Neutrinoless Double-Beta Decay
and the
Nature of Neutrinos

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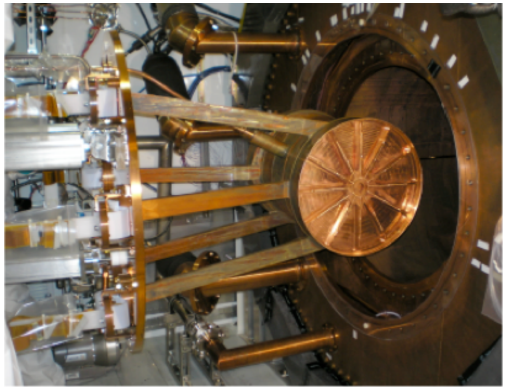
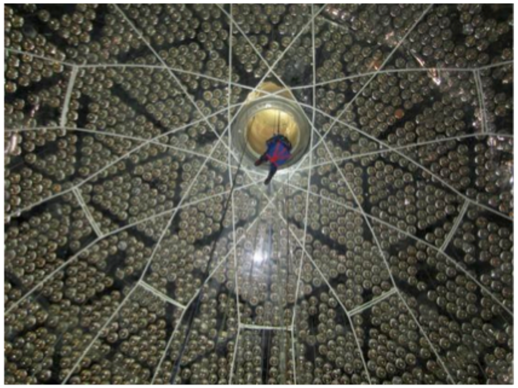
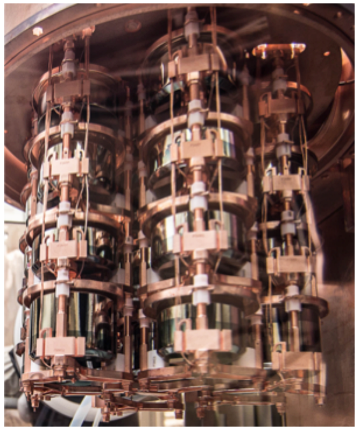
Outline

- Majorana neutrinos and the Mass Hierarchy
- Neutrinoless Double-Beta Decay
  - Why bother?
  - Different experiments and detectors
  - The MAJORANA DEMONSTRATOR
  - LEGEND: Path to a tonne-scale experiment

Neutrino Questions

We have learnt a great deal about neutrinos over the past two decades. But they continue to surprise us, and many crucial questions remain.

- Is lepton number a conserved quantity?
- Is the neutrino its own antiparticle (a Majorana particle)?
- Are neutrinos responsible for leptogenesis?

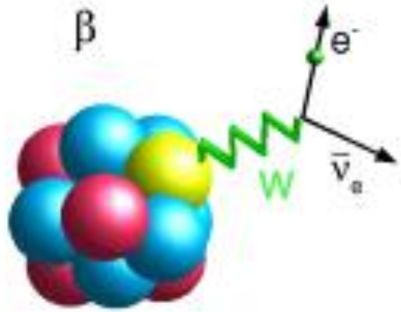
- What is the origin of the neutrino mass?

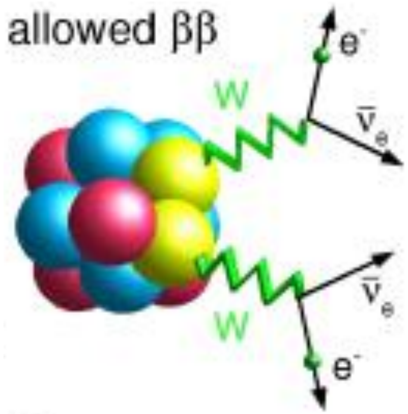
- What is the neutrino mass ordering (hierarchy)?
- What is the absolute mass scale of neutrinos?

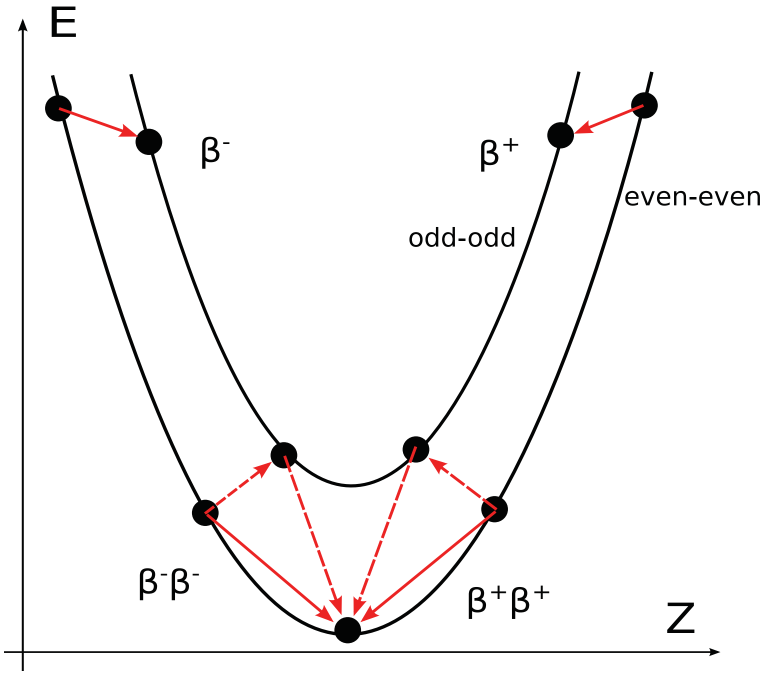
- Are there right-handed (sterile) neutrinos?

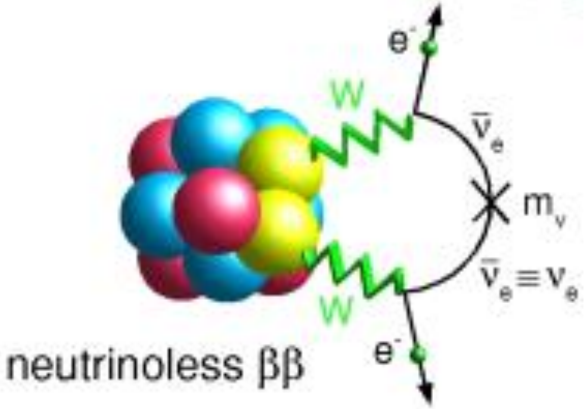
Double-Beta Decay

- Second order process
- Can compete only where single β-decay is energetically forbidden



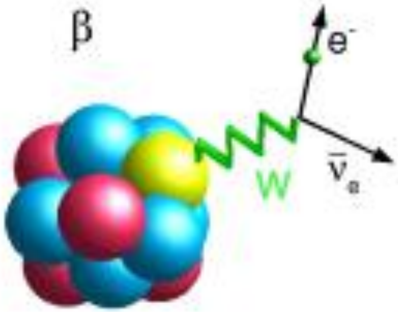






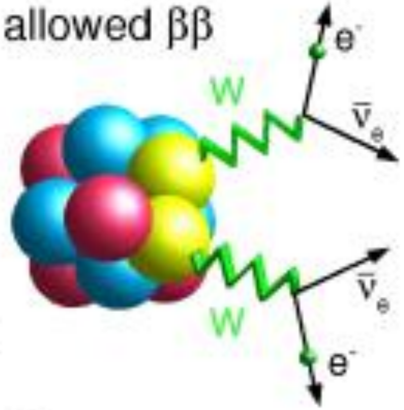
Double-Beta Decay

Beta decay



Example: $n \rightarrow p^+ + e^- + \bar{\nu}$

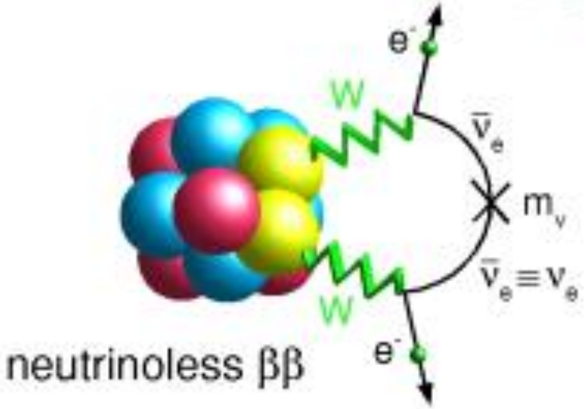
Two-neutrino double-beta decay



Example: $2n \rightarrow 2p^+ + 2e^- + 2\bar{\nu}$

Observed with half-lives ~ $10^{19} – 10^{21}$ years

Neutrinoless double-beta decay



Example: $2n \rightarrow 2p^+ + 2e^-$

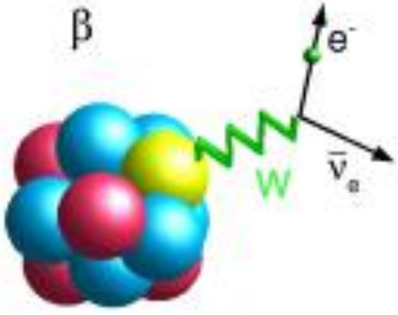
Not yet observed…

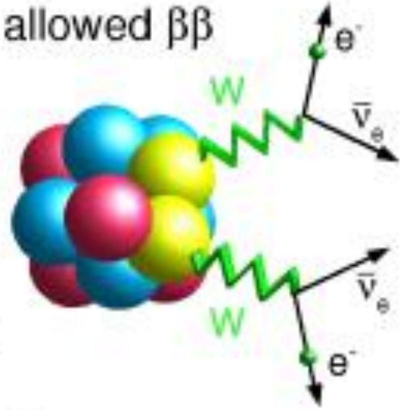
Neutrinoless Double-Beta Decay

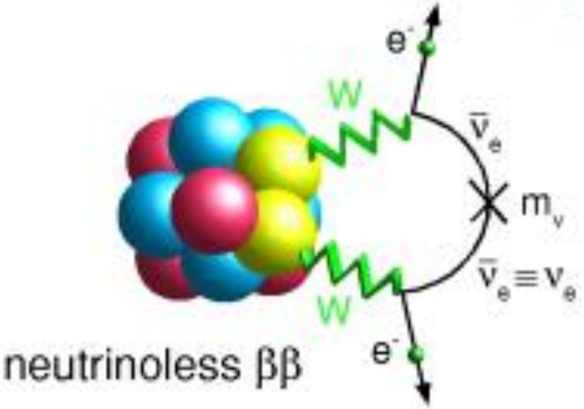
If observed, 0νββ decay would:

- Demonstrate that lepton number is not conserved
- Show that neutrinos are Majorana particles
- Provide plausible scenarios for the origin of the baryon asymmetry of the universe
- Offer a potential mechanism for the very light masses of neutrinos compared to that of the charged fermions
- Provide a model-dependent measurement of the absolute neutrino mass

All of this from a process that has no neutrinos in either the initial or the final state!

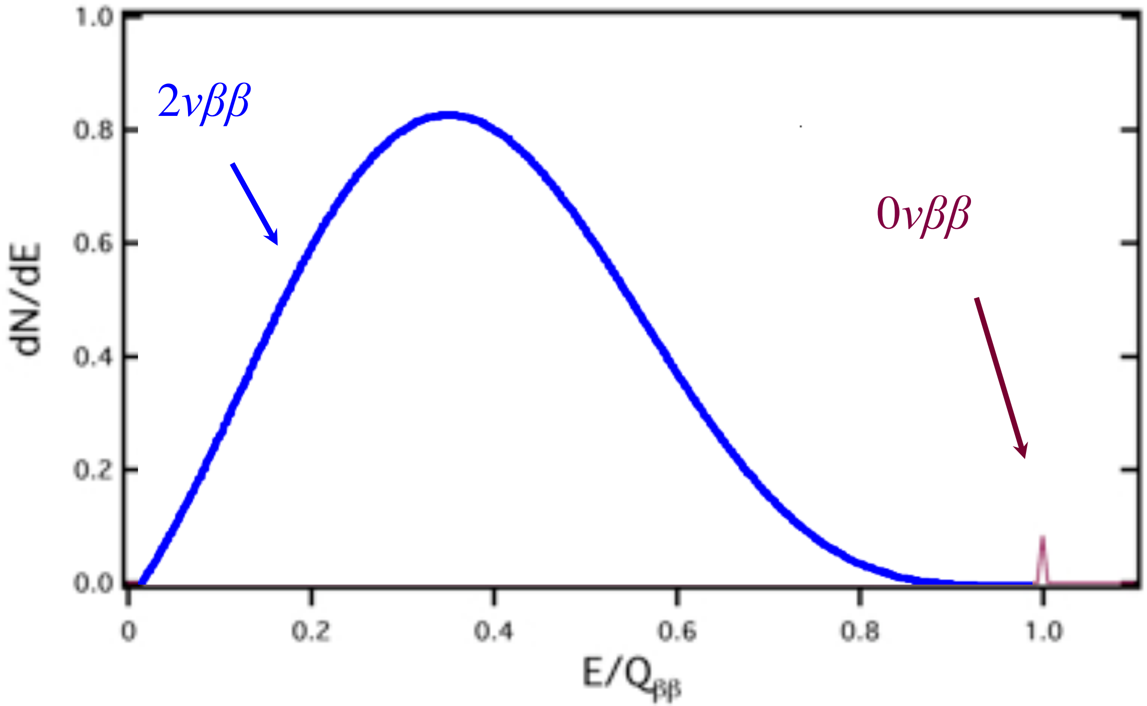




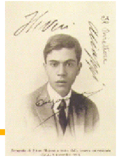


How can we tell 0νββ from 2νββ?

- In 2νββ, some fraction of the decay energy gets carried by the neutrinos
- But in 0νββ, all the decay energy must go to the electrons
- So we sum the electron energies and look for a narrow peak at the Q-value of the decay

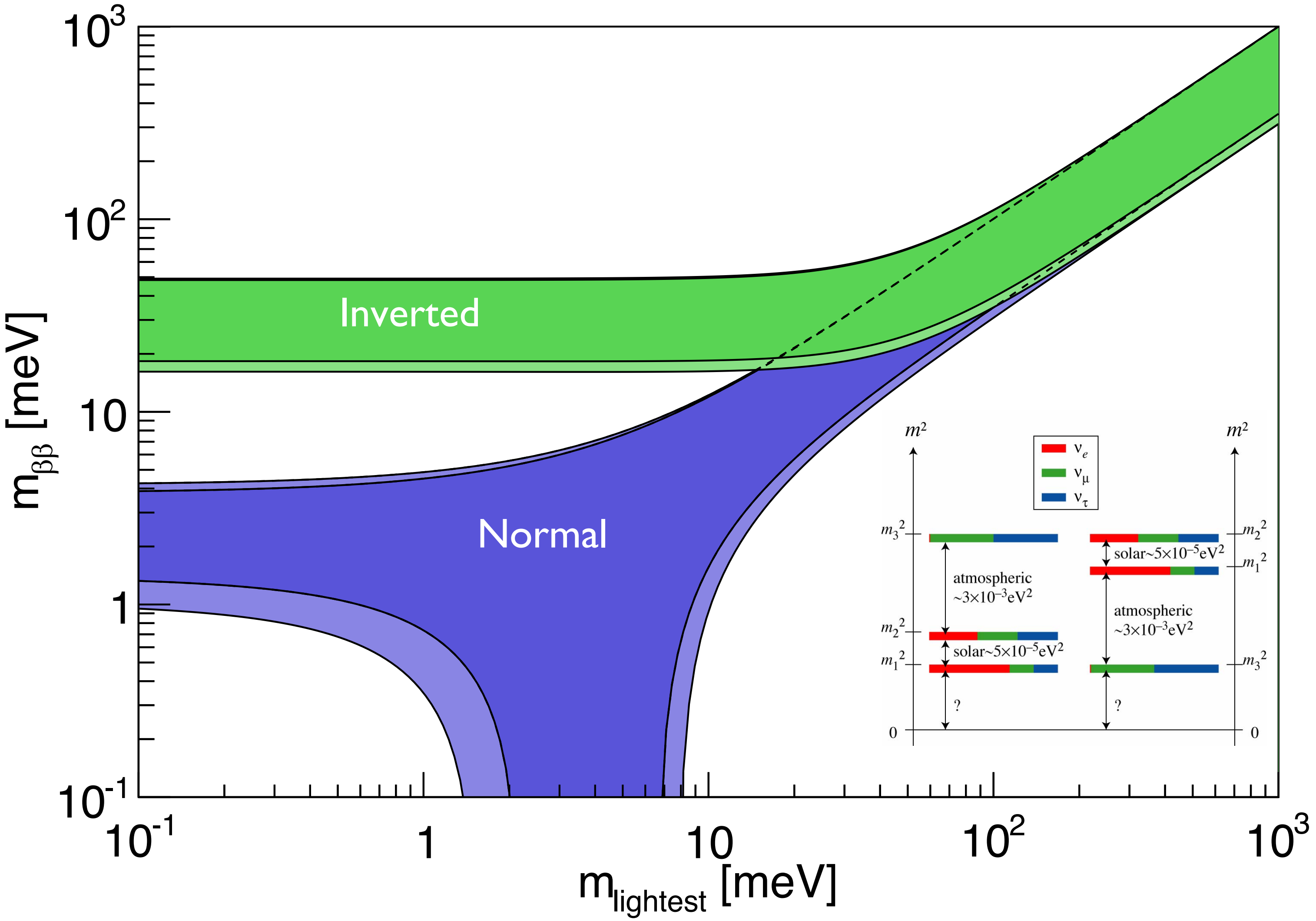


0νββ Decay Rate and <m$_{\beta\beta}$>



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

Assumes LNV mechanism is light Majorana neutrino exchange and SM interactions



0νββ Decay Rate and $<m_{\beta\beta}>$

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

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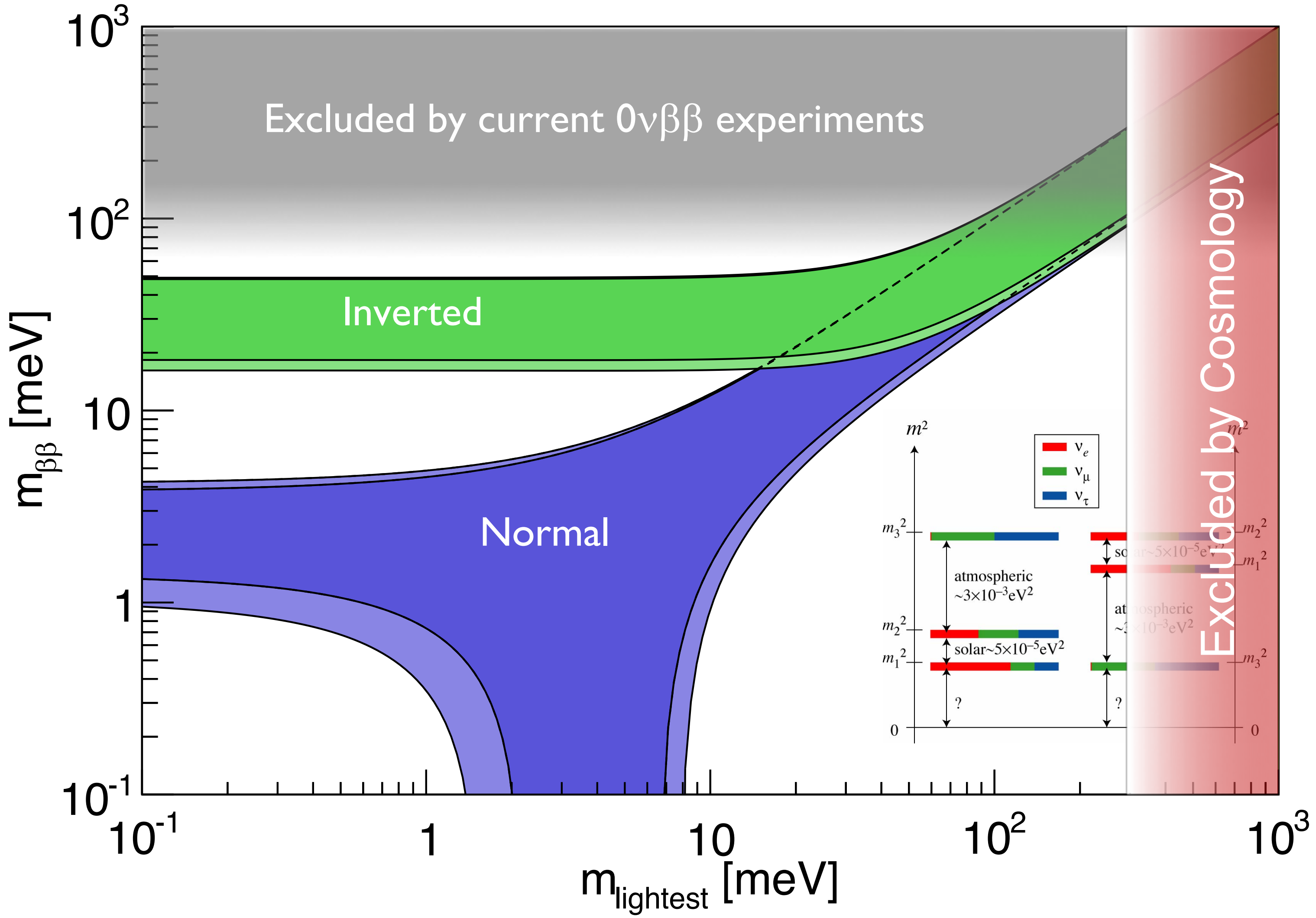
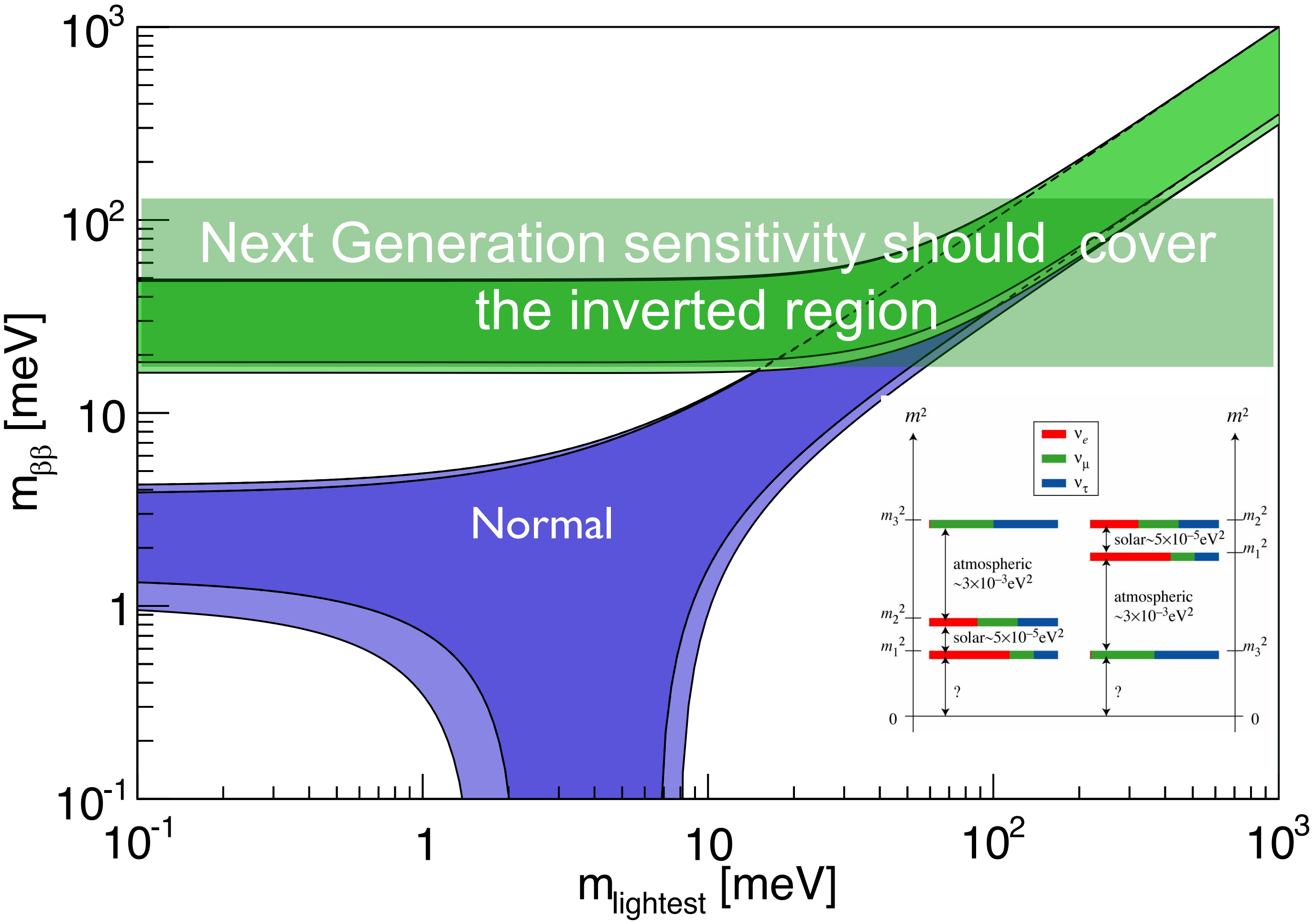


0νββ Decay Rate and $\langle m_{\beta\beta} \rangle$

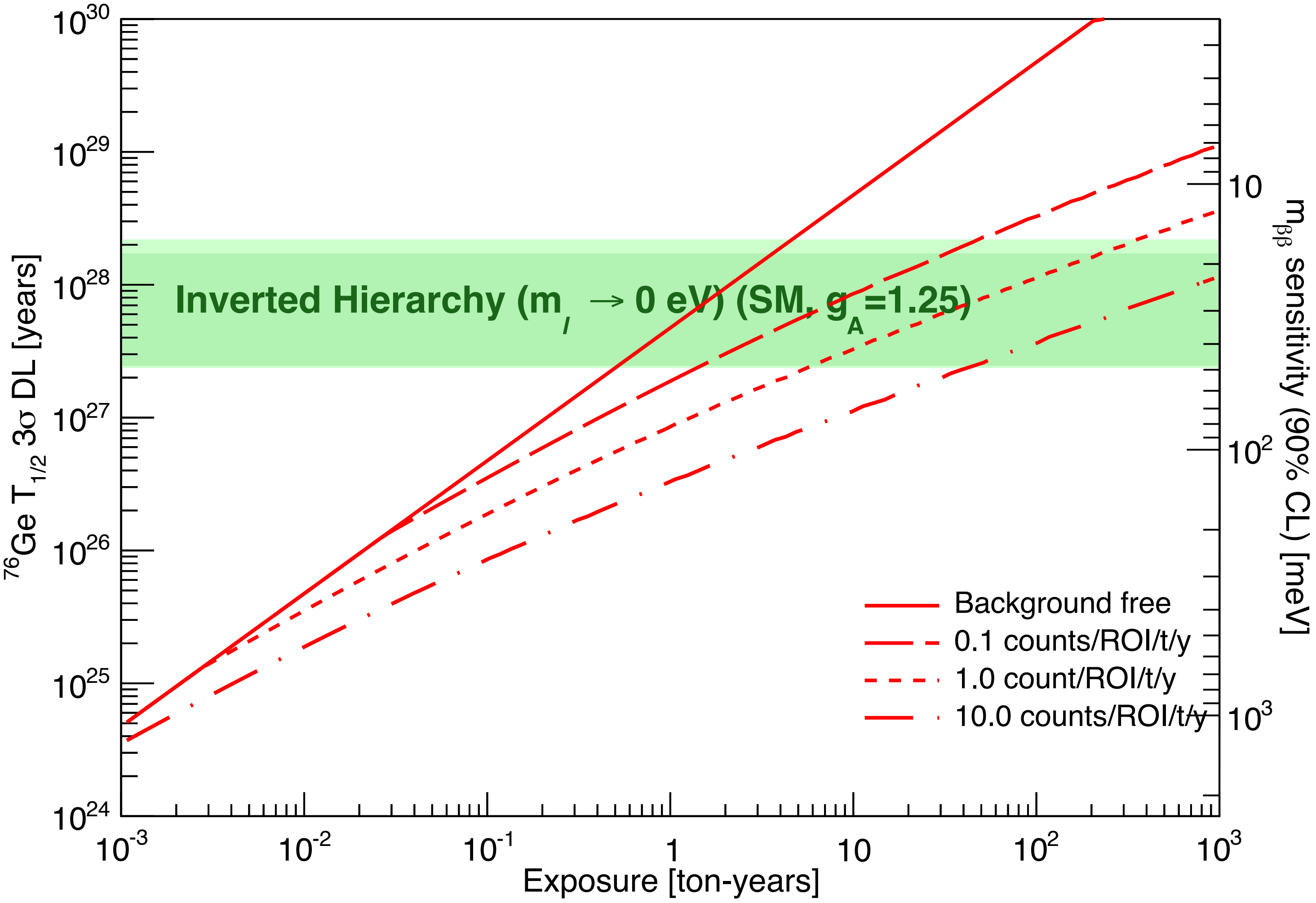
- Covering the inverted hierarchy region ($\langle m_{\beta\beta} \rangle$ ~ 15 meV) requires sensitivity to half-lives of ~ 10^{28} years.
- Corresponds to ≤ one decay per year for a tonne of material



Sensitivity for Inverted Hierarchy

To probe entire region of inverted mass hierarchy requires

- About 10 tonne-years of exposure
- Background rates of ~ 0.1 c/t/y



Sensitivity Requirements

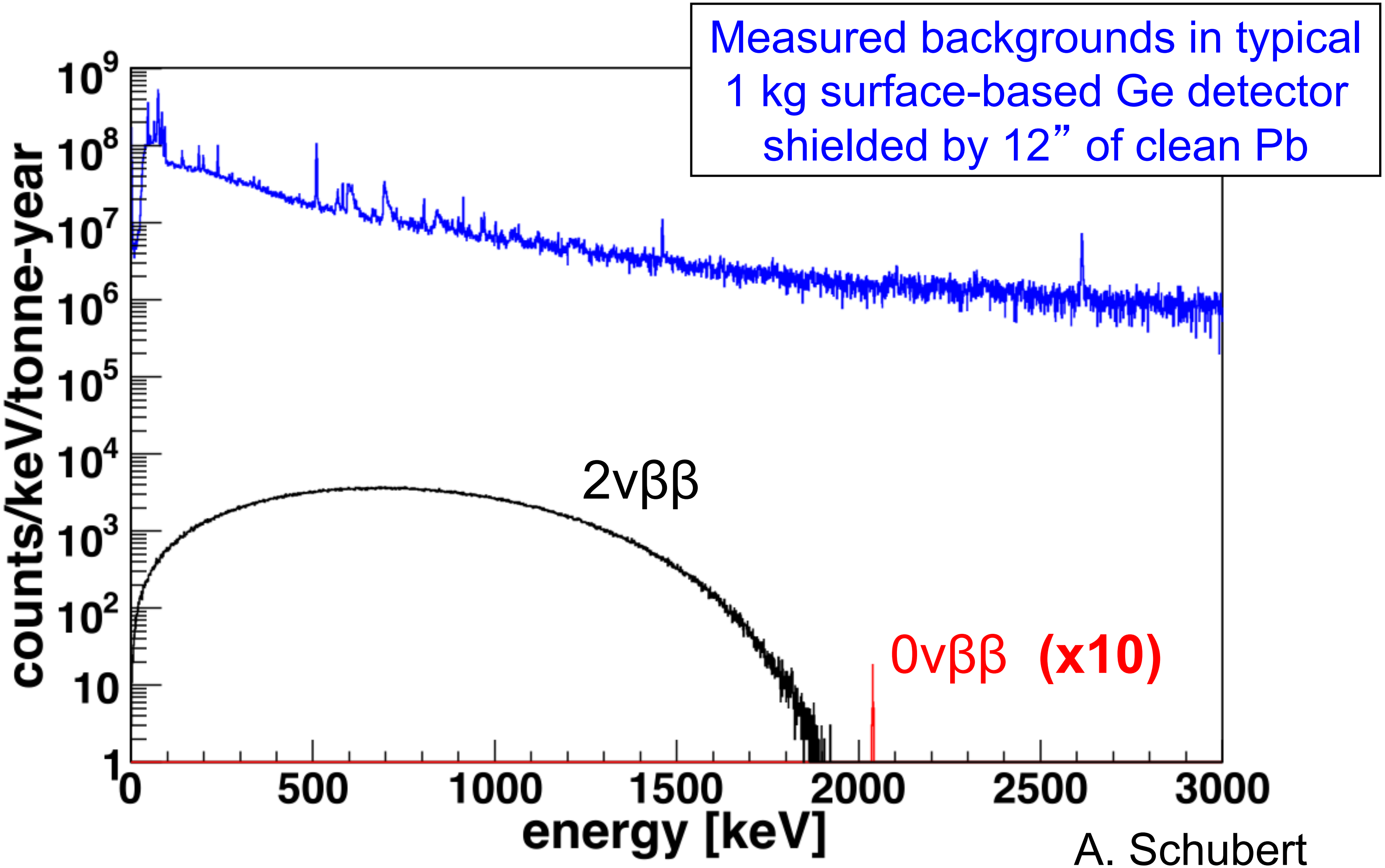
- Ten tonne-years of exposure
  - Source as detector
  - Isotopic enrichment
- Background rates of ~ 0.1 c/t/y in the $0\nu\beta\beta$ peak region (!)
  - Best possible energy resolution
  - Only ultra-clean materials
  - Active shielding

One way to think of this:

- Build seven GammaSpheres out of enriched ^{76}Ge
- Use only ultra-clean materials for cryostats, readout, cables, …
- Bury in a shield 2 km underground
- Run for 10 years
- Look for a peak with <10 counts at 2039 keV

Sensitivity for Inverted Hierarchy

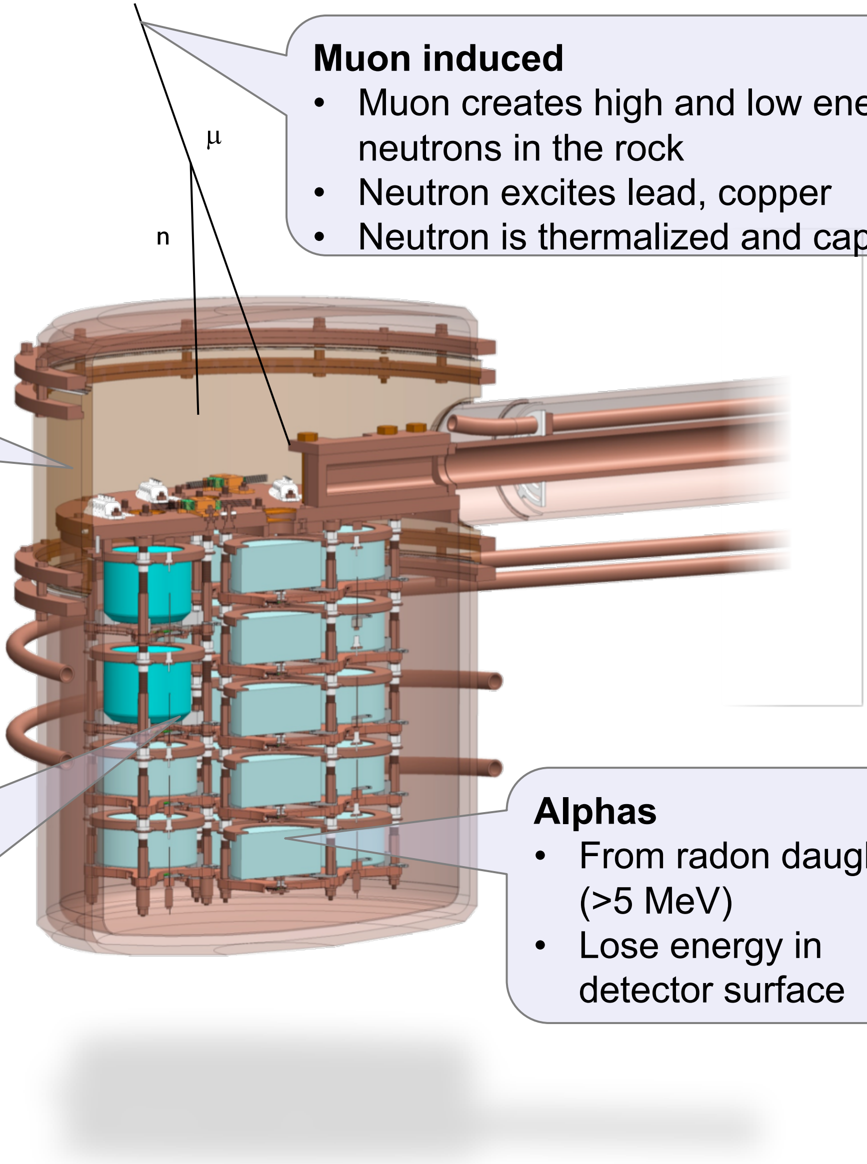
An illustration of how hard this really is…



Measured backgrounds in typical 1 kg surface-based Ge detector shielded by 12” of clean Pb

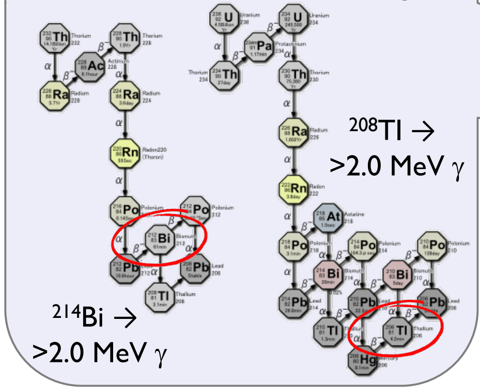
A. Schubert

It’s all about the Backgrounds



Muon induced
- Muon creates high and low energy neutrons in the rock
- Neutron excites lead, copper
- Neutron is thermalized and captured

Natural radioactivity



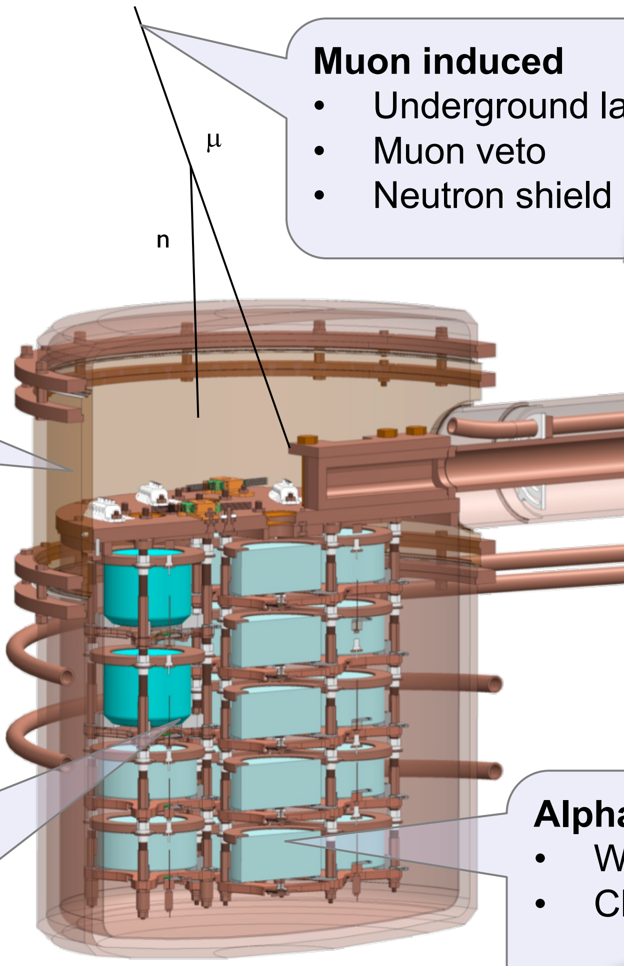
^{208}Tl →
>2.0 MeV γ

^{214}Bi →
>2.0 MeV γ

Cosmogentic activation
- High energy neutrons and muons break up copper, lead, etc. and make radioactive isotopes (e.g. Ge-68, Co-60)
- They decay and produce betas and gammas in the ROI

Alphas
- From radon daughters (>5 MeV)
- Lose energy in detector surface

How to Reduce the Backgrounds



Muon induced
- Underground lab
- Muon veto
- Neutron shield

Natural radioactivity
- High radiopurity
- Cleanliness
- Shielding

Cosmogentic activation
- Minimize above-ground time
- Copper electro-forming underground
- Analysis cuts

Alphas
- Work in glovebox
- Cleanliness

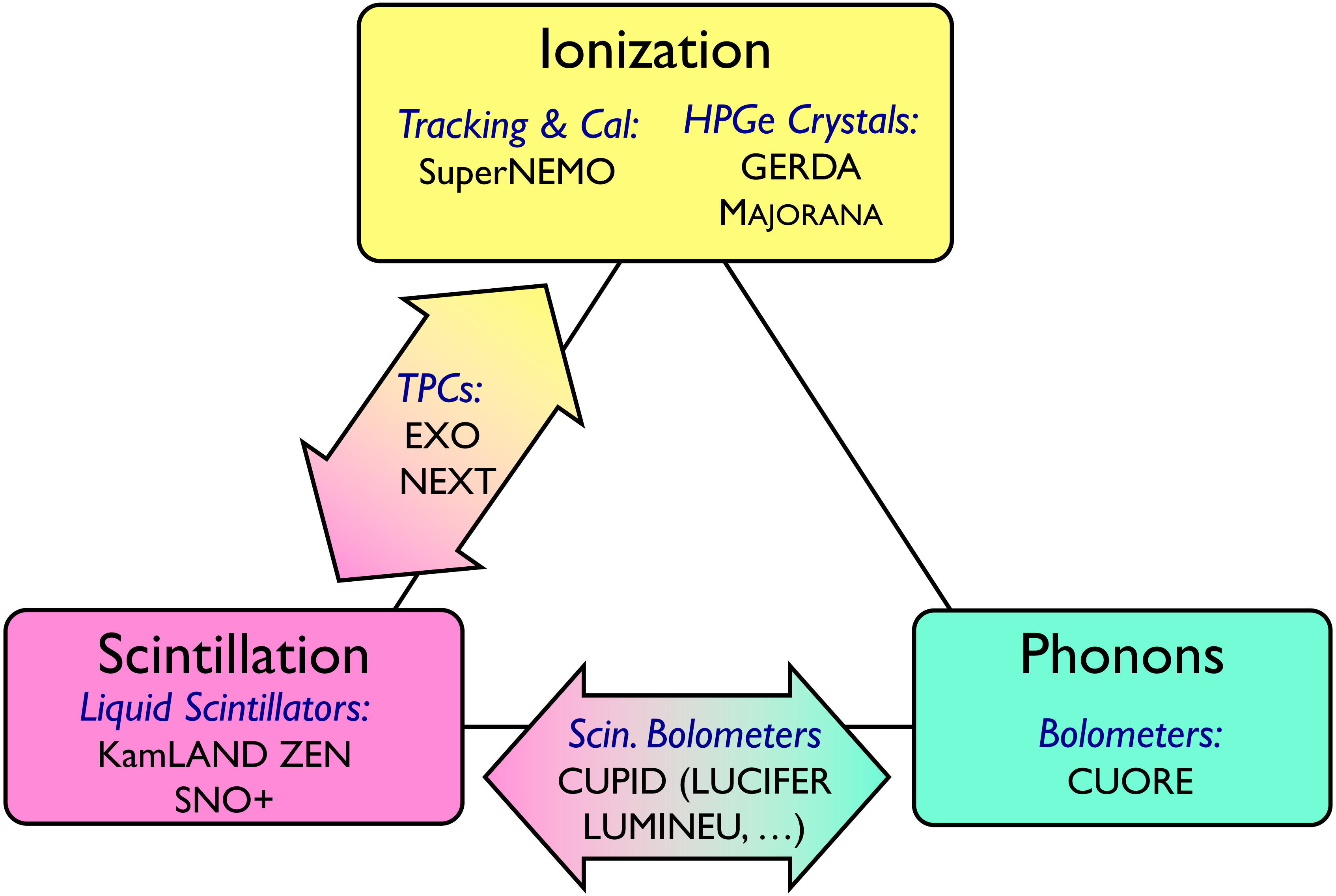
Candidate Isotopes for 0νββ Searches

- Eleven candidate isotopes:

  ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{110}Pd, ^{116}Cd, ^{124}Sn, ^{130}Te, ^{136}Xe, and ^{150}Nd

- 2νββ decay half-lives (~ 10^{19} – 10^{21} years) have been measured for all but ^{110}Pd and ^{124}Sn
- Current best limits on 0νββ decay half-lives come from three isotopes: ^{76}Ge, ^{130}Te, ^{136}Xe
- All require enrichment except possibly ^{130}Te (34%)

Detection Techniques



Ionization

Tracking & Cal:
SuperNEMO

HPGe Crystals:
GERDA
MAJORANA

TPCs:
EXO
NEXT

Scintillation

Liquid Scintillators:
KamLAND ZEN
SNO+

Scin. Bolometers
CUPID (LUCIFER
LUMINEU, …)

Phonons

Bolometers:
CUORE

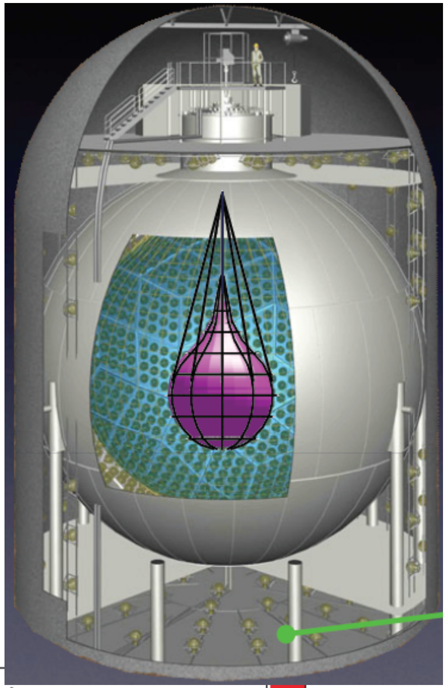
Scintillation

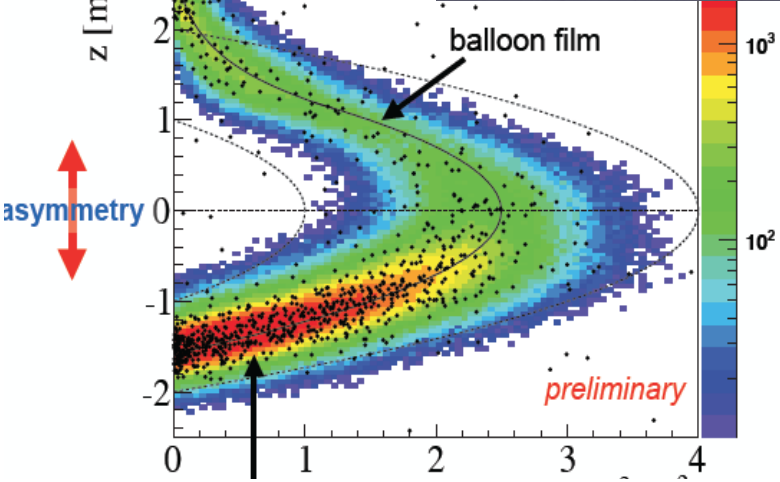
- KamLAND-Zen (^{136}Xe); SNO+ (^{130}Te)
- Doped liquid scintillators (~ 3%)

- Scalable
- Take advantage of existing detectors

- Fiducial cuts to reduce backgrounds

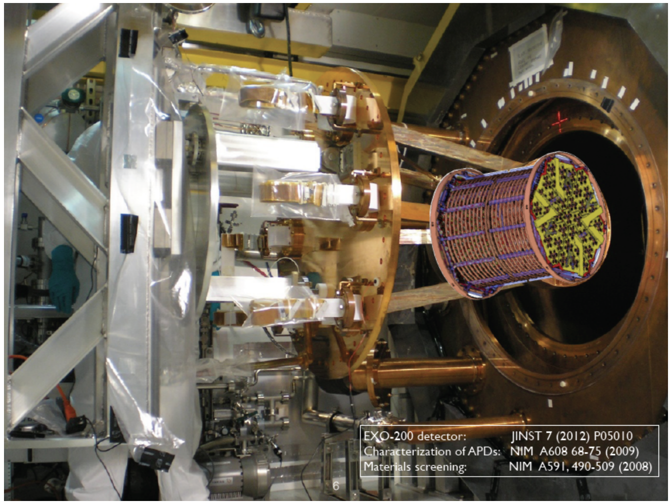
- Poorest resolution (~ 400 keV FWHM)
  - Background issues
  - 2νββ
  - Unconvincing for discovery





Time Projection Chambers

- Scintillation plus ionization
- EXO, nEXO, NEXT (^{136}Xe)

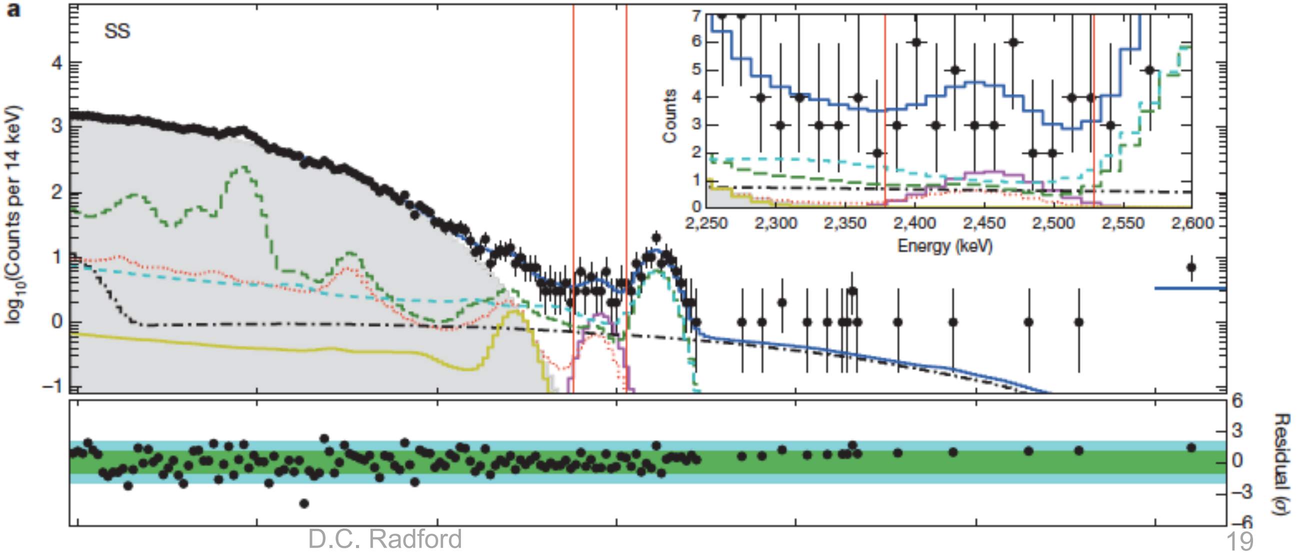


EXO-200 detector: JINST 7 (2012) P05010
Characterization of APDs: NIM A608 68-75 (2009)
Materials screening: NIM A591, 490-509 (2008)

- Multi-site event rejection

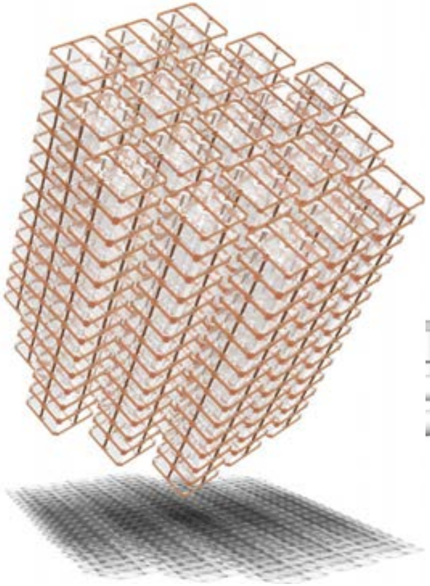
- Fiducial cuts

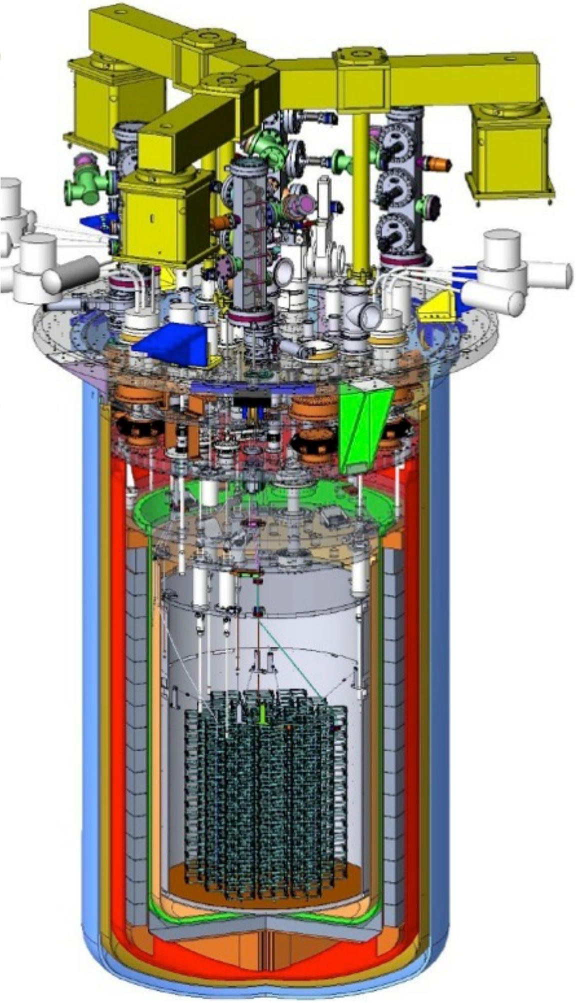
- Poor resolution (~ 90 keV FWHM)



Bolometers

- CUORE (^{130}Te)
  - Single crystals of $^{nat}TeO_2$
  - Operated at ~ 10 mK
  - NTD thermistor readout
  - World's largest dilution fridge

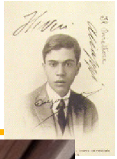




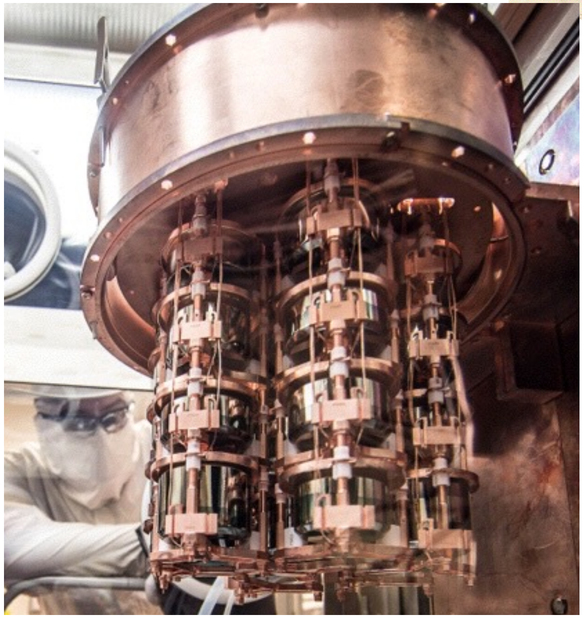
- Very good resolution
  (~ 5 keV FWHM)

- No rejection of surface-α backgrounds
- Cryogenic operation

  - R&D to develop scintillating bolometers for alpha rejection (CUPID, LUCIFER etc.)

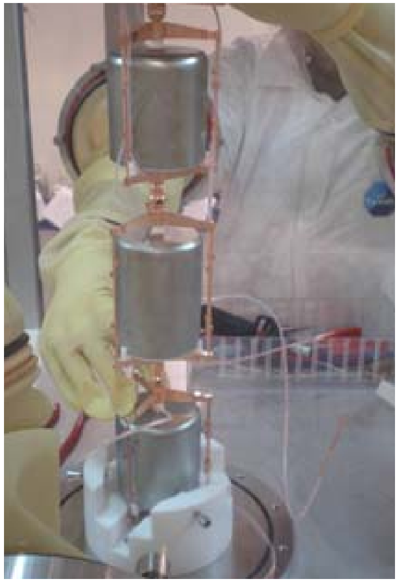


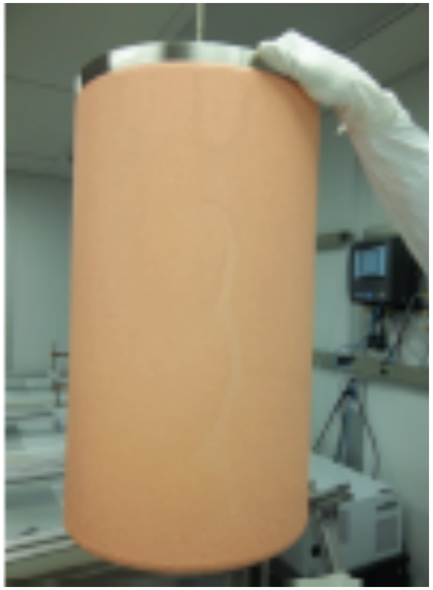
Ionization



- GERDA and Majorana (^{76}Ge)
- P-type Point Contact HPGe detectors
- 87% enriched ^{76}Ge
- Operated at ~ 80K

- Best energy resolution (< 3 keV FWHM)
- Multi-site background rejection





- GERDA (Germany/Italy) operates detectors in LAr as an active shield
- MAJORANA (US) uses vacuum cryostats made from ultra-pure Cu, electroformed underground

Advantages of ^{76}Ge

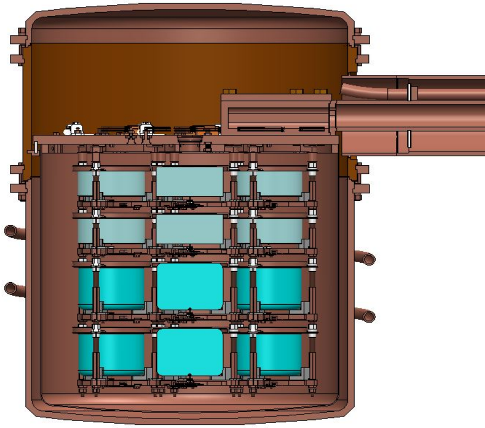
^{76}Ge offers a number of important advantages over other candidate isotopes

- Intrinsic high-purity Ge diodes
- Excellent energy resolution; 0.14% at 2.039 MeV
- Powerful background rejection
  - Pulse shape discrimination
- Well-understood technologies
  - Commercial Ge diodes
  - Large Ge arrays (GRETINA, Gammasphere)
  - Point contact detectors
- Ge as both source and detector
- Demonstrated ability to enrich from natural 7.8% to 87%

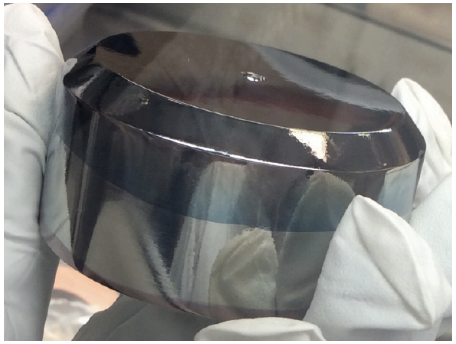
The MAJORANA DEMONSTRATOR (MJD)

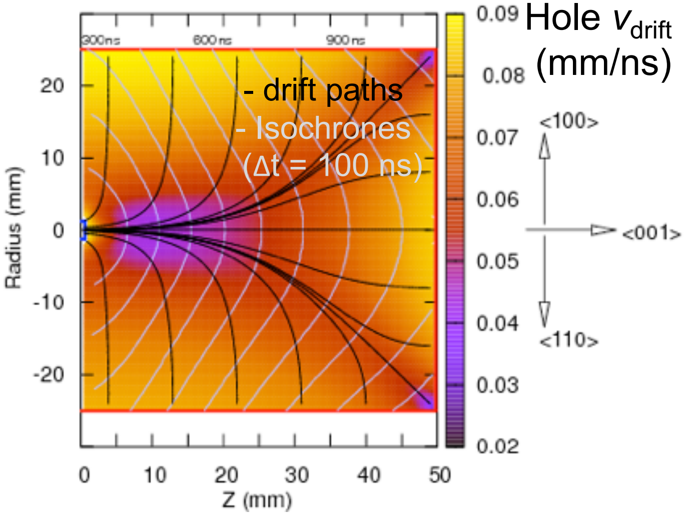
- Primary goal is to show that we can reach the ultra-low backgrounds required to justify a tonne-scale ^{76}Ge experiment
- Project construction completed and all KPPs met in Sept 2016
- Search for low-energy dark matter (light WIMPs, axions, ...)

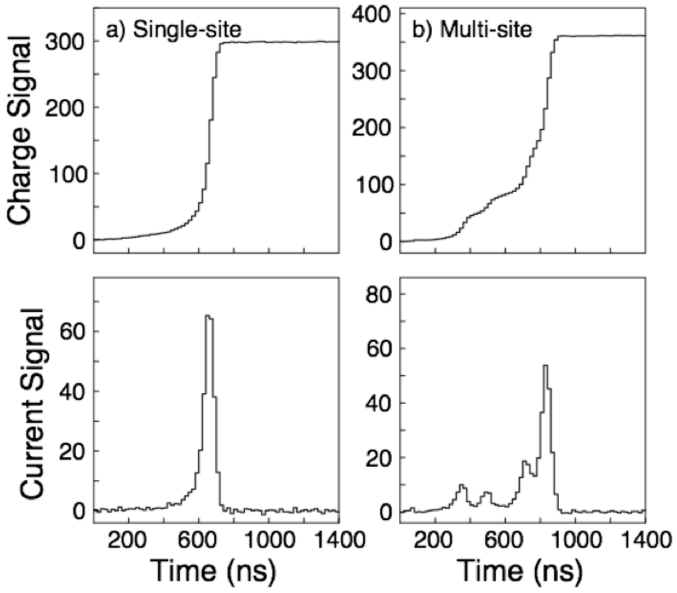
- Funded by U.S. DOE Office of Nuclear Physics and National Science Foundation
- 30 kg ^{enr}Ge + 10 kg ^{nat}Ge detectors, in two cryostats
- ^{76}Ge enriched from 7.8% to 87%
- Ultrapure materials; copper that has been electroformed and machined underground
- Passive and active shields
- At the 4850-foot level of SURF, Lead, SD



Point Contact ^{76}Ge Detectors





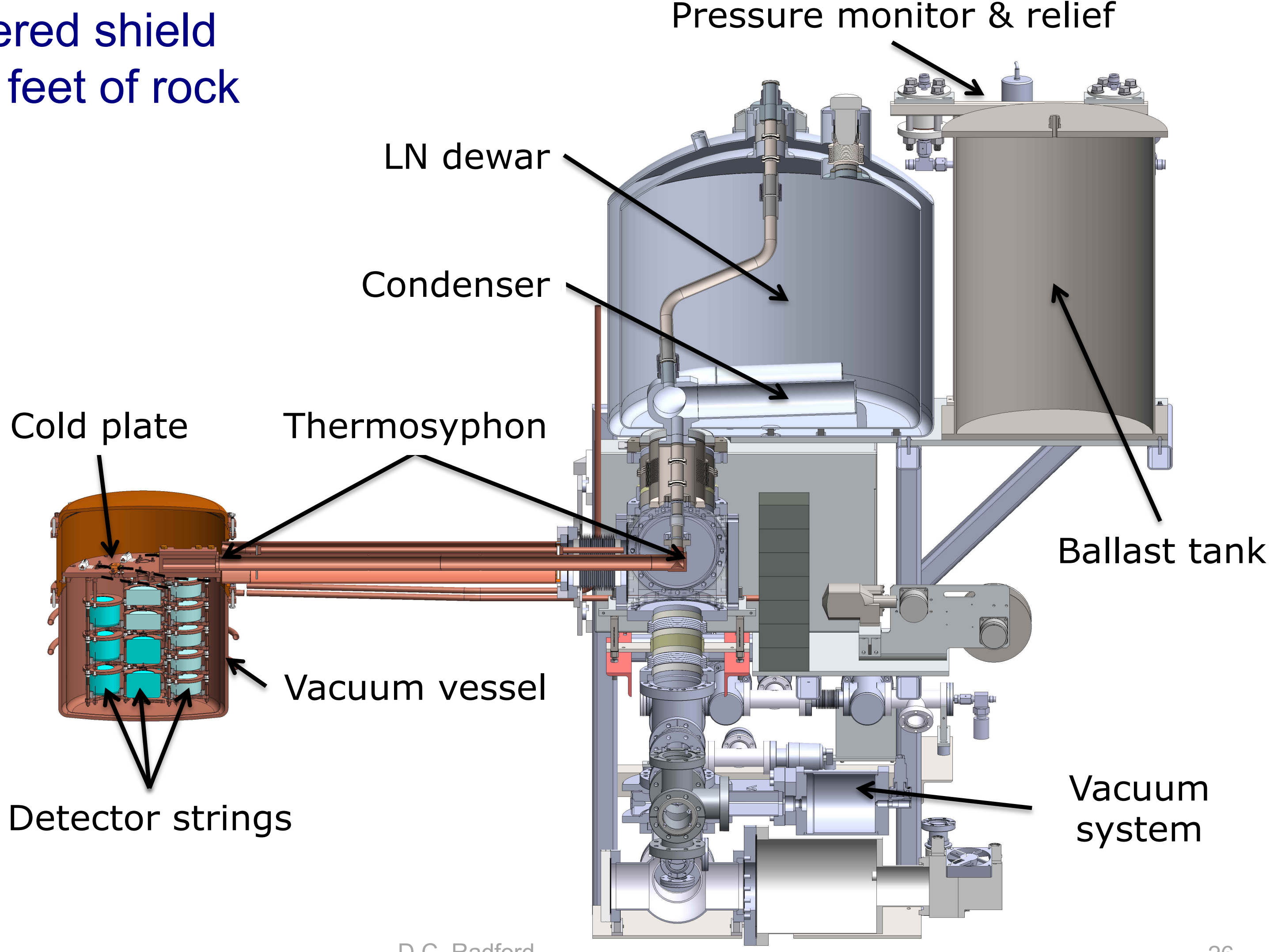


Detector Strings

Modules

Two cryostats

- Each with seven strings of detectors
- Inside a layered shield
- Under 4850 feet of rock



Pressure monitor & relief

LN dewar

Condenser

Cold plate

Thermosyphon

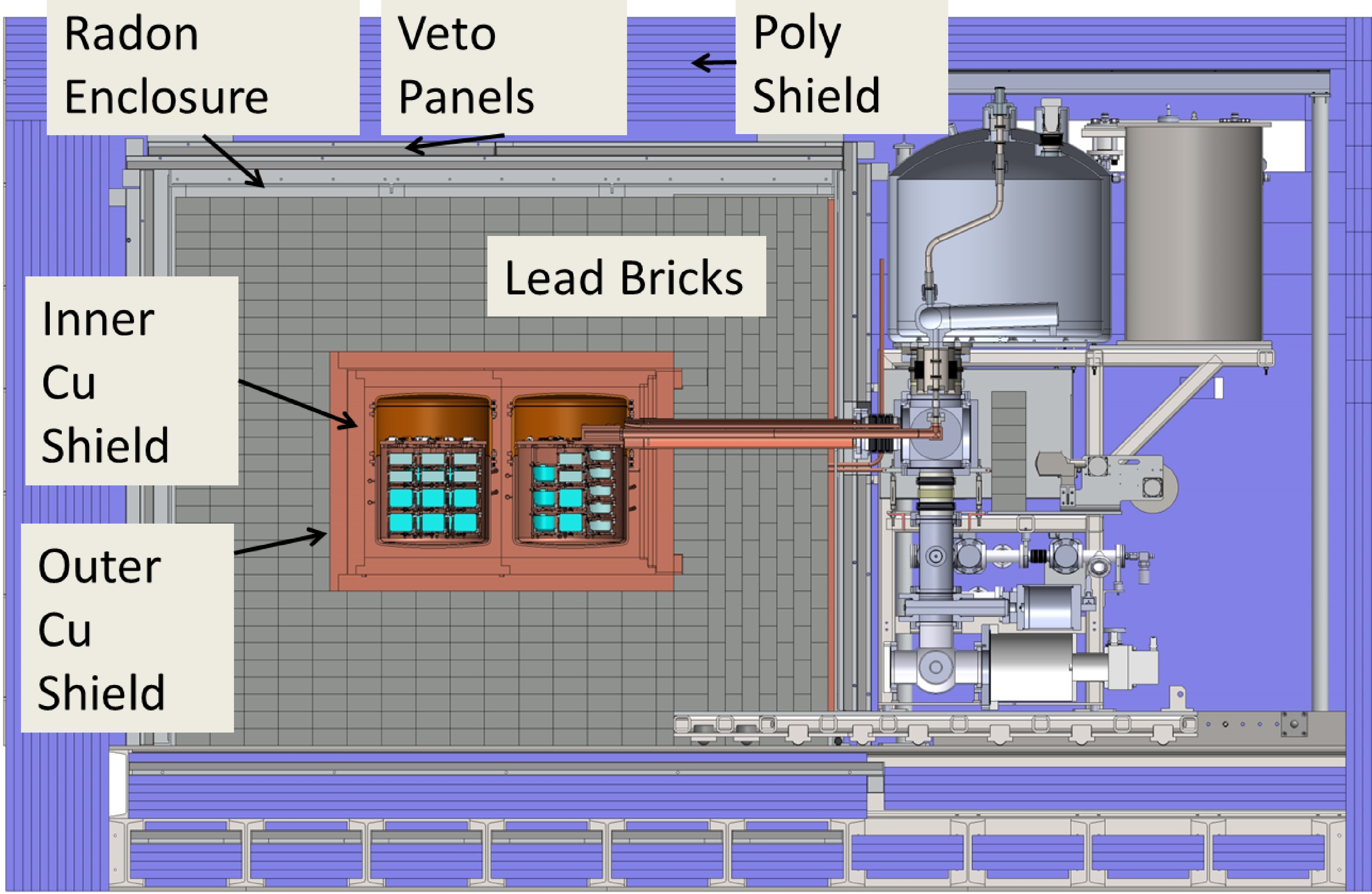
Ballast tank

Vacuum vessel

Detector strings

Vacuum system

Shield



Radon Enclosure

Veto Panels

Poly Shield

Lead Bricks

Inner Cu Shield

Outer Cu Shield

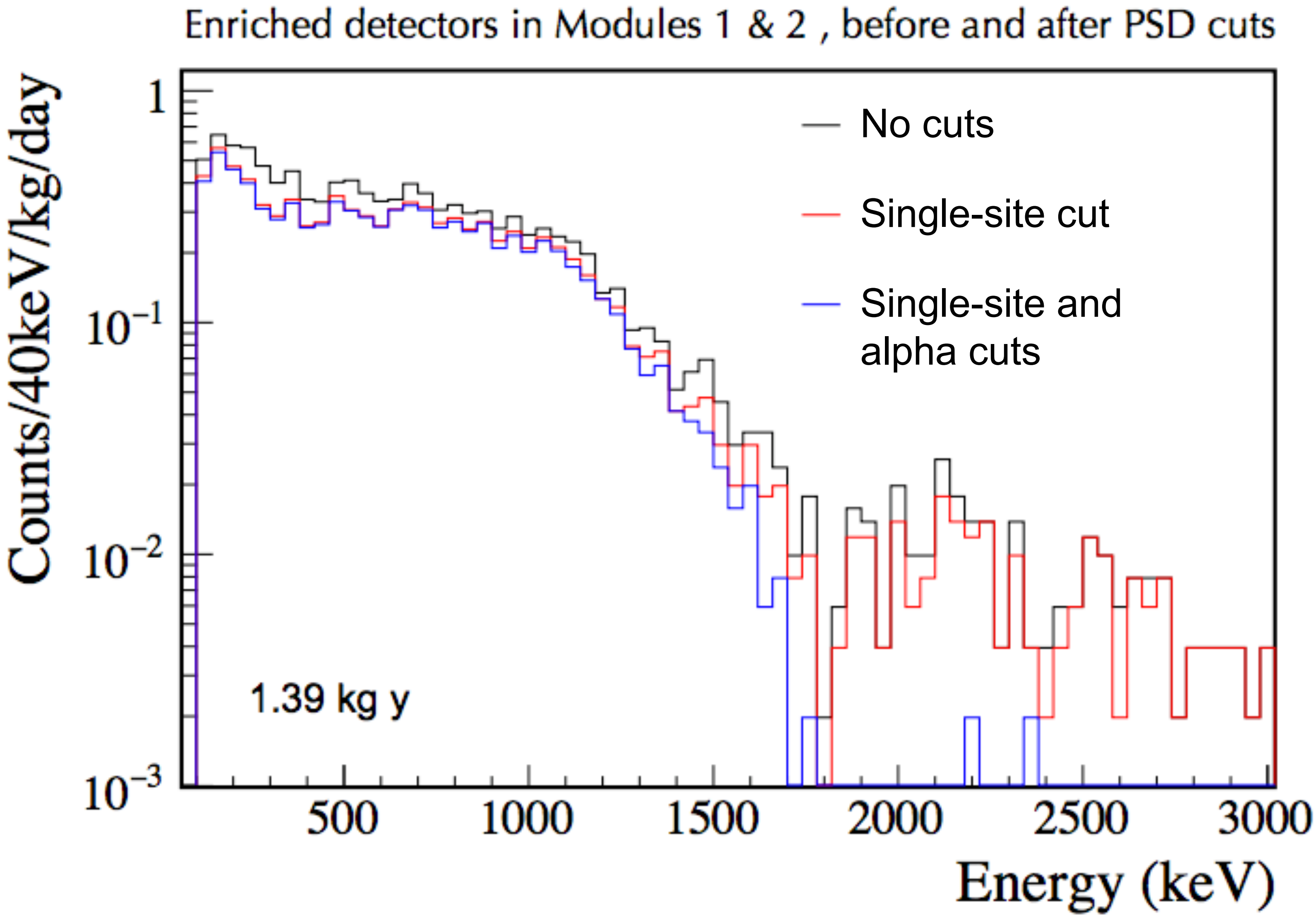
Ultra-Pure Copper

- Slow electroforming in ~ 12 large baths to produce ultra-pure copper
- Electroforming and machining both done underground to avoid cosmogenic activation (~ atoms / kg / day)

MJD Status

- Construction completed last year
  - Total of 29.5 kg in 34 enriched detectors
  - Produced from 42.5 kg of enriched material (87% ^{76}Ge)
- Modules 1 and 2 both running in-shield
- Some remaining detector issues
  - 9/34 enriched and 6/24 natural detectors currently unbiased
  - Mostly due to signal or HV connections, or blown FETs
  - One due to high leakage, two due to readout noise issues
- All CD-4 requirements met as of Sept 31, so now in operations phase
  - Now in “blind mode” data acquisition
- Calibrations for ~ 1 hour per week, remainder is background data

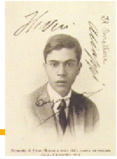
Final Spectrum

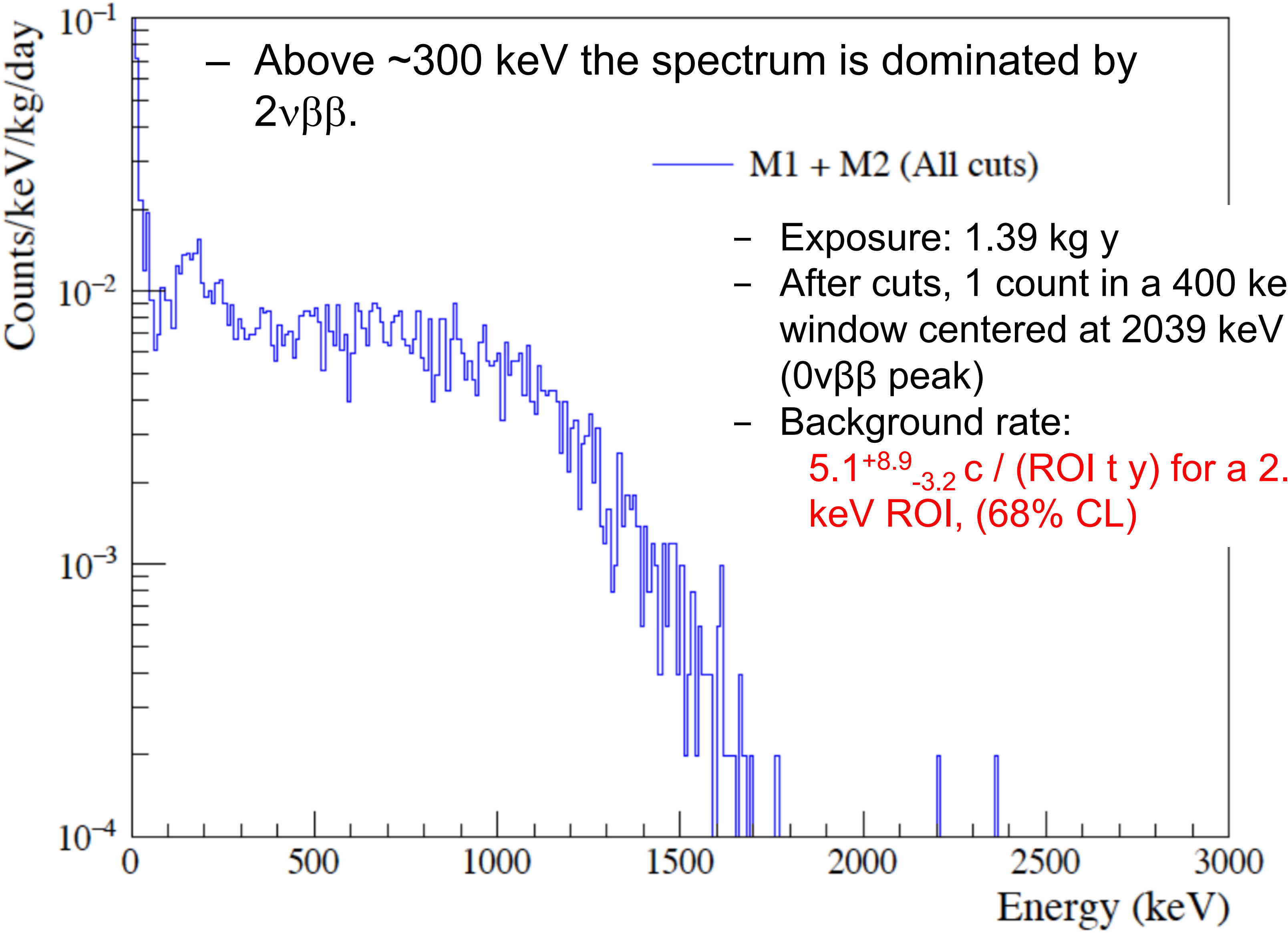


Enriched detectors in Modules 1 & 2 , before and after PSD cuts

1.39 kg y

Final Spectrum



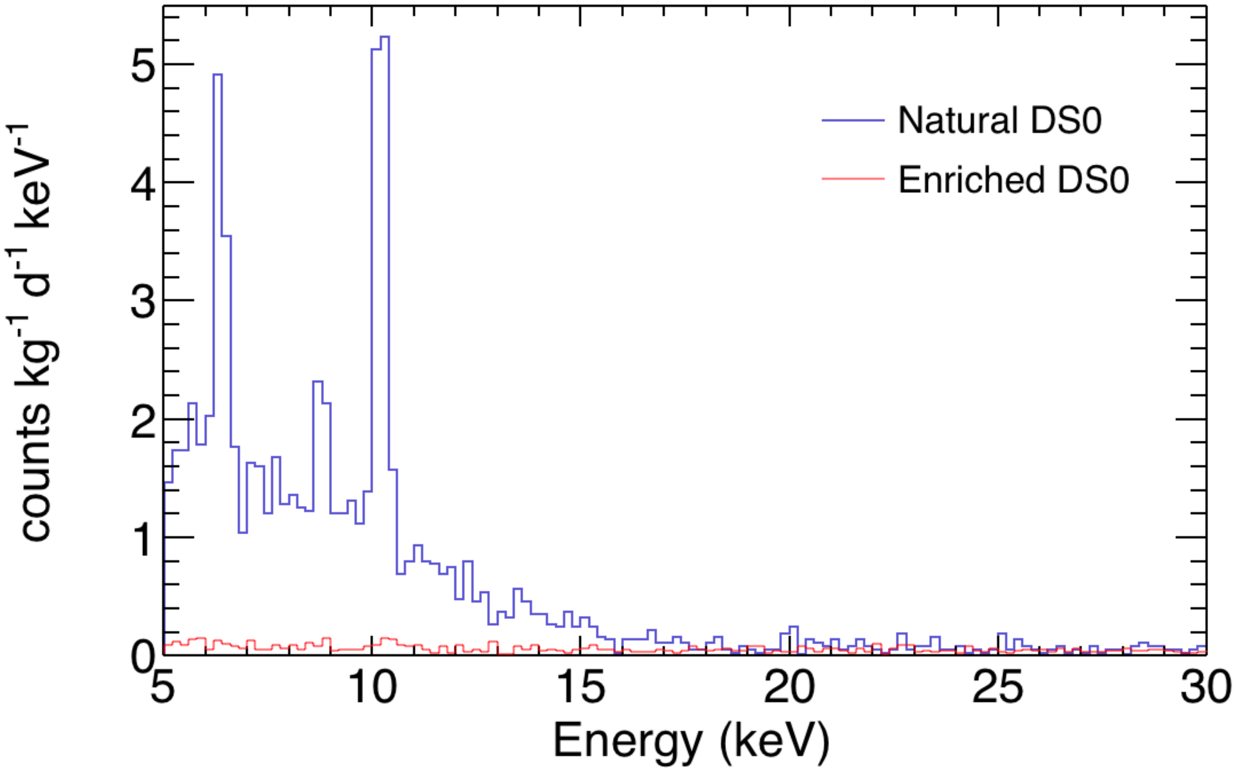


- Above ~300 keV the spectrum is dominated by 2νββ.

- Exposure: 1.39 kg y
- After cuts, 1 count in a 400 keV window centered at 2039 keV (0νββ peak)
- Background rate:
  $5.1^{+8.9}_{-3.2}$ c / (ROI t y) for a 2.8 keV ROI, (68% CL)

Low-Energy Performance - Cosmogenics

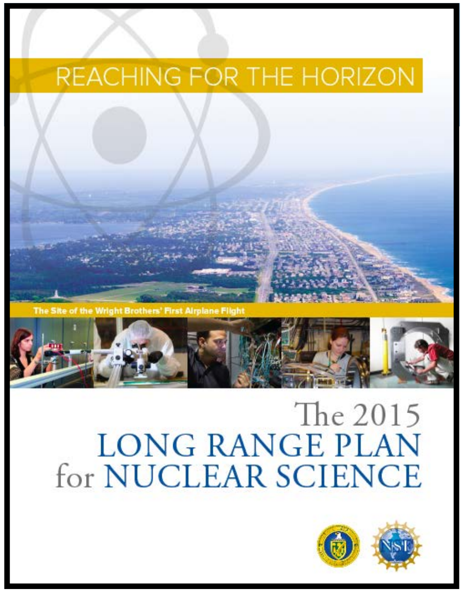
- Controlled surface exposure of enriched material
- Significant reduction of cosmogenics in the low-energy region
  - Background is even lower in DS1; ~ 0.01 cts/(kg keV d)
- Tritium dominates in natural detectors below 20 keV



Low-Energy physics:

- Pseudoscalar dark matter
- Vector dark matter
- 14.4-keV solar axion
- e^- → 3v decay
- Pauli Exclusion Principle

The Next Step


REACHING FOR THE HORIZON

The Site of the Wright Brothers' First Airplane Flight

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

RECOMMENDATION II

The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

A ton-scale instrument designed to search for this as-yet unseen nuclear decay will provide the most powerful test of the particle-antiparticle nature of neutrinos ever performed. With recent experimental breakthroughs pioneered by U.S. physicists and the availability of deep underground laboratories, we are poised to make a major discovery.

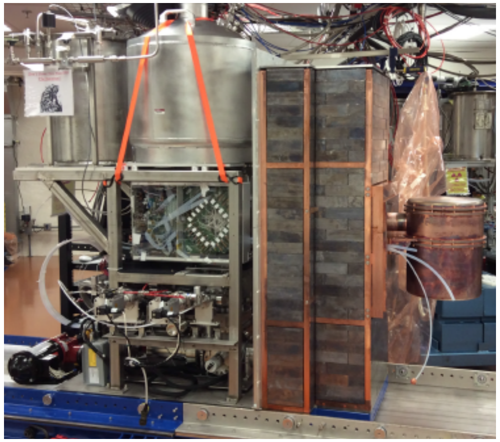
This recommendation flows out of the targeted investments of the third bullet in Recommendation I. It must be part of a broader program that includes U.S. participation in complementary experimental efforts leveraging international investments together with enhanced theoretical efforts to enable full realization of this opportunity.

MAJORANA and GERDA

MAJORANA

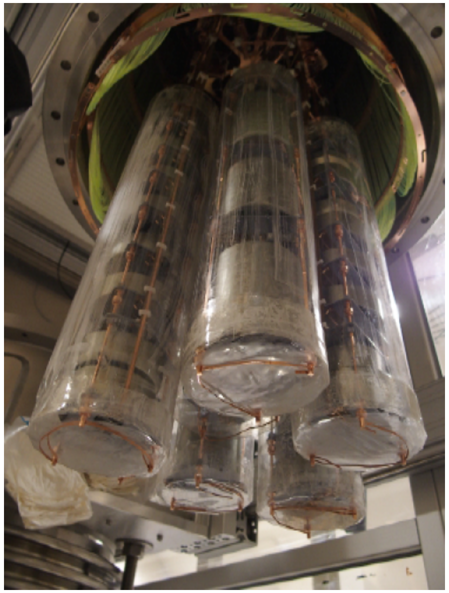
“Traditional” configuration

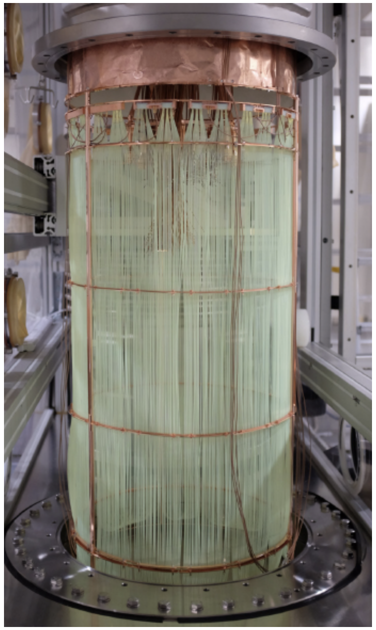
Vacuum cryostats in a passive graded shield with ultraclean materials



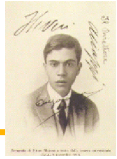
GERDA

Direct immersion in active LAr shield





LEGEND



Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Together, MAJORANA and GERDA have the

- Best energy resolution and
- Lowest backgrounds of any 0νββ experiment

We have joined together to form a new international collaboration to pursue a next-generation experiment.

Mission: "The collaboration aims to develop a phased, Ge-76 based double-beta decay experimental program with discovery potential at a half-life significantly longer than 10^{27} years, using existing resources as appropriate to expedite physics results."

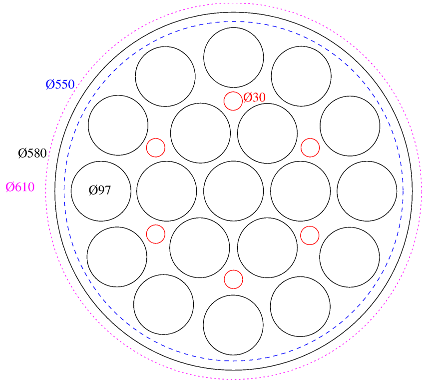
- Select best technologies, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.

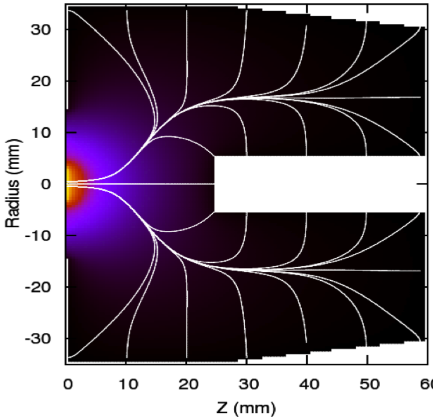
LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

First phase: LEGEND-200

- Up to 200 kg
- Modification of existing GERDA infrastructure at LNGS
- Add larger point-contact detectors
- BG goal: 0.6 c /(FWMH t y)
- Start by 2021



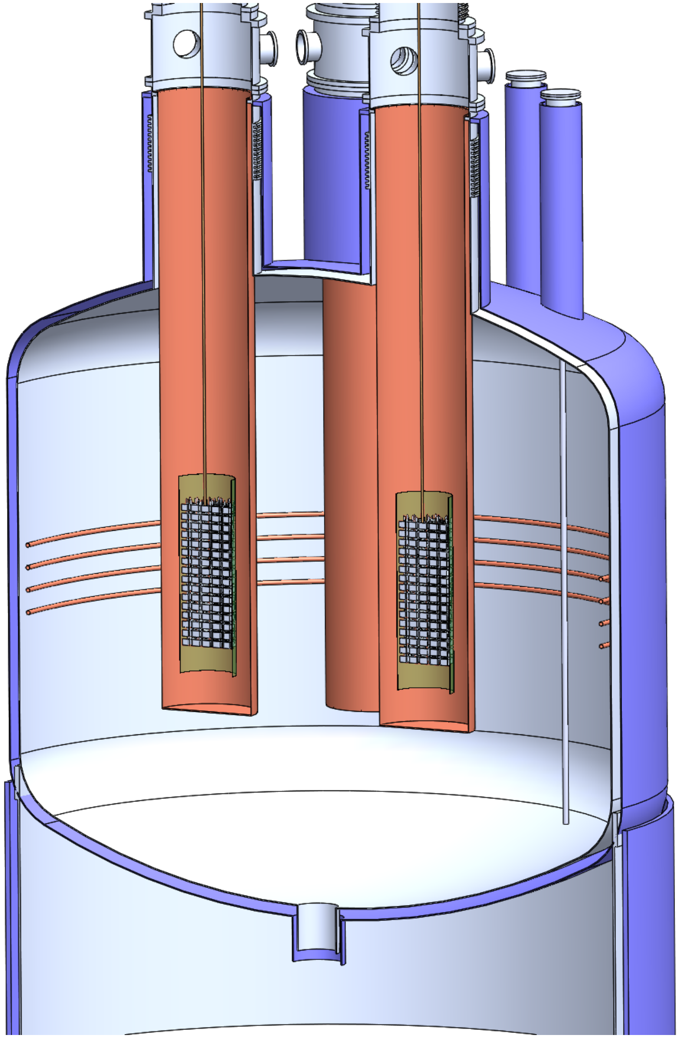


LEGEND

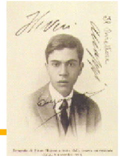
Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Subsequent stages: LEGEND-1000

- Staged 1000 kg
- Baseline design:
    - 4 - 5 payloads in LAr cryostat in separate volumes
    - Each payload 200 - 250 kg, ~100 detectors.
    - Depleted LAr in inner volumes
- Timeline connected to U.S. DOE down-select process
- BG goal: 0.1 c /(FWHM t y)
- Location TBD
- Required depth under investigation

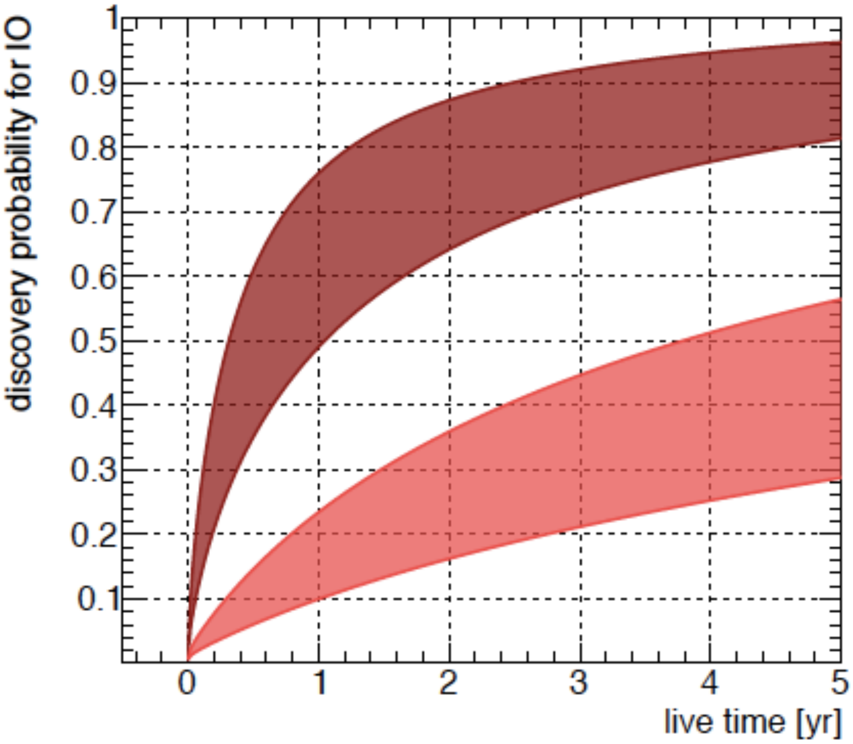


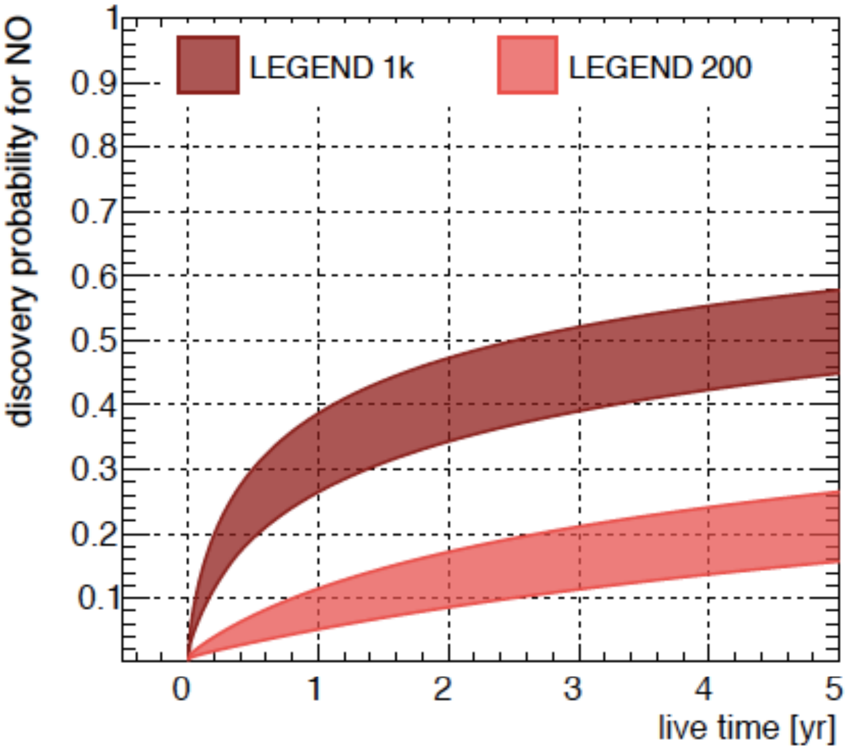
Discovery Probability



Discovery probability of next-generation neutrinoless double-beta decay experiments

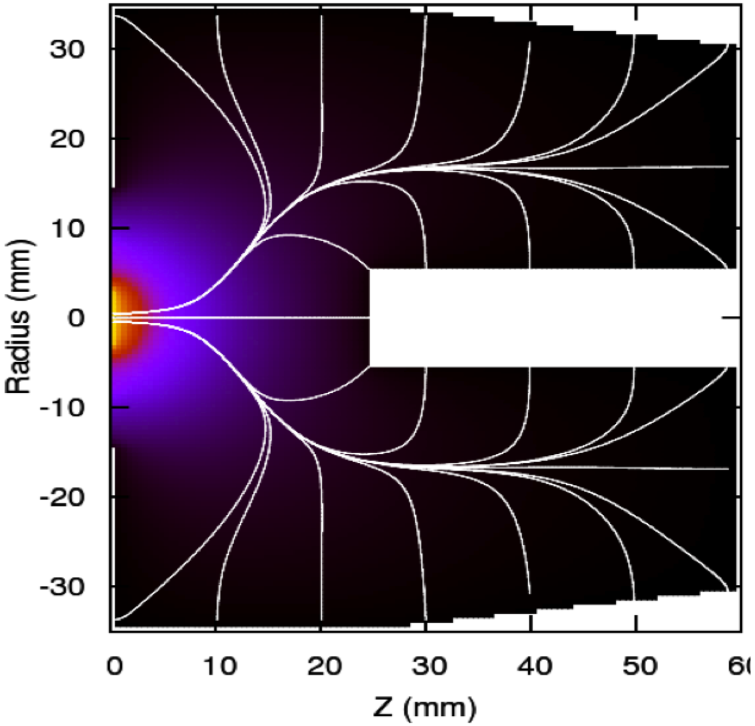
Matteo Agostini, Giovanni Benato, and Jason Detwiler arXiv:1705.02996v1





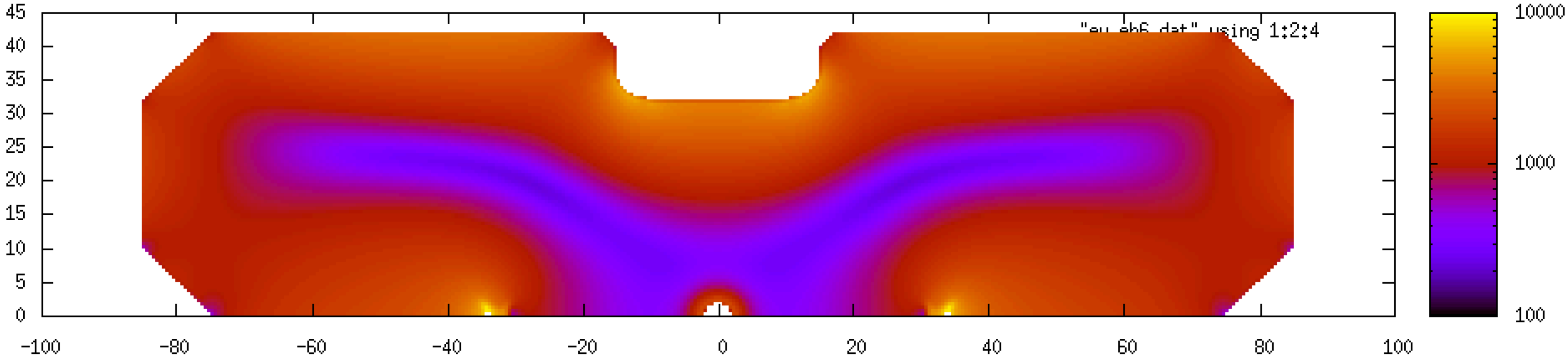
Inverted-coaxial PPC detectors

- MJD detector design is limited to ~ 1.0 kg by depletion issues
- New design: Inverted-Coaxial Point Contact
- Invented at ORNL, commercialized by Canberra as SAGe Well Detector
- Potential for much larger masses, in excess of 3 kg
- Same low capacitance, so very good low-E resolution, low thresholds
- Same excellent PSA performance
- Being investigated at ORNL with LDRD funding
- Simulations are very promising
- Prototypes on order from ORTEC and PHDs



Larger Mass Design

- PHDs are now growing pure crystals with huge diameters
- Could we make a detector with 4.5 kg mass?
- Would be by far the largest single-crystal Ge detector ever made!



Calculated field; 17 cm diameter, 4 cm thick

17.5 cm crystal, 6.8 kg

Summary

- Majorana neutrinos would give us deep insights into the New Standard Model and the matter-antimatter asymmetry of the universe.
- $0\nu\beta\beta$ experiments are the only feasible way to probe this aspect of the neutrino. Definitive tests of inverted-hierarchy Majorana neutrinos are within reach.
- The ultimate goal of the MAJORANA collaboration is to field a tonne-scale ^{76}Ge $0\nu\beta\beta$ decay search.
  - The DEMONSTRATOR aims to show that we can reach the ultra-low backgrounds required; both MJD and GERDA results are very encouraging
  - MJ and GERDA have formed LEGEND, a new international collaboration to field a next generation experiment
  - Aim for sensitivity and discovery levels at $T_{1/2} \sim 10^{28}$ years
  - Top priority for new activity in 2015 NSAC Long Range Plan
  - Down-select expected in 2-3 years
  - Construction of a first-stage 200kg experiment could begin as early as 2020

The MAJORANA Collaboration

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LEGEND

47 Institutions, 219 Scientists

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Lab. Naz. Gran Sasso
Univ. Texas
Tsinghua Univ.
Lawrence Berkeley Natl. Lab.
Leibniz Inst. Crystal Growth
Comenius Univ.
Lab. Naz. Sud
Univ. of North Carolina
Sichuan Univ.
Univ. of South Carolina
Jagiellonian Univ.
Banaras Hindu Univ.
Univ. of Dortmund
Tech. Univ. – Dresden
Joint Inst. Nucl. Res. Inst.
Nucl. Res. Russian Acad. Sci.

Collaboration formed Oct. 2016

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Max Planck Inst., Heidelberg
Dokuz Eylul Univ.
Queens Univ.

Univ. Tennessee
Argonne Natl. lab.
Univ. Liverpool
Univ. College London
Los Alamos Natl. Lab.

Lund Univ.
INFN Milano Bicocca
Milano Univ. and Milano INFN
Natl. Res. Center Kurchatov Inst.
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Max Planck Inst., Munich
Tech. Univ. Munich
Oak Ridge Natl. Lab.
Padova Univ. and Padova INFN
Czech Tech. Univ. Prague
Princeton Univ.
North Carolina State Univ.
South Dakota School Mines Tech.
Univ. Washington
Academia Sinica
Univ. Tuebingen
Univ. South Dakota
Univ. Zurich

LEGEND collaboration meeting @ LNGS, 15-17.5.2017