Search for Neutrino Decay

Shin-Hong Kim,

at US-Japan Joint Committee (April 18, 2012)

- **Introduction**
  - Motivation
  - Cosmic Infrared Background Measurement by COBE and AKARI
  - Past Results of Search for Neutrino Decay
- **Neutrino Decay**
  - Neutrino Lifetime
  - Energy Spectrum of Decay Photon and Background
- **Proposal on Search for Neutrino Decay**
  - Superconducting Tunnel Junction (STJ) Infrared Photon Detector

Collaboration Members

Japan Group

Shin-Hong Kim, Yuji Takeuchi, Ken-ichi Takemasa, Takashi Onjo, Hyun-Sang Jeong, Shinya Kanai, Kazuki Nagata (University of Tsukuba) ,
Hirokazu Ikeda, Shuji Matsuura (JAXA/ISAS) ,
Hirokazu Ishino, Atsuko Kibayashi, Satoshi Mima, Yasuki Yuasa(Okayama University) ,
Takuo Yoshida, Yusuke Shimizu, Mikiya Nagashima (Fukui University) ,
Yukihiro Kato (Kinki University) ,
Masashi Hazumi (KEK)

Korea Group

Soo-Bong Kim (Seoul National University)

US Group

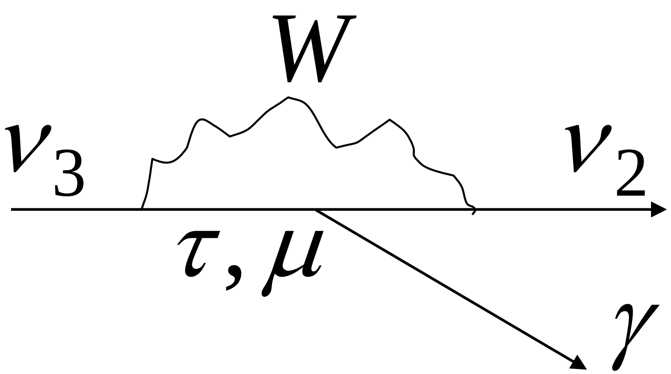
Erik Ramberg, Jonghee Yoo, Juan Estrada (Fermilab)

Introduction

Motivation of Search for Cosmic Background Neutrino Decay

● **Δm^2_{ij} have been measured accurately by neutrino oscillation experiments. but neutrino mass itself has not been measured. Can we measure it ?**

Detection of neutrino decay enables us to measure an independent quantity. Thus we can obtain neutrino mass itself from these two independent measurements.



$$E_\gamma = \frac{m_3^2 - m_2^2}{2m_3} = \frac{\Delta m_{23}^2}{2m_3}$$

Using $\Delta m_{23}^2 = (2.43 \pm 0.13) \times 10^{-3} \mathrm{eV}^2$

$E_\gamma = 10 \sim 25$ meV at ν_3 rest frame.

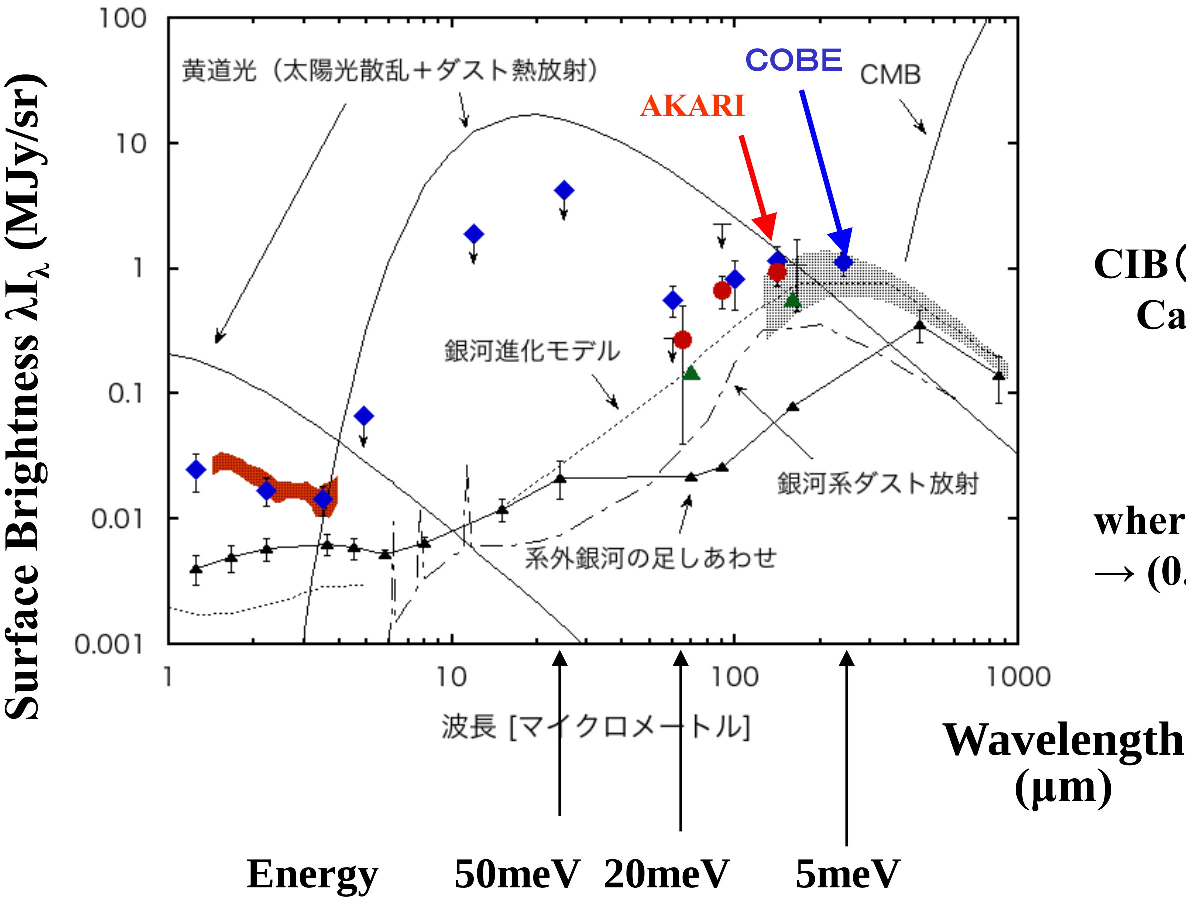
(Far - Infrared region : $\lambda = 50 \sim 125\mu$)

● **As the neutrino lifetime is very long, we need use cosmic background neutrino to observe the neutrino decay. To observe this decay of the cosmic background neutrino means a discovery of the cosmic background neutrino predicted by cosmology.**

Cosmic Infrared Background（CIB）measured by COBE and Neutrino Lifetime Limit from CIB

COBE: M. G. Hauser *et al.* Astrophys. J. 508 (1998) 25.
D. P. Finkbeiner *et al.* Astrophys. J. 544 (2000) 81.

AKARI: S. Matsuura *et al.* Astrophys. J. 737 (2011) 2.



A. Mirizzi, D. Montanino and P. Serpico, "Revisiting cosmological bounds on radiative neutrino lifetime" PRD76, 053007 (2007)

CIB（Cosmic Infrared Background）:
Calculate τ_H by the following equation:

$$\int_{E_{\rm min}}^{\varepsilon_H} \varphi_E dE < \Phi_{\rm CIB},$$

where φ_{CIB} = 24 nW m^{-2} sr^{-1}（COBE）.
→ (0.5 ~ 1) x 10^{20} sec = (1.6~3.1)x10^{12} year

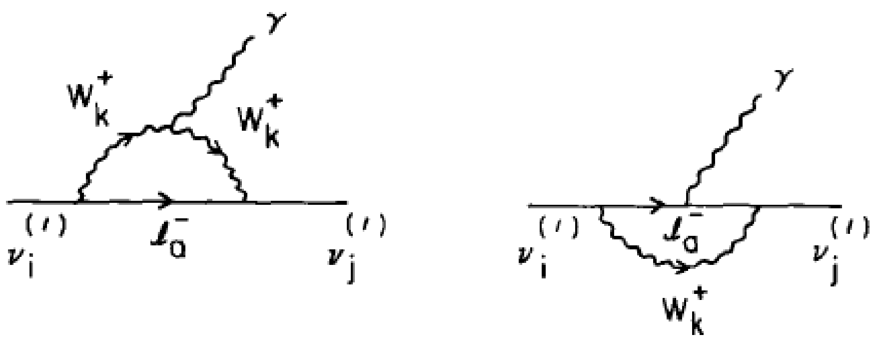
Neutrino Decay Lifetime

M. Beg, W. Marciano and M. Rudeman Phys. Rev. D17 (1978) 1395-1401
R. E. Shrock Nucl. Phys. B206 (1982) 359-379

Calculate the neutrino decay width in $SU(2)_L \times SU(2)_R \times U(1)$ model
$M(W_R)=\infty$ and $\sin\zeta = 0$ corresponds to Standard Model.

$$W_1 = W_L \cos\zeta - W_R \sin\zeta$$
$$W_2 = W_L \sin\zeta + W_R \cos\zeta$$

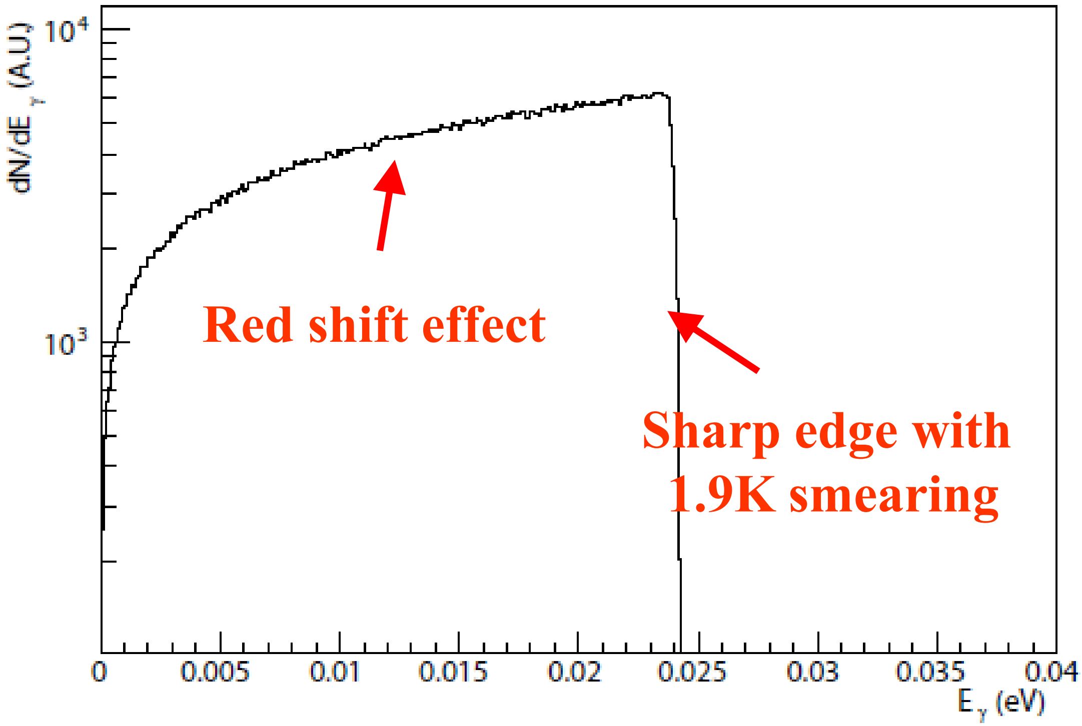
W_L and W_R are fields with pure V-A and V+A couplings, respectively, and ζ is a mixing angle.



Using a lower mass limit $M(W_R) > 715\text{GeV/c}^2$, a mixing angle limit $\zeta < 0.013$, and $m_3 = 50\text{meV}$,

$$\tau(\nu_3 \to \nu_2 + \gamma) = \boxed{1.5\times 10^{17}\,\text{year}} \quad (\ 2.1\times 10^{43}\,\text{year in Standard Model})$$

Photon Energy Spectrum from Neutrino Decay



- 1.9K neutrino motion smears the sharp edge of high energy end.

- Measured photon energy E_γ is shifted due to Doppler effect given by
$E_\gamma = E_0/(1+z)$,
Where z is a red shift and E_0 is the photon energy without Doppler shift and neutrino motion.

$$\frac{dN}{dE_\gamma dS d\Omega dt} = \frac{\rho c}{4\pi\tau H_0 E_\gamma}\left[\left(\frac{E_0}{E_\gamma}\right)^3 \Omega_M + \Omega_\Lambda\right]^{-\frac{1}{2}}$$

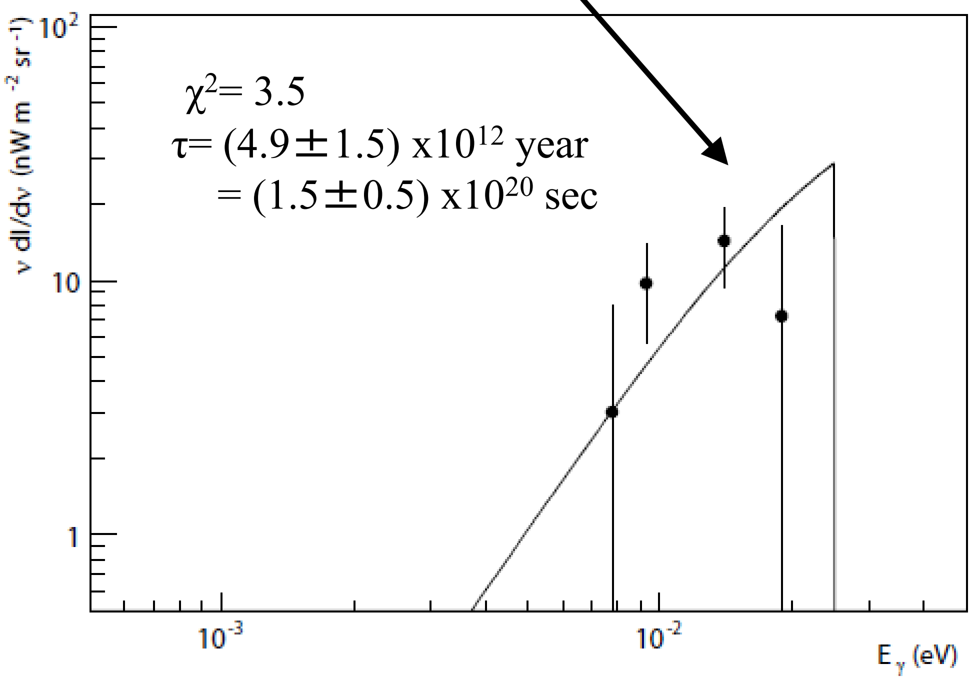
$E_{\gamma rest}$: photon energy in ν_3 rest frame, ρ : ν_3 density, τ : ν_3 lifetime,

H_0 : Hubble constant, Ω_M : Matter density (0.76), Ω_Λ : cosmological constant (0.24)

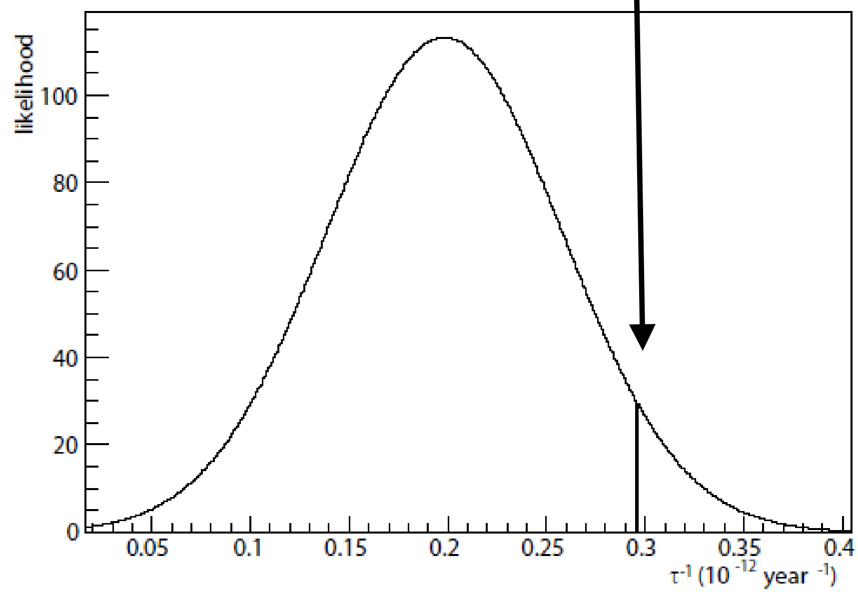
Our Estimate of Neutrino Lifetime Limit using the Cosmic Infrared Background measured by AKARI

SPITZER and AKARI measured the contribution of distant galaxies to the CIB. We obtained the neutrino lifetime limit from the AKARI CIB data (ApJ,737, 2, 2011) from which we subtracted the contribution of distant galaxies

AKARI CIB Data － Contribution of Distant Galaxies



Lifetime Limit 3.4 x 10^{12} year at 95% C.L..



Lower limit of neutrino lifetime is 3.4 x 10^{12} at 95% C.L .for m_3 = 0.05eV and m_2 = 0.01eV.

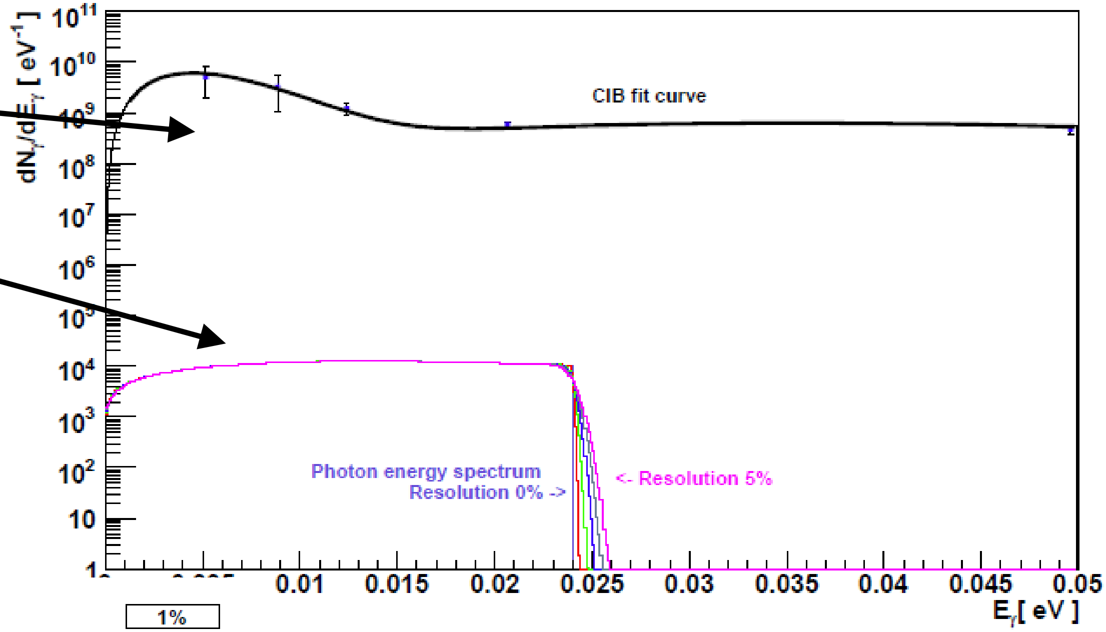
For m_3 = 0.05 ~ 0.15eV , lower limit of ν_3 lifetime at 95% C.L ranges (3.1 ~ 3.8) x 10^{12} year.

Neutrino Decay Detection Sensitivity

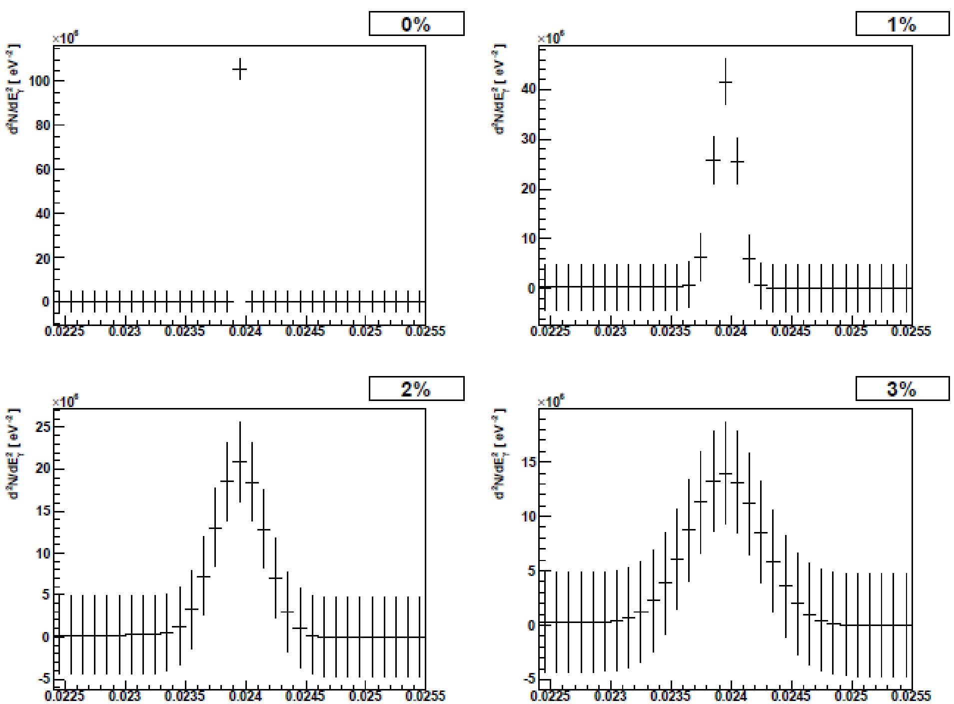
Cosmic Infrared Background +

Photon Energy Spectrum from Neutrino Decay (E_0 = 25meV, τ = 1.5 x 10^{17}year)

10-hour running with a telescope with 20cm diameter, a viewing angle of 0.1 degrees and 100% detection efficiency



dN/dE_γ



d^2N_γ/dE_γ^2

- **Need the energy resolution better than 2%. (plan to use STJ)**
- **Can observe the ν_3 decay with a mass of 50meV, and a lifetime of 1.5 x 10^{17}year at 6.7σ.**

Our paper published in JPSJ on Jan. 18th, 2012

Journal of the Physical Society of Japan **81** (2012) 024101 FULL PAPERS

DOI: 10.1143/JPSJ.81.024101

Search for Radiative Decays of Cosmic Background Neutrino using Cosmic Infrared Background Energy Spectrum

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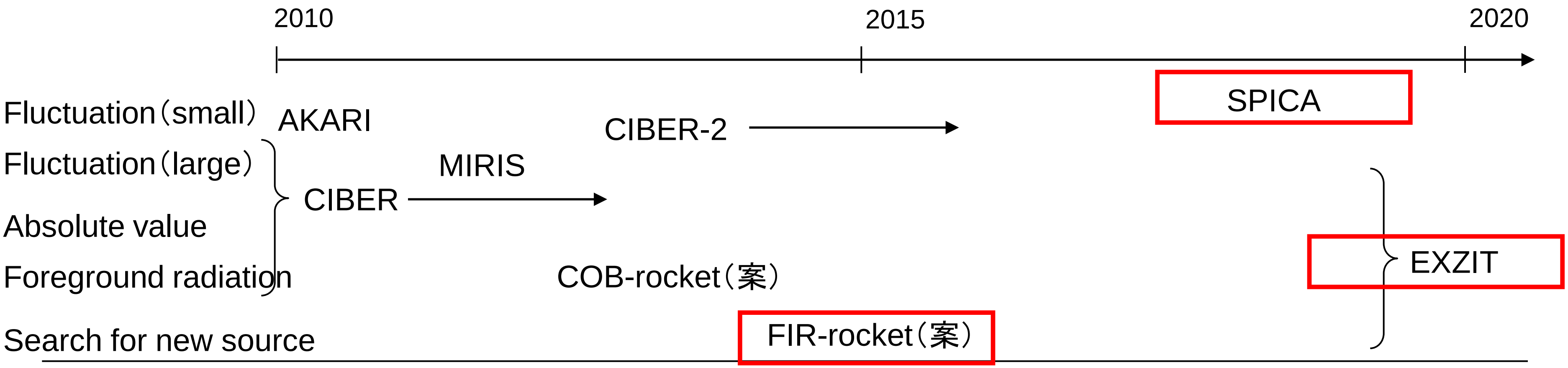
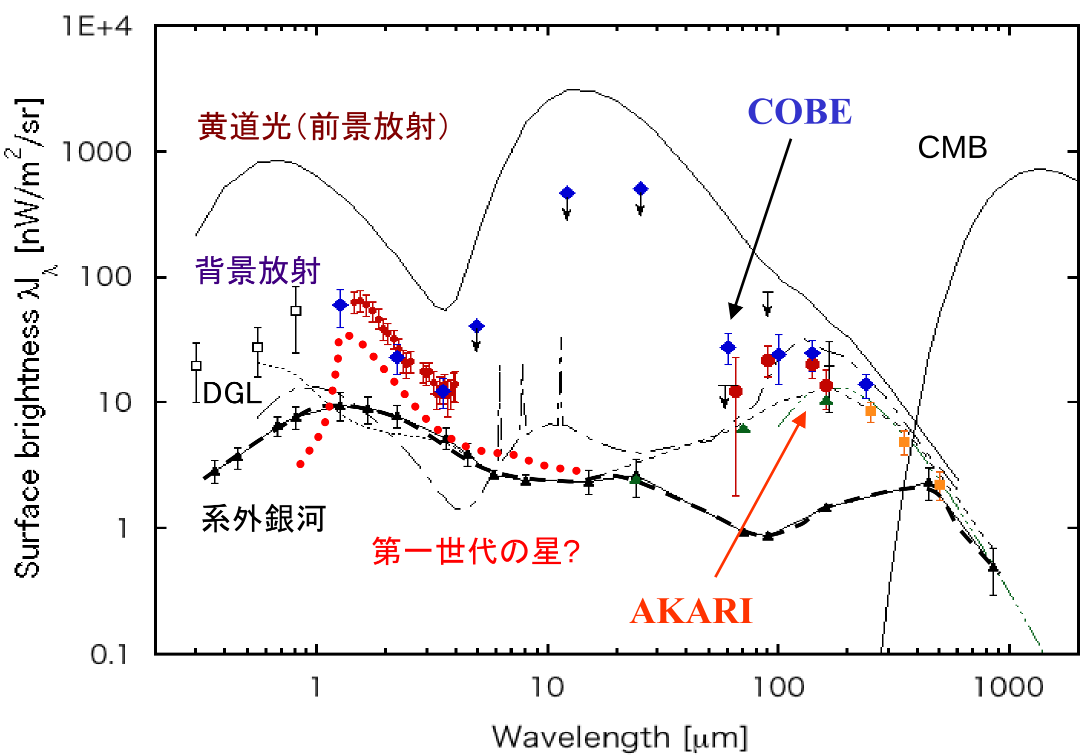
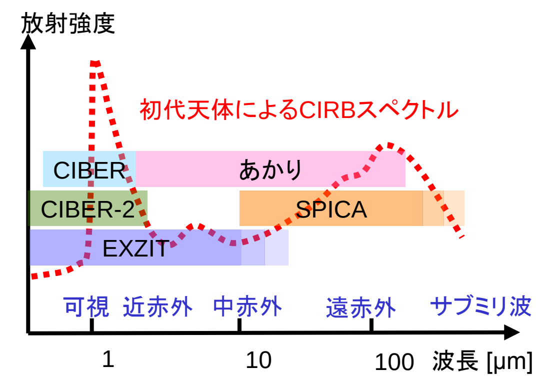
We propose to search for the neutrino radiative decay by fitting a photon energy spectrum of the cosmic infrared background to a sum of the photon energy spectrum from the neutrino radiative decay and a continuum. By comparing the present cosmic infrared background energy spectrum observed by AKARI and Spitzer to the photon energy spectrum expected from neutrino radiative decay with a maximum likelihood method, we obatined a lifetime lower limit of 3.1×10^{12} to 3.8×10^{12} years at 95% confidence level for the third generation neutrino ν_3 in the ν_3 mass range between 50 and 150 meV/c^2 under the present constraints by the neutrino oscillation measurements. In the left–right symmetric model, the minimum lifetime of ν_3 is predicted to be 1.5×10^{17} years for m_3 of 50 meV/c^2. We studied the feasibility of the observation of the neutrino radiative decay with a lifetime of 1.5×10^{17} years, by measuring a continuous energy spectrum of the cosmic infrared background.

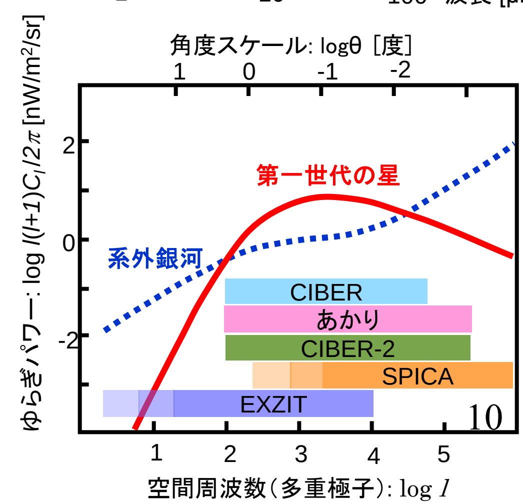
KEYWORDS: neutrino radiative decay, neutrino mass, cosmic background neutrino, cosmic infrared background, COBE, AKARI, Spitzer

CIB Observation Plan (by JAXA Dr. Matsuura)

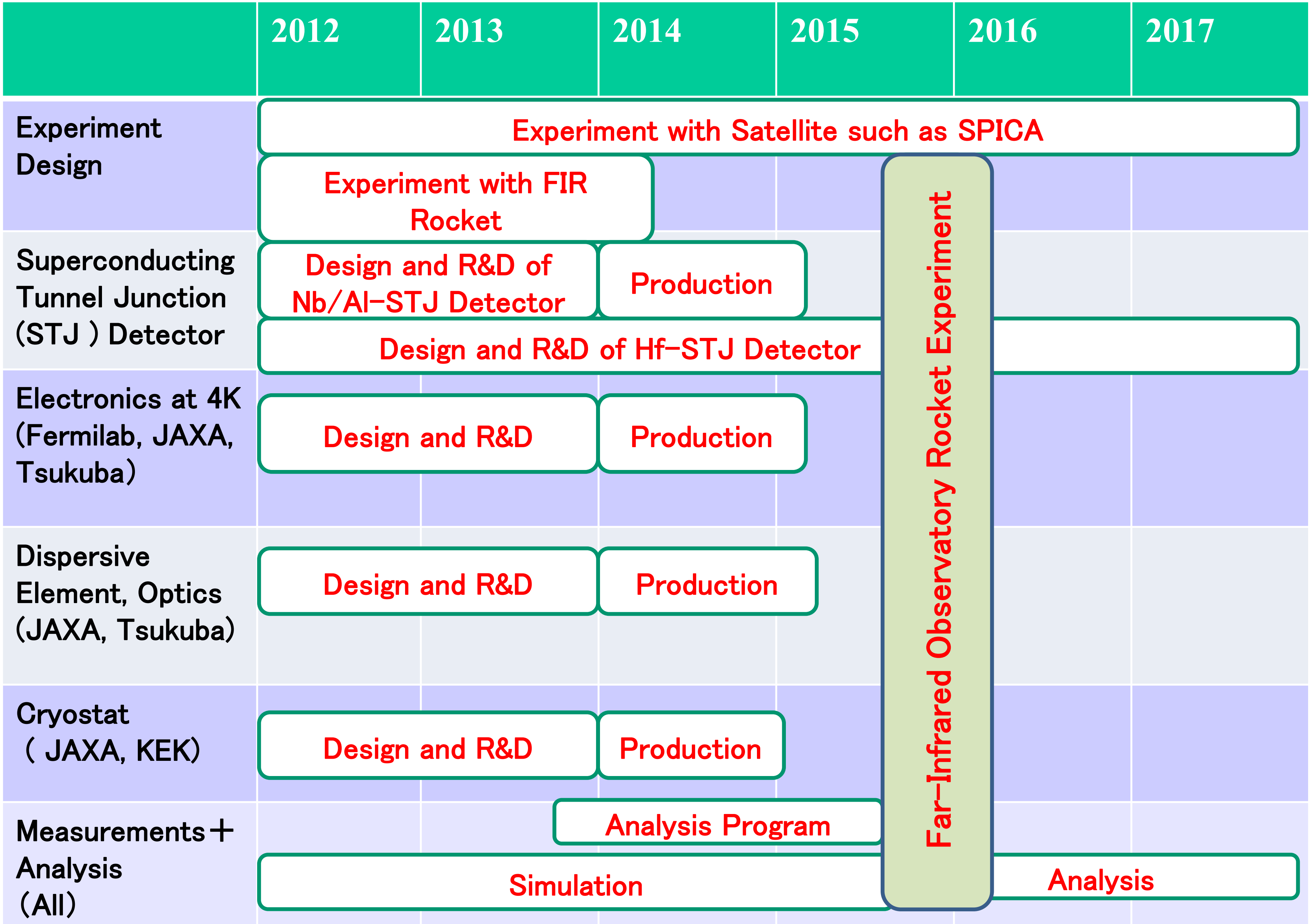








Schedule

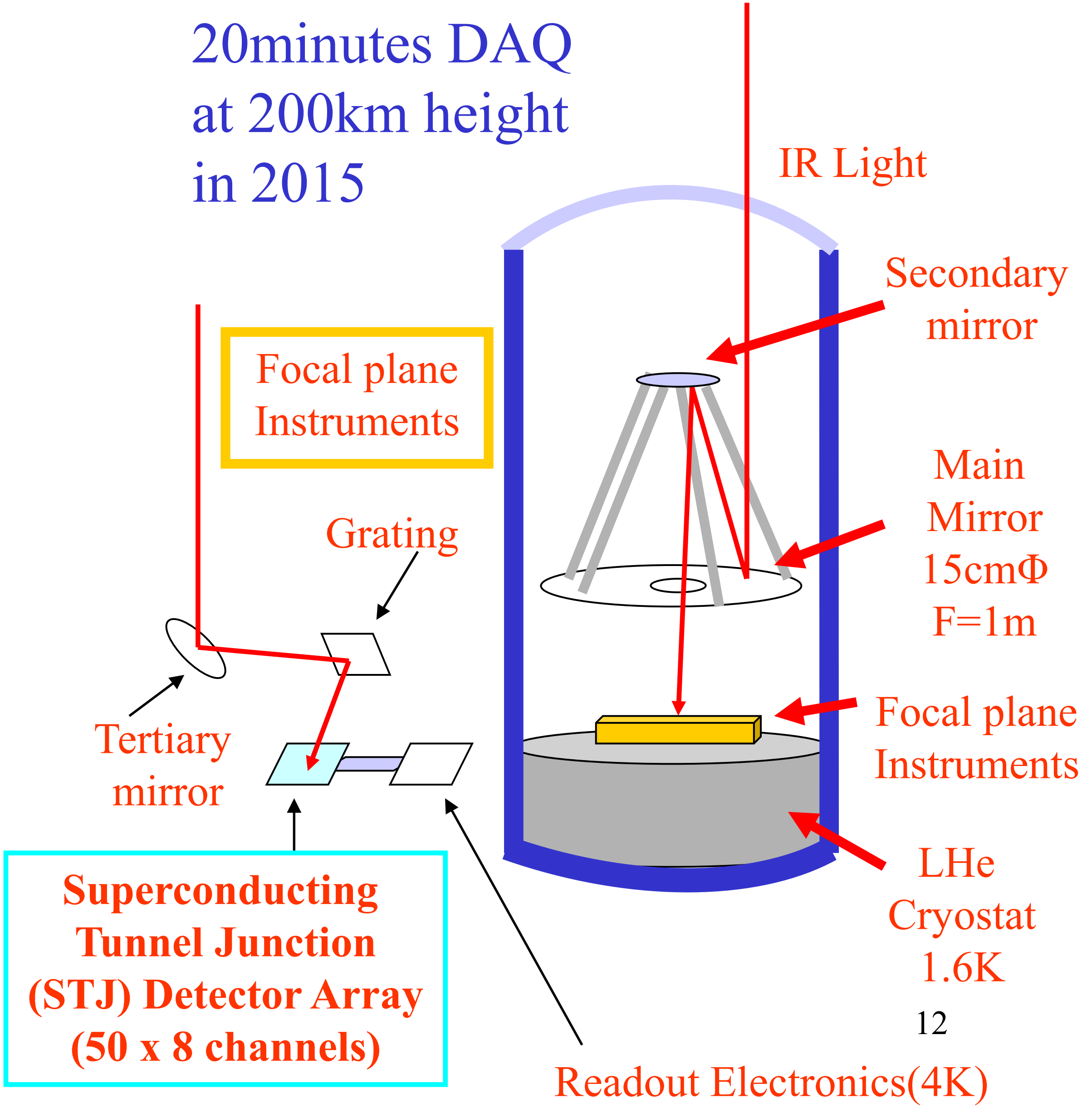

2012
2013
2014
2015
2016
2017
Experiment Design
Experiment with Satellite such as SPICA
Experiment with FIR Rocket
Superconducting Tunnel Junction (STJ) Detector
Design and R&D of Nb/Al-STJ Detector
Production
Design and R&D of Hf-STJ Detector
Electronics at 4K (Fermilab, JAXA, Tsukuba)
Design and R&D
Production
Dispersive Element, Optics (JAXA, Tsukuba)
Design and R&D
Production
Cryostat (JAXA, KEK)
Design and R&D
Production
Measurements＋Analysis (All)
Analysis Program
Simulation
Analysis
Far-Infrared Observatory Rocket Experiment

CIB Experiment for Neutrino Decay Search with JAXA Rocket

CIBER Rocket Experiment
(Feb 25, 2009)

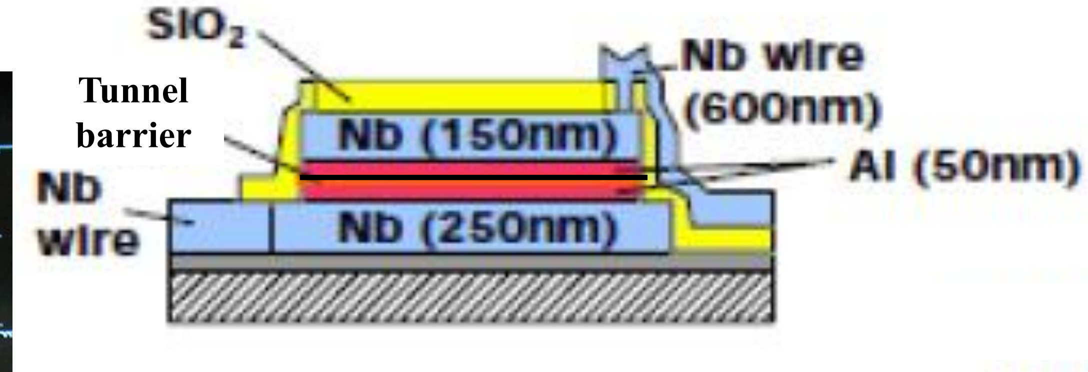
White sands, New Mexico

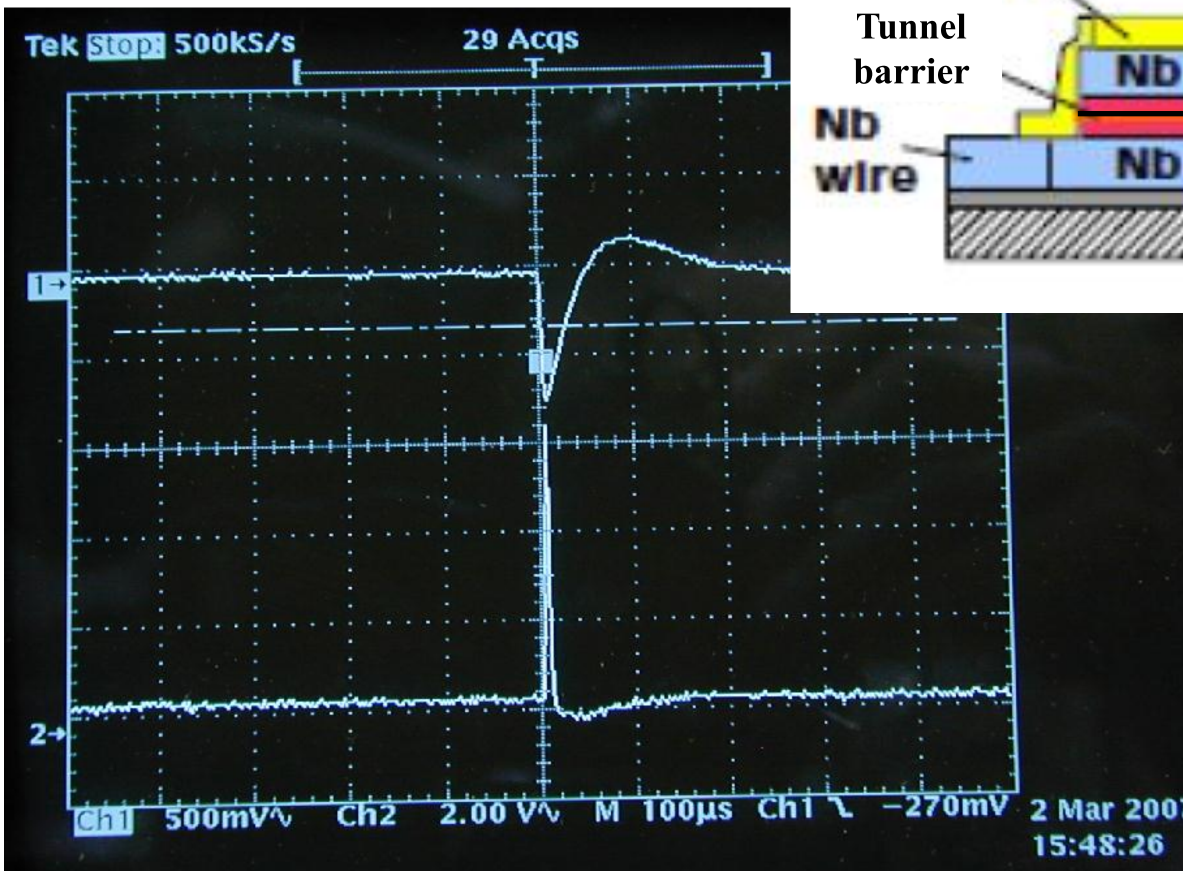
20minutes DAQ
at 200km height
in 2015



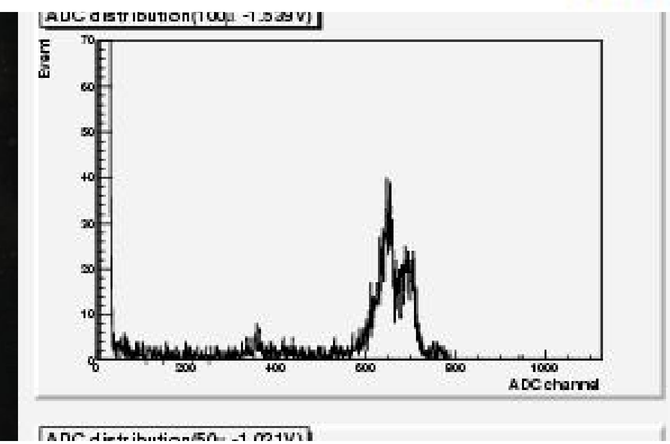
Nb/Al - STJ Response to 5.9keV X rays

We have worked on STJ (Superconducting Tunnel Junction) detector R&D since 2007.





Up: 5.9keV X ray signal after preamplifier
Down: 5.9keV X ray signal after preamp + shaper
at T=0.4K

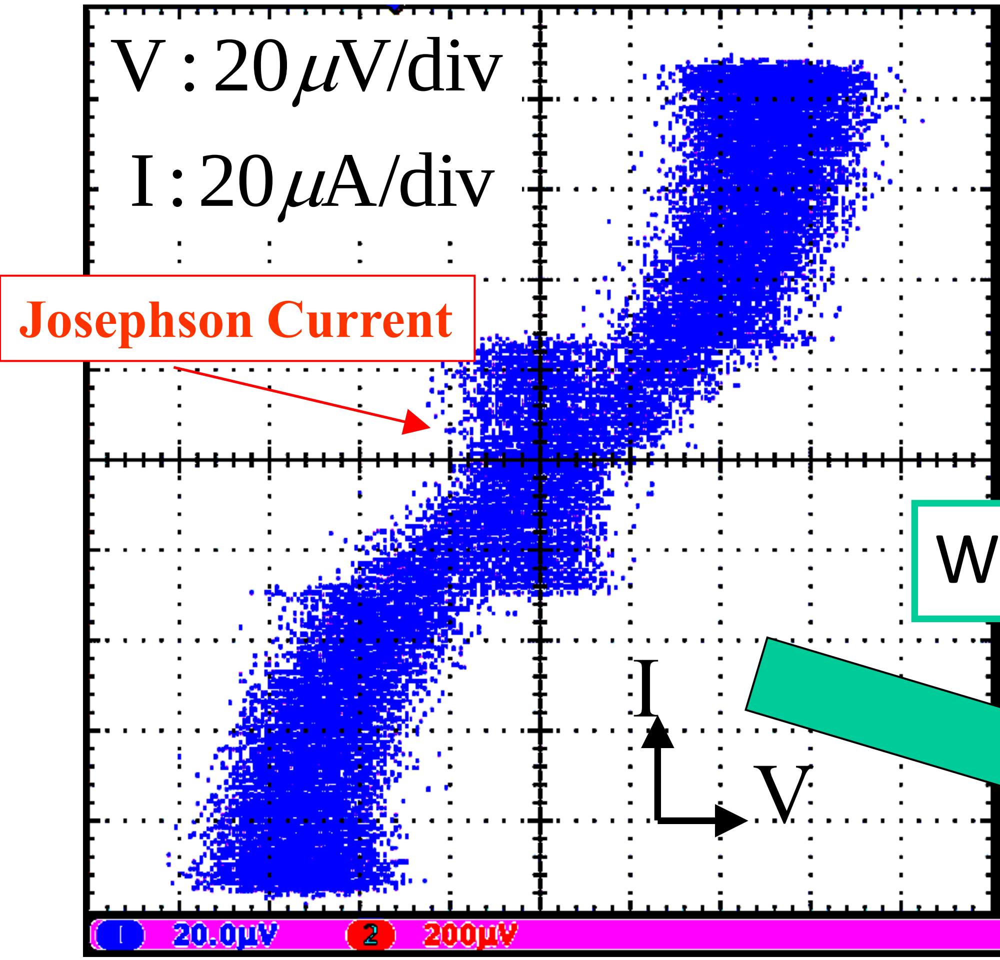


ADC output distribution

Double peak comes from that X rays are absorbed both in the upper layer and the lower layer.

Hf-STJ I-V Curve

(Oxidation Condition: 10Torr 60min.)

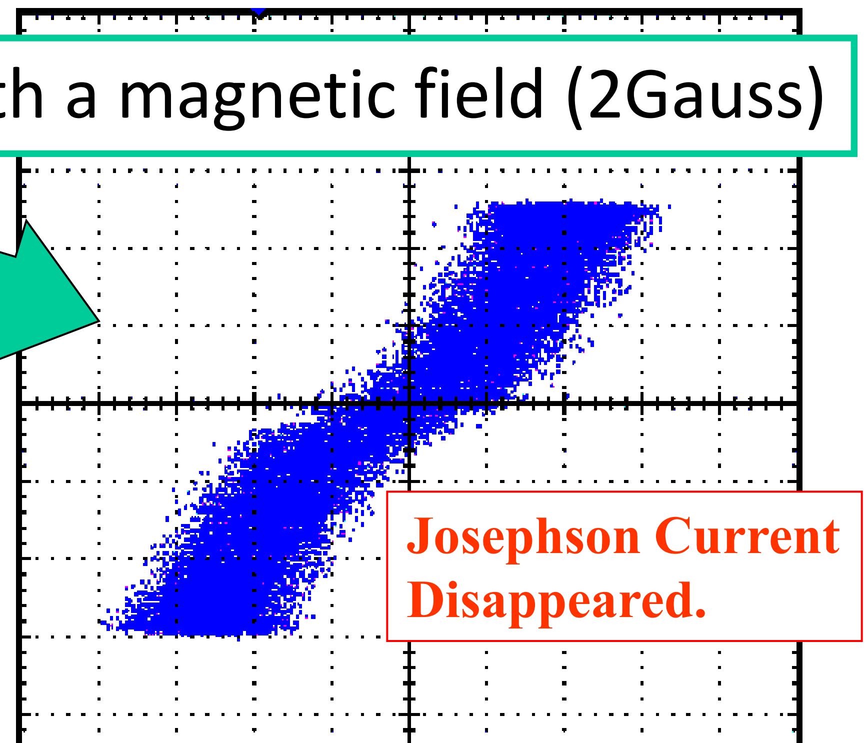


$T \sim 120\,\mathrm{mK}$

pixel size $200\,\mu\mathrm{m} \times 200\,\mu\mathrm{m}$

$I_C = 24\,\mu A, \quad R_d = 1\Omega$

With a magnetic field (2Gauss)



Hf-STJ Detector R&D in TIPP2011proceeding

Available online at www.sciencedirect.com
ScienceDirect
Physics Procedia 00 (2011) 000–000
ELSEVIER
Physics Procedia
www.elsevier.com/locate/procedia

Technology and Instrumentation in Particle Physics 2011

Development of superconducting tunnel junction photon detector using Hafnium

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[b]JAXA ISAS,3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa,252-5210,Japan
[c]RIKEN, 2-1 Hirosawa,Wako,Saitama,351-0198, Japan
[d]KEK,, 1-1 Oho, Tsukuba, Ibaraki, 305-0801, Japan
[e]Seoul National University,1 Gwanak, Gwanak-ro,Gwanak-gu, Seoul, 151-742 , Korea

Abstract

We present the development of a Superconducting Tunnel Junction (STJ) detector using Hafnium (Hf) as a photon detector which was designed to search for radiative decay of cosmic background neutrinos. The photon energy spectrum from neutrino radiative decay has a sharp edge at high energy end. To detect this sharp edge, we need a micro-calorimeter of infrared photons with high energy resolution. We have optimized the condition of producing a Hf-STJ detector and observed that a Hf-STJ detector had Josephson currents which disappeared by applying a magnetic field.

Superconducting tunnel junction (STJ) , neutrino decay, Hf-STJ

Plan

1. Design and detector R&D of CIB measurement with a FIR-rocket launched in 2015

- Multi-cell Nb/Al-STJ (Tsukuba,Fukui,Okayama)
- Low-temperature (4K) electronics (**Fermilab**, JAXA, Tsukuba)
- Dispersive element such as grating (Tsukuba, JAXA)
- Cryostat（~1K) (JAXA)

2. Superconducting detector R&D for satellite CIB measurement after 2018

- Multi-cell Hf-STJ development (Tsukuba, Fukui)

BACKUP

US Collaborators' Facility at Fermilab

- March, 2011-

  Started a collaboration with Fermilab Milli-Kelvin Facility group who will work on the readout electronics at low temperature around 4K.

Fermilab Milli-Kelvin Facility

Gustavo Cancelo, Herman Cease, Juan Estrada, Jonghee Yoo, Jiangnag Hao, Josh Frieman

Fermi National Accelerator Laboratory, Batavia, IL, 60510, USA

We propose to build a milli-Kelvin user facility at Fermilab. This facility would provide easy access to a sub-Kelvin cryogenic apparatus for the Fermilab Users. The facility will have immediate uses for SuperCDMS detector R&D, microwave kinetic inductance detector R&D (MKID), and crystal-phase low background detector R&D. Moreover, the facility would attract Users who wish to test devices such as ultra-sensitive superconducting sensors and low-noise quantum devices. An investment in a cryogen-free dilution refrigerator and related test equipment would be instrumental for future detectors and scientific experiments. In this proposal we request engineering/technical hours and support for the facility design and purchase of a cryogen-free dilution refrigerator which requires a year of lead time for delivery.

Lifetime Calculation

R. E. Schrock, Nucl. Phys. 28 (1982) 359.

Calculate the neutrino decay width in $SU(2)_L \times SU(2)_R \times U(1)$ model

$$\tau^{-1} = \frac{\alpha G_F^2}{128\pi^4}\left(\frac{m_3^2 - m_2^2}{m_3}\right)^3 \times |U_{32}|^2 |U_{33}|^2 \left[\frac{9}{64}(m_3^2 + m_2^2)\frac{m_\tau^4}{M_{W1}^4}\left(1 + \frac{M_{W1}^2}{M_{W2}^2}\right)^2 + 4m_\tau^2\left(1 - \frac{M_{W1}^2}{M_{W2}^2}\right)^2 \sin^2 2\zeta\right],$$

where α is a fine structure constant, G_F is a Fermi coupling constant, m_τ, M_{W1} and M_{W2} are masses of τ, W_1 and W_2, respectively.[21,22] U_{ij} is the (i, j)-th element of the Maki-Nakagawa-Sakata mixing matrix[23] and we took $|U_{32}| = 1/\sqrt{2}$ and $|U_{33}| = 1/\sqrt{2}$.

$$\tau^{-1} \approx \frac{\alpha G_F^2}{64\pi^4}\left(\frac{\Delta m_{32}^2}{m_3}\right)^3 m_\tau^2 \sin^2 2\zeta$$

$M_{W2} = 0.715\text{TeV}$, $\sin\zeta = 0.013$, $\Delta m_{32}^2 = 2.43\times10^{-3}\text{eV}^2$, $m_\tau = 1.78\text{GeV}$, $m_3 = 50\text{meV}$,

$$\tau = 1.5\times10^{17}\ \text{year}$$

In the standard model,

$$\tau^{-1} \approx \frac{9\alpha G_F^2}{8192\pi^4}\left(\frac{\Delta m_{32}^2}{m_3}\right)^3 (m_3^2 + m_2^2)\left(\frac{m_\tau^2}{M_W^2}\right)^2$$

Thus $\tau = 2.1\times10^{43}$ year

ref. K. Sato and M. Kobayashi, Prog. Theor. Phys. 58 (1977) 1775. and others.

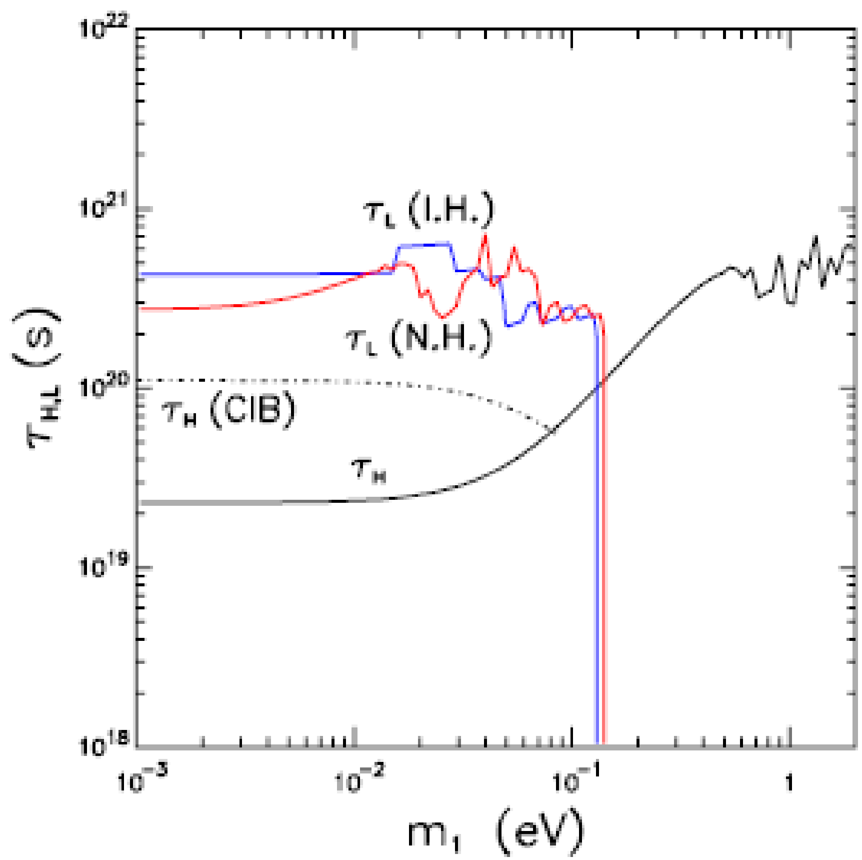
Lower Limit of Neutrino Lifetime using Cosmic Infrared and Microwave Background measured by COBE

A. Mirizzi, D. Montanino and P. Serpico, "Revisiting cosmological bounds on radiative neutrino lifetime" PRD76, 053007 (2007)

Neutrino Decay Photon Energy Spectrum φ_E .

$$\varphi_E = \frac{\Gamma_H^\gamma}{4\pi}\frac{n_H}{H(z_H)} + \frac{\Gamma_L^\gamma}{4\pi}\frac{n_L}{H(z_L)},$$

(assuming, for simplicity, a flat cosmology) $H(z) = H_0\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}$, $H_0 \simeq 73\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, which is the present Hubble expansion rate, and $\Omega_M \simeq 0.26$ and $\Omega_\Lambda \simeq 0.74$ are, respectively, the matter and the cosmologi-



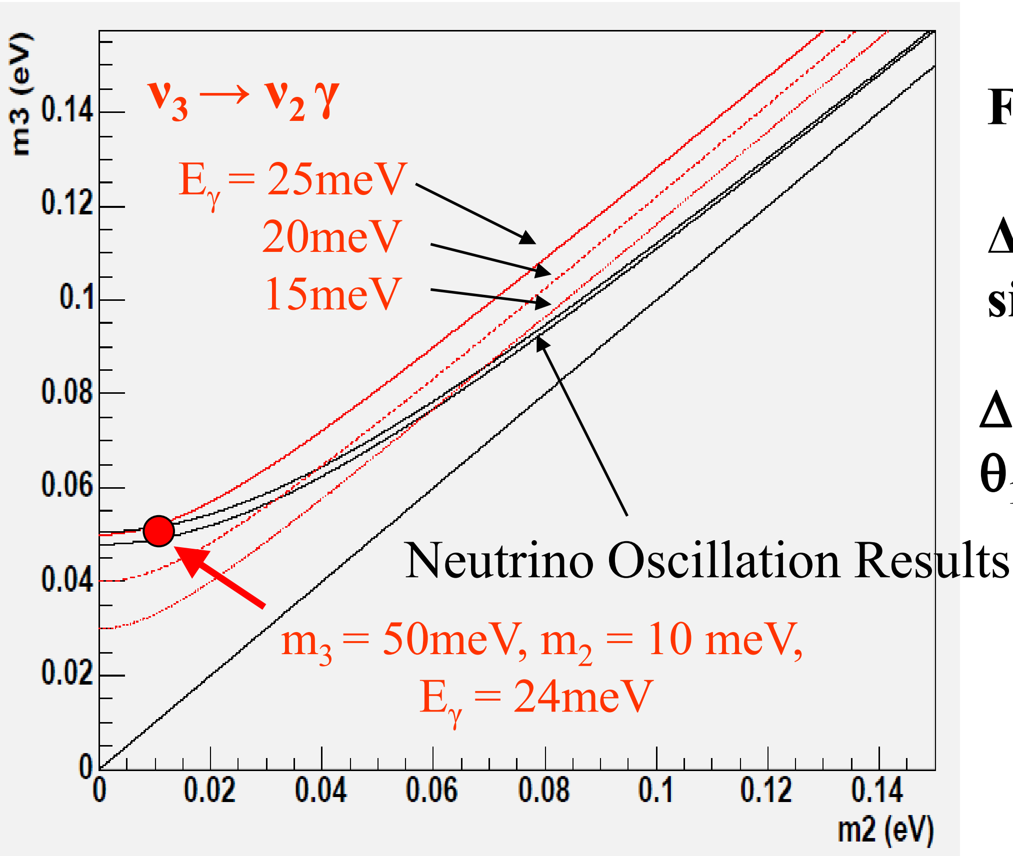
CMB（Cosmic Microwave Background）:
CMB measured with COBE-FIRAS
CMB is fitted with a sum of 2.7K Plunck distribution and φ_E.

CIB（Cosmic Infrared Background）:
Calculate τ_H by the following equation:

$$\int_{E_{\min}}^{\varepsilon_H} \varphi_E dE < \Phi_{\mathrm{CIB}},$$

where φ_{CIB} = 24 nW m^{-2} sr^{-1}（COBE）.→ (0.5 ~ 1) x 10^{20} sec = (1.6~3.1)x10^{12} year

Neutrino Mass Relation



From neutrino oscillation measurement,

$\Delta m_{23}^2 = (2.43 \pm 0.13)\ \mathrm{x}10^{-3}\mathrm{eV}^2$

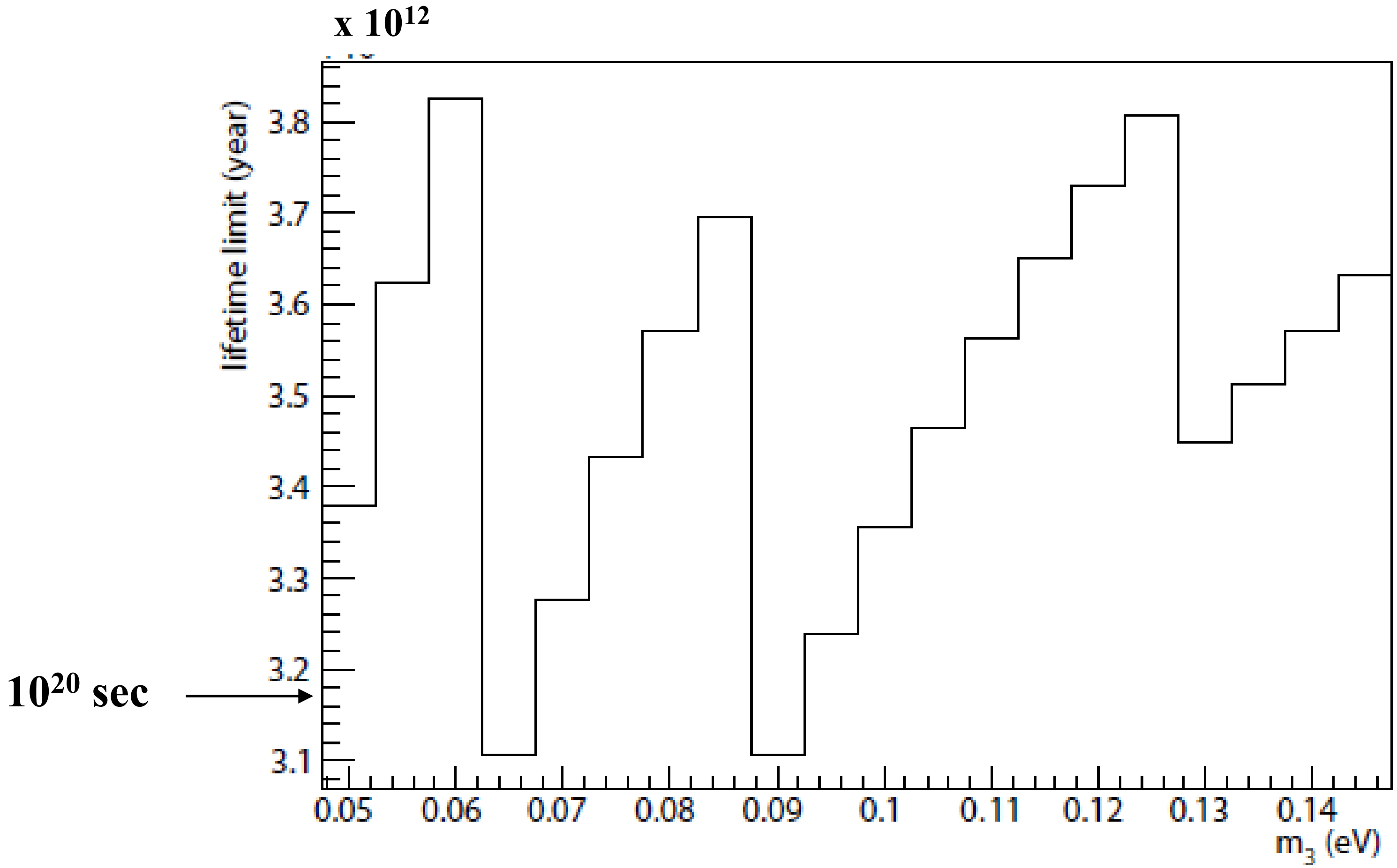
$\sin^2(2\theta_{23}) > 0.93$

$\Delta m_{12}^2 = (7.59 + 0.19/ -0.21)\ \mathrm{x}10^{-5}\mathrm{eV}^2$

$\theta_{12} = 34.4 +1.3/ -1.2$ **degrees**

* From Tritium β decay measurement, $m(\nu_e) < 2\mathrm{eV}$

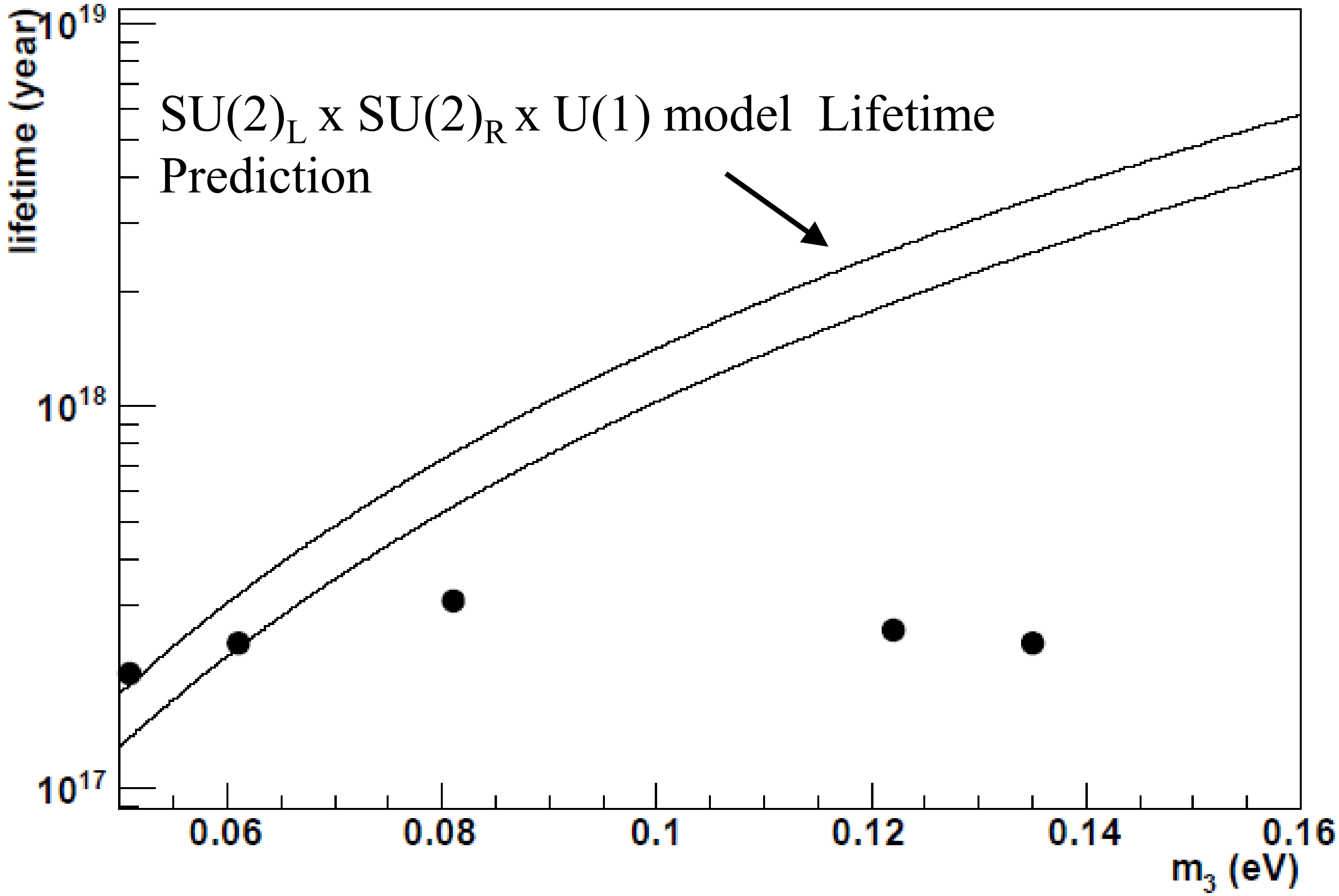
Our Estimate of Neutrino Lifetime Limit using the Cosmic Infrared Background measured by AKARI (2)



For m_3 = 0.05 ~ 0.15eV , lower limit of ν_3 lifetime at 95% C.L ranges (3.1 ~ 3.8) x 10^{12} year or（1.0 ~1.2 ）x 10^{20} sec.

$\Delta m_{23}^2 = 0.00243\ \mathrm{eV}^2$

Neutrino Decay Detection Sensitivity (2)



● 5σobservation sensitivity by 10-hour measurement with a telescope with 20 cm diameter, a viewing angle of 0.1 degree and 100% detection efficiency.

Experiment Plan

Search for cosmic background neutrino decay with far-infrared observatory rocket launched in 2015

- **Experiment Design**
- **Development of Multi-channel Nb/Al Superconducting Tunnel Junction (STJ) Infrared Photon Detector**
- **Development of Preamplifier and Shaper operating at 4K**
- **Design and Production of Dispersive Element and Optical System**
- **Design and Production of Cryostat**

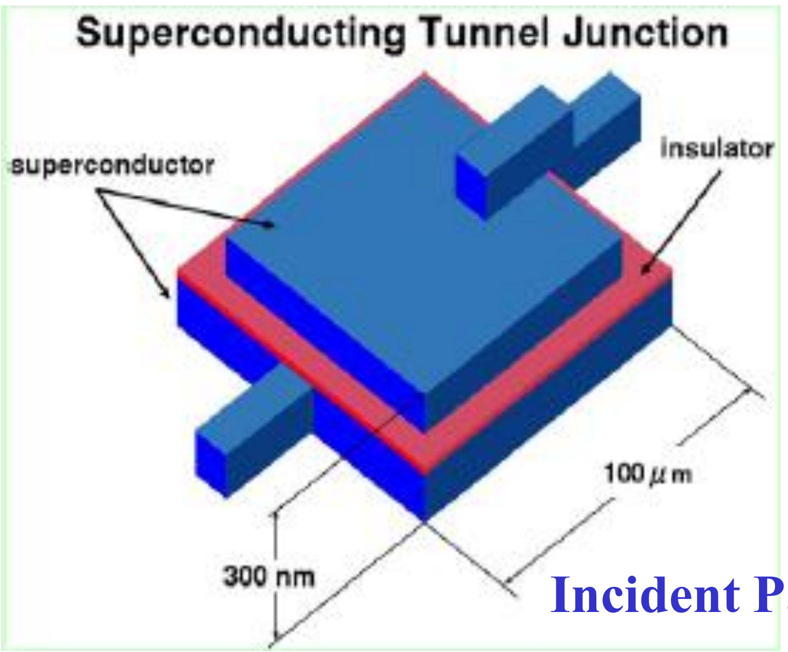
Search for cosmic background neutrino decay with far-infrared observatory satellite such as SPICA launched after 2018

- **Experiment Design**
- **Development of Hf Superconducting Tunnel Junction (STJ) Infrared Photon Detector**

Superconducting Tunnel Junction (STJ) Detector

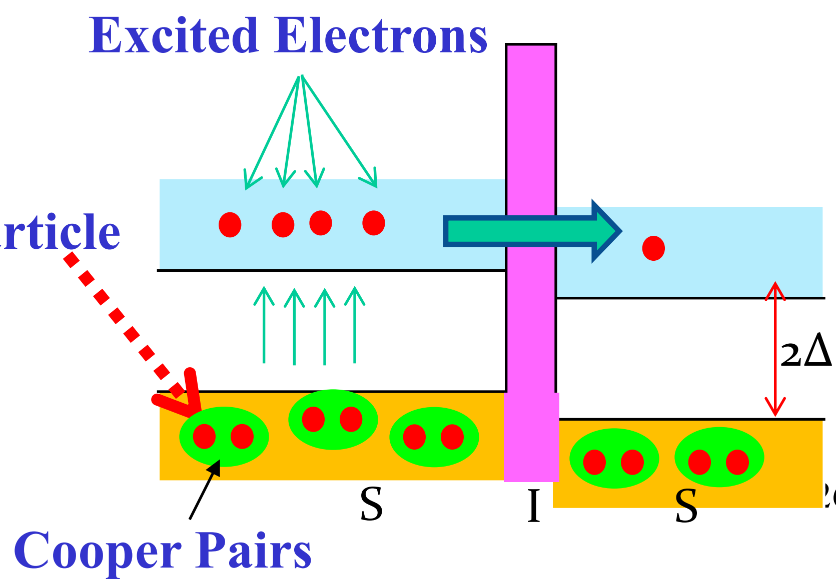
STJ (Superconducting Tunnel Junction) Detector

- Superconductor / Insulator / Superconductor Josephson Junction



At the superconducting junction, excited electrons (quasi-particles) over their energy gap go through tunnel barrier by a tunnel effect.

By measuring the tunnel current of electrons excited by an incident particle, we measure the energy of the particle.



STJ Energy Resolution

STJ Energy Resolution

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

Δ: Band gap energy
F: Fano factor (= 0.2)
E: Incident particle energy

Using Hf as a superconductor,

$$\sigma_E / E = 1.7\% \qquad \text{at } E = 25\text{meV}$$

Material	$T_c(K)$	Δ(meV)
Niobium	9.20	1.550
Aluminum	1.14	0.172
Hafnium	0.13	0.021

Tc : Critical Temperature

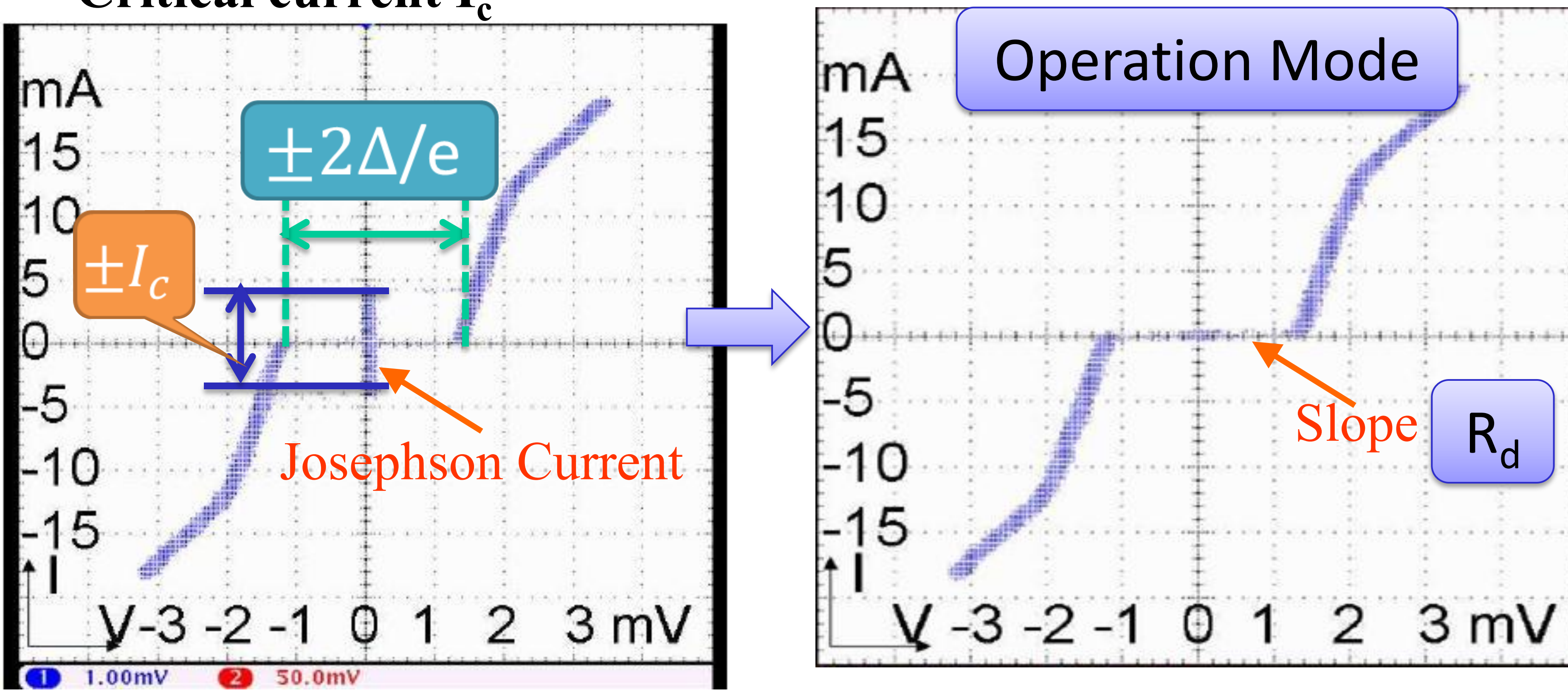
Operation is done at a temperature around 1/10 of Tc

No paper on Hf-STJ test in the world.

Basic Properties of STJ Detector

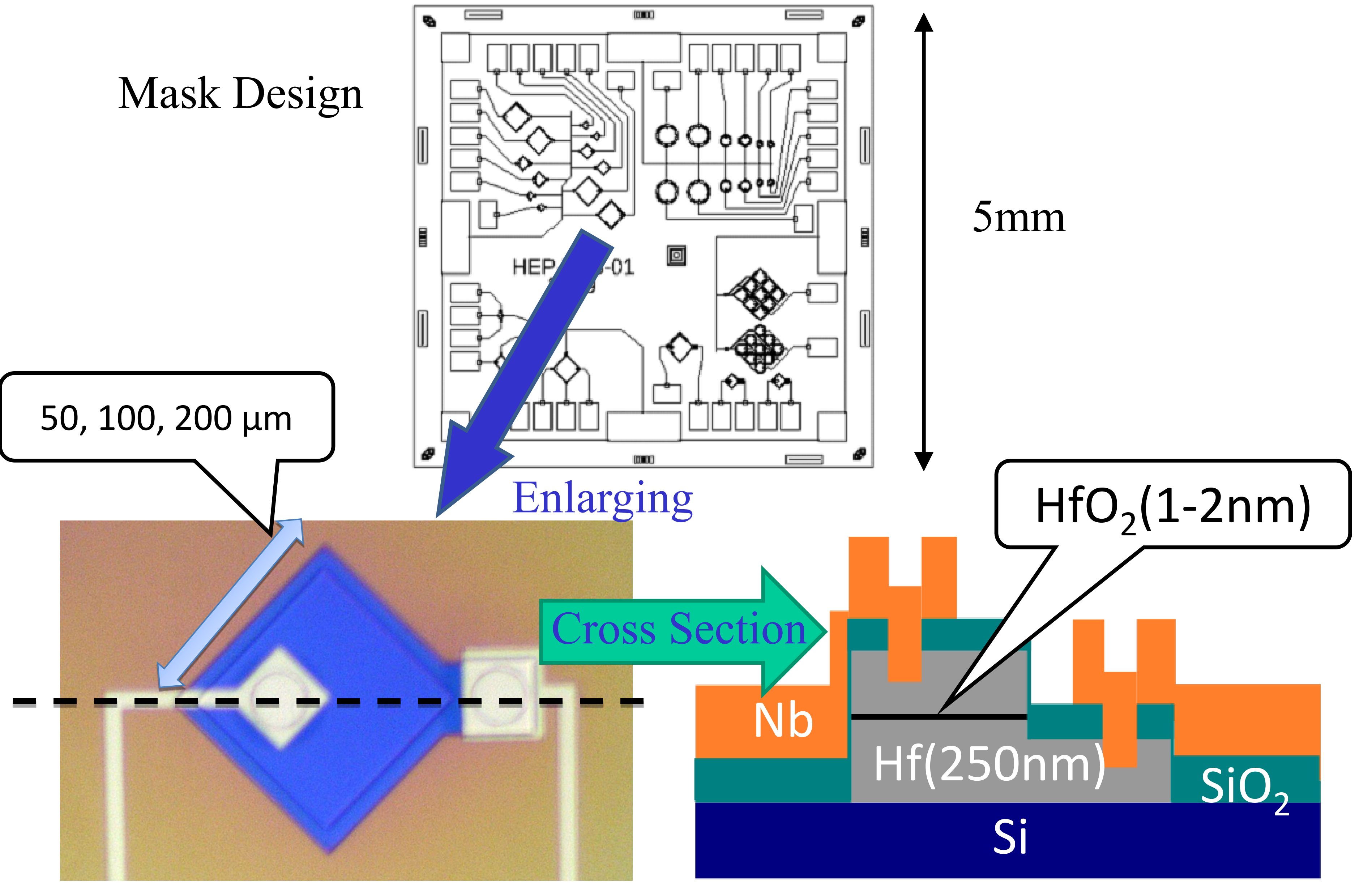
Nb-STJ current -voltage (I-V) curve

- **Leakage current (Dynamic resistance R_d in $|V| < 2\Delta/e$)**
- **Energy gap Δ**
- **Critical current I_c**



Josephson Current is suppressed by a magnetic field parallel to the insulator plane

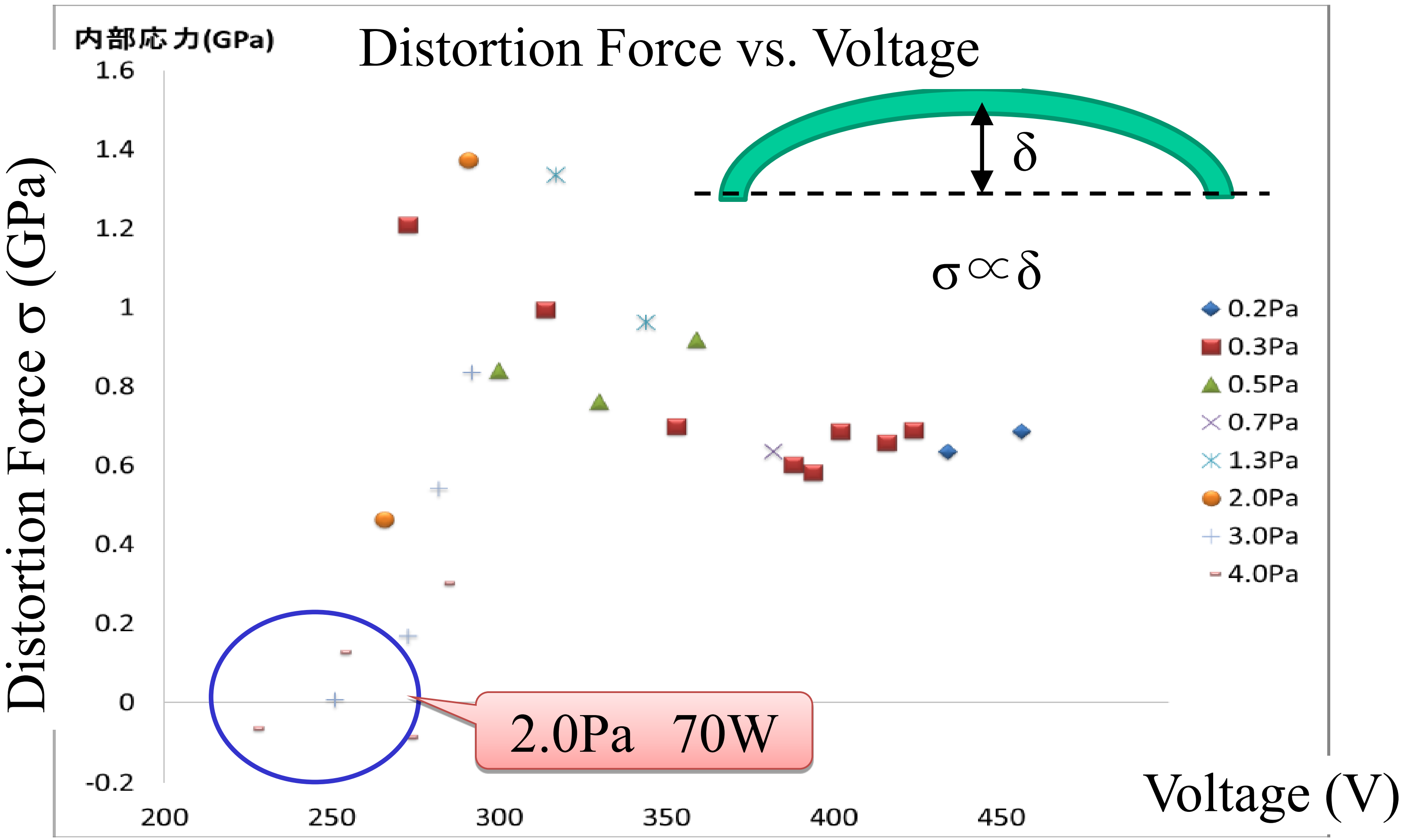
Hf-STJ Structure



R&D Status

(1) Search for the best condition for making a flat Hf layer : various pressures and voltages.

- 2.0 Pa, 70W (optimized)

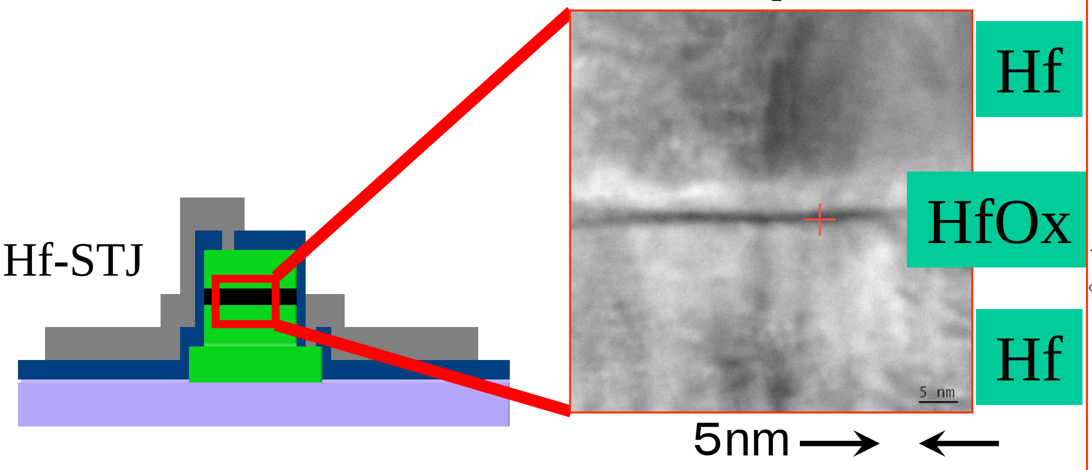


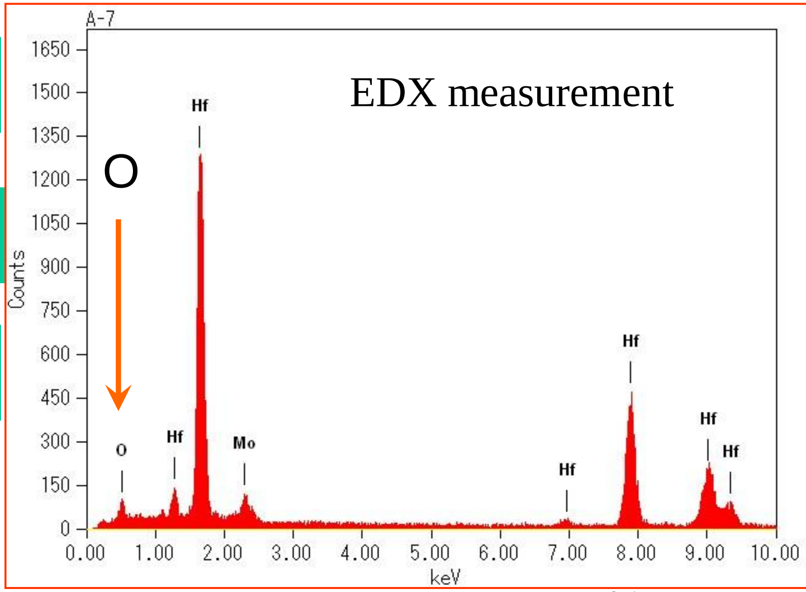
R&D Status

(2) Search for the best condition for making the insulator layer (1 – 2 nm thick) as a tunnel barrier: various pressures and periods of oxidation.

- 5 Torr, 12 minutes Oxidation sample (TEM picture)
  - **Confirmed 1.3nm-thick HfO_2 layer**

TEM picture



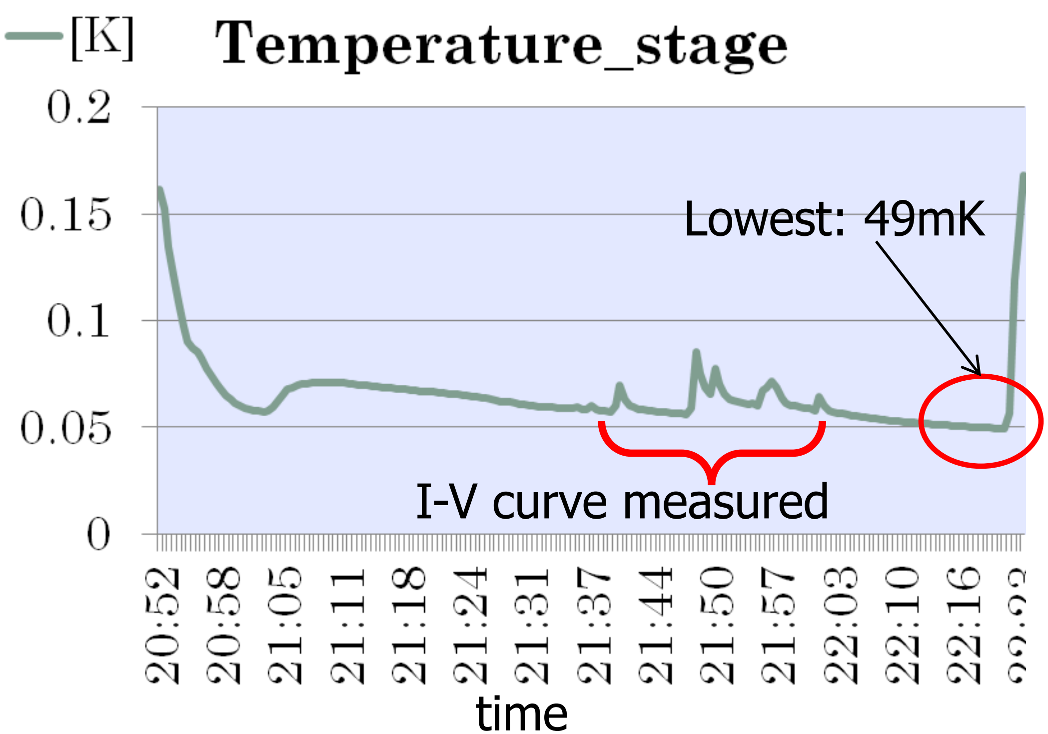


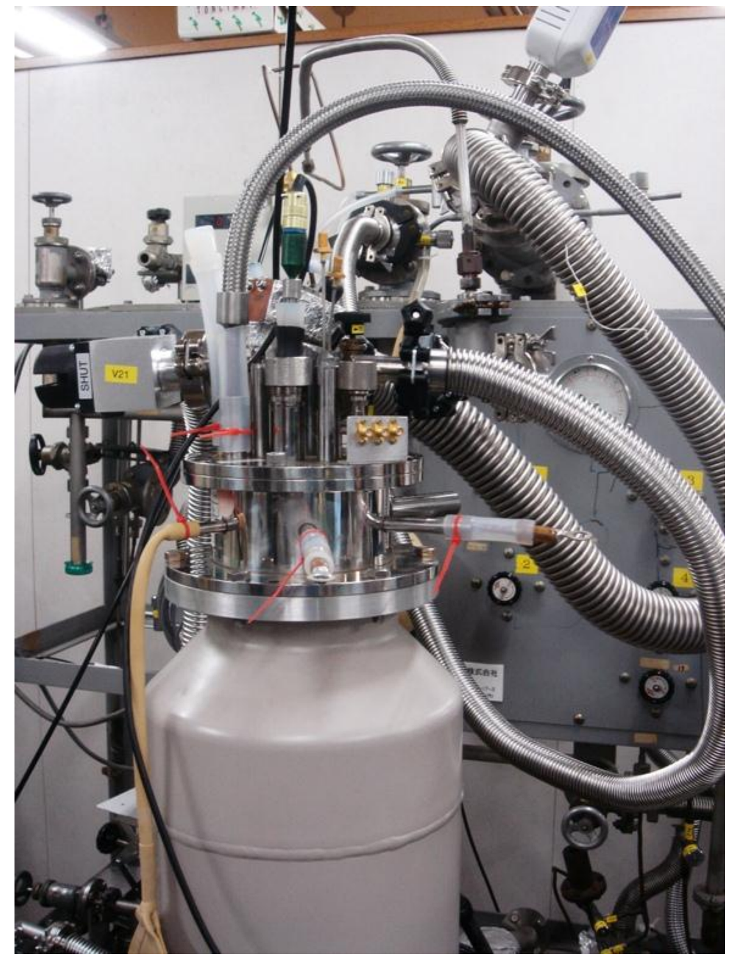
•TEM: Transmission Electron Microscope
•EDX: Energy Dispersive X-ray Spectroscopy

R&D Status

(3) Operation of He_3/He_4 Dilution Refrigerator.

- We borrowed a He_3/He_4 Dilution Refrigerator from a group of Low Temperature Material Science at University of Tsukuba in 2008.
- Achieved 49mK in July 2009.
- Achieved 40mK in October 2011.





Specification of 4K preamplifier

- Erik, Mail from me to Erik on Dec. 18, 2011

- I am sending the specifications about 4K electronics.
  If you have a mK facility at Fermilab, we can test the 4K electronics together with a Hf Superconducting detector. However even if you do not have the mK facility, when you can develop and test 4K electronics, your contribution is very useful for this experiment. About the test of Nb/Al-STJ, 0.4K is enough for the test of preamplifier with the Nb/Al-STJ.

  Our plan is to look at signals from visible photon (lambda=410nm) and near-infrared photon (lambda=1um) using a laser in 2012. For this purpose, we need a prototype preamplifier as specified below.

  In 2013, we plan to look at signals from far-infrared photon (lambda=30um) and make a prototype of multi-channel preamplifiers for Nb/Al-STJ (400 channels).

  Requirement for preamplifiers of Nb/Al-STJ and Hf-STJ is summarized below:
- Common specification: Operation temperature: ~4K Integration time: 10 usec

<For the Nb/Al-STJ and Hf-STJ prototype design>
Dynamic range < 20fC (~1.2 x 10**5 e)
from the requirement of < 4.5eV gamma (lambda=270 nm) at HF-STJ
Noise < 0.34 fC (~2100 e)
from the requirement of < 2.5% for 13.4 fC = 3 eV gamma (lambda~410 nm) at Hf-STJ
and of <20% for 1.6fC = 3 eV gamma (lambda~410 nm) at Nb/Al-STJ
Gain: 400mV/fC

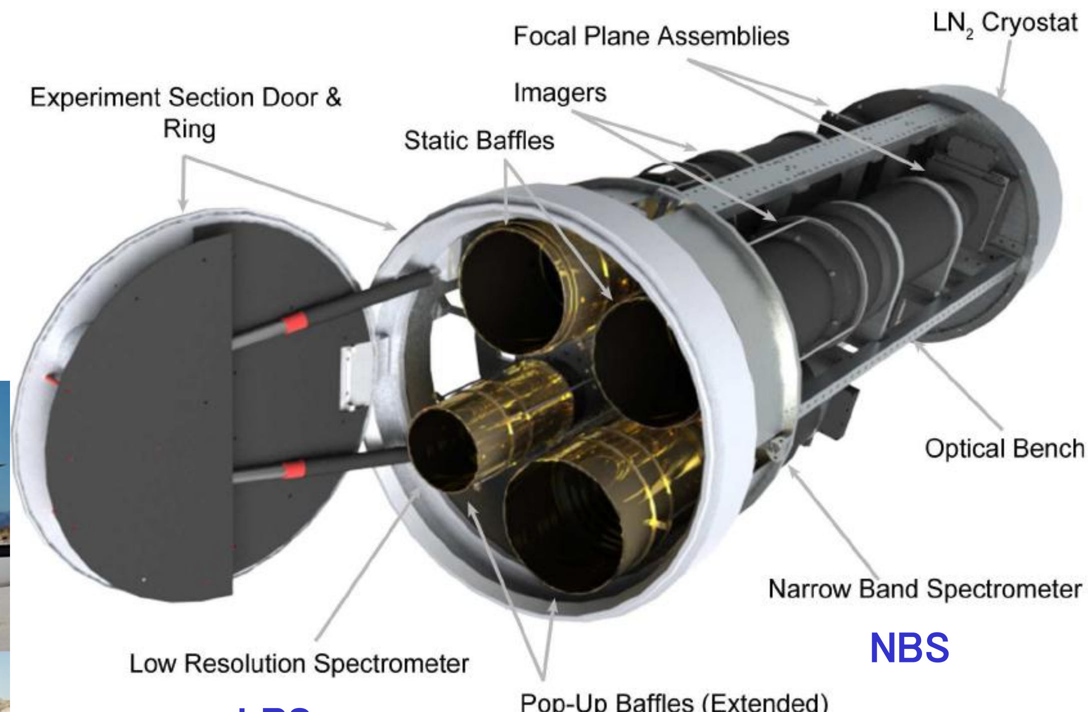
<For Nb/Al-STJ final design>
Dynamic range < 0.16fC (~1000 e)
from the requirement of < 300 meV gamma at Nb/Al-STJ
Noise < 0.0045fC (~30e)
from the requirement of <35% for 0.013 fC = 25meV gamma at Nb/Al-STJ
Gain: 10V/fC

<For Hf-STJ final design>
Dynamic range < 4.3fC (~27000 e)
from the requirement of < 45meV gamma at HF/W-STJ
Noise < 0.012fC (~80e)
from the requirement of <0.5% for 2.4 fC = 25meV gamma at Hf/W-STJ
Gain: 1V/fC

Best regards,
Shinhong

CIBER ロケット実験

CIBERロケット実験の第1回打上げの瞬間(2009年2月25日)

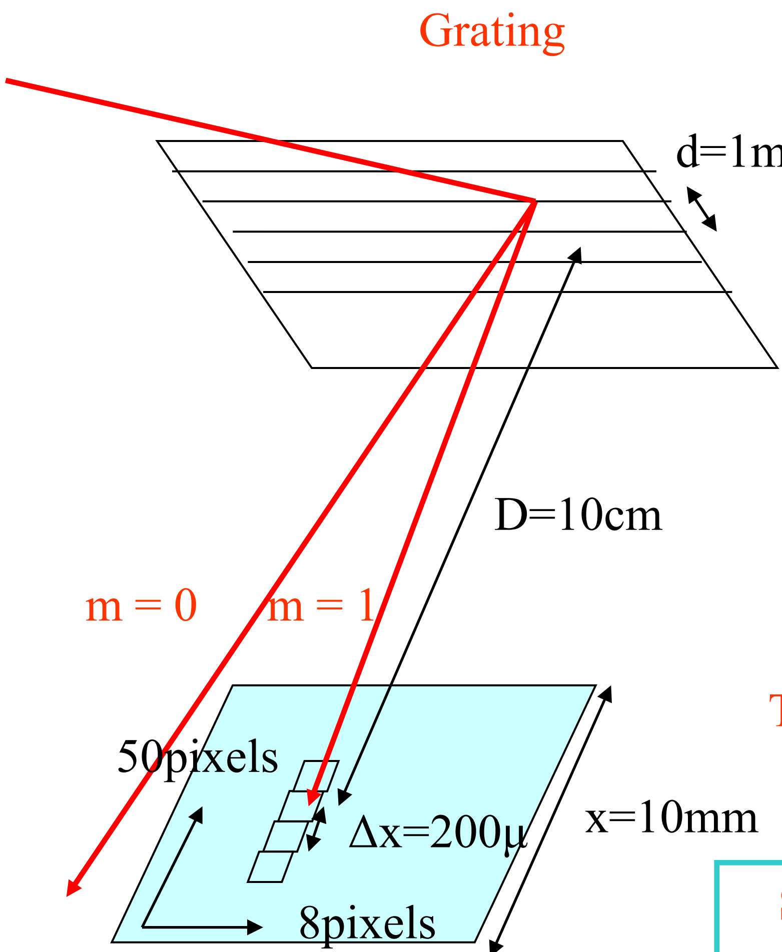


CIBER搭載装置(撮像装置Imager×2、低分散分光器LRS、高分散分光器NBS)

打上げ後に回収されたCIBERの観測装置。米国ホワイトサンズ(ニューメキシコ州)実験場

CIB Experiment for Neutrino Decay Search with JAXA Rocket

20minutes DAQ at 200km height in 2015



$d \sin\theta = \lambda$

$\rightarrow\ x = D\theta = D\lambda/d = 100\lambda$

If $\Delta x = 200\mu$, $\Delta\lambda = 2\mu$