复旦大学
现代物理研究所|核科学与技术系

Jinping bolometric experiment for neutrinoless double beta decay search

Long Ma

Institute of modern physics, Fudan University

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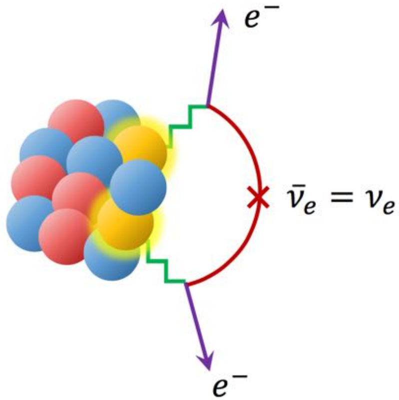
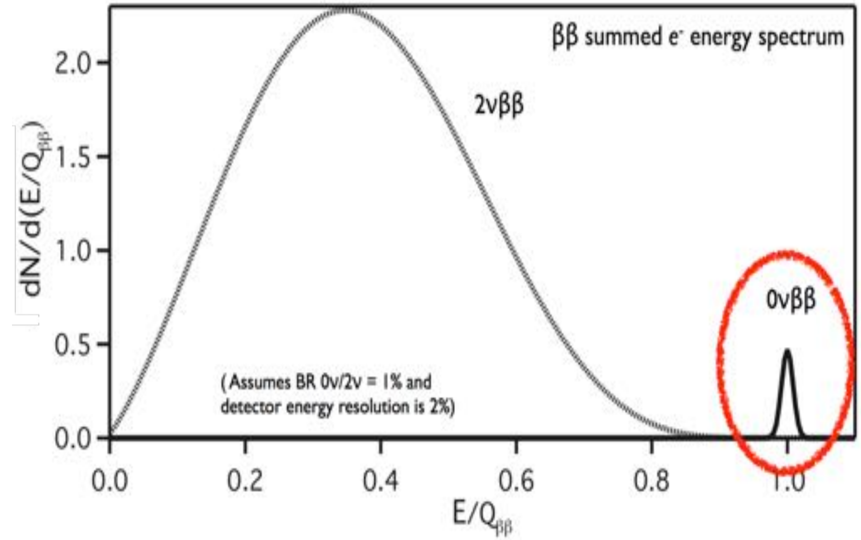
Outline

- Neutrinoless double beta decay ($0\nu\beta\beta$)
- Bolometric experiment
- CUPID-CJPL
- R&D progress
- Roadmap

Neutrinoless double beta decay (0νββ)





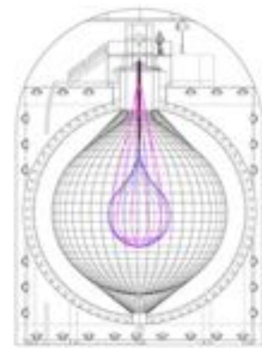
$$^{A}_{Z}X_{N} \longrightarrow {}^{A}_{Z+2}X_{N-2} + 2e^{-}$$

Observation of 0vDBD:

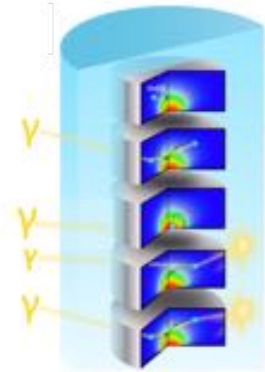
1) Show the Majorana property of neutrino: $\bar{\nu} = \nu$
2) Direct evidence of lepton number violating process
3) Model-dependent measurement of absolute neutrino mass
4) Plausible scenarios for the origin of the baryon asymmetry of the universe

0νββ experiment

CUORE
CUPID

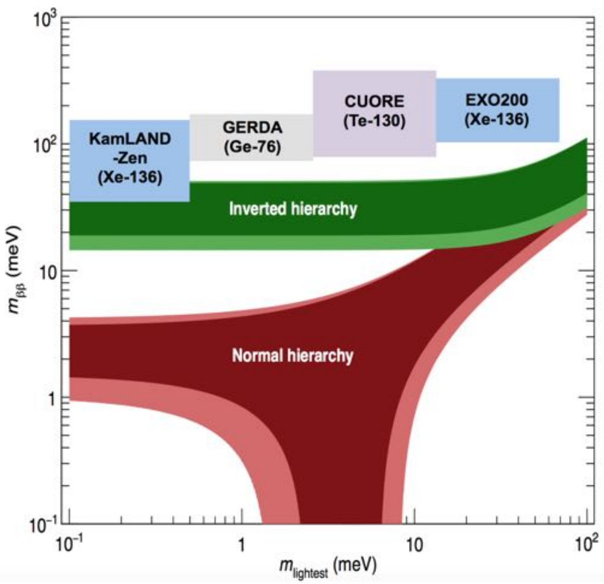


Kamland-zen
JUNO-0νββ



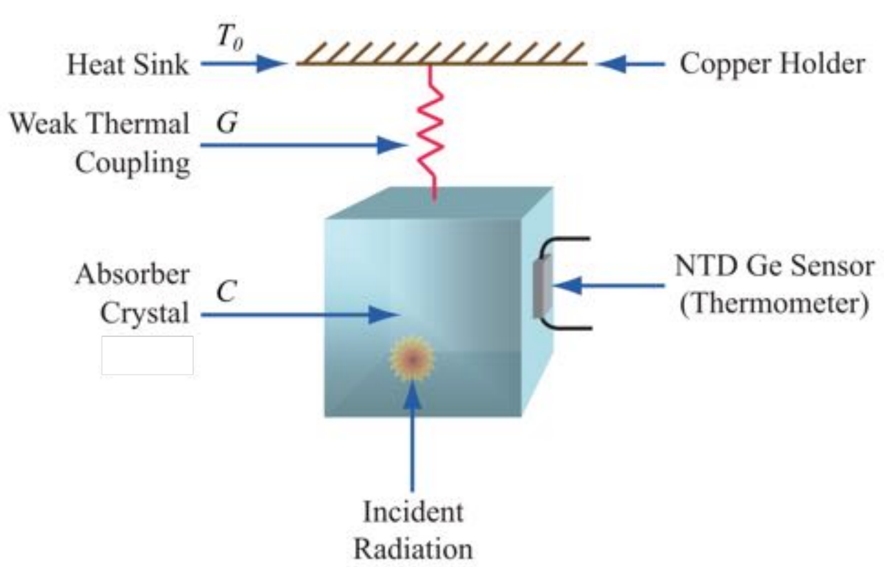
GERDA
LEGEND
CDEX-300ν

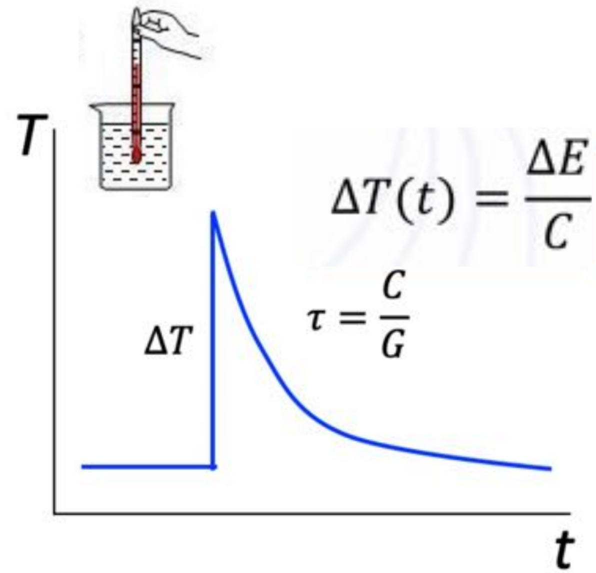
LXe: EXO-200
PandaX
HPG: PandaXIII
NνDEX



- Multiple technologies applied for 0νββ search
- Experiments based on different isotopes achieved comparable measurement sensitivity
- The next generation experiments will explore the full inverted hierarchy region of the neutrino effective Majorana mass

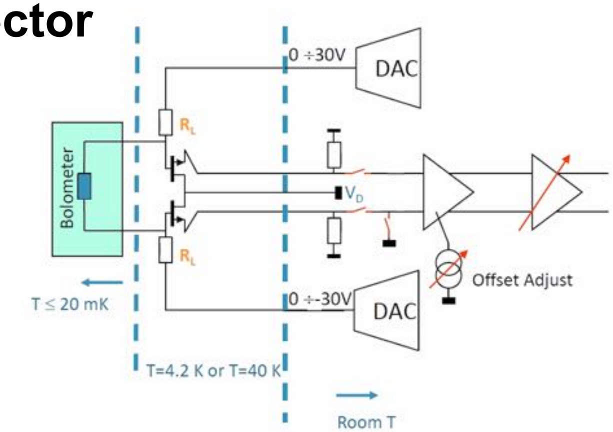
Cryogenic bolometer



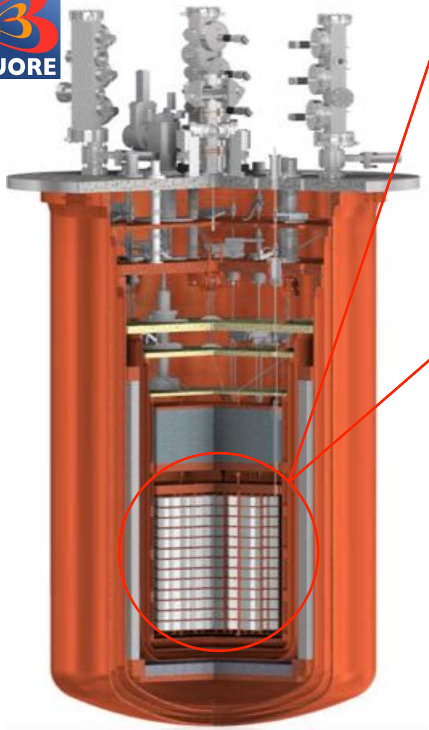


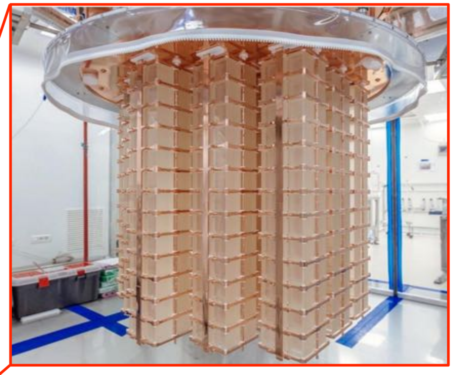
Cryogenic bolometer: low temperature particle detector

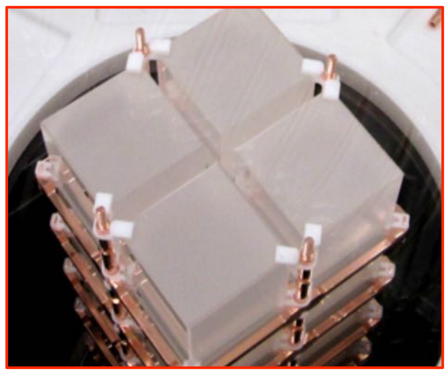
- Working at extreme low temperature (~10mK)
- High sensitivity measurement of energy deposition
- High detection efficiency (>85%) : source = detector
- High energy resolution (~0.25% FWHM)
- ➢ NTD-Ge bolometer: based on NTD-Ge thermistor (developed by LBL, Beeman)

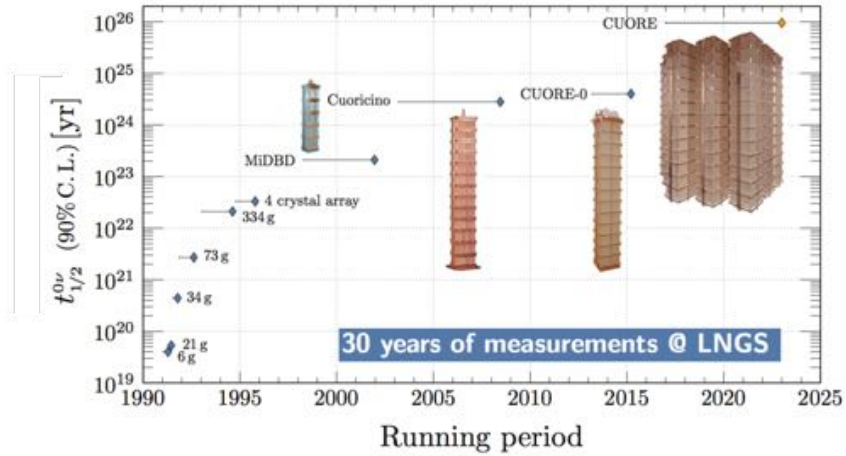


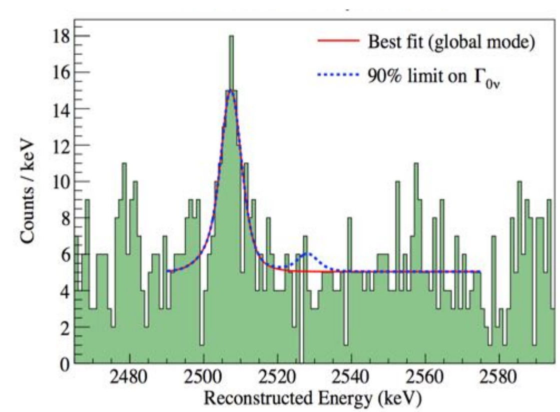
The CUORE experiment







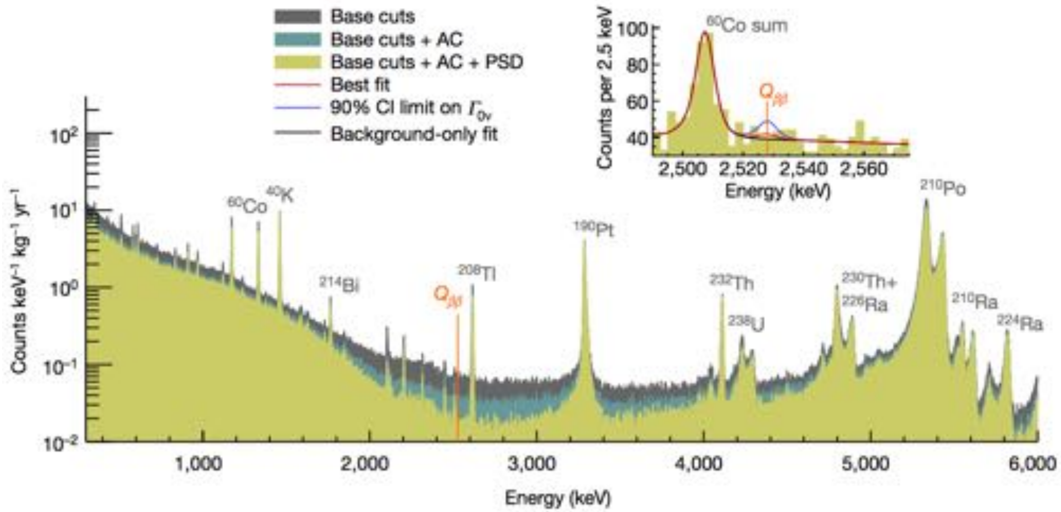


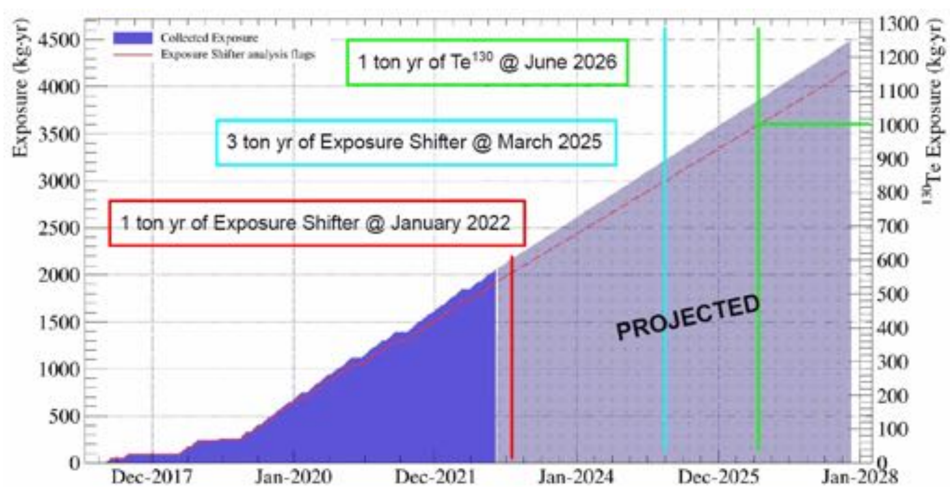


- 15 ton @4K; ~1 m^3 @6mK
- 988 TeO_2 crystals (total mass: 742kg)
- ^{130}Te mass： 206kg
- Physics goal： ^{130}Te 0νββ

Γ_E~7.0 keV(FWHM) @ 2615keV
BI(ROI): 0.0138 cts/keV/kg/yr
[Phys. Rev. Lett. 124, 122501 (2020)]

The CUORE experiment





Te-130

$T_{1/2}^{0\nu} > 2.2\text{x}10^{25}$ yr (90% C.L)
$m_{\beta\beta} < 90 - 305$ meV

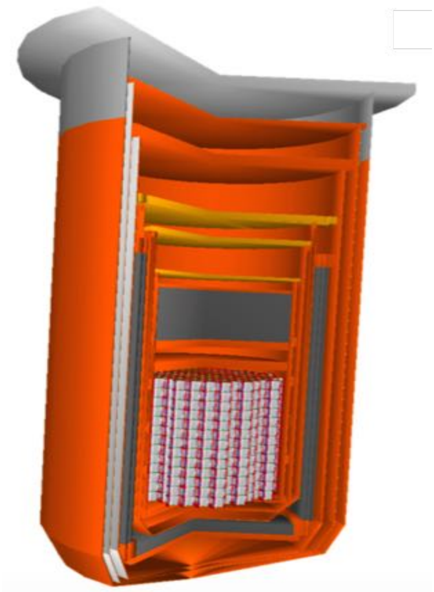
Nature 604, 53 (2022)

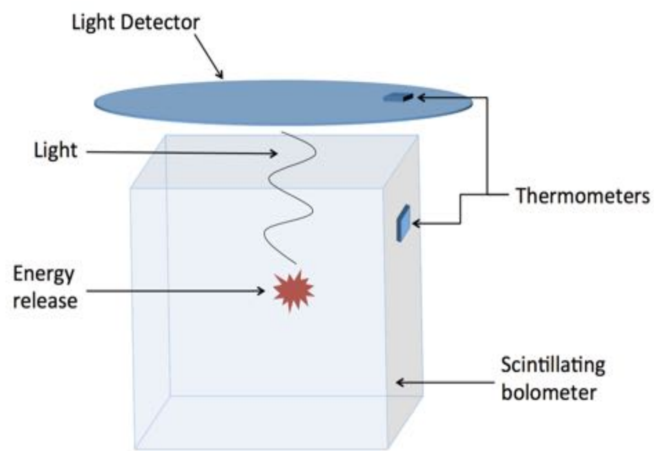
$T_{1/2}^{0\nu} > 3.2\text{x}10^{25}$ yr (90% C.L)
$m_{\beta\beta} < 75 - 350$ meV

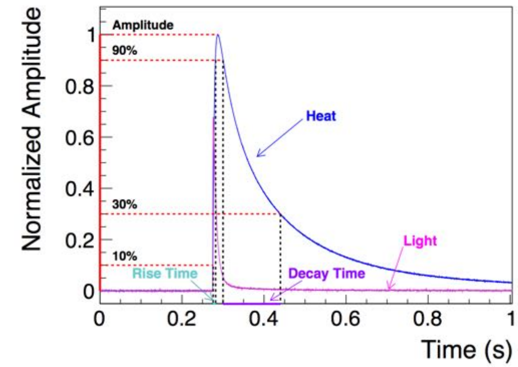
Phys. Rev. Lett. 124, 122501 (2020)

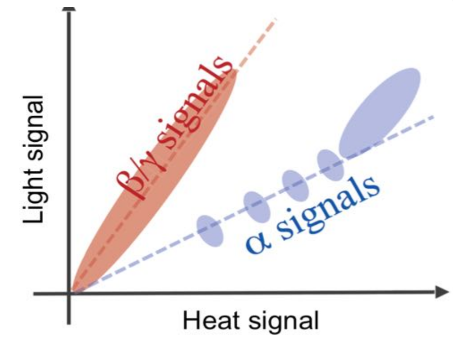
The most stringent constraint of Te-130 0νββ !

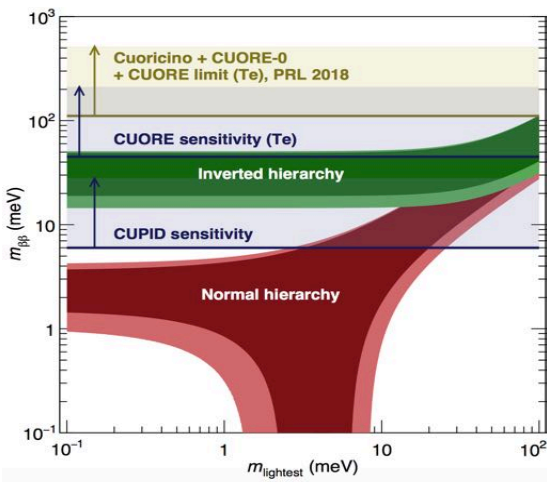
The CUPID experiment









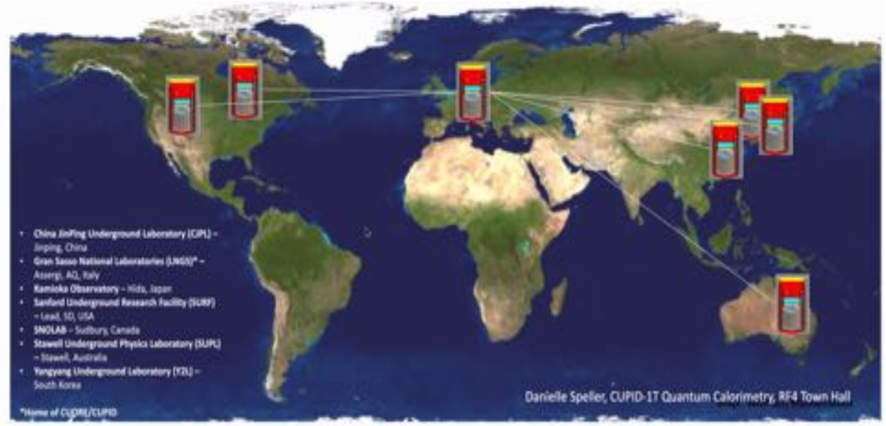


CUPID (CUORE Upgrade with Particle Identification)

- Scintillating bolometer technology
- CUORE-like infrastructure + detector upgrade
- Light-heat dual readout: particle identification (> 99.9% α rejection @ROI)
- Physics goal: $m_{\beta\beta}$< 10 meV

CUPID-China

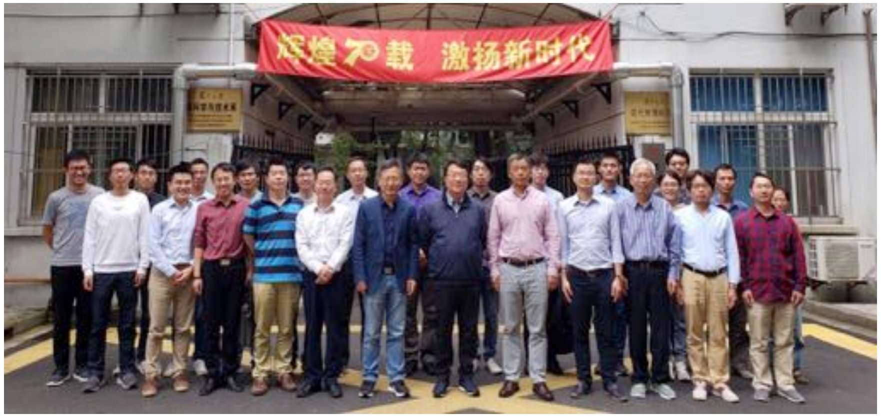
International CUPID collaboration



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

~ 30 institutes, >150 collaborators

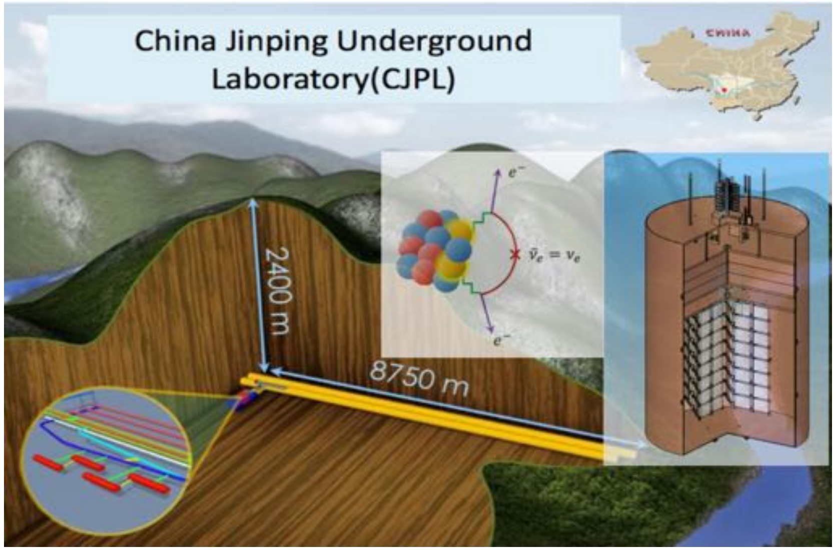
CUPID-China collaboration



~ 9 institutes, > 40 collaborators

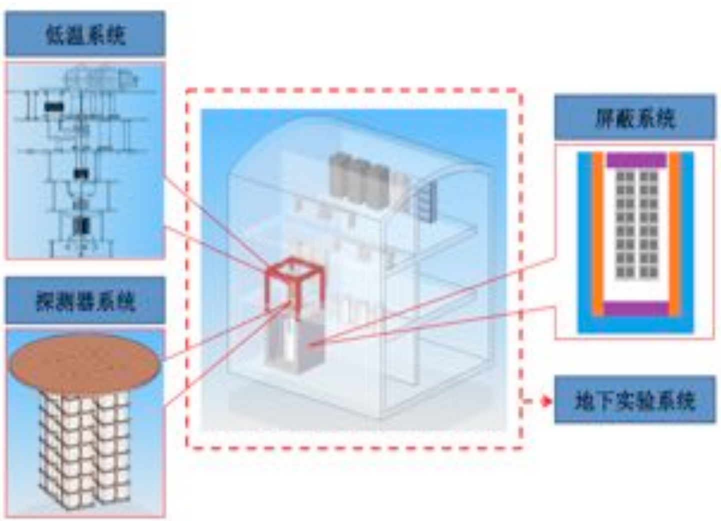
CUPID is in the early stage of technical development
CUPID-China is actively collaborating with CUPID- France, Italy and US

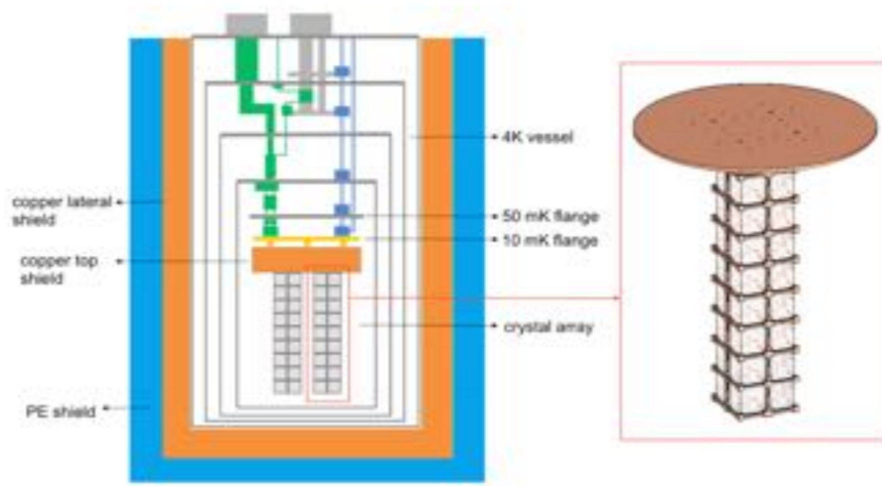
CUPID-CJPL



CUPID-CJPL: **A scintillating bolometer experiment for 0νββ search at CJPL**

- ^{100}Mo-enriched LMO crystals
- Light-heat dual readout (PID)
- Γ_Q<0.25%(FWHM), $R_{2\nu\beta\beta}$ <10^{-4}





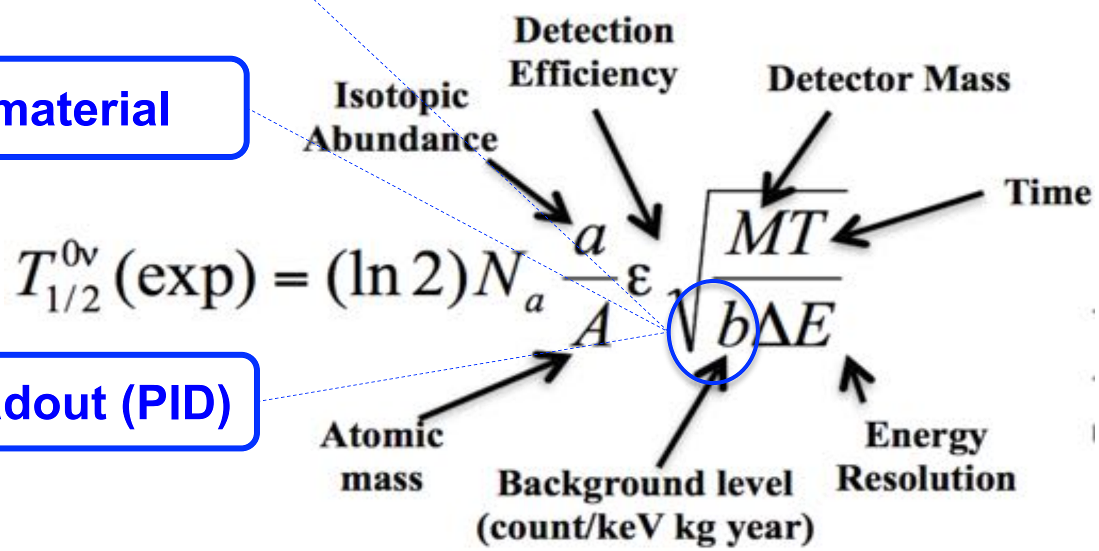
CUPID-CJPL demonstrator conceptual design		
Single crystal	Array structure	Total mass [kg]
45×45x45 mm (280g)	4x9	10

Detector R&D

High Q-value isotope

Radiopure material

Light-heat readout (PID)



$$T_{1/2}^{0\nu}(\exp) = (\ln 2) N_a \frac{a}{A} \varepsilon \sqrt{\frac{MT}{b\Delta E}}$$

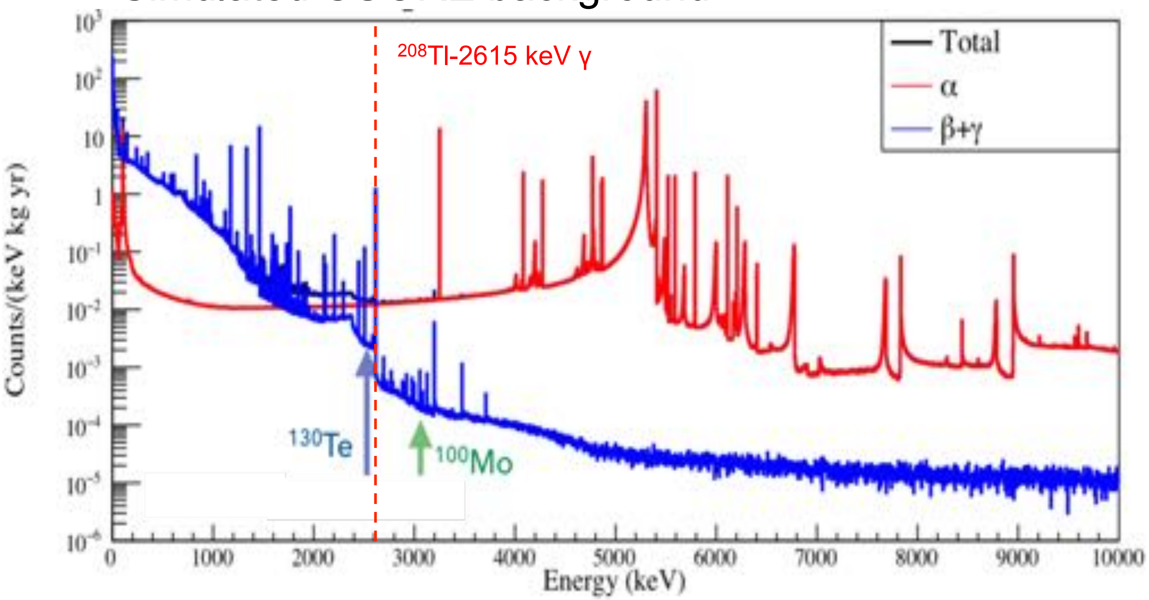
The next generation experiment requires:

- Larger detector mass
- Lower background

Detector R&D : target isotope

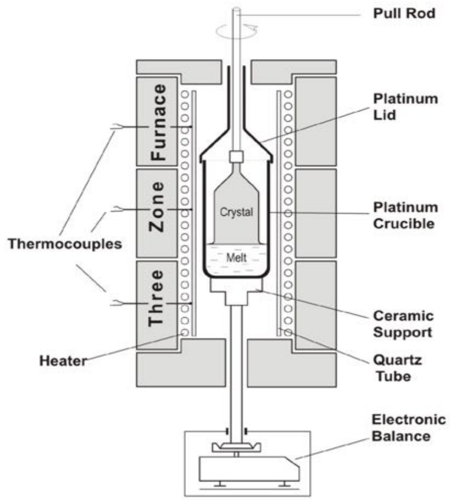
Candidate	Q (MeV)	Abund. (%)
^{48}Ca	4.271	0.19
^{76}Ge	2.040	7.8
^{82}Se	2.995	8.7
^{100}Mo	3.034	9.6
^{116}Cd	2.802	7.5
^{124}Sn	2.228	5.8
^{130}Te	2.533	34.1
^{136}Xe	2.479	8.9
^{150}Nd	3.367	5.6

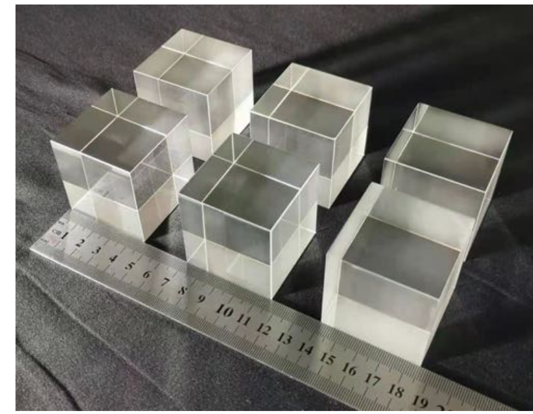
Simulated CUORE background



- **Mo-100** as a promising isotope for double beta decay study
- high $Q_{\beta\beta}$ value: ~3034 keV, above natural radioactivity endpoint
- relative high natural abundance
- theoretically high decay rate

Detector R&D: crystal





MoO_3 | Li_2CO_3

↓

synthesis and 1^{st} growth

↓

2^{nd} growth

↓

cut & polish

Li_2MoO_4

Crystal Powder

↓

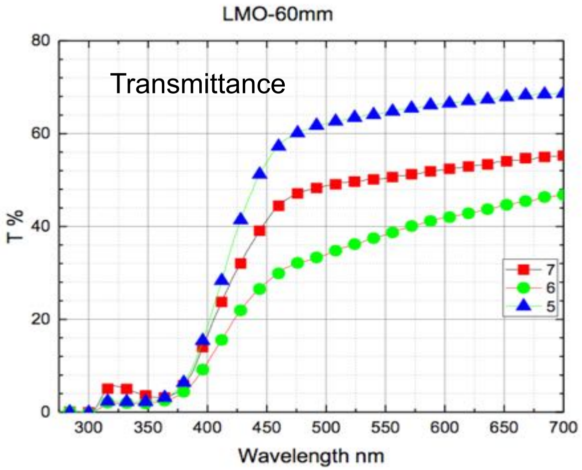
Low Enrichment

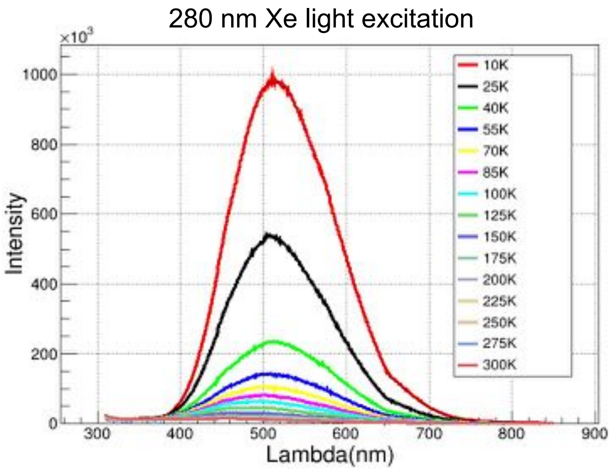
↓

High Enrichment

- ➢ Czochralski & Bridgeman growth of high purity Li_2MoO_4 crystals
- large size (Φ55x100 mm^3) cylinder ingot growth
- standard size 45x45x45 mm^3 crystal production
- improvement of material purification and zone refinement procedures
- continuous R&D on reducing impurities
- ➢ R&D on ^{100}Mo-enriched LMO crystal
- background control: ^{232}Th/^{238}U <10 μBq/kg

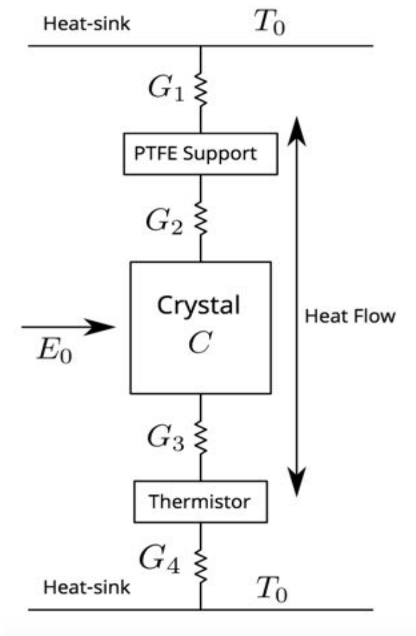
Detector R&D: crystal

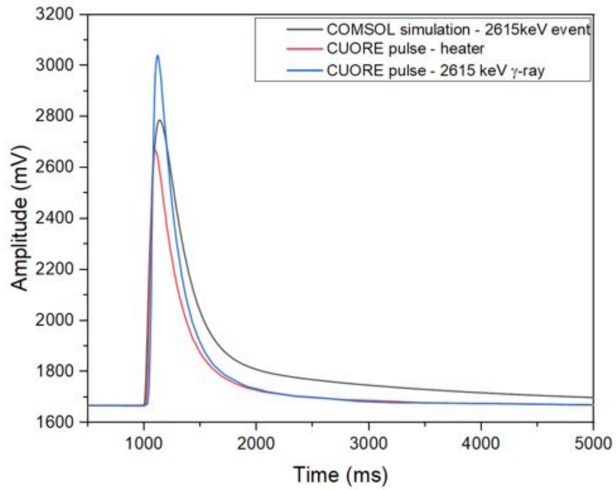


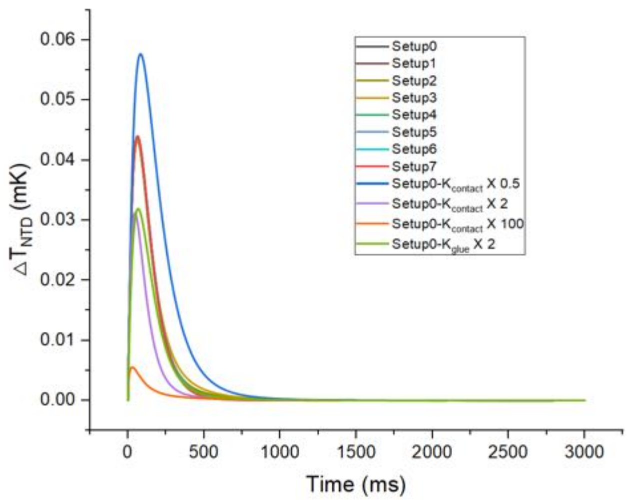


- ➢ Transmittance and scintillating property study
- • Low temperature test platform with Xe light and laser
- • Crystal tested with Xe light (280 nm) at T～10-300 K
- • Scintillating properties obtained for the Bridgman LMO
- ➢ Light transmission continuously improve through refinements in the crystal production

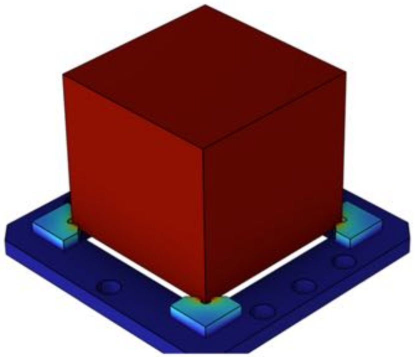
Detector R&D: bolometer module

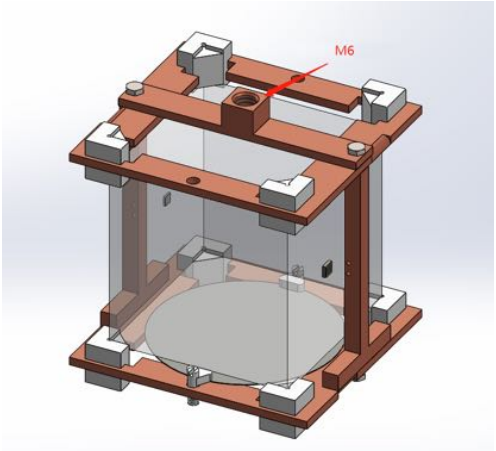






COMSOL modeling
(courtesy of Jiaxuan Cao)

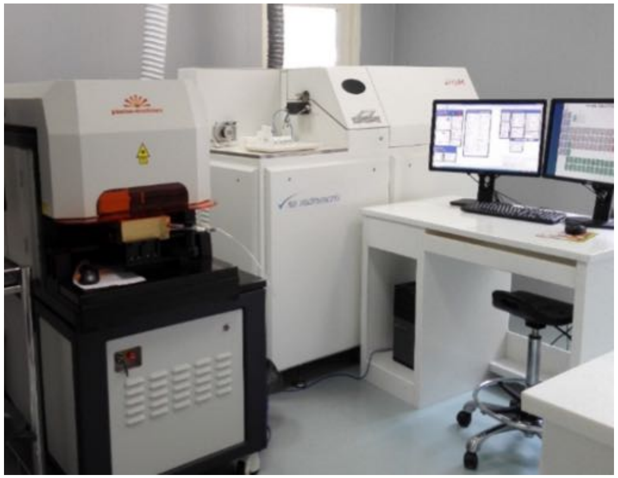




- **Bolometer module design based on multi-physics simulation**

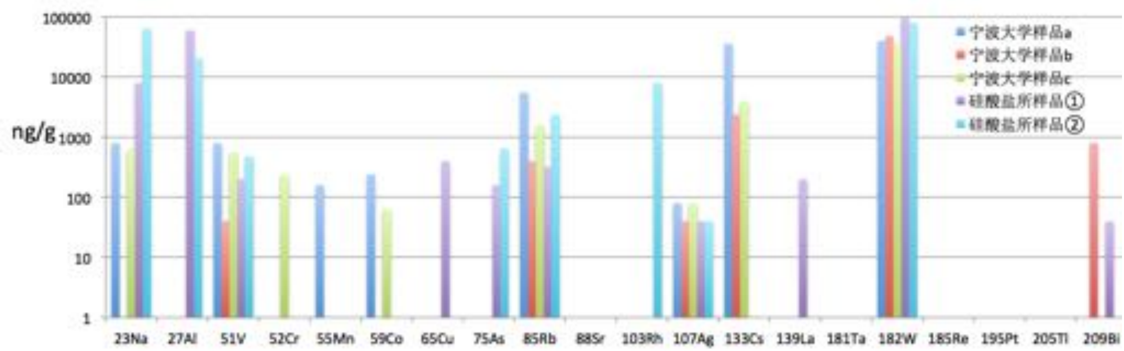
- study thermal-electric response
- evaluate pulse signal significance
- minimize material usage
- improve scintillating light collection

Radiopurity assessment



Sample	Na	Mg	Al	Ca	V	Cr	Mn	Fe	Co	Ni	Cu	Ga	Rb	Ag
	µg/kg													
LMO	< 33	< 7	< 11	< 83	60.3	15.7	< 2.4	< 1161	0.097	< 28	< 4.5	0.193	1.35	3.87

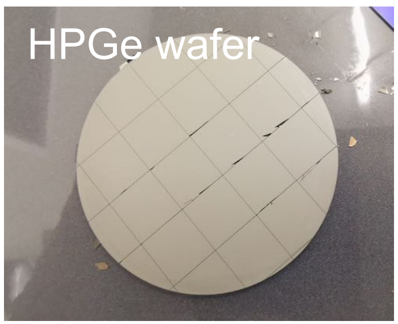
Sample	Sn	Te	Cs	Ba	Pt	Tl	Pb	Bi	K	W	^{232}Th	^{238}U
	µg/kg									mg/kg	ng/kg	
LMO	5.71	118	32.5	109	< 0.1	109	< 0.1	< 0.3	< 100	256	73.1	331

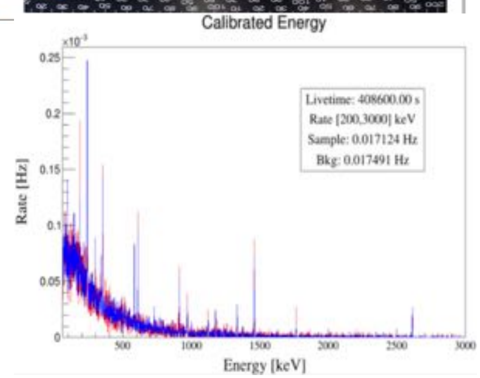


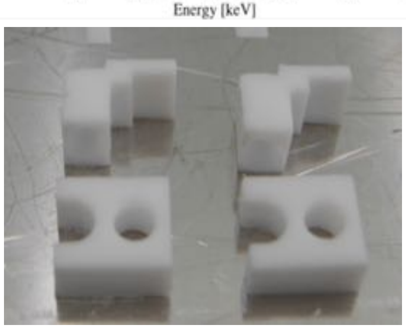
➢ **ICP-MS material QA**

- high sensitivity radiopurity assessment
- Th/U contamination measured for raw material (Li_2CO_3,MoO_3) and LMO samples
- input for experimental background evaluation

Radiopurity assessment







- **PTFE** - classical material for bolometers
- **PLA** - 3D printed, new material - radiopurity measurements

Sample	Radioactivity(Bq/kg)	
Isotope	U-238	Th-232
GX-4N-1	<2.5e-4	<8.0e-5
GX-4N-2	<1e-3	<6.5e-4
GX-5N-1	<1.8e-4	<4.5e-5
GX-5N-2	<8.5e-4	<5.5e-4
Aurubis CuOFE-1	<2.0e-4	<5.5e-5
Aurubis CuOFE-2	<6.0e-4	<4.5e-4

Radiopure material selection

- Copper: high sensitivity ICP-MS measurement (ppt level)
- HPGe chip: low background HPGe gamma spectrometer at CJPL
- PTFE & PLA material : prepared for HPGe test

Detector R&D

Vibration damping

Detection Efficiency

Isotopic Abundance

Detector Mass

Time

$$T^{0\nu}_{1/2}(\exp) = (\ln 2) N_a \frac{a}{A} \varepsilon \sqrt{\frac{MT}{b\Delta E}}$$

Atomic mass

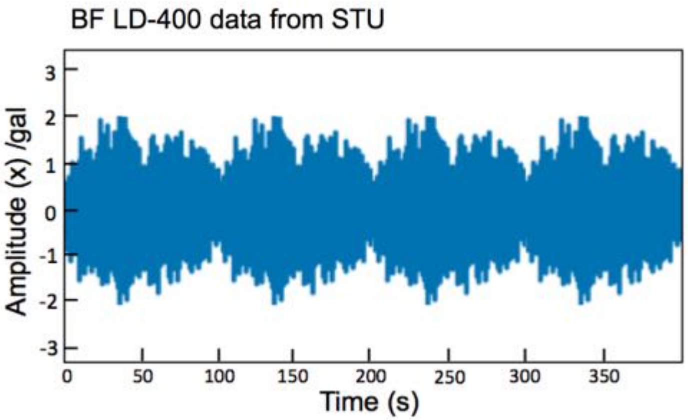
Background level (count/keV kg year)

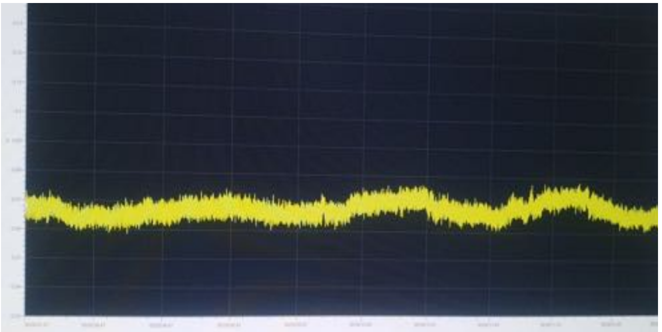
Energy Resolution

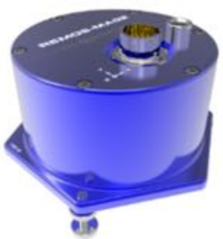
Low noise electronics

The next generation experiment requires

- Larger detector mass
- High energy resolution







Name	REMOS-WSIT
Sensitive range	±2 gal
No. channels	3
Sample rate	100/50 ps
Low frequency	0.01 Hz
High frequency	>50 Hz (100 ps)

- Relative vibration amplitude

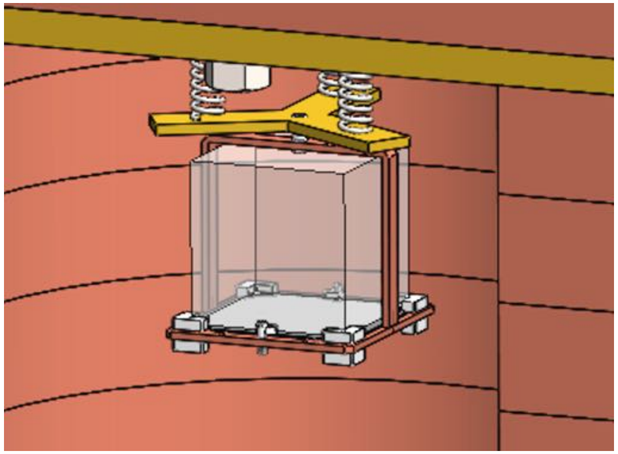
$$\frac{A}{A_0}=\frac{1}{\sqrt{(1-(\omega/\omega_0)^2)^2+4\eta^2(\omega/\omega_0)^4}}$$

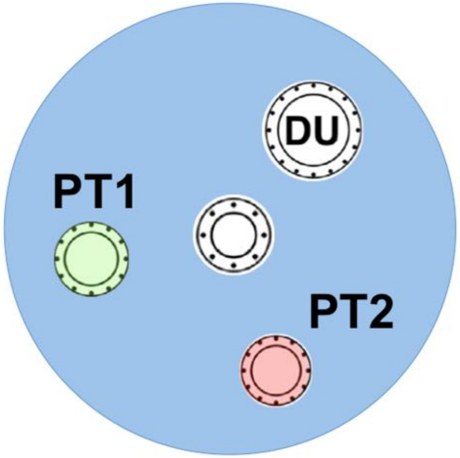
➢ **Lessons learned from CUORE**

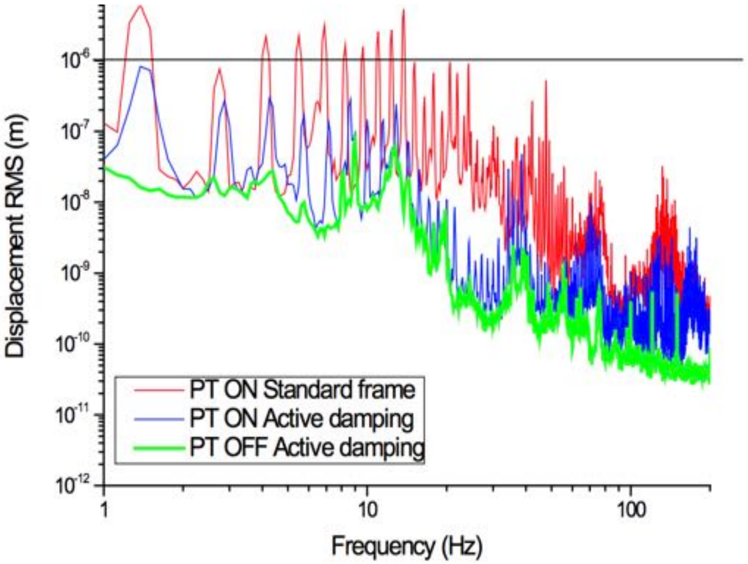
- Detector noise effect energy resolution
- Vibration from PTR is one major source
- Large displacement at low frequency (<20Hz)

➢ **On-going measurement based on high sensitivity seismic accelerometer**

Vibration damping





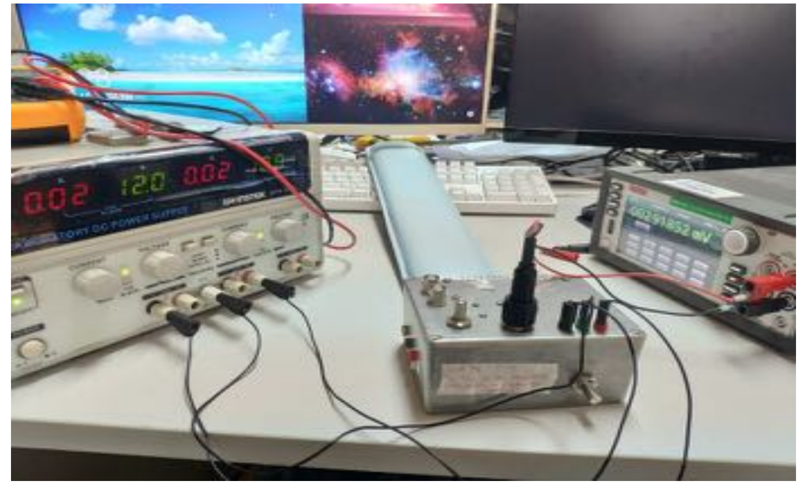


- ➢ **Two-stage vibration isolation**
- 1st-stage : active damping system (BF-AD, Minus-K)
- 2nd-stage : spring plate

- ➢ **New techniques for de-noising**
- spectrum analysis
- phase cancellation

Electronic system R&D

digital readout board

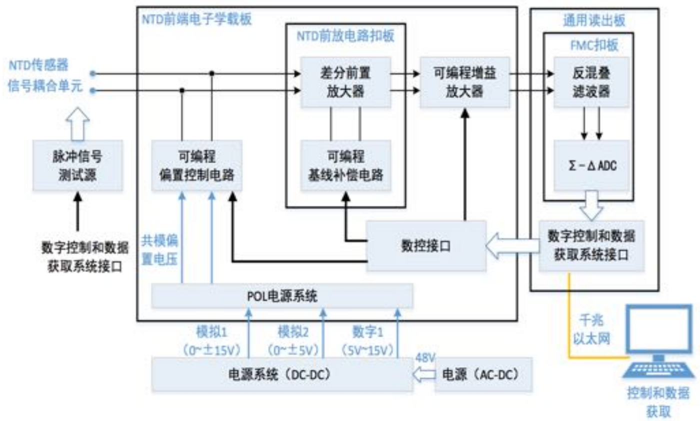


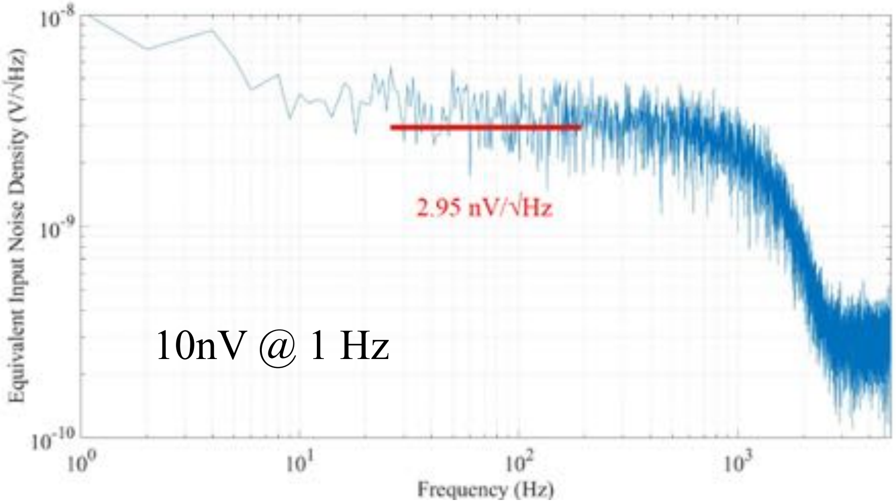
DC bias and pre-amp circuit board

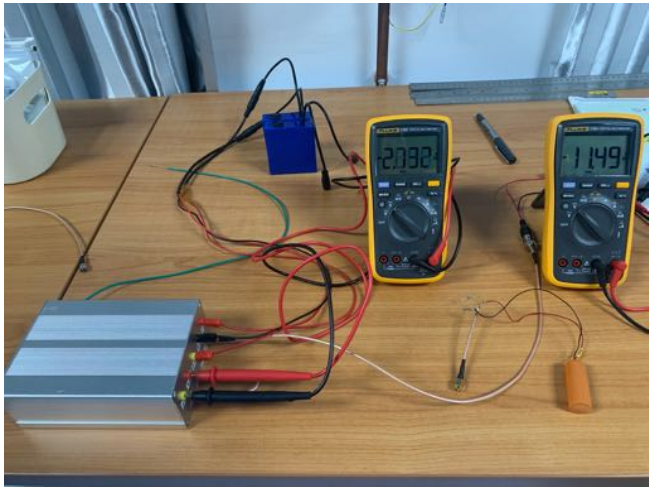
- ➢ R&D on low noise front-end and readout electronic system
- • circuit design verification
- • JFET test and performance evaluation
- • new design of the front-end board
- ➢ Technical collaboration with Milano university

Electronic system R&D

USTC Electronics Design Block Diagram



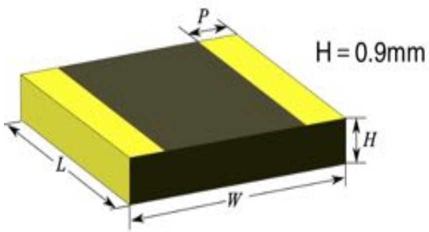


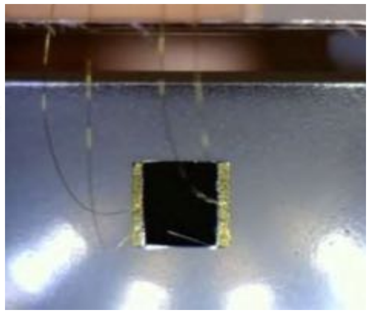


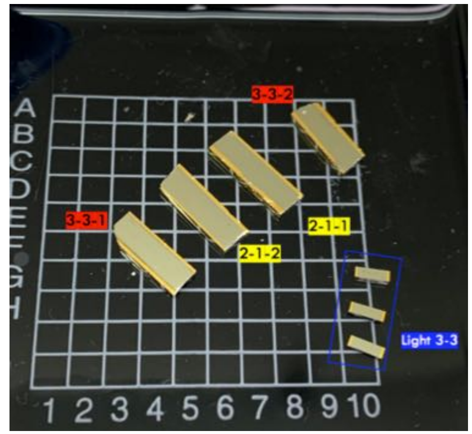
➢ Readout module test (USTC):

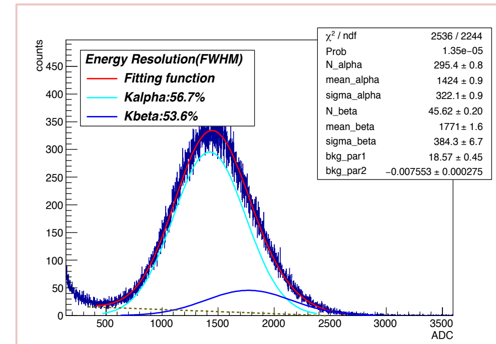
- measurement of the equivalent input noise spectral density
- relative low noise level

NTD R&D

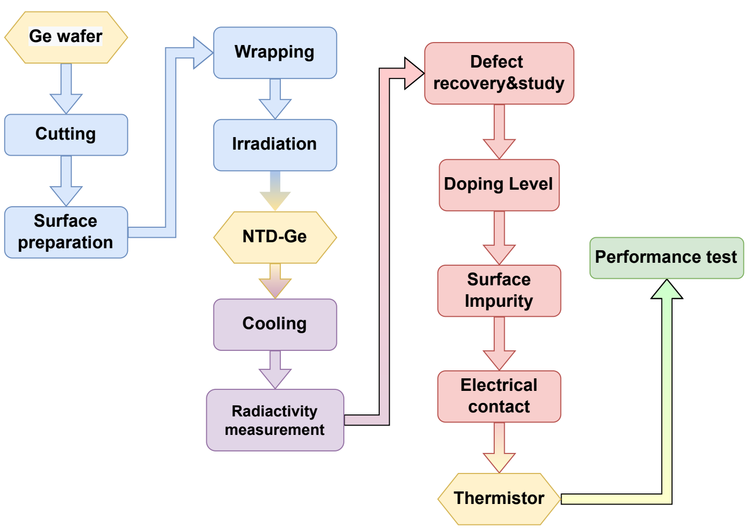








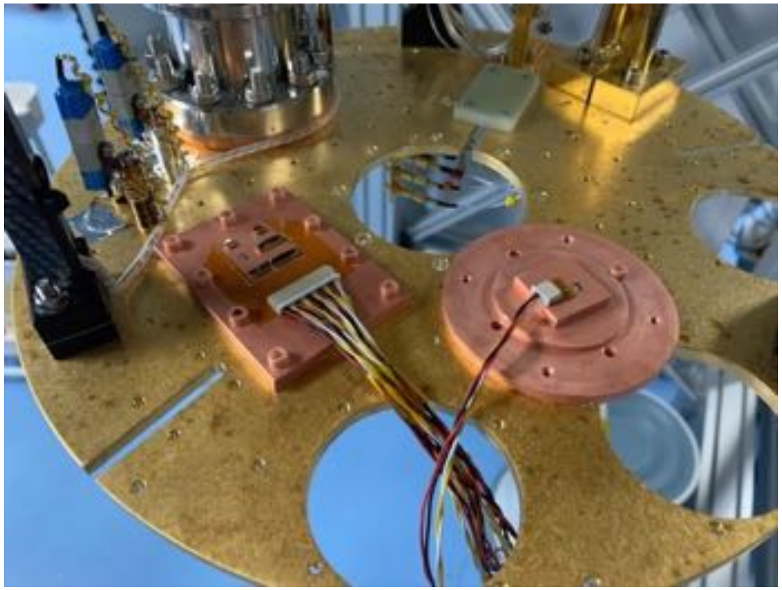
^{71}Ge Kx –ray 9.2keV

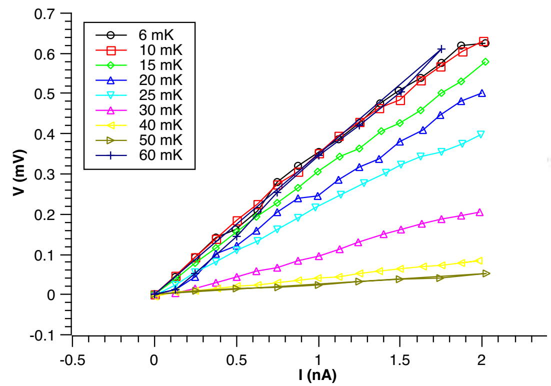


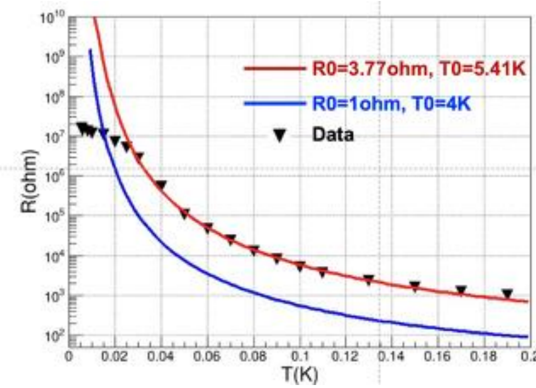
Irradiation at CIAE and machining at USTC

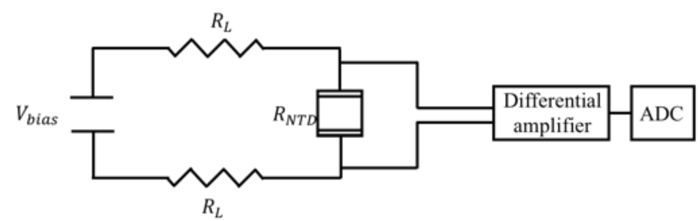
- NTD-Ge (Neutron Transmutation Doped Germanium thermistor)
  - key component for converting temperature rise into the voltage change
- Radioactivity measurement (HPGe and lanthanum bromide detector)
  - good irradiation performance

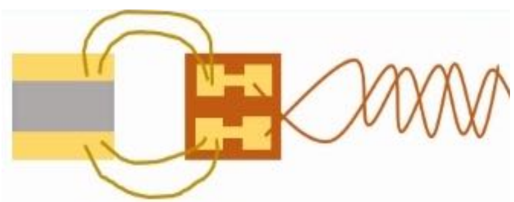
NTD R&D











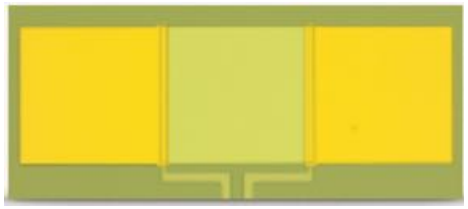
NTD: $3\times3\times1mm^3$

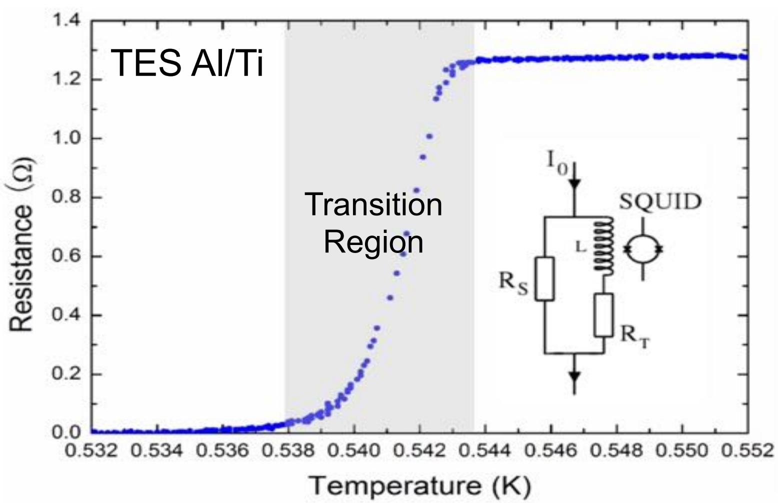
➢ **Performance test in ground DR:**

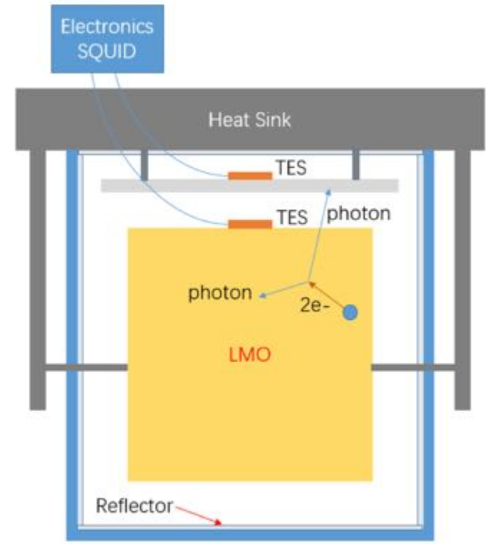
- 4 fabricated NTD and 2 reference NTD (LBL)
- I-V and R-T curve studied
- Improved test is on-going

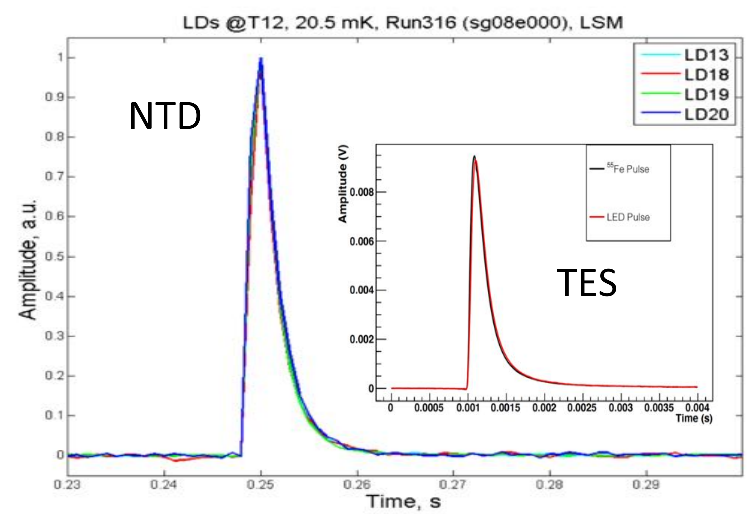
TES R&D

Transition Edge Sensor，TES





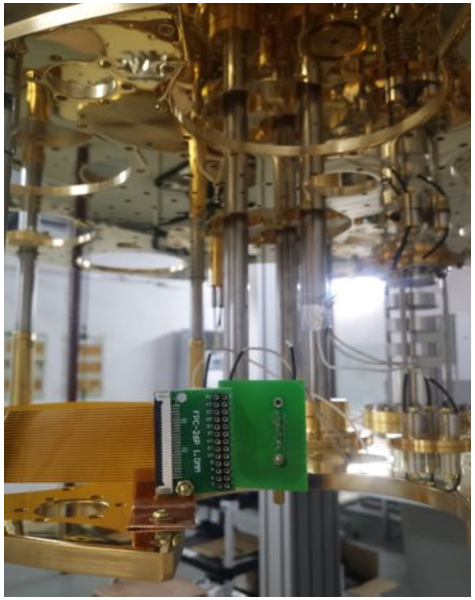




TES R&D for LMO bolometer (BNU):

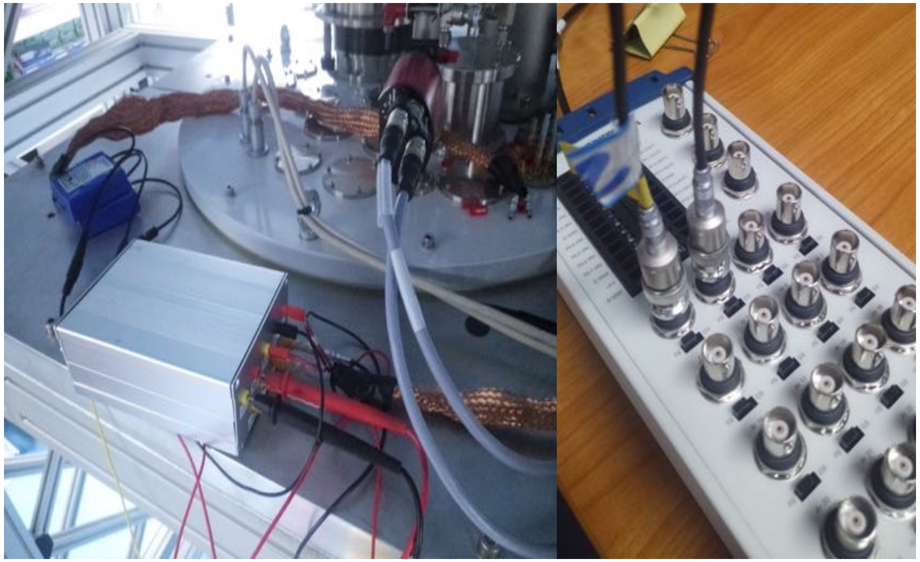
- competitive technology for fast readout
- progress in simulation and chip design

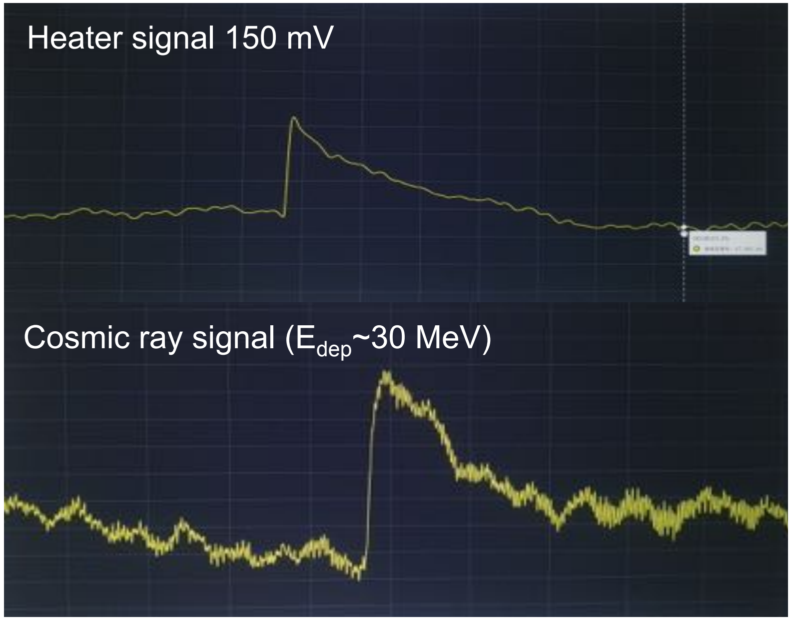
Crystal test: cryogenic system

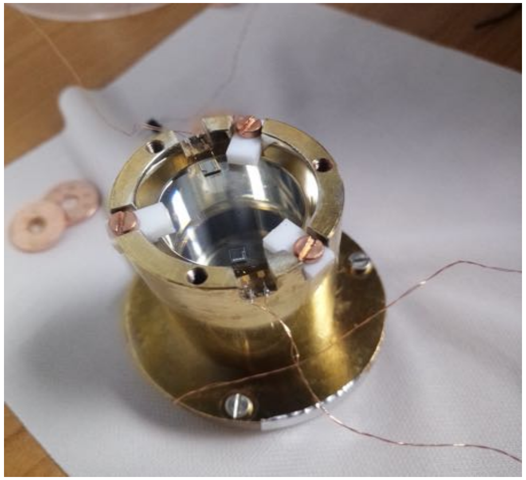


- ➢ Fudan-IMP cryogenic system
- Customized cryostat system
- Large sample space: Φ500x600 mm
- 2 PT (cooling power ≥1.8W@4.2K)
- Radiopure copper vessel (C10100)
- Inner shielding support (~250kg)
- Base T~8.8 mK, σ_T<100μK@10mK

Crystal test in the ground lab

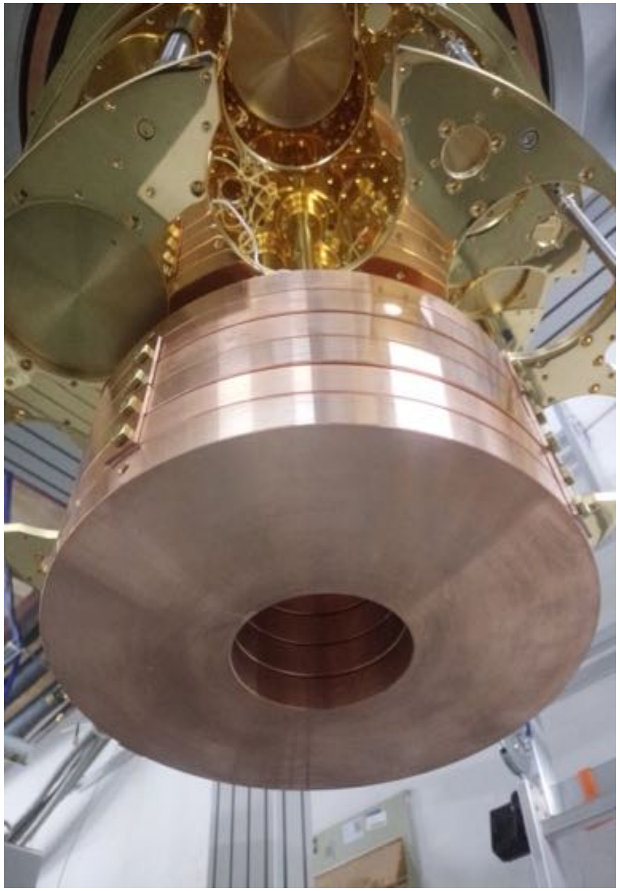


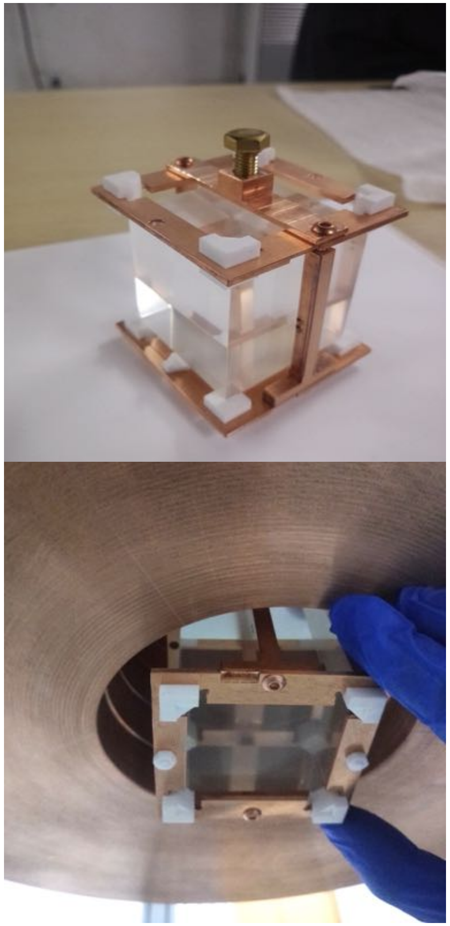


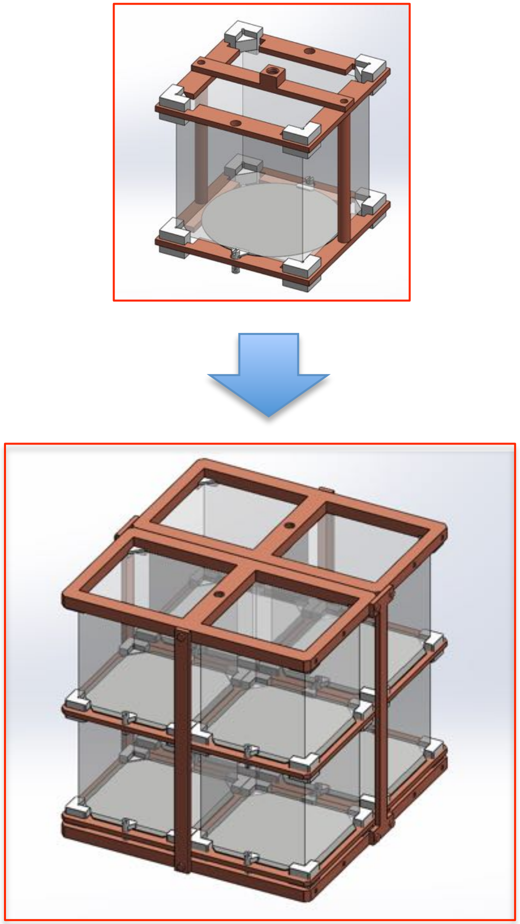


- **Ground test without background shielding (USTC)**
  - bolometer module: CSNSM setup + Ningbo crystal
  - DAQ: NI 6218 (16 bit ,16 ch) board, low pass filtering
  - indistinguishable calibration signal due to heavy environmental background
- New DAQ board is in development (32 bit, 8/16 ch, analog signal filter)

Crystal test in the ground lab

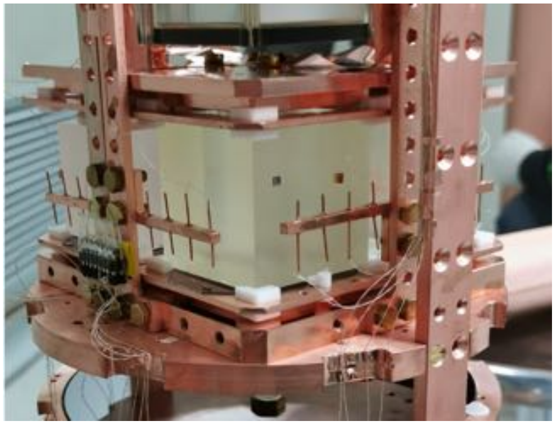


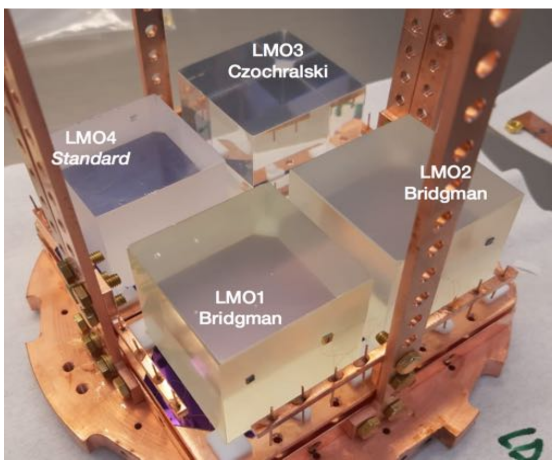


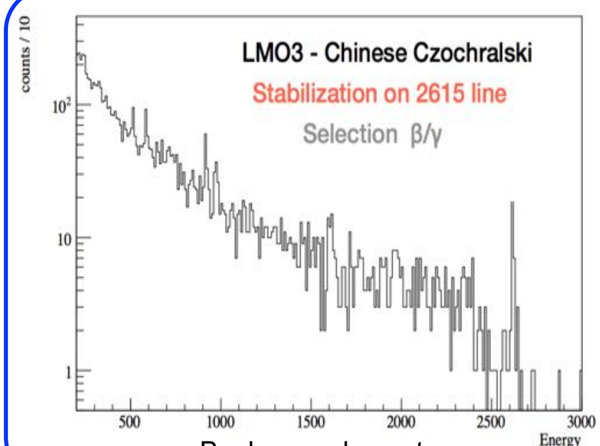


- Ground test with background shielding (FDU): cooling down and calibration study
- Underground test (LNGS): light-heat readout performance and background level

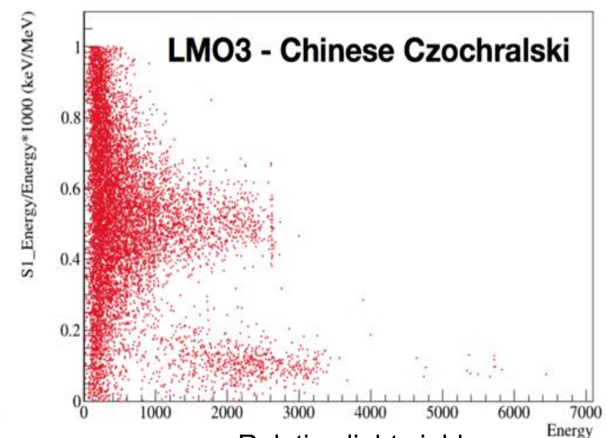
Crystal test in the underground lab







Background spectrum

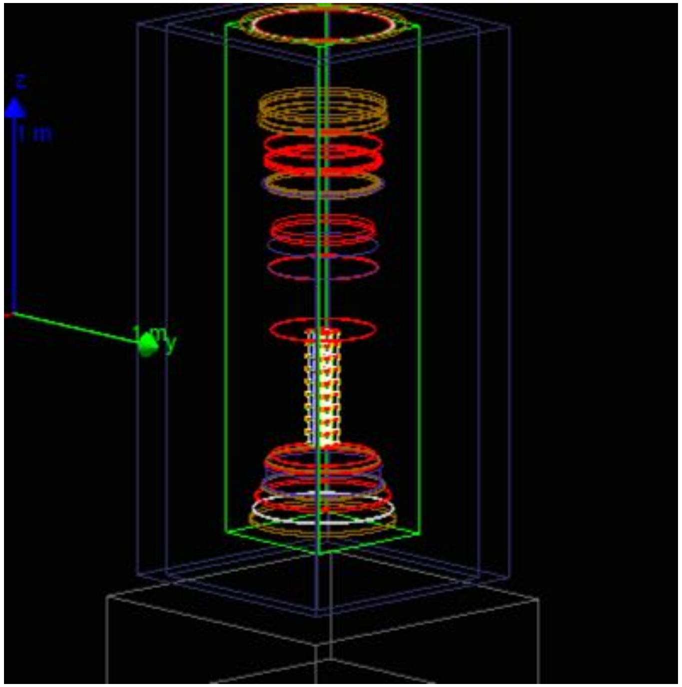


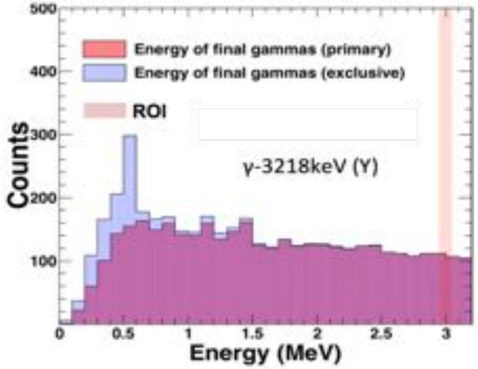
Relative light yield

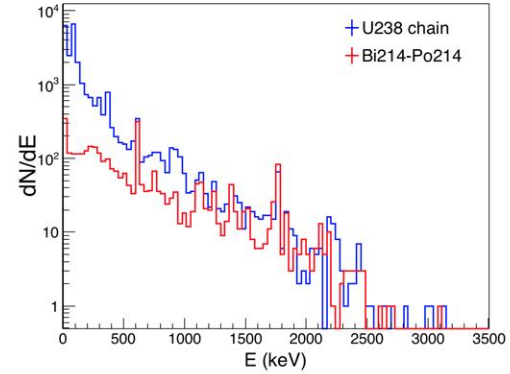
Underground test @ LNGS (2021.8)

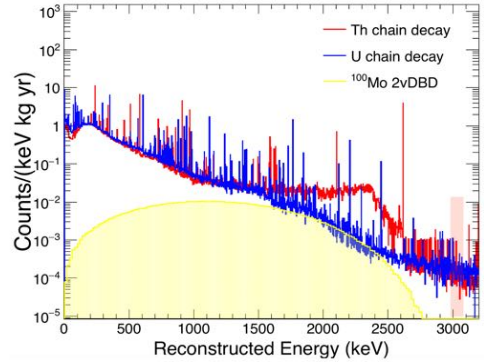
- 2 Bridgman+1 Czochralski (45x45x45 mm^3) LMO crystals produced by SICCAS and Ningbo University
- Good alpha separation and energy resolution are seen for the Czochralski crystal
- Cleaner raw materials have been selected and new crystal samples will be tested

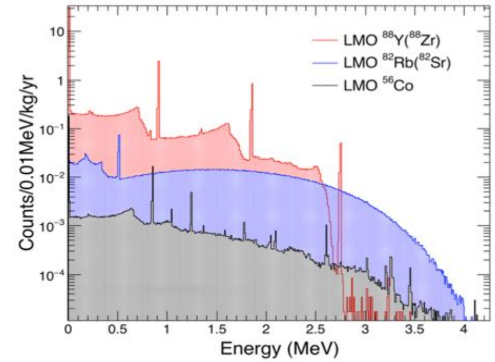
Simulation study







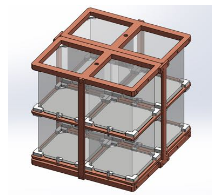




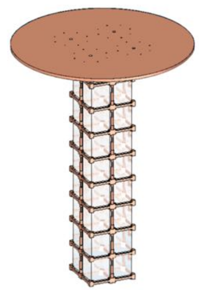
- Geant4-based simulation tool developed for the detector simulation
- Systematical studies performed:
- environmental background shielding
- material radioactive background
- cosmogenic isotope production and background contribution

CUPID-CJPL Roadmap

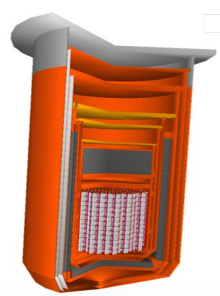
Crystal testing
(2022-2025)
6-12 natural crystals

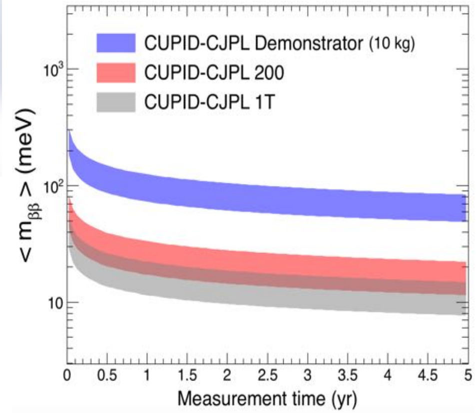


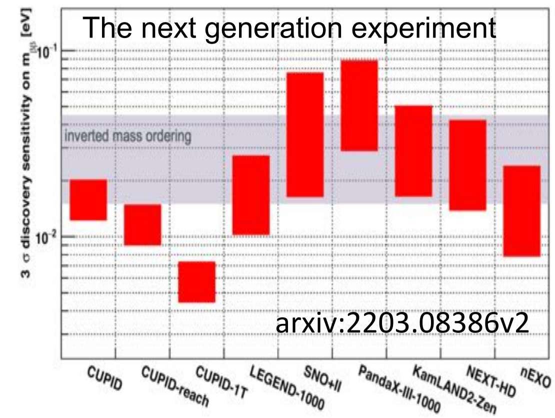
CUPID-CJPL Demo
(2025-2028)
10 kg enriched crystals



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





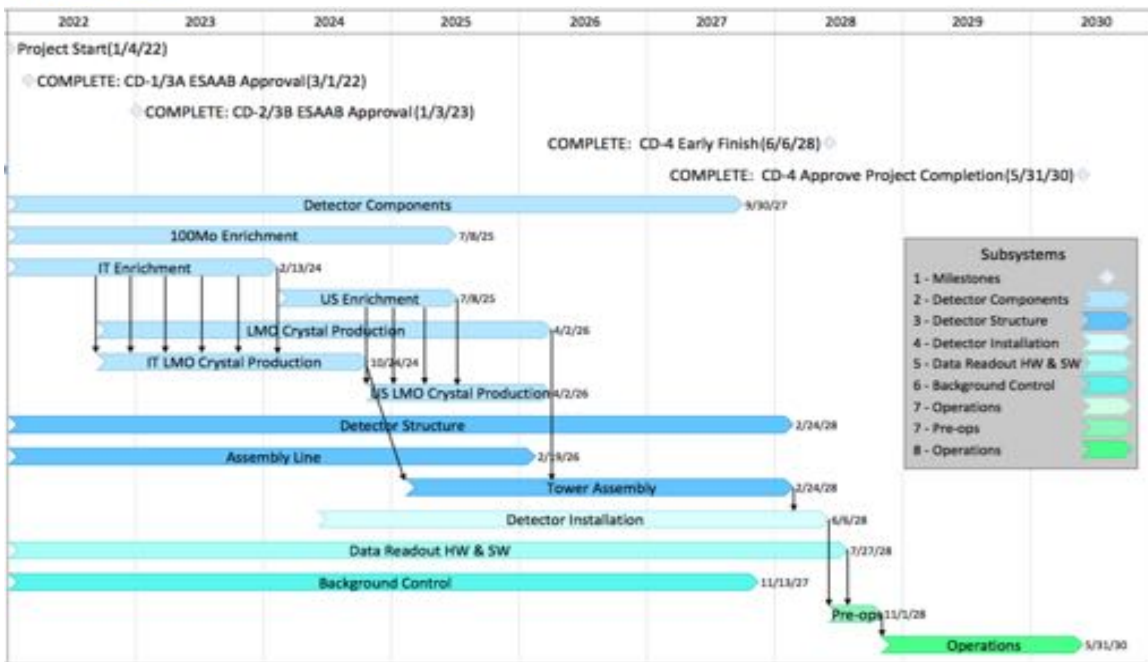


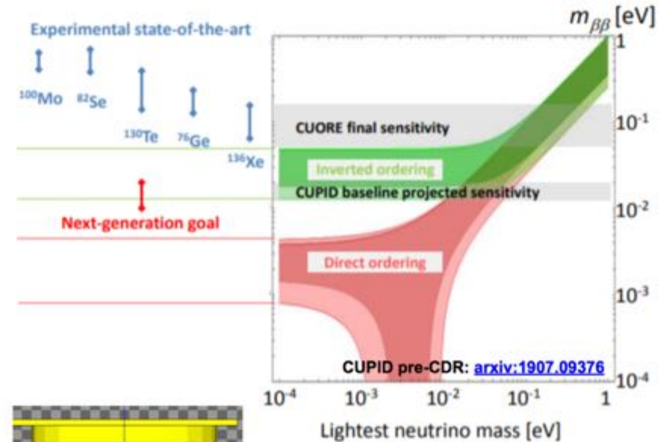
- 10 kg prototype experiment
  - demonstrate key technologies
- 200 kg+ experiment
  - competitive results
  - probe effective mass down to 10meV or lower

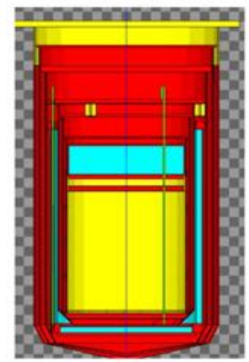
Thank you!

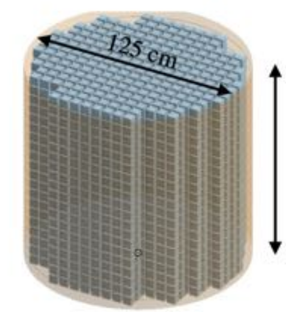
Backups: CUPID international schedule and timeline

Build a large-size CUPID-CJPL detector as a part of CUPID network detectors to achieve ultimate ton-scale sensitivity for Mo-100









CUPID-1T: HALLMARKS

1000 kg of ^{100}Mo in a new cryostat or multiple facilities world wide

Towards CUPID-1T. Snowmass 2021 Planning workshop