A study of a cryogenic particle detector for low mass WIMPs search

Darkness on the Table

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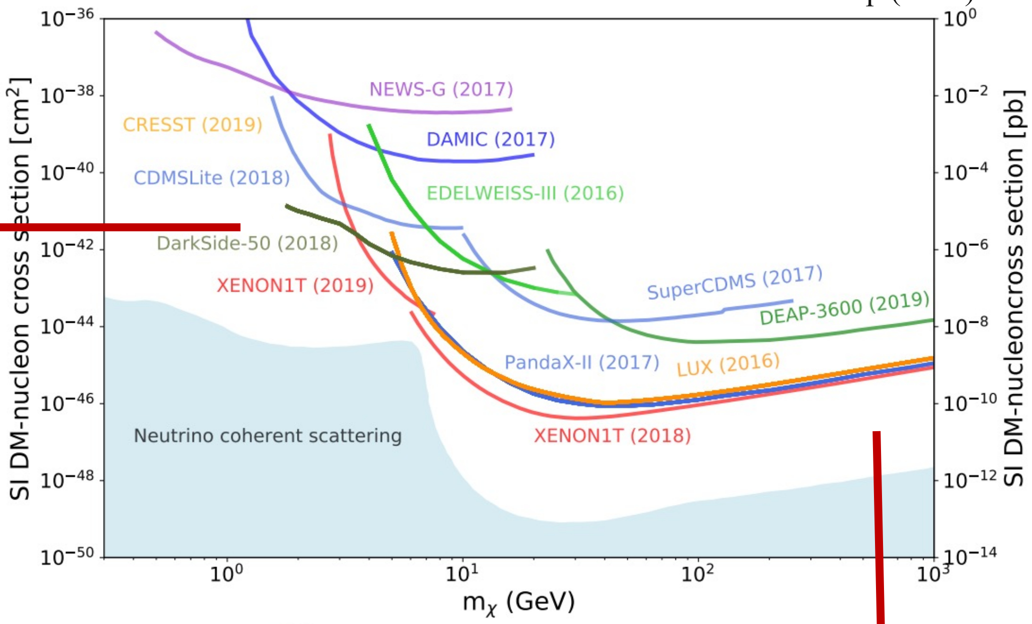
What is the Dark Matter?

- ✓ The universe is made of about 73% dark energy, about 23% dark matter, and about 4% baryons (commonly known matter).
- ✓ According to the hypothesis of dark matter, they interact only through gravity and the weak force.
- ✓ WIMPs (Weakly Interacting Massive Particles) are one of the most probable candidate for the dark matter.

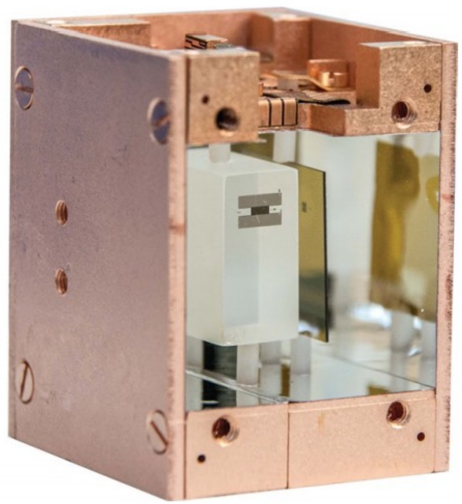
WIMP search

The current state of direct WIMP search project

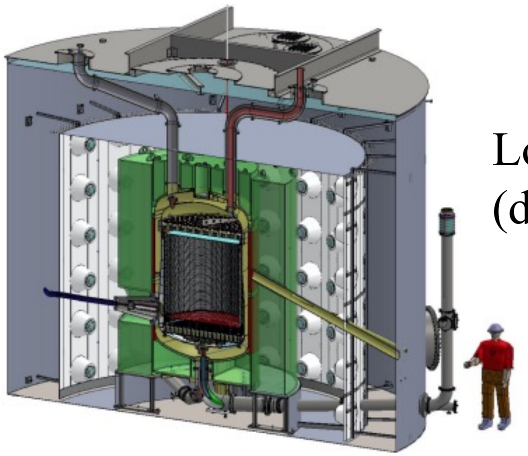
Particle Data Group (2018)



Low mass WIMP
(detector mass : 24 g)



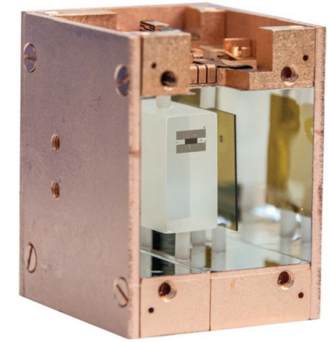
J. Low Temp. Phys. (2020) 199:537-555



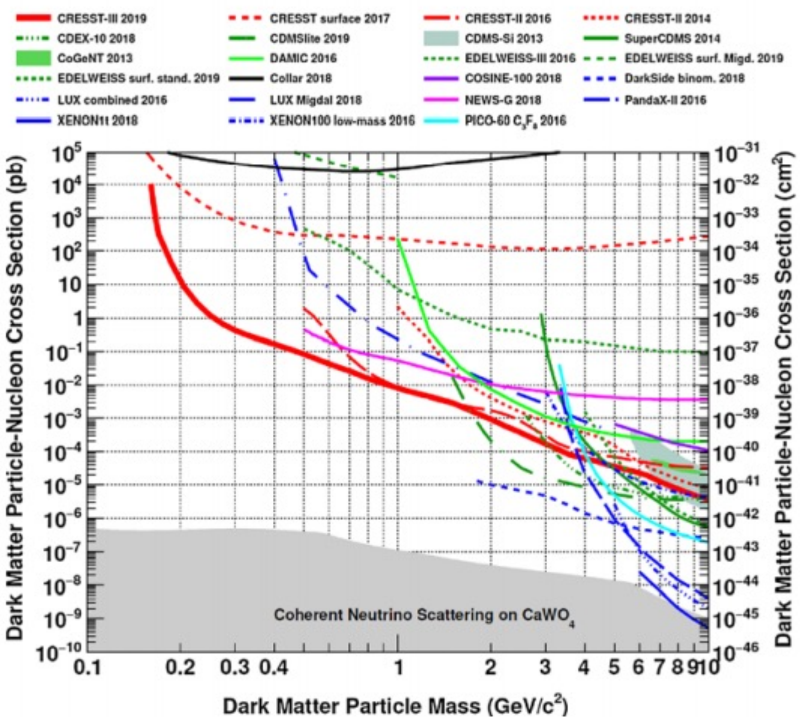
Low cross section WIMP
(detector mass : 5.6 t)

PHYS. REV. D 101, 052002 (2020)

CRESST-III results



Spin-Independent



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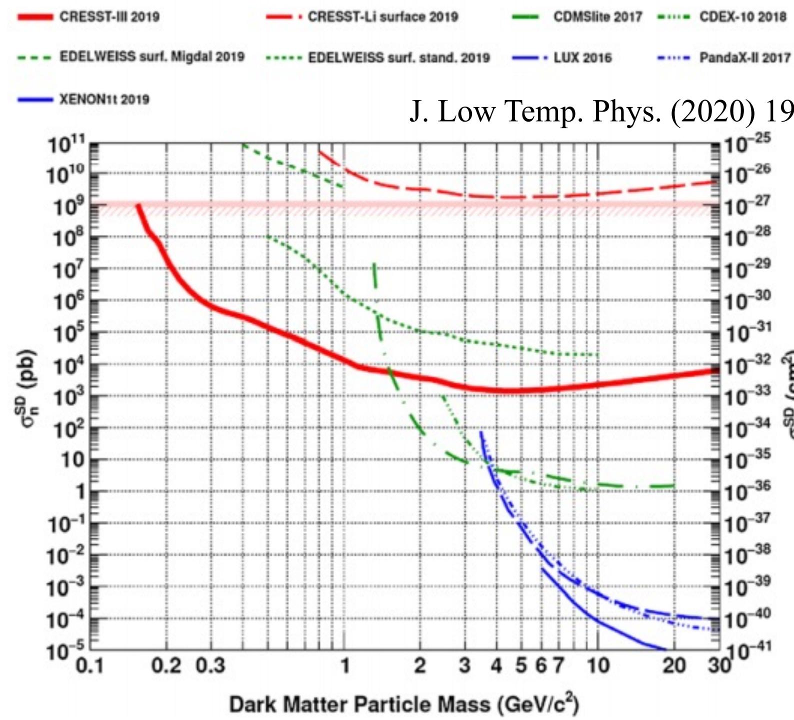

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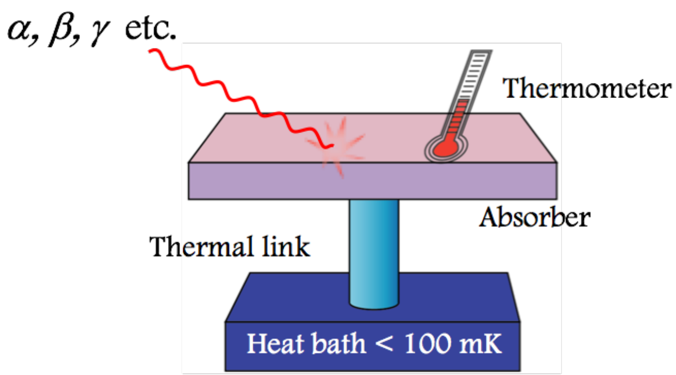
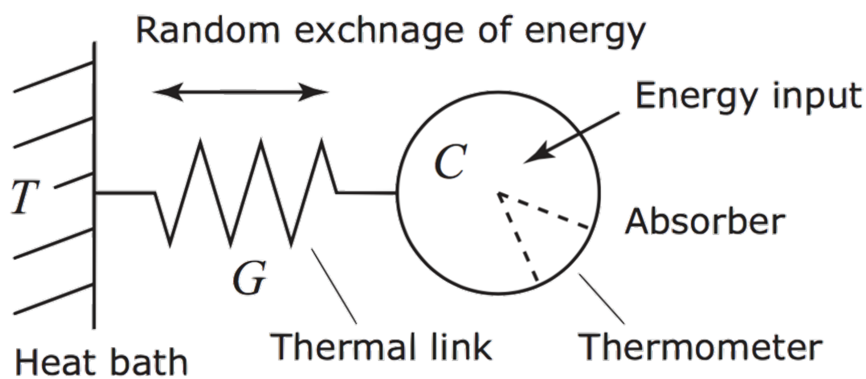
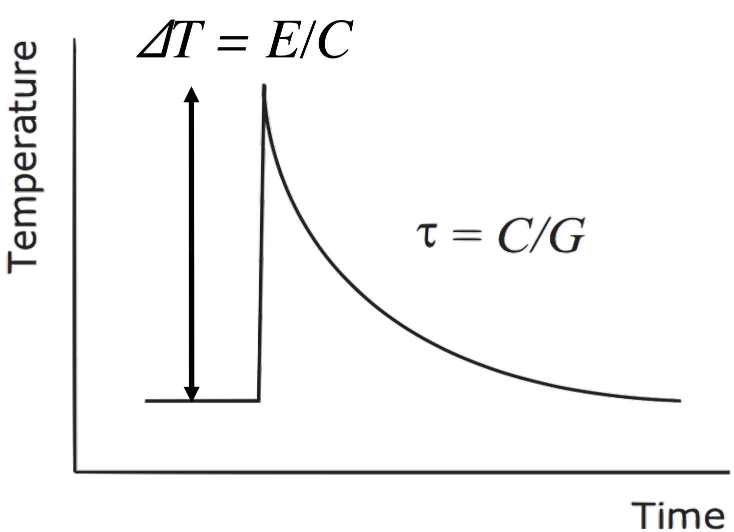
- ✓ The standard dark matter halo model (ρ_{DM} = 0.3 (GeV/c^2)/cm^3, v_Θ : 220 km/s, v_{esc} = 544 km/s)
- ✓ 2.39 kg days data (24 g $CaWO_4$, 5 months data).
- ✓ Spin-Dependent results is calculated witn ^{17}O (neuclear spin, J=5/2 , natural abundance : 0.04 %)
- ✓ 30.1 eV trigger and analysis threshold.

Low temperature detector







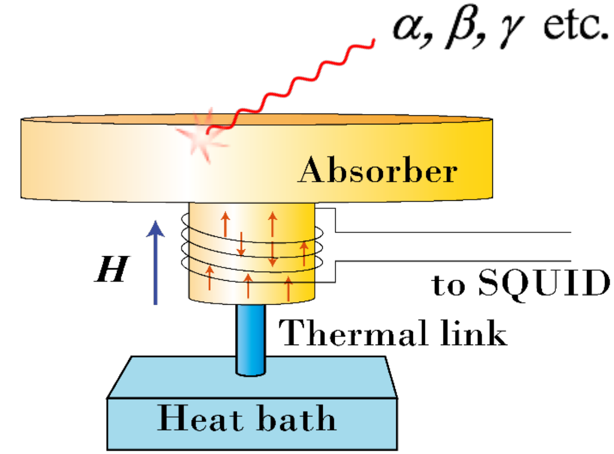
- Ideal connection of absorber and thermometer
- Electronic specific heat : $C_e \propto T$
- Lattice specific heat : $C_l \propto (T/\theta_d)^3$

Metallic Magnetic Calorimeter

(MMC)

- **Paramagnetic material with superconducting measurement circuit**

↯ δE : Occurrence of energy absorption in absorber.

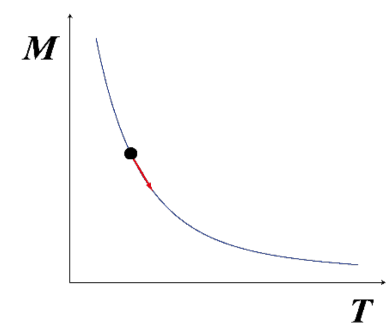


↪ $\frac{\delta E}{C_{tot}} \propto \delta T$: Temperature change.

↪ $\frac{\partial M}{\partial T}\frac{\delta E}{C_{tot}} \propto \delta M$: Magnetization change of paramagnet.

↪ $\delta M \propto \delta \Phi$: Magnetic flux change affecting SQUID.

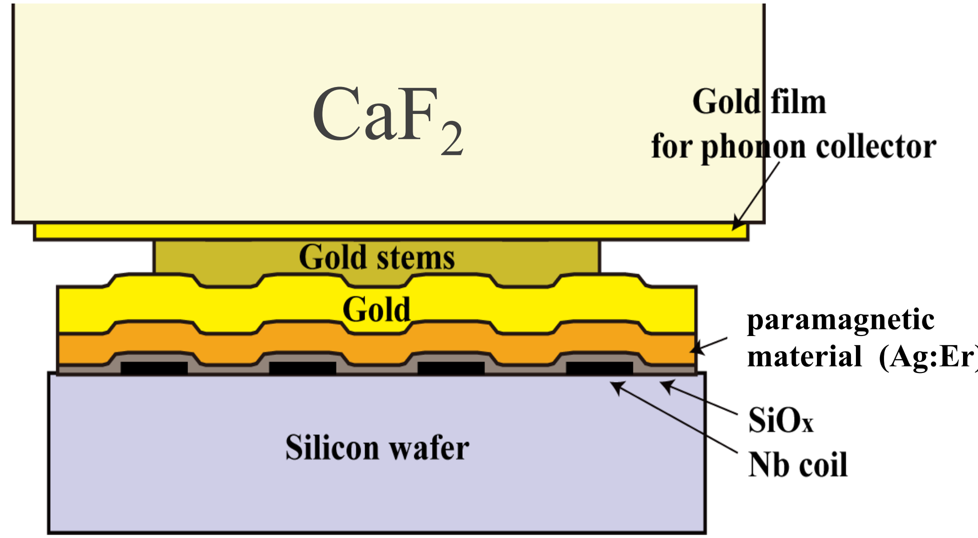
↪ $\delta \Phi \propto \delta V$: Voltage change in SQUID.

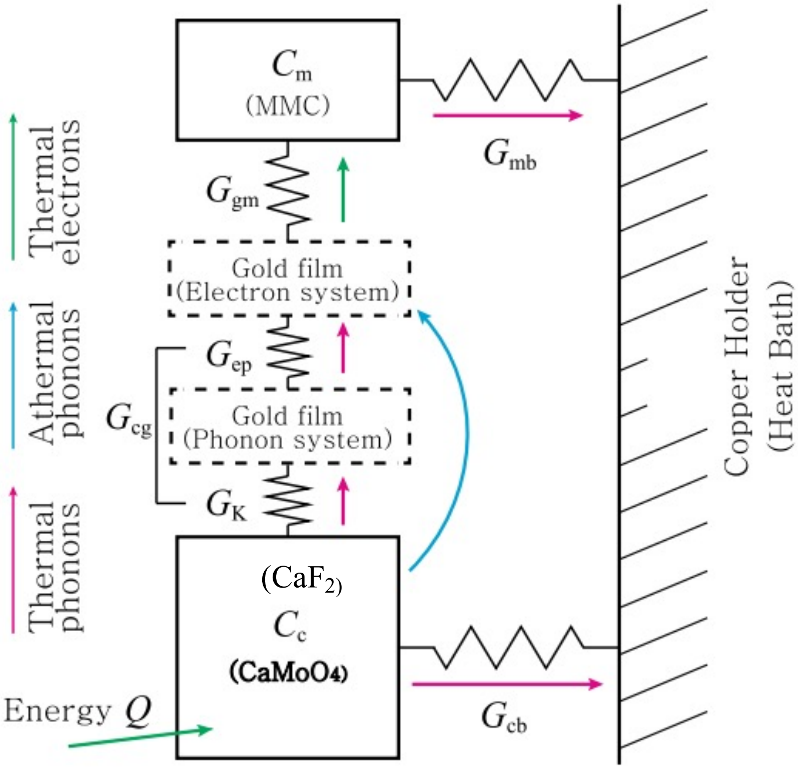


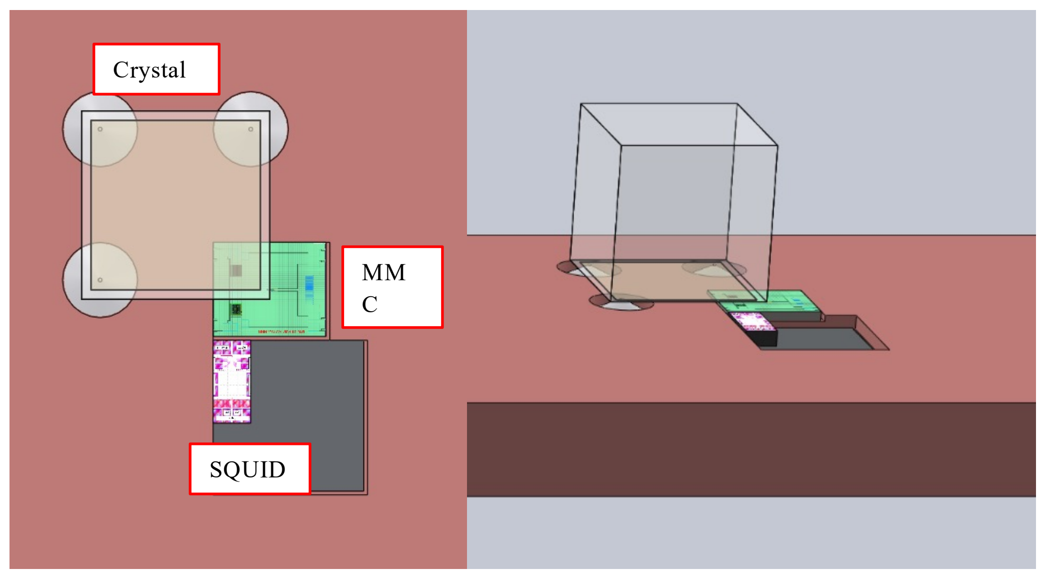
CaF_2 scintillation crystal

- ✓ The scintillation wav length has a peak at 280 nm (4.4 eV)
- ✓ The absolute light yield is 17 photons/keV (7.6% efficiency) for electric recoil event.
- ✓ Assuming the quenching for CaF2 is about 11 % (Eu doped CaF2), 1.8 photons/keV (1 photon/556 eV) will be emitted for nuclear recoil event.
- ✓ The event separation will be very challenge for below 556 eV events, even though using single photon measurement.
- ✓ The ^{19}F has natural abundance 100 % , low Z number and ½ nuclear spin which can be also used axially coupled dark matter.

Detector design



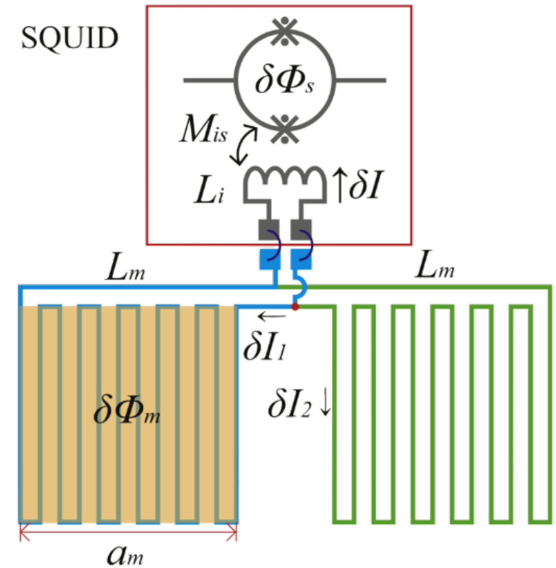




Relative signal size about SQUID

$$\delta\Phi_s = M_{is}\delta I = \frac{M_{is}}{L_m + 2(L_i + L_w)}\delta\Phi_m$$

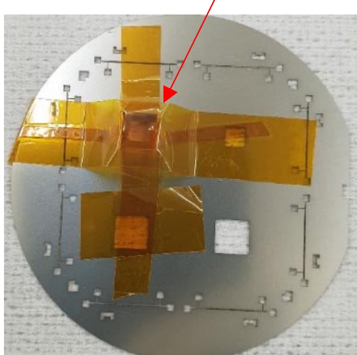
Supercond. Sci. Technol. **30** (2017) 084005 (7pp)

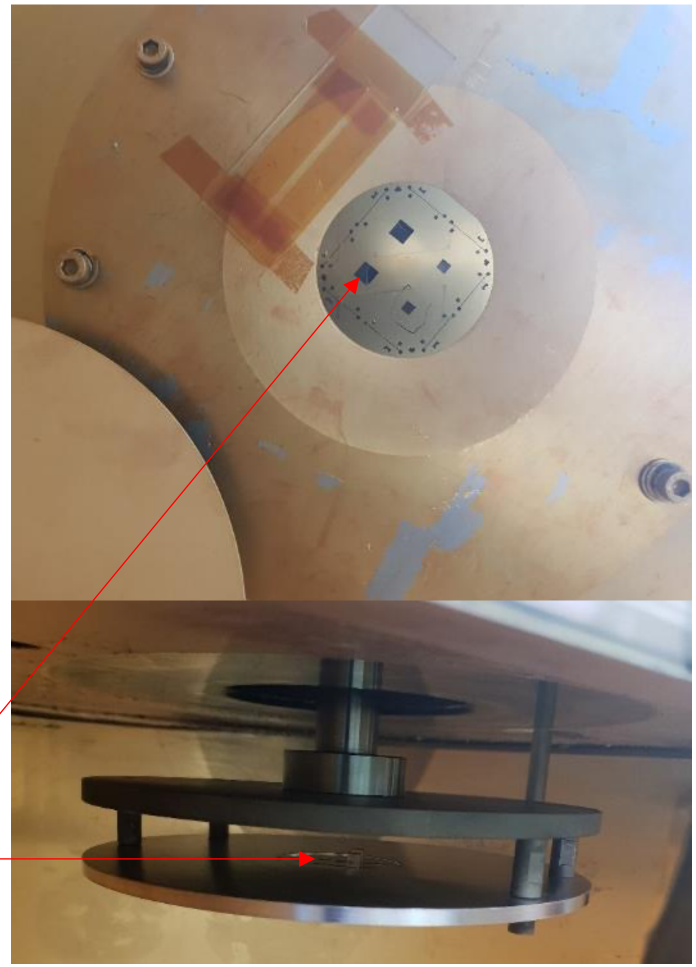


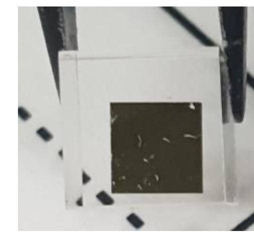
SQUID	L_i	$1/M_{is}$	Relative signal size		
			L_m : 32 nH	L_m : 8 nH	L_m : 2.88 nH
CE1K2 (IPHT)	10 nH	1.6 $\mu A/\Phi_0$	1	1.82	2.21
VC1ABlue (IPHT)	4.5 nH	6 $\mu A/\Phi_0$	0.34	0.78	1.08
X114 (PTB)	2 nH	5.3 $\mu A/\Phi_0$	0.43	1.22	1.99
XS116 (PTB)	27 nH	2.3 $\mu A/\Phi_0$	0.42	0.59	0.64
SQ3006 (Star Cryogenics)	32.3 nH	6 $\mu A/\Phi_0$	0.15	0.19	0.21

crystal preparation

Crystal

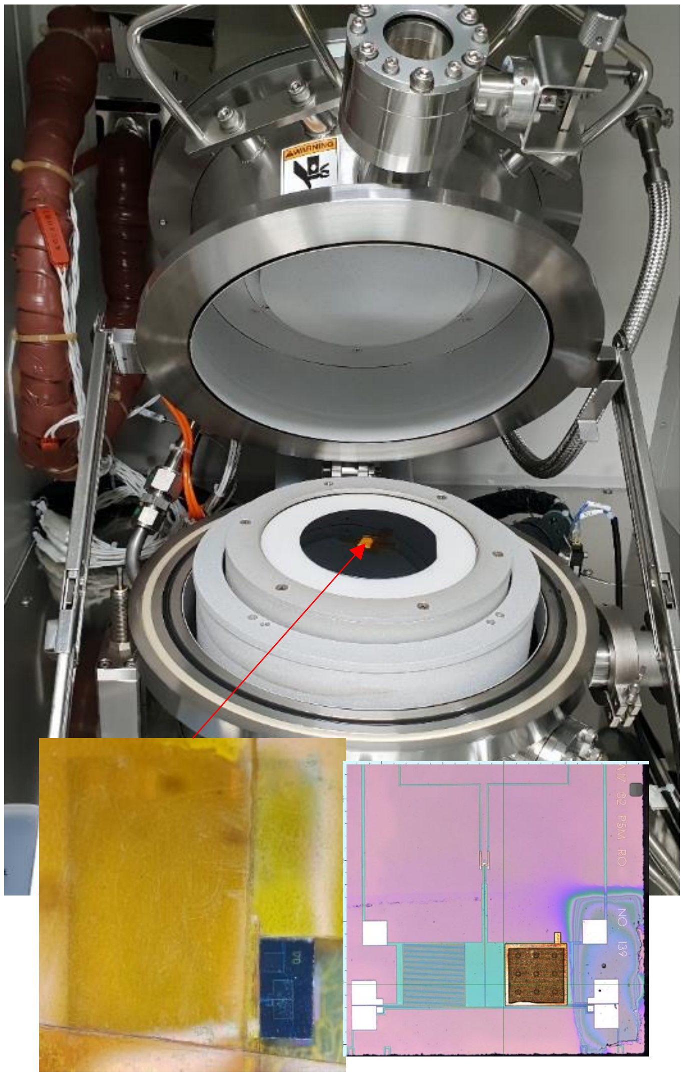


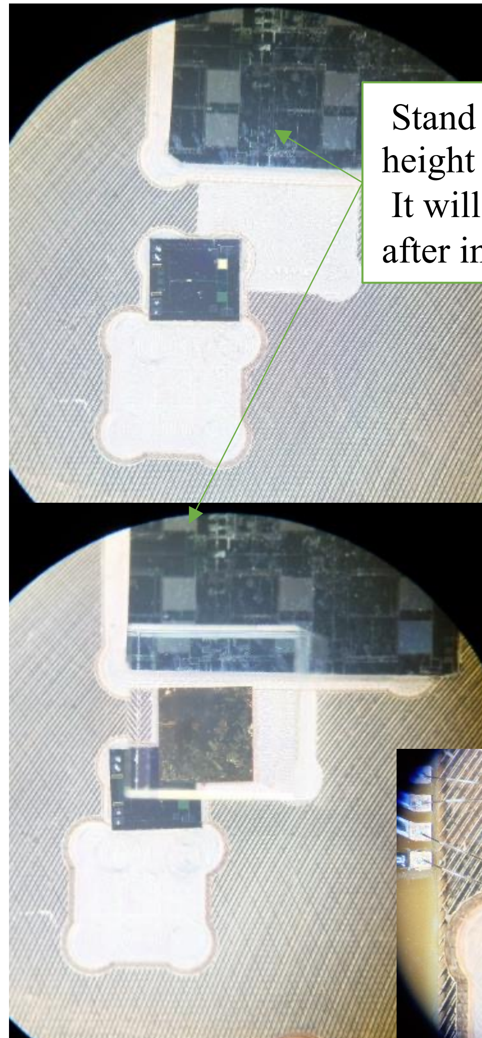




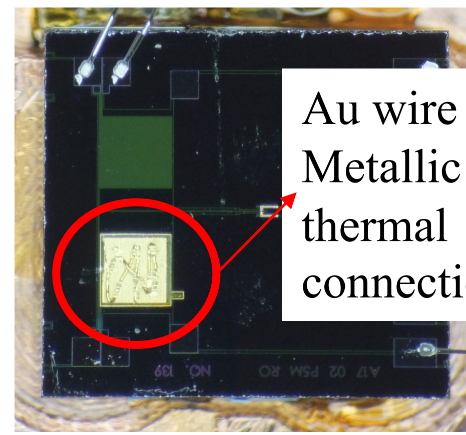
Crystal : CaF_2
Size : 5x5x5 mm^3
Mass : 0.3975 g
Phonon collector size
Area : 3x3 mm^2 & height : 300 nm

Sensors preparation

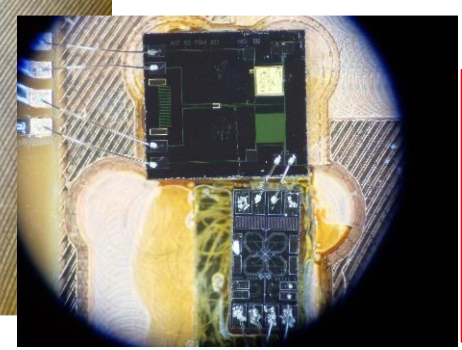




Stand to eliminate height difference.
It will be removed after install the crystal



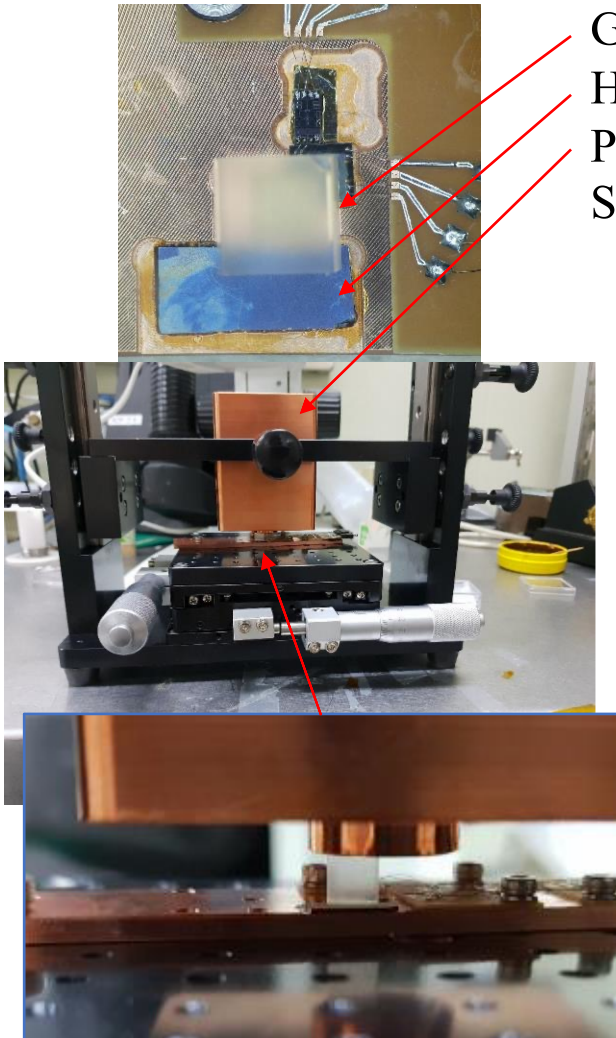
Au wire for Metallic thermal connection



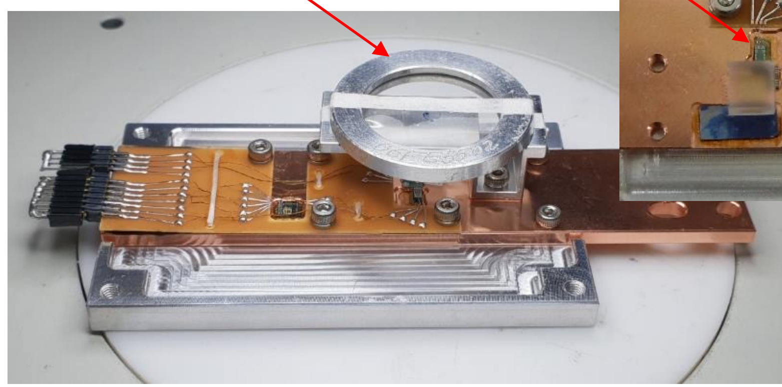
MMC
Material : Ag:Er
L_m : 8 nH

SQUID
CE1K2 (IPHT)

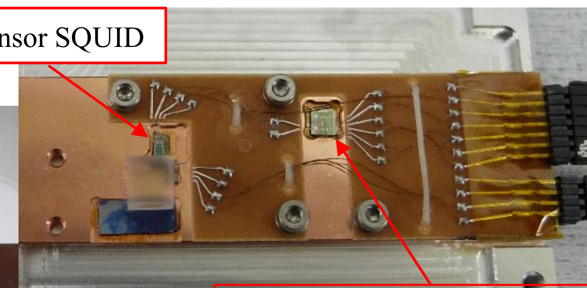
Experimental set up



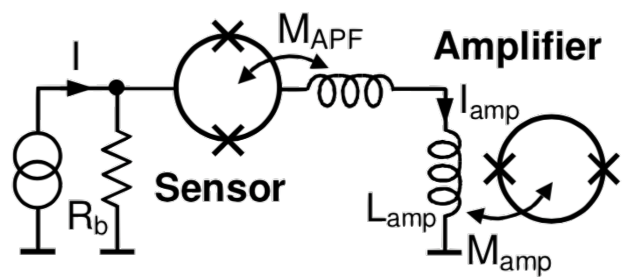
Glue : Ge vanish (for fixing)
Height matching plate : Si wafer piece
Pressing with 1.5 kg (for Metallic thermal connection)
Source : ^{55}Fe



Sensor SQUID



Amplifier SQUID
X16F (PTB)
16-SQUID array
The SQUID gain is increased 12 times

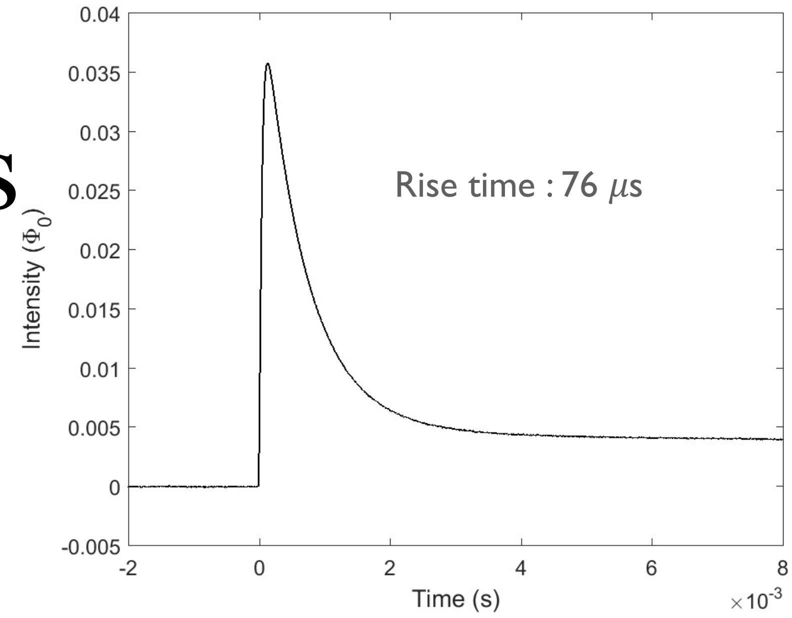


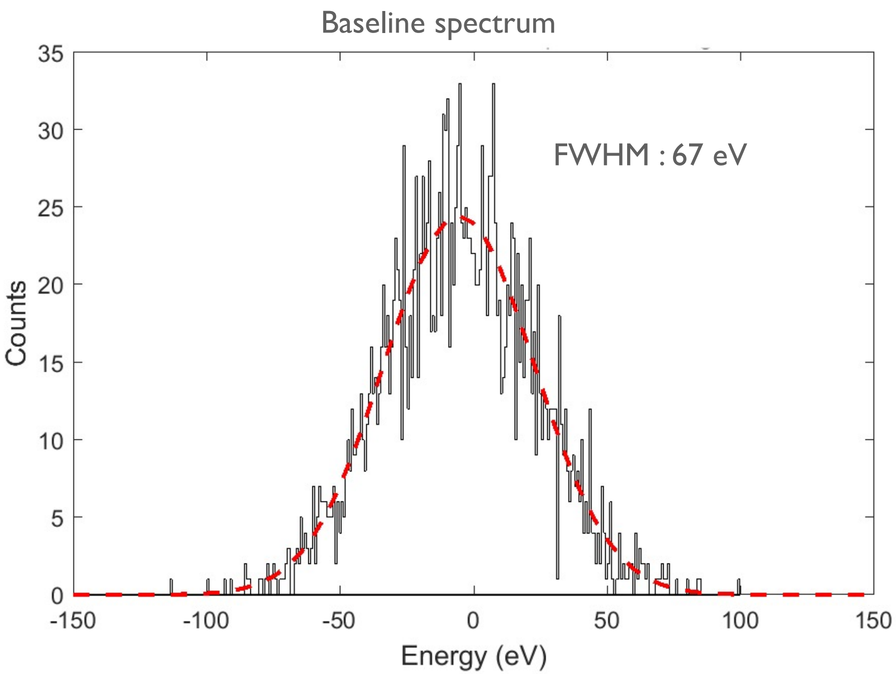
$$G_\Phi = \frac{M_{amp}}{R_b/V_\Phi + M_{dyn} - M_{APF}}$$

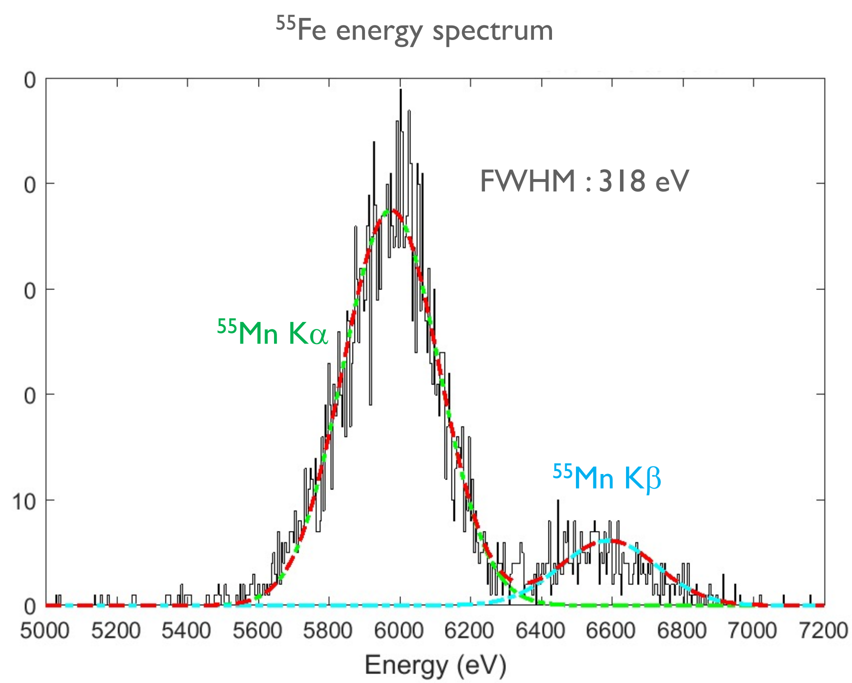
with $M_{dyn} = R_{dyn}/V_\Phi$

Paper 5EB01 at ASC2006, to appear in IEEE Trans. Appl. Supercond. 17 (2007)

Experimental results

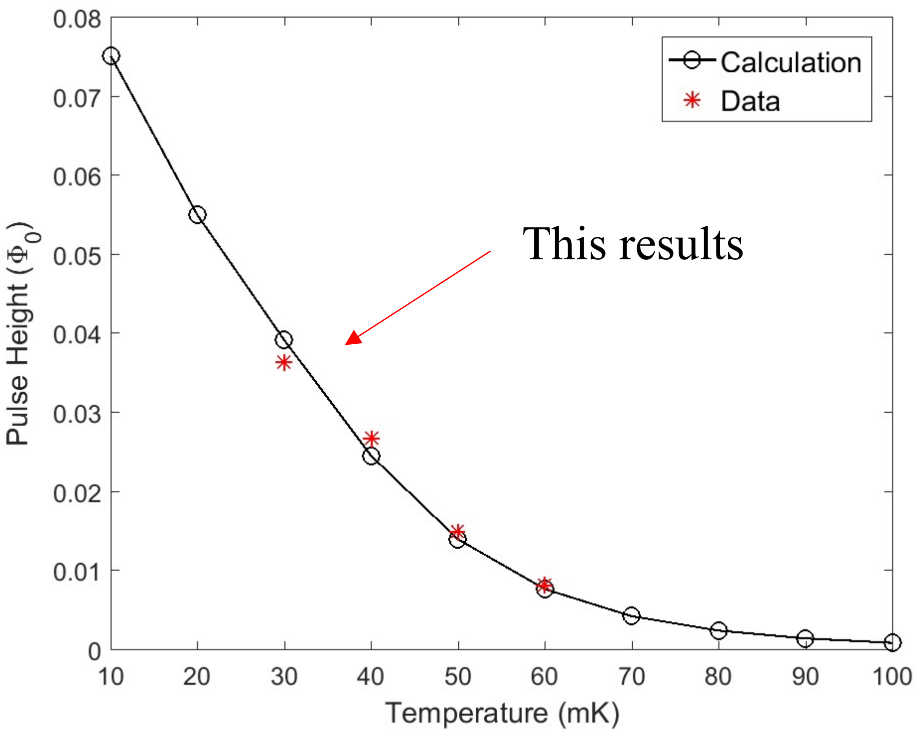


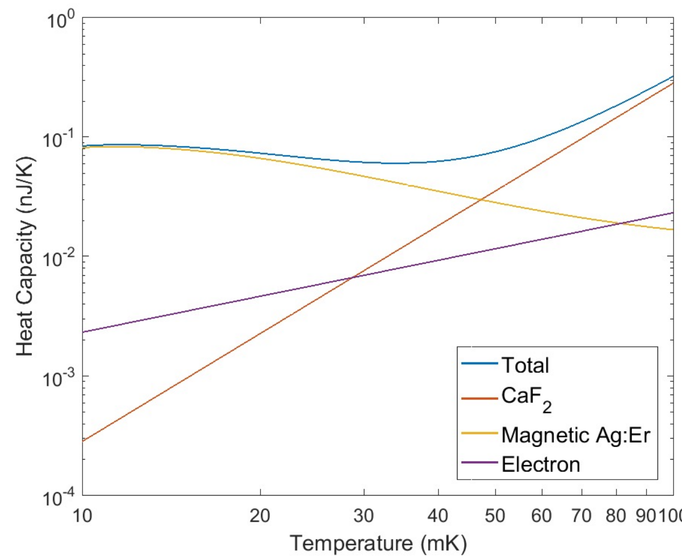


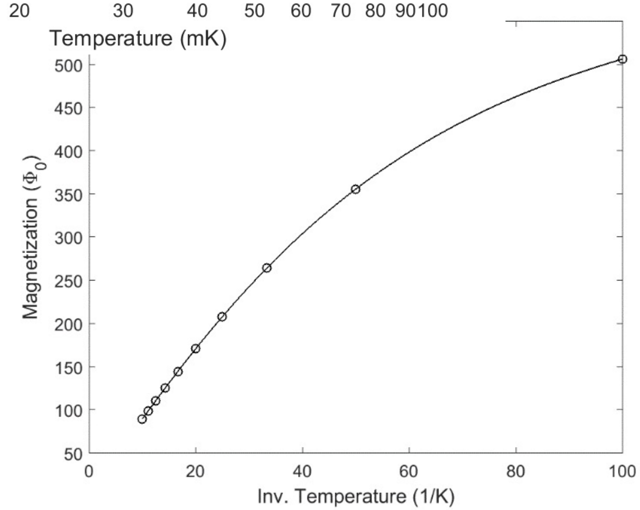


Pulse height calculation (scaled to data)

^{55}Fe Kα peak signal (5.9 keV)







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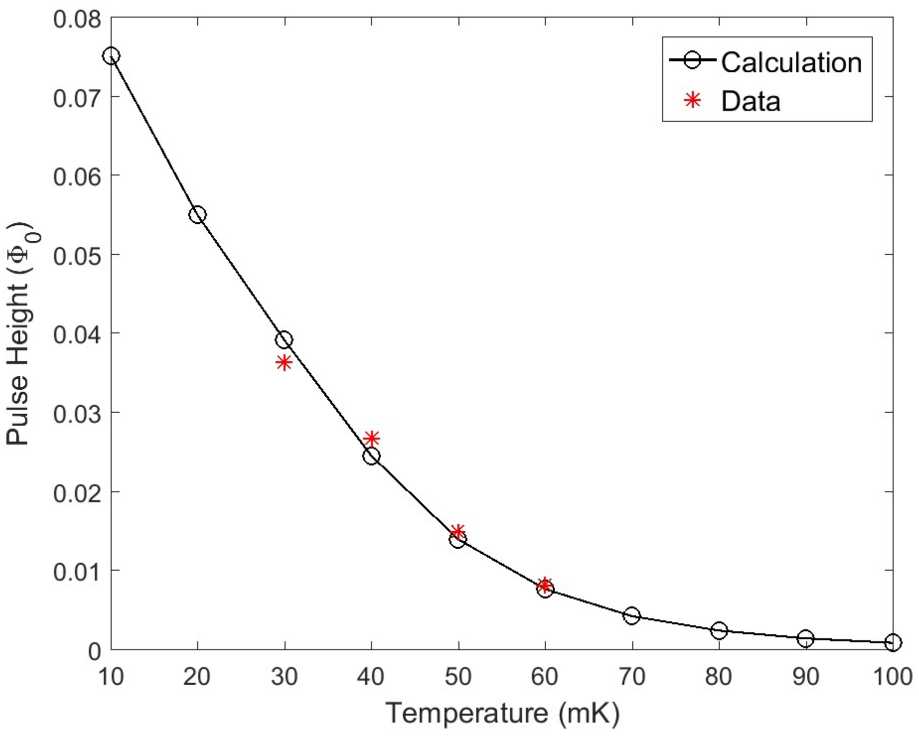
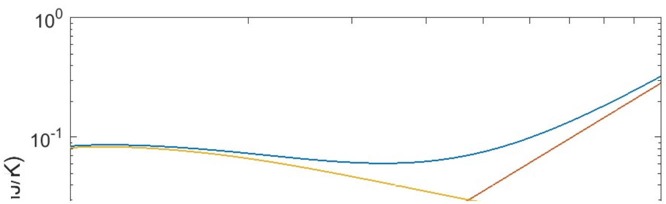
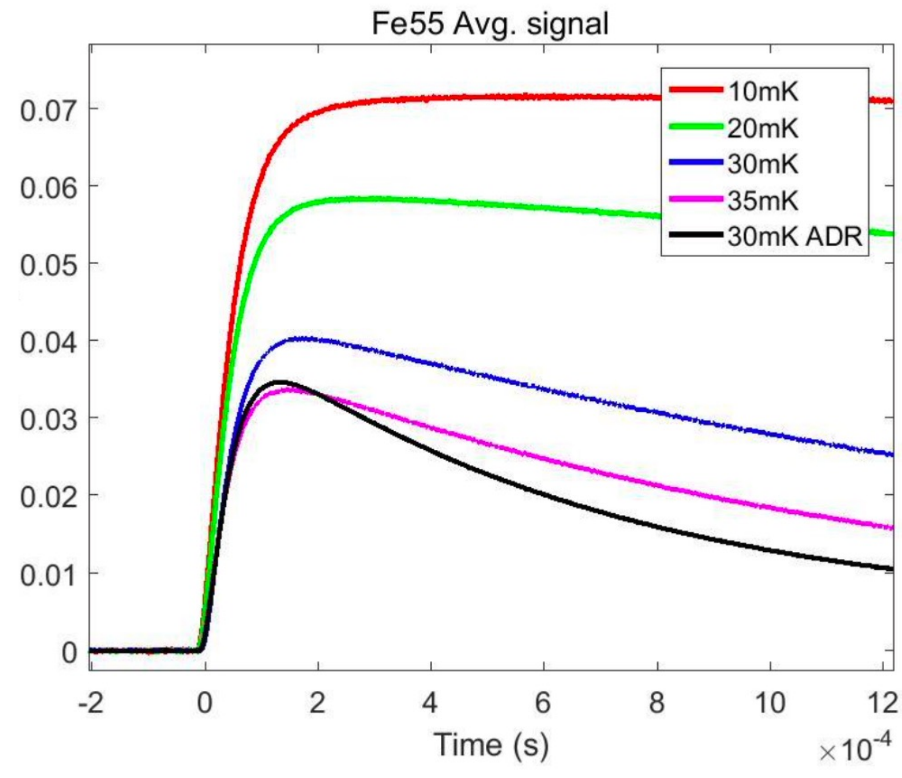
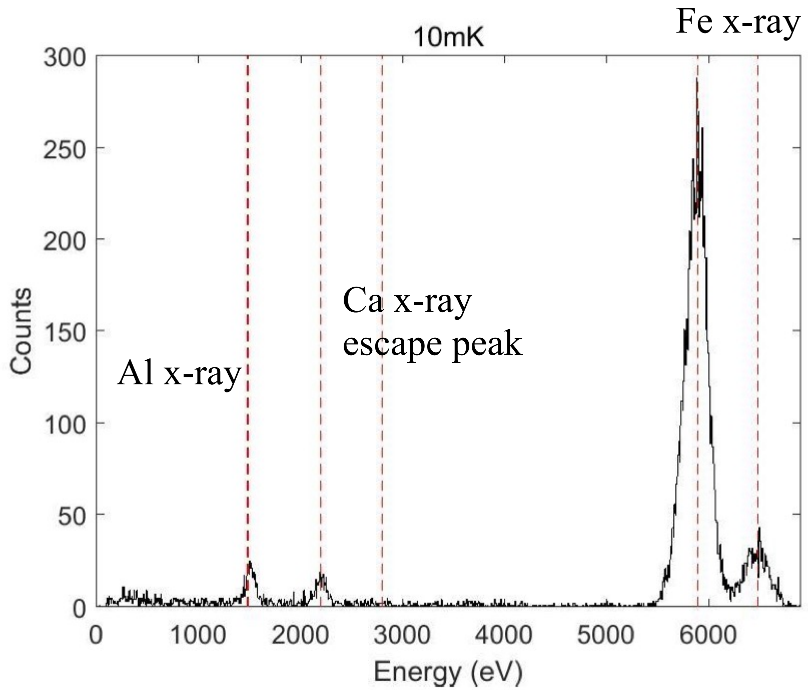
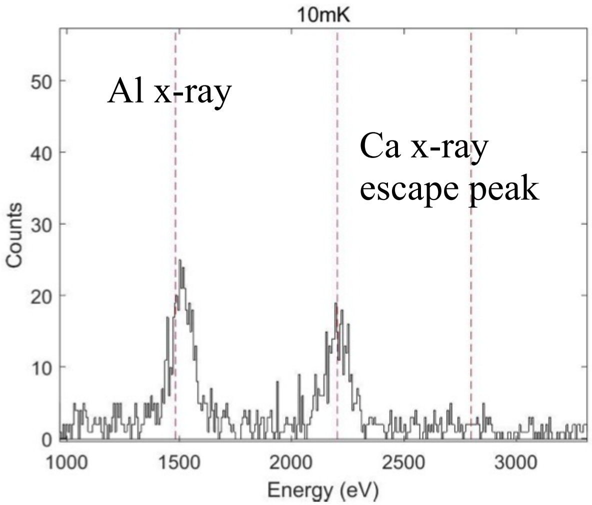


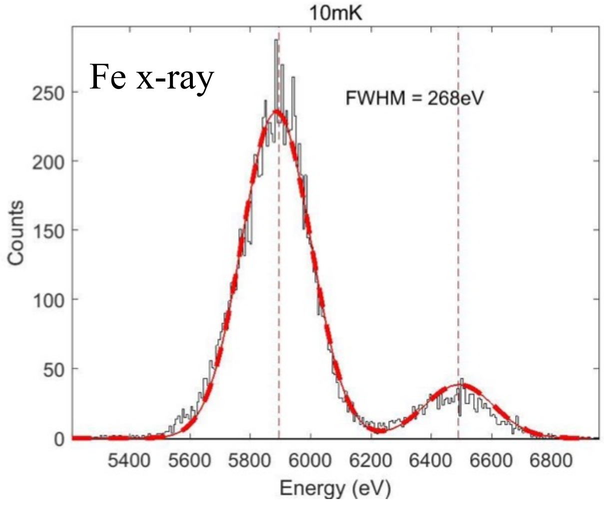




10 mK Results (Preliminary)







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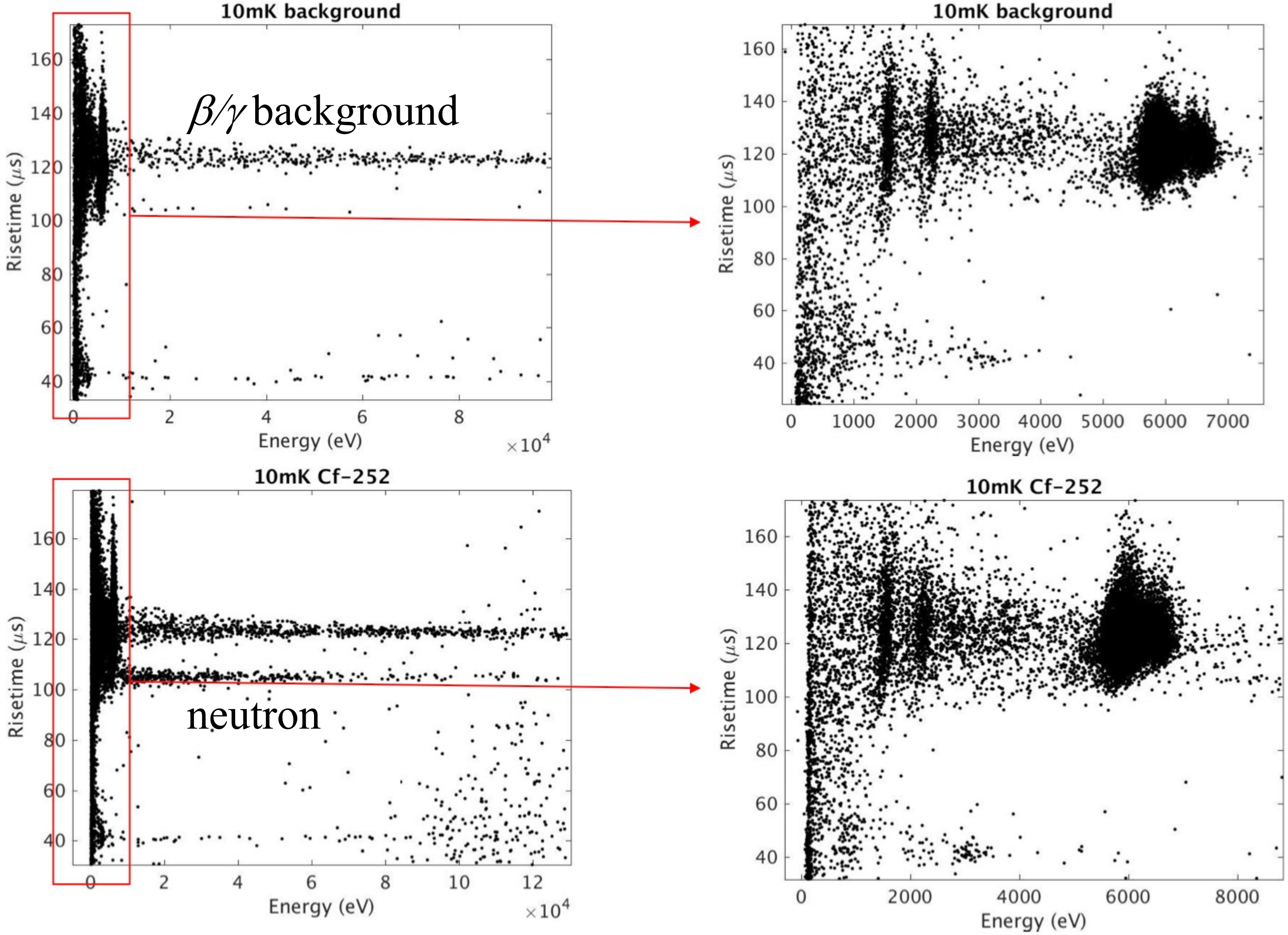

Summary & Conclusion

- ✓ The low threshold detection system was firstly studied with 5x5x5 mm^3 CaF_2 crystal for the low mass WIMP study.
- ✓ ~100 μs rise time can be achieved by direct crystal attachment to the MMC sensor.
- ✓ We could check the potential of CaF_2 cryogenic detector on tabletop experiment for low mass WIMP search.

Thank you