筑波大学
University of Tsukuba

超伝導体検出器
– SOI技術との融合による遠赤外一光子検出 STJ 開発 –

2015年11月30日 /光量子計測器開発推進室発足会議

武内勇司 (筑波大 数理物質融合科学センター)

on behalf of Neutrino Decay Collaboration

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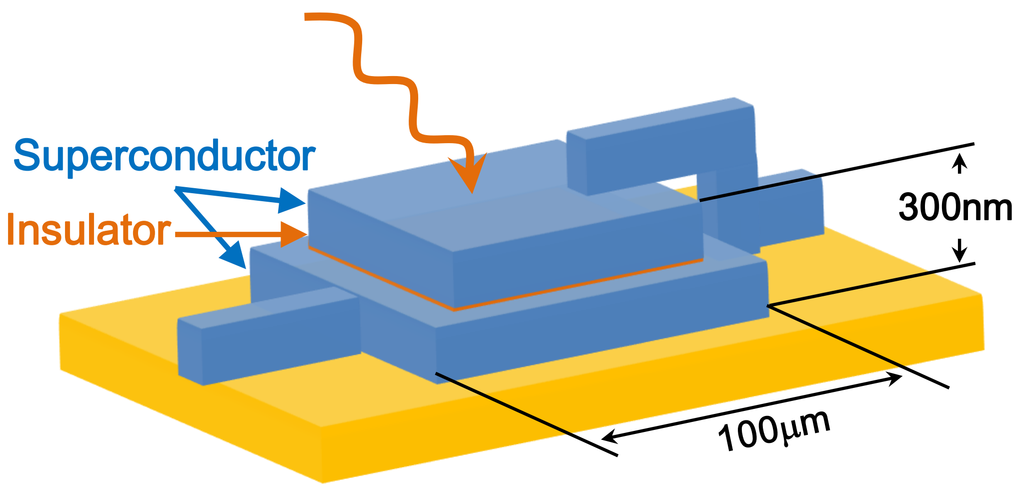
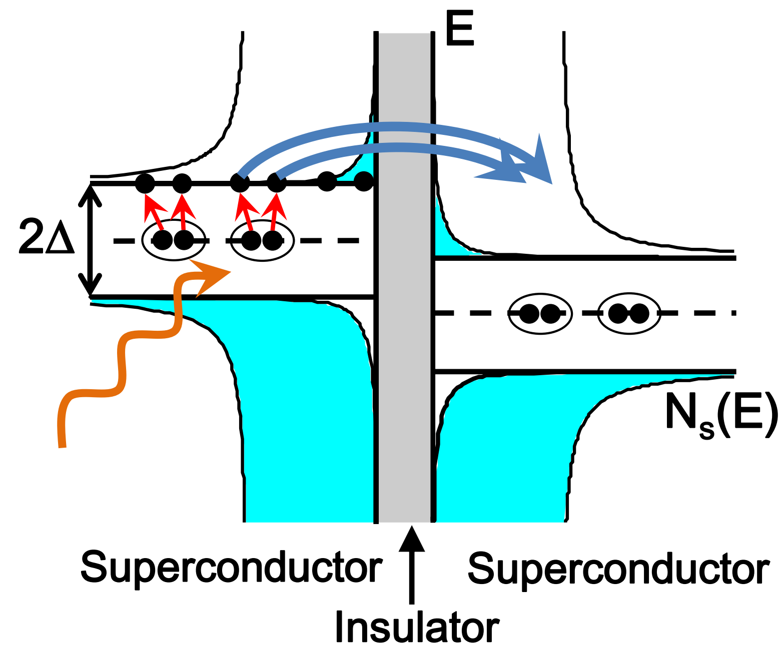
Superconducting Tunnel Junction (STJ)

- Superconductor / Insulator /Superconductor
  Josephson junction device





Δ: Superconducting gap energy

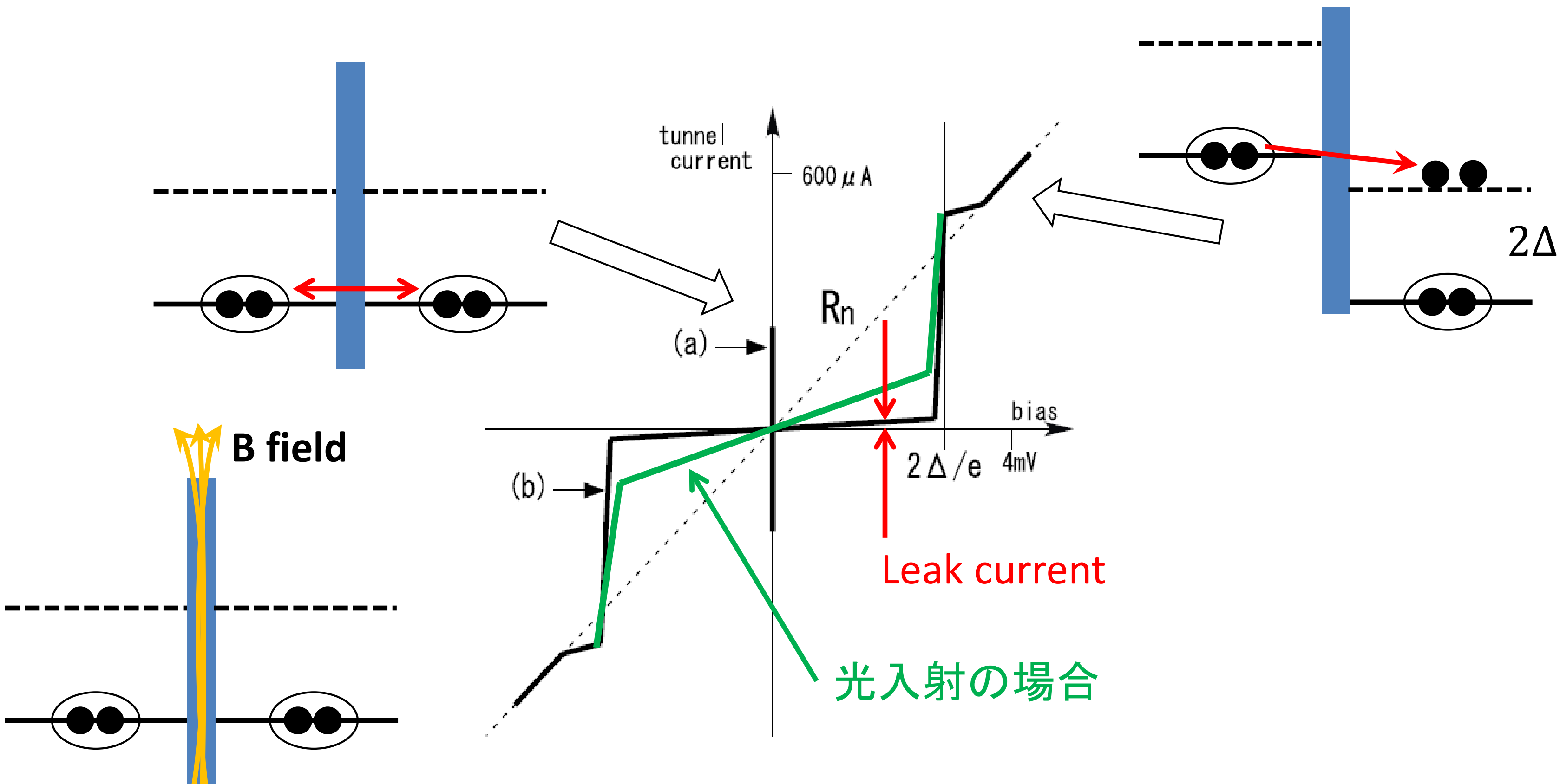
接合面を挟んで電位差(|V|<2Δ)を印加.
超伝導体に吸収された光子のエネルギーにより複数のクーパー対が解離(励起)し,
生成された準粒子によって, エネルギーに比例したトンネル電流が発生.

- 超伝導ギャップ(Δ)は遠赤外フォトンのエネルギーよりもずっと小さい ➔ 原理的には，遠赤外域一光子を検出可能
- ~μs 程度の比較的高速なパルス応答(Nbの場合) ➔ 光子計数することでS/Nの著しい向上

STJ I-V 特性

- Sketch of a current-voltage (I-V) curve for STJ

➔ The Cooper pair tunneling current (DC Josephson current) is seen at V = 0, and the quasi-particle tunneling current is seen for |V|>2Δ

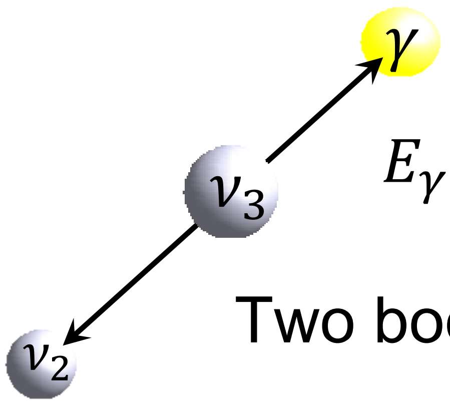


Josephson current is suppressed by magnetic field

宇宙背景ニュートリノ崩壊探索への応用

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

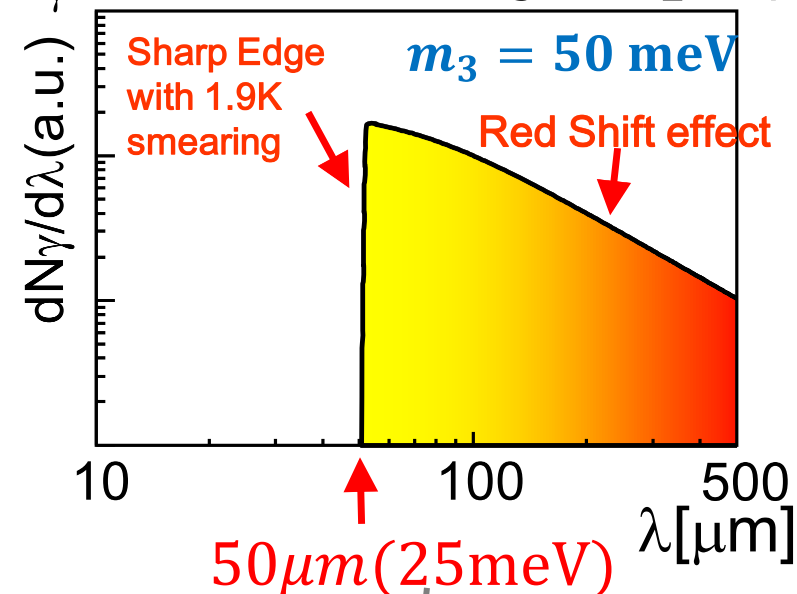
in the ν_3 rest frame

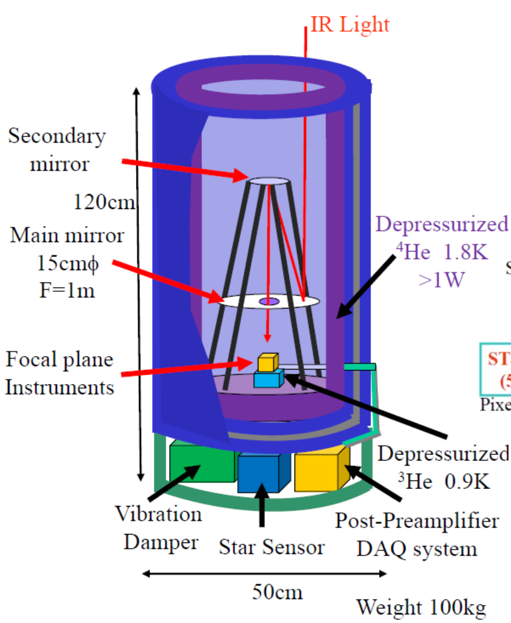


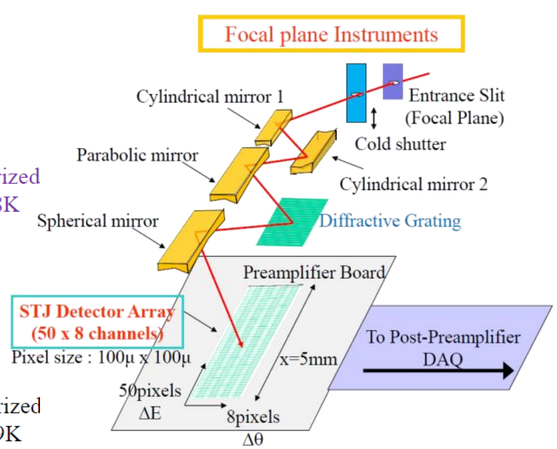
$$E_\gamma = \frac{m_3^2 - m_{1,2}^2}{2m_3}$$

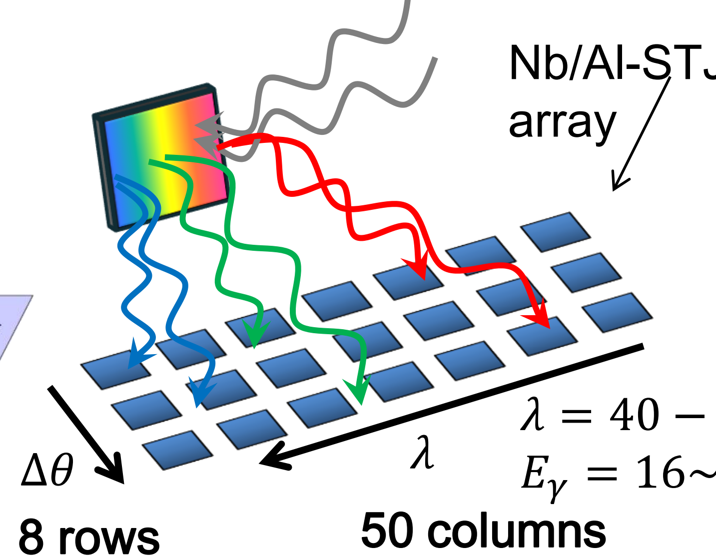
Two body decay

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





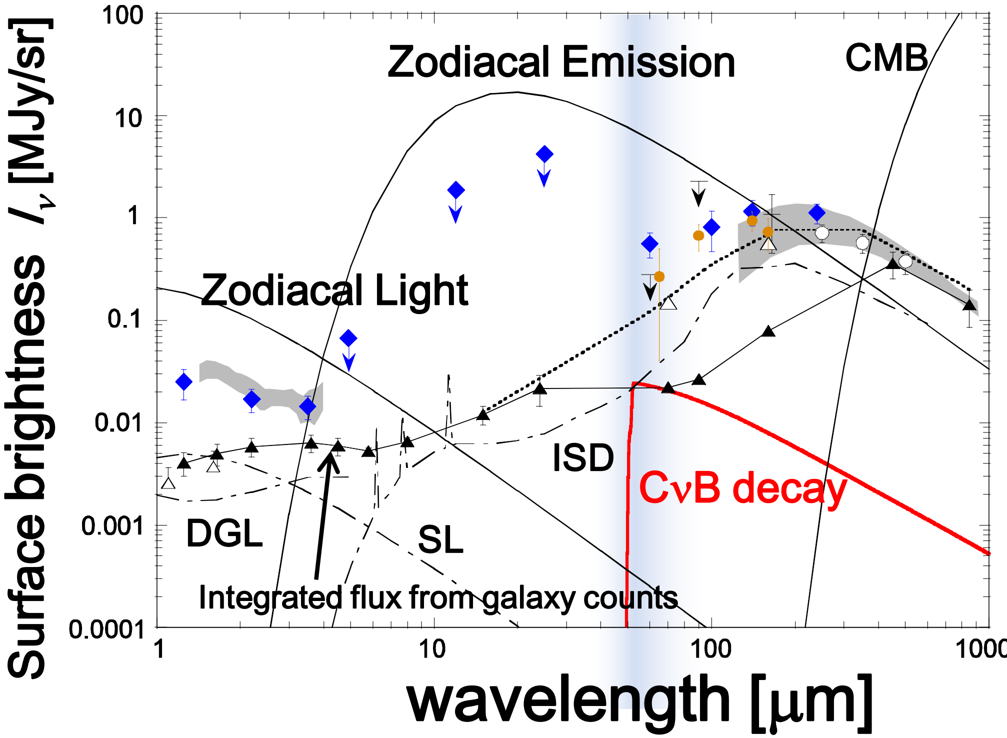




$\lambda = 40 - 80\mu m$

$E_\gamma = 16 \sim 31 \mathrm{meV}$

宇宙背景ニュートリノ崩壊探索への応用



Telescope parameters

- Main mirror
  - D=15cm, F=1m
- detector
  - 波長0.8μm あたり
    100μm x 100μm x 8 pixels
    視野角：8 x 10^{-8} sr

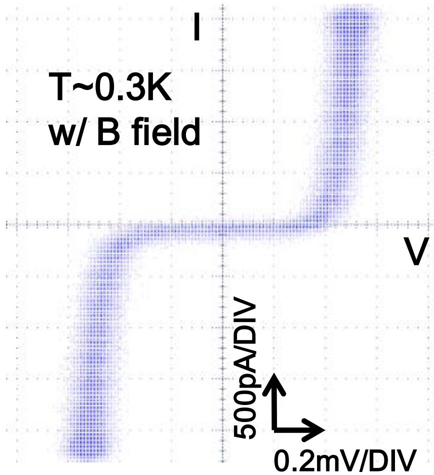
$\tau = 1 \times 10^{14}$yrs

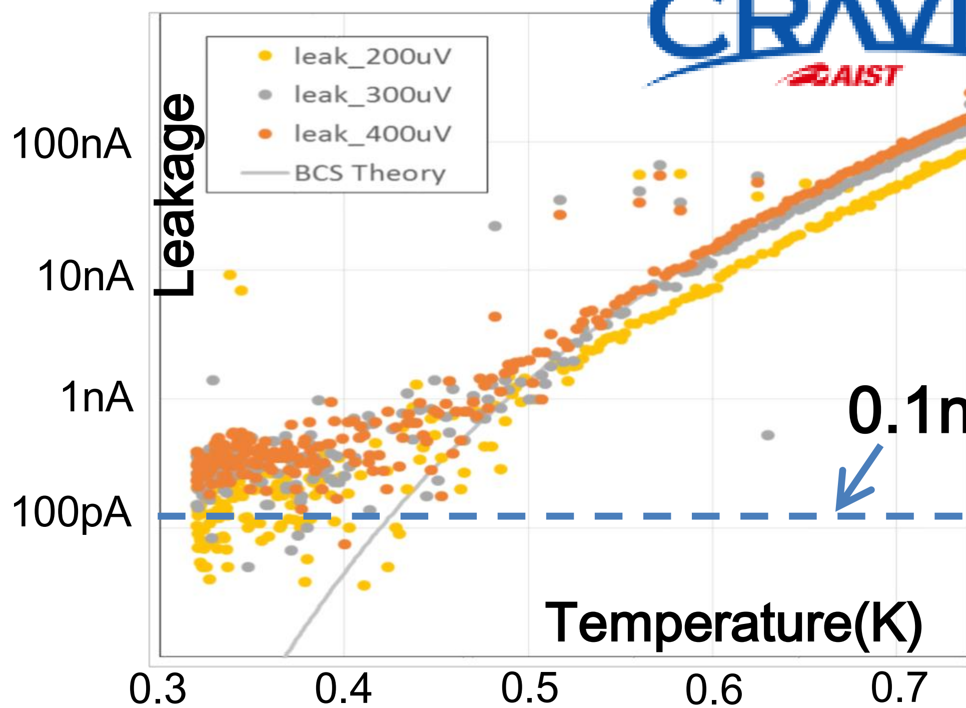
- Neutrino decay ($m_3 = 50$ meV, $\tau_\nu = 1 \times 10^{14}$yrs): I_ν=25kJy/sr
  - 3.3 x 10^{-20} W / 8pixels @ λ=50μm
- 200sec の測定でこれを検出

➔ 検出器の性能として最低でも NEP < $6.6 \times 10^{-19} W/\sqrt{Hz}$ が必要
  - 実際には，本物のフォトンによるバックグラウンド(Zodiacal emission)があるので，更に1 order 位低い必要がある　(NEP<$1 \times 10^{-19} W/\sqrt{Hz}$)

産総研 CRAVITY 製 Nb/Al-STJ

M. Ukibe et al., Jpn. J. Appl. Phys. 51, 010115 (2012)
M. Ohkubo et al., IEEE Trans. Appl. Super, 24, 2400208 (2014





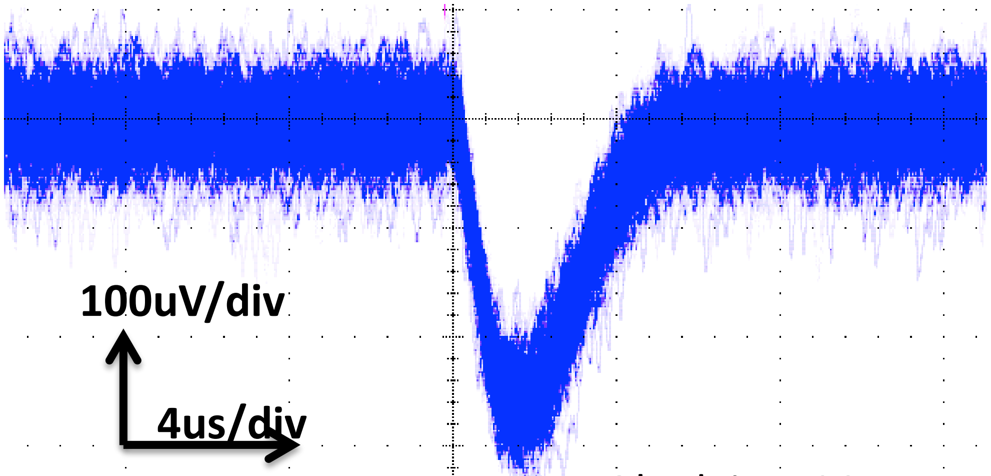
50μm × 50μm Nb/Al-STJ
fabricated in CRAVITY at AIST

- I_{leak}~0.2nA を達成
- 更に小さな junction size のものでテスト中

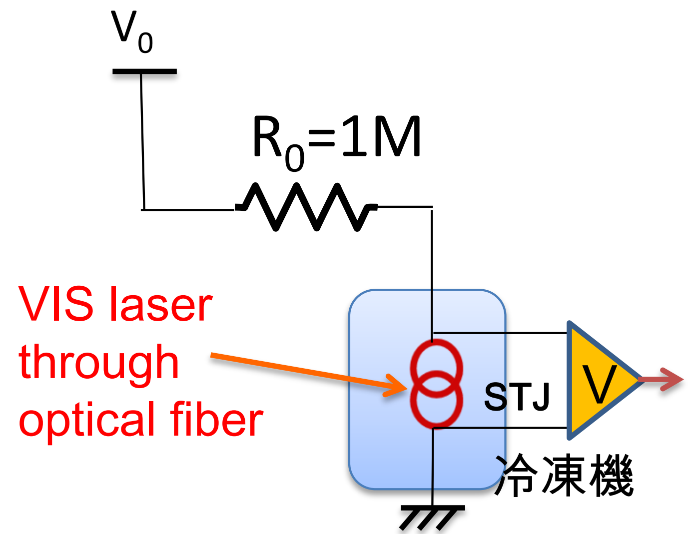
- リーク電流のショットノイズ由来のNEPは，リーク電流i_L=50pA, 超伝導ギャップエネルギーΔ=0.6meV, トラッピングゲインG=10とすると

$$\mathrm{NEP} = \frac{1.7\Delta}{\mathrm{G}}\sqrt{\frac{2i_L}{e}} \sim 4\times10^{-19} W/\sqrt{Hz}$$

STJパルス光応答特性



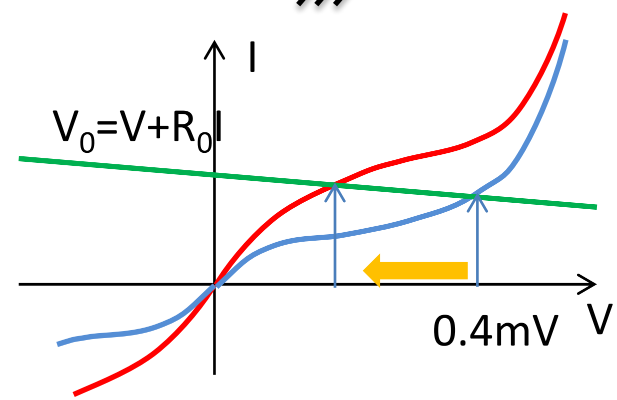
T.Okudaira, 2015.1.16



可視光(465nm)レーザーパルス応答性(AIST製 Nb/Al-STJ 100um角)

STJ 応答信号時定数: 立下り ~1μs, 立上り~2μs (もしくは，これより早い)

定電流モードの回路(右上)で測定



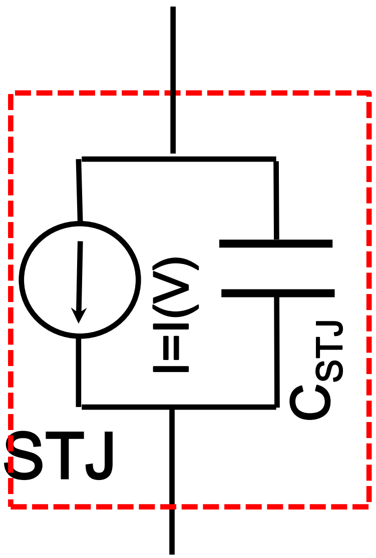
STJ I-V curve w/light w/o light

- Nb/Al-STJは，~1μs という比較的早い応答速度

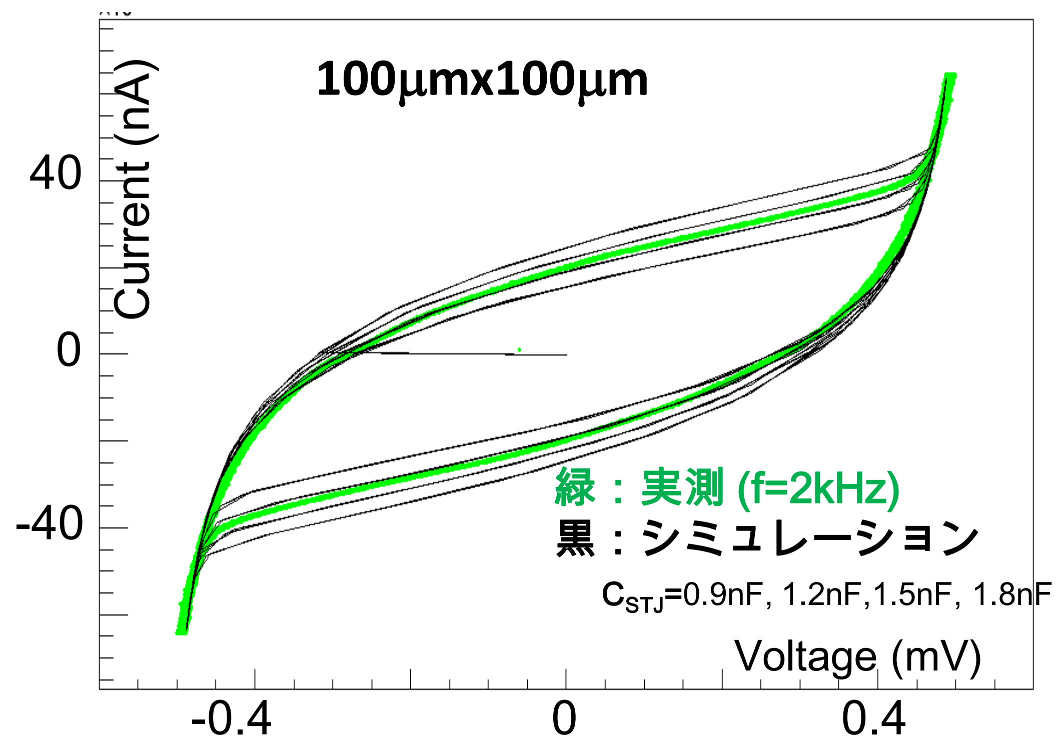
➔ 光子計数を行えば，実効的なNEPは劇的に改善可能

– 但し読出し系の帯域は>1MHzを確保する必要あり

STJ キャパシタンス測定



STJ 等価回路



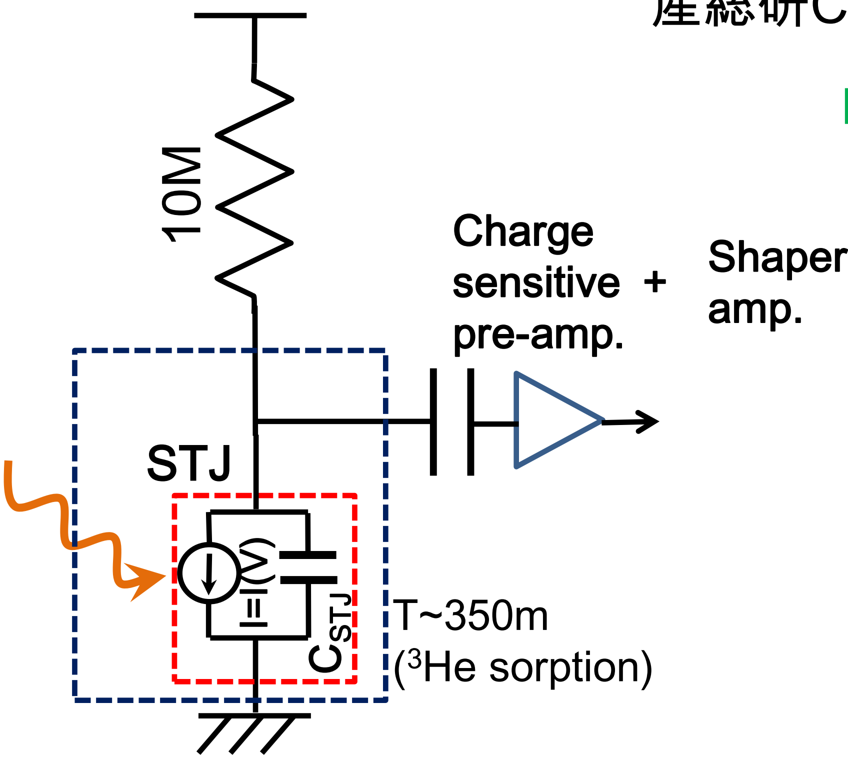
STJ は，junction size に比例したキャパシタンス

- STJのI-V測定からSTJのキャパシタンスを測定
- SIS接合面の面積に比例する成分：　~34fF/μm^2

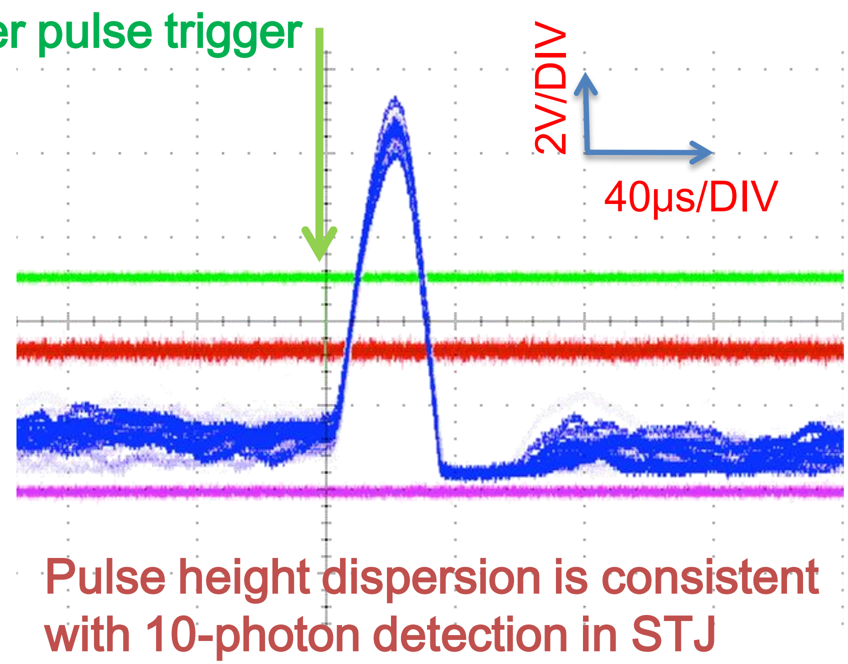
➔ 20μm角のSTJでも 14pF

➔ 低入力インピーダンスの電荷積分型アンプでの読出しが必要

100x100μm² Nb/Al-STJ response to 465nm multi-photons



産総研CRAVITY製100x100μm² Nb/Al-STJ



Nb/Al-STJ の低入力インピーダンス電荷積分アンプ読出

- 可視光パルス（波長465nm）に対する応答
- 室温に置かれた電荷積分型のアンプでの読出
  - 観測した出力電荷量は，およそ10光子の検出に対応
- 一光子検出には，読み出し系のS/N改善が必要

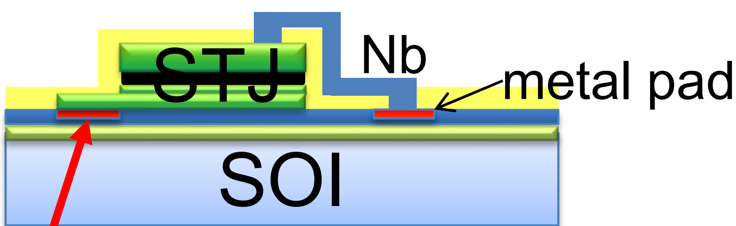
➔極低温電荷積分型アンプの開発

Development of SOI-STJ

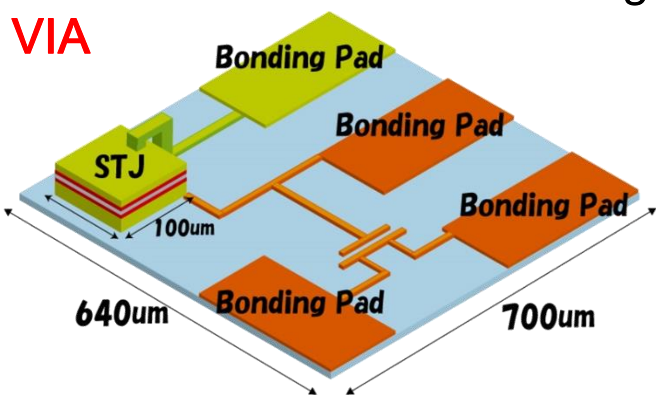
- SOI: Silicon-on-insulator
  - CMOS in FD-SOI is reported to work at 4K by T. Wada (JAXA), et al.

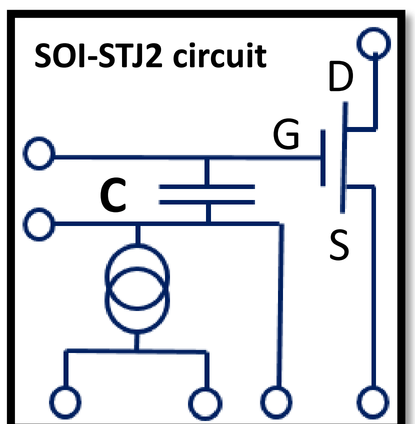
J Low Temp Phys 167, 602 (2012)

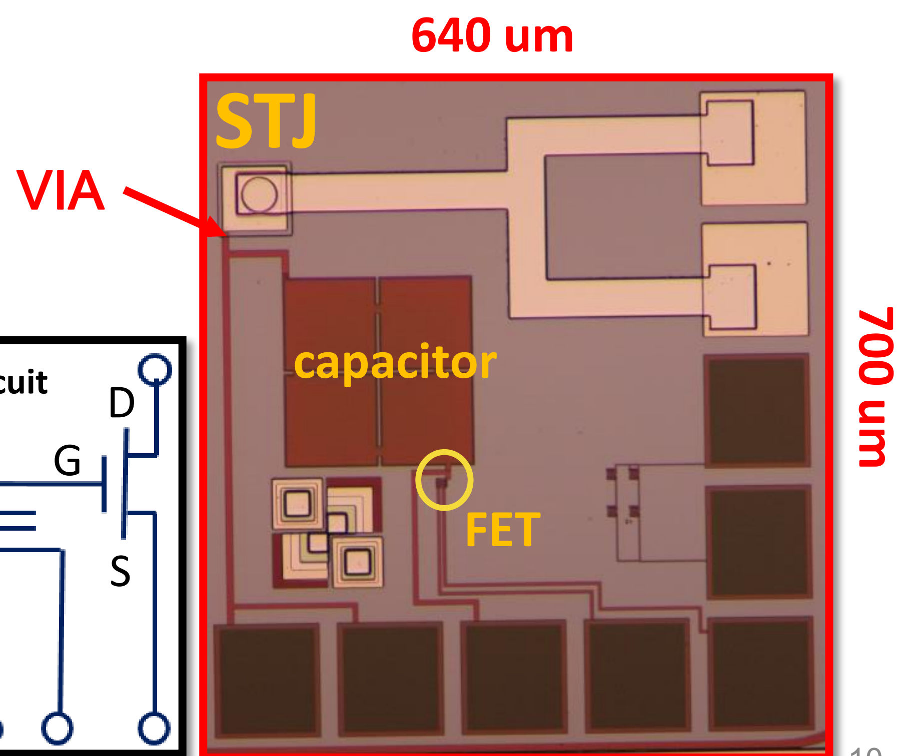
- SOI と STJ の融合 (SOI回路一体型 STJ の基礎研究)
  - STJ layers are fabricated directly on a SOI pre-amplifier board and cooled down together with the STJ
- Started test with Nb/Al-STJ on SOI with p-MOS and n-MOS FET



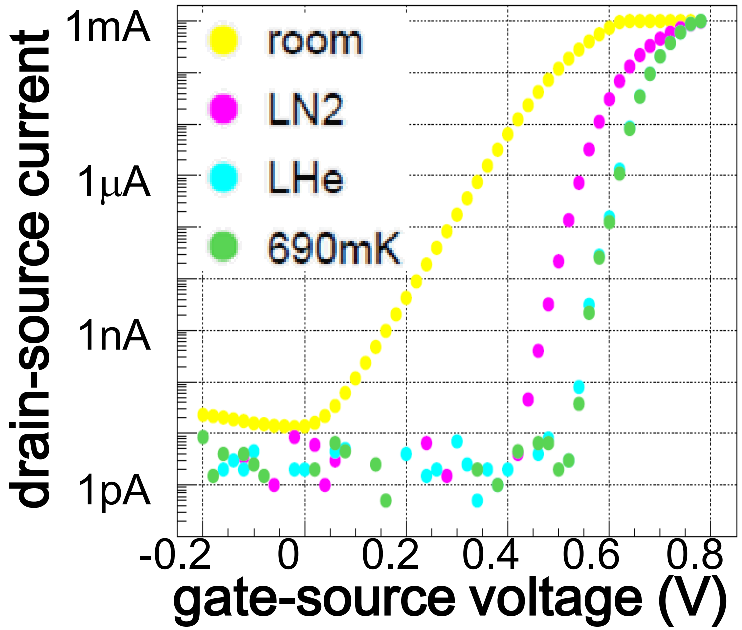
STJ lower layer has electrical contact with SOI circuit through VIA



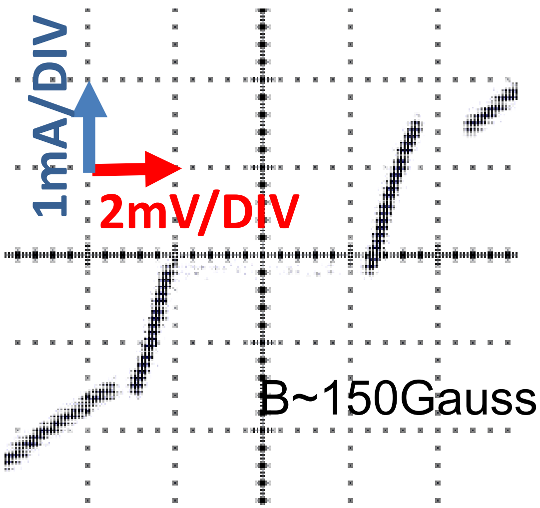




SOI上にSTJを形成後の特性



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

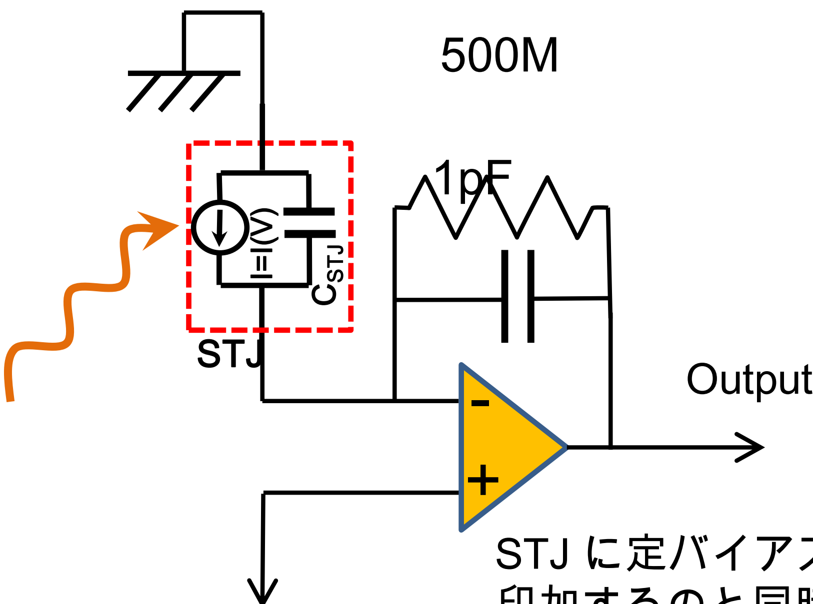


I-V curve of a STJ fabricated at KEK on a FD-SOI wafer

- Both nMOS and pMOS-FET in FD-SOI wafer on which a STJ is fabricated work fine at temperature down below 1K
  - 極低温では，スレッショルド電圧のシフト，サブスレッショルド領域のドレイン電流抑制，飽和領域でのドレイン電流の上昇など，特性が変動
- Nb/Al-STJ fabricated at KEK on FD-SOI works fine
- We are also developing SOI-STJ where STJ is fabricated at CRAVITY

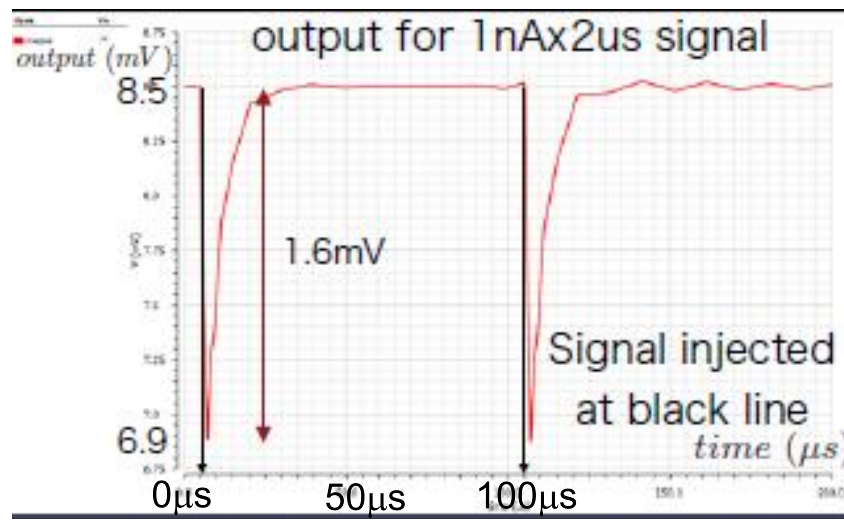
SOI Pre-amplifier development

- 遠赤外一光子検出に向け，前段階として近赤外一光子検出に最適化した電荷積分型アンプをVDEC* が提供するSPICE simulation で設計中
- 極低温での SOI MOSFET の振る舞いをシミュレーションに組み込むため KEK や JAXA と共同研究で SPICE用MOSFETパラメータを構築中
  - 様々なL(チャンネル長：L=0.4~5um)やW(チャンネル幅: W=1~10um)を持ったFETの3Kにおける特性の測定



V=0.4mV

STJ に定バイアスを印加するのと同時にSTJに発生した電荷を積分



室温でのFET パラメータを仮定したSPICE simulation
入力電荷:2fC
1.3eV(波長1μm)の一光子入射相当

* VLSI Design and Education Center(VDEC), the U. Tokyo in collaboration with Synopsys, Inc., Cadence Design Systems, Inc., and Mentor Graphics, Inc.

まとめ

- 遠赤外(50μm)の一光子検出が可能な検出器を STJ + SOI の技術を用いて開発中
  - 光子計数により，実効的にNEP で$\sim 10^{-20} W/\sqrt{Hz}$ を目指す
- Nb/Al-STJ は，産総研CRAVITY で世界最高水準の低リーク電流のものが得られている(<200pA @ 50μm角)
  - 20μm角，10μm角のものもテスト中
- SOIに技術を用いた極低温アンプによる読出し回路を開発中
  - 様々なW/LをもつSOI MOSFETの極低温でのI-V測定➔SPICE シミュレーションにもちいるFETパラメータ抽出
  - 光子計数の利点を最大限に生かす高速アンプ(帯域>1MHz)
  - SOI アンプ一体型STJの可能性

Backup

Neutrino

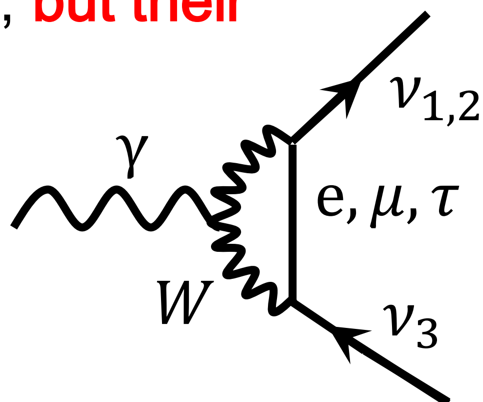
- Neutrino has 3 mass generations (ν_1, ν_2, ν_3)
- Neutrino flavor states (ν_e, ν_μ, ν_τ) are not mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

➔ Neutrino flavor oscillates during the flight, and squared mass differences (Δm_{12}^2, $|\Delta m_{23}^2|$) have been measured, **but their absolute masses are not measured yet!**

□ **Heavier neutrinos (ν_2, ν_3) are not stable**

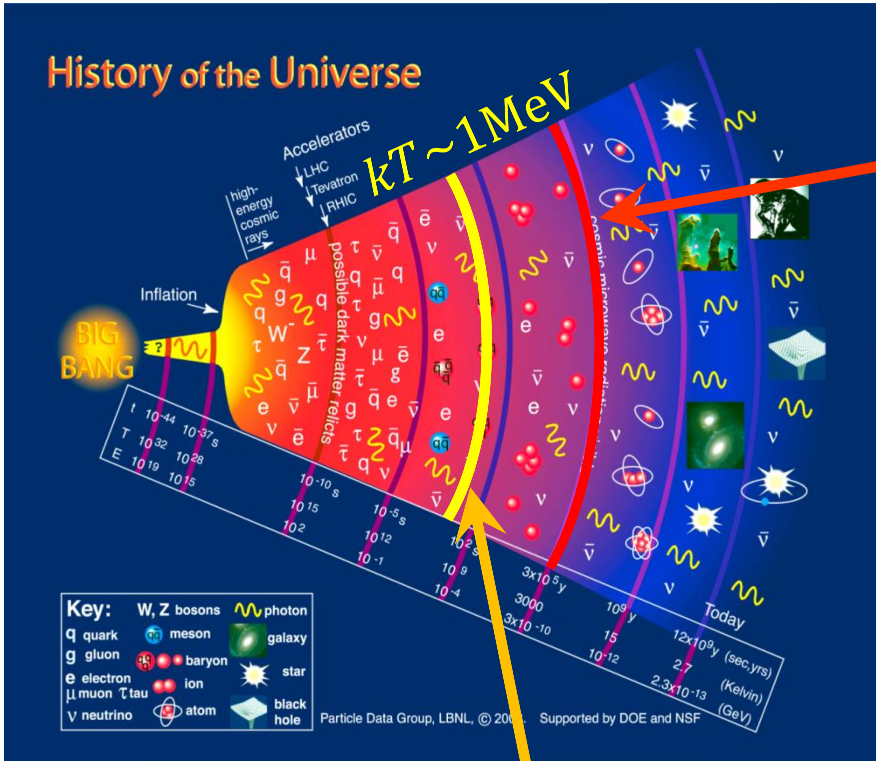
- Neutrino can decay through the loop diagrams
- $\nu_3 \rightarrow \nu_{1,2} + \gamma$
- Neutrino mass can be determined from the decay

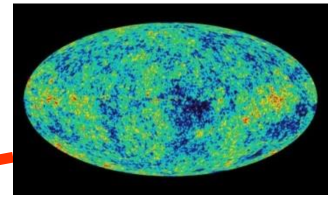


✓ However, neutrino lifetime is expected to be very long (much longer than the age of universe)

➔ We adopt Cosmic neutrino background (CνB) as the neutrino source for neutrino decay search

Cosmic neutrino background (CνB)

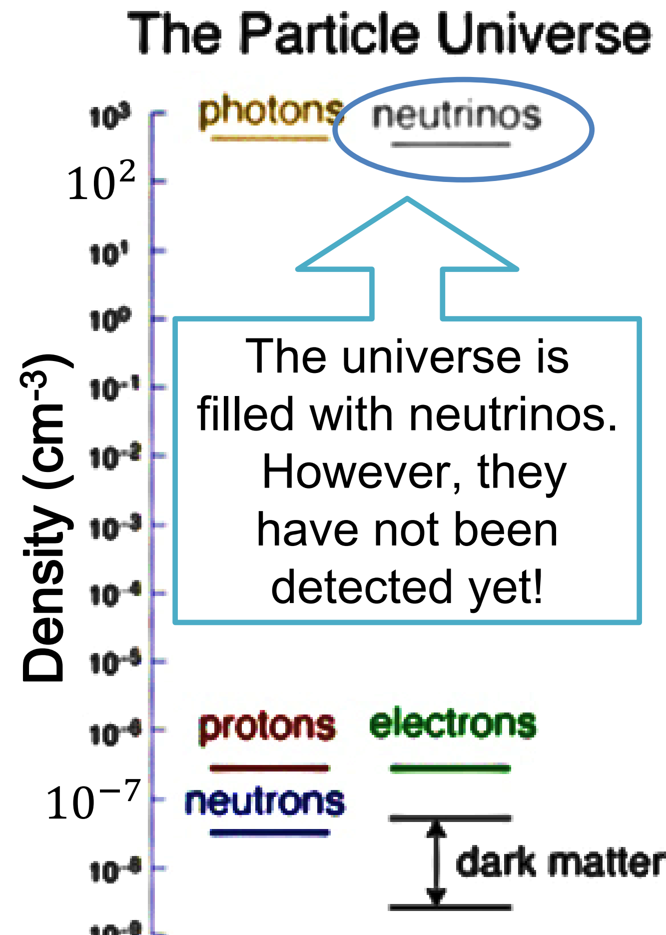




CMB

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

$T_\gamma = 2.73\ \mathrm{K}$



CνB (=neutrino decoupling)

~1s after the big bang

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

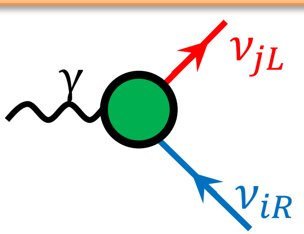
$$n_\nu + n_{\bar{\nu}} = \frac{3}{4}\left(\frac{T_\nu}{T_\gamma}\right)^3 n_\gamma = 110/\mathrm{cm}^3$$

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

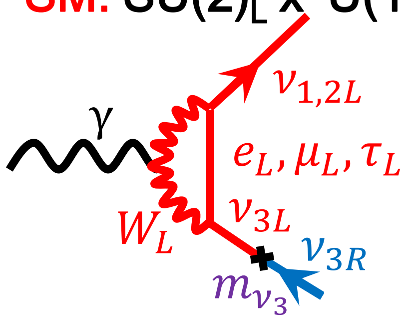
Motivation of ν-decay search in CνB

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

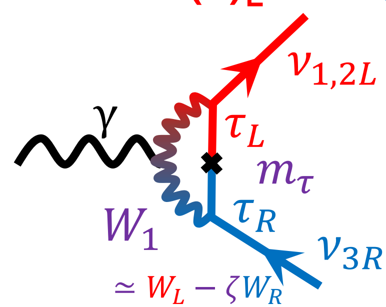


$\Gamma \sim \left(10^{43}\ yr\right)^{-1}$
Suppressed by m_ν and GIM

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

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

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



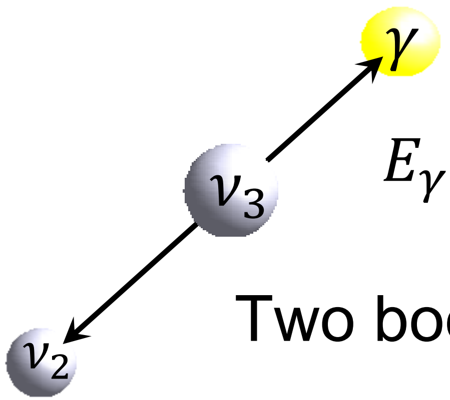
$\Gamma \sim \left(10^{17}\ yr\right)^{-1}$
Only suppressed by L-R mixing (ζ)

10^{26} enhancement to SM

Photon Energy (Wavelength) in Neutrino Decay

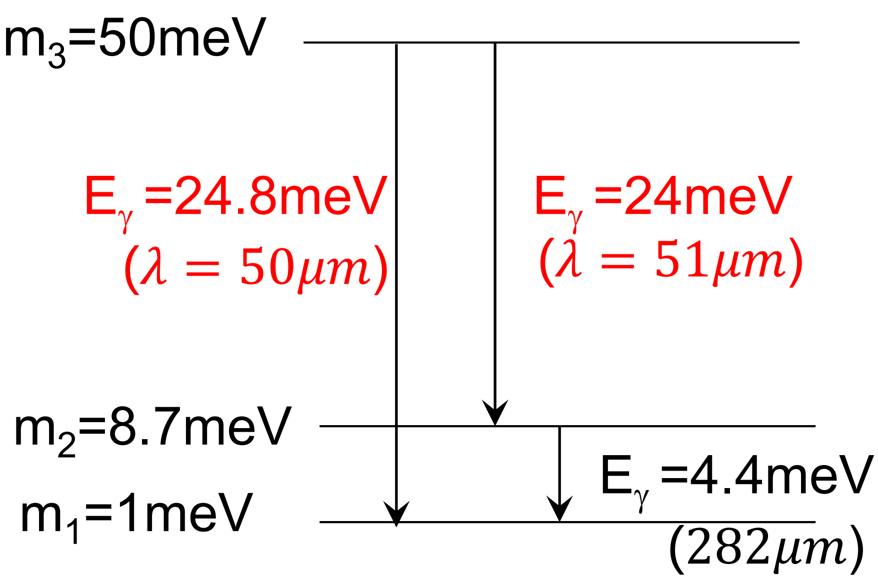
$\nu_3 \rightarrow \nu_{1,2} + \gamma$

in the ν_3 rest frame



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

Two body decay

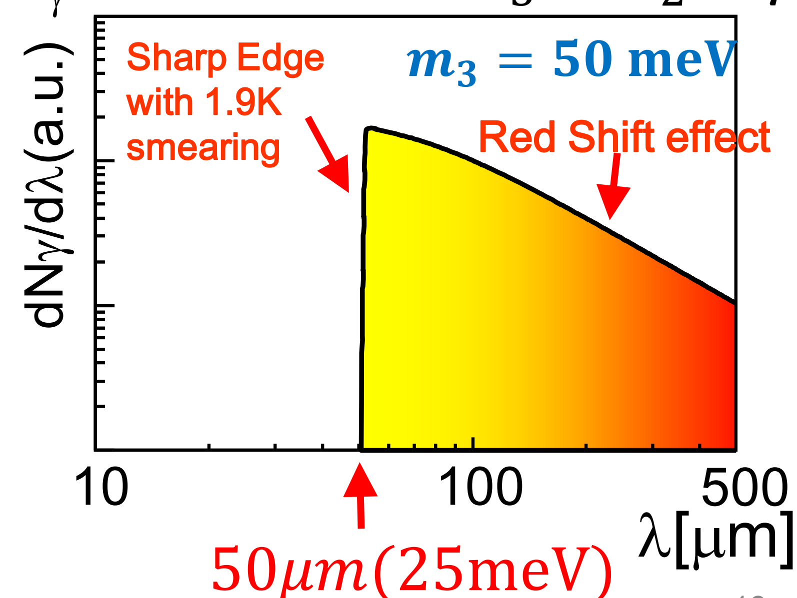


- From neutrino oscillation
  - $|\Delta m_{23}^2| = |m_3^2 - m_2^2| \sim 2.4 \times 10^{-3}\ eV^2$
  - $\Delta m_{12}^2 \sim 7.65 \times 10^{-5}\ eV^2$
- From Planck+WP+highL+BAO
  - $\sum m_i < 0.23$ eV

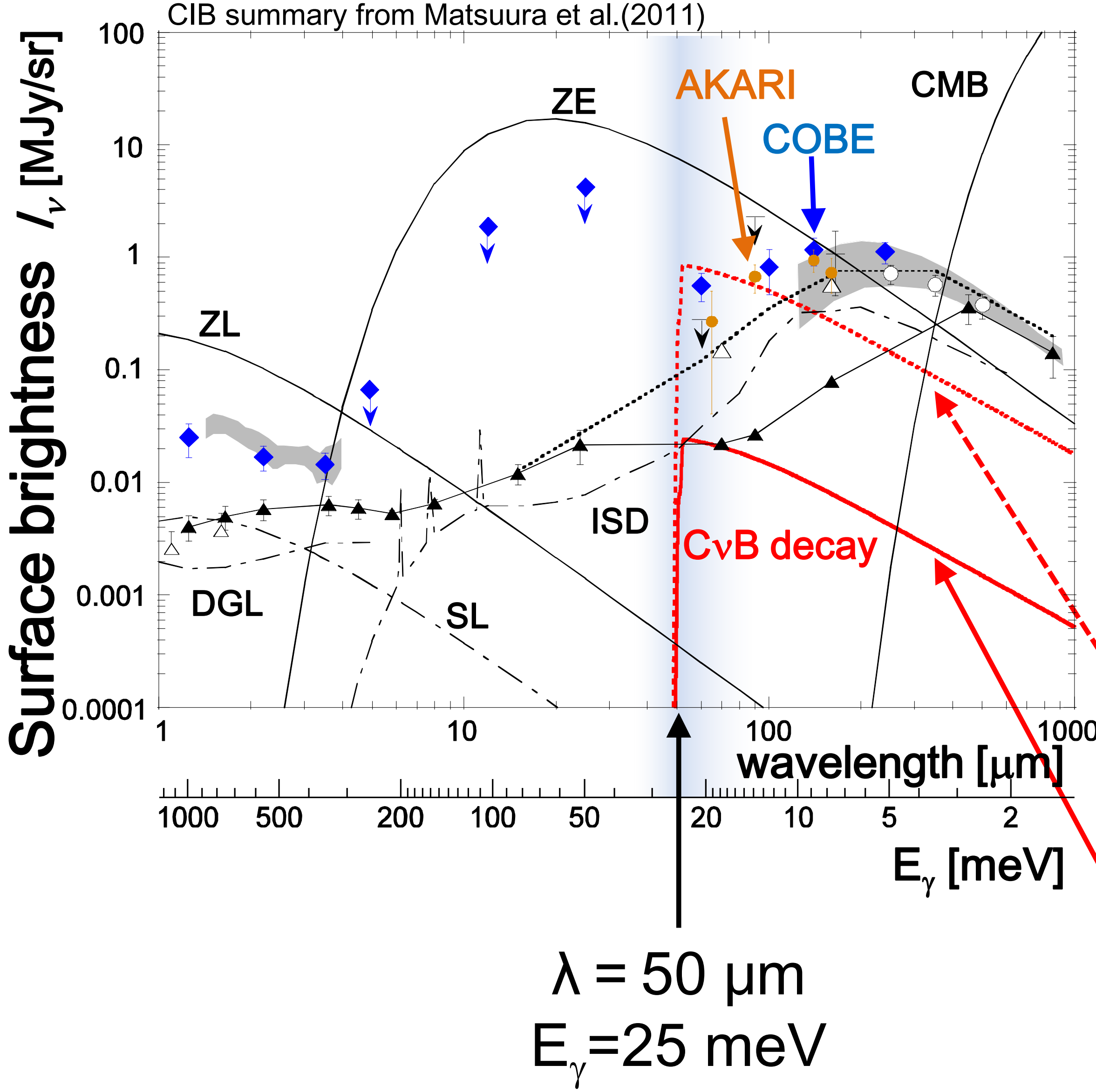
➔ 50meV<m_3<87meV

$E_\gamma^{\rm rest}$ =14~24meV (λ_γ =51~89μm)

λ_γ 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_γ spectrum

$m_3 = 50\text{meV}$

$\tau = 3 \times 10^{12}\text{yrs}$

I_ν ~ 0.8MJy/sr

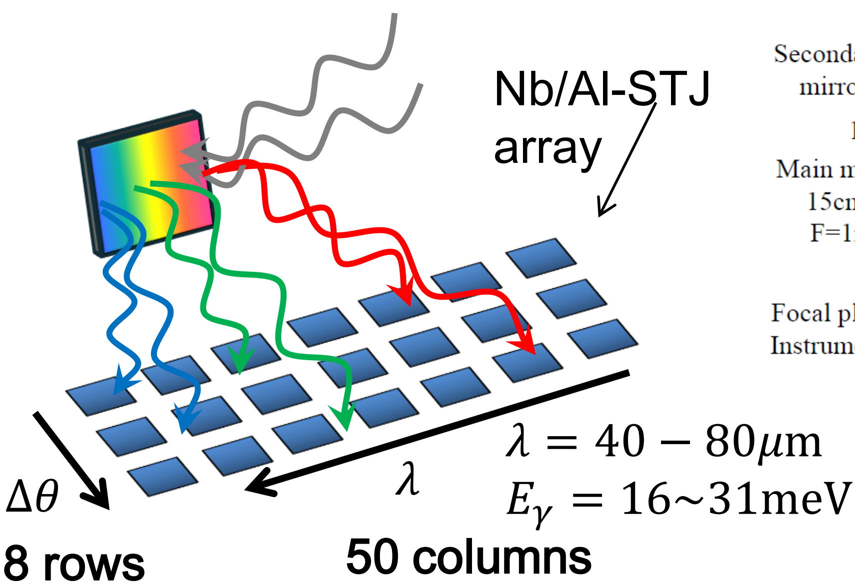
Excluded by S.H.Kim et. al 2012

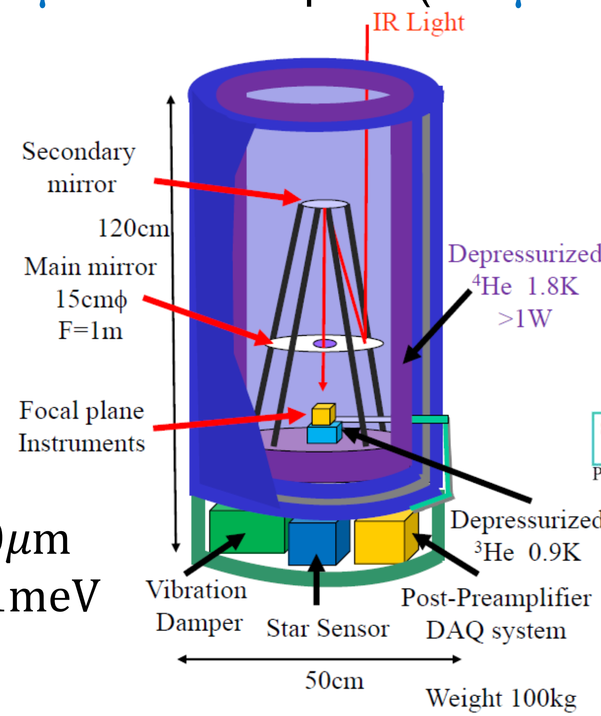
$\tau = 1 \times 10^{14}\text{yrs}$

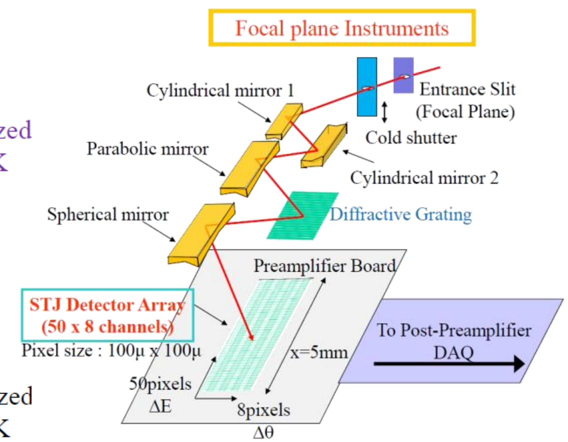
I_ν ~ 25kJy/sr

Proposed rocket experiment with a diffraction grating and Nb/Al-STJ array combination

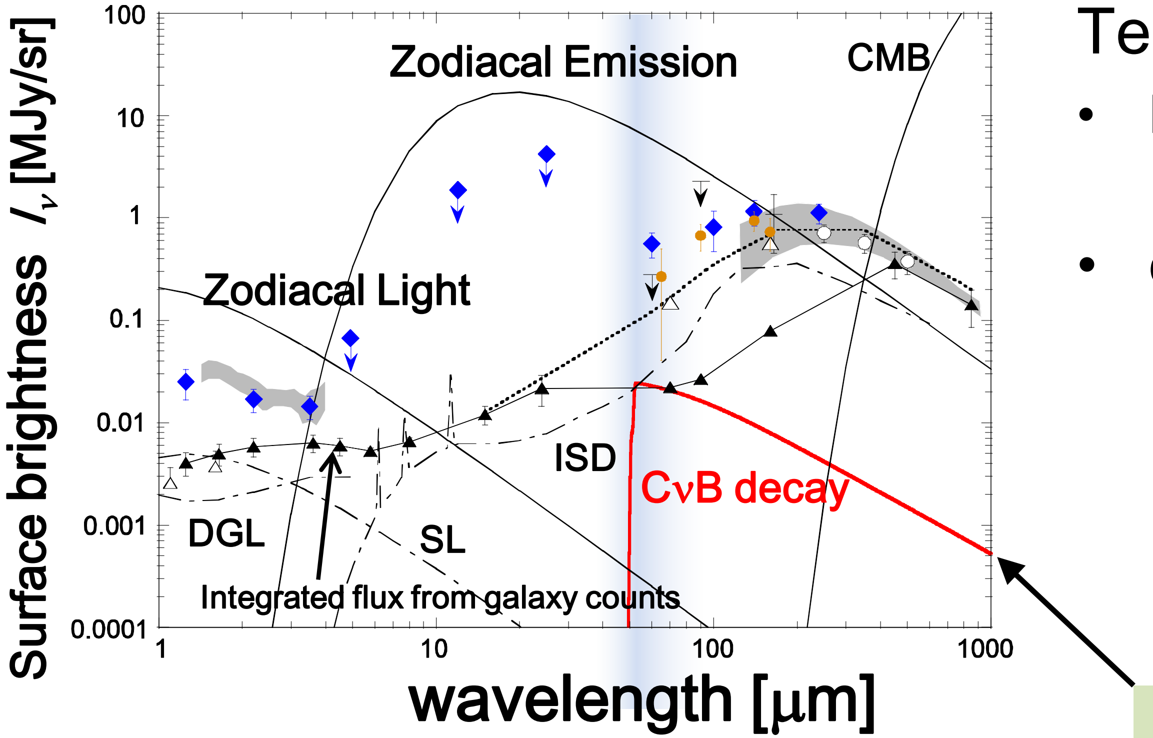
- 200-sec measurement at altitude of 200~300km
  - Telescope with diameter of 15cm and focal length of 1m
  - All optics (mirrors, filters, shutters and grating) will be cooled at ~1.8K
- At the focal point, diffraction grating covering λ=40-80μm (16-31meV) and array of Nb/Al-STJ pixels of 50(in wavelength distribution) x 8(in spatial distribution) are placed
  - Each Nb/Al-STJ pixel is used as a single-photon counting detector for FIR photon in λ=40−80μm ($\Delta\lambda = 0.8\mu m$)
  - Sensitive area of 100μmx100μm for each pixel (100μrad x 100μrad in viewing angle)







Expected precision in the spectrum measurement



Telescope parameters

- Main mirror
  - D=15cm, F=1m
- detector
  - sensitive area 100µmx100µm / pixel
  - 50 x 8 array

$$\Delta\lambda = \frac{80\mu m - 40\mu m}{50} = 0.8\mu m$$

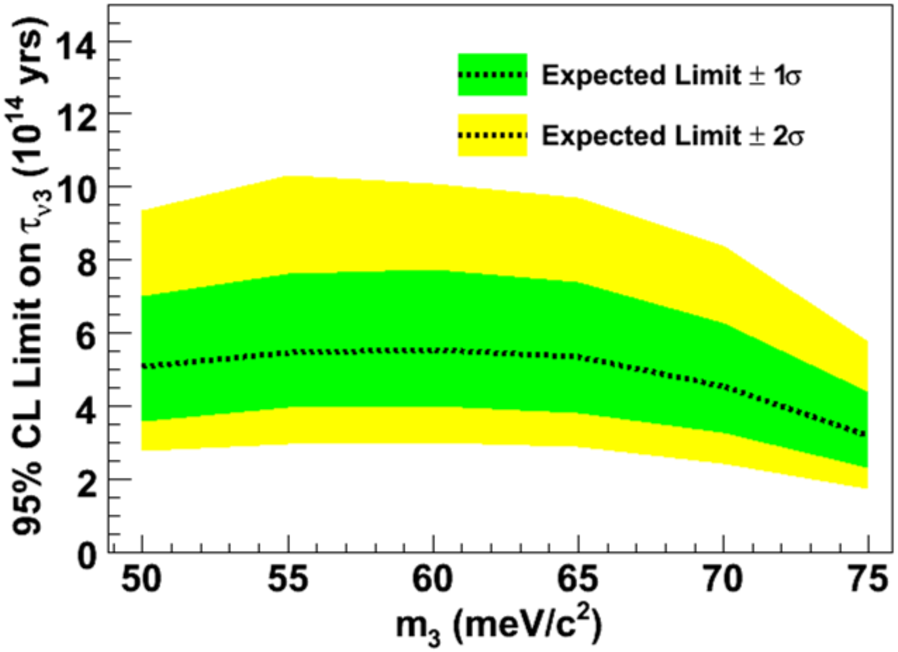
- Zodiacal emission ⇒ 343Hz / pixel
  - 200sec measurement: 0.55M events / 8 pixels (at $\lambda = 50\mu m$)
  - 0.13% accuracy measurement for each wavelength: $\delta(I_\nu)$=11kJy/sr
- Neutrino decay ($m_3 = 50$ meV, $\tau_\nu = 1 \times 10^{14}$yrs): I_ν=25kJy/sr
  - 2.3σ away from statistical fluctuation in ZE measurement

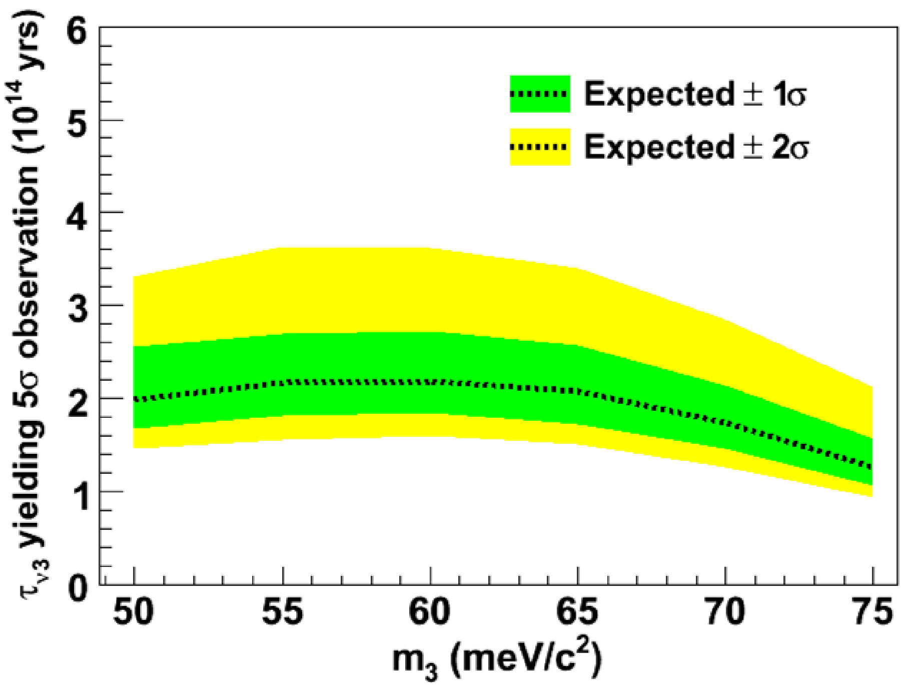
ν decay with $\tau_\nu = 10^{14}$ yrs is possible to detect, or set lower limit!

Sensitivity to neutrino decay

Parameters in the rocket experiment simulation

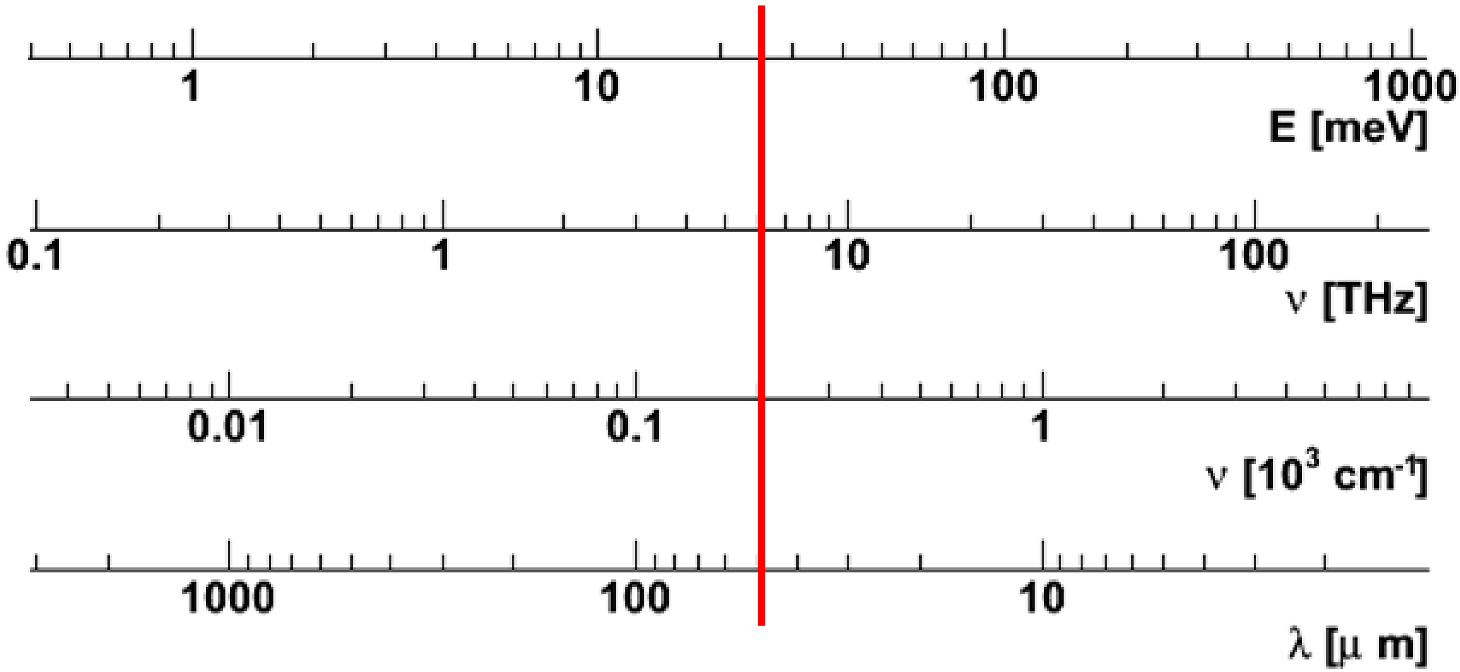
- telescope dia.: 15cm
- 50-column (λ: 40μm – 80 μm) $\times$ 8-row array
- Viewing angle per single pixel: 100μrad $\times$ 100μrad
- Measurement time: 200 sec.
- Photon detection efficiency: 100%





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

Energy/Wavelength/Frequency



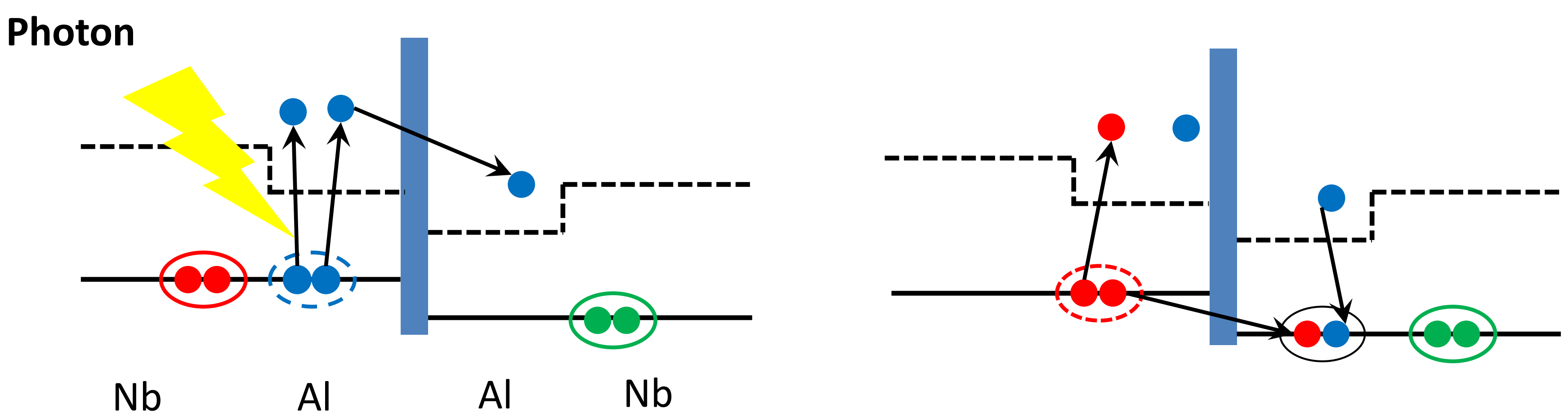
$$E_\gamma = 25 \text{ meV}$$

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

$$\lambda = 50\mu m$$

STJ back-tunneling effect

- Quasi-particles near the barrier can mediate Cooper pairs, resulting in true signal gain
  - Bi-layer fabricated with superconductors of different gaps $\Delta_{Nb} > \Delta_{Al}$ to enhance quasi-particle density near the barrier
  - Nb/Al-STJ Nb(200nm)/Al(10nm)/AlOx/Al(10nm)/Nb(100nm)
- Gain: 2～200



STJ energy resolution

Statistical fluctuation in number of quasi-particles ➔ energy resolution

➔ Smaller superconducting gap energy Δ yields better energy resolution

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

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

	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

Nb

Well-established as Nb/Al-STJ
(back-tunneling gain from Al-layers)

$N_{q.p.}$=25meV/1.7Δ=9.5

Poor energy resolution, but a single-photon detection is possible

Hf

Hf-STJ is not established as a practical photon detector yet

$N_{q.p.}$=25meV/1.7Δ=735

2% energy resolution is achievable if Fano factor <0.3 for a single-photon

検出器に要求されるNEP

Telescope parameters

- Main mirror: D=15cm, F=1m
- detector
  - 波長0.8μm (=(80μm-40μm)/50, Δν=c/50μm-c/50.8μm=94GHz)あたり
    100μm x 100μm x 8 pixels ➔ 視野角：8 x 10^{-8} sr

- Neutrino decay ($m_3 = 50$ meV, $\tau_\nu = 1 \times 10^{14}$yrs): I_ν=25kJy/sr @ λ=50μm
  $F\nu\gamma = 25\ kJy/sr \times\ 8 \times 10^{-8} sr \times \pi(15cm/2)^2 \times 94GHz = 3.3 \times 10^{-20} W/8pix$
- Zodiacal emission: I_ν=8MJy/sr @ λ=50μm
  $F_{ZE} = 1.1 \times 10^{-17} W/8pix$
- Δt 時間でF_{ZE} 積分した際の揺らぎ
  エネルギーε_γのフォトン数揺らぎ起因：$\epsilon_\gamma \sqrt{F_{ZE}\Delta t/\epsilon_\gamma} = \sqrt{\epsilon_\gamma\ F_{ZE}\Delta t}$
- 測定条件，検出器要件を決める不等式

$$NEP \times \sqrt{2\Delta t} < \sqrt{\epsilon_\gamma\ F_{ZE}\Delta t}\ < F\nu\gamma\Delta t$$

➔ Δt>40sec (1σ), Δt>200sec (2.2σ)

➔ $\mathrm{NEP} < 1.5 \times 10^{-19} W/\sqrt{Hz}$ for Δt=200sec with 8 pix