Cryogenic phonon-scintillating bolometer technology and its applications

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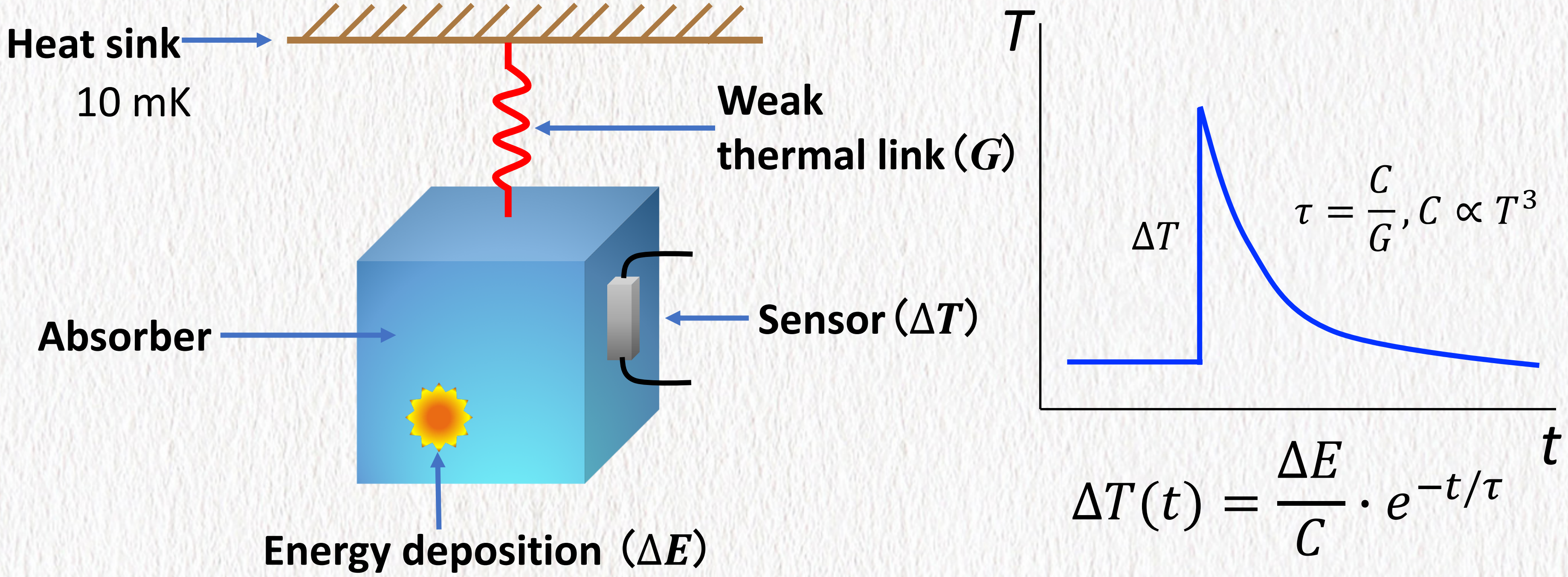
Outline

- ❀ **Cryogenic phonon-scintillating bolometer**
  - ❈ Basic principle
  - ❈ Typical applications
- ❀ **$CdMoO_4$/Li_2MoO_4/Gd_2SiO_5 bolometer for $0\nu\beta\beta$ search**
- ❀ **$PbWO_4$ bolometer for reactor CEνNS observation**
- ❀ **Summary**

Cryogenic Phonon Detector/ Low Temperature Detector

- ❀ Particle detector based on **phonon detection**

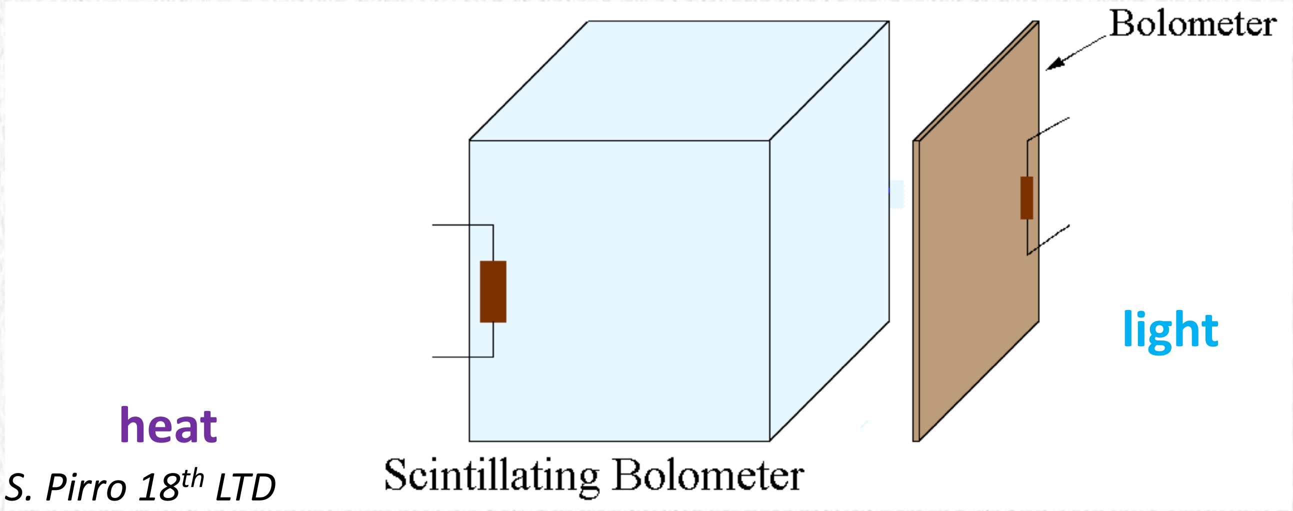


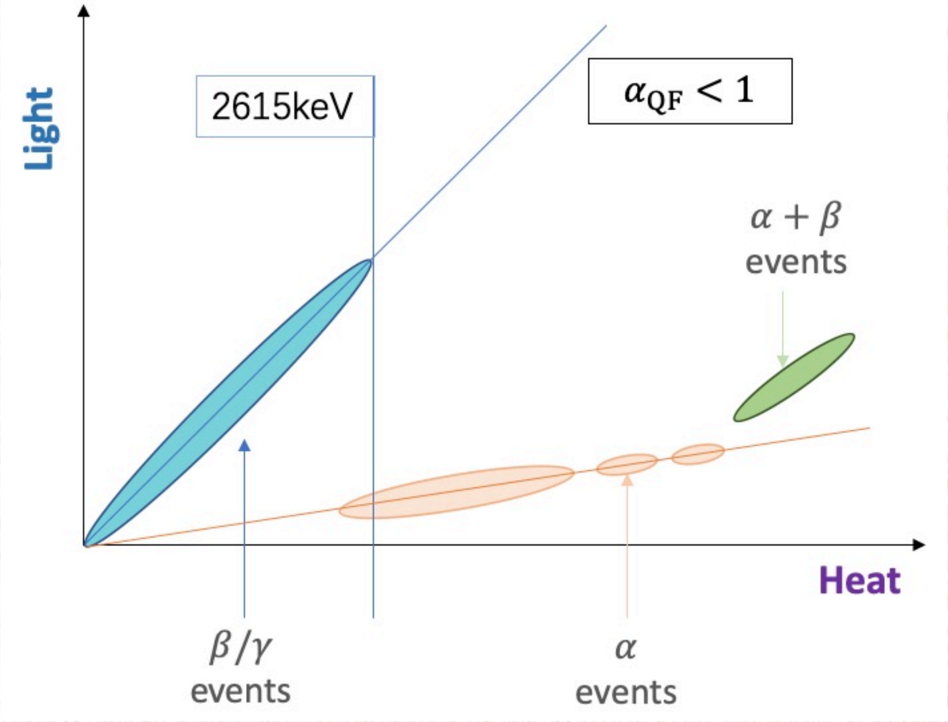
$$\Delta T(t) = \frac{\Delta E}{C} \cdot e^{-t/\tau}$$

- ❀ **Main components**
  - ❈ **Absorber**, interaction between particle and material, energy deposition
  - ❈ **Sensor**, measure the temperature increase of the absorber
  - ❈ **Heat sink + Weak thermal link**, provide stable low temperature and energy release

Cryogenic phonon-scintillating bolometer

❀ Absorber = Scintillating crystal, **light-heat** double readout





❀ **Advantages**

- Wide selection of absorber material
- **Low energy threshold** (~15 eV)
- **Good energy resolution** (5.3 keV@2.6 MeV, **2‰**)
- **Particle identification**, light-heat double readout → background suppression

Typical applications of CPD *(LTD 18th, Andrea Giuliani's talk)*

Low energy physics (MeV, keV, eV)

Signal width μs – hundreds ms

Good energy resolution

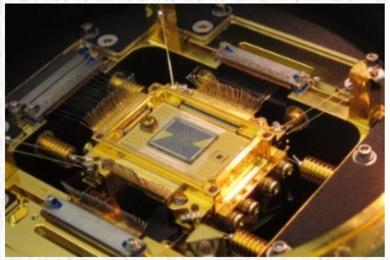
Light dark matter search

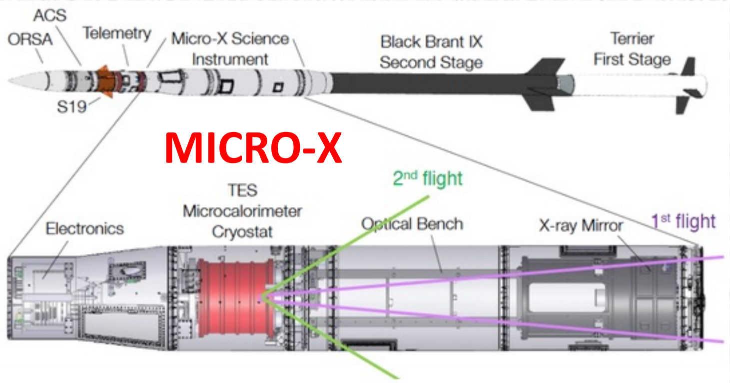
Rare decay search: α decay, **$0\nu\beta\beta$**

CEνNS

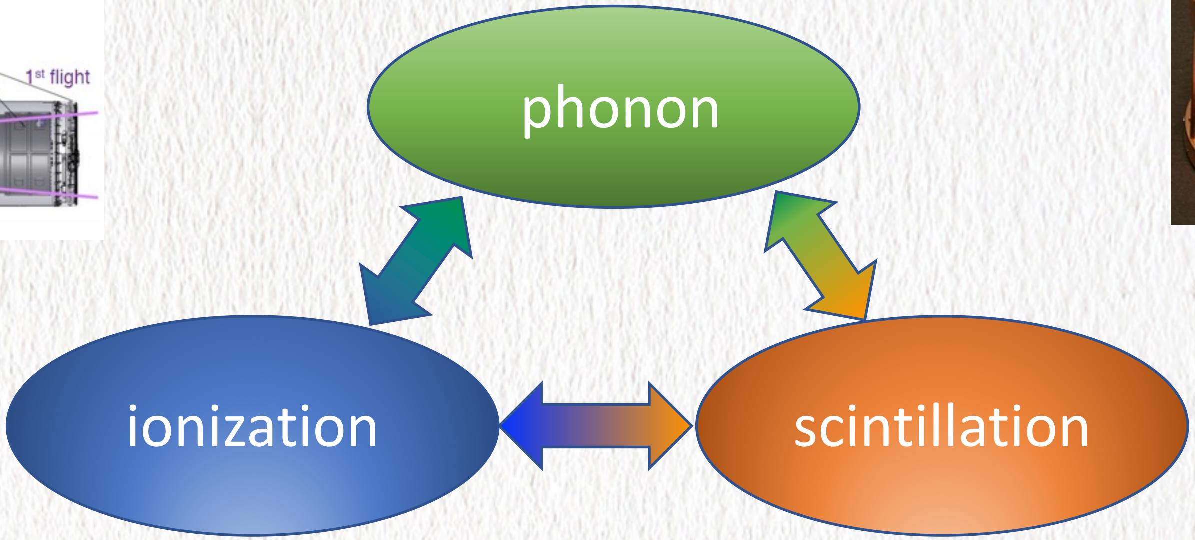
Soft X-ray precision measurement

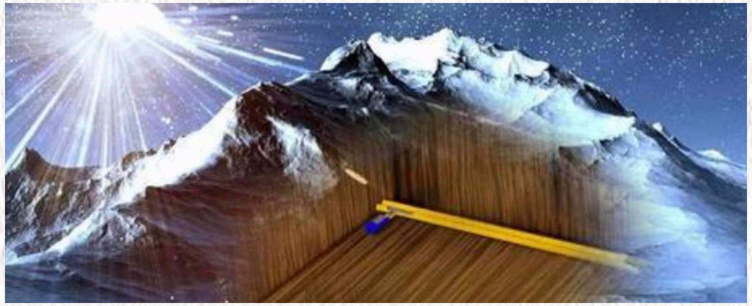
……

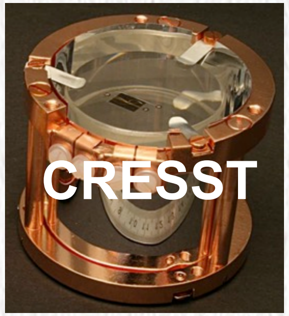


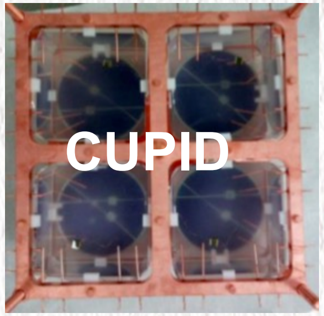


Space









Underground

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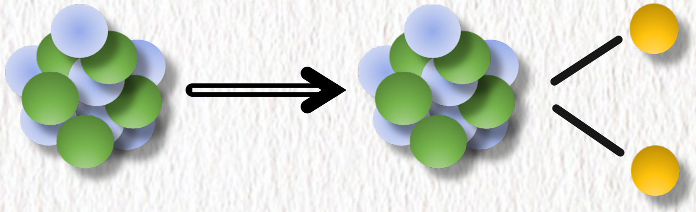
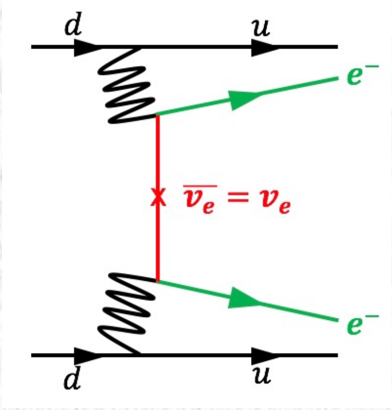
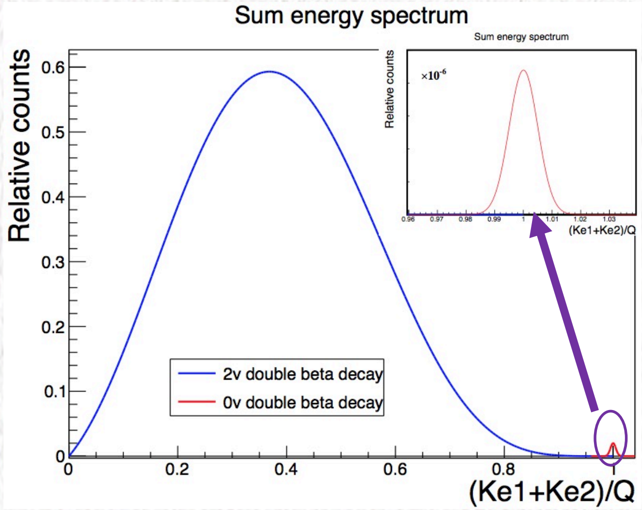
0νββ search and bolometer method

❀ Neutrinoless double beta decay $0\nu\beta\beta$

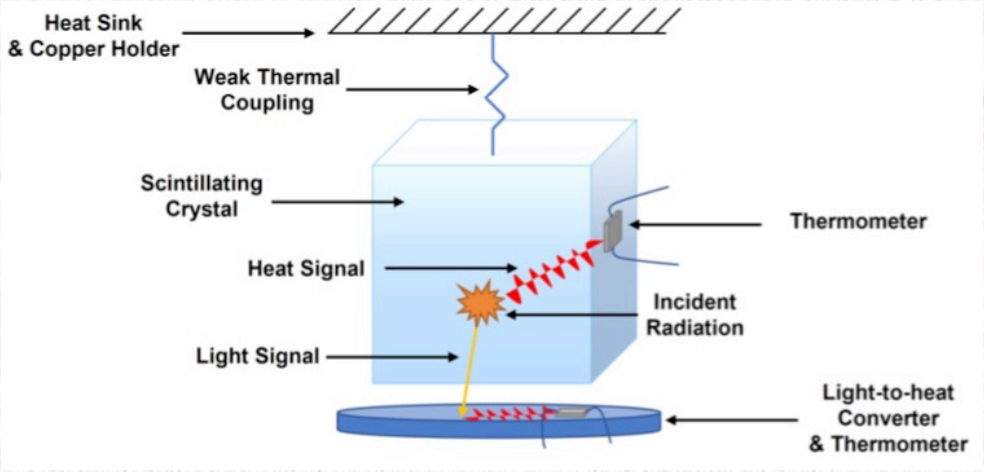


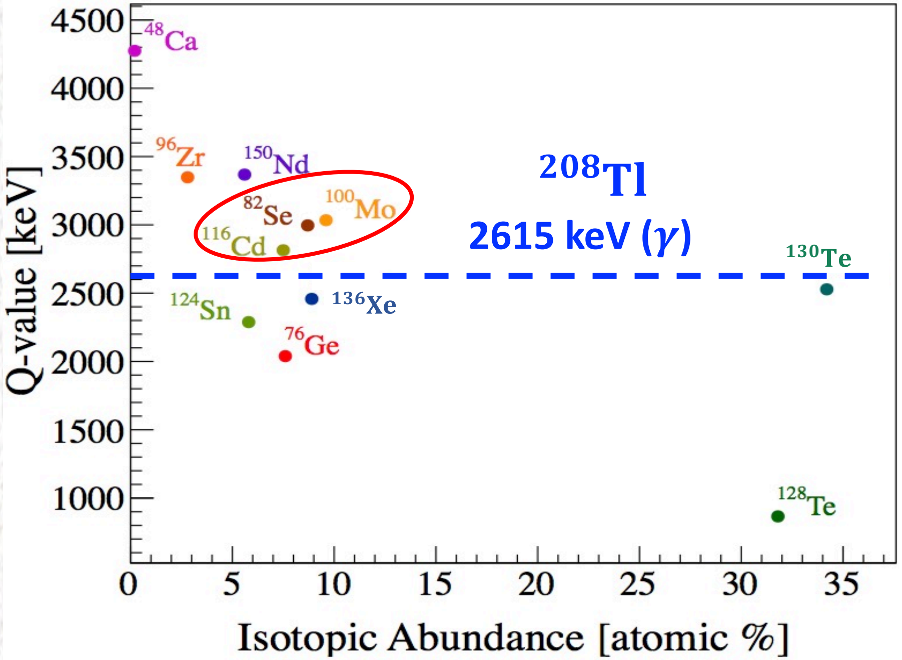
$(A,Z) \rightarrow (A,Z+2) + 2e^-$





❀ Light-heat double readout scintillating bolometer

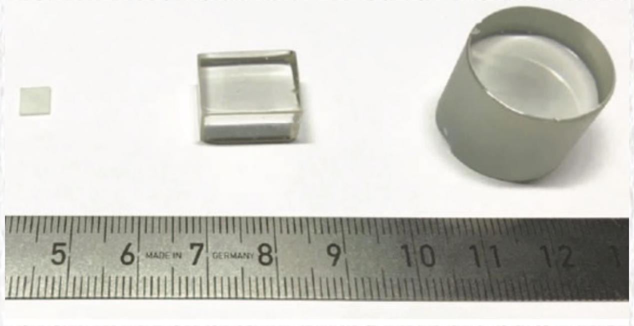




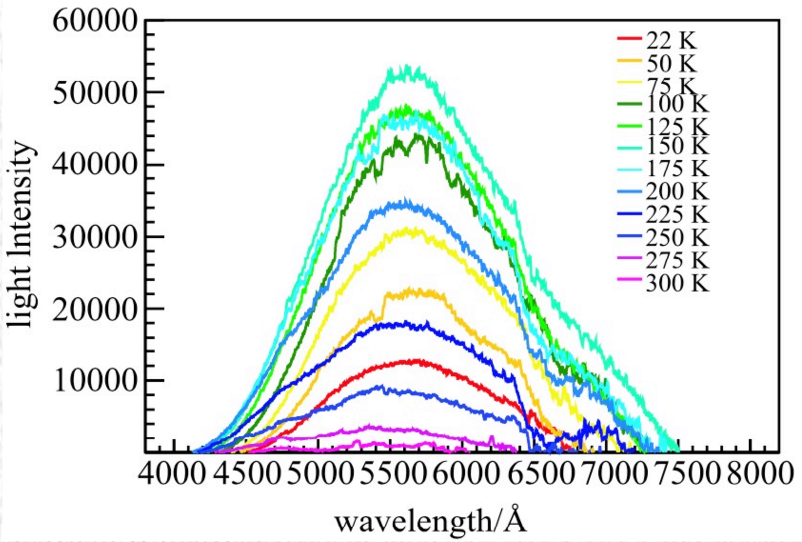
$CdMoO_4$ crystal (^{100}Mo 3034 keV, ^{116}Cd 2813 keV)

***M. Xue**, Y. Zhang, H. Peng, CPC, Vol.41, No. 4, 2017*

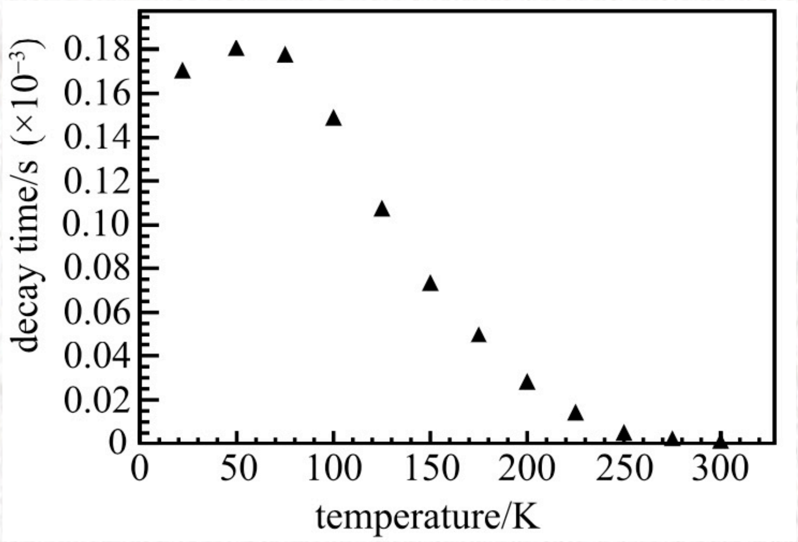
❀ CMO crystal scintillation properties in a wide temperature range 20 -300 K



CMO crystal from NBU



CMO light yield



CMO decay time

❀ excited with a laser beam of 355 nm, wavelength exhibited broad emission bands peaked at 551 nm

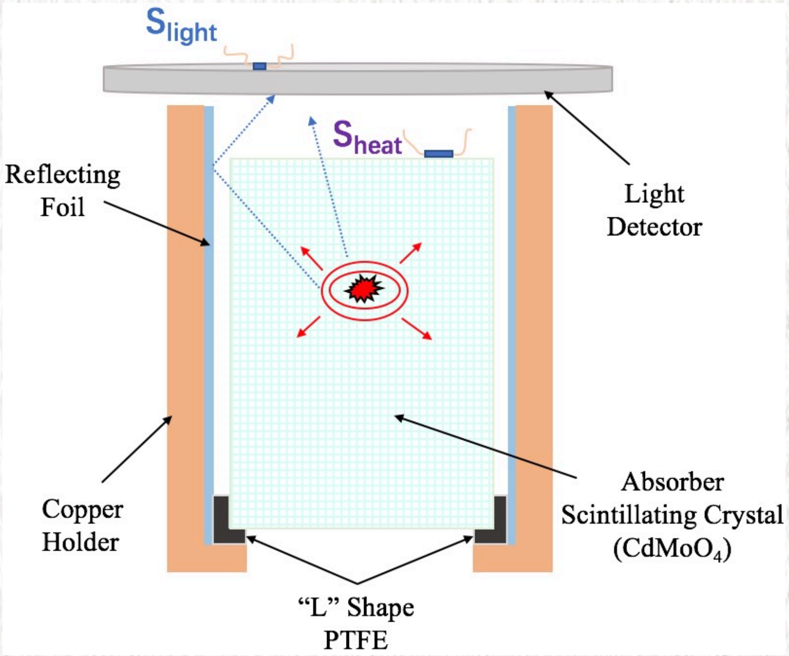
❀ Very faint light at room temperature, reached a maximum at approximately 150 K

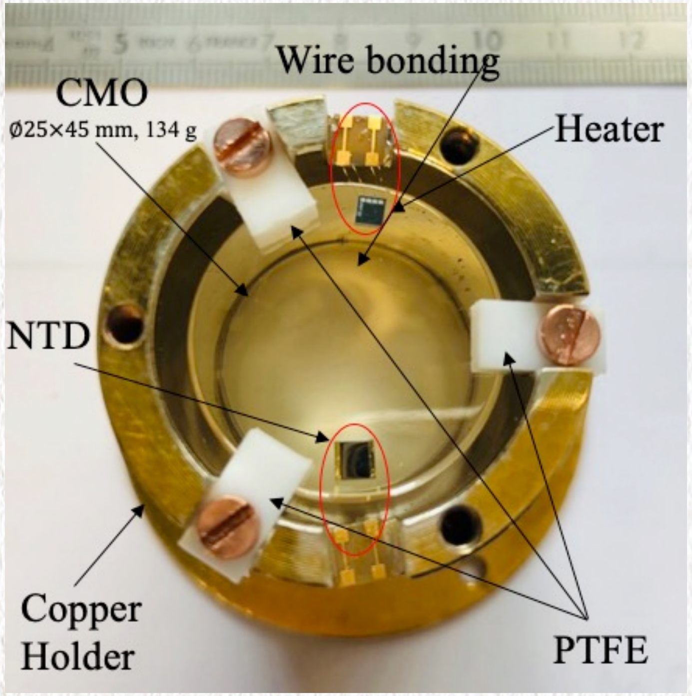
❀ μs scintillation decay time

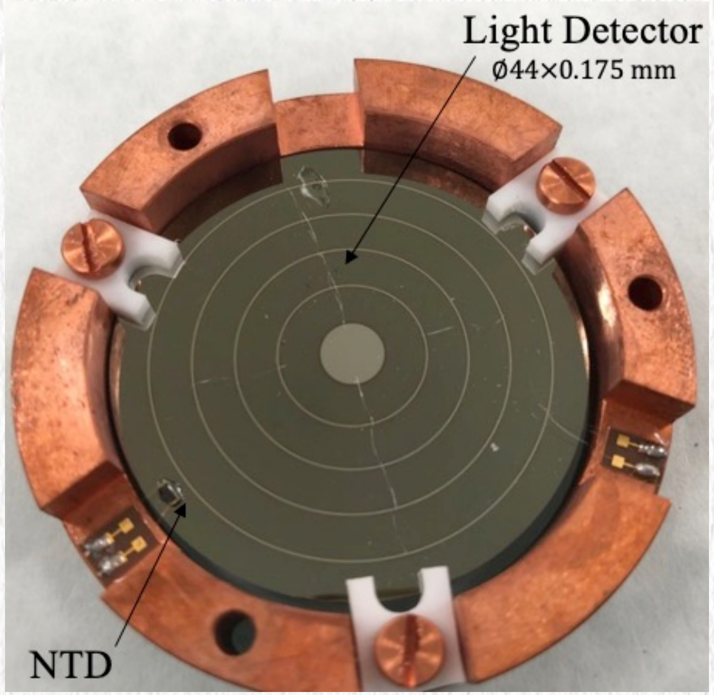
$CdMoO_4$ scintillating bolometer R&D

❀ Design and fabrication

M. Xue, Y. Zhang, H. Peng, NIM A, 943, 162395, 2019





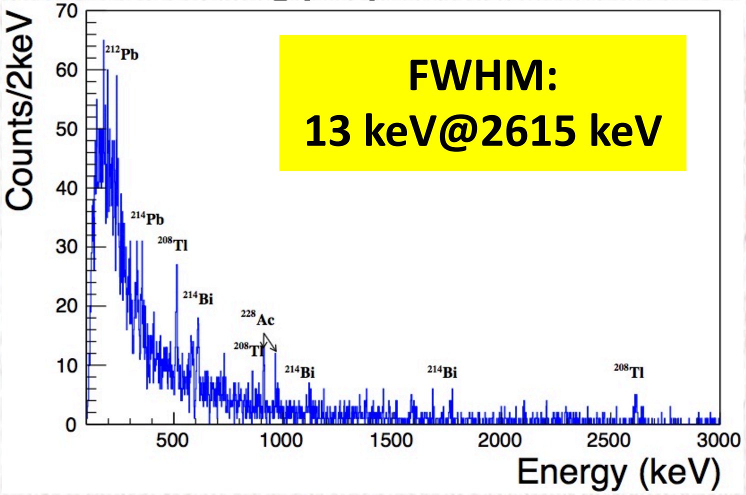


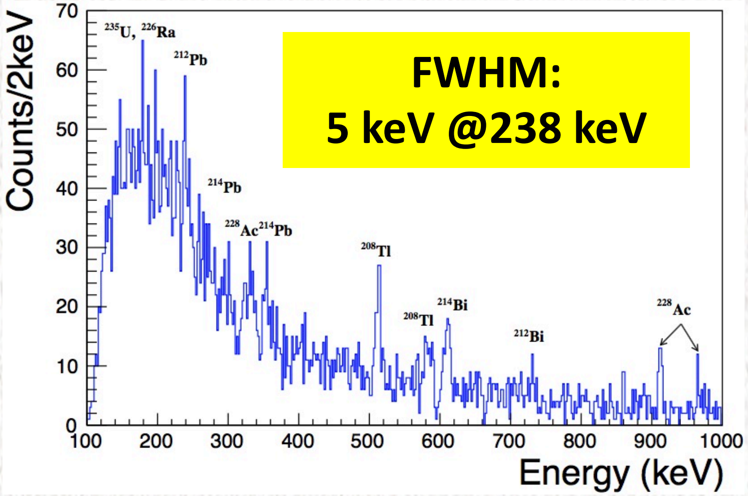
CMO scintillating bolometer, both readout of light and heat

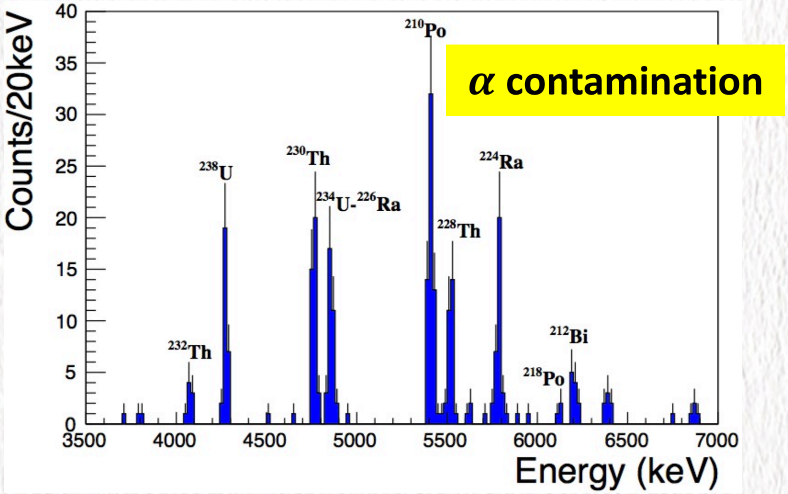
❀ Running at 25 mK in Orsay DU, triggerless data

Detector performance

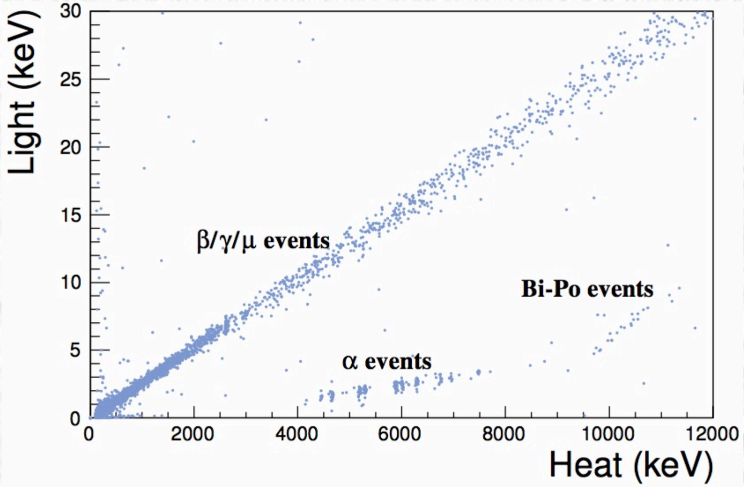
❀ Energy spectrum

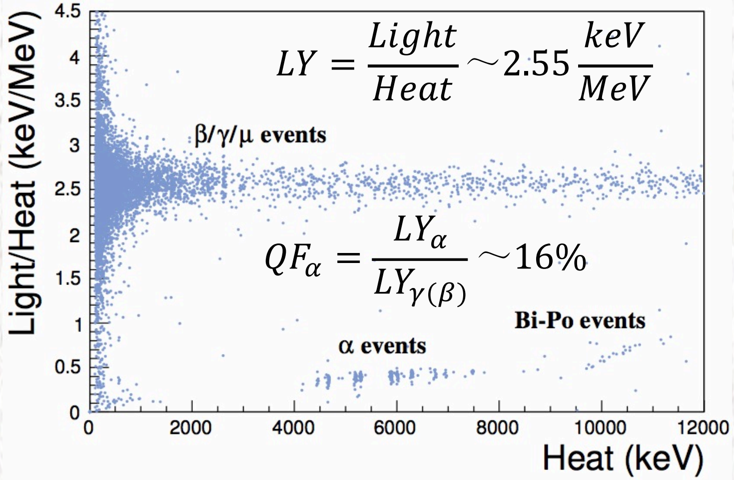


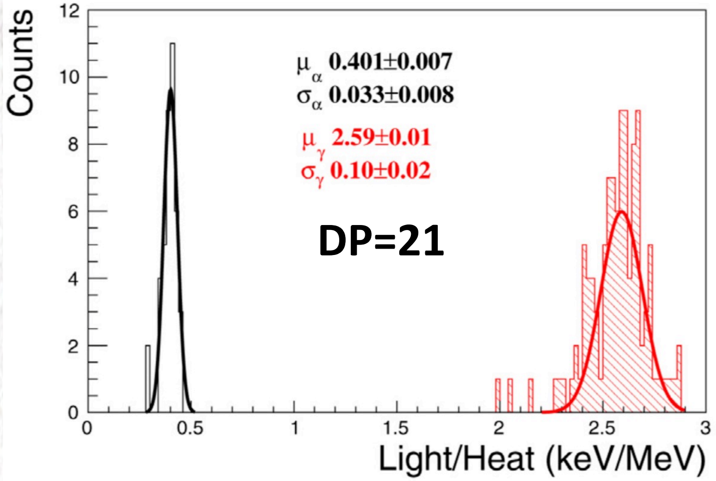




❀ Light yield and quenching factor, discrimination power

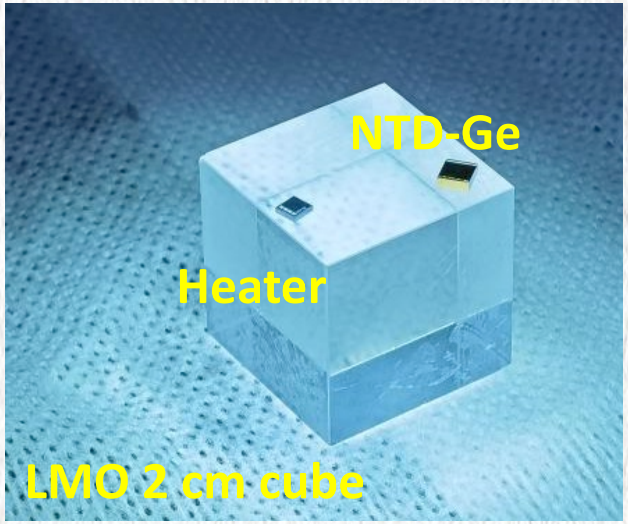


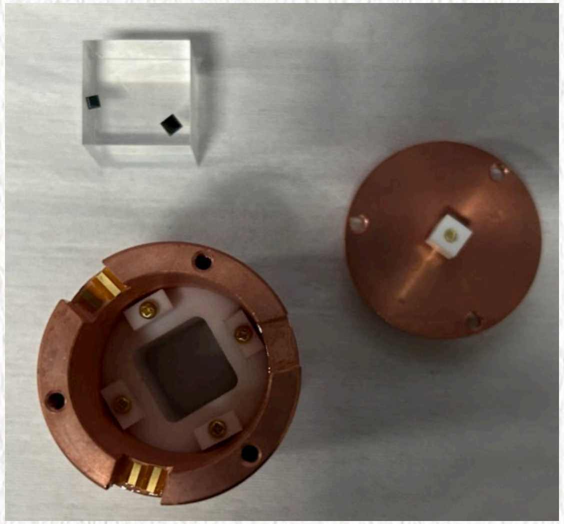


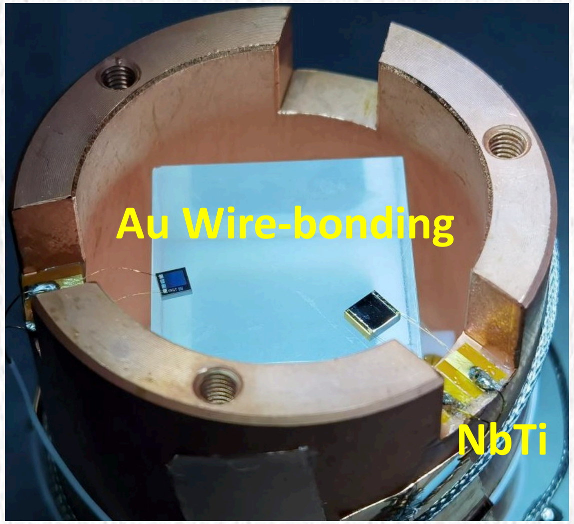


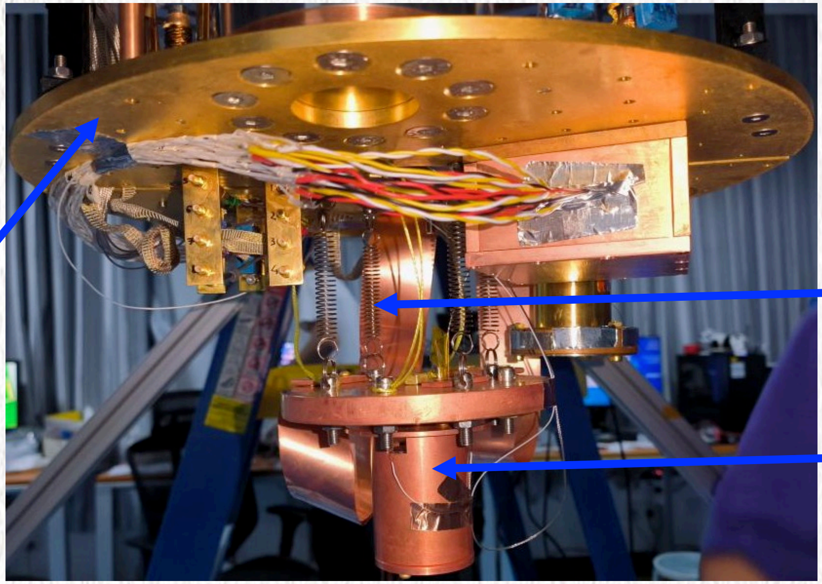
Li_2MoO_4 bolometer R&D (^{100}Mo 3034 keV)

❀ Small LMO 2×2×2 cm^3









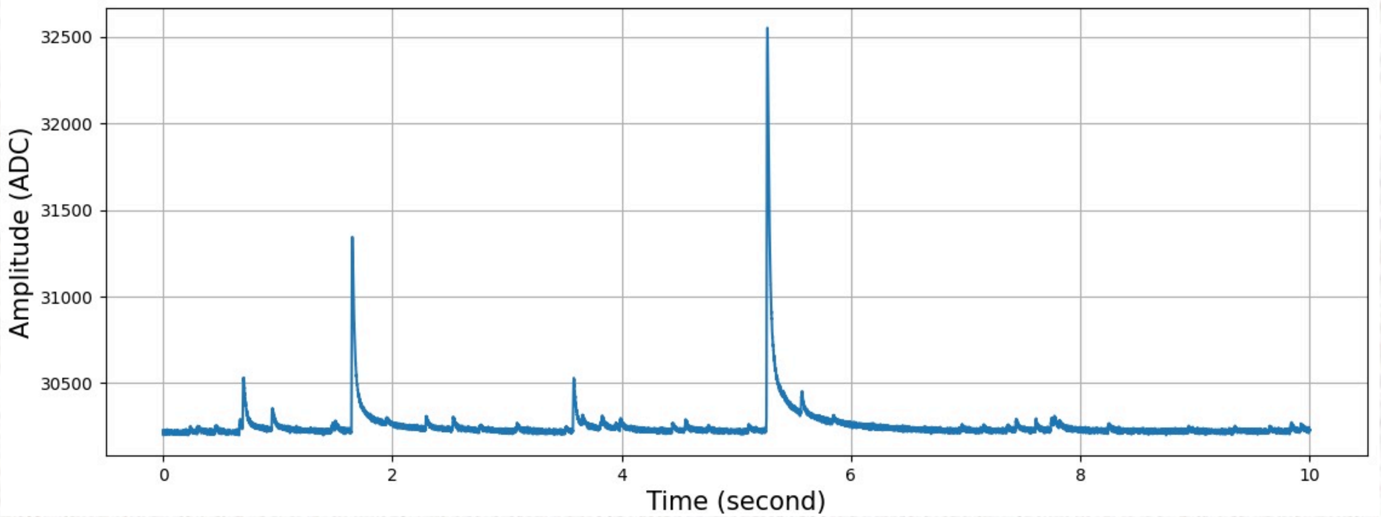
Spring

LMO bolometer

Li_2MoO_4 bolometer readout

❀ Running @10 mK in USTC_DU

Under construction of radioactive shielding

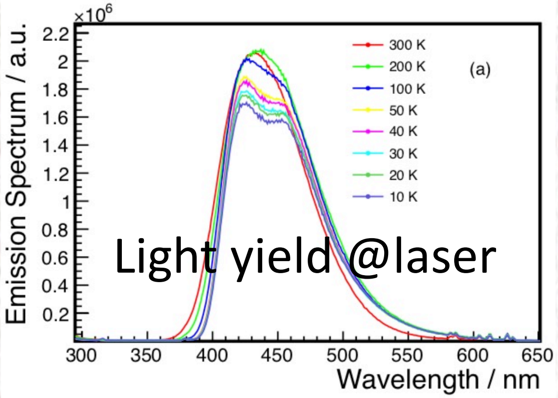


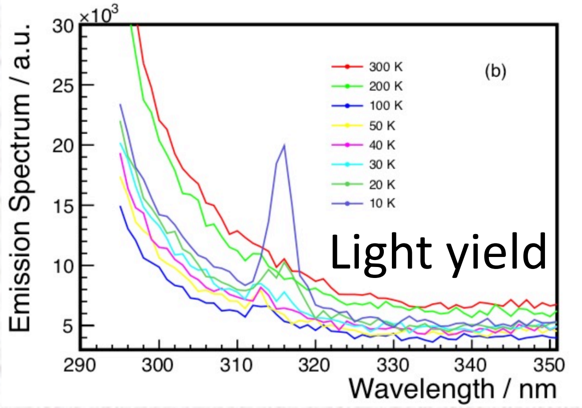
LMO heat readout in a 10 s time window

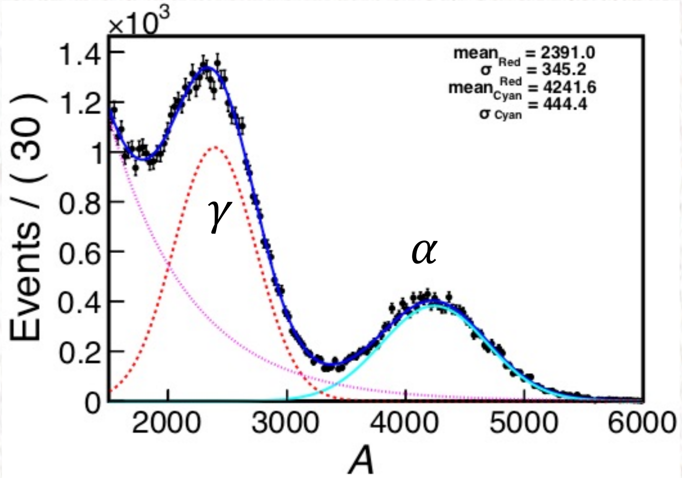
Gd_2SiO_5:Ce crystal and bolometer R&D (^{160}Gd 1730 keV)

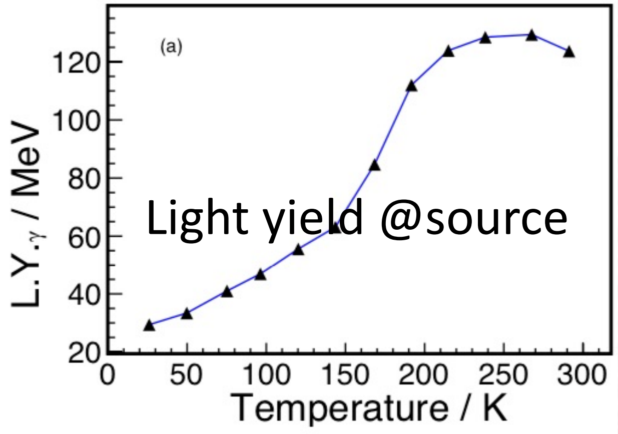
*Z. Jia, **M. Xue**, Y. Zhang, H. Peng, IEEE TNS, 2023*

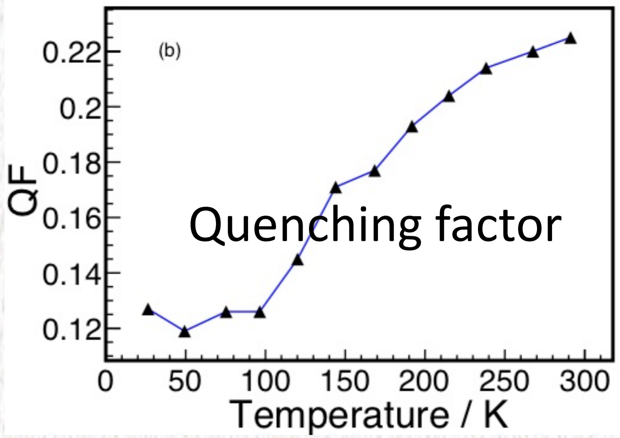
- ❀ GSO crystal scintillation properties in a wide temperature range 10 -300 K
- ❀ Laser and radioactive sources (^{241}Am: α 5.48 MeV, ^{137}Cs: γ 662 keV)











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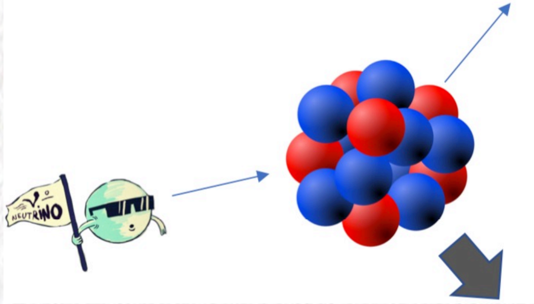
Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)

Akimov et al., Science 357, 1123-1126 (2017)

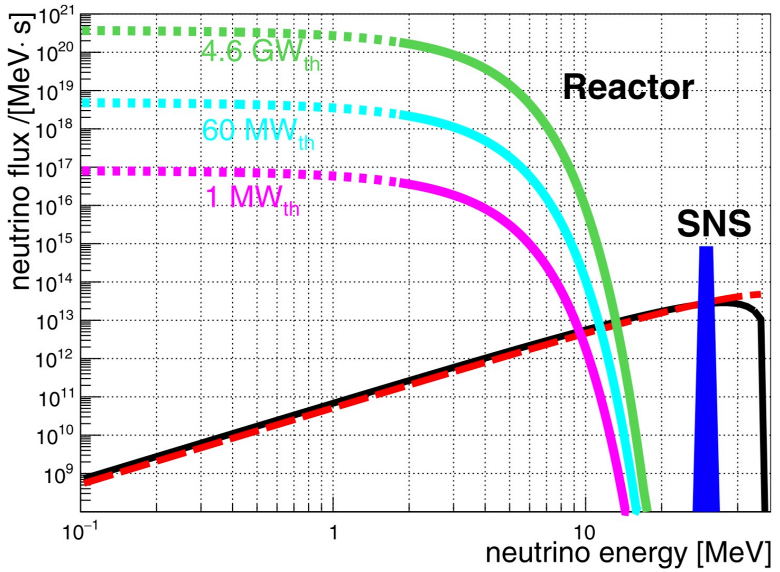
- Coherent interaction between neutrino and the whole nucleus, $\upsilon + A \rightarrow \upsilon + A$, with **fruitful physics**
- **Conditions**: kinetic energy initial $\boldsymbol{E_\nu \lesssim 100\ MeV}$
- **Cross section** of CEνNS, More than **two orders of magnitude** larger

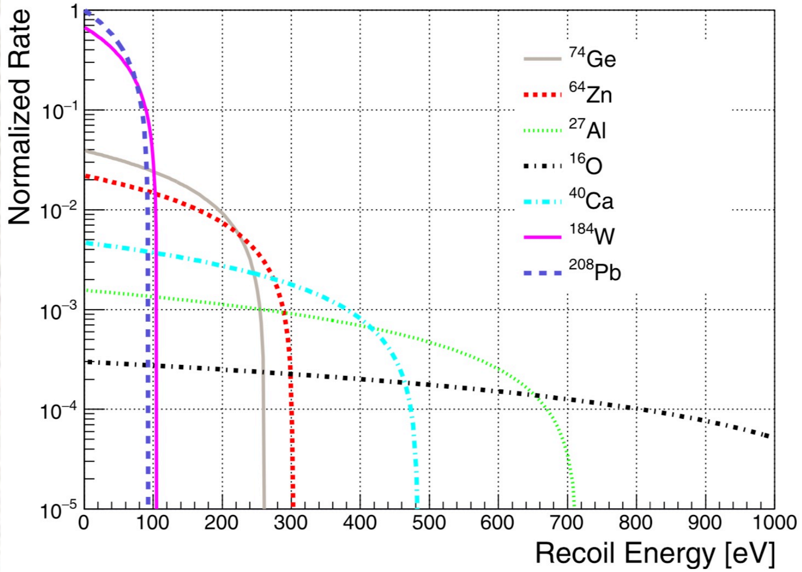
$$\sigma_{\upsilon A} \approx \sigma_0^{SM}\frac{E^2}{M} = \frac{G_F^2 E^2}{4\pi}\boldsymbol{N^2}$$



Exchange of neutral Z bosons

- From SNS to Reactor





① υ-source: high flux with low E

② nuclei: large **N** vs. lower E_R keV, eV

Heavier nuclides → large $\sigma_{\upsilon A}$
reactor neutrinos → **sub-keV** recoil energy

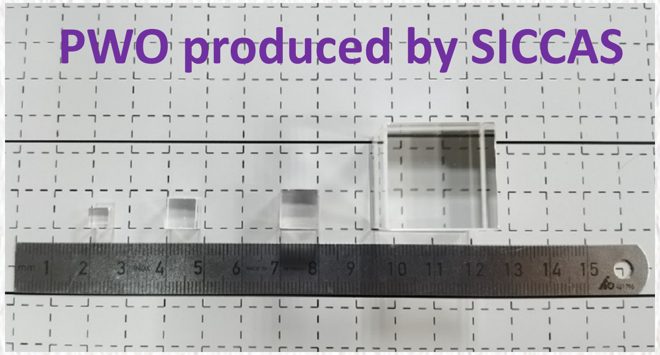
③ detectors: low E_{th} vs. bkg control

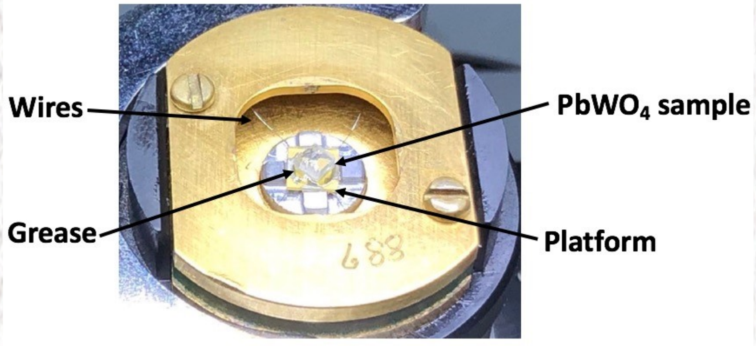
Neutron-enriched cryogenic bolometer

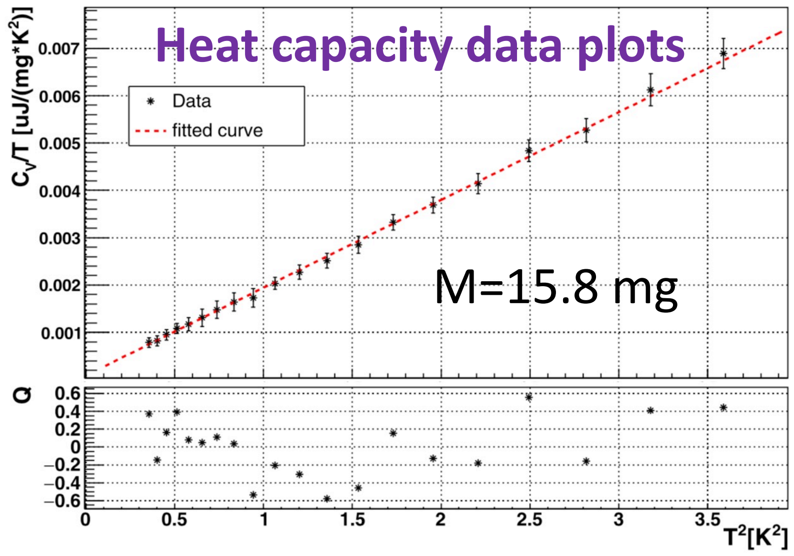
Low temperature specific heat of $PbWO_4$

L. Zhang, **M. Xue**, L. Han, H. Peng, NIM A, 1043, 167469, 2022

- Essential idea for using PWO in reactor neutrino CEνNS experiment:
  - **Neutron-enriched** elements to enhance interaction rates
  - **Low heat capacity** (C) at working temperature (10 mK) to guarantee sensitivity to such small recoil energy deposition, $C \propto T^3$





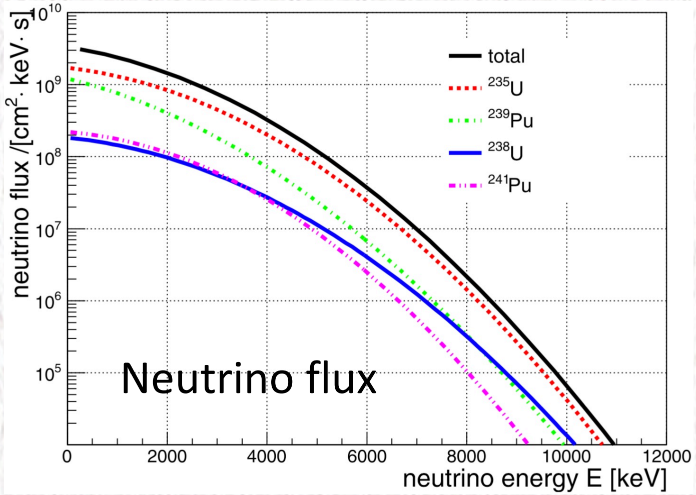


- Experiment test, PPMS, relaxation technique, 500 mK -2 K
- Obtain the Debye temperature $\boldsymbol{\theta_D = (238 \pm 5)}$ **K**
- **HC of** 1 gram PWO detector unit cell is about 2 pJ/K at 10mK

PWO would be the absorber candidate using cryogenic detector to searching for reactor neutrino CEνNS

PWO-CPD CEνNS event rate with China Taishan Reactor

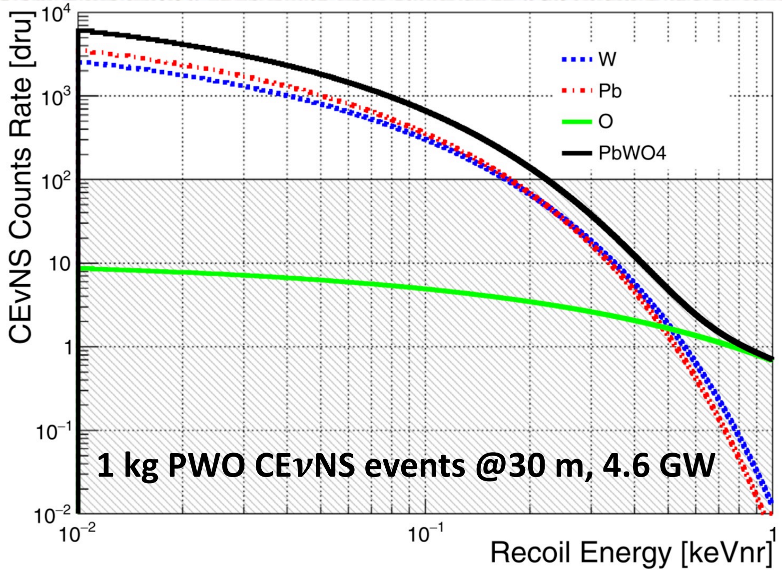
- China Taishan Reactor
  - Located at Taishan in Guangzhou
  - Is going to serve JUNO experiment
  - 30 m near one of the reactor cores (4.6 GWth)
  - Neutrino flux $\mathbf{6.7\times10^{16}\ \nu/(m^2\cdot s)}$



- 1 kg PWO crystal absorber
  - **100 dru** flat background benchmark estimation
  - signal events are dominant in **E_R<200 eV**
  - requires the **E_{th} below O(100) eV**

	counts/[kg day] E_{th} = 10 eV	counts/[kg day] E_{th} = 20 eV	counts/[kg day] E_{th} = 50 eV
$PbWO_4$	221.0	170.8	88.5
W	96.9	75.7	40.1
Pb	123.1	94.2	47.7
O	1.0	0.9	0.7

1 dru = 1 event/kg/day/keV



Summary

- ❀ The low temperature detector based on **phonon detection** has the advantages of **high energy resolution**, **low energy threshold** and very low background noise.
- ❀ Scintillating bolometer with light-heat double readout has the capability of **particle identification**.
- ❀ Become one of the most competitive detection techniques for searching for **frontier physics**, including neutrinoless double beta decay, dark matter, axions, etc.
- ❀ New Molybdate crystal (**$CdMoO_4$, Li_2MoO_4**) and **GSO** crystal are taken as bolometer absorbers for $0\nu\beta\beta$ search (^{100}Mo, ^{116}Cd, ^{160}Gd).
- ❀ Study of a CEνNS experiment at a reactor (China Taishan) with a **$PbWO_4$**-based bolometer.

Thank you

Additional slides