Development of STJ with FD-SOI cryogenic amplifier as a far-infrared single photon detector for COBAND experiment

17th International workshop on Low Temperature d Detectors (LTD17)

Jul. 17-21, 2017 / Kurume City Plaza, Kurume

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COBAND collaboration

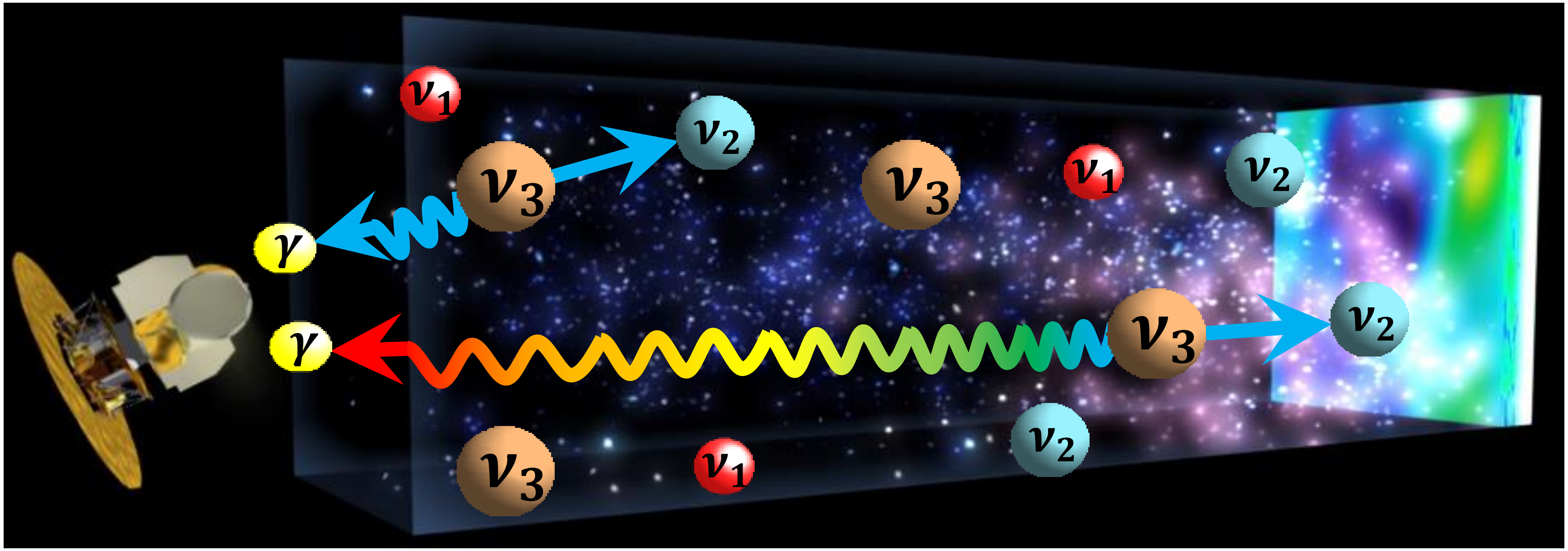
COBAND (COsmic BAckground Neutrino Decay)

Search for Neutrino decay in Cosmic background neutrino

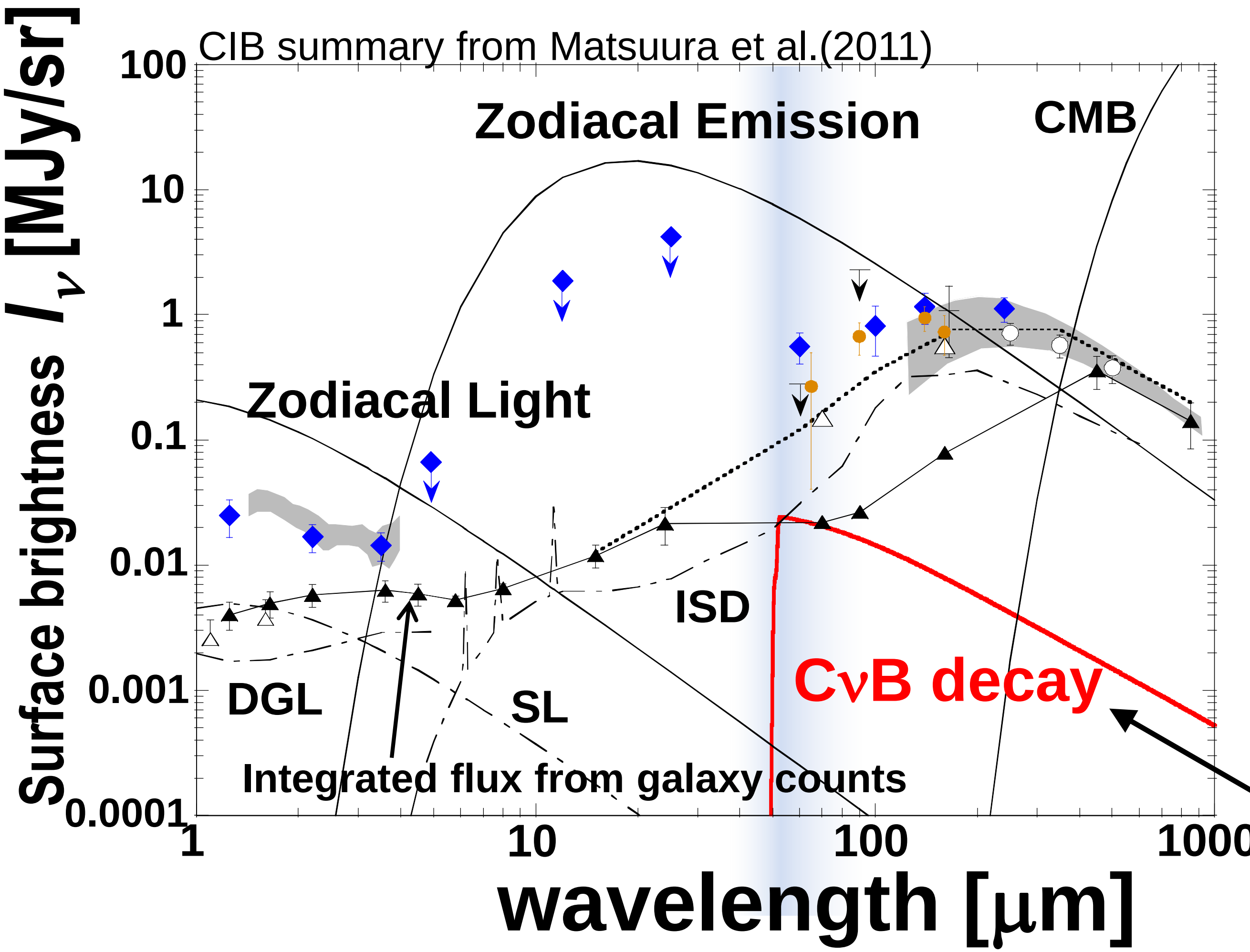
➔To be observed as far infrared photons of λ~50μm

COBAND Rocket Experiment

- 200-sec measurement at an altitude of 200~300km
- Aiming at a sensitivity to 10^{14} years for the neutrino lifetime



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

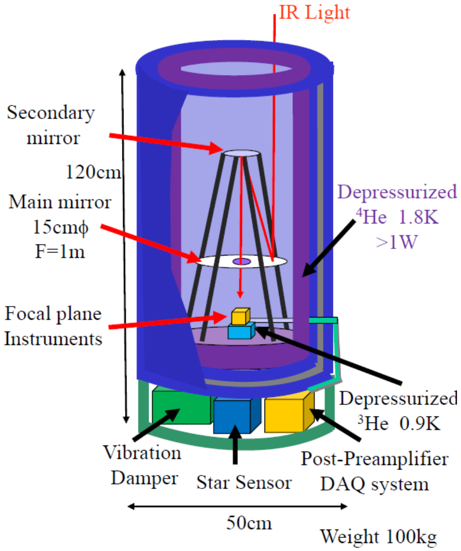
No other source has such a sharp edge structure!!

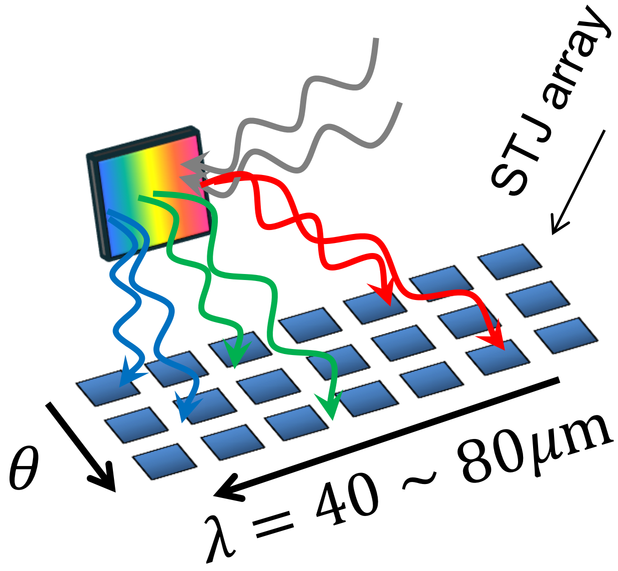
Proposal for COBAND Rocket Experiment

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

JAXA sounding rocket S-520

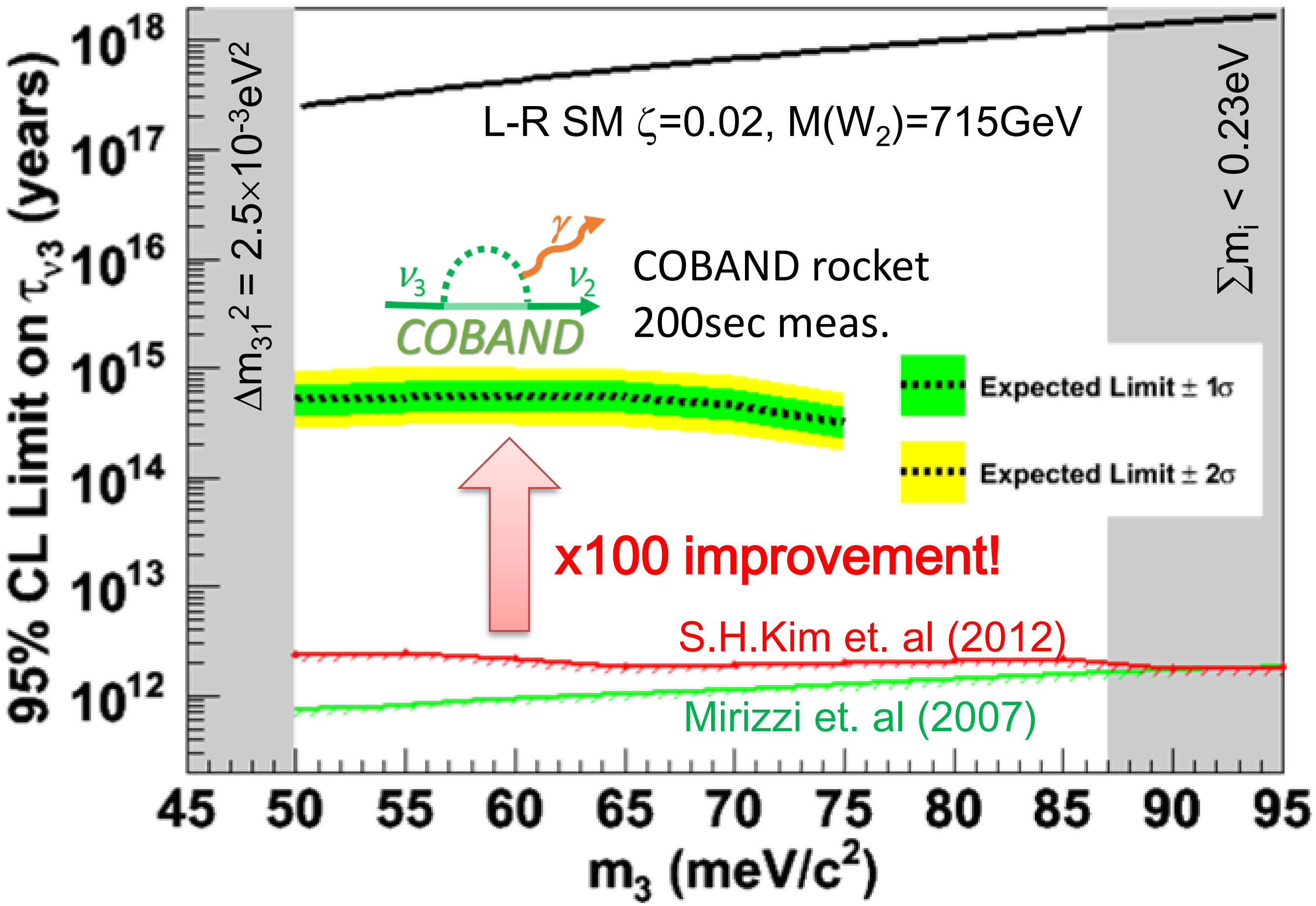
- Telescope with **15cm diameter** and **1m focal length**
- At the focal point, a diffraction grating covering **λ=40-80μm** and an array of photo-detector pixels of **50(λ) x 8(θ)** are placed.
- Each pixel has **100μmx100μm** sensitive area.





COBAND rocket experiment sensitivity

- 200-sec measurements with a sounding rocket
- 15cm dia. and 1m focal length telescope and grating in 40~80μm range
- Each pixel in 100μm×100μm×8×50pix. array counts number of photons



Requirements for the photo-detector 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)

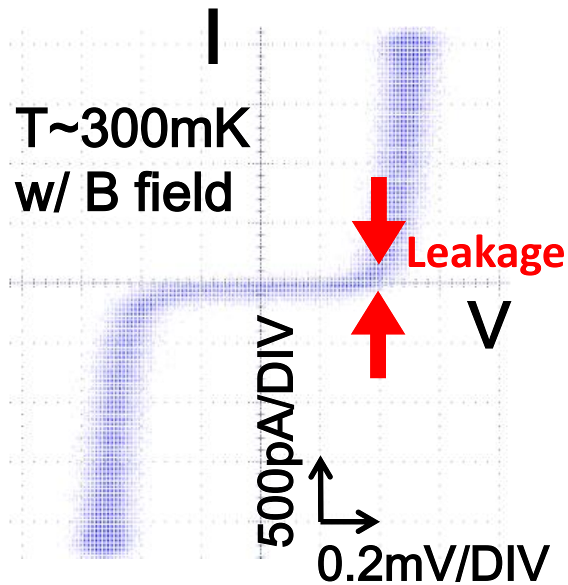
$$\rightarrow \mathrm{NEP} = \epsilon_\gamma \sqrt{2 f_\gamma} \sim 1\times10^{-19}\, W/\sqrt{Hz}$$

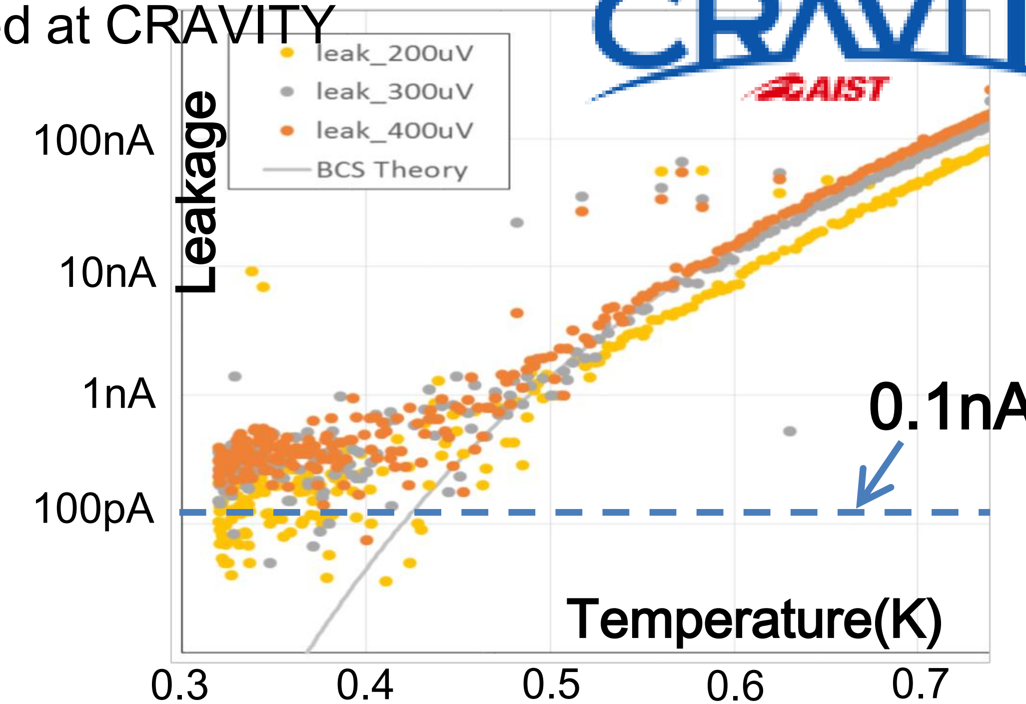
We are trying to achieve $\mathrm{NEP} \sim 10^{-19}\, W/\sqrt{Hz}$ **by using**

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

Nb/Al-STJ development at CRAVITY

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





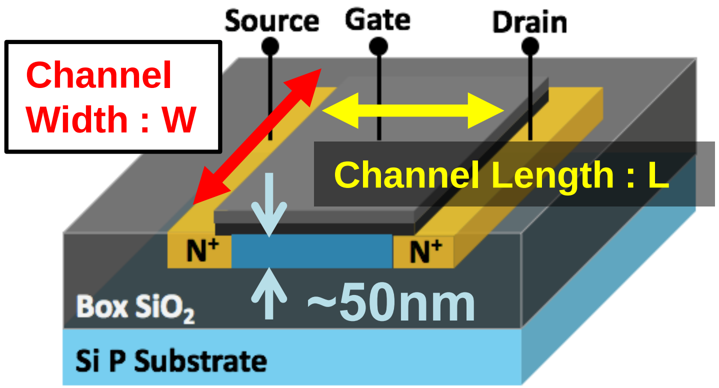
I_{leak}~200pA for 50μm sq. STJ, and achieved 50pA for 20μm sq.

➔ This satisfies our requirement!

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

FD-SOI-MOSFET at cryogenic temperature

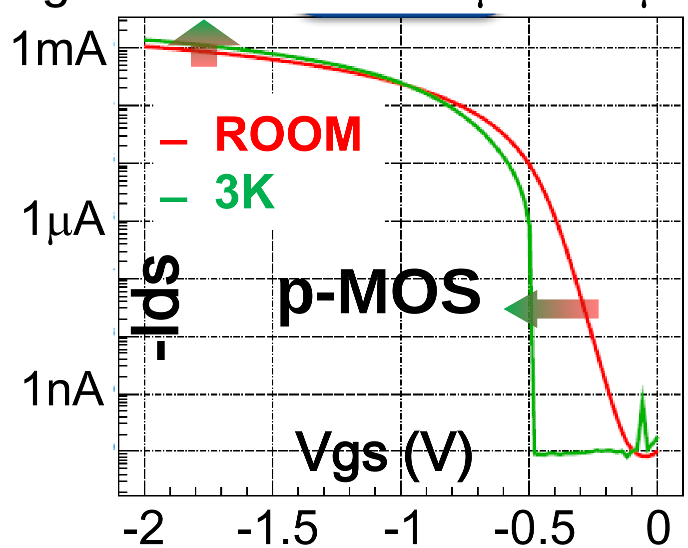
FD-SOI : **F**ully **D**epleted – **S**ilicon **O**n **I**nsulator

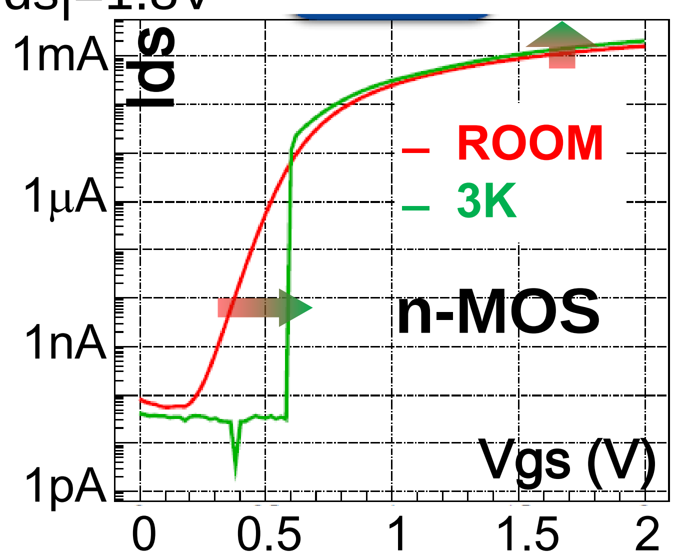


- Very thin channel layer in MOSFET on SiO_2
- No floating body effect caused by charge accumulation in the body
- FD-SOI-MOSFET is reported to work at 4K

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

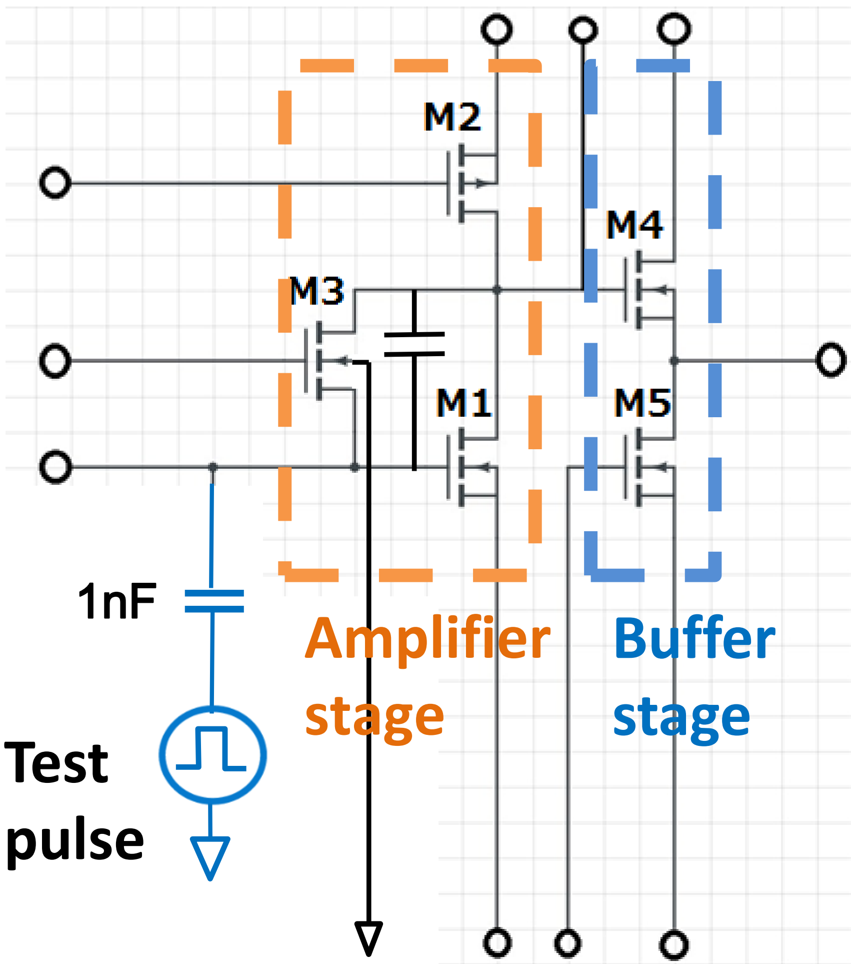
Id-Vg curve of W/L=10μm/0.4μm at |Vds|=1.8V

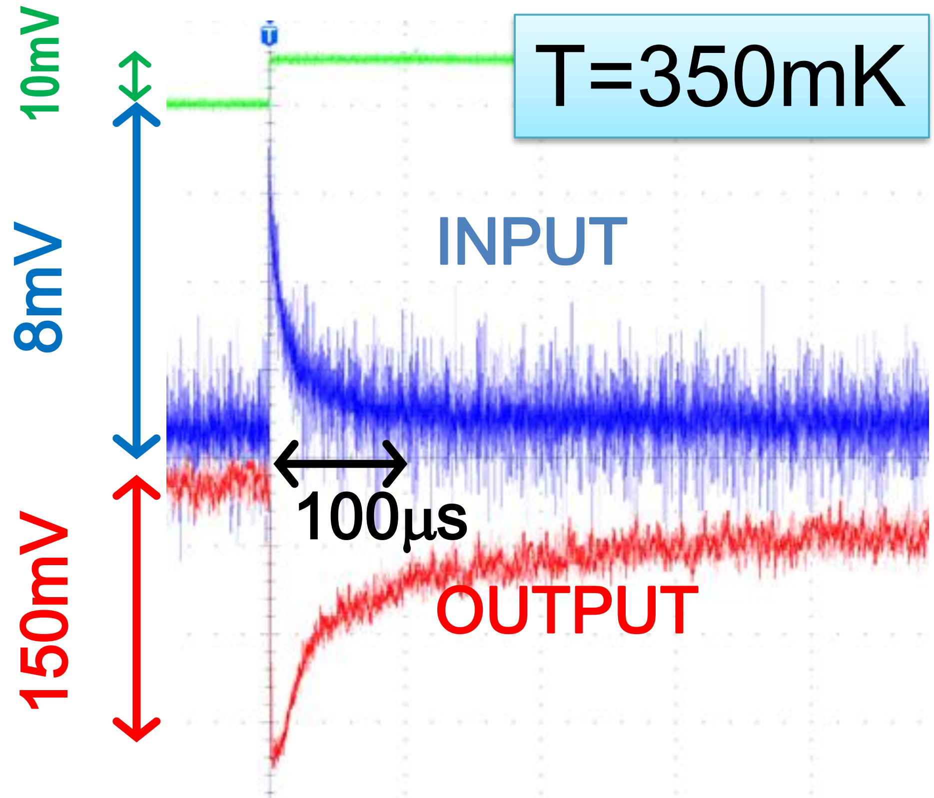




Both p-MOS and n-MOS show excellent performance at 3K and below.

SOI prototype amplifier for demonstration test



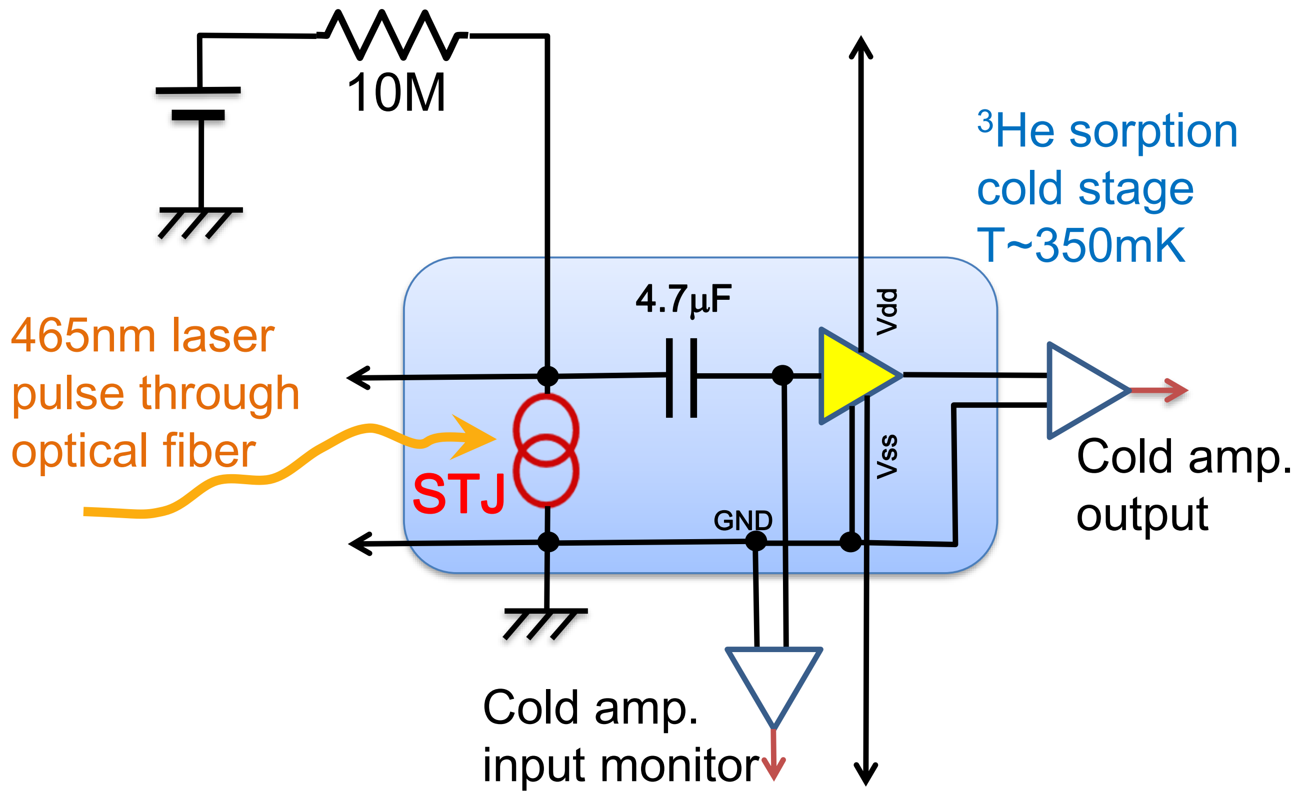


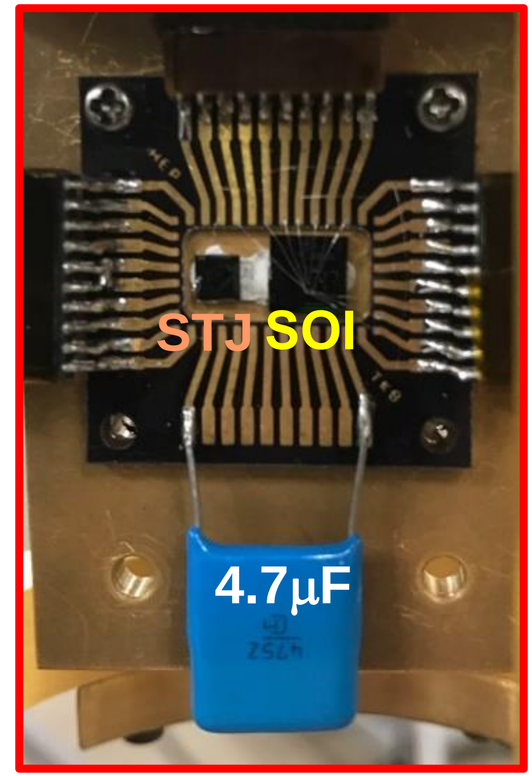
Test pulse input through C=1nF at T=3K and 350mK

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

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

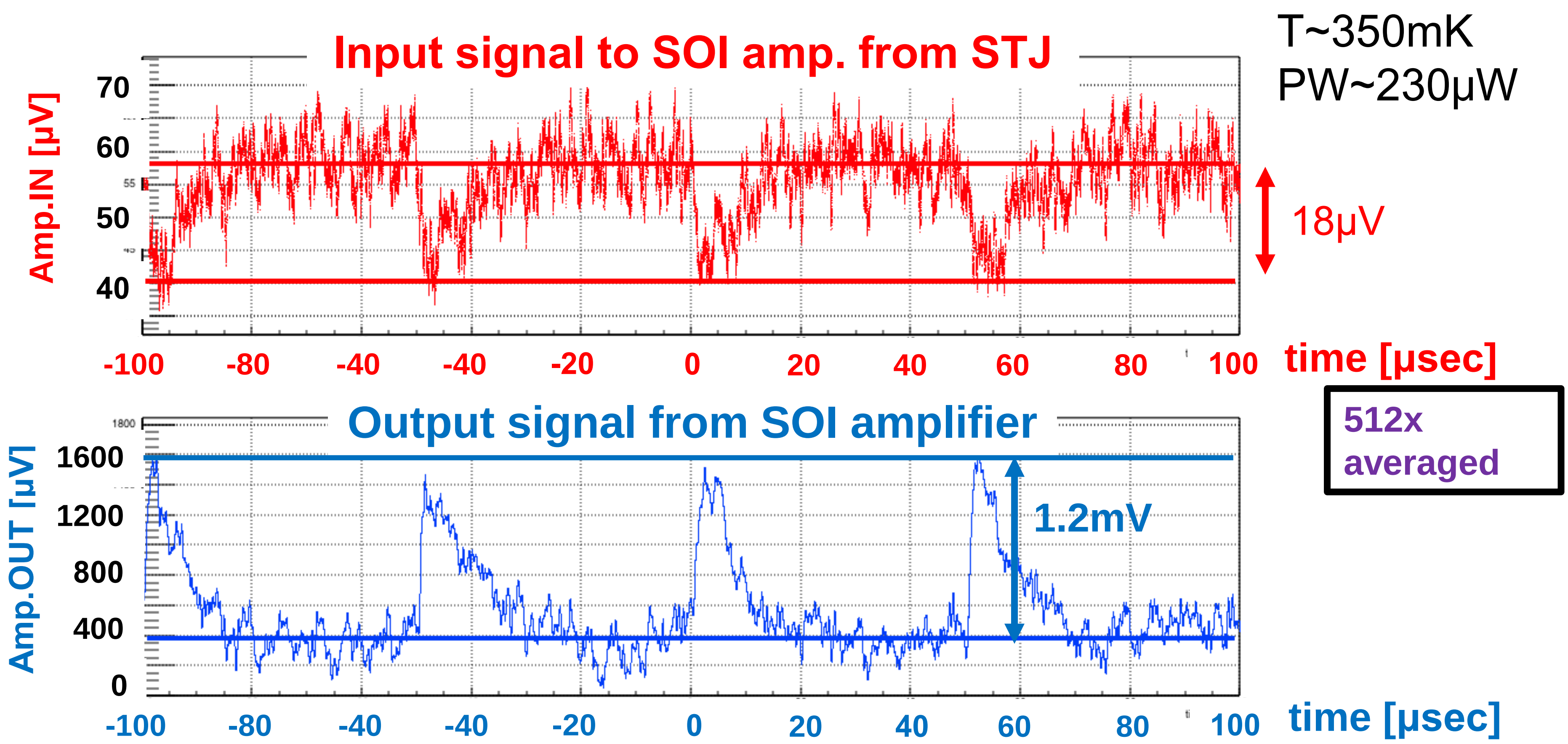
STJ response to laser pulse amplified by Cold amplifier





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

STJ response to laser pulse amplified by Cold amplifier



We observe 20μm sq. Nb/Al-STJ responses to laser pulses of λ=465nm amplified by SOI amplifier situated at T=350mK

Summary

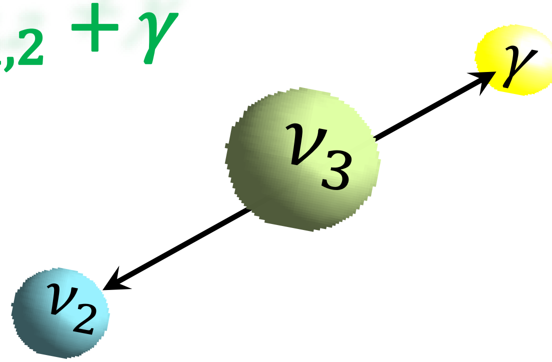
- We propose COBAND experiment to search for neutrino radiative decay in cosmic neutrino background.
- Requirements for the detector is a photo-detector with NEP~10^{-19} W/√Hz.
- Nb/Al-STJ array with a diffractive for the sounding rocket experiment.
  - Nb/Al-STJs fabricated at CRAVITY satisfy our requirements.
  - Cryogenic FD-SOI amplifiers are under development and we demonstrated STJ signal amplification by a prototype SOI amplifier at T~350mK.
- 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.

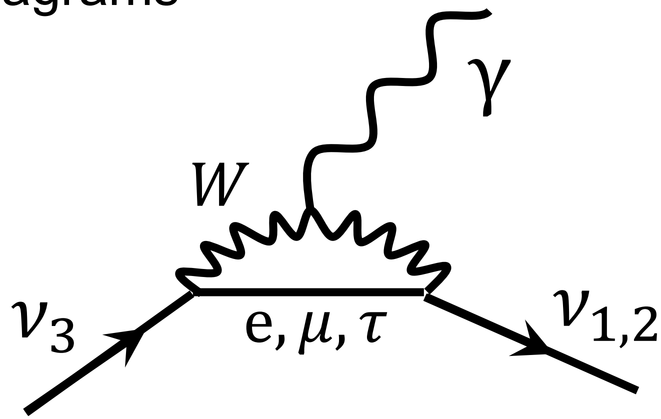
* SOI design in this work is supported by VDEC, the U. Tokyo in collaboration with Synopsys, Inc., Cadence Design Systems, Inc., and Mentor Graphics, Inc.

Backup

COBAND (COsmic BAckground Neutrino Decay)

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



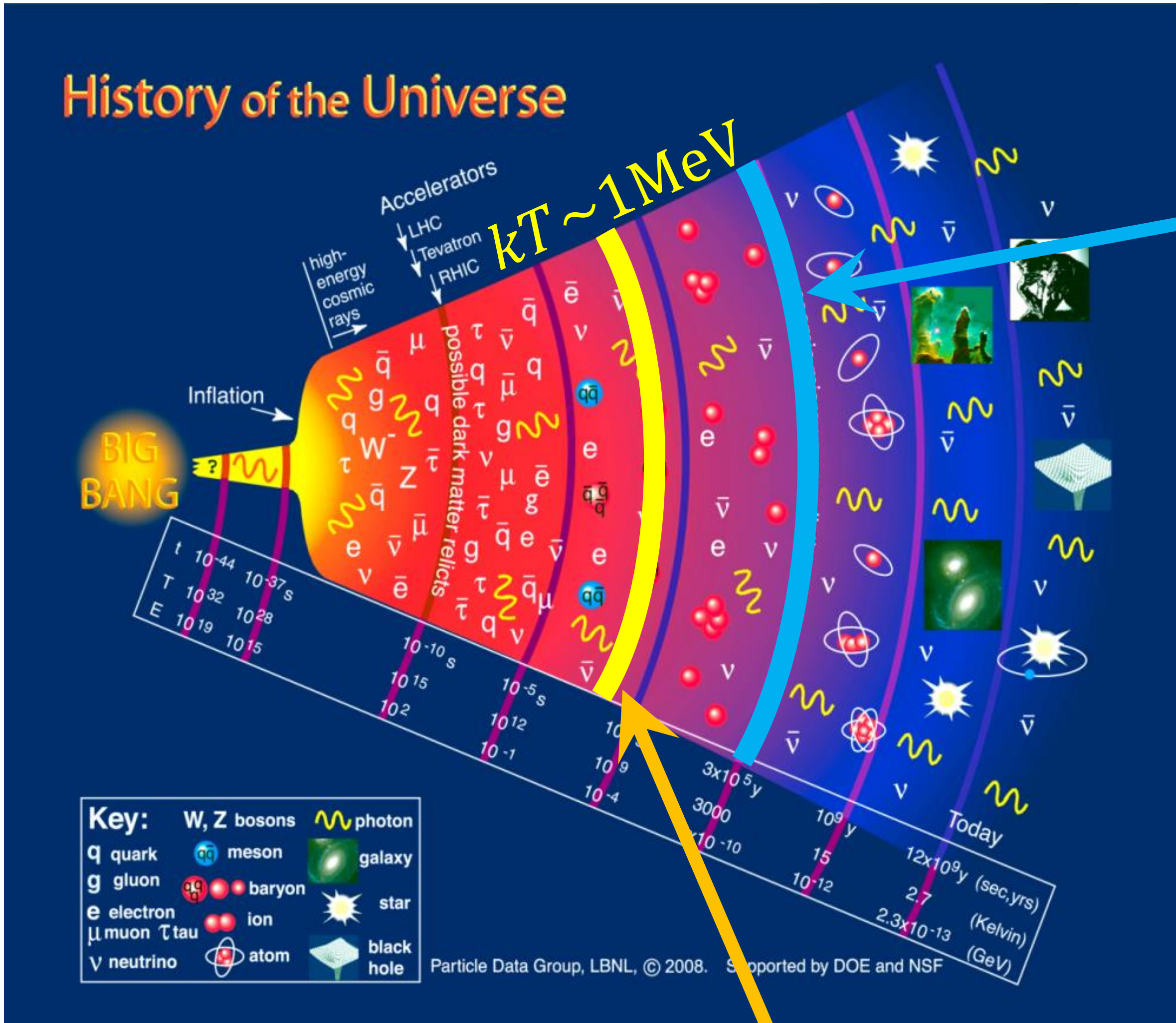


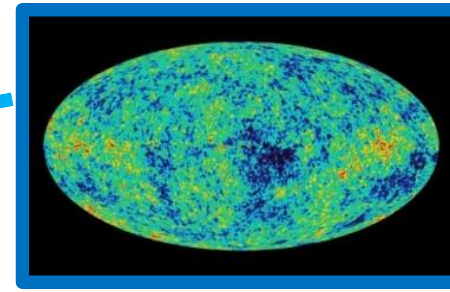
✓ However, the lifetime is expected to be much longer than the age of the universe

➔ 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)

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

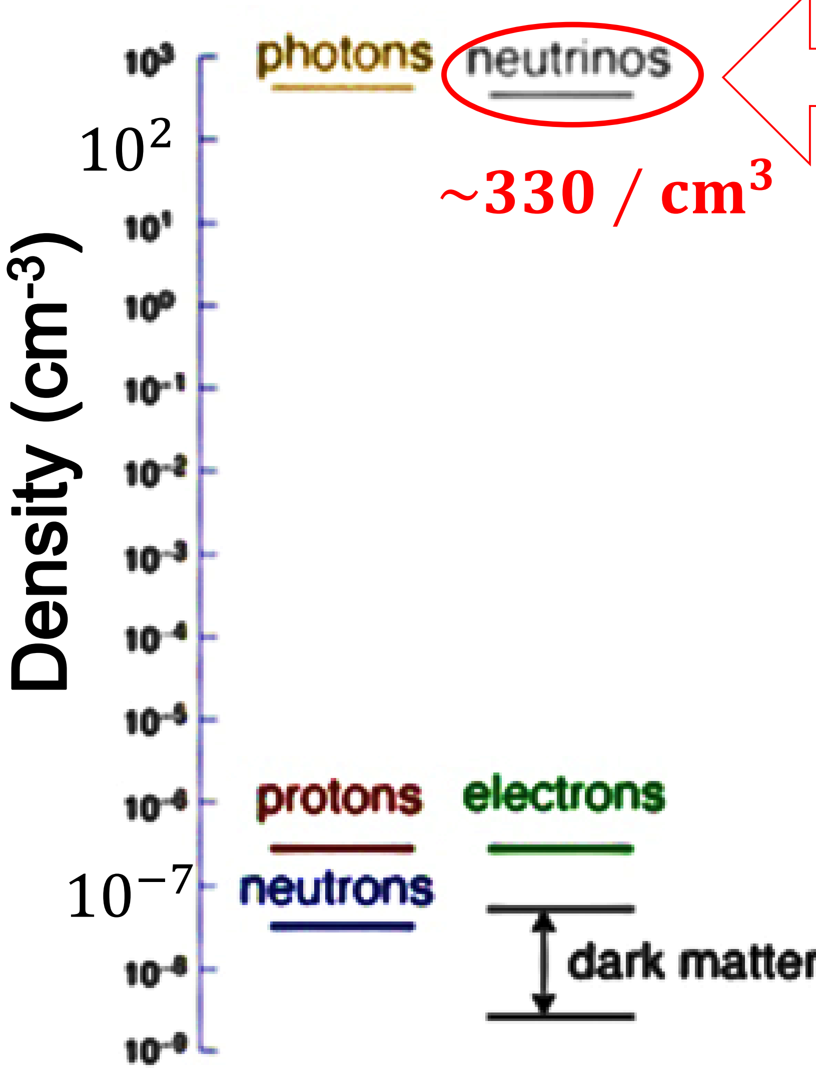
$T_\gamma = 2.73\ K$

~380,000yrs after the Big Bang

CνB (=neutrino decoupling)

~1sec after the big bang

Cosmic background neutrino (CνB)



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

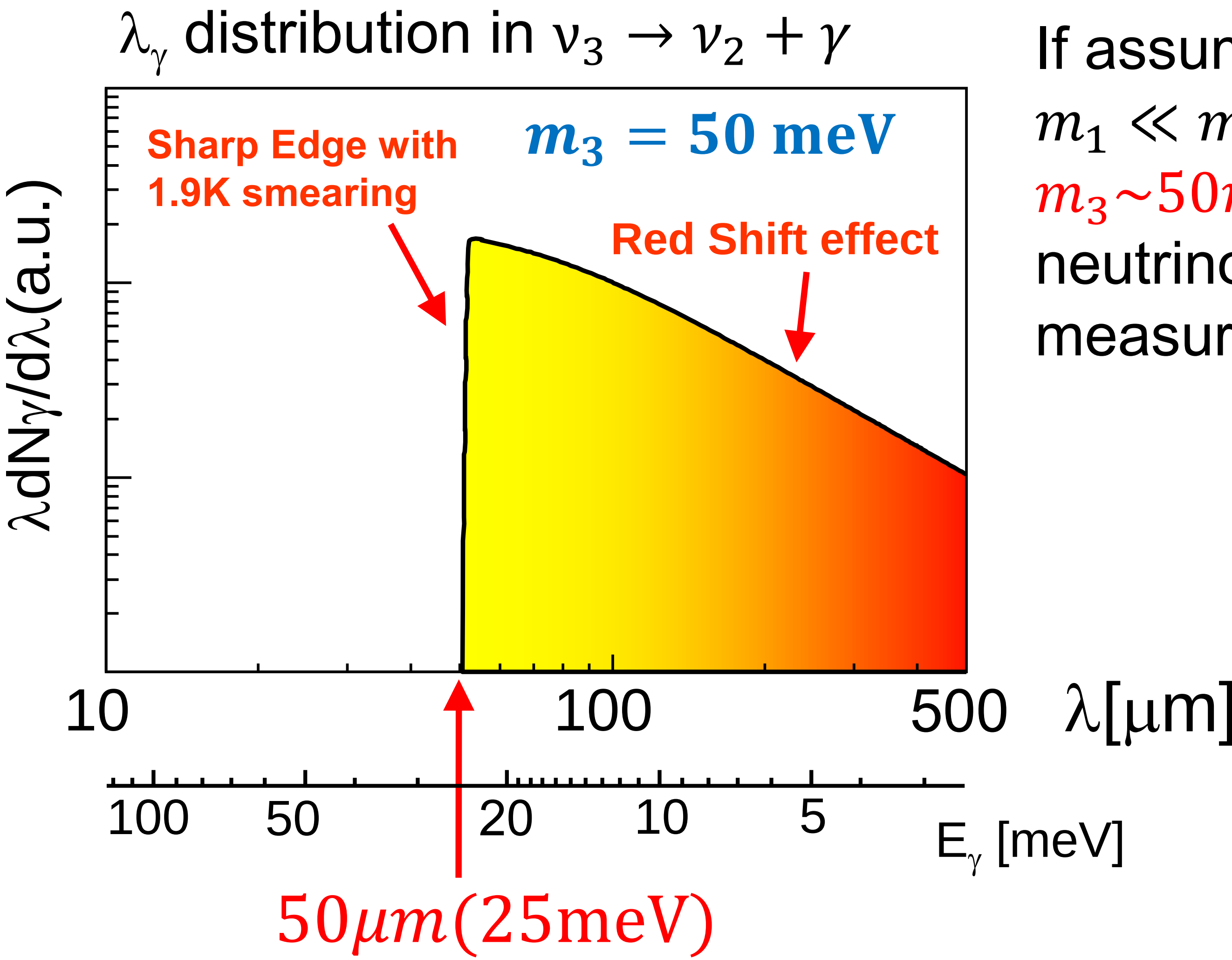
$$n_\nu + n_{\bar{\nu}} = \frac{3}{4}\left(\frac{T_\nu}{T_\gamma}\right)^3 n_\gamma$$

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

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

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

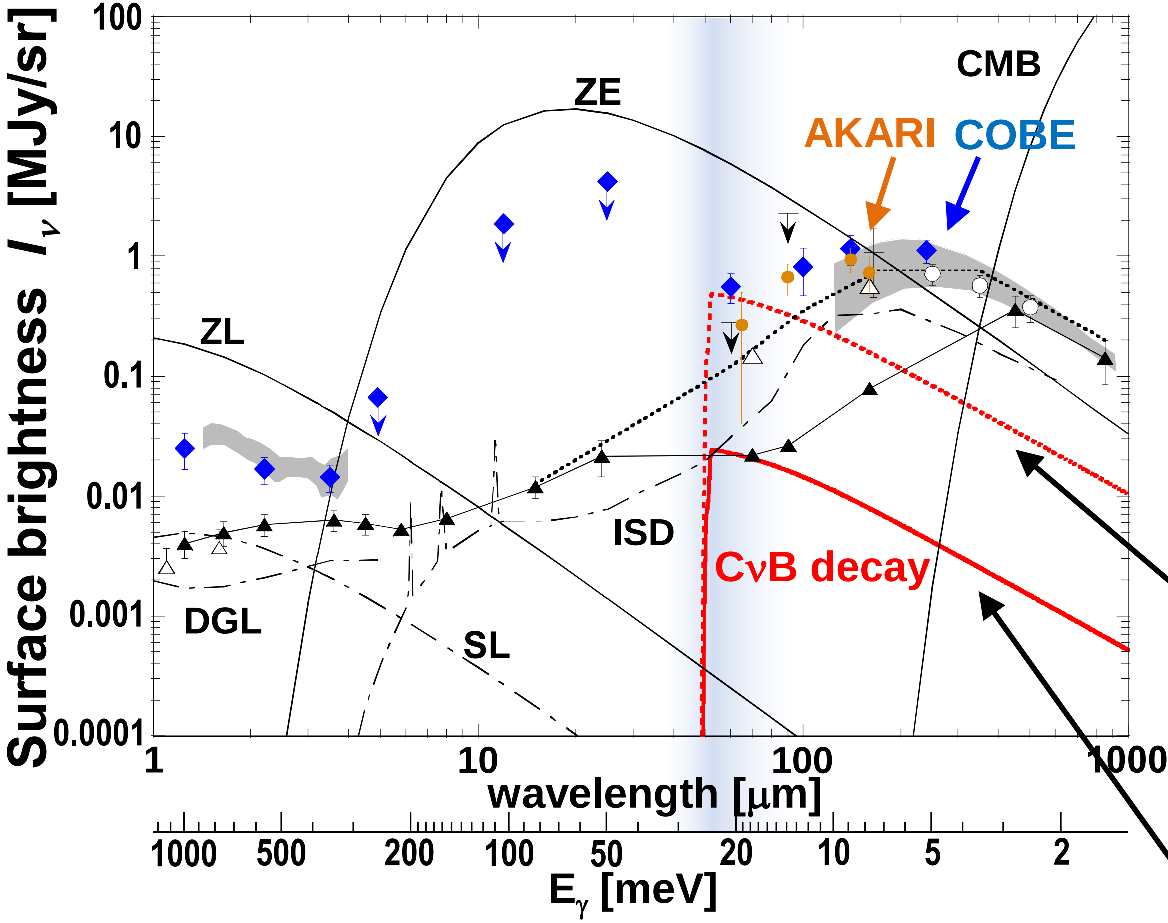
Expected photon wavelength spectrum from CνB decays



If assume
$m_1 \ll m_2 < m_3$,
$m_3 \sim 50meV$ from neutrino oscillation measurements

No other source has such a sharp edge structure!!

CνB radiative decay and Backgrounds



Zodiacal Emission

I_ν~8MJy/sr

Cosmic Infrared Background (CIB)

I_ν~0.1~0.5MJy/sr

CνB decay

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

I_ν~0.5MJy/sr

Excluded (S.H.Kim 2012)

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

I_ν~25kJy/sr

at λ = 50μm

Expected E_γ spectrum

for $m_3 = 50\text{meV}$

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

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Soo-Bong Kim (Seoul National University)

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
- Left-Right symmetric model predicts $\tau = O(10^{17})$ 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

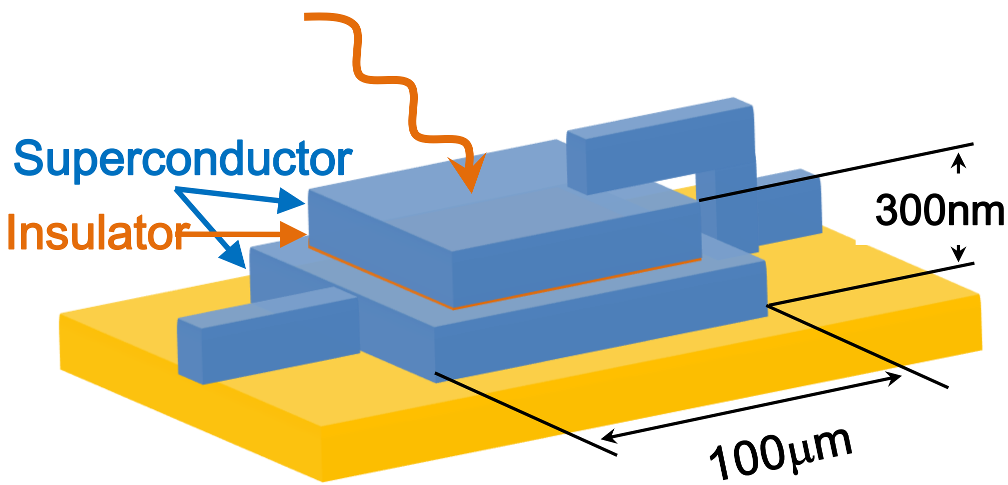
Existing FIR photo-detectors

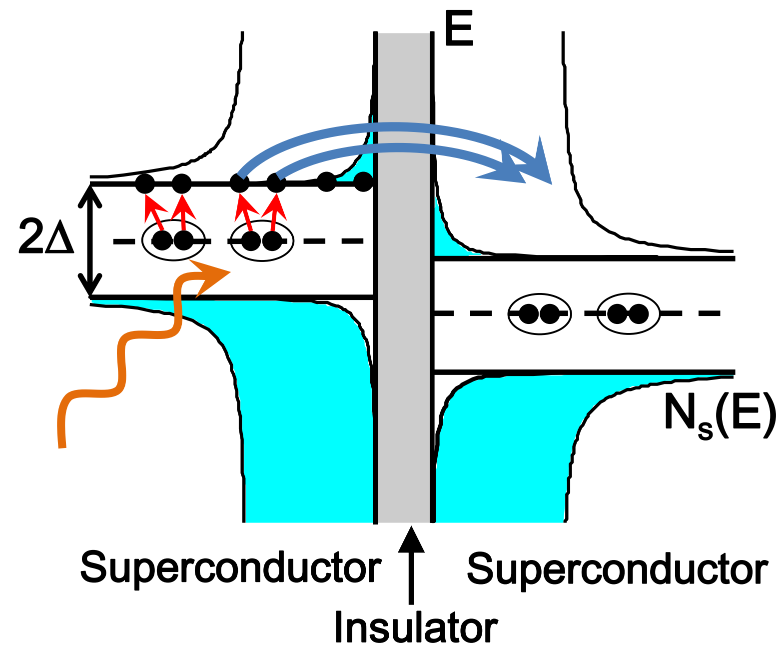
Detectors	λ(μm)	Operation Temp.	NEP ($W/Hz^{1/2}$)	
Monolithic Ge:Ga	50-110	2.2K	~ 10^{-17}	Akari-FIS
Stressed Ge:Ga	60-210	0.3K	~0.9×10^{-17}	Herschel-PACS

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

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

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

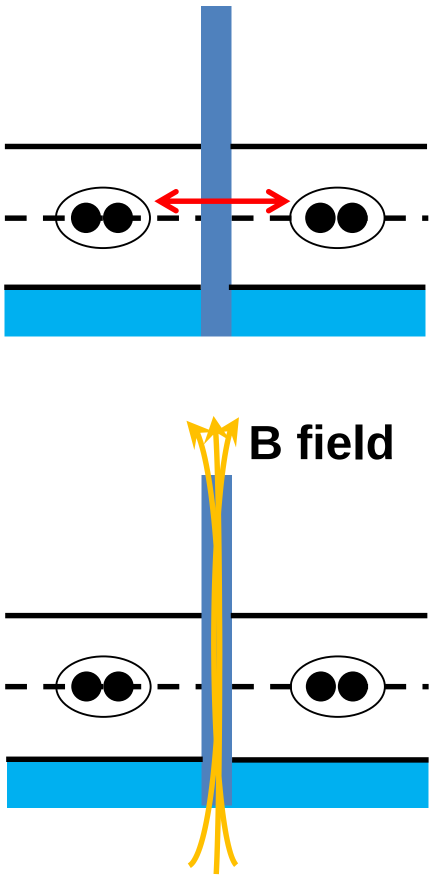
➔Smaller superconducting gap energy Δ yields better energy resolution

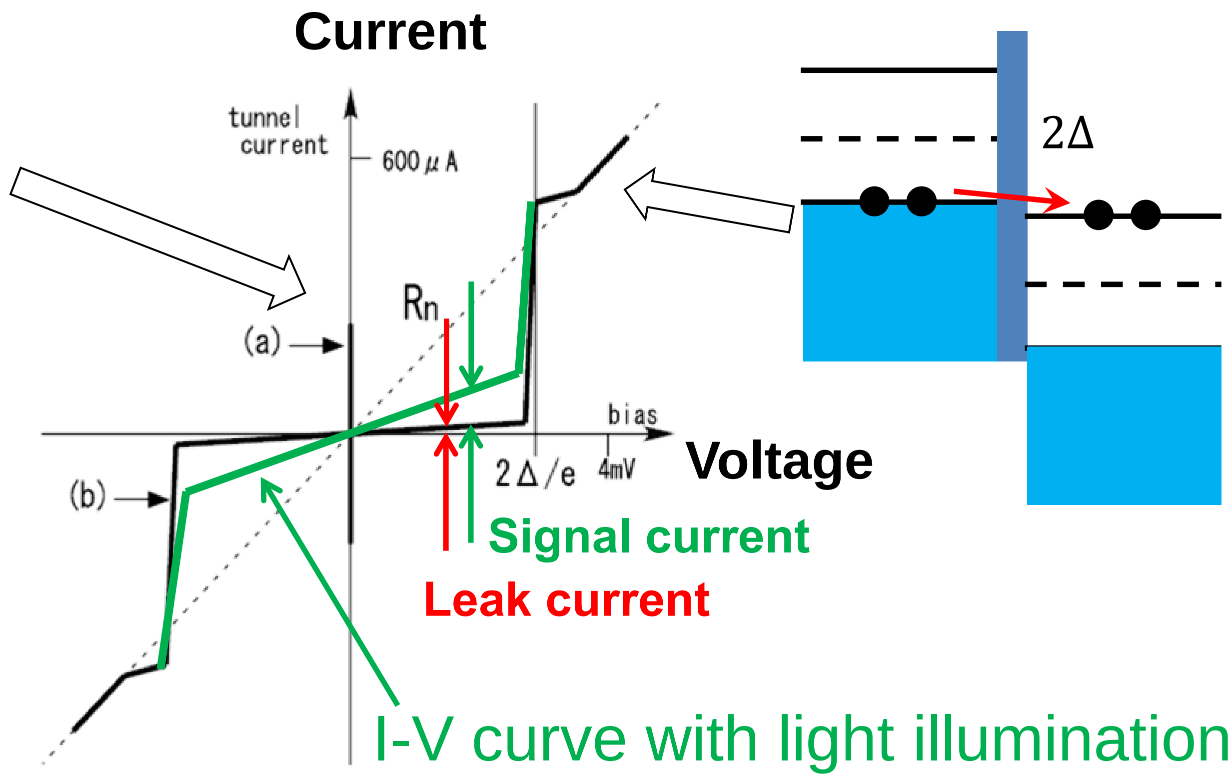
Δ: Superconducting gap energy
F: fano factor (~0.2 for Nb)
E: Photon energy
G: Back-tunneling gain

	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 current-voltage curve





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

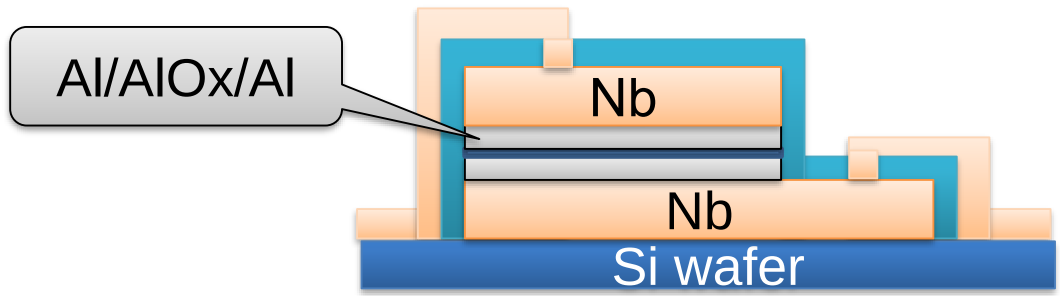
Optical signal readout

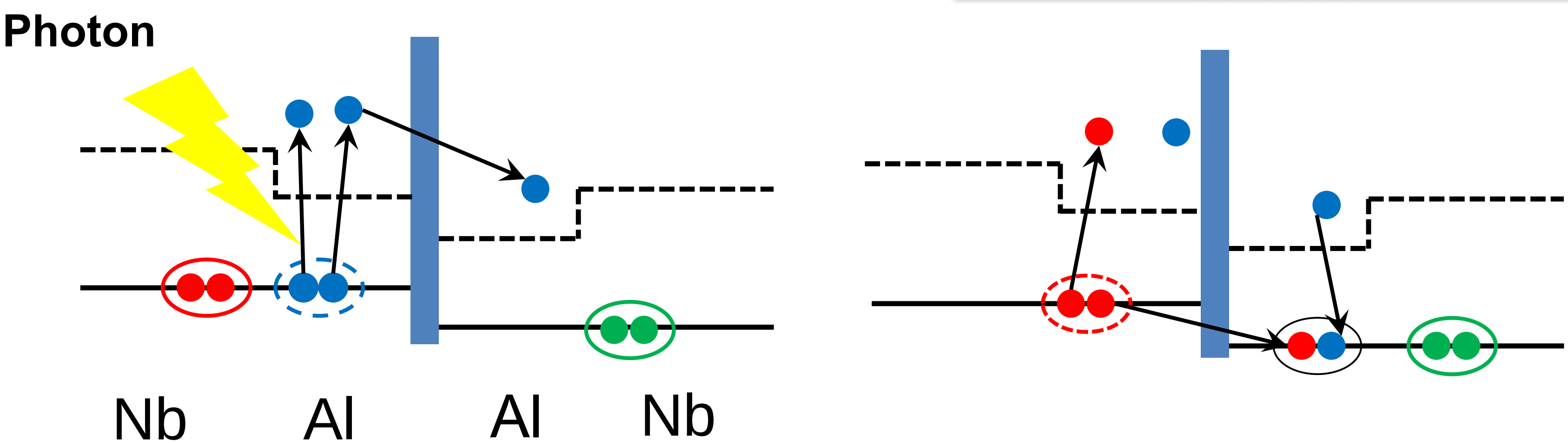
➔ Apply a constant bias voltage (|V|<2Δ) across the junction and collect tunneling current of quasi particles created by photons

✓ Leak current causes background noise

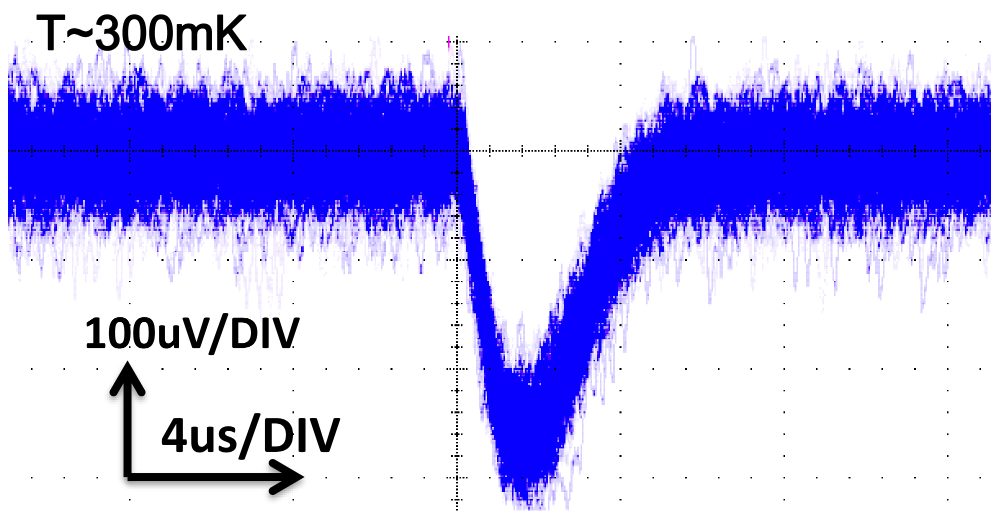
STJ back-tunneling effect

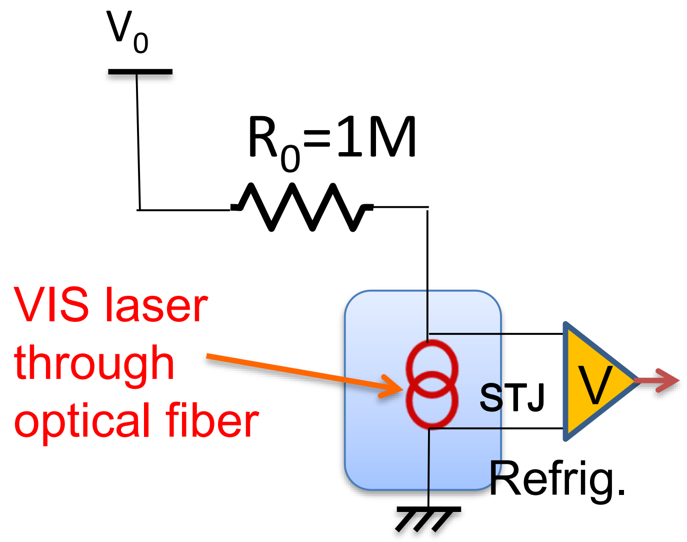
- Bi-layer fabricated with superconductors of different gaps $\Delta_{Nb} > \Delta_{Al}$ to enhance quasi-particle density near the barrier
  - Quasi-particle near the barrier can mediate multiple Cooper pairs
- Nb/Al-STJ Nb(200nm)/Al(70nm)/AlOx/Al(70nm)/Nb(200nm)
- Gain: ～10





STJ response to pulsed laser





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

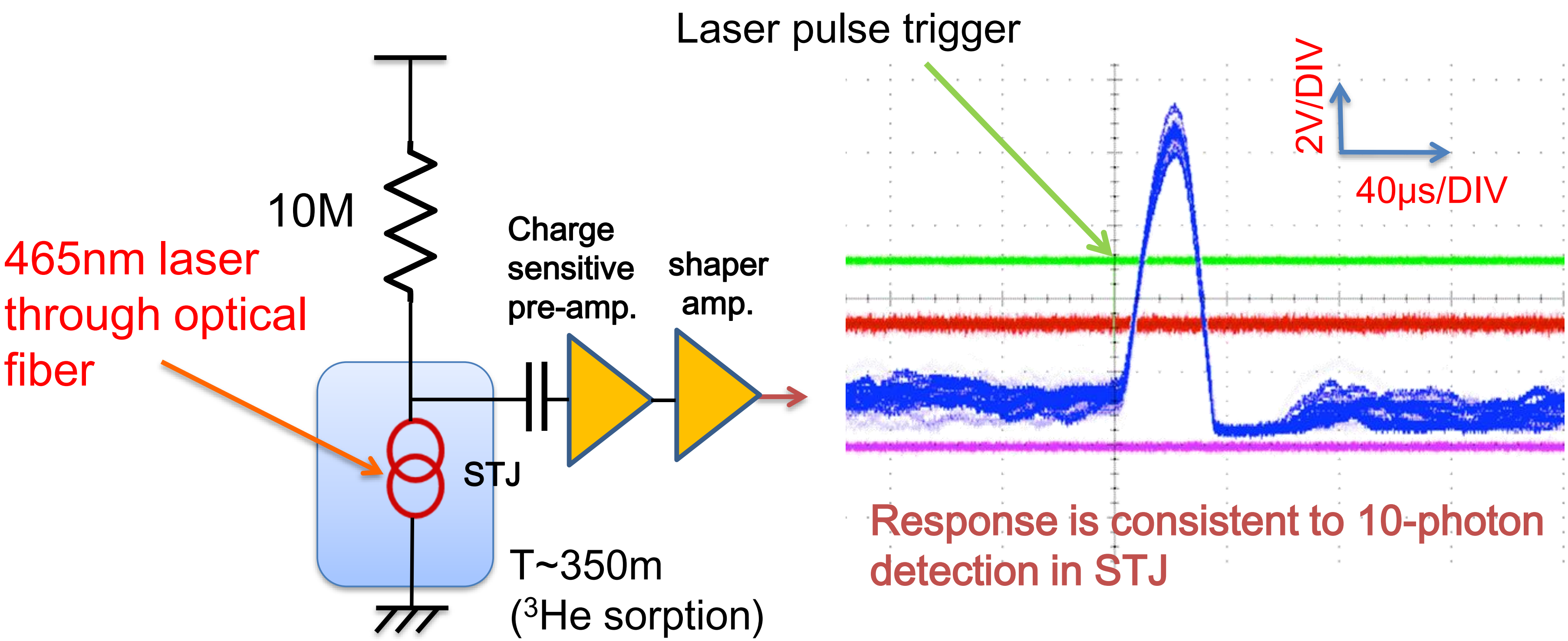
CRAVITY Nb/Al-STJ 100μm sq.

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

100x100μm² 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.

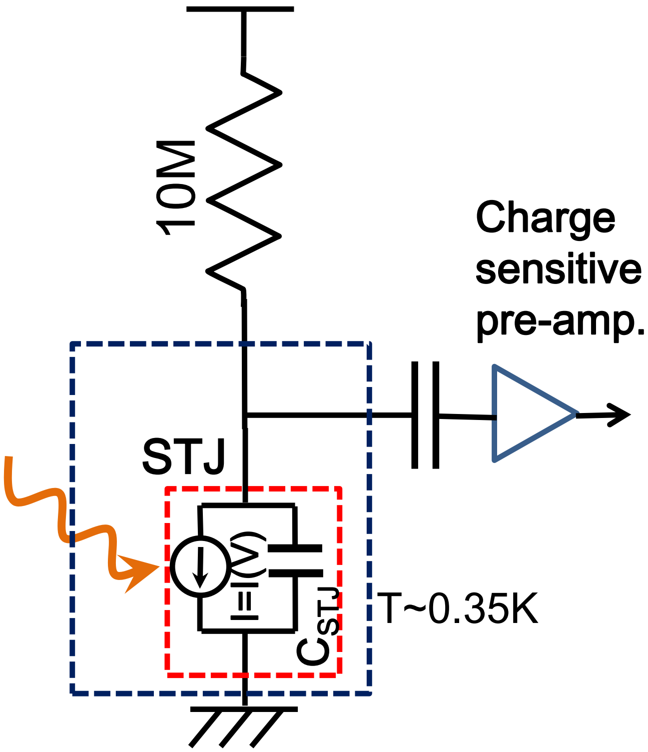
Need ultra-low noise readout system for STJ signal

➔Considering a cryogenic pre-amplifier placed close to STJ

SOI 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.

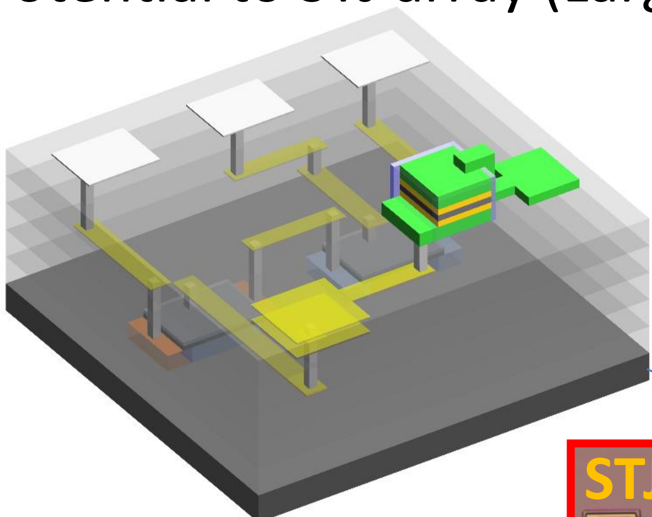
➔ We designed SOI op-amp which has >1MHz freq. response, and submitted to the next SOI MPW run. We'll test the amplifier in this winter.

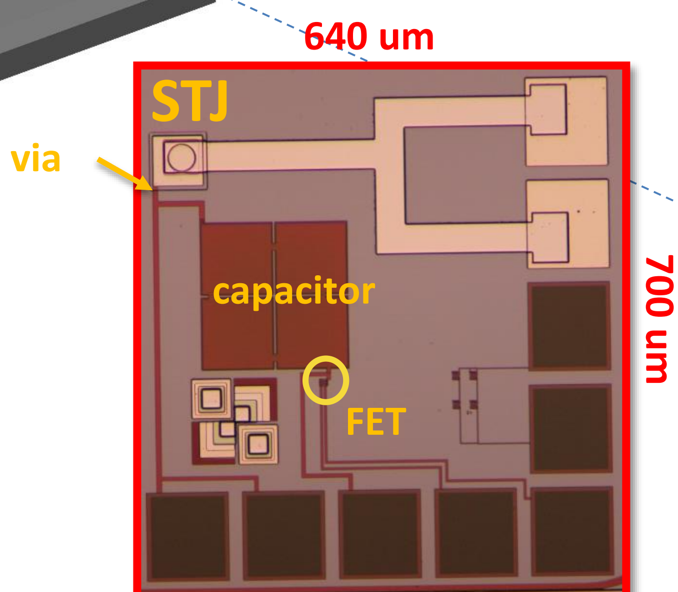


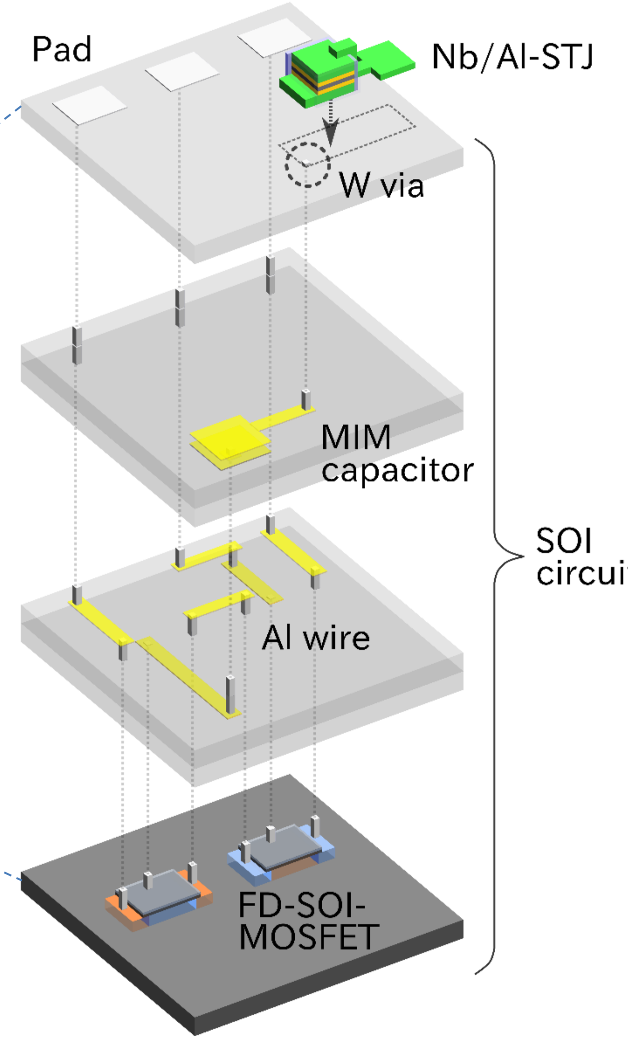
SOI-STJ (STJ directly on SOI) development

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

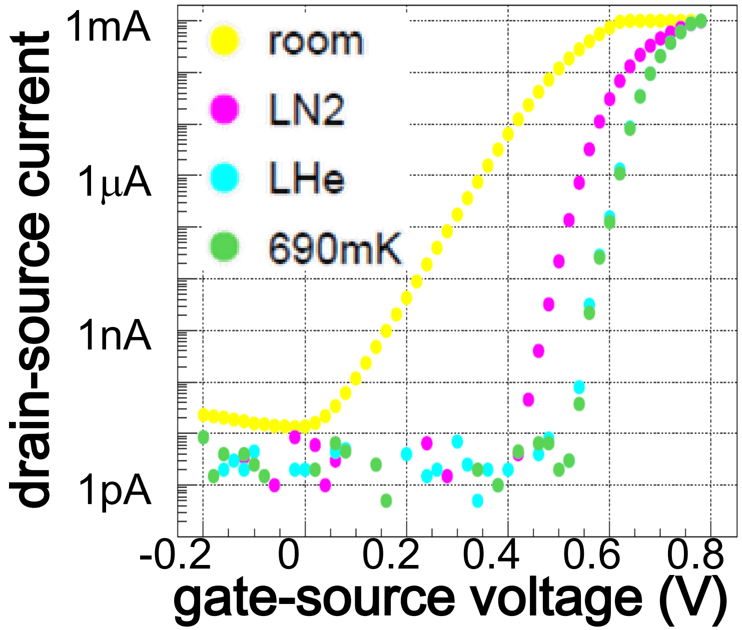
☐ Potential to STJ array (Large area STJ)



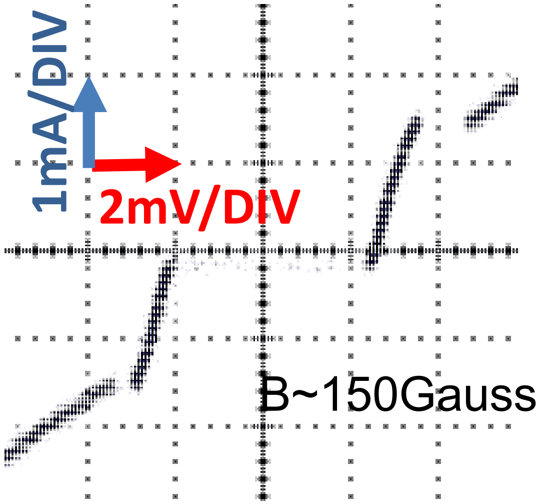




FD-SOI on which STJ is fabricated



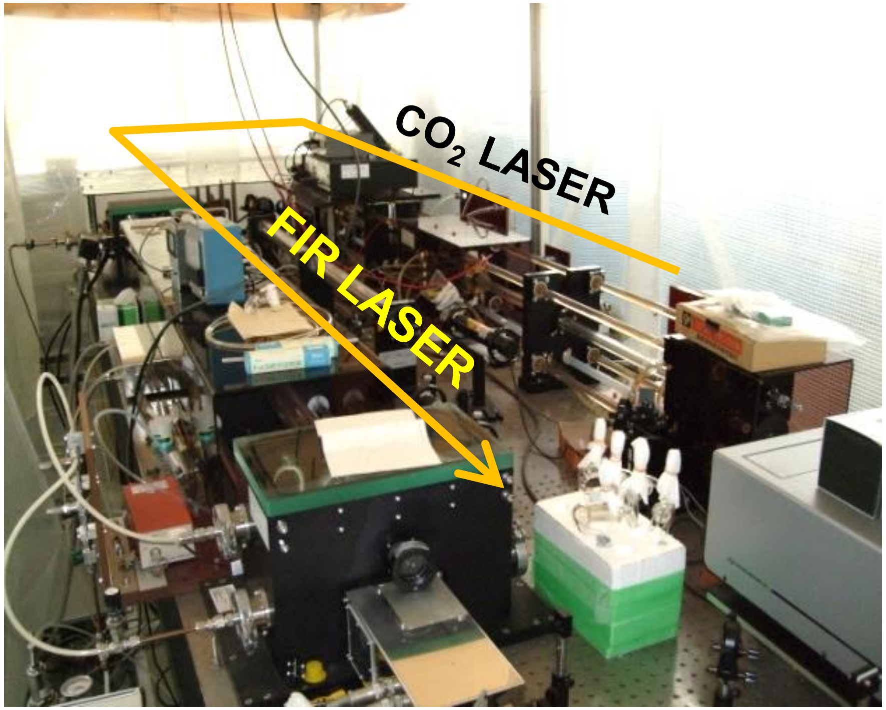
nMOS-FET in FD-SOI wafer on which a STJ is fabricated at KEK

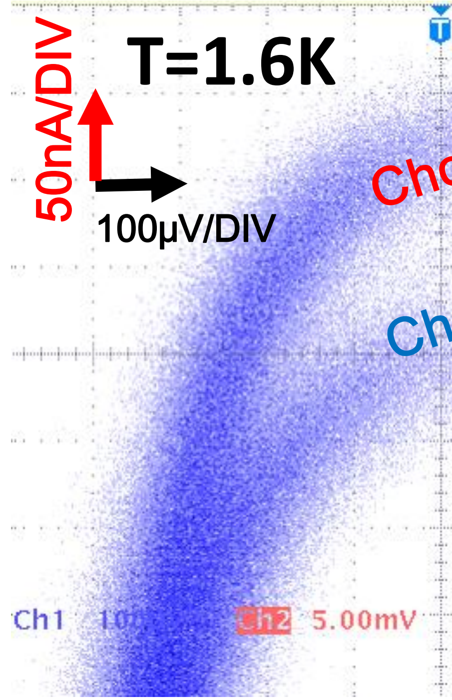


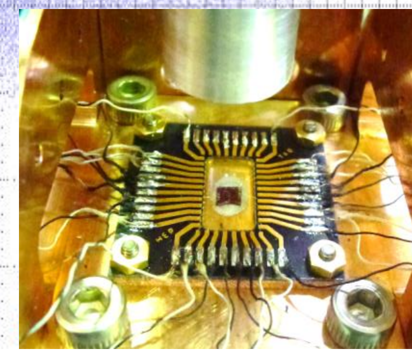
I-V curve of a STJ fabricated at KEK on a FD-SOI wafer

- 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

Calibration of STJ by Far-infrared Laser







200μm sq. Nb/Al-STJ by CRAVITY

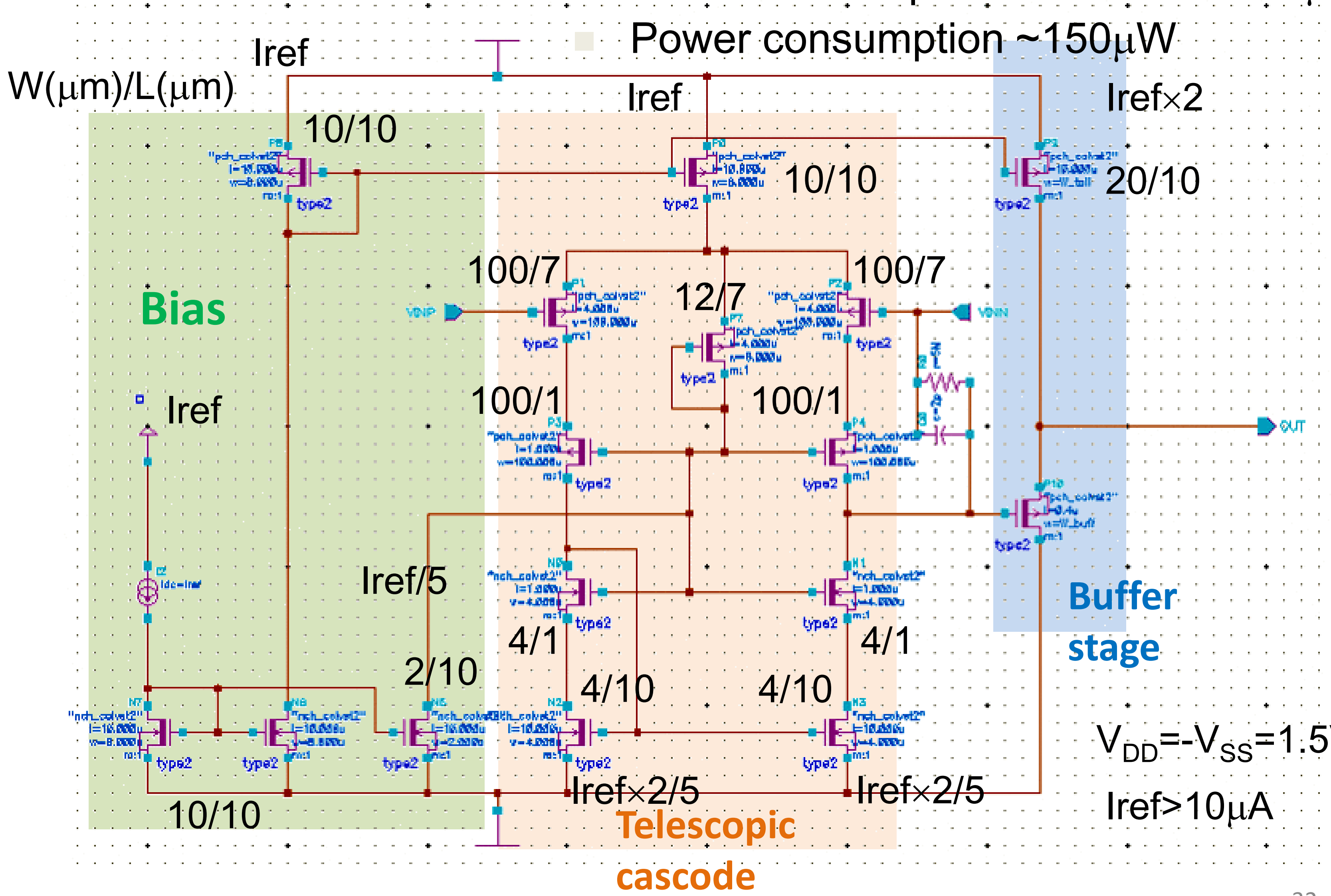
A Nb/Al-STJ is illuminated by FIR laser through a chopper (f=40~200Hz) using a far-infrared molecular laser apparatus at FIR-UF (U. of Fukui)

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

Op-amp Circuit for STJ design

Evaluating now!

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



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

Iref>10μA

COBAND project