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Supernova Neutrino Detection with LEGEND

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on behalf of the LEGEND collaboration

SNvD 2023@LNGS
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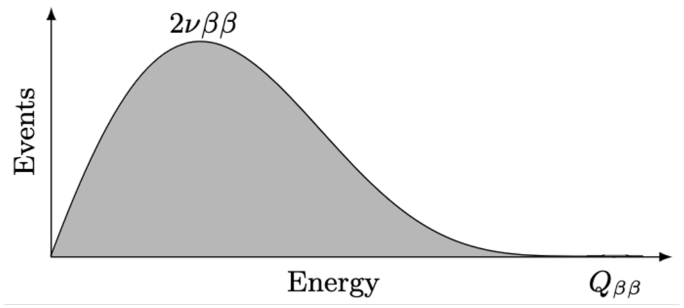
LA-UR-23-25517

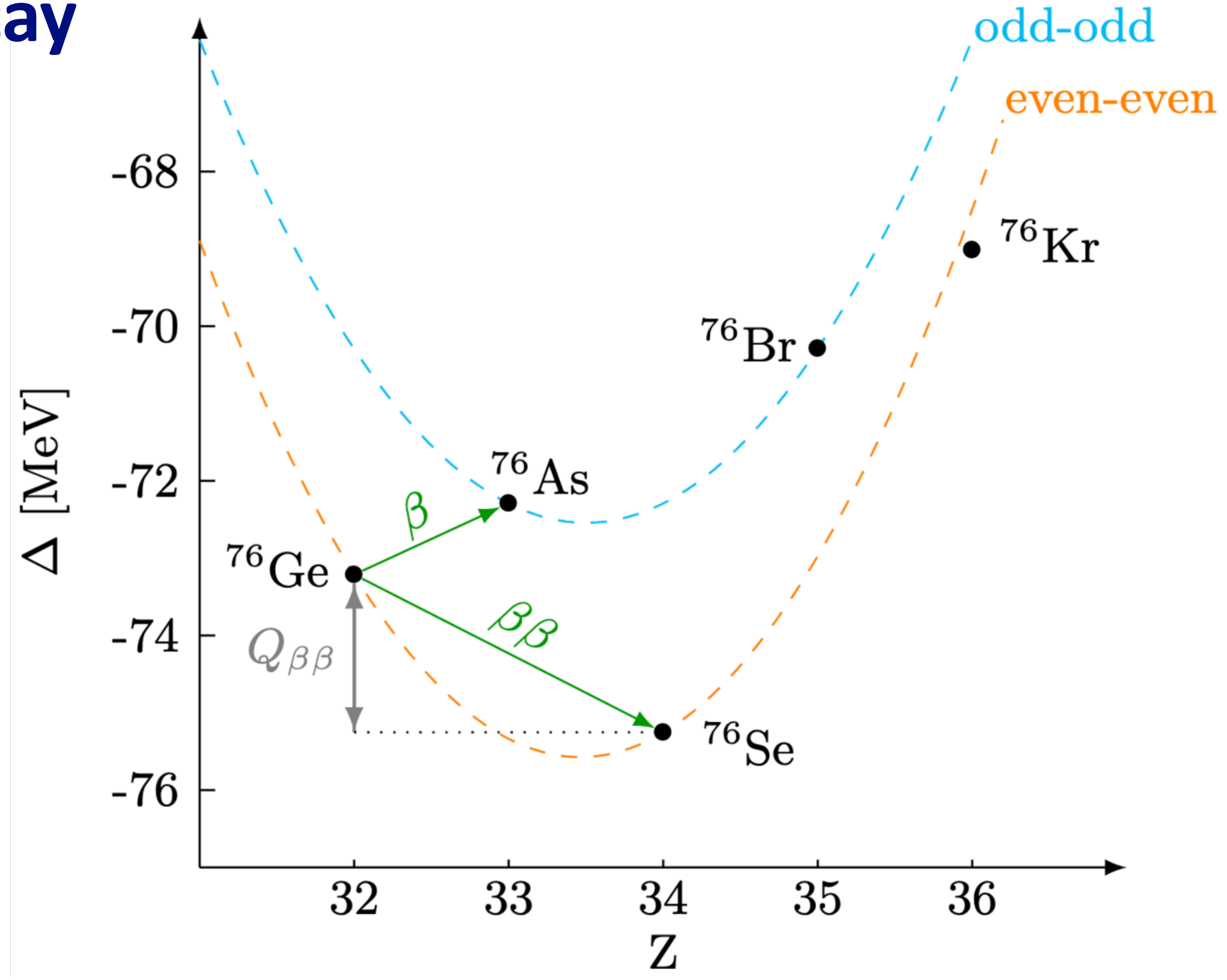
LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

Two-Neutrino Double Beta Decay

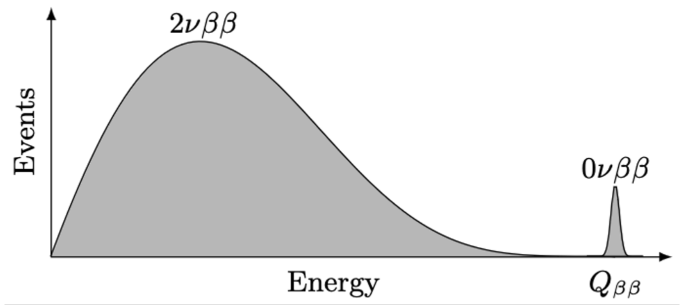
- Double beta decay
  - Energetically allowed
  - $2\nu\beta\beta$ conserves lepton number
  - Continuous beta spectrum up to $Q_{\beta\beta}$

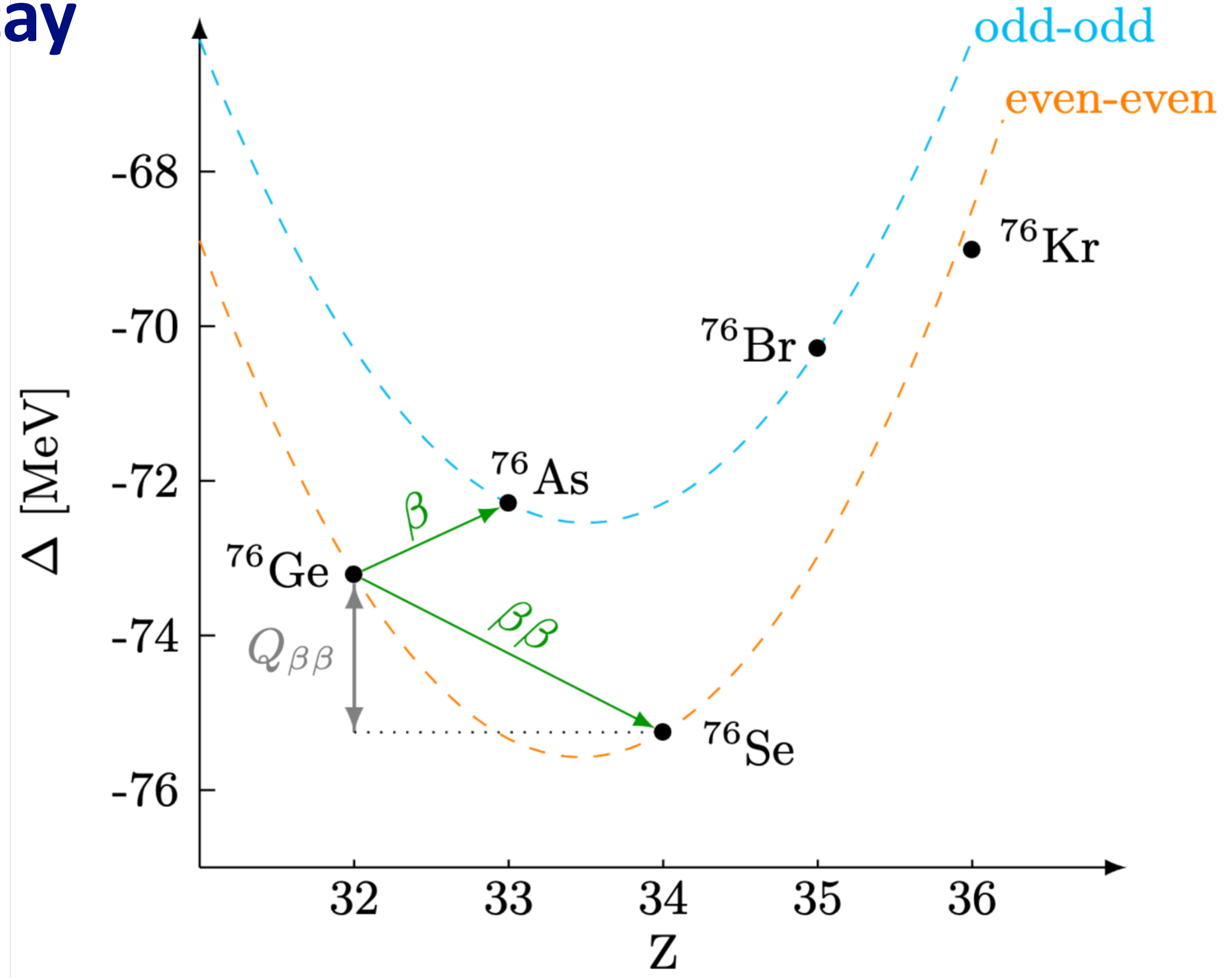




Two-Neutrino Double Beta Decay

- Double beta decay
  - Energetically allowed
  - $2\nu\beta\beta$ conserves lepton number
  - Continuous beta spectrum up to $Q_{\beta\beta}$
- But what if the neutrino was its own antiparticle?



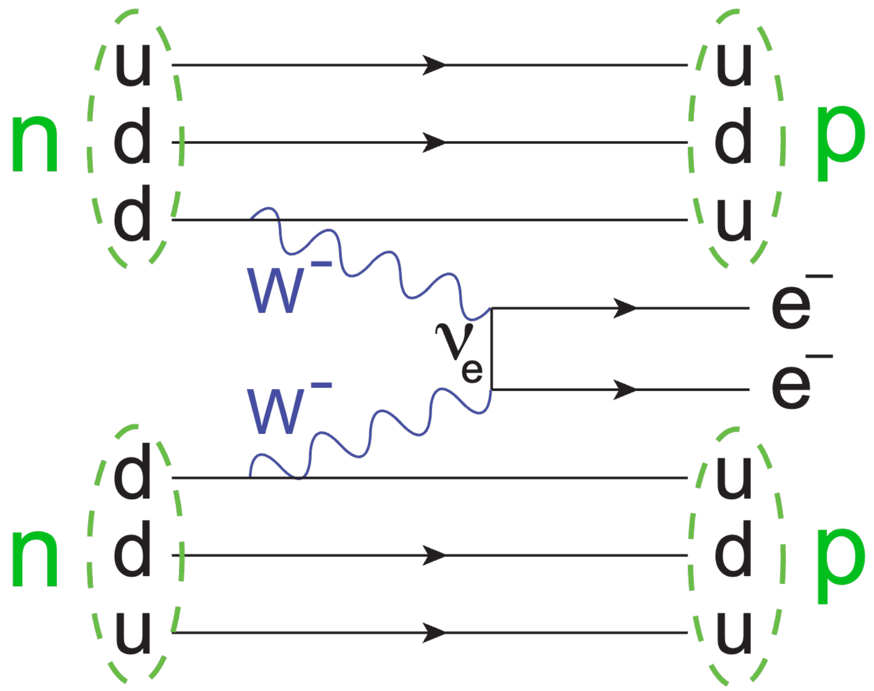


arXiv:2202.01787

The Case for Neutrinoless Double Beta Decay

- The discovery of $0\nu\beta\beta$ would **completely change** our understanding of the laws of our Universe
  - Lepton number is not conserved
  - Neutrinos are Majorana particles
  - Explains the matter-antimatter asymmetry via leptogenesis
  - Provides a mechanism for neutrino mass generation

- The LEGEND Collaboration is searching for this process in a ton-scale experiment with the ^{76}Ge isotope



LEGEND Concept

- **L**arge **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless $\beta\beta$ **D**ecay
- Merger of two successful programs: **GERDA** and **MAJORANA**
  - Each based on high-purity Ge detectors enriched in ^{76}Ge

MAJORANA

- Radiopurity of nearby parts
- Low noise electronics improves PSD
- Low energy threshold

GERDA

- LAr veto
- Low-A shield, no Pb

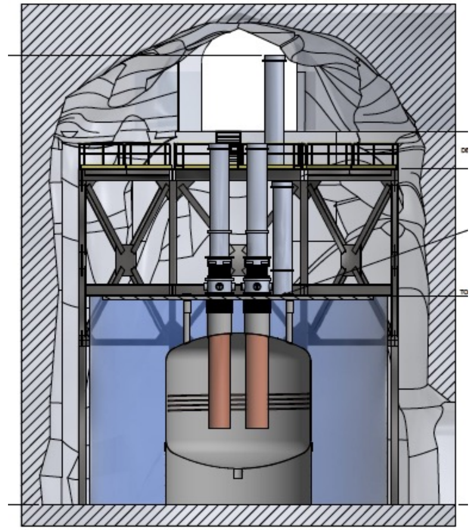
Both

- Clean fabrication techniques
- Control of surface exposure
- Development of large point-contact detectors
- Lowest background and best resolution $0\nu\beta\beta$ experiments

Phased approach

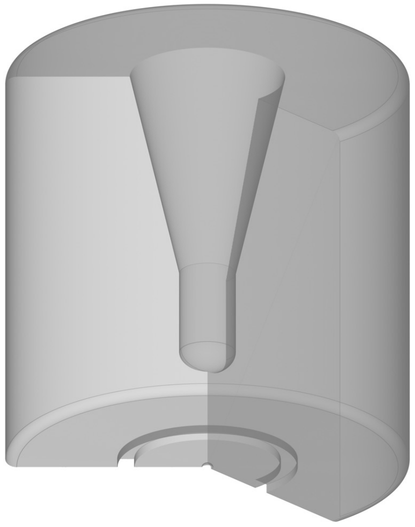
LEGEND-200 (now!)

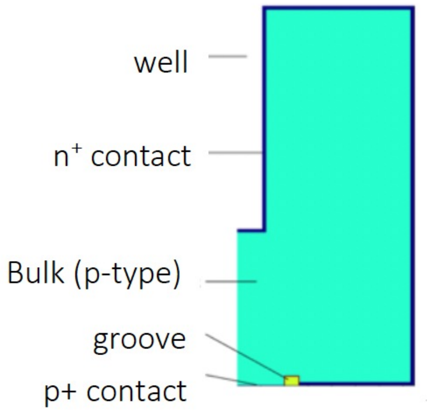
LEGEND-1000 (in design)

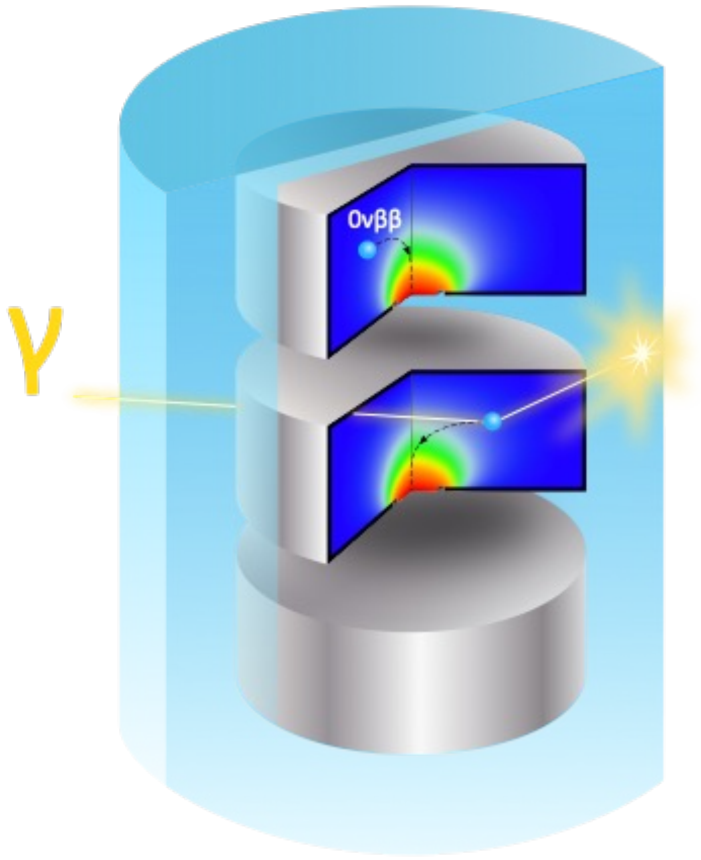


High-Purity Germanium Detectors

- A well-established detector concept
  - Point-contact detection scheme
- Used in **MAJORANA** and **GERDA**
  - Ionization detectors
  - Low background
  - Enriched in ^{76}Ge for $0\nu\beta\beta$ searches
  - Can be directly immersed in LAr







LEGEND-200: Experimental Design

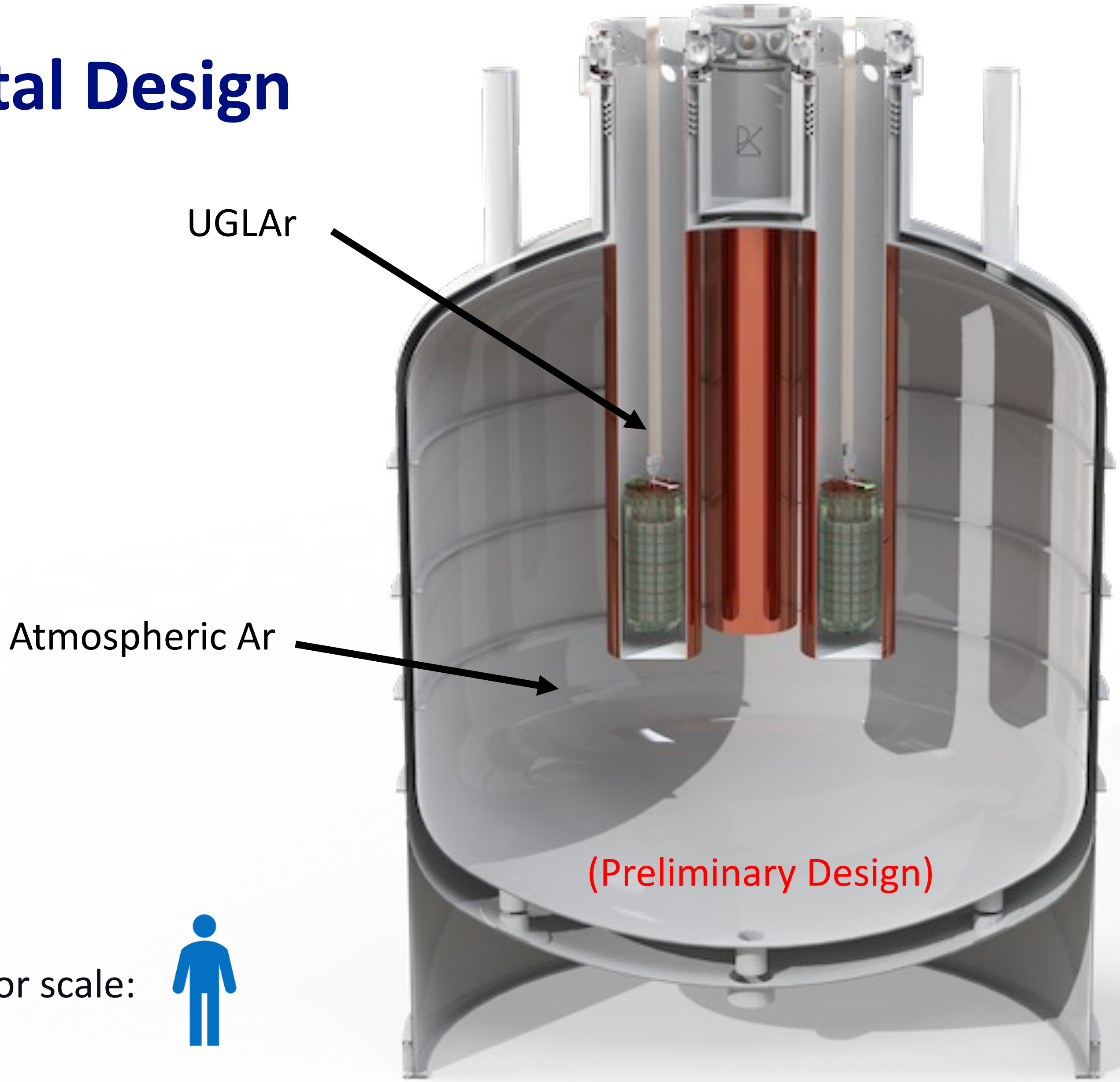
- **200 kg** of HPGe detectors
  - Taking data now!
- Using existing **GERDA** infrastructure at **LNGS**
  - Atmospheric liquid argon
  - Anticipated exposure of **1 t-yr**
  - 2.5 keV FWHM resolution at $Q_{\beta\beta}$
  - Mix of Ge detector geometries (PPC, BEGe, ICPC)
- **Background goal**: $< 2\times10^{-4}$ cts/(keV kg yr)
  - Improved electronics
  - Improved pulse shape discrimination methods
  - Improved LAr veto

Person for scale:

LEGEND-1000: Experimental Design

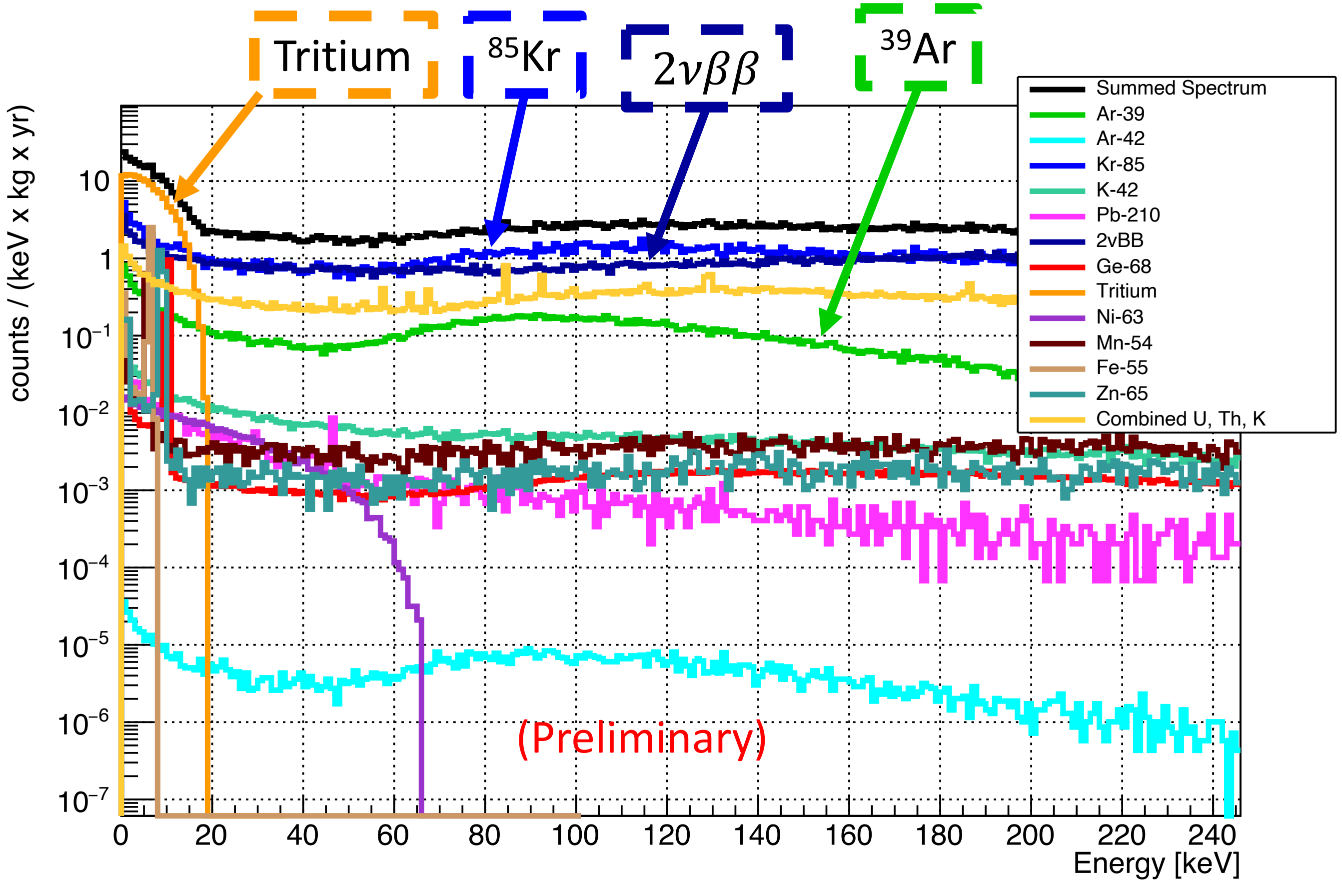
- **1000 kg** of HPGe detectors
  - Operated in a bath of **underground-sourced** LAr
  - Anticipated exposure: **10 t-yr**
  - Site to be selected
  - ~400 ICPC HPGe detectors
- **Background goal:**
  - $< 10^{-5}$ cts/(keV kg yr)

See: LEGEND-1000 pCDR, arXiv:2107.11462



Person for scale:

“Low” Energy Background Model for L-1000

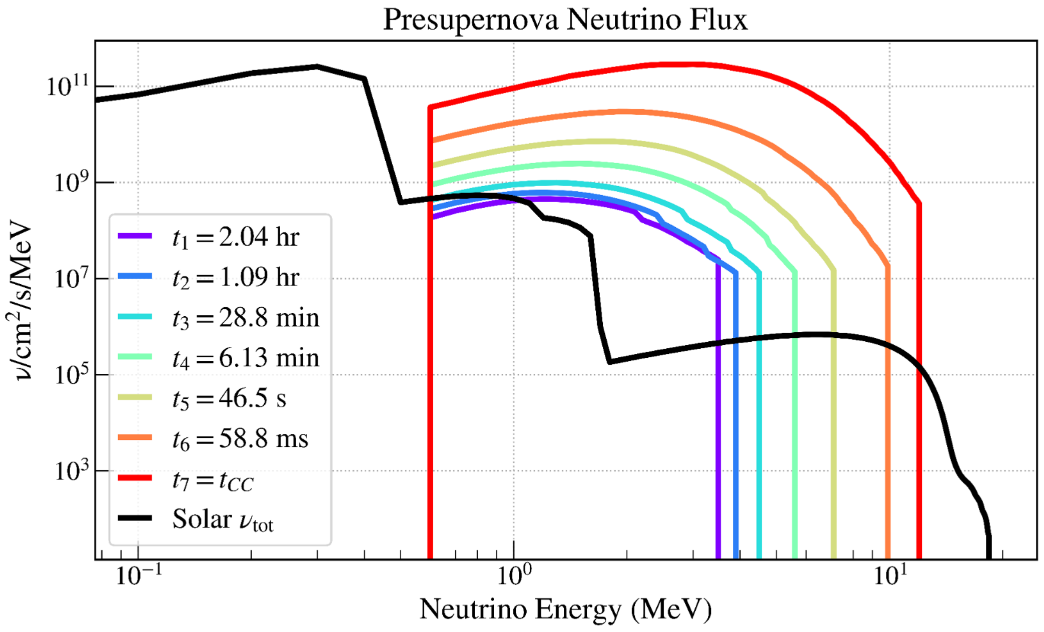


Jackson Waters Master’s Thesis (UNC)

- Simulation of background over all energies via **Geant4** framework
- Uses **L-1000 geometry**
- Assumes **underground-sourced** LAr
- Includes detector **surface effects**
- **No analysis cuts** included in this comparison

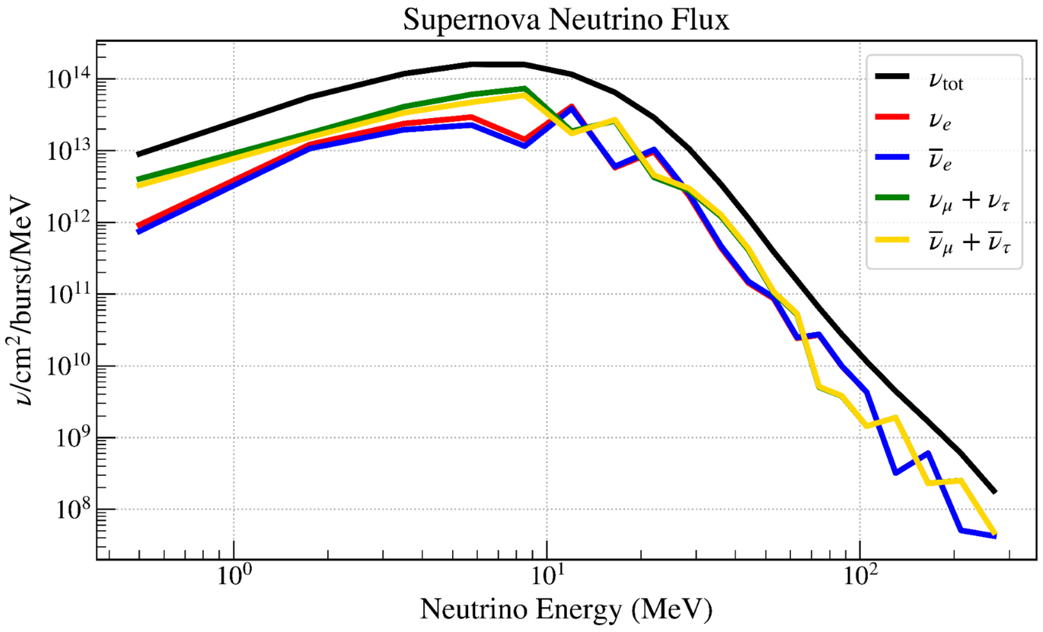
Presupernova and Supernova Neutrino Flux

- Could be sensitive to both phenomena originating from supernovae



For PreSN, assume: $m = 15M_{\odot}$, $d = 200$ pc

Patton *et al* 2017 *ApJ* **851** 6



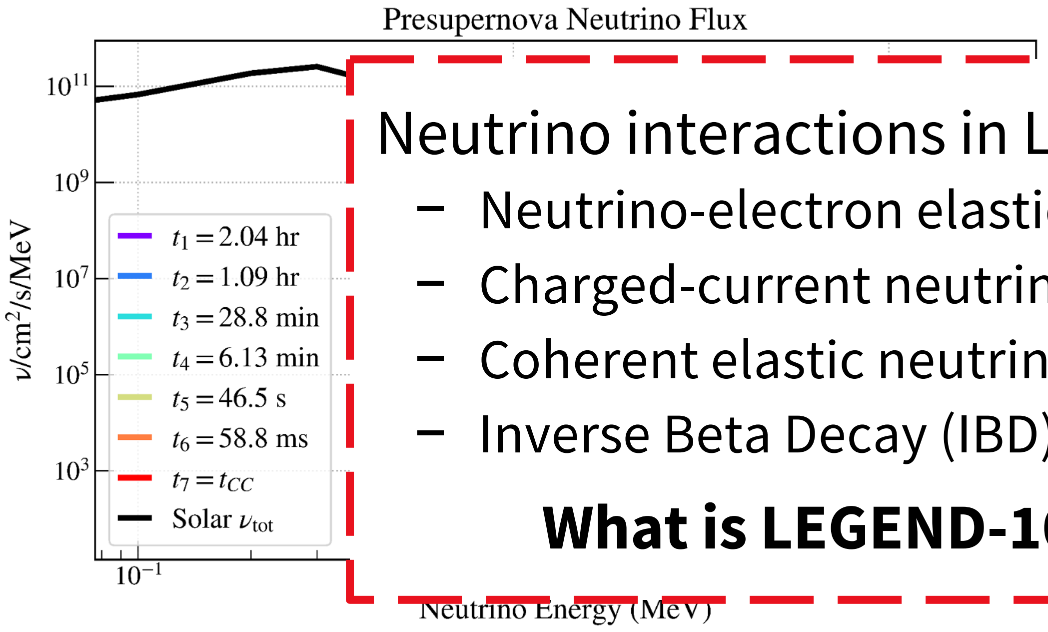
For SN, assume: $m = 20M_{\odot}$, $d = 200$ pc, $t = 20$ s

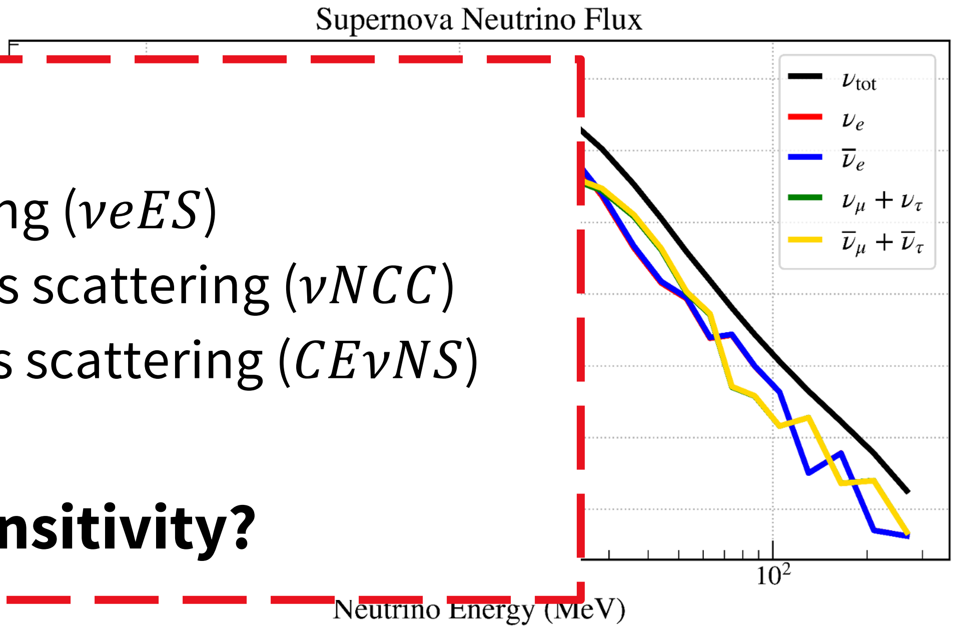
Nakazato *et al* 2013 *ApJS* **205** 2

Plots by CJ Nave (UW)

Presupernova and Supernova Neutrino Flux

- Could be sensitive to both phenomena originating from supernovae





Neutrino interactions in LEGEND:

- Neutrino-electron elastic scattering (νeES)
- Charged-current neutrino-nucleus scattering (νNCC)
- Coherent elastic neutrino-nucleus scattering ($CE\nu NS$)
- Inverse Beta Decay (IBD)

What is LEGEND-1000's sensitivity?

For PreSN, assume: $m = 15M_\odot$, $d = 200$ pc
Patton *et al* 2017 *ApJ* **851** 6

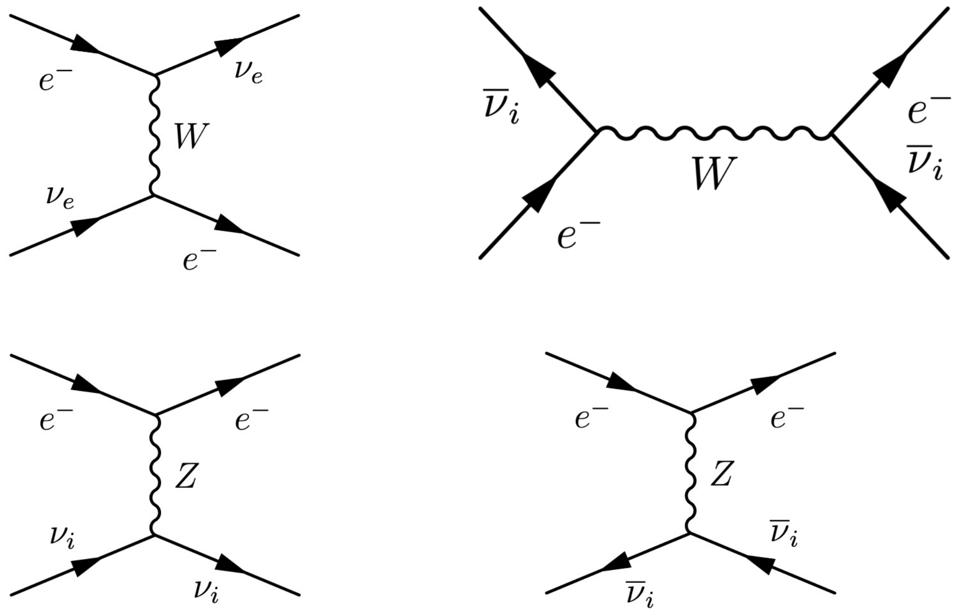
For SN, assume: $m = 20M_\odot$, $d = 200$ pc, $t = 20$ s
Nakazato *et al* 2013 *ApJS* **205** 2

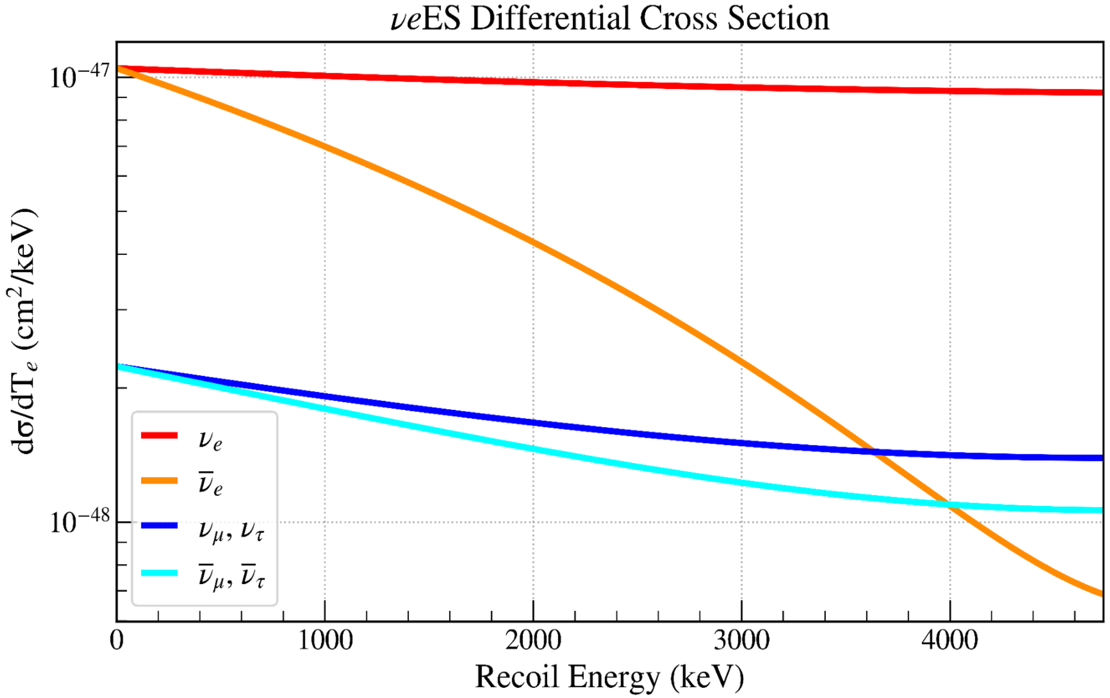
Plots by CJ Nave (UW)

Neutrino-Electron Elastic Scattering (νeES)

- Contributions to rate originate from both neutral and charged current
  - Different cross section for different neutrino types

$$\nu_x\,(\overline{\nu}_x) + e^- \rightarrow \nu_x\,(\overline{\nu}_x) + e^-$$





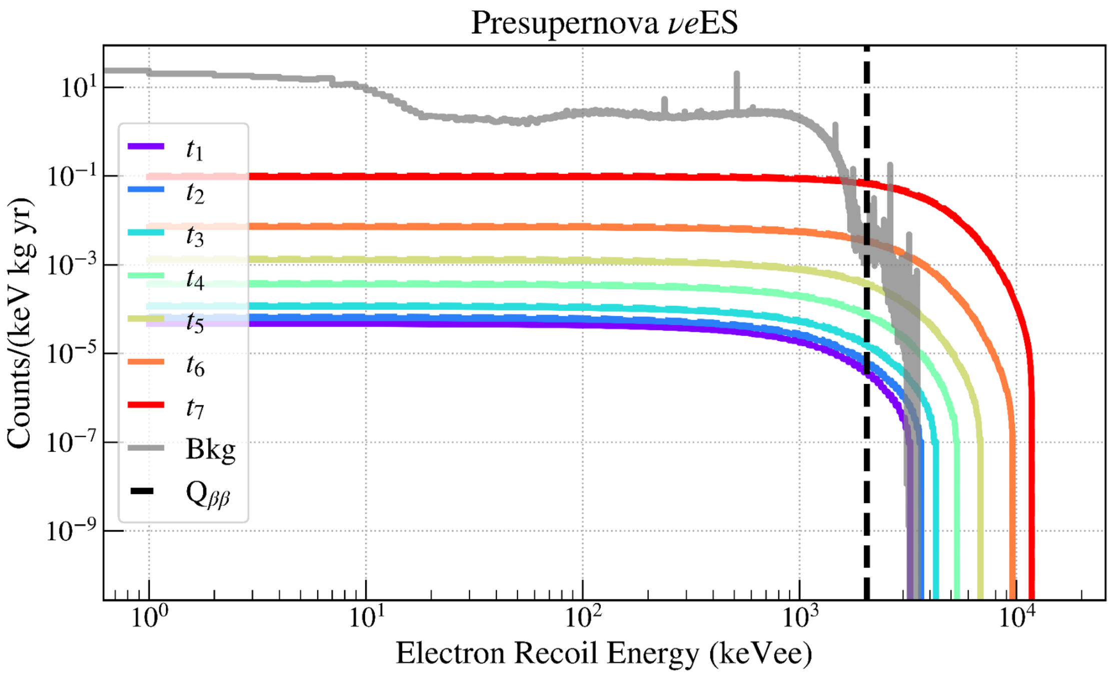
$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi}\left[(g_V + g_A)^2 + (g_V - g_A)^2\left(1 - \frac{T}{E_\nu}\right)^2 + (g_A^2 - g_V^2)\left(\frac{m_e T}{E_\nu^2}\right)\right]$$

Plot by CJ Nave (UW)

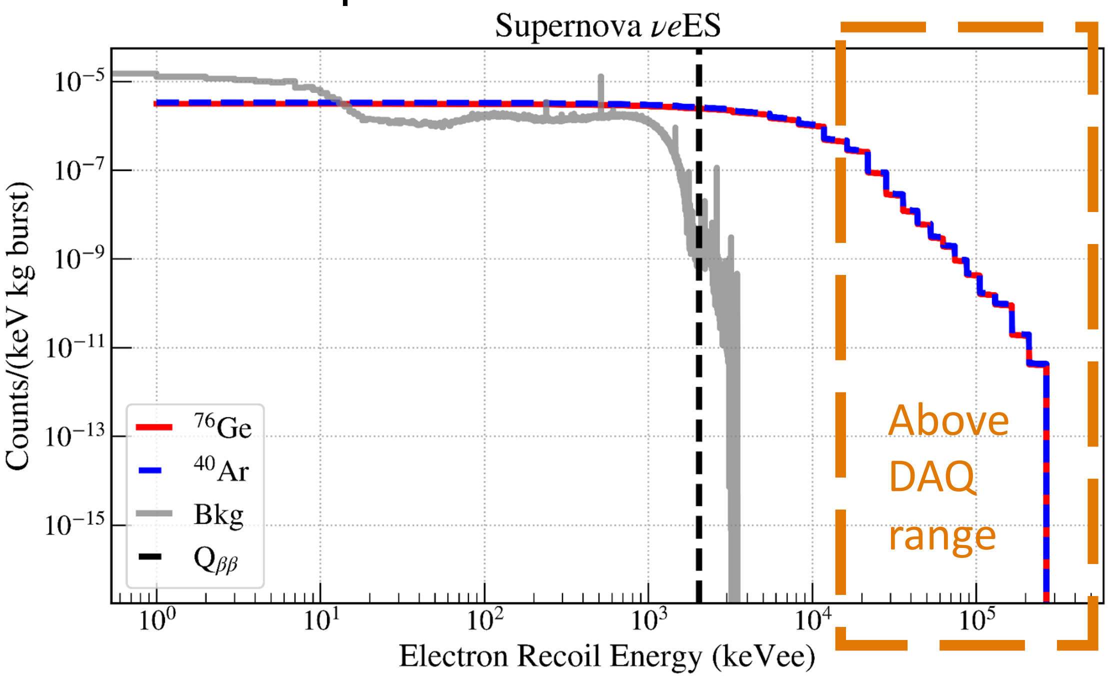
Assuming: $m = 20M_\odot$, $d = 200$ pc, $t = 20$ s

Supernova νeES in LEGEND-1000

- **PreSN**:
  - Background is well above the PreSN rate for most energies



- **SN**:
  - Expect **~2** evts/burst/ton from **background**
  - Expect **~25** evts/burst/ton for both **Ge** and **Ar** over spectrum

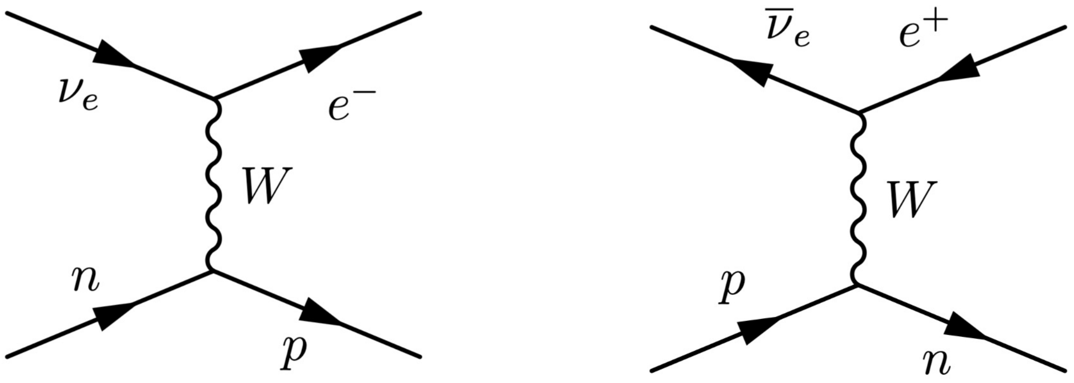


Plots by CJ Nave (UW)

Charged-Current Neutrino-Nucleus Scattering (νNCC)

- Interaction changes proton number
- In Germanium-76:
  - $\nu_e + {}^{76}\text{Ge} \rightarrow {}^{76}\text{As}^* + e^-$
  - $\bar{\nu}_e + {}^{76}\text{Ge} \rightarrow {}^{76}\text{Ga}^* + e^+$
- In Argon-40:
  - $\nu_e + {}^{40}\text{Ar} \rightarrow {}^{40}\text{K}^* + e^-$
  - $\bar{\nu}_e + {}^{40}\text{Ar} \rightarrow {}^{40}\text{Cl}^* + e^+$

$$\nu_e\,(\overline{\nu}_e) + {}^{A}_{Z}\text{X} \rightarrow {}_{Z\pm1}^{\ \ A}\text{Y} + e^{\mp}$$



$$\sigma_k = \frac{G_F^2 \cos^2\theta_c}{\pi} E_e p_e F(Z, E_e) \times \left[B(F)_k + \left(\frac{g_A}{g_V}\right)^2 B(GT)_k \right]$$

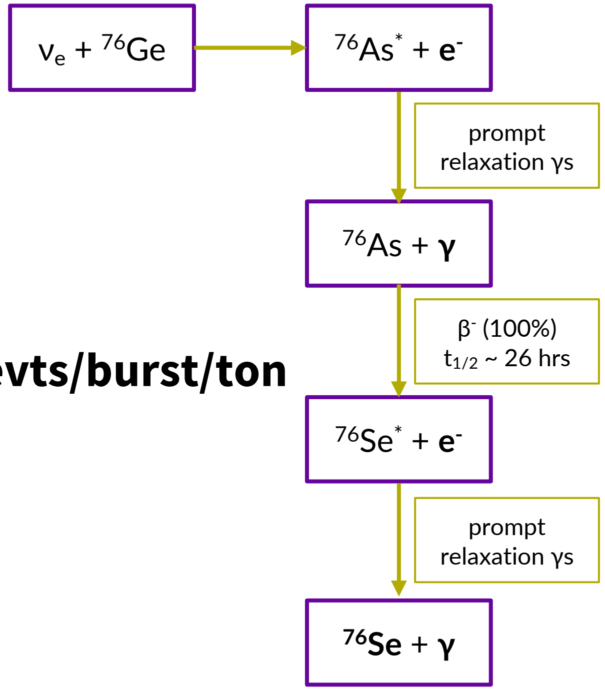
Assuming: $m = 20M_{\odot}$, $d = 200$ pc, $t = 20$ s

Supernova νNCC in LEGEND-1000

$$\sigma_k = \frac{G_F^2 \cos^2\theta_c}{\pi} E_e p_e F(Z, E_e) \times \left[B(F)_k + \left(\frac{g_A}{g_V}\right)^2 B(GT)_k \right]$$

- What event chains could LEGEND observe?

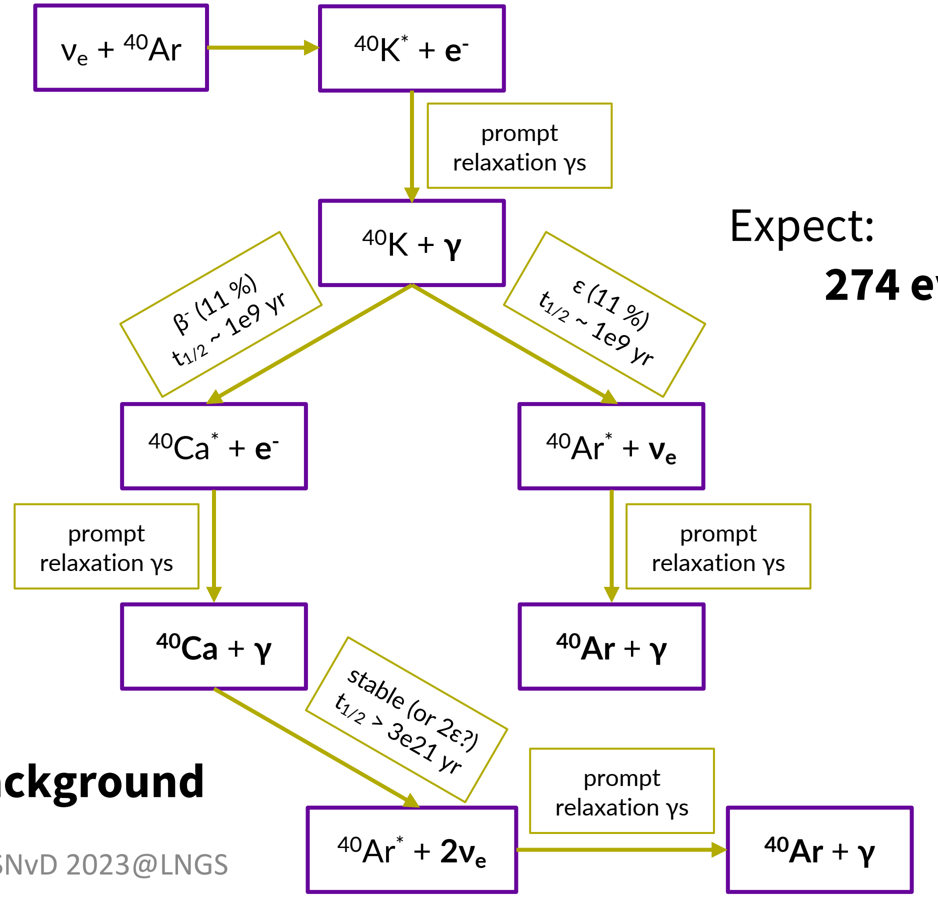
Ge → As*



Expect:

438 evts/burst/ton

Ar → K*



Expect:

274 evts/burst/ton

Expect **~2** evts/burst/ton from **background**

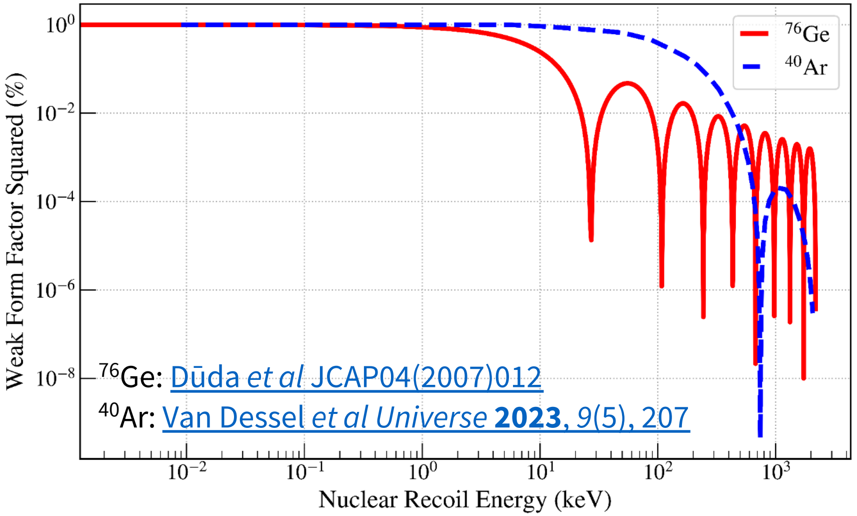
Coherent elastic neutrino-nucleus scattering ($CE\nu NS$)

Plots by CJ Nave (UW)

- Nuclear recoil which deposits energy in either a Ge detector or the liquid Ar
  - Some amount of energy creates ionization, which we can detect
  - Detection will require low thresholds

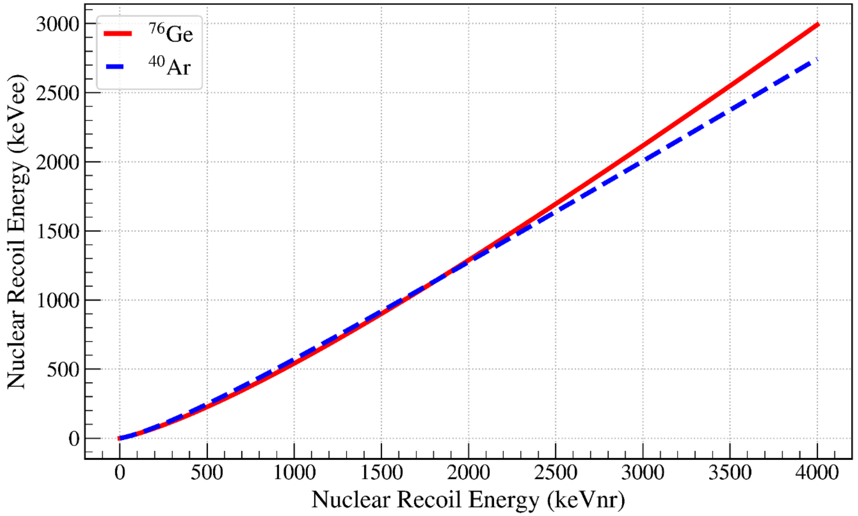
$$\nu_x\left(\overline{\nu}_x\right)+{}^{A}_{Z}\mathrm{X}\rightarrow\nu_x\left(\overline{\nu}_x\right)+{}^{A}_{Z}\mathrm{X}$$

$$\frac{d\sigma}{dT_N}=\frac{G_F^2 M_N}{4\pi}\left(1-\frac{M_N T_N}{2E_\nu^2}\right)Q_W^2 F_W^2(Q)$$



^{76}Ge: Dūda *et al* JCAP04(2007)012

^{40}Ar: Van Dessel *et al Universe* **2023**, *9*(5), 207



^{76}Ge: Li Ph.D. Thesis, Duke University (2022)

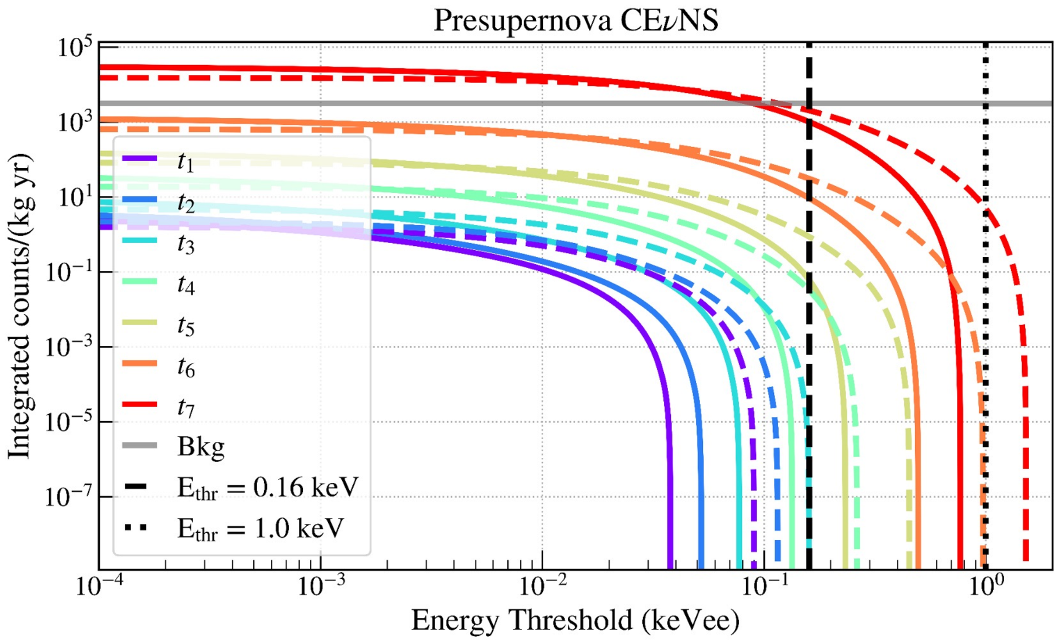
^{40}Ar: ARIS Collaboration, PRD 97, 112005 (2018)

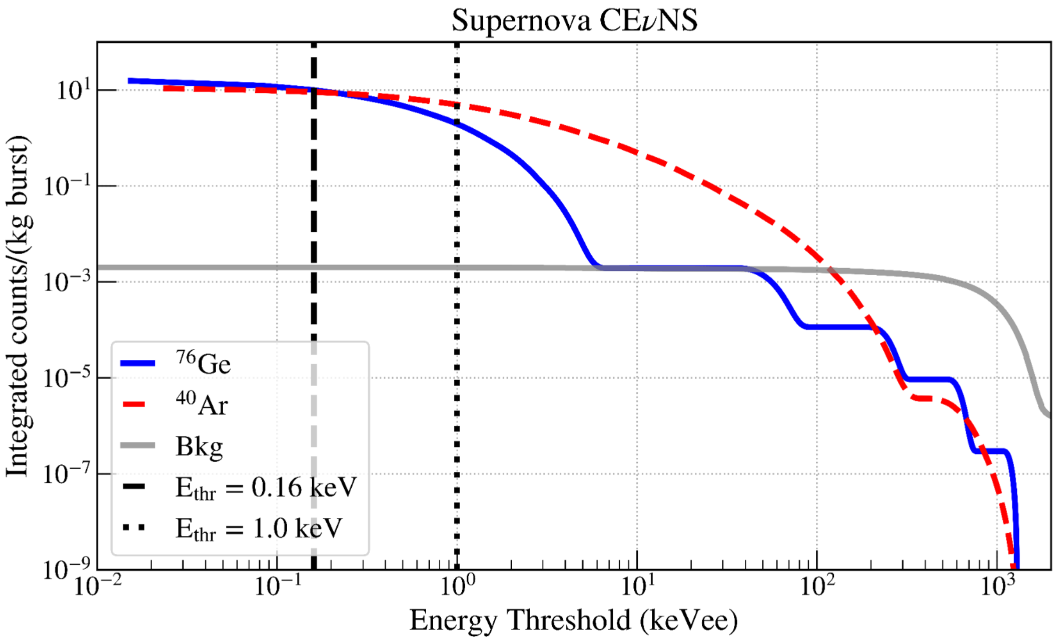
Assuming: $m = 20M_{\odot}$, $d = 200$ pc, $t = 20$ s

Supernova $CE\nu NS$ in LEGEND-1000

- **PreSN**:
  - Background is higher than SN rate until perhaps ~1 ms before core collapse

- **SN** between 1 keV and 10 keV:
  - Expect $\sim\mathbf{0.1}$ evts/burst/ton from **background**
  - Expect $\geq \mathbf{10^3}$ evts/burst/ton in **Ge** and **Ar**





Plots by CJ Nave (UW)

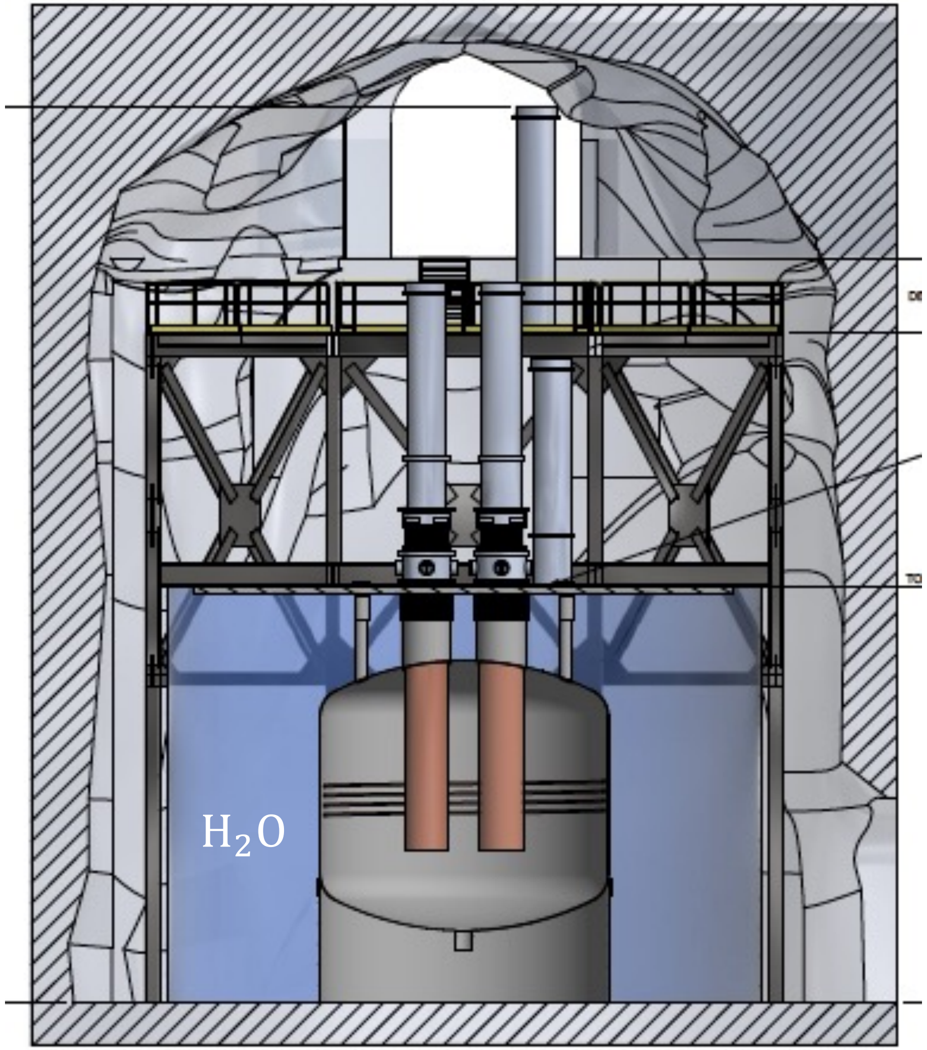
Assuming: $m = 20M_{\odot}$, $d = 200$ pc, $t = 20$ s

Supernova Inverse Beta Decay (IBD)

- LEGEND-1000 will have a kiloton-scale water shield instrumented with PMTs
  - Designed as a muon veto
- Electron antineutrinos incident on water will result in a high rate of IBD

$$\bar{\nu}_e + p \rightarrow n + e^+ \qquad \sigma = \frac{G_F^2 E_e p_e}{\pi} |U_{ud}|^2 (1 + 3g_A^2)$$

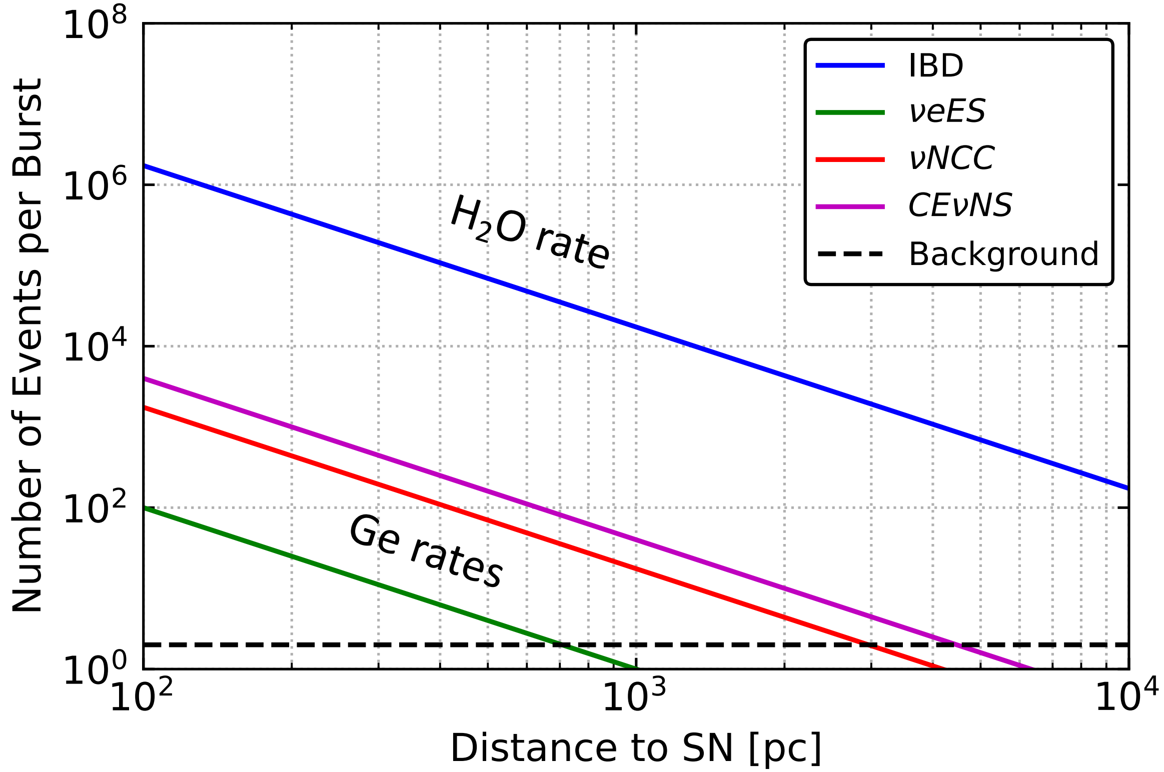
- Expect $\mathbf{4.3 \times 10^5}$ **evts/burst** in L-1000
  - Expected background: 1.2 evts/burst



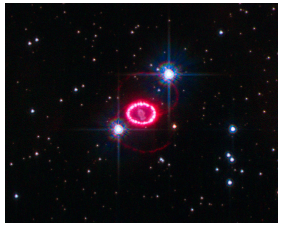
Assuming: $m = 20M_{\odot}, t = 20$ s

Supernova Neutrinos: Counts vs. Distance

- We have been assuming 200 pc (imagine Betelgeuse)
  - What about farther distances?
  - Counts scale as $\sim \mathbf{1/r^2}$



- **IBD** is our **strongest channel**
- Distances up to **O(1) kpc**, also expect significant counts for the other interactions



Summary and Outlook

- LEGEND-1000 is **uniquely sensitive** to many neutrino interaction channels
  - $\nu eES, \nu NCC, CE\nu NS$, IBD
  - Thanks to the **combination** of Ge, LAr, and water shield
- May observe some effects of **presupernova neutrinos** as an **increasing rate**
- Expect **significant counts** of **supernova neutrinos** over background
- **Complementary** to other experiments searching for supernova neutrinos

LEGEND Collaboration for $0\nu\beta\beta$

- Large international collaboration
  - ~55 institutions, ~280 members
  - MAJORANA + GERDA + more!

Goal: Achieve sensitivity of $T_{1/2}^{0\nu\beta\beta} \sim 10^{28}$ **yr** in ^{76}Ge

Backup

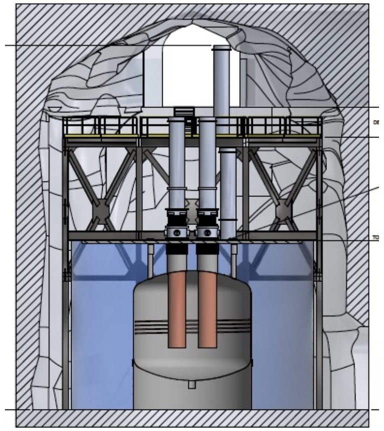
LEGEND Overview

Mission: “The collaboration aims to develop a phased, **Ge-76 based** double-beta decay experimental program with discovery potential at a **half-life beyond 10^{28} years, using existing resources as appropriate to expedite physics results**.”

Select best technologies, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.

MAJORANA	GERDA	Both
- Radiopurity of nearby parts (FETs, cables, Cu mounts, etc.) - Low noise electronics improves PSD - Low energy threshold (helps reject cosmogenic background)	- LAr veto - Low-A shield, no Pb	- Clean fabrication techniques - Control of surface exposure - Development of large point-contact detectors - Lowest background and best resolution $0\nu\beta\beta$ experiments

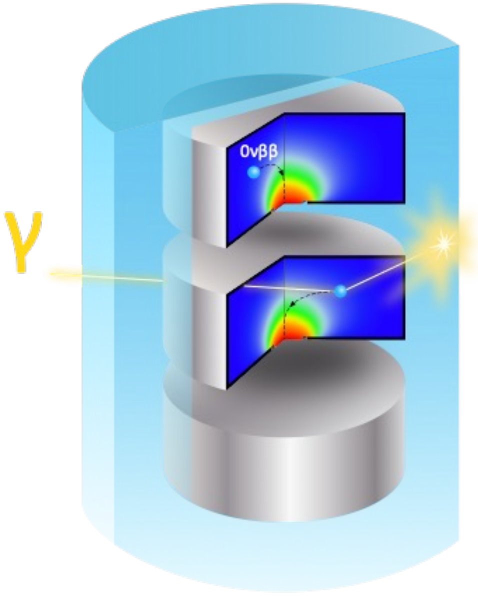
First phase:
- Deploy 200 kg in upgrade of existing infrastructure at LNGS
- BG goal: <0.6 cts/(FWHM t yr)
- Discovery sensitivity at a half-life of 10^{27} years
- Currently taking data

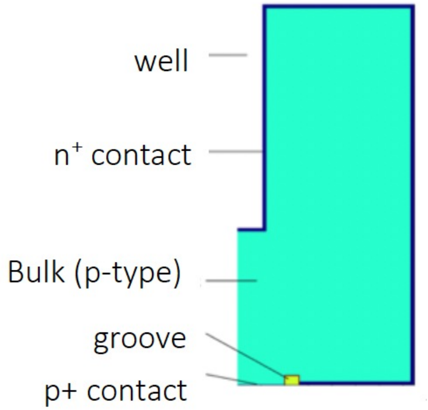


Subsequent stages:
- 1000 kg, staged via individual payloads
- Timeline connected to review process
- BG goal <0.03 cts/(FWHM t yr)
- Location to be selected

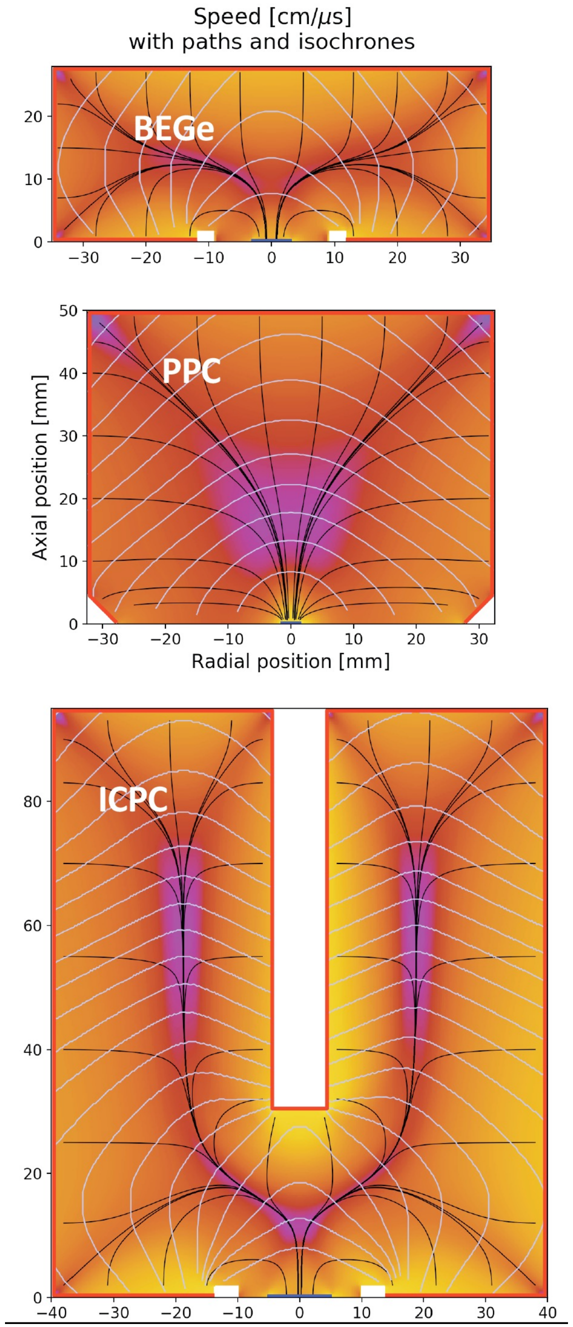
High-Purity Germanium Detectors

- Most detectors will be of ICPC type
  - Large mass, good drift time, high surface area to volume ratio



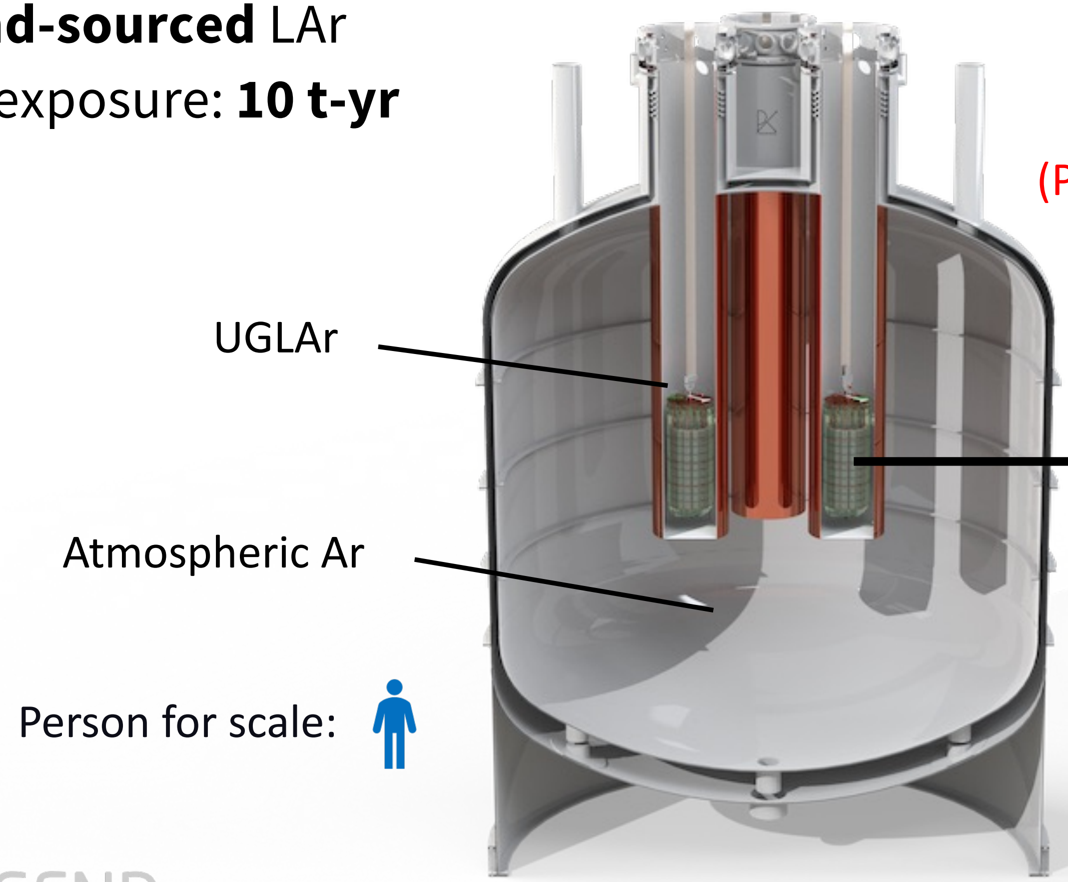


R. J. Cooper et al., NIMA 629 (2011), 303-310

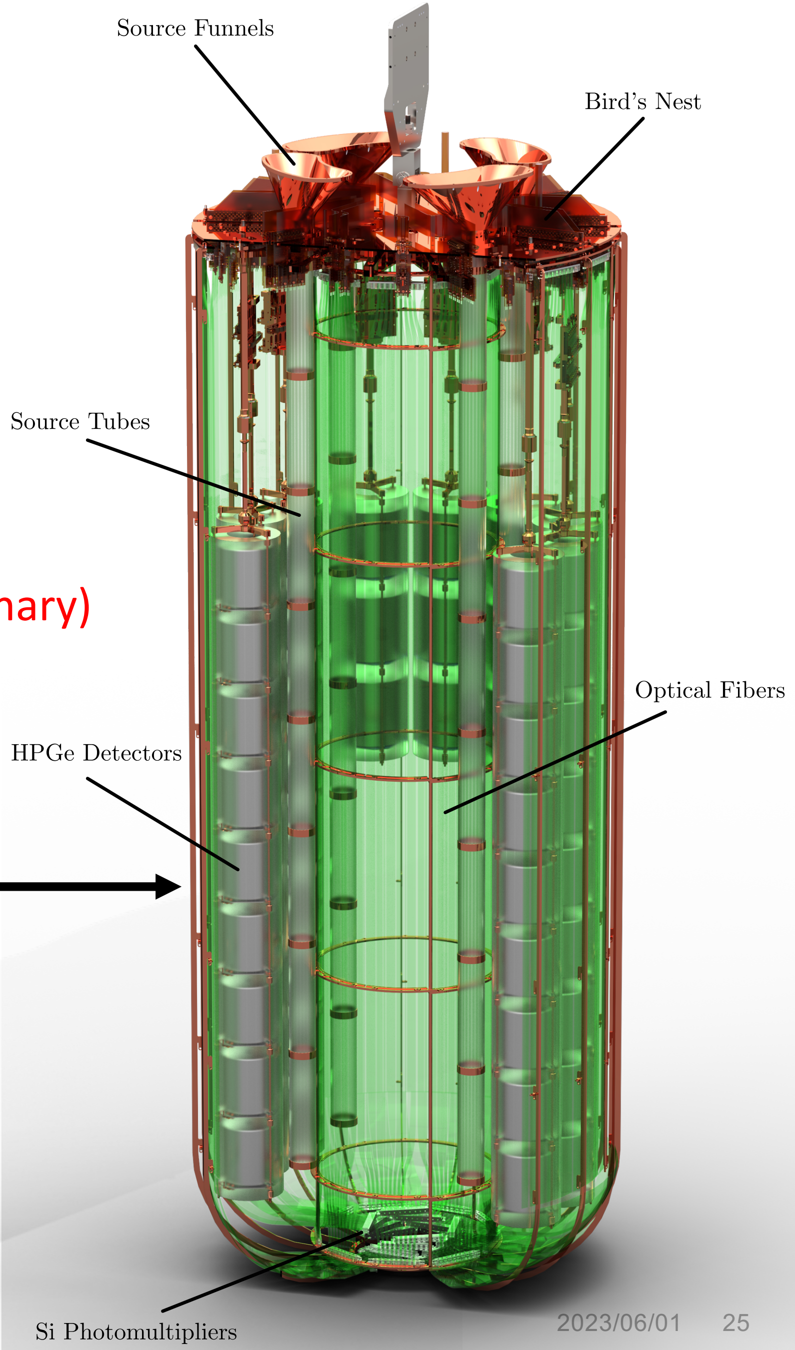


LEGEND-1000: Module Schematic

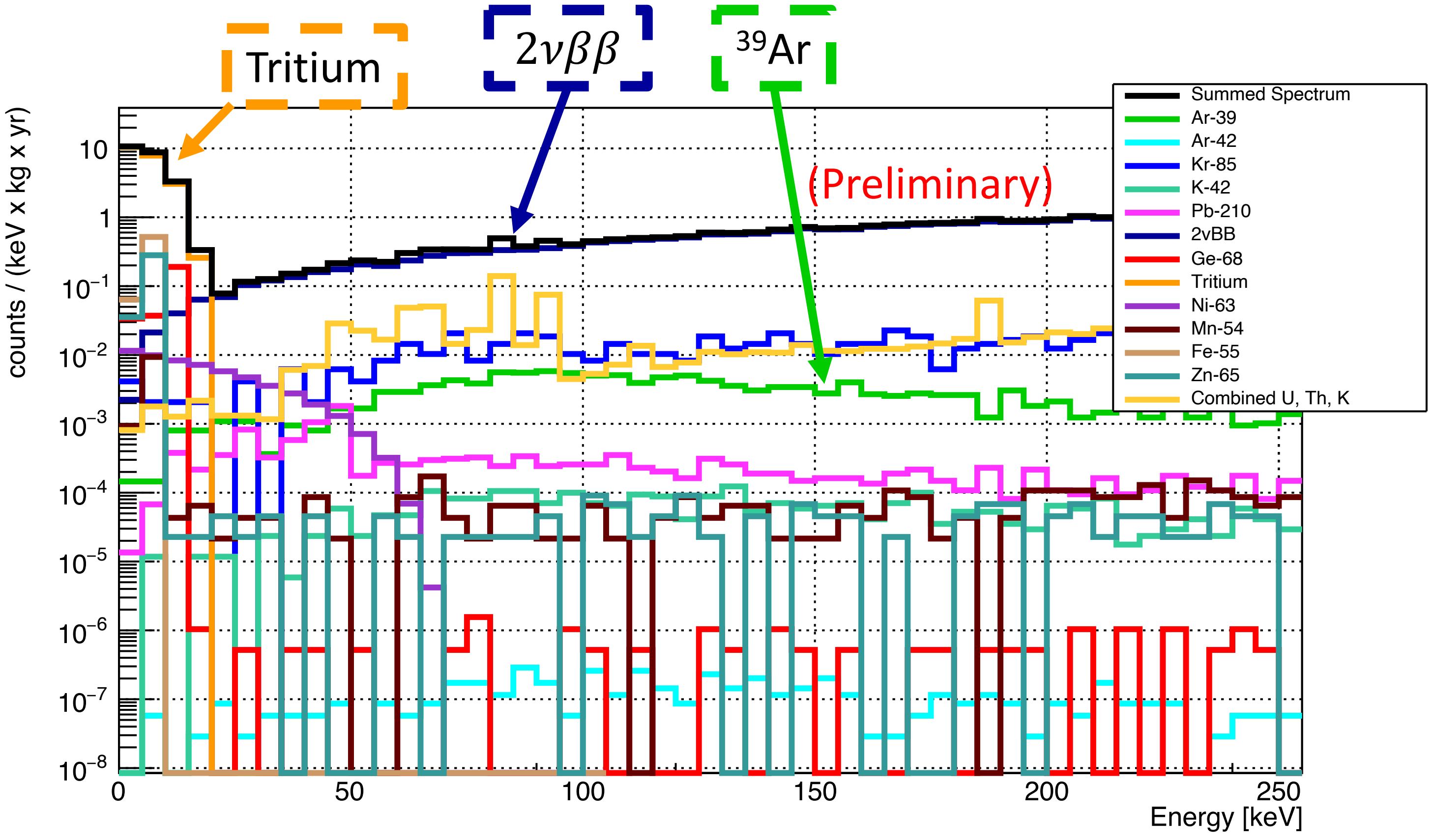
- **1000 kg** of HPGe detectors
  - Operated in a bath of **underground-sourced** LAr
  - Anticipated exposure: **10 t-yr**



(Preliminary)

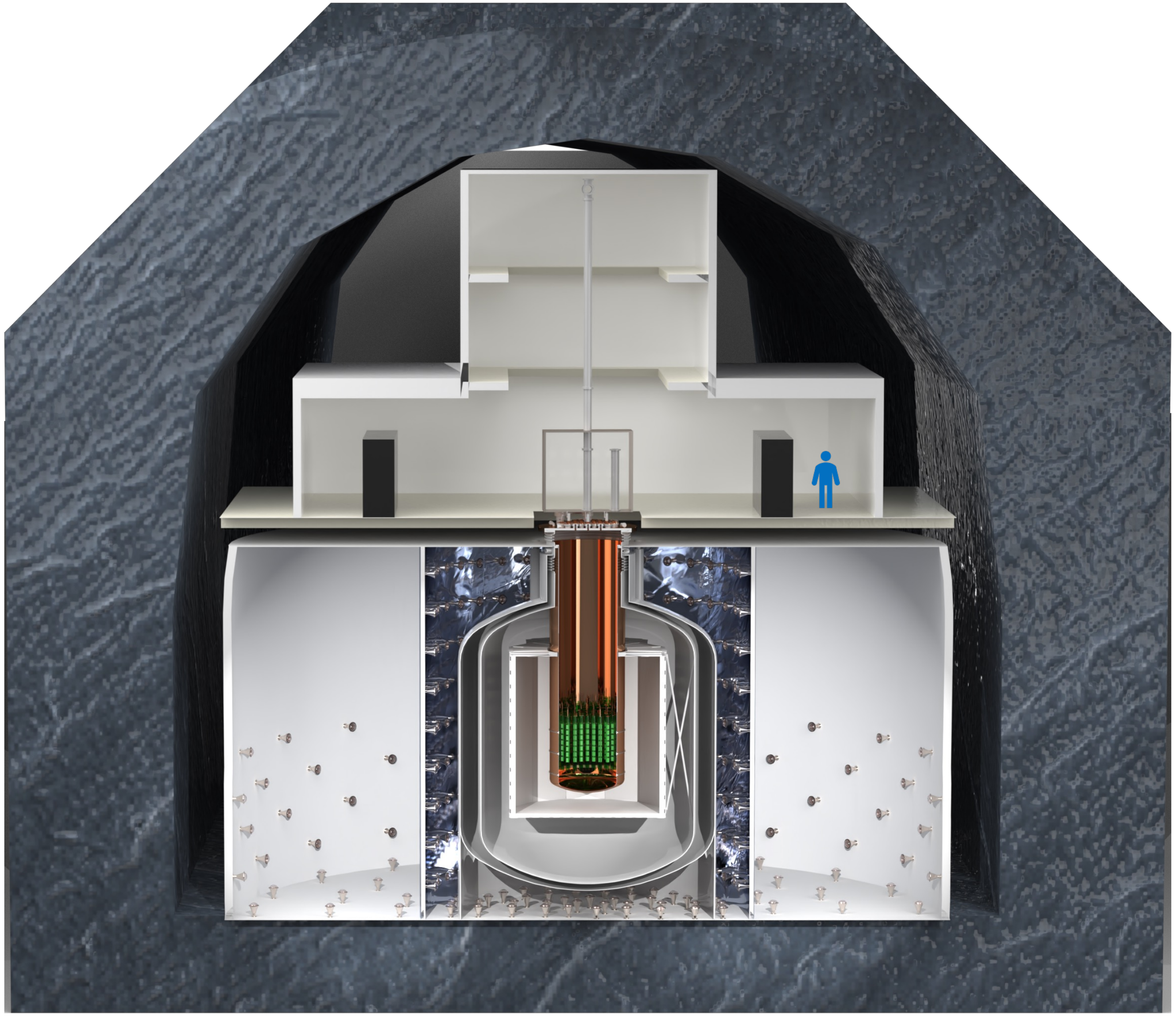


“Low” Energy Background Model for L-1000 *With Cuts*

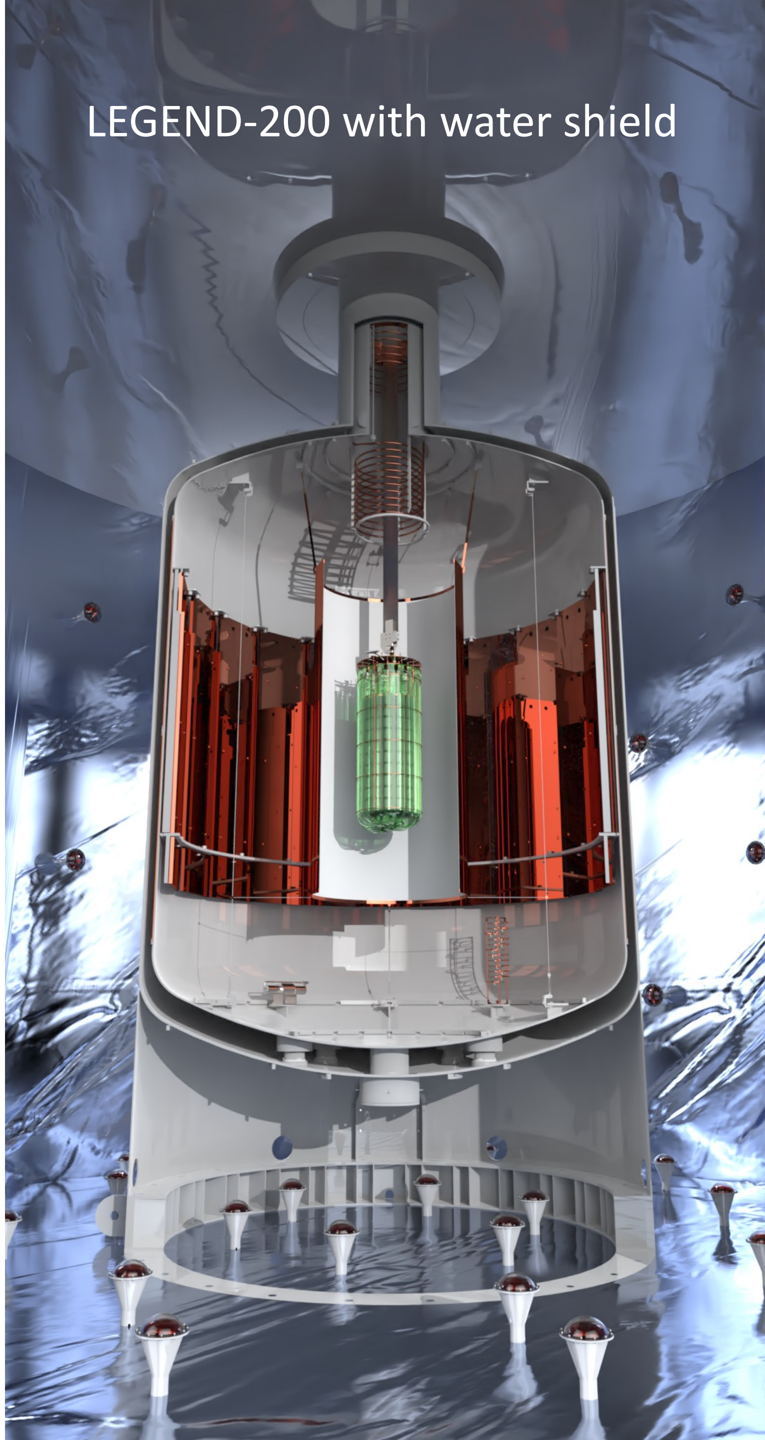


Jackson Waters Master’s Thesis (UNC)

- Simulation of background over all energies via Geant4 framework
- Uses L-1000 geometry
- Assumes underground-sourced LAr
- Includes detector surface effects
- With analysis cuts on:
  - Detector surface events
  - Multiplicity
  - LAr scintillation



(Preliminary Design for LEGEND-1000 at LNGS)



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LEGEND