

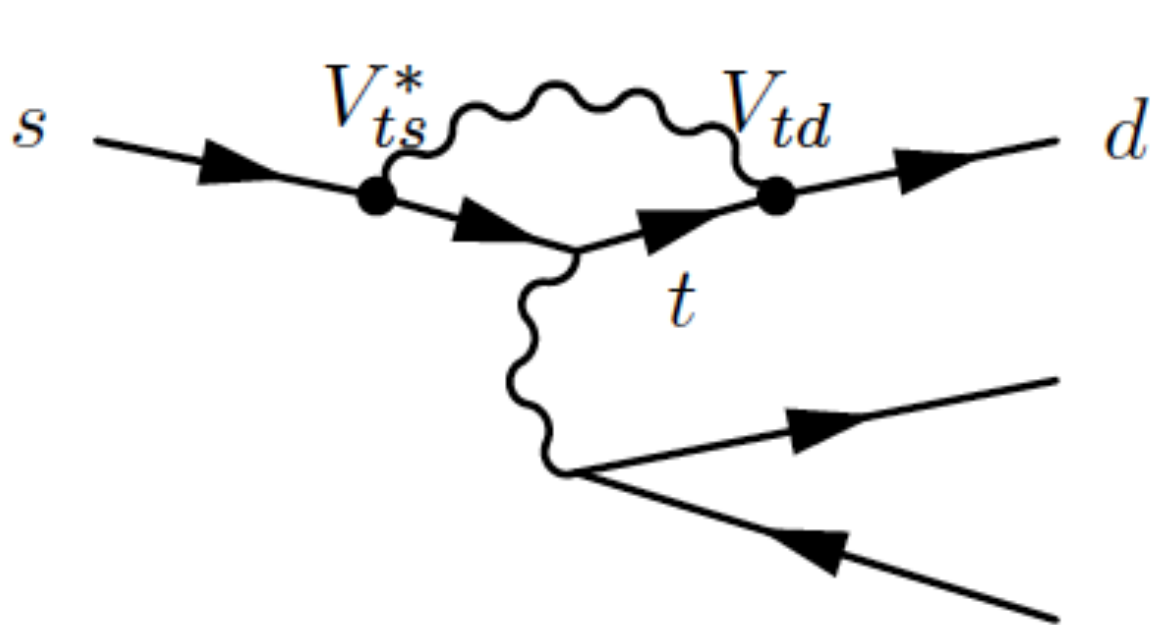
KOTO実験での  
結晶シンチレータ両端読みだしによる  
カロリメータアップグレード

南條 創  
(大阪大学)

# New Physics Search

- High Energyに新物理
  - Energy Frontier → LHC
  - Intensity Frontier
    - $\Delta E \times \Delta T \sim h$  : まれ → 高エネルギー
    - 標準モデル = background process
      - 強い抑制
      - 正確な予測

# Flavor Changing Neural Current



$$\begin{array}{c}
 u \\
 c \\
 t
 \end{array}
 \begin{pmatrix}
 d & s & b \\
 \boxed{1} & \boxed{\lambda} & \lambda^3 \\
 -\lambda & 1 & \lambda^2 \\
 \lambda^3 & -\lambda^2 & 1
 \end{pmatrix}$$

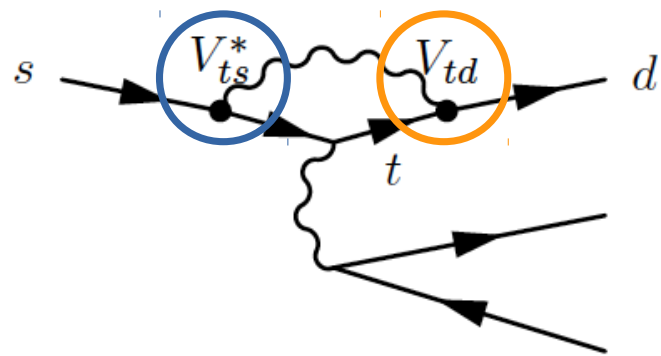
- FCNC process (down  $\rightarrow$  up  $\rightarrow$  down)

- $b \rightarrow d$       ex)  $B \rightarrow \mu \mu$
- $b \rightarrow s$       ex)  $B_s \rightarrow \mu \mu$
- $s \rightarrow d$       ex)  $K \rightarrow \pi \nu \nu$

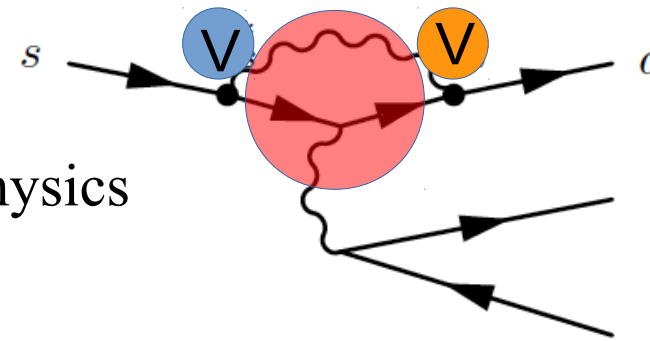
- GIM suppression

- 中間のu, c, tの寄与はキャンセル  $\rightarrow 0$  (ユニタリ) : まれ
- topの寄与が最大 (質量差) : エネルギースケール大  $\rightarrow$  比較的正確

# Strangness



+ New Physics



$\lambda \sim 0.23$

Potential to explore O(100) TeV

$$\begin{matrix} u \\ c \\ t \end{matrix} \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \lambda^3 & -\lambda^2 & 1 \end{pmatrix} \begin{matrix} d \\ s \\ b \end{matrix}$$

$\times \sim 100$

$$\underbrace{|V_{ts}^* V_{td}|}_{K \text{ system}} \sim 5 \cdot 10^{-4} \ll \underbrace{|V_{tb}^* V_{td}|}_{B_d \text{ system}} \sim 10^{-2} < \underbrace{|V_{tb}^* V_{ts}|}_{B_s \text{ system}} \sim 4 \cdot 10^{-2}$$

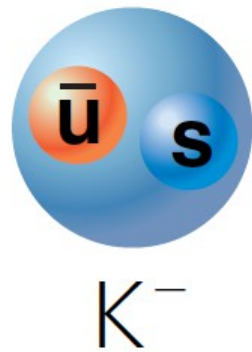
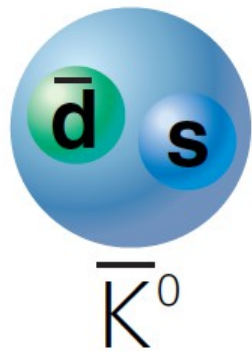
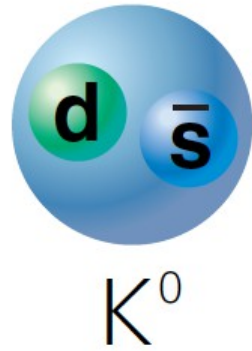
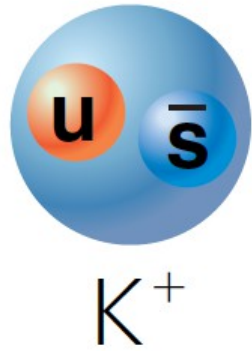
$s \rightarrow d$  : 標準モデル : フレーバ遷移に最大の抑制

新物理 : フレーバ遷移

CKM同様 : Minimal Flavor violation

O(1) : Generic model  $\rightarrow$  高エネルギー

# Kaon



$$K_S \sim \left( |K^0\rangle + |\bar{K}^0\rangle \right) / \sqrt{2}$$

$$K_L \sim \left( |K^0\rangle - |\bar{K}^0\rangle \right) / \sqrt{2}$$

- 質量 : 0.5 GeV
- 寿命
  - $K_L$  50ns 15m
  - $K_S$  100ps 3cm
  - $K^+$  10ns 4m

$$K_L \rightarrow \pi^0 \nu \nu$$

- Rare

$$Br(\text{SM}) = (3.00 \pm 0.30) \times 10^{-11}$$

Buras '15

- Accurate  $\sim 2\%$

- CP violation

$$\mathcal{A}(K_L) \propto \mathcal{A}(K^0) - \mathcal{A}(\overline{K}_0) \propto \text{Im}(\mathcal{A}_{s \rightarrow d})$$

- Related process

$$K^+ \rightarrow \pi^+ \nu \nu \quad \mathcal{A}(K^+) \propto |\mathcal{A}_{s \rightarrow d}|$$

Indirect limit :

$$Br(K_L) < 4.4 \times Br(K^+) \rightarrow 1.5 \times 10^{-9} (90\% C.L.)$$

Measured value  
 $(1.73^{+1.15}_{-1.05}) \times 10^{-10}$

Direct limit :

$$Br(K_L) < 2.6 \times 10^{-8} (90\% C.L.)^{10}$$

# New Physics Models

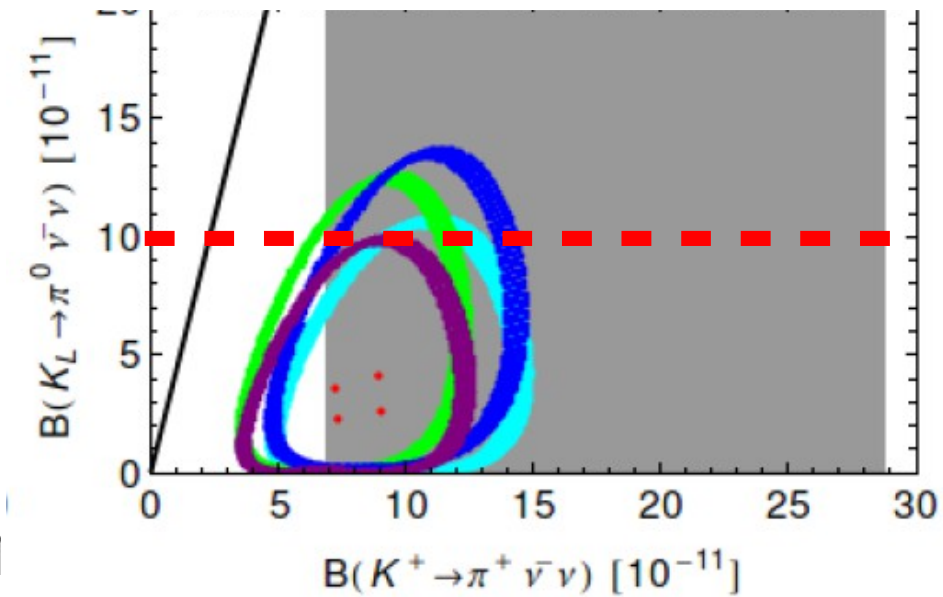
$$K_L \rightarrow \pi^0 \nu \bar{\nu} < 2.6 \times 10^{-8}$$

v.s.

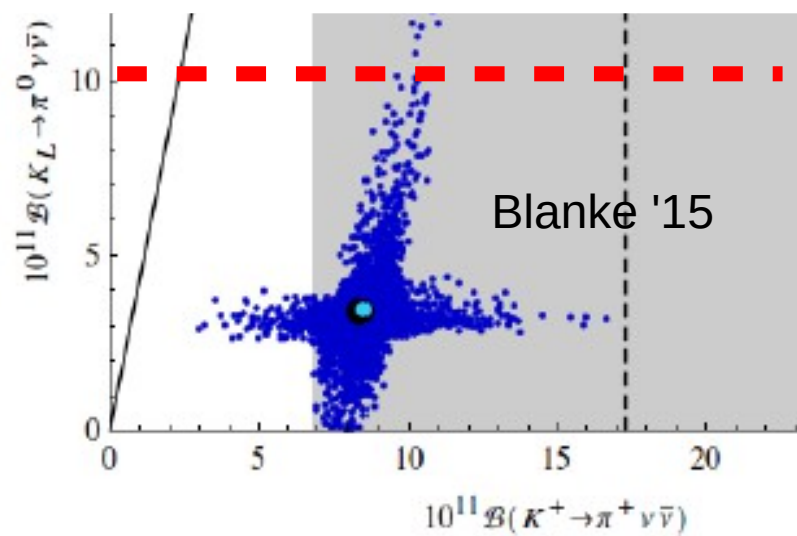
$$K^+ \rightarrow \pi^+ \nu \bar{\nu} (1.7 \pm 1.1) \times 10^{-10}$$

Z'

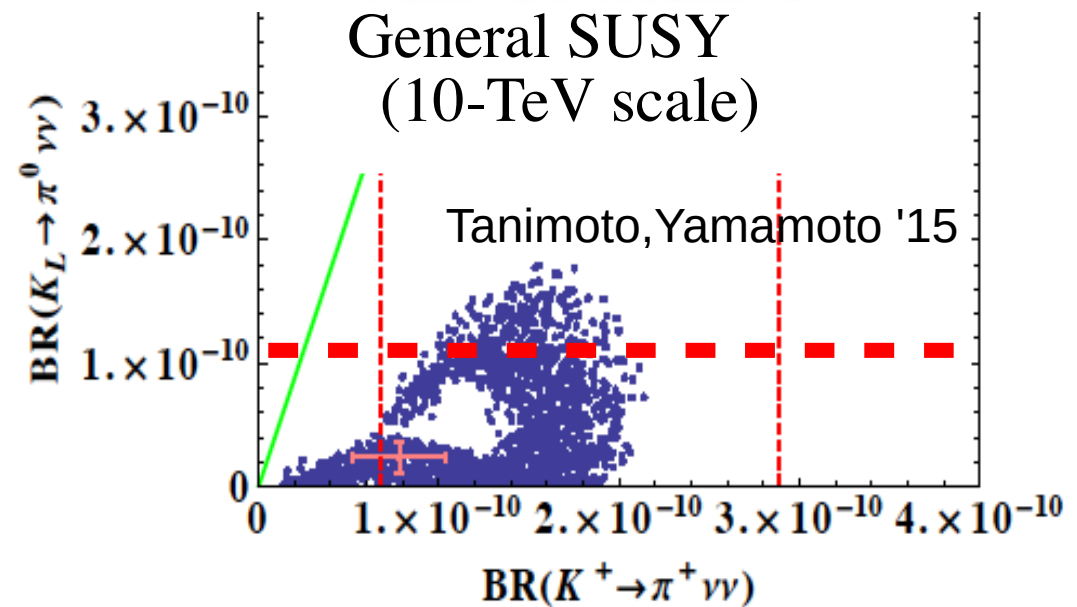
( $m_{Z'} = 500$  TeV) Burlas '15



Littlest Higgs with T-parity  
(Symmetry breaking scale 3 TeV)

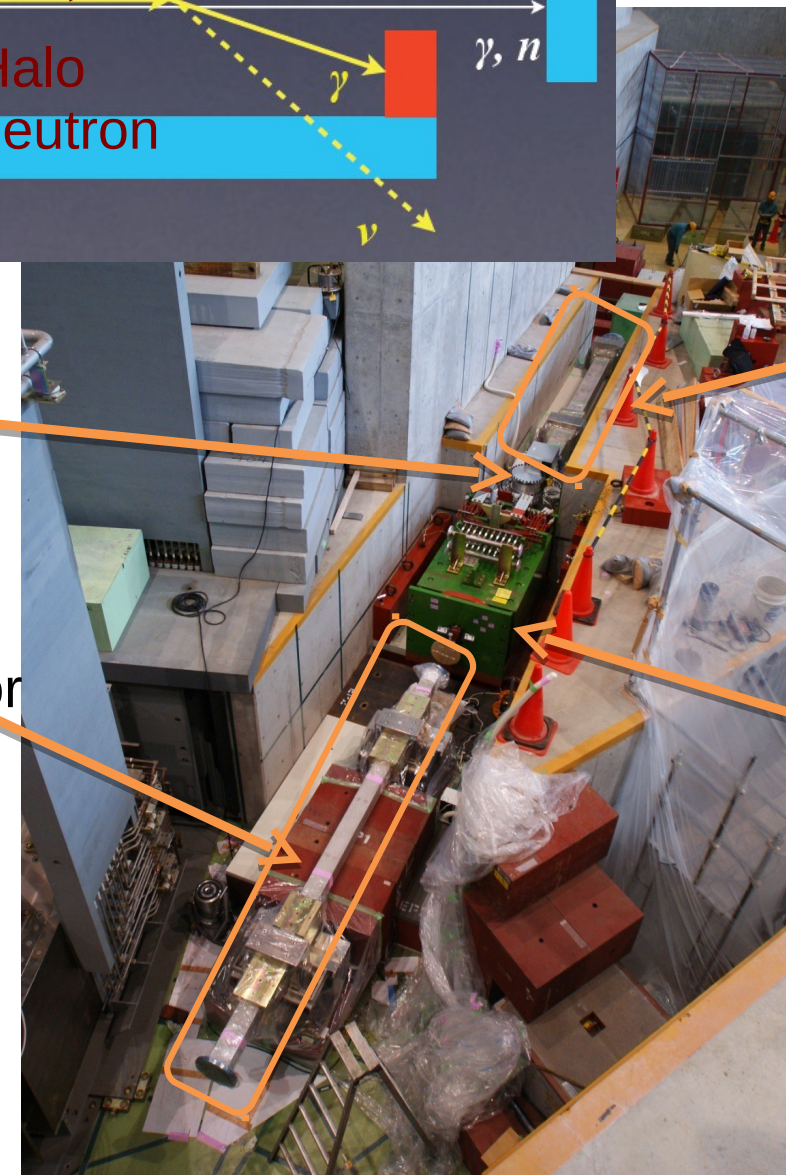
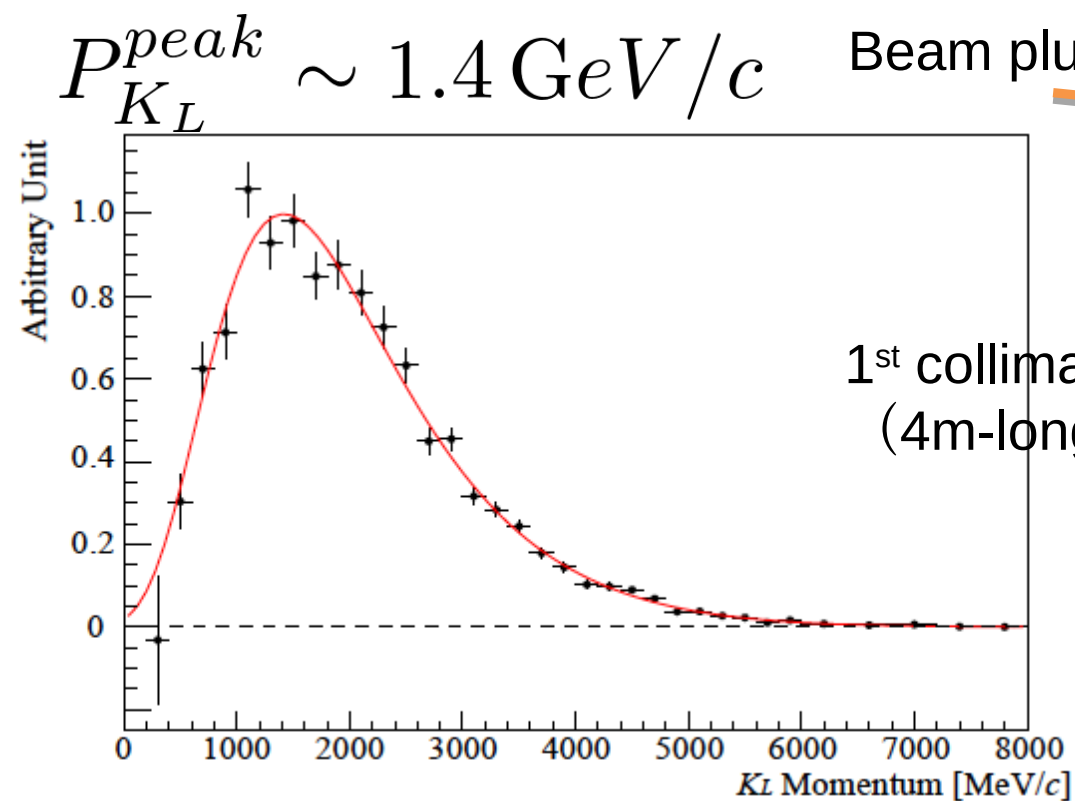
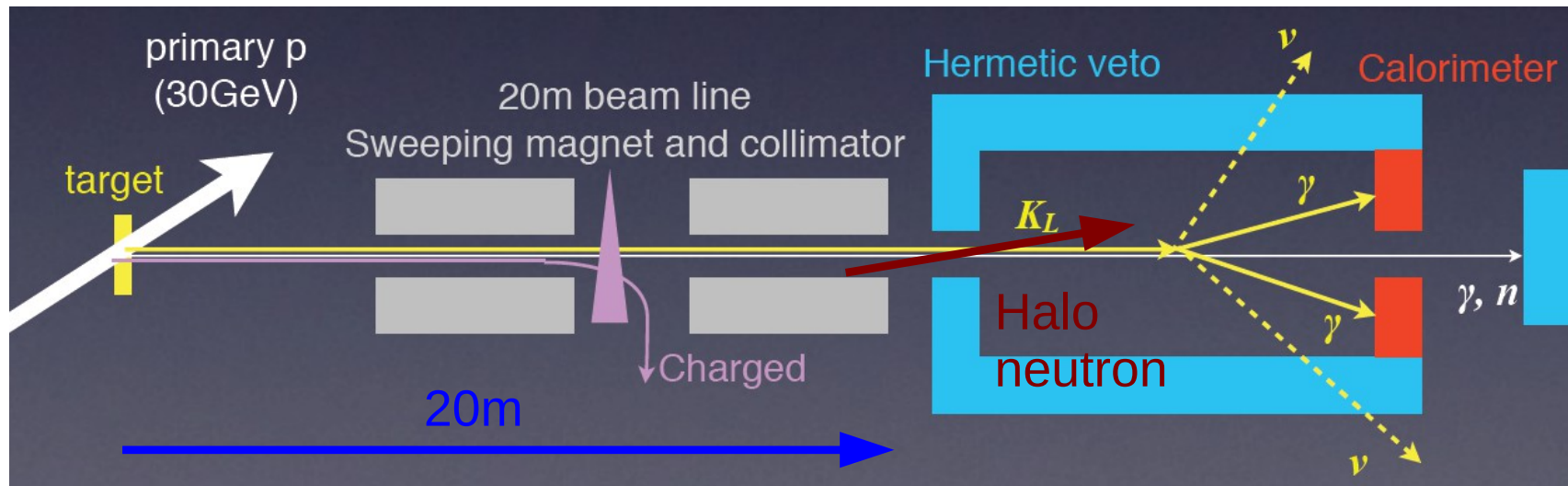


General SUSY  
(10-TeV scale)





# KOTO実験-Beam-



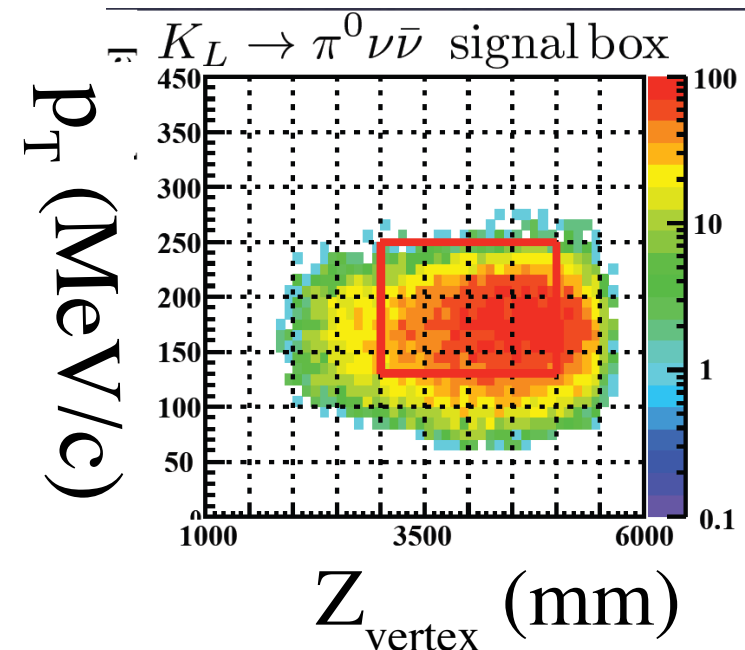
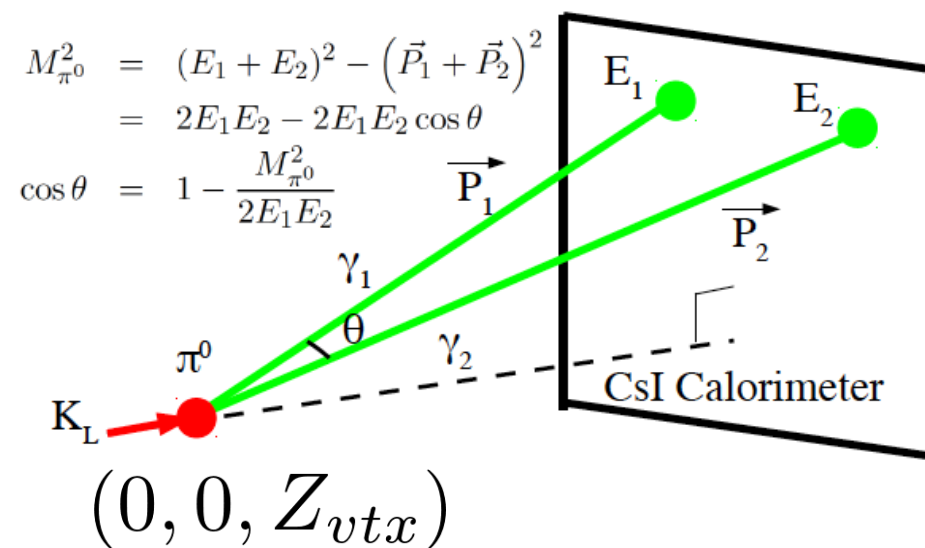
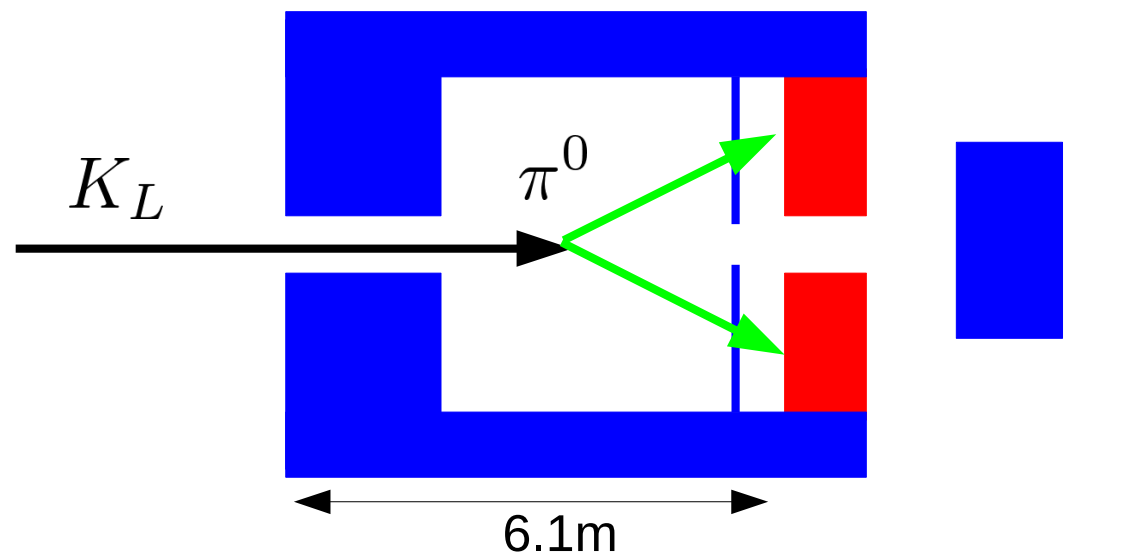


# KOTO実験 -検出器-

- $2\gamma + \text{nothing}$  → **Calorimeter** +
- Beam constraint → “pencil beam”

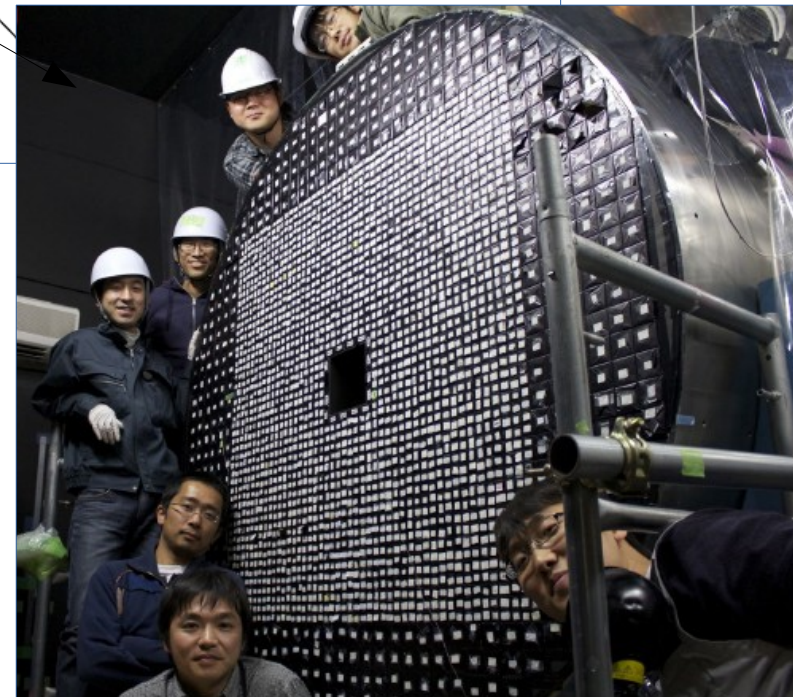
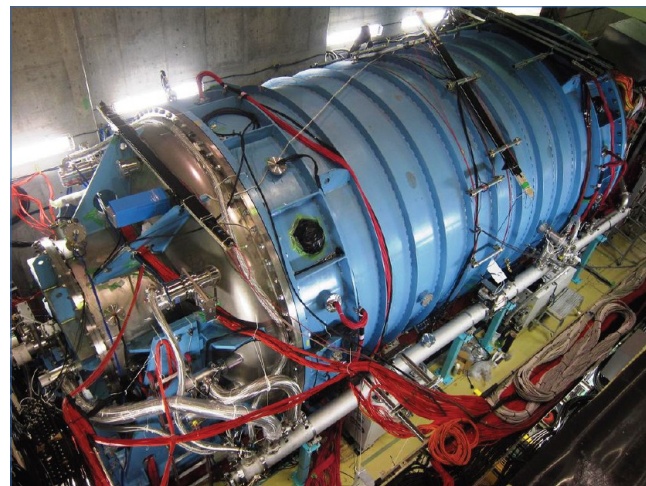
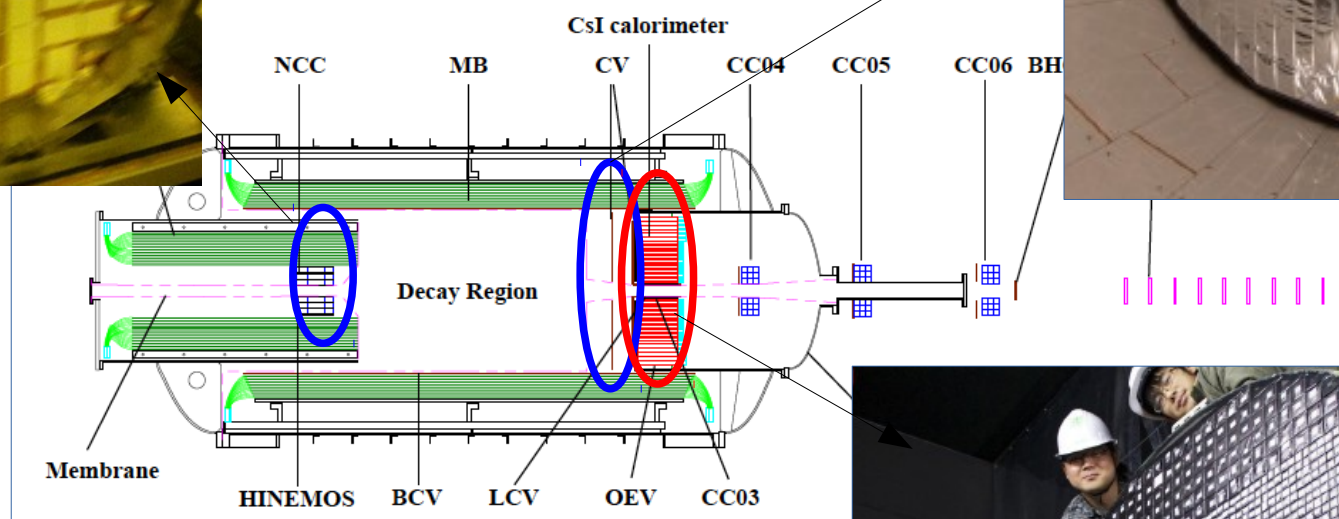
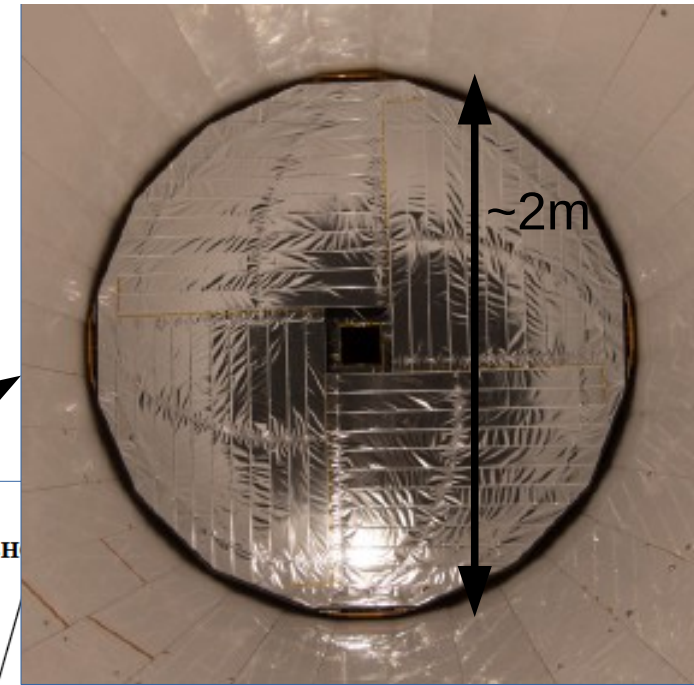
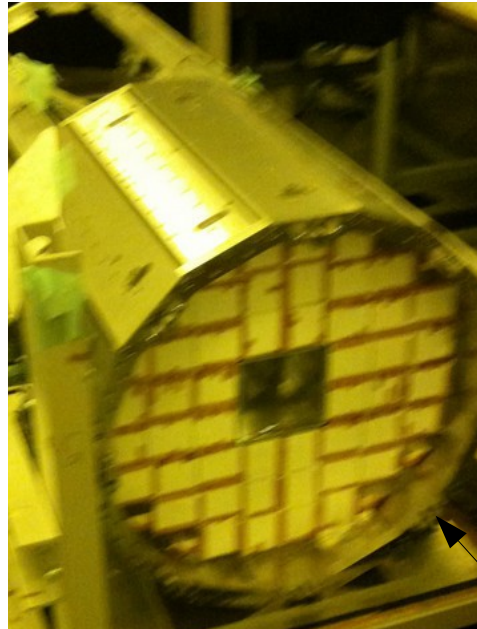
## Veto detectors

Decay Modes	Branching Fraction
$K_L \rightarrow \pi^0 \nu \bar{\nu}$	$(2.4 \pm 0.4) \times 10^{-11}$
$K_L \rightarrow \pi^\pm e^\mp \nu$	$(40.55 \pm 0.11) \%$
$K_L \rightarrow \pi^\pm \mu^\mp \nu$	$(27.04 \pm 0.07) \%$
$K_L \rightarrow 3\pi^0$	$(19.52 \pm 0.12) \%$
$K_L \rightarrow \pi^+ \pi^- \pi^0$	$(12.54 \pm 0.05) \%$
$K_L \rightarrow 2\pi^0$	$(8.64 \pm 0.06) \times 10^{-4}$
$K_L \rightarrow 2\gamma$	$(5.47 \pm 0.04) \times 10^{-4}$



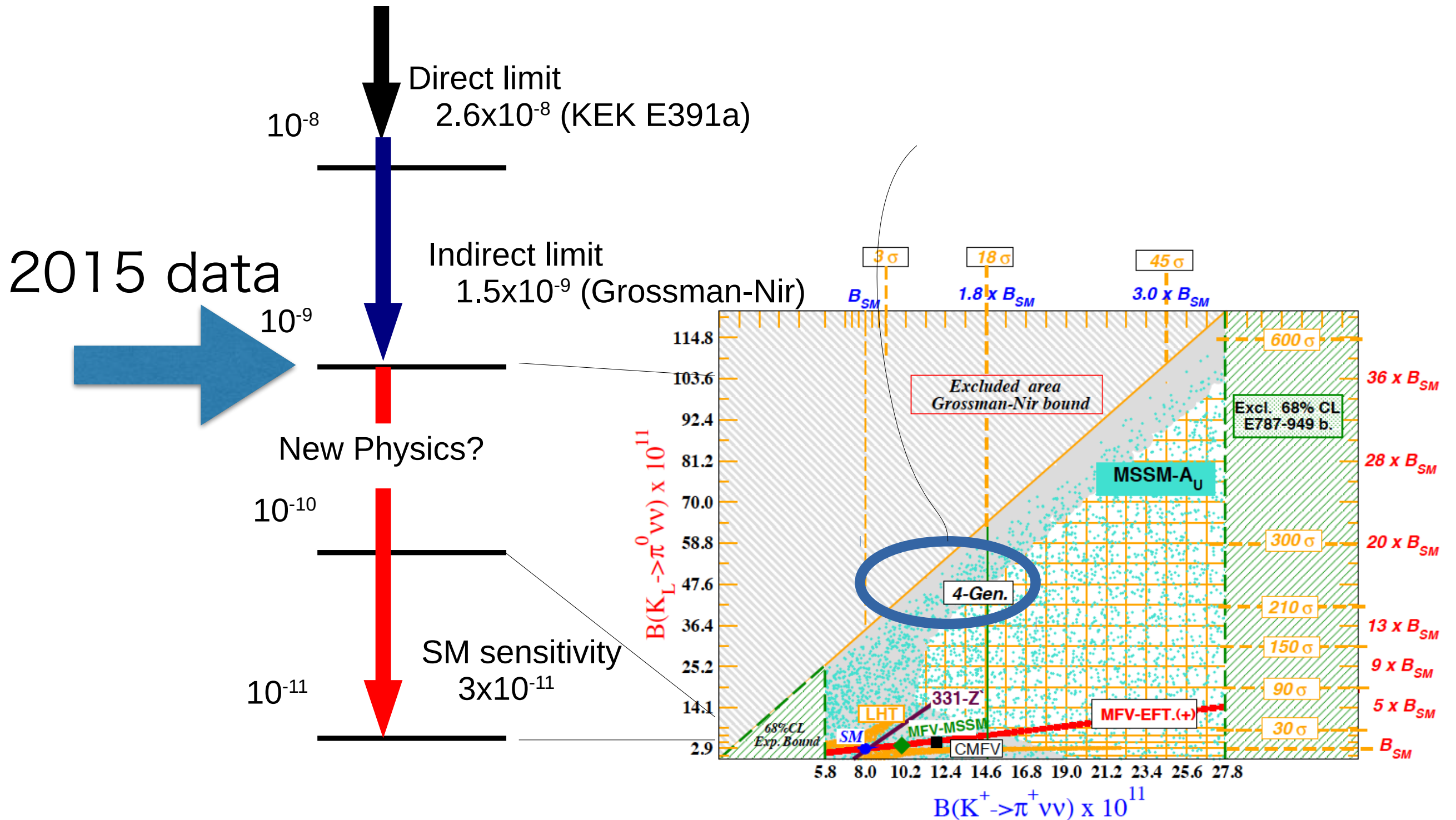
# Detector

Veto :  $\gamma$ /charged  
 $10^{-4} - 10^{-6}$  reduction





# Status



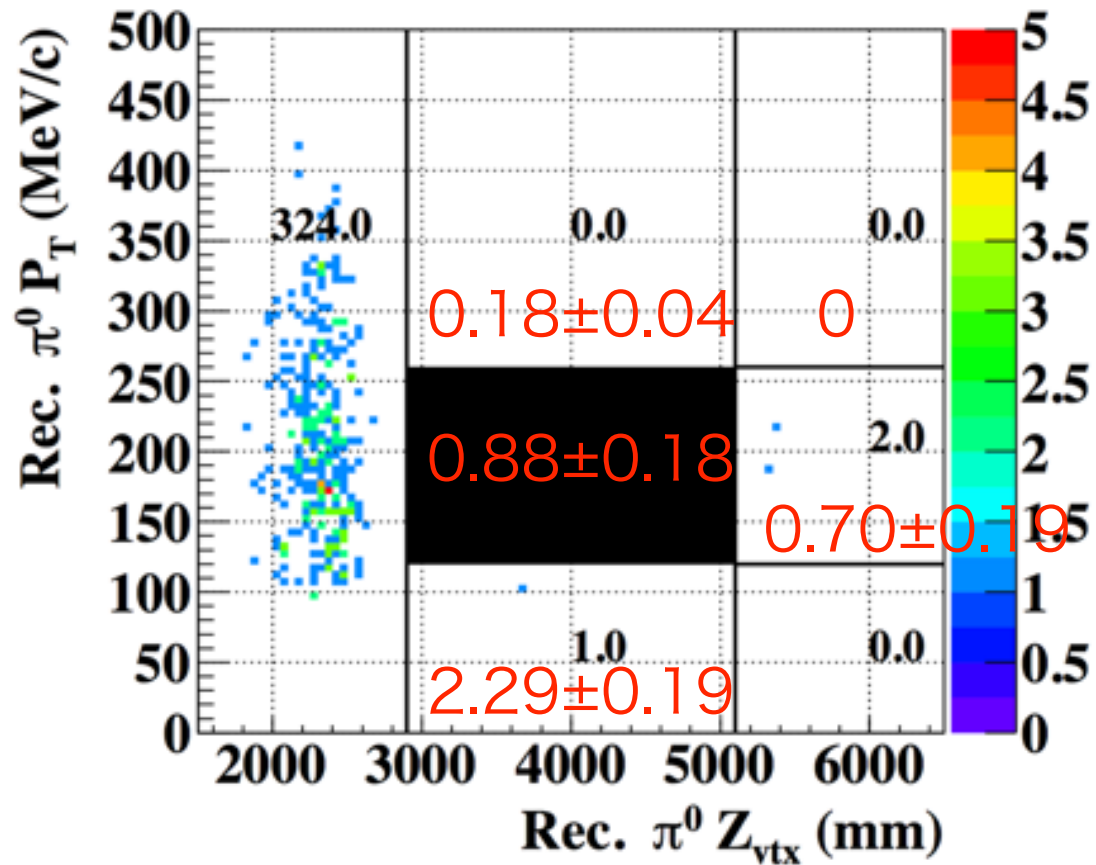
June 2010 by F. Mescia & C. Smith

<http://www.Inf.infn.it/wg/vus/content/Krare.html>

# 解析状況

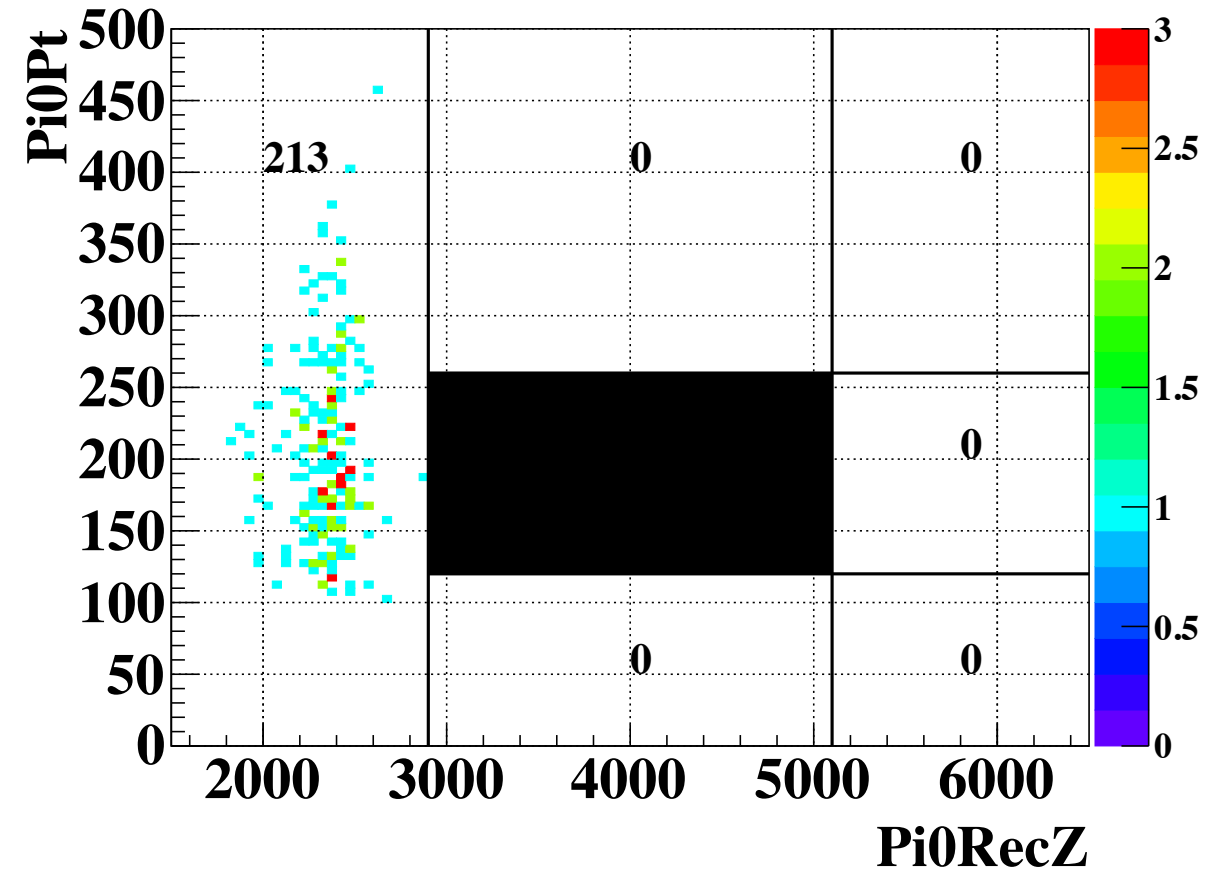
2015Data

Sensitivity :  $1.2 \times 10^{-9}$



2017Data

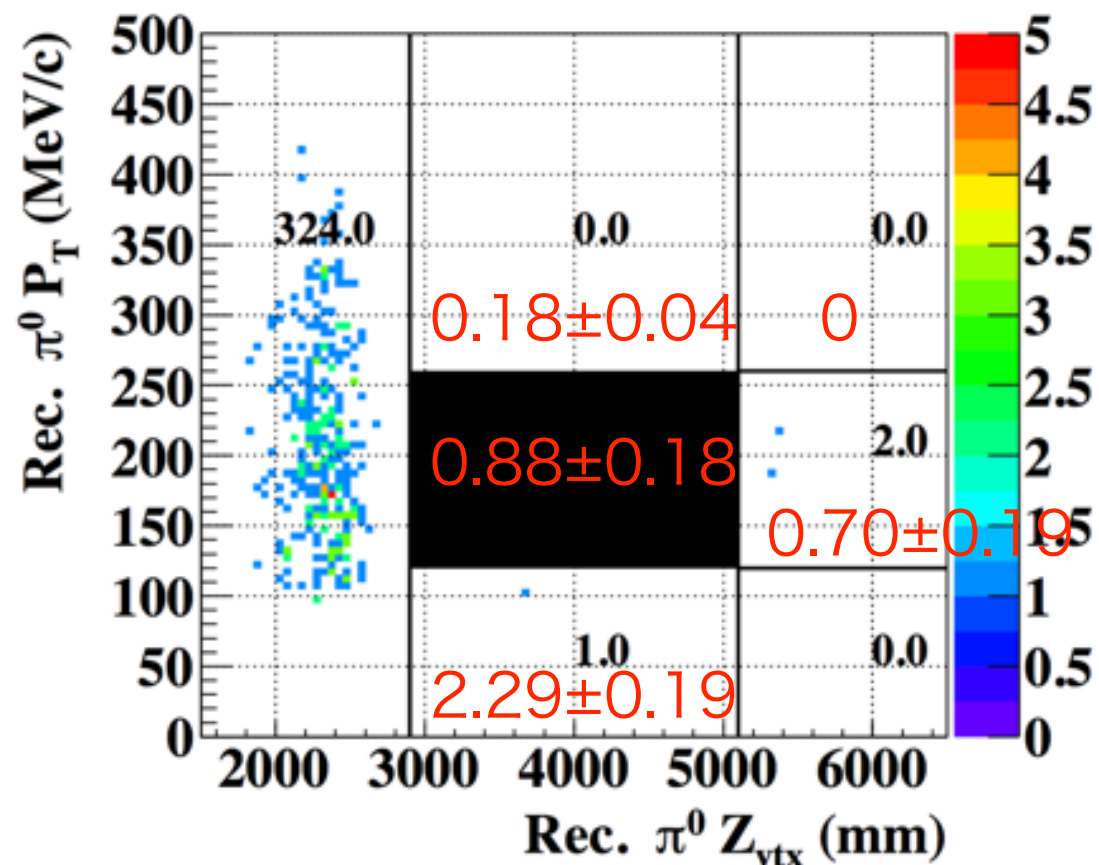
Sensitivity :  $1.7 \times 10^{-9}$



- 2015 Data : Will open box before June 2018

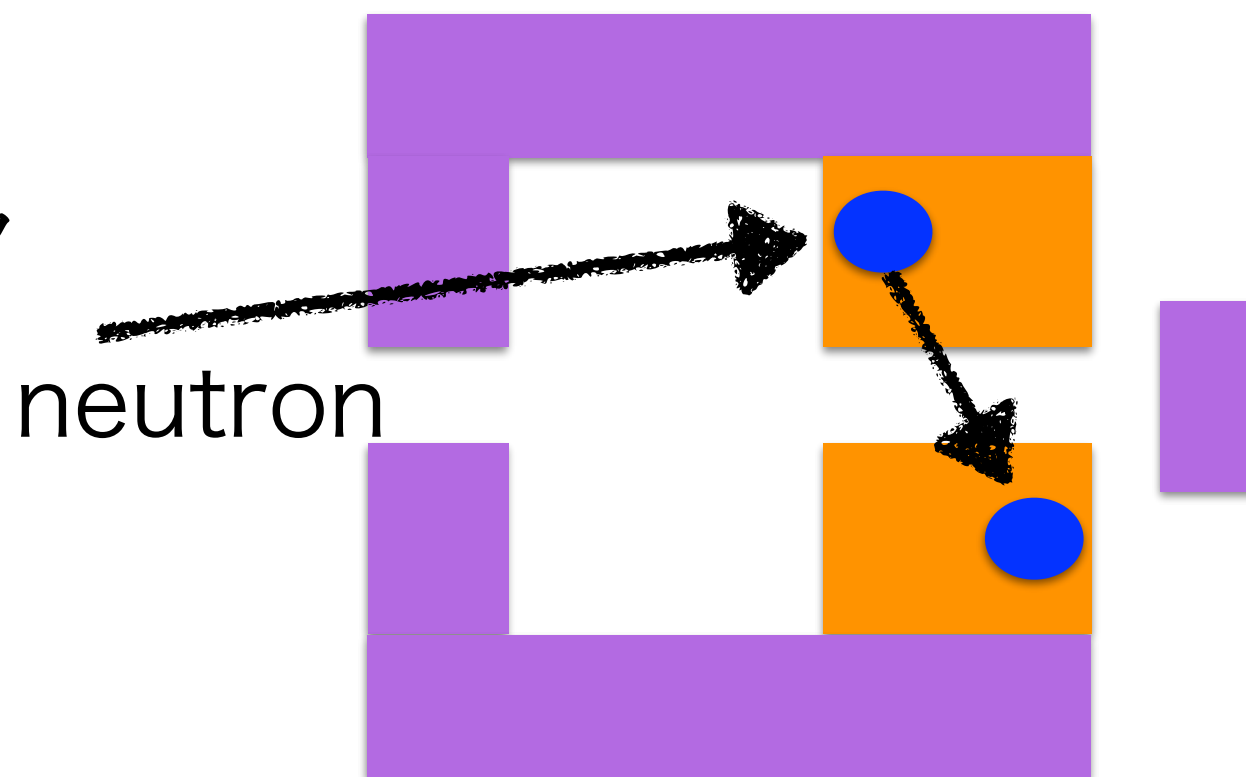
# 解析状況

2015Data



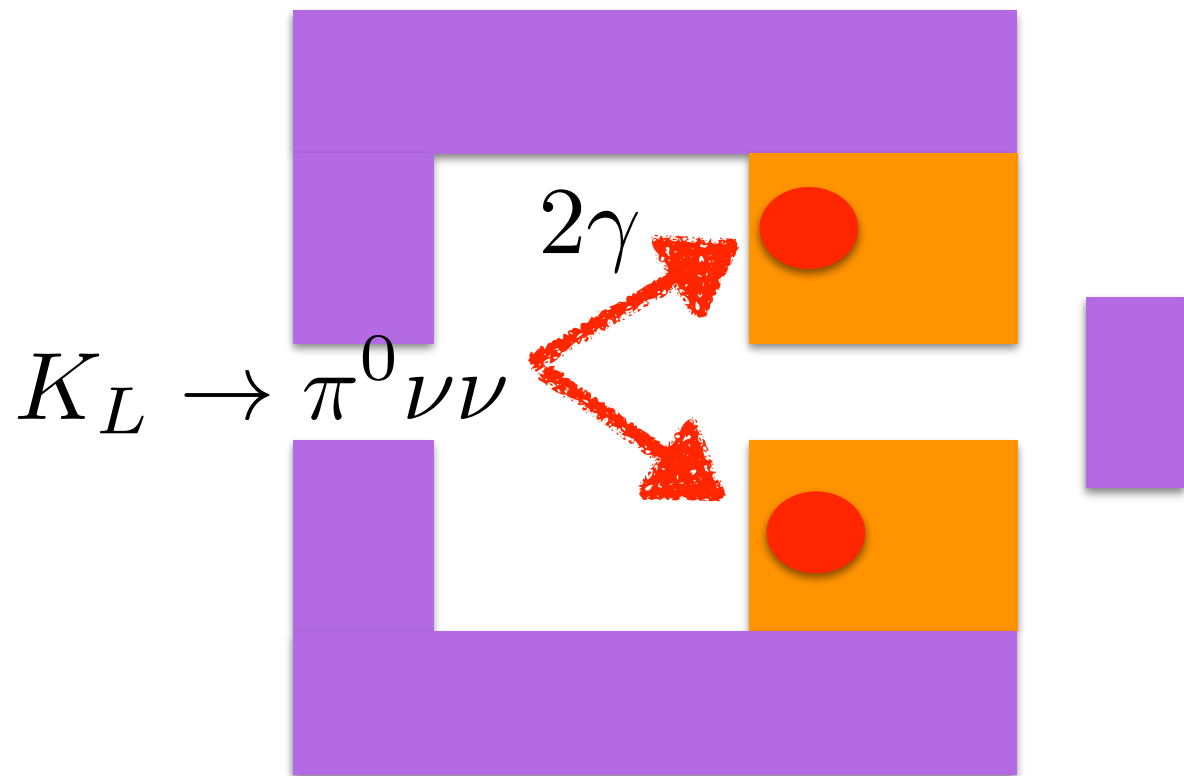
	New
KL->2pi0	$0.07 \pm 0.07$
KL->pi+pi-pi0	$0.18 \pm 0.05$
NCC	$0.13 \pm 0.07$
Hadron cluster	$0.26 \pm 0.08$
CV-pi0	$< 0.14$
CV-eta	0.05
KL->2gamma	$0.02 \pm 0.02$
KL->3pi0 fast	$< 0.01$
Masking Ke3	$< 0.094$
Masking K3pi0	$0.17 \pm 0.12$
Sum	$0.88 \pm 0.18$

- 最大の背景事象
  - ハドロンクラスタ

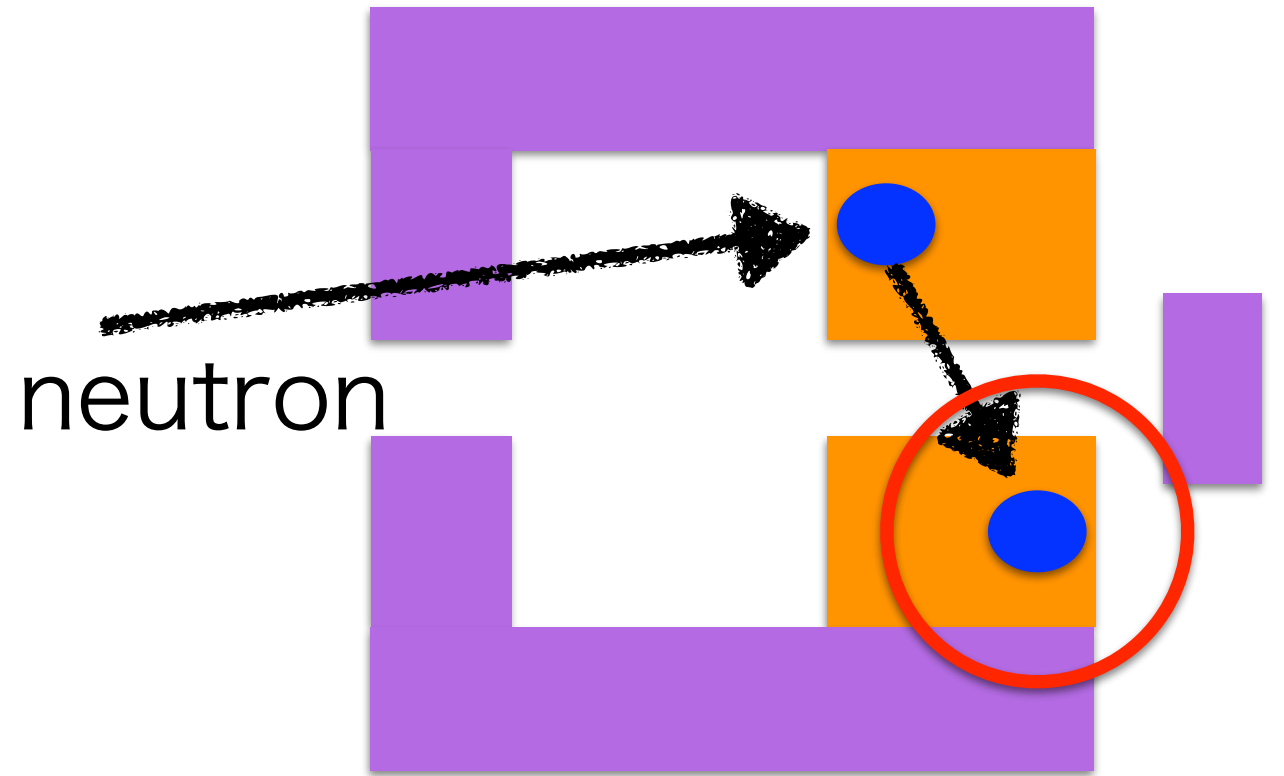


# 信号・背景事象

Signal

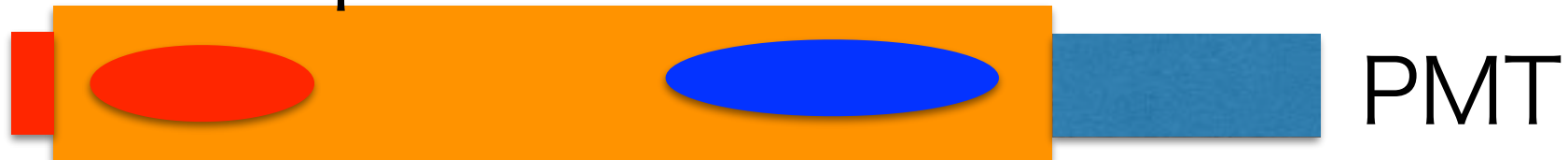


Background



undoped CsI : 50cm

MPPC



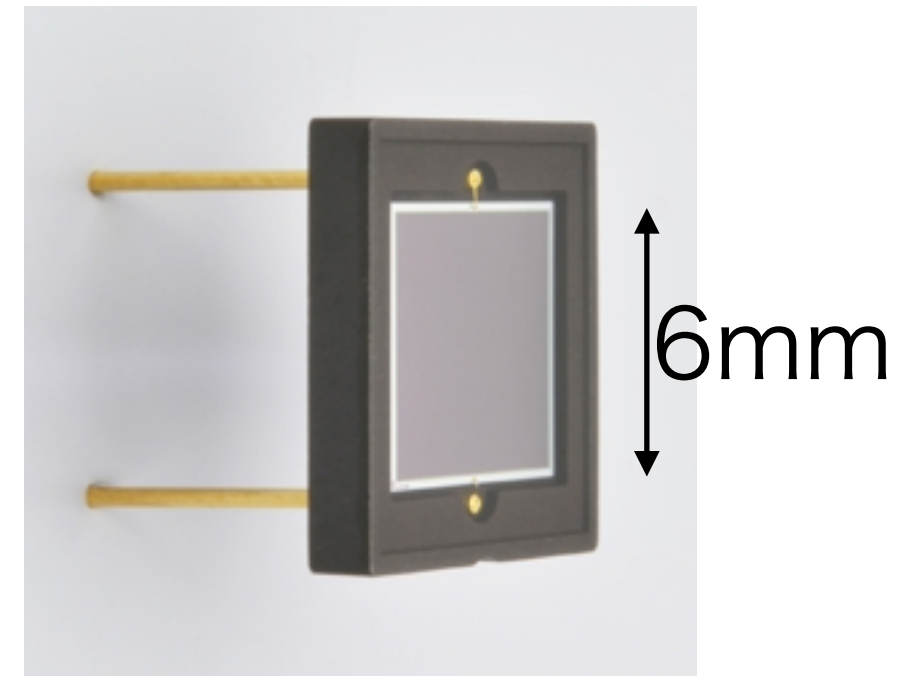
Timing difference ( $\Delta T = T_{\text{MPPC}} - T_{\text{PMT}}$ )

$$\Delta T(\gamma) < \Delta T(n)$$

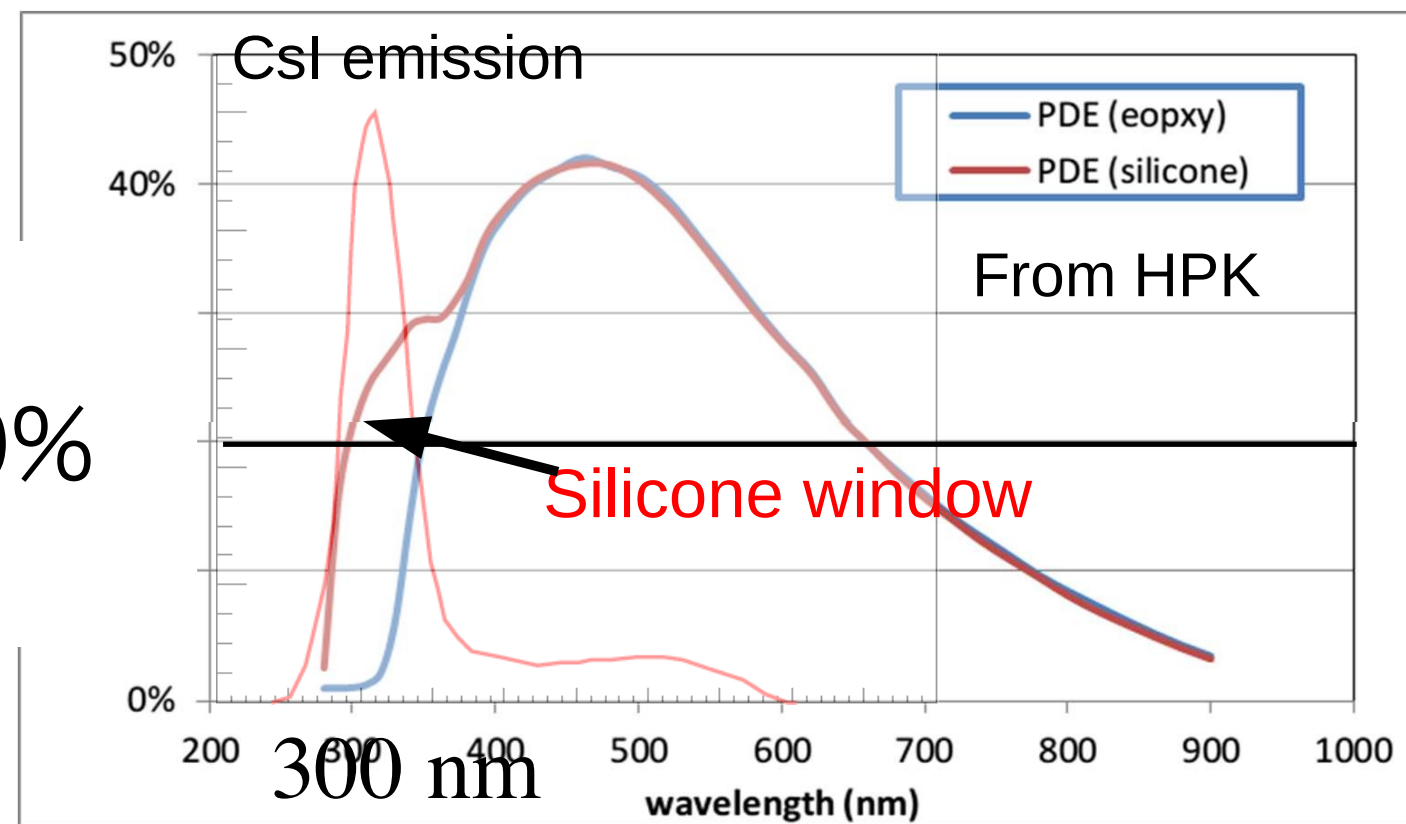


# MPPC

- 半導体光センサ
  - 低物質質量 (0.02X<sup>0</sup>)
- シリコン窓 : UV sensitive
- 6mm角 + 50 $\mu$ m角ピクセル
  - ピクセル数: 14,400
  - Gain :  $1.7 \times 10^6$
  - Dark rate 2-6MHz



PDE 20%

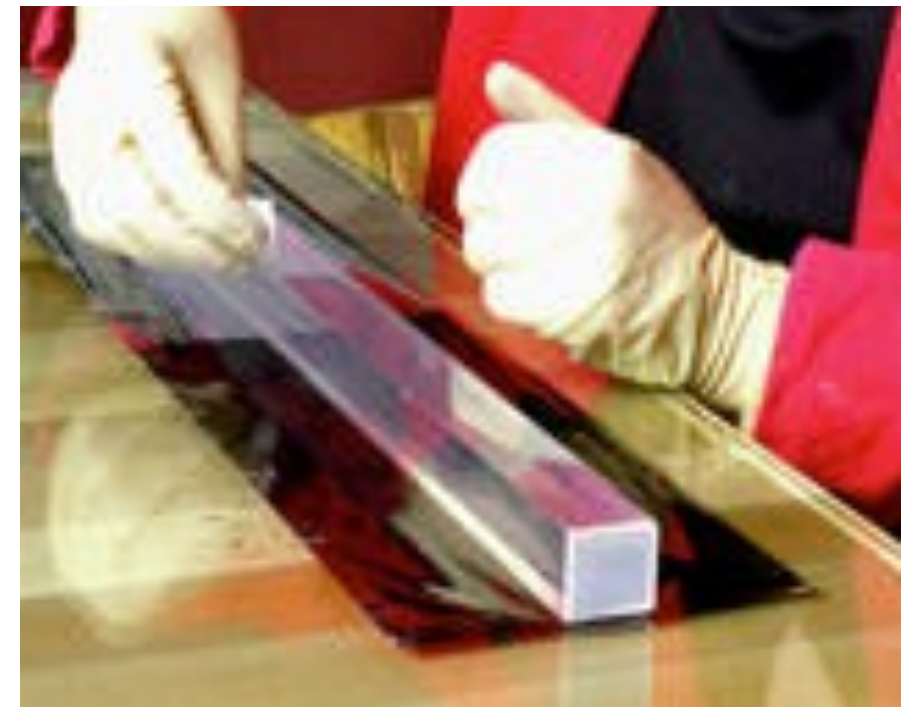
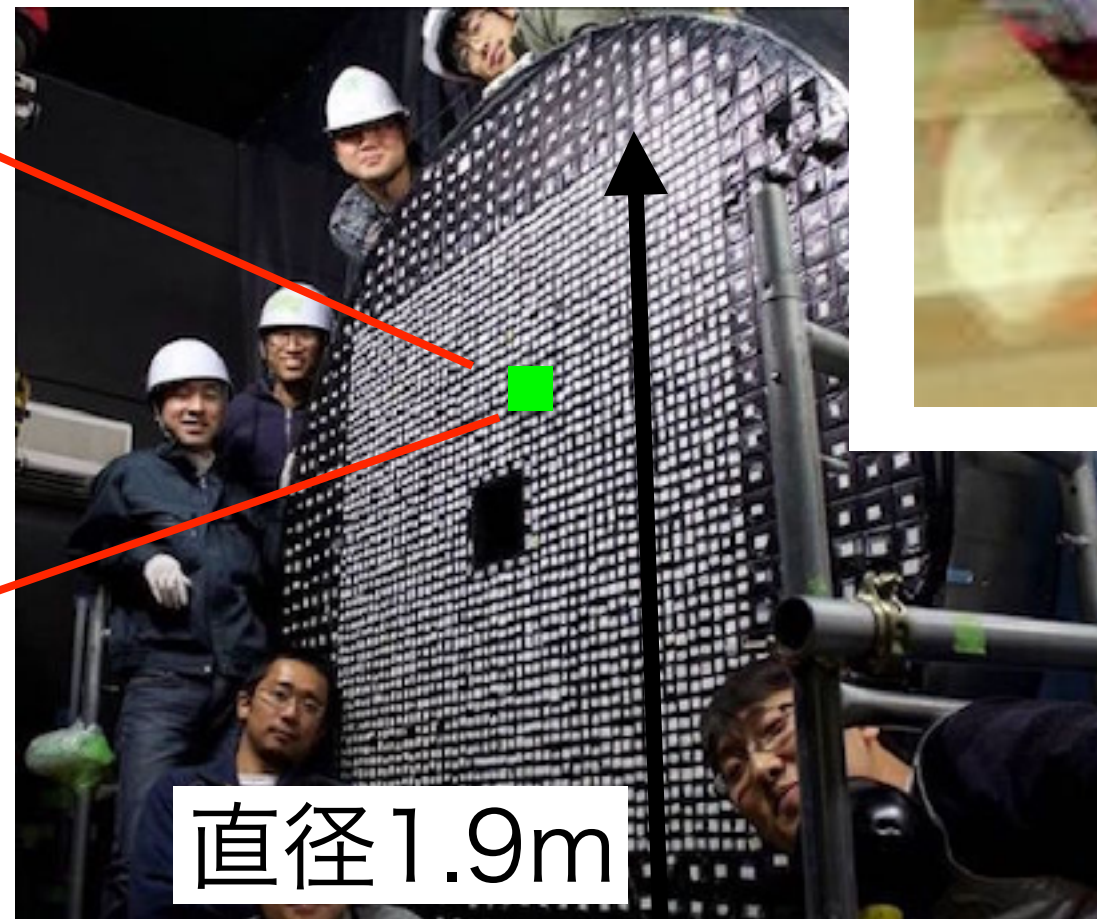
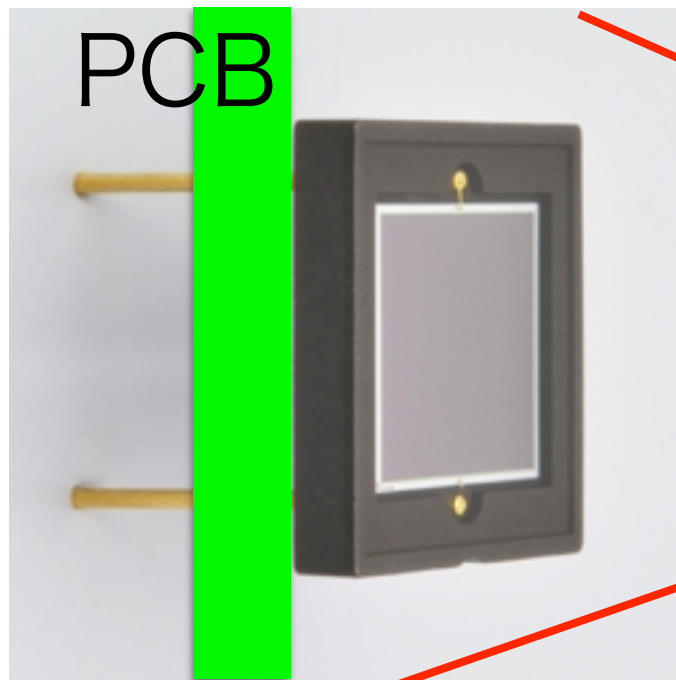


# カロリメータアップグレード

結晶 2.5cm角(2240個) + 5cm角(476個)

6mm角 MPPC 1個 4個

4096 MPPCs



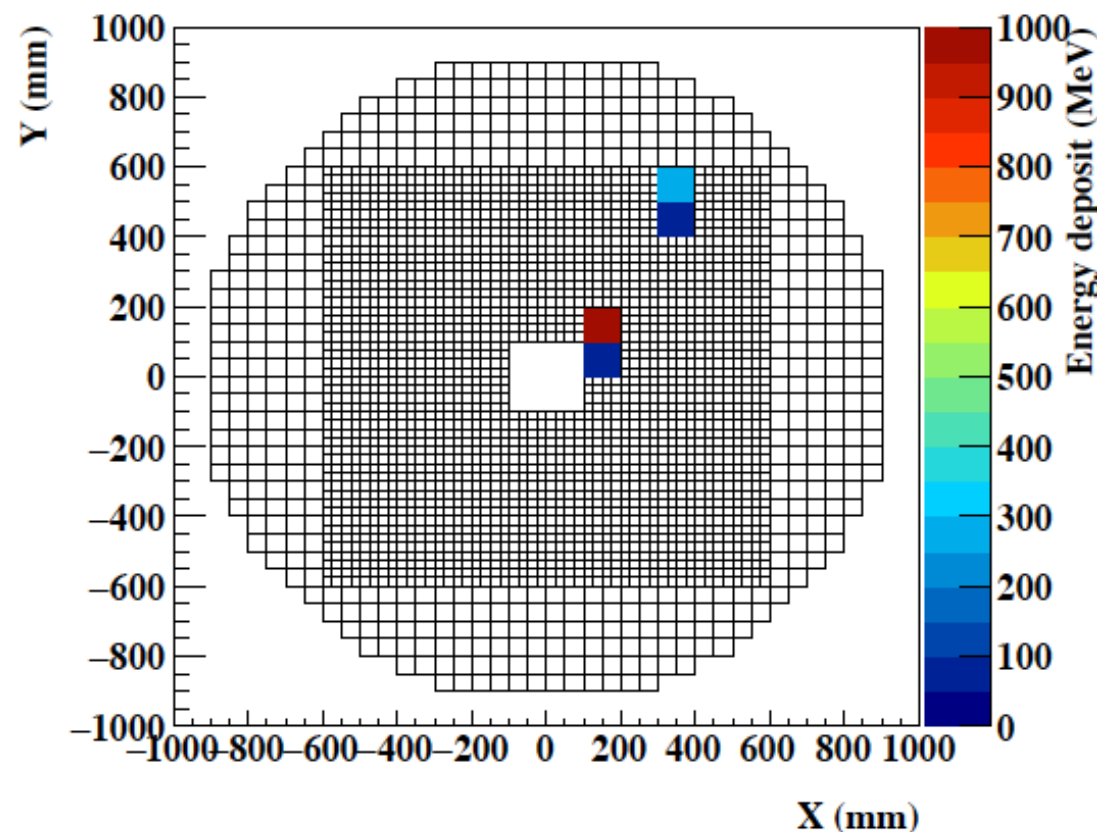
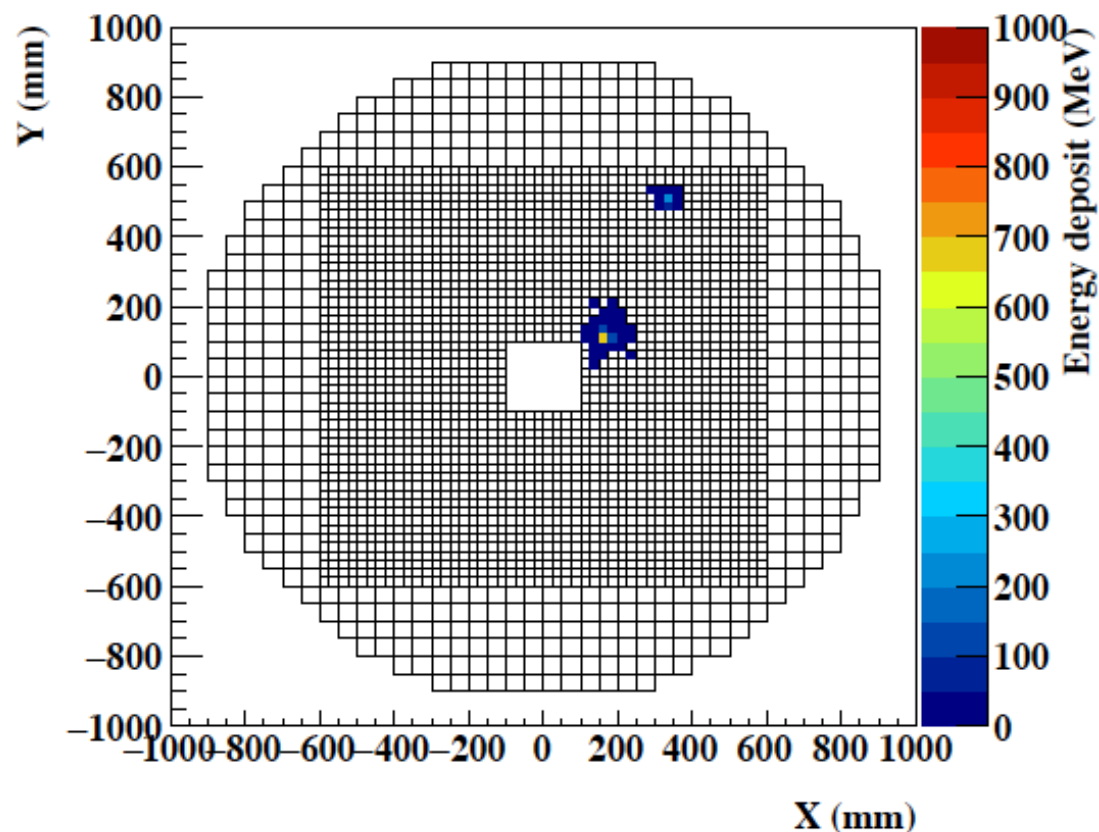
Vacuum

# グループ読み出し

- 10cm × 10cm領域 → 読み出しチャンネル数256
- モリエール長 ~3.5cm
  - PMT読み出し：エネルギーと微細構造
  - MPPC読み出し：時間差 → 深さ方向位置

Display :  $\pi^0\nu\nu$  : crystal energy >3MeV

10cm x 10cm group energy >50MeV





# カロリメータアップグレード

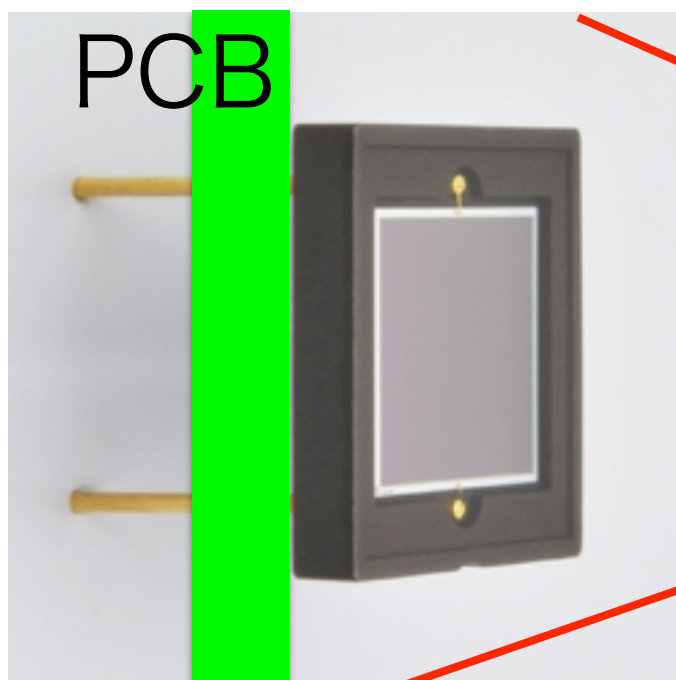
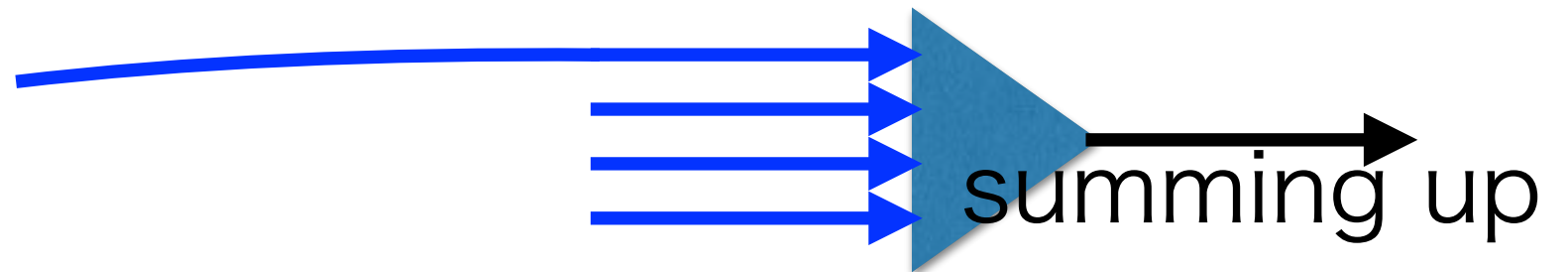
4096 MPPCs

1024 cables

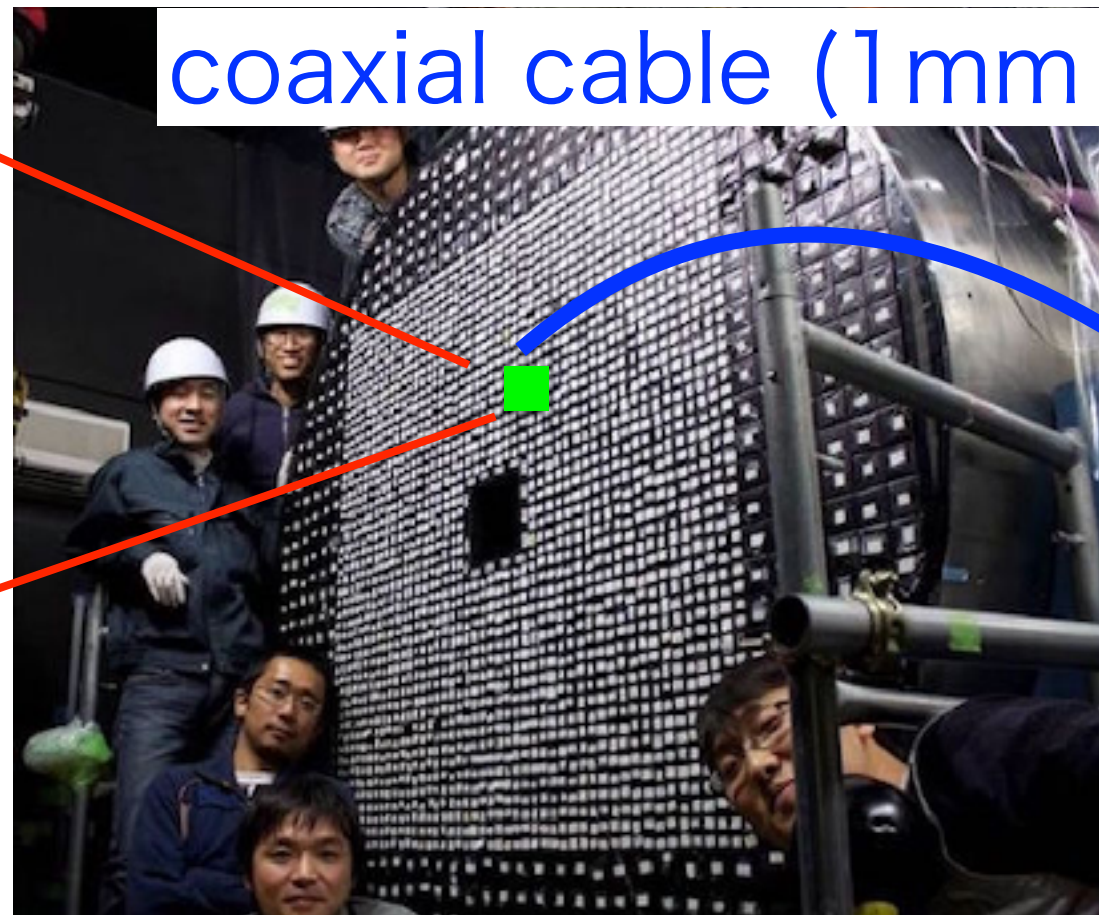
256 Amps->ADC



4-MPPC  
connection



coaxial cable (1mm  $\phi$ )



Amp  
Controller

Vacuum

読み出し: 10cm角領域→256チャンネル

125MHz ADC

# 性能評価 (実験)

$\gamma$  /neutron beam

@RCNP

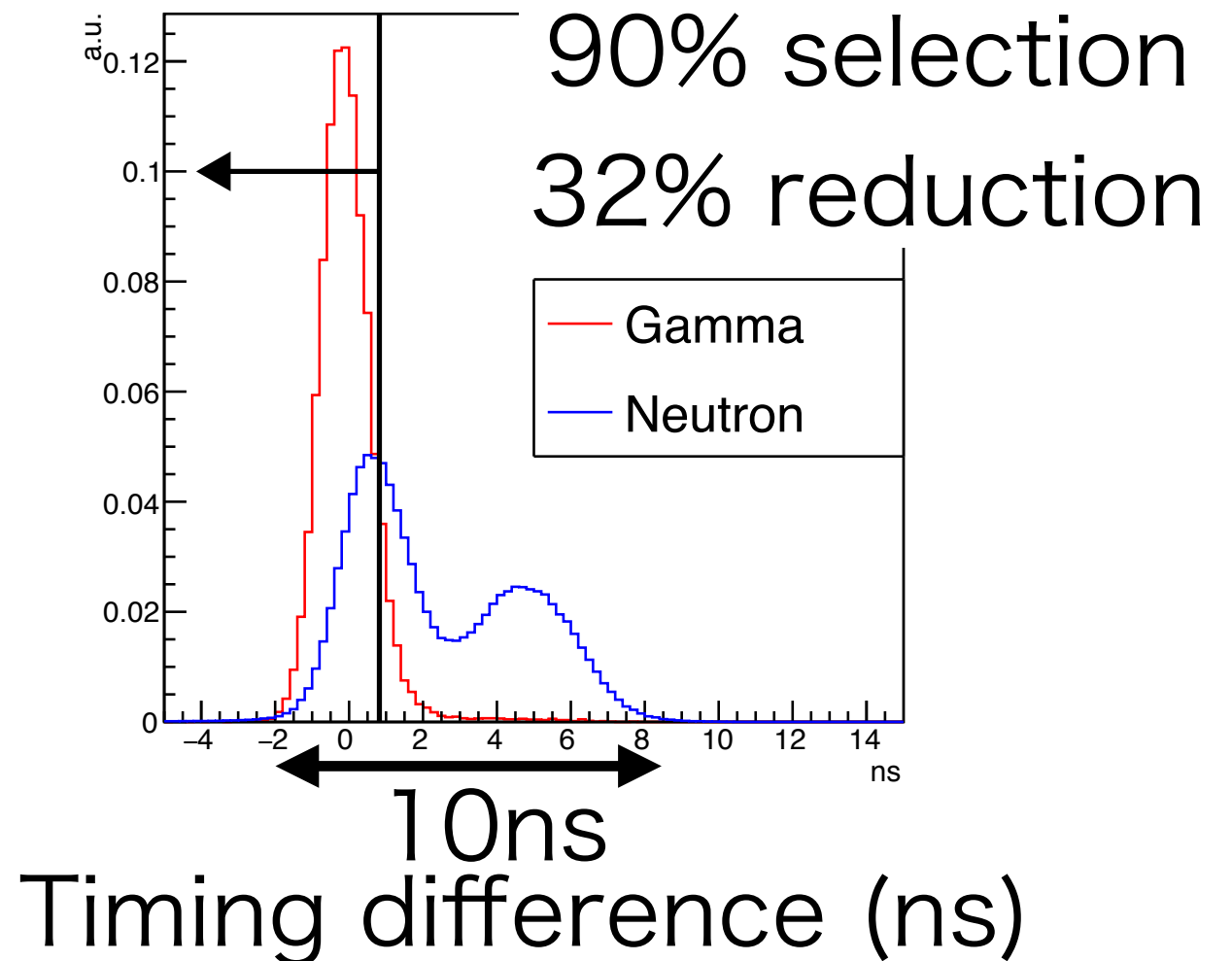
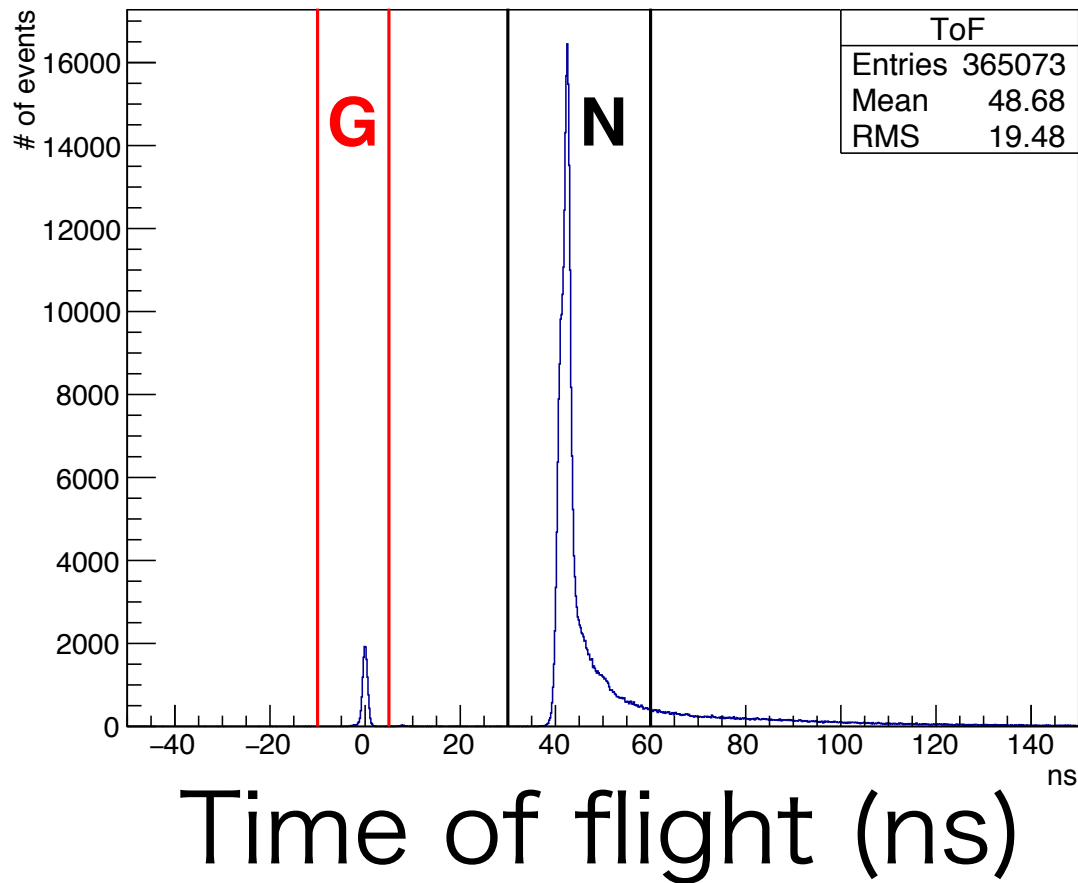
pulse beam

proton

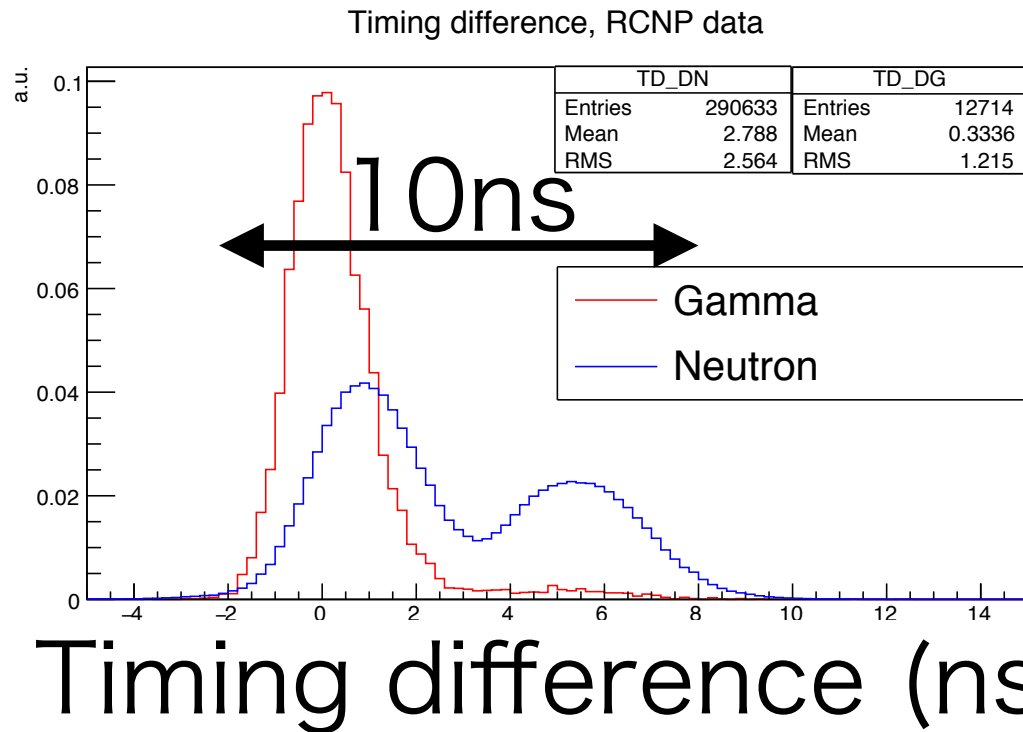
neutron (~400MeV) undoped CsI : 50cm



Observed  $\gamma$  /neutron timing difference

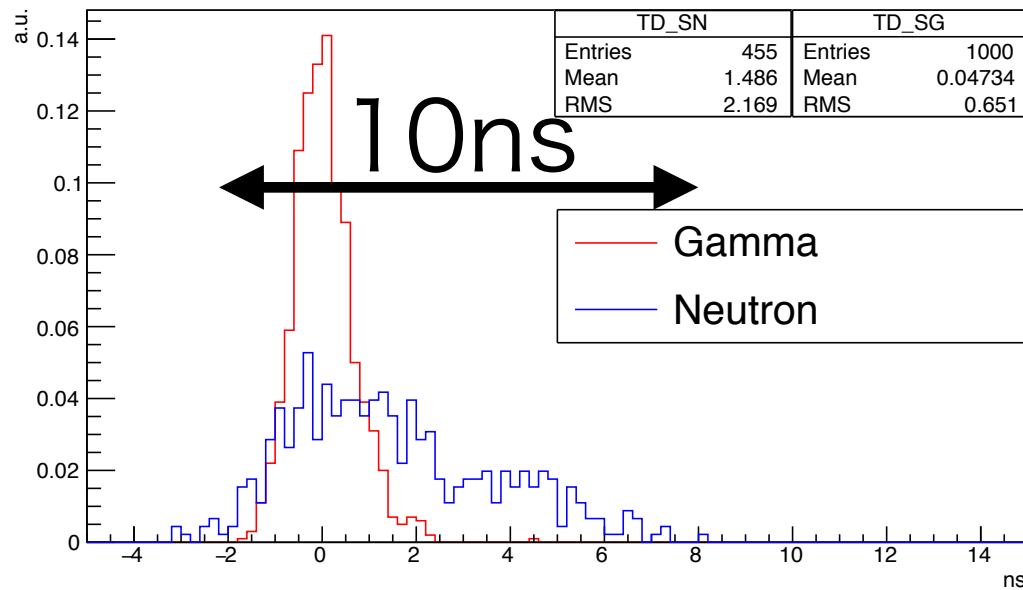


# Simulation

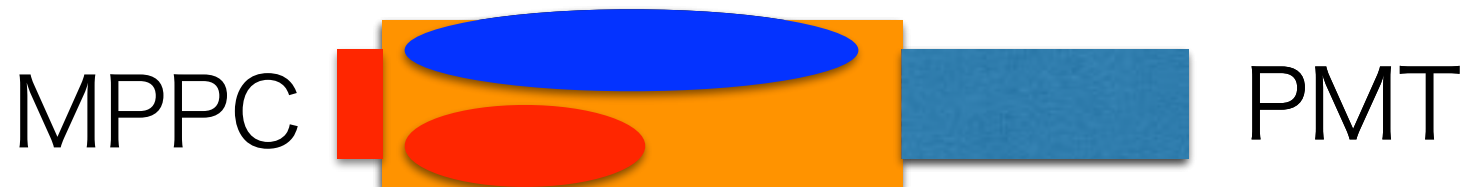


Data

Reproducibility

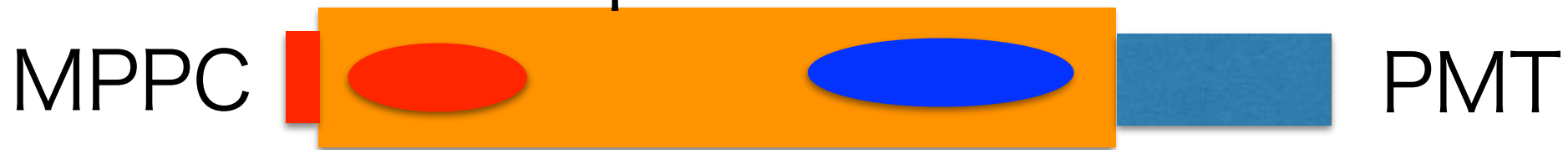
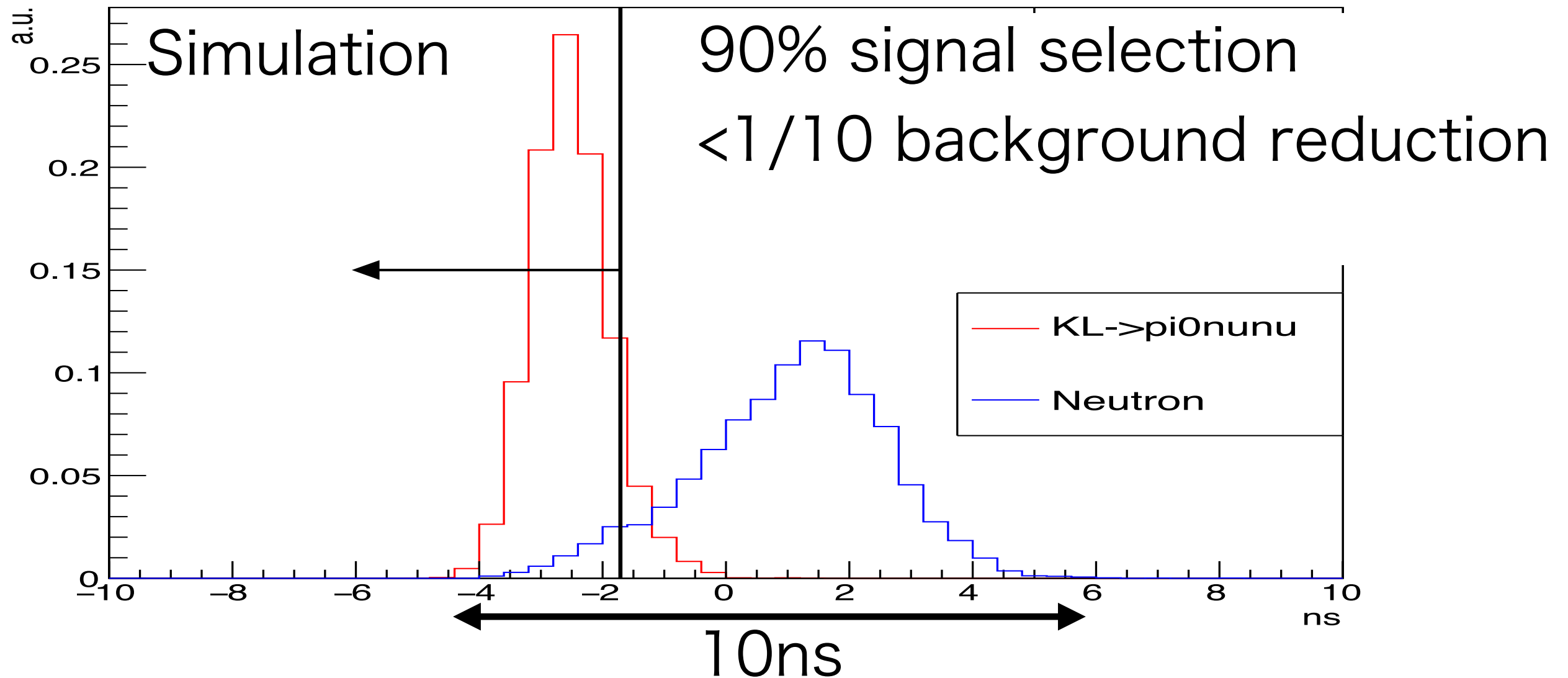


Simulation





# 削減能力 (Simulation)



# カロリメータアップグレード

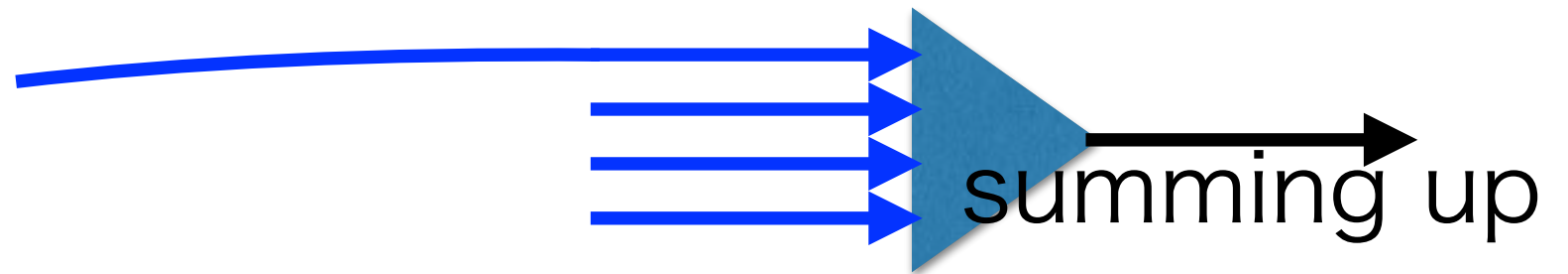
4096 MPPCs

1024 cables

256 Amps->ADC



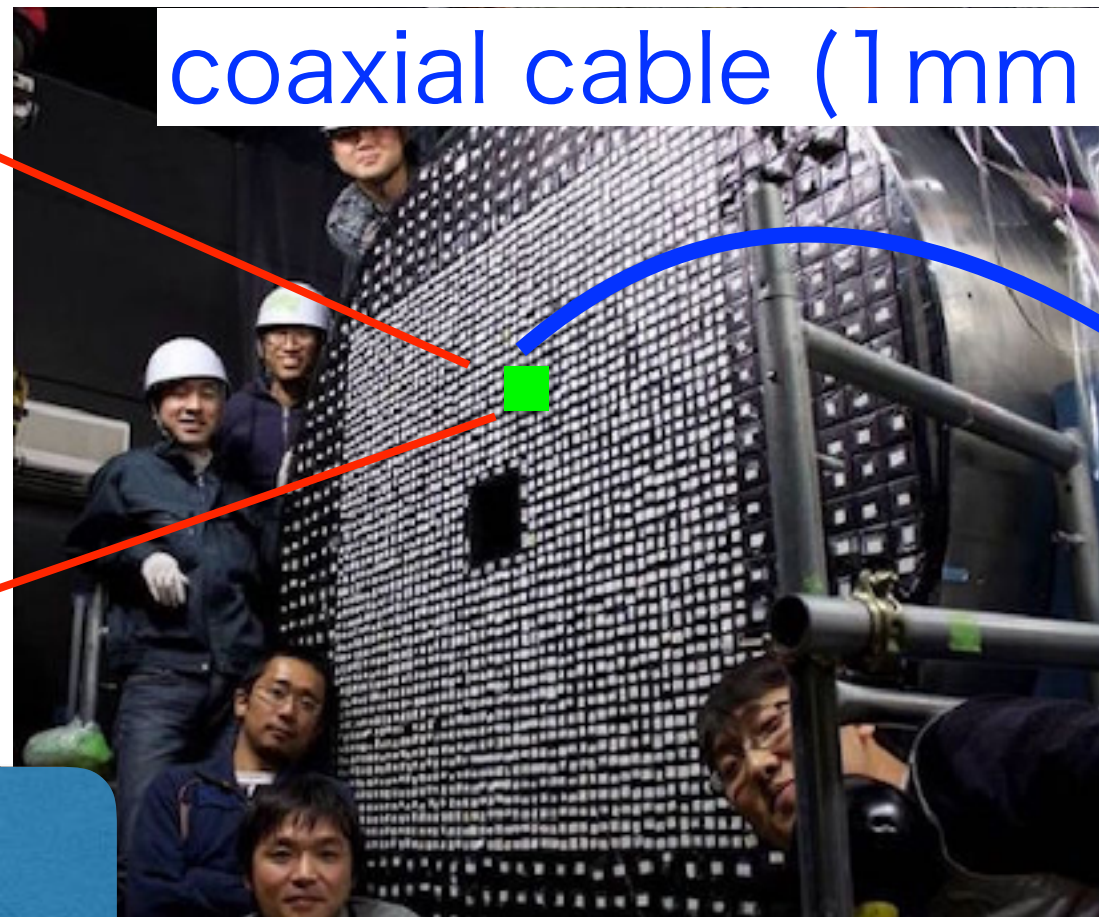
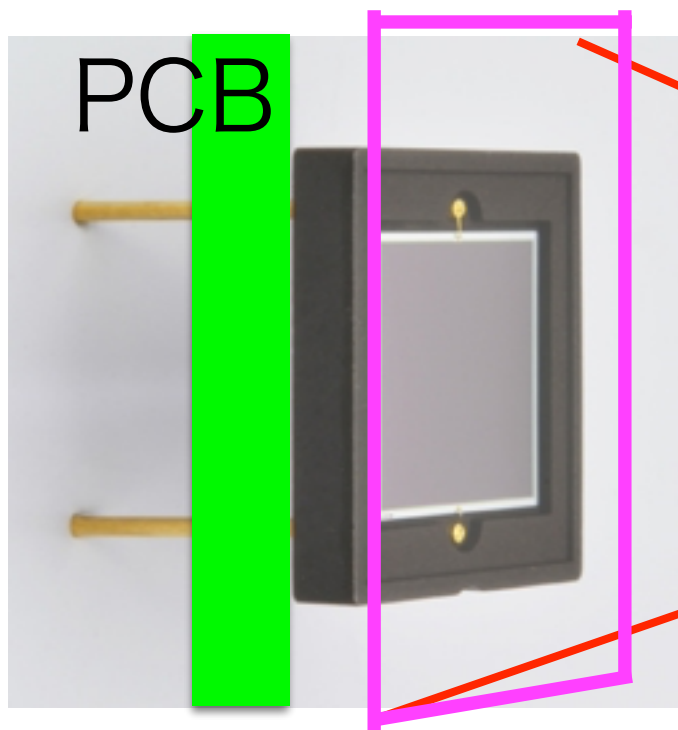
4-MPPC  
connection



quartz plate

coaxial cable (1mm  $\phi$ )

PCB



Amp  
Controller

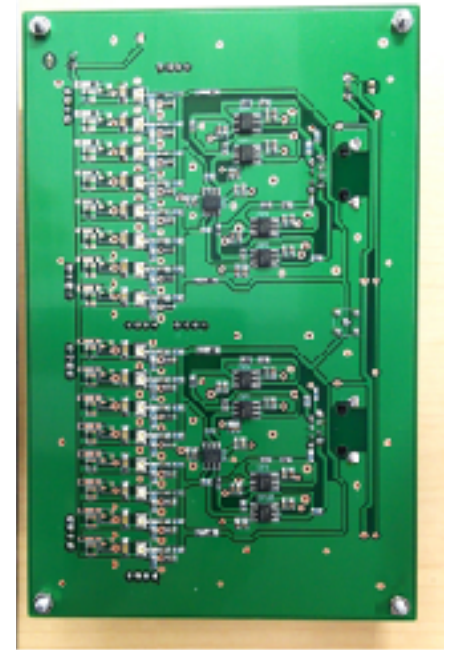
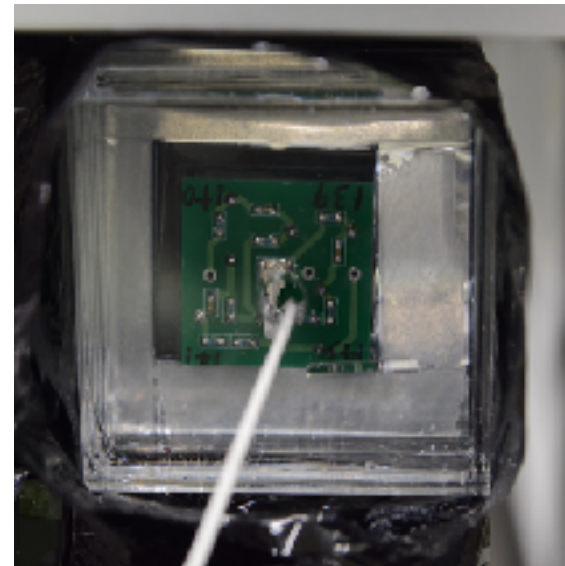
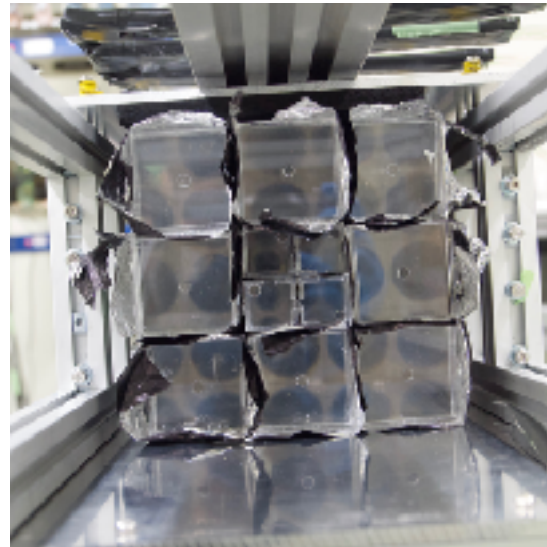
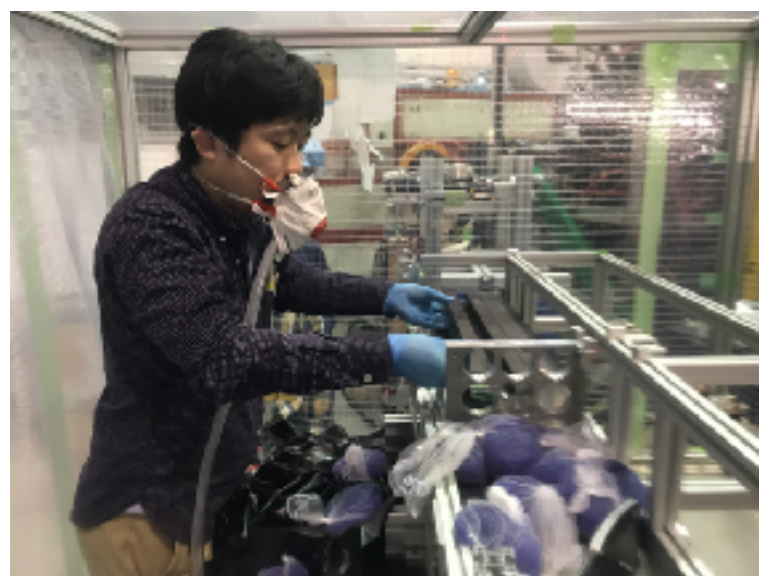
Vacuum

中性子フルエンス  
 $10^9$  1MeV-n/cm<sup>2</sup>

125MHz ADC



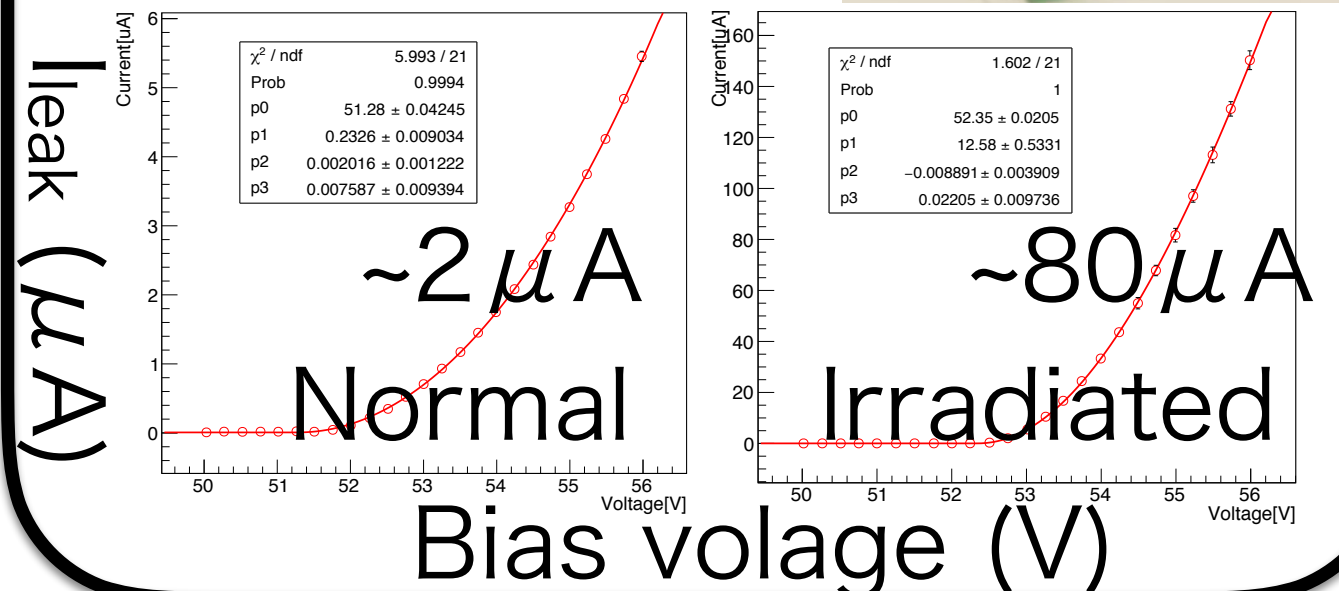
# Realistic setup with $e^+$ beam



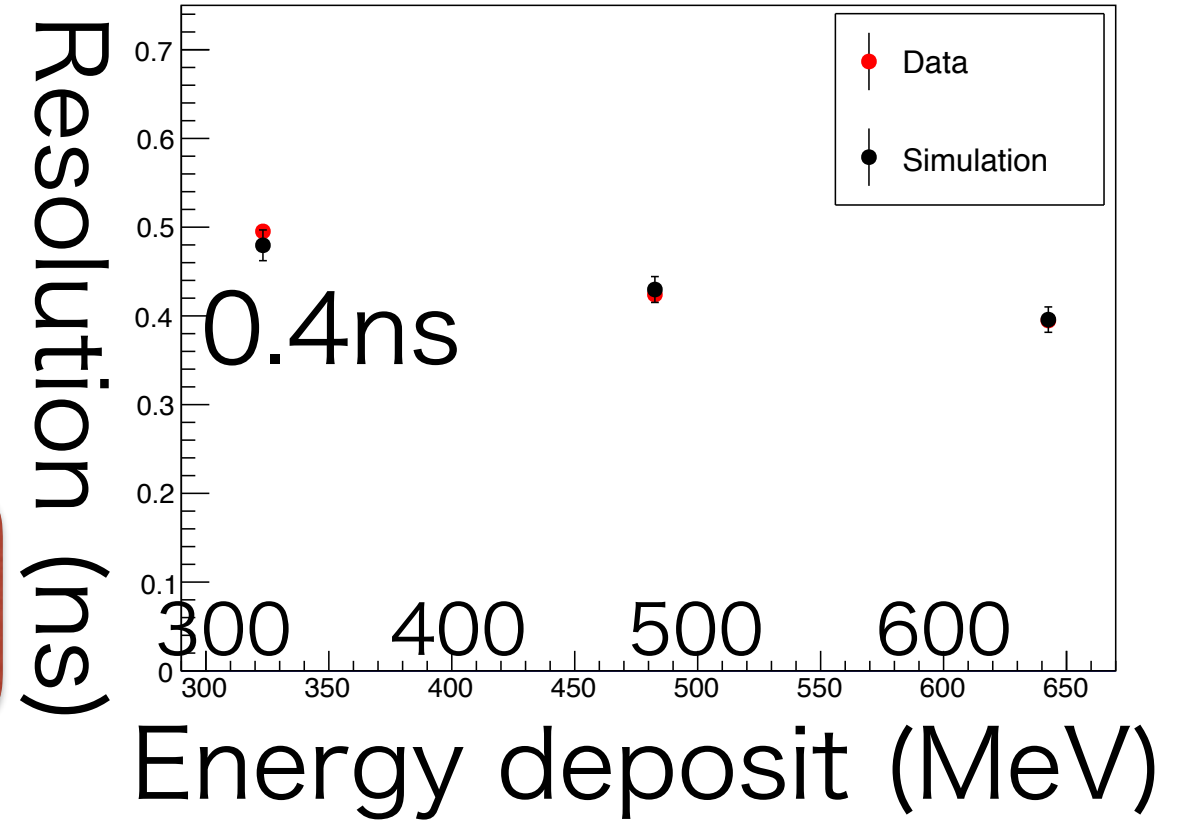
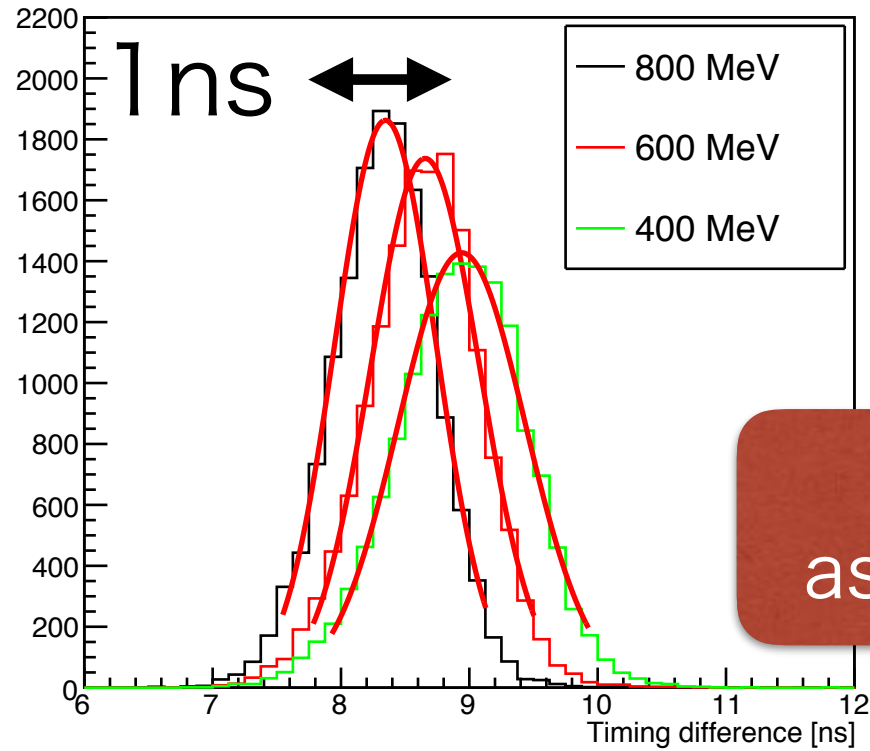
$e^+$  beam  
200-800 MeV/c



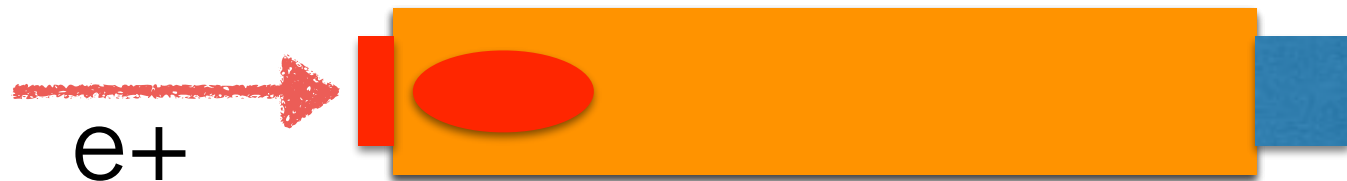
100kW x 3 snowmass year  
 $10^9 n_{eq}/cm^2$



# Results with $e^+$ beam

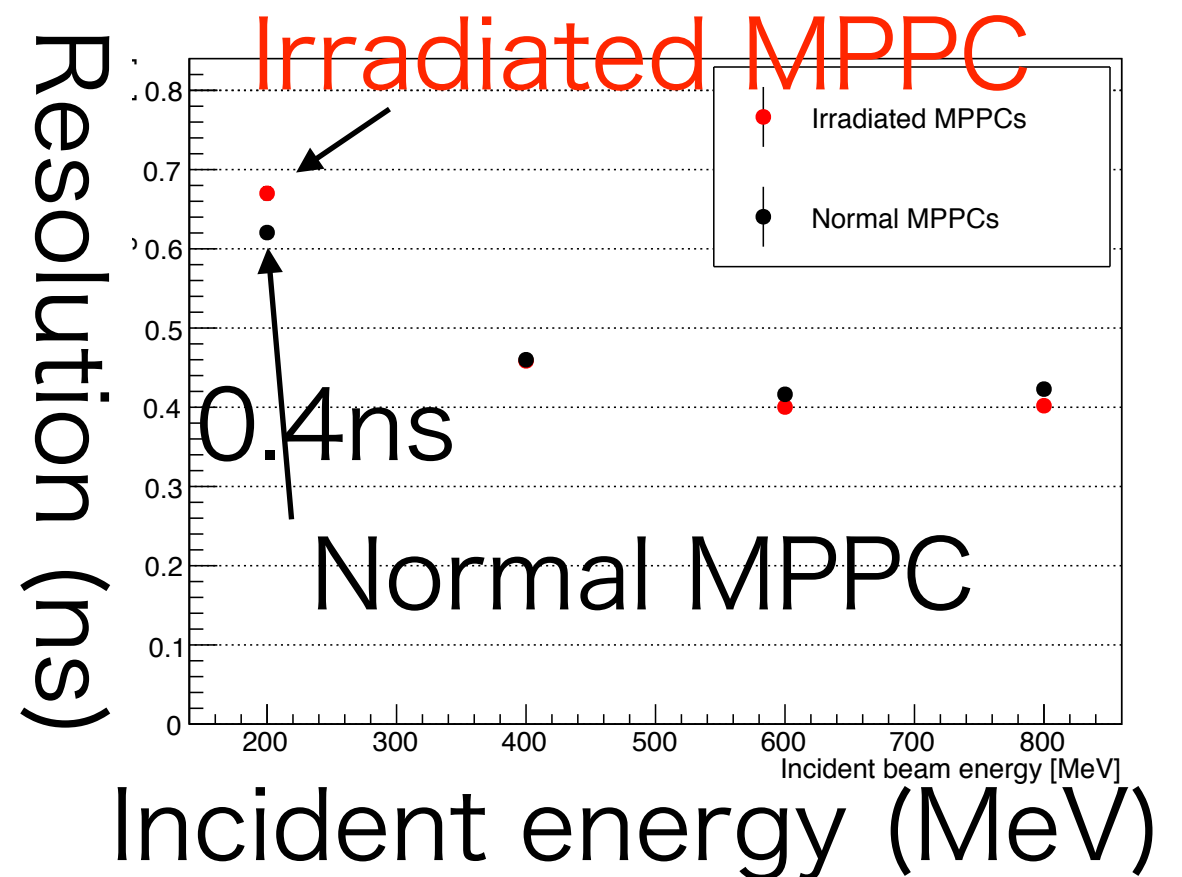


Timing difference (ns)



Works as expected

Irradiated MPPC works



# まとめと今後

- KOTO実験のカロリメータアップグレード
  - undoped CsI結晶
  - PMTとMPPCの両端読み出し
- 性能
  - 時間差分解能→背景事象削減 1/10
  - 放射線損傷→影響小
- 今後
  - 実機へのインストール 2018年 6月-12月
  - 新物理領域の探索

+HV

Readout

