March 5, 2018

Development of Superconducting Tunnel Junction Infrared Photon Detector for Cosmic Background Neutrino Decay Search
– COBAND Experiment –

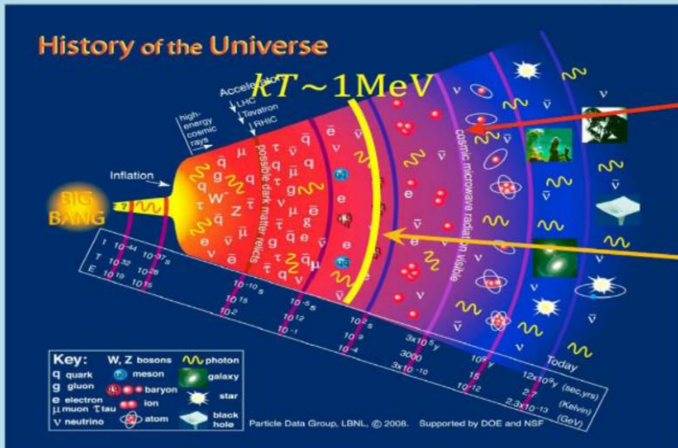
Shin-Hong Kim （University of Tsukuba, TCHoU）
for COBAND collaboration

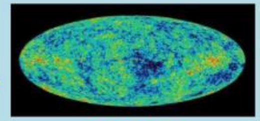
at the close-out meeting of
“the Unification and Development of the Neutrino Frontier”

筑波大学
宇宙史研究センター
Tomonaga Center for the History of the Universe

COBAND

COBAND (COsmic BAckground Neutrino Decay) Collaboration





CMB

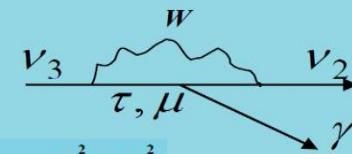
$n_\gamma = 411/\text{cm}^3$

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

CνB

$$n_\nu = n_{\bar{\nu}} = \frac{3}{4}\left(\frac{T_\nu}{T_\gamma}\right)^3 \frac{n_\gamma}{2} = 56/\text{cm}^3$$

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



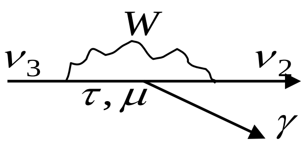
$$E_\gamma = \frac{m_3^2 - m_2^2}{2m_3}$$

S.H. Kim, Y. Takeuchi, K. Takemasa, K. Nagata, K. Kasahara, S. Yagi, R. Wakasa, R. Senzaki, K. Moriuchi, C. Asano, T. Iida (University of Tsukuba),
S. Matsuura (Kwansei Gakuin University),
H. Ikeda, T. Wada, K. Nagase, S.Baba (JAXA),
Y. Arai, I. Kurachi, M. Hazumi (KEK),
T. Yoshida, M. Sakai, T. Nakamura (University of Fukui),
Y. Kato (Kindai University),
K. Kiuchi, S. Mima (RIKEN),
H. Ishino, H. Kibayashi (Okayama University),
S. Shiki, G. Fujii, M. Ukibe, M. Ohkubo (AIST),
S. Kawahito (Shizuoka University),
E. Ramberg, P. Ruvinov, D. Sergatskov (Fermilab),
S.B. Kim (Seoul National University)

COBAND

Motivation of Search for Cosmic Background Neutrino Decay

- **Why three generations ? Why such mass hierarchy with large mass differences ?**
  Only neutrino masses are not measured . To determine the neutrino mass itself is an important subject.
  Neutrino decay observation can determine the neutrino mass.



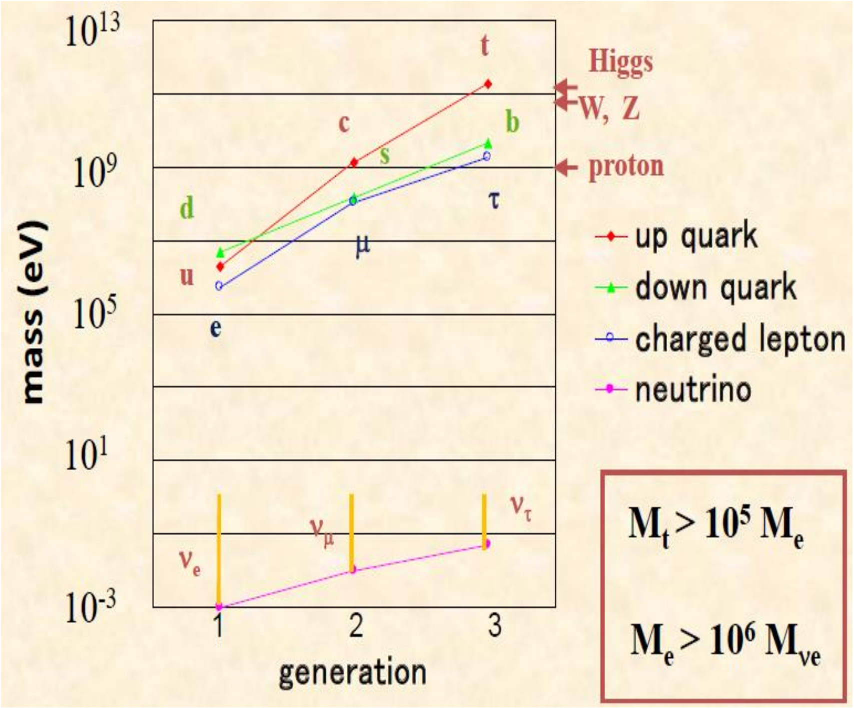
$$\nu_3 \rightarrow \nu_2 + \gamma$$

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

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.

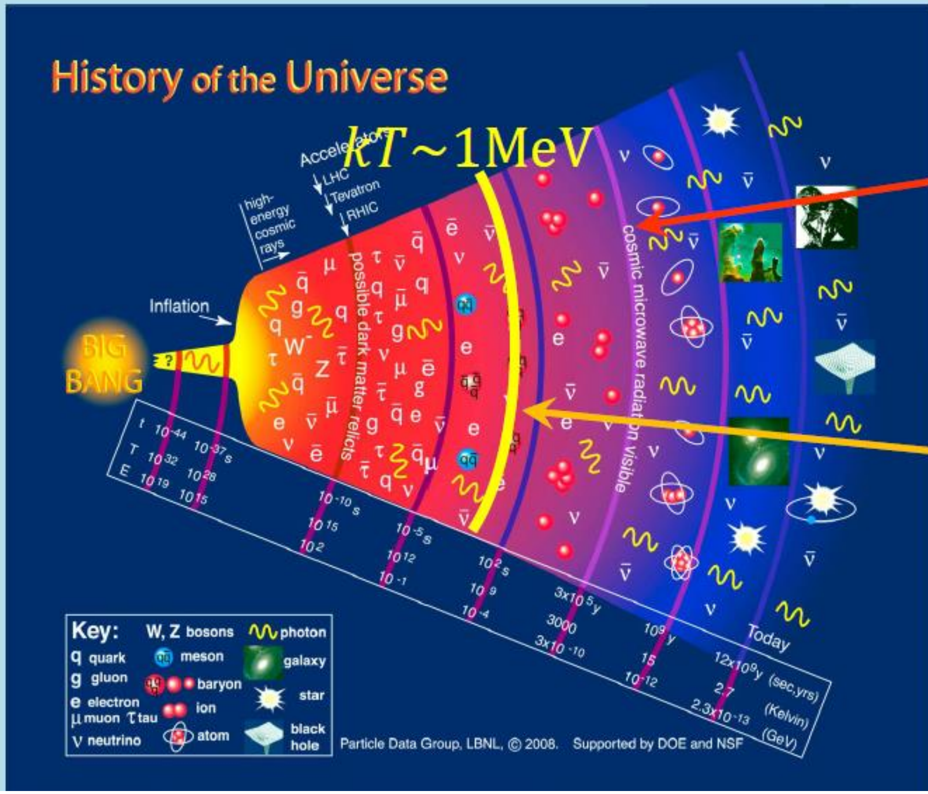
(Far - Infrared region $\lambda = 50 \sim 125\ \mu$)

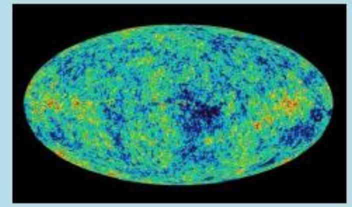


- **As the neutrino lifetime is very long, we need use cosmic background neutrino to observe the neutrino decay. To observe this decay of the cosmic background neutrino means a discovery of the cosmic background neutrino predicted by cosmology.**

- **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

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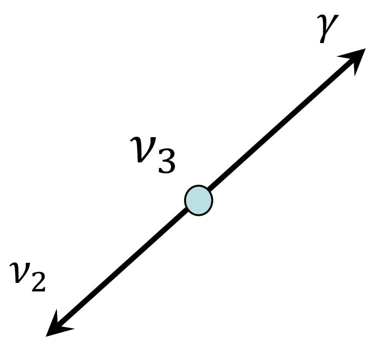
$$= 56/\mathrm{cm}^3$$
$$T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma = 1.95\mathrm{K}$$

- **A few seconds after Big Bang → Cosmic Background Neutrino (CνB) became free.**
- **300,000 years after Big Bang → Cosmic Microwave Background (CMB) became free.**

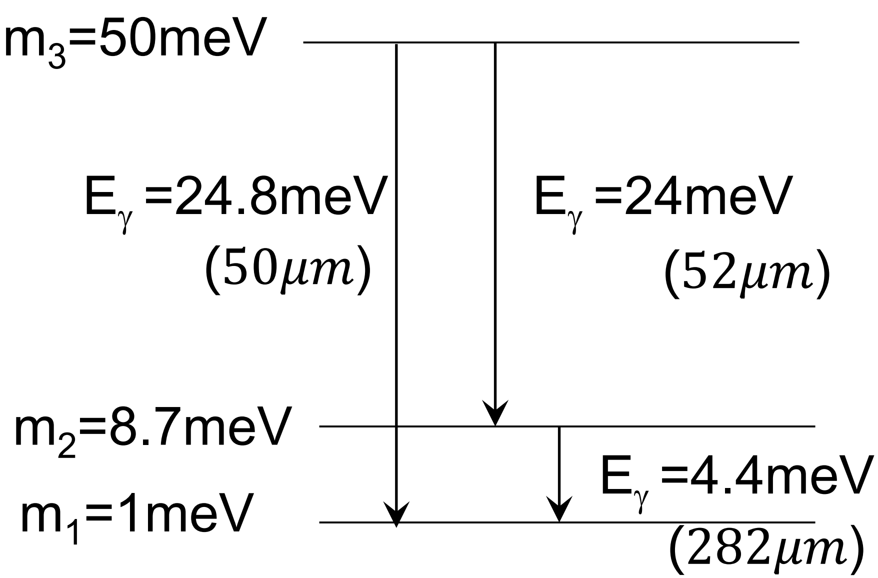
Photon Energy from Neutrino Decay

Neutrino decay

$$\nu_3 \rightarrow \nu_{2,1} + \gamma$$



$$E_\gamma = \frac{m_3^2 - m_{1,2}^2}{2m_3}$$

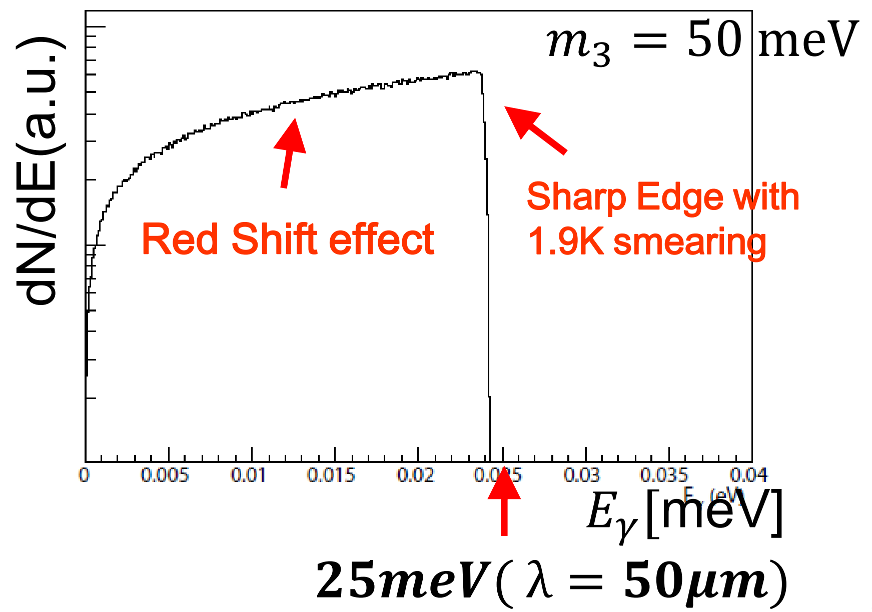


- **Neutrino oscillation results**
  - $|\Delta m_{23}^2| = |m_3^2 - m_2^2| \sim 2.4 \times 10^{-3}\ eV^2$
  - $\Delta m_{12}^2 \sim 7.65 \times 10^{-5}\ eV^2$
- **Space observatory results (Planck+WP+highL+BAO)**
  - $\sum m_i < 0.23\ eV$

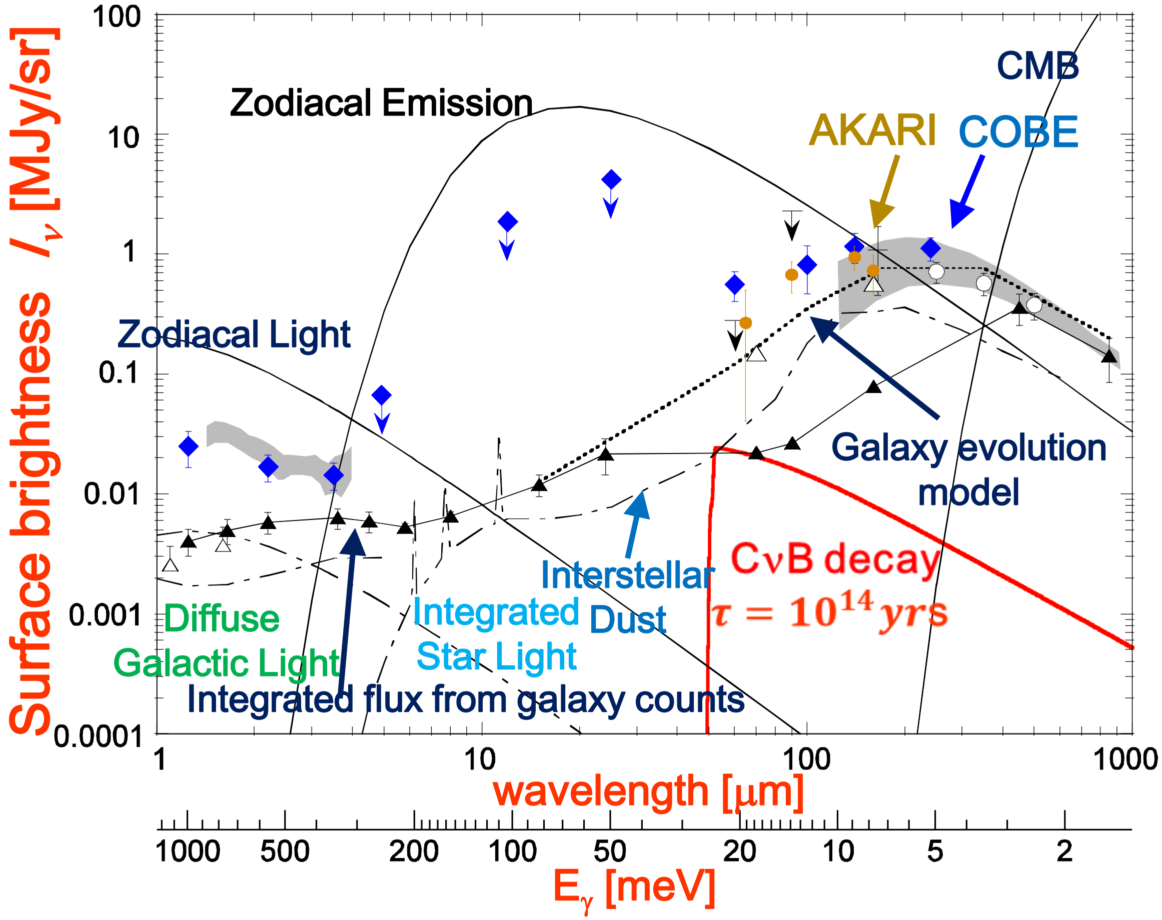
➔ **50meV<m_3<87meV**

E_γ =14~24meV (λ_γ =51~89μm)

Photon energy distribution $\nu_3 \rightarrow \nu_2 + \gamma$



Photon Energy Spectrum from Outer Space



Cosmic Infrared Background (CIB) measurements (● AKARI, ◆ COBE)

There was an excess of the CIB measured by COBE and AKARI over the prediction by galaxy evolution model.

Sources at FIR: dusts of far galaxies or far blackhole, or CνB decay ?

Our paper published in JPSJ on Jan. 18th, 2012

Journal of the Physical Society of Japan **81** (2012) 024101 FULL PAPERS

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Search for Radiative Decays of Cosmic Background Neutrino using Cosmic Infrared Background Energy Spectrum

Shin-Hong KIM*, Ken-ichi TAKEMASA, Yuji TAKEUCHI, and Shuji MATSUURA[1]

Graduate School of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Ibaraki 305-8571, Japan

[1]*Institute of Space and Astronautical Science, JAXA, Sagamihara 252-5210, Japan*

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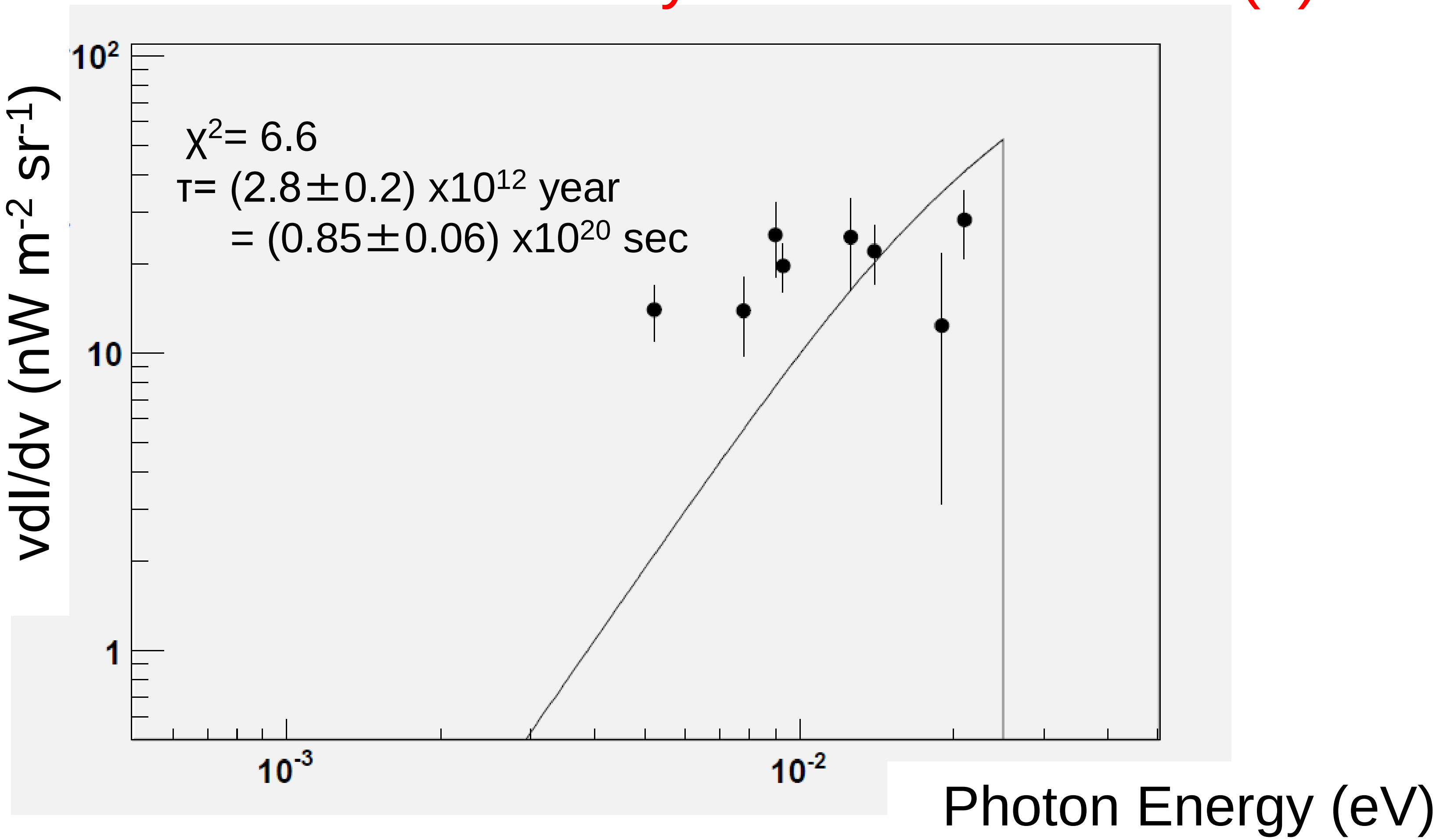
We propose to search for the neutrino radiative decay by fitting a photon energy spectrum of the cosmic infrared background to a sum of the photon energy spectrum from the neutrino radiative decay and a continuum. By comparing the present cosmic infrared background energy spectrum observed by AKARI and Spitzer to the photon energy spectrum expected from neutrino radiative decay with a maximum likelihood method, we obatined a lifetime lower limit of 3.1×10^{12} to 3.8×10^{12} years at 95% confidence level for the third generation neutrino ν_3 in the ν_3 mass range between 50 and 150 meV/c^2 under the present constraints by the neutrino oscillation measurements. In the left–right symmetric model, the minimum lifetime of ν_3 is predicted to be 1.5×10^{17} years for m_3 of 50 meV/c^2. We studied the feasibility of the observation of the neutrino radiative decay with a lifetime of 1.5×10^{17} years, by measuring a continuous energy spectrum of the cosmic infrared background.

KEYWORDS: neutrino radiative decay, neutrino mass, cosmic background neutrino, cosmic infrared background, COBE, AKARI, Spitzer

Search Region: $\lambda =$ 35〜250μm （$E_\gamma =$ 35〜5meV）

In Rocket experiment, $\lambda =$ 40〜80μm （$E_\gamma =$ 31〜15meV）

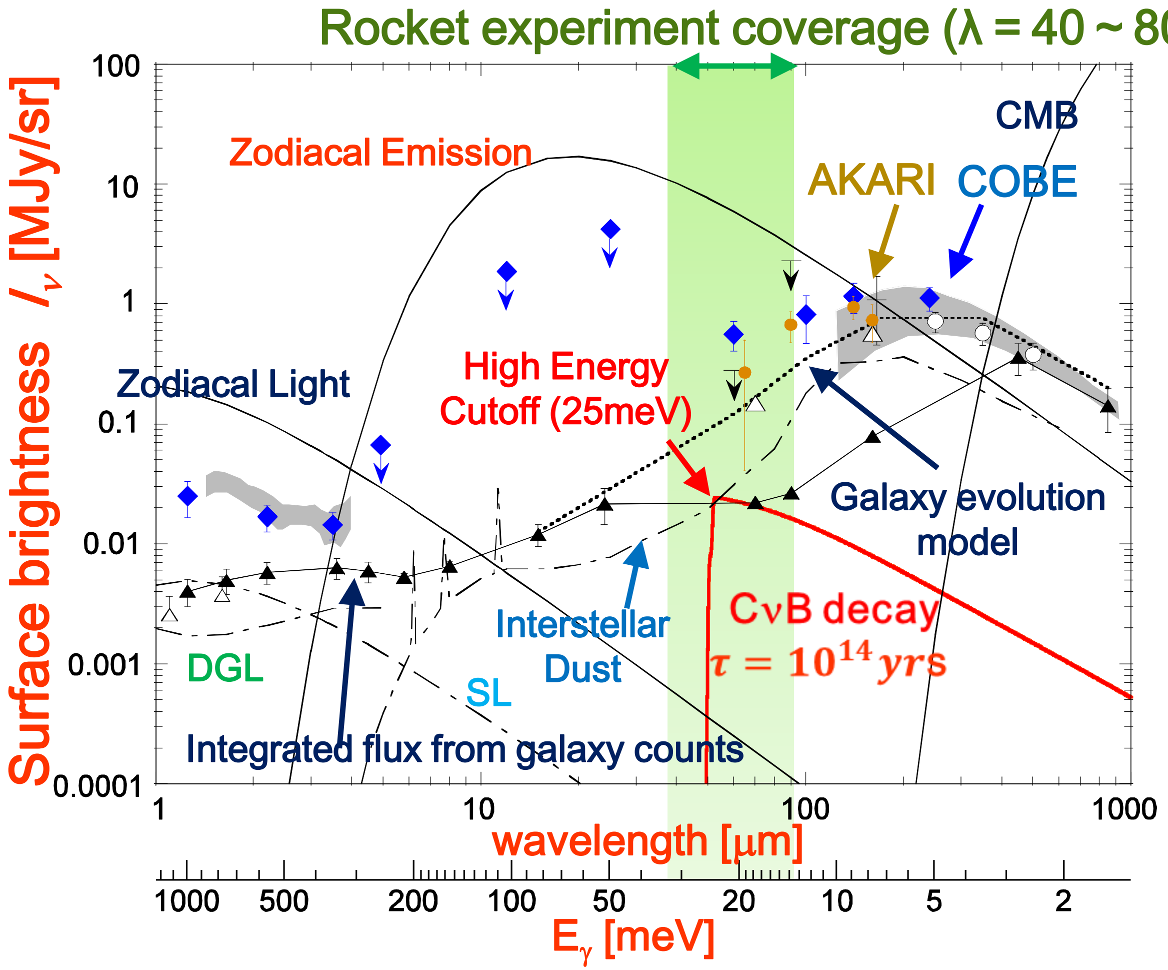
Lower Limit of Lifetime from the Energy Spectrum Fit the CIB measured by COBE and AKARI(1)



Using the CIB at 60, 100 (ApJ, 544, 81, 2000), 140, 240 μm (ApJ, 508, 25, 1998), 65, 90, 140, and 160 μm (arXiv:1002.3674, 2010), the photon energy spectrum from neutrino radiative decay gives a lifetime lower limit of 2.4 x 10^{12} year at 95% C.L. for m_3 = 0.05eV and m_2 = 0.01eV. (My calculation)

Cosmic Background Neutrino Decay Search (COBAND)

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 $E_\gamma \sim 25\,\mathrm{meV} (\lambda = 50\mu m)$
- 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

COBAND (COsmic BAckground Neutrino Decay Search) Experiment

Rocket Experiment Plan: 5minutes data acquisition at 200 km height in 2019.

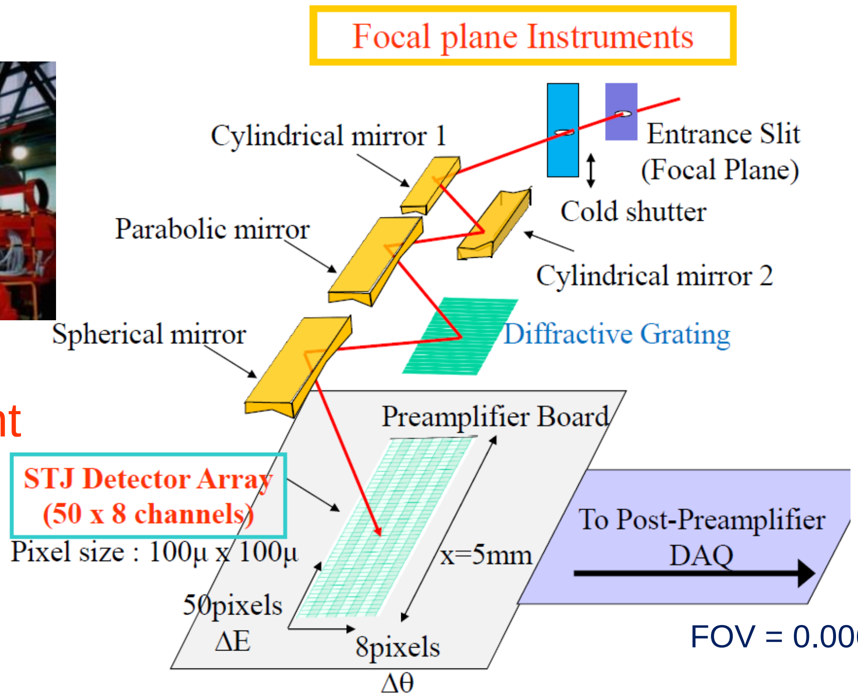
Improve the current limit of lifetime $\tau(\nu_3)$ by two orders of magnitude (~10^{14}years).

»Superconducting Tunneling Junction (STJ) detectors in development

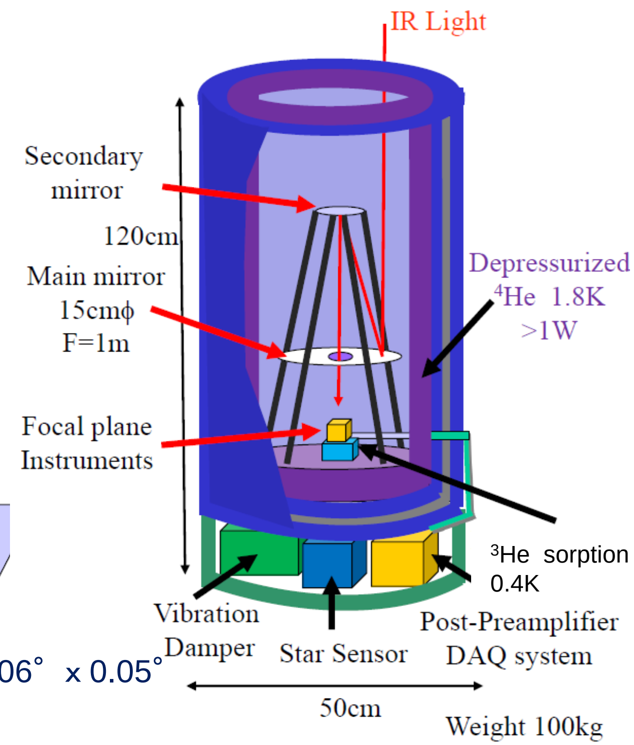
> **Array of 50 Nb/Al-STJ pixels with diffractive grating covering $\lambda = 40 - 80\mu m$**

JAXA Rocket
CIB Experiment

(Feb 2, 1992)



FOV = 0.006° x 0.05°



Satellite experiment after 2025 → **sensitivity of $\tau(\nu_3)$ ~10^{17}year**

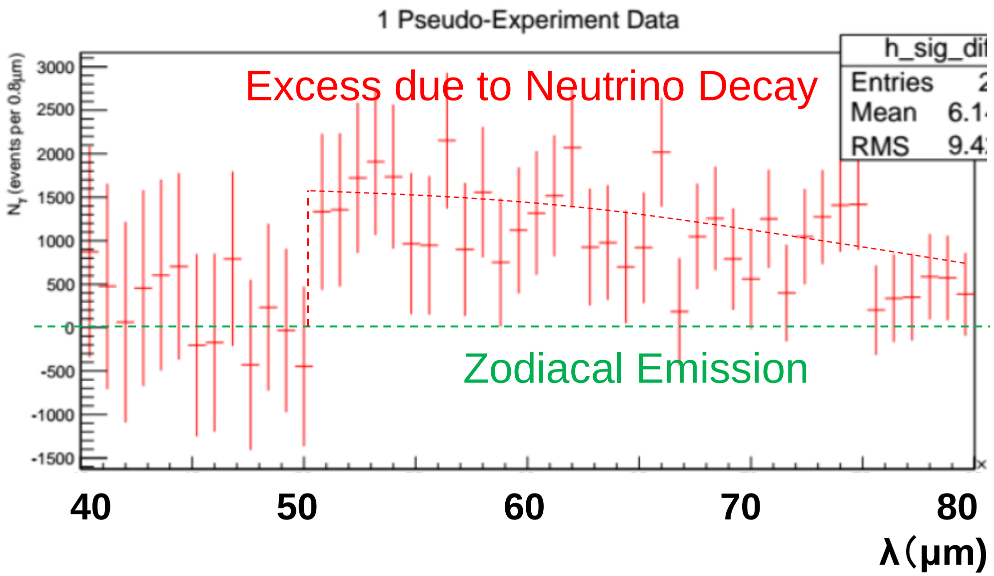
> STJ using Hafnium: Hf-STJ for satellite experiment (S. H. Kim et al. JPSJ 81,024101 (2012))

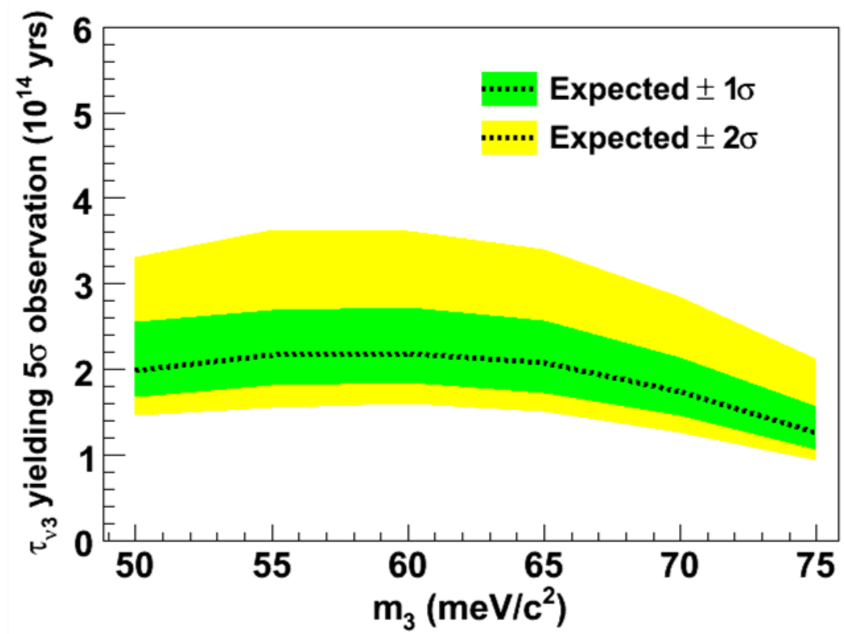
- $\Delta = 20\mu$eV : Superconducting gap energy for Hafnium
- $N_{q.p.} = 25\text{meV}/1.7\Delta = 735$ for 25meV photon: $\Delta E/E < 2\%$ if Fano-factor is less than 0.3

Sensitivity to Neutrino Decay

Parameters in the rocket experiment simulation

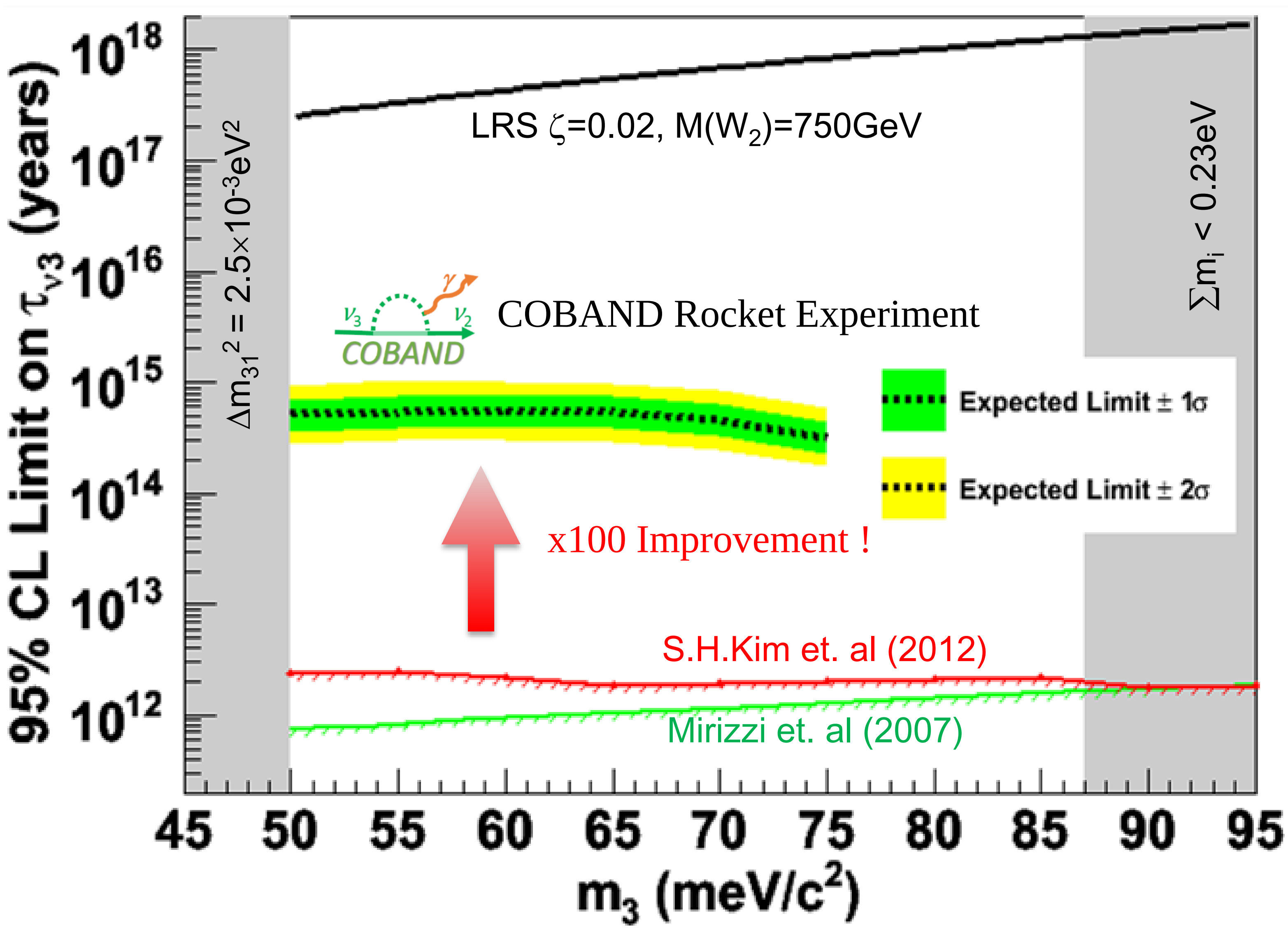
- telescope diameter: 15cm
- 50-column (λ: 40μm – 80 μm) $\times$ 8-row array
- Viewing angle per single pixel: 100μrad $\times$ 100μrad
- Measurement time: 200 sec.
- Photon detection efficiency: 100%





- If ν_3 lifetime were 2×10^{14} yrs, the signal significance is at 5σ level

COBAND Experiment Sensitivity to Neutrino Decay



Requirement for the photon detector in COBAND rocket experiment

- Sensitive area of 100μm×100μm for each pixel
- High detection efficiency for a far-infrared single-photon in $\lambda = 40\mu m \sim 80\mu m$
- Dark count rate less than 300Hz (expected real photon rate)

$$\rightarrow \quad \text{NEP} = \epsilon_\gamma \sqrt{2 f_\gamma} \sim 1\times10^{-19}\ W/\sqrt{Hz}$$

(Noise Equivalent Power) , where ϵ_γ is a photon energy and f_γ is a photon rate.

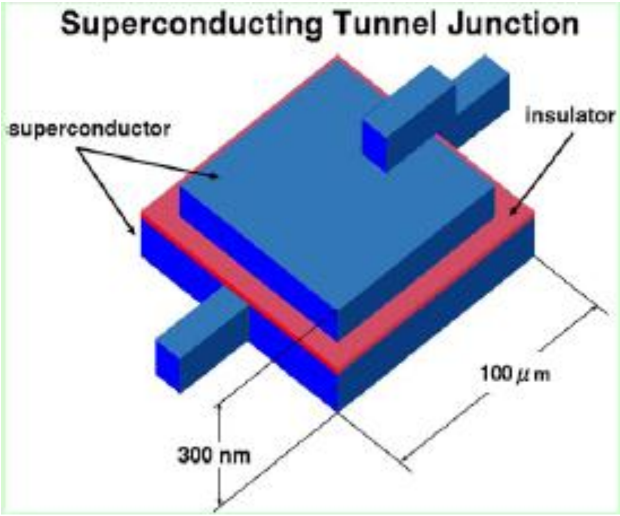
We are trying to achieve NEP $\sim 10^{-19}\ W/\sqrt{Hz}$ by using

- Superconducting Tunneling Junction detector
  (leakage current per pixel < 100pA)
- Cryogenic amplifier readout

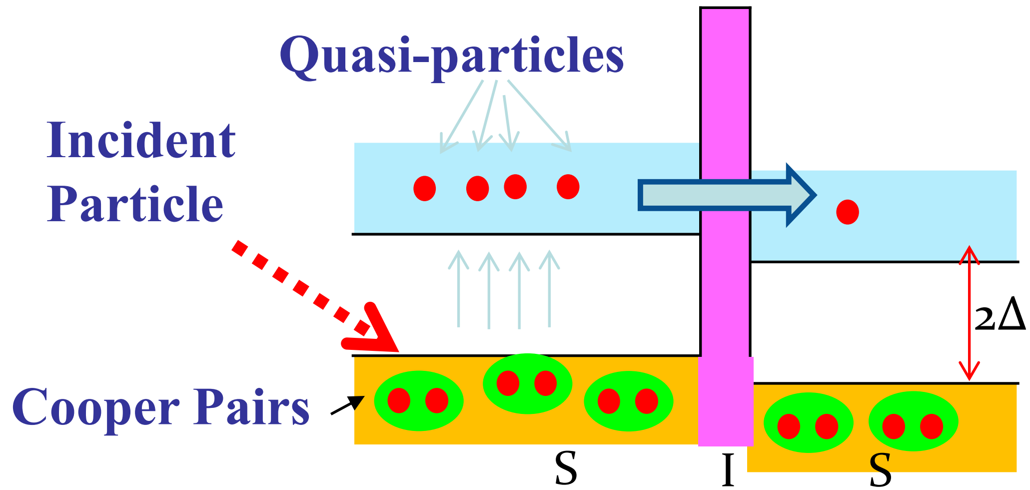
R&D Status of Superconducting Tunnel Junction Detector for COBAND experiment

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.

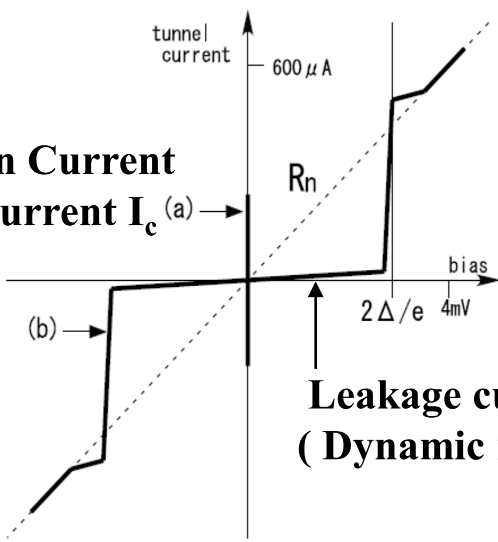


Energy gap Δ

current-voltage (I-V) curve for STJ

Josephson Current

Critical current I_c



Leakage current

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

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

STJ Energy Resolution

STJ Energy Resolution

$$\sigma_E = \sqrt{1.7\Delta(FE)}$$

Using Hf as a superconductor,

$$\sigma_E / E = 1.7\% \quad \text{at } E = 25\text{meV}$$

Δ: Band gap energy
F: Fano factor (= 0.2)
E: Incident particle energy

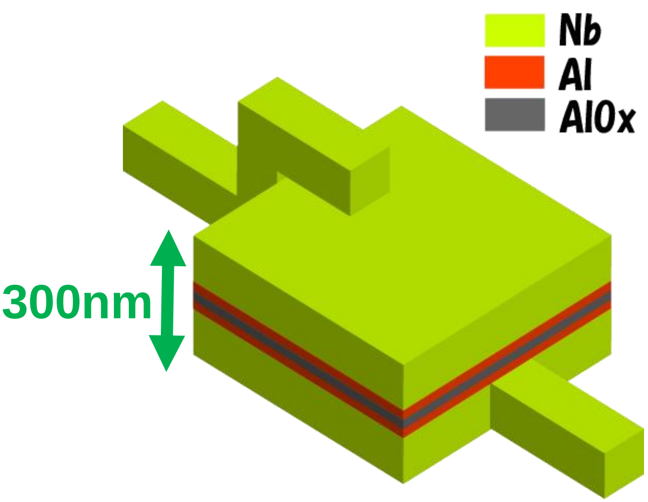
Material	$T_c(K)$	$\Delta(\text{meV})$
Niobium	9.20	1.550
Aluminum	1.14	0.172
Hafnium	0.13	0.021

Tc : Critical Temperature

Operation is done at a temperature around 1/10 of Tc

We reported that Hf-STJ worked as a STJ in 2011.

Nb/Al-STJ Photon Detector



Back tunneling Effect → Trapping Gain

Quasi-particles near the barrier can mediate Cooper pairs, resulting in true signal gain

- Bi-layer fabricated with superconductors of different gaps $\Delta_{Nb} > \Delta_{Al}$ to enhance quasi-particle density near the barrier
- Nb(200nm)/Al(70nm)/AlOx/Al(70nm)/Nb(100nm)

  $\Delta_{Nb/Al} = 0.57\text{meV}$

Number of Quasi-particles in Nb/Al-STJ

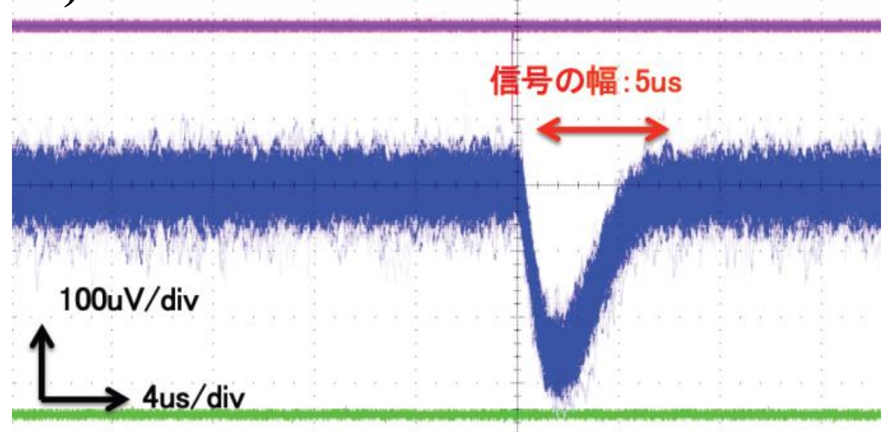
$$N_q = G_{Al}\, E_0/1.7\Delta$$

G_{Al} : Trapping Gain in Al(~10)
E_0 : Photon Energy
Δ : E-Gap in superconductor

For 25meV single photon

$$N_q = 10\,\frac{25\ meV}{1.7 * 0.57\ meV}$$
$$= 250\ e$$

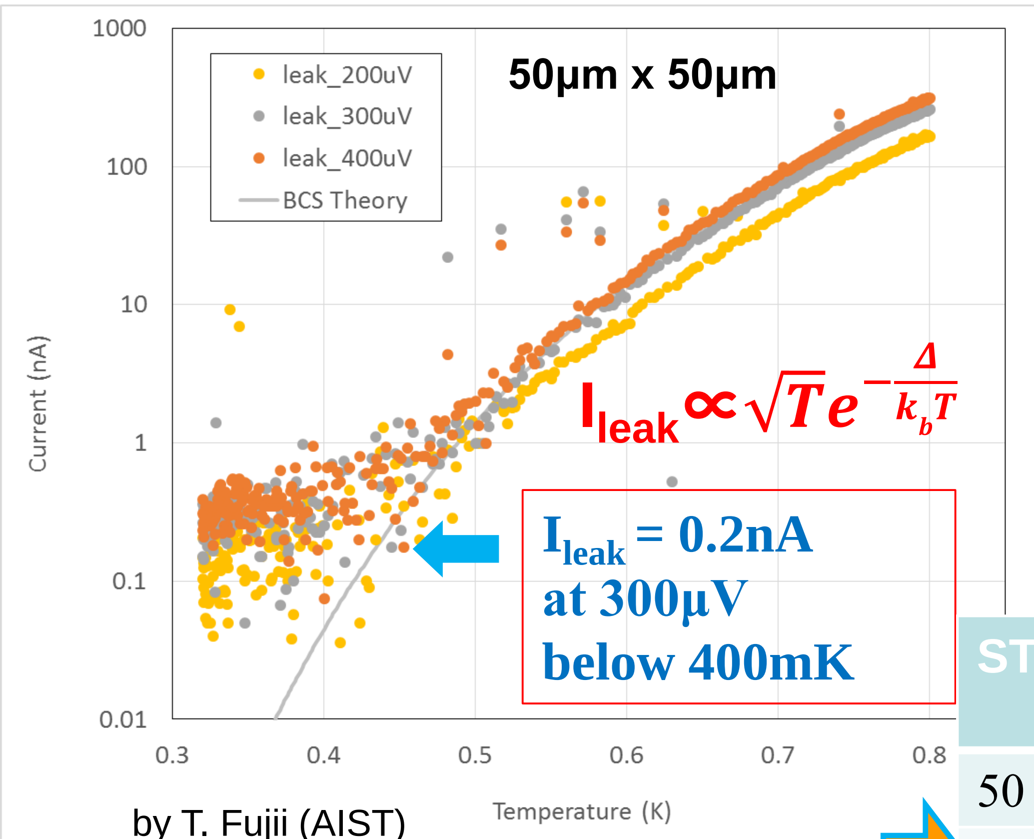
Response of Nb/Al-STJ to visible laser light pulse (λ=465nm) at 350mK



Leakage Current of Nb/Al-STJ

- **Leakage current I_{leak} is required to be below 100pA to detect a single far-infrared photon (λ= 40 -80μm) .**

Temperature Dependence of Leakage Current



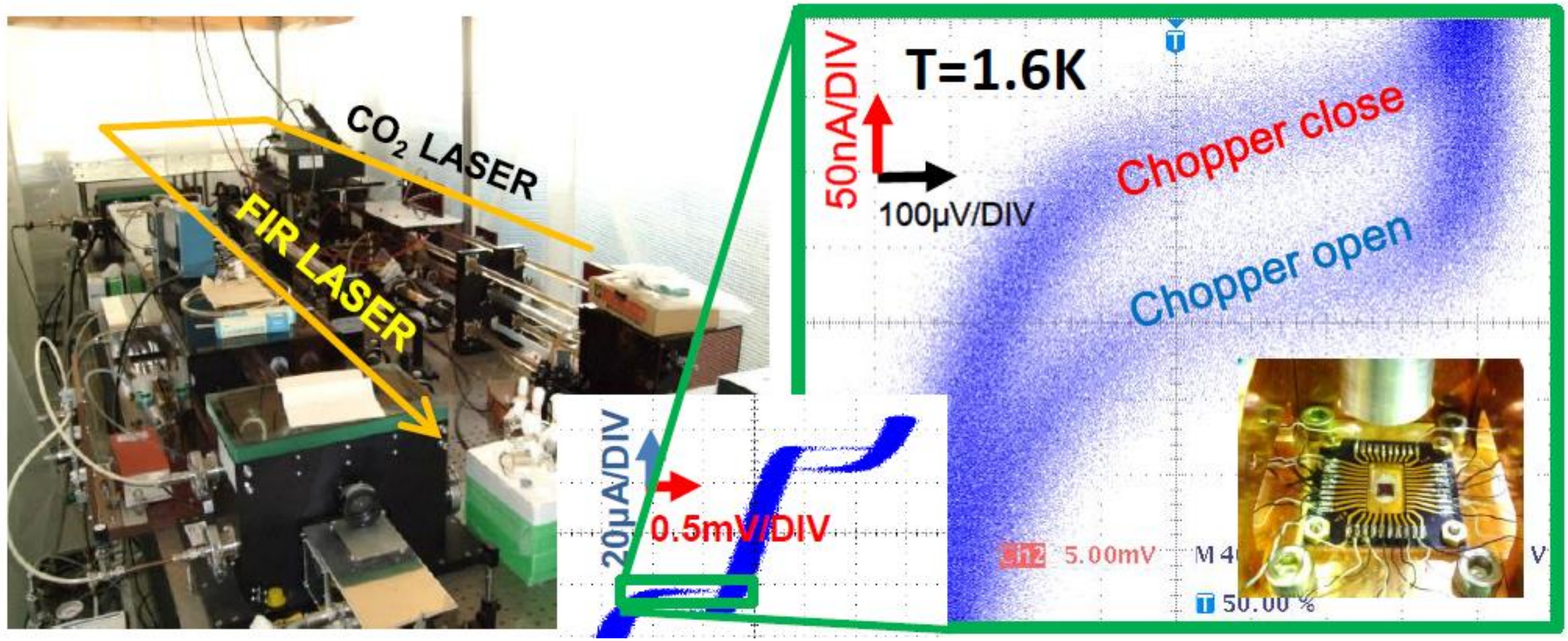
In 2014,
AIST group joined us and produced Nb/Al-STJ with AIST CRAVITY processing system.
Leakage current has satisfied our requirement of 0.1nA .

STJ size	# of samples	I_{leak} at 0.3mV
50 x 50μm^2	18	224±29 pA
20 x 20 μm^2	7	**39±13 pA**
10 x 10 μm^2	20	**14±7 pA**

Test Results of Nb/Al-STJ with Far-Infrared laser

Far-Infrared Laser at University of Fukui
(λ=57.2μm)

Nb/Al-STJ Response to Far-Infrared Laser

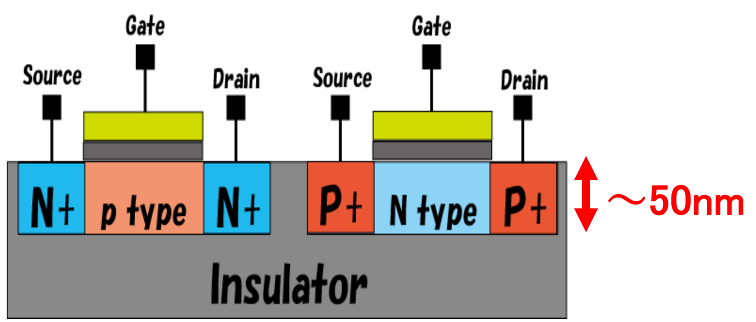


- 200μm-square Nb/Al-STJ made at AIST CRAVITY system
- Laser light was turned on and off with a chopper at a frequency of 200Hz. Measured the change of the I-V curve between the laser on and off to be 50~100nA in current.

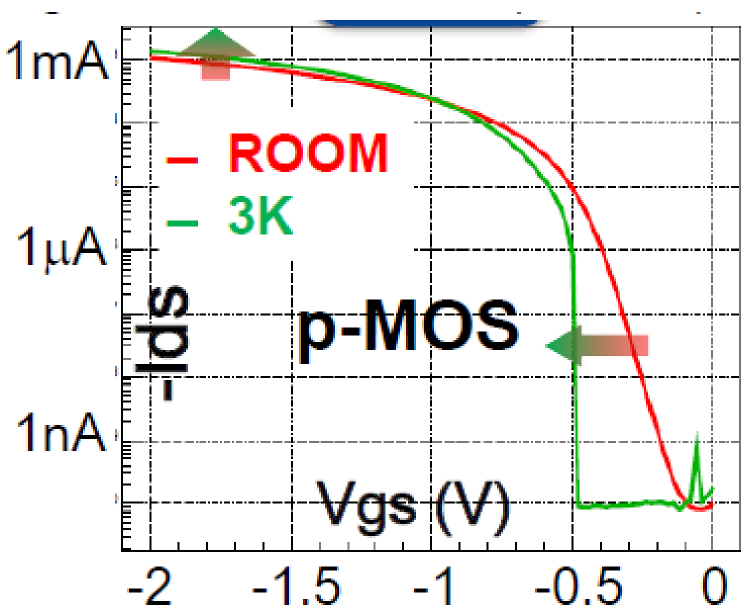
R&D Status of SOI Cryogenic Preamplifier for STJ

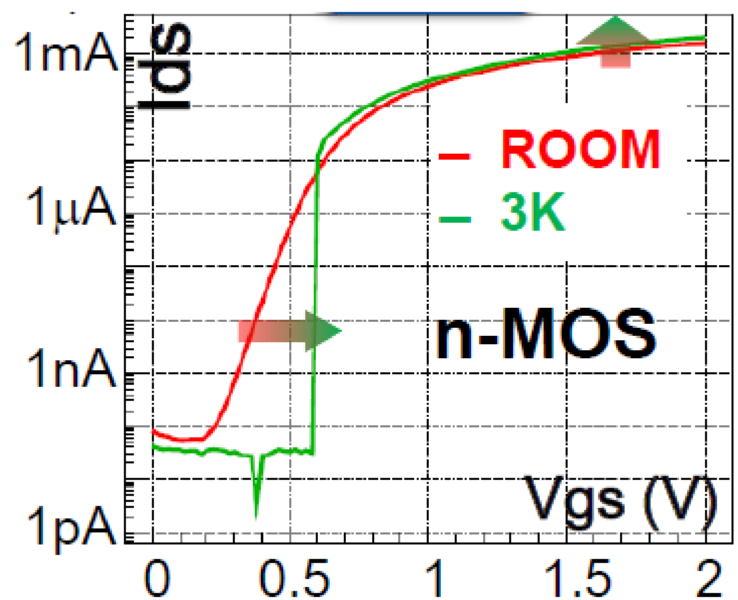
FD-SOI-MOSFET at Cryogenic Temperature

FD-SOI (Fully Depleted Silicon-On-Insulator) device was proved to operate at 4K by a JAXA/KEK group (AIPC 1185,286-289(2009)). It has the following characteristics:
low-power consumption, high speed, easy large scale integration and <u>suppression of charge-up by high mobility carrier due to thin depletion layer(～50nm).</u>



Ids-Vgs Curve of W/L=10μm/0.4μm at |Vds| = 1.8V

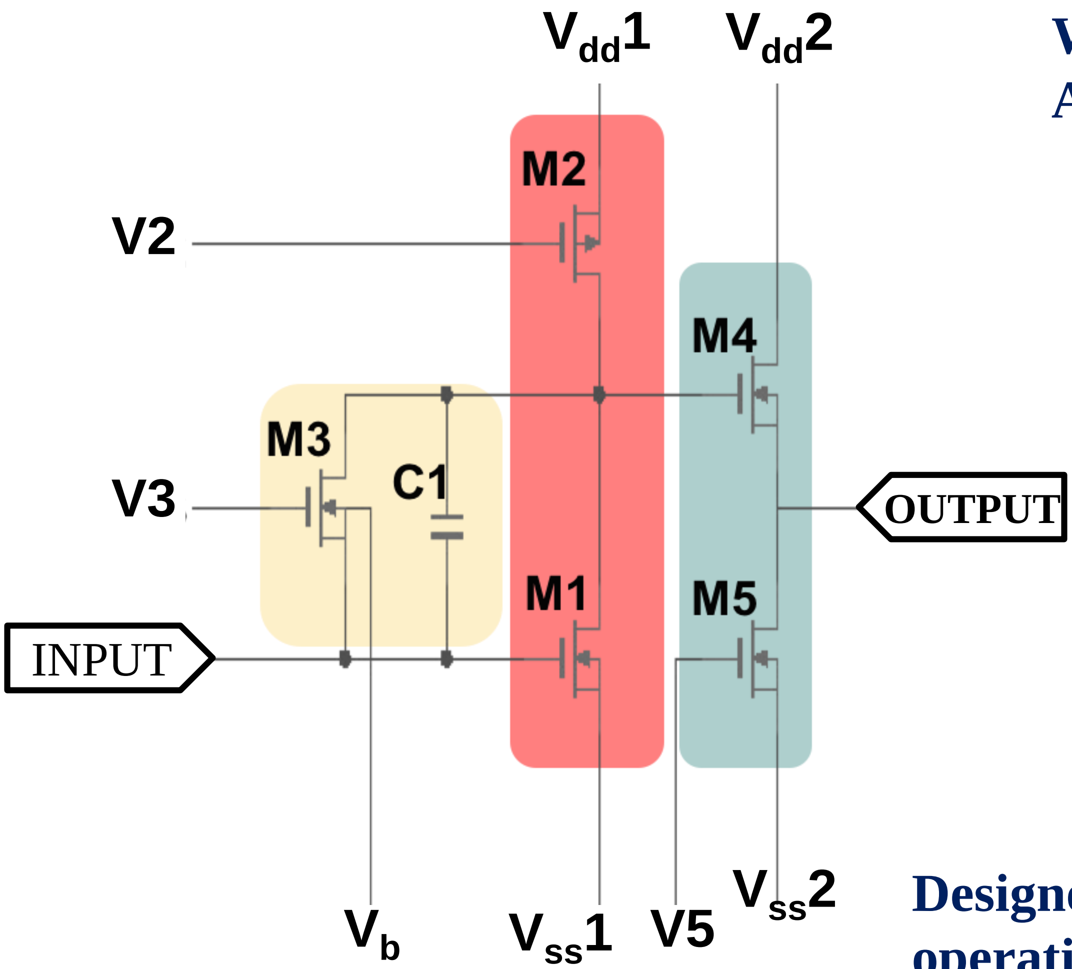




Both p-MOS and n-MOS show excellent performance at 3K and below.

SOI Cryogenic Amplifier

SOI-STJ4 (the 4th prototype)



We updated the SOI cryogenic Amplifier for Nb/Al-STJ.

Amplification
Replace the resistance by a SOIFET as a current source (M2).

Feedback
Use the feedback between the drain and the gate of M1 to apply a stable bias voltage (M3).

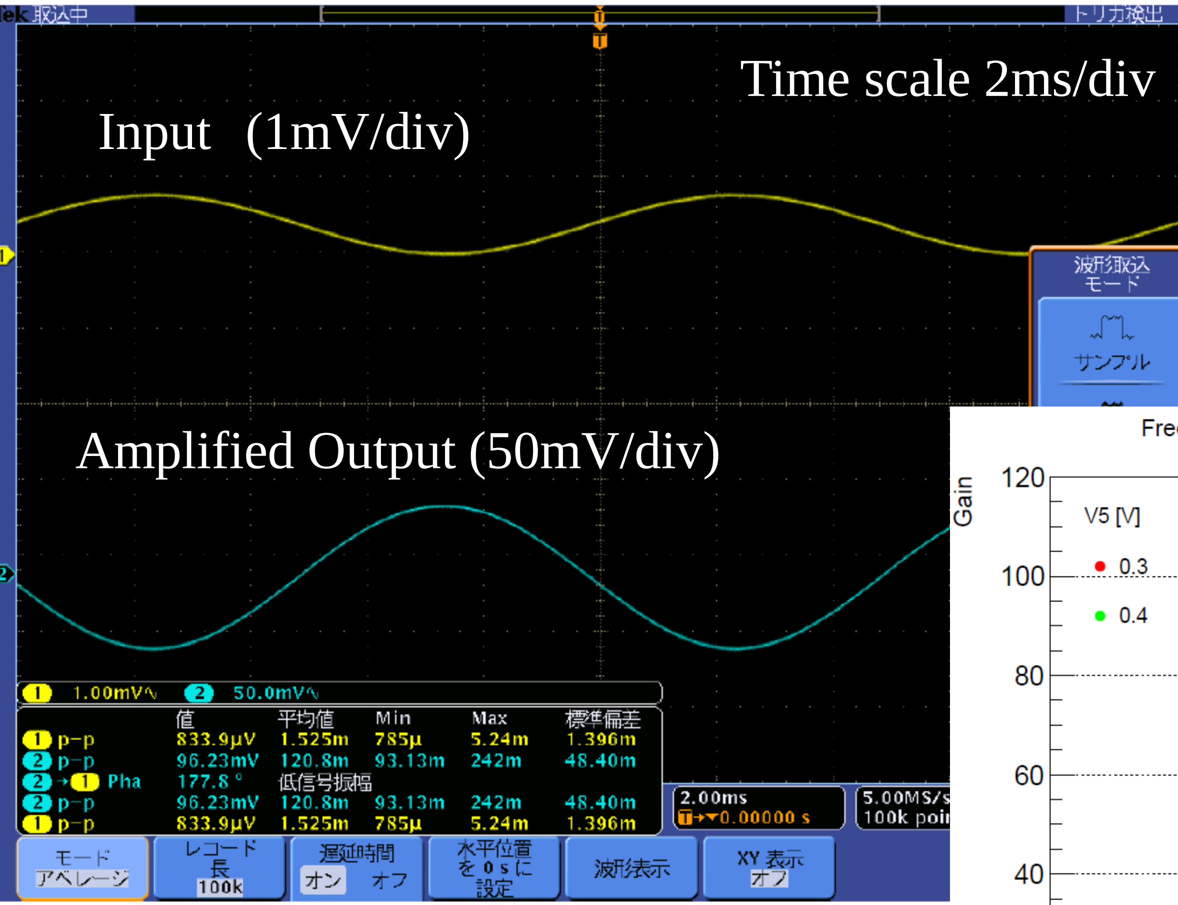
Buffer
Add the follower to reduce the output impedance (M4 and M5).

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

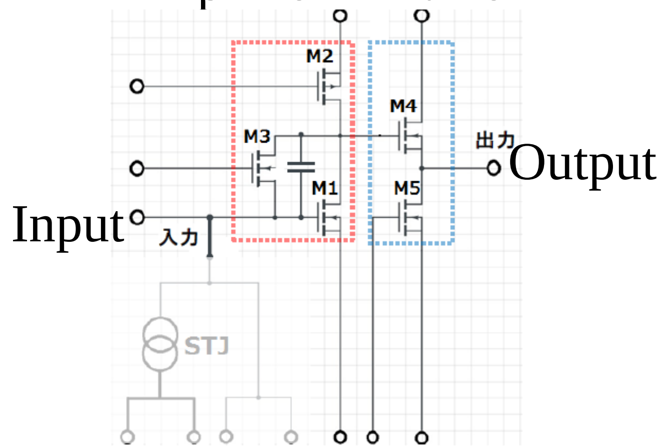
This SOI amplifier board was made by LAPIS semiconductor company.

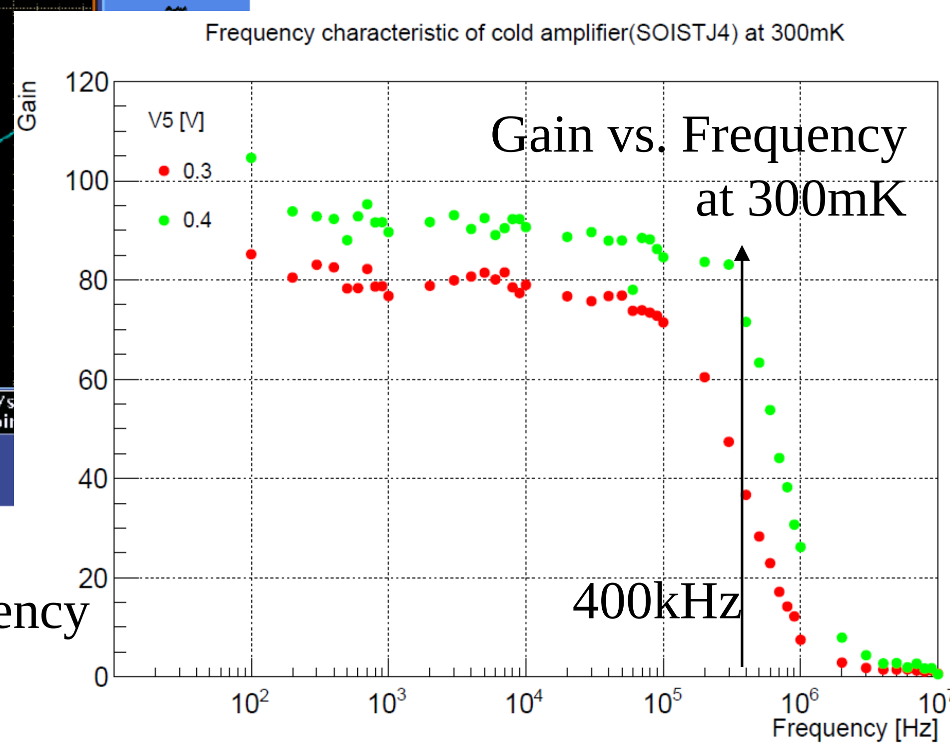
Test Results of the SOI Cryogenic Amplifier

Input and Amplified Output



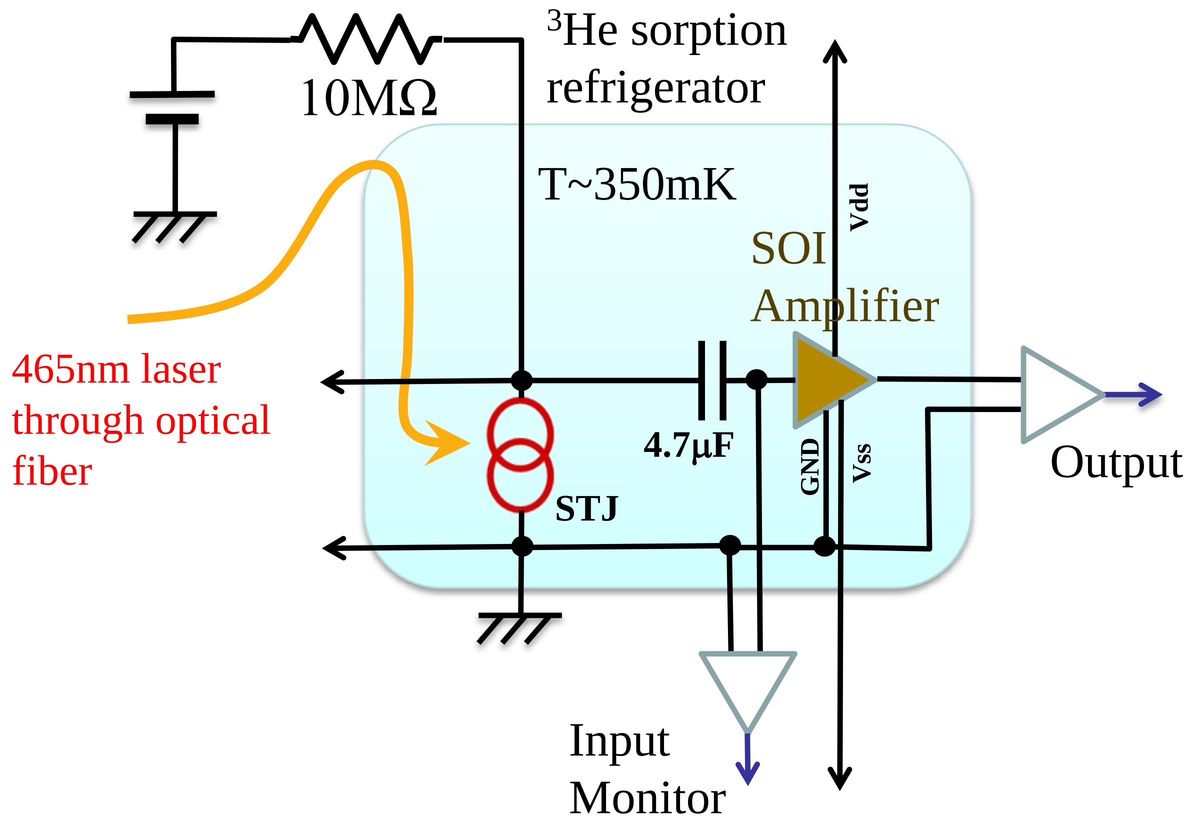
Amplifier + Buffer

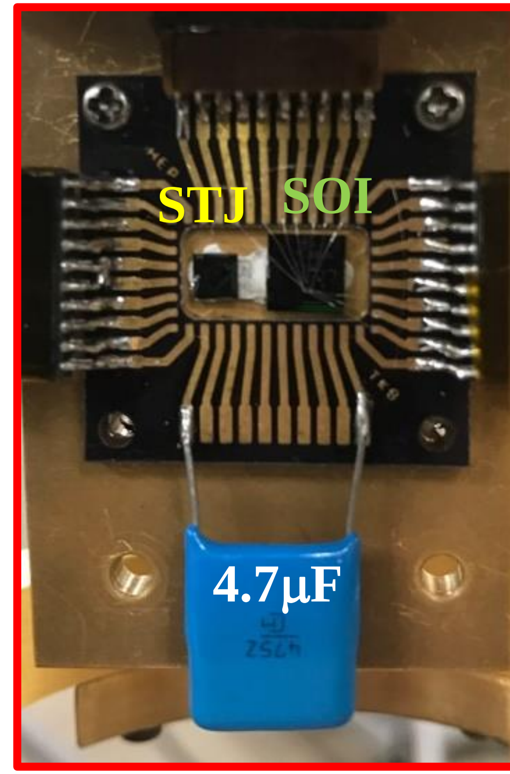




Gain of 80 was achieved for a signal frequency up to 400kHz signals at 300mK.

Setup of STJ Signal Amplification with the SOI Cryogenic Amplifier

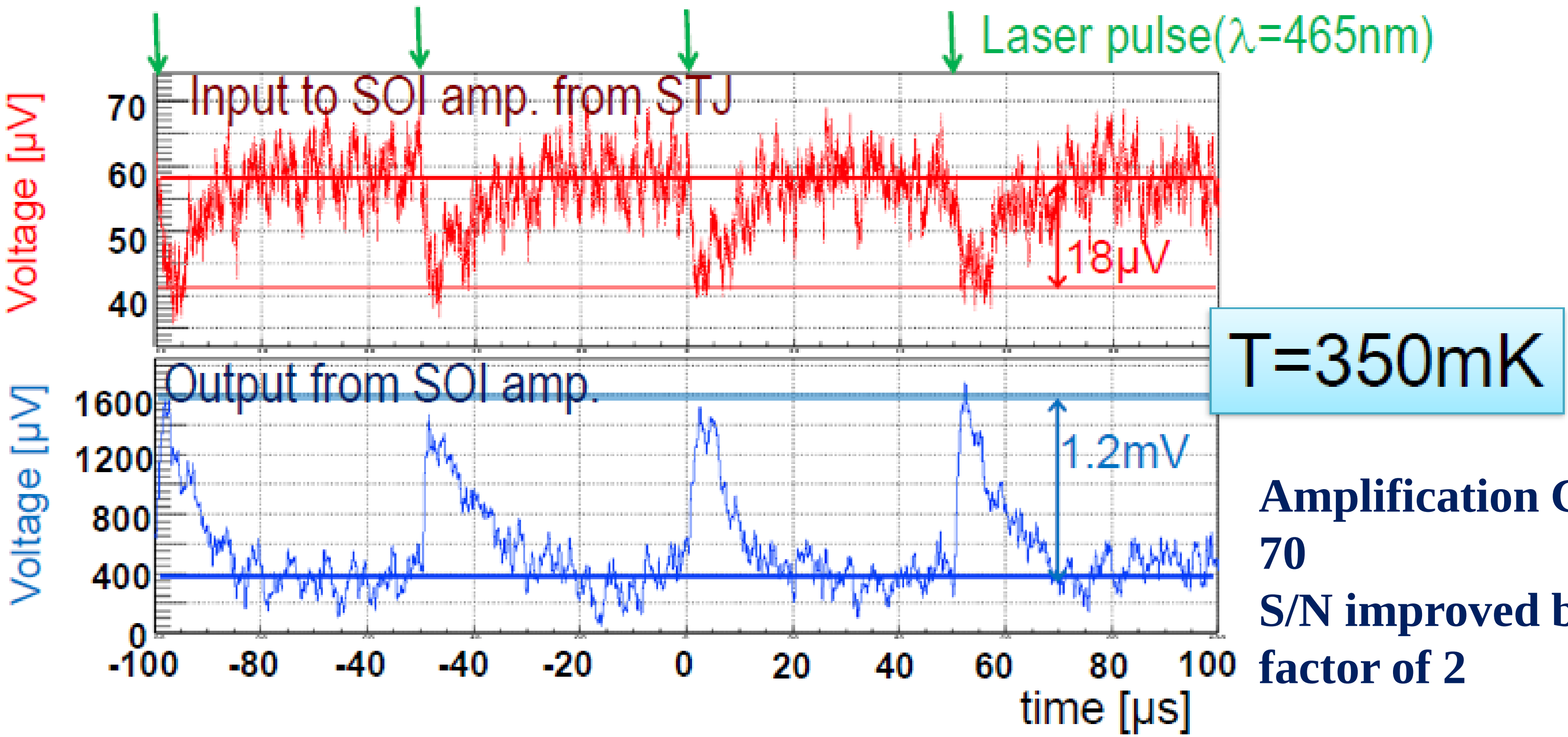




- 20μm-square Nb/Al-STJ with SOI-STJ4 amplifier through 4.7μF capacitance.
- Input impedance of the SOI amplifier is about 20kΩ.
  - STJ operation at a constant current mode.
  - STJ bias cable capacitance is around 1nF : Z=160Ω for 1μs signal.

STJ signal amplified with the SOI cryogenic preamplifier

Nb/Al-STJ laser light response signal was amplified with this SOI cryogenic preamplifier at 350mK.

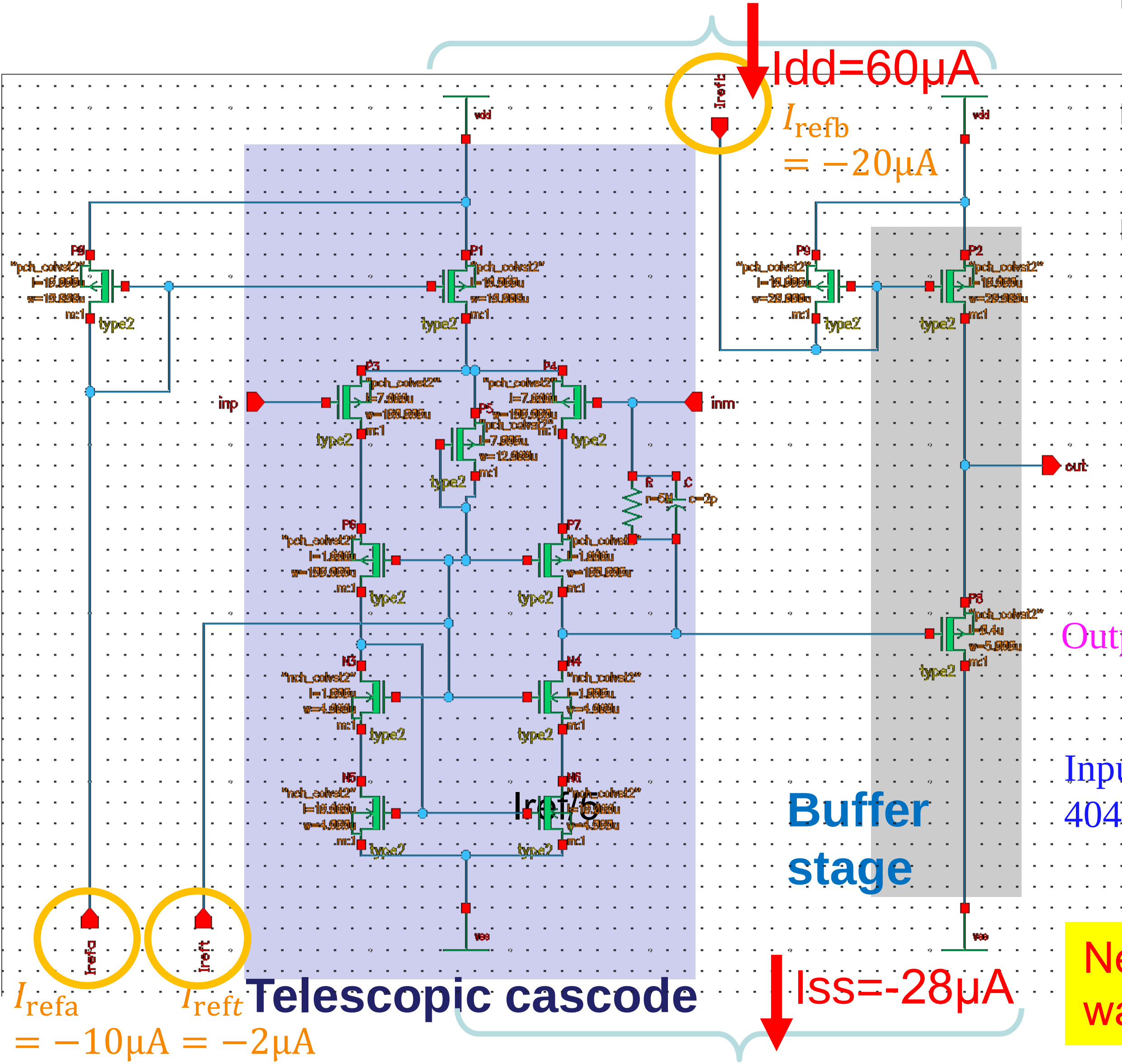


Amplification Gain : 70

S/N improved by a factor of 2

Development of the SOI cryogenic preamplifier is now moving to the stage of the final design for COBAND experiment.

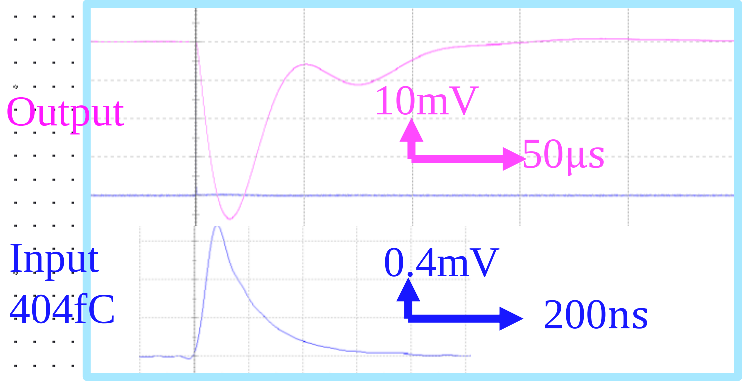
Charge Amp. Circuit for STJ (SOI-STJ5 design)



- telescopic cascode differential amplifier
- Feedback C(2pF) x R (5MOhm) = 10μs
- Power consumption ~150μW

This cryogenic charge amplifier test is underway.

Working at 3K



Next cryogenic charge amplifier was designed with a higher gain.

Poster by R. Wakasa "R&D of cryogenic SOI amplifier for COBAND experiment "

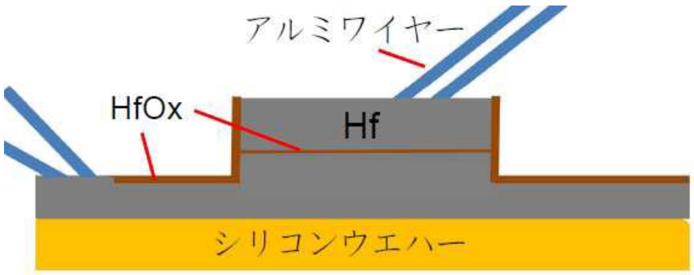
R&D Status of Hf-STJ

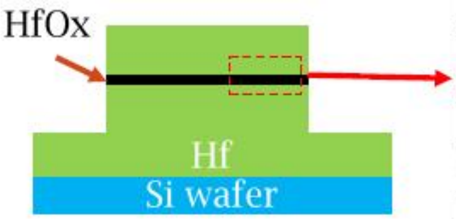
R&D Status of Hf-STJ

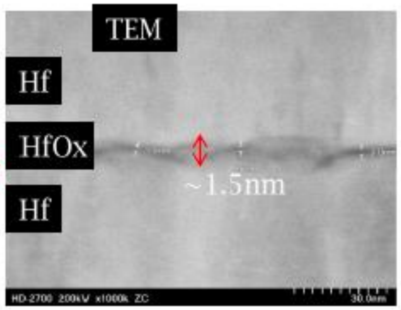
Goal: Measure energy of a single far-infrared photon for neutrino decay search experiment within 2% energy resolution.

Micro-calorimeter: Hf-STJ can generate enough quasi-particles from cooper pair breakings to achieve 2% energy resolution for photons with E_γ = 25meV.

Direct wire bonding on Hf layer



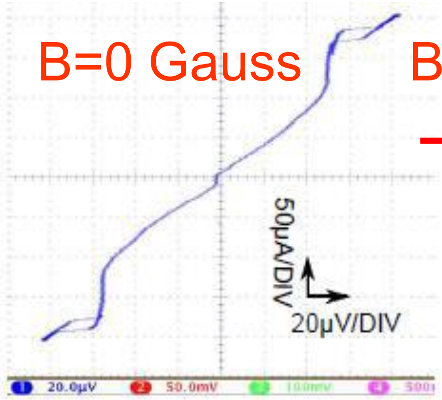


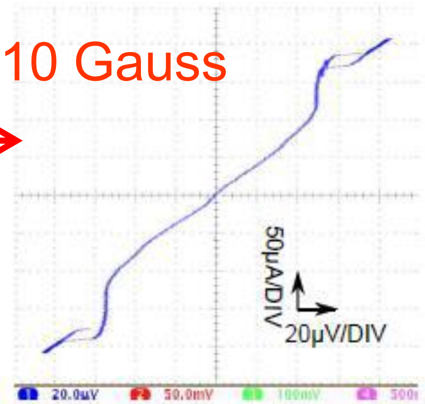


I-V curve of Hf-STJ (**100x100μm²**)

- T~40mK, I_c=10μA, **R_d=0.6Ω**

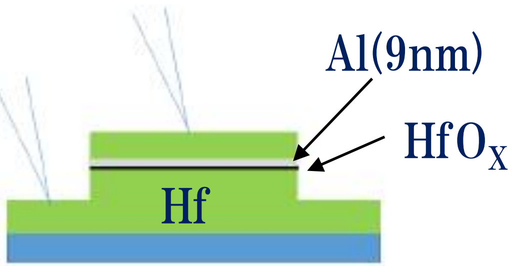
STJ size	# of samples	R_d
200 x 200μm²	3	0.22±0.01 Ω
100 x 100 μm²	3	0.60±0.10 Ω

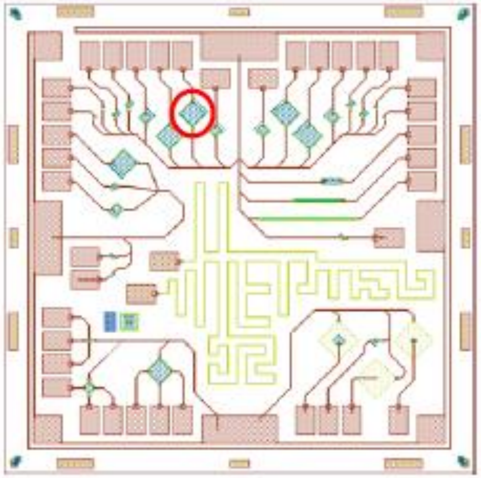


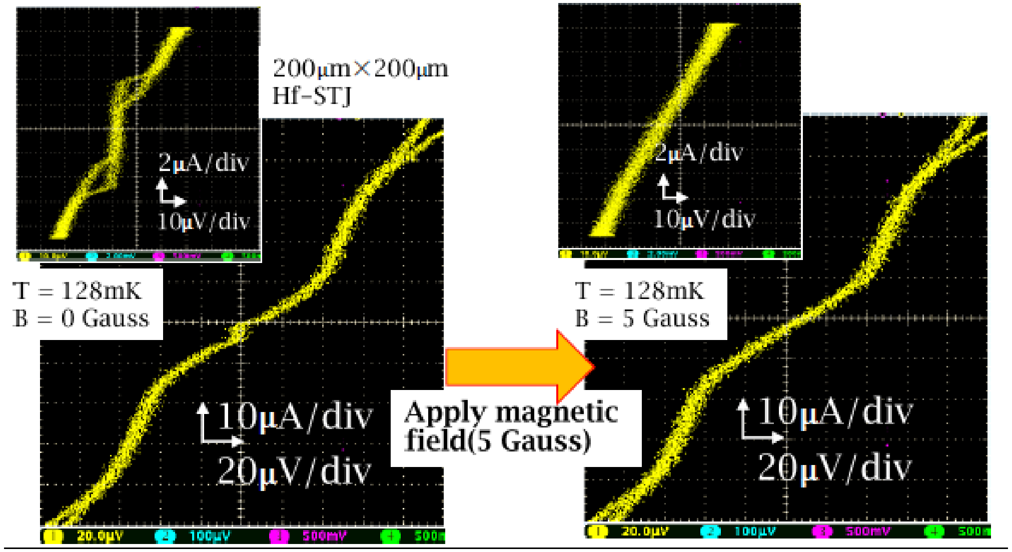


Latest Results of Hf-STJ R&D

In 2016, we made a thin aluminum layer (9nm) on the HfO layer (1-2 nm) to improve the insulation of the HfO_X layer. $Hf/Al/HfO_X/Hf$-STJ



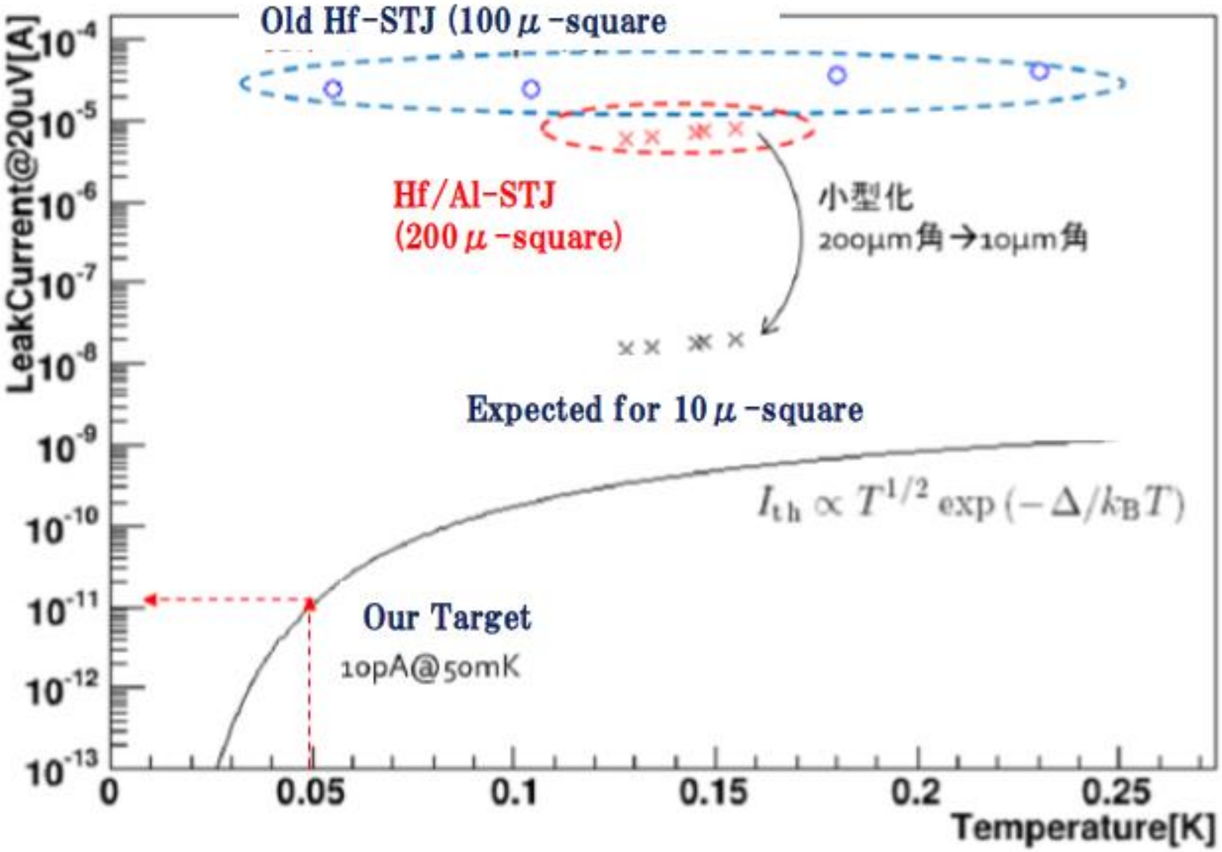




I_{leak} = 5 μA at 10 μV.
R_d = 2Ω
Dynamic Resistance was improved by a factor of 15 in $Hf/Al/HfO_X/Hf$-STJ.

Leakage Current of Hf-STJ

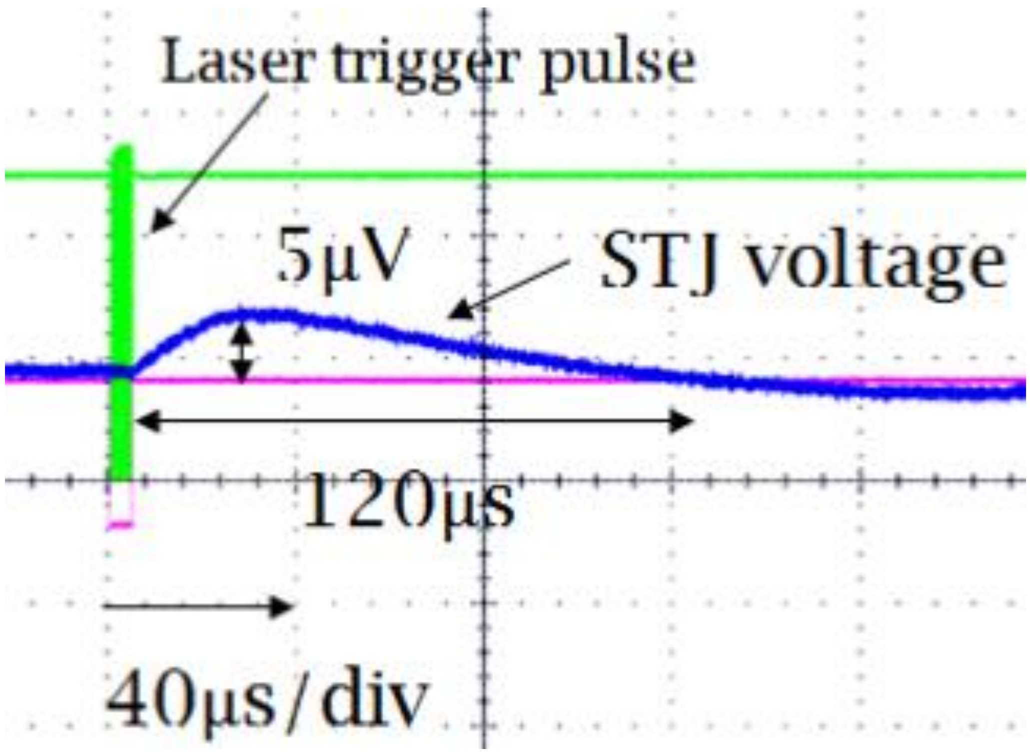
- $Hf/Al/HfO_X/Hf$-STJ reduced the leakage current to one-tenth.
- By making the size smaller, we will be able to decrease the leakage current by a factor of 1/400.
- By decreasing the operation temperature, we will be able to decrease the leakage current significantly.



Response of Hf-STJ to Laser Pulse Light

Hf/Al/HfO_X/Hf-STJ

Visible light laser (λ=465nm)　10Hz duration



Response speed (120μs) is slower than Nb/Al-STJ response speed (around a few μs).

Summary

- R&D of STJ detectors and the design of the COBAND rocket experiment are underway.
  - Nb/Al-STJ satisfied our requirement for leakage current less than 100pA.
  - Cryogenic amplifier with the SOI technology worked at 300mK.

    We have succeeded in amplifying the STJ signal with the SOI cryogenic amplifier.
  - Hf-STJ signal for visible laser light was observed.

- Many applications of the STJ detector as
  a single photon detector in the far-infrared range,
  a very low energy particle detector,
  X-ray detector with very high energy resolution
  and so on.

COBAND WEB page http://hep.px.tsukuba.ac.jp/coband/eng/