Development of Superconducting Tunnel Junction Photon Detector using Hafnium

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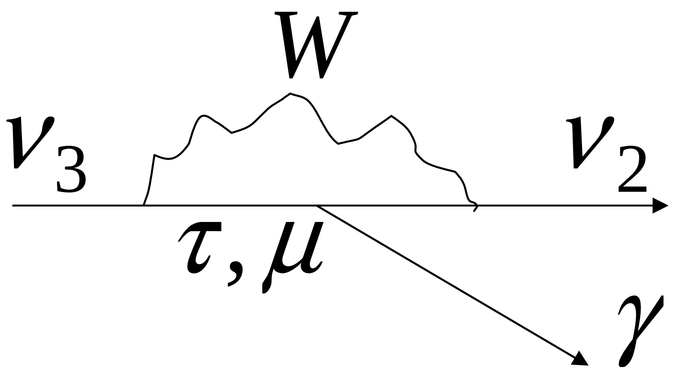
June 11, 2011 at TIPP2011

- Motivation
- Superconducting Tunnel Junction (STJ) Detector
- Status of Hf-STJ Development

Motivation

Search for radiative decay of cosmic background neutrino

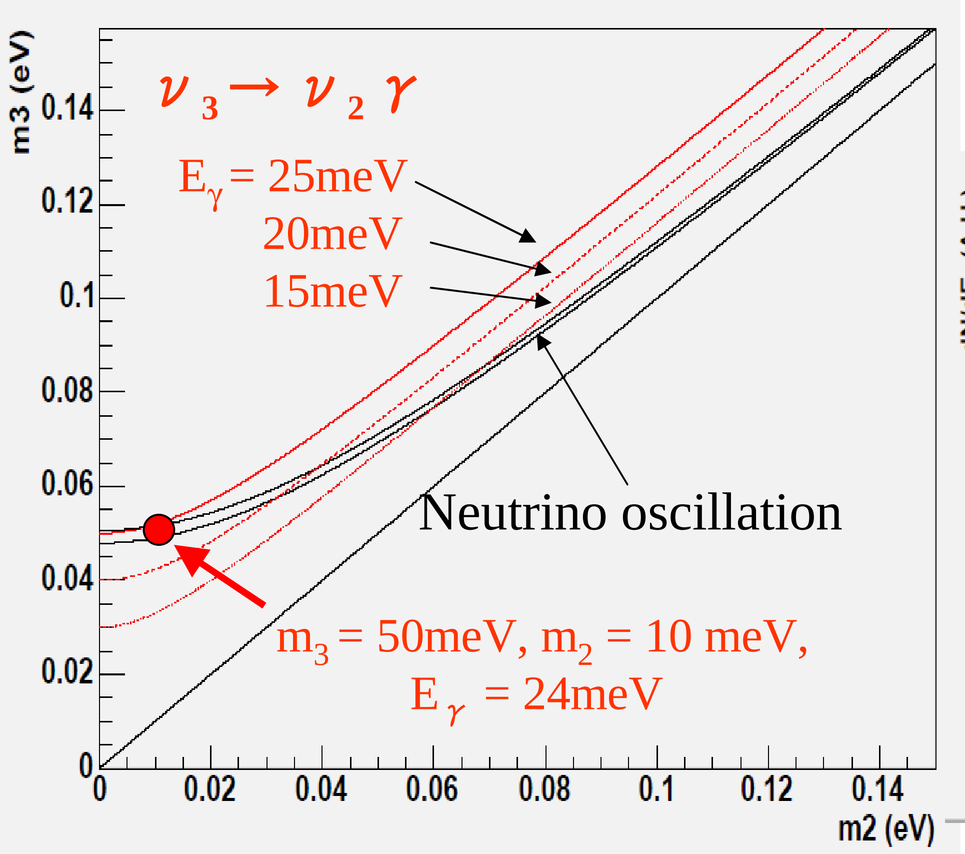
- Δm^2_{ij} have been measured accurately by neutrino oscillation experiments. but neutrino mass itself has not been measured. Can we measure it ?
  Detection of neutrino decay enables us to measure an independent quantity of the difference between squares of neutrino mass. Thus we can obtain neutrino mass itself from these two independent measurements.



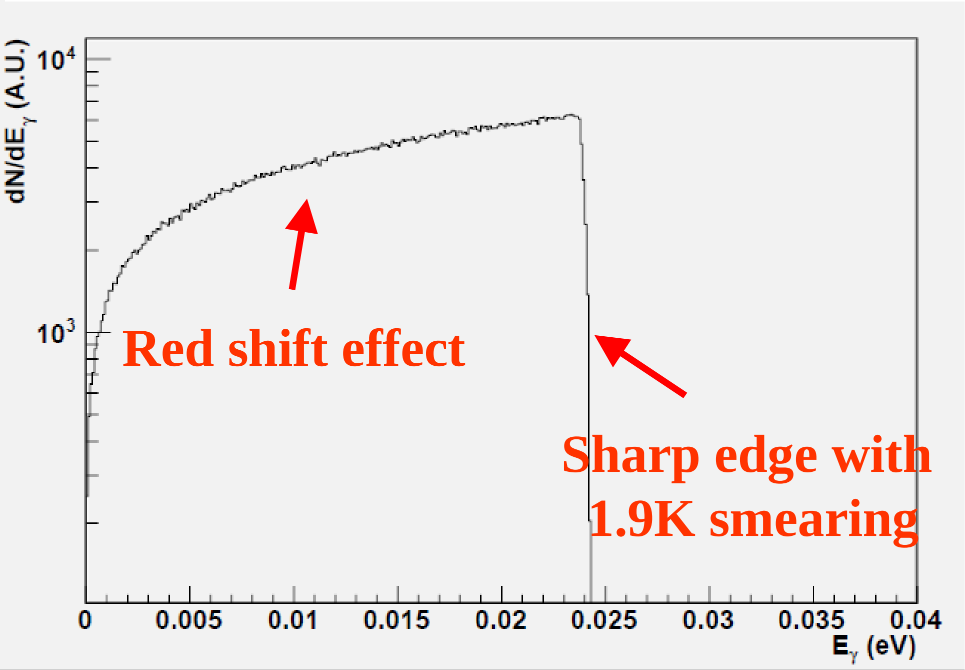
$$E_\gamma = \frac{m_3^2 - m_2^2}{2m_3} = \frac{\Delta m_{23}^2}{2m_3}$$

- 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.

Neutrino Mass Relations and Expected Photon Energy Spectrum



Decay Photon Energy Spectrum



Results from direct measuremenmt

(Tritium Decay)

$m(\nu_e) < 2\text{eV}$

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

$E_{\gamma rest}$: 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)

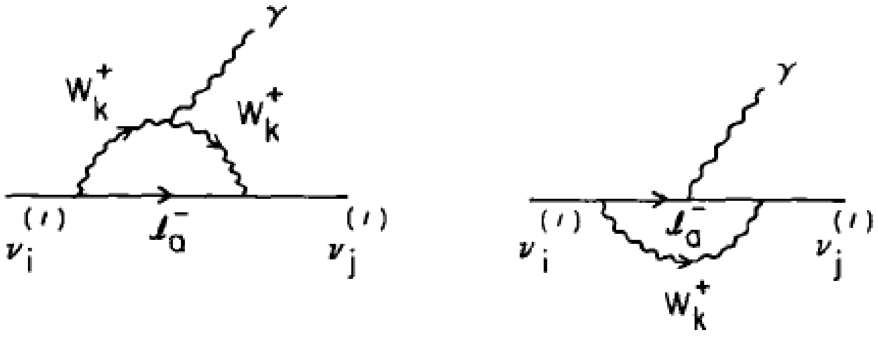
Neutrino Decay Lifetime

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.

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

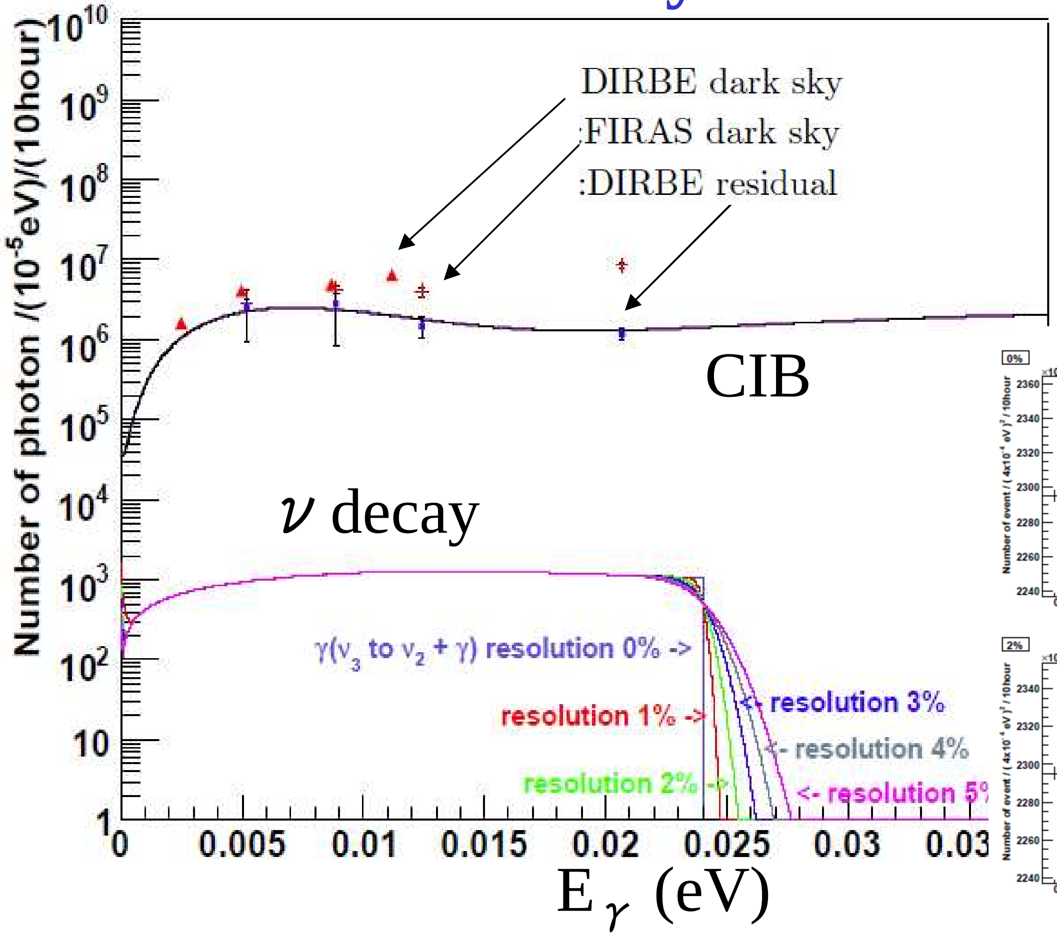


W_L and W_R are fields with pure V-A and V+A couplings, respectively, and ζ is a mixing angle.

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

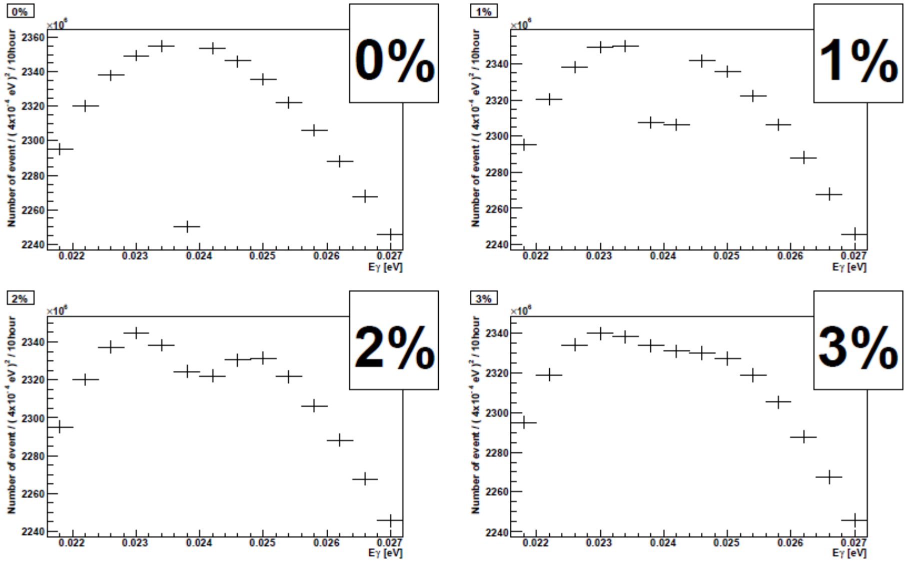
$$\tau(\nu_3 \rightarrow \nu_2 + \gamma) = \boxed{1.5\times10^{17}\ \mathrm{year}} \quad (\ \ 2.1\times10^{43}\ \mathrm{year\ \ in\ Standard\ Model})$$

the CIB(Cosmic Infrared Background) and the Decay Photon Energy Spectrum



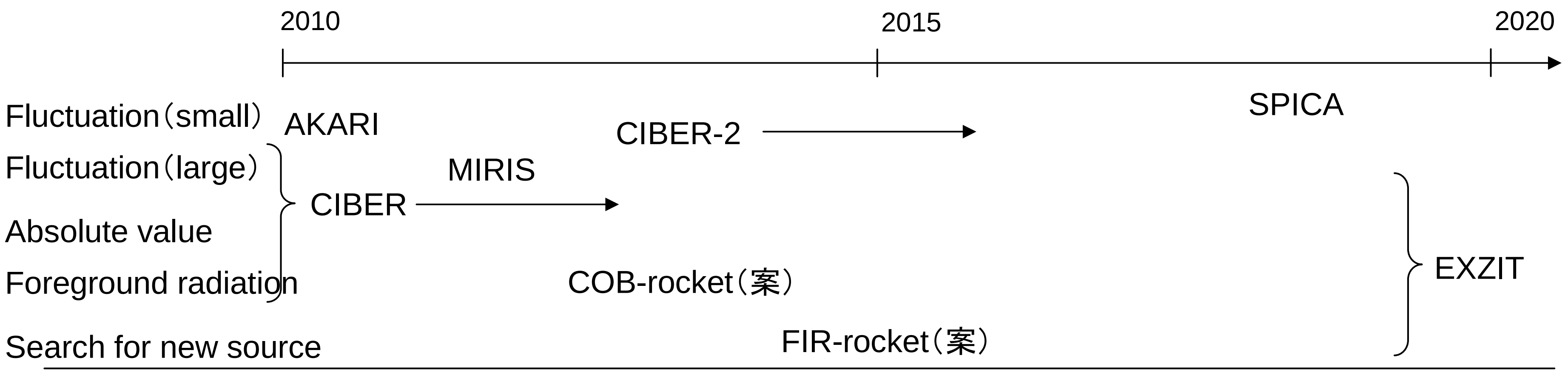
with a telescope of 20cm diameter and 0.1 degree viewing angle

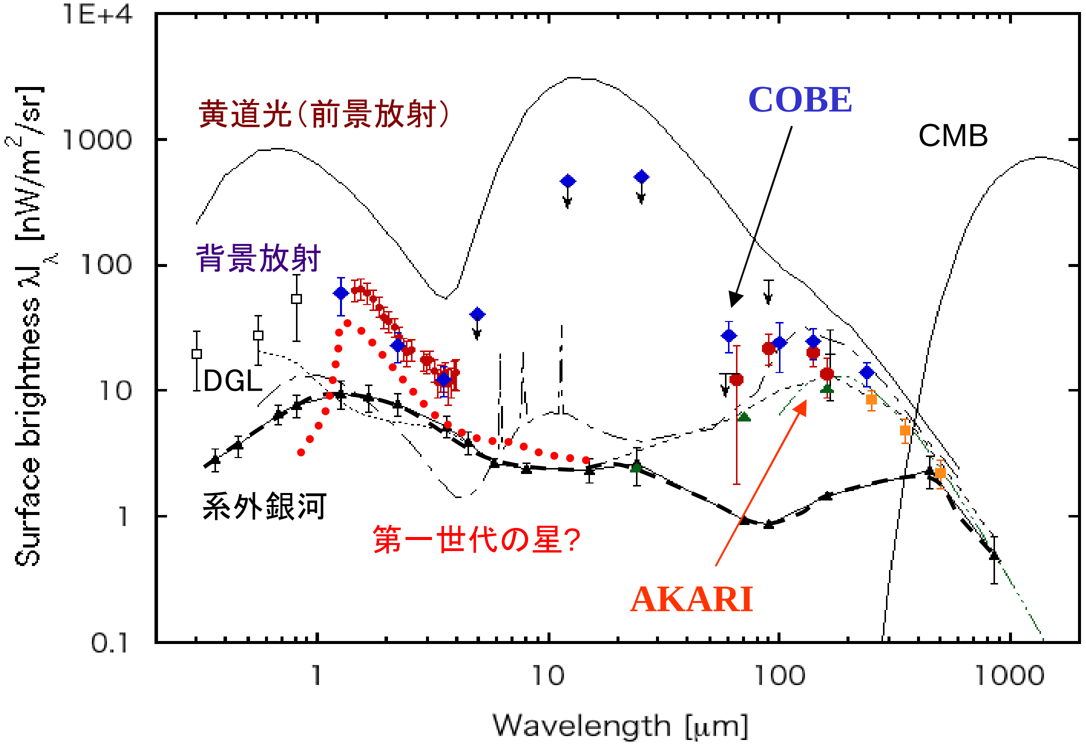
$dN(E_\gamma)/dE_\gamma$
for CIB + ν decay

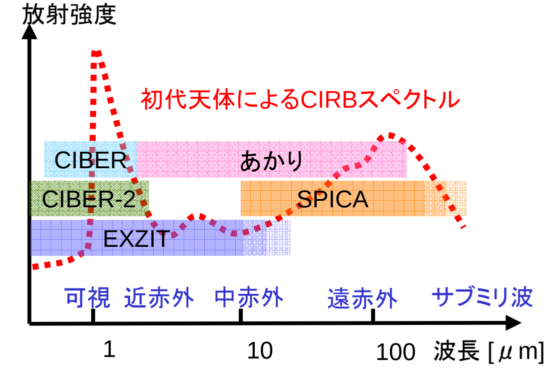


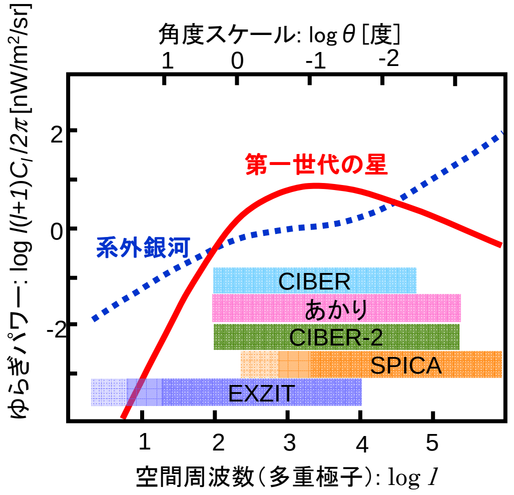
- The energy resolution is required to be better than 2% at 25meV.
- Expected 5σ observation lifetime is 1.5 x 10^{17} year with a telescope of 20cm diameter, 0.1 degree viewing angle and 3 hour running for m_3 of 50meV .
- NEP (Noise Equivalent Power) is required to be less than 3 x 10^{-19} WHz$^{-1/2}$.

CIB Observation Plan (by JAXA Dr. Matsuura)









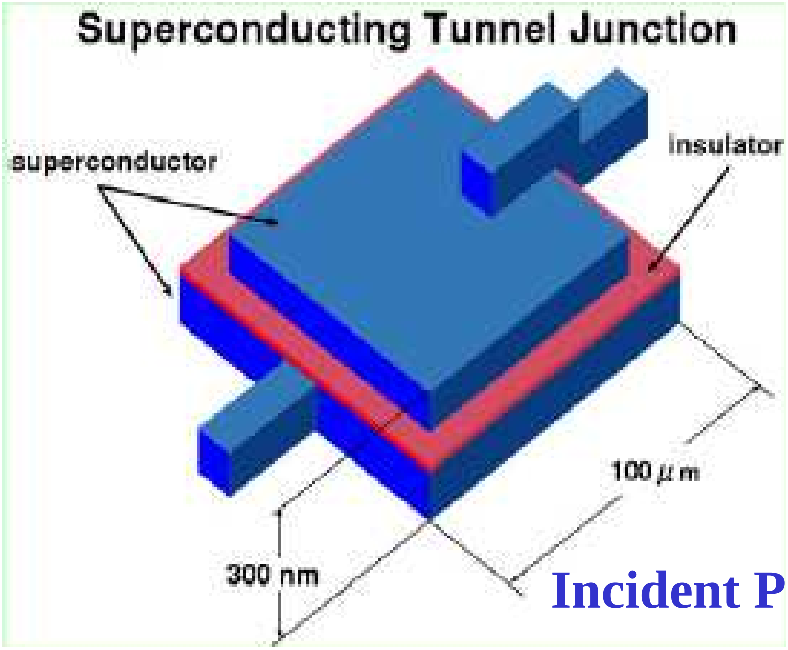
Superconducting Tunnel Junction (STJ) Detector

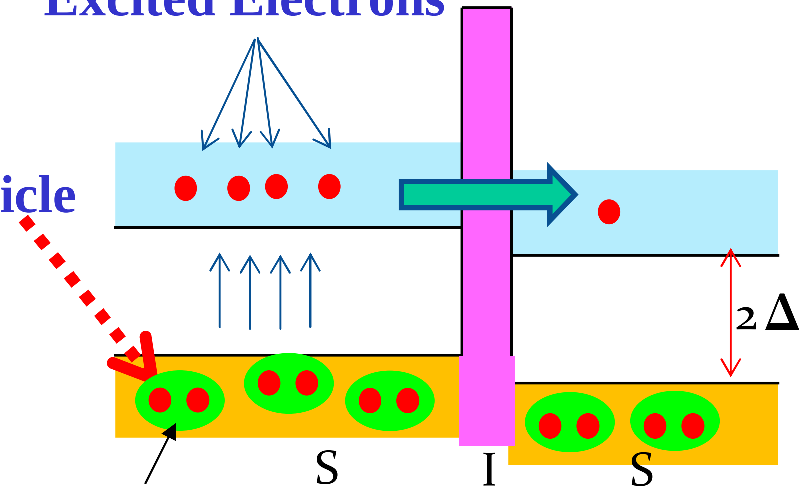
STJ (Superconducting Tunnel Junction) Detector

- 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

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

Using Hf as a superconductor,

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

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

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

Tc : Critical Temperature

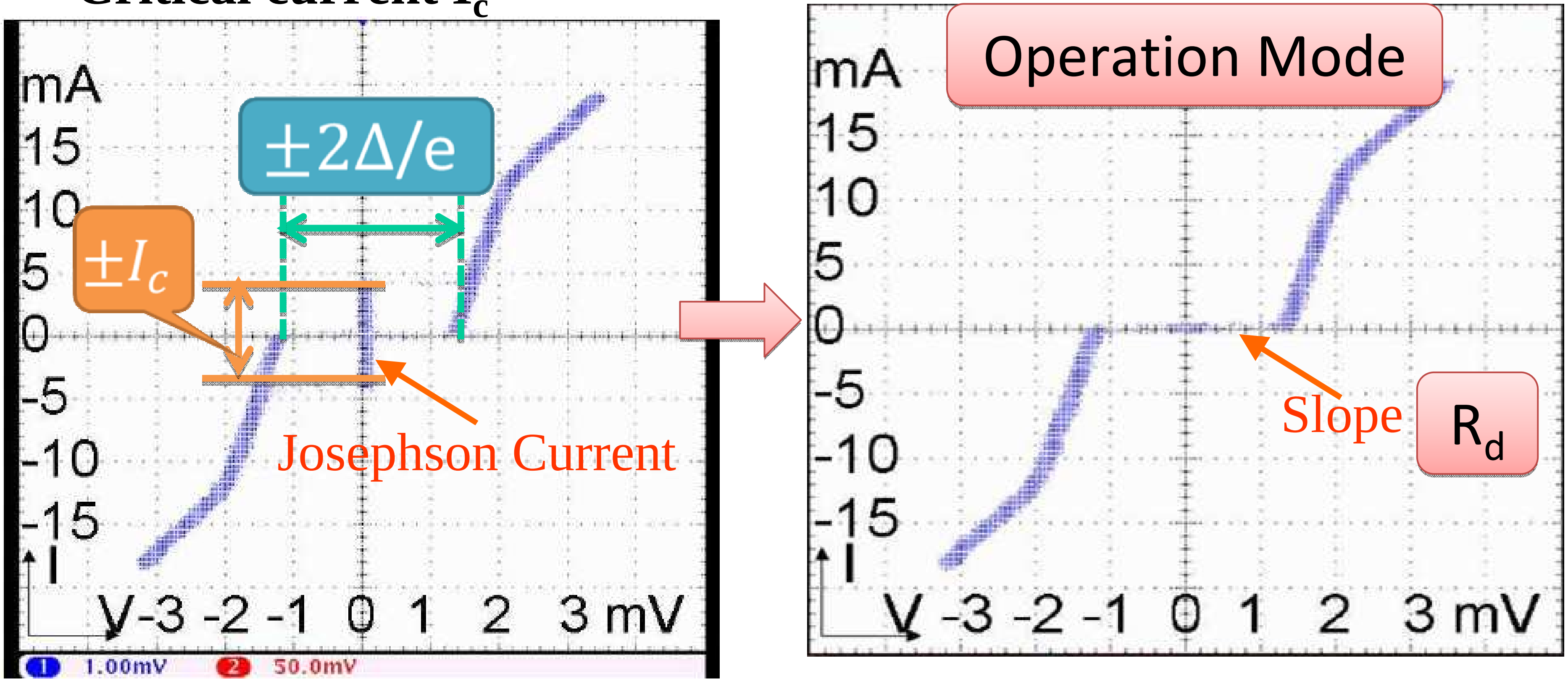
Operation is done at a temperature around 1/10 of Tc

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**


$\pm 2\Delta/e$

$\pm I_c$

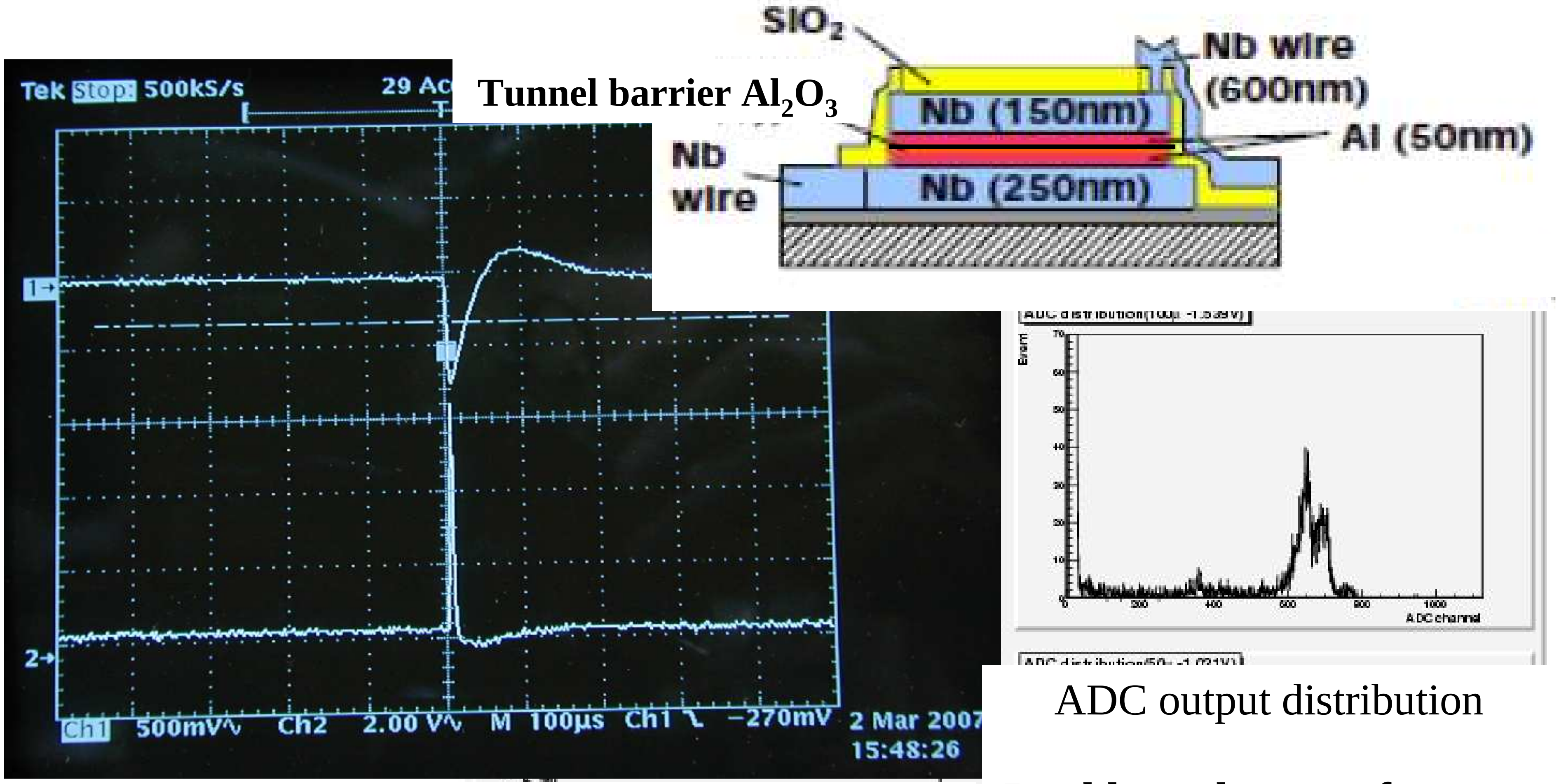
Josephson Current

Operation Mode

Slope R_d

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

Nb/Al - STJ Response to 5.9keV X rays



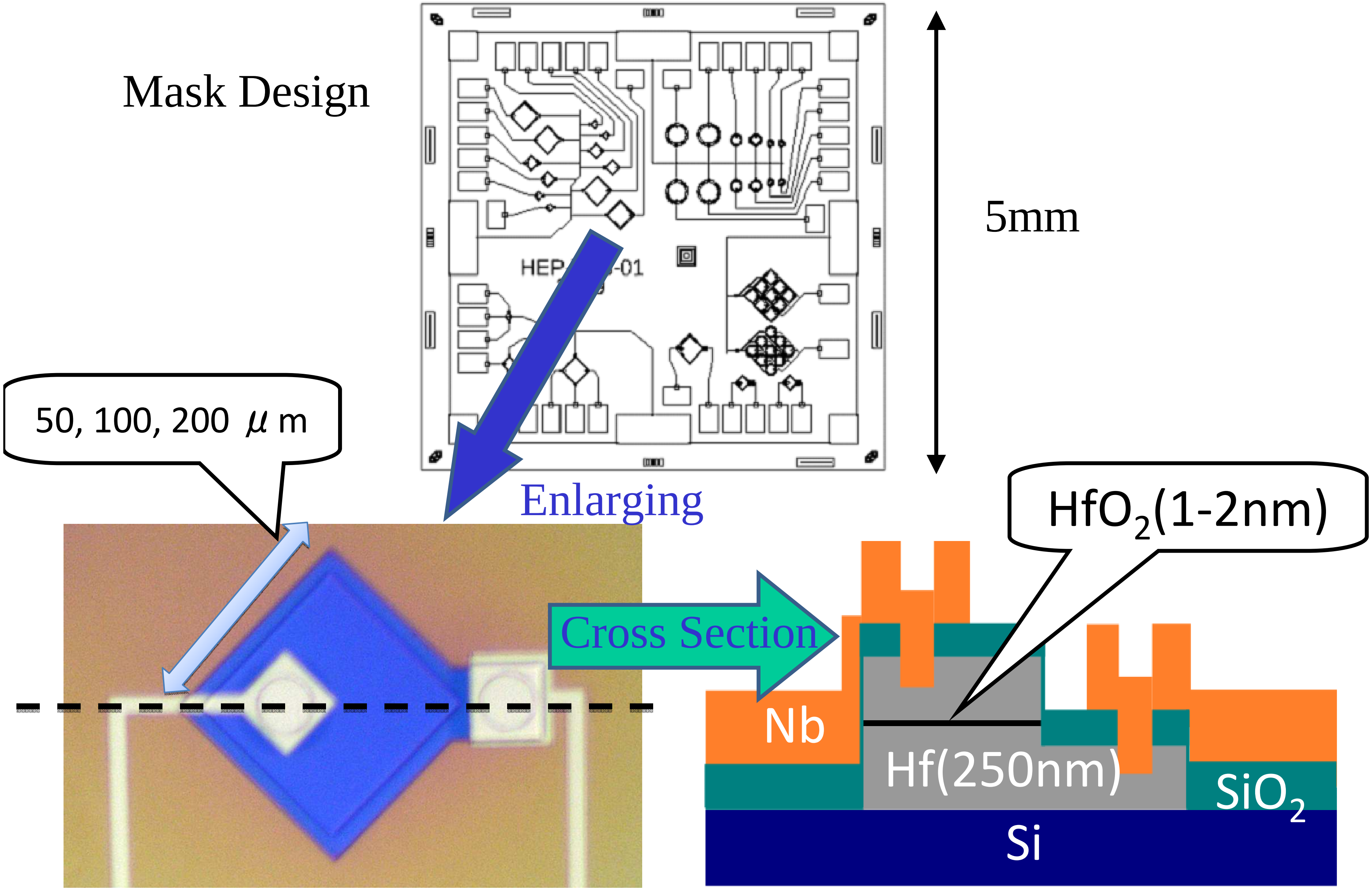
ADC output distribution

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

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

Status of Hf-STJ Development

Hf-STJ Structure



Mask Design

5mm

Enlarging

50, 100, 200 μm

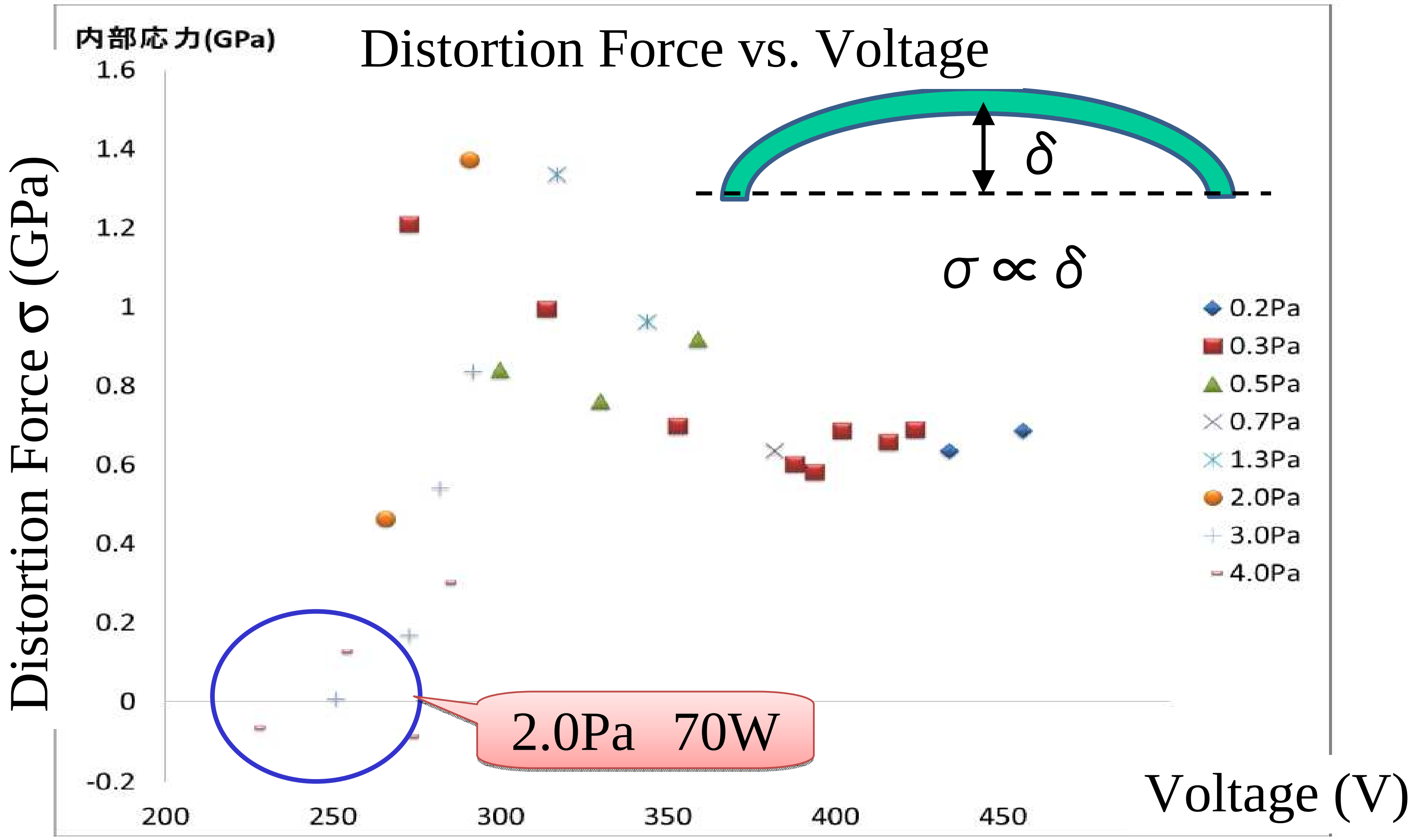
Cross Section

HfO_2(1-2nm)

R&D Status

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

- 2.0 Pa, 70W (optimized)

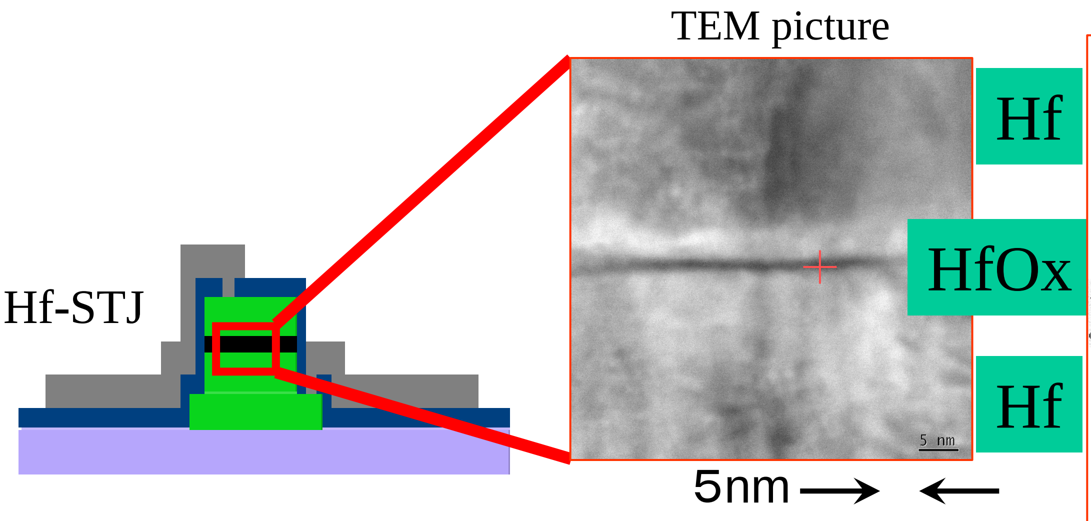


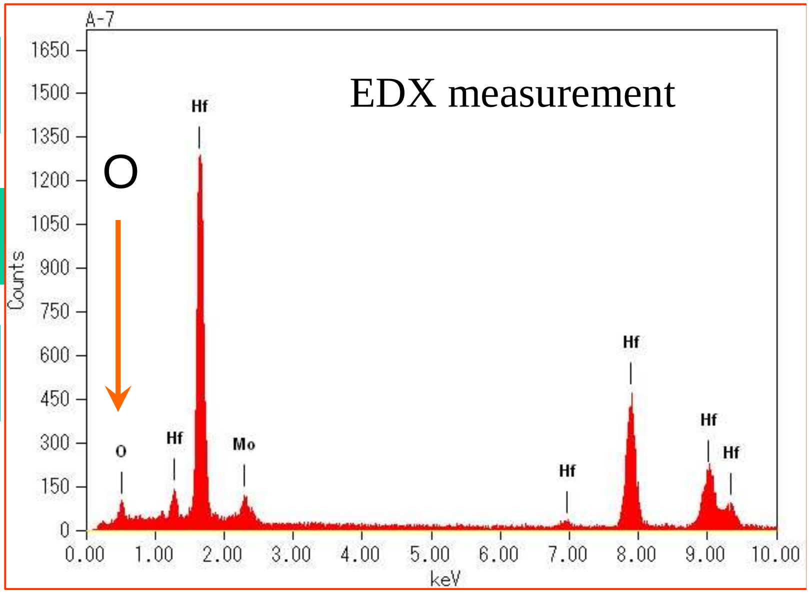
Distortion Force vs. Voltage

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**





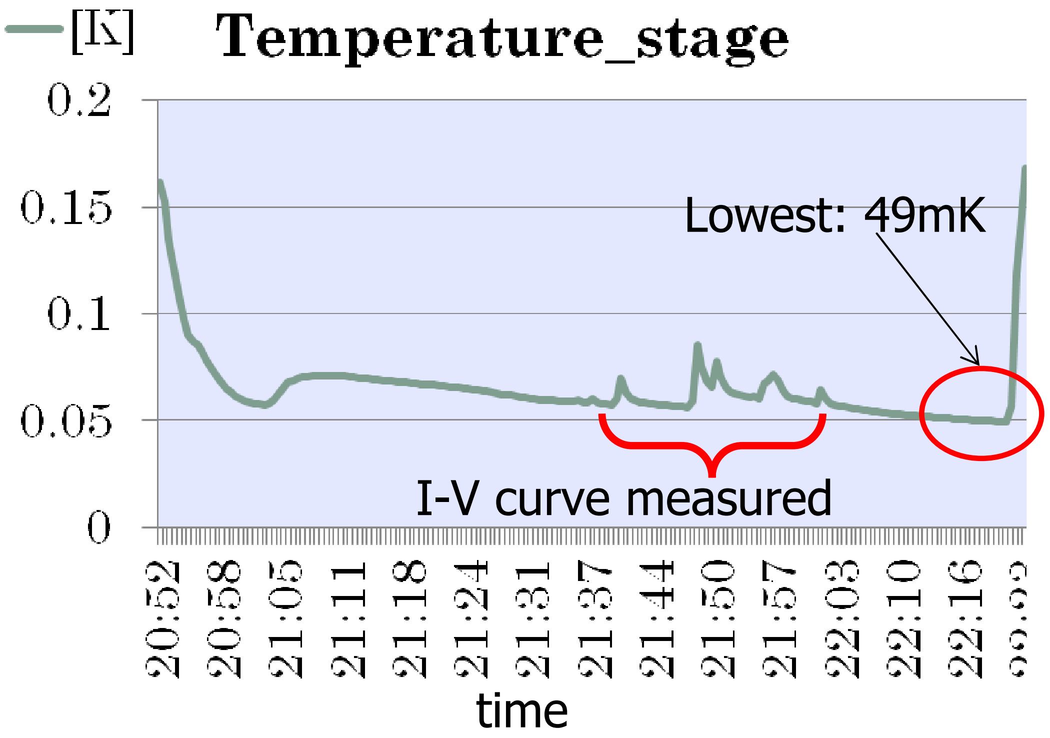
•TEM: Transmission Electron Microscope

•EDX: Energy Dispersive X-ray Spectroscopy

R&D Status

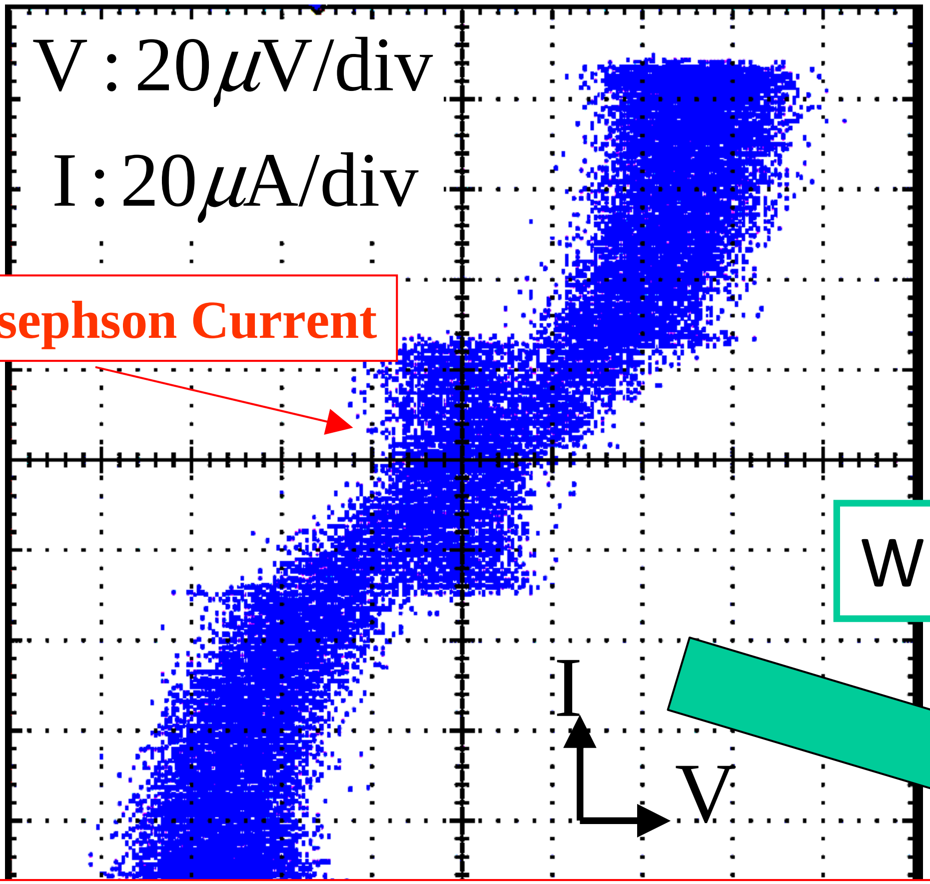
(3) Operation of He_3/He_4 Dilution Refrigerator.

- 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.



Hf-STJ I-V Curve

(Oxidation Condition: 10Torr 60min.)



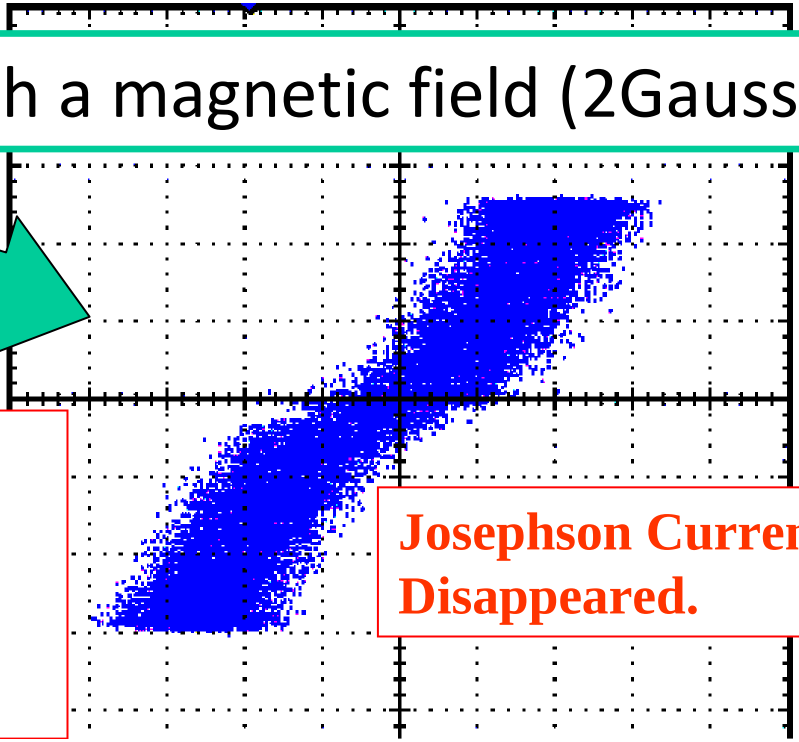
Josephson Current

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

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)



Josephson Current Disappeared.

- **First observation of Josephson current with Hf-STJ.**
- **Need to reduce the large leakage current and the large noise**

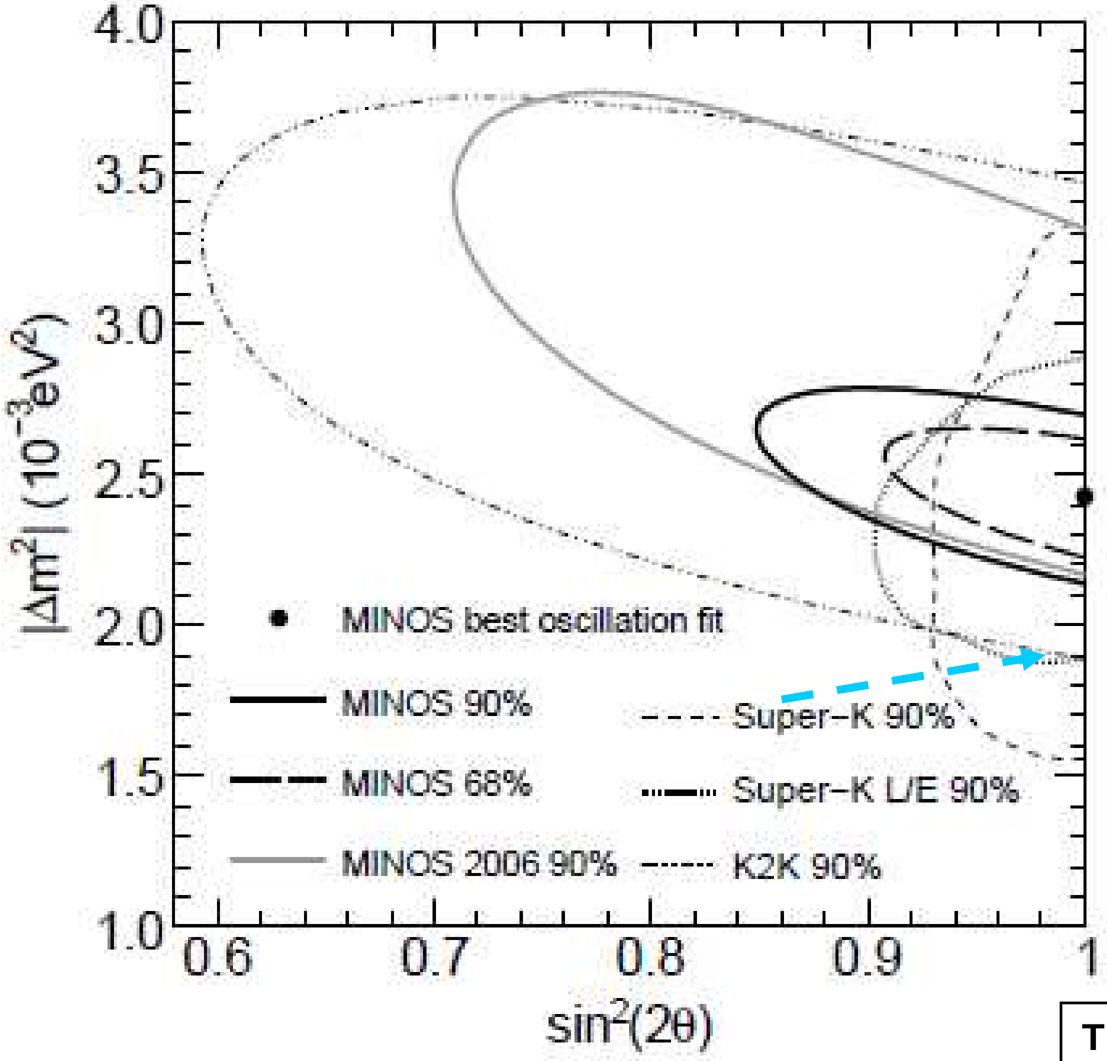
Plans

Superconducting Detector R&D

- 2011-2012: Develop a single cell Hf-STJ
  and low-temperature electronics
  (to see the Infrared photon signal).
- 2013- : Multi-cell Hf-STJ development
- 2011- : Hf-MKID (Microwave Kinetic Inductance Detectors)
  development

BACKUP

MINOS, K2K and Super-K Experiment Results

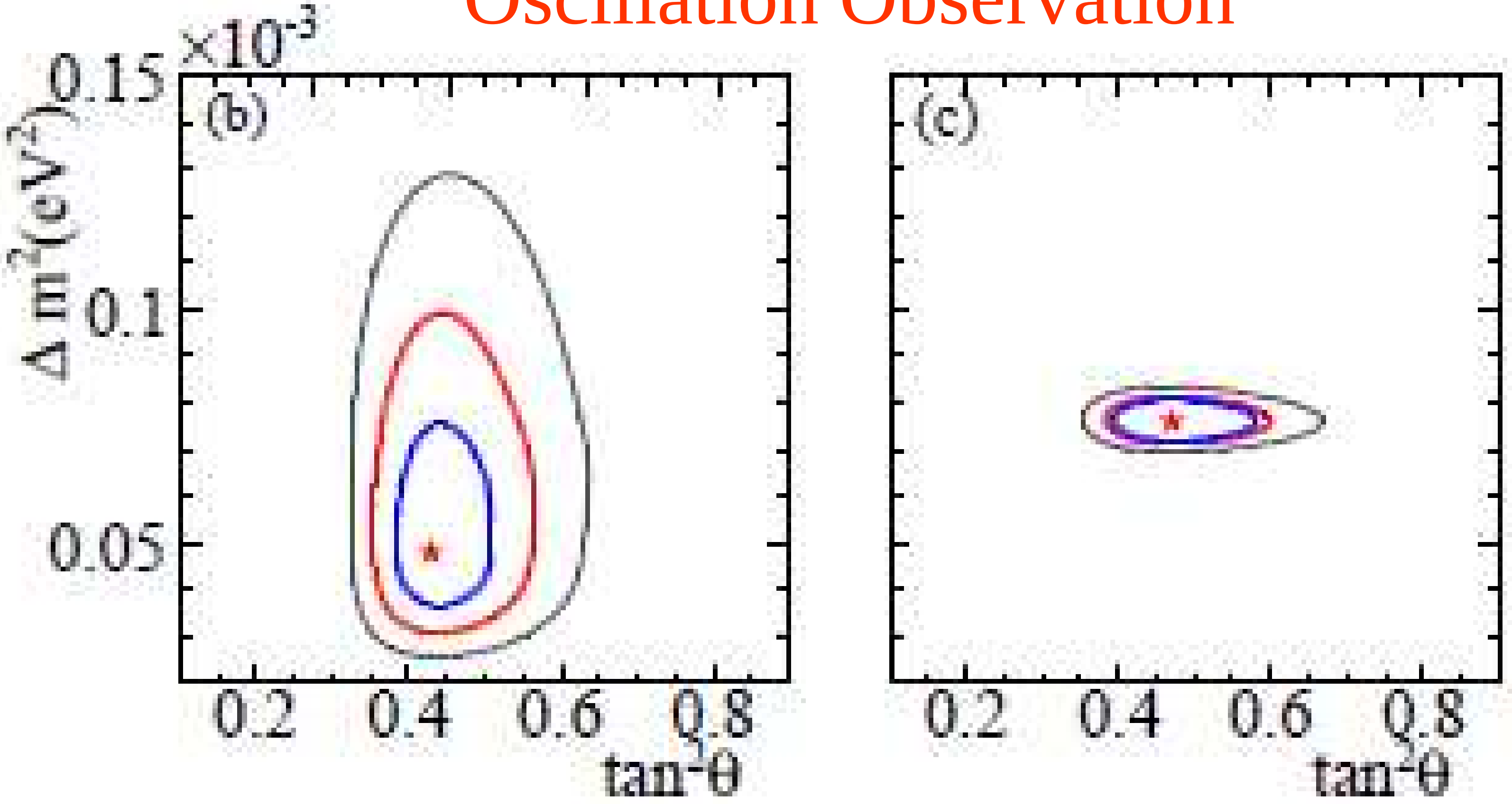


MINOS Best Fit
$\Delta m_{23}^2 = (2.43 \pm 0.13) \times 10^{-3} eV^2$

Super-K Best Fit
$\sin^2(2\theta_{23}) > 0.93$

Three independent measurements agree with each other.

Results from Kamland and Solar Neutrino Oscillation Observation



- ☐ (b) Solar Global: SNO, SK, Cl, Ga, Borexino
- ☐ (c) Solar Global + KamLAND :

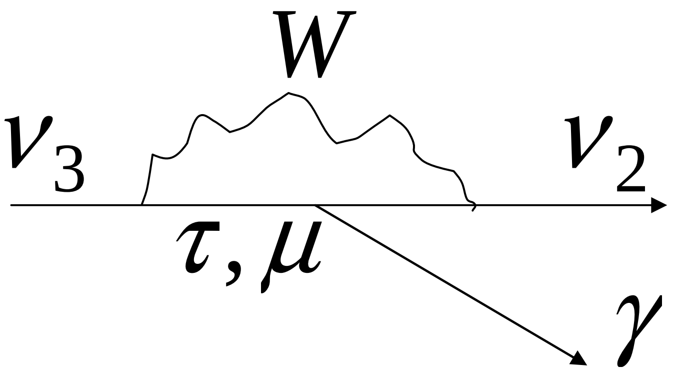
$\Delta m_{12}^2 = (7.59 + 0.19/ -0.21)\ \mathrm{x}10^{-5}\mathrm{eV}^2$

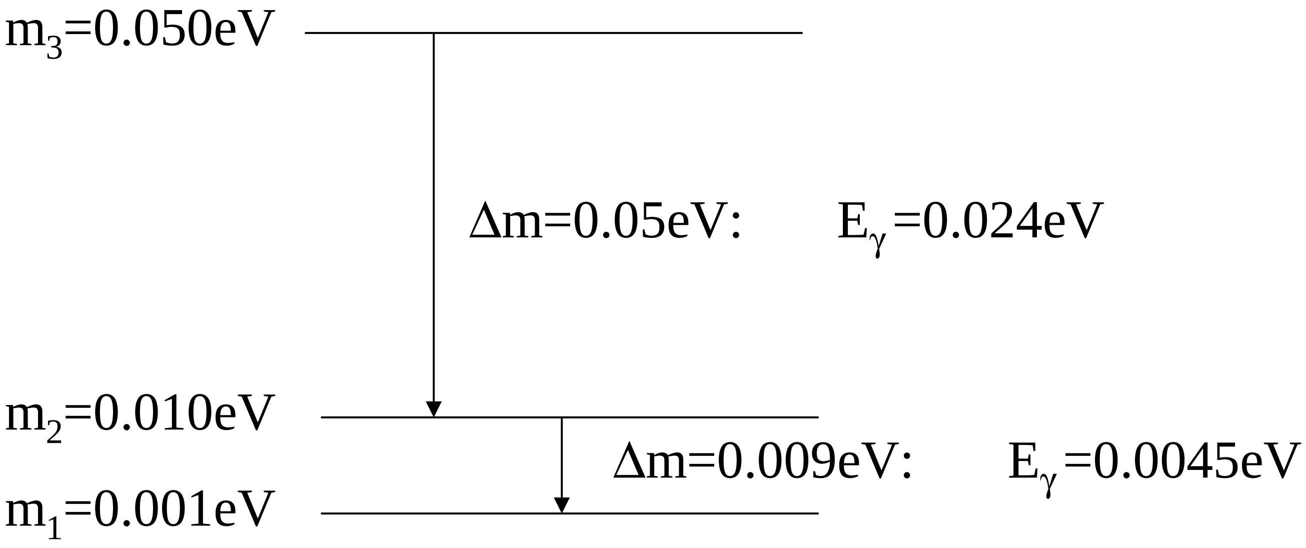
$\theta_{12} = 34.4 +1.3/ -1.2$ degrees

Neutrino Masses and Decay Photon Energy

$$\nu_3 \rightarrow \nu_2 + \gamma$$

$$\nu_2 \rightarrow \nu_1 + \gamma$$



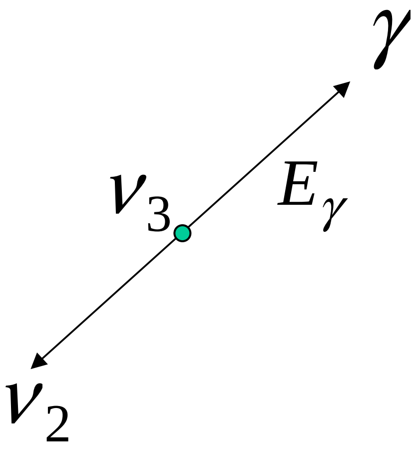

m_3=0.050eV

Δm=0.05eV: E_γ=0.024eV

m_2=0.010eV

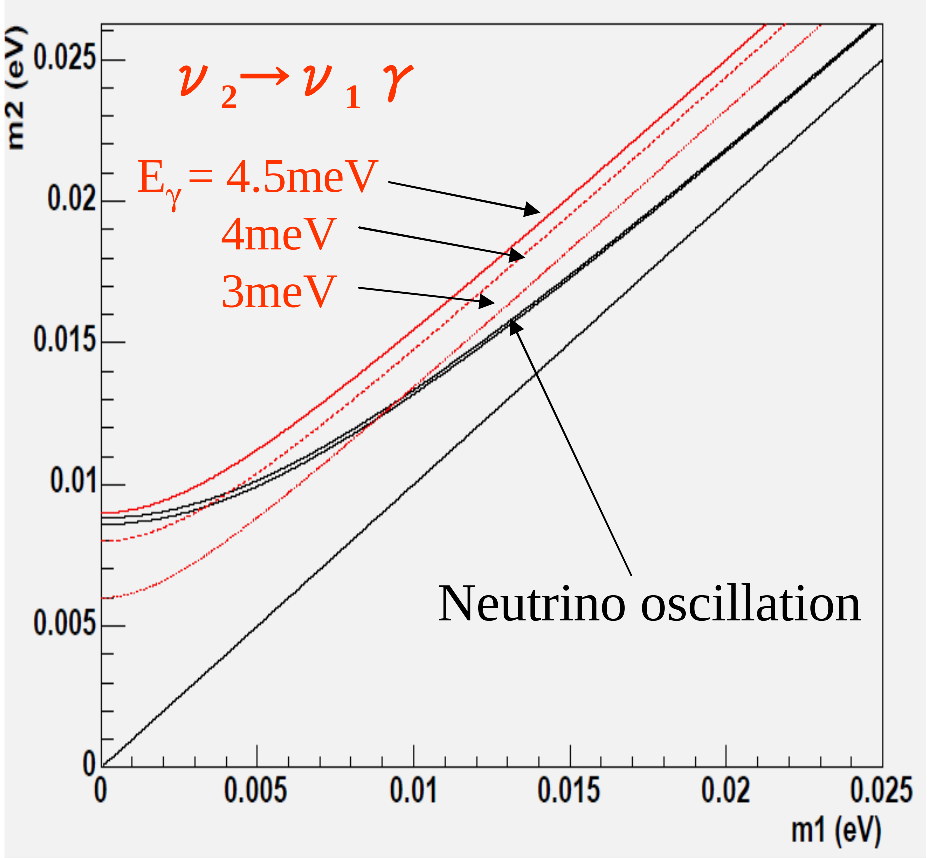
Δm=0.009eV: E_γ=0.0045eV

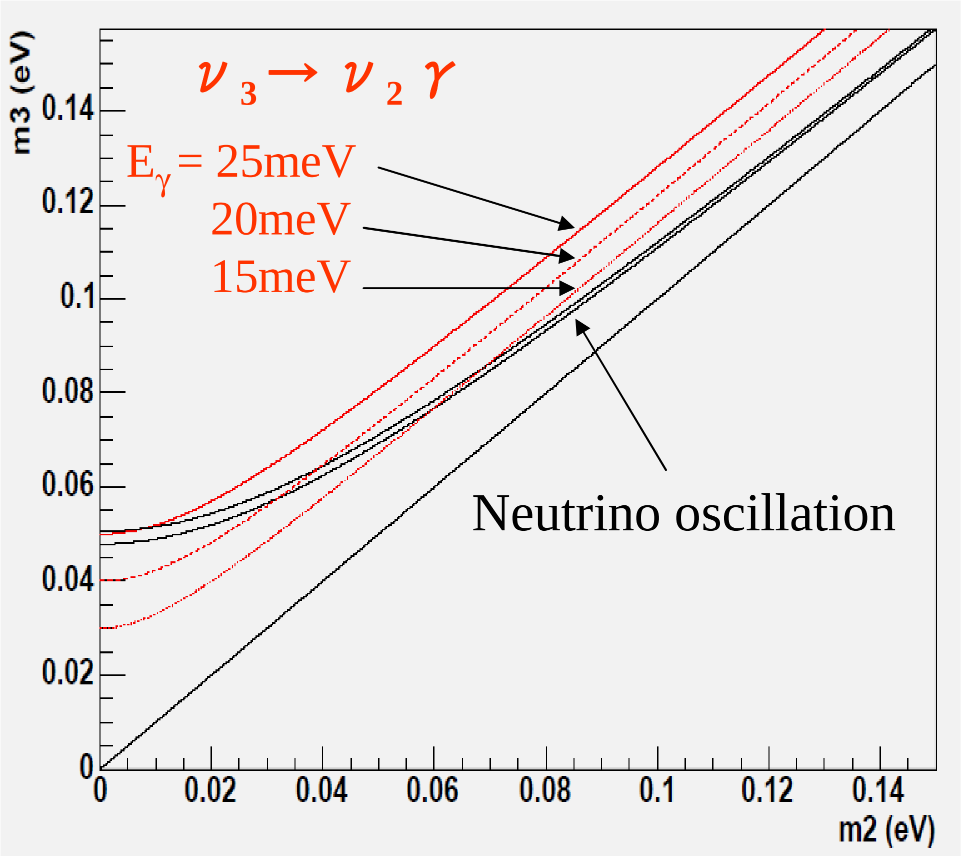
m_1=0.001eV



$$m_3 = E_\gamma + \sqrt{E_\gamma^2 + m_2^2}, \qquad E_\gamma = \frac{m_3^2 - m_2^2}{2m_3}$$

Mass Relations from Neutrino Oscillation Results and Neutrino Decay

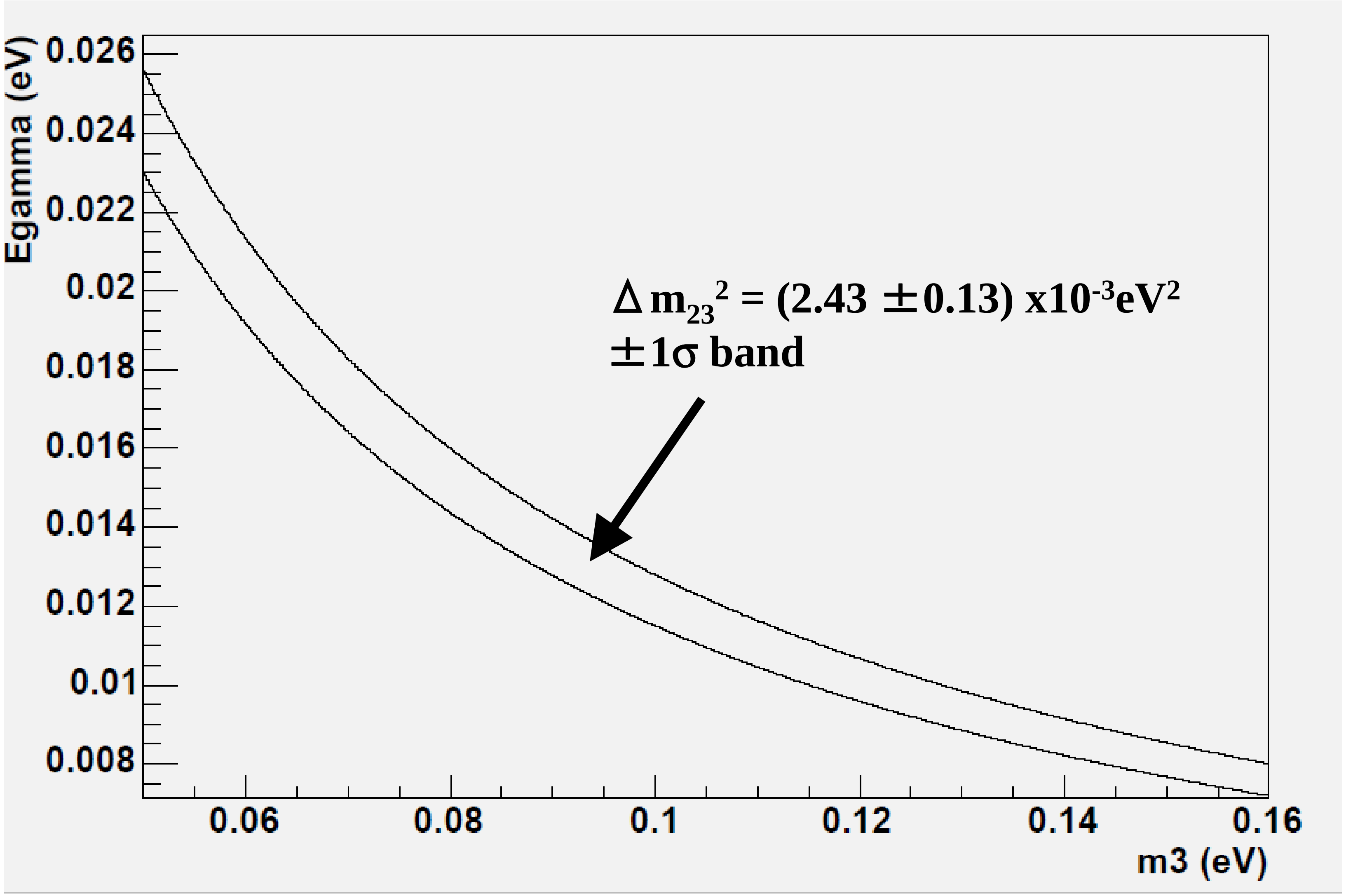




Results from direct measuremenmt (Tritium Decay)

$m(\nu_e) < 2\text{eV}$

Decay Photon Energy versus m_3

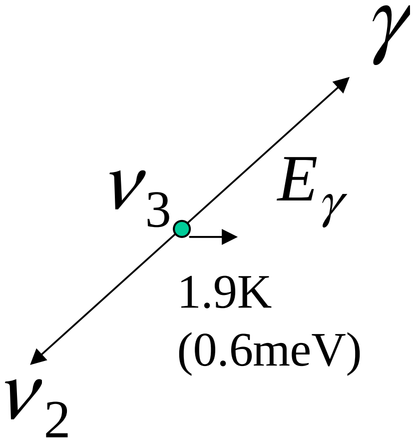


$\Delta m_{23}^2 = (2.43 \pm 0.13) \times 10^{-3} \mathrm{eV}^2$

$\pm 1\sigma$ band

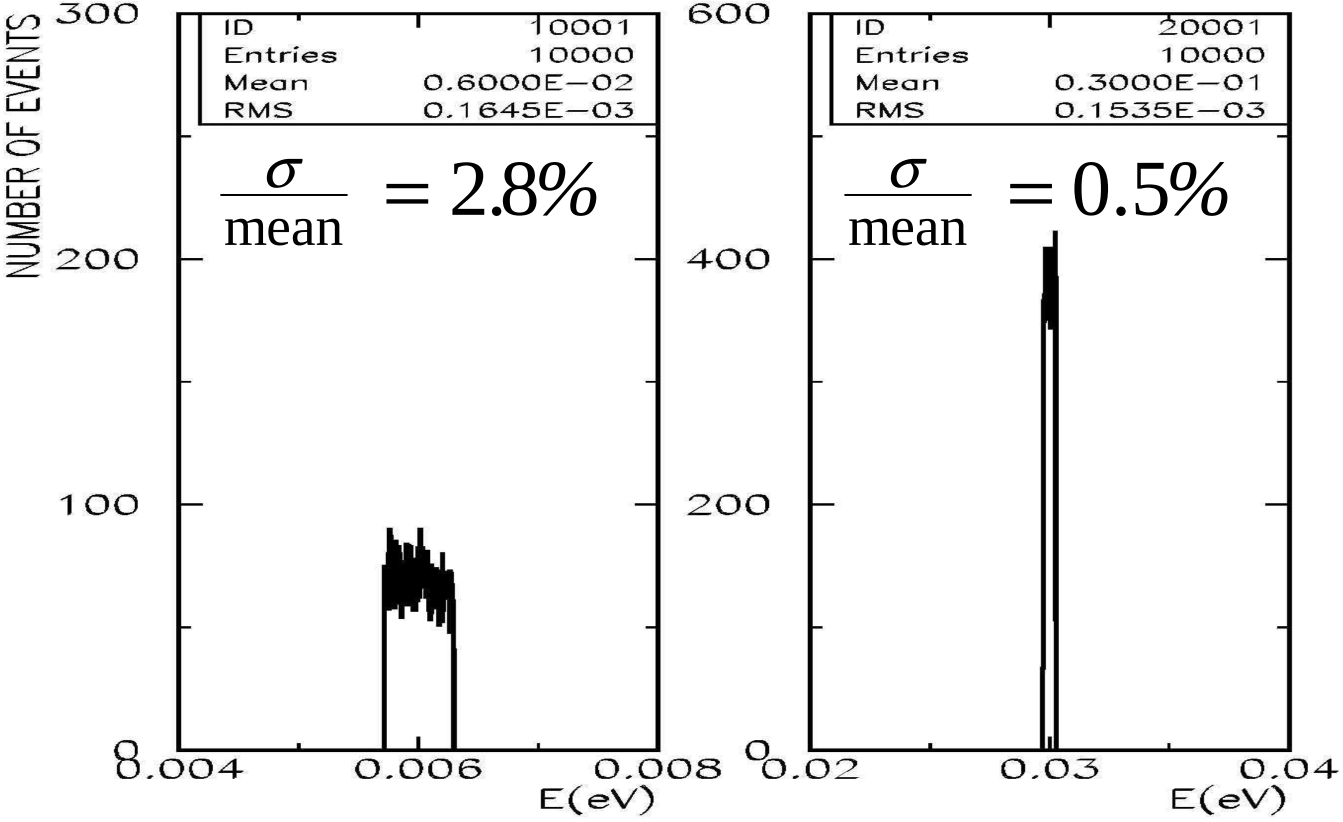
Spectra of Decay Photon Energy after1.9K ν Smearing

Energy distributioin of cosmic background neutrino is a Planck distribution
with a temperature of 1.9K（0.6meV).



$$\nu_2 \rightarrow \nu_1 + \gamma \qquad \nu_3 \rightarrow \nu_2 + \gamma$$

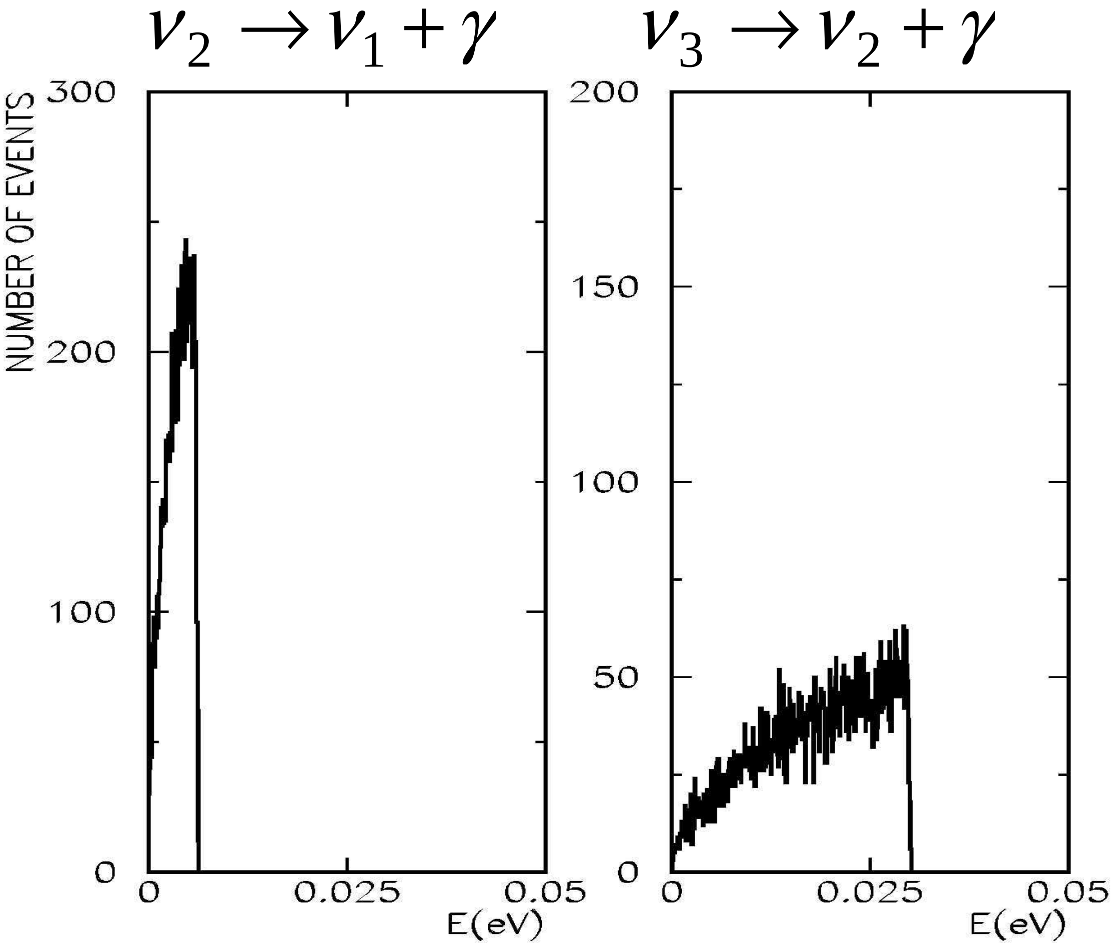
$$\mathrm{E}_\gamma = 0.006\mathrm{eV} \qquad \mathrm{E}_\gamma = 0.03\mathrm{eV}$$



$$\frac{\sigma}{\mathrm{mean}} = 2.8\% \qquad \frac{\sigma}{\mathrm{mean}} = 0.5\%$$

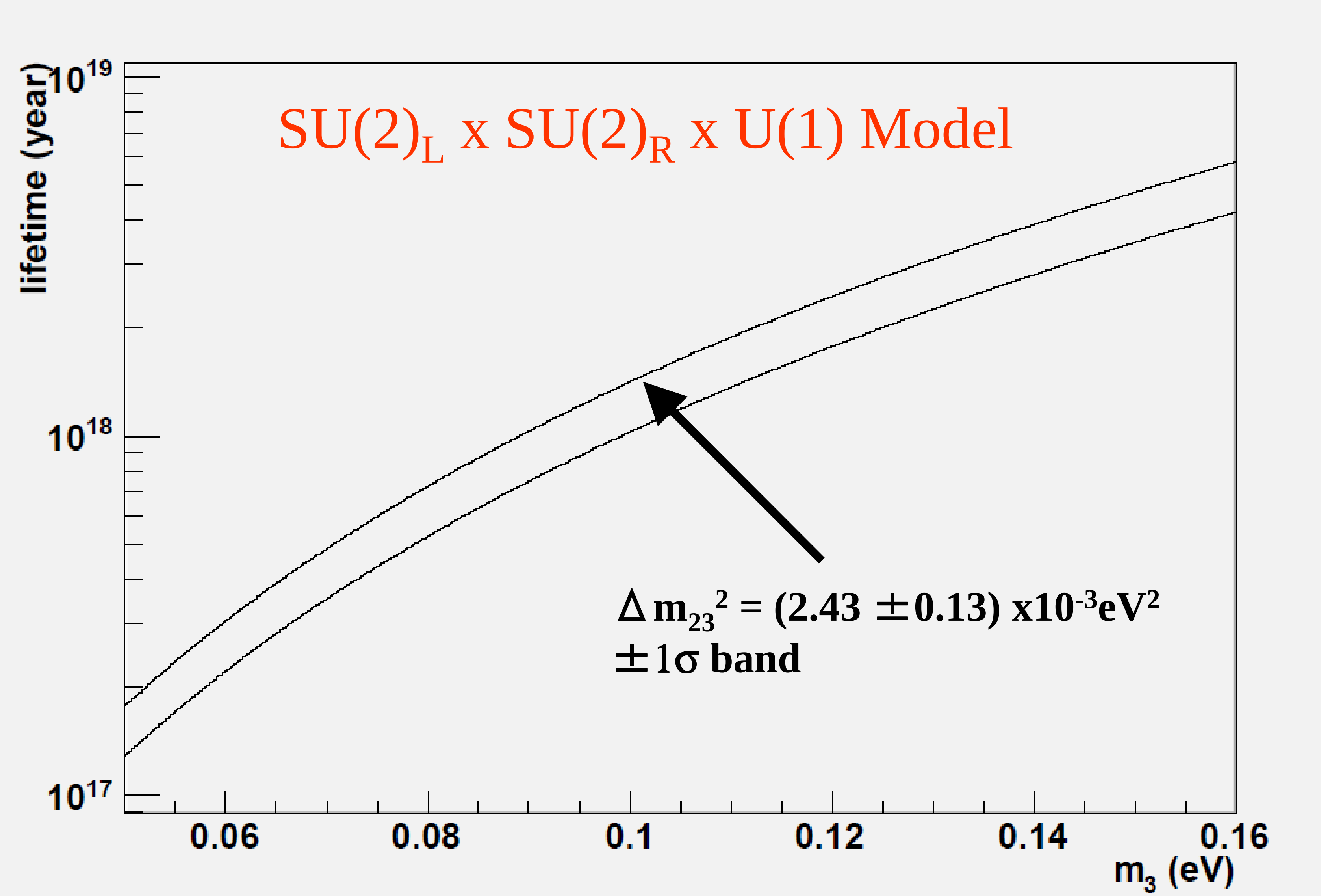
Red Shift Effect on the Photon Energy Spectra

Observed photon energy E_γ is given by $E_\gamma = E_{\gamma\,\mathrm{rest}}/(1+z)$, where z is a red shift and $E_{\gamma\,\mathrm{rest}}$ is a photon energy without Doppler shift.



$\nu_2 \rightarrow \nu_1 + \gamma$ $\nu_3 \rightarrow \nu_2 + \gamma$

ν_3 Decay Lifetime versus m_3

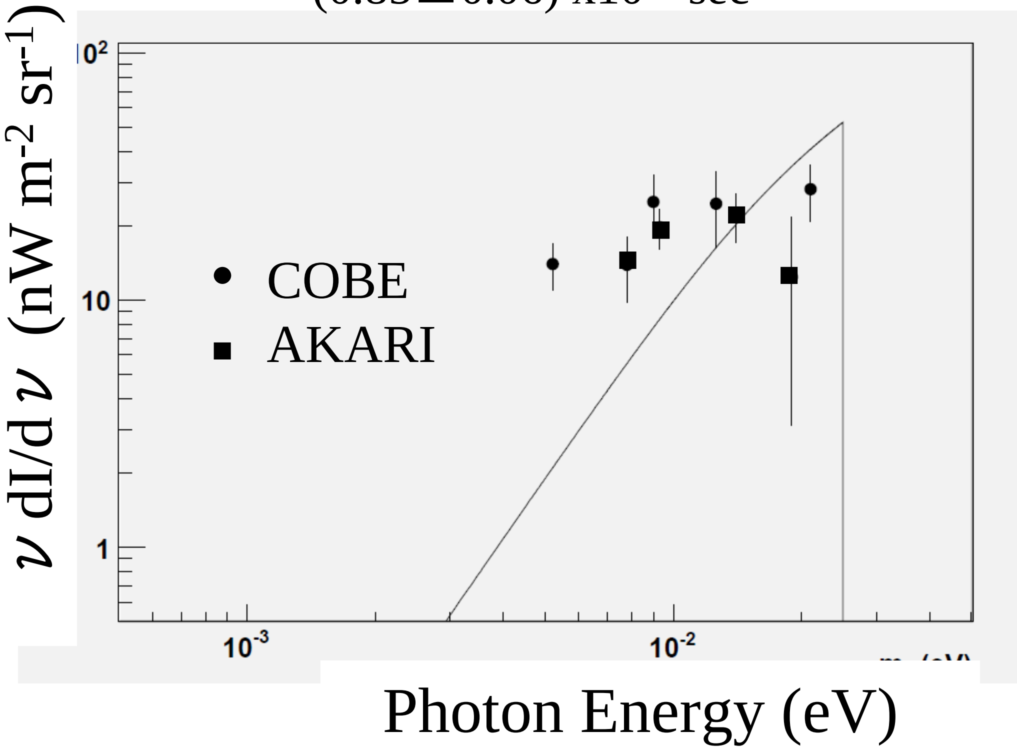


$SU(2)_L$ x $SU(2)_R$ x U(1) Model

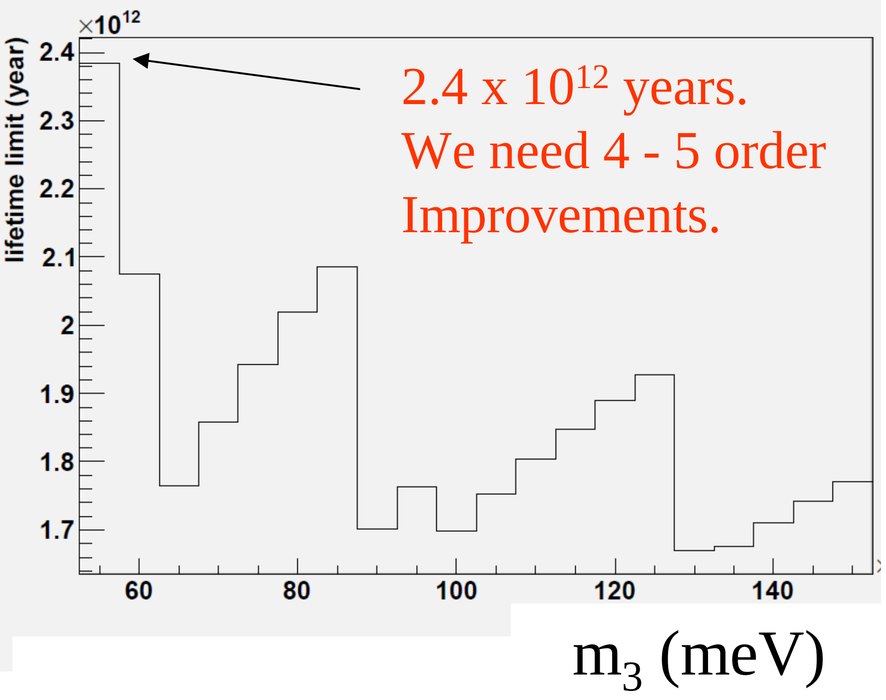
$\Delta m_{23}^2 = (2.43 \pm 0.13)$ x10^{-3}eV^2
±1σ band

Lower Limit of Lifetime from the Energy Spectrum Fit to the CIB measured by COBE and AKARI

$\chi^2 = 6.6$
$\tau = (2.8 \pm 0.2) \times 10^{12}$ year
$= (0.85 \pm 0.06) \times 10^{20}$ sec



Lifetime limit vs m_3



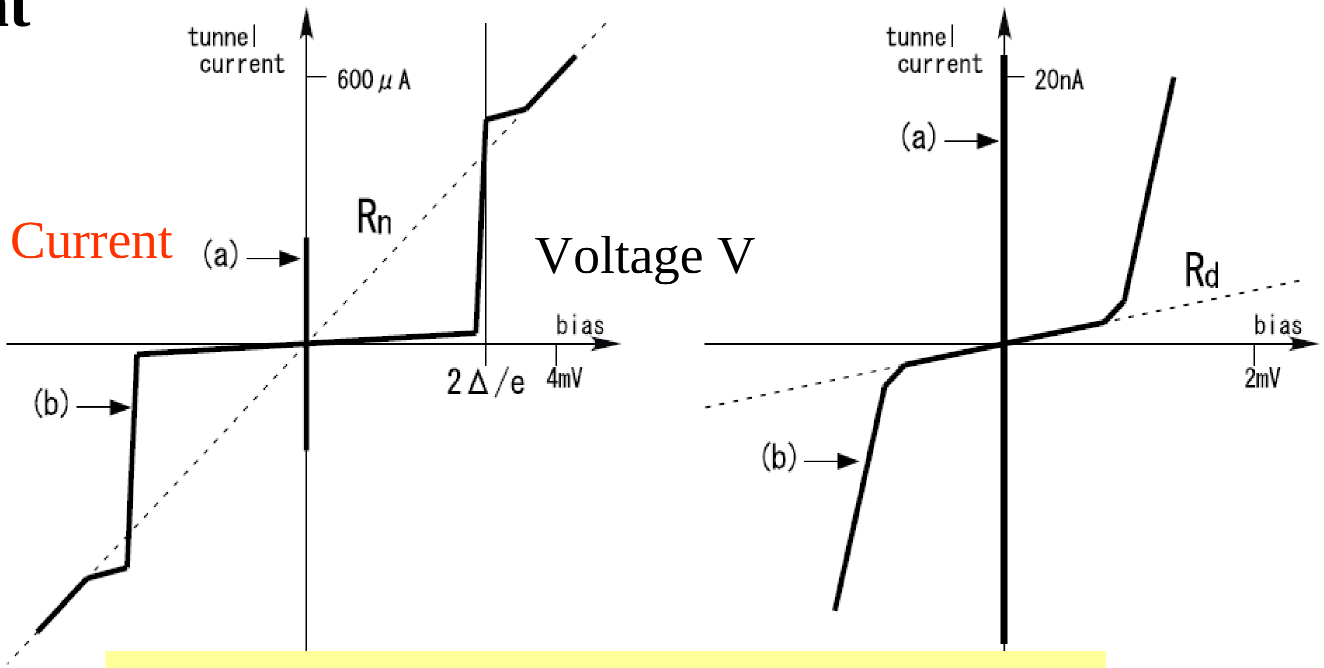
2.4×10^{12} years.
We need 4 - 5 order
Improvements.

Using the CIB at 60, 100 (ApJ, 544, 81, 2000), 140, 240 μm (ApJ, 508, 25, 1998), 65, 90, 140, and 160 μm (arXiv:1002.3674, 2010), the photon energy spectrum from neutrino radiative decay gives a lifetime lower limit of 2.4×10^{12} year at 95% C.L. for $m_3 = 0.05$eV and $m_2 = 0.01$eV. (My calculation)

Basic Properties of STJ Detector

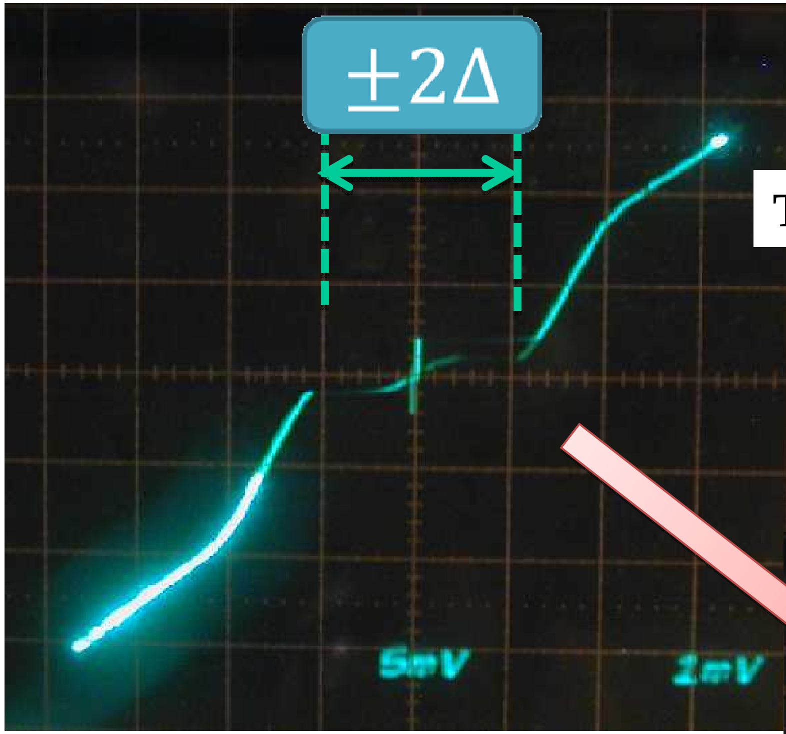
By measuring the curve of current -voltage (I-V curve), we know

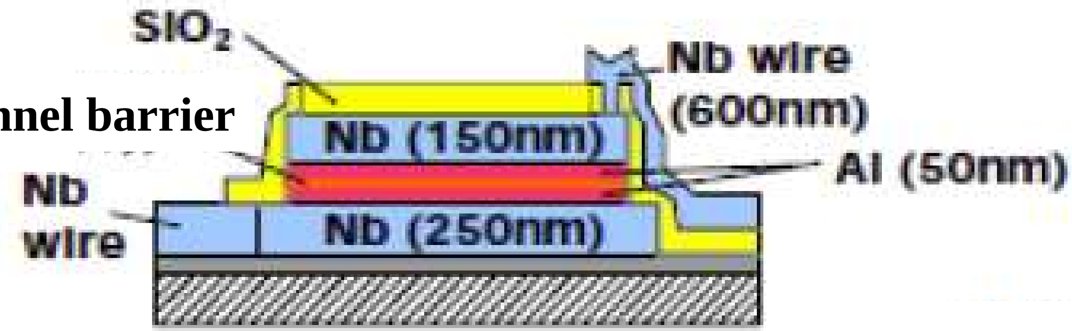
- **Superconducting phase transition**
- **Josephson junction**
- **Leakage current**
- **Energy gap**

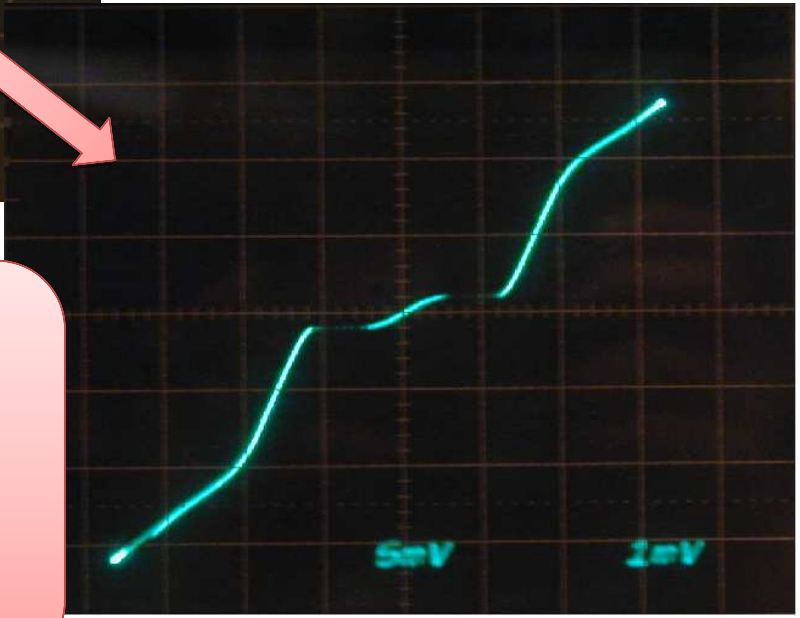


Critical Voltage Vc : 2Δ/e mV
Critical Current Ic : a few ~ a few 100 μA

Nb/Al - STJ IV Curve







T = 0.4K

V: 1mV/div
(horizontal)
I: 5 mA/div
(vertivcal)

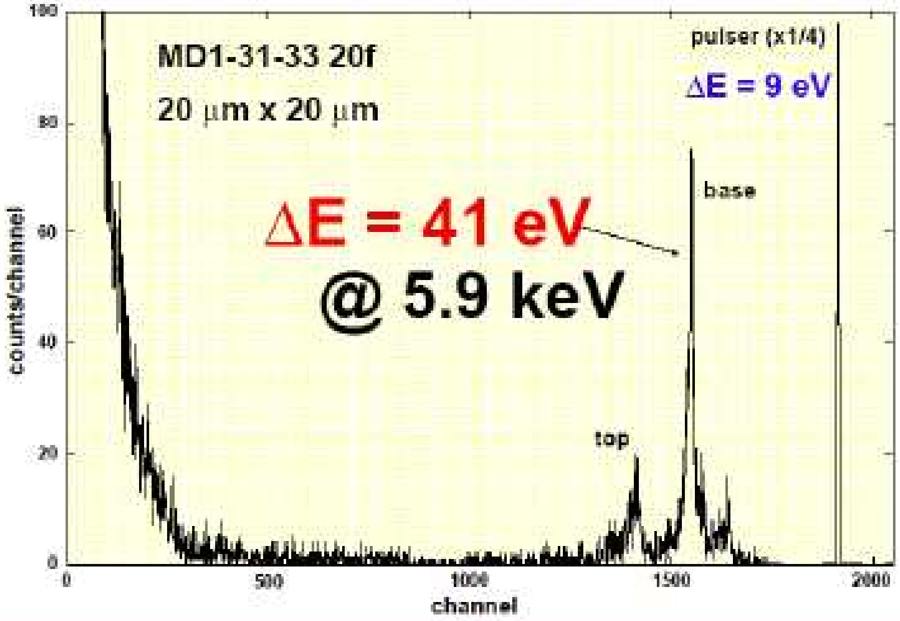
Josephson Current is suppressed by a magnetic field

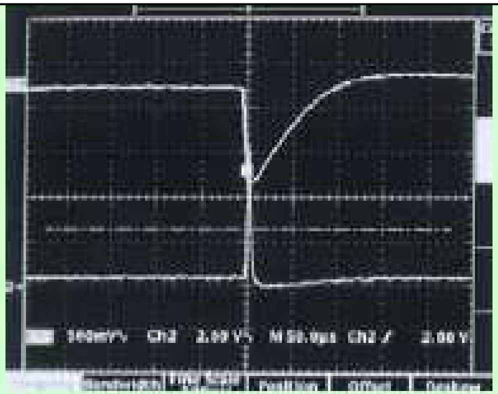
Nb/Al - STJ Response to 5.9keV X rays by RIKEN group

^{55}Fe X線源使用

Nb/Al/AlOx/Al/Nb

5.9keV X ray signal

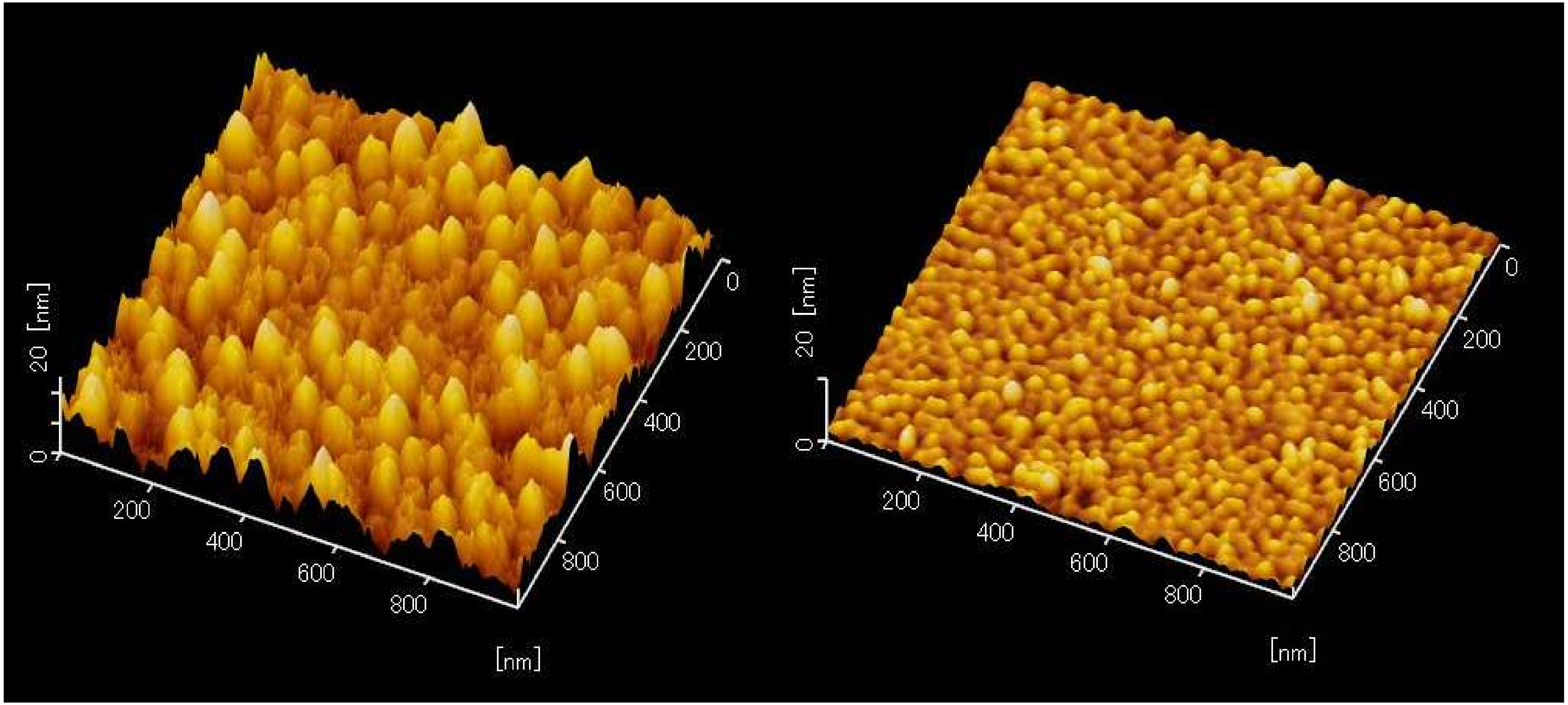




Double peak comes from that X rays are absorbed both in the upper layer and the under layer.

H.Sato et al., Jpn. J. Appl. Phys. 39 (2000) p5090

Surface Flatness measured with AFM



2.0Pa 70W

No Distortion

RMS 3.5nm

1/4

0.5Pa 50W

Distortion Force ~1.4GPa

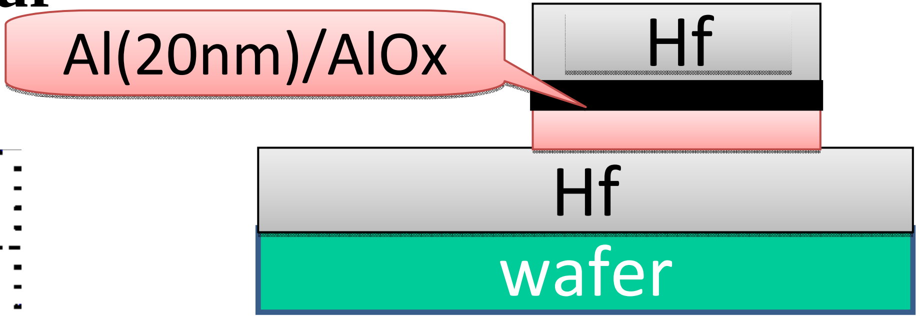
RMS 0.9nm

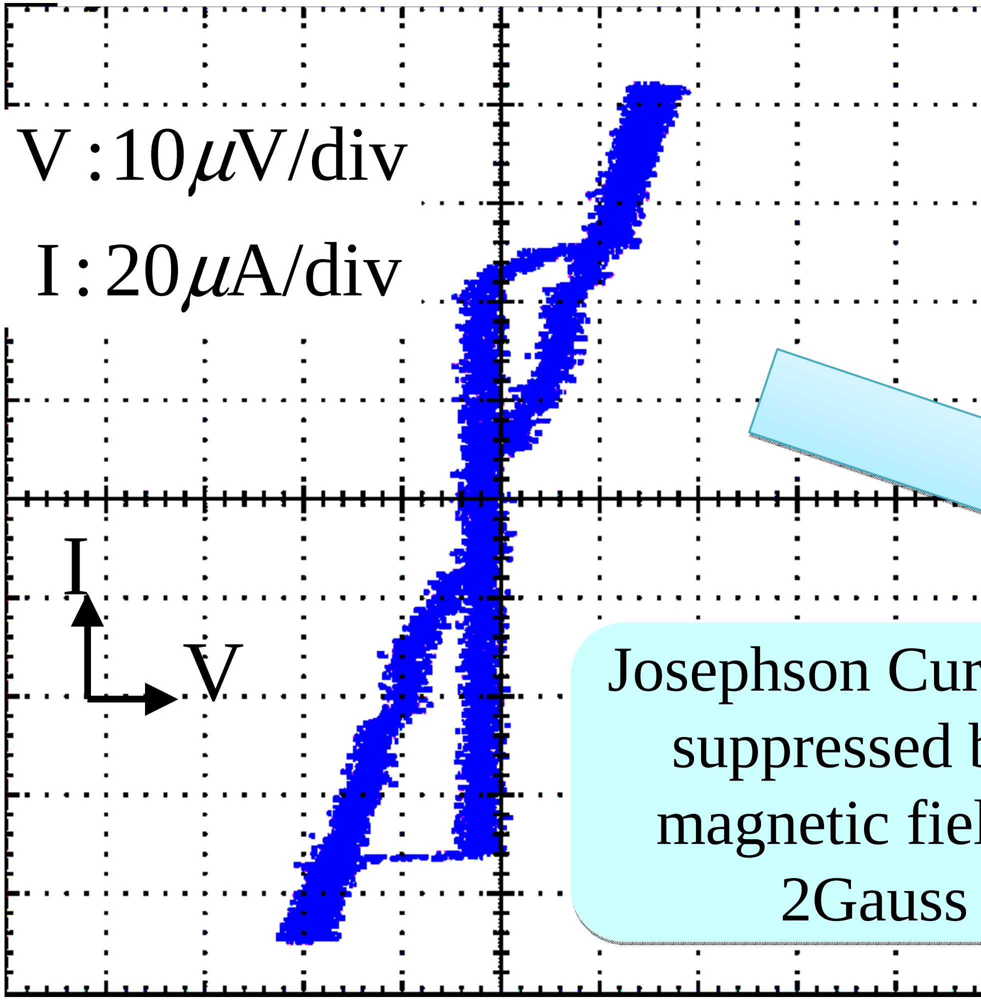
*** AFM : Atomic Force Microscopy**

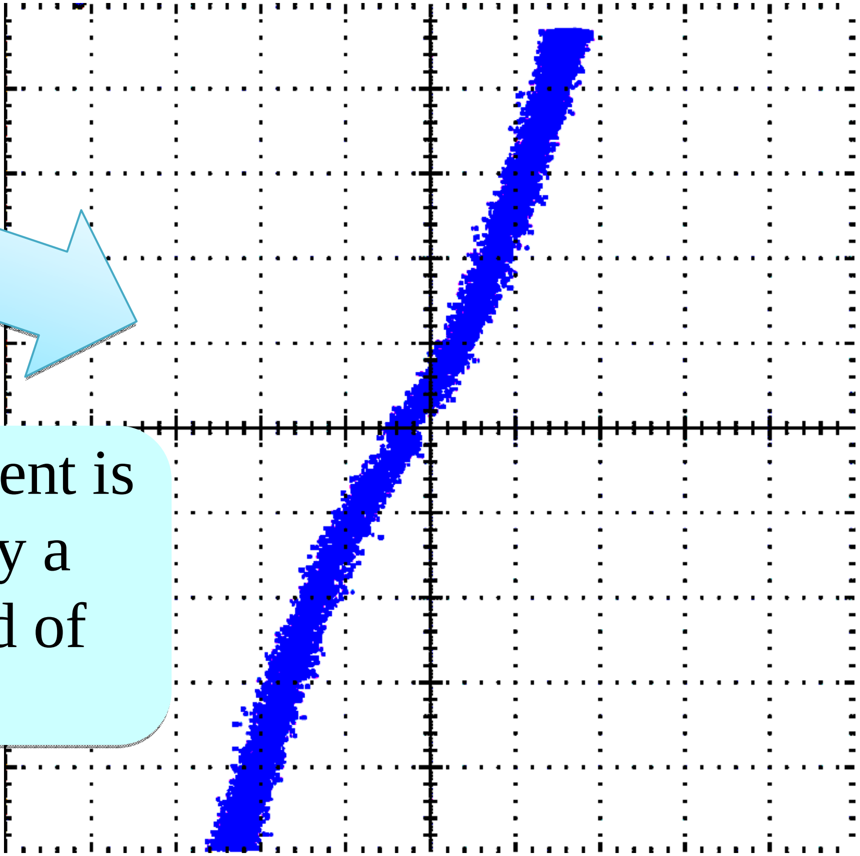
Hf/Al/AlOx/Hf-STJ I-V Curve

Oxidation Condition: 30Torr 1hour

Leak Current and I_c are high.





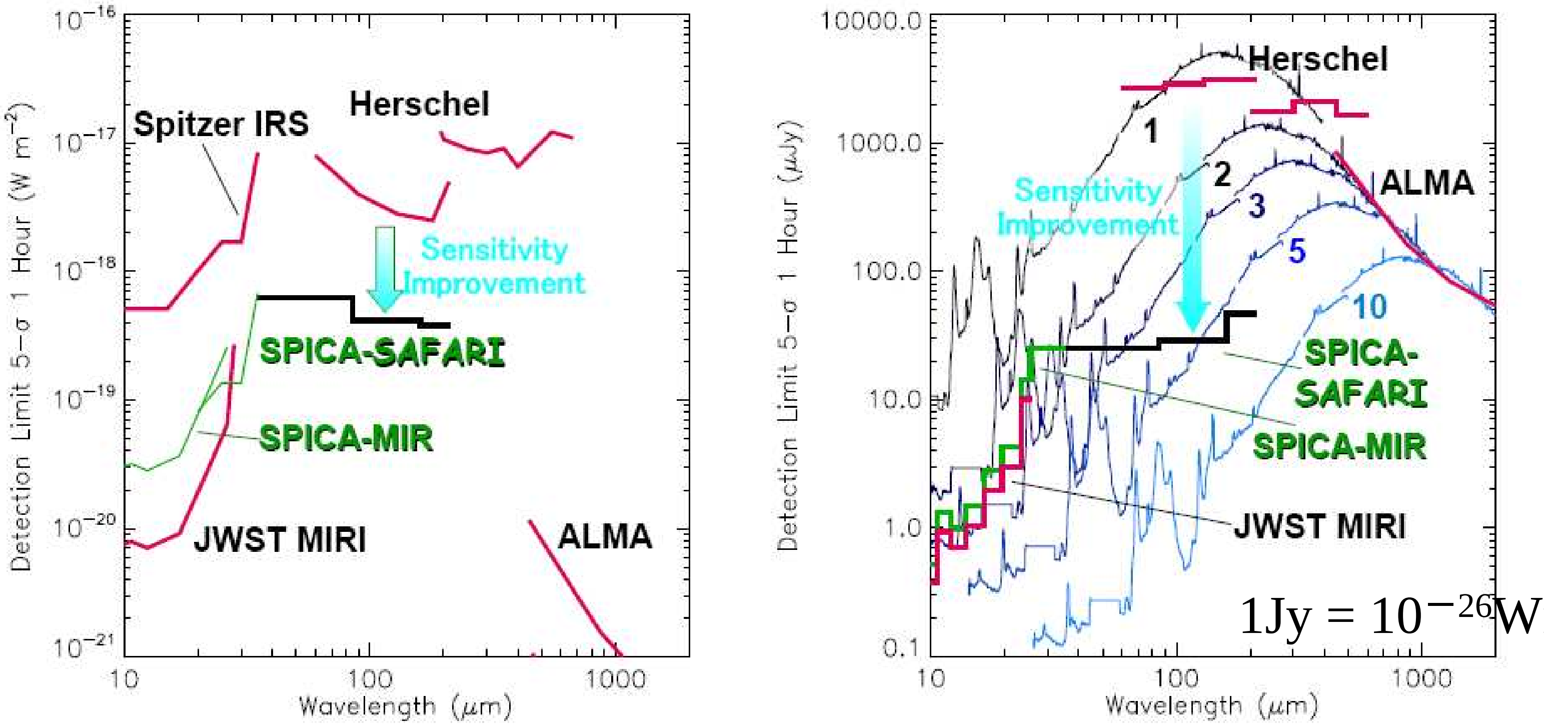


Josephson Current is suppressed by a magnetic field of 2Gauss

SPICA SENSITIVITY

By Yasuo Doi at SPICAWorkshop Dec 16-17, 2010

Expected sensitivity
Spectroscopic (left) & photometric (right)



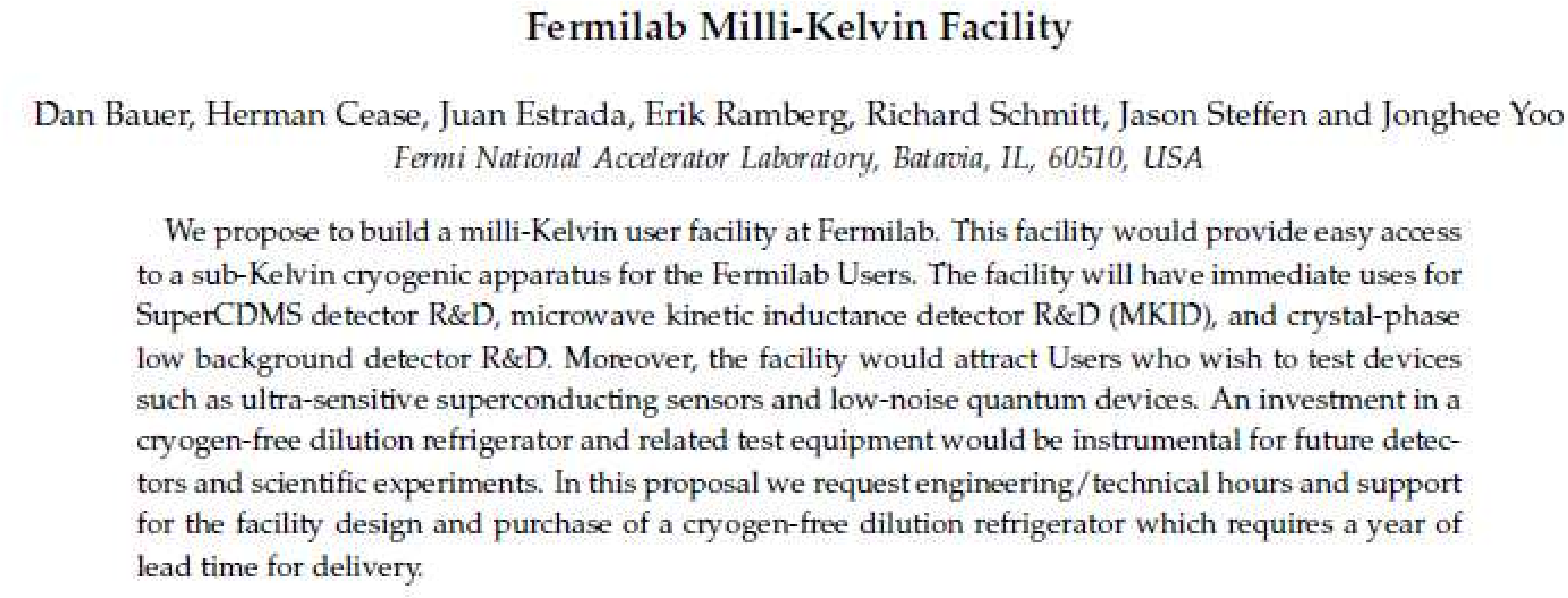
1Jy = 10^{-26}Wm^{-2}Hz^{-1}

SPICA (launched in 2018) sensitivity: For photons with a wavelength of 30−200μ, 1-hour measurement gives 5σ limit of 4×10^{-19}Wm^{-2}.
Assuming the signal spreads uniformly over FOV 0.1degree (6.0arcmin), 5σ limit is 3.2×10^{-12}Wm^{-2}sr^{-1}. NEP=2×10^{-19} WHz$^{-1/2}$ is good enough.

Plans

Superconducting Detector R&D

- 2011- start a collaboration with Fermilab Milli-Kelvin Facility group who will work on the readout electronics at low temperature around 1K.



Fermilab Milli-Kelvin Facility

Dan Bauer, Herman Cease, Juan Estrada, Erik Ramberg, Richard Schmitt, Jason Steffen and Jonghee Yoo
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.