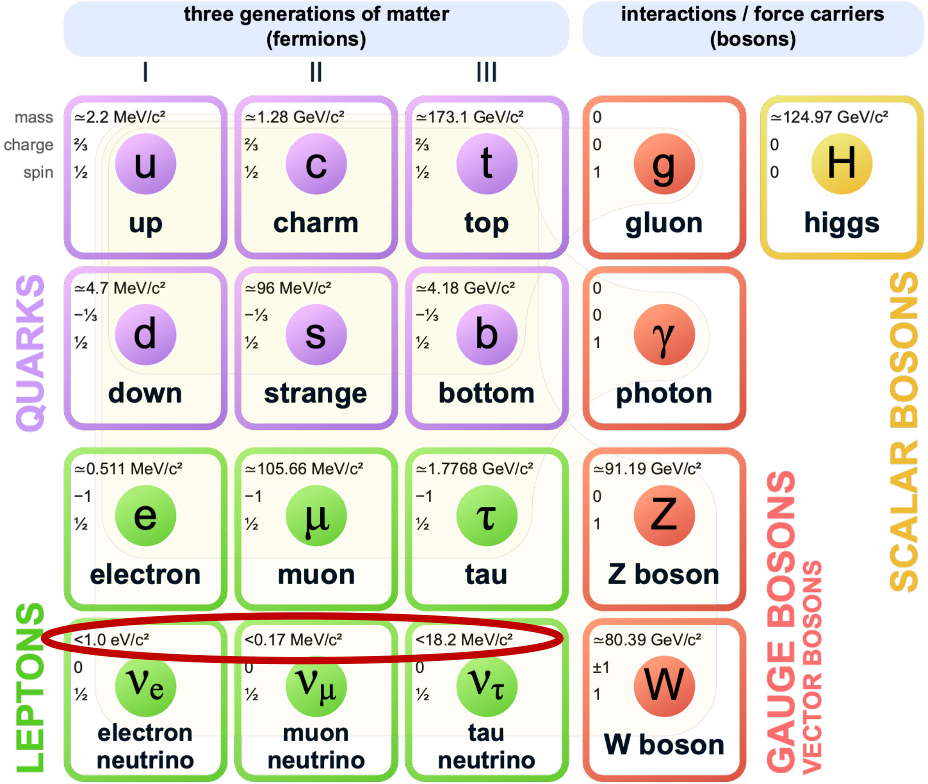
Walter C. Pettus

Searches for Neutrinoless Double Beta Decay

30 September 2021

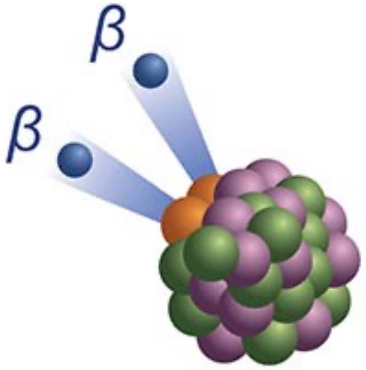
INDIANA UNIVERSITY

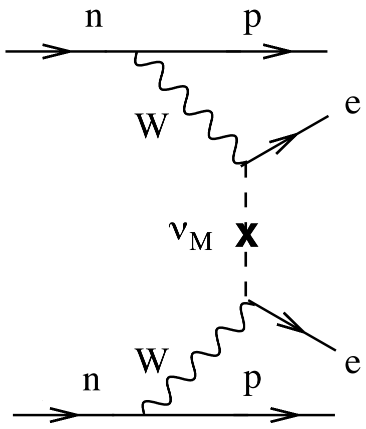
Neutrino Mass ~~Problem~~ Opportunity



- What is the neutrino mass?
- Why is the neutrino mass so much smaller than other fermion masses?
- How much CP violation in lepton sector?
- Other new physics hiding with neutrinos?

Neutrinoless Double Beta Decay (0νββ)





Searching for theoretical process:

- $(\mathrm{A,Z}) \rightarrow (\mathrm{A,Z}+2) + 2\mathrm{e}^-$
  - Contrast with $(\mathrm{A,Z}) \rightarrow (\mathrm{A,Z}+2) + 2\mathrm{e}^- + 2\bar{\nu}_e$, observed

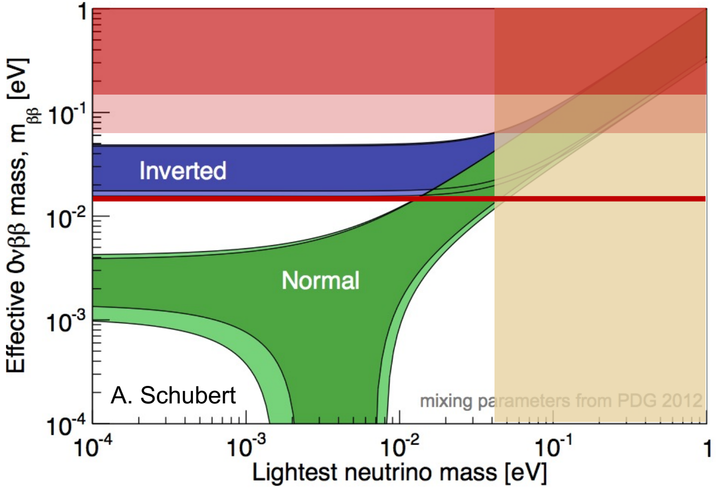
0νββ always implies new physics

- Lepton number violating process (ΔL=2)
- Majorana neutrinos generate 0νββ
- Majorana neutrinos help explain small observed neutrino masses via see-saw mechanism
- Leptogenesis as ingredient for explaining matter-antimatter asymmetry

Sensitivity to Neutrino Mass

- Half-life of 0νββ related to neutrino mass scale
  - $\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}|M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$
  - $\langle m_{\beta\beta}\rangle = \left|\sum U_{ei}^2 m_i\right|$

Current 0νββ limits



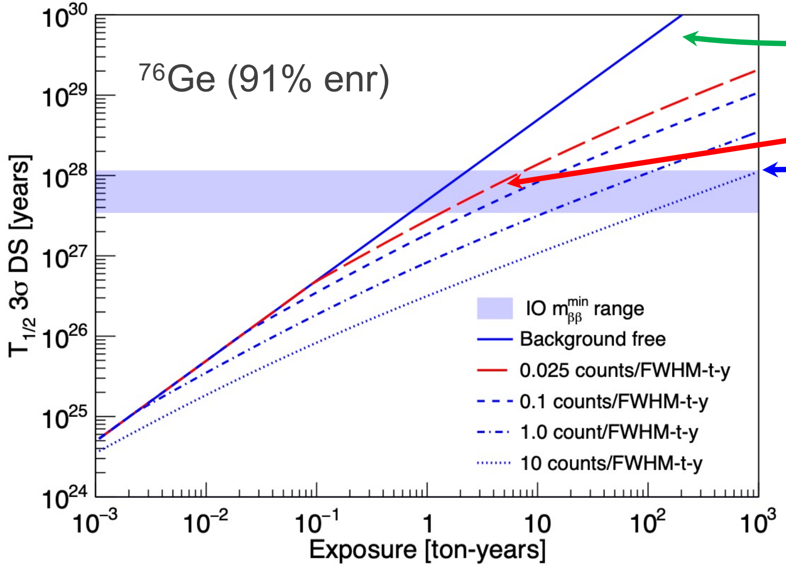
Next-generation, "tonne-scale" 0νββ experiment goal

Current cosmological limits (direct neutrino mass limits)

Experimental Sensitivity

- Current world-leading sensitivity:
  - $T_{1/2} \approx 10^{26}$ yr
- Next-generation target sensitivity:
  - $T_{1/2} \approx 10^{28}$ yr

x100 in $T_{1/2}$, x10 in $m_{\beta\beta}$



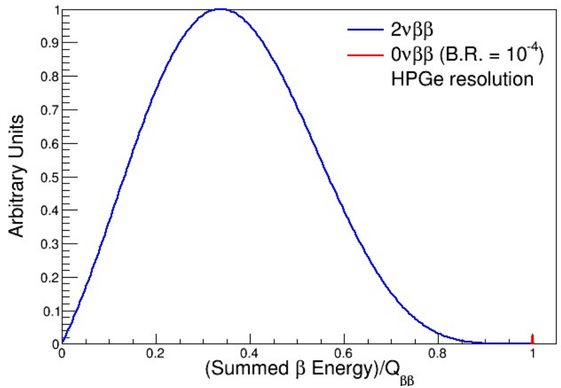
background-free: linear scaling

quasi-background-free

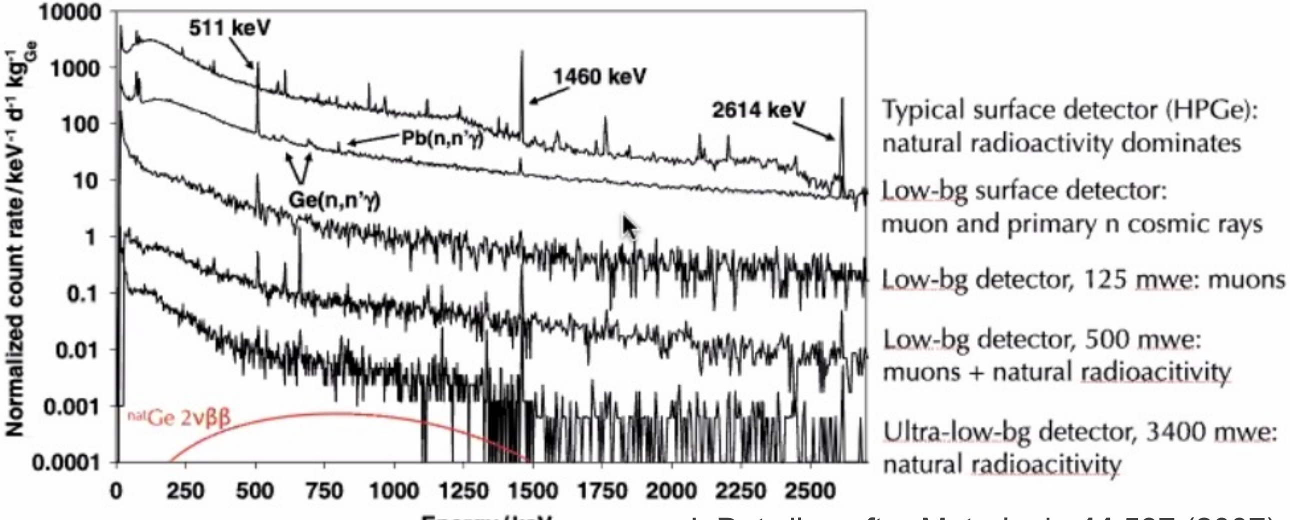
high background: square-root scaling

Experimental Backgrounds

- Experimental goal is to measure monoenergetic peak at $Q_{\beta\beta}$



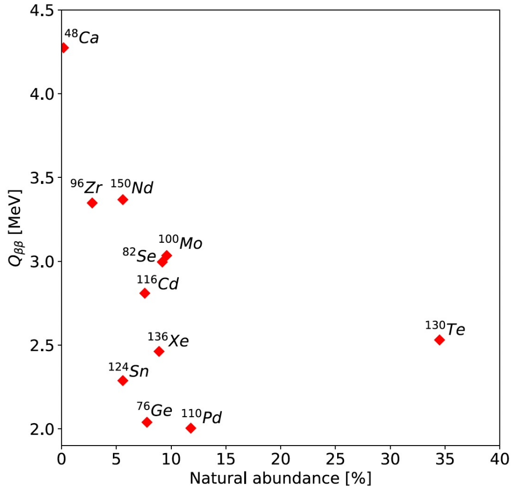
- But this signal is buried under other backgrounds…



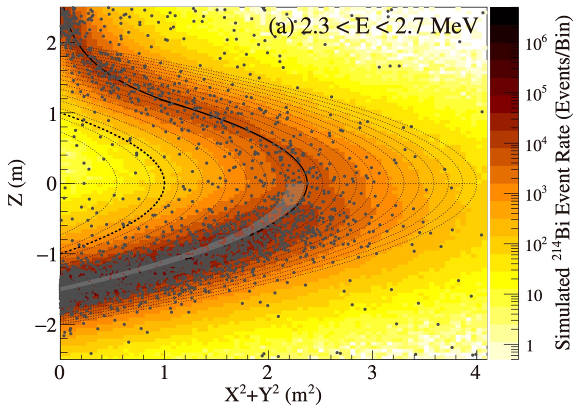
J. Detwiler, after Metrologia **44** 587 (2007)

Experimental Considerations

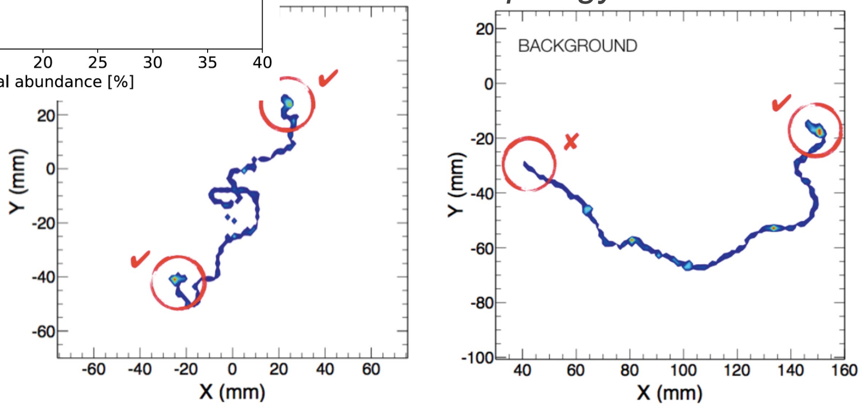
- Maximize exposure
  - Larger source
  - Higher enrichment*
  - Higher efficiency
- Minimize background
  - Deep underground
  - Material purity
  - Energy resolution
  - Decay Q-value*
  - Background rejection via cuts**



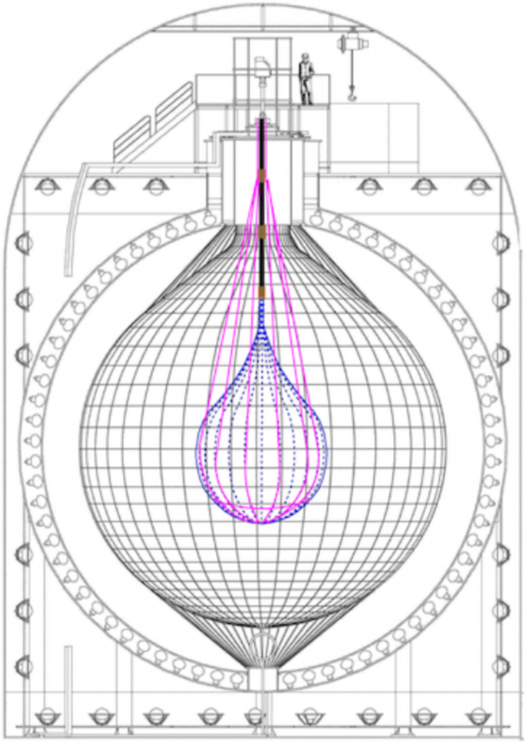
KamLAND: Fiducialization



NEXT: Topology Simulation

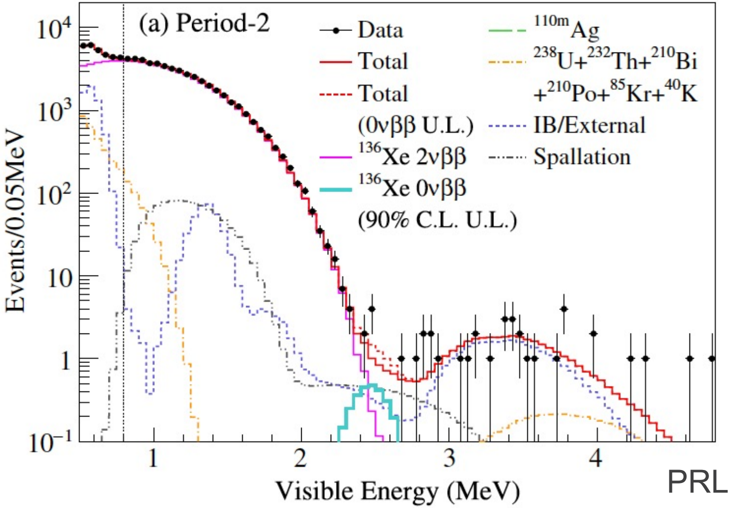


KamLAND-Zen



From Aobo Li, TAUP21

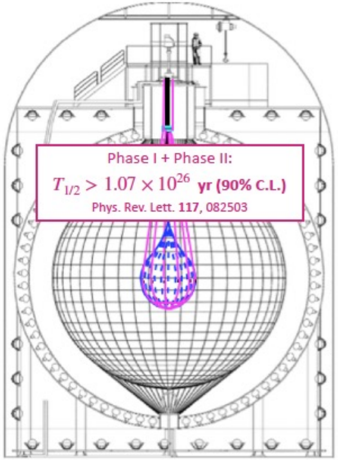
- Builds on successful KamLAND detector and physics program
- ^{136}Xe dissolved in liquid scintillator inner volume
- First experiment to reach $T_{1/2} > 10^{26}$ yr exclusion



PRL **117**, 082503 (2016)

KamLAND-Zen Upgrades

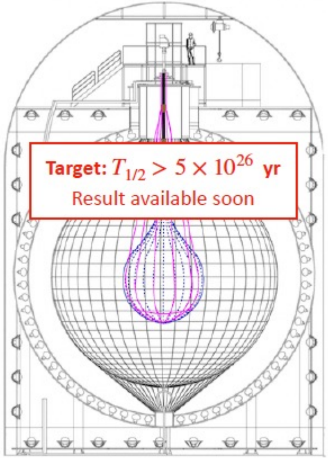
Past



KamLAND-Zen 400:

- Mini-balloon Radius = 1.54 m
- Xenon mass = 320 ~ 380 kg
- Duration: 2011 ~ 2015

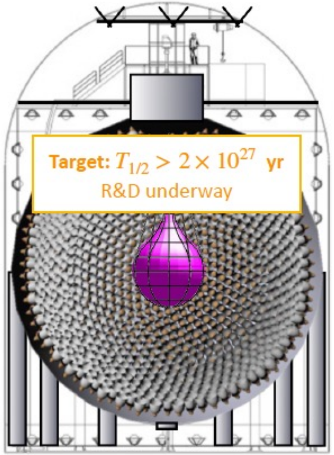
Present



KamLAND-Zen 800:

- Mini-balloon Radius = 1.90 m
- Xenon mass = 745 kg
- Data taking starts Jan. 2019

Future



KamLAND2-Zen:

- Xenon mass ~ 1ton
- Aiming at 100% Photocoverage
- PEN scintillation balloon film

- Stay tuned for results soon from KamLAND-Zen 800
  - x10 reduction in balloon backgrounds
  - x2 exposure available

Adapted from Aobo Li, TAUP21

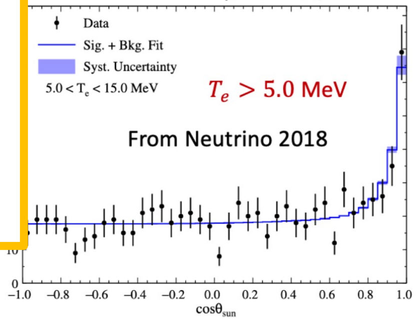
SNO+

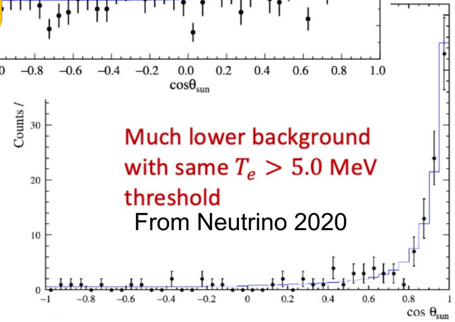
- Builds on successful SNO detector and physics program
  - Liquid scintillator active volume replaces heavy water
  - Tellurium compound dissolved in LS
    - >1.3 tonne ^{130}Te at 0.5% ^{nat}Te loading
- Water phase 2017-2019, LS fill complete April 2021

Further proposals for liquid scintillator based searches include THEIA, ZICOS
New technologies for background rejection like NuDot, CROSS

  - Target sensitivity of $T_{1/2} = 2 \cdot 10^{26}$ yr
  - Future upgrade to 3% loading

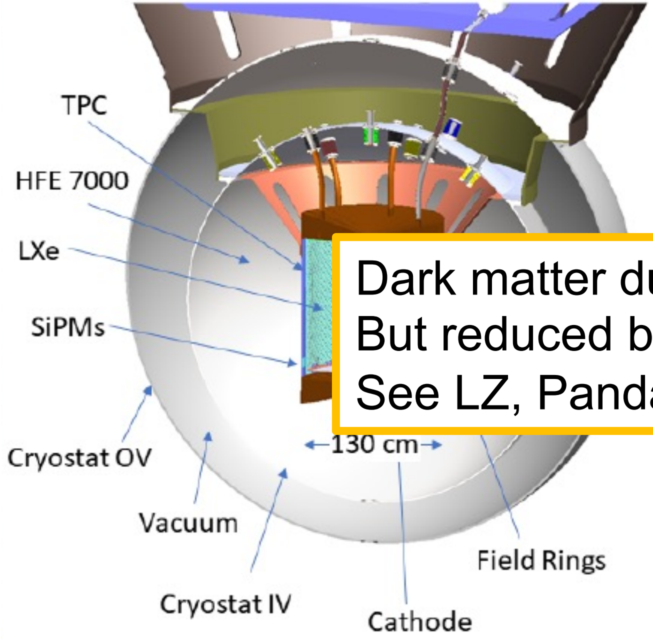
Phys. Rev. D **99**, 012012





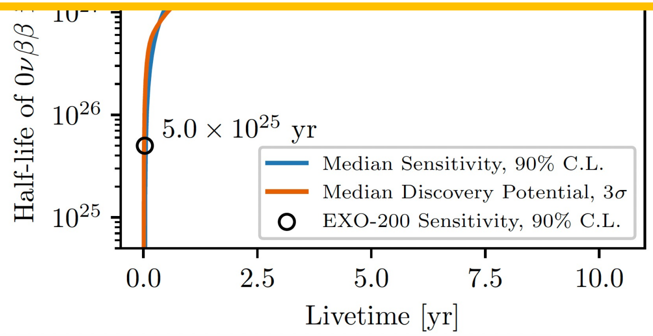
nEXO

- Builds on EXO-200 program (2011-2018)
- Single-phase LXe time projection chamber
  - Monolithic single drift volume of 1.2 m length
- Proposed 5 tonne target enriched to 90% in ^{136}Xe
- Solid xenon barium tagging under investigation



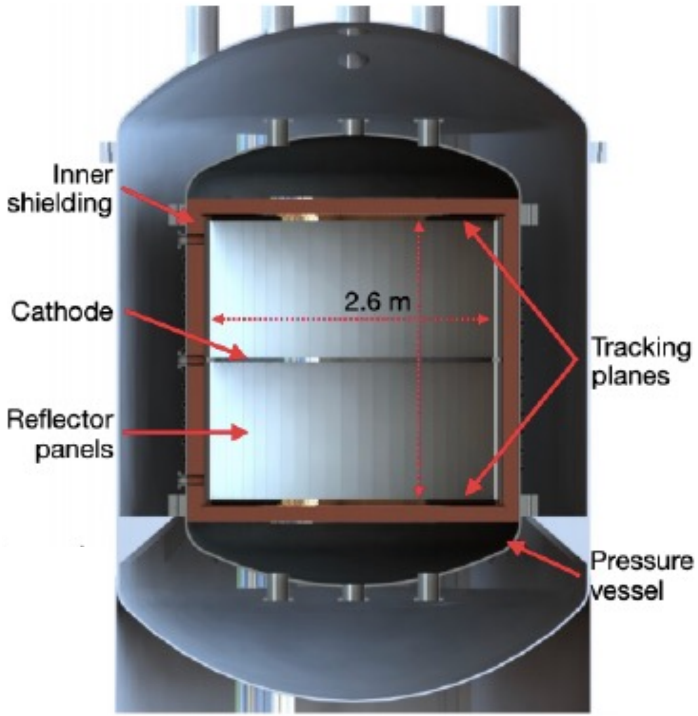
Adapted from Ako Jamil, TAUP21

Dark matter dual-phase xenon TPC's also have sensitivity
But reduced by non-enrichment, design choices
See LZ, PandaX-4T, DARWIN



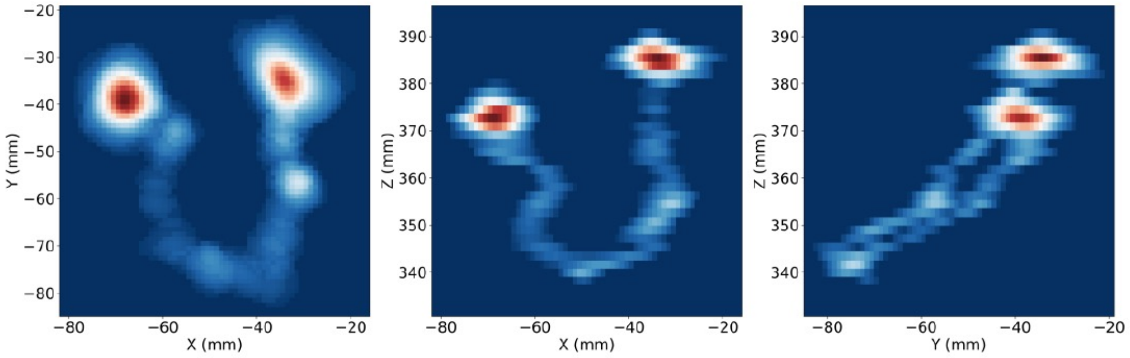
pCDR: arXiv1805.11142
Sensitivity: arXiv 2106.16243

NEXT & PandaX-III



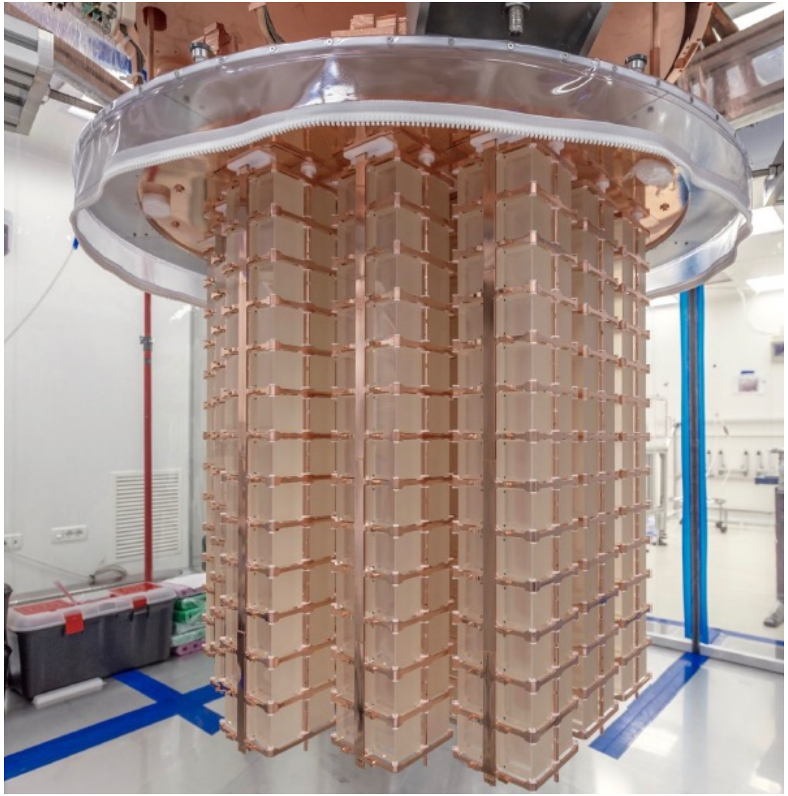
Adapted from Alberto Usón Andrés, TAUP21

- Distinct R&D programs focused on high-pressure gaseous xenon TPC technologies
  - Centered at Canfranc (Spain) and CJPL (China)
  - Evolving from O(10) to O(100) kg in next ~5 years
- Topological information provides powerful background rejection
- Barium-tagging technologies being pursued



JHEP 7 (2021) 146

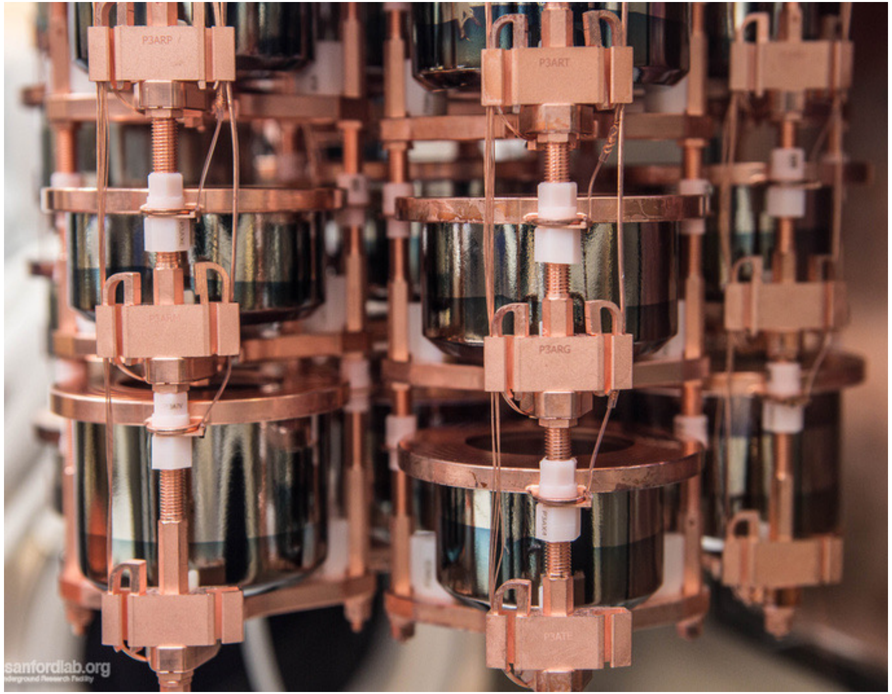
CUORE & CUPID



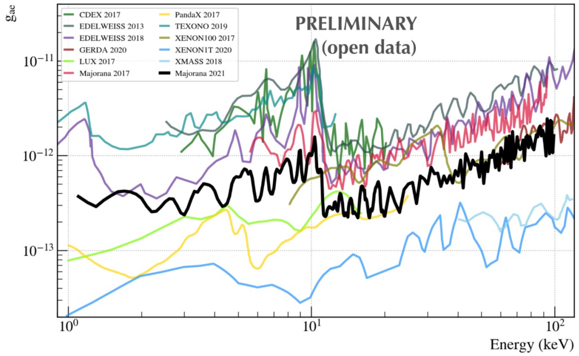
- Array of cryogenic TeO_2 bolometers operated at 10 mK
  - 988 channels with 206 kg ^{130}Te
- R&D towards ZnSe and $LiMoO_4$ scintillating bolometers
- Best half-life sensitivity for 3 isotopes in program!
- Proposed path to tonne-scale sensitivity with $LiMoO_4$ technology

- *See Miriam Olmi's talk, next*

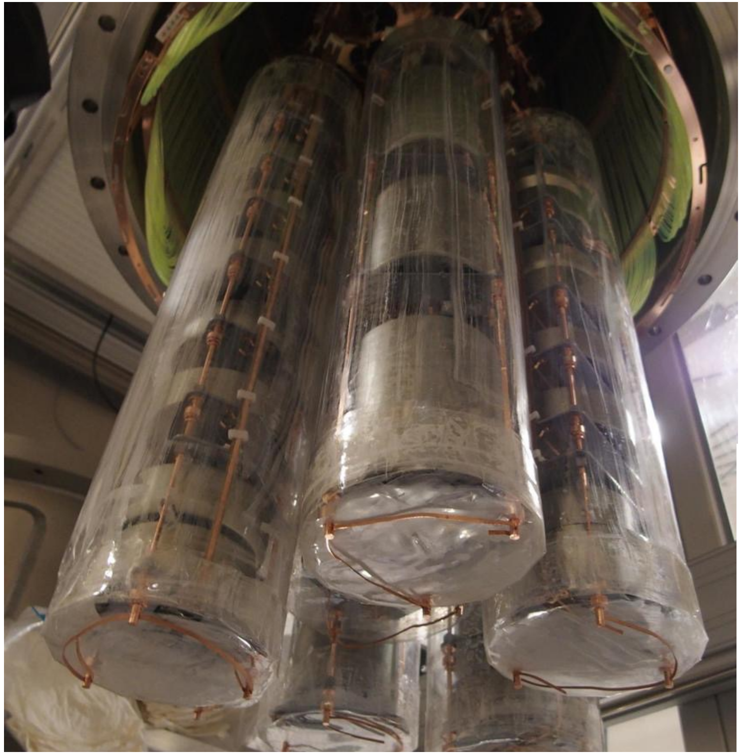
MAJORANA DEMONSTRATOR



- Array of point-contact germanium detectors in vacuum cryostat
  - Low-background materials and low-noise electronics developed
- 30 kg enriched to 88% in ^{76}Ge
- Best energy resolution at $Q_{\beta\beta}$, 0.12%
- Leading sensitivity to excited states decay, BSM physics

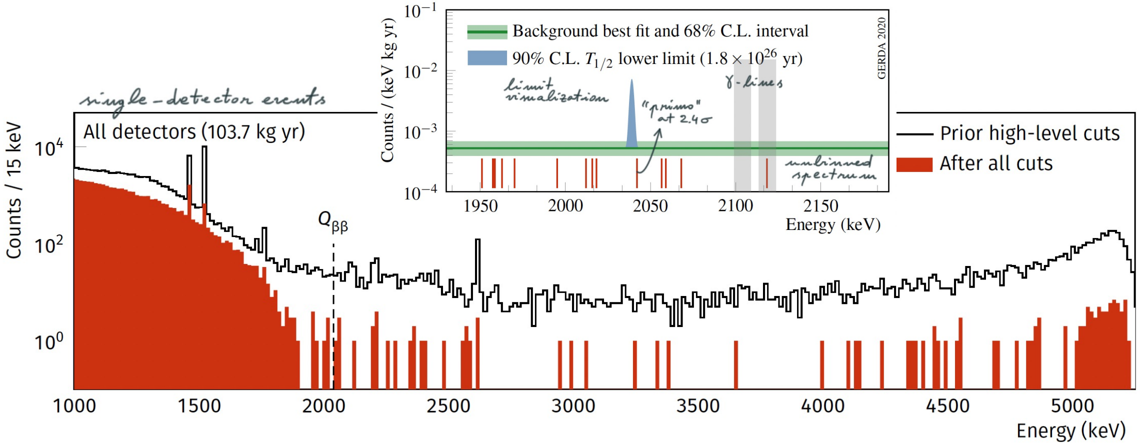


GERDA

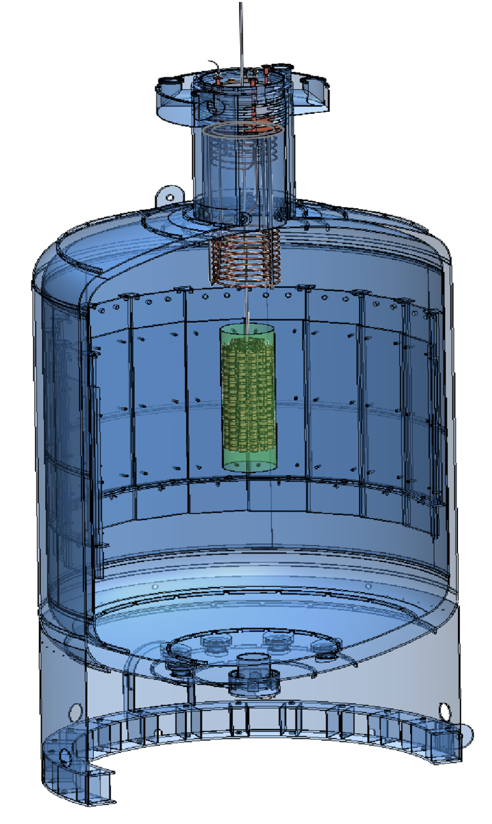


Adapted from Luigi Pertoldi, PANIC21

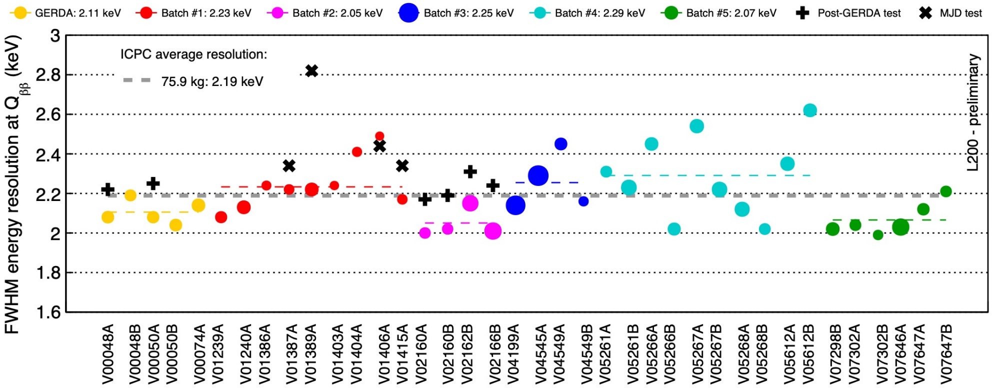
- Array of point-contact germanium detectors immersed in liquid argon active veto
  - Critical background-reduction technology validated and characterized
- ~40 kg enriched in ^{76}Ge
- Achieved $T_{1/2} > 1.8 \cdot 10^{26}$ yr sensitivity
- Background index $5 \cdot 10^{-4}$ cts / (keV kg yr)
  - Achieved quasi-background free operation
  - No background observed in ROI in exposure



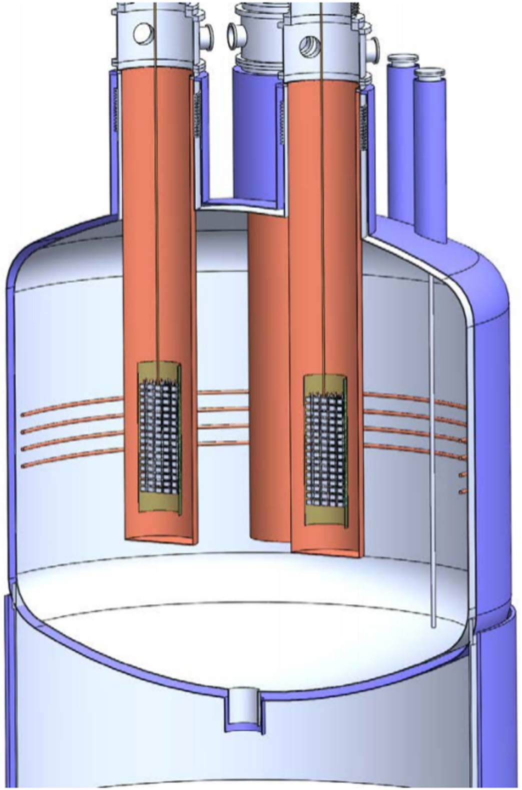
LEGEND-200



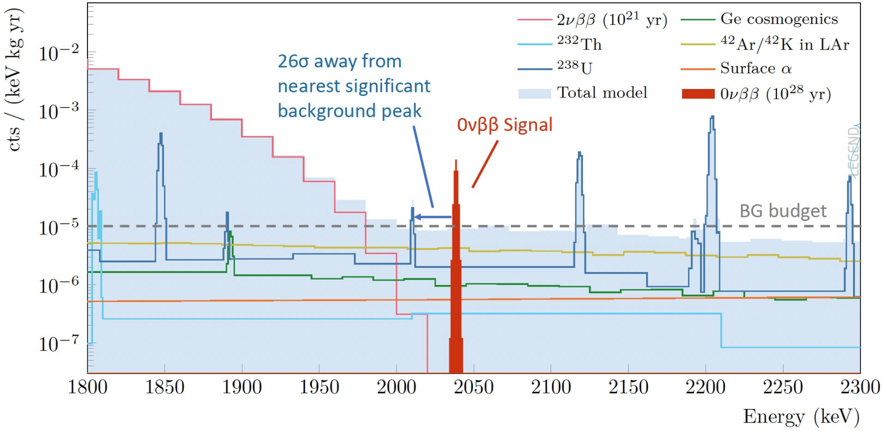
- 200 kg of enriched point-contact detectors in GERDA LAr cryostat
  - Point-contact detectors from both predecessors
  - Plus new larger mass (2+ kg) detectors
- Successor to Majorana and GERDA
  - Leverages advances from separate programs
- Commissioning now at LNGS, datataking this year
- Sensitivity goal of 10^{27} yr in 5 yr run



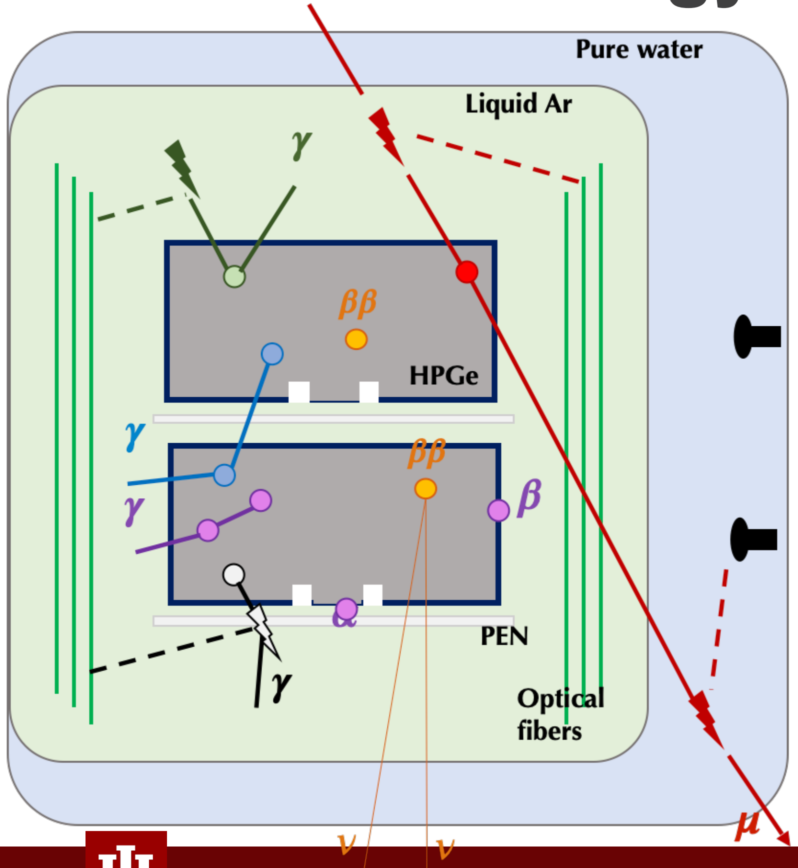
LEGEND-1000



- Proposed tonne-scale continuation of ^{76}Ge program
- Independent payloads for phased deployment
- Underground argon volumes reduce surface bg
  - Developed by DarkSide dark matter experiment
- Proposes lowest background, best resolution



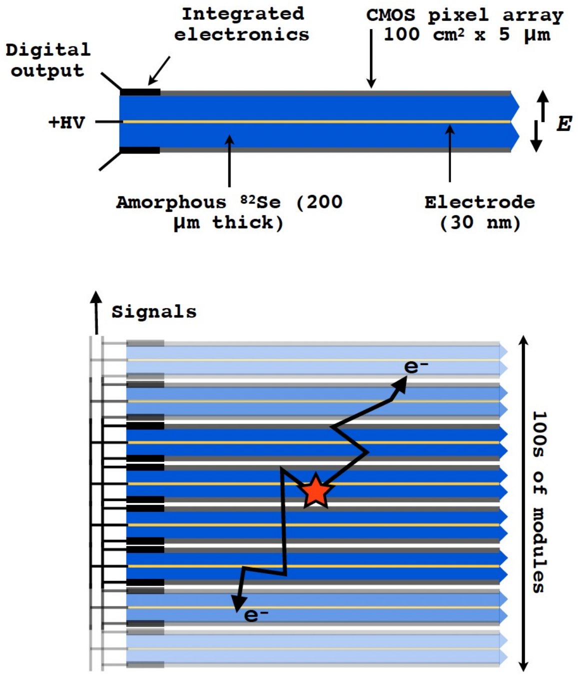
LEGEND Strategy



- Signal is single-site bulk events with no coincidence
- Pulse shape discrimination (PSD) for multi-site and surface events
- Ge detector anti-coincidence veto
- Scintillating PEN plate
- LAr veto: Ar scintillation light read by fibers + PMT's
- Muon veto: Cherenkov light & plastic scintillator

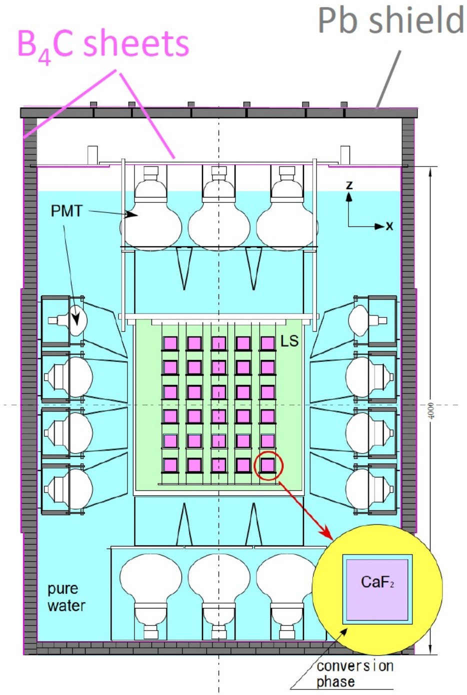
Plus Many Other Technologies

SELENA: pixel array to capture topology



Adapted from Alvaro Chavarria, TAUP21

CANDLES: exploit high ^{48}Ca Q-value



Adapted from Yuto Minami, TAUP21

Summary

- Several current experiments have achieved 10^{26} yr results, experiments in preparation target 10^{27} yr
- Community driving towards next-generation sensitivity to ~10^{28} yr, covering inverted mass ordering space
- Proposing experiments capable of discovery, not just limit setting
- Technologies exploit diverse strategies, non-overlapping systematics
- Different isotopes mature and will address underlying physics
- Theory advancing in step to interpret results

Outlook

- Continued results coming from operating experiments
  - KamLAND-Zen 800, CUORE…
- Promising new experiments coming online soon
  - LEGEND-200, SNO+…
- Vibrant R&D into game-changing technologies
  - CUPID, NEXT, SELENA…
- Mature experiments proposed for next-generation sensitivity with strong funding support
  - US DOE portfolio review, July 2021
  - North America-European Summit, *now*
  - Independent programming in Asia