



中国科学技术大学

University of Science and Technology of China

Bolometer-based CE ν NS Research

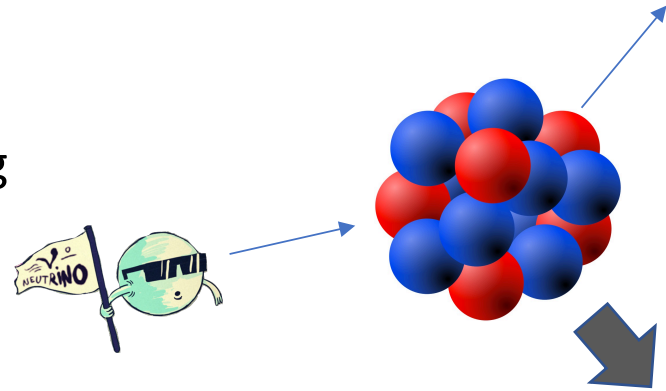
Mingxuan XUE, Luxin Zhang, Liang Han, Yunlong Zhang, Haiping Peng, Zizong Xu

*State Key Laboratory of Particle Detection and Electronics
University of Science and Technology of China*



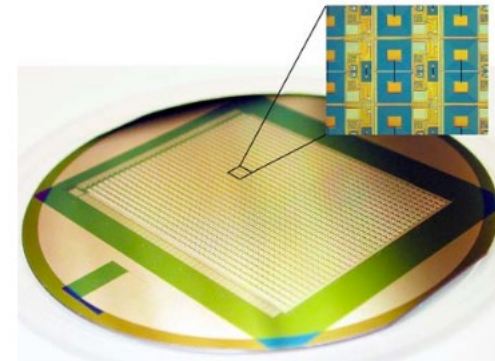
➤ Motivation

- Coherent neutrino-nuclear scattering
- The COHERENT Experiment
- Experiments overview



➤ Tungstate-based Cryogenic Detector

- Principle
- Absorber/sensor
- Cryogenic system
- Counting rate estimation
- Detector simulation



➤ Plans & Summary

Coherent Neutrino-nuclear Scattering

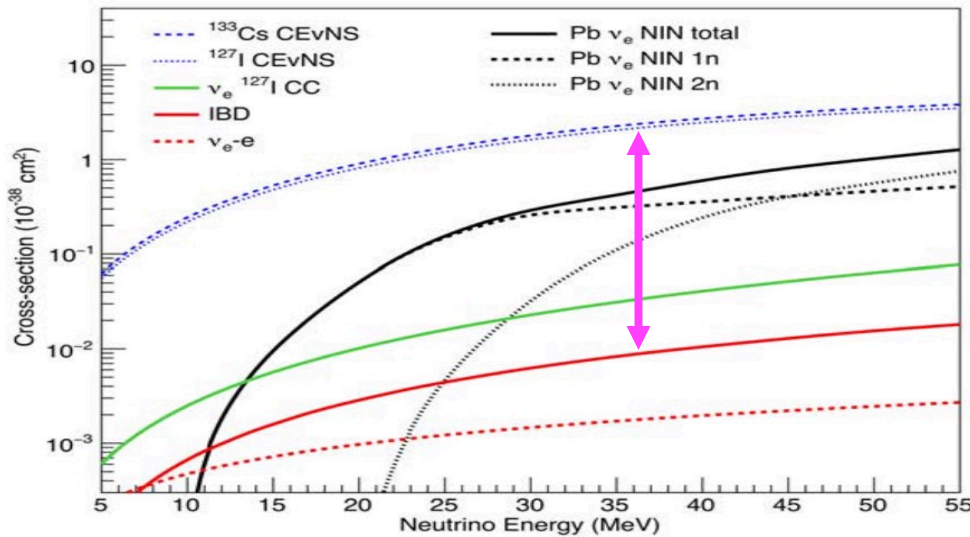
- Coherent condition:

$$\lambda = h/q \geq R \longrightarrow E \sim q \leq hc/R \approx O(10) \text{ MeV}$$

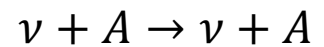
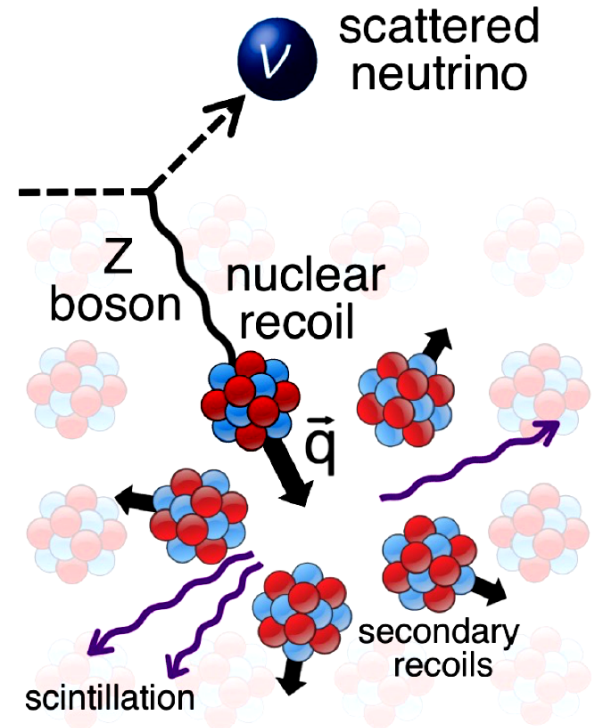
Plank constant $\hbar c = 200 \text{ MeV} \cdot \text{fm}$;
Nucleus radius $R = 10 \text{ fm}$

a sufficiently small momentum exchange (q)

- Cross section of CEvNS



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

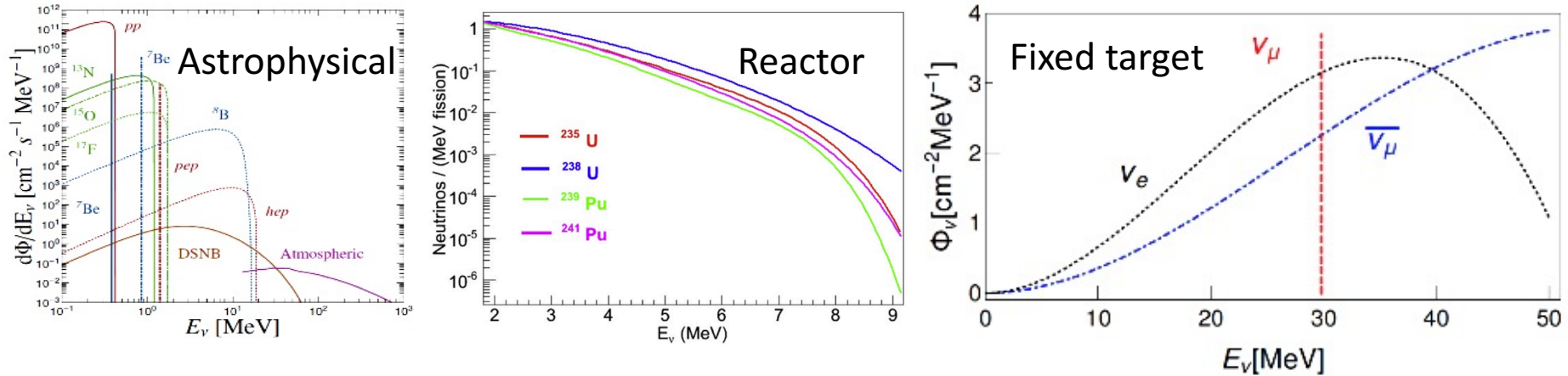


exchange of neutral Z bosons

Coherent Neutrino-nuclear Scattering

➤ Challenges:

① ν -source: high intensive flux with low-energy $E < 100\text{MeV}$



② nuclei: heavier for large N vs. lower recoil energy $T \sim \text{keV}$, even eV

$$T_{\max} \approx \frac{2E^2}{M + 2E} \approx \frac{2E^2}{M} \leq \mathbf{O(10)} \text{ keV} \quad \text{nucleus mass } M$$

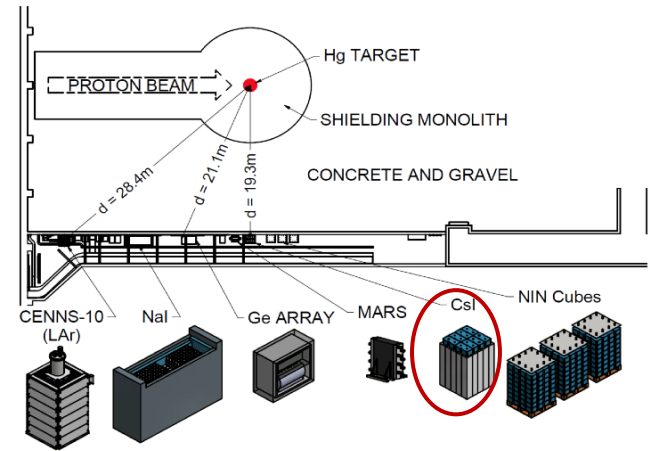
③ detector: very-low-threshold $E_{\text{thres}} \sim \text{tens eV}$ vs. background control

Low threshold, low background, high energy resolution, high sensitivity

➤ Fruitful physics

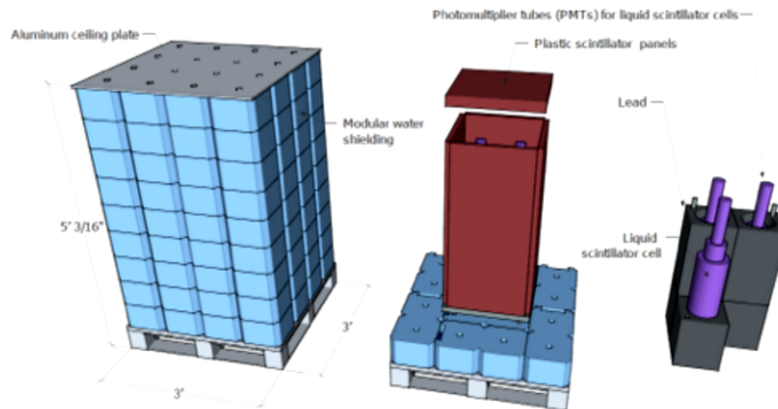
The COHERENT Experiment

- Spallation Neutron Source (SNS) @ Oak Ridge
 - ✓ 1 MW pulsed (60 Hz, 700ns) proton beam (1 GeV)
 - ✓ ν from stopped π/μ -DAR $\rightarrow E(\nu_i) < 50\text{MeV}$
 - ✓ Background suppression by $10\mu\text{s}$ beam timing window
 - ✓ “ ν -alley” deployed 20-30m from target

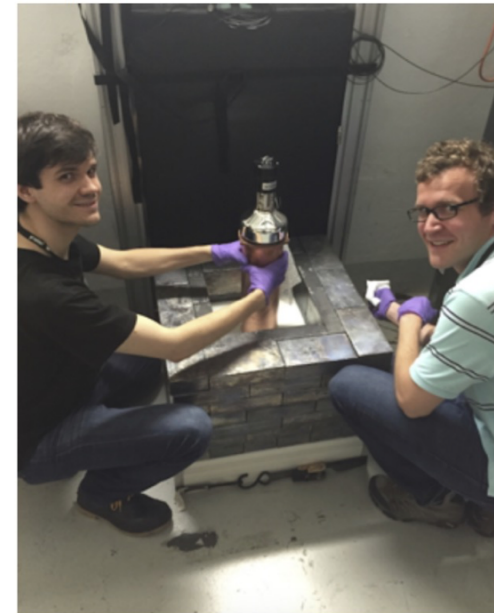


Approx ν flux at CsI[Na] location
 $1e7 \nu / \text{cm}^2 / \text{s} / \text{flavor}$

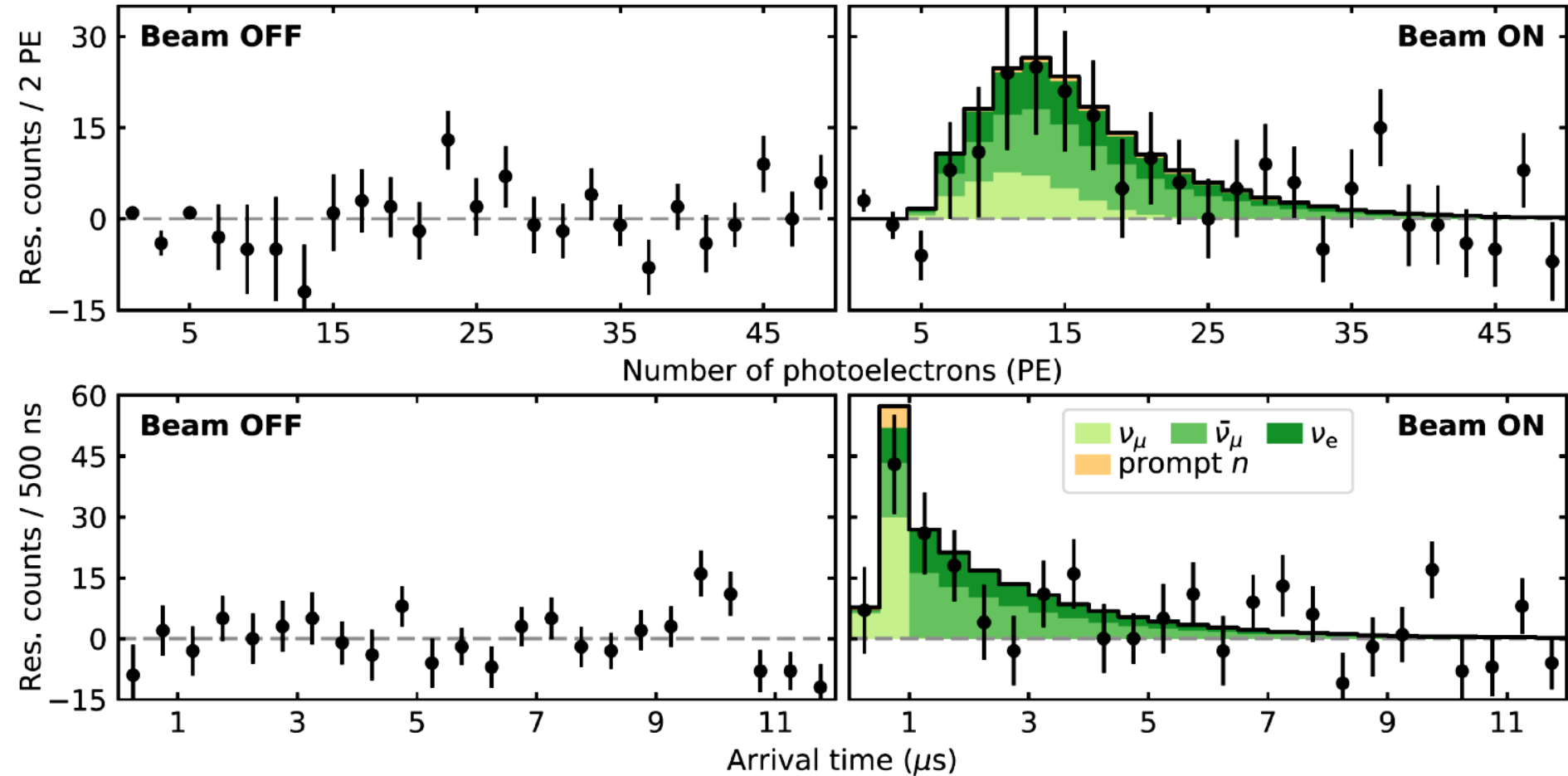
- Detector: 14.6kg of CsI(Na)



- ✓ Flux $\sim 10^7 \nu/\text{cm}^2/\text{s}/\text{flavor}$
- ✓ Background: n-induced ν (NIN) in Pb-shield



The COHERENT Experiment



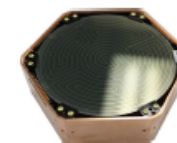
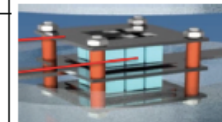
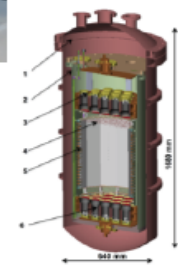
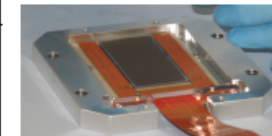
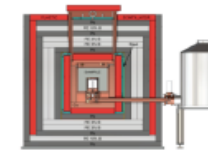
Significance: 6.7-sigma confidence level

[[arXiv:1708.01294](https://arxiv.org/abs/1708.01294)]

Proposed reactor CEvNS experiments

The importance of this process has generated a broad array of proposals for potential CEvNS detectors: superconducting devices, **cryogenic detectors**, modified semiconductors, noble liquids, and inorganic scintillators, among others.

Experiment	Technology	Location
CONUS	HPGe	Germany
Ricochet	Ge, Zn bolometers	France
CONNIE	Si CCDs	Brazil
RED	LXe dual phase	Russia
Nu-Cleus	Cryogenic CaWO_4 , Al_2O_3 calorimeter array	Europe
MINER	Ge iZIP detectors	USA

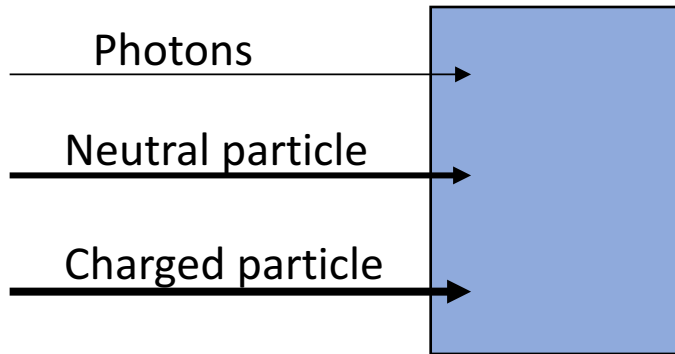


Novel low-background, low-threshold technologies

Principles of Cryogenic Detector

- LTD (Low Temperature Detector) or CPD (Cryogenic Particle Detector)

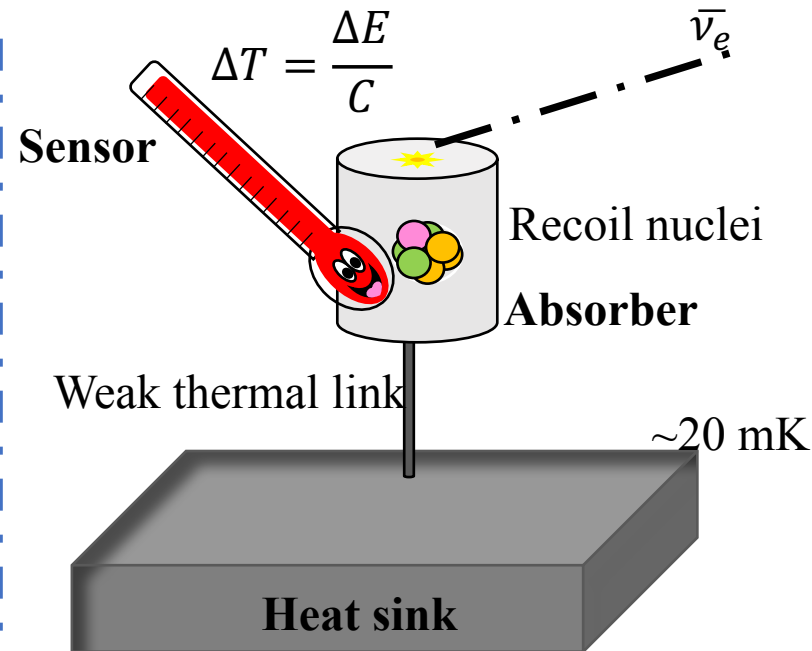
Particle detector based on **phonon** or **quasi-particle** detection



- $\sim 90\% \Delta E$ convert to phonons, Heat signal
- $< 10\% \Delta E$ convert to electron-ion (hole) pairs, or scintillation fluorescence

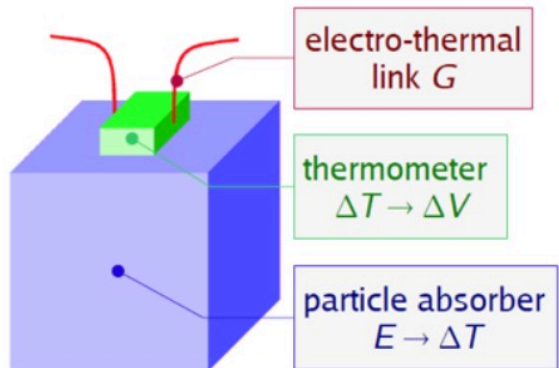
- Bolometer components

- **Absorber**: particle energy deposition in the absorber;
- **Sensor**: measure the temperature increase of the absorber, good connection and conduction coefficient between absorber and sensor;
- **Heat sink**

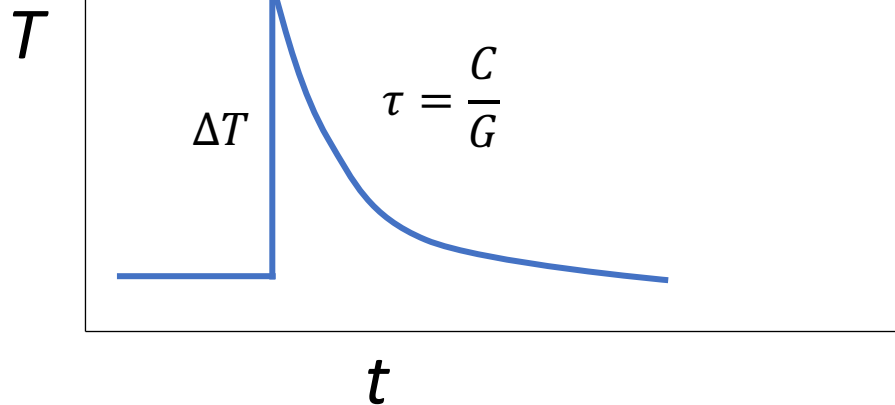


➤ Properties of bolometers

- ① Wide choice of different absorber material
- ② High energy resolution FWHM (0.3% @ 2615 keV)
- ③ Low energy threshold for particle detection
- ④ Particle identification capability in hybrid measurements of heat-light (ionization) energies



$$\Delta T = \frac{\Delta E}{C} \Rightarrow \Delta V$$



The **absorber** allows conversion from energy to heat (phonons)

For semi-conductors and superconductors, only lattice vibrations contribute to thermal capacitance ($C \sim T^3$)

Small detectors & low temperatures
= **lower thresholds**

Absorber

Heat capacity as :

$$C(T) = \beta \frac{m}{M} \left(\frac{T}{\Theta_D} \right)^3$$

Where $\beta = 1944 \text{ JK}^{-1} \text{ mol}^{-1}$, m is the absorber mass, and M is the molecular weight, Θ_D is the Debye temperature.

Material	Molar mass [g]	Θ_D [K]	C [JK⁻¹T³]	Num N	T_{max}(eV)
Ge	73	374	5.1×10⁻⁷	~41	265
Zn	65.4	327	8.5×10⁻⁷	~35	295
<i>Al₂O₃</i>	101.9	1041	1.7×10⁻⁸	-	-
CaWO₄	287.9	335	1.8×10⁻⁷	-	-
Pb	207.2	105	8.1×10⁻⁶	~125	93
W	183.84	400	1.7×10⁻⁷	~110	105
PbWO₄	455.04	237	3.2×10⁻⁷	-	-

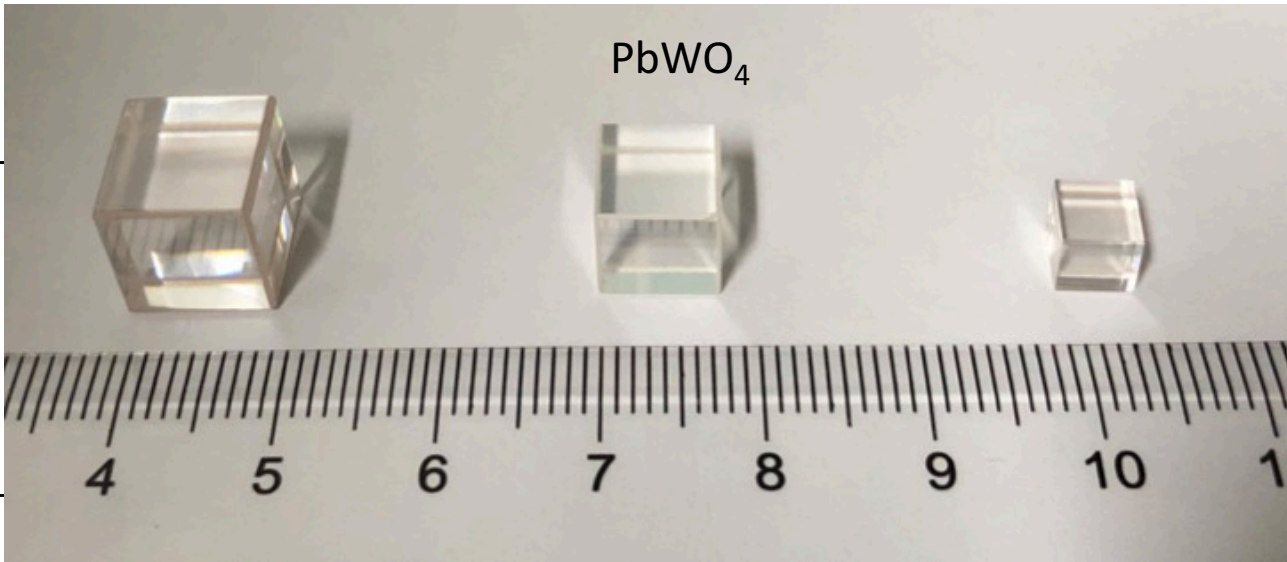
* m=1g; Ev=3MeV

Absorber

Material	Mass (g)	Cube Size (mm)	C (T=10mK) (J/K)	$\Delta T(\Delta E=20 \text{ eV})$ μK	$\Delta T(\Delta E=100 \text{ eV})$ μK
W <i>19.35 g/cm³</i>	0.5	3.0	8.26×10^{-14}	38.74	193.70
	0.8	3.5	1.32×10^{-13}	24.24	121.21
	1.0	3.7	1.65×10^{-13}	19.39	96.97
	2.42	5.0	4.00×10^{-13}	7.99	40.00
CaWO ₄ <i>~6 g/cm³</i>	0.5	4.4	8.98×10^{-14}	35.63	178.17
	0.8	5.1	1.44×10^{-13}	22.27	111.36
	1.0	5.5	1.80×10^{-13}	17.81	89.08
	0.75	5.0	1.35×10^{-13}	23.75	118.78
PbWO ₄ <i>8.28 g/cm³</i>	0.5	3.9	1.60×10^{-13}	20.00	100.00
	0.8	4.6	2.57×10^{-13}	12.45	62.25
	1.0	5.0	3.21×10^{-13}	9.97	49.84

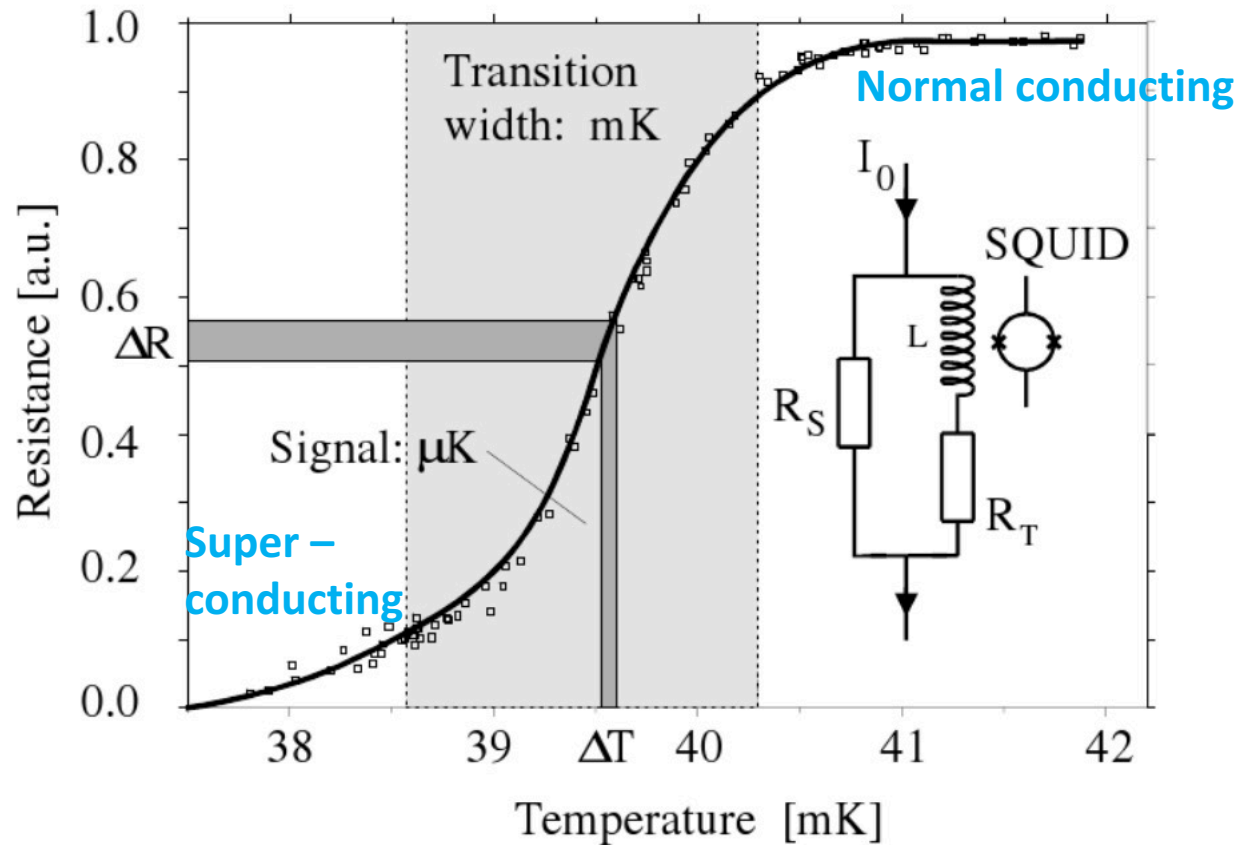
Absorber

Material	Mass (g)	Cube Size (mm)	C (T=10mK) (J/K)	$\Delta T(\Delta E=20 \text{ eV})$ μK	$\Delta T(\Delta E=100 \text{ eV})$ μK
W 19.35 g/cm^3	0.5	3.0	8.26×10^{-14}	38.74	193.70
	0.8	3.5	1.32×10^{-13}	24.24	121.21
					96.97
CaWO ₄ $\sim 6 \text{ g/cm}^3$					40.00
					178.17
					111.36
					89.08
PbWO ₄ 8.28 g/cm^3					118.78
	0.8	4.6	2.57×10^{-13}	12.45	62.25
	1.0	5.0	3.21×10^{-13}	9.97	49.84



Sensors

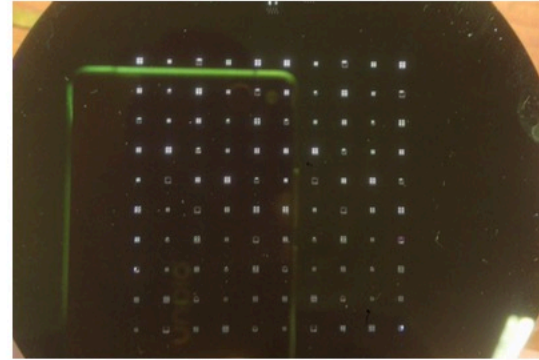
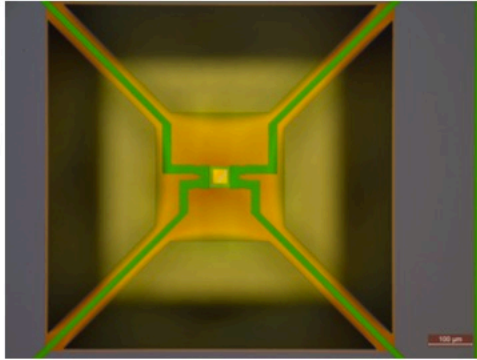
➤ TES (Transition-edge Sensor)



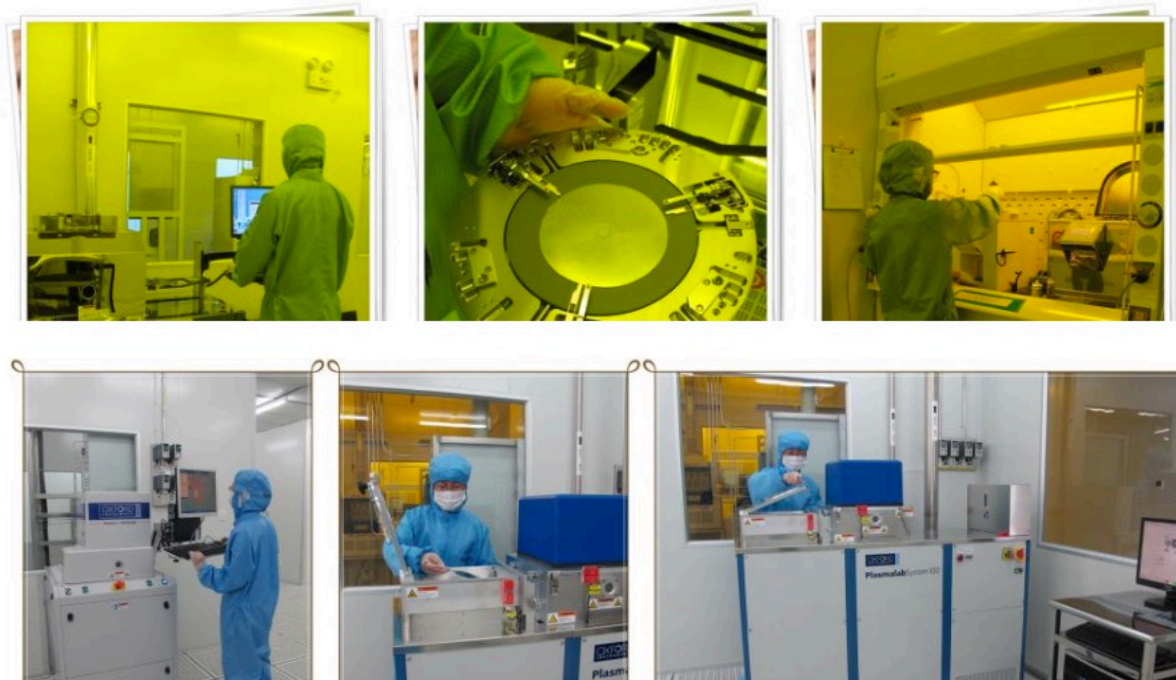
- Small changes in temperature can be captured by TES, which allow great sensitivity to small temperature depositions;
- Readout of TES done using SQUID amplifiers, quantum-limited magnetometers, ideal for small currents;
- Golden wire bonding ;
- Now, using TES can get the low threshold ~ 15 eV.

Sensors

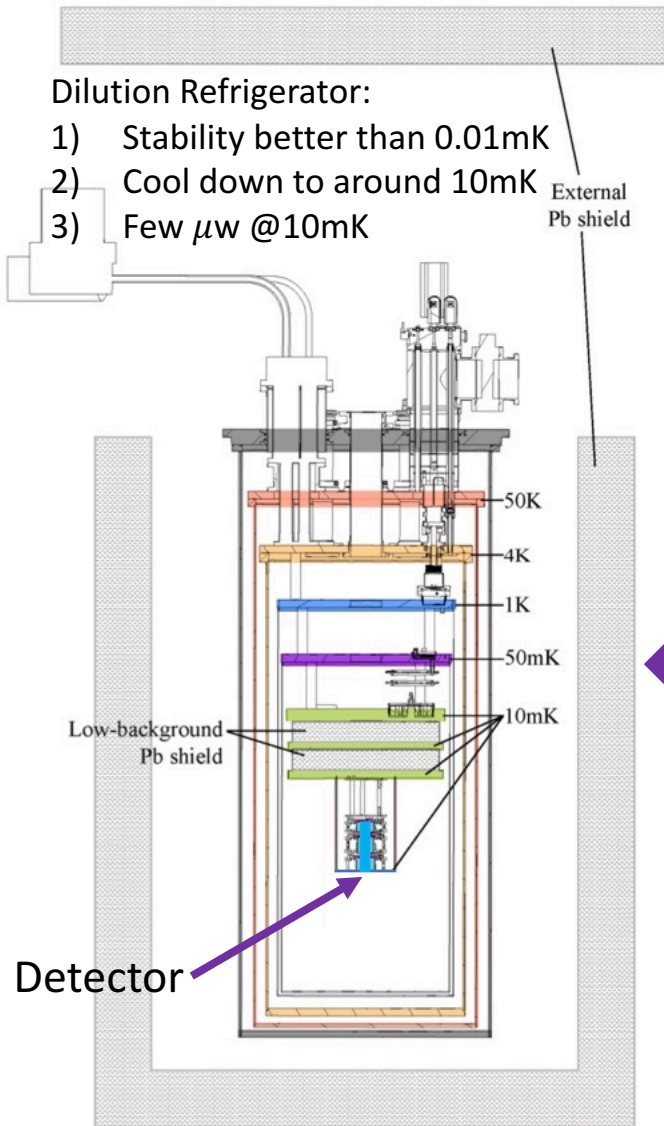
- Multiple TES samples in USTC, fabricated in Nano Fab.



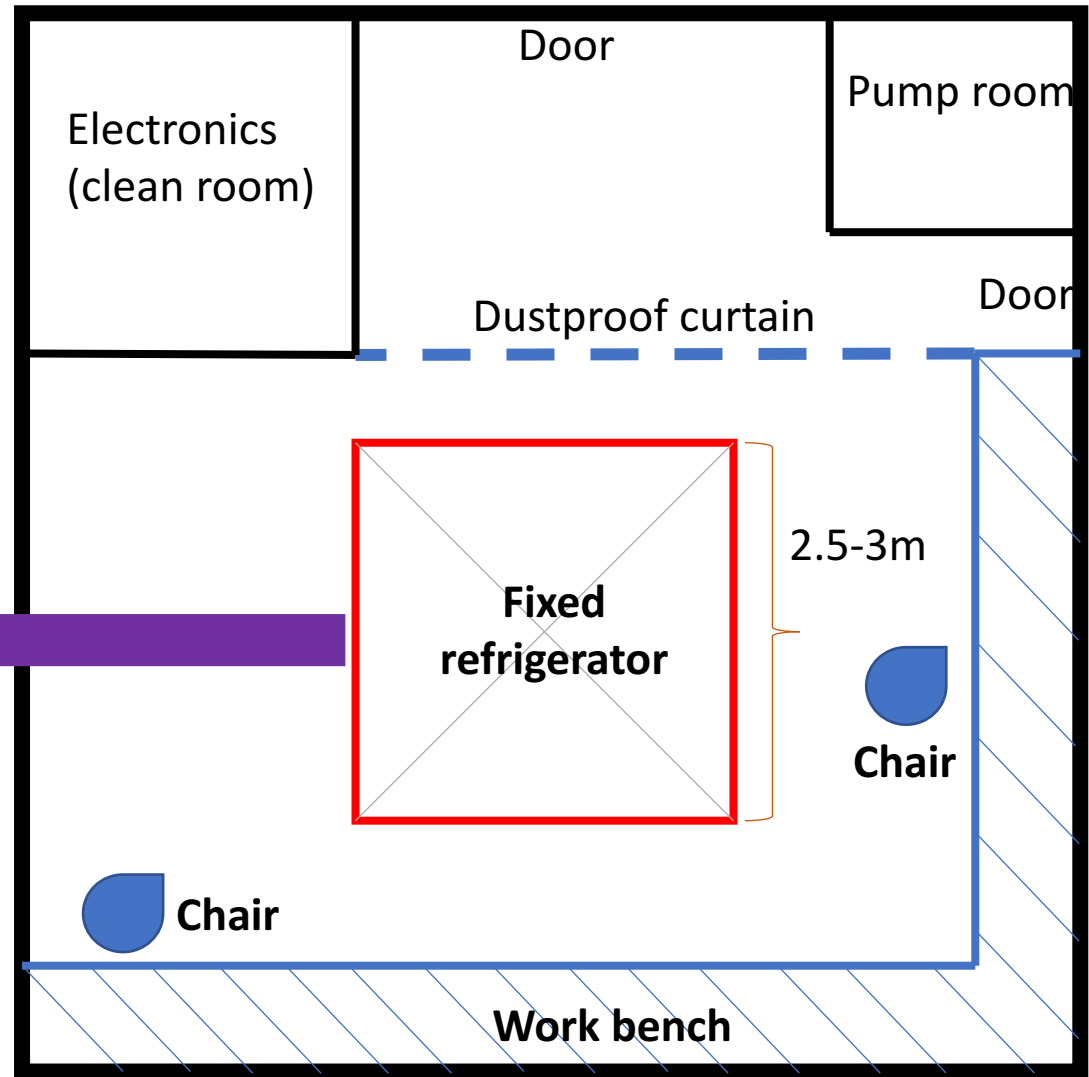
Prof. Zhou Xingxiang's group



Cryogenic System



A schematic view of the WO4-based experiment arrangement

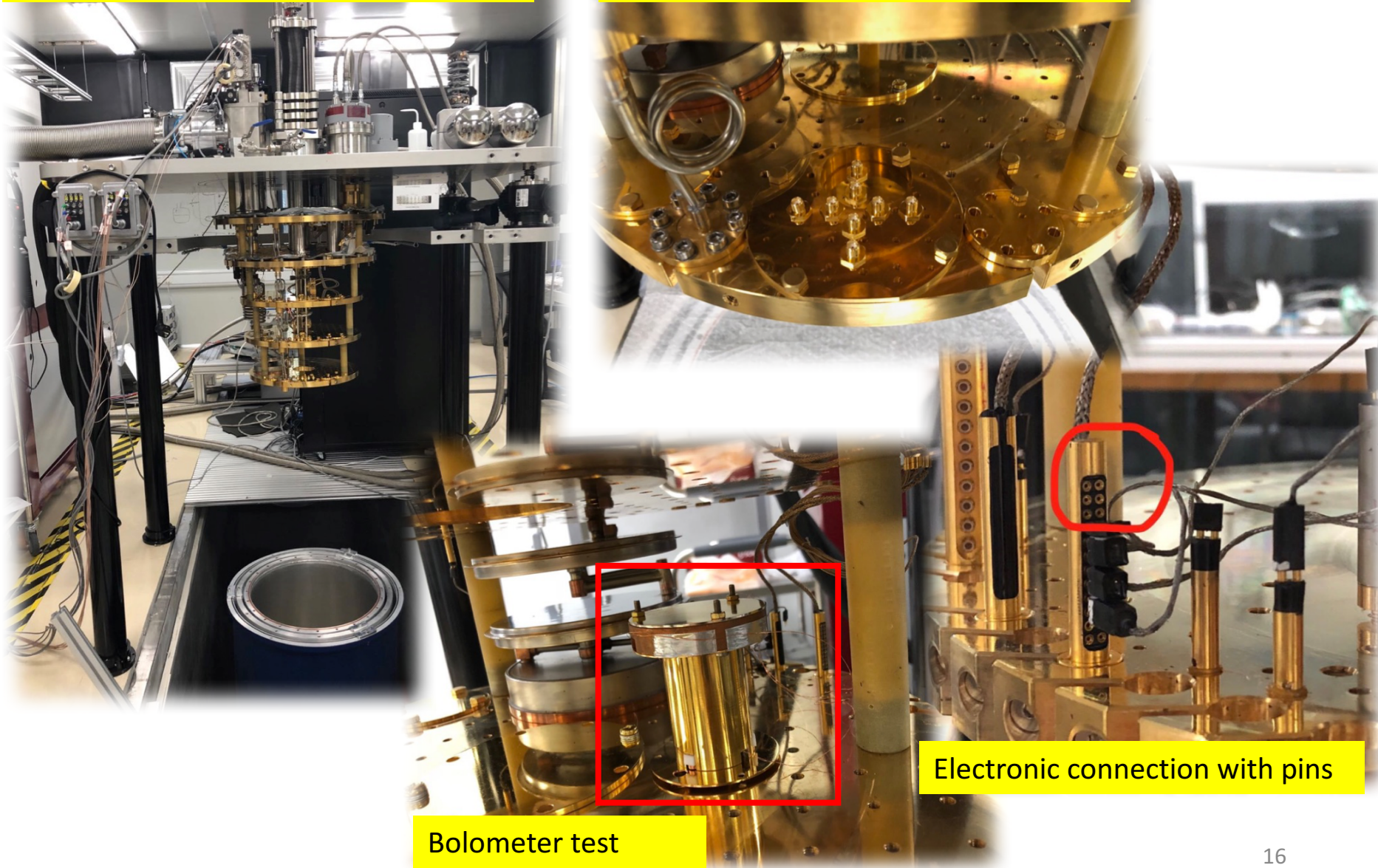


Schematic diagram of the laboratory layout

Cryogenic System

~8mK Dilution refrigerator in USTC

Easy connection with mK Plate

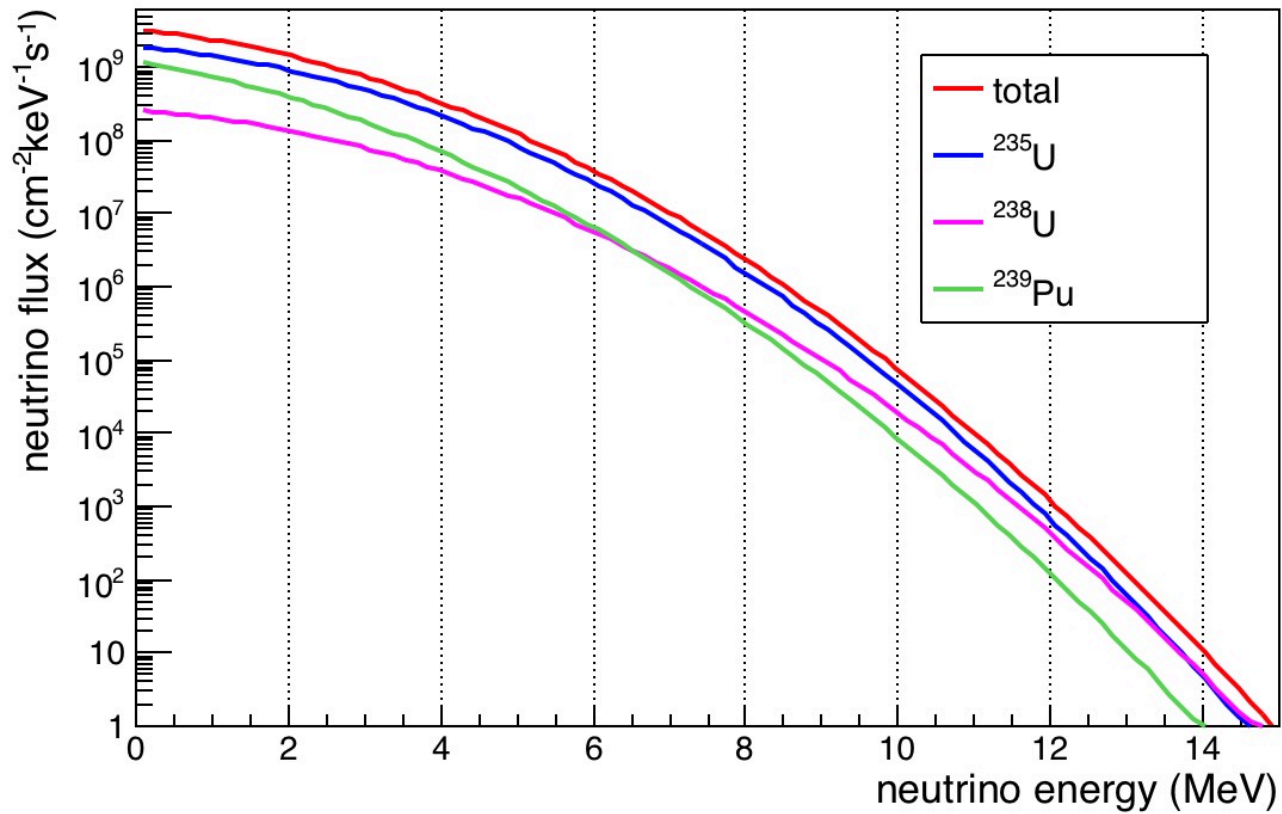


Bolometer test

Electronic connection with pins

Event Estimation

Reactor neutrino source ${}^A_Z X \rightarrow {}^{A}_{Z+1} Y + e^{-} + \bar{\nu}_e$



Event Estimation

Total cross section of CEvNS:

$$\frac{d\sigma}{dE_R} = \frac{G_F^2}{8\pi(\hbar c)^4} \left((4 \sin^2 \theta_W - 1) \cdot Z + N \right)^2 \cdot m_N \cdot \left(2 - E_R m_N / E_\nu^2 \right) |f(q)|^2$$

Rewritten as:

$$\frac{d\sigma(E_\nu, E_R)}{dE_R} = \frac{\sigma_0^{SM}}{m_N} \left(1 - \frac{E_R m_N}{2E_\nu^2} \right)$$

and,

$$\sigma_0^{SM} = \frac{G_F^2 m_N^2 |f(q)|^2}{4\pi(\hbar c)^4} \left((4 \sin^2 \theta_W - 1) \cdot Z + N \right)^2$$

E_R nucleus recoil energy; E_ν neutrino energy;

Fermi coupling constant, $G_F = 1.166364 \times 10^{-5} \text{ GeV}^2$; $\hbar c = 1$;

Weak mixing angle θ_W , $1 - 4\sin^2 \theta_W = 0.0454$; $Z=74$; $N=110$;

Mass of W, $m_N = 1.715 \times 10^5 \text{ MeV}$; Nucleus form factors $f(q) = 1$

Event Estimation Results

Total counting rate using CaWO_4 bolometers with conditions:

- reactor power **Wth = 4.6 GW**
- the distance between detector and reactor core **L = 30 m**
- low threshold **Eth = 10eV**
- the mass of each CWO crystal **m=1g**

$$\textit{Total Event} = 0.16/\textit{day}$$

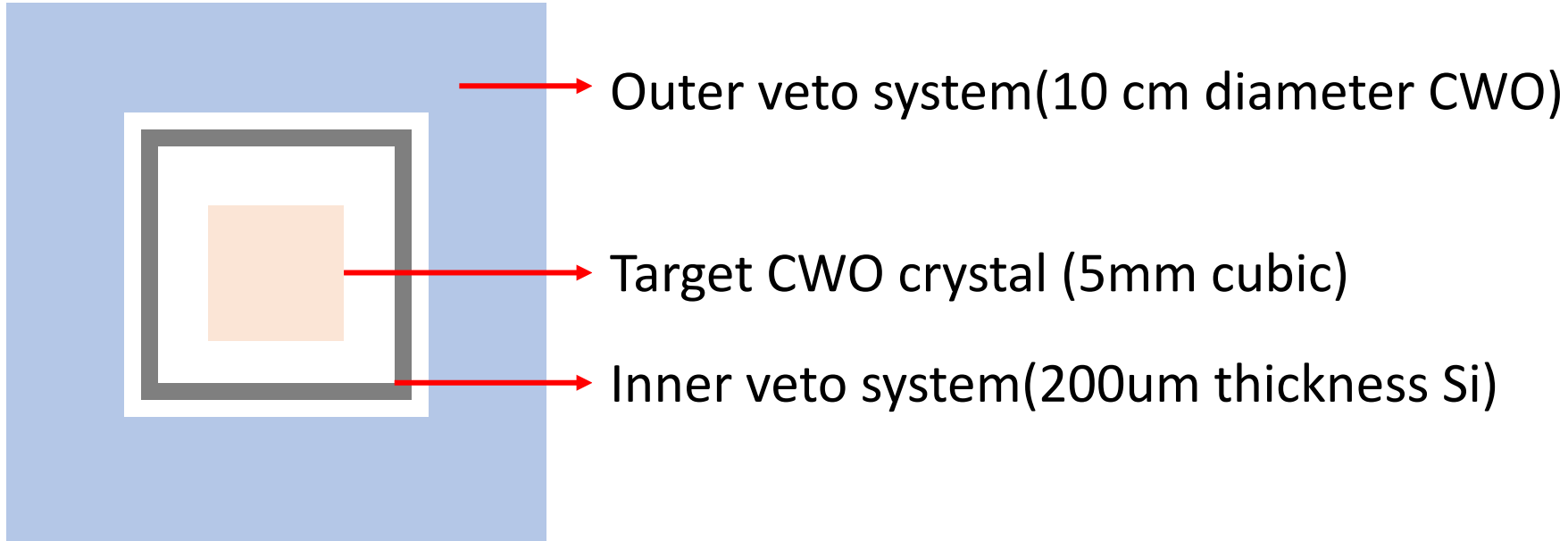
$$\textit{Total Event} = 1.46/\textit{array} \cdot \textit{day}$$

$$1 \textit{ array} = 3 \times 3 \text{ CWO crystals}$$



Simulation

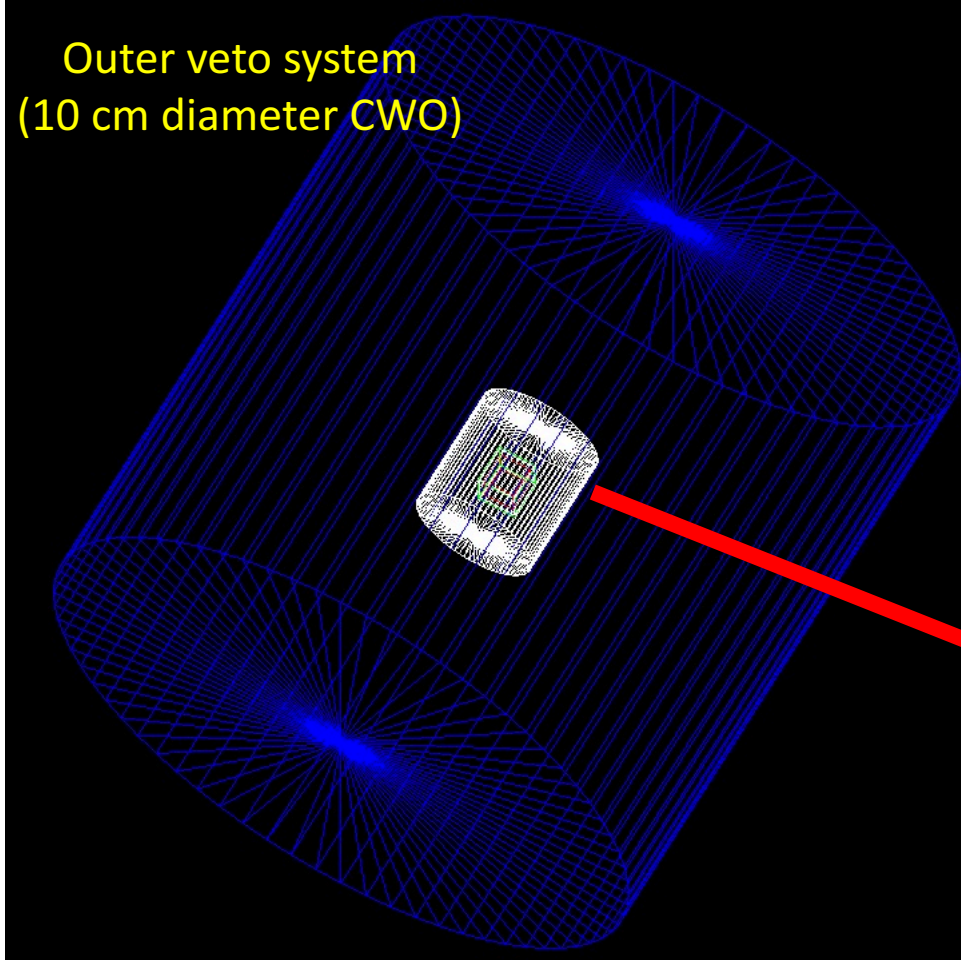
Detector Construction



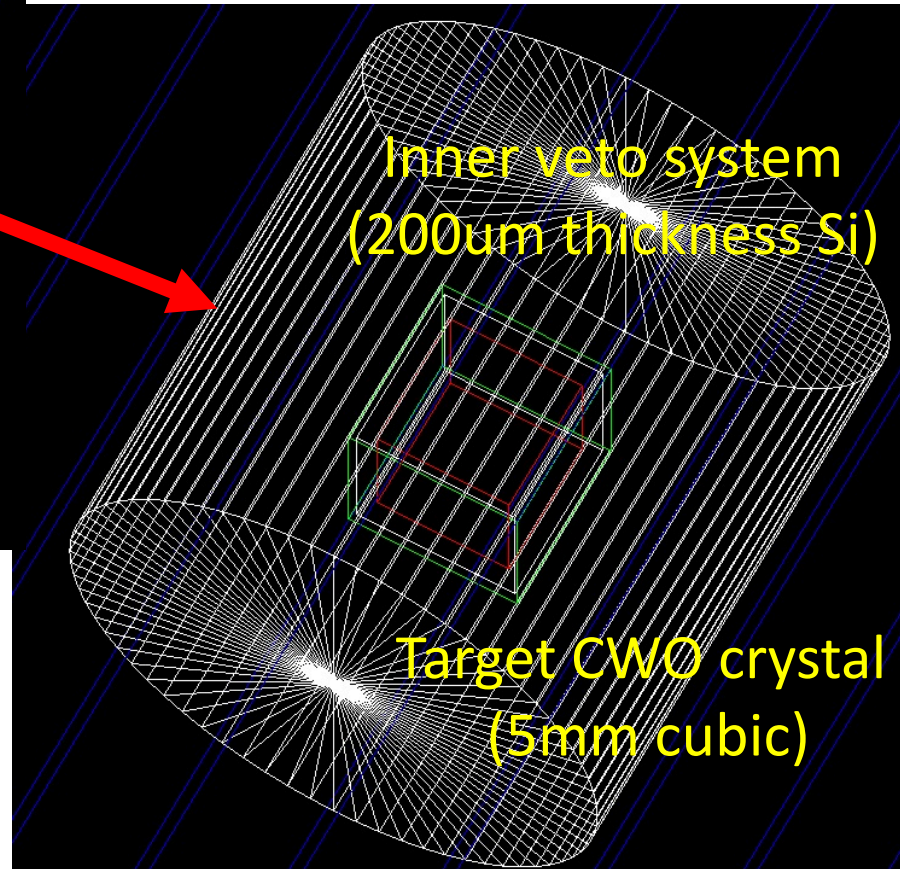
- 1. Target crystal CWO** with an extremely low threshold of $\mathcal{O}(\lesssim 10eV)$
- 2. Inner veto** as a 4π active veto against surface beta and alpha decays
- 3. Massive outer veto** against external gamma/neutron radiation

Detector Construction

Outer veto system
(10 cm diameter CWO)



Inner veto system
(200 μ m thickness Si)

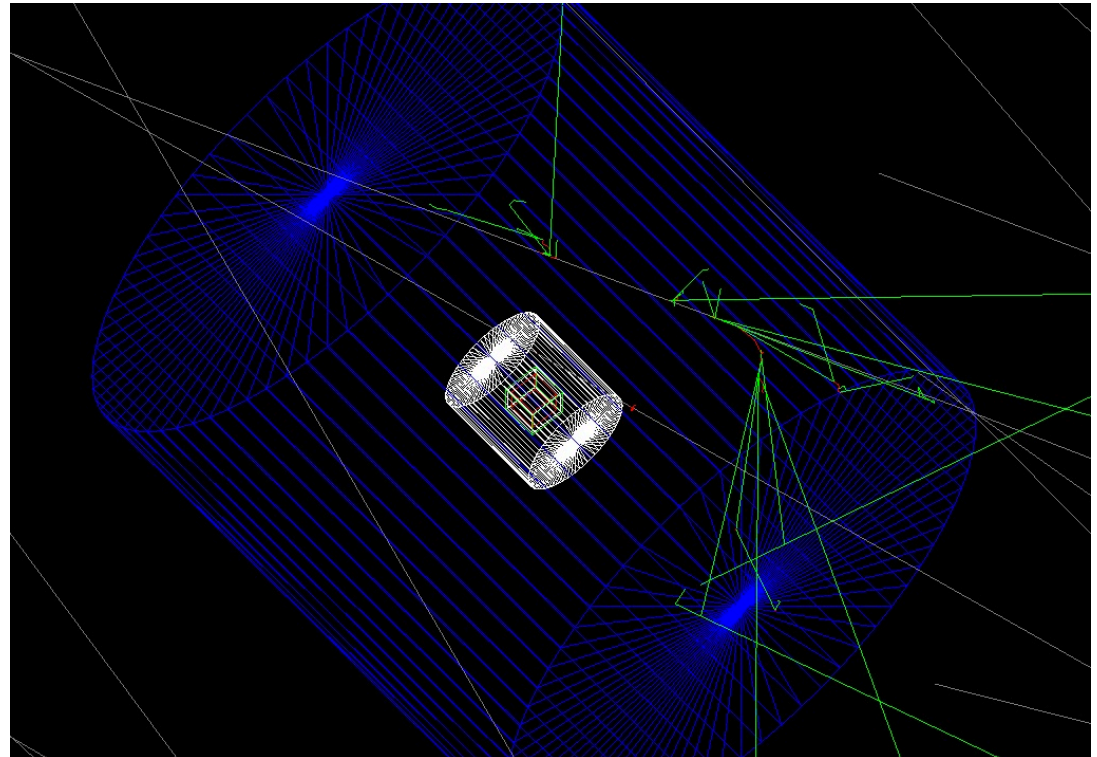


Target CWO crystal
(5mm cubic)

Background Simulation

Background Sources

- From target CWO itself, like beta/gamma decay from U/Th chains.
- From detector materials, like inner veto system, supporting structure.
- From surroundings, neutrons, muons.



Plans & Summary

Plans:

- Detector simulation work
- Crystal coating with TES film test
- Readout electronic system

Summary:

- Coherent neutrino-nucleus scattering is highly interesting
- Bolometers-based CEvNS research:
 - Ultralow energy thresholds down to the 10eV regime;
 - Encapsulation of the small calorimeters by cryogenic veto detectors
 - Ability to operate the detectors above ground in a high-rate environment

Plans & Summary

Plans:

- Detector simulation work
- Crystal coating with TES film test
- Readout electronic system

Summary:

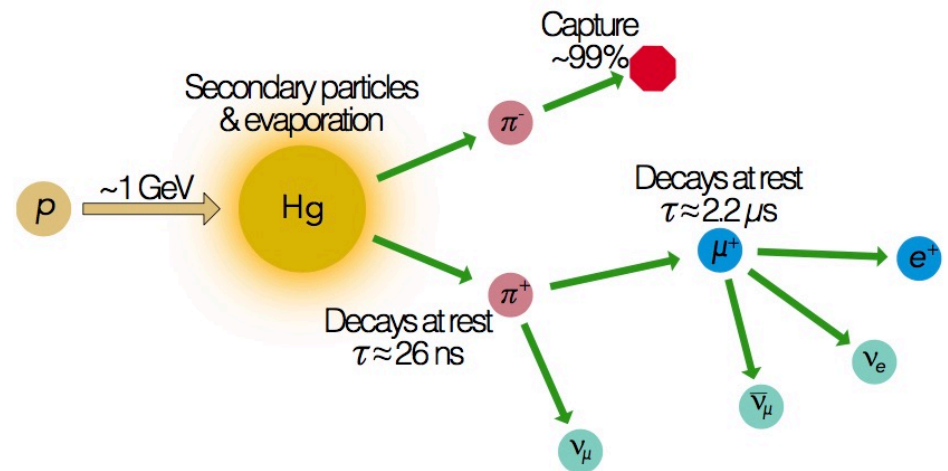
- Coherent neutrino-nucleus scattering is highly interesting
- Bolometers-based CEvNS research:
 - Ultralow energy thresholds down to the 10eV regime;
 - Encapsulation of the small calorimeters by cryogenic veto detectors
 - Ability to operate the detectors above ground in a high-rate environment

Thank you

Backup slides

Neutrino source

- Neutrinos at SNS are a result of the decay of pions and muons created in a mercury target by a pulsed ($\sim 1\text{ GeV}$) proton beam.
- 60hz of $\sim 1\ \mu\text{s}$ -wide (Proton-on-target) POT spills.
- Approximately 5×10^{20} POT are delivered per day.
- This allows us to isolate the steady-state environmental backgrounds from 10 $\sim \mu\text{s}$ windows.

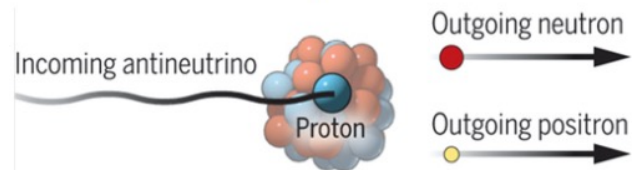


Neutrino energy range $\sim [16, 53]\text{ MeV}$.

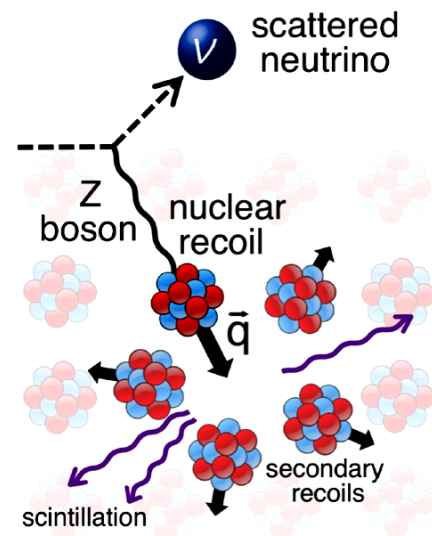
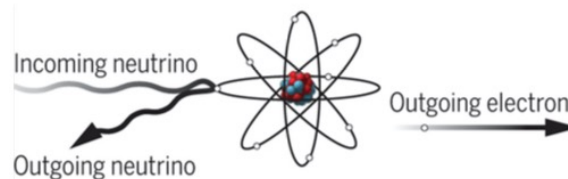
反应堆中微子与物质相互作用

1. 被氢核（即质子）俘获，生成一个电子和一个中子，称为**反贝塔衰变反应（IBD）**，这是最常用的探测方式；
2. 在**电子上散射**，她的反应几率比IBD小几倍，而且很难和本底分开，只有少数几个实验采用，测量中微子磁矩；
3. 在**原子核内的核子上散射**，她不仅反映几率小，而且由于原子核很重，就像一个乒乓球（中微子）撞上铅球（原子核）一样，铅球几乎得不到能量，因此极难探测，没有人用。
4. 对于低能中微子，有可能发生一种相干散射过程，与3相似，但中微子一次不是跟一个核子，而是跟**原子核内的所有的核子发生散射**。

Inverse-beta decay



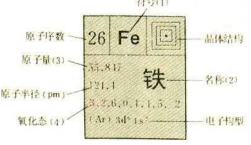
Neutrino-electron scattering



Nucleus – absorber

周期
族

1	I A																18	0											
1	1 H																	2 He											
1	1.00794 — 1, -1 1s ¹																	4.002602 — — 1s ²											
2	3 Li	4 Be	II A																10 Ne										
2	6.941 152.0 — 1s ² 2s ¹	9.012182 111.3 — 1s ² 2s ²																	20.1797 — — 1s ² 2s ² 2p ⁶										
3	11 Na	12 Mg																	18 Ar										
3	22.989768 185.8 — 1, -1 (Ne) 3s ¹	24.305 159.9 — 2 (Ne) 3s ²																	39.948 — — (Ne) 3s ² 3p ⁶										
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr											
4	39.0983 227.2 — 1, -1 (Ar) 4s ¹	40.078 197.4 — 2 (Ar) 4s ²	44.95591 164.1 — 3, 2 (Ar) 3d ¹ 4s ²	47.88 144.8 — 4, 3, 2, 0, -1 (Ar) 3d ² 4s ²	50.9415 131.1 — 3, 4, 3, 2, 0, ±1 (Ar) 3d ³ 4s ²	51.9961 124.9 — 3, 6, 2, 5, 4, 0, ±1, -2 (Ar) 3d ⁵ 4s ¹	54.93805 136.6 — 2, 4, 6, 7, 3, 0, ±1, -3, 5 (Ar) 3d ⁵ 4s ²	55.847 124.1 — 3, 2, 6, 0, 1, 4, 5, -2 (Ar) 3d ⁶ 4s ²	58.9332 125.3 — 2, 3, 0, 4, ±1 (Ar) 3d ⁷ 4s ¹	58.69 124.6 — 2, 3, 0, 4, ±1 (Ar) 3d ⁸ 4s ²	63.546 127.8 — 2, 1, 3 (Ar) 3d ⁹ 4s ¹	65.39 133.3 — 2 (Ar) 3d ¹⁰ 4s ²	69.723 122.1 — 3, 1 (Ar) 3d ¹⁰ 4s ² 4p ¹	72.61 122.5 — 4, 2 (Ar) 3d ¹⁰ 4s ² 4p ²	74.92159 124.8 — 3, 5, -3 (Ar) 3d ¹⁰ 4s ² 4p ³	78.96 116.1 — 4, 6, -2, 2, 1 (Ar) 3d ¹⁰ 4s ² 4p ⁴	79.904 — — -1, 7, 5, 4, 3, 6, 1 (Ar) 3d ¹⁰ 4s ² 4p ⁵	83.80 — — (Ar) 3d ¹⁰ 4s ² 4p ⁶											
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe											
5	85.4678 247.5 — 1, -1 (Kr) 5s ¹	87.62 217.4 — 2 (Kr) 5s ²	88.90585 164.1 — 3 (Kr) 4d ¹ 5s ²	91.224 142.9 — 4, 3, 2 (Kr) 4d ² 5s ²	92.90638 143 — 5, 4, 2, 3, -1 (Kr) 4d ³ 5s ²	95.94 136.3 — 6, 5, 4, 3, 0, 1, ±2 (Kr) 4d ⁴ 5s ²	(98) 137.1 — 7, 4, 6, 5, 0, ±1, 2, 3 (Kr) 4d ⁵ 5s ²	101.07 132.5 — 3, 4, 2, 0, ±1 (Kr) 4d ⁶ 5s ²	102.9055 134.5 — 4, 3, 2, 0, ±1 (Kr) 4d ⁷ 5s ²	106.42 137.6 — 1, 2 (Kr) 4d ⁸ 5s ²	107.8682 144.5 — 3, 1 (Kr) 4d ⁹ 5s ¹	112.411 149.0 — 2, 1 (Kr) 4d ¹⁰ 5s ²	114.82 102.6 — 3, 1 (Kr) 4d ¹⁰ 5s ² 5p ¹	118.71 140.5 — 4, 2 (Kr) 4d ¹⁰ 5s ² 5p ²	121.75 145 — 3, 5, -3 (Kr) 4d ¹⁰ 5s ² 5p ³	127.60 143.2 — 4, 6, -2, 2, 1 (Kr) 4d ¹⁰ 5s ² 5p ⁴	126.90447 — — 5, 7, -4, 3, 1 (Kr) 4d ¹⁰ 5s ² 5p ⁵	131.29 — — (Kr) 4d ¹⁰ 5s ² 5p ⁶											
6	55 Cs	56 Ba	57~71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn											
6	132.90543 265.5 — 1, -1 (Xe) 6s ¹	137.327 217.4 — 2 (Xe) 6s ²	La~Lu 镧系	178.49 166.4 — 4, 3, 2 (Xe) 4f ¹⁴ 5d ² 6s ²	180.9479 143 — 5, 4, 2, 3, -1 (Xe) 4f ¹⁴ 5d ³ 6s ²	183.85 137.1 — 6, 5, 4, 3, 0, 1, ±2 (Xe) 4f ¹⁴ 5d ⁴ 6s ²	186.207 137.1 — 7, 4, 6, 3, 5, 2, ±1, 0 (Xe) 4f ¹⁴ 5d ⁵ 6s ²	190.2 133.8 — 4, 8, 6, 2, 3, 5 (Xe) 4f ¹⁴ 5d ⁶ 6s ²	192.22 135.7 — 4, 3, 6, 2, 0 (Xe) 4f ¹⁴ 5d ⁷ 6s ²	195.08 138.8 — 4, 2, 3, 0, 5, 6 (Xe) 4f ¹⁴ 5d ⁸ 6s ¹	196.96654 144.2 — 3, 1 (Xe) 4f ¹⁴ 5d ⁹ 6s ¹	203.59 150.3 — 2, 1 (Xe) 4f ¹⁴ 5d ¹⁰ 6s ²	204.3833 170.4 — 1, 3 (Xe) 4f ¹⁴ 5d ¹⁰ 6s ² 6p ¹	207.2 175.0 — 2, 4 (Xe) 4f ¹⁴ 5d ¹⁰ 6s ² 6p ²	208.98037 154.8 — 3, 5, -3 (Xe) 4f ¹⁴ 5d ¹⁰ 6s ² 6p ³	(209) 167.3 — 4, 2, 6, -2 (Xe) 4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁴	(210) — — 5, -1, 7, 3, 1, 0 (Xe) 4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁵	(222) — — (Xe) 4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁶											
7	87 Fr	88 Ra	89~103	104 Uuq	105 Uup	106 Uuh	107 Uue	108 Uuo	109 Uuq																				
7	(223) — — (Rn) 7s ¹	226.0254 — — (Rn) 7s ²	Ac~Lr 锕系	(261) — — (Rn) 5f ¹⁴ 6d ¹ 7s ²	(262) — — (Rn) 5f ¹⁴ 6d ² 7s ²	(263) — — (Rn) 5f ¹⁴ 6d ³ 7s ²	(262) — — (Rn) 5f ¹⁴ 6d ⁴ 7s ²	(265) — — (Rn) 5f ¹⁴ 6d ⁵ 7s ²	(266) — — (Rn) 5f ¹⁴ 6d ⁶ 7s ²																				



注: (1) 固—固体, 红—气体, 绿—液体, 空心字—人造元素。(2) 注*的是放射性元素。(3) C为基础, () 表示半衰期最长的同位素。(4) 红—常见氧化态, 第一个数字为最稳定氧化态。
 □ 面心立方 □ 体心立方 □ 密排六角 ▲ 金刚石结构 □ 四方 ▲ 三角(菱形) □ 六角 ■ 复杂立方 □ 正交 ▽ 单斜 结构符号能表示同素异构, 外部符号为高温相, 内部符号为低温相, 例如, 铈在较低温为密排六角, 在较高温为体心立方

元素 周期表

镧系	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
	138.9055 187.7 — 3 (Xe) 5d ¹ 6s ¹	140.115 182.4 — 3, 4 (Xe) 4f ¹ 5d ¹ 6s ²	140.90765 182.8 — 3, 4 (Xe) 4f ² 5d ¹ 6s ²	144.24 182.2 — 3, 2, 4 (Xe) 4f ³ 5d ¹ 6s ²	(145) — — 3 (Xe) 4f ⁴ 5d ¹ 6s ²	150.36 180.2 — 3 (Xe) 4f ⁵ 5d ¹ 6s ²	151.965 198.3 — 3, 2 (Xe) 4f ⁶ 5d ¹ 6s ²	157.25 180.1 — 3 (Xe) 4f ⁷ 5d ¹ 6s ²	158.92534 178.3 — 3, 4 (Xe) 4f ⁸ 5d ¹ 6s ²	162.50 177.5 — 3 (Xe) 4f ⁹ 5d ¹ 6s ²	164.93032 176.7 — 3 (Xe) 4f ¹⁰ 5d ¹ 6s ²	167.26 175.8 — 3 (Xe) 4f ¹¹ 5d ¹ 6s ²	168.93421 174.7 — 3 (Xe) 4f ¹² 5d ¹ 6s ²	173.04 183.9 — 3, 2 (Xe) 4f ¹³ 5d ¹ 6s ²	174.967 173.5 — 3 (Xe) 4f ¹⁴ 6s ²
锕系	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr
	227.0278 187.8 — (Rn) 6d ¹ 7s ²	232.0381 179.8 — 4, 3 (Rn) 5f ¹ 6d ² 7s ²	231.03588 160.6 — 5, 4, 3 (Rn) 5f ² 6d ¹ 7s ²	238.02891 138.5 — 5, 3, 4, 3, 5 (Rn) 5f ³ 6d ² 7s ²	237.0482 131 — 4, 3, 5, 6, 7 (Rn) 5f ⁴ 6d ² 7s ²	(244) — — 3, 4, 5, 6, 2 (Rn) 5f ⁵ 6d ² 7s ²	(243) — — 3, 4, 5, 6, 2 (Rn) 5f ⁶ 6d ² 7s ²	(247) — — 3, 4 (Rn) 5f ⁷ 6d ² 7s ²	(247) — — 3, 4 (Rn) 5f ⁸ 6d ² 7s ²	(251) — — 3, 2, 4 (Rn) 5f ⁹ 6d ² 7s ²	(252) — — 3, 2 (Rn) 5f ¹⁰ 6d ² 7s ²	(257) — — 3, 2 (Rn) 5f ¹¹ 6d ² 7s ²	(258) — — 3, 2, 1 (Rn) 5f ¹² 6d ² 7s ²	(259) — — 2, 3 (Rn) 5f ¹³ 6d ² 7s ²	(260) — — 3 (Rn) 5f ¹⁴ 6d ² 7s ²

Interaction – detection

$$\frac{d\sigma_{\nu A}}{dT}(E, T) = \sigma_0^{\text{SM}} \cdot \left(1 - \frac{MT}{2E^2}\right)$$

$$\sigma_0^{\text{SM}} = \frac{G_F^2 M}{4\pi} [Q_W^n N F_n(q^2) - Q_W^p Z F_p(q^2)]^2 \approx \frac{G_F^2 M}{4\pi} [N - Q_W^p Z]^2 \approx \frac{G_F^2 M}{4\pi} N^2$$

根据上述公式, T 的变化范围: $0 \leq \frac{MT}{2E^2} \leq 1$; 即核反冲动能 T : $0 \leq T \leq \frac{2E^2}{M}$

$$M_{Ge}(\Delta = -71.298) = 73 \times 931.45 + \Delta(^{73}_{32}Ge) = 67924.55 \text{ MeV}; T_{Gemax}(E_\nu = 3 \text{ MeV}) = 265 \text{ eV}$$

$$M_{Mo}(\Delta = -88.795) = 96 \times 931.45 + \Delta(^{96}_{42}Mo) = 89330.405 \text{ MeV}; T_{Gemax}(E_\nu = 3 \text{ MeV}) = 201.5 \text{ eV}$$

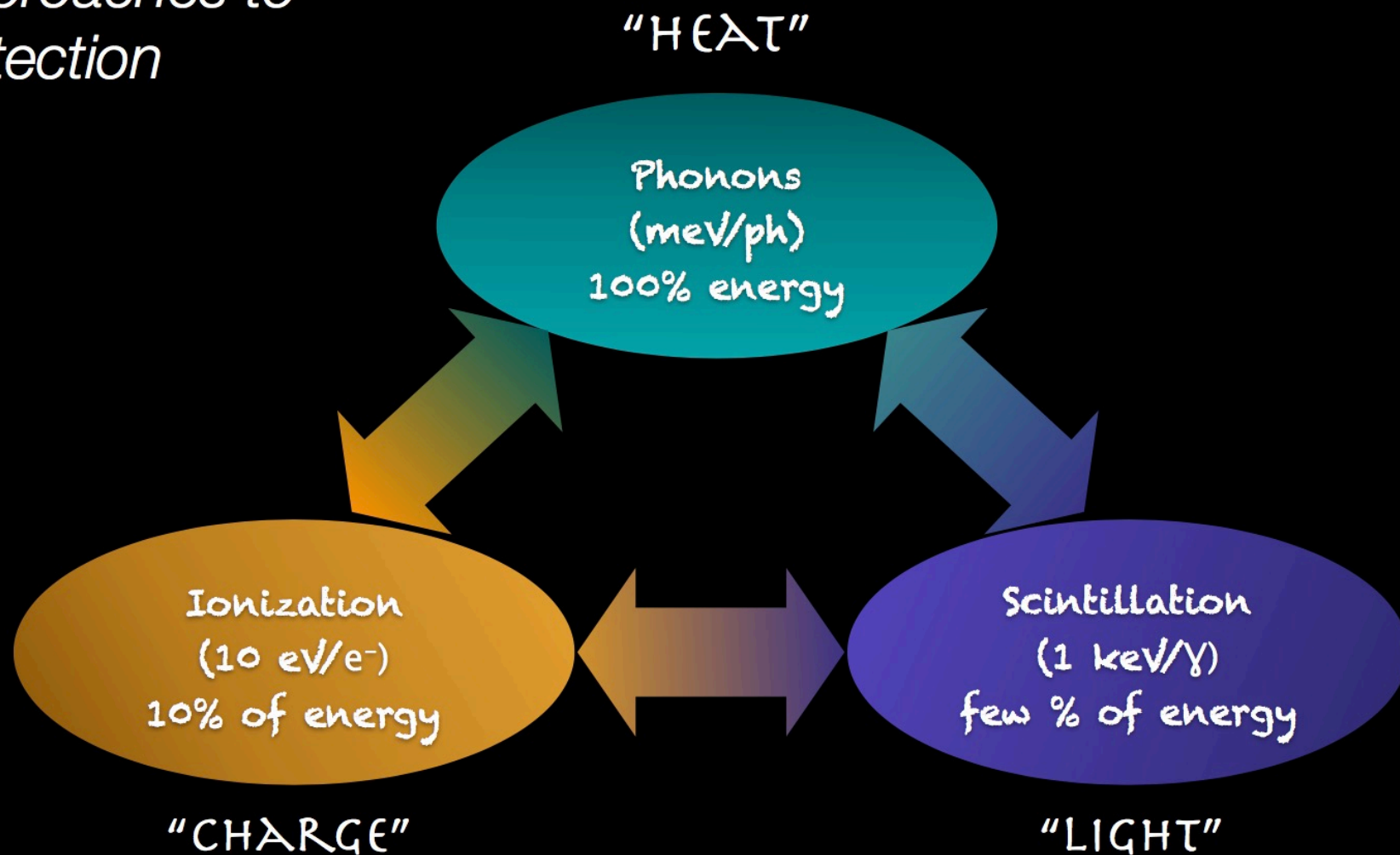
$$M_W(\Delta = -45.705) = 184 \times 931.45 + \Delta(^{184}_{74}W) = 171341.10 \text{ MeV}; T_{Gemax}(E_\nu = 3 \text{ MeV}) = 105.1 \text{ eV}$$

$$M_{Pb}(\Delta = -22.452) = 207 \times 931.45 + \Delta(^{207}_{82}Pb) = 192787.70 \text{ MeV}; T_{Gemax}(E_\nu = 3 \text{ MeV}) = 93.3 \text{ eV}$$

$$M_{Zn}(\Delta = -66.000) = 64 \times 931.45 + \Delta(^{64}_{30}Zn) = 59546.8 \text{ MeV}; T_{Gemax}(E_\nu = 3 \text{ MeV}) = 302.2 \text{ eV}$$

$$M_{Cd}(\Delta = -90.018) = 114 \times 931.45 + \Delta(^{114}_{48}Cd) = 106095.28 \text{ MeV}; T_{Gemax}(E_\nu = 3 \text{ MeV}) = 169.7 \text{ eV}$$

Different Approaches to Detection





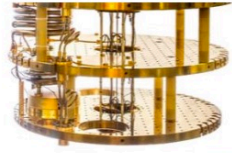
主要集成厂商

- Leiden



CF-DR Models	Tmin (mK)	Q@100mK (μ W)	Q @120mK (μ W)
CF-2500 Maglev*	< 8	1800	2500
CF-2000 Maglev	< 8	1400	2000
CF-1400 Maglev	< 8	1000	1400
CF-1000 Maglev	< 8	700	1000

*in development



主要集成厂商

- Oxford Instruments



	With DU7-500 dilution unit	With DU7-300 dilution unit
Base T:	8 mK typical, < 10 mK guaranteed	8 mK typical, < 10 mK guaranteed
At 100 mK:	500 μ W typical, 450 μ W guaranteed	300 μ W typical, 250 μ W guaranteed
At 20 mK:	15 μ W typical, 12 μ W guaranteed	10 μ W typical, 8 μ W guaranteed

TritonXL

3mK typical, <4mK guaranteed
1000mW@100mK
25mW@20mK

NEW cooling power where you need it

- 500 μ W at 100 mK
- 15 μ W at 20 mK

Complete magnet integration

- Fully designed, built, tested and guaranteed by Oxford Instruments
- Early detachable sample lead connectors

NEW design features for easiest operation and highest reliability, with:

- Single person operation
- Software control
- Easy access to coil stage

Fast sample change and maximum sample size

- Unique bottom-loading sample puck design for best in-class wiring capability and sample change

OXFORD INSTRUMENTS
The Business of Science



主要集成厂商

- Bluefors



	BF-XLD400		BF-XLD1000	
	GUARANTEED	EXPECTED	GUARANTEED	EXPECTED
Base temperature	10 mK	8 mK	10 mK	8 mK
Cooling power @ 20 mK	15 μ W	18 μ W	30 μ W	34 μ W
Cooling power @ 100 mK	400 μ W	600 μ W	1000 μ W	1100 μ W
Cooling power @ 120 mK	600 μ W	800 μ W	1400 μ W	1600 μ W
Cool-down time to base	24 hrs	22 hrs	24 hrs	22 hrs



主要集成厂商

- Janis

无特别型号
客户定制

