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

Neutrino Frontier Workshop 2017

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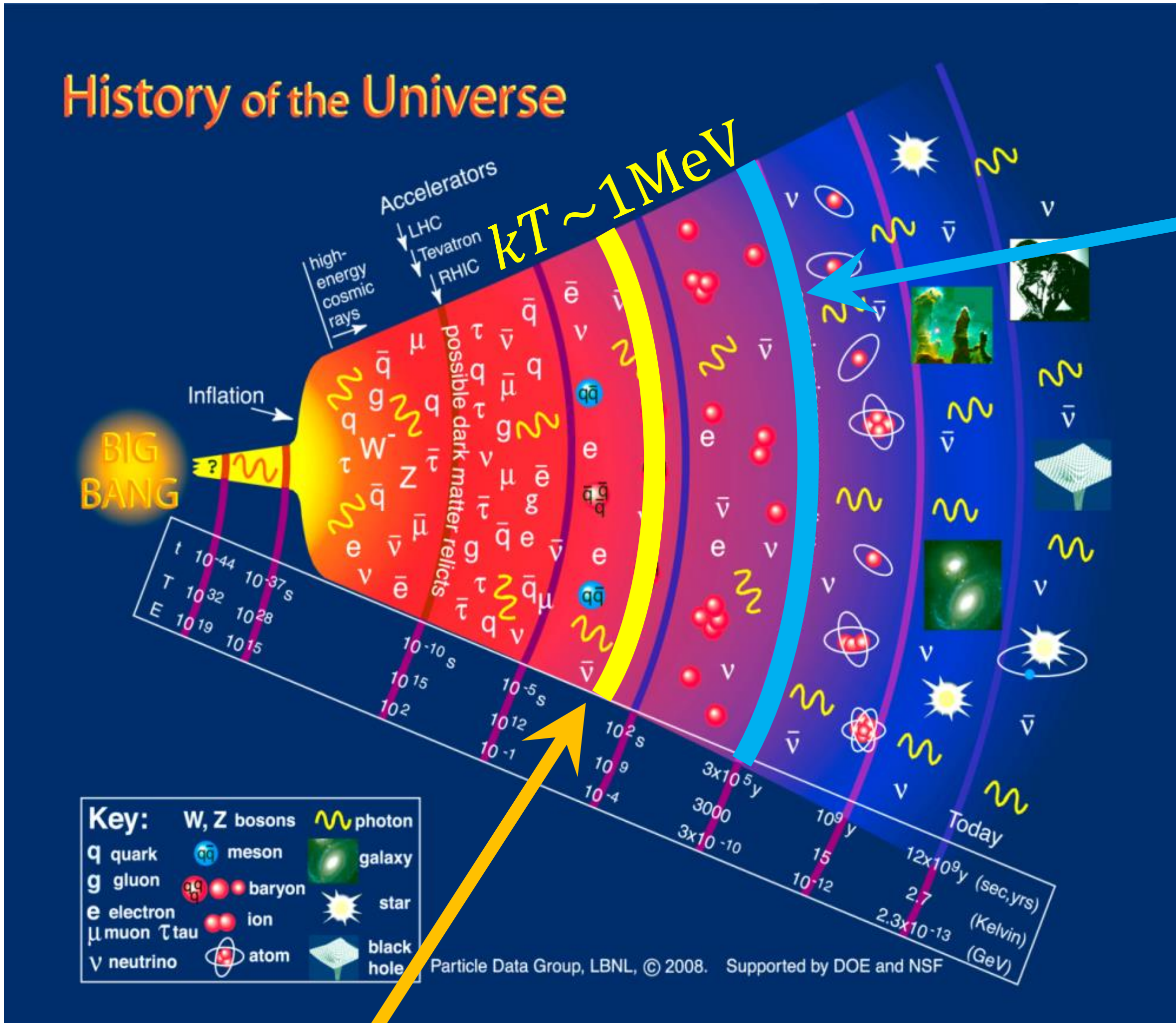
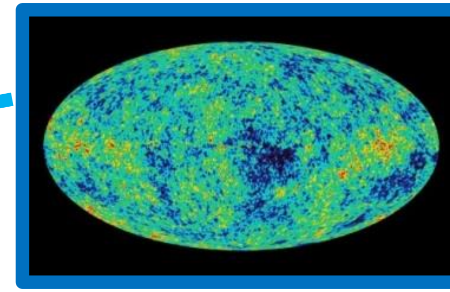
on behalf of COBAND Collaboration

Cosmic neutrino background (CνB)





CMB

(=Photon decoupling)

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

$T_\gamma = 2.73\ K$

~380,000yrs after the Big Bang

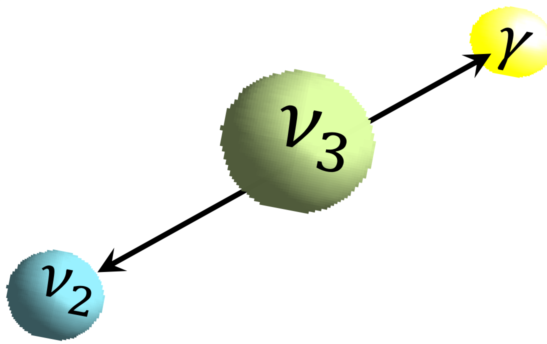
CνB (=neutrino decoupling)

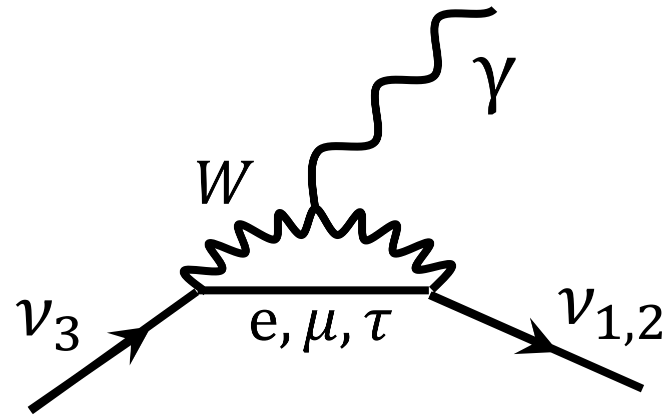
~1sec after the big bang

$n(\nu_3 + \bar{\nu}_3) \sim 110/\text{cm}^3$

Neutrino Decay

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



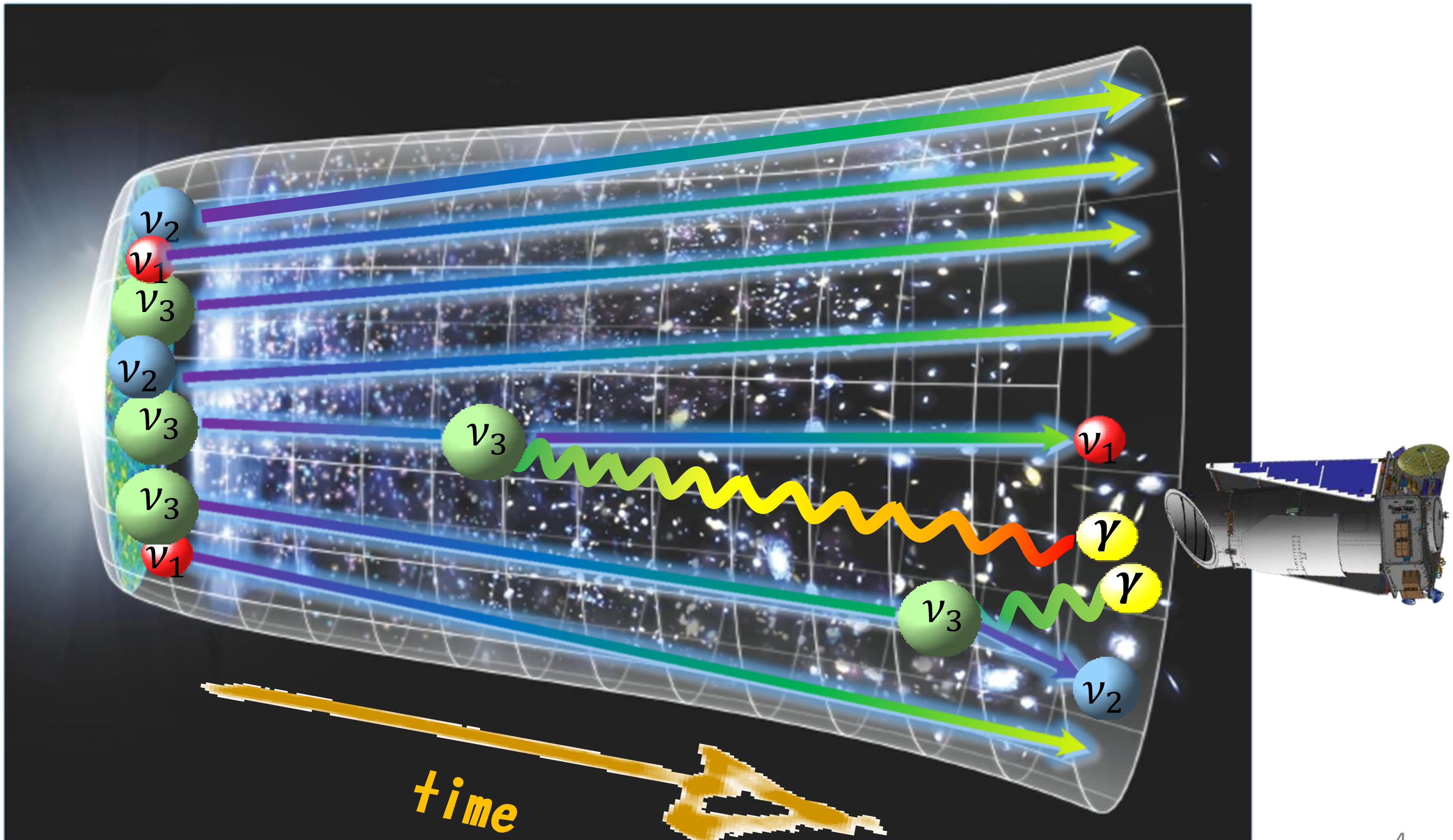


➔ We search for neutrino decay using Cosmic Background Neutrino (CνB) as the neutrino source

COBAND (COsmic BAckground Neutrino Decay)

Search for Neutrino decay in Cosmic background neutrino

➔To be observed as photons in neutrino decays



COBAND Collaboration Members (As of Nov. 2017)

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Motivation of ν-decay search in CνB

ν_3 Lifetime

- Standard Model expectation: $\tau = O(10^{43})$ yrs
- Experimental lower limit: $\tau = O(10^{12})$ yrs
- L-R sym. model prediction: $\tau = O(10^{17})$ yrs

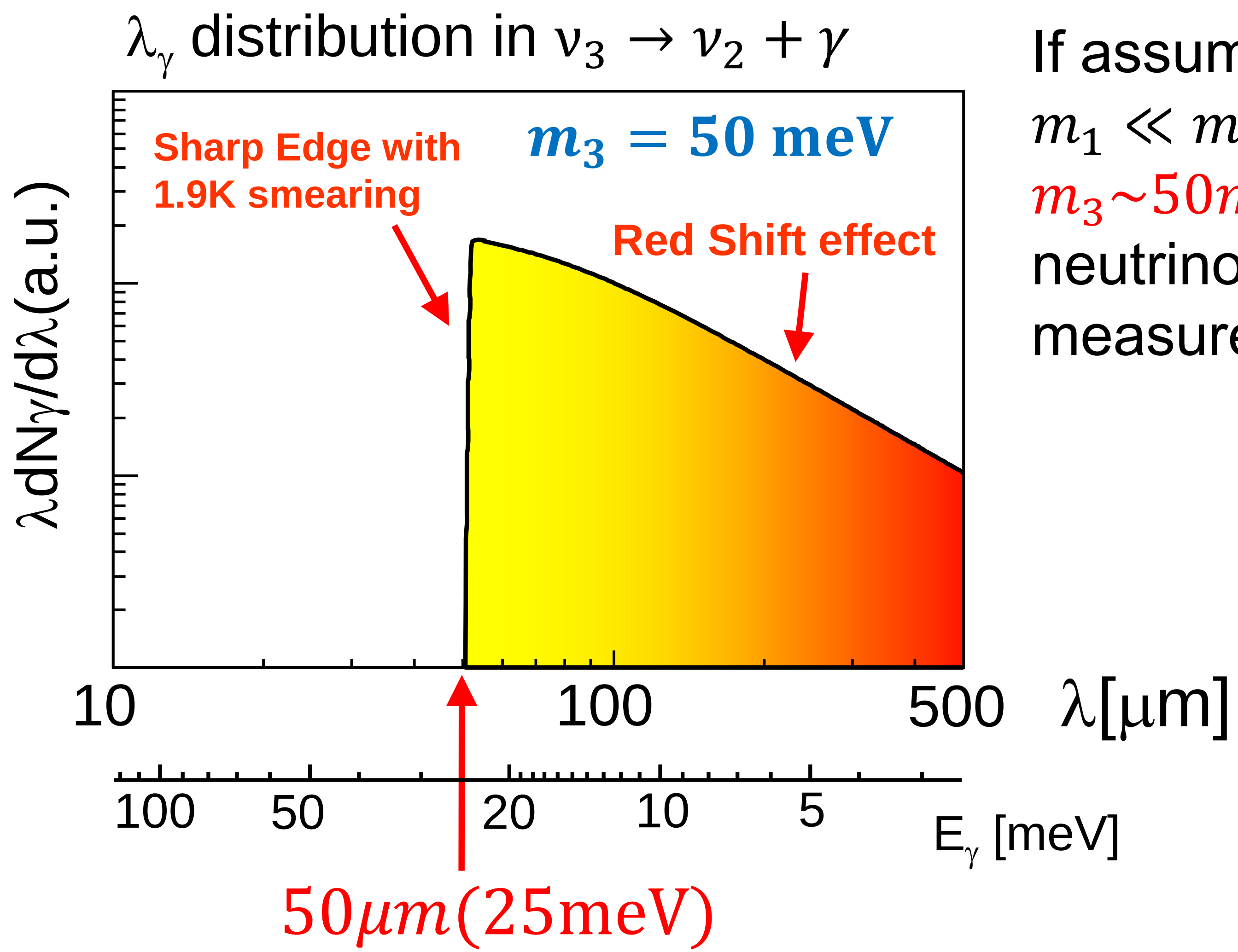
for W_L-W_R mixing angle $|\zeta| \sim 0.02$

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 $O(10^{13} - 10^{17})$ yrs

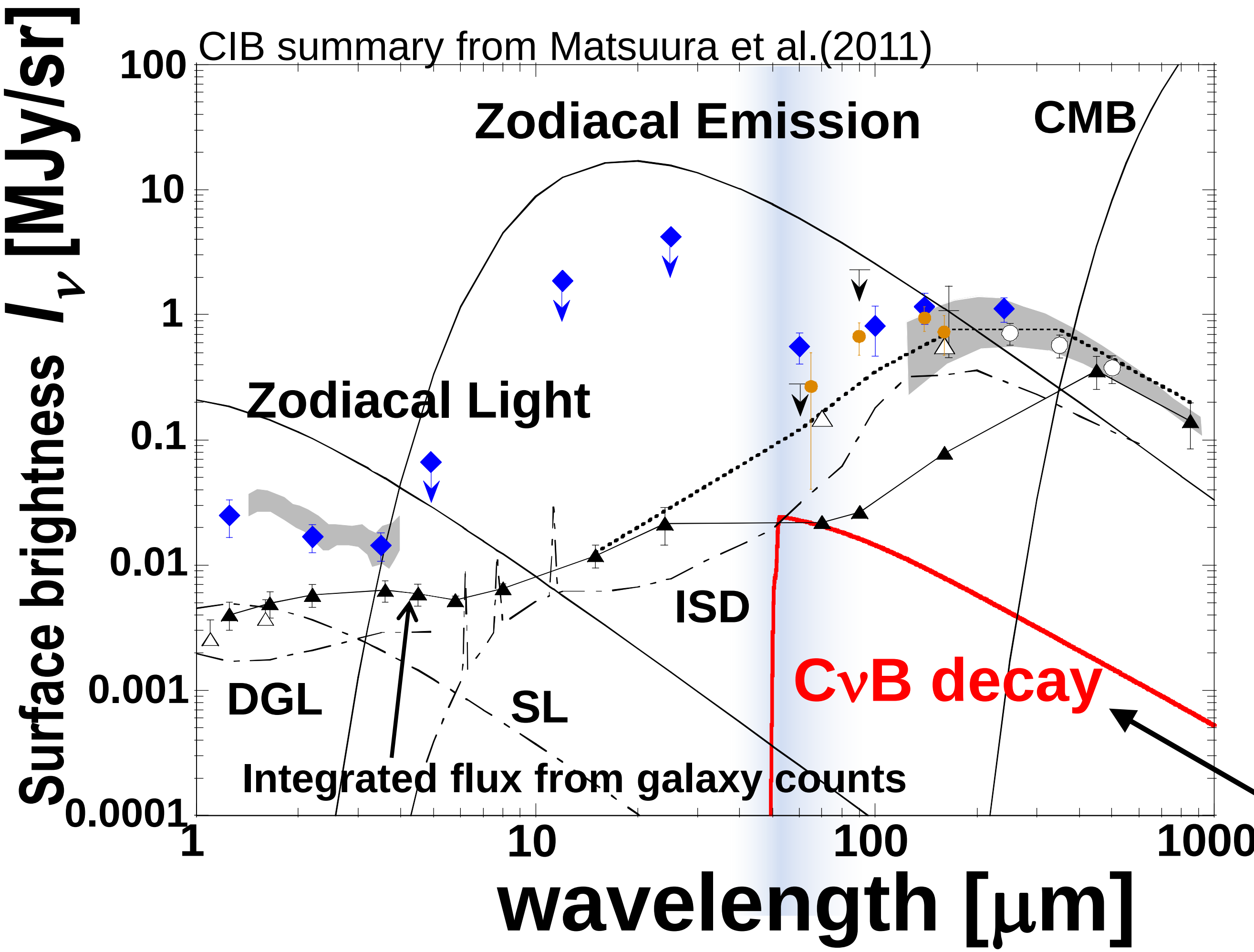
Expected photon wavelength spectrum from CνB decays



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!!

Neutrino Decay signal and backgrounds



Zodiacal Emission

I_{ZE}=8MJy/sr

Neutrino Decay

I_ν=25kJy/sr

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

$m_3 = 50$ meV

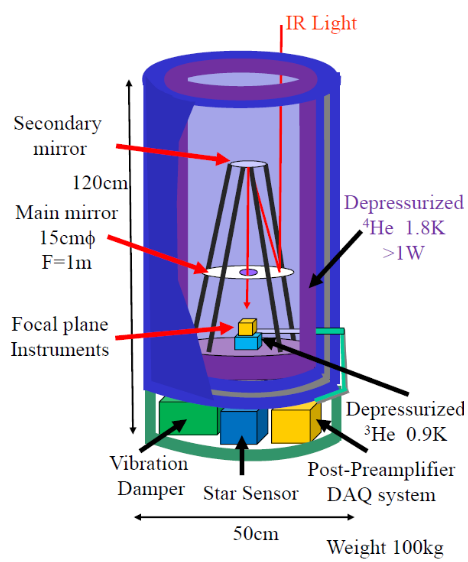
The sharp edge in the spectrum is ν decay unique signature.

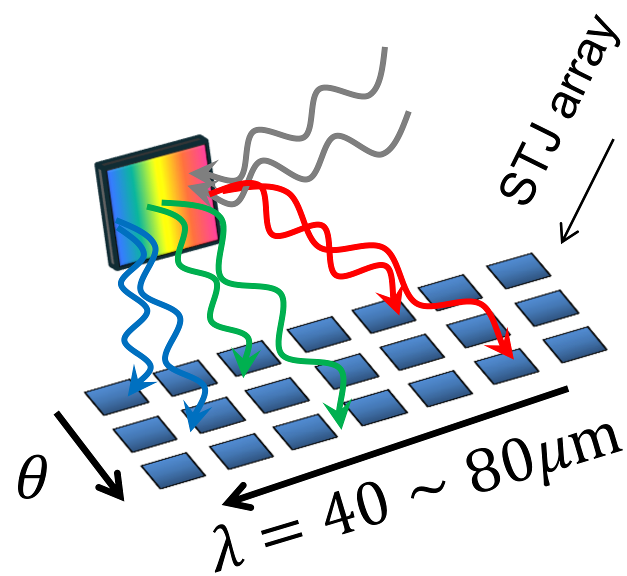
Proposal for COBAND Rocket Experiment

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

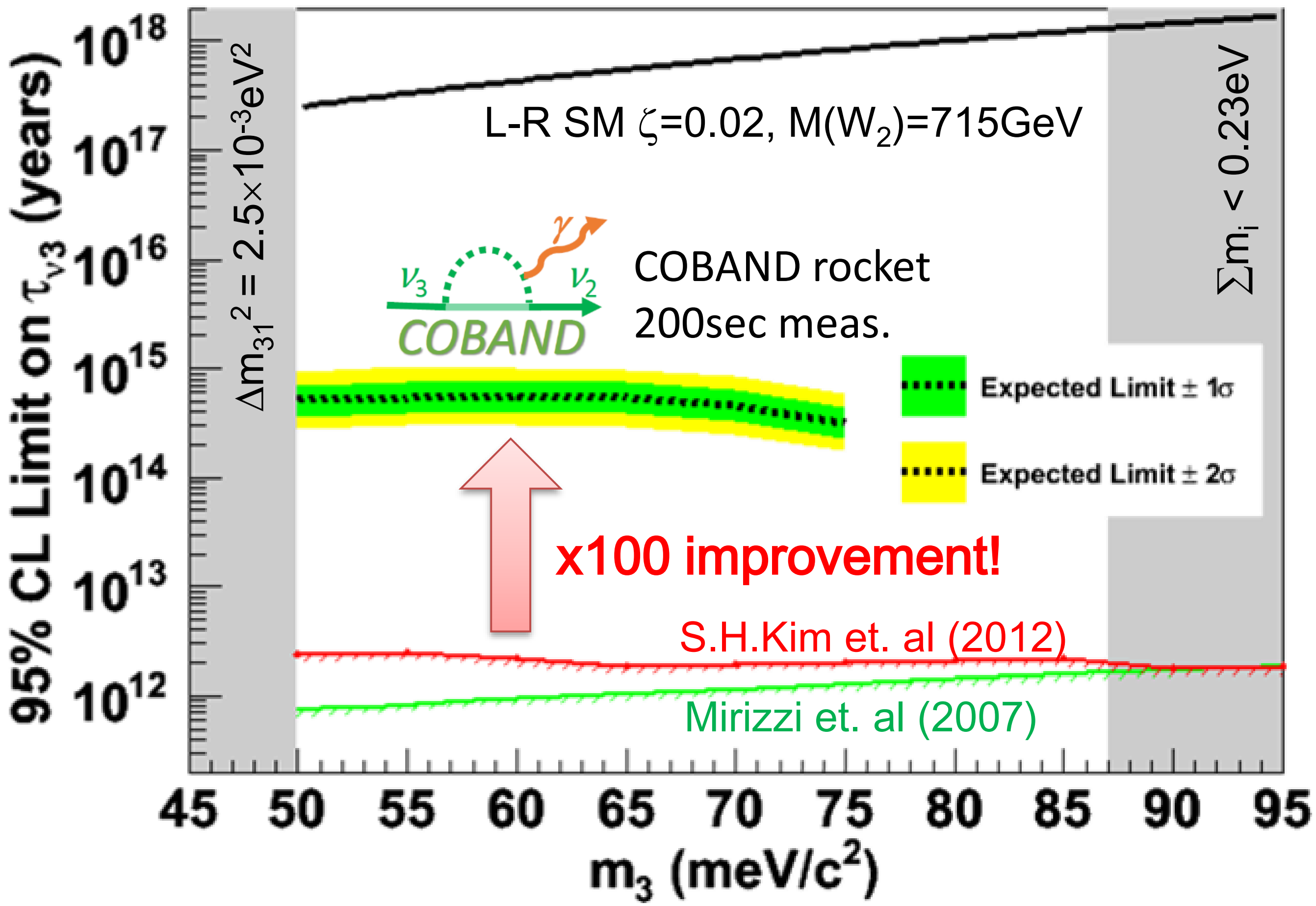
JAXA sounding rocket S-520

- Telescope with **15cm diameter** and **1m focal length**
- At the focal point, a diffraction grating covering **λ=40-80μm** and an array of photo-sensor pixels of **50(λ) x 8(θ)** are placed.
- Each pixel has **100μmx100μm** sensitive area and ability of **single-photon detection**.





COBAND rocket experiment sensitivity



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

Requirements for the photo-sensor in COBAND rocket experiment

- Sensitive area of 100μm×100μm for each pixel
- High detection efficiency for a far-infrared single-photon in λ=40μm ~ 80μm
- Dark count rate less than 300Hz (expected real photon rate)

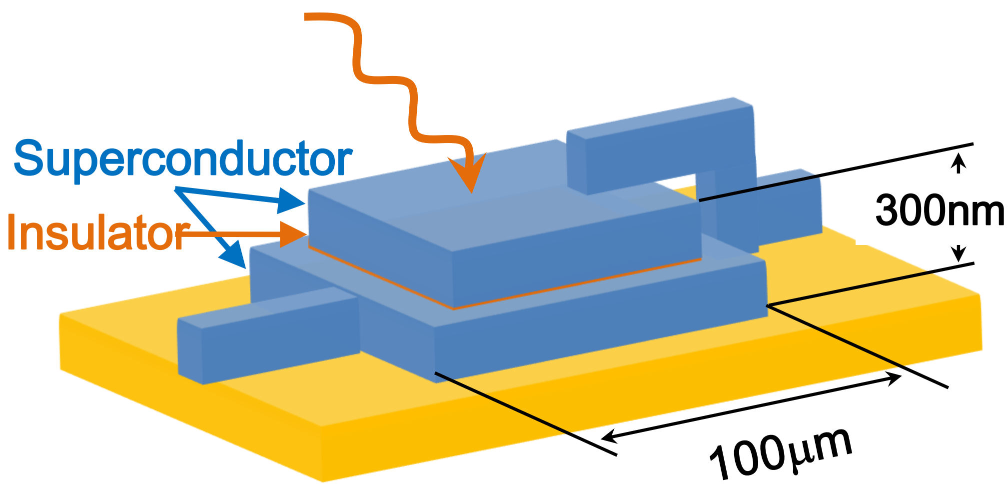
$$\rightarrow \mathrm{NEP} = \epsilon_\gamma \sqrt{2 f_\gamma} \sim 1\times 10^{-19}\, W/\sqrt{Hz}$$

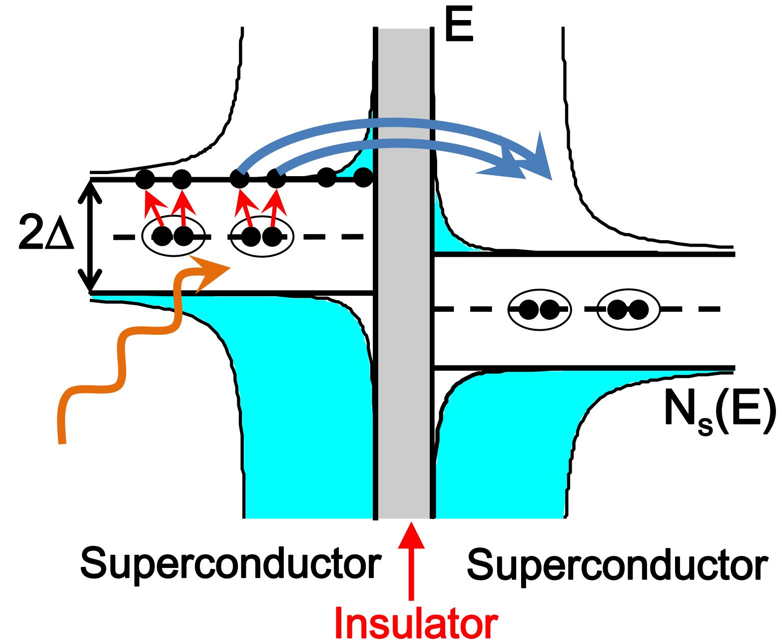
We are trying to achieve $\mathrm{NEP} \sim 10^{-19}\, W/\sqrt{Hz}$ **by using**

- **Superconducting Tunneling Junction detector**
- **Cryogenic amplifier readout**

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/1.7Δ×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

K.Takemasa's talk "R&D Status of 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

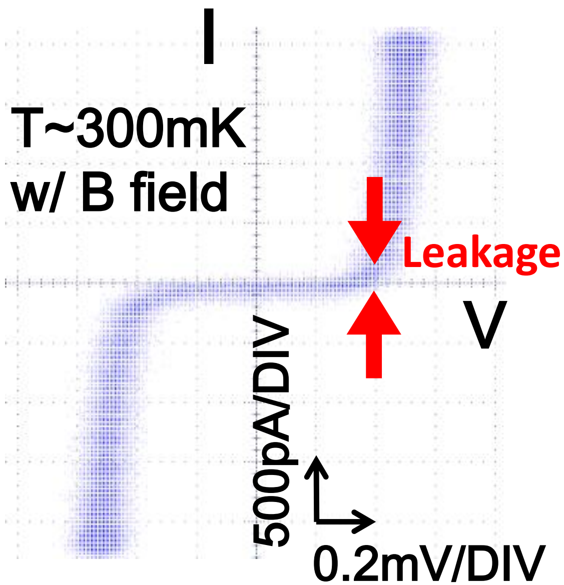
if Fano factor <0.3 for Hf

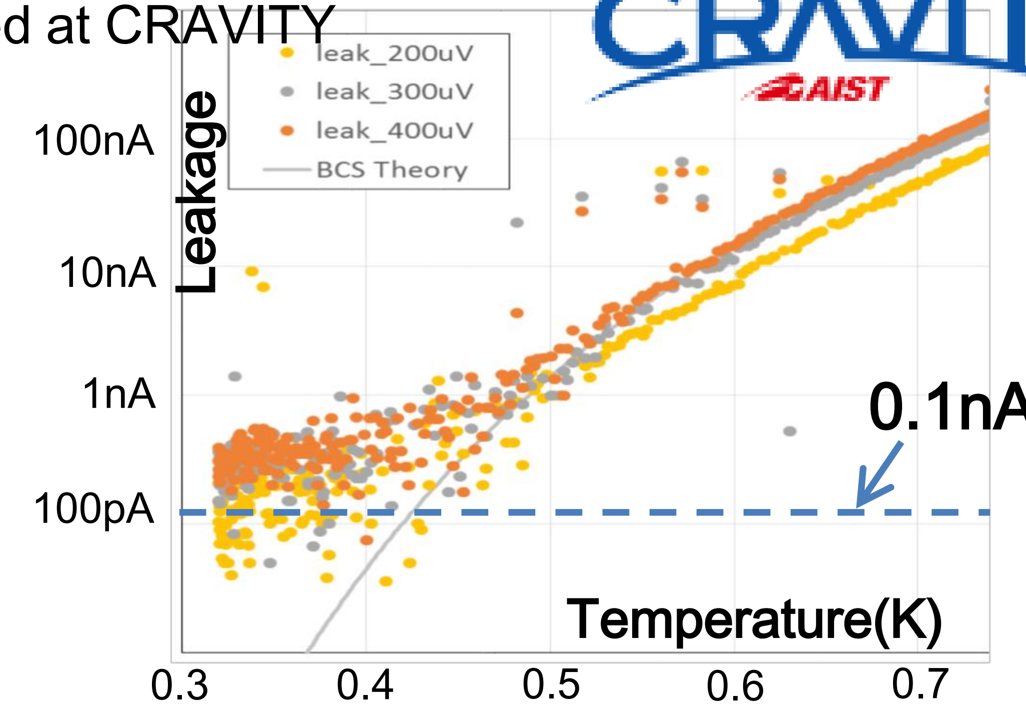
➔ Spectrum measurement without a diffraction grating

➔ Developing for a future satellite experiment

Nb/Al-STJ development at CRAVITY

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





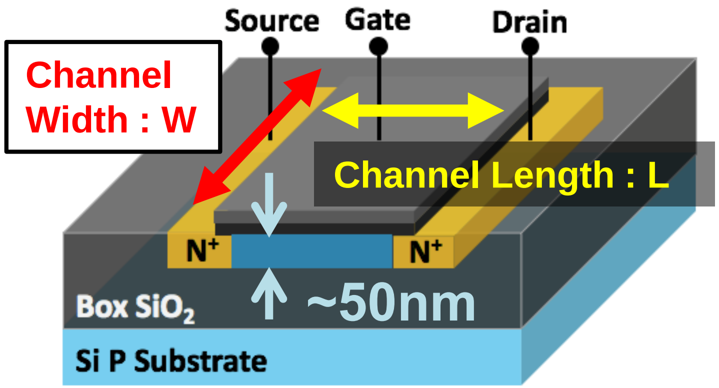
I_{leak}~200pA for 50μm sq. STJ, and achieved 50pA for 20μm sq.

➔ This satisfies our requirement!

Far-infrared single photon detection is feasible with this Nb/Al-STJ sensor and a cryogenic amplifier which can be deployed in close proximity to the STJ.

FD-SOI-MOSFET at cryogenic temperature

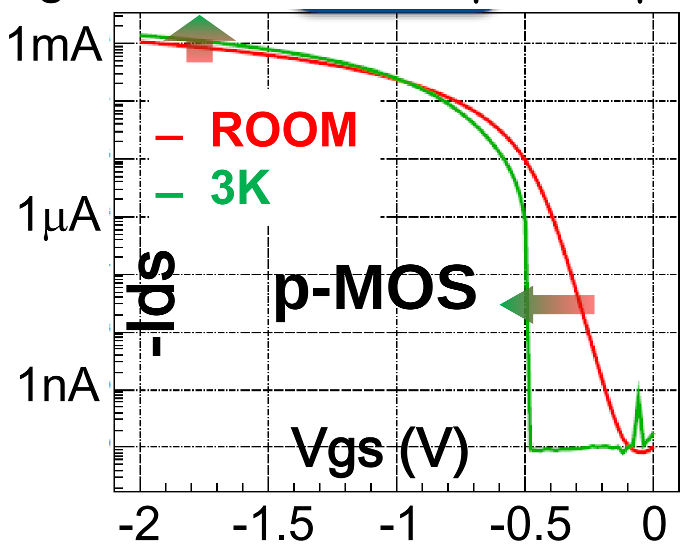
FD-SOI : **F**ully **D**epleted – **S**ilicon **O**n **I**nsulator

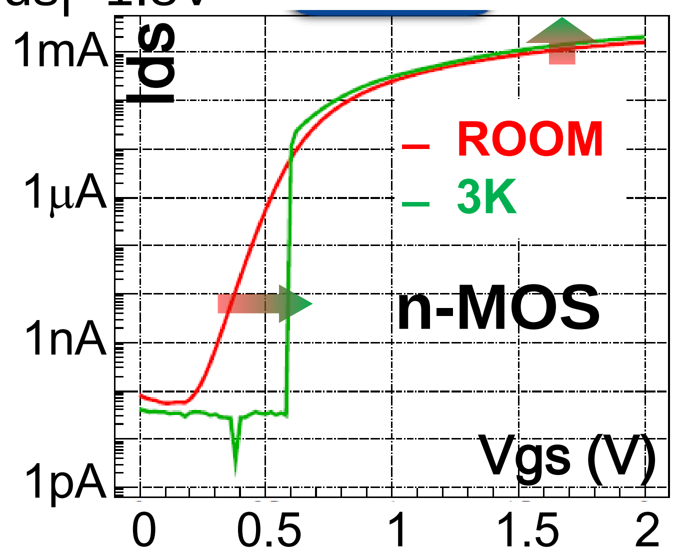


- Very thin channel layer in MOSFET on SiO_2
- No floating body effect caused by charge accumulation in the body
- FD-SOI-MOSFET is reported to work at 4K

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

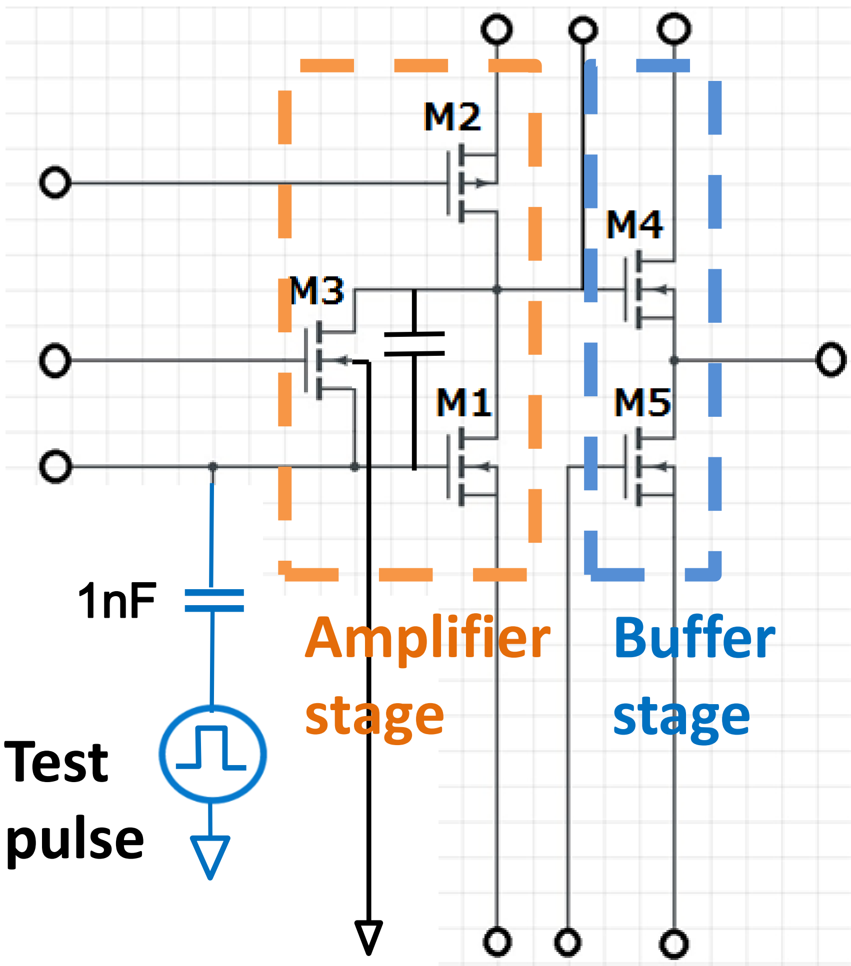
Id-Vg curve of W/L=10μm/0.4μm at |Vds|=1.8V

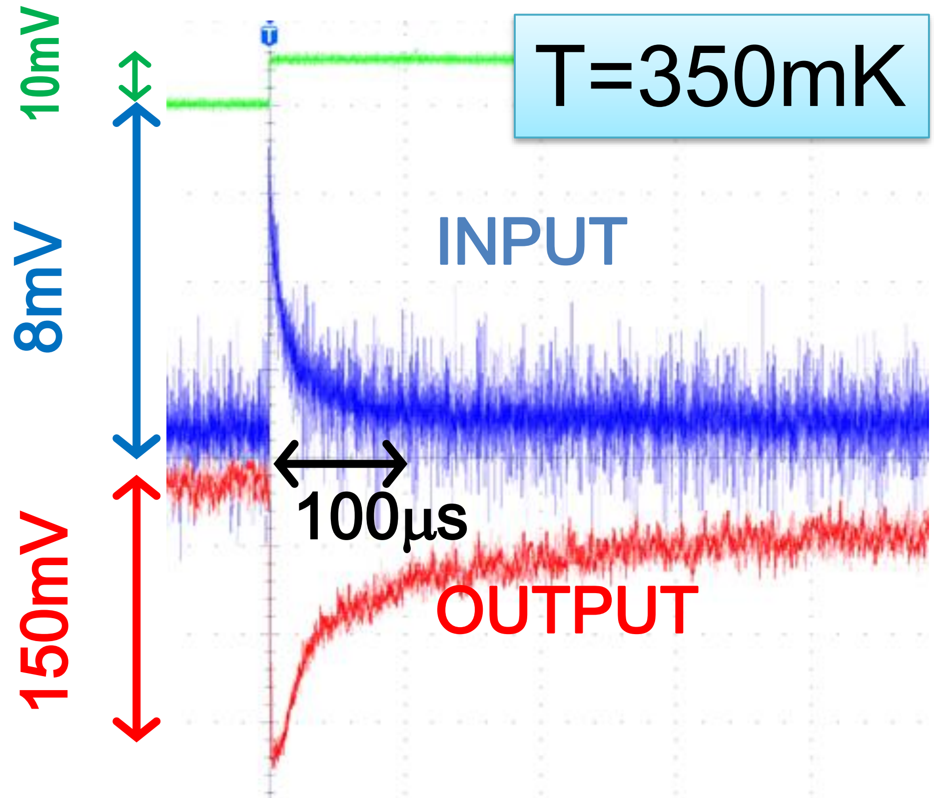




Both p-MOS and n-MOS show excellent performance at 3K and below.

SOI prototype amplifier for demonstration test



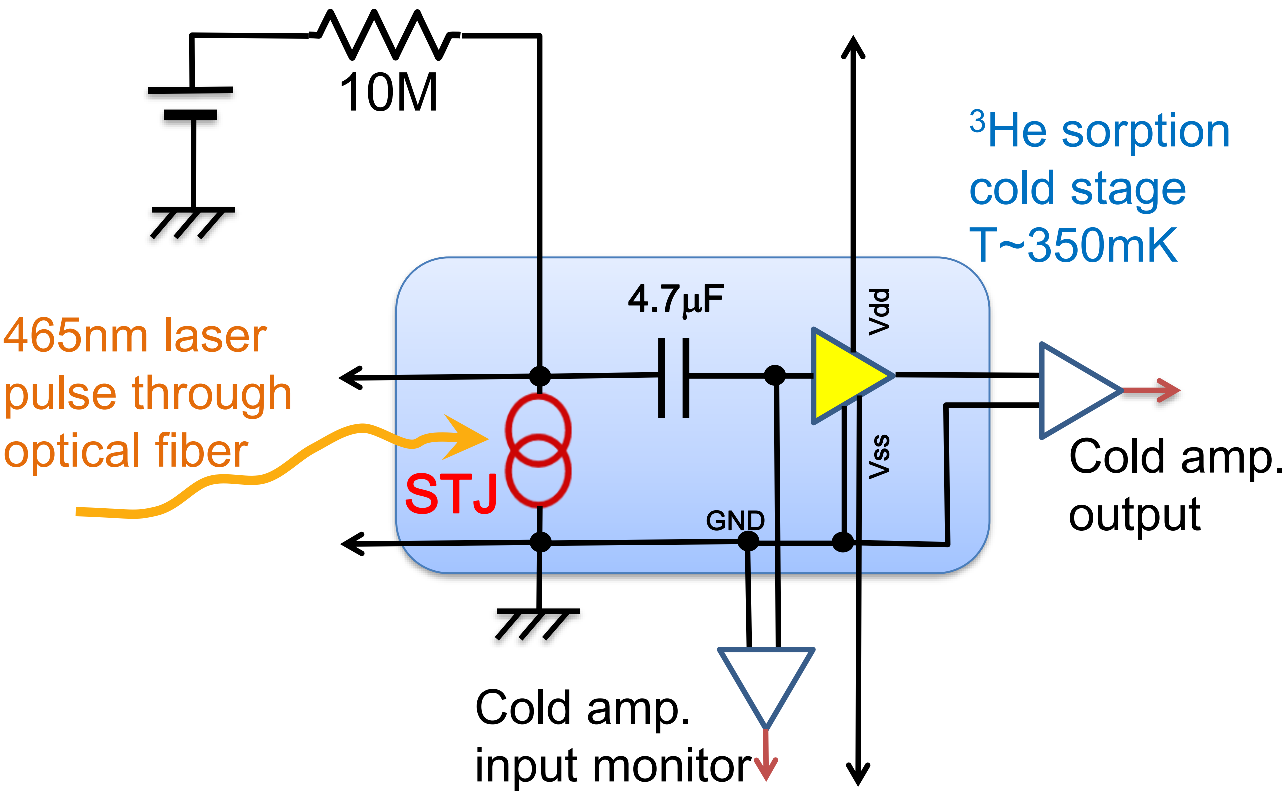


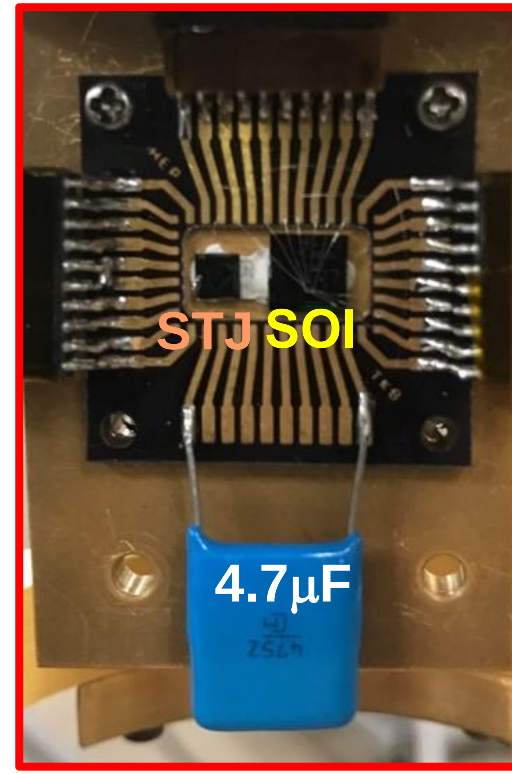
Test pulse input through C=1nF at T=3K and 350mK

- Power consumption: ~100μW
- Output load: 1MΩ and ~0.5nF

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

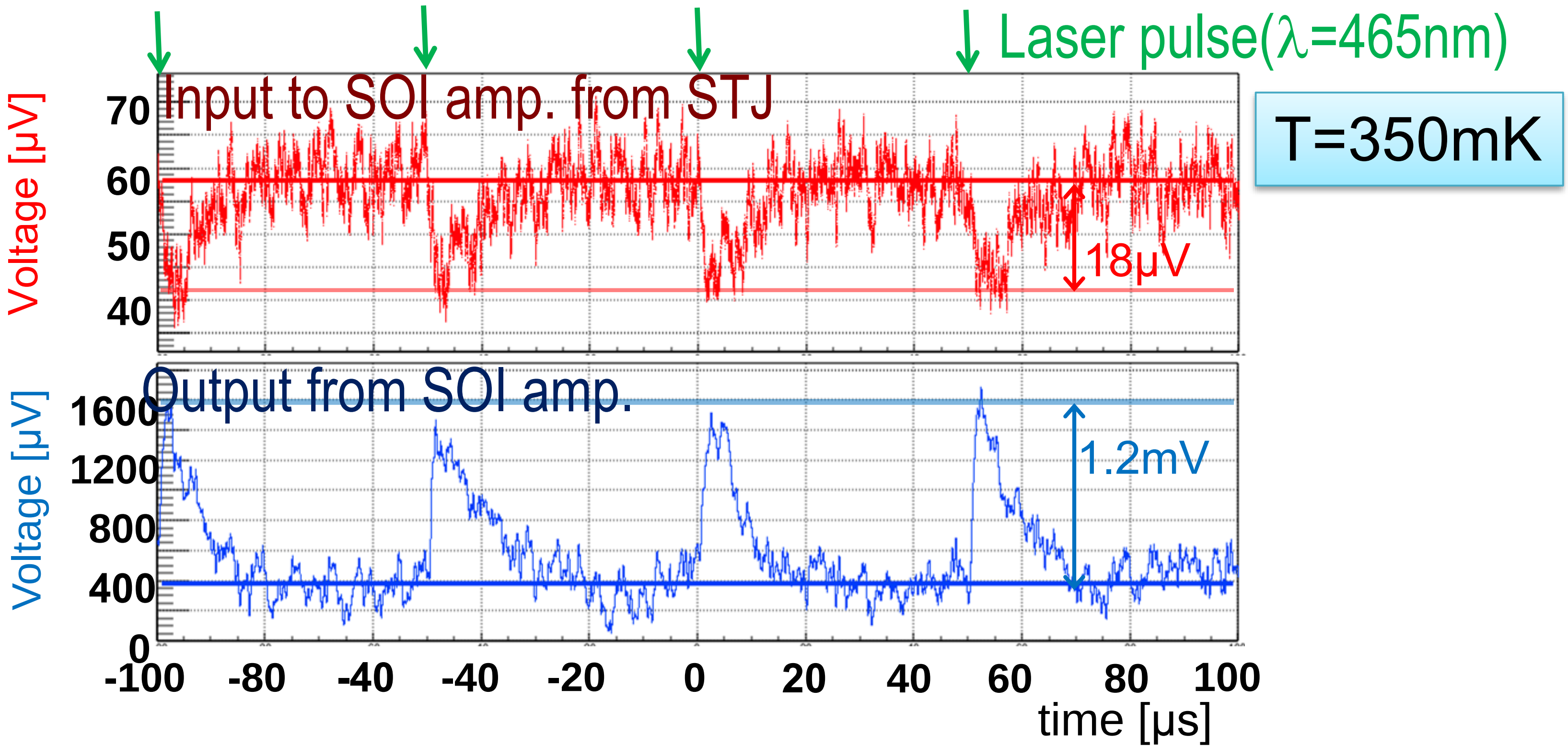
Amplification of STJ response to laser pulse on cold stage





We connect 20μm sq. Nb/Al-STJ and SOI amplifier on the cold stage through a capacitance

Amplification of STJ response to laser pulse on cold stage

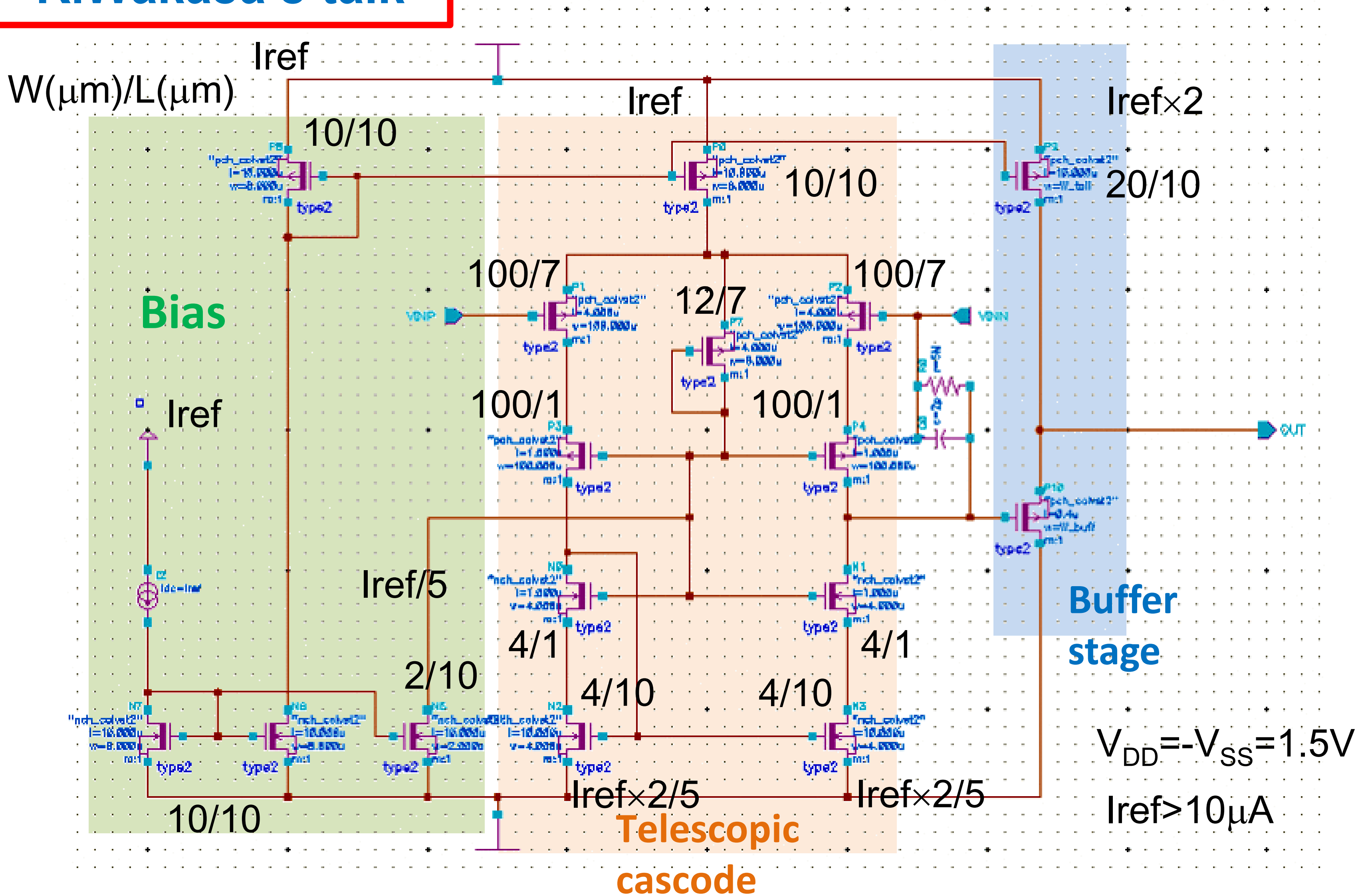


Demonstrated to show amplification of Nb/Al-STJ response to laser pulse by SOI amplifier situated close to STJ at T=350mK

Development of SOI cryogenic amplifier for STJ signal readout is now moving to the stage of design for practical use !

Charge sensitive amplifier design for STJ single photon detection

R.Wakasa's talk



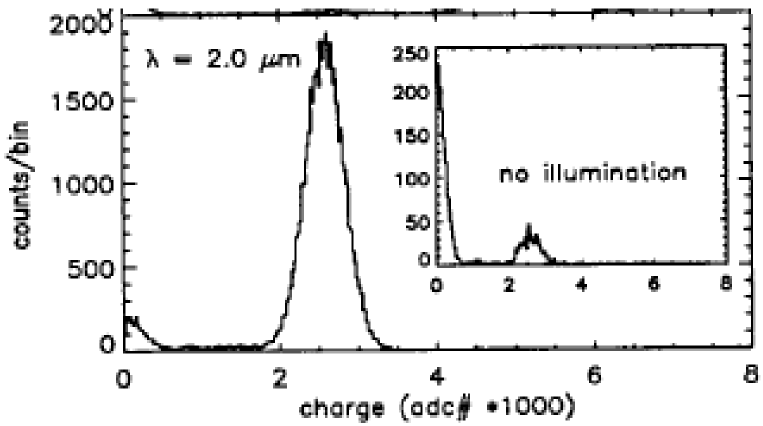
Summary

- We propose a sounding rocket experiment to search for neutrino radiative decay in cosmic neutrino background, and a following satellite experiment .
- Nb/Al-STJ array with a grating for the rocket experiment.
  - Demonstrated STJ signal amplification by a prototype SOI amplifier at T~350mK
  - Now we design and develop SOI cryogenic amplifier for practical use ➔ R. Wakasa's talk
- Hf-STJ ➔ K. Takemasa's talk

- **C. Asano "Single Photon Detection by Nb/Al-STJ with Cryogenic SOI Amplifier for COBAND experiment"**
- **K.Nishimura "A Far-Infrared Pulsed Light Source to Calibrate STJ Detectors for COBAND Experiment"**
- **Y.Takeuchi "Feasibility of sub-GeV mass dark matter search using STJ detector for COBAND experiment"**

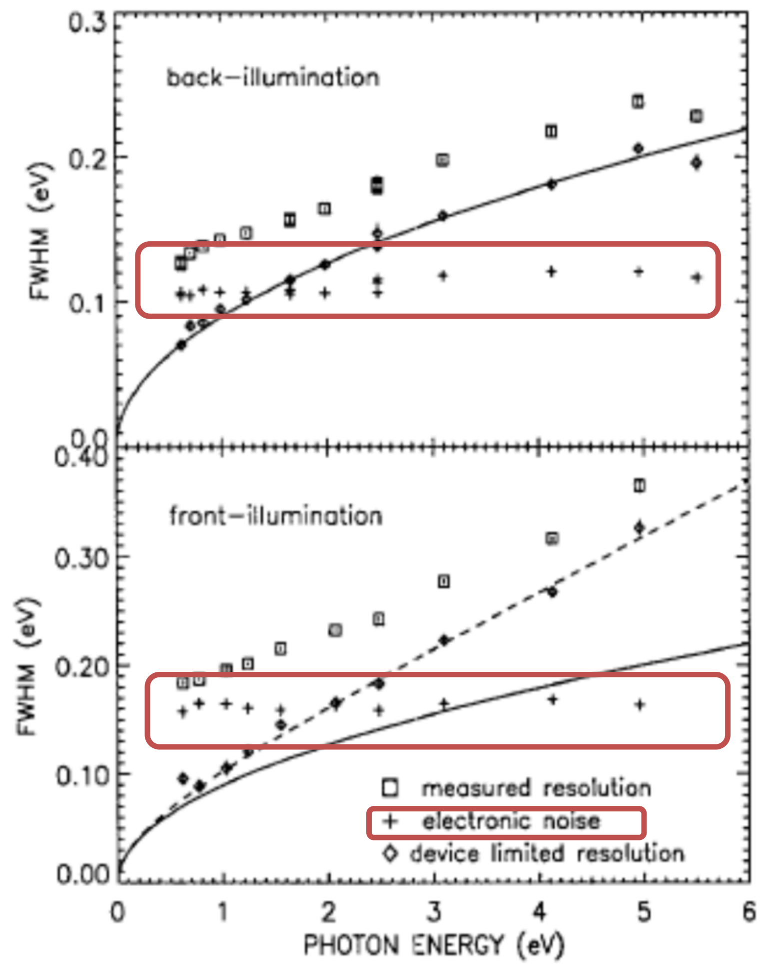
Backup

STJ energy resolution for near infrared photon



P. Verhoeve et. al 1997

- 30μm sq. Ta/Al-STJ
- ΔE~130meV @ E=620meV(λ=2μm)
- Charge sensitive amplifier at room temp.
  - Electronic noise ~ 100meV



In sub-eV ~ several-eV region, STJ gives the best energy resolution among superconductor based detectors, but limited by readout electronic noise.

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**

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

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

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

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

- 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

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

Existing FIR photo-detectors

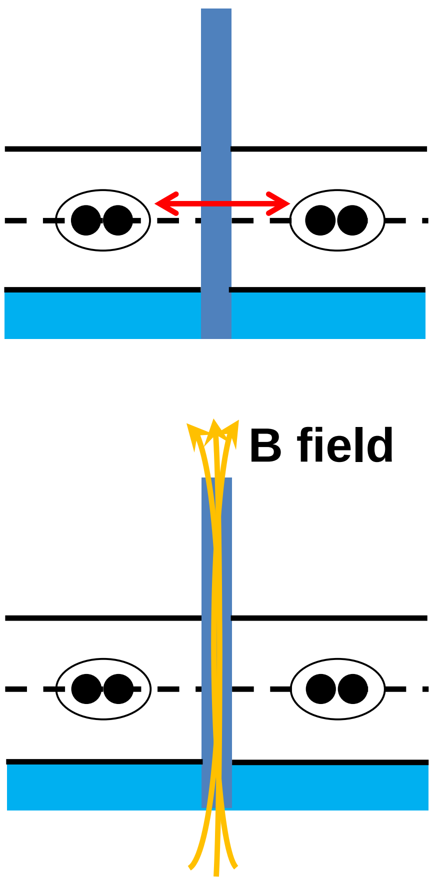
Detectors	λ(μm)	Operation Temp.	NEP ($W/Hz^{1/2}$)	
Monolithic Ge:Ga	50-110	2.2K	$\sim 10^{-17}$	Akari-FIS
Stressed Ge:Ga	60-210	0.3K	$\sim 0.9\times10^{-17}$	Herschel-PACS

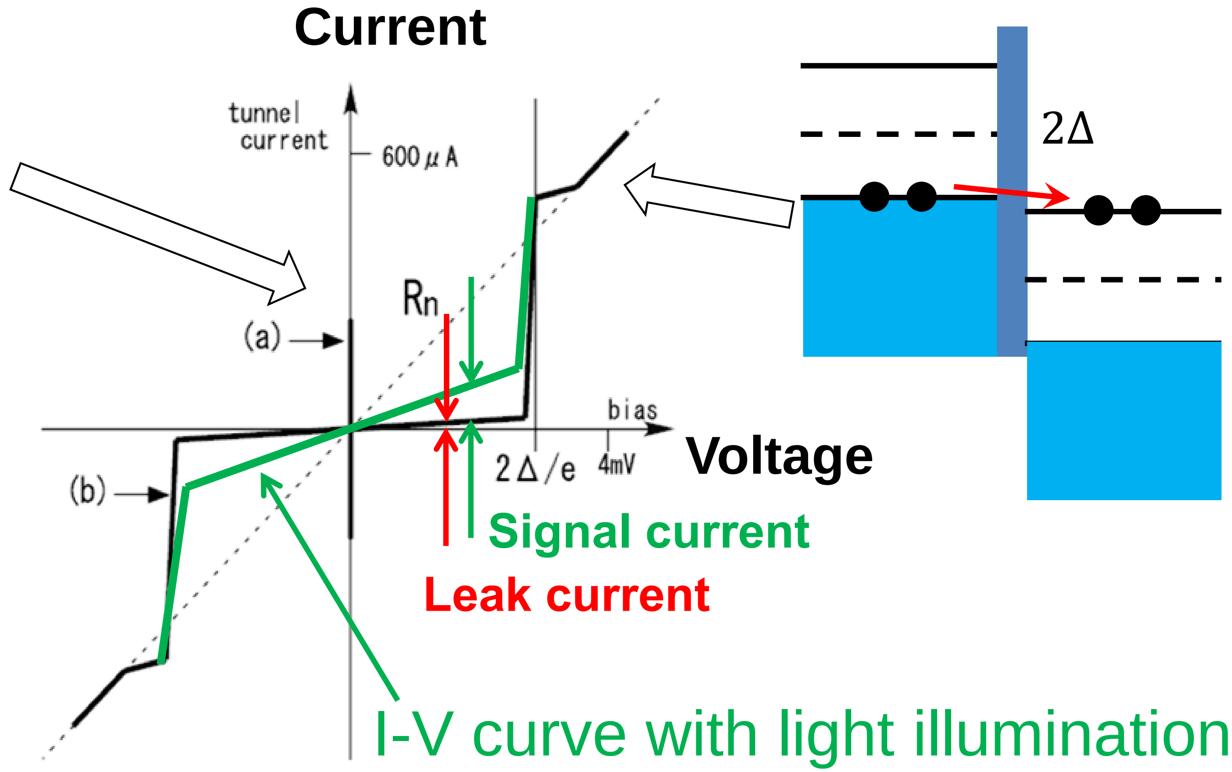
Need more than 2 orders improvement from existing photoconductor-based detectors

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**

STJ current-voltage curve





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

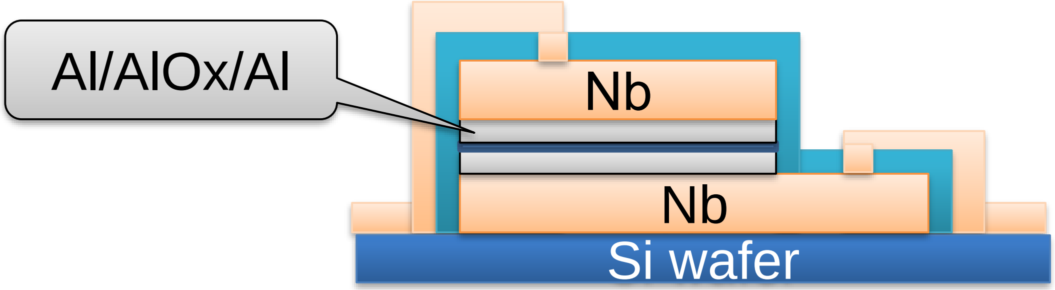
Optical signal readout

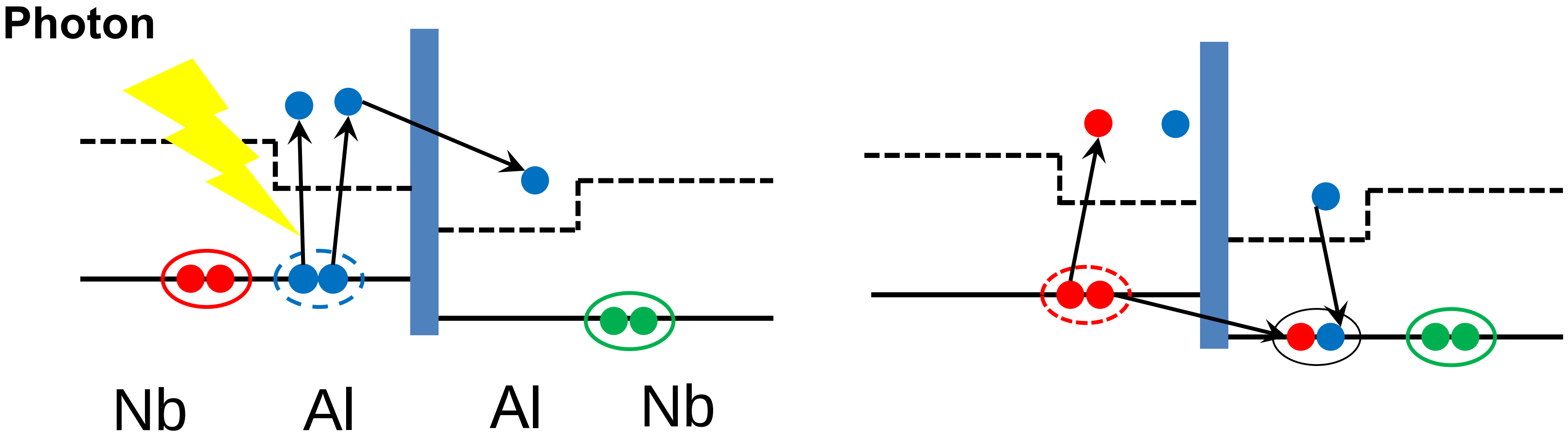
➔ Apply a constant bias voltage (|V|<2Δ) across the junction and collect tunneling current of quasi particles created by photons

✓ Leak current causes background noise

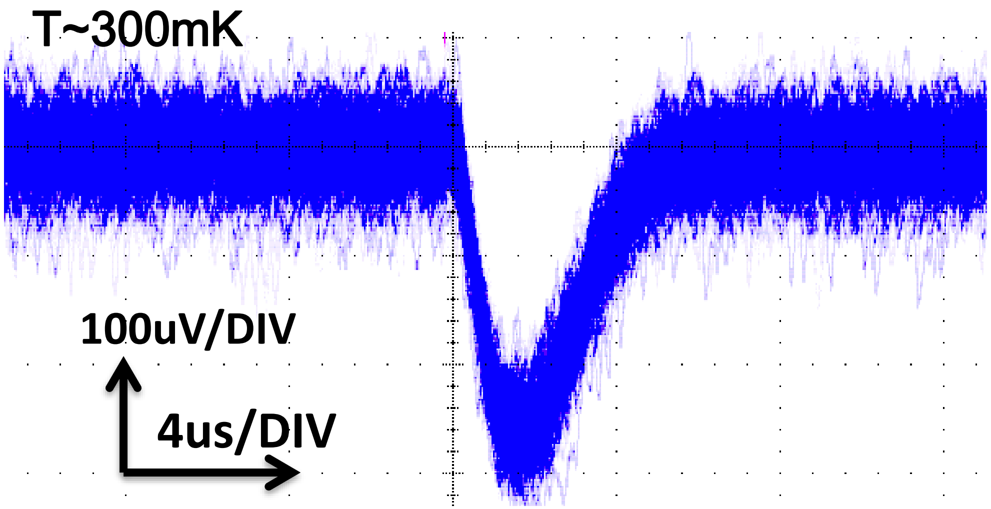
STJ back-tunneling effect

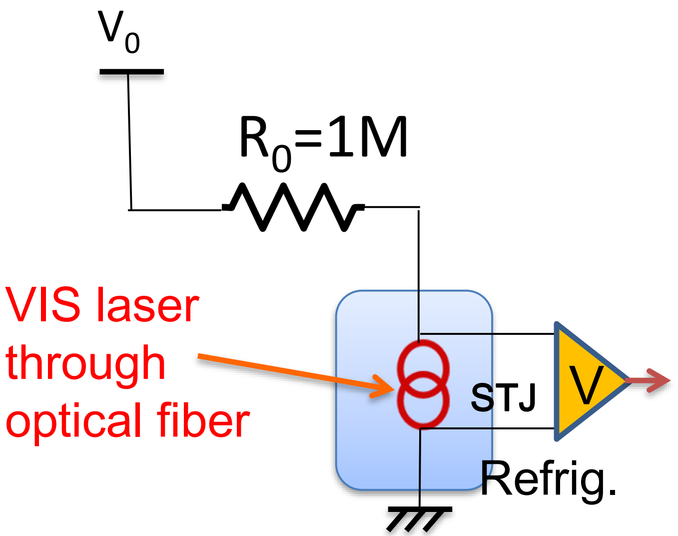
- Bi-layer fabricated with superconductors of different gaps $\Delta_{Nb} > \Delta_{Al}$ to enhance quasi-particle density near the barrier
  - Quasi-particle near the barrier can mediate multiple Cooper pairs
- Nb/Al-STJ Nb(200nm)/Al(70nm)/AlOx/Al(70nm)/Nb(200nm)
- Gain: ∼10





STJ response to pulsed laser





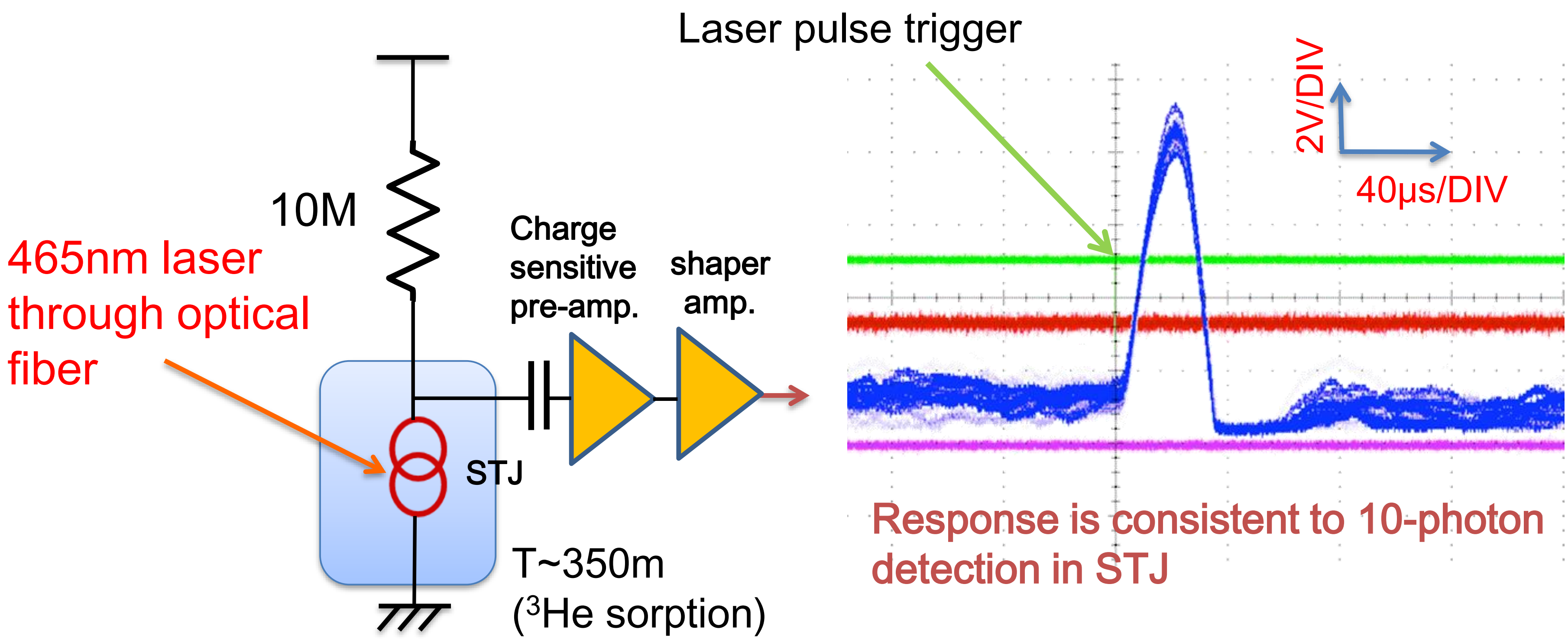
Nb/Al-STJ response to pulsed laser (465nm)
CRAVITY Nb/Al-STJ 100μm sq.

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



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.

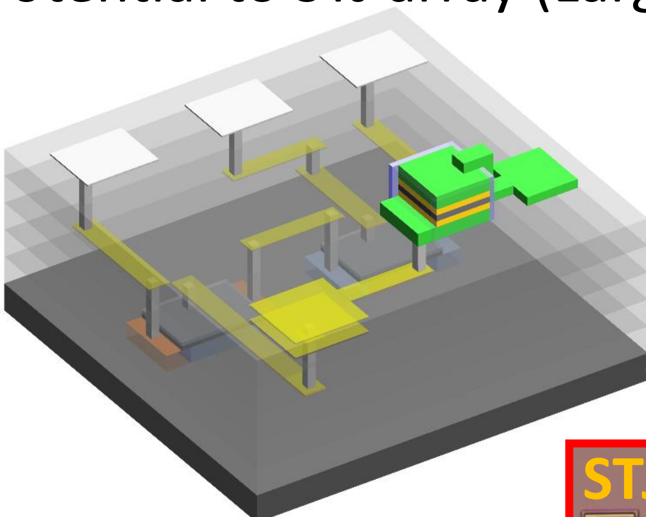
Need ultra-low noise readout system for STJ signal

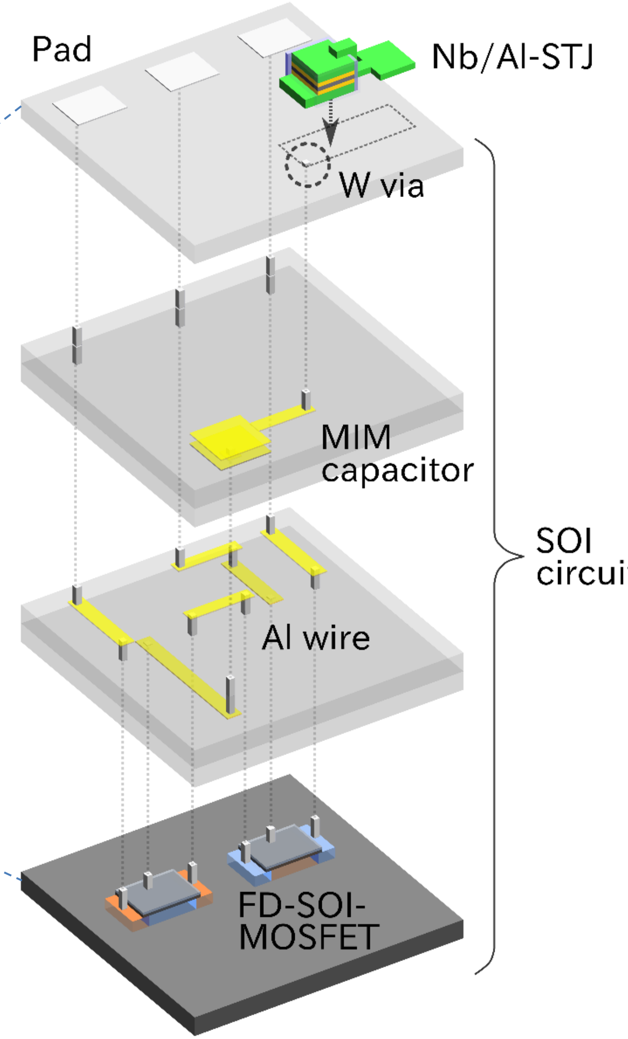
➔ Considering a cryogenic pre-amplifier placed close to STJ

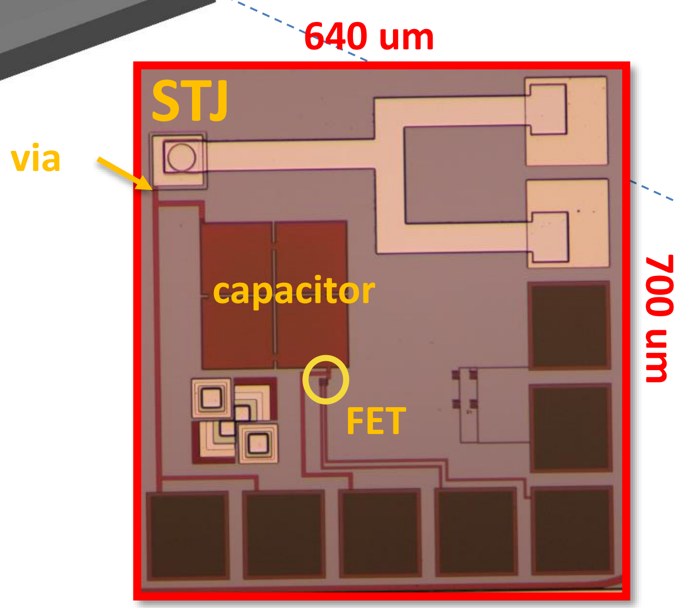
SOI-STJ (STJ directly on SOI) development

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

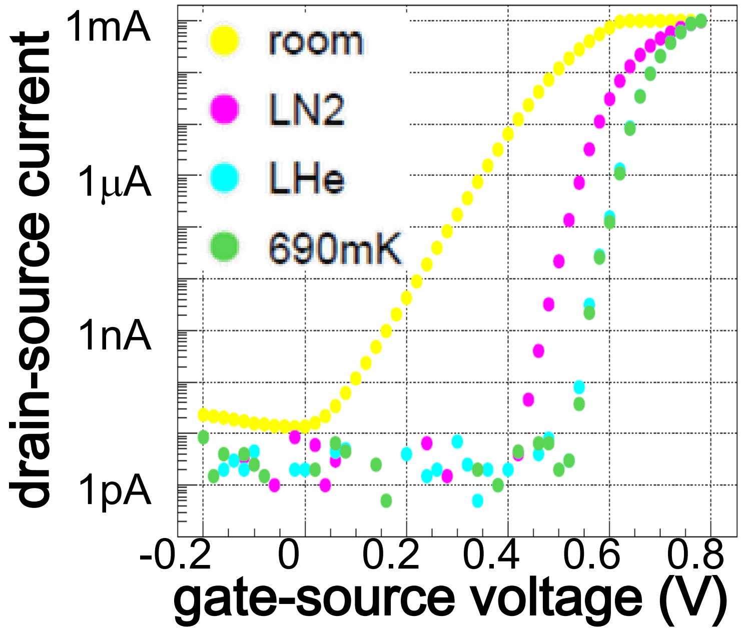
□ Potential to STJ array (Large area STJ)



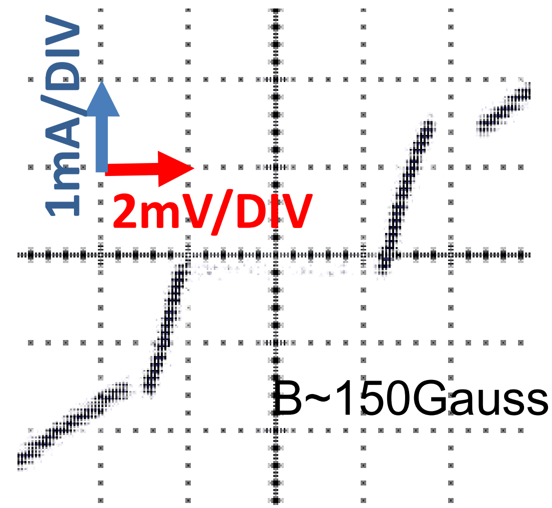




FD-SOI on which STJ is fabricated



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