Majorana Neutrinos, Searches for Neutrinoless Double Beta Decay & Opportunities at China JinPing Laboratory

Huan Zhong Huang (黄焕中)
Department of Physics and Astronomy
University of California, Los Angeles 90095
huang@physics.ucla.edu

Institute of Modern Physics (现代物理研究所)
Fudan University (复旦大学)

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Outline

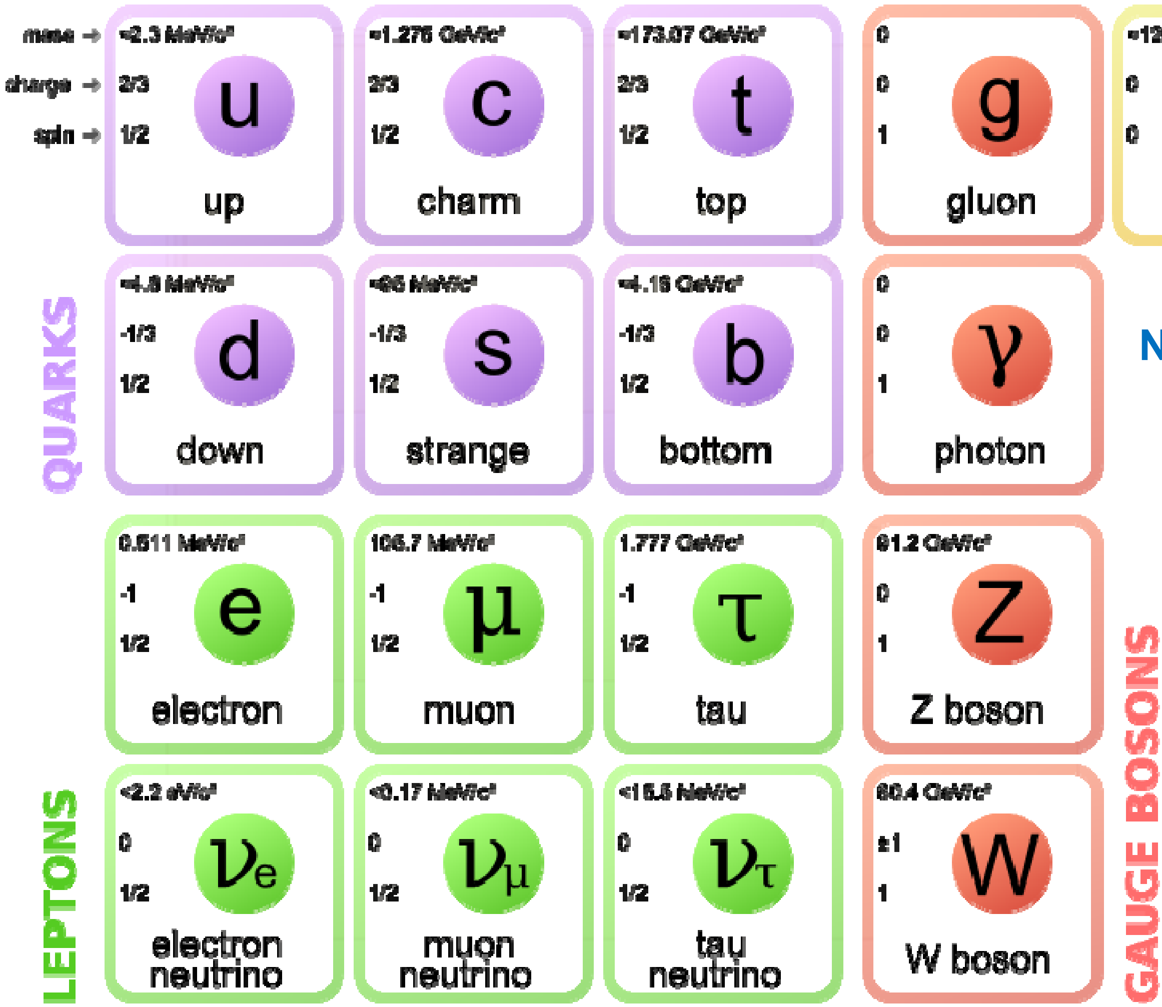
1) Introduction to Neutrino Properties

2) Majorana Neutrinos and
   Neutrinoless Double Beta Decay (0vbb)

3) Selected Technology Choices for 0vbb –
   HPGe – LEGEND, CDEX
   LXe-TPC -- nEXO
   Crystal Bolometer – CUORE/CUPID
   …….

4) Perspective at CJPL

Leptons and Flavor



Neutrino – Nobel Prize

-- 1995 Reines ν_e (1953);
Perl $\tau \rightarrow \nu_\tau$ (1977)

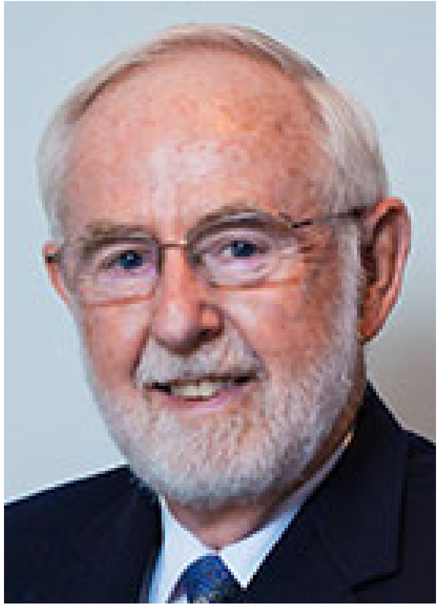
-- 1988 Lederman, Schwartz, Steinberger ν_μ (1962)

-- 2002 Davis and Koshiba cosmic ν

-- 2015 Kajita and McDonald ν oscillations

Nobel Prize in Physics 2015

Takaaki Kajita



Arthur B. McDonald

"For the discovery of neutrino oscillations, which shows that neutrinos have mass"

Neutrino Mixing

Pontecorvo-Maki-Nakagawa-Sakata Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Parametrize the PMNS matrix as:

$$\underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar, reactor}} \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{12} \end{pmatrix}}_{\text{reactor and accelerator}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{Atmospheric, accelerator}} \underbrace{\begin{pmatrix} e^{i\delta_1} & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{0\nu\beta\beta}$$

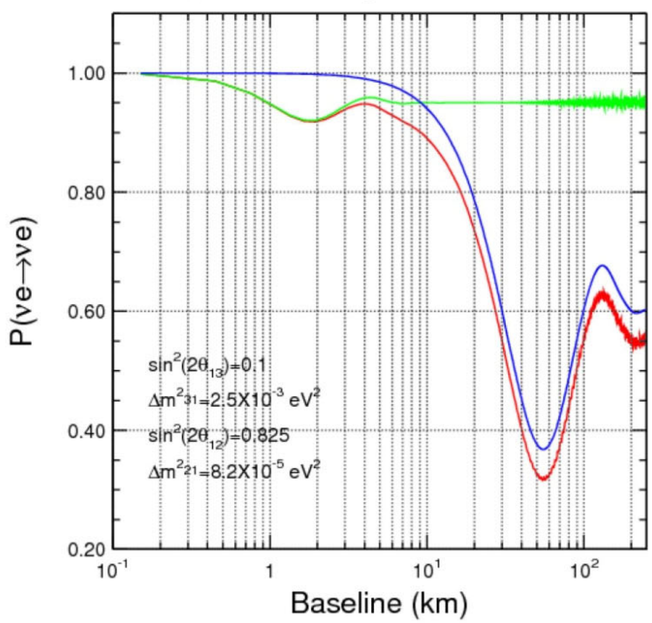
θ_{12} = ~ 32° θ_{13} = 8.5° θ_{23} ~ 45°

δ CP violation in lepton sector ?!

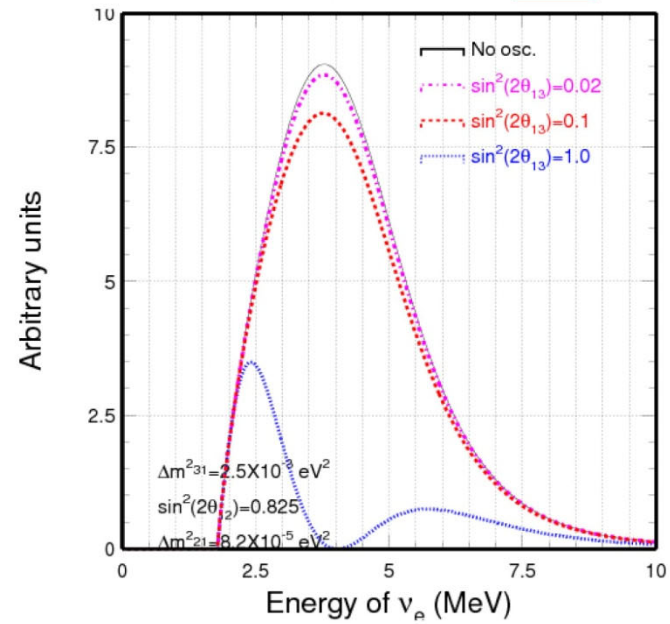
Reactor $\bar{\nu}_e$ oscillations

$$
\begin{aligned}
P(\nu_e \to \nu_e) = 1 \quad &- \quad \sin^2 2\theta_{13} \sin^2(1.27 \Delta m^2_{31} L/E) \\
&- \quad \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2(1.27 \Delta m^2_{21} L/E)
\end{aligned}
$$

Osc prob. (integrated over E) vs distance

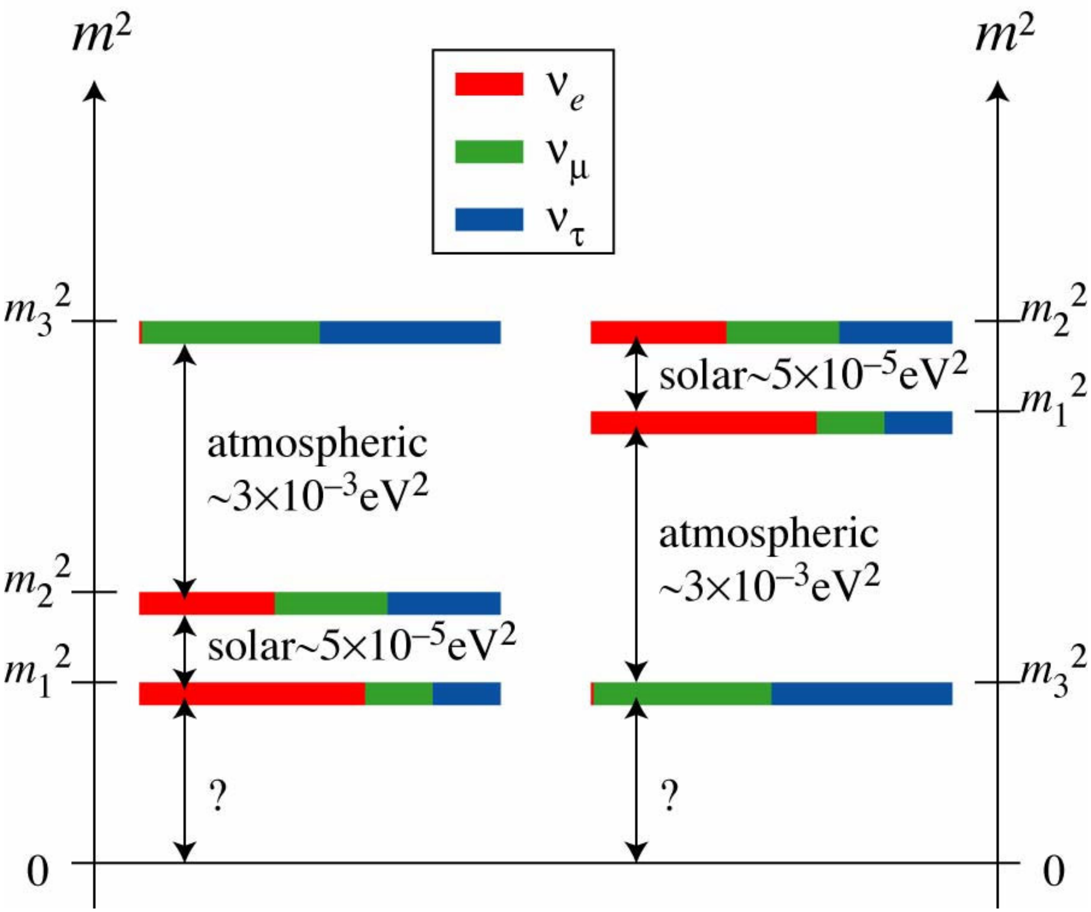


Osc. spectrum at 2km



Reactor ν_e disappearance = *unambiguous* measurement of $\sin^2 2\theta_{13}$

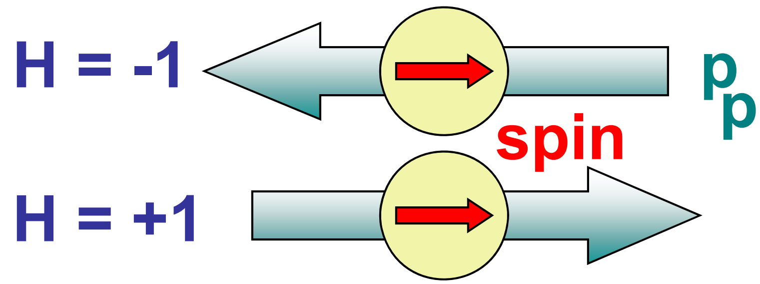
Neutrino Mass and Mixing Parameters



Parameter	Best Fit Value
$\sin^2\theta_{12}$	$0.307^{+0.024}_{-0.021}$
$\sin^2\theta_{23}$	$0.386^{+0.024}_{-0.021}$
$\sin^2\theta_{13}$	0.0241 ± 0.0025

Majorana Particles

Helicity



For massless particles, neutrino => H eigenstate
neutrino with masses ➔ H not exact quantum #

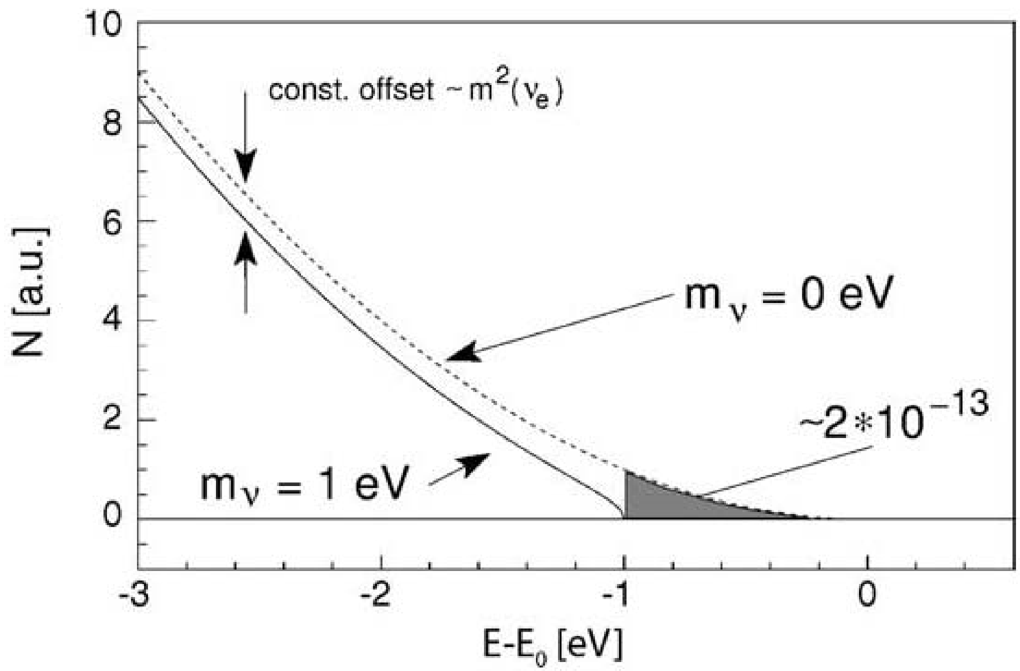
Dirac Particles ➔ particle and anti-particle different
- -- electron (q=-1) and positron (q = +1)
- -- quarks (q) and anti-quarks (-q)

Majorana Particles ➔ particle and anti-particle same
- -- neutral particle, fermion
- -- beyond Standard Model (lepton # violation)

Measuring Neutrino Masses

1) Direct Measurement
tritium decays
E_0 = 18.6 keV

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



2) Effective Majorana Mass

$$\langle m_{\beta\beta} \rangle = \sum_{i=1}^{3} |U_{ei}|^2 \, m_i \varepsilon_i$$

ε_i – CP phase for neutrinos

3) Precise Cosmological Measurement

$$\langle m_\Sigma \rangle = \sum_{i=1}^{3} m_i$$

Neutrino Physics Program

Critical Questions for Future Neutrino Physics Program

1) Are neutrinos their own anti-particles?
   Dirac or Majorana neutrinos
   Majorana – lepton violation, masses

2) What are the scale of neutrino masses and the hierarchy of the neutrino mass ordering?

3) Do neutrinos violate the CP symmetry and contribute to the matter-antimatter asymmetry?

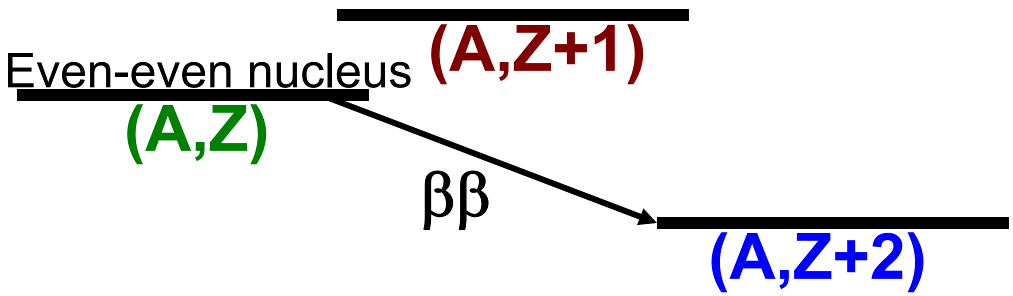
4) Are there sterile neutrinos?

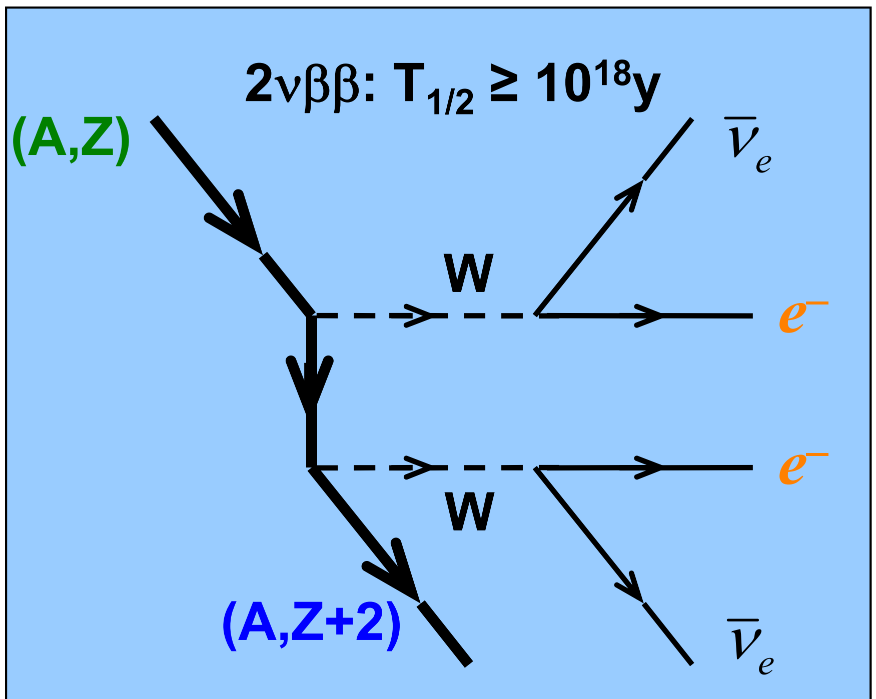
Double Beta Decay

2νββ

1935

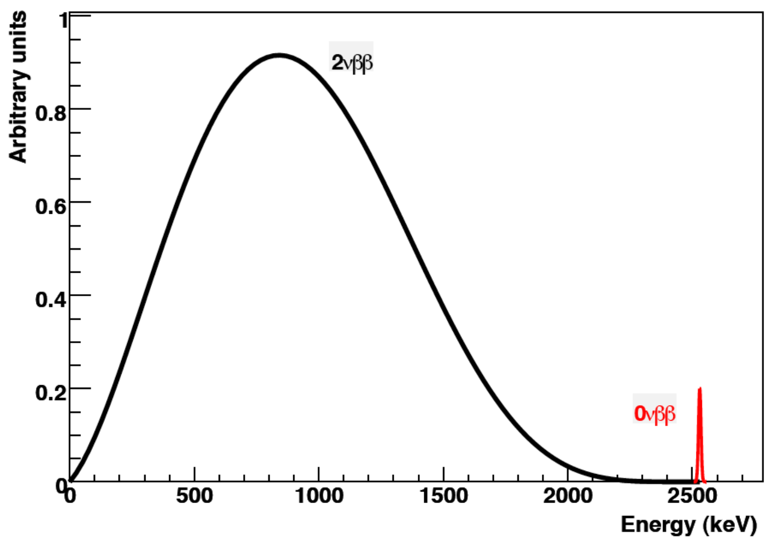
M. Goeppert-Mayer

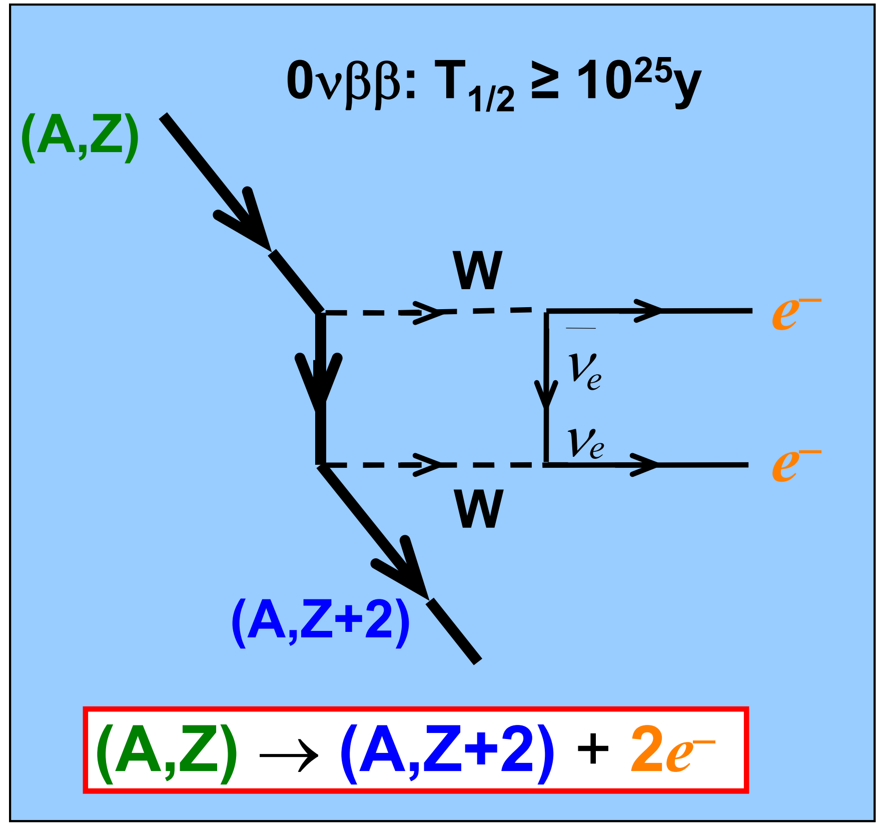




$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\,\bar{\nu}_e$$

Majorana Neutrinos?





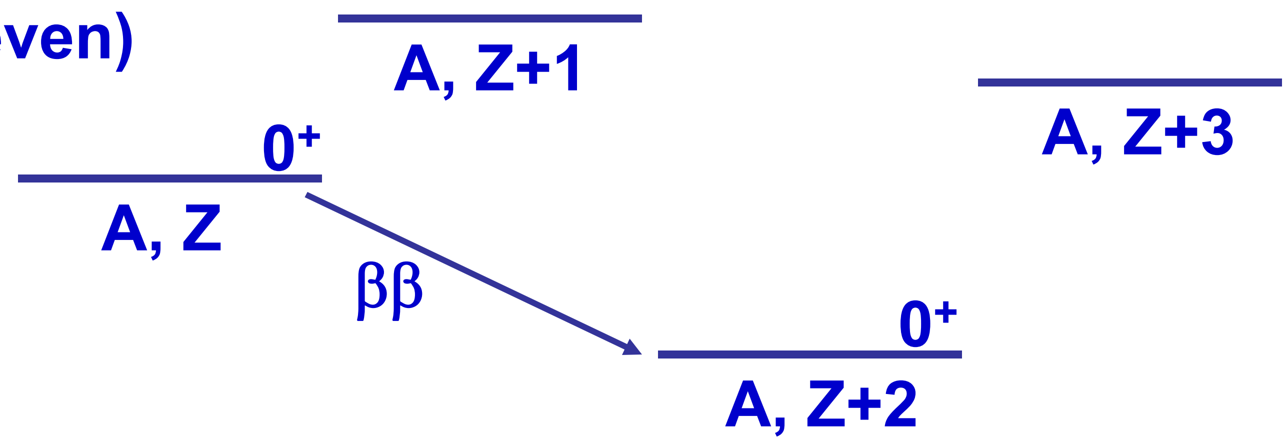
Majorana → neutrino = anti-neutrino

Lepton Number violation !

Double Beta Decay Candidates

Normal beta-decay is energetically forbidden, while double beta-decay from (A,Z) → (A, Z+2) is energetically allowed:

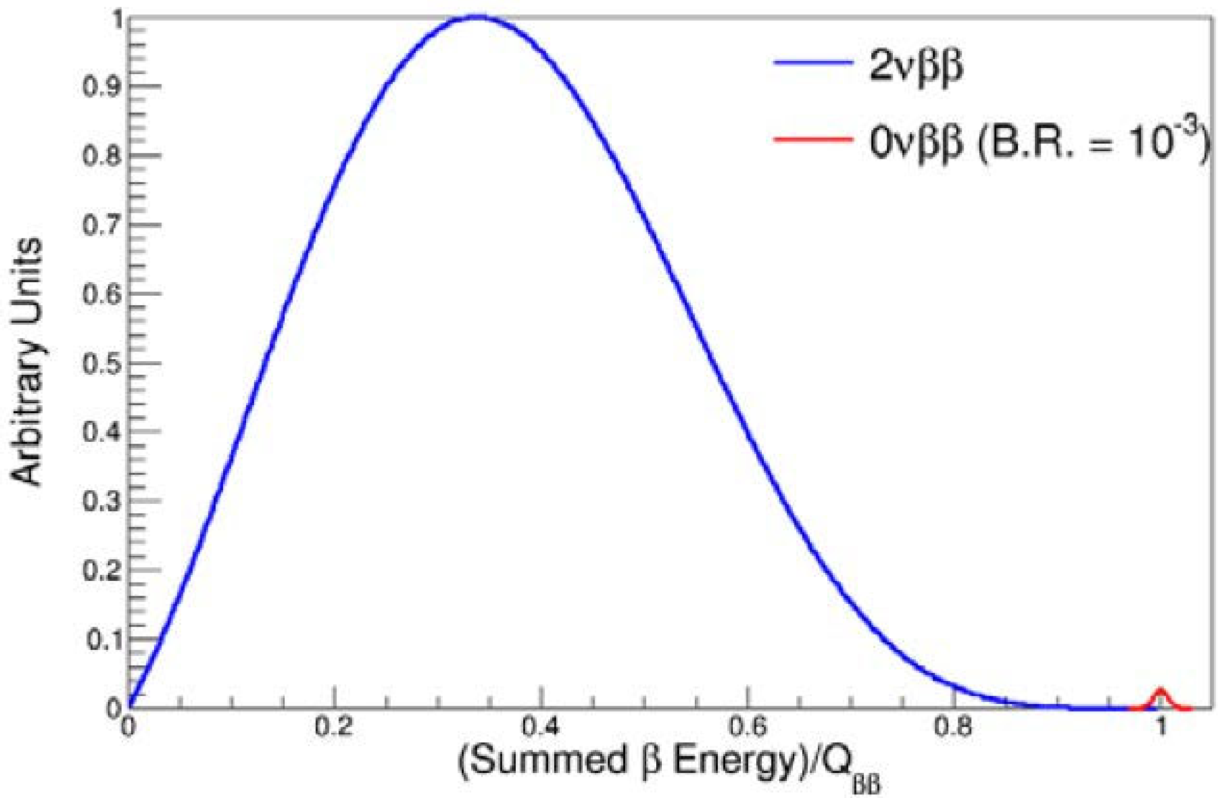
(A=even, Z=even)



Some candidates:

^{48}Ca, ^{70}Zn, ^{76}Ge, ^{80}Se, ^{86}Kr, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd

Experimental Search for 0νββ



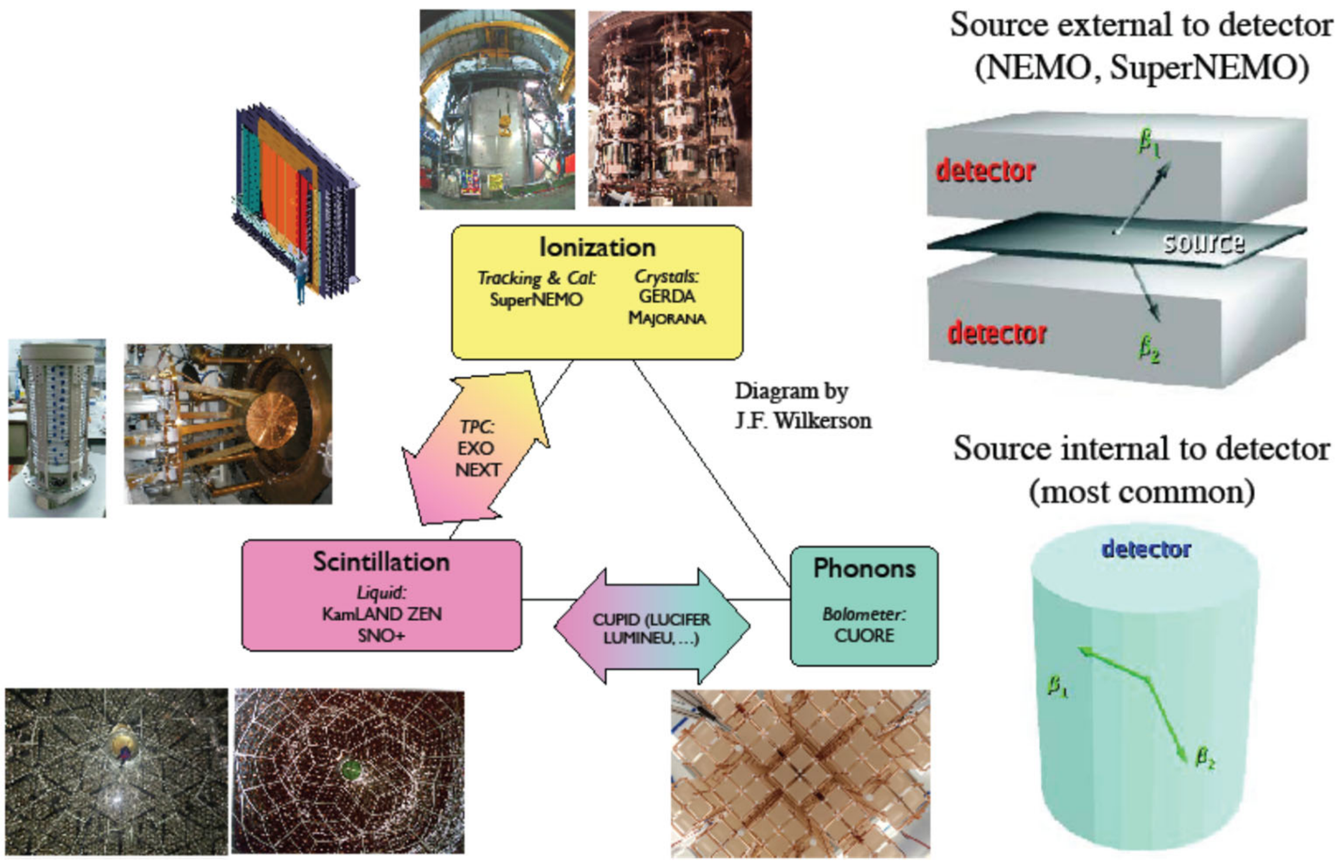
2νββ decays are irreducible background !

We do not know the relative rate!

0νββ/2νββ < 10^{-6}

Detector energy resolution very important !

Diverse Experimental Program



Most mature technologies are:

- **HPGe – LEGEND and CDEX**
- **LXe-TPC – nEXO, and DM Detectors**
- **Crystal Bolometer – CUORE/CUPID**
- **Liquid Scintillators – KamLAND-Zen, SNO+, JUNO**

Next Generation Experiment

Figure of Merit

$$\left[T^{0\nu}_{1/2}\right]^{-1} = \frac{\left|\langle m_\nu \rangle\right|^2}{m_e^2} F_N$$

Isotopic fraction

Detector Mass

Detector efficiency

$$F_N \propto \varepsilon \frac{a}{A}\left[\frac{MT}{B\Gamma}\right]^{1/2}$$

Running time

Atomic mass

Background

Detector resolution

1) Isotope enrichment
2) Mass
3) Resolution
4) Background

Isotope Choice

CUPID

^{100}Mo

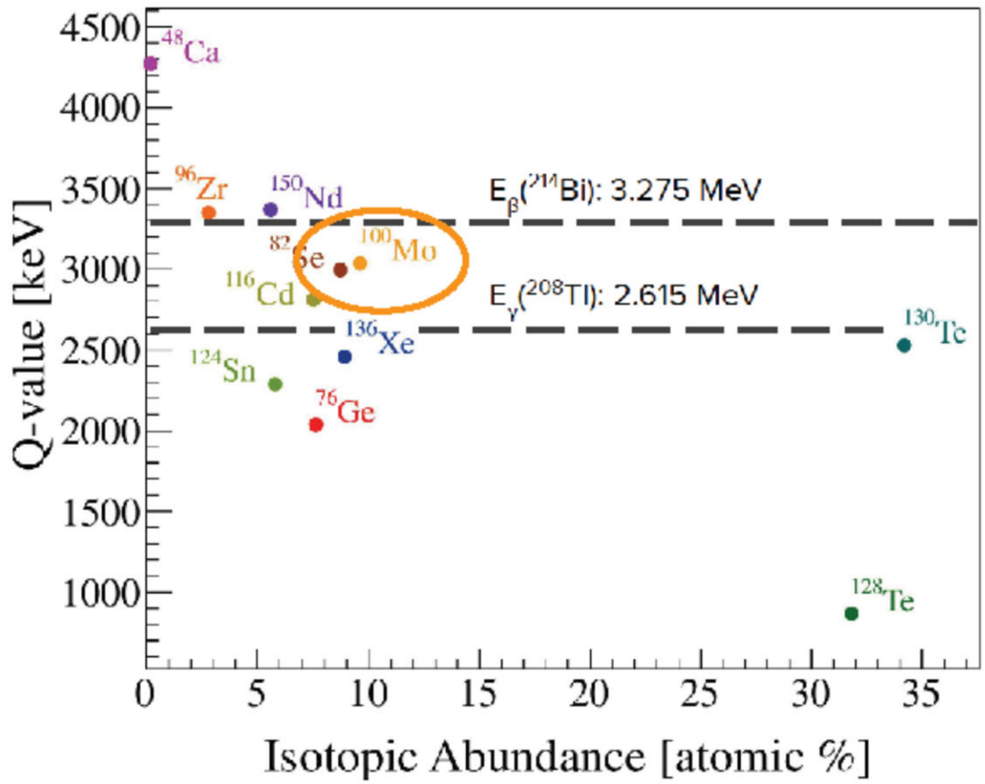
- High isotopic abundance
- Enrichment possible
- $Q_{\beta\beta}$ above end point of β or γ radiation
- Scintillating crystal available
- Large scale crystal production possible

Advantages of Bolometric Approach

Detectors and infrastructure are decoupled.

Same cryogenic infrastructure re-usable with different isotopes and/or crystals

Perfect for test of discovery or precision measurements



Selected Technology Choices for $0\nu\beta\beta$ –

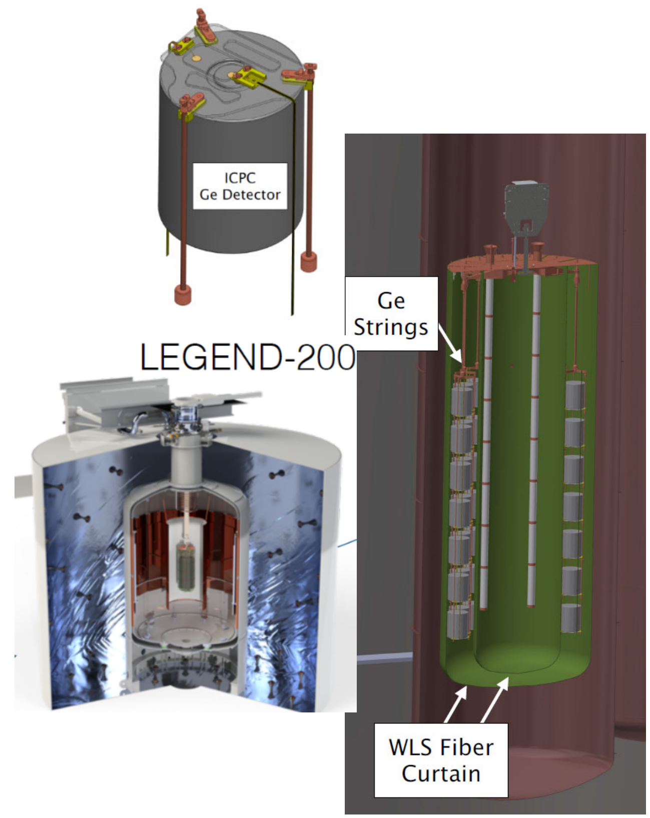
HPGe – LEGEND

LXe-TPC -- nEXO

Crystal Bolometer – CUORE/CUPID

Gerda and Majorana Demonstrators → LEGEND

- **GERDA** : BEGe, LAr instrumentation, cryostat in water shield, fast detector deployment, …
  - Achieved lowest background of any $0\nu\beta\beta$ detector
- **MJD**: PPC, EFCu, low-noise front-end electronics,…
  - Achieved best resolution of any $0\nu\beta\beta$ detector
- **LEGEND-200**; combined effort, with newer Inverted-Coaxial Point Contact (ICPC) detectors, LAr shielding, etc
- Merged Collaboration is roughly 60:40 US / Europe

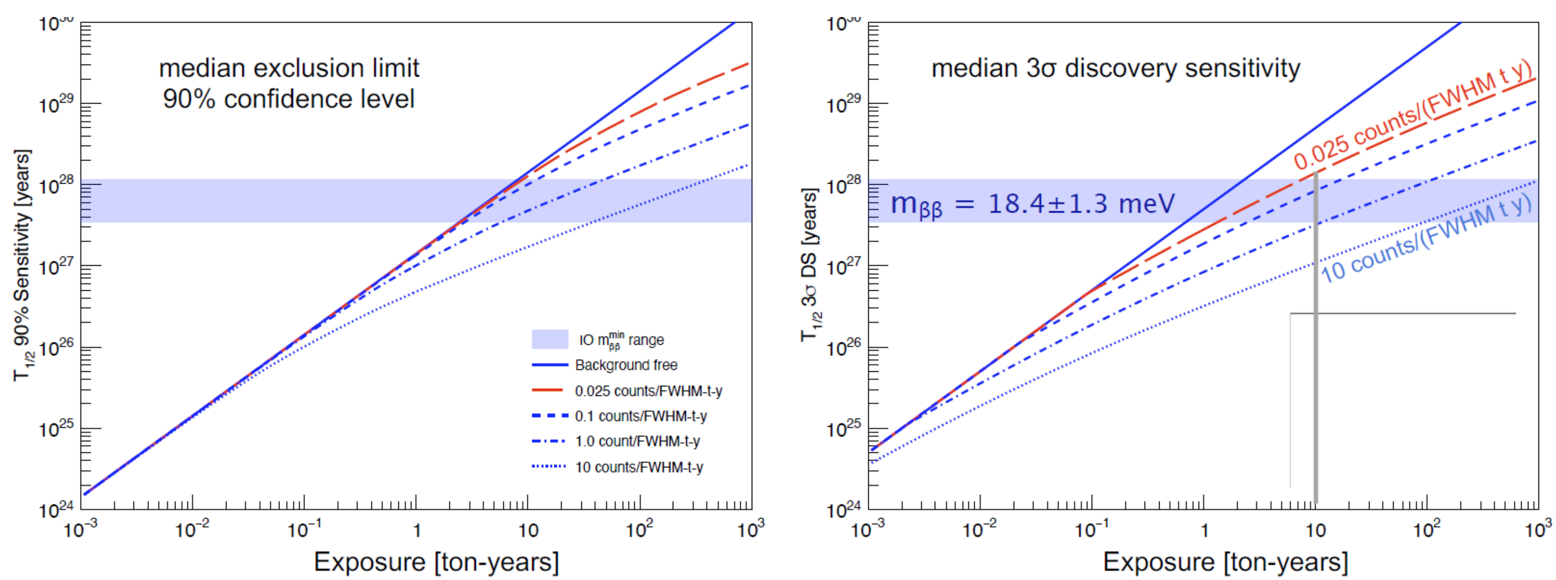


PPC: p-type Point Contact Ge detectors
BEGe: (modified) Broad Energy Ge detectors
EFCu: Electroformed copper

LEGEND advantages:
energy resolution and ultra-low background

- **Background-free implies Sensitivity is *linearly* proportional with exposure**
- **Background-limited implies Sensitivity proportional to square root of exposure**

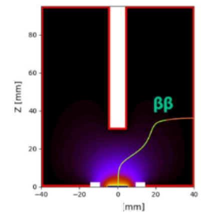
Goal: Red lines below at 0.025 cts/FWHM t y

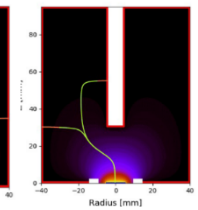


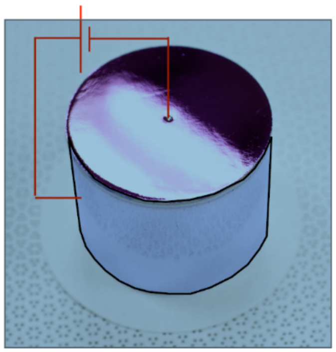
Requires a background level **50x lower** than GERDA

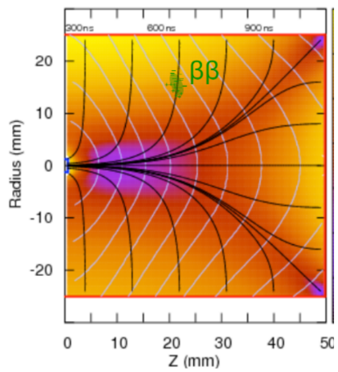
LEGEND → Important Innovations

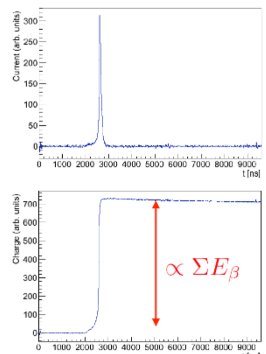
- **ICPC: Inverted-Coaxial Point Contact detectors**
  - **4 x lower backgrounds**
  - **Event topology discrimination**
  - **Excellent "single vs multi-site" determination**

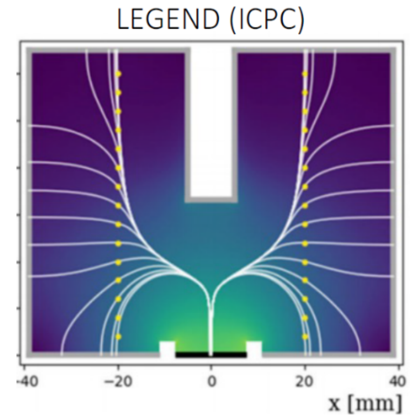




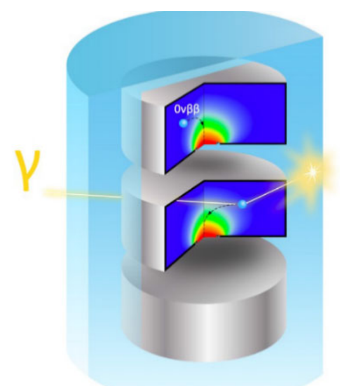


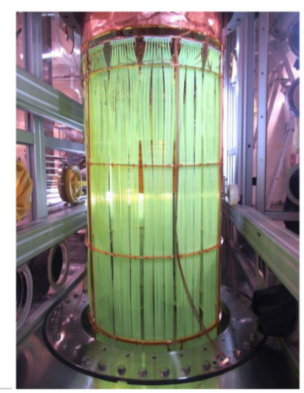






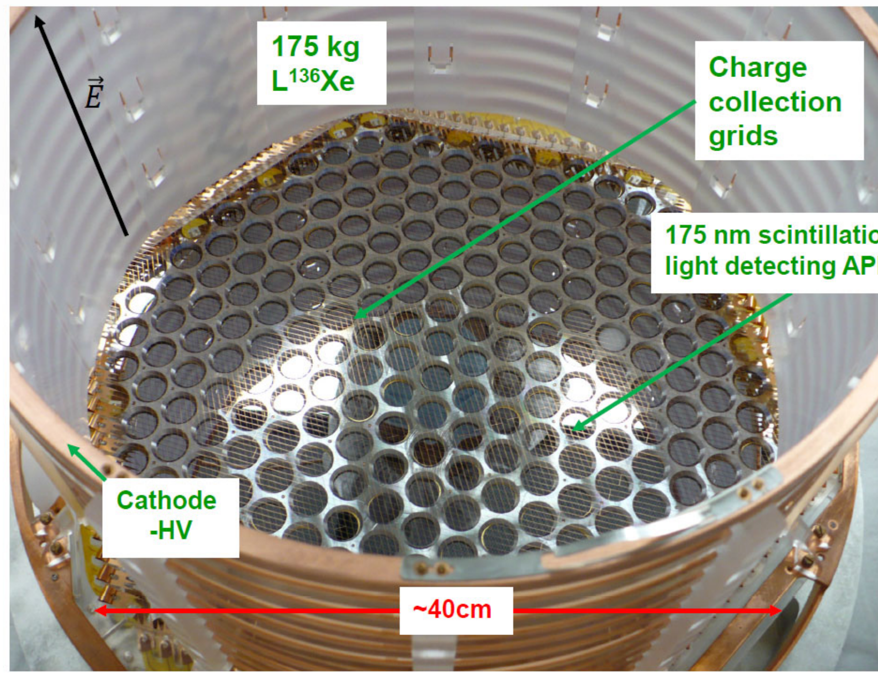
- **LAr active shield using underground liquid argon** (background reduction of ^{42}Ar by x1400 assumed from related DarkSide-50 measurement)





nEXO → Evolved from EXO-200 Demonstrator

- An event, interior to the volume produces both scintillation light and ionization
- This provides 3D location of event
- Together resolution is optimized
- Backgrounds from nearer to surfaces will be different in rate vs. the central region. This concept is critical to the idea of a much larger geometry … nEXO



Final result

Phase I+II: 234.1 kg yr of ^{136}Xe exposure

Limit: $T_{1/2}^{0\nu\beta\beta} > 3.5\text{x}10^{25}$ yr (90% CL)

$\langle m_{\beta\beta} \rangle$ < (93 -286) meV

Sensitivity: $5.0\text{x}10^{25}$ yr

nEXO: Monolithic / Homogeneous Detector

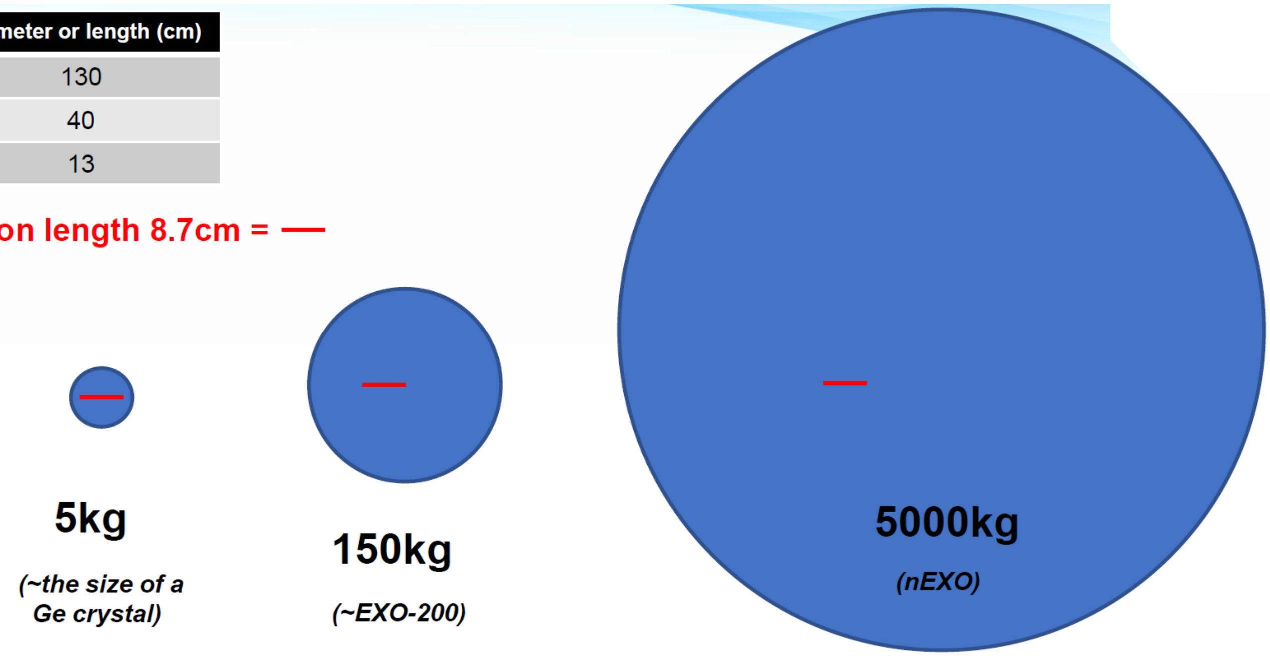
STRATEGY: Exploit both **Position and Energy** to in a multi-parameter analysis to understand **S/B** in a predictable manner, and thus **extrapolate the background rate in the ROI for the inner ~1 Ton fiducial volume**

→**signal is uniform in any volume element**

→**background depends on distance to surfaces**

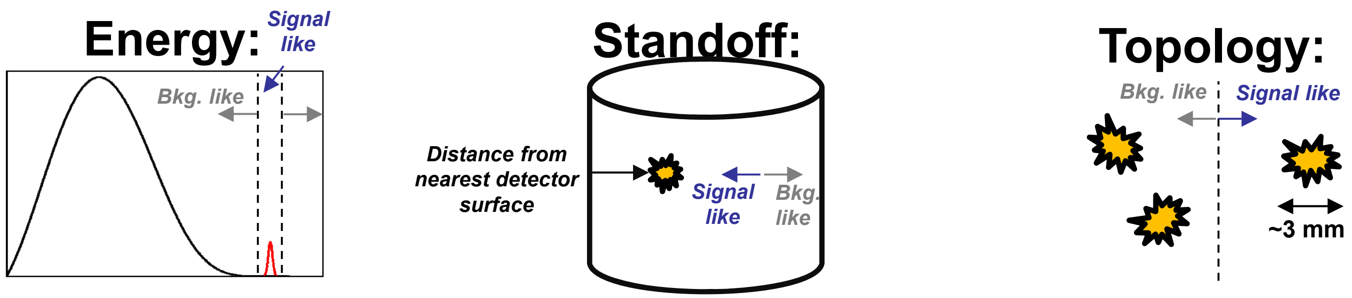
LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

2.5 MeV γ attenuation length 8.7cm = —

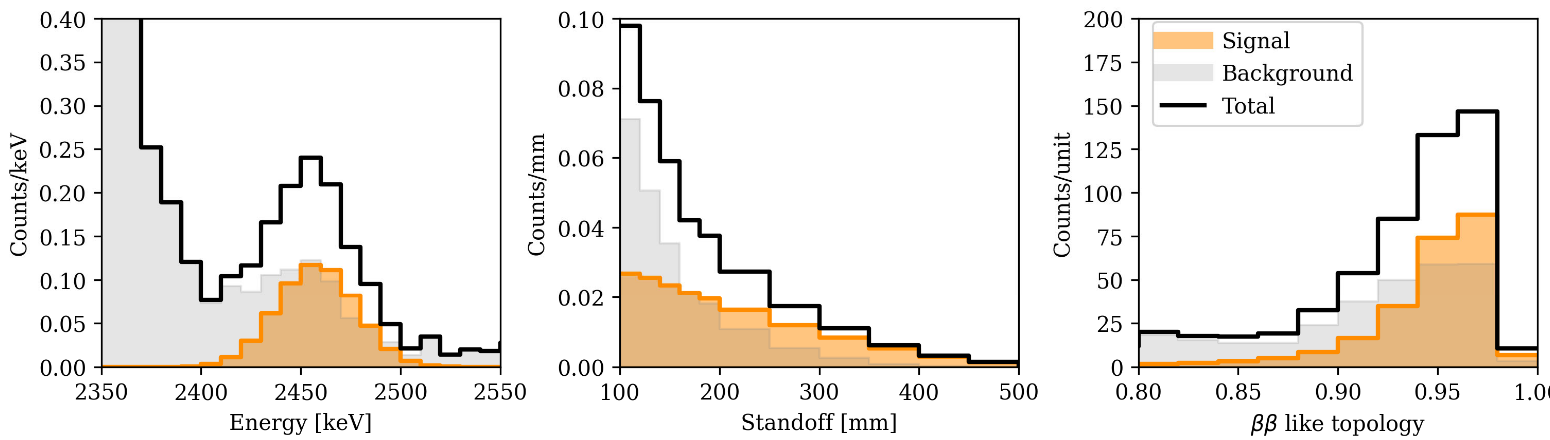


nEXO: Efficient rejection of backgrounds from multi-site events

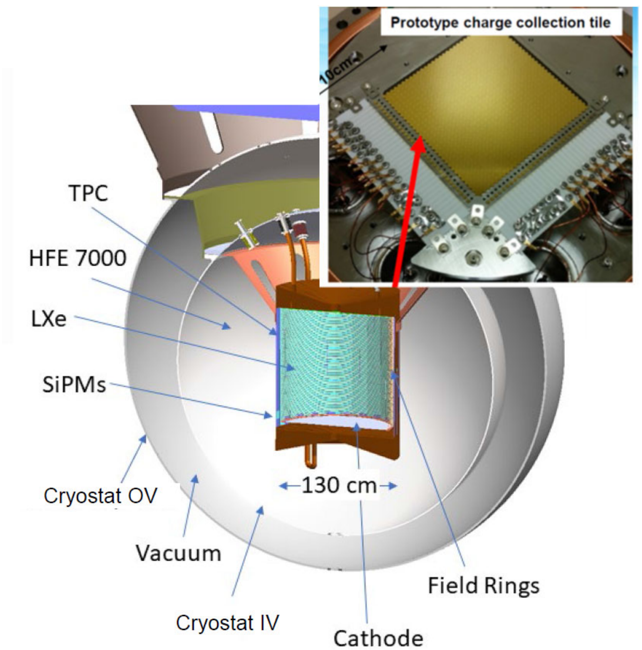
(based on EXO-200 experience)

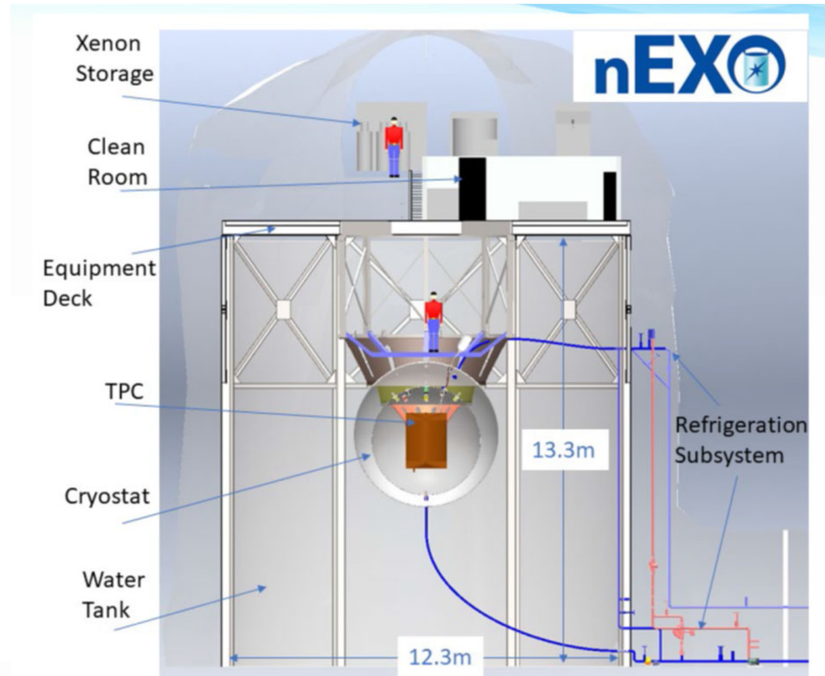


1D projections of simulated nEXO signal and backgrounds:

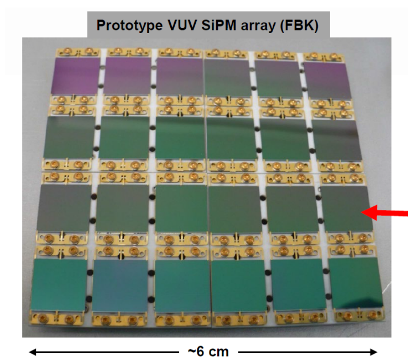


nEXO: Design Concept





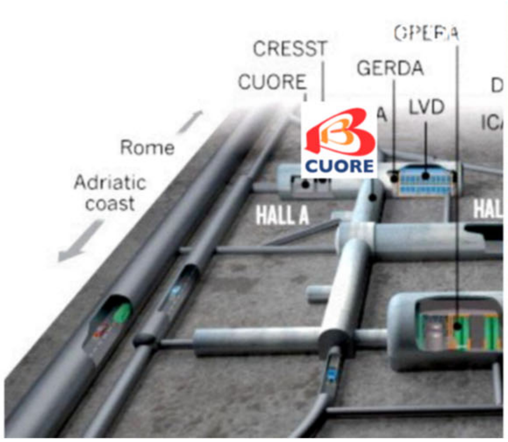
Would like to use the SNOLAB Cryopit

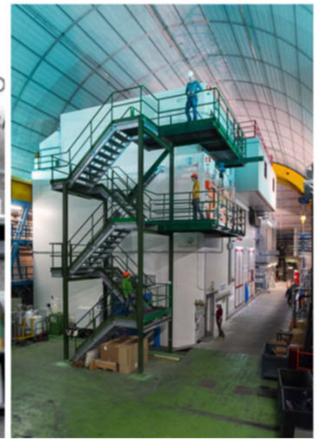


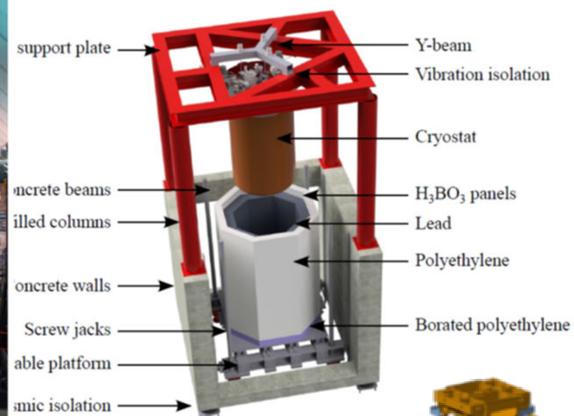
Recall: 175 nm VUV scintillation light .. Non trivial for SiPMs

Collaboration: 185 members from 32 institutions and 9 countries

CUPID – CUORE Upgrade with Particle IDentification

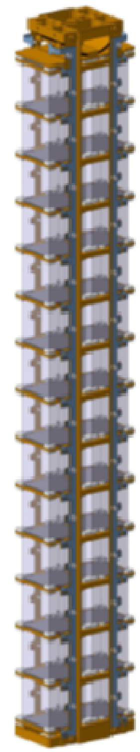


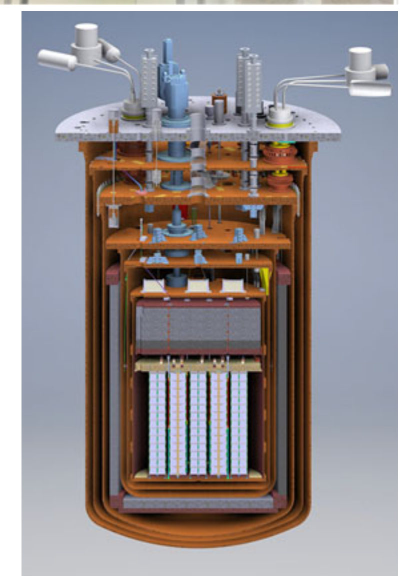




International Collaboration:
CUPID – Italy
CUPID – US
CUPID – France
CUPID – China

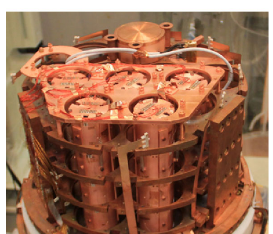
Collaboration: 150 members from 30 institutions and 7 countries


Tower



CUPID Demonstrator

- 20 enriched $Li_2{}^{100}MoO_4$ (97% enrichment) crystals, 2.26 kg of ^{100}Mo
- Ge light detectors and NTD thermistors


EPJ C 80, 44 (2020)

INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

The CUORE collaboration

CUORE

CSNSM

Universitas Studii Paduani

Yale

INFN LNGS

Berkeley Lab

Cal Poly
San Luis Obispo

Alma Mater Studiorum A.D. 1088

Università degli Studi di Cassino e del Lazio Meridionale
Sol per noctem

UCLA

SINAP

University of South Carolina

Massachusetts Institute of Technology

VirginiaTech
Invent the Future®

Lawrence Livermore National Laboratory

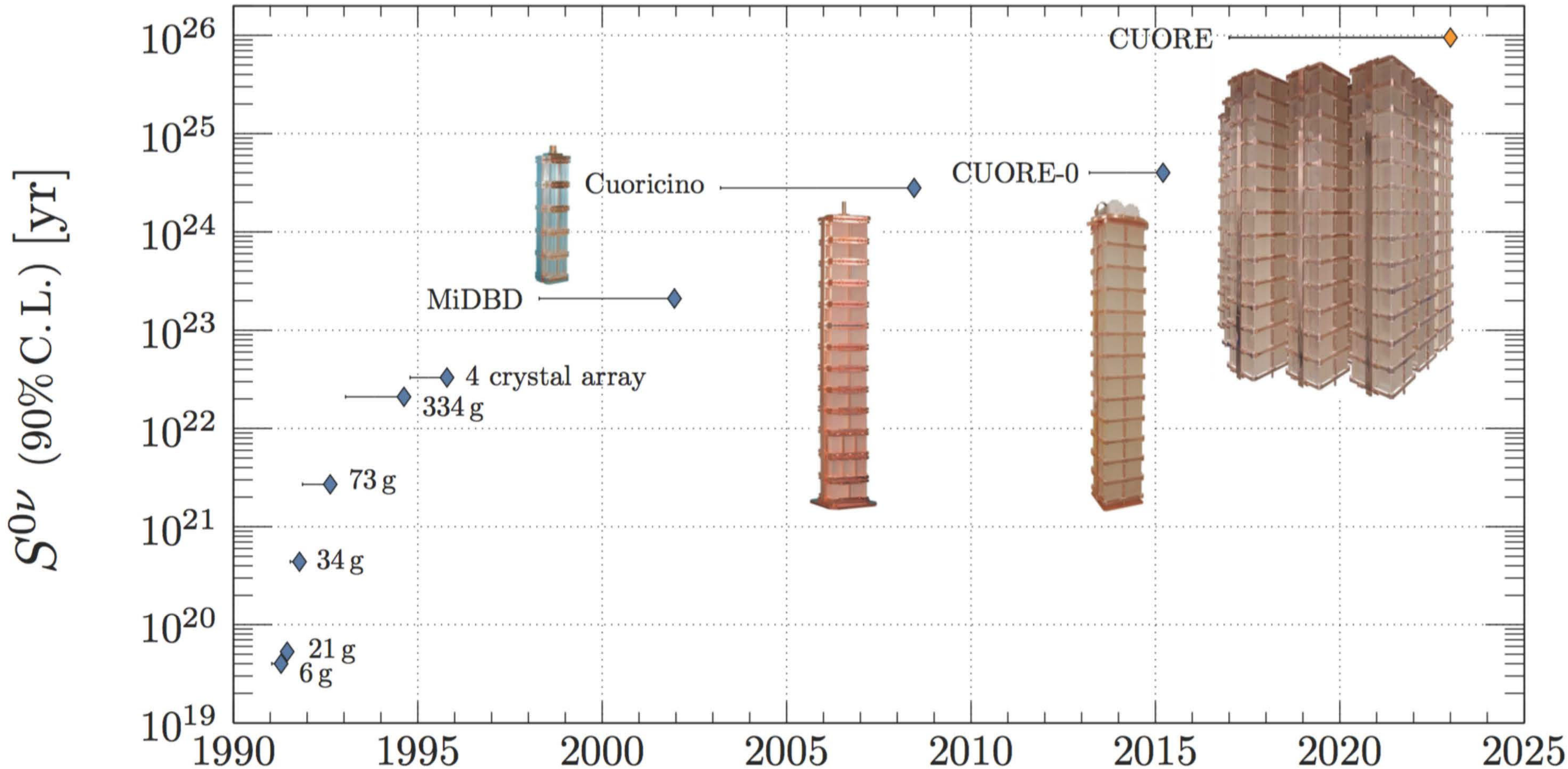
Sapienza Università di Roma

Università degli Studi di Milano Bicocca

Shanghai Jiao Tong University

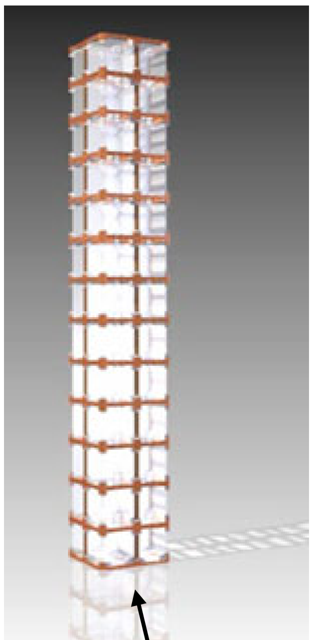
CUORE

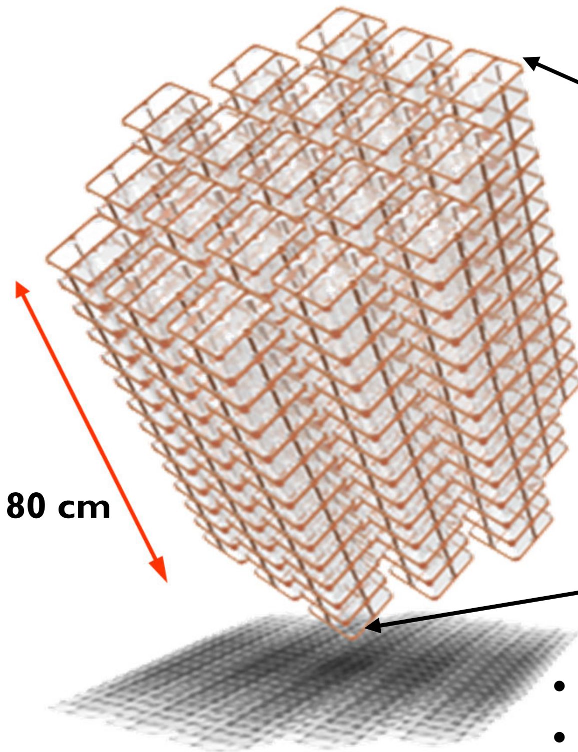
> 20 years of Detector Development

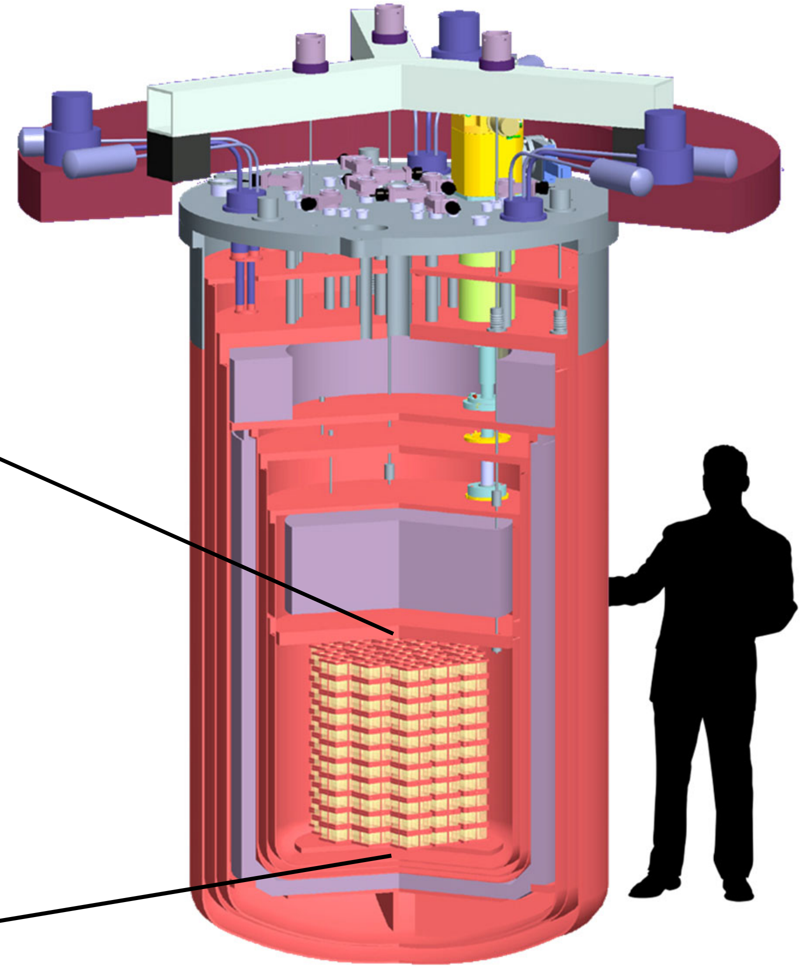


CUORE

CUORE: Cryogenic Underground Observatory for Rare Events will be a tightly packed array of **988 Bolometers** - M ~ 200 kg of ^{130}Te



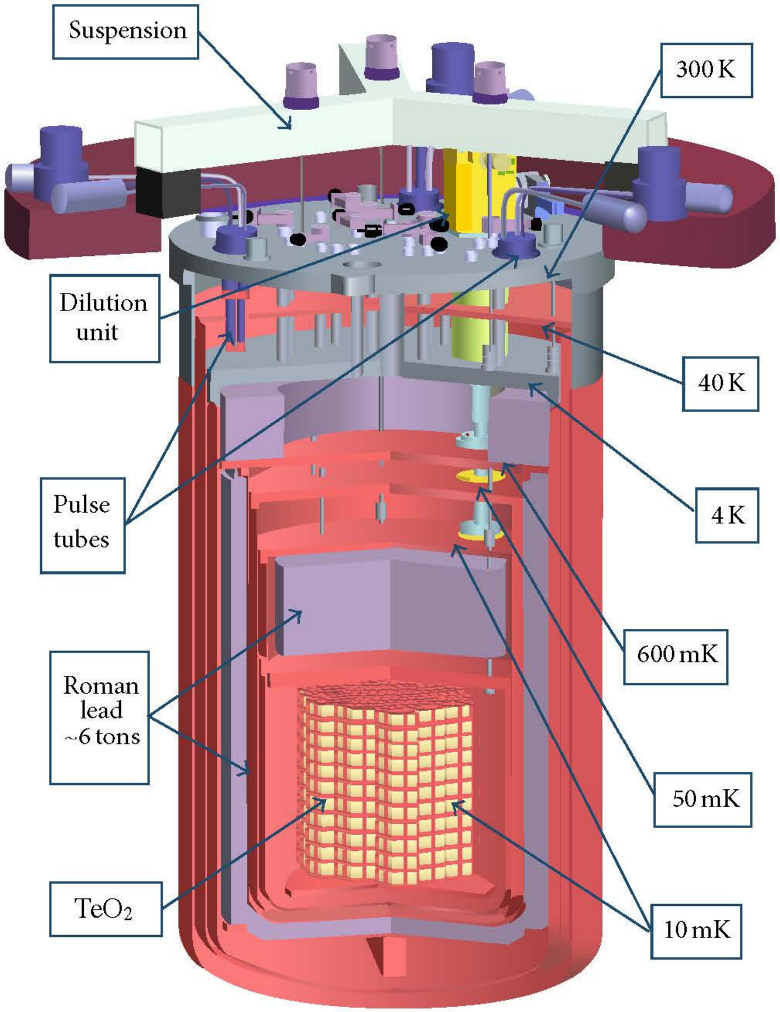


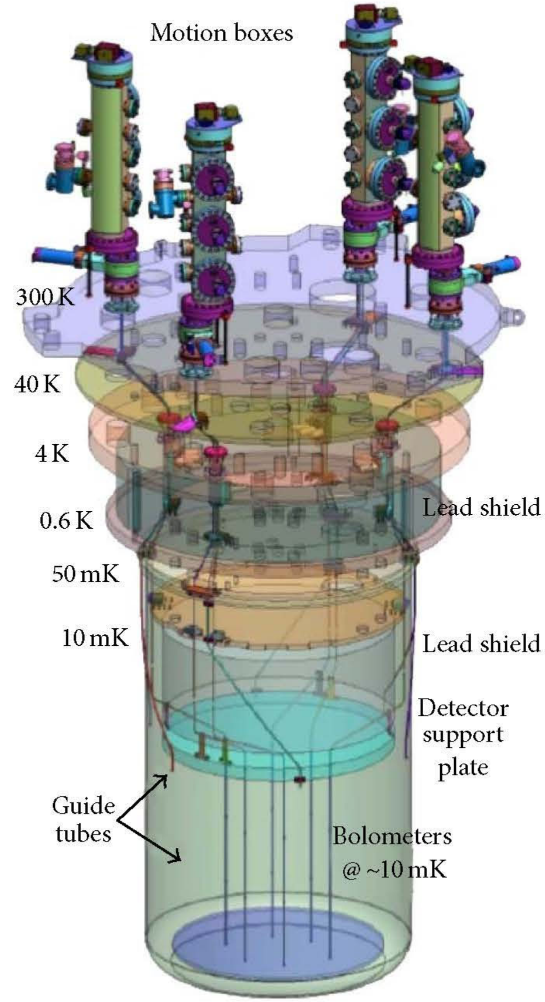


19 CUORICINO-like towers with 13 planes of 4 crystals each

- **Operated at Gran Sasso laboratory**
- **Special cryostat built w/ selected materials**
- **Cryogen-free dilution refrigerator**
- **Shielded by several lead shields**

CUORE Cryostat





CUORE 1 ton*year Data

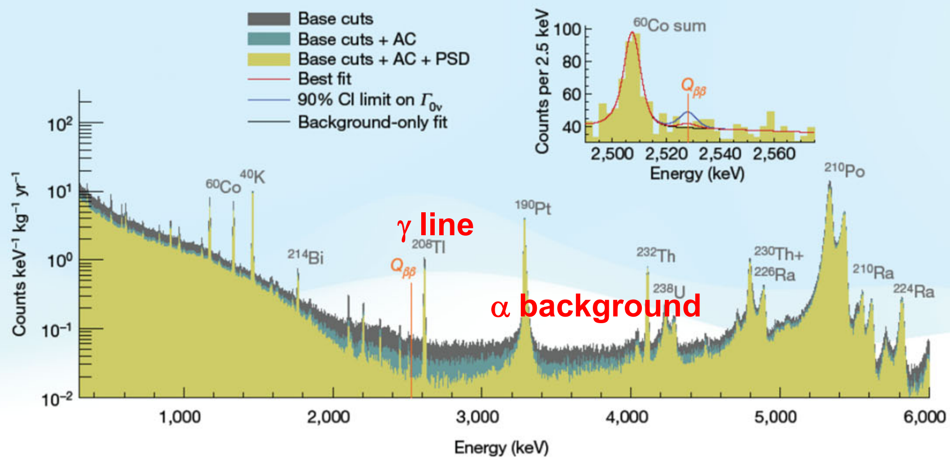
Nature, 604, 53-58 (2022)

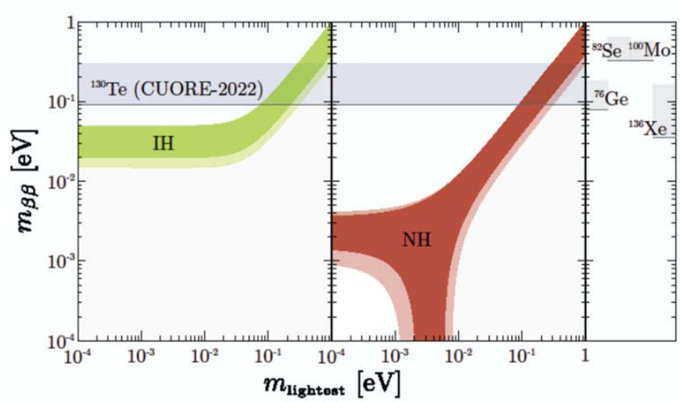
Search for 0νββ

Current Status

- No peak found in an exposure of 1038.4 kg x yr (288 in ^{130}Te) at $Q_{\beta\beta}$
- At $Q_{\beta\beta}$: (7.8 ± 0.5) keV FWHM
- BKG: (1.49 ± 0.04) x10^{-2} c/keV/kg/yr
- **$T_{1/2}(0\nu) > 2.2\times10^{25}$ yr** @ 90% C.I.
- $m_{\beta\beta} >$ (90 - 305) meV

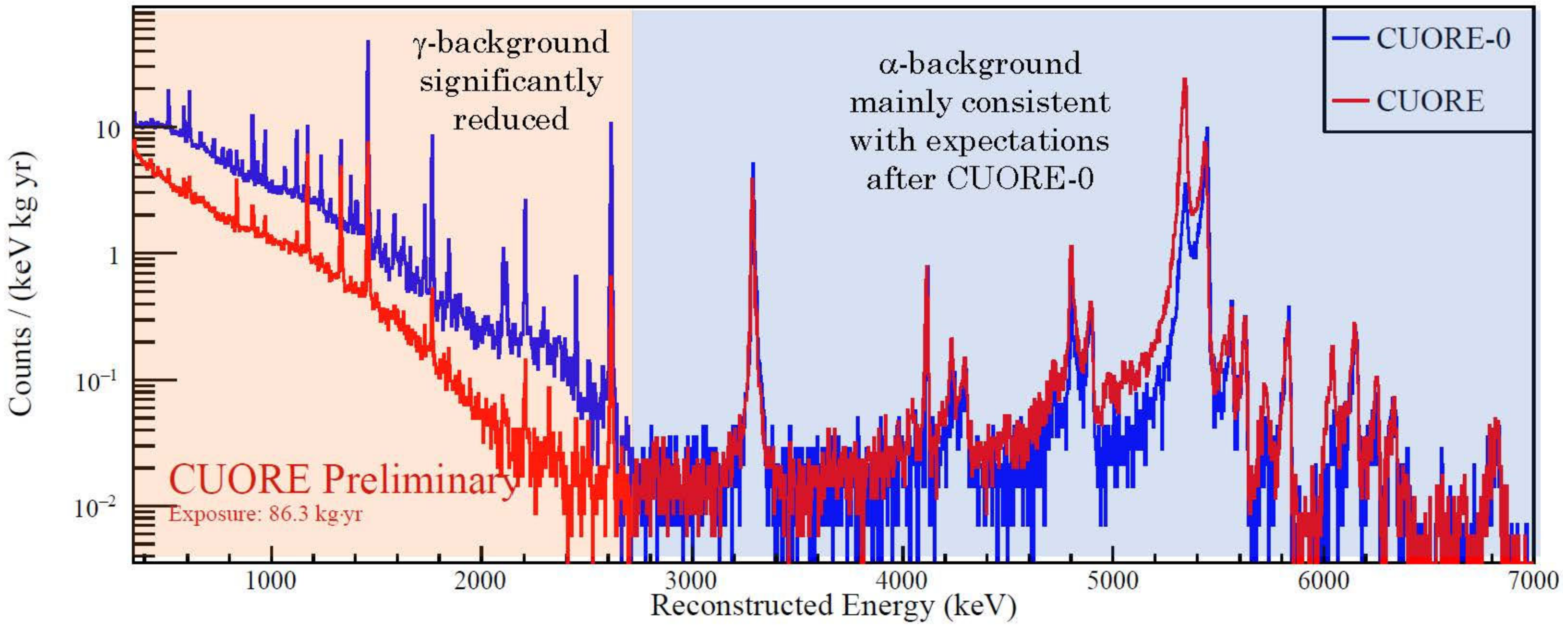
``Search for Majorana neutrinos exploiting millikelvin cryogenic with CUORE"
Nature, 604, 53-58 (2022)





Over 2 Ton*Year now, will reach 3 Ton*Year in 2024

CUORE Background Level
TeO_2 not low enough; alpha background



Background Level: design goal 1.0×10^{-2} cts/keV/kg/year
$(1.4 \pm 0.1)\times10^{-2}$ cts/keV/kg/year

Reduce background by 100 → PID remove alpha
→ $Q_{\beta\beta}$ > 2615 keV gamma

From CUORE to CUPID

Key Technologies for the advancement:

1) **Heat-light dual readout**

   Particle Identification of a and g background

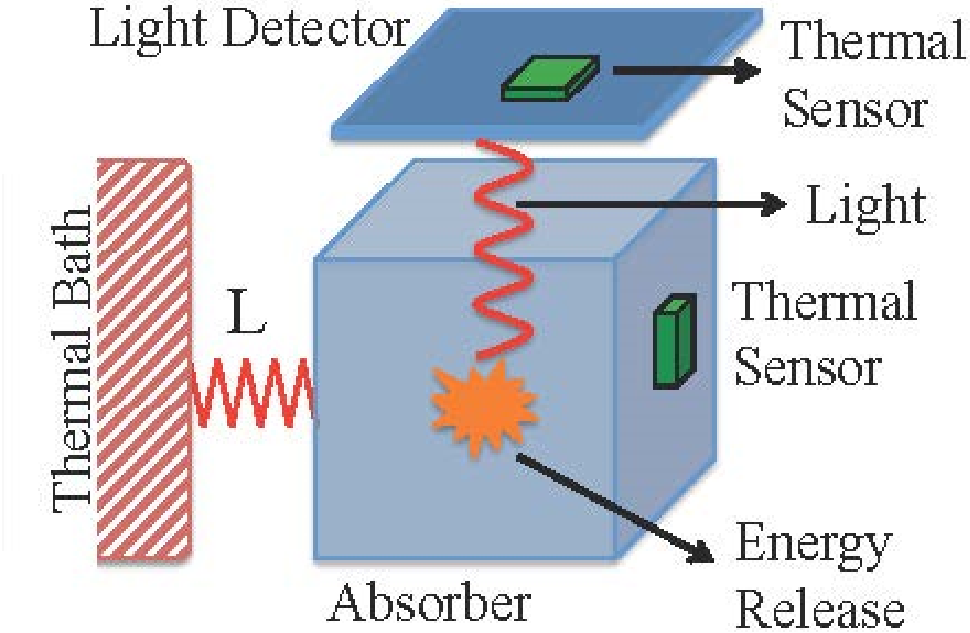
   -- remove background in the a region

2) **Scintillating LMO Crystals**

   Mo-100 0nbb Q_{bb} 3034 keV > 2615 keV ^{208}Tl

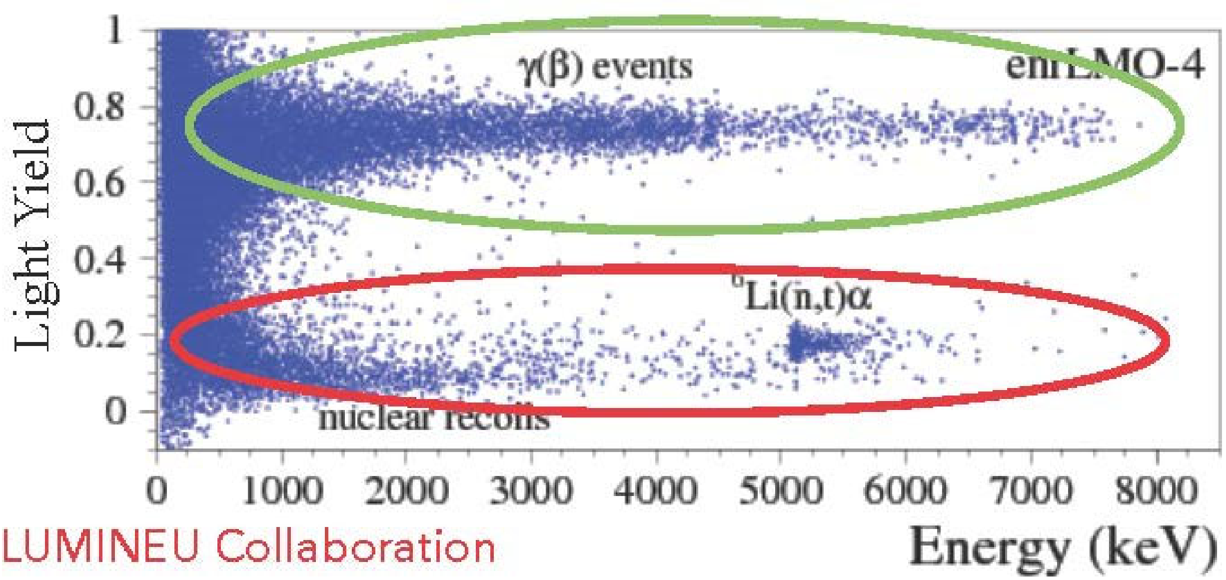
Suppress background by more than two orders of magnitude

Dual Readout Scheme



CUPID-France
Andrea Giuliani
@CSNSM Orsay

Most Promising Choice !



LUMINEU Collaboration

Candidate for Double beta Decays

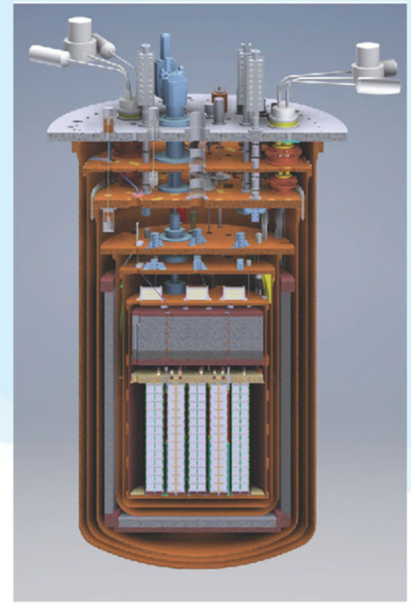
γ 2615 **keV from ^{208}Tl – major bkgd**

	Q (MeV)	Abund.(%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.528	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

Very Competitive Detector Technology

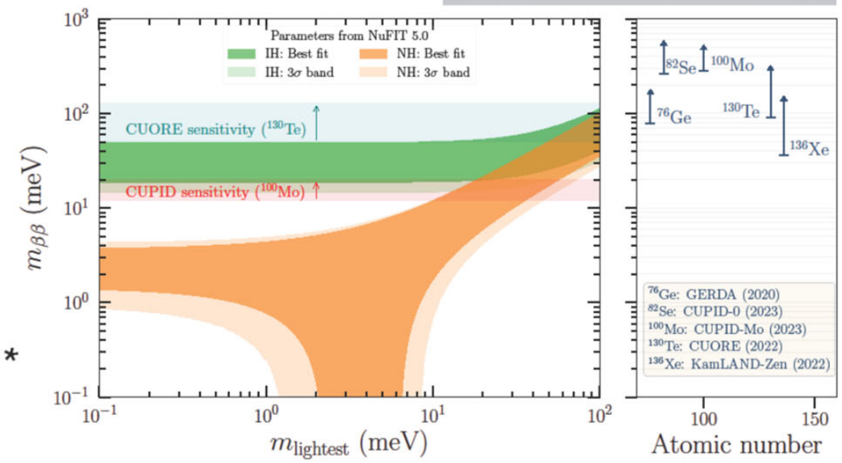
CUPID

- Since 2021 a collaboration: about 60 IT, 40 US, 25 FR, China, Russia, Ukraine, Spain, for a total of >70 FTE.
- Deploy 472 kg $Li_2{}^{100}MoO_4$ crystals (240 kg of ^{100}Mo)
- Exploit CUORE cryogenic facility (+ its upgrade)
- 5 keV FWHM at $Q_{\beta\beta}$
- Background goal: 10^{-4} c/keV/kg/yr



Discovery Sensitivity @ 3 σ

- $T_{1/2} > 1.1\mathrm{x}10^{27}$ yr ($m_{\beta\beta}$: 12-20 meV)
- $T_{1/2} > 2.2\mathrm{x}10^{27}$ yr ($m_{\beta\beta}$: 8.4-14 meV) - *reach**



(*) *reach*: same parameters but factor 5 improvement on background

CUPID Long Term Roadmap

CUPID Sensitivity

Baseline

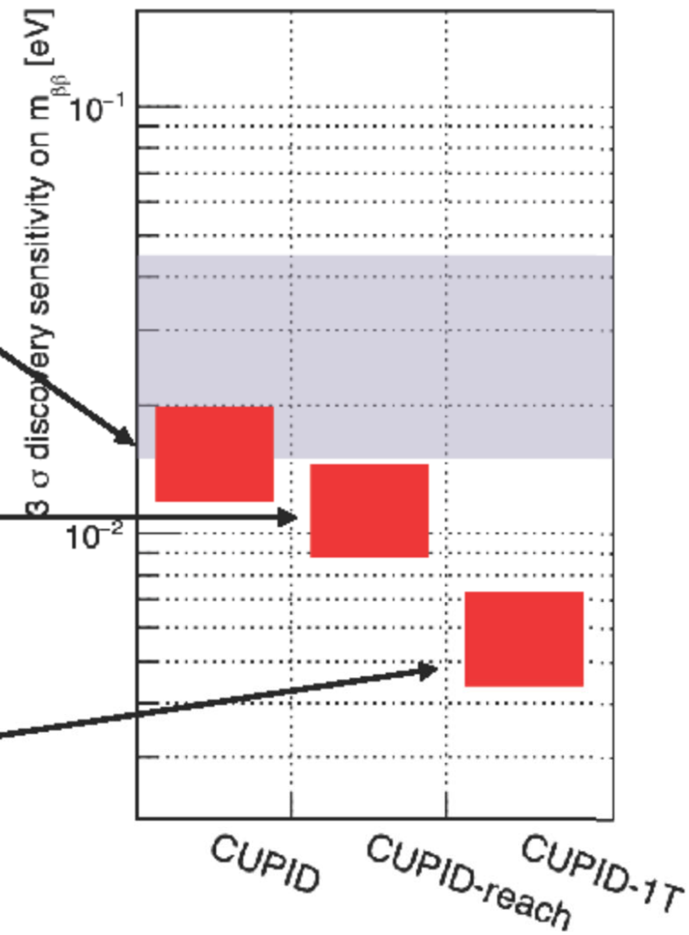
- Mass: 472 kg (**240 kg**) of $Li_2{}^{100}MoO_4$ (^{100}Mo) for **10** yrs
- Energy resolution: **5 keV** FWHM
- Background: **10^{-4}** cts/keV.kg.yr
- Discovery sensitivity **$T_{1/2} > 1\times10^{27}$ yr (3σ)**
- Conservative, limited R&D. Ready to build now

Reach

- R&D for further background reduction
- Discovery sensitivity **$T_{1/2} > 2\times10^{27}$ yr (3σ)**

1-Ton

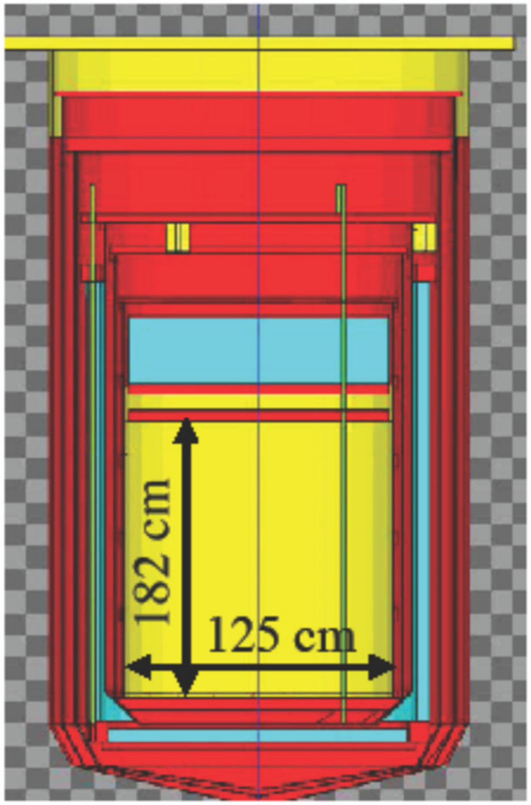
- 1000 kg of ^{100}Mo
- Discovery sensitivity **$T_{1/2} > 8\times10^{27}$ yr (3σ)**



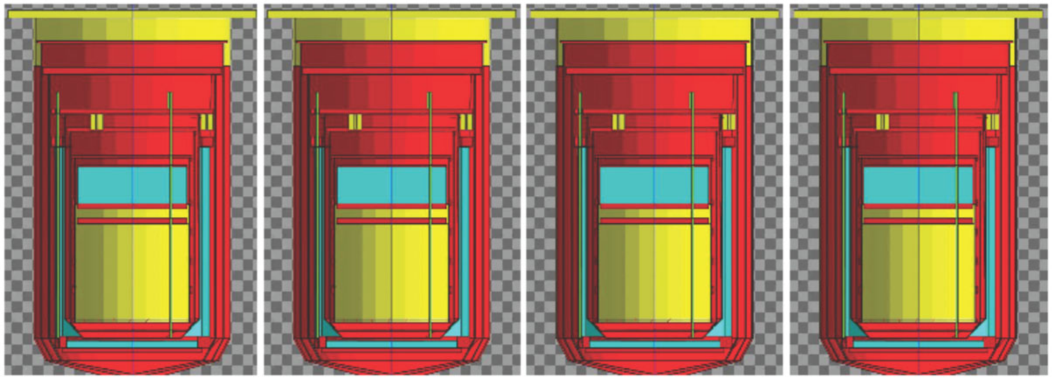
CUPID-1T is within technical reach, limited by timeline and cost
CUPID sensitivity meets goals of 2015 LRP

CUPID-CJPL plans for CUPID-Reach-like Detector

CUPID-1T Detector Options



1000 kg of ^{100}Mo
Single large cryostat



4x250 kg of ^{100}Mo
A "flock" of CUPIDs around the world

CJPL – Ideal Laboratory for CUPID-1T

CUPID-China Collaboration

~ 9 institutes
> 40 collaborators

CUPID-China is actively collaborating with CUPID- France, Italy and US

Advantages for $0\nu\beta\beta$ Crystal Detector at CJPL

Key technologies for $0\nu\beta\beta$ crystal bolometer detector

1) **Radio-pure crystals with low radioactive background**

2) **Enriched $0\nu\beta\beta$ elements suitable for crystals**

3) **Temperature sensors and readout electronics**
   Neutron-Transmutation Doped (NTD) sensor
   Transition Edge Sensor (TES)

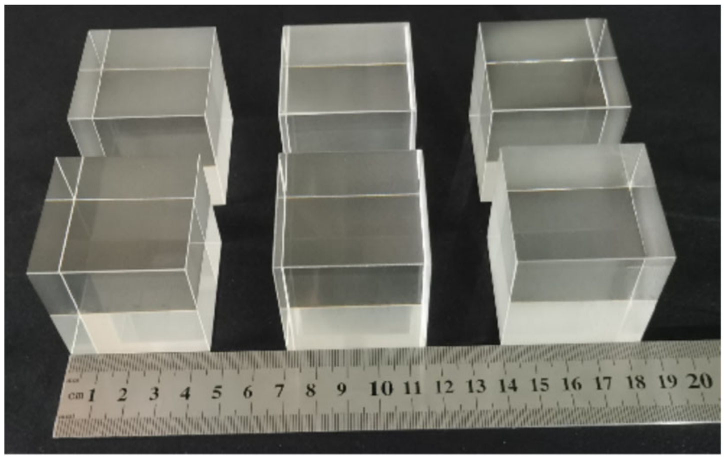
Other advantages:
Cost effective technology

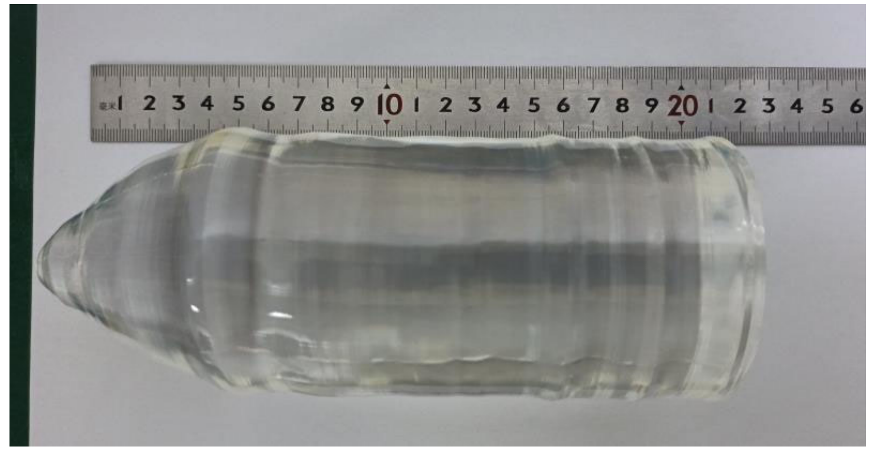
CJPL: best underground lab in the world
low cosmic background
low environmental background

CUPID-CJPL is suitable for CJPL $0\nu\beta\beta$ scientific program

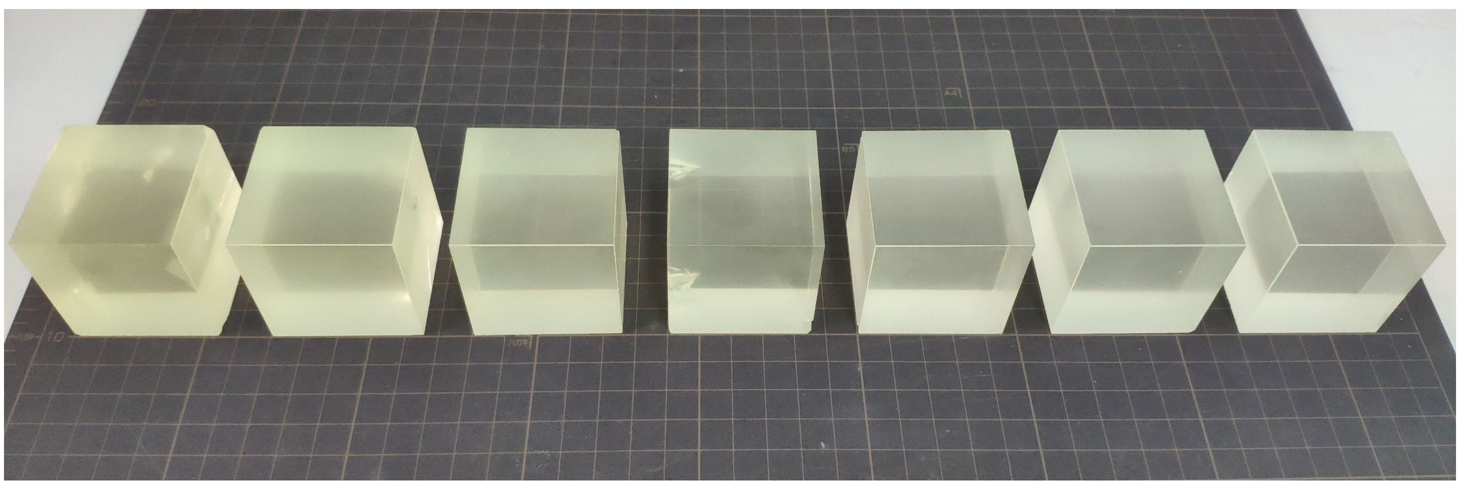
晶体生长的提拉法和下降法技术日益完善

提拉法生长的LMO

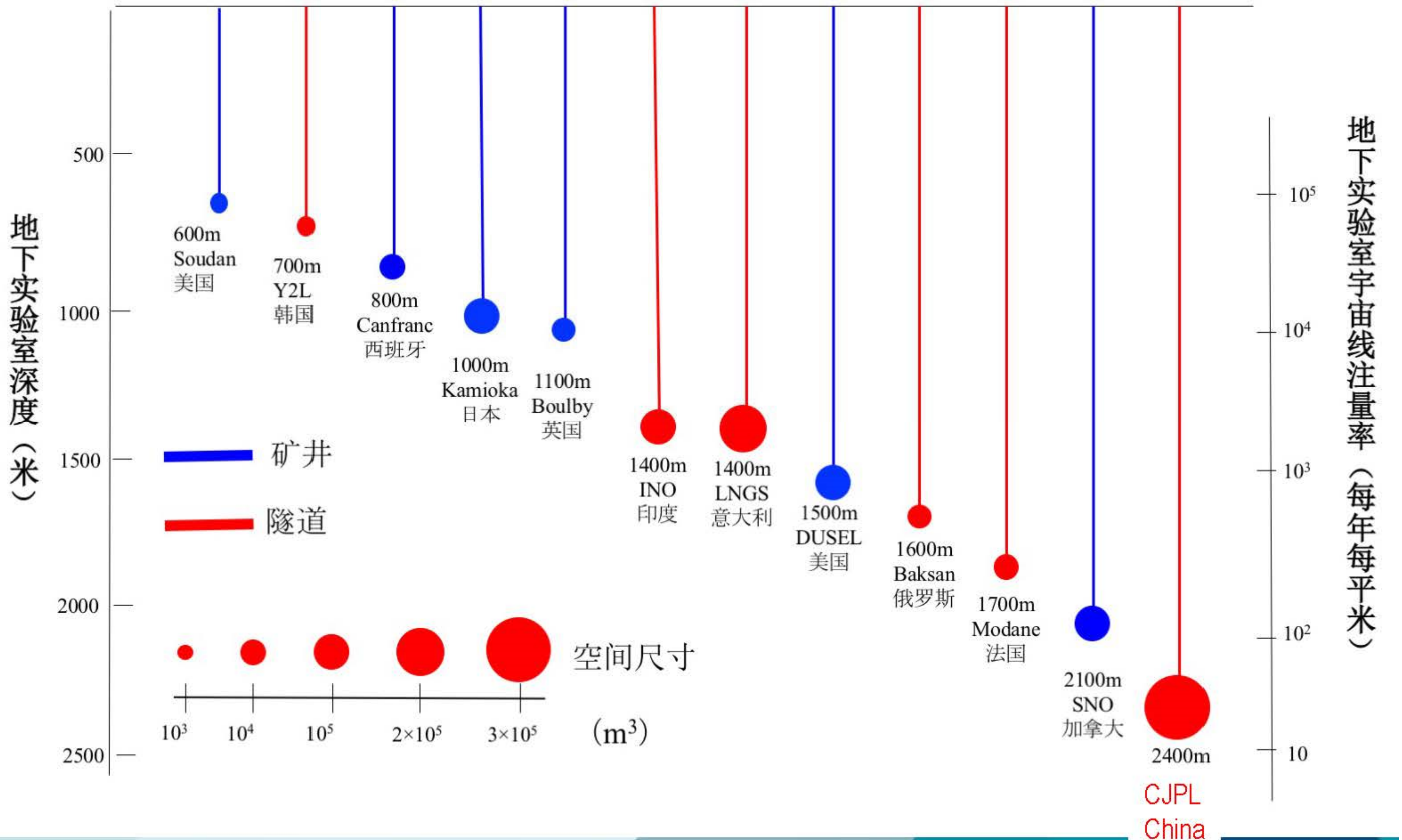




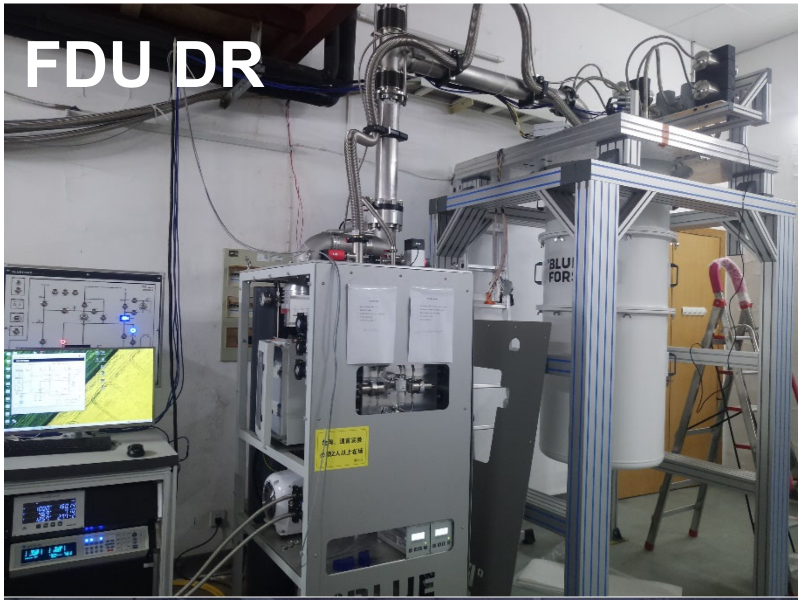
下降法生长的晶体质量显著提高

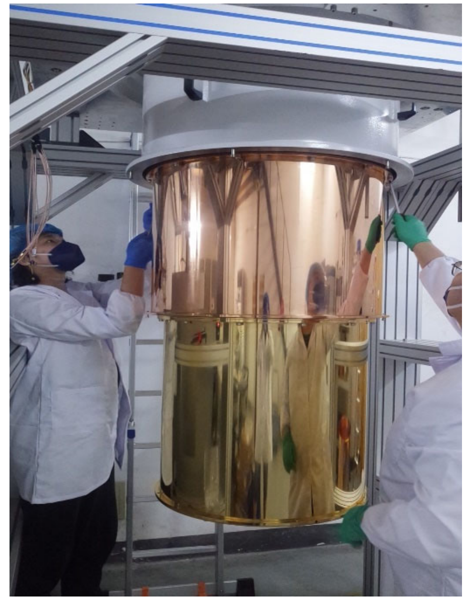


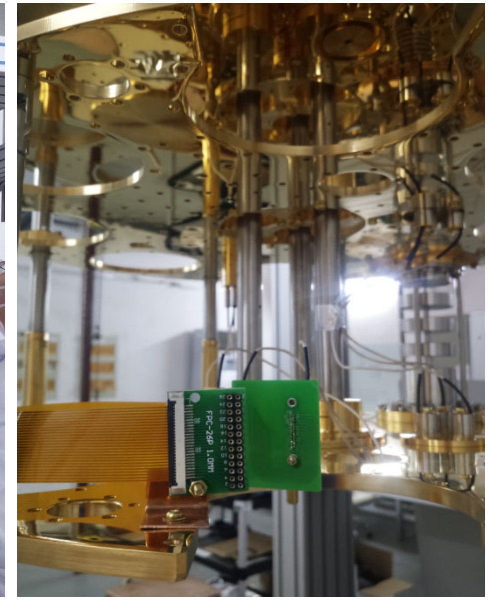
Best Underground Laboratory in the World !

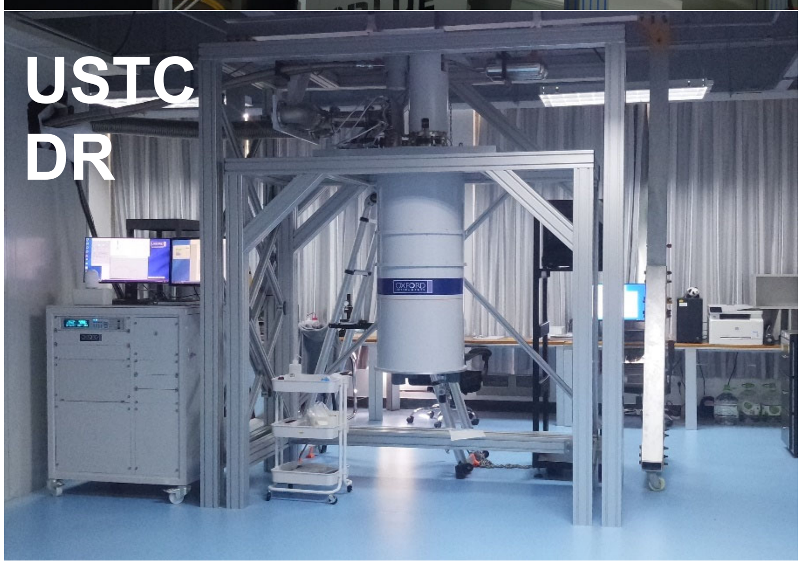


Cryogenic System at Fudan and USTC





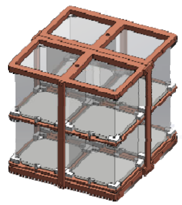




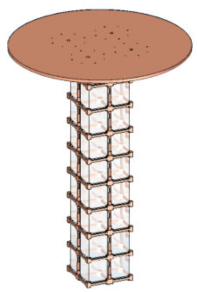
- ➢ **Fudan-IMP cryogenic system**
- **Customized cryostat system**
- **Large sample space: Φ500x600 mm**
- **2 PT (cooling power ≥1.8W@4.2K)**
- **Radiopure vessel (CuOFE-C10100)**
- **Inner shielding support (~300 kg)**

CUPID-CJPL Roadmap

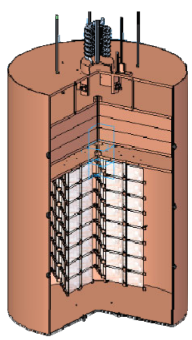
Crystal testing
(2022-2025)
6-12 natural crystals

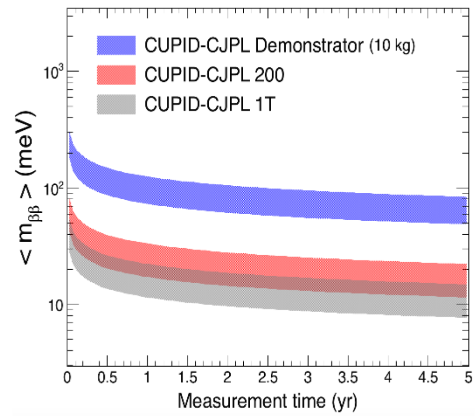


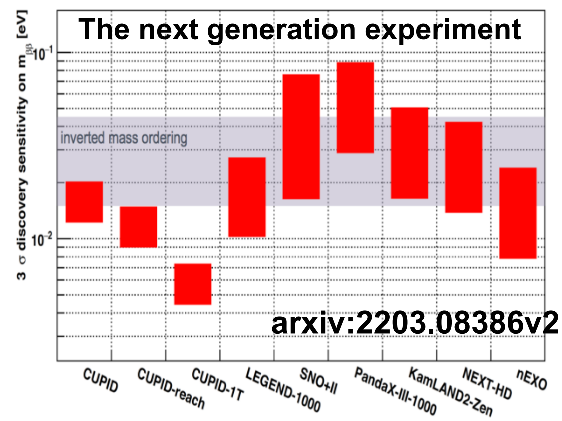
CUPID-CJPL Demo
(2026-2028)
10 kg enriched crystals



CUPID-CJPL-200/1T
(2028+)
> 250 kg enriched crystals







- **10 kg experiment**
  - **- low enrichment**
  - **- demonstrate key technologies**
- **250 kg+ experiment**
  - **- high enrichment**
  - **- probe m_{bb} down to 10meV**

Multiple Approaches Preferred

CUORE/CUPID -- $^{130}Te/^{100}Mo$

-- Excellent Energy Resolution (FWHM 0.2%)

-- Cost Effective

-- Particle ID Technique for Background Reduction

GERDA/MAJORANA/LEGEND/CDEX -- ^{76}Ge

-- Ultra-Low Background Possible

-- Detector Segmentation and Pulse Shape Analysis Possible

-- Costly !

nEXO/HPXe/NvDeX -- $^{136}Xe/^{82}SeF_6$

-- Easy to Scale Up

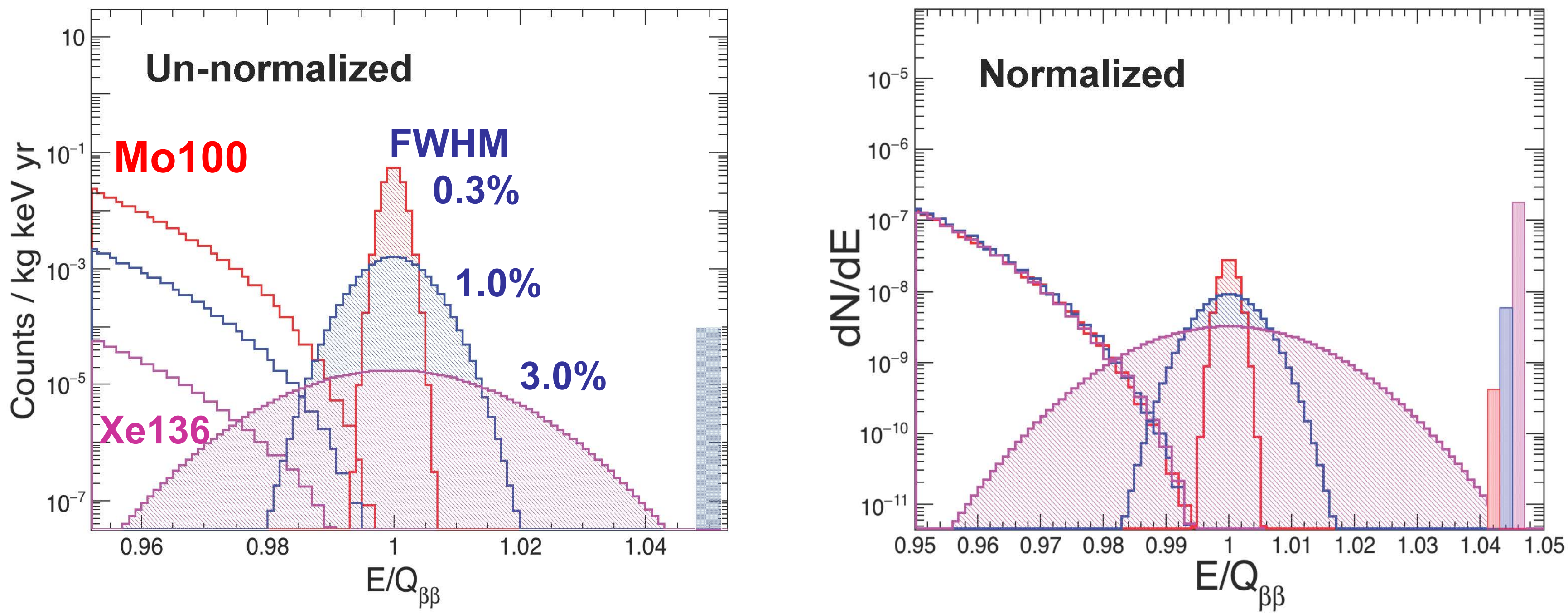
-- Ba^+ Tagging / FWHM ~1%

-- Tracking Could Be Powerful

Measure different isotopes to establish 0vbb process !

Background and Energy Resolution!!

0vbb ROI (0vbb/2vbb ~ 10^{-7})



Color bands : Expected total background level (~ 10^{-4} cts/keV kg yr)

Mo100 $T^{2\nu}_{1/2}$ ~ 7.0 x 10^{18} years

Xe136 $T^{2\nu}_{1/2}$ ~ 2.1 x 10^{21} years

Development of 0vbb Experiments at CJPL

1) CDEX towards 0vbb Experiment
   (HPGe)

2) PandaX towards 0vbb Experiment
   ($L^{Nat}Xe$ TPC)

3) TPC with Novel Readout
   (HP SeF_6 Gas)

4) CUORE Upgrade with PID (CUPID) at CJPL
   (Crystal bolometer technology)

Bright Future Ahead

Neutrinos can lead to new frontiers

1) Neutrinos and the New Paradigm
   -- neutrino masses, Dirac/Majorana and CP violation
   FAR beyond the Standard Model

2) Neutrinos and the Unexpected
   -- Many discoveries in recent years, what surprises and
   extraordinary properties ahead?

3) Neutrinos and Cosmos
   -- # of neutrinos, neutrino masses – large structures
   CP violation – matter/anti-matter asymmetry

Recent technology development → ready for next generation of 0vbb experiments

A unique opportunity for nuclear science frontier at CJPL

The END

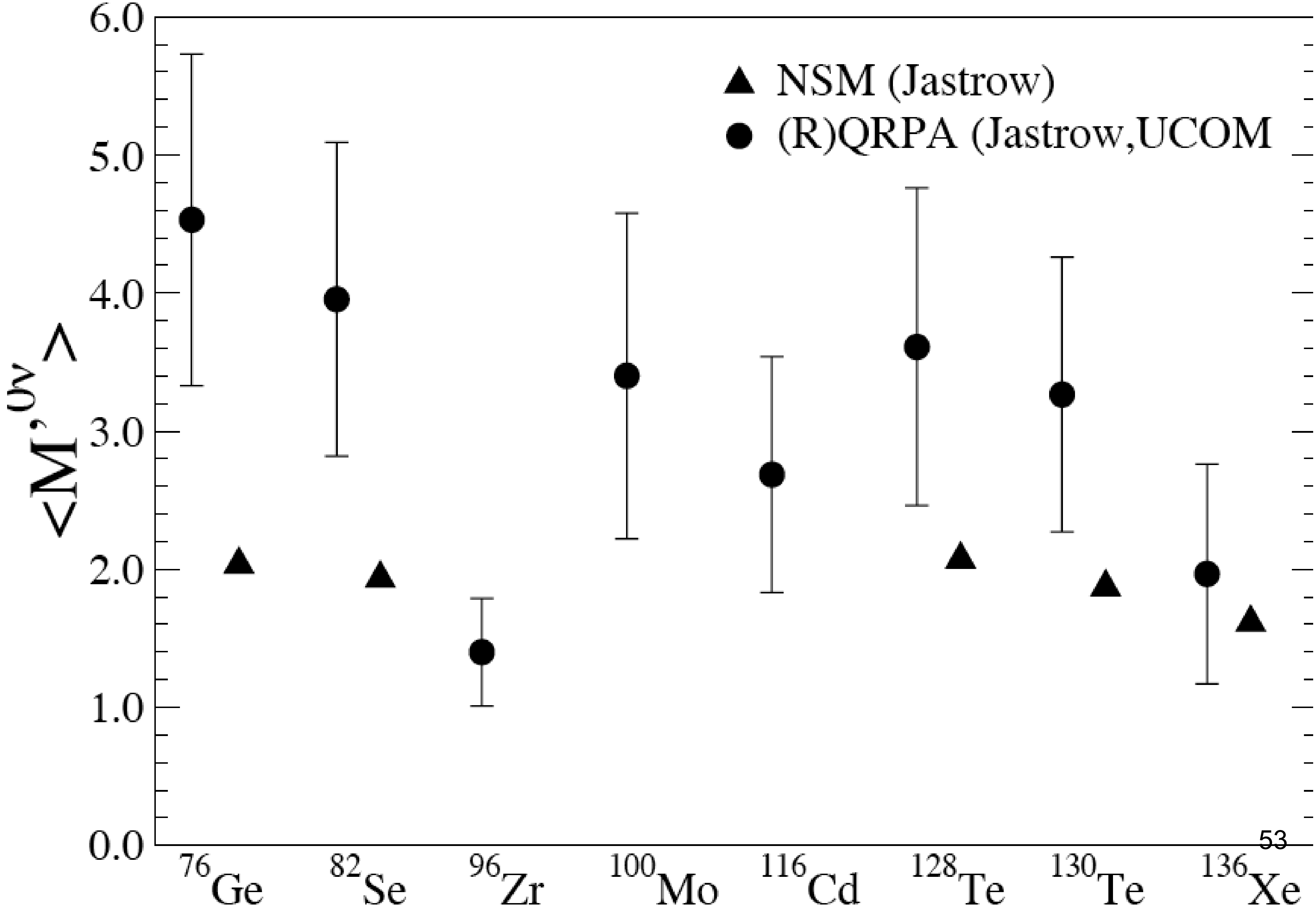
2016 Breakthrough Prize in Fundamental Physics

Kam-Biu Luk, Yifang Wang, and the Daya Bay Collaboration
Koichiro Nishikawa and the K2K and T2K Collaboration
Atsuto Suzuki and the KamLAND Collaboration
Arthur B. McDonald and the SNO Collaboration
Takaaki Kajita, Yoichiro Suzuki and the SuperK Collaboration

For the fundamental discovery and exploration of neutrino oscillations, revealing a new frontier beyond, and possibly far beyond, the standard model of particle physics.

Neutrino oscillation ← flavor states are not the mass eigenstates !

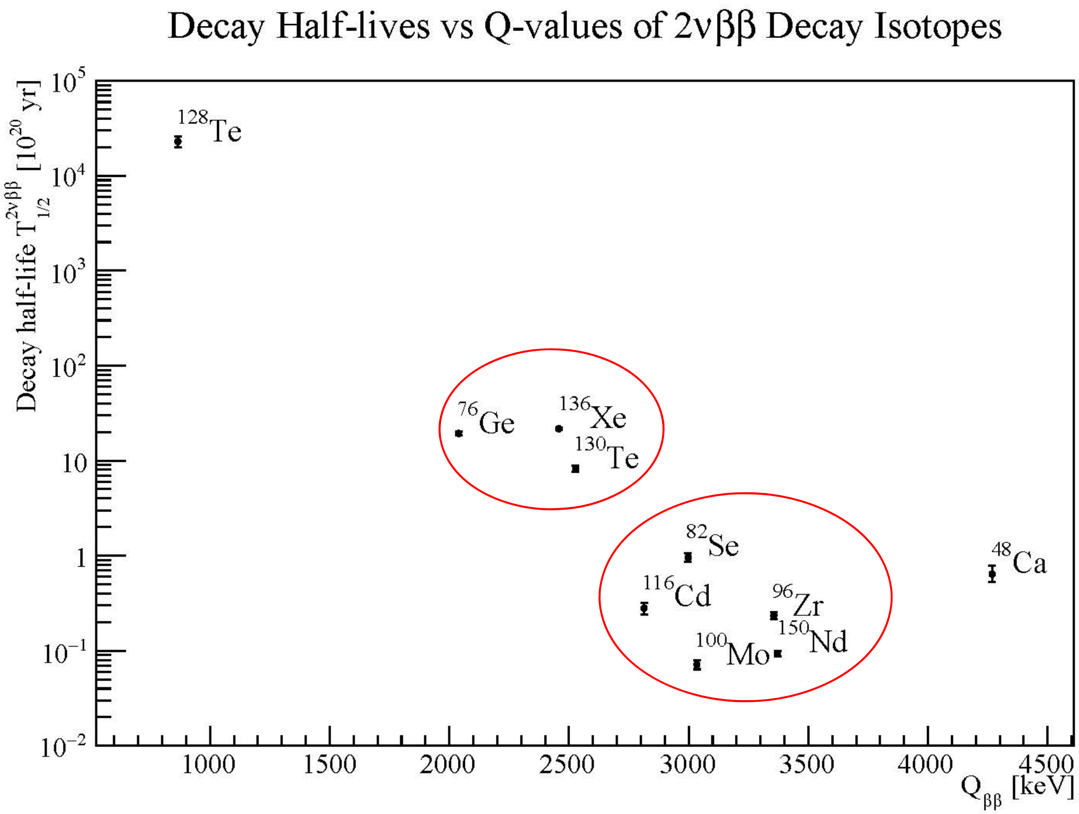
Full estimated range of $M^{0\nu}$ within QRPA framework and comparison with NSM (higher order currents now included in NSM) – P. Vogel



Comments on Isotopes

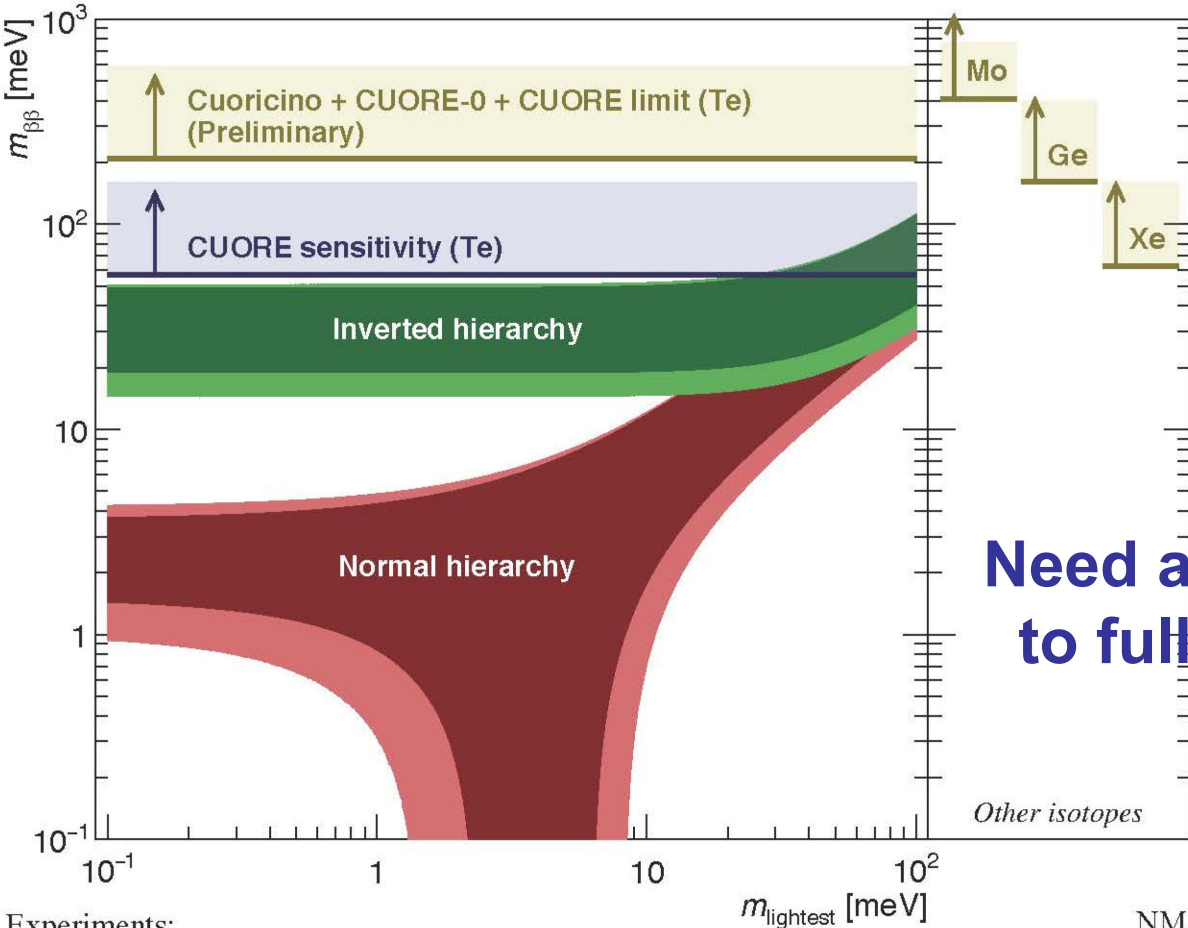
Enrichment Challenges

Te	**^{128}Te -- 31.7%**
	^{130}Te – 34.1%
Xe	**^{134}Xe – 10.4%**
	^{136}Xe – 8.9%
Mo	**^{98}Mo – 24.3%**
	^{100}Mo – 9.7%
Se	**^{80}Se -- 49.8%**
	^{82}Se – 8.8%
Ge	**^{74}Ge -- 36.5%**
	^{76}Ge – 7.8%



Te, Xe and Mo relatively less expensive to enrich
Bolometer technology can work with Te/Mo well

Constraints on $m_{\beta\beta}$



$T_{0\nu}(^{130}Te) > 6.6 \times 10^{24}$ yr
$m_{\beta\beta} <$ 210 - 590 meV

Need another factor of 10 to fully cover the IH region !

Experiments:

- ^{130}Te: 6.6×10^{24} yr [this analysis]
- ^{76}Ge: 5.3×10^{25} yr [Nature **544**, 47 (2017)]
- ^{136}Xe: 1.1×10^{26} yr [Phys. Rev. Lett. **117**, 082503 (2016)]
- ^{100}Mo: 1.1×10^{24} yr [Phys. Rev. D **89**, 111101 (2014)]
- CUORE sensitivity: 9×10^{25} yr

NME:

- Phys. Rev. C 91, 034304 (2015)
- Phys. Rev. C 87, 045501 (2013)
- Phys. Rev. C 91, 024613 (2015)
- Nucl. Phys. A 818, 139 (2009)
- Phys. Rev. Lett. 105, 252503 (2010)