

COBAND実験に向けたSTJ+SOIアンプ開発現状と sub-GeV領域ダークマター粒子探索への応用

武内勇司（素粒子構造部門）

TCHoU構成員会議

2019/6/3

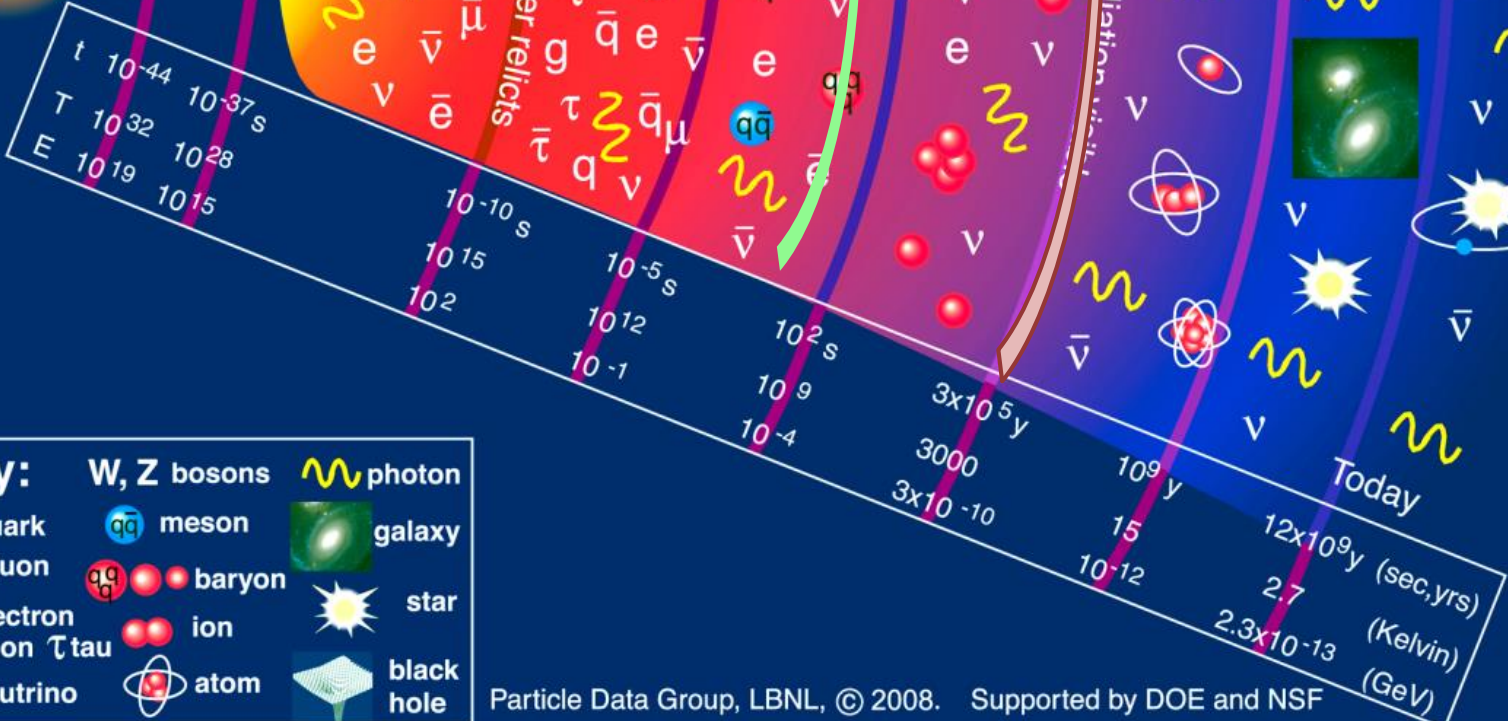
History of the Universe

CνB
Cosmic Neutrino Background

CMB

BIG BANG

Inflation



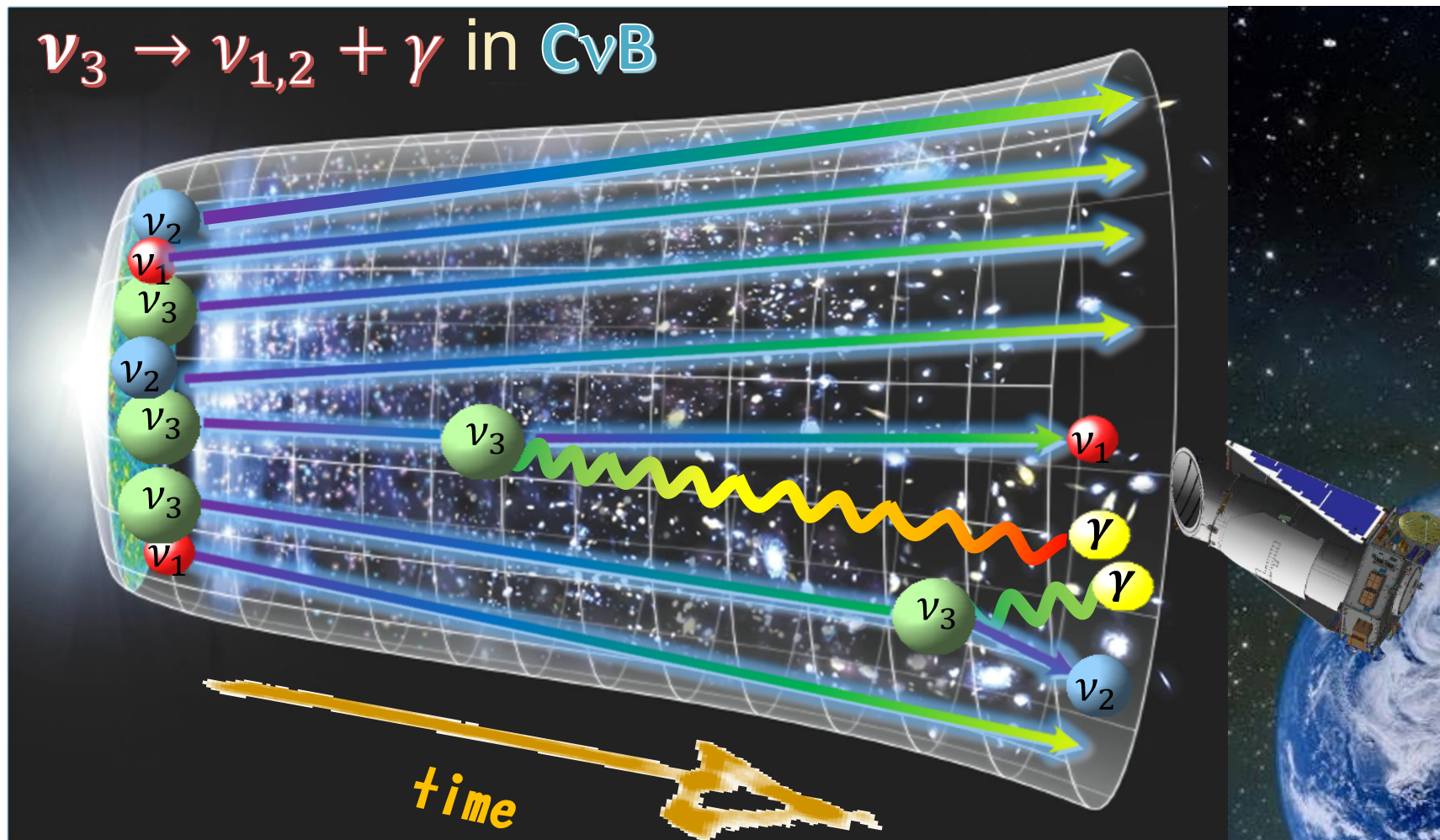
Key:

- W, Z bosons
- quark (q)
- gluon (g)
- electron (e)
- muon (μ)
- tau (τ)
- neutrino (ν)
- photon (γ)
- meson (qq̄)
- baryon (qqq)
- ion (e⁻)
- atom
- galaxy
- star
- black hole

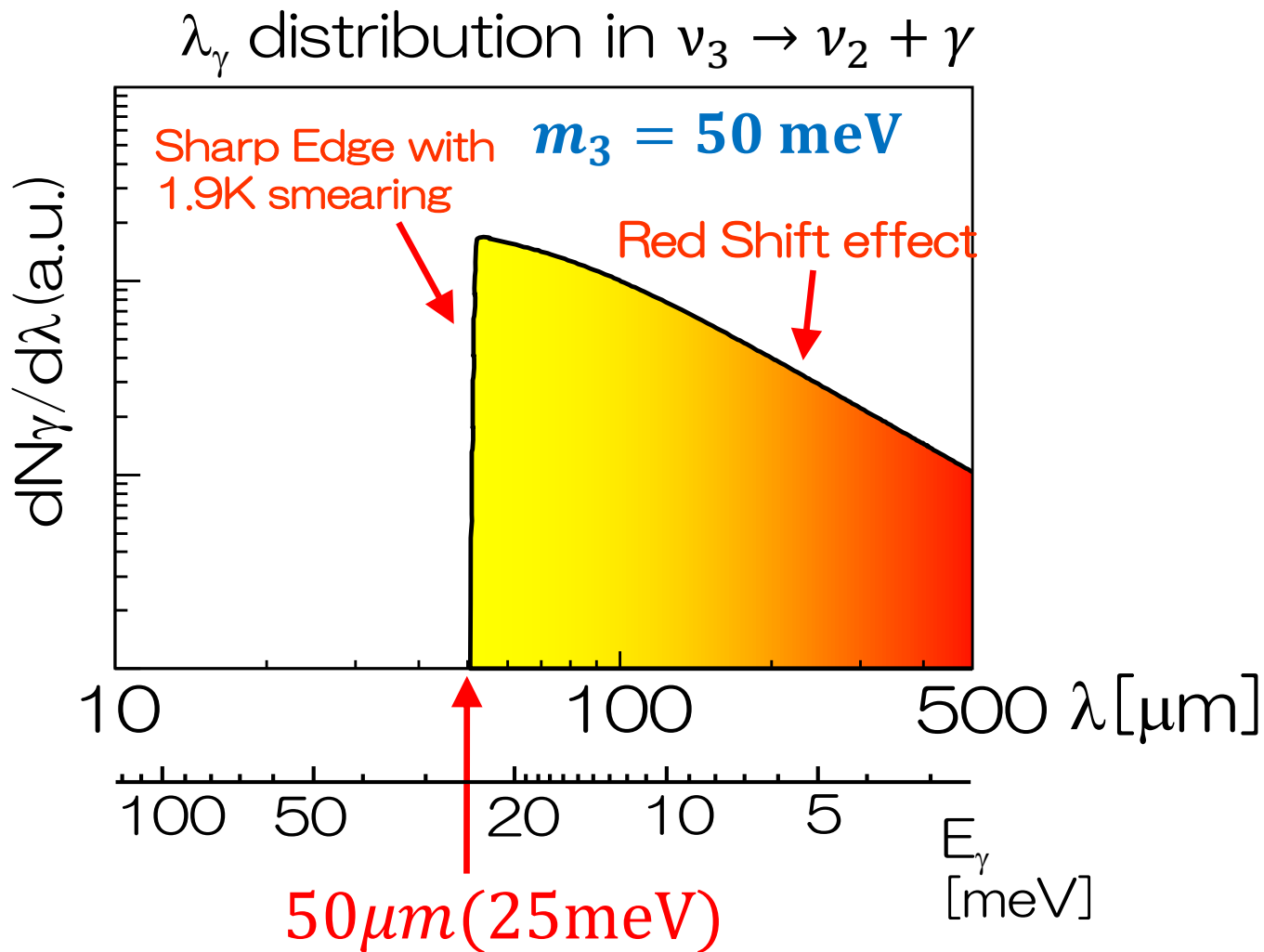
「宇宙背景ニュートリノ」の「ニュートリノ崩壊」

波長約 $50\mu\text{m}$ (遠赤外線)の光として観測 (ν_3 静止系で)

- 遠方の宇宙からの崩壊光は、波長が引き伸ばされる(赤方偏移)

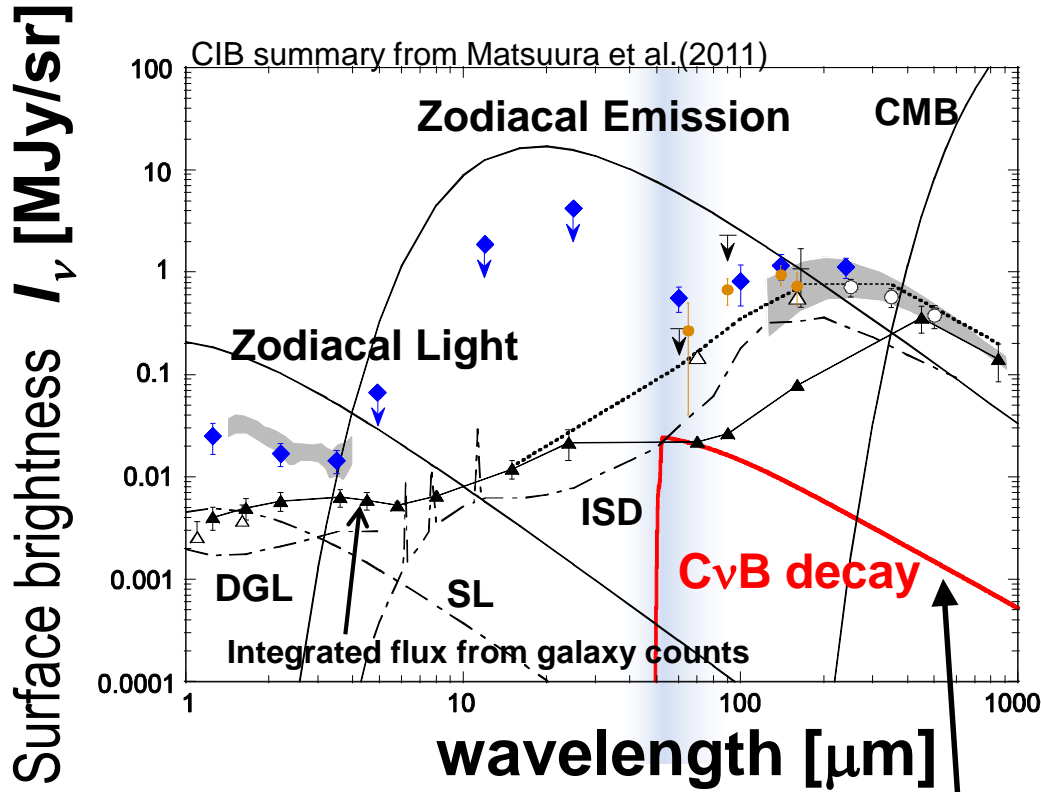


期待される宇宙背景ニュートリノの崩壊光の波長分布



このような鋭いエッジを持った分布をつくる光源は他にない

COBANDロケット実験における光検出器要求



Zodiacal Emission

- $I_{ZE} = 8 \text{ MJy/sr}$
- $1.1 \times 10^{-17} \text{ W} / 8 \text{ pix}$
- @ $\lambda = 50 \mu\text{m}$

Neutrino Decay

- $I_\nu = 25 \text{ kJy/sr}$
- $3.3 \times 10^{-20} \text{ W} / 8 \text{ pix}$
- @ $\lambda = 50 \mu\text{m}$

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

$$m_3 = 50 \text{ meV}$$

COBAND実験において光検出器に要求される性能

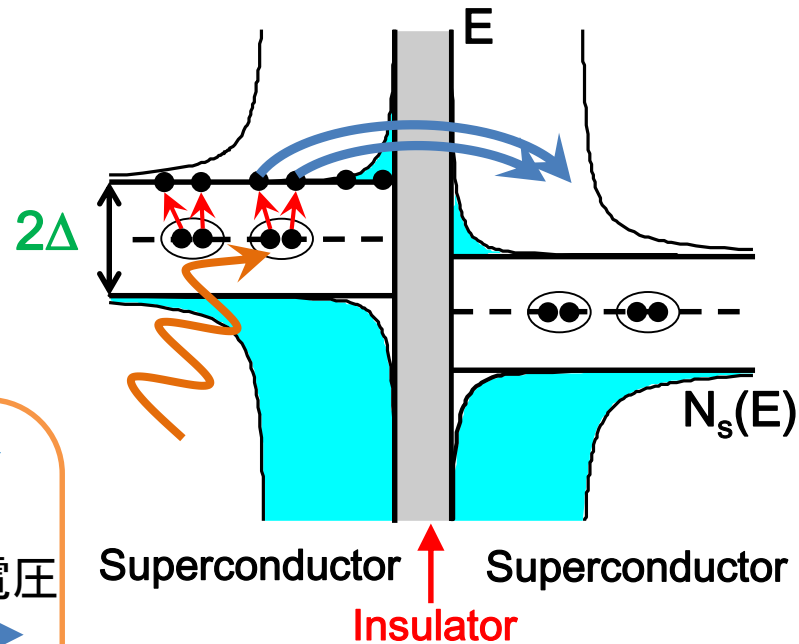
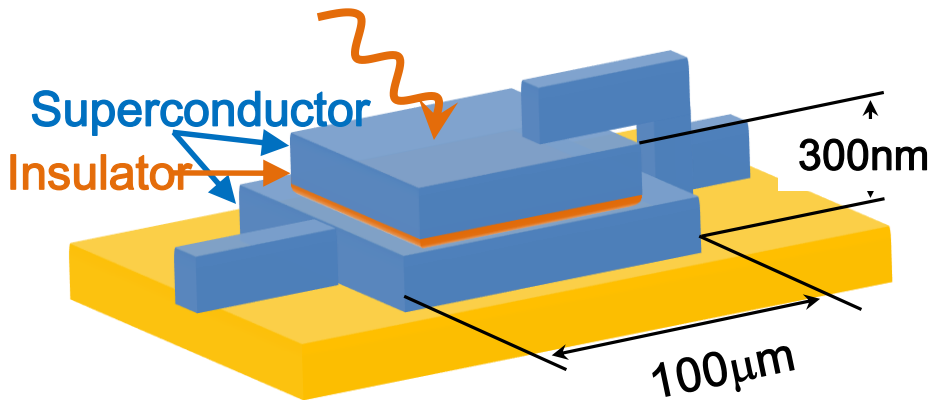
1ピクセルあたり

- $100\mu\text{m} \times 100\mu\text{m}$ の有感領域
- $\lambda=40 \sim 80\mu\text{m}$ の光子1個ずつを高い効率で検出
- Dark count レートは期待される(ほぼ黄道光からの)実光子レート約300Hz に対して無視できる程度であることが必要

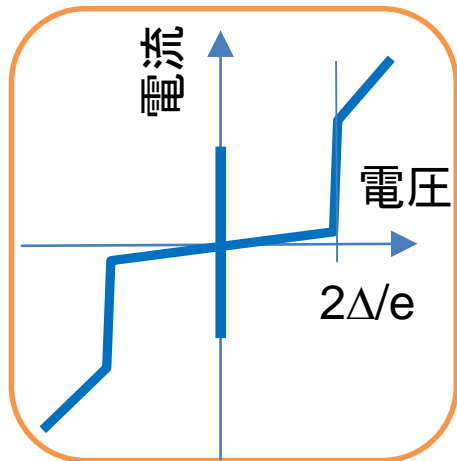
$$- \text{NEP} = \epsilon_{\gamma} \sqrt{2f_{\gamma}}$$

→ NEP $\sim 1 \times 10^{-19} \text{ W} / \sqrt{\text{Hz}}$ per 1pix に相当

超伝導トンネル接合素子(STJ) 光子検出器



ジョセフソン接合に特徴的な
電流-電圧曲線
ジョセフソン電流は磁場を印
加して抑制



Superconductor ↑ Insulator Superconductor

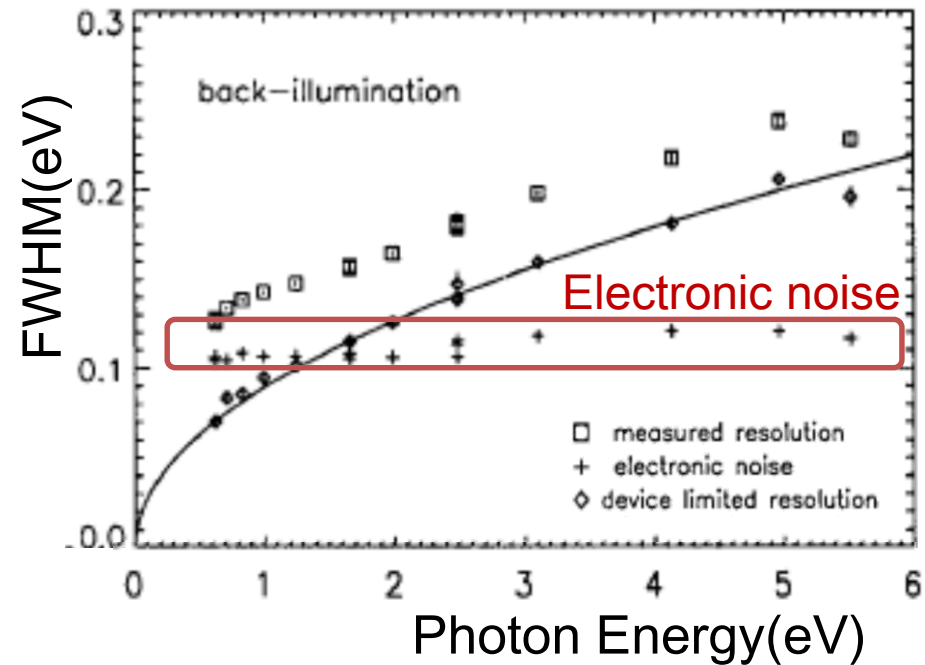
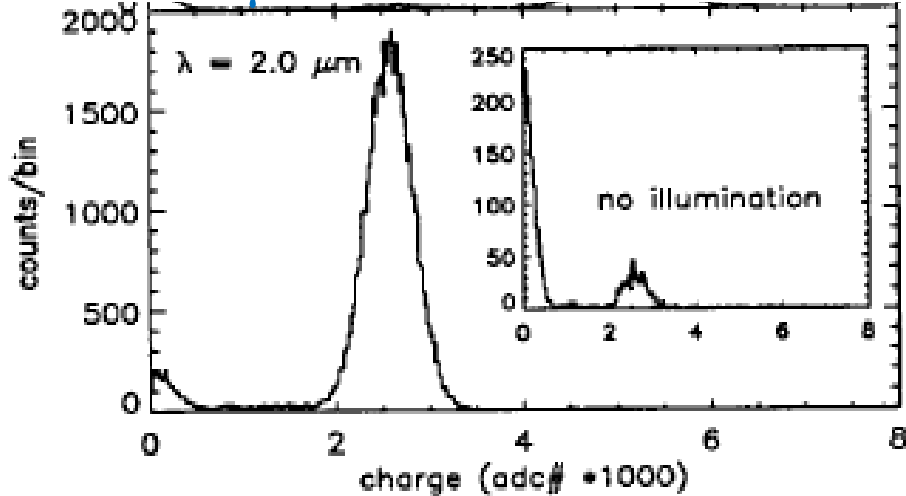
Δ : 超伝導ギャップエネルギー

上下電極に電位差 ($|V| < 2\Delta/e$) を印加．吸収された光子のエネルギーに
比例した準粒子のトンネル電流が発生

遠赤外光子のエネルギーよりも小さな Δ → 遠赤外光子検出可能
比較的高速な応答 ($\sim \mu\text{s}$) → 光子計数に適する

他グループによる STJ の現状

$\lambda=2\mu\text{m}$ の光子のエネルギー測定



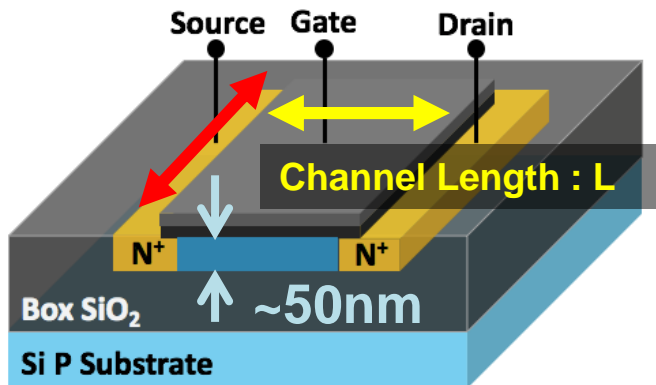
P. Verhoeve et. al 1997

- $30\mu\text{m}$ 角 Ta/Al-STJ
- $\Delta E \sim 130\text{meV}$ @ $E=620\text{meV}$ ($\lambda=2\mu\text{m}$)
- 室温アンプによる読出し
 - Electronic noise: $\sim 100\text{meV}$

近～中赤外域でSTJは最高のエネルギー分解能を達成．分解能は読出し回路由来のノイズで制限されている．

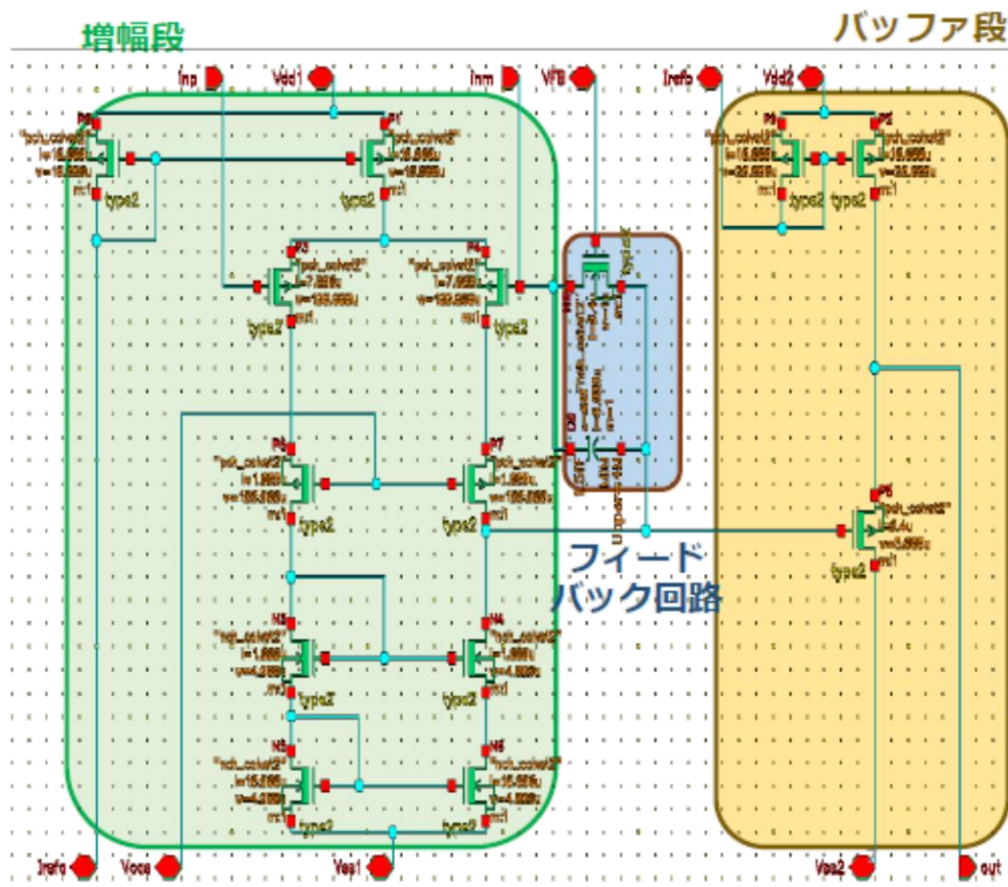
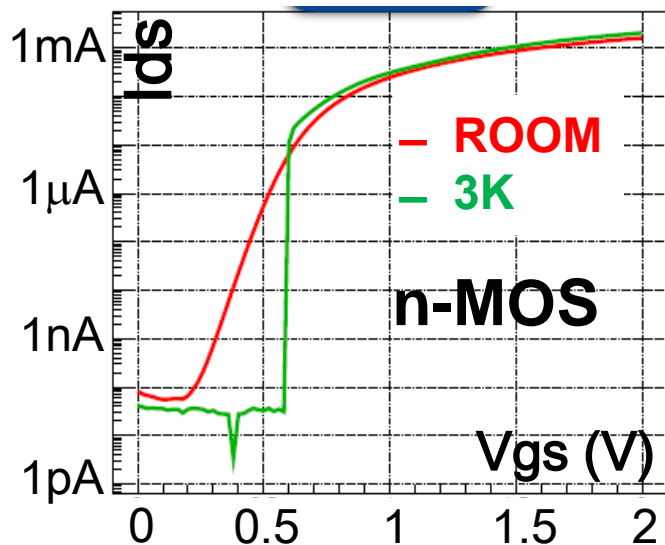
極低温下でのFD-SOI-MOSFET

FD-SOI : **F**ully **D**epleted – **S**ilicon **O**n **I**nsulator



- SiO₂上の非常に薄いシリコン層に形成されたMOSFET
- 通常のバルクMOSFETは極低温では動作せず

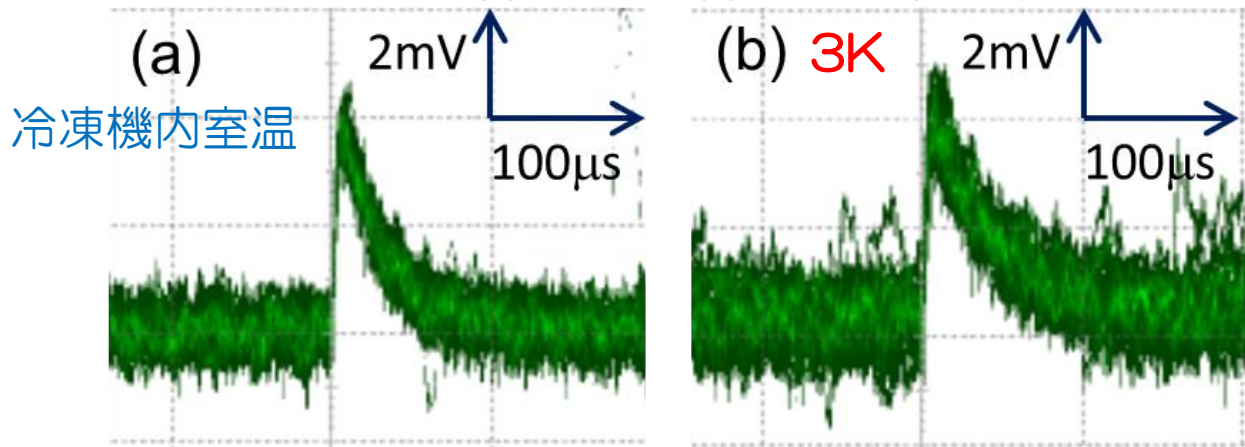
Id-Vg 曲線



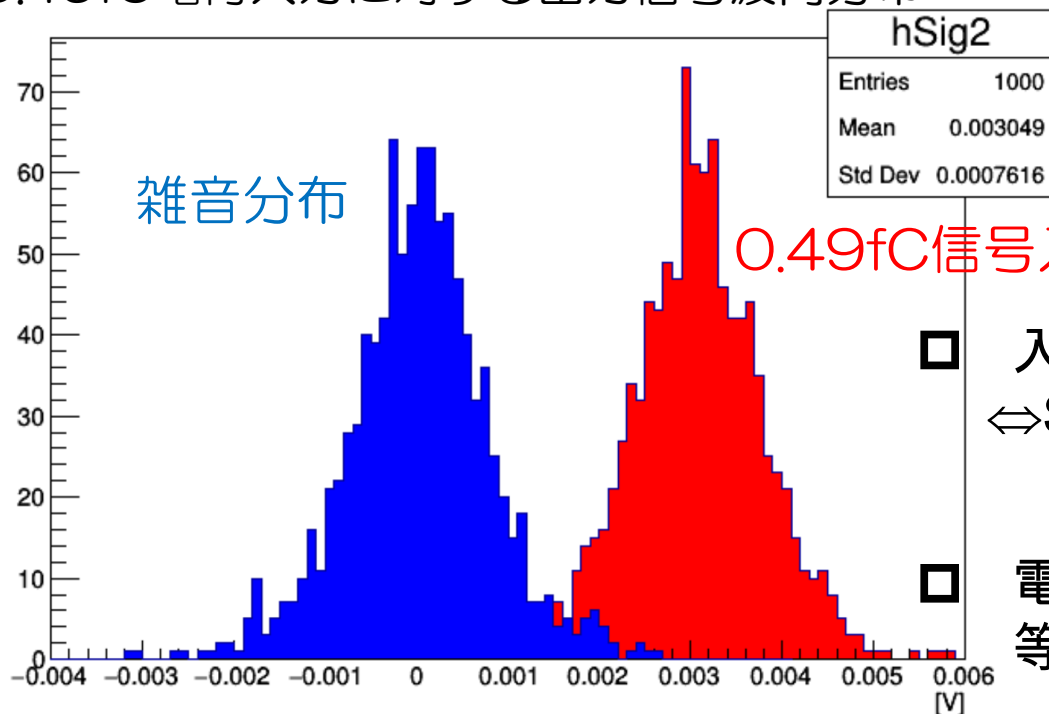
試作SOI極低温電荷積分型増幅器

SOI極低温電荷積分型増幅器

0.49fC電荷入力に対する出力信号波形



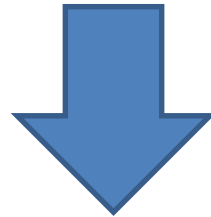
0.49fC電荷入力に対する出力信号波高分布



- 入力換算雑音電荷 0.1fC
⇔STJからの出力電荷期待値
1fC/1eV
- 電荷-電圧ゲインを大きくする
等改善の余地あり.

COBANDが目指す25meVの単一光子を捕えることのできるセンサーに別の応用は無いだろうか？

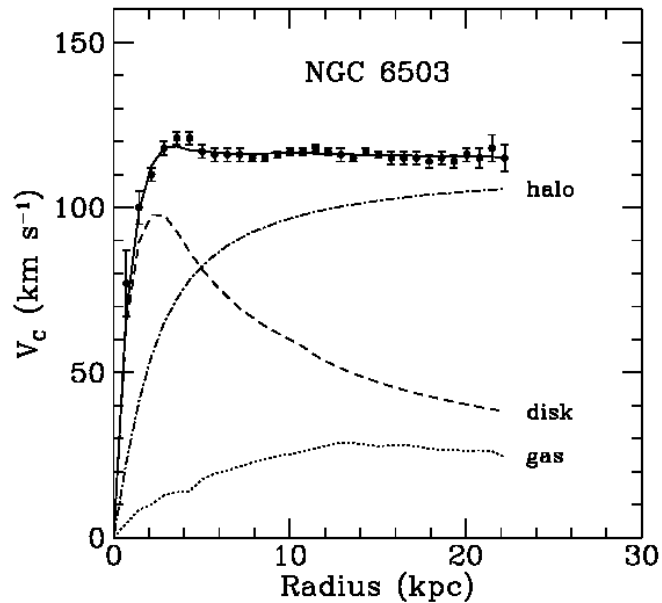
- STJは、eV以下のエネルギー領域に大きなアドバンテージ
- STJは、大面積・大容量は今のところ苦手



小さい断面積方向の探索は無理と割り切って、軽い暗黒物質方向の未踏領域にターゲットを絞る

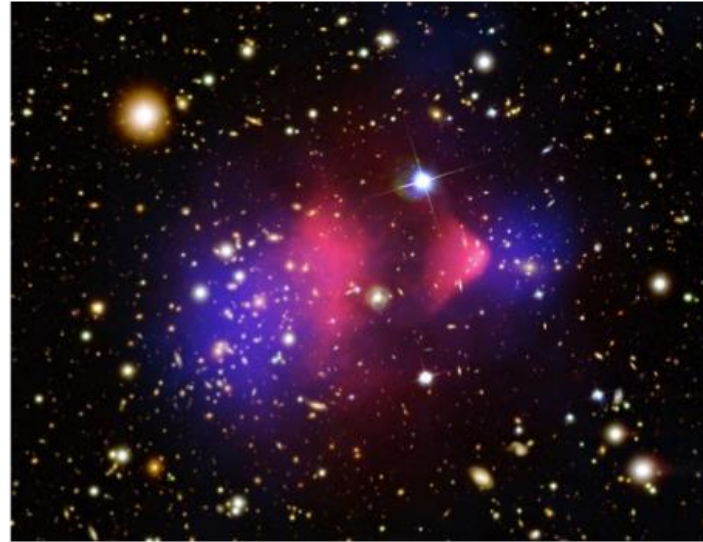
Dark Matterの間接証拠

Galactic scale



Begeman et. al. (1991).

Galaxy cluster scale



Clowe et. al. (2006).

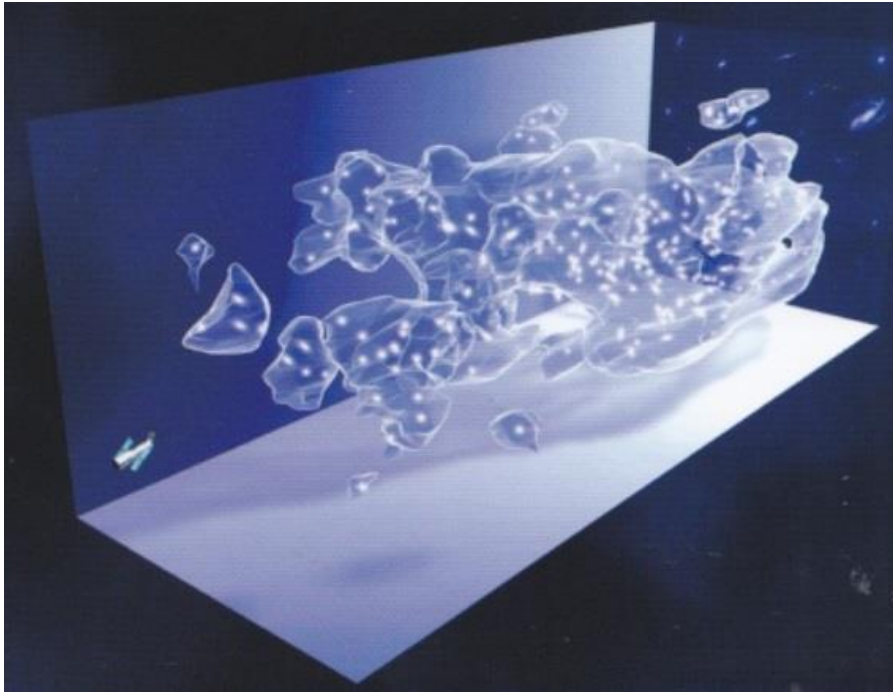
二つの銀河団が衝突したあとの様子

弾丸銀河団(大きな銀河団を小さな銀河団がすり抜けた. この時小さな銀河団のガスが弾丸のような形状になった.)

ガスの分布(ピンク): 衝突でお互い干渉しあう
質量の分布(青): 質量の分布

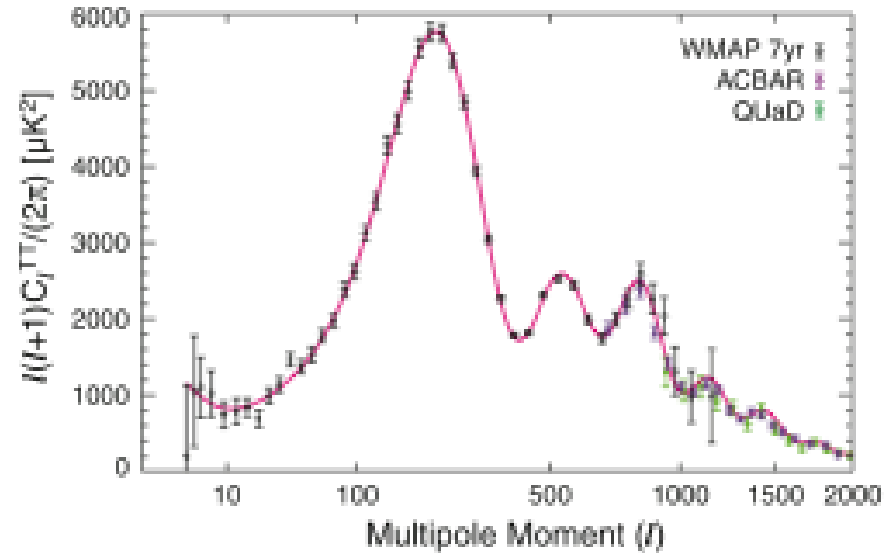
Dark Matterの間接証拠

Galaxy cluster scale



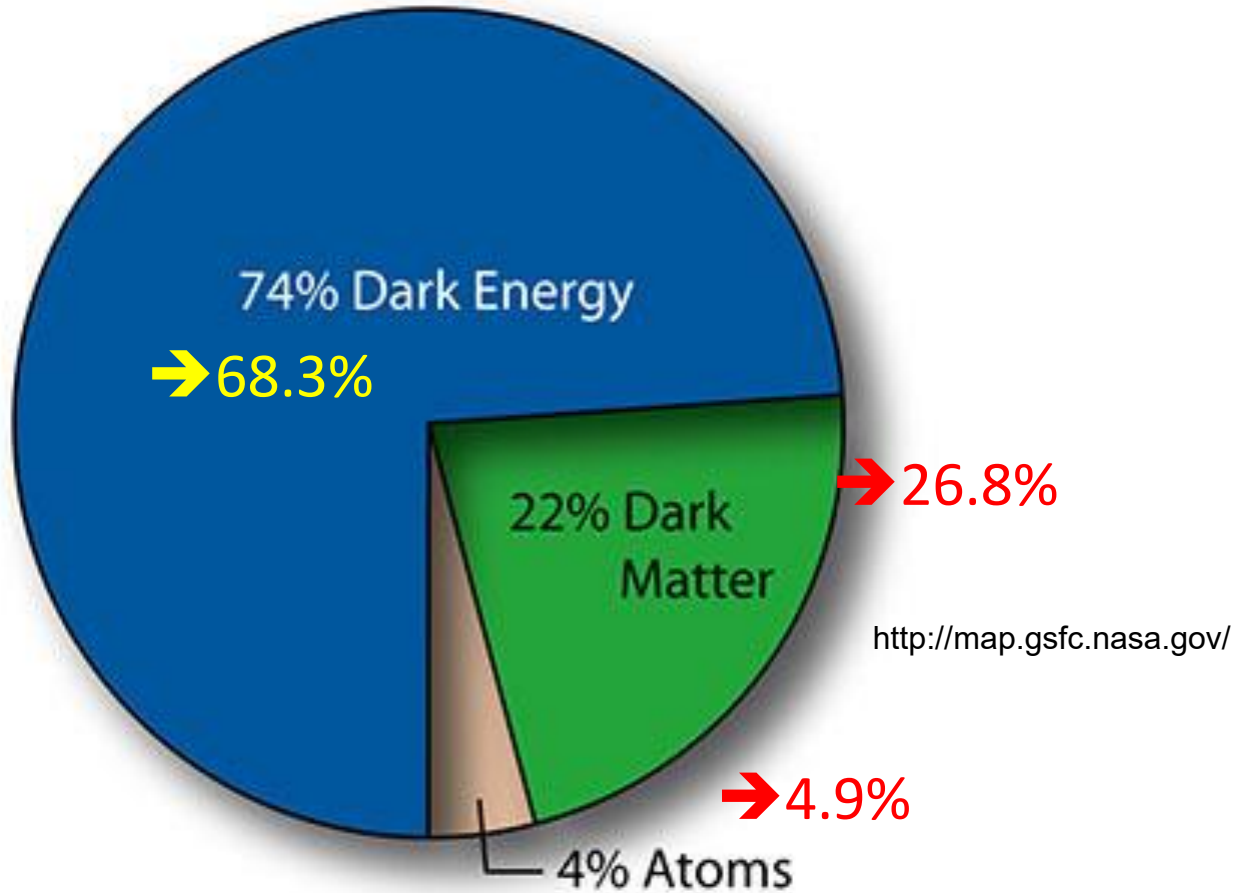
COSMOSプロジェクト

Cosmological scale



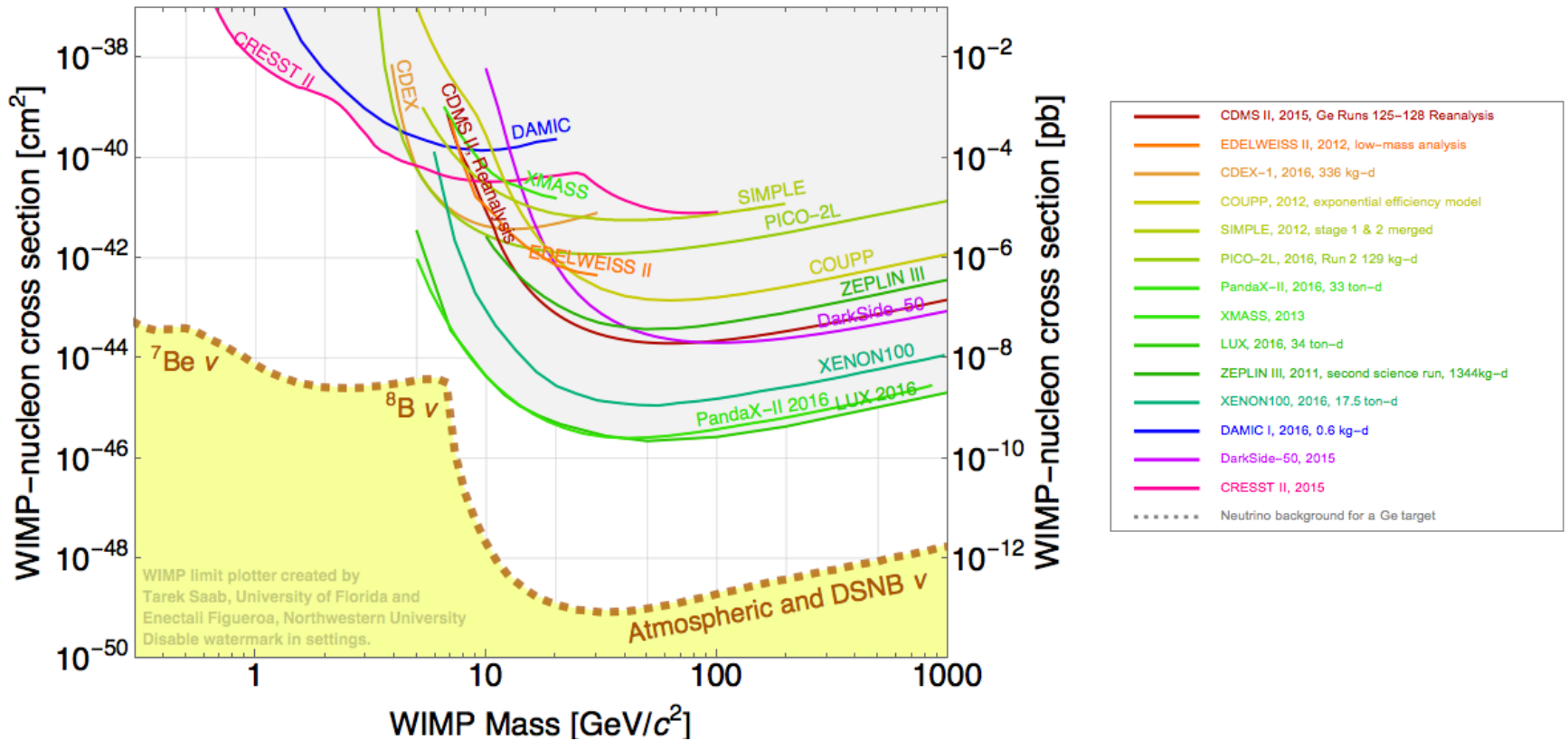
Komatsu et. al. (2010).

密度



宇宙にある物質のおよそ80%は
非バリオン暗黒物質

Dark Matter 直接測定

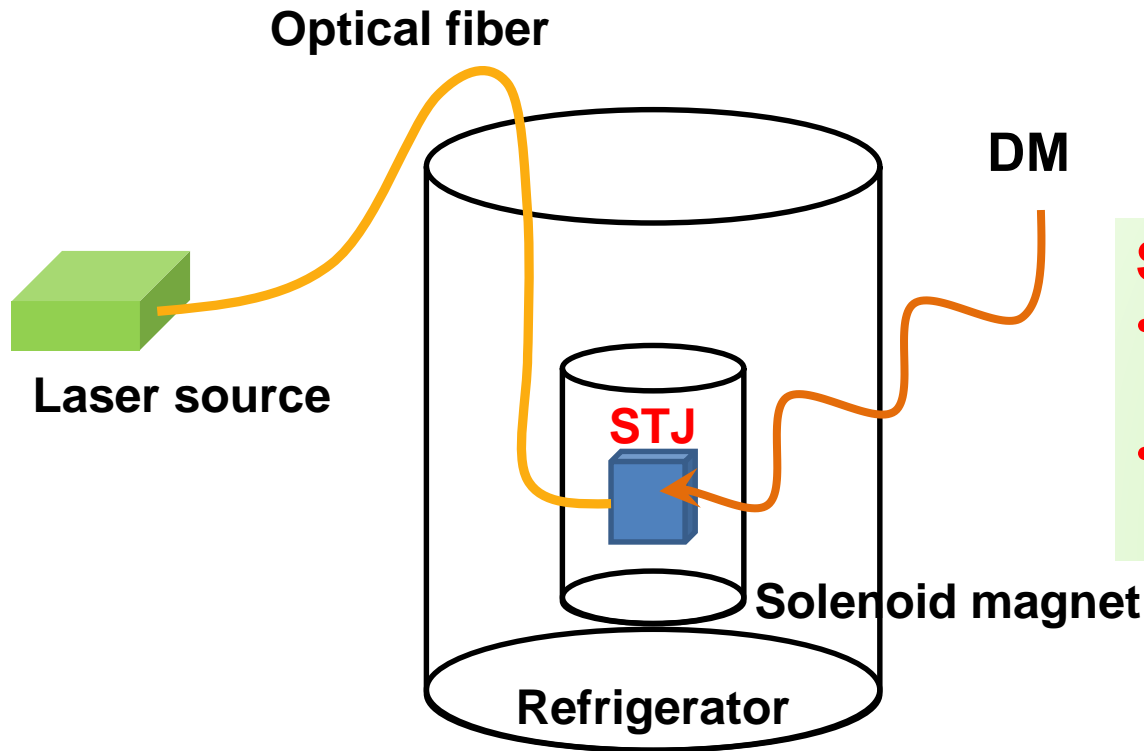


http://cdms.berkeley.edu/limitplots/mm/WIMP_limit_plotter.html

Light Dark Matter

- If DM interacts via weak interaction, annihilation cross section is of the order $m_{\tilde{\chi}}^2/M_Z^4$
- In the early universe, LDM would be produced abundantly, and less annihilated before freeze out.
 - ➔ This leads to a higher density of DM than currently observed.
 - ➔ Thus, lower limit of DM mass is to be 2 GeV (Lee-Weinberg bound).
- However, there are some loopholes for LDM existence lighter than 2GeV, such as an interaction via a lighter boson mediation.
 - ➔ LDM is worth to search for

Setup



STJ

- 100 μm sq. \times 1 μm thick
- $\times 10$ cells
- 3 hours

^3He sorption refrigerator
Solenoid magnet
STJ
Optical fiber & Laser source

That's all

Velocity distribution

Maxwell-Boltzmann distribution

$$f(v) = \frac{4}{v_{\text{mp}}^3 \sqrt{\pi}} v^2 \exp\left(-\frac{v^2}{v_{\text{mp}}^2}\right)$$

$$v_{\text{mp}} = v_{\odot} = 220 \text{ km/s}$$

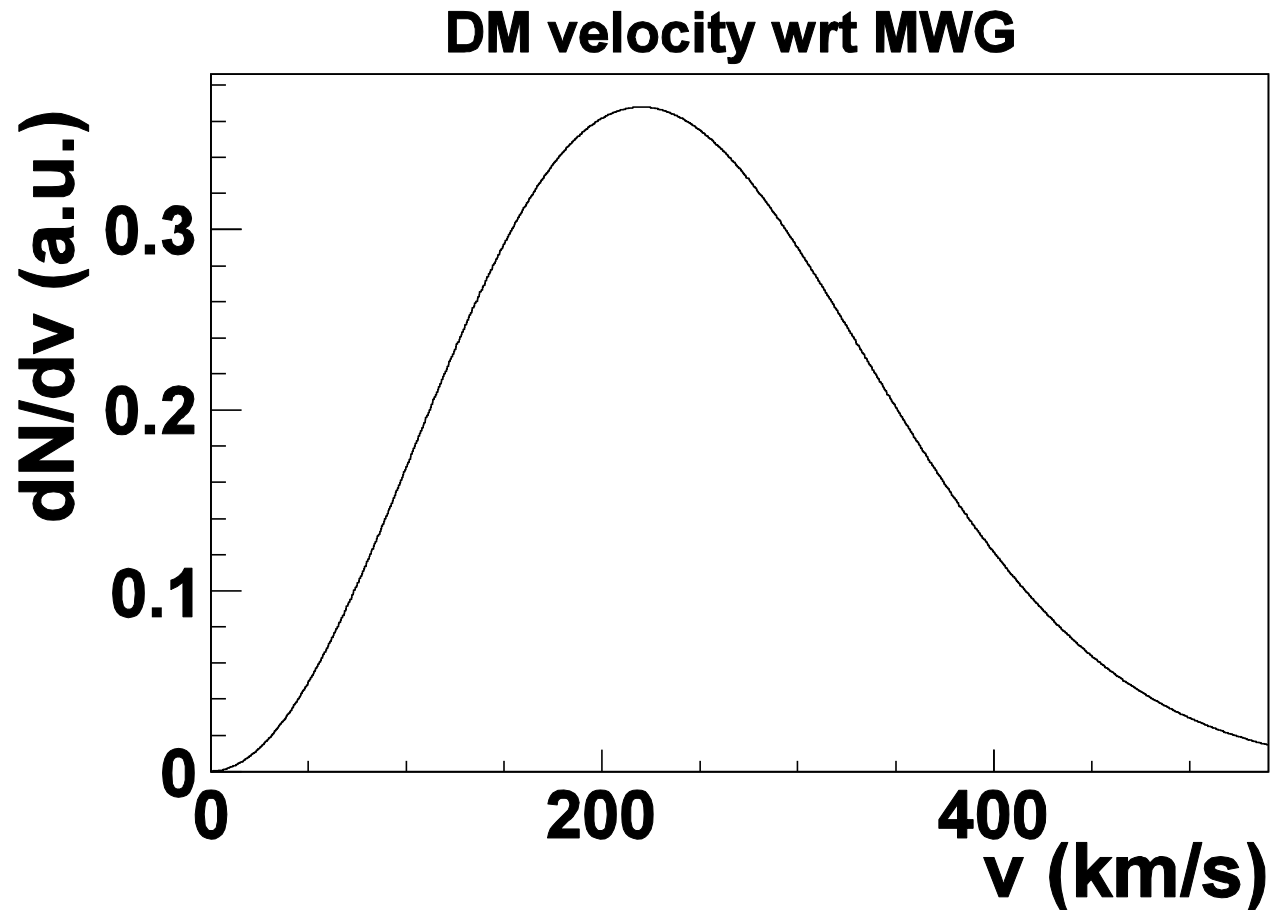
v_{\odot} : the solar system in the Milky way galaxy

- $v_{\odot} = 220 \text{ km/s}$ ($222 \pm 20 \text{ km/s}$)
 - F. J. Kerr and D. Lynden-Bell (1986), “Review of galactic constants”
- $v_{\odot} = 238 \pm 14 \text{ km/s}$
 - Honma et. al (2012) <http://pasj.asj.or.jp/v64/n6/640136/640136.pdf>

Velocity distribution wrt the Milky way galaxy

$$v_{\text{mp}} = 220 \text{ km/s}$$

$$v_{\text{esc}} = 540 \text{ km/s}$$



DM parameters

- Mass density of the dark matter around the solar system

$$0.3 \text{ GeV}/c^2 \cdot \text{cm}^{-3}$$

- Earth velocity w.r.t. the Milky way galaxy

$$v_{\oplus} \cong v_{\odot} + 15 \cos \left(2\pi \frac{t - 152.5}{365.25} \right) \text{ km/s}$$

- Maximum on June 2.

- Escape velocity from the Milky way galaxy

- 544 (498~608) km/s [The RAVE Survey, M.C.Smith et al. (2007)]

- References

- R. W. Schnee, Introduction to Dark Matter Experiments
arXiv:1101.5205v1

- D.G.Cerdeno and A.M.Green, Direct detection of WIMPs (2010)
arXiv:1002.1912v1

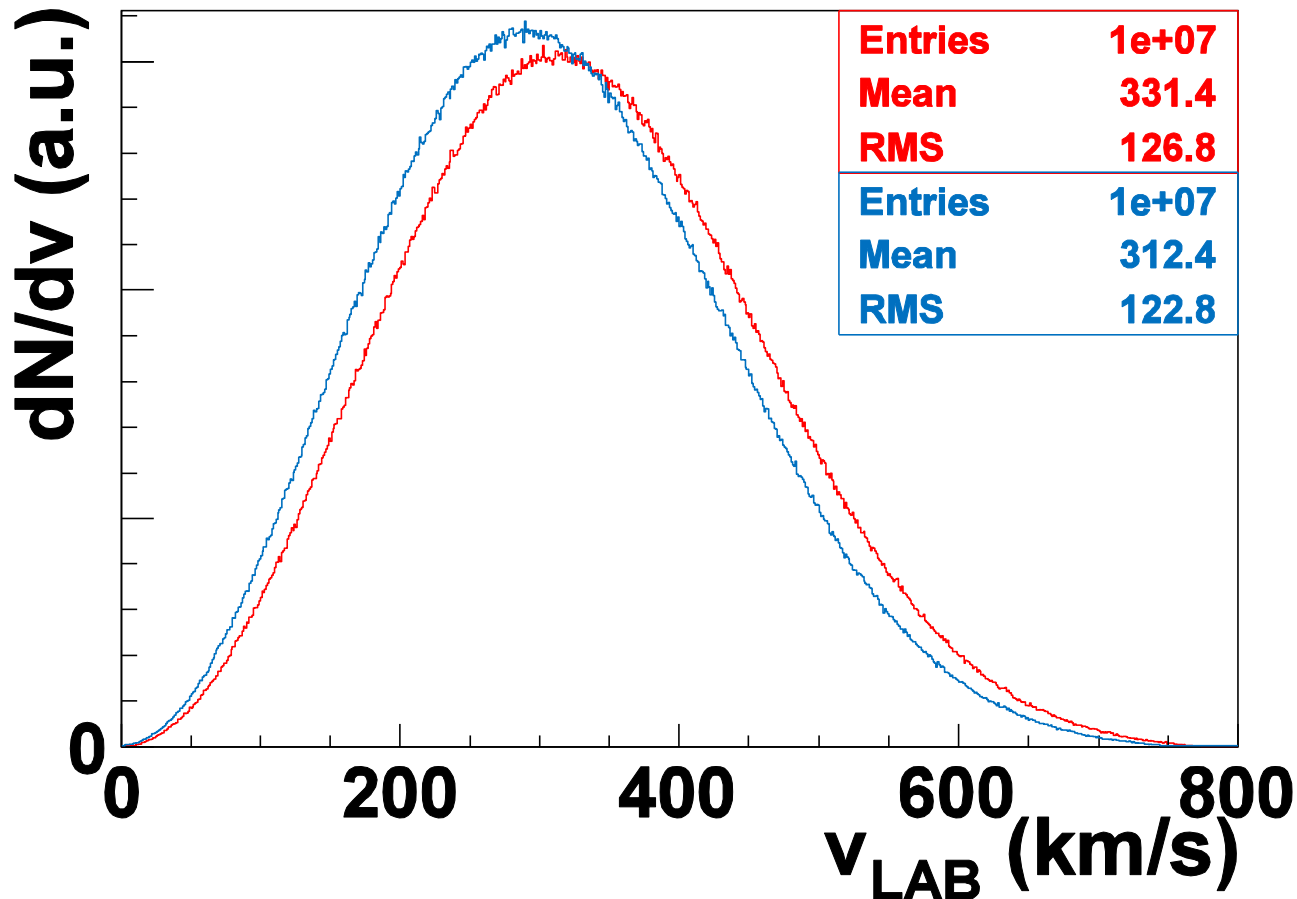
Velocity distribution wrt the earth

$$v_{\text{DM}} \oplus v_{\oplus}$$

$$v_{\oplus} = (220 + 15) \text{ km/s}$$

$$v_{\oplus} = (220 - 15) \text{ km/s}$$

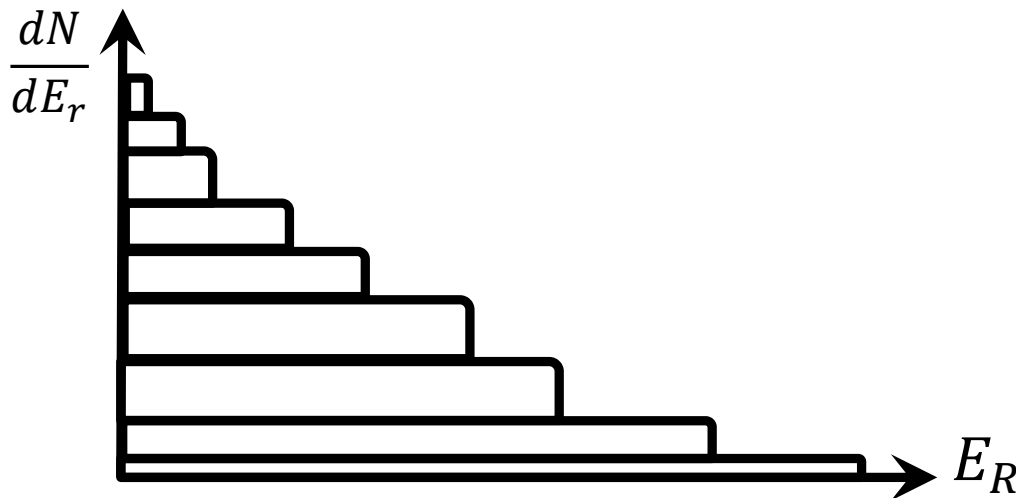
DM velocity wrt LAB



Recoil energy distribution

- Elastic scattering
- In the CM frame, the DM particle scatters off a nucleus with an angle θ isotropically (zero-momentum transfer case $F^2=1$)
 - $\cos\theta$ distributes uniformly between -1 and 1

$$E_R = \frac{\mu_A^2 v^2}{M_A} (1 - \cos\theta^*) \quad \mu_A \equiv \frac{M_X M_A}{M_X + M_A}$$



Recoil energy distribution

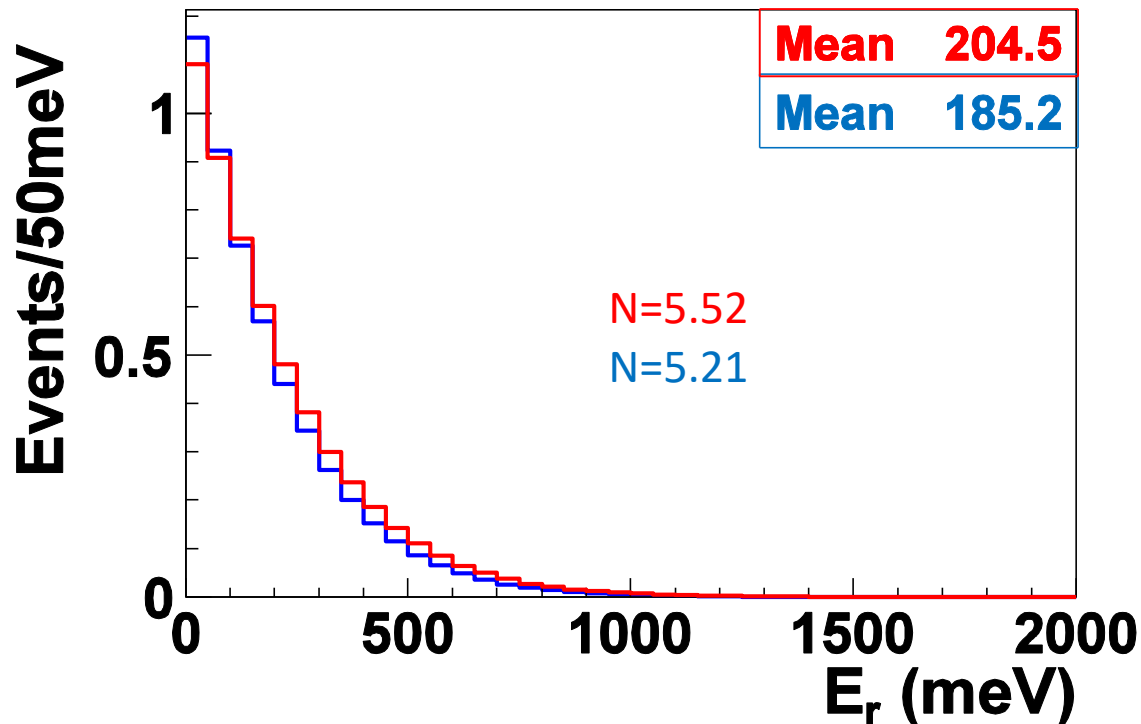
Number of interacted DM in velocity $[v, v+dv]$

$$\frac{dN}{dv} = \rho_{DM} f(v) v \sigma_A N \Delta t$$

- ρ_{DM} : DM density = $0.3 \text{ GeV}/c^2 \cdot \text{cm}^{-3} / M_\chi$
- $f(v)$: DM velocity distribution $\int f(v) dv = 1$
- σ_A : DM-nucleus cross-section
- N : number of target nuclei
- Δt : measurement time

Expected recoil energy distribution

- $M_X = 0.1 \text{ GeV}$, $\sigma_A = 1 \text{ mb} = 10^{-27} \text{ cm}^2$
 - Target: ^{93}Nb (92.9u) $100\mu\text{m} \times 100\mu\text{m} \times 1\mu\text{m} \times 10$
 - Measurement time: 10000sec
- $v_{\oplus} = (220 + 15) \text{ km/s}$
 $v_{\ominus} = (220 - 15) \text{ km/s}$

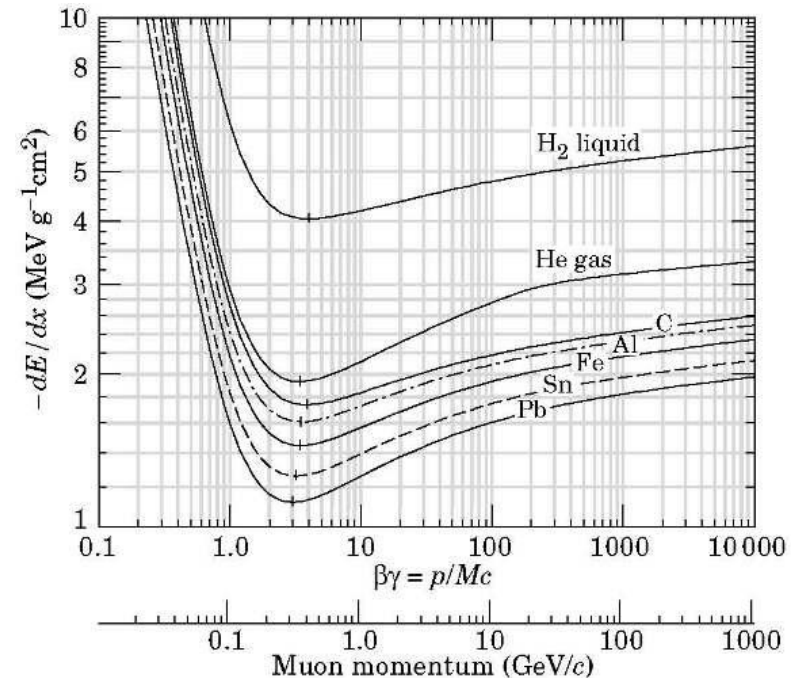


background from cosmic muon and Nb isotopes

- Maximum sensitive area: $100\mu\text{m} \times 100\mu\text{m} \times 10$
- Muon rate: Suppose ~ 1 muon / cm^2/min
- 0.001 muons/min = **0.167 muons /10000sec**

MIP energy deposit for $1\mu\text{m}$ -thick Nb

- $\rho = 8.57\text{g} \cdot \text{cm}^{-3}$
- $dE/dx > 1.2\text{ MeV} \cdot \text{g}^{-1} \cdot \text{cm}^2$
- **$\Delta E > 1.03\text{ keV}$**
- Muon rate is low and energy deposit is too large!
- ^{93}Nb and ^{27}Al are stable and at 100% natural abundance



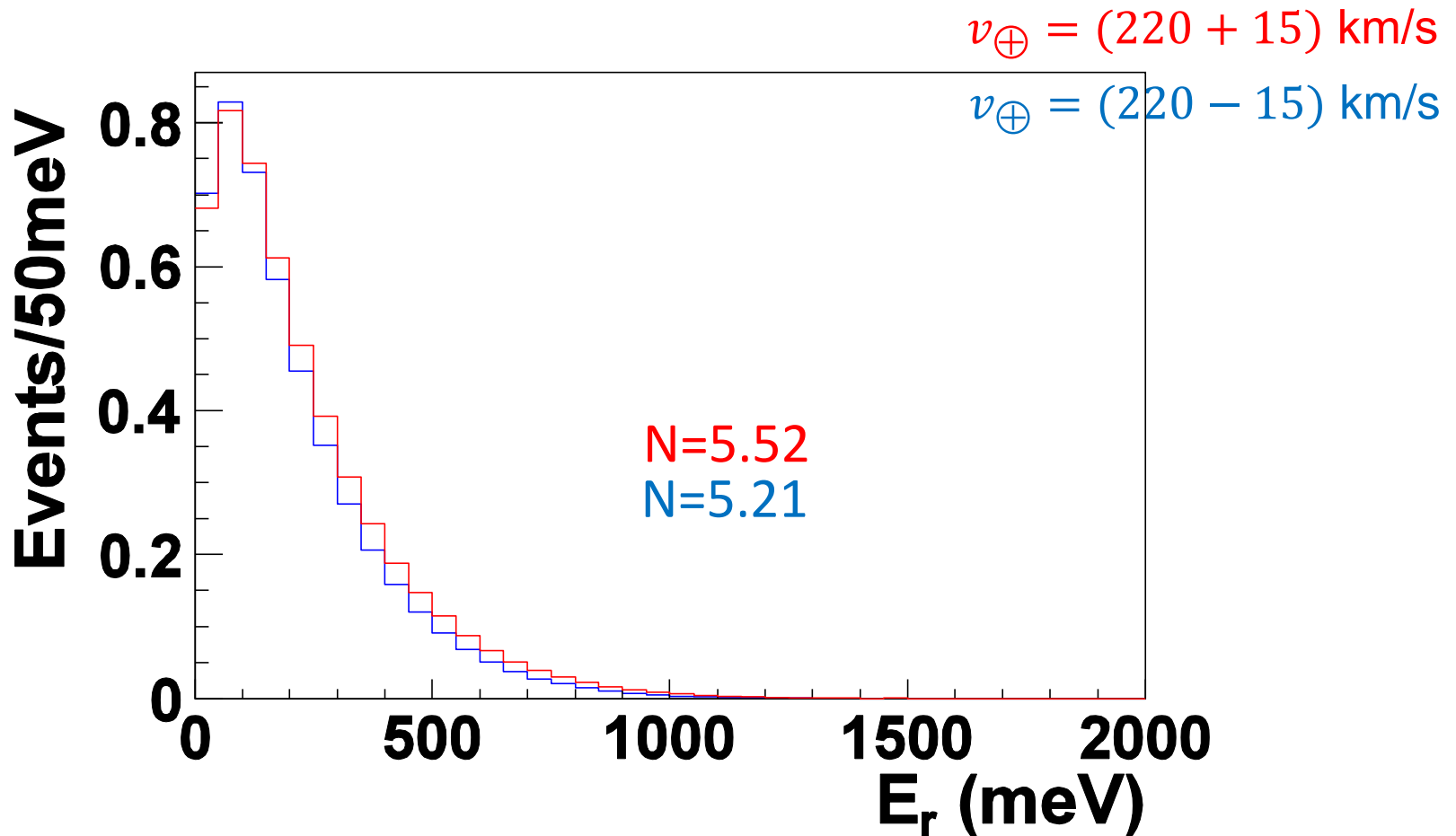
Negligible source of background.

Noise from fluctuation in STJ leak current

- Fluctuation in signal charge: $\sigma_Q = \sqrt{e\Delta T_{\text{int}} I_{\text{leak}}} = 0.04\text{fC}$
 - Assume signal pulse integration time is $\Delta T_{\text{int}} = 1\mu\text{s}$
 - Assume the STJ leak current is $I_{\text{leak}} = 10\text{nA}$
- $Q = eG_{\text{Al}} E / 1.7\Delta = 7.85 \times 10^{-4}\text{fC/meV} \cdot E$
 - $\Delta=1.2\text{meV}$, $G_{\text{Al}}=10$
- $\sigma_E = 50.9\text{meV}$
- $10000\text{s}/1\mu\text{s}=10^{10}$
- If we set threshold at **350meV** (6.88σ , $\text{prob}=3\times 10^{-12}$), $\text{Nbkg}=0.03$ are expected.

Expected recoil energy distribution w/ σ_E

- Energy resolution: $\sigma_E = \sqrt{(1.7\Delta)FE \oplus 50.9\text{meV}}$
 - Suppose $F=0.2$, then $\sqrt{(1.7\Delta)F \cdot 350\text{meV}} \sim 11.95\text{meV}$



Single Event Sensitivity and 90%CL limit

- $M_X = 0.1 \text{ GeV}$, $\sigma_A = 1 \text{ mb} = 10^{-27} \text{ cm}^2$
- Target: ^{93}Nb (92.9u) $100\mu\text{m} \times 100\mu\text{m} \times 1\mu\text{m} \times 10$
- Measurement time: 10000sec
- If we set threshold at 350meV, $N(+)=1.04$, $N(-)=0.83$ and $N_{\text{bkg}}=0.03$ are expected.

Single event sensitivity: $\sigma_A(\text{S. E. S.}) = 1.07 \times 10^{-27} \text{ cm}^2$
90%CL cross section upper limit: $2.46 \times 10^{-27} \text{ cm}^2$

Cross section

- Momentum transfer q^2 is very small, usually the zero momentum transfer case is assumed: σ_0^{XA}
- Spin-independent (SI) and spin-dependent (SD)

$$\sigma_0^{XA} = \frac{4\mu_A^2}{\pi} [Zf_p + (A - Z)f_n]^2 + \frac{32G_F^2\mu_A^2 J + 1}{\pi J} (a_p \langle S_p \rangle + a_n \langle S_n \rangle)^2$$

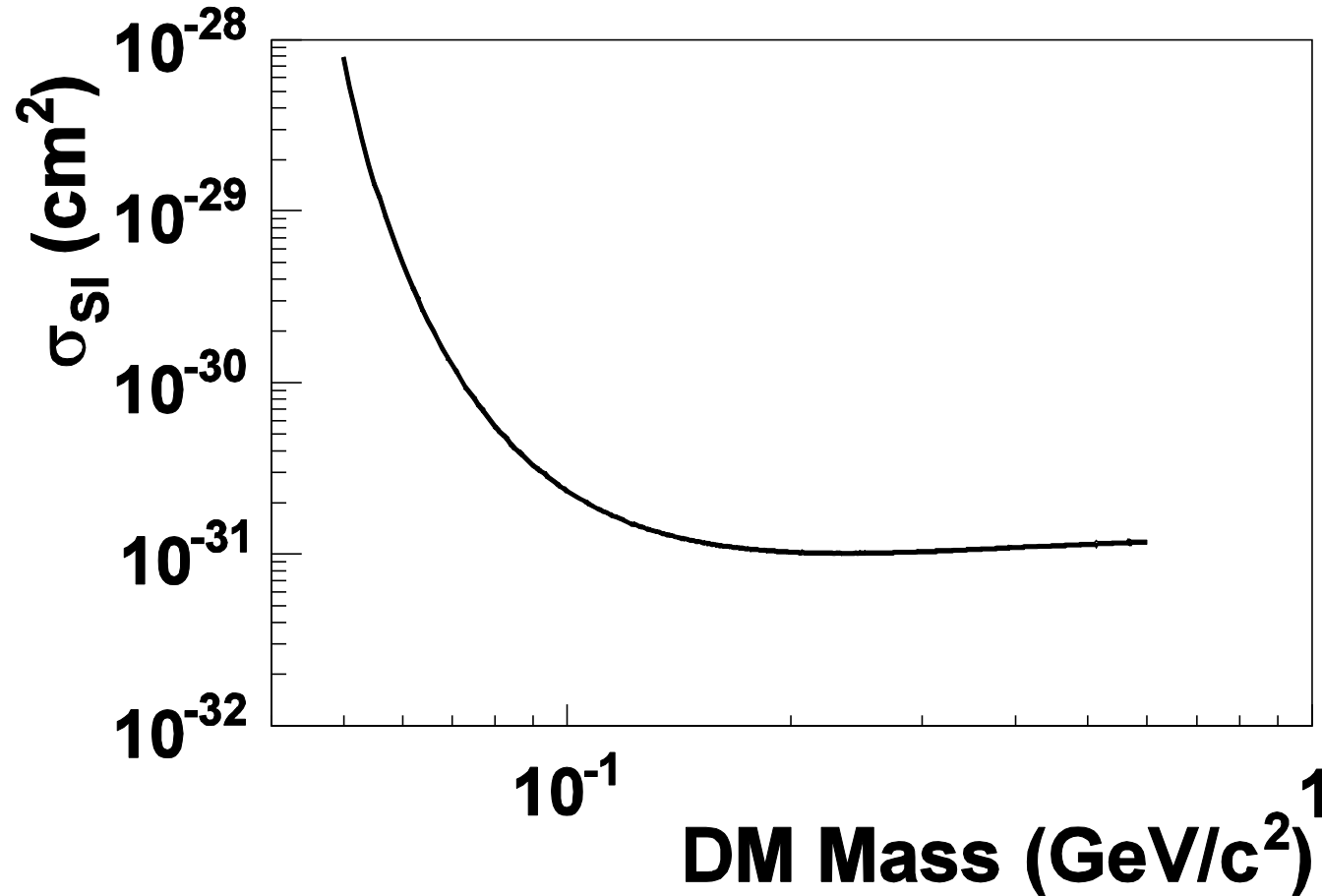
- For SI, assume $f_p \approx f_n$, then define $\sigma_{SI} \equiv \frac{4\mu_n^2 f_n^2}{\pi}$ as DM-nucleon cross section, we get

$$\sigma_{0,SI}^{XA} = \sigma_{SI} \frac{\mu_A^2}{\mu_n^2} A^2$$

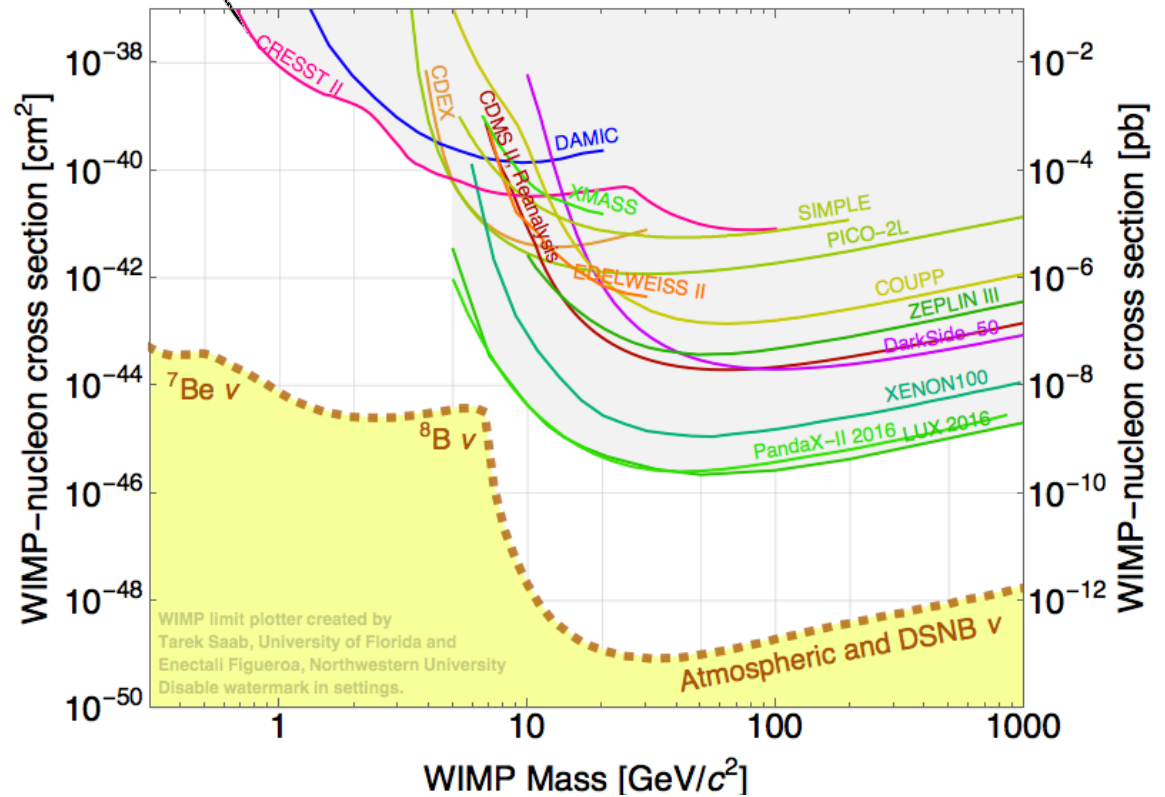
Nb: 92.9u, n: 1.01u, DM: 0.1GeV(0.107u) $\rightarrow \frac{\mu_A^2}{\mu_n^2} = 1.22$

90%CL σ_{SI} upper limit: $2.33 \times 10^{-31} \text{ cm}^2$

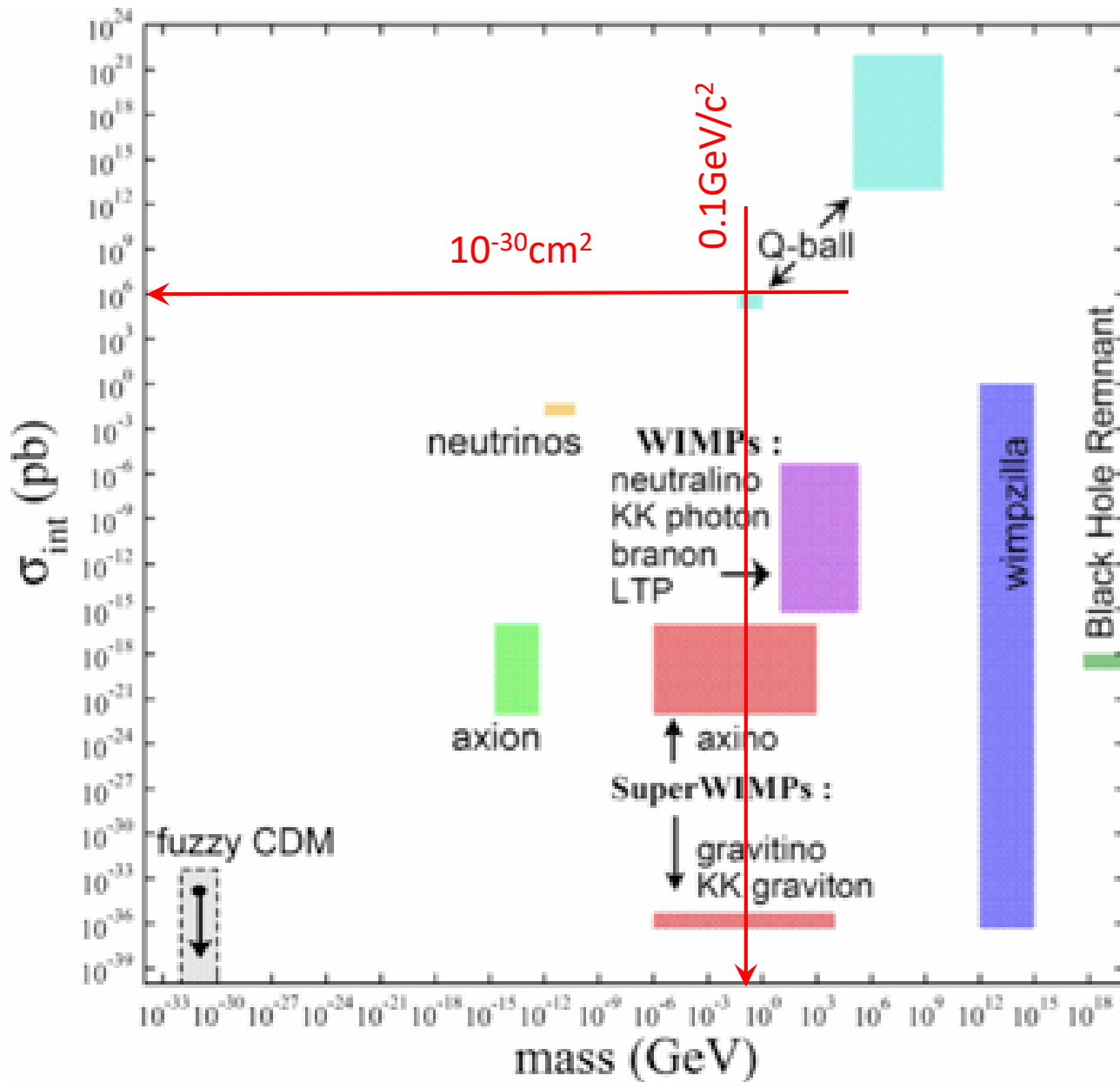
Cross section



We can exclude here



http://cdms.berkeley.edu/limitplots/mm/WIMP_limit_plotter.html



Axel Lindner's slide
 An experimental Expedition into a new Particle Habitat at smallest Masses
 (2011.9.28)

H. Baer's slide
 5th Patras Workshop on Axions, WIMPs and WISPs, 2009

まとめ

- COBAND実験用に開発中のSTJが使用できる(COBAND実験の要求値よりも緩い)
- $100\mu\text{m}$ 角 \times $1\mu\text{m}$ 厚 \times 10セル, 3時間弱(10000sec)の測定で新しい Limit が得られ, Q-Ball 模型のあるパラメータ領域を殺せる.
- 地上で実験可能. 光学系, 装置アライメント等のセットアップは不要. COBAND実験で必須のSTJと光子とのカップリングを気にする必要もなし.
- エネルギー校正に量子カスケード中赤外レーザー($\lambda \sim 10\mu\text{m}$)または, 福井大の遠赤外線レーザーが使用できる.

backup

Corrected M-B statistics

Maxwell-Boltzmann distribution

$$\sum_i n_i = N \quad \sum_i n_i \epsilon_i = E$$

δn_i : perturbation from equilibrium

$$\sum_i \delta n_i = 0 \quad \sum_i \delta n_i \epsilon_i = 0$$

Distribute indistinguishable N particles to partitions where i -th partition has n_i particles. The number of the possible states is

$$W = \frac{1}{n_1! n_2! \dots} \quad \ln W \sim - \sum_i (n_i \ln n_i - n_i)$$

which is stationary with the perturbation of δn_i on the constraints above.

$$\delta \{ - \sum_i (n_i \ln n_i - n_i) \} + \alpha (\sum_i \delta n_i) + \beta (\sum_i \delta n_i \epsilon_i) = 0$$

$$\sum_i \delta n_i (-\ln n_i + \alpha + \beta \epsilon_i) = 0$$

$$n_i = \exp(-\alpha - \beta \epsilon_i)$$

Velocity distribution

Maxwell-Boltzmann distribution

$$\frac{dn}{d^3\vec{v}} = A' \exp(-\beta E) \text{ where } E = \frac{1}{2} m v^2 + U_0$$

For isotropic velocity distribution $d^3\vec{v} = 4\pi v^2 dv$

$$\frac{dn}{dv} = A v^2 \exp\left(-\frac{\beta m}{2} v^2\right) \quad \int_0^\infty \frac{dn}{dv} dv = A \sqrt{\frac{\pi}{2}} (\beta m)^{-\frac{3}{2}} = 1$$

With normalization $\frac{dn}{dv} = \sqrt{\frac{2}{\pi}} (\beta m)^{\frac{3}{2}} v^2 \exp\left(-\frac{\beta m}{2} v^2\right)$

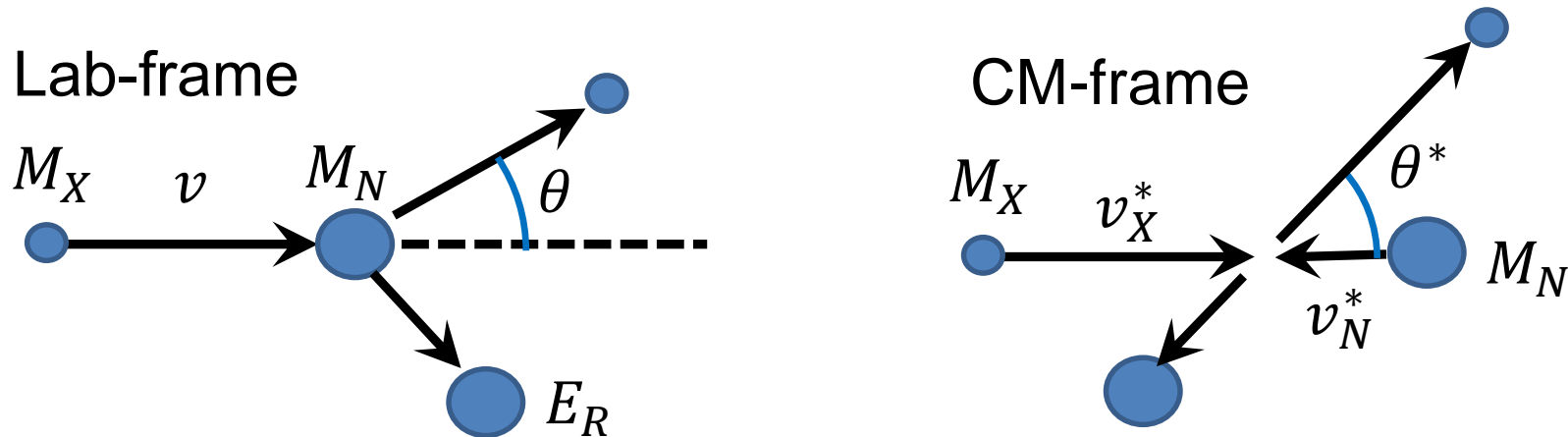
$$v_{\text{mp}}^2 = \frac{2}{\beta m} \quad \langle v^2 \rangle = \frac{3}{\beta m} = \frac{3}{2} v_{\text{mp}}^2 \quad \langle v \rangle^2 = \frac{8}{\pi \beta m} = \frac{4}{\pi} v_{\text{mp}}^2$$

$$\rightarrow f(v) = \frac{4}{v_{\text{mp}}^3 \sqrt{\pi}} v^2 \exp\left(-\frac{v^2}{v_{\text{mp}}^2}\right) \quad v_{\text{mp}} = 220 \text{ km/s}$$

N.R. two-body elastic scattering

- Momentum in CM: $p^* = \mu_N v$ $\mu_N \equiv \frac{M_X M_N}{M_X + M_N}$
- CM-LAB velocity (= particle N velocity in CM): $v_N^* = \frac{p^*}{M_N}$
- Recoil energy in LAB(rest frame of the target):

$$E_R = \frac{1}{2} M_N v_N^{*2} [(1 - \cos\theta^*)^2 + \sin^2 \theta^*]$$
$$= \frac{p^{*2}}{M_N} (1 - \cos\theta^*)$$



N.R. two-body elastic scattering

Fermi Golden rule

$$W_{fi} = 2\pi |M_{fi}|^2 \rho(E_f)$$

- transition probability per unit time: $W_{fi} = \frac{N_f}{N_i} = \frac{n_i v \sigma}{n_i V} = \frac{v}{V} \sigma$

$$d\sigma = \frac{2\pi V}{v} |M_{fi}|^2 d\rho \quad (\text{Normalization } \int \rho dV = 1)$$

- In CM

$$E_f = \frac{p^{*2}}{\mu} \quad dE_f = \frac{p^* dp^*}{\mu} = v dp^*$$

- Number of final states per unit energy

$$\rho(\Omega, E_f) d\Omega dE_f = \frac{V}{(2\pi)^3} d\vec{p}^{*'} = \frac{V p^{*2}}{(2\pi)^3} dp^* d\Omega = \frac{V p^{*2}}{(2\pi)^3 v} dE_f d\Omega$$
$$d\rho = \rho d\Omega = \frac{V \mu^2 v}{(2\pi)^3} d\Omega$$

$$\frac{d\sigma}{d\Omega} = \frac{V^2}{4\pi^2} \mu^2 |M_{fi}|^2 \quad \sigma = 4\pi \frac{d\sigma}{d\Omega} = \frac{V^2}{\pi} \mu^2 |M_{fi}|^2$$

Radioactive isotopes in STJ

- Si: 4.99×10^{22} atoms/cm³
 - Density 28.1g/mol, 12.1mL/mol
- Nb: 5.56×10^{22} atoms/cm³
 - Density 8.57 g/cm³, 92.9 g/mol
 - 5.56×10^{15} atoms in $100\mu\text{m} \times 100\mu\text{m} \times 1\mu\text{m} \times 10$
- Thorium series: ^{232}Th ($\tau_{1/2}=1.4 \times 10^{10}$ yrs)
- Uranium series: ^{238}U ($\tau_{1/2}=4.5 \times 10^9$ yrs)

Q-ball とは？

- バリオン数を持った複素スカラー場 ϕ

$$L = \partial_\mu \phi^* \partial^\mu \phi - V(\phi)$$

- $V(\phi) = m|\phi|^2 - \lambda|\phi|^4$ のような形だとソリトンとして真空中に安定に存在する.
- バリオン数を生成できる.
- 暗黒物質とバリオンの量が同じような量であることが自然に説明できる.