Bolometer-based CEvNS Research

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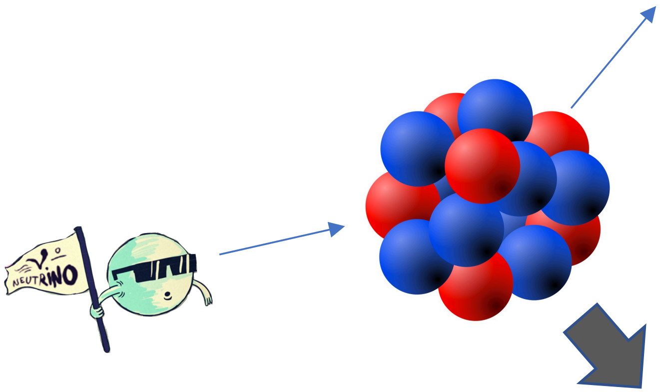
Outline

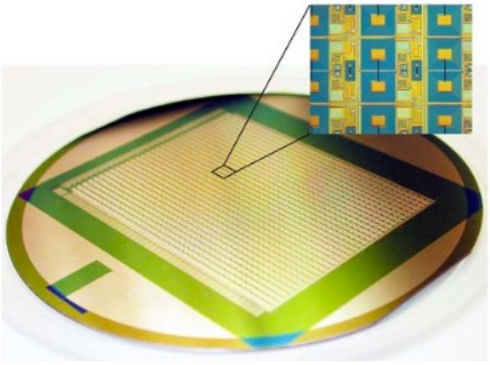
➢ Motivation

- ➢ 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

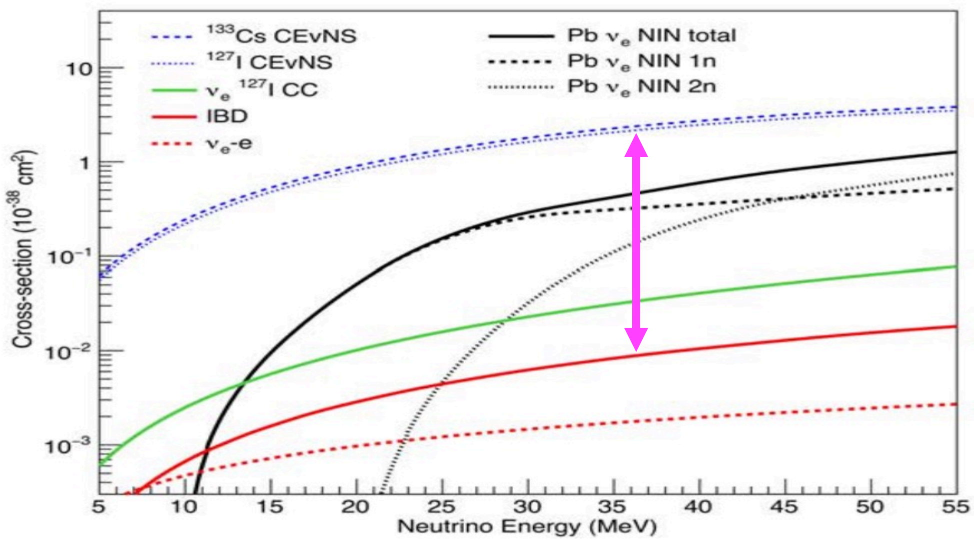
- Coherent condition:

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

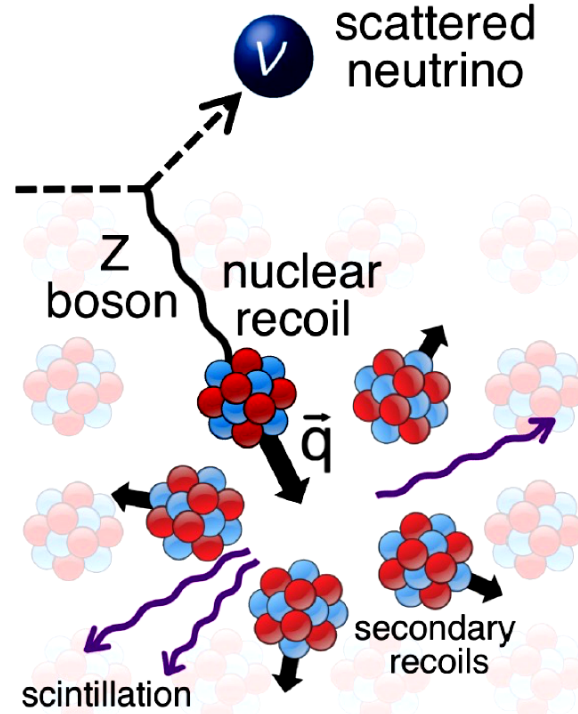
Plank constant $\hbar c$=200MeV·fm;
Nucleus radius R=10fm

a sufficiently small momentum exchange (q)

- Cross section of CEvNS



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



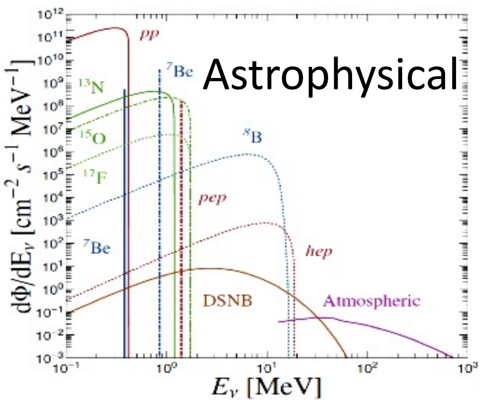
$$\nu + A \rightarrow \nu + A$$

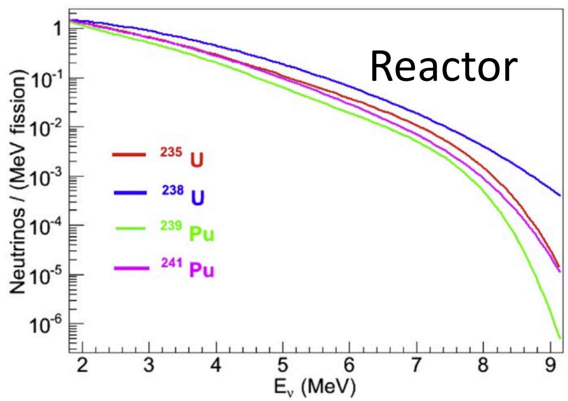
exchange of neutral Z bosons

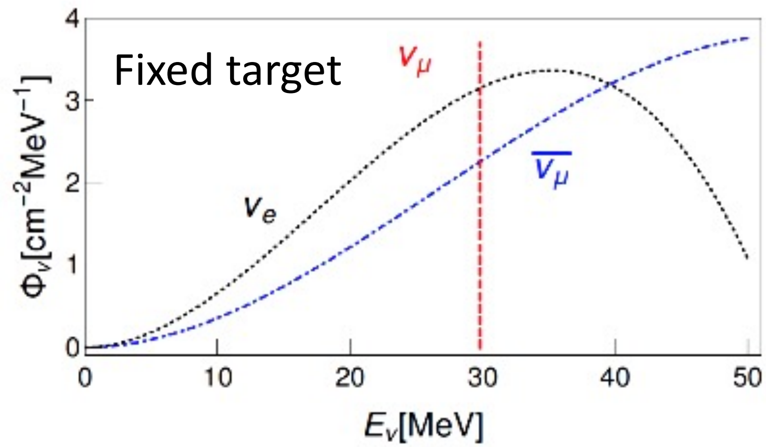
Coherent Neutrino-nuclear Scattering

➢ Challenges:

① ν-source: high intensive flux with low-energy E < 100MeV







② nuclei: heavier for large N vs. lower recoil energy T ~ keV, even eV

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

nucleus mass M

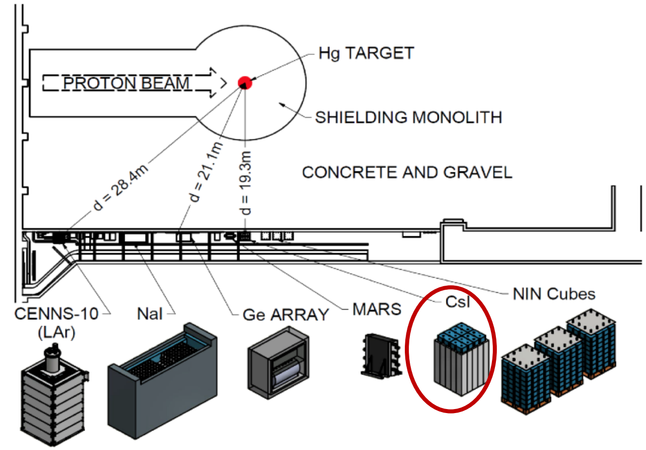
③ detector: very-low-threshold E_{thres} ~ tens eV vs. background control

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

➢ Fruitful physics

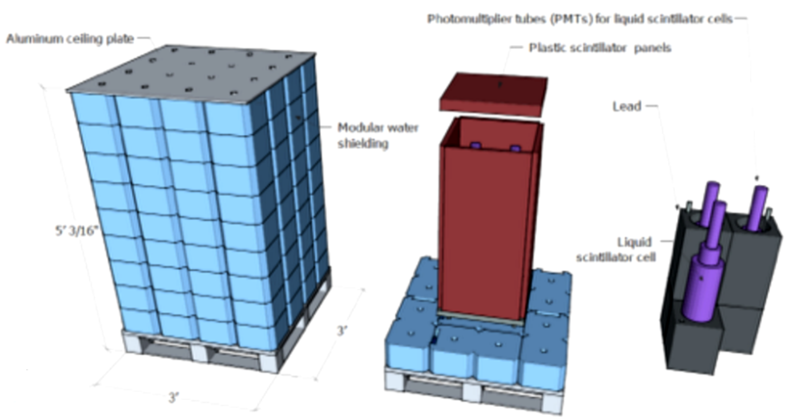
The COHERENT Experiment

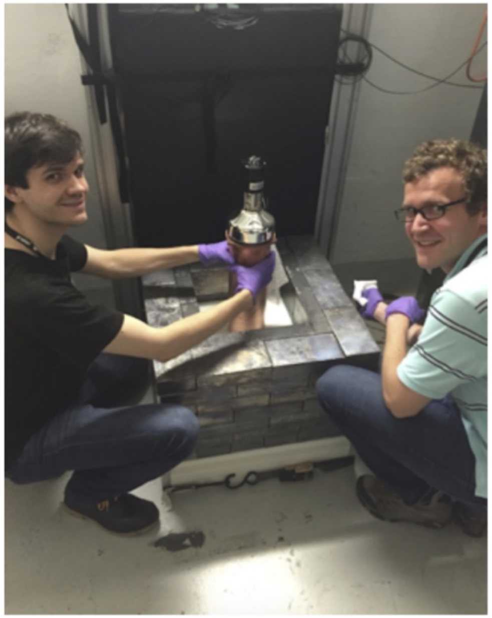
- ➢ Spallation Neutron Source (SNS) @ Oak Ridge
  - ✓ 1 MW pulsed (60 Hz, 700ns) proton beam (1 GeV)
  - ✓ ν from stopped π/μ-DAR → $E(\nu_i) < 50$MeV
  - ✓ Background suppression by 10μs beam timing window
  - ✓ "ν-alley" deployed 20-30m from target



Approx ν flux at CsI[Na] location
1e7 ν / cm² / s / flavor

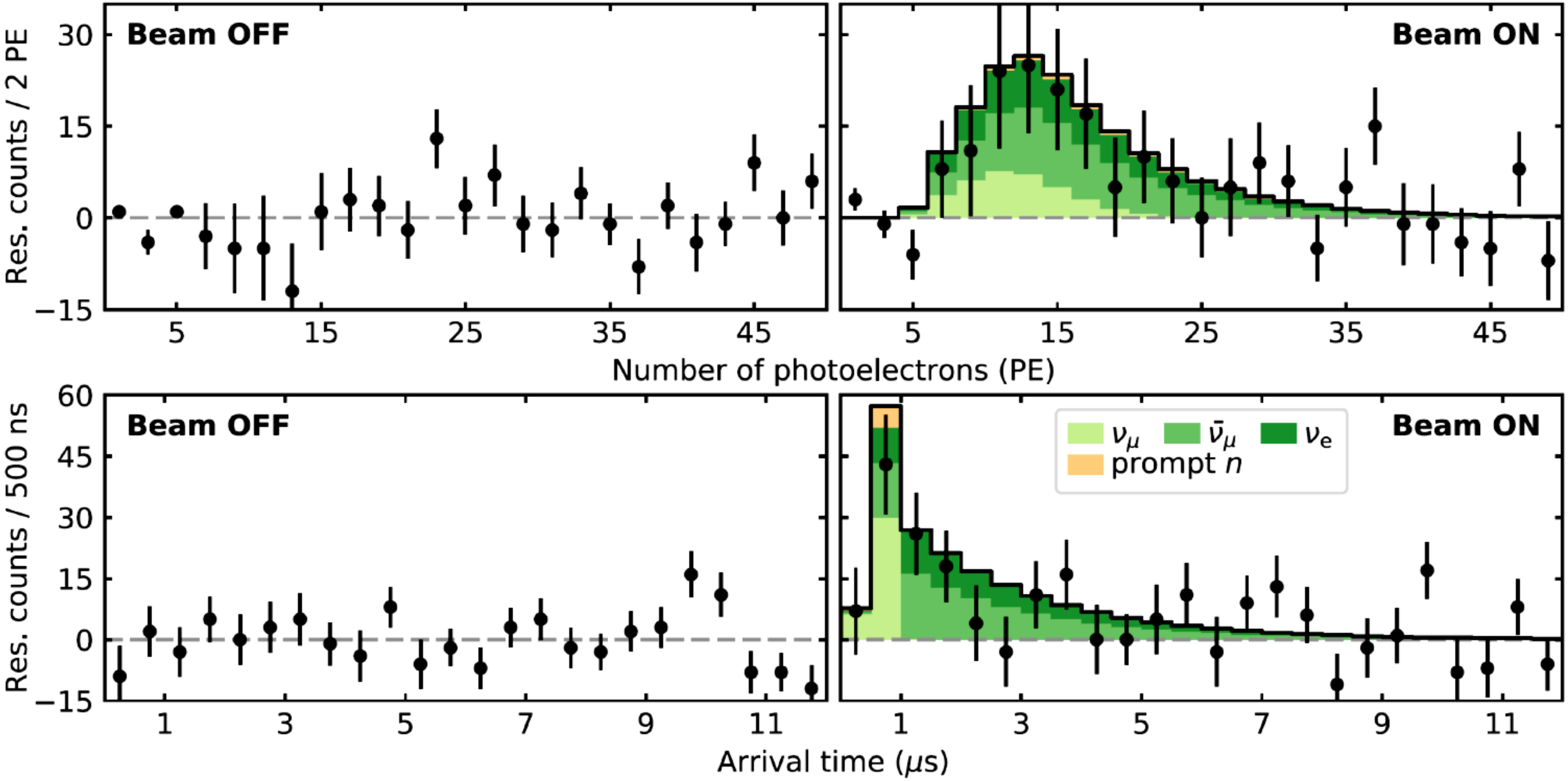
- ➢ Detector: 14.6kg of CsI(Na)





  - ✓ Flux ~ 10^7 ν/cm²/s/flavor
  - ✓ Background: n-induced ν (NIN) in Pb-shield

The COHERENT Experiment



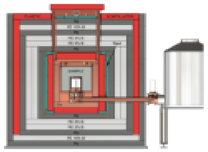
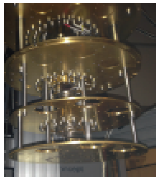
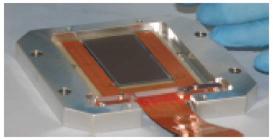
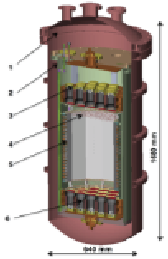
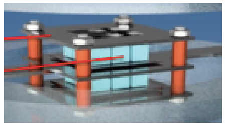
Significance: 6.7-sigma confidence level

[arXiv: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

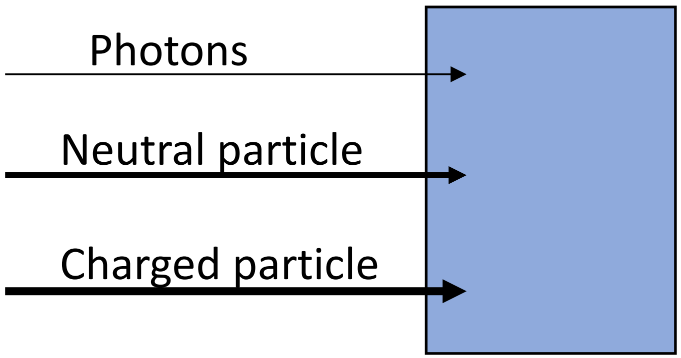

Novel low-background, low-threshold technologies

[Y.F.Li talk @ USTC]

Principles of Cryogenic Detector

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

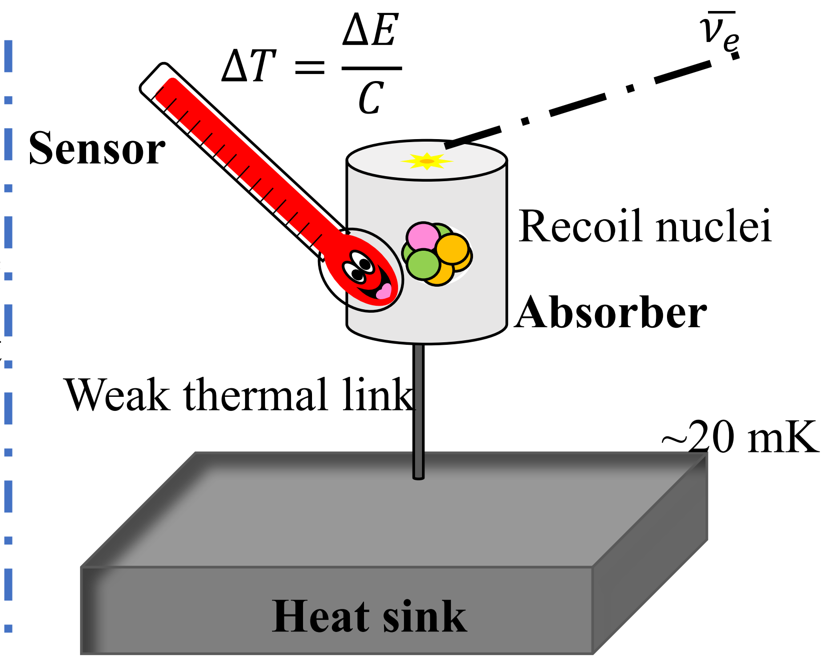
Particle detector based on **phonon** or **quasi-particle** detection



- ~90% ΔE convert to phonons, Heat signal
- <10% ΔE 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**



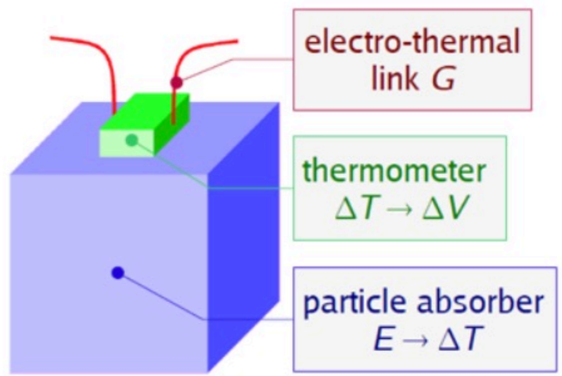
- Properties of bolometers

① Wide choice of different absorber material

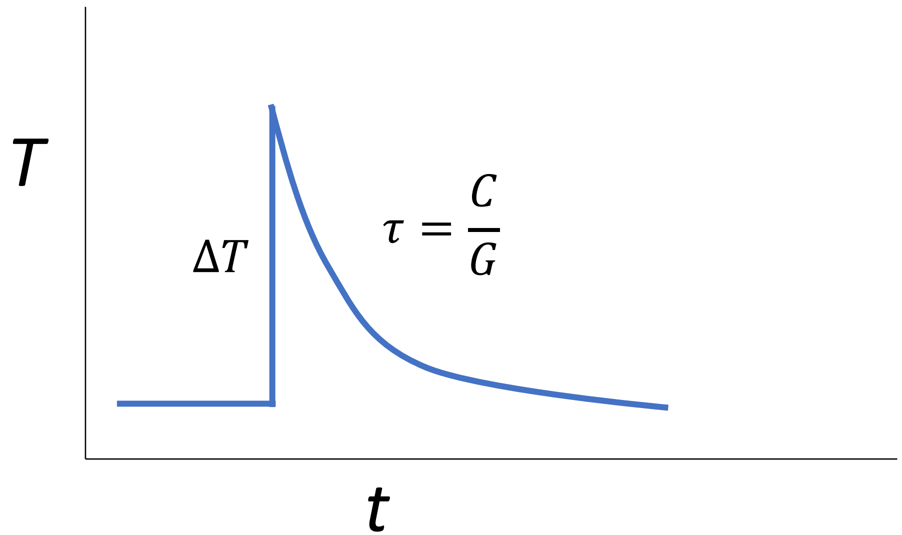
② High energy resolution FWHM (0.3%@2615keV)

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 :

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

Where $\beta = 1944 \text{ J}K^{-1}mol^{-1}$, 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 [$JK^{-1}T^3$]	Num N	T_{max}(eV)
Ge	73	374	5.1×10^{-7}	~41	265
Zn	65.4	327	8.5×10^{-7}	~35	295
Al_2O_3	101.9	1041	1.7×10^{-8}	-	-
$CaWO_4$	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
$PbWO_4$	455.04	237	3.2×10^{-7}	-	-

* m=1g; Ev=3MeV

Absorber

Material	Mass (g)	Cube Size (mm)	C (**T=10mK**) (J/K)	$\Delta T(\Delta E=20\ eV)$ μK	$\Delta T(\Delta E=100\ eV)$ 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
	1.0	3.7	1.65×10^{-13}	19.39	96.97
	2.42	5.0	4.00×10^{-13}	7.99	40.00
$CaWO_4$ $\sim6\ g/cm^3$	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
$PbWO_4$ $8.28\ g/cm^3$	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

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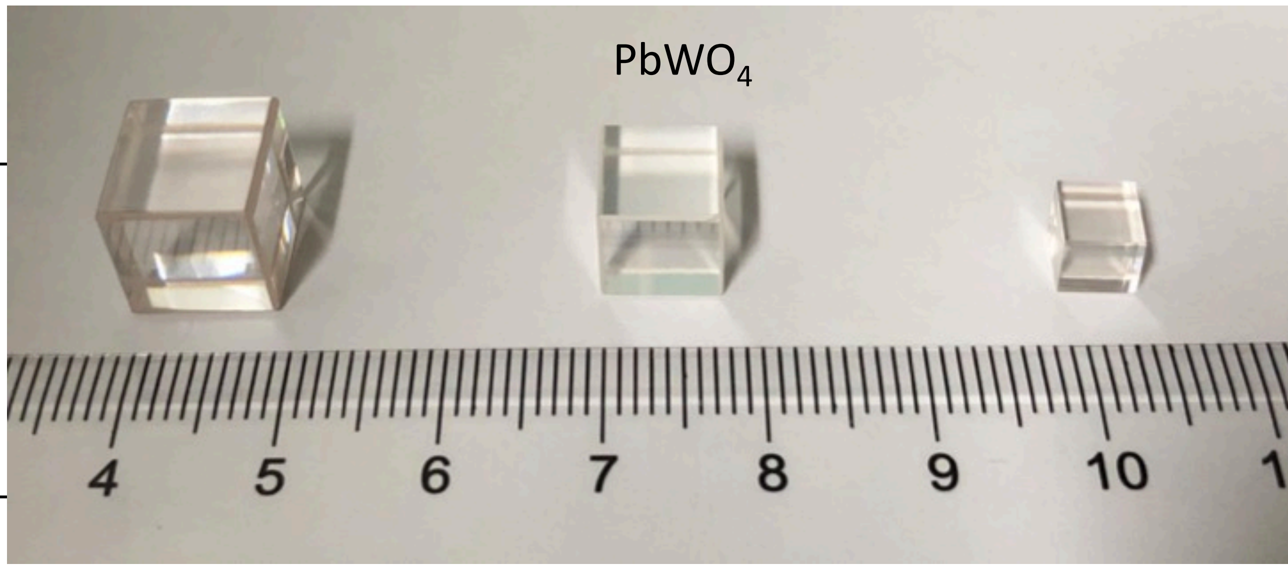
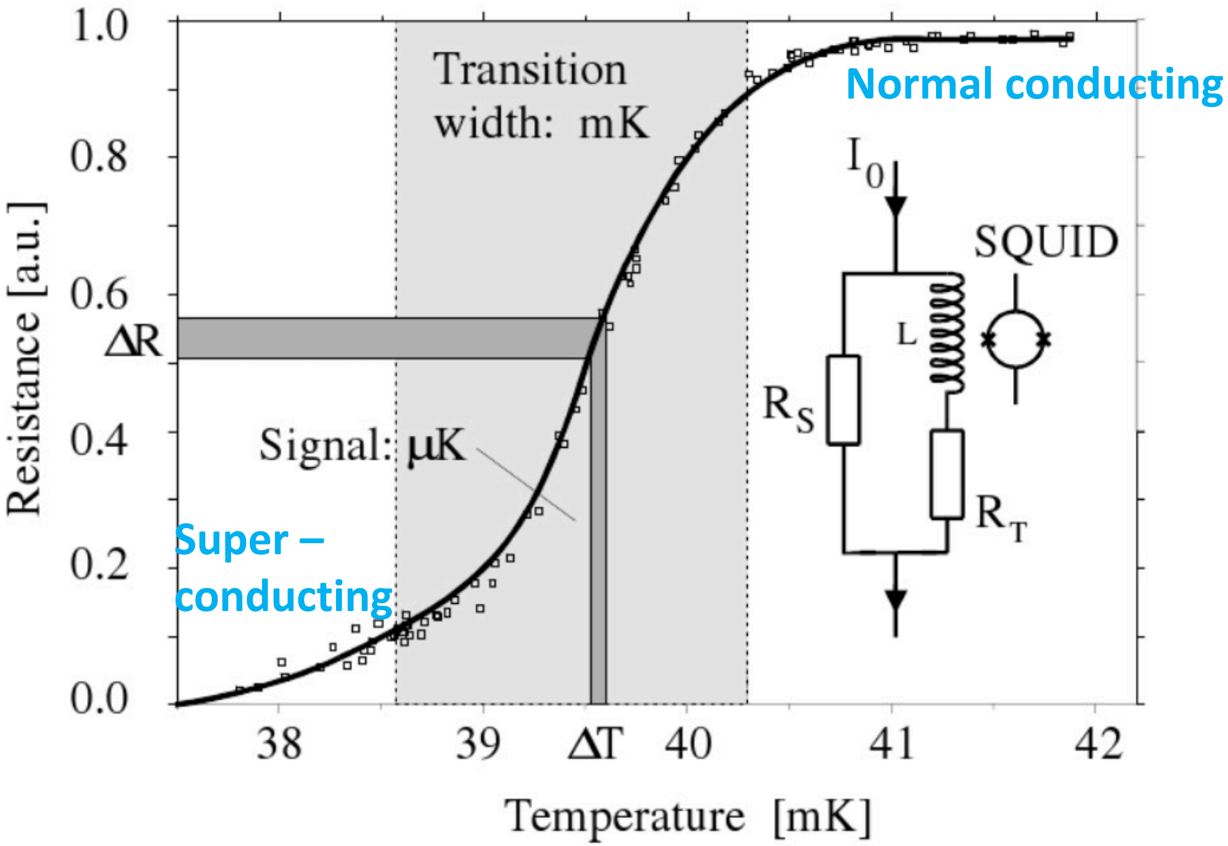


Sensors

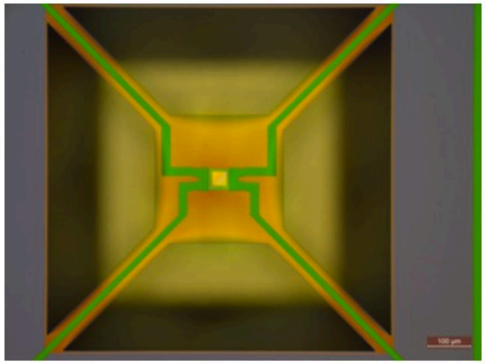
- TES (Transition-edge Sensor)

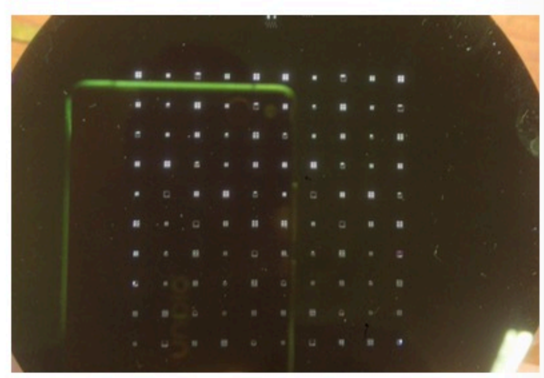


- Small changes in temperature can be captured by TES, which allow great sensitivity to small temperature depositions;
- Readout of TES done using SQUID amplifiers, quantum-limited magnetometers, ideal for small currents;
- Golden wire bonding ;
- Now, using TES can get the low threshold ~15 eV.

Sensors

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

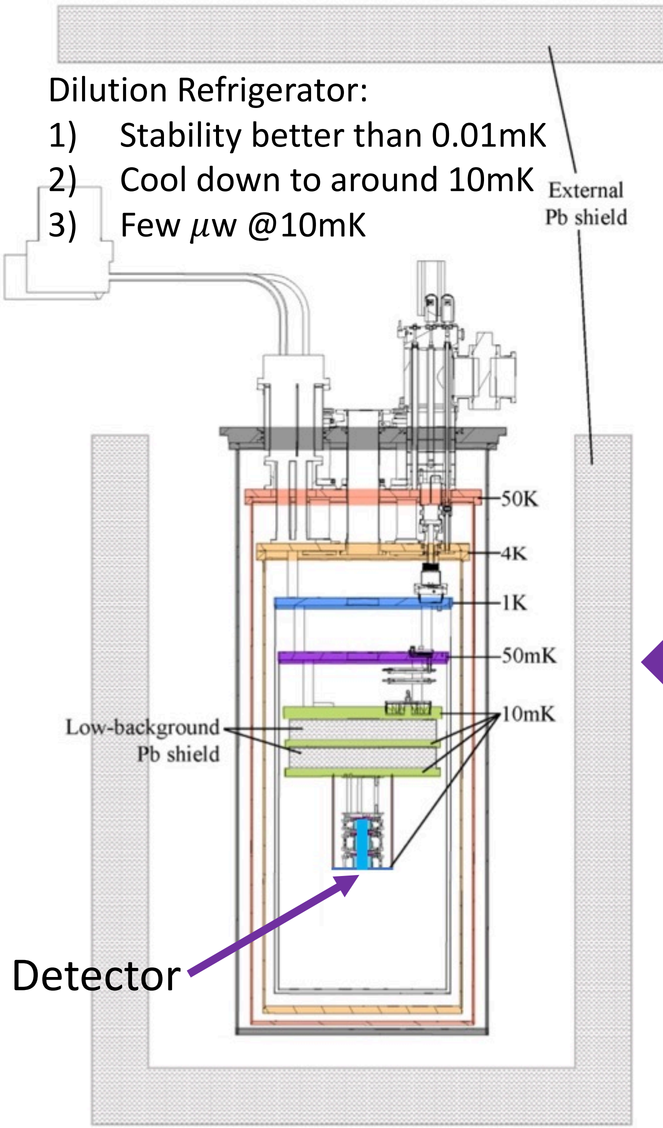




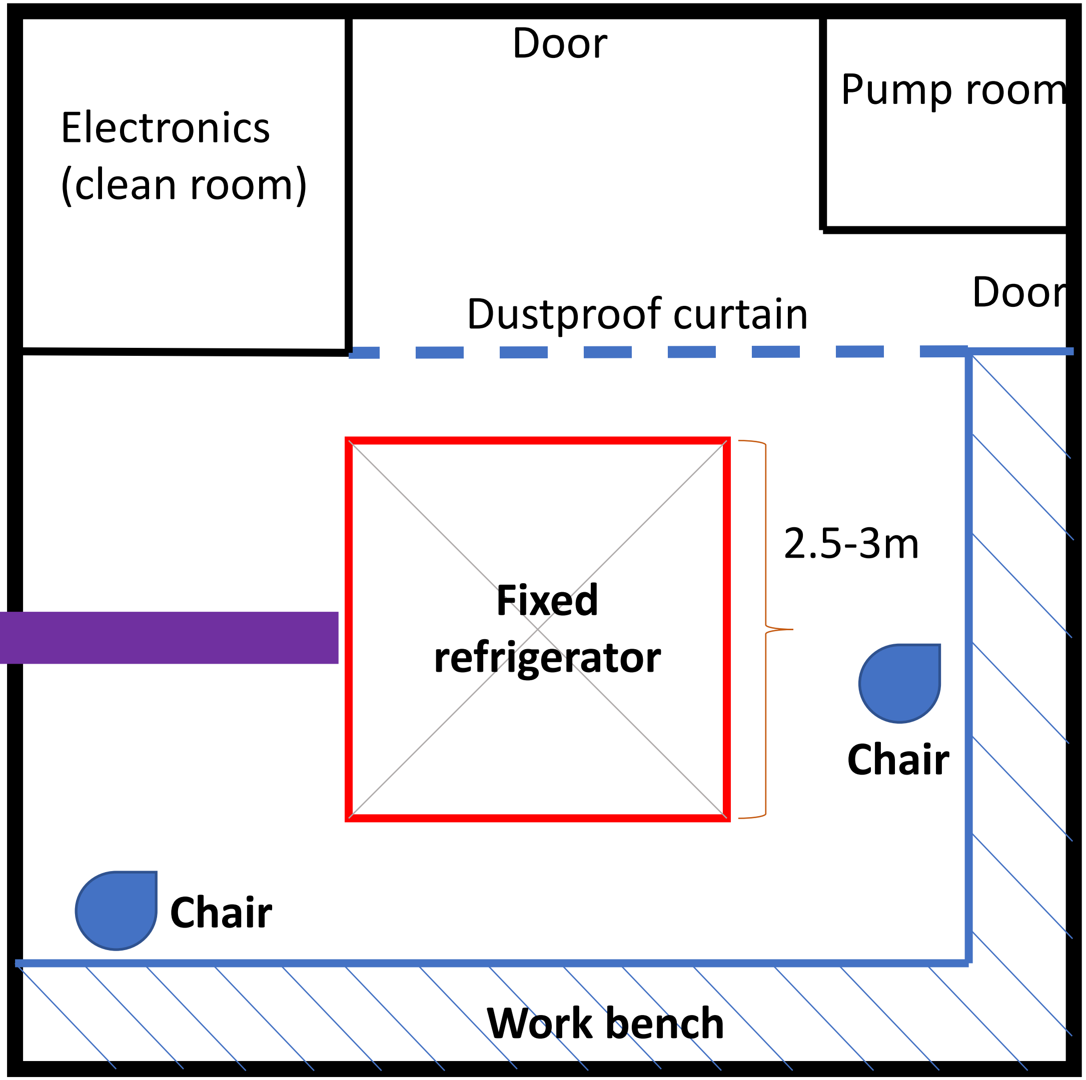
Prof. Zhou Xingxiang's group

Cryogenic System

Dilution Refrigerator:
1) Stability better than 0.01mK
2) Cool down to around 10mK
3) Few μw @10mK



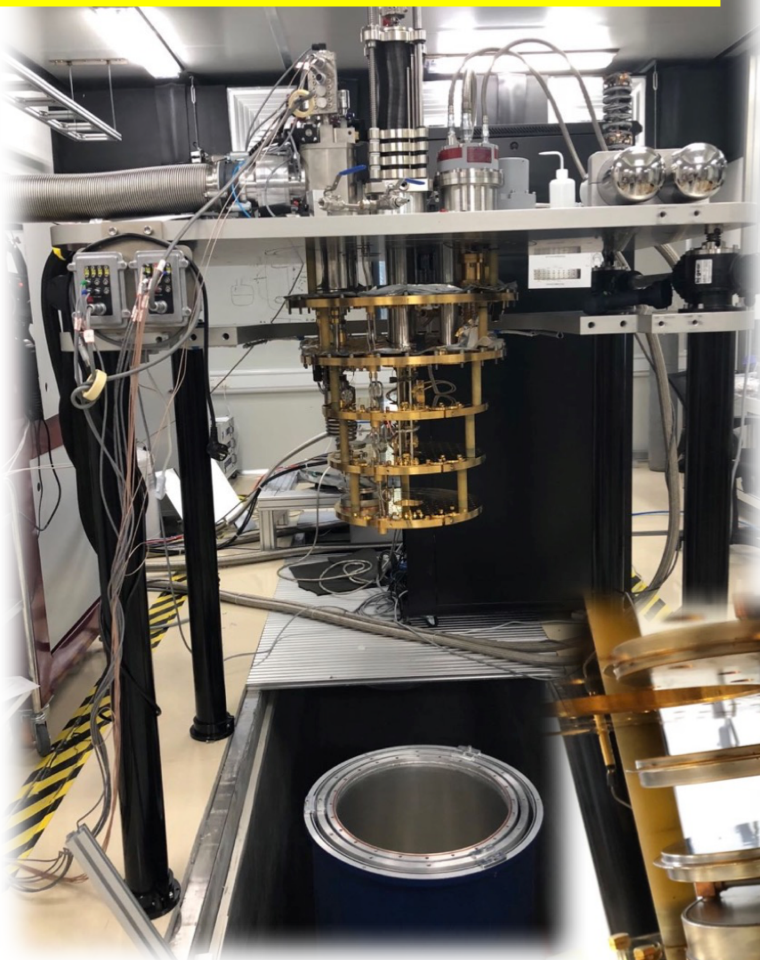
A schematic view of the WO4-based experiment arrangement



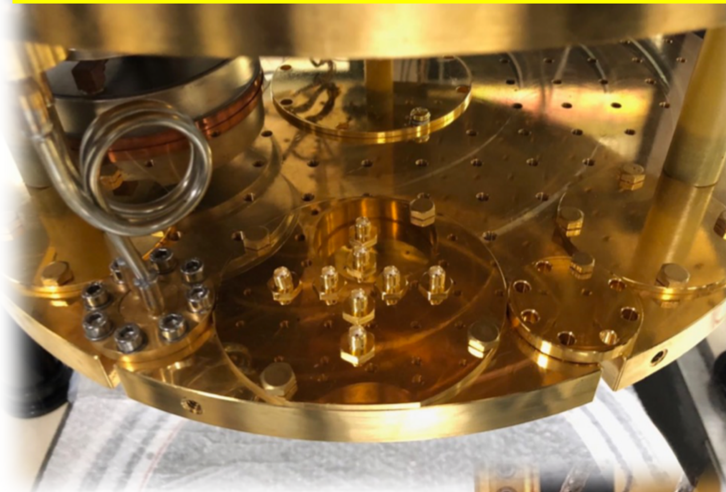
Schematic diagram of the laboratory layout

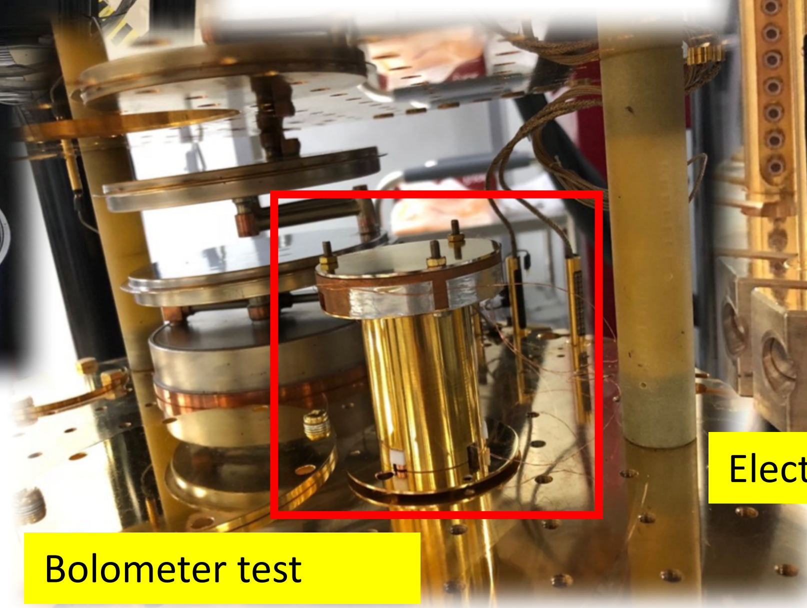
Cryogenic System

~8mK Dilution refrigerator in USTC

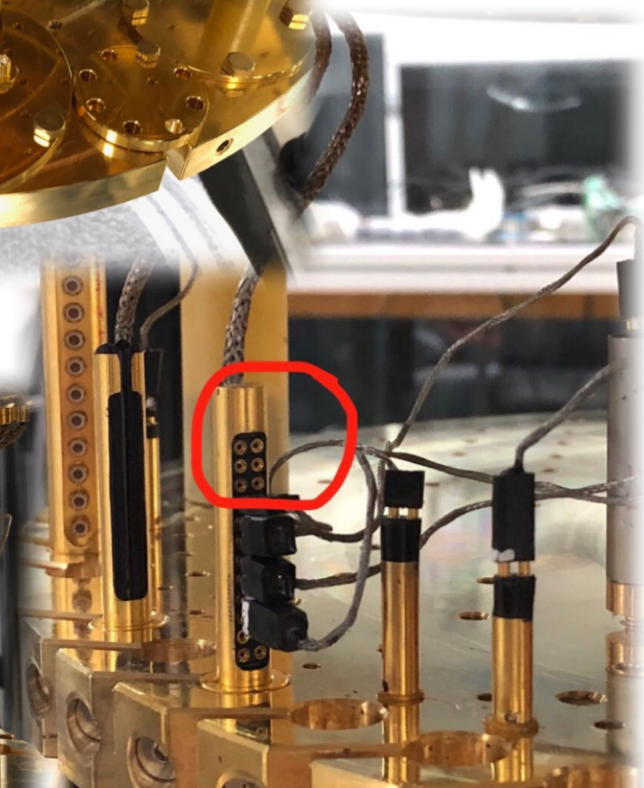


Easy connection with mK Plate





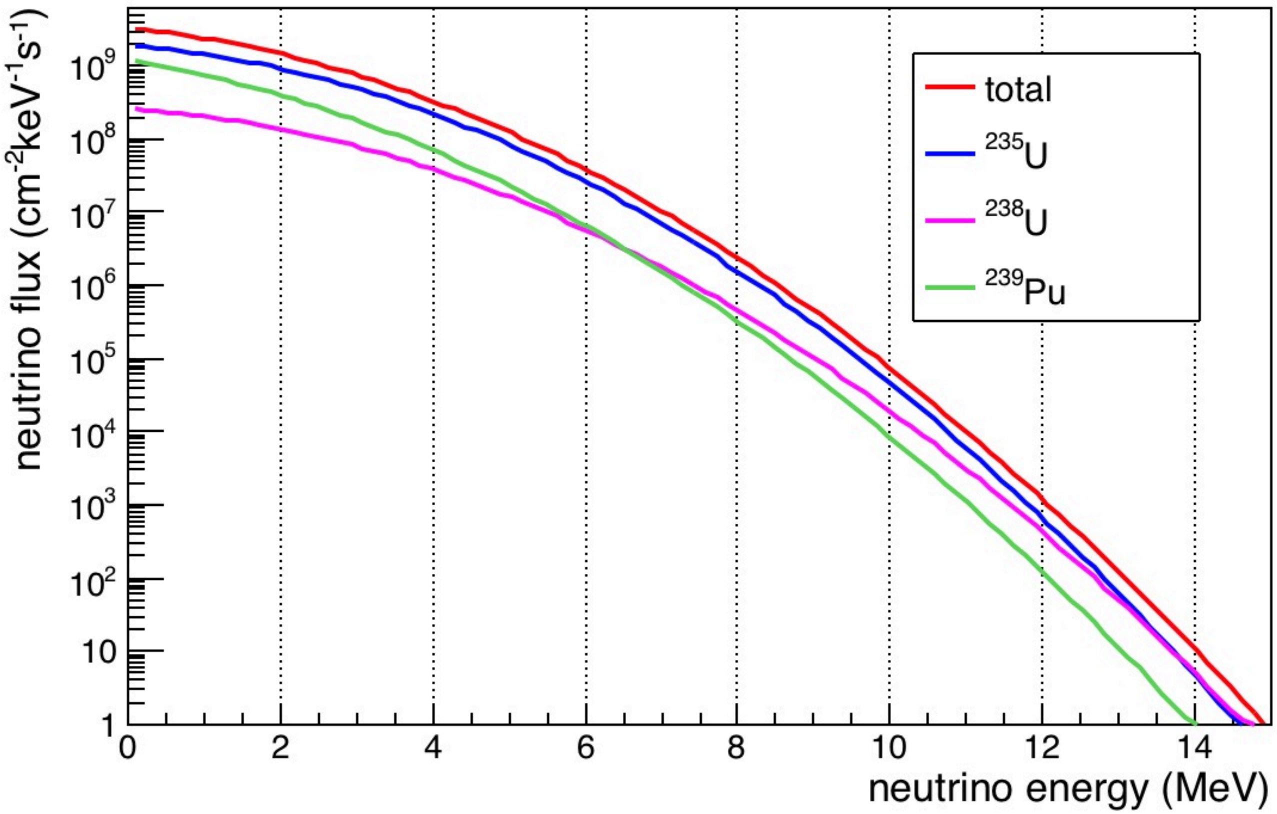
Bolometer test



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:

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

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, $G_F = 1.166364\times10^{-5}\ GeV^2$; $\hbar c = 1$;

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

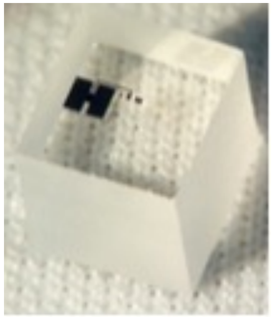
Mass of W, $m_N = 1.715\times10^5\ MeV$; Nucleus form factors $f(q)$ =1

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**

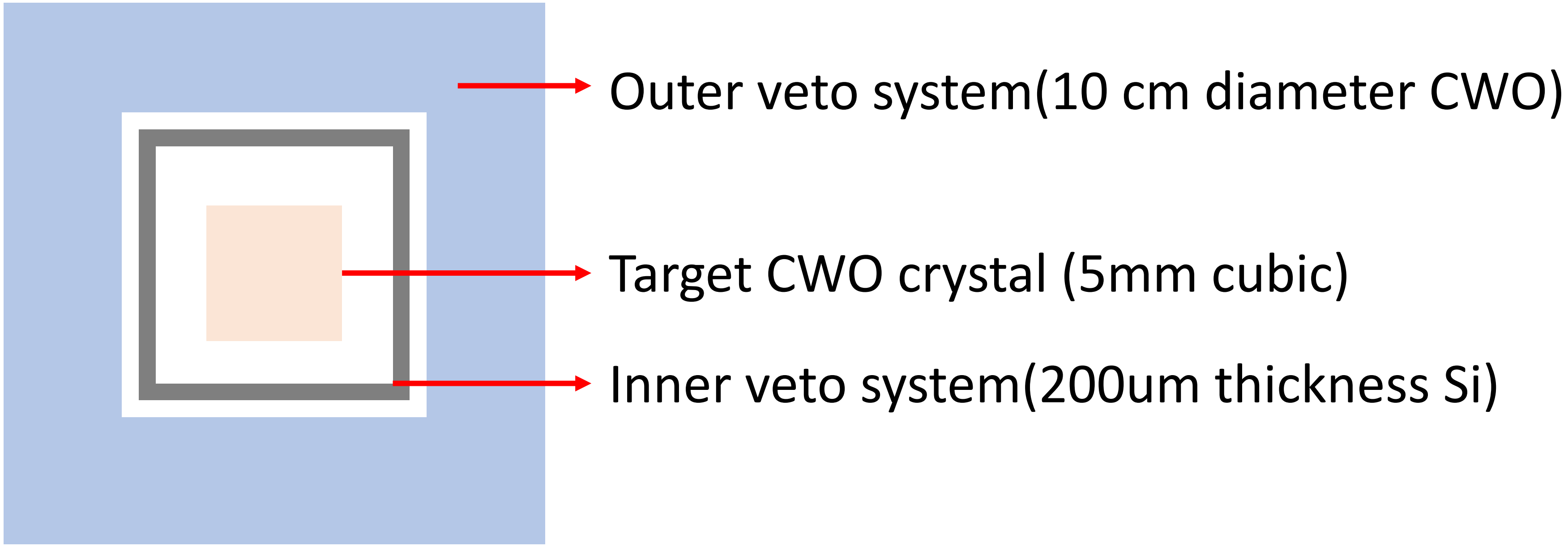
$$Total\ Event = 0.16/day$$
$$Total\ Event = 1.46/array \cdot day$$
$$1\ array = 3 \times 3 \text{ CWO crystals}$$



Thank Prof. Li Yufeng for doing cross check

Simulation

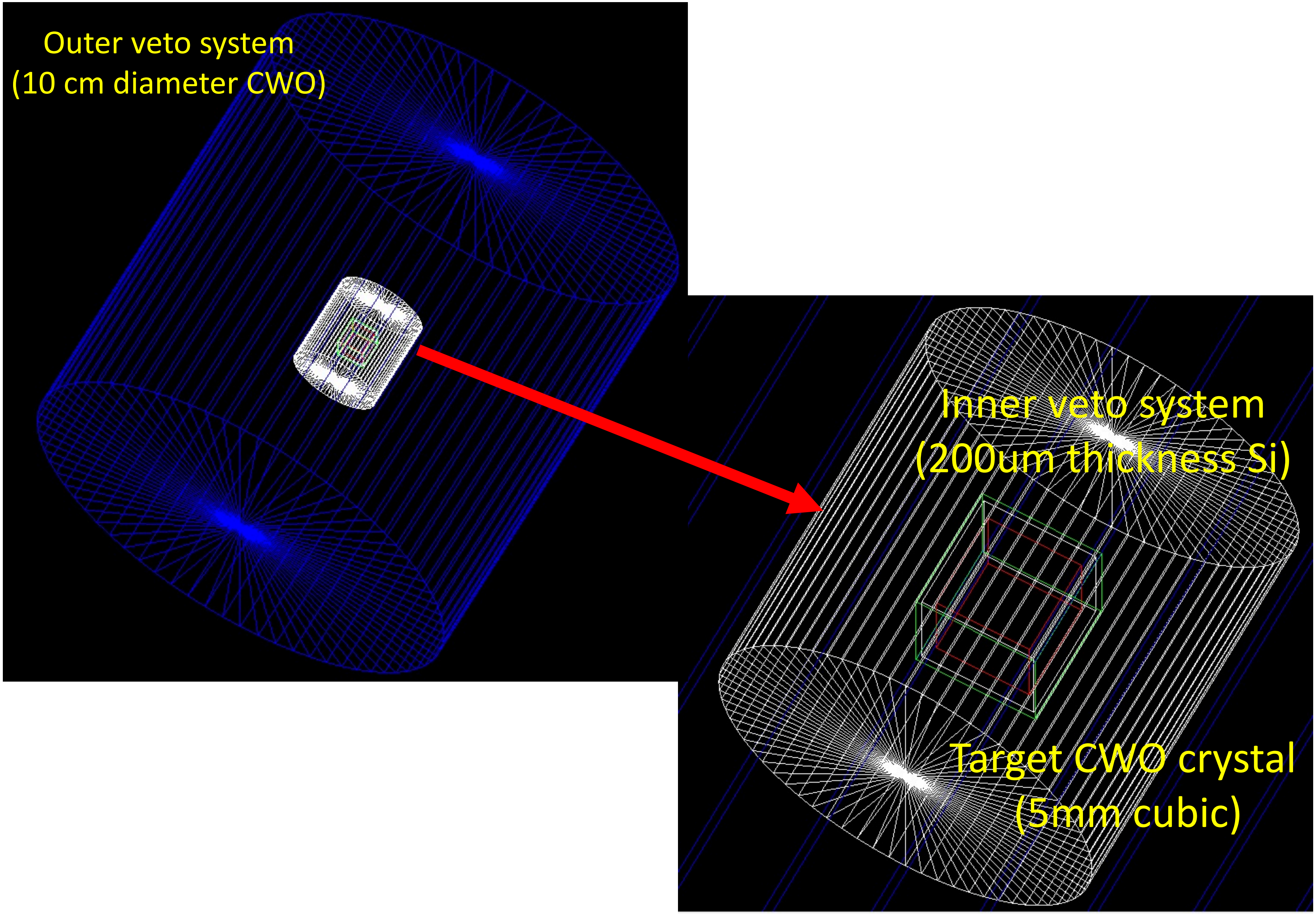
Detector Construction



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

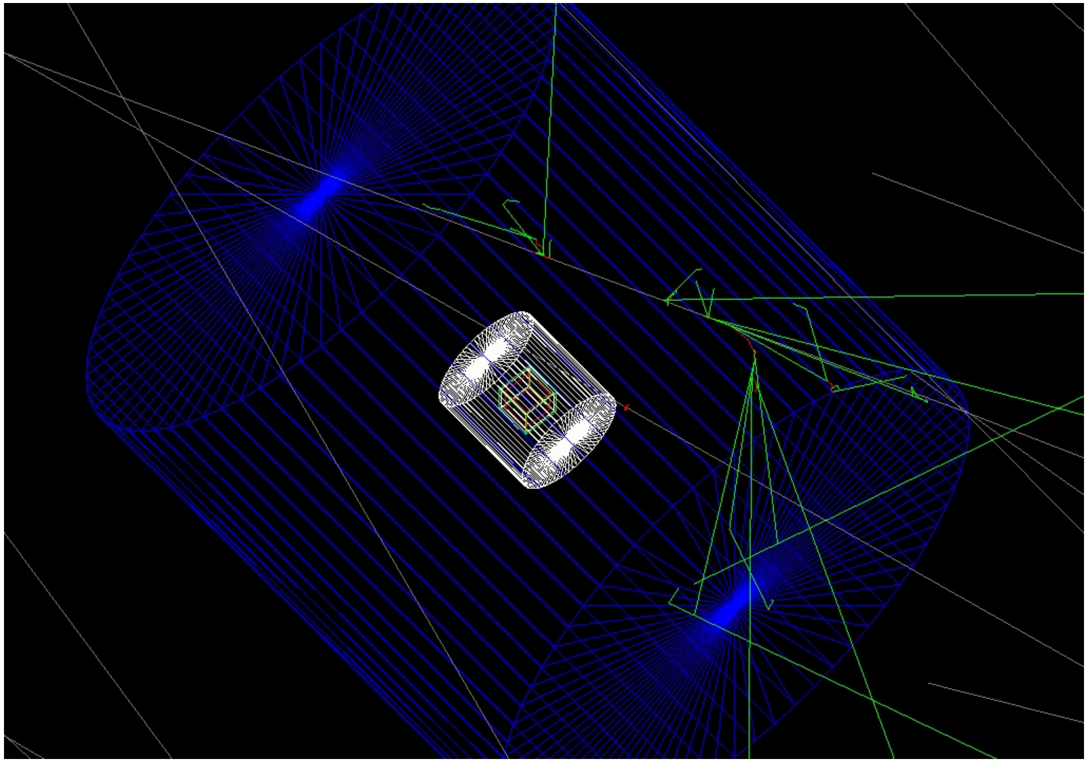
The ν-cleus experiment: A gram-scale fiducial-volume cryogenic detector for the first detection of coherent neutrino-nucleus scattering

Detector Construction



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

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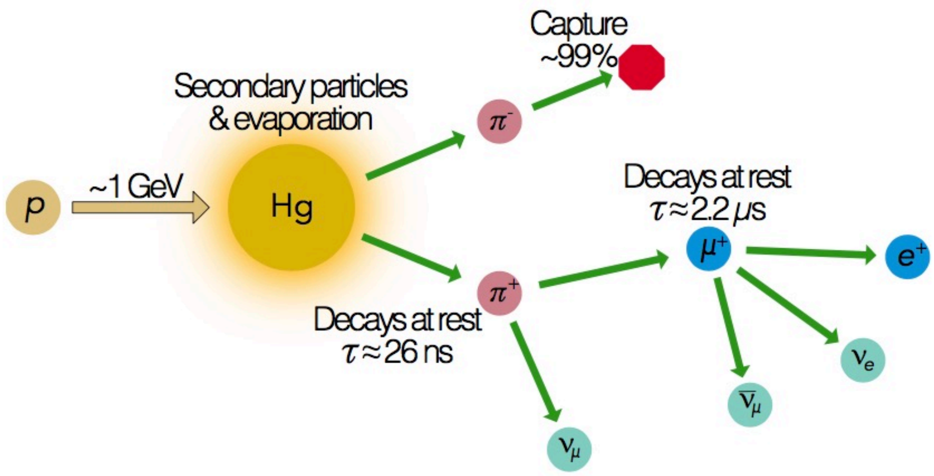
Thank you

Backup slides

Neutrino source

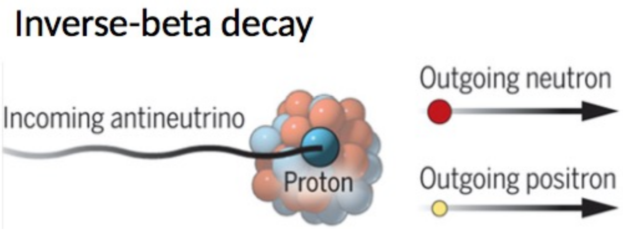
- Neutrinos at SNS are a result of the decay of pions and muons created in a mercury target by a pulsed (~1GeV) proton beam.
- 60hz of ~1 μs-wide (Proton-on-target) POT spills.
- Approximately 5×10^{20} POT are delivered per day.
- This allows us to isolate the steady-state environmental backgrounds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



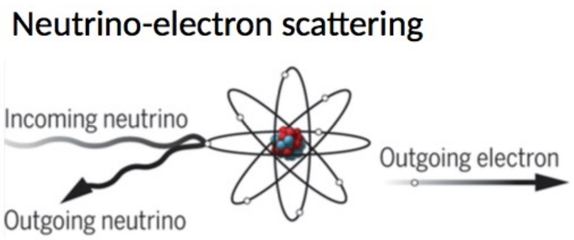
Neutrino energy range ~[16, 53]MeV.

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;

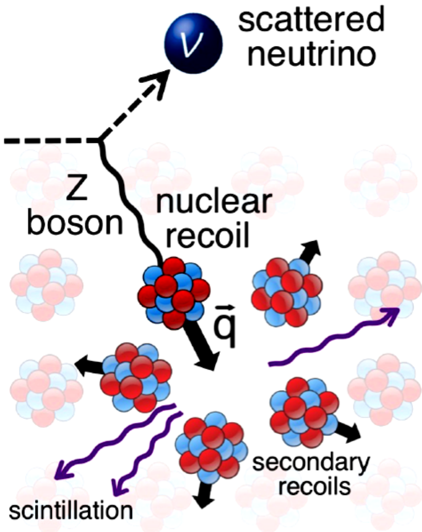


2. 在电子上散射，她的反应几率比IBD小几倍，而且很难和本底分开，只有少数几个实验采用，测量中微子磁矩;

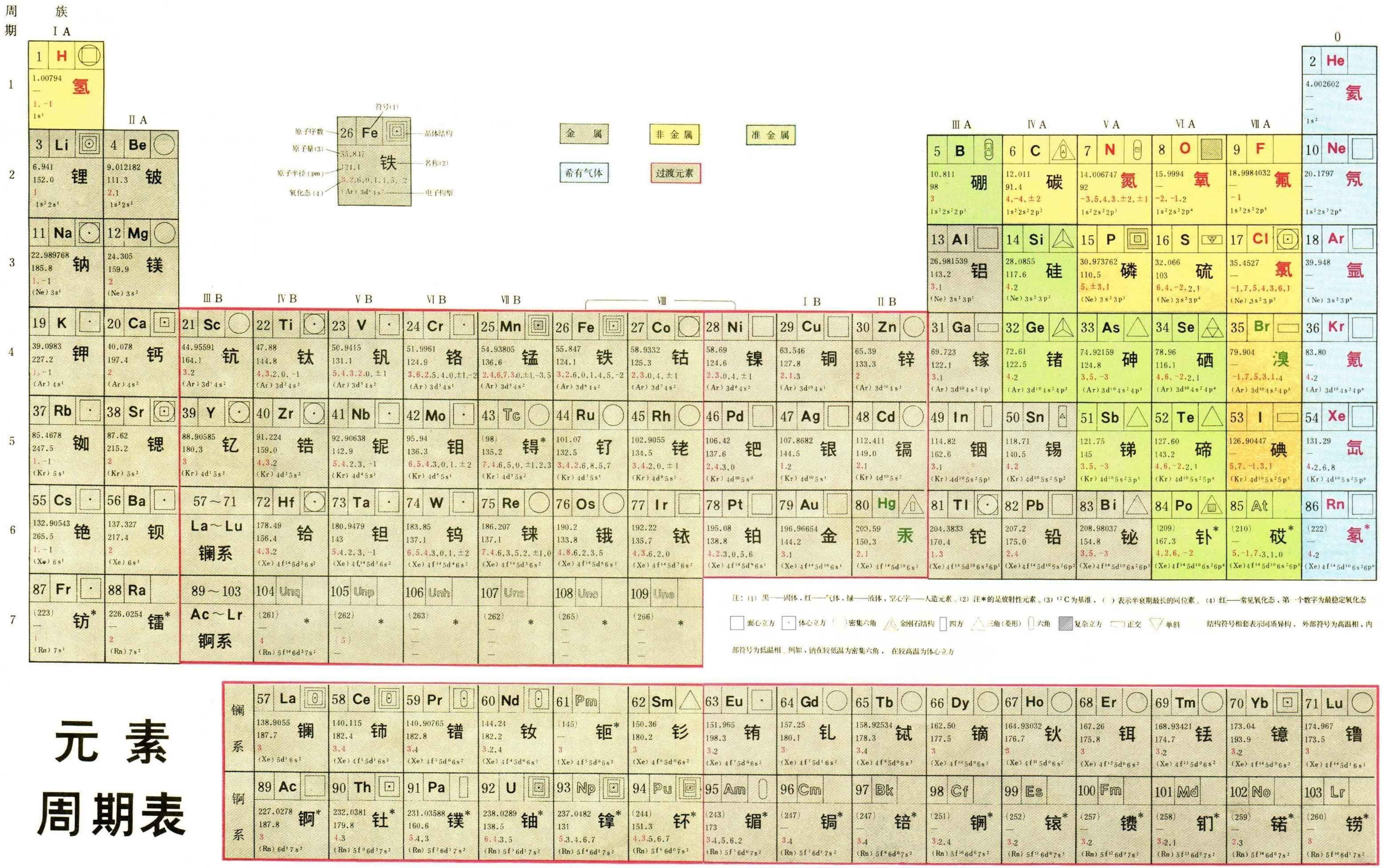


3. 在原子核内的核子上散射，她不仅反映几率小，而且由于原子核很重，就像一个乒乓球（中微子）撞上铅球（原子核）一样，铅球几乎得不到能量，因此极难探测，没有人用。

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。



Nucleus – absorber



Interaction – detection

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

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

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

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

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

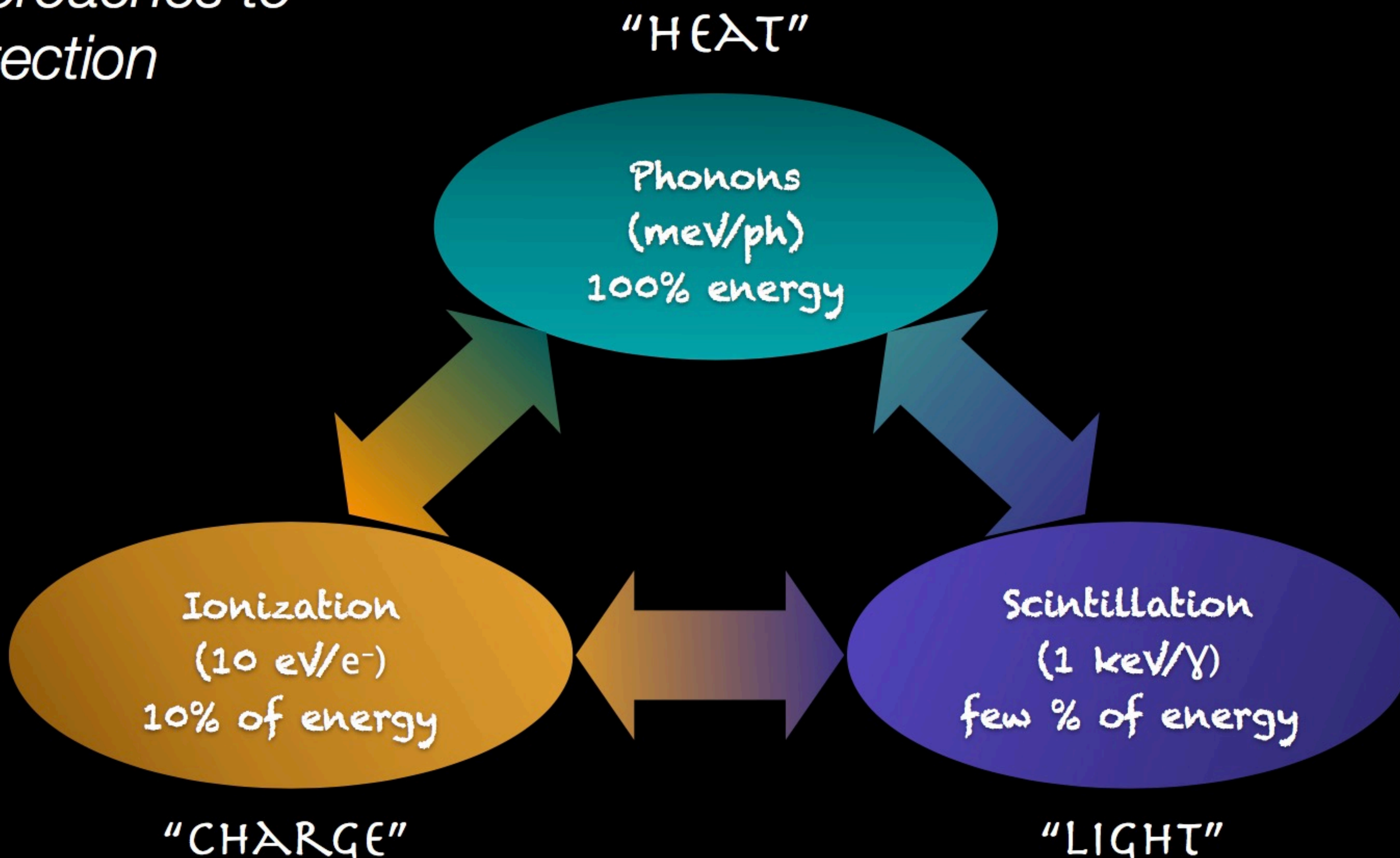
$M_{W}(\Delta = -45.705) = 184 \times 931.45 + \Delta({}^{184}_{74}W) = 171341.10MeV; T_{Gemax}(E_\nu = 3MeV) = 105.1eV$

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

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

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

Different Approaches to Detection

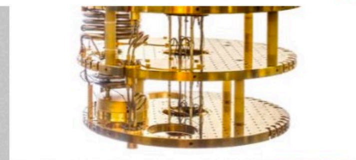


主要集成厂商

- Leiden

CF-DR Models	Tmin (mK)	Q@100mK (μW)	Q @120mK (μW)
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 μW typical, 450 μW guaranteed	300 μW typical, 250 μW guaranteed
At 20 mK:	15 μW typical, 12 μW guaranteed	10 μW typical, 8 μW guaranteed

TritonXL

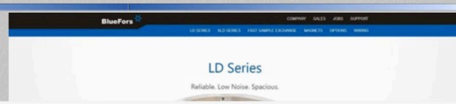
3mK typical, <4mK guaranteed

1000mW@100mK

25mW@20mK

主要集成厂商

- Bluefors



BF-XLD400

	GUARANTEED	EXPECTED
Base temperature	10 mK	8 mK
Cooling power @ 20 mK	15 μW	18 μW
Cooling power @ 100 mK	400 μW	600 μW
Cooling power @ 120 mK	600 μW	800 μW
Cool-down time to base	24 hrs	22 hrs

BF-XLD1000

	GUARANTEED	EXPECTED
Base temperature	10 mK	8 mK
Cooling power @ 20 mK	30 μW	34 μW
Cooling power @ 100 mK	1000 μW	1100 μW
Cooling power @ 120 mK	1400 μW	1600 μW
Cool-down time to base	24 hrs	22 hrs

主要集成厂商

- Janis

无特别型号

客户定制