R&D of Hf-STJ as FIR single-photon spectrometer for COBAND

TGSW2022 session 5-9

Universe Evolution and Matter Origin

online

Sep. 27, 2022

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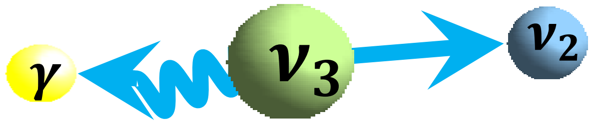
for the COBAND collaboration

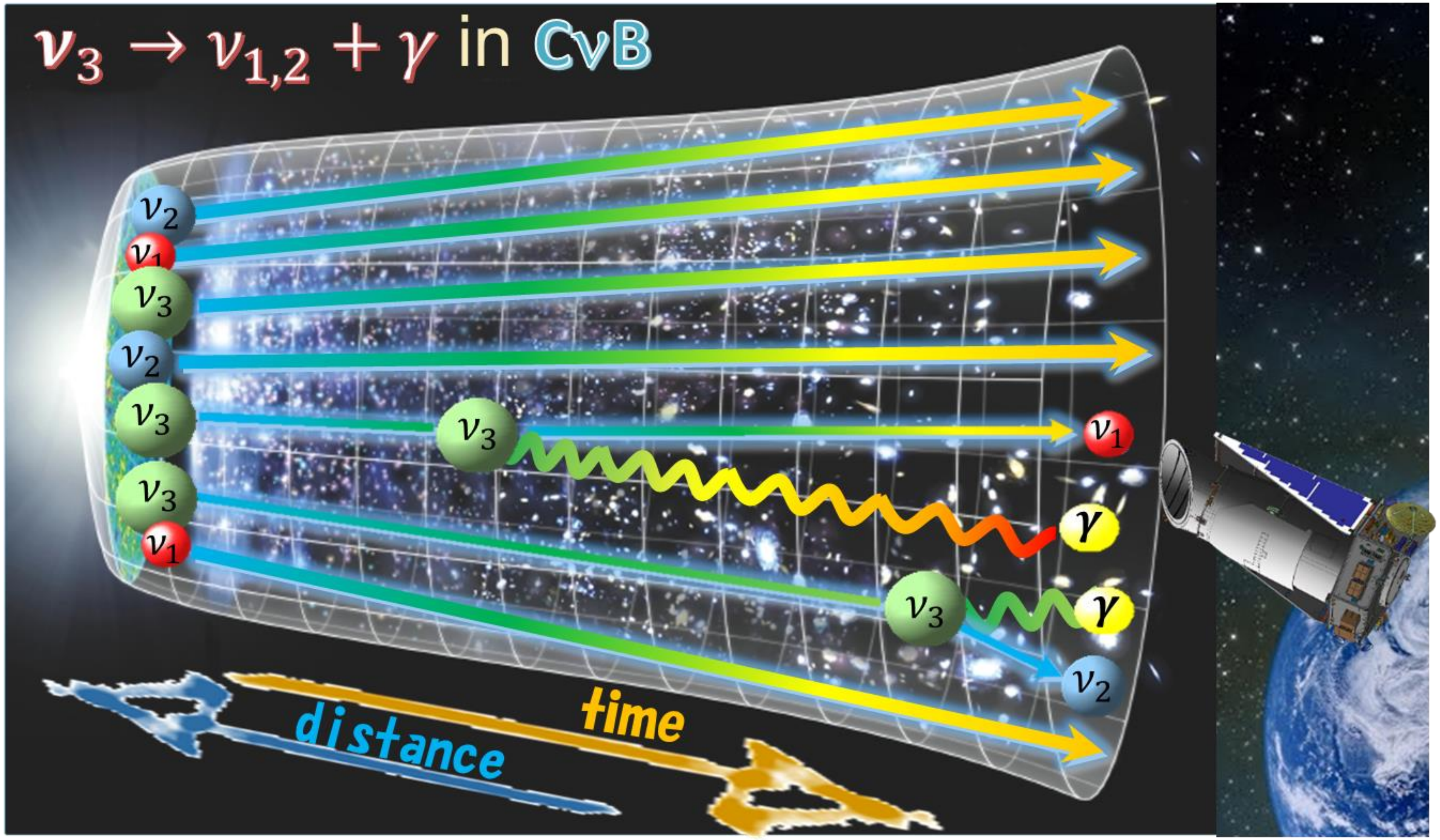
COBAND(Cosmic Background Neutrino Decay)

Search for Neutrino decay in Cosmic background neutrino

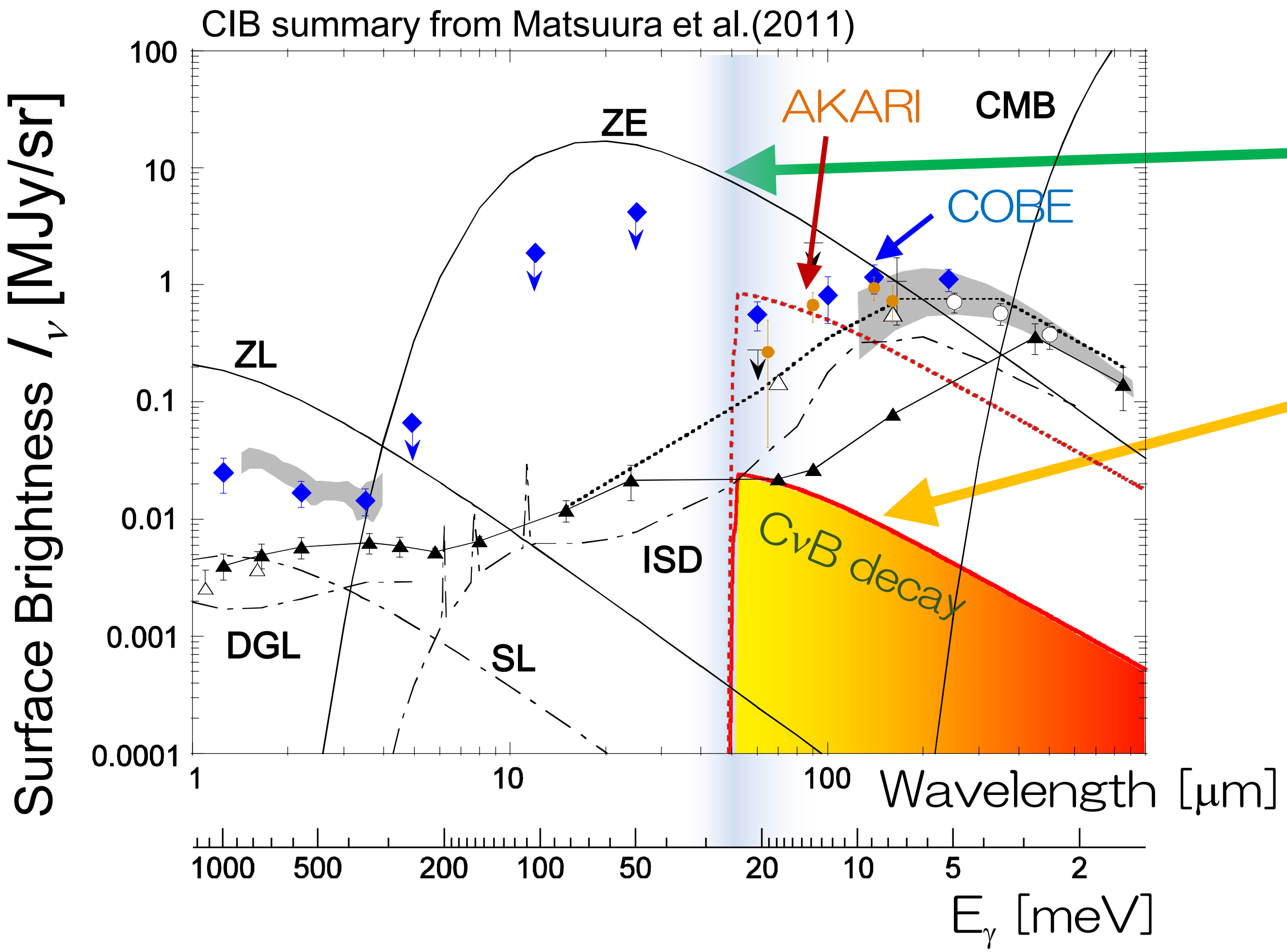
➔To be observed as FIR photons around λ~50μm



Neutrino Decay



Neutrino Decay signal and backgrounds



Zodiacal Emission

Expected Neutrino Decay signal

$\tau = 1 \times 10^{14}$yrs

$\boldsymbol{m_3 = 50\ \mathrm{meV}}$

Current experimental lower limit is 10^{12} yrs

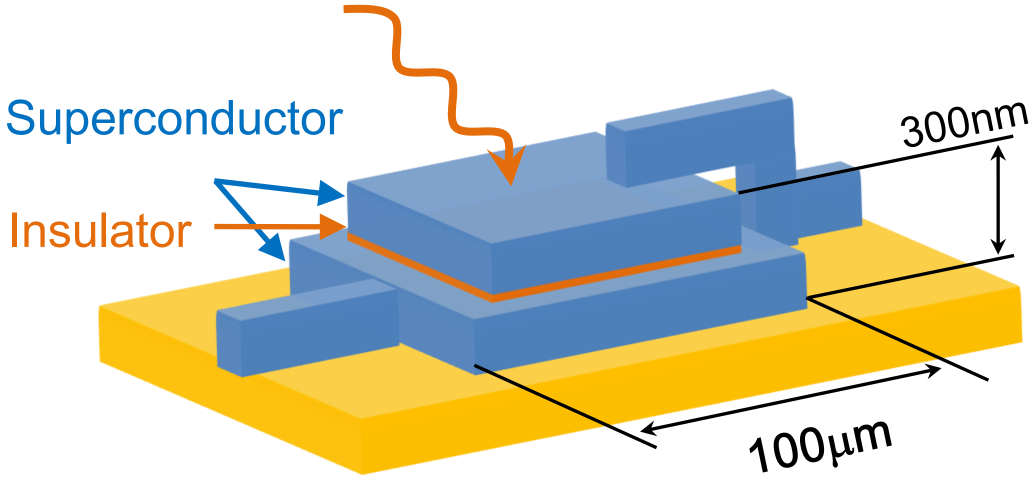
We can identify ν decay signal by highly precise measurement of photon energy spectrum around **λ~50μm**

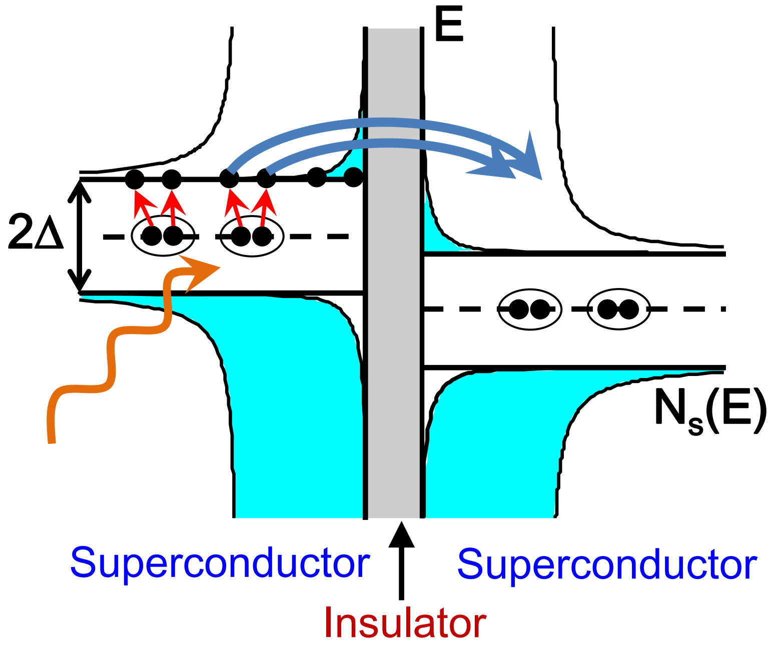
➔ Require for the detector to detect and measure single photon energy at **λ~50μm**

Superconducting Tunnel Junction (STJ)

Superconductor / Insulator /Superconductor (SIS)

Josephson junction device





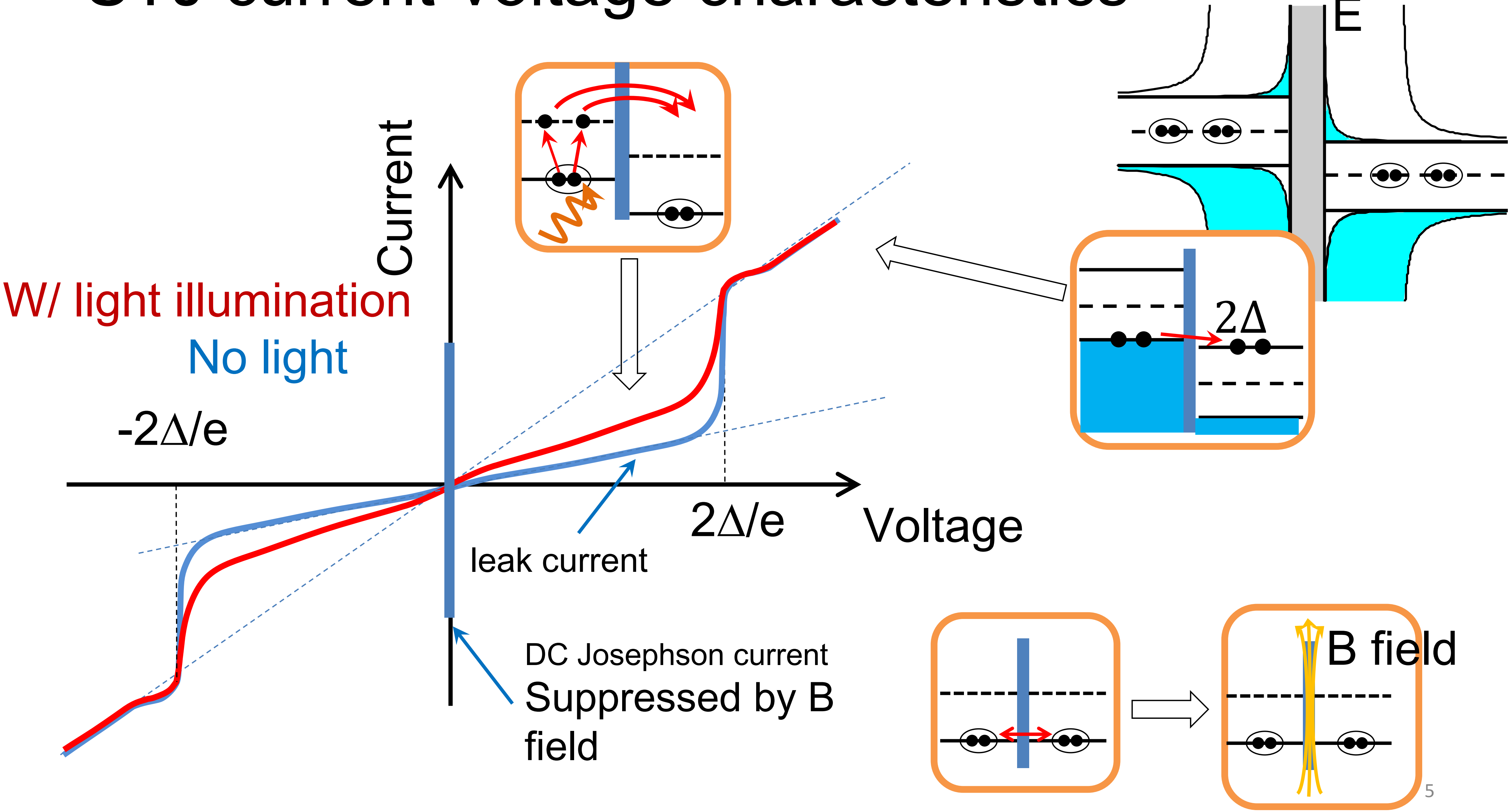
Δ: Superconducting gap energy

A constant bias voltage (|V|<2Δ/e) is applied across the junction.

A photon absorbed in the superconductor breaks Cooper pairs and creates tunneling current of quasi-particles proportional to the deposited photon energy.

- Much lower gap energy (Δ) than FIR photon ➔ Can detect FIR photon and measure its energy.

STJ current-voltage characteristics



STJ candidates

	Si	Nb	Al	Hf
Tc[K]		9.23	1.20	0.165
Δ[meV]	1100	1.550	0.172	0.020

Nb/Al-STJ

- Well-established and commonly used.
- Δ~0.6meV by the proximity effect from Al
- Operation temp. <400mK
- Back-tunnelling gain G ~10
- $N_{q.p.}$=25meV/1.7Δ×10~ 250 σ_E/E~10% for E=25meV (λ~**50**μ**m**)

➔ 25meV single-photon detection is feasible ideally.

➔ Candidate for the rocket experiments with diffraction grating.

Hf-STJ

- Not established as a practical photo-detector yet by any group
- $N_{q.p.}$=25meV/1.7Δ~ 735
- 2% energy resolution for a 25meV single-photon is achievable

➔ Spectrum measurement without a diffraction grating.

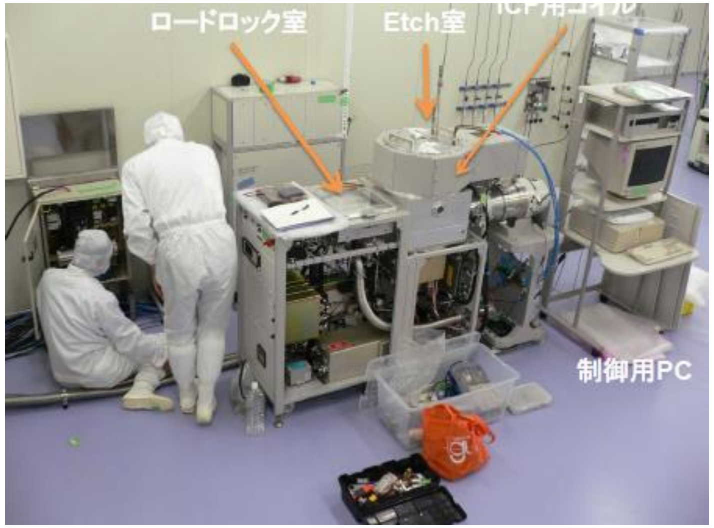
➔ Developing for a future satellite experiment

Superconducting device process equipment at KEK clean room

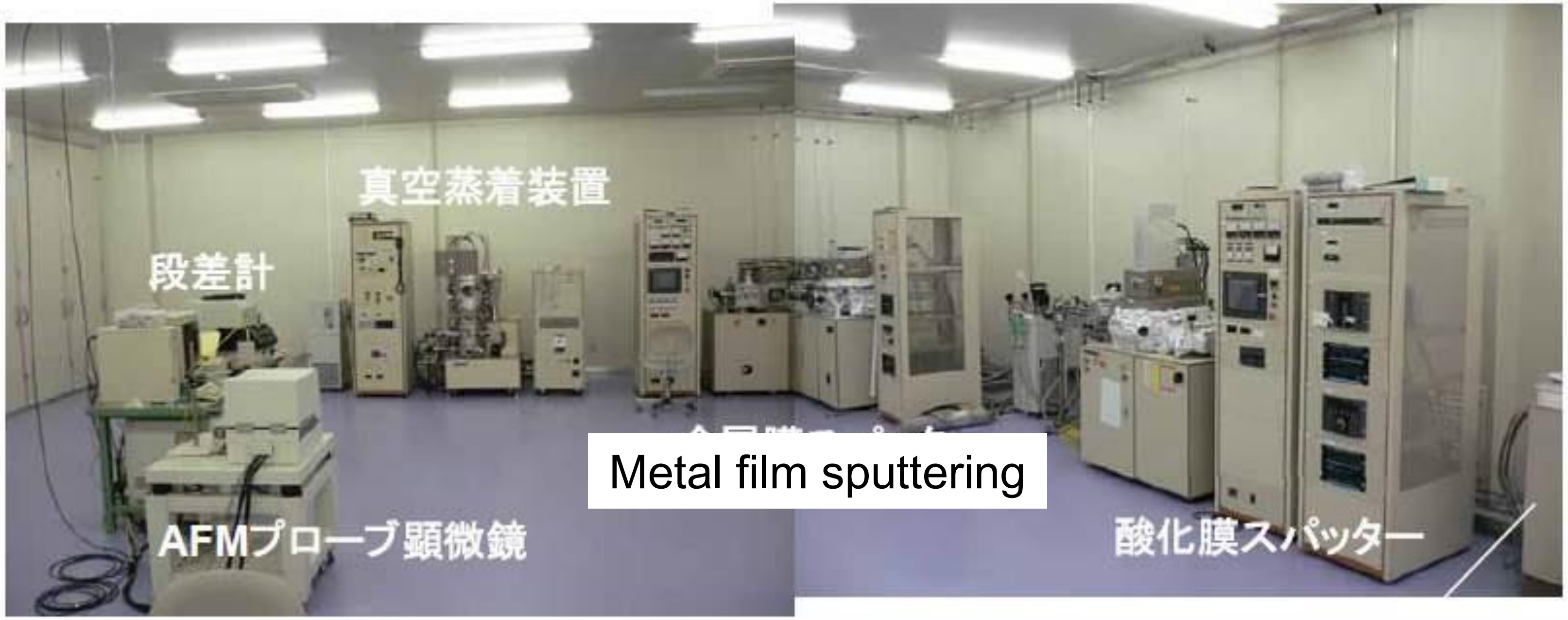
Hf-STJ samples are fabricated at KEK clean room by our group.

- Successful in etching Hf layer in 2008.
- Confirm SIS junction by Hf-HfOx-Hf in 2010.
- Confirm Hf-STJ response to visible light pulse in 2013.

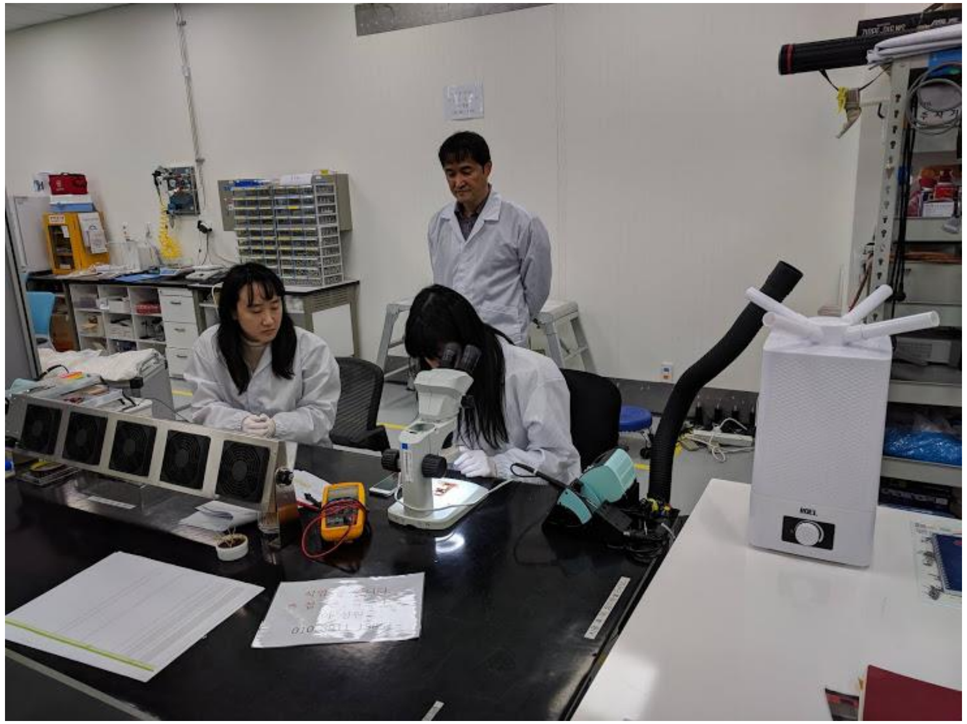
ICP-RIE

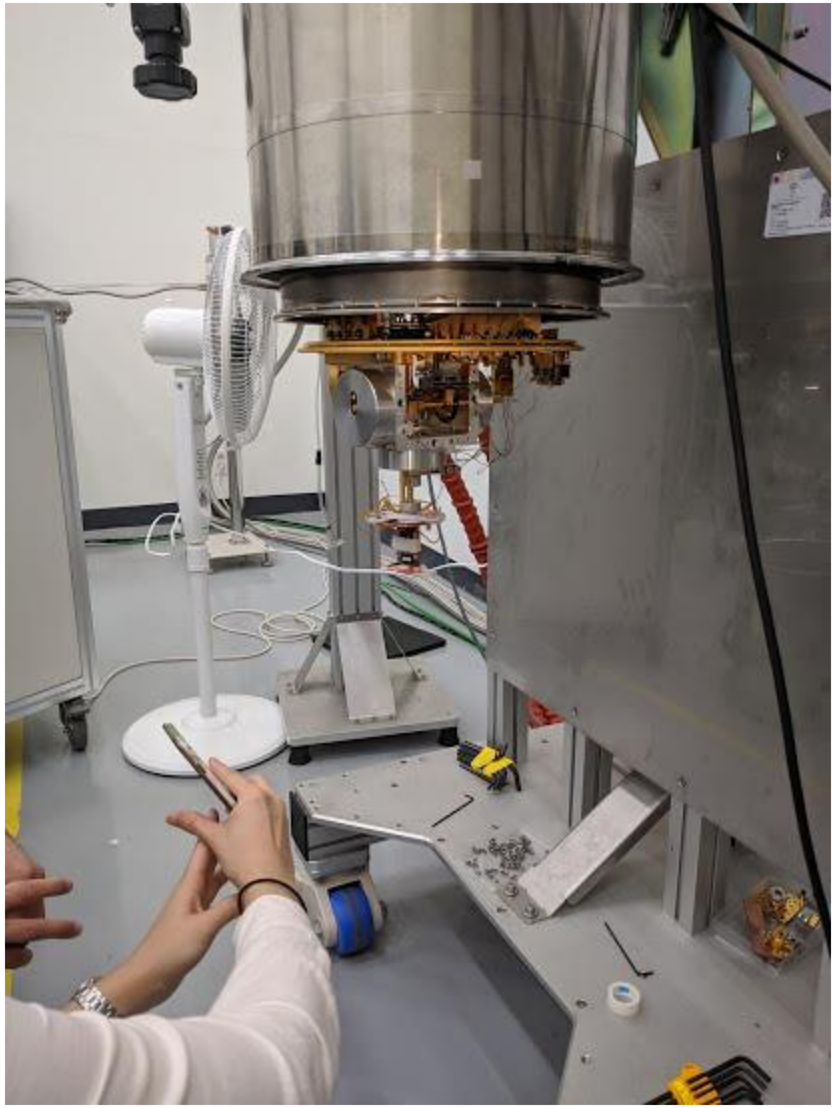


Aligner in yellow hat



X-ray illumination test at IBS CUP in Jun. 2019



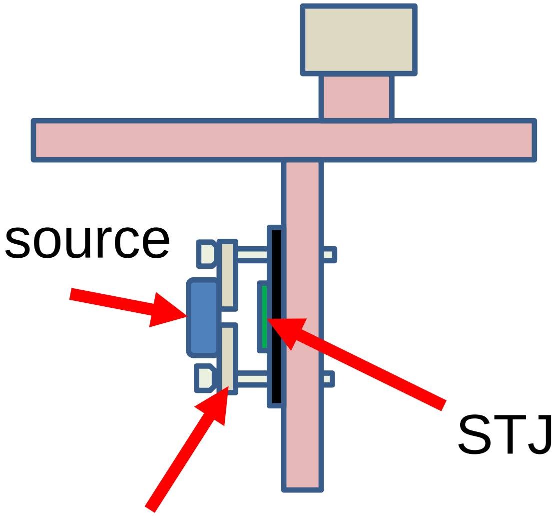


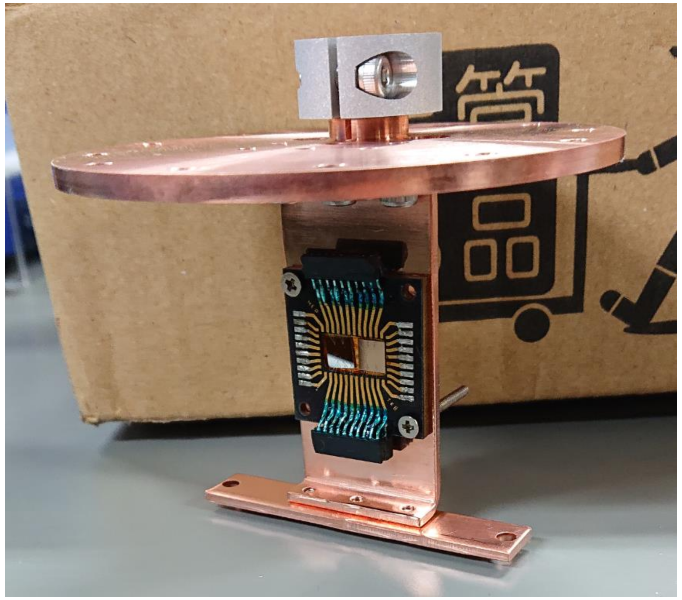
- Adiabatic Demagnetization Refrigeration (ADR) at temperature down to 30mK
- Hf-STJ I-V
- Hf-STJ response to X-ray photon (^{55}Fe)

X-ray illumination test at IBS CUP in Jun. 2019

On ADR cold stage

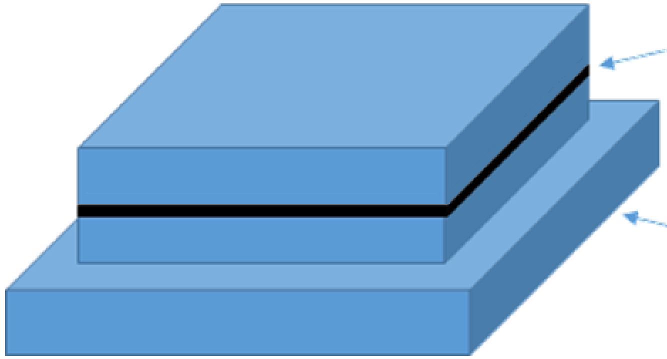
- STJ samples
- Cu collimator
- X-ray source (^{55}Fe) sealed in polyester tape
- Solenoid coil with persistent current switch

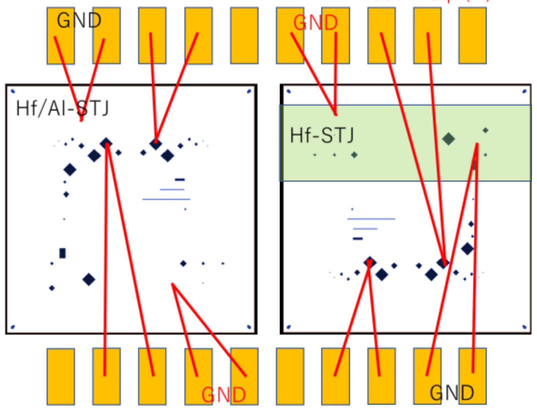


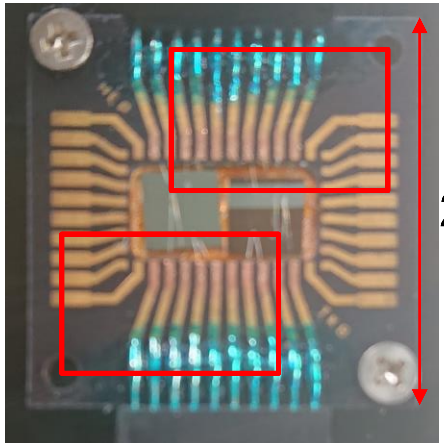


cold stage

200μm×200μm

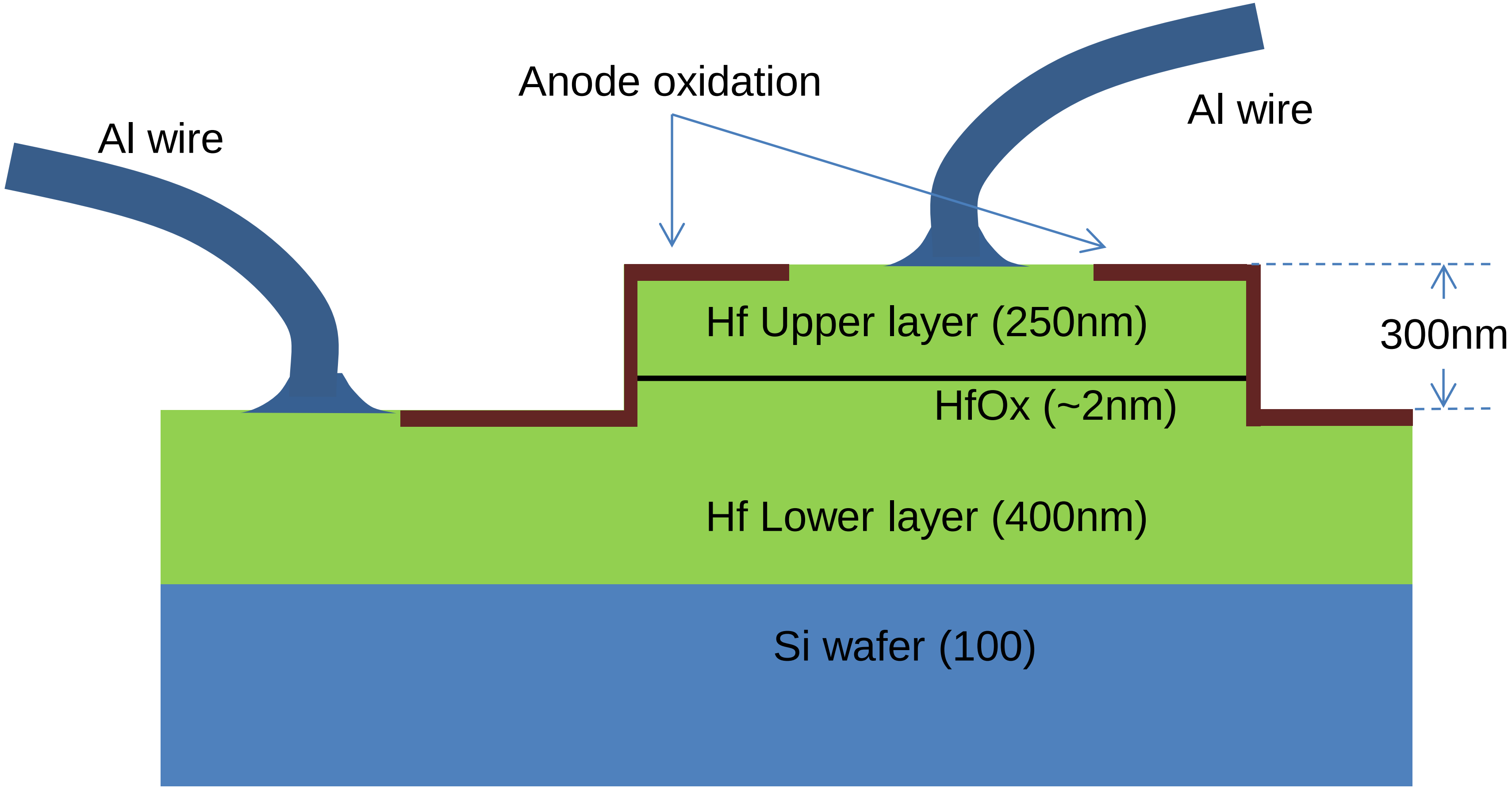




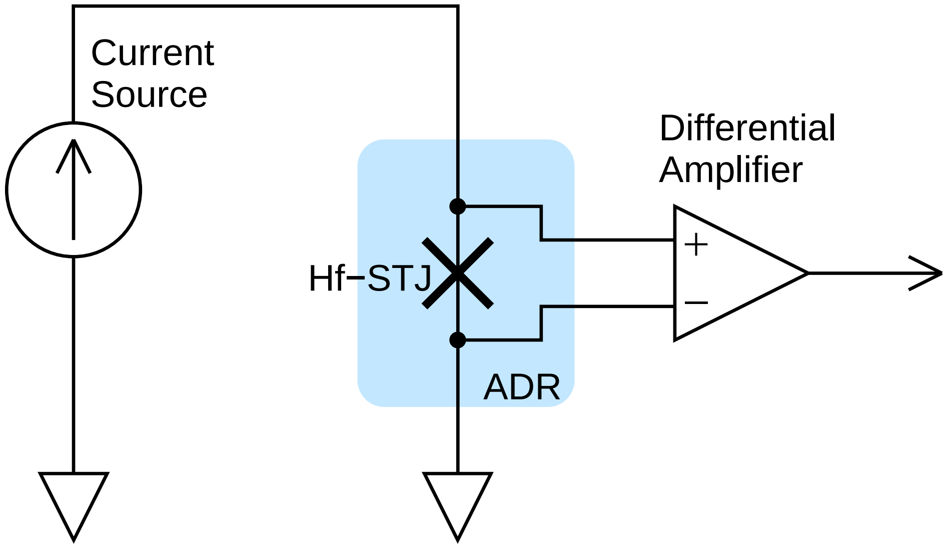


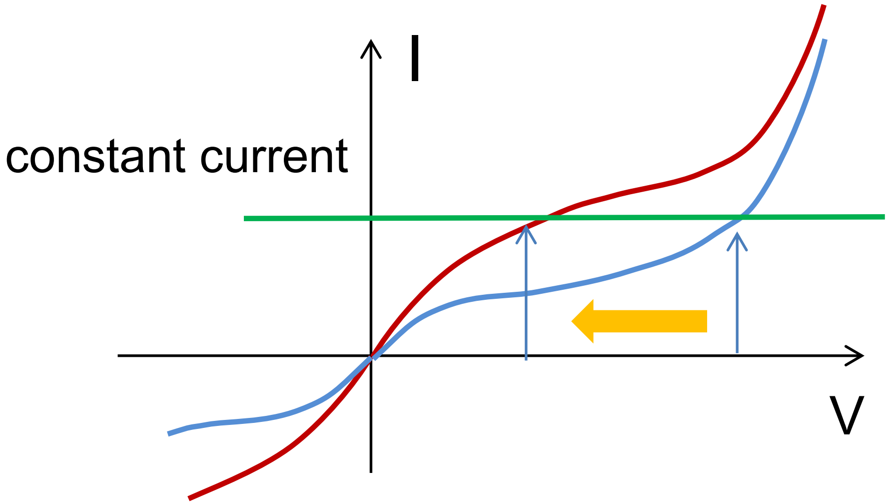
chip carrier

200μm sq. Hf-STJ sample under test



Setup for I-V curve and X-ray response measurements at the IBS CUP





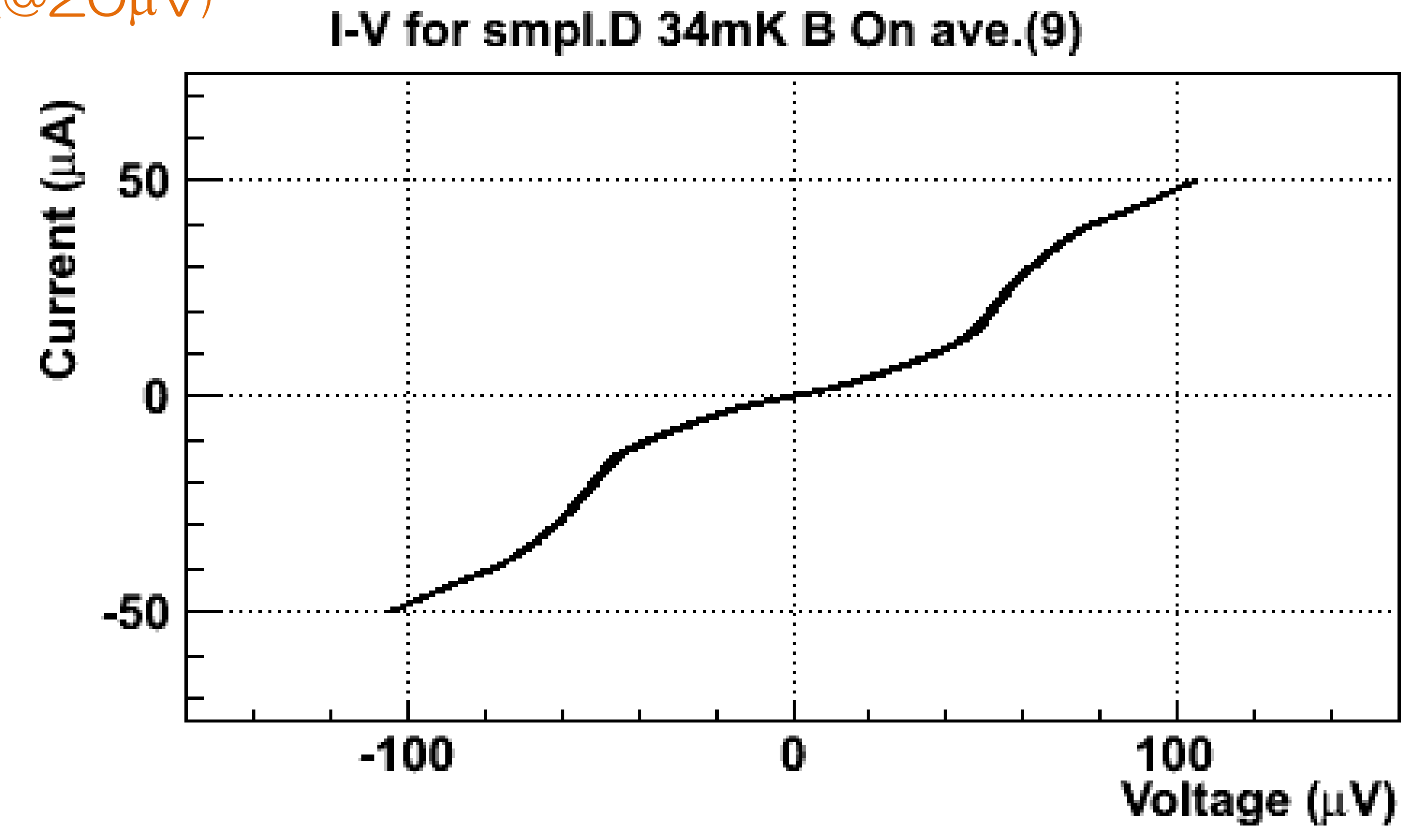
STJ I-V curve w/ light w/o light

- Sinusoidal current on STJ for I-V measurement
- Constant current on STJ for X-ray response measurement
- Voltage of STJ is read with differential amp. placed at room temp.
- X-ray signal is shown up as a negative pulse in STJ voltage.

I-V curve about 34mK w/ B field

200μm square Hf-STJ @ T~34mK

- Applied magnetic field ~10G on STJ
- Leak current of ~3μA(@20μV)



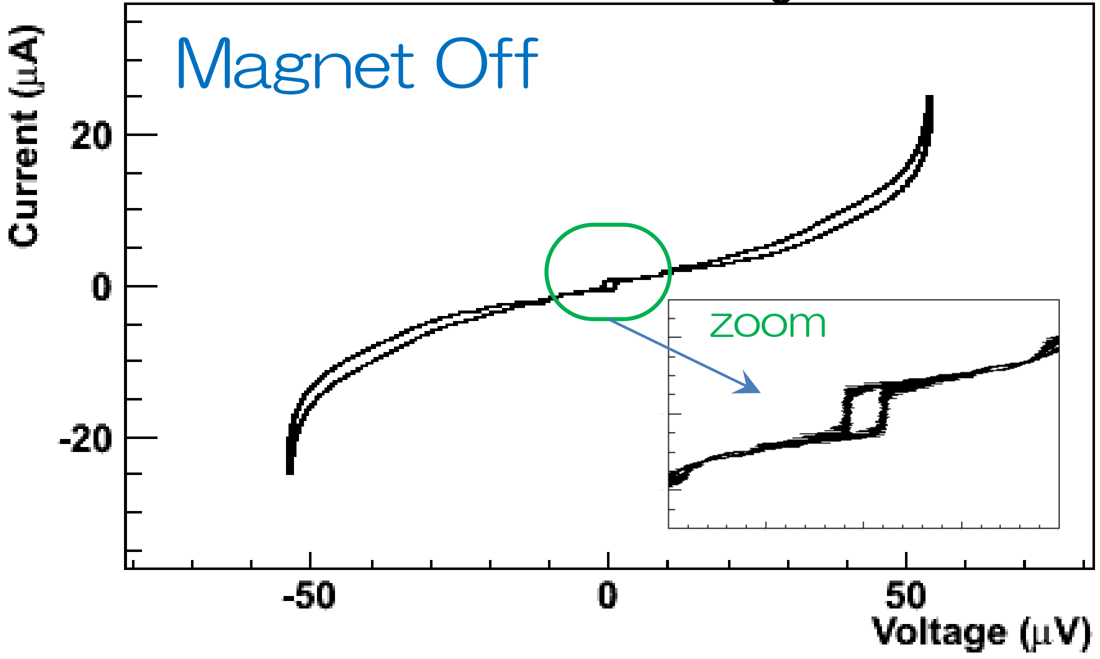
This leakage is actually much larger than our expectation. (Our goal is ~pA)

I-V curve about 30mK w/o and w/ B field

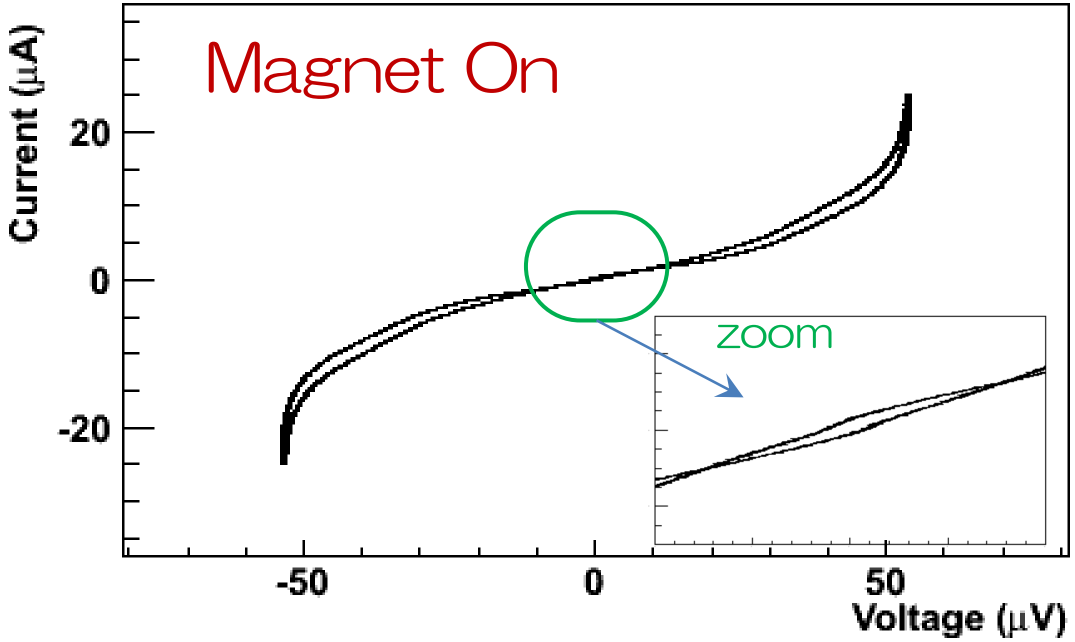
200μm square Hf-STJ @ T～30mK

- DC Josephson current is shown up without magnetic field, and it is suppressed with magnetic field (～10G).

I-V curve at 30mK in no magnetic field

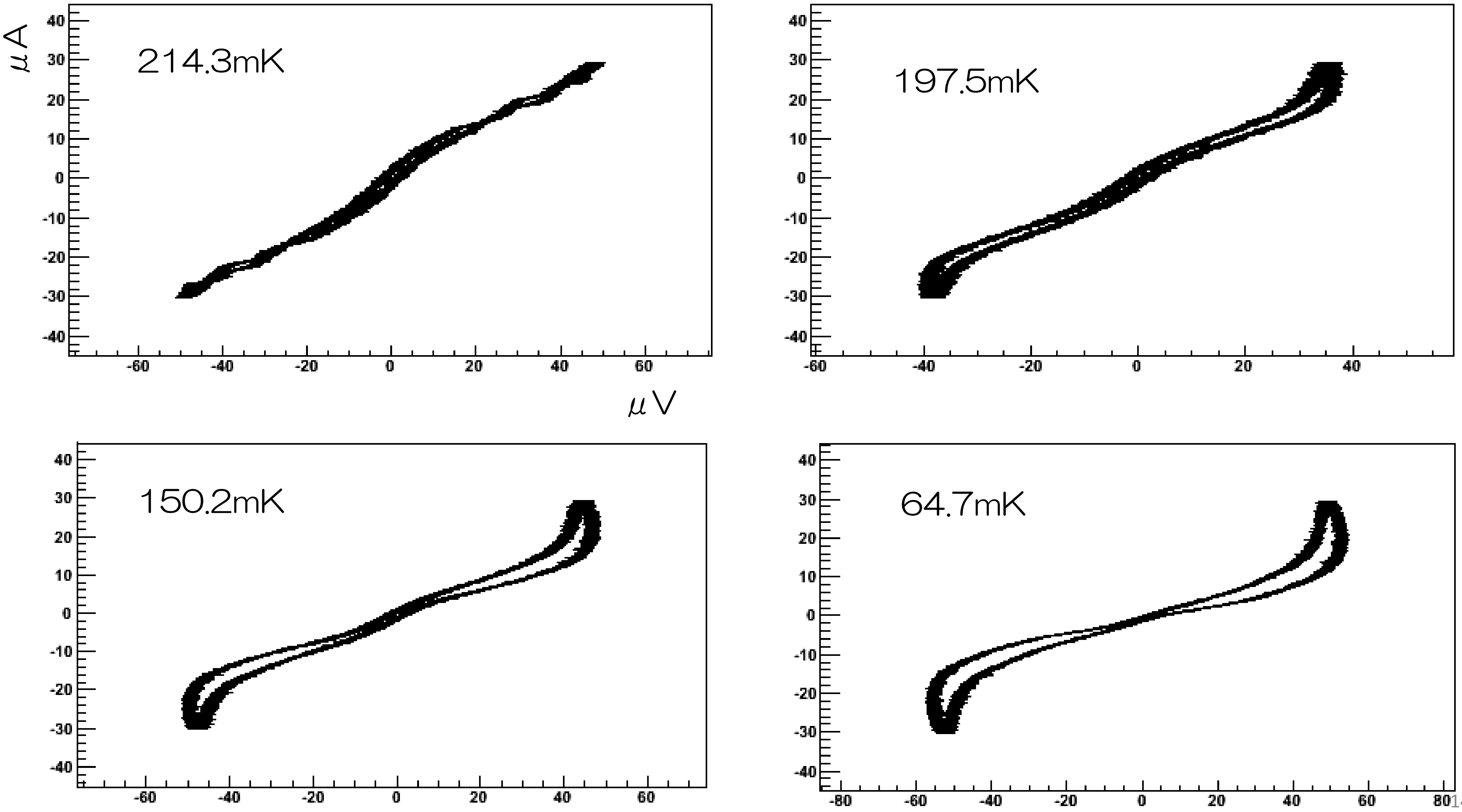


I-V curve at 31mK in magnetic field



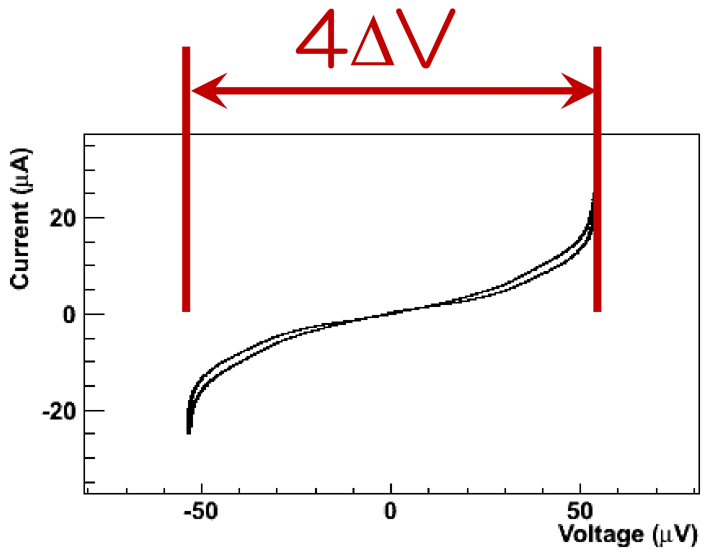
This confirms the SIS junction on the STJ.

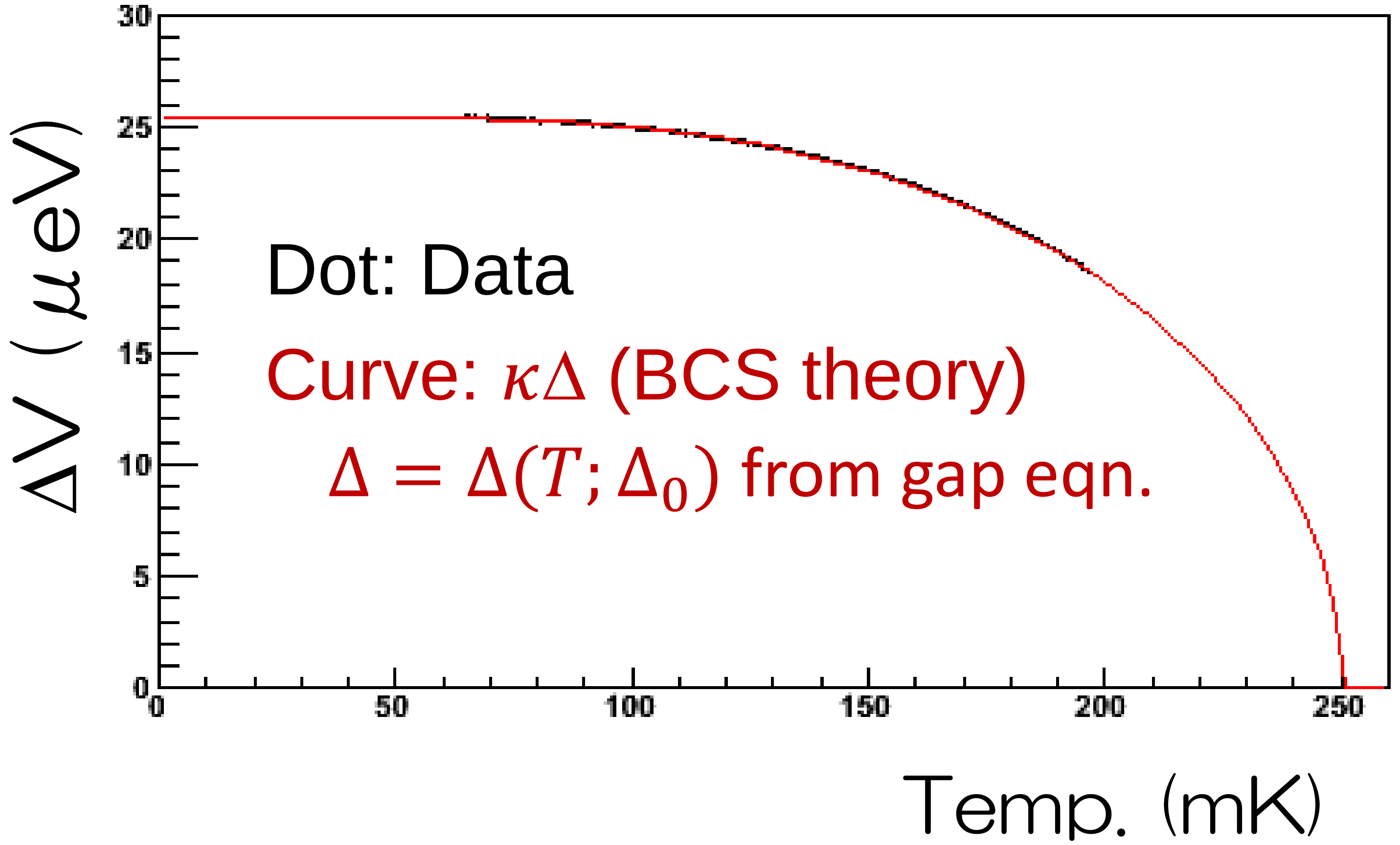
Temperature dependence of I-V curve



Temperature dependence of Gap energy

Define ΔV from I-V curve





- Temperature dependence of ΔV matched the BCS theory very well.
- Found to be $T_c = 250.31 \pm 0.03mK$

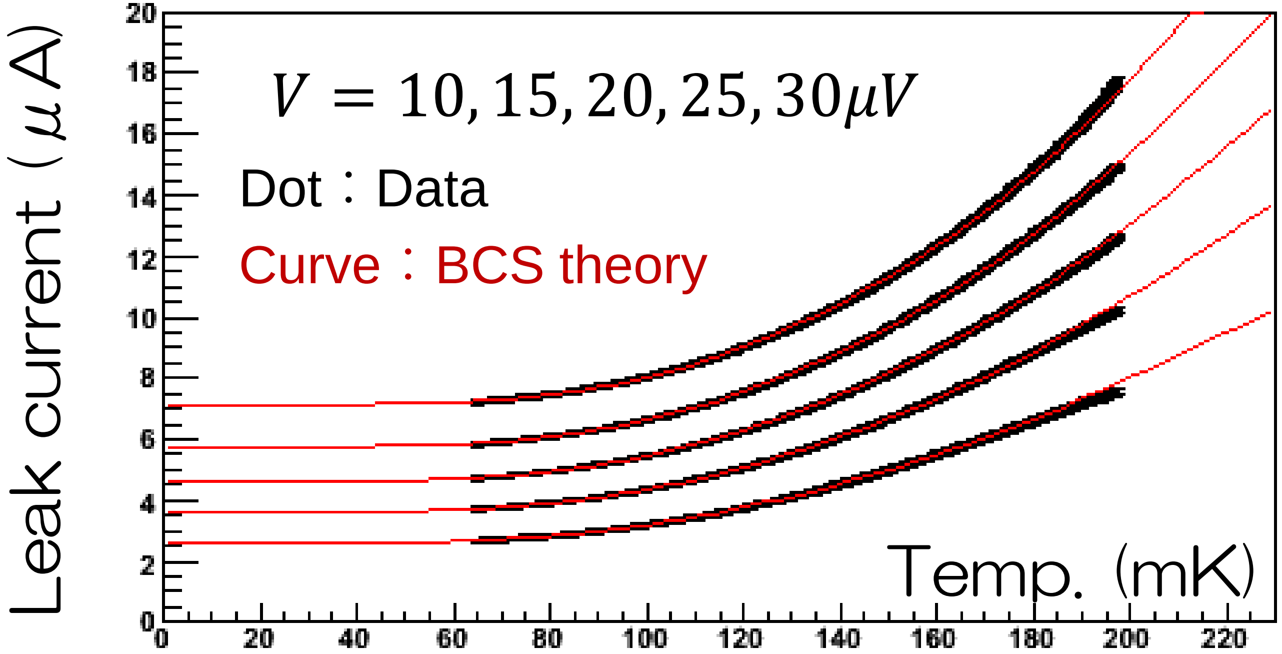
Temperature dependence of Leakage

$$I_{th} = P_0 \sqrt{\frac{\Delta}{kT_c}\frac{T}{T_c}} \exp\left(-\frac{\Delta}{kT_c}\frac{T_c}{T}\right) + P_2$$

BCS theory (P.W.Epperlein 1978)

$\Delta = \Delta(T; \Delta_0)$ from gap eqn.

Assuming $T_c = 250.31mK$, $\frac{\Delta_0}{kT_c} \sim 1.7639$



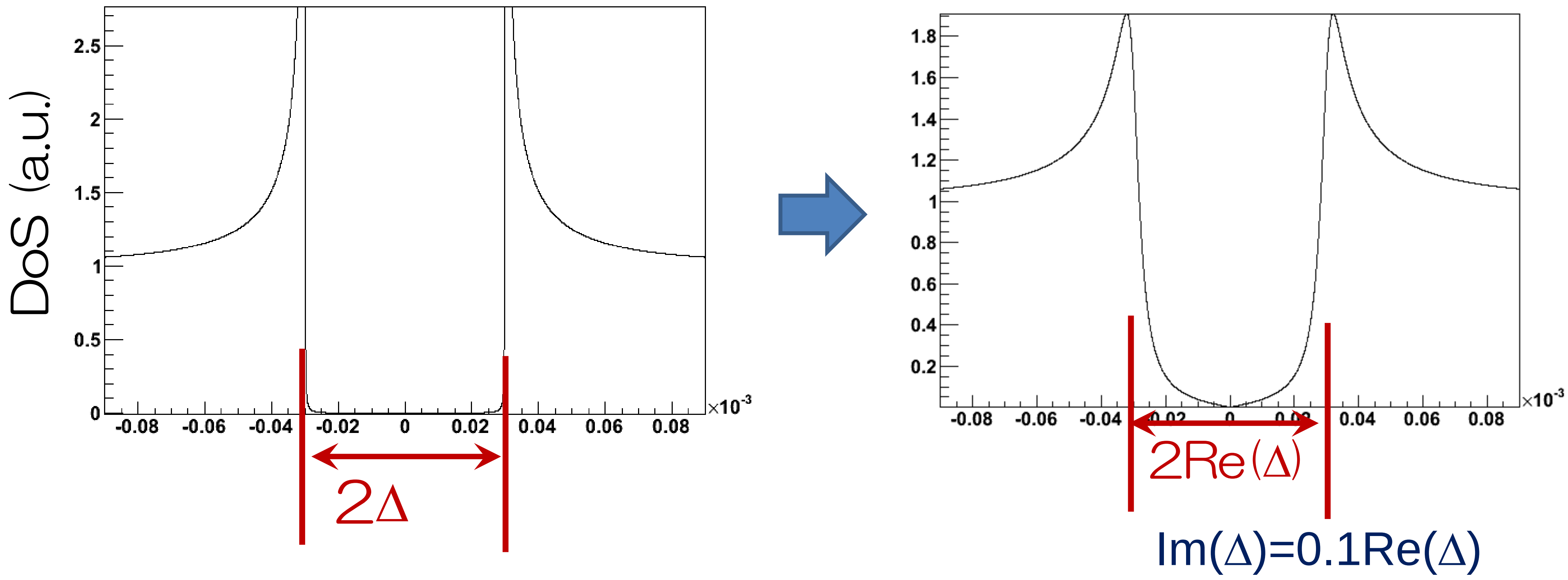
Extracted Δ_0 from fit

10μV: 27.59 μeV
15μV: 28.38 μeV
20μV: 29.52 μeV
25μV: 30.63 μeV
30μV: 31.62 μeV

- Temperature dependence of leakage matched the BCS theory.
- Found to be $\Delta_0 \sim 30\mu V$

Imaginary component in gap energy?

- Because of quasi-particle lifetime, gap energy Δ has imaginary part. (Mitrovic 2007).
- In this case, density of state distribution changes



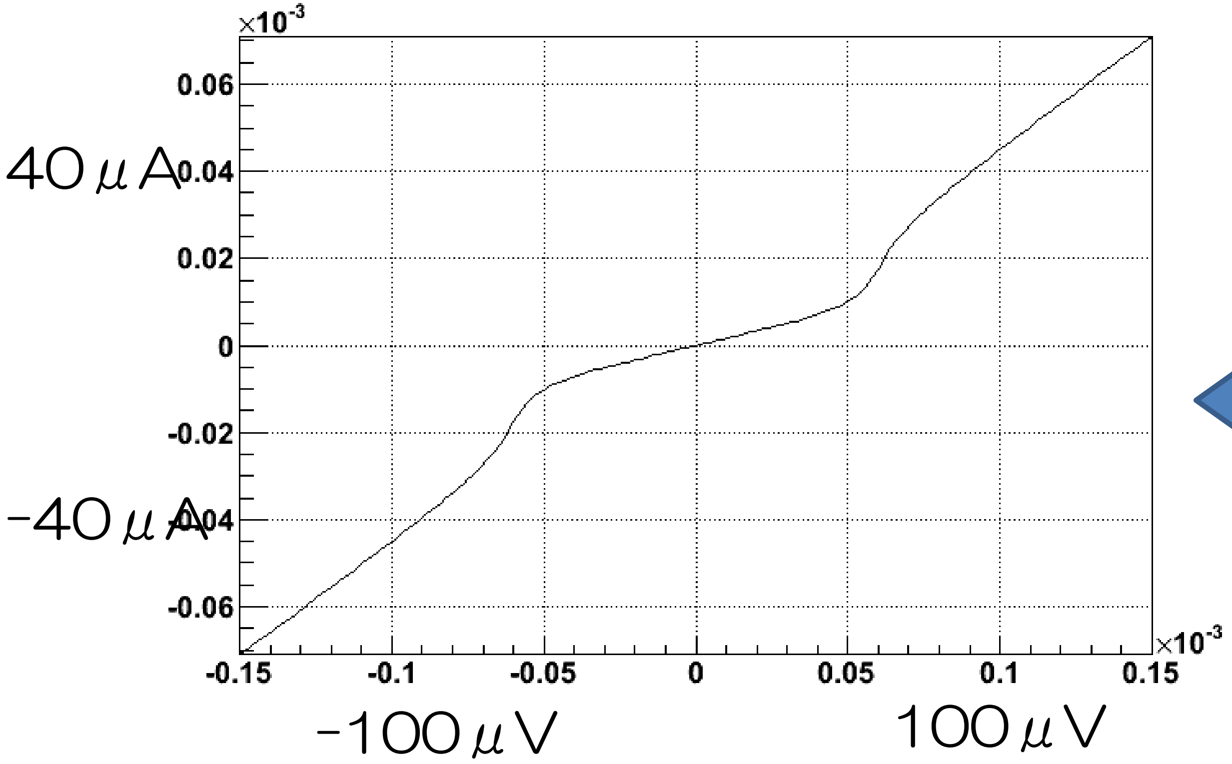
Imaginary component in gap energy?

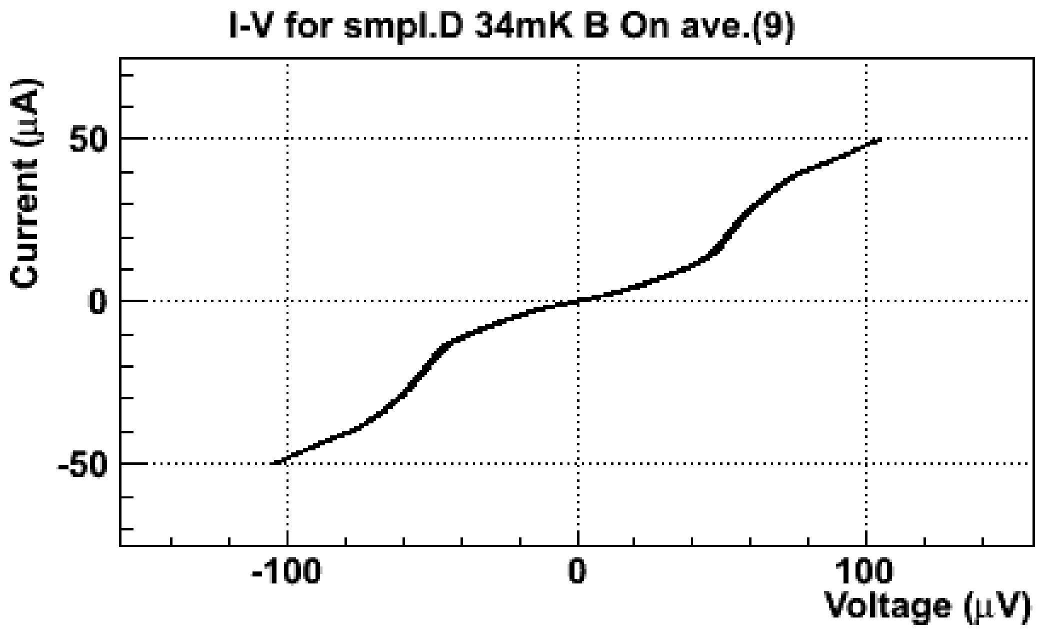
- Assume the following

  normal region resistance: 3Ω

  $\Delta = 30\mu eV + i \cdot 3\ \mu eV$

- Also assume existence of parallel normal current path of resistance: 6 Ω





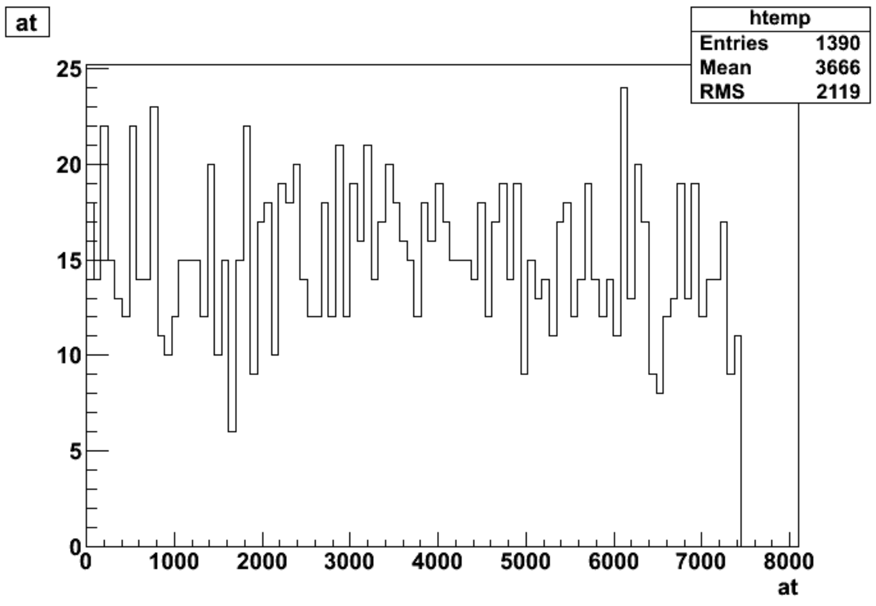
Not perfectly, but closer I-V curve is reproducible on these assumptions.

Response to X-ray photon

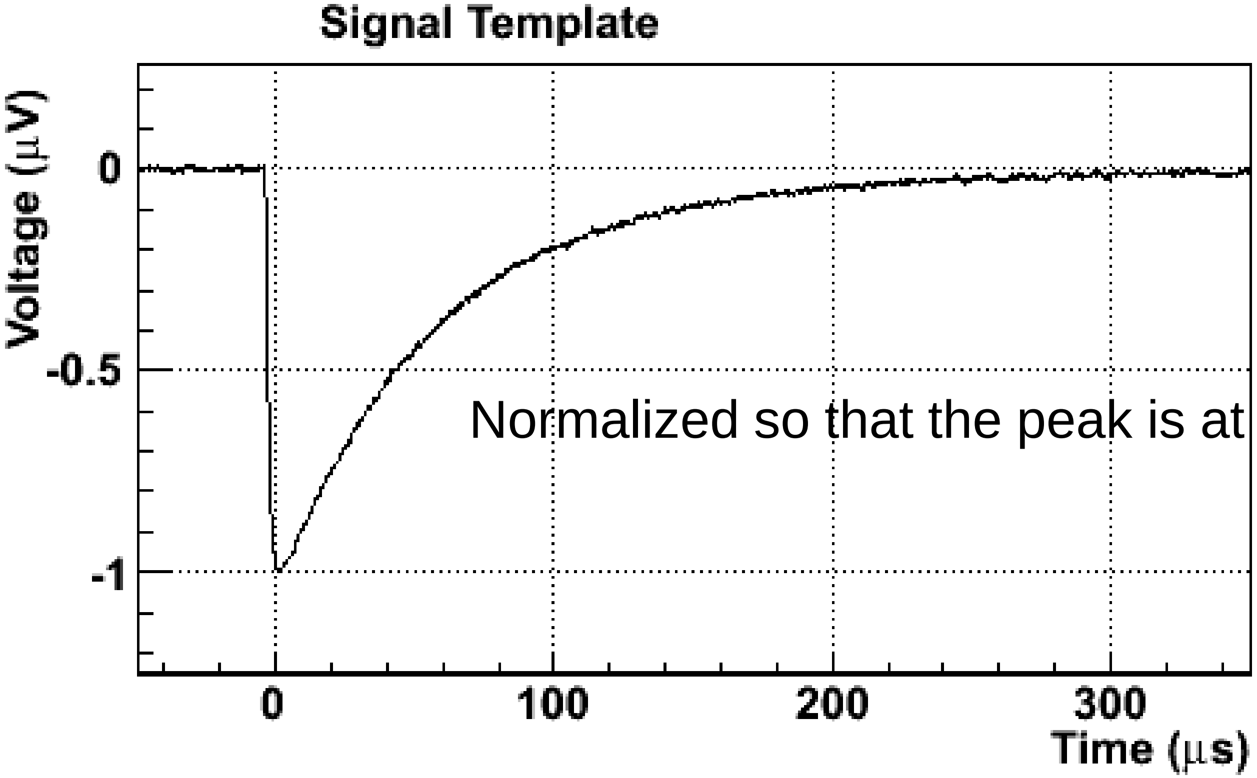
X-ray Signal waveform template

Apply I=1μA (corresponding to V〜9.2μV) on Hf-STJ @ T〜32mK

- Set trigger at -1.1μV for falling pulse in AC coupled readout
- Get 1390 events in 〜2 hours
- Obtain the signal template from these events.



Trigger time since the first event(sec)



Normalized so that the peak is at -1μV

Fit observed signal to the template

Use the region from -50μs to 200μs in the template (1250points)

- Amplitude and baseline are fitting parameters.
- Scan Δt from -50μs) to +50 μs) for RSS minimum

$$RSS \equiv \sum_i \{Av(t_i) + V_0 - V(t_i + \Delta t)\}^2 \qquad t_i \in [-50\mu s, 200\mu s]$$

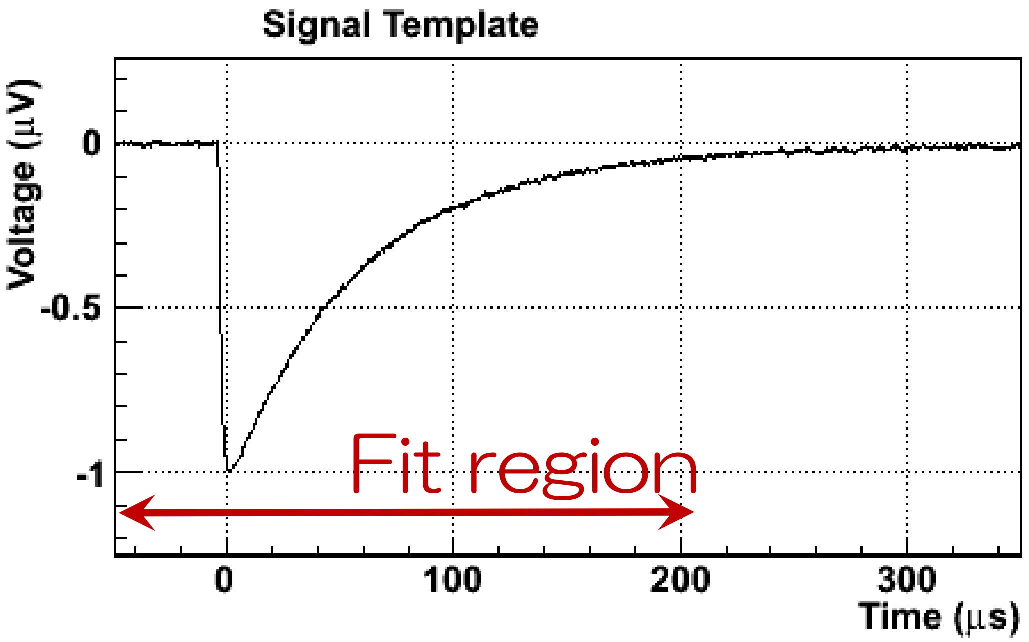
$v(t_i)$: template waveform at t_i

$V(t_i)$: observed waveform at t_i

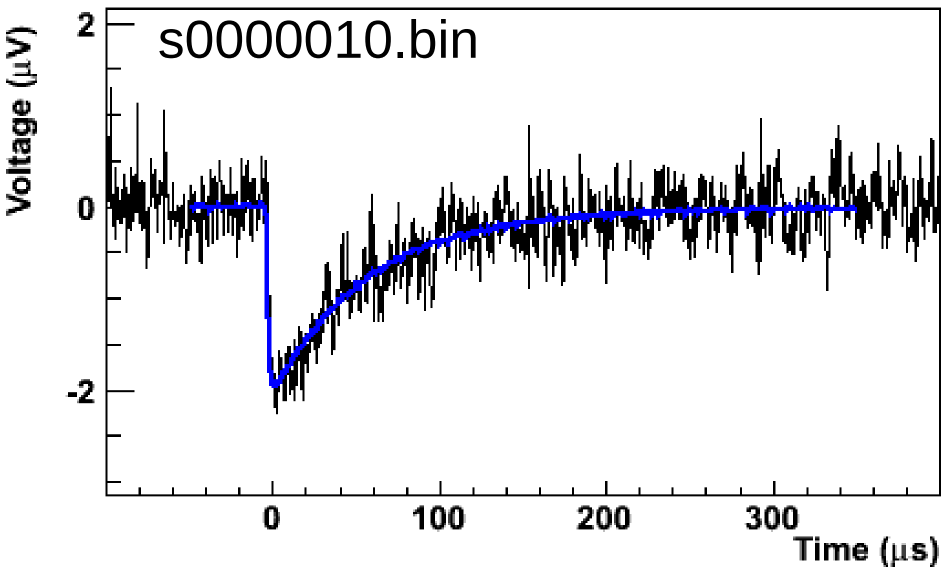
A: Amplitude

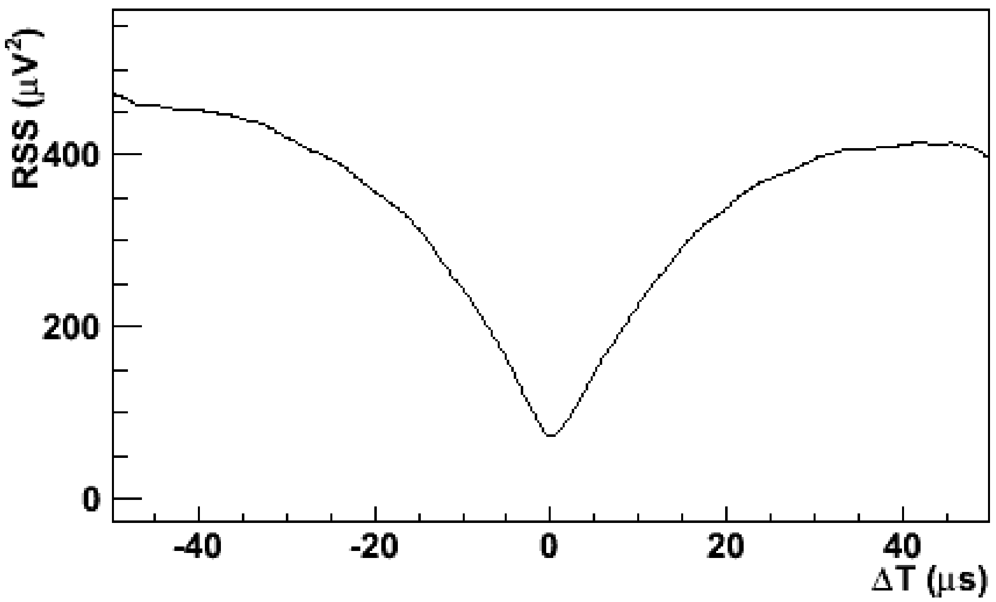
V_0: Baseline

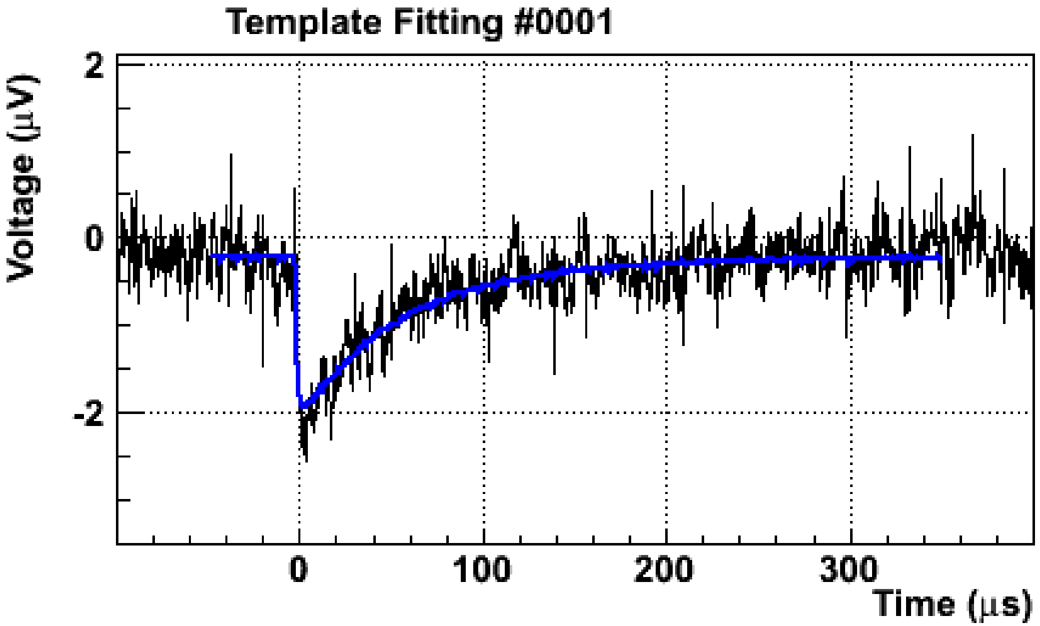
From each event, we extract Amplitude, Δt, and baseline.

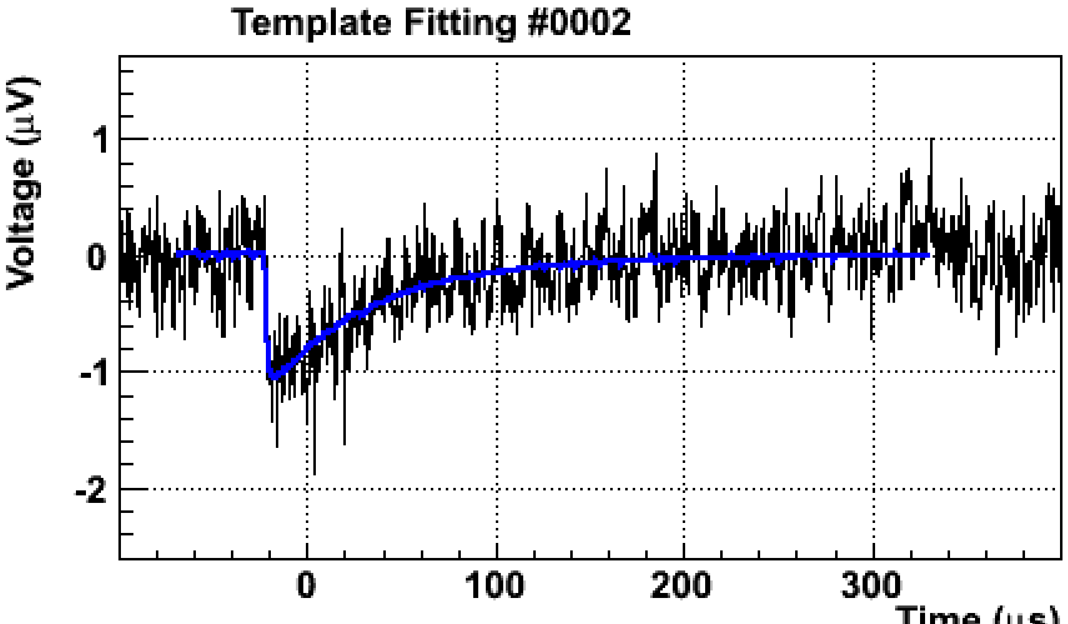


Example of Signal waveform fit

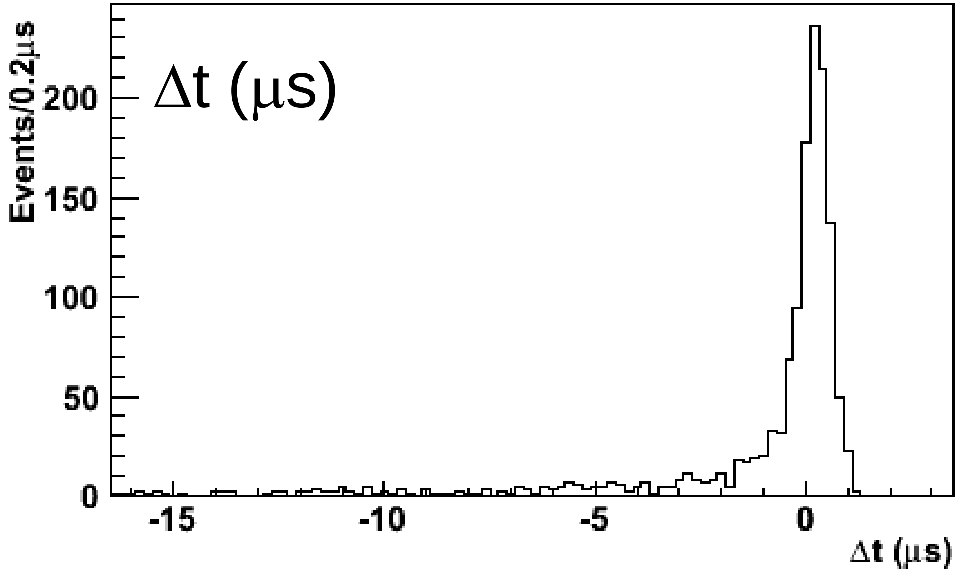


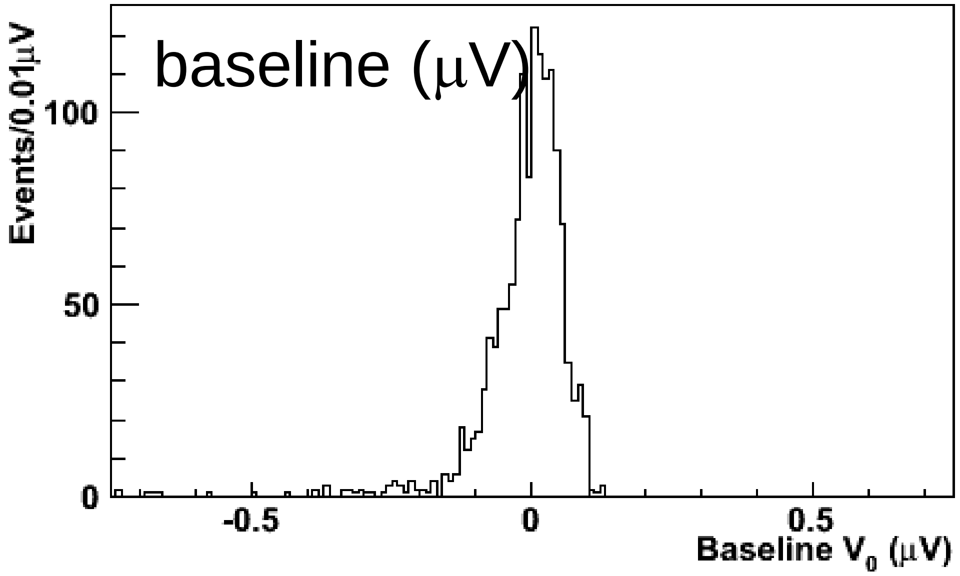


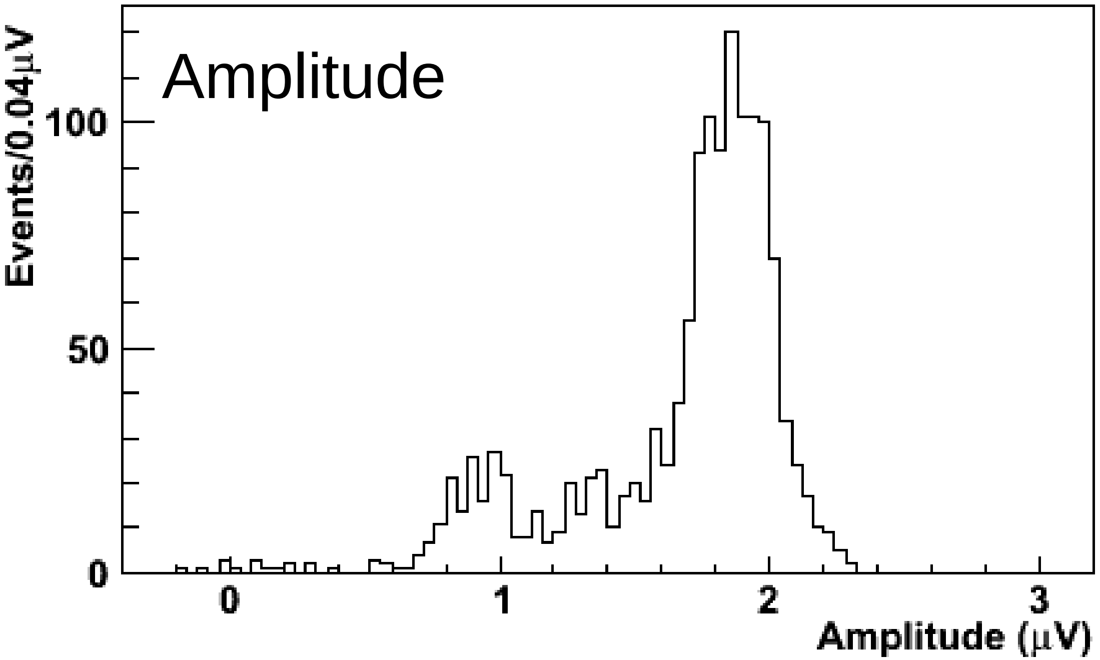




Distributions of Δt, baseline, and amplitude

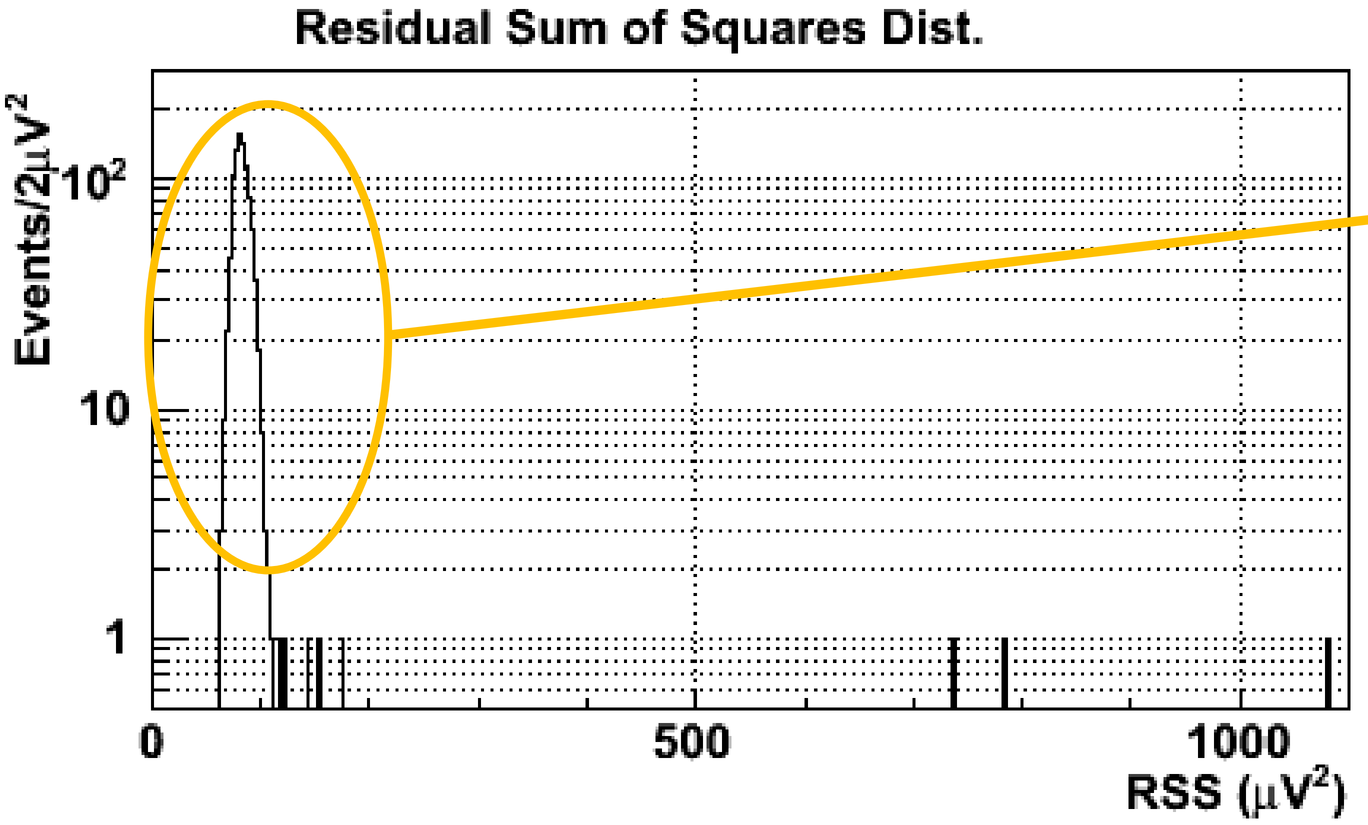


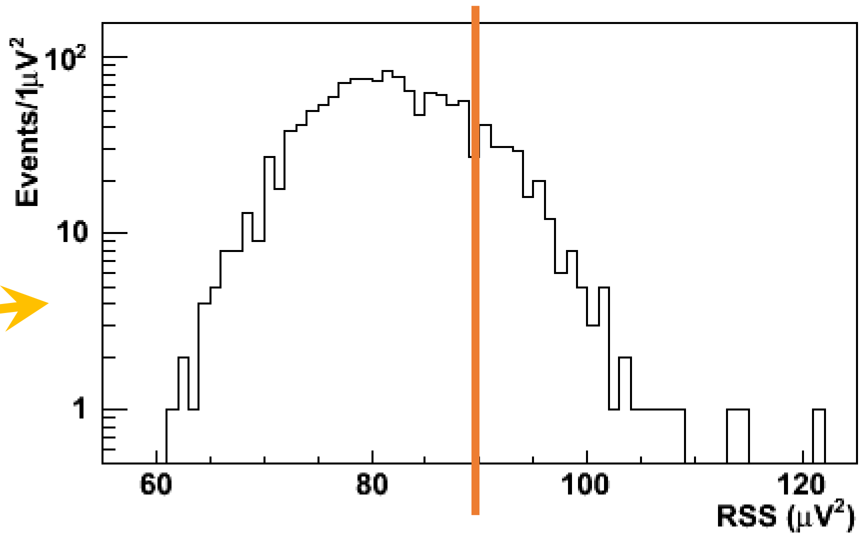




Residual Sum of Squares (RSS) distribution

Least squares fitting of 1250pts





Selection criteria

|baseline| <0.2μV

RSS <90μV²

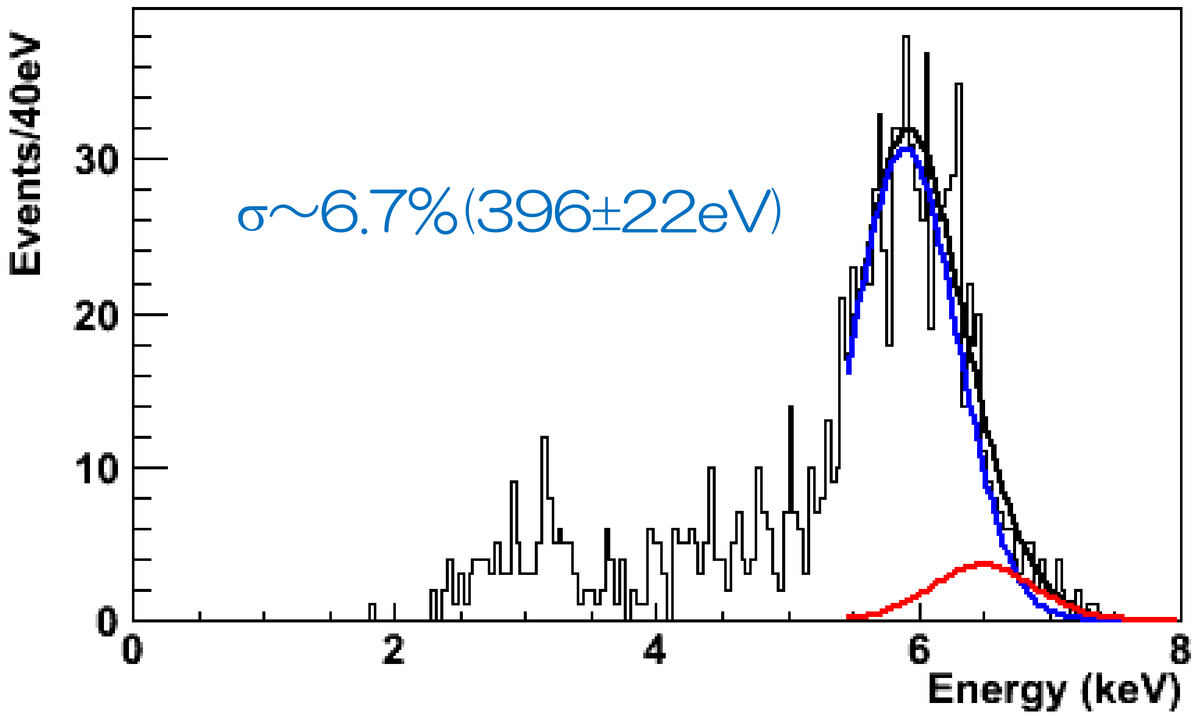
Energy distribution

After selection on fit parameters for candidates, 1138 events left.

- Kα1+Kα2 X-rays with energy of 5.9 keV and a probability about 24.4%,
- Kβ X-rays with nominal energy of 6.5 keV and a probability about 2.85%

Assuming Kα:Kβ ratio and peak energies and same σ for Kα and Kβ,
We fit the distribution and scaled.

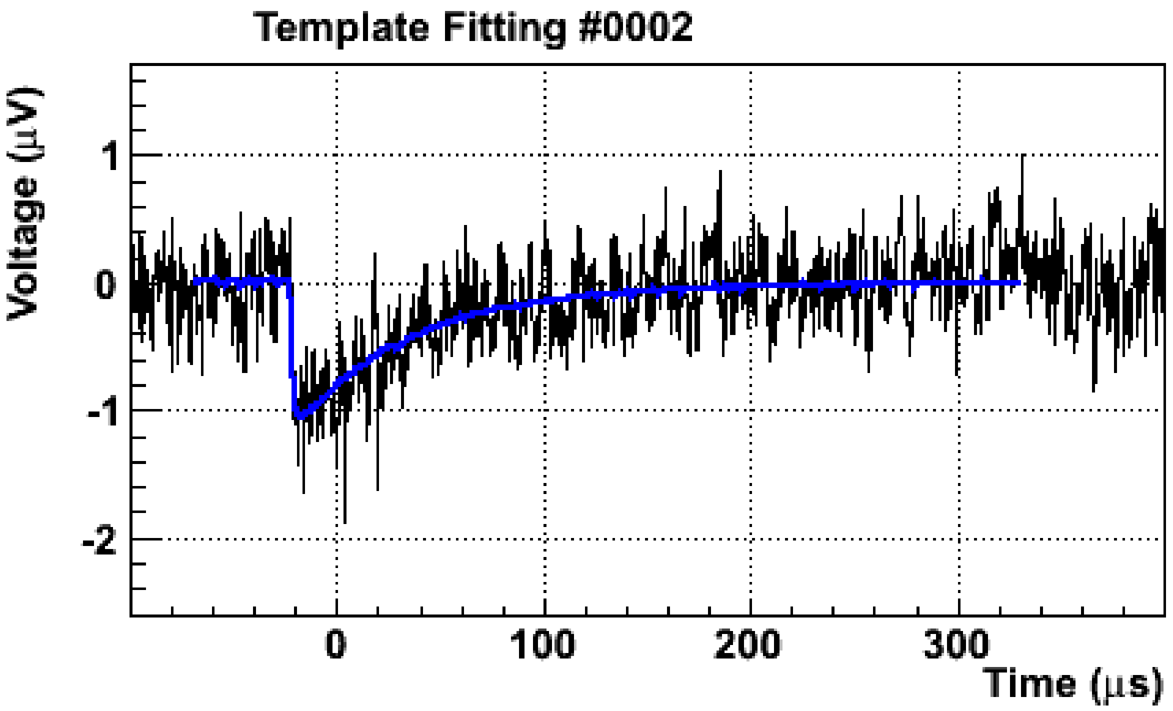
We found the energy resolution is
6.7% (396±22eV)

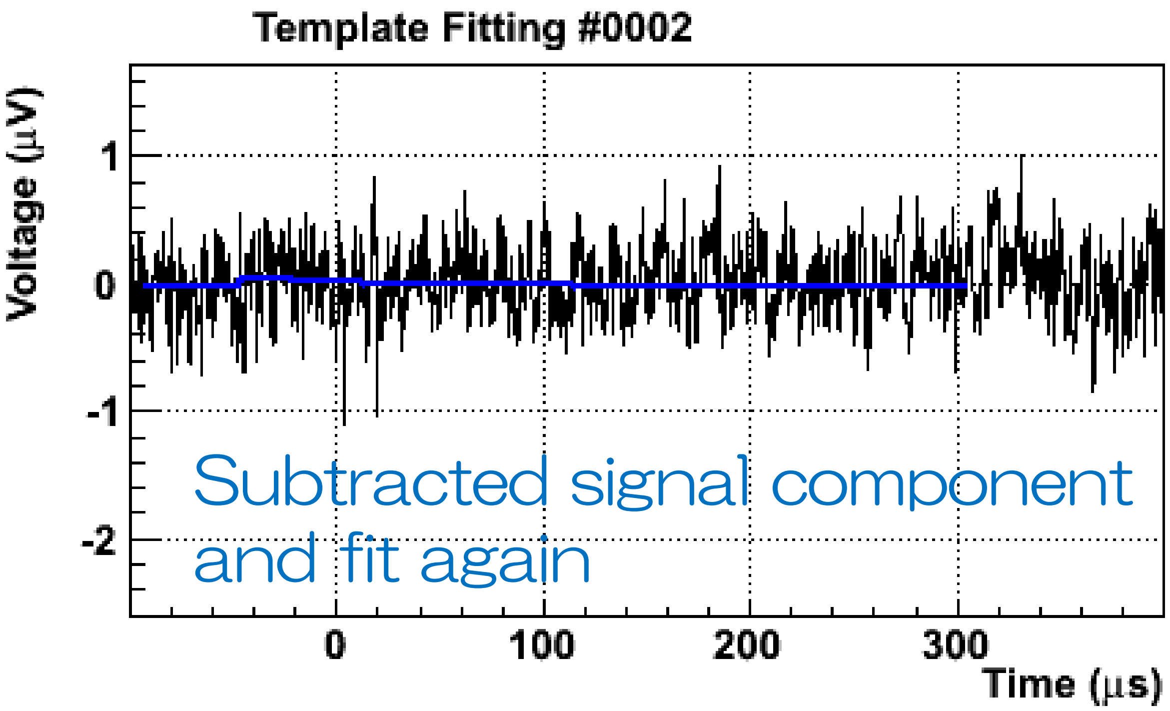


Pedestal distribution

We estimate pedestal distribution by forging pedestal waveforms from triggered events themselves.

- Once fit nominal waveform to signal template, and get fit parameters (amplitude, baseline, Δt)
- Use amplitude and Δt (not baseline), subtract signal component from waveform.
- After subtraction, fit again to the signal template.





Mean and r.m.s. in each time bin after subtraction

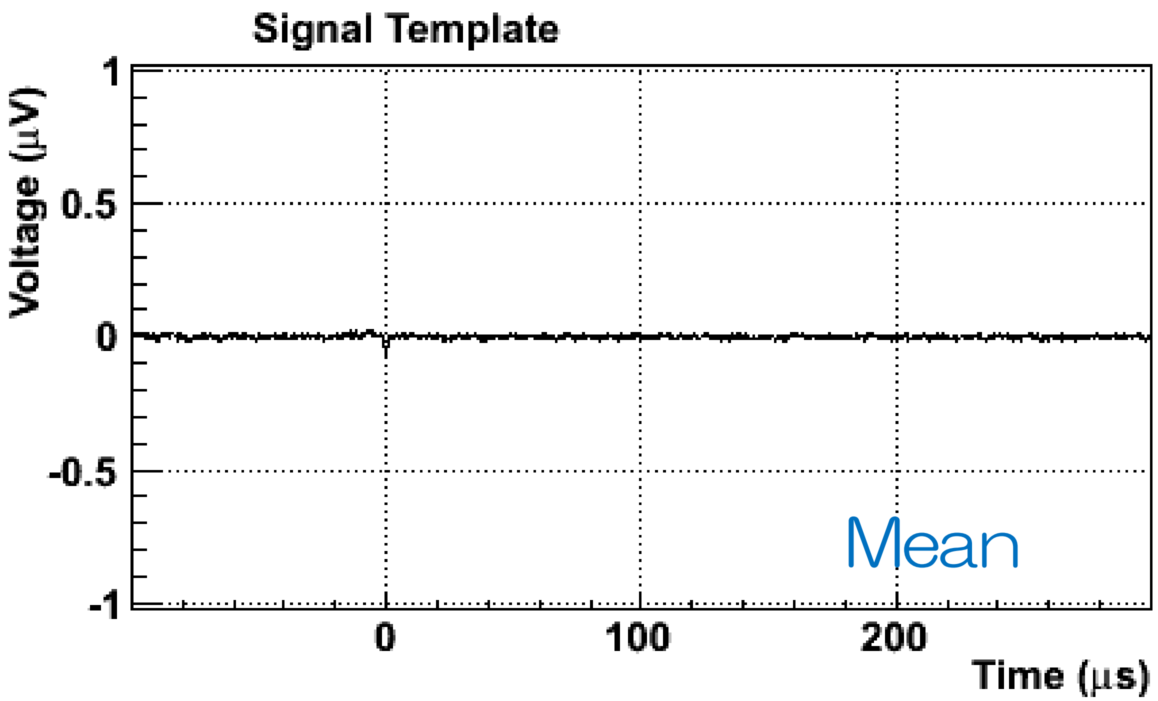
for the subtraction methodology check

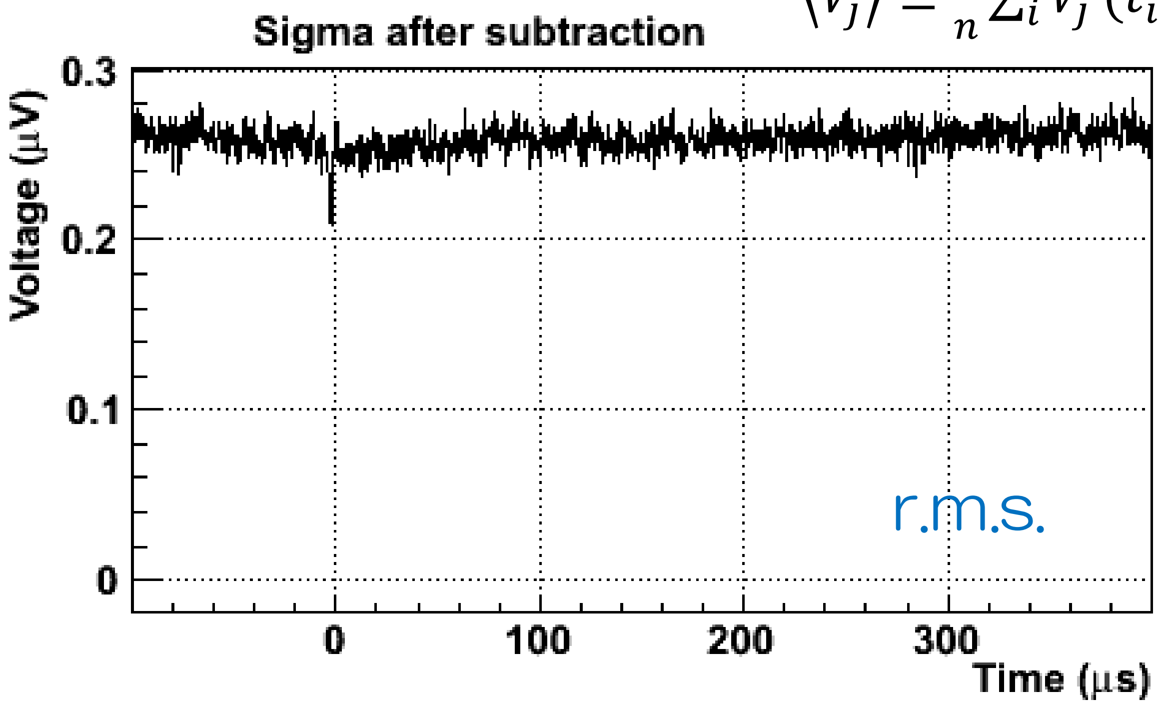
For subtracted waveforms $V_j(t_i)$, calculate mean and rms after candidate selection

Mean: $\bar{V}(t_i) \equiv \frac{1}{N}\sum_j V_j\,(t_i)$

r.m.s.: $\mathrm{rms}(t_i) \equiv \sqrt{\frac{1}{N}\sum_j \left(V_j(t_i) - \langle V_j\rangle\right)^2}$

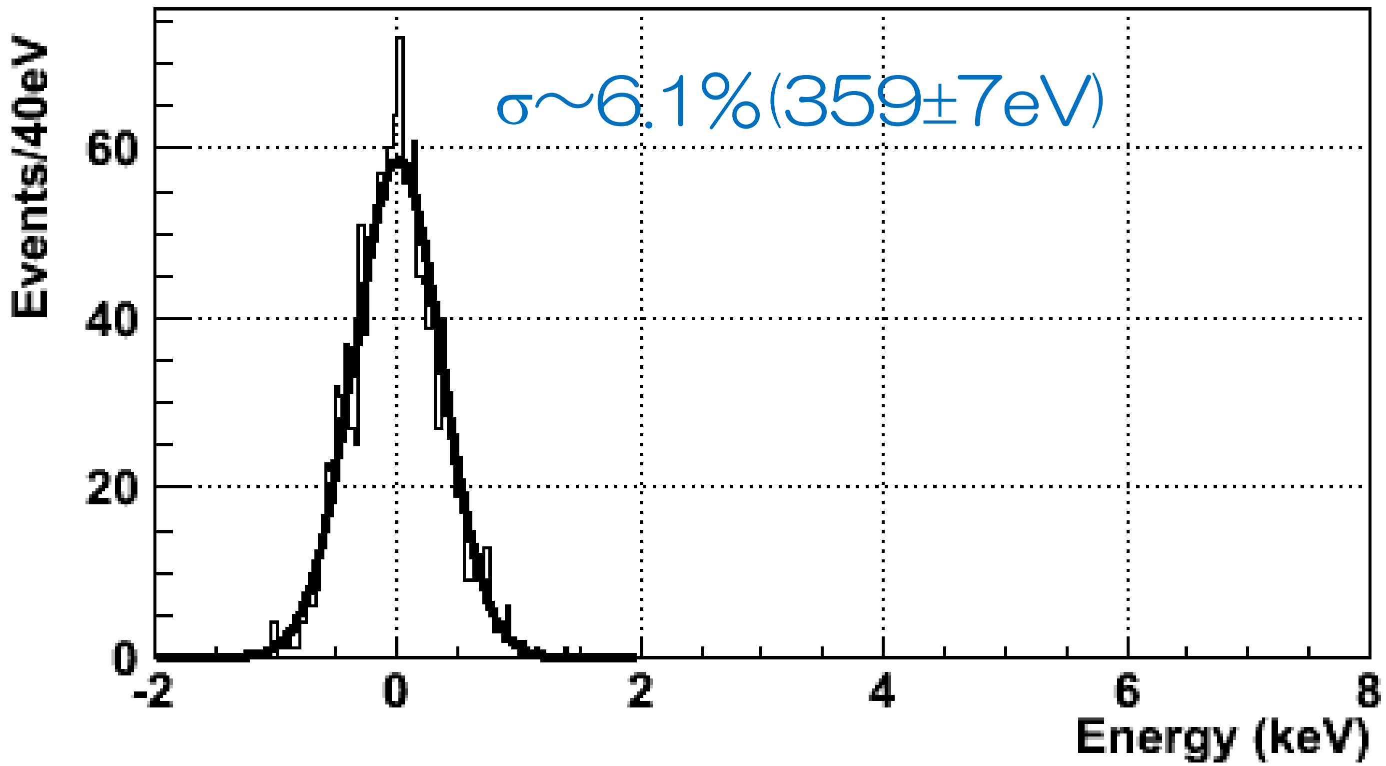
$\langle V_j\rangle \equiv \frac{1}{n}\sum_i V_j\,(t_i)$





Signal component subtraction seems to work fine to mimic pedestal events.

Amplitude distribution extracted from fits over signal subtracted events



- Sigma of measured energy distribution for pedestal samples forged from subtraction events is found to be 6.1% (359eV), which is almost comparable to sigma of signal events.

Summary

- Hf-STJ is under development for application to COBAND project, aiming at far-infrared single photon detector and spectrometer.
- We successfully fabricated Hf-STJs with confirmed SIS junction and tested them with X-ray source.
- We measured and compare temperature dependence of I-V curve of Hf-STJ with BCS theory. Unexpectedly large leakage is likely due to large imaginary component of gap energy as well as normal current path other than SIS junction.

- We confirmed the clear signals for X-ray single photon from ^{55}Fe with a Hf-STJ sample and found that energy resolution is about 6.7% for 5.9keV.

  These are the world first results for Hf-STJ.

- Currently the energy resolution is dominated by pedestal noise. This could be due to readout noise, where we have a plenty room to improvement on this.