IWSSD2014 November 8, 2014

Development of Superconducting Tunnel Junction Photon Detectors for Cosmic Background Neutrino Decay Search

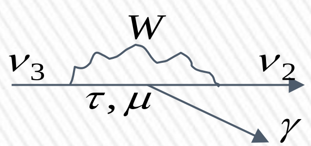
Shin-Hong Kim (University of Tsukuba)
for Neutrino Decay collaboration

Neutrino Decay Collaboration
S.H. Kim, Y. Takeuchi, K. Takemasa, K. Kiuchi, K. Nagata, K. Kasahara, T. Okudaira, T. Ichimura, M. Kanamaru, K.Moriuchi, R. Senzaki (University of Tsukuba), H. Ikeda, S. Matsuura, T. Wada (JAXA/ISAS), H. Ishino, H. Kibayashi (Okayama University), S. Mima (RIKEN), T. Yoshida, K. Orikasa, R. Hirose (University of Fukui), Y. Kato (Kinki University), M. Hazumi, Y. Arai (KEK), E. Ramberg, J.H. Yoo, M. Kozlovsky, P. Ruvinov, D. Sergatskov (Fermilab), S.B. Kim (Seoul National University)

- Introduction
  - Motivation
  - Proposal on Search for Cosmic Background Neutrino Decay
  - Preparatory Rocket experiment
- R&D of Superconducting Tunnel Junction (STJ) Detector

Motivation of Search for Cosmic Background Neutrino Decay

- **Only neutrino mass is unknown in elementary particles. Detection of neutrino decay enables us to measure an independent quantity of Δm^2 measured by neutrino oscillation experiments. Thus we can obtain neutrino mass itself from these two independent measurements.**



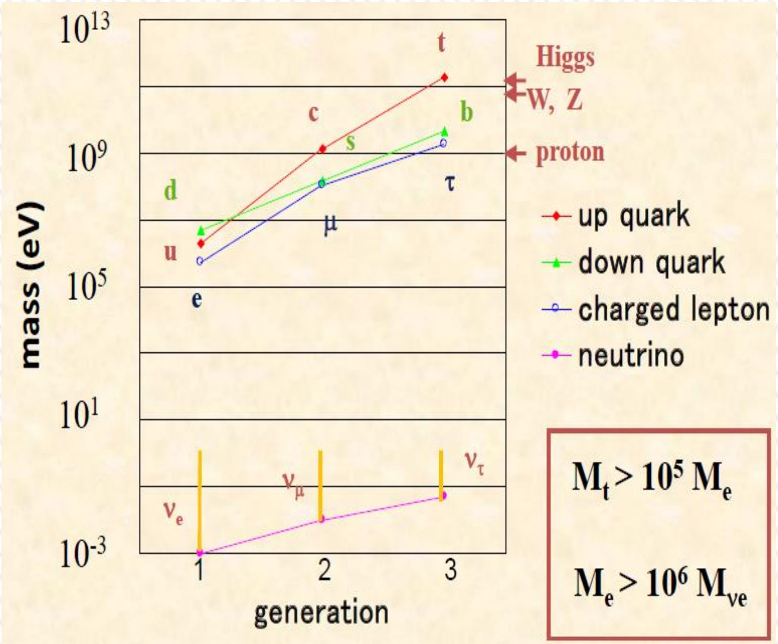
$$\nu_3 \rightarrow \nu_2 + \gamma$$

$$E_\gamma = \frac{m_3^2 - m_2^2}{2m_3} = \frac{\Delta m_{23}^2}{2m_3}$$

Using $\Delta m_{23}^2 = (2.43 \pm 0.09) \times 10^{-3}\,\mathrm{eV}^2$

$E_\gamma = 10 \sim 25$ meV at ν_3 rest frame.

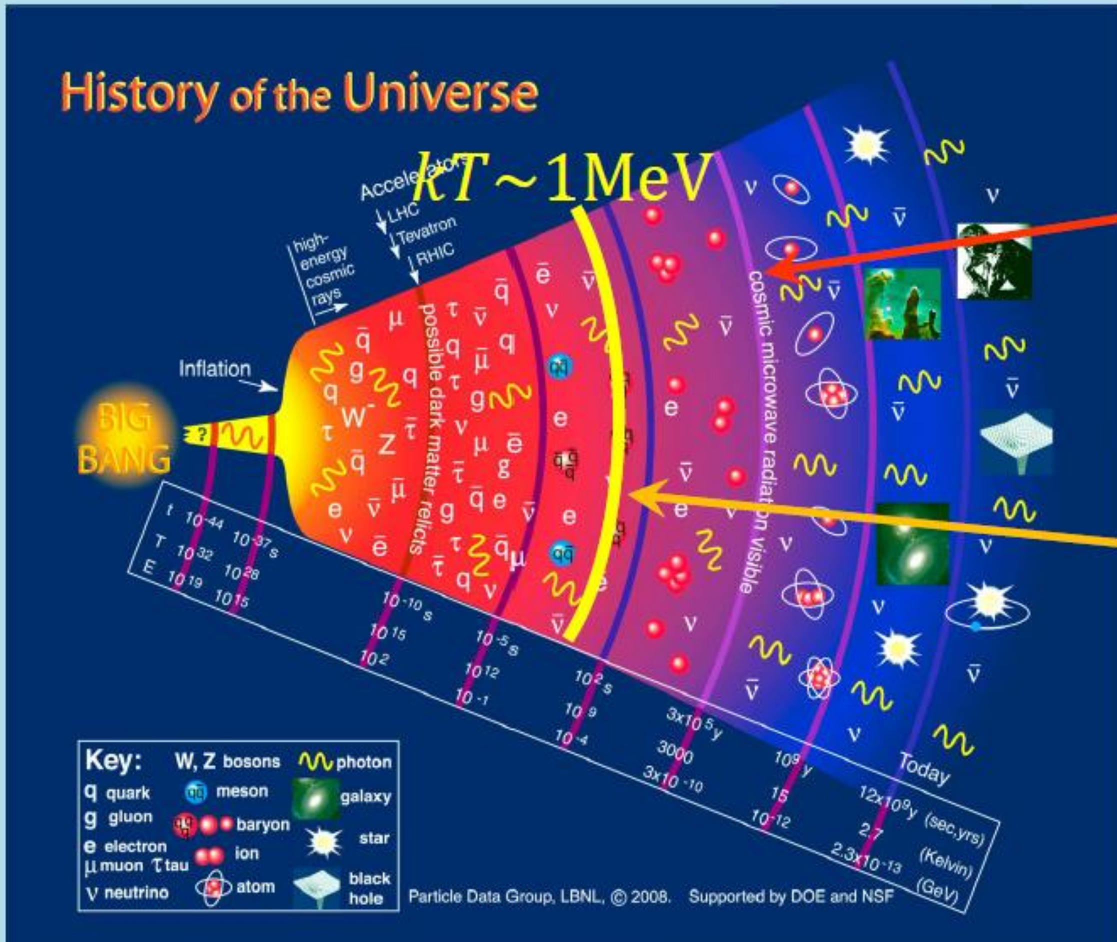
(Far-Infrared region $\lambda = 50 \sim 125\ \mu$)

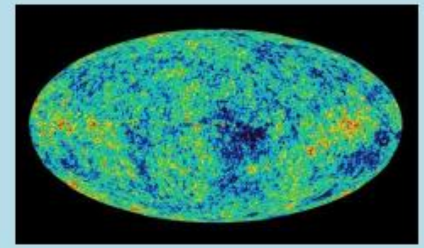


- **As the neutrino lifetime is very long, we need use cosmic background neutrino to observe the neutrino decay. To observe this decay of the cosmic background neutrino means a discovery of the cosmic background neutrino predicted by cosmology.**

- **Left-Right symmetric model predicts the neutrino lifetime larger than 10^{17} year while the standard model predicts 2 x 10^{43} year. Measured neutrino lifetime limit $\tau > 3 \times 10^{12}$ year.**

Big-Bang Cosmology and Cosmic Background Neutrino (CνB)





CMB

$$n_\gamma = 411/\mathrm{cm}^3$$

$$T_\gamma = 2.73\ \mathrm{K}$$

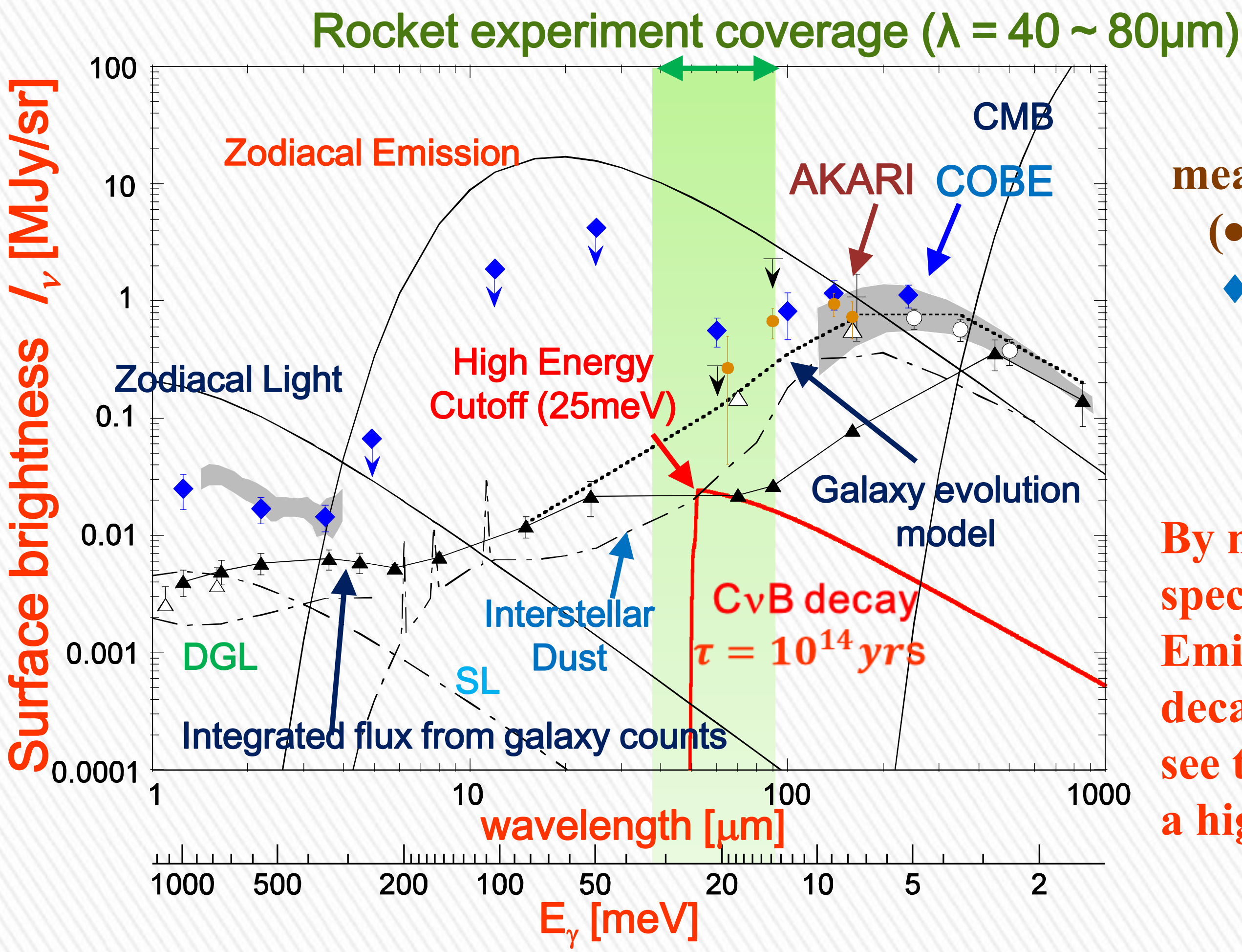
CνB

$$n_\nu = n_{\bar{\nu}} = \frac{3}{4}\left(\frac{T_\nu}{T_\gamma}\right)^3 \frac{n_\gamma}{2}$$

$$= 56/\mathrm{cm}^3$$

$$T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma = 1.95\mathrm{K}$$

Signal of Cosmic Background Neutrino Decay and its Backgrounds



CIB measurements (● AKARI, ◆ COBE)

By measuring the energy spectrum of the Zodiacal Emission with the CνB decay continuously, we can see the CνB decay signal as a high energy cutoff.

Requirements for the detector

- Continuous spectrum of photon energy around $E_\gamma \sim 25\,\mathrm{meV}(\lambda = 50\mu\mathrm{m})$
- Energy measurement for single photon with better than 2% resolution for $E_\gamma = 25\mathrm{meV}$ to identify the sharp edge in the spectrum
- Rocket and/or satellite experiment with this detector

JAXA Rocket Experiment for Neutrino Decay Search

Plan: 5minutes data acquisition at 200 km height in 2017 in earliest.

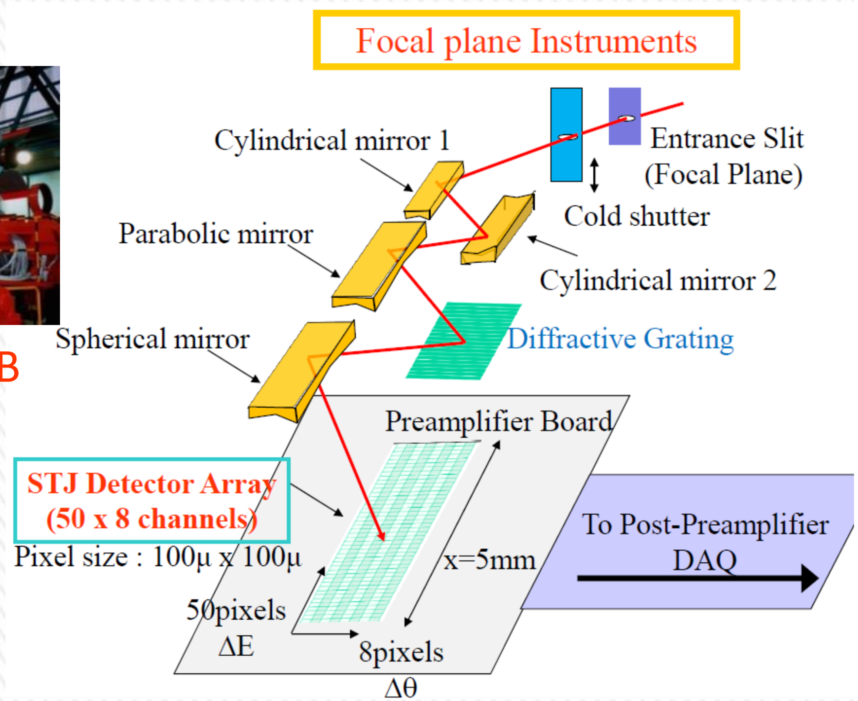
Improve the current limit of lifetime $\tau(\nu_3)$ by two orders of magnitude (~10^{14}years).

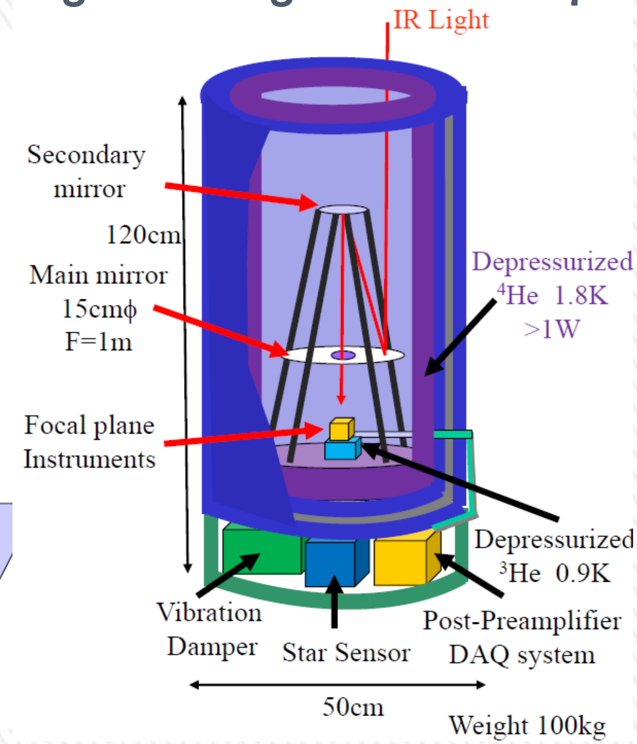
» Superconducting Tunneling Junction (STJ) detectors in development

- Array of 50 Nb/Al-STJ pixels with diffraction grating covering $\lambda = 40 - 80\mu m$

JAXA Rocket CIB Experiment

(Feb 2, 1992)



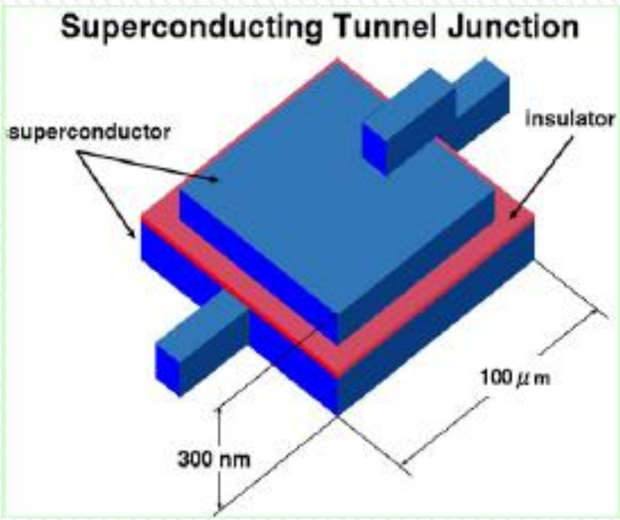


Satellite experiment after 2020 → sensitivity of $\tau(\nu_3)$ ~10^{17}year

- STJ using Hafnium: Hf-STJ for satellite experiment (S. H. Kim et al. JPSJ 81,024101 (2012))
  - $\Delta = 20\mu eV$: Superconducting gap energy for Hafnium
  - $N_{q.p.} = 25meV/1.7\Delta = 735$ for 25meV photon: $\Delta E/E < 2\%$ if Fano-factor is less than 0.3

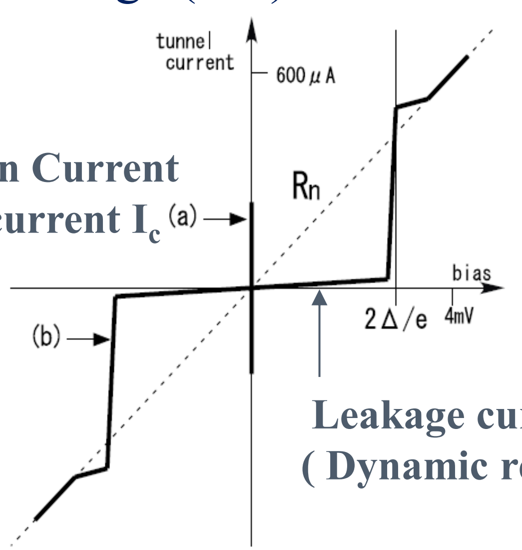
STJ (Superconducting Tunnel Junction）Detector

» Superconductor / Insulator / Superconductor Josephson Junction



At the superconducting junction, quasi-particles over their energy gap go through tunnel barrier by a tunnel effect. By measuring the tunnel current of quasi-particles excited by an incident particle, we measure the energy of the particle.

current-voltage (I-V) curve for STJ

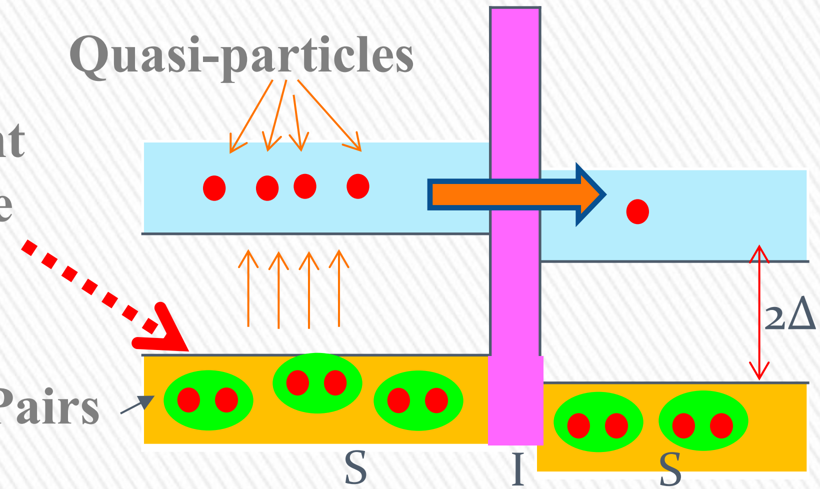


Josephson Current

Critical current I_c

Leakage current

(Dynamic resistance R_d in $|V| < 2\Delta/e$)



Energy gap Δ

Material	$T_c(K)$	Δ(meV)
Niobium	9.20	1.550
Aluminum	1.14	0.172
Hafnium	0.13	0.021

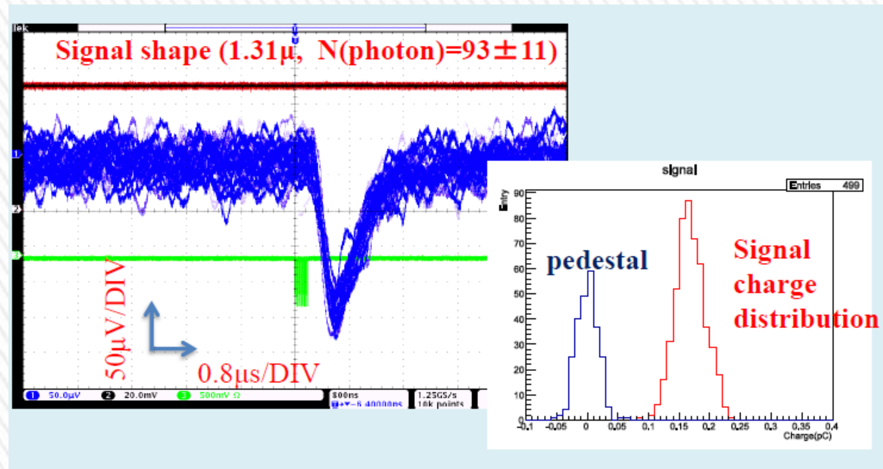
R&D of Superconducting Tunnel Junction (STJ) Detctor

Nb/Al-STJ

Goal: detection of a single far-infrared photon in the energy range of 15 – 30 meV (λ = 40 –80 μm) for the rocket experiment for neutrino decay search.

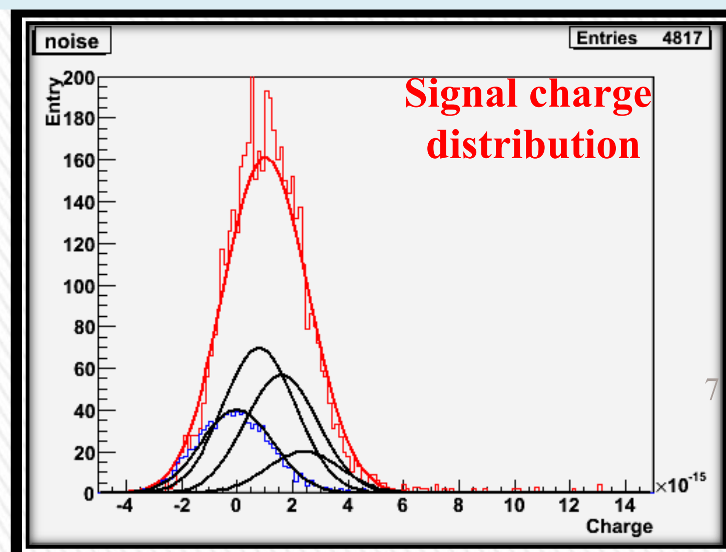
Signal of Nb/Al-STJ (100 x 100 μm^2) to infrared (1.31 μm) light at 1.9K.

Time spread at FWHM is 1 μsec.
The number of photon : 93±11
(from the spread of
the signal charge distribution).



the response of Nb/Al-STJ (4 μm^2) to the visible light (465nm) at 1.9K.
a single photon peak is separated from pedestal by 1 σ.

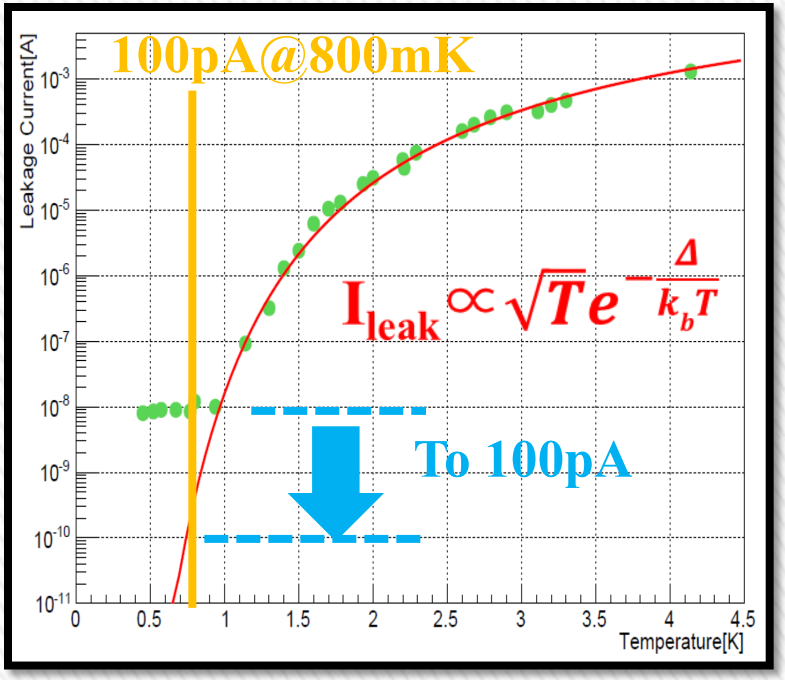
The signal charge distribution (Red histogram) is fitted by four Gaussians of 0, 1, 2 and 3 photon peaks. Single photon peak has a mean of 0.4fC and σ of 0.4fC.



Requirement for the cold amplifier of STJ readout

We need the preamplifier operated at extremely low temperature to detect a single far-infrared photon ($\lambda = 40 - 80\,\mu m$) .

Temperature Dependence of Leakage Current with Nb/Al-STJ(100x100μm^2)



● Operation at ultra-low temperature

- Requirement for leakage current of Nb/Al-STJ is below 100pA.

    We reduce it by using smaller one.

  Thermal excitation($\propto \sqrt{T} e^{-\frac{\Delta}{k_b T}}$)

We need to make cooler 800mK.

➡ **1. Operation below 800mK**

^{3}He sorption refrigerator is our candidate

● Low power consumption

- Typical cooling power of our refrigerator is 400 μ W.

➡ **2. Power consumption of the amplifier should be as low as possible.**

● Response speed

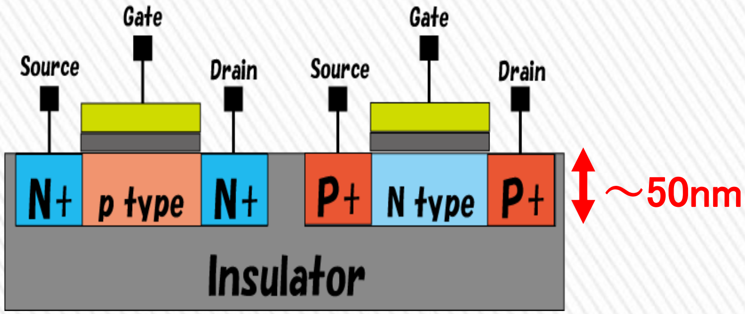
- The integration time of charge is 2-4 μ s.

➡ **3. Amplification gain should be large enough up to 1MHz.**

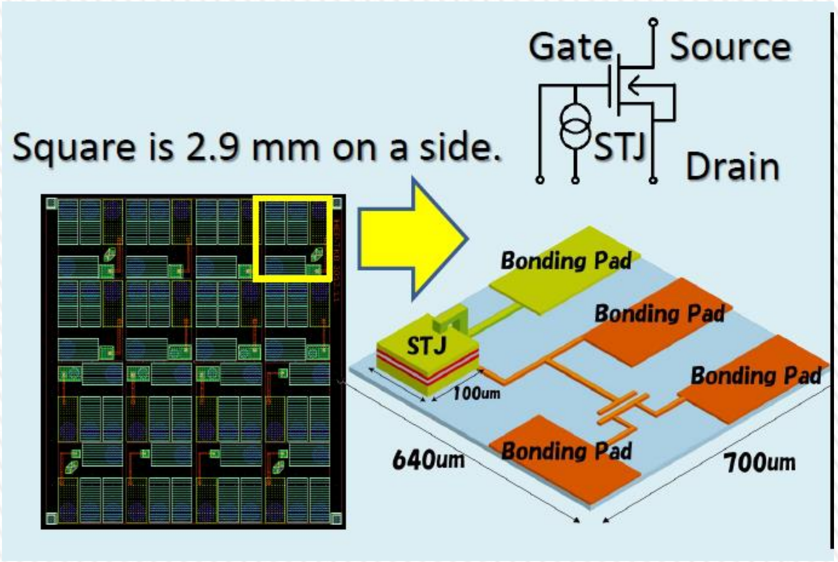
R&D of SOI-STJ Detctor

FD-SOI (Silicon-On-Insulator) device was proved to operate at 4K by a JAXA/KEK group (AIPC 1185,286-289(200 FD-SOI 9)). It has the following characteristics:
low-power consumption, high speed, easy large scale integration and suppression of charge-up by high mobility carrier due to thin depletion layer(～50nm).

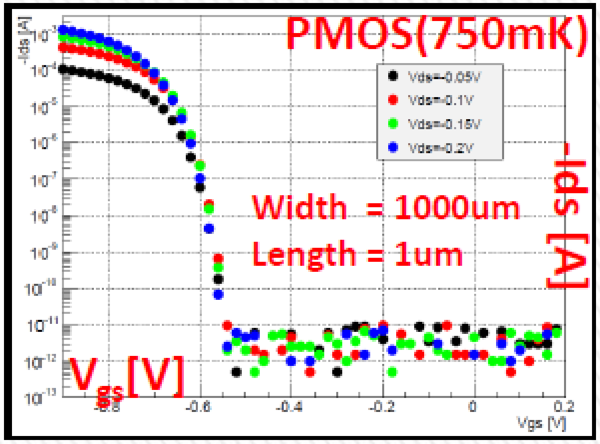
FD-SOI -MOSFET



To improve the signal-to-noise ratio and to make multi-pixel device easily, we made a SOI-STJ detector where we processed Nb/Al-STJ on a SOI transistor board.

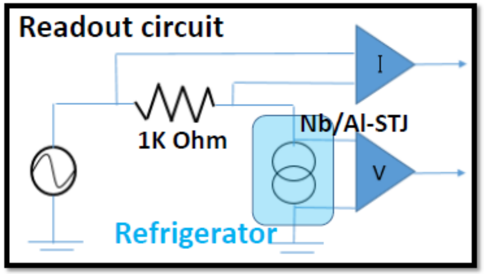


We confirmed that both Nb/Al-STJ detector and SOI MOSFET worked normally at 750mK.



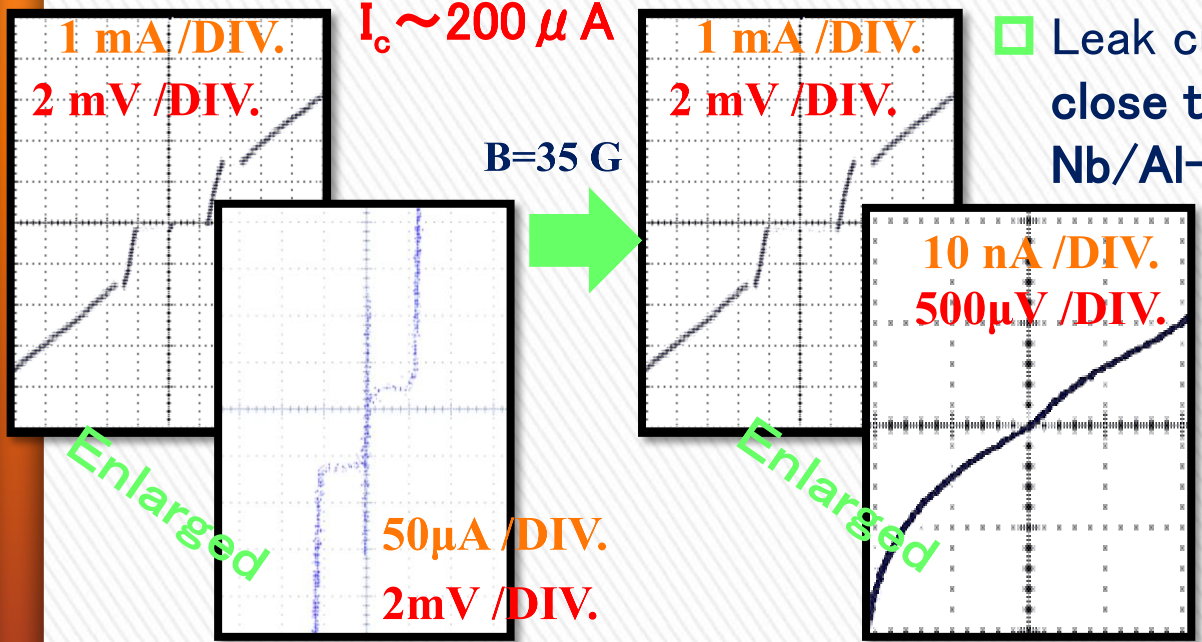
Performance of Nb/Al-STJ in SOI-STJ Detector

We measured the I-V curve of the Nb/Al-STJ (50 x 50 μm^2 junction) processed on the SOI wafer at **700mK** with a dilution refrigerator.



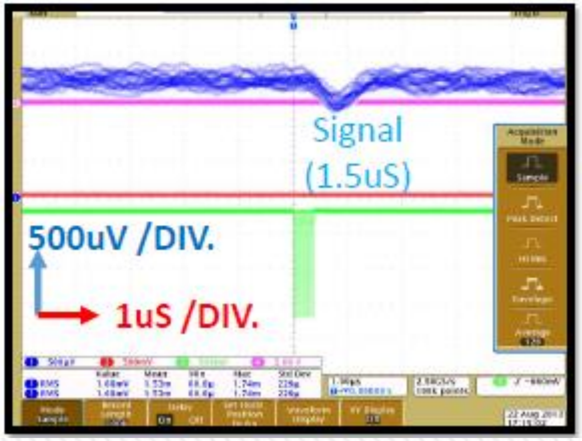
I-V curve of Josephson Junction

$I_c \sim 200\,\mu A$



- Leak current @ 0.5mV is **6nA. It is close to our best record of normal Nb/Al-STJ(100um x 100um) <u>10nA</u>**.

- **Signal of Nb/Al-STJ in SOI-STJ for 465nm laser pulse.**



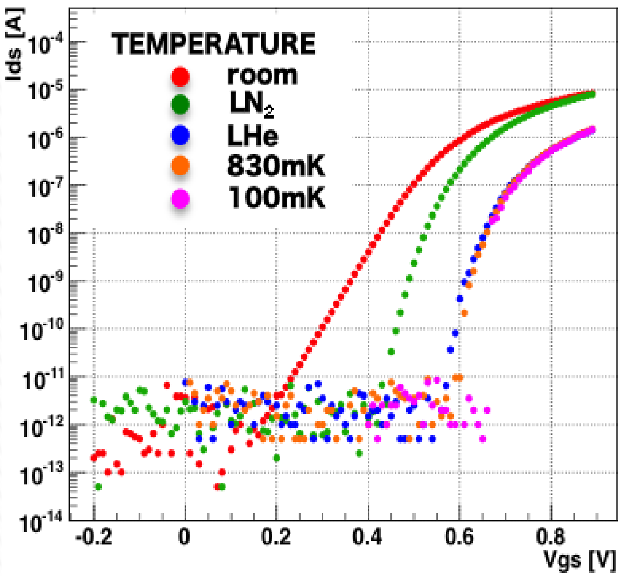
- Quality Factor ($R_{dynamic}/R_{normal}$) **On Si wafer : 5 x 10^5**
  On SOI wafer : 3 x 10^5

Performance of SOIFET in SOI-STJ detector

- **Temperature dependence**

  I-V curves at various temperatures.

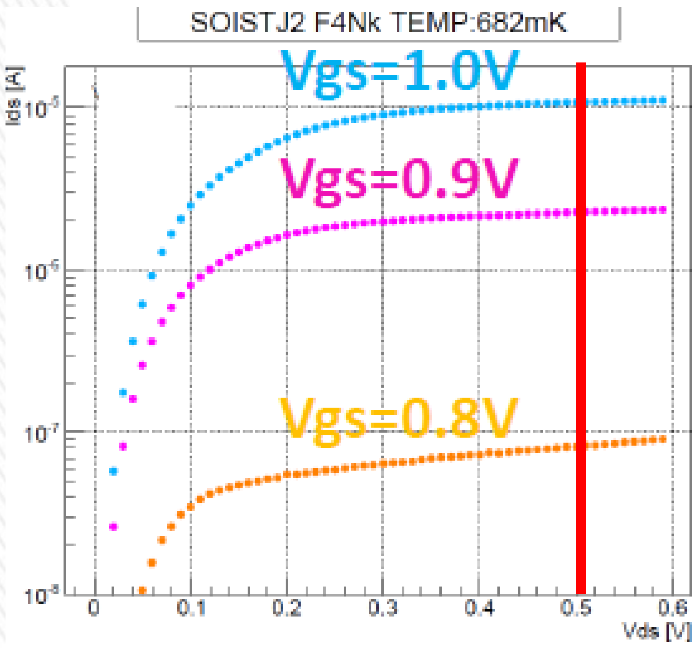
  SOIFET can be operated at 100mK.



- **Power consumption (at 680mK)**

  Bias voltage of SOIFET in saturation region (red line) : 0.5 V

  Current (I_{ds})of FET in saturation region at V_{gs} = 0.8V : 0.09 μA

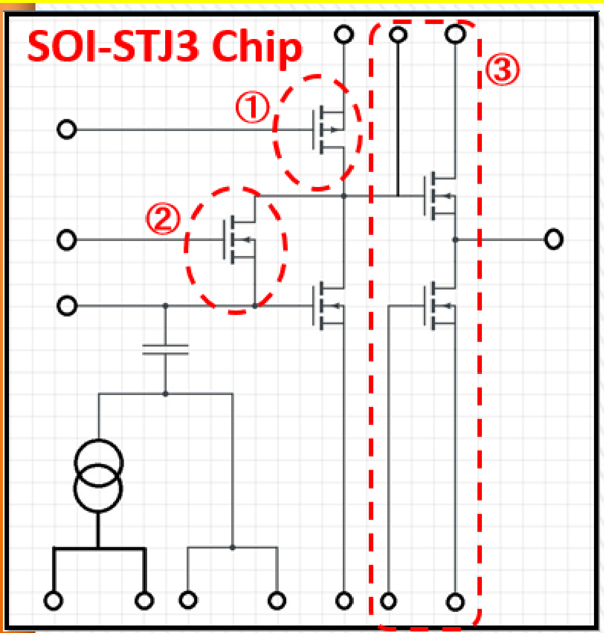


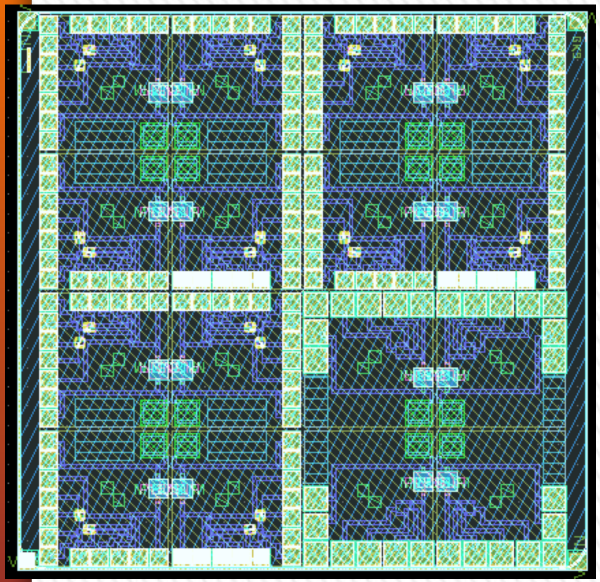
Power consumption = 0.5 V × 0.09 μA

= 45 nW/FET

for W/L=1.42μm/0.42μm

Future Plan of SOI-STJ R&D





We are updating the SOI-STJ design for the amplification of the Nb/Al-STJ signal.

1. Replace the resistance to SOIFET that we use as a current source.
2. Use the feedback between the drain and the gate to apply a stable bias voltage
3. Add the follower to reduce the output impedance.

Designed the ratio (W/L) to set the operation power consumption below 120 μ W.

AIST group joined us on the SOI-STJ R&D and is processing the SOI on the STJ3 board made by LAPIS.

We will measure the response of this new SOI-STJ to laser light soon.

R&D of Superconducting Tunnel Junction (STJ) Detctor

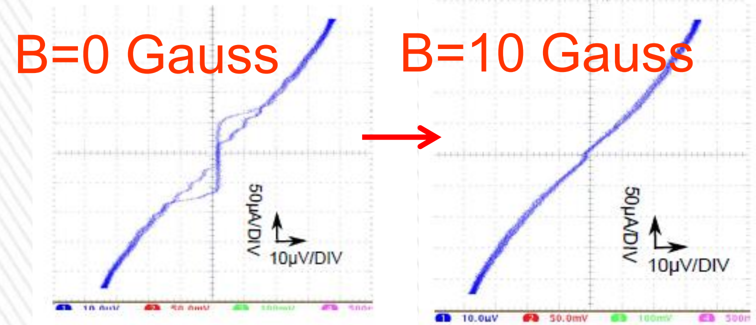
Hf-STJ

Goal: Measure energy of a single far-infrared photon for neutrino decay search experiment within 2% energy resolution.

Micro-calorimeter: Hf-STJ can generate enough statistics of quasi-particles from cooper pair breakings to achieve 2% energy resolution for photon with $E_\gamma = 25$ meV.

Material	$T_c(K)$	Δ(meV)
Niobium	9.20	1.550
Aluminum	1.14	0.172
Hafnium	0.13	0.021

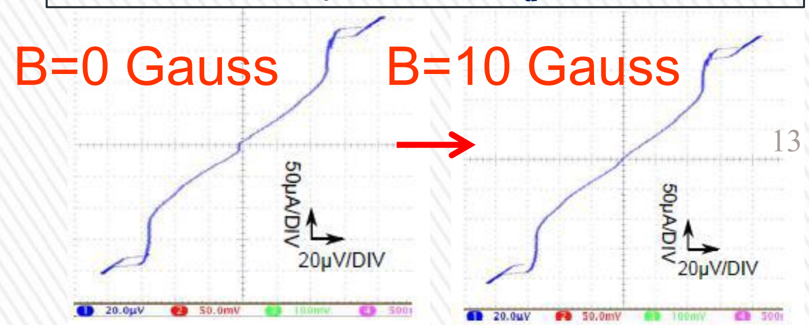
I-V curve of Hf-STJ (**200x200μm^2**)
- T~80mK, I_c=60μA, **R_d=0.2Ω**



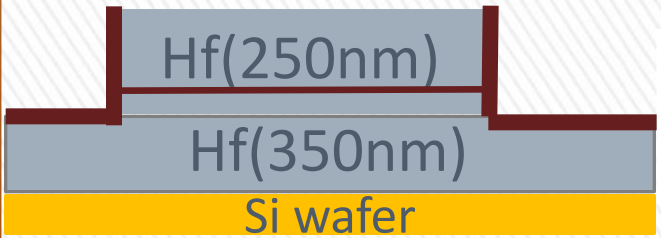
Hf-STJ (100x100μm^2) shows smaller leakage current than **Hf-STJ (200x200μm^2)** which we have established to work as a STJ in 2011.

The work to reduce a large leakage current of Hf-STJ is underway.

I-V curve of Hf-STJ (**100x100μm^2**)
- T~40mK, I_c=10μA, **R_d=0.6Ω**



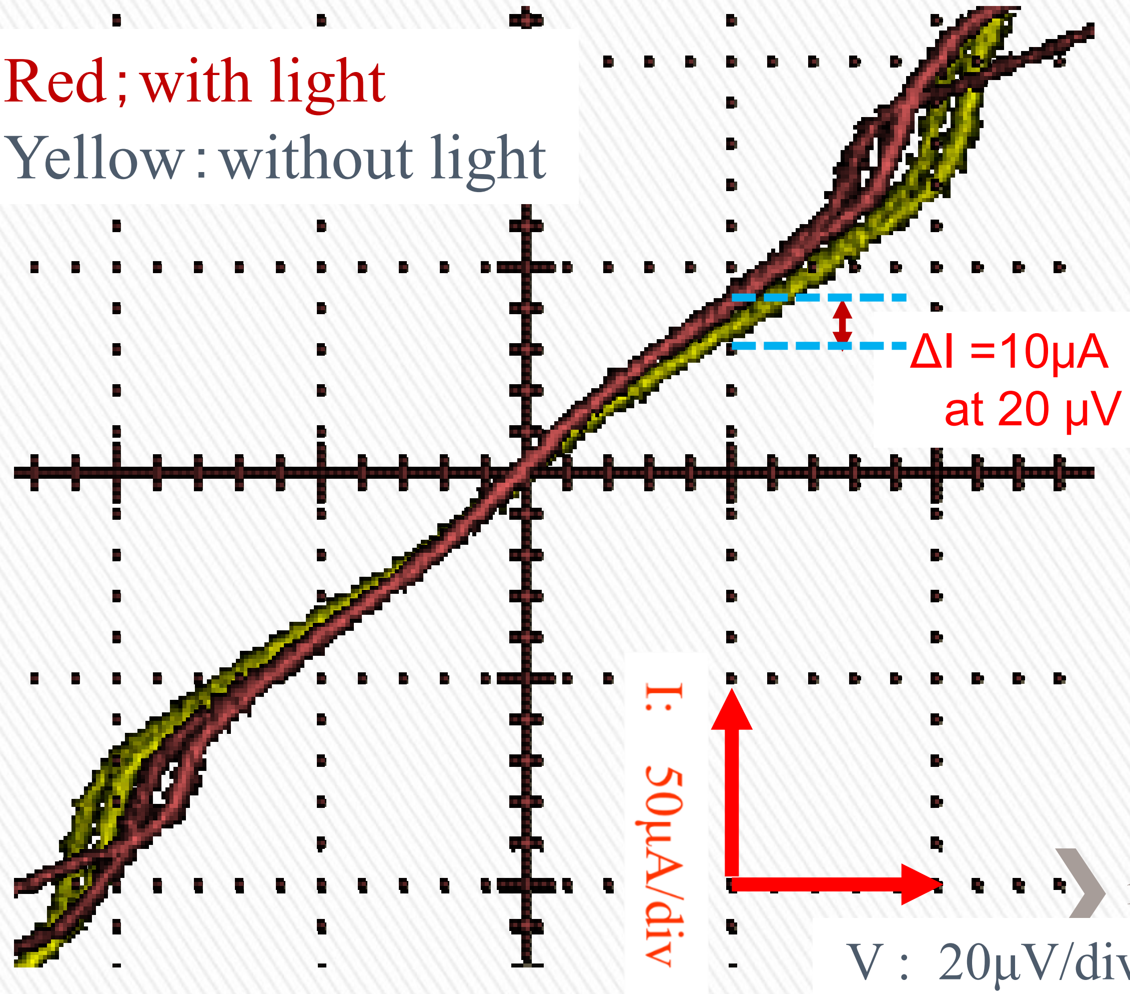
Hf-STJ Response to DC visible light



HfOx : 20Torr,1hour 1.5nm

$100\times100\mu m^2$
T=39~53mK
R_d=0.6Ω

I-V Curve with and without visible laser light (λ=465nm f=100kHz)



We are testing smaller Hf-STJ's to decrease the leakage current.

Summary

1. We are developing STJ-based detectors to detect a single far-infrared photon in energy range between 15 and 30meV to search for the cosmic background neutrino decay with a rocket or satellite experiment.

2. The SOI-STJ detector where Nb/Al-STJ's were processed on a SOIFET board is being developed. Both SOIFET and STJ are working well in the SOI-STJ detector below 800mK.

3. Hf-STJ response to the visible light was observed. Improvement to reduce the leakage current is underway.