CUPID, CUPID-China
&
Crystal Bolometer for 0νββ at CJPL

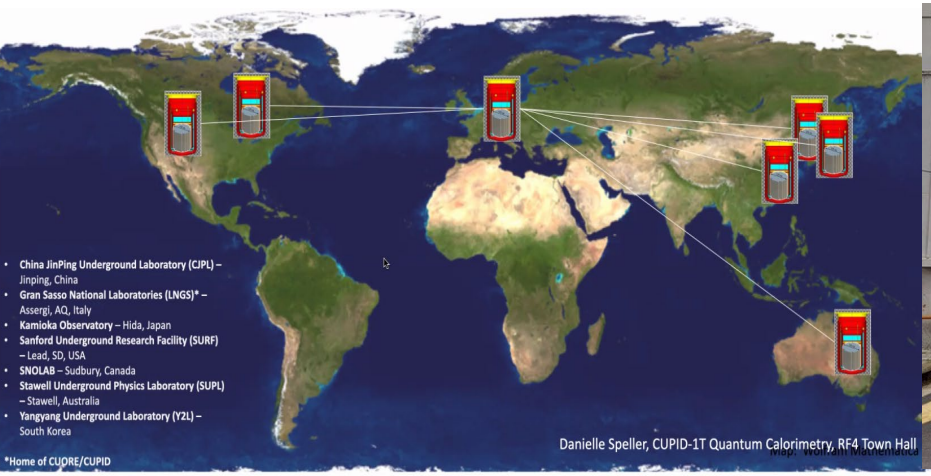
黄焕中 (Huan Zhong Huang)
现代物理研究所 (Institute of Modern Physics)
复旦大学 (Fudan University)
&
Department of Physics and Astronomy
University of California, Los Angeles

For CUPID-China Collaboration
May 9, 2023

感谢SICCAS袁辉，BNU刘圆圆，USTC薛明萱，Fudan马龙提供资料和讨论

CUPID-China Collaboration

International CUPID collaboration



CUPID-China collaboration

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

~ 30 institutes, >150 collaborators

~ 9 institutes
> 40 collaborators

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

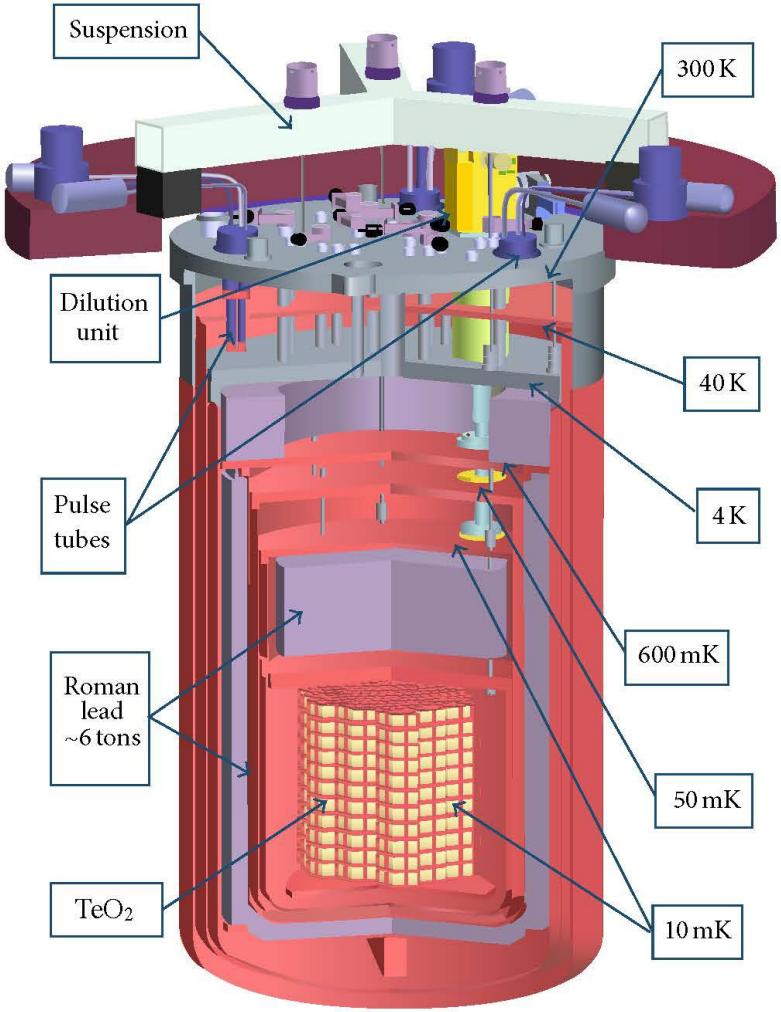
Outline

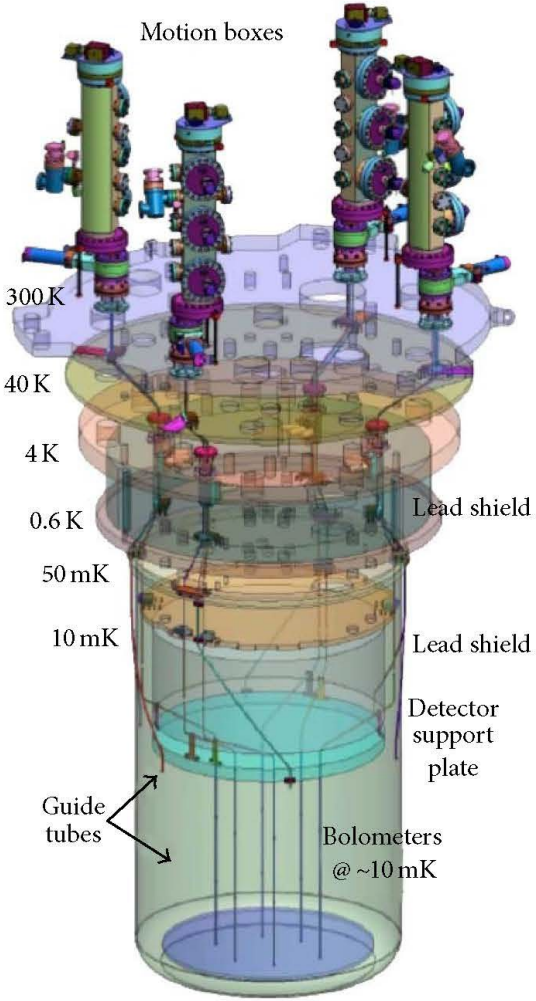
1) CUORE Status and CUPID Plan

2) CUPID-China Plan and R&D Status

3) Plan Towards a CUPID-CJPL Detector

CUORE Cryostat





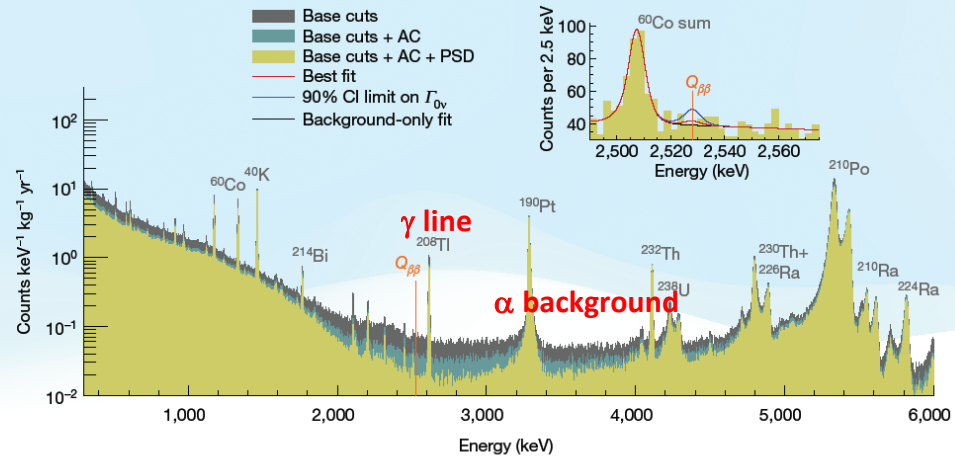
CUORE 1 ton*year Data

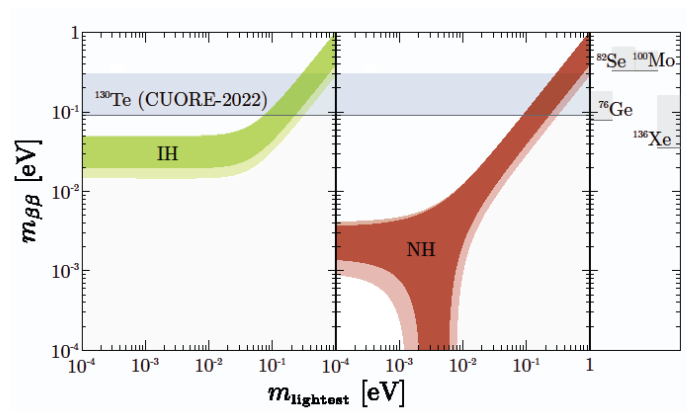
Nature, 604, 53-58 (2022)

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

From CUORE to CUPID

Key Technologies for the advancement:

1) Heat-light dual readout

Particle Identification of α and γ background

-- remove background in the α region

2) Scintillating LMO Crystals

Mo-100 $0\nu\beta\beta$ $Q_{\beta\beta}$ 3034 keV > 2615 keV ^{208}Tl

Suppress background by more than two orders of magnitude

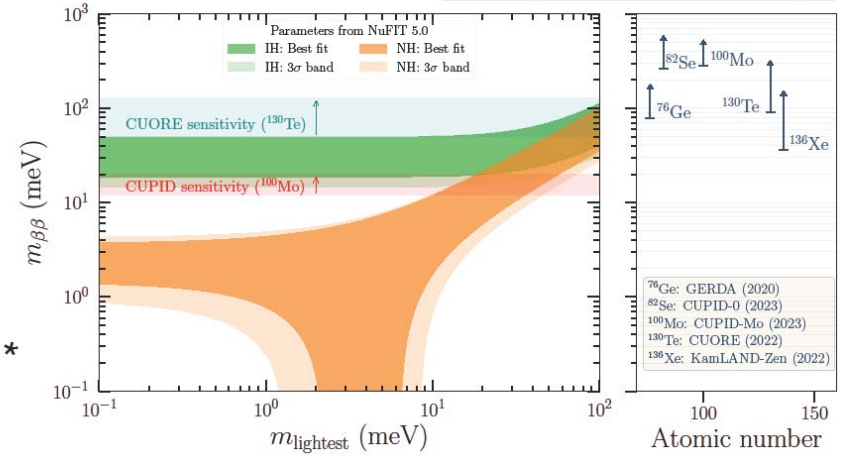
CUPID

- 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

- $T_{1/2}$ > 1.1x10^{27} yr ($m_{\beta\beta}$: 12-20 meV)
- $T_{1/2}$ > 2.2x10^{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

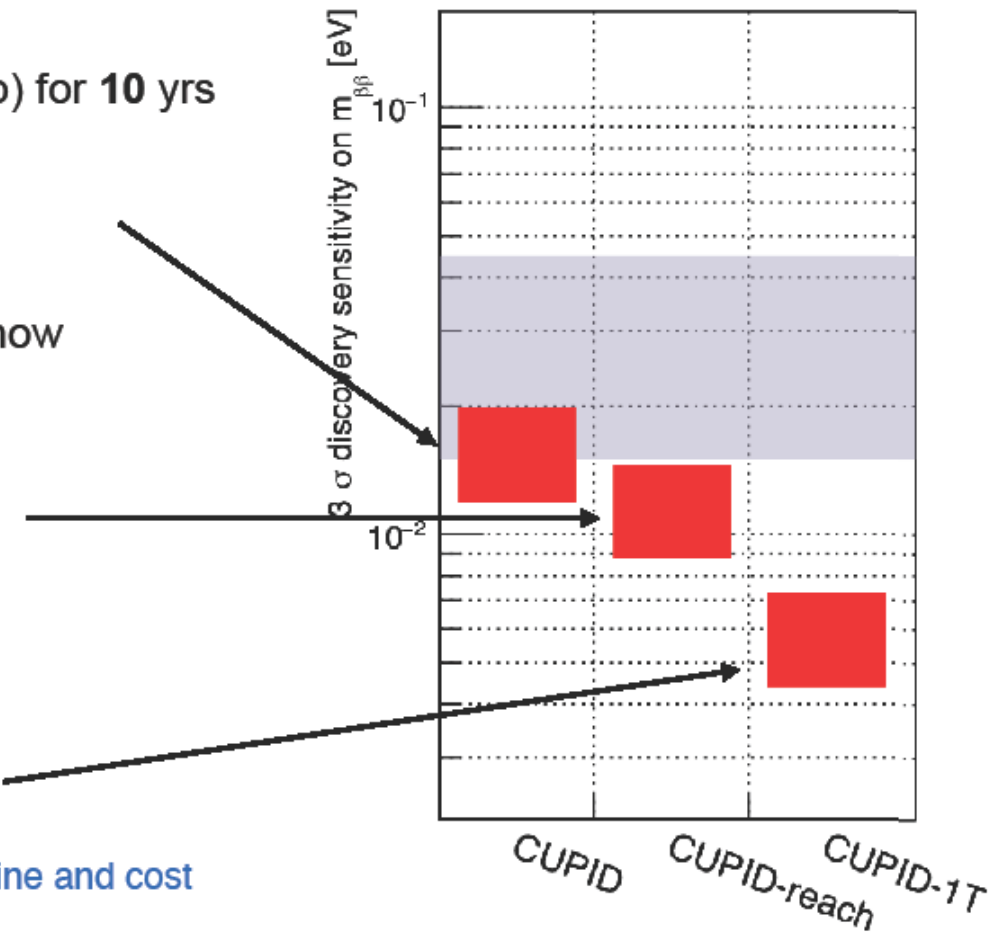
- Mass: 472 kg (**240 kg**) of $Li_2{}^{100}MoO_4$ (^{100}Mo) for **10** yrs
- Energy resolution: **5 keV** FWHM
- Background: **10^{-4}** cts/keV.kg.yr
- Discovery sensitivity **$T_{1/2} > 1\times10^{27}$ yr (3σ)**
- Conservative, limited R&D. Ready to build now

Reach

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

1-Ton

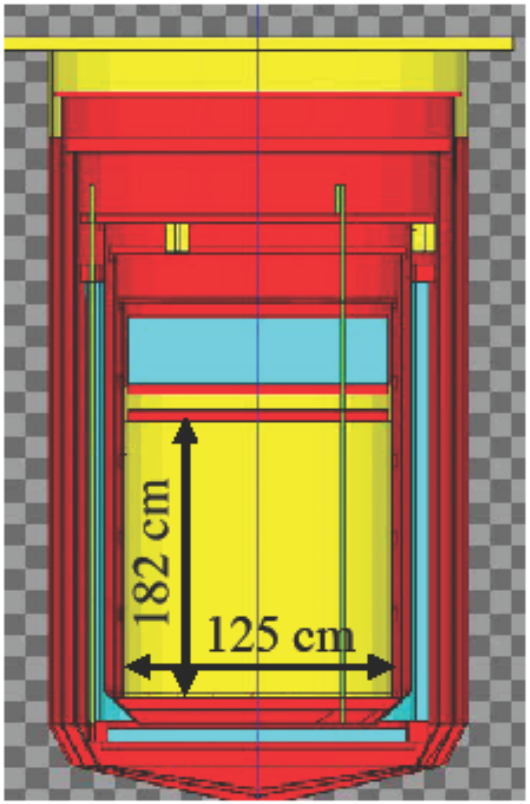
- 1000 kg of ^{100}Mo
- Discovery sensitivity **$T_{1/2} > 8\times10^{27}$ yr (3σ)**



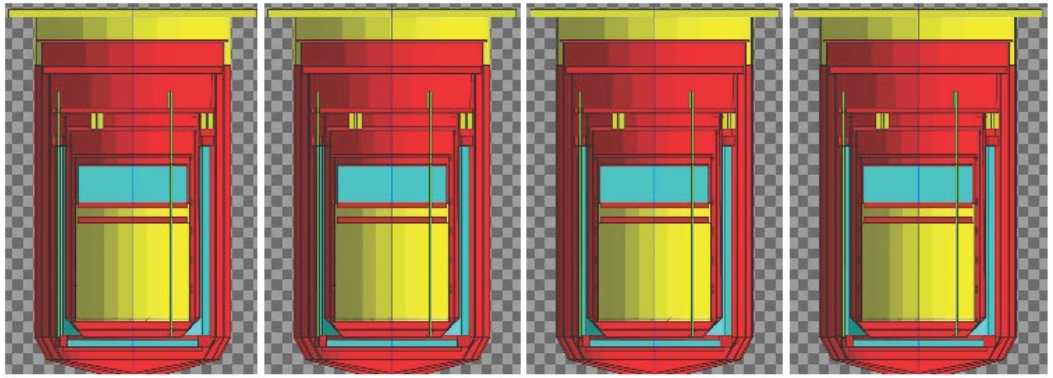
CUPID-1T is within technical reach, limited by timeline and cost
CUPID sensitivity meets goals of 2015 LRP

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 Plan and R&D Status

1) Participate in the CUPID Experiment at LNGS
   - Enriched LMO Crystals – paid by CUPID
   - Crystal Production QA Testing
     - (material essay and crystal validation testing)
   - Contribution to filter and digitization board

(~ 1千万RMB硬件，~1千万RMB物理研究国际合作项目）

2）Development CUPID-CJPL Detector at CJPL
   - R&D Project
   - Aim at sensitivity higher than the CUPID-Baseline
     - Timeline compatible with CUPID
   - International partners will participate in CUPID-CJPL too！

Major CUPID-China R&D Project

LMO Crystal Production and Material QA
SICCAS, Ningbo and SINAP （NSFC）

Novel Readout with Transition Edge Sensor
Beijing Normal University, IHEP and others （NSFC）

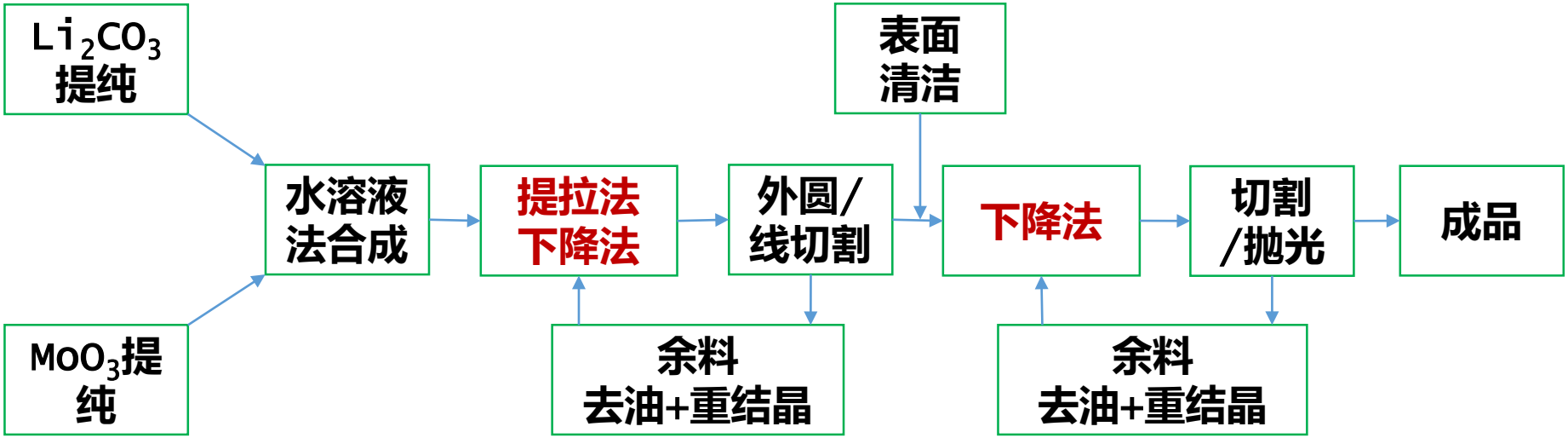
Bolometer Readout Electronics and NTD Development
USTC （MOST）

Crystal Testing Lab and Prototype CUPID-Demonstrator Design
Fudan and USTC （MOST）

Crystal R&D Project

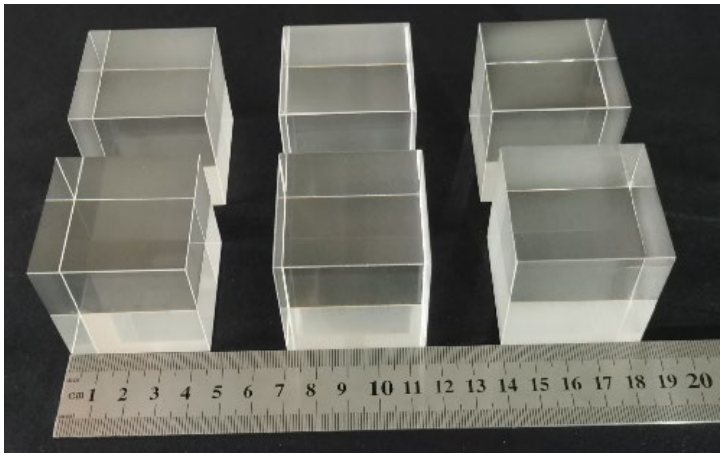
SICCAS – 袁辉、朱勇等
宁波大学 – 陈红兵组
张江实验室/SINAP – 曹喜光、李玉兰等

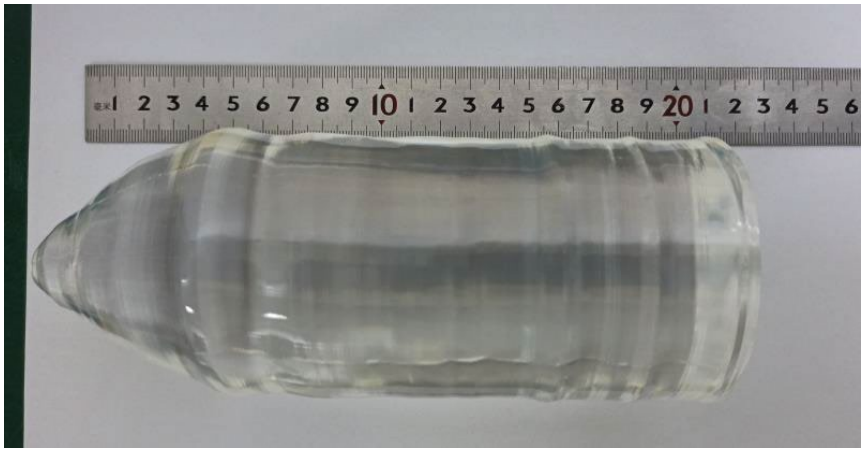
已经建成制备自然材料的LMO晶体的原料提纯、晶体生长与加工工艺技术
可以小批量生长CUPID要求尺寸的晶体



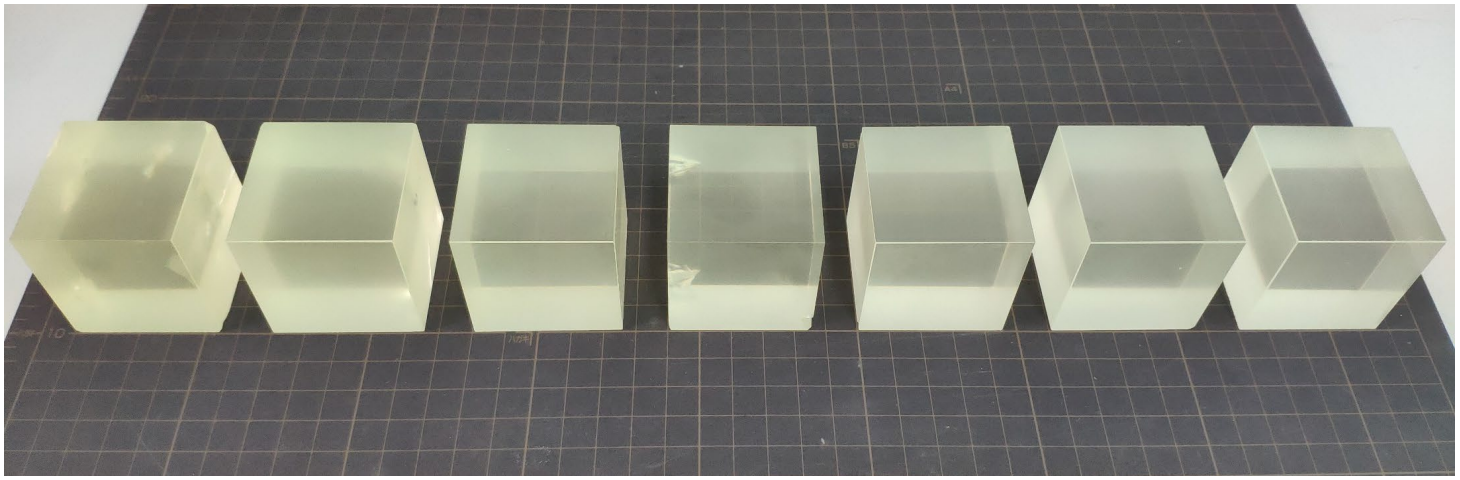
晶体生长的提拉法和下降法技术日益完善

提拉法生长的LMO





下降法生长的晶体质量显著提高



Crystal R&D Future Goals

1） 结合提拉法和下降法晶体生长优势，完善晶体批量生长的最佳方案

2）购买公斤级的Mo-100富集材料，研制生产高纯低本底富集晶体

3）探索晶体生长和加工过程中的富集材料回收，再提纯技术工艺，提高富集材料的利用率并保证晶体质量

意大利CUPID合作组原则上同意和CUPID-China合作，推动富集晶体研制，争取6个月内取得初步结果

4）研制闪烁光发光性能优于现有LMO晶体的Mo基晶体 – e.g., NMO 晶体

TES Readout R&D

北师大刘圆圆教授负责的研究团队 （北师大，高能所等）

灵敏的快时间响应读出系统：光探测效率 + 压低事件重叠几率

研制工作温度~ 10 mK的TES薄膜

AlMn 合金薄膜

W 薄膜

建立TES模拟系统，探索TES读出系统，优化探测器设计

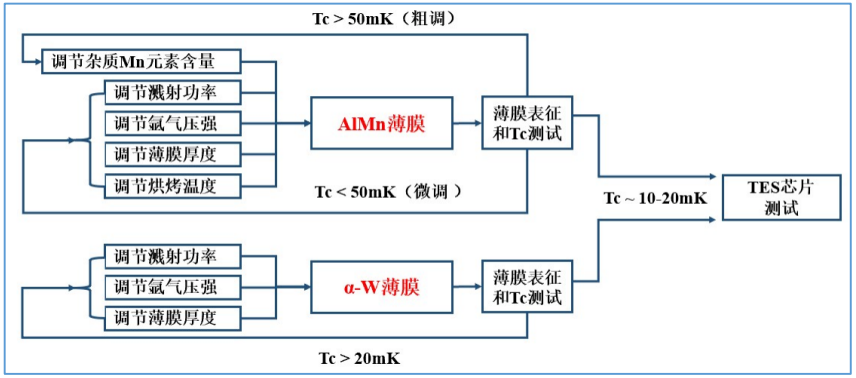
□ TES薄膜制备及测试

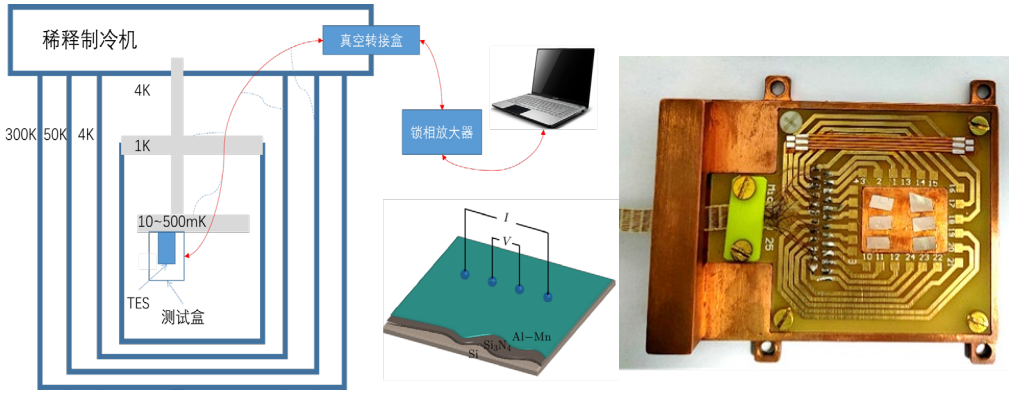
AlMn合金薄膜

- 定制了多种Al/Mn不同比例的靶材，研究靶材、薄膜厚度、烘烤温度对Tc的显著影响
- 确定Tc<50mK所需靶材
- 通过摸索溅射参数，实现Tc~10-20mK目标

W薄膜

- 摸索功率、厚度、气压等溅射参数影响，利用退火实验，实现α-W相薄膜的制备
- 优化参数，实现Tc~10-20mK目标

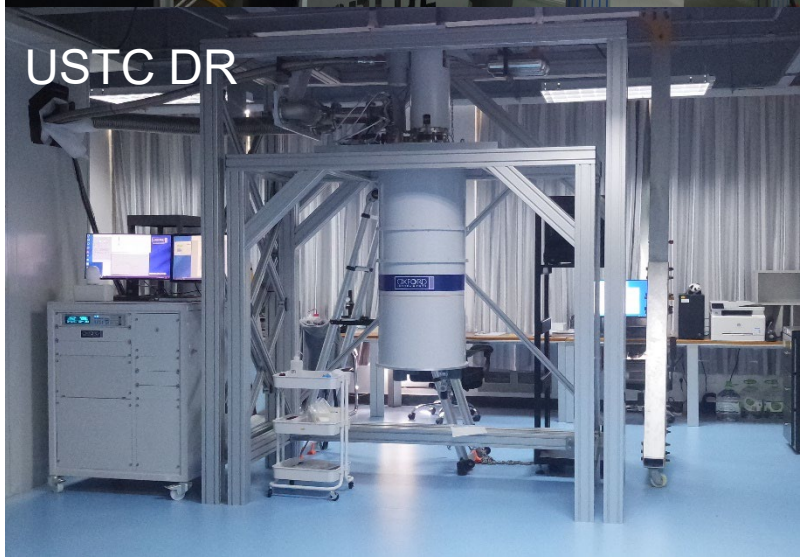


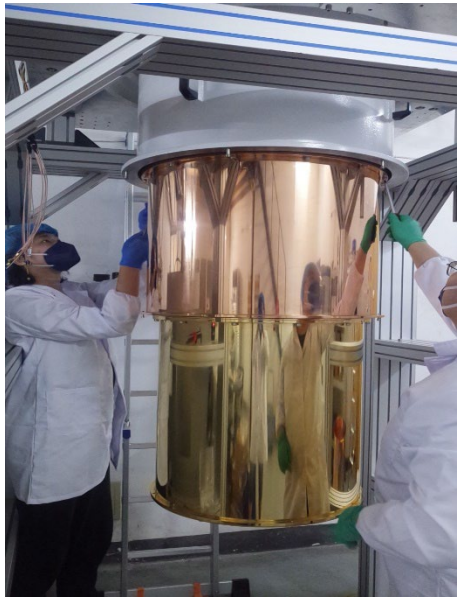


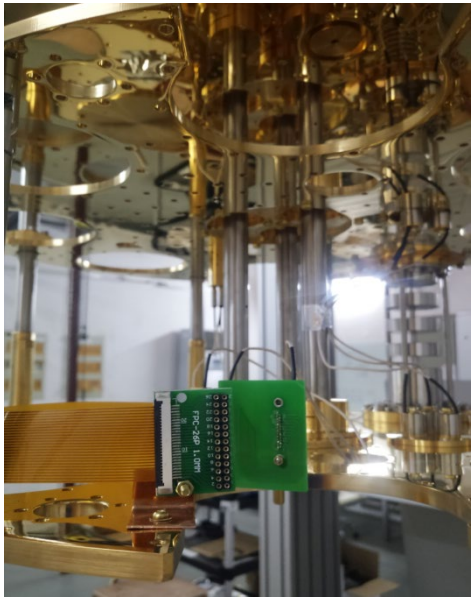
薄膜测试

详细请看北师大吕莎莎5/9下午报告

Crogenic System at Fudan and USTC







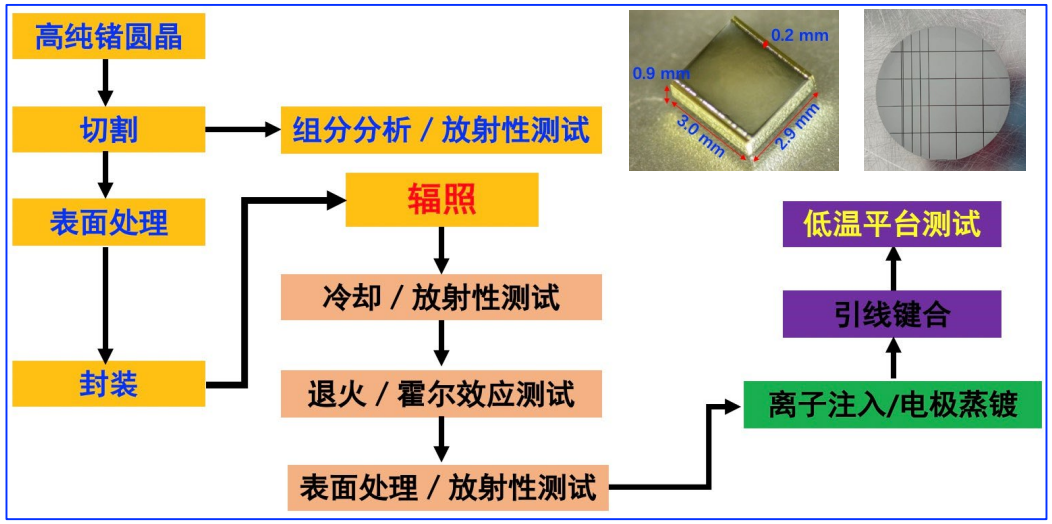
- Fudan-IMP cryogenic system
- Customized cryostat system
- Large sample space: Φ500x600 mm
- 2 PT (cooling power ≥1.8W@4.2K)
- Radiopure vessel (CuOFE-C10100)
- Inner shielding support (~300 kg)

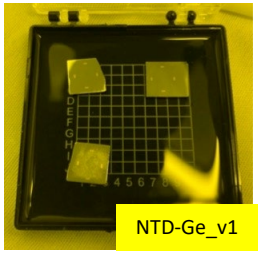
USTC – 薛明萱 + 学生
Fudan – 马龙 + 学生

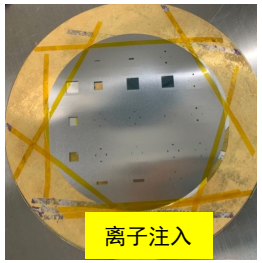
详细请看中科大薛明萱，段德勇，曹嘉璇5/9下午报告

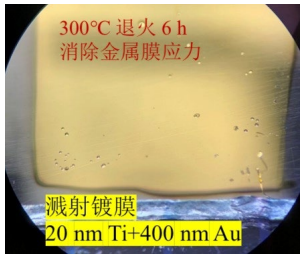
USTC

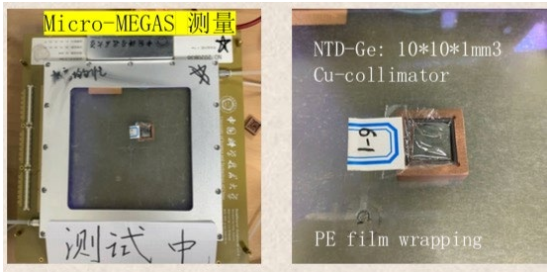
深冷低温半导体温度传感器NTD-Ge研制



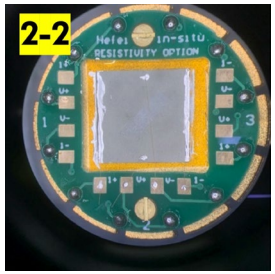


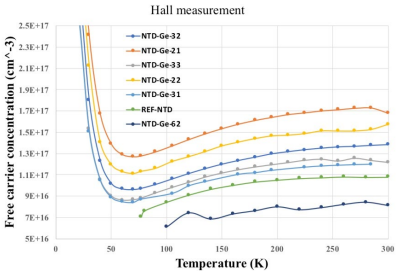




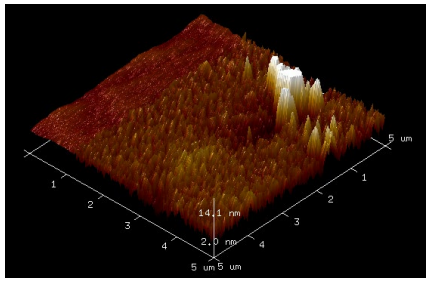


放射性/中子注量测试





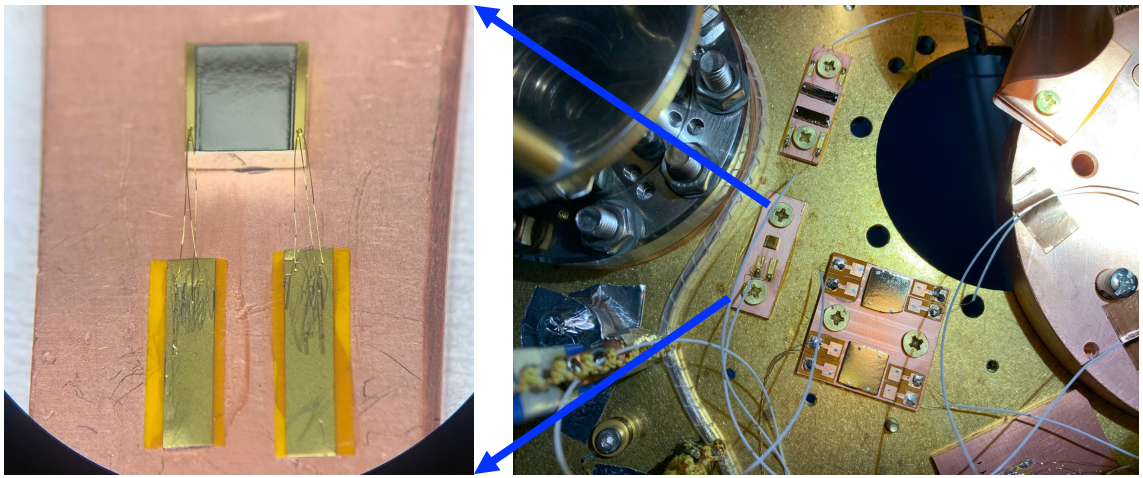
霍尔效应测试

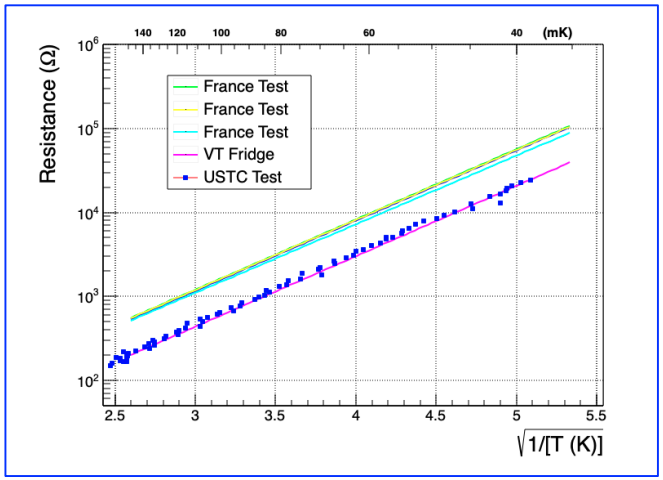


抛光/刻蚀 Rq&Ra<3 nm

NTD-Ge低温测试平台

- 初步搭建一套NTD-Ge深冷mK低温性能测试平台，获得**I-V、R-T曲线**
- 对CUPID 41B系列NTD-Ge展开性能测试，获得结果与VT USA、Orsay France等一致



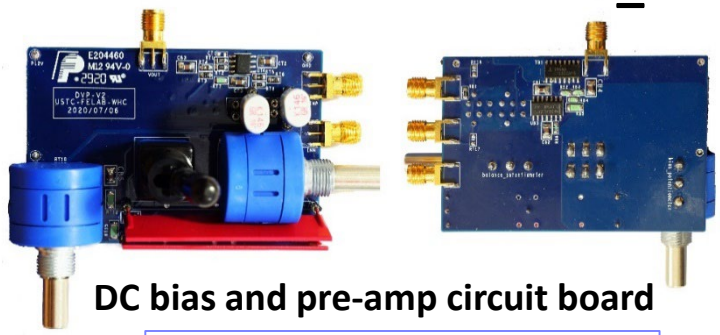


NTD_41B bonding and mK test @USTC，T_0=3.7 K

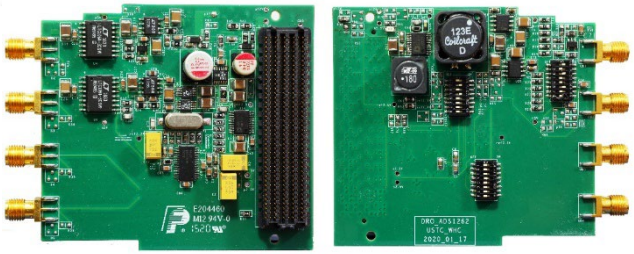
USTC readout electronics and DAQ

Front-End Design and Prototyping

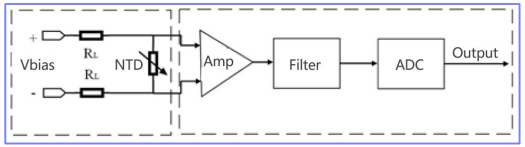
- **Circuit module and test_V1**

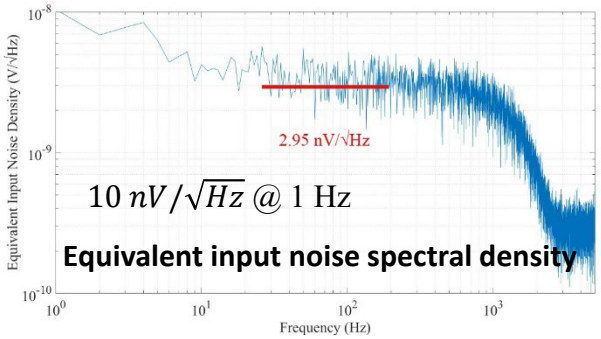


DC bias and pre-amp circuit board

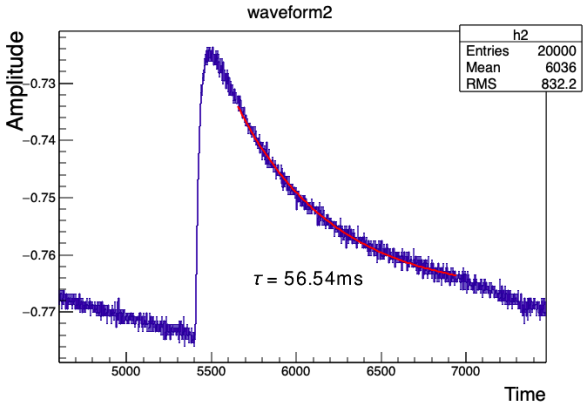


Digital readout board



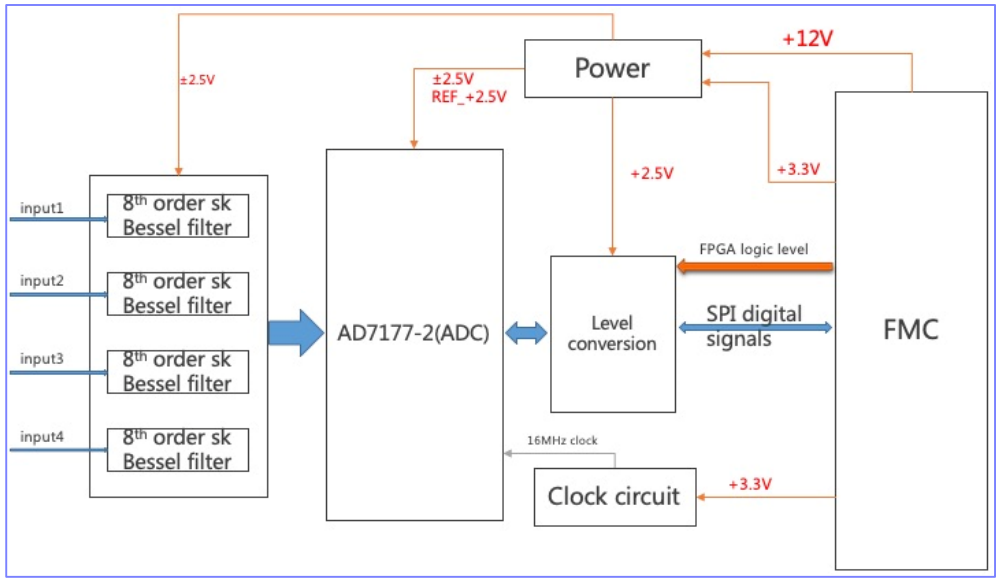


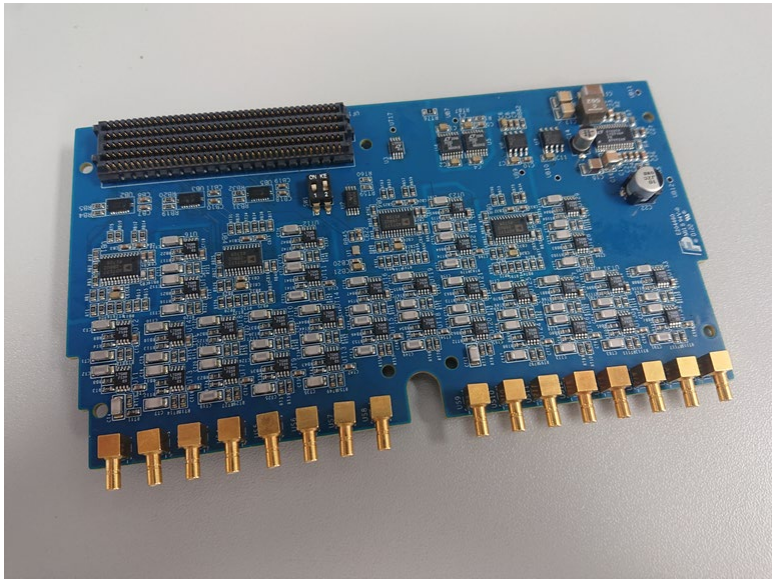
Equivalent input noise spectral density



CMO_small with USTC electronics in a Leiden DU

Bessel Filter and Digitization Board



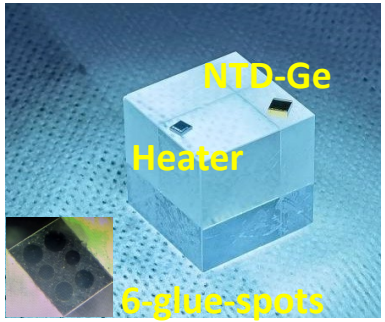


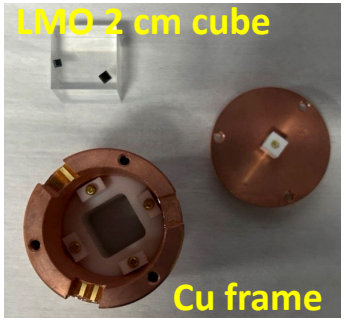
Low noise frond end electronics and read out system of NTD-Ge

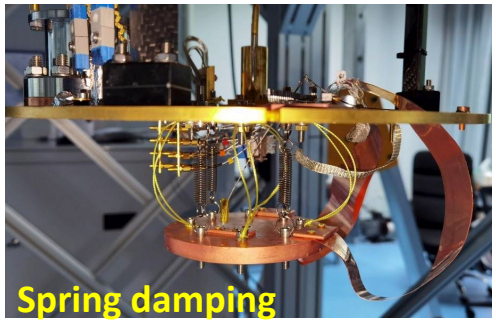
- Verify the key circuit design
- lab testing/ with the detector system
- Amp part, more effort next step
- Digital part
  - waiting for lab test, improvement and upgrade

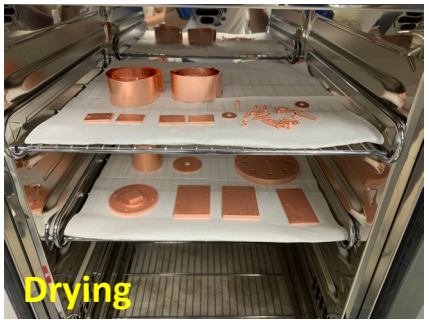
USTC&Fudan LMO量热器研制

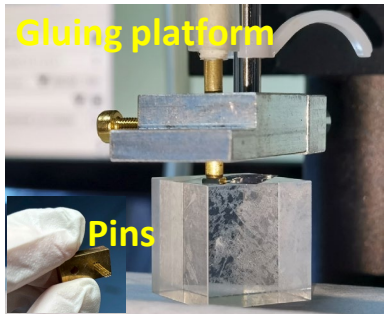
紫铜框架/PTFE支架/螺丝等清洗 → NTD/Heater等胶点阵列耦合晶体 → 探测器组装及电学引线 → 探测器安装至制冷机冷盘

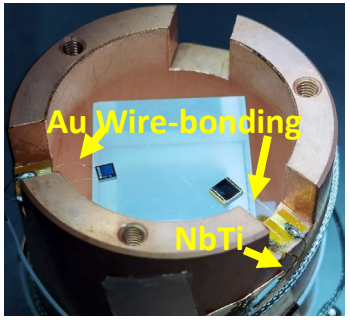


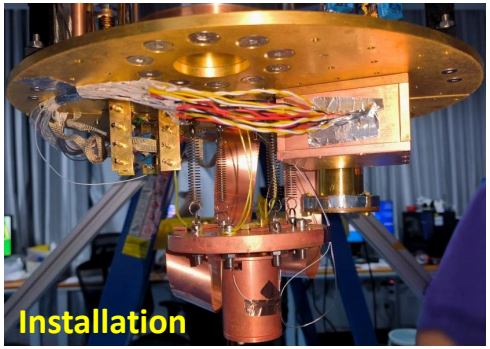




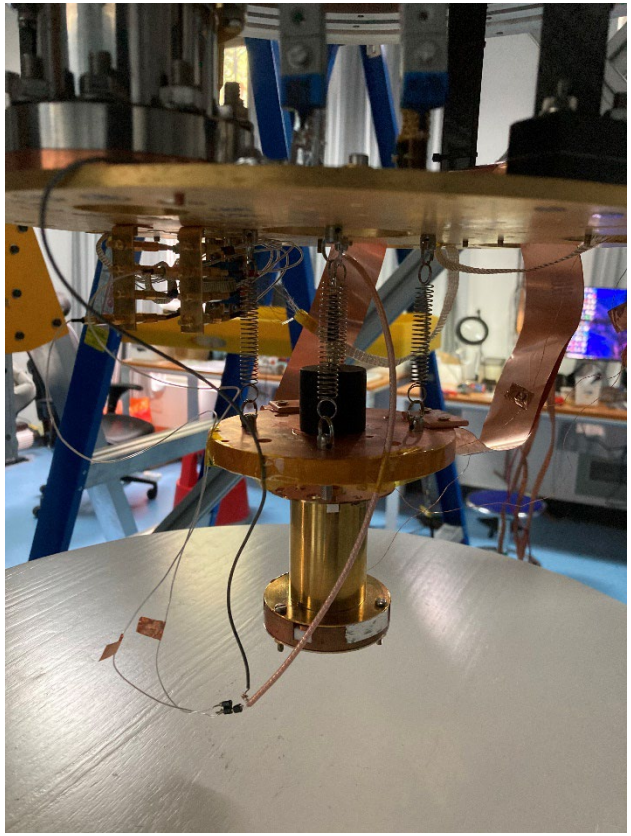


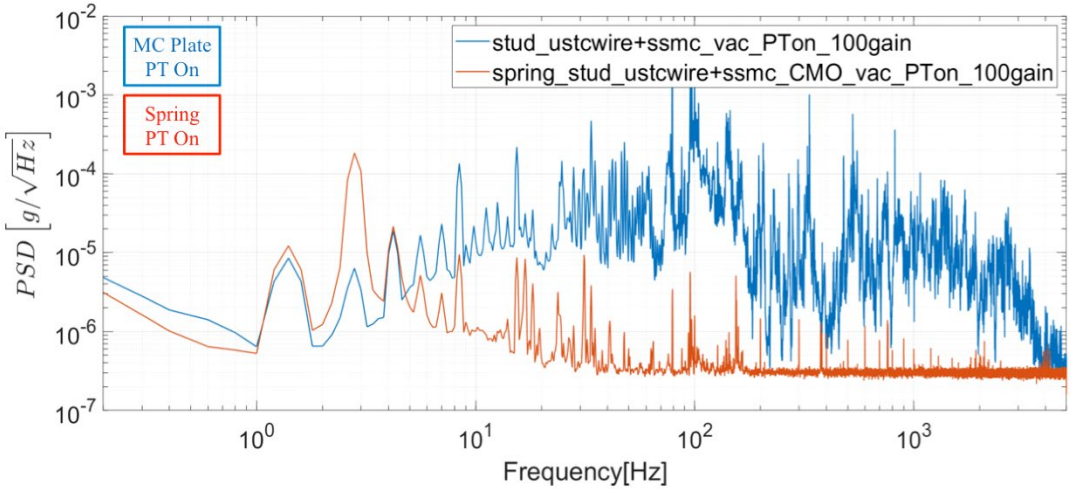


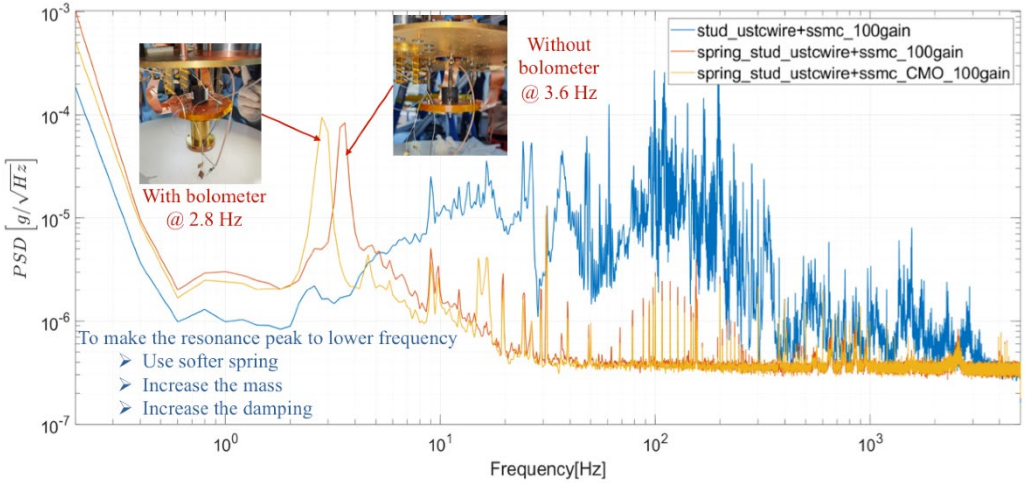




R&D direction: Vibration damping



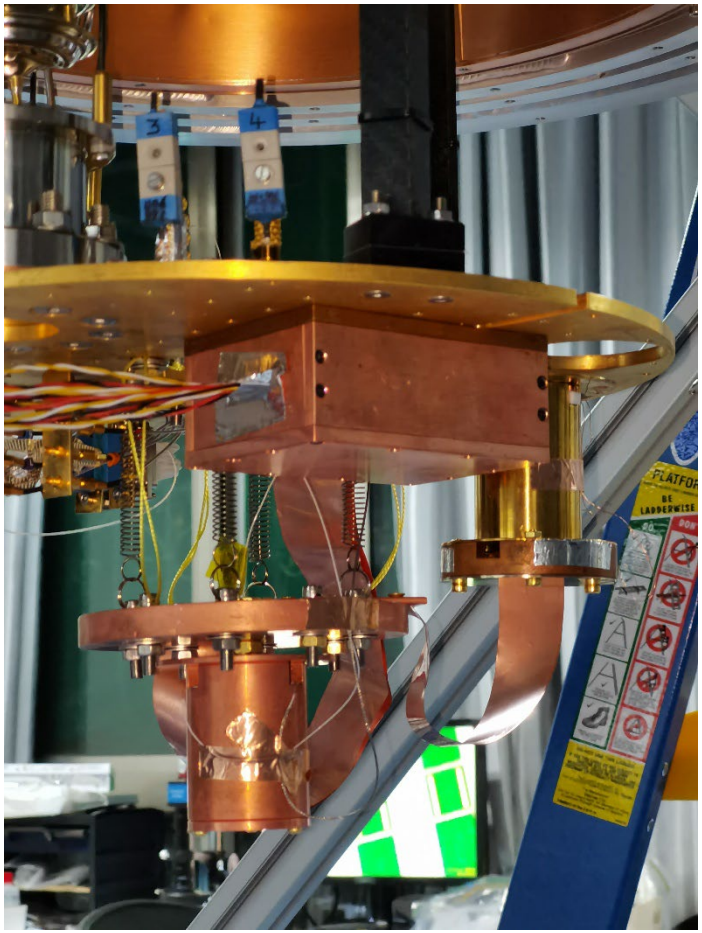


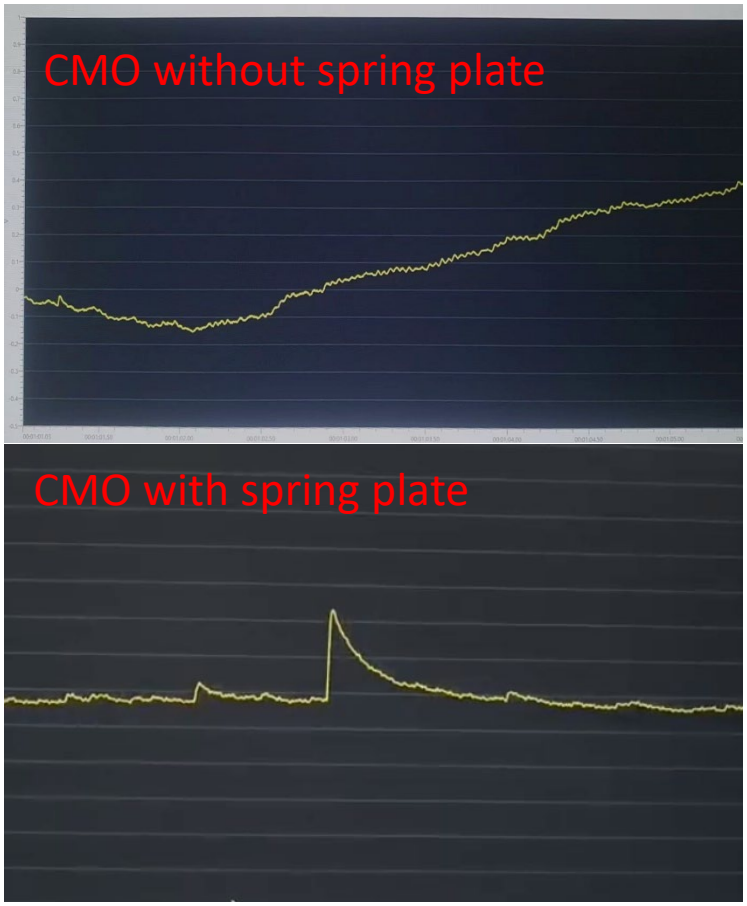


- ➢ R&D on the spring damping system
- damping performance evaluated for various frequency regions

FDU：曹嘉璇
USTC：段德勇

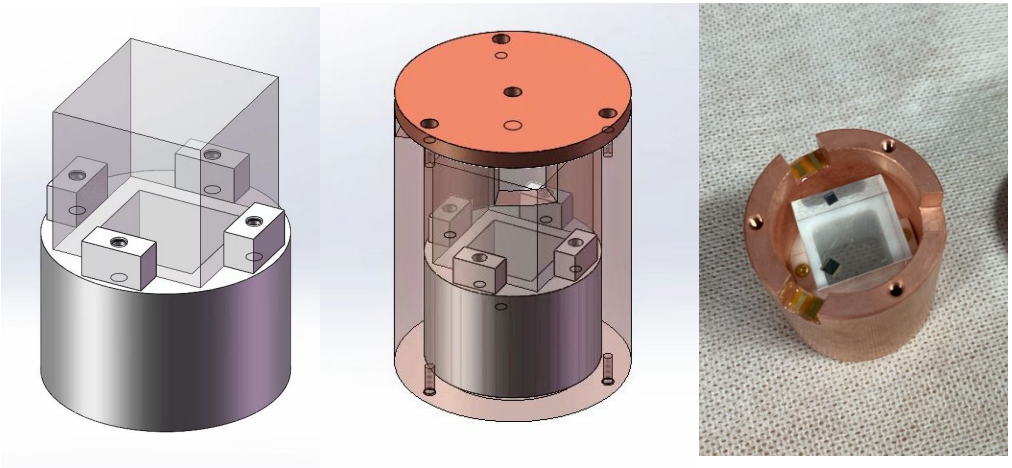
R&D direction: Vibration damping

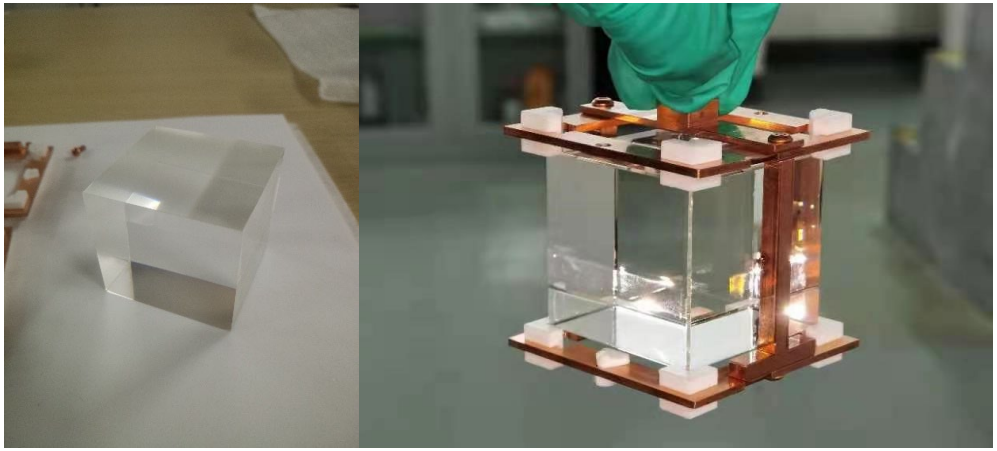




- Bolometer test run for the vibration damping performance study
- the drifting baseline tend to be stable using spring damping (k~500 N/m)

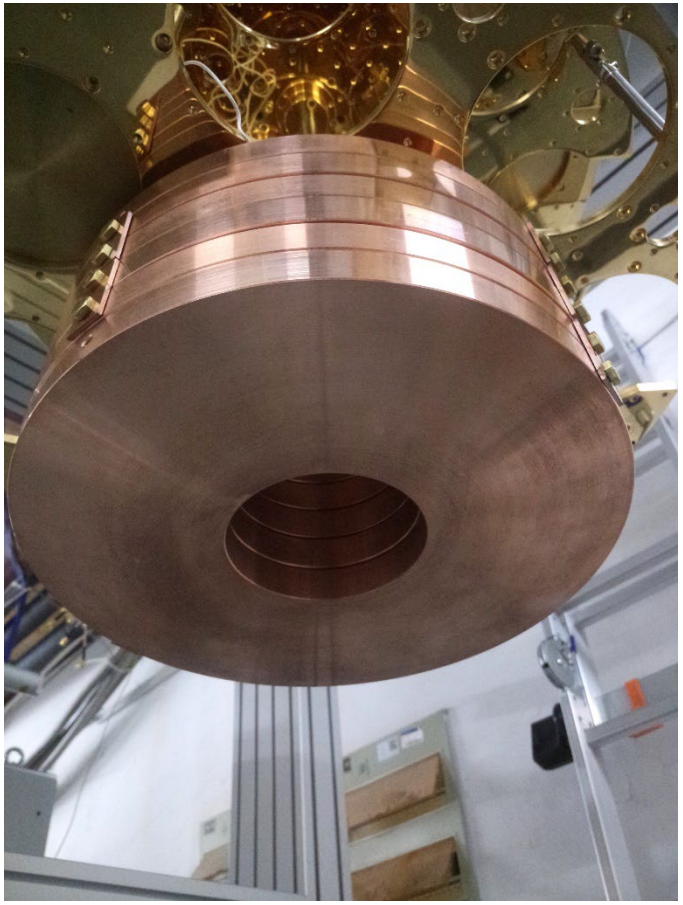
R&D direction: Module design

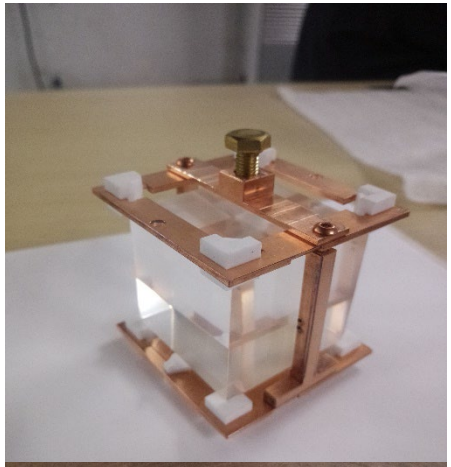


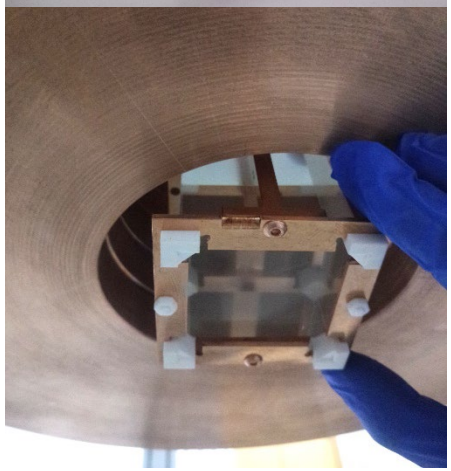


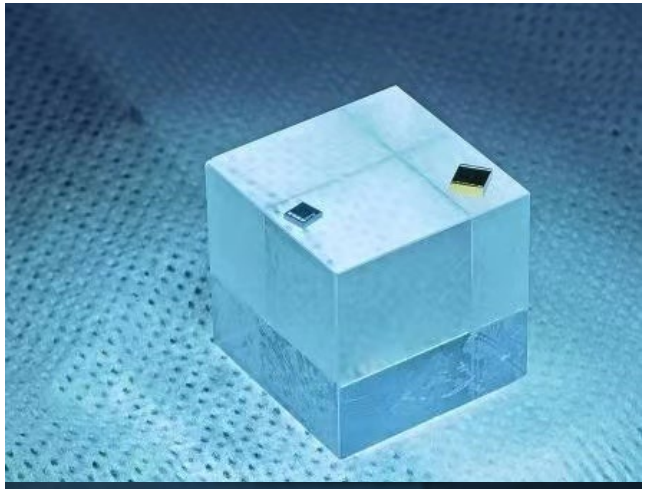
- Different supporting structures for small and standard size crystals

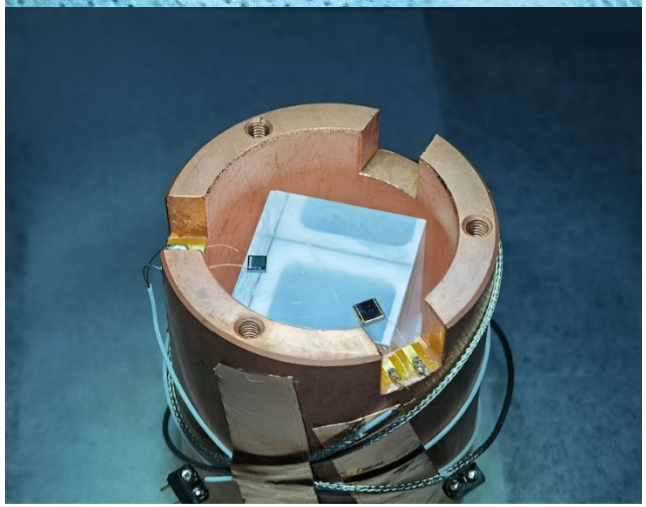
R&D direction: Crystal test











- Ground test without/with shields in the ground lab

CUPID-China Status and Plan

CUPID-China 合作组：

1）可以生长自然丰度的LMO晶体，本底水平满足CUPID实验要求

2）预计近期可以生长和测试富集L^{100}MO晶体

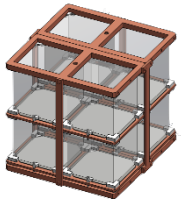
3）建设低温晶体测试平台，将申请入住锦屏实验室，建立低温低本底无中微子双贝塔衰变物理实验室（2023年底或2024年初）

4）今后两年实现TES快响应读出系统和新型电子学读出系统研制

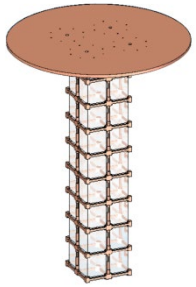
5）参与CUPID在意大利LNGS的探测器建设；建立在CJPL的国际CUPID-CJPL实验合作组

CUPID-CJPL Roadmap

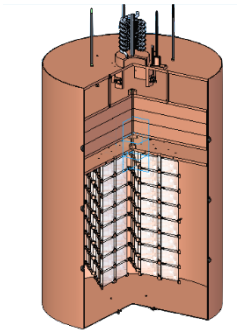
Crystal testing
(2022-2025)
6-12 natural crystals

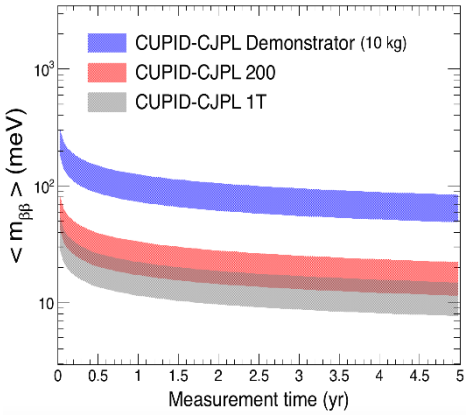


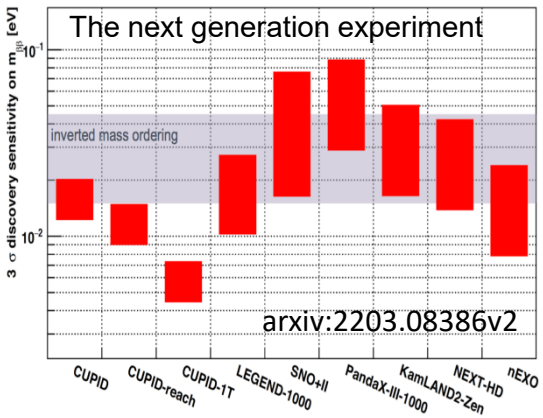
CUPID-CJPL Demo (2026-2028)
10 kg enriched crystals



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



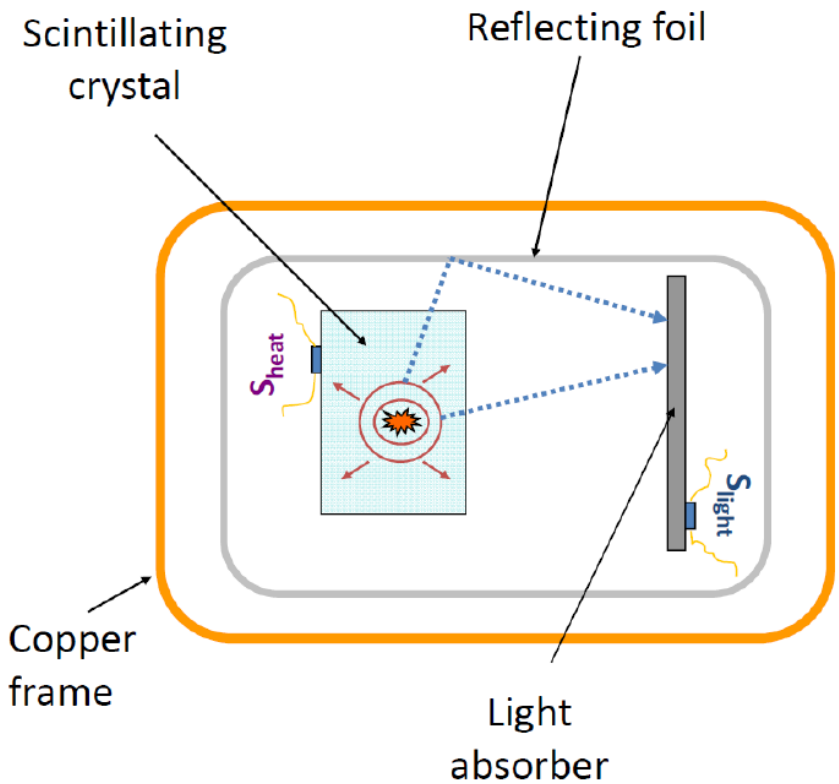


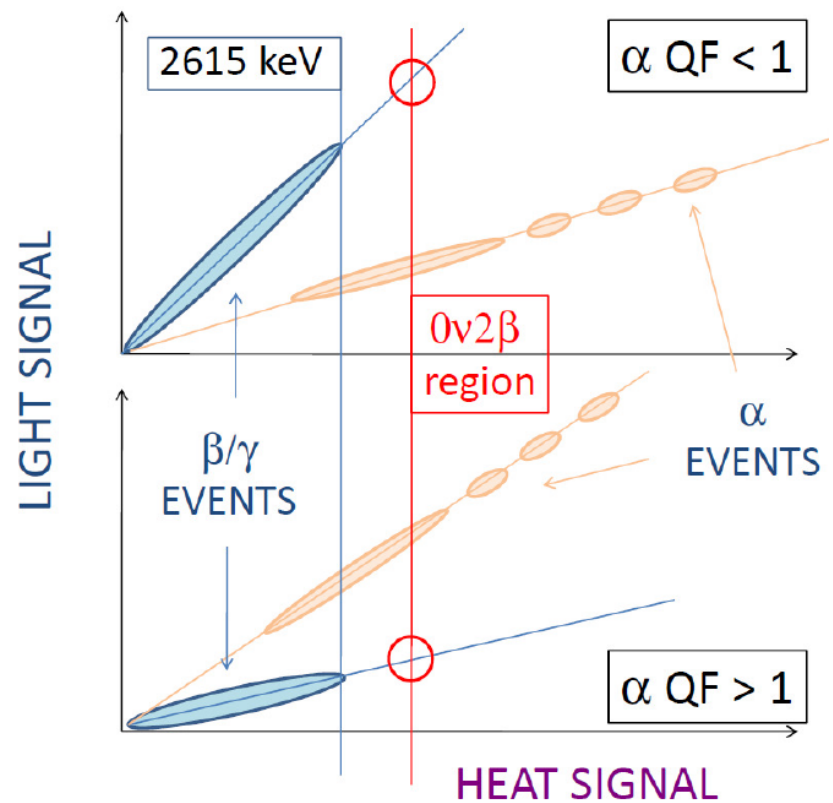


- 10 kg experiment
  - low enrichment
  - demonstrate key technologies
- 250 kg+ experiment
  - high enrichment
  - probe m_{bb} down to 10meV

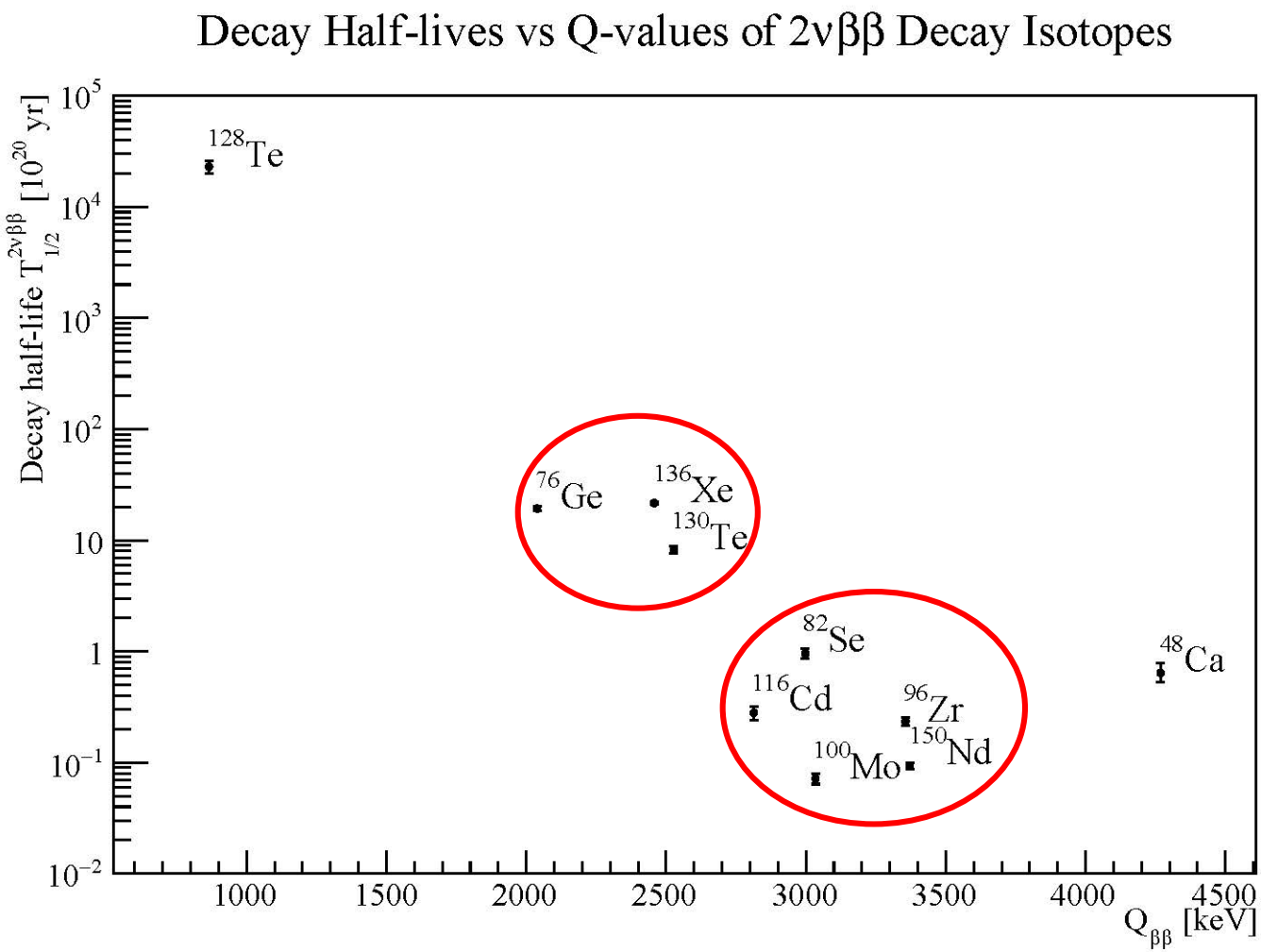
Thank You !

Central role of luminescent bolometers in CUPID





Is there a preferred Isotope for 0vbb search?



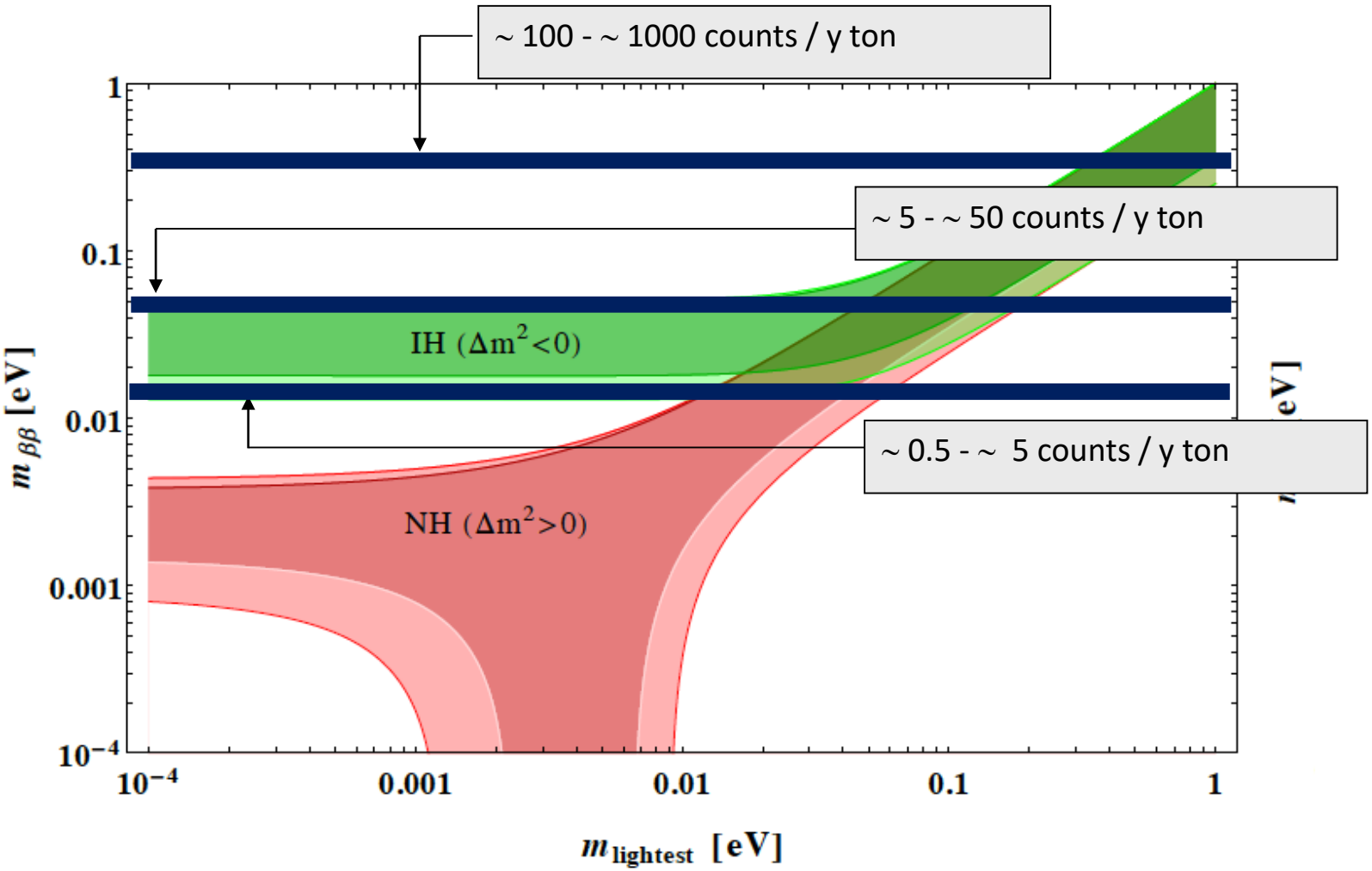
Two groups of isotopes? ^{130}Te and ^{100}Mo attractive choice !

Candidate for Double beta Decays

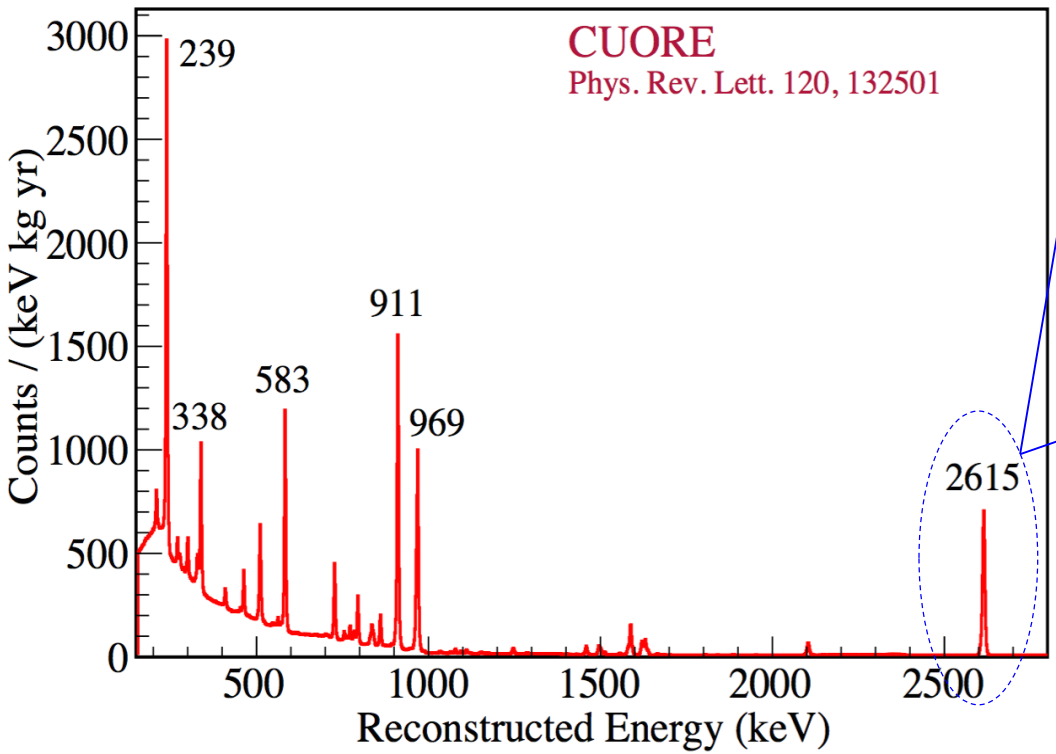
γ 2615 keV from ^{208}Tl – major background

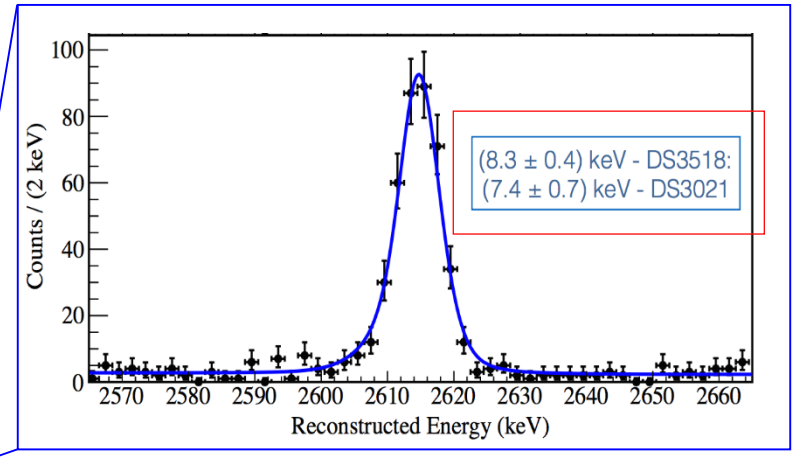
	Q (MeV)	Abund.(%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	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

Challenges for 0vbb Searches

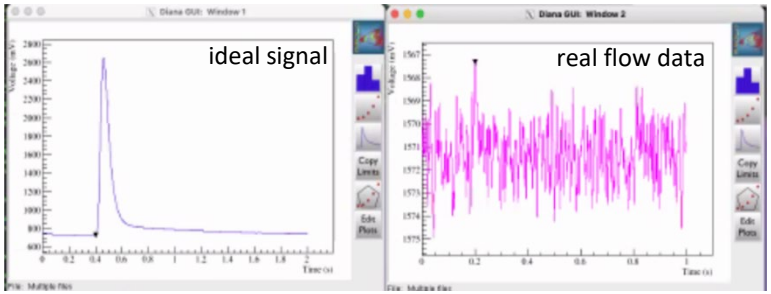


R&D direction: Vibration damping





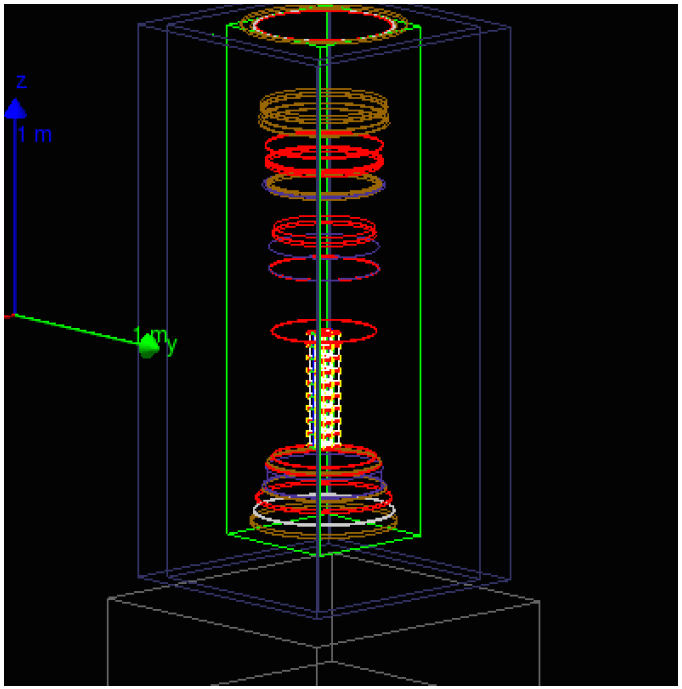
Expected : 5 keV FWHM @2615keV

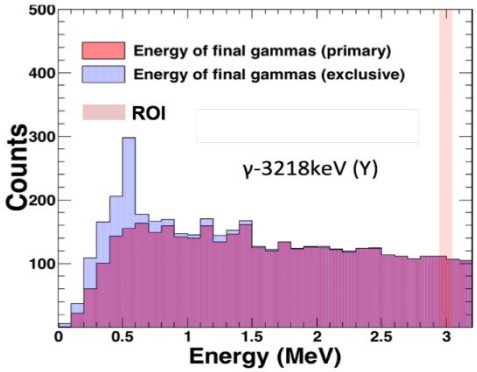


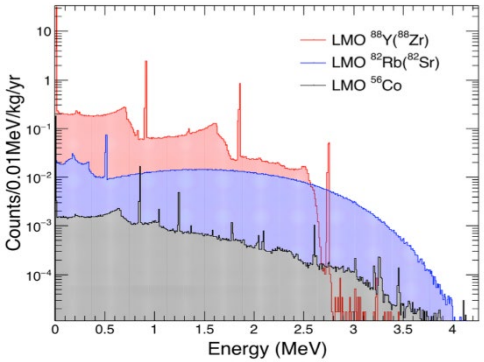
➢ Lessons learned from CUORE

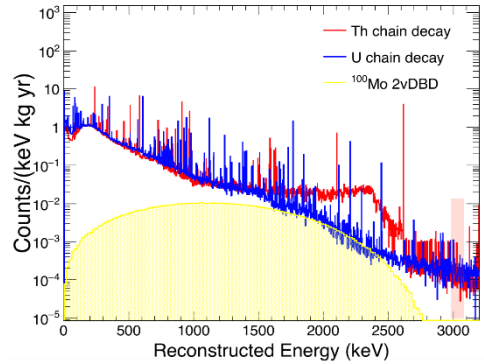
--- vibration noise has non-negligible effect on the energy resolution

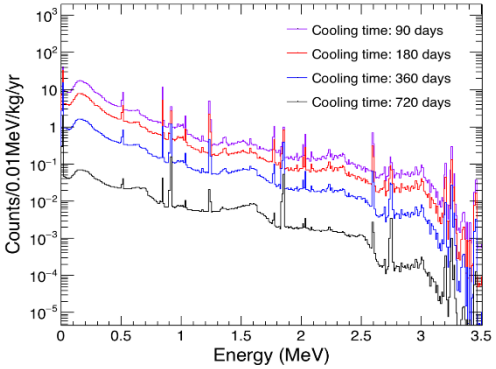
R&D direction: Simulation study







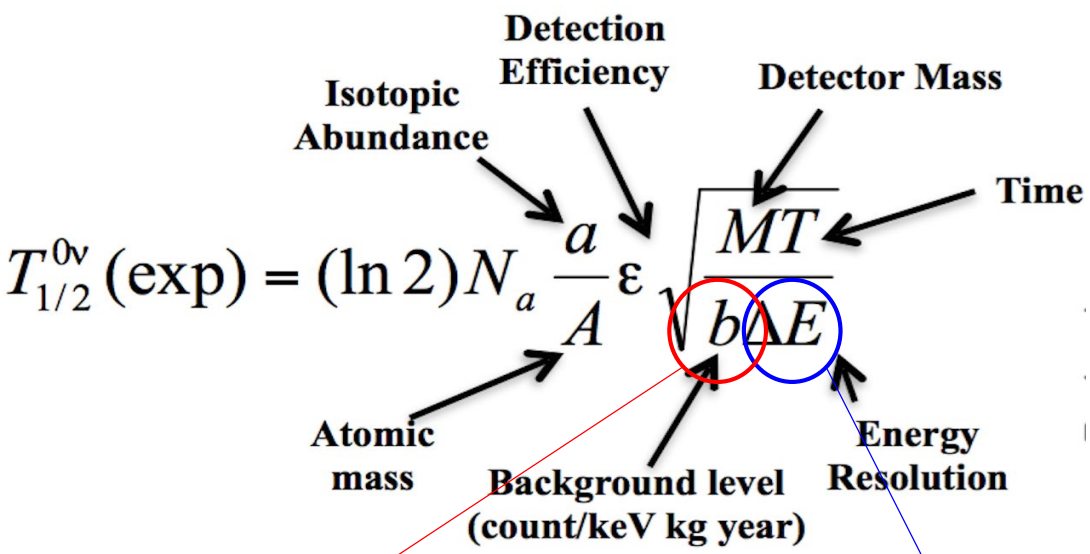




- ➢ Geant4-based simulation tool developed for detector simulation
- ➢ Systematical studies performed for:
- environmental background shielding
- material radioactive background
- cosmogenic isotope production and background

W. Chen, L. Ma, H. Z. Huang et al, Eur. Phys. J. C 82: 549 (2022)

- Experimental challenge – > Sensitivity
- The next generation experiment requires
- Better energy resolution
- Lower radioactive background



Material selection

Vibration mitigation