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

\[ 0 \nu \beta \beta \]

- Matter creation process! (irrespective of mechanism)
- Must measure summed electron kinetic energy to distinguish from Standard-Model 2\( \nu \) 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 \( \sim 1 \) 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): $T_{1/2} > 3 \times 10^{25}$ yrs

• Future goal:
  ~2 OoM improvement in $T_{1/2}$
  • Covers IO
  • Up to 50% of NO
  • Factor of ~few in $\Lambda$
  • An aggressive experimental goal

\[
\frac{1}{T_{1/2}} = G_{01} g_A^4 \left( M^{0\nu} + \frac{g_N^2}{g_A^2} m_{\pi\nu}^2 M^{0\nu}_{\text{cont}} \right)^2 \frac{m_{\beta\beta}^2}{m_e^2}
\]
Current Limits and Future Goals

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  - $^{130}$Te (CUORE): $T_{1/2} > 3 \times 10^{25}$ yrs

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

NO, QRPA
Uniform $\Sigma$ prior

$\text{next-generation goal}$
Current Limits and Future Goals

• Present best limits:
  
  • $^{136}\text{Xe}$ (KamLAND-Zen): $T_{1/2} > 10^{26}$ yrs
  
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  • $^{130}\text{Te}$ (CUORE): $T_{1/2} > 3 \times 10^{25}$ yrs

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\[
\frac{1}{T_{1/2}} = G_{01} g_A^4 \left( M^{0\nu} + \frac{g_\nu^{NN}}{g_A^2} \frac{m_e^2}{M_{\text{cont}}} \right)^2 \frac{m_{\beta\beta}^2}{m_e^2} + \frac{m_N^2}{m_e^2} G^4 g^4 M^2 \left( \frac{v}{\Lambda} \right)^6 + \ldots
\]
Current Limits and Future Goals

- Present best limits:
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    - An aggressive experimental goal
Experimental Focus: Discovery

- Energy is the only observable that is both necessary and sufficient for discovery of $0\nu\beta\beta$ decay: effectively a Poisson counting experiment.

- Relevant parameters: sensitive exposure and sensitive background.

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

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

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

Requirements:

- **High exposure**
- **Low background**

Target sensitivity

- 76Ge

- Requirements:
  - High exposure
  - Low background

Diagram showing the relationship between sensitive exposure and $T_{1/2}$ for a discovery sensitivity $3\sigma$. The shaded area represents the target sensitivity, with dotted lines indicating different backgrounds and exposures.

**Mathematical expressions**

- $\mathcal{E}$: Sensitive exposure
- $\mathcal{B}$: Sensitive background
- $T_{1/2}$: Half-life
- $N_A$: Avogadro's number
- $m_\alpha$: Mass of alpha particle
- $S_{3\sigma}$: Signal significance
- $\mathcal{B}\mathcal{E}$: Background efficiency

**Equations**

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

**Graphical Representation**

- Axes: Sensitive exposure [t$_{iso}$ yr], Discovery sensitivity [yr]
- Legends: 0 cts/t$_{iso}$ ROI yr, $10^{-2}$ cts/t$_{iso}$ ROI yr, $10^{-3}$ cts/t$_{iso}$ ROI yr, $10^{-4}$ cts/t$_{iso}$ ROI yr, $10^{-5}$ cts/t$_{iso}$ ROI yr, $10^{-6}$ cts/t$_{iso}$ ROI yr, $10^{-7}$ cts/t$_{iso}$ ROI yr
Experimental Techniques

- Bolometers (CUPID, AMoRE, CANDLES IV)
  - Measure $E$ ($\sigma \sim 0.1-0.3\%$) from phonons; granularity gives position info
  - Instrumenting with photon detectors for background rejection

- External trackers (SuperNEMO)
  - Trackers + calorimeters, measure $E$ ($\sigma \sim 3-10\%$) + tracks / positions + PID

- Scintillators (KamLAND2-Zen, SNO+, Theia, ZICOS)
  - Measure $E$ ($\sigma \sim 3-10\%$) + position from scintillation light; some PID

- Semiconductors (LEGEND, SELENA)
  - Measure $E$ ($\sigma \sim 0.05-0.3\%$) from ionization; some tracking / position sensitivity

- TPCs (nEXO, NEXT, PandaX, AXEL, NvDEx, DARWIN, LZ)
  - Collect scintillation + ionization: measure $E$ ($\sigma \sim 0.4-3\%$) + tracks / position + PID
<table>
<thead>
<tr>
<th>Collaboration</th>
<th>Isotope</th>
<th>Technique</th>
<th>mass (0νββ isotope)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>CANDLES-III</td>
<td>48Ca</td>
<td>305 kg CaF$_2$ crystals in liquid scintillator</td>
<td>0.3 kg</td>
<td>Operating</td>
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<td>CANDLES-IV</td>
<td>48Ca</td>
<td>CaF$_2$ scintillating bolometers</td>
<td>TBD</td>
<td>R&amp;D</td>
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<tr>
<td>GERDA</td>
<td>76Ge</td>
<td>Point contact Ge in active LAr</td>
<td>44 kg</td>
<td>Complete</td>
</tr>
<tr>
<td>MAJORANA DEMONSTRATOR</td>
<td>76Ge</td>
<td>Point contact Ge in Lead</td>
<td>30 kg</td>
<td>Operating</td>
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<td>LEGEND 200</td>
<td>76Ge</td>
<td>Point contact Ge in active LAr</td>
<td>200 kg</td>
<td>Construction</td>
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<tr>
<td>LEGEND 1000</td>
<td>76Ge</td>
<td>Point contact Ge in active LAr</td>
<td>1 tonne</td>
<td>R&amp;D</td>
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<tr>
<td>SuperNEMO Demonstrator</td>
<td>82Se</td>
<td>Foils with tracking</td>
<td>7 kg</td>
<td>Construction</td>
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<td>SELENA</td>
<td>82Se</td>
<td>Se CCDs</td>
<td>&lt;1 kg</td>
<td>R&amp;D</td>
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<td>NvDEx</td>
<td>82Se</td>
<td>SeF$_6$ high pressure gas TPC</td>
<td>50 kg</td>
<td>R&amp;D</td>
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<td>ZICOS</td>
<td>90Zr</td>
<td>10% $^{106}$Zr in liquid scintillator</td>
<td>45 kg</td>
<td>R&amp;D</td>
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<td>AMoRE-I</td>
<td>$^{100}$Mo</td>
<td>$^{48}$CaMoO$_4$ scintillating bolometers</td>
<td>6 kg</td>
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<td>AMoRE-II</td>
<td>$^{100}$Mo</td>
<td>Li$_2$MoO$_4$ scintillating bolometers</td>
<td>100 kg</td>
<td>Construction</td>
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<td>CUPID</td>
<td>$^{100}$Mo</td>
<td>Li$_2$MoO$_4$ scintillating bolometers</td>
<td>250 kg</td>
<td>R&amp;D</td>
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<tr>
<td>COBRA</td>
<td>$^{116}$Cd/$^{130}$Te</td>
<td>CdZnTe detectors</td>
<td>10 kg</td>
<td>Operating</td>
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<tr>
<td>CUORE</td>
<td>$^{130}$Te</td>
<td>TeO$_2$ Bolometer</td>
<td>206 kg</td>
<td>Operating</td>
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<tr>
<td>SNO+</td>
<td>$^{130}$Te</td>
<td>0.5% $^{130}$Te in liquid scintillator</td>
<td>1300 kg</td>
<td>Construction</td>
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<td>SNO+ Phase II</td>
<td>$^{130}$Te</td>
<td>2.5% $^{130}$Te in liquid scintillator</td>
<td>8 tonnes</td>
<td>R&amp;D</td>
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<tr>
<td>Theia-Te</td>
<td>$^{130}$Te</td>
<td>5% $^{130}$Te in liquid scintillator</td>
<td>31 tonne</td>
<td>R&amp;D</td>
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<tr>
<td>KamLAND-Zen 400</td>
<td>$^{136}$Xe</td>
<td>2.7% in liquid scintillator</td>
<td>370 kg</td>
<td>Complete</td>
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<tr>
<td>KamLAND-Zen 800</td>
<td>$^{136}$Xe</td>
<td>2.7% in liquid scintillator</td>
<td>750 kg</td>
<td>Operating</td>
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<tr>
<td>KamLAND2-Zen</td>
<td>$^{136}$Xe</td>
<td>2.7% in liquid scintillator</td>
<td>~tonne</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>EXO-200</td>
<td>$^{136}$Xe</td>
<td>Xe liquid TPC</td>
<td>160 kg</td>
<td>Complete</td>
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<tr>
<td>nEXO</td>
<td>$^{136}$Xe</td>
<td>Xe liquid TPC</td>
<td>5 tonnes</td>
<td>R&amp;D</td>
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<tr>
<td>NEXT-WHITE</td>
<td>$^{136}$Xe</td>
<td>High pressure GXe TPC</td>
<td>~5 kg</td>
<td>Operating</td>
</tr>
<tr>
<td>NEXT-100</td>
<td>$^{136}$Xe</td>
<td>High pressure GXe TPC</td>
<td>100 kg</td>
<td>Construction</td>
</tr>
<tr>
<td>PandaX</td>
<td>$^{136}$Xe</td>
<td>High pressure GXe TPC</td>
<td>~tonne</td>
<td>R&amp;D</td>
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<td>AXEL</td>
<td>$^{136}$Xe</td>
<td>High pressure GXe TPC</td>
<td>~tonne</td>
<td>R&amp;D</td>
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<td>DARWIN</td>
<td>$^{136}$Xe</td>
<td>Xe liquid TPC</td>
<td>3.5 tonnes</td>
<td>R&amp;D</td>
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<td>LZ</td>
<td>$^{136}$Xe</td>
<td>Xe liquid TPC</td>
<td>R&amp;D</td>
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<td>Theia-Xe</td>
<td>$^{136}$Xe</td>
<td>3% in liquid scintillator</td>
<td>50 tonnes</td>
<td>R&amp;D</td>
</tr>
</tbody>
</table>
Outline

• Introduction

• Experiments
  • Bolometers
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  • Scintillators
  • Semiconductors
  • TPCs

• Experimental summary
Bolometers: CUPID

- 250 kg of $^{100}$Mo in 1500 Li$_2$MoO$_4$ 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% $\alpha$ rejection, >99.9% $\beta/\gamma$ acceptance
  - No further R&D needed
- Background goal: 0.5 c/(FWHM t y) dominated by $2\nu\beta\beta$ pile-up and U/Th $\gamma$ 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
Bolometers: AMoRE

- 100 kg of $^{100}$Mo in >95% enriched Li$_2$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$^{100}$MoO$_4$ crystals

- Background goal: <0.05 c/(keV t y) dominated by $2\nu\beta\beta$ pile-up

- Limit sensitivity (5 years): $T_{1/2} > 8 \times 10^{26}$ yr

- AMoRE-I with 13 CaMoO$_4$ + 5 Li$_2$MoO$_4$ (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
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: $T_{1/2} > 6 \times 10^{22}$ y)
  - Next system: operate as scintillating bolometers with MMC phonon readout and Ge wafer for photons

- Crystal performance measurements
  - Good $\alpha$ discrimination
  - $E$ resolution $\sigma = 2\%$ at $Q_{\beta\beta}$ (position uniformity)
  - Purity improved x~10

- $^{48}$Ca enrichment: laser isotope separation
  - Proof-of-principle complete
  - Scaling up for mass-production

- See poster 446
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• Experimental summary
External Trackers: SuperNEMO

- Foils of isotope viewed by tracker, calorimeter
  - Foils can be made of any $\beta\beta$ isotope (SuperNEMO now $^{82}$Se)
  - Full PID($e^-$, $e^+$, $\gamma$ and $\alpha$), $\beta\beta$ kinematics, and topology: $E_{\text{single}}$, $E_{\text{sum}}$, $x$, $y$, $z$, $t$, $\cos\theta$: can be used to probe exchange mechanism

- Builds off of NEMO success: most precise 2ν$\beta\beta$ 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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• Experimental summary
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 $2
\beta\beta$ tail and $^8B$ solar $\nu$ 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

- $4 \text{ t} \rightarrow 6.5 \text{ t}^{130}\text{Te}$ 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 $\sim 10 \text{ c/(FWHM t yr)}$ dominated by $^8\text{B}$ solar $\nu$ scattering
- Limit sensitivity (10 years): $T_{1/2} > 10^{27} \text{ yr}$
- Plan to increase loading after only 2.5 years of running in Phase I (1.3 t $^{130}\text{Te}$)
- See posters 424, 425, 432, 533, 544
Scintillators: Theia and ZICOS

- **Theia-Te/Xe:** balloon of isotope-loaded LAB in 100 kt WbLS detector
  - 5% natTe (31 tons) or 3% enrXe (50 tons) (other isotopes possible)
  - 3% / $\sqrt{E}$ resolution, Cherenkov separation
  - Dominant background: solar $\nu$
    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: 2$\nu$$\beta\beta$ tail
    Limit sensitivity (10 years): $T_{1/2} > 10^{27}$ yr
  - R&D / design in progress, 2027 start at Kamioka. See poster 66

From Y. Fukuda and G. Orebi Gann
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• Experimental summary
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 xtal 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

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**LEGEND-1000 Backgrounds**

- **L1000 BG goal** (SNOLab)
  
<table>
<thead>
<tr>
<th>Category</th>
<th>Backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>U, Th Chains</td>
<td>10$^{-7}$</td>
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<tr>
<td>Underground Ar</td>
<td>10$^{-6}$</td>
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<tr>
<td>Ge Cosmogenics</td>
<td>10$^{-4}$</td>
</tr>
<tr>
<td>Surface $\alpha$</td>
<td>10$^{-2}$</td>
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<tr>
<td>Cosmic Rays</td>
<td>10$^{-1}$</td>
</tr>
<tr>
<td>Total</td>
<td>10$^{-6}$</td>
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</tbody>
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**LEGEND-1000 Concept**

Test deployment

Spring 2020
Semiconductors: SELENA

- Amorphous $^{82}$Se x-ray detectors readout by CMOS pixel array
  - Stack to achieve high density, high mass array
  - 5 $\mu$m 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)

J. Detwiler

MC: x1000 $\beta$ rejection with 50% $\beta\beta$ acceptance

J. Inst. 12, P03022 (2017) and A. Chavarria
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• Experimental summary
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 $\sim$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
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
$^{136}$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
TPCs: PandaX, AXEL, NvDEX

• **PandaX**
  - PandaX-4T (360 kg $^{136}\text{Xe}$): upgrade of PandaX-II dual-phase LXe TPC for DM @CJPL, commissioning by end of 2020. 30T upgrade in planning.
  - PandaX-III: $0\nu\beta\beta$-focused HPGXe TPC with ~100 kg $^{136}\text{Xe}$ using micromegas readout. Limit sensitivity: $9\times10^{-25}$ 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**
  - $^{86}\text{SeF}_6$ HP gas TPC with Topmetal CMOS readout
  - 100 kg vessel designed, construction at CJPL starting next year

From K. Han, A. Ichikawa, Y. Mei
DM Dual-Phase LXe TPCs: LZ, DARWIN

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

- **DARWIN**
  - 50 t evolution of XENON experiment: 3.5 tons \text{136}Xe
  - Background \sim 0.2 \text{c/(FWHM t y)} dominated by radioactivity, \text{137}Xe
  - Discovery sensitivity (10 years): \( T_{1/2} > 10^{27} \) y
  - Data taking scheduled to start 2027
Other R&D: LiquidO, R2D2

- **LiquidO**
  - Opaque loaded LS + WS fibers: tracking / PID in LS with very high loading
  - Prototyping 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)
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- Experimental summary
Isotope Mass

$[\text{kg}_{iso}]$

10
$10^2$
$10^3$
$10^4$

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

$^76\text{Ge}$

$^136\text{Xe}$

$^130\text{Te}$

$^{100}\text{Mo}$

$^48\text{Ca} + ^{82}\text{Se} + ^{96}\text{Zr} \ldots$
Lower efficiency due primarily to fiducialization.
Next generation experiments:
<1 bkg count/year
Discovery Sensitivity Comparison

J. Detwiler

Agostini, Benato, JD, Menendez, Vissani
Discovery Sensitivity Comparison

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Sensitive Exposure [mol (_{\text{iso}}) yr]</th>
<th>Sensitive Background [cts / (mol (_{\text{iso}}) yr)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MJD</td>
<td>3x10(^{-3}) yr</td>
<td>3x10(^{-2}) yr</td>
</tr>
<tr>
<td>K-Zen 400</td>
<td>3x10(^{-3}) yr</td>
<td>3x10(^{-2}) yr</td>
</tr>
<tr>
<td>GERDA-II</td>
<td>3x10(^{-3}) yr</td>
<td>3x10(^{-2}) yr</td>
</tr>
<tr>
<td>NEXT-100</td>
<td>3x10(^{-3}) yr</td>
<td>3x10(^{-2}) yr</td>
</tr>
<tr>
<td>K-Zen 800</td>
<td>3x10(^{-3}) yr</td>
<td>3x10(^{-2}) yr</td>
</tr>
<tr>
<td>EXO-200</td>
<td>3x10(^{-3}) yr</td>
<td>3x10(^{-2}) yr</td>
</tr>
<tr>
<td>PandaX-III</td>
<td>3x10(^{-3}) yr</td>
<td>3x10(^{-2}) yr</td>
</tr>
<tr>
<td>LZ</td>
<td>3x10(^{-3}) yr</td>
<td>3x10(^{-2}) yr</td>
</tr>
<tr>
<td>CUORE</td>
<td>3x10(^{-3}) yr</td>
<td>3x10(^{-2}) yr</td>
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<tr>
<td>SNO+</td>
<td>3x10(^{-3}) yr</td>
<td>3x10(^{-2}) yr</td>
</tr>
<tr>
<td>SNO+II</td>
<td>3x10(^{-3}) yr</td>
<td>3x10(^{-2}) yr</td>
</tr>
<tr>
<td>K2-Zen</td>
<td>3x10(^{-3}) yr</td>
<td>3x10(^{-2}) yr</td>
</tr>
<tr>
<td>PandaX 1T</td>
<td>3x10(^{-3}) yr</td>
<td>3x10(^{-2}) yr</td>
</tr>
<tr>
<td>COPID</td>
<td>3x10(^{-3}) yr</td>
<td>3x10(^{-2}) yr</td>
</tr>
<tr>
<td>DARWIN</td>
<td>3x10(^{-3}) yr</td>
<td>3x10(^{-2}) yr</td>
</tr>
<tr>
<td>NEXT-HD</td>
<td>3x10(^{-3}) yr</td>
<td>3x10(^{-2}) yr</td>
</tr>
<tr>
<td>nEXO</td>
<td>3x10(^{-3}) yr</td>
<td>3x10(^{-2}) yr</td>
</tr>
<tr>
<td>LEGEND-200</td>
<td>3x10(^{-3}) yr</td>
<td>3x10(^{-2}) yr</td>
</tr>
<tr>
<td>LEGEND-1000</td>
<td>3x10(^{-3}) yr</td>
<td>3x10(^{-2}) yr</td>
</tr>
</tbody>
</table>

Legend:
- \(m_{\beta\beta}(Mo) = 17\) meV
- \(m_{\beta\beta}(Te) = 17\) meV
- \(m_{\beta\beta}(Xe) = 17\) meV
- 1x10\(^{-3}\) yr
- 3x10\(^{-3}\) yr
- 1x10\(^{-2}\) yr
- 3x10\(^{-2}\) yr
- 1x10\(^{-1}\) yr
- 3x10\(^{-1}\) yr
- 1x10\(^{0}\) yr
- 3x10\(^{0}\) yr
- 1x10\(^{1}\) yr
- 3x10\(^{1}\) yr
- 1x10\(^{2}\) yr
- 3x10\(^{2}\) yr
- 1x10\(^{3}\) yr
- 3x10\(^{3}\) yr
- 1x10\(^{4}\) yr
- 3x10\(^{4}\) yr
- 1x10\(^{5}\) yr
- 3x10\(^{5}\) yr

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Agostini, Benato, JD, Menendez, Vissani

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Discovery Sensitivity Comparison

- **Legend-200**
- **LEGEND-1000**
- **EXO-200**
- **nEXO**
- **NEXT-1000**
- **NEXT-HD**
- **DARWIN**
- **LZ**
- **CUORE**
- **PandaX-III**
- **K-Zen 400**
- **K-Zen 800**
- **GERDA-II**

**Discovery Sensitivity** Comparison

- **Running or Completed**

- **SNO+**
- **SNO+II**

**Preliminary**

- **Agostini, Benato, JD, Menendez, Vissani**

- **m$_{\beta\beta}$(Mo)=17 meV**
- **m$_{\beta\beta}$(Te)=17 meV**
- **m$_{\beta\beta}$(Xe)=17 meV**

**Sensitive exposure [mol$_{iso}$ yr]**

**Sensitive background [cts / (mol$_{iso}$ ROI yr)]**

**100Mo**

**130Te**

**136Xe**

**76Ge**

**EDF NME**

**3x10$^{25}$ yr**

**1x10$^{26}$ yr**

**1x10$^{27}$ yr**

**1x10$^{28}$ yr**
Discovery Sensitivity Comparison
Discovery Sensitivity Comparison

preliminary

recent

\[ 99.7\% \text{ CL discovery sensitivity [eV]} \]

\[ 3 \times 10^{-10} \]

\[ 1 \times 10^{-10} \]

\[ 1 \times 10^{-14} \text{ TeV} \]

\[ \Lambda \text{ (dim9): NSM, QRPA} \]

\[ \Lambda \text{ (dim7): NSM, QRPA} \]

J. Detwiler
Discovery Sensitivity Comparison

- GERDA-II
- MJD
- LEGEND-200
- LEGEND-1000
- EXO-200
- nEXO
- NEXT-100
- NEXT-HD
- DARWIN
- LZ
- PandaX-Ill
- K-Zen 400
- K-Zen 800
- K2-Zen
- SNO+
- SNO+II
- CUORE
- CUPID
- Amore-II

- GERDA-II
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- SNO+
- SNO+II
- CUORE
- CUPID
- Amore-II

99.7% CL discovery sensitivity [eV]

10^{-2} - 10^{-1}
m_{\nu} 99.7\% CL discovery sensitivity [eV]

10^{-3} - 10^{-1}
99.7\% CL discovery sensitivity [PeV]

Preliminary
Agostini, Benato, JD, Menendez, Vissani
Discovery Sensitivity Comparison
Discovery Sensitivity Comparison

- GERDA-II
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- SNO+
- SNO+II
- CUORE
- CUPID
- Amore-II

99.7% CL discovery sensitivity [eV]

- 10^{-2}
- 10^{-1}
- 1

- 14 TeV

- 10^{-3}
- 10^{-2}
- 1
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!