Majorana Neutrinos，Neutrinoless Double Beta Decays & Opportunities at CJPL

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Outline

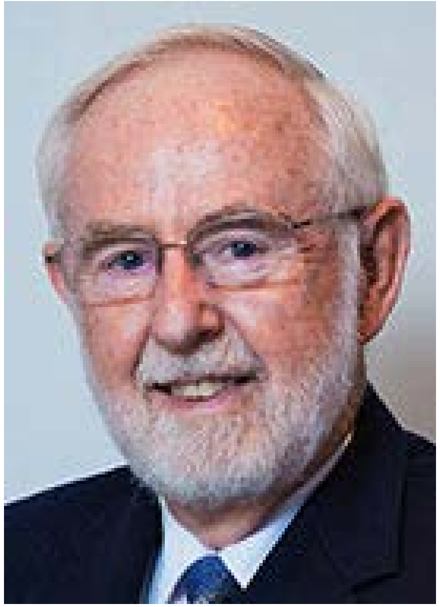
1) Majorana Neutrinos and
   Neutrinoless Double Beta Decay (0vbb)

2) CUORE (Cryogenic Underground Observatory
   for Rate Events) Results

3) CUPID-China Collaboration and Crystal
   Bolometer Development in China

Nobel Prize in Physics 2015

Takaaki Kajita



Arthur B. McDonald

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

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 !

Dirac or Majorana Particles

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)**

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?

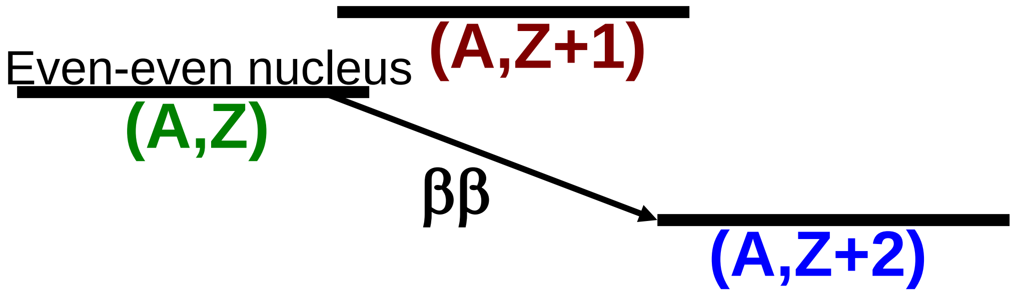
4) Are there sterile neutrinos?

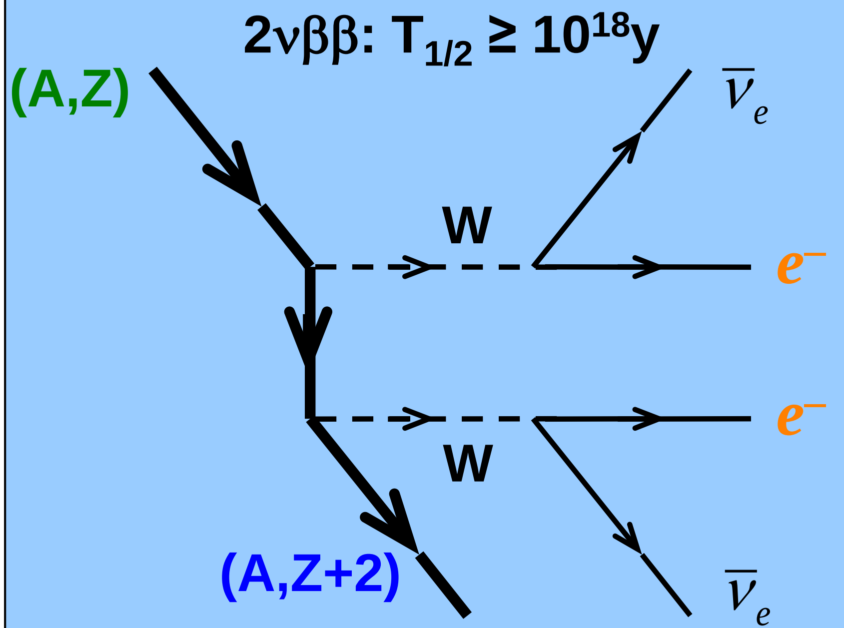
Double Beta Decay

2νββ

1935

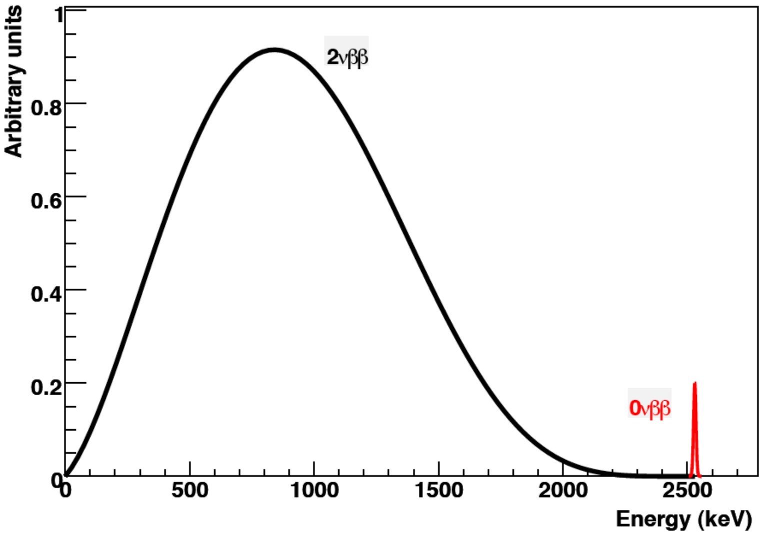
M. Goeppert-Mayer

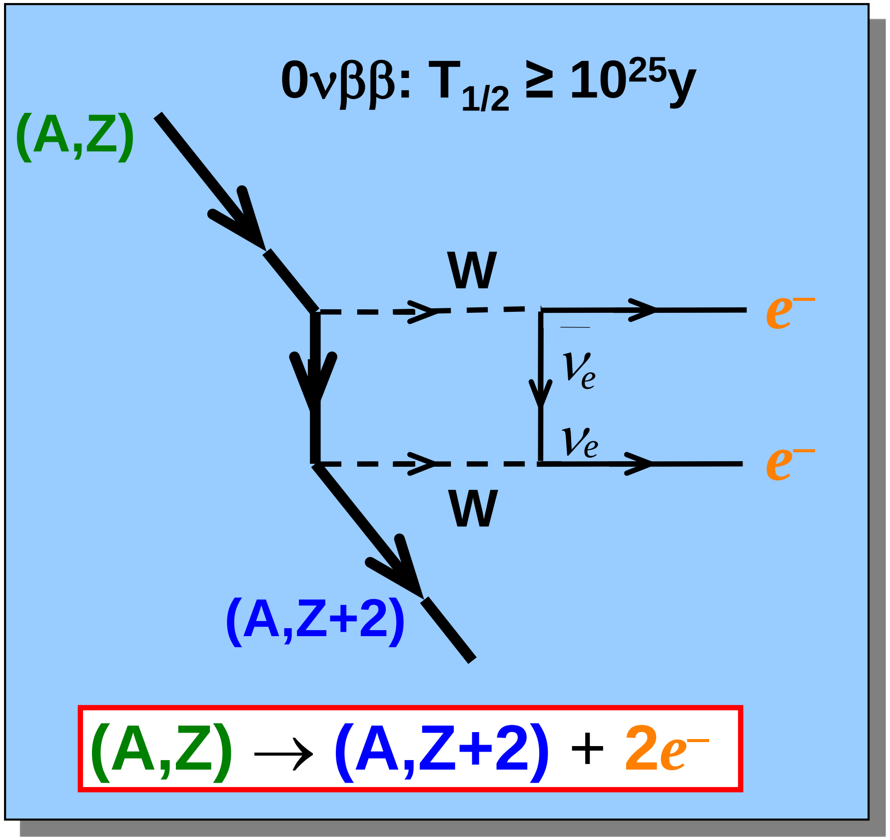




$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\ \bar{\nu}_e$

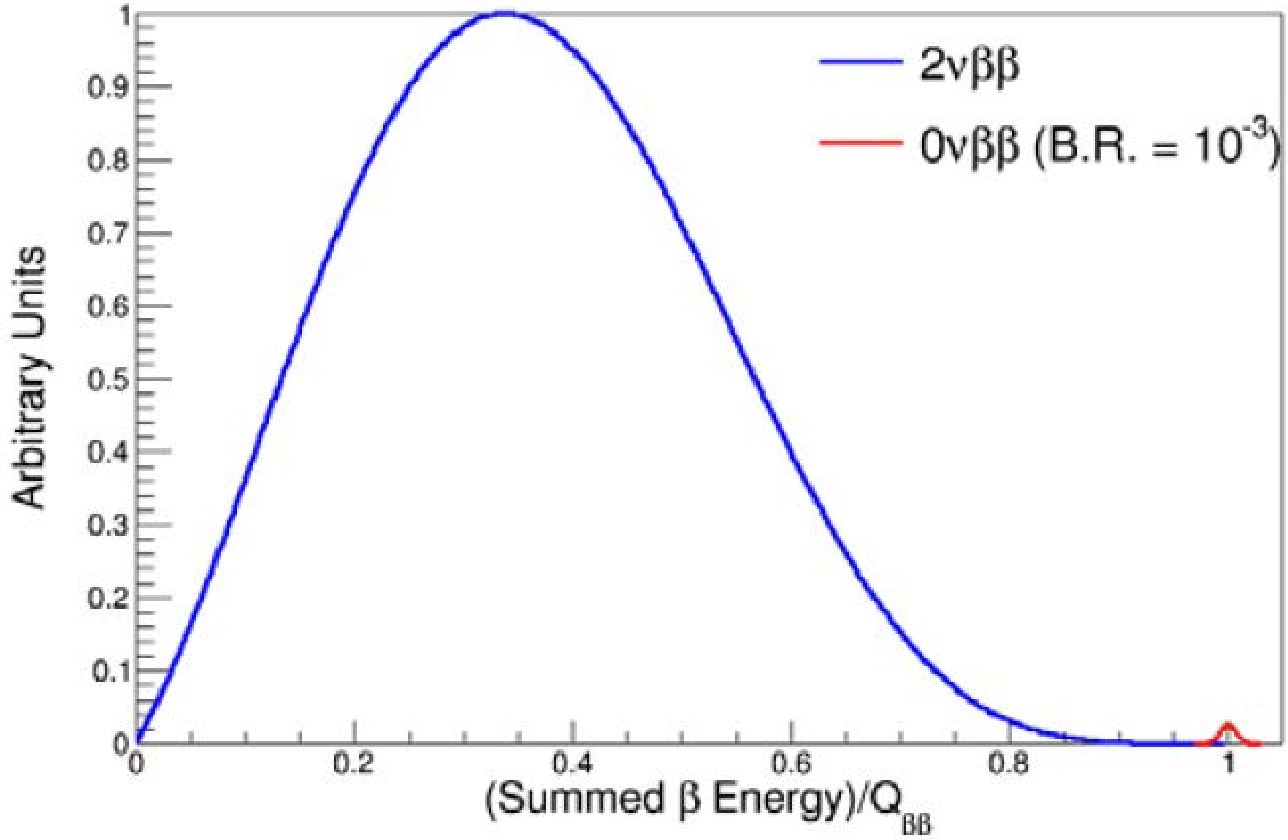
Majorana Neutrinos?





Majorana → neutrino = anti-neutrino
Lepton Number violation !

Experimental Search for 0νββ

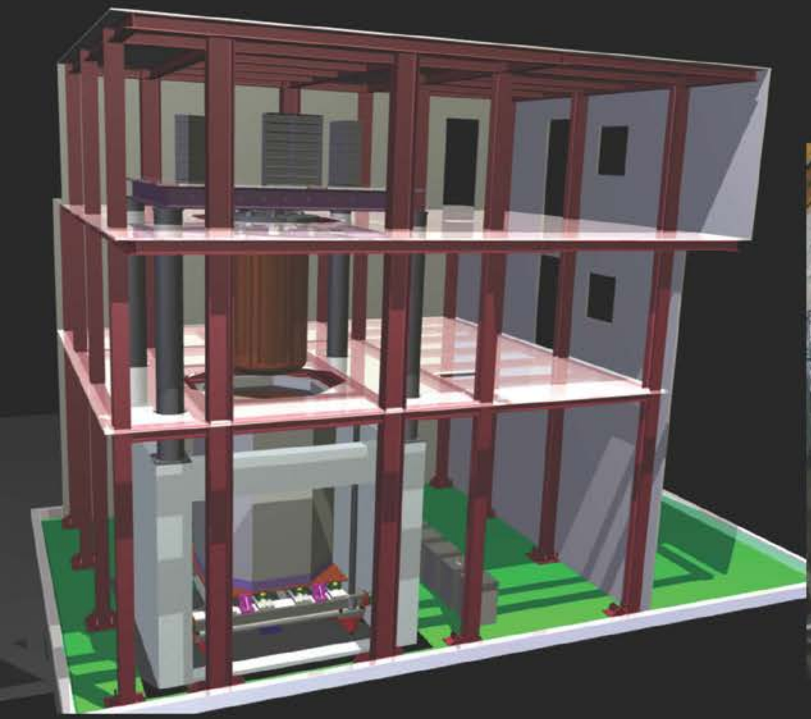


2νββ decays are irreducible background !
We do not know the relative rate!

The CUORE collaboration

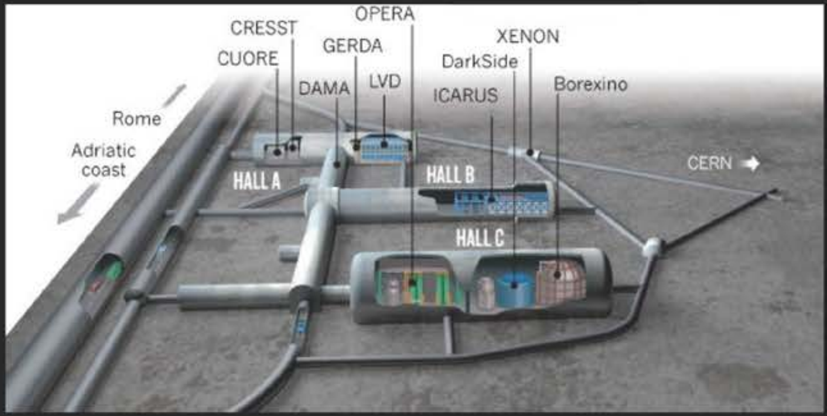
CSNSM
Università degli Studi di Padova
Yale
INFN LNGS
Berkeley Lab
Cal Poly San Luis Obispo
The University of California 1868
Università di Genova
Massachusetts Institute of Technology
Lawrence Livermore National Laboratory
Virginia Tech Invent the Future®
Sapienza Università di Roma
Università degli Studi di Milano Bicocca
Shanghai Jiao Tong University
Alma Mater Studiorum Università di Bologna A.D. 1088
Università degli Studi di Cassino e del Lazio Meridionale
UCLA
SINAP
University of South Carolina
CUORE

CUORE @ LNGS



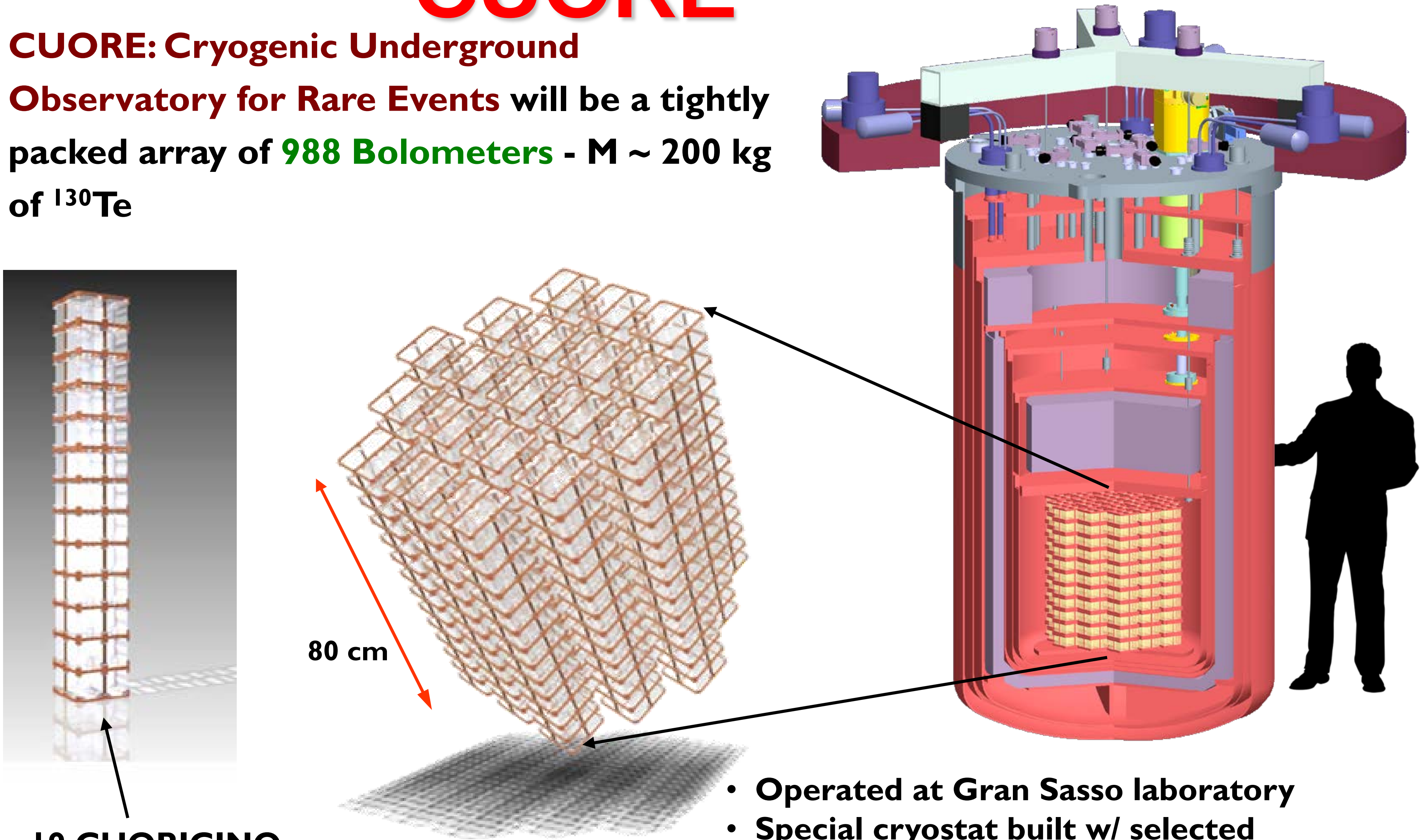
Three story building

- Ground floor: pumps, compressors & shielding
- First floor: clean room (Gluing, Assembly & Cryostat)
- Second floor: service area, front-end & DAQ



CUORE

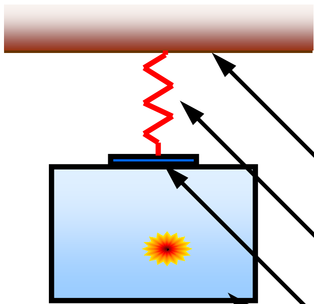
CUORE: Cryogenic Underground Observatory for Rare Events will be a tightly packed array of **988 Bolometers** - M ~ 200 kg of ^{130}Te



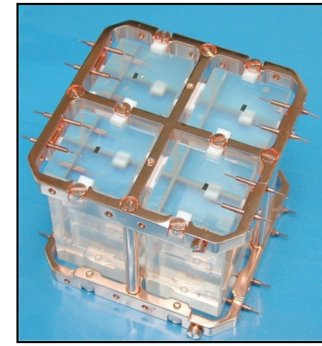
19 CUORICINO-like towers with 13 planes of 4 crystals each

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

Bolometer

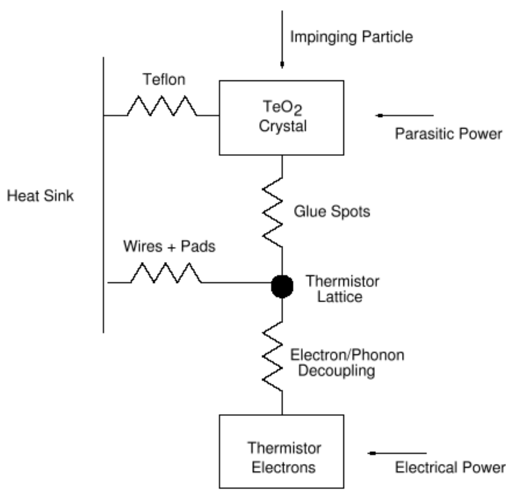


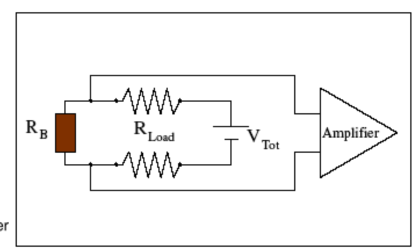
TeO_2 Bolometer: Source = Detector



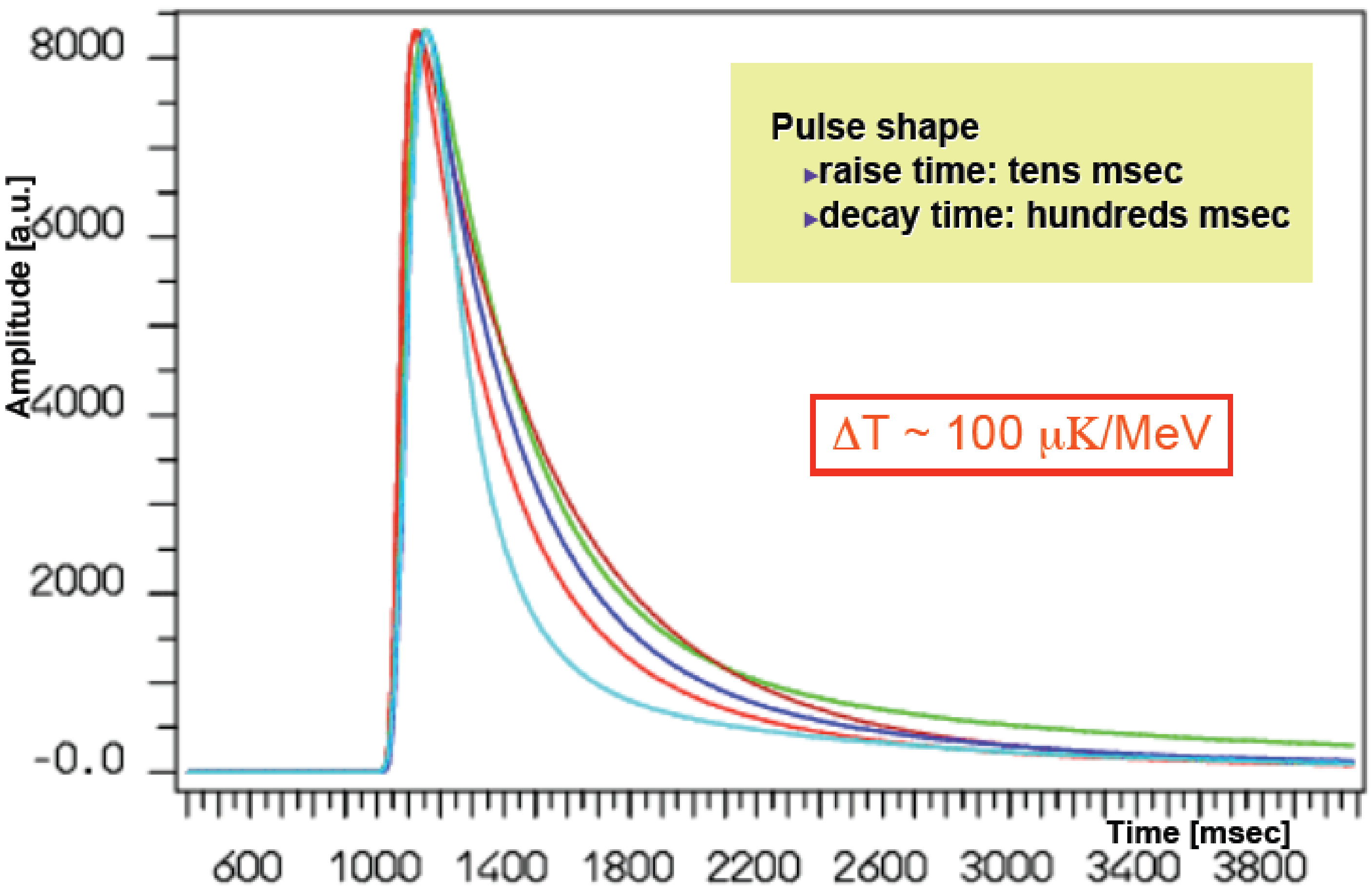
Heat sink: ~8-10 mK
Thermal coupling: Teflon
Thermometer: NTD Ge thermistor
Absorber: TeO_2 crystal

CUORE Crystals from SICCAS!





Signal from NTD Ge Thermistor

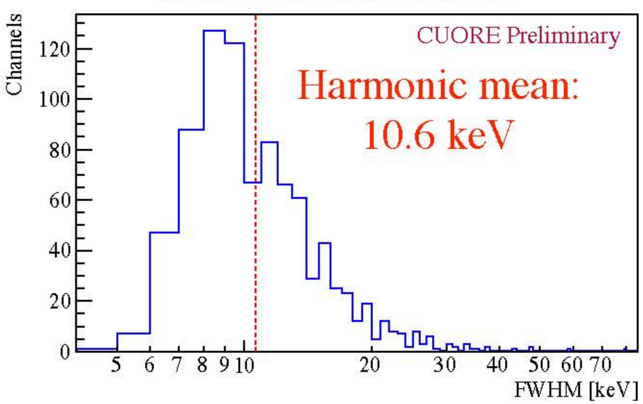


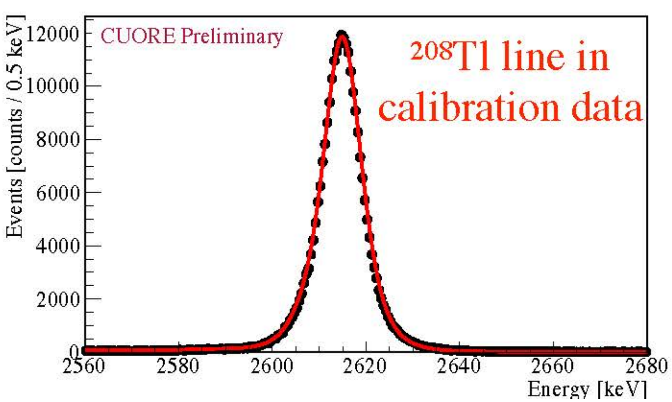
Energy resolution

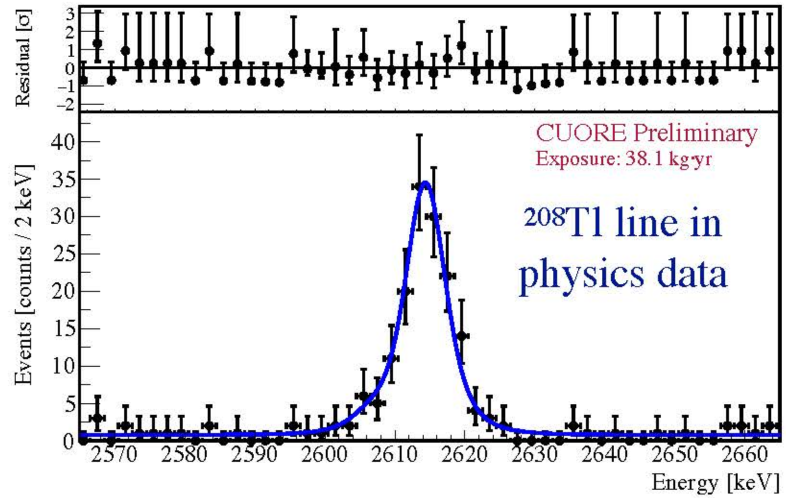
- Selected 899 (90%) “golden” channels:
  - Channels discarded due to high noise or PSA issues
  - could be recovered in the future
- Average energy resolution in calibration runs: 10.6 keV FWHM

Significantly better performance in physics data:
(7.9 ± 0.6) keV FWHM

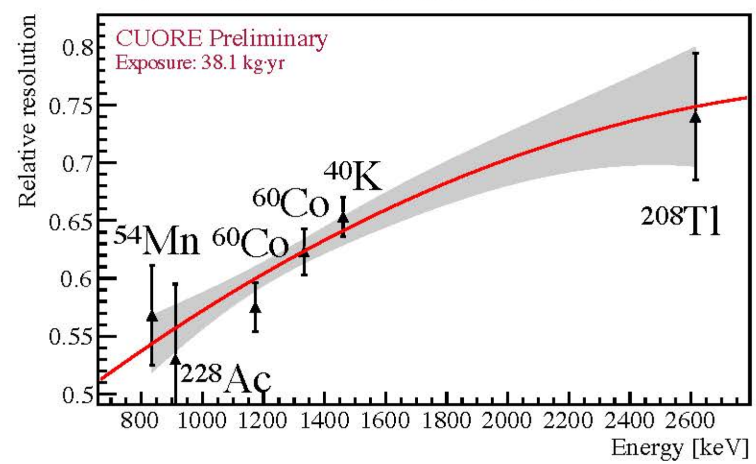
Calibration resolution at 2615 keV



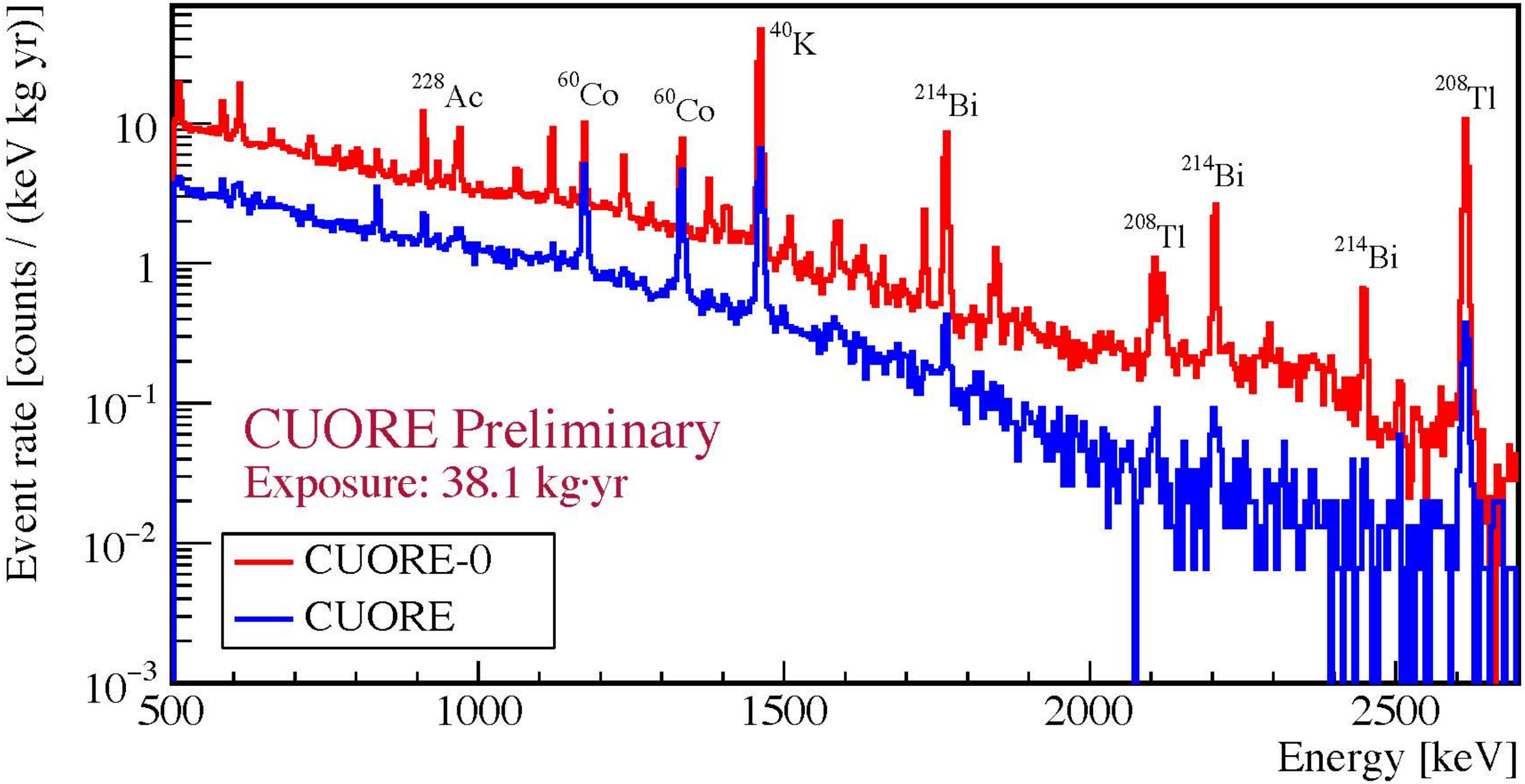




Resolution relative to 2615 keV calibration line

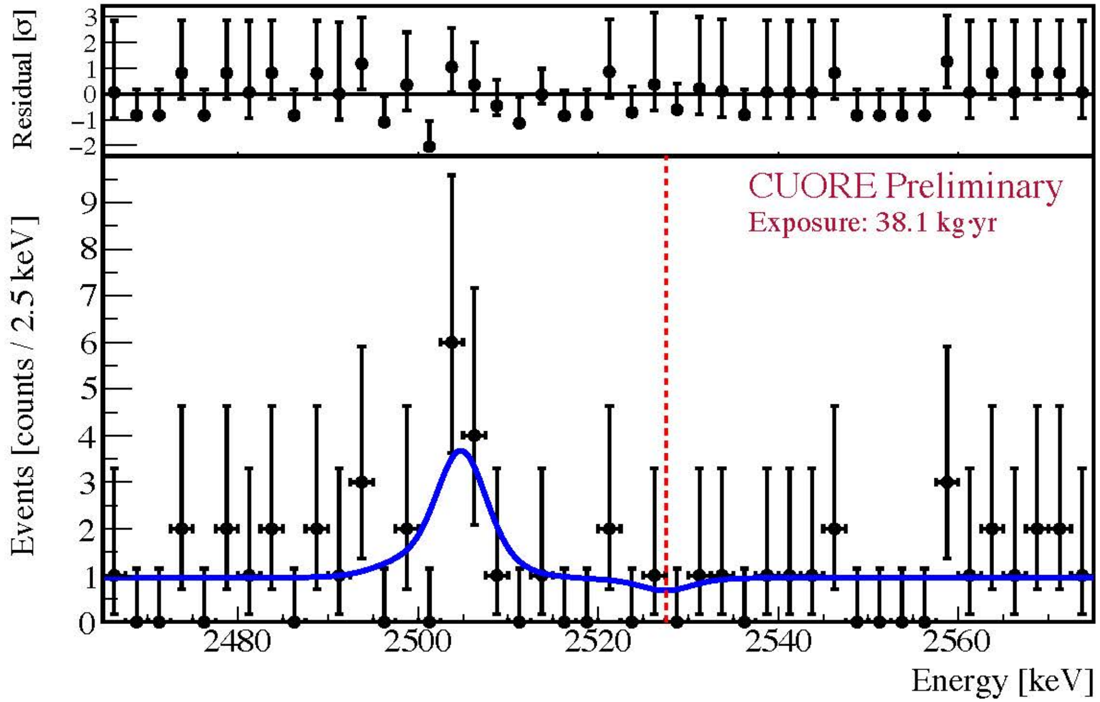


CUORE Background Spectrum



- Significant reduction in the γ region with respect to CUORE-0 (as expected)
- Spectrum is consistent with the background expectations

$0\nu\beta\beta$ Fit

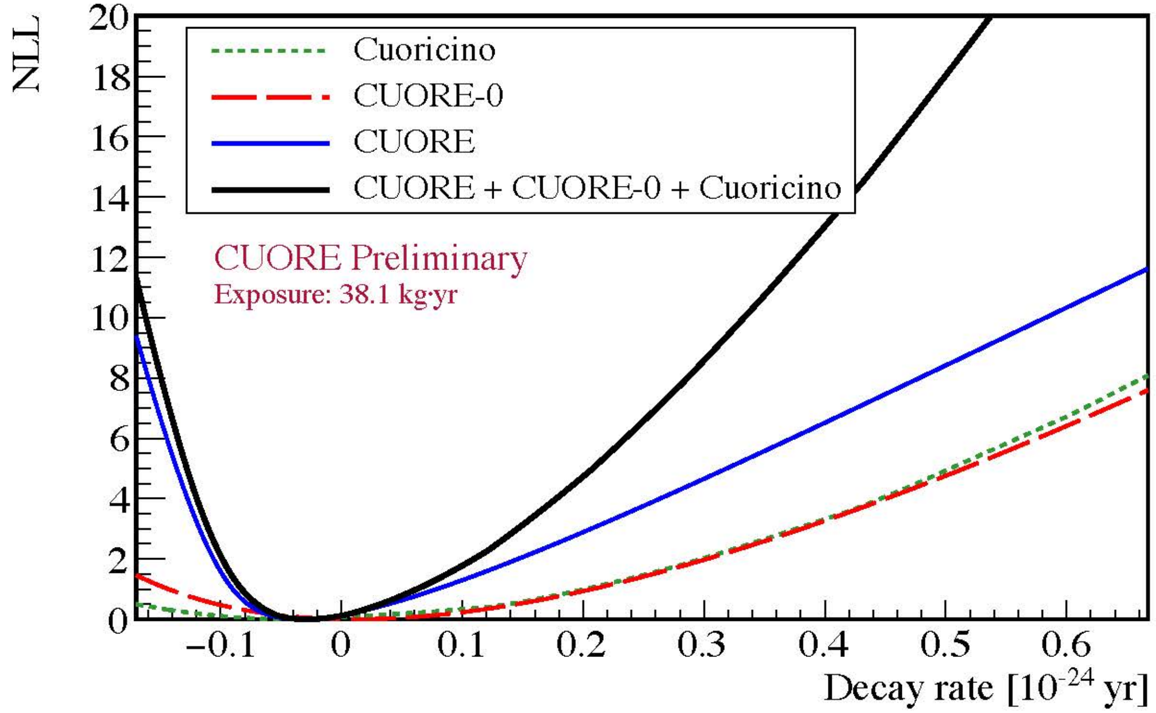


Region of interest	[2565..2575] keV
Overall efficiency	(55.3 ± 3.0)%
Events in the ROI	50
Best fit for ^{60}Co mean	(2504.8 ± 1.2) keV
ROI background index	$(9.8_{-1.5}^{+1.7}) \times 10^{-3}$ counts/(keV·kg·yr)
Best fit decay rate	$[-0.03_{-0.04}^{+0.07}$ (stat.) ± 0.01 (syst.)] $\times 10^{-24}$ yr^{-1}

Combination with Previous Results

We combine the CUORE result with the existing ^{130}Te data:

- Cuoricino: 19.8 kg·yr [Phys.Rev. **C78**, 035502 (2008)]
- CUORE-0: 9.8 kg·yr [Phys.Rev.Lett. **115**, 102502 (2015)]



Bayesian limit @ 90% c.i. (flat prior for $\Gamma_{\beta\beta}$>0): $T_{1/2}^{0\nu\beta\beta} > 6.6 \times 10^{24}$ years

Profile likelihood ("frequentist") limit @ 90% CL: $T_{1/2}^{0\nu\beta\beta} > 8.1 \times 10^{24}$ years

W. Rolke et al., NIM A**551**, 493(2005)

Scaling CUORE and Beyond

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

Figure of Merit

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

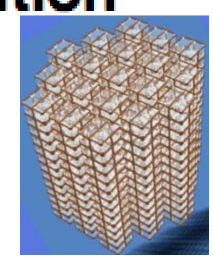
Background

Detector resolution

CUORICINO → CUORE

Numerator up by ~20

Denominator down by ~20



Candidate for Double beta Decays

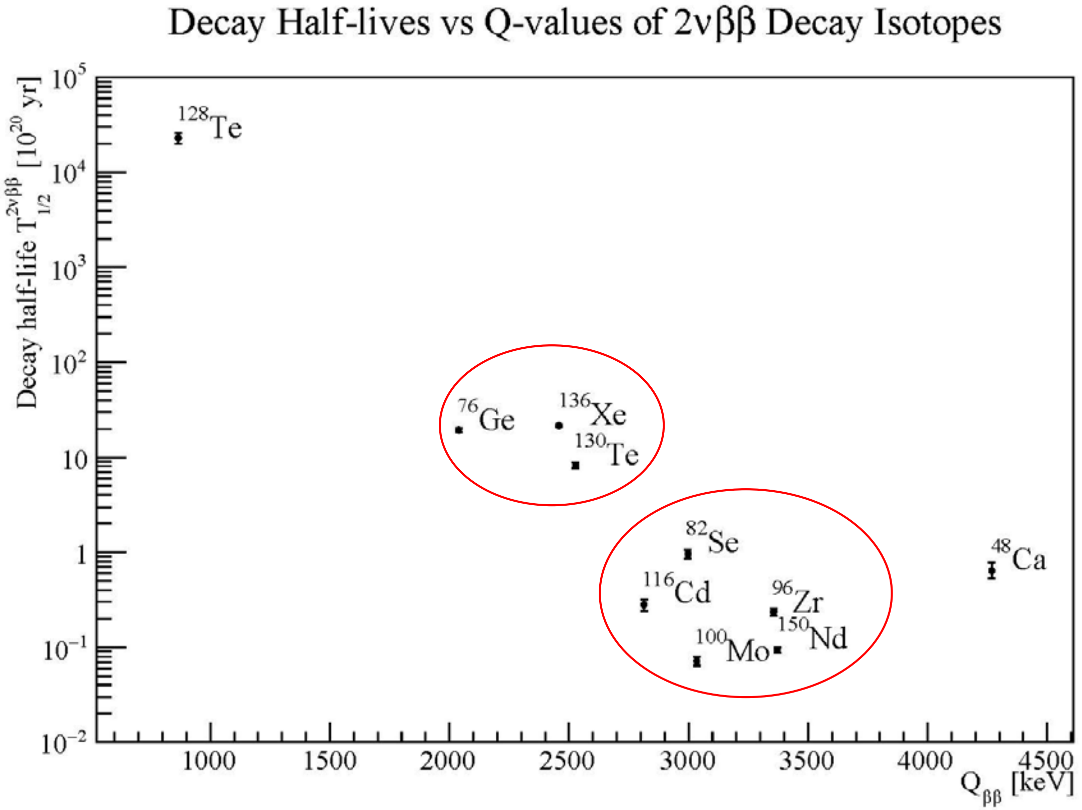
$E\gamma^{bk}$=2.615 MeV

	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

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

CUPID-China Collaboration

CUPID – CUORE Upgrade with Particle IDentification

---- Develop Low Temperature Bolometer Technology for next generation of 0vbb experiment with > 1 ton effective 0vbb isotope

International Collaboration:

CUPID – Italy

CUPID – US

CUPID – France

CUPID – China

复旦，上海应用物理研究所，上海硅酸盐研究所，上海交大，中国科大，宁波大学，清华，北京师大

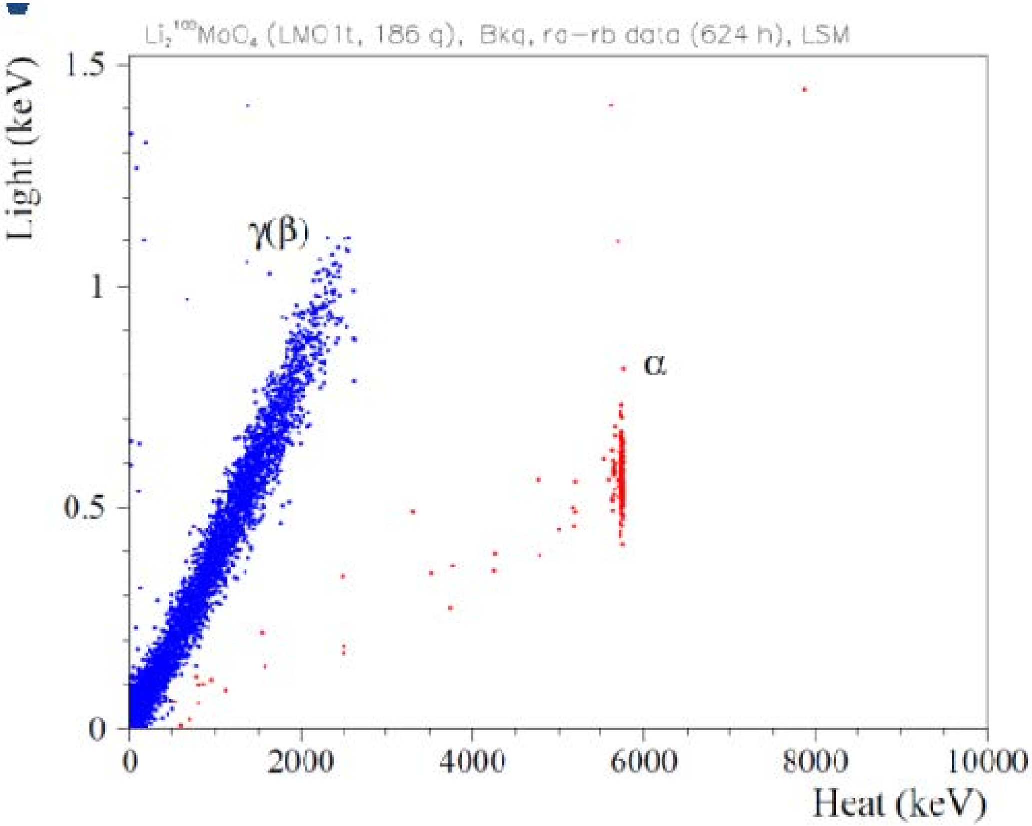
@中国锦屏地下实验室（CJPL）

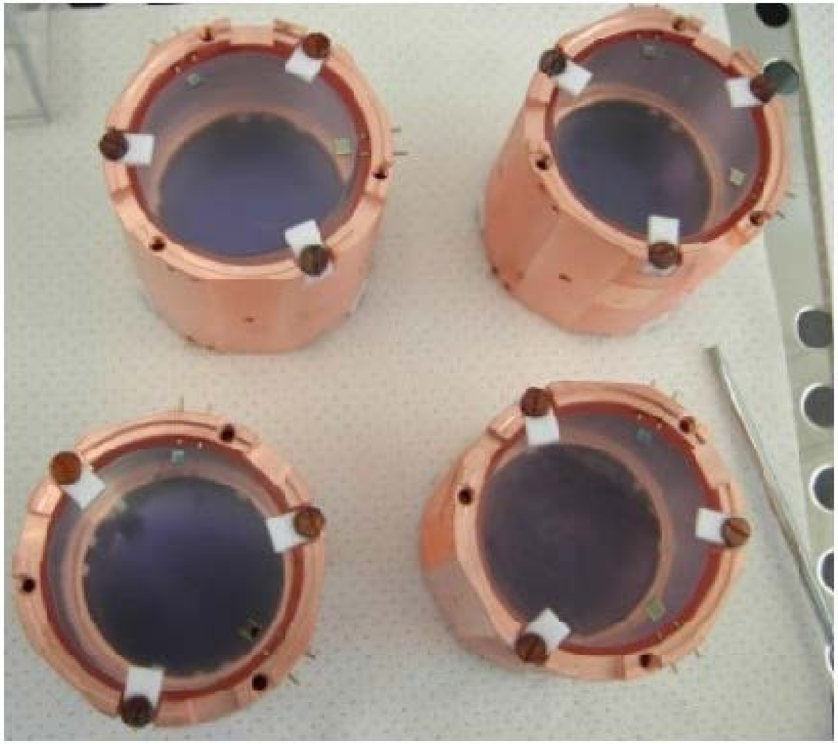
3-5 年 – 掌握和研发最先进低温晶体量热器技术，达到新一代吨级探测器的本底要求 1c/keV/ton/year

5-10年 – 建造和运行新一代0vbb探测器（TeO_2和Li_2MoO_4）

Support and/or Join CUPID-China Project !!

CUPID-Mo R&D Effort





Li_2MoO_4 (LMO) – Very Promising Technology
Ningbo University/SICCAS can grow Radiopure LMO
Set up Cryogenic Testing Lab at CJPL for a Demostrator

Multiple Approaches Preferred

CUORE-- ^{130}Te/ ^{130}Mo

- -- Excellent Energy Resolution (FWHM 0.2%)
- -- Cost Effective
- -- Background Elimination (Q > 2615 keV)
- -- Particle ID Technique

GERDA/MAJORANA -- ^{76}Ge

- -- Low Background Possible With Active LAr
- -- Detector Segmentation and Pulse Shape Analysis Possible
- -- Very Costly !

EXO/HPXe -- ^{136}Xe

- -- Scale Up
- -- Ba^+ Tagging Challenging / FWHM ~1%
- -- Tracking Could Be Powerful

Measure different isotopes to establish 0vbb process !

Future Perspective

Neutrinos can lead to new frontiers

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

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

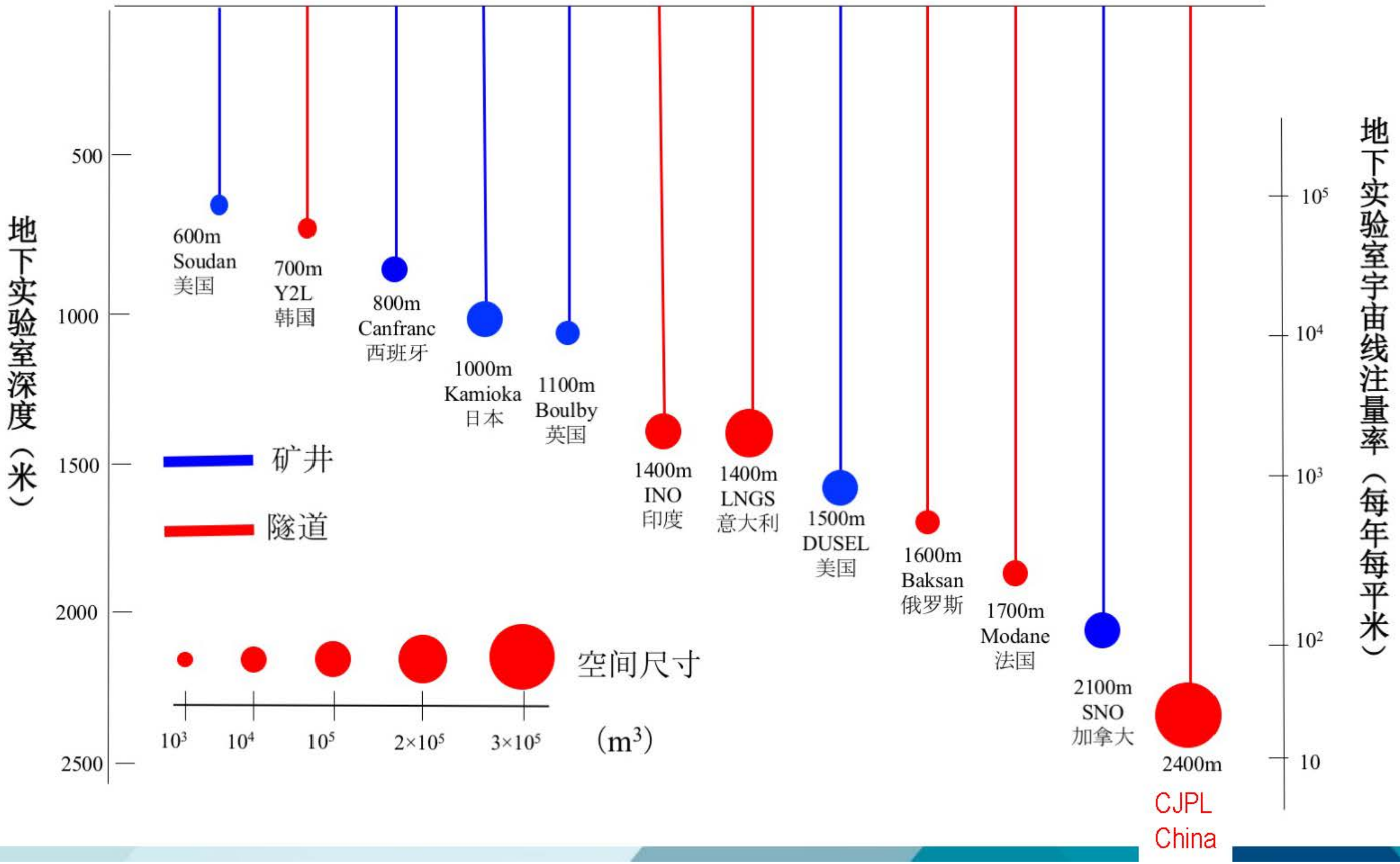
3) Neutrinos and Cosmos
   -- # of neutrinos, neutrino masses – large structures
   CP violation – matter/anti-matter asymmetry

Recent technology development → verge of next generation of 0vbb experiment

A unique opportunity for Chinese Nuclear Physics

Need to demonstrate viable technology in a few years

Best Underground Laboratory in the World !



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