COBAND

Development of FD-SOI cryogenic amplifier for application to STJ readout in COBAND experiment

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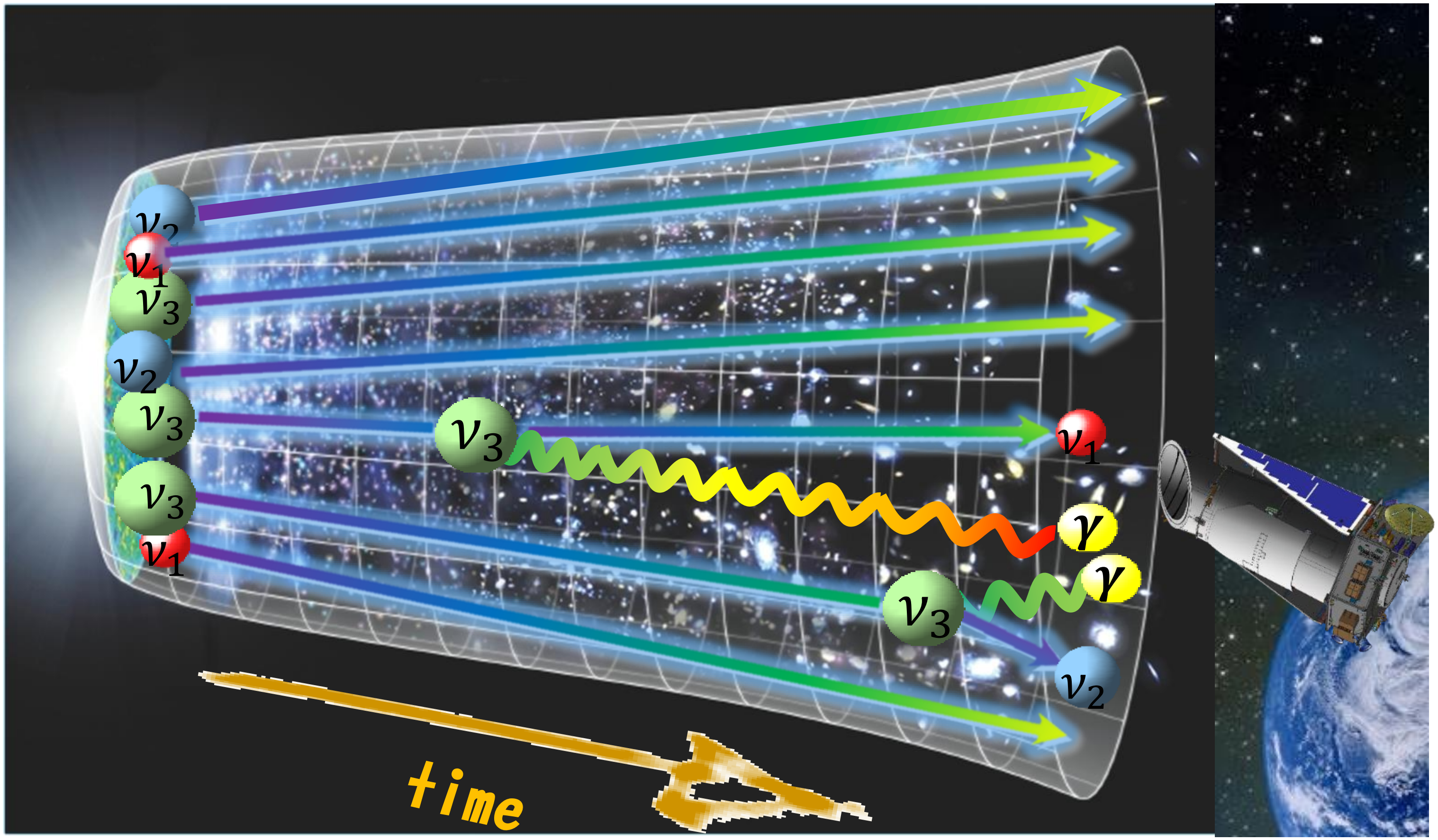
COBAND collaboration

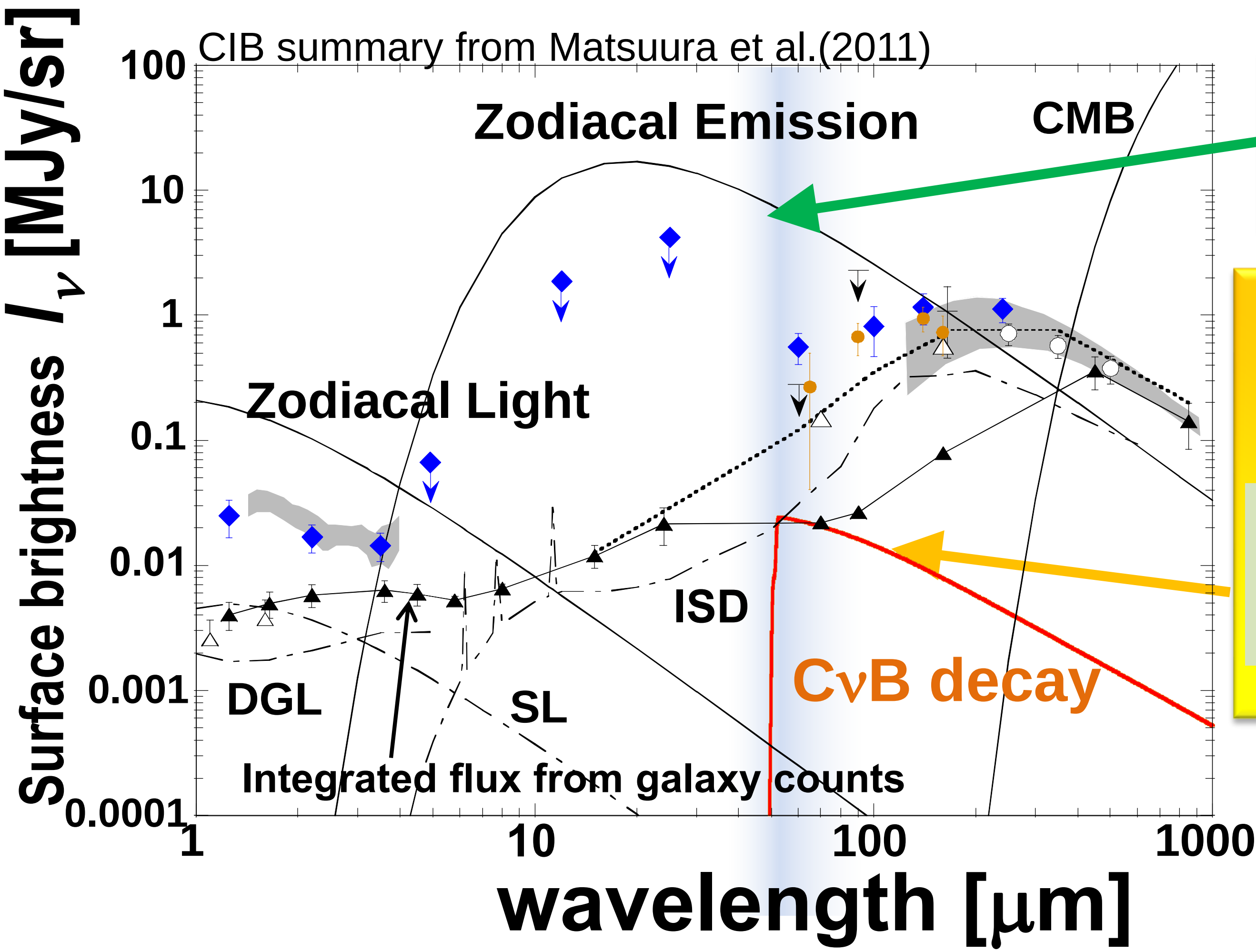
COBAND(Cosmic Background Neutrino Decay)

Search for Neutrino decay in Cosmic background neutrino

➔ To be observed as FIR photons around λ~50μm in the overwhelming zodiacal emission



Neutrino Decay signal and backgrounds



Zodiacal Emission

Expected Neutrino Decay signal

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

$m_3 = 50\ \text{meV}$

Current experimental lower limit is 10^{12} yrs

We can identify ν decay signal by highly precise measurement of photon energy spectrum around **λ~50μm**

Requirements for the photo-detector for sensitivity to neutrino lifetime of τ=10[14] yr$s$ in COBAND 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)

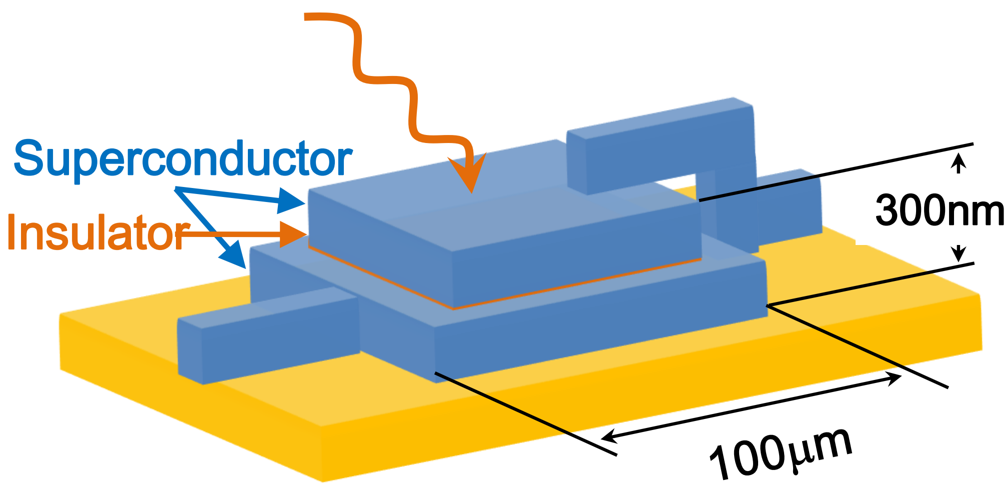
$$\Rightarrow \mathrm{NEP} = \epsilon_\gamma \sqrt{2 f_\gamma} \sim 1\times 10^{-19}\, W/\sqrt{Hz}$$

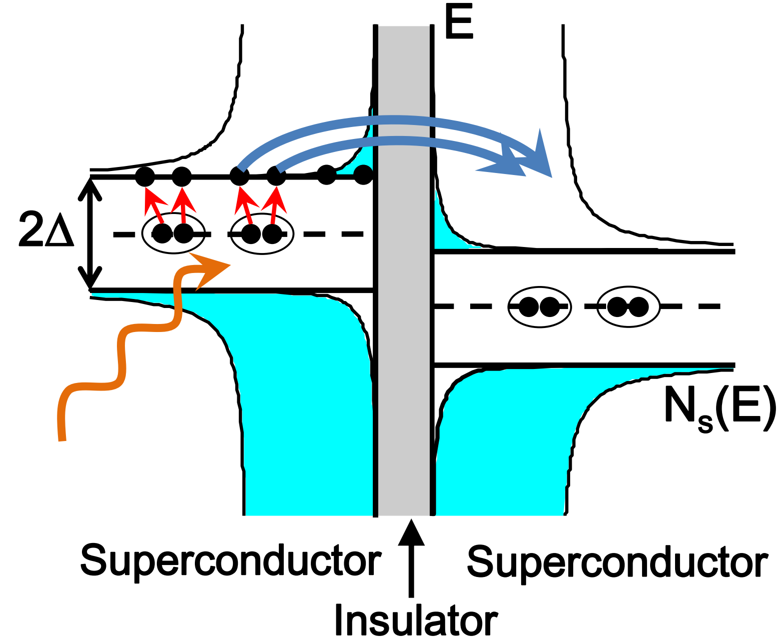
We are trying to achieve $\mathrm{NEP} \sim 10^{-19}\, W/\sqrt{Hz}$ **by using**

- **Superconducting Tunnel Junction (STJ) sensor**
- **Cryogenic amplifier readout**

Superconducting Tunnel Junction (STJ) Sensor

- Superconductor / Insulator /Superconductor
  Josephson junction device





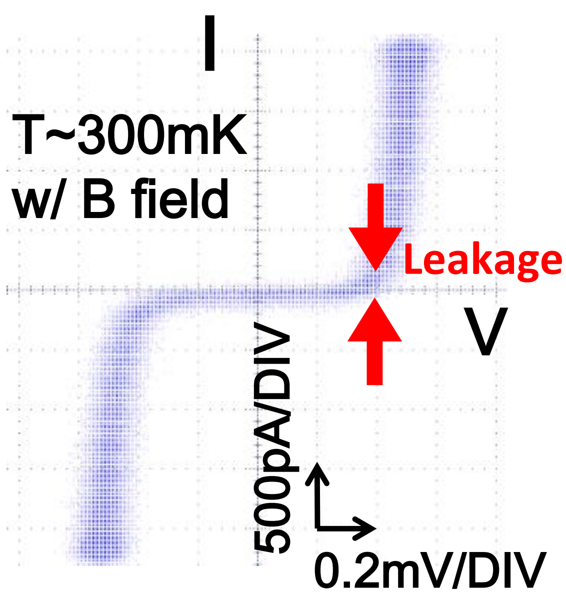
Δ: Superconducting gap energy

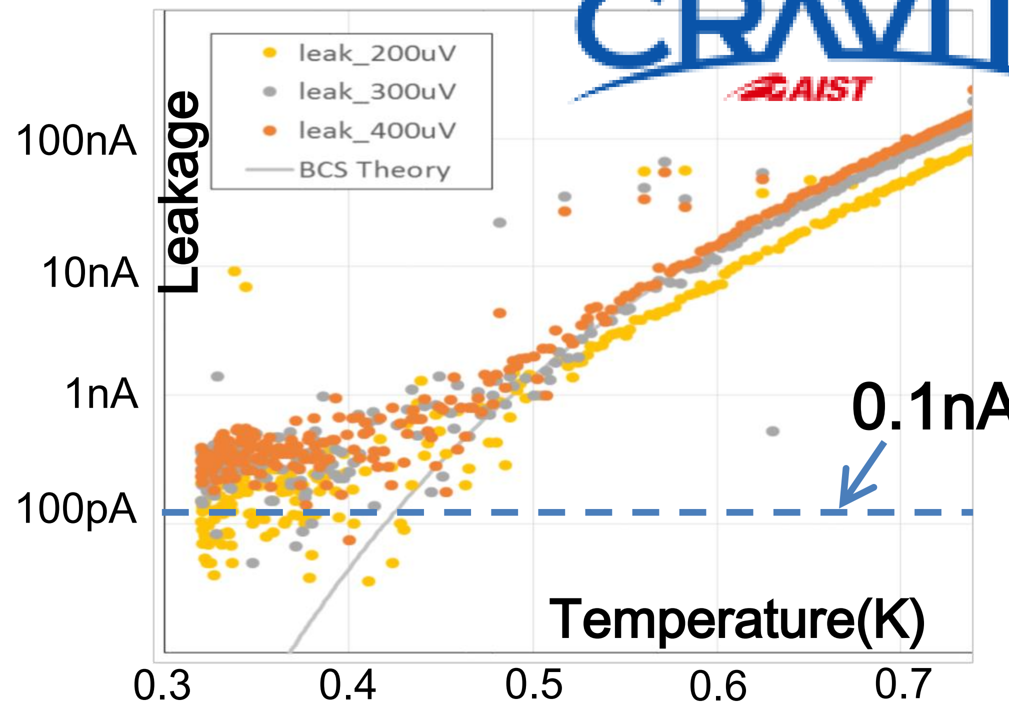
A constant bias voltage (|V|<2Δ) is applied across the junction.
A photon absorbed in the superconductor breaks Cooper pairs and creates tunneling current of quasi-particles proportional to the deposited photon energy.

- Much lower gap energy (Δ) than FIR photon ➔ Can detect FIR photon
- Faster response (~μs) ➔ Suitable for single-photon counting

Nb/Al-STJ development at CRAVITY

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





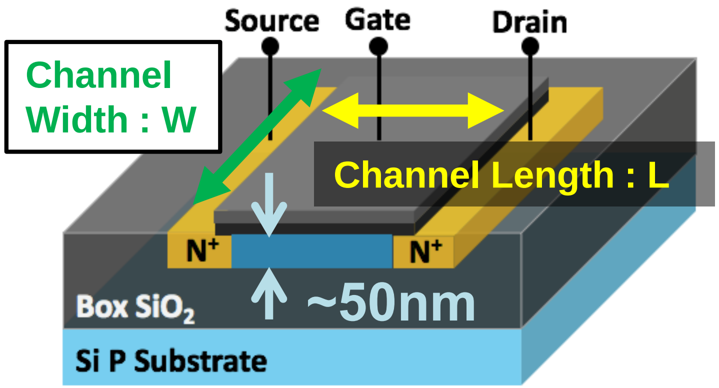
I_{leak}~200pA for 50μm sq. STJ, and achieved 50pA for 20μm sq.

➔ 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

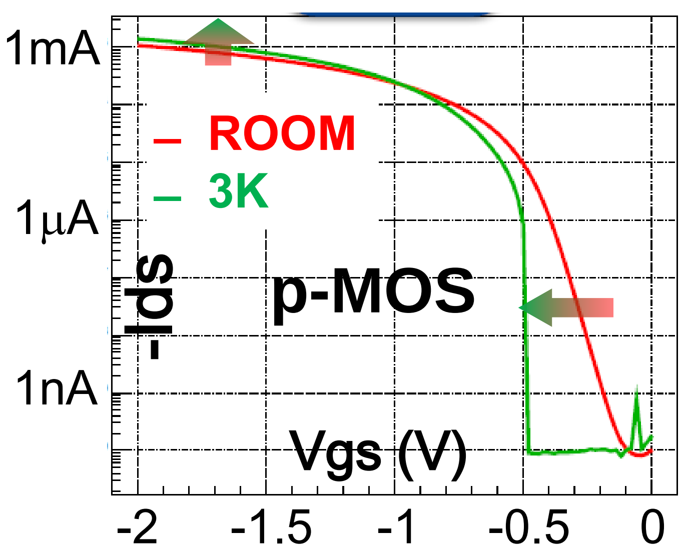
FD-SOI : Fully Depleted – Silicon On Insulator

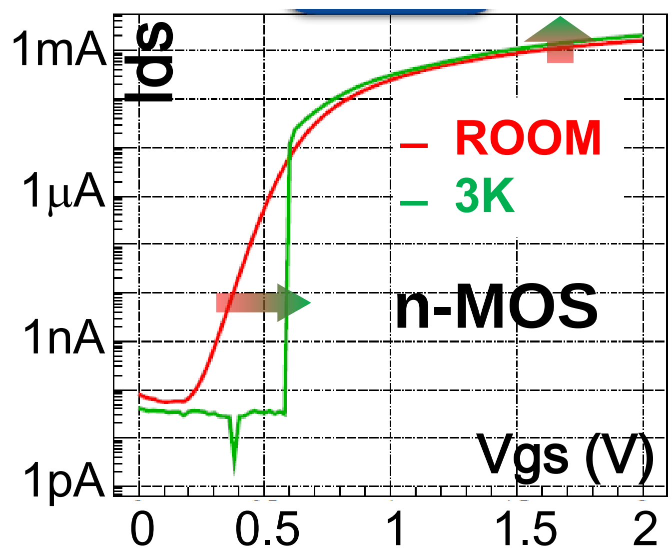


- Very thin channel layer in MOSFET on SiO_2
- No floating body effect caused by charge accumulation in the body
- FD-SOI-MOSFET is reported to work at 4K

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



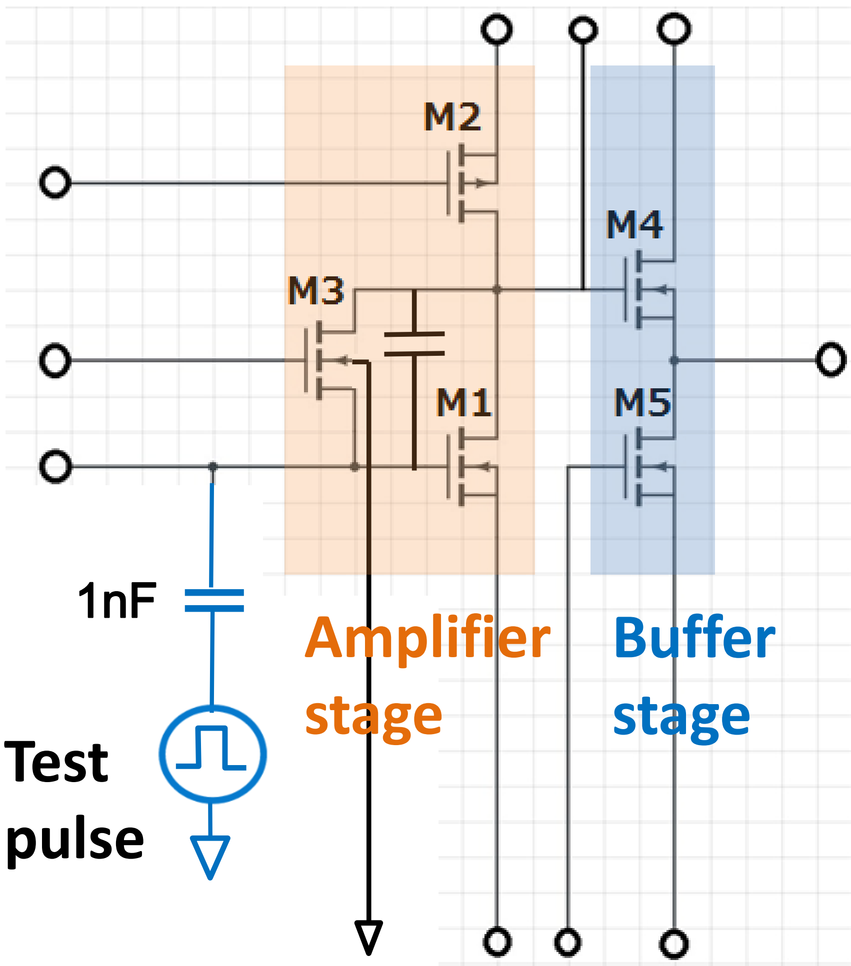


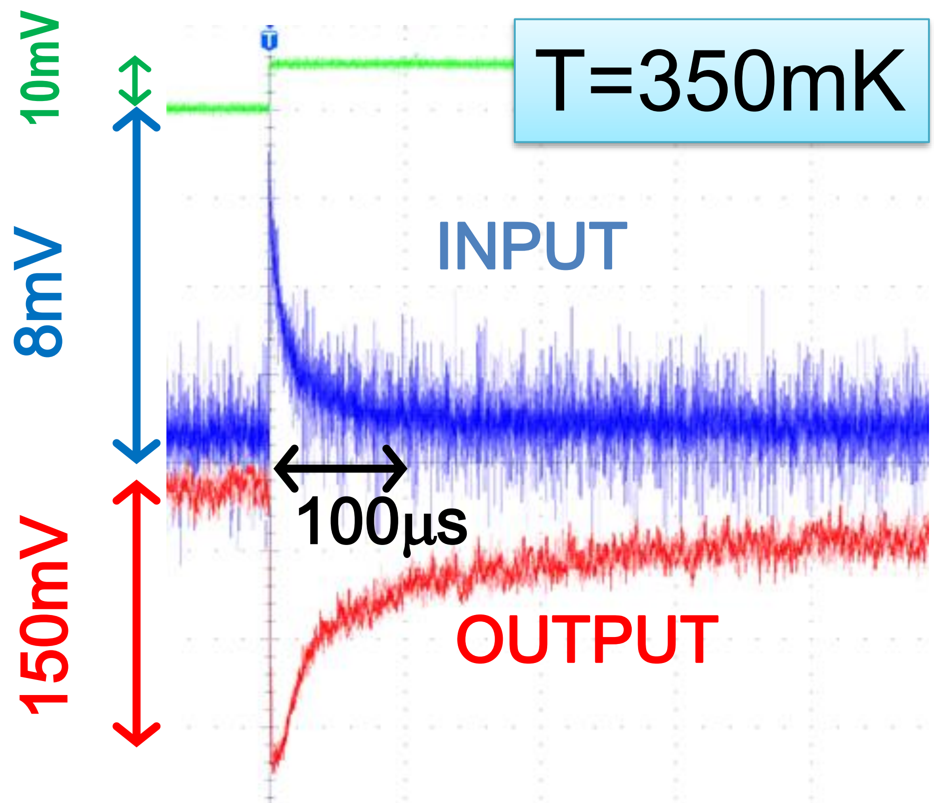
Increasement of drain current

Shift in V_{TH}

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

SOI prototype amplifier for demonstration test

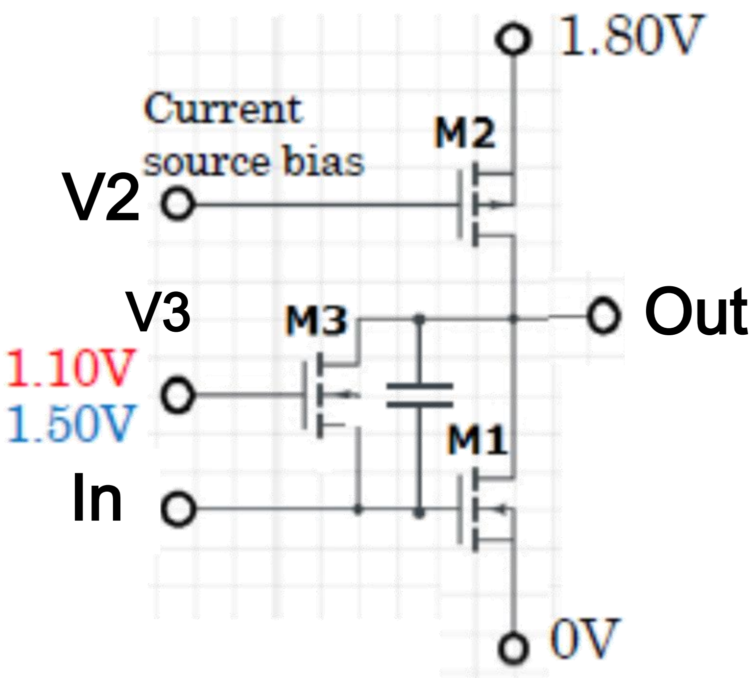


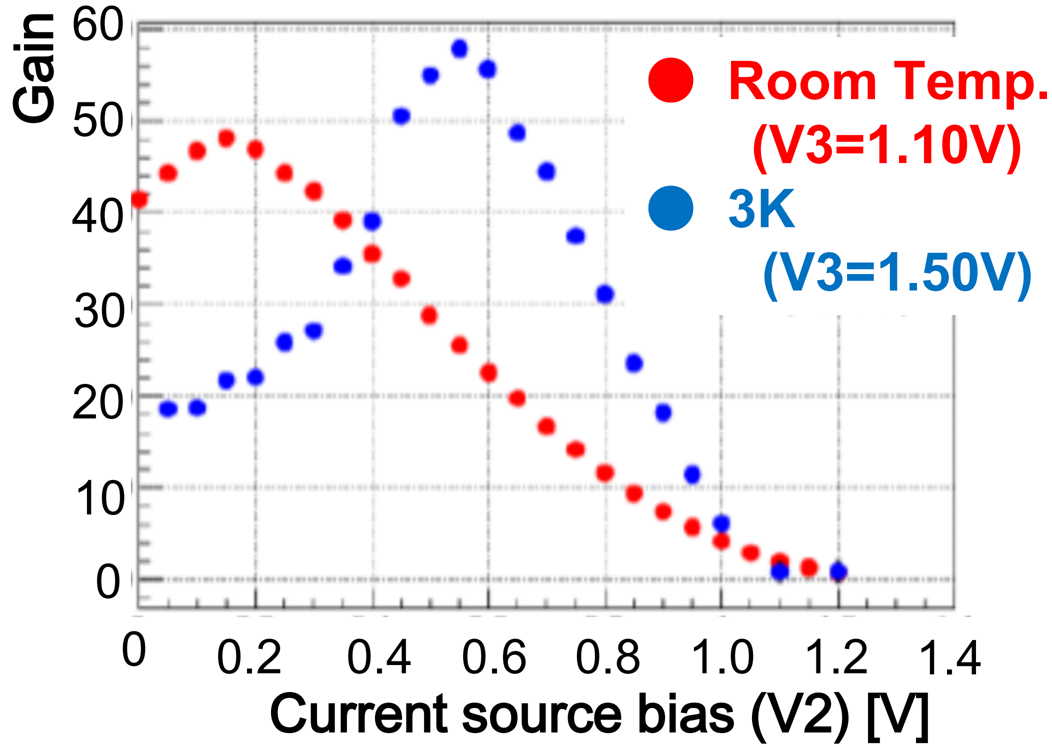


Test pulse input through C=1nF at T=3K and 350mK

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

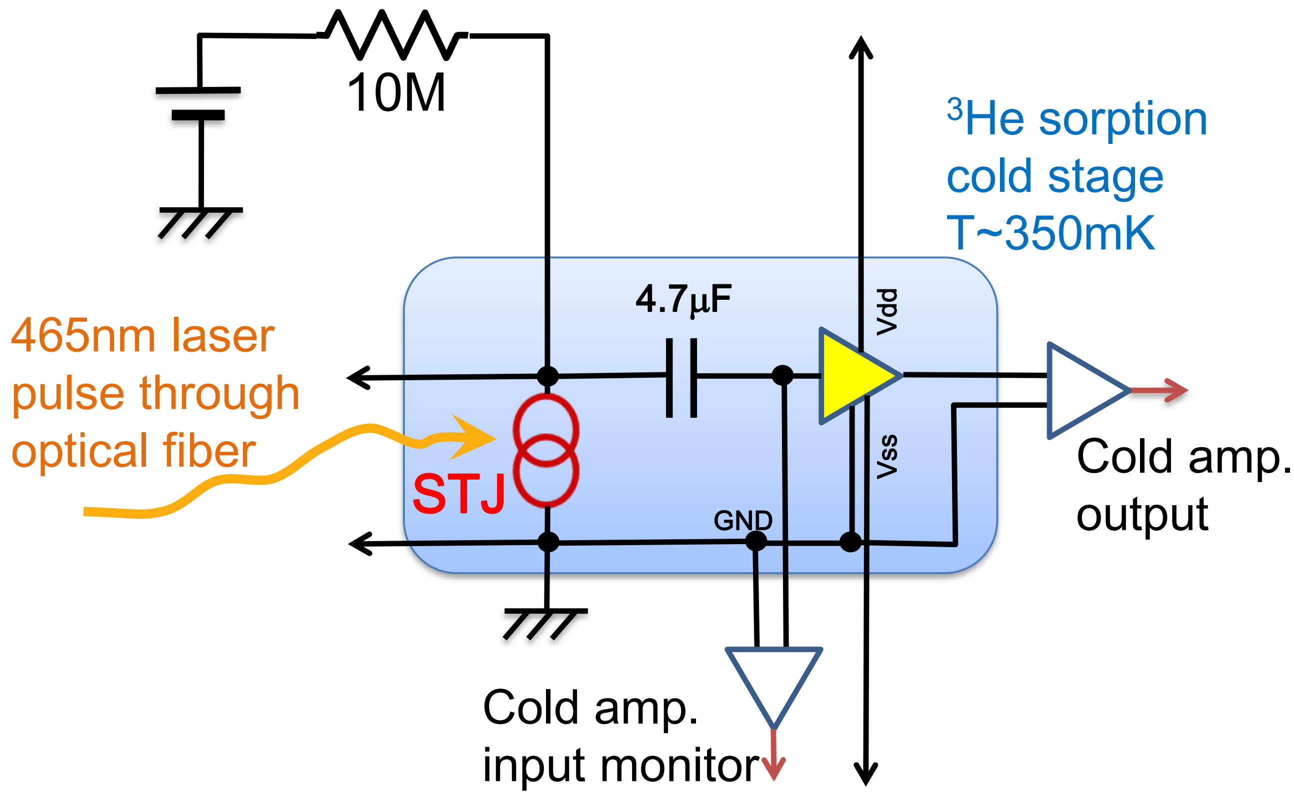
SOI prototype amplifier for demonstration test: Common source stage

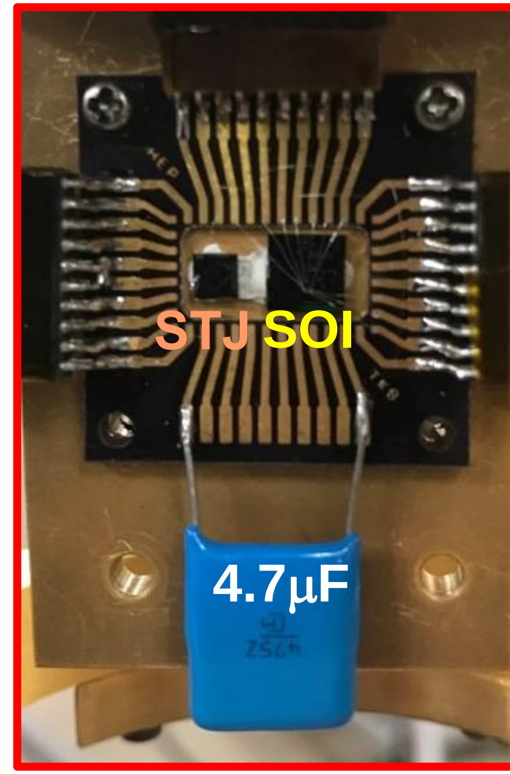




We can compensate the effect of shifts in the thresholds by adjusting bias voltages to archive similar gain!

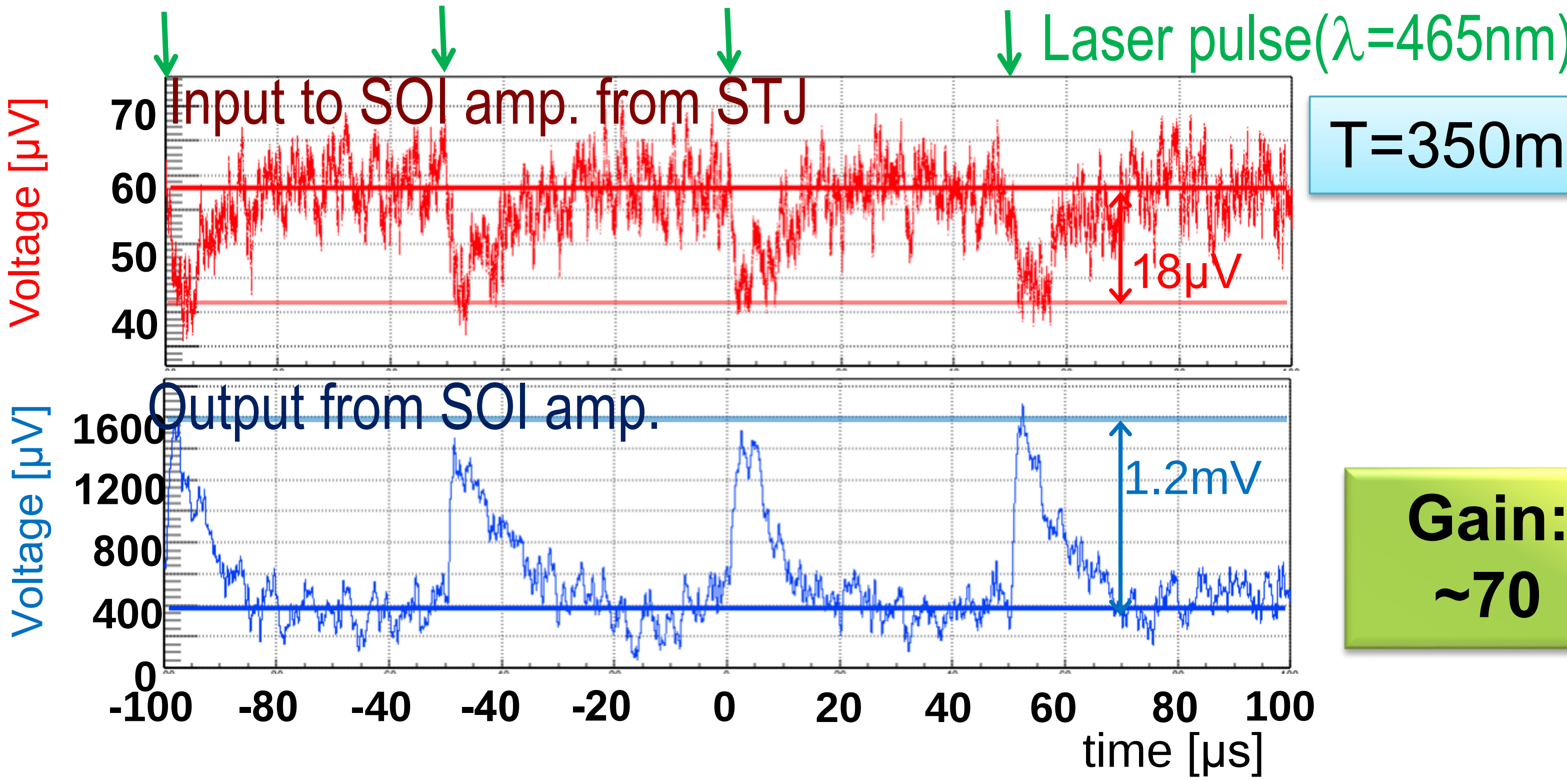
Demonstration Test for Amplification of STJ response to laser pulse on cold stage





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

Demonstration Test for Amplification of STJ response to laser pulse on cold stage



T=350mK

Gain: ~70

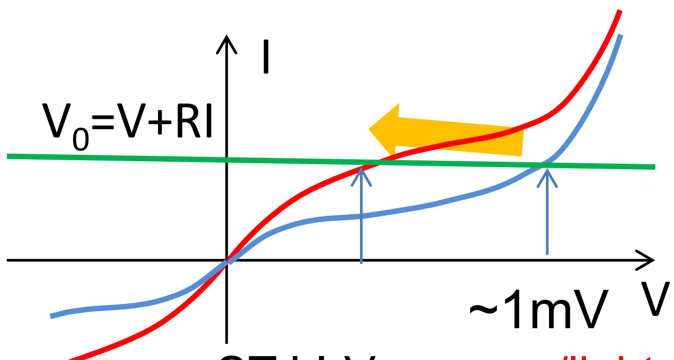
Demonstrated to show amplification of Nb/Al-STJ response to laser pulse by SOI amplifier situated close to STJ at T=350mK

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

STJ readout by Constant Current and Constant Voltage operation

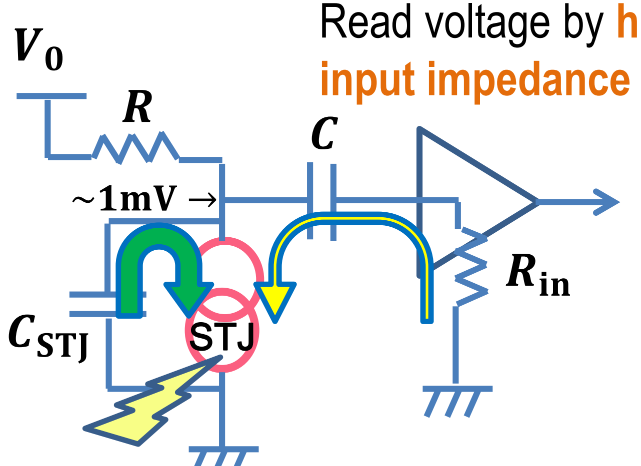
CC operation

Biasing STJ with large R keeps constant current on STJ



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

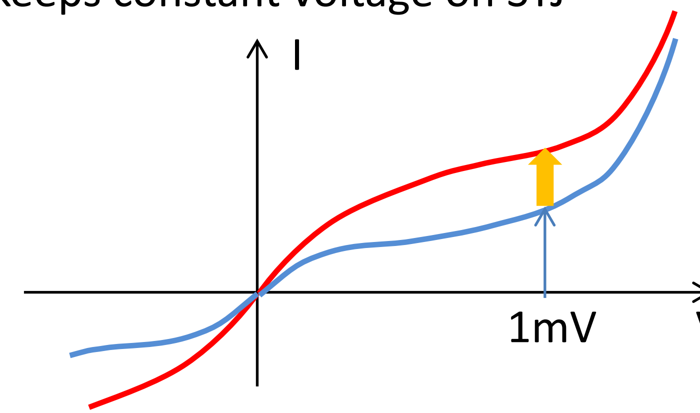
Read voltage by high input impedance amp.



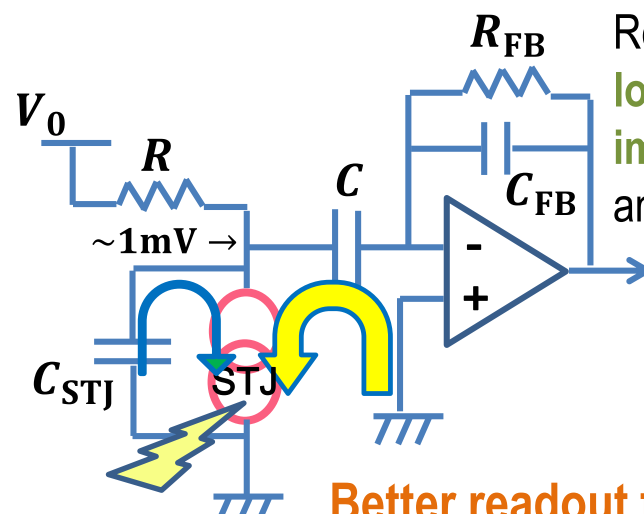
Large fraction of signal is lost through C_{STJ}

CV operation

STJ connection to virtual short through C keeps constant voltage on STJ



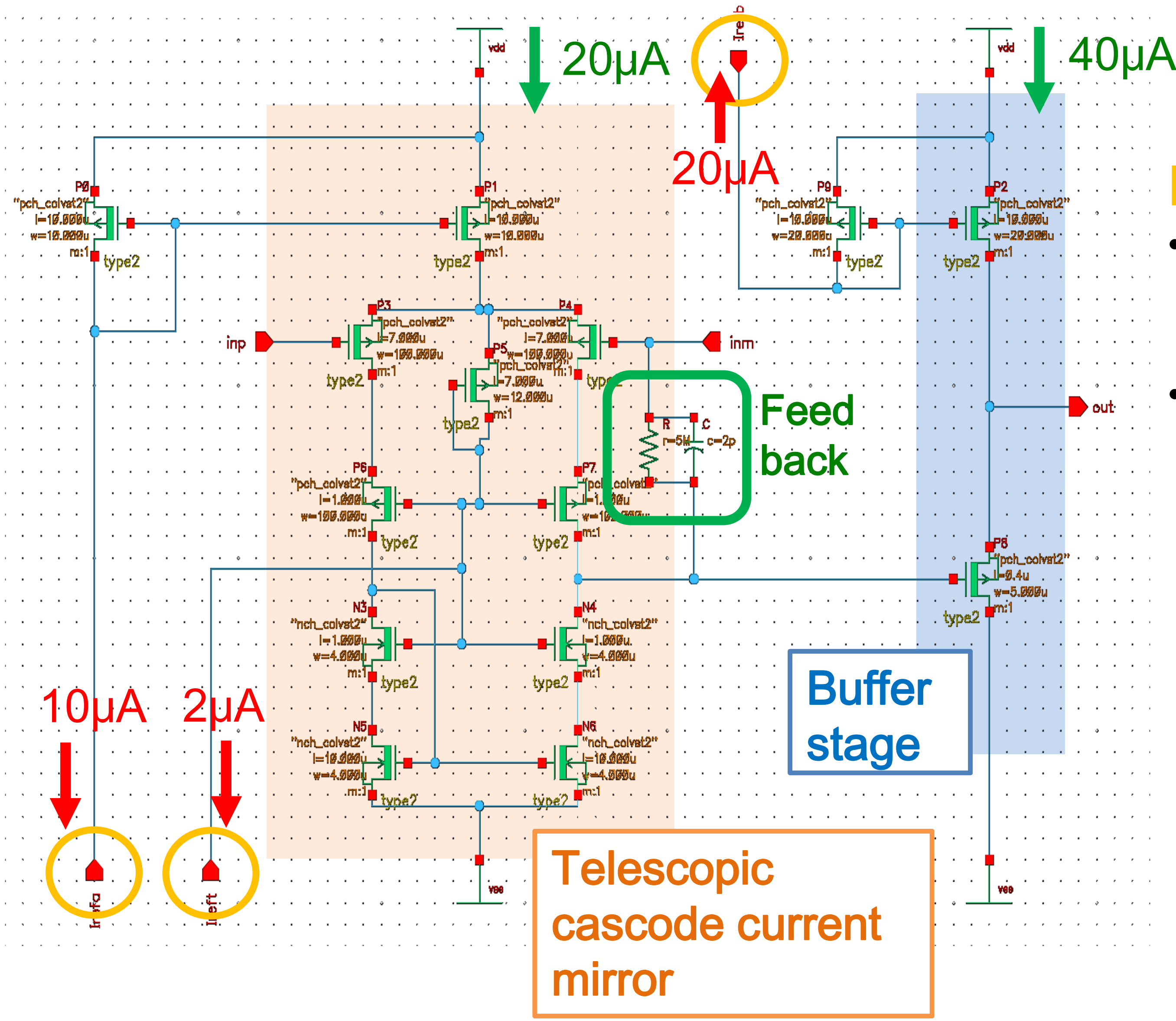
Read charge by low input impedance amp.



Better readout for STJ

Charge sensitive amplifier

Differential amplifier with negative feedback of CR



Differential amp.

- Negative feedback with C=3pF and R=5MΩ
- GBWP~2MHz

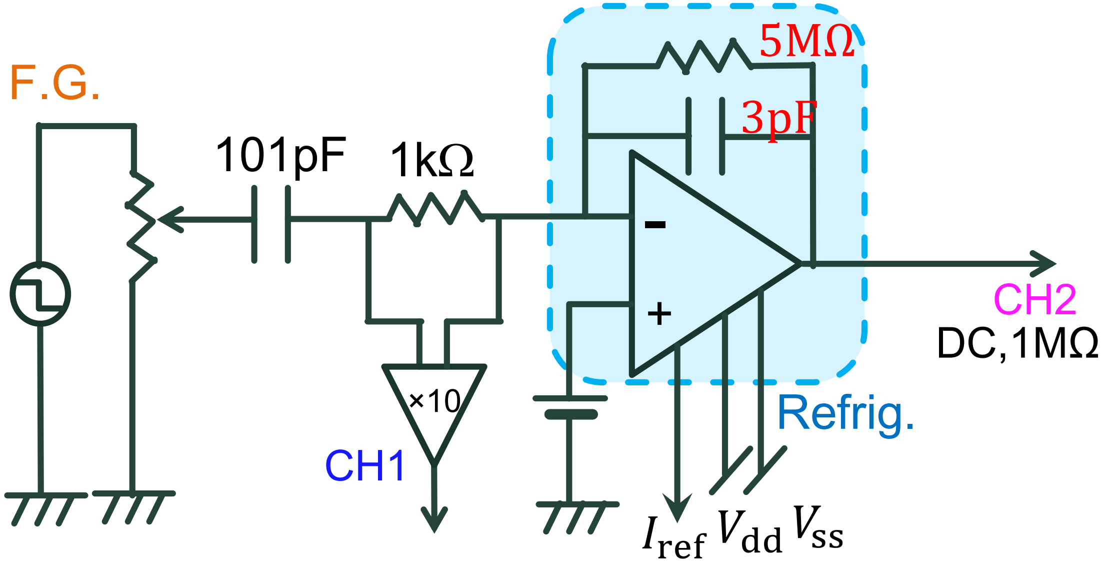
Power consumption

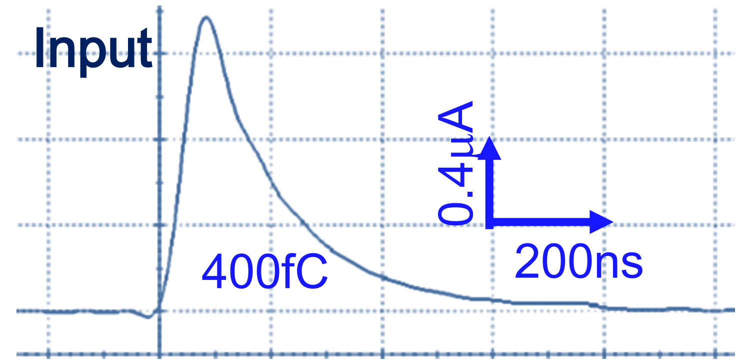
$$V_{dd} - V_{ss} = 3V$$

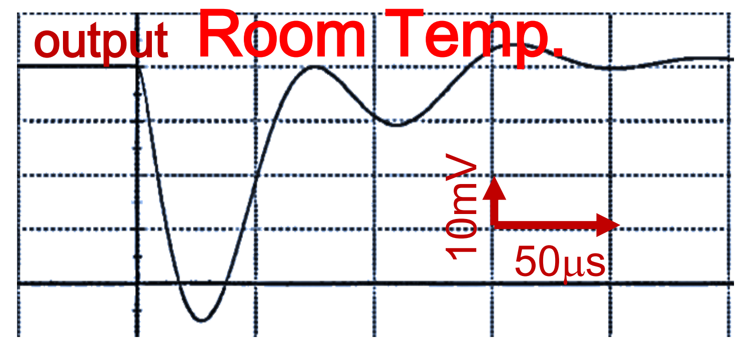
$$I_{total} = 40\mu A$$

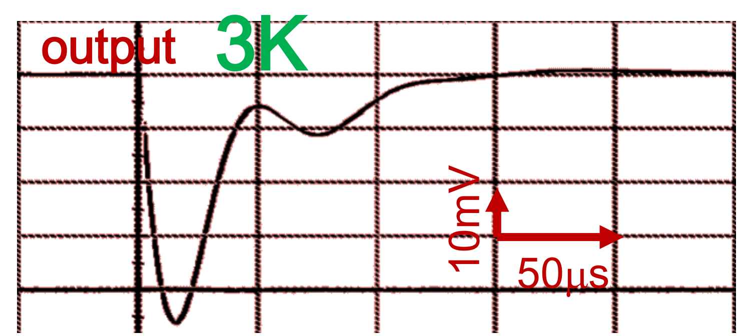
➔~120μW

Response to charge injection



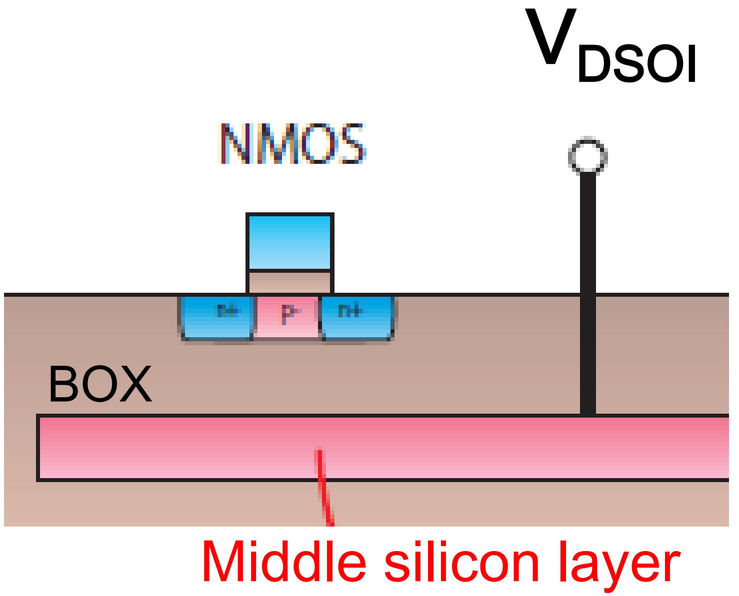


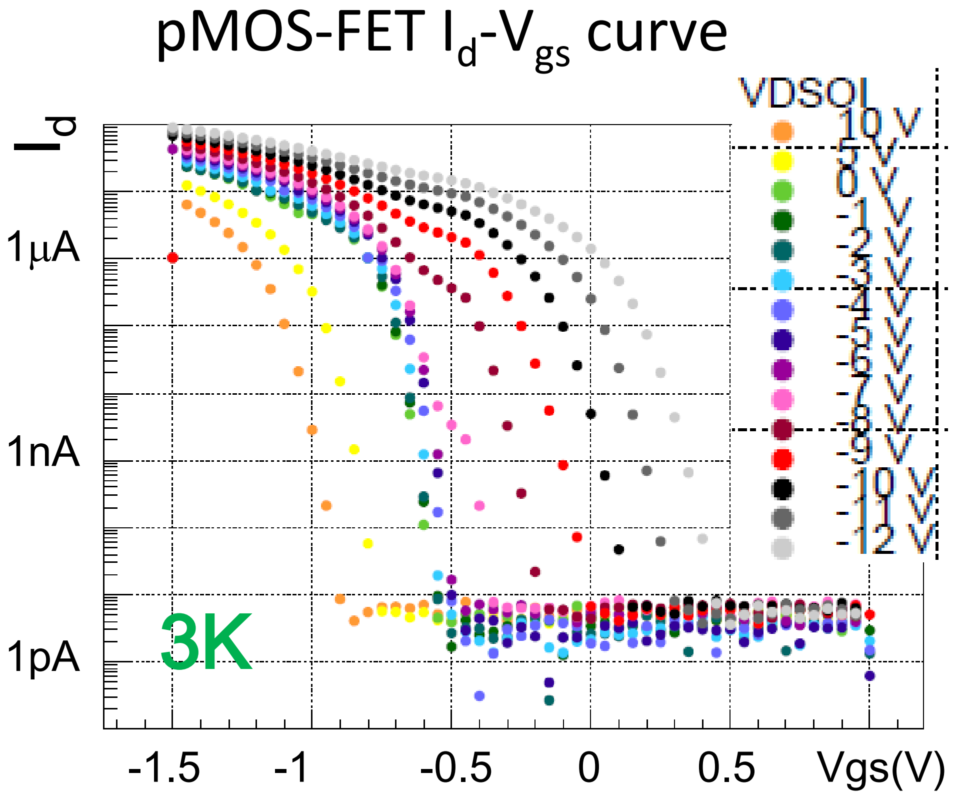




- Input charge ~400fC
- Observed gain: ~45mV/400fC~1/9pF
  - Due to stray capacitance in wire bonding used for feedback CR?
- Show almost same performance in 3K to one in room temp.
- Now we are working on STJ signal readout with this amp.
- We are developing amp. with smaller C
  - Target: C=200e/0.5mV ~ 60fF

FET Threshold voltage control in Double-SOI at cryogenic temp.





Vth control by V_{DSOI} at room temperature is well established.

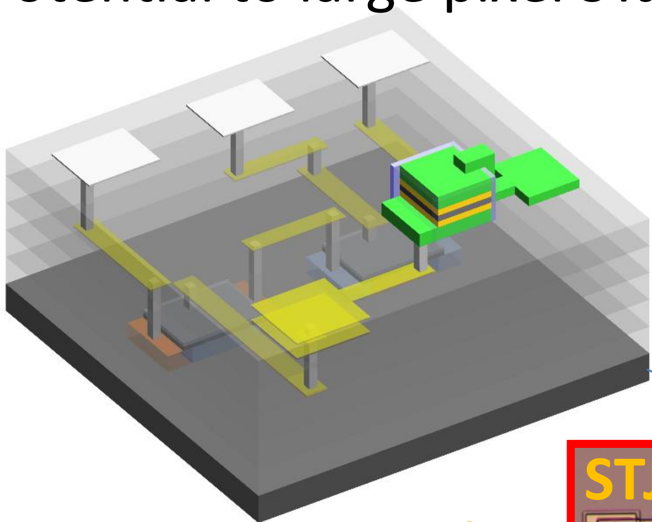
We found Vth control is also possible at cryogenic temperature

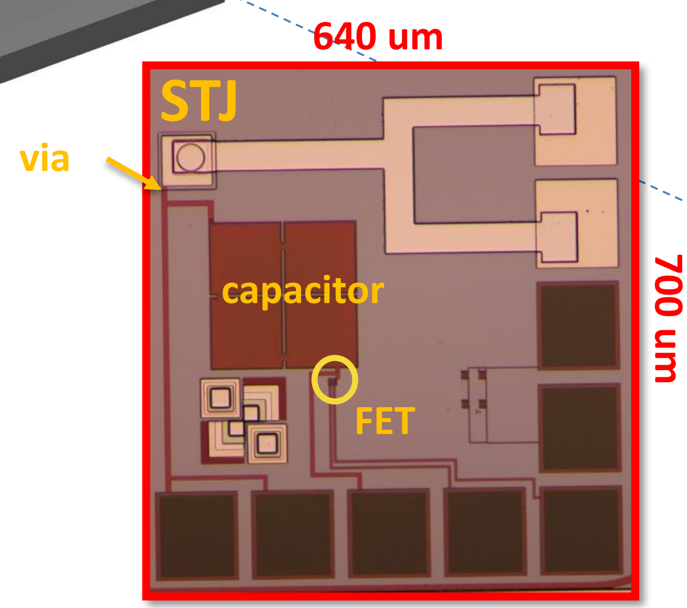
- Can compensate shift of Vth in cryogenic temp.
- Can realize a FET with steep rising of I_d around V_{gs}=0 ➔ Potential to ultra-low power consumption device

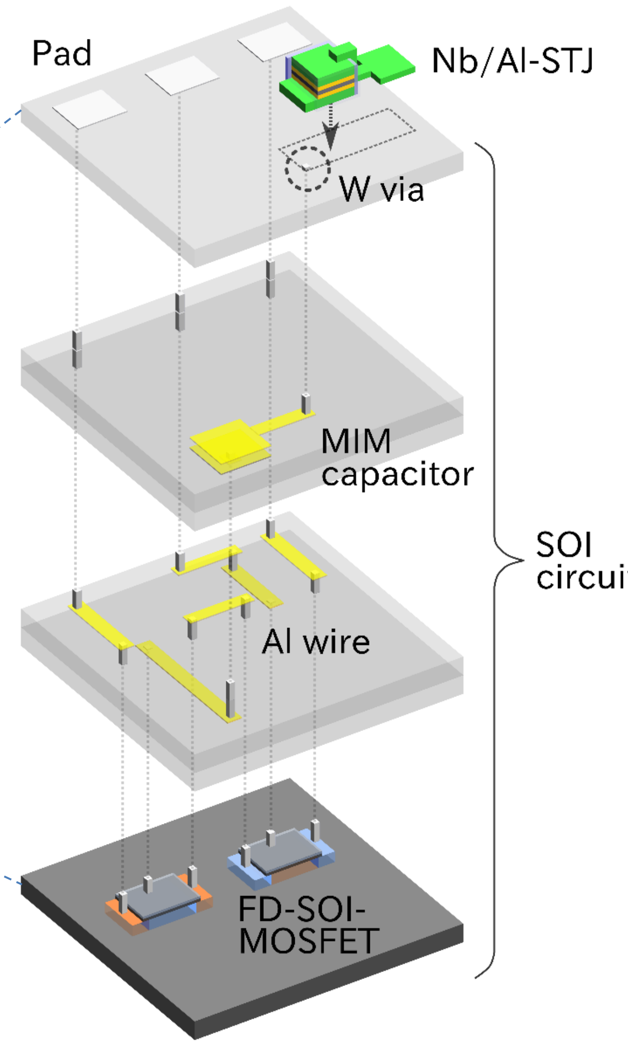
Development of Direct Intergradation of STJ on SOI (SOI-STJ)

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

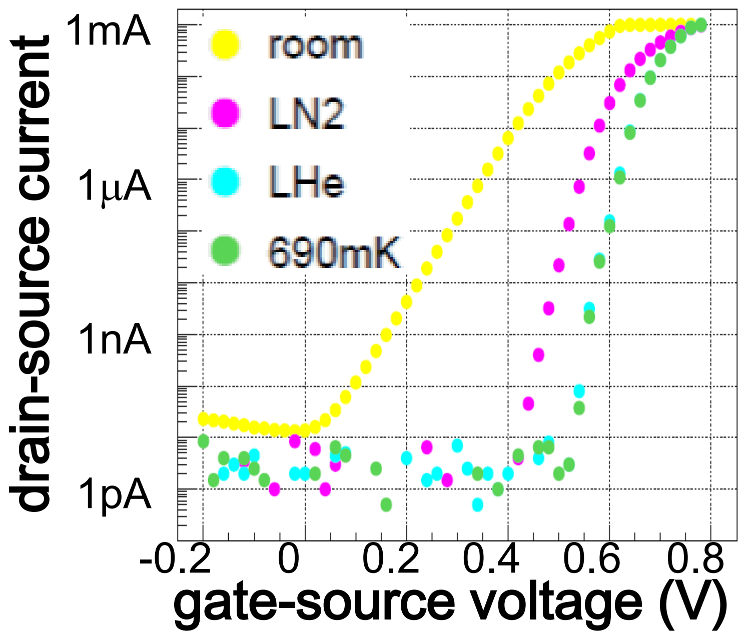
☐ Potential to large pixel STJ with readout



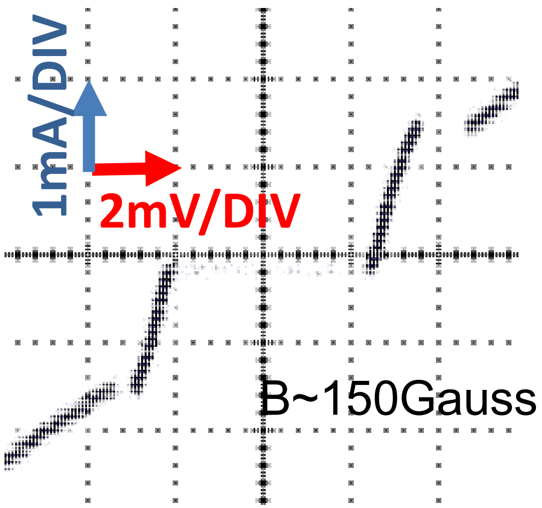




FD-SOI on which STJ is fabricated



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 to ~100mK
- We are also developing SOI-STJ fabrication at CRAVITY

Summary

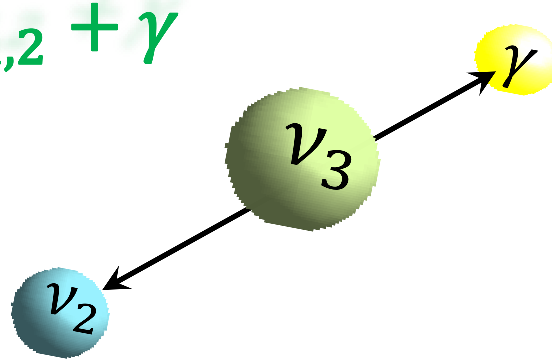
- In COBAND project, we require a photo-detector with NEP~10^{-19} W/√Hz to detect single FIR photon (λ~50μm).
- We are developing Nb/Al-STJ with cryogenic amplifier readout.
  - Nb/Al-STJs fabricated at CRAVITY satisfy our requirements.
  - Cryogenic FD-SOI amplifiers are under development and we demonstrated STJ signal amplification by a prototype SOI amplifier at T~350mK.
- We are designing and testing more practical readout for STJ signal with low input impedance charge integration amplifier.
  - Using SOI technology, a wealth of knowledge in circuit at room temperature is available even at cryogenic temperature almost as it is.

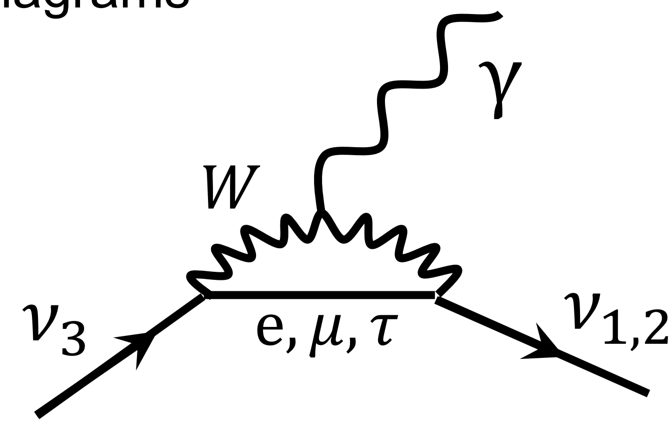
* SOI design in this work is supported by VDEC, the U. Tokyo in collaboration with Synopsys, Inc., Cadence Design Systems, Inc., and Mentor Graphics, Inc.

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



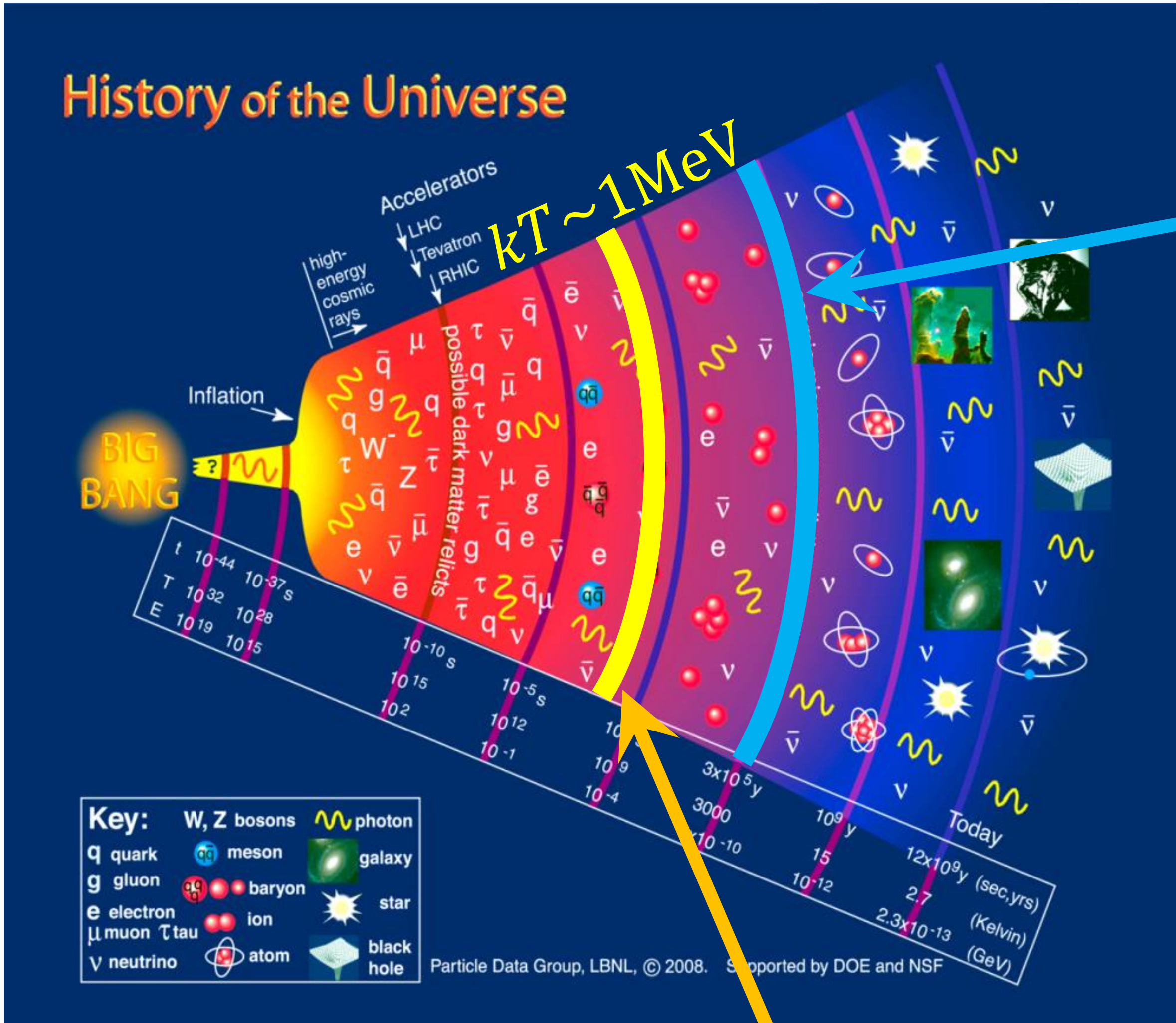


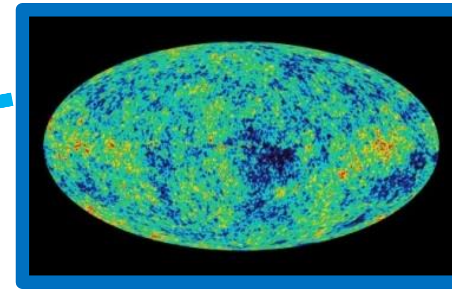
✓ However, the lifetime is expected to be much longer than the age of the universe

➔ 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)

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

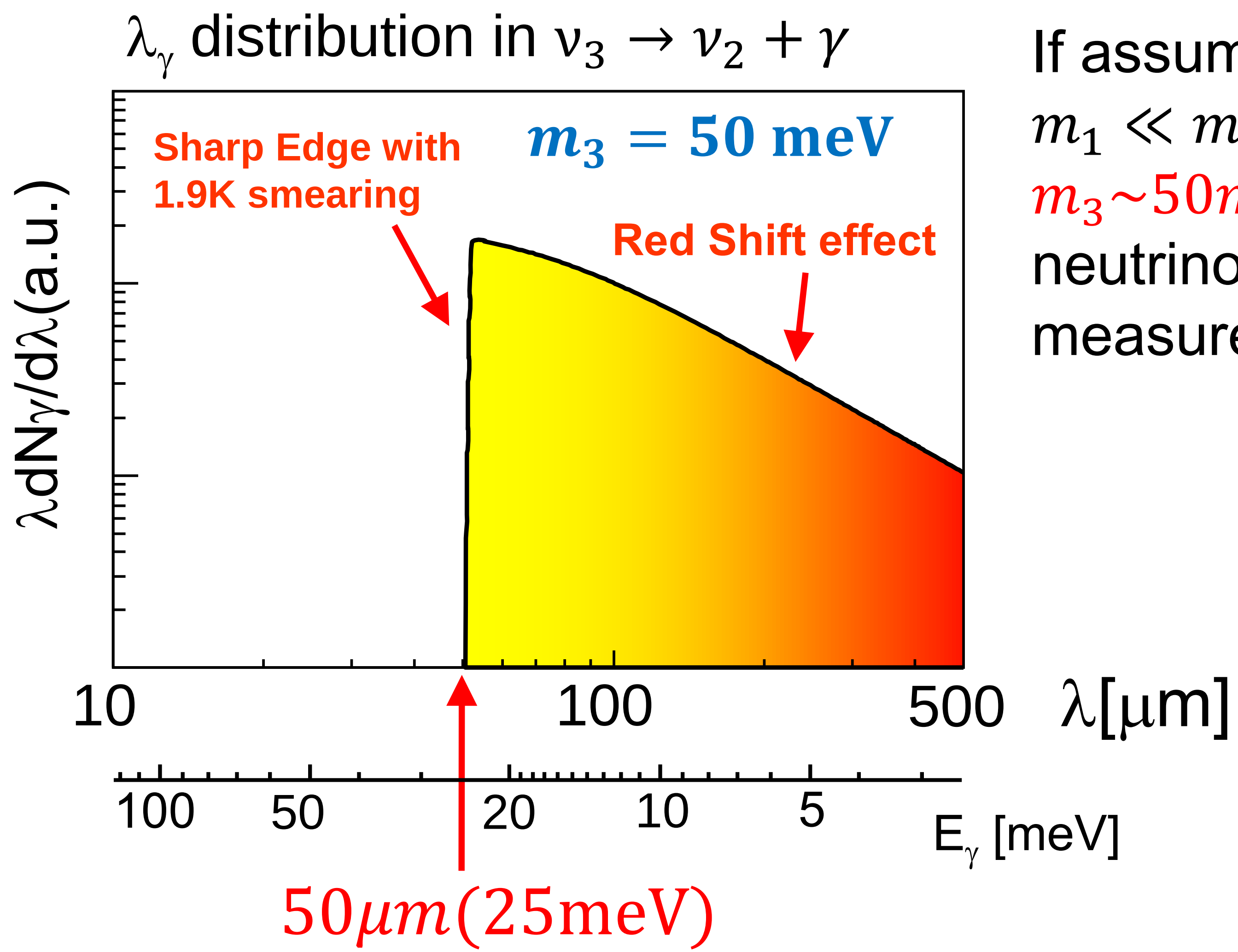
$T_\gamma = 2.73\ K$

~380,000yrs after the Big Bang

CνB (=neutrino decoupling)

~1sec after the big bang

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!!

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
  - $m_3 = \left(m_3^2 - m_{1,2}^2\right)/\left(2E_\gamma\right)$

➔ 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	$\sim 10^{-17}$	Akari-FIS
Stressed Ge:Ga	60-210	0.3K	$\sim 0.9 \times 10^{-17}$	Herschel-PACS

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

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

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

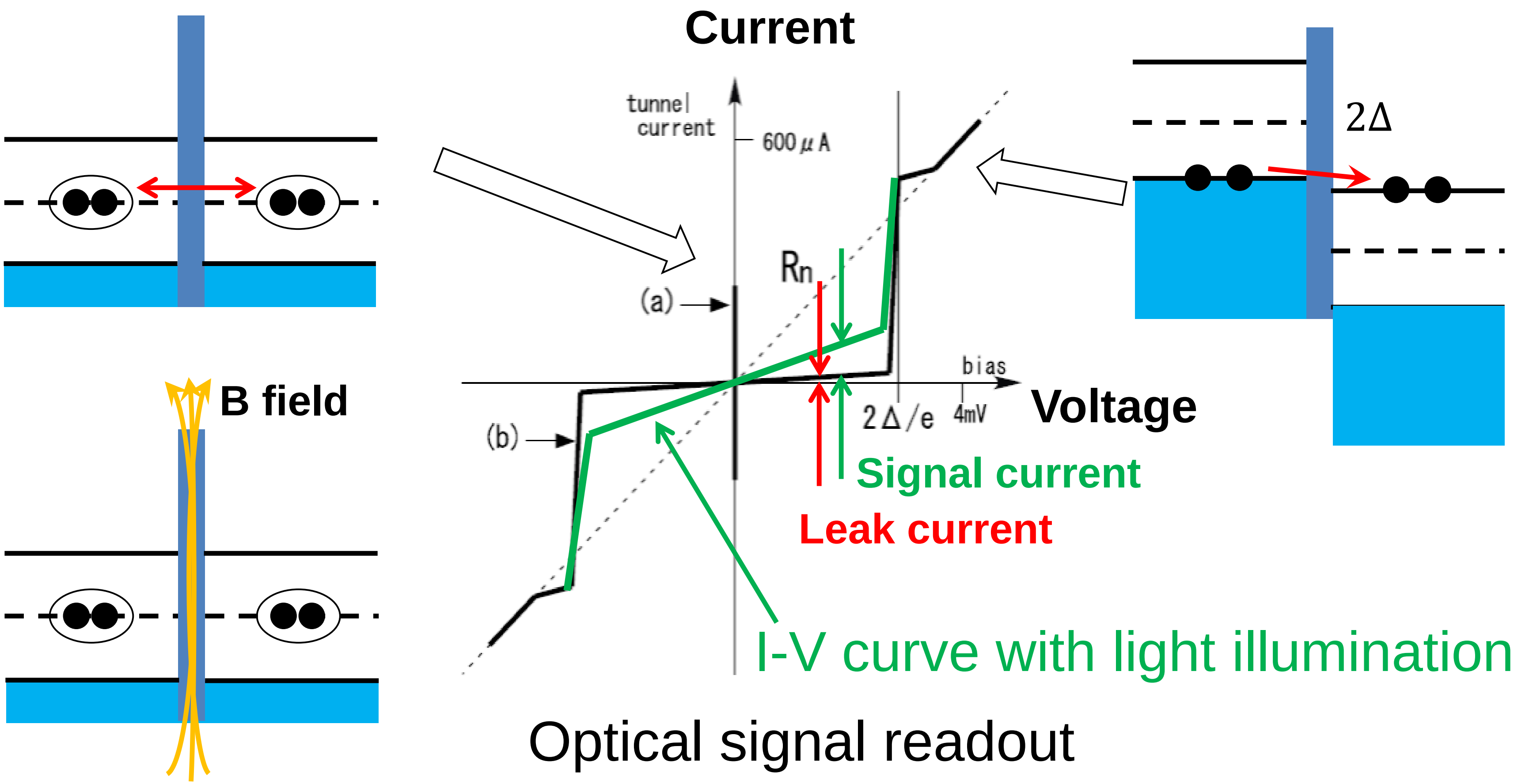
➔ Smaller superconducting gap energy Δ yields better energy resolution

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

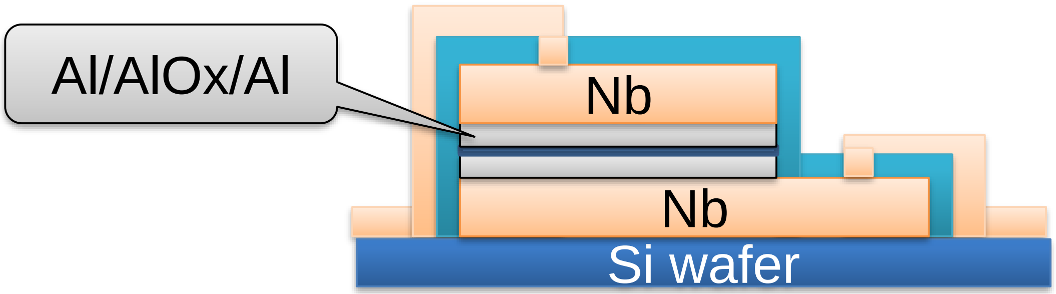
Optical signal readout

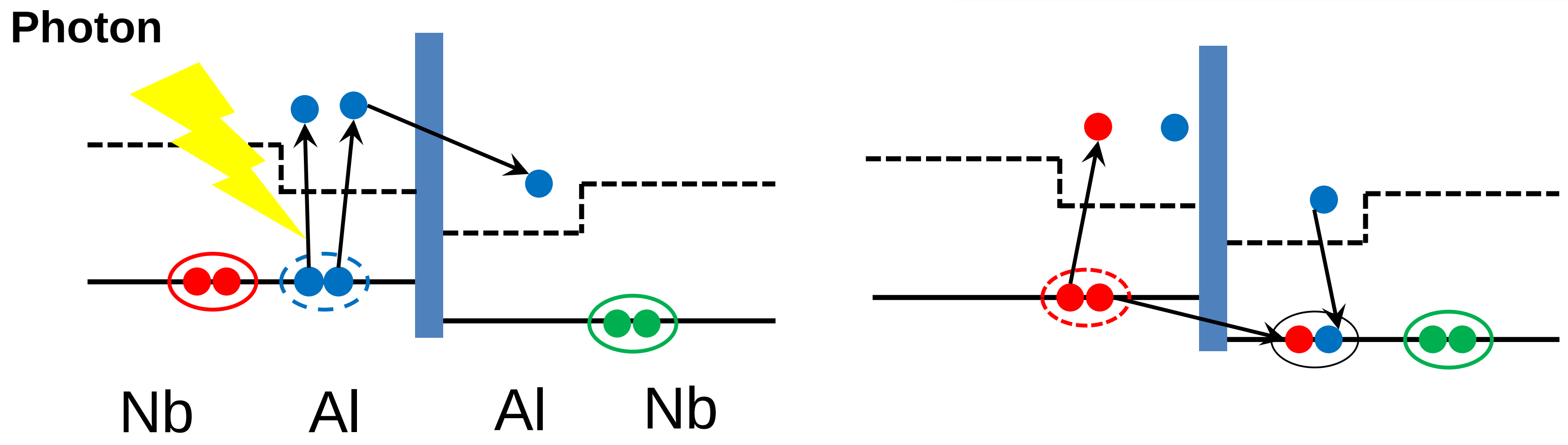
➔ Apply a constant bias voltage (|V|<2Δ) across the junction and collect tunneling current of quasi particles created by photons

✓ 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



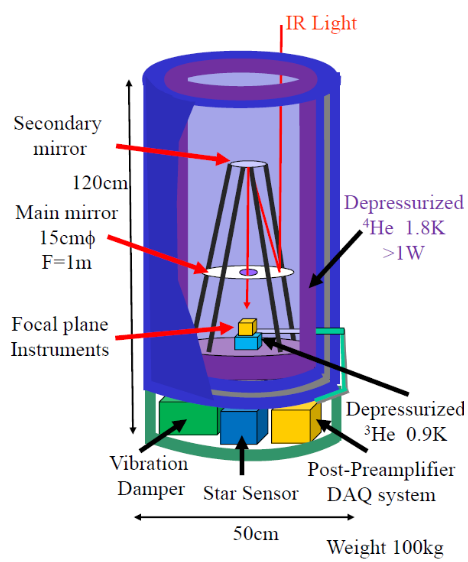


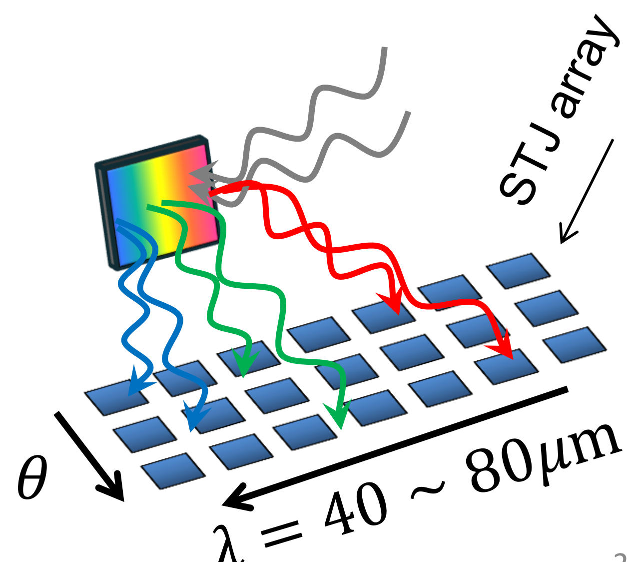
Proposal for COBAND Rocket Experiment

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

JAXA sounding rocket S-520

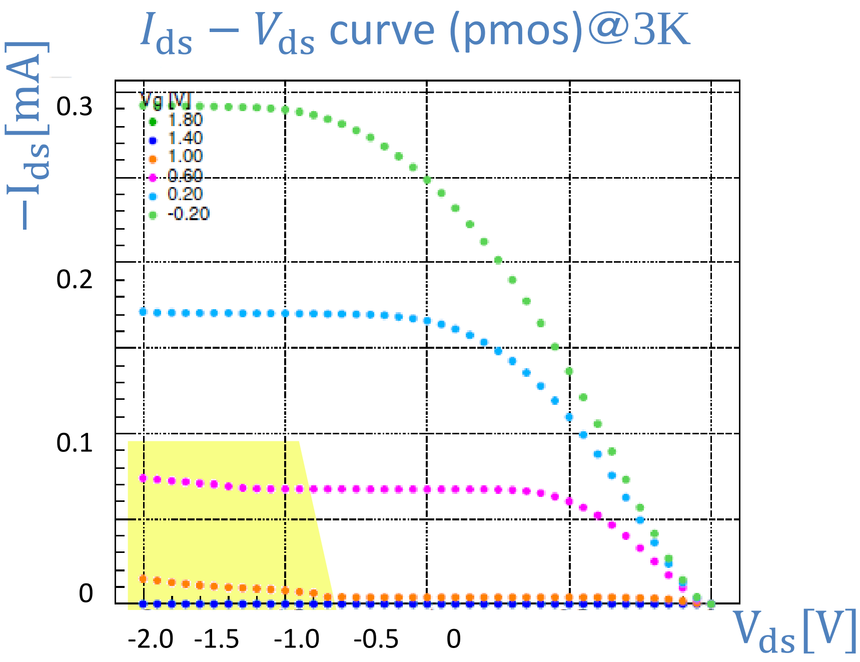
- Telescope with **15cm diameter** and **1m focal length**
- At the focal point, a diffraction grating covering **λ=40-80μm** and an array of photo-detector pixels of **50(λ) x 8(θ)** are placed.
- Each pixel has **100μmx100μm** sensitive area.

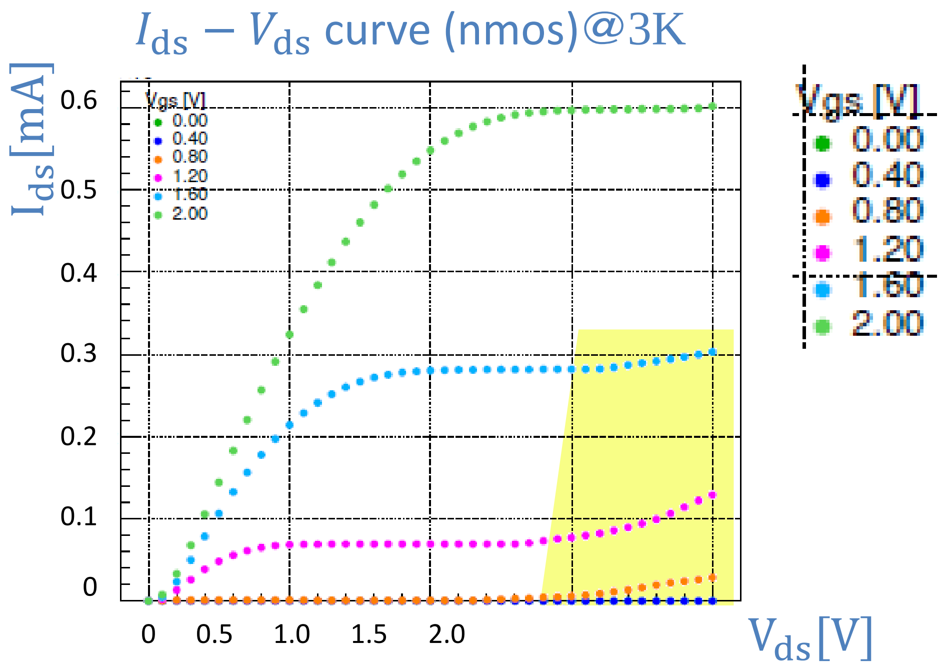




Drain Avaranche

W/L=10μm/5μm





In the region of $|V_{gs}| < |V_{ds}|$, drain current causes drastic increasement. We need to be care not to use this region in design.