

Cosmic Background Neutrino Decay Search – COBAND Experiment –

Continuous Spectral Measurement in Far-Infrared Region using STJ

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

at Fermilab



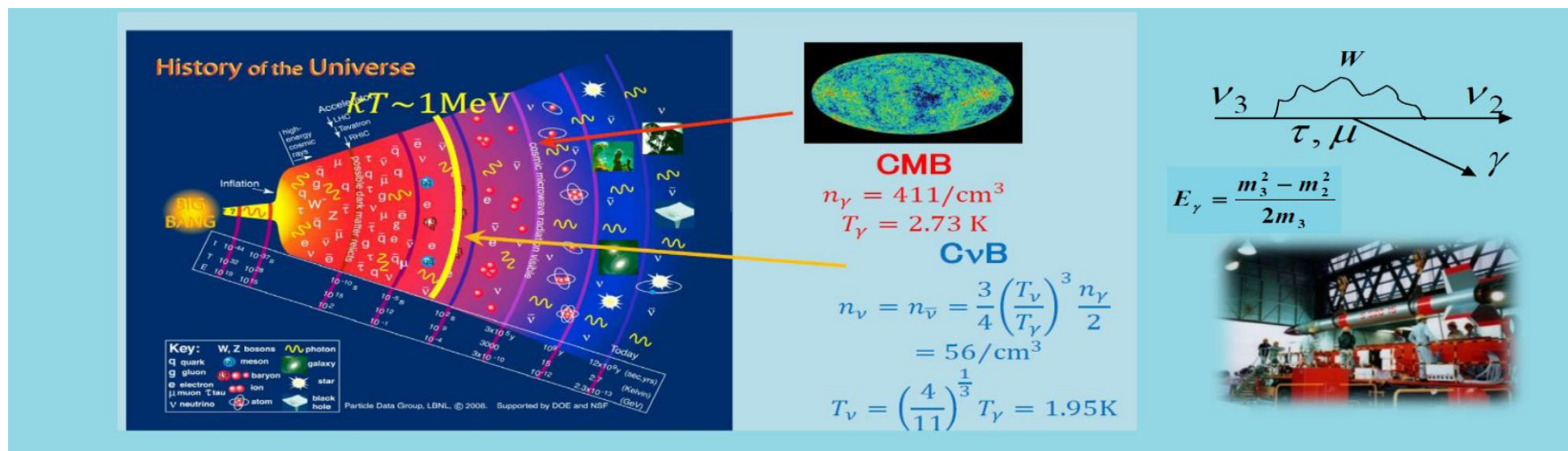
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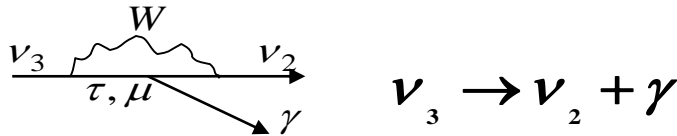
COBAND (COsmic Background Neutrino Decay) Collaboration



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Motivation of Search for Cosmic Background Neutrino Decay

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

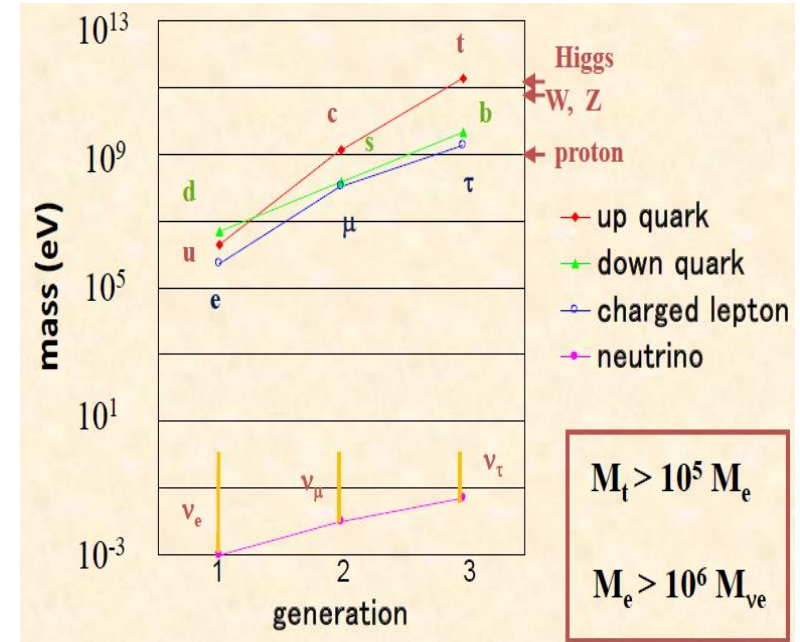


$$E_\gamma = \frac{m_3^2 - m_2^2}{2m_3} = \frac{\Delta m_{23}^2}{2m_3}$$

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

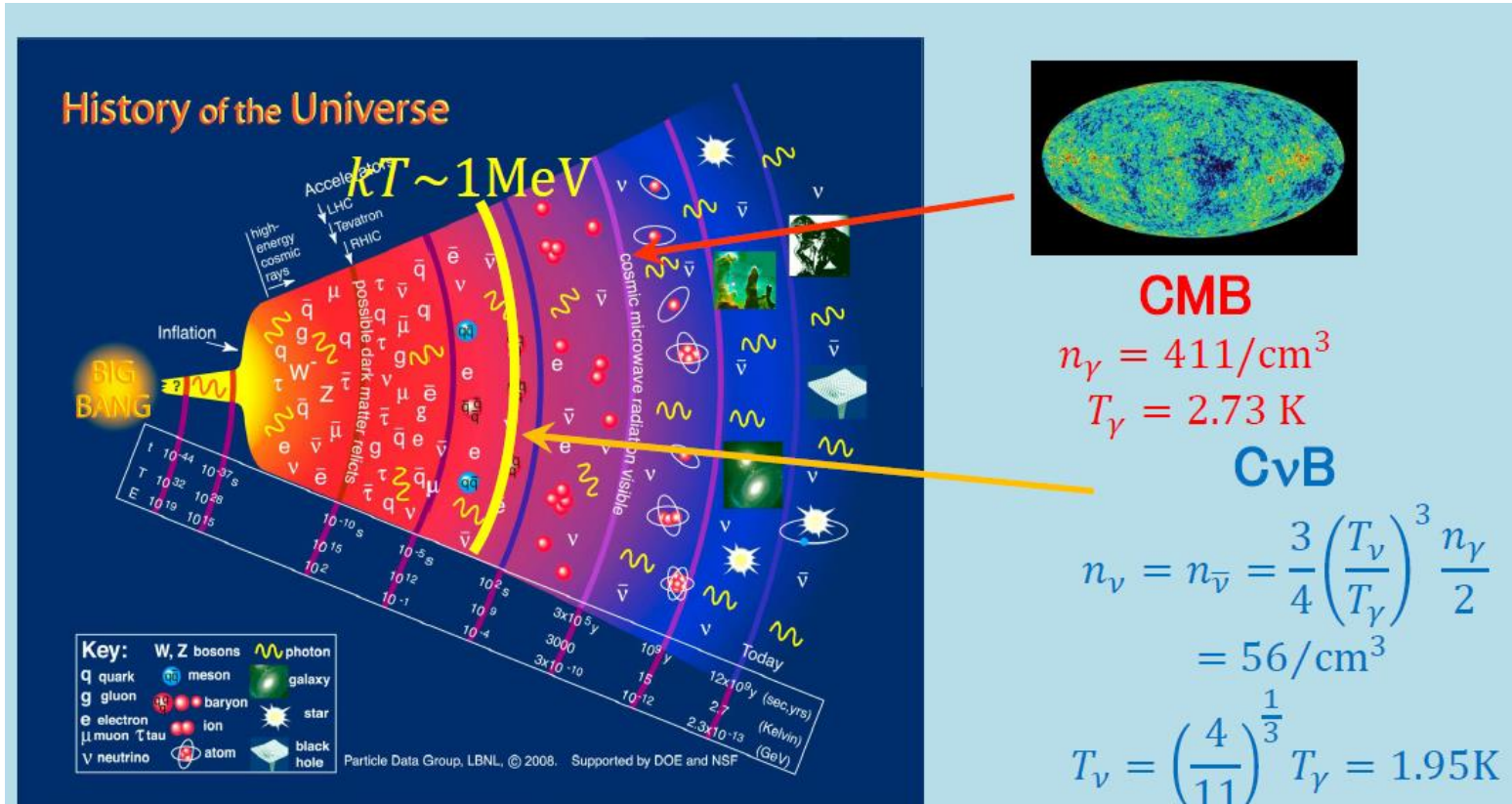
$E_\gamma = 10 \sim 25 \text{ meV}$ at ν_3 rest frame.

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



- As the neutrino lifetime is very long, we need use cosmic background neutrino to observe the neutrino decay. To observe this decay of the cosmic background neutrino means a discovery of the cosmic background neutrino predicted by cosmology.
- Left-Right symmetric model predicts the neutrino lifetime larger than 10^{17} year while the standard model predicts 2×10^{43} year. Measured neutrino lifetime limit $\tau > 3 \times 10^{12}$ year.

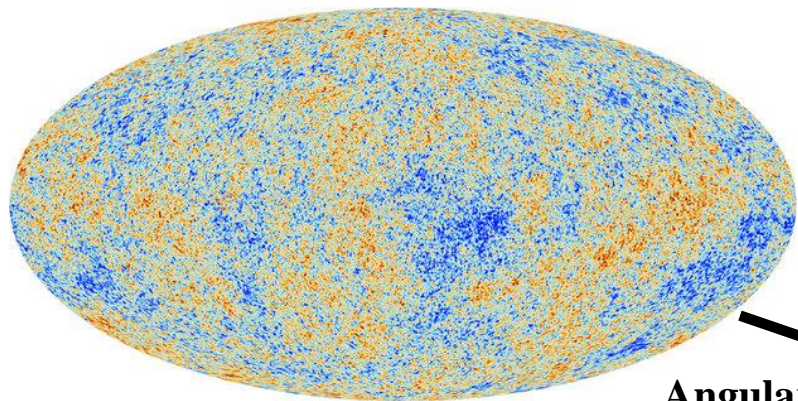
Big-Bang Cosmology and Cosmic Background Neutrino (CvB)



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

Large Scale Structure of the Universe and CvB

Temperature fluctuation of CMB
observed by Planck satellite



Angular
correlation
at high
temperature

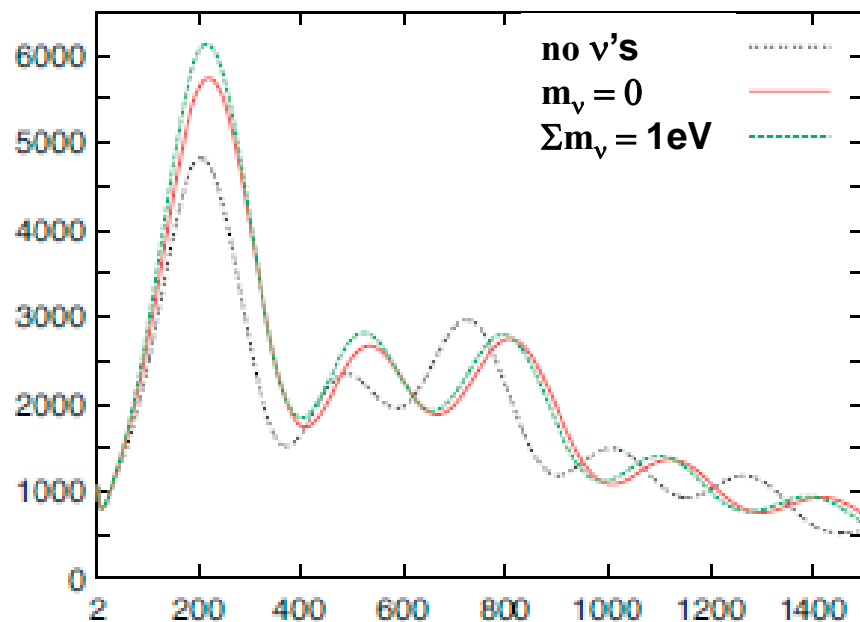
Decision Factor of Temperature
Fluctuation:

Dark matter, Dark energy, **Neutrino**



Matter density
or Large scale structure of the Universe

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

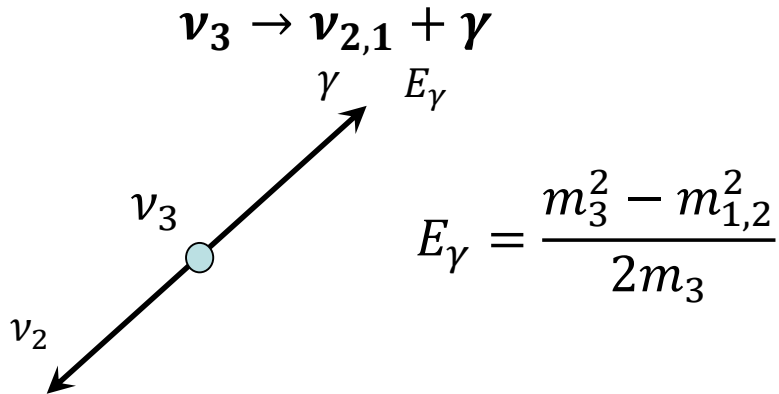


Large Angular scale($180^\circ / l$) Small
High Temperature = High Galaxy matter density
CvB exists \rightarrow large angular correlation at high angle
higher neutrino mass \rightarrow larger angular correlation
at high angle

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

Photon Energy from Neutrino Decay

Neutrino decay

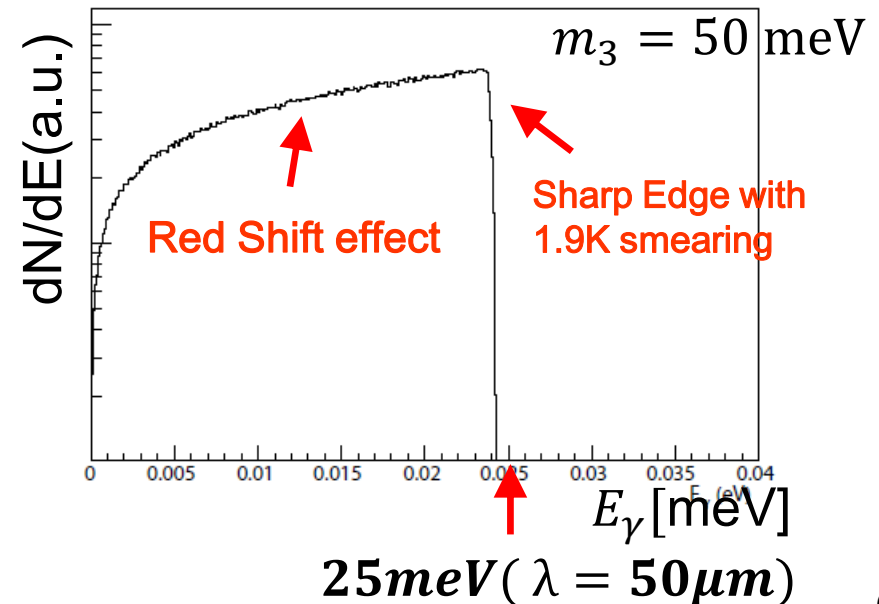
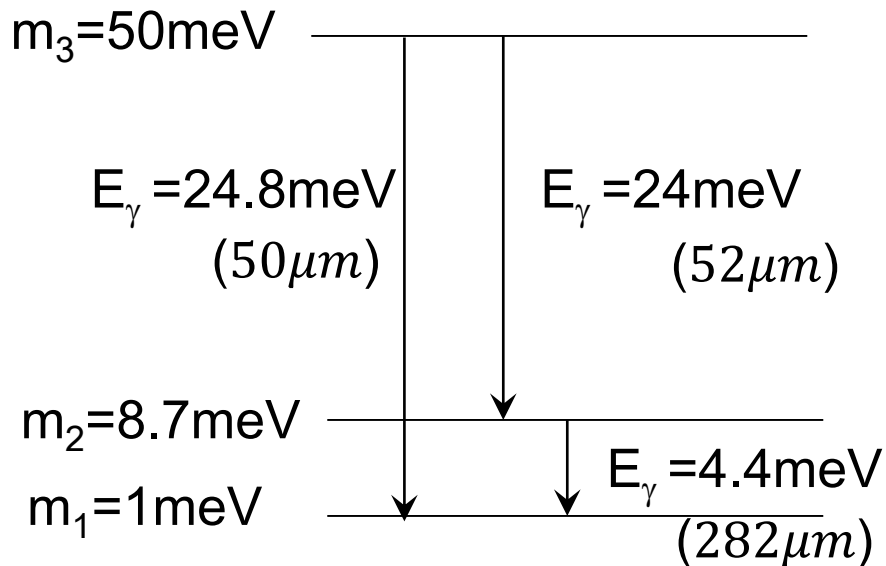


- Neutrino oscillation results
 - $|\Delta m_{23}^2| = |m_3^2 - m_2^2| \sim 2.4 \times 10^{-3} \text{ eV}^2$
 - $\Delta m_{12}^2 \sim 7.65 \times 10^{-5} \text{ eV}^2$
- Space observatory results
(Planck+WP+highL+BAO)
 - $\Sigma m_i < 0.23 \text{ eV}$

→ $50\text{meV} < m_3 < 87\text{meV}$

$E_\gamma = 14 \sim 24\text{meV}$ ($\lambda_\gamma = 51 \sim 89\mu\text{m}$)

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



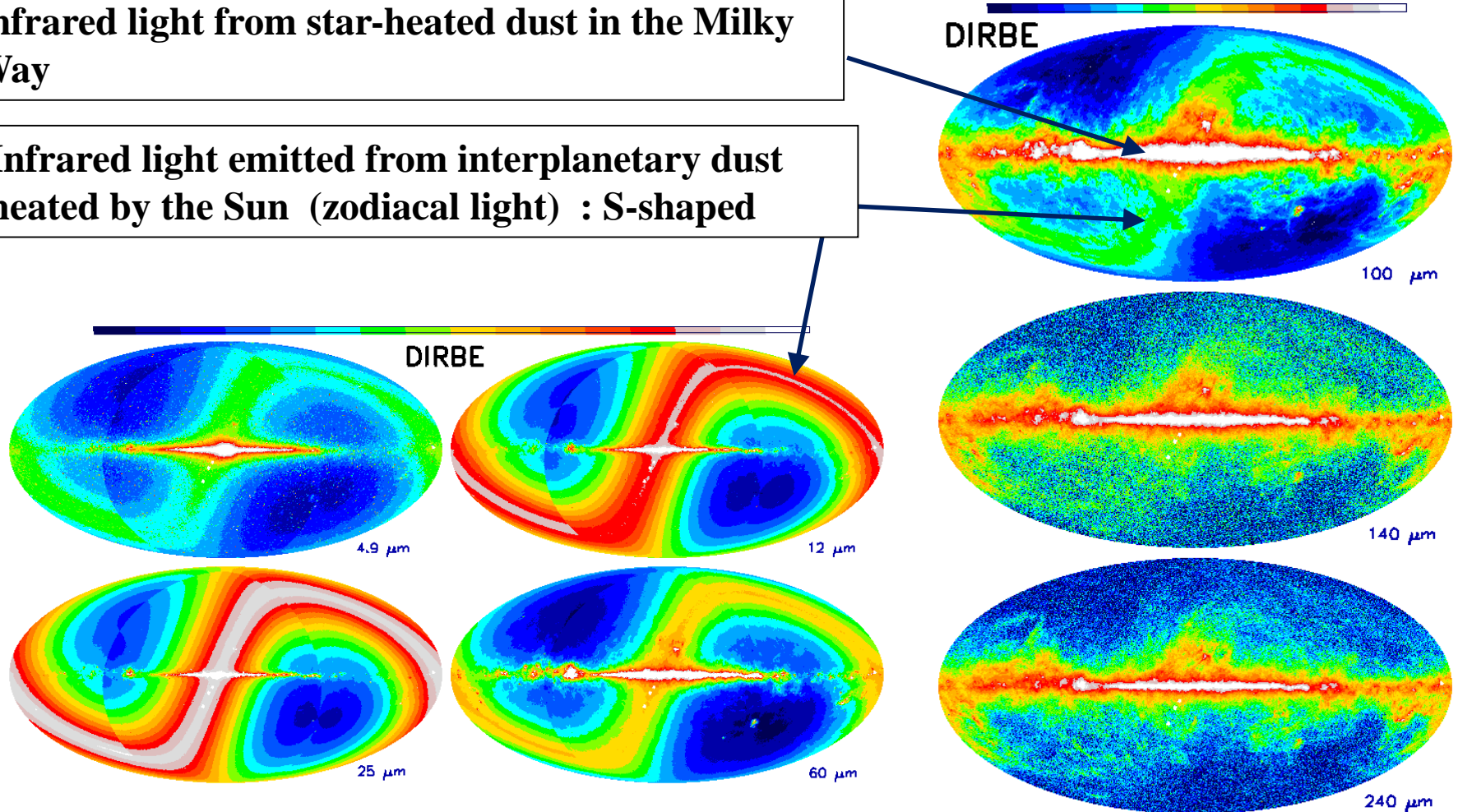
Cosmic Infrared Background Radiation

Cosmic Infrared Background Observation by COBE

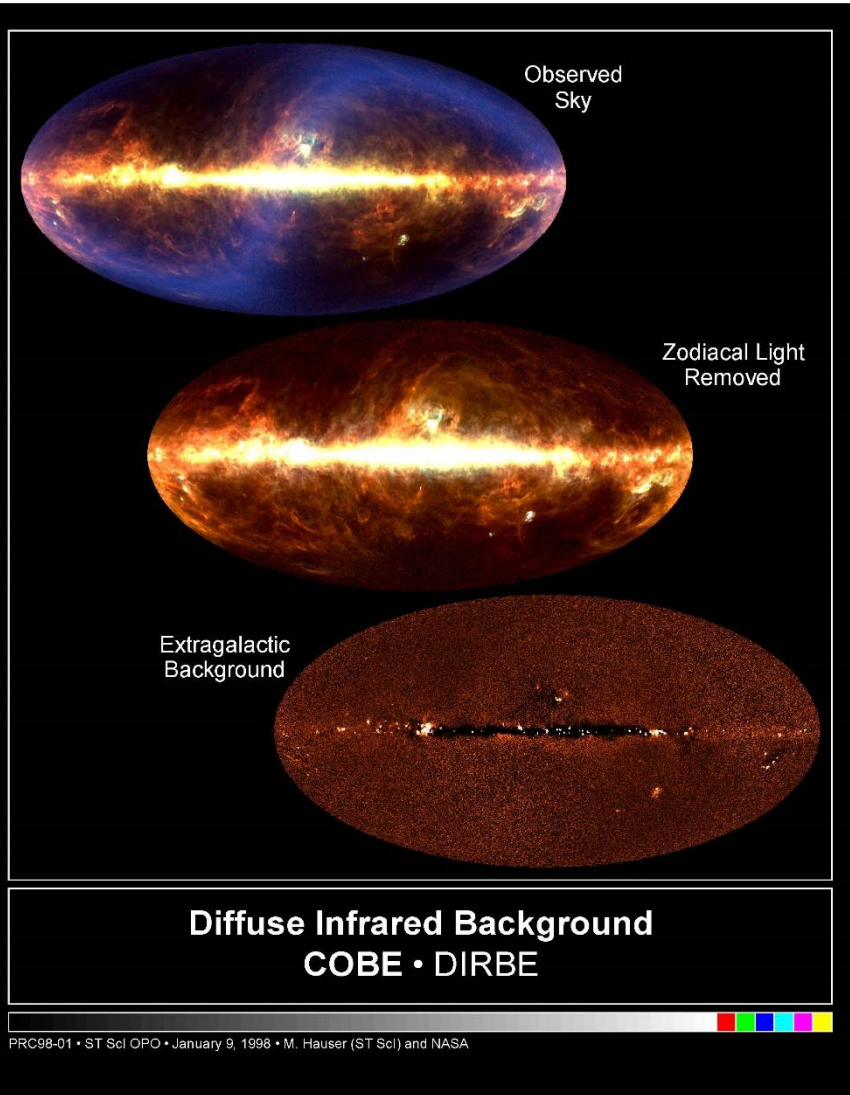
January 1998 (Press Release): COBE (Cosmic Background Explorer) announced the first observation of the cosmic infrared background (CIB)

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 $\lambda = 60 \mu\text{m}$ (blue), $100 \mu\text{m}$ (green) and $240 \mu\text{m}$ (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.

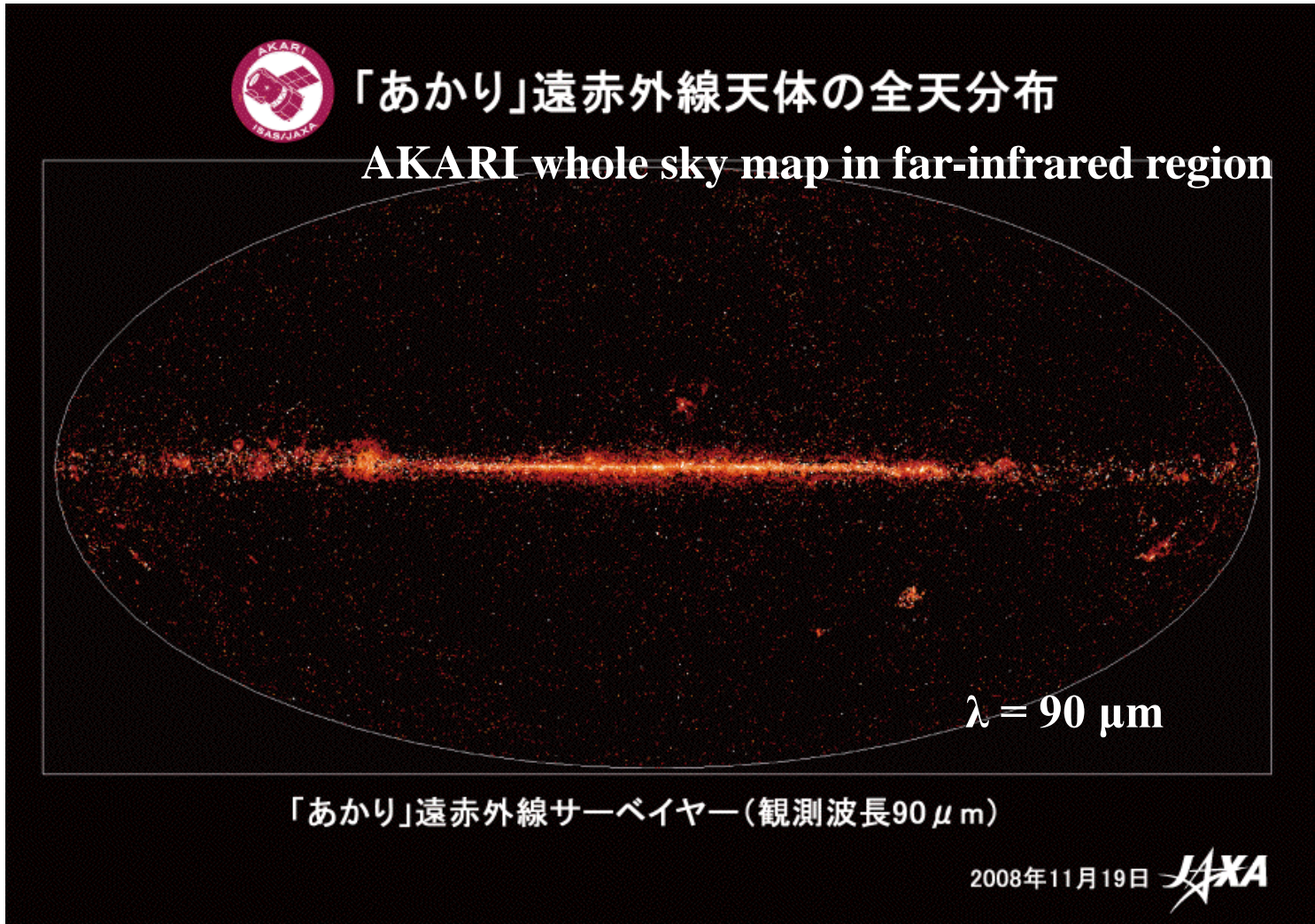
(Bottom)

After removing the infrared light from our solar system and Galaxy at $\lambda = 240\mu\text{m}$.

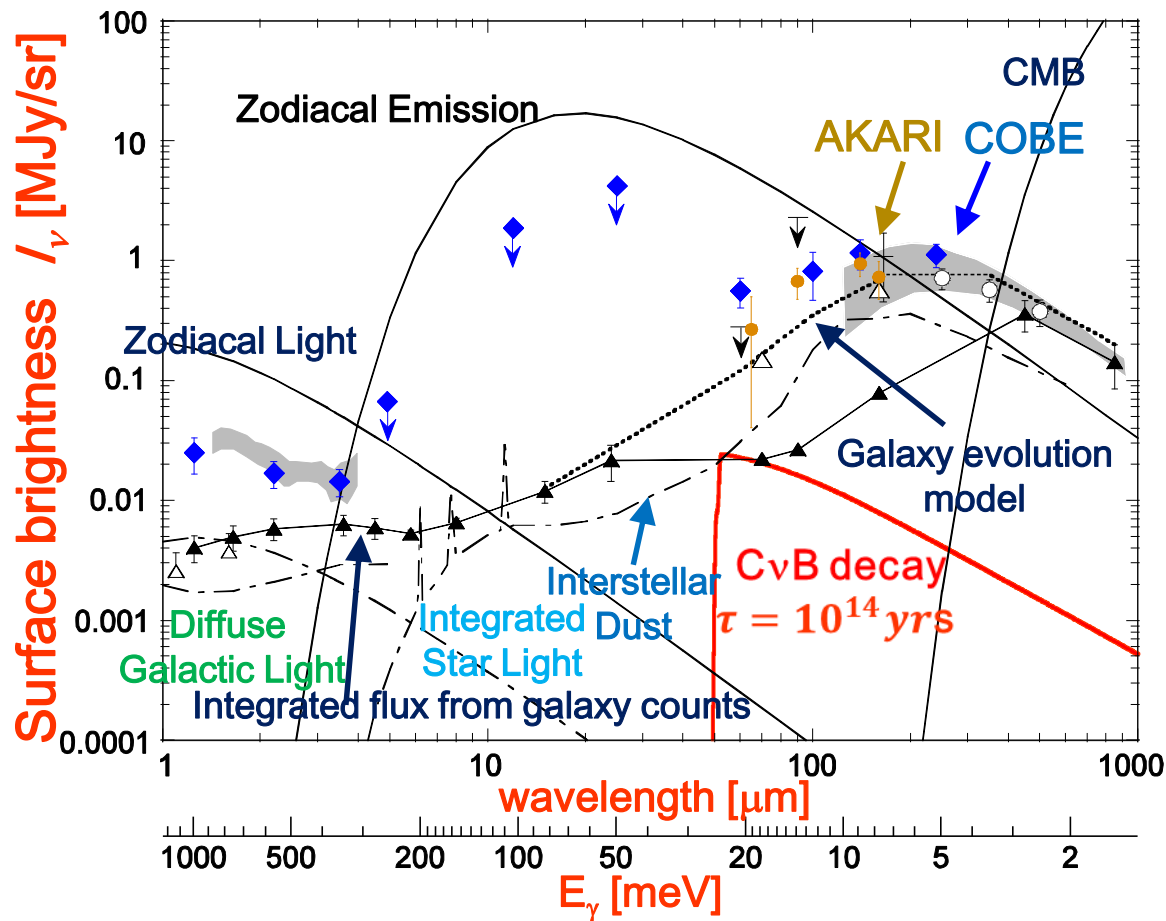
COBE announced that they observed the extragalactic residual infrared light called “Cosmic Infrared Background” at the 240 and 140 micrometer wavelength.

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 CvB decay ?

Sources of NIR: first-generation stars Ly- α ?

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](https://doi.org/10.1143/JPSJ.81.024101)

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

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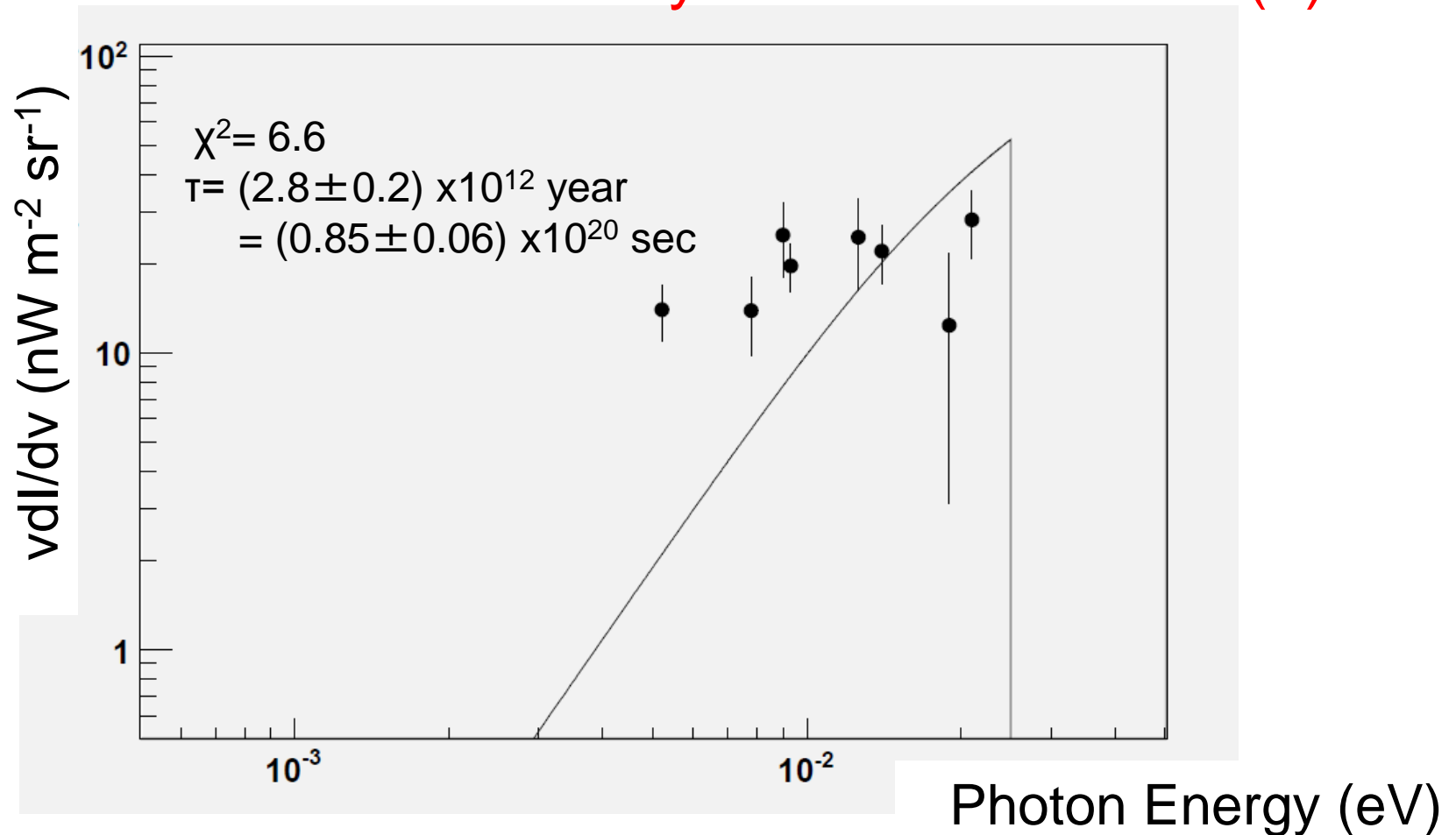
We propose to search for the neutrino radiative decay by fitting a photon energy spectrum of the cosmic infrared background to a sum of the photon energy spectrum from the neutrino radiative decay and a continuum. By comparing the present cosmic infrared background energy spectrum observed by AKARI and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

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

Search Region: $\lambda = 35 \sim 250 \mu\text{m}$ ($E_\gamma = 35 \sim 5 \text{ meV}$)

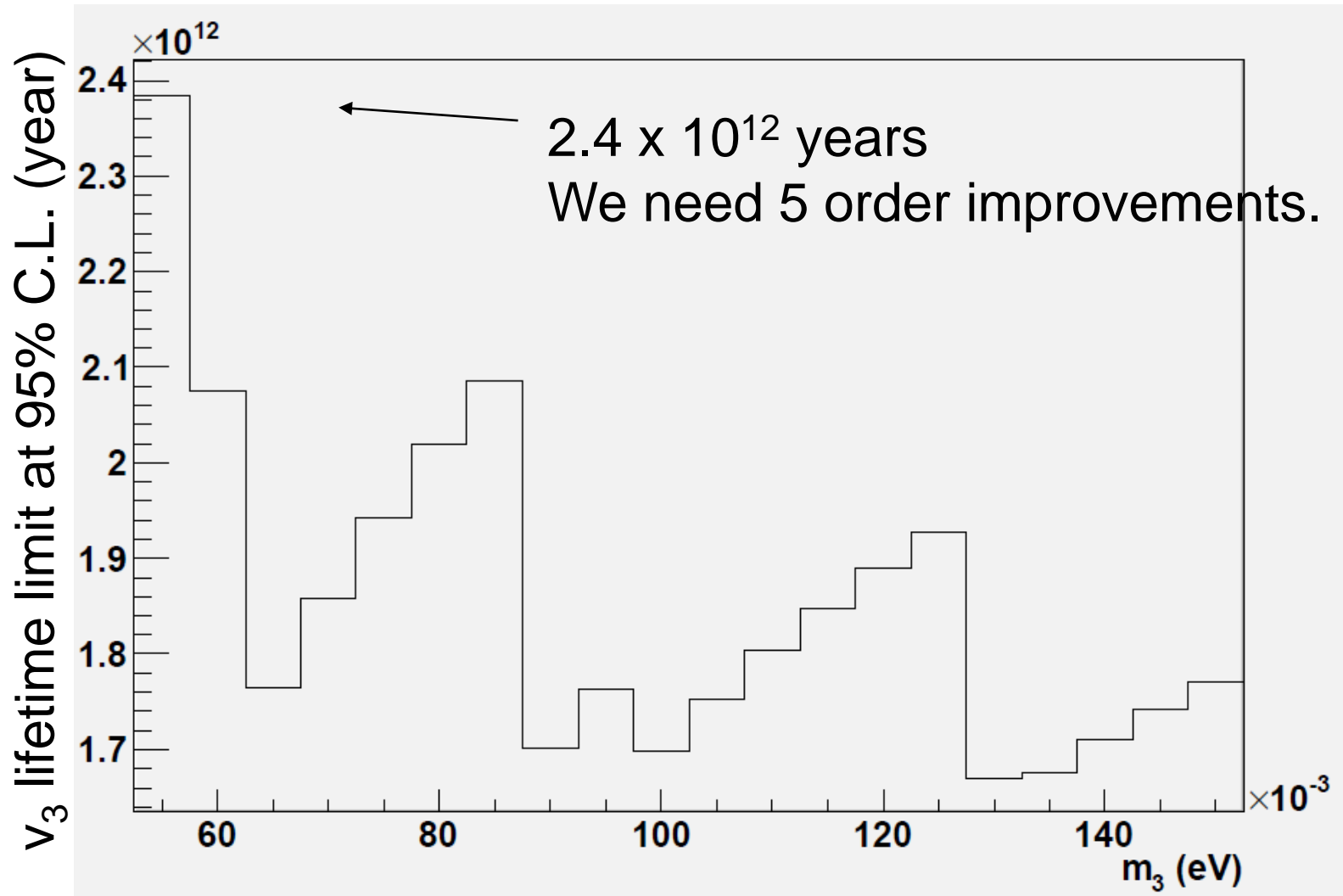
In Rocket experiment, $\lambda = 40 \sim 80 \mu\text{m}$ ($E_\gamma = 31 \sim 15 \text{ meV}$)

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 $2.4 \times 10^{12} \text{ year}$ at 95% C.L. for $m_3 = 0.05\text{eV}$ and $m_2 = 0.01\text{eV}$.
(My calculation)

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

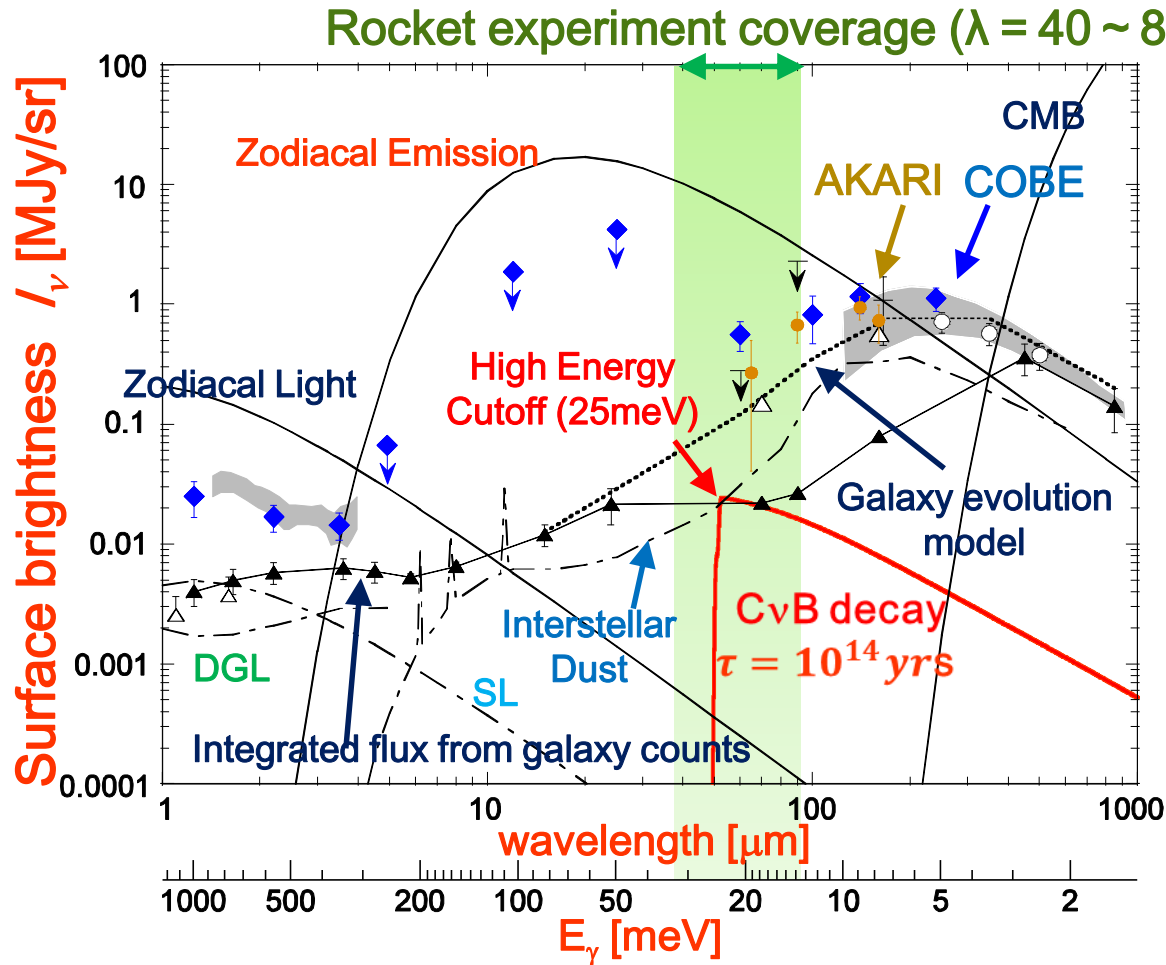


ν_3 mass (eV)

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

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 CvB decay continuously, we can see the CvB decay signal as a high energy cutoff.

Requirements for the detector

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

COBAND (COsmic BACKGROUND Neutrino Decay Search) Experiment

Rocket Experiment Plan: 5minutes data acquisition at 200 km height in 2019.
Improve the current limit of lifetime $\tau(\nu_3)$ by two orders of magnitude ($\sim 10^{14}$ years).

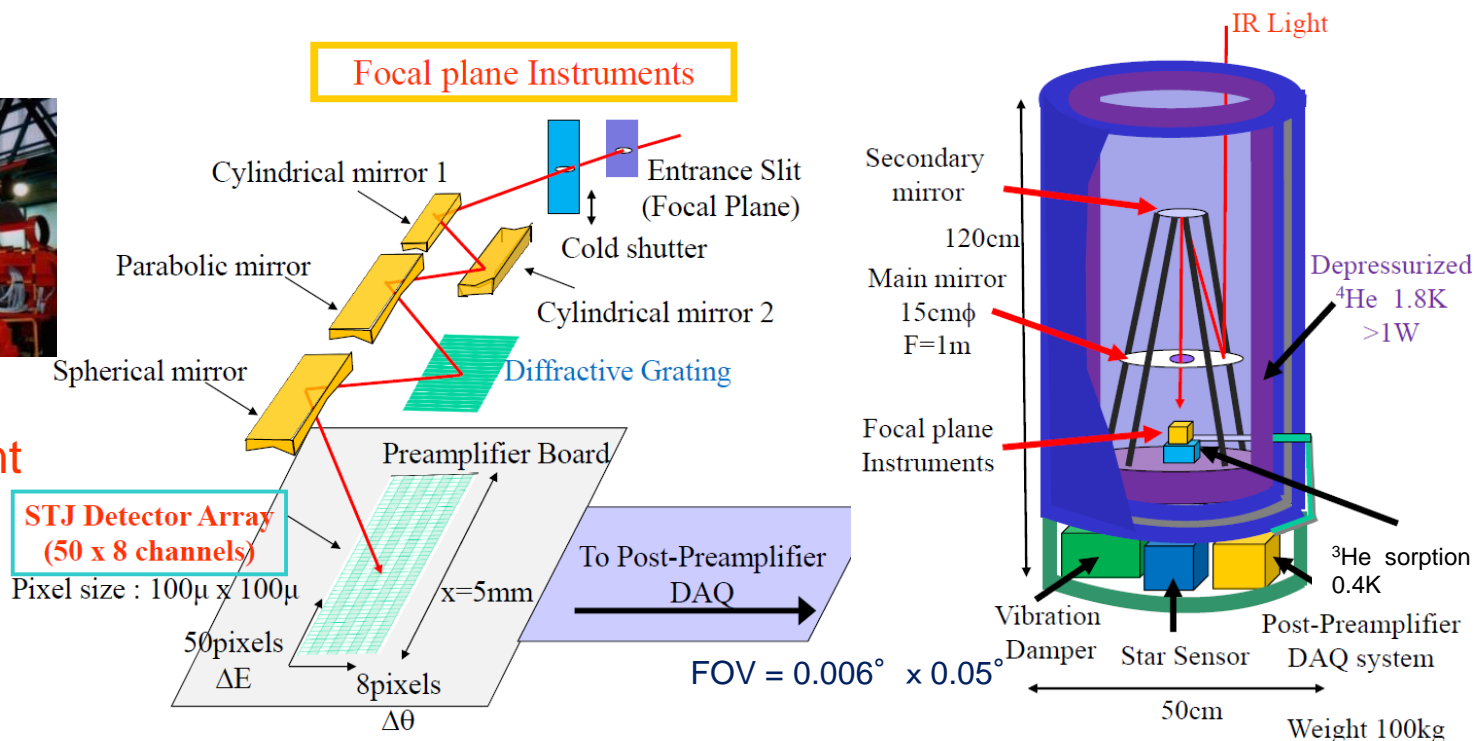
» Superconducting Tunneling Junction (STJ) detectors in development

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



JAXA Rocket
CIB Experiment

(Feb 2, 1992)



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

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

- $\Delta = 20 \mu\text{eV}$: 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

Zodiacal Emission

Thermal emission from the interplanetary dust cloud

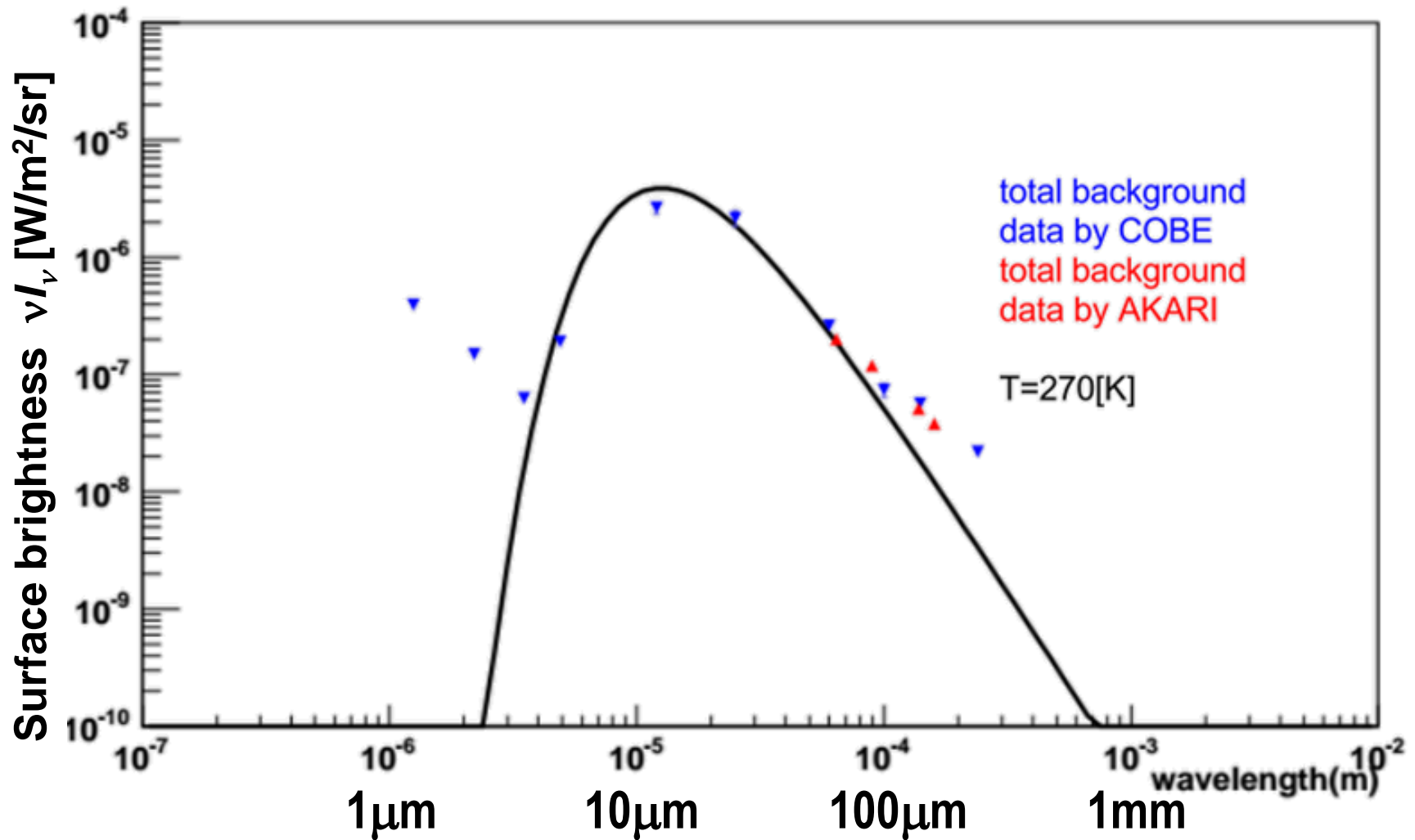
$$I_\nu = \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/kT) - 1} \\ \times A \left(\frac{\nu}{c} \times 10^{-5} \right)^B \text{ Wm}^{-2}\text{sr}^{-1}$$

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

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

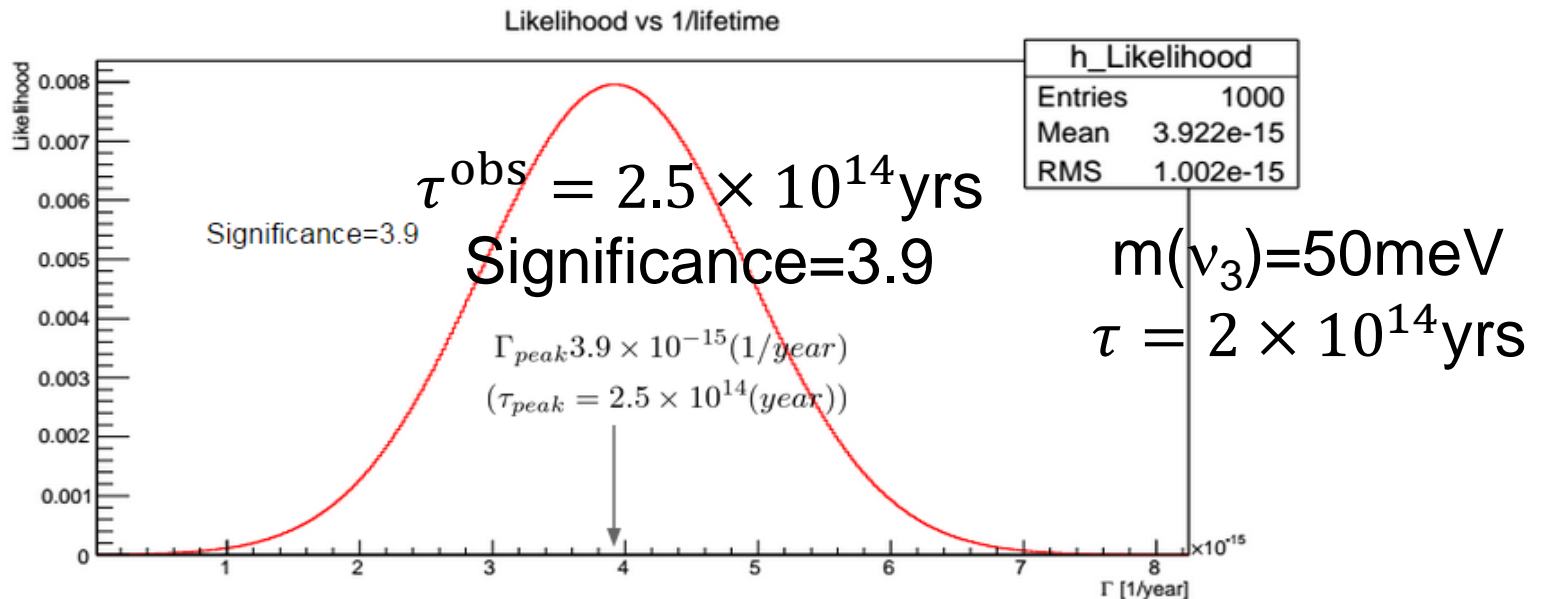
Zodiacal Emission(ZE) is overwhelmingly dominating. Here we consider only ZE as the background.

Zodiacal Emission



Discovery Potential for Neutrino Decay

1. Create a pseudo-data for ND and ZE expectation on assumption of ν_3 mass and lifetime: $N_{\text{obs}}(m^{\text{true}}, \Gamma^{\text{true}})$
2. Calculate expected distribution of ND+ZE on assumption of ν_3 mass and lifetime: $N_{\text{exp}}(m, \Gamma)$
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

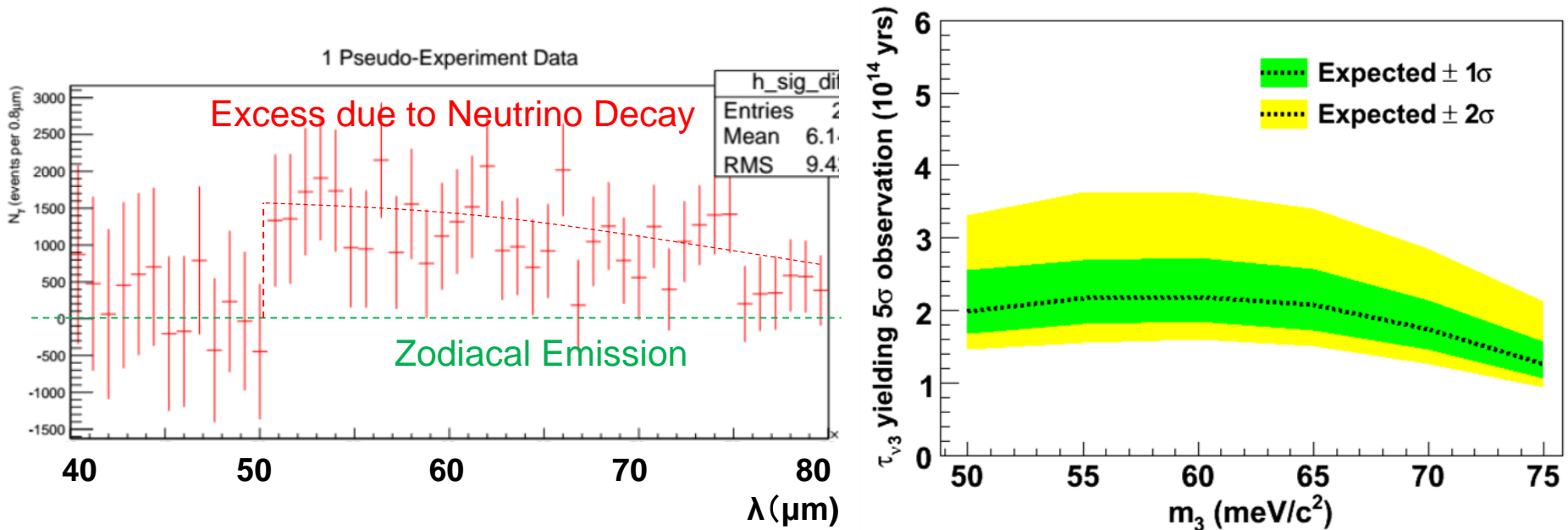
telescope diameter: 15cm

50-column (λ : 40 μm – 80 μm) \times 8-row array

Viewing angle per single pixel: 100 μrad \times 100 μrad

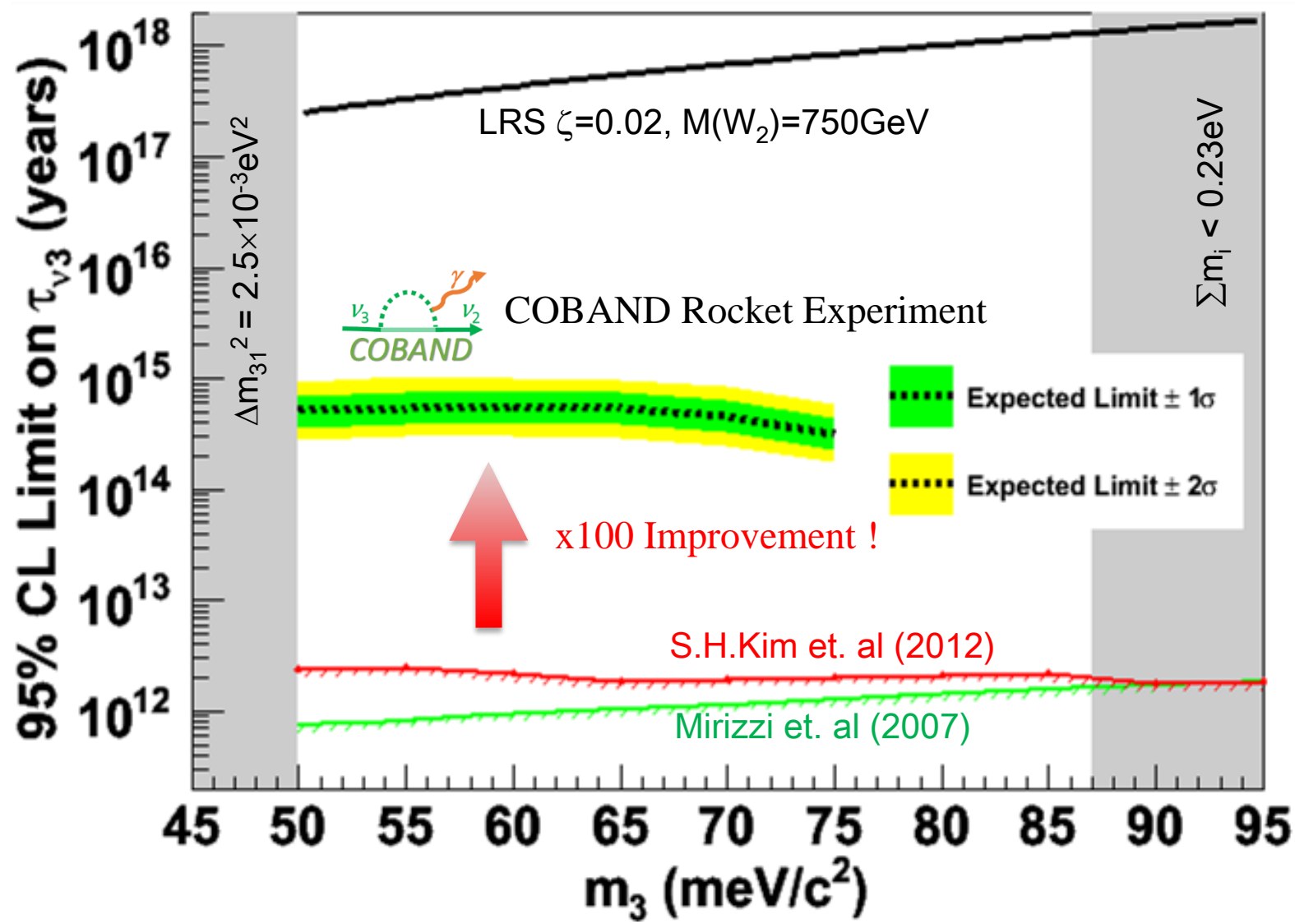
Measurement time: 200 sec.

Photon detection efficiency: 100%



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

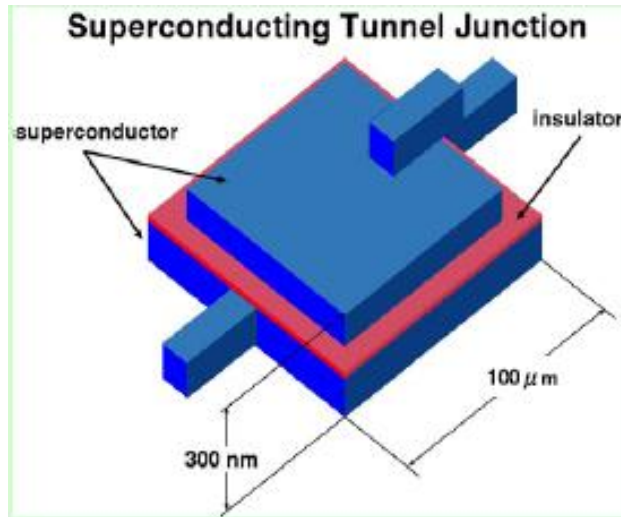
COBAND Experiment Sensitivity to Neutrino Decay



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

STJ (Superconducting Tunnel Junction) Detector

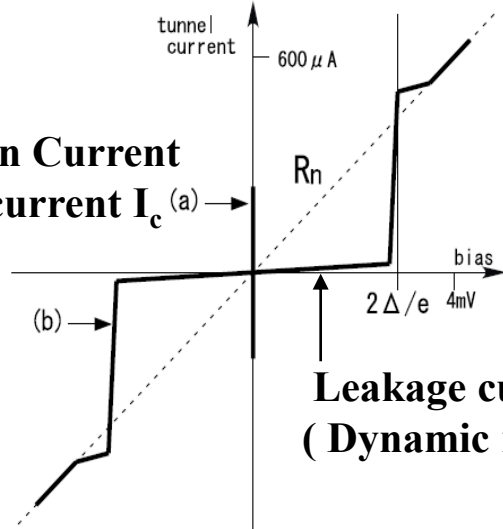
Superconductor / Insulator / Superconductor Josephson Junction



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.

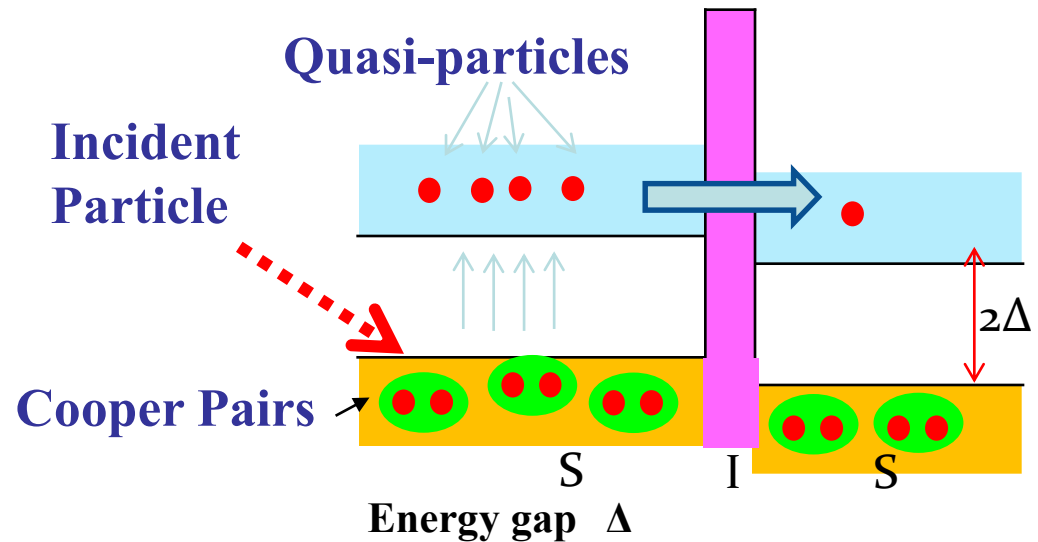
current-voltage (I-V) curve for STJ

Josephson Current
Critical current I_c (a) →



Leakage current

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



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

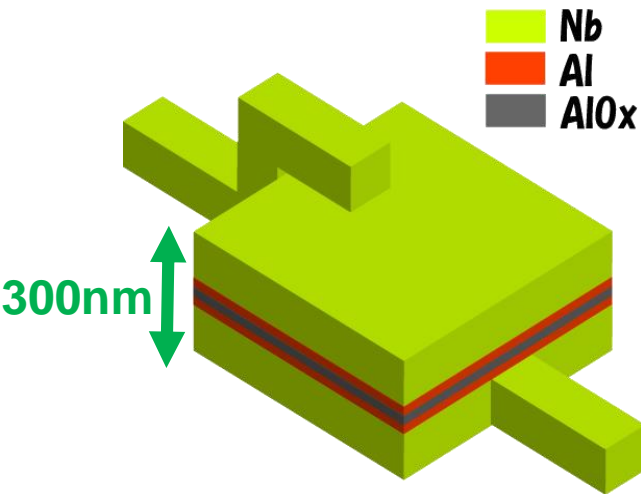
Material	$T_c(K)$	$\Delta(\text{meV})$
Niobium	9.20	1.550
Aluminum	1.14	0.172
Hafnium	0.13	0.021

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



Number of Quasi-particles in Nb/Al-STJ

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

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

E_0 : Photon Energy

Δ : E-Gap in superconductor

For 25meV single photon

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

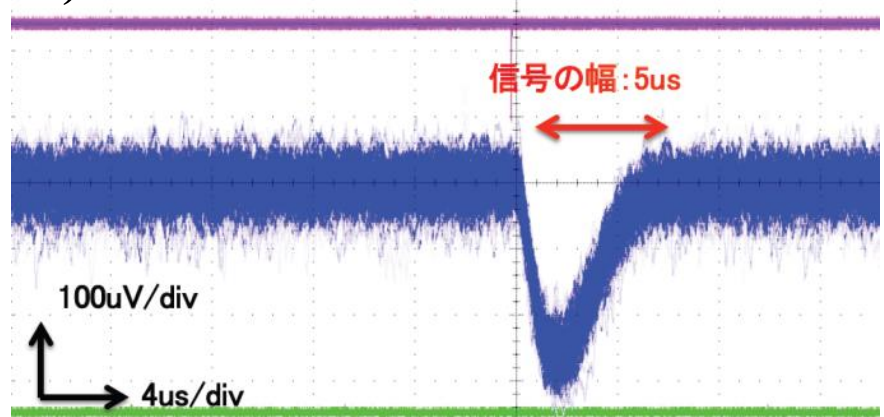
Back tunneling Effect → Trapping Gain

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)

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

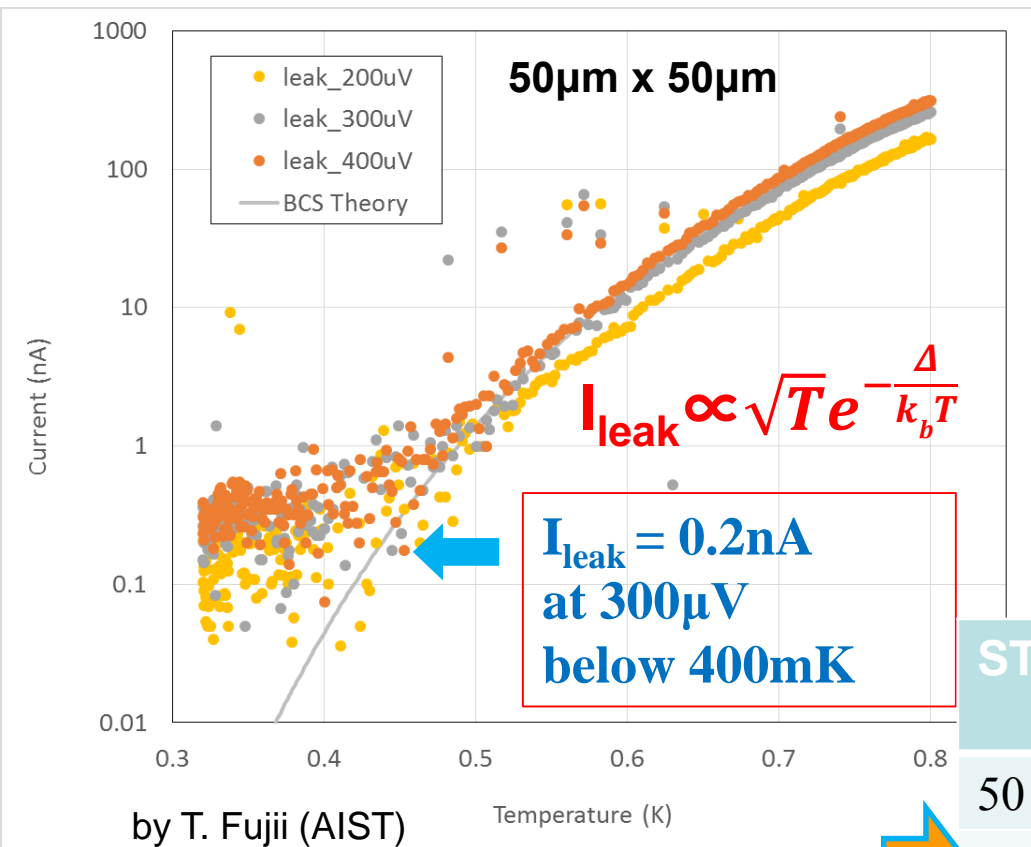
Response of Nb/Al-STJ to visible laser light pulse ($\lambda=465\text{nm}$) at 350mK



Leakage Current of Nb/Al-STJ

- Leakage current I_{leak} is required to be below 0.1nA to detect a single far-infrared photon ($\lambda = 40 - 80\mu\text{m}$).

Temperature Dependence of Leakage Current



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

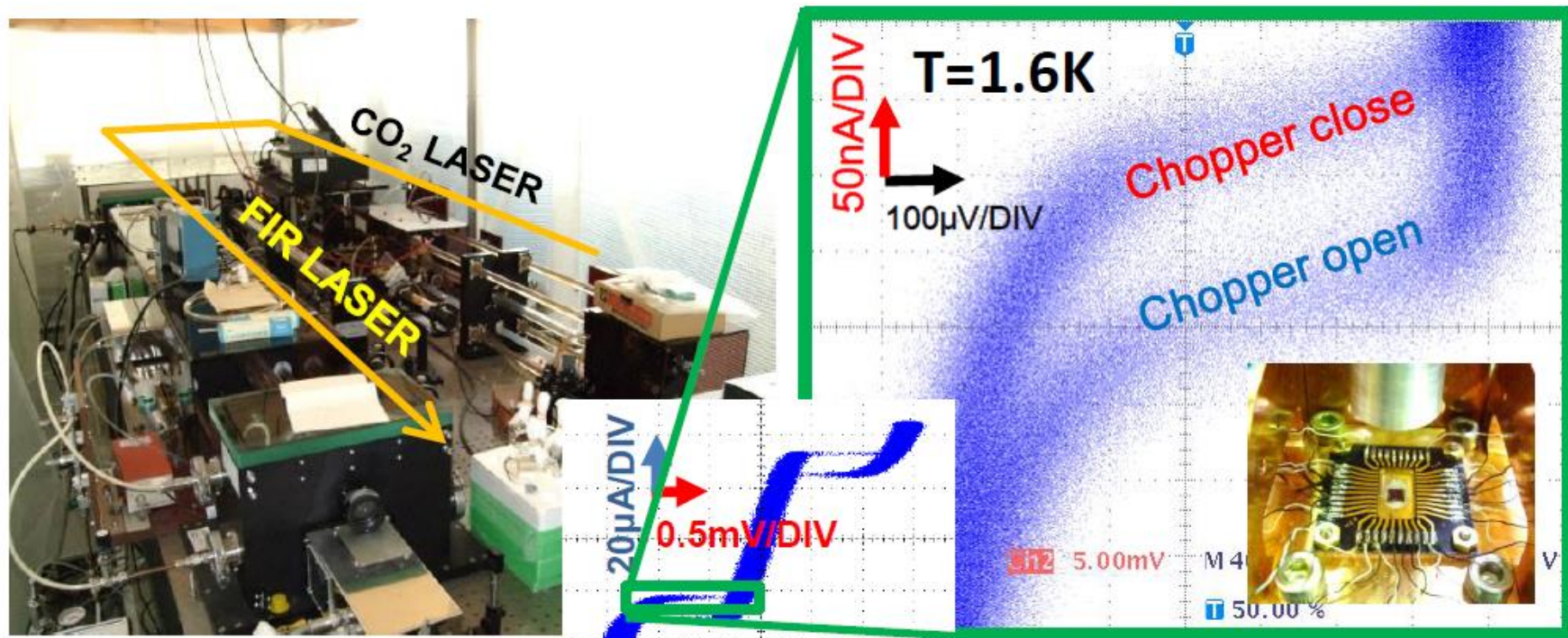


STJ size	# of samples	I_{leak} at 0.3mV
50 x 50 μm^2	18	224 \pm 29 pA
20 x 20 μm^2	7	39 \pm 13 pA
10 x 10 μm^2	20	14 \pm 7 pA

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

Far-Infrared Laser at University of Fukui
($\lambda=57.2\mu\text{m}$)

Nb/Al-STJ Response to Far-Infrared Laser

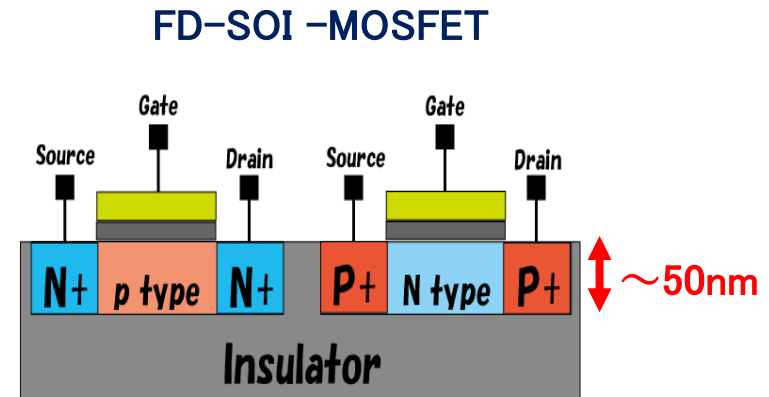


- 20μm-square Nb/Al-STJ made at AIST CRAVITY system
- Laser light was turned on and off with a chopper at a frequency of 200Hz. Measured the change of the I-V curve between the laser on and off to be 50~100nA in current.

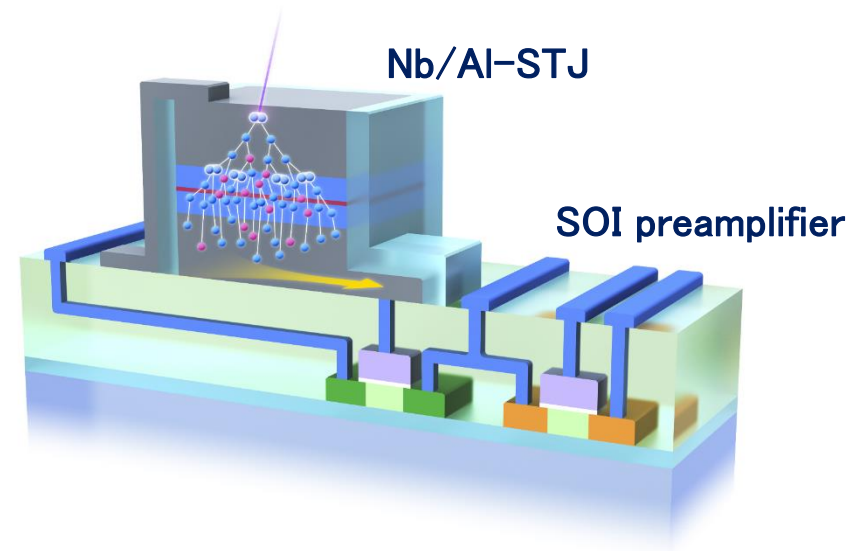
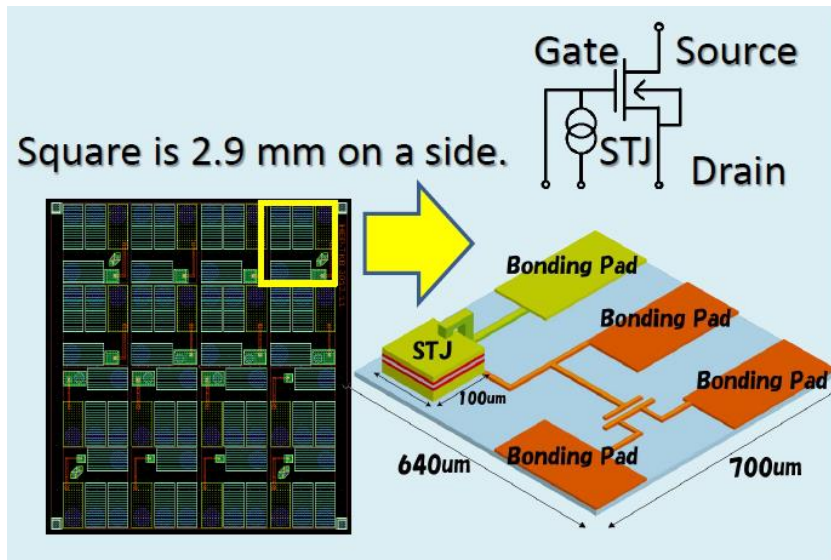
R&D Status of SOI Cryogenic Preamplifier for STJ

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($\sim 50\text{nm}$).

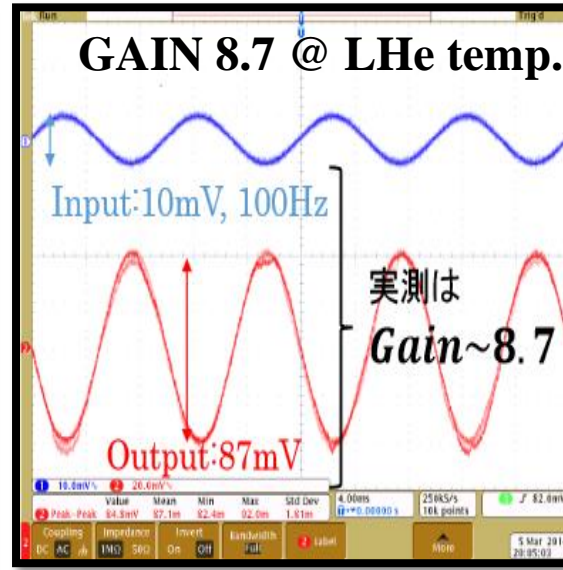
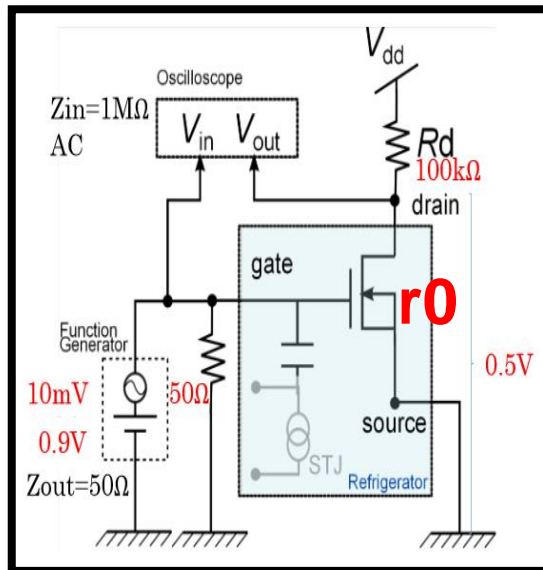
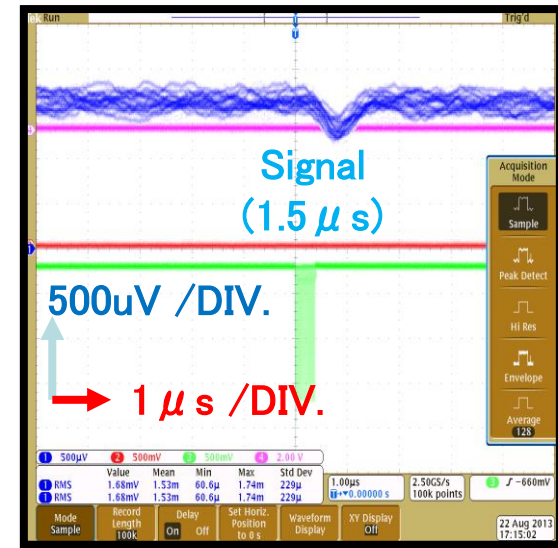


To improve the **signal-to-noise ratio** and to make **multi-pixel device** easily, we made a SOI-STJ detector where we processed Nb/Al-STJ on a SOI transistor board.



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.

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

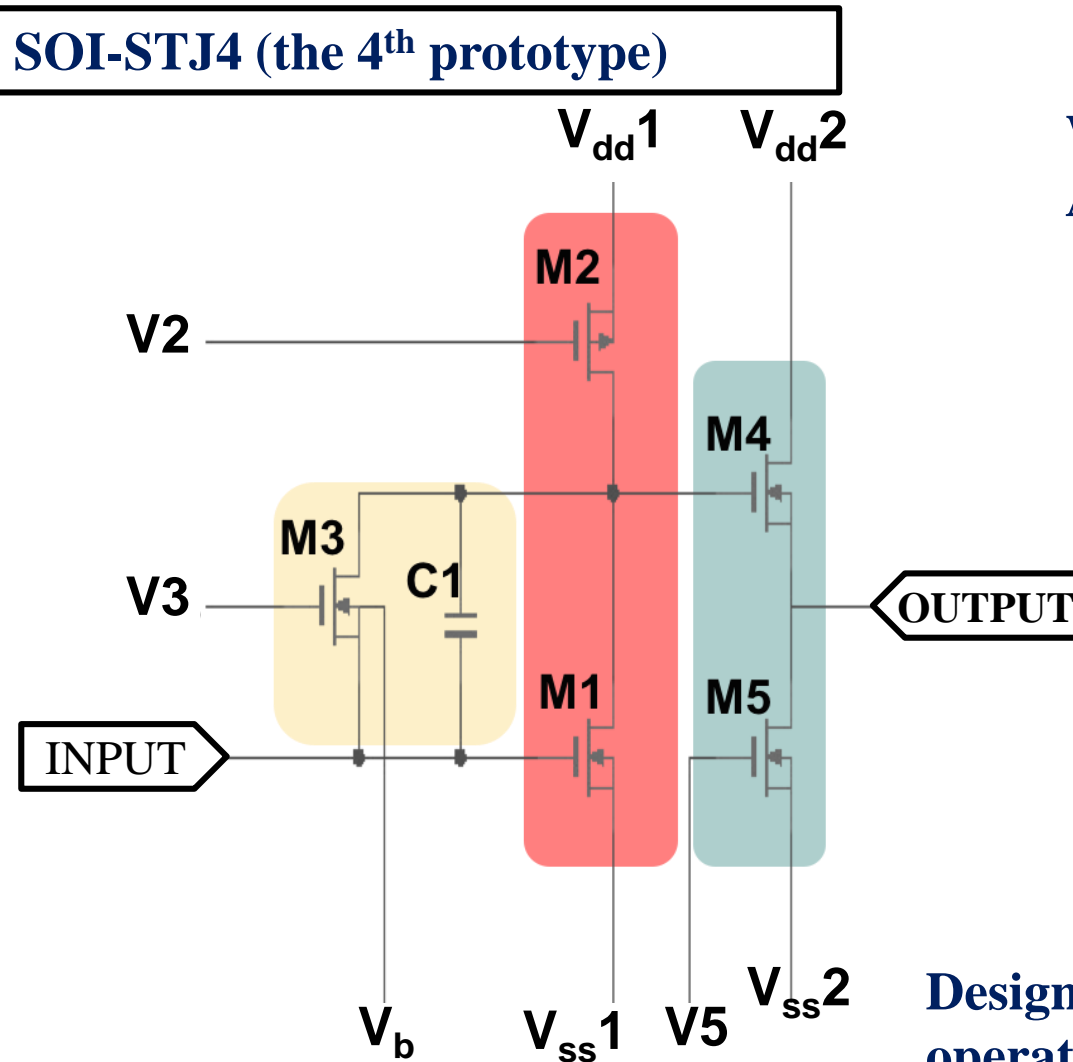
Use the feedback between the drain and the gate of M1 to apply a stable bias voltage (M3).

Buffer

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

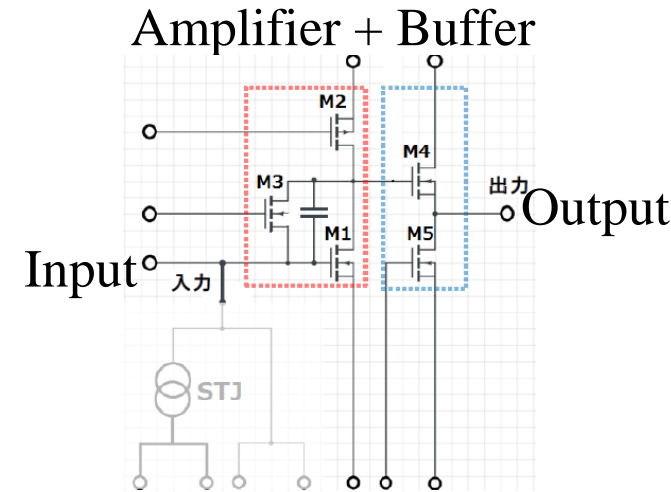
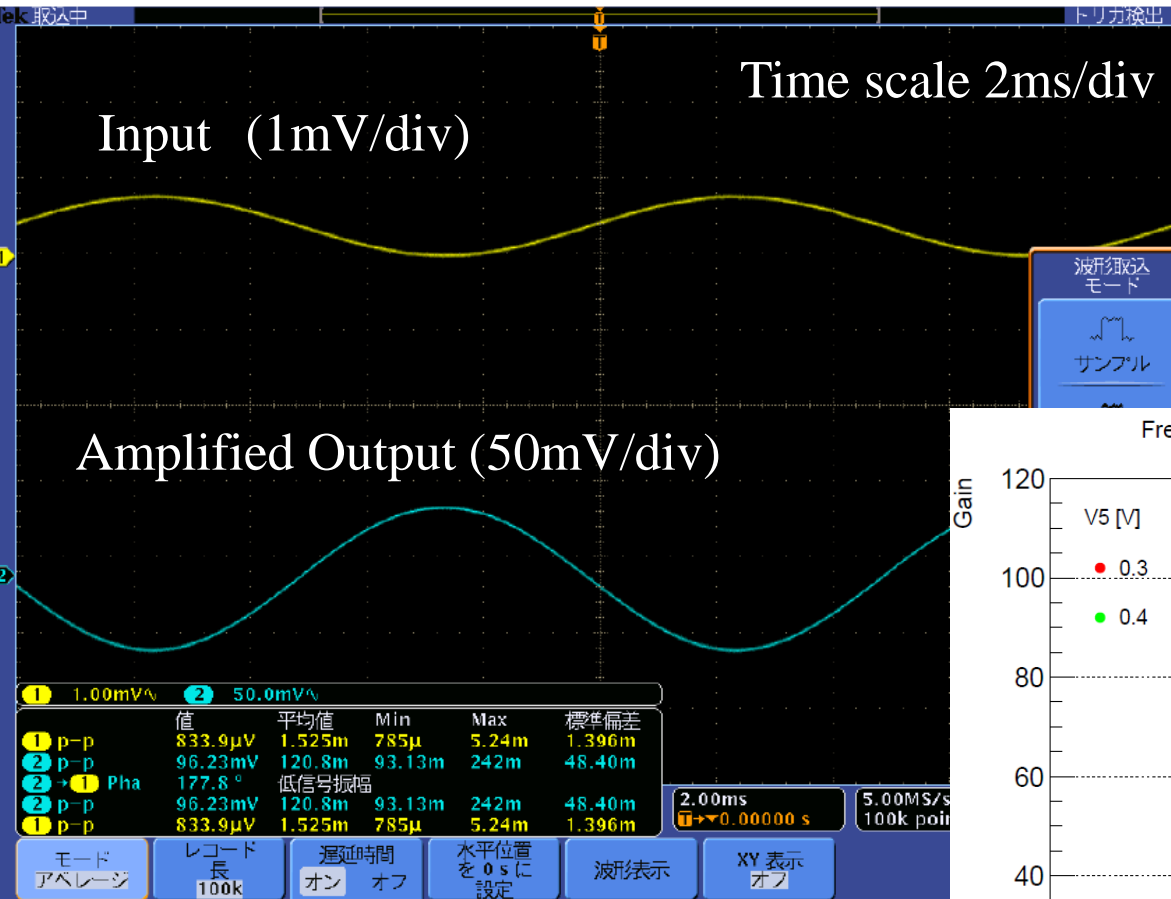
Designed the ratio (W/L) to set the operation power consumption below 120 μ W.

This SOI amplifier board was made by LAPIS semiconductor company.

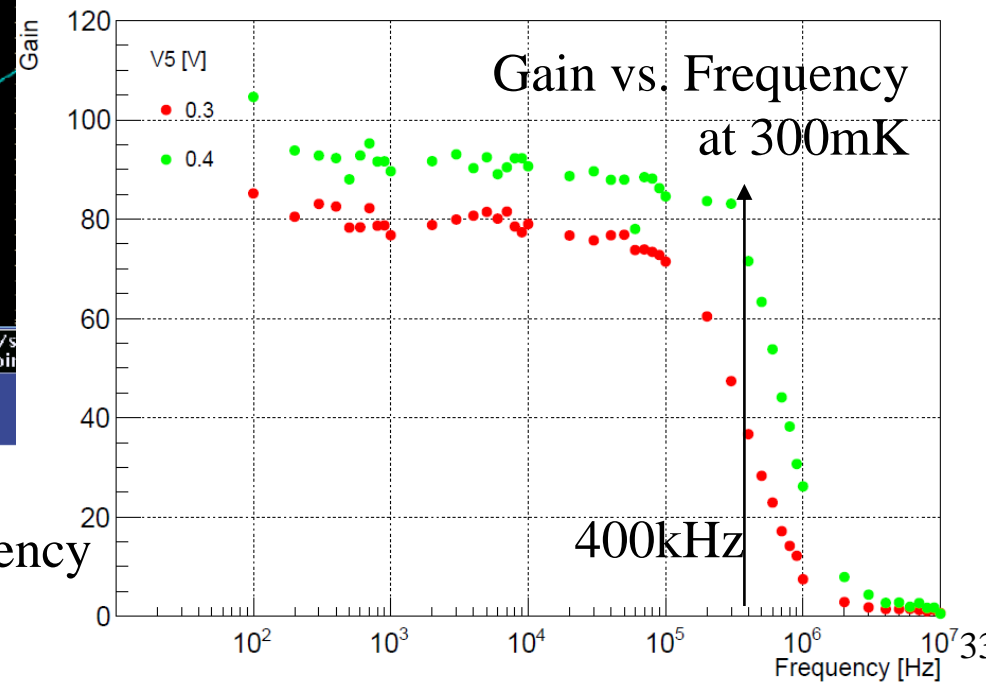


Test Results of the SOI Cryogenic Amplifier

Input and Amplified Output

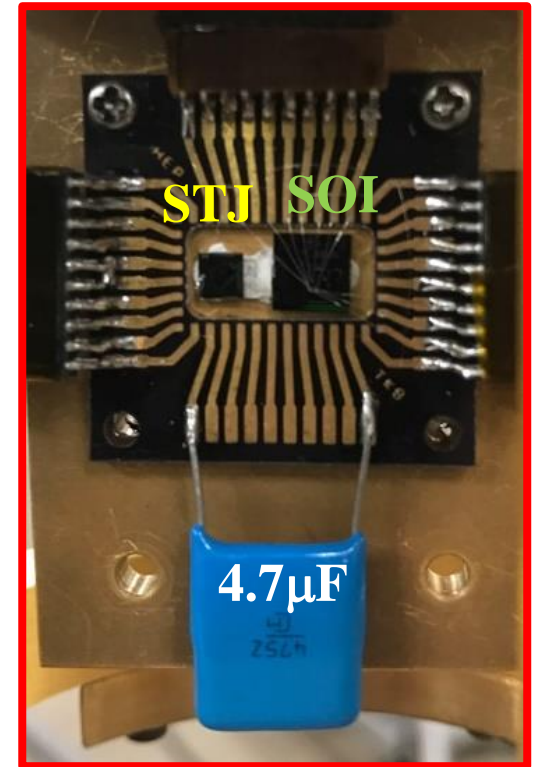
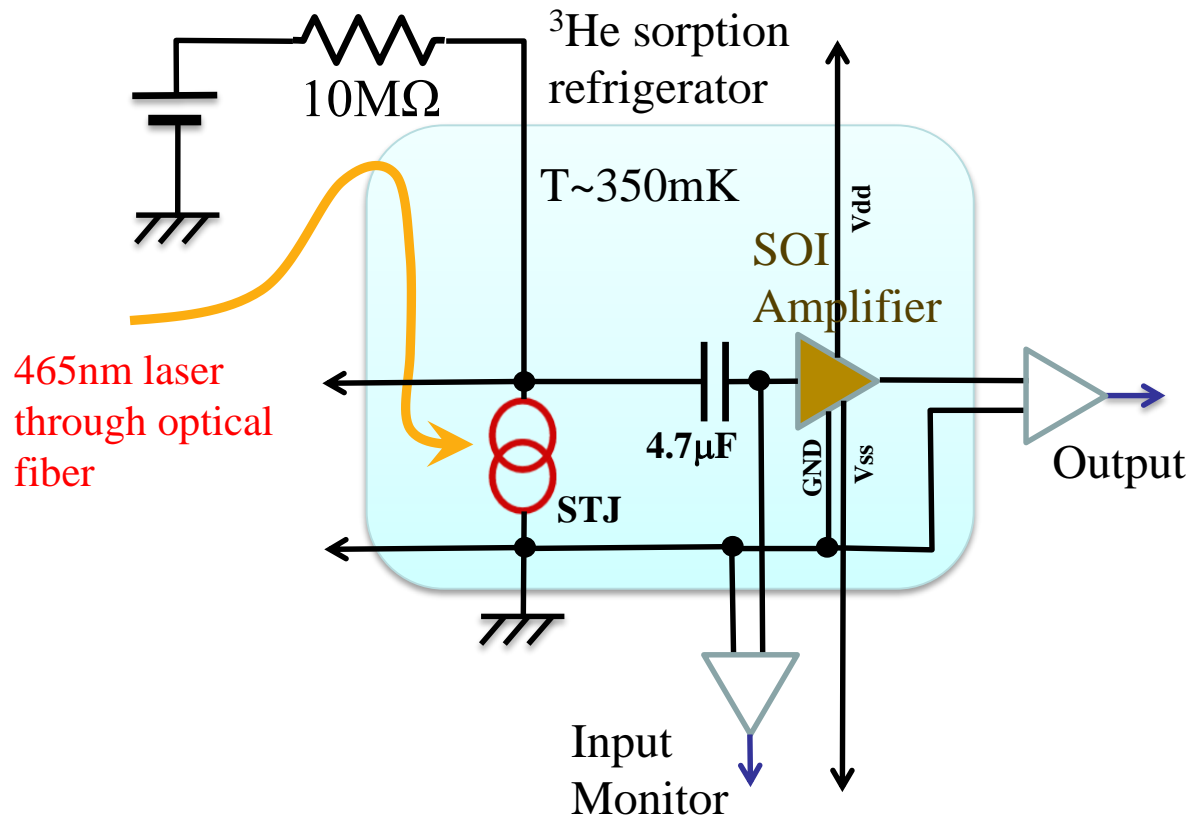


Frequency characteristic of cold amplifier(SOISTJ4) at 300mK



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

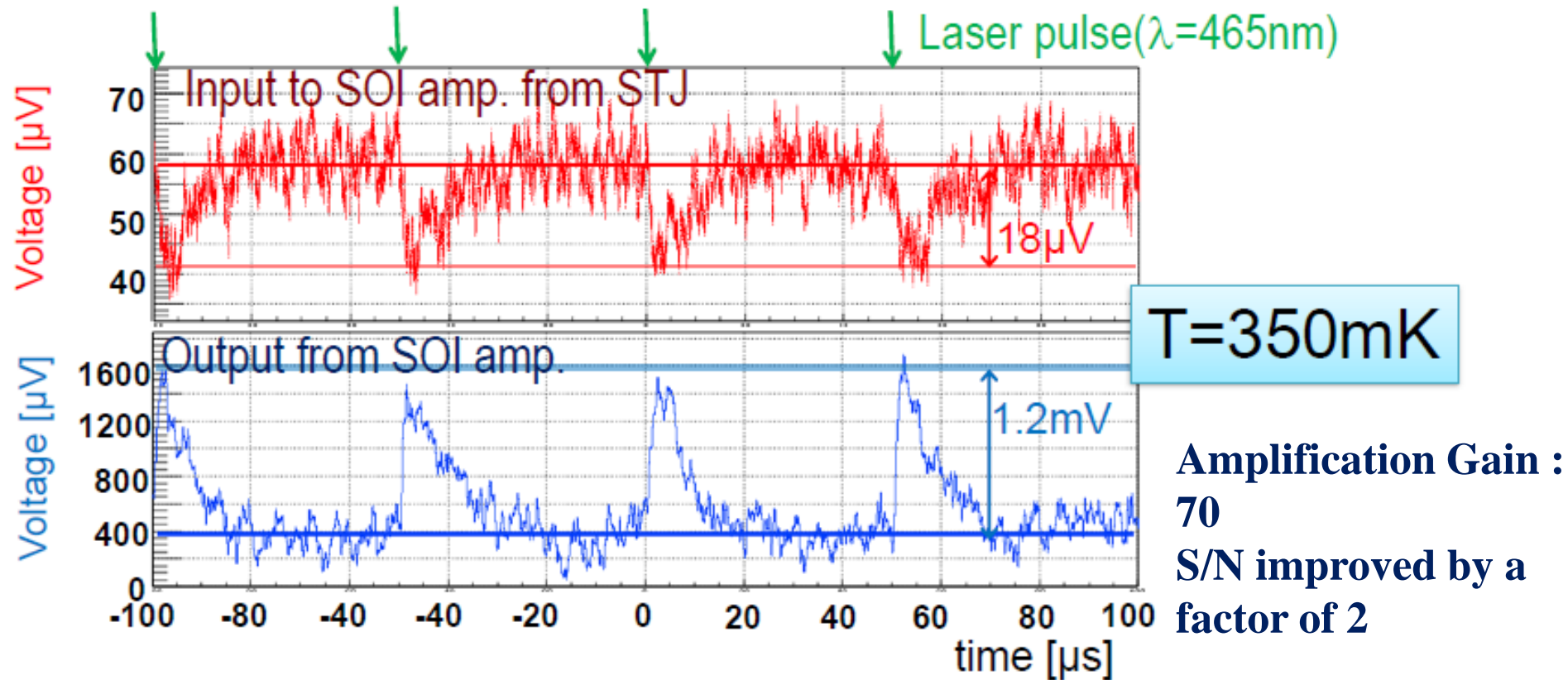
Setup of STJ Signal Amplification with the SOI Cryogenic Amplifier



- $20\mu\text{m}$ -square Nb/Al-STJ with SOI-STJ4 amplifier through $4.7\mu\text{F}$ capacitance.
- Input impedance of the SOI amplifier is about $20\text{k}\Omega$.
 - **STJ operation at a constant current mode.**
 - STJ bias cable capacitance is around 1nF : $Z=160\Omega$ for $1\mu\text{s}$ 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.



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

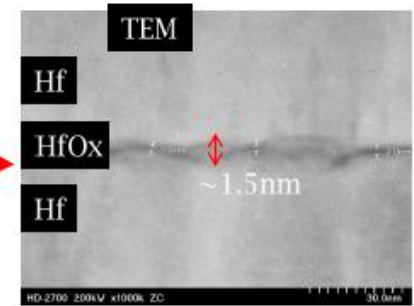
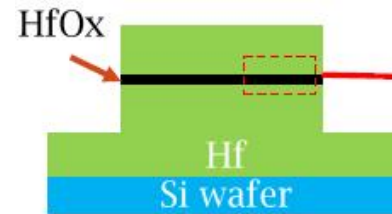
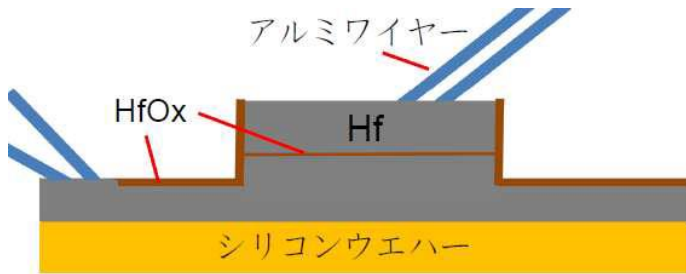
R&D Status of Hf-STJ

R&D Status of Hf-STJ

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

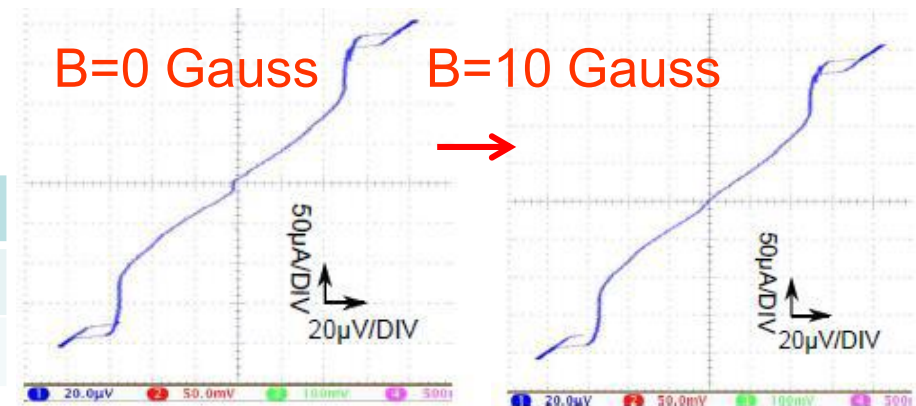
Micro-calorimeter: Hf-STJ can generate enough quasi-particles from cooper pair breakings to achieve 2% energy resolution for photons with $E_\gamma = 25\text{meV}$.

Direct wire bonding on Hf layer



I-V curve of Hf-STJ ($100 \times 100 \mu\text{m}^2$)

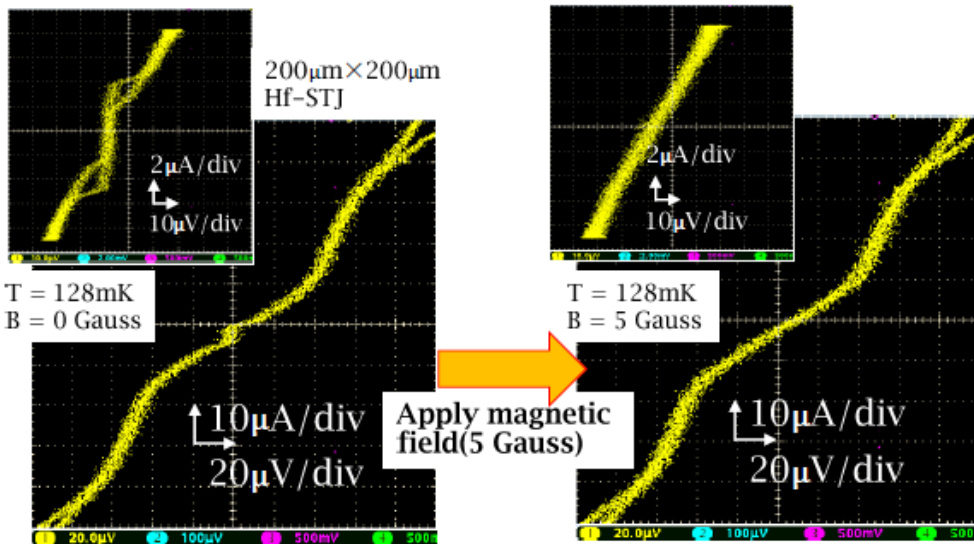
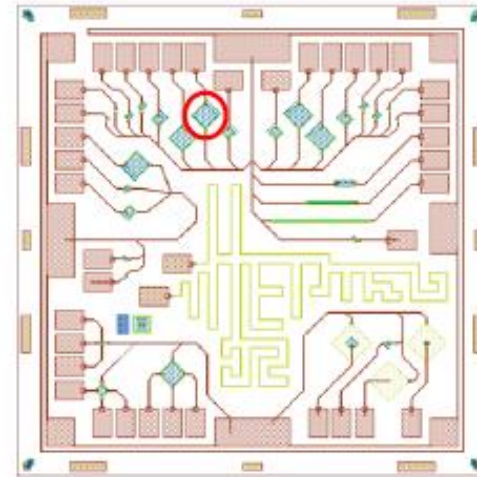
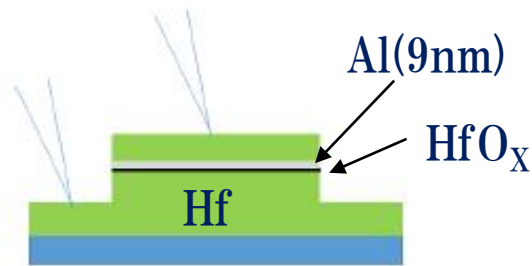
- $T \sim 40\text{mK}$, $I_c = 10 \mu\text{A}$, $R_d = 0.6 \Omega$



STJ size	# of samples	R_d
$200 \times 200 \mu\text{m}^2$	3	$0.22 \pm 0.01 \Omega$
$100 \times 100 \mu\text{m}^2$	3	$0.60 \pm 0.10 \Omega$

Latest Results of Hf-STJ R&D

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



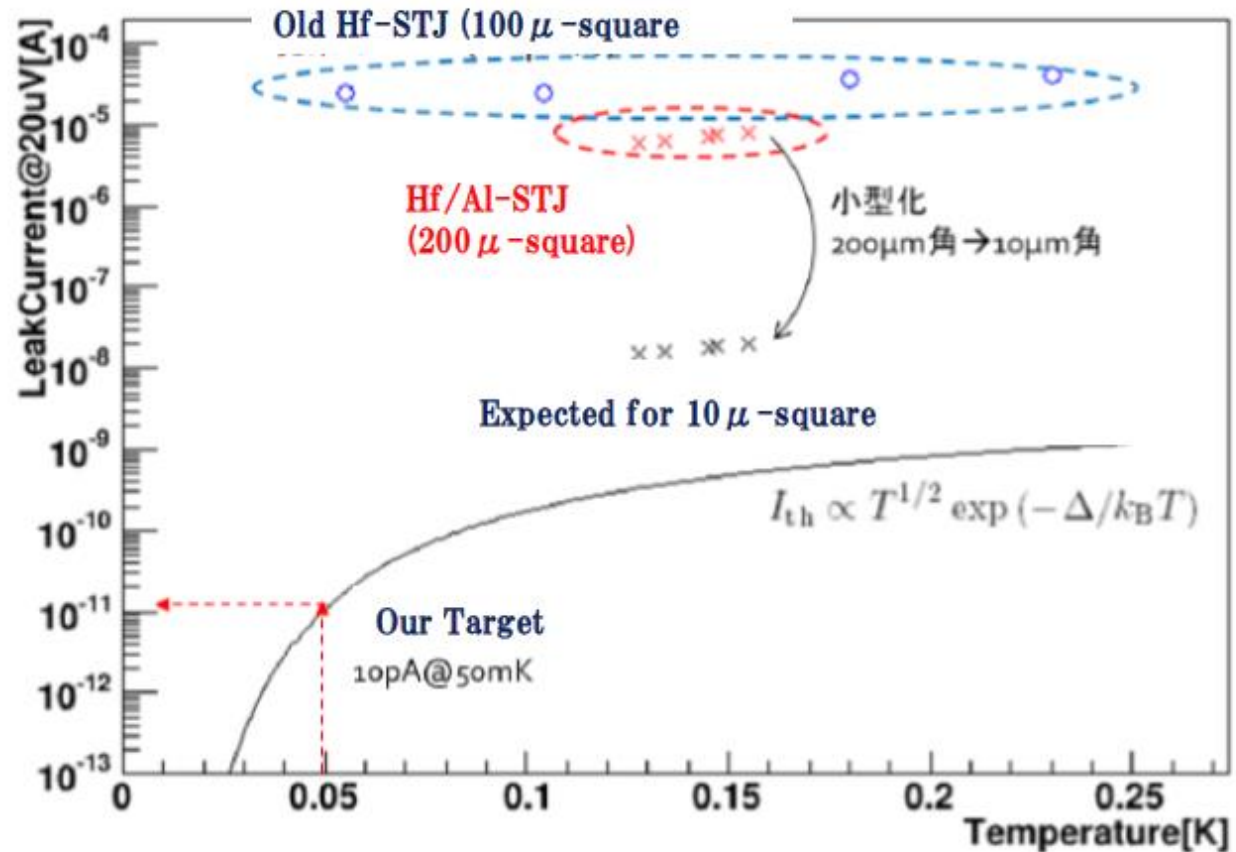
$$I_{\text{leak}} = 5 \mu\text{A at } 10 \mu\text{V.}$$

$$R_d = 2 \Omega$$

Dynamic Resistance was improved by a factor of 15 in Hf/Al/HfO_x/Hf-STJ.

Leakage Current of Hf-STJ

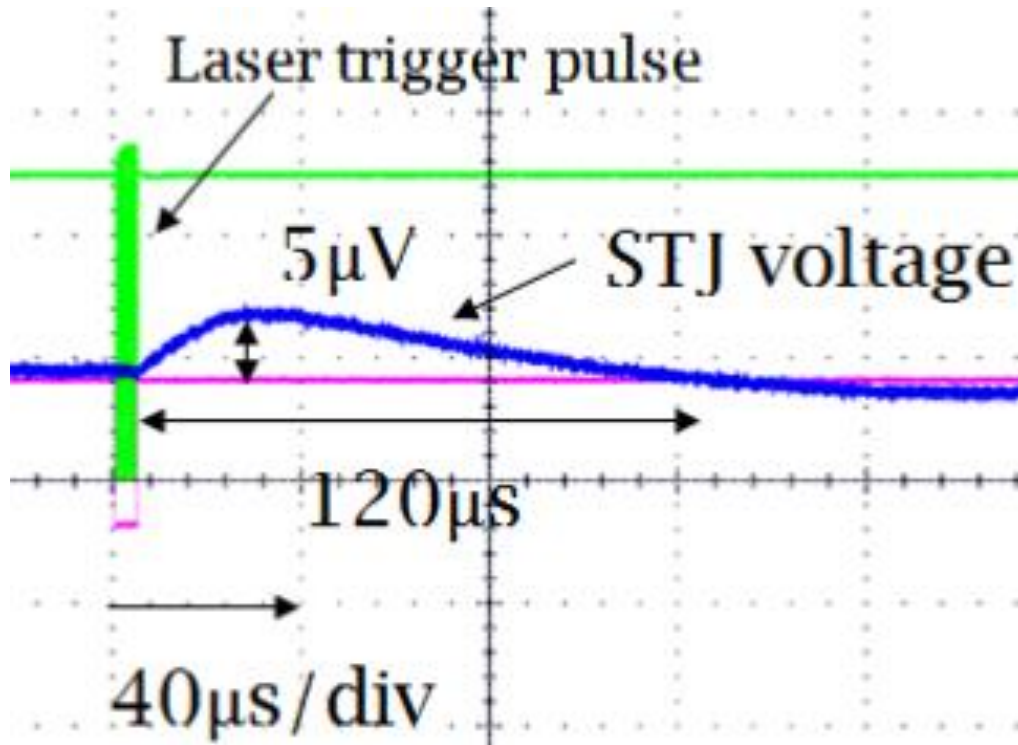
- Hf/Al/HfO_x/Hf-STJ reduced the leakage current to one-fourth.
- By making the size smaller, we will be able to decrease the leakage current by a factor of 1/400.
- By decreasing the operation temperature, we will be able to decrease the leakage current significantly.



Response of Hf-STJ to Laser Pulse Light

Hf/Al/HfO_x/Hf-STJ

Visible light laser ($\lambda = 465\text{nm}$) 10Hz duration



Response speed ($120\mu\text{s}$) is slower than Nb/Al-STJ response speed (around a few μs).

Schedule

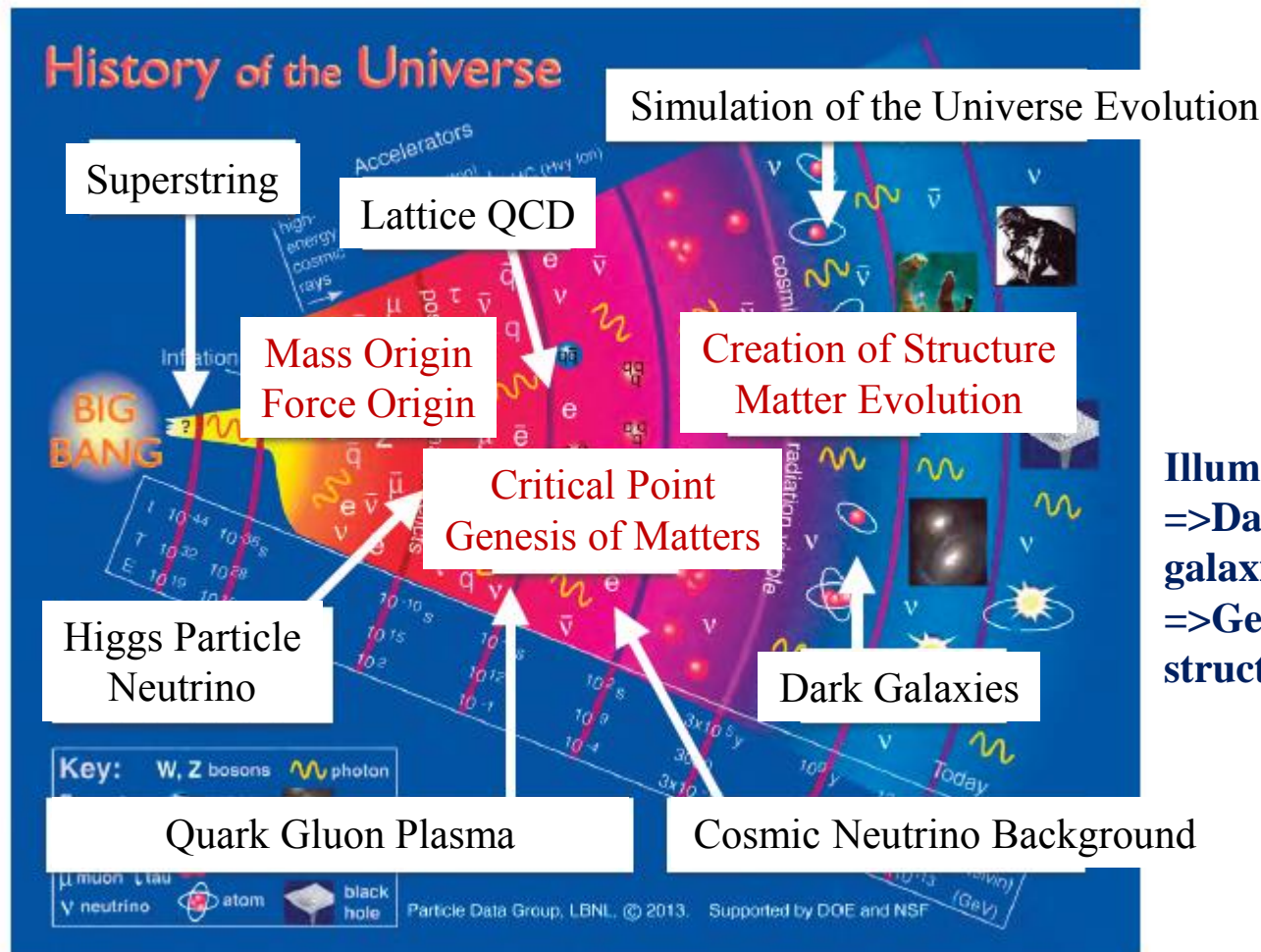
	2016	2017	2018	2019	2020	2021
Experiment Design	Experiment design with Satellite such as SPICA					
	Experiment design with FIR Rocket					
Superconducting Tunnel Junction (STJ) Detector	R&D of Nb/Al-STJ		Production			
	Design and R&D of Hf-STJ Detector				(for Satellite Experiment)	
Preamplifier at 1K and Post-Preamp (Fermilab, JAXA, KEK, AIST, Tsukuba)	Design and R&D		Production		Design, R&D, Production	
Dispersive Element, Optics	Design and R&D		Production		Design, R&D, Production	
Cryostat	Design and R&D		Production		Design, R&D, Production	
Measurements + Analysis		Analysis Program				
	Simulation				Analysis	

Far-Infrared Observatory Rocket Experiment

Research Core for the History of the Universe

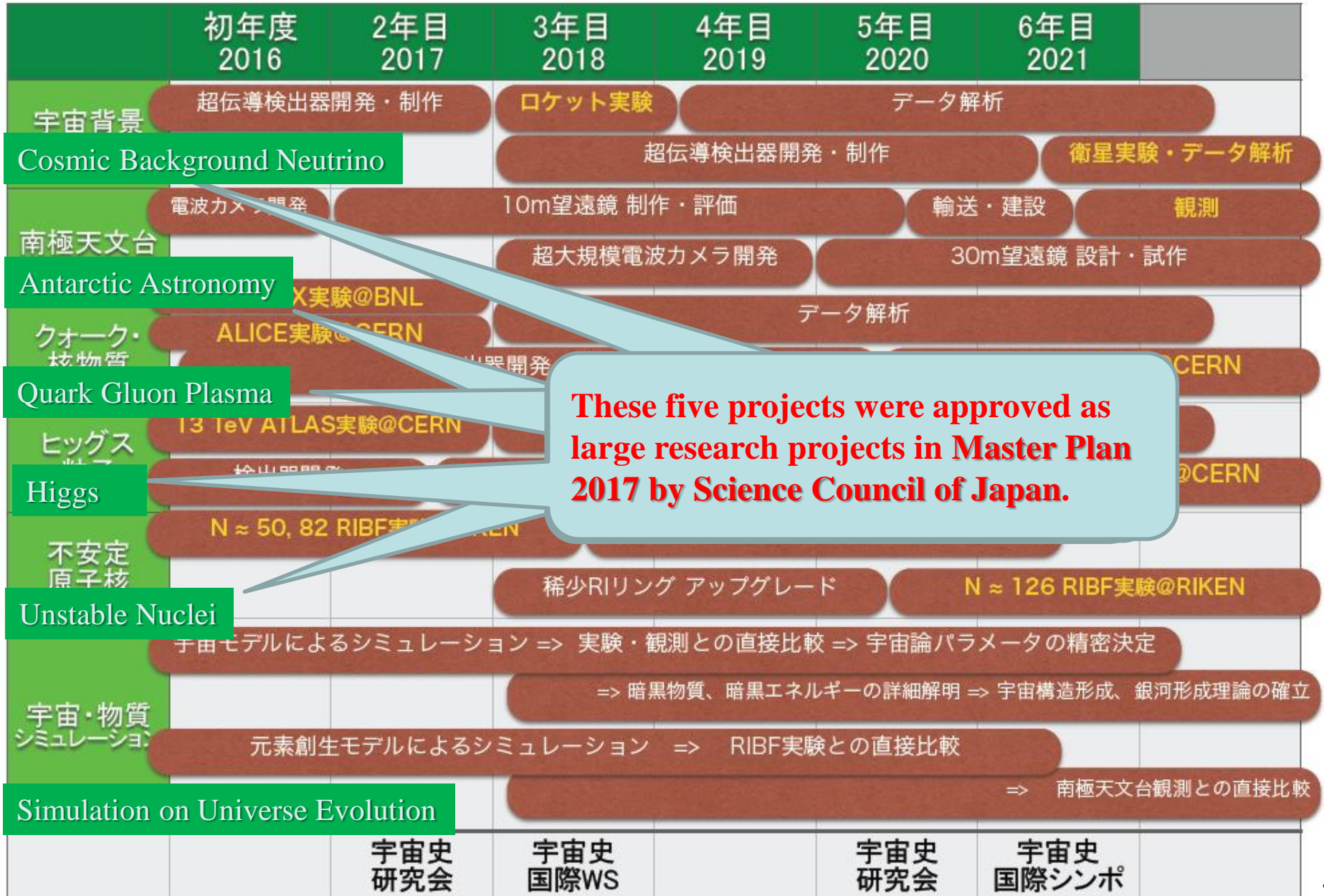
under Center for integrated Research in Fundamental Science and Engineering,
University of Tsukuba (founded on Sep. 1, 2014)

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 Research Core for the History of the Universe



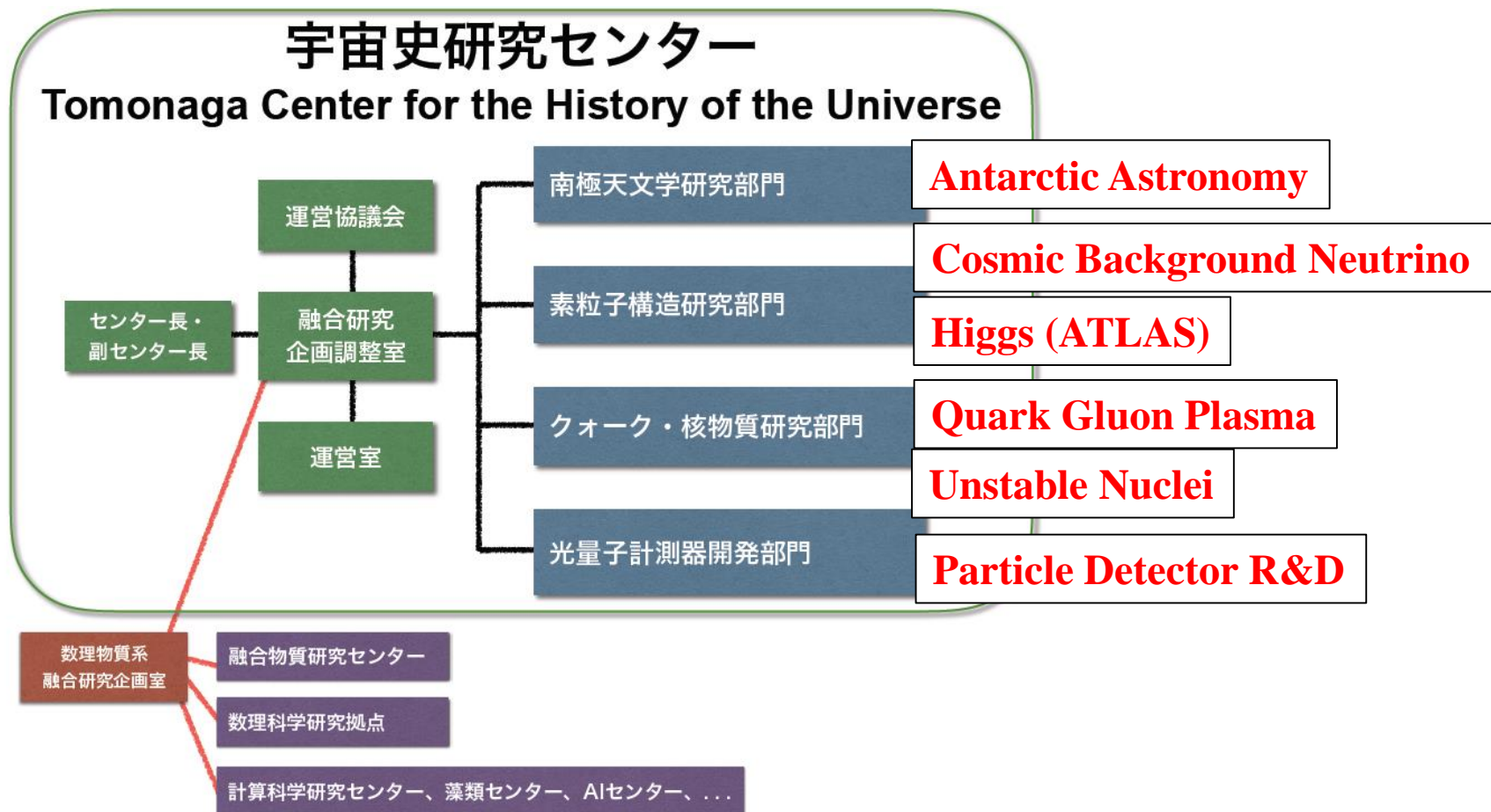
Research Core for the History of the Universe

Tomonaga Center for the History of the Universe



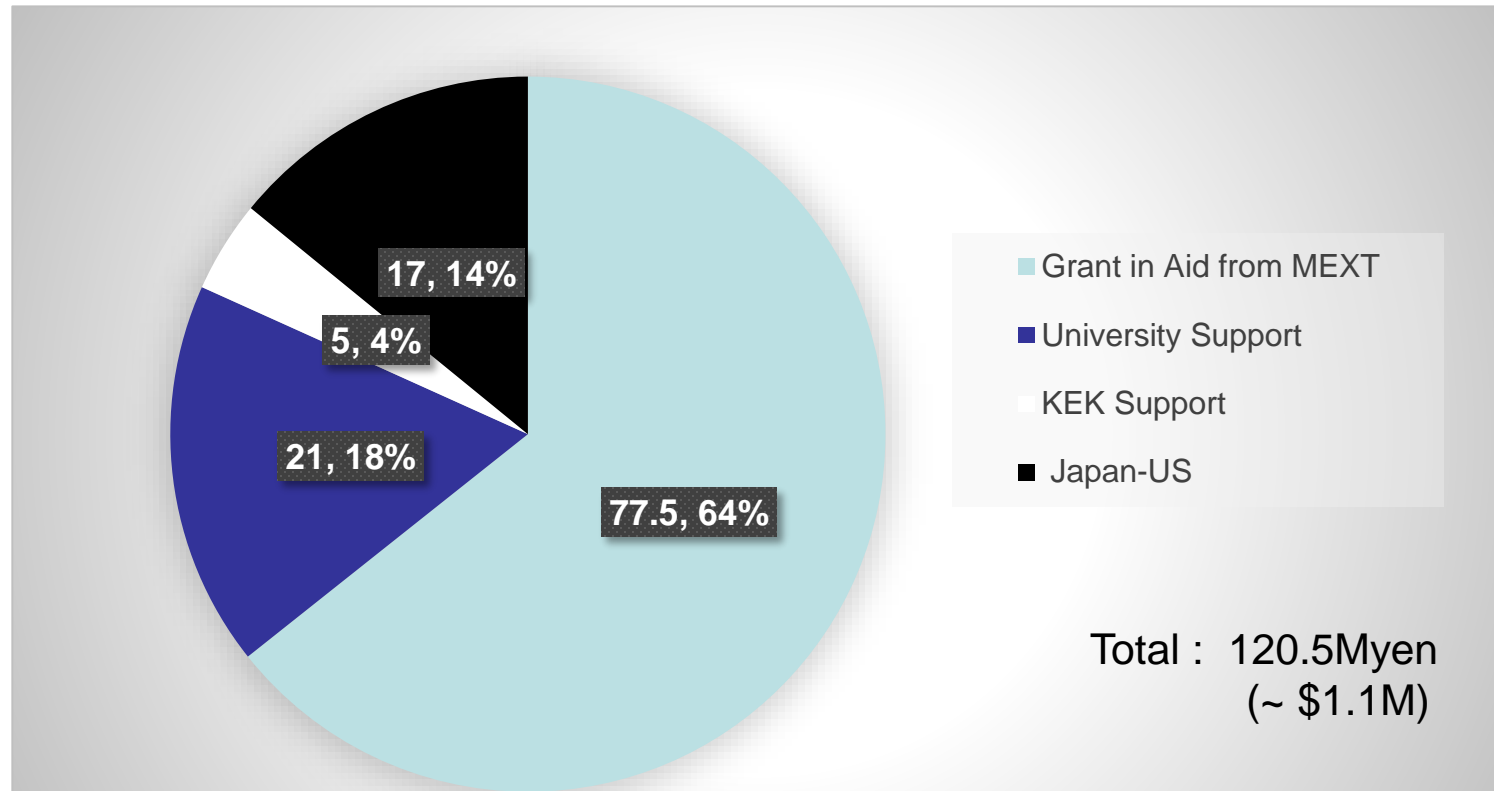
Re-Organization

From Oct. 2017



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, 2016	21.0 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.
 - Determination of the neutrino mass
 - origin of elementary particle mass spectra
 - Discovery of the cosmic background neutrino
 - new probe of the very early universe
- New far-infrared photon detector is being developed:
 - Nb/Al-STJ satisfied our requirement for leakage current less than 0.1pA
 - Cryogenic amplifier with the SOI technology worked at 300mK
We have succeeded in amplifying the STJ signal with the SOI cryogenic amplifier.
 - Aiming at one photon detection in the far-infrared range
 - applicable to the other fields such as X-ray energy measurement with higher energy resolution.

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

People who will join COBAND collaboration are very welcome.

Please join us.

BACKUP

Cosmic Background Neutrino

Fermi and Bose Distribution Function

$$F(E) = \frac{1}{e^{(E-\mu)/kT} \pm 1}$$

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

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

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

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

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

Temperature:

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

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

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

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

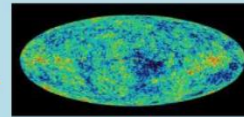
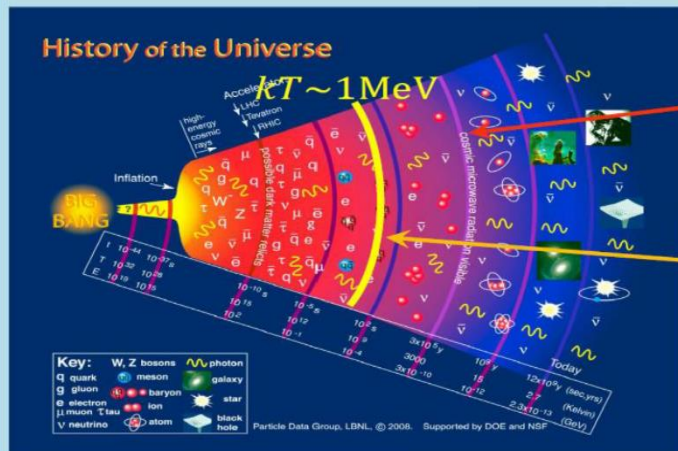
The present entropies of photons and neutrinos, $s_{\gamma 0}$ and $s_{\nu 0}$ are given by

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

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

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

Cosmic Background Neutrino



CMB

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

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

CvB

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

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

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

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



Temperature:

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

Number density:

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

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

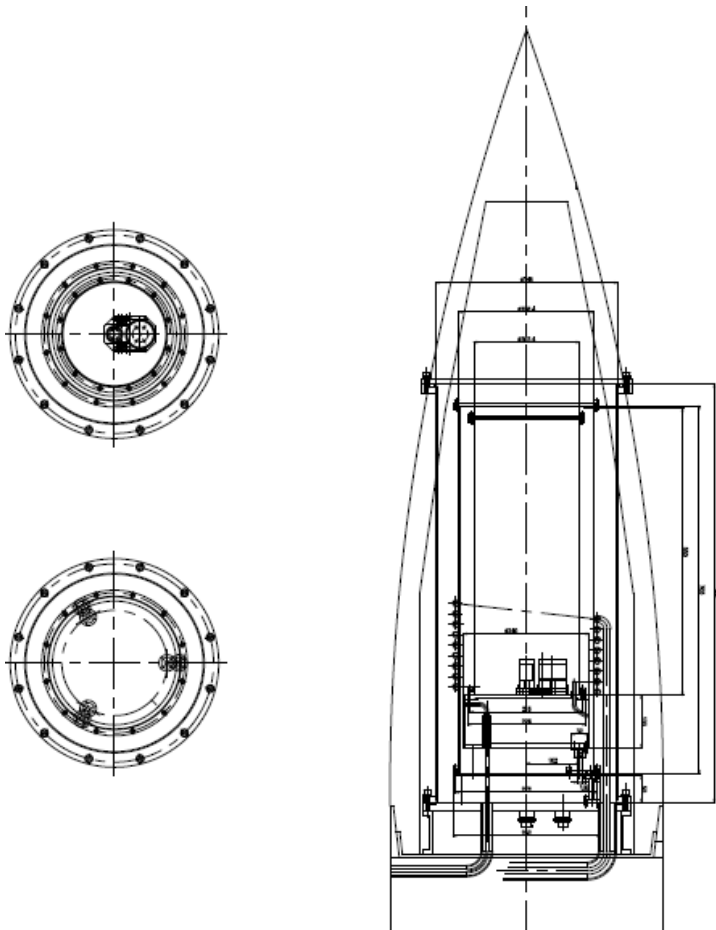
$$\rightarrow n_\nu = \frac{3}{4} \left(\frac{T_\nu}{T_\gamma} \right)^3 \frac{n_\gamma}{2}$$

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

Prototype of Cryostat for the Rocket Experiment

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

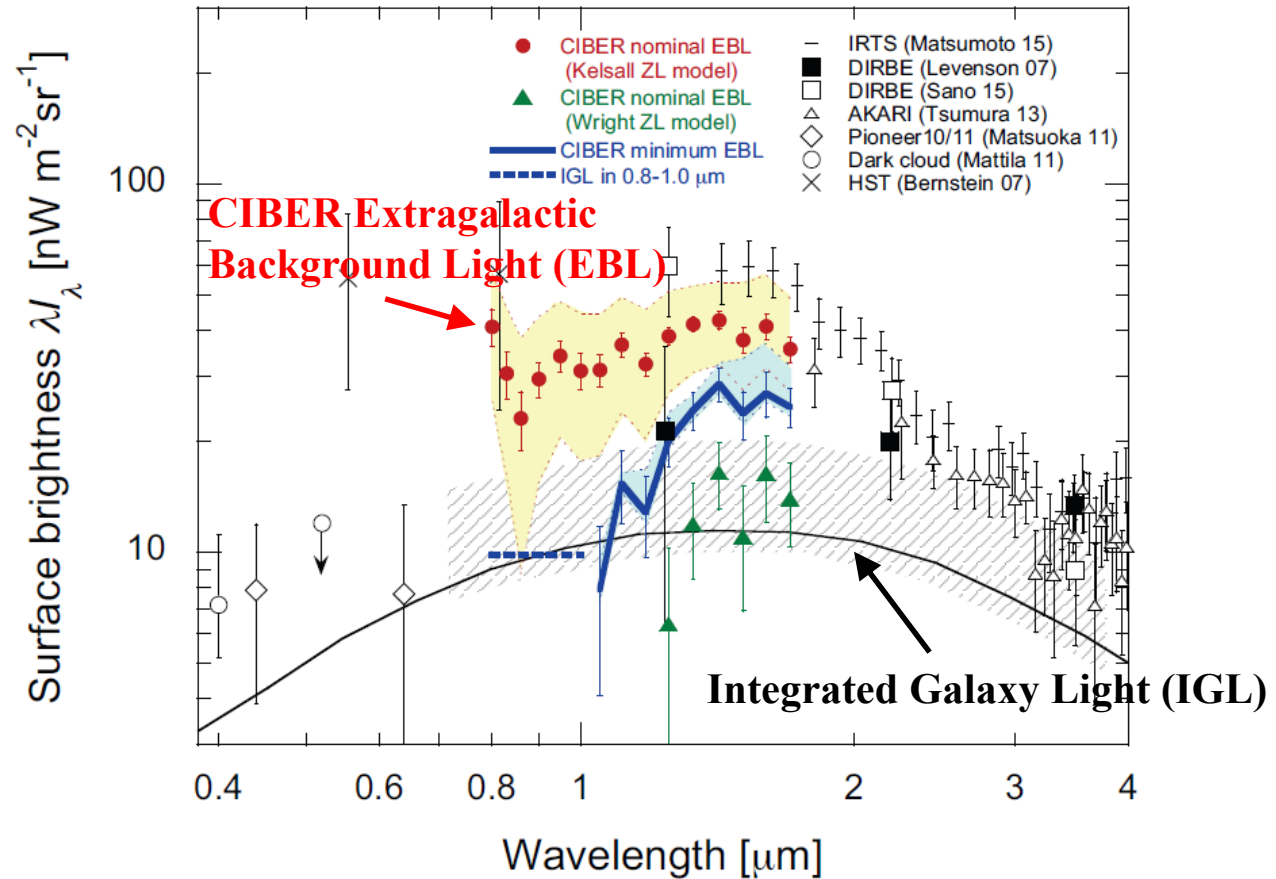
We will test Nb/Al-STJ inside of this cryostat with far-infrared(50μ) photon beam at Fukui this winter.



Made by Jeck Tohri company.

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 .

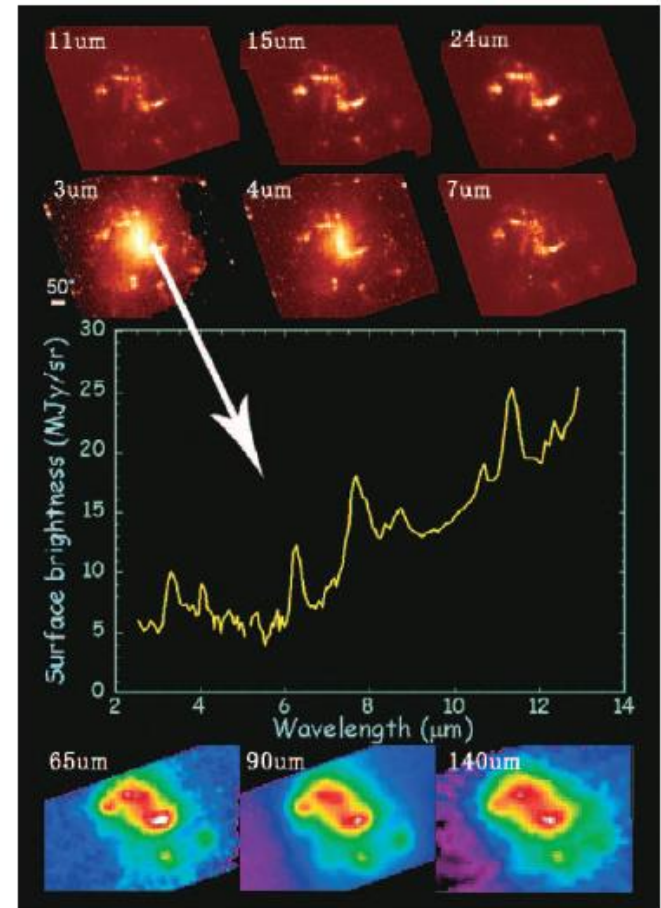
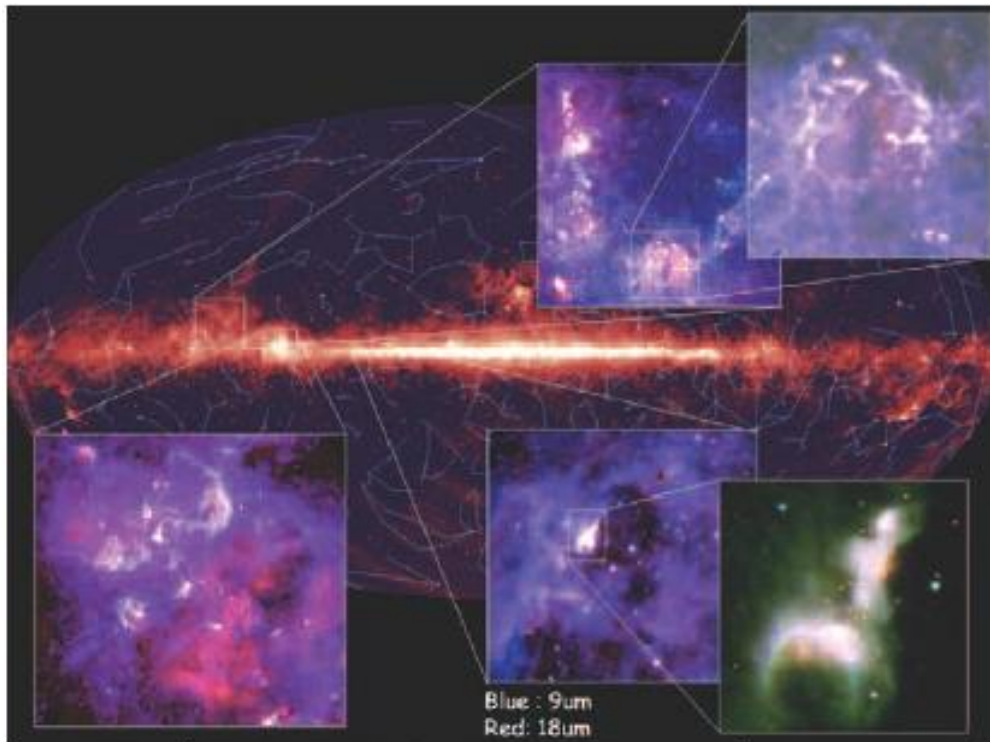
CIBER collaboration plans to do CIBER-2 rocket experiment which has 10 times larger sensitivity.

Astrophysics with NIR and FIR by AKARI



- NIR and FIR from interstellar gas \rightarrow 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

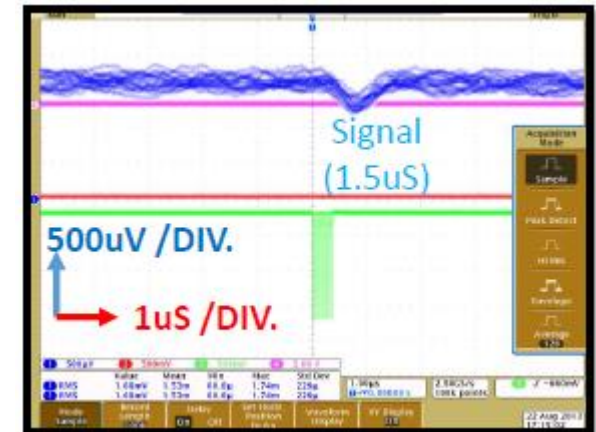
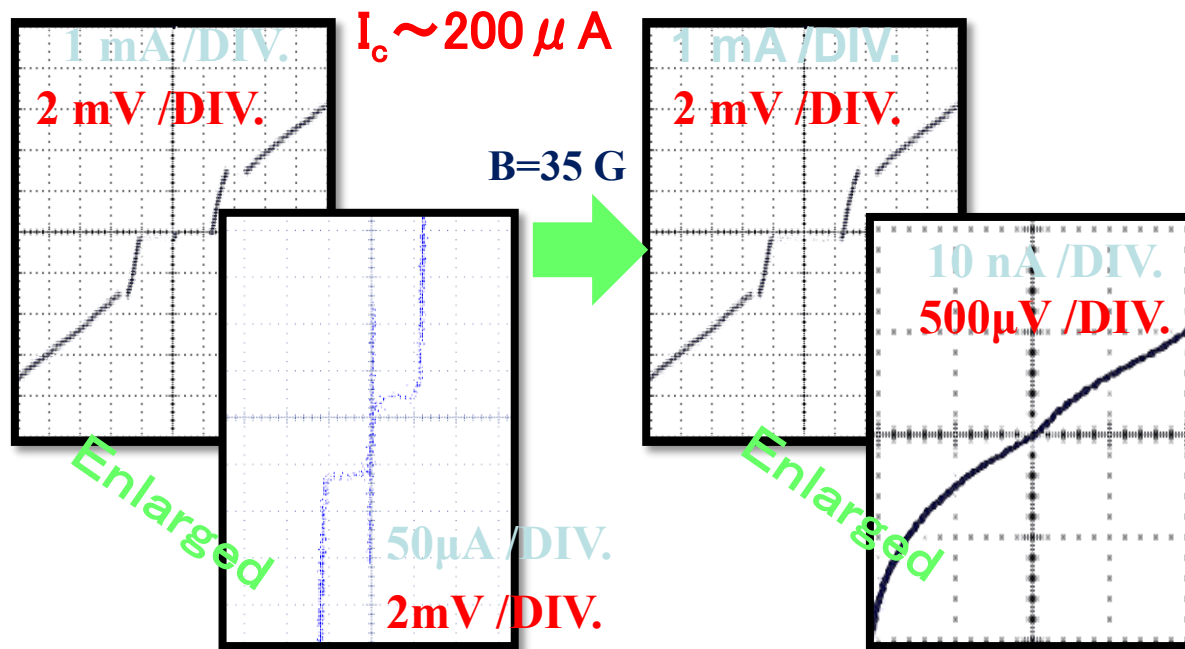
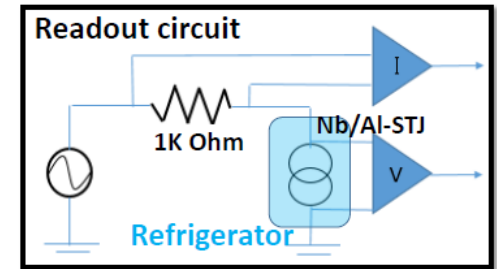


Molecular cloud IR in the arm of NGC1313 measured by AKARI

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

We measured the I-V curve of the Nb/Al-STJ ($50 \times 50 \mu\text{m}^2$ junction) processed on the SOI wafer at **700mK** with a dilution refrigerator.

□ I-V curve of Josephson Junction



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

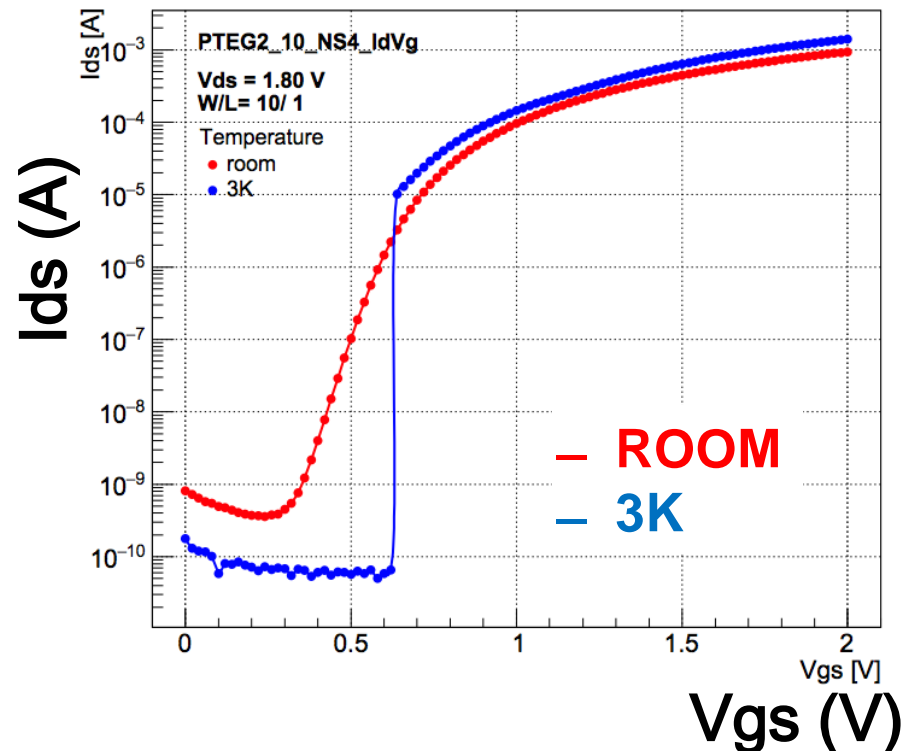
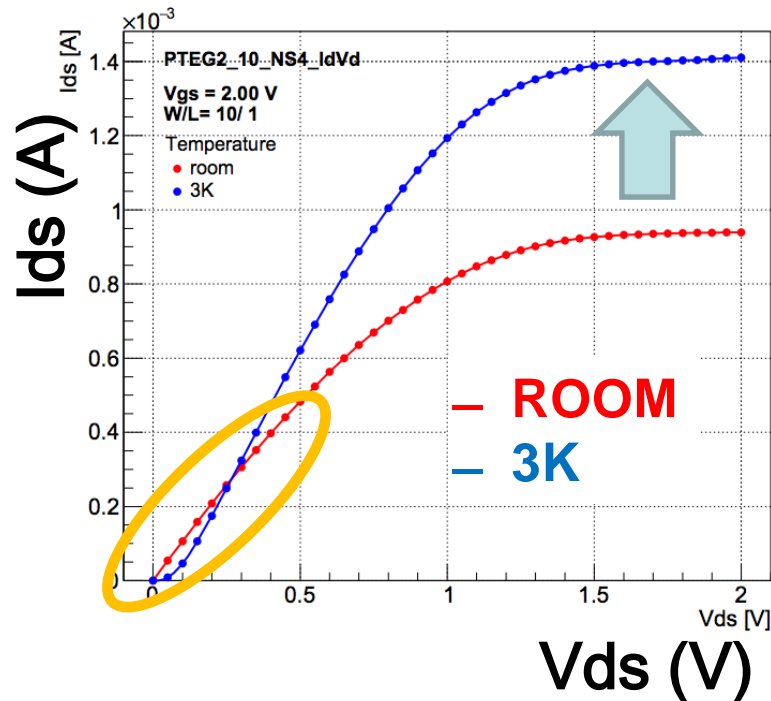
Performance of SOIFET at Cryogenic Temperature

Saturating current is higher as the temperature becomes lower.

Non-linearity was found at cryogenic temperature near threshold region. This problem was solved by improving LDD(Lightly Doped Drain).

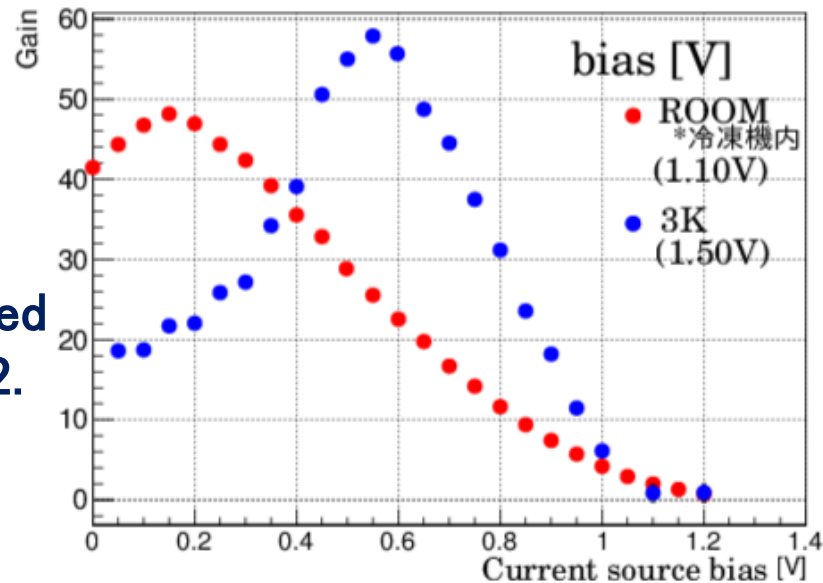
At cryogenic temperature (3K),

- Threshold rise in I_{ds} - V_{ds} curve become much sharper.
- Subthreshold current is suppressed.

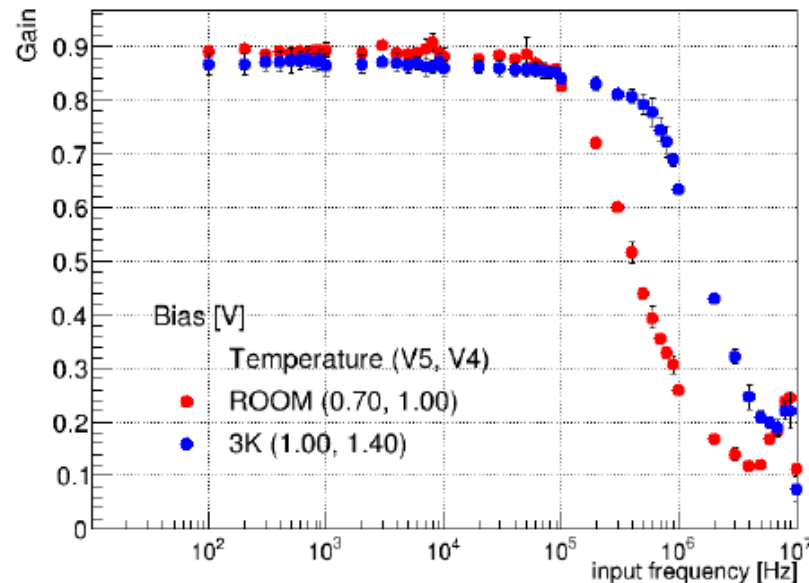


Test Results of the cryogenic SOI preamplifier

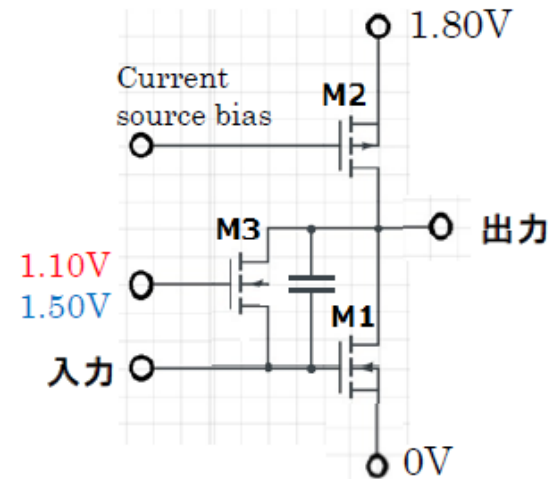
Amplifier gains are around 50 both at room temperature and 3K with adjusted bias voltages of M2.



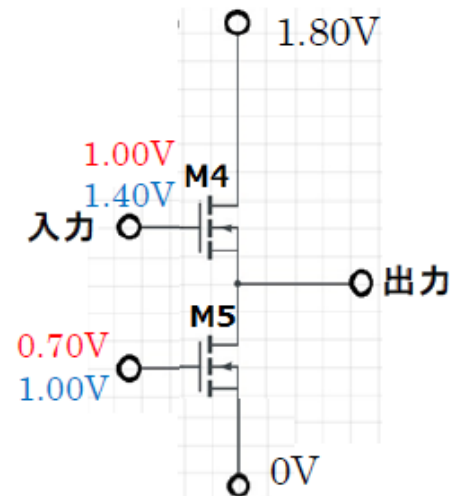
Bandwidth of buffer is enough high for the amplifier of STJ signal (up to 200kHz) both at room temperature and 3K.



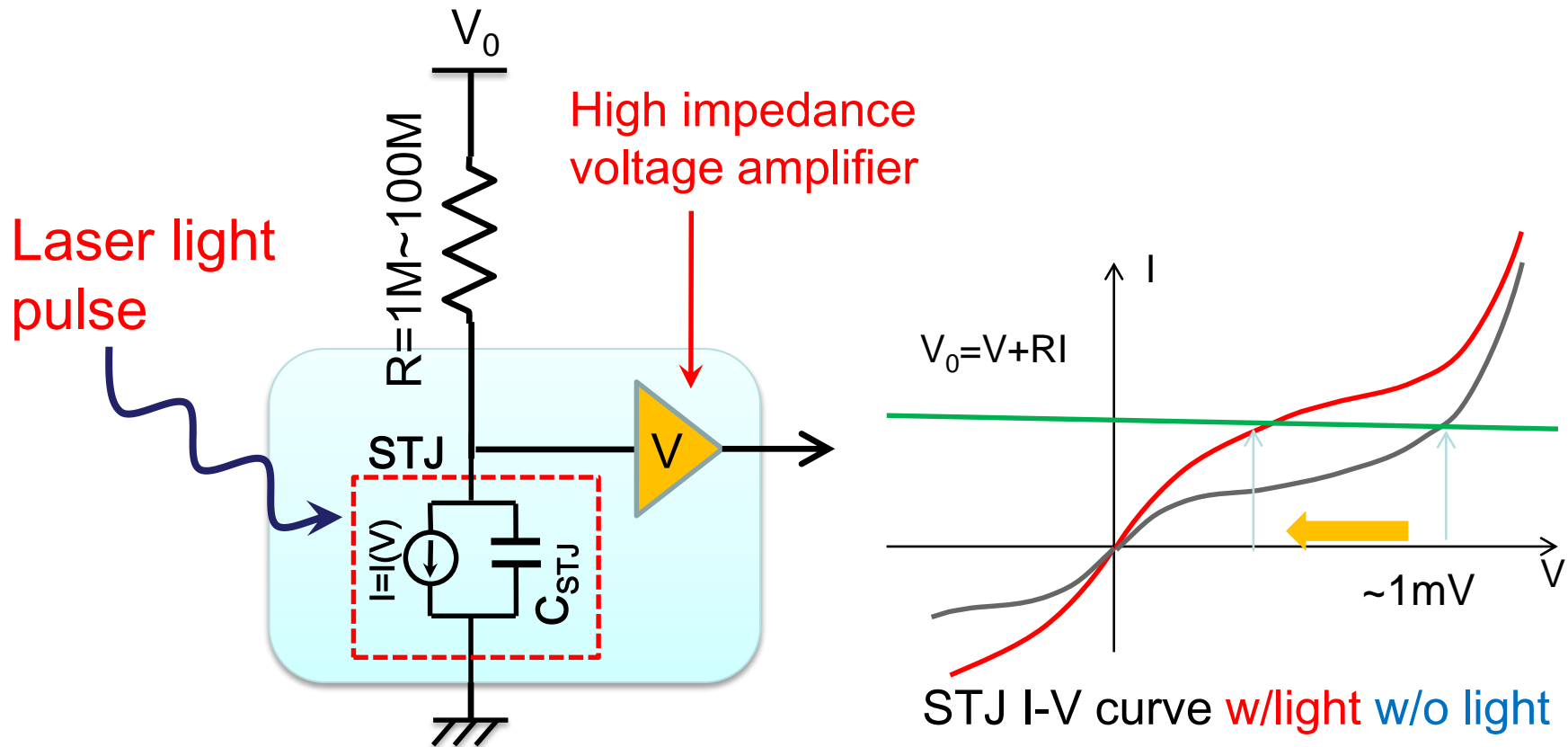
Amplifier



Buffer



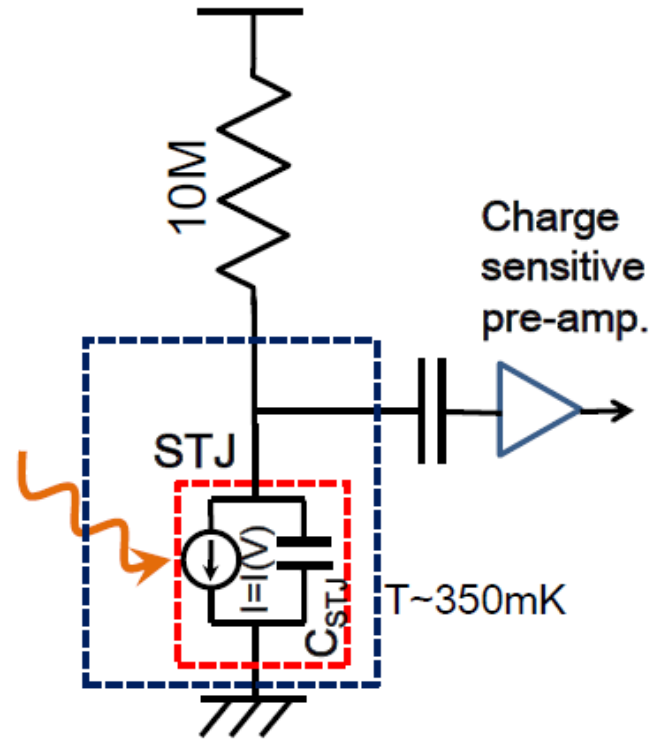
STJ response at a constant current mode



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

Development of SOI Charge sensitive preamplifier (SOISTJ5)

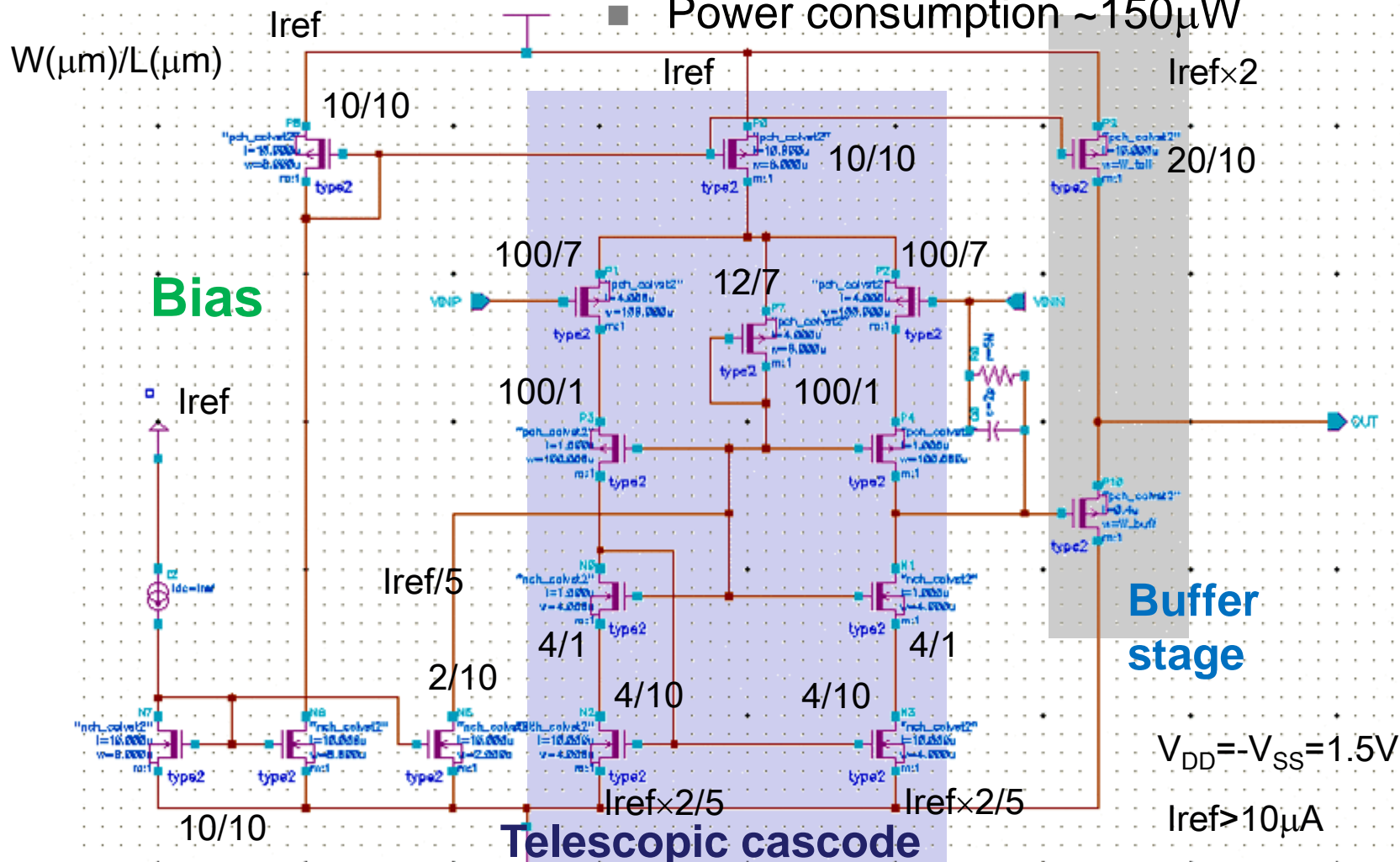
- STJ capacitance is not so small (20pF for 20 μ m square STJ).
- STJ response speed is a few μ sec.
- STJ operation at a constant voltage mode is favorable.
 - Low input impedance charge amplifier operational for 1MHz.



Op-amp Circuit for STJ (SOI-STJ5 design)

This cryogenic charge amplifier test is now underway.

- telescopic cascode differential amplifier
- Feedback $C=2\text{pF}$ x $R=5\text{M}\Omega = 10\mu\text{s}$
- Power consumption $\sim 150\mu\text{W}$



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

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

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

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.