Search for neutrino radiative decay and the status of the far-infrared photon detector development

1st CiRfSE Workshop

Mar. 12-13, 2015 / University of Tsukuba, Japan

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for Neutrino Decay Collaboration

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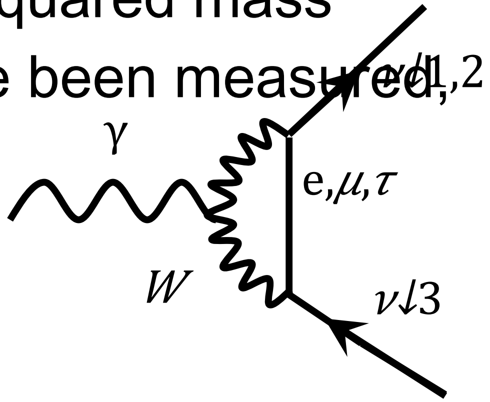
- Summary

Neutrino

- Neutrino has 3 mass generations (ν_1, ν_2, ν_3)
- Neutrino flavor states (ν_e, ν_μ, ν_τ) are not mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

➔ Neutrino flavor oscillates during the flight, and squared mass differences (Δm_{12}^2, $|\Delta m_{23}^2|$) have been measured, **but their absolute masses is not measured yet!**



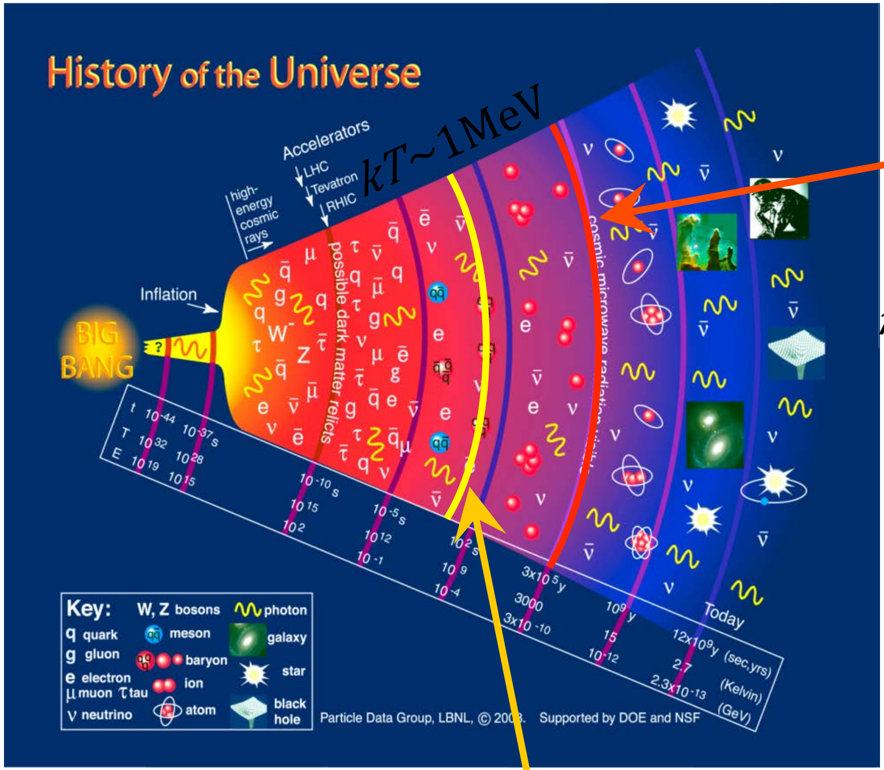
☐ Neutrino can decay through the loop diagram

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

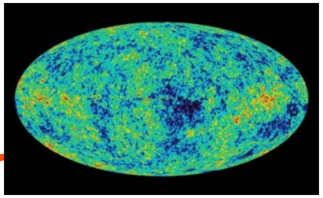
✓ Neutrino lifetime is expected to be very long

➔ use Cosmic neutrino background (CνB) as the best neutrino source for neutrino decay search

Cosmic neutrino background (CνB)



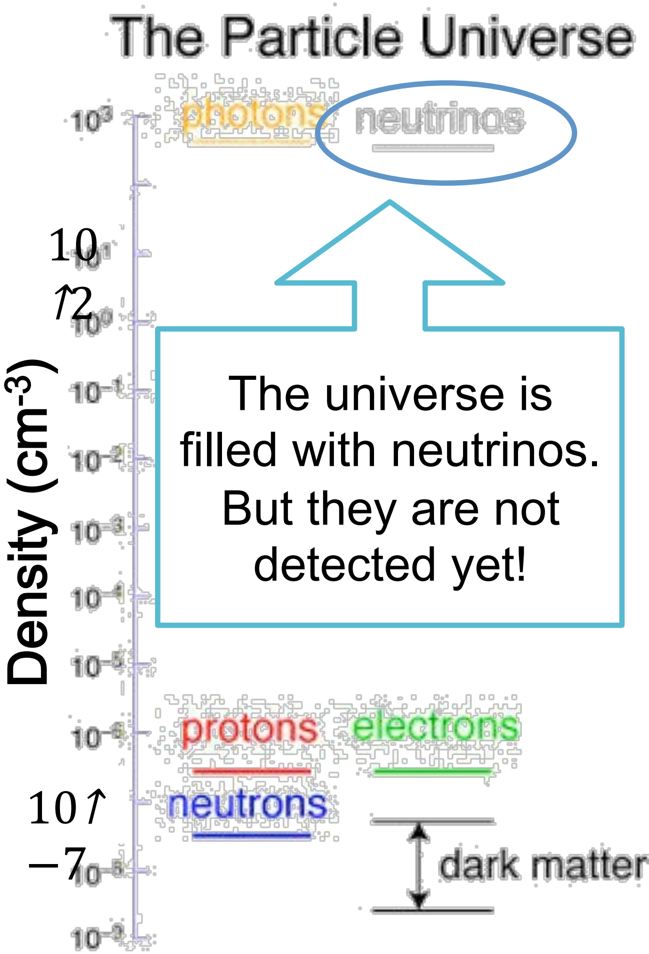
$kT \sim 1\,\mathrm{MeV}$



CMB

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

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



10^{2}

10^{-7}

The universe is filled with neutrinos. But they are not detected yet!

CνB (~1s after big bang)

$n_\nu + n_{\bar\nu} = \frac{3}{4}\left(T_\nu / T_\gamma\right)^3 n_\gamma = 110/\mathrm{cm}^3$

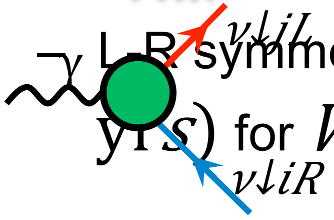
$T_\nu = (4/11)^{1/3}\, T_\gamma = 1.95\mathrm{K}$

$\langle p_\nu \rangle = 0.5\,\mathrm{meV}/c$

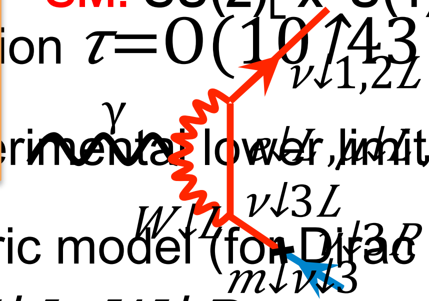
Motivation of ν-decay search in CνB

- Search for $\nu_3 \rightarrow \nu_{1,2} + \gamma$ in cosmic neutrino background (CνB)
  - Direct detection of CνB
  - Direct detection of transition magnetic dipole moment of neutrino
  - 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 $\tau(\nu_3) = O(10^{17}\ \mathrm{yrs})$
  - ion $\tau = O(10^{43}\ \mathrm{yrs})$
  - erimental lower limit $\tau > O(10^{12}\ \mathrm{yrs})$
  - L-R symmetric model (for Dirac neutrino) predicts down to $\tau = O(10^{17}\ \mathrm{yrs})$ for W_L-W_R mixing angle $\zeta < 0.02$

Magnetic moment term (L-R coupling)
$\bar{\nu}_{jL}\, \sigma_{\mu\nu} q^\nu\, \nu_{iR}$



SM: SU(2)$_L$ x U(1)$_Y$

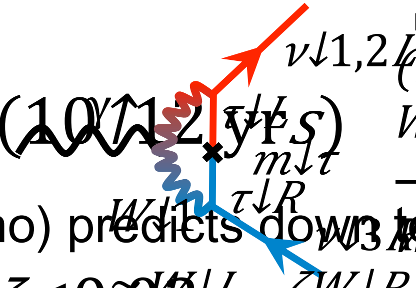


$\Gamma \sim (10^{43}\ yr)^{-1}$

Suppressed by m_ν and GIM

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

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



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

$W_1 \simeq W_L - \zeta W_R$

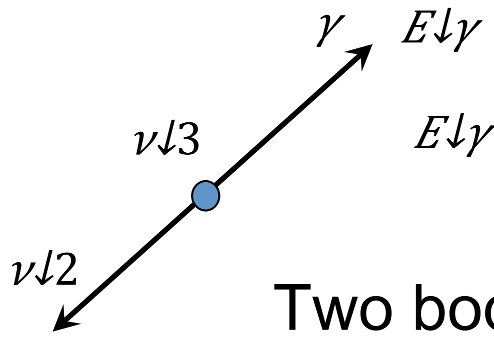
$\Gamma \sim (10^{17}\ yr)^{-1}$

Only suppressed by L-R mixing (ζ)

10^{26} enhancement to SM

Photon Energy in Neutrino Decay

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



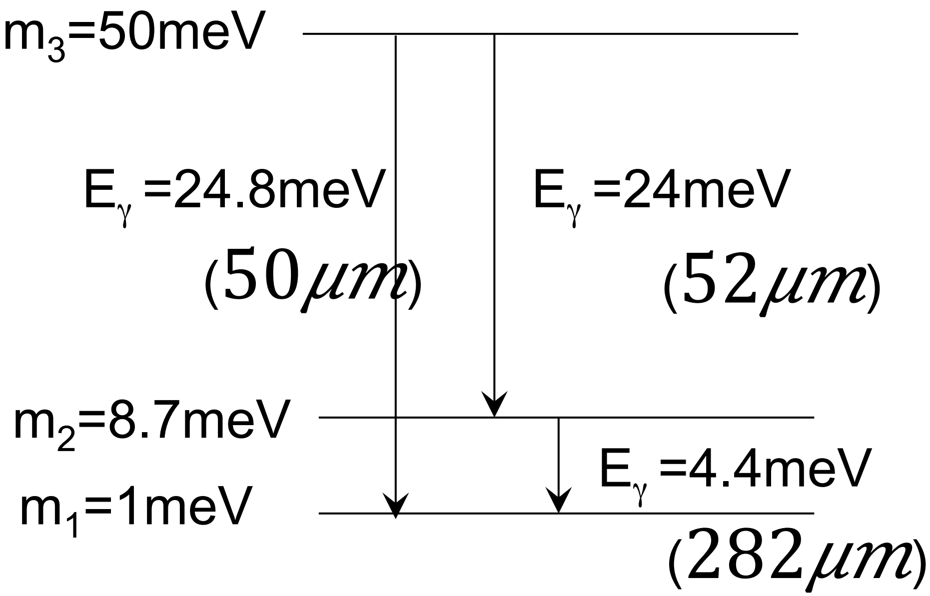
Two body decay

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

- From neutrino oscillation
  - $|\Delta m_{23}^2| = |m_3^2 - m_2^2| \sim 2.4\times10^{-3}\ eV^2$
  - $\Delta m_{12}^2 \sim 7.65\times10^{-5}\ eV^2$
- From Planck+WP+highL+BAO
  - $\sum m_i < 0.23$ eV

➔ 50meV< m_3 <87meV

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



m$_3$=50meV

m$_2$=8.7meV

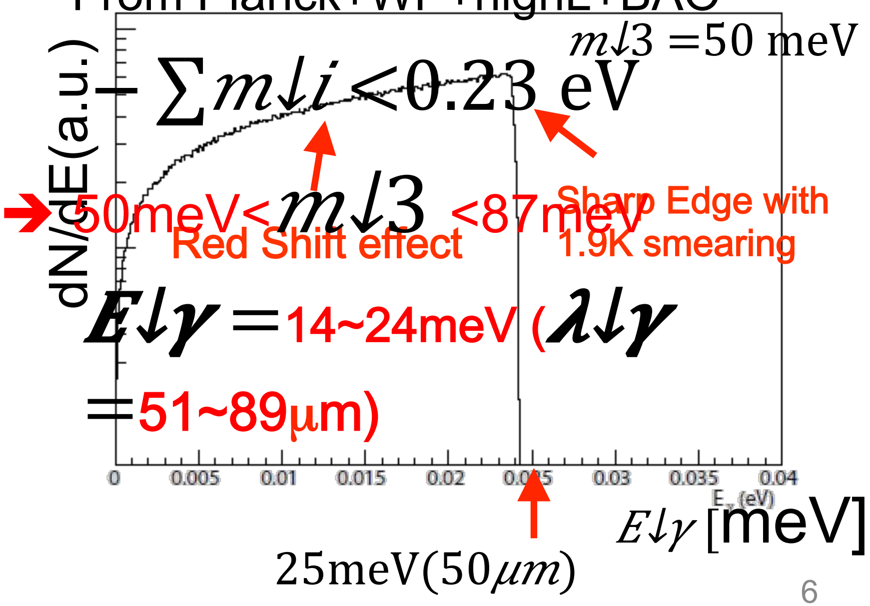
m$_1$=1meV

E$_\gamma$ =24.8meV ($50\mu m$)

E$_\gamma$ =24meV ($52\mu m$)

E$_\gamma$ =4.4meV ($282\mu m$)

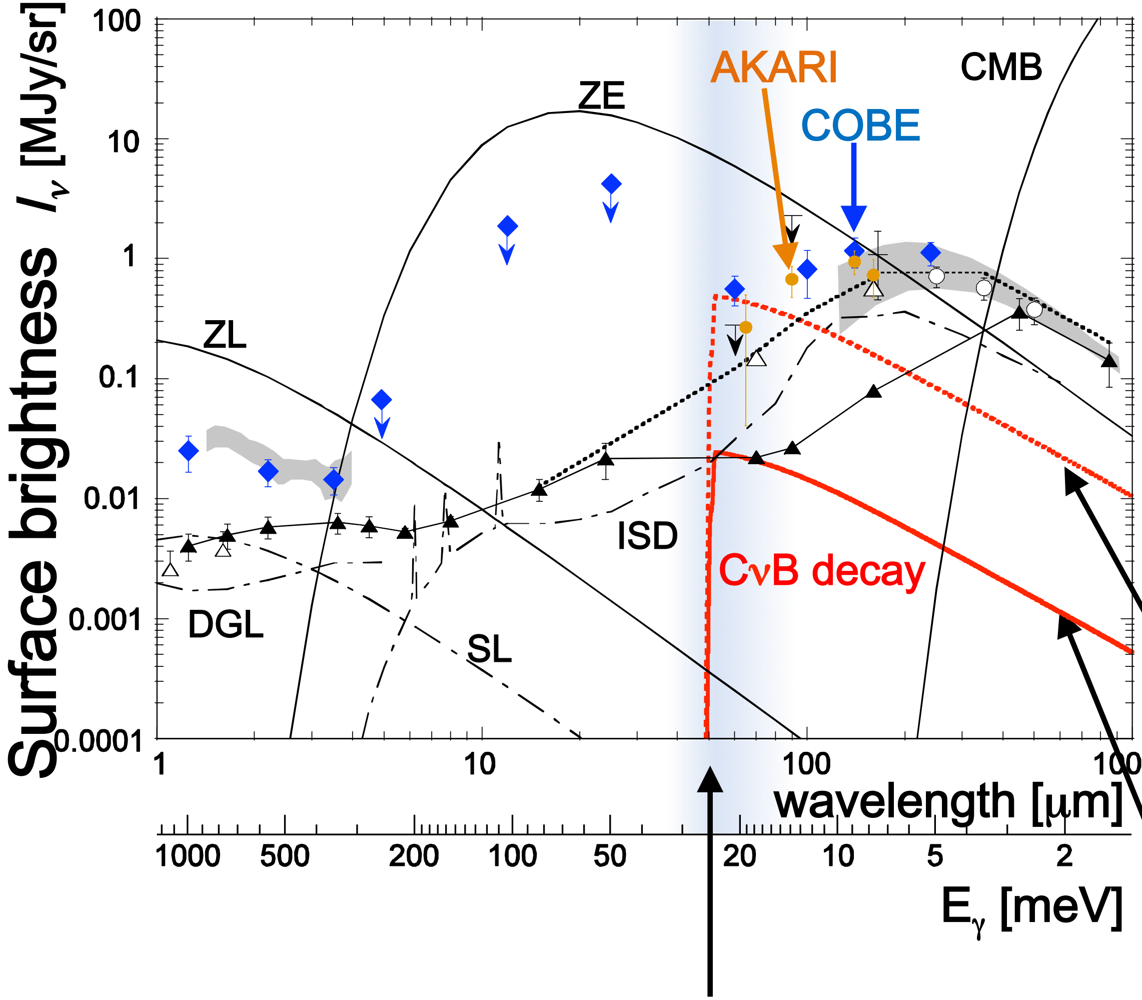
E_γ distribution in $\nu_3 \rightarrow \nu_2 + \gamma$



Red Shift effect

Sharp Edge with 1.9K smearing

Backgrounds to CνB decay



λ = 50 μm
E_γ=25 meV

at λ = 50μm

Zodiacal Emission

I_ν ~ 8 MJy/sr

CIB

λI_λ ~ 0.1-0.5 MJy/sr

CνB decay

Expected E_γ spectrum

m_3 =50meV

$\tau=5\times10^{12}$ yrs

I_ν ~ 0.5MJy/sr

$\tau=1\times10^{14}$ yrs

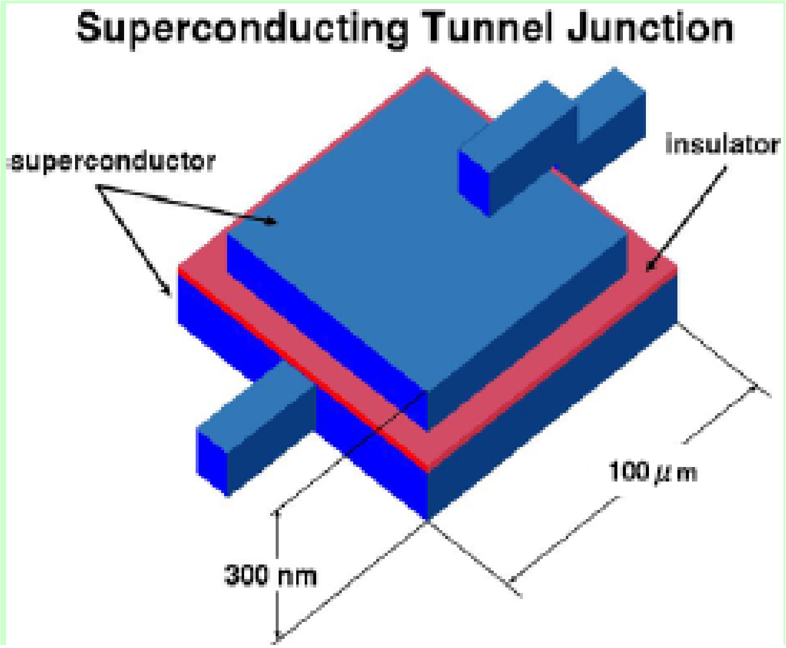
I_ν ~ 25kJy/sr

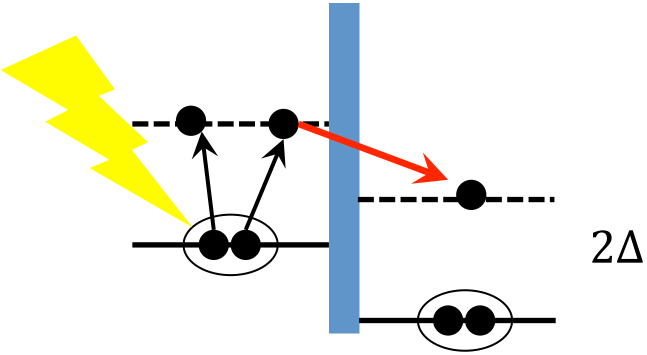
Detector requirements

- Continuous spectrum of photon energy around λ=50μm (far infrared photon) with highly precise accuracy
  - Photon-by-photon energy measurement with better than 2% resolution for $E_\gamma = 25\,\mathrm{meV}$ (λ=50μm) to achieve better S/N as well as to identify the sharp edge in the spectrum
  - A ground-based experiment is impossible, so rocket and/or satellite experiments with this detector are required
- **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 the rocket experiment aiming at improvement of current lower limit for $\boldsymbol{\tau(\nu_3)}$ by 2 order : O(10^{14} yrs) in a 200-sec measurement**
  - STJ using Hafnium: Hf-STJ for satellite experiment
    - $\Delta = 20\,\mu\mathrm{eV}$: Superconducting gap energy for Hafnium
    - $N_{\mathrm{q.p.}} = 25\,\mathrm{meV}/1.7\Delta = 735$ for 25meV photon: $\Delta E/E < 2\%$ if

STJ(Superconducting Tunnel Junction) Detector

- Superconductor / Insulator /Superconductor Josephson junction device

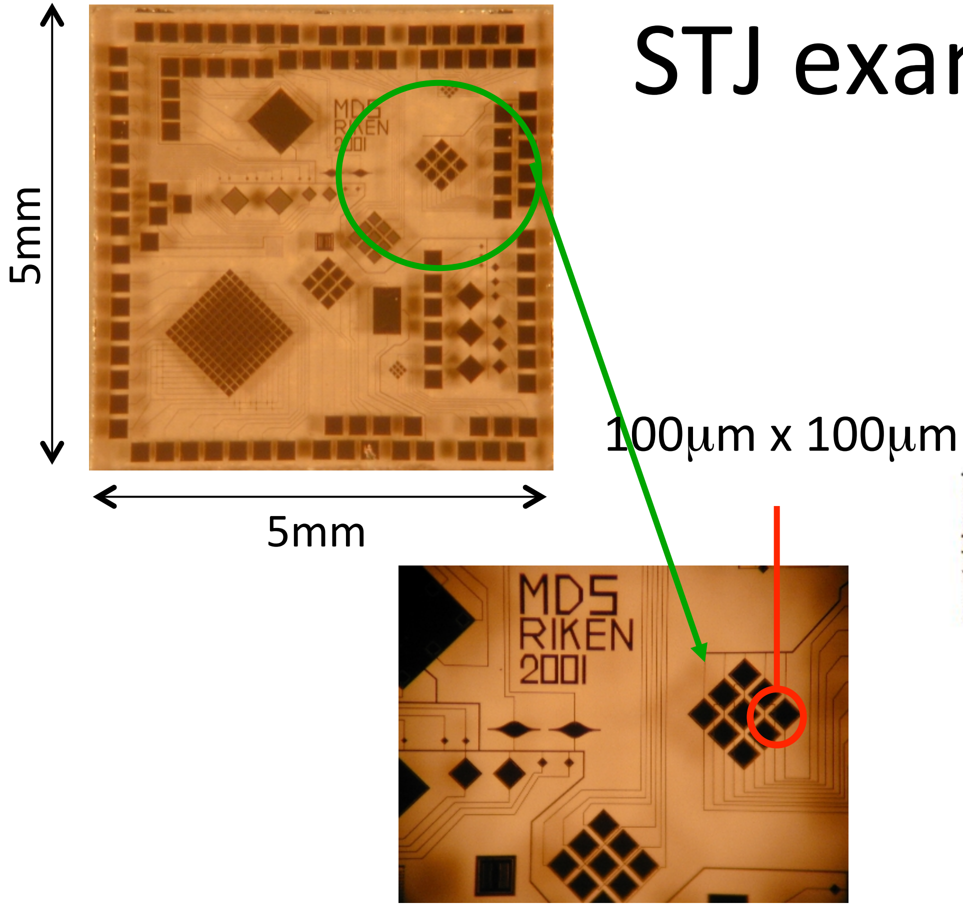




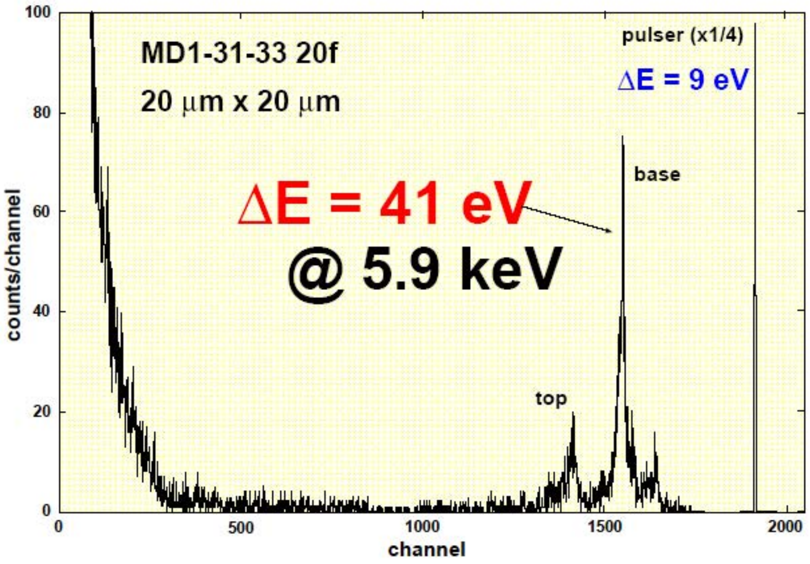
Δ: Superconducting gap energy

A bias voltage (|V|<2Δ) is applied across the junction.
A photon absorbed in the superconductor breaks Cooper pairs and creates tunneling current of quasi-particles proportional to the photon energy.

STJ examples



5.9KeV X-ray



H. Sato (RIKEN)

- STJs are already in practical use as a single photon spectrometer for a photon ranging from near-infrared to X-ray, and show excellent performances comparing to conventional semiconductor detectors

But no example for far-infrared photon so far

STJ energy resolution

Statistical fluctuation in number of quasi-particles determines energy resolution

→ Smaller superconducting gap energy Δ yields better energy resolution

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

Δ: Superconducting gap energy
F: fano factor
E: Photon energy

	Si	Nb	Al	Hf
Tc[K]		9.23	1.20	0.165
Δ[meV]	1100	1.550	0.172	0.020

Tc :SC critical temperature
Need ~1/10Tc for practical operation

Nb

Well-established as Nb/Al-STJ (back-tunneling gain from Al-layers)

$N_{q.p.}$=25meV/1.7Δ=9.5

Poor energy resolution, but photon counting is possible in principle

Hf

Hf-STJ is not established as a practical photon detector

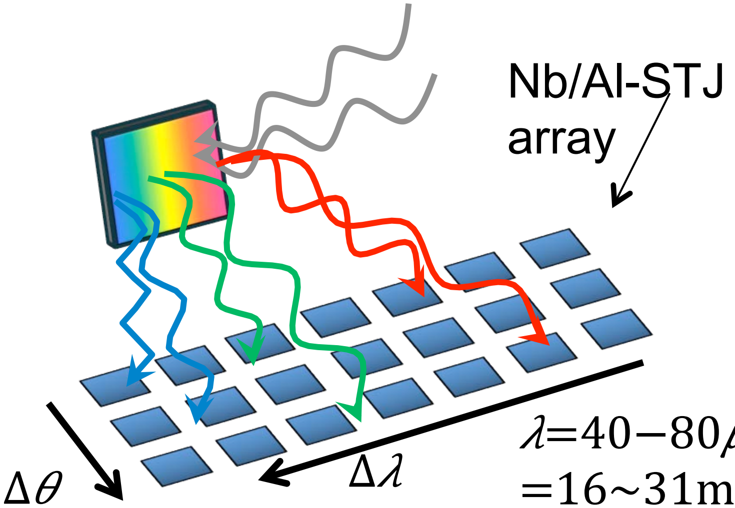
$N_{q.p.}$=25meV/1.7Δ=735

2% energy resolution is achievable if Fano factor <0.3

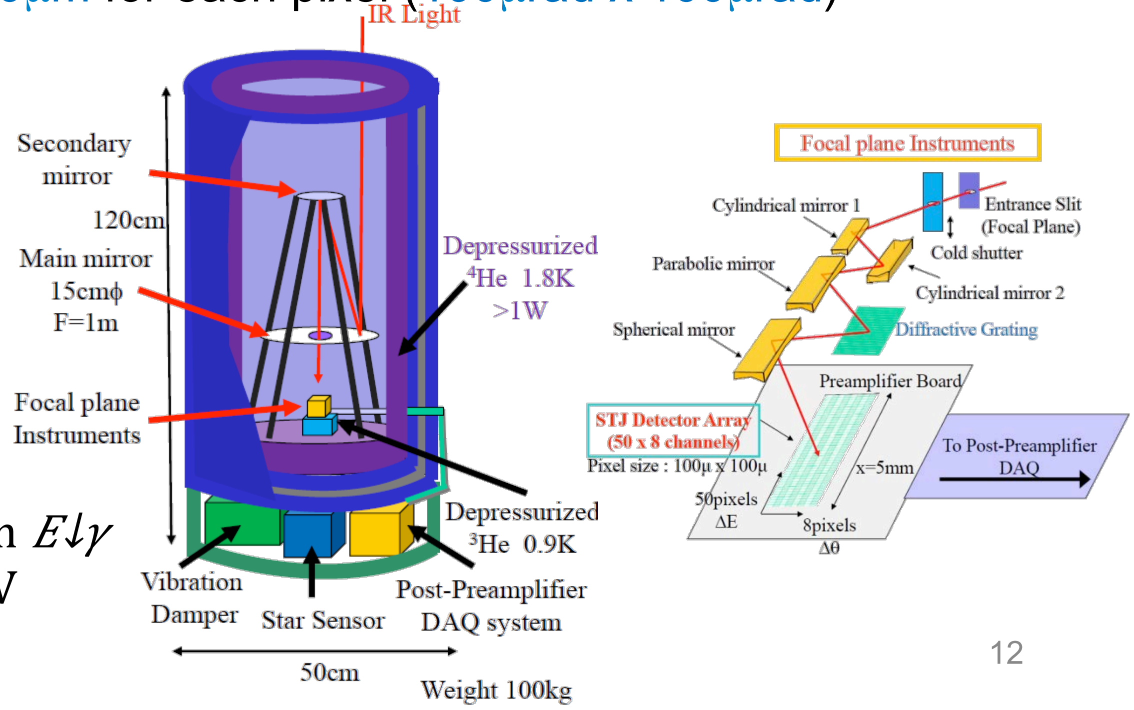
In both cases, developments are challenging

Proposal of a rocket experiment

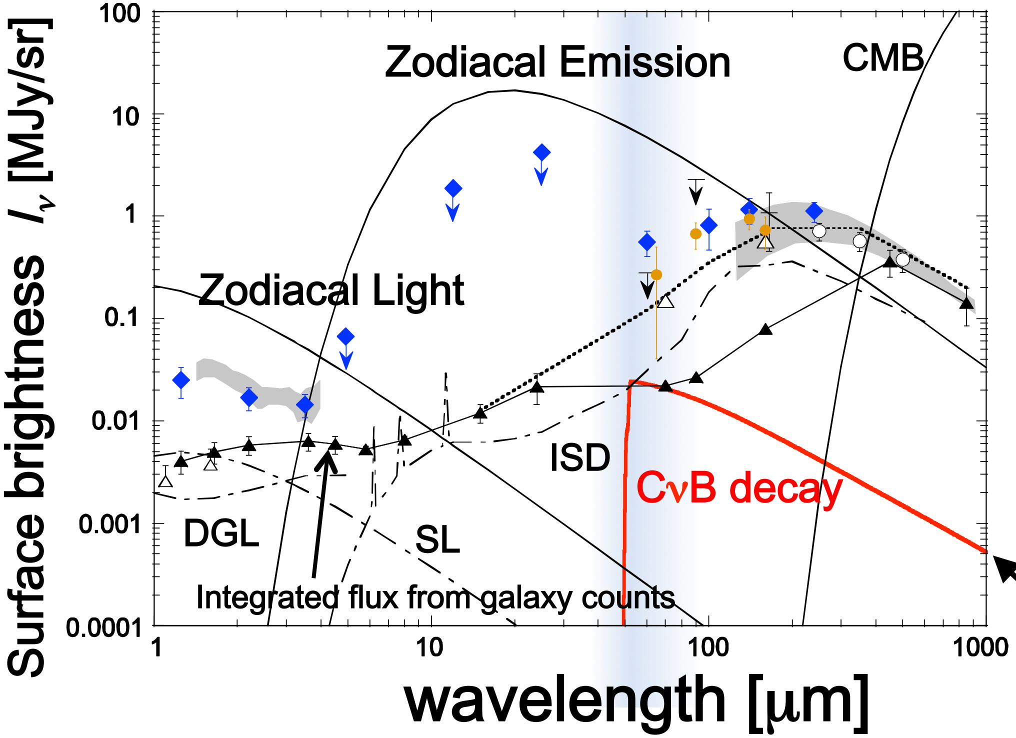
- Expect 200s measurement at altitude of 200~300km
  - Telescope with diameter of 15cm and focal length of 1m
  - All optics (mirrors, filters, shutters and grating) will be cooled below 4K
- Diffraction grating covering λ=40-80μm (16-31meV) and array of Nb/Al-STJ pixels: 50(λ) x 8(θ)
  - ☐ Use each Nb/Al-STJ pixel as a single-photon counting detector for FIR photon of $\lambda=40-80\mu m$ ($\Delta\lambda=0.8\mu m$)
  - ☐ sensitive area of 100μmx100μm for each pixel (100μrad x 100μrad)



$\lambda=40-80\mu m$ E_{γ} $=16\sim31\mathrm{meV}$



Expected accuracy in the spectrum measurement



Telescope parameters

- Main mirror
  - D=15cm, F=1m
- detector
  - sensitive area 100μmx100μm/ pixel
  - 50 x 8 array

$\Delta\lambda = 80\mu m - 40\mu m / 50 = 0.8\mu m$

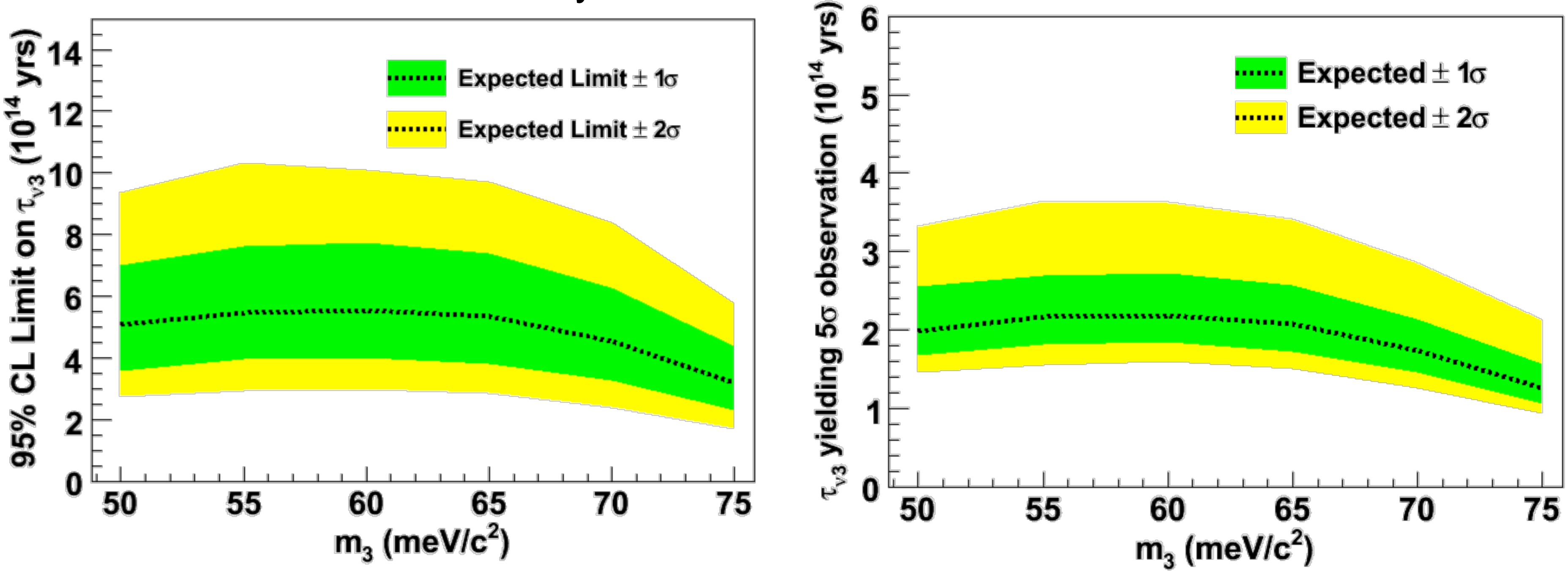
$\tau = 1\times 10^{14}$ yr

- Zodiacal emission ⇒ 343Hz / pixel
  - 200sec measurement: 0.55M events / 8 pixels (at $\lambda = 50\mu m$)
  - 0.13% accuracy measurement for each wavelength: $\delta(I_\nu)$=11kJy/sr
- ν decay with $\tau_\nu = 10^{14}$ yrs is possible to detect, or set :

Sensitivity to neutrino decay

Parameters in the rocket experiment simulation

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

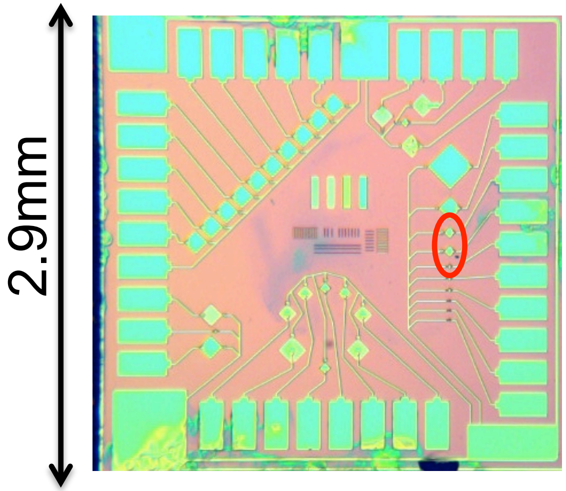


- Can set lower limit on ν_3 lifetime at 4-6 × 10^{14} yrs if no neutrino decay observed
- If ν_3 lifetime were 2 × 10^{14} yrs, can observe the signal at 5σ significance level

Status of Nb/Al-STJ photon detector development

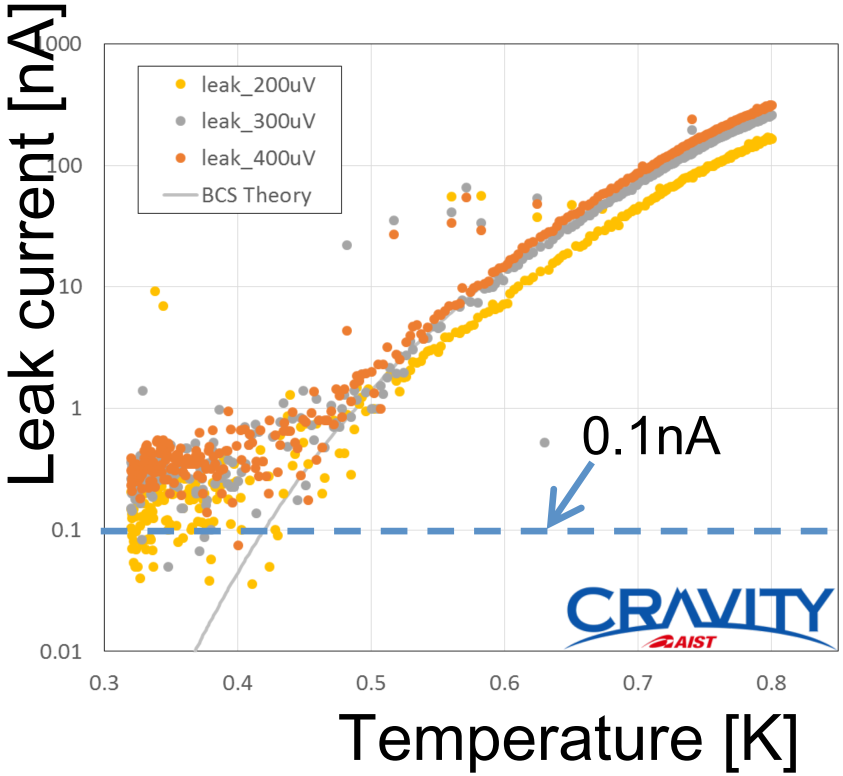
Requirements for Nb/Al-STJ

- Single photon detection for E_γ=25meV (λ=50μm)
  - Detection efficiency: ~1
- Dark count rate < 30Hz ➔ STJ leak current < 0.1nA
- Sensitive area: 100μm × 100μm



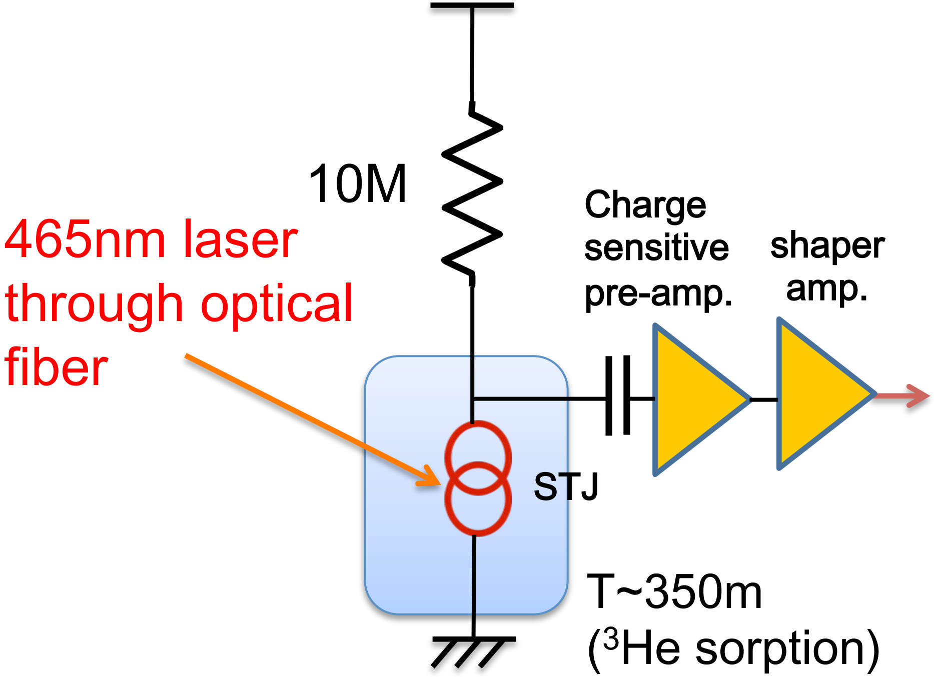
50μm × 50μm Nb/Al-STJ fabricated at CRAVITY in AIST

- I_{leak}<1nA achieved at AIST
- We will try STJs with a smaller junction size



100x100μm^2 Nb/Al-STJ response to 465nm multi-photons

100x100μm^2 Nb/Al-STJ fabricated at CRAVITY



465nm laser through optical fiber

10M

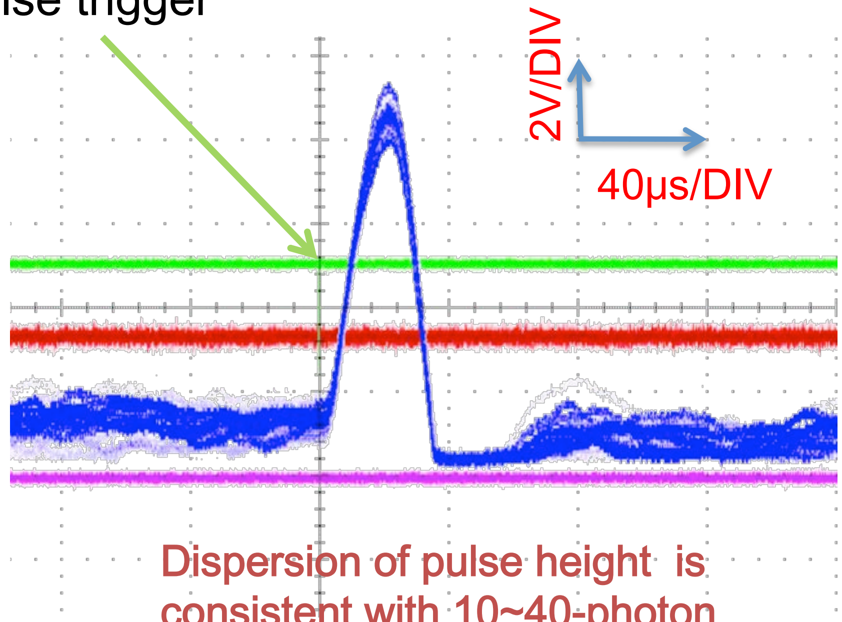
Charge sensitive pre-amp.

shaper amp.

STJ

T~350m (^{3}He sorption)

Laser pulse trigger



Dispersion of pulse height is consistent with 10~40-photon detection in STJ

We observed a response of Nb/Al-STJs to NIR-VIS photons at nearly single photon level

- Response time of STJ: O(1μs)

Due to the readout noise, we have not achieved FIR single photon detection

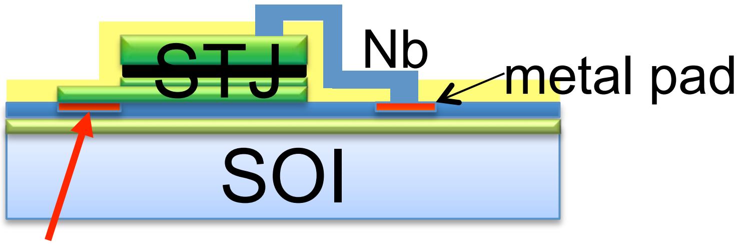
➔Need ultra-low noise readout system for STJ signal

Development of SOI-STJ

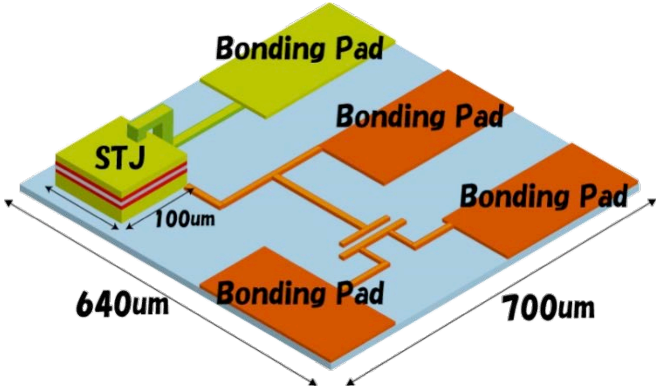
- SOI: Silicon-on-insulator
  - CMOS in FD-SOI is reported to work at 4.2K by T. Wada (JAXA), et al.

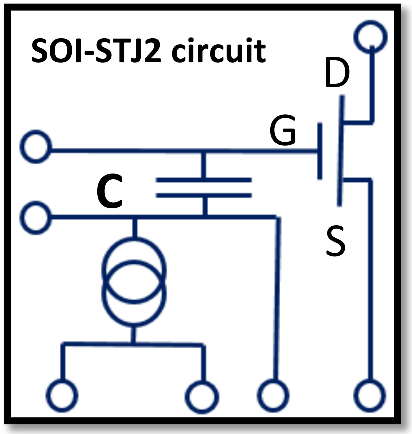
Phys. 167, 602 (2012)

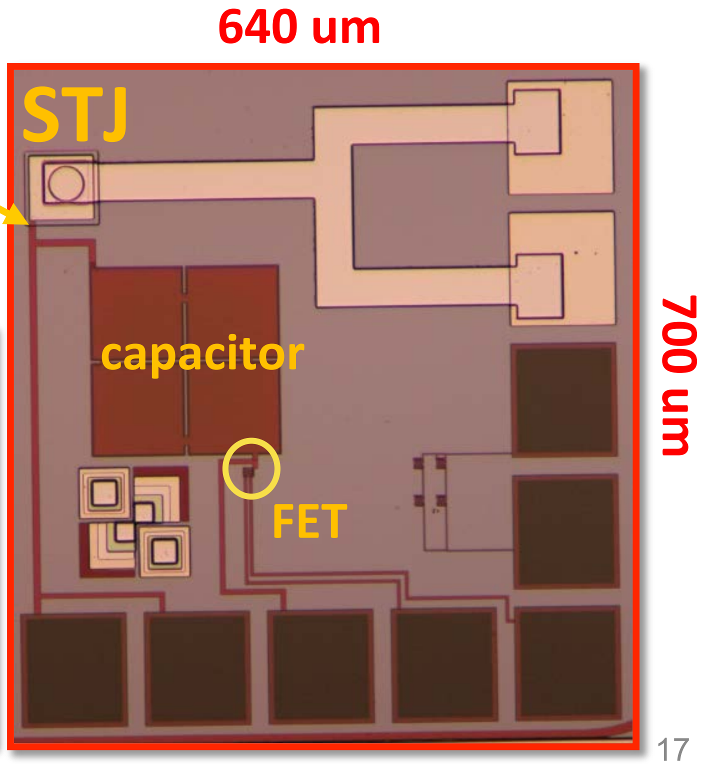
- A development of SOI-STJ for our application
  - STJ layer is fabricated directly on SOI pre-amplifier and cooled down together with STJ
- Started test with Nb/Al-STJ on SOI with p-MOS and n-MOS FET



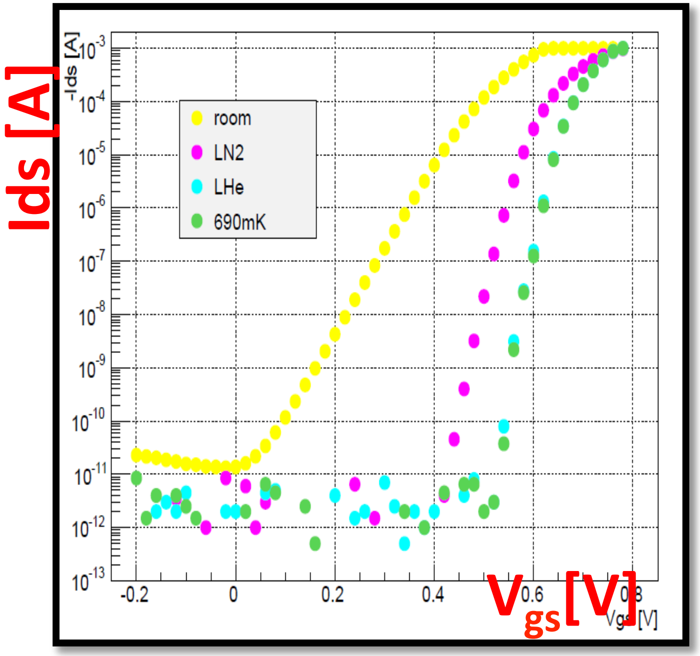
STJ lower layer has electrical contact with SOI circuit



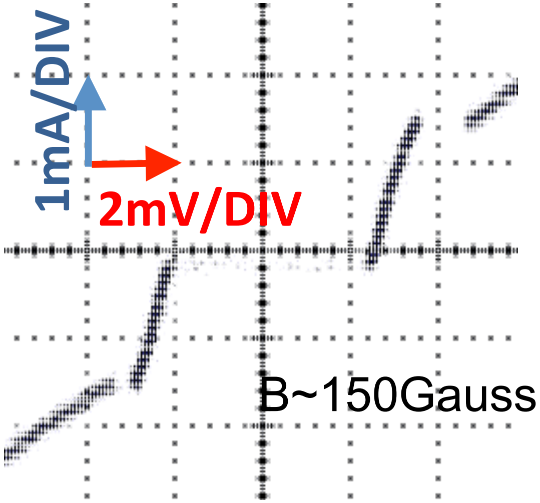




FD-SOI on which STJ is fabricated



nMOS-FET in FD-SOI wafer on which a STJ is fabricated at KEK

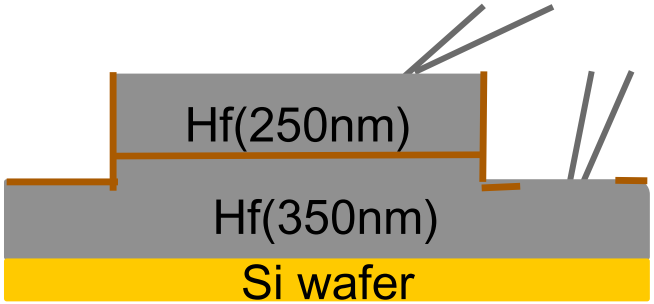


I-V curve of a STJ fabricated at KEK on a FD-SOI wafer

- Both nMOS and pMOS-FET in FD-SOI wafer on which a STJ is fabricated work fine at temperature down to ~100mK
- We are also developing SOI-STJ where STJ is fabricated at CRAVITY
- Charge sensitive pre-amplifier in SOI for STJ readout is also under development

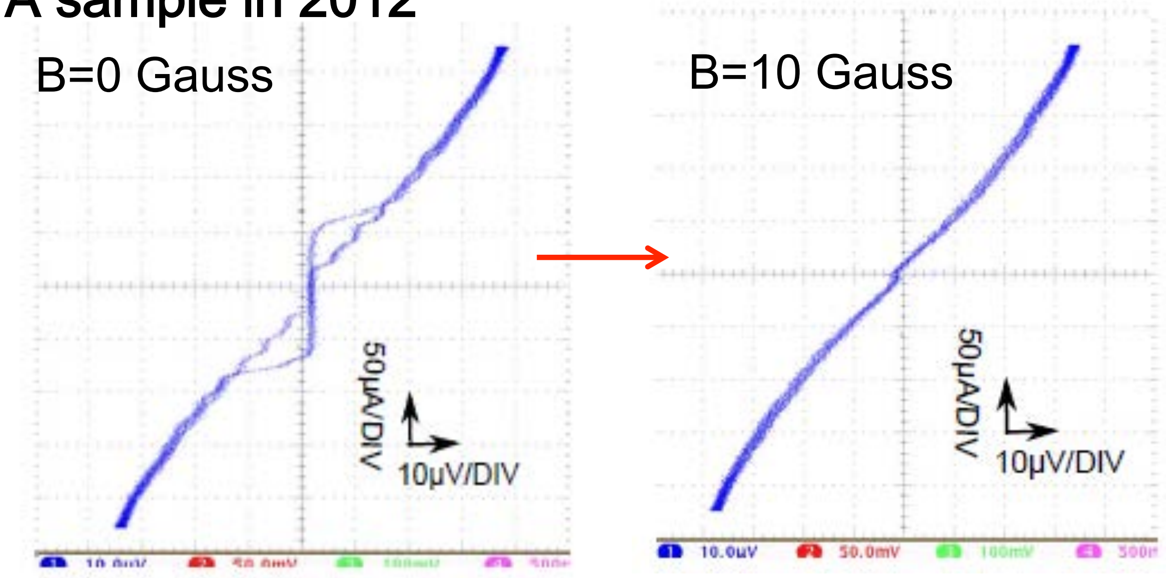
Hf-STJ development

- We succeeded in observation of Josephson current by Hf-HfOx-Hf barrier layer in 2010 (S.H.Kim et. al, TIPP2011)



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

A sample in 2012



$200\times200\mu m^2$

T=80~177mK

$I_c=60\mu A$

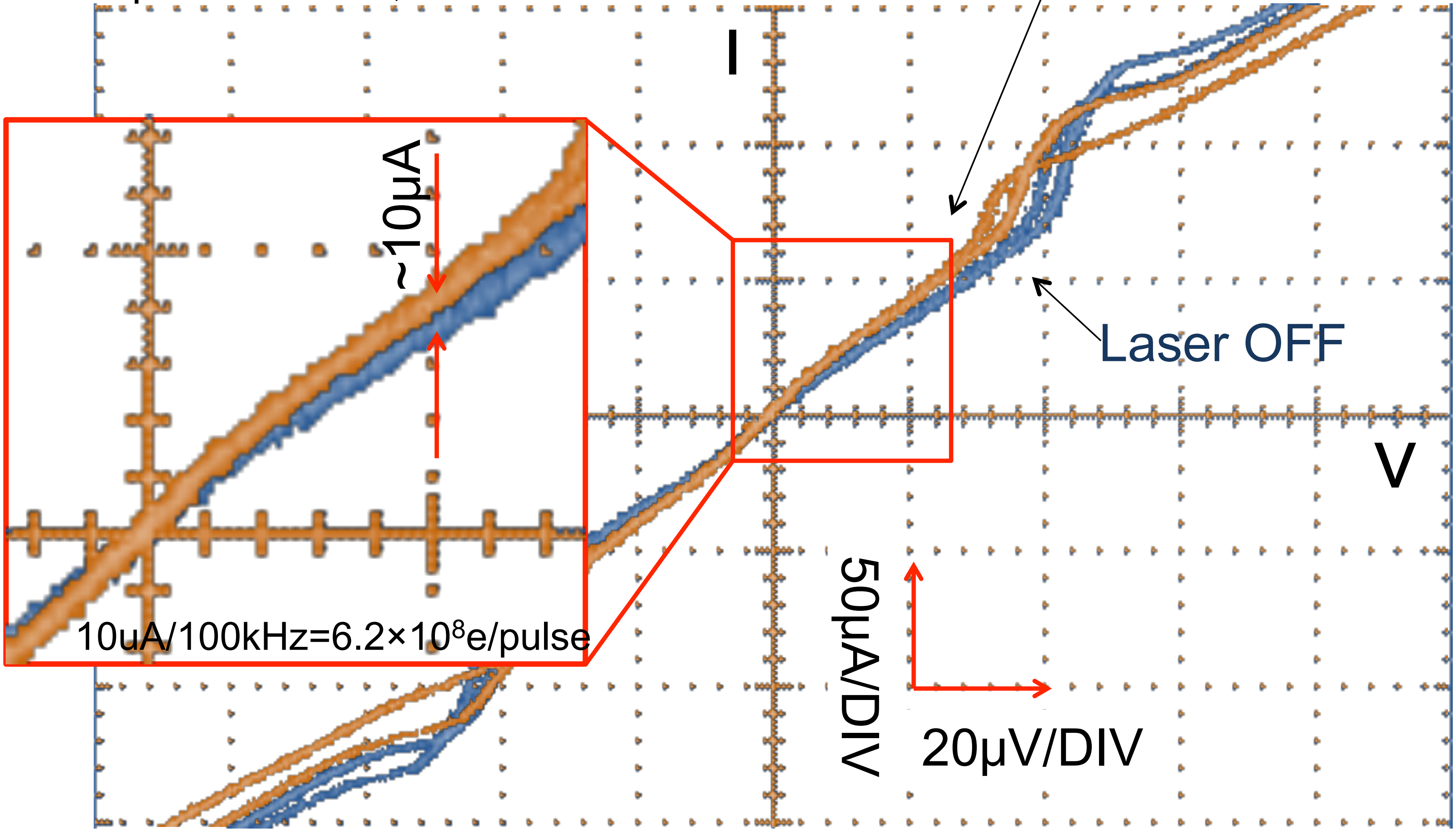
$I_{leak}=50\mu A@V_{bias}=10\mu V$

$R_d=0.2\Omega$

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)

Hf-STJ Response to DC-like VIS light

Laser pulse: 465nm, 100kHz



10uA/100kHz=6.2×10^{8}e/pulse

We observed an increase of tunnel current in Hf-STJ response to visible light

Summary

- We propose an experiment to search for neutrino radiative decay in cosmic neutrino background.
- Requirements for the detector is an ability of photon-by-photon energy measurement with better than 2% energy resolution for $E{\downarrow}\gamma = 25$ meV ($\lambda = 50 \mu m$)
- Nb/Al-STJ array with grating and Hf-STJ are considered for the experiments and under development.
  - Nb/Al-STJ fabricated at CRAVITY almost meets our requirement.
  - FD-SOI readout for STJ signal is promising and under development.
  - Hf-STJ development is in progress, but need much improvement.
- It is possible to improve the neutrino lifetime lower limit up to O(10^{14}yrs) for 200-sec measurement in a rocket experiment with the detector.