Development of Far-infrared Spectrophotometers based on Superconducting Tunnel Junction (STJ) for COBAND Experiment

Neutrino Frontier Workshop 2016

Nov. 28-30, 2016 / Yunokuni Tensyo, Kaga

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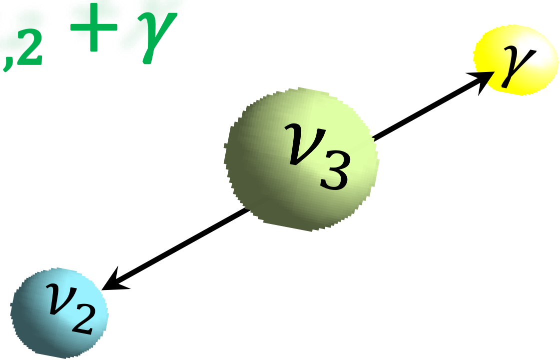
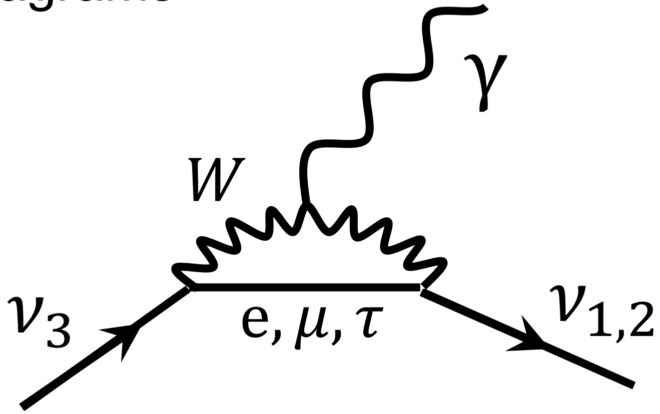
on behalf of COBAND Collaboration

COBAND (COsmic BAckground Neutrino Decay)

- **Heavier neutrinos in mass-eigenstate (ν_2, ν_3) are not stable**
  - Neutrino can decay through the loop diagrams
  - $\boldsymbol{\nu_3 \rightarrow \nu_{1,2} + \gamma}$



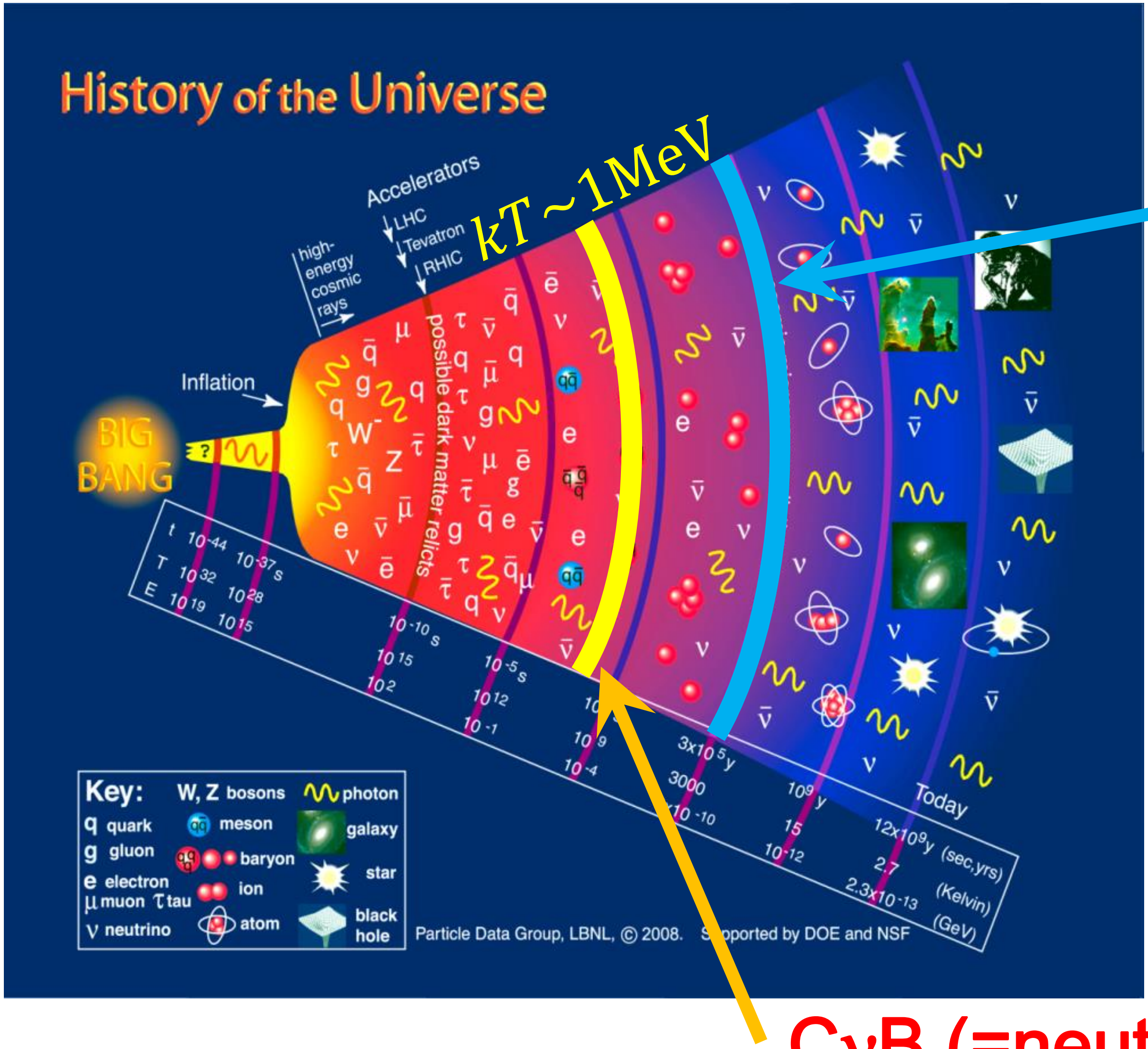


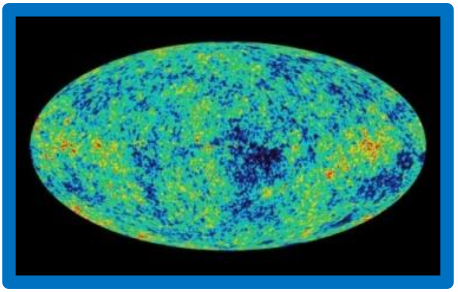
✓ However, the lifetime is expected to be much longer than the age of the universe

➔ We search for neutrino decay using Cosmic Background Neutrino (CνB) as the neutrino source

$$\boldsymbol{\rho(\nu_3 + \bar{\nu}_3) \sim 110/\mathrm{cm}^3}$$

Cosmic background neutrino (CνB)





CMB

(=Photon decoupling)

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

$T_\gamma = 2.73\ K$

~380,000yrs after the Big Bang

CνB (=neutrino decoupling)

~1sec after the big bang

COBAND Collaboration Members (As of Nov. 2016)

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Motivation of ν-decay search in CνB

ν_3 Lifetime

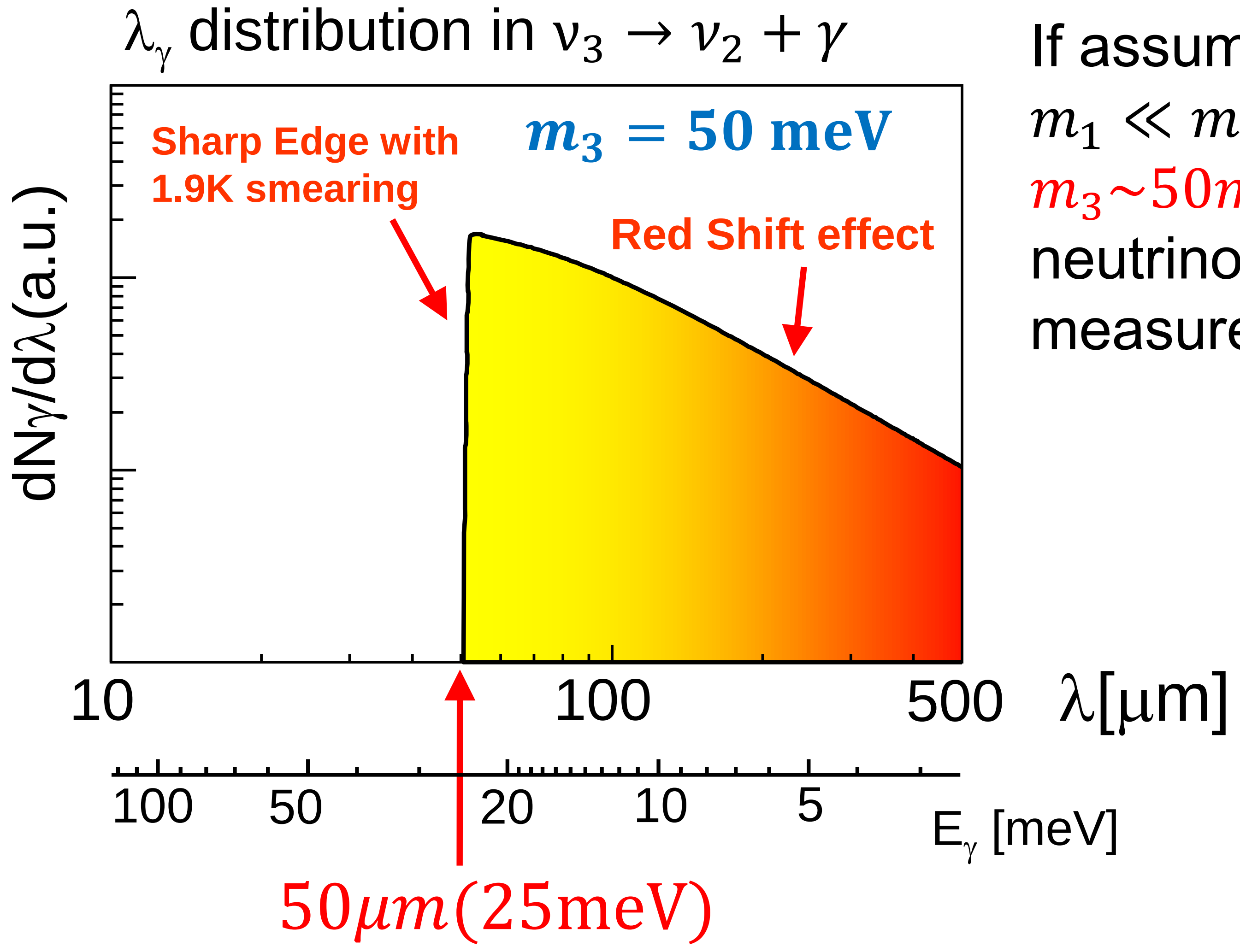
- Standard Model expectation: $\tau = \mathrm{O}(10^{43})\ \mathrm{yrs}$
- Experimental lower limit: $\tau = \mathrm{O}(10^{12})\ \mathrm{yrs}$
- Left-Right symmetric model predicts $\tau = \mathrm{O}(10^{17})\ \mathrm{yrs}$ for W_L-W_R mixing angle $|\zeta| \sim 0.02$

If we observed the neutrino radiative decay at the lifetime much shorter than the SM expectation, it would be

- Physics beyond the Standard Model
- Direct detection of CνB
- Determination of the neutrino mass
  - $m_3 = (m_3^2 - m_{1,2}^2)/(2E_\gamma)$

➔ Aiming at a sensitivity to ν_3 lifetime in $\mathrm{O}(10^{13} - 10^{17})\ \mathrm{yrs}$

Expected photon wavelength spectrum from CνB decays



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

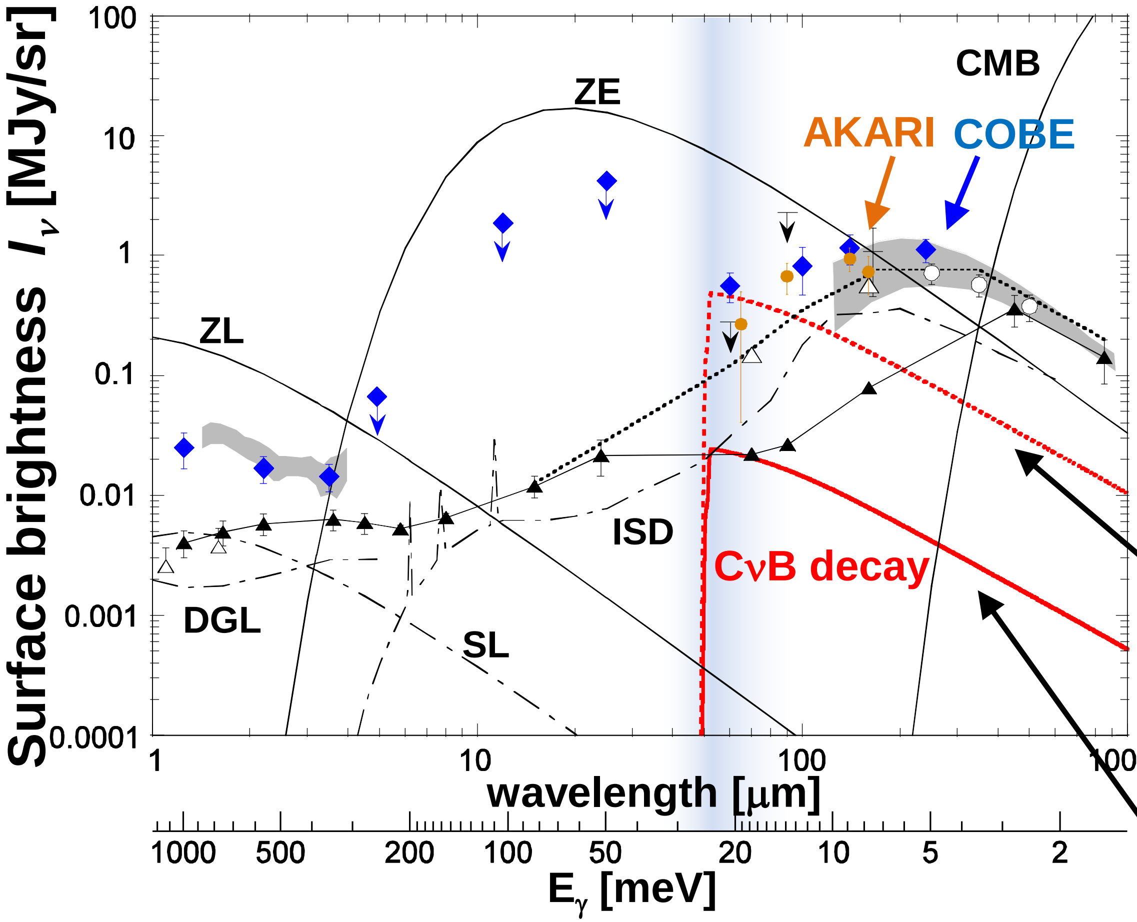
If assume

$m_1 \ll m_2 < m_3$,

$m_3 \sim 50 meV$ from neutrino oscillation measurements

No other source has such a sharp edge structure!!

CνB radiative decay and Backgrounds



Expected E_γ spectrum

for $m_3 = 50\text{meV}$

$1\text{Jy} = 10^{-26} W/m^2 \cdot Hz$

Zodiacal Emission

I_ν~8MJy/sr

Cosmic Infrared Background (CIB)

I_ν~0.1~0.5MJy/sr

CνB decay

$\tau = 5 \times 10^{12}\text{yrs}$

I_ν~0.5MJy/sr

Excluded (S.H.Kim 2012)

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

I_ν~25kJy/sr

at λ = 50μm

Proposal for COBAND Rocket Experiment

Aiming at a sensitivity to ν lifetime for $\tau(\nu_3) = O(10^{14})\ yrs$

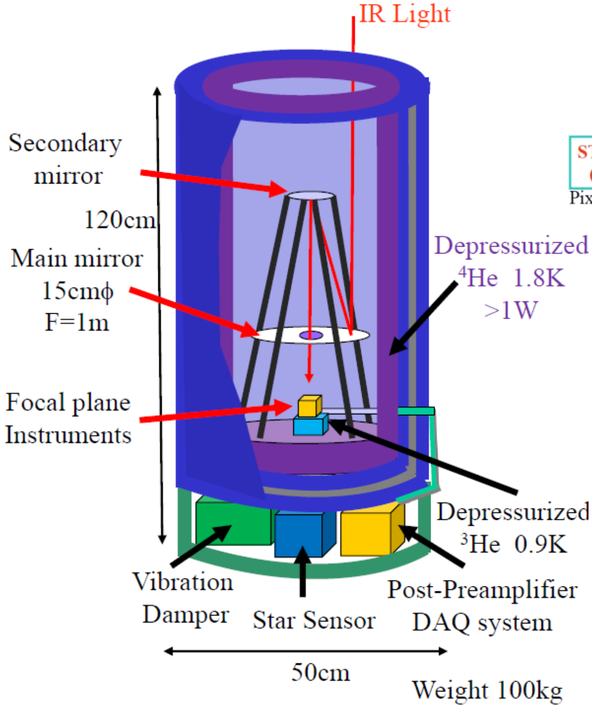
- JAXA sounding rocket S-520
  - http://www.isas.jaxa.jp/e/enterp/rockets/sounding/s520.shtml
  - Diameter: 520mm
  - Payload: 100kg
  - Altitude: 300km

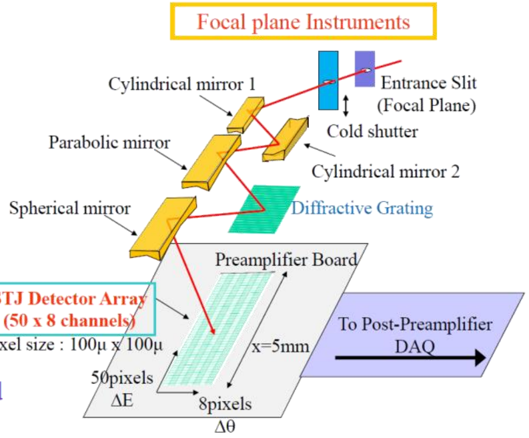
- 200-sec measurement at altitude of 200~300km
  - Telescope with diameter of 15cm and focal length of 1m
  - All optics (mirrors, filters, shutters and grating) will be cooled at ~1.8K

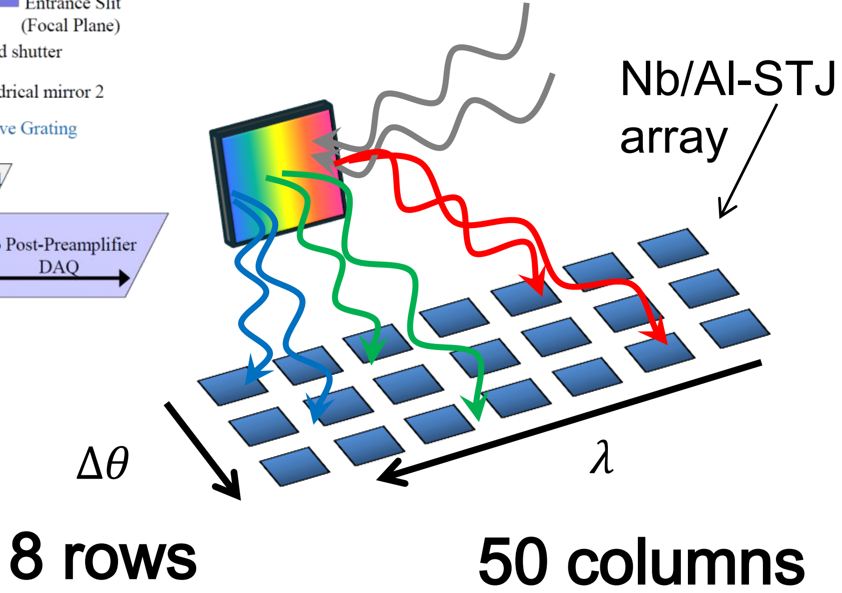
Proposal for COBAND Rocket Experiment

At the focal point, diffraction grating covering **λ=40-80μm (16-31meV)** and array of photo-detector pixels of **50(in wavelength distribution) x 8(in spatial distribution)** are placed

- Each pixel **counts FIR photons** in λ=40−80μm ($\Delta\lambda = 0.8\mu m$)
- Sensitive area of **100μmx100μm** for each pixel (**100μrad x 100μrad** in viewing angle)



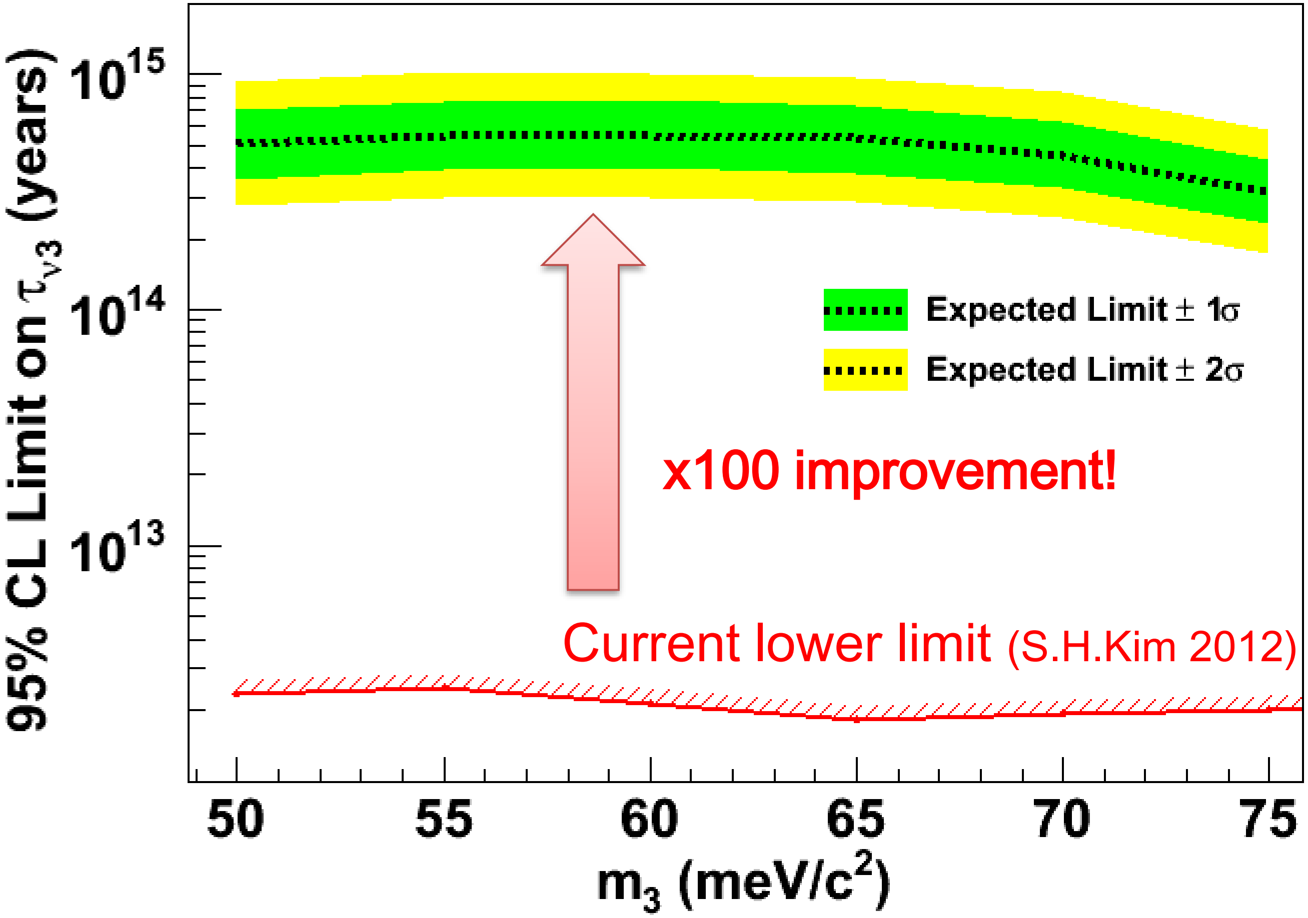




$$\lambda = 40 - 80\mu m$$
$$E_\gamma = 16{\sim}31\text{meV}$$

Sensitivity to neutrino decay

Parameters in the rocket experiment simulation are assumed.

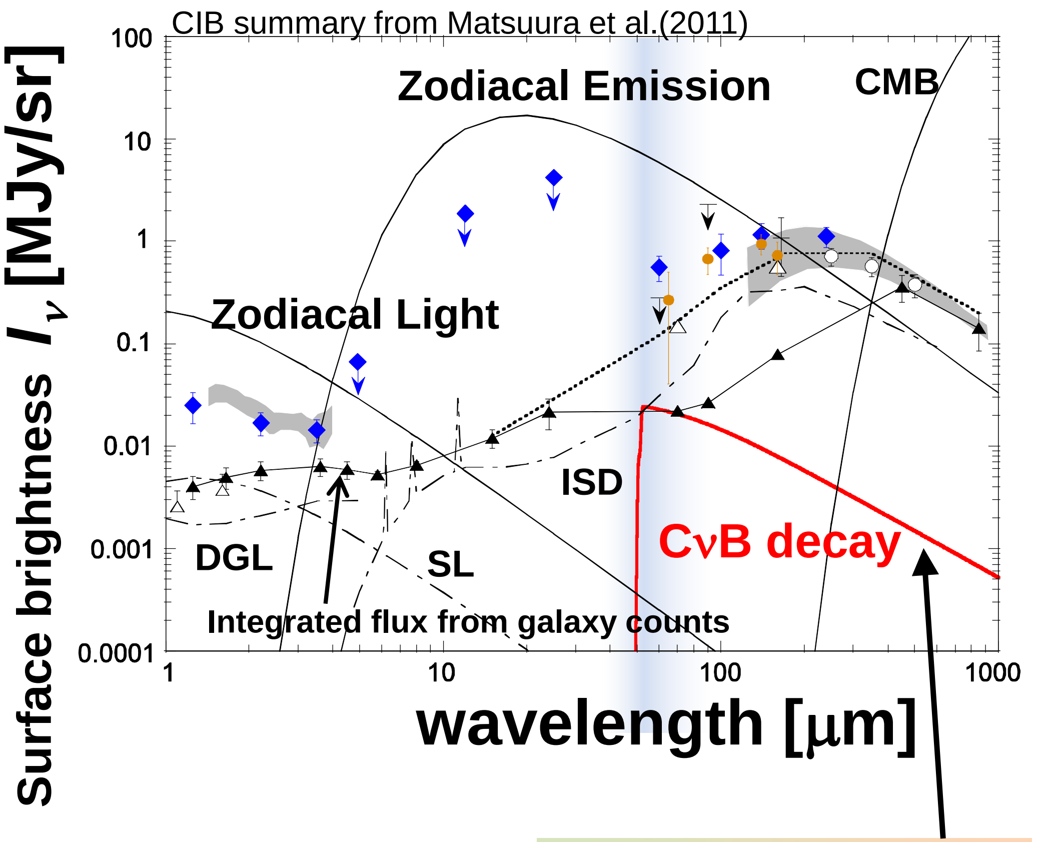


x100 improvement!

Current lower limit (S.H.Kim 2012)

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

Requirements for the photo-detector in the rocket experiment


CIB summary from Matsuura et al.(2011)

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

$$\boldsymbol{m_3 = 50\ \mathrm{meV}}$$

Zodiacal Emission

- I_{ZE}=8MJy/sr

➔1.1×10^{-17} W / 8pix

@ λ=50μm

Neutrino Decay

- I_ν=25kJy/sr

➔3.3×10^{-20} W / 8pix

@ λ=50μm

Noise Equivalent Power (NEP) Requirements for the photo-detector

- ☐ Neutrino decay ($m_3 = 50$ meV, $\tau_\nu = 10^{14}$yrs): I_ν=25kJy/sr @ λ=50μm

$$P_{ND} = 25\ kJy/sr \times 8 \times 10^{-8} sr \times \pi(15cm/2)^2 \times \Delta\nu$$
$$= 3.3 \times 10^{-20} W/8pix$$

- ☐ Zodiacal emission: I_ν=8MJy/sr @ λ=50μm

$$P_{ZE} = 1.1 \times 10^{-17} W/8pix$$

◆ Shot noise in P_{ZE} integrated over an interval Δt

- Fluctuation in number of photons with energy ϵ_γ: $\sqrt{\epsilon_\gamma P_{ZE} \Delta t}$

$$\frac{NEP}{\sqrt{2\Delta t}} \times \Delta t \ll \sqrt{\epsilon_\gamma P_{ZE} \Delta t} \ll P_{ND} \Delta t$$

➔ Δt>200sec

➔ $\mathrm{NEP} \sim \mathrm{O}(10^{-20})\ W/\sqrt{Hz}$ for 1pix

Existing FIR photo-detectors

Detectors	λ(μm)	Operation Temp.	NEP ($W/Hz^{1/2}$)	
Monolithic Ge:Ga	50-110	2.2K	~ 10^{-17}	Akari-FIS
Stressed Ge:Ga	60-210	0.3K	~0.9×10^{-17}	Herschel-PACS

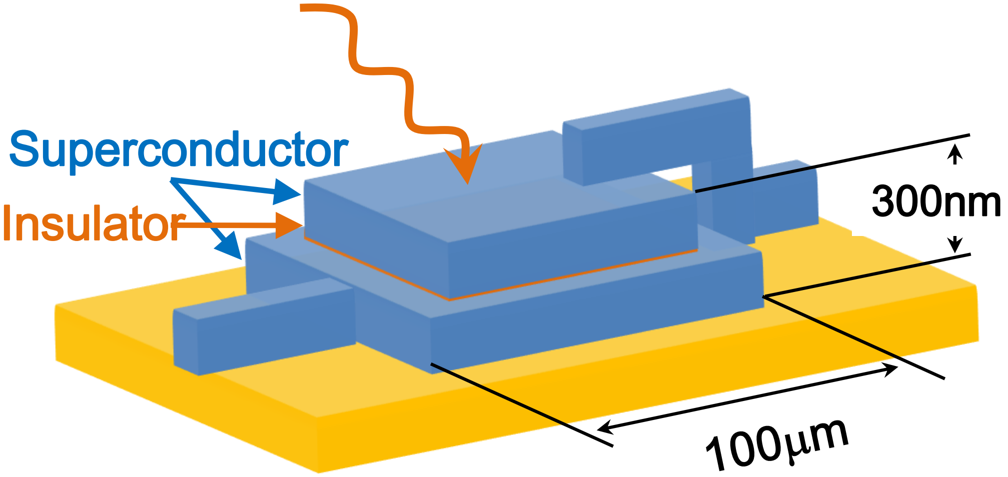
Need more than 2 orders improvement from existing photoconductor-based detectors

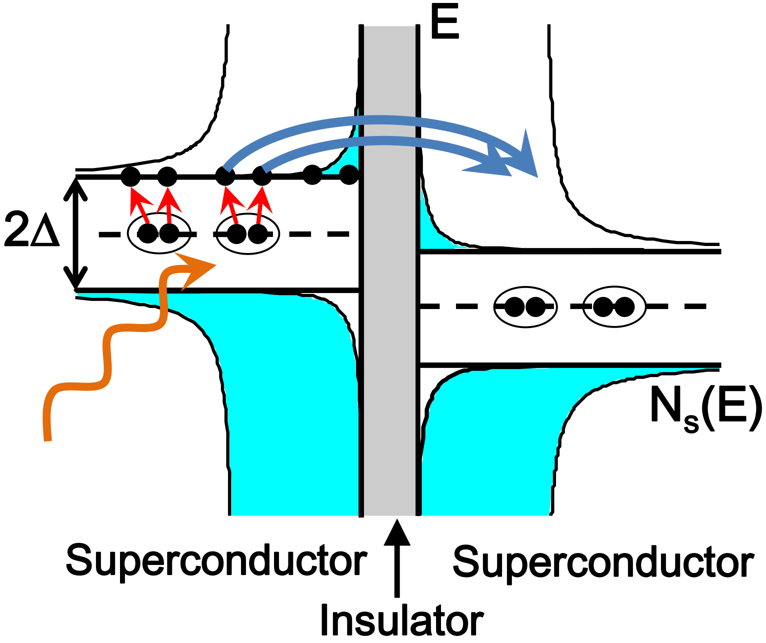
We are trying to achieve $\mathrm{NEP} \sim \mathrm{O}(10^{-20})\ W/\sqrt{Hz}$ **by using**

- **Superconducting tunneling junction detector**
- **FIR single-photon counting technique**

Superconducting Tunnel Junction (STJ) Detector

- Superconductor / Insulator /Superconductor
  Josephson junction device





Δ: Superconducting gap energy

A constant 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
- Faster response (~μs) ➔ Suitable for single-photon counting

STJ energy resolution

Signal = Number of quasi-particles

$$N_{q.p.} = G\frac{E_\gamma}{1.7\Delta}$$

Resolution = Statistical fluctuation in number of quasi-particles

$$\sigma_E/E = \sqrt{(1.7\Delta)F/E}$$

➔Smaller superconducting gap energy Δ yields better energy resolution

Δ: Superconducting gap energy
F: fano factor (~0.2 for Nb)
E: Photon energy
G: Back-tunneling gain

	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

STJ candidates

Nb/Al-STJ

- Well-established
  - Δ~0.6meV by the proximity effect from Al
  - Operation temperature <400mK
  - Back-tunnelling gain G~10
- $N_{q.p.}$=25meV/1.7$\Delta\times$10~ 250 σ_E/E~0.1 for E=25meV

➔25meV single-photon detection is feasible in principle

➔Developing for the rocket experiment

Hf-STJ

- Not established as a practical photo-detector yet by any group
- $N_{q.p.}$=25meV/1.7Δ~ 735
- 2% energy resolution for a 25meV single-photon is achievable if Fano factor <0.3 for Hf

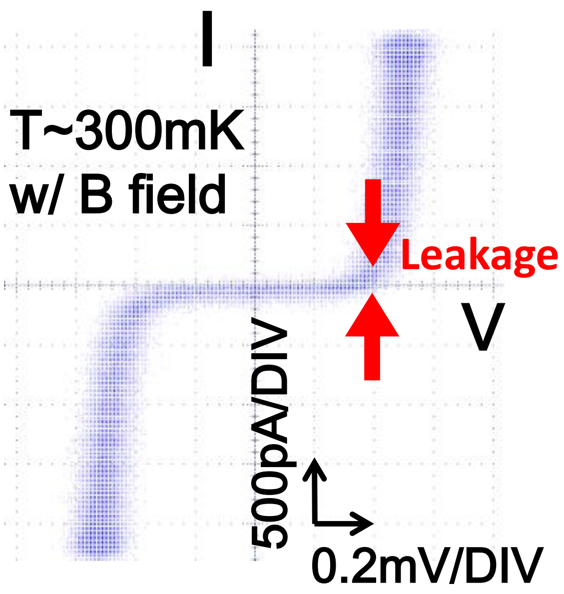
➔Spectrum measurement without a diffraction grating

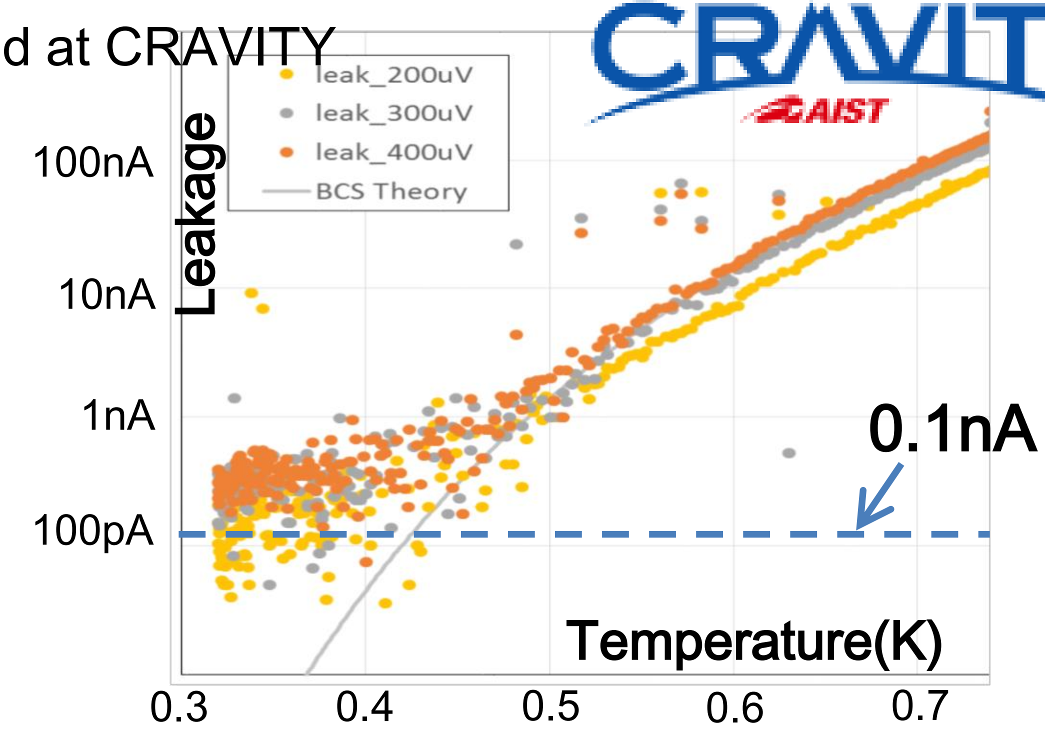
➔Developing for a future satellite experiment

K.Takemasa "R&D Status of Hf-STJ" on 30th

Nb/Al-STJ development at CRAVITY

50μm sq. Nb/Al-STJ fabricated at CRAVITY





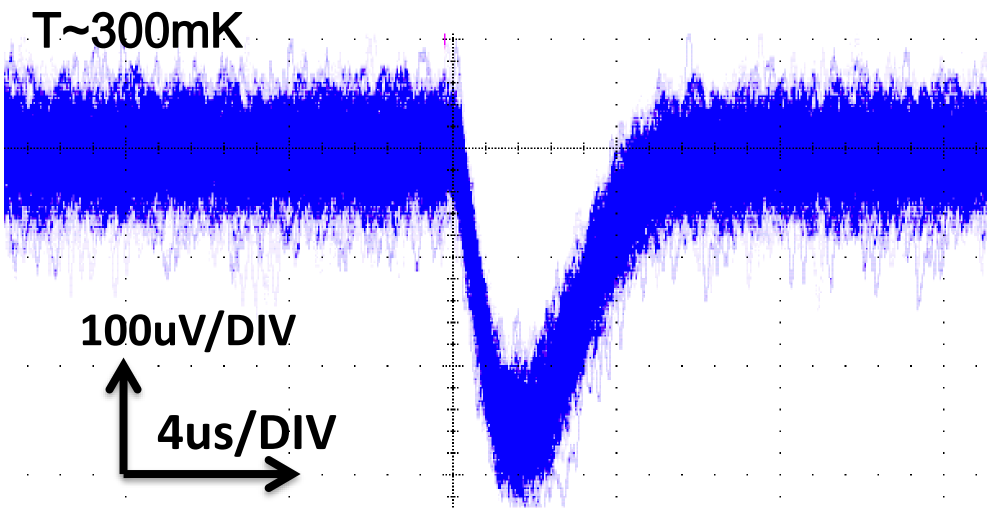
- I_{leak}~200pA for 50μm sq. STJ, and achieved 50pA for 20μm sq.
- The shot noise from the leak current in case of $i_{leak}=50\text{pA}$, $\Delta=0.6\text{meV}$ and G=10

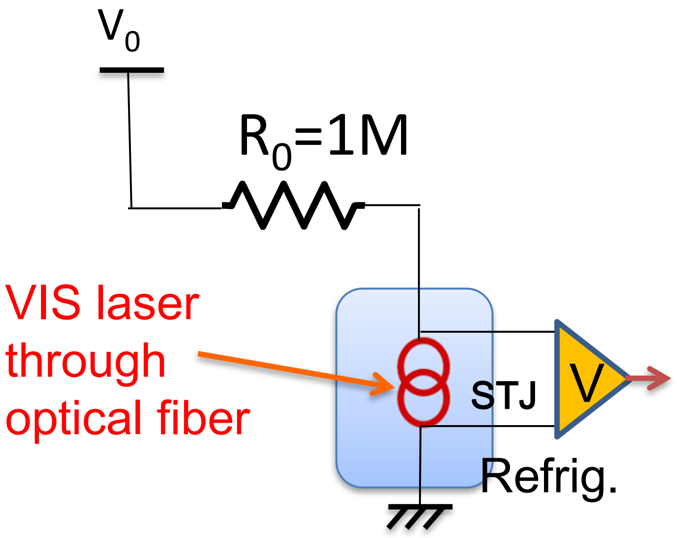
$$\mathrm{NEP} = \frac{1.7\Delta}{\mathrm{G}}\sqrt{\frac{2i_L}{e}} \sim 4\times10^{-19}\ W/\sqrt{Hz}$$ (Without photon counting)

- Photon counting will yield an improvement by more than one order.

Meets our requirements!

STJ response to pulsed laser





Nb/Al-STJ response to pulsed laser (465nm)

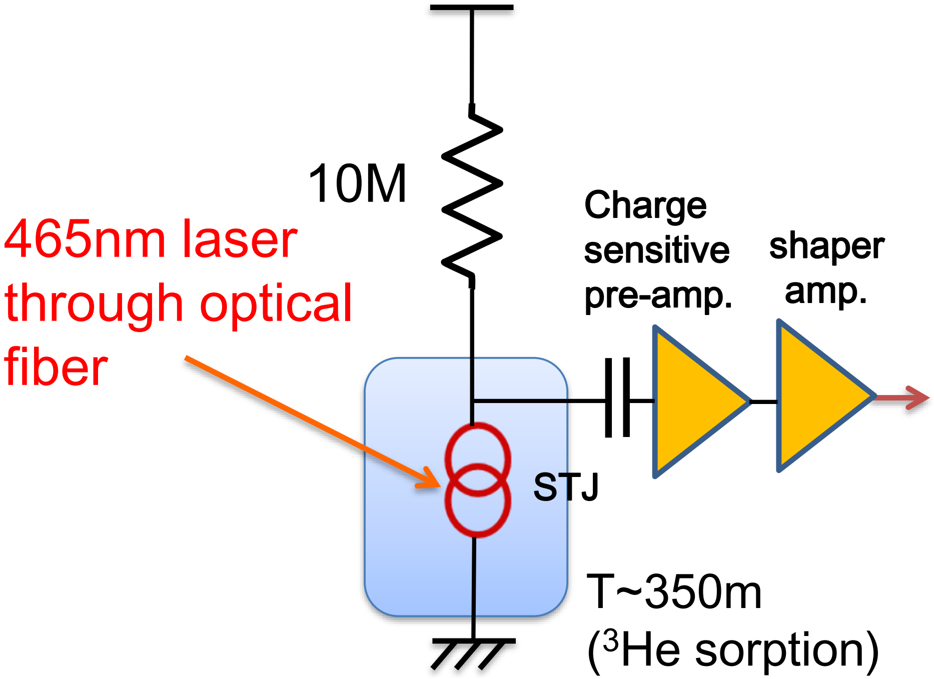
CRAVITY Nb/Al-STJ 100μm sq.

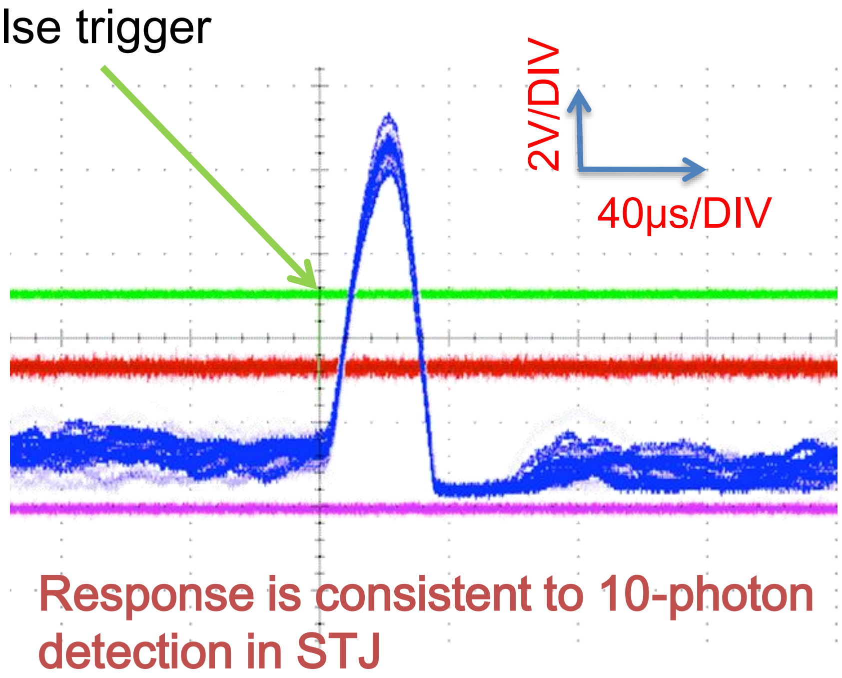
Nb/Al-STJ has ~1μs response time.

➔ We can improve NEP by photon counting in 1μs integration time

- However we need faster readout system than f>1MHz

100x100μm^2 Nb/Al-STJ response to 465nm pulsed laser





Response is consistent to 10-photon detection in STJ

We observed NIR-VIS laser pulse at few-photon level with a charge-sensitive amplifier placed at the room temperature.
Due to the readout noise, a FIR single-photon detection is not achieved yet.

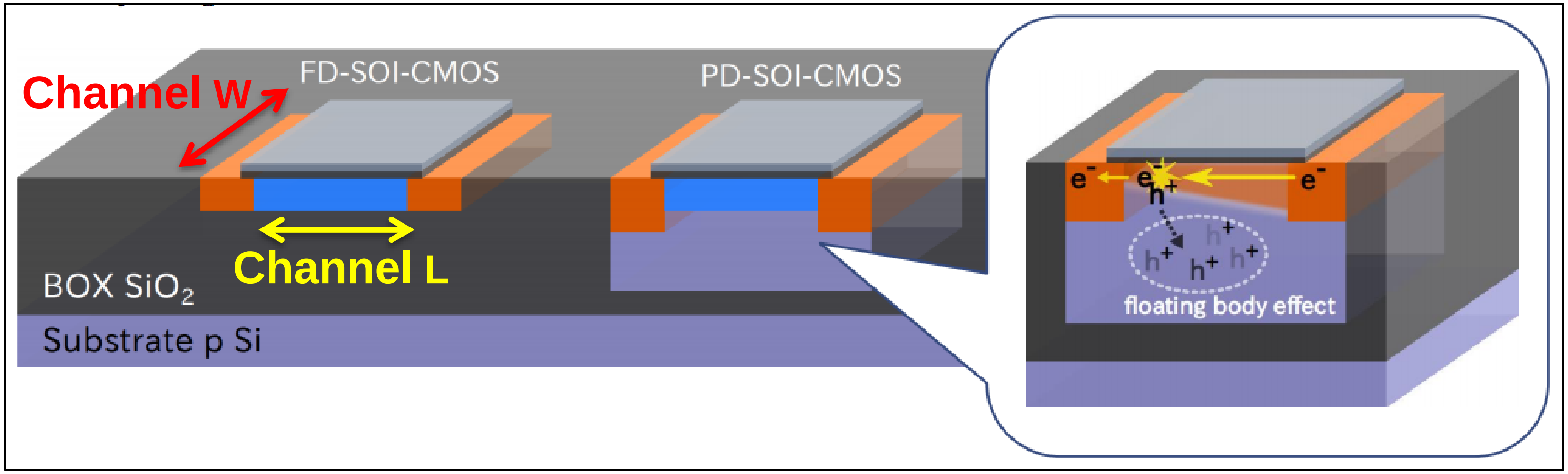
Need ultra-low noise readout system for STJ signal
➔Considering a cryogenic pre-amplifier placed close to STJ

FD-SOI-MOSFET at Cryogenic temperature

FD-SOI : Fully Depleted – Sillicon On Insulator

- ✓ Very thin channel layer in MOSFET
  - ◆ No floating body effect caused by charge accumulation in the body
- ✓ FD-SOI-MOSFET is reported to work at 4K

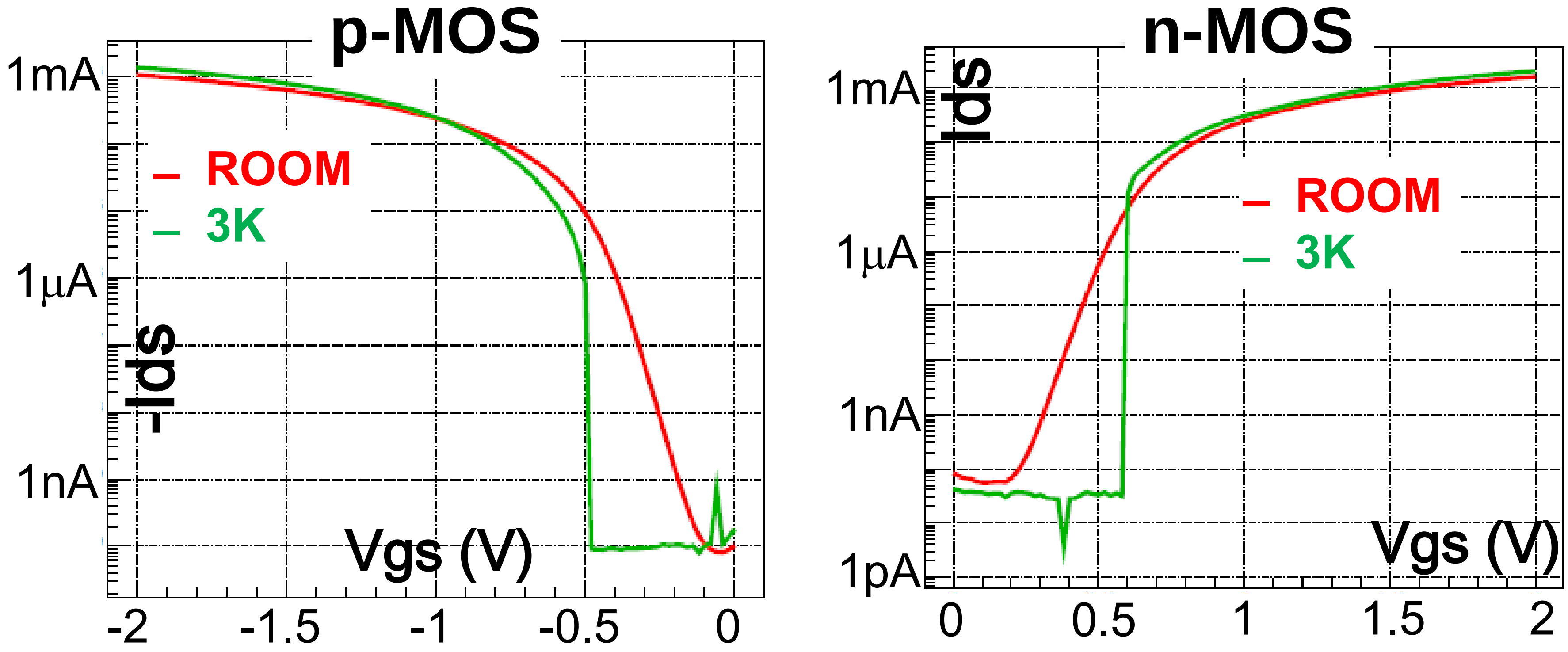
JAXA/ISIS **AIPC 1185,286-289(2009)**
J Low Temp Phys 167, 602 (2012)



S.Yagi “R&D Status of Nb/Al-STJ with SOI cryogenic preamplifier” on 30th
R.Wakasa “ニュートリノ崩壊光探索に向けた極低温増幅器の開発と現状” on Poster

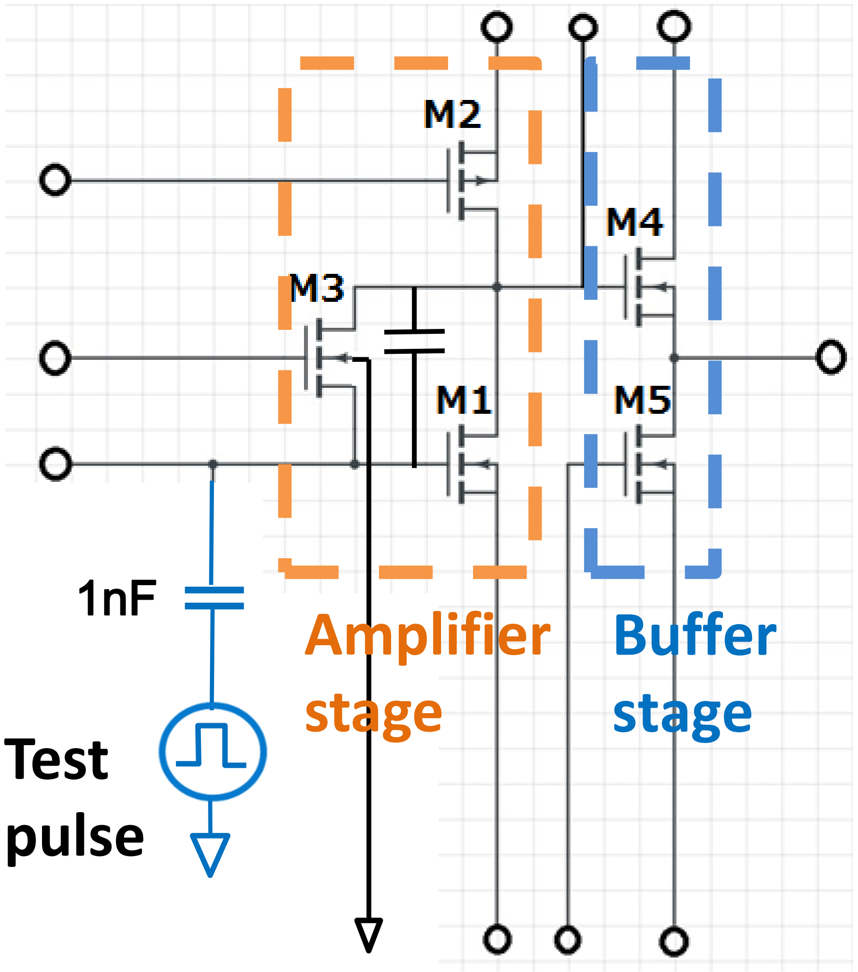
FD-SOI MOSFET I_d-V_g curve

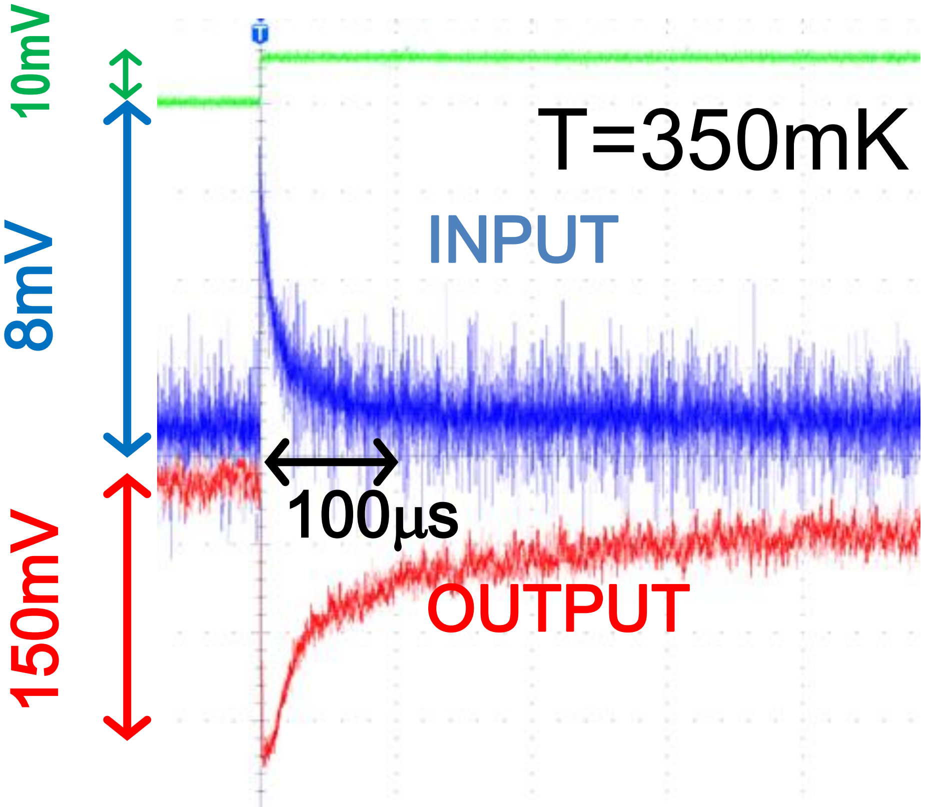
- Id-Vg curve of W/L=10μm/0.4μm at |Vds|=1.8V



- Both p-MOS and n-MOS show excellent performance at 3K (We confirmed they function down to 300mK).
- Threshold shifts, sub-threshold current suppression and increase of the carrier mobility at low temperature.

SOI prototype amplifier





Test pulse input through C=1nF capacitance at T=3K and 350mK

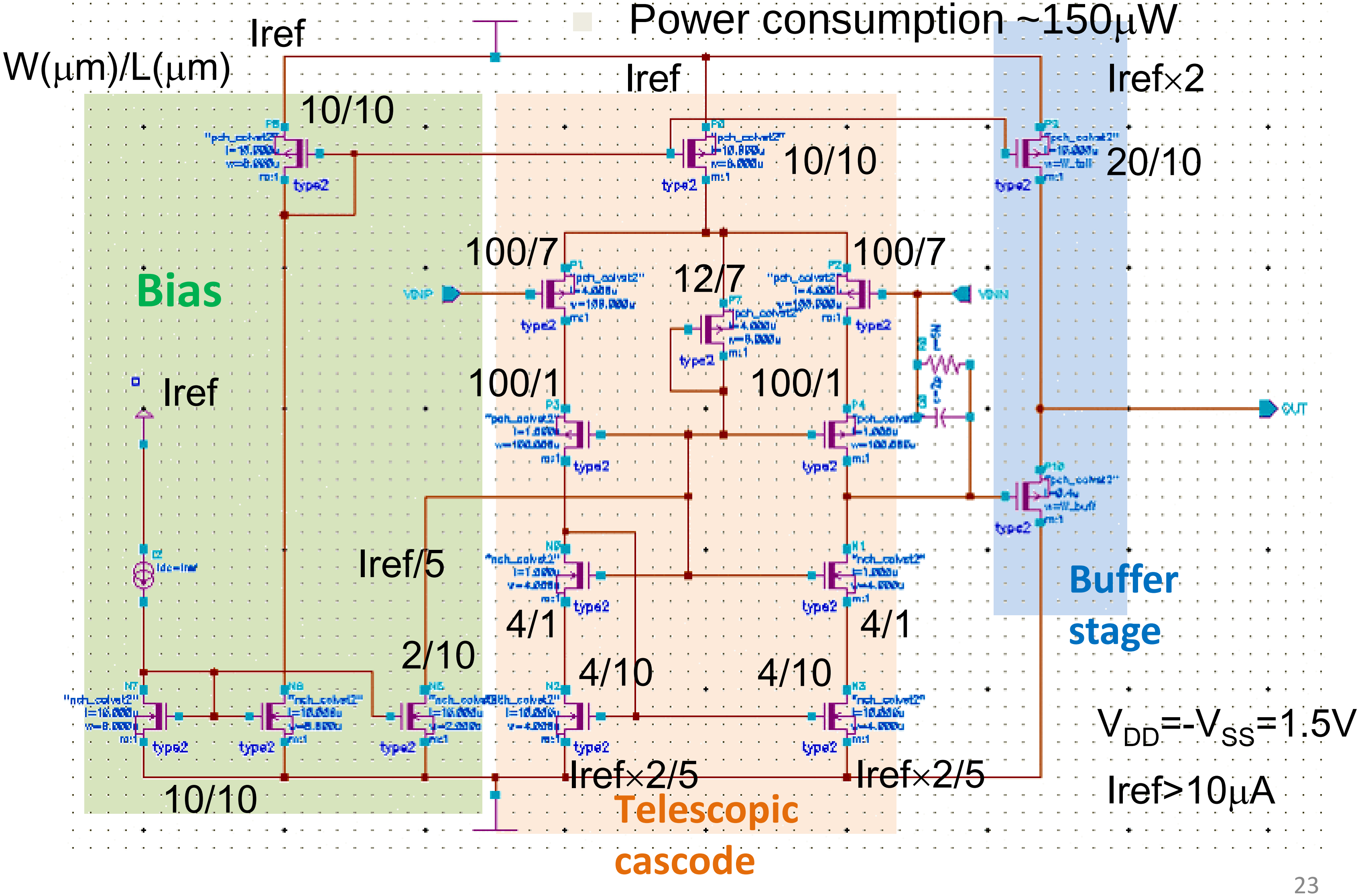
- Power consumption ~100µW

We can compensate the effect of shifts in the thresholds by adjusting bias voltages.

Op-amp Circuit for STJ design

Arriving in this winter!

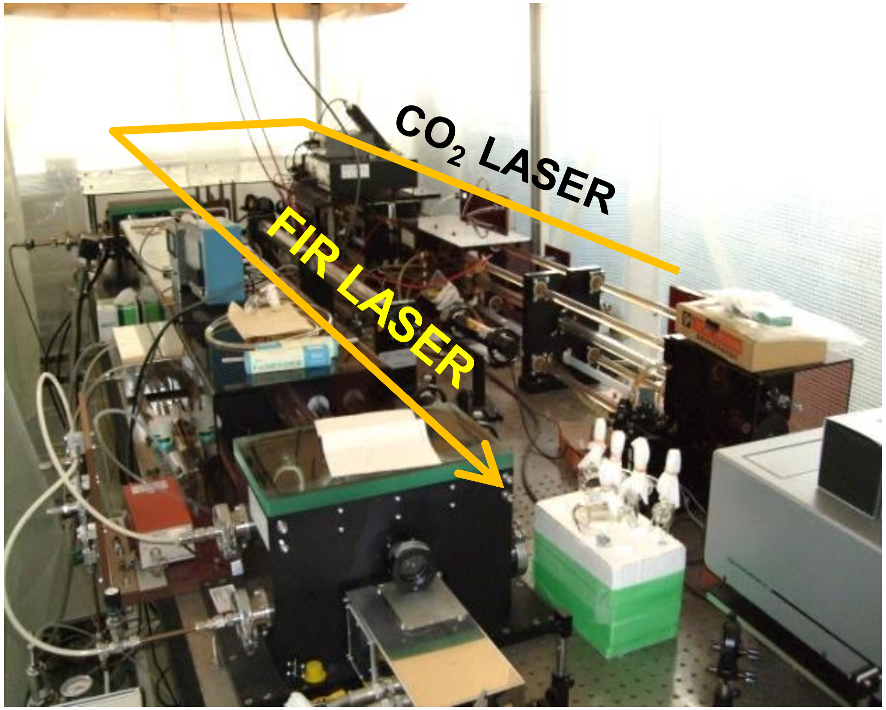
- telescopic cascode differential amplifier
- Feedback C=2pF x R=5MOhm = 10μs
- Power consumption ~150μW

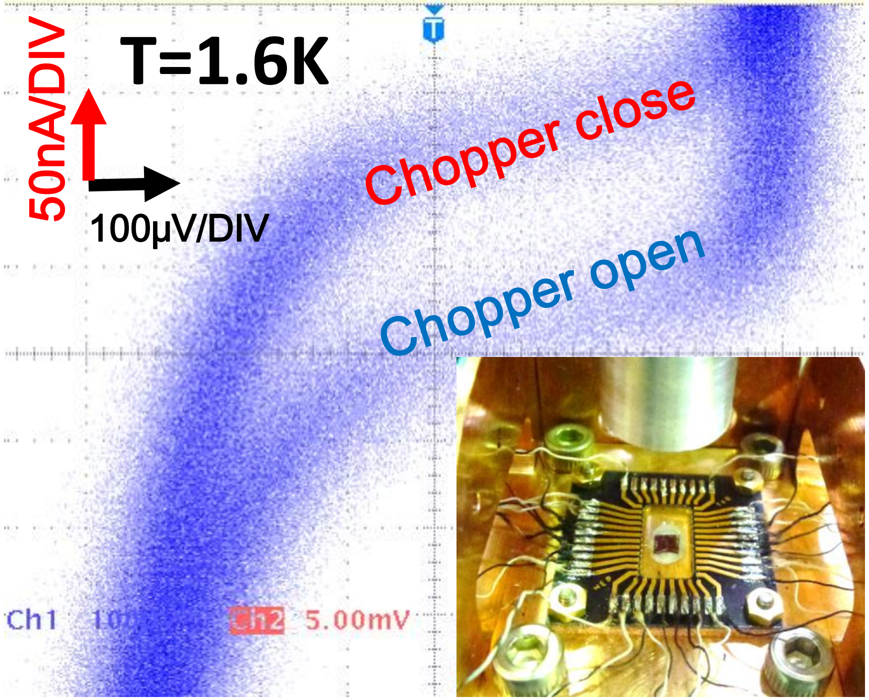


$V_{DD}=-V_{SS}=1.5V$

Iref>10μA

Calibration of STJ by Far-infrared Laser





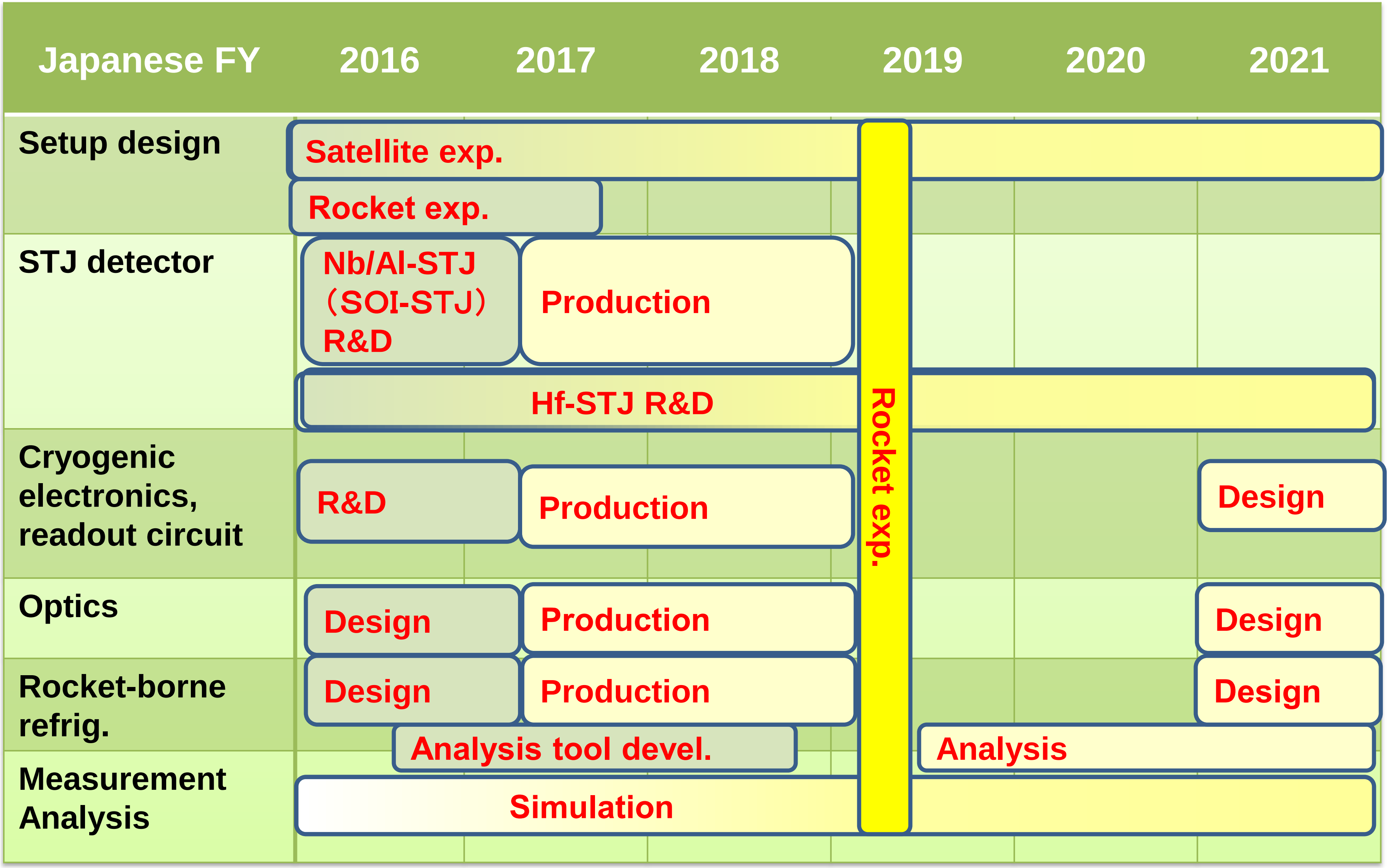
200μm sq. Nb/Al-STJ by CRAVITY

A Nb/Al-STJ is illuminated by FIR laser through a chopper (f=40~200Hz) using a far-infrared molecular laser apparatus at FIR-UF (U. of Fukui)

- Observed a signal current of ~100nA in response to a 57.2μm laser
- FIR source for the STJ calibration is going ready!

C.Asano “COBAND実験におけるSTJ検出器較正用遠赤外光源開発” **on Poster**

COBAND project



Japanese FY	2016	2017	2018	2019	2020	2021
Setup design	Satellite exp. Rocket exp.			Rocket exp.		
STJ detector	Nb/Al-STJ (SOI-STJ) R&D Hf-STJ R&D	Production				
Cryogenic electronics, readout circuit	R&D	Production				Design
Optics	Design	Production				Design
Rocket-borne refrig.	Design Analysis tool devel.	Production		Analysis		Design
Measurement Analysis	Simulation					

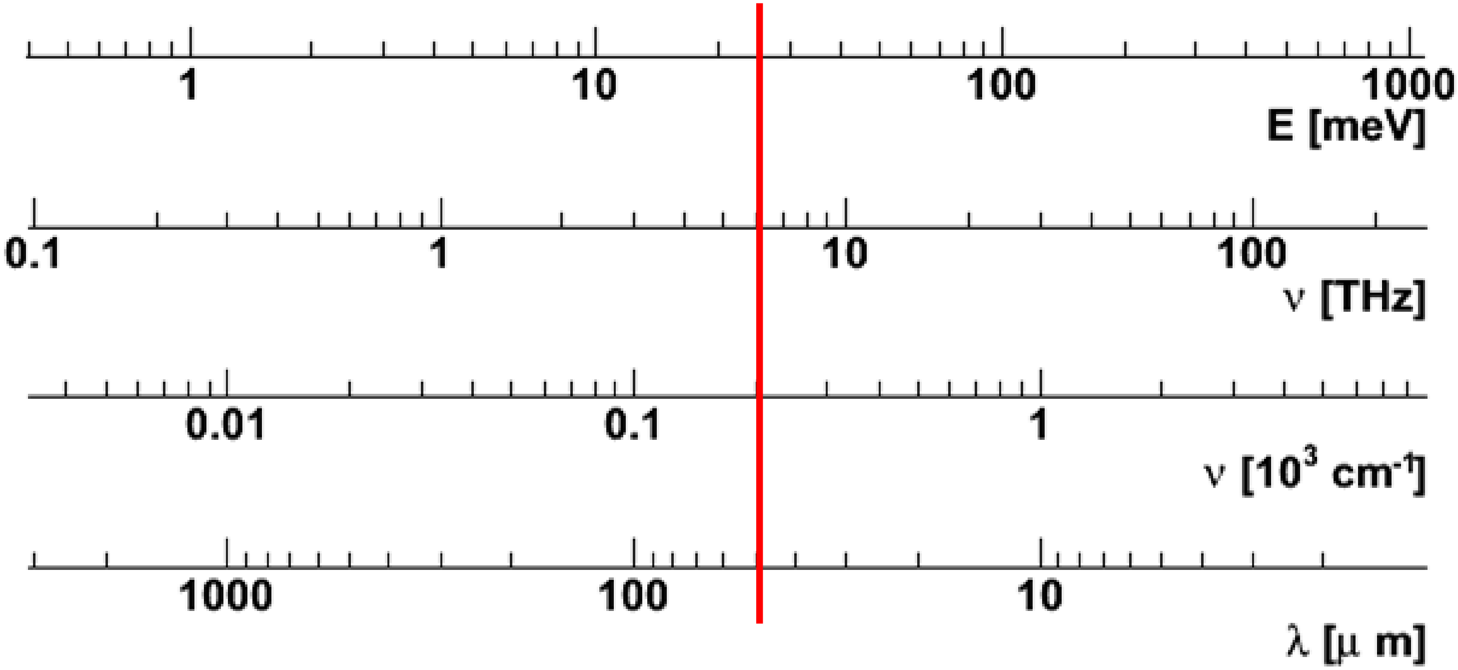
Summary

- We propose a sounding rocket experiment to search for neutrino radiative decay in cosmic neutrino background, and a following satellite experiment .
- Requirements for the detector is a photo-detector with NEP~O(10^{-20}) W/√Hz.
- Nb/Al-STJ array with a diffractive for the rocket experiment.
  - Nb/Al-STJ fabricated at CRAVITY meets our requirements.
  - FD-SOI readout is under development and almost ready for STJ signal amplification at cryogenic temperature.
  - FIR calibration for STJ is going to be ready.
- 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.

- **K.Takemasa “R&D Status of Hf-STJ” on 30th**
- **S.Yagi “R&D Status of Nb/Al-STJ with SOI cryogenic preamplifier” on 30th**
- **R.Wakasa “ニュートリノ崩壊光探索に向けた極低温増幅器の開発と現状” on POSTER**
- **C.Asano “COBAND実験におけるSTJ検出器較正用遠赤外光源開発” on POSTER**

Backup

Energy/Wavelength/Frequency



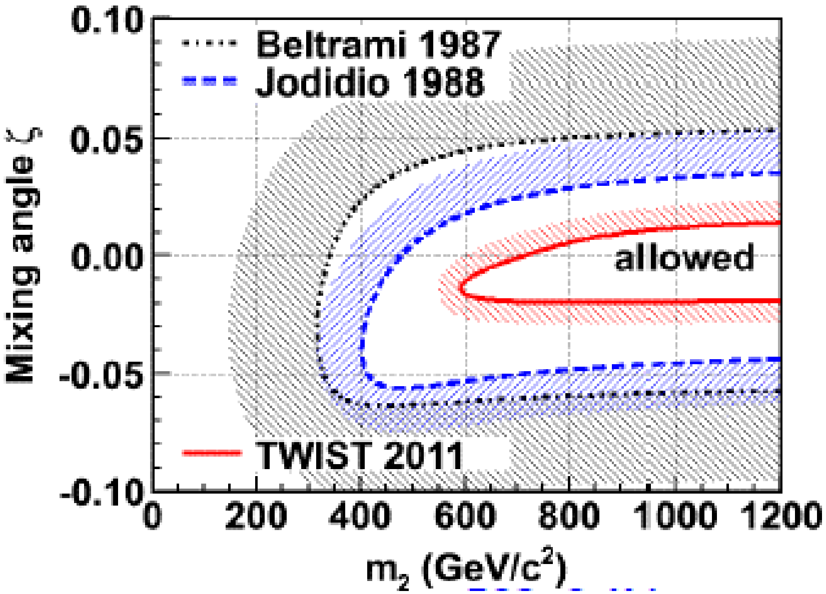
$$E_\gamma = 25 \text{ meV}$$

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

$$\lambda = 50\mu m$$

Limit on LRSM parameters from TWIST

Manifest LRS 90%CL

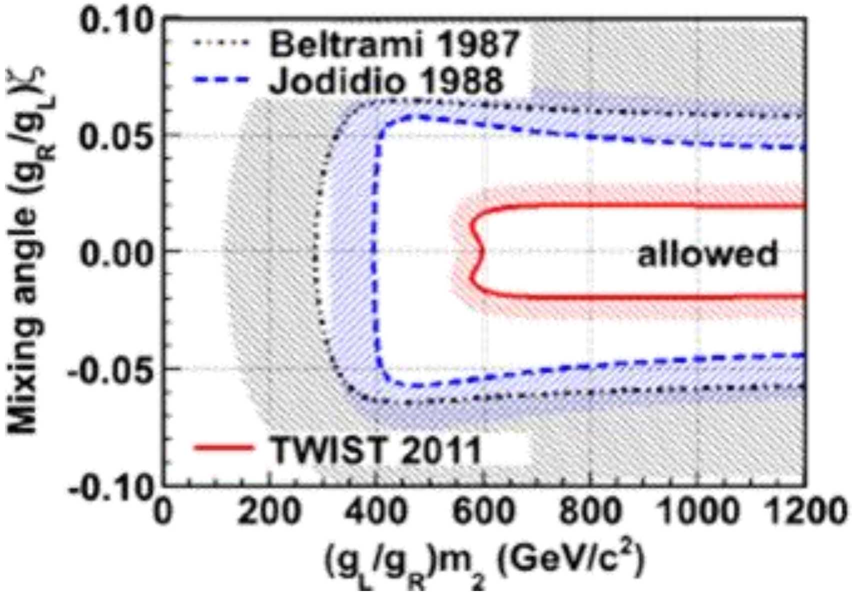


$$M_{W_2} > 592\ GeV$$

$$-0.020 < \zeta < +0.017$$

- ❑ Other **W'** direct search mass limits
  - ATLAS: >1.49 TeV/c², 95%CL (LLWI11)
  - CMS: >1.58 TeV/c², 95%CL (LLWI11)
  - CMS: >1.36 TeV/c², 95%CL (2011)
  - CDF: >1.12 TeV/c², 95%CL (2011)
  - D0: >1.0 TeV/c², 95%CL (2008)

Non-manifest LRS 90%CL

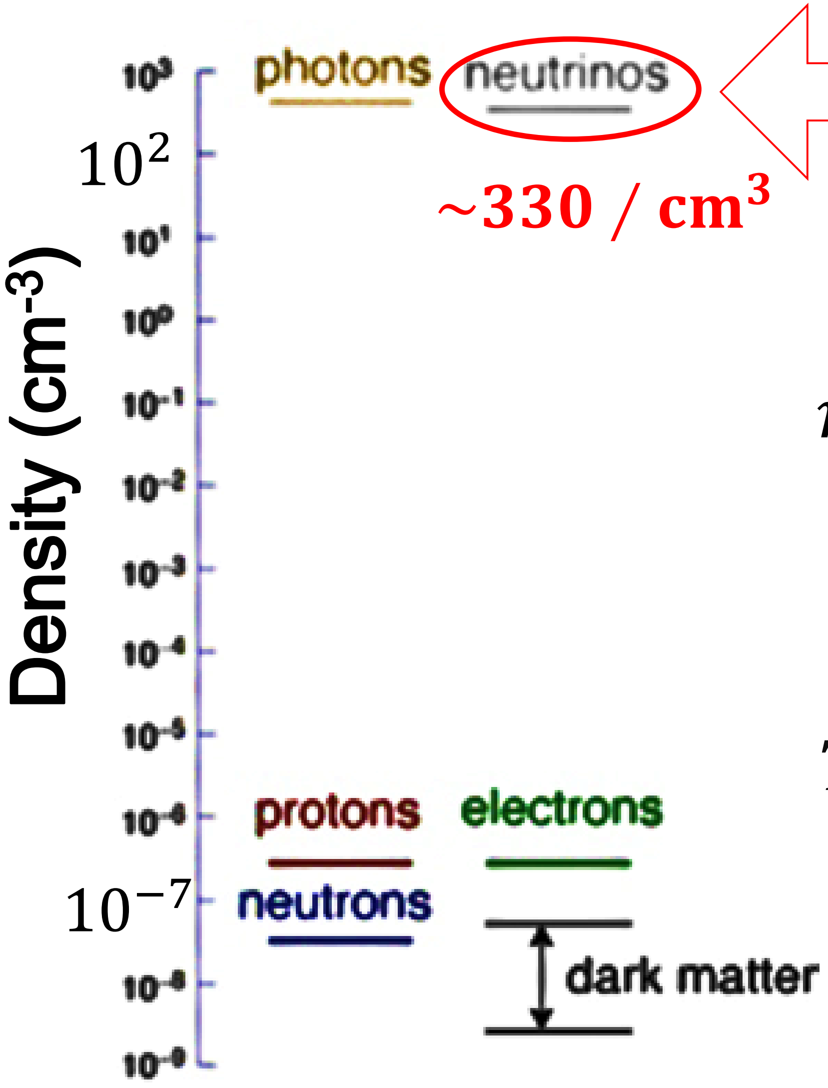


$$(g_L/g_R)M_{W_2} > 578\ GeV$$

$$-0.020 < (g_L/g_R)\zeta < +0.020$$

- ❑ Other limits on mixing angle ζ
  - Hardy and Towner: <0.0005 (MLRS), <0.04 (generalized)
  - K decay: <0.004 (MLRS)

Cosmic background neutrino (CνB)



$\sim 330\ /\ \mathrm{cm}^3$

The universe is filled
with neutrinos.
However, they have not
been detected yet!

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

$$= 110/\mathrm{cm}^3/\text{generation}$$

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

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

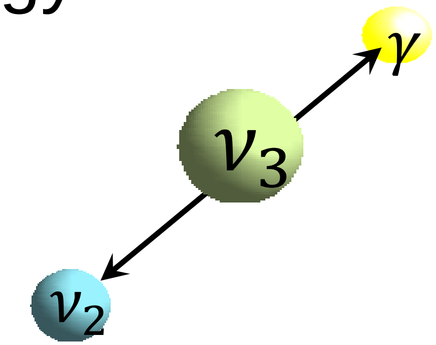
Neutrino Mass and Photon Energy

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

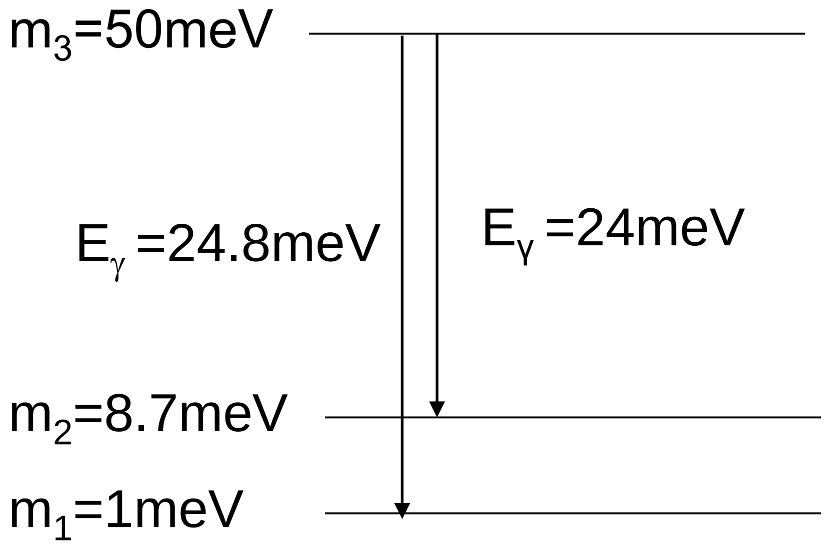
➔50meV<m_3<87meV

E_γ =14~24meV

λ_γ =51~89μm



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



m_3=50meV

E_γ =24.8meV

E_γ =24meV

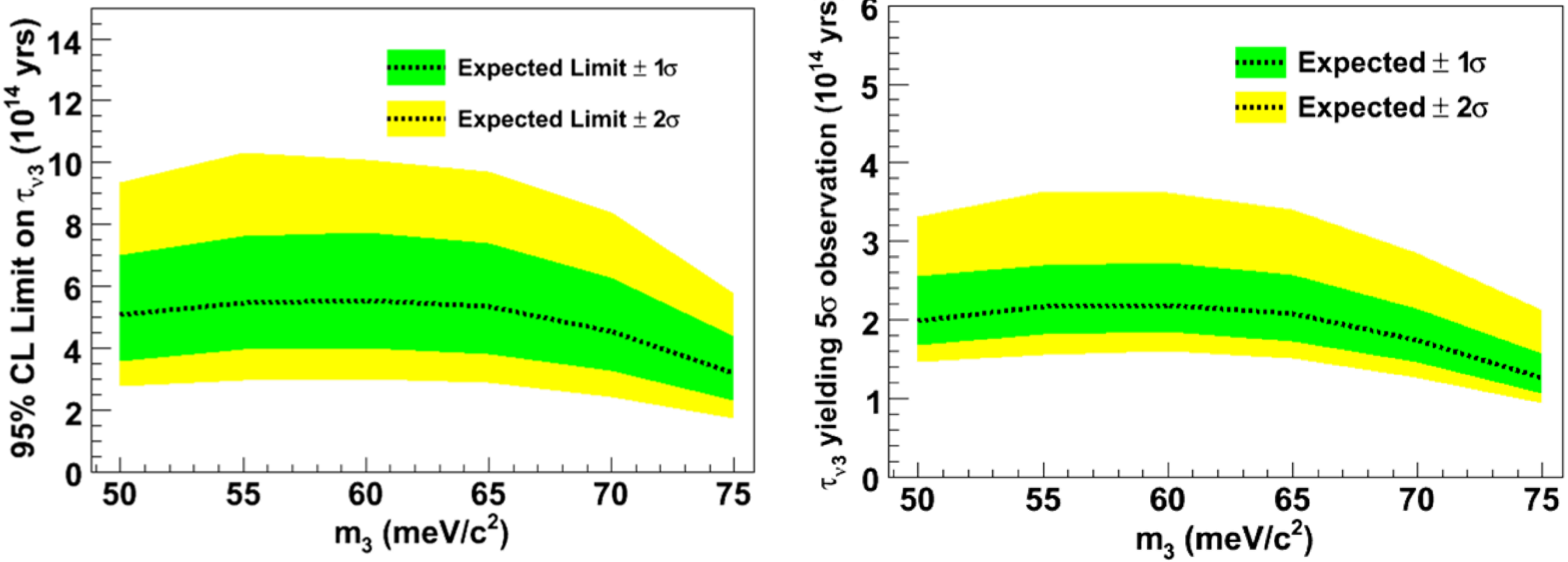
m_2=8.7meV

m_1=1meV

Sensitivity to neutrino decay

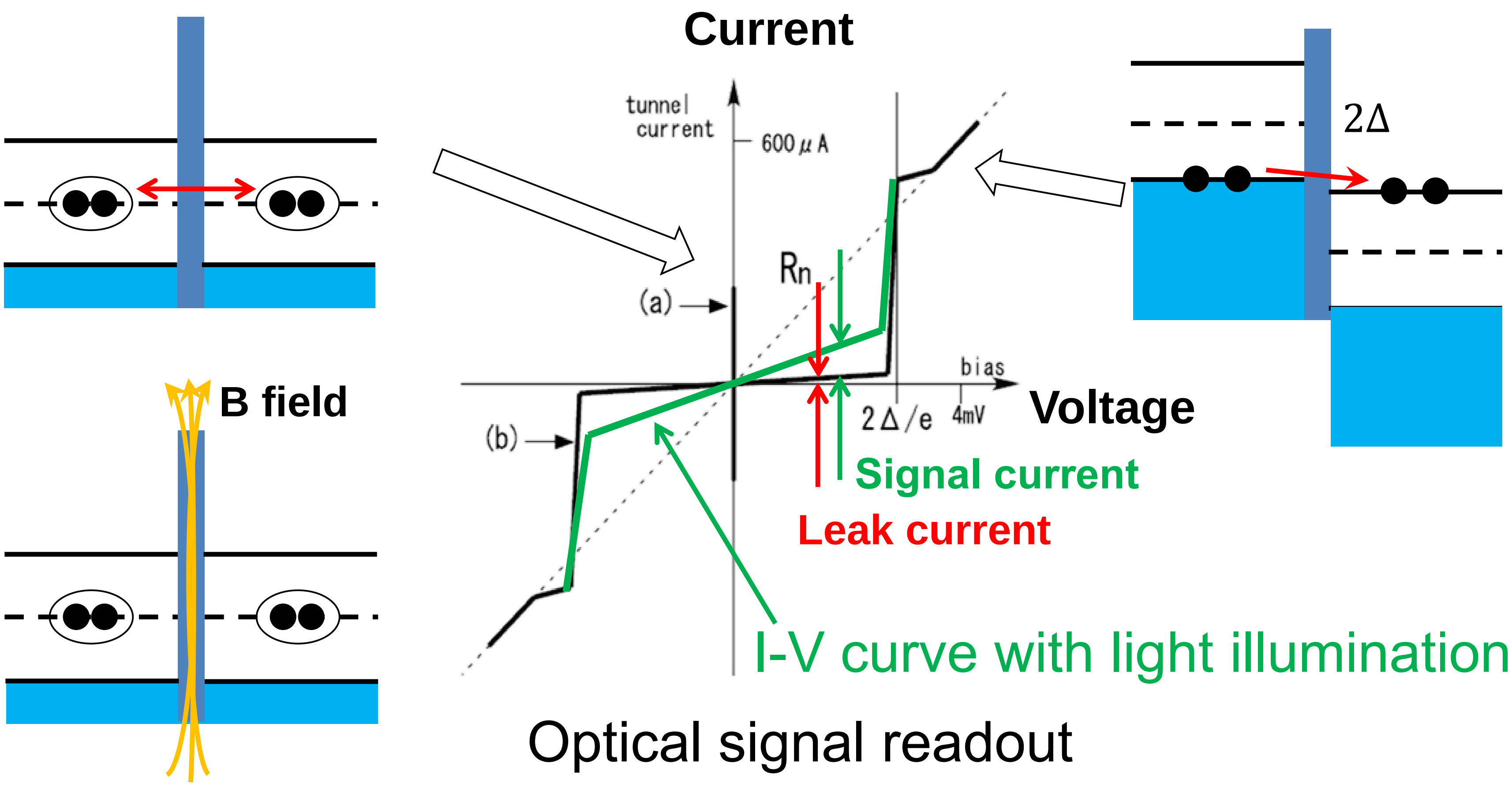
Parameters in the rocket experiment simulation

- telescope dia.: 15cm
- 50-column (λ: 40μm – 80 μm) × 8-row 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
- If ν_3 lifetime were 2 × 10^{14} yrs, the signal significance would be at 5σ level

STJ current-voltage curve



Tunnel current of Cooper pairs (Josephson current) is suppressed by applying magnetic field

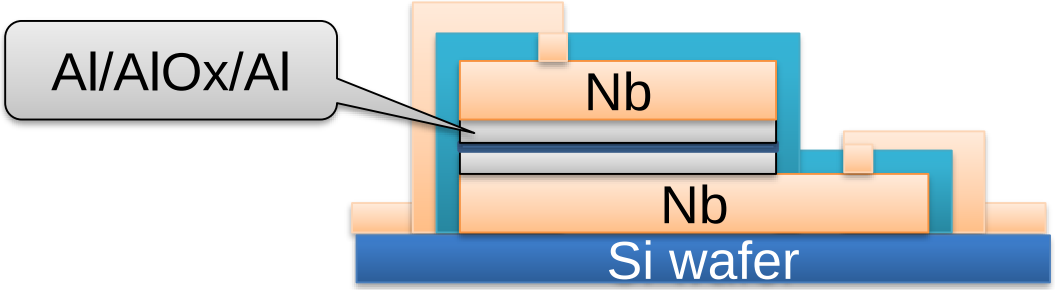
Optical signal readout

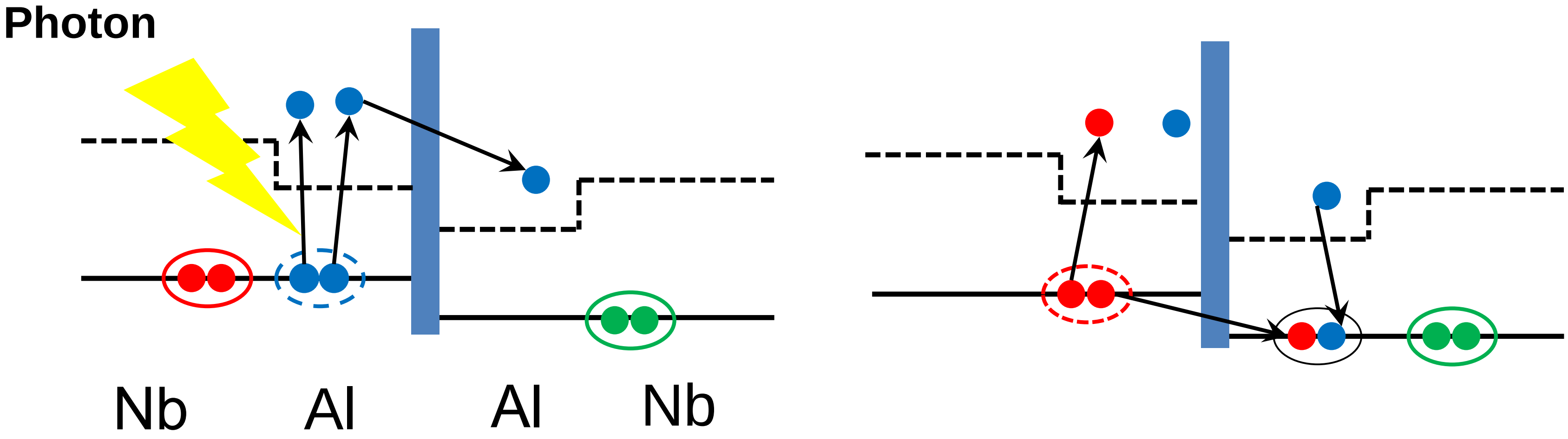
➔ Apply a constant bias voltage (|V|<2Δ) across the junction and collect tunneling current of quasi particles created by photons

✓ Leak current causes background noise

STJ back-tunneling effect

- Bi-layer fabricated with superconductors of different gaps $\Delta_{Nb}>\Delta_{Al}$ to enhance quasi-particle density near the barrier
  - Quasi-particle near the barrier can mediate multiple Cooper pairs
- Nb/Al-STJ Nb(200nm)/Al(70nm)/AlOx/Al(70nm)/Nb(200nm)
- Gain: ～10





Detector NEP required for COBAND rocket experiment

What's NEP (Noise Equivalent Power)?

- The signal power yielding unit signal-to-noise ratio in unit bandwidth for a photo-detector

$$NEP = \frac{F}{S/N\sqrt{\Delta f}}$$

F: Radiant flux(W)

S/N: signal-to-noise ratio of the detector ouput

Δf : detector bandwidth(Hz)

- A smaller NEP means a more sensitive detector.
- A detector with $NEP = 10^{-12} W/\sqrt{Hz}$ can detect
  - 1pW signal with S/N=1 after 0.5-sec integration.
  - 0.1pW signal with S/N=1 after 50-sec integration.

Detector NEP required for COBAND rocket experiment

Viewing angle of the photo-detector

- Telescope main mirror: **D=15cm, F=1m**

➢ **100μm x 100μm x 8 pixels**

➔ **Viewing angle : 8 x $(100\mu m/1m)^2$ = 8 x 10^{-8} sr**

$\Delta\nu$ per one wavelength division after diffraction grating:

➢ One wavelength division: (80μm - 40μm) / 50 = 0.8μm

➢ $\Delta\nu$=c/50μm-c/50.8μm=94GHz @λ=50μm

Hereafter on the assumption of 100% quantum efficiency at the photo-detector

Detector NEP required for COBAND rocket experiment

- ☐ Neutrino decay ($m_3 = 50$ meV, $\tau_\nu = 10^{14}$yrs): **I_ν=25kJy/sr @ λ=50μm**

$$\boldsymbol{F_{ND} = 25\, kJy/sr \times\ 8 \times 10^{-8} sr \times \pi(15cm/2)^2 \times 94GHz}$$

$$\boldsymbol{= 3.3 \times 10^{-20} W/8pix}$$

- ☐ Zodiacal emission: **I_ν=8MJy/sr @ λ=50μm**

$$\boldsymbol{F_{ZE} = 1.1 \times 10^{-17} W/8pix}$$

◆ The fluctuation in the F_{ZE} integration over Δt interval

- The fluctuation in # of photons: $\epsilon_\gamma \sqrt{F_{ZE}\Delta t/\epsilon_\gamma} = \sqrt{\epsilon_\gamma\, F_{ZE}\Delta t}$

◆ Conditions of the requirements on Δt and NEP

$$\frac{NEP}{\sqrt{2\Delta t}} \times \Delta t \ll \sqrt{\epsilon_\gamma\, F_{ZE}\Delta t} \ll F_{\mathrm{ND}}\Delta t$$

➔ Δt>40sec (1σ) Δt>200sec (2.2σ per Δλ=0.8μm)

➔ NEP $\ll 3 \times 10^{-19} W/\sqrt{Hz}$ for 8 pix

➔ NEP $\ll 8.4 \times 10^{-19} W/\sqrt{Hz}$ for 1pix

Shot noise from a detector leak current

- ☐ R [A/W] : Detector responsivity
- ☐ i_L [A] : leak current

The charge from the leakage after T [sec] integration: $i_L T$ [C]

The number of charge carriers after averaging: $i_L T/e$

The fluctuation in the current: $\frac{e}{T}\sqrt{\frac{i_L T}{e}}$

The fluctuation in the measured incident power: $\frac{1}{R}\sqrt{\frac{e i_L}{T}}$

$$\frac{NEP}{\sqrt{2\mathrm{T}}} = \frac{1}{R}\sqrt{\frac{e i_L}{T}} \quad \text{i.e.} \quad NEP = \frac{1}{R}\sqrt{2 e i_L}$$

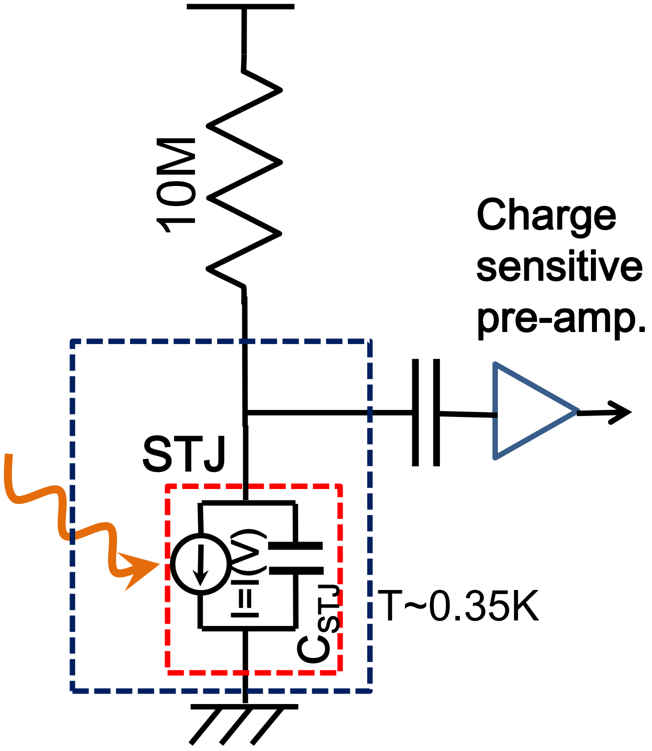
For STJ: $\mathrm{N}_{\mathrm{q.p.}} = G\,\frac{E_\gamma}{1.7\Delta}$ i.e. $\mathrm{R} = G\,\frac{e}{1.7\Delta}$

$$NEP = \frac{1.7\Delta}{G}\sqrt{\frac{2 i_L}{e}}$$

SOI charge-sensitive pre-amplifier development

- STJ has comparably large capacitance: >20pF for 20μm sq. STJ.
  - ➔A low input impedance charge-sensitive amplifier is required for STJ single-photon signal readout.
- STJ response time is ~1μs.

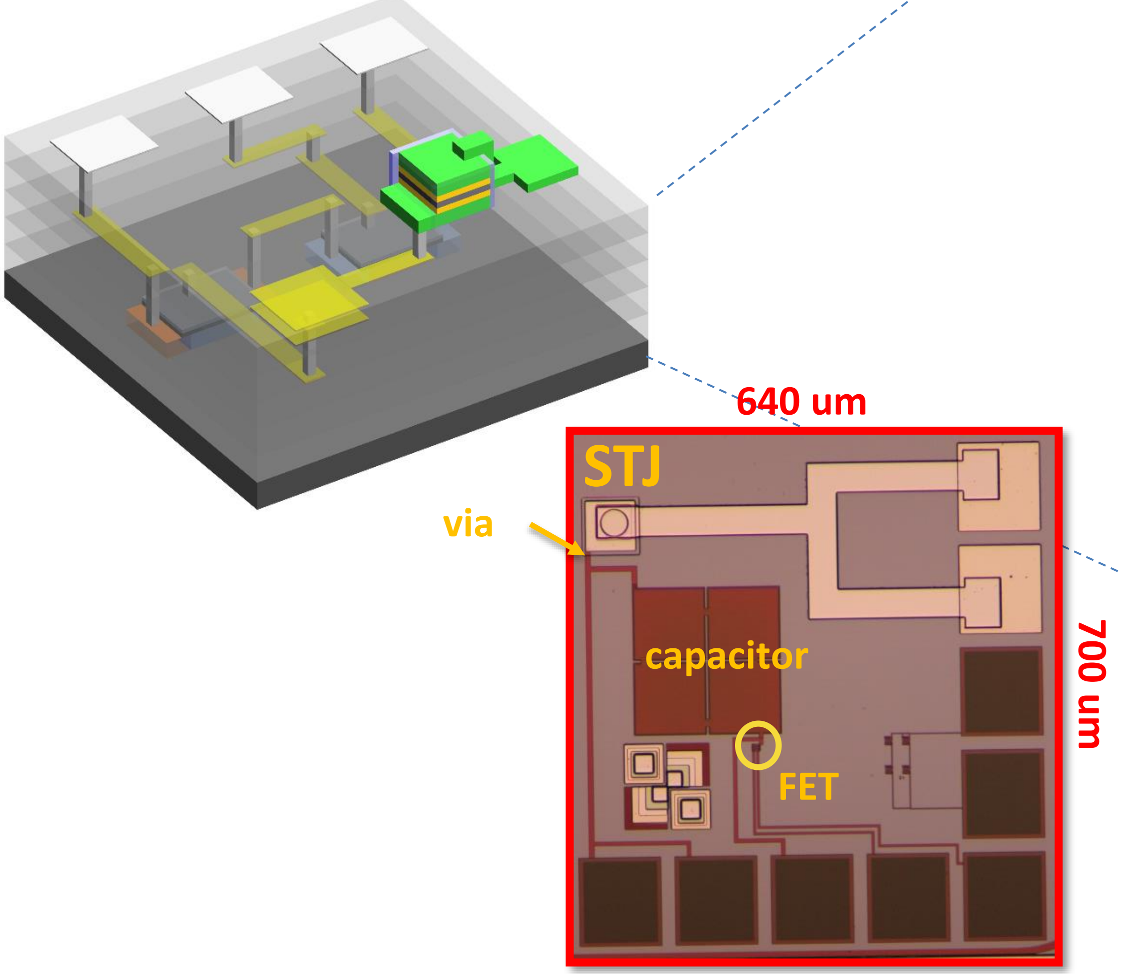
➔We designed SOI op-amp which has >1MHz freq. response, and submitted to the next SOI MPW run. We'll test the amplifier in this winter.

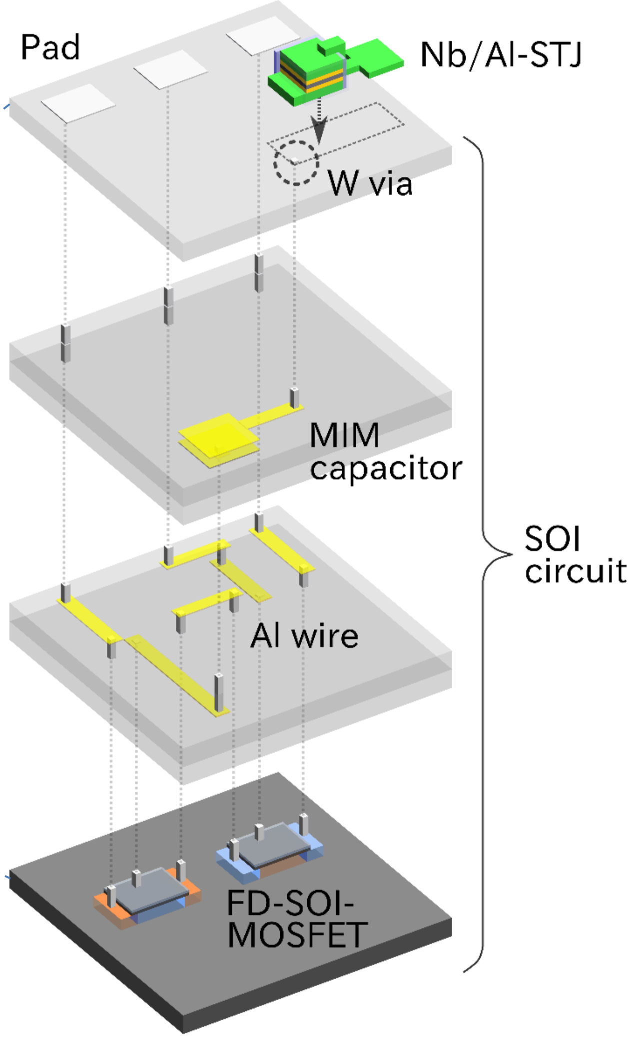


SOI-STJ (STJ directly on SOI) development

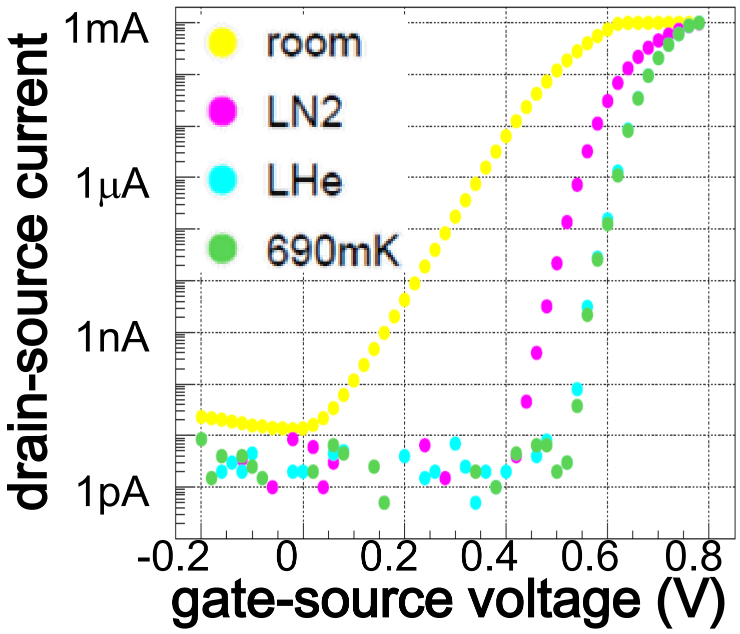
- STJ layers are fabricated directly on a SOI pre-amplifier board and cooled down together with the STJ

☐ Potential to STJ array (Large area STJ)

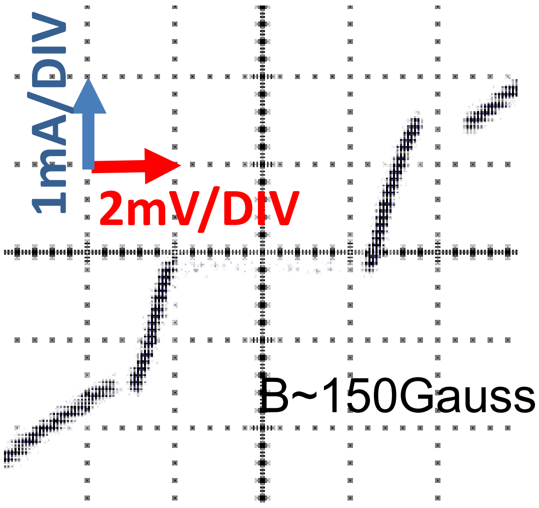




FD-SOI on which STJ is fabricated



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