Search for Cosmic Background Neutrino Decay with STJ detectors

Yuji Takeuchi (Univ. of Tsukuba)
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Fermilab WH3NW

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Collaboration Members (Japan-US collab.: Search for Neutrino Decay)

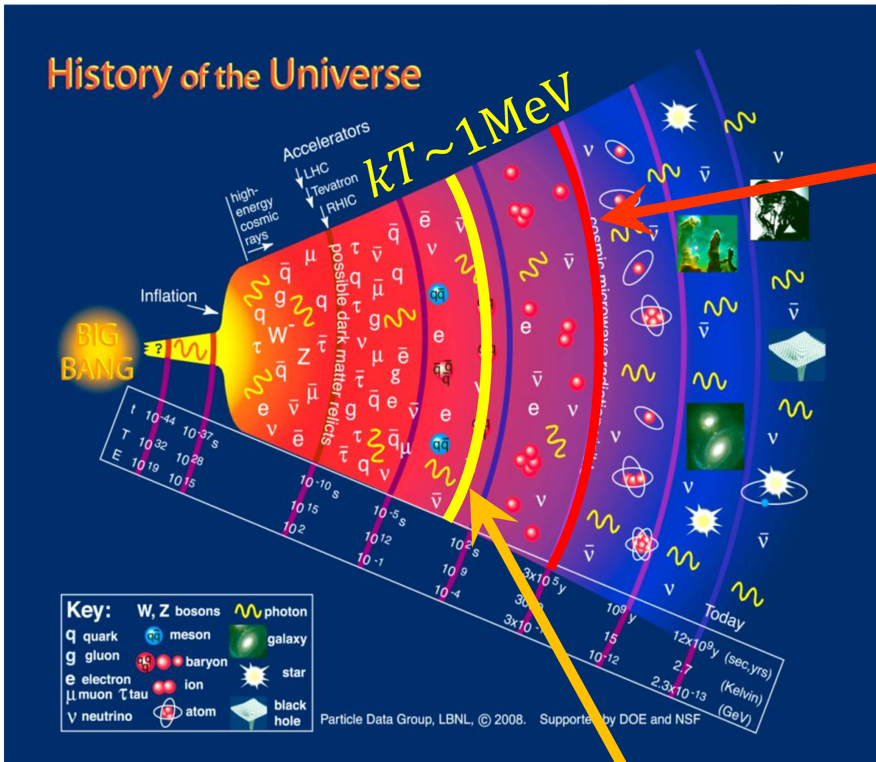
- As of Aug. 2013

Japan Group
Shin-Hong Kim, Yuji Takeuchi, Kenji Kiuchi, Kanai, Kazuki Nagata, Kota Kasahara, Tatsuya Ichimura, Takuya Okudaira, Kouya Moriuchi, Ren Senzaki (University of Tsukuba),
Hirokazu Ikeda, Shuji Matsuura, Takehiko Wada (JAXA/ISAS) ,
Hirokazu Ishino, Atsuko Kibayashi, Yasuki Yuasa(Okayama University) ,
Takuo Yoshida, Yusuke Shimizu, Mikiya Nagashima (Fukui University) ,
Satoshi Mima (RIKEN),
Yukihiro Kato (Kinki University) ,
Masashi Hazumi, Yasuo Arai (KEK)

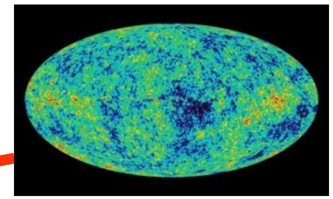
US Group
Erik Ramberg, Mark Kozlovsky, Paul Rubinov, Dmitri Sergatskov, Jonghee Yoo (Fermilab)

Korea Group
Soo-Bong Kim (Seoul National University)

Cosmic neutrino background (CνB)



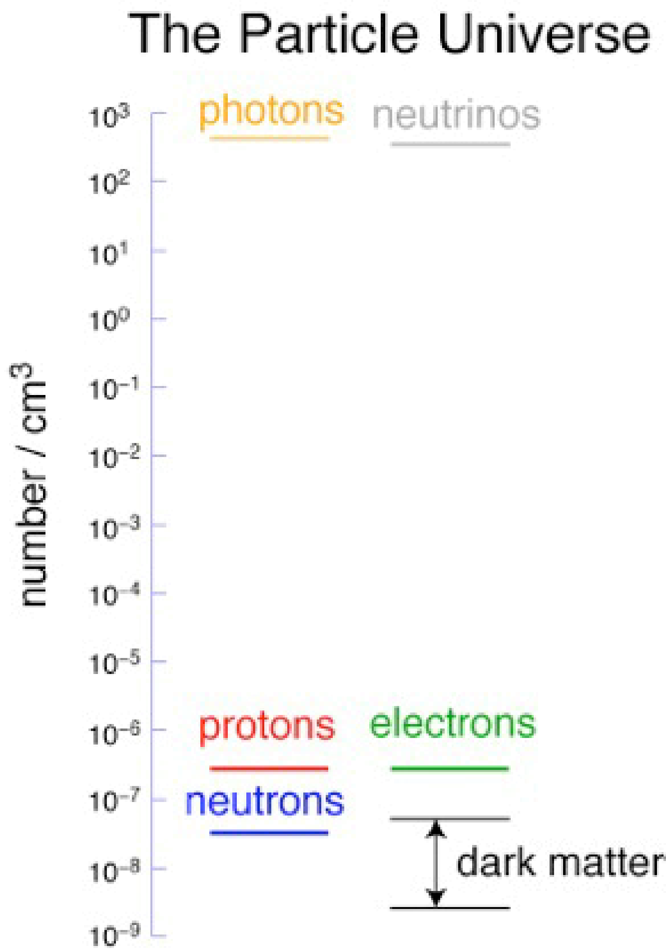
$kT \sim 1\mathrm{MeV}$



CMB

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

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



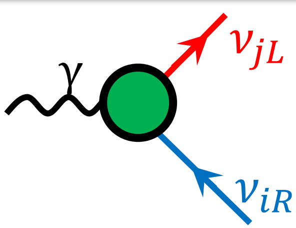
CνB

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

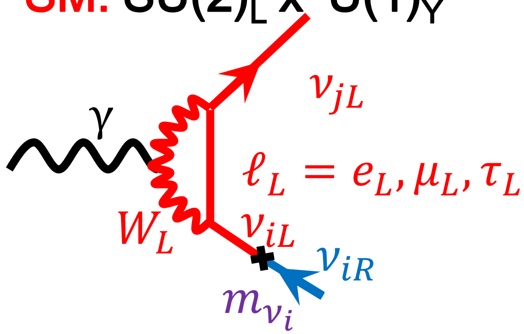
Motivation

- Search for $\nu_3 \to \nu_{1,2} + \gamma$ in cosmic neutrino background (CνB)
  - Direct detection of CνB
  - Direct detection of neutrino magnetic moment
  - Direct measurement of neutrino mass: $m_3 = (m_3^2 - m_{1,2}^2)/2E_\gamma$
- Aiming at sensitivity of detecting γ from ν decay for $\tau(\nu_3) = O(10^{17}\text{yr})$
  - Current experimental lower limit $\tau > O(10^{12}\text{yr})$
  - SM expectation $\tau = O(10^{43}\text{yr})$
  - L-R symmetric model (for Dirac neutrino) predicts $\tau = O(10^{17}\text{yr})$

Neutrino magnetic moment term
$\bar{\nu}_{jL}\sigma_{\mu\nu}\nu_{iR}$



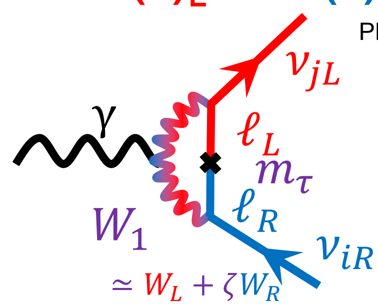
SM: $SU(2)_L \times U(1)_Y$



$\Gamma \sim (10^{43}\ yr)^{-1}$
Suppressed by m_ν, GIM

LRS: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

PRL 38,(1977)1252, PRD 17(1978)1395



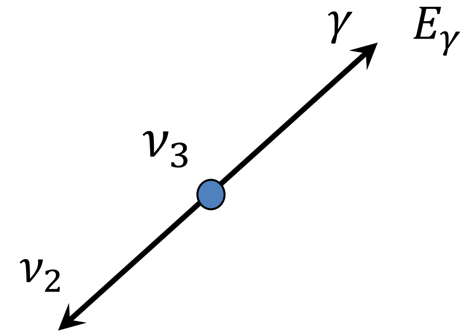
$$\begin{pmatrix} W_1 \\ W_2 \end{pmatrix} = \begin{pmatrix} \cos\zeta & -\sin\zeta \\ \sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W_L \\ W_R \end{pmatrix}$$

10^{26} enhancement to SM

$\Gamma \sim (10^{17}\ yr)^{-1}$
Suppressed only by $\zeta \sim 0.01$

Photon Energy in Neutrino Decay

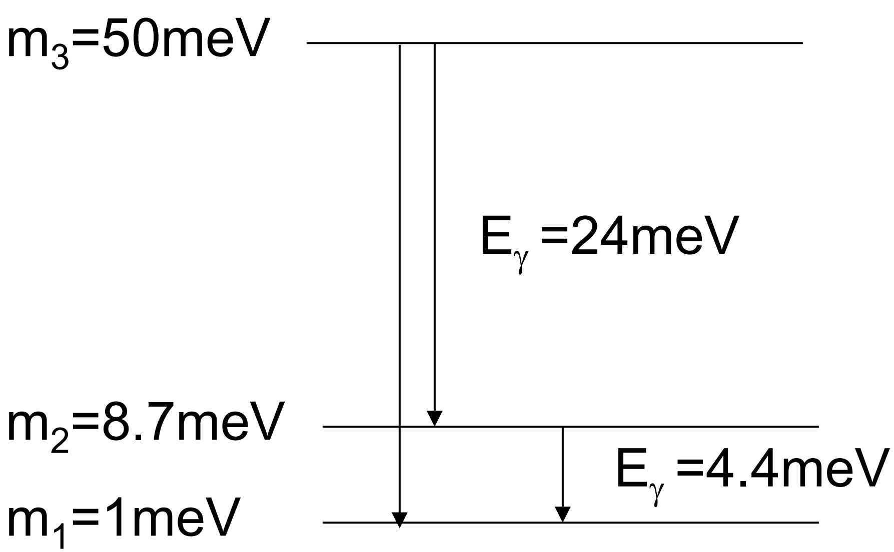
$$\nu_3 \rightarrow \nu_{1,2} + \gamma \qquad E_\gamma = \frac{m_3^2 - m_{1,2}^2}{2m_3}$$



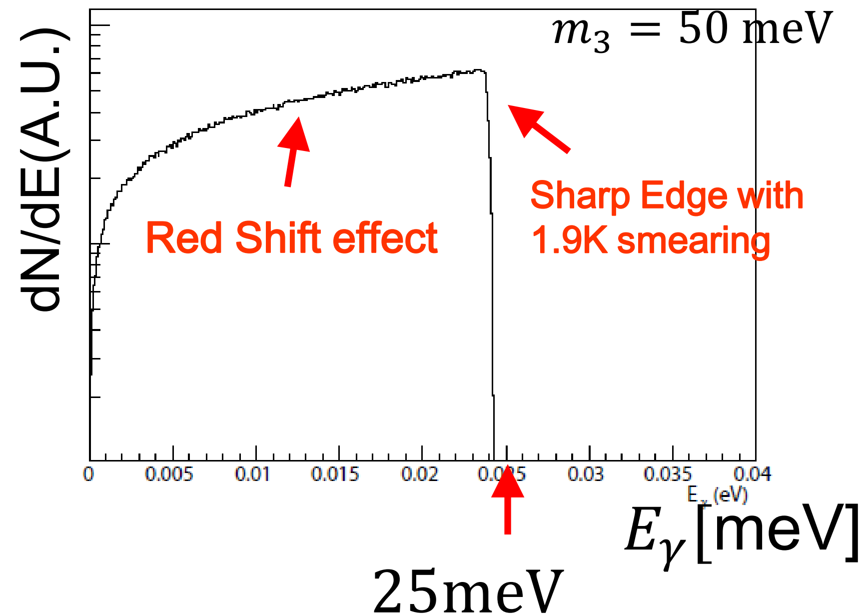
- From neutrino oscillation
  - $\Delta m_{23}^2 = |m_3^2 - m_2^2| = 2.4 \times 10^{-3}\ eV^2$
  - $\Delta m_{12}^2 = 7.65 \times 10^{-5}\ eV^2$
- From CMB fit (Plank+WP+highL+BAO)
  - $\sum m_i < 0.23$ eV

➔ 50meV<m_3<87meV, E_γ =14~24meV

λ_γ =51~89μm



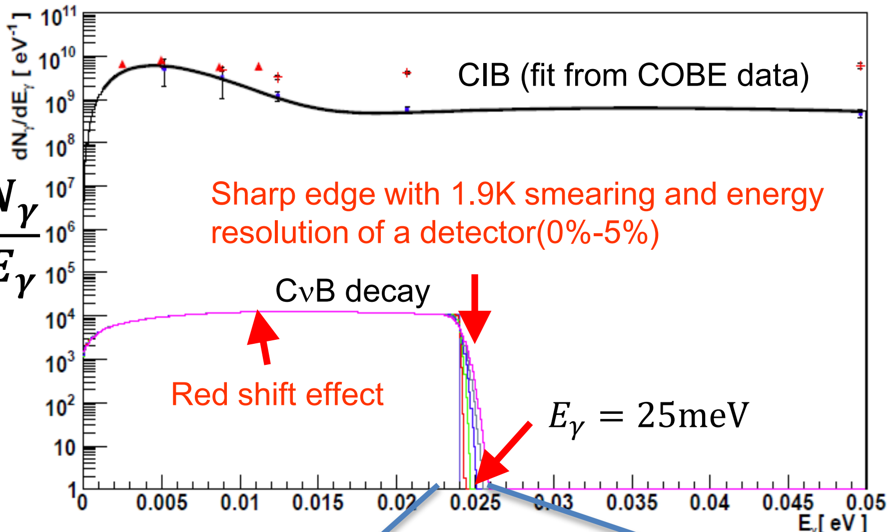
E_γ distribution in $\nu_3 \rightarrow \nu_2 + \gamma$



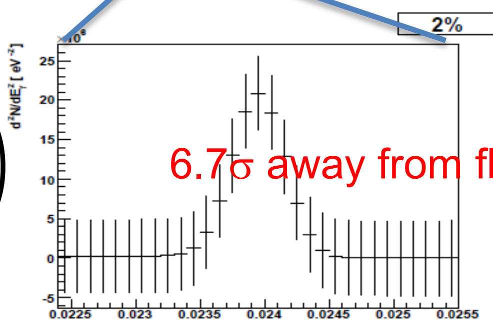
Feasibility of photon detection from CνB decay

Expected E_γ spectrum: $m_3 = 50\text{meV}$ and $\tau(\nu_3) = 1.5 \times 10^{17}\text{yr}$

$$\frac{dN_\gamma}{dE_\gamma}$$



$$-\frac{d}{dE_\gamma}\left(\frac{dN_\gamma}{dE_\gamma}\right)$$

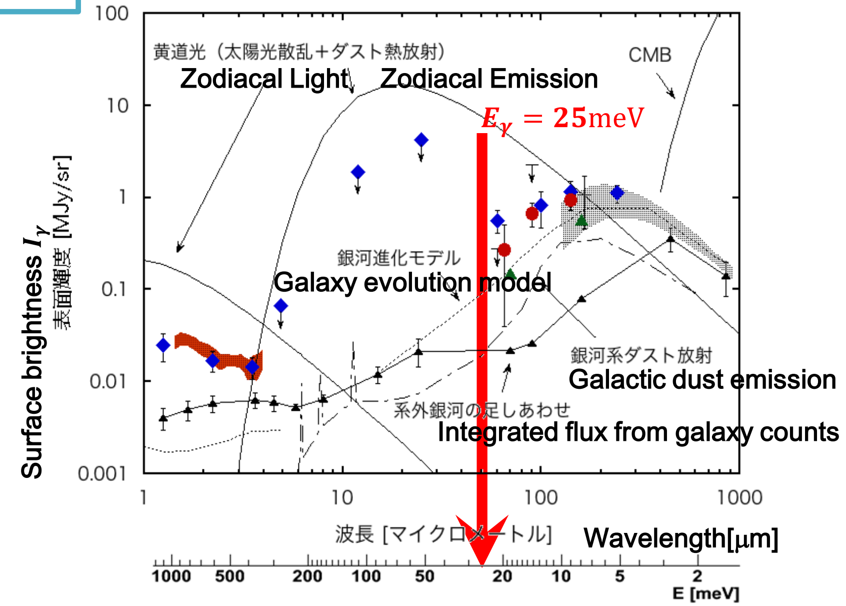


Differential photon energy spectrum from CνB decay + CIB (w/ 2% energy resolution)

Statistical uncertainties in N_γ are taken into account in the error bars

CIB measurements(● AKARI, ♦ COBE)

Astrophys. J. 737 (2011) 2



Simulation(JPSJ 81 (2012) 024101)

- If we assumed
  - $m_3 = 50$ meV and $\tau(\nu_3) = 1.5 \times 10^{17}\text{yr}$
  - No zodiacal foreground emission
  - 10 hour measurement
  - 20cm diameter and 0.1° viewing angle telescope
  - A photon detector with 2% energy resolution

➔ We can detect photon from CνB decay photon at 6.7σ significance

Neutrino lifetime lower limit from AKARI data

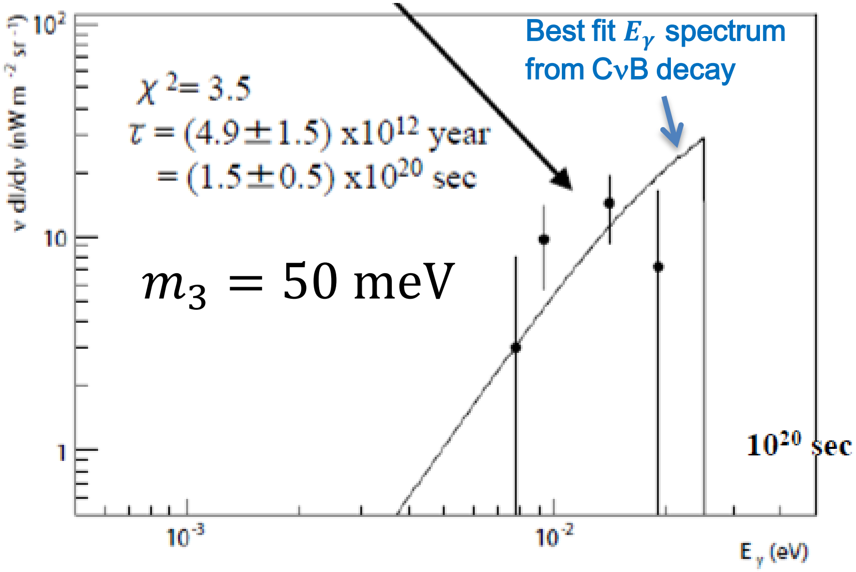
Journal of the Physical Society of Japan **81** (2012) 024101 FULL PAPERS
DOI: 10.1143/JPSJ.81.024101

Published in Jan. 2012

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

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

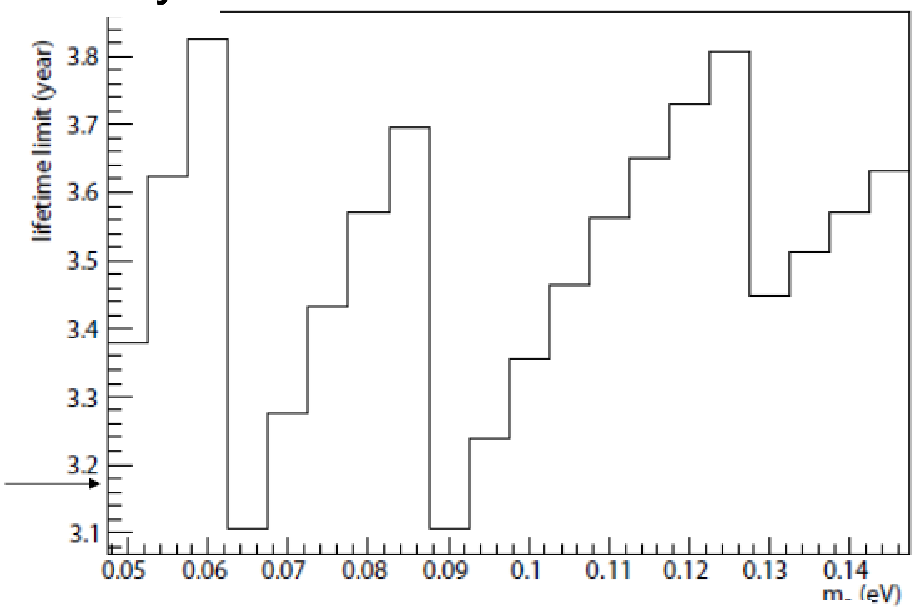
AKARI CIB data after subtracting foregrounds



Fit CIB data to E_γ spectrum expected from ν decay assuming all contribution to CIB is only from ν decay

ν_3 lifetime lower limit as a function of m_3

x10^{12} yr



$m_3 = 50$ meV~ 150 meV

Detector requirements

- Requirements for detector
  - Energy measurement for single photon with better than 2% resolution for $E_\gamma = 25\mathrm{meV}$ ($\lambda = 50\mu\mathrm{m}$, far infrared photon)
  - Rocket and satellite experiment with this detector

- **Superconducting Tunneling Junction (STJ) detectors in development**
  - Array of 50 Nb/Al-STJ pixels with diffraction grating covering $\lambda = 40 - 80\mu\mathrm{m}$
    - **For rocket experiment aimed at launching in 2016 in earliest, aiming at improvement of lower limit for $\tau(\nu_3)$ by 2 order**
  - STJ using Hafnium: Hf-STJ for satellite experiment (after 2020)
    - $\Delta = 20\mu\mathrm{eV}$: Superconducting gap energy for Hafnium
    - $N_{\mathrm{q.p.}} = 25\mathrm{meV}/\Delta = 735$ for 25meV photon: $\Delta E/E < 2\%$ if Fano-factor is less than 0.3

Energy resolution of STJ

Energy resolution of STJ is limited by fluctuation of number of quasi-particles
➔ Smaller superconducting gap energy gives better energy resolution

Energy resolution of STJ

$$\delta E_{FWHM} = 2.35\sqrt{(1.7\Delta)FE}$$

Δ: Gap energy
F: Fano factor
E: Incident photon energy

In case of Hf, number of quasi-particles is N=25meV/1.7Δ=735 ⟷ **In case of Nb, N=9.5**

$\Delta E/E < \sqrt{F/N} = 3.7\sqrt{F}\%$ @25meV

If Fano factor <0.3, 2% energy resolution is achievable

No report on practical Hf-STJ in the world

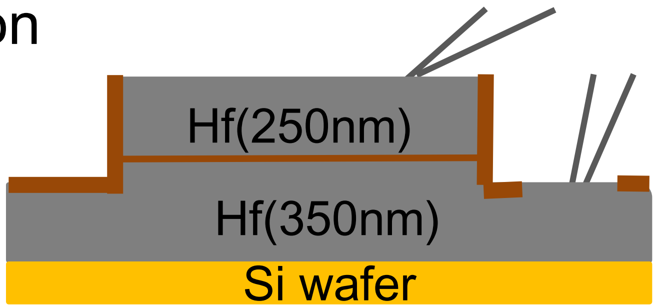
	Si	Nb	Al	Hf
Tc[K]		9.23	1.20	0.165
Δ[meV]	1100	1.550	0.172	0.020
Hc[G]		1980	105	13

Tc :Critical temperature
STJ operation temperature: 1/10 T_C
Hc :Critical magnetic field

By K. Nagata

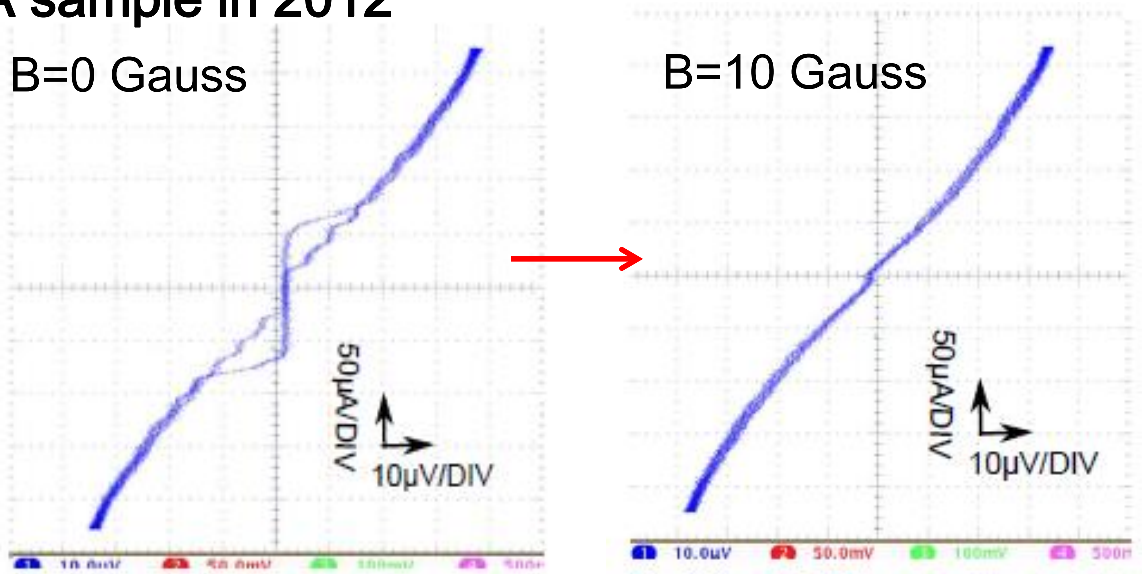
Hf-STJ development

- We succeeded in observation of Josephson current by Hf-HfOx-Hf barrier layer for the first time in the world in 2010



HfOx：20Torr,1hour
anodic oxidation：
45nm

A sample in 2012



$200\times200\mu m^2$

T=80~177mK

I_c=60μA

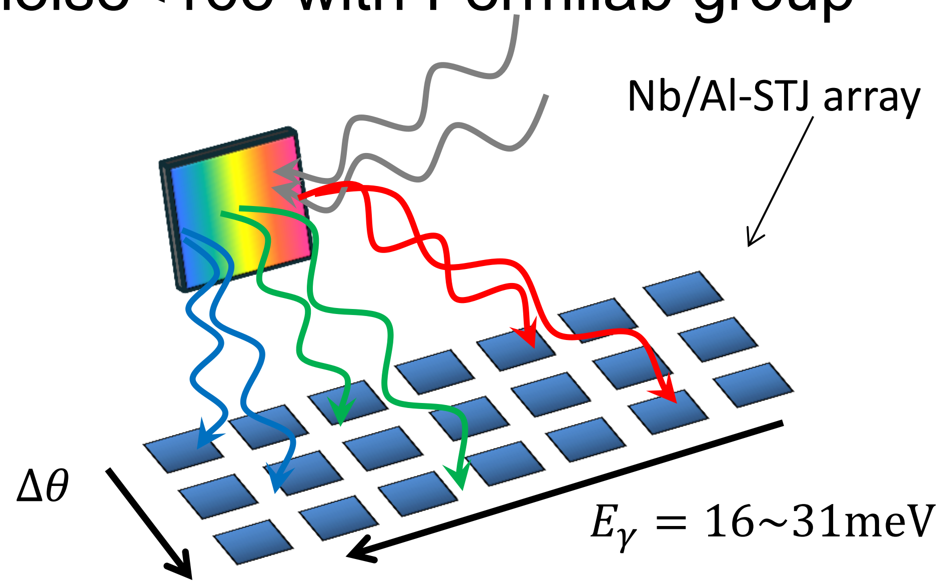
I_{leak}=50μA@V_{bias}=10μV

R_d=0.2Ω

However, to use this as a detector, much improvement in leak current is required. (I_{leak} is required to be at pA level or less)

Far Infrared Photon Spectroscopy with Diffraction Grating + Nb/Al-STJ Array

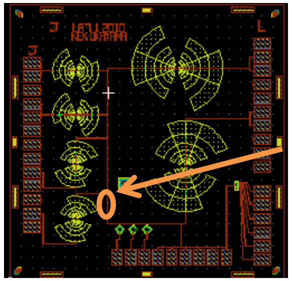
- Diffraction grating covering $\lambda = 40 - 80\mu\text{m}$ (16-31meV)
- Array of Nb/Al-STJ pixels
  - We use each Nb/Al-STJ pixel as a single-photon counting detector with extremely good S/N for FIR photon of $E_\gamma = 16{\sim}31\text{meV}$
  - $\Delta = 1.5\ \text{meV}$ for Nb: $N_{\text{q.p.}} = 60{\sim}120$ (assuming x10 for back-tunneling gain)
  - Expected average rate of photon detection is ~12kHz for a single pixel
- Developing ultra-low temperature preamplifier to achieve noise<16e with Fermilab group



Assuming $1\mu s$ for STJ response time, for 25meV single photon counting

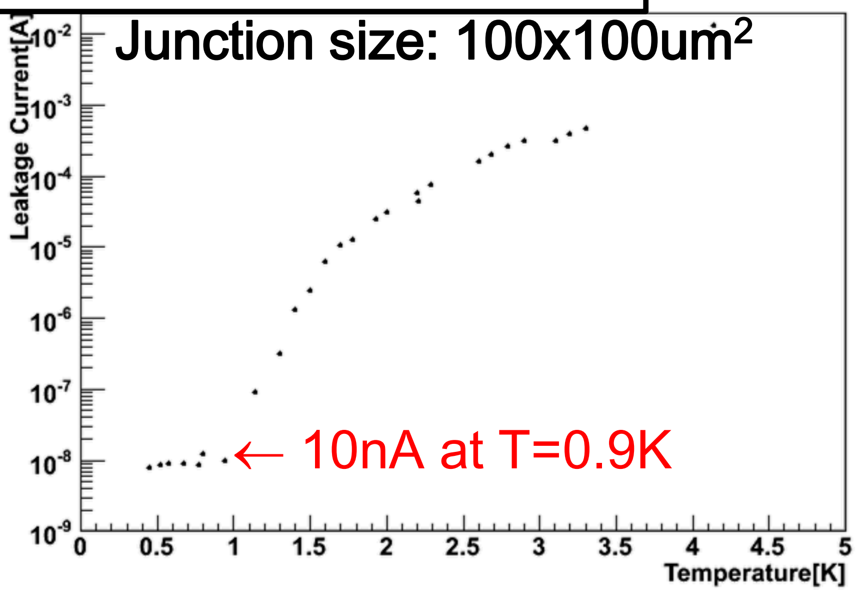
- STJ leak current <0.1nA

Temperature dependence of Nb/Al-STJ leak current



This Nb/Al-STJ is provided by S. Mima (Riken)

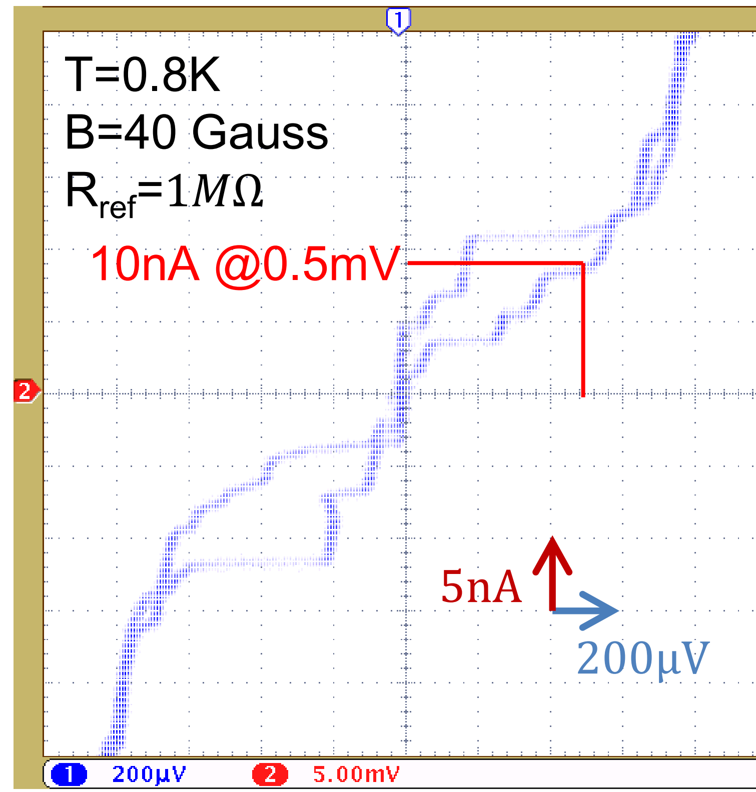
Temperature dependence



Need T<0.9K for detector operation

➔ Need to ^{3}He sorption or ADR for the operation

$100x100um^2$ Nb/Al-STJ I-V curve

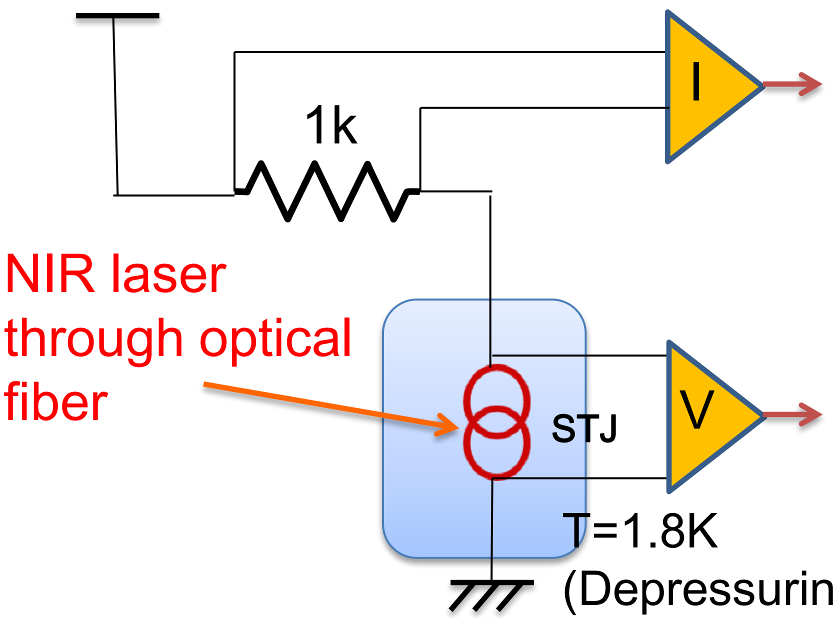


If assume leak current is proportional to junction size, can achieve 0.1nA leak current to **$\sim 100\mu m^2$** junction size

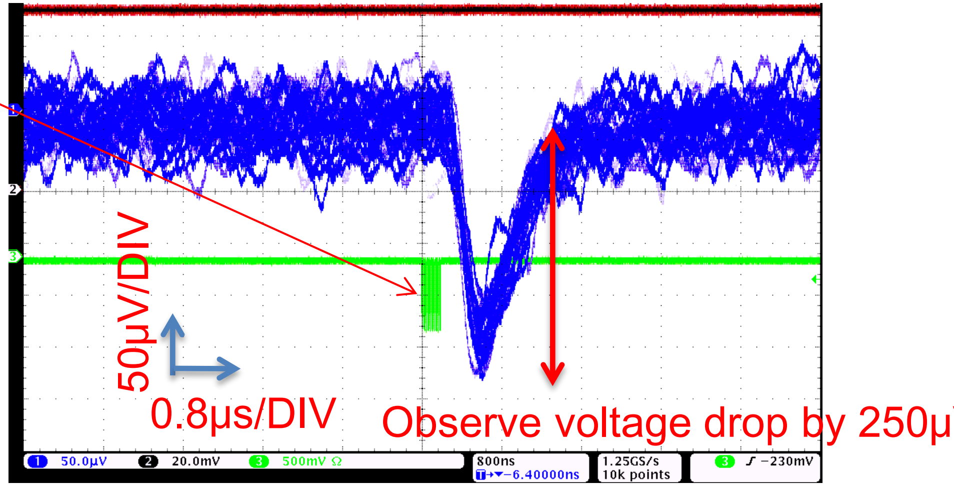
by T. Okudaira

Nb/Al-STJ response to NIR photons

10 laser pulses in 200ns (each laser pulse has 56ps width



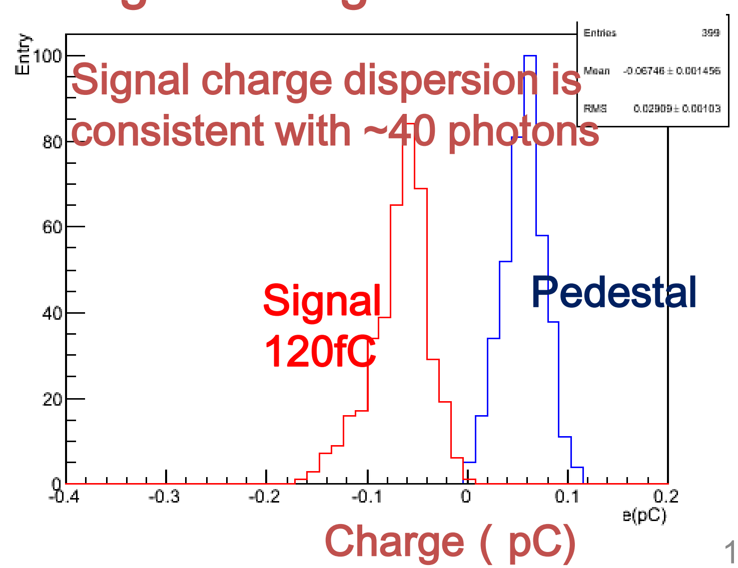
Response to NIR laser pulse (λ=1.31μm)



We observed a response to NIR photons

- Response time ~1μs
- Corresponding to 40 photons (Assuming incident photon statistics)
- Back-tunneling gain 45 (assuming 40 photons corresponds 120fC)

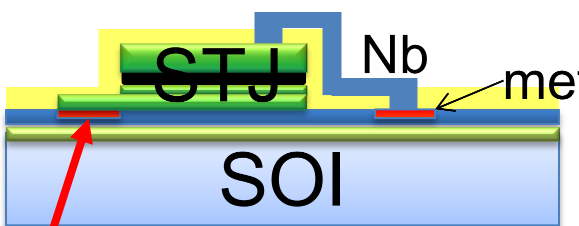
Signal charge distribution



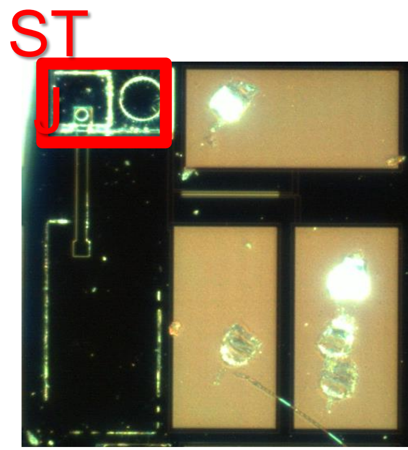
By Kota Kasahara

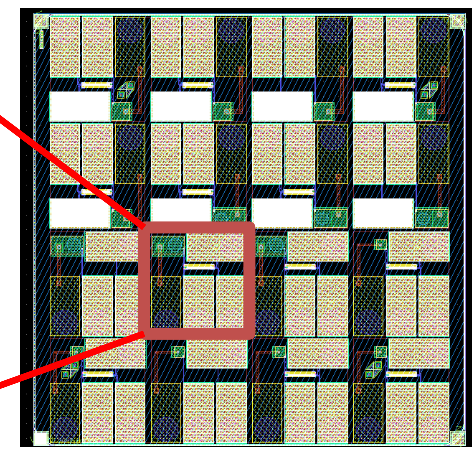
Development of SOI-STJ

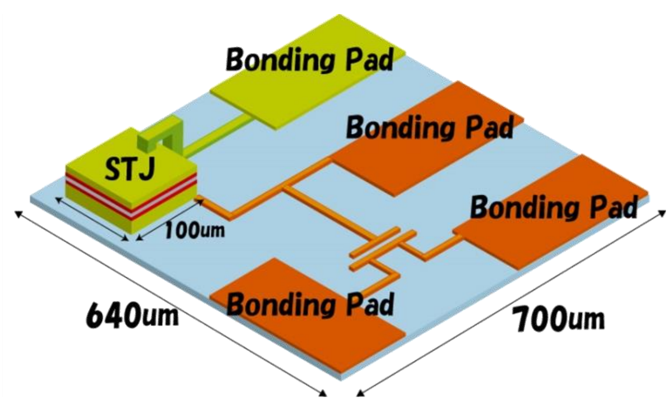
- SOI: Silicon-on-insulator
  - CMOS in SOI is reported to work at 4.2K by T. Wada (JAXA), et al. Phys. 167, 602 (2012)
- A development of SOI-STJ for our application with Y. Arai (KEK)
  - STJ layer sputtered directly on SOI pre-amplifier
- Started test with Nb/Al-STJ on SOI with p-MOS and n-MOS FET

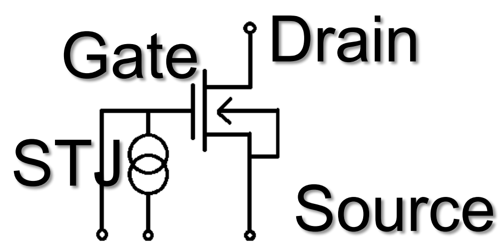


STJ lower layer has electrical contact with SOI circuit



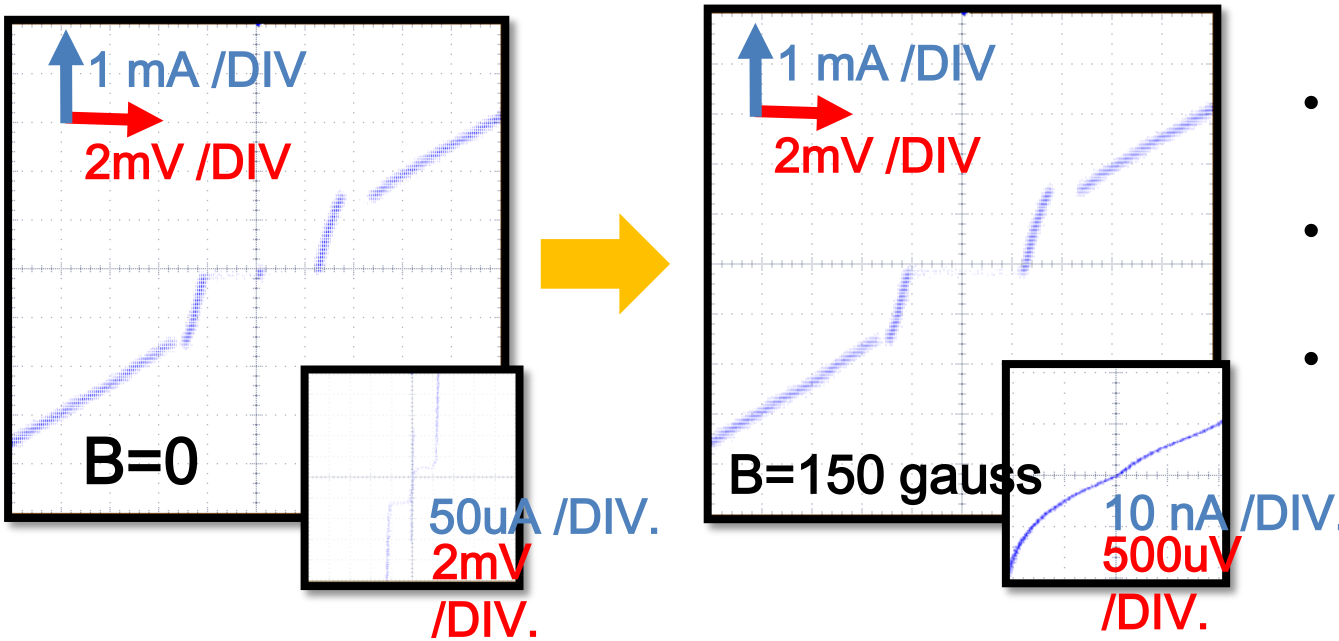




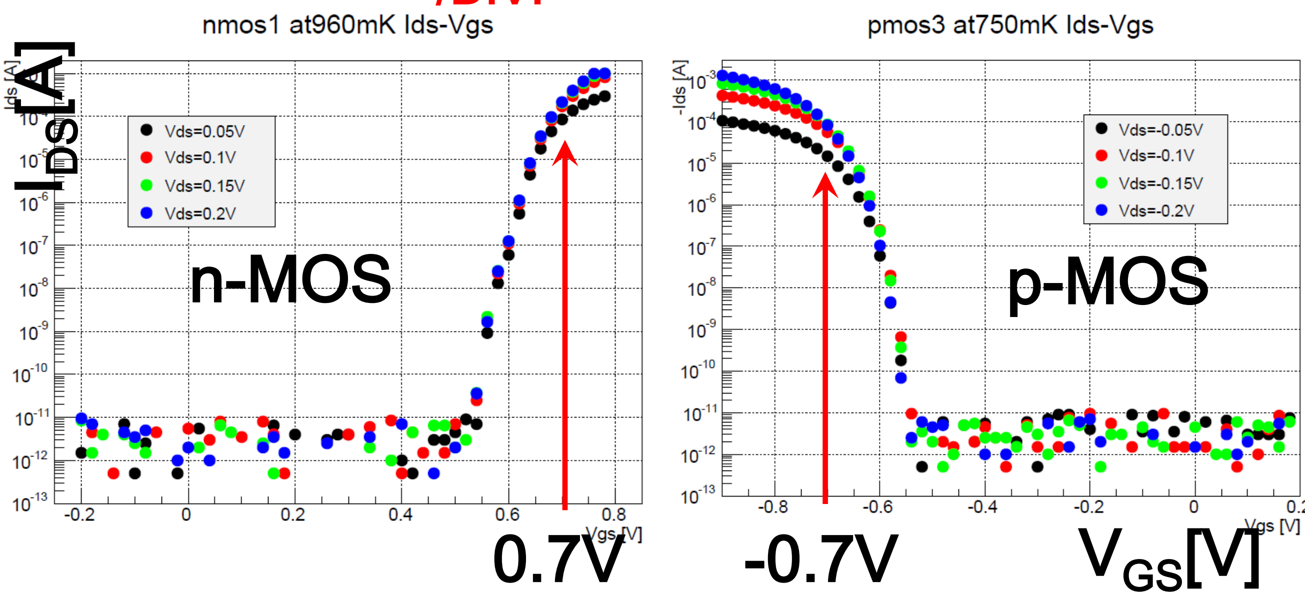


Development of SOI-STJ

by K. Kasahara



- We formed Nb/Al-STJ on SOI
- Josephson current observed
- Leak current is 6nA @V_{bias}=0.5mV, T=700mK



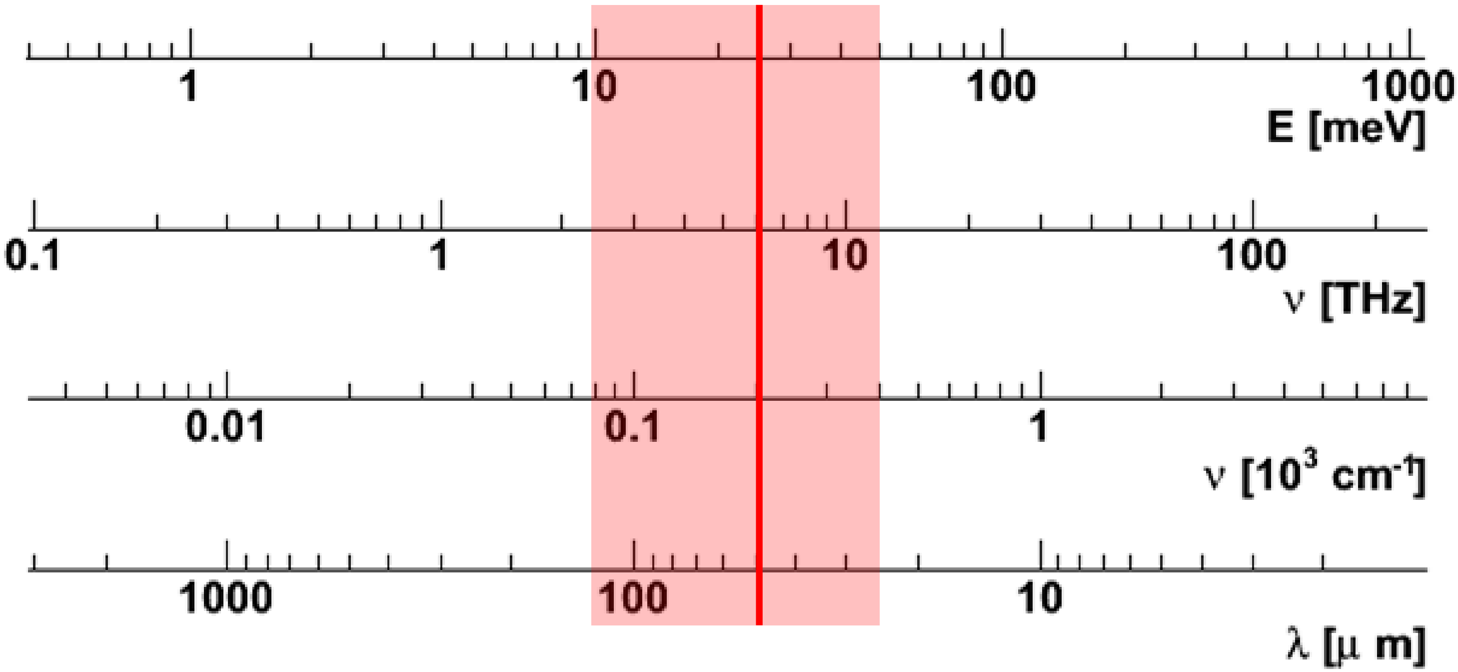
- n-MOS and p-MOS in SOI on which STJ is formed
- Both n-MOS and p-MOS works at T=750~960mK

Summary

- We propose an experiment to search for neutrino radiative decay in cosmic neutrino background
  - There is some chance to observe to neutrino radiative decay if we assume L-R symmetric model
- We are developing a detector to measure single photon energy with <2% resolution for $E_\gamma = 25\mathrm{meV}$.
  - Nb/Al-STJ array with grating and Hf-STJ are being considered
- We've confirmed to SIS structure in our Hf-STJ prototypes
  - Much improvement in leakage current is required for a practical use
- Development of readout electronics for Nb/Al-STJ is underway
  - As the first milestone, aiming to single NIR photon counting
  - Several ultra low temperature amplifier candidates are under development. SOI-STJ is one of promising candidates

Backup

Energy/Wavelength/Frequency



$$E_\gamma = 25 \text{ meV}$$

$$\nu = 6 \text{ THz}$$

$$\lambda = 50\mu m$$

Feasibility of FIR single photon detection

- Assume typical time constant from STJ response to pulsed light is ~1μs
- Assume leak current is 0.1nA

$$0.1nA = 6.25 \times 10^8 e/s = 6.25 \times 10^2 e/\mu s$$

Fluctuation due to electron statistics in 1μs is

$$\sqrt{6.25 \times 10^2} e/\mu s = 25\, e/\mu s$$

While expected signal charge for 25meV are

$$25\text{meV}/1.7\Delta \times 10e = \frac{25\text{meV}}{1.7 \times 1.5\text{meV}} \times 10e = 98e$$

(Assume back tunneling gain x10)

More than 3sigma away from leakage fluctuation