宇宙背景ニュートリノ崩壊探索ロケット実験設計と検出器開発

武内勇司 (筑波大)
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ニュートリノフロンティア研究会
＠クロス・ウェーブ府中

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- As of Dec. 2013

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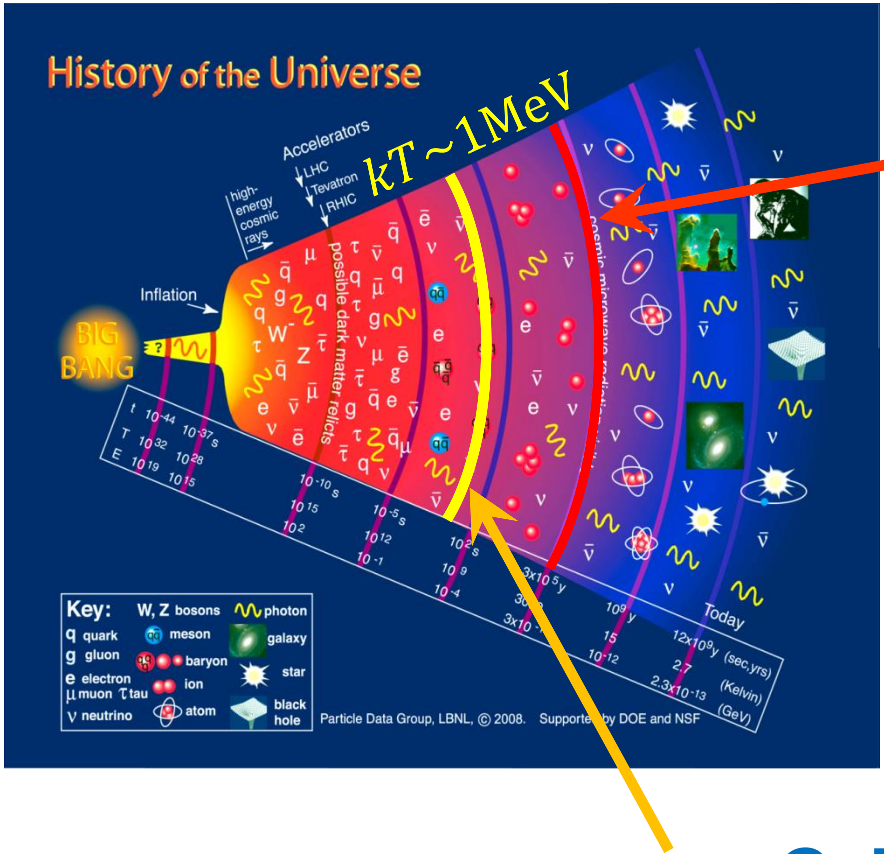
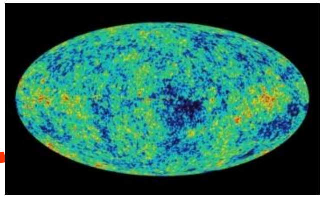
Cosmic neutrino background (CνB)

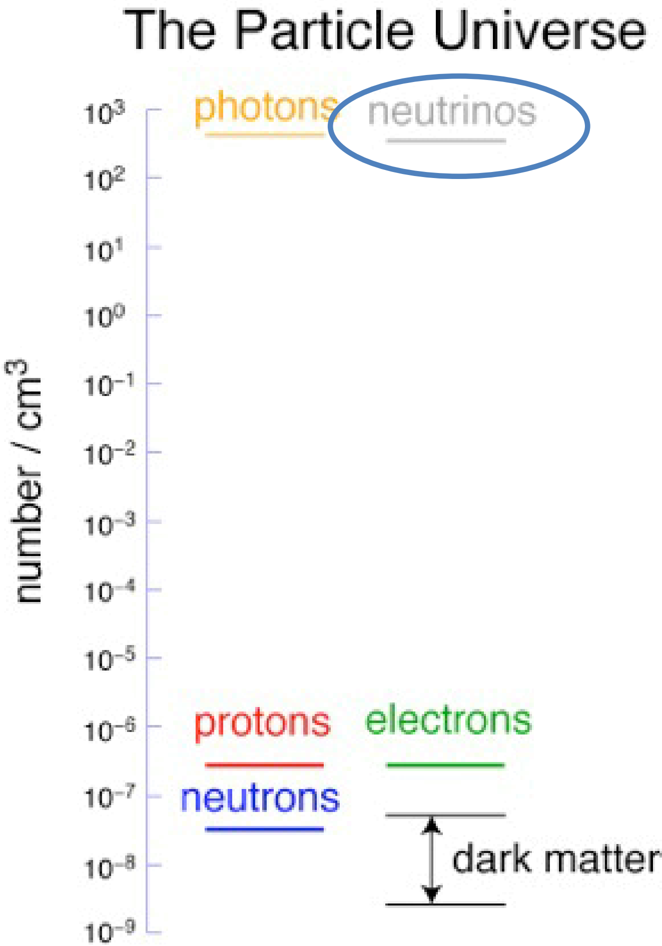




CMB

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

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



CνB

$$n_\nu = n_{\bar{\nu}} = \frac{3}{4}\left(\frac{T_\nu}{T_\gamma}\right)^3 \frac{n_\gamma}{2} = 56/\text{cm}^3 \qquad T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma = 1.95\text{K}$$

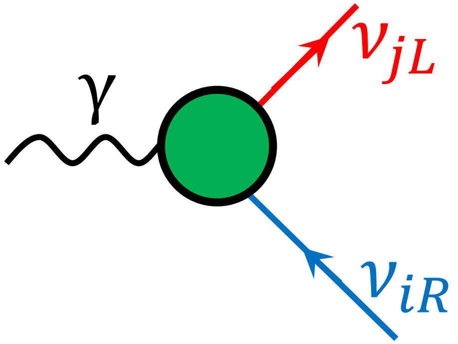
Motivation

- Search for $\nu_3 \rightarrow \nu_{1,2} + \gamma$ in cosmic neutrino background (CνB)
  - Direct detection of CνB
  - Direct detection of neutrino magnetic dipole moment
  - Direct measurement of neutrino mass: $m_3 = \left(m_3^2 - m_{1,2}^2\right)/2E_\gamma$
- Aiming at sensitivity of detecting γ from ν decay for $\tau(\nu_3) = \mathrm{O}(10^{17}\mathrm{yr})$
  - SM expectation $\tau = \mathrm{O}(10^{43}\mathrm{yr})$
  - Current experimental lower limit $\tau > \mathrm{O}(10^{12}\mathrm{yr})$
  - L-R symmetric model (for Dirac neutrino) predicts down to $\tau = \mathrm{O}(10^{17}\mathrm{yr})$ for W_L-W_R mixing angle $\zeta < 0.02$

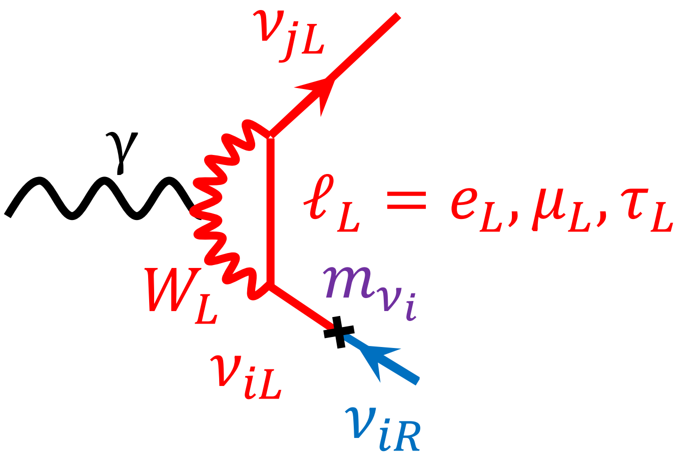
Neutrino Magnetic Dipole Moment

Neutrino magnetic moment term

$\bar{\nu}_{jL} i\sigma^{\mu\nu} q_{\nu} \nu_{iR}$



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

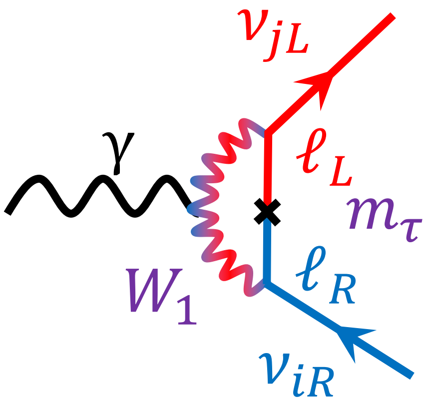


Suppressed by m_{ν}, GIM

$\Gamma \sim (10^{43}\ yr)^{-1}$

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

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



10^{26} enhancement to SM

$\Gamma \sim (10^{17}\ yr)^{-1}$

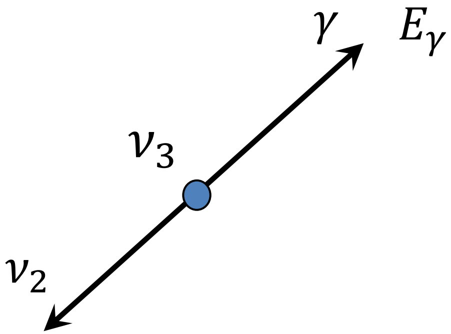
Suppressed only by $\zeta \sim 0.02$

$W_1 \simeq W_L - \zeta W_R$

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

Photon Energy in Neutrino Decay

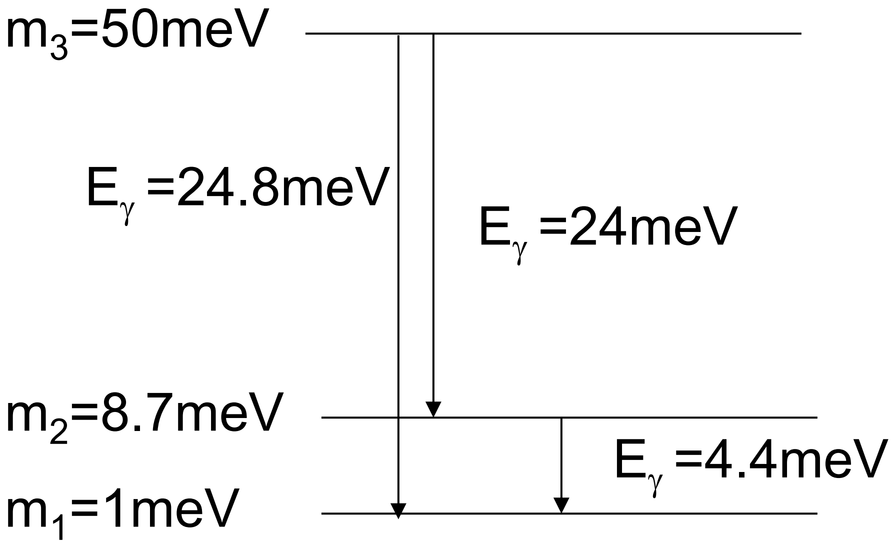
$$\nu_3 \rightarrow \nu_{1,2} + \gamma \qquad E_\gamma = \frac{m_3^2 - m_{1,2}^2}{2m_3}$$



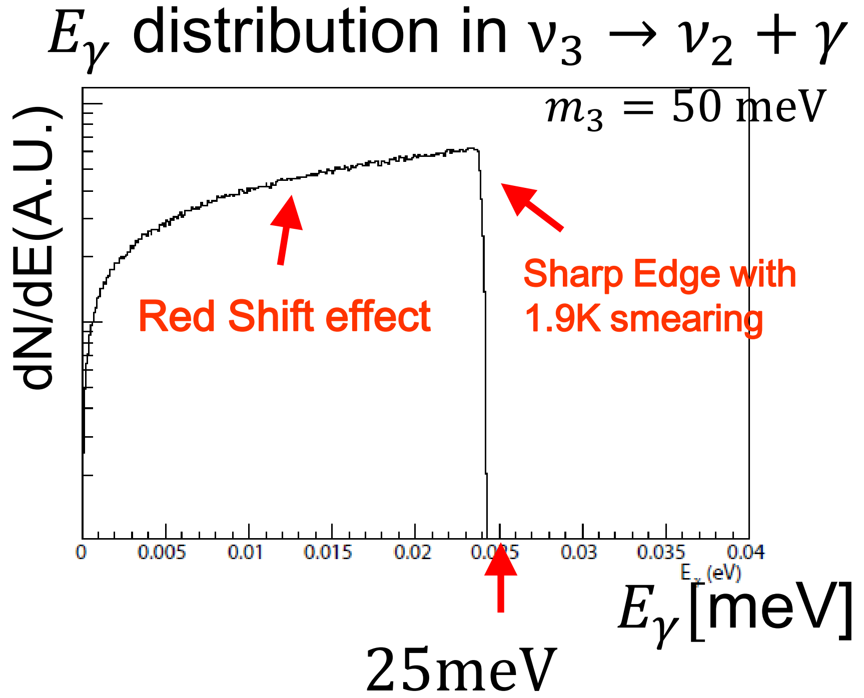
- From neutrino oscillation
  - $\Delta m_{23}^2 = |m_3^2 - m_2^2| = 2.4 \times 10^{-3}\ eV^2$
  - $\Delta m_{12}^2 = 7.65 \times 10^{-5}\ eV^2$
- From CMB fit (Plank+WP+highL+BAO)
  - $\sum m_i < 0.23$ eV

➔ 50meV<m_3<87meV, E_γ =14~24meV

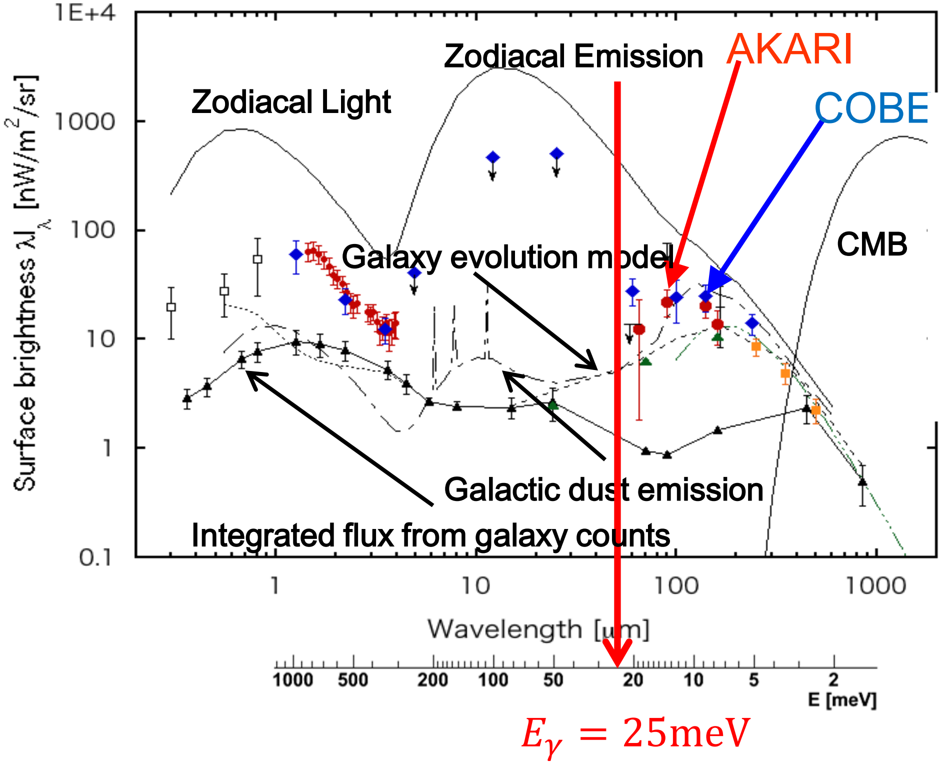
λ_γ =51~89µm



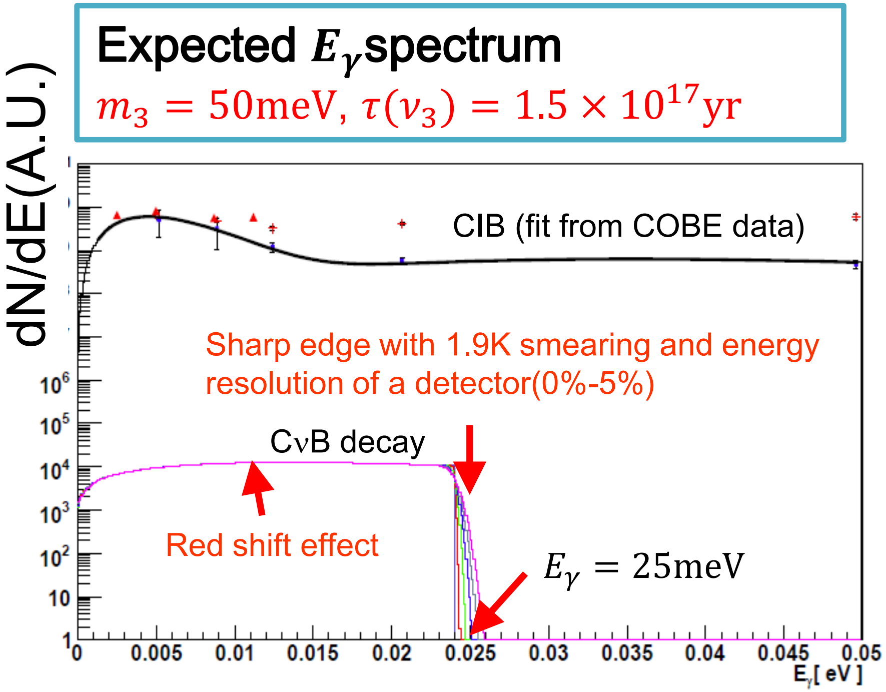
E_γ distribution in $\nu_3 \rightarrow \nu_2 + \gamma$



Backgrounds to CνB decay



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



Expected E_γ spectrum

$m_3 = 50\mathrm{meV}, \tau(\nu_3) = 1.5 \times 10^{17}\mathrm{yr}$

Sharp edge with 1.9K smearing and energy resolution of a detector(0%-5%)

Red shift effect

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

- ニュートリノ崩壊光($m_3 = 50\mathrm{meV}, \tau(\nu_3) = 1.5 \times 10^{17}\mathrm{yr}$を仮定)の~3x$10^4$倍の宇宙赤外線背景放射(CIB)
- 更に黄道光がCIB観測データ(COBE)の約20倍

Neutrino lifetime lower limit from AKARI data

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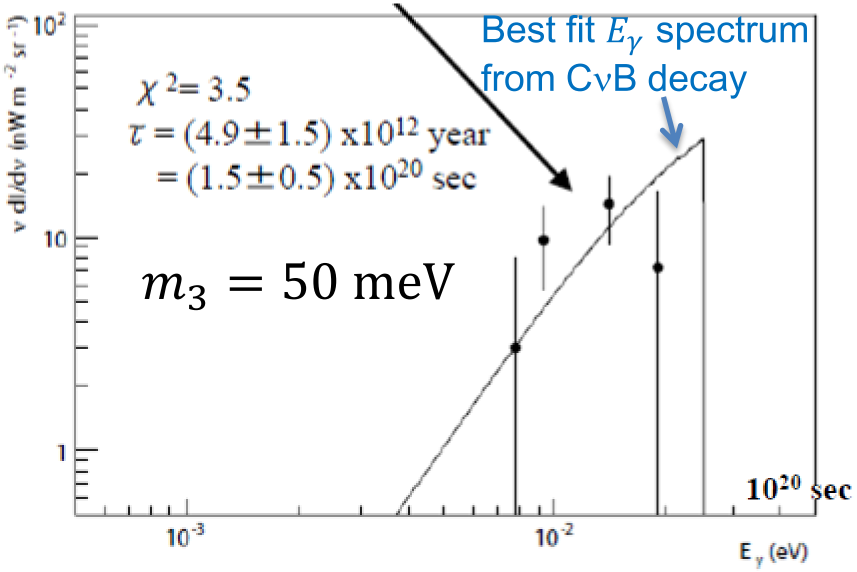
Search for Radiative Decays of Cosmic Background Neutrino using Cosmic Infrared Background Energy Spectrum

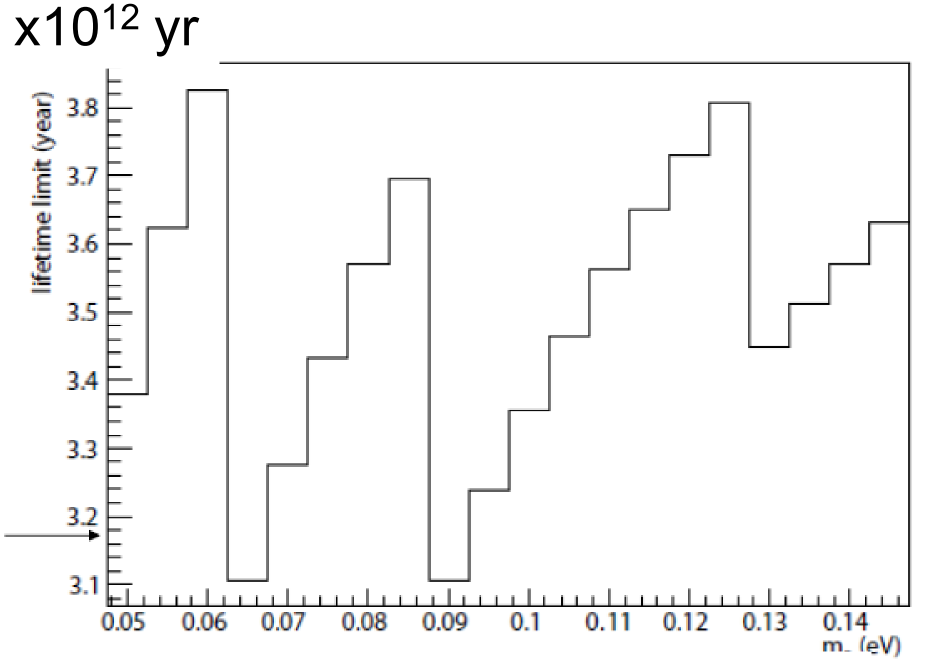
Shin-Hong KIM*, Ken-ichi TAKEMASA, Yuji TAKEUCHI, and Shuji MATSUURA[1]

AKARI CIB data after subtracting foregrounds and distant galaxies



Fit CIB data to E_γ spectrum expected from ν decay assuming all contribution to CIB is only from ν decay

ν_3 lifetime lower limit as a function of m_3



$m_3 = 50$ meV~ 150 meV

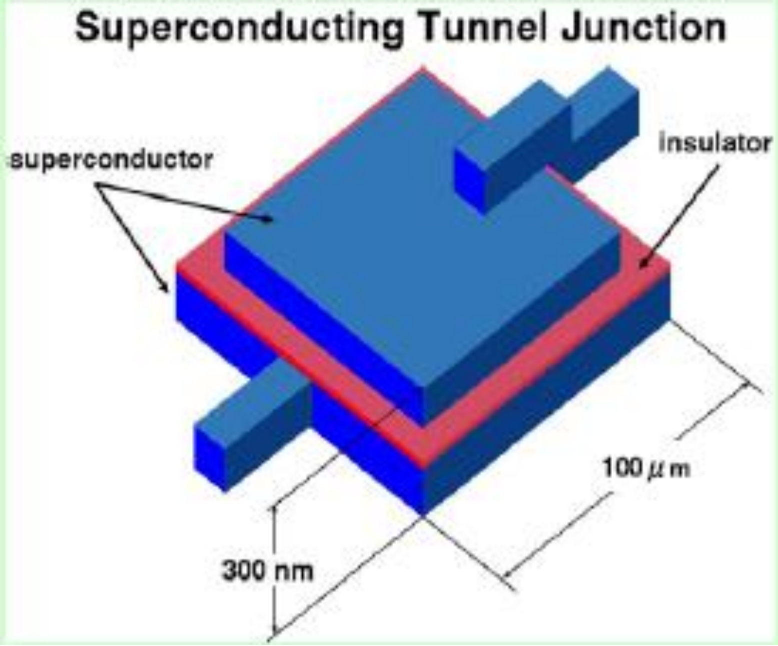
Detector requirements

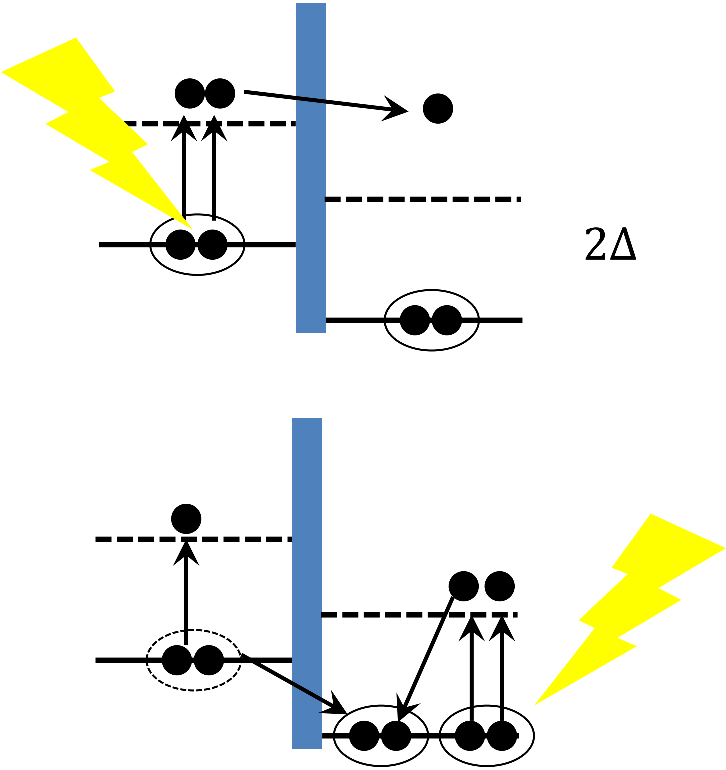
- Requirements for detector
  - Continuous spectrum of photon energy around $E_\gamma \sim 25\ \mathrm{meV} (\lambda = 50\mu\mathrm{m}$, far infrared photon)
  - Energy measurement for single photon with better than 2% resolution for $E_\gamma = 25\mathrm{meV}$ to identify the edge spectrum
  - Rocket and satellite experiment with this detector

- **Superconducting Tunneling Junction (STJ) detectors in development**
  - Array of 50 Nb/Al-STJ pixels with diffraction grating covering $\lambda = 40 - 80\mu\mathrm{m}$
    - **For rocket experiment aimed at launching in 2016 in earliest, aiming at improvement of lower limit for $\tau(\nu_3)$ by 2 order**
  - STJ using Hafnium: Hf-STJ for satellite experiment (after 2020)
    - $\Delta = 20\mu\mathrm{eV}$: Superconducting gap energy for Hafnium
    - $N_{\mathrm{q.p.}} = 25\mathrm{meV}/1.7\Delta = 735$ for 25meV photon: $\Delta E/E < 2\%$ if Fano-factor is less than 0.3

STJ(超伝導トンネル接合)検出器

- Superconducting Tunnel Junction
- 超伝導体 / 絶縁体 / 超伝導体のジョセフソン接合素子





上下の超伝導電極間に電位差を与える
放射線(光)によって励起された準粒子が
トンネル電流として観測

STJのエネルギー分解能

発生する準粒子の個数のゆらぎがエネルギー分解能の限界を決める

➔超伝導ギャップエネルギーが小さいものが有利

STJのエネルギー分解能

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

Δ: バンドギャップエネルギー
F: fano factor
E: 放射線のエネルギー

Nbの場合の発生準粒子数
N=25meV/1.7Δ=9.5個

Energy resolution はないがphoton counting は可能

Hfを用いた場合の発生準粒子数
N=25meV/1.7Δ=735個

$\Delta E/E < \sqrt{F}/\sqrt{N} = \sqrt{F}/\sqrt{735} = 3.7\sqrt{F}$ % @25meV

Fano factor <0.3なら分解能2%を達成可能

	Si	Nb	Al	Hf
Tc[K]		9.23	1.20	0.165
Δ[meV]	1100	1.550	0.172	0.020
Hc[G]		1980	105	13

Tc :相転移温度

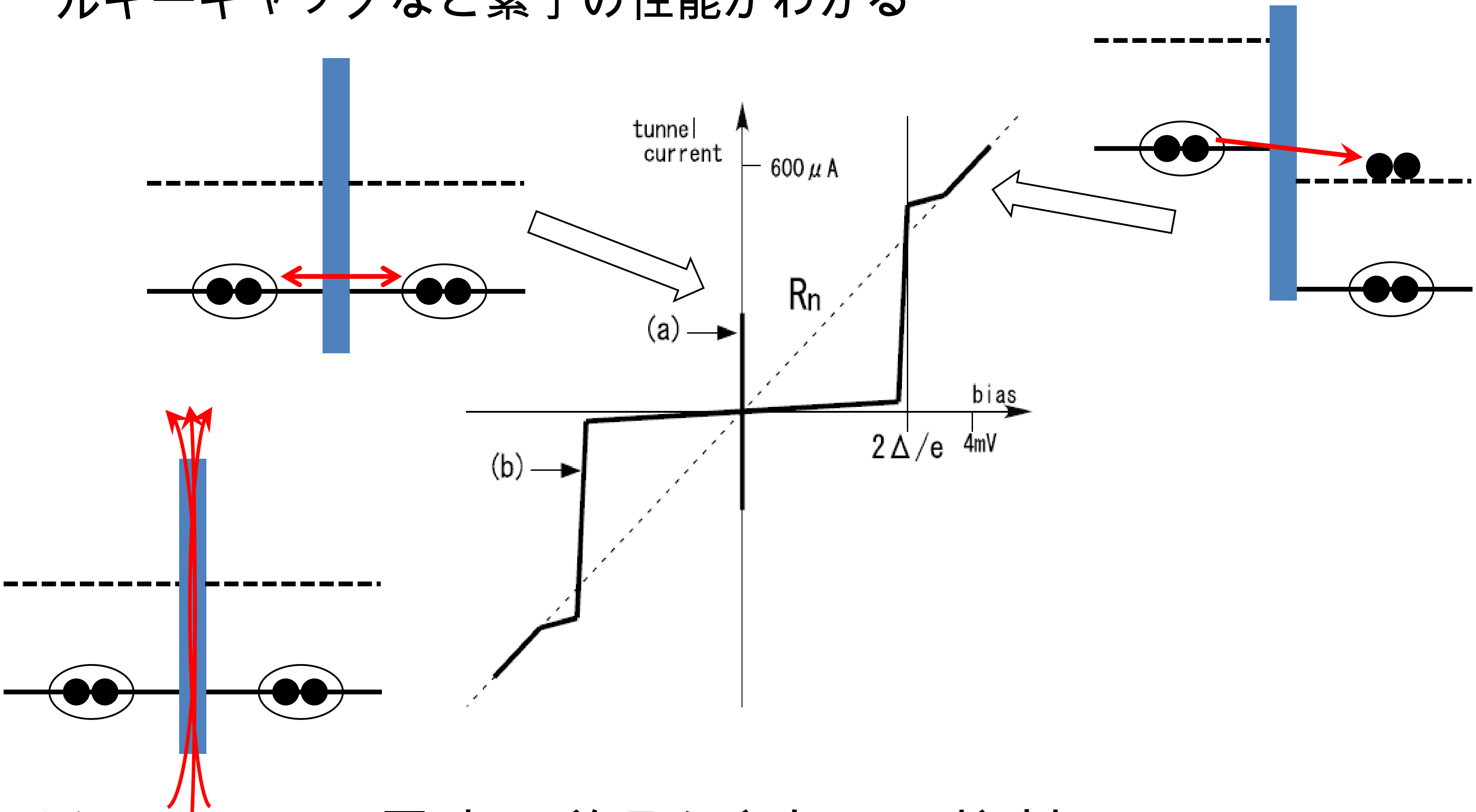
超伝導膜に用いた金属のTc（相転移温度）の1/10程度で安定動作

Hc :臨界磁場

STJ検出器の性能評価法

- STJの電流電圧(I-V)特性を測定

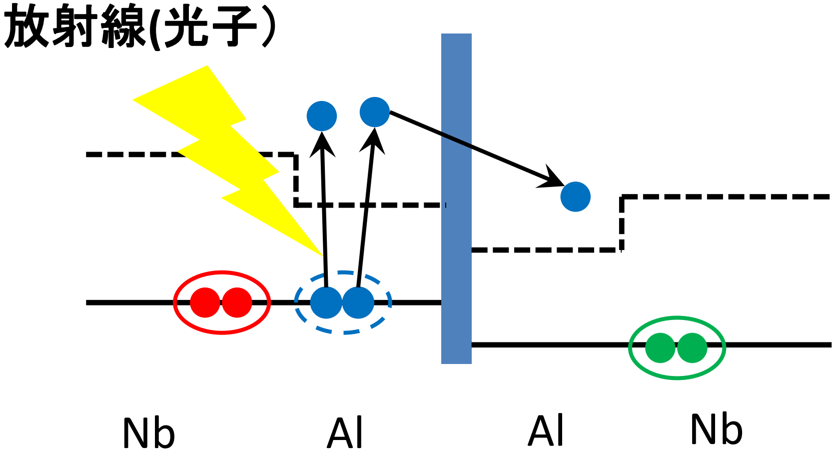
➔ STJの超伝導転移，ジョセフソン接合の有無，リーク電流，エネルギーギャップなど素子の性能がわかる

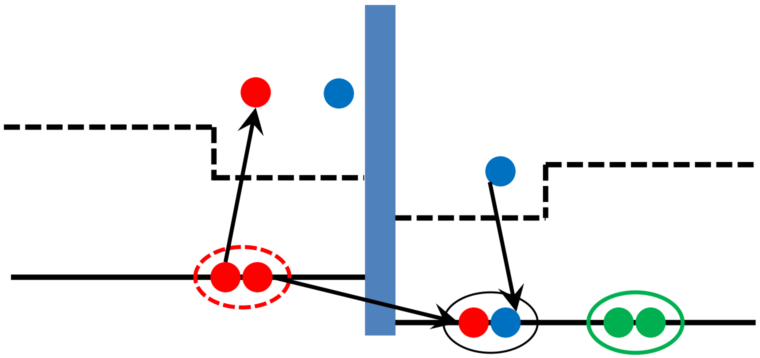


■ ジョセフソン電流は磁場を印加して抑制

STJバックトンネリング増幅効果

- トンネルバリアの近傍の準粒子は，次々とトンネル効果を引き起こし電荷を増幅する
  - トンネルバリアの近傍の準粒子の存在確率を上げるためトラップ層を置く
  - Nb/Al-STJ　Nb(200nm)/Al(10nm)/AlOx/Al(10nm)/Nb(100nm)
    - 近接効果によりAlの超伝導転移温度はNbの転移温度に近づく
- 増幅効果 2～200倍



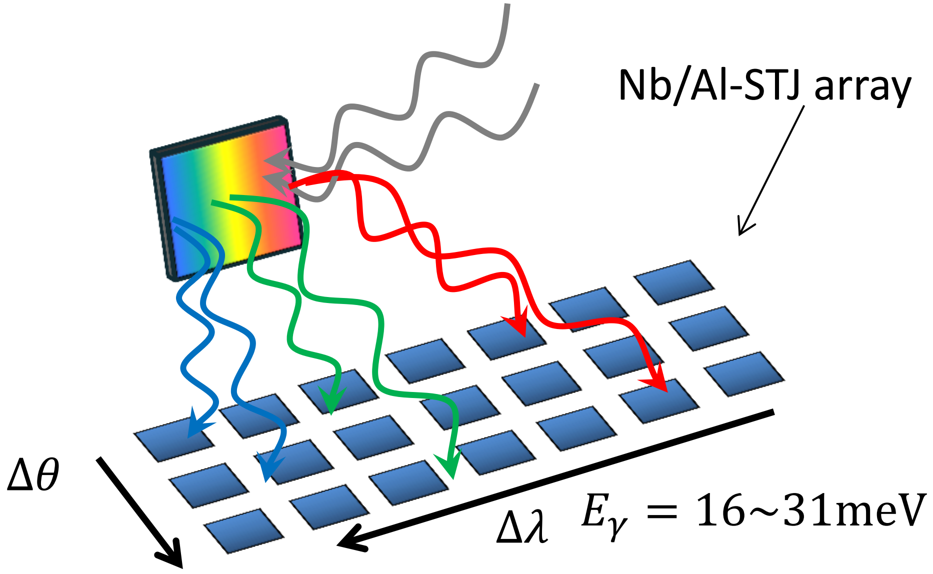


FIR photon spectroscopy with diffraction grating + Nb/Al-STJ array

- Diffraction grating covering $\lambda = 40 - 80\mu\text{m}$ (16-31meV)
- Array of Nb/Al-STJ pixels: 50(λ)x8(θ)
  - We use each Nb/Al-STJ cell as a single-photon counting detector with extremely good S/N for FIR photon of $E_\gamma = 16\sim31\text{meV}$
  - $\Delta = 1.5\ \text{meV}$ for Nb: $N_{\text{q.p.}} = 60\sim120$ if consider factor 10 by back-tunneling
  - Expected average rate of photon detection is ~350Hz for a single pixel
- Need to develop ultra-low temperature (<2K) preamplifier
  - In collaboration with Fermilab Milli-Kelvin Facility group (Japan-US collaboration: Search for Neutrino Decay)
  - **SOI-STJ in development with KEK**

Assuming $1\mu s$ for STJ response time, requirements for STJ

- Leak current <0.1nA



Need T<0.9K for detector operation

➔ Need to ^{3}He sorption or ADR for the operation

Feasibility of FIR single photon detection

- Assume typical time constant from STJ response to pulsed light is ~1μs
- Assume leak current is 0.1nA

$$0.1nA = 6.25 \times 10^{8} e/s = 6.25 \times 10^{2} e/\mu s$$

Fluctuation due to electron statistics in 1μs is

$$\sqrt{6.25 \times 10^{2}} e/\mu s = 25\, e/\mu s$$

While expected signal charge for 25meV are

$$25\mathrm{meV}/1.7\Delta \times 10e = \frac{25\mathrm{meV}}{1.7\times 1.5\mathrm{meV}} \times 10e = 98e$$

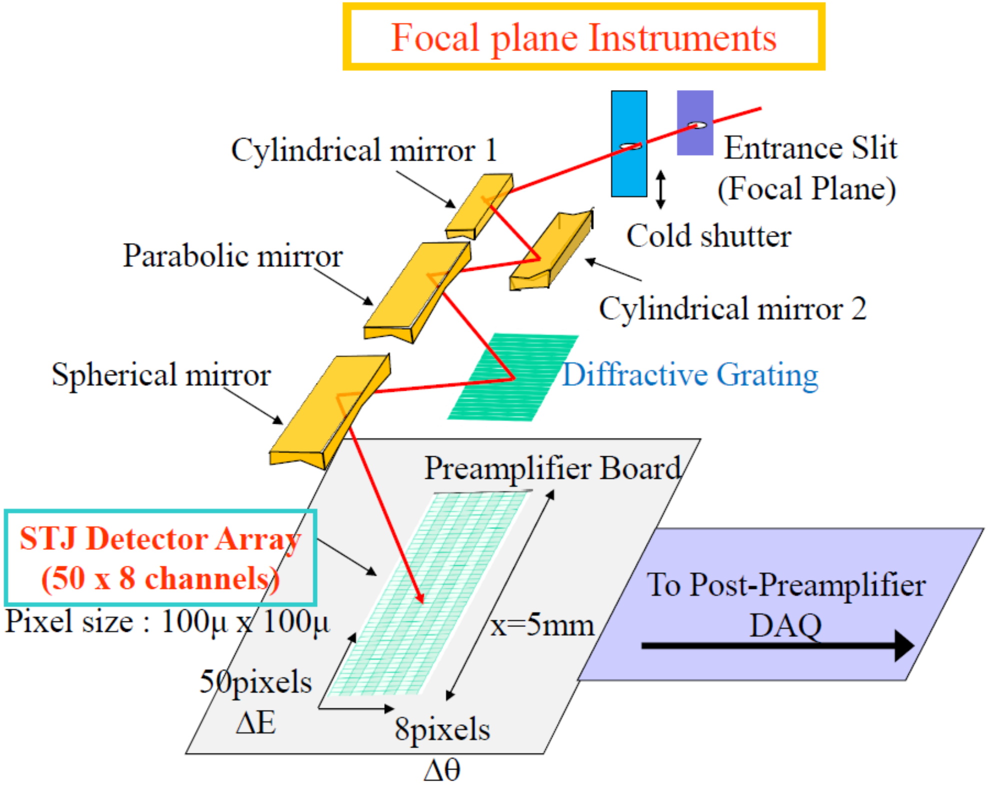
(Assume back tunneling gain x10)

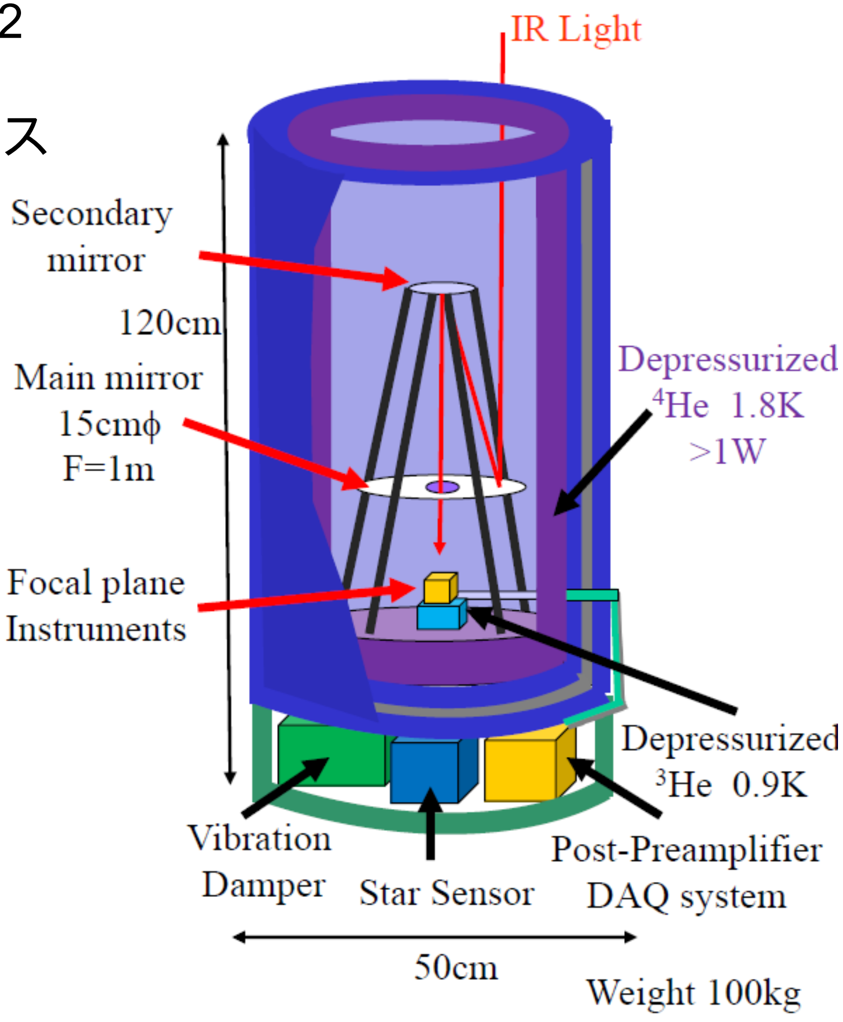
More than 3sigma away from leakage fluctuation

- Requirement for amplifier
  - Noise<16e
  - Gain: 1V/fC → V=16mV

JAXA Rocket Experiment for Neutrino Decay Search

- JAXAのロケット実験
  - □ ロケットで高度200km~300kmまで上昇．約5分の観測
  - □ 検出器，光学系，冷凍機のR&D完了から2年程度で打ち上げ可能 (2016年~)
  - □ $\lambda = 40 - 80\mu m$ (16-31meV)の範囲で連続スペクトラムを測定(回折格子で50分割)
    - 100µm x 100µm x 50x8 array



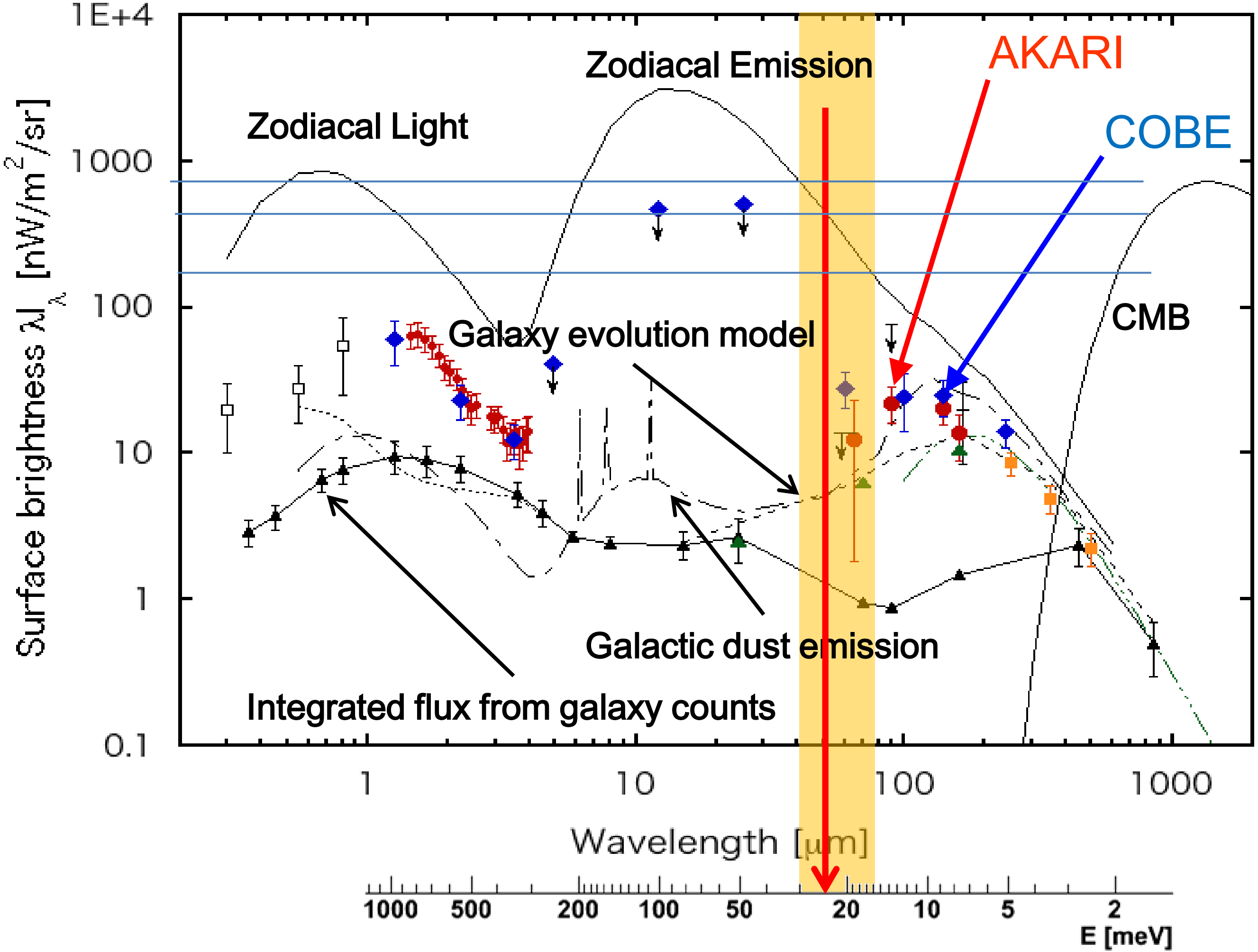


Focal length 1m

Cosmic Infrared Background measured by COBE and AKARI

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.

ロケット実験観測範囲 40μ m ～80μ m



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

Zodiacal Emission

- λI_λ~500nW/m^2/sr

CIB (COBE)

- λI_λ~30nW/m^2/s

Neutrino decay

for $\tau = 5 \times 10^{12}\mathrm{yr}$

- λI_λ~30nW/m^2/s

for $\tau = 1.5 \times 10^{17}\mathrm{yr}$

- λI_λ~1pW/m^2/s

at λ = 50μm

JAXA Rocket Experiment for Neutrino Decay Search
Event Rate and expected Lifetime Limit

- 前景放射強度(黄道光): λI_λ~500nW/m²/sr at λ = 50μm
- Pixelあたりの立体角: $\Delta\Omega = \left(\frac{100\mu m}{1m}\right)^2 = 1\times10^{-8}\mathrm{sr}$
- 望遠鏡口径: S=π x 0.075² m²

Pixelあたりの前景放射レート

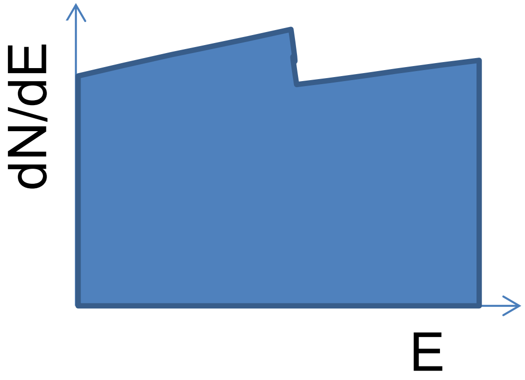
$$\lambda I_\lambda \cdot S \cdot \Delta\Omega = 0.88\times10^{-16}W = 0.55\times10^{3}eV/s$$

$$\Delta\lambda/\lambda = \frac{80\mu m - 40\mu m}{50}/50\mu m = 0.016$$

$$\Delta\lambda/\lambda \cdot \lambda I_\lambda \cdot S \cdot \Delta\Omega/E_\gamma = \frac{8.8eV/s}{25meV} \sim 350Hz$$

Measurements for 200s x 50 pixel x 8列

→ N=28M events / 50x8 pixels



Sensitivity to detecting an edge spectrum

→ $\delta(\lambda I_\lambda) \sim 2\sqrt{N}/N \cdot \lambda I_\lambda$ =0.19nW/m²/sr

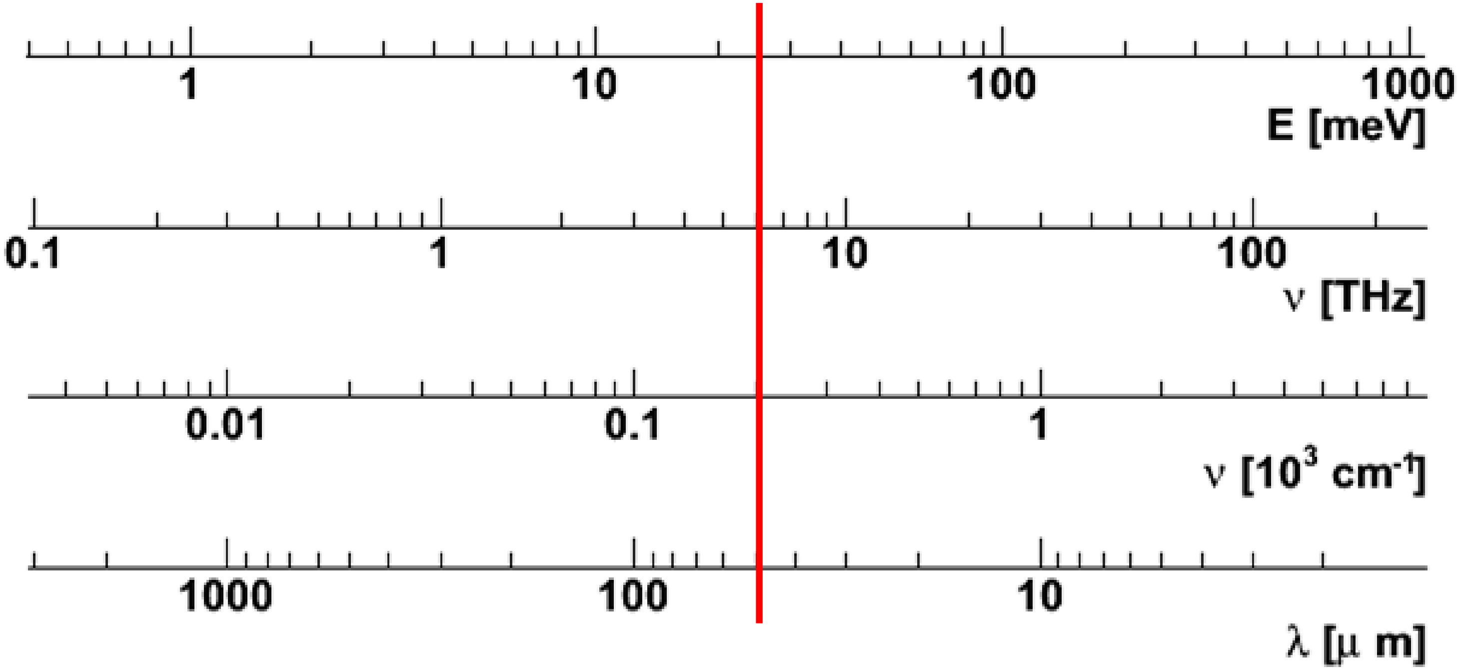
$\tau(\nu_3) > 10^{14}$ yr (95%CL)の寿命下限設定が可能

Summary

- 宇宙背景ニュートリノ崩壊探索実験ためのロケット実験を提案
  - 高度200kmで約5分の遠赤外域分光測定
  - Nb/Al-STJ arrayと回折格子の組み合わせによる波長$\lambda = 40 - 80\mu\mathrm{m}$の連続スペクトラム
  - $\tau(\nu_3) > 10^{14}$ yr (95%CL)の寿命下限設定(現在の下限値を1~2桁改善)
- R&D
  - Nb/Al-STJによる25meV(50μm)フォトンの1光子計数
    - leakage <0.1nA, 受光面積100μmx100μm/pixel, back-tunneling gain>10
  - そのための超低ノイズアンプ(極低温アンプnoise <16e, gain>1V/fC): SOI-STJなど
  - 分光素子・ 光学系の設計:望遠鏡口径 15cmΦ, 焦点距離1m
  - ロケット搭載クライオスタットの設計 (<0.9K)
    - LHe減圧(1.8K) + ^{3}He sorption
  - DAQ

Backup

Energy/Wavelength/Frequency



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

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

$$\lambda = 50\mu m$$

Feasibility of VIS/NIR single photon detection

- Assume typical time constant from STJ response to pulsed light is ~1μs
- Assume leakage is 160nA

$$160nA = e \times 10^{12}/s = e \times 10^{6}/\mu s$$

Fluctuation from electron statistics in 1μs is

$$e \times \sqrt{10^{6}}/\mu s = 10^{3} e/\mu s$$

While expected signal for 1eV are

(Assume back tunneling gain x10)

$$1eV/1.7\Delta \times 10e = \frac{1eV}{1.7 \times 1.5meV} \times 10 = 4 \times 10^{3} e$$

More than 3sigma away from leakage fluctuation

Nb/Al-STJによる可視光分光

- 国立天文台
  - λ=475nm