Development of Superconducting Tunnel Junction Detectors as a far-infrared single photon detector for neutrino decay search

TIPP 2014 Conference

Jun. 2nd-6th, 2014 / Amsterdam, The Netherlands

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Contents

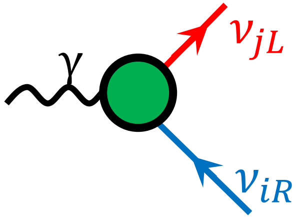
- Introduction to neutrino decay search
- STJ detector developments
  - Rocket experiment with Nb/Al-STJ
  - Hf-STJ development
- Summary

Motivation of ν-decay search in CνB

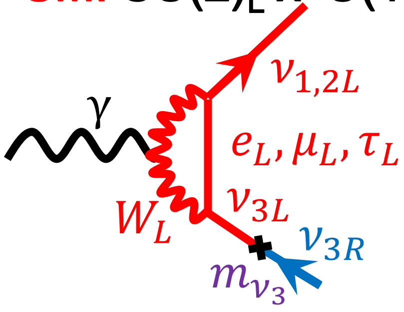
- Search for $\nu_3 \rightarrow \nu_{1,2} + \gamma$ in cosmic neutrino background (CνB)
  - Direct detection of CνB
  - Direct detection of transition magnetic dipole moment of neutrino
  - Direct measurement of neutrino mass: $m_3 = \left(m_3^2 - m_{1,2}^2\right)/2E_\gamma$
- Aiming at sensitivity of detecting γ from ν decay for $\tau(\nu_3) = \mathrm{O}(10^{17}\mathrm{yr})$
  - SM expectation $\tau = \mathrm{O}(10^{43}\mathrm{yr})$
  - Current experimental lower limit $\tau > \mathrm{O}(10^{12}\mathrm{yr})$
  - L-R symmetric model (for Dirac neutrino) predicts down to $\tau = \mathrm{O}(10^{17}\mathrm{yr})$ for W_L-W_R mixing angle $\zeta < 0.02$

Neutrino magnetic moment term

$\bar{\nu}_{jL}\sigma_{\mu\nu}\nu_{iR}$



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



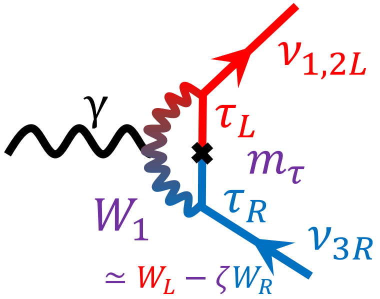
$\Gamma \sim \left(10^{43}\ yr\right)^{-1}$

Suppressed by m_ν, GIM

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

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

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



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

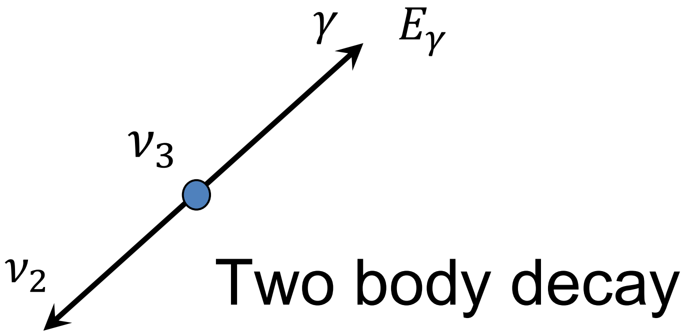
Suppressed only by $\zeta \sim 0.02$

10^{26} enhancement to SM

Photon Energy in Neutrino Decay

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

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

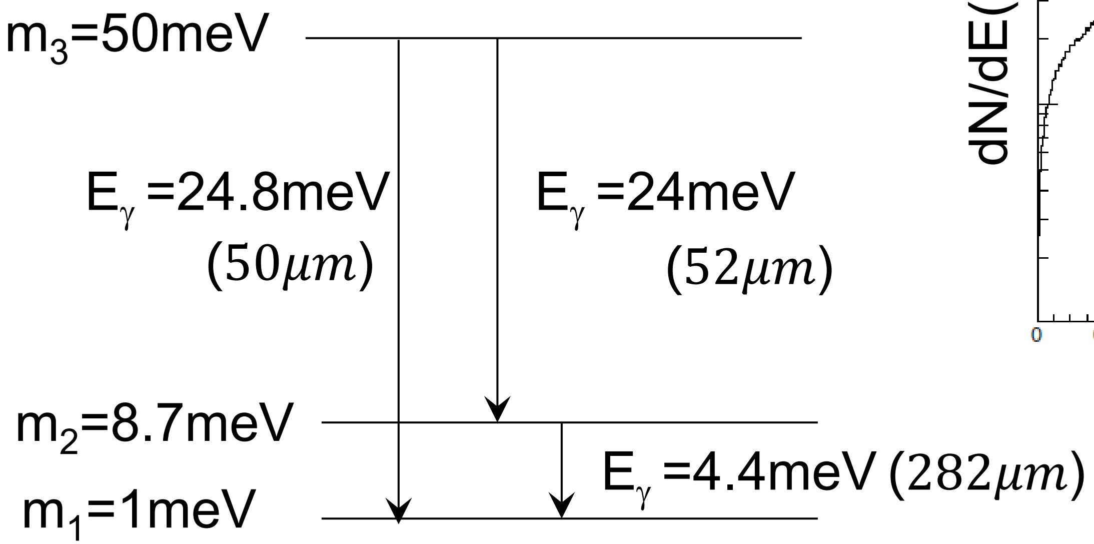


Two body decay

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

➔ 50meV<m_3<87meV, $\boldsymbol{E_\gamma}$ =**14~24meV**

$\boldsymbol{\lambda_\gamma}$ =**51~89μm**



m$_3$=50meV

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

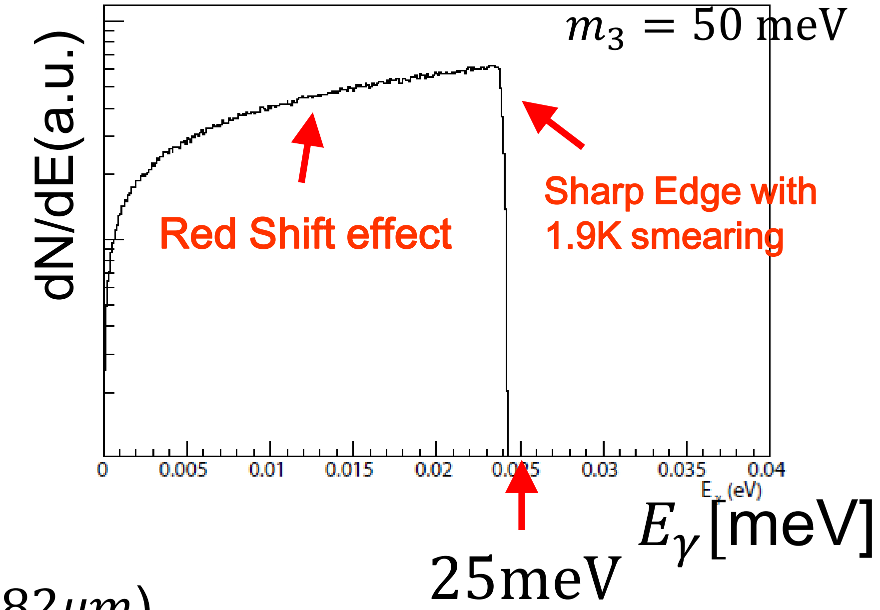
E$_\gamma$ =24meV ($52\mu m$)

m$_2$=8.7meV

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

m$_1$=1meV

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

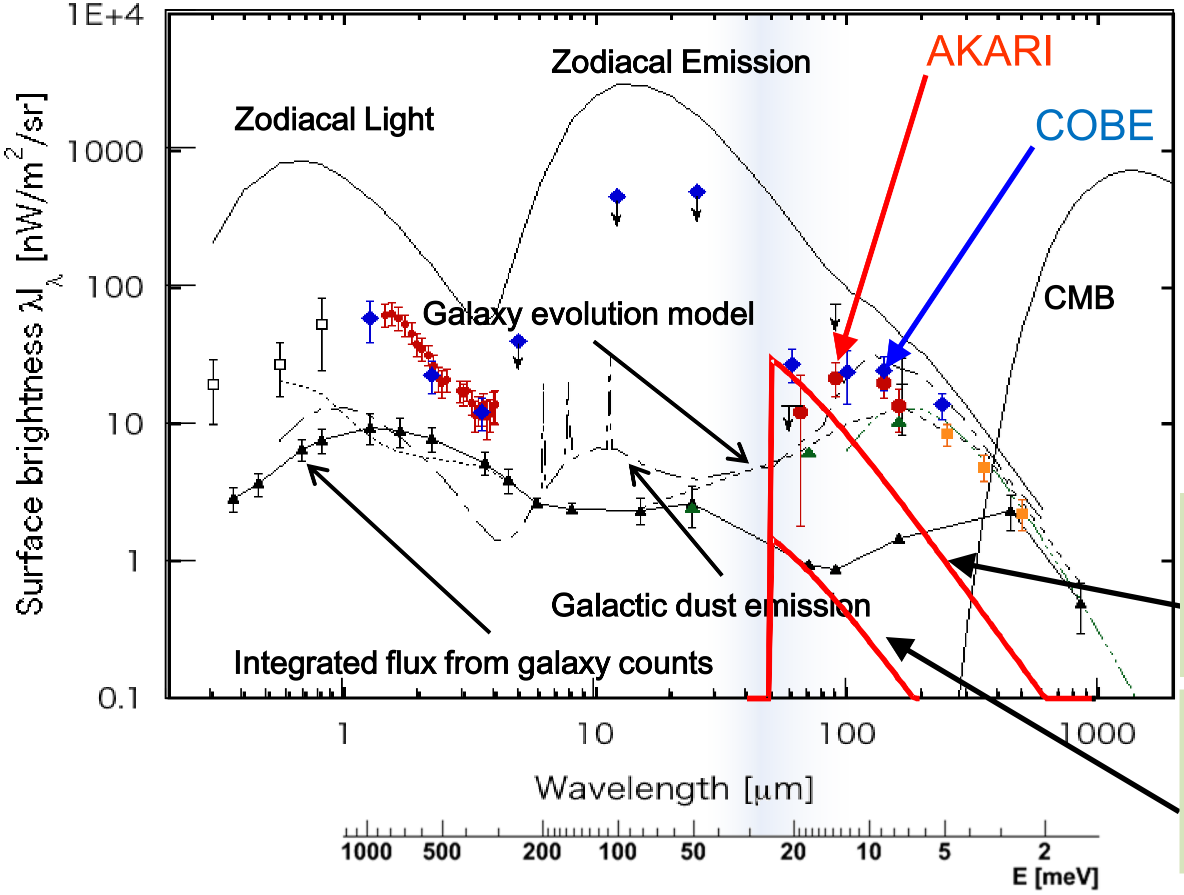


Red Shift effect

Sharp Edge with 1.9K smearing

25meV

CIB and ZE Backgrounds to CνB decay



Expected E_γ spectrum
$m_3 = 50\text{meV}$

ν-decay ($\tau = 5 \times 10^{12}\text{yr}$)
λI_λ~30nW/m²/s

ν-decay ($\tau = 1 \times 10^{14}\text{yr}$)
λI_λ~1.5nW/m²/s

Zodiacal Emission
λI_λ~500nW/m²/sr

CIB (COBE)
λI_λ~30nW/m²/s

ν-decay ($\tau = 1 \times 10^{17}\text{yr}$)
λI_λ~1.5pW/m²/s

at $E_\gamma = 25\text{meV}$ (λ = 50μm)

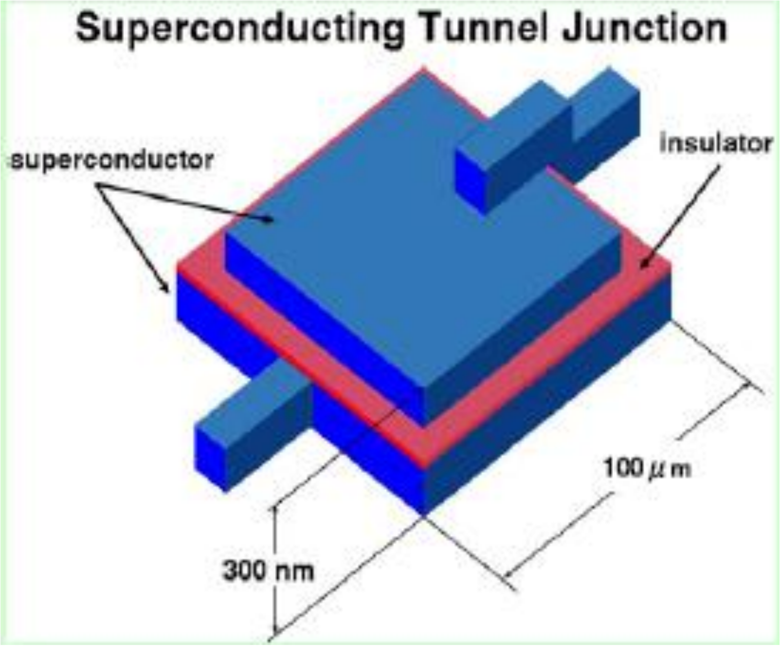
Detector requirements

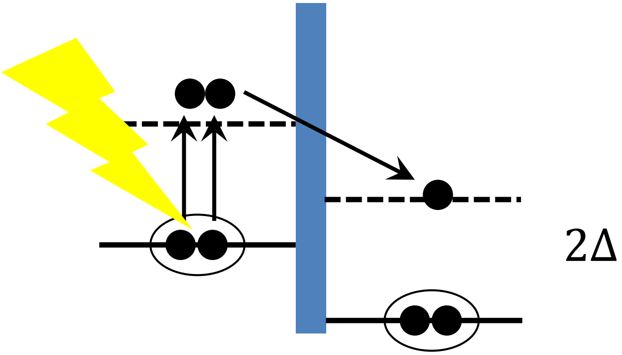
- Requirements for detector
  - Continuous spectrum of photon energy around $E_\gamma \sim 25\ \mathrm{meV} (\lambda = 50\mu\mathrm{m}$, far infrared photon)
  - Energy measurement for single photon with better than 2% resolution for $E_\gamma = 25\mathrm{meV}$ to identify the sharp edge in the spectrum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

- **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 aiming at launching in two years after the detector R&D completion (in 2017 in earliest), expecting improvement of current lower limit for $\tau(\nu_3)$ by 2 order : O(10^{14}yr)**
  - STJ using Hafnium: Hf-STJ for satellite experiment (after 2020)
    - $\Delta = 20\mu\mathrm{eV}$: Superconducting gap energy for Hafnium
    - $N_{\mathrm{q.p.}} = 25\mathrm{meV}/1.7\Delta = 735$ for 25meV photon: $\Delta E/E < 2\%$ if Fano-factor is less than 0.3

STJ(Superconducting Tunnel Junction) Detector

- Superconducting / Insulator /Superconducting Josephson junction device



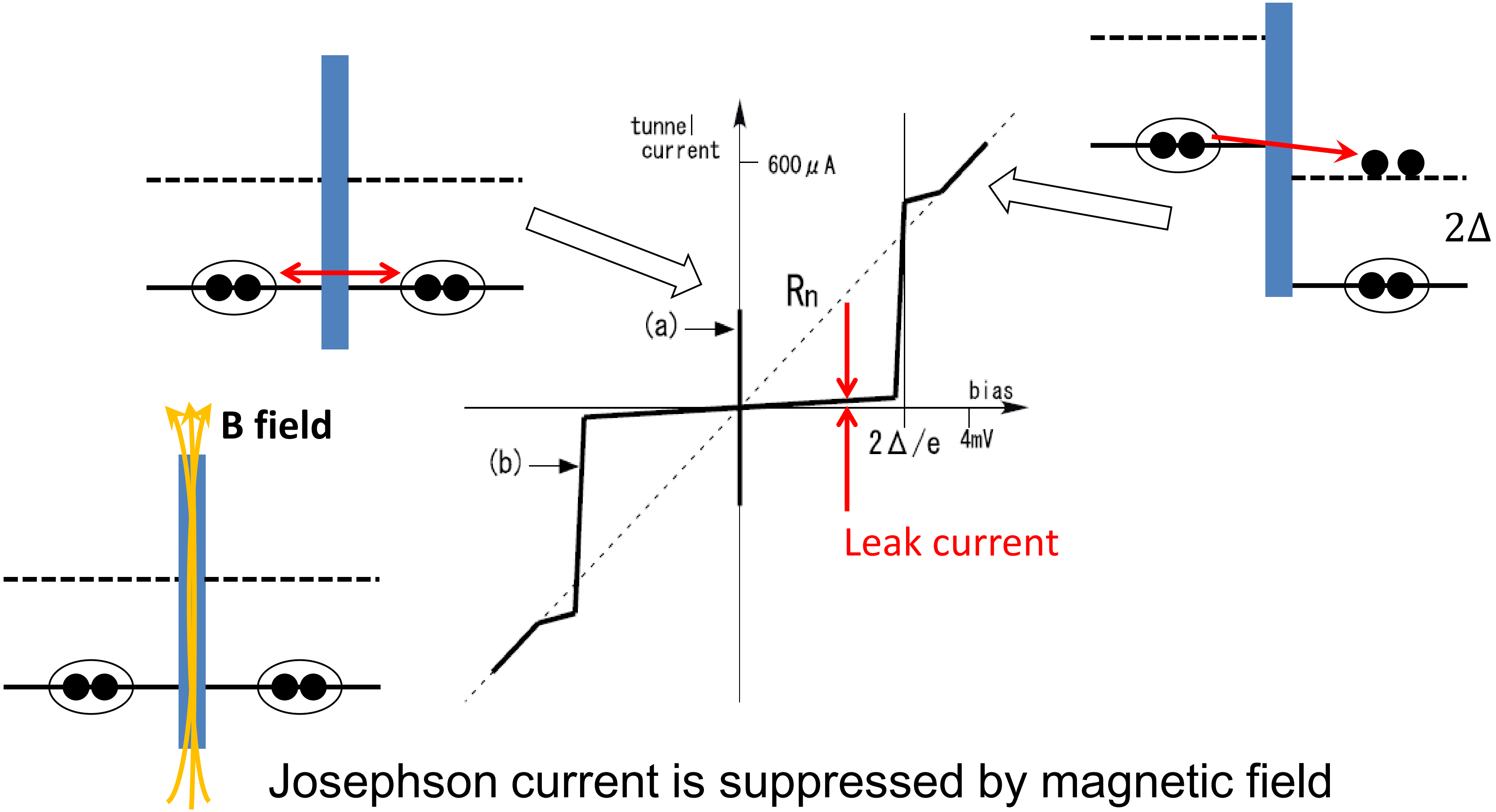


A bias voltage V is applied across the junction.
A photon absorbed in the superconductor breaks Cooper pairs and creates tunneling current of quasi-particles proportional to the photon energy.

STJ 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|>2Δ



Josephson current is suppressed by magnetic field

STJ energy resolution

Statistical fluctuation in number of quasi-particles determines STJ 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-layer)

$N_{q.p.}$=25meV/1.7Δ=9.5

Poor energy resolution, but photon counting is possible

Hf

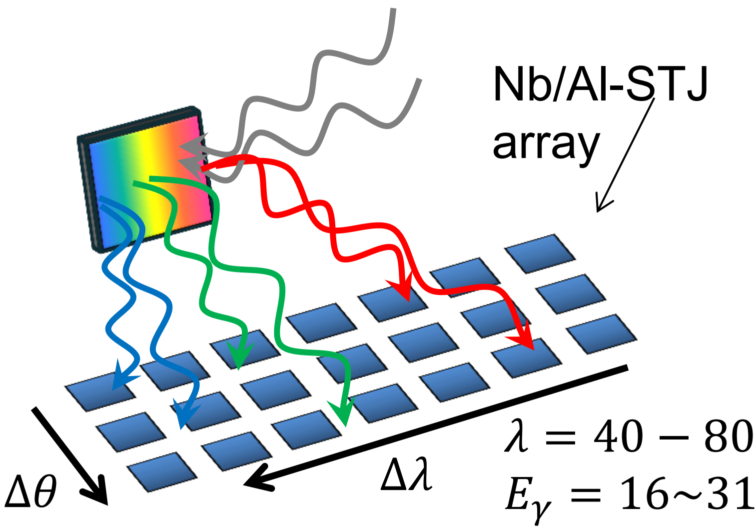
Hf-STJ as a photon detector is not established

$N_{q.p.}$=25meV/1.7Δ=735

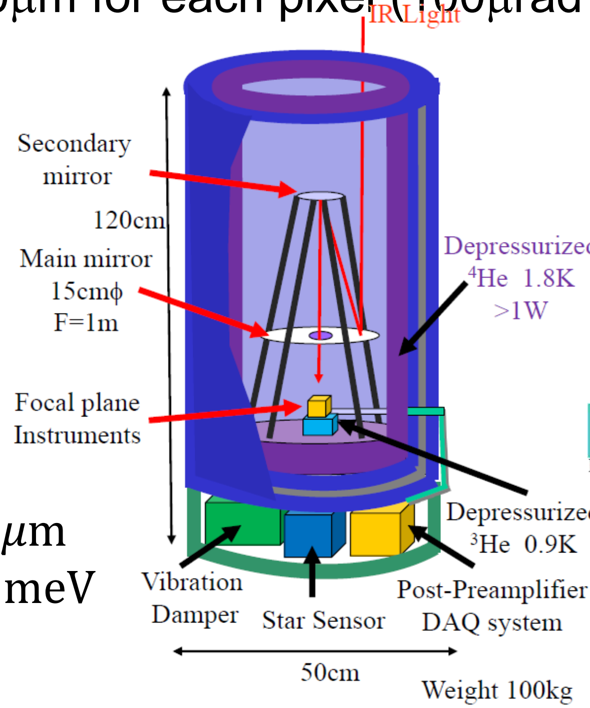
2% energy resolution is achievable if Fano factor <0.3

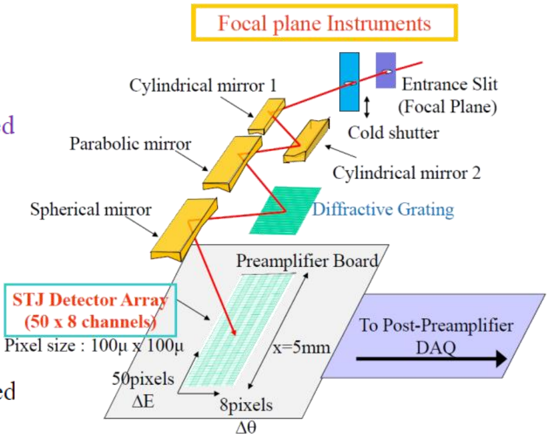
FIR single photon spectroscopy with diffraction grating + Nb/Al-STJ array for JAXA rocket experiment

- Expect 200sec. 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)x8(θ)
  - ☐ Use each Nb/Al-STJ pixel as **a single-photon counting detector** for FIR photon of $E_\gamma = 16\sim31\text{meV}$
  - ☐ sensitive area of 100μmx100μm for each pixel (100μrad x 100μrad)

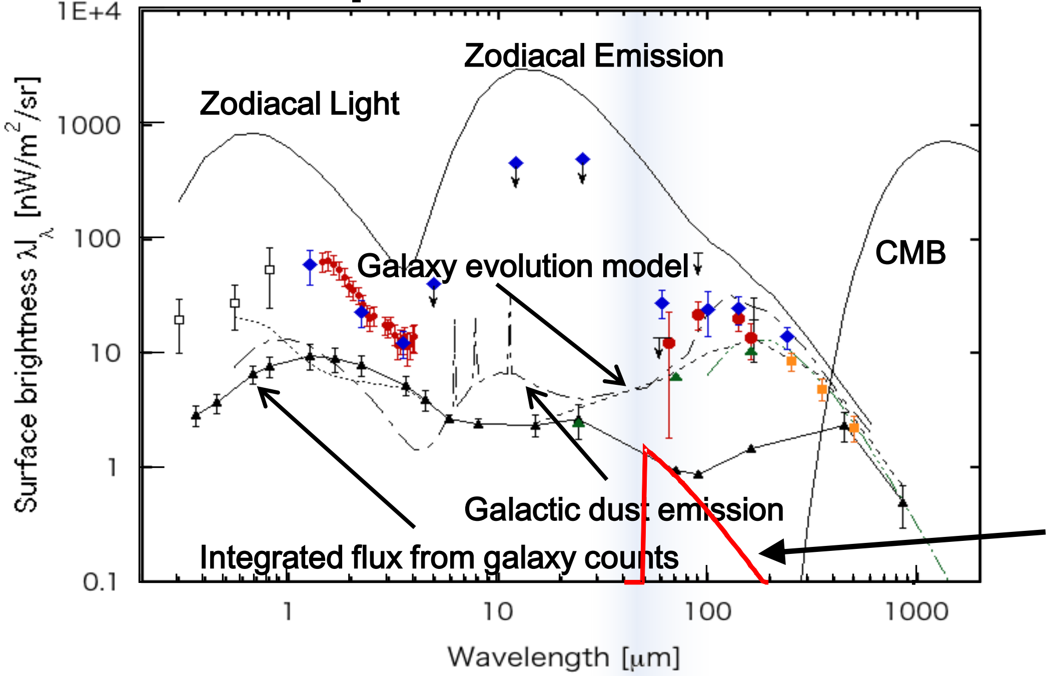


$$\lambda = 40 - 80\mu m$$
$$E_\gamma = 16\sim31\text{meV}$$





Expected Photon rate per 1pixel



$\boldsymbol{\tau_\nu = 1 \times 10^{14}}$ **yr**

Telescope

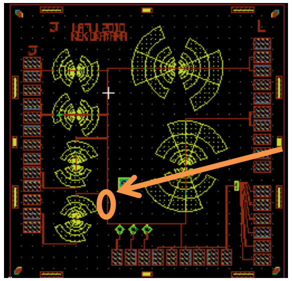
- $S = \pi \left(\frac{15cm}{2}\right)^2$
- $\Delta\Omega = \left(\frac{100\mu m}{1m}\right)^2 = 0.01\mu\ sr$
- $\Delta\lambda = \frac{40\mu m}{50} = 0.8\mu m$

- Zodiacal emission ⇒ 343Hz / pixel
  - 200sec measurement: 0.55M events / 8 pixels (at $\lambda = 50\mu m$)
  - 0.13% accuracy measurement for each wavelength

    $\boldsymbol{\delta(\lambda I_\lambda)}$=0.6nW/m^2/sr
- Neutrino decay ($\tau_\nu = 1 \times 10^{14}$yr)
  - $\boldsymbol{\lambda I_\lambda}$=1.5nW/m^2/sr
  - 2.3σ away from fluctuation in zodiacal emission measurement

ν with $\boldsymbol{\tau_\nu = 1 \times 10^{14}}$ yr is possible to detect!

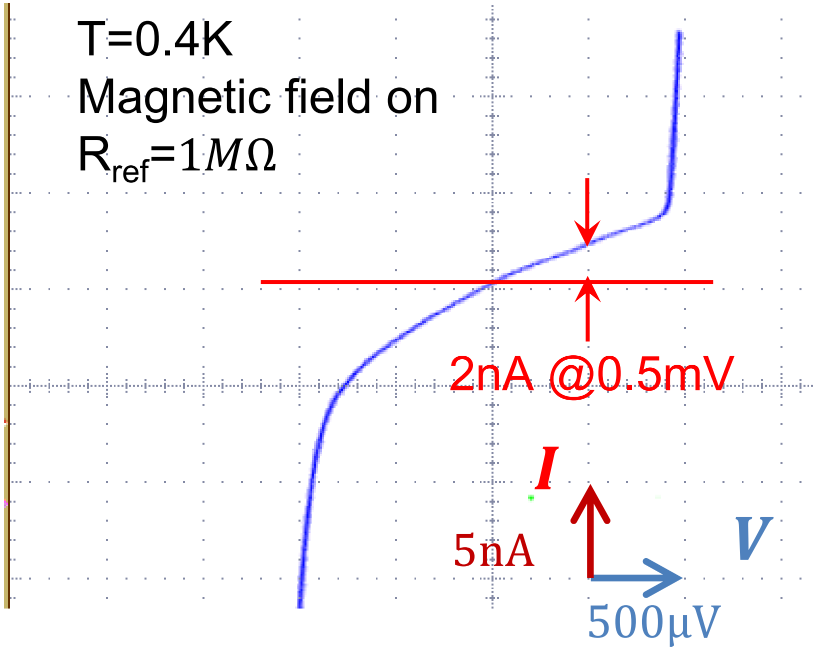
Temperature dependence of Nb/Al-STJ leak current

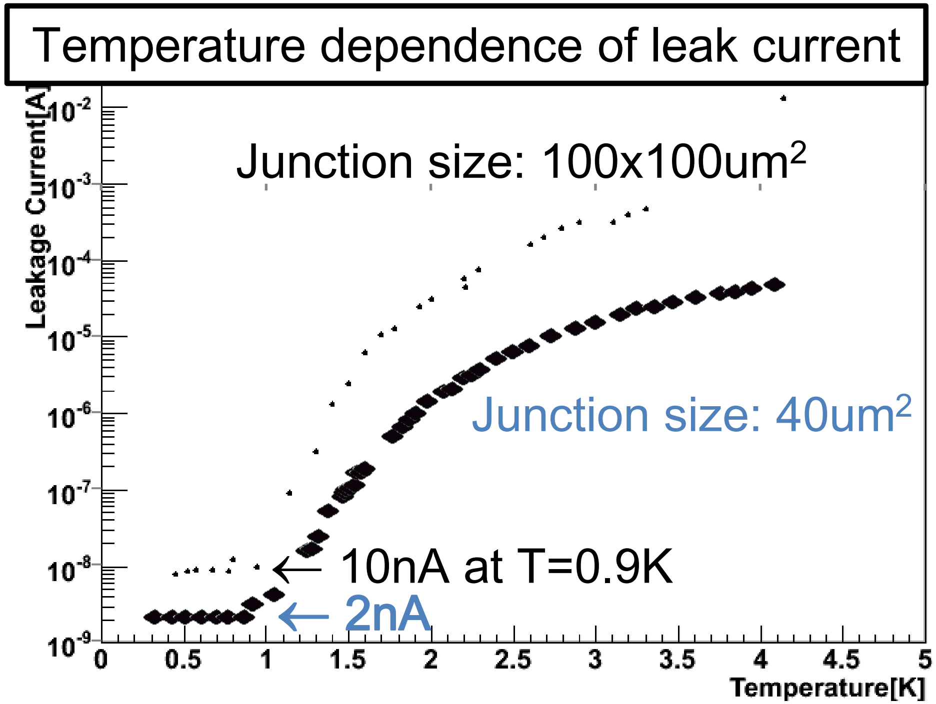


This Nb/Al-STJ is produced by S. Mima (Riken)

Need I_{leak}<0.1nA for single photon counting with S/N>10^3

40um² Nb/Al-STJ I-V curve





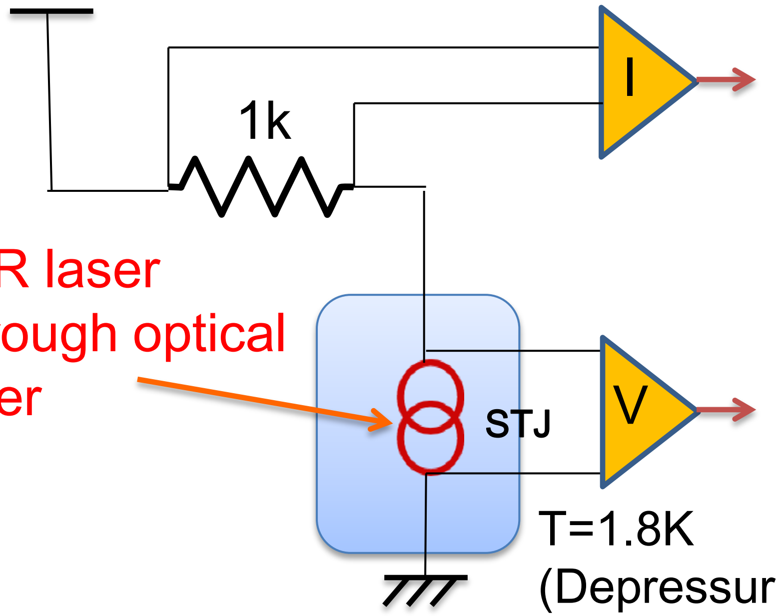
Leak current can be reduced by using small junction size. We are testing STJ of 4μm² junction size

Need T<0.9K for detector operation
➔ Use ^{3}He sorption or ADR for the operation in rocket experiment

T. Okudaira

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

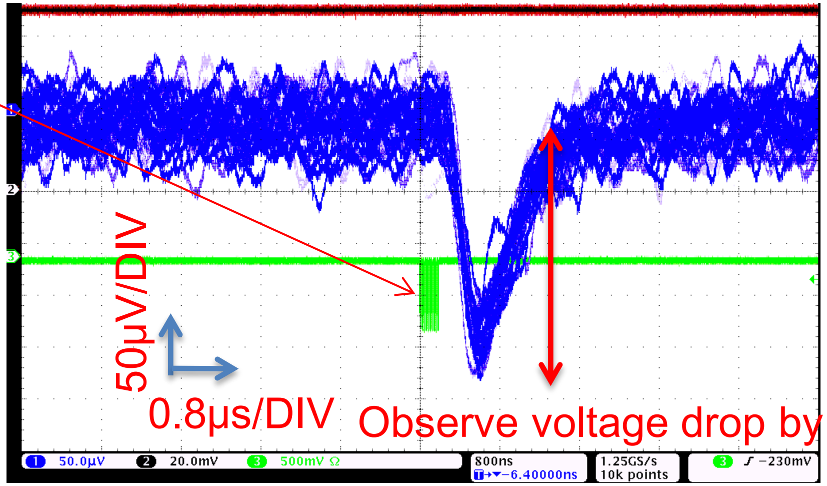
10 laser pulses in 200ns



NIR laser through optical fiber

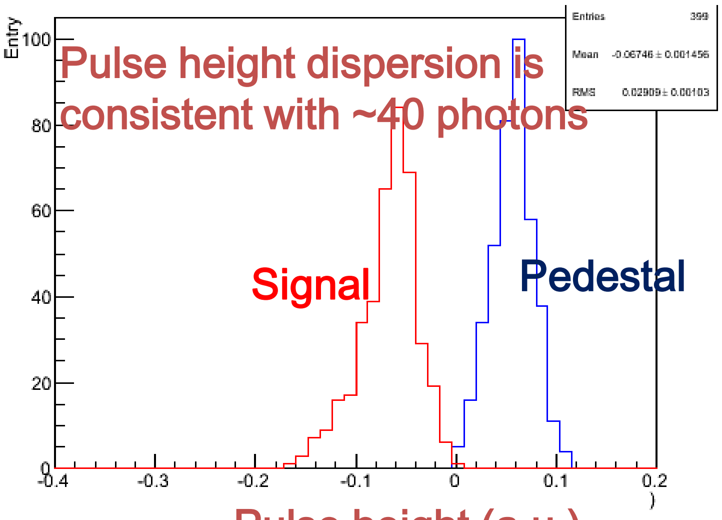
T=1.8K (Depressuring LHe)

Response to NIR laser pulse (λ=1.31μm)



Observe voltage drop by 250μV

Signal pulse height distribution



Pulse height dispersion is consistent with ~40 photons

-Pulse height (a.u.)

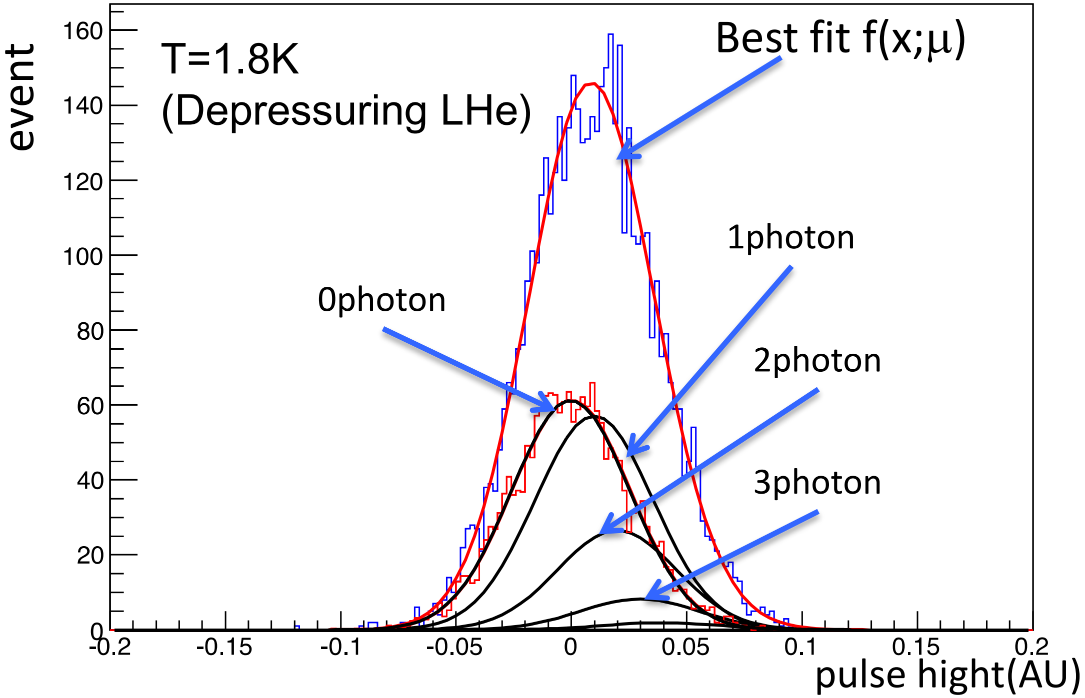
We observed a response to NIR photons

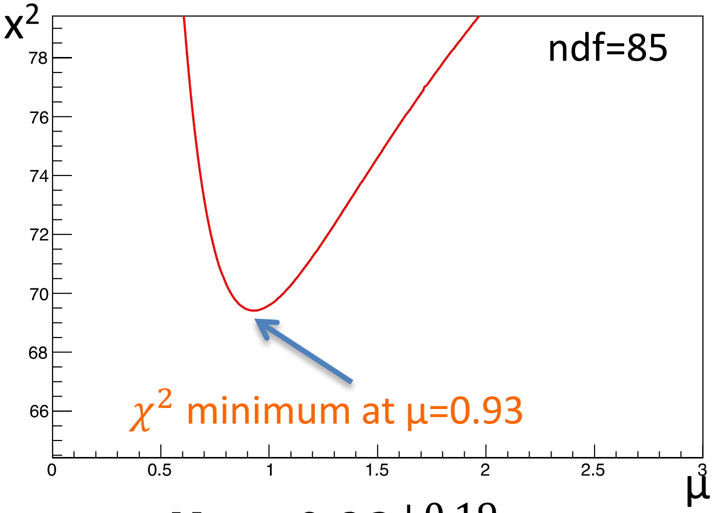
- Response time ~1μs
- Corresponding to 40 photon detection (estimated by statistical fluctuations in number of detected photons)

4μm^2 Nb/Al-STJ response to VIS light at single photon level

Assuming a Poisson distribution convoluted with Gaussian which has same sigma as pedestal noise:

$$f(x;\mu) = N_{\mathrm{tot}} \sum_{n} \frac{\mu^n e^{-\mu}}{n!} \cdot \frac{1}{\sqrt{2\pi}\sigma_p} \exp\left[- \frac{\left\{ x - n\left(\frac{M}{\mu}\right) \right\}^2}{2\sigma_p^2} \right]$$





$$N_\gamma = 0.93^{+0.19}_{-0.14}$$

Currently, readout noise is dominated, but we are detecting VIS light at single photon level

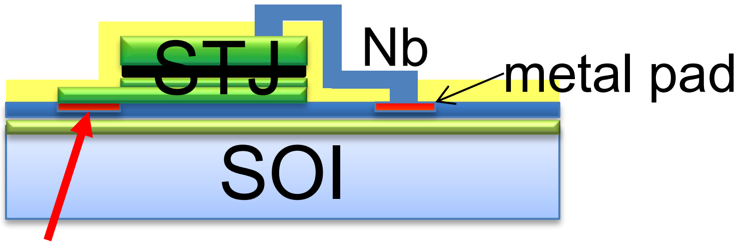
K. Kasahara

Development of SOI-STJ

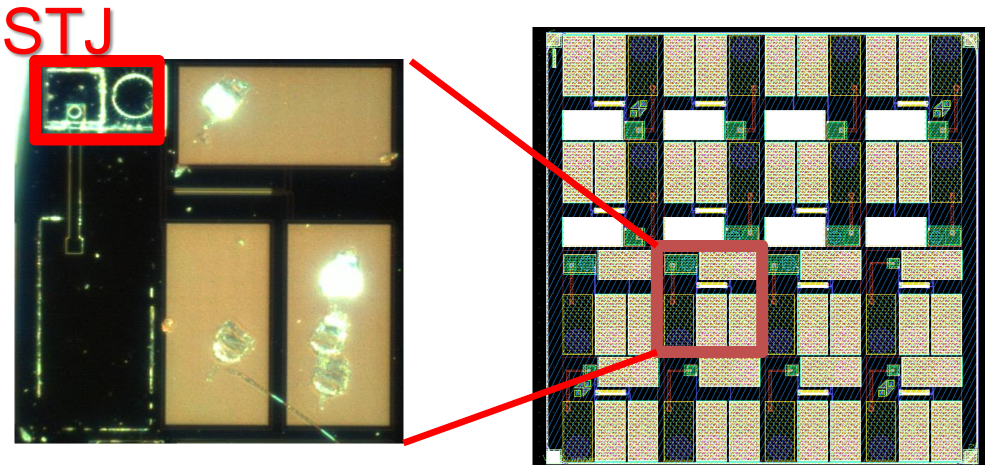
- SOI: Silicon-on-insulator
  - CMOS in SOI is reported to work at 4.2K by T. Wada (JAXA), et al.

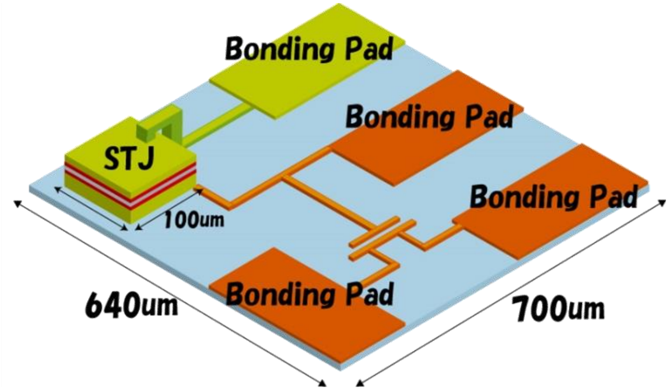
Phys. 167, 602 (2012)

- 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



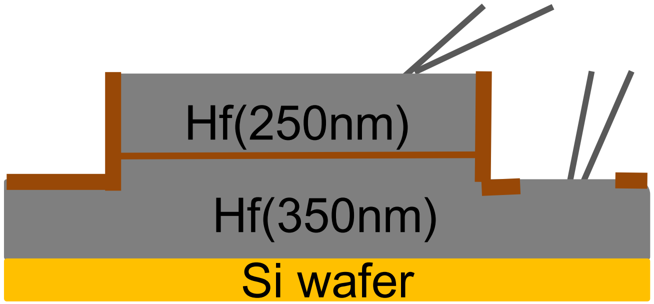


K. Kasahara's talk for detail
Photon detectors session3 at 15:00 on 6th

K. Nagata

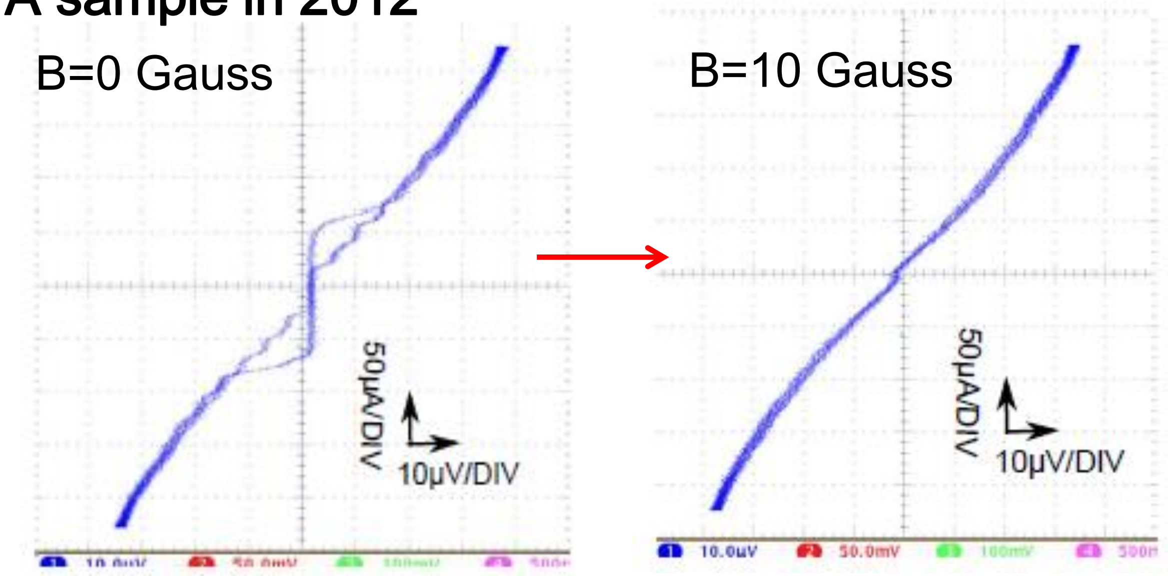
Hf-STJ development

- 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



$200 \times 200 \mu m^2$

T=80~177mK

$I_c=60\mu A$

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

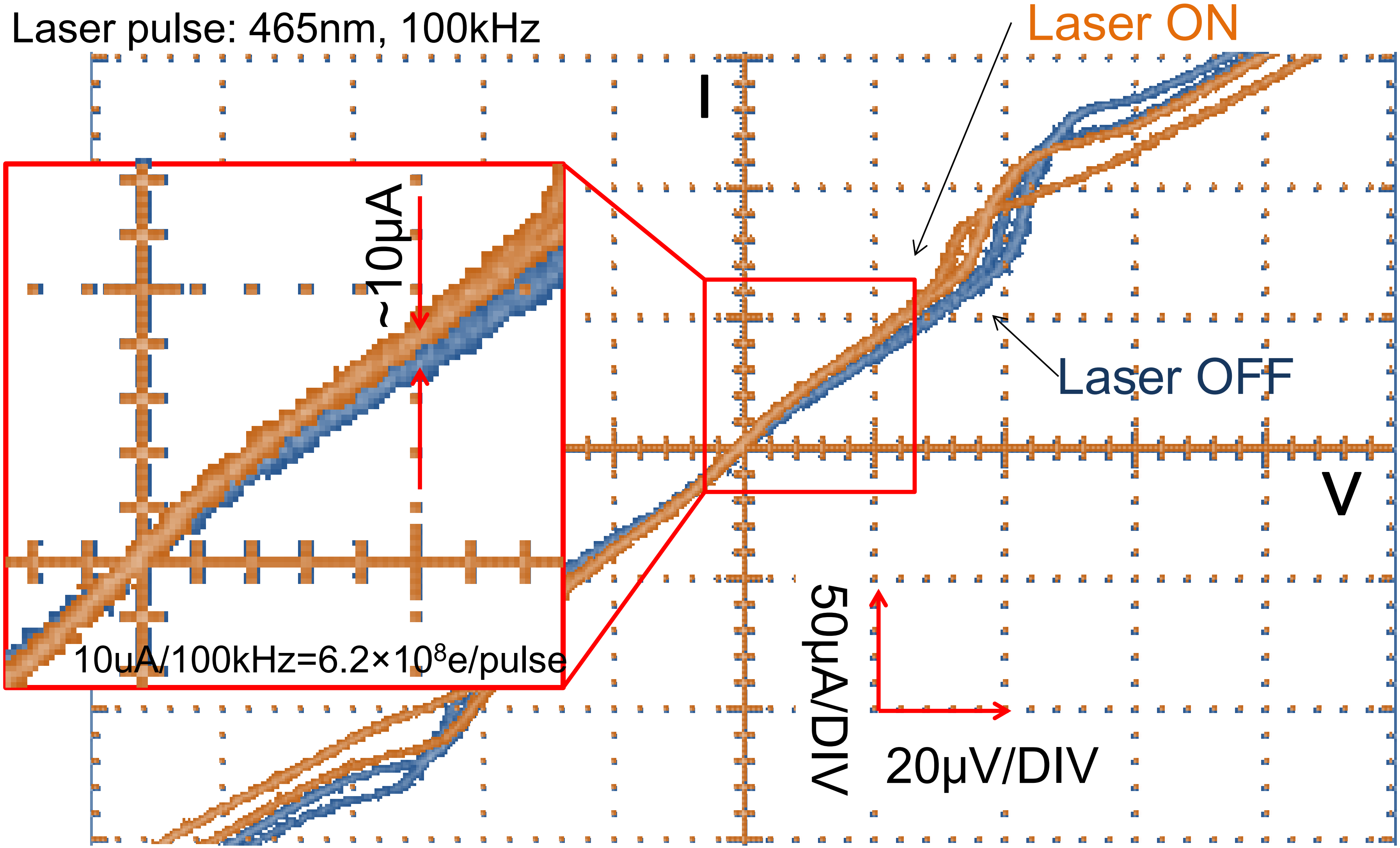
$R_d=0.2\Omega$

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)

K. Nagata

Hf-STJ Response to DC-like VIS light

Laser pulse: 465nm, 100kHz



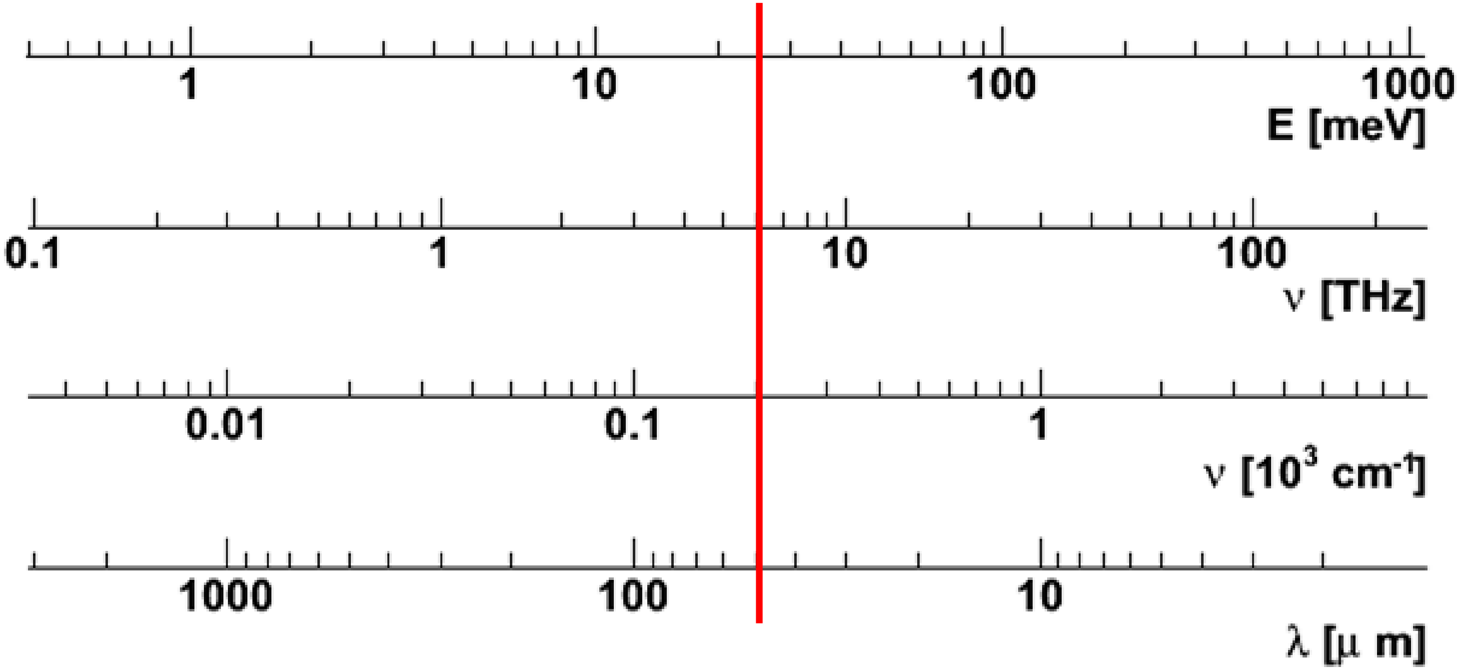
We observed Hf-STJ response to visible light

Summary

- We propose an experiment to search for neutrino radiative decay in cosmic neutrino background
- 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 observed Nb/Al-STJ response to VIS light at single photon level, but readout noise is currently dominated.
- We’ve confirmed the SIS structure in our Hf-STJ prototypes and observed quasi-particle tunneling current from response to VIS light illumination
  - but much improvement in leakage current is required for a practical usage
- Development of readout electronics for Nb/Al-STJ is underway
  - As the first milestone, aiming to single VIS/NIR photon counting
  - Several ultra low temperature amplifier candidates are under development. SOI-STJ is one of promising candidates

Backup

Energy/Wavelength/Frequency

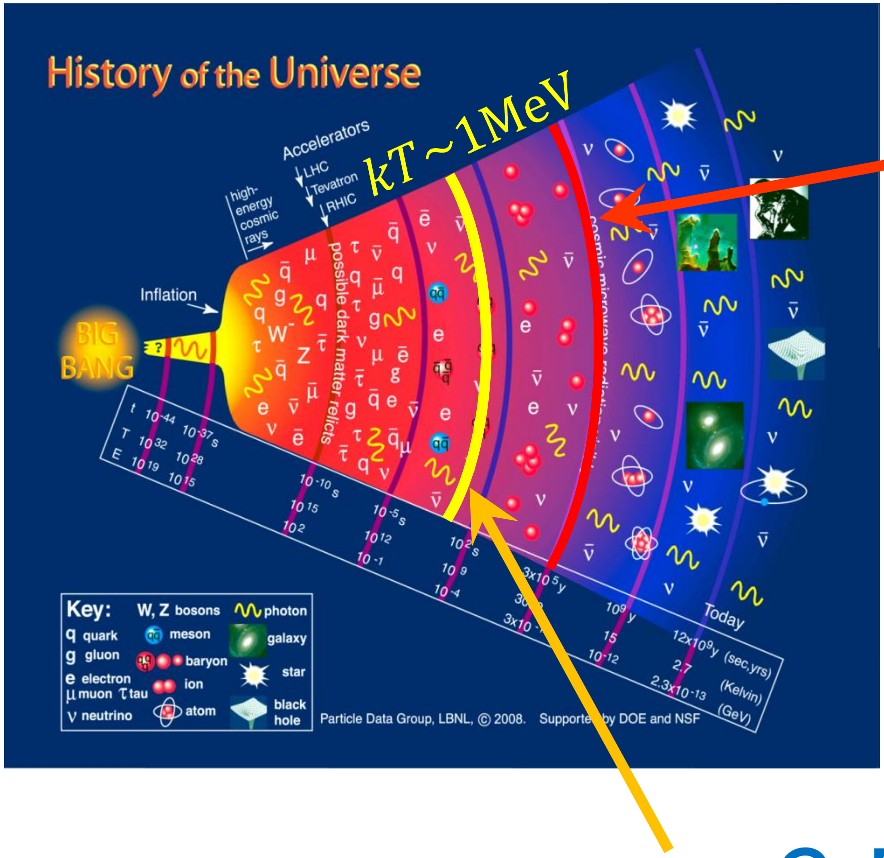


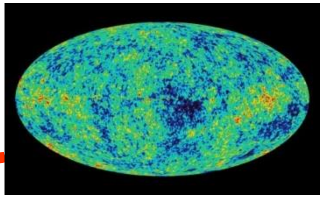
$$E_\gamma = 25\ \text{meV}$$

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

$$\lambda = 50\mu m$$

Cosmic neutrino background (CνB)

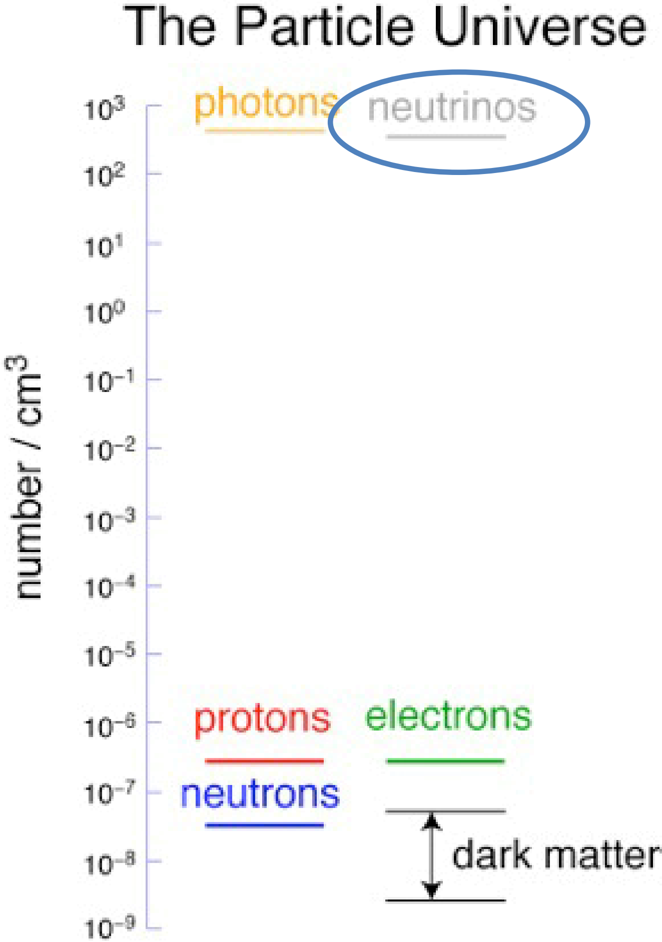




CMB

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

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

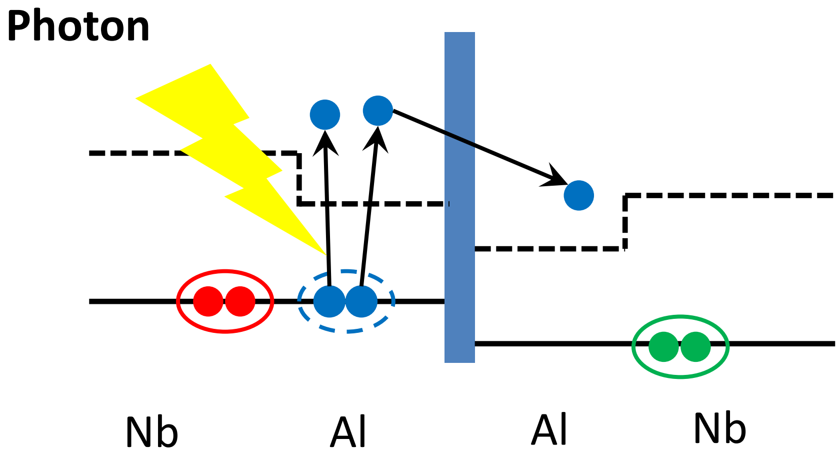


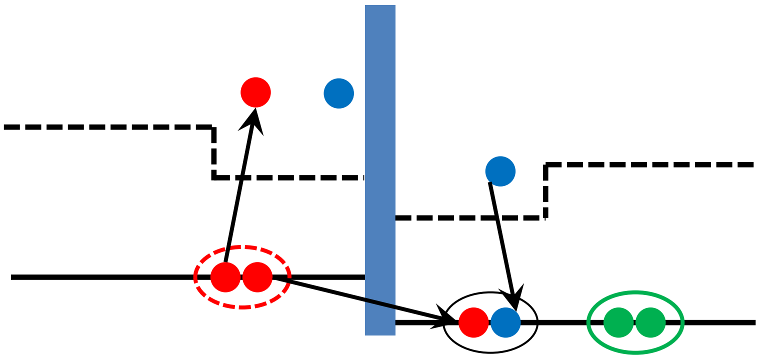
CνB

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

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





Feasibility of VIS/NIR single photon detection

- Assume typical time constant from STJ response to pulsed light is ~1μs
- Assume leakage is 160nA

$$160nA = e \times 10^{12}/s = e \times 10^{6}/\mu s$$

Fluctuation from electron statistics in 1μs is

$$e \times \sqrt{10^{6}}/\mu s = 10^{3} e/\mu s$$

While expected signal for 1eV are

(Assume back tunneling gain x10)

$$1eV/1.7\Delta \times 10e = \frac{1eV}{1.7 \times 1.5meV} \times 10 = 4 \times 10^{3} e$$

More than 3sigma away from leakage fluctuation

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

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

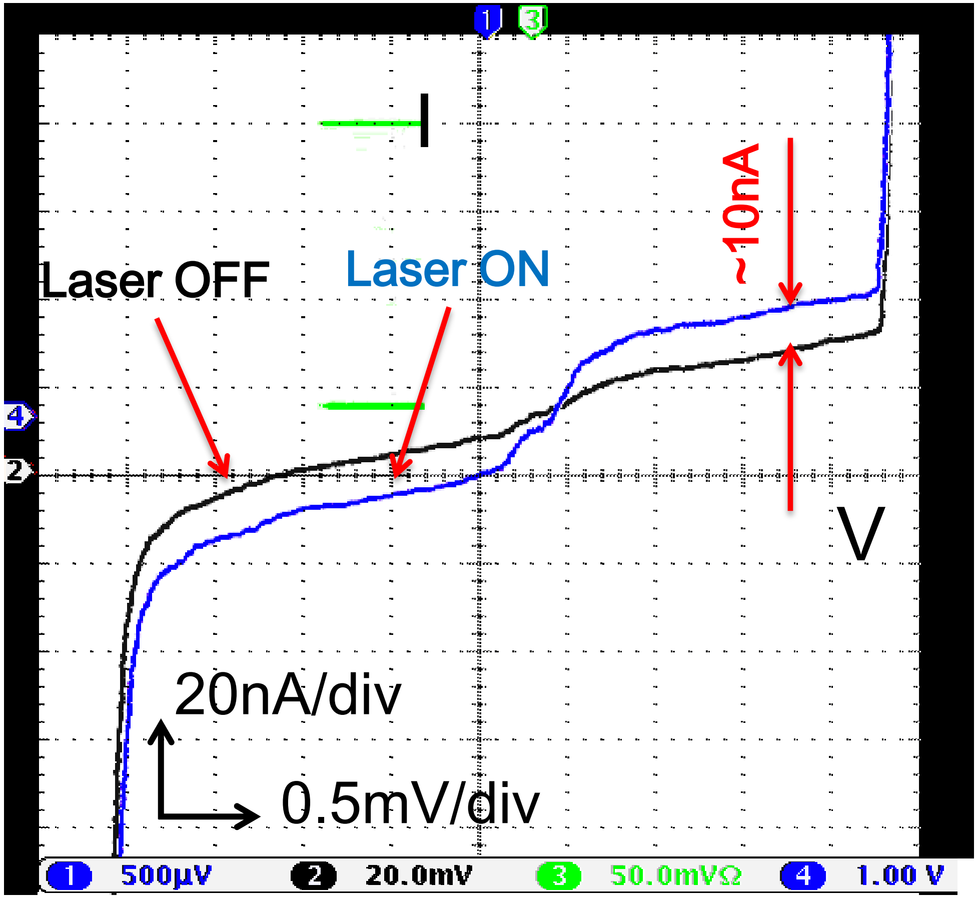
(Assume back tunneling gain x10)

More than 3sigma away from leakage fluctuation

- Requirement for amplifier
  - Noise$<$16e
  - Gain: 1V/fC → V=16mV

4μm^2 Nb/Al-STJ response to DC-like VIS light

VIS laser pulse (465nm) 20MHz illuminated on 4μm^2 Nb/Al-STJ



10nA/20MHz=0.5×10^{-15} C =3.1×10^3 e

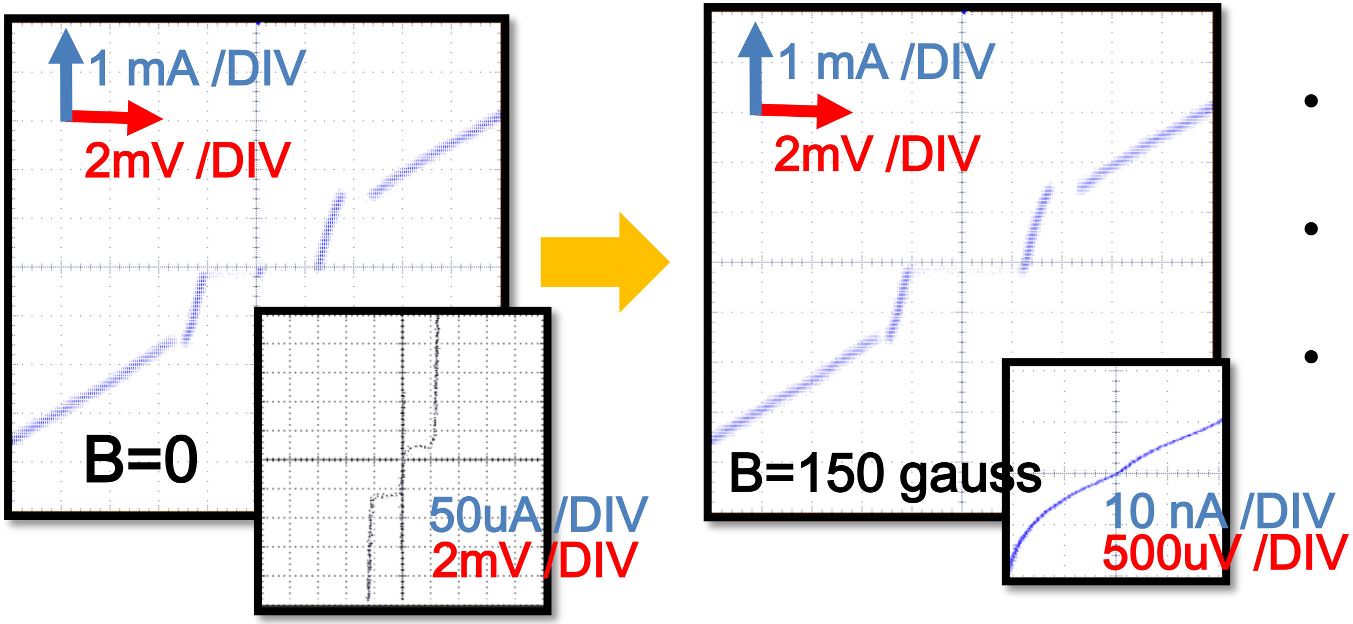
0.45 photons/laser pulse is given in previous slide

Gain from Back-tunneling effect

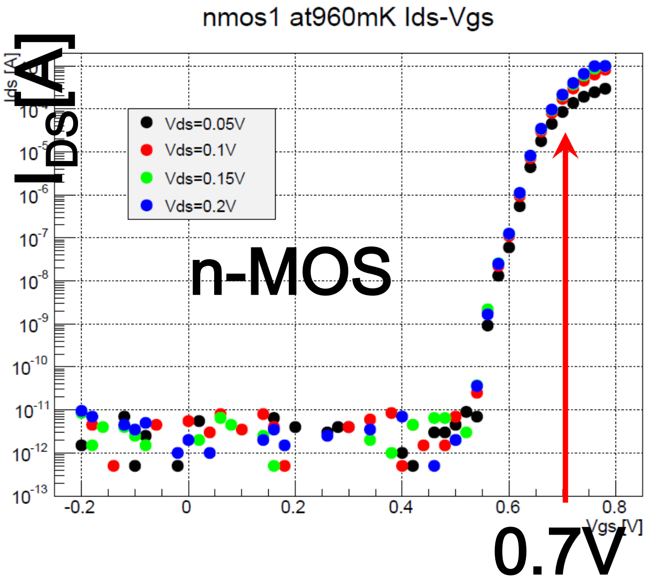
G_{al}=6.7

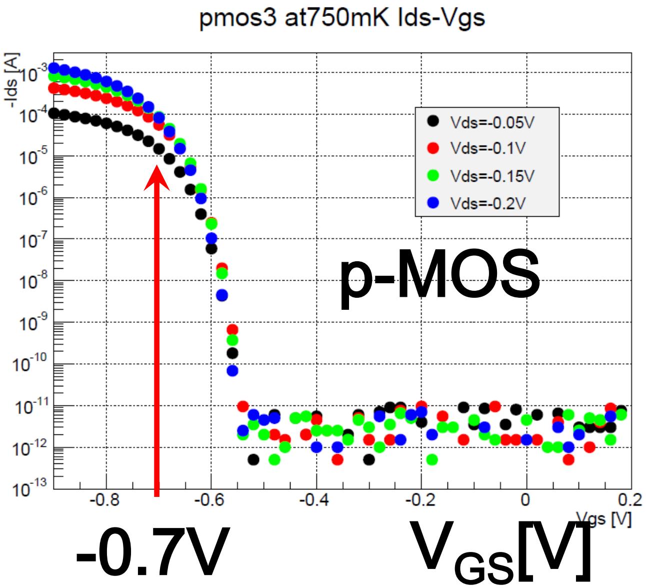
Development of SOI-STJ

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

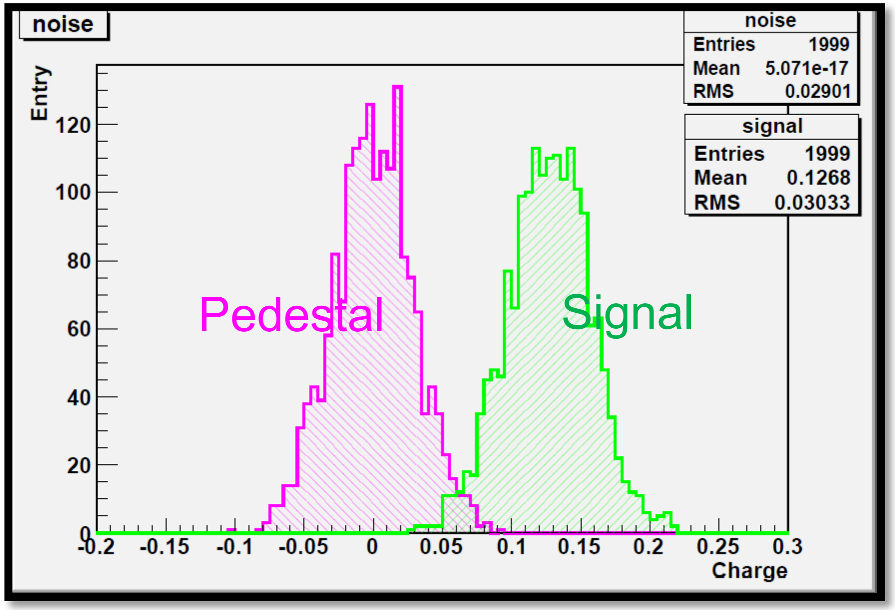
STJ on SOI response to laser pulse

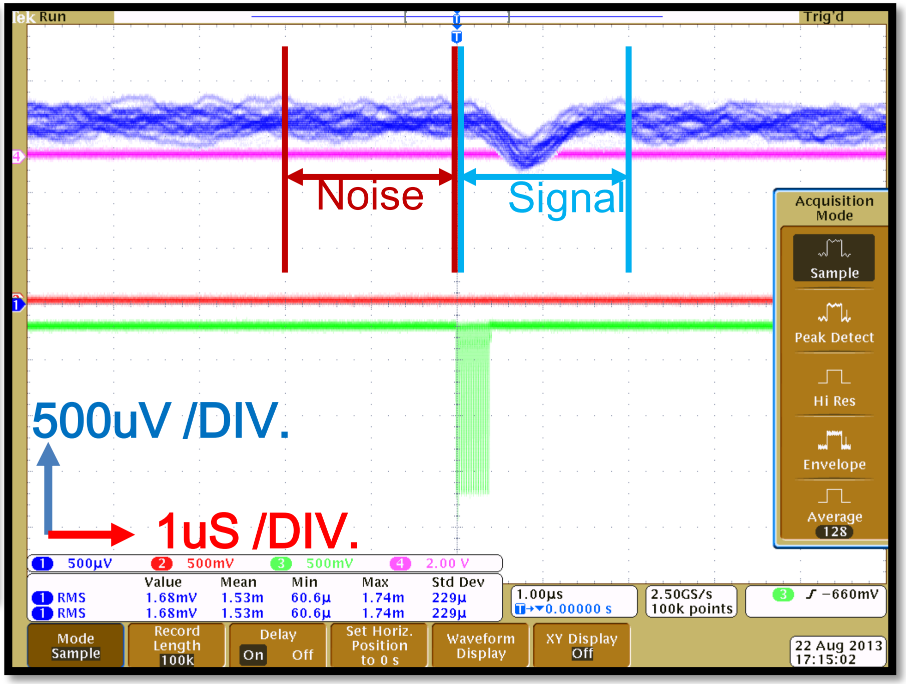
Iluminate 20 laser pulses (465nm, 50MHz) on 50x50um^2 STJ which is formed on SOI

Estimated number of photons from output signal pulse height distribution assuming photon statistics

$$N\gamma = \frac{M^2}{\sigma^2 - \sigma_p{}^2} \sim 206 \pm 112$$

M : Mean
σ : signal RMS
σ_p : pedestal RMS





① 500µV ② 500mV ③ 500mV ④ 2.00 V

	Value	Mean	Min	Max	Std Dev
① RMS	1.68mV	1.53m	60.6µ	1.74m	229µ
① RMS	1.68mV	1.53m	60.6µ	1.74m	229µ

1.00µs
T→▼0.00000 s

2.50GS/s
100k points

③ ∫ −660mV

22 Aug 2013
17:15:02

Confirmed STJ formed on SOI responds to VIS laser pulses