dominated by $2\nu\beta\beta$ tail and ^{8}B solar ν scattering
- Limit sensitivity (5 years): $T_{1/2} > 2 \times 10^{27}$ yr
- Upgrade preparations underway, will proceed following 5-year run of KamLAND-Zen 800
- See posters 82, 106, 222, 230, 411, 499



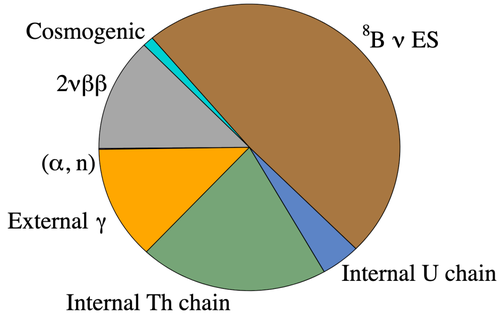
Scintillators: SNO+ Phase II

- 4 t → 6.5 t ^{130}Te via increased loading in LAB
  - Up to several percent with improved light yield
  - Can use existing SNO+ Phase I Te loading systems
- Inexpensive, no detector upgrade required
- Background ~10 c/(FWHM t y) dominated by ^{8}B solar ν scattering
- Limit sensitivity (10 years): $T_{1/2} > 10^{27}$ yr
- Plan to increase loading after only 2.5 years of running in Phase I (1.3 t ^{130}Te)
- See posters 424, 425, 432, 533, 544

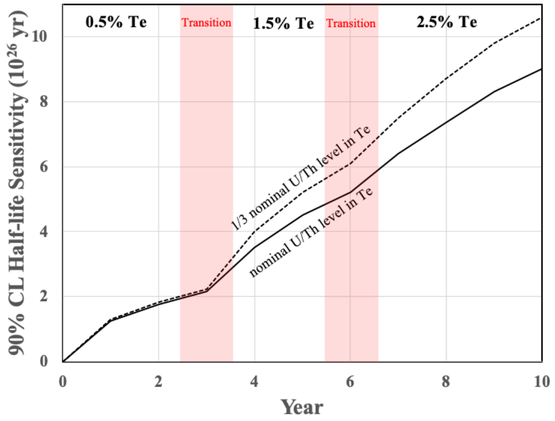




ROI Backgrounds in FV



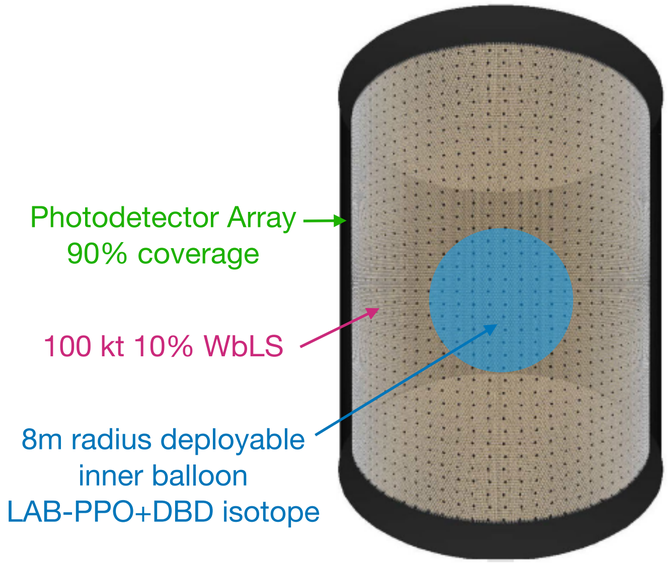
SNO+ Phased Loading Plan



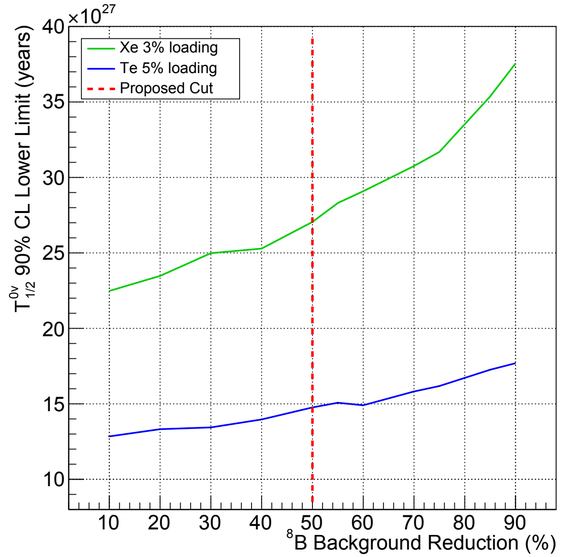
From S. Biller

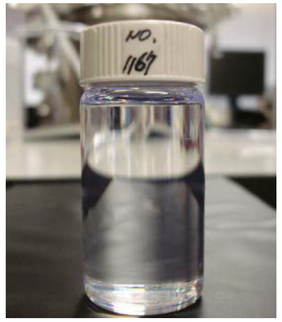
Scintillators: Theia and ZICOS

- Theia-Te/Xe: balloon of isotope-loaded LAB in 100 kt WbLS detector
  - 5% ^{nat}Te (31 tons) or 3% enrXe (50 tons) (other isotopes possible)
  - 3% / $\sqrt{E}$ resolution, Cherenkov separation
  - Dominant background: solar ν
    Limit sensitivity (10 years): $T_{1/2} > 10^{28}$ yr
  - R&D in progress. See posters 253, 312, 475, 543
- ZICOS: 10% $Zr(iPrac)_4$ loaded in Anisole
  - 865 kg ^{96}Zr (50% enriched)
  - 3% resolution at $Q_{\beta\beta}$, Cherenkov separation
  - Dominant background: 2νββ tail
    Limit sensitivity (10 years): $T_{1/2} > 10^{27}$ yr
  - R&D / design in progress, 2027 start at Kamioka. See poster 66



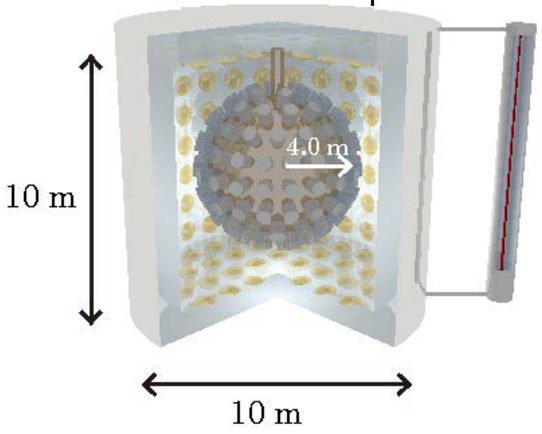
Theia100 detector concept





10% $Zr(iPrac)_4$

ZICOS concept



From Y. Fukuda and G. Orebi Gann

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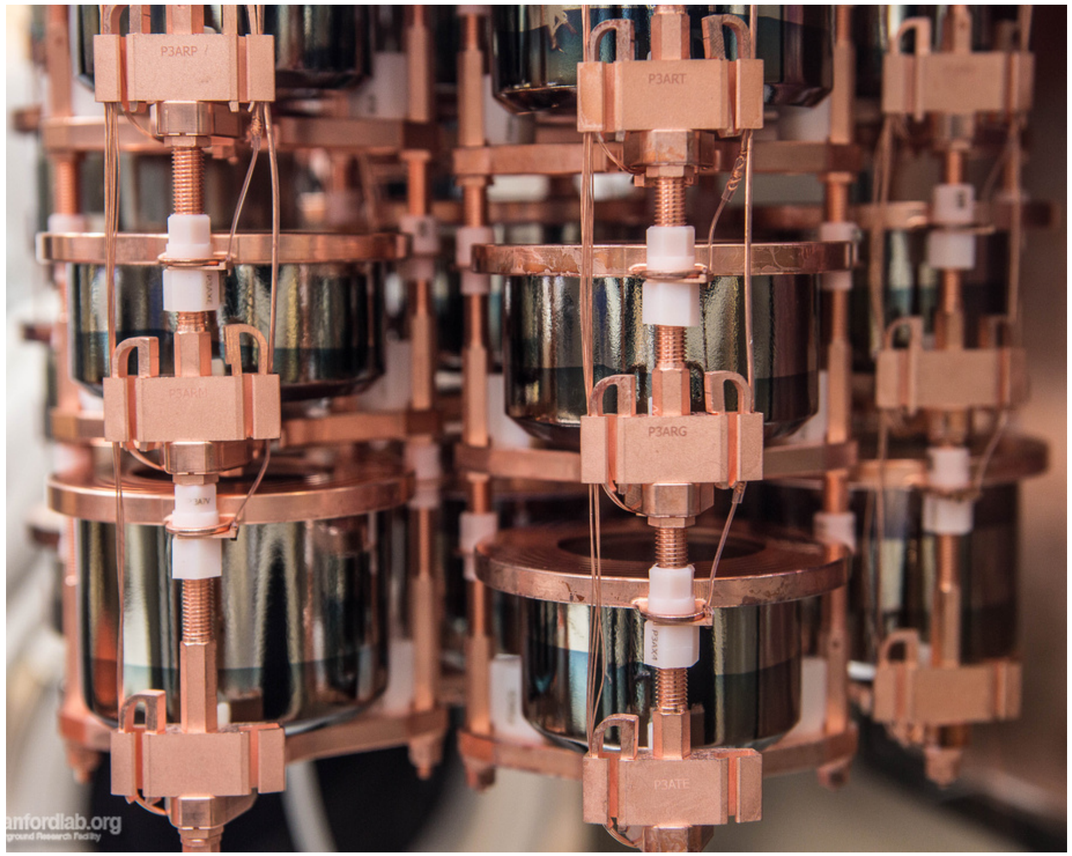
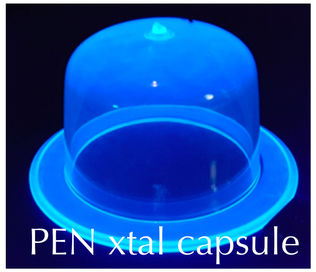
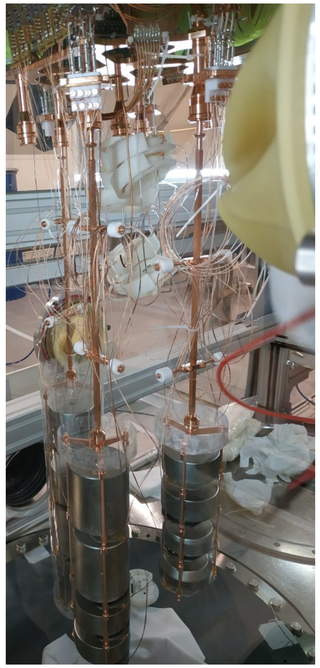


Majorana

Semiconductors: LEGEND

- 1 ton 90% enr. ^{76}Ge in HPGe "PPC" array with active LAr veto
  - ~2.5 keV *E* resolution at $Q_{\beta\beta}$
  - Excellent multi-site and surface alpha background rejection
- Combines MJD clean materials, low-noise electronics with GERDA's active LAr veto
- 4 x 250 kg arrays of ~3 kg xtals in depleted LAr instrumented with SiPM+WLS fibers, location TBD
- Background goal: <0.03 cts/(FWHM t yr)
  dominated by radioactivity, above-ground HPGe activation
- Discovery sensitivity (10 years): $T_{1/2} > 10^{28}$ yr
- LEGEND-200: first 200 kg in GERDA infrastructure under construction, data taking starts 2021
  - BG goal: <0.6 cts/(FWHM t yr)
  - Discovery Sensitivity: $T_{1/2} > 10^{27}$ yr
- PreCDR in preparation. Timeline coordinated with LEGEND 200, US downselect
- See posters 80, 113, 284, 311, 341, 365, 392, 483

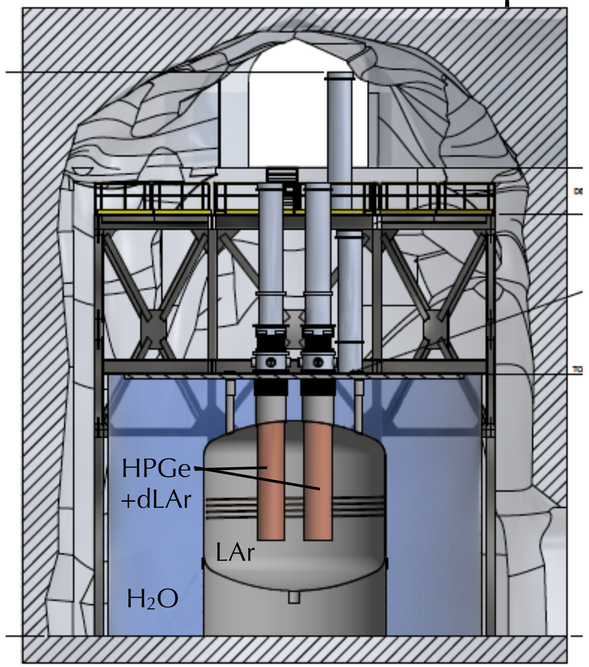




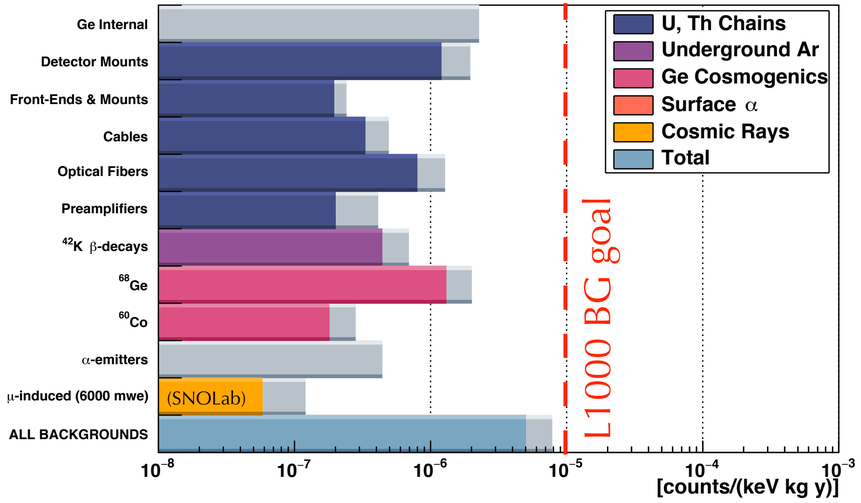
test deployment
Spring 2020

large detector
R&D

LEGEND-1000 Concept

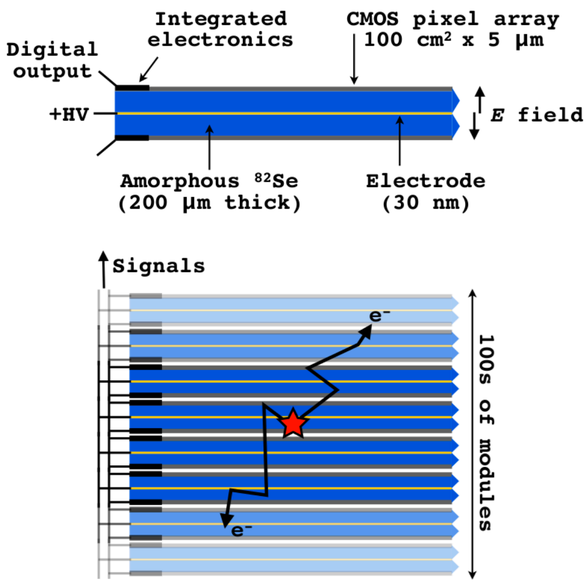


LEGEND-1000 Backgrounds

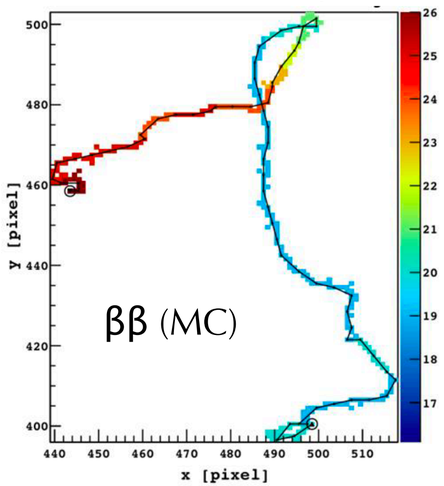


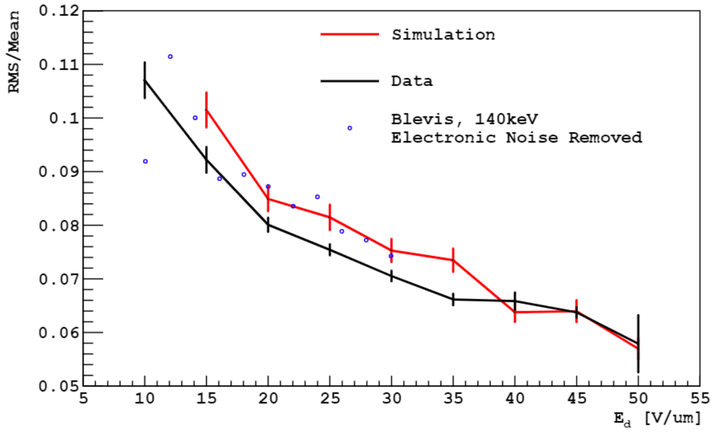
Semiconductors: SELENA

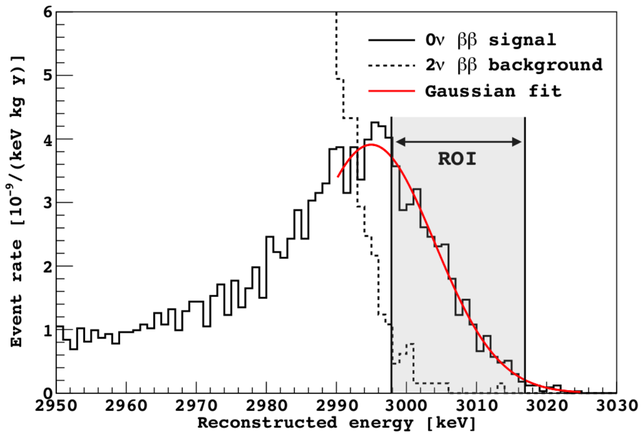
- Amorphous ^{82}Se x-ray detectors readout by CMOS pixel array
  - Stack to achieve high density, high mass array
  - 5 μm pixel size gives full track reconstruction
- Estimated background ~0.001 c/(FWHM t y) dominated by natural radioactivity
- Industrial production + low background indicates sensitivity to Normal Ordering mass scale
- Recently measured *E* response of single-pixel device
- Next step: multi-pixel prototype with Topmetal CMOS (see later slides)



MC: x1000 β rejection with 50% ββ acceptance







J. Inst. **12**, P03022 (2017) and A. Chavarria

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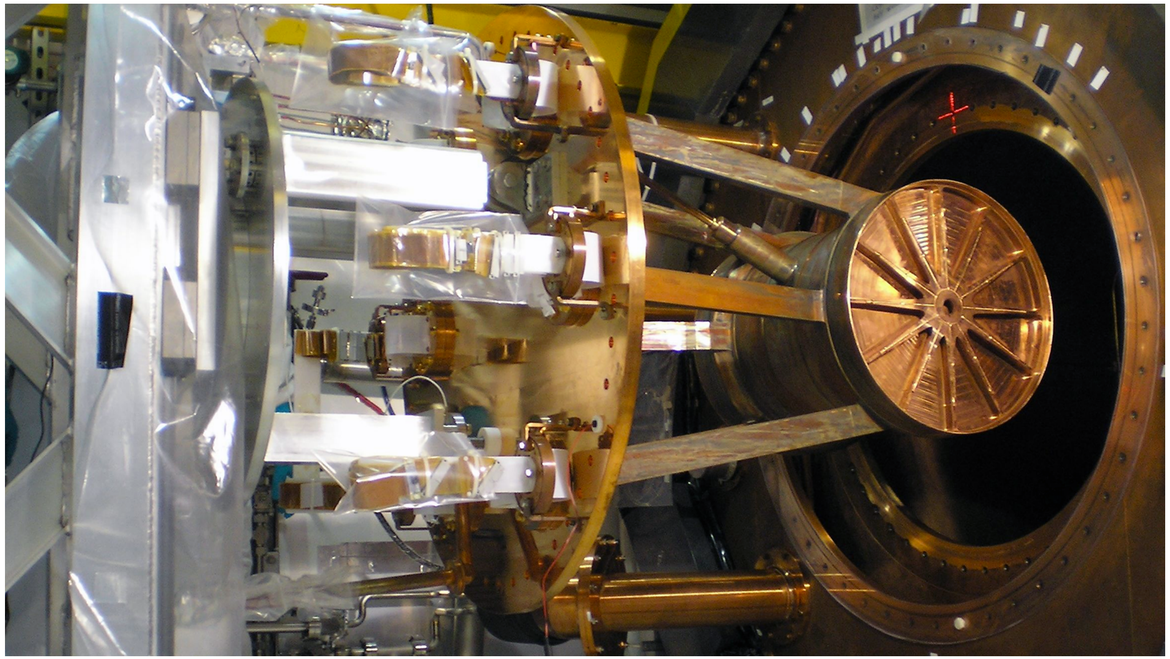
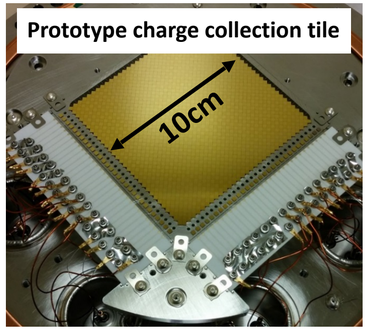
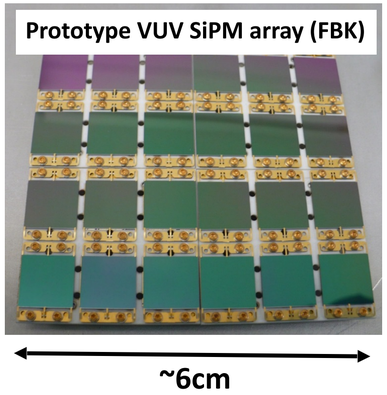


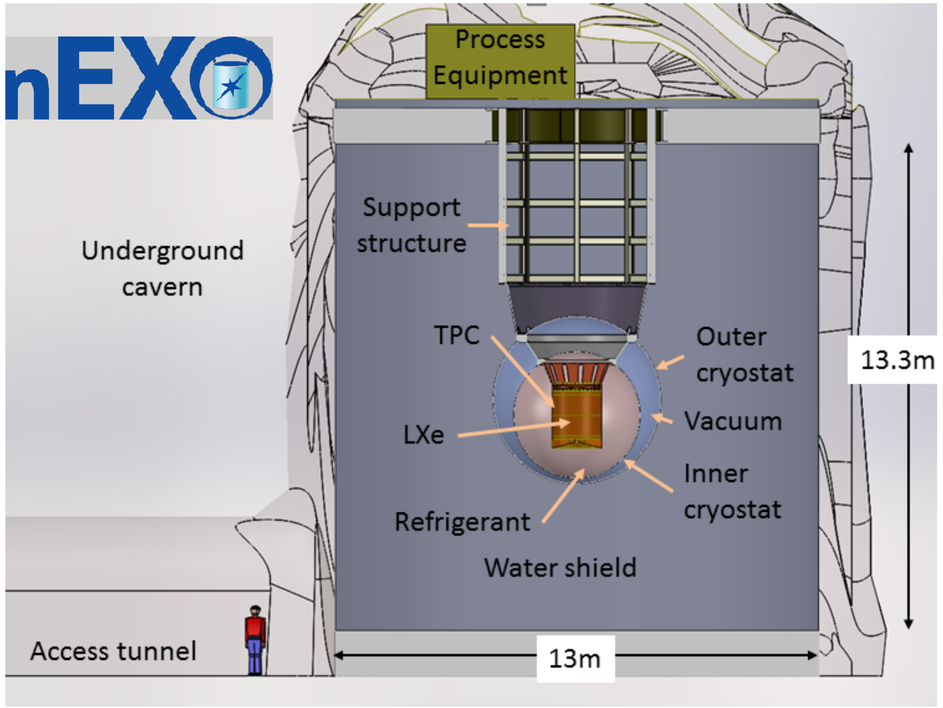
EXO-200

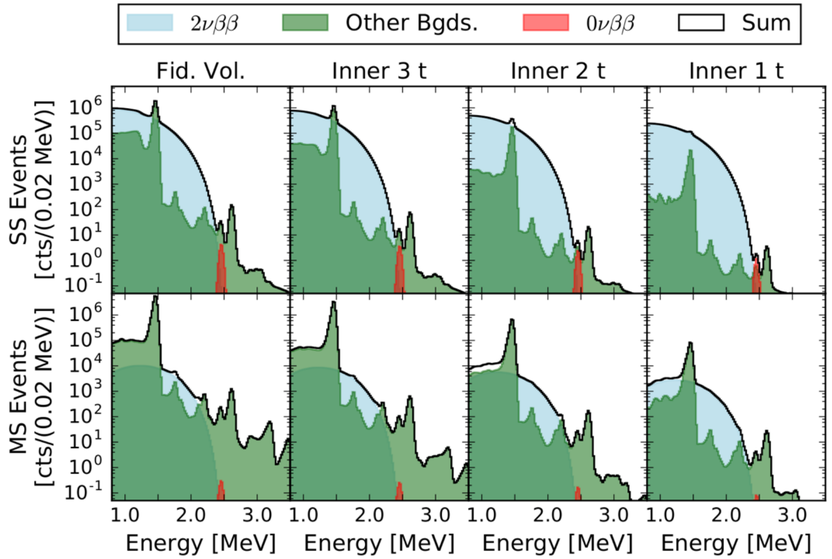
TPCs: nEXO

- 5 tons of 90% enr. ^{136}Xe in LXe TPC
  - Ionization and scintillation both contribute to *E* reconstruction
  - Also: tracking / topology / position reconstruction
- Upgrade of successful EXO-200 design
  - Improved light and charge collection
  - Self-shielding, only one drift volume
- Innermost region BG ~0.1 c/(FWHM t y) dominated by natural radioactivity
- Discovery sensitivity for 10 years livetime (update coming soon): $T_{1/2} > 5.7 \times 10^{27}$ yr
- Option to instrument with final state Ba tagging (next next slide)
- PreCDR online. Planning to deploy in SNOLab. Timeline coordinated with US downselect.
- See posters: 54, 60, 84, 226, 413, 415, 461, 548, 620





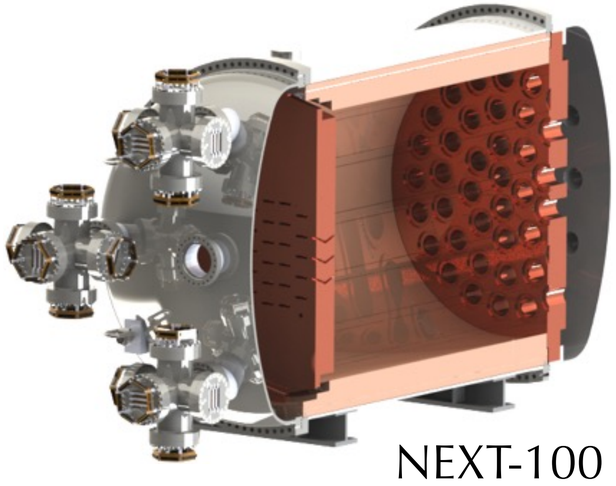




arXiv:1805.11142, PRC **97** 0655034 (2018), and G. Gratta

TPCs: NEXT-HD

- High-pressure gas EL TPC with 1 ton ^{136}Xe
  - *E* resolution 0.8% FWHM at $Q_{\beta\beta}$ demonstrated
  - Improved tracking over LXe TPC
- Extrapolation of NEXT-100 design
  - PMTs → SiPMs with reduced radioactivity
  - Lower diffusion gas mixture (Xe/He)
- Background ~0.1 c/(FWHM t y) dominated by natural radioactivity
- Limit sensitivity (10 years): $T_{1/2} > 3 \times 10^{27}$ yr
- Option to instrument with final state Ba tagging: NEXT-BOLD (see next slide)
- Will follow NEXT-100 (starts this year)
- See posters 107, 144



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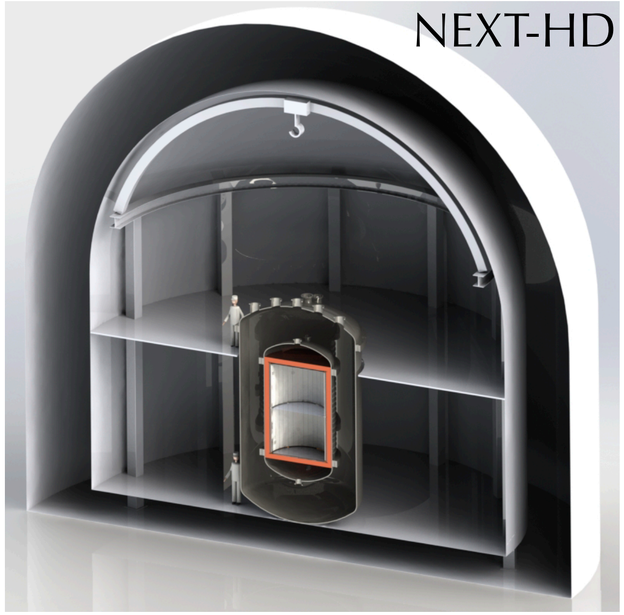
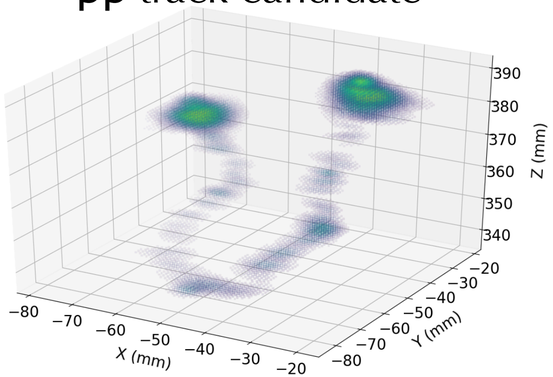
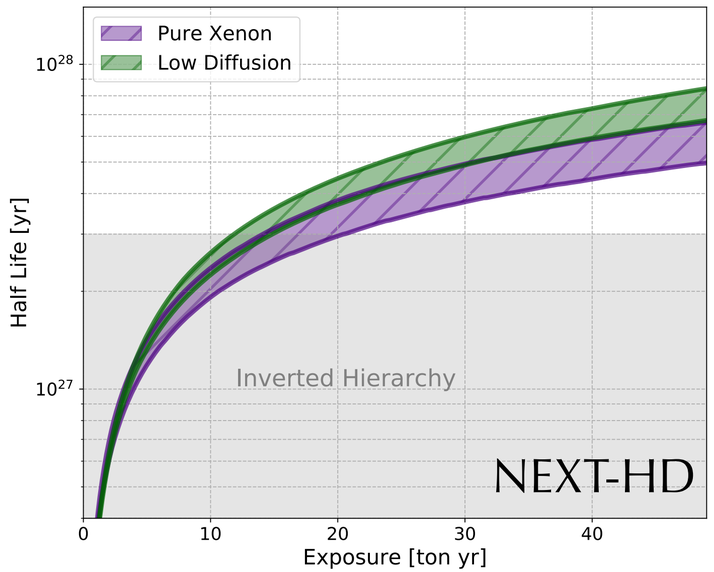


ββ track candidate

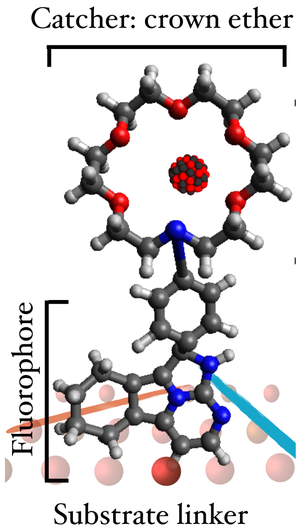


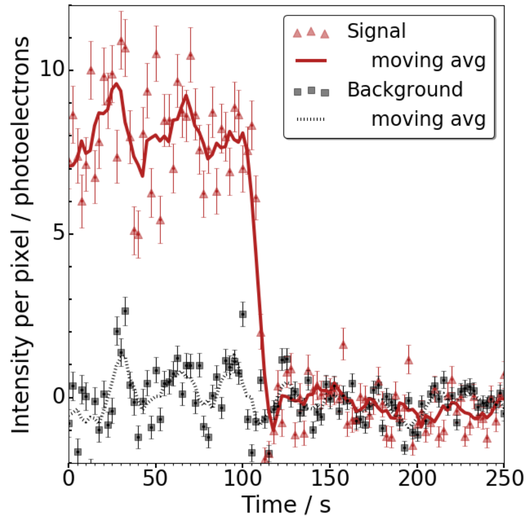


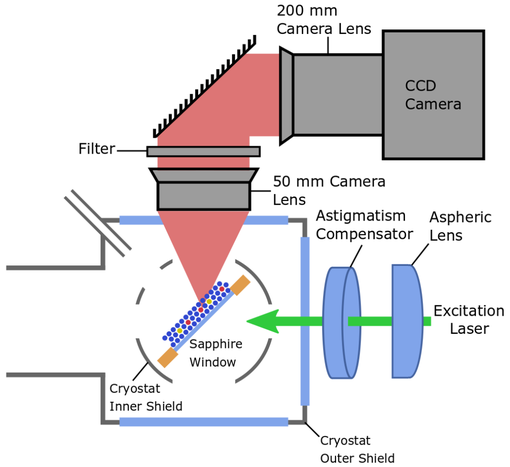
From J. J. Gomez-Cadenas

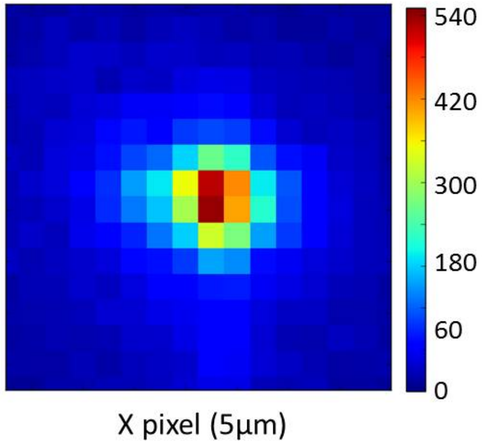
^{136}Xe Daughter Nucleus Tagging

- NEXT: radio frequency carpet sweeps ions to region with switched-fluorescent molecules. Single-molecule sensitivity demonstrated in Xe background.
- nEXO: freeze Ba in Xe, transport via probe to imaging stage, lase and image. Single-atom sensitivity demonstrated.
- Enables background-free searches if high efficiency can be achieved.
- See posters 150, 193, 226







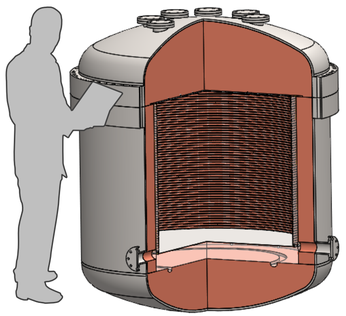


PRL **120**, 132504 (2018); Nature **569**, 203 (2019); Nature doi:10.1038/s41586-020-2431-5 (2020)

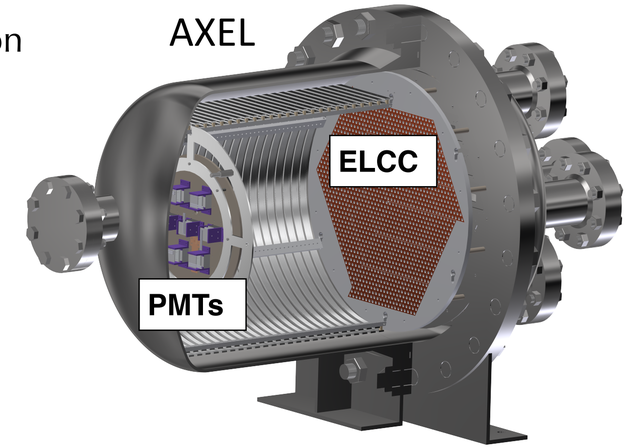
TPCs: PandaX, AXEL, NvDEX

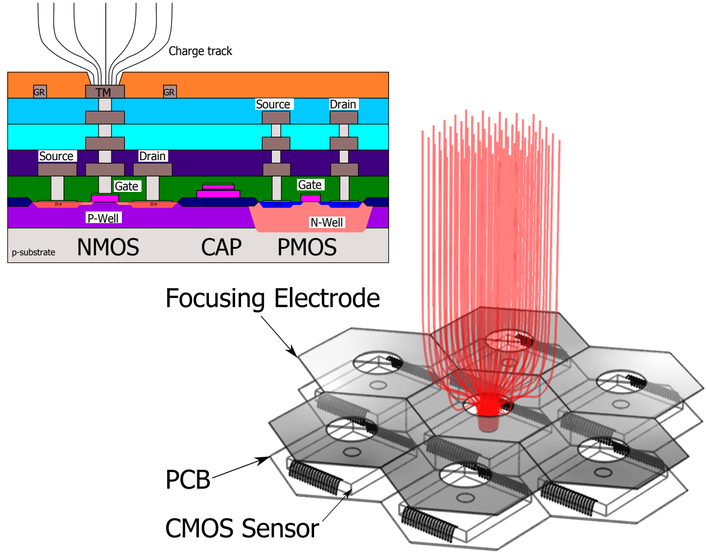
- PandaX
  - PandaX-4T (360 kg ^{136}Xe): upgrade of PandaX-II dual-phase LXe TPC for DM @CJPL, commissioning by end of 2020. 30T upgrade in planning.
  - PandaX-III: 0νββ-focused HPGXe TPC with ~100 kg ^{136}Xe using micromegas readout. Limit sensitivity: 9x10^{25} y. Construction underway, commissioning in 2020. 1T upgrade in planning
- AXEL
  - HPGXe TPC with Electroluminescence Light Collection Cell (ELCC) readout
  - 10L proof-of-principle demonstrated. 180L prototype under construction at Kyoto U. 40 kg upgrade planned for ~2024.
- NvDEX
  - $^{86}SeF_6$ HP gas TPC with Topmetal CMOS readout
  - 100 kg vessel designed, construction at CJPL starting next year

PandaX-4T LXe TPC



PandaX-III GXe TPC



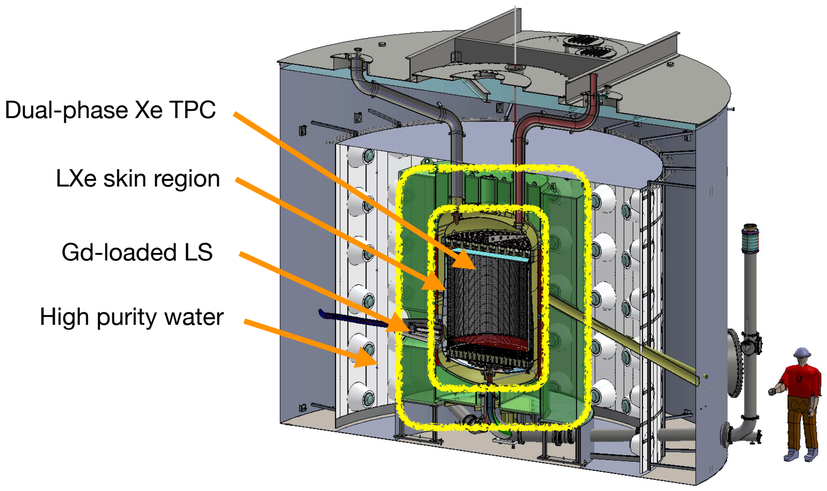


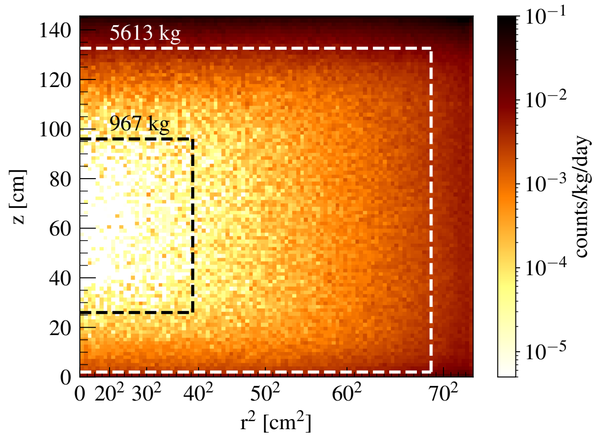
Topmetal CMOS Technology

From K. Han, A. Ichikawa, Y. Mei

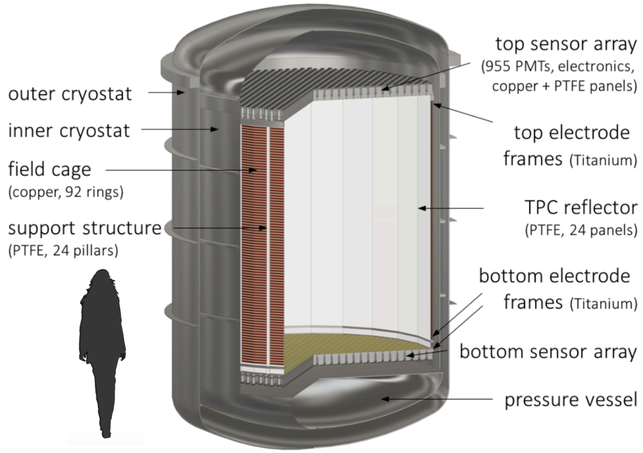
DM Dual-Phase LXe TPCs: LZ, DARWIN

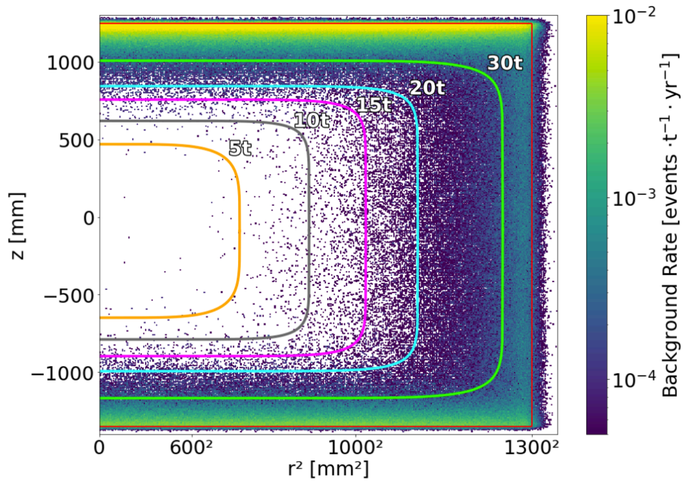
- LZ
  - 7 tons ^{nat}Xe, 500 kg ^{136}Xe in active volume
  - Background ~10 c/(FWHM t y) dominated by radioactivity
  - Limit sensitivity (1000 days): $T_{1/2} > 10^{26}$ y (x10 for upgrade with ^{enr}Xe)
  - Starting commissioning at SURF





- DARWIN
  - 50 t evolution of XENON experiment: 3.5 tons ^{136}Xe
  - Background ~0.2 c/(FWHM t y) dominated by radioactivity, ^{137}Xe
  - Discovery sensitivity (10 years): $T_{1/2} > 10^{27}$ y
  - Data taking scheduled to start 2027

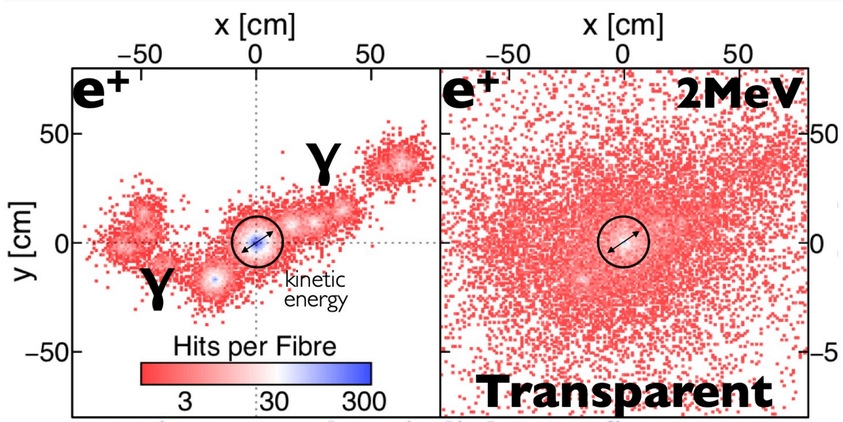


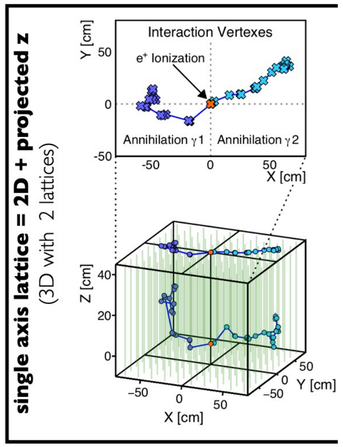


From K. Lesko, L. Baudis

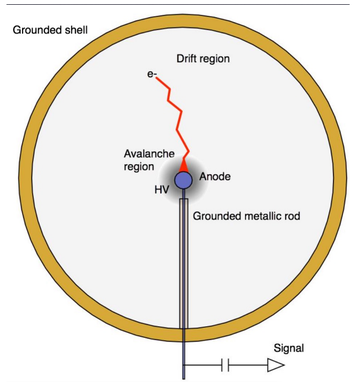
Other R&D: LiquidO, R2D2

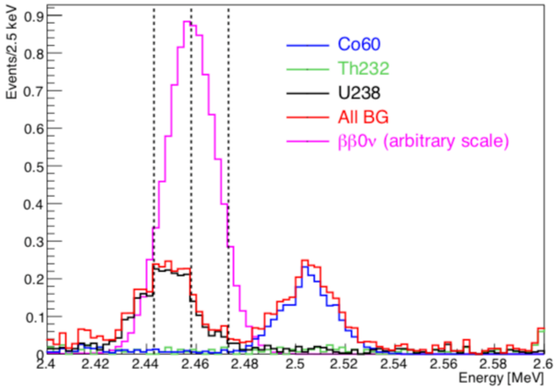
- LiquidO
  - Opaque loaded LS + WS fibers: tracking / PID in LS with very high loading
  - Protyping underway
  - See arXiv:1908.02859, 1908.03334





- R2D2
  - Spherical Xenon gas TPC
  - Test ongoing with 8 kg prototype, plans for 50 kg upgrade
  - See JINST **13**, P01009 (2018)

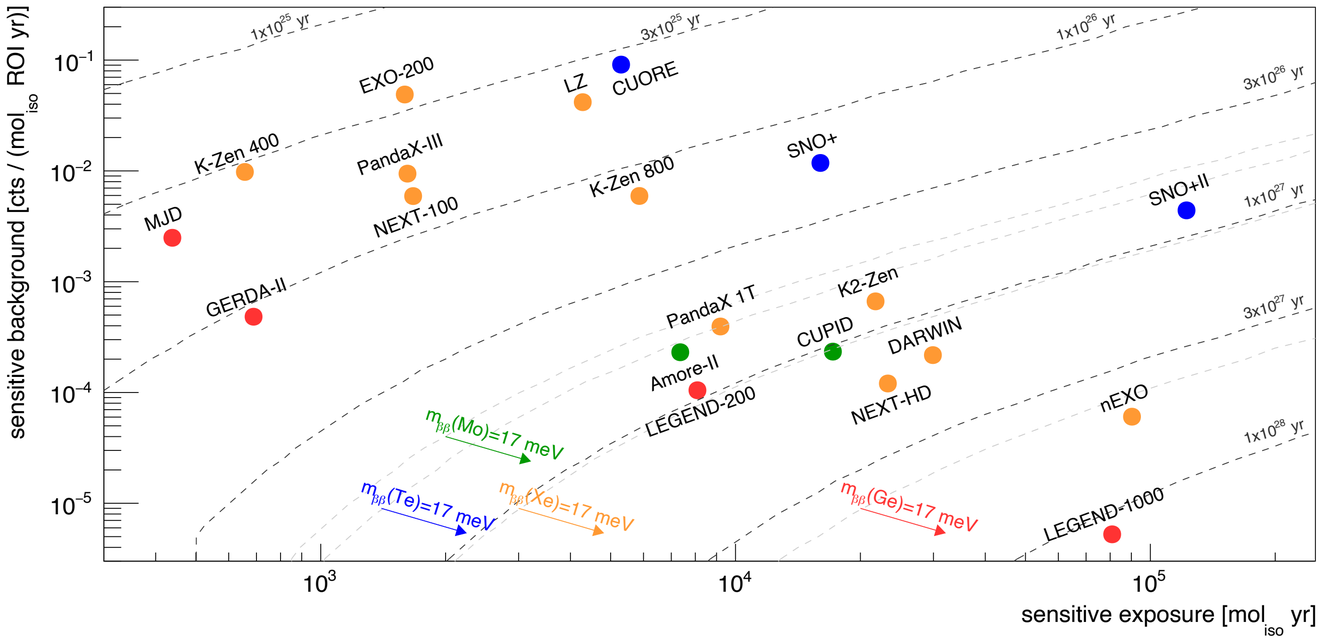


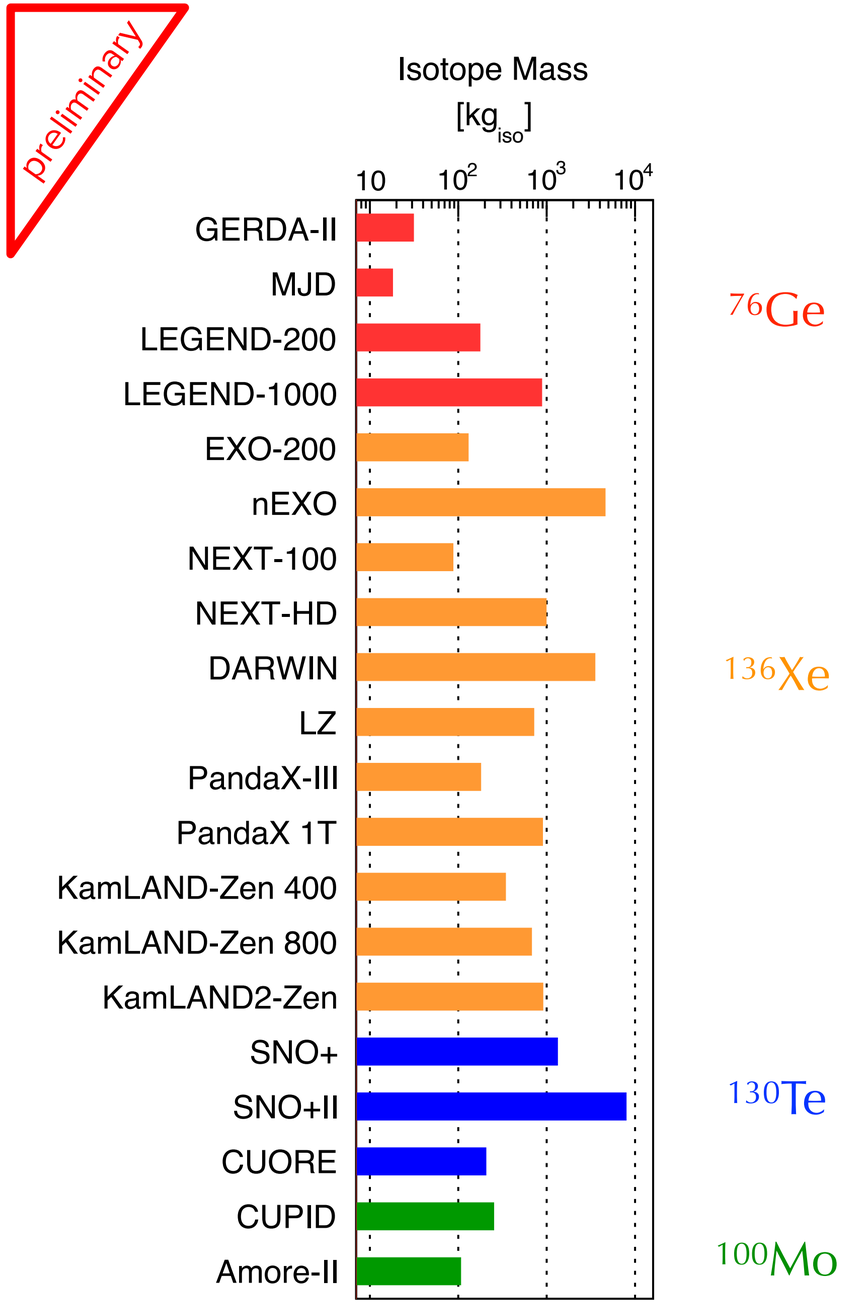


From A. Cabrera, A. Meragaglia

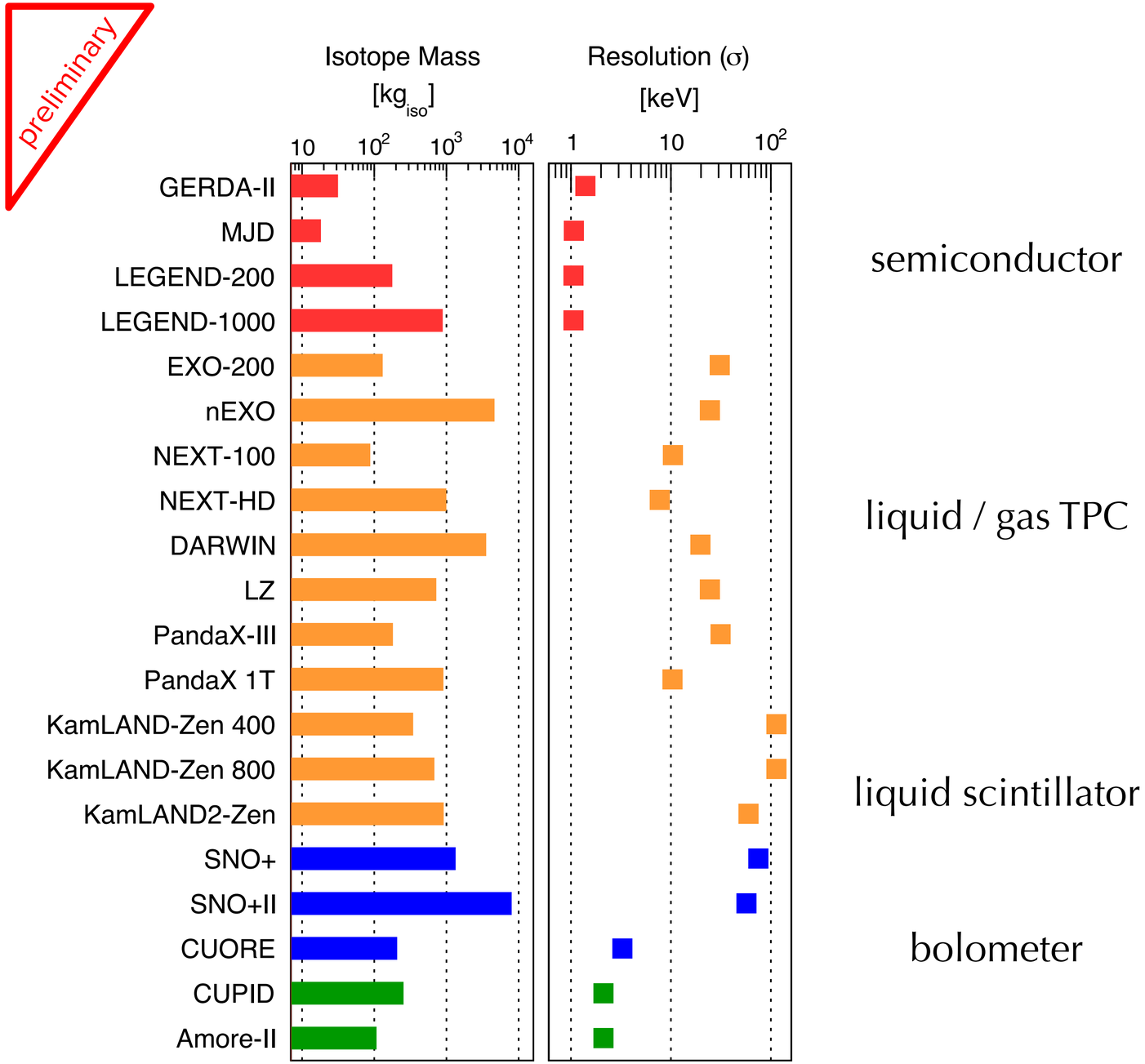
Outline

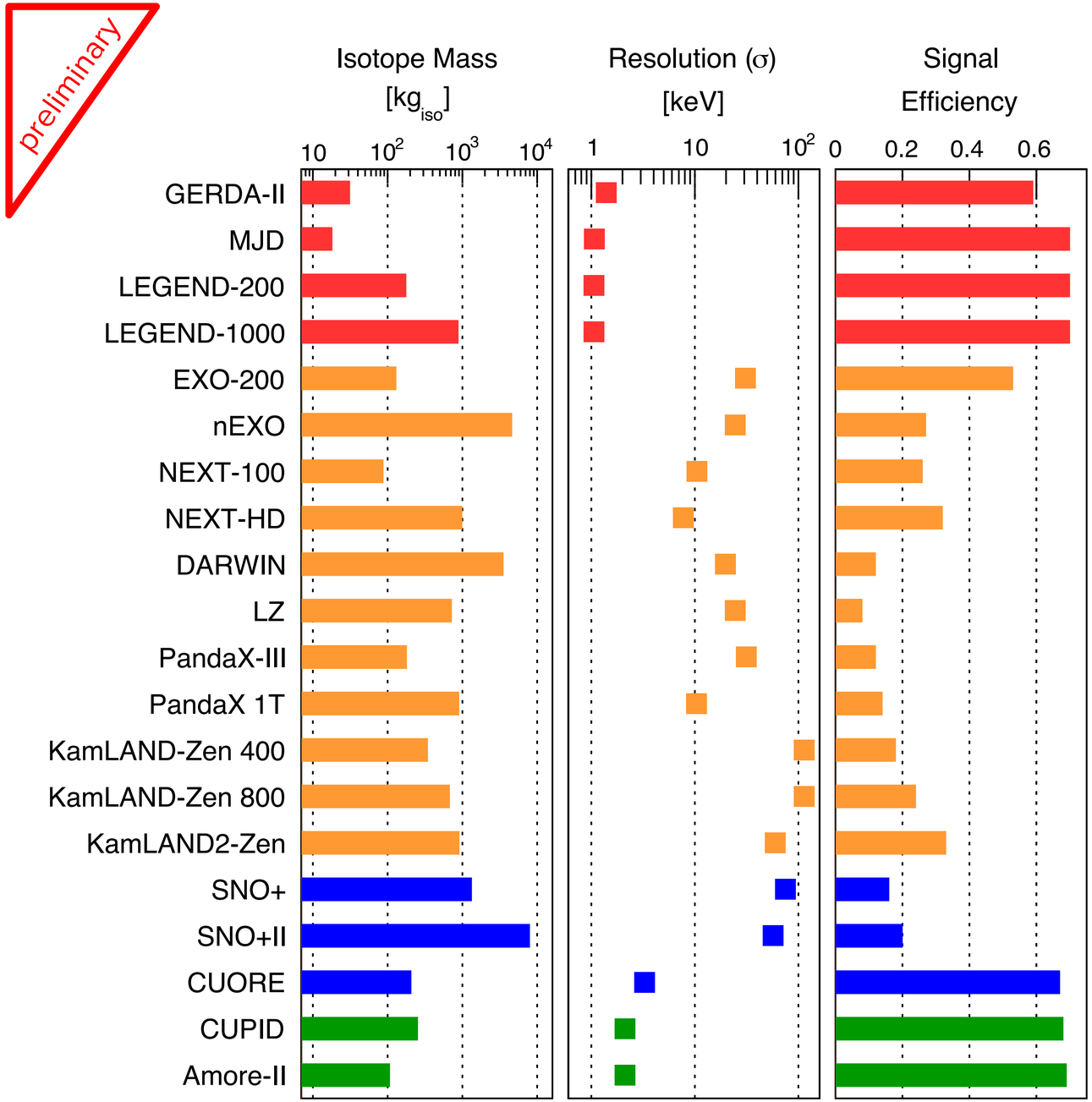
- Introduction
- Experiments
  - Bolometers
  - External Trackers
  - Scintillators
  - Semiconductors
  - TPCs
- Experimental summary



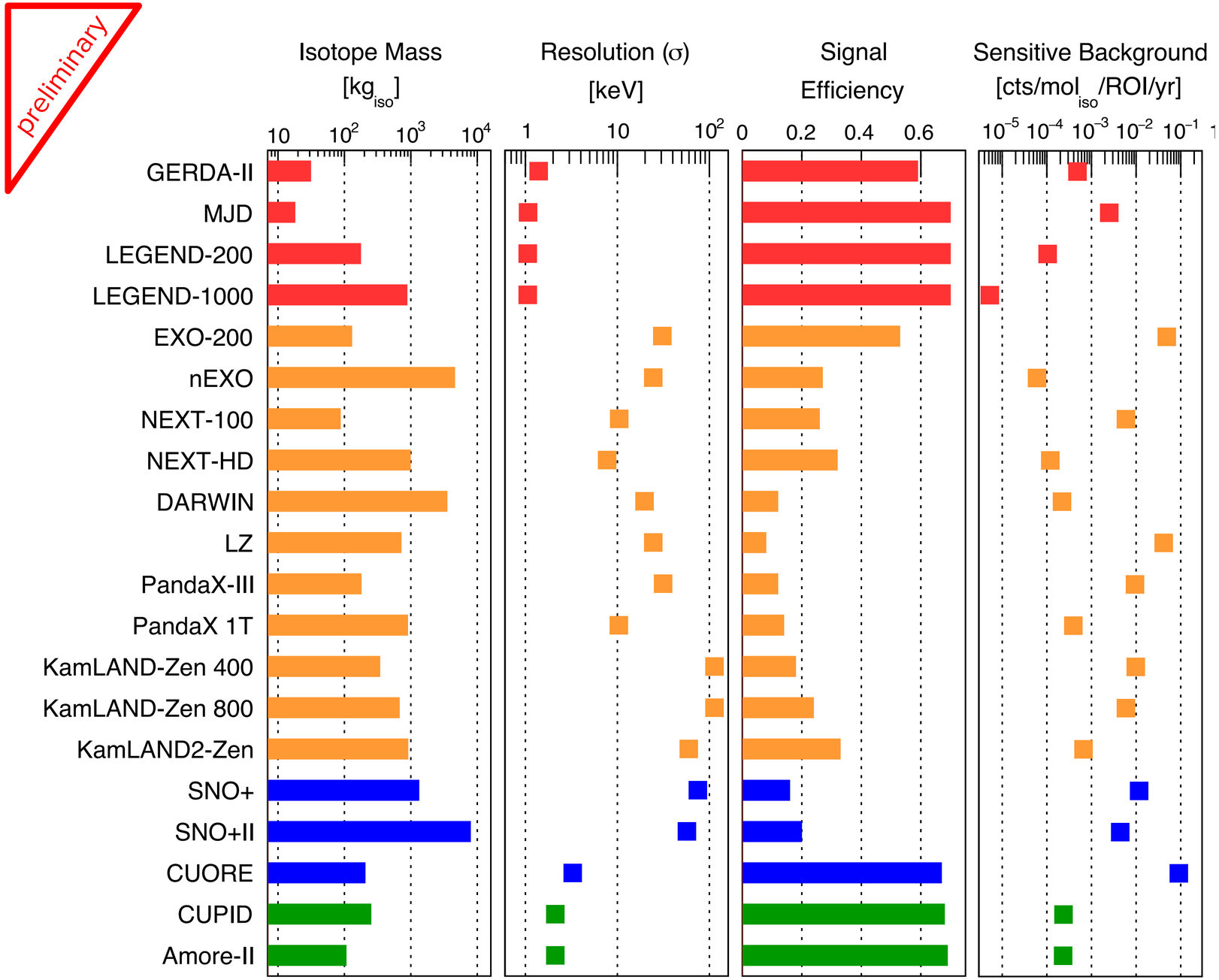


+ ^{48}Ca + ^{82}Se + ^{96}Zr ...


preliminary
Isotope Mass
[kg_iso]
Resolution (σ)
[keV]
10
10^2
10^3
10^4
1
10
10^2
GERDA-II
MJD
LEGEND-200
LEGEND-1000
EXO-200
nEXO
NEXT-100
NEXT-HD
DARWIN
LZ
PandaX-III
PandaX 1T
KamLAND-Zen 400
KamLAND-Zen 800
KamLAND2-Zen
SNO+
SNO+II
CUORE
CUPID
Amore-II
semiconductor
liquid / gas TPC
liquid scintillator
bolometer



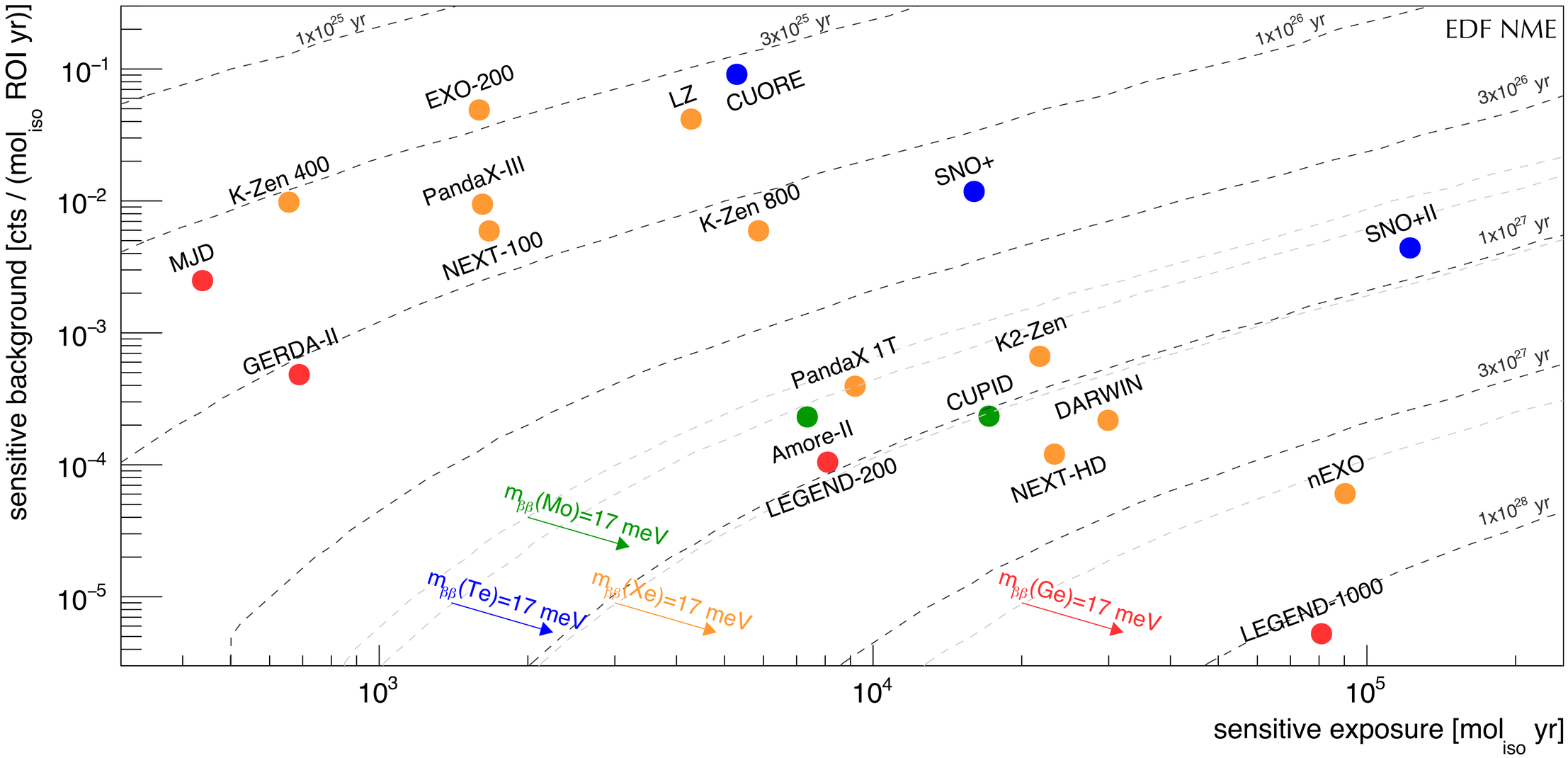
Lower efficiency due primarily to fiducialization



Next generation experiments:
<1 bkg count/year

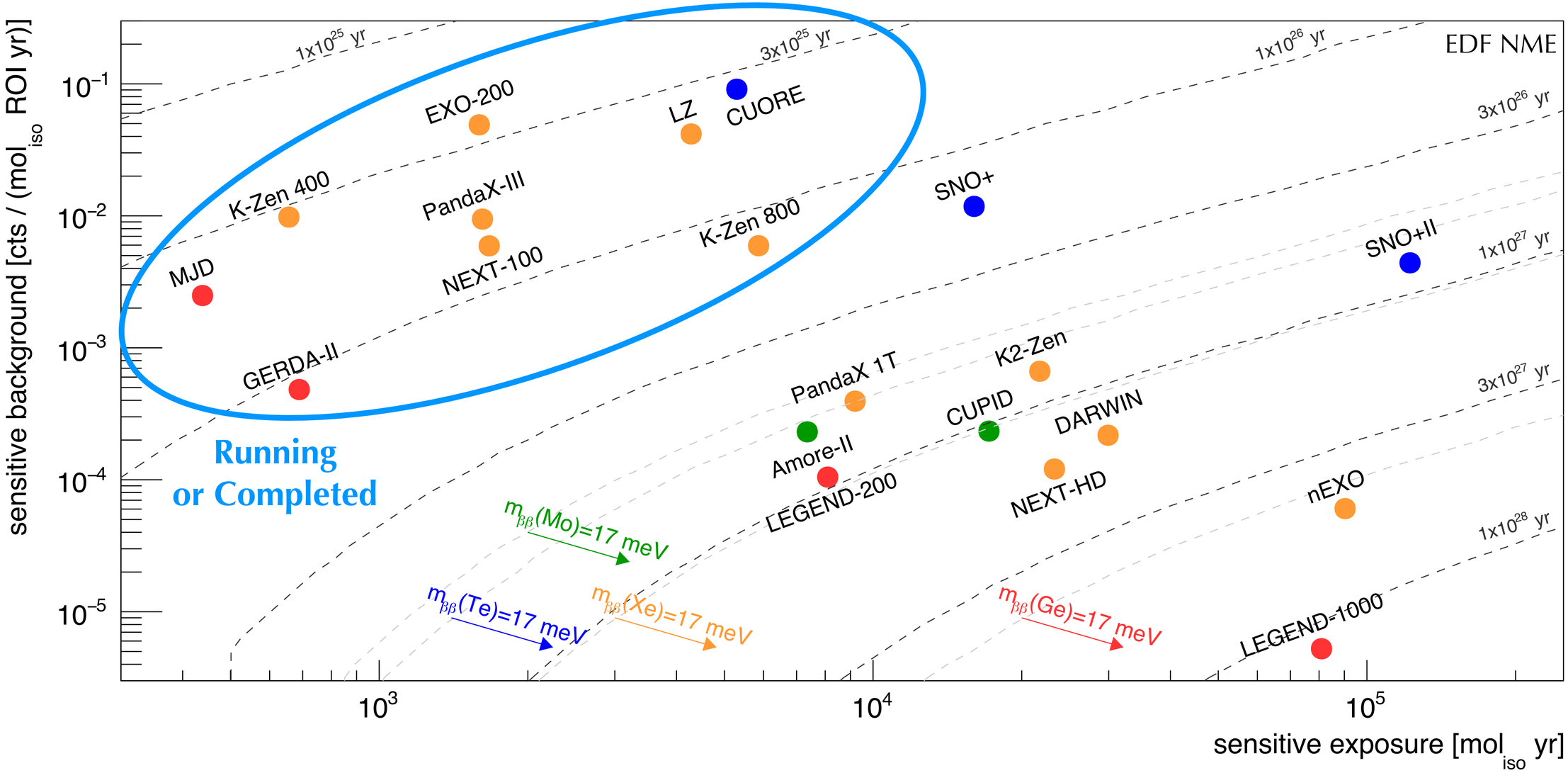
preliminary

Discovery Sensitivity Comparison



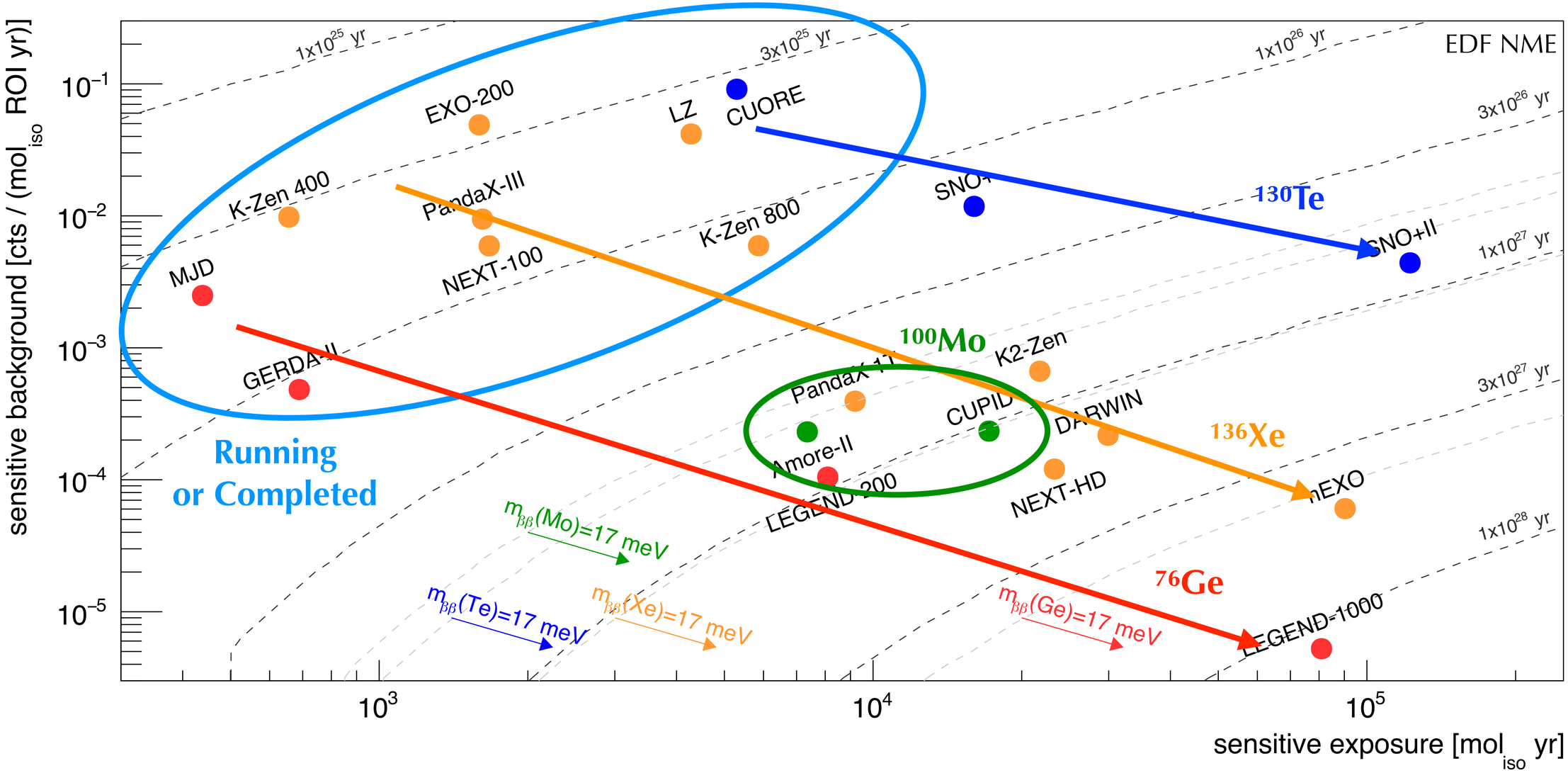
preliminary

Discovery Sensitivity Comparison



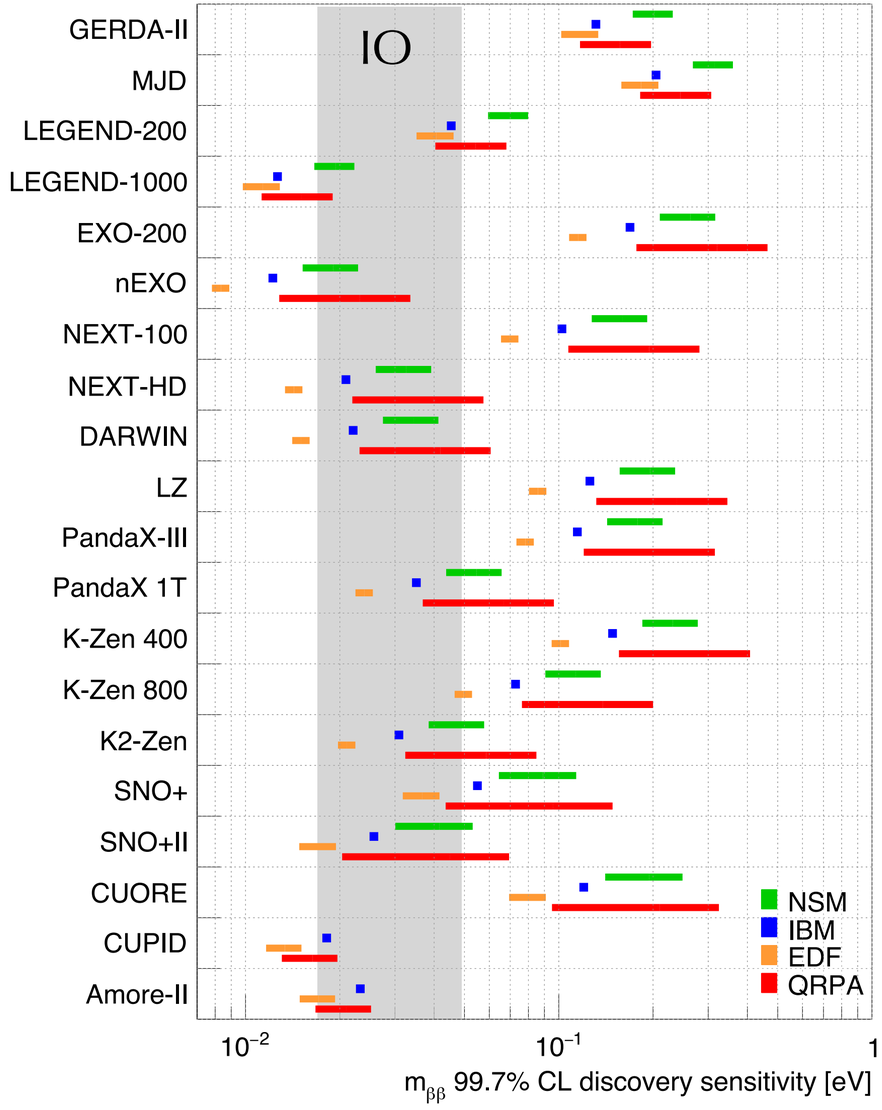
preliminary

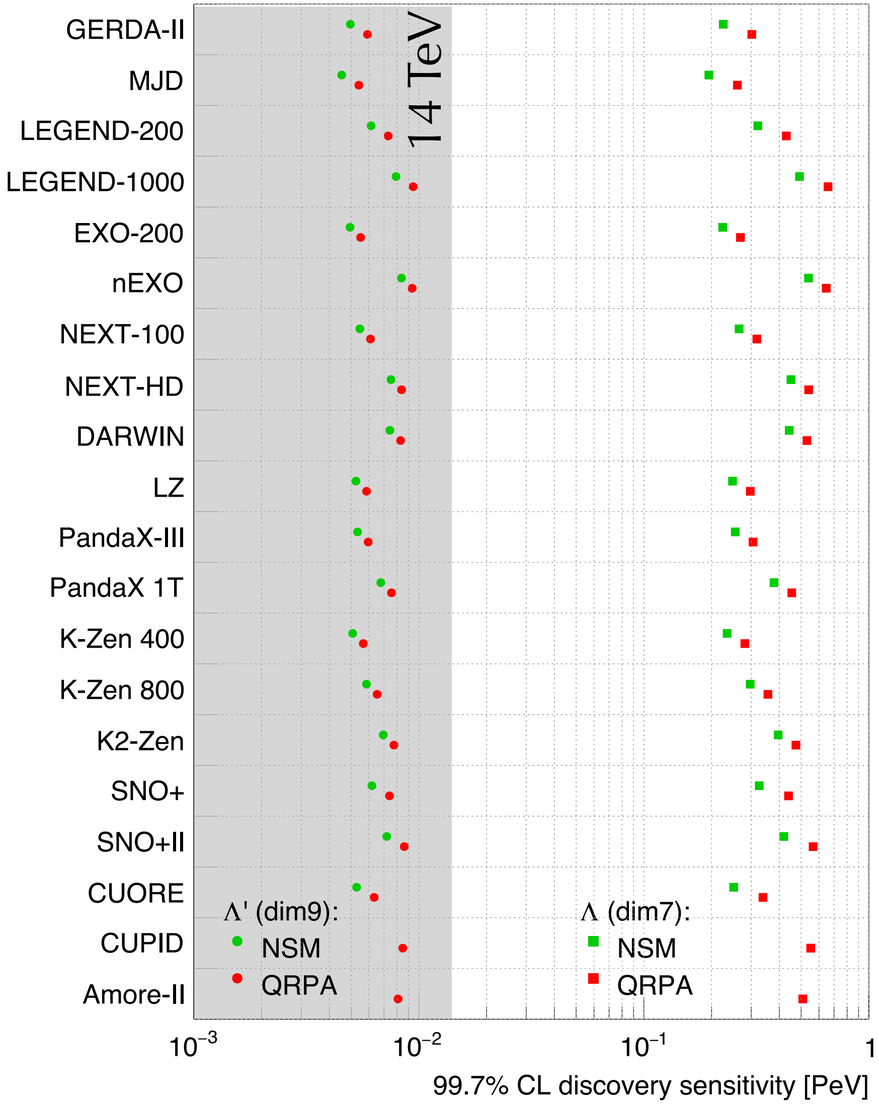
Discovery Sensitivity Comparison



preliminary

Discovery Sensitivity Comparison

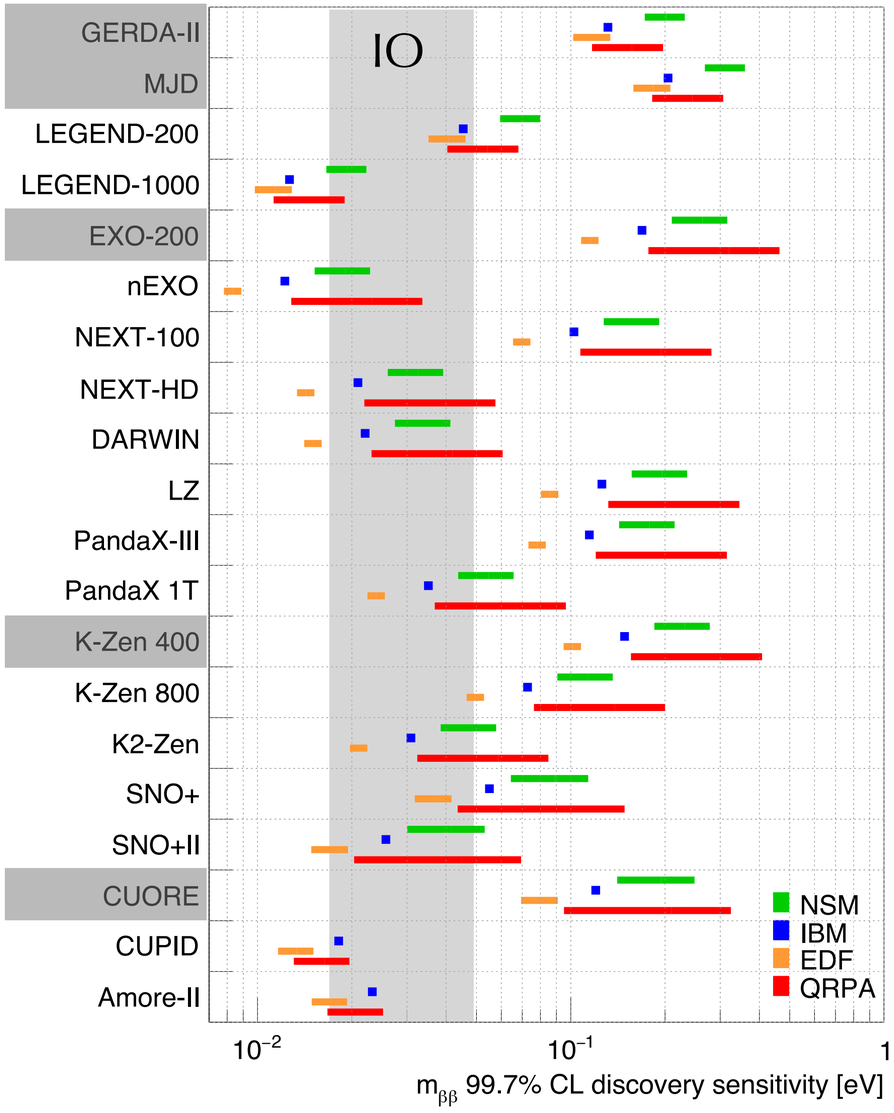


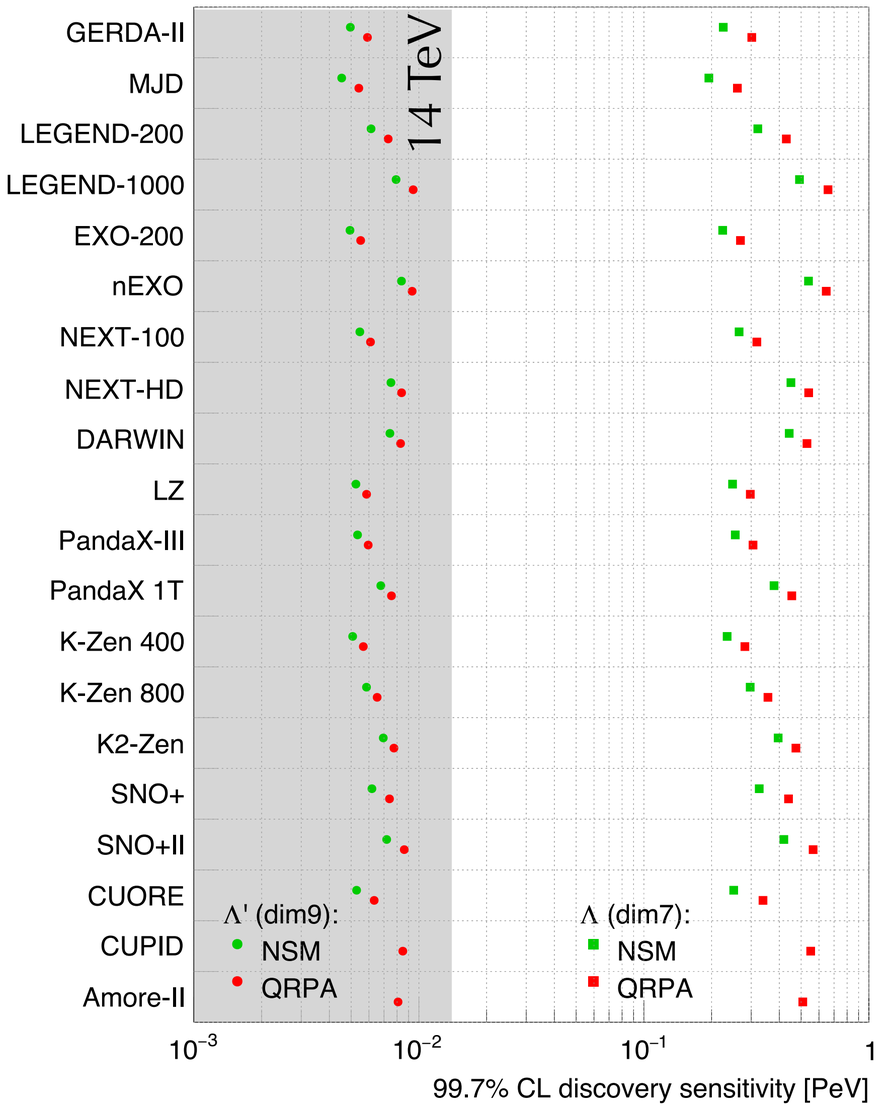


preliminary

Discovery Sensitivity Comparison

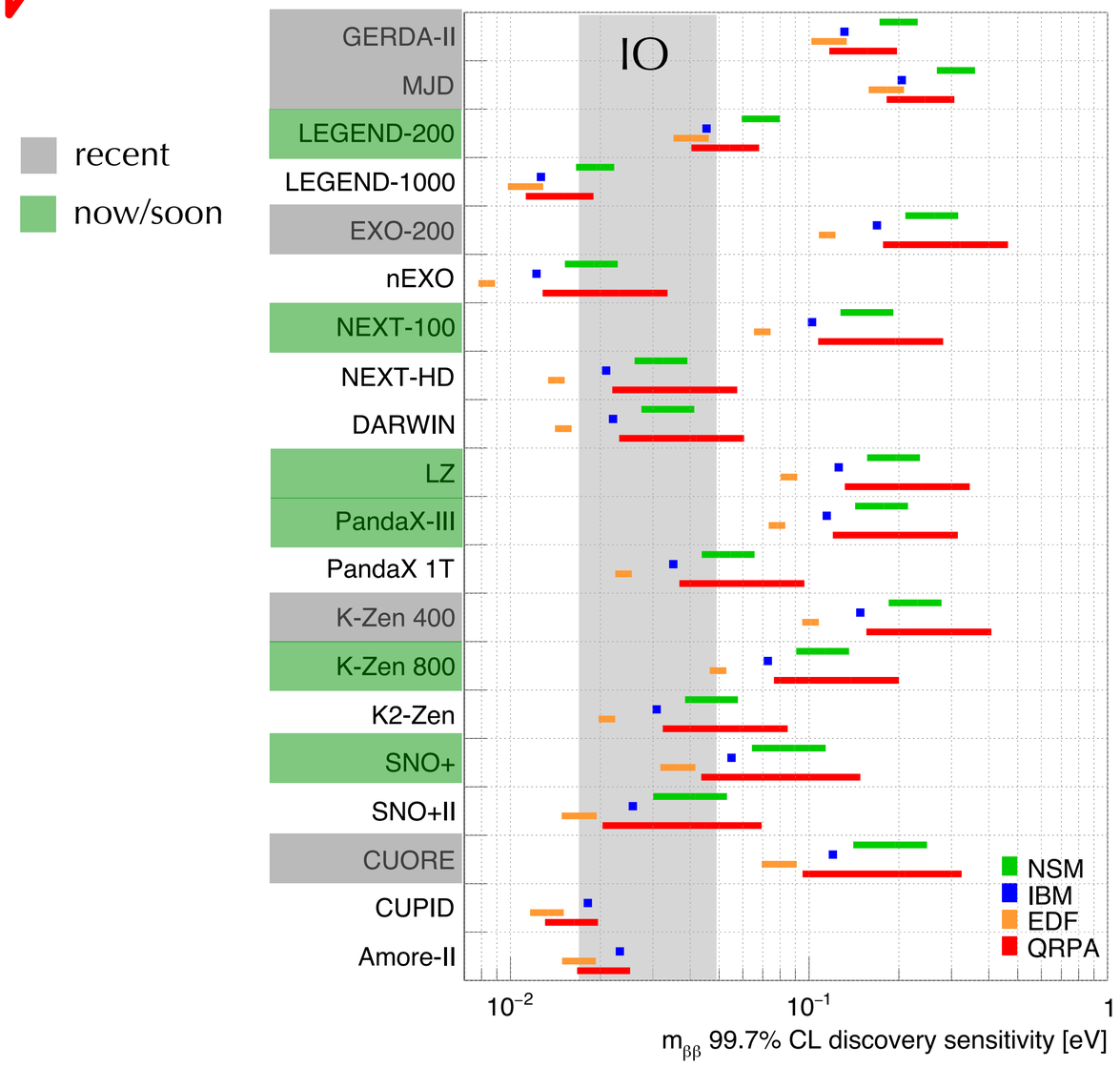
recent

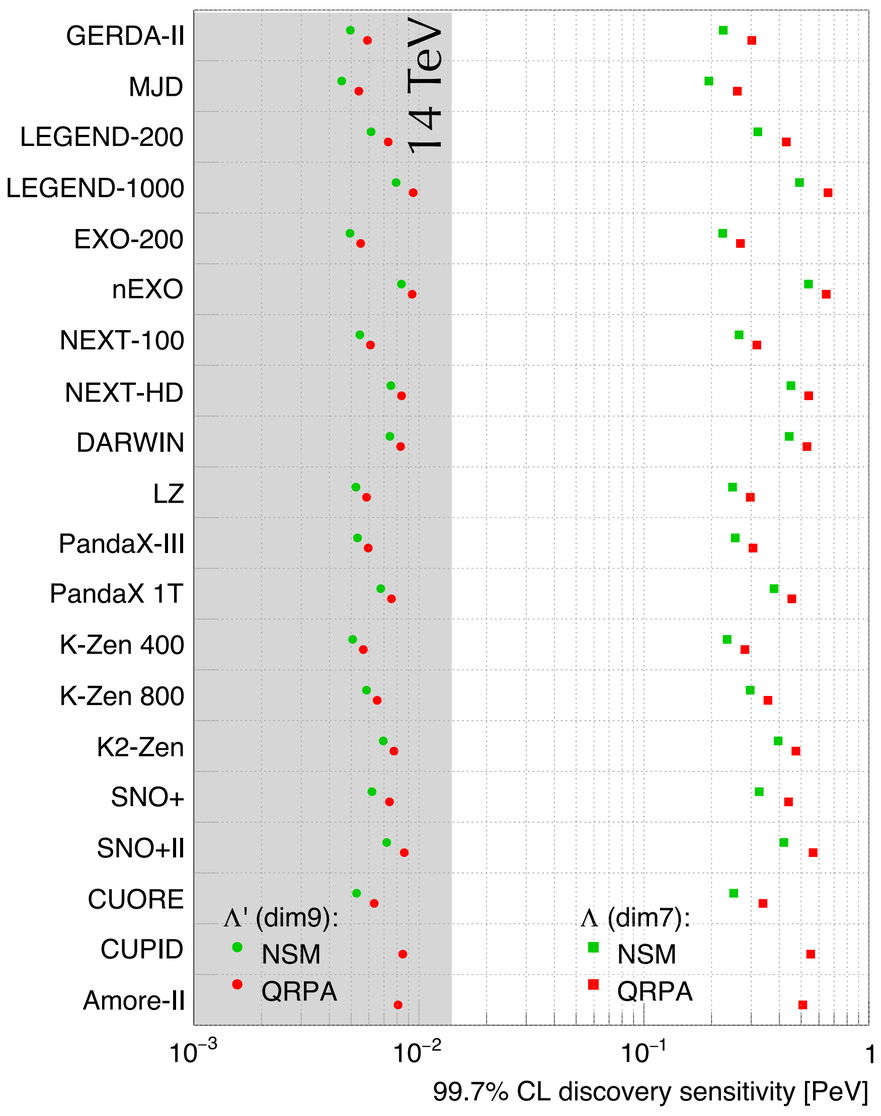




preliminary

Discovery Sensitivity Comparison





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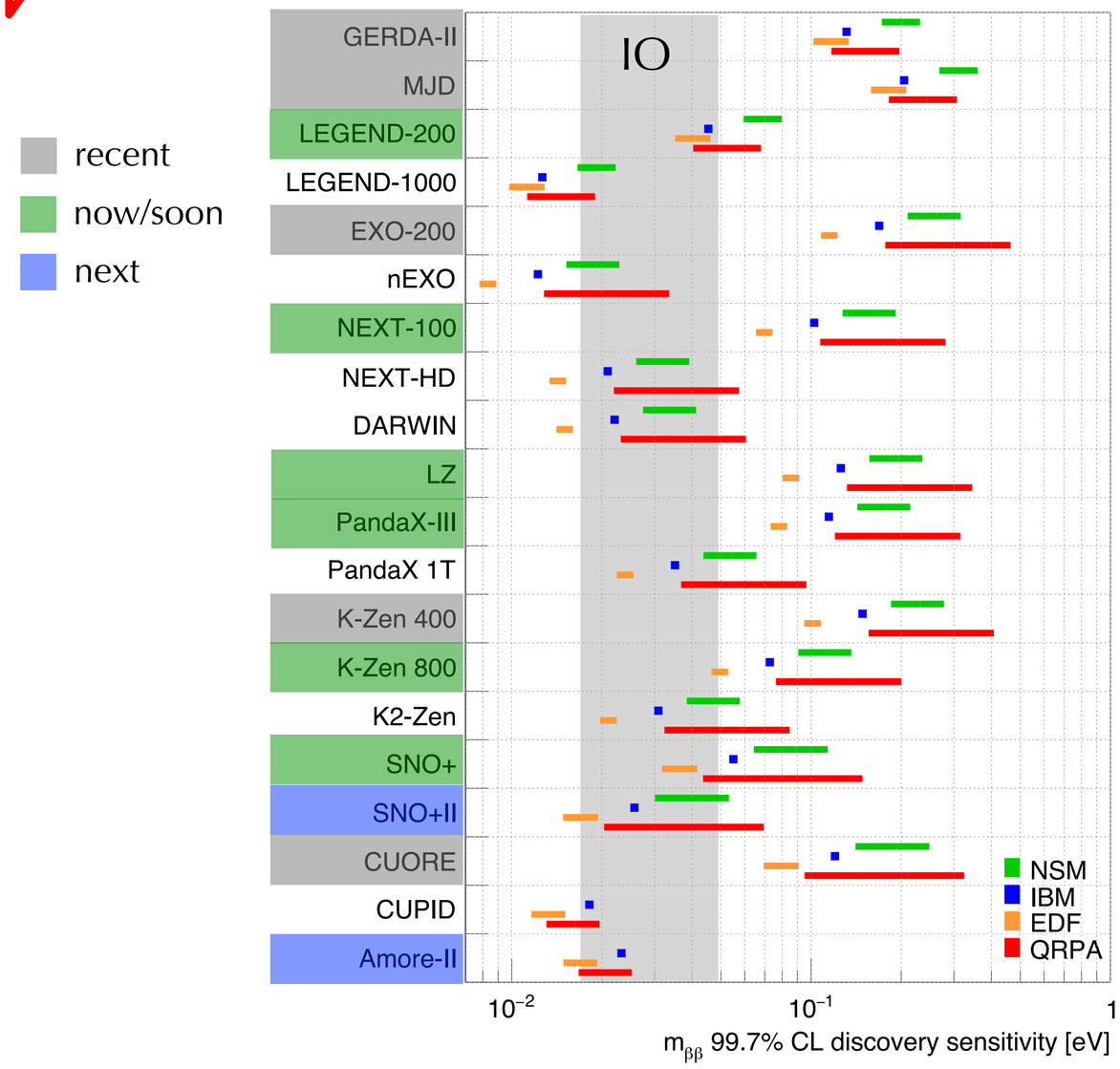
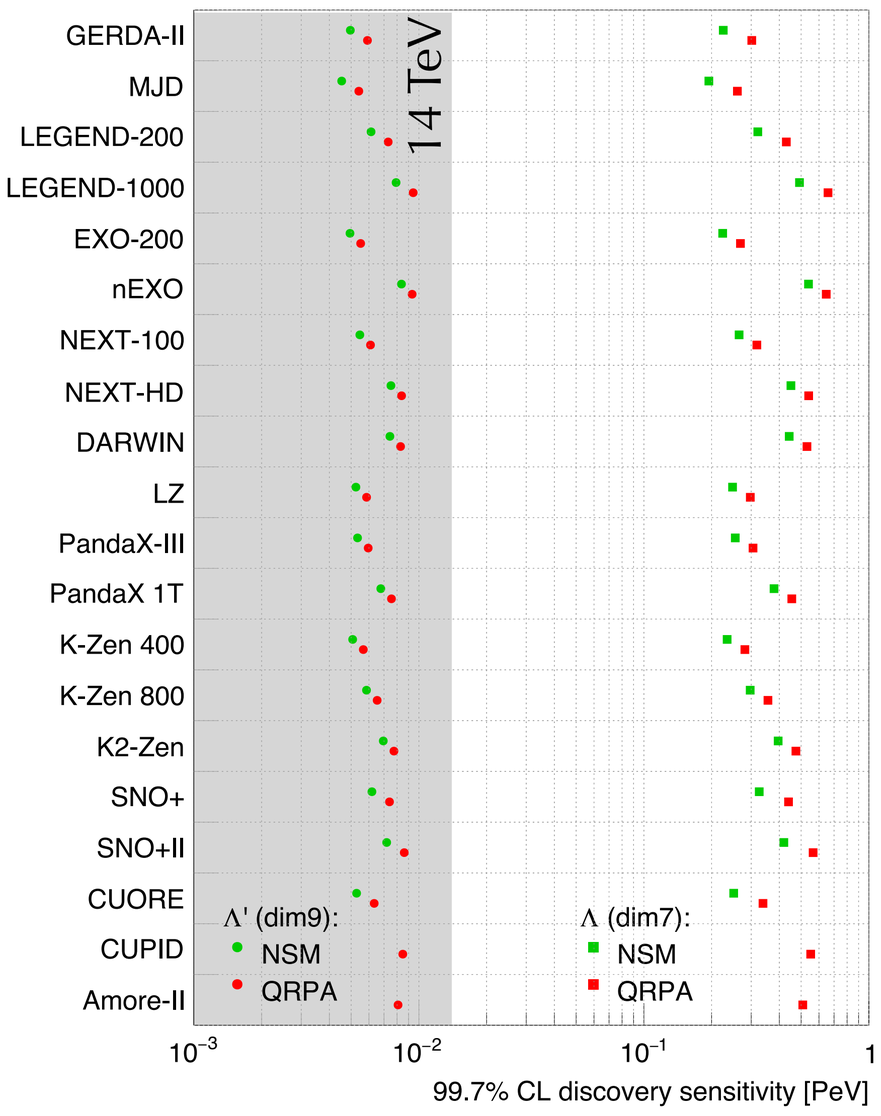
Discovery Sensitivity Comparison





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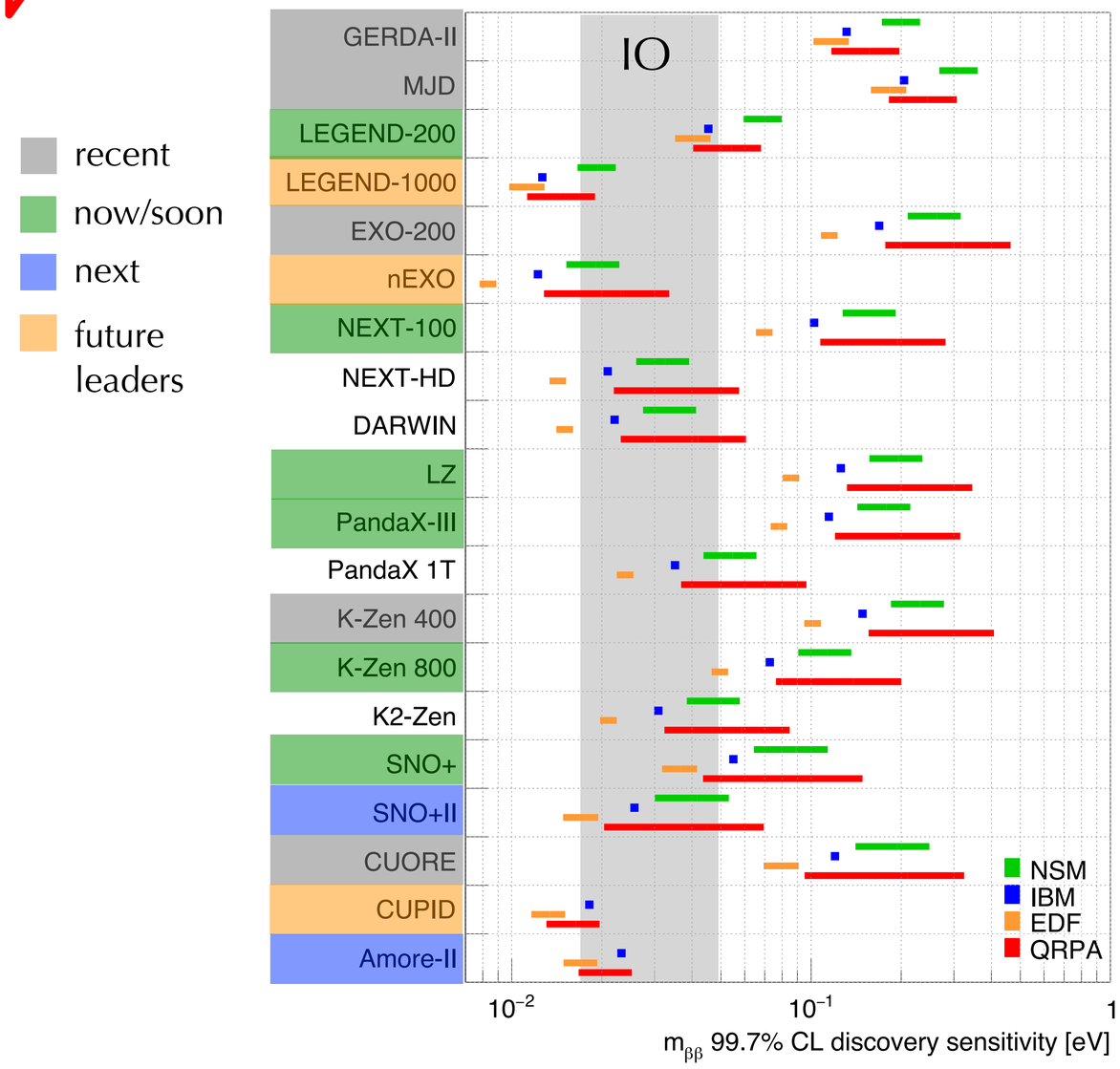
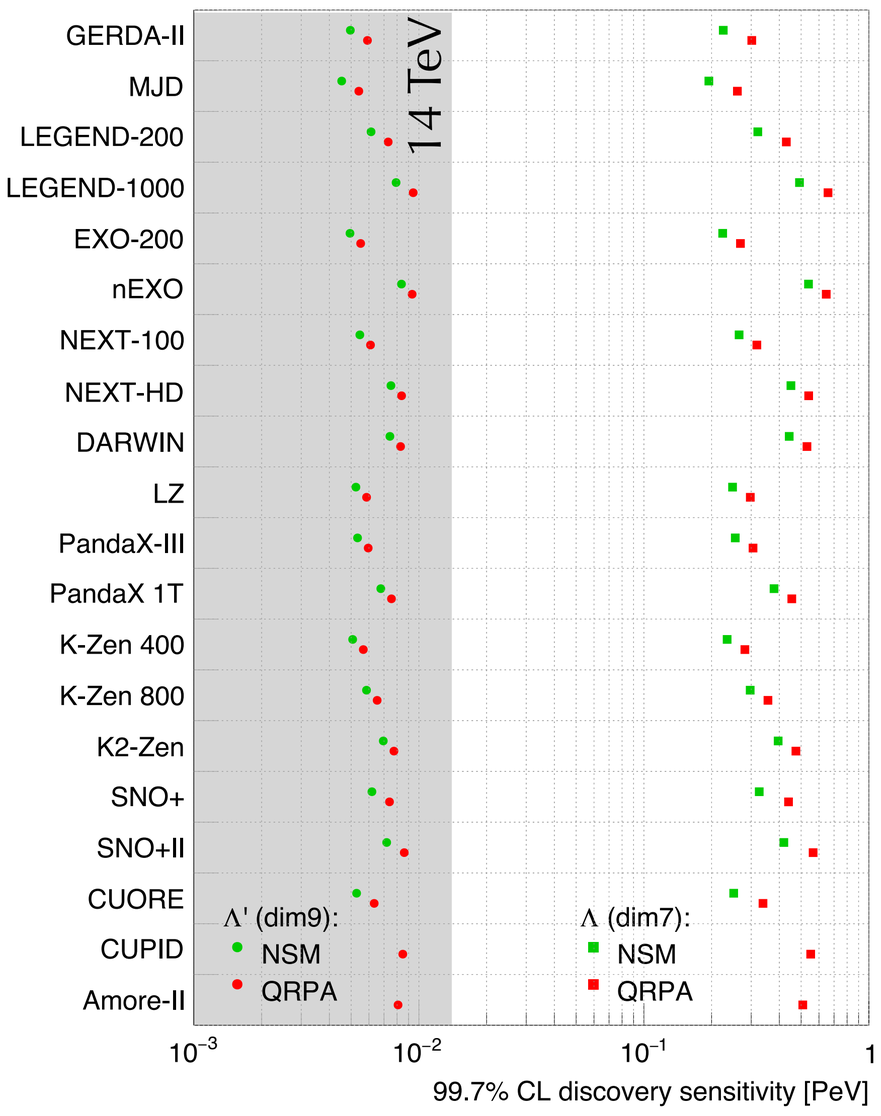
Discovery Sensitivity Comparison





Summary

- The international experimental program is robust and aggressive
- A steady march in sensitivity improvement is expected for at least a decade in multiple isotopes
- New techniques are being pursued to take us beyond the IO
- Discovery could come at any time!