筑波大学
宇宙史研究センター
Tomonaga Center for the History of the Universe

筑波大学
University of Tsukuba

Superconducting Tunnel Junction Detectors

International Workshop on Next Generation Nucleon Decay and Neutrino Detectors (NNN17)

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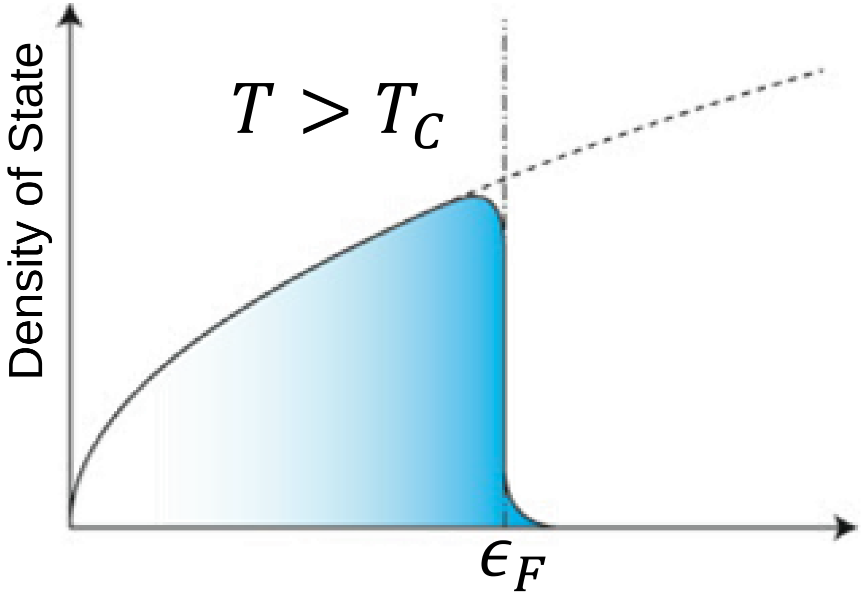
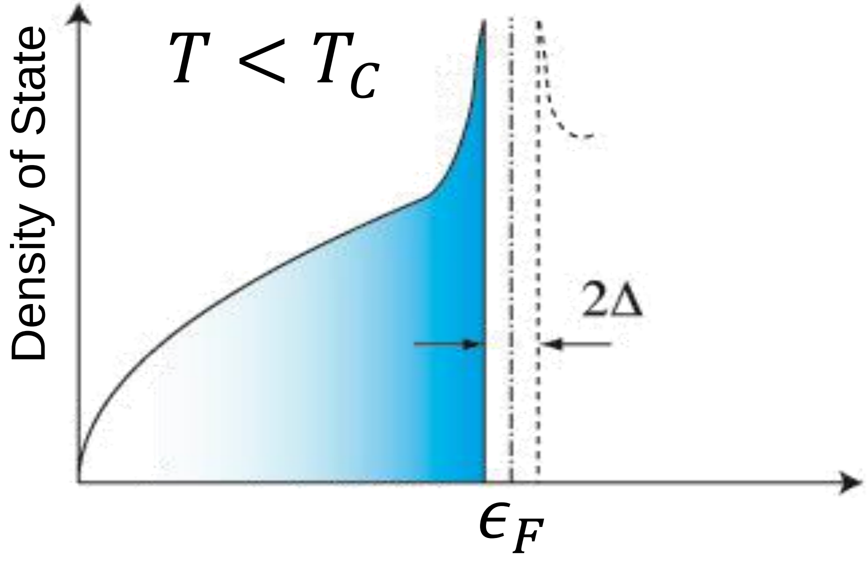
Contents

- Introduction to Superconducting tunnel Junction (STJ)
- Cryogenic amplifier development using silicon-on-insulator for STJ signal amplification.
- Application of low energy threshold STJ
  - COBAND (cosmic background neutrino decay search)

Superconducting energy gap





In superconducting state, a pair of electrons around ϵ_F forms Cooper pair with binding energy of 2Δ. ➔ DOS has a gap energy.

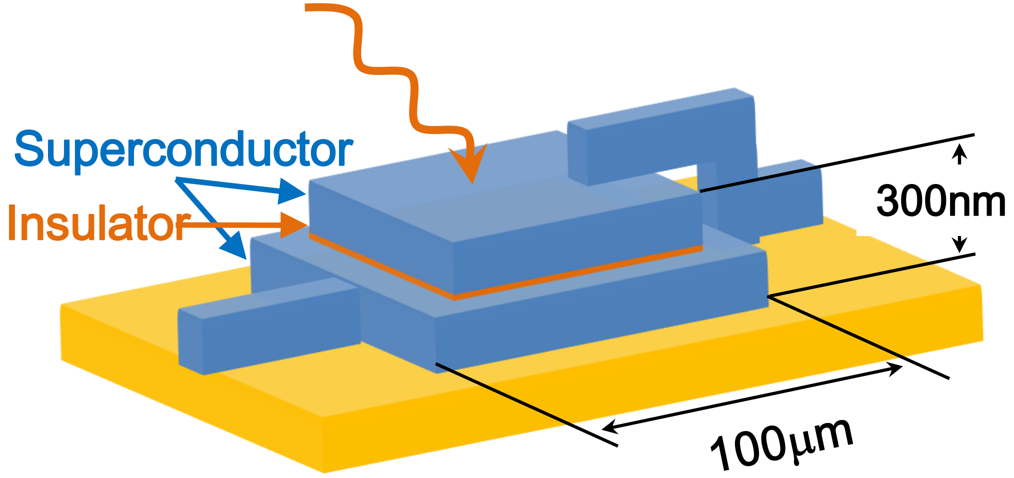
	Si	Nb	Ta	Al	Hf
Tc[K]		9.23	4.48	1.20	0.165
Δ[meV]	1100	1.550	0.7	0.172	0.020

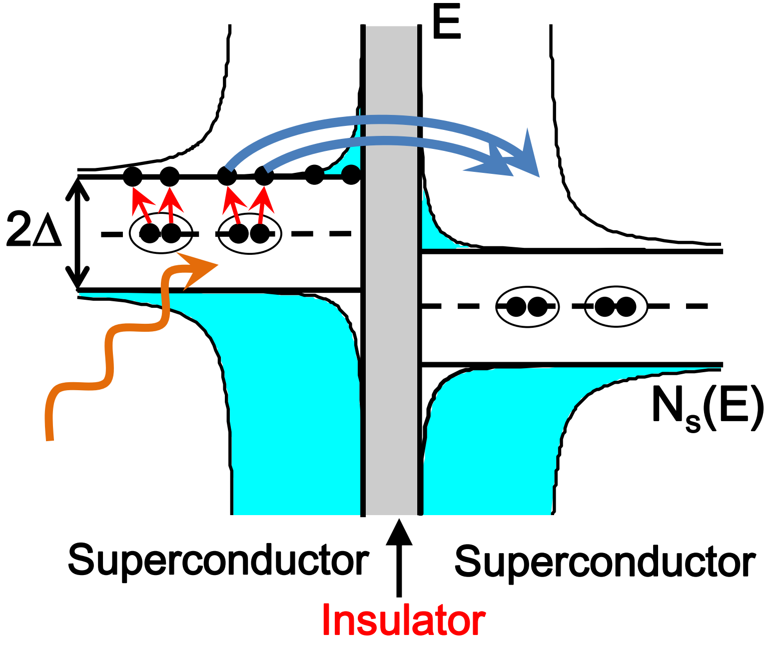
$\Delta \sim 1.8 k_B T_C$ (BCS theory)

Superconducting Tunnel Junction (STJ) Detector

Superconductor / Insulator /Superconductor

Josephson junction device

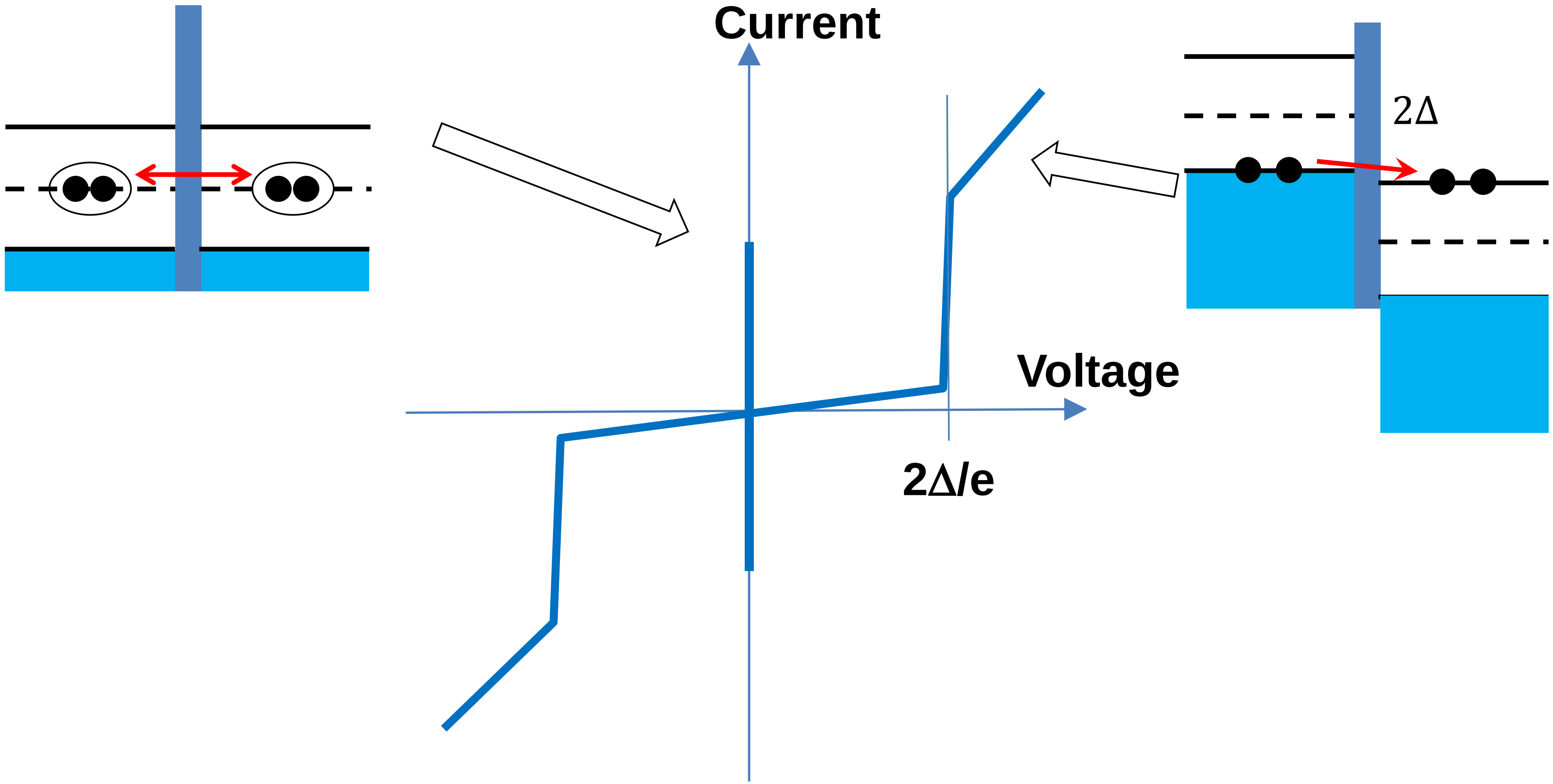




Δ: Superconducting gap energy

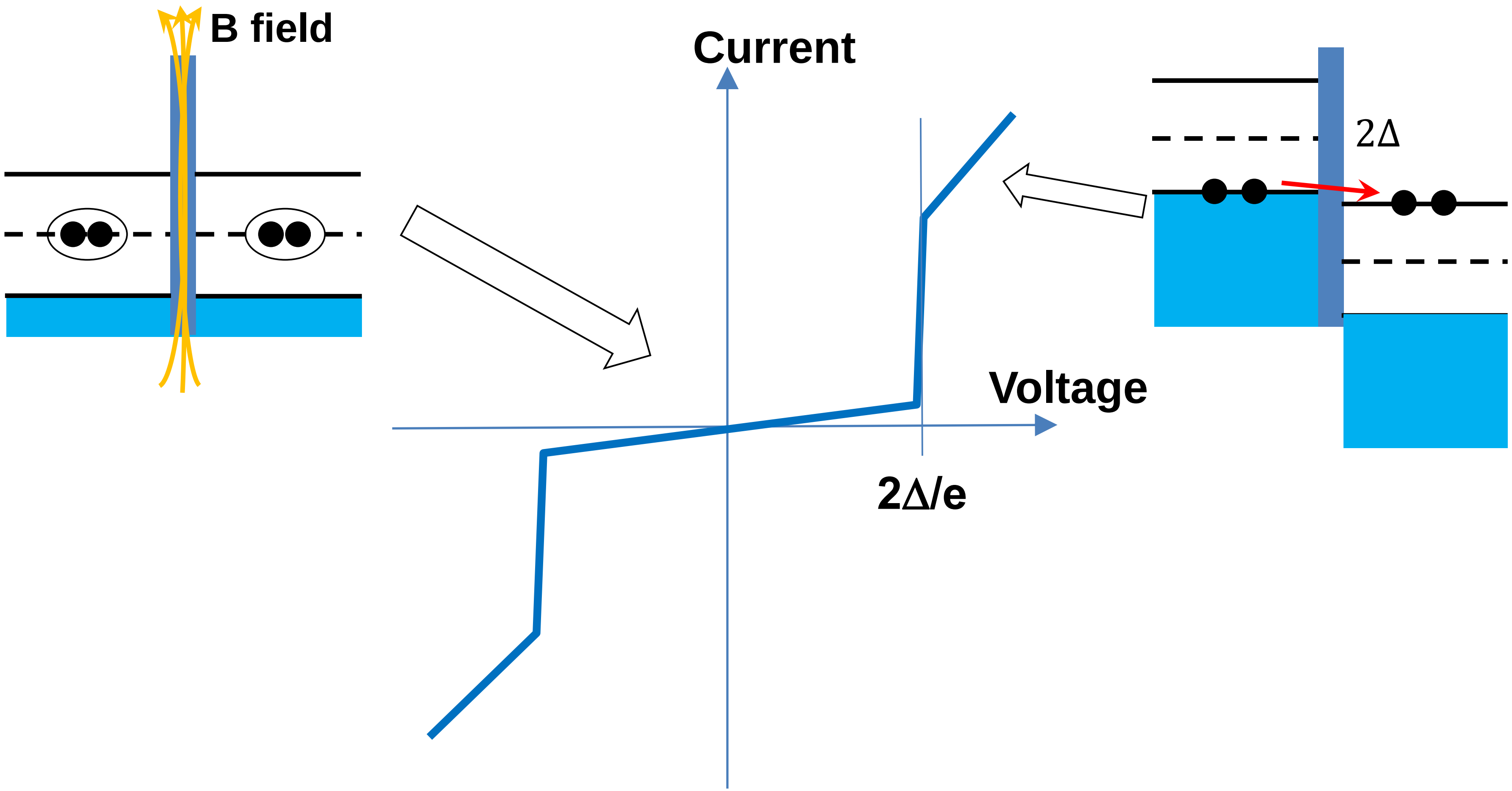
- A constant bias voltage (|V|<2Δ/e) is applied across the junction.
- An energy absorbed in the superconductor breaks Cooper pairs and creates tunneling current of quasi-particles proportional to the deposited energy.

STJ current-voltage curve



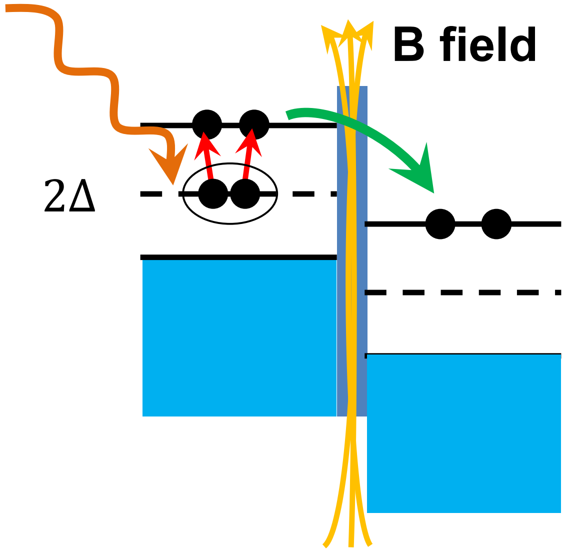
Tunnel current of Cooper pairs (Josephson current) is seen at V=0

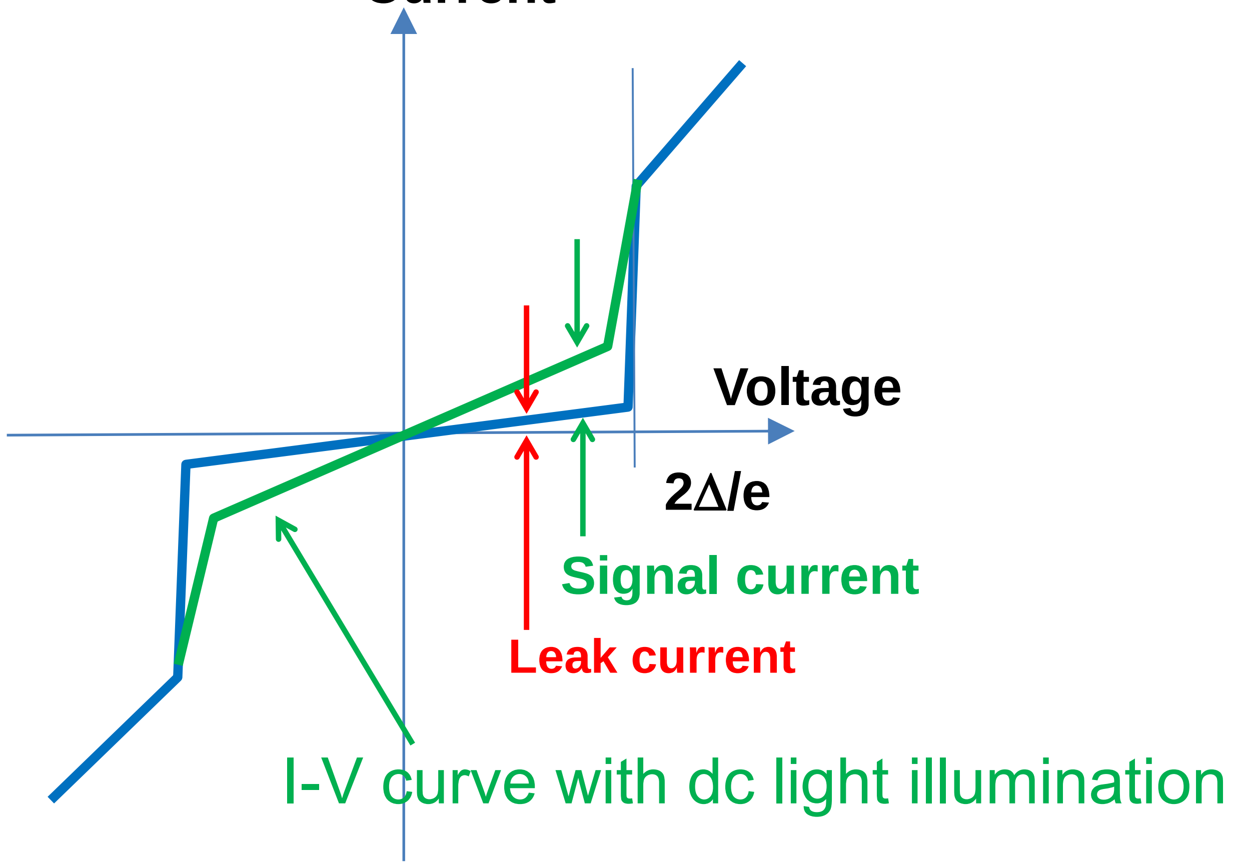
STJ current-voltage curve



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

STJ current-voltage curve





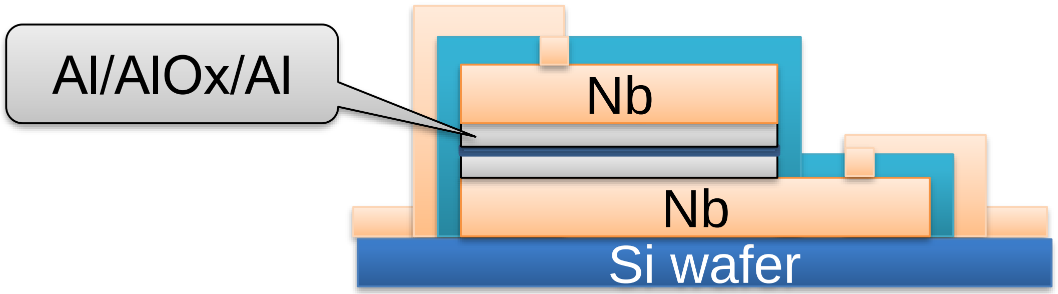
Signal readout

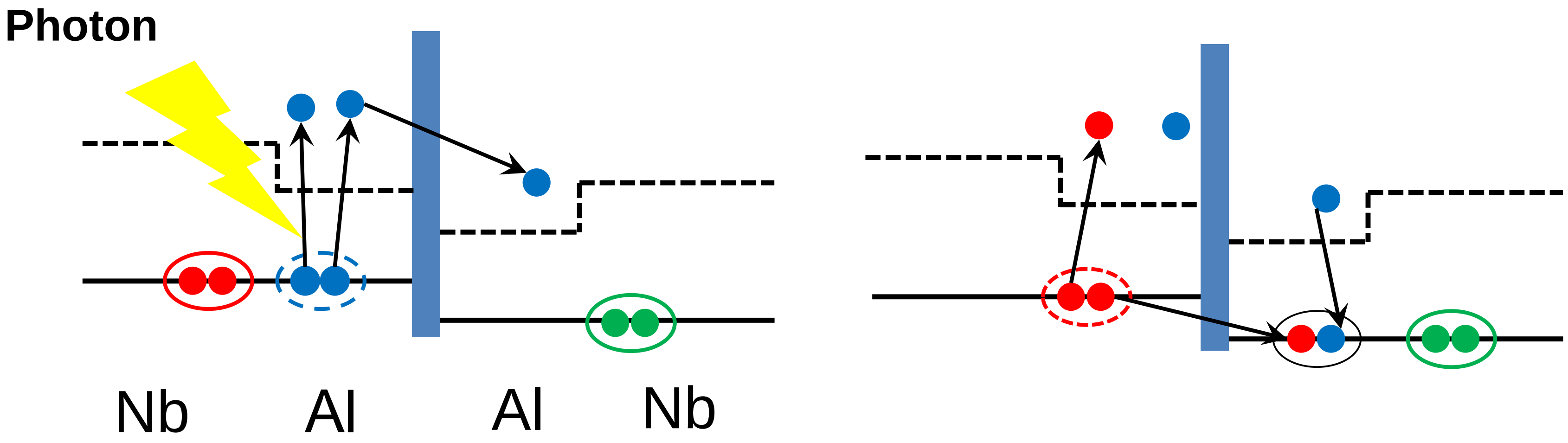
➔ Apply a constant bias voltage (|V|<2Δ/e) across the junction and collect tunnel current of quasi particles created by energy deposition

✓ Leak current causes background noise

STJ back-tunneling effect

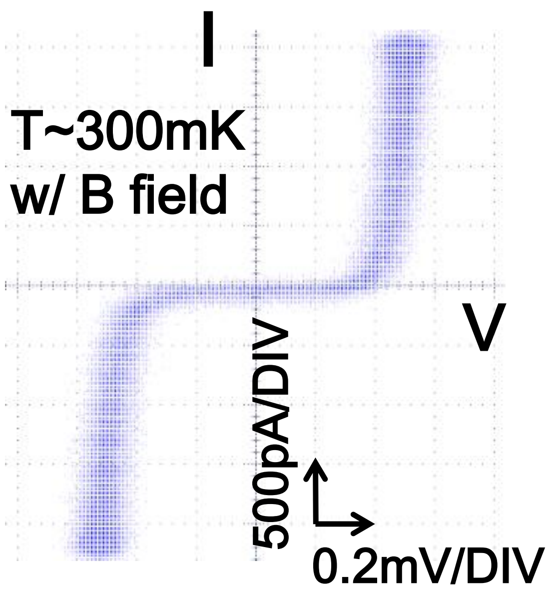
- Bi-layer fabricated with superconductors of different gaps $\Delta_{Nb} > \Delta_{Al}$ to enhance quasi-particle density near the barrier
  - Quasi-particle near the barrier can mediate multiple Cooper pairs
- Nb/Al-STJ Nb(200nm)/Al(70nm)/AlOx/Al(70nm)/Nb(200nm)
- Gain: >10

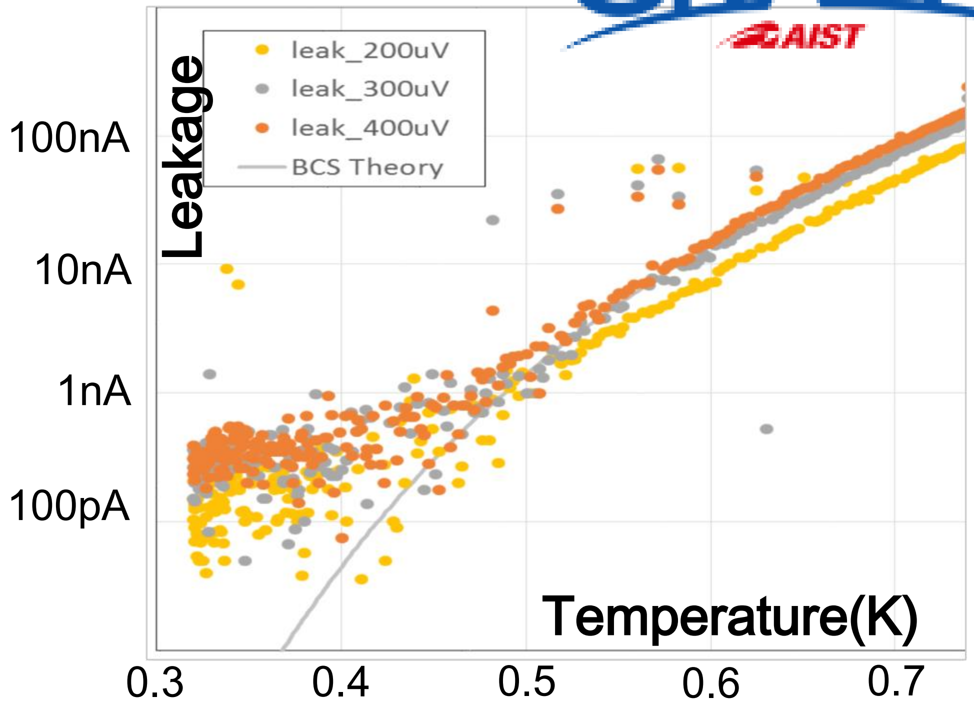




Nb/Al-STJ development at AIST/CRAVITY

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

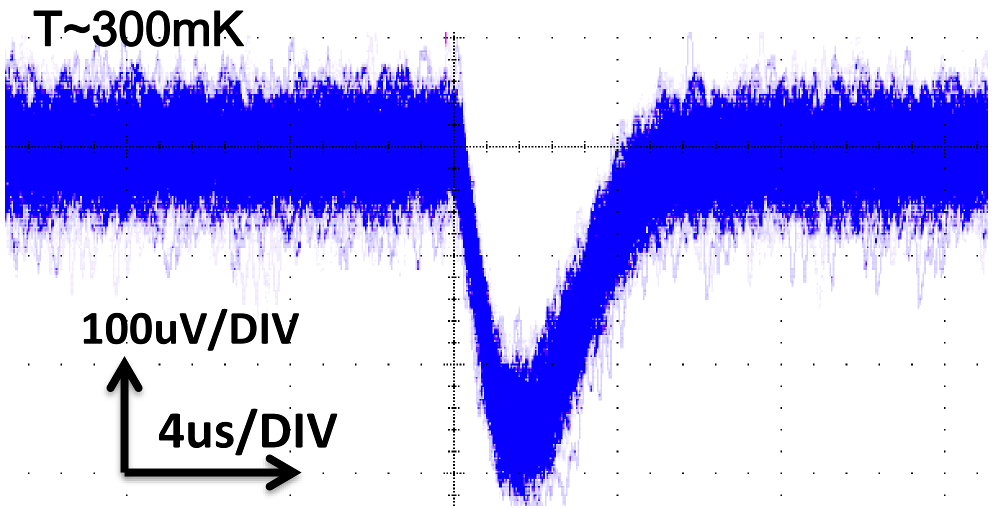


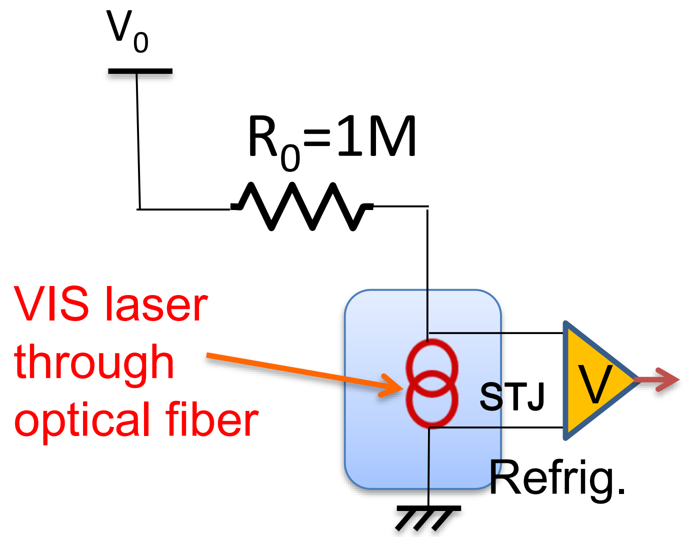


- I_{leak}~200pA for 50μm sq. STJ, and achieved 50pA for 20μm sq.

Need ~1/10Tc for practical operation

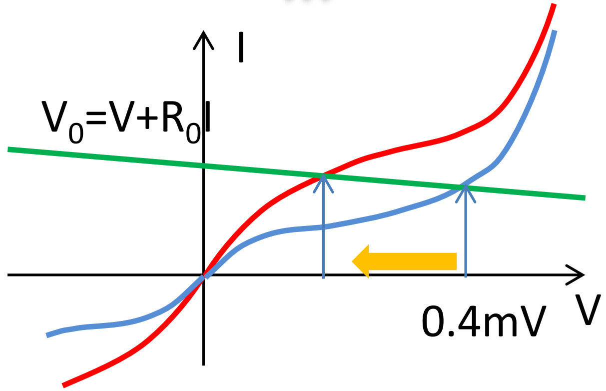
Nb/Al-STJ response to pulsed laser





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

CRAVITY Nb/Al-STJ 100um sq.



STJ I-V curve w/light w/o light

- Nb/Al-STJ has ~1μs response time.

Nb/Al-STJ has faster response than other superconductor based detectors

➔ suitable for single photon (single particle) detection

STJ energy resolution

Signal = Number of quasi-particles created by cooper pair breakings

$$\frac{E_\gamma}{1.7\Delta}$$

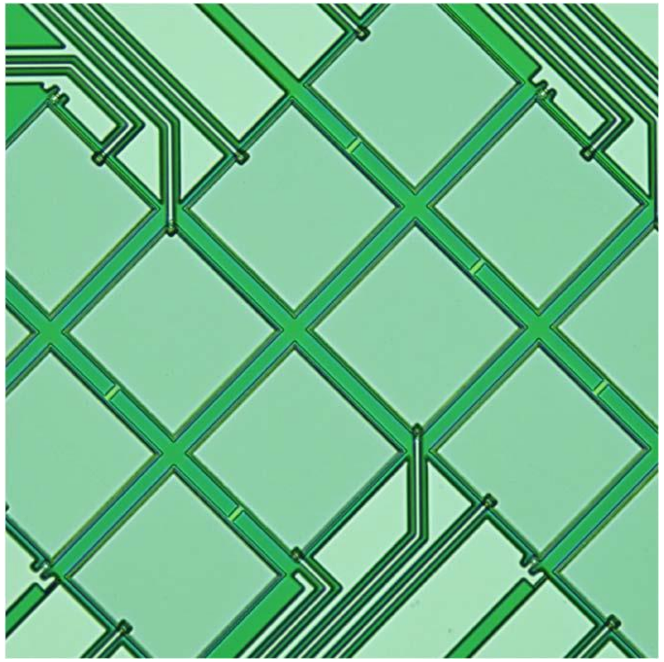
Resolution = Statistical fluctuation in number of quasi-particles

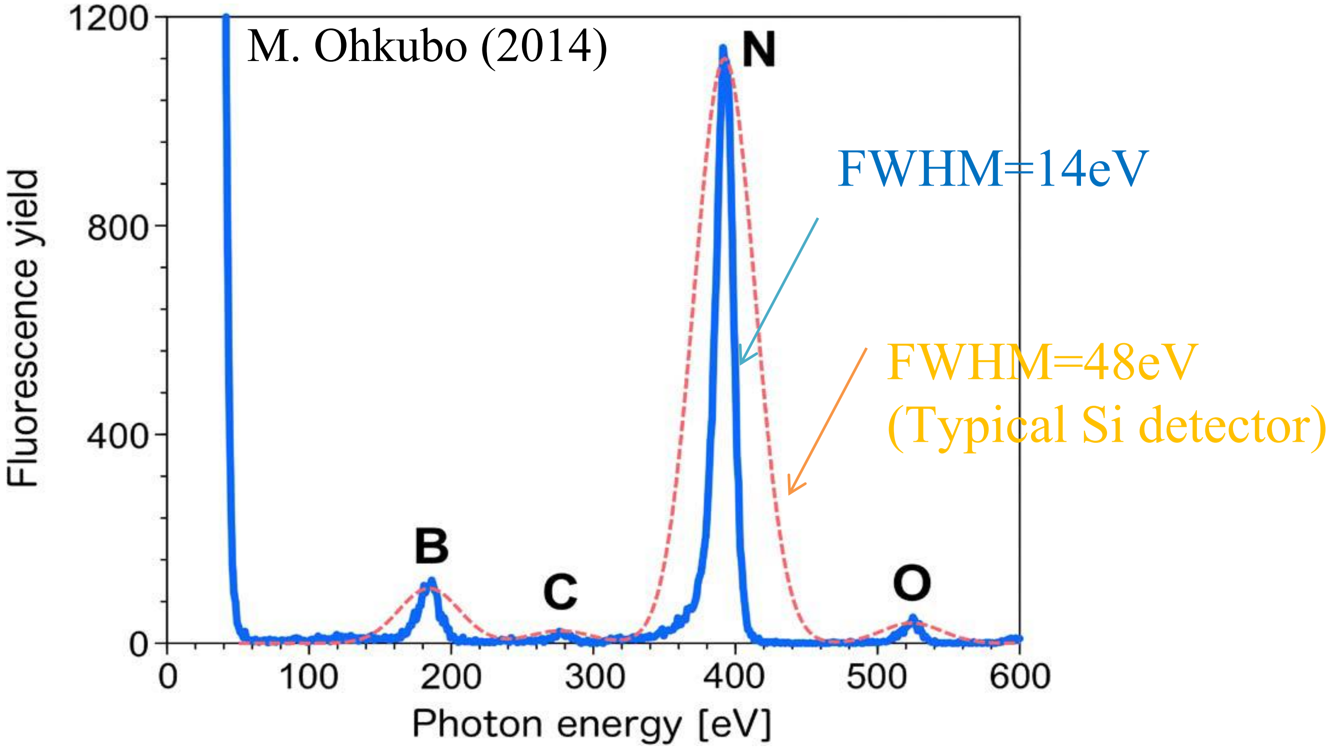
$$\sigma_E \sim \sqrt{(1.7\Delta)FE}$$

➔Smaller superconducting gap energy Δ yields better energy resolution, but need smaller Tc

Δ: Superconducting gap energy
F: fano factor
E: Deposited energy

STJ energy resolution for X-ray

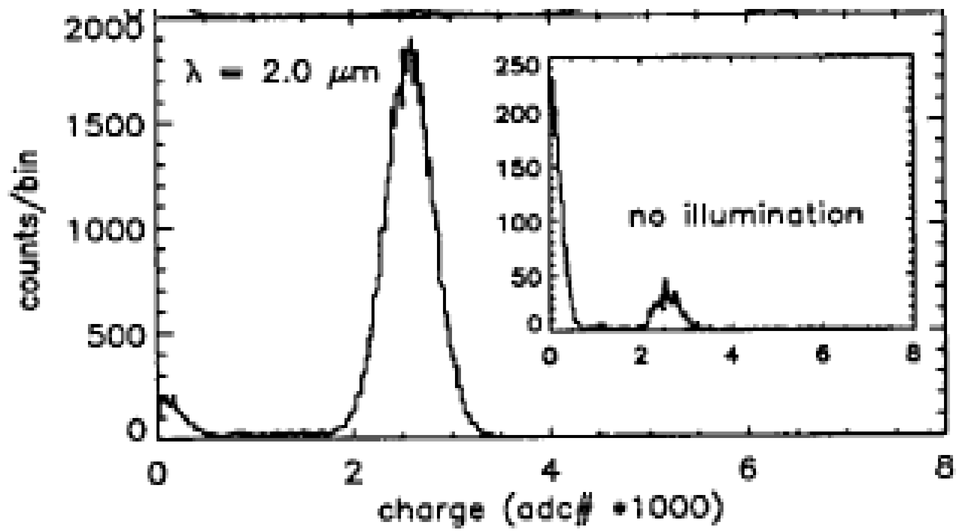


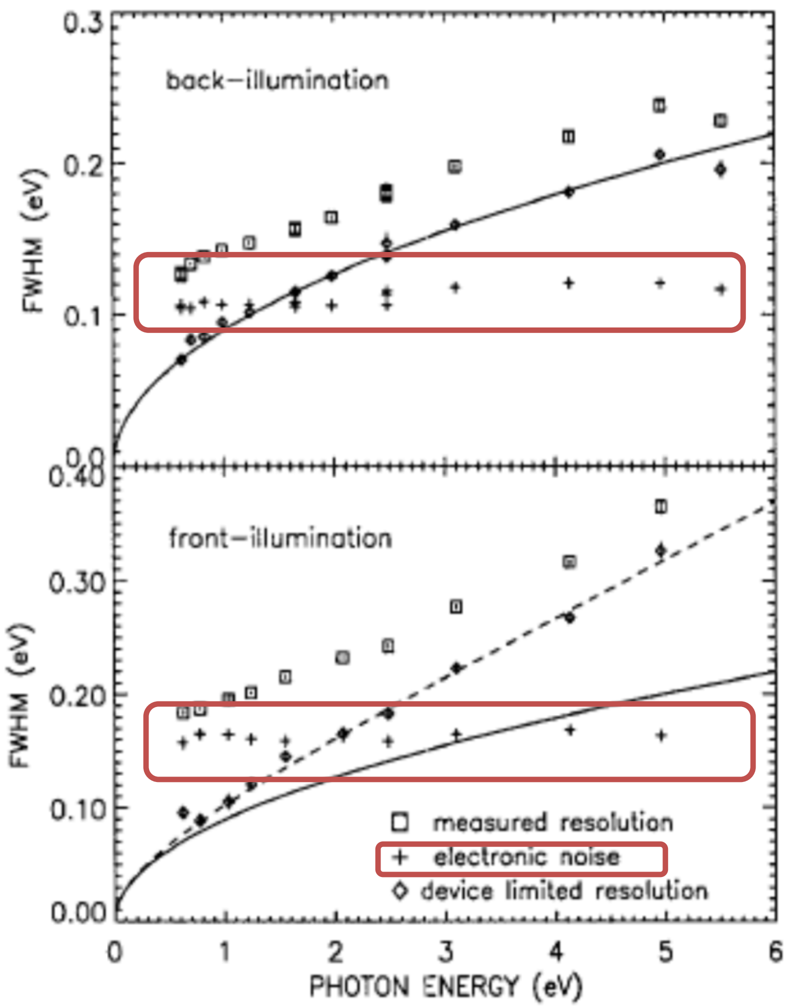


- 100-pixel Nb/Al-STJ of 200μm sq. size (4mm^2 in total) fabricated at CRAVITY
- X-ray Absorption Fine Structure (XAFS) Spectrometry in Synchrotron Radiation Facilities
- X-ray fluorescence spectra for BN sample with C and O contamination by the STJ

In this energy region, however, transition edge sensor (TES) gives best energy resolution: ΔE =1.6eV @E=6keV

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.

STJ summary

- Typical size: 10μm~200μm square size × 100nm~1μm thickness per pixel
  - AIST group achieved 100-pixel STJ sensor
- Need magnetic field ~100gauss
- Operate typically at 1/10×Tc
- Superconductor with smaller Δ is better, but it has smaller Tc
- Wide energy range: meV ~ keV
  - Suitable usage of the STJ is single photon/particle detection in sub-eV ~ several-eV
- In sub-eV range, the energy resolution is limited by readout electronic noise

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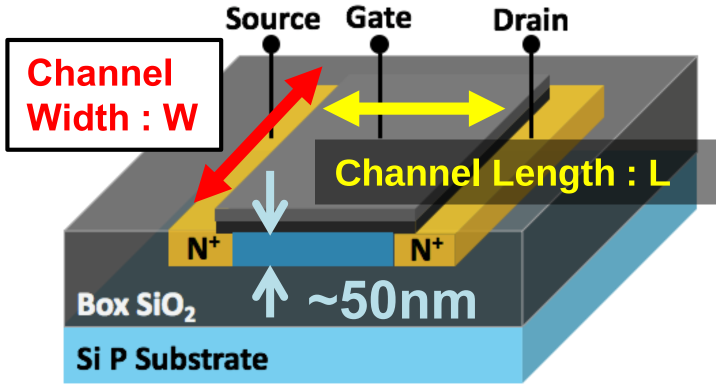
COBAND collaboration is developing cryogenic amplifier to amplify STJ signal at cold stage

FD-SOI-MOSFET at cryogenic temperature

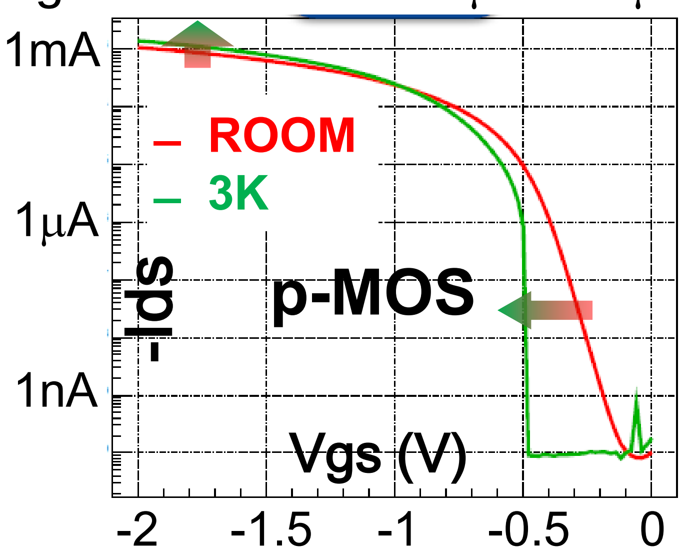
FD-SOI : Fully Depleted – Silicon On Insulator

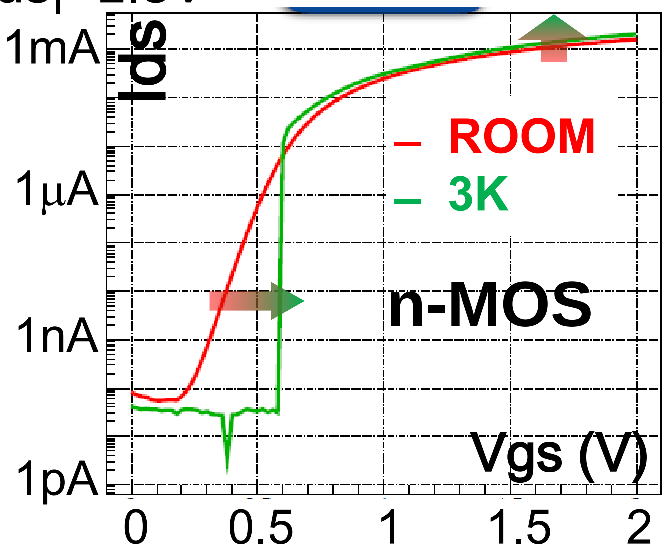


- Very thin channel layer in MOSFET on SiO_2
- No floating body effect caused by charge accumulation in the body
- FD-SOI-MOSFET is reported to work at 4K

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

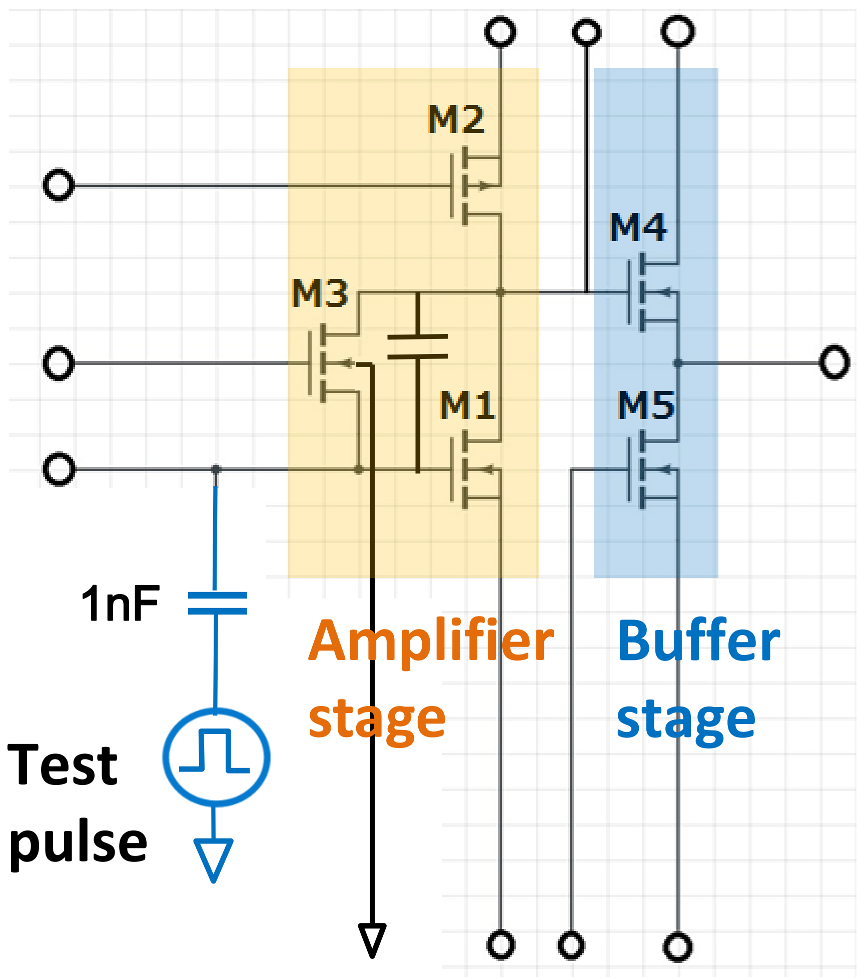
Id-Vg curve of W/L=10μm/0.4μm at |Vds|=1.8V

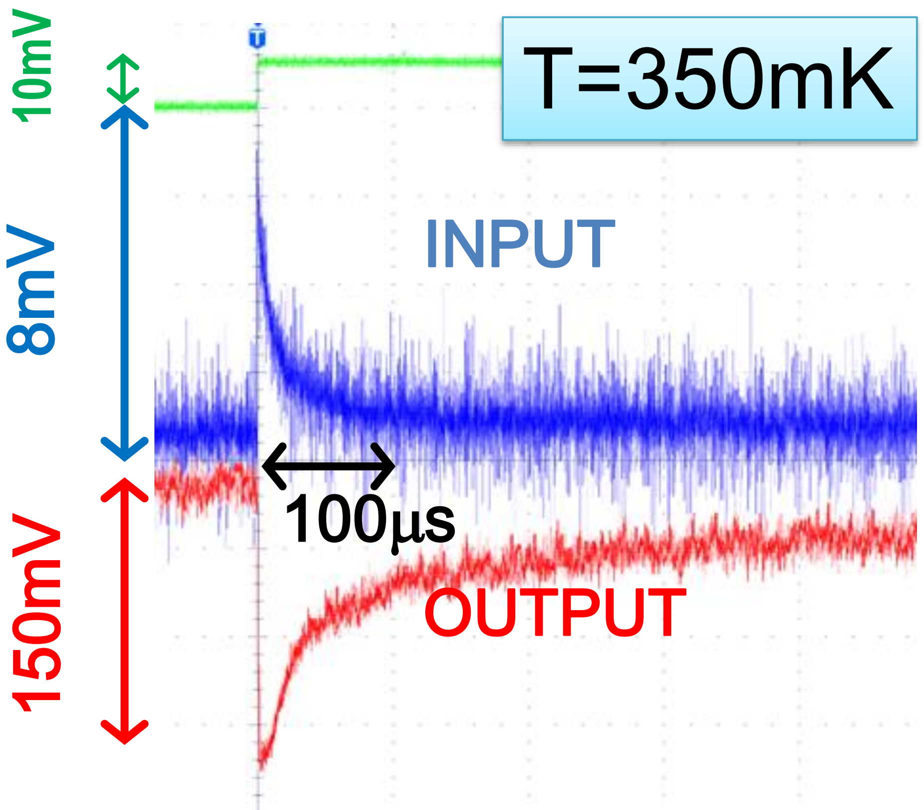




Both p-MOS and n-MOS show excellent performance at 3K and below.

SOI prototype amplifier for demonstration test

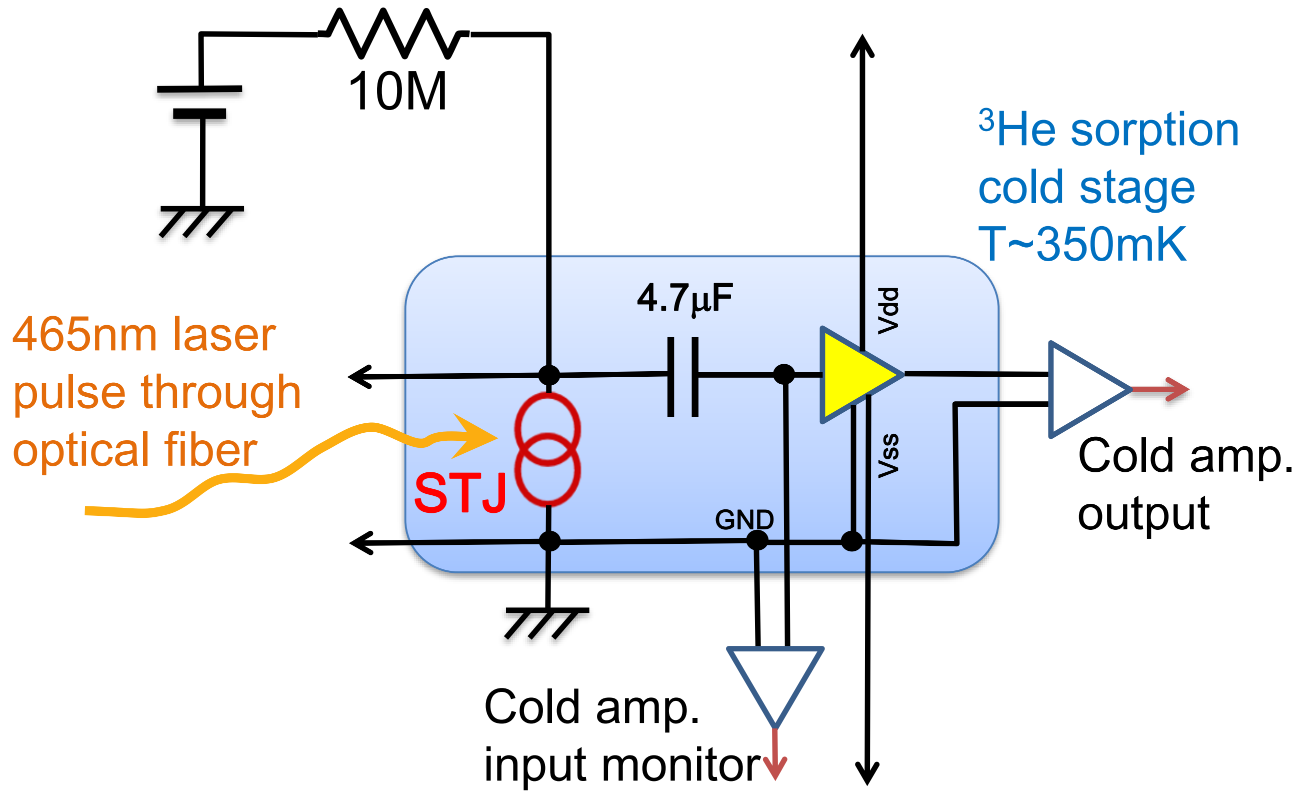




Test pulse input through C=1nF at T=350mK

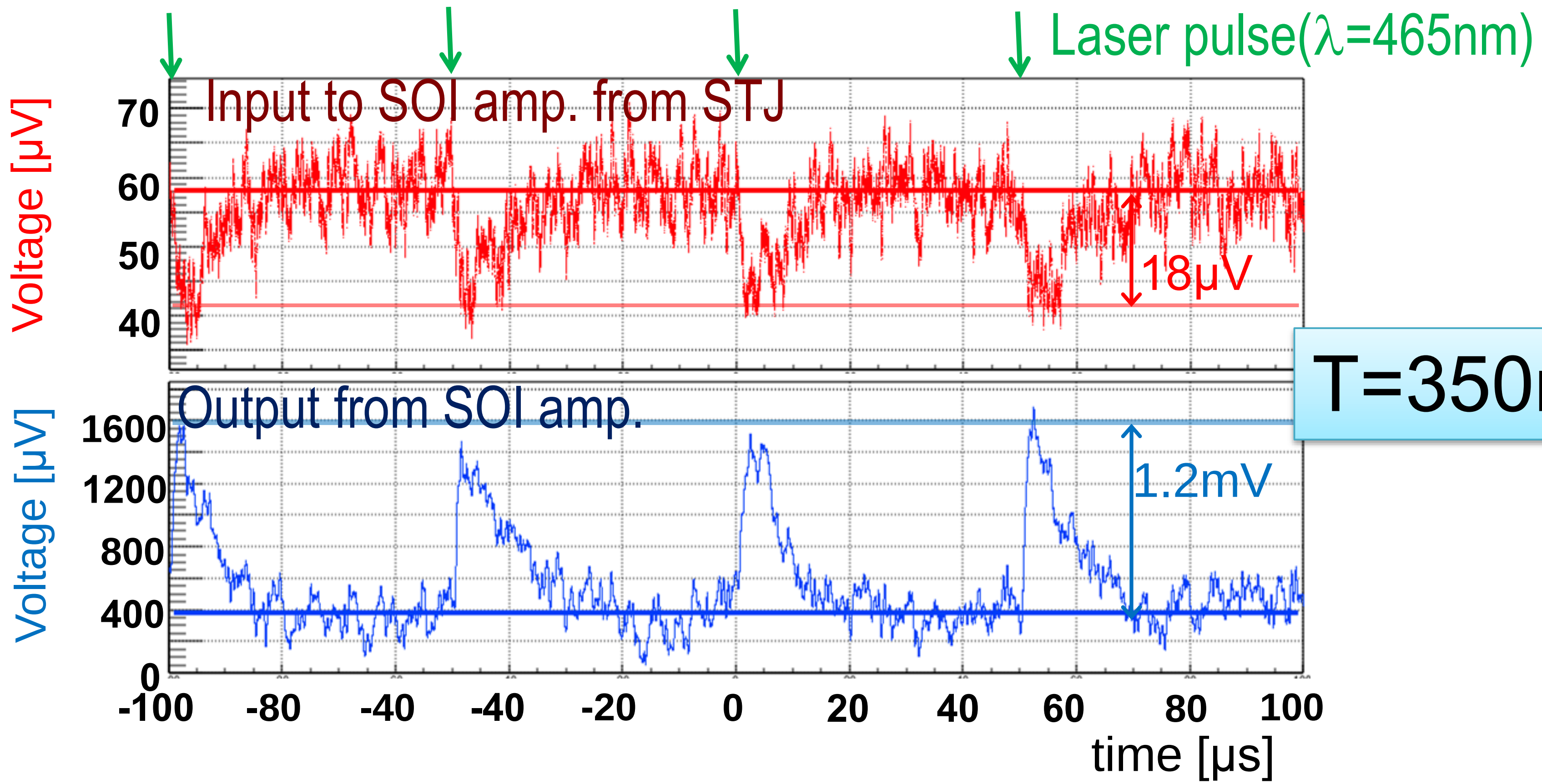
- Power consumption: ~100μW
- Output load: 1MΩ and ~0.5nF

STJ response to laser pulse amplified by Cold amplifier



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



T=350mK

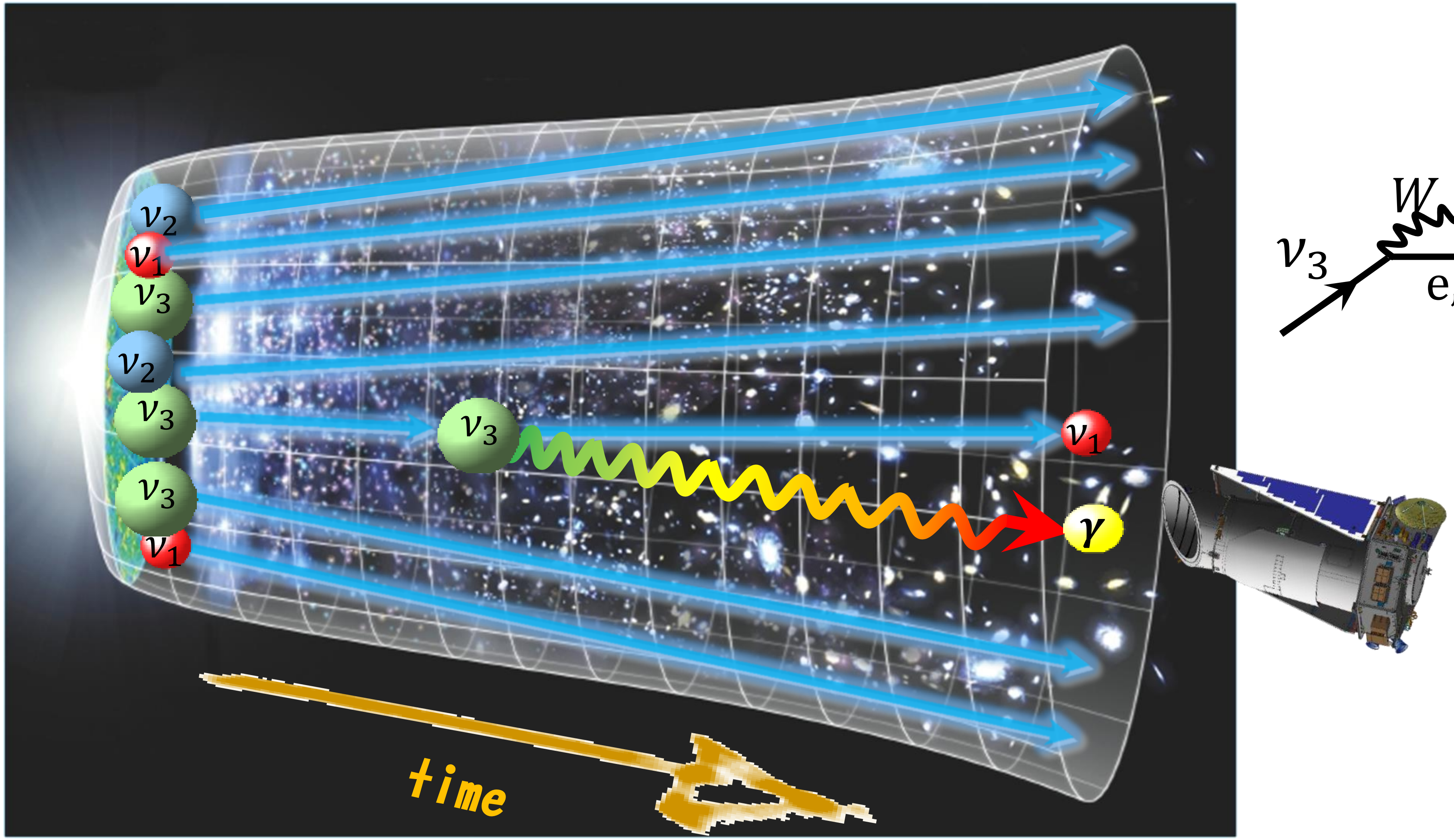
Demonstrated to show amplification of Nb/Al-STJ response to laser pulse by SOI amplifier situated close to STJ at T=350mK

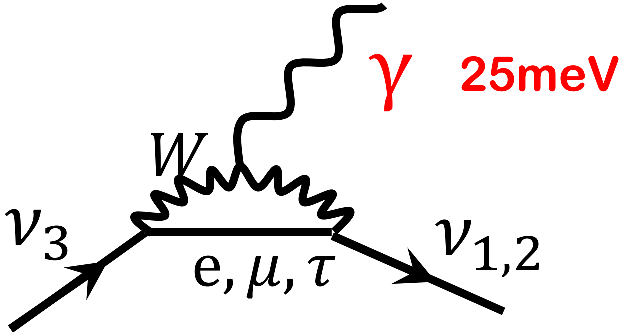
Development of SOI cryogenic amplifier for STJ signal readout is now moving to the stage of design for practical usage!

COBAND (COsmic BAckground Neutrino Decay)

Search for Neutrino decay in Cosmic background neutrino

➔To be observed as far infrared photons of λ~50μm (E~ 25meV)





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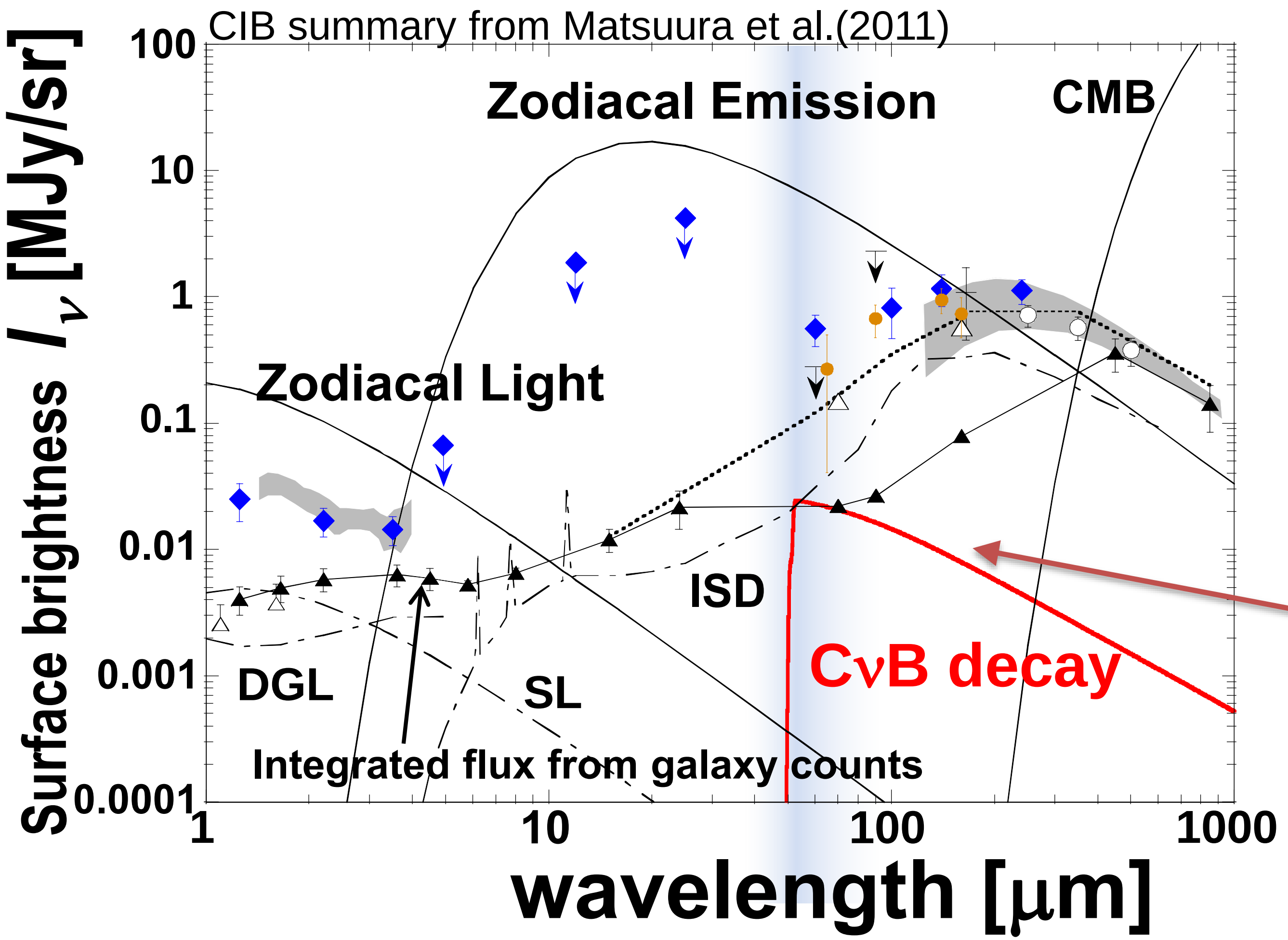

$\tau = 1 \times 10^{14}$yrs

$m_3 = 50$ meV

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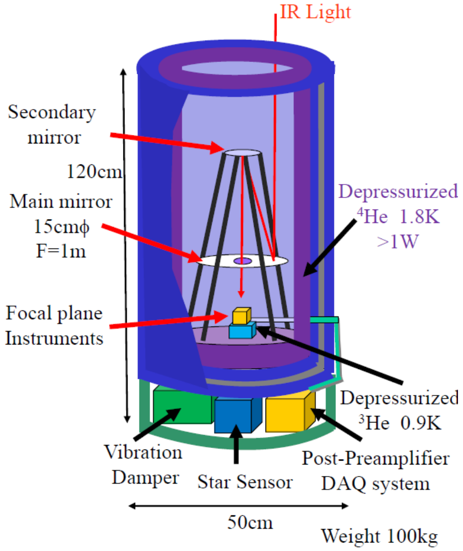
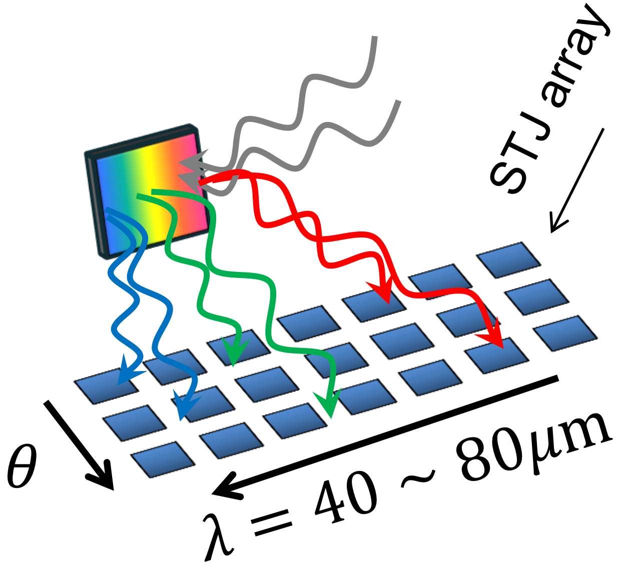
COBAND Rocket Experiment

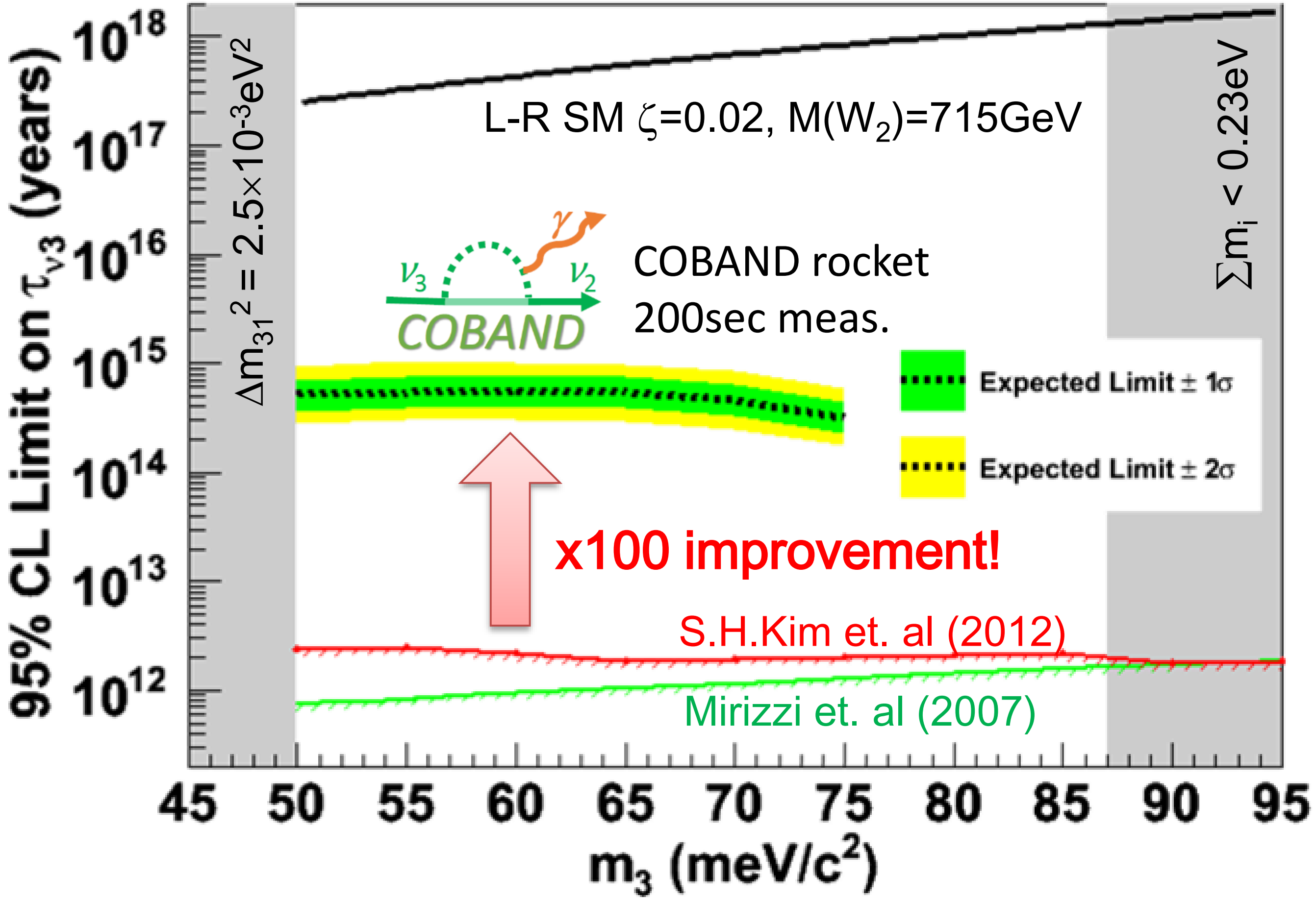
- 200-sec measurement at an altitude of 200~300km
- Aiming at a sensitivity to 10^{14} years for the neutrino lifetime





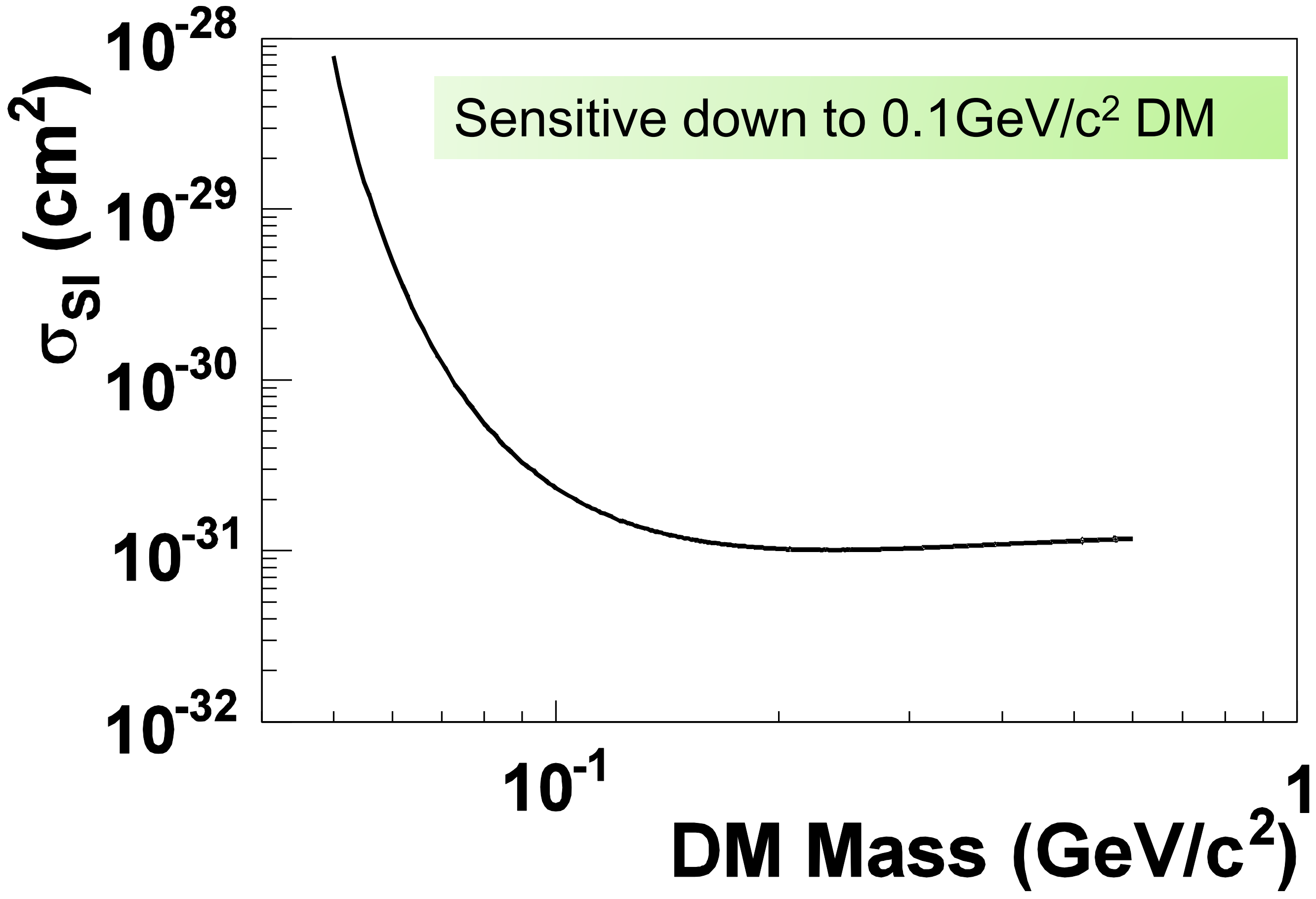
COBAND rocket experiment sensitivity

- 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



Sub-GeV Dark Matter Search

- Target: ^{93}Nb (92.9u) 100μm × 100μm × 1μm × 10pix
- Measurement time: 10000 sec (~2.8hours)
- Assume negligible dark count above 350meV threshold



Summary

- STJ is the most powerful detector for energy detection in sub-eV ~ several-eV, though it has weakness in its small sensitive area
- SOI Cryogenic amplifiers for STJ readout is under development and we performed demonstration of STJ signal amplification by a prototype SOI amplifier at T~350mK.
  - SOI cryogenic amplifier is expected to extract maximum potential of STJ
- COBAND collaboration propose an experimental search for neutrino radiative decay in cosmic neutrino background using STJ.

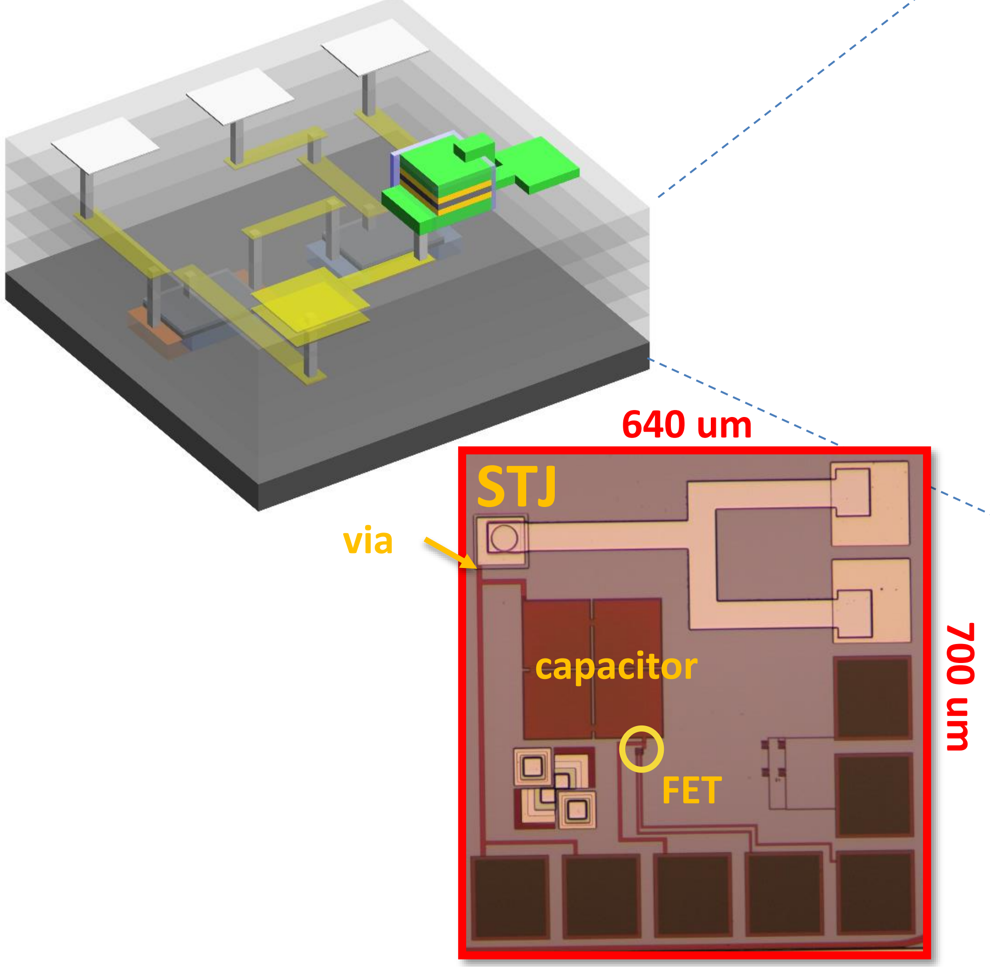
STJ with SOI cryogenic amplifier has a potential to be the most powerful low energy threshold detector.

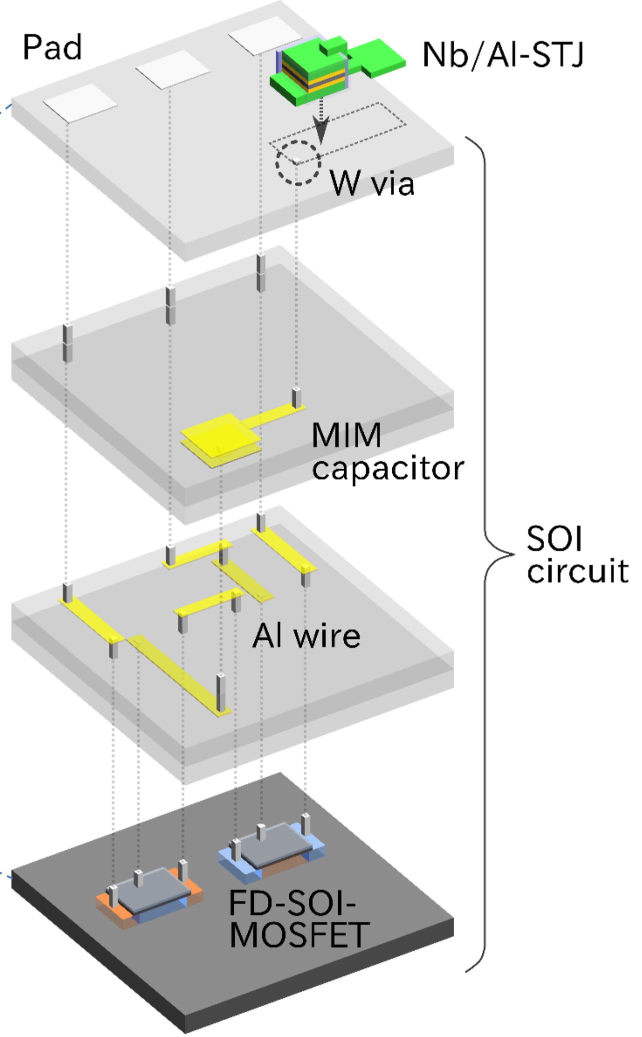
Backup

SOI増幅回路一体型STJ検出器(SOI-STJ)

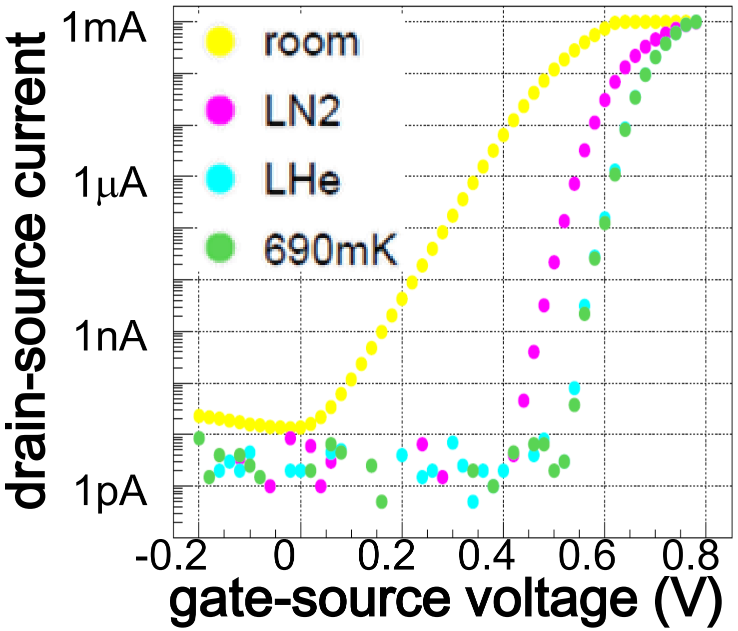
STJ layers are fabricated directly on a SOI pre-amplifier board and cooled down together with the STJ

- Potential to large pixel array integration

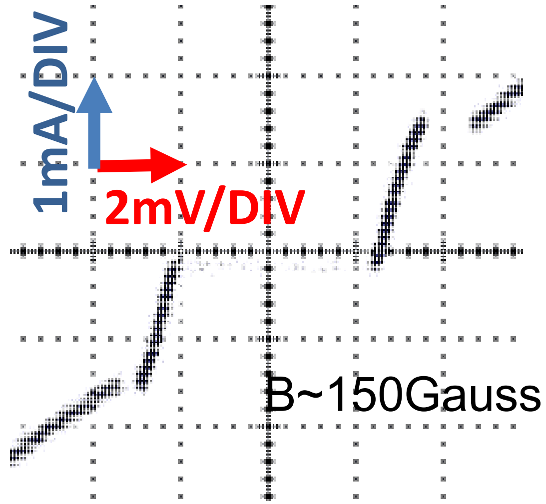




FD-SOI on which STJ is fabricated



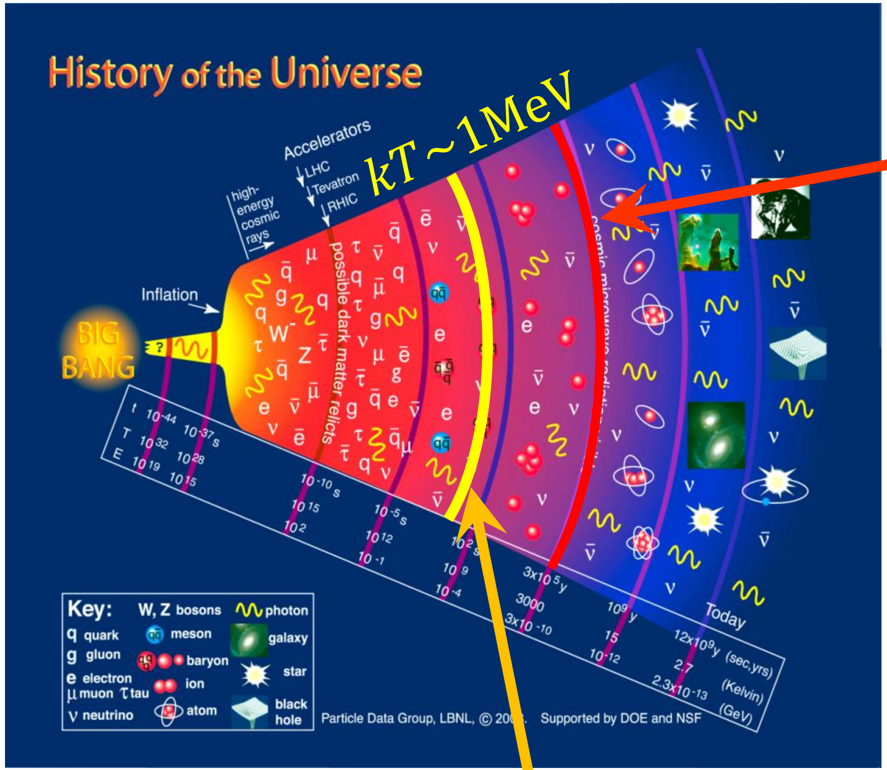
nMOS-FET in FD-SOI wafer on which a STJ is fabricated at KEK

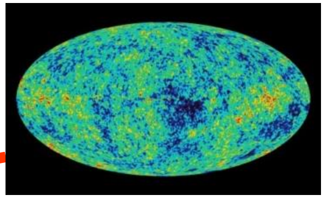


I-V curve of a STJ fabricated at KEK on a FD-SOI wafer

- 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

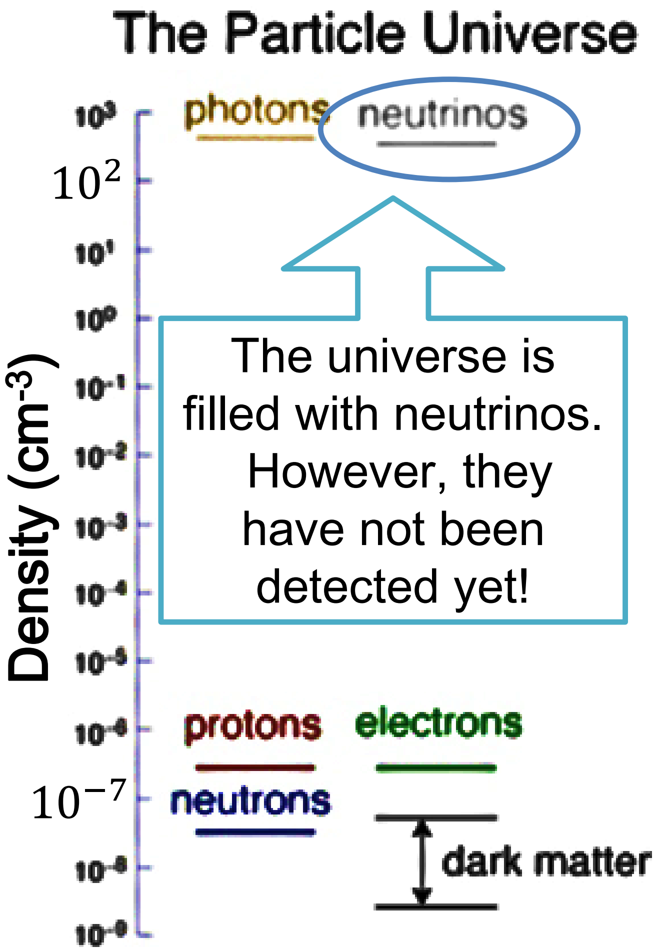
Cosmic neutrino background (CνB)





CMB

$$n_\gamma = 411/\text{cm}^3$$
$$T_\gamma = 2.73\ \text{K}$$



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

CνB (=neutrino decoupling)
~1s after the big bang

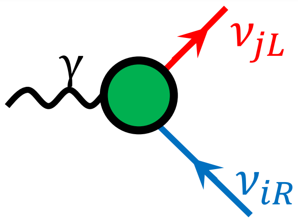
$$T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma = 1.95\text{K} \qquad n_\nu + n_{\bar{\nu}} = \frac{3}{4}\left(\frac{T_\nu}{T_\gamma}\right)^3 n_\gamma = 110/\text{cm}^3$$

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

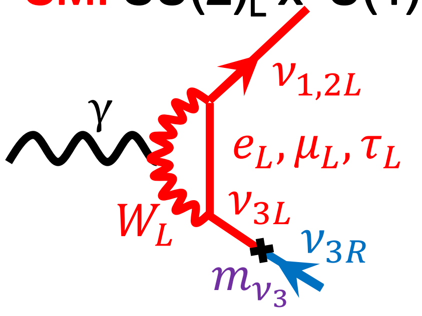
Motivation of ν-decay search in CνB

- Search for $\nu_3 \to \nu_{1,2} + \gamma$ 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 $\tau(\nu_3) = O(10^{17}\mathrm{yrs})$
  - Standard Model expectation: $\tau = O(10^{43}\mathrm{yrs})$
  - Experimental lower limit: $\tau > O(10^{12}\mathrm{yrs})$
  - L-R symmetric model (for Dirac neutrino) predicts down to $\tau = O(10^{17}\mathrm{yrs})$ for W_L-W_R mixing angle $\zeta < 0.02$

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

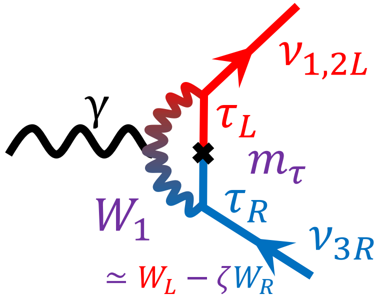


SM: SU(2)$_L$ x U(1)$_Y$



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

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



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

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

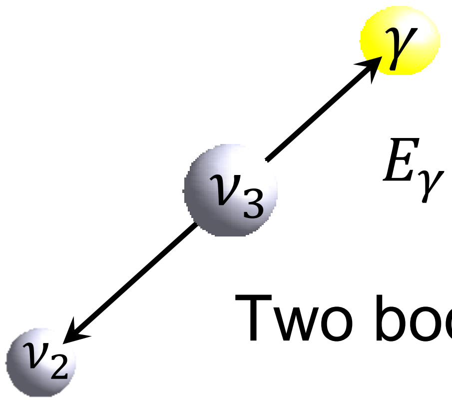
$$\begin{pmatrix} W_1 \\ W_2 \end{pmatrix} = \begin{pmatrix} \cos\zeta & -\sin\zeta \\ \sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W_L \\ W_R \end{pmatrix}$$

10^{26} enhancement to SM

Photon Energy (Wavelength) in Neutrino Decay

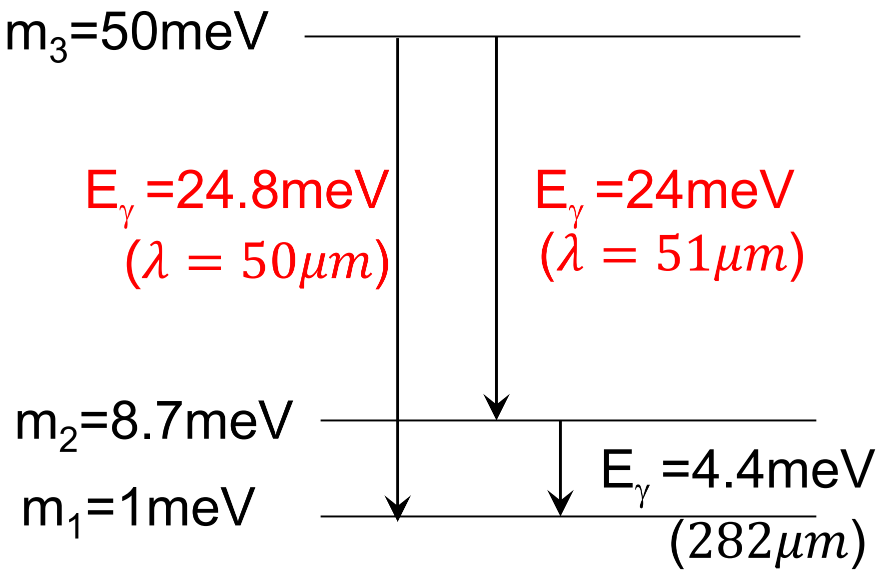
$\nu_3 \rightarrow \nu_{1,2} + \gamma$

in the ν_3 rest frame



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

Two body decay

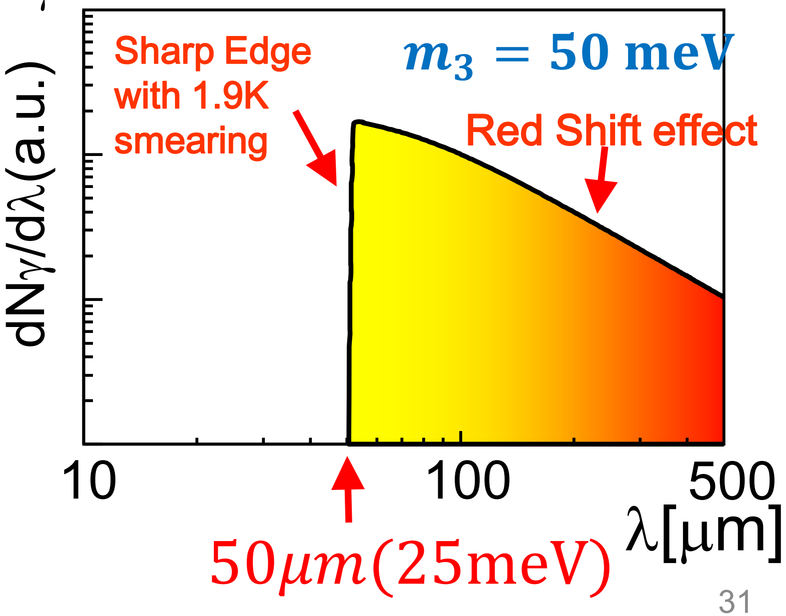


- From neutrino oscillation
  - $|\Delta m_{23}^2| = |m_3^2 - m_2^2| \sim 2.4 \times 10^{-3}\ eV^2$
  - $\Delta m_{12}^2 \sim 7.65 \times 10^{-5}\ eV^2$
- From Planck+WP+highL+BAO
  - $\sum m_i < 0.23$ eV

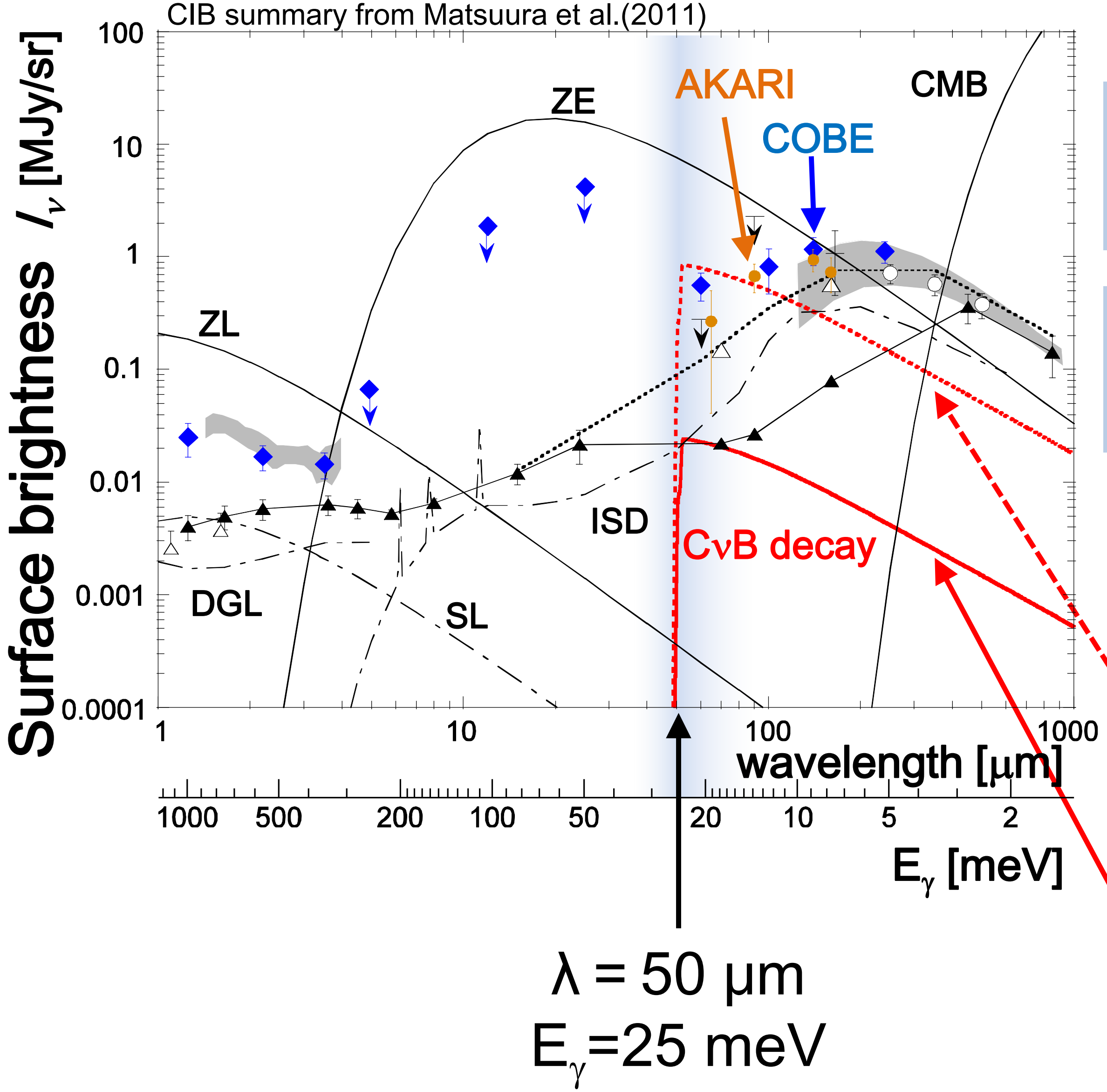
➔ 50meV< m_3 <87meV

E_γ^{rest} =14~24meV (λ_γ =51~89μm)

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



CνB decay signal and Backgrounds



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