Search for Neutrinoless Double Beta Decay: Recent Results and Future Prospects

Karsten M. Heeger
Yale University
CIPANP, May 19, 2015
Neutrinos - The First 85 Years

1930 Pauli postulates neutrinos

1933 Fermi names neutrinos, formulates weak interactions theory

1938 Ray Davis detects solar neutrinos.

1956 Reines & Cowan report the first evidence of neutrinos

1957 Pontecorvo: Neutrinos may oscillate

1958 Goldhaber, Grodzins, & Sunyar at BNL demonstrate left-handed helicity

1957 Pontecorvo: Neutrinos may oscillate

1962 Steinberger, Lederman, Schwartz, et al demonstrate $\nu_e$ & $\nu_\mu$

1987 SN 1987A

1998 SuperK reports evidence for oscillation of atmospheric neutrinos.

2001/2002 SNO finds evidence for solar $\nu_e$ flavor change.

2003 KamLAND discovers disappearance of reactor $\nu_e$

2007 Borexino detection of $^7$Be solar neutrinos

2012 Daya Bay, RENO, Double Chooz measure $\theta_{13}$
Neutrinos Oscillate and Have Mass

Neutrino Oscillation experiments
- Neutrinos undergo flavor-changing oscillations
- Neutrinos have mass

Why is neutrino mass so small?
How small is it?
What is the mass generating mechanism?
Neutrino Mass and Hierarchy

We know
- mass splitting
- mixing angles
- minimum mass

\[ \Delta m_{\text{atm}}^2 \rightarrow m_\nu > 0.045 \text{ eV} \]

We don’t know
- mass ordering
- absolute scale
- CP phases
- nature of neutrino mass
Early Days of Double Beta Decay

1930, Pauli

Fig. 5. Energy distribution curve of the beta-rays.

1932, Fermi

1935, Goeppert Mayer

1937, Majorana

\[ \nu = \bar{\nu} \]
Double Beta Decay

\[ 2\nu_{\beta\beta} \]

Proposed in 1935 by Maria Goeppert-Mayer

**Observed in several nuclei**

\[ T_{1/2} \sim 10^{19} - 10^{21} \text{ yrs} \]

\[ 0\nu_{\beta\beta} \]

Proposed in 1937 by Ettore Majorana

**Not observed yet**

\[ T_{1/2} \geq 10^{25} \text{ y} \]

\[ (N, Z) \rightarrow (N - 2, Z + 2) + e^- + e^- \]

\( \Delta L = 2: \) total lepton number violation (LNV)

nuclei are a laboratory to study lepton number violation at nuclear energies
Physics of Neutrinoless Double Beta Decay

B-L conserved in Standard Model

0νββ is the most powerful and comprehensive probe of Lepton Number Violation, sensitive to new physics over a vast range of scales, with far reaching implications

Observation of 0νββ would be direct evidence for new physics

Demonstrate that neutrinos are Majorana fermions

Probe new mechanism of neutrino mass generation, reaching up to GUT scale

Probe key ingredient needed to generate cosmic baryon asymmetry via leptogenesis. Sakharov conditions.

Proposed experiments have discovery potential in a variety of mechanisms
Double Beta Decay Mechanism

**Standard**

Light Majorana neutrino exchange

\[
\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu} g_A^4 \left| M^{(0\nu)} \right|^2 \langle m_{\beta\beta} \rangle^2
\]

\[
\langle m_{\beta\beta} \rangle^2 = \left| \cos^2 \theta_{12} \cos^2 \theta_{13} m_1 + \exp^{2i\lambda_2} \sin^2 \theta_{12} \cos^2 \theta_{13} m_2 + \exp^{2i(\lambda_3 - \delta_{CP})} \sin^2 \theta_{13} m_3 \right|^2
\]

**Effective Majorana Mass**

unknown phases

uncertainty form oscillation parameters (90% CL)

inverted hierarchy

normal hierarchy

nuclear matrix elements
Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

**2ν mode:** conventional 2nd order process in nuclear physics

$$\Gamma_{2\nu} = G_{2\nu} |M_{2\nu}|^2$$

$G$ are phase space factors

**0ν mode:** hypothetical process only if $M_\nu \neq 0$ AND $\nu = \bar{\nu}$

$$\Gamma_{0\nu} = G_{0\nu} |M_{0\nu}|^2 \left\langle m_{\beta\beta} \right\rangle^2$$

$G_{0\nu} \sim Q^5$
Observable Half Life of $0^{\nu}\beta\beta$

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$

$T_{1/2}^{0\nu} = 0^{\nu}\beta\beta$ half-life

$G^{0\nu}(Q, Z) = $ phase space factor ($\propto Q^5$)

$M^{0\nu} = $ nuclear matrix element

$\langle m_{\beta\beta} \rangle = $ effective $\beta\beta$ neutrino mass

$m_e = $ electron mass

**Half lives** are determined by
- phase space factor (high-Q value desirable)
- nuclear matrix elements

**Nuclear matrix elements** are calculated theoretically with different models

**Effective neutrino mass can be inferred** from half-live measurement
Experimental Sensitivity

$T_{1/2}^{0\nu}$ sensitivity \( \propto a \cdot \varepsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}} \)

- $a = $ source isotopic abundance
- $\varepsilon = $ detection efficiency
- $M = $ total mass
- $t = $ exposure time
- $b = $ background rate at $0\nu\beta\beta$ energy
- $\delta E = $ energy resolution

0νββ source with high isotopic abundance

Detector with high detection efficiency, good energy resolution, low-background

Experiment long exposure time, large total mass of isotope
Search for $0\nu\beta\beta$ - Observable Signature

Experimental Signature of $0\nu\beta\beta$
- peak at the transition Q-value
- enlarged by detector resolution
- over unavoidable $2\nu\beta\beta$ background

Example: $^{130}\text{Te}$

$Q(^{130}\text{Te})=2527$ keV
energy
= key event signature
Nuclear Structure in Double Beta Decay

Nuclear structure connects experimental rates to parameters of interaction, requires mechanism dependent nuclear matrix elements.

\[ T_{1/2} = \left( \frac{G_{0\nu}^4 |M_{0\nu}|^2}{m_e} \right)^{-1} \]

\[ Q(130\text{Te}) = 2527 \text{ keV}, \text{ good Q-value above Compton edge of 2615 keV line} \]

High natural abundance

Example: \(^{130}\text{Te}\)

Range of \(T_{1/2}\) depending on nuclear matrix element

Karsten Heeger, Yale University  CIPANP, May 19, 2015
Isotopes and Sensitivity to $<m_{\nu\beta\beta}>$

For Ge, Te, Xe, Nd

$\left[ T_{1/2}^{0\nu} \right]^{-1} = G_{0\nu} g_A^4 |M_{0\nu}|^2 \left( \frac{\langle m_{\beta\beta} \rangle}{m_e} \right)^2$

Isotopes have comparable sensitivities in terms of rate per unit mass

Ref: Robertson
MPL A28, 2013, 1350021
arXiv:1301.1323
0νββ Signals and Backgrounds

An experimental challenge of rare events

Most measured half lives of 2νββ are O(10^{21}) years

- Compare to lifetime of Universe: 10^{10} years
- Compare to Avogadro’s number 6 x 10^{23}
- Mole of isotope will produce ~ 1 decay/day

If it exists, half lives of 0νββ would be longer
(^{130}_{\text{Te}} limits is > 10^{24} years)

<table>
<thead>
<tr>
<th>Half life (years)</th>
<th>Signal (cts/tonne-year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^{25}</td>
<td>500</td>
</tr>
<tr>
<td>5 x 10^{26}</td>
<td>10</td>
</tr>
<tr>
<td>10^{27}</td>
<td>1</td>
</tr>
<tr>
<td>10^{28}</td>
<td>0.1</td>
</tr>
</tbody>
</table>

\[
T^{0\nu}_{1/2} \propto \epsilon_{\text{eff}} \cdot I_{\text{abundance}} \cdot \text{Source Mass} \cdot \text{Time}
\]

background free

\[
T^{0\nu}_{1/2} \propto \epsilon_{\text{eff}} \cdot I_{\text{abundance}} \cdot \sqrt{\frac{\text{Source Mass} \cdot \text{Time}}{Bkg \cdot \Delta E}}
\]

background limited

backgrounds do not always scale with detector mass
Sensitivity vs Background

Example: $^{76}$Ge, similar sensitivities for other isotopes

ROI: Region of interest can be single or multidimensional (E, spatial, …)

Background control and reduction are key

J. Detwiler
J. Wilkerson
0νββ Backgrounds and Mitigation

Potential Backgrounds
- Primordial, natural radioactivity in detector components: U, Th, K
- Backgrounds from cosmogenic activation while material is above ground (ββ-isotope or shield specific, $^{60}$Co, $^3$H... )
- Backgrounds from the surrounding environment: external γ, (α,n), (n,α), Rn plate-out, etc.
- μ-induced backgrounds generated at depth: Cu,Pb(n,n’ γ), ββ-decay specific(n,n),(n,γ), direct μ
- 2 neutrino double beta decay (irreducible, E resolution dependent)

Reduce Backgrounds
- ultra-pure materials
- shielding
- deep underground
- ...

Discriminate Backgrounds
- energy resolution
- tracking (even topology)
- fiducial fits
- pulse shape discrimination (PSD)
- particle ID
- ...
*0νββ Detection Techniques*

![Diagram of detection techniques]

**Ionization**
- Tracking & Calorimetry: SuperNEMO
- Crystals: GERDA, Majorana

**Scintillation**
- Liquid: KamLAND Zen, SNO+

**TPC:** EXO, NEXT

**Phonons**
- Phonons+Light: CUPID, Lucifer, Lumineau

**Phonons**
- Bolometer: CUORE

*Combining detection techniques for improved event identification and background rejection*
Pushing experimental techniques to an extreme: coldest space in Universe, cleanest radiation detector, deepest laboratory, cleanest tracking chamber, etc…
0νββ Efforts Worldwide

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Isotope</th>
<th>Isotopic Mass</th>
<th>Start of Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUORE0, CUORE</td>
<td>$^{130}\text{I}$</td>
<td>~11 Kg, ~210 Kg</td>
<td>2013 (Running), 2015</td>
</tr>
<tr>
<td>EXO-200</td>
<td>$^{136}\text{I}$</td>
<td>~200 Kg</td>
<td>2011</td>
</tr>
<tr>
<td>GERDA I/II</td>
<td>$^{76}\text{I}$</td>
<td>~34 Kg</td>
<td>2011/15</td>
</tr>
<tr>
<td>KamLAND-Zen</td>
<td>$^{136}\text{I}$</td>
<td>~300 Kg</td>
<td>2012 (Running)</td>
</tr>
<tr>
<td>MAJORANA</td>
<td>$^{76}\text{I}$</td>
<td>~30 Kg</td>
<td>2015</td>
</tr>
<tr>
<td>NEXT</td>
<td>$^{136}\text{I}$</td>
<td>~100 Kg</td>
<td>2016</td>
</tr>
<tr>
<td>SNO+</td>
<td>$^{130}\text{I}$</td>
<td>~800 Kg</td>
<td>2016 ?</td>
</tr>
<tr>
<td>SuperNEMO</td>
<td>$^{82}\text{I}$</td>
<td>~7 Kg</td>
<td>2016</td>
</tr>
</tbody>
</table>

selection of most prominent efforts
Recent Results - Gerda Phase 1 ($^{76}$Ge)

- 87% enriched $^{76}$Ge detectors in LAr
- $Q_{\beta\beta} = 2039$ keV
- 14.6 kg of 86% enriched Ge detectors from H-M, IGEX (4.8 keV FWHM @ $Q_{\beta\beta}$)
- 3 kg of 87% enriched BEGe enriched detectors (3.2 keV FWHM @ $Q_{\beta\beta}$)
- Single-site, multi-site pulse shape discrimination

- 21.6 kg-year exposure
- Frequentist
  $T_{1/2} > 2.1 \times 10^{25}$ y (90% CL)
- Bayesian
  $T_{1/2} > 1.9 \times 10^{25}$ y (90% CL)

GERDA Collaboration, PRL 111 (2013) 122503

→G. Benato
Recent Progress - Majorana Dem. ($^{76}\text{Ge}$)

- MJD Prototype module installed and taking data in shield since July 2014. Simulations and analysis of data are underway.

One detector spectrum within a string mounted in the prototype cryostat and inside shield. FWHM 3.2 keV at 2.6 MeV

- Module 1 with more than half of all enriched detectors will go in-shield in a few days and start operation soon.

- Assembly of strings for Module 2 is underway. Anticipate completion by end of 2015.

- Expecting data from the completed Demonstrator in 2016.

⇒ Wenqin Xu
Recent Results - EXO-200 \(^{136}\text{Xe}\)

- Enriched Liquid Xe in TPC
  - \(Q_{\beta\beta} = 2457.8\) keV
  - 200 kg of 80.6% enriched \(^{136}\text{Xe}\)
  - 75.6 kg fiducial mass,
  - 100 kg years exposure
  - Combine Scintillation-Ionization signal for improved resolution (88 keV FWHM @ \(Q_{\beta\beta}\))
  - Single site - Multisite discrimination

\[ T_{1/2} > 1.1 \times 10^{25} \text{ yr (90\% CL)} \]


→ M. Tarka
Recent Results - KamLAND-Zen

- \(^{\text{enr}}\text{Xe}\) in liquid scintillator, balloon of R=1.5 m
- \(Q_{\beta\beta} = 2457.8\) keV
- Phase 1
  - 179 kg (2.44% by Xe wt.) 91.7% enriched\(^{136}\text{Xe}\)
  - R=1.35 m fiducial cut
  - 213.4 days, with 89.5 kg years exposure
  - 400 keV FWHM @ \(Q_{\beta\beta}\)
  - evidence for \(^{110m}\text{Ag}\) contamination
    \(T_{1/2} > 1.9 \times 10^{25}\) y (90% CL)
- Phase 2
  - 383 kg (2.96% by Xe wt.)
  - R=1 m fiducial cut
  - 114.8 days, with 27.6 kg years exposure
  - \(^{110m}\text{Ag}\) contamination reduced by x10
    \(T_{1/2} > 1.3 \times 10^{25}\) y (90% CL)

Combined (1&2) \(T_{1/2} > 2.6 \times 10^{25}\) y (90% CL)

KamLAND ZEN Collaboration, Shimizu, Neutrino 2014

⇒ B. Berger
Recent Results - CUORE-0 (\(^{130}\)Te)

- 11 kg \(^{130}\)Te (34% nat.) bolometer (10 m)
- \(Q_{\beta\beta}=2527.5\) keV
- Array of 52 5x5x5 cm\(^3\) TeO\(_2\) crystals
- 9.8 kg - years exposure
- FWHM of 5.1 keV

\[ T_{1/2} > 2.7 \times 10^{24} \text{ y (90\% CL)} \] CUORE-0
\[ T_{1/2} > 4.0 \times 10^{24} \text{ y (90\% CL)} \] CUORE-0 & Cuoricino

arXiv: 1504.2454

\(\Rightarrow\) T. O’Donnell
Recent Progress - CUORE ($^{130}$Te)

All 988 bolometers (206 kg of $^{130}$Te) built and assembled into towers

Cryostat Commissioning Underway

Detector installation expected in 2015
No $0\nu\beta\beta$ Signal Yet!

Limits on Effective Neutrino Mass

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**CUORE-0 Results**

$$\langle m_{\beta\beta} \rangle < 270 - 650 \text{ meV}$$

1) IBM-2 (PRC 91, 034304 (2015))
2) QRPA (PRC 87, 045501 (2013))
3) pnQRPA (PRC 024613 (2015))
4) ISM (NPA 818, 139 (2009))
5) EDF (PRL 105, 252503 (2010))

Including additional Shell-Model NME

$$\langle m_{\beta\beta} \rangle < 270 - 760 \text{ meV}$$

1) IBM-2 (PRC 91, 034304 (2015))
2) QRPA (PRC 87, 045501 (2013))
3) pnQRPA (PRC 024613 (2015))
4) Shell Model (PRC 91, 024309 (2015))
5) ISM (NPA 818, 139 (2009))
6) EDF (PRL 105, 252503 (2010))

→ J. Engel
Towards a Next-Generation Experiment

Goals/Requirements
- Expect signals of 1 count/tonne-year for half-lives of $10^{27}$ years, or $\langle m_{\beta\beta} \rangle \sim 15$ meV.
- For discovery aim for S:B of better than 1:1 in region of interest
- Region of interest can be single dimension (e.g. energy) or multi-dimensional (e.g. energy+fiducial)

Next Steps
International collaborations are building on current efforts using multiple isotopes:
- $^{76}$Ge: large Ge experiment, HPGE crystals, ton-scale
- $^{82}$Se: SuperNEMO, tracking and calorimeter, 100kg scale
- $^{136}$Xe:
  - nEXO, liquid TPC, 5 tonnes
  - NEXT/BEXT, high pressure gas TPC, tonne-scale
  - KamLAND-Zen, scintillator
- $^{130}$Te:
  - CUPID, bolometers+scintillation/Cherenkov light
  - SNO+ phase II, scintillator
- other efforts worldwide
- staged approach possible, some experiments pursue isotopic enrichment
Next Steps - SuperNEMO ($^{82}$Se)

- Thin foil with tracking and calorimeter, based on successful NEMO3 detector.
- Planar and modular design: $\sim 100$ kg of enriched isotopes
  (20 modules $\times \sim 5$-7 kg)
- Starting with single Demonstrator module, ($7$ kg of $^{82}$Se) to show scalability
- $T_{0\nu1/2} > 6.5 \times 10^{24} \gamma \rightarrow \langle m\nu \rangle < 0.20 - 0.40$ eV @ (90 % C.L.)

SuperNEMO

- 100 kg of $^{82}$Se running for 5 years
- $T_{0\nu1/2} > 1 \times 10^{26} \gamma$ (90 % C.L.) $\langle m\nu \rangle < 40$-100 meV
- $T_{0\nu1/2} = 2 \times 10^{25} \gamma$ (5$\sigma$)

**Demonstrator (1 module):**

Source (40 mg/cm$^2$) 4 x 3 m$^2$

Tracking: drift chamber ~2000 cells in Geiger mode

Calorimeter: scintillators + PMTs
  ~550 PMTs+scint. blocks

Passive water shield
Next Steps - Ge Experiment ($^{76}\text{Ge}$)

- **MAJORANA** and GERDA are working towards the establishment of a single international $^{76}\text{Ge}$ $0\nu\beta\beta$ collaboration. (Name not set: Ge1T, LSGe, …)
- Envision a phased, stepwise implementation;  
  e.g. $250 \rightarrow 500 \rightarrow 1000$ kg  
  5 yr 90% CL sensitivity: $T_{1/2} > 3.2 \cdot 10^{27}$ yr  
  10 yr 3\sigma discovery: $T_{1/2} \sim 3 \cdot 10^{27}$ yr
- Moving forward predicated on *demonstration* of projected backgrounds by MJD and/or GERDA
- Anticipate down-select of best technologies, based on results of the two experiments
Next Steps - CUPID

phonon+photon

• Cherenkov light or scintillation to distinguish \( \alpha \) from \( \beta/\gamma \) (\(^{130}\text{TeO}_2\), \(^{82}\text{Se}\), \(^{116}\text{CdWO}_4\), and \(^{100}\text{MoO}_4\))

• More rejection power needed: 99.9% \( \alpha \) background suppression. Light detector R&D for better resolution.

• Background free search.

\[ m_{\beta\beta} \sim (M \cdot t)^{-1/2}, \text{ not } (M \cdot t)^{-1/4} \]
Next Steps - CUPID

- Next-generation bolometric tonne-scale experiment. Based on the CUORE design, CUORE cryogenics
  - Largest cryostat and DU built; mature technology
- 988 enriched (90%) crystals, PID with light detection
  - TeO₂: phonons + Cherenkov detector
  - Options: ZnSe, ZnMoO₄, CdWO₄ (phonons + scintillation)
- Aim for zero-background measurement
- Sensitivity to inverted hierarchy region
  - CUORE geometry and background model
  - 99.9% α rejection @ >90% signal efficiency (5σ separation of α and β)
  - 5 keV FWHM resolution
  - Aim for nearly zero background measurement:
    background goal <0.02 events / (ton-year)
  - Half-life sensitivity (2-5)×10²⁷ years in 10 years (3σ)
  - mββ sensitivity 6-20 meV (3σ)

Next Steps - SNO+ ($^{130}$Te)

- 3% loading of Te already demonstrated
- Detector response model from Phase I predicts Phase II response
- Plug-in replacement of SNO+ PMTs with R5912-HQE more than doubles light yield for Phase II
- Additional wavelength-shifter R&D could further improve this
- Containment bag R&D necessary to achieve cleanliness
- Can leverage KamLAND-Zen and BOREXINO knowledge

**Phase II:**
- $T_{1/2} > 7 \times 10^{26}$ y (90% CL, natural)
- $T_{1/2} > 10^{27}$ y (90% CL, enriched)
- $T_{1/2} > 4 \times 10^{26}$ y (3σ, natural)

External $\gamma$ and $^8$B backgrounds are fixed (but fewer in ROI because of increased light yield)

N. Barros
Next Steps - nEXO ($^{136}\text{Xe}$)

- 5 tonnes of $^{enr}\text{Xe}$
- nEXO 5 yr 90% CL sensitivity: $T_{1/2} > 6.6 \cdot 10^{27}$ yr
- LXe homogeneous imaging TPC similar to EXO-200:
  - baseline: install at SNOLAB (cosmogenic background reduced wrt EXO-200)
  - simultaneous measurement: energy, spatial extent, location, particle ID
  - Multi-parameter approach improves sensitivity: strengthens proof in case of discovery
  - inverted hierarchy covered with a well proven detector concept
  - possible later upgrade for Ba retrieval/tagging: start accessing normal hierarchy
Next Steps - KamLAND Zen ($^{130}$Xe)

KamLAND-Zen is a top runner and being improved.

KamLAND-Zen 89.5 kg-yr

$\langle m_{\beta\beta} \rangle < 160 \text{ to } 330 \text{ meV} \quad @90\% \text{ C.L.}$

the world best

KamLAND-Zen 2nd phase (2013 fall -)

100 times $^{110m}$Ag reduction expected

KamLAND-Zen 600kg

with clean mini-balloon

KamLAND2-Zen : high QE PMT, high yield LS, light concentrator

$\sigma_{\text{eff}}(2.6\text{MeV})=4\% \rightarrow <2.5\%$

Super-KamLAND-Zen

R&D for pressurized Xe

R&D for scintillation film

R&D for $\beta/\gamma$ discrimination (high sensitivity imaging)

Various low BG measurement can be accommodated.
Next Steps - BEXT ($^{136}$Xe)

- **NEXT with a Magnetic field**
- **HP$^{136}$Xe TPC + EL for high E- resolution + tracking capability**
- **Tonne-scale sensitivity:** $m_{\beta\beta} < 15 \text{ meV in } 10 \text{ t-y}$

NEW - 10 kg prototype at the LSC

1% FWHM @ 662 keV! → 0.5% at $Q_{\beta\beta}$
Towards Exploring the Inverted Hierarchy

Ton scale experiments will make discovery if
- spectrum has inverted ordering
- $m_{\text{lightest}} > 50$ meV (irrespective of ordering)

$T_{1/2} \sim 10^{24} \text{ yrs}$
$\sim 1 \text{ eV}$
kg scale

$T_{1/2} \sim 10^{25-10^{26}} \text{ yrs}$
$\sim 100$ meV
30-200kg scale

$T_{1/2} \sim 10^{27-10^{28}} \text{ yrs}$
$\sim 15$ meV
ton scale (phased)

Improvement of x100 over current results

Significant discovery potential
Summary

Neutrinoless double beta ($0\nu\beta\beta$) is the most powerful and comprehensive probe of lepton number violation ($\Delta L=2$).

Observation would establish lepton number violation, demonstrate that neutrinos are Majorana, and indicate physics beyond Standard Model.

Current experiments probe half lives of $10^{25}$-$10^{26}$ years and are demonstrating background reduction and scalability of experimental techniques. Expect new results in next 2-3 years.

**Tonne-scale experiments have significant discovery potential, reaching half lives of $10^{27}$-$10^{28}$ years.**

Ready for a world-wide program of $0\nu\beta\beta$ searches with different techniques and isotopes, underground locations are available.

**We are poised to look for $0\nu\beta\beta$ down to $<m_{bb}> \sim 15$ meV, covering the inverted hierarchy.**

Exciting years ahead!

Many thanks to all colleagues who contributed with slides to this talk.