October 16, 2018

# Cosmic Background Neutrino Decay Search – COBAND Experiment –

## Continuous Spectral Measurement in Far-Infrared Region using STJ

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for COBAND collaboration

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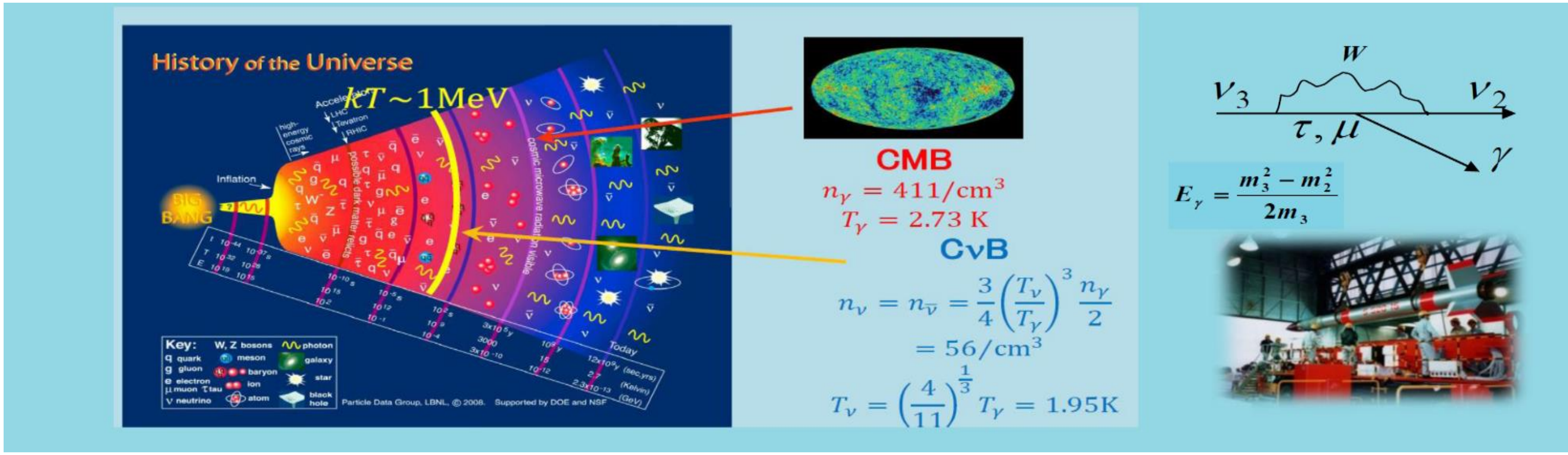
Tomonaga Center for the History of the Universe

COBAND

# COBAND (COsmic BAckground Neutrino Decay) Collaboration

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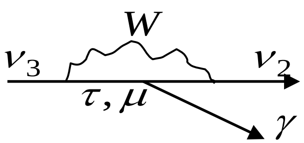
# Motivation of Search for Cosmic Background Neutrino Decay

- **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.**



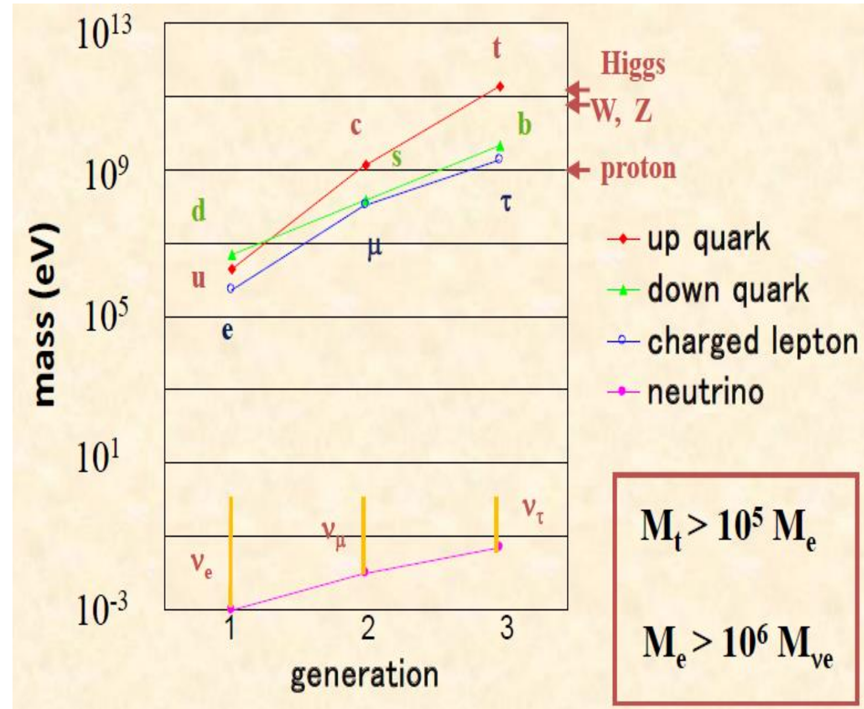

$$\nu_3 \rightarrow \nu_2 + \gamma$$

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

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

$E_\gamma = 10 \sim 25$ meV at $\nu_3$ rest frame.

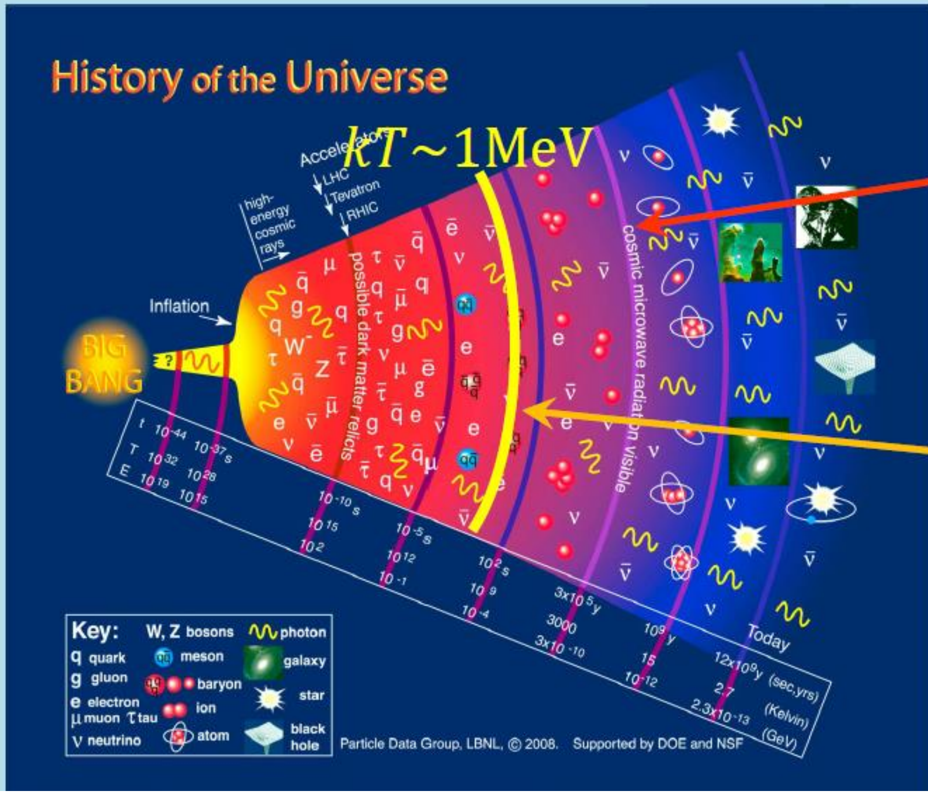
(Far - Infrared region $\lambda = 50 \sim 125\ \mu$)

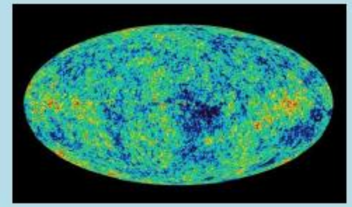



- **As the neutrino lifetime is very long, we need use cosmic background neutrino to observe the neutrino decay. To observe this decay of the cosmic background neutrino means a discovery of the cosmic background neutrino predicted by cosmology.**

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

# Big-Bang Cosmology and Cosmic Background Neutrino (CνB)



**CMB**

$$n_\gamma = 411/\mathrm{cm}^3$$
$$T_\gamma = 2.73\ \mathrm{K}$$

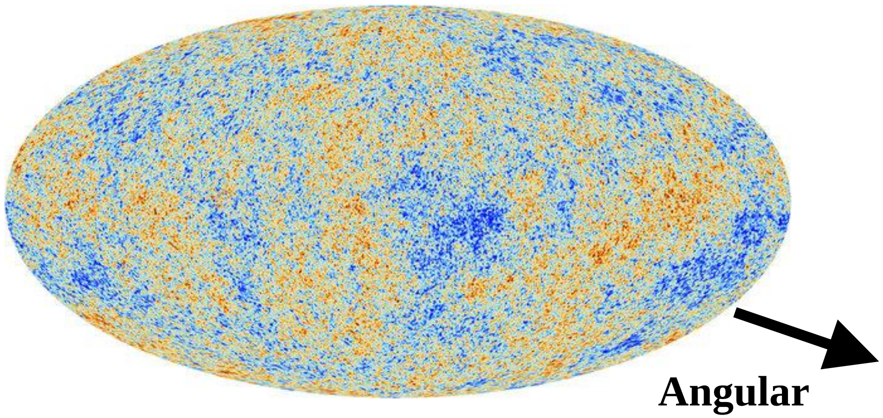
**CνB**

$$n_\nu = n_{\bar{\nu}} = \frac{3}{4}\left(\frac{T_\nu}{T_\gamma}\right)^3 \frac{n_\gamma}{2}$$
$$= 56/\mathrm{cm}^3$$
$$T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma = 1.95\mathrm{K}$$

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

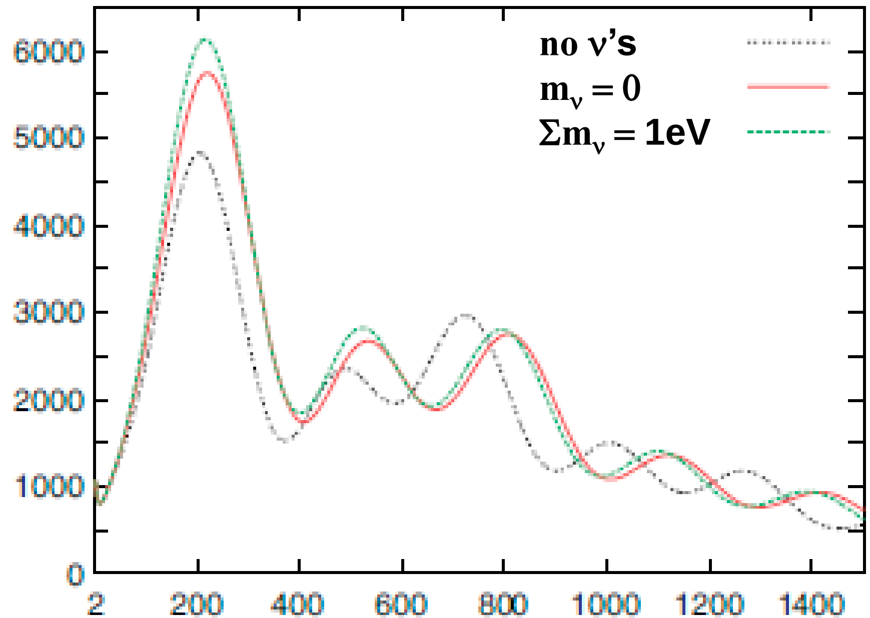
# Large Scale Structure of the Universe and CνB

Temperature fluctuation of CMB observed by Planck satellite



Angular correlation at high temperature

Theoretical prediction on Power Spectra of the angular correlation of the CMB temperature fluctuation （depending on the neutrino mass）




Large Angular scale(180° /*l*) Small

High Temperature ＝ High Galaxy matter density

CνB exists → large angular correlation at high angle

higher neutrino mass → larger angular correlation at high angle

Decision Factor of Temperature Fluctuation：

Dark matter, Dark energy, Neutrino

↓

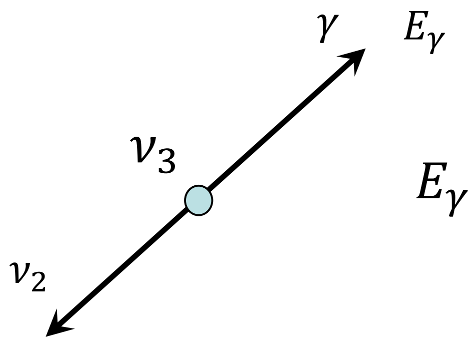
Matter density or Large scale structure of the Universe

Ref. J. Lesgourgues, S. Pastor Phys. Rep. 429 (2006) 307

# Photon Energy from Neutrino Decay

**Neutrino decay**

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

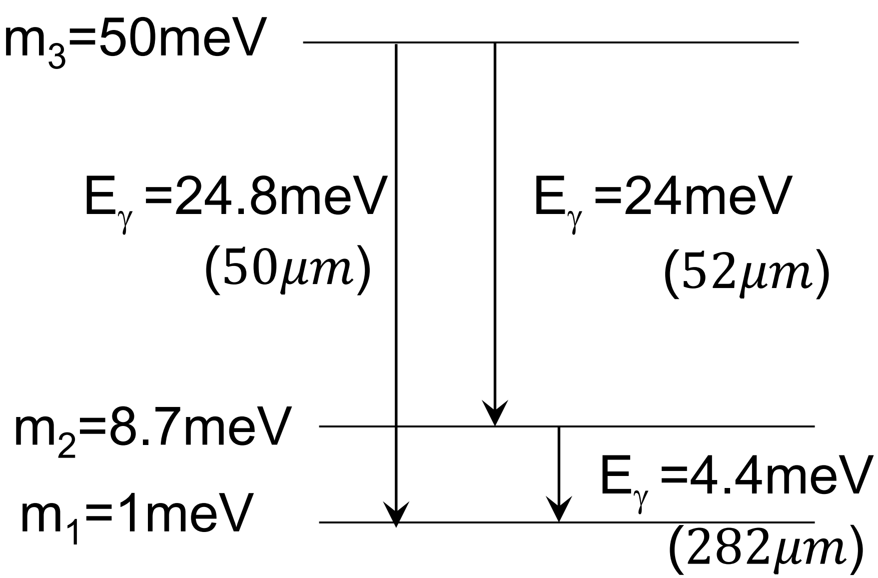



$$E_\gamma = \frac{m_3^2 - m_{1,2}^2}{2m_3}$$

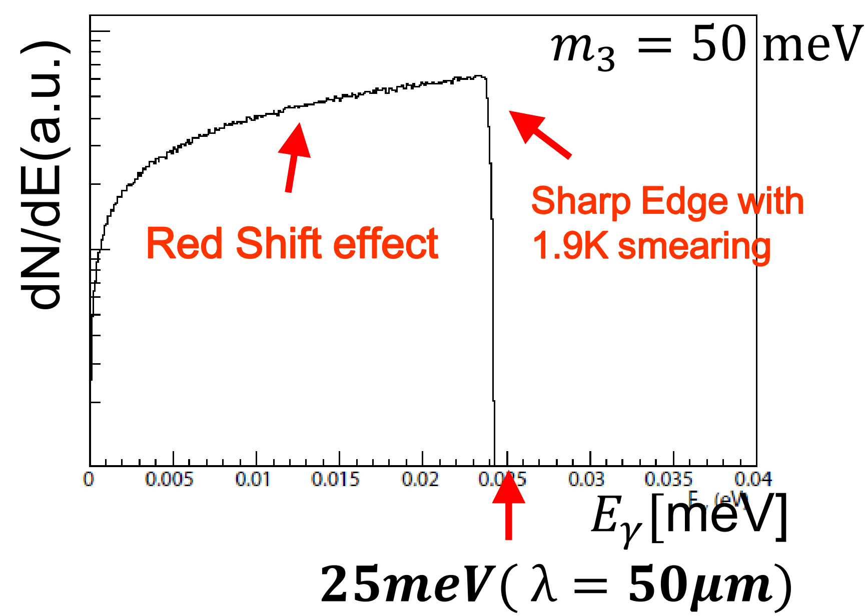
- **Neutrino oscillation results**
  - $|\Delta m_{23}^2| = |m_3^2 - m_2^2| \sim 2.4 \times 10^{-3}\ eV^2$
  - $\Delta m_{12}^2 \sim 7.65 \times 10^{-5}\ eV^2$
- **Space observatory results (Planck+WP+highL+BAO)**
  - $\sum m_i < 0.23\ eV$

➔ **50meV<$m_3$<87meV**

**$E_\gamma$ =14~24meV ($\lambda_\gamma$ =51~89μm)**




**Photon energy distribution** $\boldsymbol{\nu_3 \rightarrow \nu_2 + \gamma}$



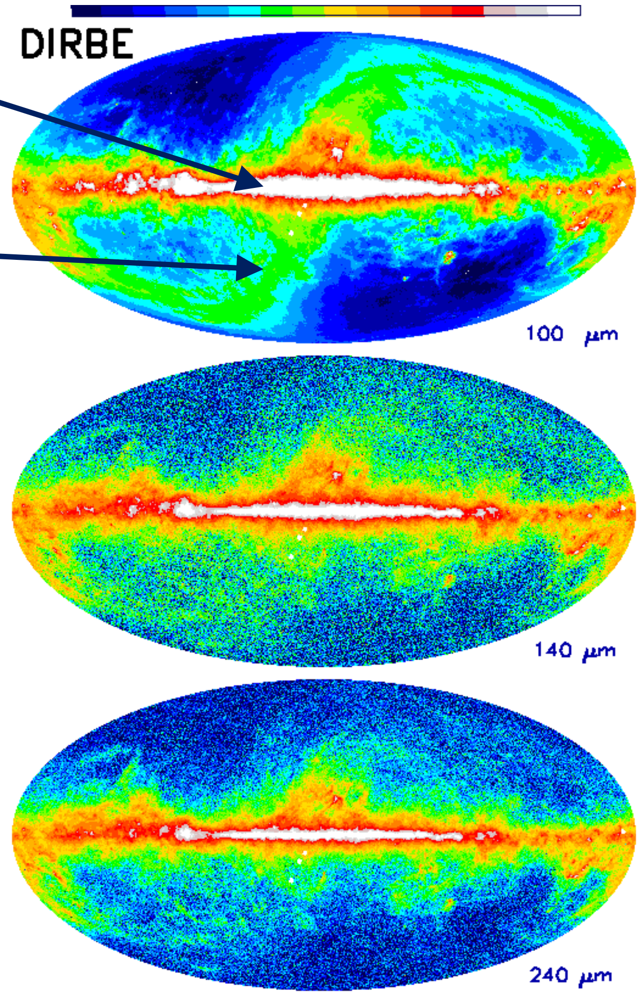
# Cosmic Infrared Background Radiation

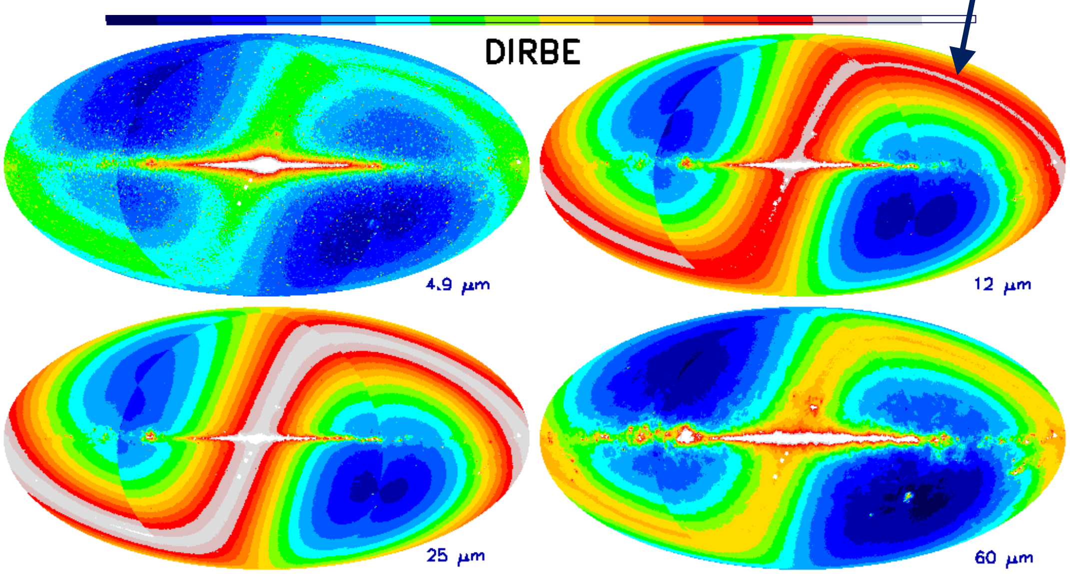
# Cosmic Infrared Background Observation by COBE

**January 1998 (Press Release): COBE (Cosmic Background Explorer) announced the first observation of the cosmic infrared background (CIB)**

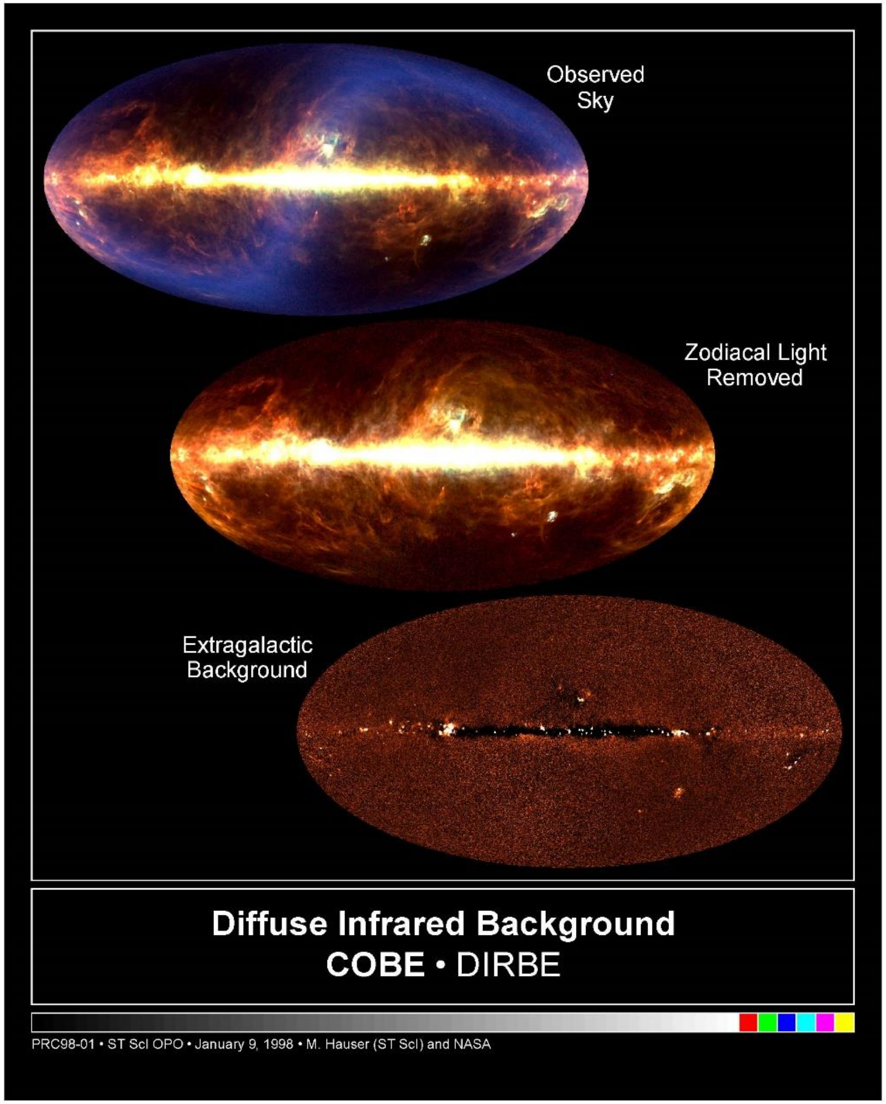
**Infrared light from star-heated dust in the Milky Way**

**Infrared light emitted from interplanetary dust heated by the Sun (zodiacal light) : S-shaped**



# Cosmic Infrared Background Observation by COBE




**(Top)**
**Observed Sky at λ = 60 μm(blue), 100 μm (green) and 240 μm(red).**
**Horizontal band corresponds to Infrared light from interstellar gas in the plane of our Milky Way Galaxy. The blue S-shaped region corresponds to Infrared light from interplanetary dust in the solar system called zodiacal emission.**

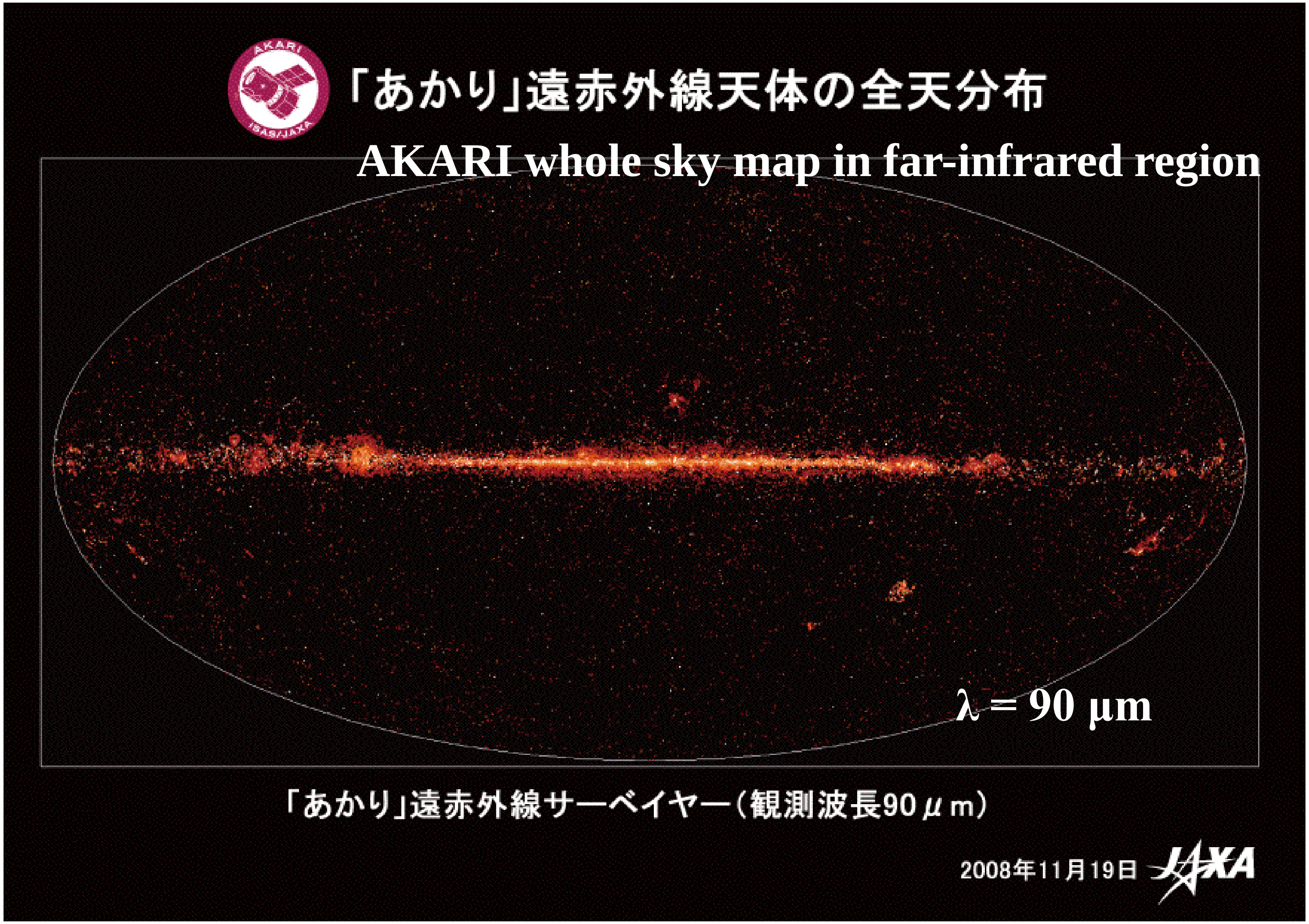
**(Middle)**
**After removing the zodiacal emission.**

**(Bottom)**
**After removing the infrared light from our solar system and Galaxy at λ = 240μm.**

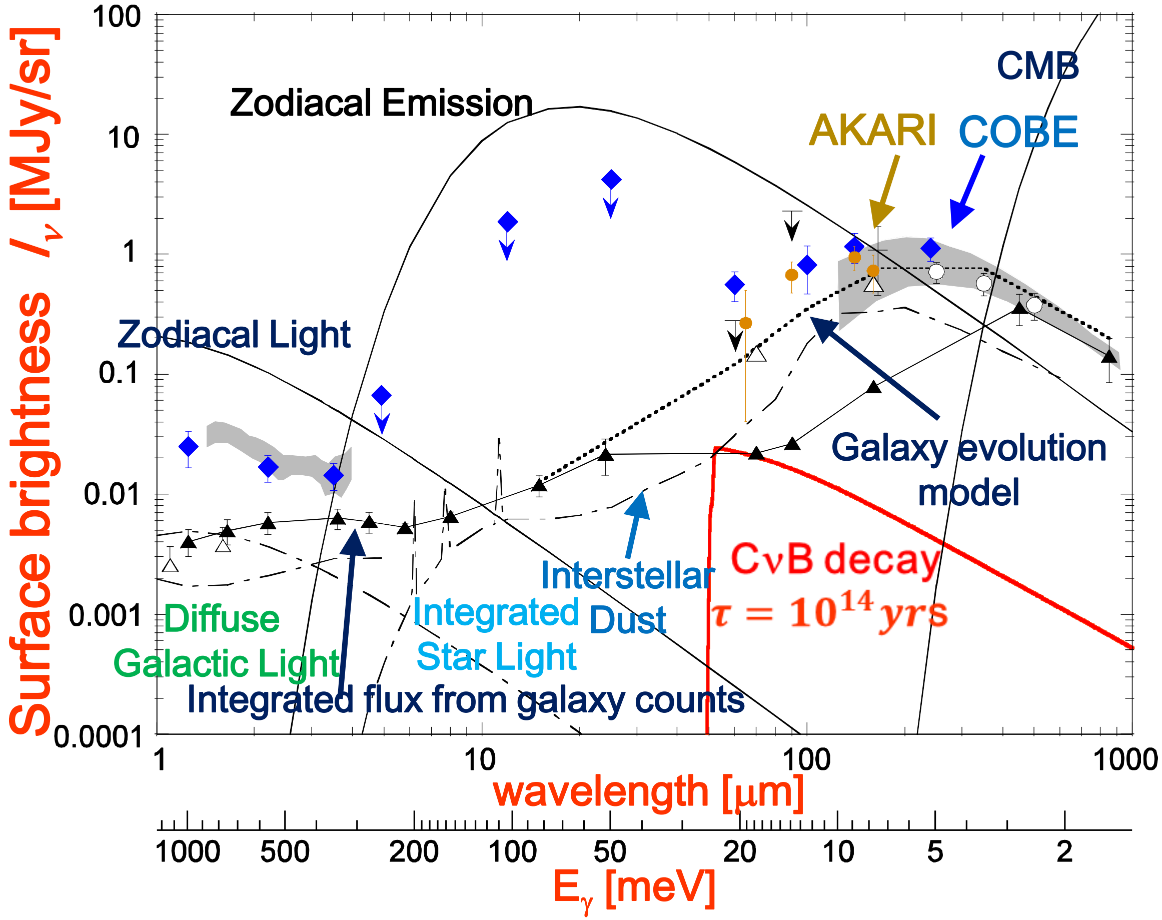
**COBE announced that they observed the extragalactic residual infrared light called "Cosmic Infrared Background" at the 240 and 140 micrometer wavelength.**

# Cosmic Far-Infrared Background Observation by AKARI

**November 2008 : AKARI ( JAXA Infrared Imaging Satellite) observed 64,000 stars and galaxies at wavelengths of 65, 90, 140 and 160 μm. Made a whole sky map. They extracted CIB map from this observation.**



# Photon Energy Spectrum from Outer Space




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
DOI: 10.1143/JPSJ.81.024101

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

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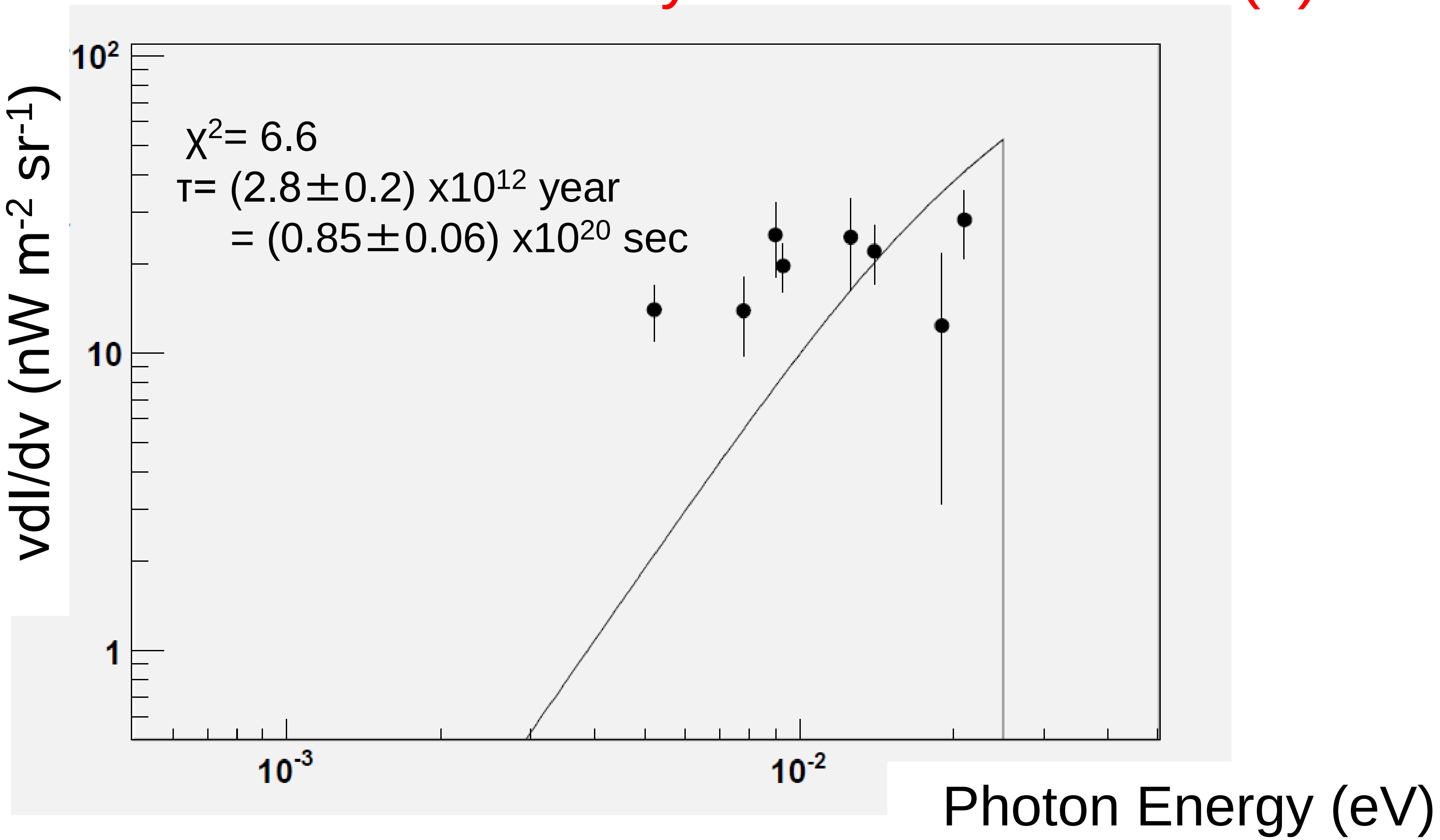
We propose to search for the neutrino radiative decay by fitting a photon energy spectrum of the cosmic infrared background to a sum of the photon energy spectrum from the neutrino radiative decay and a continuum. By comparing the present cosmic infrared background energy spectrum observed by AKARI and Spitzer to the photon energy spectrum expected from neutrino radiative decay with a maximum likelihood method, we obatined a lifetime lower limit of $3.1 \times 10^{12}$ to $3.8 \times 10^{12}$ years at 95% confidence level for the third generation neutrino $\nu_3$ in the $\nu_3$ 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 $\nu_3$ is predicted to be $1.5 \times 10^{17}$ 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 $1.5 \times 10^{17}$ 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

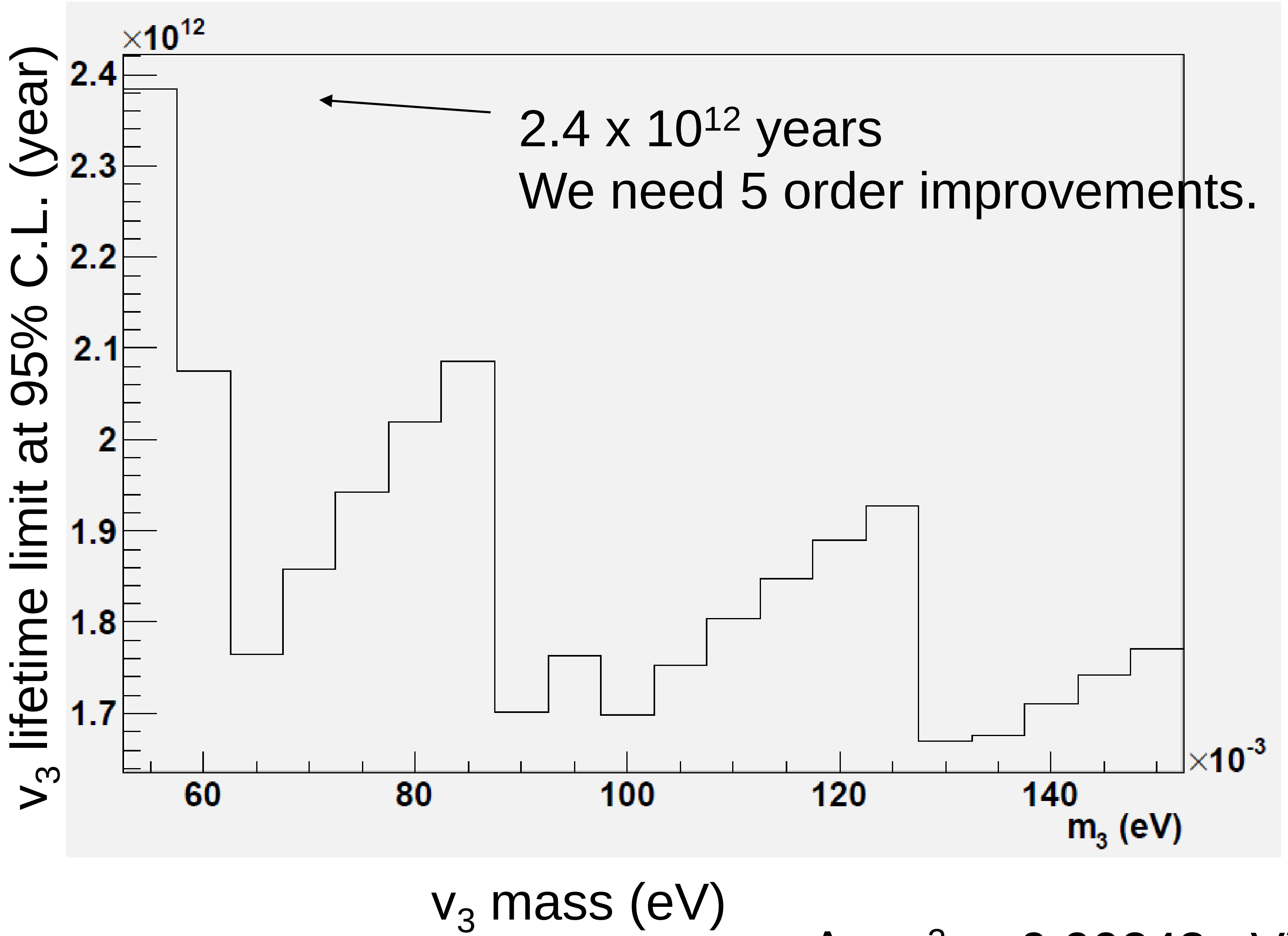
Search Region: $\lambda$ = 35～250μm （$E_\gamma$ = 35～5meV）
In Rocket experiment, $\lambda$ = 40～80μm （$E_\gamma$ = 31～15meV）

# 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 )

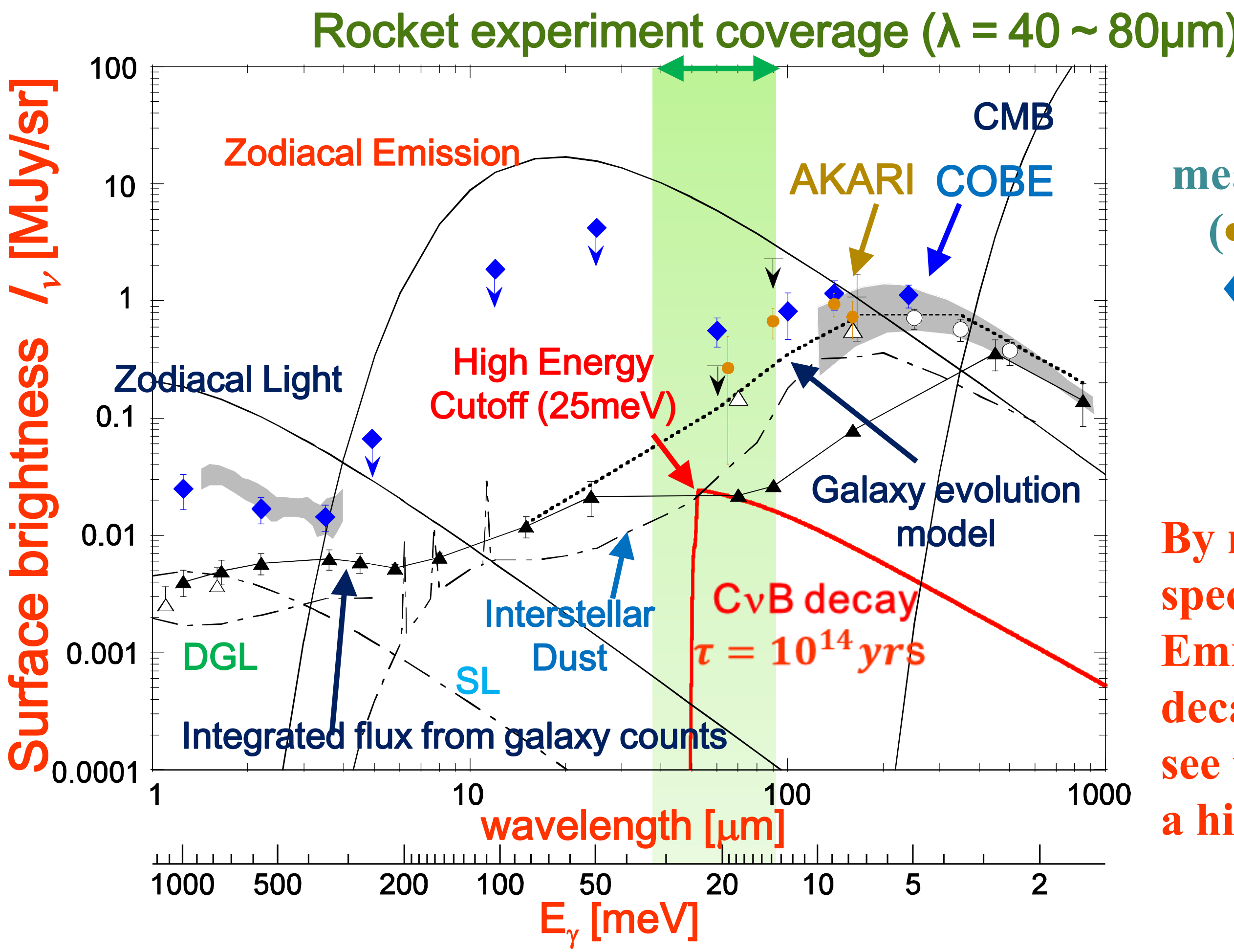
# Lower Limit of Lifetime from the Energy Spectrum Fit to the CIB measured by COBE and AKARI(2)




$\Delta m_{23}^2 = 0.00243\ eV^2$

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

# COBAND (COsmic BAckground Neutrino Decay Search) Experiment

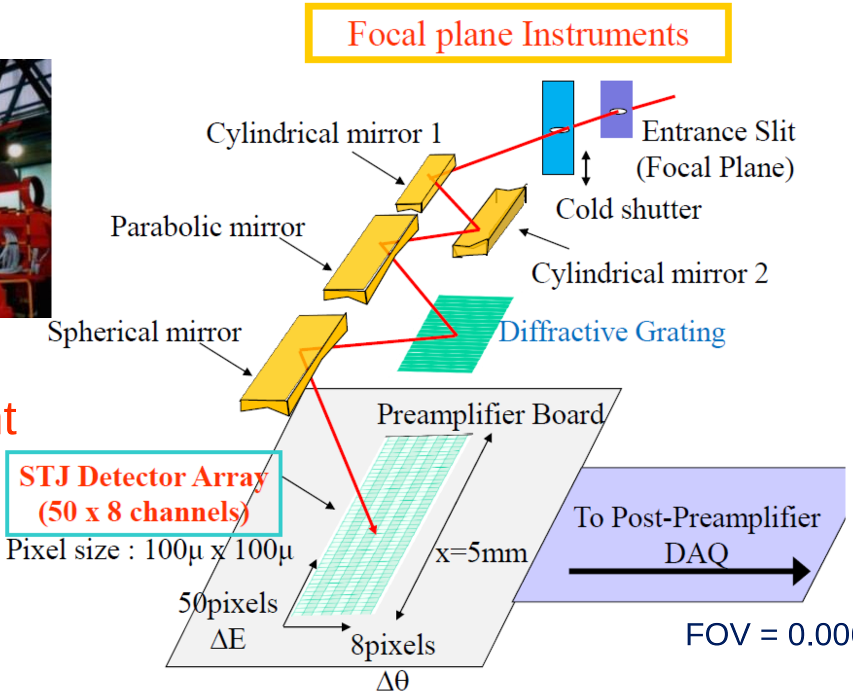
**Rocket Experiment** Plan: 5minutes data acquisition at 200 km height in 2021-22.
Improve the current limit of lifetime $\tau(\nu_3)$ by two orders of magnitude ( ~$10^{14}$years).

»**Superconducting Tunneling Junction (STJ) detectors in development**

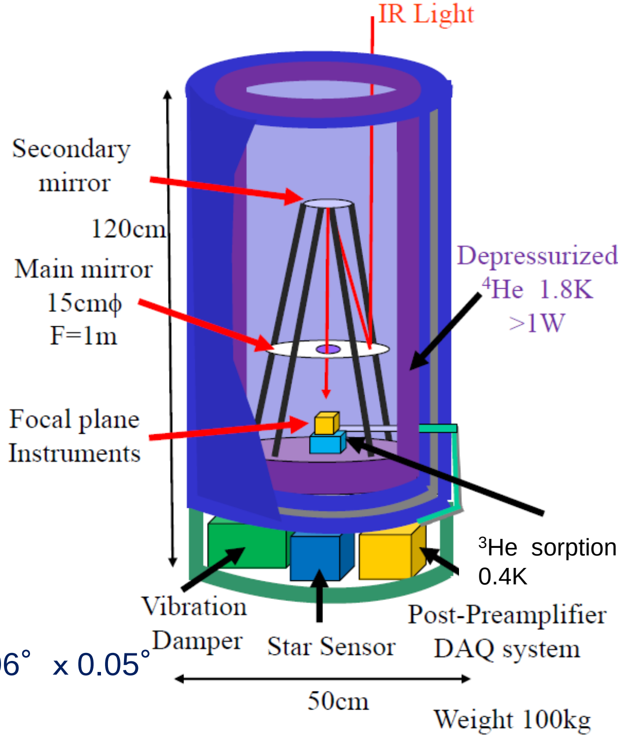
> **Array of 50 Nb/Al-STJ pixels with diffractive grating covering $\boldsymbol{\lambda = 40 - 80\mu m}$**

JAXA 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
- $N_{\text{q.p.}} = 25\text{meV}/1.7\Delta = 735$ for 25meV photon: $\Delta E/E < 2\%$ if Fano-factor is less than 0.3

# COBAND Rocket Experiment

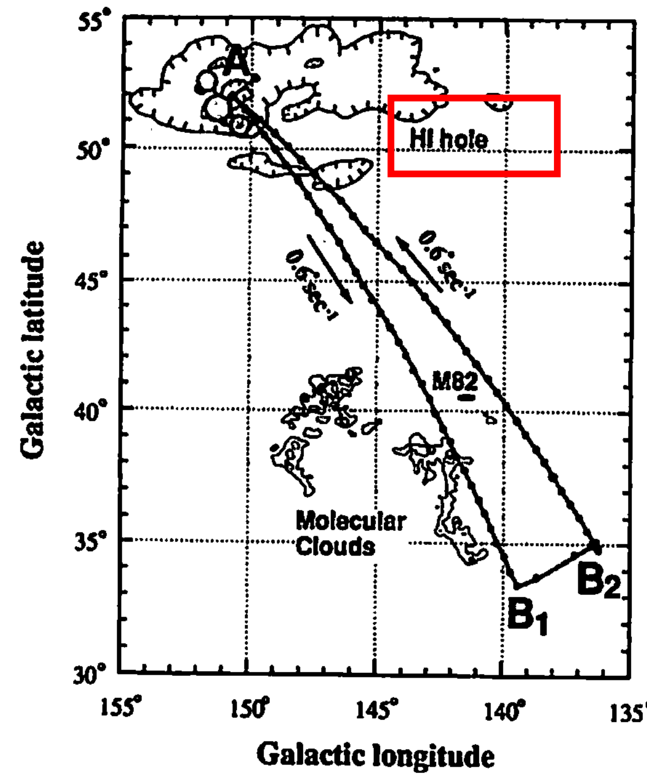
We measured CIB in the same points as S520-15 experiment measured the CIB in 1992.

**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" → "$B_1$" ($0.^\circ6\ s^{-1}$) |
| + 255s– | point to "$B_2$" |
| + 277s–310s | scan "$B_2$ → "A" ($0.^\circ6\ s^{-1}$) |
| + 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° )

# Zodiacal Emission

Thermal emission from the interplanetary dust cloud

$$I_\nu = \frac{2h\nu^3}{c^2}\frac{1}{\exp(h\nu/kT) - 1}$$

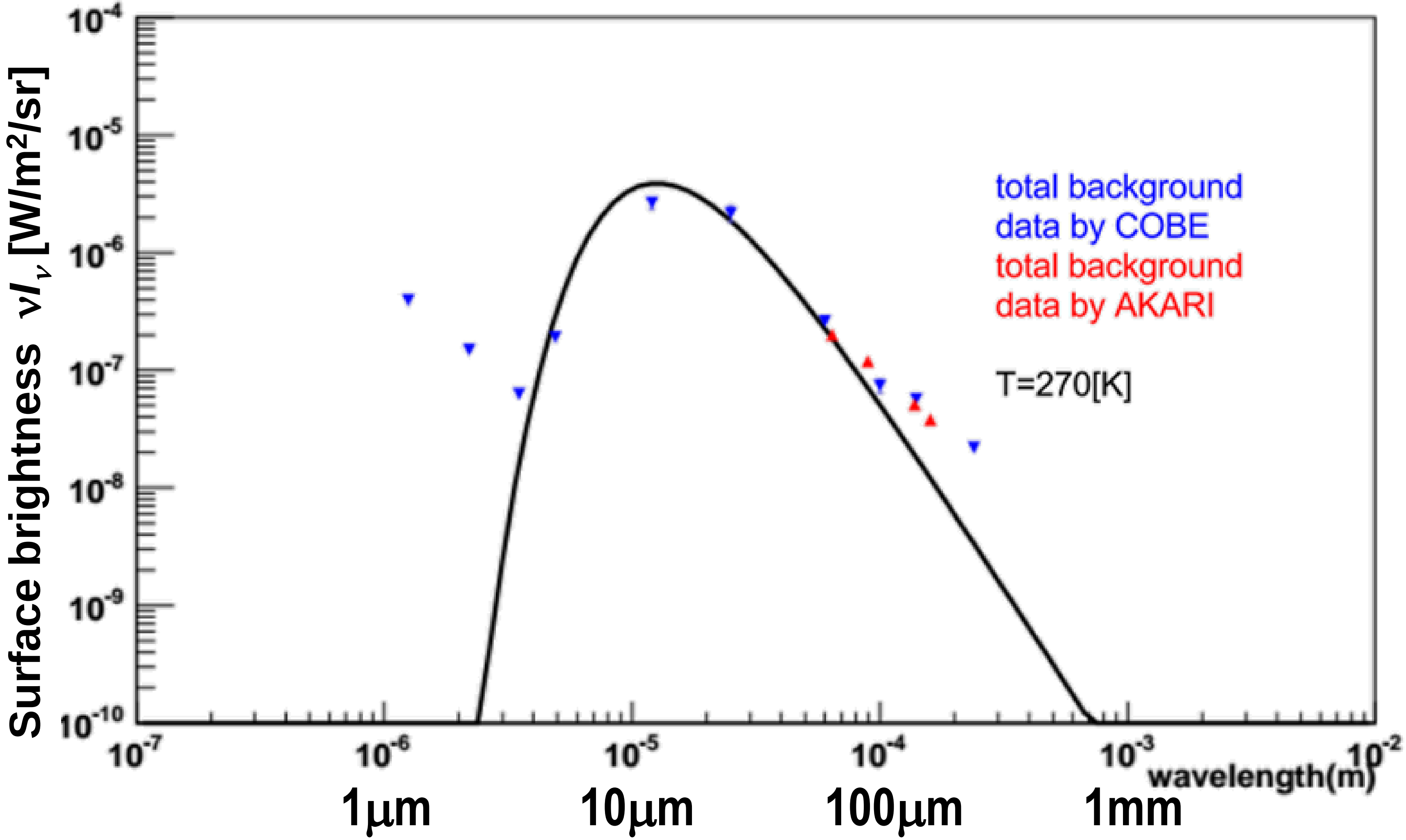
$$\times A\left(\frac{\nu}{c} \times 10^{-5}\right)^B \ \mathrm{Wm^{-2}sr^{-1}}$$

$T = 270K$, $A = 6 \times 10^{-8}$, $B = 0.3$

$h$ [Js], $c$ [m/s], $\lambda$ [m]

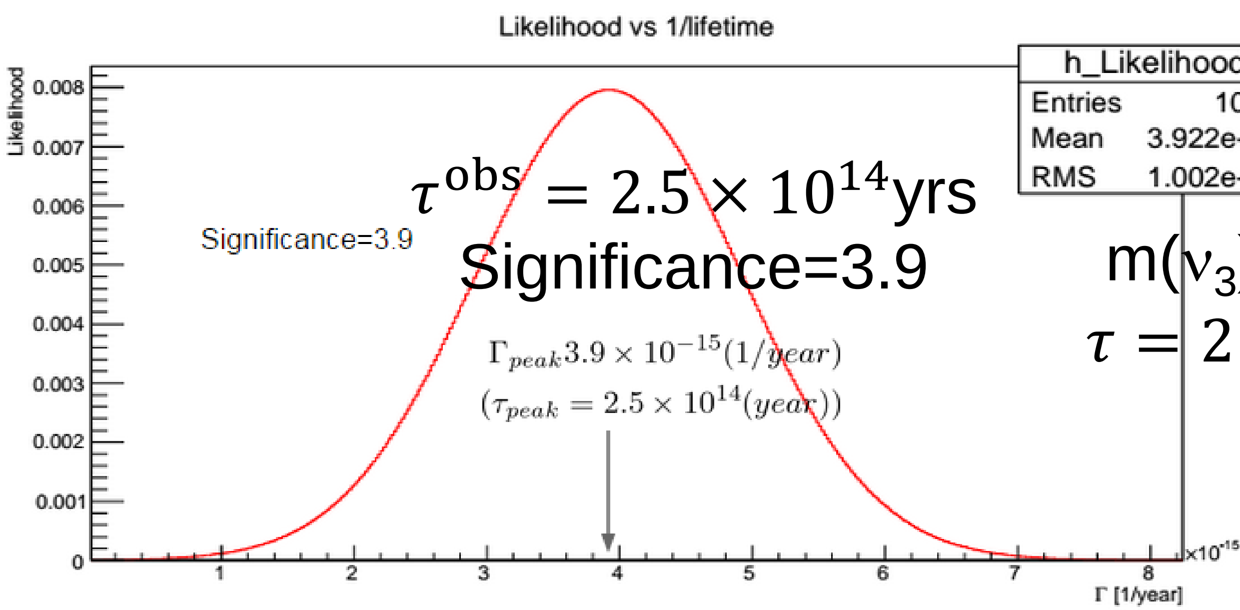
Zodiacal Emission(ZE) is overwhelmingly dominating. Here we consider only ZE as the background.

# Zodiacal Emission



# Discovery Potential for Neutrino Decay

1. Create a pseudo-data for ND and ZE expectation on assumption of $\nu_3$ mass and lifetime: $N_{obs}(m^{true}, \Gamma^{true})$
2. Calculate expected distribution of ND+ZE on assumption of $\nu_3$ mass and lifetime: $N_{exp}(m, \Gamma)$
3. Calculate likelihood of the pseudo-data as a function of the decay width for each neutrino mass
4. Obtain the most probable decay width and its significance



# Sensitivity to Neutrino Decay

Parameters in the rocket experiment simulation

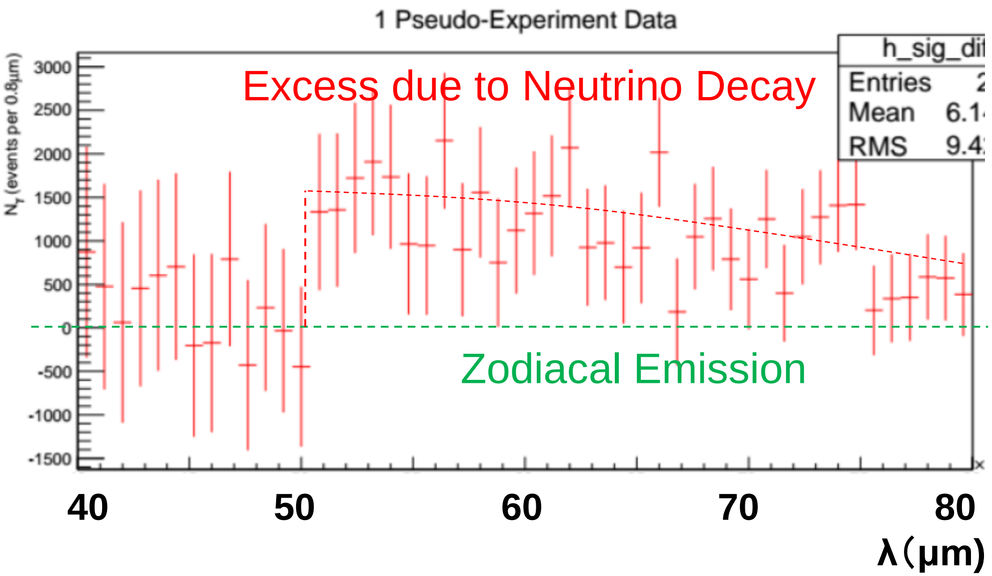
telescope diameter: 15cm

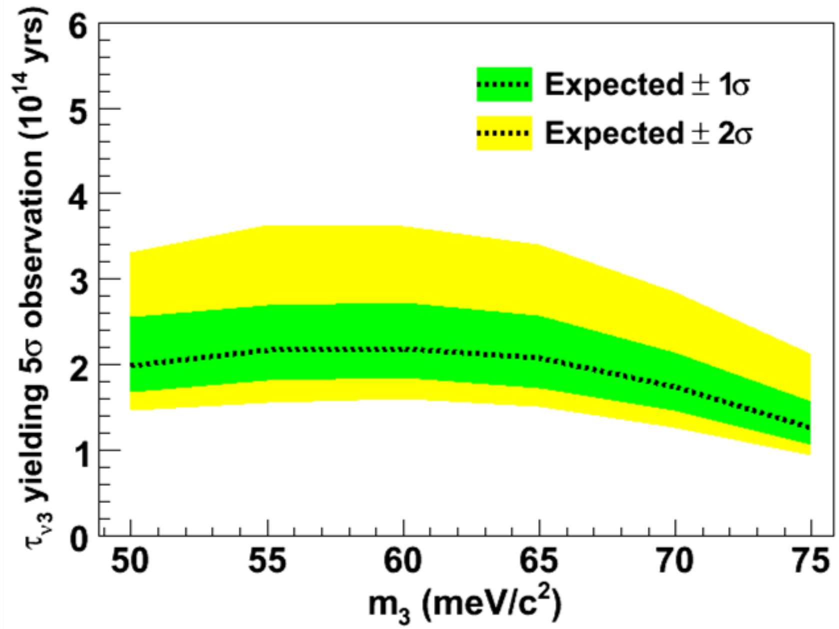
50-column ($\lambda$: 40μm – 80 μm) × 8-row array

Viewing angle per single pixel: 100μrad × 100μrad

Measurement time: 200 sec.

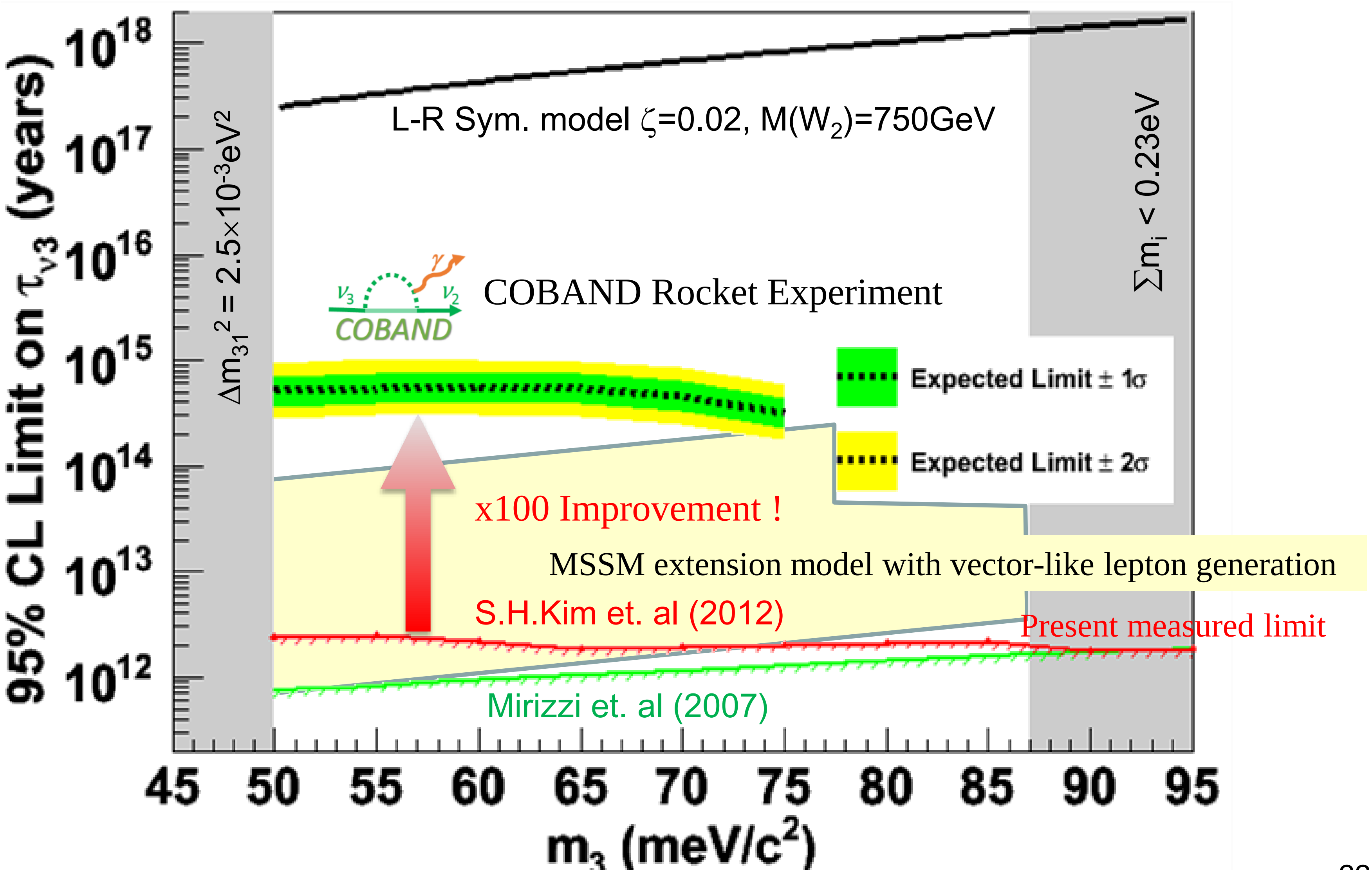
Photon detection efficiency: 100%




- If $\nu_3$ lifetime were $2 \times 10^{14}$ 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 $\epsilon_\gamma$ is a photon energy and $f_\gamma$ is a photon rate.

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

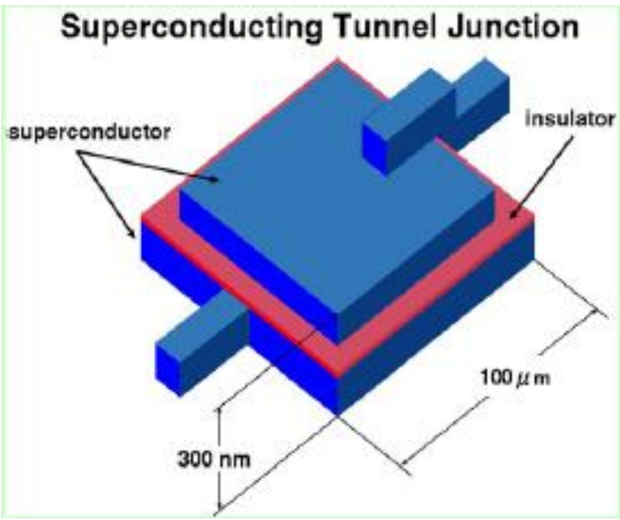
- Superconducting Tunneling Junction detector

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

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

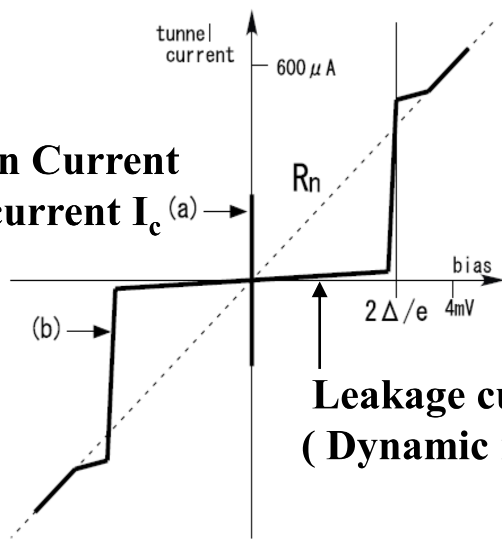
# STJ (Superconducting Tunnel Junction）Detector

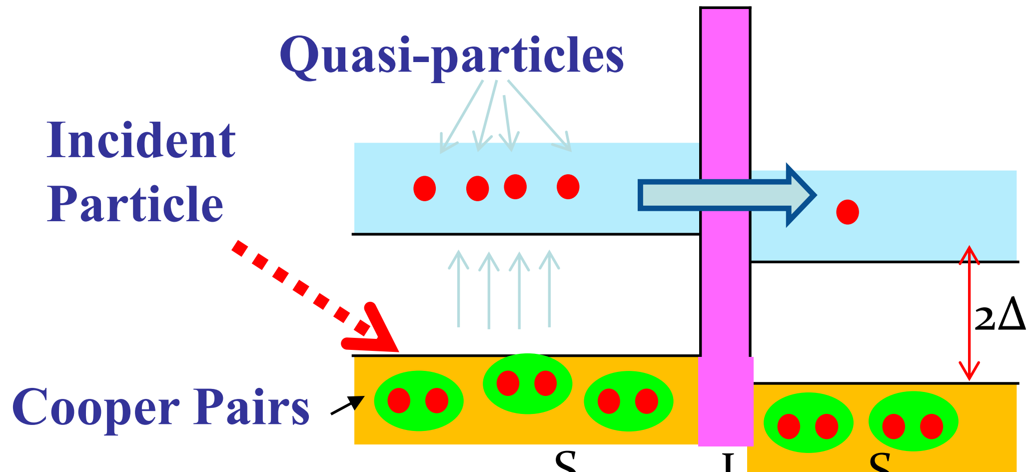
Superconductor / Insulator / Superconductor Josephson Junction




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.

current-voltage (I-V) curve for STJ




| Material | $T_c(K)$ | $\Delta$(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

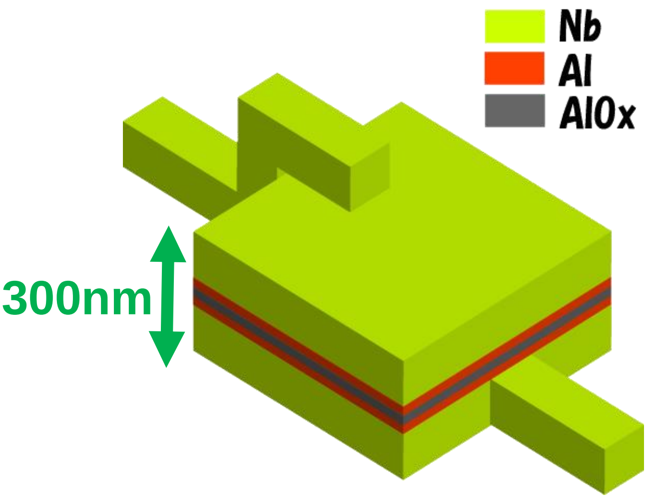
| Material | $T_c(K)$ | $\Delta(\text{meV})$ |
|---|---|---|
| Niobium | 9.20 | 1.550 |
| Aluminum | 1.14 | 0.172 |
| Hafnium | 0.13 | 0.021 |

**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**

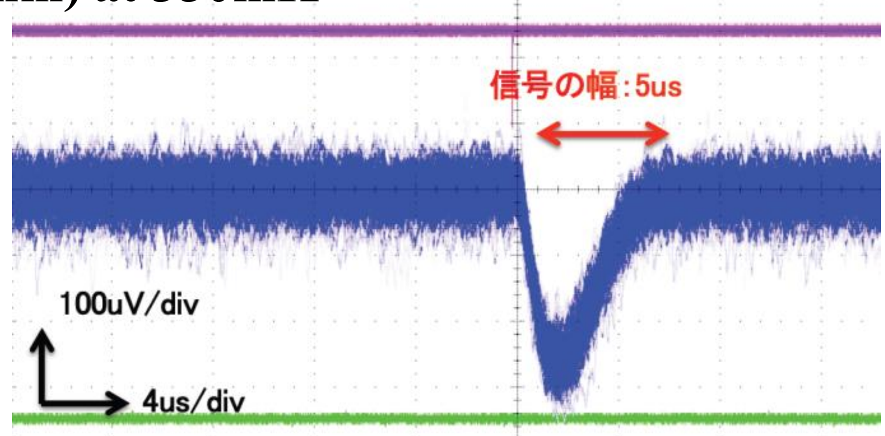
$$N_q = G_{Al} \, E_0 / 1.7\Delta$$

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

**For 25meV single photon**

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

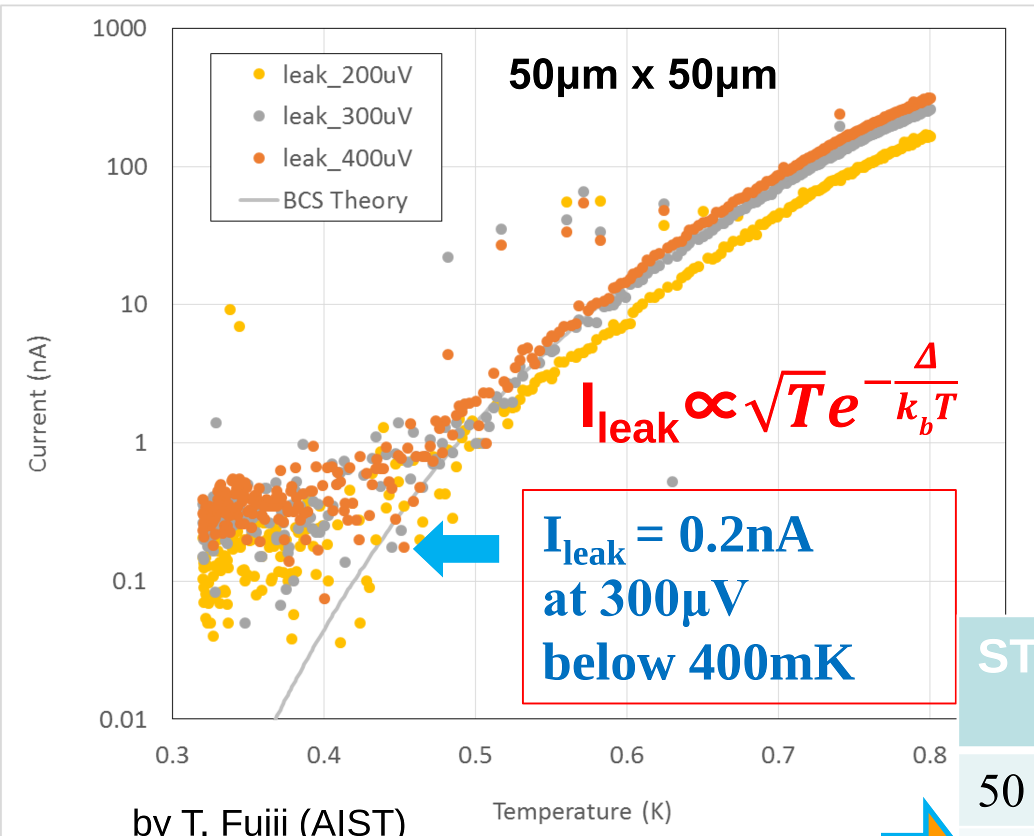
**Response of Nb/Al-STJ to visible laser light pulse (λ=465nm) at 350mK**



# Leakage Current of Nb/Al-STJ

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

**Temperature Dependence of Leakage Current**




by T. Fujii (AIST)

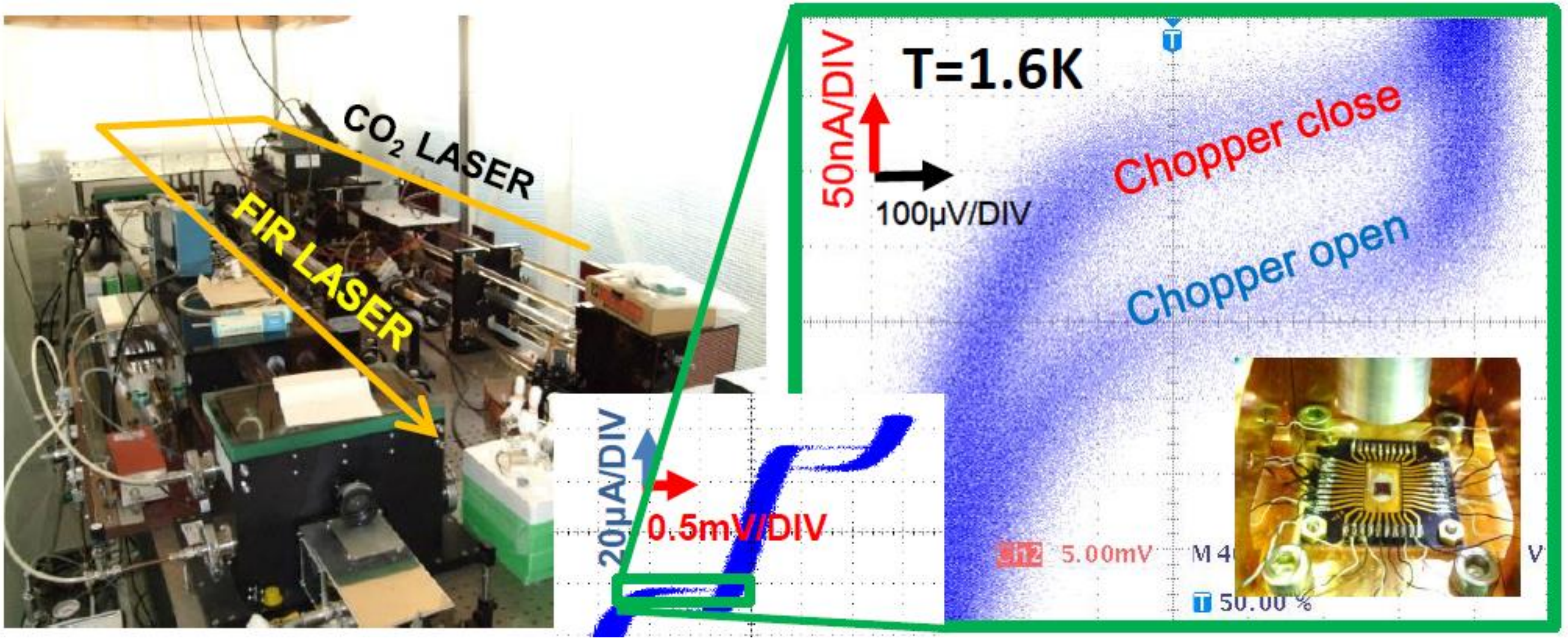
In 2014,
AIST group joined us and produced Nb/Al-STJ with AIST CRAVITY processing system.
Leakage current has satisfied our requirement of 0.1nA .

| 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
( $\lambda$=57.2$\mu$m )

Nb/Al-STJ Response to Far-Infrared Laser

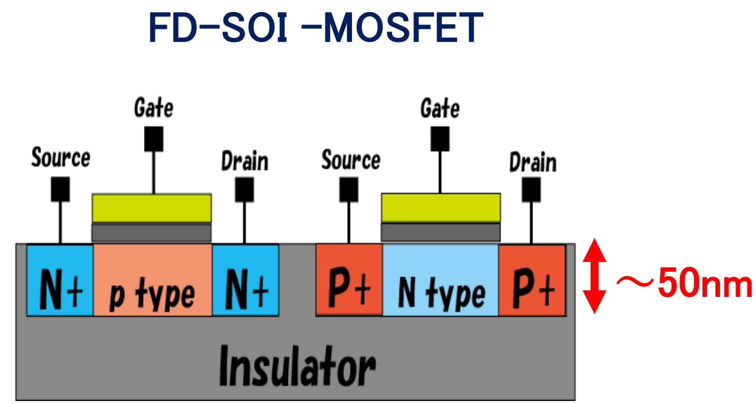



- 20$\mu$m-square Nb/Al-STJ made at AIST CRAVITY system
- Laser light was turned on and off with a chopper at a frequency of 200Hz. Measured the change of the I-V curve between the laser on and off to be 50~100nA in current.

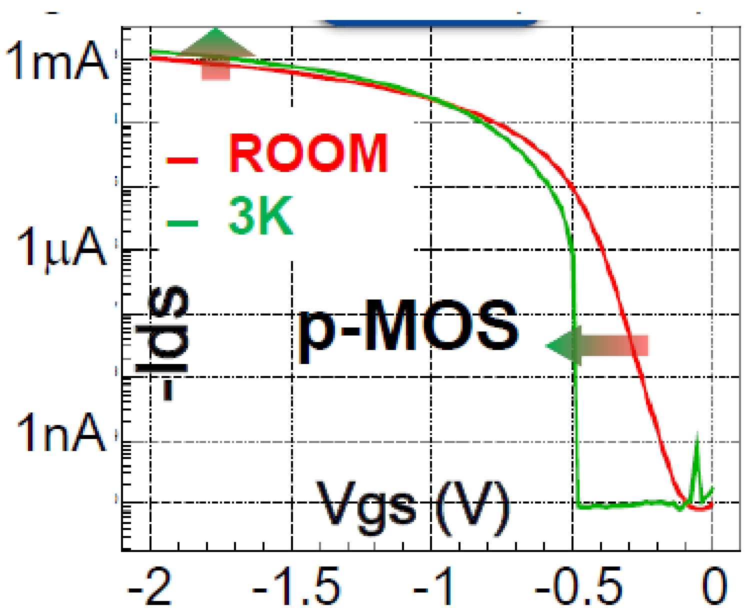
# R&D Status of SOI Cryogenic Preamplifier for STJ

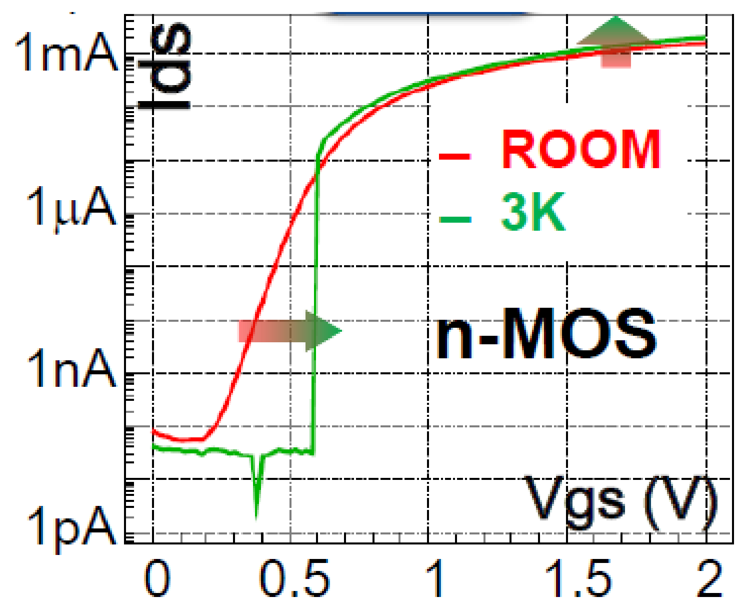
# FD-SOI-MOSFET at Cryogenic Temperature

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

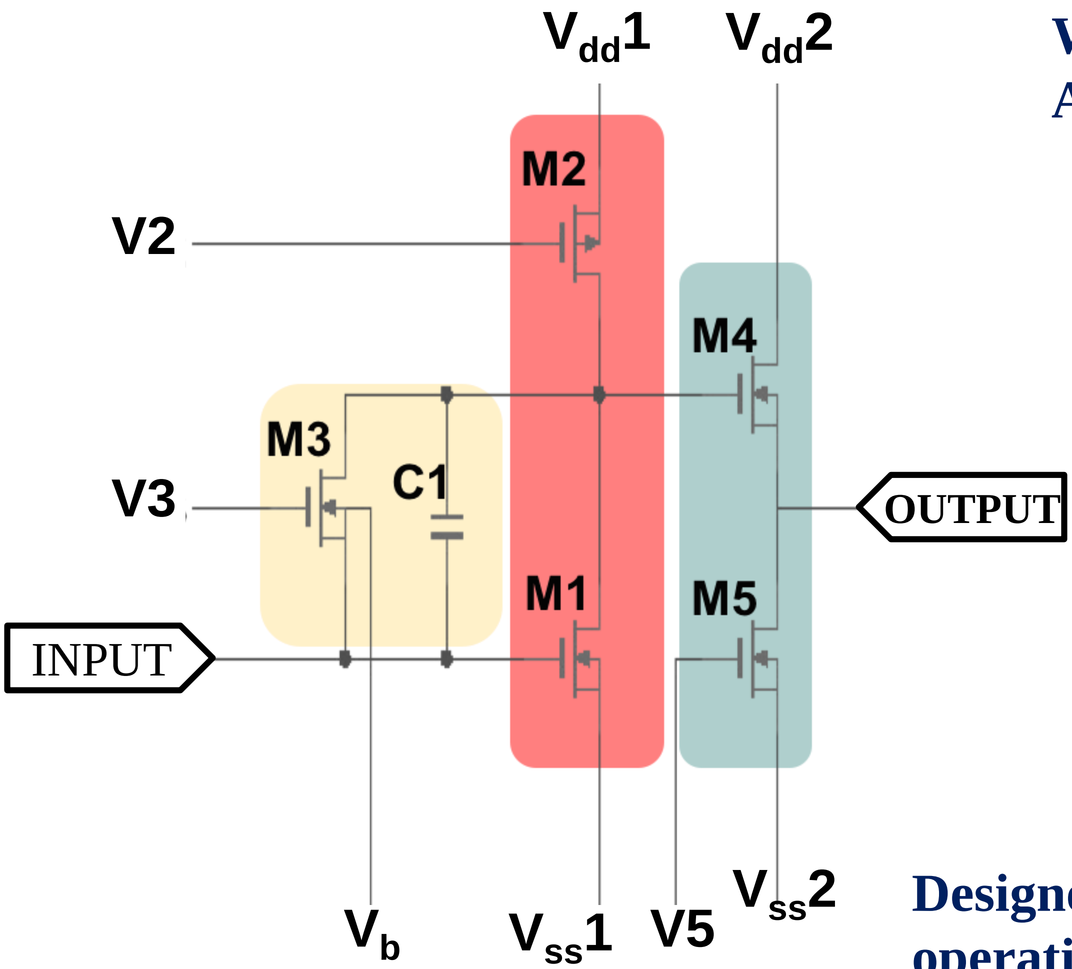



**Both p-MOS and n-MOS show excellent performance at 3K and below.**

# SOI Cryogenic Amplifier

SOI-STJ4 (the 4th prototype)




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

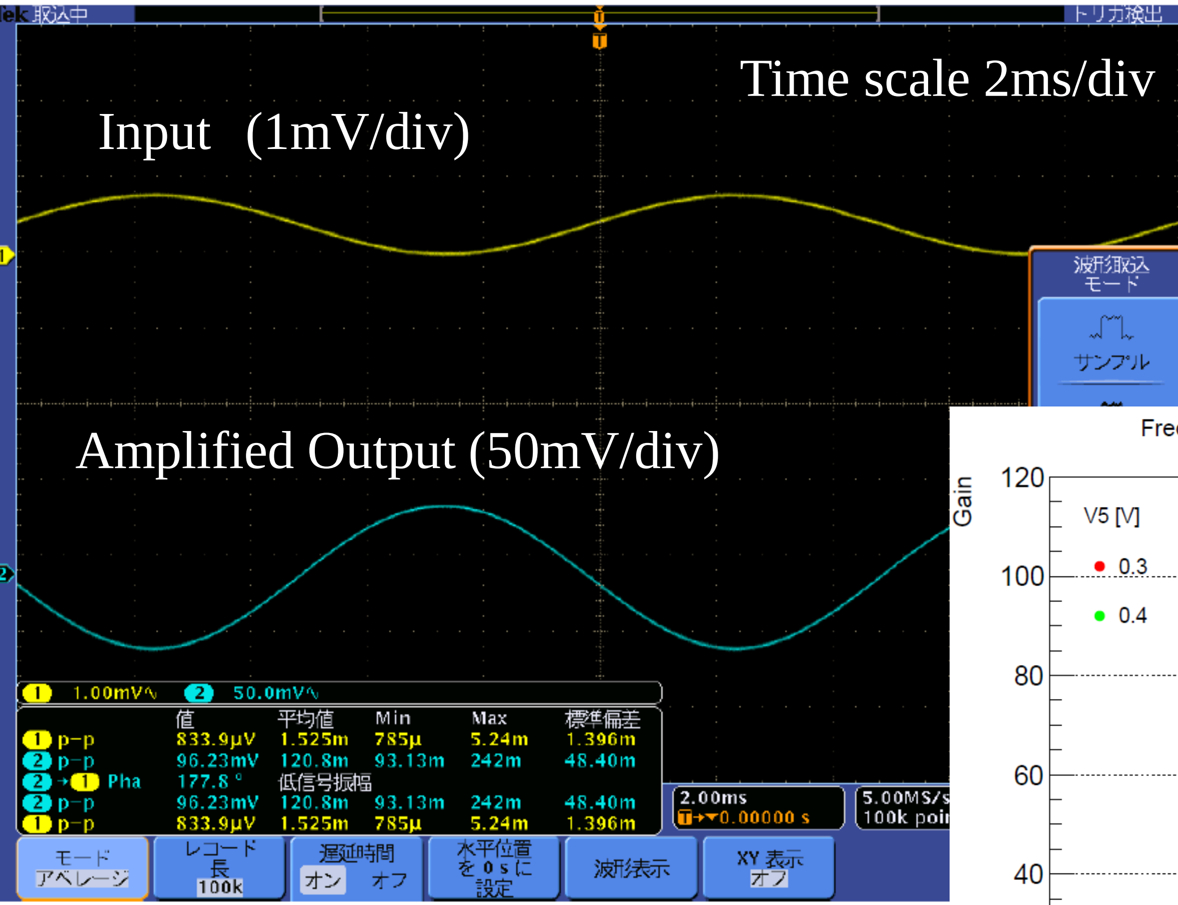
**Amplification**
Replace the resistance by a SOIFET as a current source (M2).
**Feedback**
Use the feedback between the drain and the gate of M1 to apply a stable bias voltage (M3).
**Buffer**
Add the follower to reduce the output impedance (M4 and M5).

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

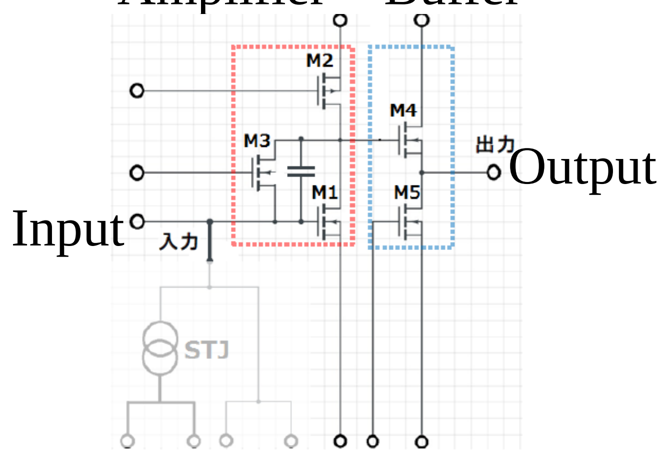
This SOI amplifier board was made by LAPIS semiconductor company.

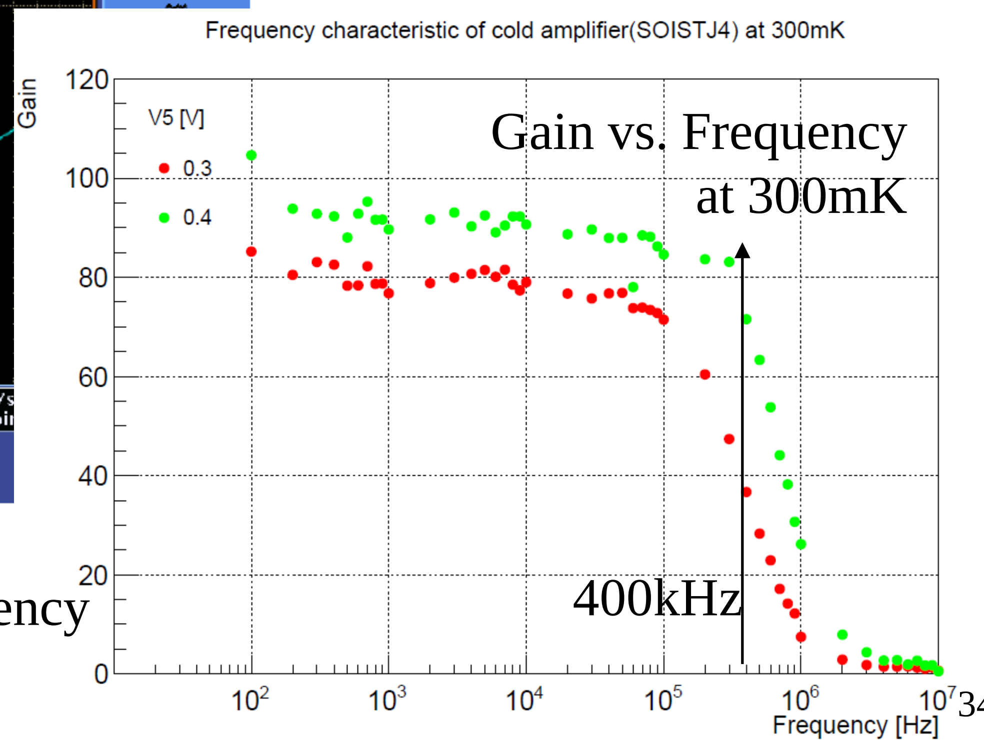
# Test Results of the SOI Cryogenic Amplifier

Input and Amplified Output



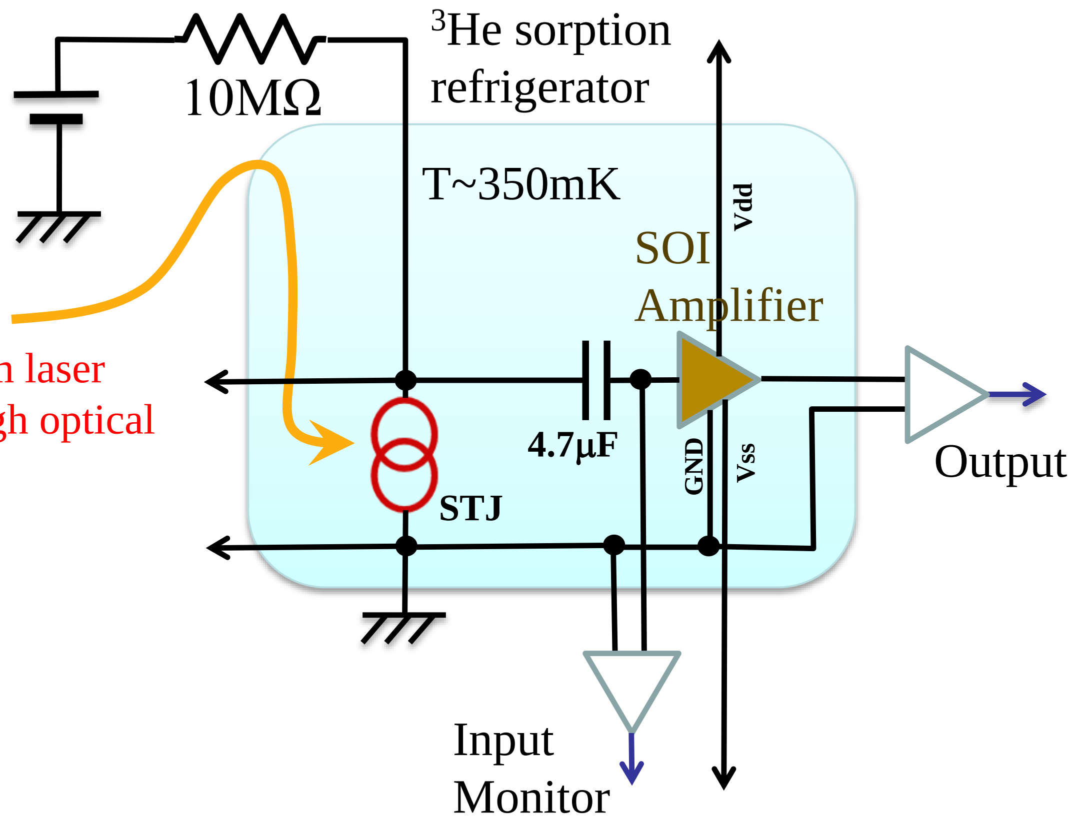

Amplifier + Buffer

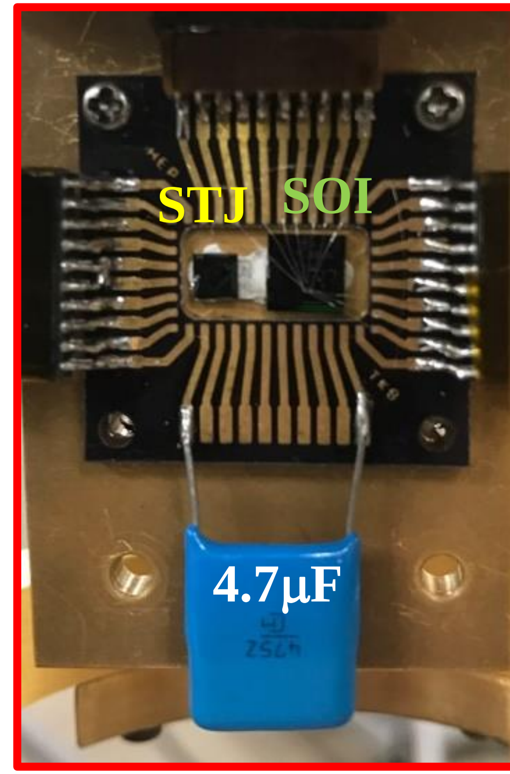



Gain of 80 was achieved for a signal frequency up to 400kHz signals at 300mK.

# Setup of STJ Signal Amplification with the SOI Cryogenic Amplifier

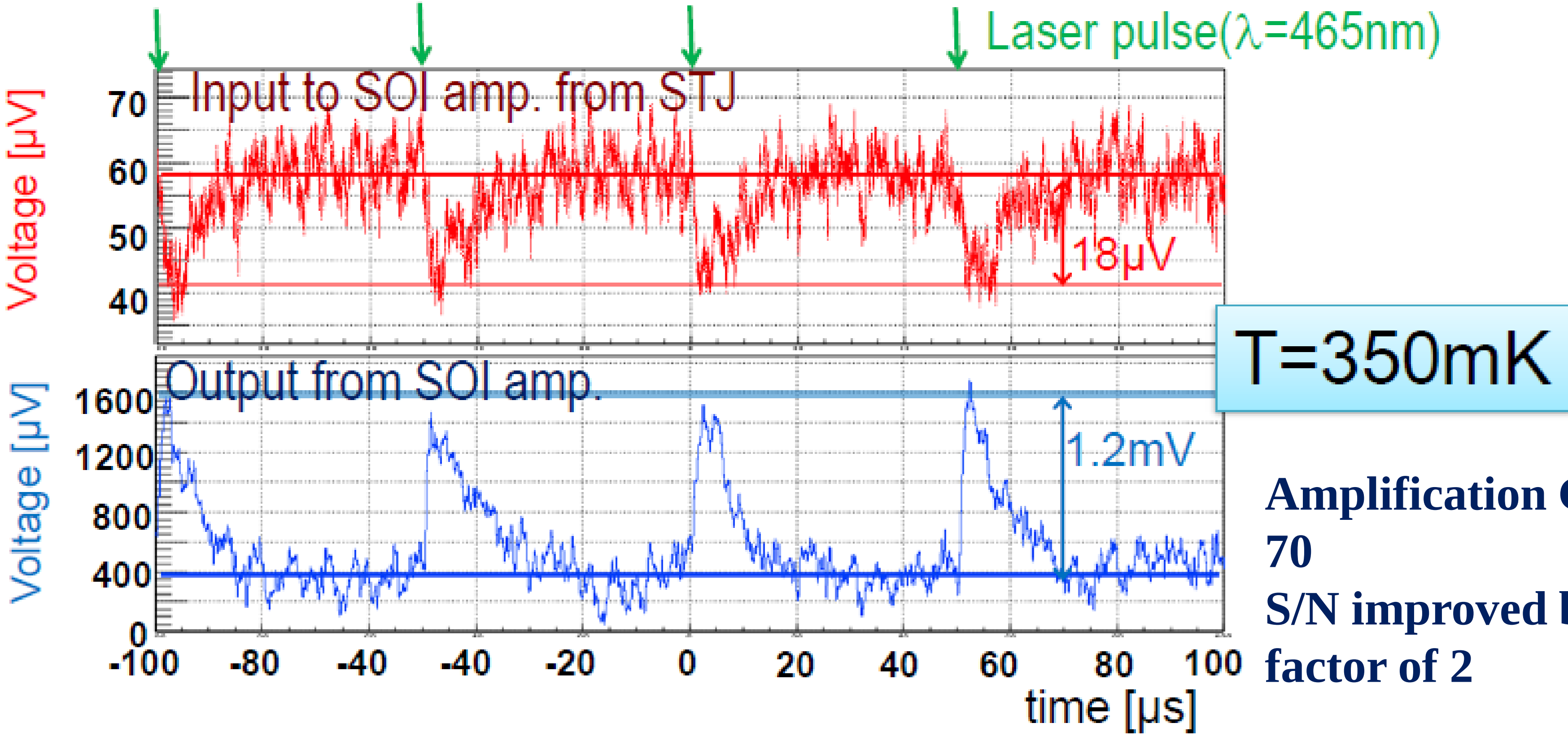



- **20μm-square Nb/Al-STJ with SOI-STJ4 amplifier through 4.7μF capacitance.**
- **Input impedance of the SOI amplifier is about 20kΩ.**
  - **STJ operation at a constant current mode.**
  - **STJ bias cable capacitance is around 1nF : Z=160Ω for 1μs signal.**

# STJ signal amplified with the SOI cryogenic preamplifier

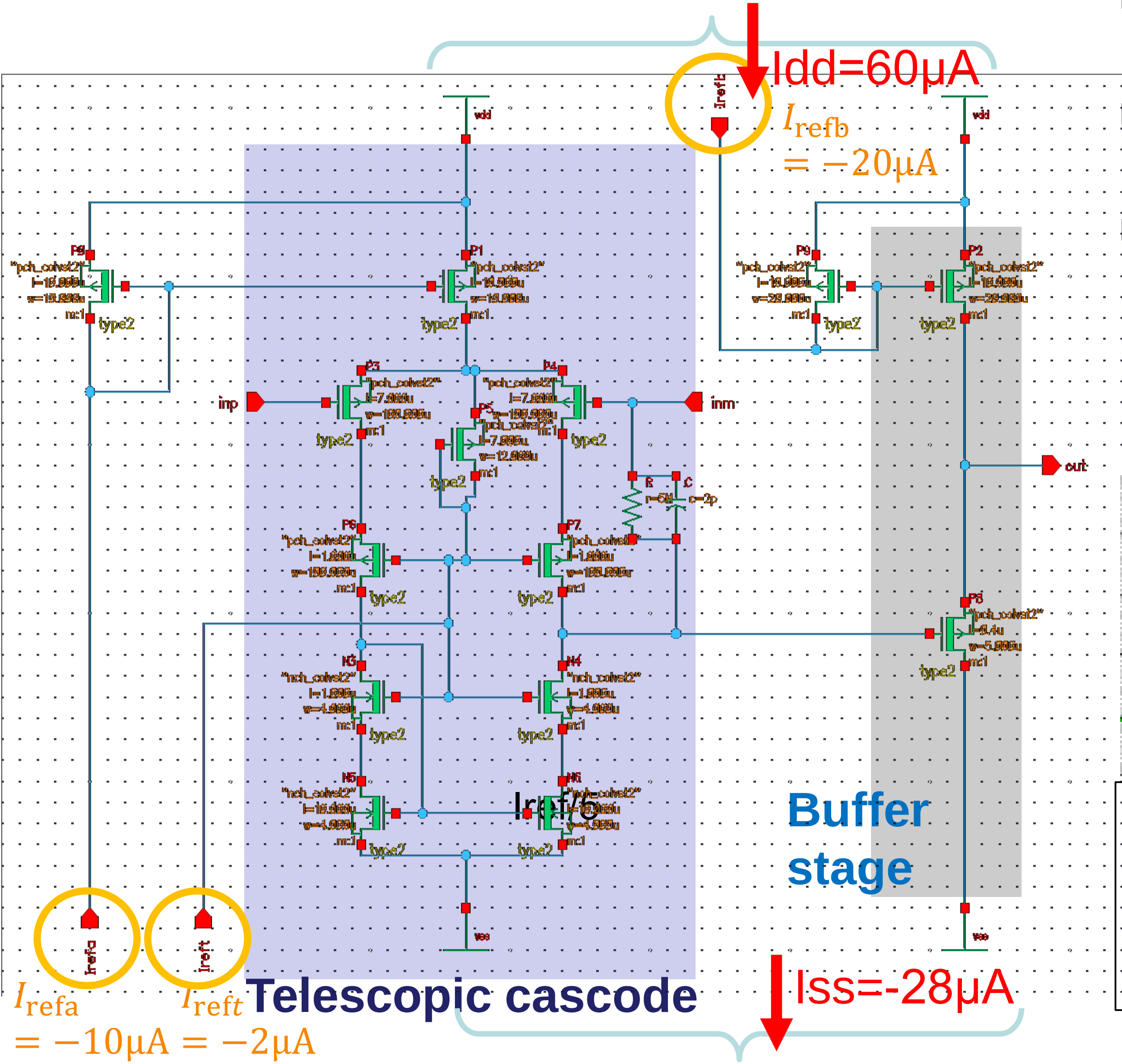
**Nb/Al-STJ laser light response signal was amplified with this SOI cryogenic preamplifier at 350mK.**




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

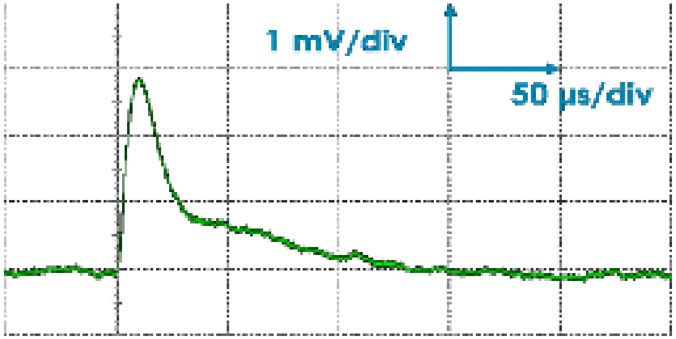
**Development of the SOI cryogenic preamplifier is now moving to the stage of the final design for COBAND experiment.**

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




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

Test Result of this cryogenic charge amplifier.

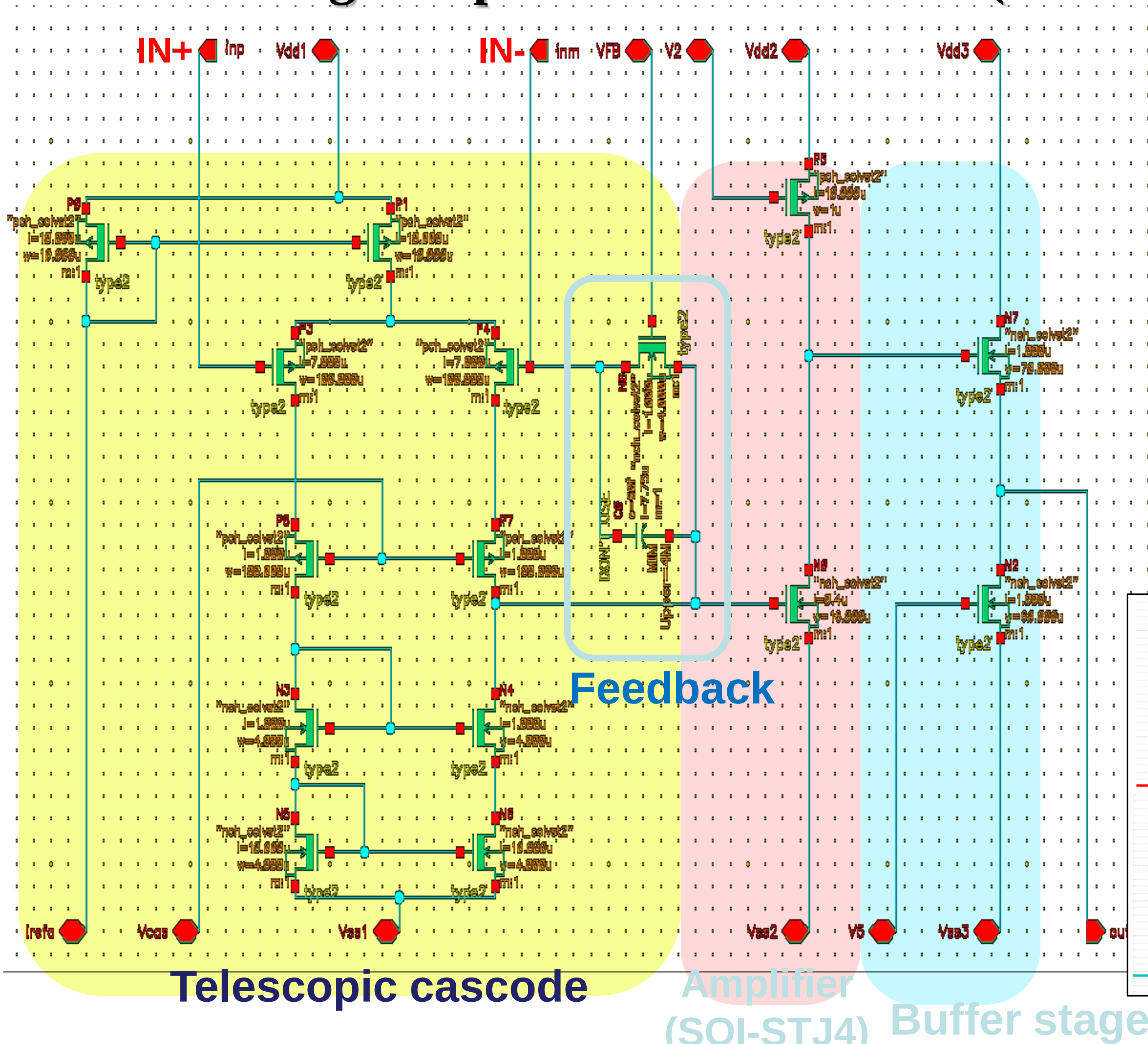



STJ signal for visible laser pulse light was amplified by this cryogenic charge amplifier at 350mK.



Next cryogenic charge amplifier was designed with a higher gain for far-infrared photon detection.

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




Feedback capacitance

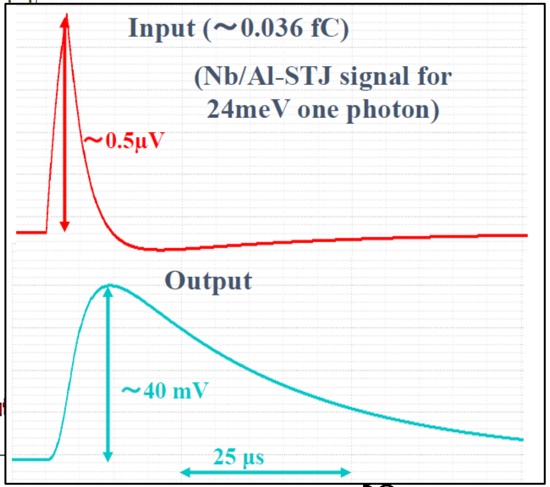
2pF → 60fF

Power Consumption

~150μW

24meV one photon (0.03fC) gives ~40mV Output

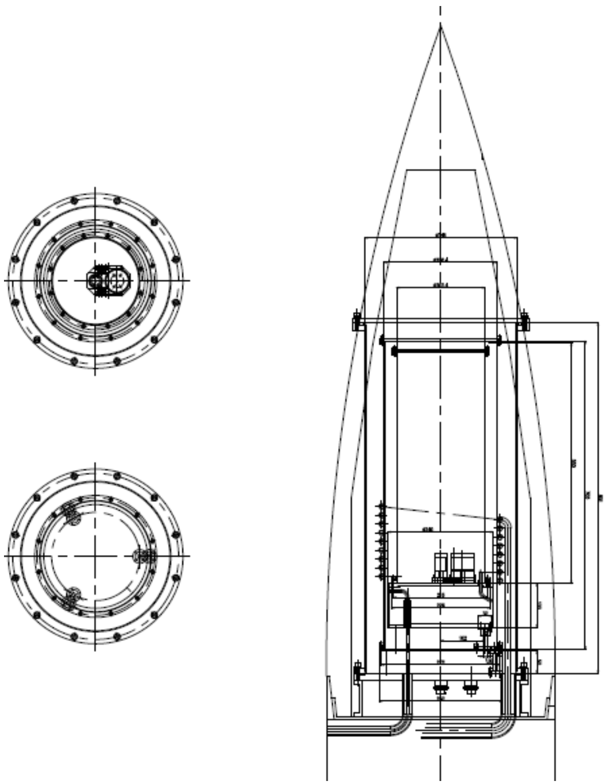
Simulation Result



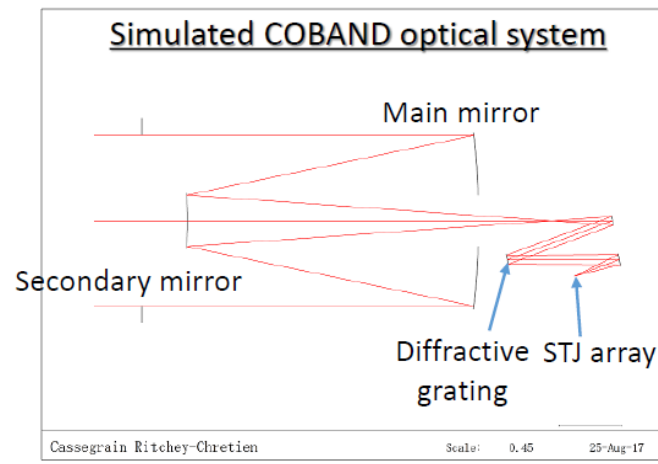

**This charge amplifier is now at our University and will be tested soon.**

# Prototype of Cryostat for the Rocket Experiment

In April 2017, a prototype of the cryostat for the rocket experiment was made. This is a $^{3}$He sorption 0.3K refrigerator inside of $^{4}$He depressurized 1.8K refrigerator. (For now it does not have a $^{3}$He sorption 0.3K refrigerator inside yet.)



We are working on the simulation study on the optics in order to make a final design of COBAND optical system.



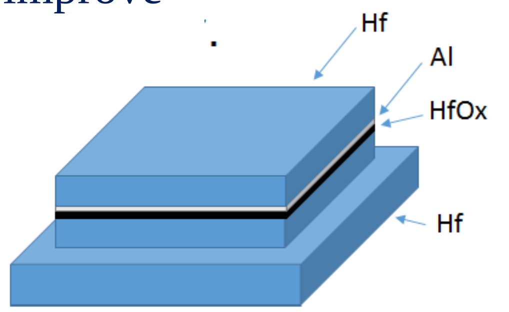

Made by Jeck Tohri company.

We will test Nb/Al-STJ inside of this cryostat with far-infrared(50μ) photon beam at Fukui this winter.

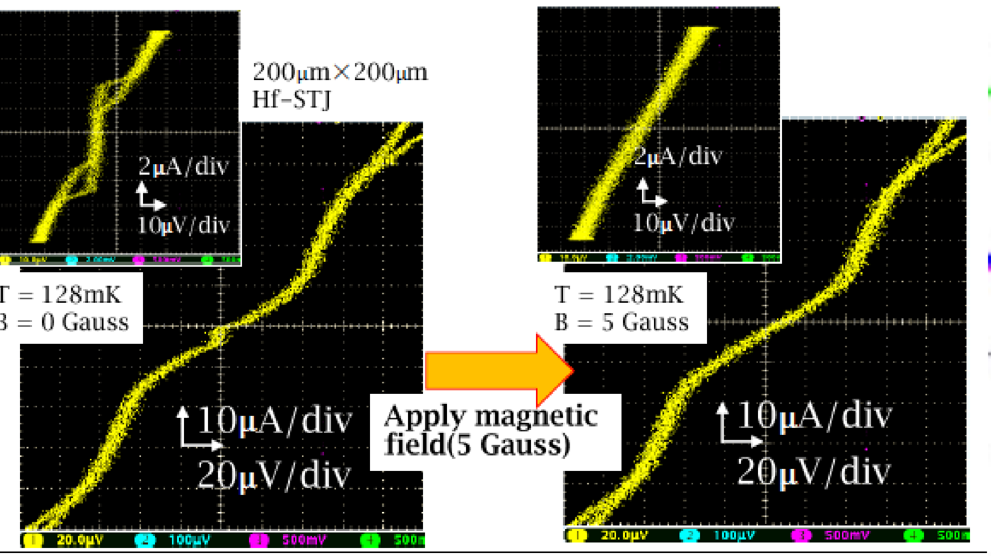
# R&D Status of Hf-STJ

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

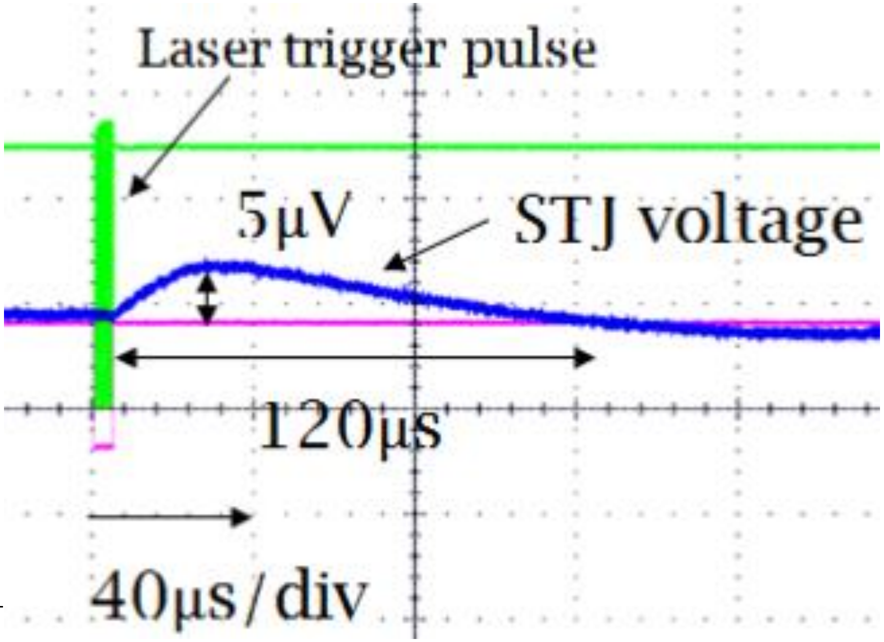
We made a thin aluminum layer (9nm) on the HfO layer (1-2 nm) to improve the insulation of the $HfO_X$ layer. Hf/Al/$HfO_X$/Hf-STJ




$\Delta = 20 \sim 30\mu eV$
Leakage current = 5μA@128mK
for 200μm-square sample.

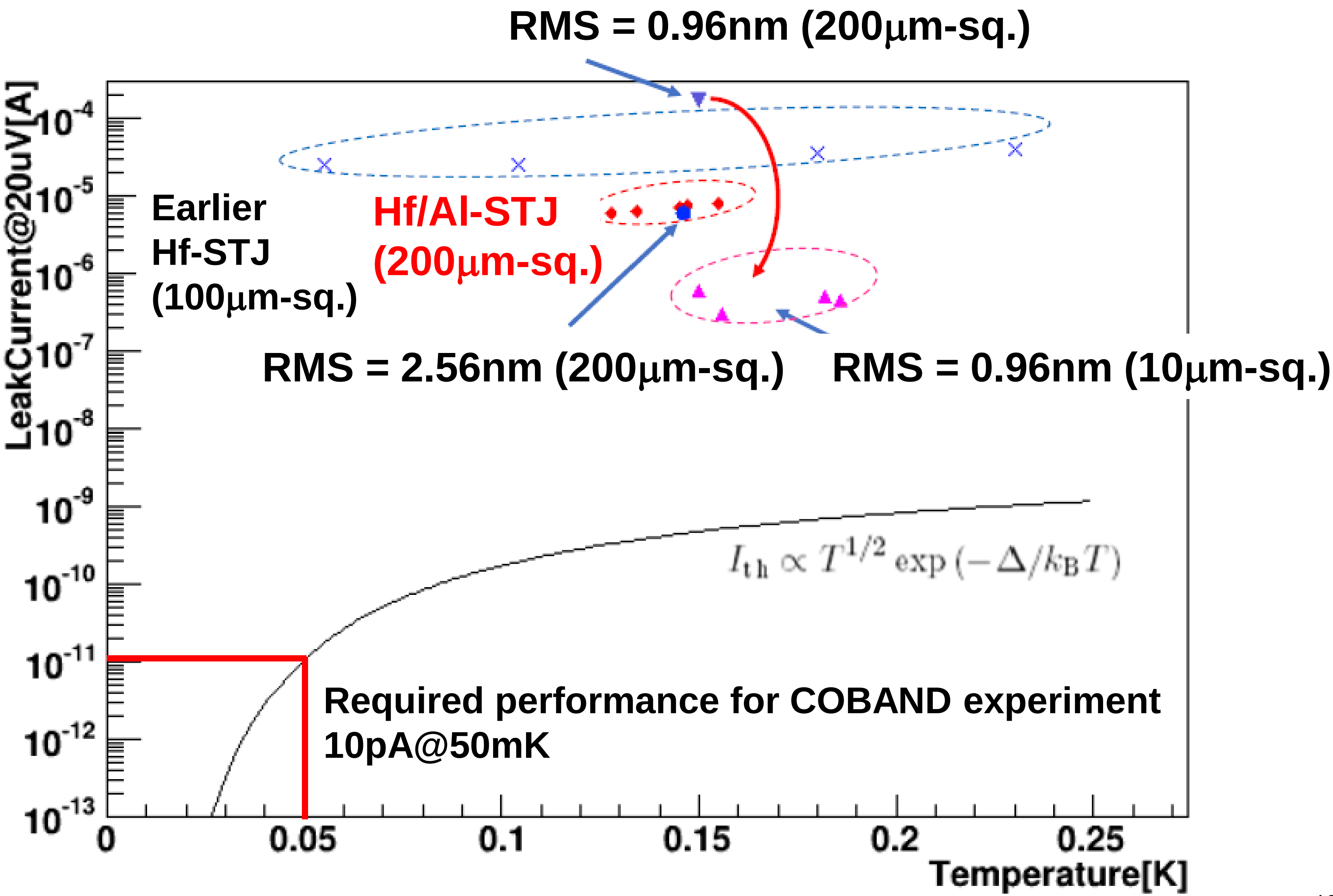



Visible light laser (λ=465nm) 10Hz duration




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

# Improvement of Hf-STJ Leakage Current



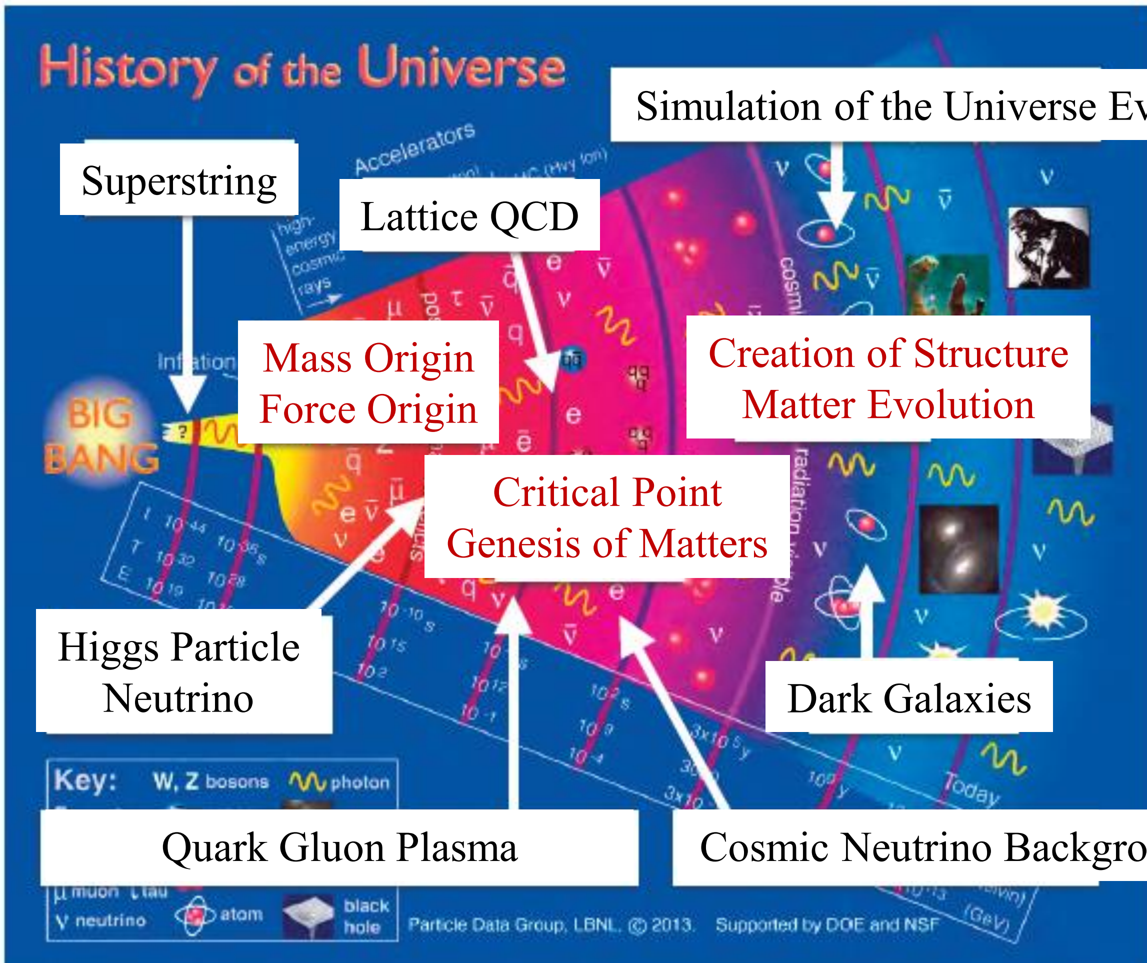
# Research Core for the History of the Universe

under Center for integrated Research in Fundamental Science and Engineering, University of Tsukuba (founded on Sep. 1, 2014)

筑波大学 University of Tsukuba

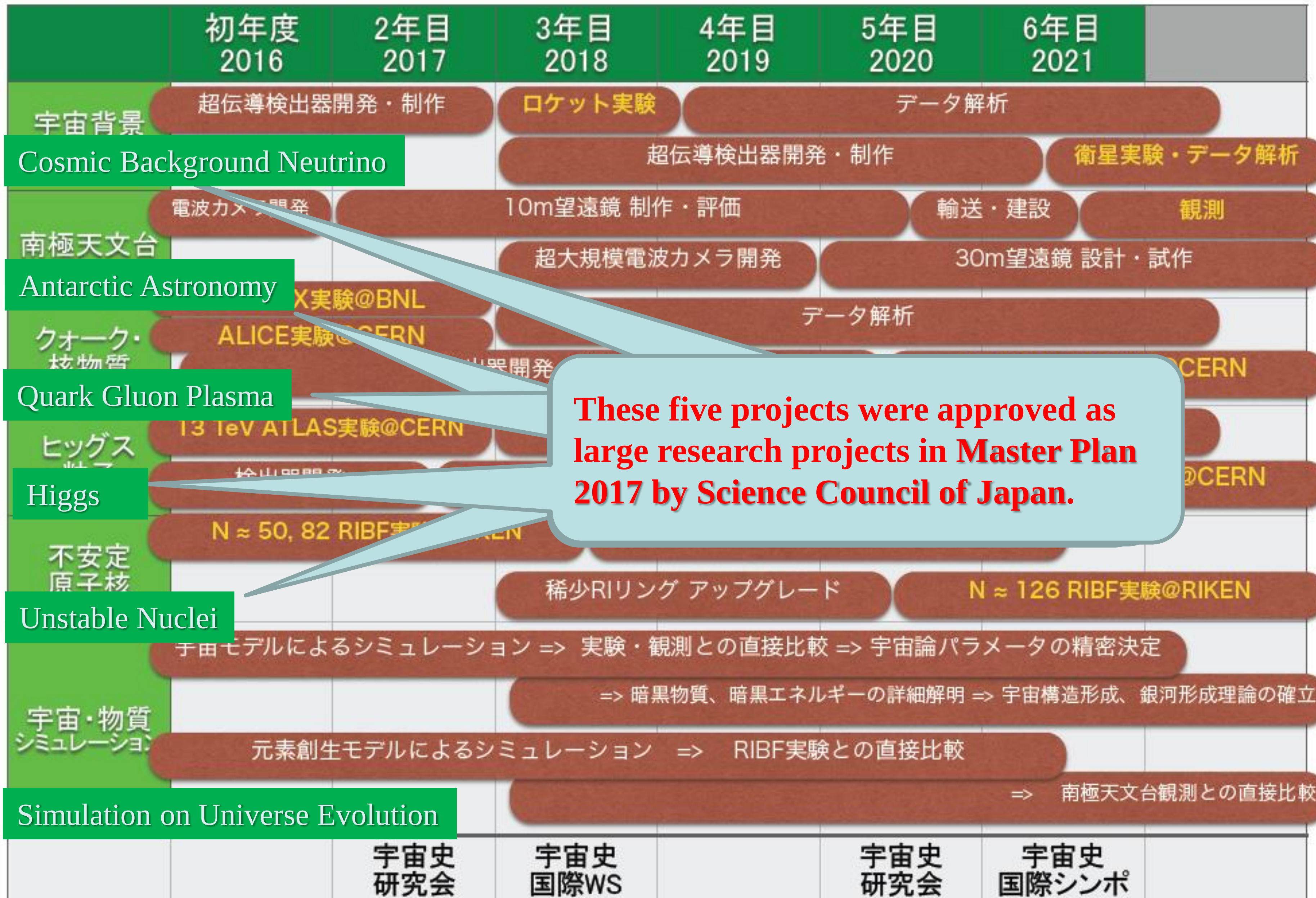
CiRfSE

**Mission: coordinate the studies in elementary particles, quark nuclear matters and astrophysics to construct an integrated view of the History of the Universe.**




**Illuminate the "Darkness":**
**=>Dark matter, Dark energy , Dark galaxies**
**=>Genesis of matters, creation of structure and their evolution**

# Schedule of Projects on the History of the Universe

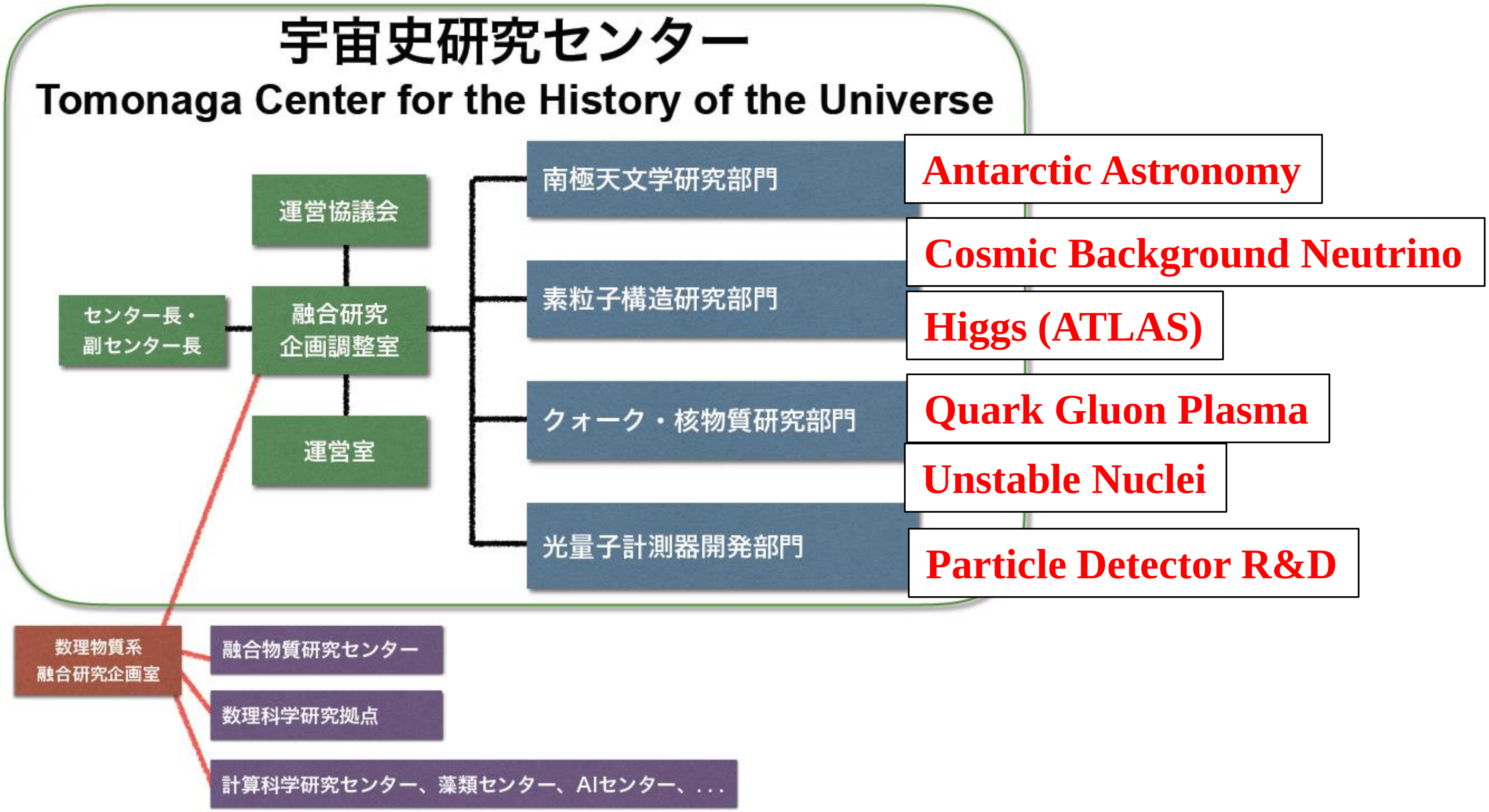


# Research Core for the History of the Universe

# Tomonaga Center for the History of the Universe

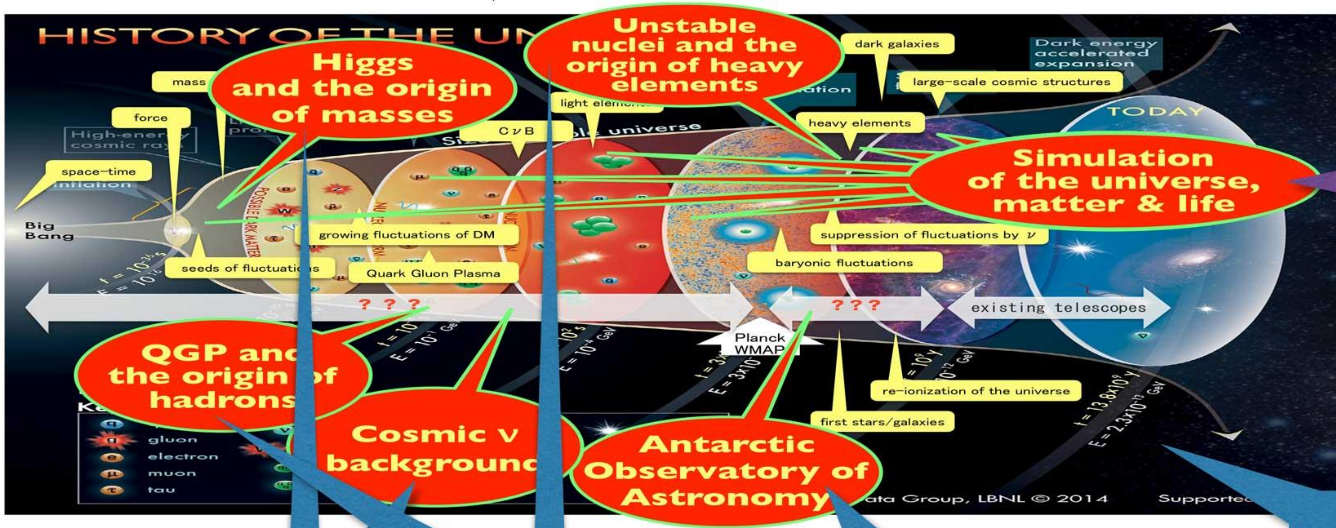
## Re-Organization

From Oct. 2017

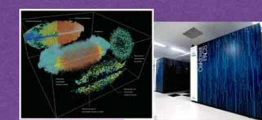


From Oct. 2017

# Tomonaga Center for the History of the Universe



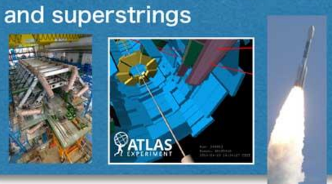

## Center for Computational Sciences



JICFuS JCAHPC

## Division of Elementary Particles

- Higgs precision study by ATLAS experiment
- Detection of cosmic neutrino background by COBAND experiment
- Theory of quantum gravity and superstrings

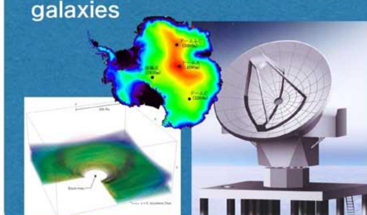



## Division of Quark Nuclear Matters

- QGP study by ALICE and STAR experiments
- Study of unstable nuclei by RI-beam factory
- QCD simulations towards QGP and nuclear matters

## Division of Antarctic Astrophysics

- Construction of Antarctic Observatory of Astronomy towards dark galaxies
- Simulation of universe and galaxies



## Division of Photon and Particle Detectors

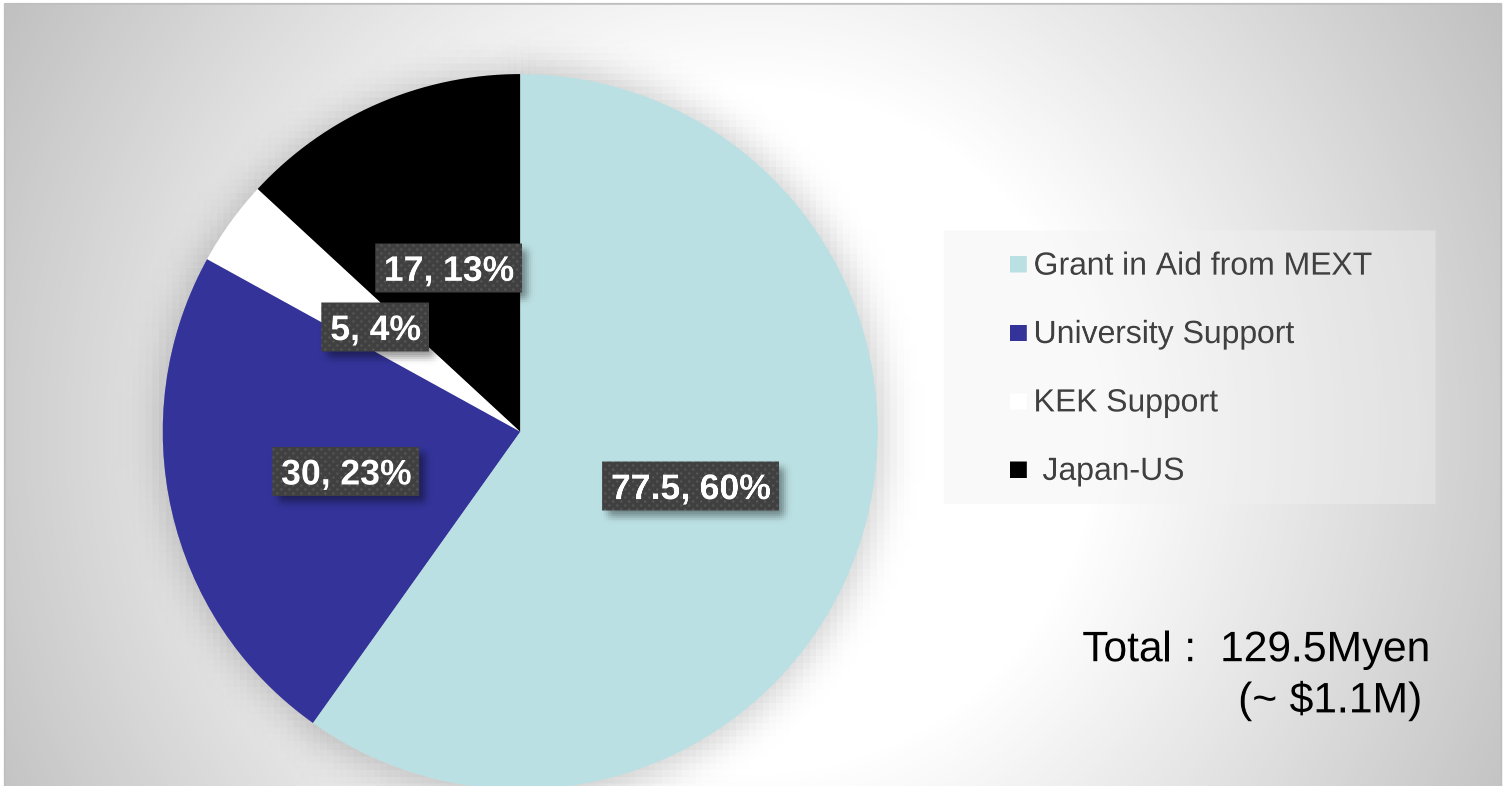
- Development of PPD by superconducting and SOI technologies


Tsukuba Research Center for Energy Materials Science

TIA-ACCELERATE, . . .

**Approved for October 2017 to March 2022 (10,500kYen/year).**
**Budget for Postdocs, Detector R&D and travel expenses.**

# R&D Budgets for the COBAND in the period of JFY2013-2017




| | | | |
|---|---|---|---|
| Grant in Aid "Neutrino" from MEXT | R&D of Superconducting Infrared Detector for Neutrino Decay Experiment | JFY2013－2017 | 77.5 MYen |
| University Support | $^3$He Sorption Refrigerator | JFY2013－2017 | 30.0 MYen |
| KEK Support | Cooperative Project of University of Tsukuba and KEK | JFY2013-2016 | 5.0 MYen |
| Japan-US Project | Neutrino Decay Search Experiment Cooperative | JFY2012-2014 | 17.0 MYen |

# 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/**

**People who will join COBAND collaboration are very welcome.**

**Please join us.**

BACKUP

# Neutrino Lifetime by Left-Right Symmetric Model

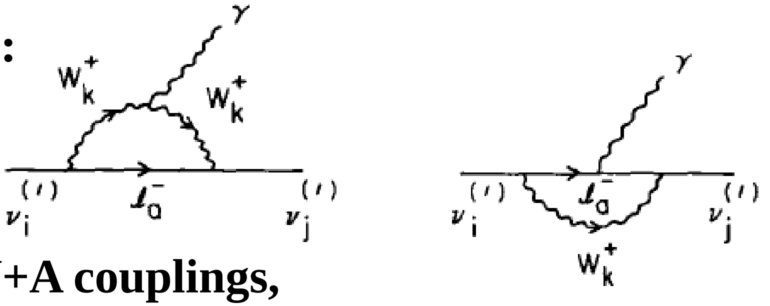
**In the Left - Right Symmetric Model $SU(2)_L \otimes SU(2)_R \otimes U(1)$**

**(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 $\zeta$ 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 $\alpha$ is a fine structure constant, $G_F$ is a Fermi coupling constant, $m_\tau$, $M_{W1}$ and $M_{W2}$ are masses of $\tau$, $W_1$ 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 $M(W_R) > 715$GeV, a mixing angle limit $\zeta < 0.02$, and $m_3 = 50$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

Amin Aboubrahim,[2,*,‖] Tarek Ibrahim,[1,2,†,§,‖] and Pran Nath[3,4,‡,¶]

[1]*Department of Physics, Faculty of Science, University of Alexandria, Alexandria 21511, Egypt*
[2]*Department of Physics, Faculty of Sciences, Beirut Arab University, Beirut 11-5020, Lebanon*
[3]*Department of Physics, Northeastern University, Boston, Massachusetts 02115-5000, USA*
[4]*KITP, University of California, Santa Barbara, California 93106-4030, USA*
(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

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

# MSSM extension model with a vectorlike lepton generation

PHYSICAL REVIEW D 88, 013019 (2013)

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

Amin Aboubrahim,[2,*,∥] Tarek Ibrahim,[1,2,†,§,∥] and Pran Nath[3,4,‡,¶]

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

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 $\psi_1$ as the tau neutrino, $\psi_2$ as the heavier mass eigenstate, $\psi_3$ as the muon neutrino and $\psi_4$ as the electron neutrino. To make contact with the normal neutrino hierarchy we relabel the states so that

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

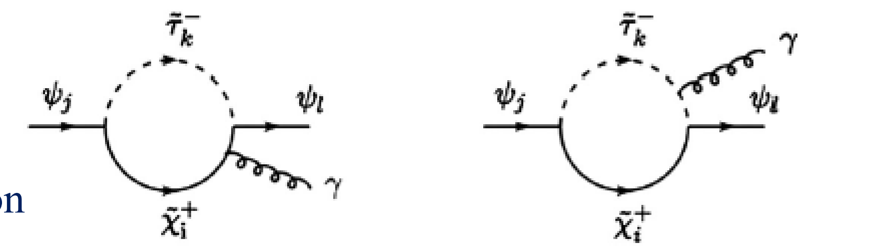
which we assume has the mass hierarchical pattern

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

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) | $m_{\nu_3} = 5.2 \times 10^{-11}$ <br> $m_{\nu_2} = 9.2 \times 10^{-12}$ <br> $m_{\nu_1} = 9.7 \times 10^{-13}$ |
|---|---|---|
| (i) $m_{\chi^\pm} = 256$ GeV | $\mu_2$ | $1.2 \times 10^{-10}$ |
| $m_{\tilde{\tau}} = 162$ GeV | $\mu_1$ | $2.5 \times 10^{-13}$ |
| | $\nu_3$ lifetime | $3.9 \times 10^{14}$ yr |
| (ii) $m_{\chi^\pm} = 267$ GeV | $\mu_2$ | $4.6 \times 10^{-10}$ |
| $m_{\tilde{\tau}} = 202$ GeV | $\mu_1$ | $1.3 \times 10^{-12}$ |
| | $\nu_3$ lifetime | $2.5 \times 10^{14}$ yr |
| (iii) $m_{\chi^\pm} = 268$ GeV | $\mu_2$ | $2.2 \times 10^{-10}$ |
| $m_{\tilde{\tau}} = 158$ GeV | $\mu_1$ | $1.1 \times 10^{-13}$ |
| | $\nu_3$ lifetime | $1.8 \times 10^{14}$ yr |
| (iv) $m_{\chi^\pm} = 272$ GeV | $\mu_2$ | $-7.6 \times 10^{-10}$ |
| $m_{\tilde{\tau}} = 195$ GeV | $\mu_1$ | $-1.3 \times 10^{-13}$ |
| | $\nu_3$ lifetime | $8.8 \times 10^{13}$ yr |

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

# Publications

1. "Development of Superconducting Tunnel Junction Photon Detectors with Cryogenic Preamplifier for COBAND experiment", S. H. Kim *et al*., to be published in Proceeding of TIPP2017
2. "Development of Superconducting Tunnel Junction Detector using Hafnium for COBAND experiment"(Poster presentation), K.Takemasa *et al.*, , to be published in Proceeding of TIPP2017
3. "Development of Superconducting Tunnel Junction detectors as a far-infrared photon-by-photon spectrometer for neutrino decay search", Y. Takeuchi *et al.,* Instrumentation and Measurement Technology Conference (I2MTC), 2015 IEEE International, 551 - 555 (2015), DOI:10.1109/I2MTC.2015.7151327
4. "Development FD-SOI MOSFET amplifiers for integrated read-out circuit of superconducting-tunnel-junction single-photon-detectors" K. Kiuchi *et al.* , Proceedings of International Workshop on SOI Pixel Detector, FERMILAB-CONF-15-355-E-TD (2015) arXiv:1507.07424
5. "Development of Superconducting Tunnel Junction Detectors as a far-infrared single photon detector for neutrino decay search", Y. Takeuchi et al., PoS(TIPP2014)155
6. "Development of Superconducting Tunnel Junction Photon Detector on SOI Preamplifier Board to Search for Radiative decays of Cosmic Background Neutrino", K. Kasahara *et al*., PoS(TIPP2014)074
7. "Search for Cosmic Background Neutrino Decay", S. H. Kim *et al.,* JPS Conf. Proc. 1, 013127 (2014)
8. "Search for Radiative Decays of Cosmic Background Neutrino using Cosmic Infrared Background Energy Spectrum", S.H.Kim, K.Takemasa, Y.Takeuchi, and S.Matsuura, JPSJ 81 (2012) 024101, arXiv:1112.4568
9. “Development of superconducting tunnel junction photon detector using Hafnium”, S.H.Kim , H.S. Jeong, K. Kiuchi, S. Kanai, T. Onjo, K. Takemasa, Y. Takeuchi, H. Ikeda, S. Matsuura, H. Sato,M. Hazumi, and S.B. Kim, Physics Procedia 37 (2012) 667-674 (Proceedings of TIPP2011)

# Cosmic Background Neutrino

*Fermi and Bose Distribution Function* $\quad F(E) = \frac{1}{e^{(E-\mu)/kT} \pm 1}$

*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* $\quad \rho = g \int \frac{d^3p}{(2\pi)^3} E F(E) = g \left(\frac{7}{8}\right)^F \frac{\pi^2}{30} T^4$

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

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

*Temperature:*

Below 3MeV, ν 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:

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

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

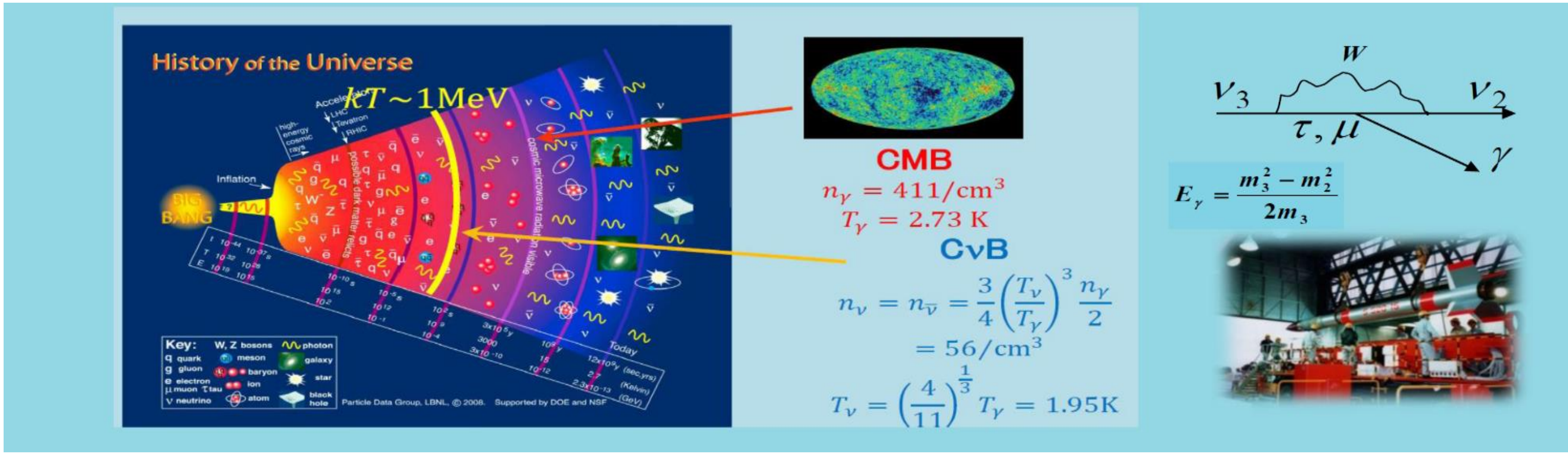
The present entropies of photons and neutrinos, $s_{\gamma 0}$ and $s_{\nu 0}$ are given by

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

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

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

# Cosmic Background Neutrino




*Temperature:*

$T_\nu$= 1.95K

*Number density:*

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

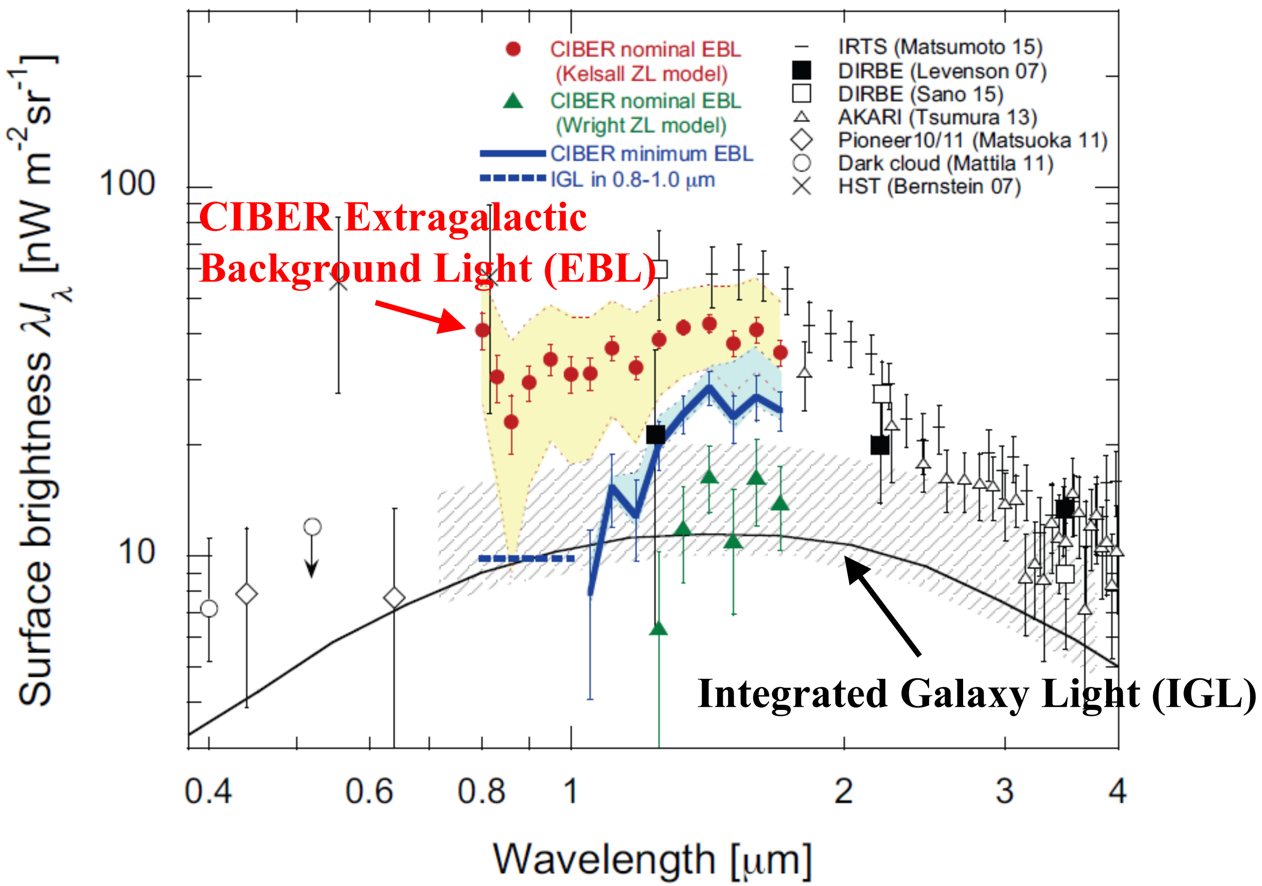
where *g* is the spin degree of freedom, and *F* = 1( for fermions) and 0 (for bosons).

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

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

# Near-Infrared Photon Energy Spectrum from Outer Space

**April 2017 (Press Release): CIBER rocket experiment measured the energy spectrum of the cosmic infrared background (CIB) in the near-infrared region. They found an excess of the CIB spectrum over the prediction by integrated galaxy light (IGL).**

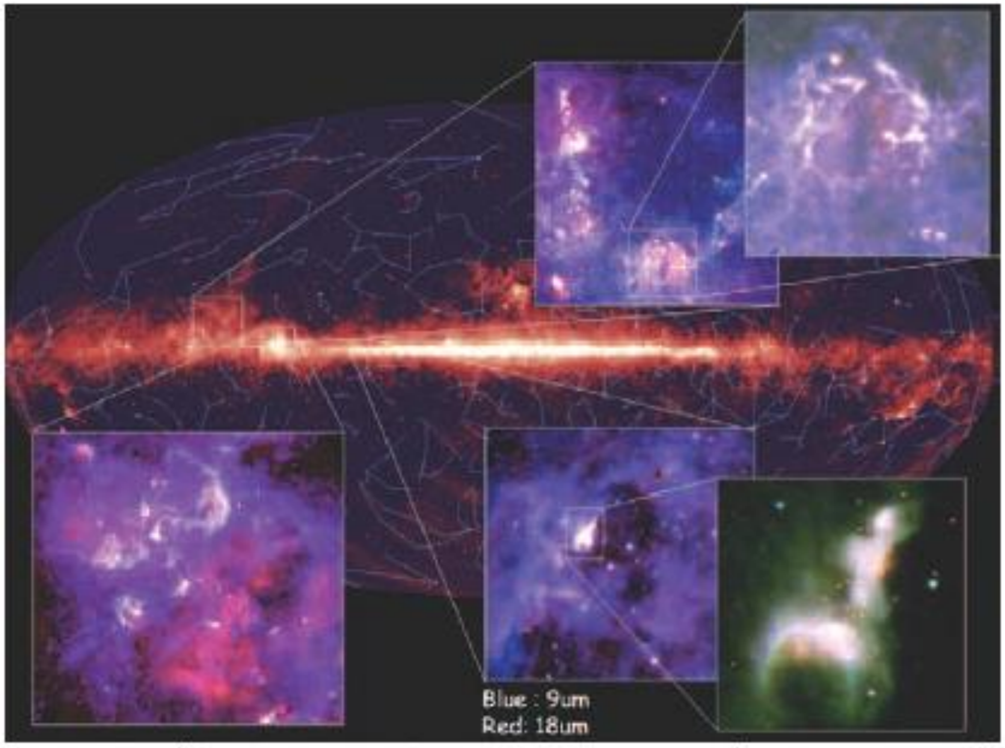


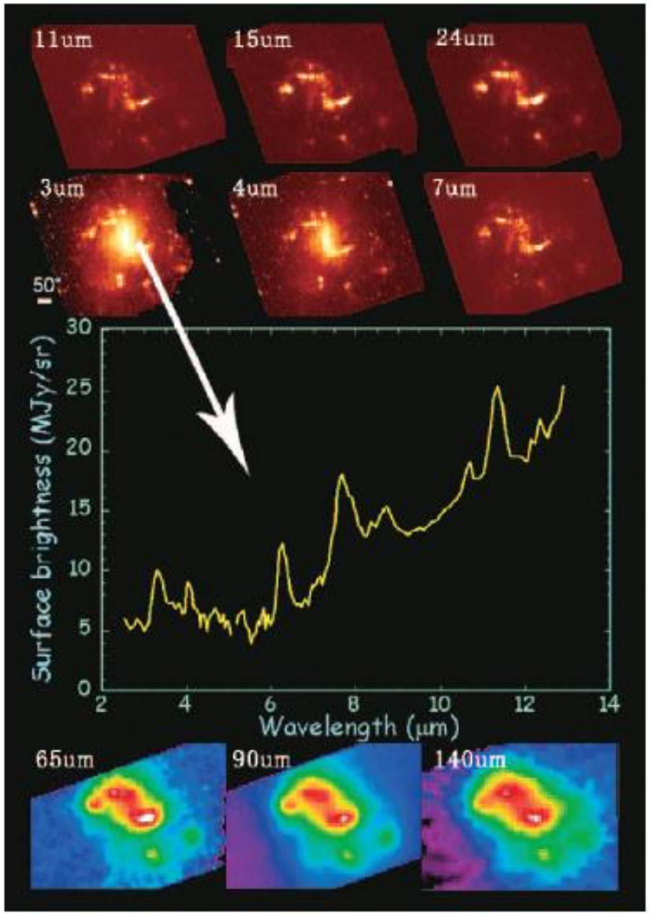

**This excess might be due to first-generation stars Ly-α.**
**CIBER collaboration plans to do CIBER-2 rocket experiment which has 10 times larger sensitivity.**

# Astrophysics with NIR and FIR by AKARI


- **NIR and FIR from interstellar gas → Formation and evolution of galaxies, stars and dusts**
- **NIR: Search for first-generation stars using Ly-α line.**
- **FIR: Search for first-generation heavy element dusts.**

Map of NIR from Milky Way Galaxy measured by AKARI




Molecular cloud IR in the arm of NGC1313 measured by AKARI

# Existing FIR photo-detectors

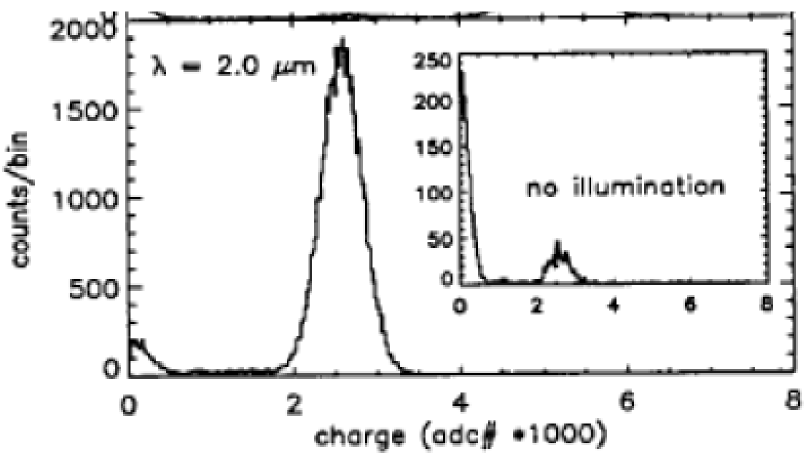
| Detectors | λ(μm) | Operation Temp. | NEP ($W/Hz^{1/2}$) | |
|---|---|---|---|---|
| Monolithic Ge:Ga | 50-110 | 2.2K | $\sim 10^{-17}$ | Akari-FIS |
| Stressed Ge:Ga | 60-210 | 0.3K | $\sim 0.9\times10^{-17}$ | Herschel-PACS |

Need more than 2 orders improvement from existing photoconductor-based detectors

We are trying to achieve $\mathrm{NEP} \sim O(10^{-20})\ W/\sqrt{Hz}$ **by using**

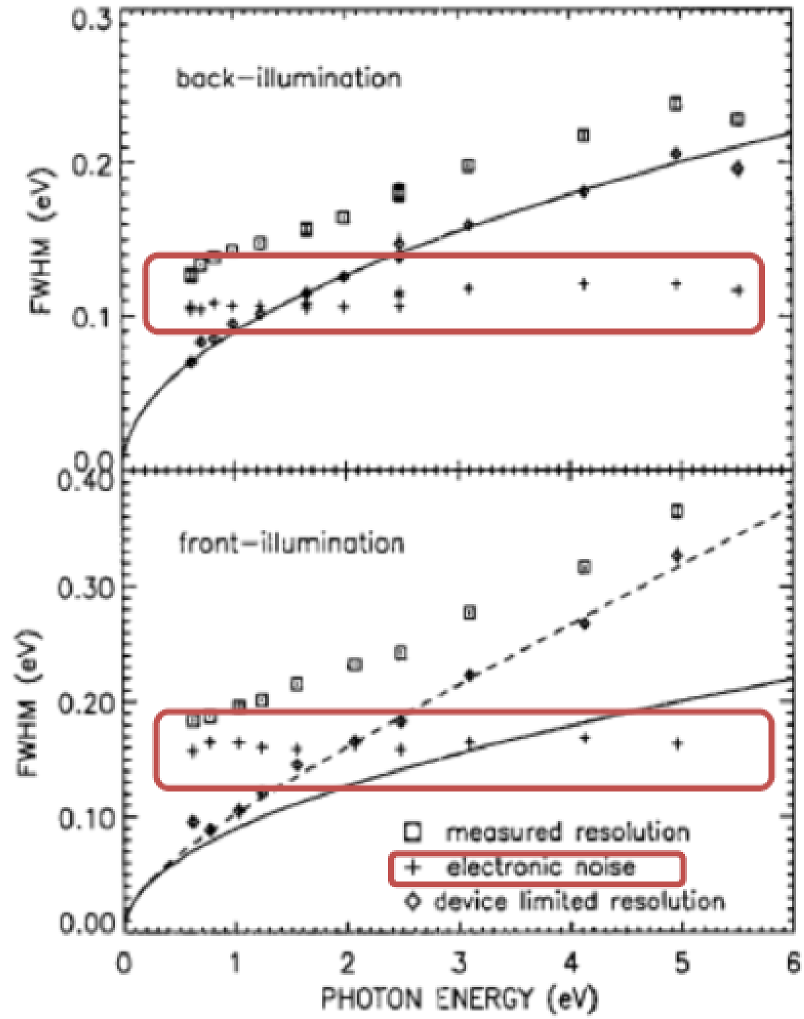
- **Superconducting tunneling junction detector**
- **FIR single-photon counting technique**

# STJ Energy Resolution for Near-Infrared Photon




P. Verhoeve et. al 1997

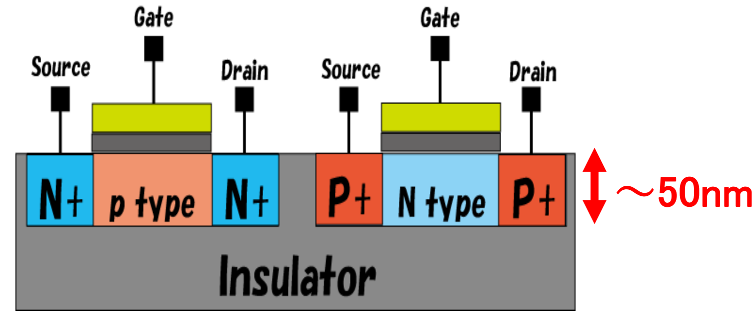
- 30μm sq. Ta/Al-STJ
- ΔE~130meV @ E=620meV(λ=2μm)
- Charge sensitive amplifier at room temp.
  - Electronic noise ~ 100meV



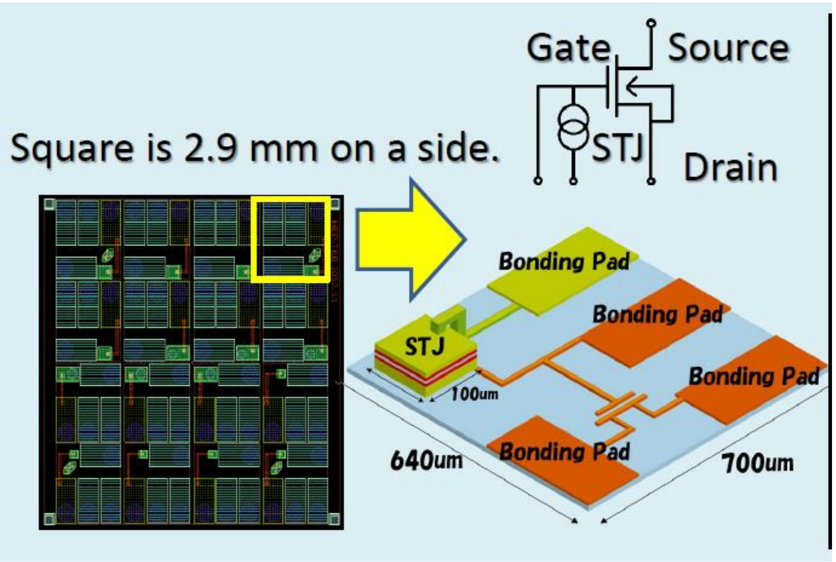

In sub-eV ~ several-eV region, STJ gives the best energy resolution among superconductor based detectors, but limited by readout electronic noise.

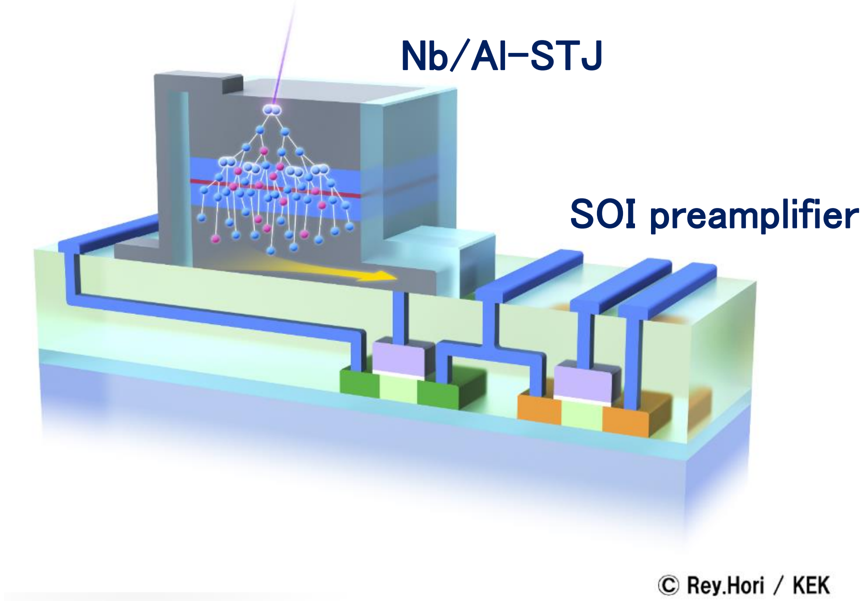
# R&D of SOI-STJ Detector

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).



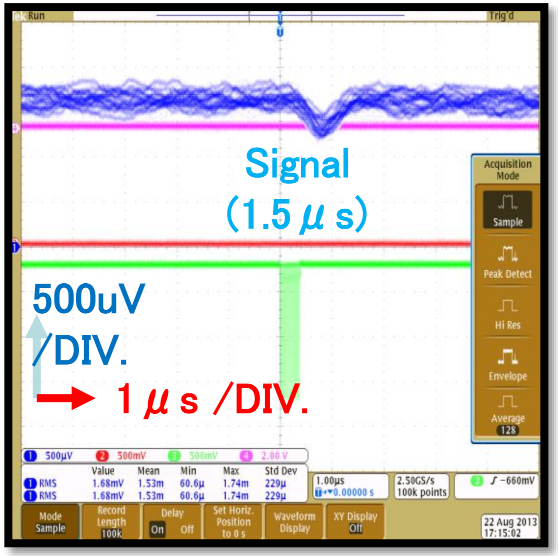

To improve the signal-to-noise ratio and to make multi-pixel device easily, we made a SOI-STJ detector where we processed Nb/Al-STJ on a SOI transistor board.

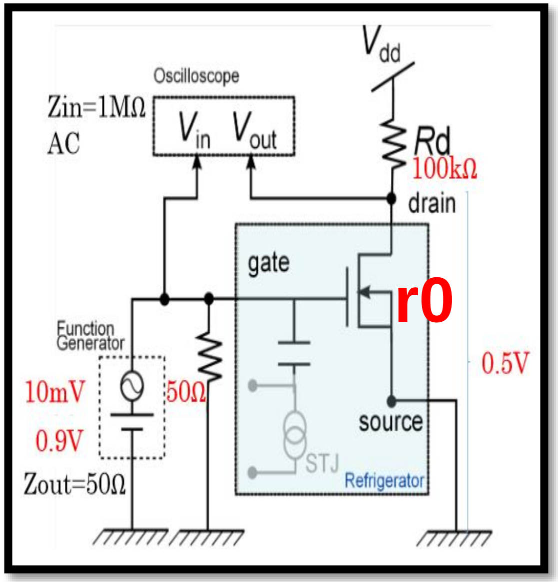


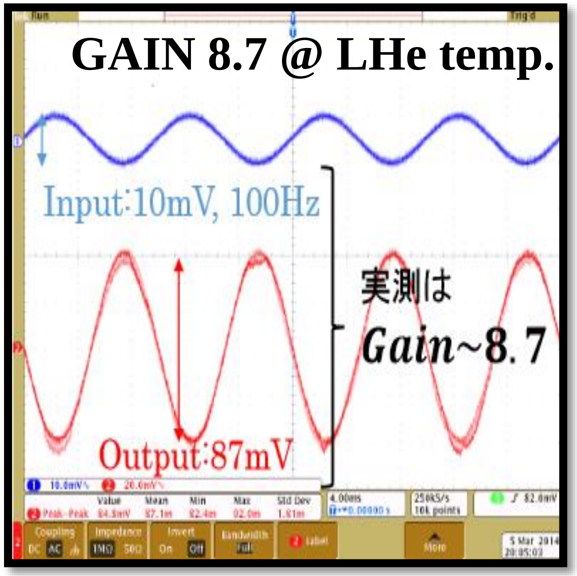



# Performance of STJ and SOIFET in SOI-STJ detector

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



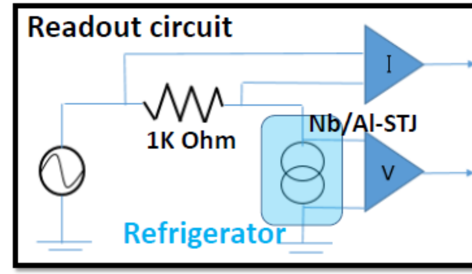




- We confirmed that the SOI-FET work as a preamplifier with a gain of 8.7 at 4K up to 100kHz.

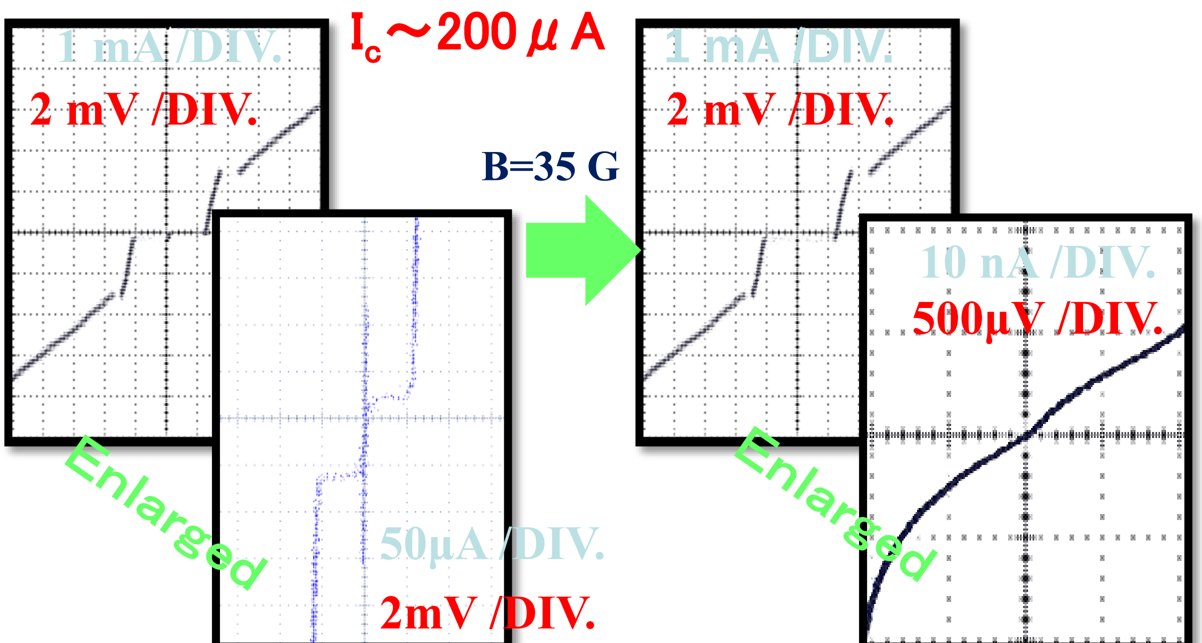
# Performance of Nb/Al-STJ in SOI-STJ Detector

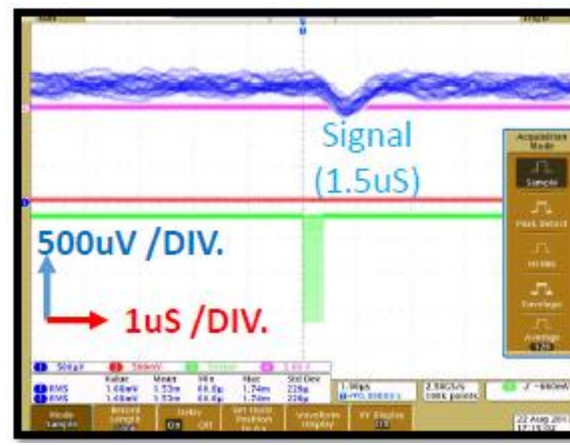
We measured the I-V curve of the Nb/Al-STJ (50 x 50 $\mu m^2$ junction) processed on the SOI wafer

at **700mK** with a dilution refrigerator.



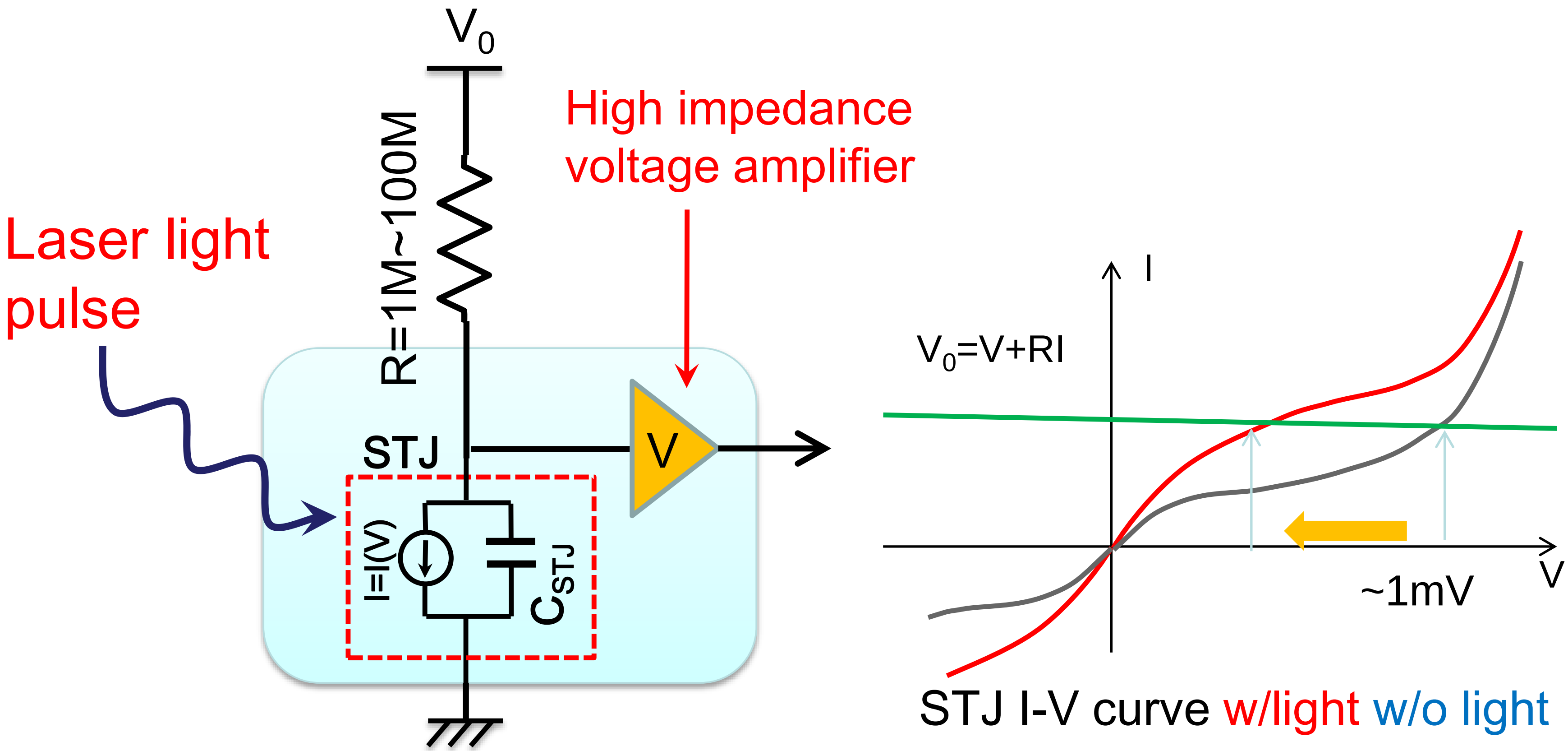

- **I-V curve of Josephson Junction**




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

# STJ response at a constant current mode




- STJ has a large resistance in series.
  → constant current mode
- STJ response to light is observed as a voltage drop.

# COBAND Collaboration
# ( Cosmic Background Neutrino Decay Search)

**A part of the consortium of the History of the Universe**

**Seoul National Univ.**
**S. B. Kim**
**STJ detector**

**Fukui Univ.**
**T. Yoshida**
**FIR photon beam source**

**Kindai Univ.**
**Y. Kato**
**Data transfer**

**FNAL**
**E. Ramberg**
**Electronics**

**KEK**
**Y. Arai, M. Hazumi**
**Electronics**

**Univ. of Tsukuba**
**S. H. Kim, Y. Takeuchi**
**STJ detector, Electronics, Cryostat, Optical system**

**JAXA/ISAS**
**T. Wada, H. Ikeda**
**Rocket, Electronics**

**Kwansei Gakuin Univ.**
**S. Matsuura**
**Cryostat, Optical system**

**AIST**
**M. Ohkubo, M. Ukibe**
**SOI-STJ detector**

**RIKEN**
**S. Mima**
**STJ detector**

**Okayama Univ.**
**H. Ishino**
**STJ detector**

**Shizuoka Univ.**
**S. Kawahito**
**Electronics**

**2015 Shizuoka Univ. Kwansei Gakuin Univ.**

**2014 AIST**

**2011 FNAL, Okayama Univ., Fukui Univ., Kindai Univ.**

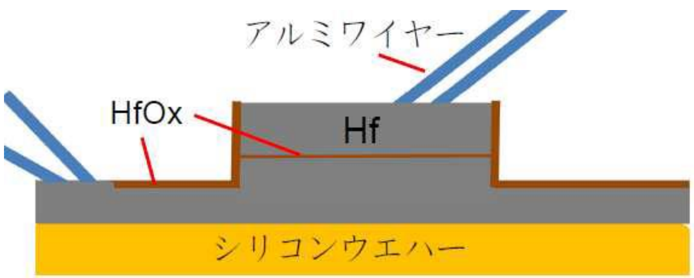
**2007 Univ. of Tsukuba, JAXA/ISAS, RIKEN, KEK, Seoul National Univ.**

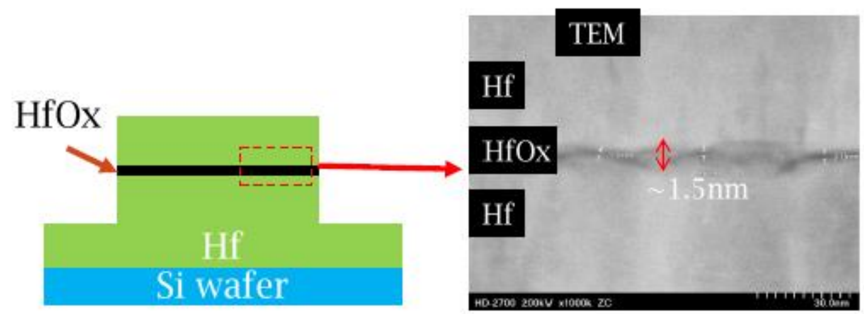
# R&D Status of Hf-STJ

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.

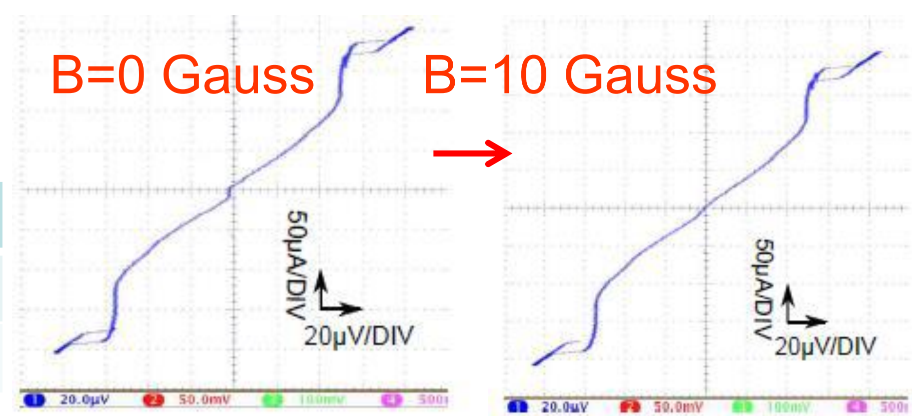
**Direct wire bonding on Hf layer**




I-V curve of Hf-STJ (**100x100μm²**)

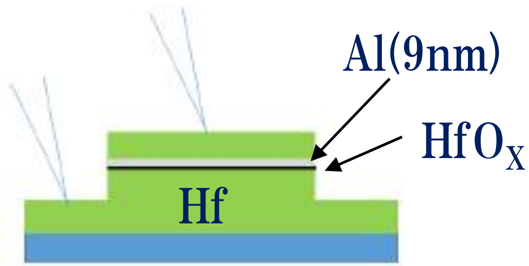
- T~40mK, $I_c$=10 μA, **$R_d$=0.6Ω**

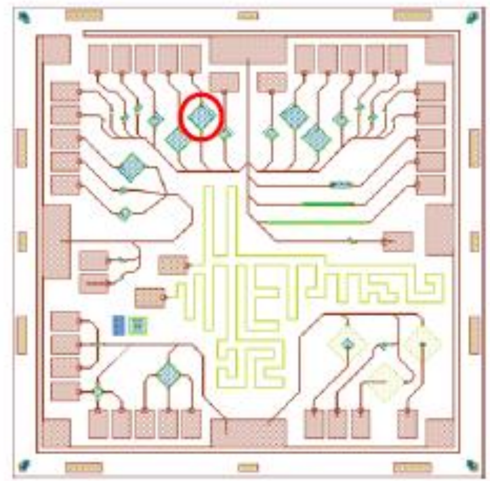


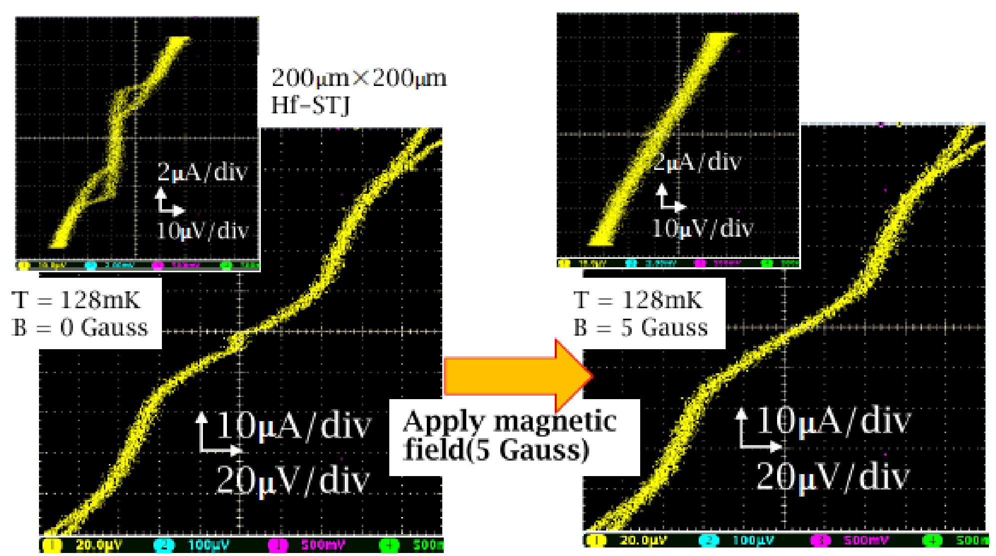

| STJ size | # of samples | $R_d$ |
|---|---|---|
| 200 x 200μm² | 3 | 0.22±0.01 Ω |
| 100 x 100 μm² | 3 | 0.60±0.10 Ω |

# Results of Hf/Al-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.

# Improvement of Hf-STJ Leakage Current

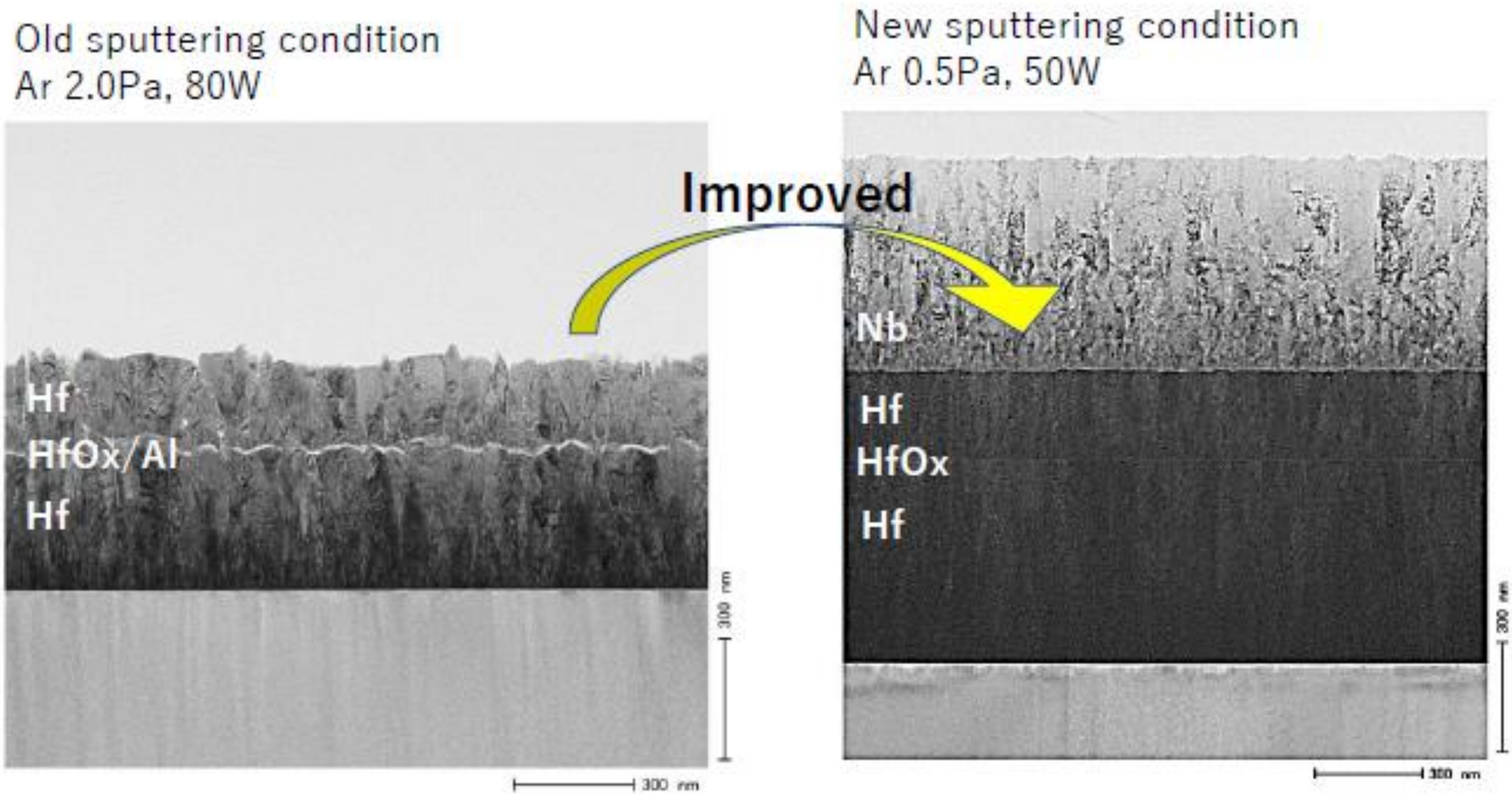
- Hf-STJ was proved to work  as a photon detector.
- To satisfy our leakage current requirement for COBAND experiment, we need decrease the leakage current of Hf-STJ.

We are working on this improvement by the following methods:

- Optimize the Hf sputtering conditions to make Hf surface smoother. Because the imperfect insulator layer causes high leakage current.
- Downsize Hf-STJ. Because the leakage current is proportional to the junction size.

# Improvement of Hf Surface Smoothness

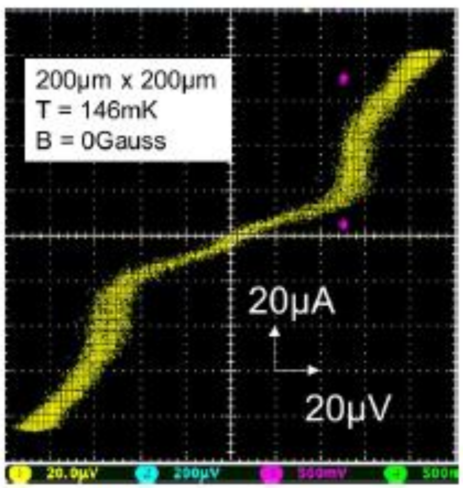
We improved the Hf surface smoothness by optimizing the Hf sputtering parameters.



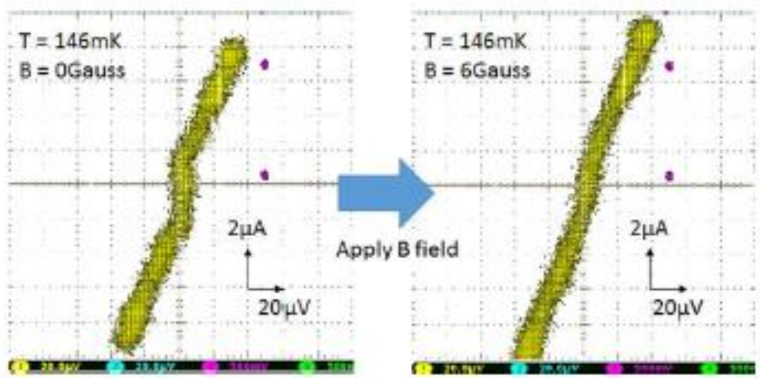
# Hf-STJ with Improved Smoothness

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.

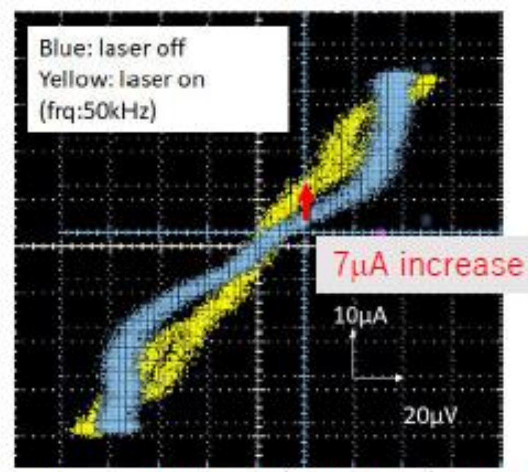


IV characteristic



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

IV characteristic (near 0V, 6Gauss)



Response to visible($\lambda$=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).