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Development of Superconducting Tunnel Junction Far-Infrared Photon Detectors for Cosmic Background Neutrino Decay Search - COBAND Experiment

Shin-Hong Kim (University of Tsukuba/TCHoU)
for COBAND Collaboration

COBAND Collaboration
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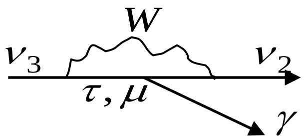
- **Introduction**
  - **Motivation**
  - **COsmic BAckground Neutrino Decay search (COBAND) experiment**
- **R&D of Superconducting Tunnel Junction (STJ) Detector**

Motivation of Search for Cosmic Background Neutrino Decay

- To determine the neutrino mass itself by neutrino decay observation.



$$\nu_3 \to \nu_2 + \gamma$$

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

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

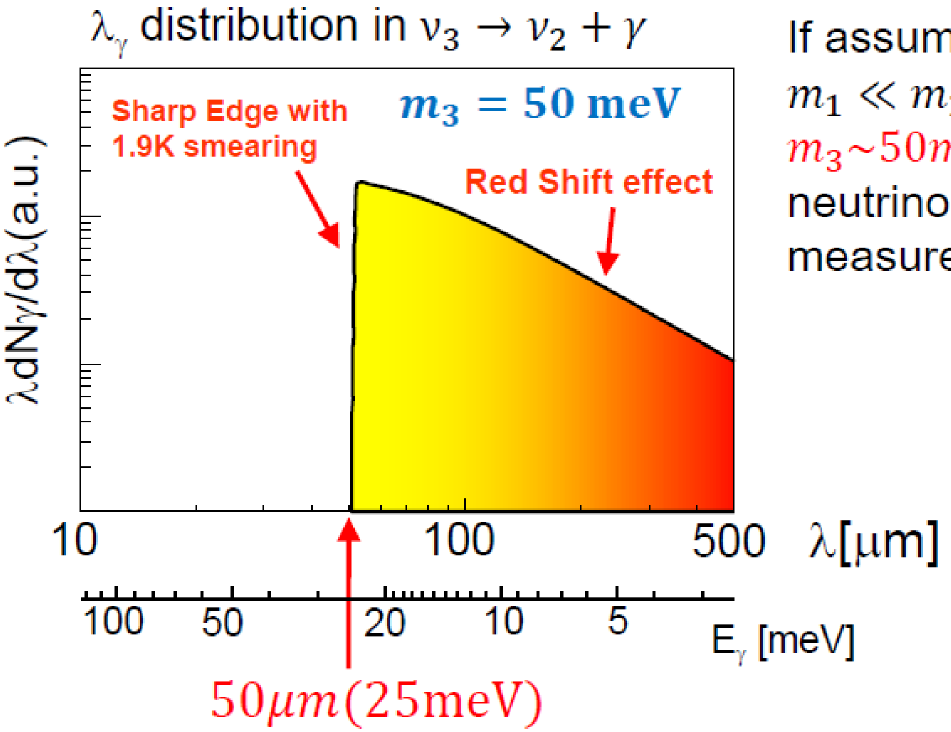
$E_\gamma = 10 \sim 25$ meV at ν_3 rest frame.

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

- As the neutrino lifetime is very long, we need use the cosmic background neutrino (CνB) as a huge neutrino source. Measured neutrino lifetime limit τ > 3 x 10^{12} year.

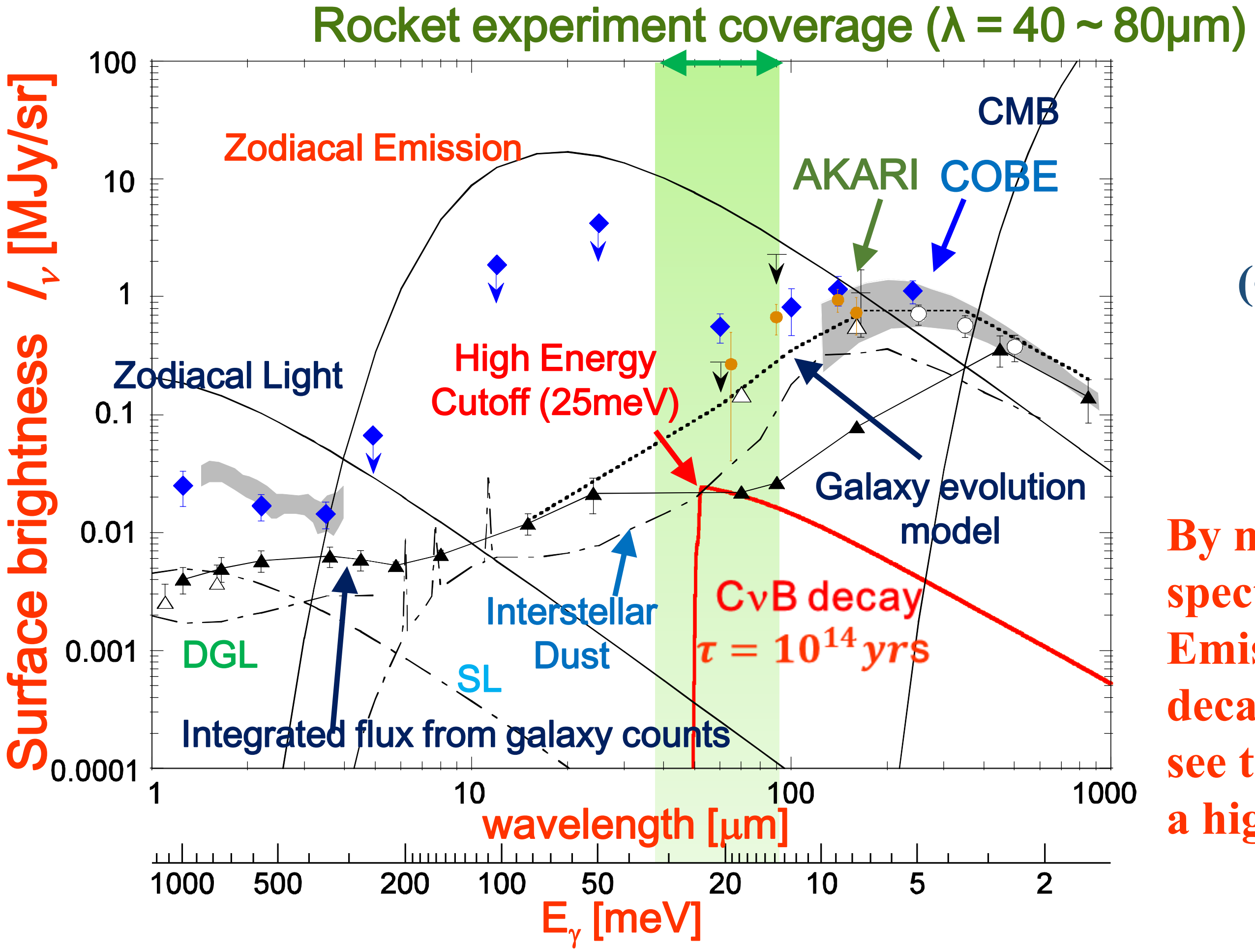
- To observe this decay means a discovery of the cosmic background neutrino predicted by cosmology.

λ_γ distribution in $\nu_3 \to \nu_2 + \gamma$



If assume
$m_1 \ll m_2 < m_3$,
$m_3 \sim 50 meV$ from neutrino oscillation measurements

Signal of Cosmic Background Neutrino Decay and its Backgrounds



Cosmic Infrared Background (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

COBAND (COsmic BAckground Neutrino Decay Search) Experiment

Rocket Experiment Plan: 5minutes data acquisition at 200 km height in 2020-21.

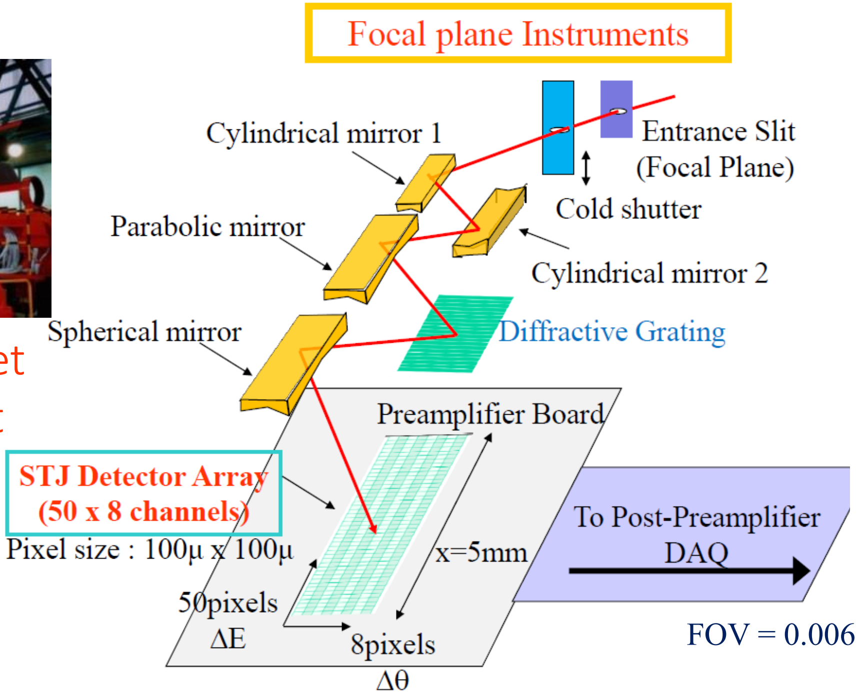
JAXA Sounding Rocket S520

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

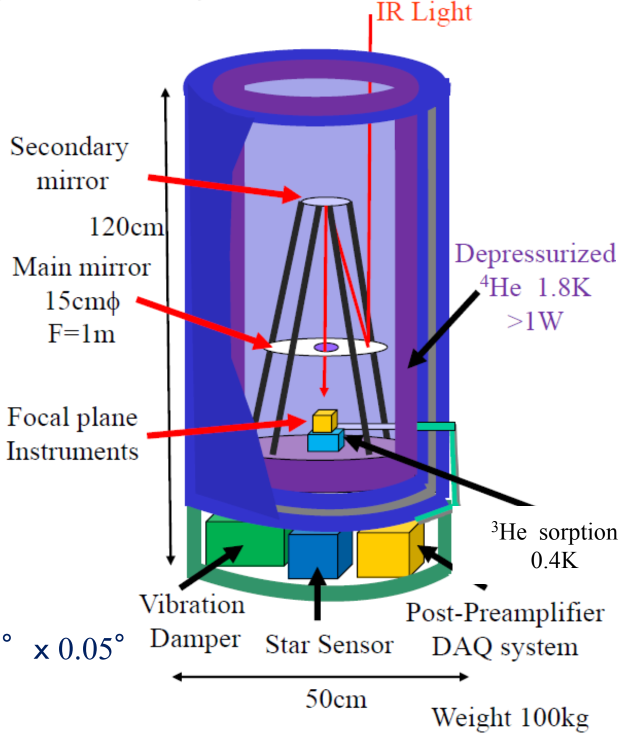
»Superconducting Tunneling Junction (STJ) detectors in development

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

JAXA S520 Rocket
CIB Experiment
(Feb 2, 1992)



FOV = 0.006° x 0.05°



Satellite experiment after 2025 →sensitivity of $\tau(\nu_3)$ ~10^{17}year (L-R symmetric model prediction)

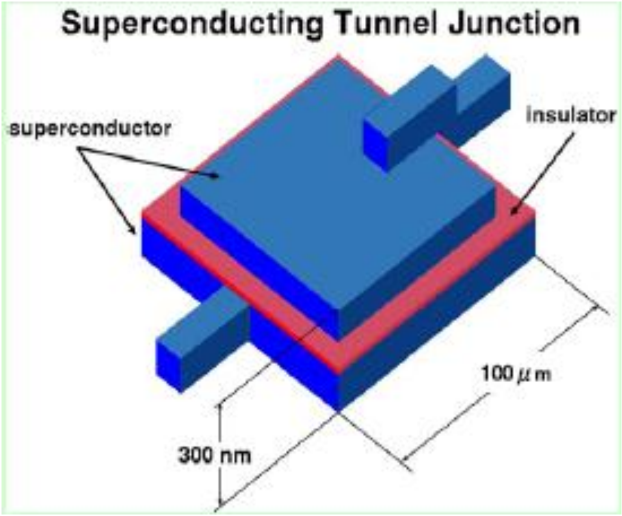
> STJ using Hafnium: Hf-STJ for satellite experiment (S. H. Kim et al. JPSJ 81,024101 (2012))

- $\Delta = 20\mu$eV : Superconducting gap energy for Hafnium

  Microcalorimeter $\Delta E/E < 2\%$ without diffractive grating.

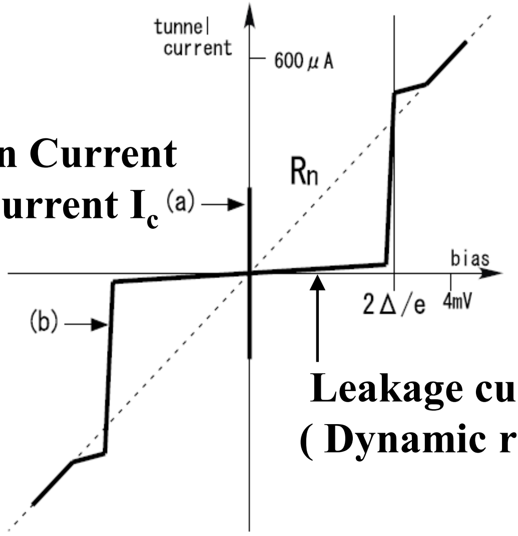
STJ (Superconducting Tunnel Junction）Detector

- 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

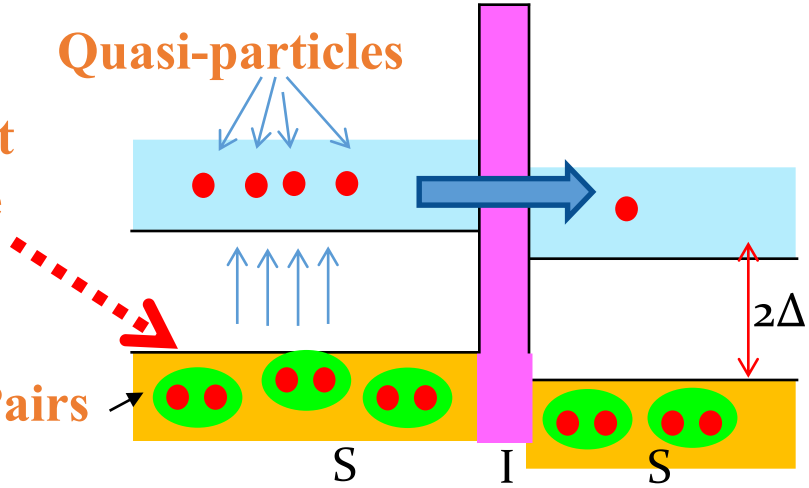


Josephson Current

Critical current I_c

Leakage current

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



Quasi-particles

Incident Particle

Cooper Pairs

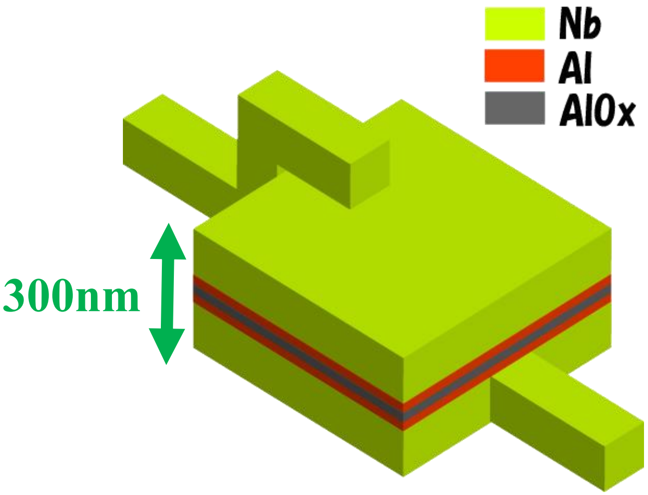
2Δ

S I S

Energy gap Δ

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

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)

    $\Delta_{Nb/Al} = 0.57\text{meV}$
- Gain: 2～200 (10 for Al)

Number of Quasi-particles in Nb/Al-STJ

$$N_q = \mathrm{GAl}\, {}^{E_0}\!/_{1.7\Delta}$$

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

For 25meV single photon $N_q = 250$ e

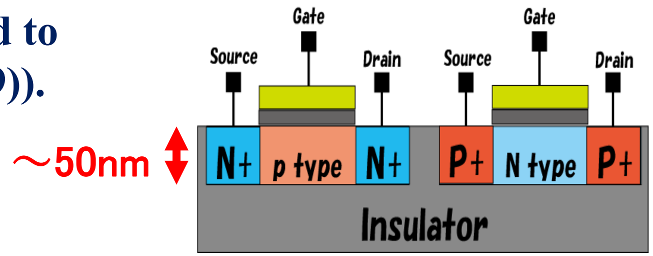
Requirement for detector

- Leakage current $I_{leak} < 0.1$nA: Done
- Noise integrated in 10μs < 30e: Cryogenic amplifier is needed

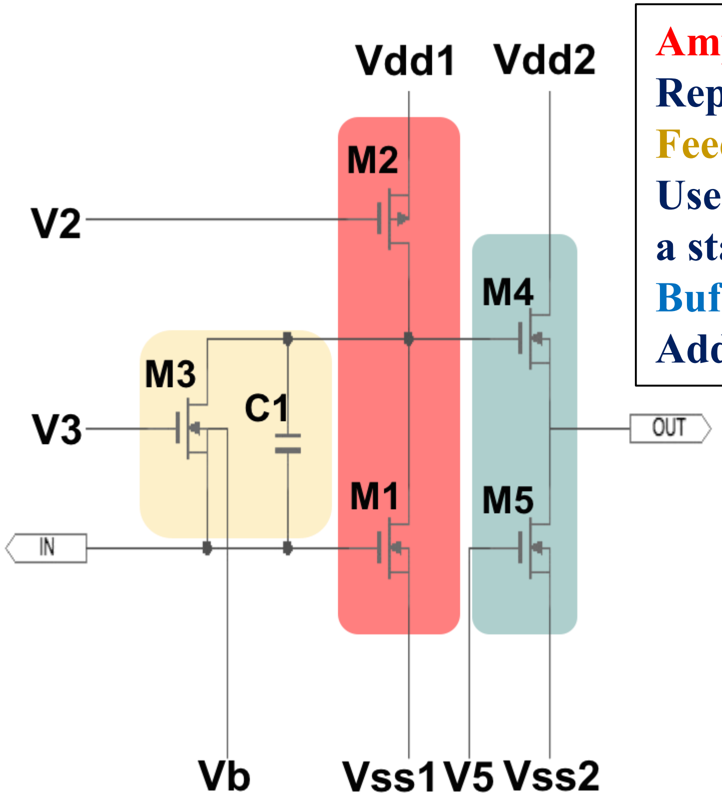
SOI Cryogenic Amplifier

FD-SOI (Fully Depleted Silicon-On-Insulator) device was proved to operate at 4K by a JAXA/KEK group (AIPC 1185,286-289(2009)).

FD-SOI −MOSFET



SOI-STJ4 (the 4th prototype)



Amplification

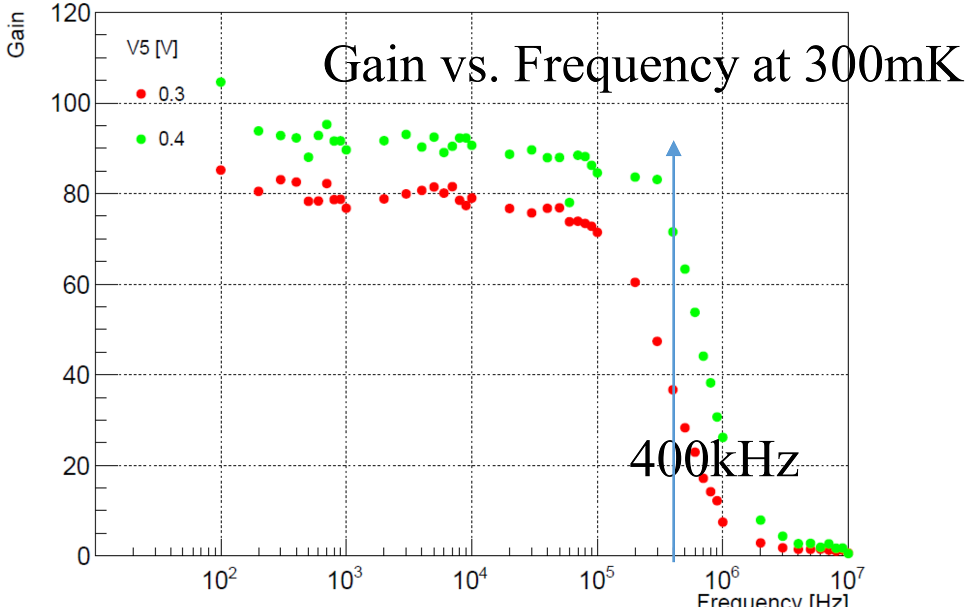
Replace the resistance by a SOIFET as a current source (M2).

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).



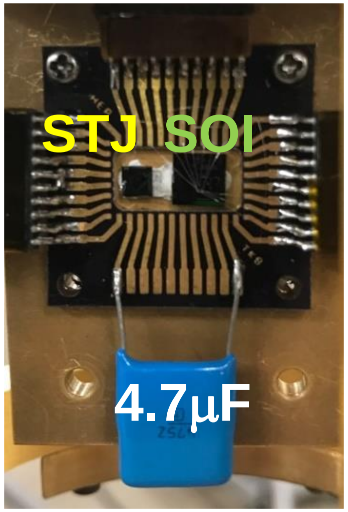
Gain vs. Frequency at 300mK

400kHz

This SOI amplifier board was made by LAPIS semiconductor company.

STJ signal amplified with the SOI cryogenic preamplifier

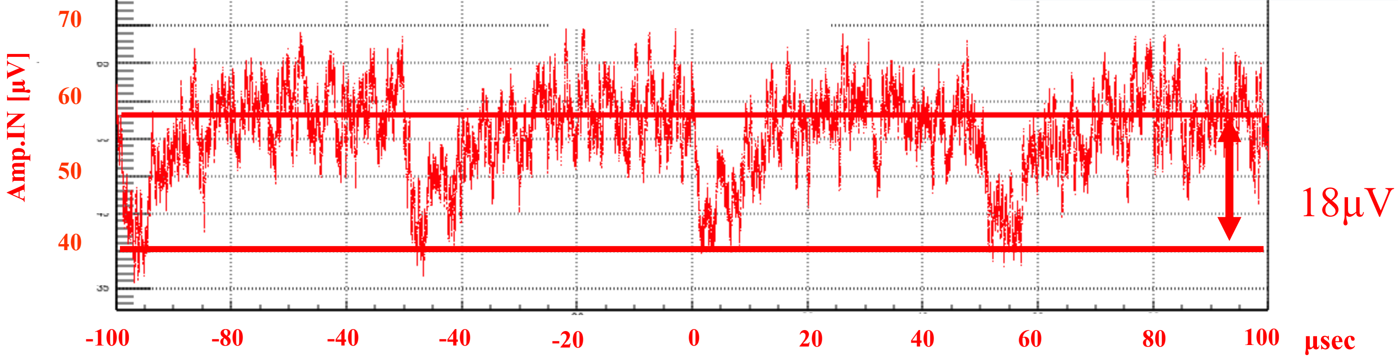
Nb/Al-STJ laser light response signal was amplified with this SOI cryogenic amplifier.



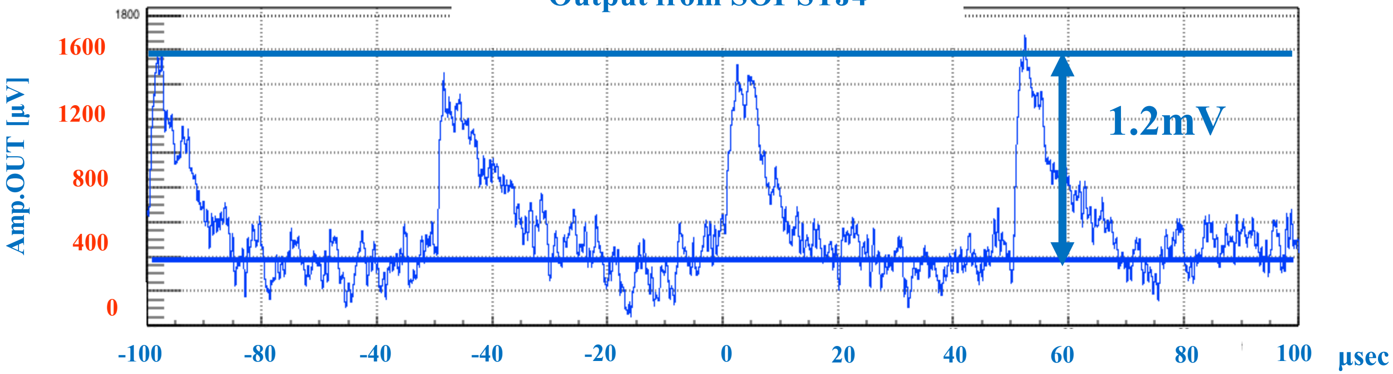
STJ signal to visible laser λ= 465nm, 20kHz

T=350mK
Laser: λ=465nm,f=20kHz

STJ Signal

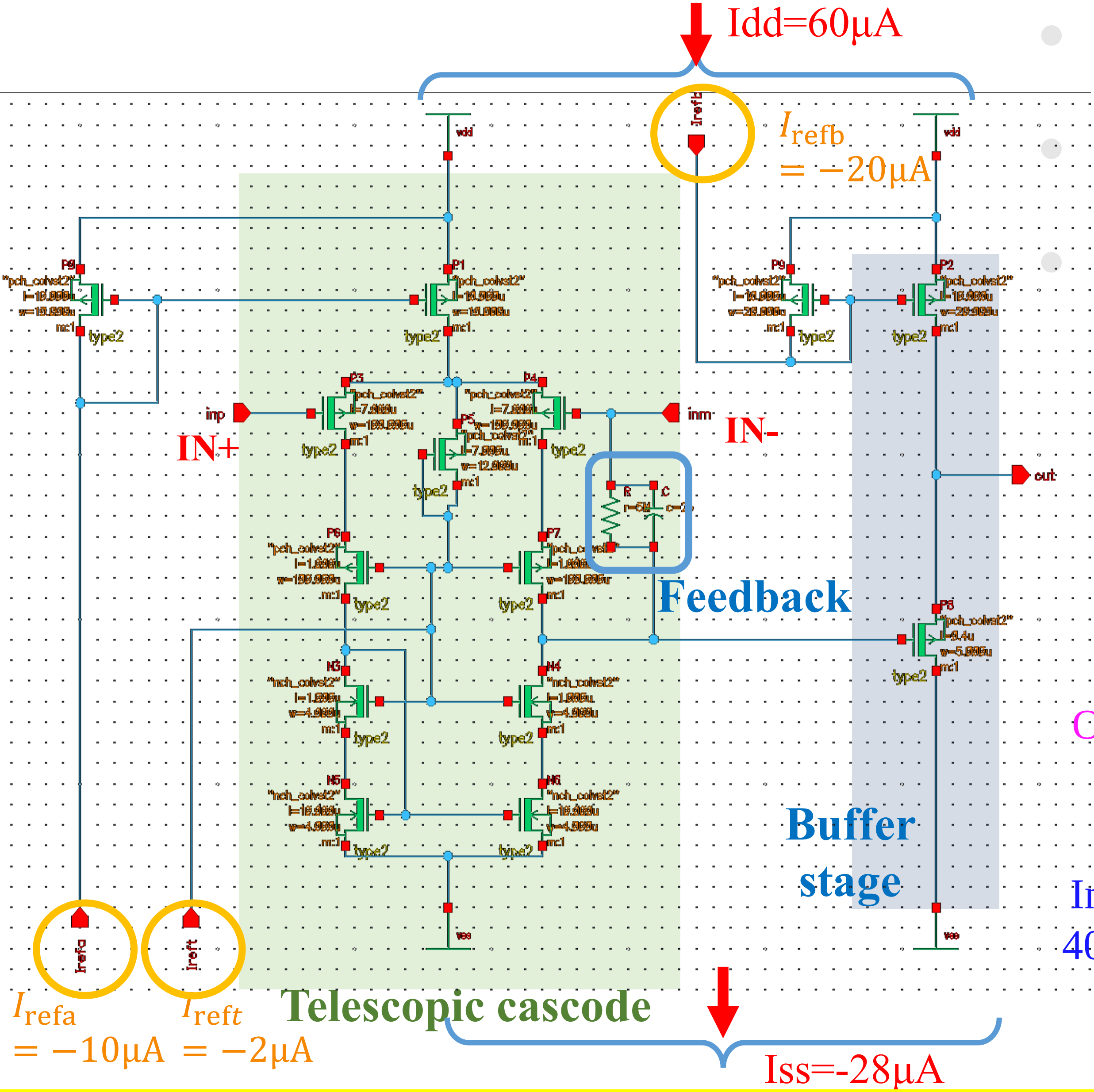


Output from SOI-STJ4



Amplification Gain : 70
S/N improved by a factor of 2

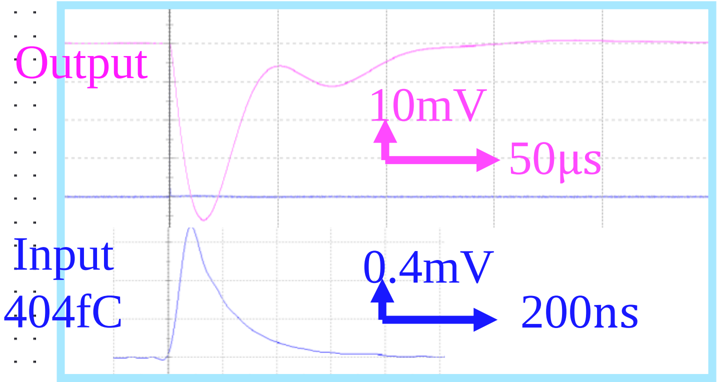
Charge Amplifier Circuit for STJ (SOI-STJ5 design)



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

Test of this cryogenic charge amplifier is underway.

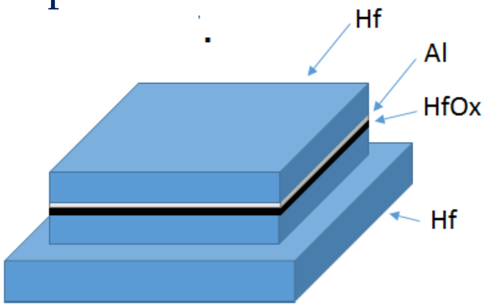
Working at 3K



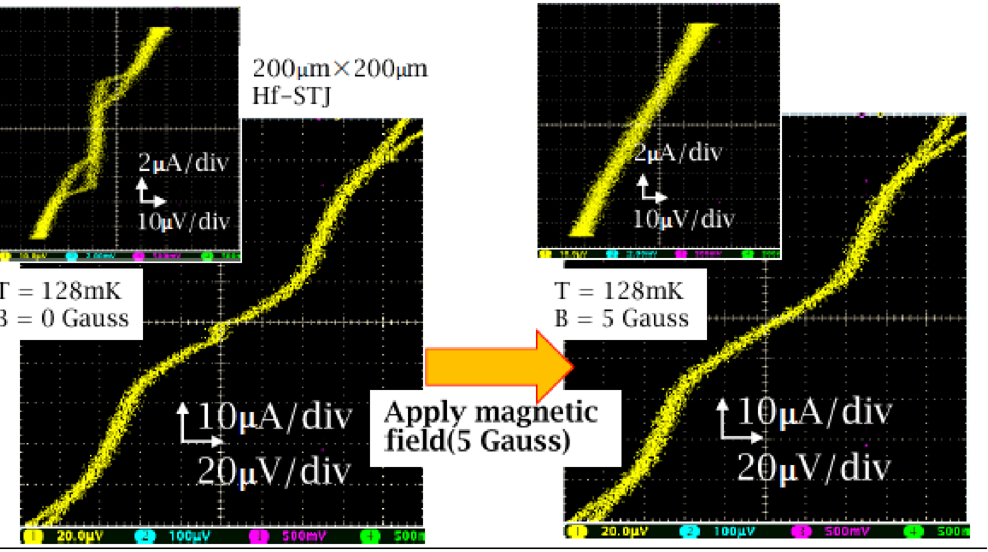
Next cryogenic charge amplifier was designed with a higher gain to see a 25meV single photon.

R&D Status of Hf-STJ - Laser Light Response

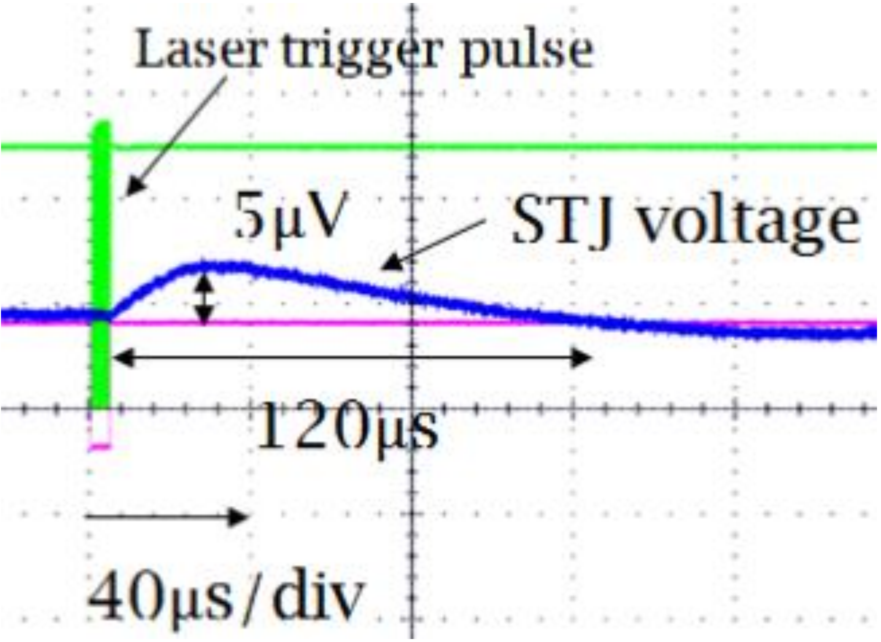
We made a thin aluminum layer (9nm) on the HfO layer (1-2 nm) to improve the insulation of the HfO_X layer.   Hf/Al/HfO_X/Hf-STJ



Δ = 20 ∼ 30μeV
Leakage current = 5μA@128mK
for 200μm-square sample.



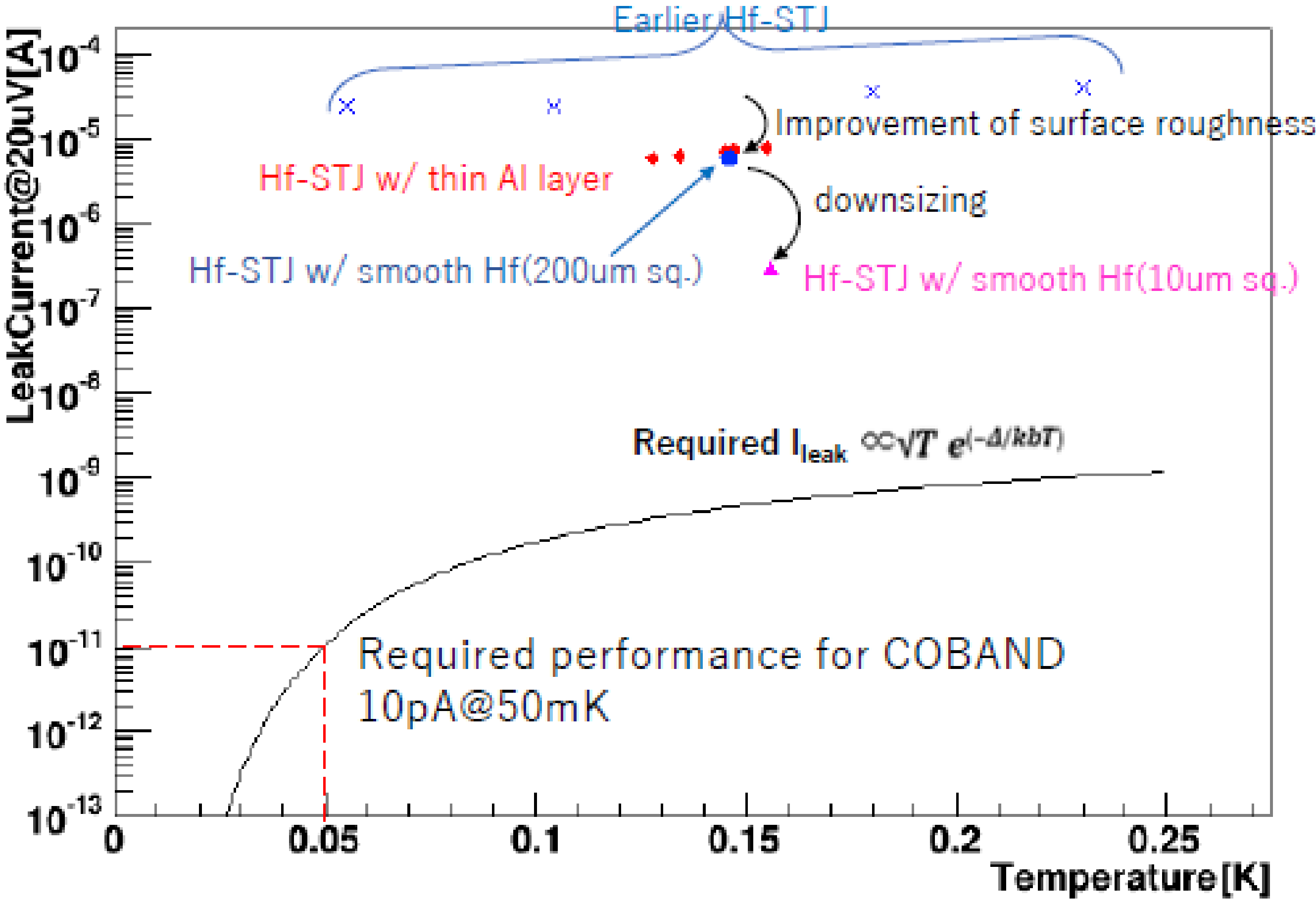
Visible light laser (λ=465nm)   10Hz duration



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

Improvement of Hf-STJ Leakage Current

- Hf/Al/HfO$_X$/Hf-STJ reduced the leakage current to one-tenth.
- Hf-STJ with smoothed Hf layer reduced the leakage current to one-tenth.
- Small size Hf-STJ (10μ-square) reduced the leakage current to 1/24.



We are working on the study on downsizing of Hf-STJ.

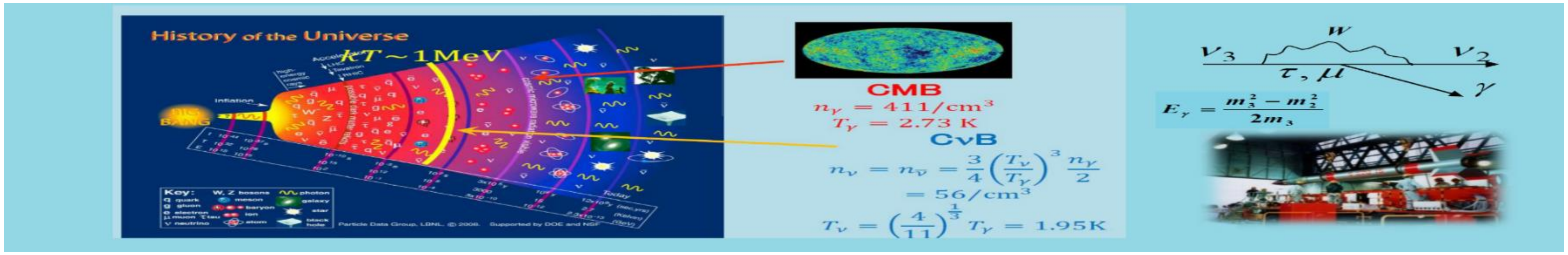
We plan to lower the operation temperature using another better dilution refrigerator.

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.

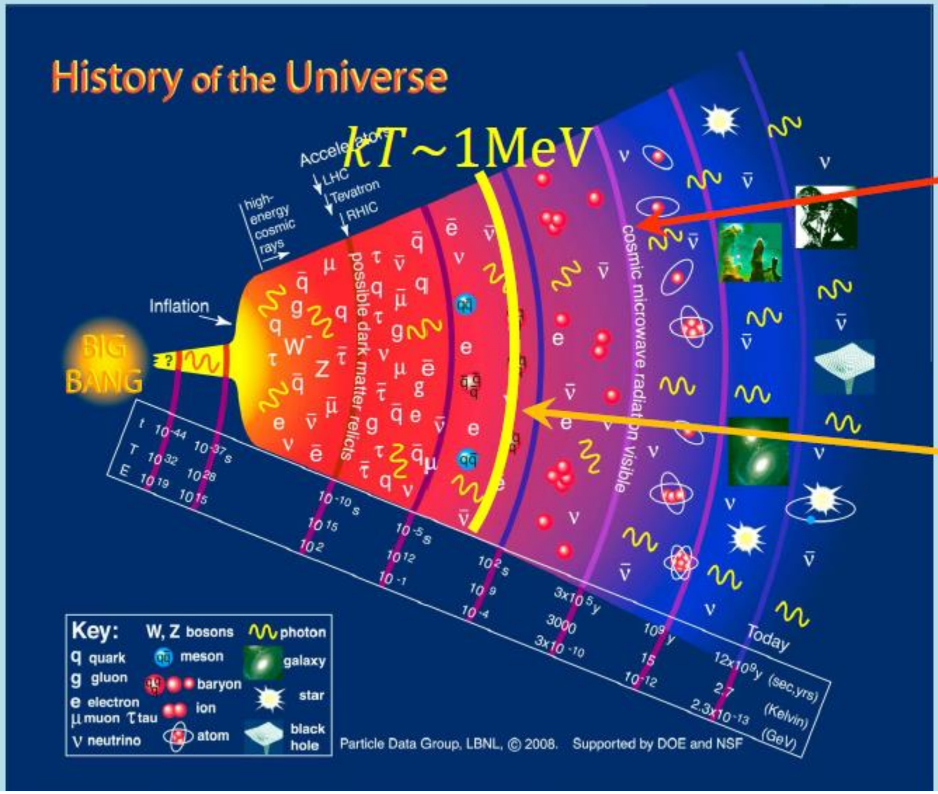
- Many applications of the STJ detector as
  a single photon detector in the far-infrared range,
  a very low energy particle detector,
  X-ray energy measurement with very higher energy resolution
  and so on.

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

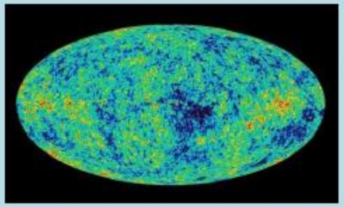


BACKUP

Big-Bang Cosmology and Cosmic Background Neutrino (CνB)



Particle Data Group, LBNL, © 2008. Supported by DOE and NSF



CMB

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

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

CνB

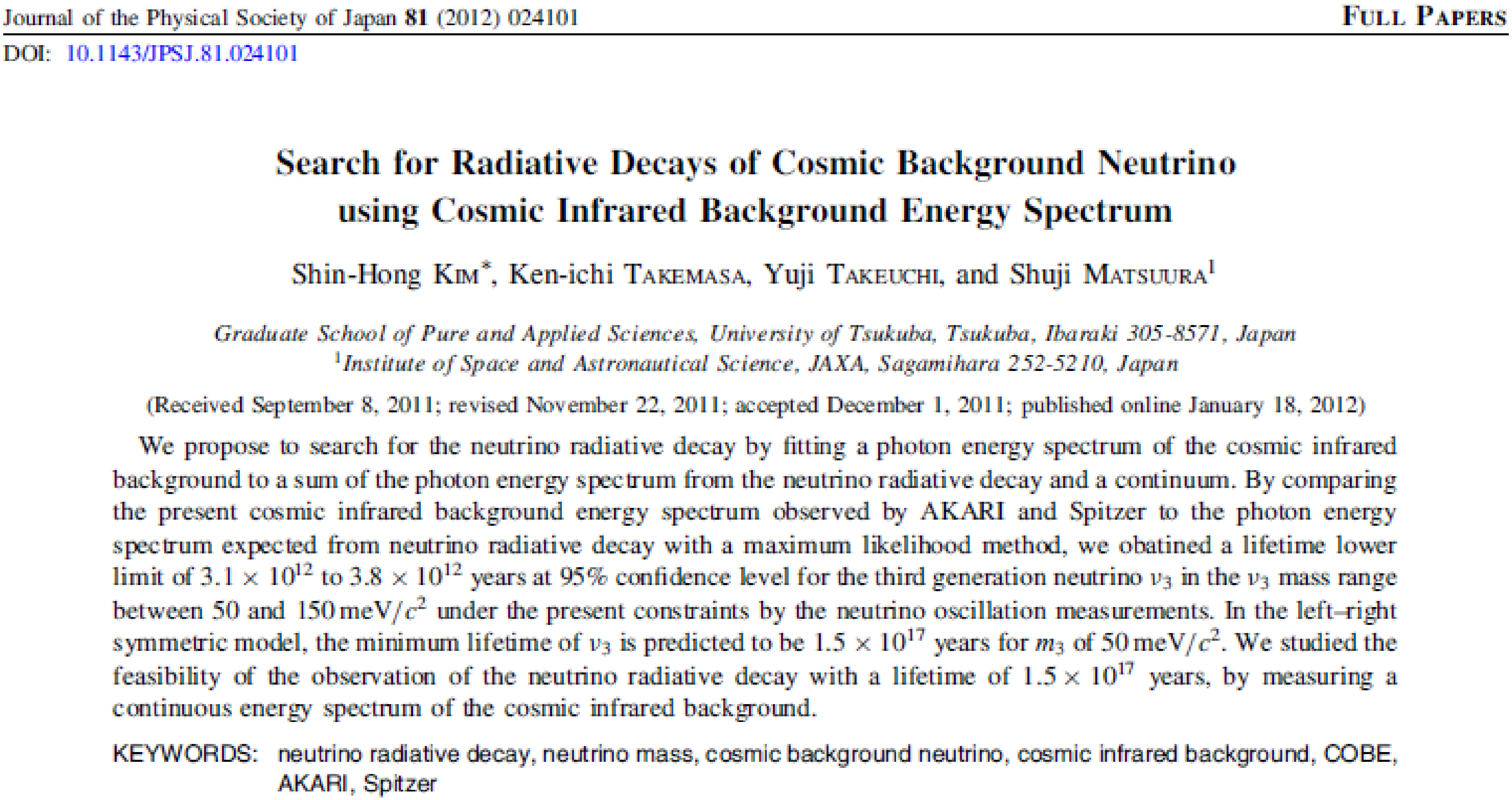
$$n_\nu = n_{\bar{\nu}} = \frac{3}{4}\left(\frac{T_\nu}{T_\gamma}\right)^3 \frac{n_\gamma}{2}$$

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

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

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

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



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

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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.

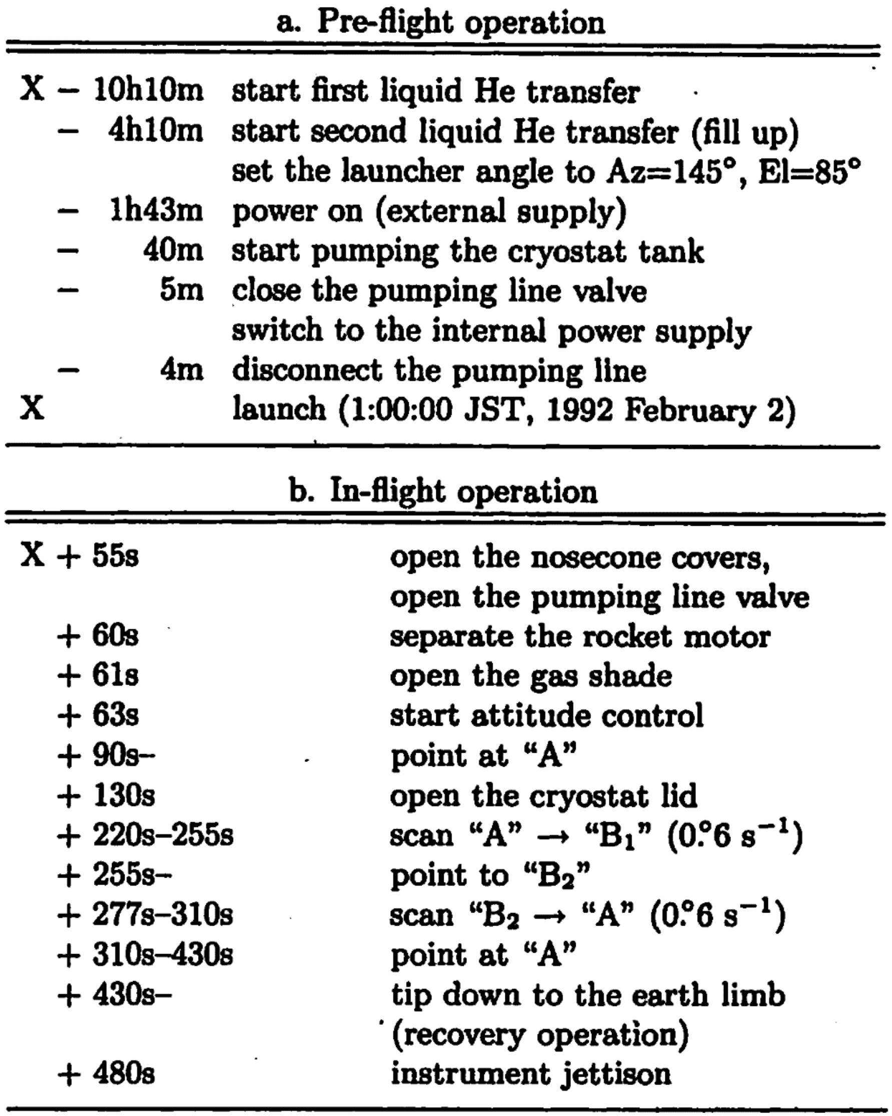
KEYWORDS: neutrino radiative decay, neutrino mass, cosmic background neutrino, cosmic infrared background, COBE, AKARI, Spitzer

Search Region: λ＝ 35～250μm （E_γ ＝ 35～5meV）

In Rocket experiment, λ＝ 40～80μm （E_γ ＝ 31～15meV）

COBAND Rocket Experiment

We measured CIB in the same points as S520−15 experiment measured the CIB in 1992. 方向からの宇宙赤外線

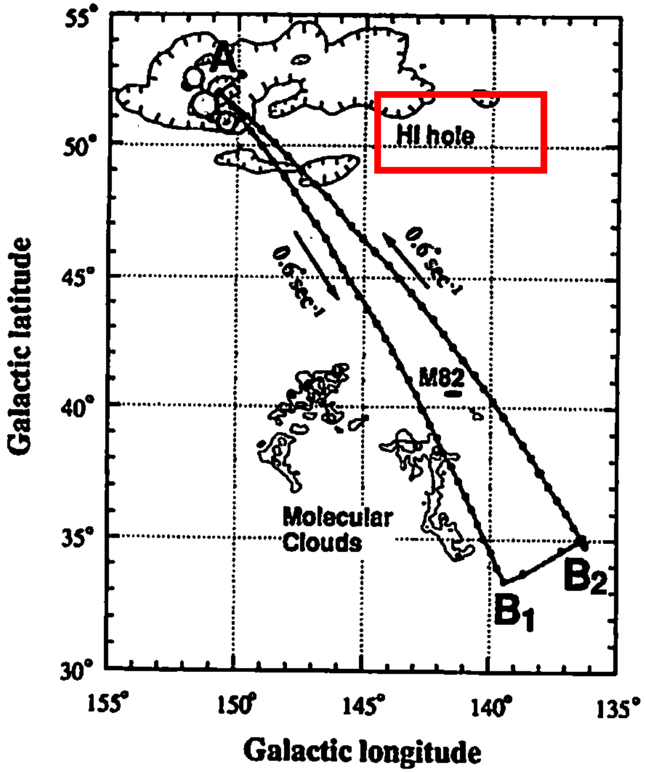


a. Pre-flight operation

X − 10h10m	start first liquid He transfer
− 4h10m	start second liquid He transfer (fill up) set the launcher angle to Az=145°, El=85°
− 1h43m	power on (external supply)
− 40m	start pumping the cryostat tank
− 5m	close the pumping line valve switch to the internal power supply
− 4m	disconnect the pumping line
X	launch (1:00:00 JST, 1992 February 2)

b. In-flight operation

X + 55s	open the nosecone covers, open the pumping line valve
+ 60s	separate the rocket motor
+ 61s	open the gas shade
+ 63s	start attitude control
+ 90s–	point at "A"
+ 130s	open the cryostat lid
+ 220s–255s	scan "A" → "B_1" ($0\overset{\circ}{.}6\ \mathrm{s}^{-1}$)
+ 255s–	point to "B_2"
+ 277s–310s	scan "B_2 → "A" ($0\overset{\circ}{.}6\ \mathrm{s}^{-1}$)
+ 310s–430s	point at "A"
+ 430s–	tip down to the earth limb (recovery operation)
+ 480s	instrument jettison



Measured Points

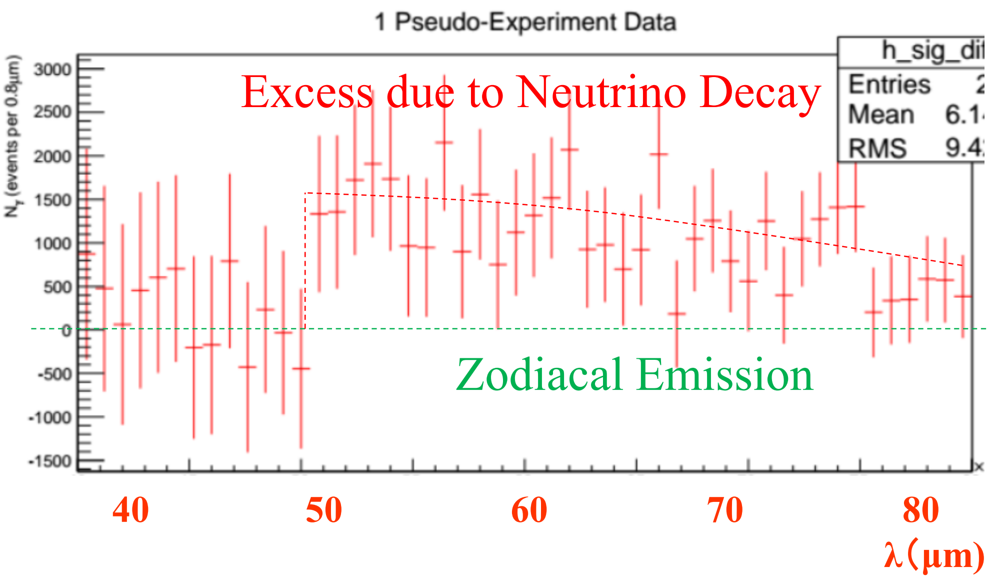
These are the same as S520−15.

A（Galactic Latitude 52° Galactic Longitude 151° ）

Sensitivity to Neutrino Decay

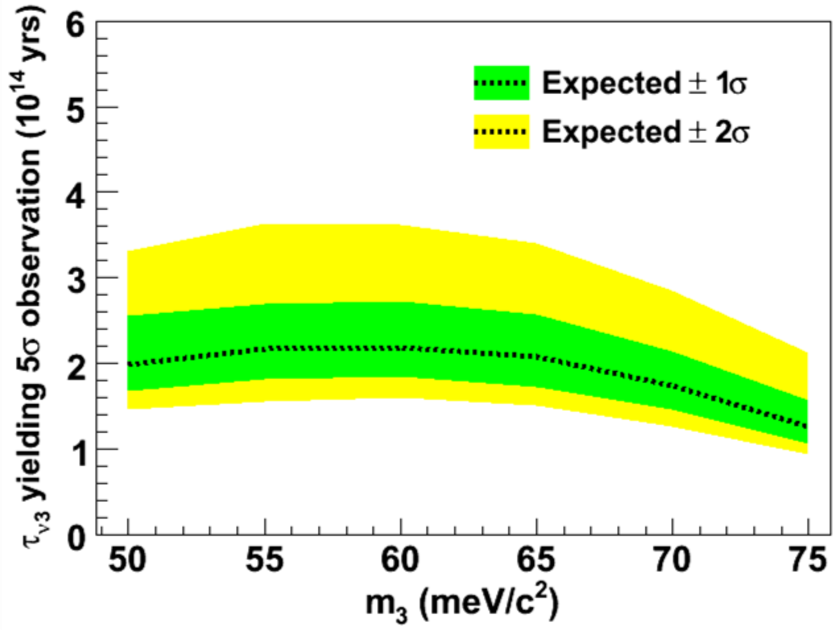
Parameters in the rocket experiment simulation

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



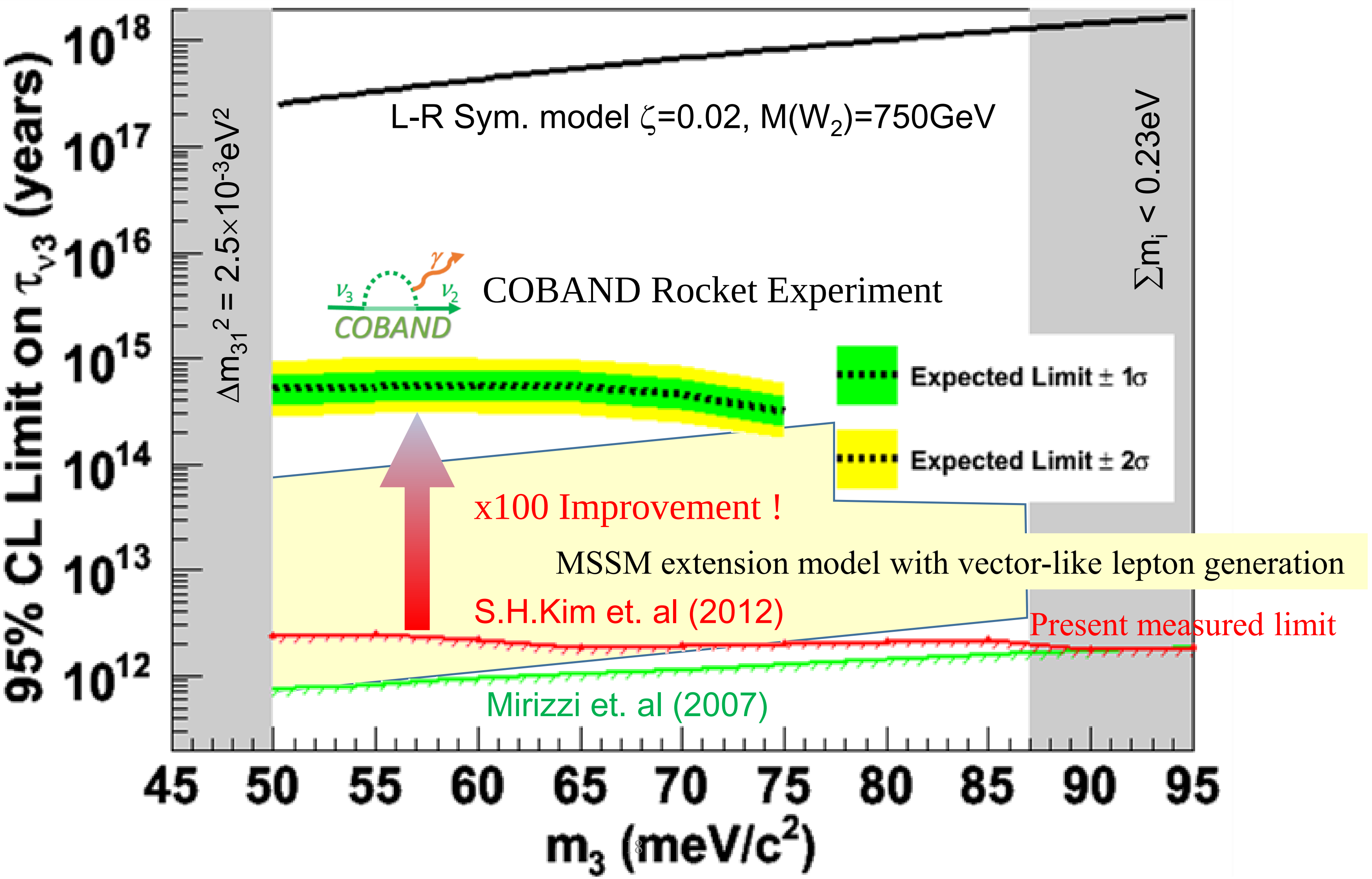
Excess due to Neutrino Decay

Zodiacal Emission

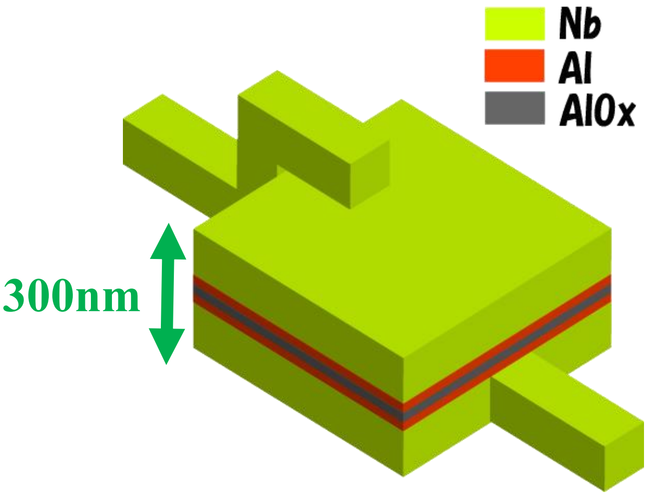


- If ν_3 lifetime were 2×10^{14} yrs, the signal significance is at 5σ level

COBAND Experiment Sensitivity to Neutrino Decay



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)

    $\Delta_{Nb/Al} = 0.57\mathrm{meV}$
- Gain: 2～200 (10 for Al)

Number of Quasi-particles in Nb/Al-STJ

$$N_q = \mathrm{GAl}\,{}^{E_0}/_{1.7\Delta}$$

G_{Al} : Trapping Gain in Al(~10)

E_0 : Photon Energy

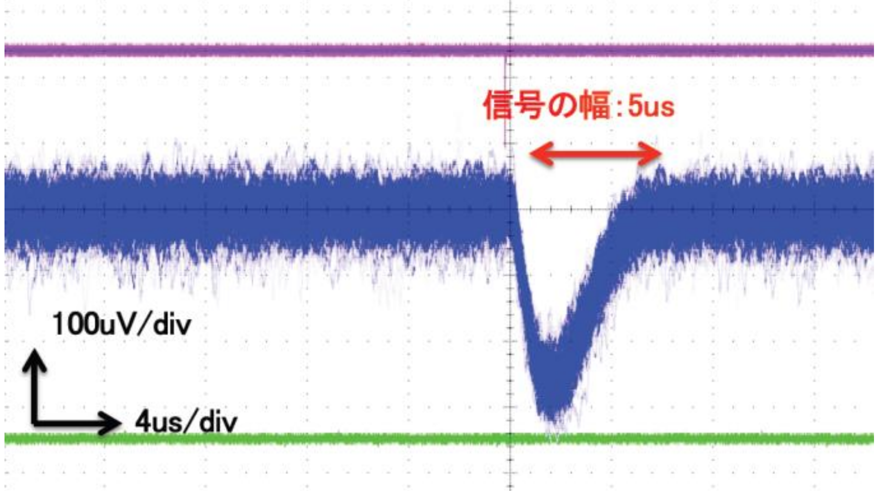
Δ : E-Gap in superconductor

For 25meV single photon $N_q = 250\ \mathrm{e}$

Requirement for detector

- ● **Leakage current $I_{leak} < 0.1\mathrm{nA}$: Done**
- ● **Noise integrated in 10μs < 30e: cryogenic amplifier is needed**

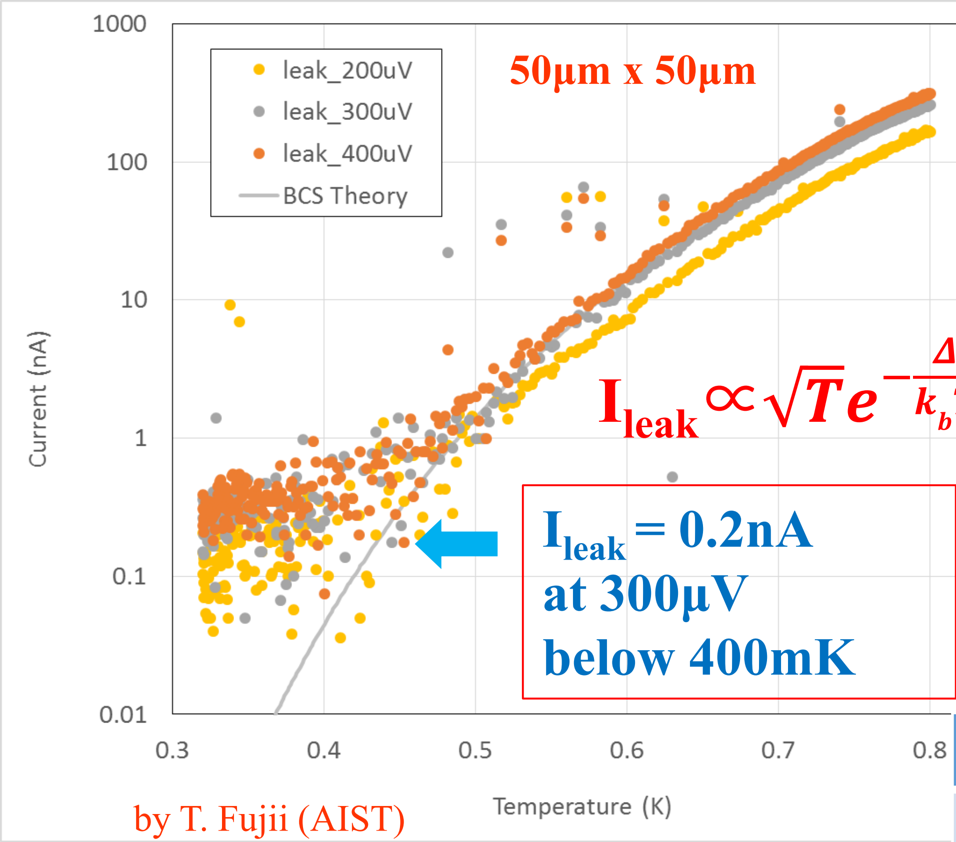
Response of Nb/Al-STJ to visible laser light pulse (λ=465nm) at 350mK



Leakage Current of Nb/Al-STJ

- **Leakage current I_{leak} is required to be below 0.1nA to detect a single far-infrared photon (λ= 40 -80μm) .**

Temperature Dependence of Leakage Current



50μm x 50μm

$$I_{leak} \propto \sqrt{T} e^{-\frac{\Delta}{k_b T}}$$

I_{leak} = 0.2nA
at 300μV
below 400mK

by T. Fujii (AIST)

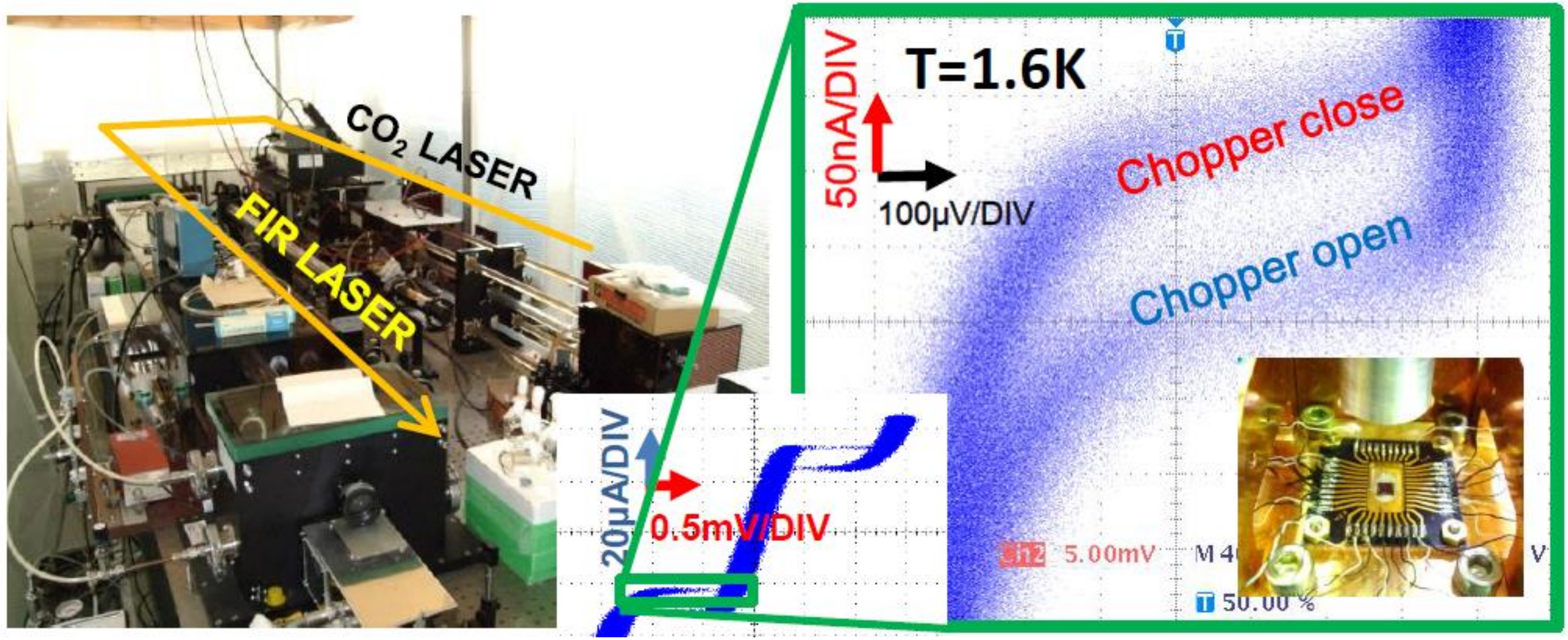
In 2014,
AIST group joined us and produced Nb/Al-STJ with AIST CRAVITY processing system.
Leakage current has satisfied our requirement of 0.1nA .

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

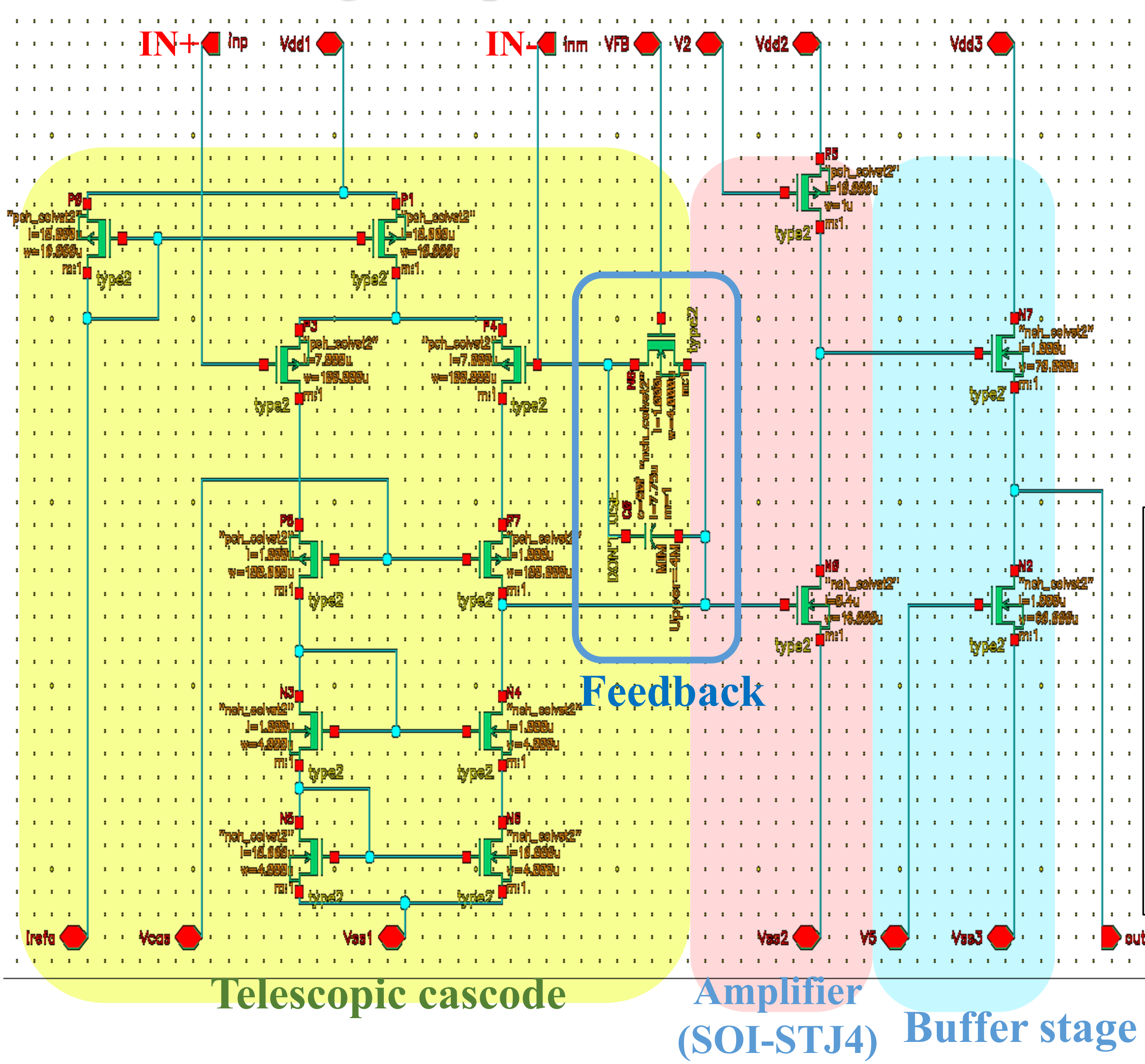
Far-Infrared Laser at University of Fukui
（ λ=57.2μm ）

- Nb/Al-STJ Response to Far-Infrared Laser



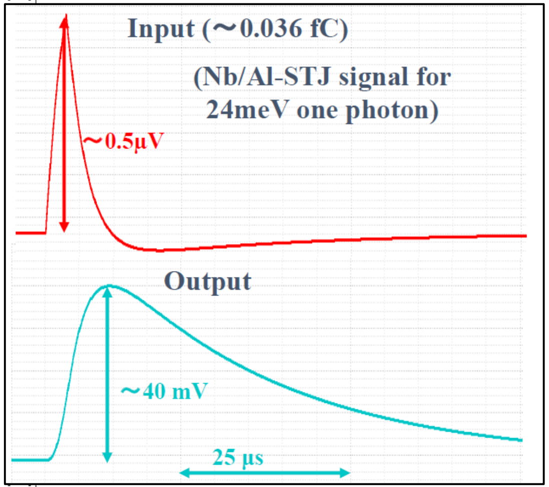
- 20μm-square Nb/Al-STJ made at AIST CRAVITY system
- Laser light was turned on and off with a chopper at a frequency of 200Hz. Measured the change of the I-V curve between the laser on and off to be 50~100nA in current.

New Charge Amplifier Circuit for STJ (SOI-STJ6 design)



- Feedback capacitance 2pF ⟶ 60fF
- Power Consumption ~150μW
- 24meV one photon (0.03fC) gives ~40mV Output

Simulation Result



This charge amplifier will arrive at our University soon.

Cosmic Background Neutrino

$\mathit{Fermi\ and\ Bose\ Distribution\ Function} \qquad F(E) = \dfrac{1}{e^{(E-\mu)/kT} \pm 1}$

where + for fermions and - for bosons, and E is energy and μ is a chemical potential.

For $\mu \ll T$ *and* $m \ll T$,

Energy density $\rho = g\int \frac{d^3p}{(2\pi)^3} EF(E) = g\,(\frac{7}{8})^F \frac{\pi^2}{30} T^4$

Number density $n = g\int \frac{d^3p}{(2\pi)^3} F(E) = g(\frac{3}{4})^F \frac{\zeta(3)}{\pi^2} T^3$

Entropy $s = \frac{4\rho}{3T} = g(\frac{7}{8})^F \frac{2\pi^2}{45} T^3$

Temperature:

Below 3MeV, v is decoupled from other particles because the weak interaction cross section becomes too small.

Below 1MeV, $e^+e^- \to \gamma\gamma$ is possible, but $\gamma\gamma \to e^+e^-$ is impossible. so photons are reheated by this process. The entropies before and after this time are equal to each other:

$\mathit{Entropy} \quad s \propto g\,(\frac{7}{8})^F T^3$ *g*=2(for γ), 2(for e^- or e^+), 1(for v or anti-v)

where *g* is the spin degree of freedom, and *F* = 1(for fermions) and 0 (for bosons).

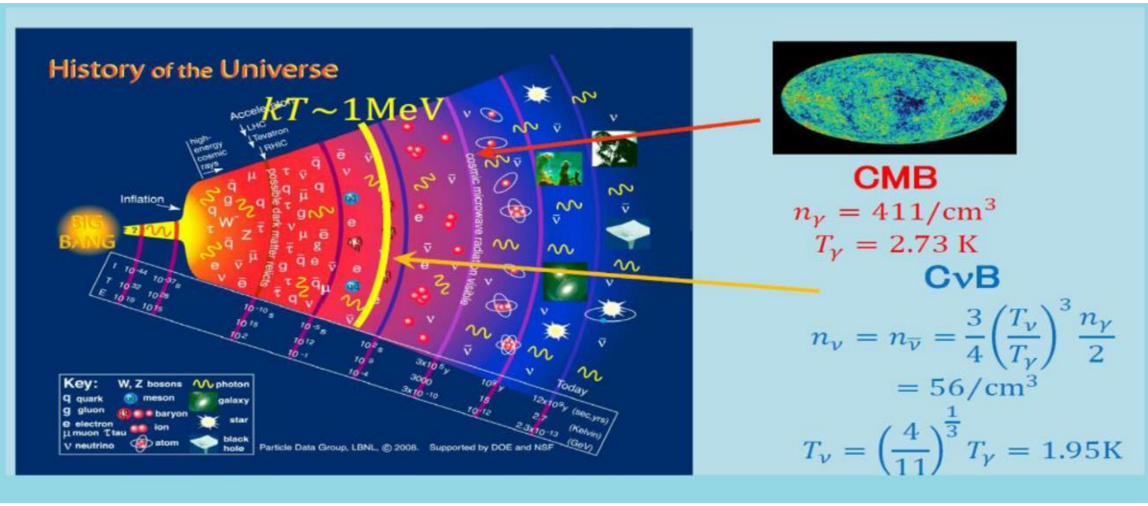
The present entropies of photons and neutrinos, $s_{\gamma 0}$ and $s_{\nu 0}$ are given by

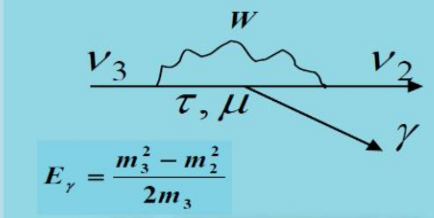
$s_{\gamma 0} = a^3\left(s_\gamma + s_{e^- + e^+}\right)$, $s_{\nu 0} = a^3 s_\nu$ $\quad \mathit{where\ a\ is\ a\ scale\ factor}$.

$\to \quad \frac{s_{\nu 0}}{s_{\gamma 0}} = \frac{s_\nu}{s_\gamma + s_{e^- + e^+}} = \frac{2\times\frac{7}{8}}{2+4\times\frac{7}{8}} = \frac{7}{22} \qquad \therefore ,\ s_{\nu 0} = \frac{7}{22} s_{\gamma 0}$

$2 \times \frac{7}{8} T_\nu^3 = \frac{7}{22} \times 2T_\gamma^3 \quad \to \quad T_\nu = (\frac{4}{11})^{\frac{1}{3}} T_\gamma \qquad As\ \ T_\gamma = 2.73K, \quad \therefore\ T_\nu = 1.95\text{K}$

Cosmic Background Neutrino





Temperature:

$$T_\nu = 1.95\mathrm{K}$$

Number density:

As $\mu / T \ll 1$, $\quad n \propto g \left(\frac{3}{4}\right)^F T^3$

where *g* is the spin degree of freedom, and *F* = 1(for fermions) and 0 (for bosons).

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

$$\therefore n_{\nu_\alpha} \approx n_{\bar{\nu}_\alpha} \approx 56\mathrm{cm}^{-3} \quad (\alpha = e, \mu, \tau)$$

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)

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

(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

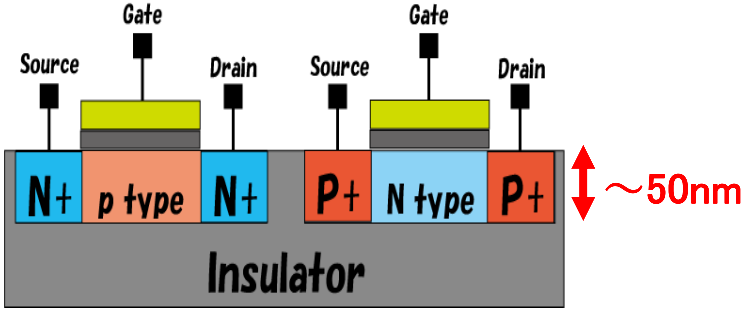
- Superconducting Tunneling Junction detector

  (leakage current per pixel < 100pA)
- Cryogenic amplifier readout

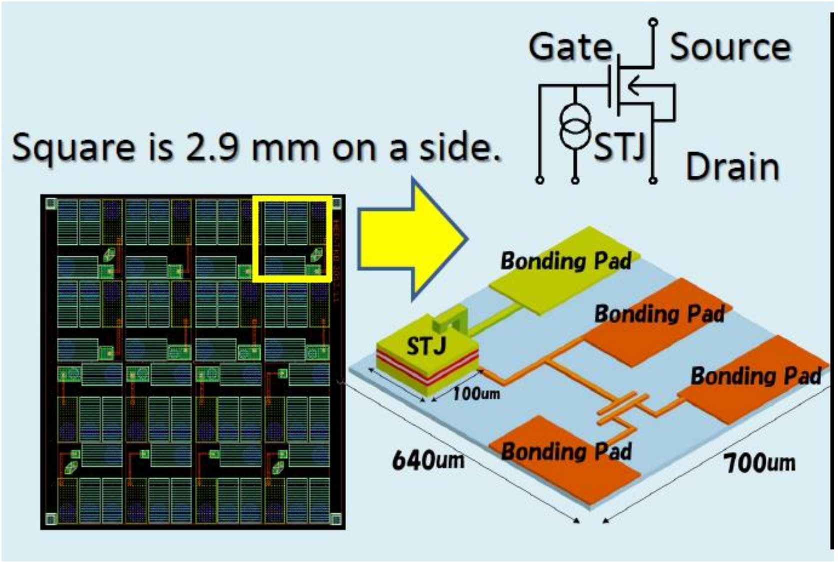
R&D of SOI-STJ Detector

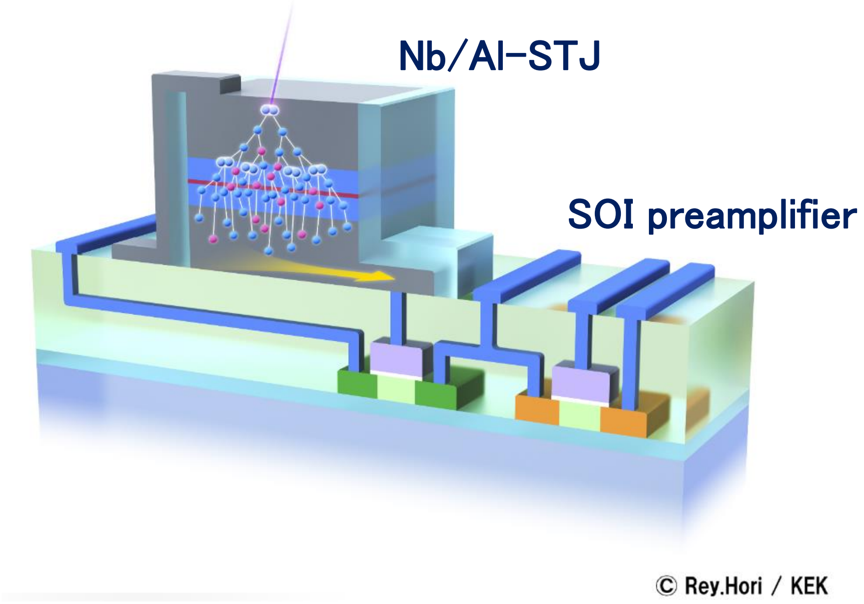
FD-SOI (Fully Depleted Silicon-On-Insulator) device was proved to operate at 4K by a JAXA/KEK group (AIPC 1185,286-289(200 FD-SOI 9)). It has the following characteristics: low-power consumption, high speed, easy large scale integration and suppression of charge-up by high mobility carrier due to thin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





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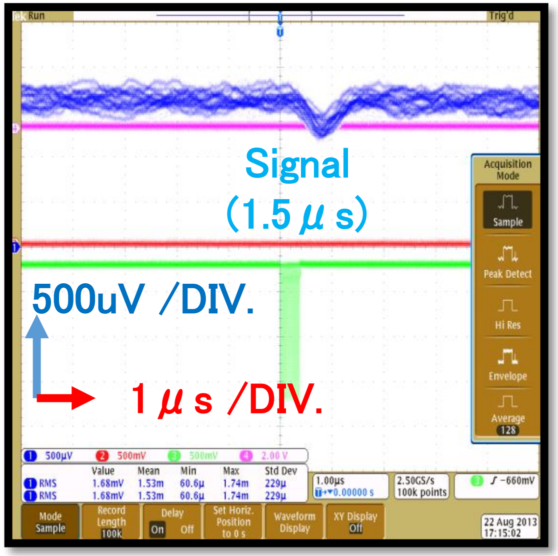
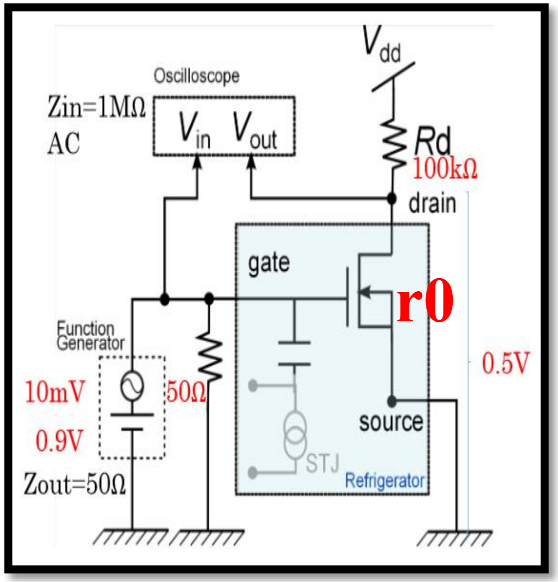
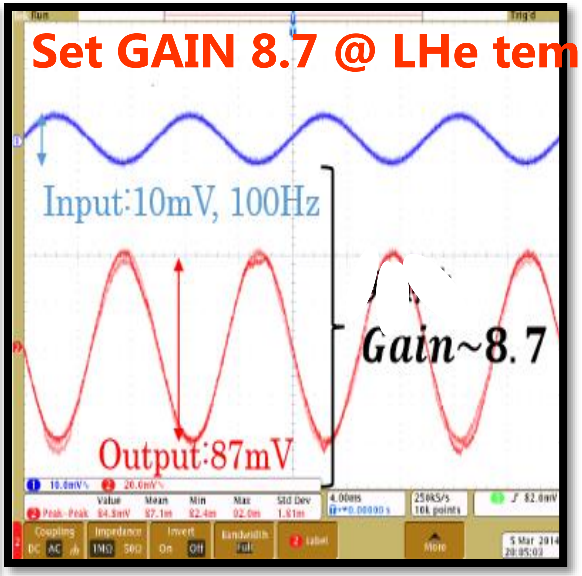
Performance of STJ and SOIFET in SOI-STJ detector

- ☐ **We observed the signal of Nb/Al-STJ processed on the SOI board to 465nm laser pulse at 700mK.**





Set GAIN 8.7 @ LHe temp.



- ☐ **We confirmed that the SOI-FET work as a preamplifier with a gain of 8.7 at 4K up to 100kHz.**

Zodiacal Emission

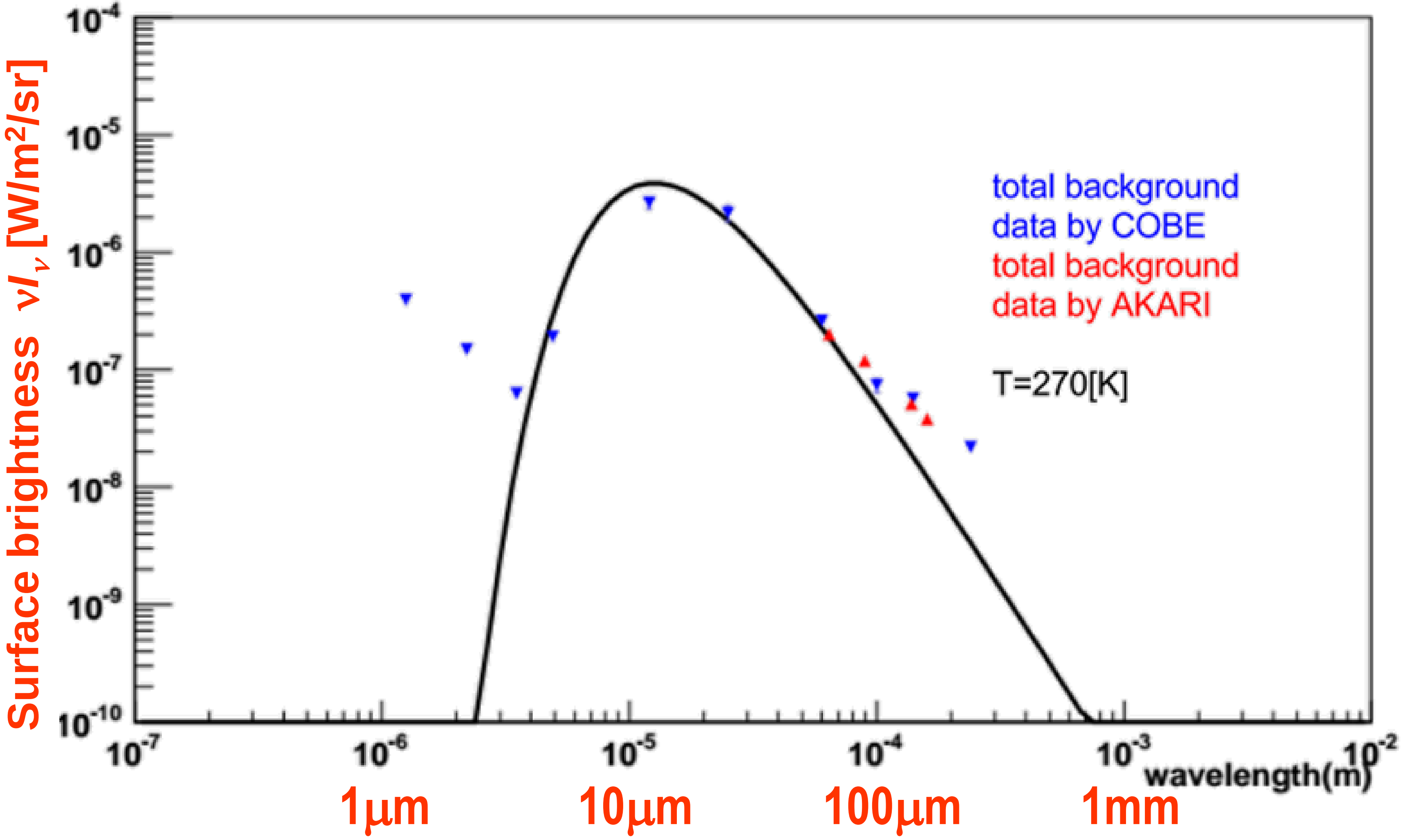
Thermal emission from the interplanetary dust cloud

$$I_\nu = \frac{2h\nu^3}{c^2}\frac{1}{\exp(h\nu/kT)-1} \times A\left(\frac{\nu}{c}\times 10^{-5}\right)^B \ \mathrm{Wm^{-2}sr^{-1}}$$

- $T = 270K$, $A = 6 \times 10^{-8}$, $B = 0.3$
- h [Js], c [m/s], λ [m]

Zodiacal Emission(ZE) is overwhelmingly dominating. Here we consider only ZE as the background.

Zodiacal Emission



STJ Energy Resolution

STJ Energy Resolution

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

Using Hf as a superconductor,

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

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

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

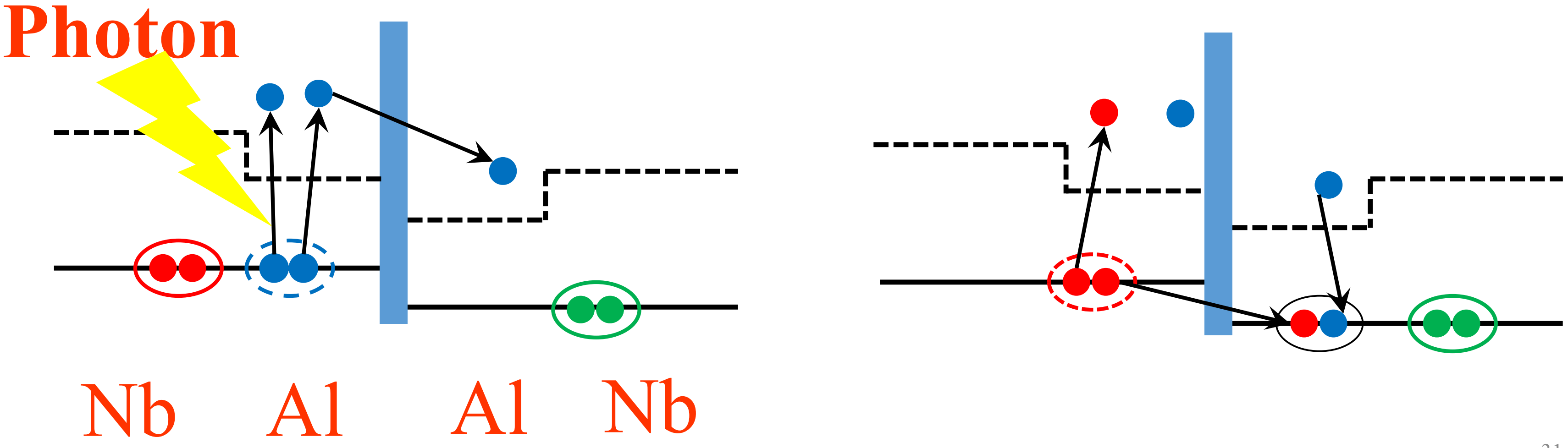
Tc : Critical Temperature

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

We reported that Hf-STJ worked as a STJ in TIPP2011.

STJ back tunneling effect

- 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/Al-STJ Nb(200nm)/Al(10nm)/AlOx/Al(10nm)/Nb(100nm)
- Gain: 2～200



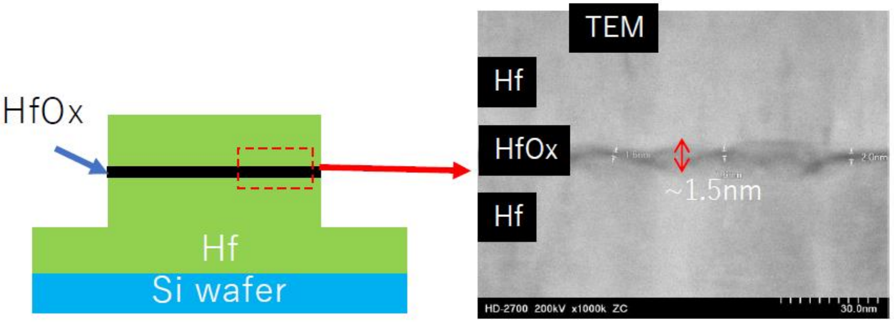
R&D Status of Hf-STJ

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 $E\gamma$ = 25meV.

Earlier version of our Hf-STJ in 2011

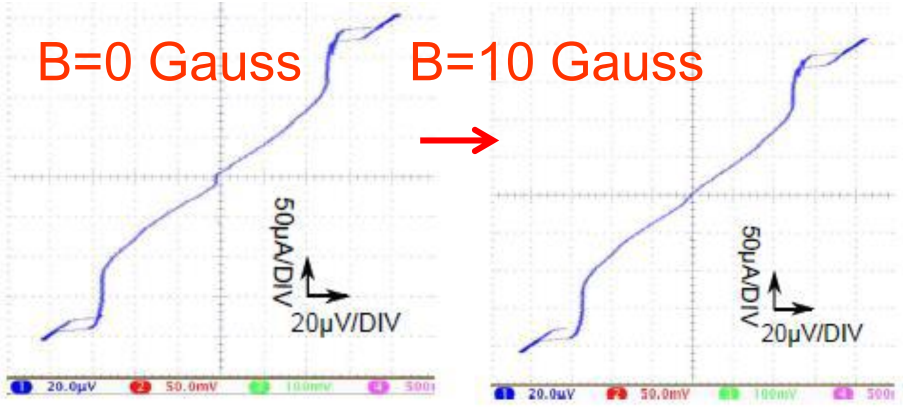
- Structure: Hf/HfOx/Hf =250nm/1.5nm/300nm
- Leakage current 20μA@50mK, 20μV for 100μm-square sample
  (our requirement :10pA)



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

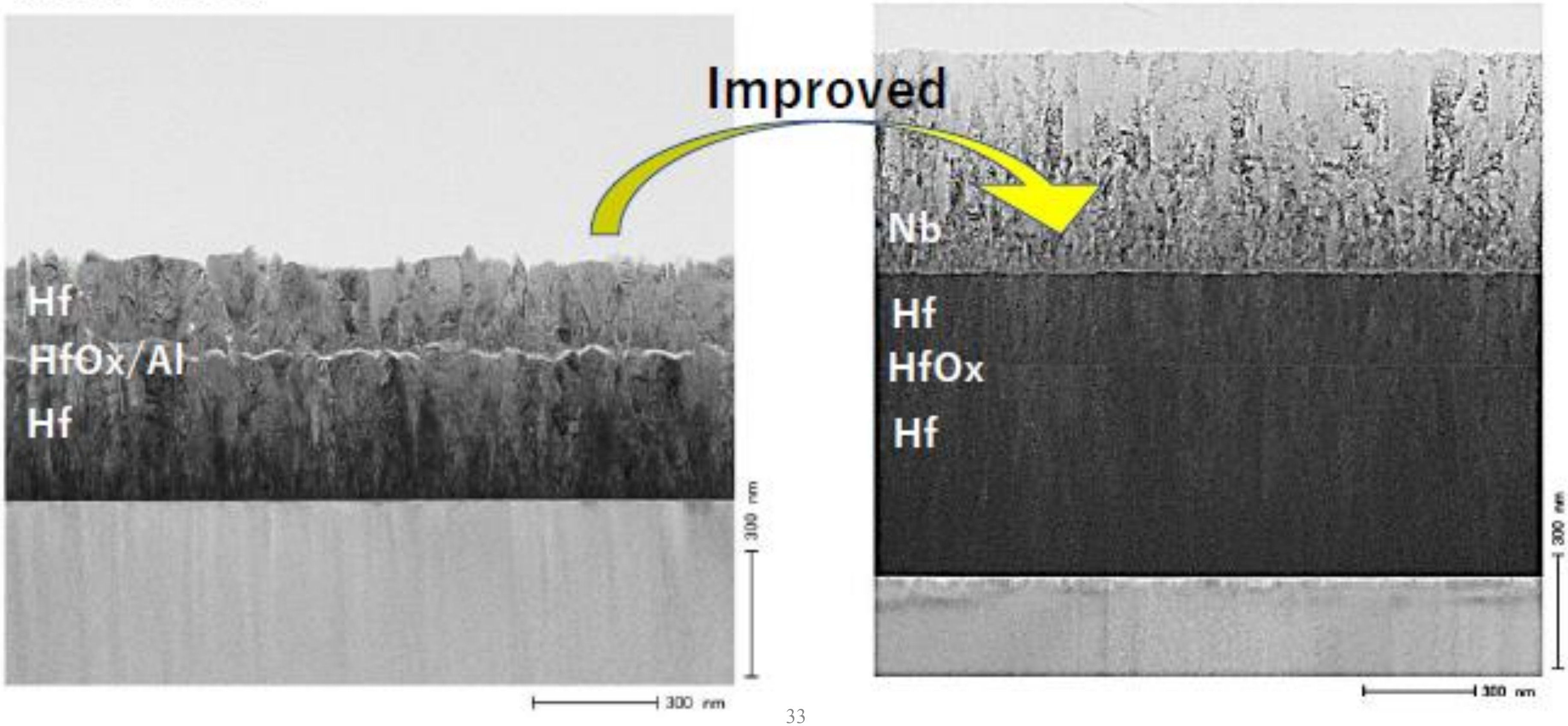
I-V curve of Hf-STJ (**100x100μm²**)

- T~40mK, I_c=10μA, **R_d=0.6Ω**



Improvement of Hf Surface Smoothness

- We improved the Hf surface smoothness by optimizing the Hf sputtering parameters.



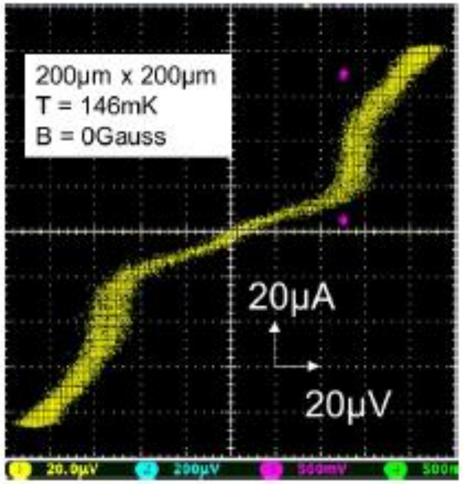
Old sputtering condition
Ar 2.0Pa, 80W

New sputtering condition
Ar 0.5Pa, 50W

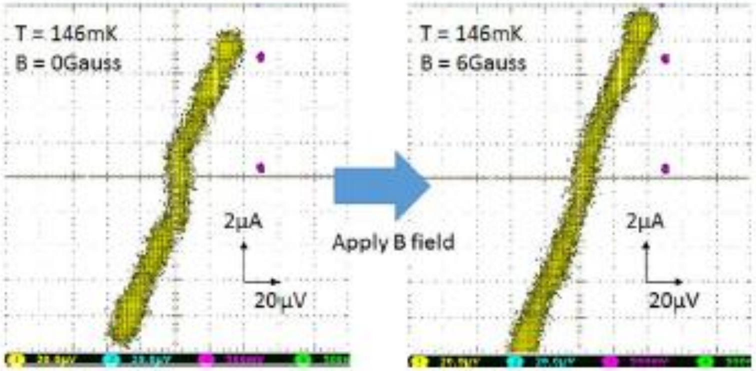
Hf-STJ with Improved Smoothness

200µ square Hf-STJ with improved smoothness. Wire bonding readout line.

- ●Josephson current is 2µA.
- ●Effective energy gap Δ = 25µeV.
- ●Leakage current at 20µV is 7µA.

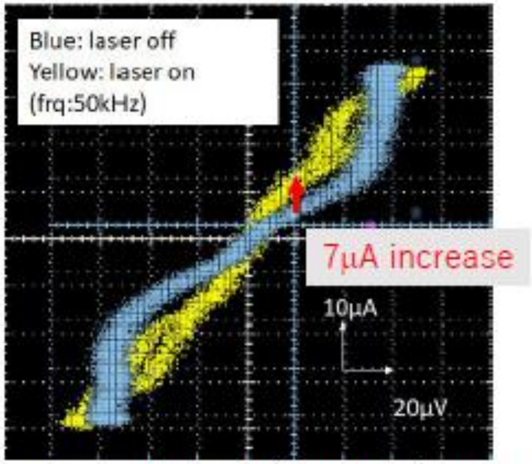


IV characteristic



IV characteristic (near 0V, B=0Gauss)

IV characteristic (near 0V, 6Gauss)

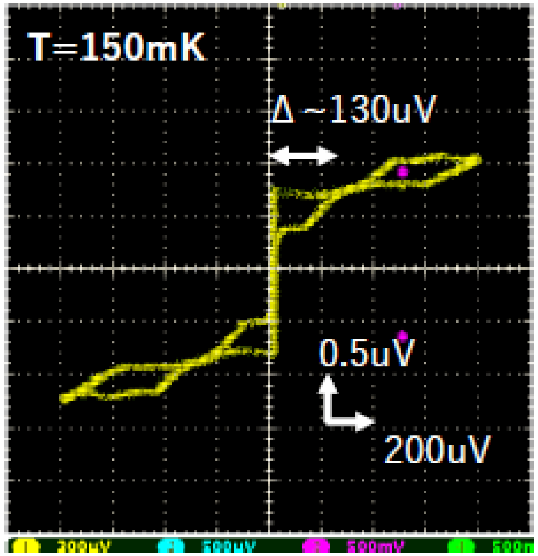


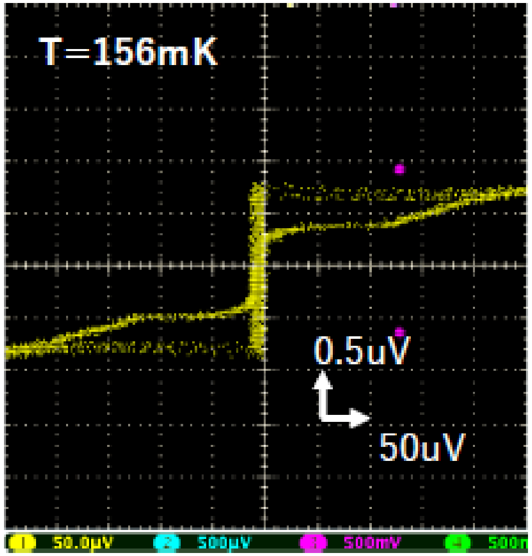
Response to visible(λ=465nm) DC-like laser light
T = 140mK, 9Gauss B field is applied.

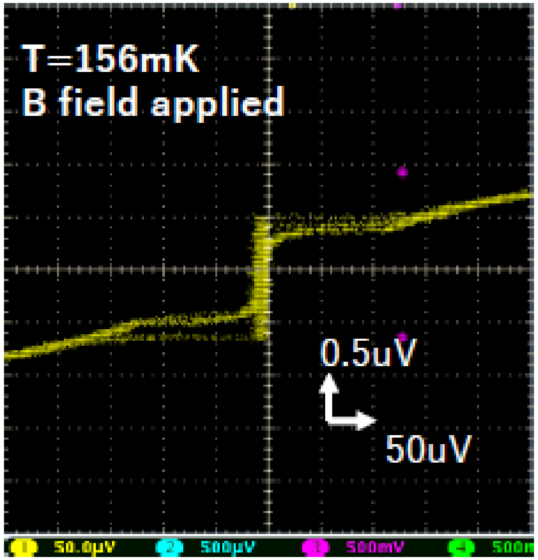
Small-size Hf-STJ with improved smoothness

10μ-square Hf-STJ. Signal line was made by sputtered Nb line not by wire bonding.

- Josephson current is 0.7μA.
- Effective energy gap Δ = 130μeV.
- Leakage current at 20μV is 0.3μA (1/24 of 200μ-square Hf-STJ).







Neutrino Lifetime by Left-Right Symmetric Model

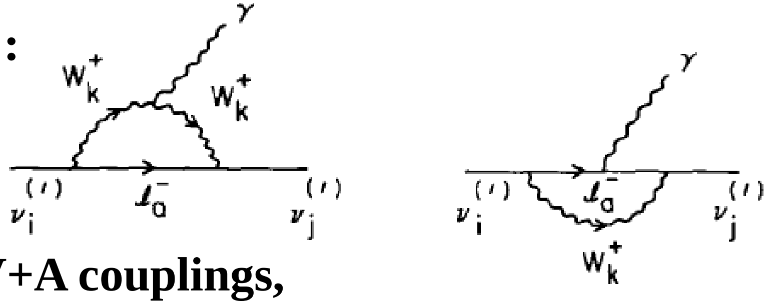
In the Left - Right Symmetric Model $SU(2)_L \otimes SU(2)_R \otimes U(1)$

(PRL 38, 1252(1977), PRD 17, 1395(1978) NP B206, 359(1982)),

there are two Weak Boson mass eigenstates:

$$W_1 = W_L \cos\zeta - W_R \sin\zeta,$$

$$W_2 = W_L \sin\zeta + W_R \cos\zeta.$$



W_L and W_R are fields with pure V-A and V+A couplings, respectively, and ζ is a mixing angle.

$$\tau^{-1} = \frac{\alpha G_F^2}{128\pi^4}\left(\frac{m_3^2-m_2^2}{m_3}\right)^3 \times |U_{32}|^2|U_{33}|^2\left[\frac{9}{64}(m_3^2+m_2^2)\frac{m_\tau^4}{M_{W1}^4}\left(1+\frac{M_{W1}^2}{M_{W2}^2}\right)^2 + 4m_\tau^2\left(1-\frac{M_{W1}^2}{M_{W2}^2}\right)^2 \sin^2 2\zeta\right],$$

where α is a fine structure constant, G_F is a Fermi coupling constant, m_τ, M_{W1} and M_{W2} are masses of τ, W_1 and W_2, respectively.[21, 22] U_{ij} is the (i, j)-th element of the Maki-Nakagawa-Sakata mixing matrix[23] and we took $|U_{32}| = 1/\sqrt{2}$ and $|U_{33}| = 1/\sqrt{2}$.

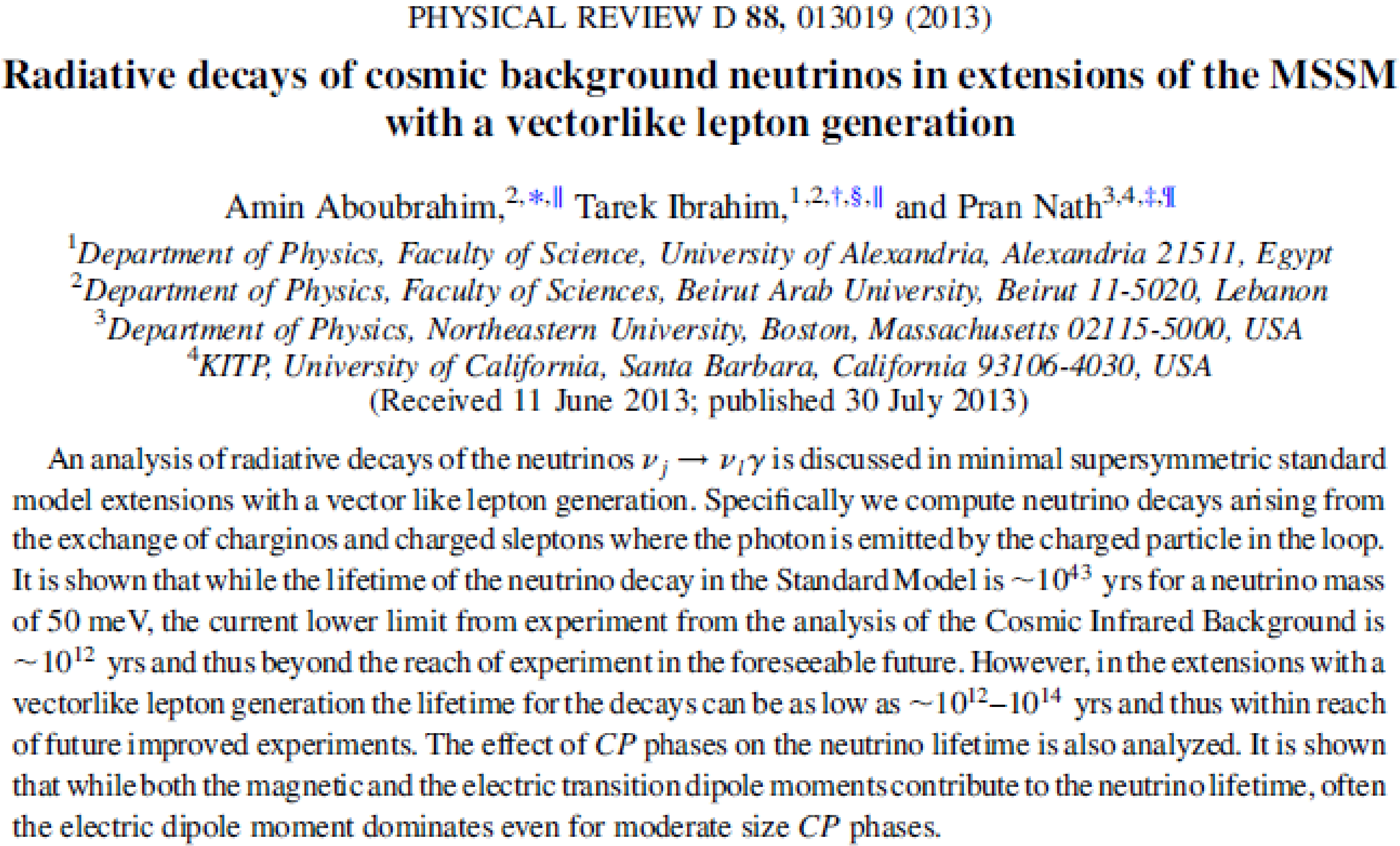
$$\tau^{-1} = \frac{\alpha G_F^2}{128\pi^4}\left(\frac{\Delta m_{32}^2}{m_3}\right)^3 m_\tau^2 \sin^2 2\zeta$$

Using a lower mass limit $M(W_R) > 715\text{GeV}$, a mixing angle limit $\zeta < 0.02$, and $m_3 = 50\text{meV}$,

$\tau = 1.5 \times 10^{17}$ year

Measured neutrino lifetime limit $\tau < 3 \times 10^{12}$ year from CIB results measured by COBE and AKARI

Other papers citing our JPSJ paper



PHYSICAL REVIEW D 88, 013019 (2013)

Radiative decays of cosmic background neutrinos in extensions of the MSSM with a vectorlike lepton generation

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(Received 11 June 2013; published 30 July 2013)

An analysis of radiative decays of the neutrinos $\nu_j \to \nu_i \gamma$ is discussed in minimal supersymmetric standard model extensions with a vector like lepton generation. Specifically we compute neutrino decays arising from the exchange of charginos and charged sleptons where the photon is emitted by the charged particle in the loop. It is shown that while the lifetime of the neutrino decay in the Standard Model is $\sim 10^{43}$ yrs for a neutrino mass of 50 meV, the current lower limit from experiment from the analysis of the Cosmic Infrared Background is $\sim 10^{12}$ yrs and thus beyond the reach of experiment in the foreseeable future. However, in the extensions with a vectorlike lepton generation the lifetime for the decays can be as low as $\sim 10^{12}$–10^{14} yrs and thus within reach of future improved experiments. The effect of *CP* phases on the neutrino lifetime is also analyzed. It is shown that while both the magnetic and the electric transition dipole moments contribute to the neutrino lifetime, often the electric dipole moment dominates even for moderate size *CP* phases.

MSSM extension with a vectorlike lepton generation

→ $\tau_\nu \sim 10^{12} \sim 10^{14}$ years

MSSM extension model with a vectorlike lepton generation

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$SU(3)_C \times SU(2)_L \times U(1)_Y$

$Q = T_3 + Y$

$$\psi_{iL} \equiv \begin{pmatrix} \nu_{iL} \\ l_{iL} \end{pmatrix} \sim \left(1, 2, -\frac{1}{2}\right), \qquad l^c_{iL} \sim (1, 1, 1), \qquad \nu^c_{iL} \sim (1, 1, 0), \qquad i = 1, 2, 3 \tag{3}$$

$$\chi^c \equiv \begin{pmatrix} E^c_L \\ N^c_L \end{pmatrix} \sim \left(1, 2, \frac{1}{2}\right), \qquad E_L \sim (1, 1, -1), \qquad N_L \sim (1, 1, 0). \tag{4}$$

vectorlike lepton generation

V+A interaction

$$\begin{pmatrix} \nu_{\tau_R} \\ N_R \\ \nu_{\mu_R} \\ \nu_{e_R} \end{pmatrix} = D^\nu_R \begin{pmatrix} \psi_{1_R} \\ \psi_{2_R} \\ \psi_{3_R} \\ \psi_{4_R} \end{pmatrix}, \qquad \begin{pmatrix} \nu_{\tau_L} \\ N_L \\ \nu_{\mu_L} \\ \nu_{e_L} \end{pmatrix} = D^\nu_L \begin{pmatrix} \psi_{1_L} \\ \psi_{2_L} \\ \psi_{3_L} \\ \psi_{4_L} \end{pmatrix}. \tag{17}$$

In Eq. (16) $\psi_1, \psi_2, \psi_3, \psi_4$ are the mass eigenstates for the neutrinos, where in the limit of no mixing we identify ψ_1 as the tau neutrino, ψ_2 as the heavier mass eigenstate, ψ_3 as the muon neutrino and ψ_4 as the electron neutrino. To make contact with the normal neutrino hierarchy we relabel the states so that

$$\nu_1 = \psi_4, \qquad \nu_2 = \psi_3, \qquad \nu_3 = \psi_1, \qquad \nu_4 = \psi_2, \tag{18}$$

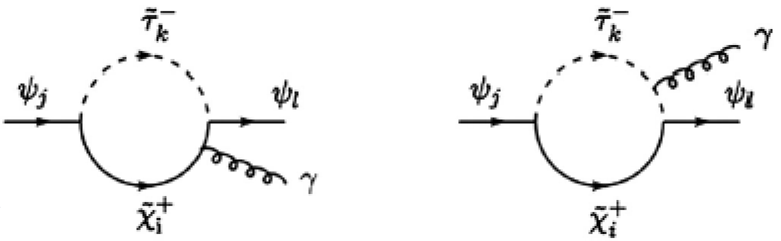
which we assume has the mass hierarchical pattern

$$m_{\nu_1} < m_{\nu_2} < m_{\nu_3} < m_{\nu_4}. \tag{19}$$

PHYSICAL REVIEW D 89, 055009 (2014)

Large neutrino magnetic dipole moments in MSSM extensions

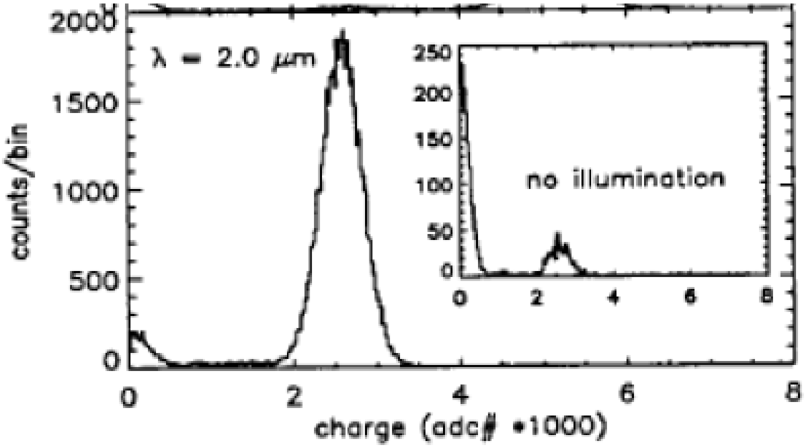
Amin Aboubrahim,[2,*] Tarek Ibrahim,[1,2,†] Ahmad Itani,[2,‡] and Pran Nath[3,§]



	Neutrino mass eigenvalues (GeV)	$m_{\nu_3} = 5.2 \times 10^{-11}$ $m_{\nu_2} = 9.2 \times 10^{-12}$ $m_{\nu_1} = 9.7 \times 10^{-13}$
(i) $m_{\chi^\pm} = 256$ GeV	μ_2	1.2×10^{-10}
$m_{\tilde\tau} = 162$ GeV	μ_1	2.5×10^{-13}
	ν_3 lifetime	3.9×10^{14} yr
(ii) $m_{\chi^\pm} = 267$ GeV	μ_2	4.6×10^{-10}
$m_{\tilde\tau} = 202$ GeV	μ_1	1.3×10^{-12}
	ν_3 lifetime	2.5×10^{14} yr
(iii) $m_{\chi^\pm} = 268$ GeV	μ_2	2.2×10^{-10}
$m_{\tilde\tau} = 158$ GeV	μ_1	1.1×10^{-13}
	ν_3 lifetime	1.8×10^{14} yr
(iv) $m_{\chi^\pm} = 272$ GeV	μ_2	-7.6×10^{-10}
$m_{\tilde\tau} = 195$ GeV	μ_1	-1.3×10^{-13}
	ν_3 lifetime	8.8×10^{13} yr

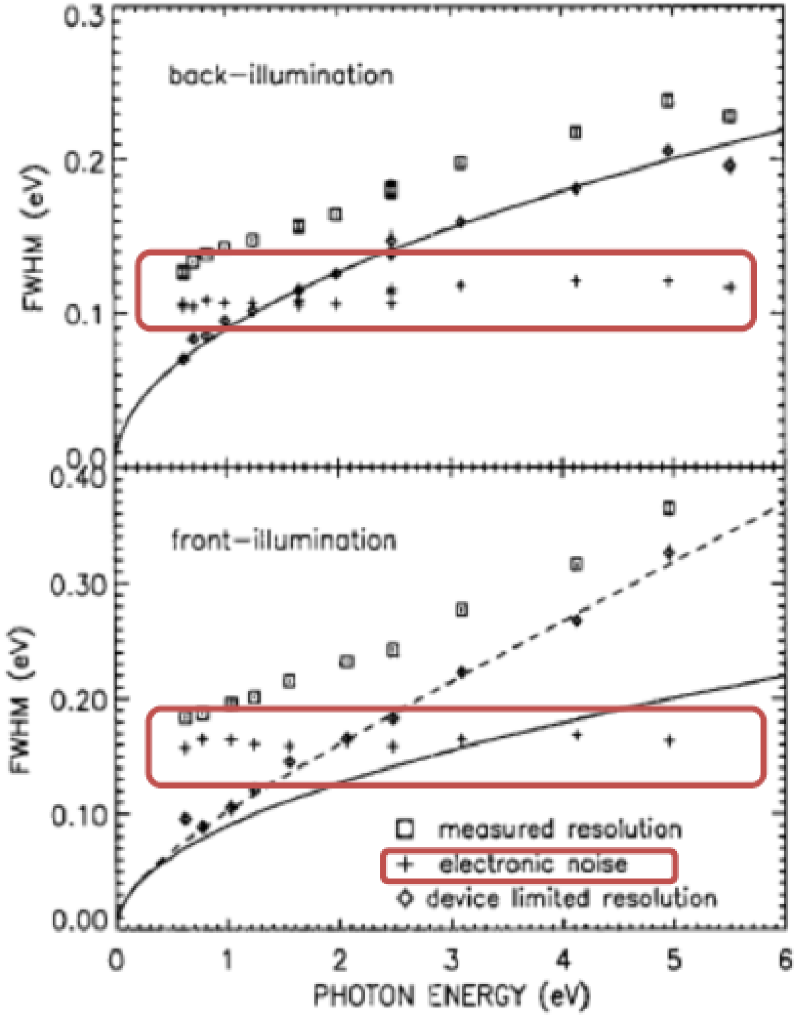
$$-\mathcal{L}_{CC} = \frac{g}{2\sqrt{2}} W^\dagger_\rho \{\bar\nu_\tau \gamma^\rho (1-\gamma_5)\tau + \bar\nu_\rho \gamma^\mu (1-\gamma_5)\mu + \bar\nu_e \gamma^\rho (1-\gamma_5) e + \bar N \gamma^\rho (1+\gamma_5) E\} + H.c. \tag{24}$$

STJ Energy Resolution for Near-Infrared Photon



P. Verhoeve et. al 1997

- 30μm sq. Ta/Al-STJ
- ΔE~130meV @ E=620meV(λ=2μm)
- Charge sensitive amplifier at room temp.
  - Electronic noise ~ 100meV



In sub-eV ~ several-eV region, STJ gives the best energy resolution among superconductor based detectors, but limited by readout electronic noise.