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Neutrino Decay Search

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- **Introduction**
  - Motivation
  - Proposal on Search for Cosmic Background Neutrino Decay
  - Rocket experiment

- **R&D of Superconducting Tunnel Junction (STJ) Detector**
  - Results of R&D in JFY2014
  - Future Plan

Neutrino Decay Collaboration

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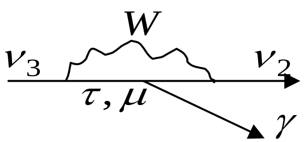
Motivation of Search for Cosmic Background Neutrino Decay

- **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.**



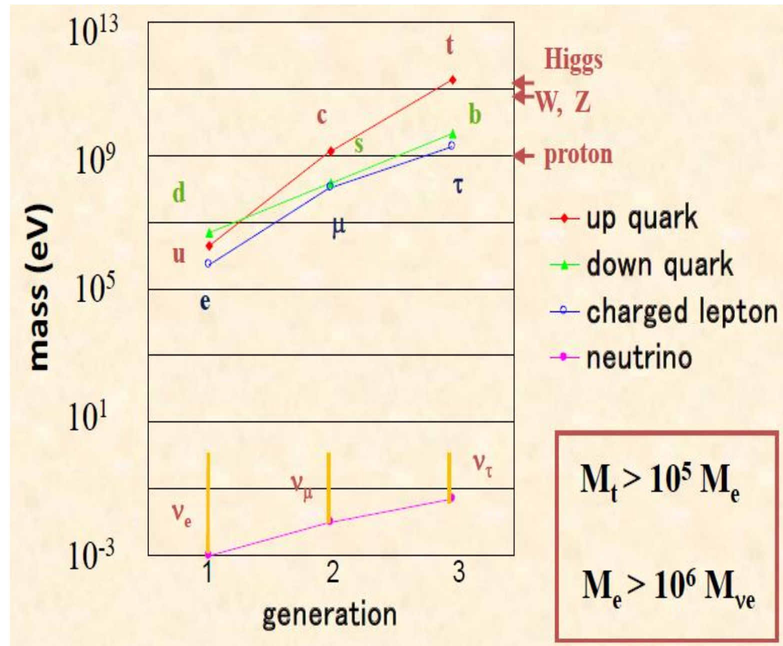
$$\nu_3 \rightarrow \nu_2 + \gamma$$

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

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

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

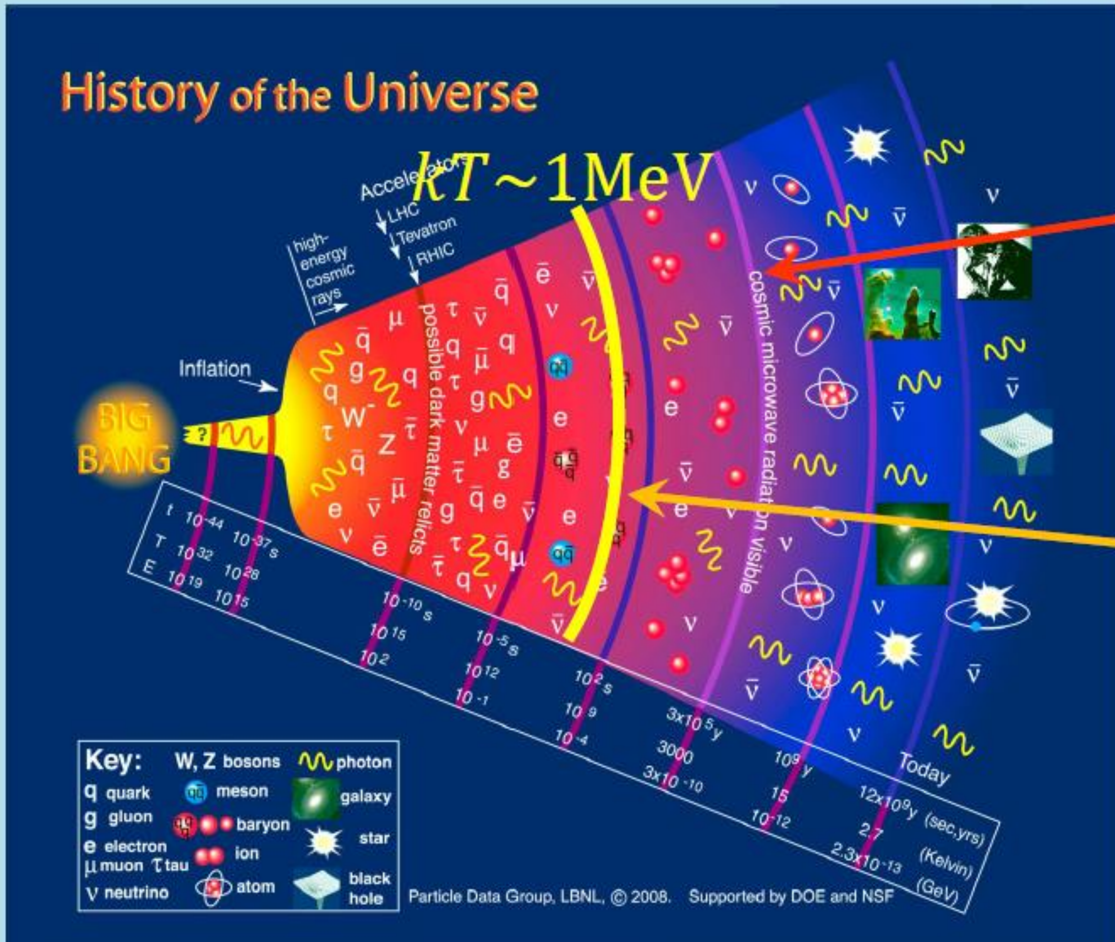
(Far-Infrared region $\lambda = 50 \sim 125\ \mu$)

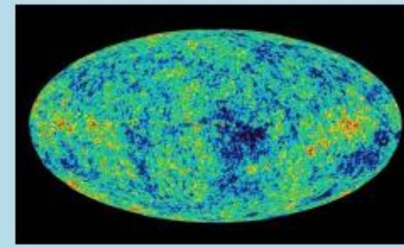


- **As the neutrino lifetime is very long, we need use cosmic background neutrino to observe the neutrino decay. To observe this decay of the cosmic background neutrino means a discovery of the cosmic background neutrino predicted by cosmology.**

- **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 (CνB)





CMB

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

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

CνB

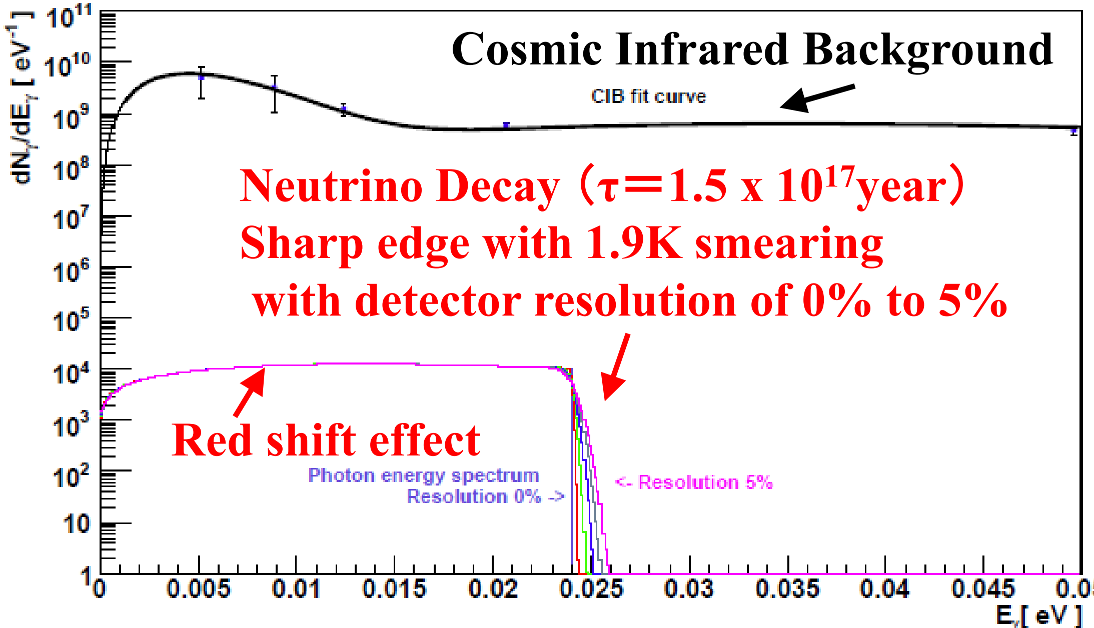
$$n_\nu = n_{\bar{\nu}} = \frac{3}{4}\left(\frac{T_\nu}{T_\gamma}\right)^3 \frac{n_\gamma}{2}$$

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

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

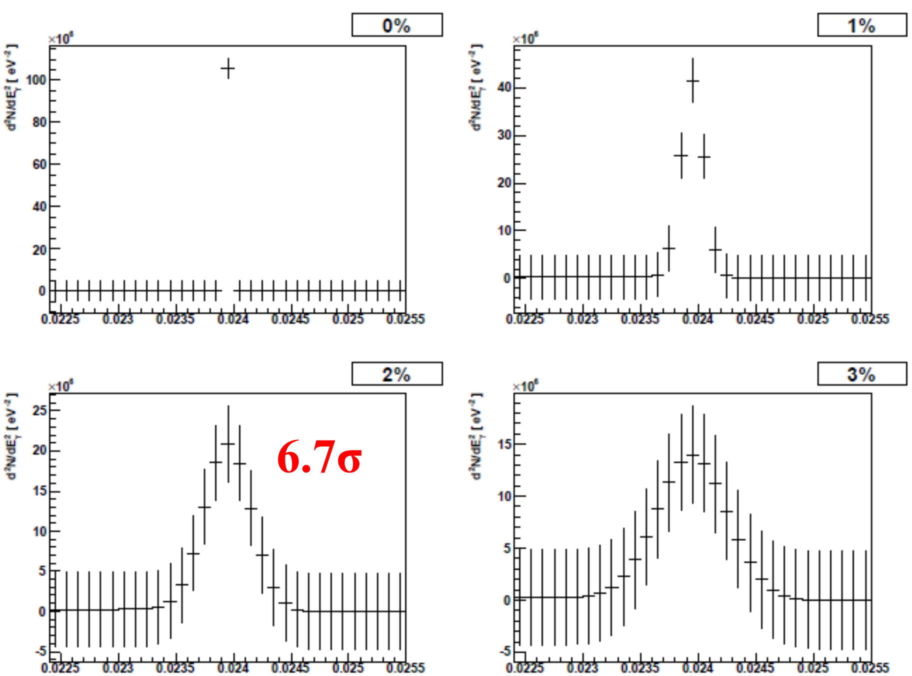
Neutrino Decay Detection Sensitivity

10-hour running with a telescope with 20cm diameter, a viewing angle of 0.1 degrees and 100% detection efficiency (Satellite Experiment)



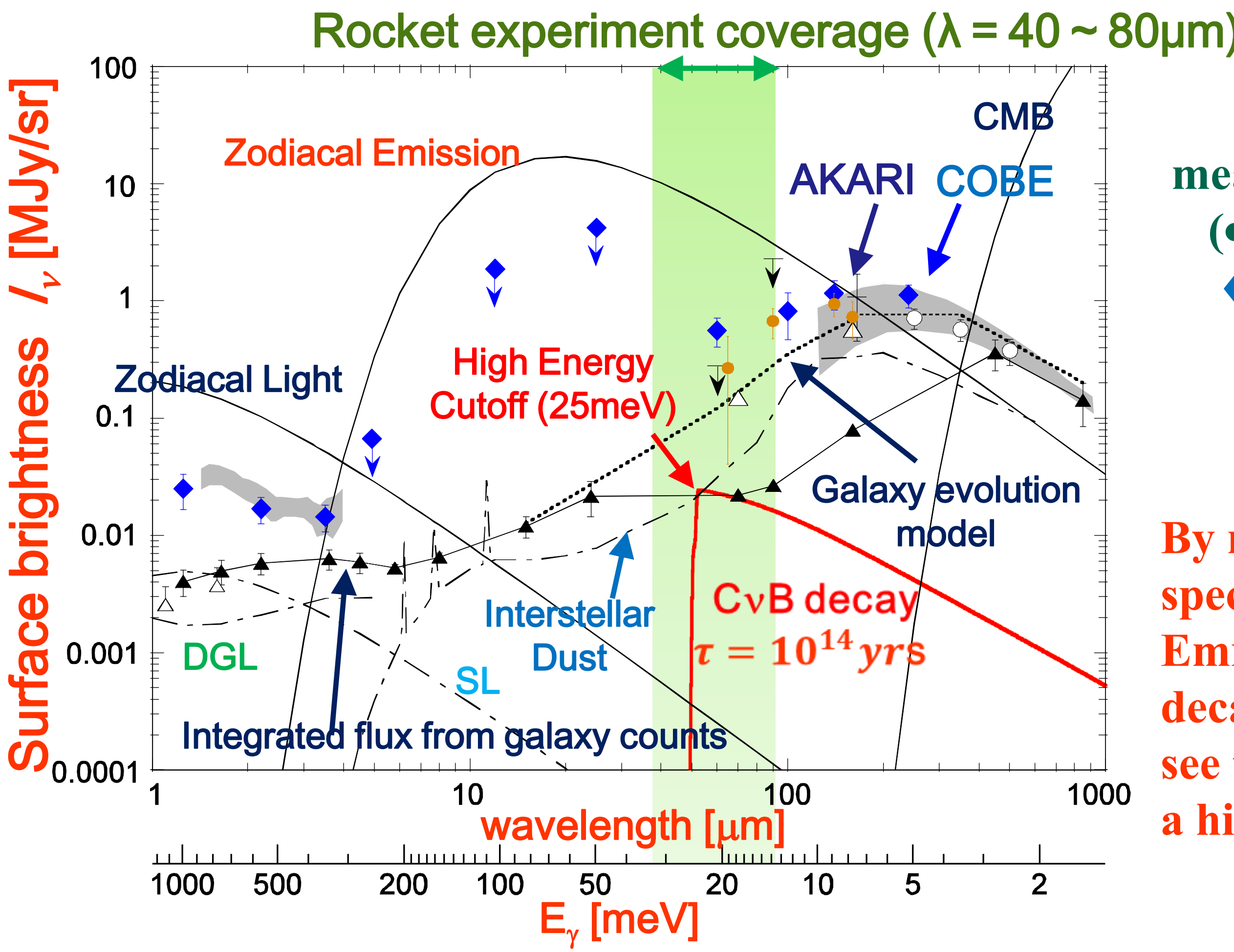
dN/dE_γ

$- d^2N_\gamma/dE_\gamma^2$



- **Need the energy resolution better than 2%.**
- **Can observe the ν_3 decay with a mass of 50meV, and a lifetime of 1.5×10^{17}year at 6.7σ.**

Signal of Cosmic Background Neutrino Decay and its Backgrounds



CIB measurements (● AKARI, ♦ COBE)

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

Requirements for the detector

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

JAXA Rocket Experiment for Neutrino Decay Search

Plan: 5minutes data acquisition at 200 km height in **2018.**

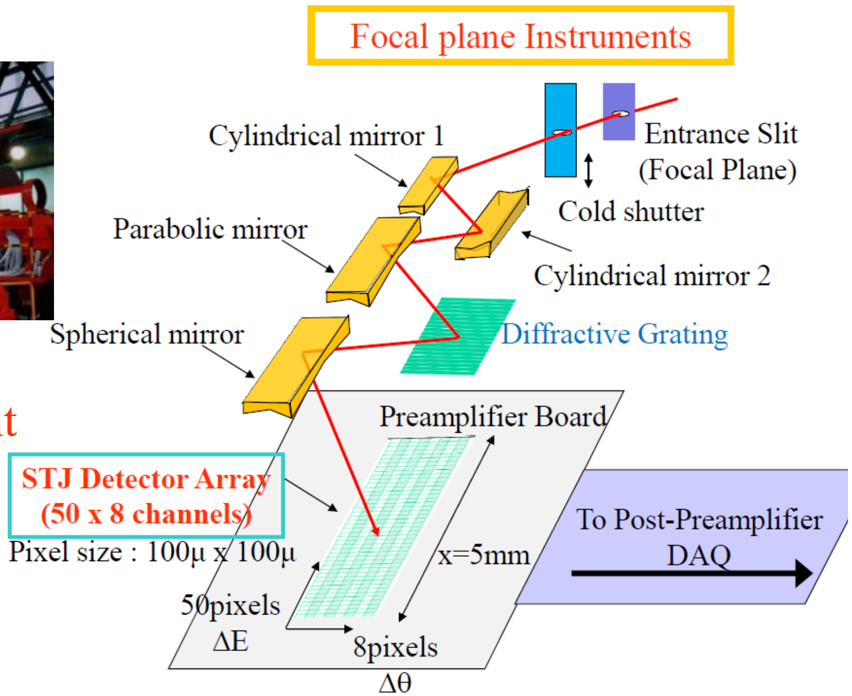
Improve the current limit of lifetime $\tau(\nu_3)$ by two orders of magnitude ($\sim 10^{14}$years).

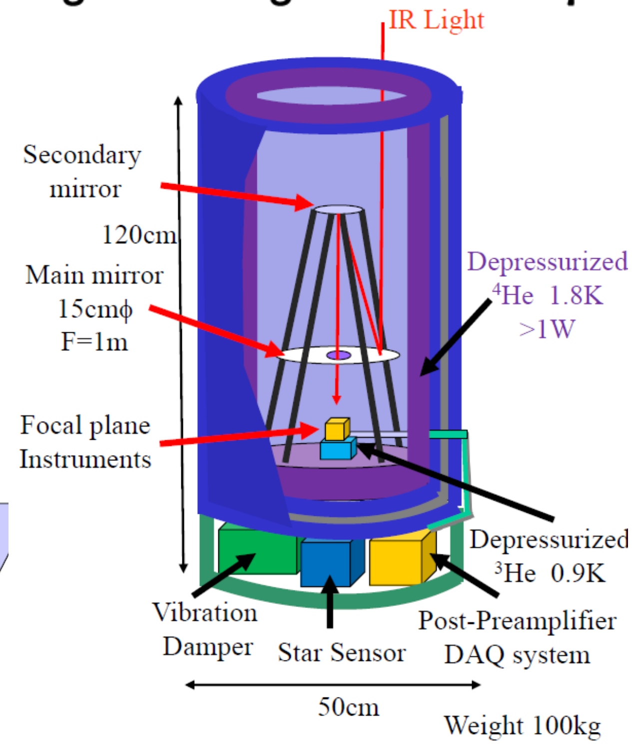
» Superconducting Tunneling Junction (STJ) detectors in development

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

JAXA Rocket
CIB Experiment

(Feb 2, 1992)





Satellite experiment after 2020 → 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))

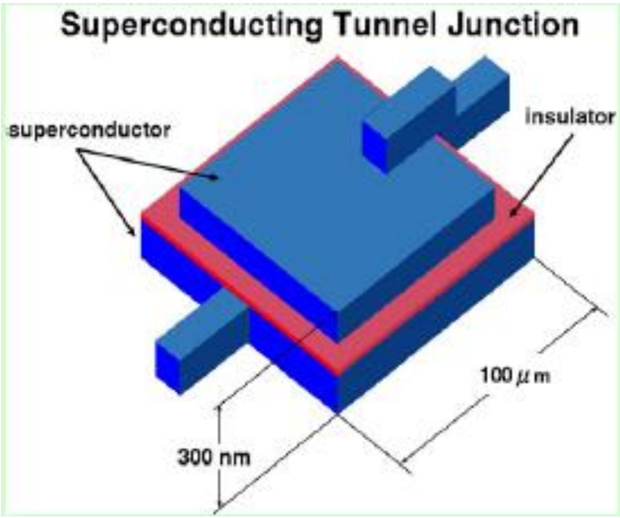
- $\Delta = 20\mu eV$: Superconducting gap energy for Hafnium
- $N_{q.p.} = 25meV/1.7\Delta = 735$ for 25meV photon: $\Delta E/E < 2\%$ if Fano-factor is less than 0.3

Schedule

	2015	2016	2017	2018	2019	2020
Experiment Design	Experiment design with Satellite such as SPICA					
	Experiment design with FIR Rocket			Far-Infrared Observatory Rocket Experiment		
SuperconductingTunnel Junction (STJ) Detector	Design and R&D of Nb/Al-STJ (SOI-STJ)	Production				
	Design and R&D of Hf-STJ Detector					
Preamplifier at 2K and Post-Preamp (Fermilab, JAXA, KEK, AIST, Tsukuba)	Design and R&D	Production				
Dispersive Element, Optics	Design and R&D	Production				
Cryostat	Design and R&D	Production				
Measurements + Analysis		Analysis Program				
	Simulation				Analysis	

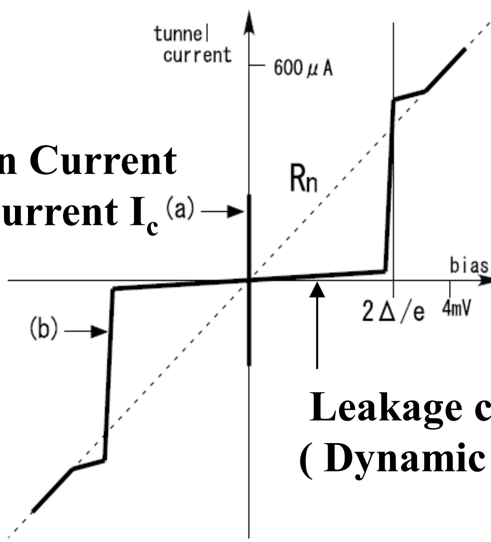
STJ (Superconducting Tunnel Junction) Detector

- Superconductor / Insulator / Superconductor Josephson Junction



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

current-voltage (I-V) curve for STJ



Josephson Current

Critical current I_c

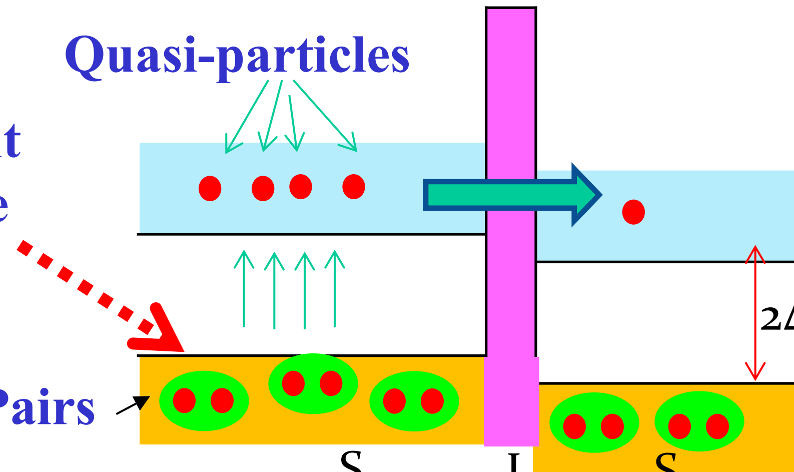
Leakage current

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

Quasi-particles

Incident Particle

Cooper Pairs



Energy gap Δ

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

STJ Energy Resolution

STJ Energy Resolution

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

Using Hf as a superconductor,

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

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

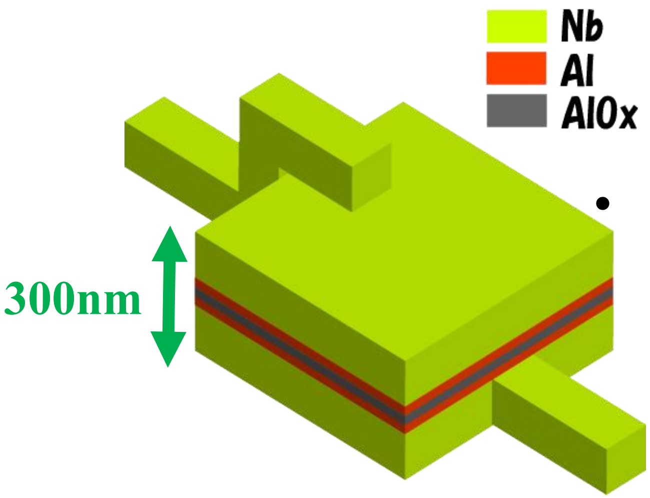
Material	$T_c(K)$	Δ(meV)
Niobium	9.20	1.550
Aluminum	1.14	0.172
Hafnium	0.13	0.021

Tc : Critical Temperature

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

We reported that Hf-STJ worked as a STJ in 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/Al-STJ Nb(200nm)/Al(10nm)/AlOx/Al(10nm)/Nb(100nm)
- Gain: 2～200

Number of Quasi-particles in Nb/Al-STJ

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

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

For 25meV single photon

$$N_q = 10 \frac{25\ meV}{1.7 * 1.550\ meV}$$
$$= 95\ e$$

	Si	Nb	Al
Tc[K]		9.23	1.20
Δ[meV]	1100	1.550	0.172

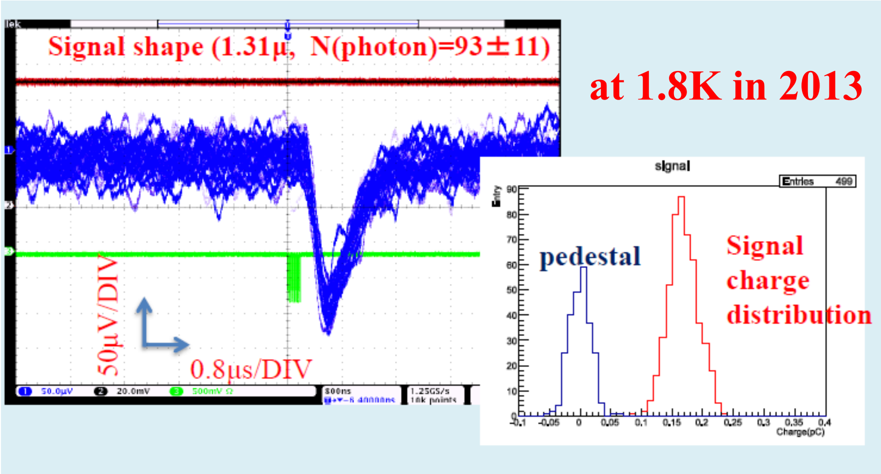
R&D of Superconducting Tunnel Junction (STJ) Detector

Nb/Al-STJ

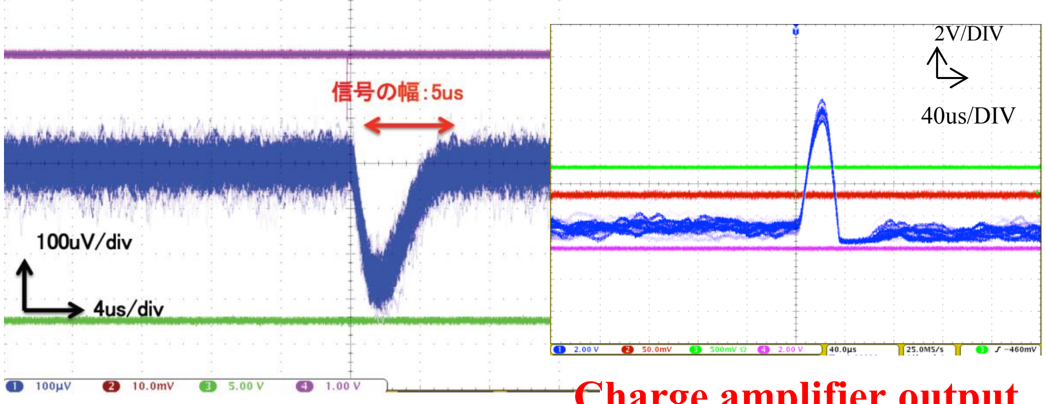
Goal: detection of a single far-infrared photon in the energy range of 15 – 30 meV (λ= 40 -80μm) for the rocket experiment for neutrino decay search.

Improvement of R&D in JFY2014

- **Test Setup**
  ^{4}He depressurization refrigerator (1.8K)
  → ^{3}He sorption refrigerator without refrigerant(0.3K)
    - rapid test cycle (2days)
    - short preparation period (1day)
- **Structure of Nb/Al-STJ**
  Nb/Al/Al_2O_3/Al/Nb layer thickness (Energy gap)
  100nm/10nm/1nm/10nm/200nm (Δ＝1.2meV)
  →100nm/70nm/1nm/70nm/120nm (Δ＝0.57meV))
  made with AIST CRAVITY processing system



Signal for 465nm laser light at 0.4K in 2014



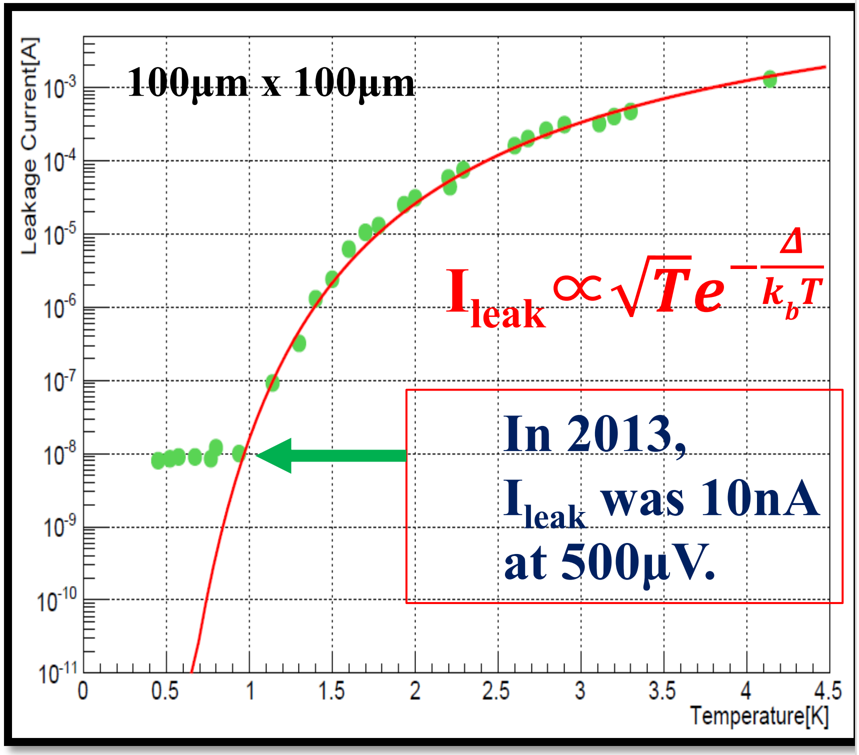
Charge amplifier output For N(photon)~10

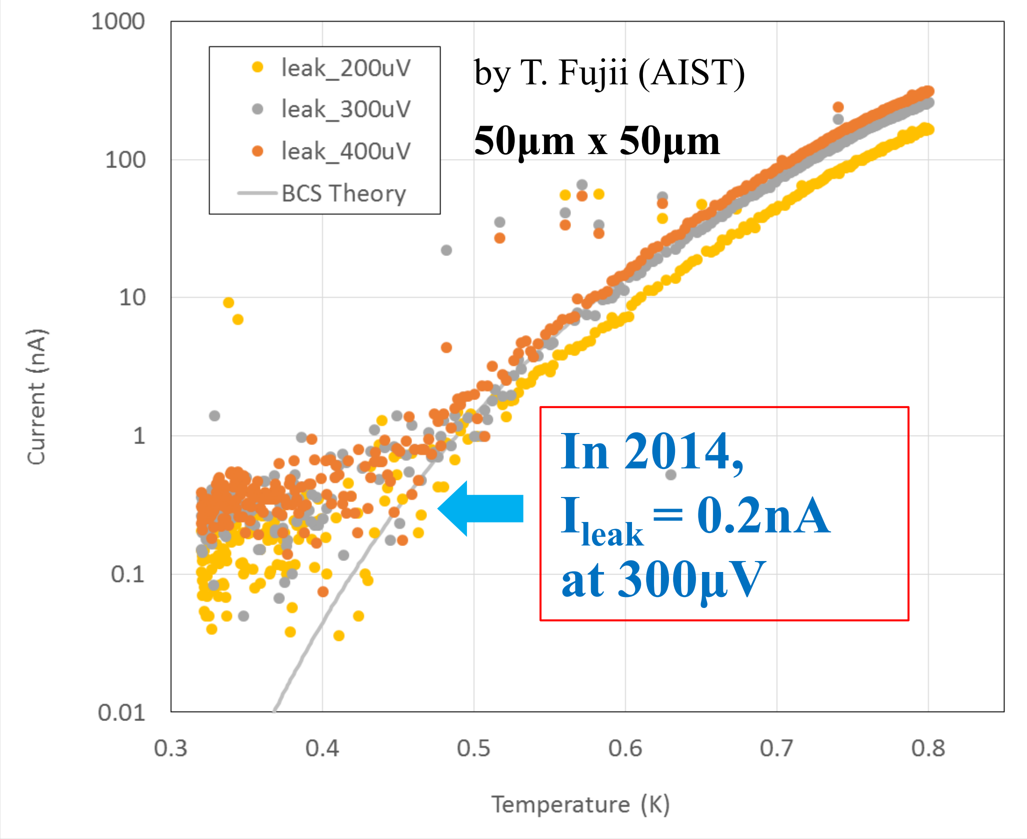
S/N ratio has been improved by a factor of 10.

Requirement for Leakage Current of Nb-Al/STJ

- Leakage current I_{leak} should be below 0.1nA to detect a single far-infrared photon (λ = 40 –80 μ m) .

Temperature Dependence of Leakage Current





In 2014,
AIST group joined us and produced Nb/Al-STJ with AIST CRAVITY processing system.

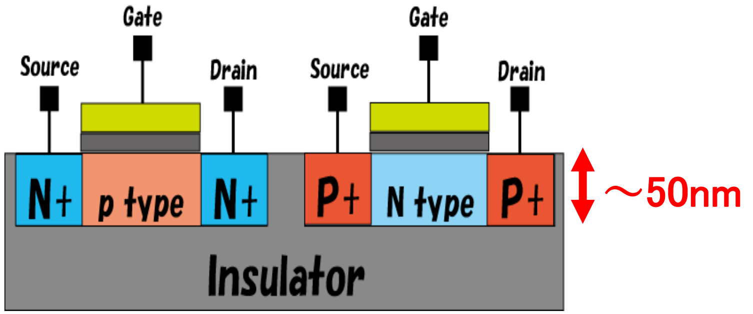
Leakage current has satisfied our requirement of 0.1nA .

STJ size	# of samples	I_{leak} at 0.3mV
50 x 50μm²	18	224±29 pA
20 x 20 μm²	7	**39±13 pA**
10 x 10 μm²	20	**14±7 pA**

R&D of SOI-STJ Detector

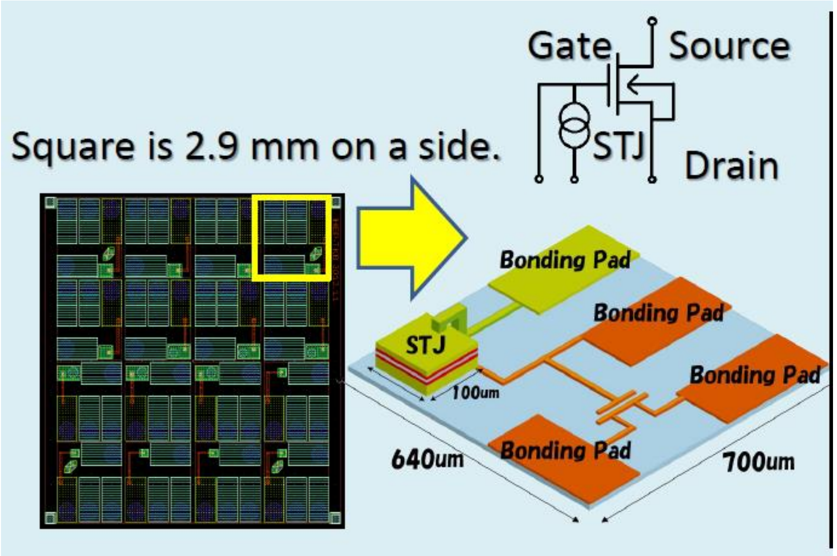
FD-SOI (Silicon-On-Insulator) device was proved to operate at 4K by a JAXA/KEK group (AIPC 1185,286-289(200 FD-SOI 9)). It has the following characteristics:
low-power consumption, high speed, easy large scale integration and suppression of charge-up by high mobility carrier due to thin depletion layer(～50nm).

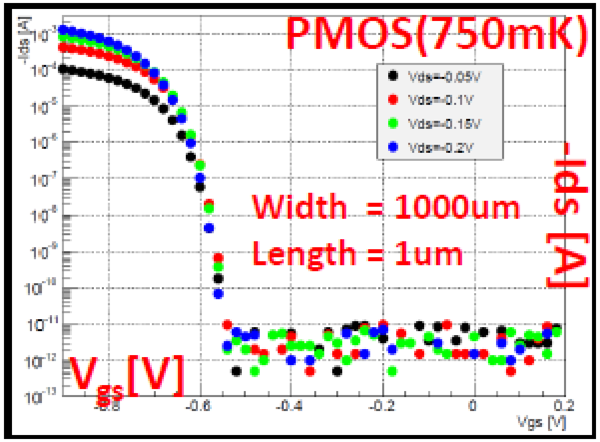
FD-SOI -MOSFET



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

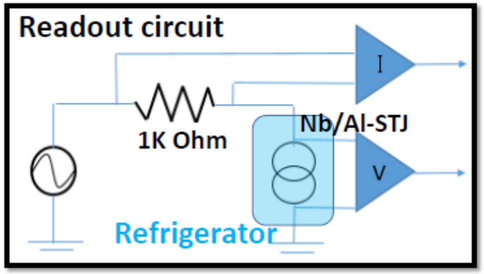
We confirmed that both Nb/Al-STJ detector and SOI MOSFET worked normally at 750mK.



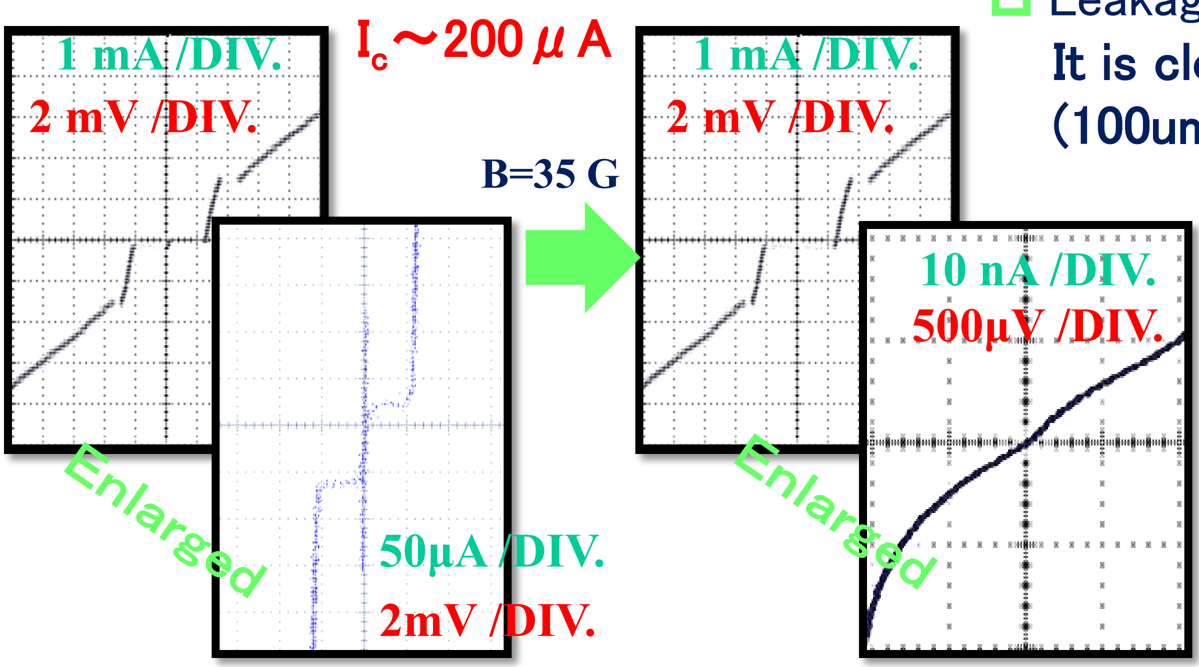


Performance of Nb/Al-STJ in SOI-STJ Detector

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

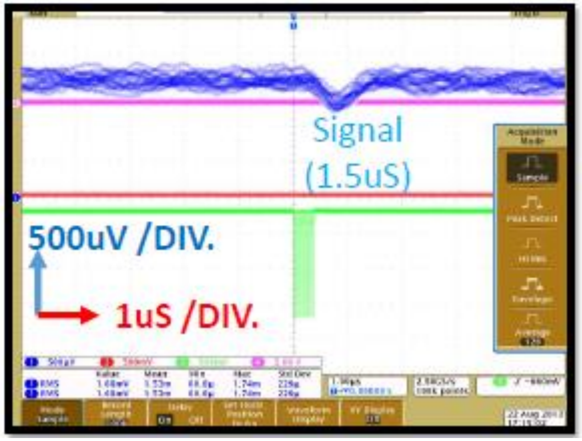


☐ I-V curve of Josephson Junction



☐ Leakage current @ 0.5mV is **6nA**.
It is close to the normal Nb/Al-STJ (100um x 100um) leakage of 10nA.

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

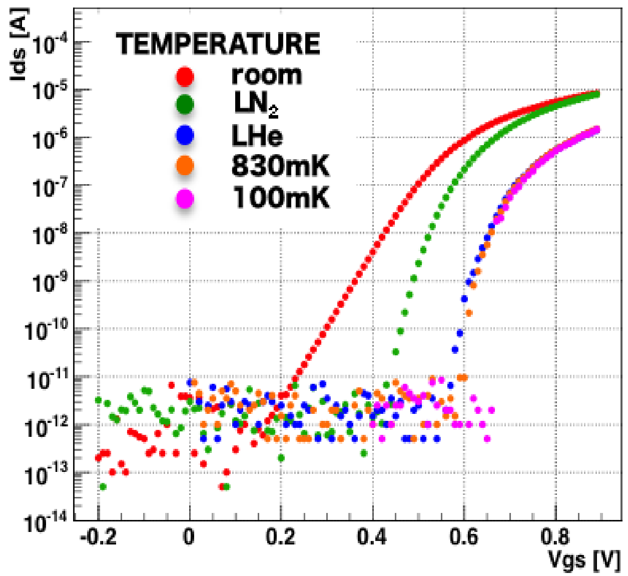


☐ Quality Factor ($R_{dynamic}/R_{normal}$)

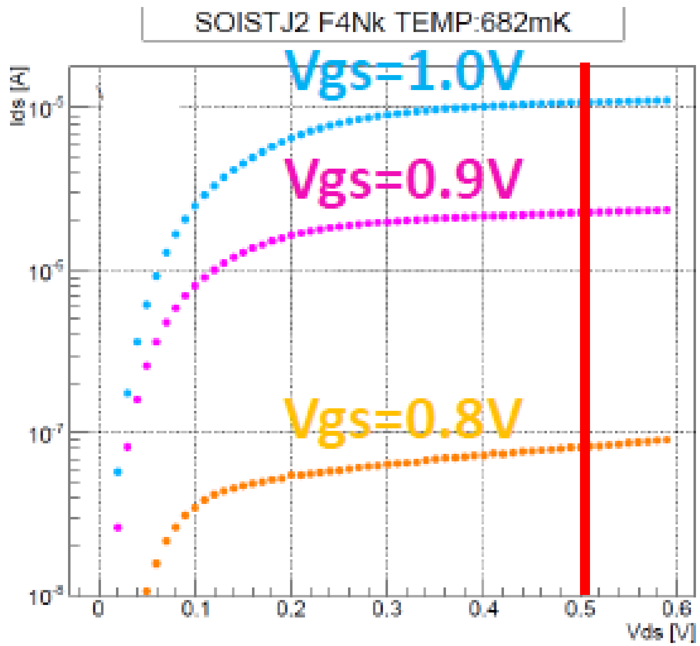
On Si wafer : 5 x 10^5
On SOI wafer : 3 x 10^5

Performance of SOIFET in SOI-STJ Detector

- **Temperature dependence**
  I-V curves at various temperatures.
  SOIFET can be operated at 100mK.



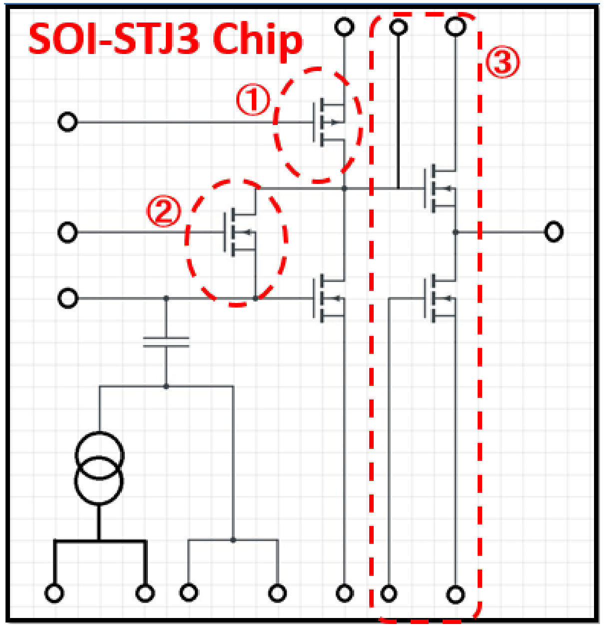
- **Power consumption (at 680mK)**
  Bias voltage of SOIFET in saturation region (red line) : 0.5 V
  Current (I_{ds}) of FET in saturation region at V_{gs} = 0.8V : 0.09 μA

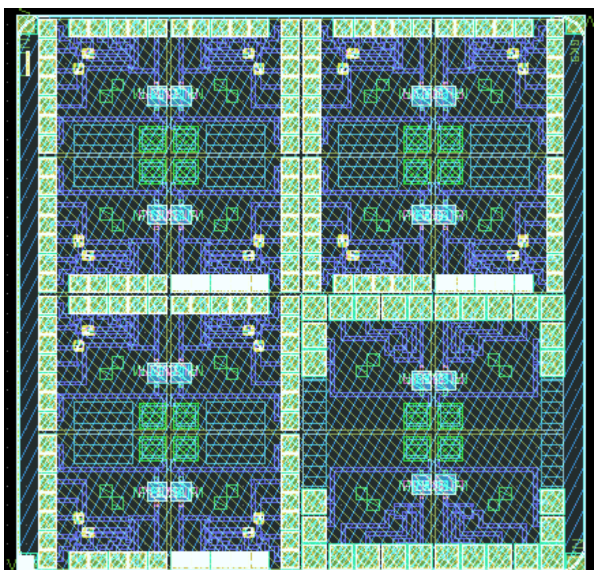


Power consumption = 0.5 V × 0.09 μA

= 45 nW/FET for W/L=1.42μm/0.42μm

New SOI−STJ R&D





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

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

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

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

SOI transistor worked normally at 360mK.

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

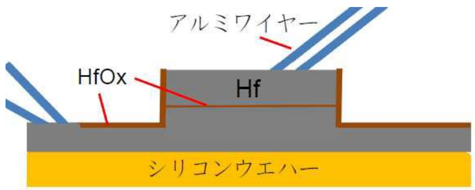
R&D of Superconducting Tunnel Junction (STJ) Detector

Hf-STJ

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

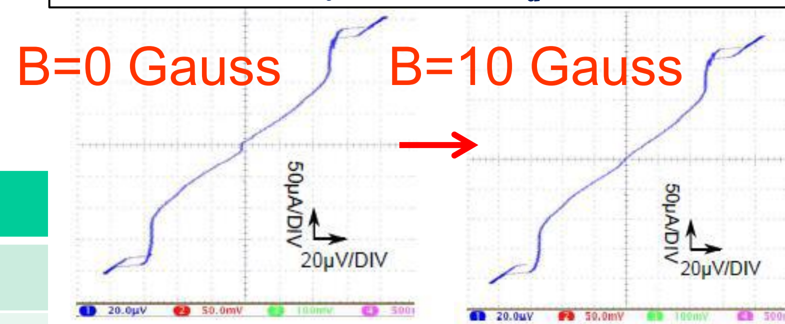
Micro-calorimeter: Hf-STJ can generate enough statistics of quasi-particles from cooper pair breakings to achieve 2% energy resolution for photon with $E_\gamma = 25$ meV.

Direct wire bonding on Hf layer



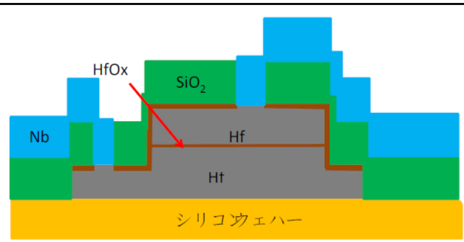
STJ size	# of samples	R_d
200 x 200μm²	3	0.22±0.01 Ω
100 x 100 μm²	3	0.60±0.10 Ω

I-V curve of Hf-STJ (**100x100μm²**)
- T~40mK, I_c=10 μA, **R_d=0.6Ω**

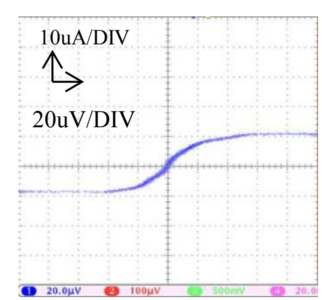


We are working on the work to reduce a large leakage current of Hf-STJ.

Hf readout line on Hf layer



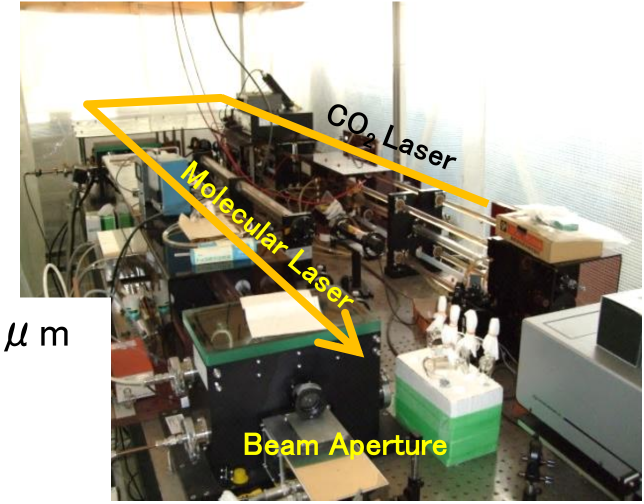
I-V curve of Hf-STJ (**50x50μm²**)
- T~79mK,
- I(leak)= 10 μA at 40 μV
- Not SIS structure. The connection between Hf readout and Hf layer is OK.



Far-Infrared Molecular Laser

(U. Fukui/Chubu U.)

CO_2 Laser → **exite** → Alcohol Vapor (CH_3OH, CD_3OH, …) → **emit** → Far-Infrared Beam (Continuous Waves)

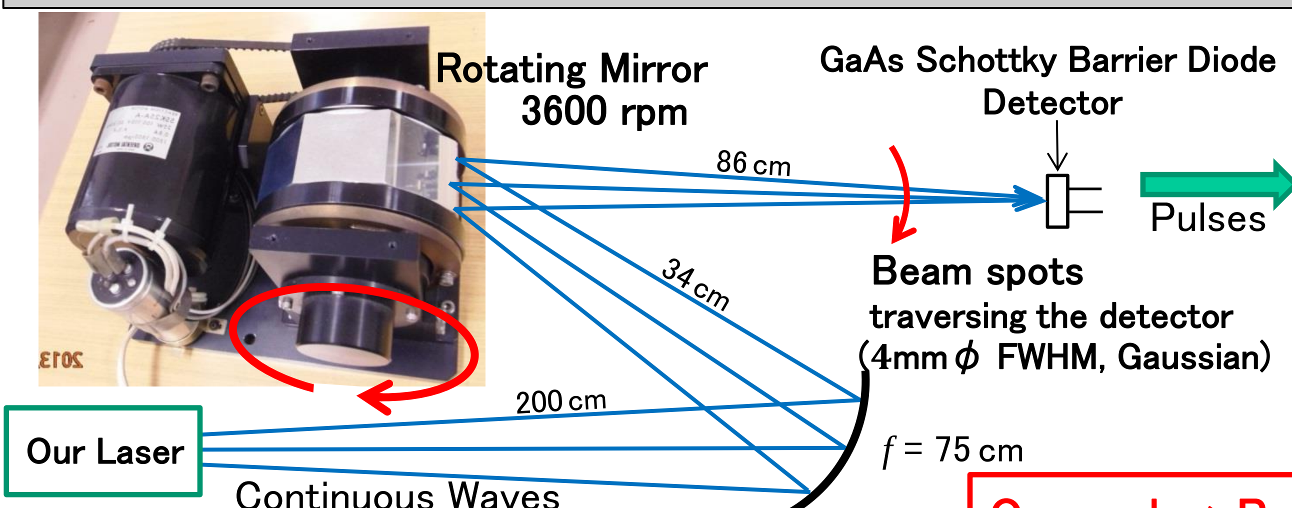


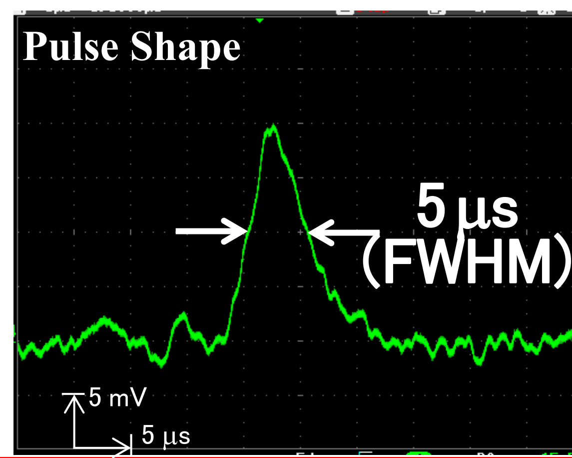
- can emit any one of ~70 monochromatic lines btwn $\lambda = 40 - 500\,\mu m$ (31–2.5meV) by selecting an alcohol and a CO_2 laser frequency.
- Beam diameter : 7mm ($1/e^2$), Beam divergence : 20mrad ($1/e^2$), Power : 1mW – 1W depending on the wavelength.

The monochromatic lines we confirmed so far :

$\lambda = 43.7\,\mu m$ (28 meV), $52.9\,\mu m$ (23 meV), $86.4\,\mu m$ (14 meV), $118.8\,\mu m$ (10 meV), $453.4\,\mu m$ (2.7meV), ·

Conversion of continuous waves to pulses by rotating mirrors (to evaluate the STJ with pulses)





$\lambda = 118.8\,\mu m$ (10 meV)
Alcohol : CH_3OH
CO_2 laser frequency : 9P(36)

Concave Mirror to focus the beam on the Detector

Our goal → Pulse width $\leq 1\ \mu s$ along:
- improving the beam focusing system,
- longer distance from Rotating Mirror to Detector.

Data transfer system from rocket to earth station

Data size

of STJ sensor: 50 pixel X 8 row = 400 pixel
Event rate: 300 Hz/pixel X 400 pixel = 120 kHz
Data size: ADC 7 bit, time info. 10bit,
pixel address 9bit

Requirement of transfer rate
➡ more than 3.12 Mbps

Rocket has one transmitter (1.6 Mbps, S-band) as the standard telemetry system .

But it has to transfer all data (including the rocket and all component information).

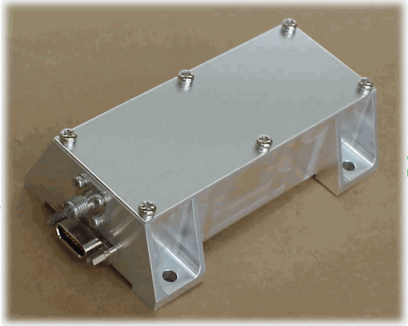
We plan to be equipped with one optional transmitter having enough transfer rate

-- Rocket can be equipped with two transmitter component (some rocket exp. had two components)

-- Addnics corp. can make the high rate transmitter system (**5 Mbps** is OK)

-- Using two transmitter can be a robust system

-- Earth station has a sufficient ability of receiving data (50 Mbps, S-band)



2.2 GHz transmitter for rocket by Addnics (from addnics HP)

Plan :

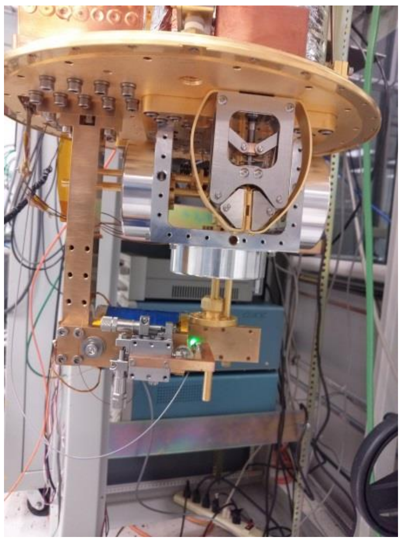
✓ define the design of high rate transmitter with company
✓ define the data format

Combined test of STJ and cold-amplifier at Fermilab

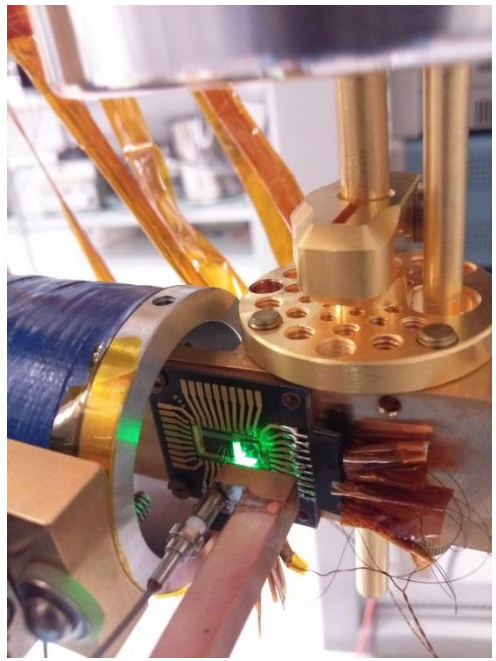
Combined test of the Nb/Al-STJ and the cold preamplifier at Fermilab

August 26 , 2014～September 12（6 US members + 6 Japan members）:

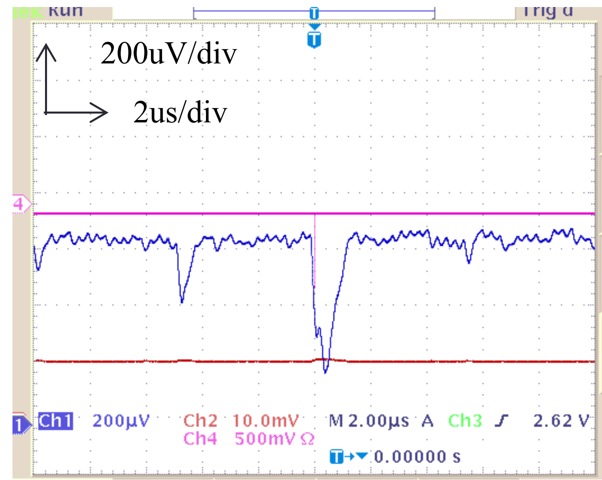
Test was done with an ADR at MilliKelvin Facility at Fermilab



ADR at MilliKelvin Facility at Fermilab

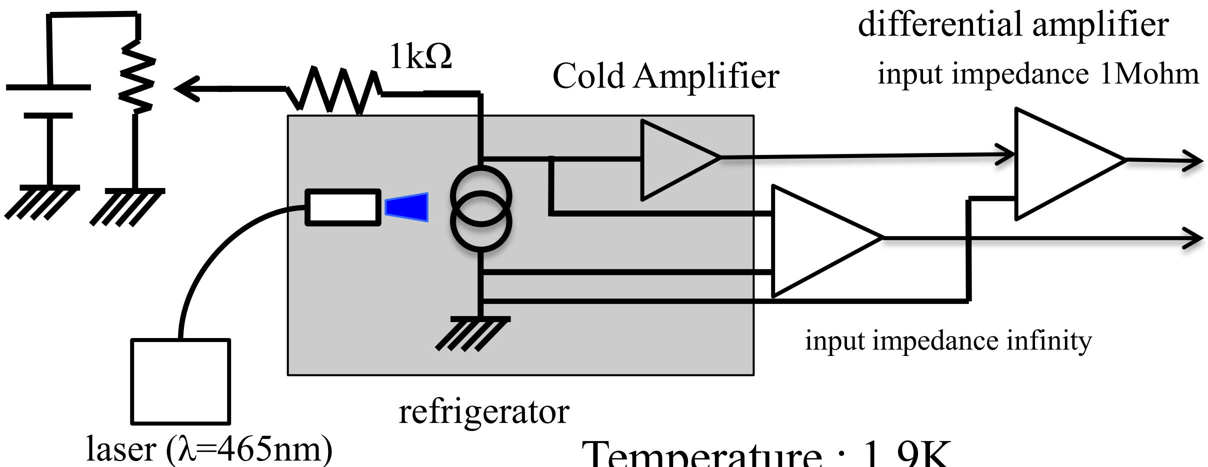


Laser light spot was used for the alignment of light fiber.

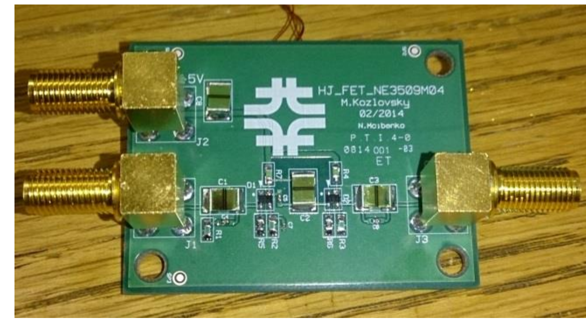


We obtained the response to the laser light (465nm) with the newly designed Al/Nb-STJ (20um x 20um) . No cold-amplifier this time.

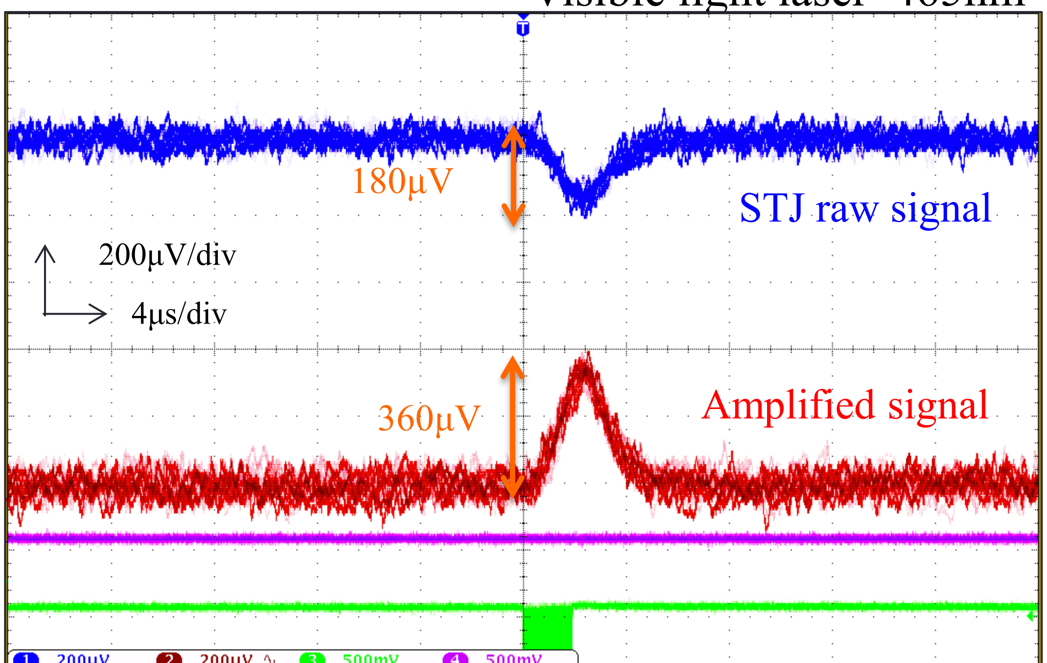
STJ signal amplified with a cold HEMT amplifier made by Fermilab group



Cold amplifier made by Fermilab group



Temperature : 1.9K
Visible light laser 465nm



STJ signal was amplified with this cold amplifier.
Developing higher gain amplifier.

Fermilab group also joined the R&D of the SOI cold amplifier.

Summary of Results in JFY2014

- **Succeeded in decreasing the leakage current of Nb/Al-STJ detector from 10nA to 0.04nA below our requirement of 0.1nA.**
- **Observed 5μs pulse laser beam of far infrared light with wavelengths between 44 and 450μm.**
- **The small-size Hf-STJ is being developed to reduce the leakage current.**
- **We had the following results on the cold-amplifier R&D:**

1. **We made prototypes of SOI-STJ detector. The SOI and the STJ in the SOI-STJ detector worked normally below 800mK. The SOI transistor was found to work at 100mK.**
2. **The cold amplifier developed at Fermilab worked to amplify the real signal of the Nb/Al-STJ to the visible laser light.**

Publications

3 Papers, 9 Talks in the International Conferences ,

4 Master Theses, 10 Talks in Domestic Workshops

Plan of R&D in JFY2015

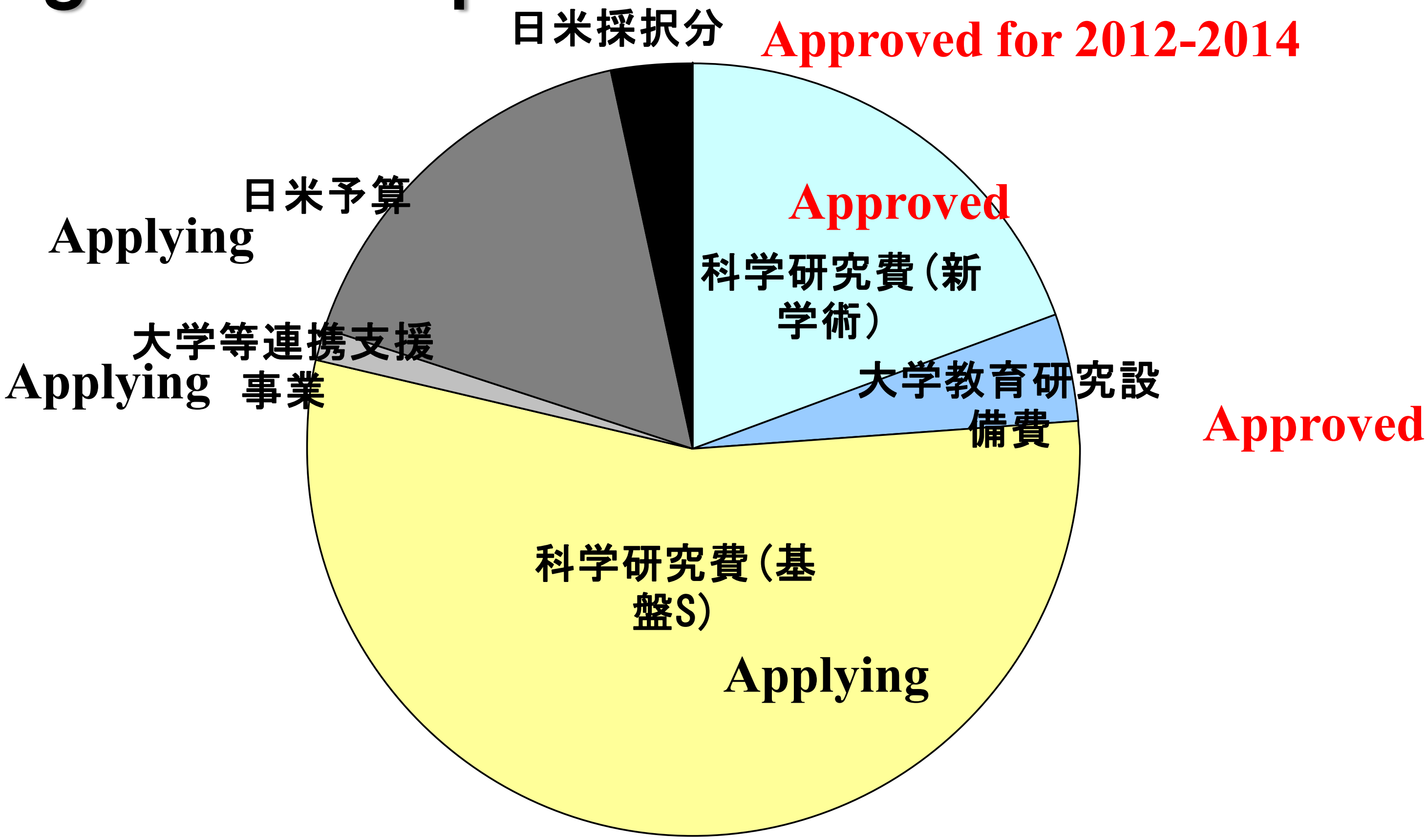
- Make smaller Hf-STJ of 20μm x 20μm and 100μm x 10μm, and detect a signal of infrared one photon.

- R&D target of the cold preamplifier is to develop the SOI-STJ detector and the SOI cold amplifier to detect an infrared one photon signal from the Nb/Al-STJ detector.
- Test a multi-pixel Nb/Al-STJ detector.
- Far-infrared beam（wavelength 40μ～200μ）will be developed. With this beam, we will test the Nb/Al-STJ.

- R&D of readout electronics such as shaper and ADC is started.
- Continue the design of data transfer system.

- Design and make a prototype of the optical system such as a grating and mirrors for telescope.
- Design and make a prototype of a refrigerator loaded on the rocket.

Budgets in the period of JFY2013-2018



筑波大学教育研究設備費	無冷媒3He吸収型冷凍機	JFY2013　Approved	16,000 kYen
科学研究費補助金新学術領域「ニュートリノ」計画研究	ニュートリノ崩壊探索実験に用いる超伝導赤外線検出器の開発	JFY2013－2017　Approved	70,800 kYen
科学研究費補助金基盤（S）	宇宙背景ニュートリノ崩壊探索ロケット実験	JFY2015-2019　Applying	198,000 kYen
KEK大学等連携支援事業	筑波大-KEK連携を核としたつくば教育研究拠点の構築に向けて（内素粒子分）	JFY2015　Applying	5,000 kYen

Budget Plan in JFY 2015 (April 2015-March 2016)

	Cost (x 1,000Yen)	
Data Acquisition System	1,200	Japan
Improvement of Refrigerator	1,200	Japan
Far-infrared light source	1,000	Japan
Dispersive Element, optical system	1,000	Japan
Superconducting Tunnel Junction Dtector Prototype	2,400	Japan
SOI amplifier board	1,200	Japan
Electronics (preamplifier at 3K etc.)	6,800	Fermilab
Expenses at Fermilab (rent-a-car etc.)	200	Fermilab
total	15,000	

Summary

1. We are developing the STJ-based detectors to detect a single far-infrared photon in energy range between 15 and 30meV to search for the cosmic background neutrino decay with a rocket experiment in 2018 and a satellite experiment.

2. The leakage current of Nb/Al-STJ has been now achieved below our requirement of 0.1nA. The S/N ratio was improved by a factor of 10 compared with JFY2013.

3. The SOI-STJ detector where Nb/Al-STJ was processed on a SOIFET board is being developed. Both SOIFET and STJ are working well in the SOI-STJ detector below 400mK.

4. The small-size Hf-STJ is being developed to reduce the leakage current.

BACKUP

Publications and Talks on STJ R&D in JFY2014 (1)

Papers and Proceedings

1. "Development of Superconducting Tunnel Junction Detectors as a far-infrared single photon detector for neutrino decay search", Y. Takeuchi et al. To be published as Proceedings of Science(TIPP2014)155
2. "Development of Superconducting Tunnel Junction Photon Detector on SOI Preamplifier Board to Search for Radiative decays of Cosmic Background Neutrino", K. Kasahara et al. , Proceedings of Science(TIPP2014)074
3. "Search for Cosmic Background Neutrino Decay", S. H. Kim et al., JPS Conf. Proc. 1, 013127 (2014)

Talks in International Conferences

1. "Development of Superconducting Tunnel Junction Detector Using Hafnium for Neutrino Decay Search" K.Takemasa IEEE nuclear science symposium and medical imaging conference 2014@Seattle, USA, Nov. 8-15, 2014
2. “Development of Superconducting Tunnel Junction Photon Detector with SOI Preamplifier Board to Search for Radiative Decays of Cosmic Background Neutrino", T. Okudaira, (Poster), IEEE nuclear science symposium and medical imaging conference 2014, Seattle, USA, Nov. 8-15, 2014
3. "Development of Superconducting Tunnel Junction Photon Detectors for Cosmic Background Neutrino Decay Search" S.H. Kim 2nd International Workshop on Superconducting Sensors and Detectors (IWSSD2014)@Shanghai, China, Nov. 5-8, 2014
4. ”Experimental search for the cosmic background neutrino decay in the cosmic far-infrared background", Y. Takeuchi Tsukuba Global Science Week 2014(TGSW2014) @Tsukuba, Japan Sep.28-30, 2014
5. ”Development of Superconducting Tunnel Junction Photon Detector with SOI Preamplifier board to Search for Radiative decays of Cosmic Background Neutrino", T.Okudaira TGSW2014@Tsukuba, Japan Sep.28-30, 2014
6. "Development of Superconducting Tunnel Junction Detectors as a far-infrared single photon detector for neutrino decay search" Y. Takeuchi Technology and Instrumentation in Particle Physics 2014 (TIPP 2014)@Amsterdam, the Netherlands, Jun. 2-6, 2014
7. "Development of Superconducting Tunnel Junction Photon Detector on SOI Preamplifier Board to Search for Radiative Decays of Cosmic Neutrino Background" K.Kasahara Technology and Instrumentation in Particle Physics 2014 (TIPP 2014)@Amsterdam, the Netherlands, Jun. 2-6, 2014

Publications and Talks on STJ R&D in JFY2014 (2)

Master Theses

1. 笠原宏太「ニュートリノ崩壊からの遠赤外光探索のためのSOI-STJ一体型検出器の開発研究」修士論文（筑波大）2014年2月　数理物質科学研究科長賞受賞
2. 奥平琢也「ニュートリノ崩壊光探索のためのニオブとアルミニウムを用いた超伝導トンネル接合素子光検出器の開発研究」修士論文（筑波大）2015年2月
3. 市村龍哉「ニュートリノ崩壊光探索のためのハフニウムを用いた超伝導トンネル接合素子光検出器の研究開発」修士論文（筑波大）2015年2月
4. 金丸昌弘「ニュートリノ崩壊探索ロケット実験の設計のためのシミュレーション解析」修士論文（筑波大）2015年2月

Talks in JPS and Domestic Workshops

1. "Development of STJ detector for cosmic background neutrino decay search", K. Takemasa, 新学術領域研究「ニュートリノフロンティア」研究会 2014, 山梨県，2014年12月21-23日
2. "R&D status of the SOI-STJ detector", T. Okudaira, 新学術領域研究「ニュートリノフロンティア」研究会 2014
3. "R&D status of the cold preamplifier", R. Senzaki, 新学術領域研究「ニュートリノフロンティア」研究会 2014
   "Far-Infrared source R&D", R. Hirose, 新学術領域研究「ニュートリノフロンティア」研究会 2014
4. "宇宙背景ニュートリノ輻射崩壊探索実験に向けたSOI-STJ一体型遠赤外光検出器開発", 武内勇司, 第4回可視赤外線観測装置技術ワークショップ 2014年12月3-4日
5. "ニュートリノ崩壊光子探索用STJ検出器の較正に用いる遠赤外線源の開発", 廣瀬龍太, 日本物理学会2014年秋季大会, 2014年9月18日
6. "ニュートリノ崩壊光探索のためのNb/Al-STJの研究開発V", 森内航也, 日本物理学会2014年秋季大会,2014年9月19日
7. "ニュートリノ崩壊からの遠赤外光探索のためのSOI-STJ検出器の研究開発", 先崎蓮, 日本物理学会2014年秋季大会,2014年9月19日
8. "ニュートリノ崩壊光探索のためのNb/Al-STJの研究開発IV"，奥平琢也，日本物理学会第69回年次大会，2014年3月29日
9. "ニュートリノ崩壊からの遠赤外光探索のためのSOI-STJ検出器の研究開発II"，笠原宏太，日本物理学会第69回年次大会，2014年3月29日