Experimental Overview of Neutrinoless Double Beta Decay

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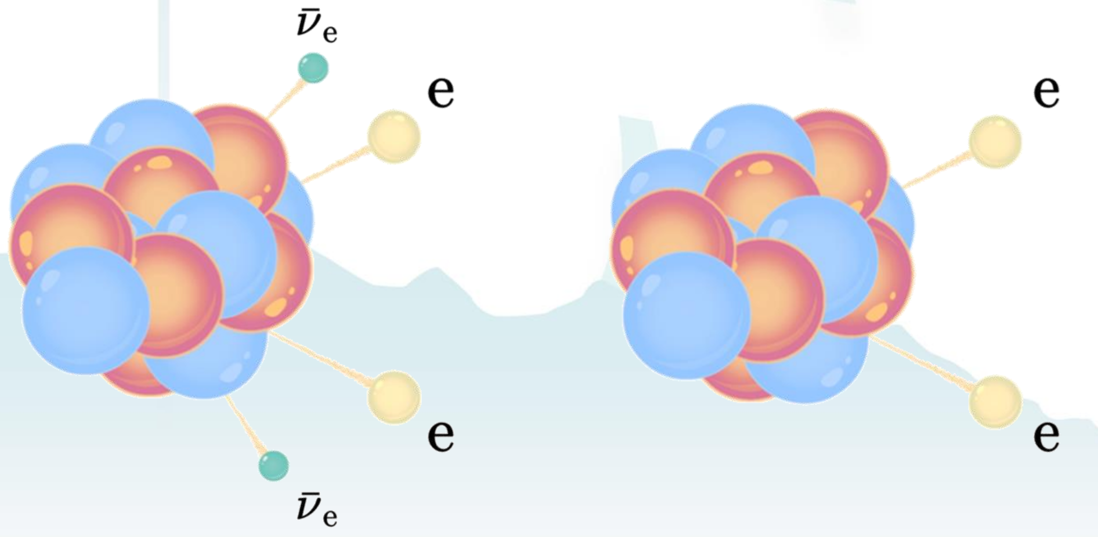
2025.11.29

Workshop on Neutrinos and related New Physics Research, 2025.11, Zhuhai

Outline

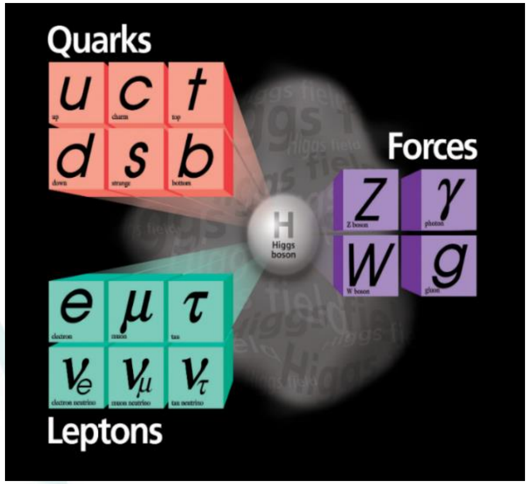
- **Neutrinoless Double Beta Decay**
- **Experimental searches for Neutrinoless Double Beta Decay**
- **Neutrinoless Double Beta Decay experiments in China**
- **Summary**



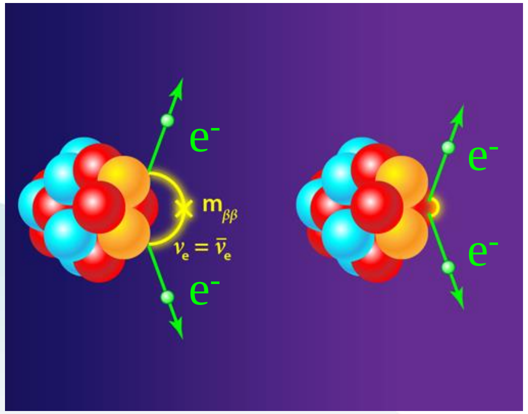
Two Neutrinos Double Beta Decay   Neutrinoless Double Beta Decay

Neutrinoless Double Beta Decay (0νββ)

- **Questions for neutrino physics**
  - Neutrino mass and mass hierarchy
  - Dirac or Majorana nature of neutrino
  - Neutrino species
  - …



- **If 0νββ decay observed**
  - Neutrino behaves as a Majorana particle
  - Lepton number conservation violated
  - Neutrino absolute mass
  - Neutrino mass order
  - …



$$(A,Z) \rightarrow (A,Z+2) + 2\,e^- + Q_{\beta\beta}$$

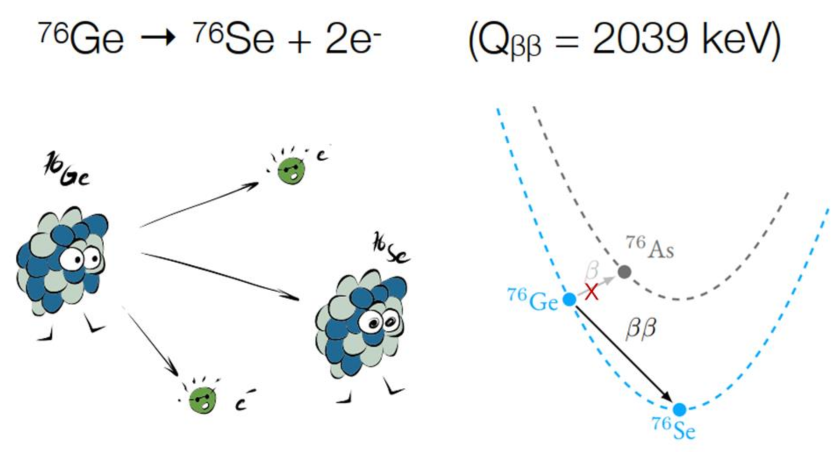
Experimental searches for 0νββ

- **Isotope (source) choice**
  - High $Q_{\beta\beta}$ value (lower background)
  - High abundance or Industrial enrichment (lower cost)

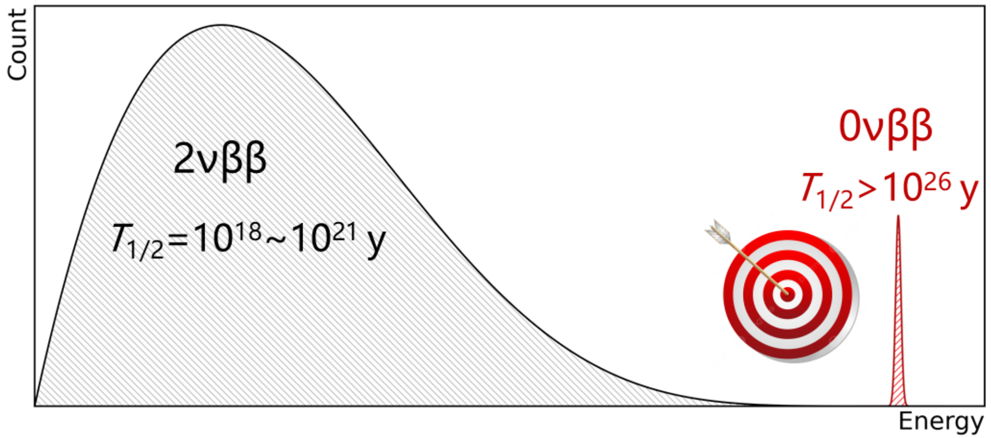
ββ decay isotopes

Isotope	Daughter	$Q_{\beta\beta}$ (keV)[a]	f_{nat} (%)[b]	f_{enr} (%)[c]
^{48}Ca	^{48}Ti	4267.98(32)	30.187(21)	16
^{76}Ge	^{76}Se	2039.061(7)	37.75(12)	92
^{82}Se	^{82}Kr	2997.9(3)	38.82(15)	96.3
^{96}Zr	^{96}Mo	3356.097(86)	32.80(2)	86
^{100}Mo	^{100}Ru	3034.40(17)	39.744(65)	99.5
^{116}Cd	^{116}Sn	2813.50(13)	37.512(54)	82
^{130}Te	^{130}Xe	2527.518(13)	34.08(62)	92
^{136}Xe	^{136}Ba	2457.83(37)	38.857(72)	90
^{150}Nd	^{150}Sm	3371.38(20)	35.638(28)	91

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



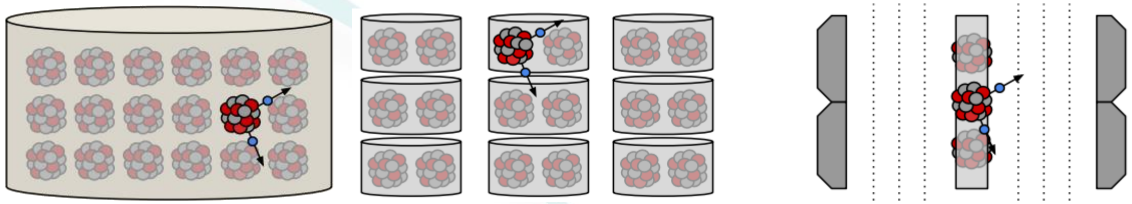
$$ {}^{A}_{Z}\mathrm{N} \rightarrow {}^{\;\;A}_{Z+2}\mathrm{N} + 2e^{-} + 2\bar{\nu}_e $$



Experimental searches for 0νββ

- **Detector technology choice**
  - Excellent energy resolution (~keV)
  - Low background (~cts/t/y)
  - High detection efficiency
  - Scalability (~kg → ~t)

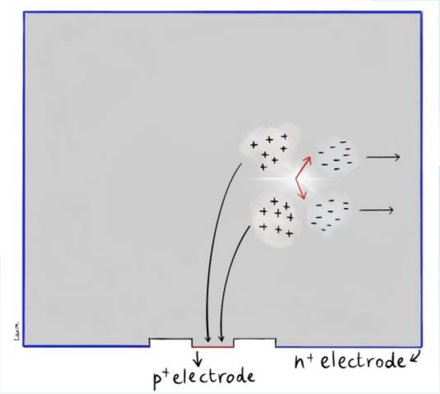
Christoph Wiesinger's talk, TAUP 2025



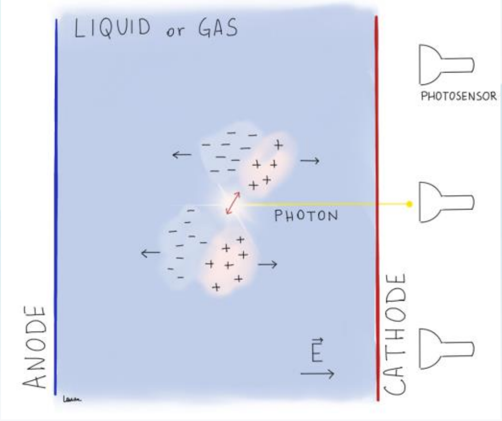
Monolithic detectors | Array detectors | Tracking calorimeters

Source = detector | Source ≠ detector

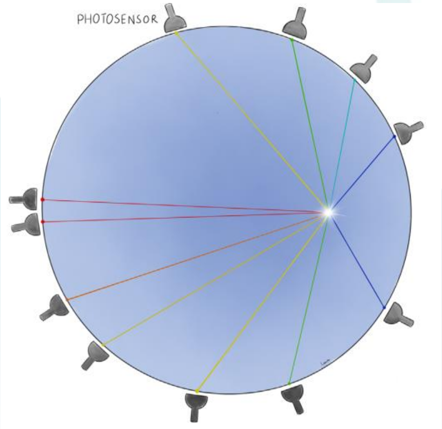
Semiconductor (HPGe)



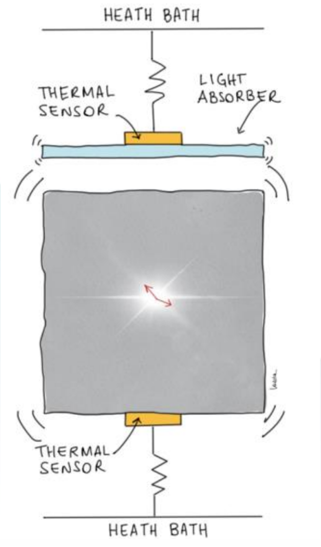
Xenon TPC



Liquid scintillator



Cryogenic calorimeter



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

Experimental searches for 0νββ

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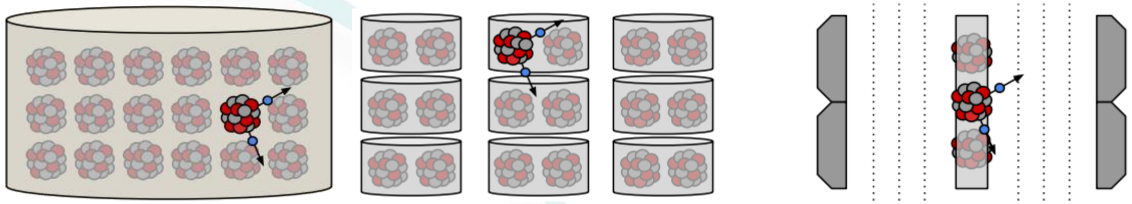
Christoph Wiesinger, TAUP 2025

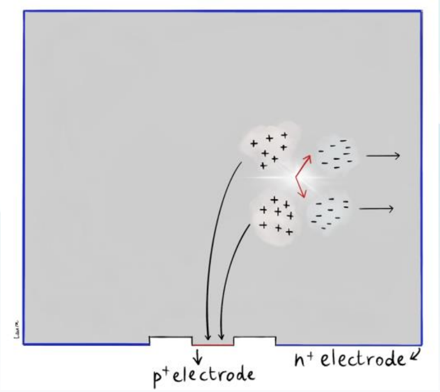


Monolithic detectors | Array detectors | Tracking calorimeters

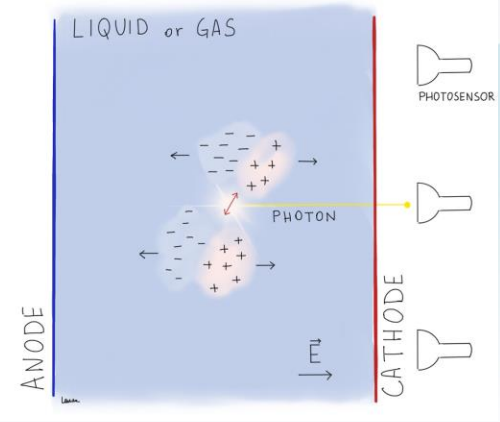
Source = detector | *Source ≠ detector*

No perfect isotope, mix of theoretical and experimental preferences

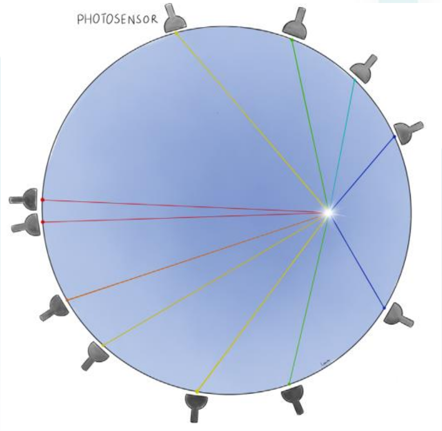
Semiconductor (HPGe)



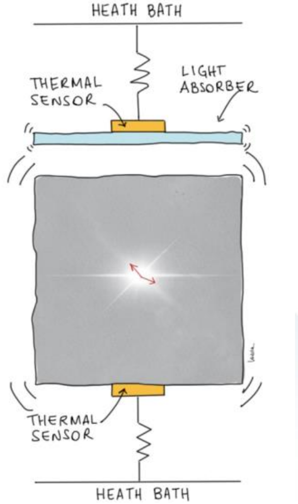
Xenon TPC



Liquid scintillator



Cryogenic calorimeter



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

$0\nu\beta\beta$ Experiments

- vibrant field
- several isotopes and detector technologies with specific features
- no time to cover all of them
- overview of some representative exp.

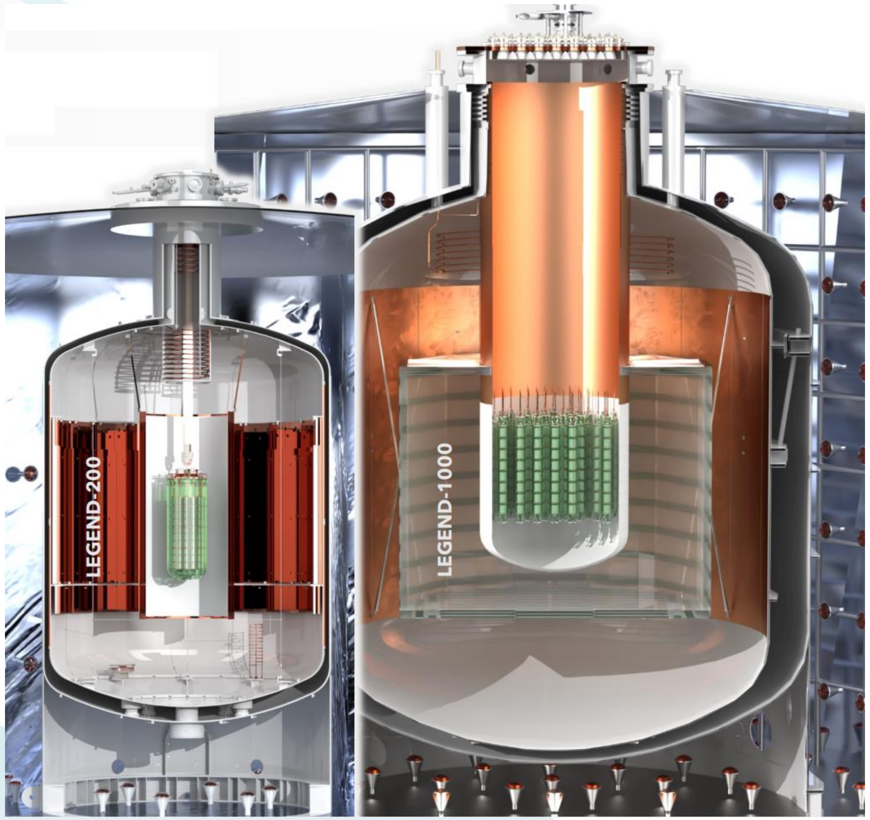
arXiv:2212.11099

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	

LEGEND: a phased approach

[Alberto Garfagnini, TAUP 2025]

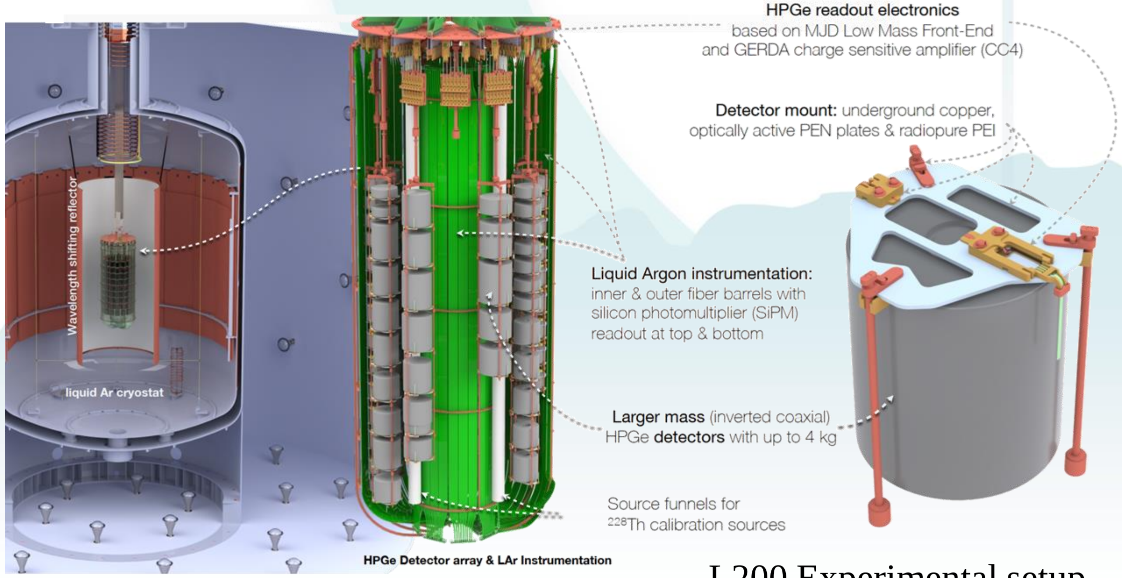
- **LEGEND-200**
  - Up to 200 kg of enrGe detectors
  - Uses GERDA infrastructure in Hall A, LNGS
  - Operational since 2023
  - Goals:
    - 1 ton·yr of exposure;
    - Background ~ 2×10^{-4} cts / (keV·kg·yr)
    - $T_{1/2} > 10^{27}$ yr $\mapsto m_{\beta\beta} \sim 30 - 70$ meV
- **LEGEND-1000**
  - 1000 kg of ^{enr}Ge detectors
  - Uses new infrastructure in Hall C, LNGS
  - Goals:
    - 10 ton·yr of exposure; Background ~ 10^{-5} cts / (keV·kg·yr)
    - $T_{1/2} > 10^{28}$ yr $\mapsto m_{\beta\beta} \sim 9 - 21$ meV



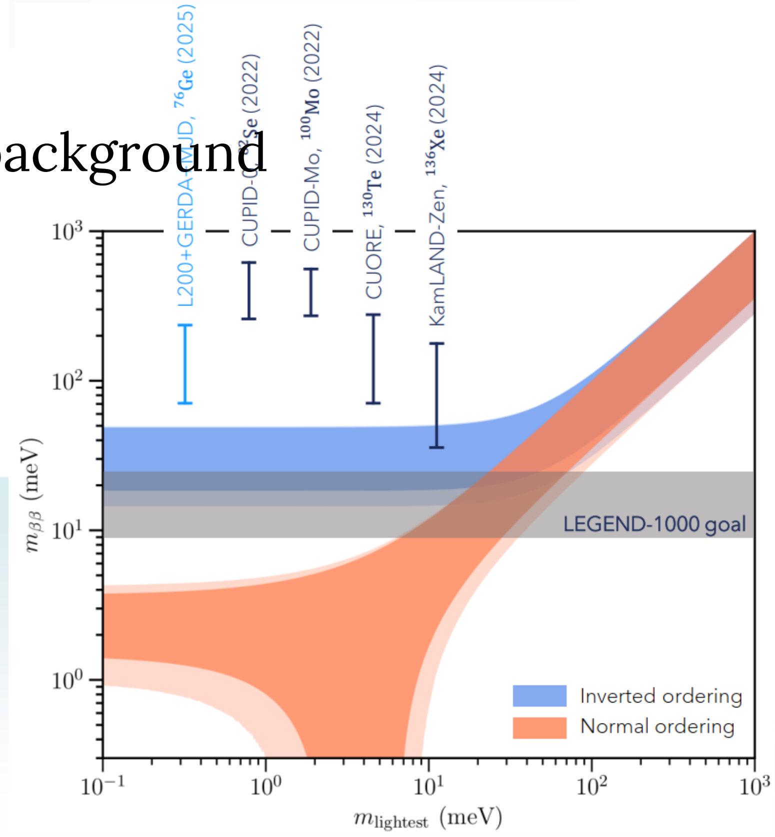
LEGEND-200

[Alberto Garfagnini, TAUP 2025]

- Stable operations and excellent performance with 142 kg of enrGe
- First LEGEND-200 0νββ results based on 61 kg·yr
- $T_{1/2}$ sensitivity of 2.8×10^{26} yr (90% CL), combined with Gerda and MJD
- New limit on $m_{\beta\beta}$ < 75-200 meV (90% CL)
- Data taking restart soon
  - more large-mass ICPC det. and lower near-comp. background



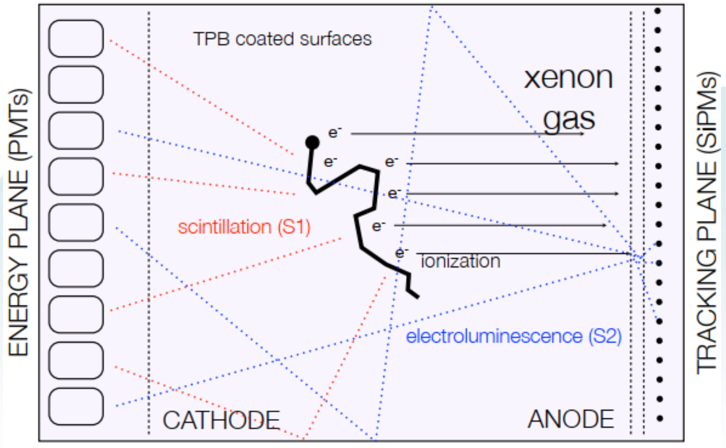
L200 Experimental setup

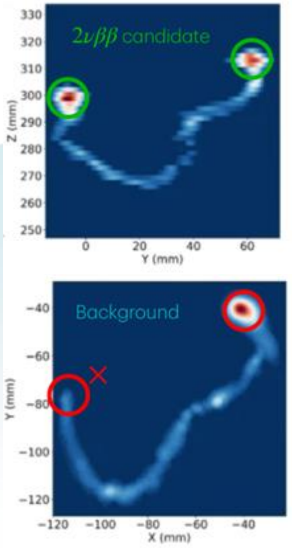


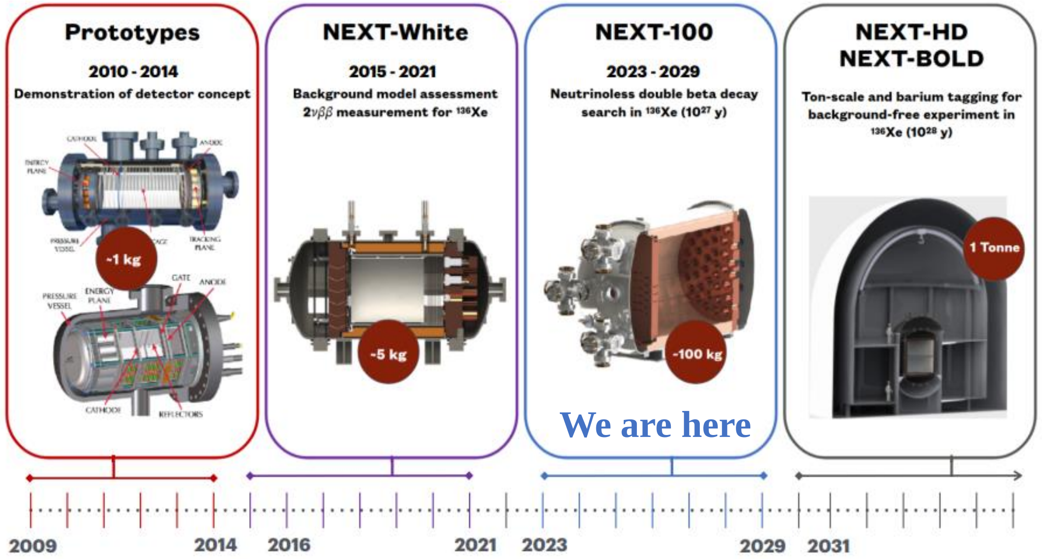
NEXT-100

[S.Torelli, TAUP 2025]

- High pressure Xe gas TPC with tracking capabilities to reject backgrounds
- NEXT-White results with fiducial mass 3.5 kg of Xe (~90.9% ^{136}Xe)
  - 1% FWHM @ 2.6MeV; $T_{1/2} > 1.3 \times 10^{24}$ y
- **NEXT-100** @ Canfranc
  - Operation started in May 2024 @ 4 bar and Commissioning concluded
  - Operations @ 10 bar for search expected by 2026
  - Keep 1% FWHM, expected O(10^{26}) y sensitivity after 3 y running
  - Demo. scalability to ton-scale



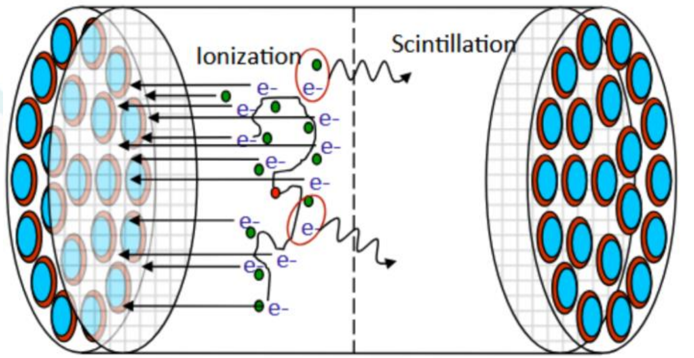




EXO and nEXO

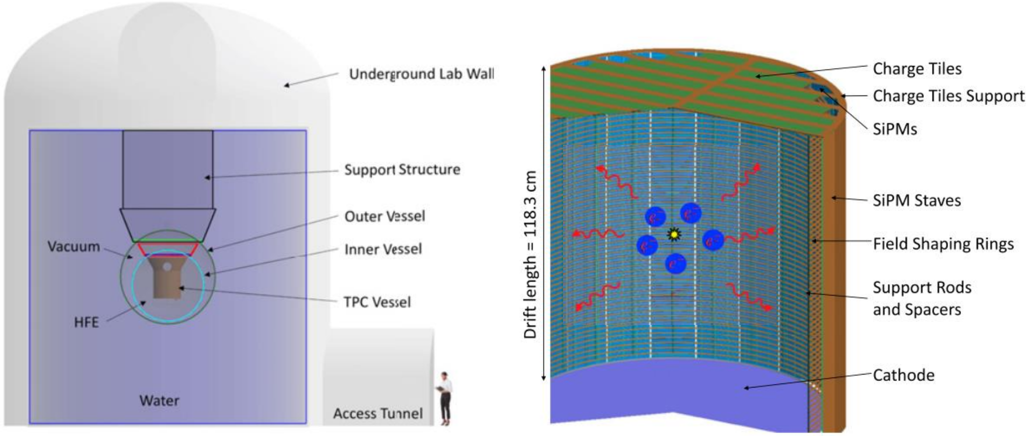
[Thomas Brunner, TAUP 2025]
[G. Adhikari et al., J. Phys. G: Nucl. Part. Phys. 49 (2022) 015104]
[Chambers et al., Nature 569 (2019) 7755]

- EXO-200 liquid Xe TPC
  - 2011–2018 active @ WIPP
  - 200 kg LXe (≈ 130 kg of LXe in active volume)
  - 80.672% ^{136}Xe and 19.098% ^{134}Xe
  - First observation of 2νββ decay of ^{136}Xe in 2011
  - $T_{1/2} > 3.5 \times 10^{25}$ y for 0νββ decay of ^{136}Xe



EXO-200

- nEXO proposal
  - 5 t LXe TPC enriched to 90% in ^{136}Xe
  - Collecting scint. light and ionization electrons
  - Ba tagging development
  - Goal: $T_{1/2} > 10^{28}$ y for 0νββ decay of ^{136}Xe

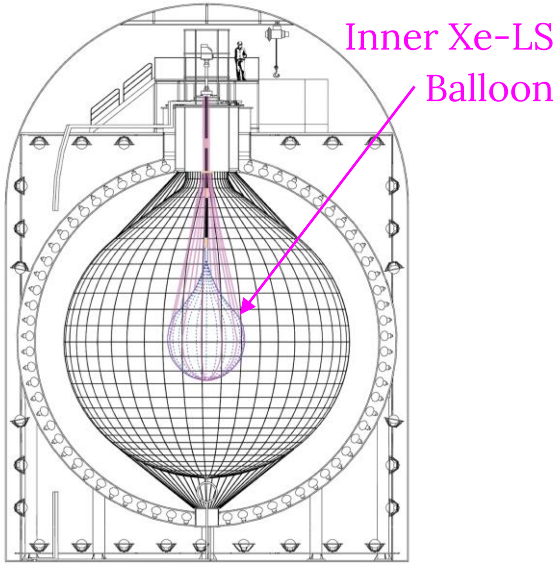


nEXO in SNOLAB's cryopit

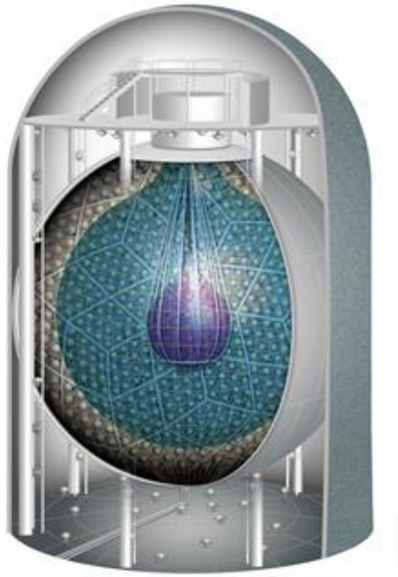
KamLAND-Zen

[Kelly Weerman, TAUP 2025]

- KamLAND as a neutrino detector
  - 1 kt liquid scintillator with 3.2 kt water Cherenkov det.
  - 1000 underground in Kamioka mine
- KamLAND-Zen 800 (Feb. 2019 – Jan. 2024)
  - Xe-LS balloon, ⌀3.8m, 24t, containing 745 kg Xe (91% ^{136}Xe)
  - 2.1 ton·yr ^{136}Xe with energy resolution 4% @ 2.46MeV
  - Leading limit: $T^{0\nu}_{1/2} > 3.8 \times 10^{26}$ yr ($m_{\beta\beta} < (28 - 122)$meV)
- KamLAND-Zen2 construction ongoing
  - Scintillation inner balloon (PEN): larger fiducial volume
  - Improved energy resolution: 2% @ 2.46MeV
  - Dead-time free electronics: higher neutron tagging efficiency
  - Running expected 2028-2033
  - Goal: $T^{0\nu}_{1/2} > 2 \times 10^{27}$ yr ($\langle m_{\beta\beta}\rangle = 20$ meV)



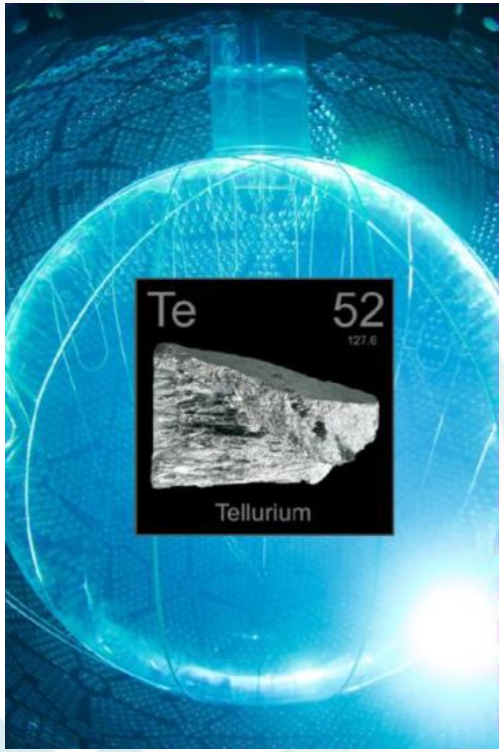
KamLAND-Zen

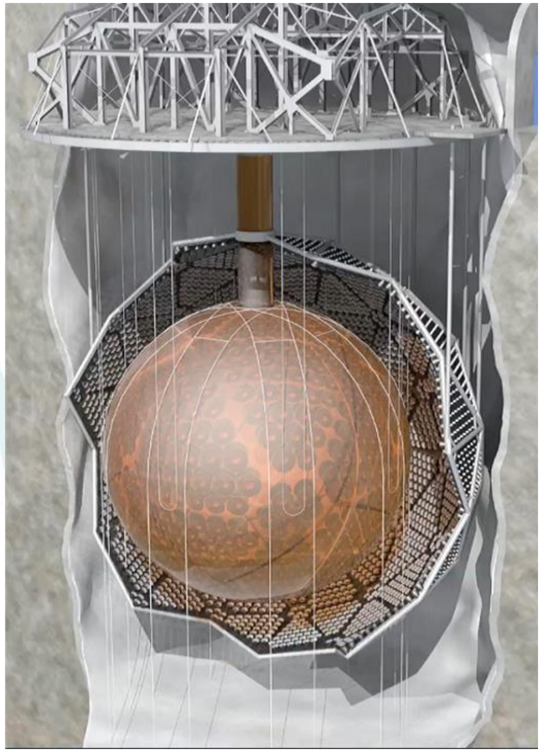


KamLAND-Zen2

SNO+ Tellurium Double Beta Decay

- 780 t liquid scintillator neutrino detector
- Staged Loading of ^{nat}Te (34% ^{130}Te)
  - ~1.3t ^{130}Te for 0.5% loading
  - up to 1.5% Te
  - energy resolution ~ 4% @ 2.5 MeV
- Projected sensitivity
  - > 2.0×10^{26} yr, 3 yr, 0.5% loading
  - > 7.4×10^{26} yr, 5 yr, 1.5% loading
- Data taking timeline
  - Scintillator phase ongoing
  - Start loading end of 2025 / early 2026





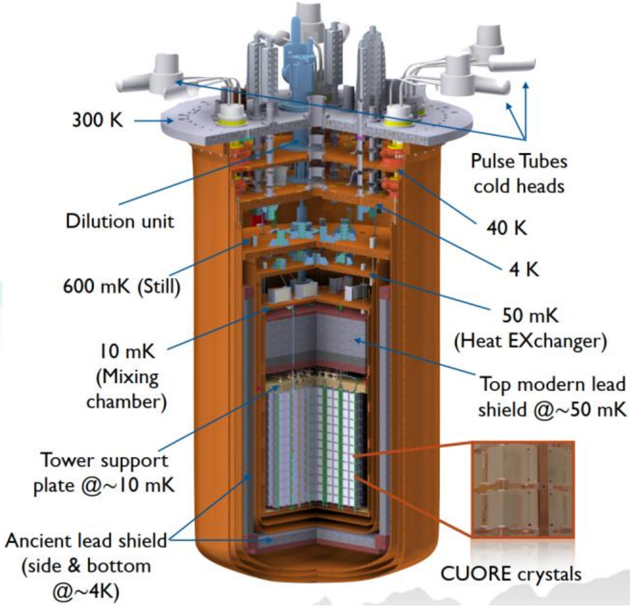
0.6 g/L PPO; 2.2 g/L PPO
Now with added bis-MSB

[M. Chen, SNOLAB Future Projects Workshop 2025]
[Christoph Wiesinger, TAUP 2025]

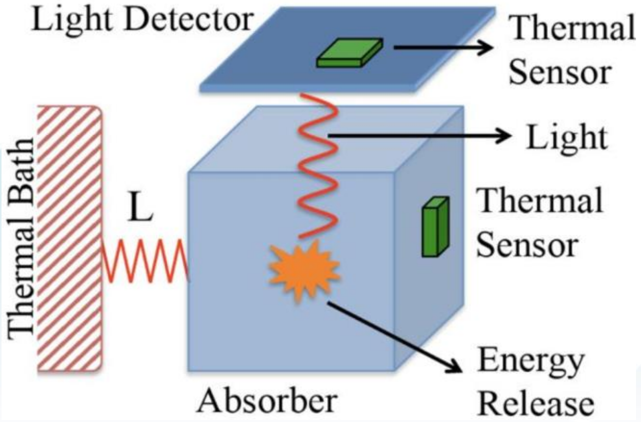
CUORE and CUPID

[A. Campani, TAUP 2025]
[I. Nutini, TAUP 2025]

- CUORE located at LNGS
  - 988 TeO_2 crystal with 742 (206) kg ${}^{nat}TeO_2$ (${}^{130}Te$)
  - calorimeters working @ 10 mK
  - energy resolution ~0.3% @ 2.53 MeV
  - background in the ROI: ~1.4×10^{-2} cts/(keV kg yr)
  - new limit: $T_{1/2} > 3.5\times10^{25}$ yr
- CUPID: CUORE Upgrade with Particle Identification
  - ${}^{100}Mo$ enriched to >95%
  - 450 kg (240 kg) $Li_2{}^{100}MoO_4$ (${}^{100}Mo$) scintillating crystals
  - Expected energy resolution ~0.16% @ 3.034 MeV
  - Expected background index < 10^{-4} cts/(keV kg yr)
  - sensitivity goal: $T_{1/2} = 10^{27}$ yr ($m_{\beta\beta}$ = 12–20 meV)
  - ready to start construction with a staged deployment
  - Early data taking in 2030 with ~80 kg ${}^{100}Mo$



CUORE setup



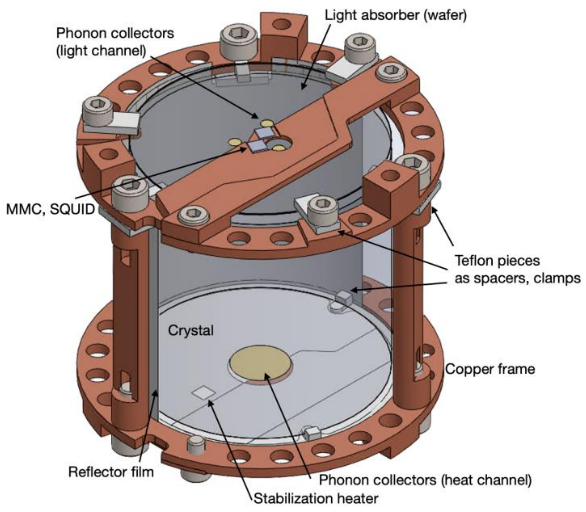
CUPID detector
with Ge-NTD sensors

AMORE

[SeungCheon Kim, TAUP 2025]

- AMoRE-I (2020-2023)
  - 700 m underground @ Y2L in Korea
  - 6.2 (3.0) kg ^{48dep}**Ca**^{100}**MoO$_4$** + **Li$_2$^{100}MoO$_4$** (95% enr. ^{100}Mo)
  - MMC Detecting phonons and scintillation at ~10 mK
  - live exposure ~ 4 kg$_{\text{Mo-100}}$ yr
  - background in ROI ~0.025 cts/(keV kg yr)
  - half-life Limit: $T_{1/2} > 2.9 \times 10^{24}$ yr
- AMoRE-II project (2025-)
  - new Yemilab with overburden of 1000 m
  - Stage-1 with 90 LMOs (27 kg) and stage-2 360 LMOs (157 kg)
  - Energy resolution ~0.3% @ 2.615 MeV
  - Aiming at background ~10^{-4} cts/(keV kg yr)
  - Goal: $T_{1/2}$ ~4×10^{26} yr with exposure > 500 kg$_{\text{Mo-100}}$ yr
  - Stage-1 installation started this fall

↓ 85 kg ^{100}Mo



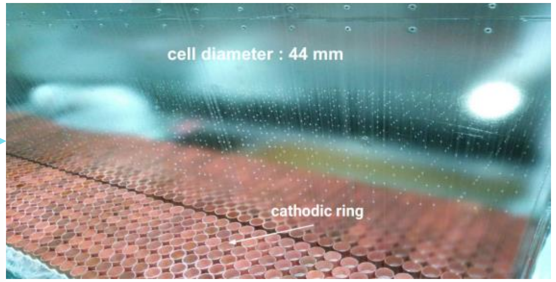
AMoRE-II detector

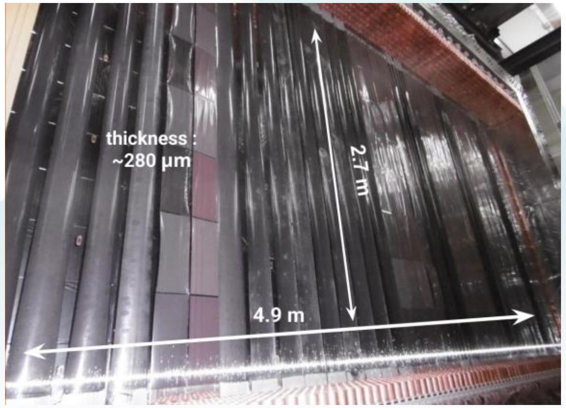
AMoRE Hall

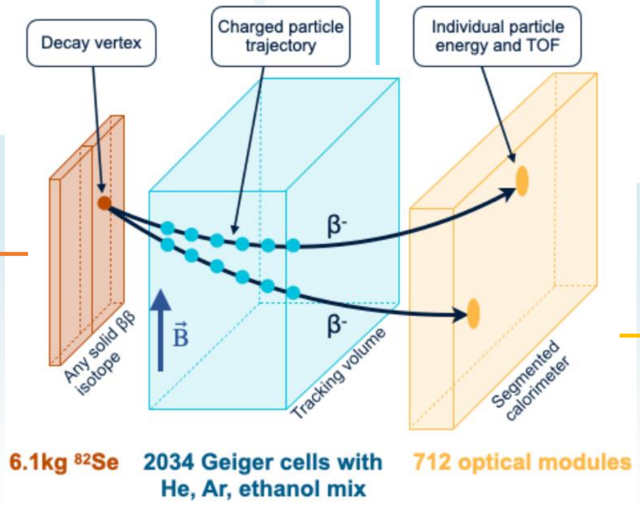
SuperNEMO demonstrator

[Roxanne Guénette, Neutrino 2024;
Xalbat Aguerre, TAUP 2025]

- Successor to NEMO-3 located at Modane
  - Unique tracker/calorimeter approach with a Magnetic field, getting full topology of the decay
  - Demo. capability of the approach and scalability for a future large-scale detector
  - Precision measurement of the $2\nu\beta\beta$ decay kinematics
  - $0\nu\beta\beta$ search background-free in the ROI (~ 3 MeV)
  - 34 ^{82}Se foils (96-99% enriched)
  - $\beta\beta$ data taking since April 10, 2025



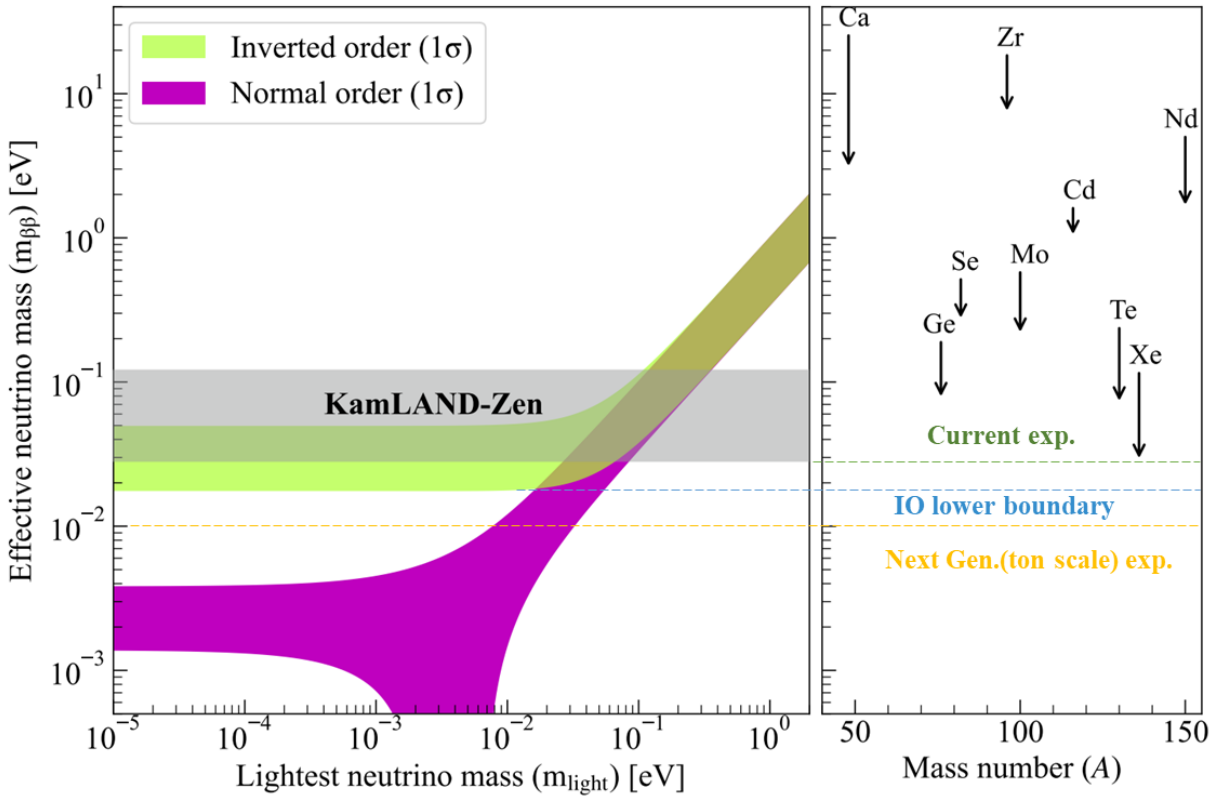




PMT +
Scintillator

Current and Next Gen. Exp. sensitivity

- Current bounds [28, 122] meV by KamLAND-Zen (^{136}Xe)
- Next Gen. will probe inverted ordering scenario & part of normal ordering space
  - e.g. [9, 21] meV by LEGEND-1000 (similar to CUPID, nEXO, ...)



Adapted from Yu et al. PRD 112, 055037 (2025)

Phase Space Factor

Effective Majorana Neutrino Mass

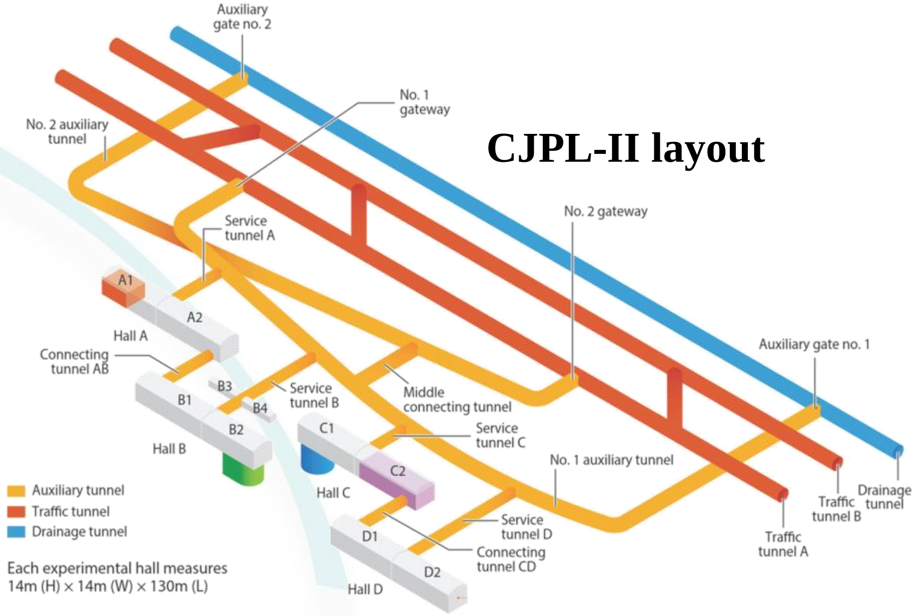
$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu} \left| M^{0\nu} \right|^2 \left(\frac{m_{\beta\beta}}{m_e} \right)^2$$

Nuclear Matrix Element

$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 m_{\nu i} \right|$$

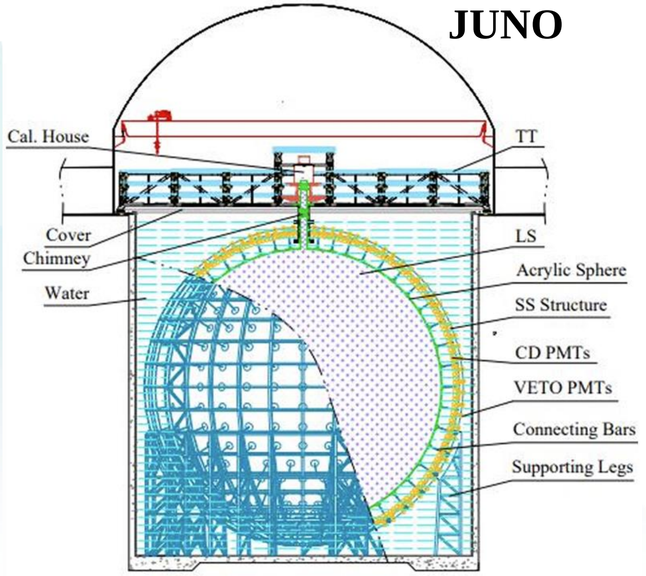
0νββ experiments in China

- **China Jinping Underground Laboratory**
  - 2400 m underground, Southwest China
  - CDEX (HPGe)
  - PandaX (Liquid Xenon TPC)
  - CUPID-CJPL (LMO Calorimeter)
  - NνDEx (SeF_6 Gas TPC)



CJPL-II layout

- **JUNO**
  - 700 m underground, Southeast China
  - JUNO-0νββ (^{130}Te or ^{136}Xe doped in liquid scintillator)



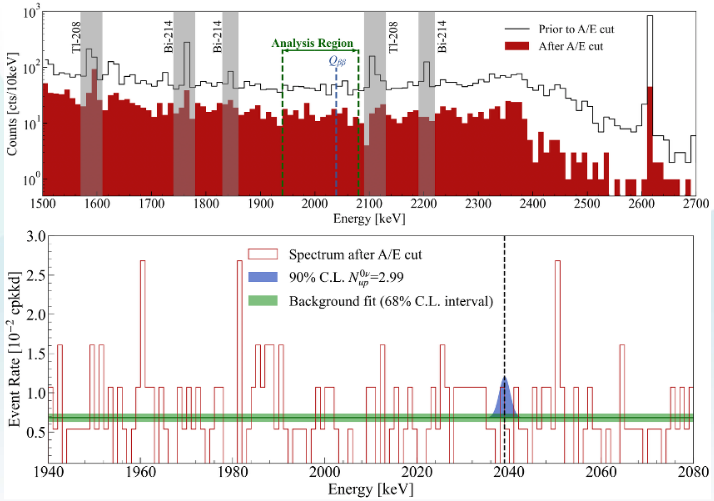
JUNO

CDEX

- ^{nat}Ge detectors for light dark matter detection @ CJPL
- ^{76}Ge 0νββ results from CDEX
  - 2017, First 0νββ result using 1 kg PPC detector
  - 2022, Study pulse shape discrimination (PSD) using a BEGe detector
  - 2024, Improved 0νββ result using 1 kg PPC & NaI veto

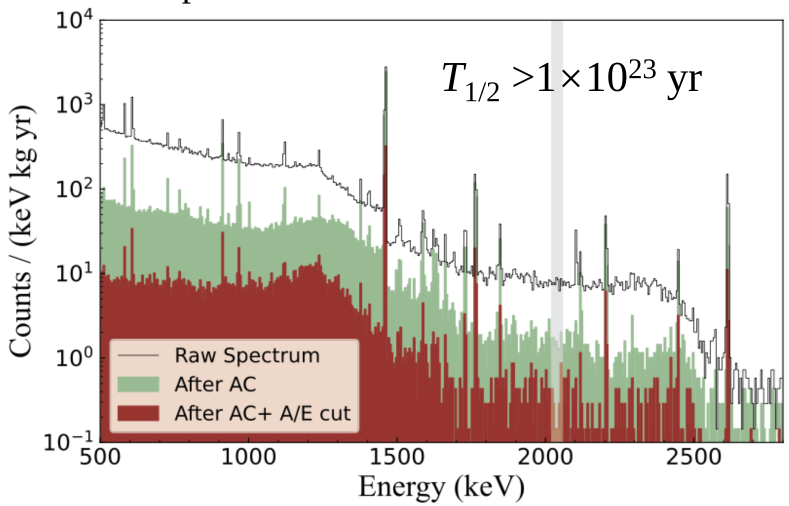
PPC det.

Result from BEGe detector



[PRD 106, 032012, 2022]

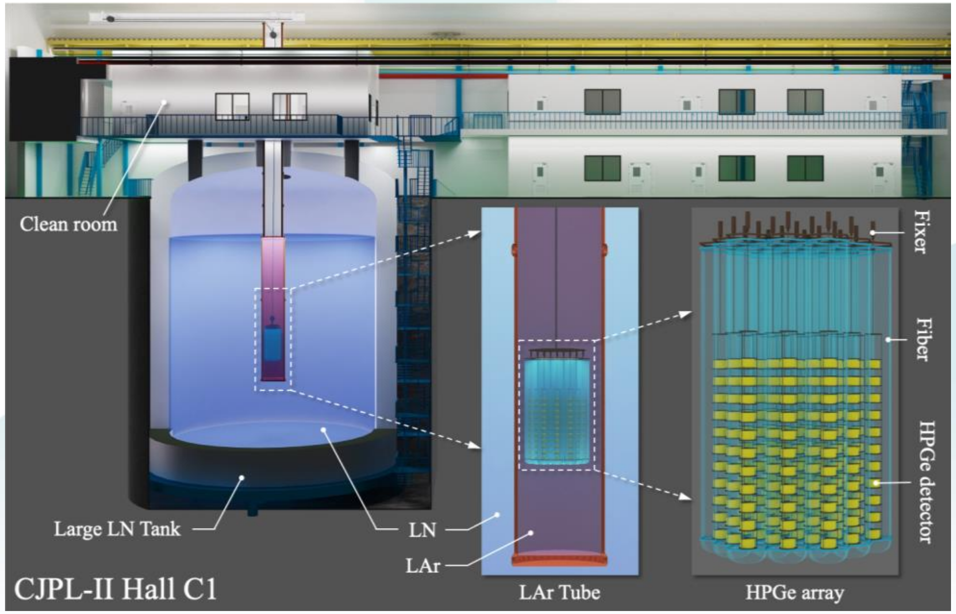
Improved result from PPC detector



[CPC 48, 101001, 2024]

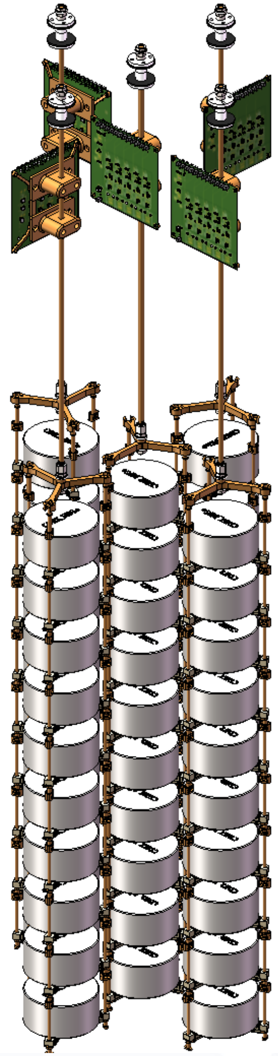
CDEX

- CDEX-300ν baseline design
  - 225 kg BEGe, ^{76}Ge enriched to >86%, immersed in 20 t LAr (veto)
  - LAr exp. tube through the central flange of 1725 m^3 LN tank
  - energy resolution ~0.12% @ 2.039 MeV
  - Background in ROI ~ 10^{-4} cts/(keV kg yr)
  - Goal: $T_{1/2} > 2.06 \times 10^{26}$ yr with 5 yr data



Experimental setup of CDEX-300ν

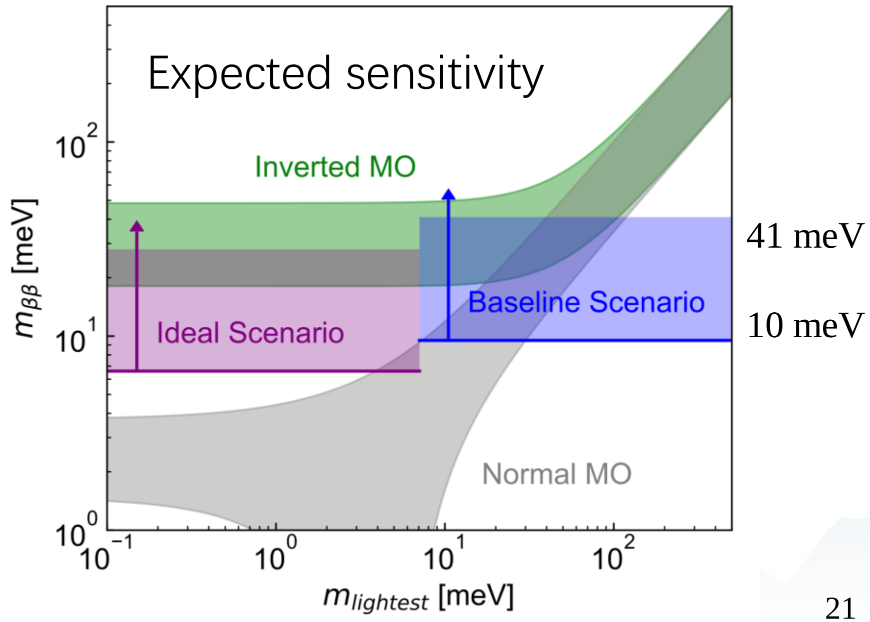
Clean room(inside)


19 strings
200 det.

PandaX

PRL 132, 152502 (2024)
Sci.Bull. 70 1779 (2025)
SCPMA 68, 221011 (2025)

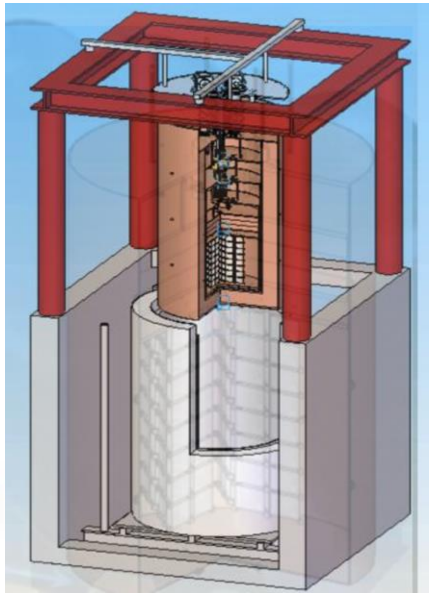
- Liquid Xe TPC for dark matter detection @ CJPL
- ^{134}Xe $2\nu\beta\beta$ and $0\nu\beta\beta$ searches at PandaX-4T
  - $T_{1/2}^{2\nu\beta\beta} > 2.8 \times 10^{22}$ yr and $T_{1/2}^{0\nu\beta\beta} > 3.0 \times 10^{23}$ yr
- ^{136}Xe $0\nu\beta\beta$ searches at PandaX-4T
  - energy resolution ~2% @ 2615 keV
  - $T_{1/2}^{0\nu\beta\beta} > 2.1 \times 10^{24}$ yr $\rightarrow m_{\beta\beta} < (0.4\sim1.6)$ eV
- PandaX-xT
  - 43 t of Xenon (active)
  - High-granularity, low-background 2-in PMT array
  - Cu/Ti vessel for improved radiopurity
  - Inner liquid scintillator veto



CUPID-CJPL

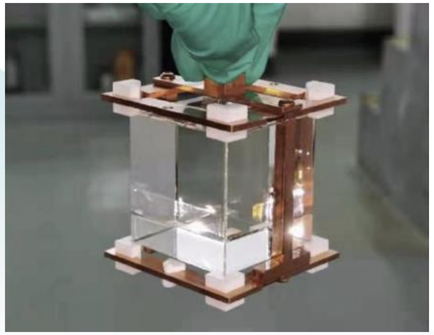
- A cryogenic bolometer testbed supporting CUPID
- CUPID-CJPL prototype @ ~10 mK
  - cryogenic bolometer facility (holding 10 kg of crystals)
  - quality assessment of CUPID LMO crystals
  - quality assessment of new readout electronics made for CUPID
  - assessment of background level of cryogenic bolometers in CJPL
- Data to build a background model

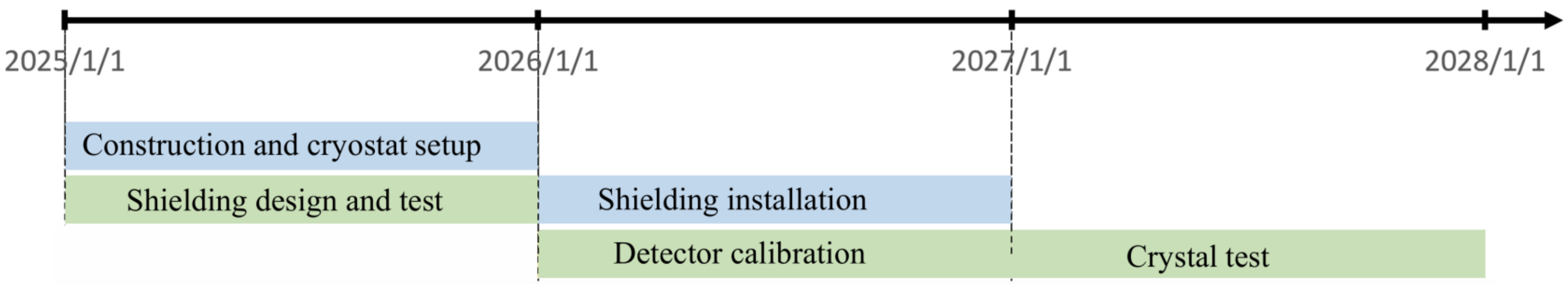
  → **MIGHT** make CJPL an option for ton scale search experiment



CUPID-CJPL setup

LMO

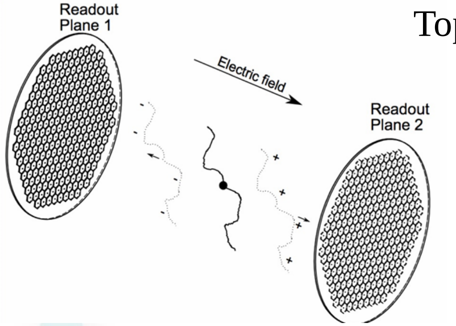




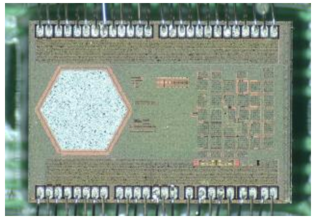
NvDEx

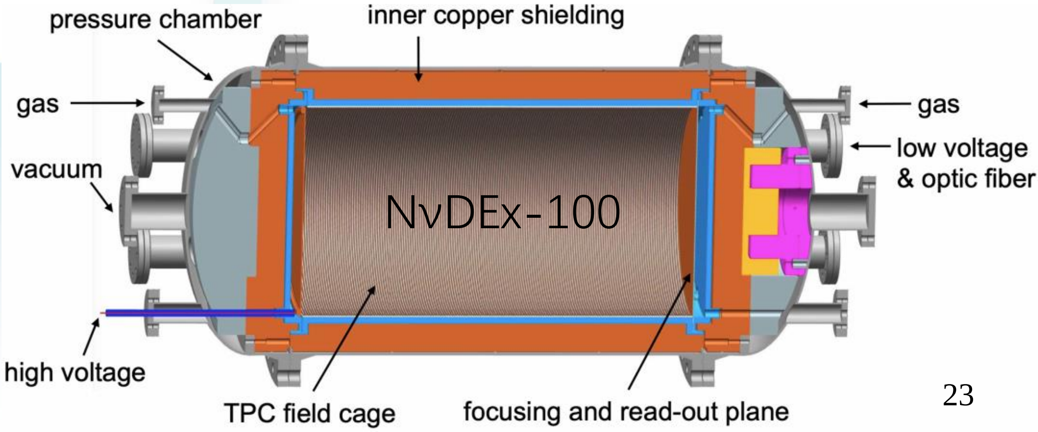
[Hao Qiu, TAUP 2025]

- High pressure $^{82}SeF_6$ gas TPC, with direct read-out by Topmetal CMOS sensors
- Better energy resolution without avalanche amplification
  - ~1% FWHM @ 2.996 MeV
- **NvDEx-100**
  - 100kg SeF_6 gas at 10 atm in the sensitive volume
  - key technology: sensor chips ENC ~50 e^- (goal 45e^-)
  - safety issue on toxic $SeF_6 \rightarrow$ Multi-layered measures
  - being built above ground
  - estimated background ~0.5 cts / (ton yr ROI)
    $\rightarrow T_{1/2} > 4\times10^{26}$ yr with 5 yrs running



Topmetal CMOS sensor



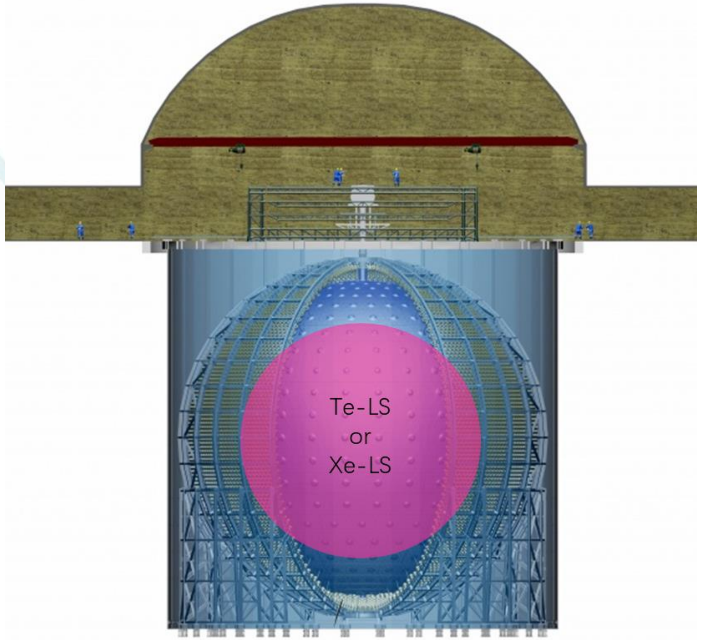


JUNO-0νββ

[Gaosong Li, TAUP 2025]

- JUNO offers a unique opportunity to search for 0νββ
  - 20 kt LS → 100 t scale isotope loading (Tellurium or Xenon)
  - Low background
  - Energy resolution < 3% @ 1 MeV

    → 2.4x better than KamLAND-Zen
- Critical R&D
  - Te route: isotope loading technology
  - Xe route: cost effective enrichment & clean balloon
  - Cosmogenic background control (700 m underground)
- Te-LS R&D program
  - 2019: Organic Te-diol compounds
  - 2024: Synthesis and purification protocol established for Te-LS production
  - 2025: 100 kg production demonstration, developing radioactive impurities removal method



Experimental Concept

Summary

- Understanding the nature of neutrinos nature is of the utmost importance
- Next gen. exp. will cover inverted neutrino mass ordering, but technologically challenging:

  [Roxanne Guénette, Neutrino 2024]

  - ambitious goals for the ton-scale experiments
  - radiopurity requirements pushing the limits of radio-assay capabilities
  - cooperating with industry becoming more challenging (and expensive)
  - community needs to come together to be stronger, while pushing on new technology development and getting funding
- Continue to cast a wide net and explore different isotopes and technologies
- Experimental efforts/proposals emerging in China based on CJPL or JUNO
- Hope we all are lucky

Thanks for your attention

Thanks to
Ke Han, Gaosong Li, Wenhan Dai,
for slides.

Photo credit: Zixing Li