LEGEND

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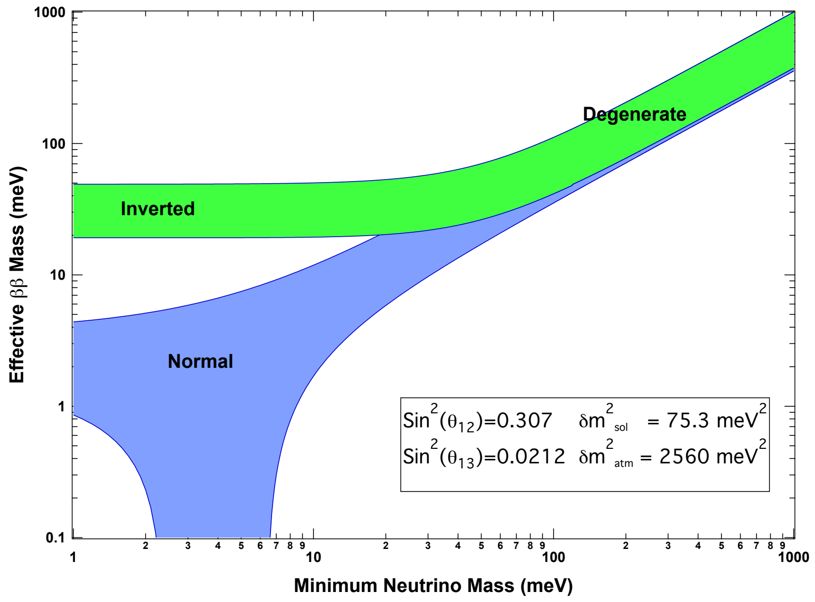
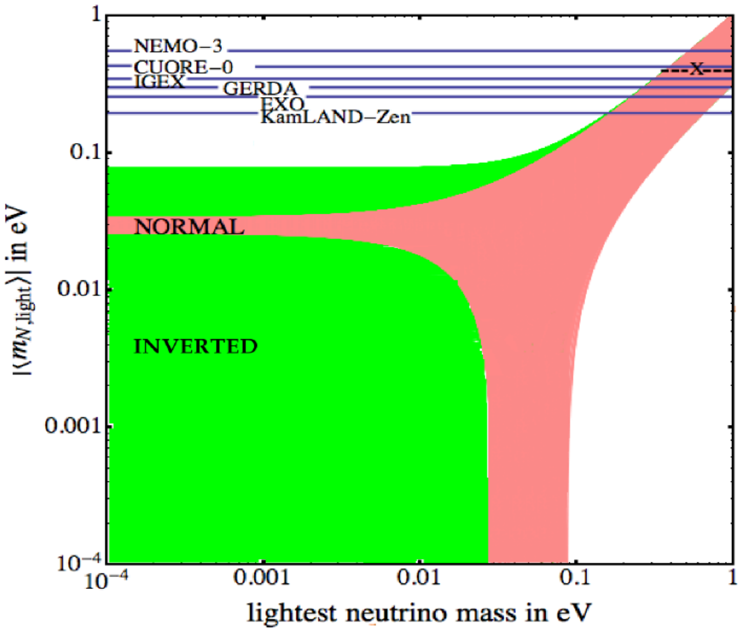
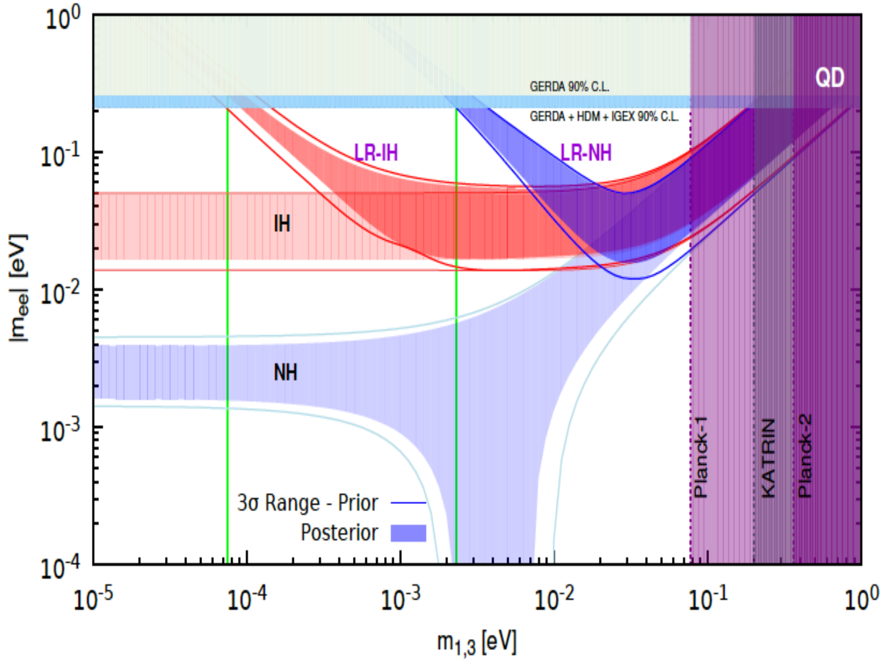
SNOLAB Futures
July 15, 2019

ββ Addresses Key Physics Regardless of Mass Ordering







3 neutrino paradigm

Light sterile neutrino contribution
An example: PRD92, 093001 (2015)
Many papers on this topic.

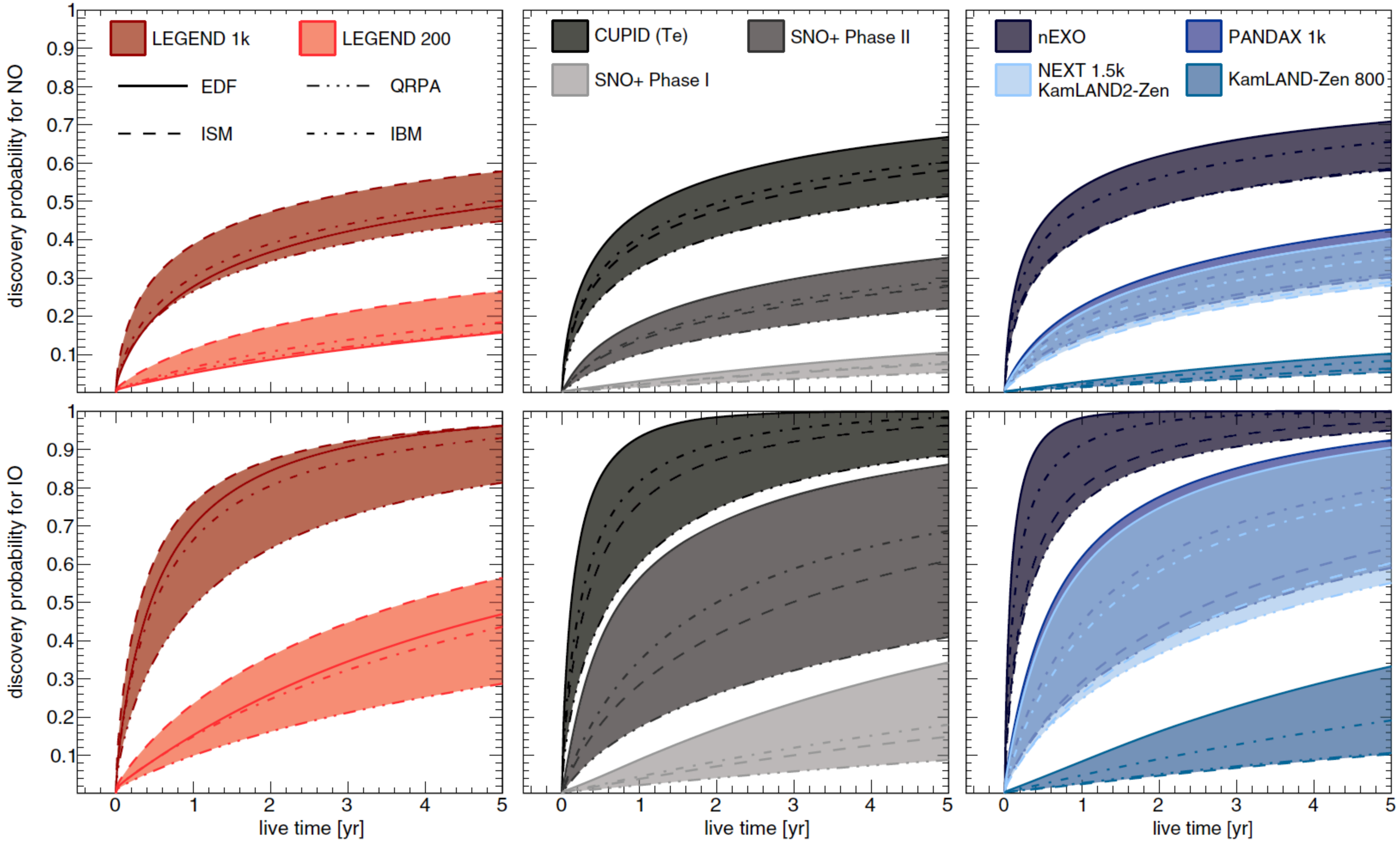
Left-Right symm., Type II contributions
From J. HEP 10, 077 (2015)
Also many papers on this topic.

If ββ is seen, the qualitative conclusions are profound, but observations in several nuclei will be required to fully understand the underlying physics.

ββ discovery potential high, even for NO

Even for the case of normal ordering of neutrino masses in a 3-ν paradigm, the discovery potential is high because the phases and lightest neutrino mass value have no a priori preferred values.

This qualitative conclusion is not changed due to cosmological constraints or if g_A quenching is included.



Example analysis from PRD 96, 053001 (2017)

Complementarity of ββ and Cosmology

- The ΛCDM model has become a 'standard model' for cosmology. Within the next decade, experiments will have sensitivity to neutrino mass below the IO boundary. However, ΛCDM has components that are not fully understood.
  - What mechanism leads to inflation?
  - What components comprise the dark matter?
  - What is dark energy?
- As a standard model with significant unknowns, ΛCDM must be well tested.
- Neutrino mass is one parameter of ΛCDM that can be measured in the laboratory and hence provides a crucial test of ΛCDM.
- ββ and direct neutrino mass experiments must be pursued as a component of cosmology.
- Additionally, cosmology measurements do not test lepton number violation or the Majorana/Dirac character of neutrinos.

The need for several ββ experiments

- With limited statistics, the signature of a small peak on a continuum background is not so distinct. Multiple results will help prove observation.
- Different isotopes studied with different techniques have different systematic uncertainties.
- Different ββ endpoints lead to different background conditions, especially in the case of unidentified γ lines.
- Different nuclear matrix elements have different uncertainties.
- Results from different isotopes can help unravel the underlying physics of the process.

The observation of lepton number violation would be convincing if detected in more than one isotope.

Large Enriched Germanium Experiment for Neutrinoless ββ Decay – LEGEND

53 institutions, About 250 scientists

LEGEND mission: "The collaboration aims to develop a phased, ^{76}Ge 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."

Univ. New Mexico
L'Aquila University and INFN
Lab. Naz. Gran Sasso
University Texas, Austin
Tsinghua University
Lawrence Berkeley Natl. Lab.
University California, Berkeley
Leibniz Inst. Crystal Growth
Comenius University

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Technical University Dresden
Joint Inst. Nucl. Res.
Duke University

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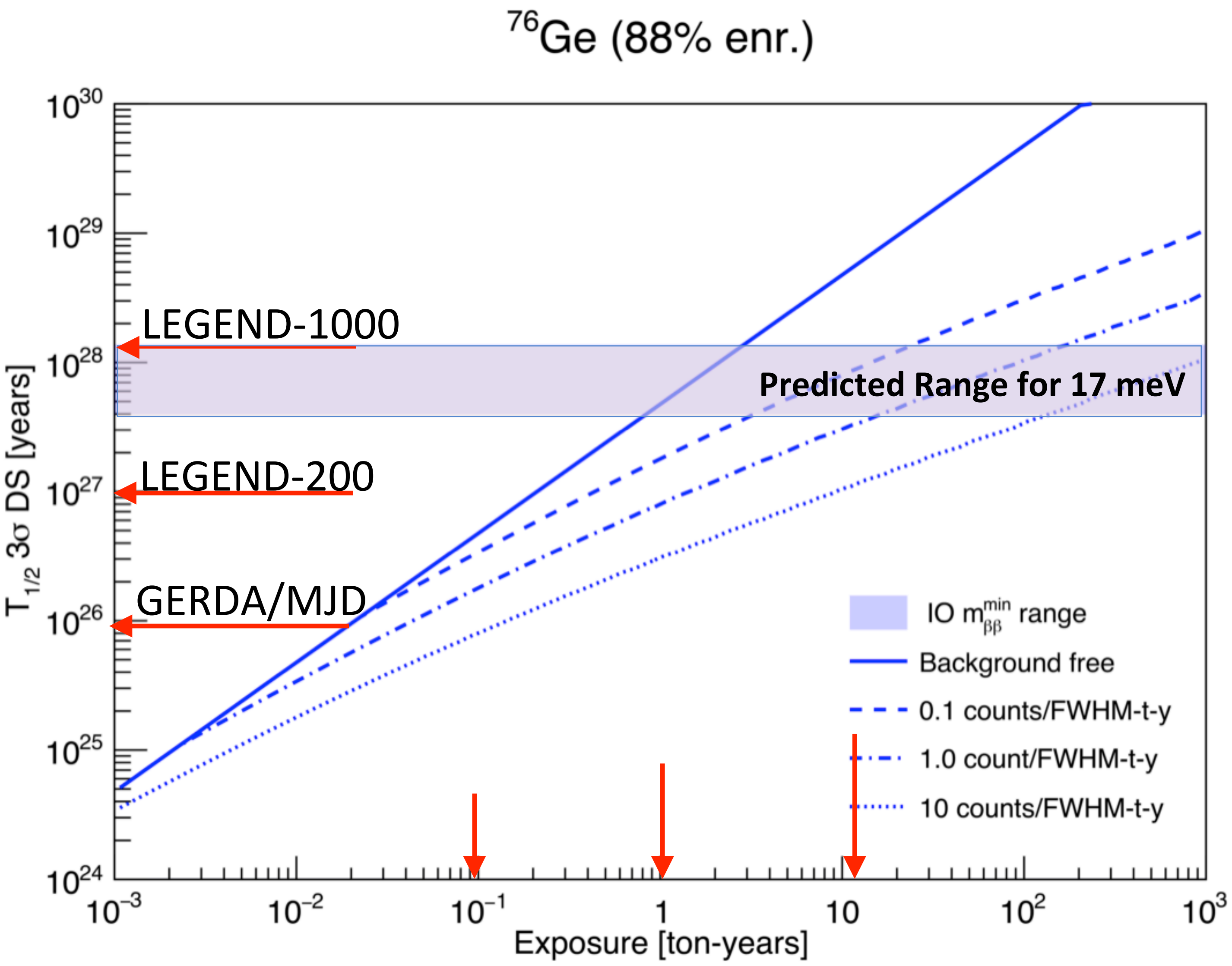
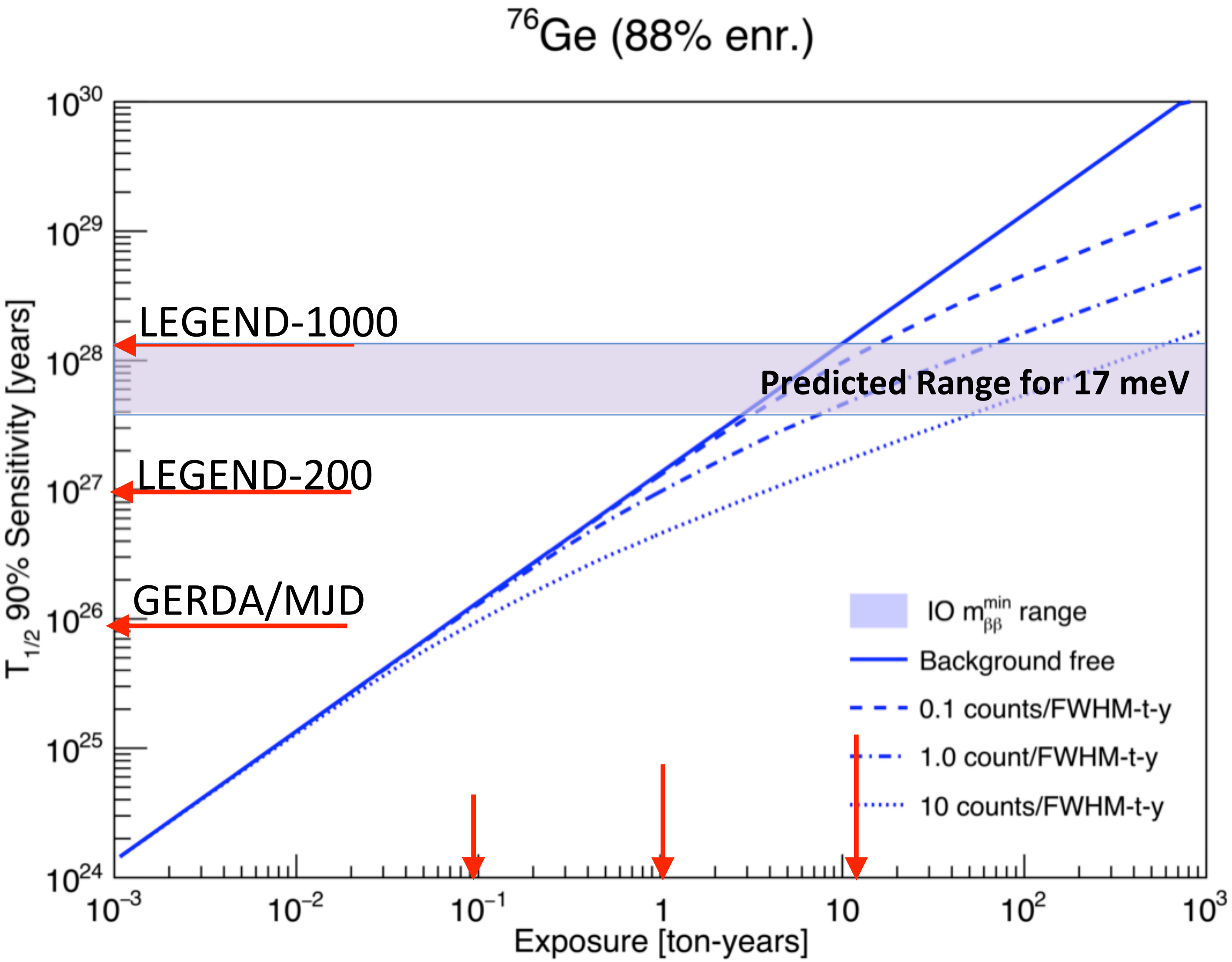
Ge Discovery Potential



>10^{28} yr or $m_{\beta\beta}$=17 meV for worst case matrix element of 3.5 and unquenched g_A.

3-σ discovery level to cover inverted ordering, given matrix element uncertainty.

Ge Sensitivity



>10^{28} yr or $m_{\beta\beta}$=17 meV for worst case matrix element of 3.5 and unquenched g_A.

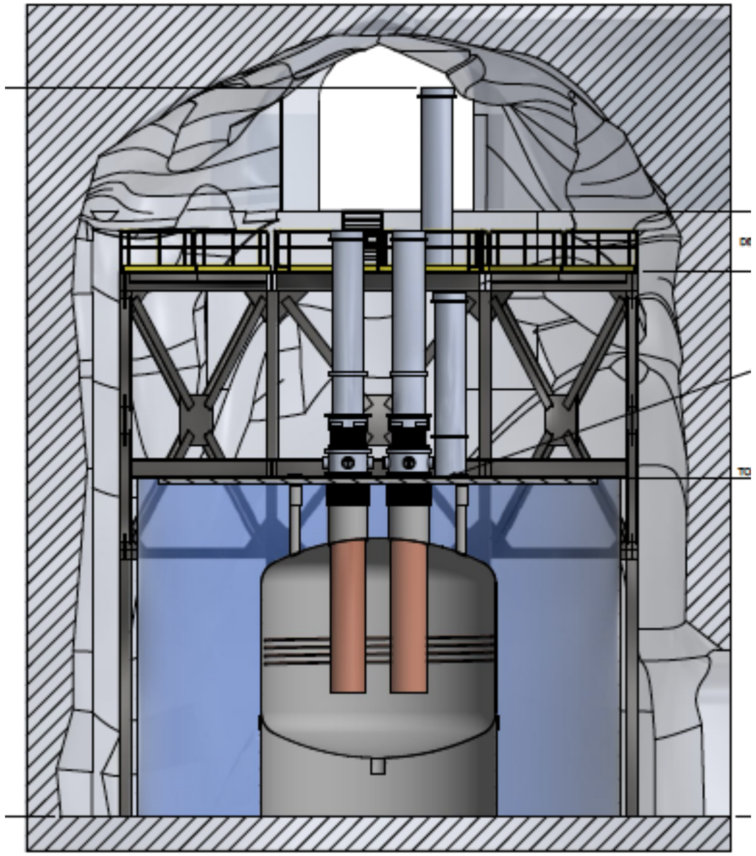
3-σ discovery level to cover inverted ordering, given matrix element uncertainty.

Note: background requirement for discovery more stringent than for sensitivity.

LEGEND (arXiv:1709.01980)

LEGEND-200:

- 200 kg in upgrade of existing infrastructure at LNGS
- Background goal 0.6 cts/(FWHM t yr)
- Data start ~2021



LEGEND-1000:

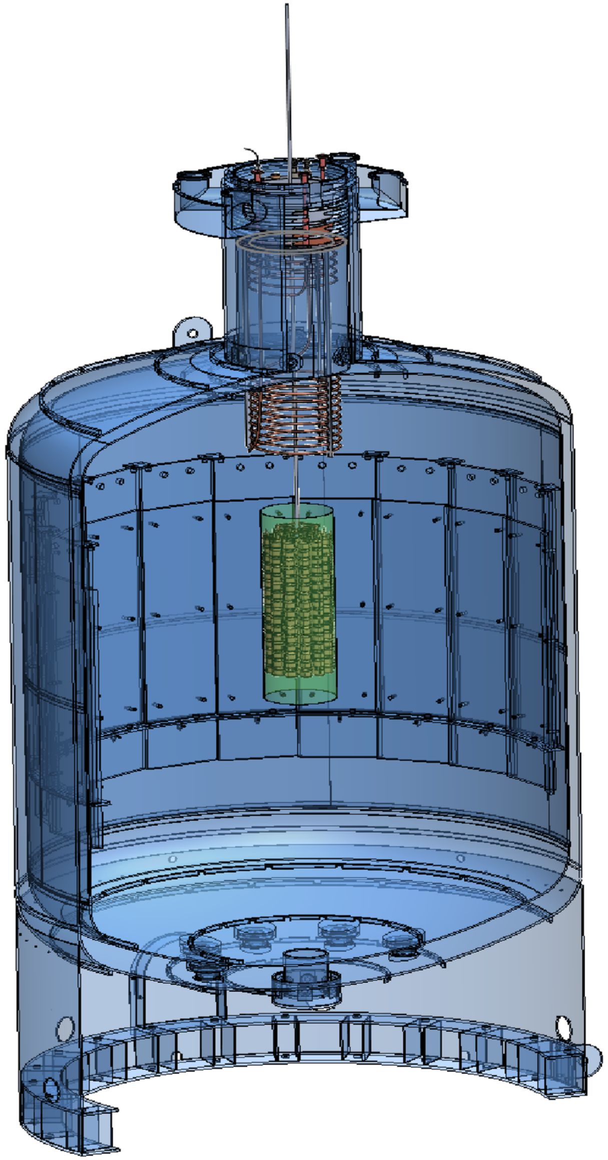
- 1000 kg, staged via individual payloads
- Timeline connected to review process
- Background goal <0.1 cts/(FWHM t yr)
- Location not yet determined
- Required depth (Ge-77m) under investigation

The Best of MAJORANA & GERDA

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

While a limit can be set independent of the energy resolution or background index, a convincing discovery requires good energy resolution and its significance strongly depends on the uncertainty of the background level and shape.

LEGEND-200



- Existing GERDA infrastructure large enough for 200 kg of enriched detectors
- Neck of cryostat 800 mm
- 14-17 strings arranged on maximum diameter of 500-550 mm
- Number of readout channels will increase substantially
  - raise clean room roof
  - new lock
  - new cabling
  - detector suspension
  - feedthroughs
- Detectors
  - BEGe's from GERDA
  - PPC's from MAJORANA (successful test in LAr)
  - new inv. coax detectors (baseline 1.5 kg)

LEGEND-200: Background Reduction

LEGEND-200: reduction of backgrounds from ^{42}K, ^{214}Bi, ^{208}Tl by x5 relative to GERDA/MAJORANA.

Feasibility of these required reduction factors have already been shown in GERDA, MAJORANA and in dedicated test stands (e.g. LArGe).

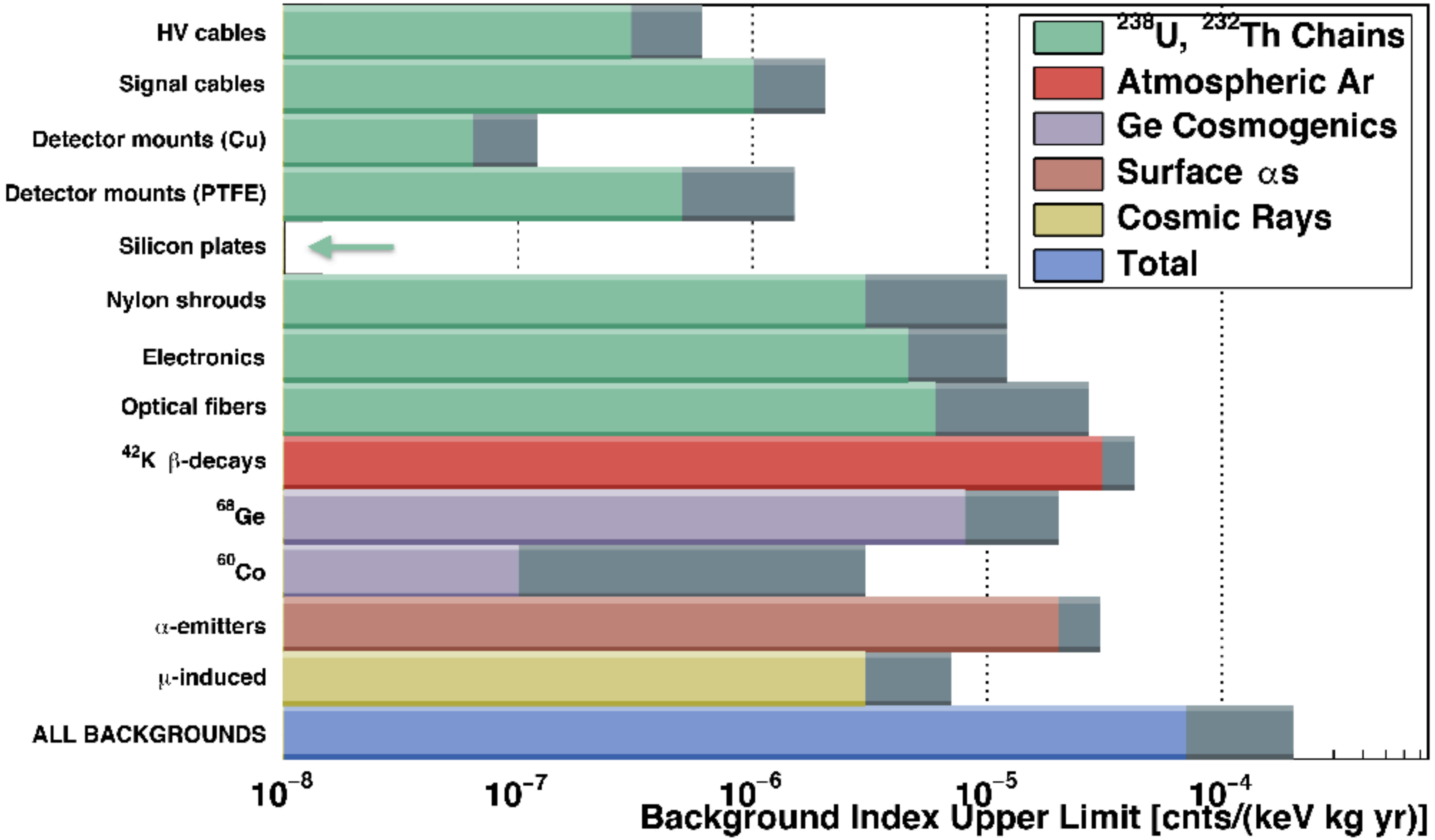
- Improved radiopurity levels (cables (x7), electro-formed Cu, PTFE, ...)
- Increased detector mass (≥x2) leads to proportional reduction from near-by parts
- Higher purity LAr: increased scintillation light yield and attenuation length
- Improved scintillation light readout (x2 shown in test stand)
- Reduction of electronic noise leads to improved PSD
- Increase n+ 'dead' layer thickness from 0.8 to 1.3 mm (x3 for ^{42}K)
- Optimized PSD analysis for n+ and p+ surface events
- Larger detectors have better surface/volume ratio reducing surface backgrounds

^{214}Bi / ^{208}Tl (first five items)

^{42}K (items four through eight)

From these developments, we expect a background reduction of at least x5 compared to GERDA/MAJORANA. The background goal will be met.

LEGEND-200 Background Projections

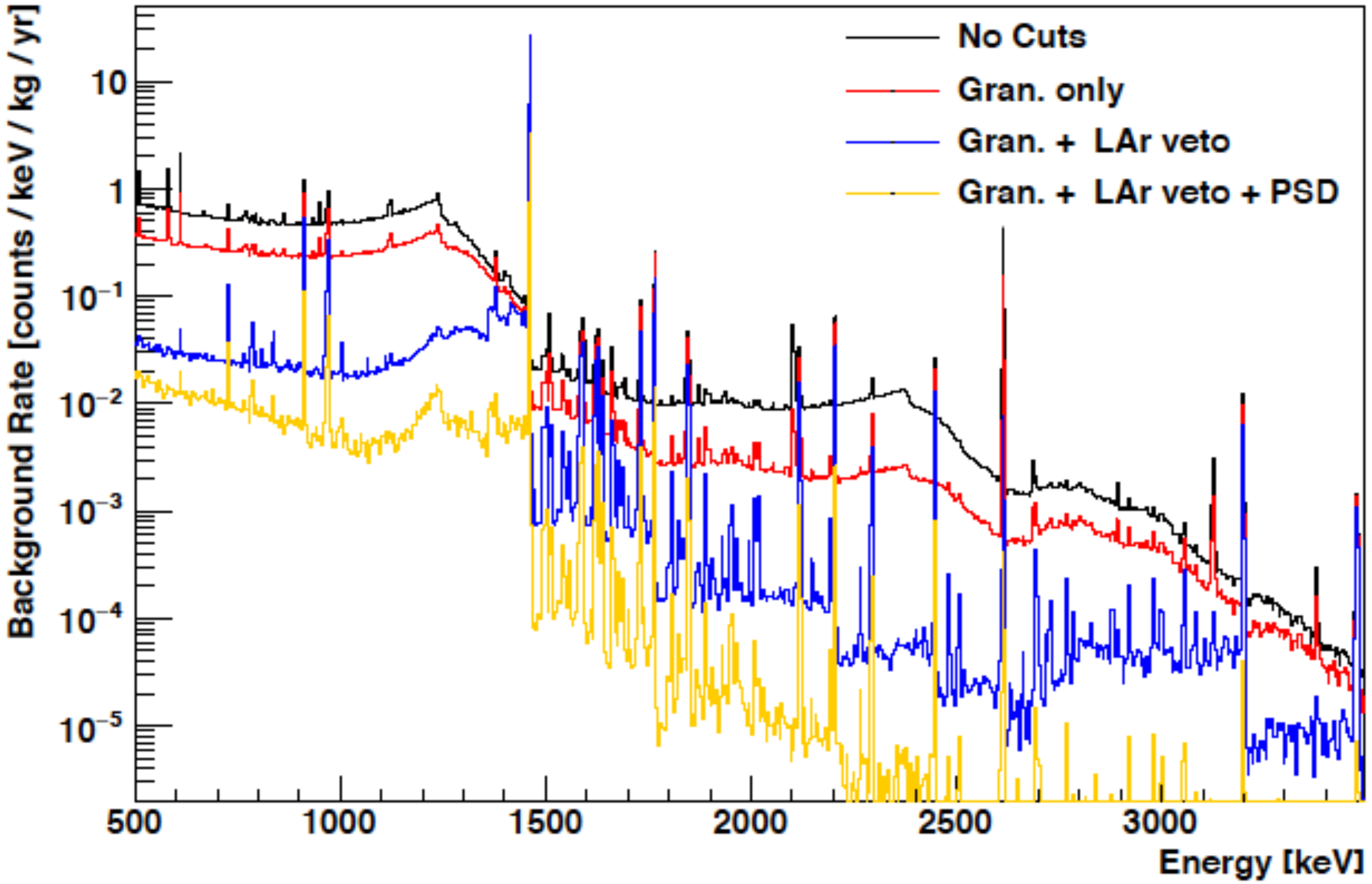


Monte Carlo simulations based on experimental data and material assays. Background rate after anti-coin., PSD, LAr veto cuts.

Assay limits correspond to the 90% CL upper limit. Grey bands indicate uncertainties in overall background rejection efficiency

$Q_{\beta\beta}$ background index upper limit: (0.7–2.)x10^{-4} cts/(keV kg yr) or 0.2-0.5 cts/(FWHM t yr)

LEGEND-200 Background Rejection



Expected upper limit total contribution from U/Th/^{40}K for all components based on GERDA and MAJORANA assays before and after cuts.

Granularity – multiple detector cut
LAr veto – no signal in LAr
PSD – pulse shape discrimination

Total: $<2\times10^{-4}$ /(keV kg yr)
= 0.5 cts/(FWHM t yr)

Present Status of LEGEND-200

- Nearly all funding in place for LEGEND-200.
- All isotope is either in-hand, on-order, or orders being prepared. Deliveries from 2 suppliers.
- Ge detector fabrication from two suppliers has begun.
  - Front-end electronics being tested. Detector unit designs being prototyped.
  - Plan to characterize detectors at HADES, ORNL and SURF.
  - About 80 inverted coax detectors (1.5-2 kg), about 150 kg
  - 28 BEGe's (0.7 kg) about 20 kg
  - 5 ICPC's (2.0 kg) about 10 kg
  - 35 PPC's (0.8 kg) about 28 kg
  - Semi Co-Ax detectors (either use as is, or recycle) about 15 kg
  - Total ~200 kg
- Lock designs and new deployment hardware well underway. Testing of new hardware continues.
- LAr veto is under construction with all parts delivered or on order. Optimization of optical components underway.
- Assay program is well underway.
- LEGEND-200 is on track to start data taking mid 2021.

LEGEND-1000 Design Criteria

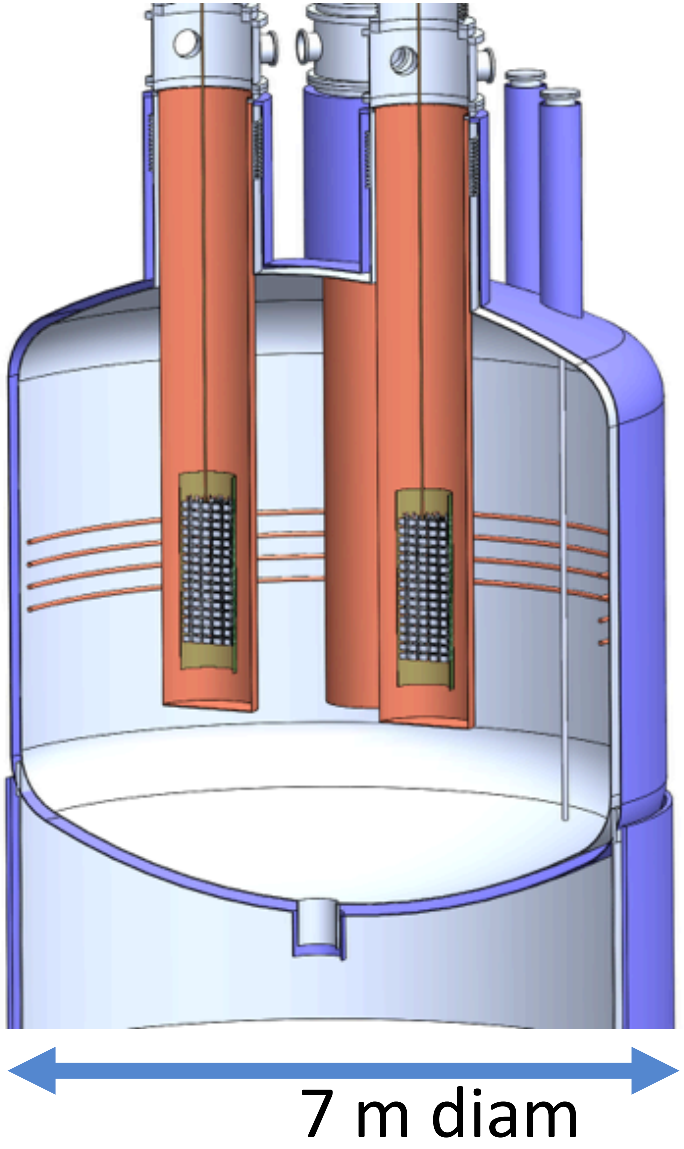
- Phased Approach towards one ton.
  - 200-500-1000 kg steps, for example.
  - Allows operation of previously installed detectors.
  - Use existing infrastructure for early phase (LEGEND-200) to obtain near-term physics results.
- Background goals for LEGEND-1000: <0.1 c/(FWHM t y).
  - Only a modest improvement over that already achieved.
  - LEGEND-200 is already at 0.6 c/(FWHM t y).
    - The reduction for LEGEND-200 is only x5 better than MAJORANA/GERDA.
    - In fact, this LEGEND-200 goal is similar to the best of the GERDA detectors.
- ~900 kg of additional enriched ^{76}Ge for 1000 kg.
- 1000 kg of p-type, point-contact Ge detectors (2-3 kg/300-500 detectors).
- Resolution ~2.5 keV FWHM@2039 keV.

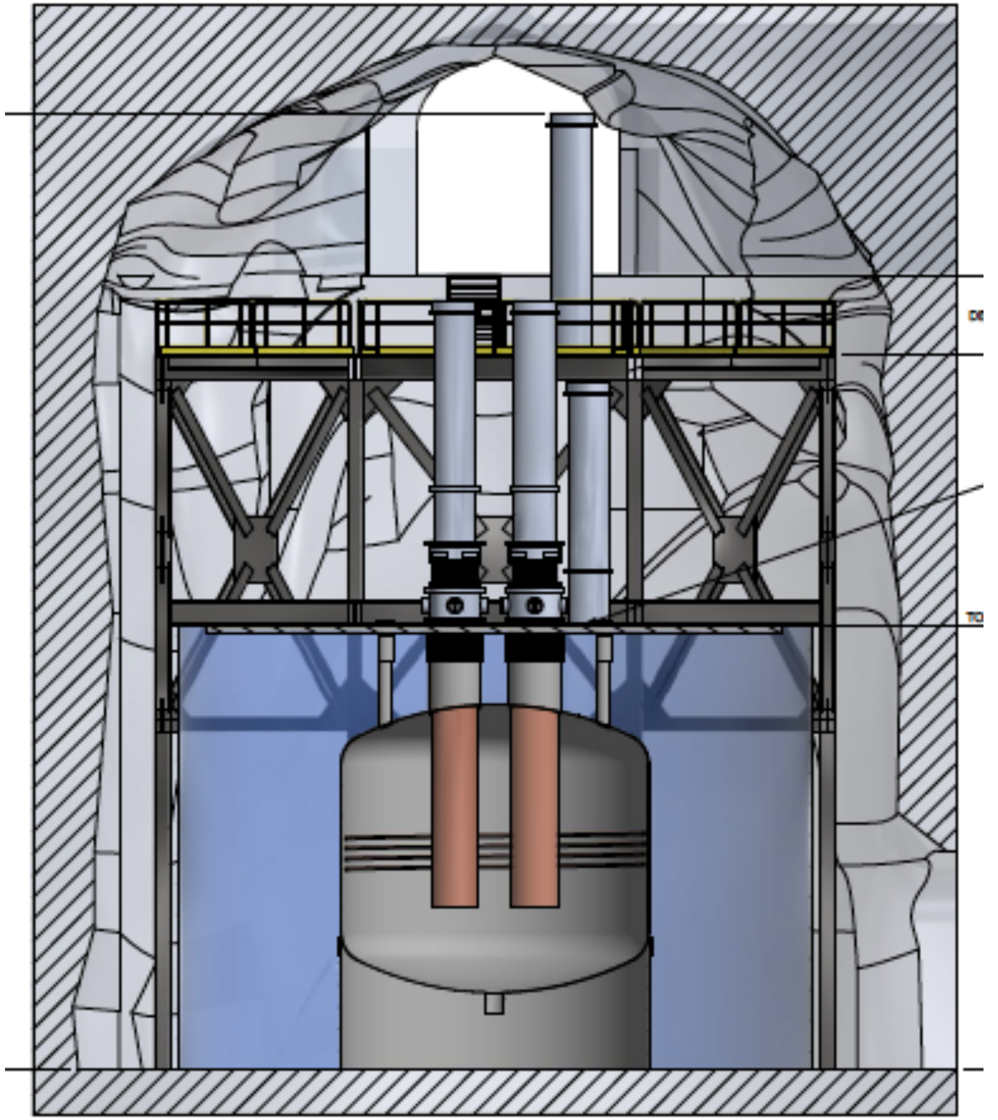
LEGEND-1000 Background Goal

- LEGEND-200 has already informed the LEGEND-1000 background estimate.
- LEGEND-200 background anticipates roughly equal contributions of U/Th, ^{42}Ar, surface α before analysis cuts.
  - Because background is so low after cuts, the model has uncertainties.
- LEGEND-1000 needs a background lower by about x6 than LEGEND-200.
- To reach this:
  - U/Th can be reduced by optimizing array spacing, minimizing opaque materials, larger detectors, better light collection, cleaner materials, improved active suppression.
  - ^{42}Ar can be eliminated by using underground sourced Ar.
  - Surface α can be reduced by improved process control.
    - Hypothesis is Rn in air at detector fabrication facility.
- LEGEND-1000 will have a higher total response and efficiency.
  - Larger detectors have a better surface to volume ratio.
  - Higher isotope fraction is now cost effective.

LEGEND-1000 Baseline Design

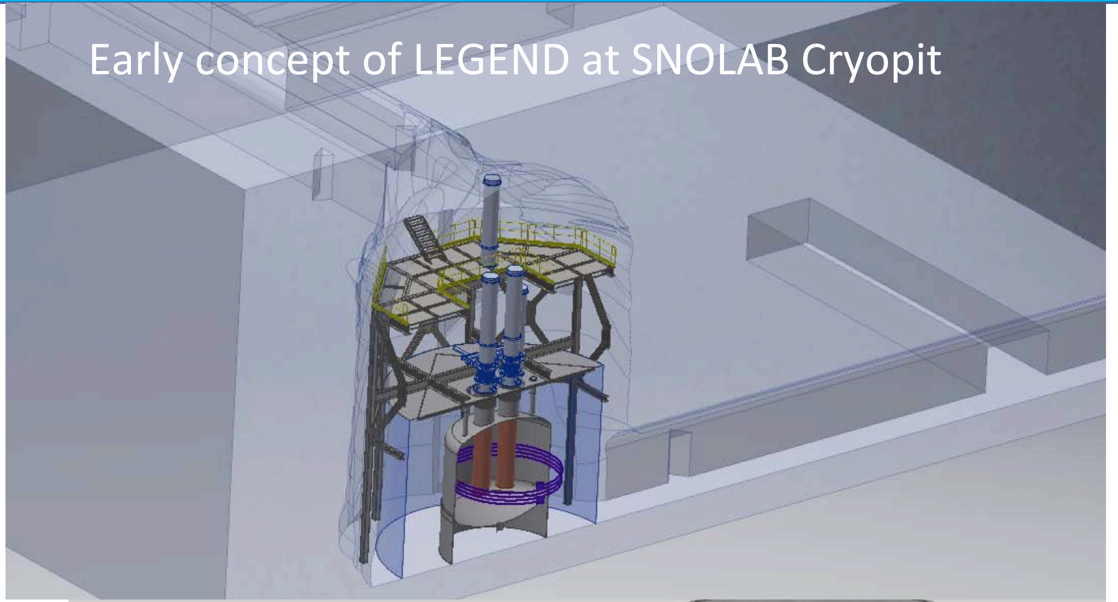
- 4 payloads of Ge detectors
  - 250 kg each
  - Data from each when deployed
  - 4 reentrant tubes on 2-m diam. circle. Tube radius is ~0.8 m
- Each payload surrounded by LAr depleted in Ar-39/Ar-42
- All payloads deployed within a cryostat of LAr. 7 m diam.
- This cryostat deployed with a water tank at least 11 m diam.

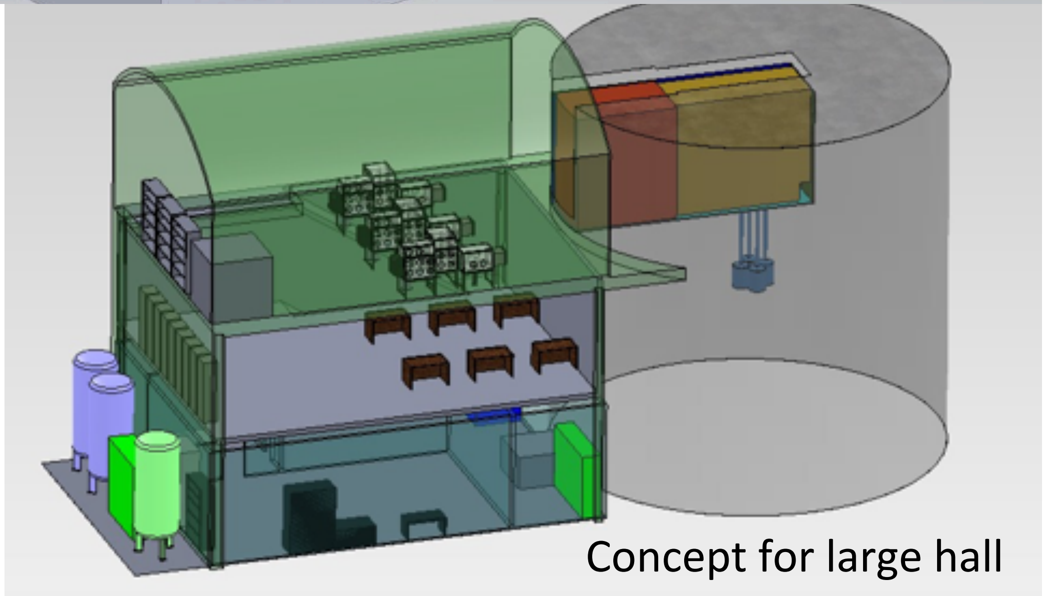




Underground Space Requirements

- Detector cavity: 12 m diam x 17 m high
- Provides about 5 m shielding in all directions
- Over the tank clean room: 4 m high
- Initial assembly clean room: 100 m^3
- Control room:
- Lay down space: staging 8m x 1m parts and 4-6 rail cars
- Tramming: ~200 trips for construction material, ~100 to fill LAr, detector delivery 30-50 trips
- Storage: 20 m^2
- Water purification: 20 m^2
- Electroforming: (If UGEF, then 50 m^2)

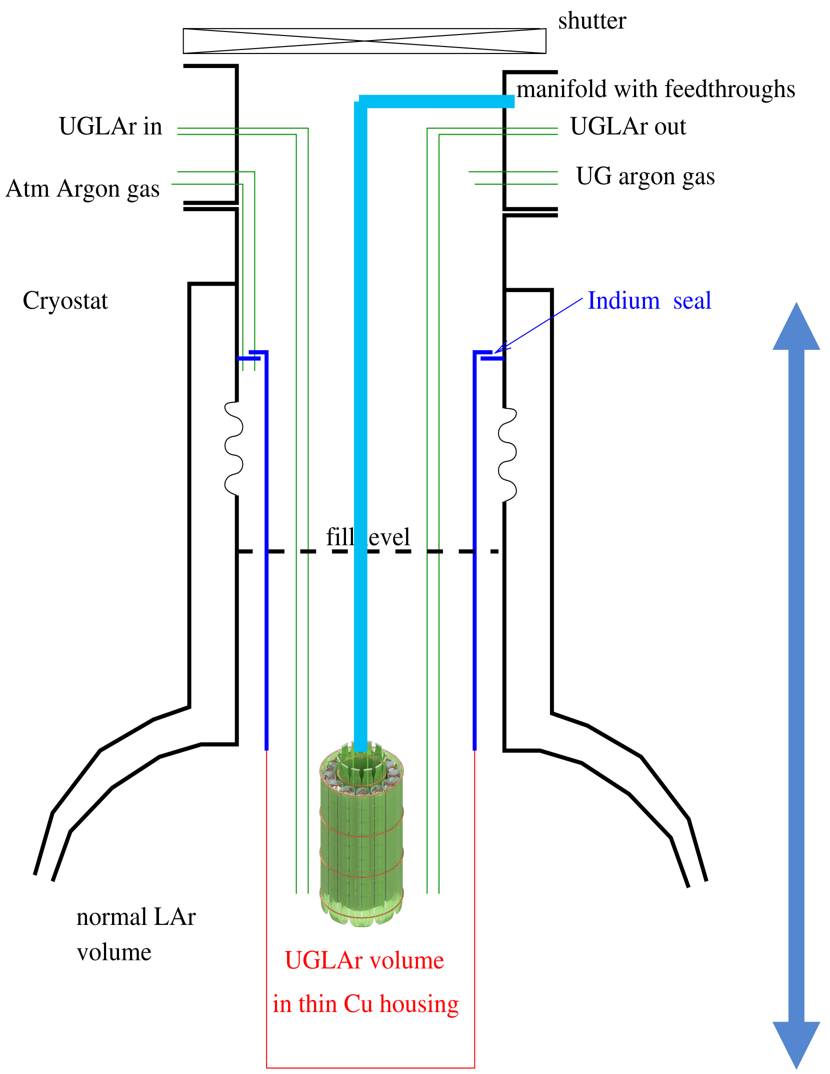

Early concept of LEGEND at SNOLAB Cryopit


Concept for large hall

UGLAr within reentrant volume near Ge

LEGEND

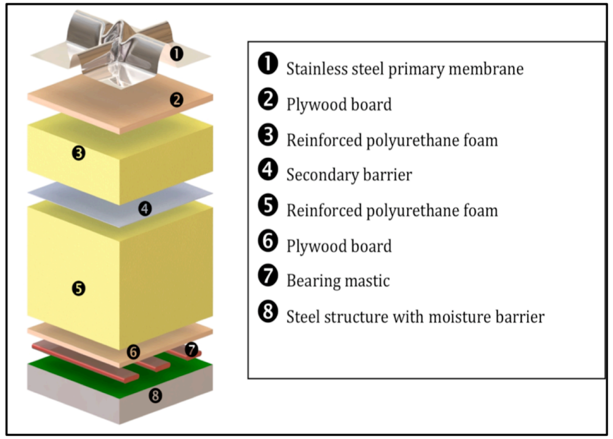
- Default design is for reentrant volumes sequestering underground sourced liquid argon.
- Eliminates Ar-42 background
  - 4 payloads, only one shown here
  - About 100 tons of isolated LAr

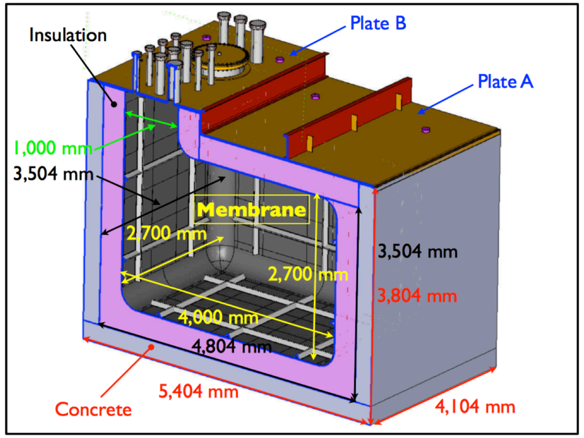


Reentrant tube
7.5 m tall
0.8 m diam

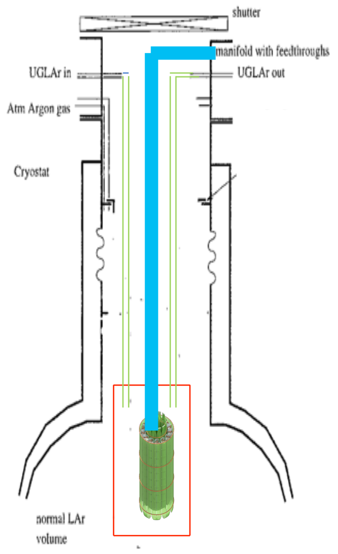
Considered Alternatives to Base Design

- Base design: reentrant UGLAr payloads submerged in a LAr cryostat contained within a water shield.
- Alternative 1: replace water shield with a large monolithic LAr shield. Use DUNE membrane technology to build the LAr tank.
  - ✘Much more LAr (x8).
  - ✓No water.
  - ✓Slower boil-off during cryogenic accident.
  - ✓Easier to assemble in situ as compared to vacuum LAr vessel.

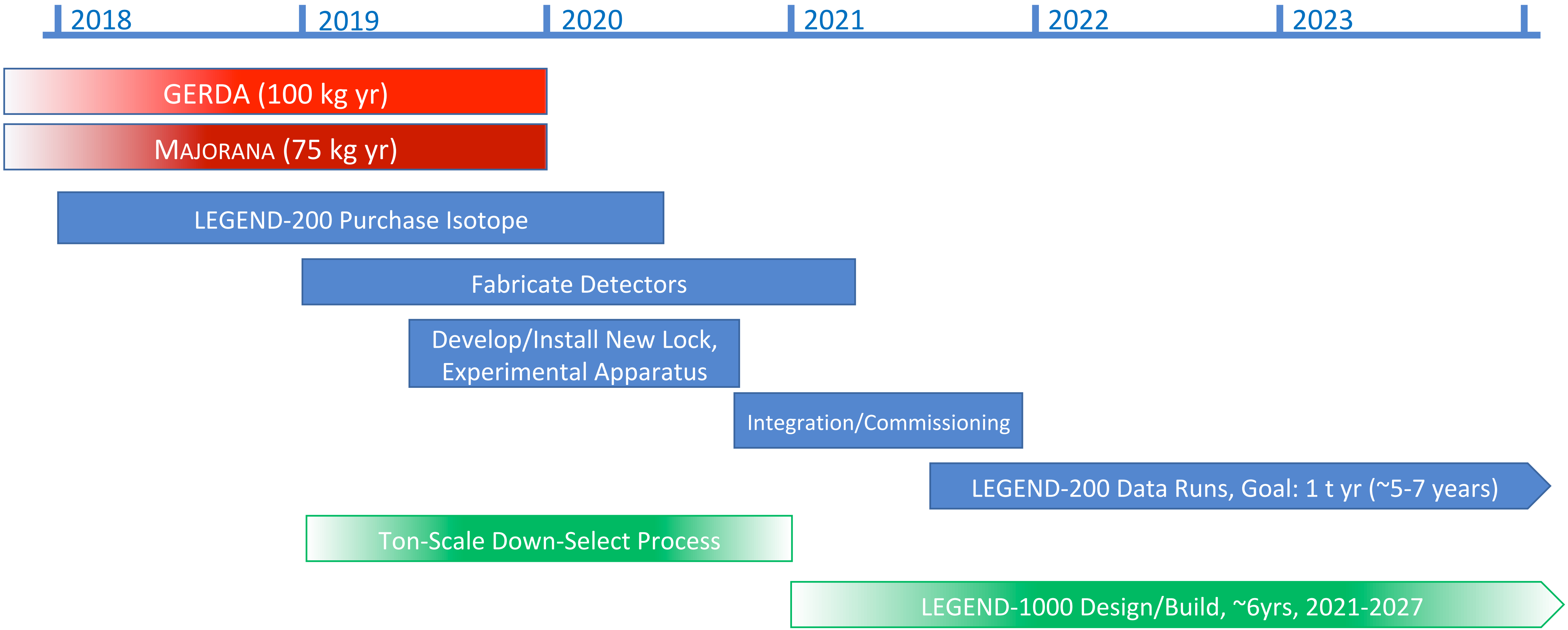




- Alternative 2: Instead of reentrant UGLAr payloads, have enclosed payload volume.
  - ✘Much harder to deploy and manage payloads. (shop stopper?)
  - ✓Less support material.
  - ✓Less UGLAr (x3-4), depending on design.



Schedules



Earliest LEGEND-1000 Data Start 2025/6

Summary

- MAJORANA and GERDA have shown the best energy resolution and background of any ββ experiments. These result in competitive limits even with small relative exposure.
- LEGEND-200 is funded and moving ahead with physics start expected 2021.
- LEGEND-1000 is under development and its design relies heavily upon the success of MAJORANA and GERDA, as well as the progress of LEGEND-200.
  - Design alternatives are being studied.
- The physics motivation for these experiments is strong and will remain so even if the neutrino mass ordering is found to be normal.
- SNOLAB is certainly deep enough and would be an excellent site for LEGEND-1000.

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