Walter C. Pettus

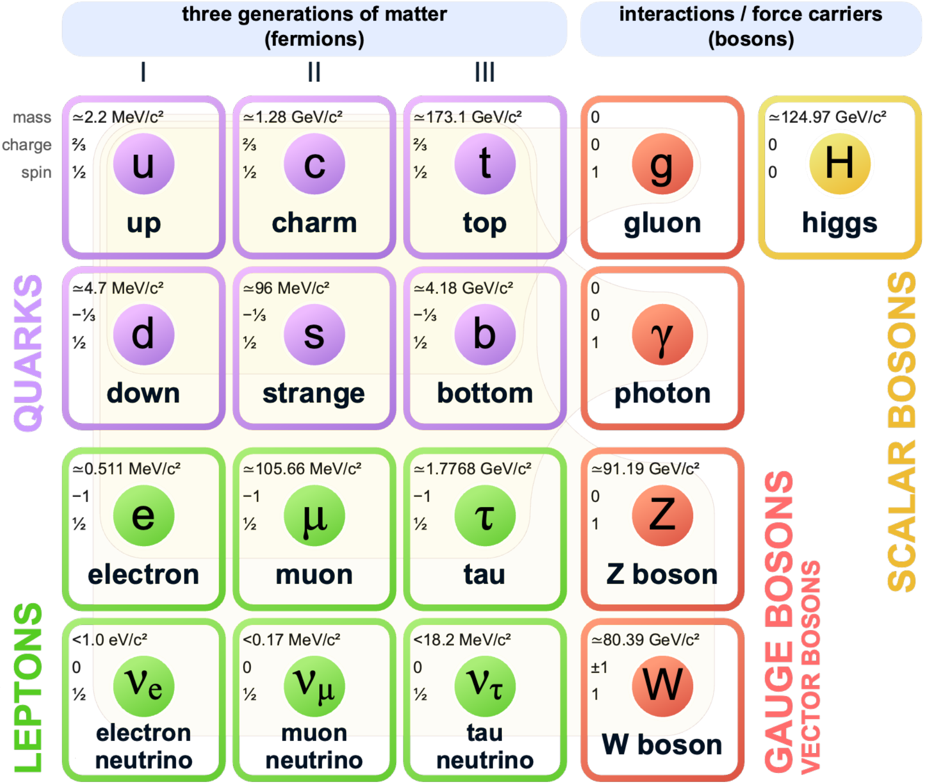
Searches for Neutrinoless Double Beta Decay

17th International Workshop on Tau Lepton Physics

7 December 2023

INDIANA UNIVERSITY

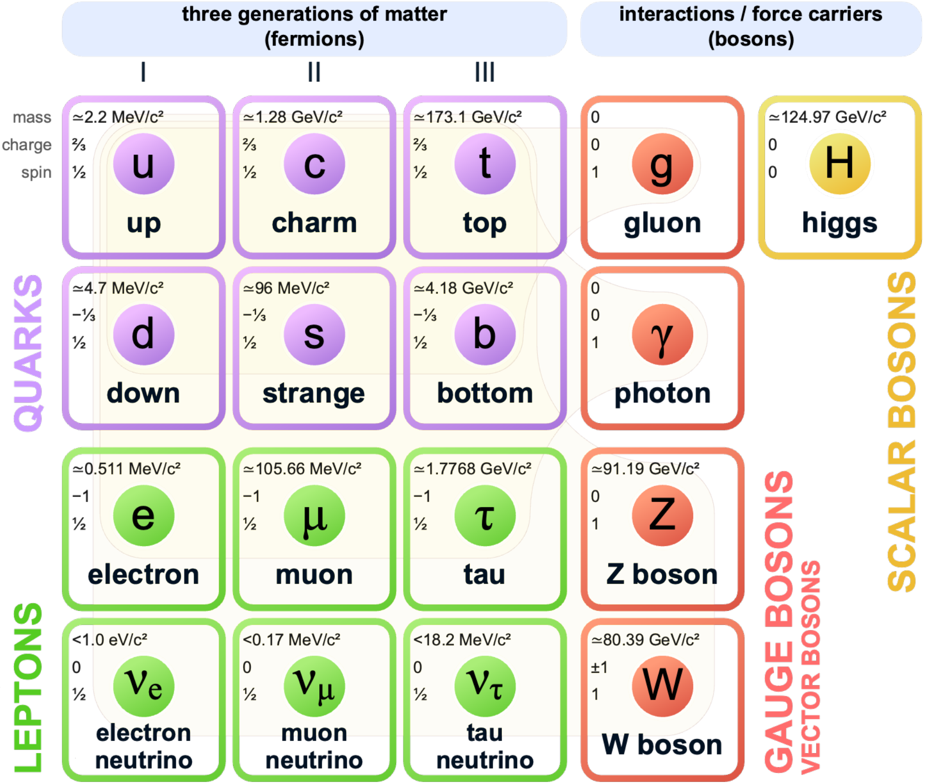
Tau Perspective on Neutrino Mass



MissMJ, Cush – Wikimedia Commons

- This talk is focused on electron neutrino (and electron signals)
- Broad class of neutrino experiments that don’t bother measuring the neutrino

Tau Perspective on Neutrino Physics



	three generations of matter (fermions) I	II	III	interactions / force carriers (bosons)	
mass charge spin	≃2.2 MeV/c² ⅔ ½ u **up**	≃1.28 GeV/c² ⅔ ½ c **charm**	≃173.1 GeV/c² ⅔ ½ t **top**	0 0 1 g **gluon**	≃124.97 GeV/c² 0 0 H **higgs**
QUARKS	≃4.7 MeV/c² −⅓ ½ d **down**	≃96 MeV/c² −⅓ ½ s **strange**	≃4.18 GeV/c² −⅓ ½ b **bottom**	0 0 1 γ **photon**	SCALAR BOSONS
LEPTONS	≃0.511 MeV/c² −1 ½ e **electron**	≃105.66 MeV/c² −1 ½ μ **muon**	≃1.7768 GeV/c² −1 ½ τ **tau**	≃91.19 GeV/c² 0 1 Z **Z boson**	GAUGE BOSONS VECTOR BOSONS
	<1.0 eV/c² 0 ½ ν_e **electron neutrino**	<0.17 MeV/c² 0 ½ ν_μ **muon neutrino**	<18.2 MeV/c² 0 ½ ν_τ **tau neutrino**	≃80.39 GeV/c² ±1 1 W **W boson**	

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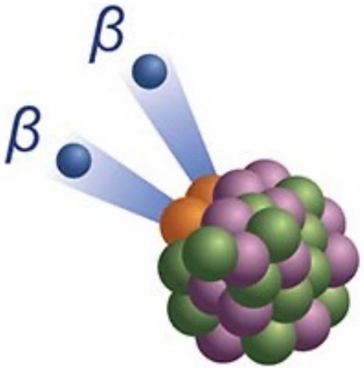
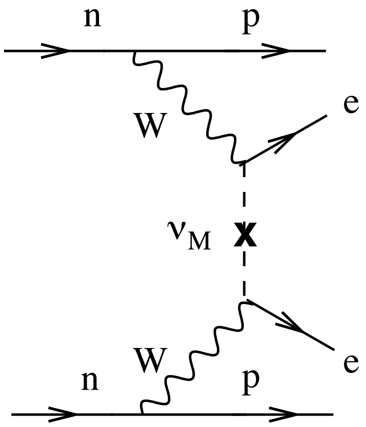
- Neutrino mass is BSM physics, motivating further study
- Neutrino flavor transformation makes it difficult to study only one neutrino

Neutrinoless Double Beta Decay (0νββ)





Searching for theoretical process:

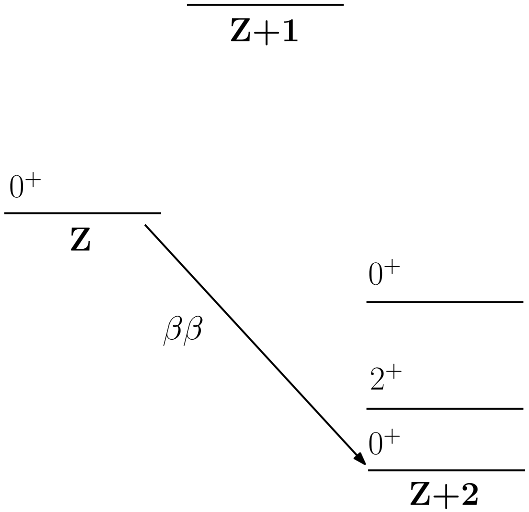
- $(\mathrm{A},\mathrm{Z}) \rightarrow (\mathrm{A},\mathrm{Z}+2) + 2\mathrm{e}^-$
  - Contrast with $(\mathrm{A},\mathrm{Z}) \rightarrow (\mathrm{A},\mathrm{Z}+2) + 2\mathrm{e}^- + 2\bar{\nu}_e$, observed

0νββ always implies new physics

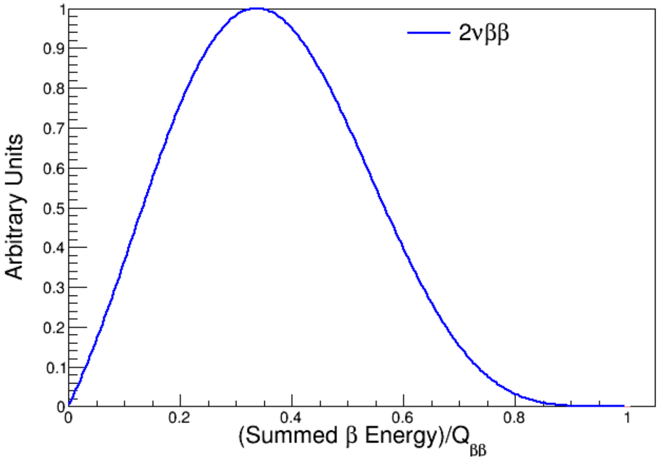
- Lepton number violating process (ΔL=2)
- Majorana neutrinos generate 0νββ
- Majorana neutrinos help explain small observed neutrino masses via see-saw mechanism
- Leptogenesis as ingredient for explaining matter-antimatter asymmetry

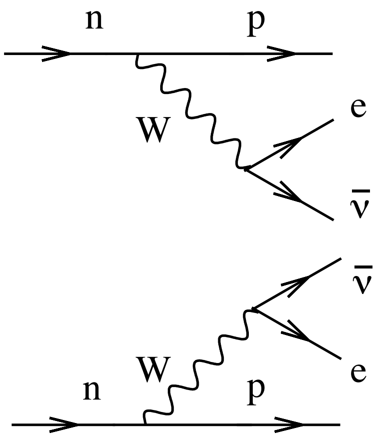
Double-Beta Decay

- Double-beta decay with two neutrinos is the rarest observed weak nuclear process
  - Half life is ~10^{20} yr

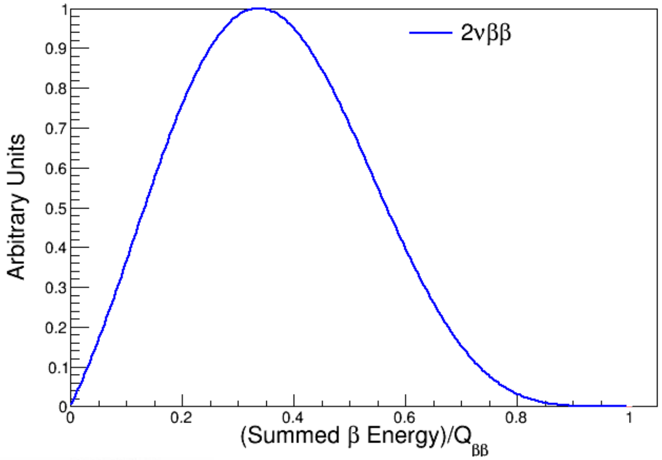


F. Avignone *et al.* Rev. Mod. Phys. 2008

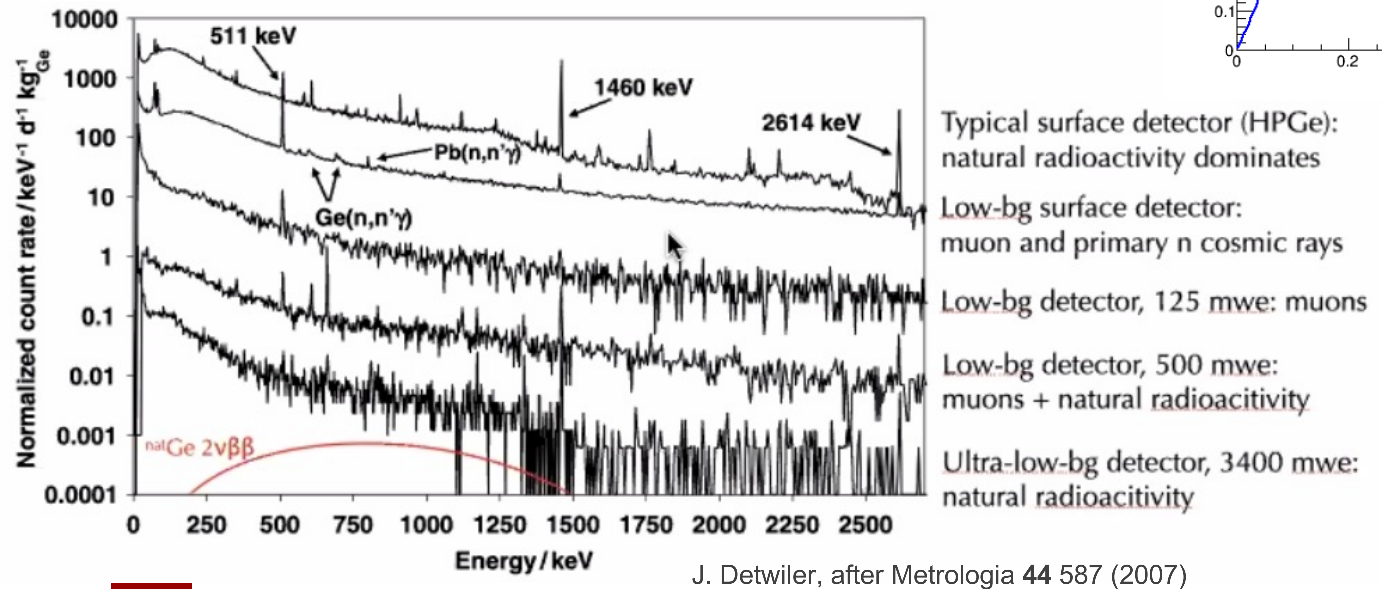




Experimental Backgrounds



- Signal is buried under myriad other backgrounds

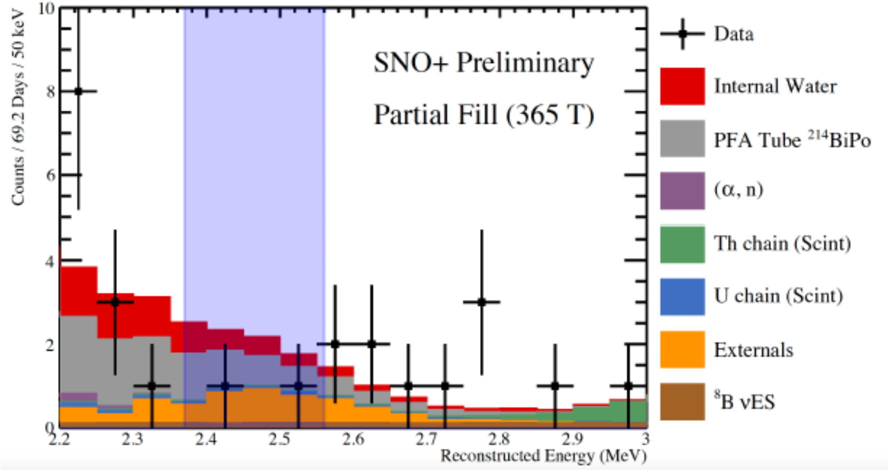


J. Detwiler, after Metrologia **44** 587 (2007)

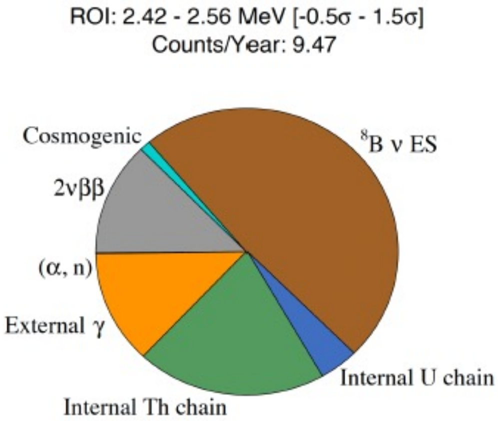
Backgrounds in Perspective: SNO+

- *Recall from Ziping’s talk Tuesday*
  - SNO+ is a 12m acrylic sphere with ~1 kton pure scintillator

Partial Fill Background

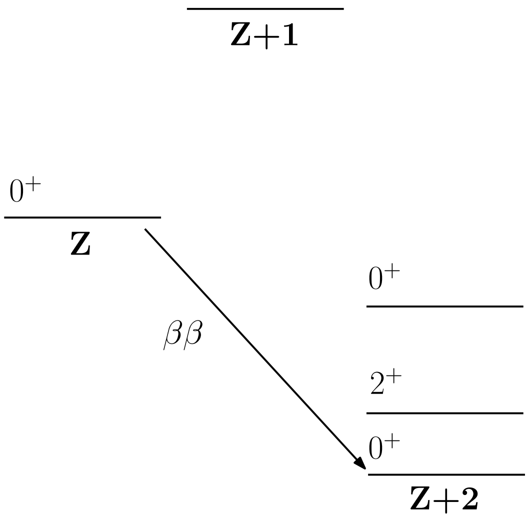


Projected Full Background

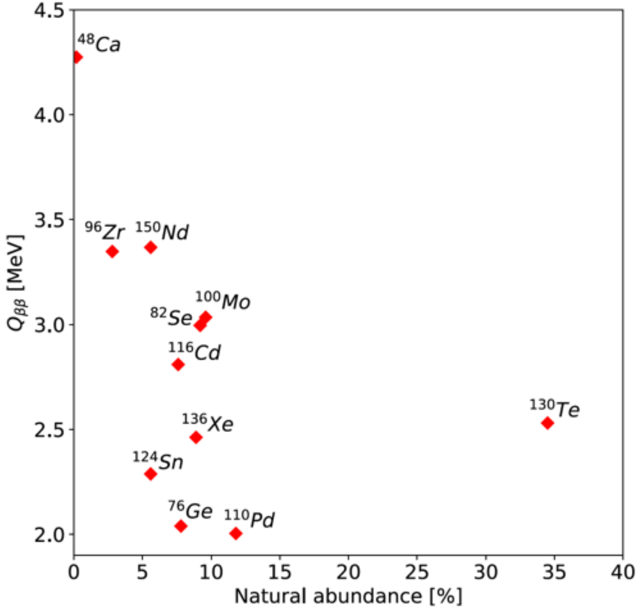


Menu of Isotopes

- O(50) isotopes are capable of ββ
  - Only directly measured in 9 isotopes



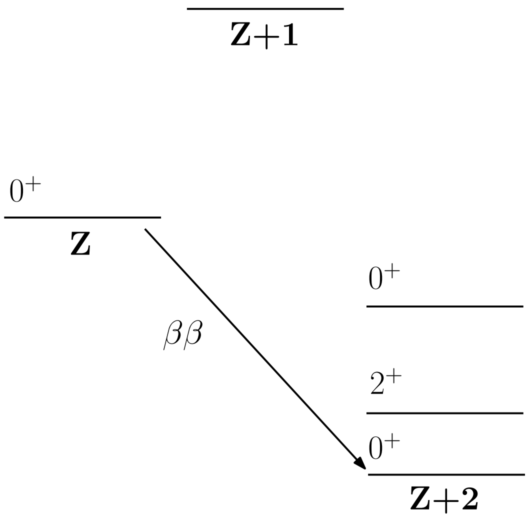
F. Avignone *et al.* Rev. Mod. Phys. 2008



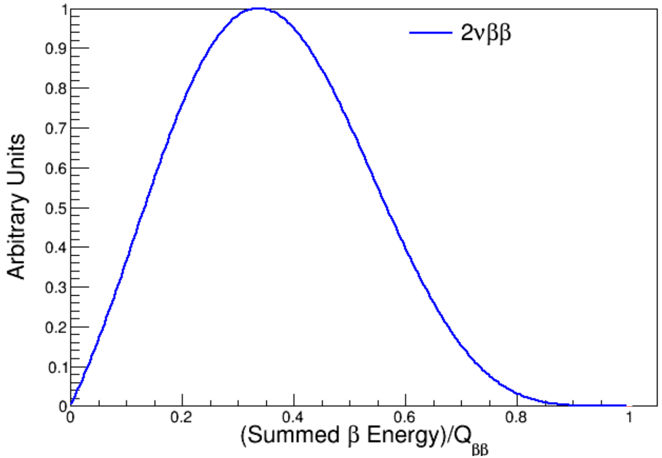
- Availability/cost of element
- Suitability of enrichment
- Compatibility with detector technology
- …

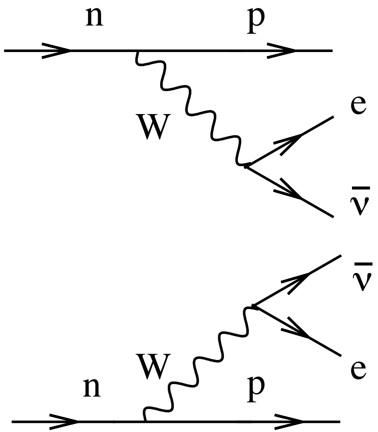
Double-Beta Decay

- Double-beta decay with two neutrinos is the rarest observed weak nuclear process



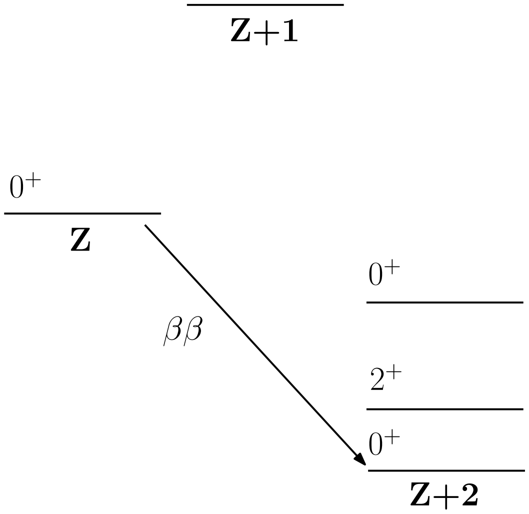
F. Avignone *et al.* Rev. Mod. Phys. 2008



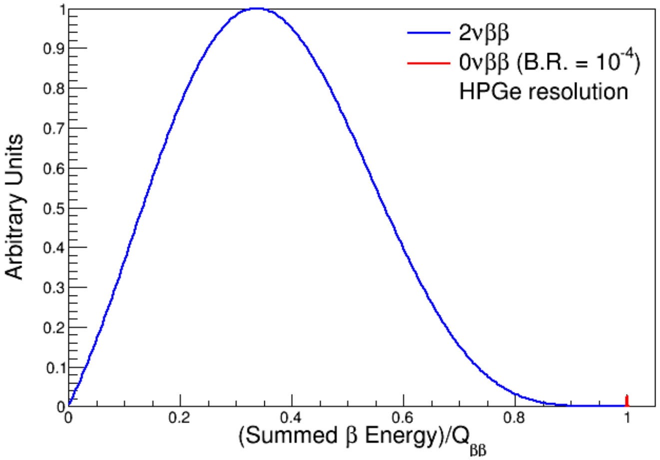


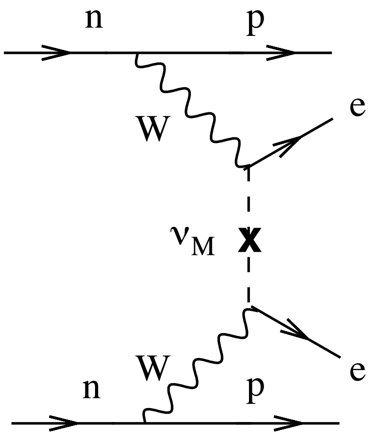
Neutrinoless Double-Beta Decay

- Neutrinoless double-beta decay is an analogous nuclear process wherein lepton number is violated



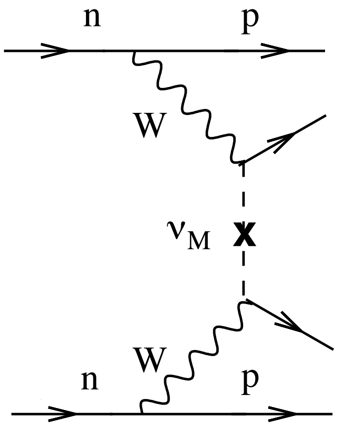
F. Avignone *et al.* Rev. Mod. Phys. 2008





From Half-Life to Neutrino Mass

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

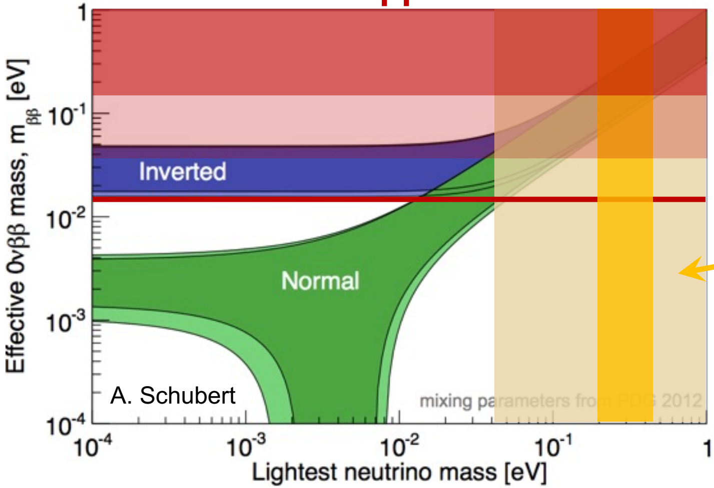


$$U'_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\phi_1} & 0 \\ 0 & 0 & e^{-i\phi_2} \end{pmatrix}$$

Sensitivity to Neutrino Mass

- Half-life of 0vββ 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 0vββ limits



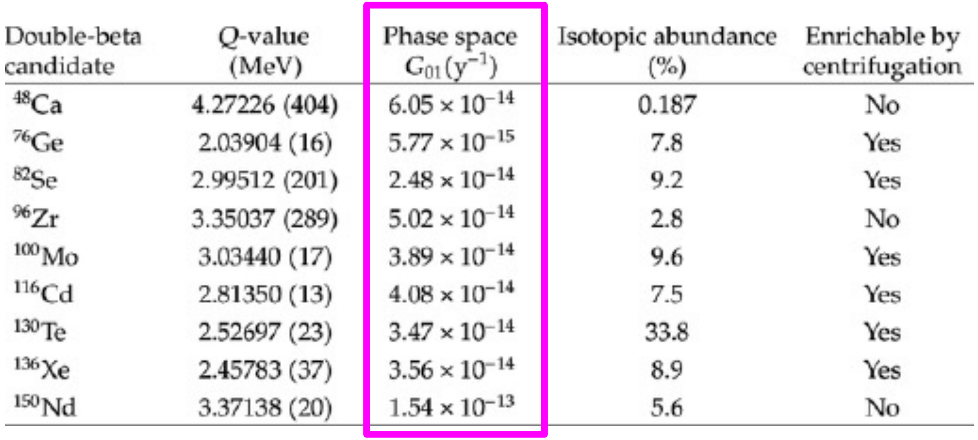
Next-generation, “tonne-scale” 0vββ experiment goal

CMB tension fits

Current cosmological limits (direct neutrino mass limits)

Plus a Dose of Theory

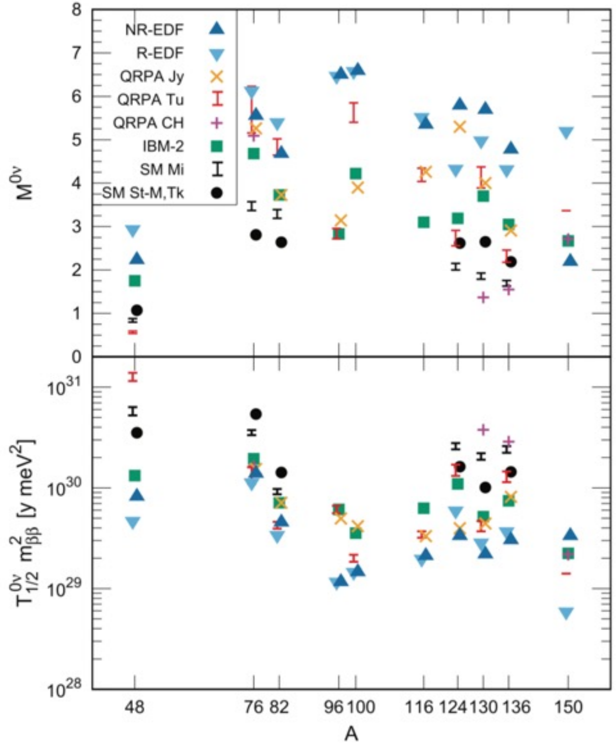
- Half-life of 0νββ related to neutrino mass scale
  - $(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$



Double-beta candidate	Q-value (MeV)	Phase space G_{01} (y^{-1})	Isotopic abundance (%)	Enrichable by centrifugation
^{48}Ca	4.27226 (404)	6.05×10^{-14}	0.187	No
^{76}Ge	2.03904 (16)	5.77×10^{-15}	7.8	Yes
^{82}Se	2.99512 (201)	2.48×10^{-14}	9.2	Yes
^{96}Zr	3.35037 (289)	5.02×10^{-14}	2.8	No
^{100}Mo	3.03440 (17)	3.89×10^{-14}	9.6	Yes
^{116}Cd	2.81350 (13)	4.08×10^{-14}	7.5	Yes
^{130}Te	2.52697 (23)	3.47×10^{-14}	33.8	Yes
^{136}Xe	2.45783 (37)	3.56×10^{-14}	8.9	Yes
^{150}Nd	3.37138 (20)	1.54×10^{-13}	5.6	No

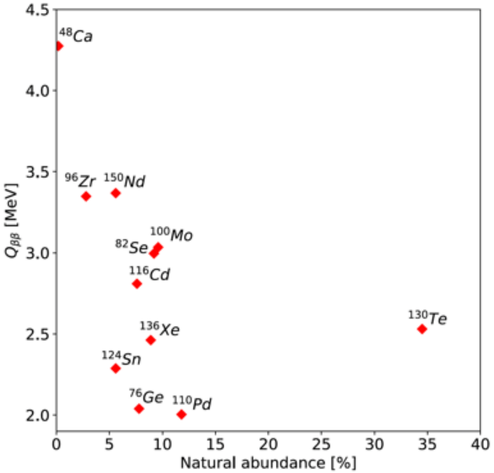
  - also g_A quenching…

Engel and Menendez,
Rep. Prog. Phys. (2017)

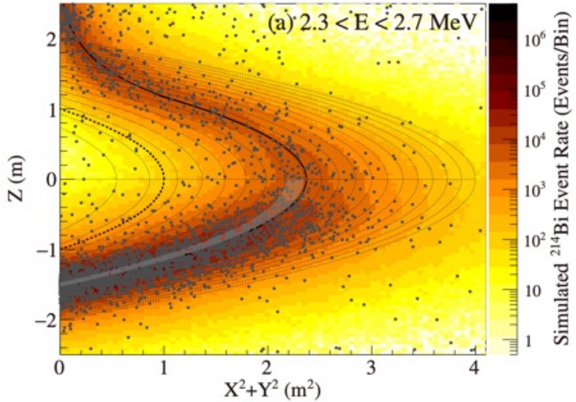


Experimental Considerations

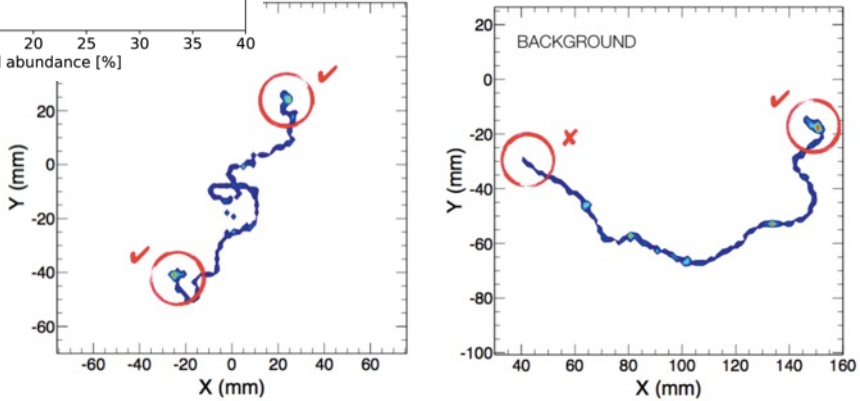
- Maximize exposure
    - Larger source
    - Higher enrichment*
    - Higher efficiency
- Minimize background
    - Deep underground
    - Material purity
    - Energy resolution
    - Decay Q-value*
    - Background rejection via cuts**



KamLAND: Fiducialization



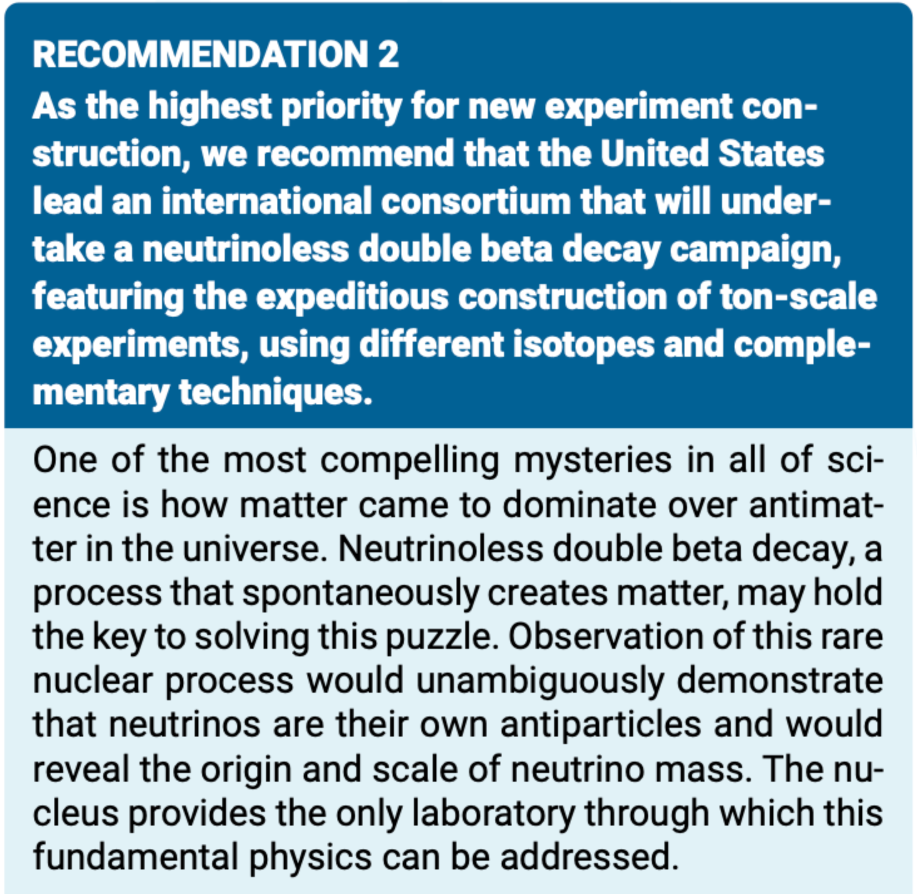
NEXT: Topology Simulation



A NEW ERA OF DISCOVERY

THE 2023 LONG RANGE PLAN FOR NUCLEAR SCIENCE

2023 | VERSION 1.1

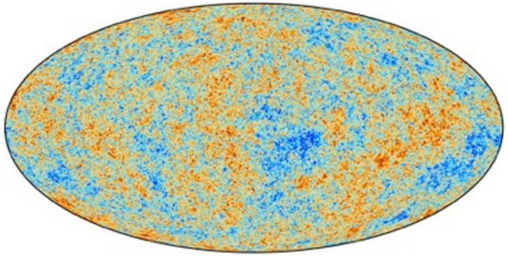


RECOMMENDATION 2

As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.

One of the most compelling mysteries in all of science is how matter came to dominate over antimatter in the universe. Neutrinoless double beta decay, a process that spontaneously creates matter, may hold the key to solving this puzzle. Observation of this rare nuclear process would unambiguously demonstrate that neutrinos are their own antiparticles and would reveal the origin and scale of neutrino mass. The nucleus provides the only laboratory through which this fundamental physics can be addressed.

Probing the Neutrino Mass Scale

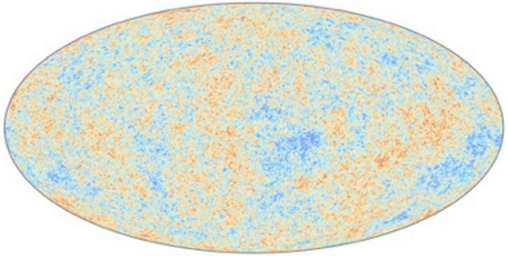


Cosmology

$$\sum m_\nu = \sum_{i=1}^{3} m_i$$

- Strongest neutrino mass limits
- Largest model dependence in interpreting limits
- Opportunity for lab probes to constrain cosmological data

Probing the Neutrino Mass Scale



Cosmology

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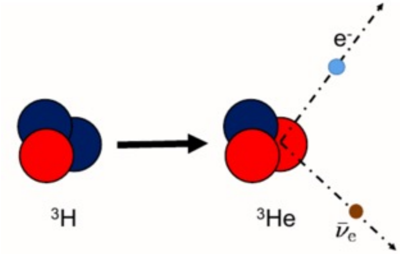
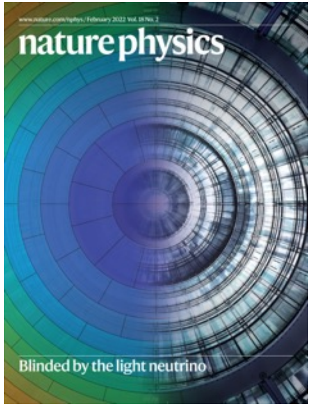


Endpoint Measurements (β-decay and EC)

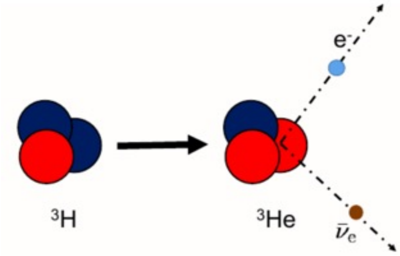
$$m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

- Complete model independence
- Weakest neutrino mass limits

Probing the Neutrino Mass Scale



- 2022: First sub-eV direct mass limits from KATRIN
- *Coming soon*: Next data release down to ~0.5 eV sensitivity



Endpoint Measurements (β-decay and EC)

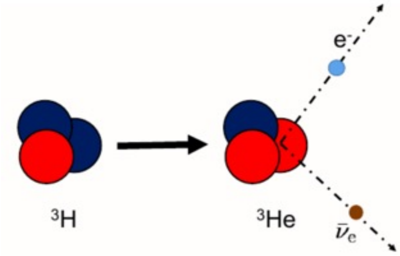
$$m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

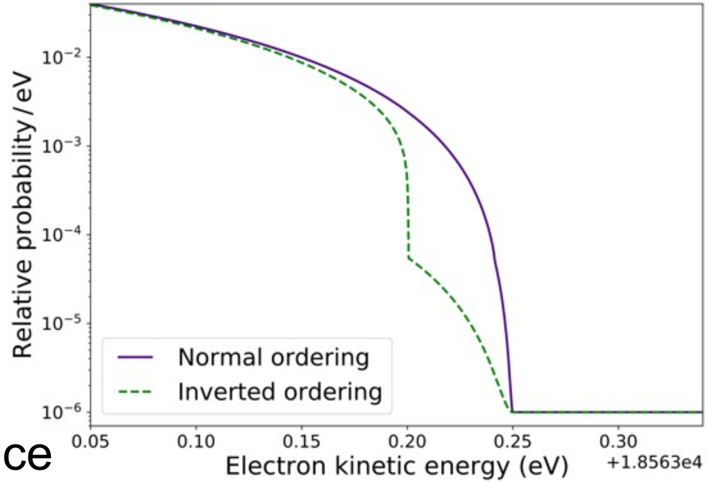
- Complete model independence

Probing the Neutrino Mass Scale

PROJECT 8

- Next-generation sensitivity to cover inverted mass ordering scale under development



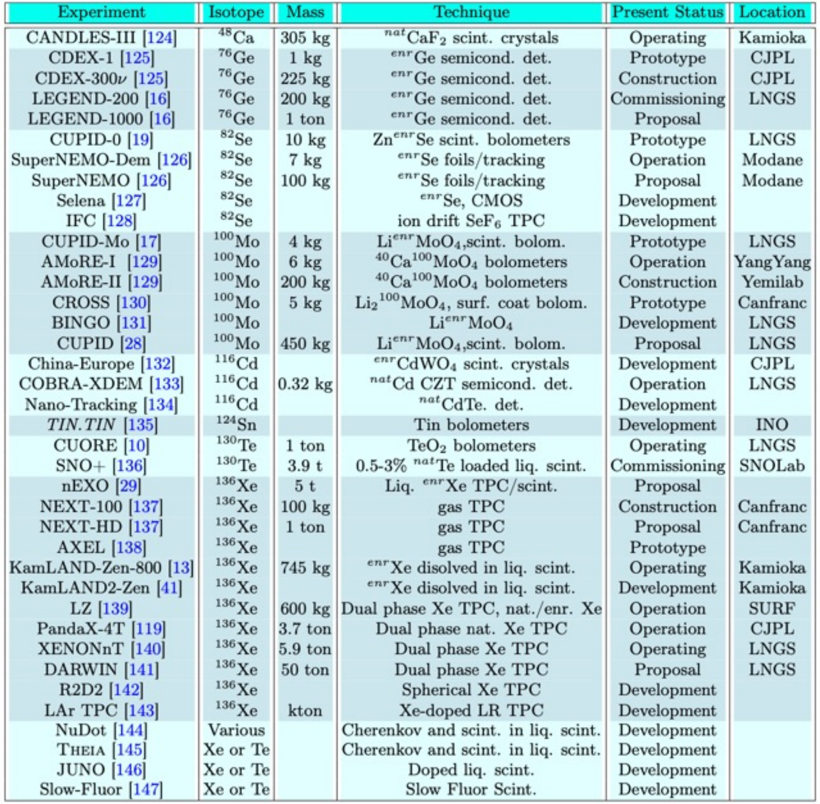


- Complete model independence

(Project 8) Phys. Rev. C **103** (2021) 065501

Electron neutrino character may be only "effective"

Too Many Experiments to Discuss

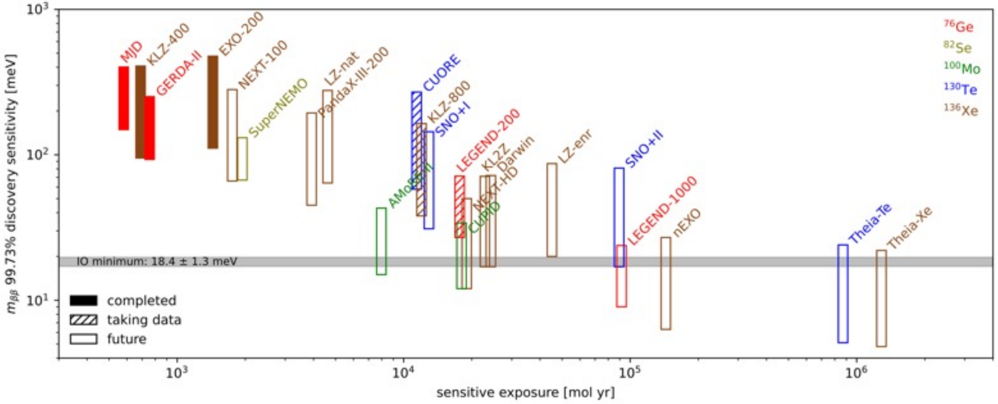


Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES-III [124]	^{48}Ca	305 kg	^{nat}CaF$_2$ scint. crystals	Operating	Kamioka
CDEX-1 [125]	^{76}Ge	1 kg	^{enr}Ge semicond. det.	Prototype	CJPL
CDEX-300ν [125]	^{76}Ge	225 kg	^{enr}Ge semicond. det.	Construction	CJPL
LEGEND-200 [16]	^{76}Ge	200 kg	^{enr}Ge semicond. det.	Commissioning	LNGS
LEGEND-1000 [16]	^{76}Ge	1 ton	^{enr}Ge semicond. det.	Proposal	
CUPID-0 [19]	^{82}Se	10 kg	Zn^{enr}Se scint. bolometers	Prototype	LNGS
SuperNEMO-Dem [126]	^{82}Se	7 kg	^{enr}Se foils/tracking	Operation	Modane
SuperNEMO [126]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal	Modane
Selena [127]	^{82}Se		^{enr}Se, CMOS	Development	
IFC [128]	^{82}Se		ion drift SeF$_6$ TPC	Development	
CUPID-Mo [17]	^{100}Mo	4 kg	Li^{enr}MoO$_4$,scint. bolom.	Prototype	LNGS
AMoRE-I [129]	^{100}Mo	6 kg	^{40}Ca^{100}MoO$_4$ bolometers	Operation	YangYang
AMoRE-II [129]	^{100}Mo	200 kg	^{40}Ca^{100}MoO$_4$ bolometers	Construction	Yemilab
CROSS [130]	^{100}Mo	5 kg	Li$_2$^{100}MoO$_4$, surf. coat bolom.	Prototype	Canfranc
BINGO [131]	^{100}Mo		Li^{enr}MoO$_4$	Development	LNGS
CUPID [28]	^{100}Mo	450 kg	Li^{enr}MoO$_4$,scint. bolom.	Proposal	LNGS
China-Europe [132]	^{116}Cd		^{enr}CdWO$_4$ scint. crystals	Development	CJPL
COBRA-XDEM [133]	^{116}Cd	0.32 kg	^{nat}Cd CZT semicond. det.	Operation	LNGS
Nano-Tracking [134]	^{116}Cd		^{nat}CdTe. det.	Development	
TIN.TIN [135]	^{124}Sn		Tin bolometers	Development	INO
CUORE [10]	^{130}Te	1 ton	TeO$_2$ bolometers	Operating	LNGS
SNO+ [136]	^{130}Te	3.9 t	0.5-3% ^{nat}Te loaded liq. scint.	Commissioning	SNOLab
nEXO [29]	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	
NEXT-100 [137]	^{136}Xe	100 kg	gas TPC	Construction	Canfranc
NEXT-HD [137]	^{136}Xe	1 ton	gas TPC	Proposal	Canfranc
AXEL [138]	^{136}Xe		gas TPC	Prototype	
KamLAND-Zen-800 [13]	^{136}Xe	745 kg	^{enr}Xe disolved in liq. scint.	Operating	Kamioka
KamLAND2-Zen [41]	^{136}Xe		^{enr}Xe disolved in liq. scint.	Development	Kamioka
LZ [139]	^{136}Xe	600 kg	Dual phase Xe TPC, nat./enr. Xe	Operation	SURF
PandaX-4T [119]	^{136}Xe	3.7 ton	Dual phase nat. Xe TPC	Operation	CJPL
XENONnT [140]	^{136}Xe	5.9 ton	Dual phase Xe TPC	Operating	LNGS
DARWIN [141]	^{136}Xe	50 ton	Dual phase Xe TPC	Proposal	LNGS
R2D2 [142]	^{136}Xe		Spherical Xe TPC	Development	
LAr TPC [143]	^{136}Xe	kton	Xe-doped LR TPC	Development	
NuDot [144]	Various		Cherenkov and scint. in liq. scint.	Development	
THEIA [145]	Xe or Te		Cherenkov and scint. in liq. scint.	Development	
JUNO [146]	Xe or Te		Doped liq. scint.	Development	
Slow-Fluor [147]	Xe or Te		Slow Fluor Scint.	Development	

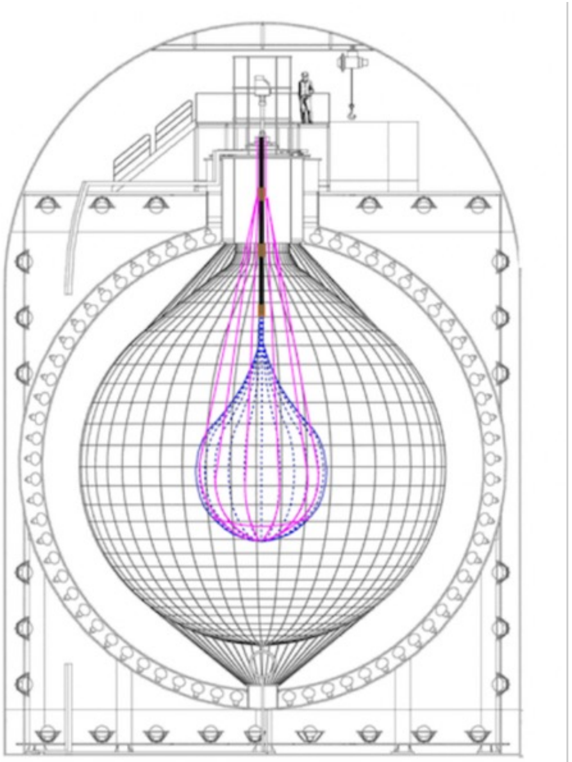
from arXiv:2212.11099

- Monolithic detectors that scale easily
- Granular detectors with excellent resolution

…but they're all striving for the same goal:



KamLAND-Zen

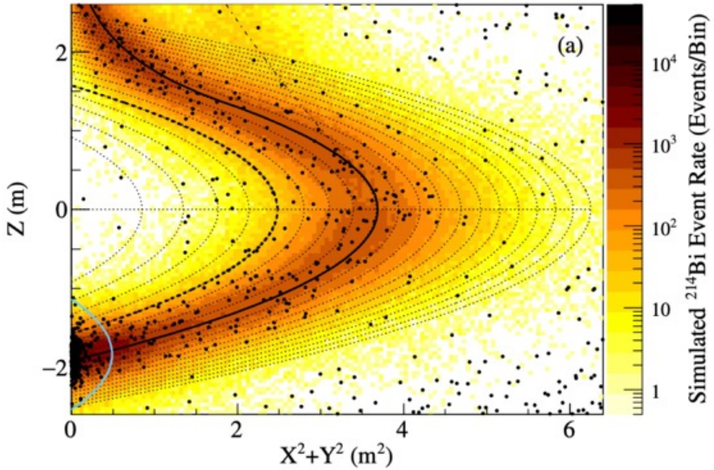


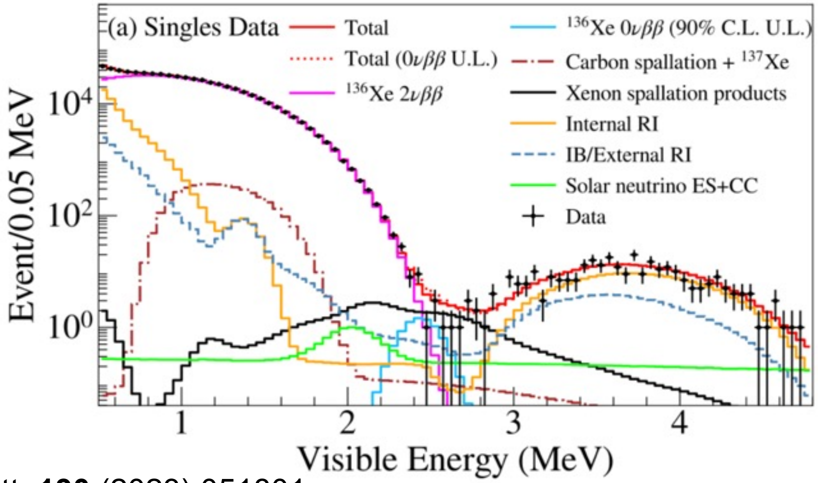
From Azusa Gando, Nu2022

- Builds on successful KamLAND detector and physics program
    - Ultra-clean large-volume liquid scintillator detector
- Inner volume segregated by clean balloon with ^{136}Xe dissolved
- Phased program scaling isotope mass and background
    - KamLAND-Zen 400 : first experiment to reach $\mathrm{T}_{1/2} > 10^{26}\ \mathrm{yr}$ exclusion
    - KamLAND-Zen 800 : current leading single-experiment sensitivity, $\mathrm{T}_{1/2} > 2.3\times10^{26}\ \mathrm{yr}$ exclusion
    - KamLAND2-Zen : planned future iteration with improved light collection, DAQ, balloon

KamLAND-Zen 800 Result

- Current experimental campaign began January 2019
  - 750 kg of ^{136}Xe (double 400 phase), cleaner material
- Current result, $T_{1/2} > 2.3\times10^{26}$ yr exclusion
  - Sensitivity target of $T_{1/2} > 5\times10^{26}$ yr





(KamLAND-Zen) Phys. Rev. Lett. **130** (2023) 051801

SNO+

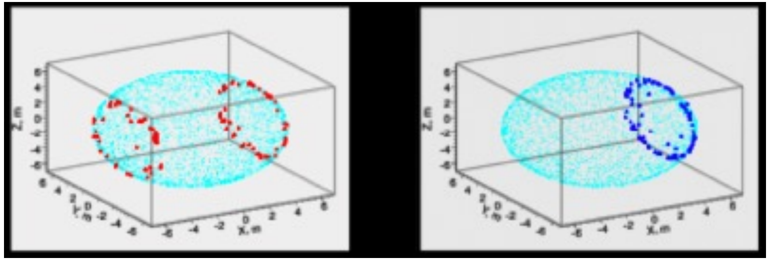

From Mark Chen, TAUP21

- 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 beginning at 0.5% ^{nat}Te loading
- Physics from commissioning phases prior to Te loading
- *See talk by Ziping Ye, Tuesday*

Future LS-Based Experiments

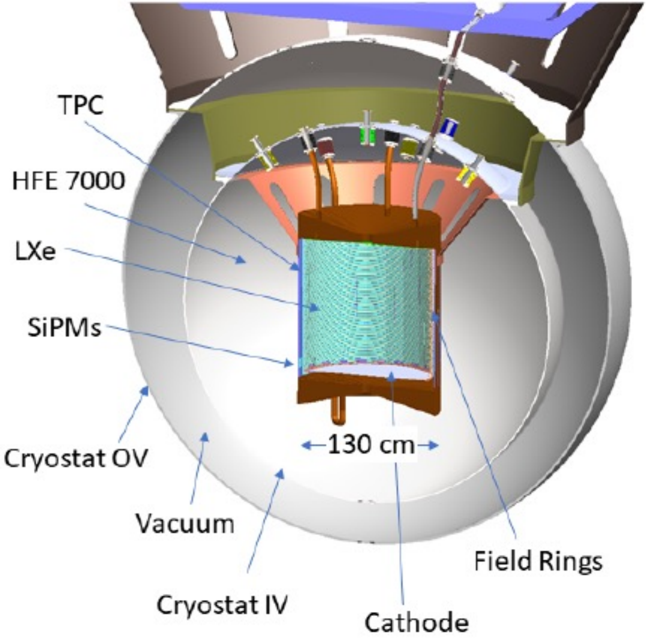
- JUNO boasts very large volume, low-background, high light-yield base
  - Could dissolve 50T of ^{136}Xe
  - Switch to 0νββ operations in 2030s?

- R&D on timing/wavelength separation of Cerenkov and scintillation signals
  - Need push on light emission (slow fluors, dichroic filler) and detection (LAPPDs)
  - Plus work on loading (quantum dots), WbLS, etc.



NuDot, THEIA

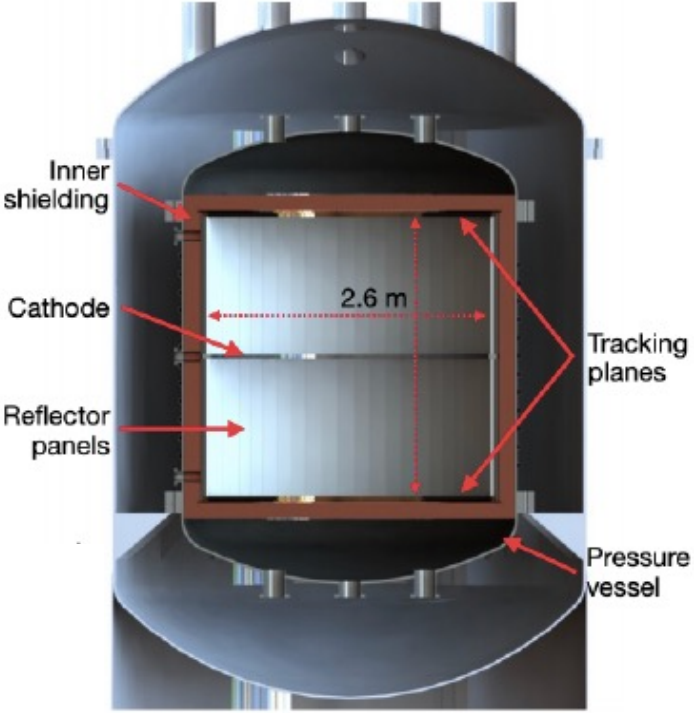
nEXO



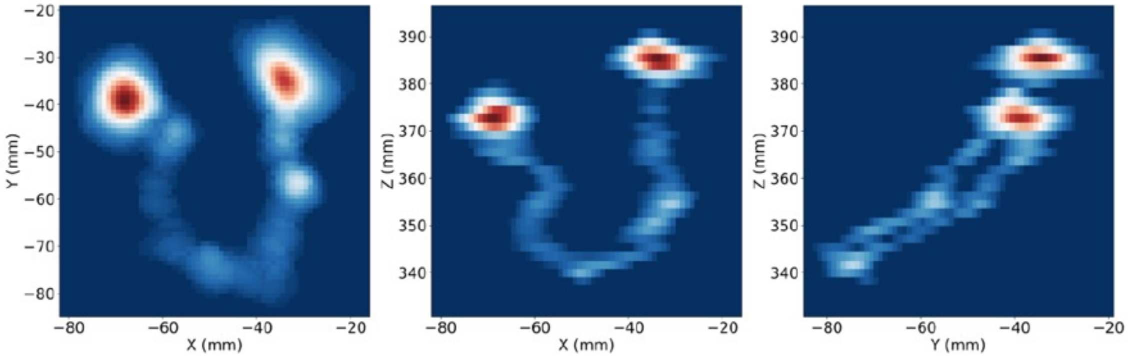
- Single-phase LXe time projection chamber
- Builds on success of EXO-200 program (2011-2018)
- Takes advantage of excellent performance of Xe TPC and self-shielding of backgrounds in scaling
  - Similar ideas proposed for dark matter experiment dual-phase Xe TPCs, but with inferior performance
- *See talk by Ryan MacClellan this afternoon*

NEXT & PandaX-III

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

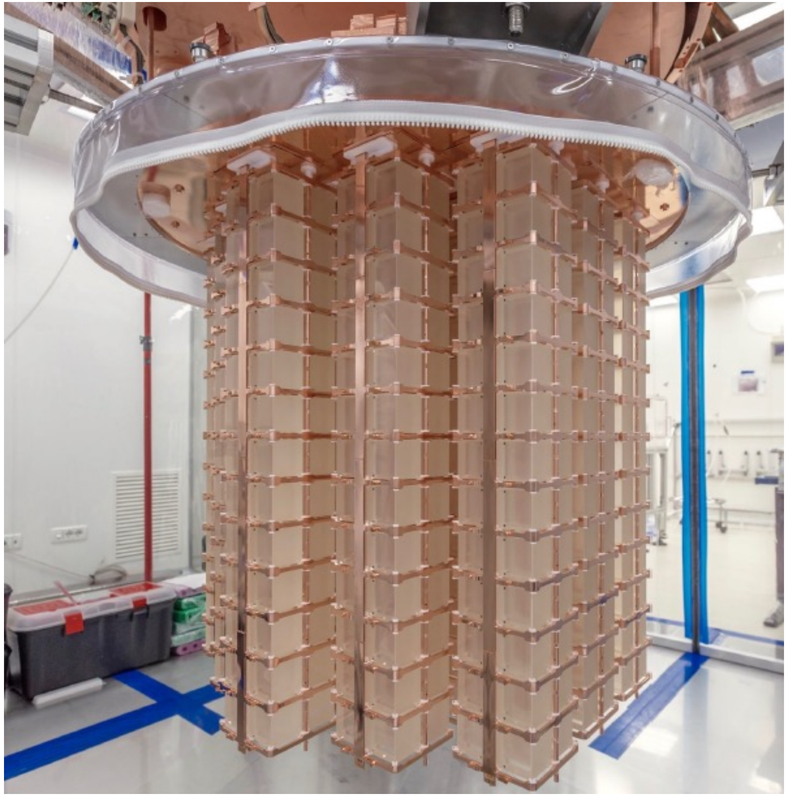


From Alberto Usón Andrés, TAUP21

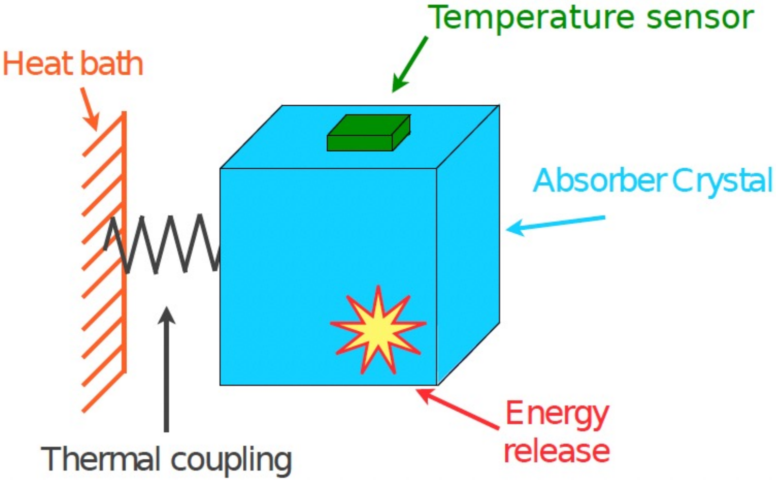


(NEXT) JHEP **7** (2021) 146

CUORE Cryogenic Underground Observatory for Rare Events

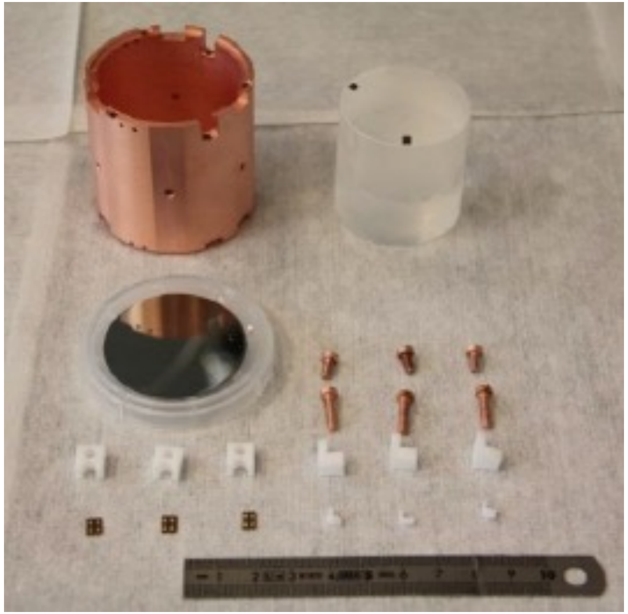


- Array of cryogenic TeO_2 bolometers operated at 10 mK
  - 988 channels with 206 kg ^{130}Te
- Operating since Spring 2017

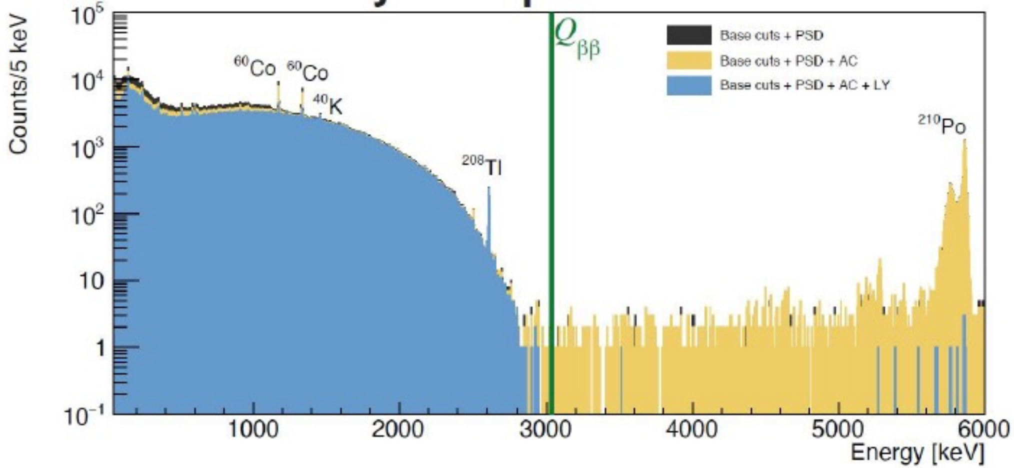


From Irene Nutini, Nu2022

CUPID: CUORE Upgrade with Particle ID



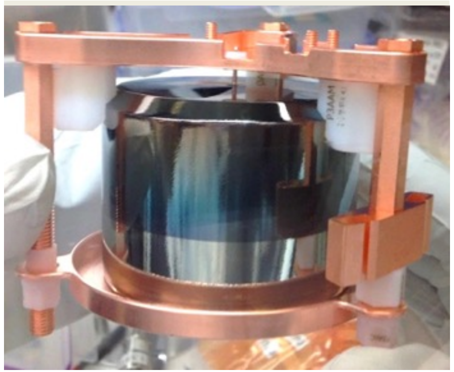
- Array of cryogenic $Li_2{}^{100}MoO_4$ bolometers
- ${}^{100}Mo$ affords higher $Q_{\beta\beta} = 3.034$ MeV
- Charge+light readout for background suppression
- Also conducted R&D tests of $Zn^{82}Se$ crystals
  - Minimal modification required to switch source

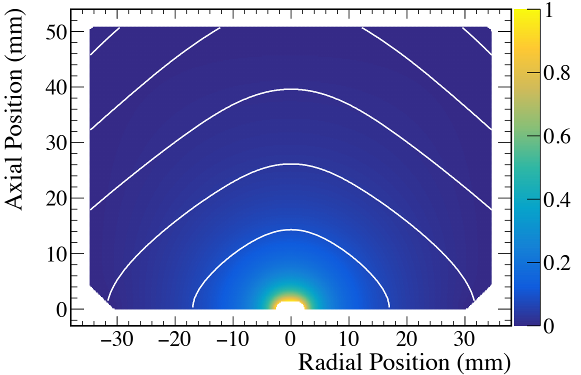


From Anastasiia Zolotarova, Nu2022

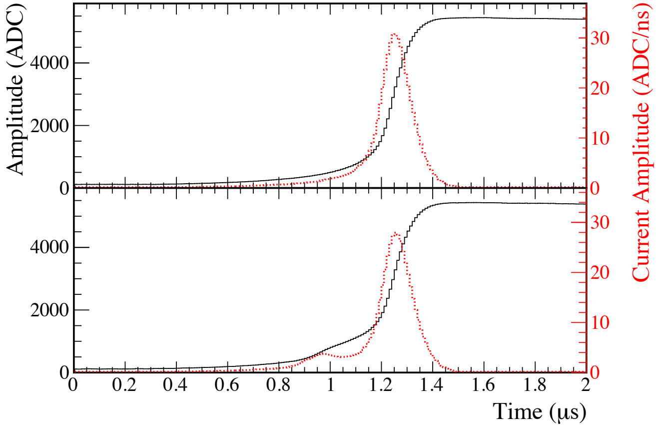
^{76}Ge Searches

- Modern germanium-based 0vββ boast the lowest backgrounds with best energy resolution for quasi-background free operation
  - GERDA + Majorana combined have best half-life sensitivity
- Share common “point-contact” germanium detector design
  - Excellent energy resolution
  - Excellent pulse shape discrimination performance
  - Low noise, low threshold for BSM searches



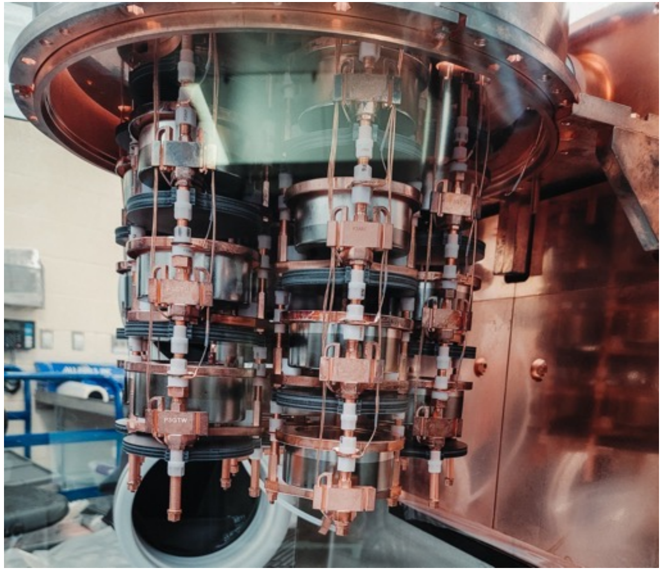


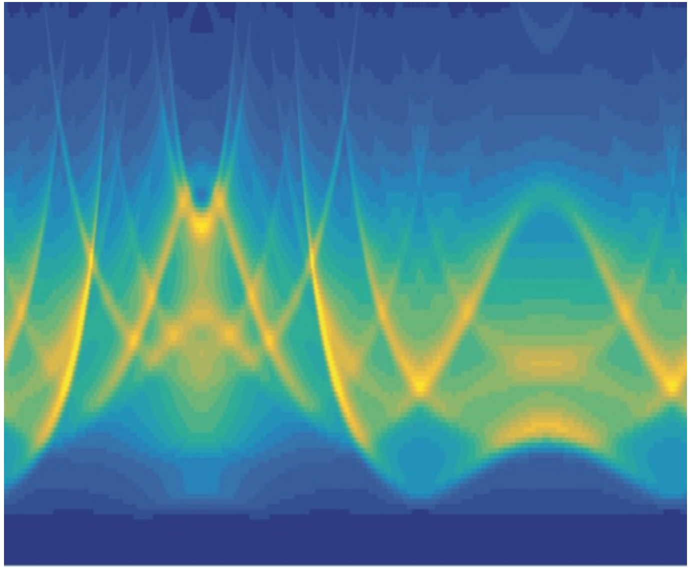
(Majorana) Phys. Rev. C **99** 065501 (2019)



MAJORANA Other Results

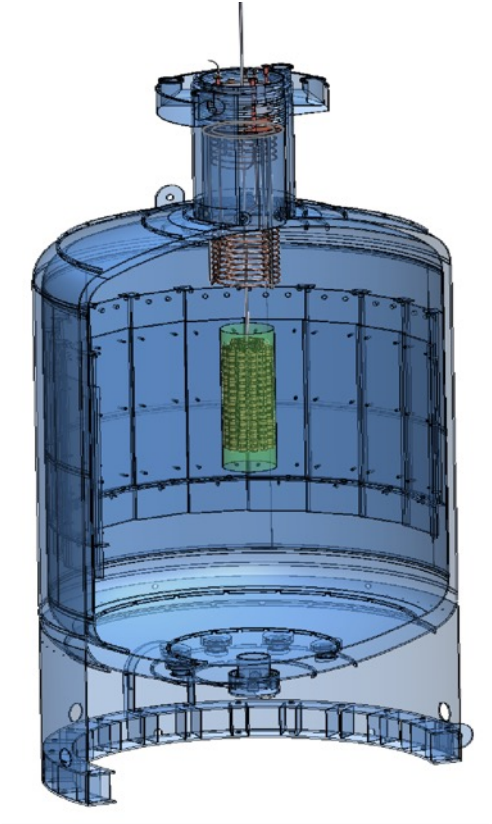
- Experiments also powerful labs to search for rare or exotic physics
  - Excellent energy resolution, low background, etc
  - Leading limits on 180mTa decay, solar axions, wavefunction collapse, dark matter…

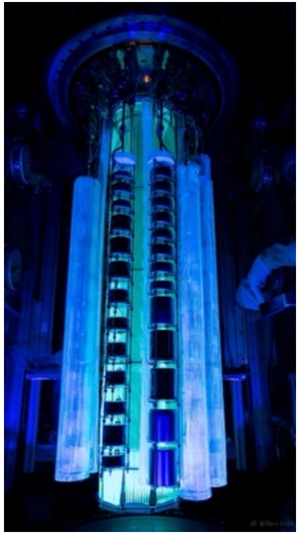




(MAJORANA) Phys. Rev. Lett. **129** (2022) 081803

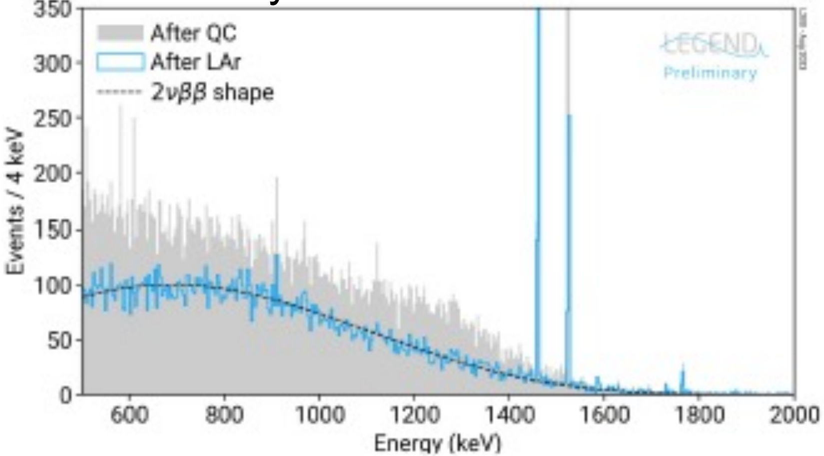
LEGEND-200



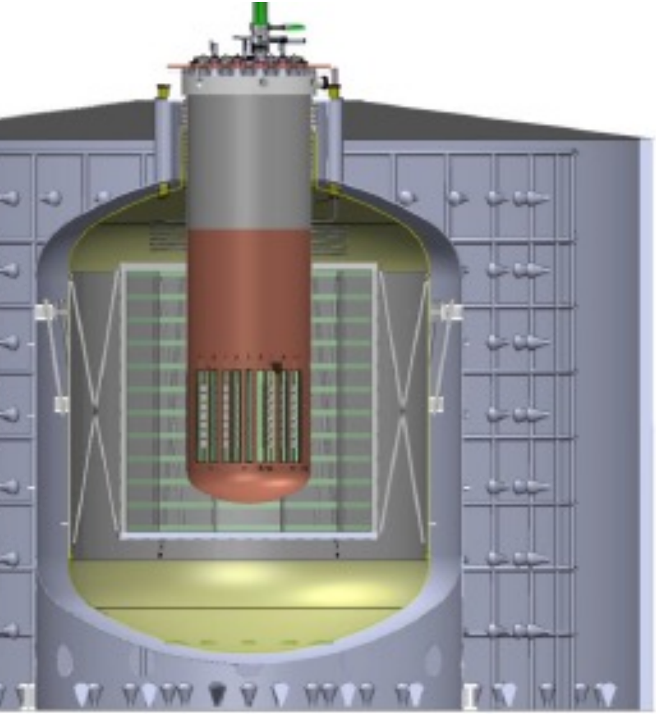


- Intermediate-scale germanium experiment formed from merger of GERDA and Majorana
  - Leveraging best advances from each experiment
- Sensitivity goal of 10^{27} yr in 5 yr run

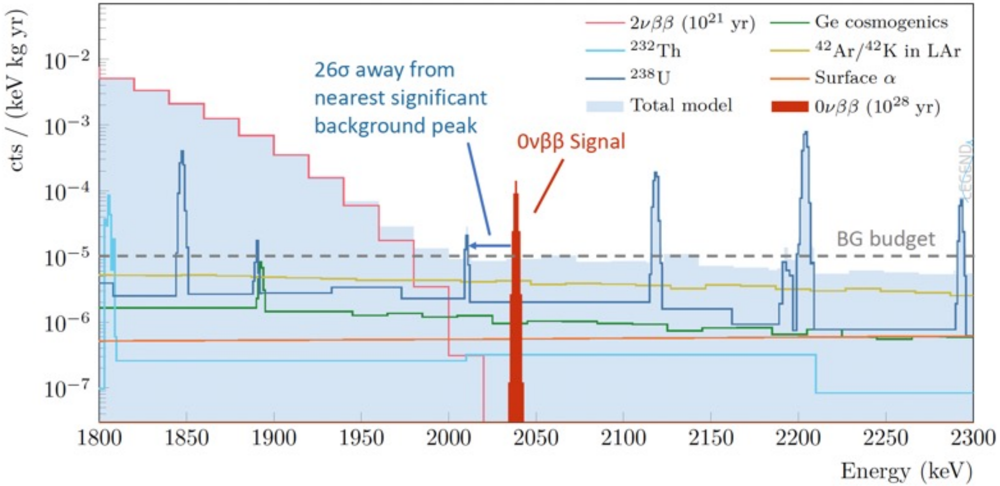
First Physics Data from TAUP '23



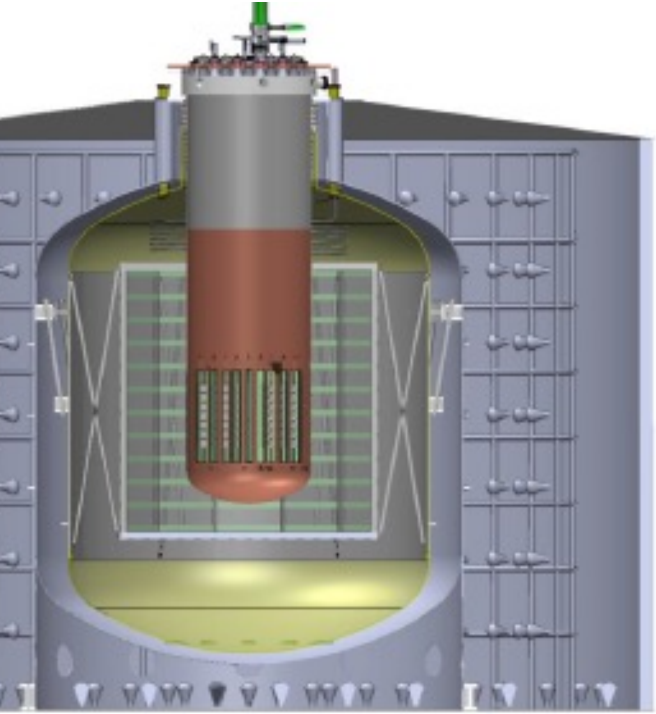
LEGEND-1000



- Tonne-scale continuation of ^{76}Ge program
- Underground argon reduces dominant surface bg
- Proposes lowest background, best resolution, greatest discovery potential



LEGEND-1000



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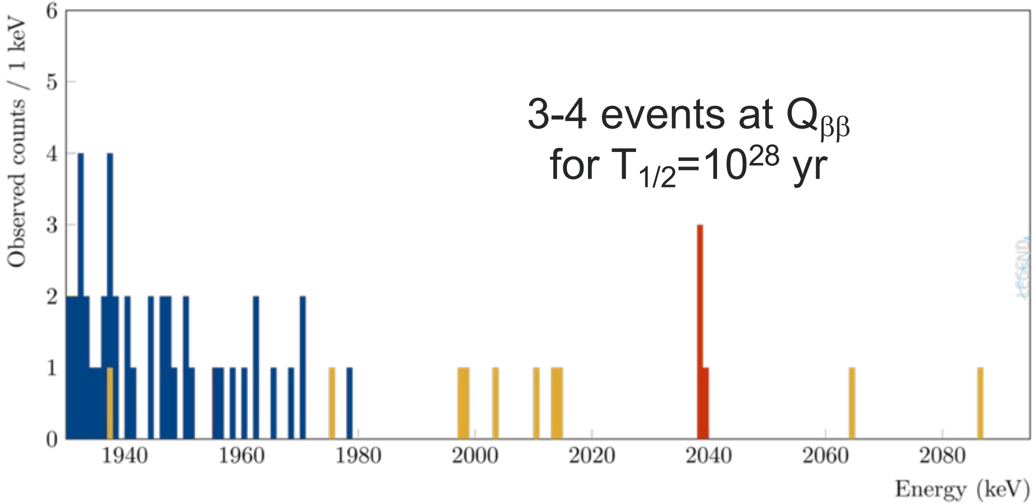
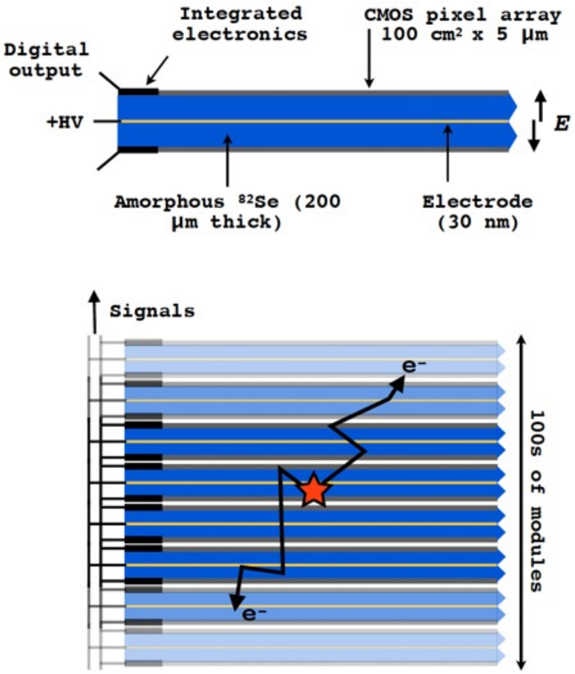


3-4 events at $Q_{\beta\beta}$
for $T_{1/2}=10^{28}$ yr

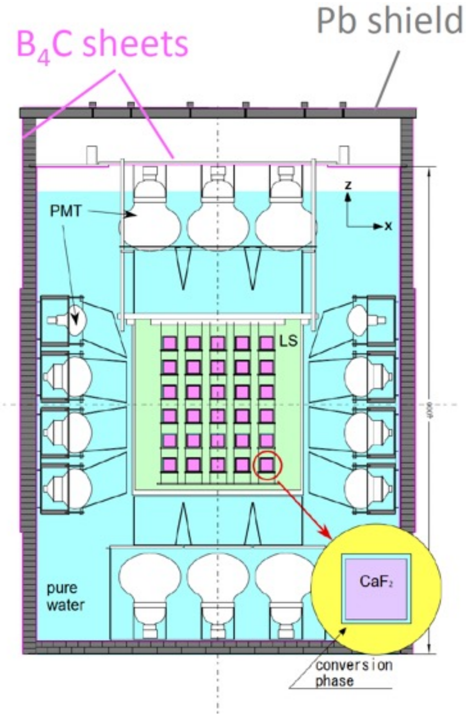
Plus Many Other Technologies

SELENA: pixel array to capture topology



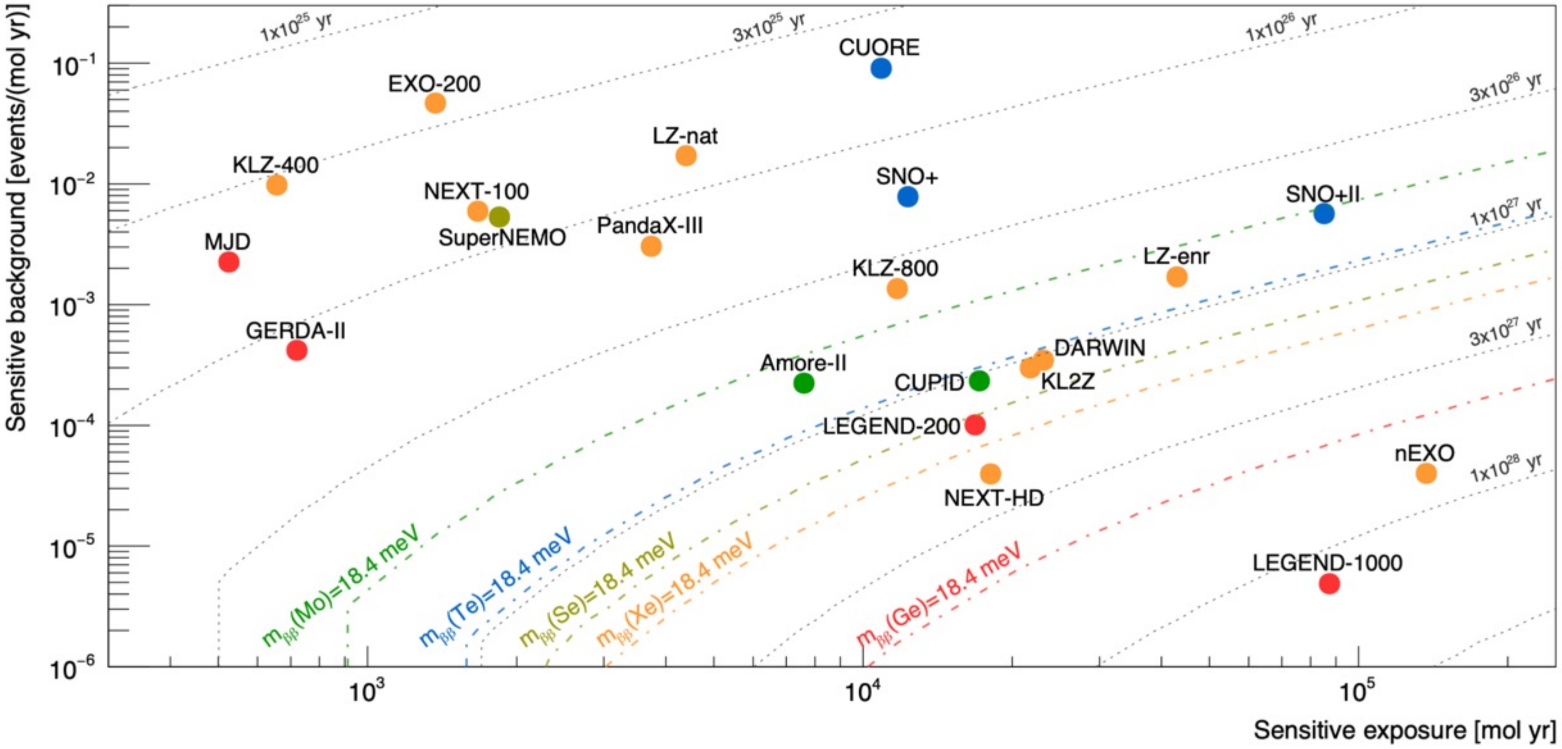
From Alvaro Chavarria, TAUP21

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



From Yuto Minami, TAUP21

The Path Ahead



M. Agostini *et al*. Rev. Mod. Phys. **95** (2023) 025002

Summary

- Discovery of neutrinoless double beta decay would fundamentally reshape what we know about particle physics
- Experimental challenges in searching for neutrinoless double beta decay are real and varied
- Broad experimental program searching for this compelling new physics
- Compelling experimental programs taking data now
- Exciting prospects to cover inverted ordering range
- R&D looking for solution to beyond-next-generation sensitivity