Development of far-infrared single-photon spectrometers based on superconducting tunnel junction for search for the cosmic background neutrino decay

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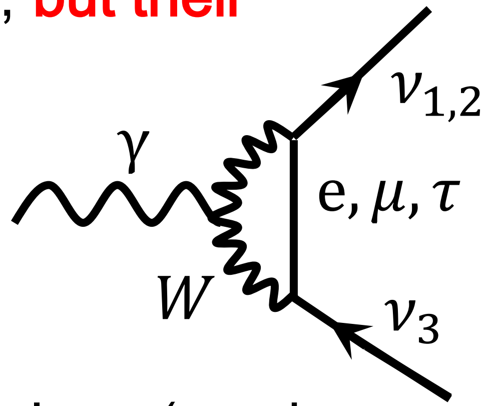
- Summary

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 are not measured yet!**



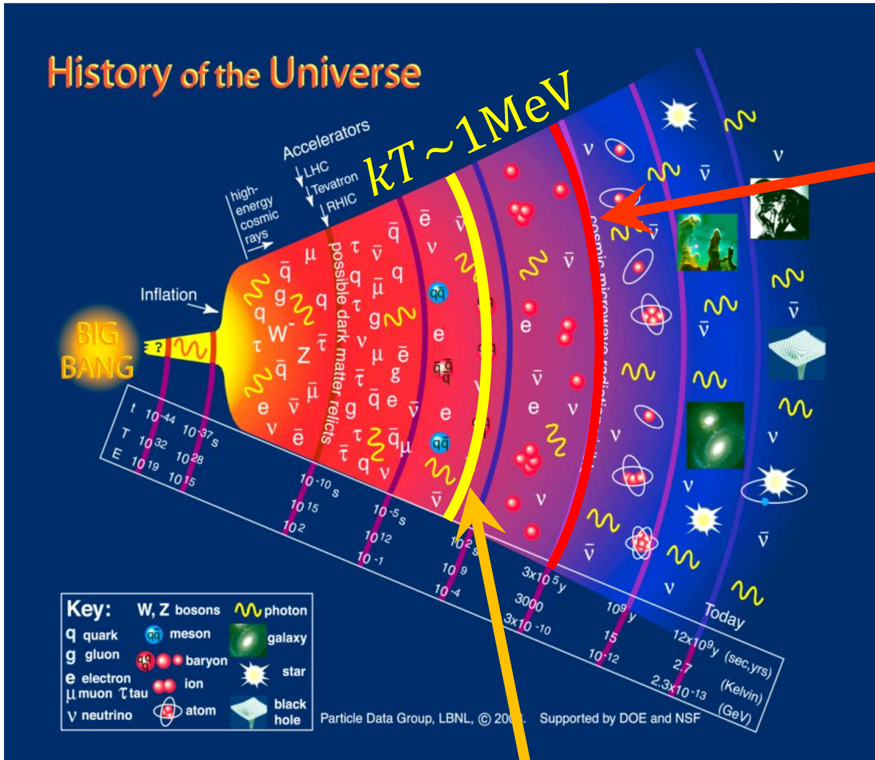
☐ **Heavier neutrinos (ν_2, ν_3) are not stable**

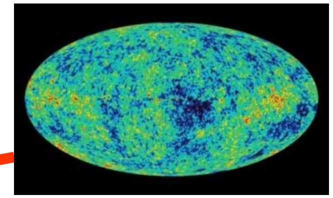
- Neutrino can decay through the loop diagrams
- $\nu_3 \rightarrow \nu_{1,2} + \gamma$
- Neutrino mass can be determined from the decay

✓ However, neutrino lifetime is expected to be very long (much longer than the age of universe)

➔ We adopt Cosmic neutrino background (CνB) as the neutrino source for neutrino decay search

Cosmic neutrino background (CνB)

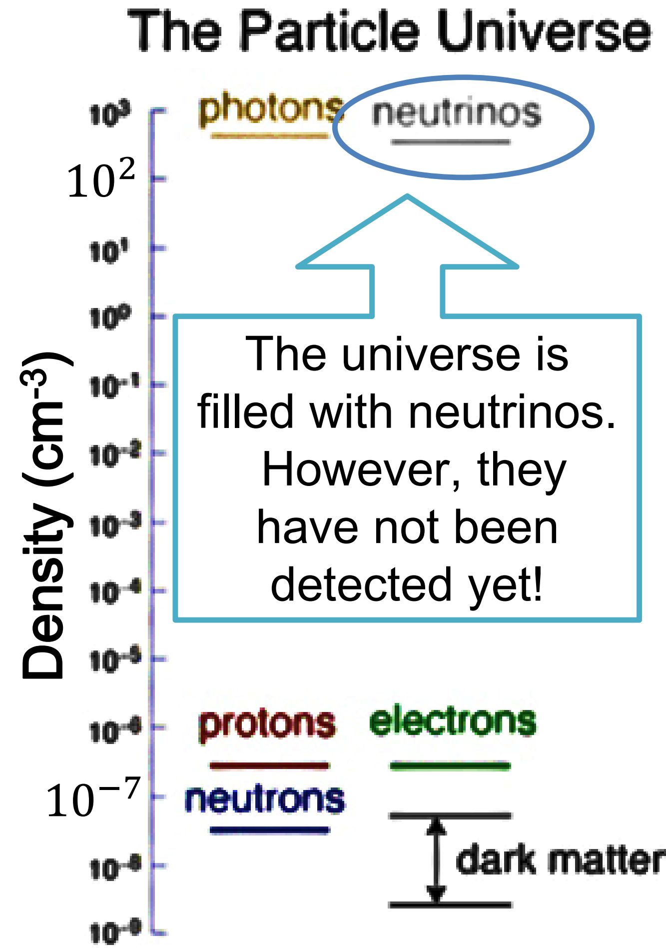




CMB

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

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



CνB (=neutrino decoupling)

~1s after the big bang

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

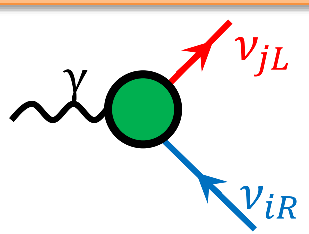
$$n_\nu + n_{\bar{\nu}} = \frac{3}{4}\left(\frac{T_\nu}{T_\gamma}\right)^3 n_\gamma = 110/\text{cm}^3$$

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

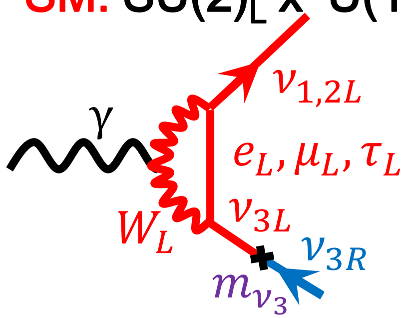
Motivation of ν-decay search in CνB

- Search for $\nu_3 \rightarrow \nu_{1,2} + \gamma$ in cosmic neutrino background (CνB)
  - Search for anomalous magnetic moment of neutrino
  - Direct detection of CνB
  - Determination of neutrino mass: $m_3 = \left(m_3^2 - m_{1,2}^2\right)/2E_\gamma$
- Aiming at a sensitivity to ν lifetime for $\tau(\nu_3) = \mathrm{O}(10^{17}\mathrm{yrs})$
  - Standard Model expectation: $\tau = \mathrm{O}(10^{43}\mathrm{yrs})$
  - Experimental lower limit: $\tau > \mathrm{O}(10^{12}\mathrm{yrs})$
  - L-R symmetric model (for Dirac neutrino) predicts down to $\tau = \mathrm{O}(10^{17}\mathrm{yrs})$ for W_L-W_R mixing angle $\zeta < 0.02$

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



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

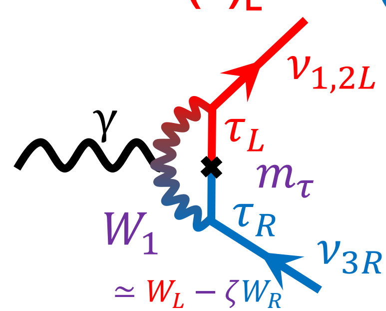


$\Gamma \sim (10^{43}\ yr)^{-1}$
Suppressed by m_ν and GIM

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

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

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



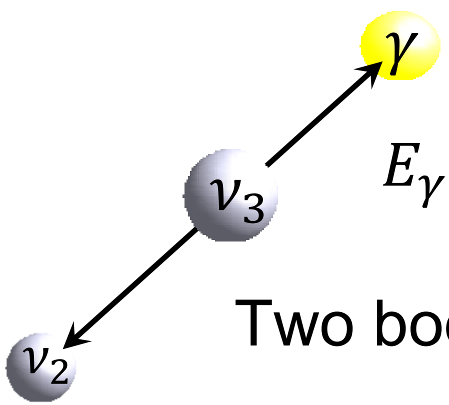
$\Gamma \sim (10^{17}\ yr)^{-1}$
Only suppressed by L-R mixing (ζ)

10^{26} enhancement to SM

Photon Energy (Wavelength) in Neutrino Decay

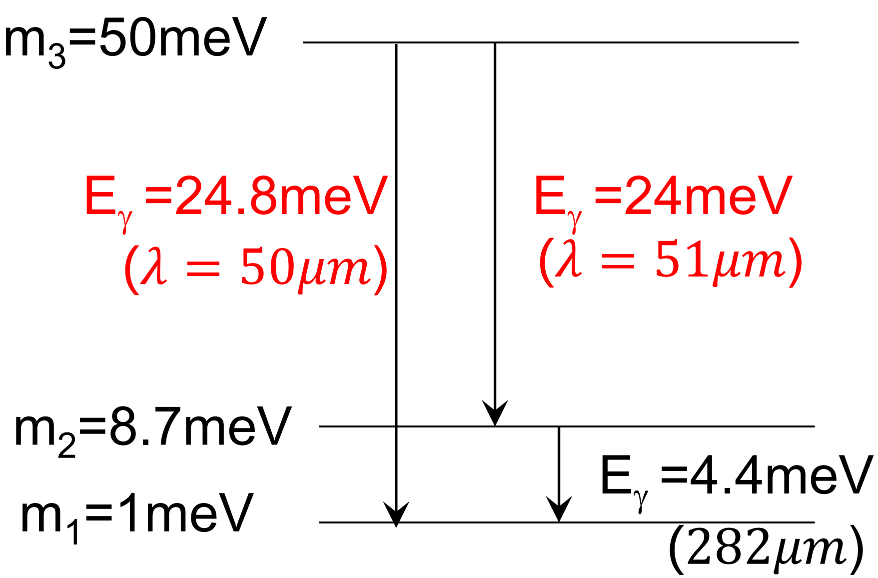
$\nu_3 \rightarrow \nu_{1,2} + \gamma$

in the ν_3 rest frame



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

Two body decay

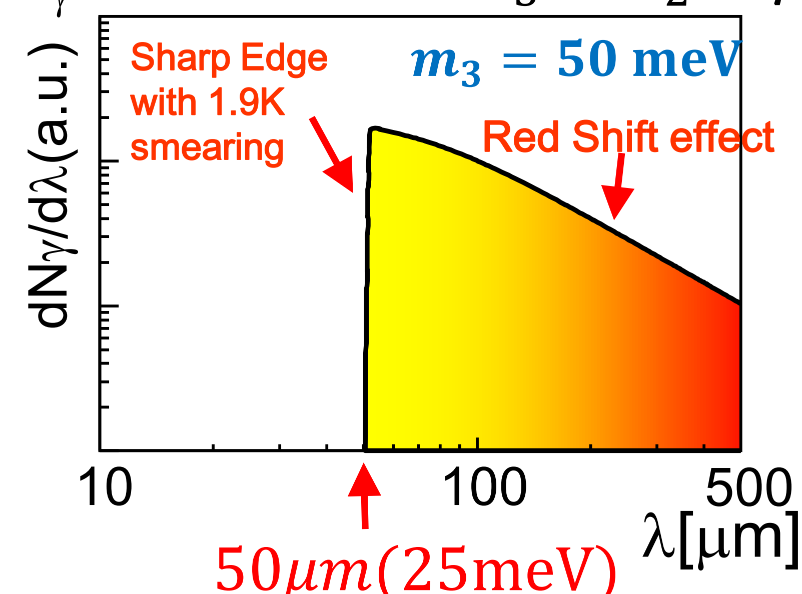


- From neutrino oscillation
  - $|\Delta m_{23}^2| = |m_3^2 - m_2^2| \sim 2.4 \times 10^{-3}\ eV^2$
  - $\Delta m_{12}^2 \sim 7.65 \times 10^{-5}\ eV^2$
- From Planck+WP+highL+BAO
  - $\sum m_i < 0.23$ eV

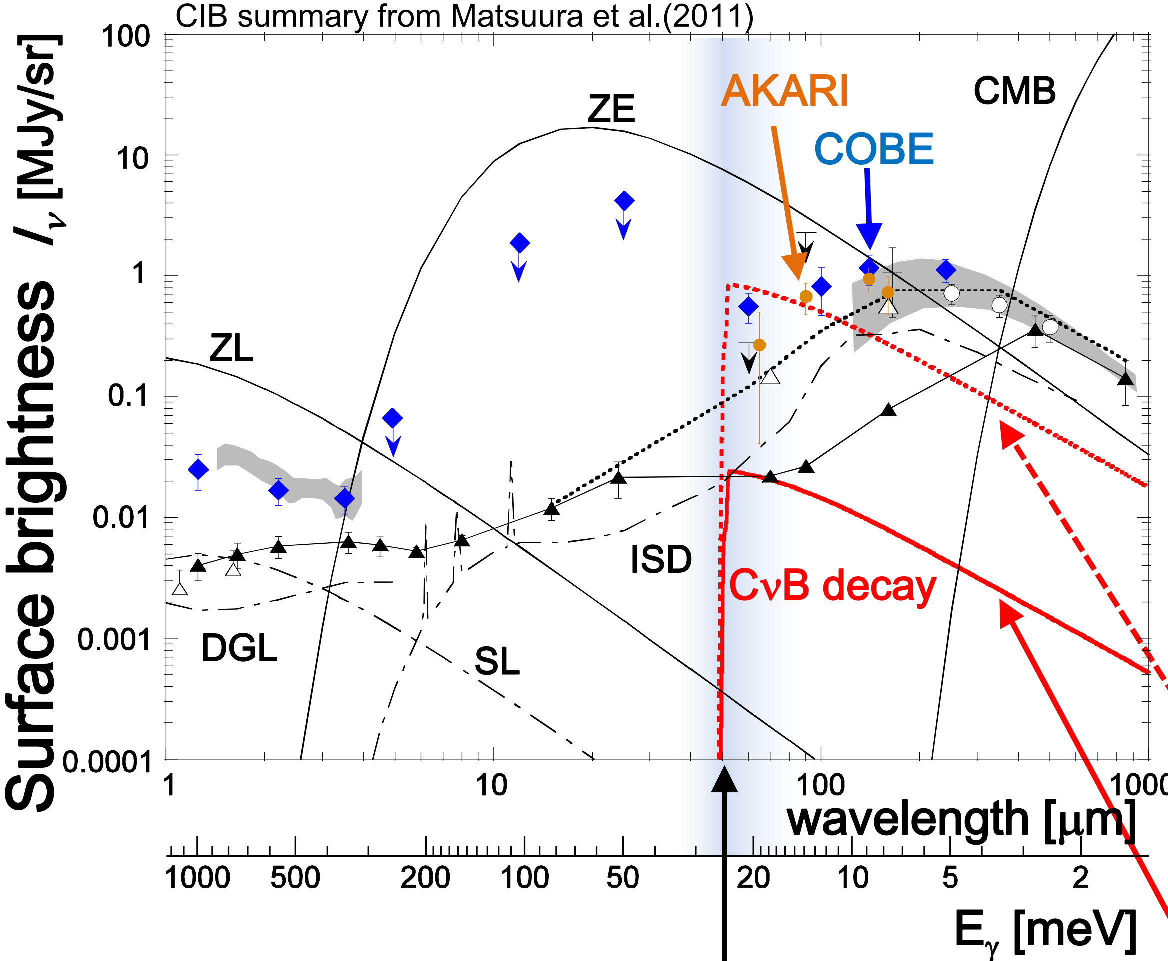
➔ 50meV<m_3<87meV

E_γ^{rest} =14~24meV (λ_γ =51~89µm)

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



CνB decay signal and Backgrounds



λ = 50 μm

E_γ=25 meV

at λ = 50μm

Zodiacal Emission(ZE)

I_ν ~ 8 MJy/sr

CIB

λI_λ ~ 0.1-0.5 MJy/sr

CνB decay

Expected $E_\gamma$spectrum

$m_3 = 50\text{meV}$

$\tau = 3 \times 10^{12}\text{yrs}$

I_ν ~ 0.8MJy/sr

Excluded by S.H.Kim et. al 2012

$\tau = 1 \times 10^{14}\text{yrs}$

I_ν ~ 25kJy/sr

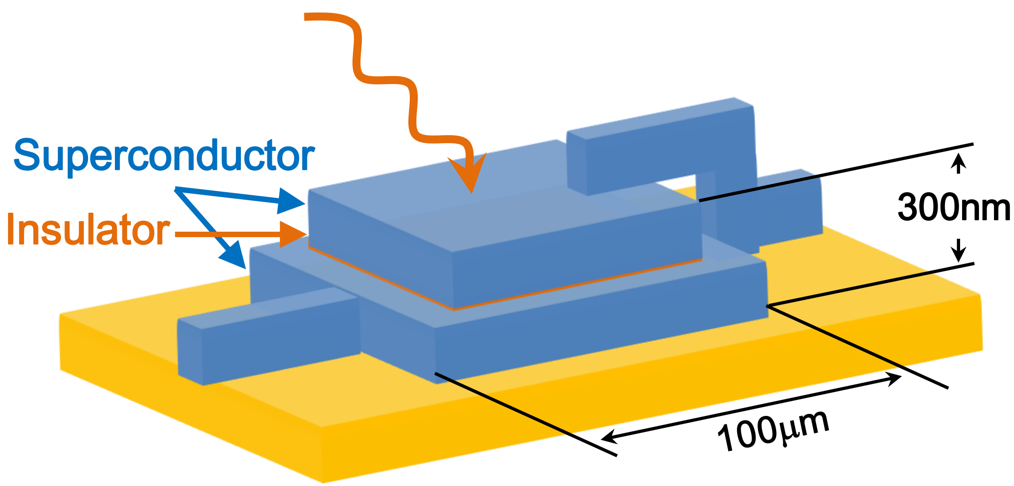
Detector requirements for neutrino decay search

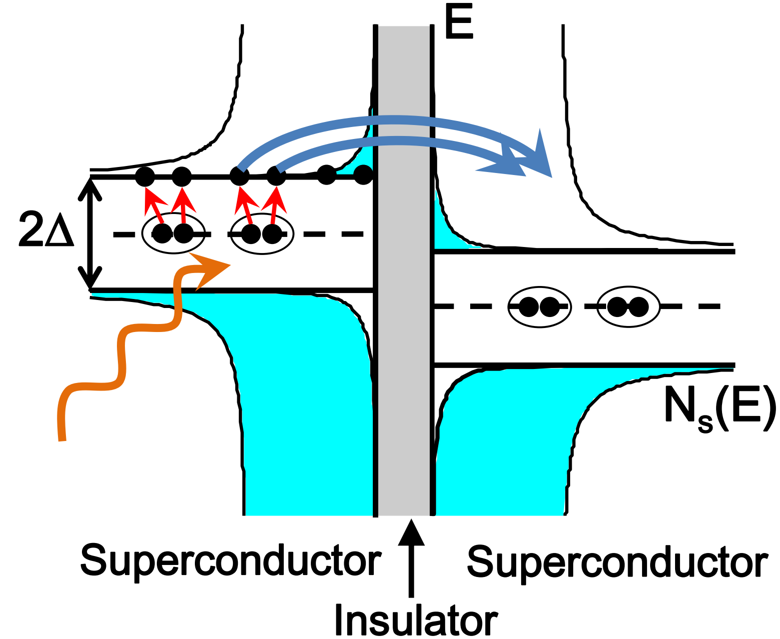
- High-precision photon energy spectrum around λ=50μm
  - Photon-by-photon spectroscopy in the far-infrared region with better than 2% resolution for $E_\gamma = 25\text{meV}$ (λ=50μm)
    - Lower dark noise in the detector
    - Identify the sharp edge in the spectrum from the neutrino decay
  - Rocket- and/or satellite-borne telescope with this detector.
    - A ground-based experiment is impossible.
- **Superconducting Tunneling Junction (STJ) detectors**
  - Array of 50 Nb/Al-STJ pixels with diffraction grating covering $\lambda = 40 - 80\mu\text{m}$
    - **For a rocket experiment aiming at O(10^{14} yrs) in a 200-sec measurement**

    ➔Improve the current experimental lower limit for $\tau(\nu_3)$ by 2 orders
  - STJ using Hafnium: Hf-STJ for a satellite experiment
    - $\Delta = 20\mu\text{eV}$: Superconducting gap energy for Hafnium
    - $N_{\text{q.p.}} = 25\text{meV}/1.7\Delta = 735$ for 25meV photon: $\Delta E/E < 2\%$ is achievable

Superconducting Tunnel Junction (STJ) 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 deposited photon energy.

- Much lower gap energy (Δ) than FIR photon ➔ Can detect FIR photon
- Fast response (~μs) ➔ Suitable for single-photon detection

STJ energy resolution

Statistical fluctuation in number of quasi-particles ➔ 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 a single-photon detection is possible

Hf

Hf-STJ is not established as a practical photon detector yet

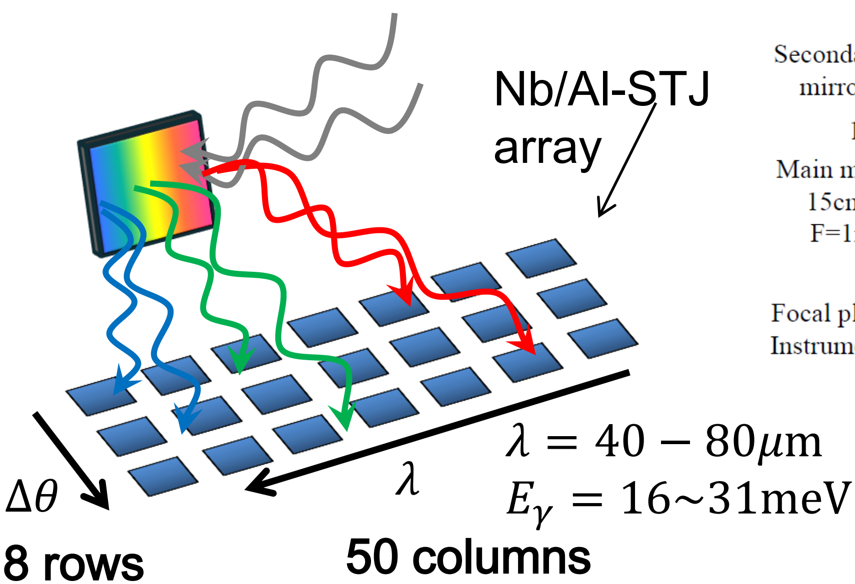
$N_{q.p.}$=25meV/1.7Δ=735

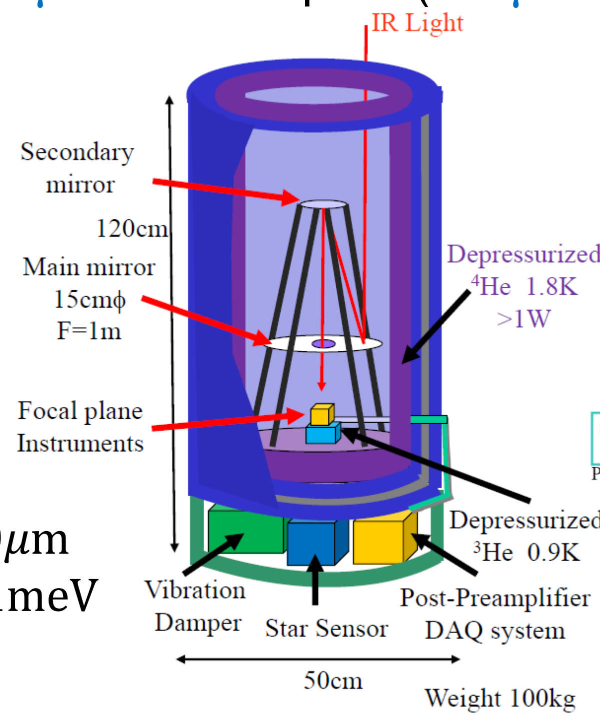
2% energy resolution is achievable if Fano factor <0.3 for a single-photon

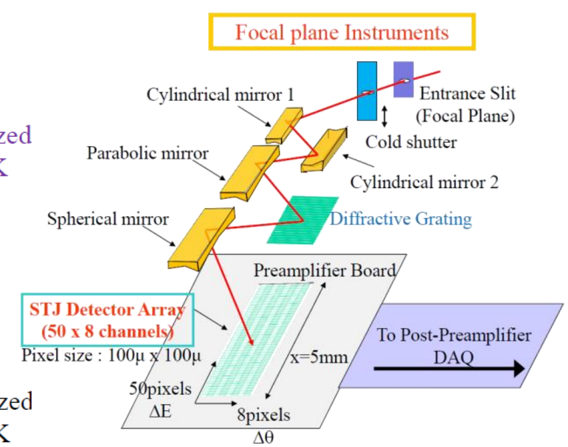
Developments are challenging, yet worthwhile

Proposed rocket experiment with a diffraction grating and Nb/Al-STJ array combination

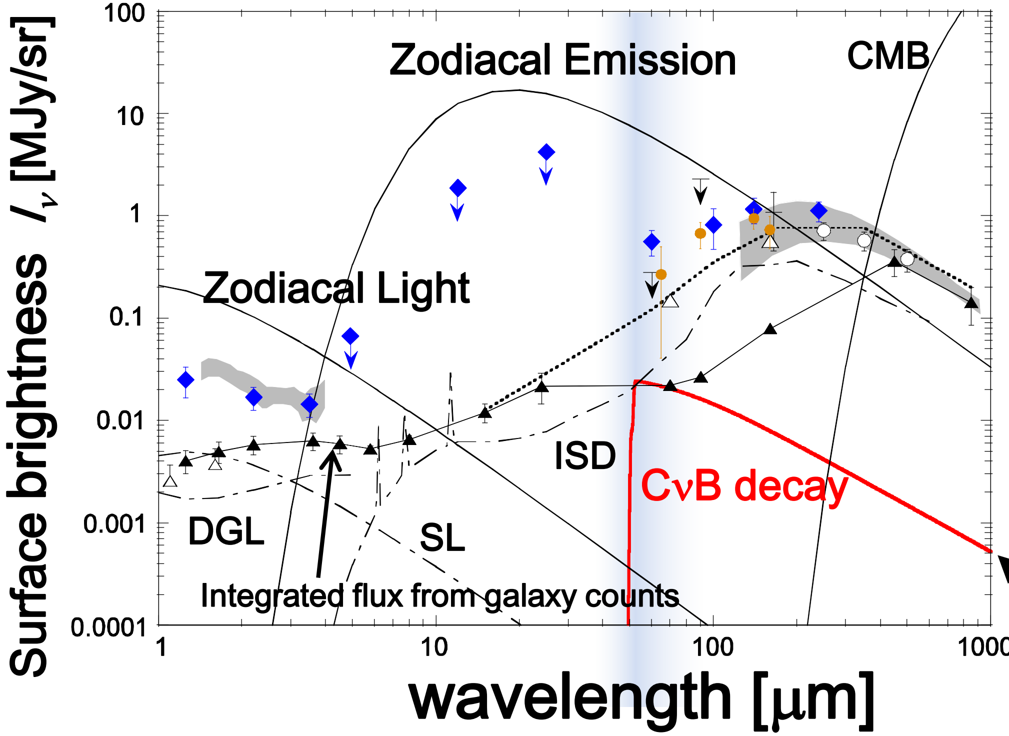
- 200-sec measurement at altitude of 200~300km
  - Telescope with **diameter of 15cm** and **focal length of 1m**
  - All optics (mirrors, filters, shutters and grating) will be cooled at ~1.8K
- At the focal point, diffraction grating covering **λ=40-80μm (16-31meV)** and array of Nb/Al-STJ pixels of **50(in wavelength distribution) x 8(in spatial distribution)** are placed
  - Each Nb/Al-STJ pixel is used as **a single-photon counting detector** for FIR photon in λ=40−80μm ($\Delta\lambda = 0.8\mu m$)
  - Sensitive area of **100μmx100μm** for each pixel (**100μrad x 100μrad** in viewing angle)







Expected precision in the spectrum measurement



Telescope parameters

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

$$\Delta\lambda = \frac{80\mu m - 40\mu m}{50} = 0.8\mu m$$

$\tau = 1 \times 10^{14}\mathrm{yrs}$

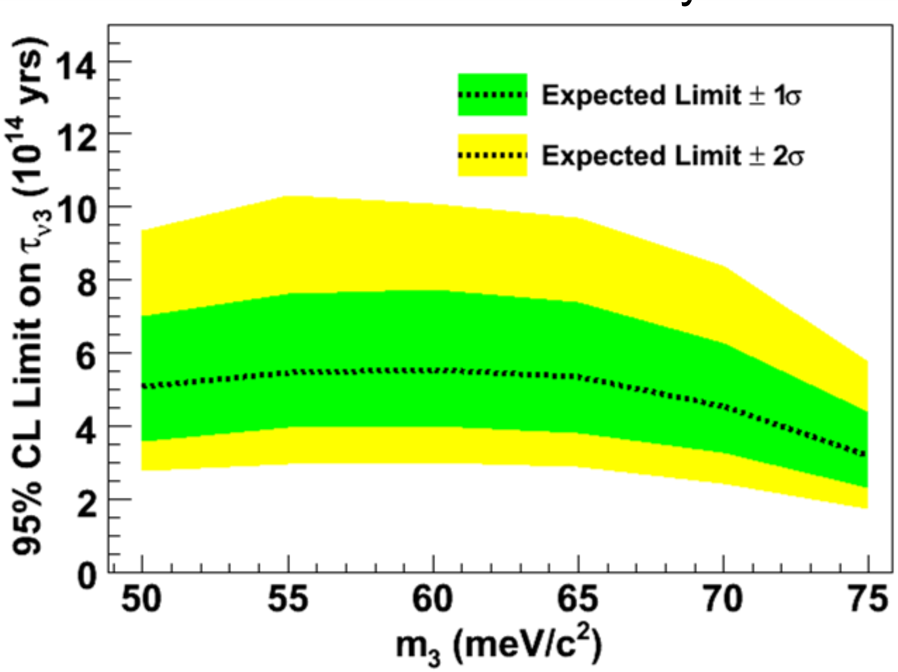
- Zodiacal emission ⇒ 343Hz / pixel
  - 200sec measurement: 0.55M events / 8 pixels (at $\lambda = 50\mu m$)
  - 0.13% accuracy measurement for each wavelength: $\delta(I_\nu)$=11kJy/sr
- Neutrino decay ($m_3 = 50$ meV, $\tau_\nu = 1 \times 10^{14}$yrs): I_ν=25kJy/sr
  - 2.3σ away from statistical fluctuation in ZE measurement

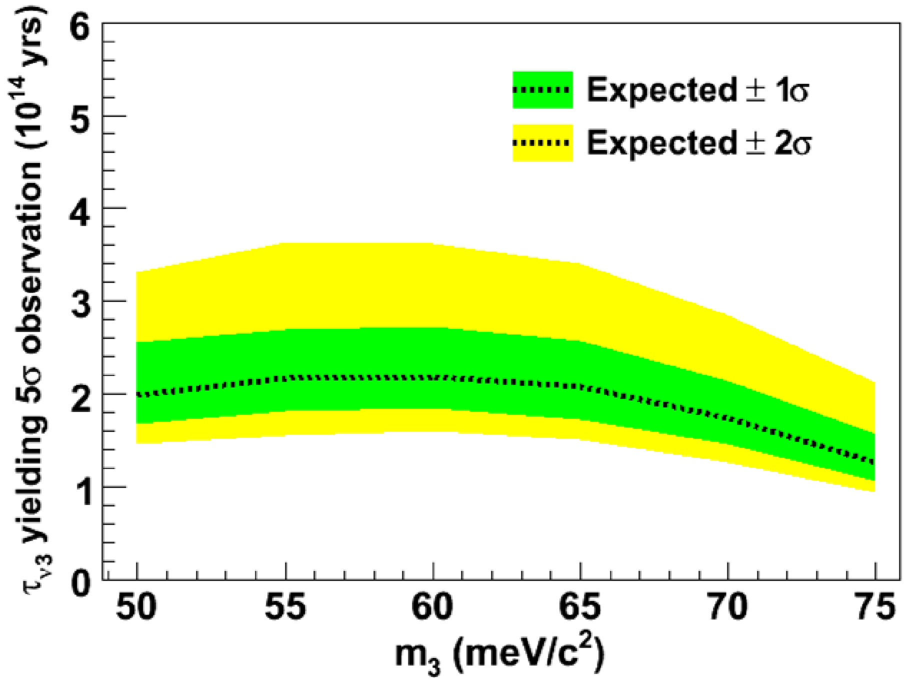
ν decay with $\tau_\nu = 10^{14}$ yrs is possible to detect, or set lower limit!

Sensitivity to neutrino decay

Parameters in the rocket experiment simulation

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



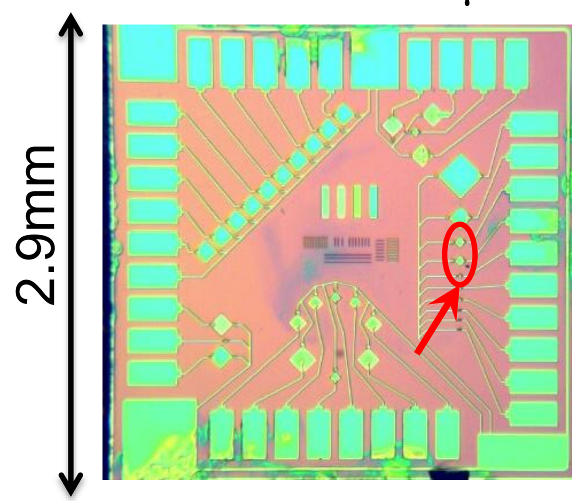


- Can set lower limit on ν_3 lifetime at 4-6 $\times$ 10^{14} yrs if no neutrino decay observed
- If ν_3 lifetime were 2 $\times$ 10^{14} yrs, the signal significance is at 5σ level

Status of Nb/Al-STJ photon detector development

Requirements for Nb/Al-STJ

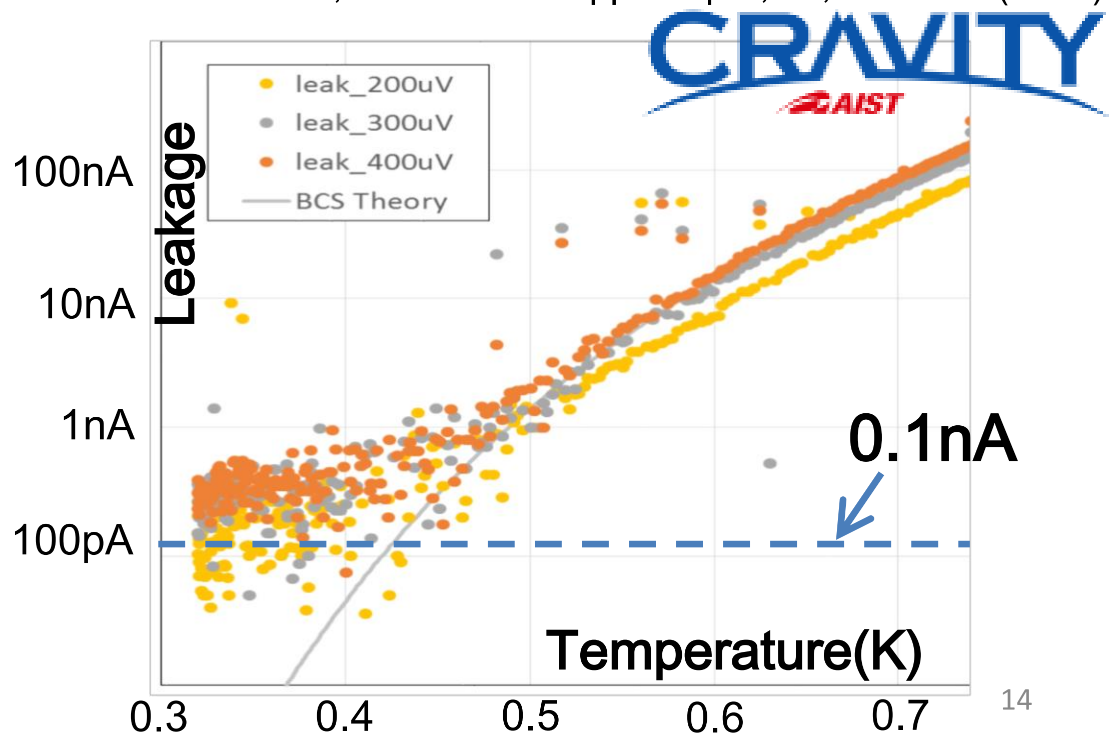
- Single-photon detection for E_γ=25meV (λ=50μm)
- Detection efficiency: ~1
- Dark count rate < 30Hz ➔ leak current < 0.1nA
- Sensitive area: 100μm × 100μm per pixel



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

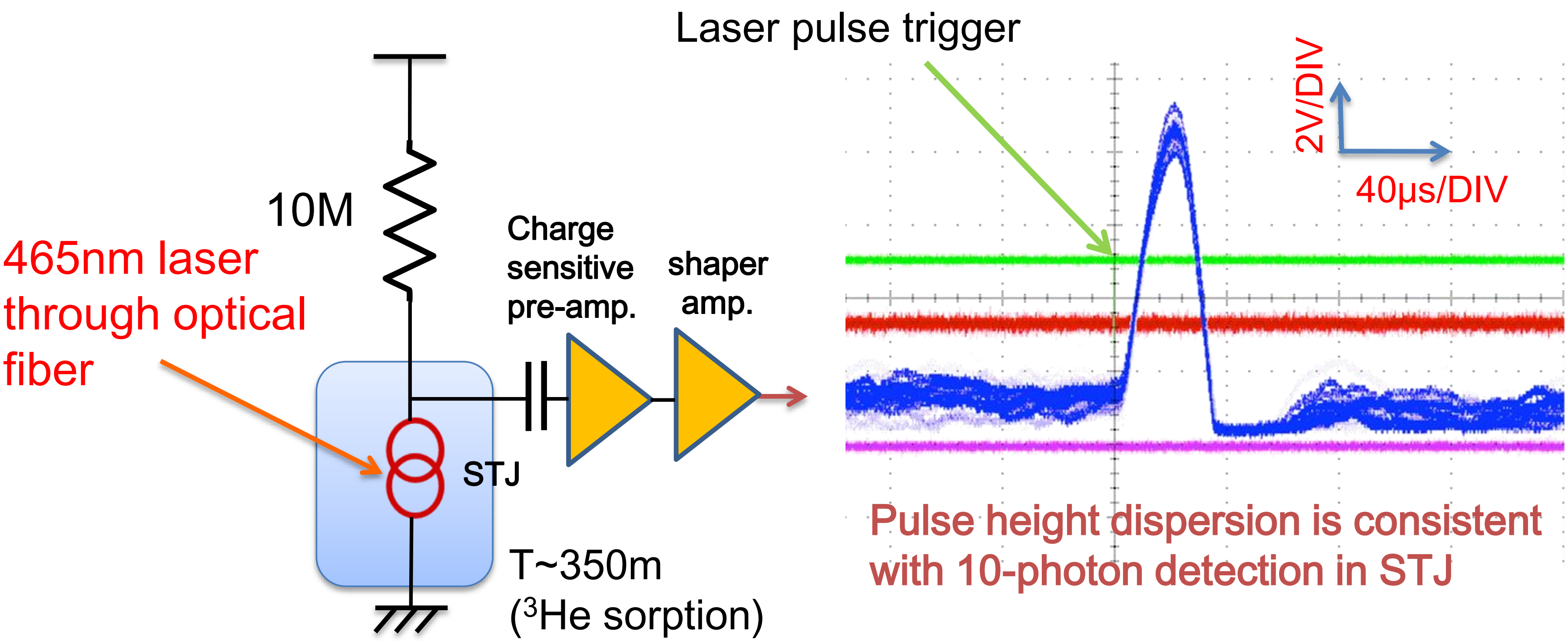
- I_{leak}<1nA achieved at AIST
- Will test STJs with a smaller junction size

M. Ukibe et al., Jpn. J. Appl. Phys. 51, 010115 (2012)
M. Ohkubo et al., IEEE Trans. Appl. Super, 24, 2400208 (2014)



100x100μm² Nb/Al-STJ response to 465nm multi-photons

100x100μm² Nb/Al-STJ fabricated at CRAVITY



A response from Nb/Al-STJs to NIR-VIS photons at single-photon level was observed with a charge-sensitive amplifier at the room temperature

- Response time of STJ: O(1μs)

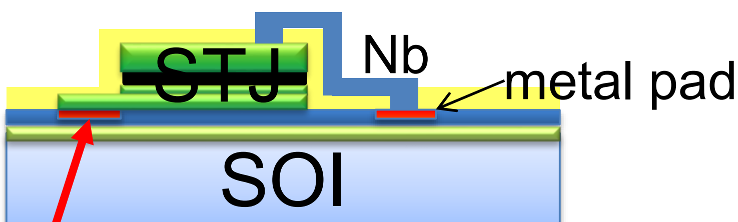
Due to the readout noise, a FIR single-photon detection is not achieved yet

➔ Need ultra-low noise readout system for STJ signal

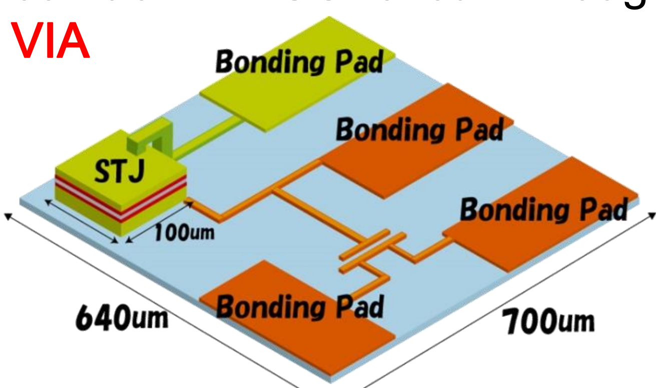
➔ Considering a cryogenic pre-amplifier close to STJ

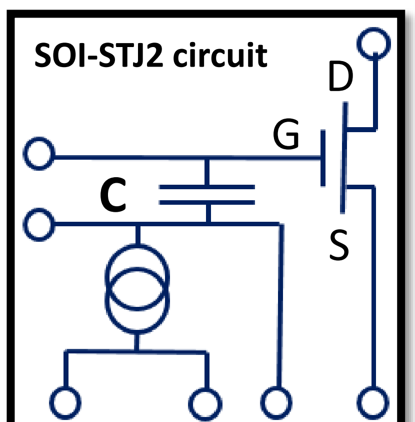
Development of SOI-STJ

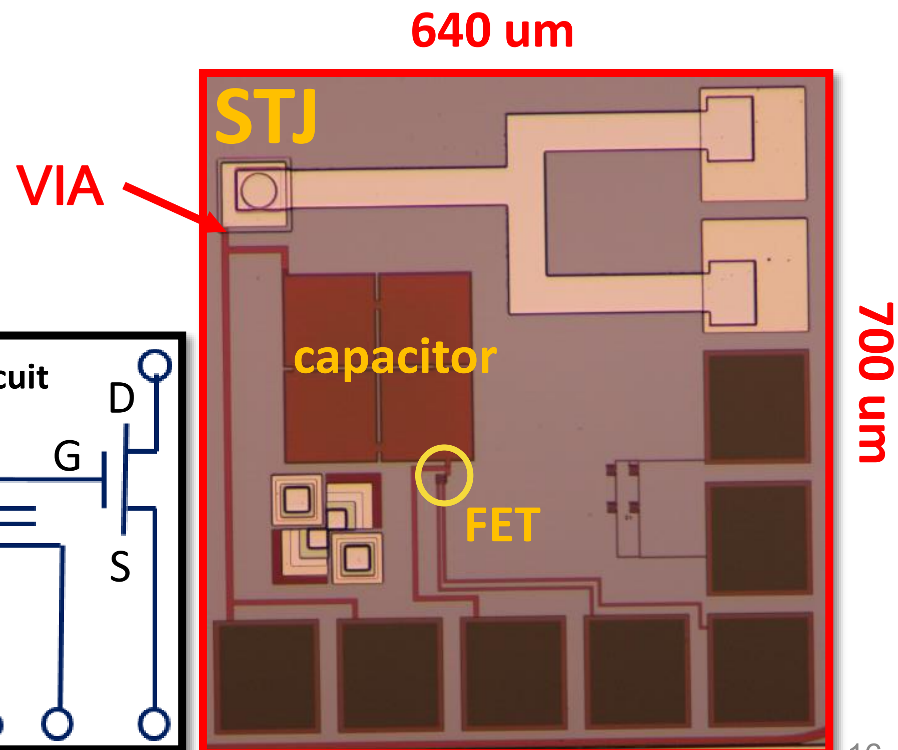
- SOI: Silicon-on-insulator
  - CMOS in FD-SOI is reported to work at 4K by T. Wada (JAXA), et al.
    J Low Temp Phys 167, 602 (2012)
- A development of SOI-STJ for our application
  - STJ layers are fabricated directly on a SOI pre-amplifier board and cooled down together with the STJ
- Started test with Nb/Al-STJ on SOI with p-MOS and n-MOS FET



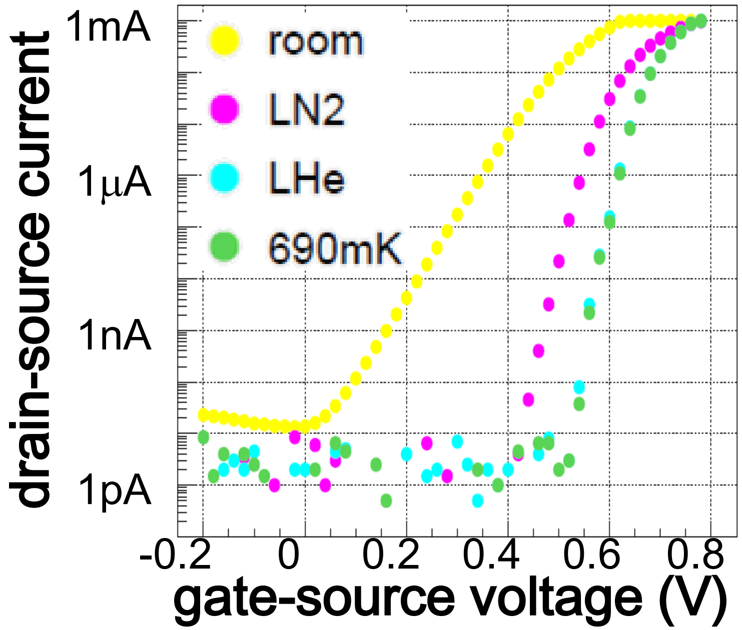
STJ lower layer has electrical contact with SOI circuit through VIA



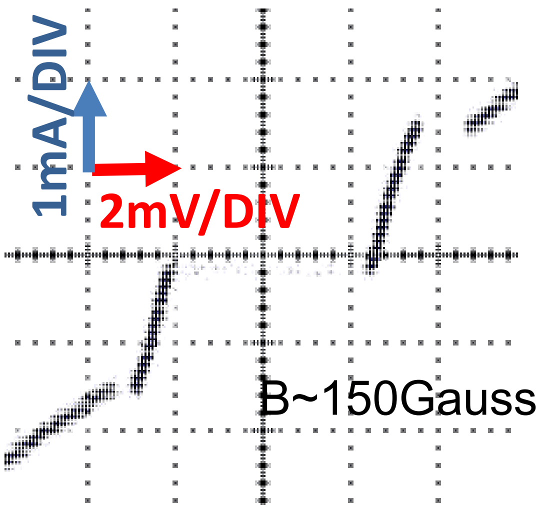




FD-SOI on which STJ is fabricated



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

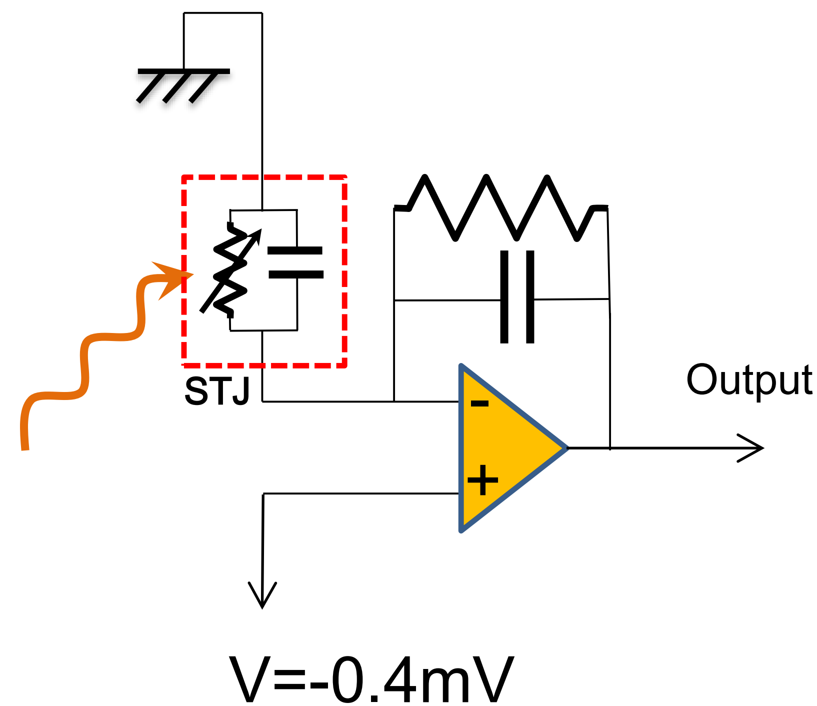


I-V curve of a STJ fabricated at KEK on a FD-SOI wafer

- Both nMOS and pMOS-FET in FD-SOI wafer on which a STJ is fabricated work fine at temperature down below 1K
- Nb/Al-STJ fabricated at KEK on FD-SOI works fine
- We are also developing SOI-STJ where STJ is fabricated at CRAVITY

Pre-amplifier development

- A charge-sensitive pre-amplifier in SOI for STJ readout is under development using the SPICE simulation supported by VDEC*
- For the circuit design, parameterization of MOSFET I_d-V_g(V_d) for the SPICE simulation is in progress with KEK and JAXA.



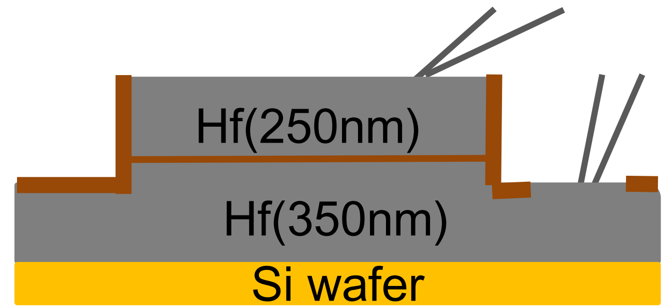
STJ readout circuit to apply a constant voltage on STJ as well as integrate the tunnel current from response to a photon.

* VLSI Design and Education Center(VDEC), the U. Tokyo in collaboration with Synopsys, Inc., Cadence Design Systems, Inc., and Mentor Graphics, Inc.

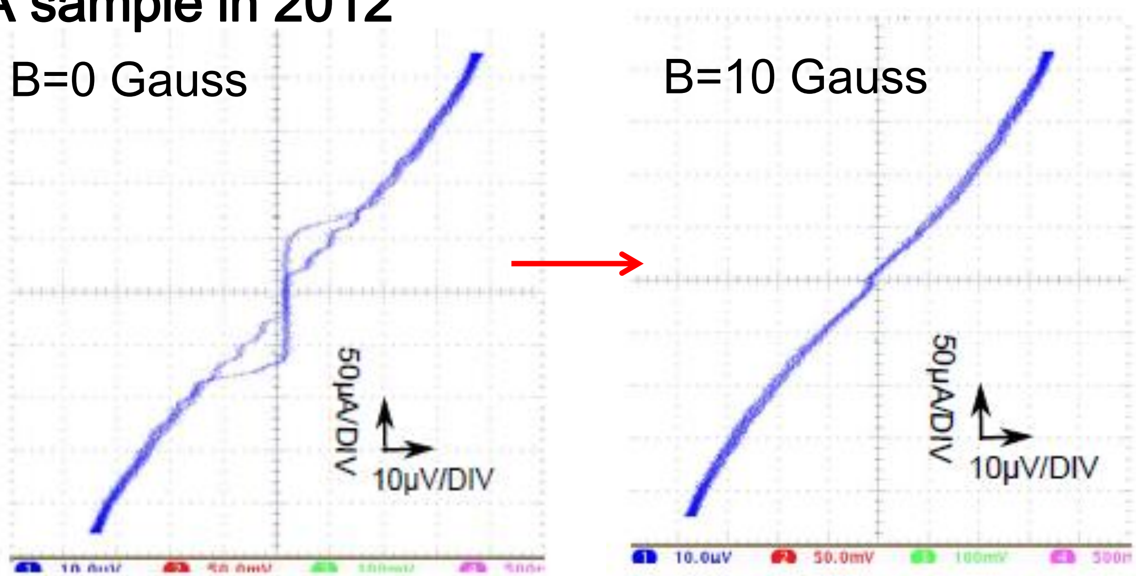
Hf-STJ development

- We succeeded in observation of Josephson current by Hf-HfOx-Hf layer in 2010

S.H.Kim et. al, TIPP2011



A sample in 2012



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

$200\times200\mu m^2$

T=80~177mK

$I_c=60\mu A$

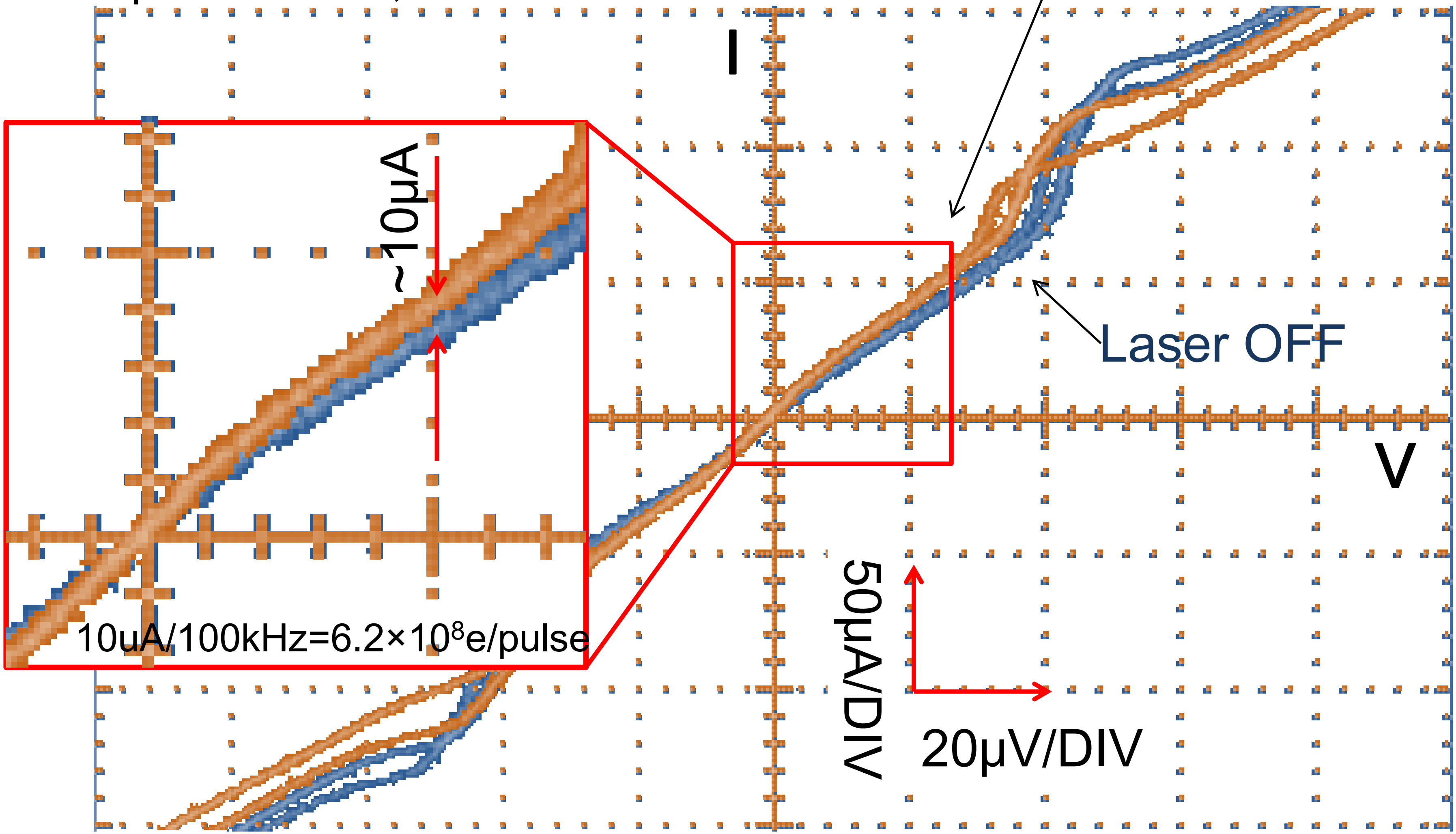
$I_{leak}=50\mu A@V_{bias}=10\mu V$

$R_d=0.2\Omega$

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

Hf-STJ Response to DC-like VIS light

Laser pulse: 465nm, 100kHz



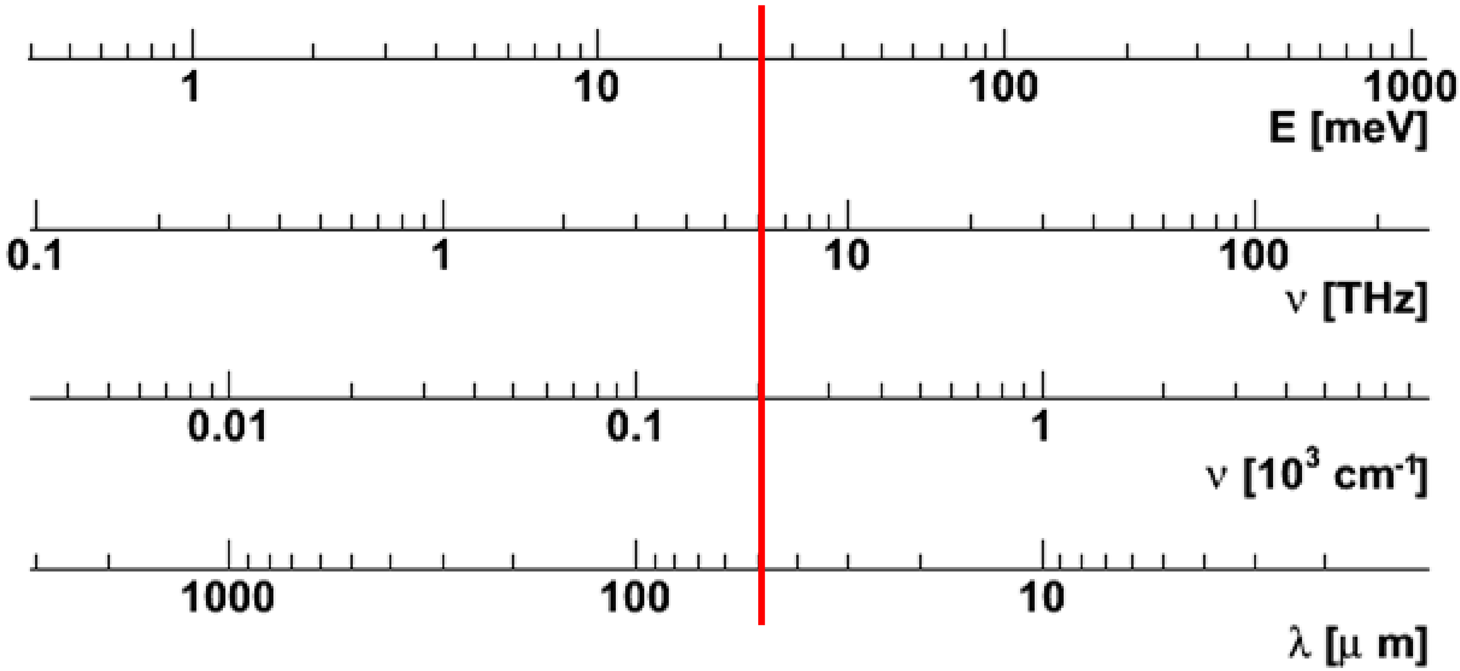
We observed an increase of tunnel current in Hf-STJ response to visible light

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 spectroscopy with better than 2% energy resolution at λ=50μm ($E_\gamma = 25$ meV) with low dark count rate (<30Hz)
- Nb/Al-STJ array with a diffractive grating and Hf-STJ are considered for the experiment.
  - Nb/Al-STJ fabricated at CRAVITY meets our requirements.
  - FD-SOI readout for STJ signal is under development.
  - Hf-STJ development is in progress, yet need much improvement.
- Improvement of the neutrino lifetime lower limit up to O(10^{14}yrs) is feasible for 200-sec measurement in a rocket-borne experiment with the detector.

Backup

Energy/Wavelength/Frequency



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

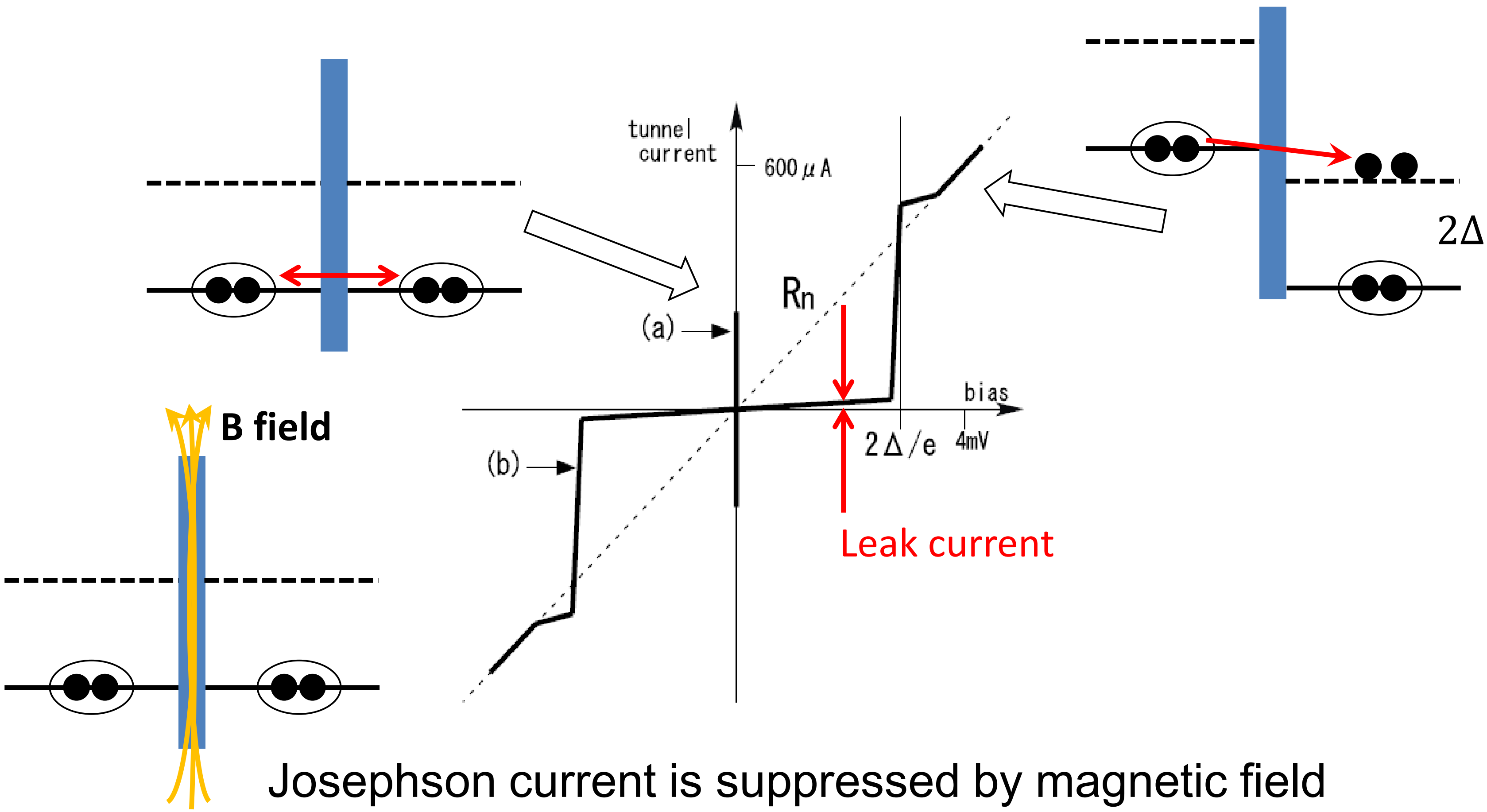
$\nu = 6 \text{ THz}$

$\lambda = 50\mu m$

STJ I-V curve

- Sketch of a current-voltage (I-V) curve for STJ

➔ The Cooper pair tunneling current (DC Josephson current) is seen at V = 0, and the quasi-particle tunneling current is seen for $|V|>2\Delta$



Josephson current is suppressed by magnetic field

STJ back-tunneling effect

- 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