Reina Maruyama
丸山玲奈

~~Associate~~ Professor of Physics & Astronomy
Yale University
she/her/hers

Barnard College Summer Astroparticle Colloquium Series

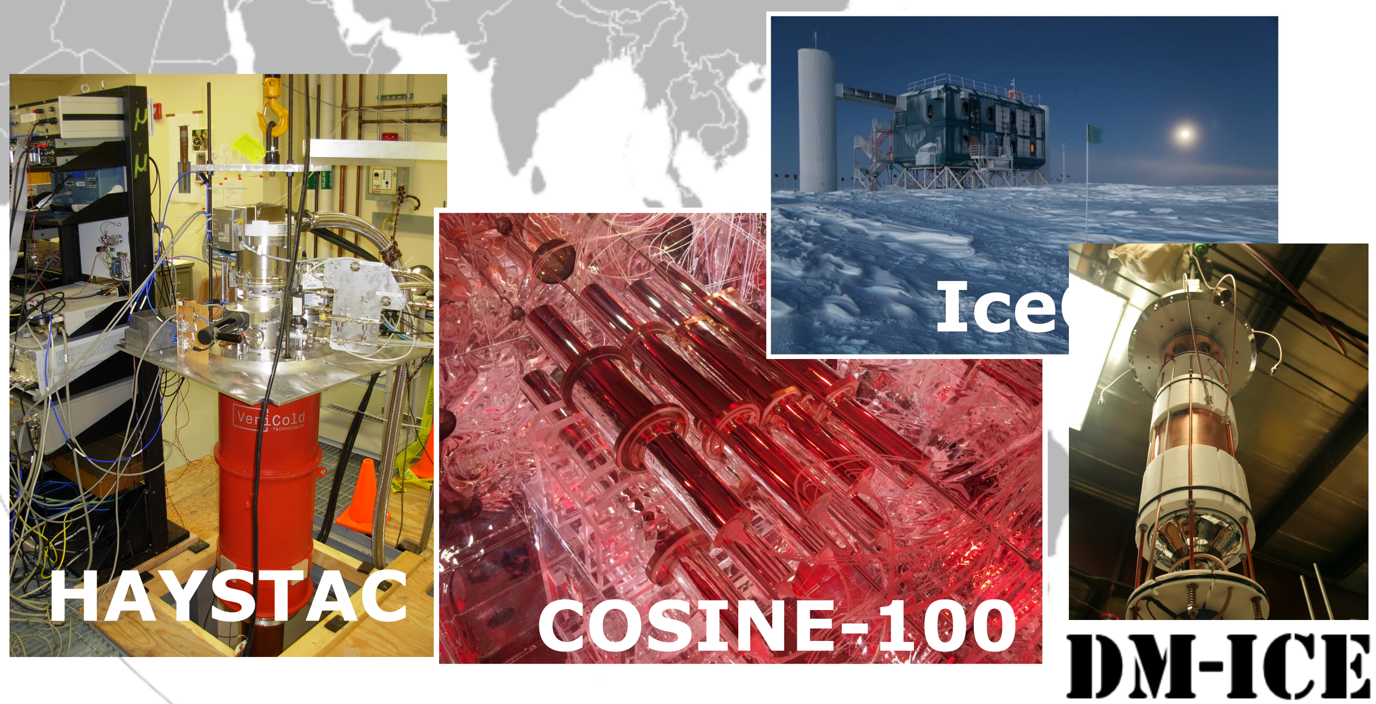
Research in Maruyama Group

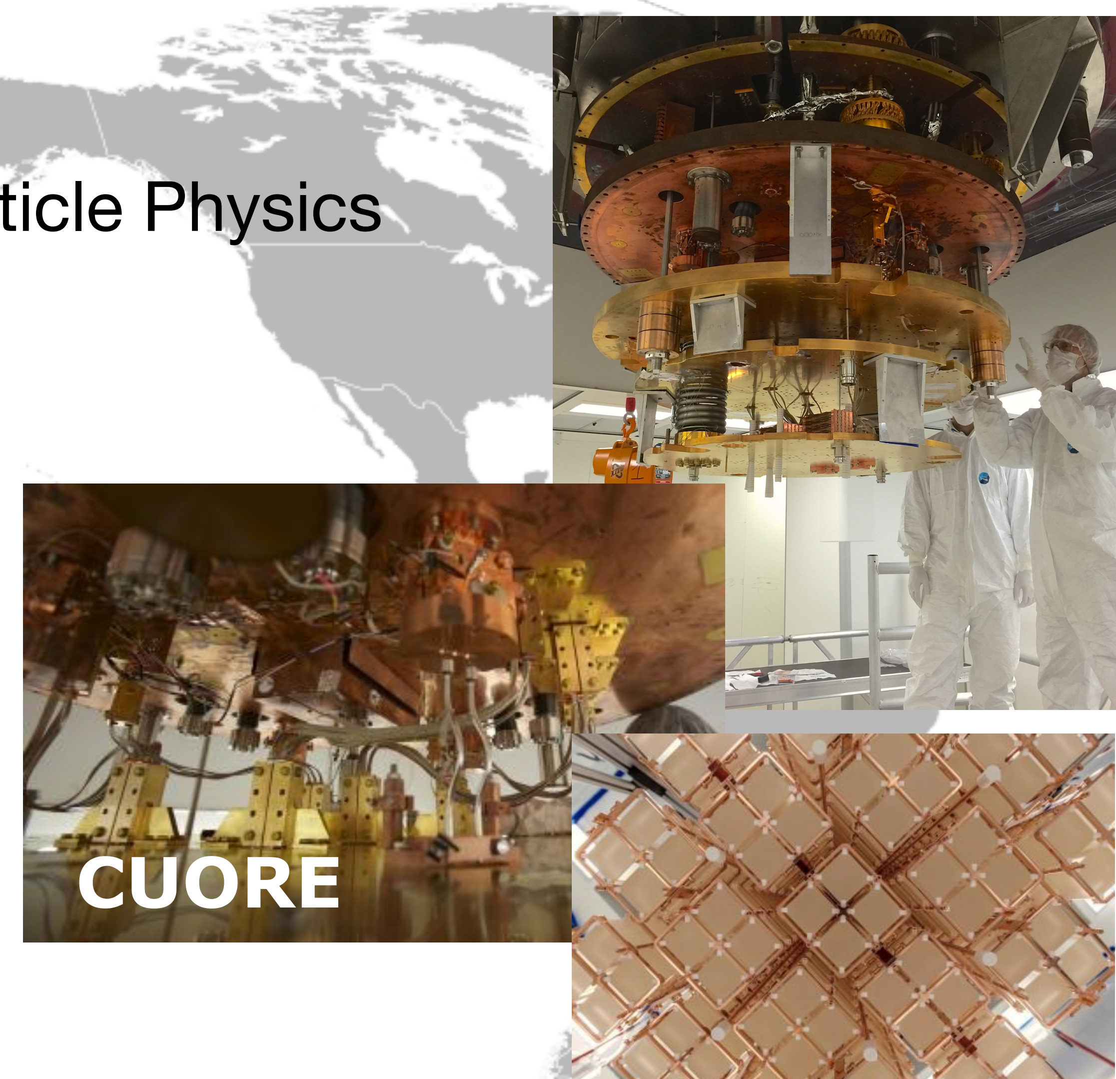
Wright Laboratory

http://maruyama-lab.yale.edu

Research

- Physics Beyond the Standard Model of Particle Physics
- Neutrinos and Dark Matter



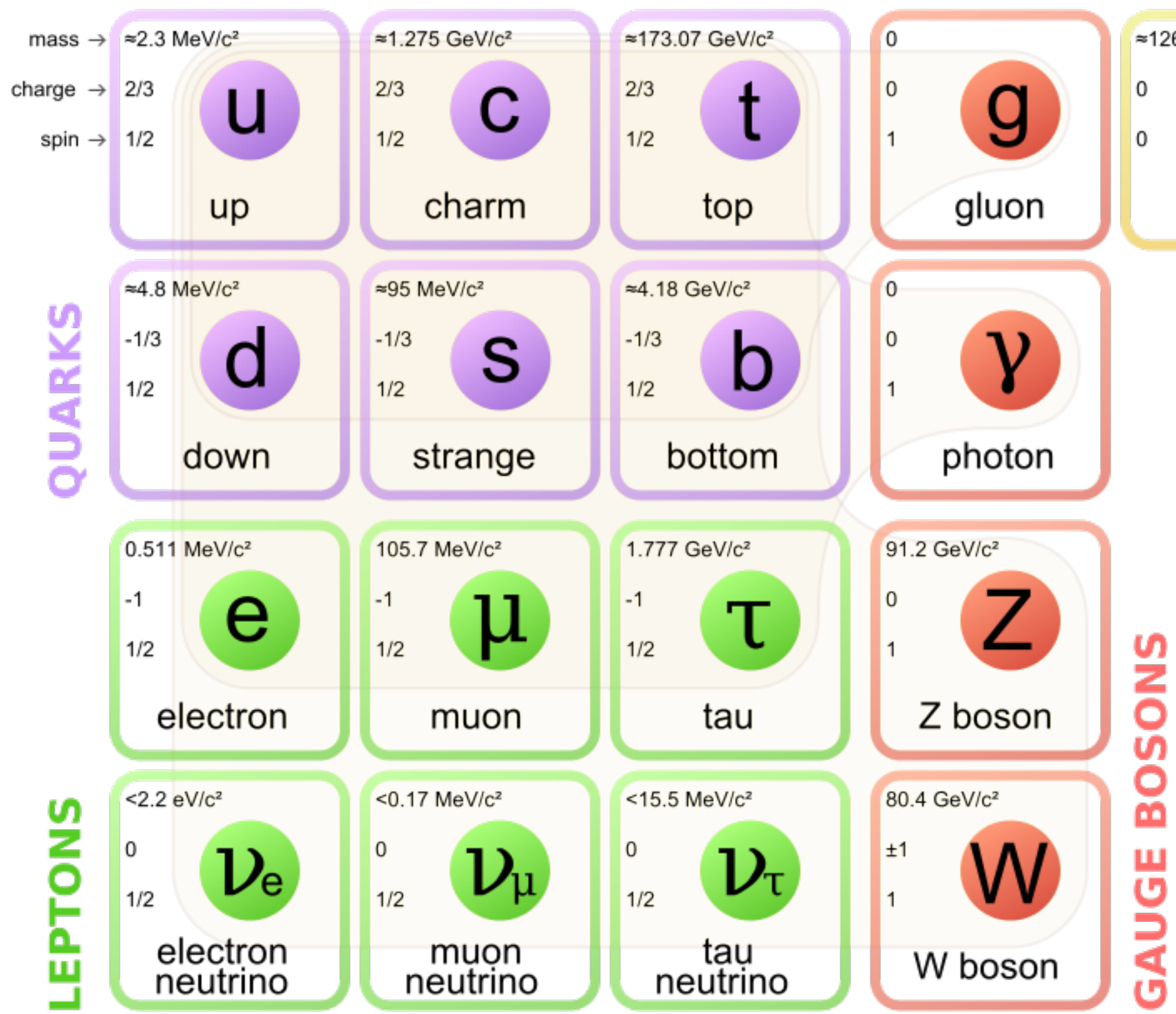


- direct detection dark matter experiment at Yale, South Pole and South Korea.
- Is DAMA really seeing dark matter?

- Neutrinoless double beta decay
- Are neutrinos their own anti-particles? Are they Majorana particles?

Yale SSGF STEWARDSHIP SCIENCE GRADUATE FELLOWSHIP WISCONSIN ICECUBE PARTICLE ASTROPHYSICS CENTER U.S. DEPARTMENT OF ENERGY Office of Science ALFRED P. SLOAN FOUNDATION 1934 NSF incomplete

The ^ Standard Model of Elementary Particles



discovery in 2012


2013

+ their anti-particle partners

- Gravity?  2017
- Dark Matter? Dark Energy?
- Neutrino Masses?
- Matter-antimatter asymmetry?

http://particleadventure.org/

History of Neutrinos

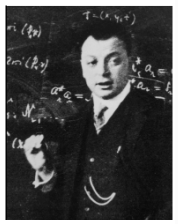
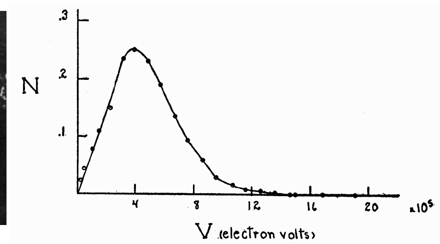
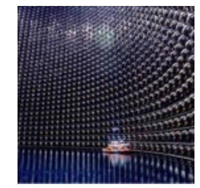



FIG. 5. Energy distribution curve of the beta-rays.

1930 Pauli postulates neutrinos

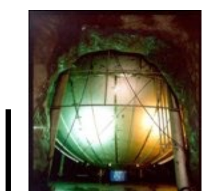
1933 Fermi names neutrinos, formulates weak interactions theory

1987
SN 1987A



1998 SuperK reports evidence for oscillation of atmospheric neutrinos.

2001/2002 SNO finds evidence for solar ν_e flavor change.

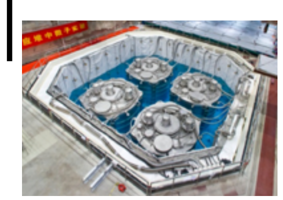


2003 KamLAND discovers disappearance of reactor ν_e

1968 Ray Davis detects solar neutrinos.

today

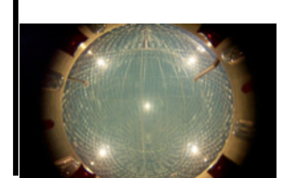
1962 Steinberger, Lederman, Schwartz, et al demonstrate ν_e & ν_μ



2012 Daya Bay, RENO, Double Chooz measure θ_{13}

1958 Goldhaber, Grodzins, & Sunyar at BNL demonstrate left-handed helicity

1957 Pontecorvo: Neutrinos may oscillate



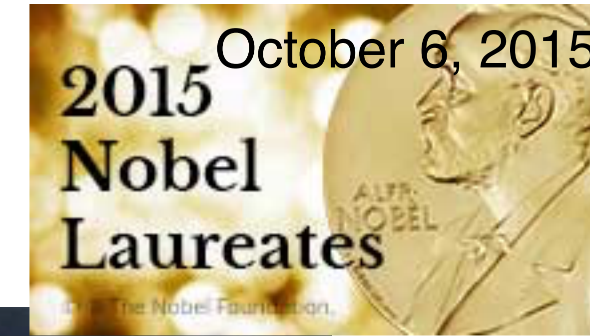
2007 Borexino detection of ^{7}Be solar neutrinos

1956 Reines & Cowan report the first evidence of neutrinos

The Nobel Prize in Physics 2015

"for the discovery of neutrino oscillation, which shows that neutrinos have mass"

October 6, 2015



Takaaki Kajita
Super-K Collaboration
University of Tokyo, Japan

Arthur B. McDonald
SNO Collaboration
Queen's University, Canada

Open Questions in 2019

What is the nature of neutrinos?

What are the values of the masses?

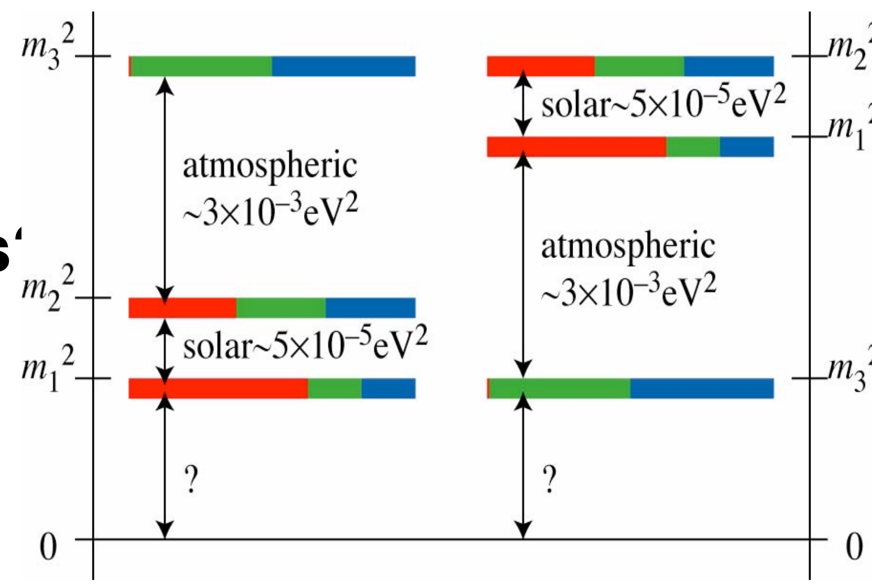
- absolute scale
- mass ordering

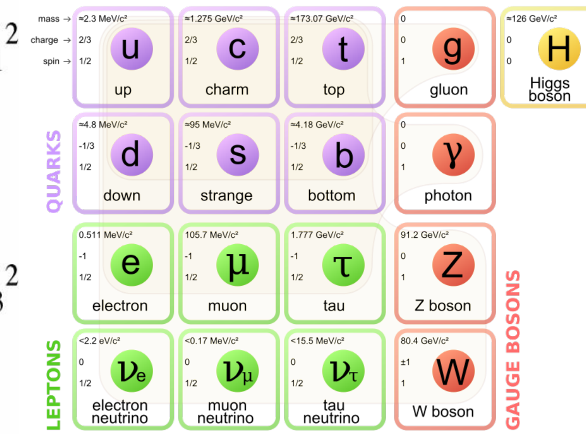
Is there CP-violation?

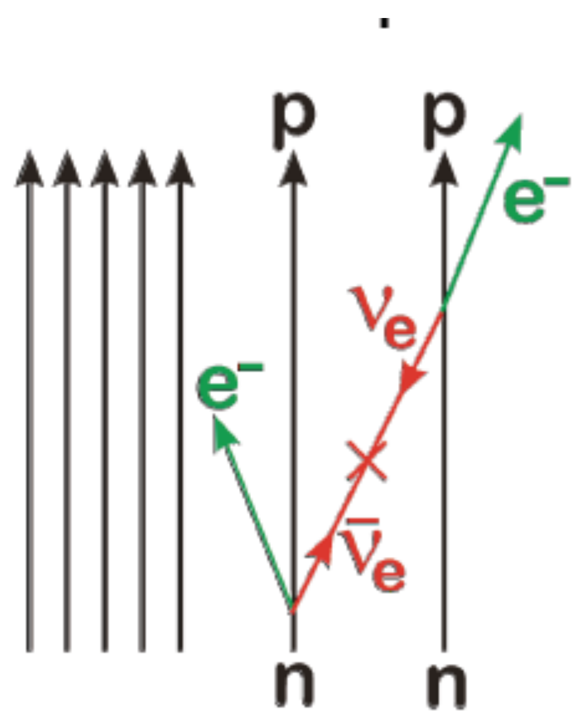
What are the precise values of mixing angles?

Is the standard picture correct?

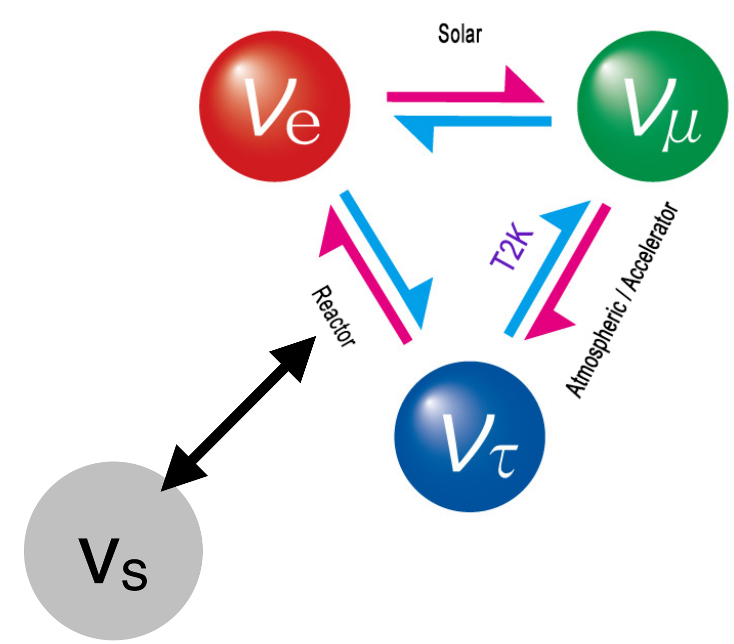
- non-standard interactions
- Sterile neutrinos?
- other effects



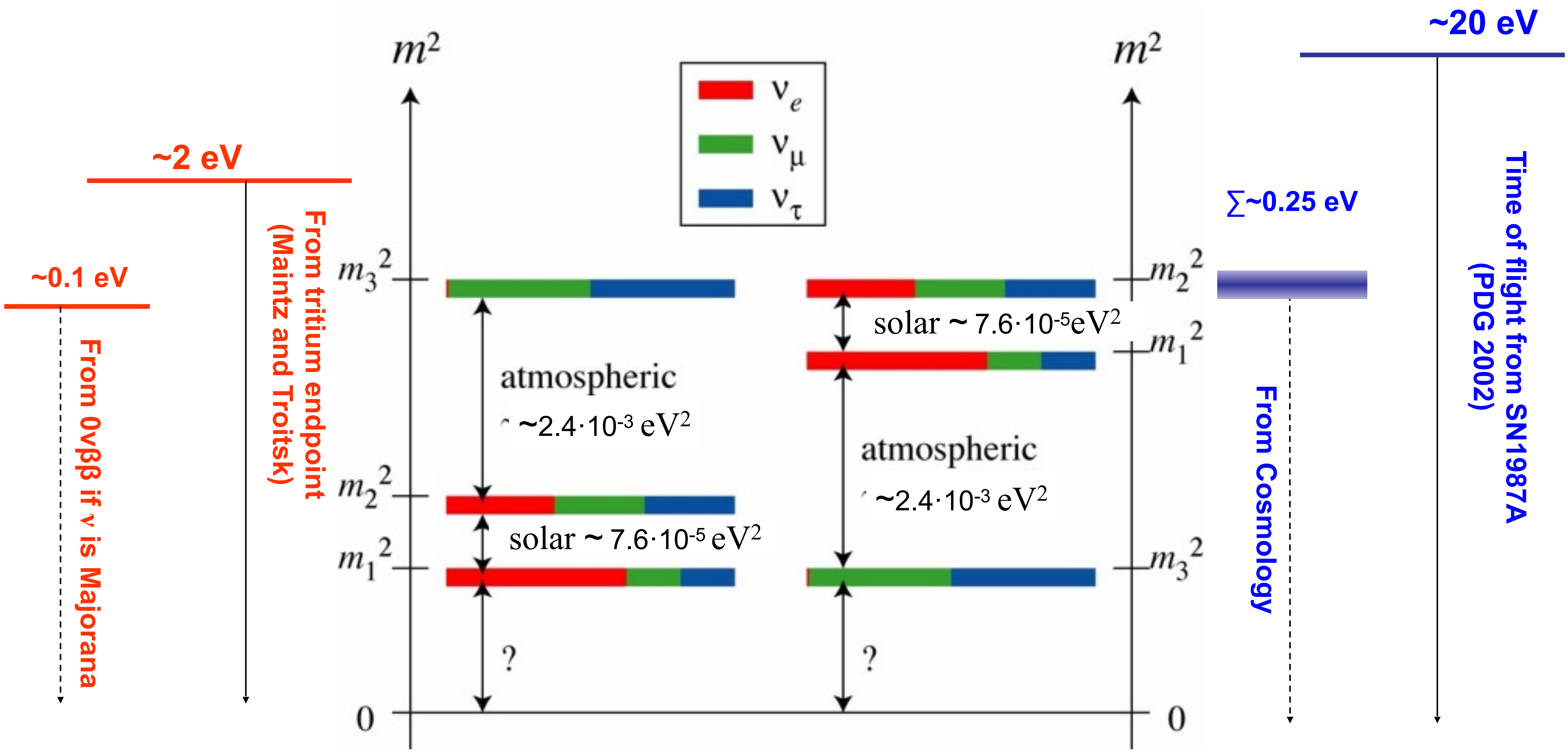




ν=ν̄ ?

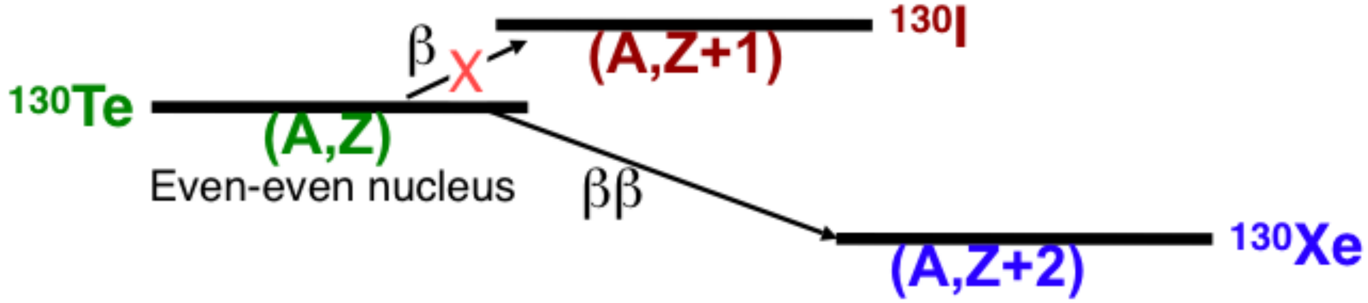


Absolute Neutrino Mass Scale



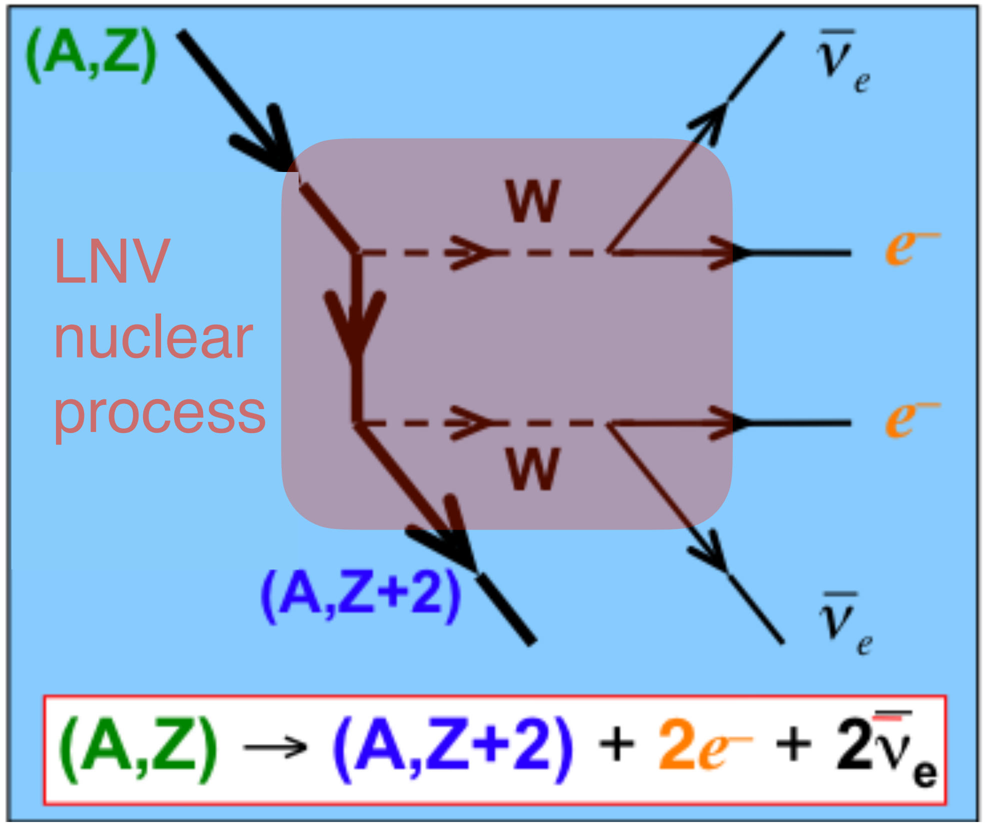
Two-neutrino double beta decay (2νββ)

for example…



Proposed in 1935 by
Maria Goeppert Mayer

(2νββ) $T_{1/2} \sim 10^{19} - 10^{21}$ yrs

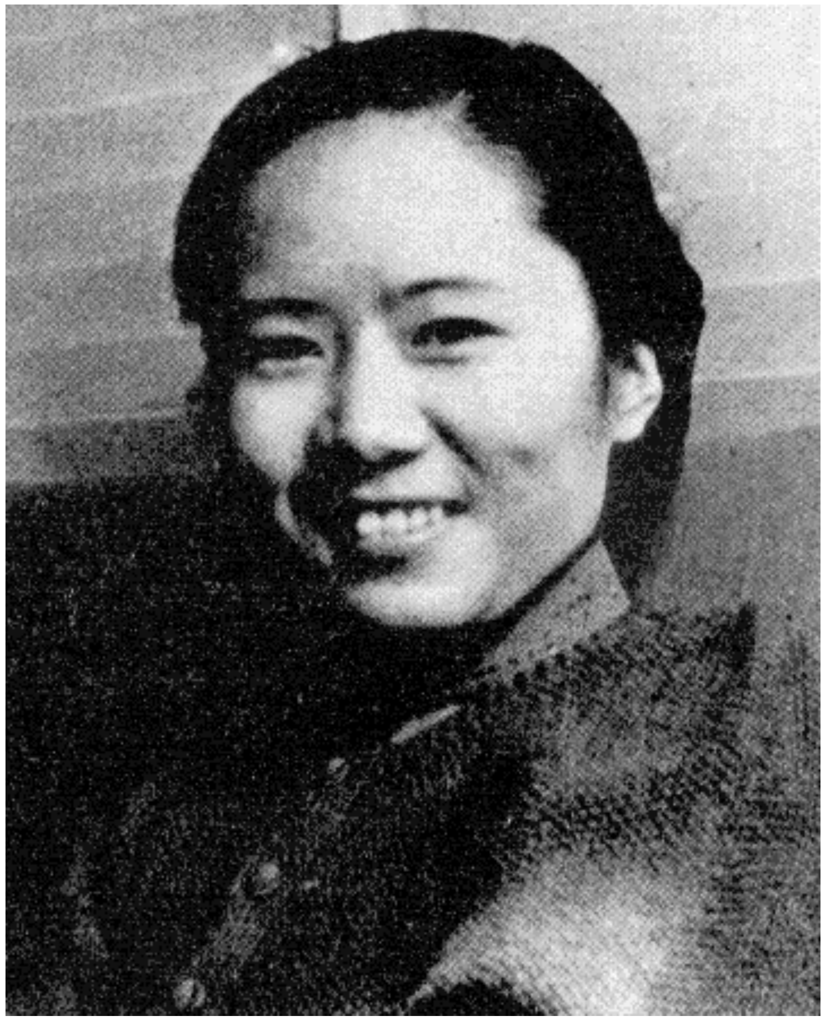


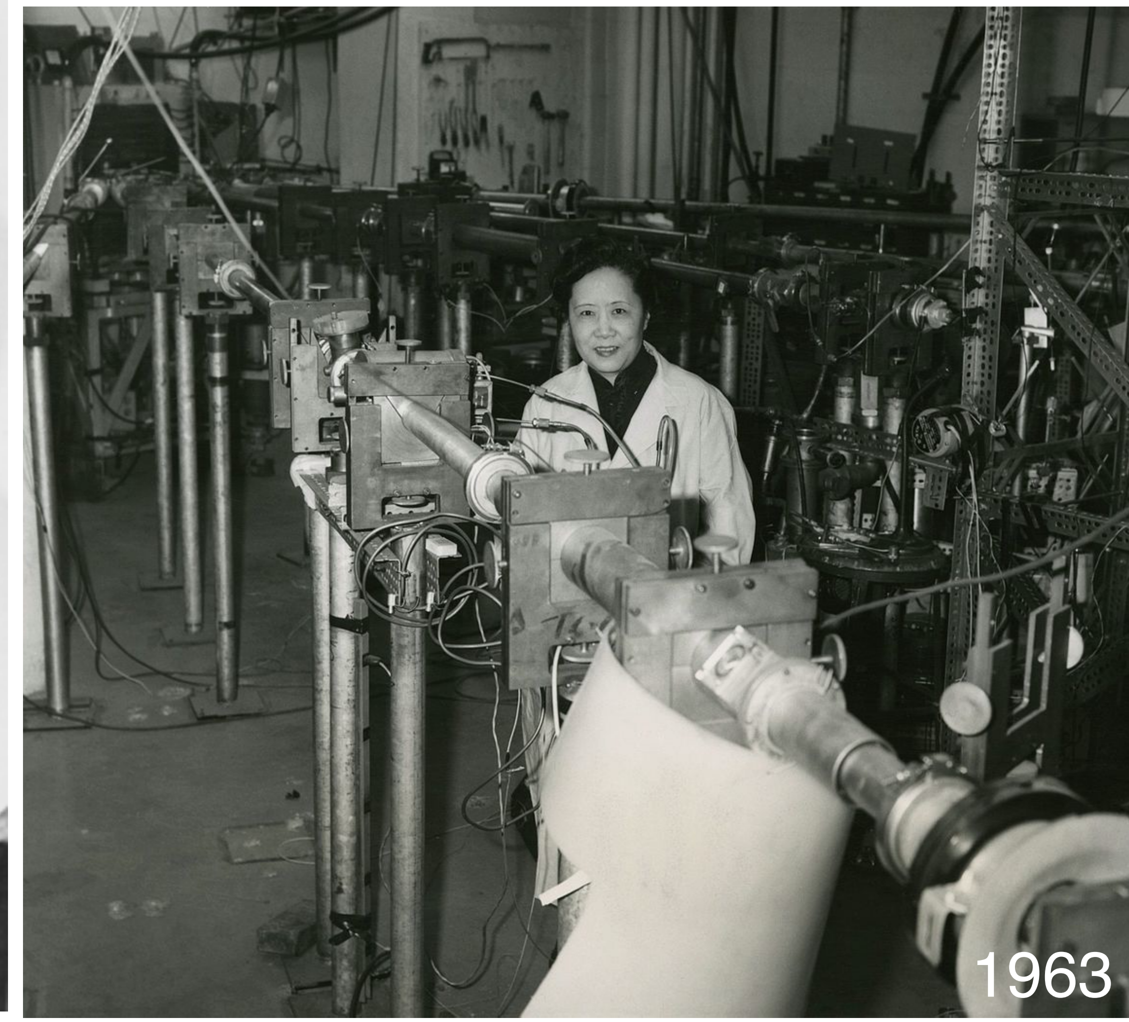
First direct observation by Moe, Elliott, and Hahn in ^{100}Mo (1988)

- Completely allowed process ✓
- Observed ✓
- No new physics beyond the Standard Model of Particle Physics

Maria Goeppert Mayer (1906 - 1972)

Parity Violation in Beta Decay: Chien-Shiung Wu
1912 - 1997 吳健雄





Parity violation in Weak Interaction
- Proposed by Lee & Yang in 1956
- Experimentally demonstrated by Wu, 1957

Lee & Yang:  1957

Parity Violation in Weak Interactions

Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

In a recent paper[1] on the question of parity in weak interactions, Lee and Yang critically surveyed the experimental information concerning this question and reached the conclusion that there is no existing evidence either to support or to refute parity conservation in weak interactions. They proposed a number of experiments on beta decays and hyperon and meson decays which would

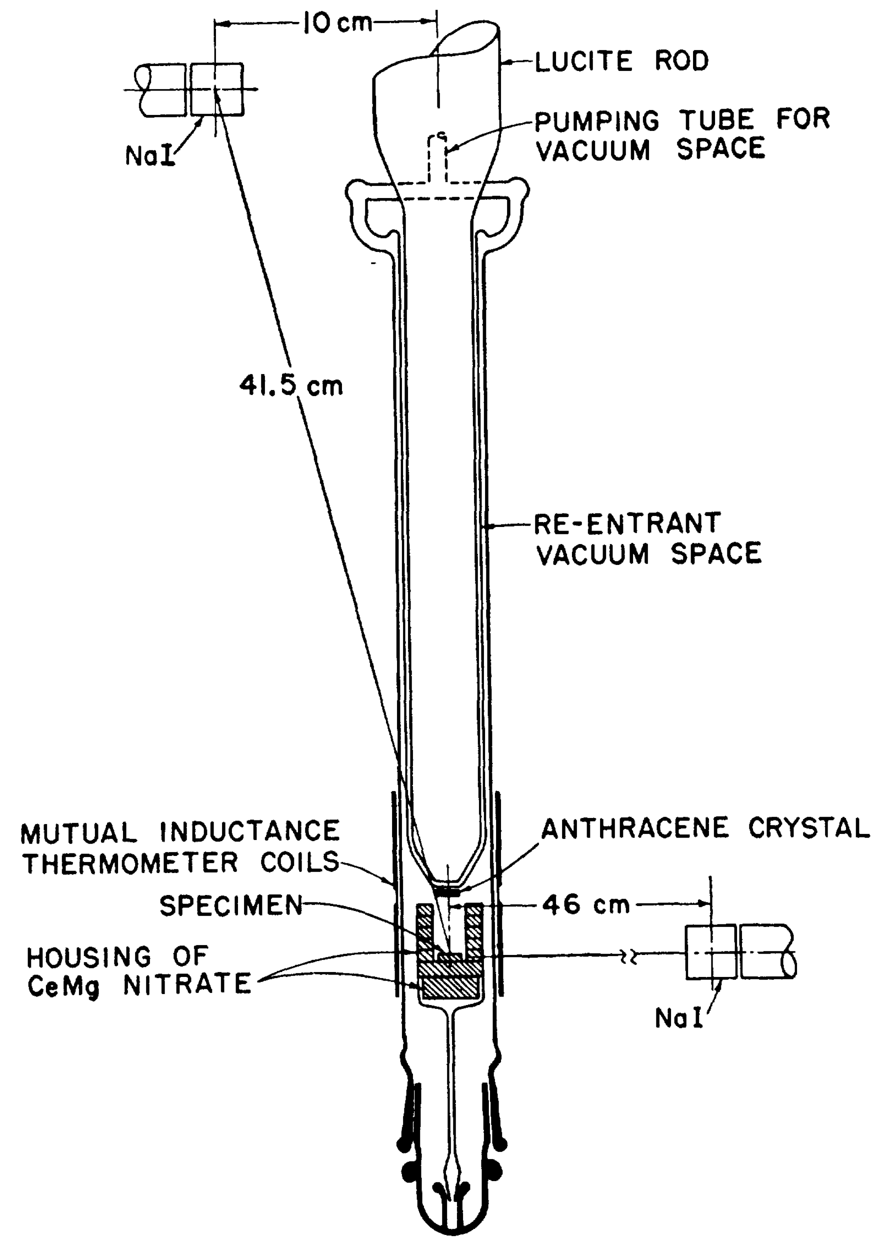


Fig. 1. Schematic drawing of the lower part of the cryostat.

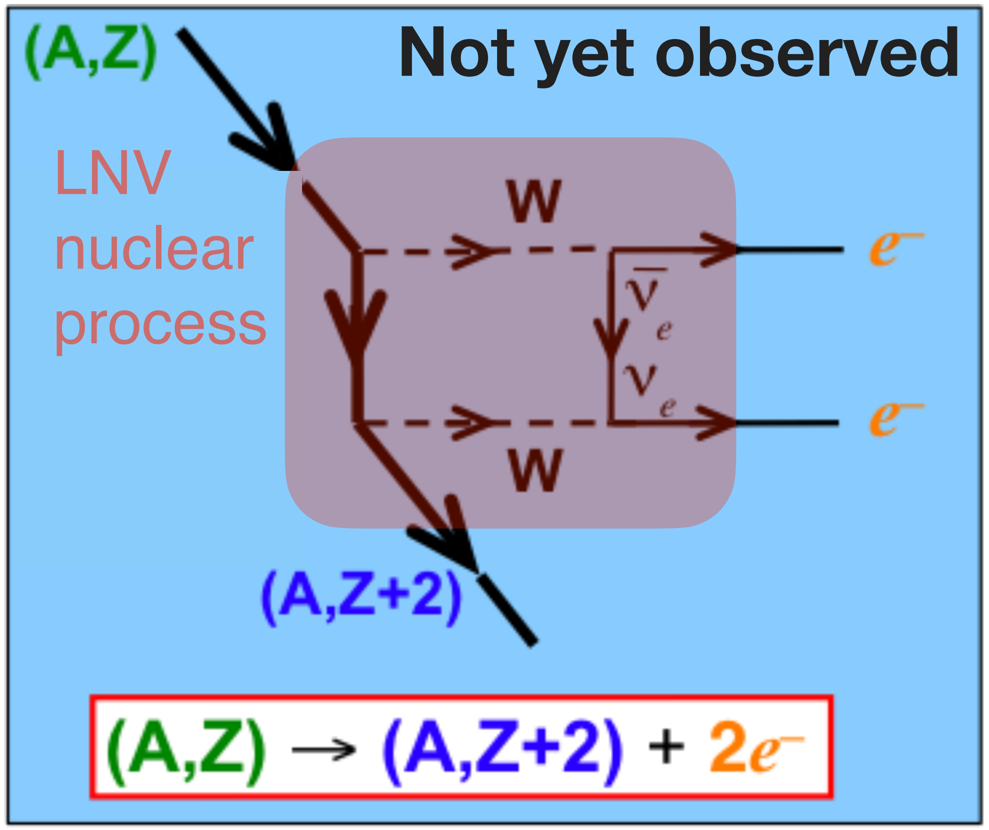
T.D.Lee and C.N.Yang, Phys.Rev.104,254 (1956)

C.S. Wu et al., Phys.Rev., 105.1413 (1957)

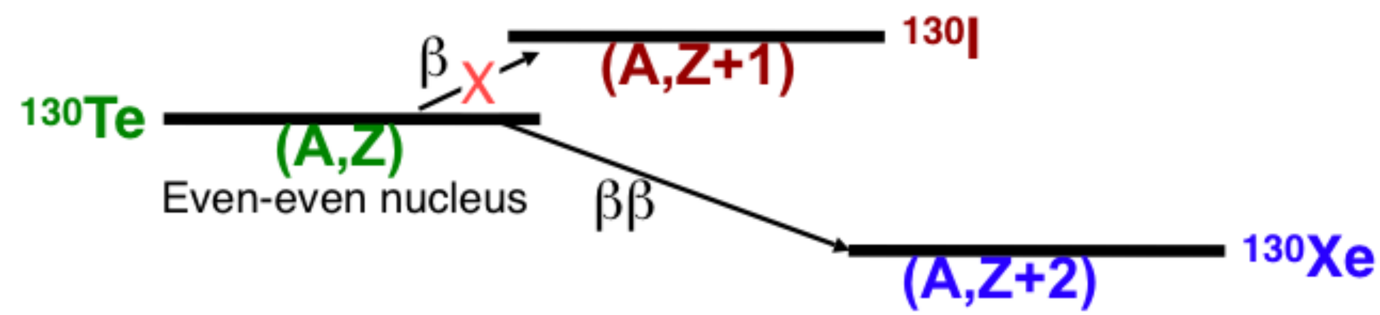
https://physics.aps.org/story/v22/st19

Zero-Neutrino Double Beta Decay (0νββ)

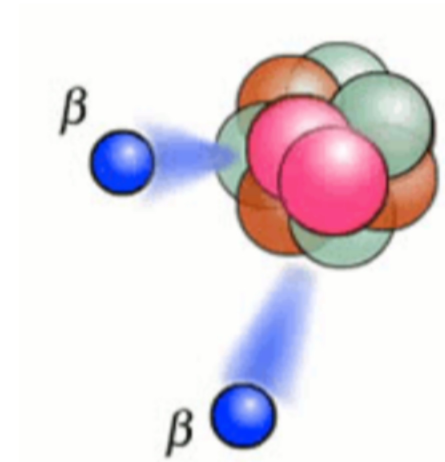
Proposed in 1937 by
Ettore Majorana



(0νββ) $T_{1/2} \geq 10^{26}$ y

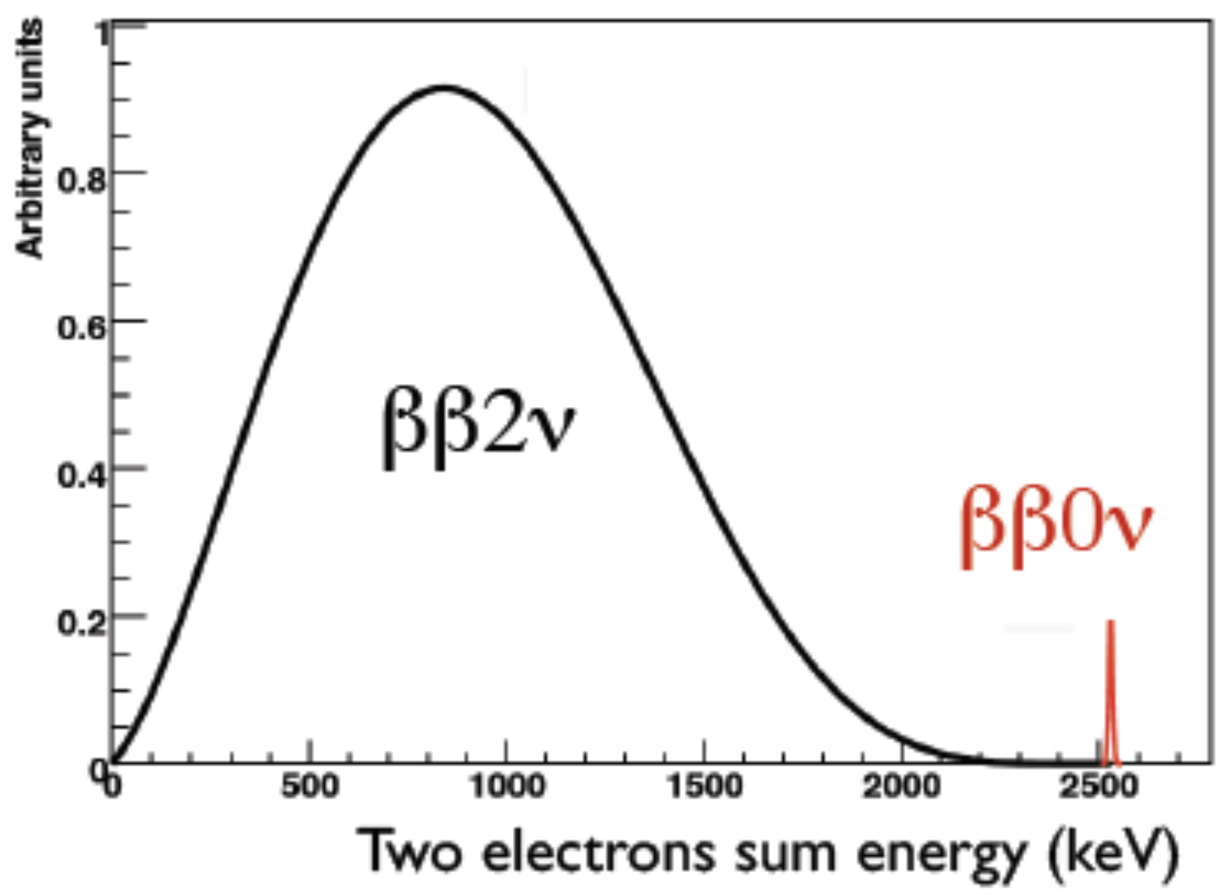


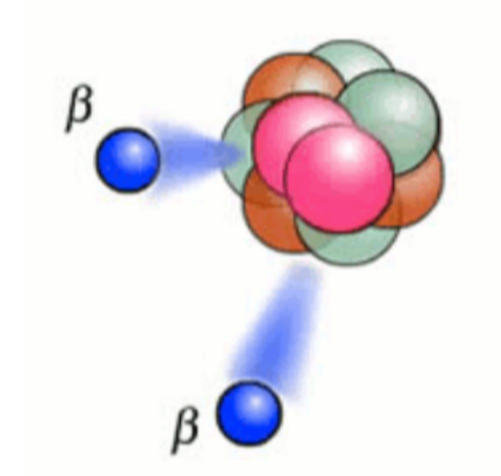
- Why is it interesting? Observation of 0vbb would mean…
  - Neutrinos must be Majorana particles (not Dirac)
  - New mass scale in nature
  - potential for absolute neutrino mass scale & hierarchy
  - explicitly violate lepton number
  - Key ingredient for standard baryogengesis via leptogenesis



Double Beta Decay Spectrum

Rev.Mod.Phys., 481-516 (2008)





compare to single beta decay

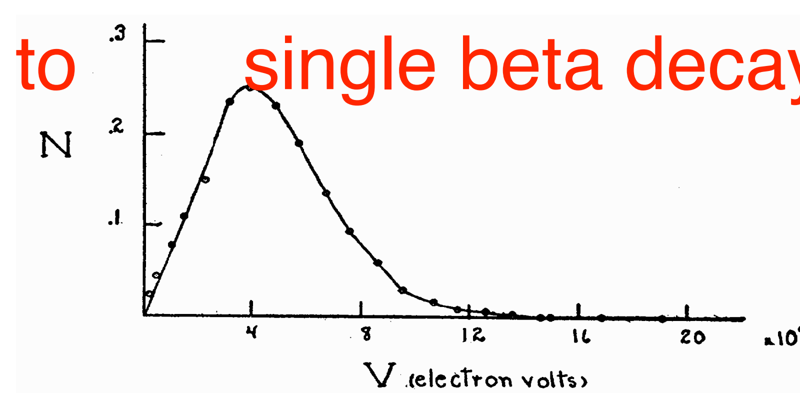


FIG. 5. Energy distribution curve of the beta-rays.

2νββ:
Sum of 2-β energies =>
spectrum similar to single beta decay

0νββ:
Sum of 2 β, full energy =>
sharp peak at end point

We measure half-lives

How Rare?

- Most measured half-lives for $2\nu\beta\beta$ are $O(10^{21})$ years
  (The longest directly observed process)
  - Compare to lifetime of the universe: 10^{10} years
  - Compare to Avogadro's number: 6×10^{23}
  - A mole of the isotope will produce ~1 decay / day
- If it exists, the half-lives of $0\nu\beta\beta$ would be much longer
  - ^{130}Te $0\nu\beta\beta$ limit is > 10^{24} years*
  - A mole of ^{130}Te produces < 1 neutrinoless decay / year
  - A half-life of 10^{26} years requires 32 kg of ^{130}Te to see 1 decay / year

Slide from J. Cushman

0νββ Decay rate

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 \frac{|\langle m_{\beta\beta}\rangle|^2}{{m_e}^2}$$

transition probability

$$\alpha \frac{m}{Q^2} \quad (Q \sim m_e)$$

phase space factor

$$G \sim G_F^4 g_A^4 m_e^5$$

nuclear matrix element

particle physics

e.g. virtual exchange of light Majorana neutrinos

$$\boxed{\langle m_{\beta\beta}\rangle = \sum_j |U_{ej}|^2 e^{i\alpha_j} m_j}$$

coherent superposition

PMNS matrix

Majorana phases

0νββ Decay rate

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 \frac{|\langle m_{\beta\beta}\rangle|^2}{{m_e}^2}$$

$$\begin{aligned} T^{0\nu}_{1/2} &= 0\nu\beta\beta \text{ half-life} \\ G^{0\nu}(Q,Z) &= \text{phase space factor } (\propto Q^5) \\ M^{0\nu} &= \text{nuclear matrix element} \\ \langle m_{\beta\beta}\rangle &= \text{effective } \beta\beta \text{ neutrino mass} \\ m_e &= \text{electron mass} \end{aligned}$$

For light neutrino exchange

PMNS Matrix

All 3 neutrinos will contribute: $\eta \sim m \rightarrow \langle m_{\beta\beta}\rangle = \sum_i U^2_{ie} m_i$

$m_{\beta\beta} \sim 1$ eV $\Longrightarrow T_{1/2} \sim 10^{24}$ years

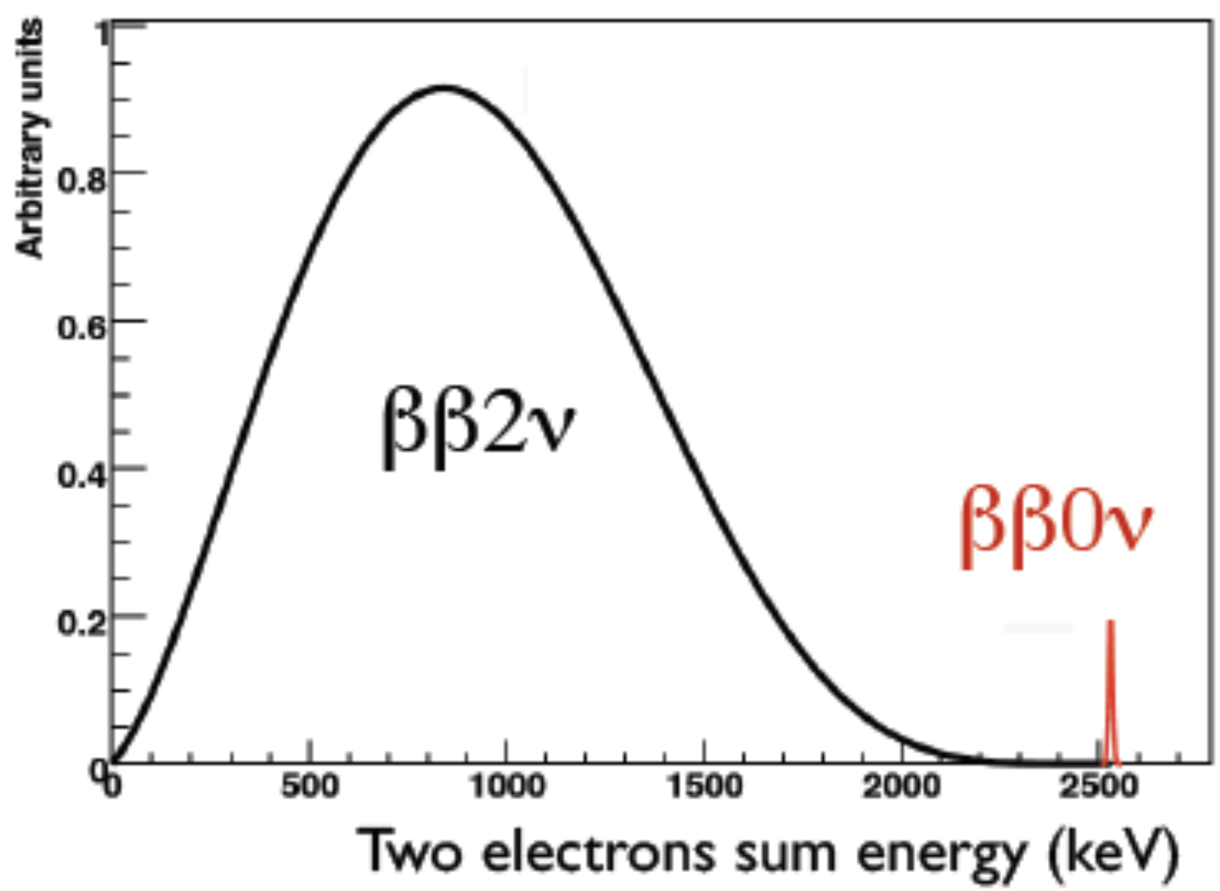
$m_{\beta\beta} \sim 0.1$ eV $\Longrightarrow T_{1/2} \sim 10^{26}$ years

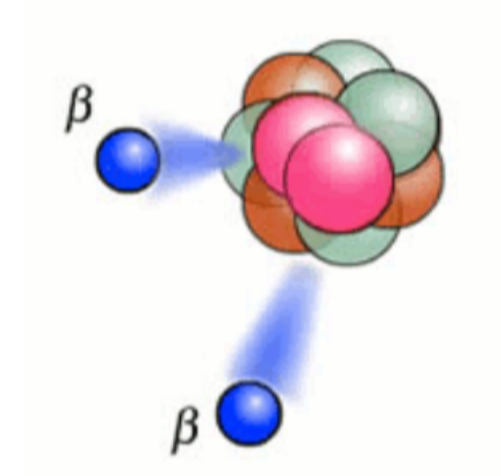
$m_{\beta\beta} \sim 0.01$ eV $\Longrightarrow T_{1/2} \sim 10^{28}$ years

Neutrinoless Double Beta Decay Experiments

Double Beta Decay Spectrum

Rev.Mod.Phys., 481-516 (2008)





compare to single beta decay

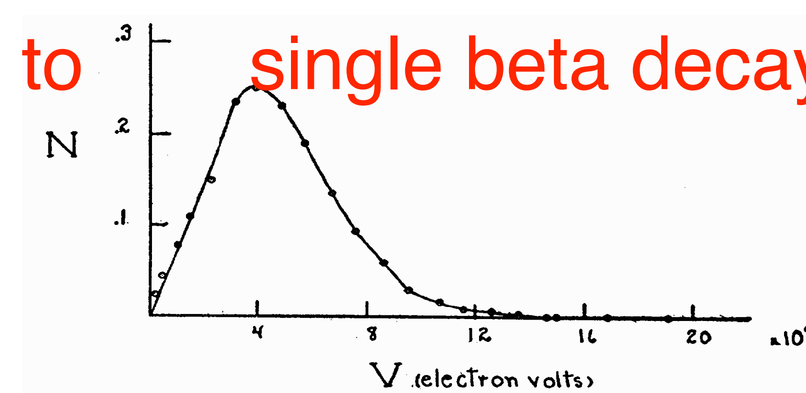


FIG. 5. Energy distribution curve of the beta-rays.

2νββ:
Sum of 2-β energies => spectrum similar to single beta decay

0νββ:
Sum of 2 β, full energy => sharp peak at end point

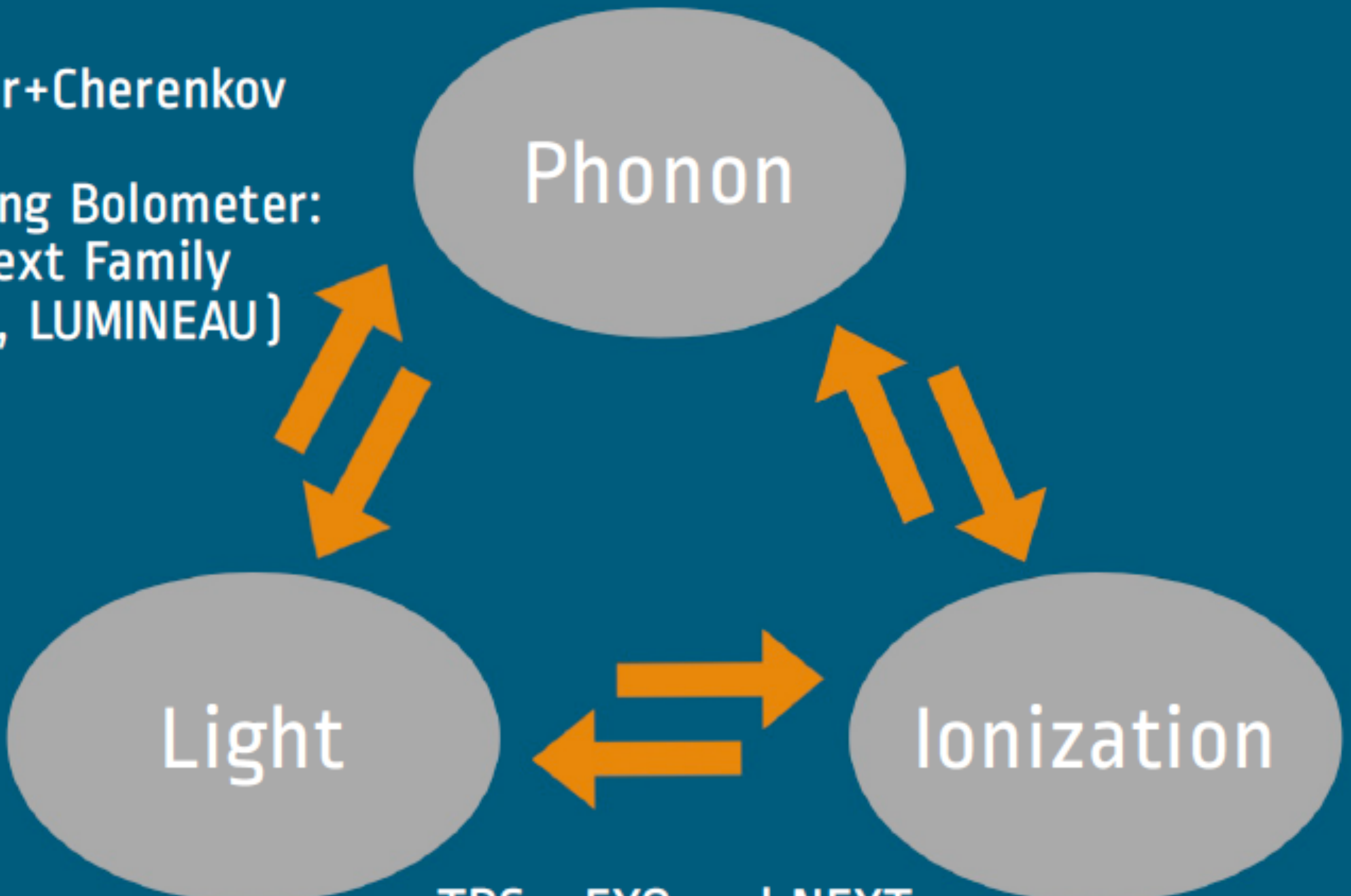
We measure half-lives

Choose a Signal:

A diagram that the direct dark matter experiments like to make.

CUORE

Bolometer+Cherenkov
or
Scintillating Bolometer:
CUORE-Next Family
(LUCIFER, LUMINEAU)
AmoRE



TPC: nEXO and NEXT

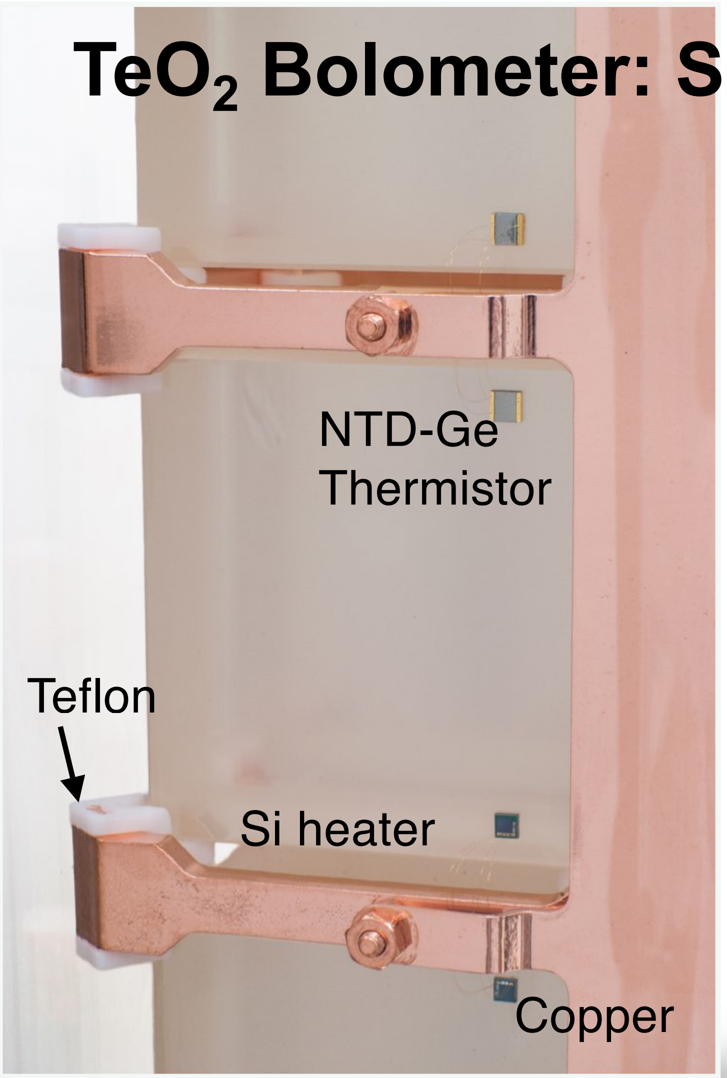
Liquid Scintillator:
KamLAND-Zen, SNO+
Scintillating Crystal:
CANDLES

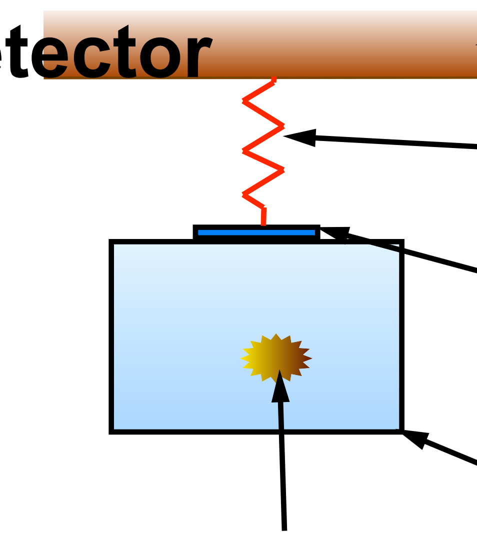
Semiconductor:
GERDA/Majorana
Tracking:
SuperNEMO, DCBA

L. Winslow

CUORE Bolometer

TeO_2 Bolometer: Source = Detector

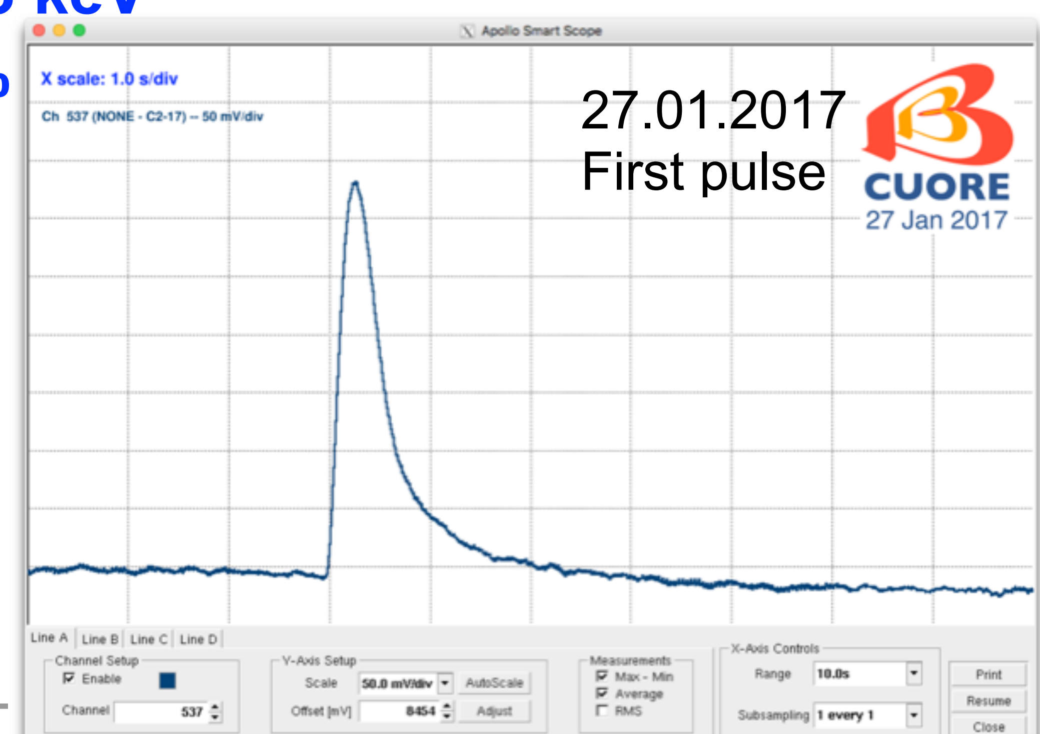




Heat sink:
Cu structure (10 mK)
Thermal coupling:
Teflon (G = 4 pW/mK)
Thermometer:
NTD Ge-thermistor (100 kΩ/μK)
Absorber:
TeO_2 crystal
(C ≅ 2 nJ/K ≅ 1 MeV / 0.1 mK)

deposited energy

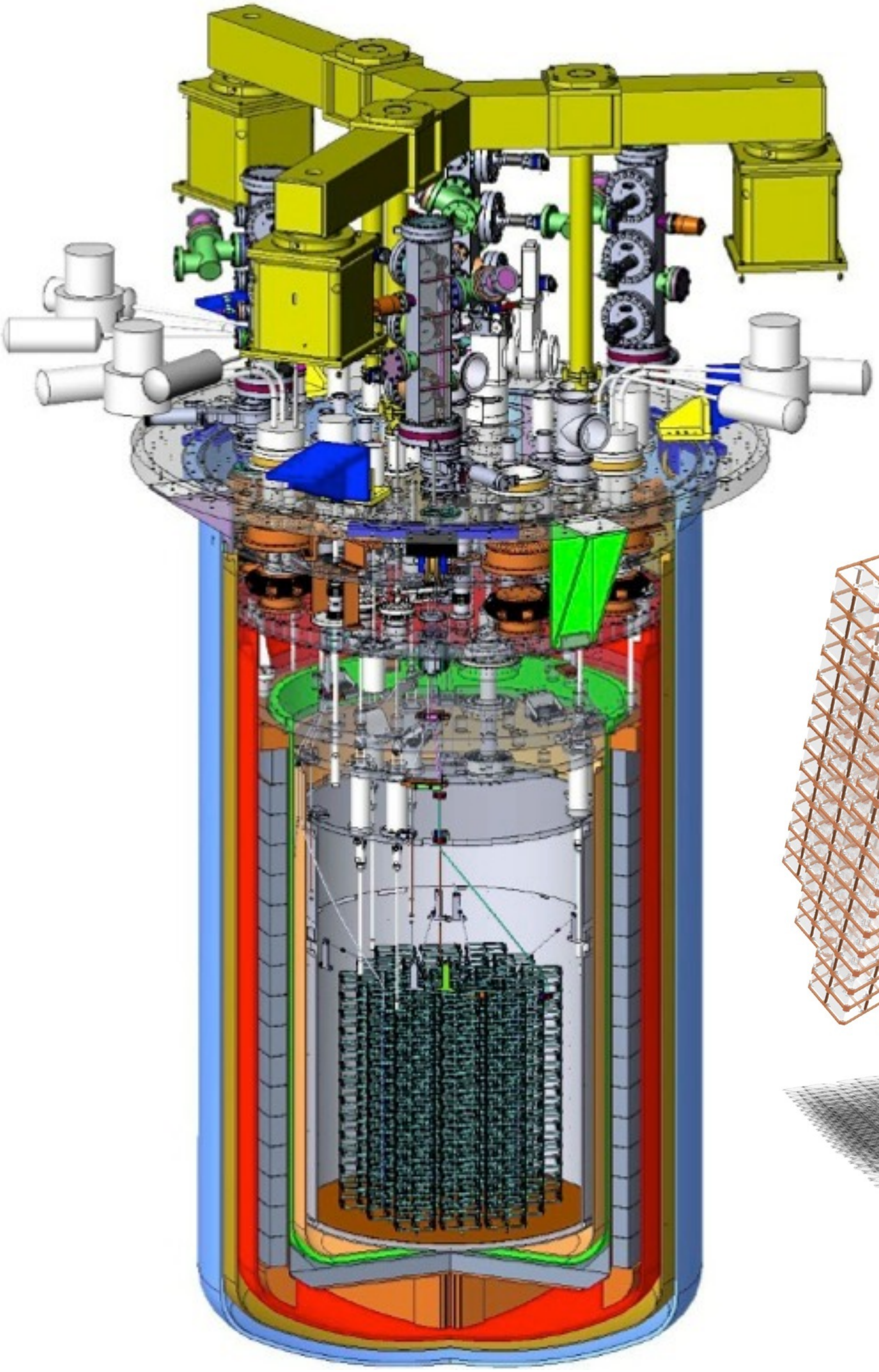
main candidate isotope: ^{130}Te
Q-value: 2526.515 ± 0.013 keV
Isotopic abundance: 34%



For E = 1 MeV: $\Delta T = E/C \cong 0.1$ mK
Signal size: 1 mV

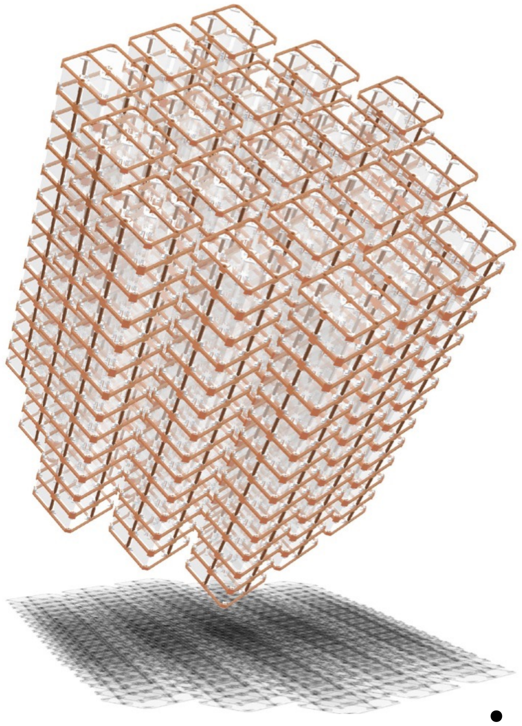
Time constant: $\tau = C/G = 0.5$ s
Energy resolution: ~ 5-10 keV at 2.5 MeV

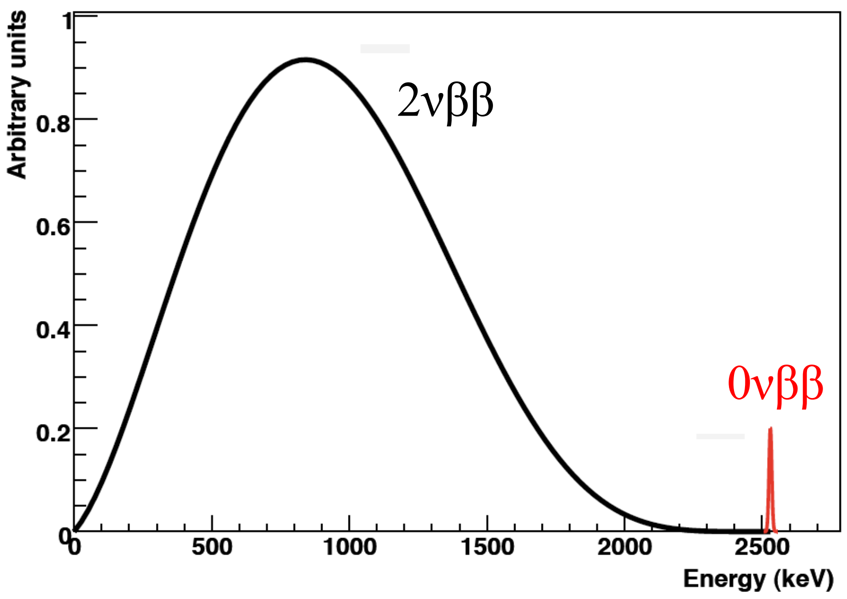
CUORE



Cryogenic Underground Observatory for Rare Events

- 988 TeO_2 crystals run as a bolometer array
  - 5x5x5 cm^3 crystal, 750 g each
  - 19 Towers; 13 floors; 4 modules per floor
  - 742 kg total; 206 kg ^{130}Te
  - 10^{27} ^{130}Te nuclei



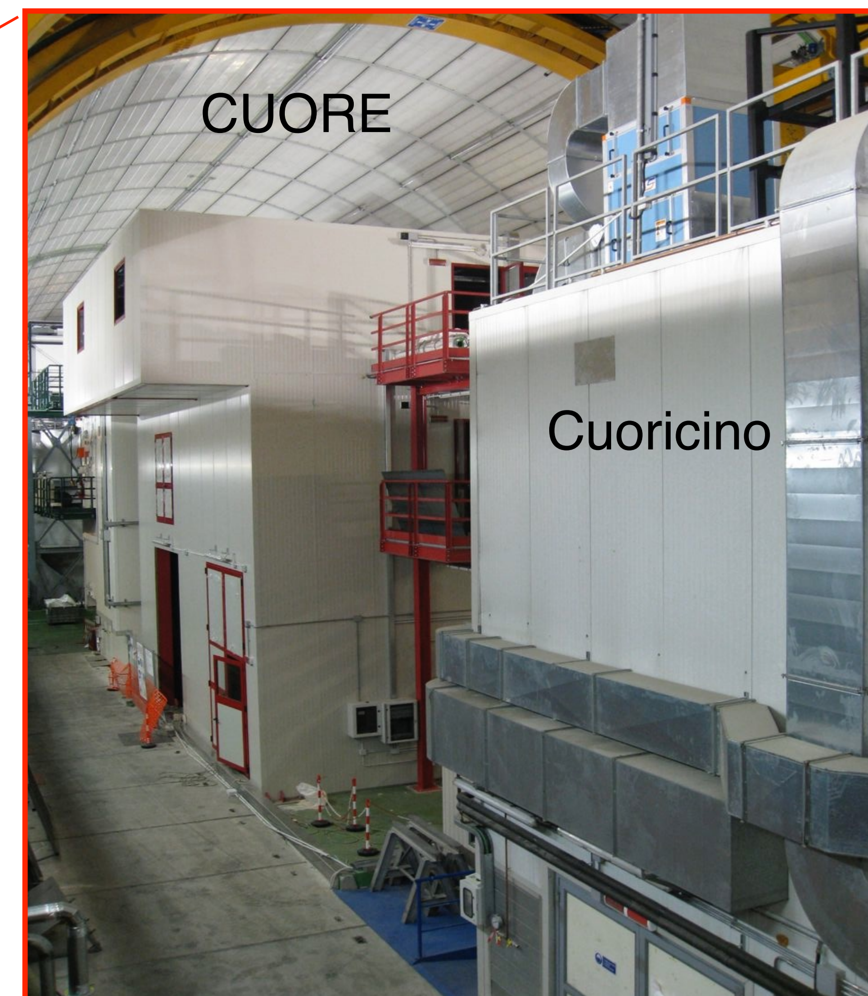


- New pulse tube dilution refrigerator and cryostat
- Radio-pure material and clean assembly to achieve low background in region of interest (ROI)

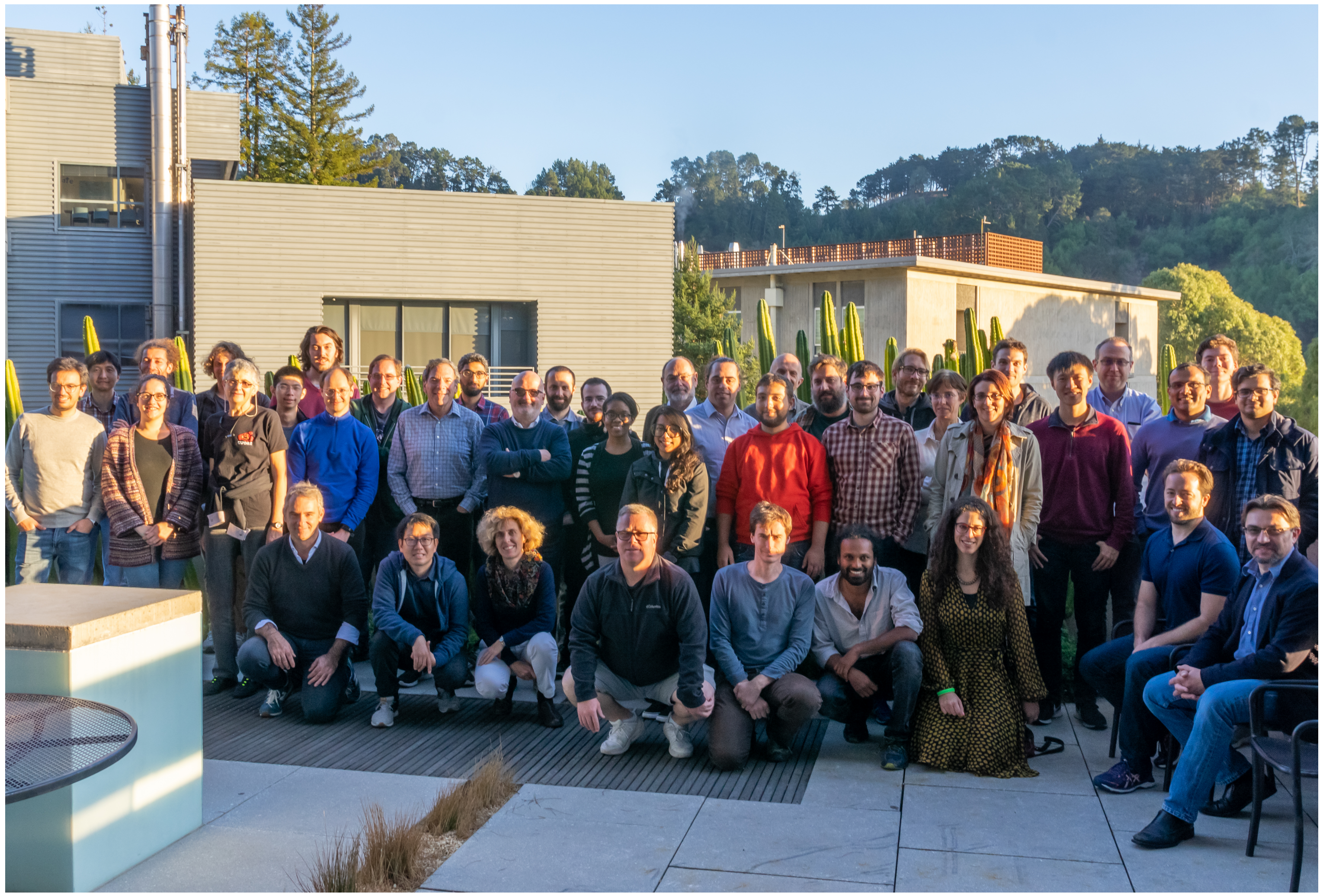
Gran Sasso National Lab, Italy

1.4-km avg. rock overburden
= 3100 m.w.e. flat overburden

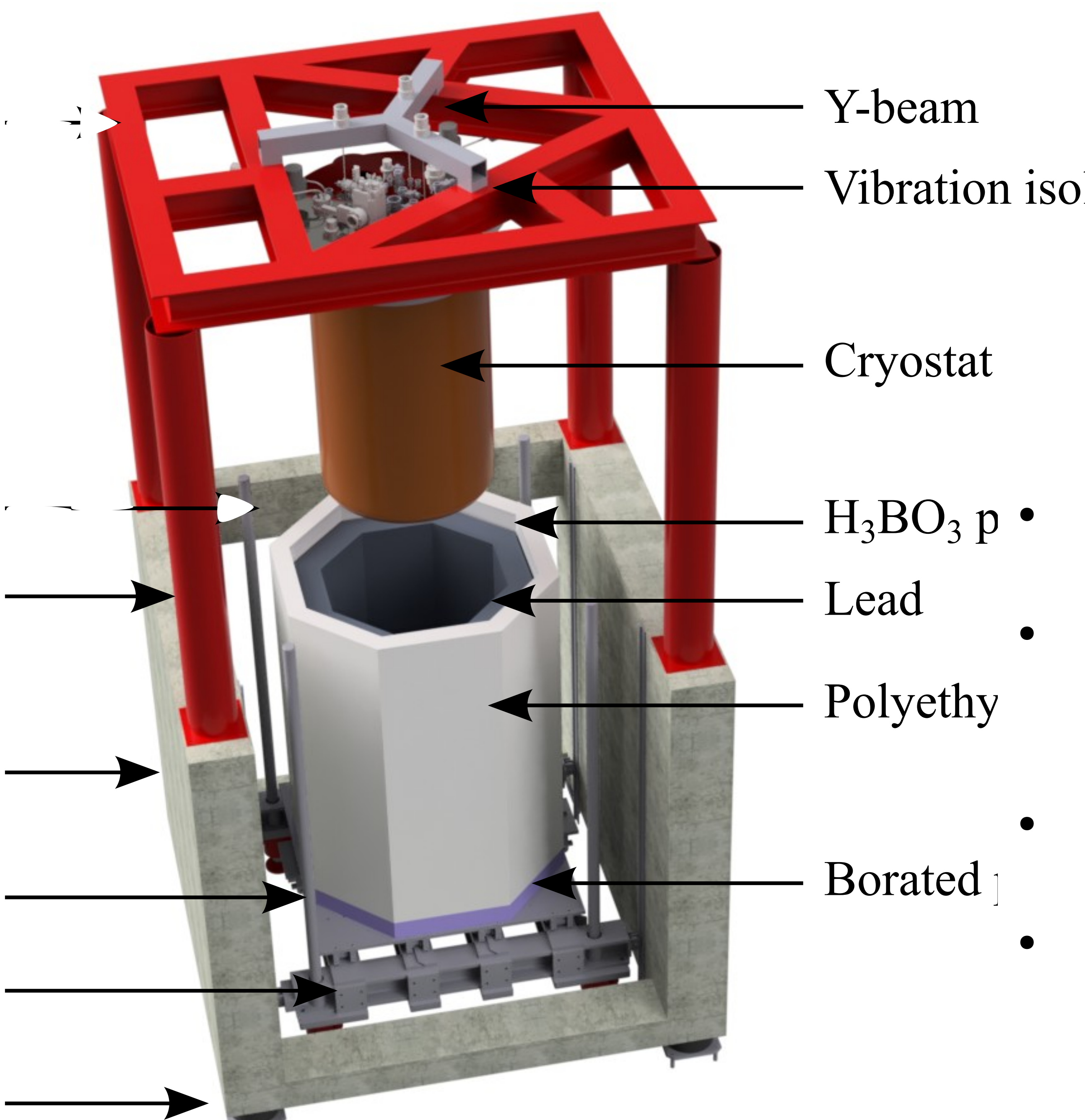
factor 10^6 reduction in muon flux to ~ 3×10^{-8} μ/(s cm^2)

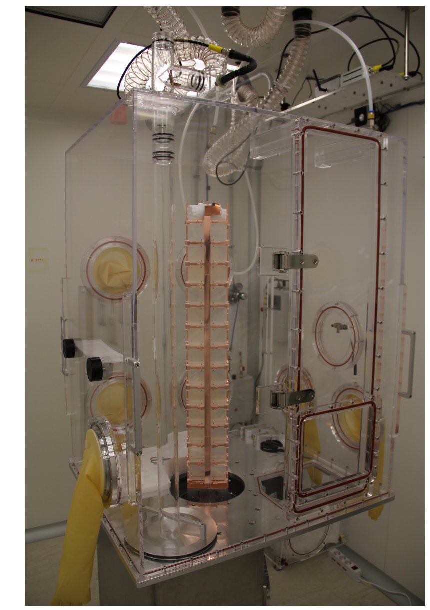


CUORE Experiment



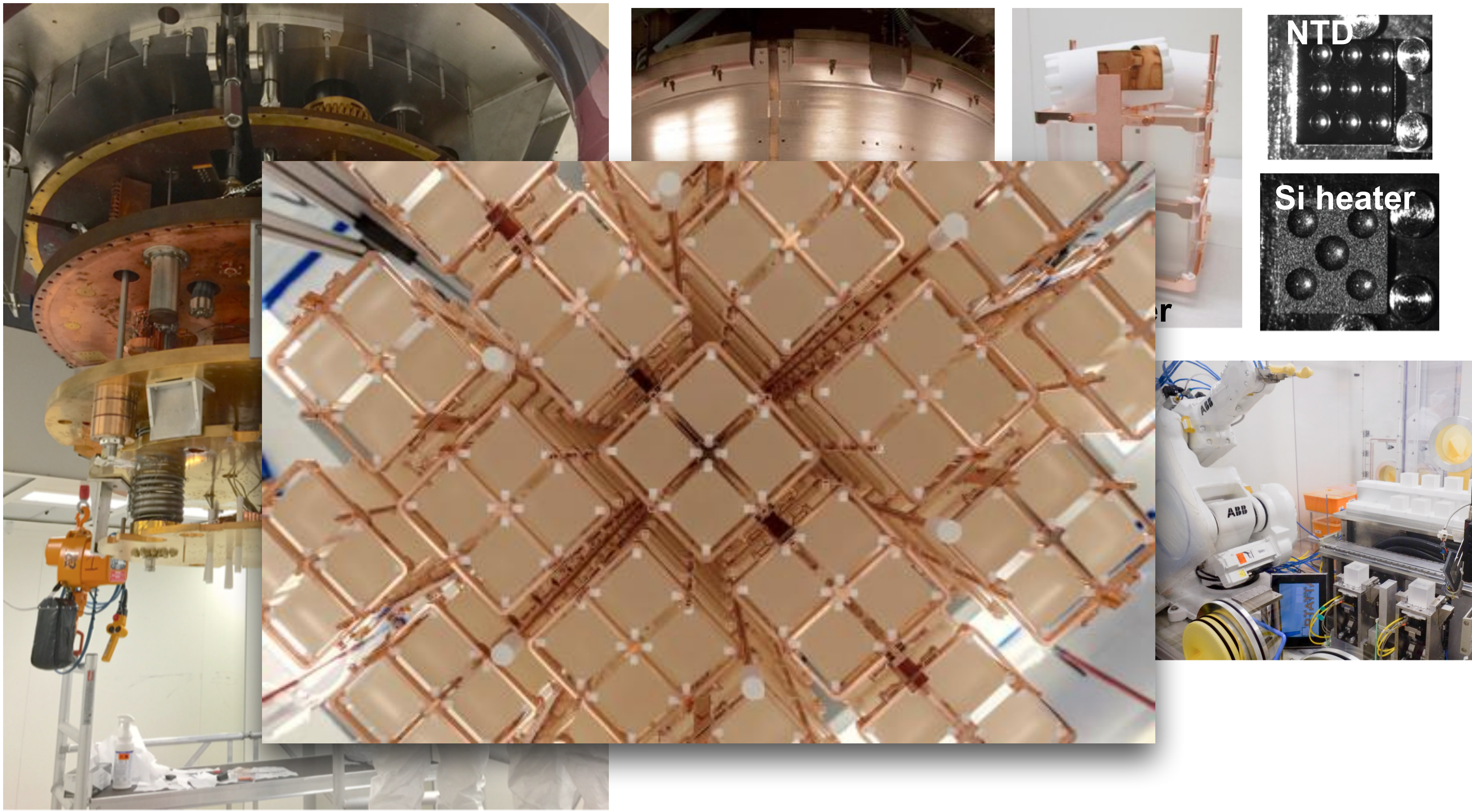
Low Background Experiment



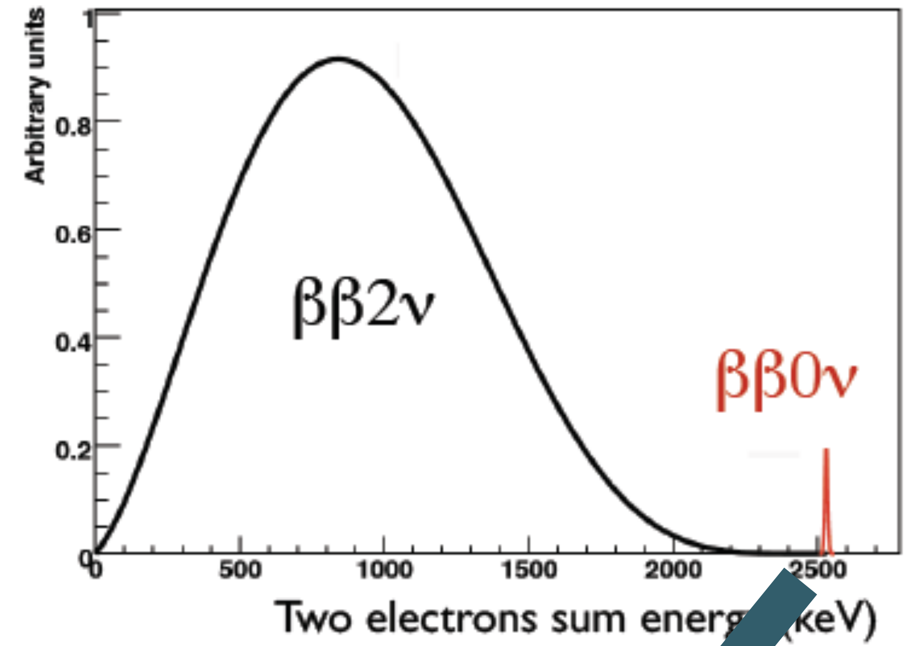


- Natural shielding from rock
- Passive lead, polyethylene, and H_3BO_3 shielding
- 70 tonne of lead, 7 tonne of cold lead
- Material selection: Ancient Lead and low radioactive copper
- Active background veto

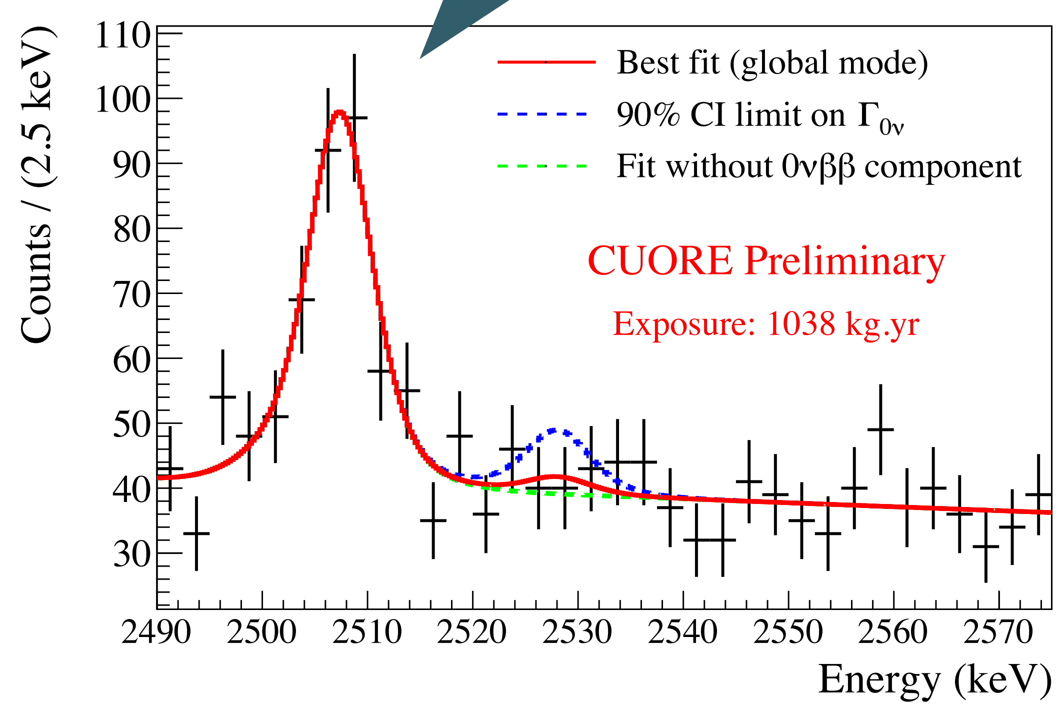
CUORE fabrication & cryostat commissioning



CUORE Results

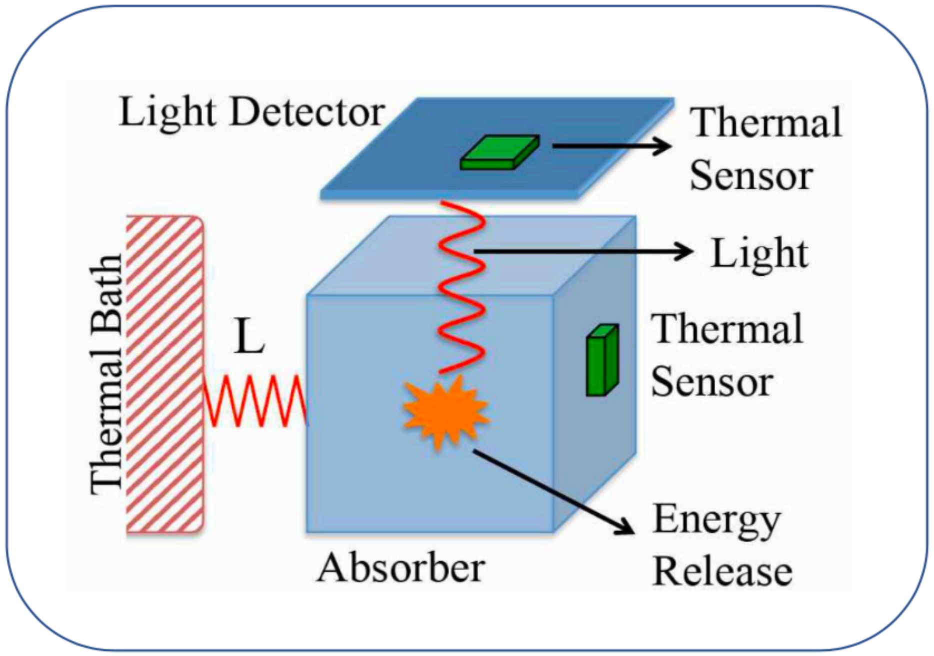


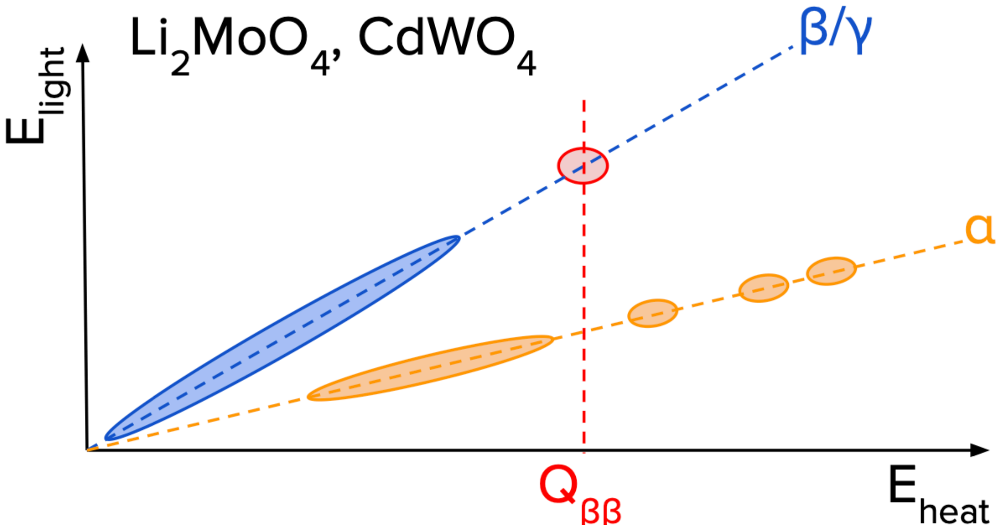
- No evidence of 0νββ
- Best fit rate: **(0.9 ± 1.4)x10^{-26}** yr^{-1}
- Background index = **1.49(4)x10^{-2}** cts/keV/kg/yr
- $T^{0\nu}_{1/2}$ > **2.2 x10^{25}** yr at 90% C.I

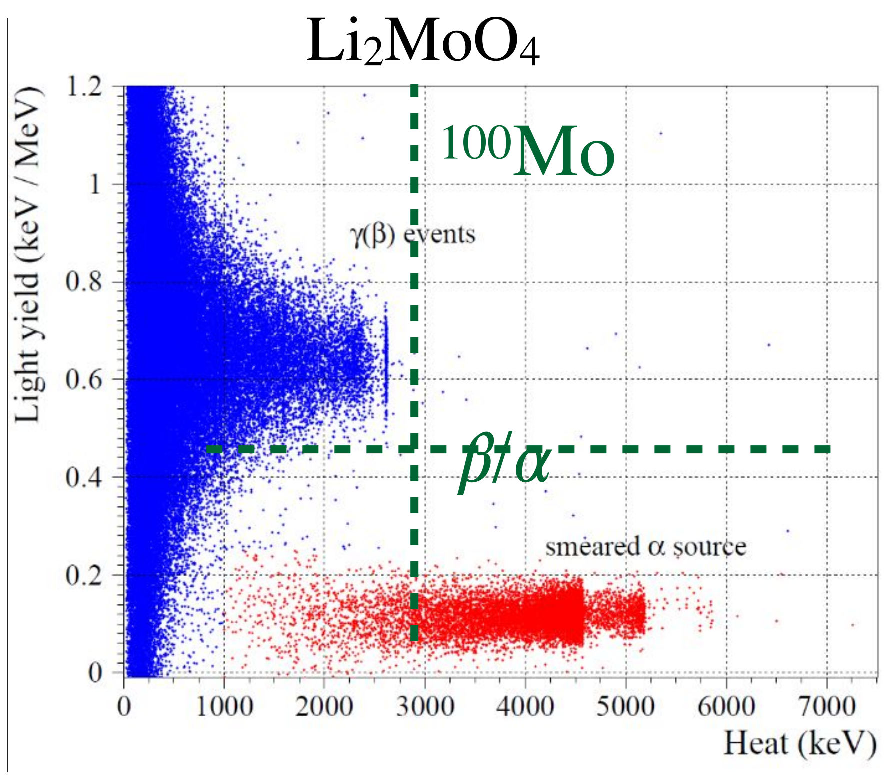


What's Next? CUPID

CUPID ^{100}Mo
heat + light
(scintillating bolometer)







Measure heat and light from energy deposition

Heat is particle independent, but light yield depends on particle type

Actively discriminate α using measured light yield

CUPID Detector

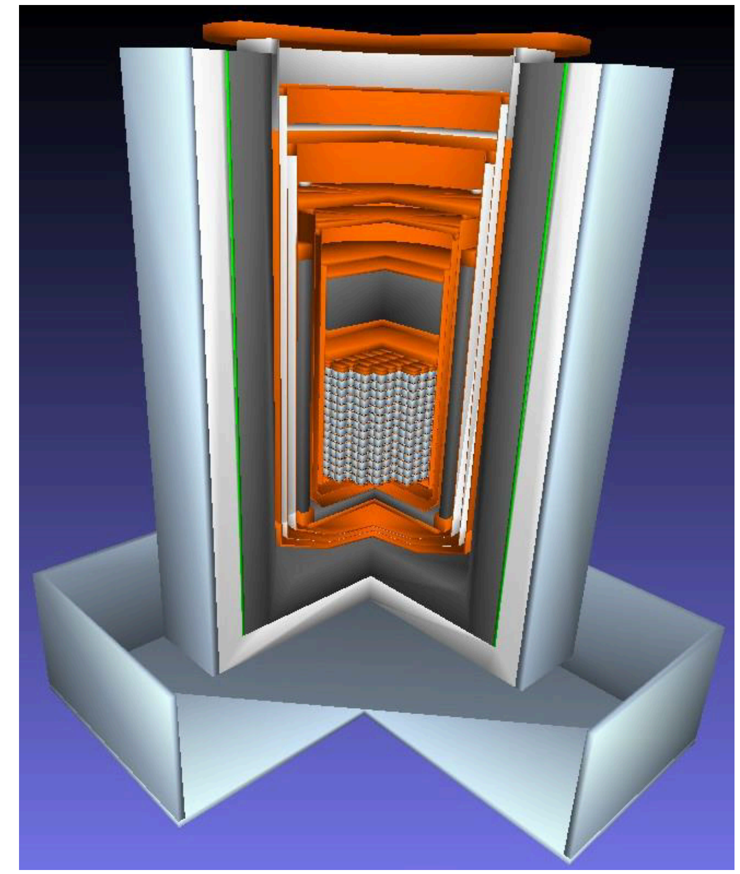
Single module: $Li_2{}^{100}MoO_4$, 45x45x45 mm, 280 g

Detector: 57 towers of 14 floors with 2 crystals each, 1596 crystals

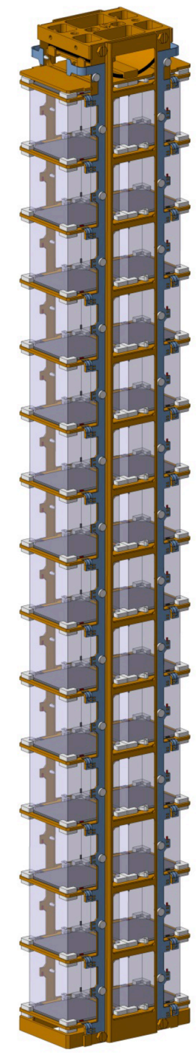
~240 kg of ^{100}Mo with >95% enrichment

~$1.6.10^{27}$ ^{100}Mo atoms

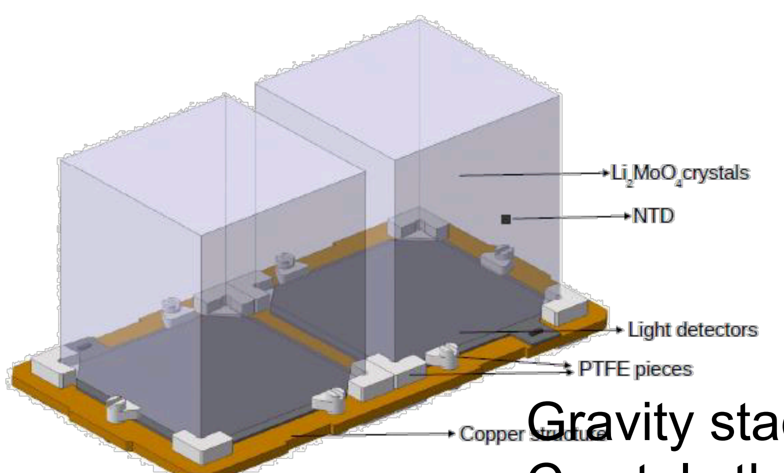
Ge light detector as in CUPID-Mo, CUPID-0



Tower

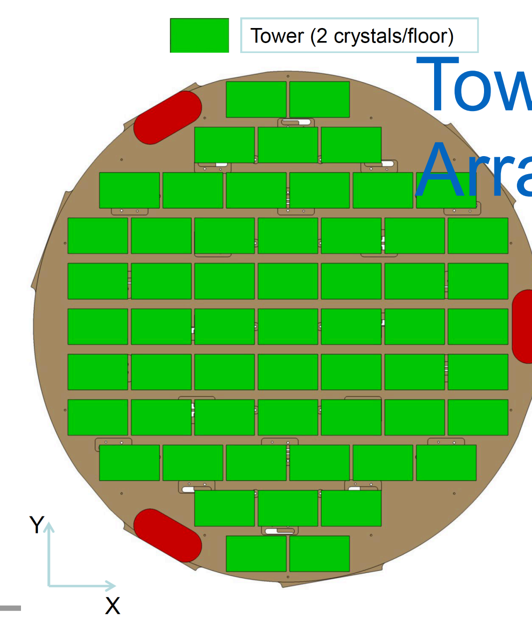


Detector Module



Gravity stacked structure
Crystals thermally interconnected

Tower Arrangement



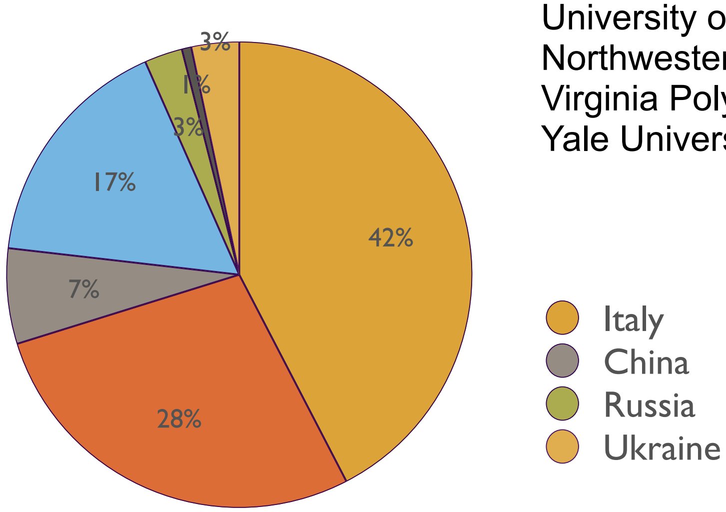
CUPID Collaboration

International collaboration builds on Italian-US partnership

Countries	Authors
Italy	64
USA	42
France	25
China	10
Ukraine	5
Russia	4
Spain	1

US Institutions

Argonne National Laboratory
Boston University
California Polytechnic State University
University of California, Los Angeles
University of California, Berkeley
Drexel University
Johns Hopkins University
Lawrence Berkeley National Laboratory
Massachusetts Institute of Technology
University of South Carolina
Northwestern University
Virginia Polytechnic Institute and State Unive
Yale University



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