

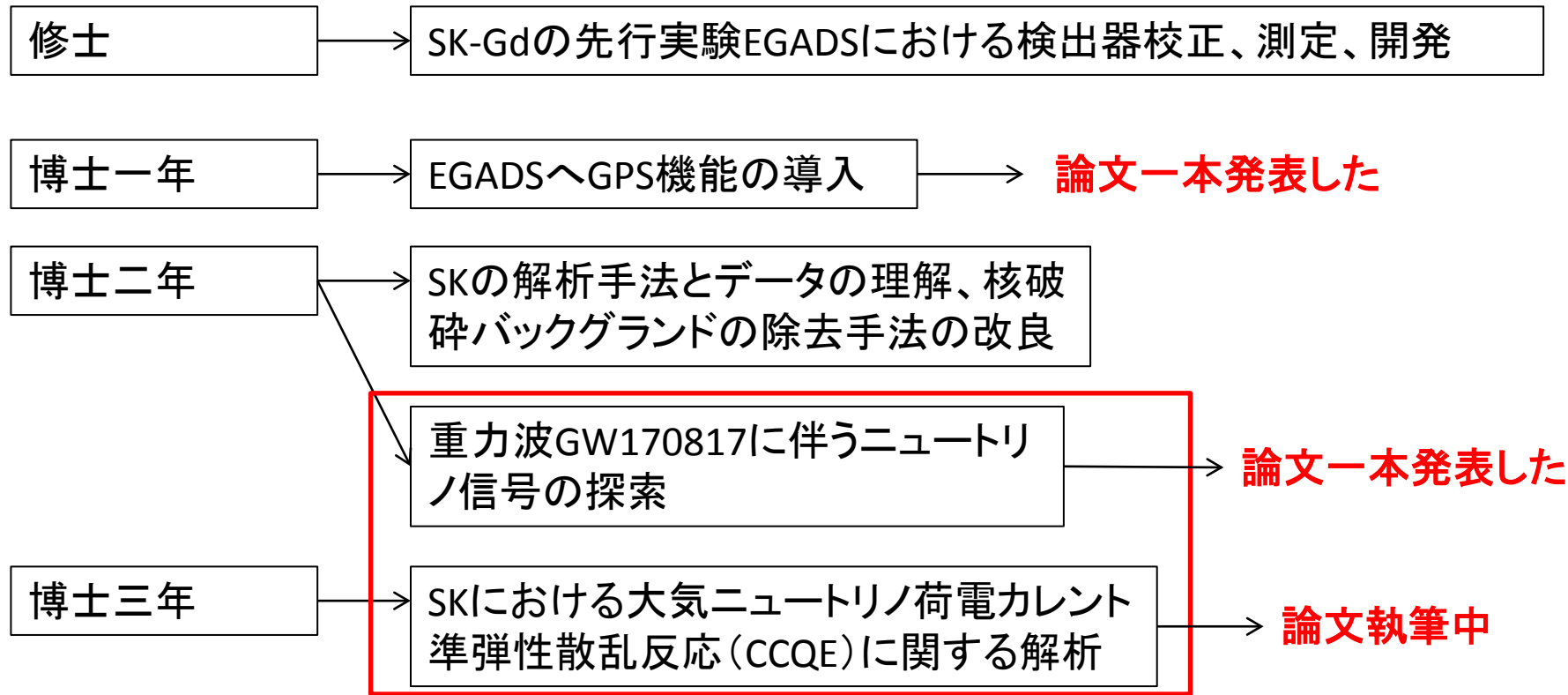
Search for astronomic neutrinos in Super-Kamiokande

岡山大学自然科学研究科

51428170 徐宸原

博士論文予備審査

これまでの研究



博士論文のテーマ

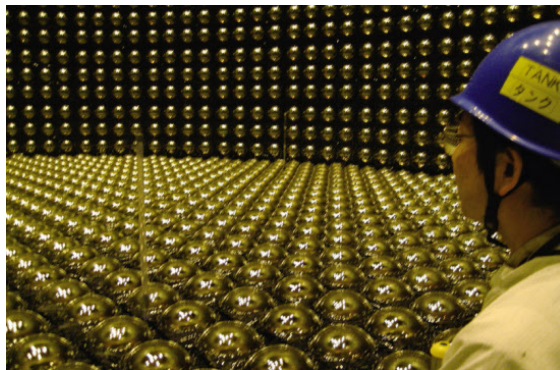
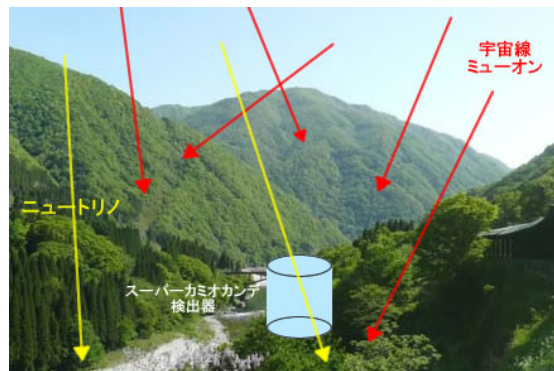
博士論文の目録

1. Physics Background
2. Super-Kamiokande Detector
3. Event Reconstruction
4. Simulation
5. Calibration
6. Data Set
7. Neutrino search associated with GW170817
8. De-excitation gamma search from CCQE reaction
9. Conclusion & Future

今日の流れ

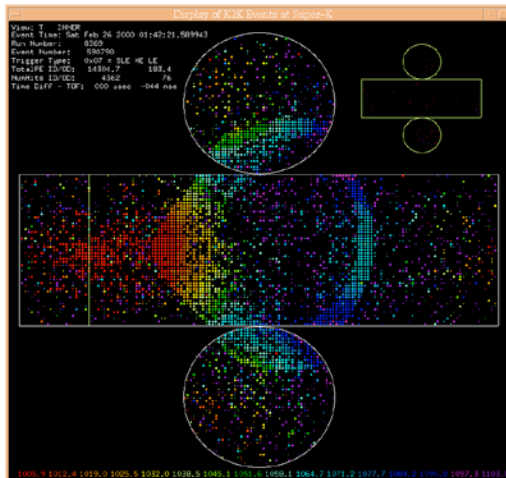
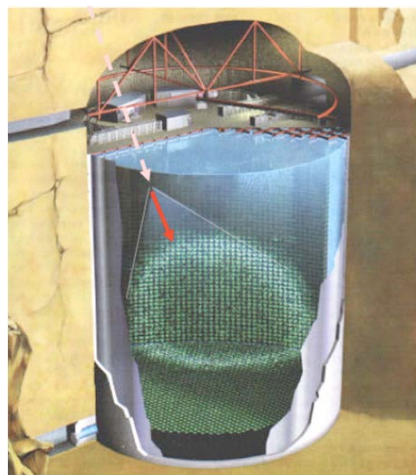
Super-Kamiokandeについて	10～15分
GW170817に伴うニュートリノ信号について	15～20分
脱励起ガンマ線探索について	5～10分

Super-KamiokaNDE



Key word :

1000m Underground
Water Cherenkov Detector
50kton pure water
22.5kton Fiducial Volume
11129 PMTs in Inner Detector



SK phase :

SK-I : 1996~2001

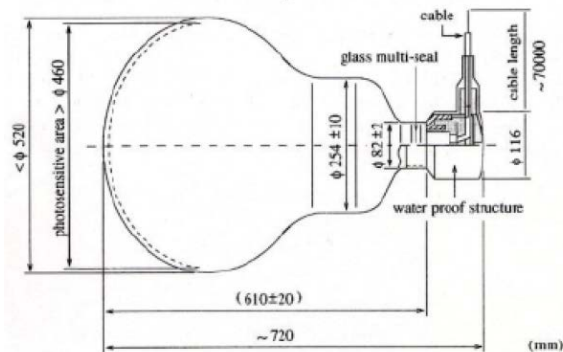
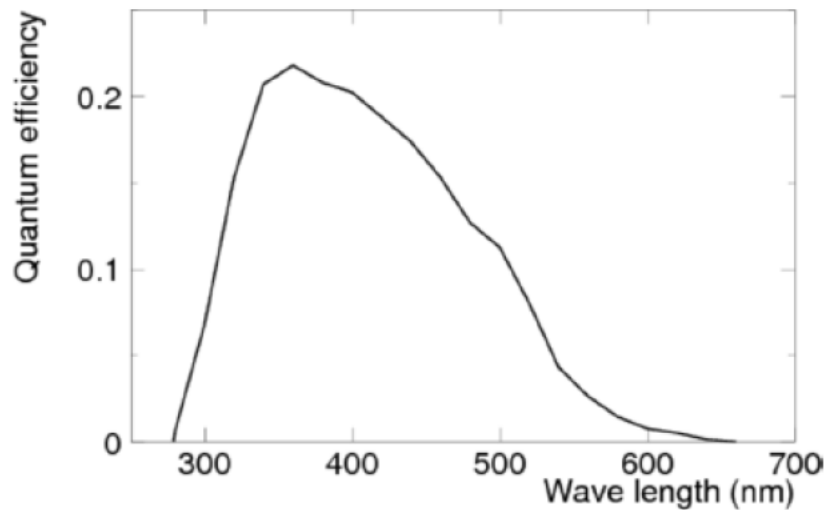
SK-II : 2002~2005

SK-III : 2006~2008

SK-IV : 2008~2018

SK-Gd : Coming Soon !

光電子増倍管(Photon Multiplier Tube)



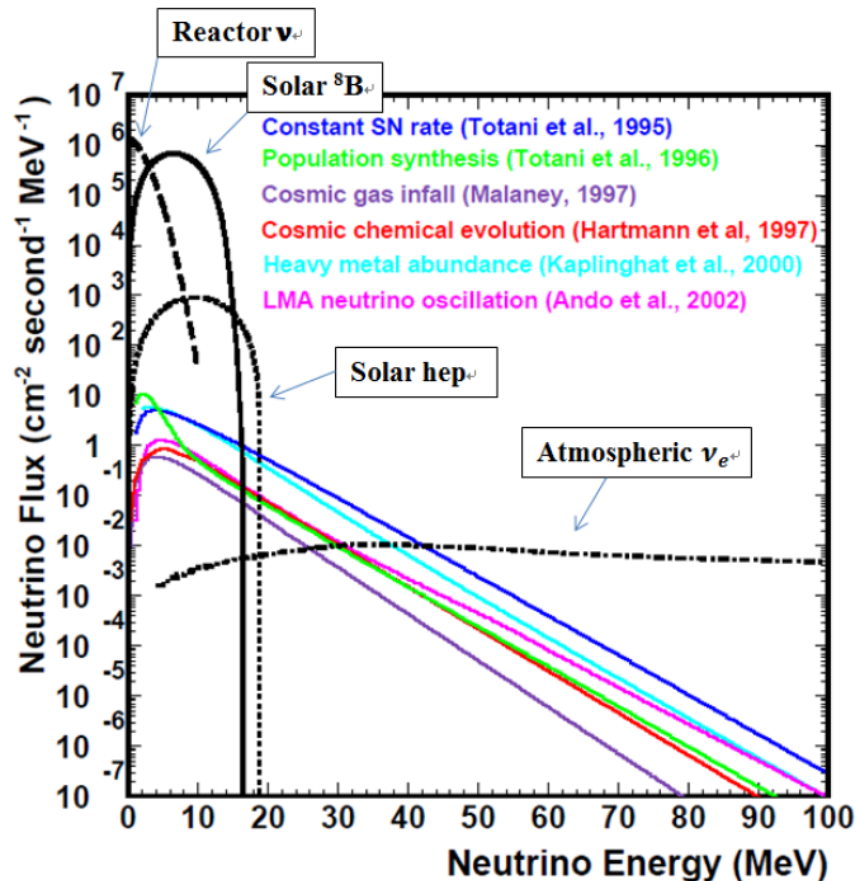
PMT:

単一光子でも検出可能

光電子が $\sim 10^7$ 倍増幅され、pC単位の電気信号へ変更される

Cherenkov光の波長領域で最大 $\sim 20\%$ の収集効率

SKで見えるニュートリノ(MeV)

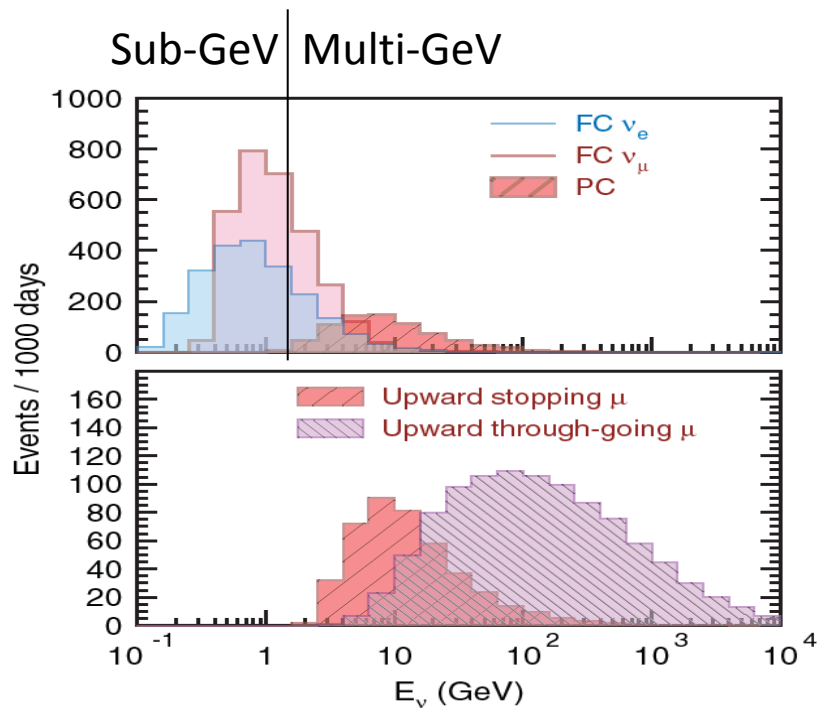


4MeV~20MeV : Solar Neutrino ν_e (${}^8\text{B}$ とhep)
 $\nu_e + e \rightarrow \nu_e + e$ (Elastic Scattering)

16MeV~30MeV : Supernova Neutrino or
 Supernova Relic Neutrino ν_x
 $\nu_x + e \rightarrow \nu_x + e$ (Elastic Scattering)
 $\bar{\nu}_e + p \rightarrow e^+ + n$ (Inverse Beta Decay)

100MeV~ : Atmospheric Neutrino $\nu_\mu/\bar{\nu}_\mu$
 Neutral Current Quasi-Elastic
 $\nu_\mu + {}^{16}\text{O} \rightarrow \nu_\mu + {}^{15}\text{N}^* + p(\nu_\mu + {}^{15}\text{O}^* + n)$
 Charged Current Quasi-Elastic
 $\nu_\mu + {}^{16}\text{O} \rightarrow \mu^- + {}^{15}\text{N}^* + p(\mu^- + {}^{15}\text{F}^* + n)$

Parent neutrino spectra

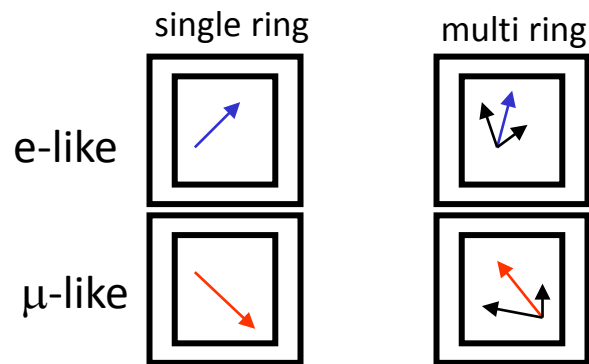


FC & PC : 100MeV ~ 10GeV

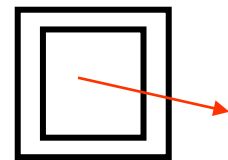
UPMU : 1.6GeV ~ 100PeV

Event categorized

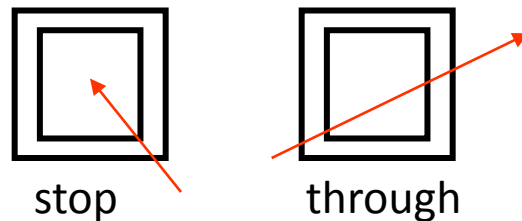
Fully-contained



Partially-contained



Upward-going muon



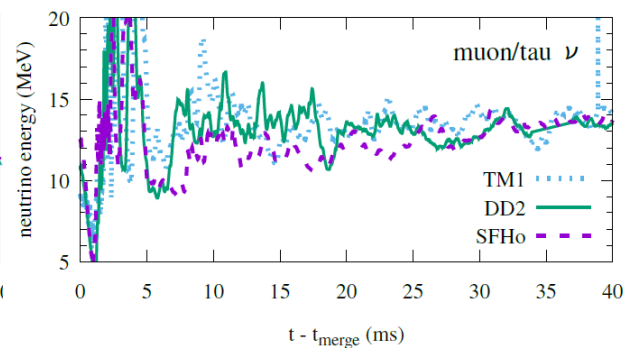
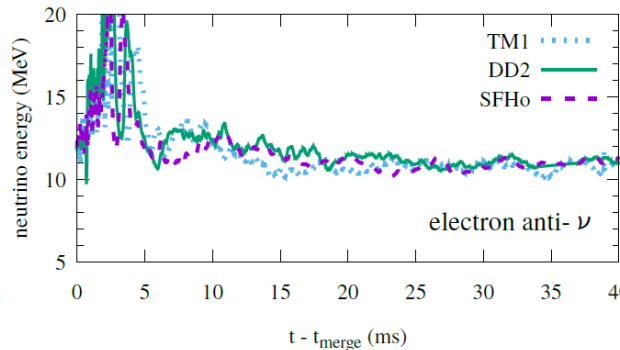
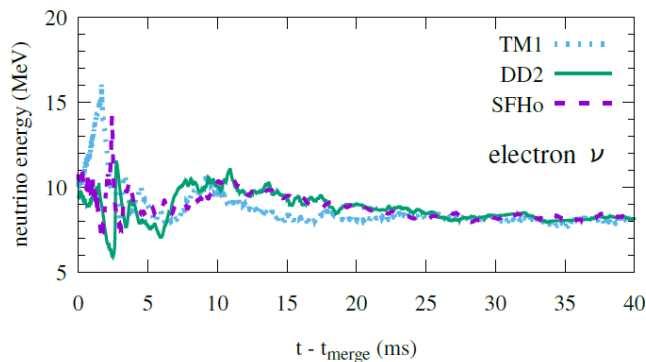
重力波GW170817に伴うニュートリノ 信号の探索

ν (MeV) Emission from NS-NS merger

Thermal ν from Binary Neutrino Star merger

1. $e^- e^+$ production from thermal photon
2. $\nu_e/\bar{\nu}_e$ from e capture by nuclei :
 $e^- + p \rightarrow \nu_e + n$, $e^+ + n \rightarrow \bar{\nu}_e + p$
3. $\nu_x/\bar{\nu}_x$ from $e^- e^+$ annihilation
 $e^+ + e^- \rightarrow \nu_x + \bar{\nu}_x$
4. Spectrum can be approximated by Fermi-Dirac Dis.
5. Most of energy emitted in 10ms, by ν in 10~30MeV

K. Kyutoku, K. Kashiya, arXiv:1710.05922



GW170817

GW170817 is the first observation of NS-NS merge GW.

Phys. Rev. Lett. **119**, 161101

Source : A merger of two neutron stars with total system mass of 2.74 solar masses, from the Galaxy NGC4993 at a luminosity distance of 40 Mpc.

Optical observation lasted 14days, so here use two kinds of time window for search : ± 500 s and 14days.

GPS Time : 2017 Aug 17 12:41:04 UT (21:41:04 JST)

SK was in LINAC test run. Beam was not running but beam pipe was inside the tank.
(Linear Electron Accelerator to generate electron into SK tank by a pipe)

GW170817 event search in 4~100MeV

Relic reduction

Bsenergy [16, 100] MeV

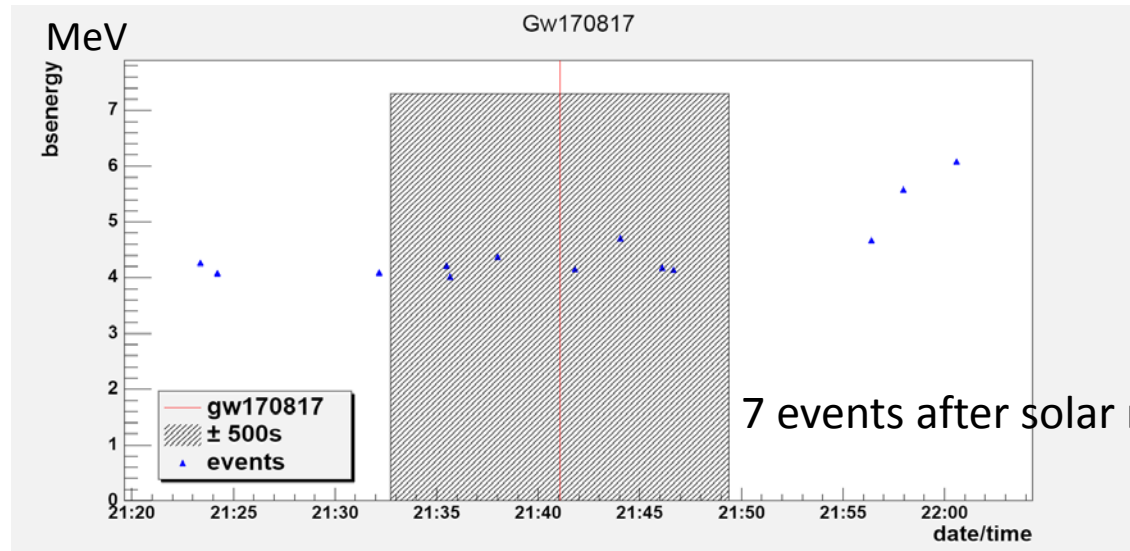
no event found in ± 500 s window

Solar reduction

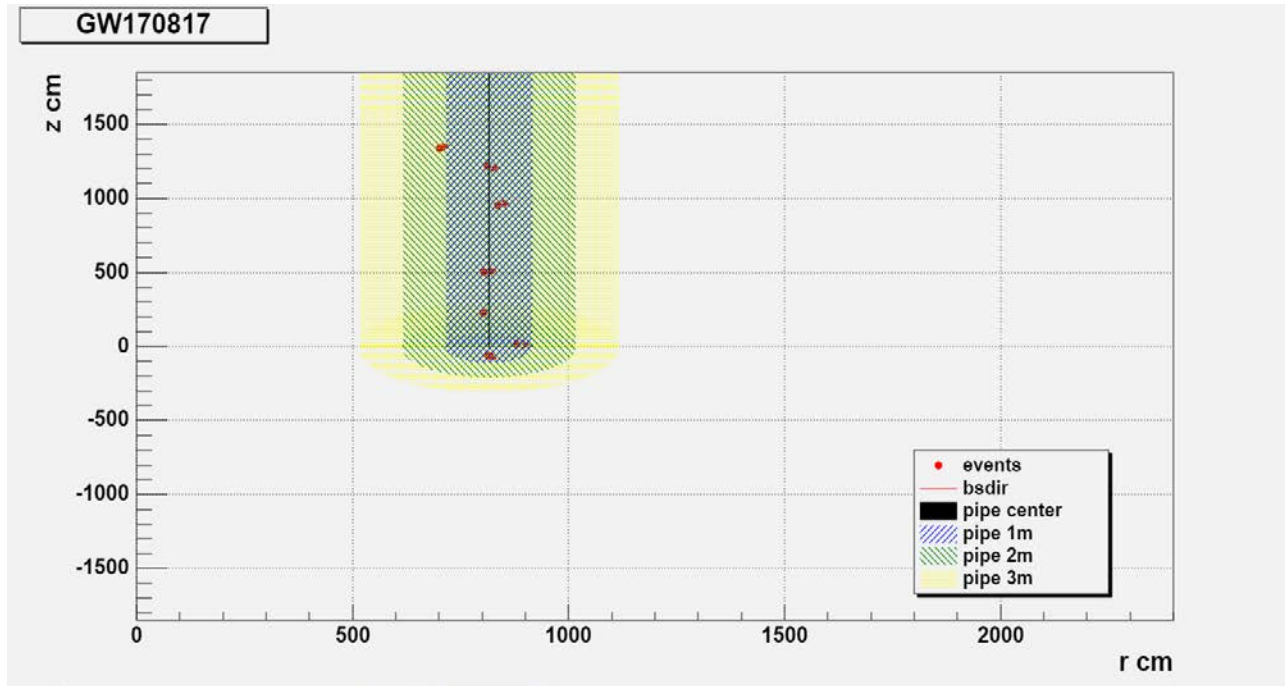
Bsenergy [4, 16] MeV

After solar reduction : 7 events in ± 500 s

After Solar reduction and Calibration source cut : 0 event left in ± 500 s



Vertex r-z of the 7 events



No event left after pipe 2m cut.

(従来の手法ではcalibration sourceから2m以内のeventが除去される)

14days search in 4~100MeV

Relic reduction [16, 100] MeV

2 event found in 14days after GW170817

Solar reduction [4, 16] MeV

So much low energy BG due to LINAC calibration runs, difficult to get physics meaning

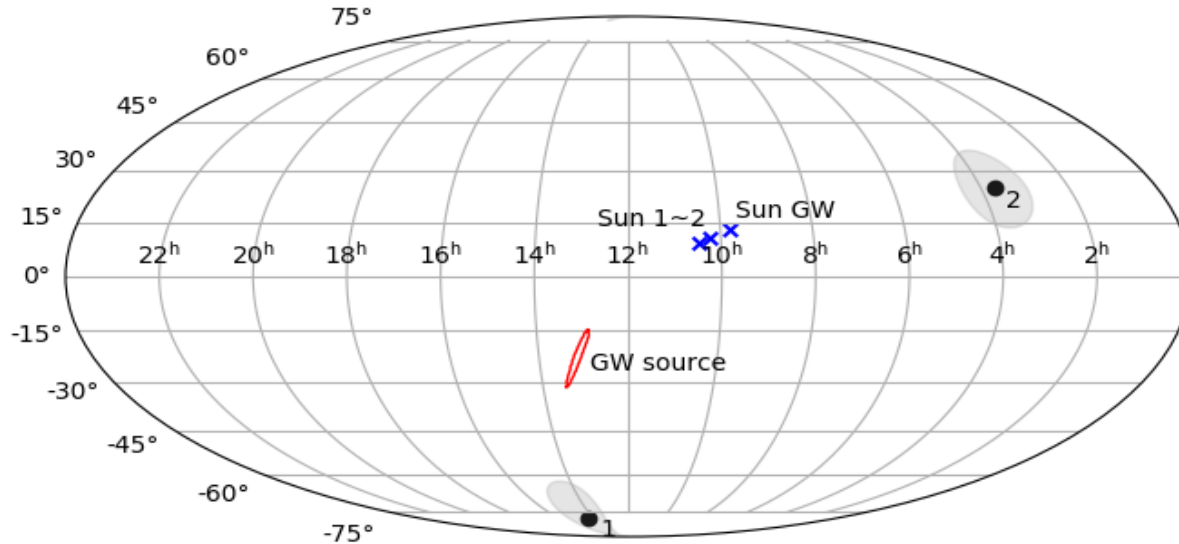
Expected Background Num : $0.00193/1000\text{sec} * 9.1527 \text{ days(Live Time)} = 1.526$

(No significant signal observed)

Possibility of Observed Num ≥ 2 : 45.08%

(最終的にはFluence Limit計算に使う)

2 events left after relic reduction in 14days after GW170817



1: 22.5MeV
2: 40.9MeV

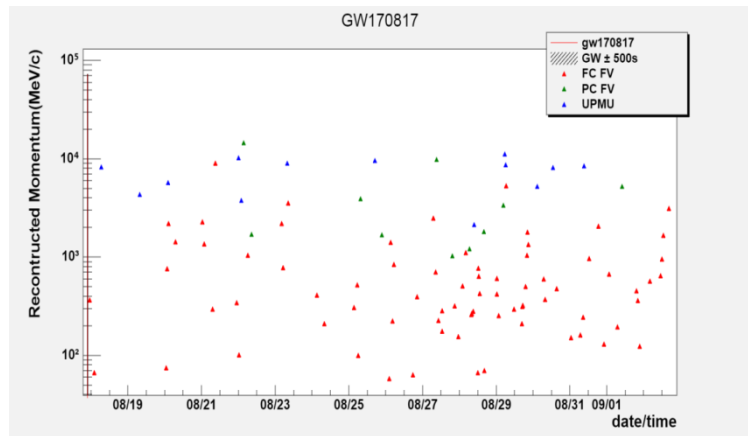
equatorial coordinate system (赤道座標、星の絶対位置を表す、地球自転に依存しない)

Points 1&2: Right Ascension and Declination of the 2 events

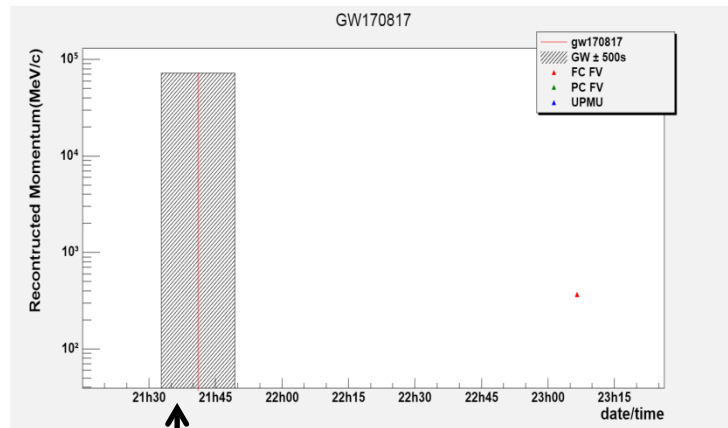
Shadow Area : angle solution

Both 2 events are far away from GW170817 source.

GW170817 event search in 100MeV~100PeV



Zoom in



No event in $\pm 500s$

No significant signal observed in 14days

Live time 11.3025 days

data set	Observed Num	SK IV average rate	Expected Num	Away from expected
FC FV cut	76	$8.09 \pm 0.05/\text{day}$	91.44	1.66 sigma lower
PC FV cut	8	$0.65 \pm 0.02/\text{day}$	7.35	0.21 sigma higher
UPMU	13	1.42 ± 0.02	16.05	0.796 sigma lower

Fluence Limit

Fluence Limit

= $\frac{\text{観測された信号数に対して90\%C.L.での数}}{\text{単位面積で1個の}\nu\text{が検出器で観測される予測数}}$ = 単位面積での ν 数の上限値

GW170817 $\Phi_\nu(\text{cm}^{-2})$		
	from FC+PC only	from UPMU only
ν_μ	5.6×10^4	$16.0^{+0.7}_{-0.6}$
$\bar{\nu}_\mu$	1.3×10^5	$21.3^{+1.1}_{-0.8}$
ν_e	4.8×10^4	-
$\bar{\nu}_e$	1.2×10^5	-
from low-energy only		
	flat spectrum	Fermi-Dirac with $E_{ave}=20$ MeV
$\bar{\nu}_e$	1.2×10^7	6.6×10^7
ν_e	1.0×10^9	3.4×10^9
$\bar{\nu}_x$	7.5×10^9	2.6×10^{10}
ν_x	6.3×10^9	2.1×10^{10}

4~100MeV :

$$\Phi_{lowe} = \frac{N_{90}}{N_T \int dE_\nu \lambda(E_\nu) \sigma(E_\nu) R(E_e, E_{vis}) \epsilon(E_{vis})},$$

100MeV~10GeV :

$$\Phi_{FC,PC} = \frac{N_{90}}{N_T \int dE_\nu \sigma(E_\nu) \epsilon(E_\nu) \lambda(E_\nu^{-2})},$$

10GeV~100PeV :

$$\Phi_{UPMU} = \frac{N_{90}}{A_{eff}(z) \int dE_\nu P(E_\nu) S(z, E_\nu) \lambda(E_\nu^{-2})}.$$

分母分子各項を徹底的に説明するよう、予備審査でcommentを頂きました

Fluence Limit for ν (4~100MeV)

$$\Phi_{lowe} = \frac{N_{90}}{N_T \int dE_\nu \lambda(E_\nu) \sigma(E_\nu) R(E_e, E_{vis}) \epsilon(E_{vis})},$$

N_{90} : 90% integral when considering a Poisson Distribution by expected rate. ($N_{90}=2.3$)

N_T : Number of Target Nuclei in SK detector volume. (Proton for $\bar{\nu}_e$ and electron for ν_x)

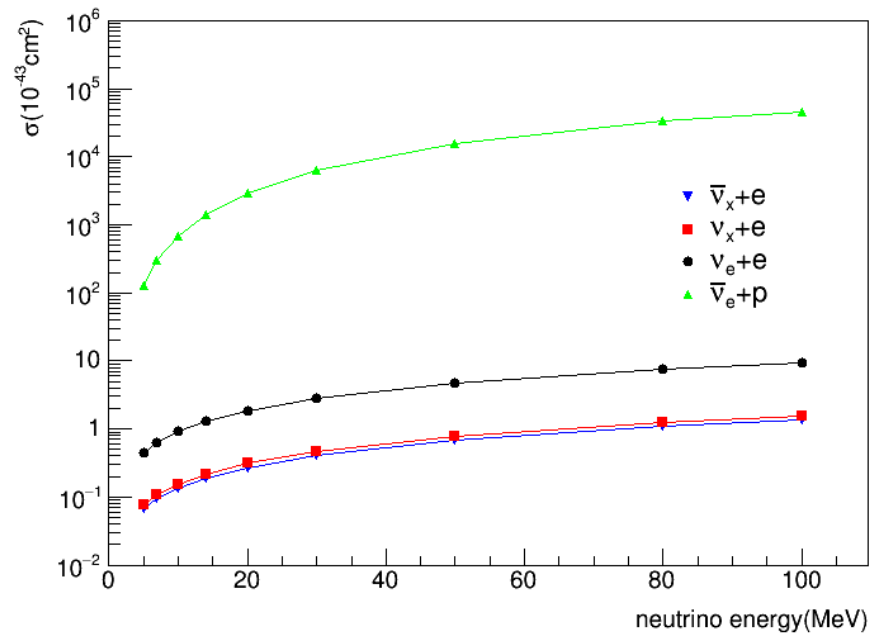
$\lambda(E_\nu)$: neutrino energy spectrum

$\sigma(E_\nu)$: cross section for ν . (IBD for $\bar{\nu}_e$ and ES for ν_x)

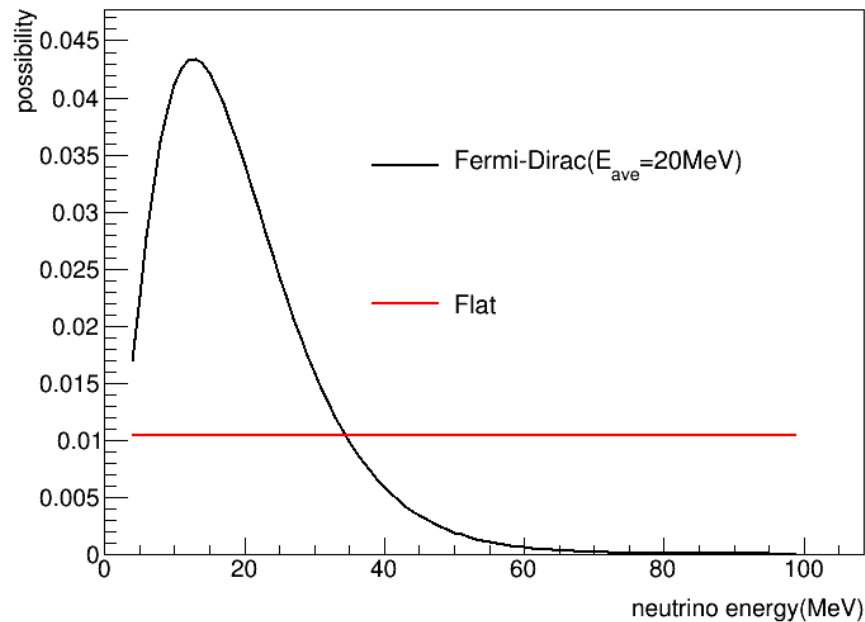
$R(E_e, E_{vis})$: Detector Response from E_e to E_{vis}

$\epsilon(E_{vis})$: Detection Efficiency for E_{vis}

$$\sigma(E_\nu)$$

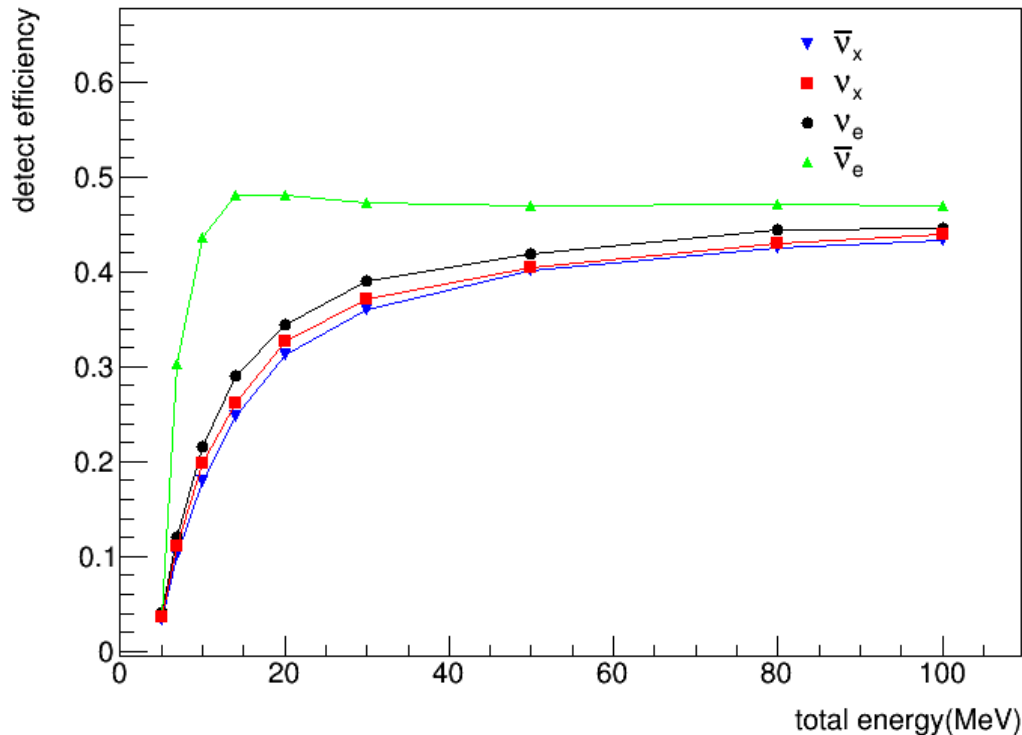


$$\lambda(E_\nu)$$



全体面積が1になるように
normalizeした

$$R(E_e, E_{vis}) \times \varepsilon(E_{vis})$$



SK simulationで4~100MeVの neutrinoを発生してタンク内で反応させ、data sampleのreduction efficiencyを考慮した上で最終的な検出効率を見積った。

PS1. 電子のenergyが低ければ低いほど、reduction efficiencyが悪くなる。

PS2. ESでは、弾かれる電子のenergyは角度によって違う。IBDで生成される陽電子energyは neutrino energyにしか依存しない。

Fluence Limit for ν (100MeV~10GeV)

$$\Phi_{FC,PC} = \frac{N_{90}}{N_T \int dE_\nu \sigma(E_\nu) \epsilon(E_\nu) \lambda(E_\nu^{-2})},$$

N_{90} : 90% integral when considering a Poisson Distribution by expected rate. ($N_{90}=2.3$)

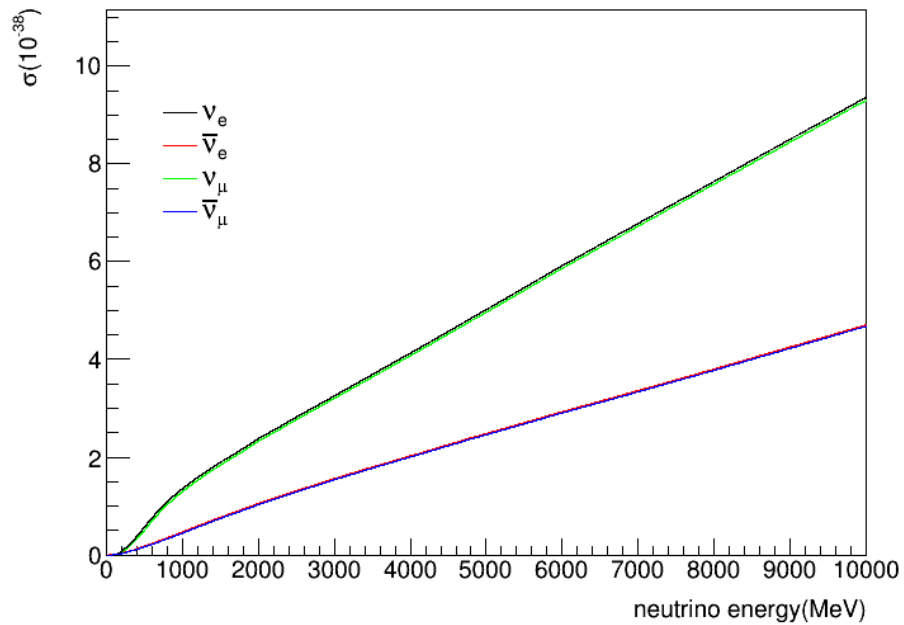
N_T : Number of Target Nuclei in SK detector volume. (Oxygen)

$\lambda(E_\nu)$: neutrino energy spectrum

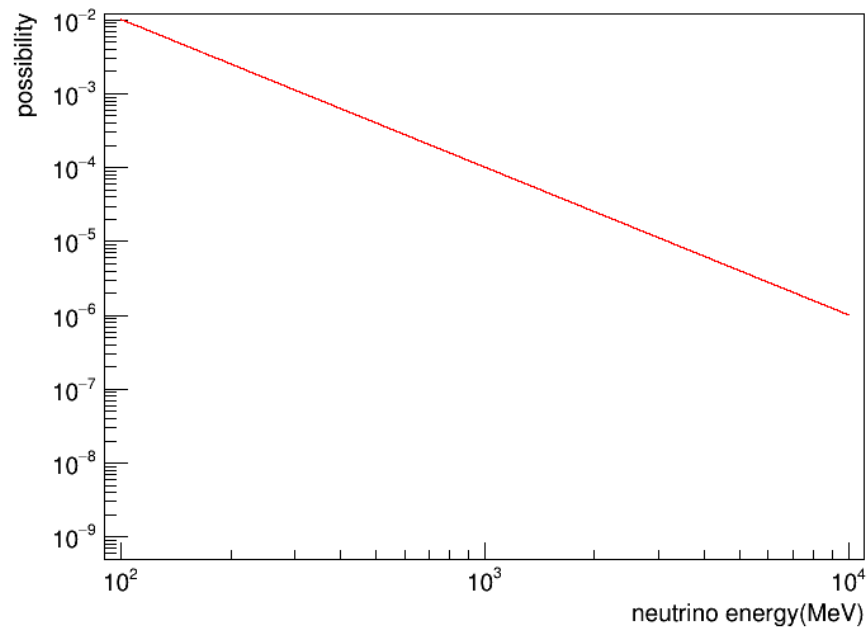
$\sigma(E_\nu)$: total cross section for ν .

$\epsilon(E_\nu)$: Detection Efficiency for E_ν

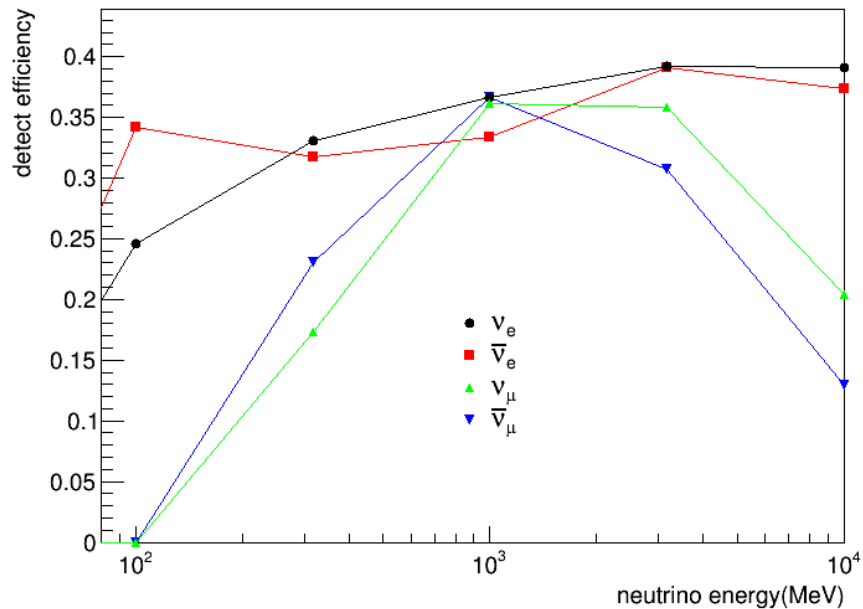
$$\sigma(E_\nu)$$



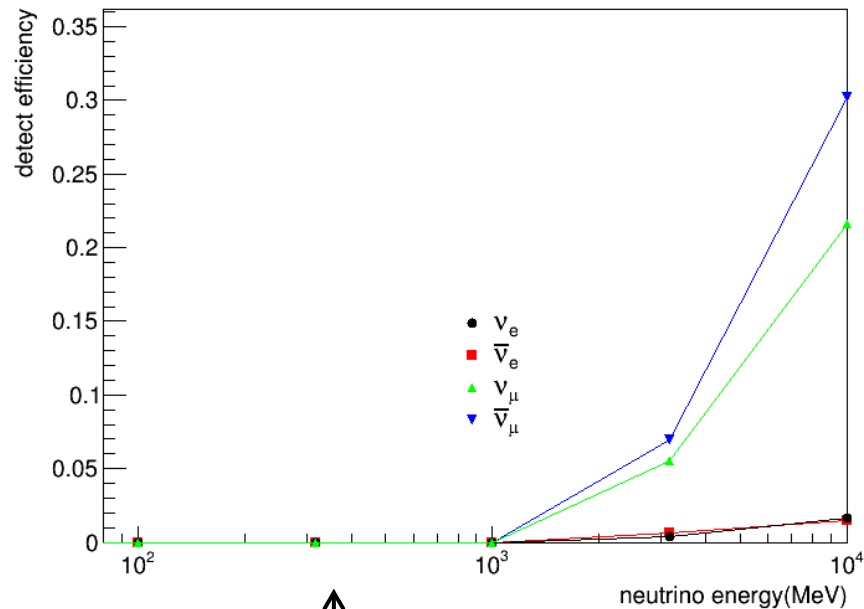
$$\lambda(E_\nu^{-2})$$



$\varepsilon(E_\nu)$ of FC



$\varepsilon(E_\nu)$ of PC



↑
Partial Containedの μ を作るには最低数百MeVが必要

Fluence Limit for ν (1.6GeV~100PeV)

$$\Phi_{UPMU} = \frac{N_{90}}{A_{eff}(z) \int dE_\nu P(E_\nu) S(z, E_\nu) \lambda(E_\nu^{-2})}.$$

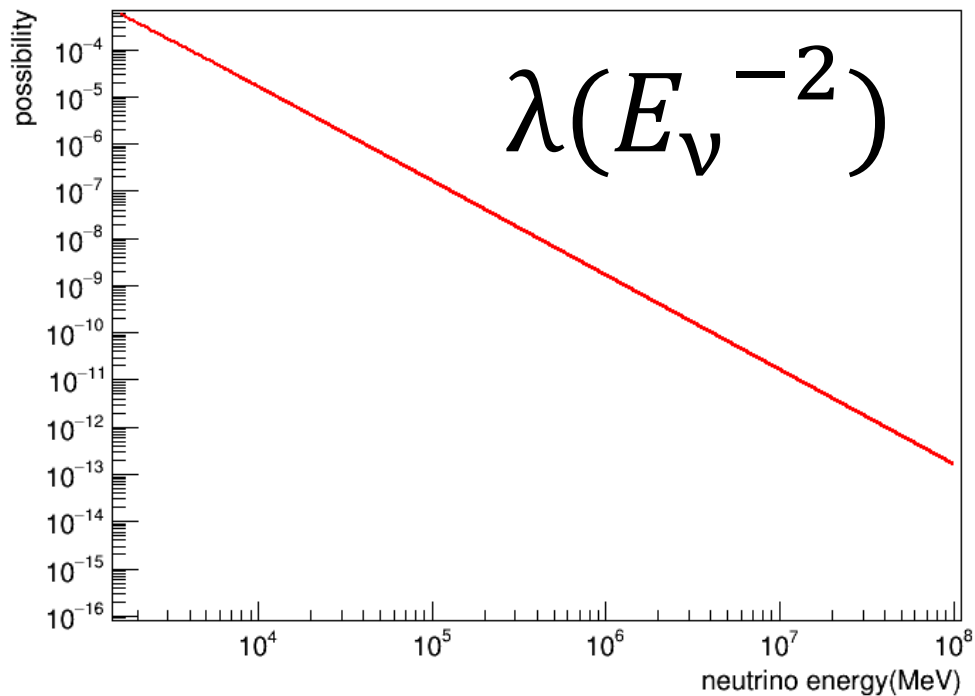
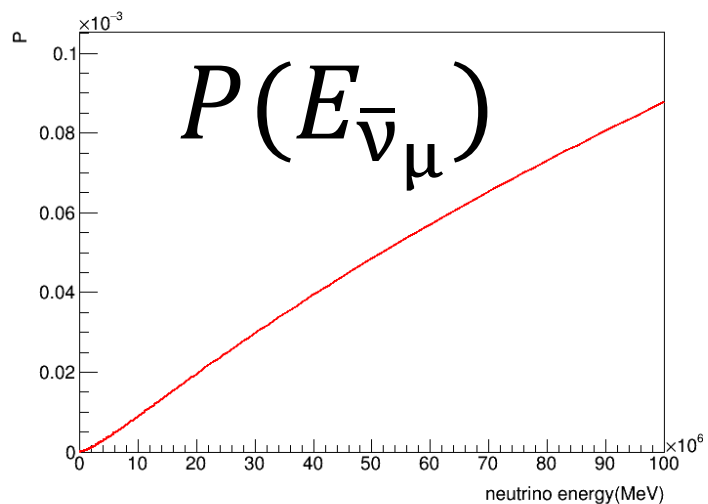
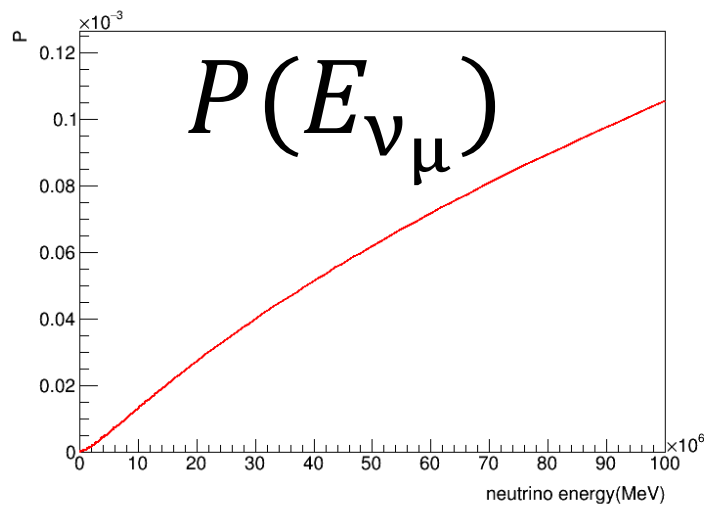
N_{90} : 90% integral when considering a Poisson Distribution by expected rate. ($N_{90}=2.3$)

$A_{eff}(z)$: effective area depending on zenith angle

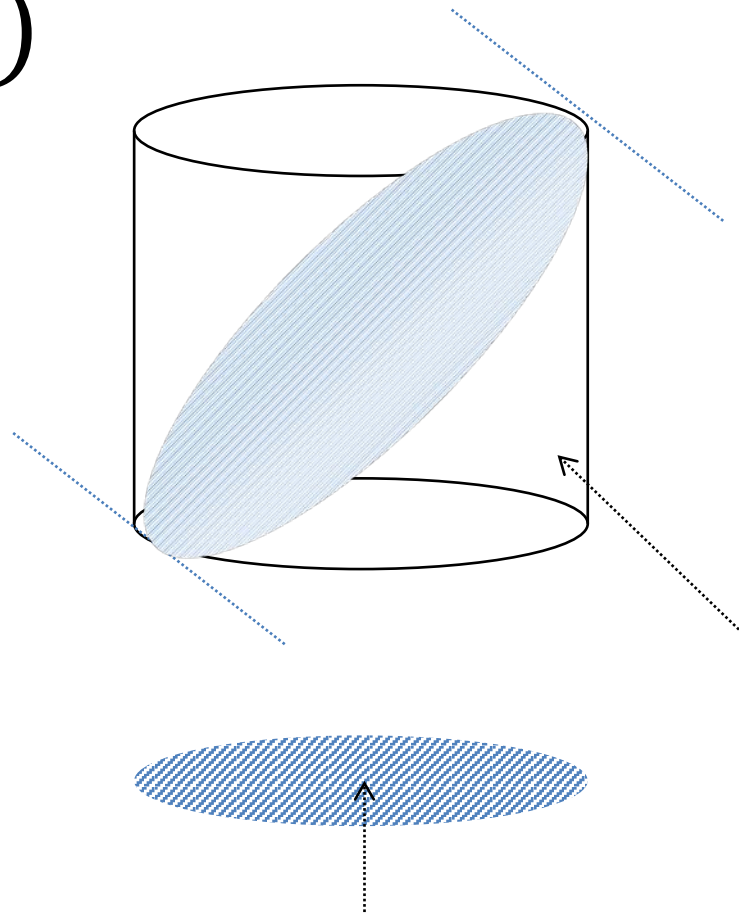
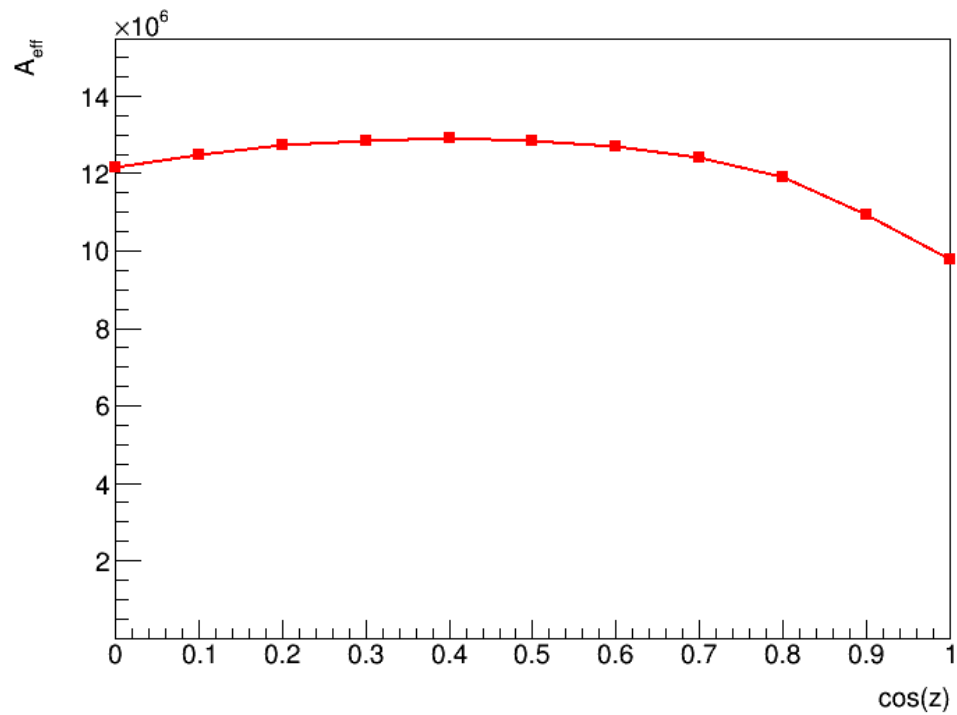
$\lambda(E_\nu)$: neutrino energy spectrum

$P(E_\nu)$: when a ν come into SK, the possibility to make a detectable μ

$S(z, E_\nu)$: shadowing of the neutrinos due to interactions in the earth



$$A_{eff}(z)$$

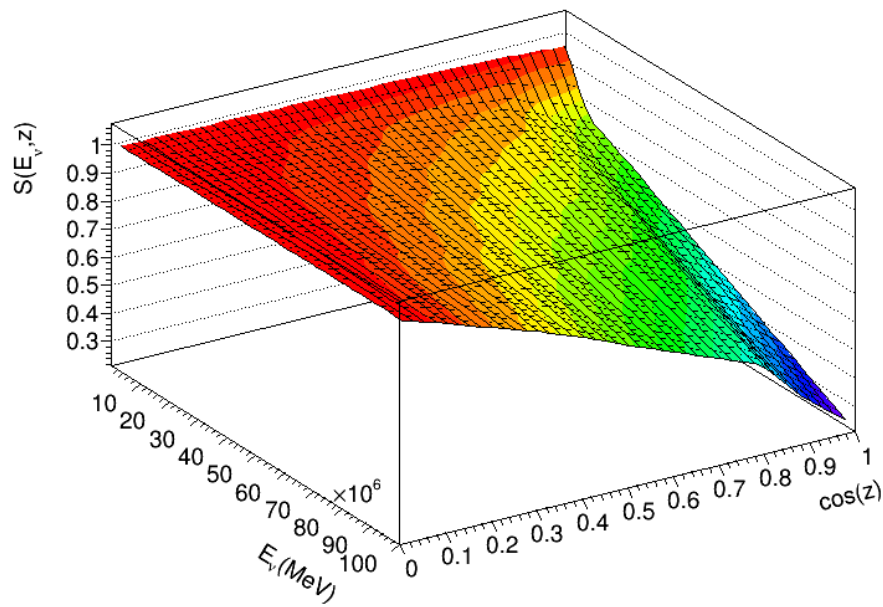
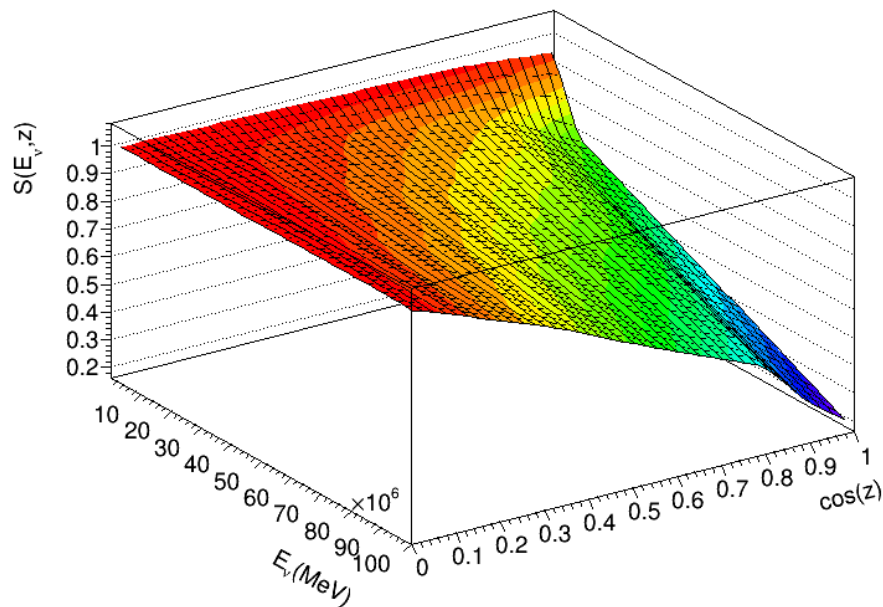


$$S(z, E_\nu)$$

S

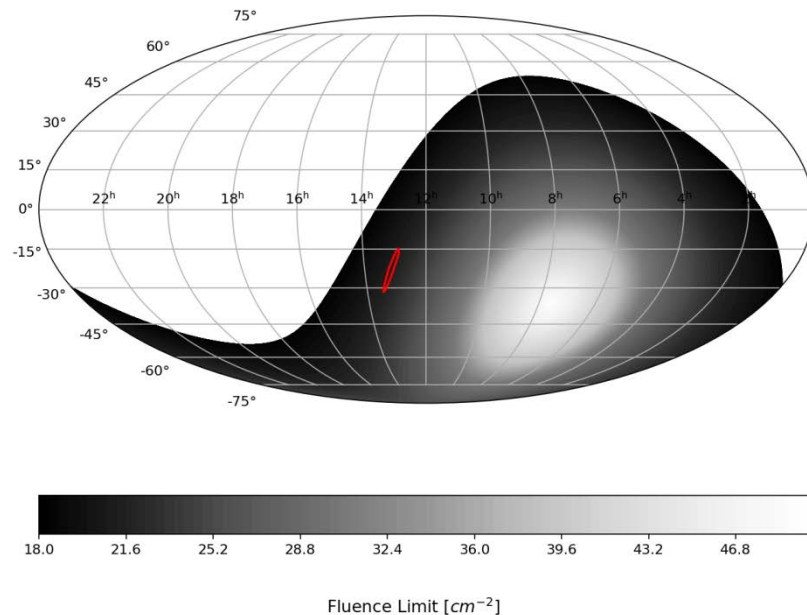
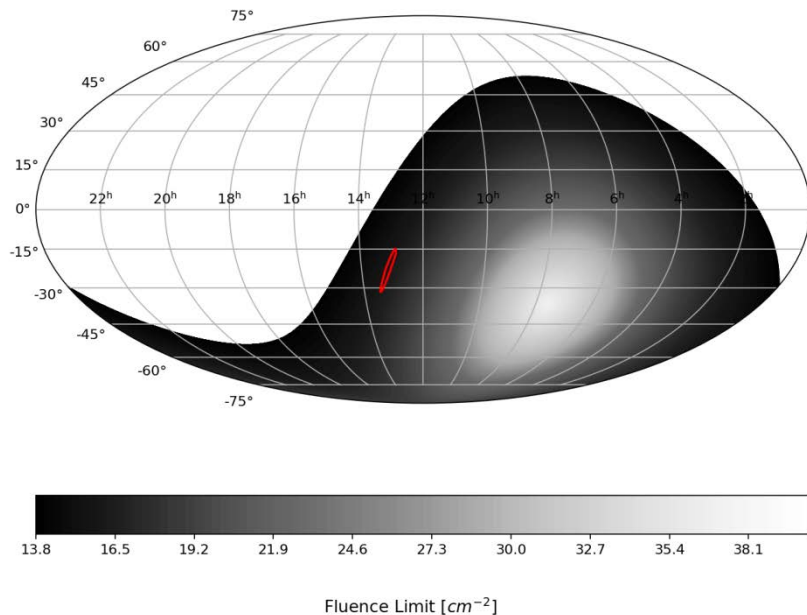
A. Vincent et.al., arXiv:1706.09895v2

S



ν が地球を通り抜ける時、物質と反応せず、SK検出器に到達する確率

z-dependent UPMU fluence limit

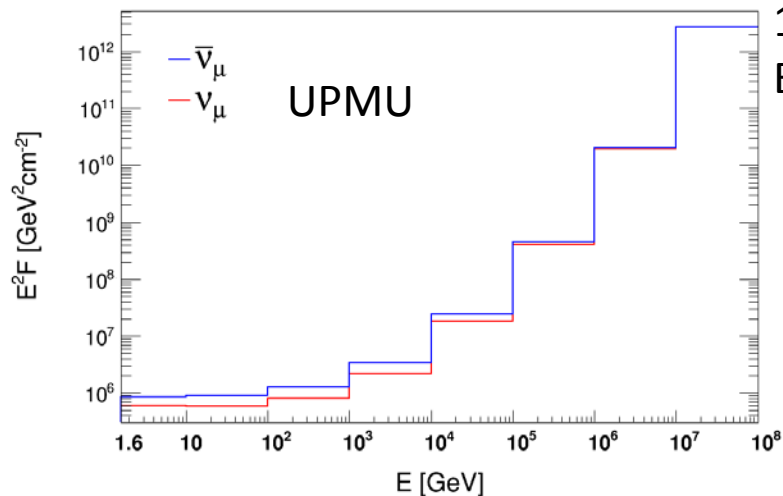


赤: LIGO fitting data by 90%C.L.

PS. GW170817が検出された時間は、発生源NGC4993はUPMUの感度ある半分にあった。

Fluence limit

GW170817 $\Phi_\nu(\text{cm}^{-2})$		
	from FC+PC only	from UPMU only
ν_μ	5.6×10^4	$16.0^{+0.7}_{-0.6}$
$\bar{\nu}_\mu$	1.3×10^5	$21.3^{+1.1}_{-0.8}$
ν_e	4.8×10^4	-
$\bar{\nu}_e$	1.2×10^5	-
from low-energy only		
	flat spectrum	Fermi-Dirac with $E_{\text{ave}}=20 \text{ MeV}$
$\bar{\nu}_e$	1.2×10^7	6.6×10^7
ν_e	1.0×10^9	3.4×10^9
$\bar{\nu}_x$	7.5×10^9	2.6×10^{10}
ν_x	6.3×10^9	2.1×10^{10}



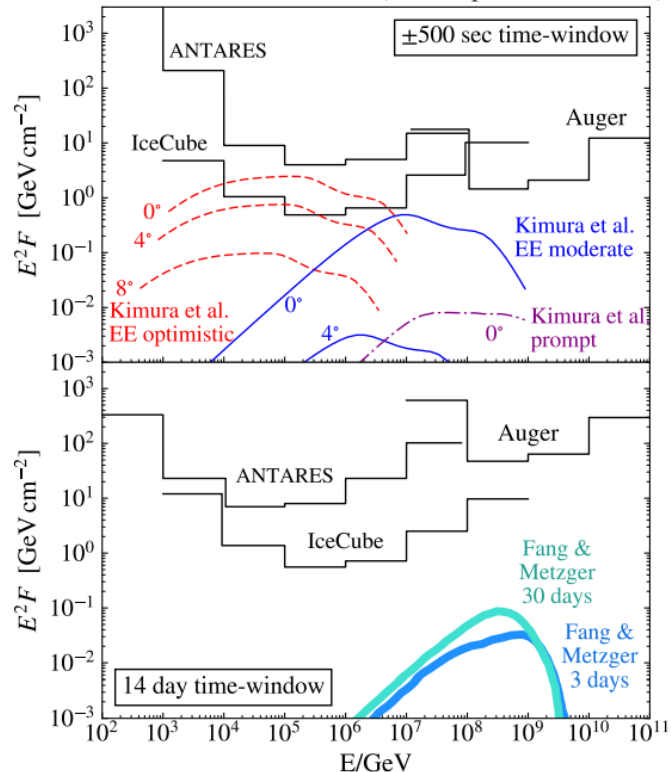
$\pm 500\text{s}$ の結果 (no signal) で積分した fluence limit

4MeV~100MeV:
Flat & Fermi-Dirac

100MeV~100PeV:
 E^{-2} spectrum

APJL, Volume 850, Number 2

GW170817 Neutrino limits (fluence per flavor: $\nu_x + \bar{\nu}_x$)



IceCube & ANTARES 実験の
Fluence limit。 (no signal)

Summary

今まで行った研究は:

1、SK-Gdに向けた先行実験であるEGADS検出器の開発及び実験測定
2016年にfirst authorとして論文を発表しました

2、重力波GW170817に伴うニュートリノ信号の探索
2018年に、corresponding authorとして論文を発表しました

← 博士論文のmain theme

3、SRNのバックグラウンドを見積る為、大気ニュートリノのCCQE反応からの脱励起ガンマ線の探索
論文執筆が終了しました。卒業するまで発表する予定

Backup

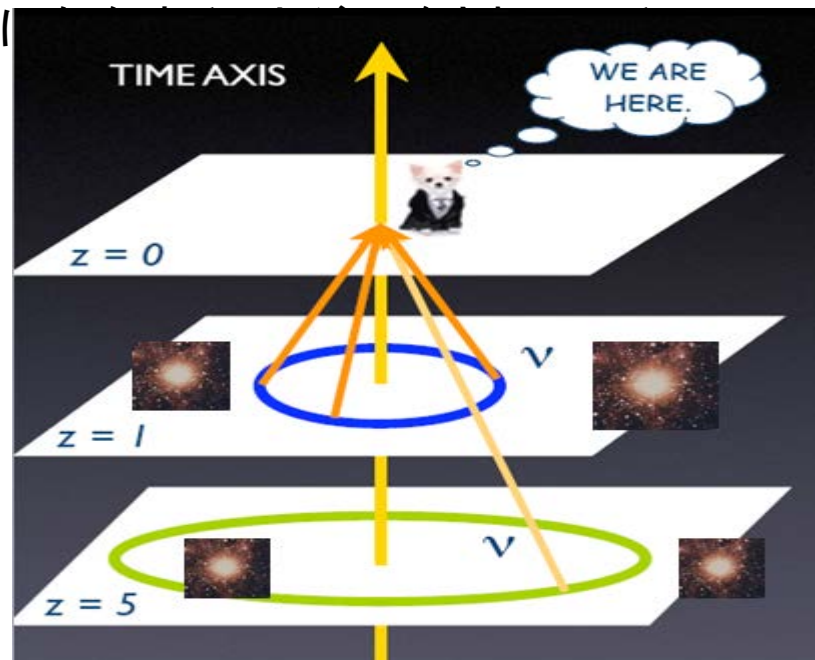
SKにおける大気ニュートリノCCQE反応 に関する解析

超新星背景ニュートリノ

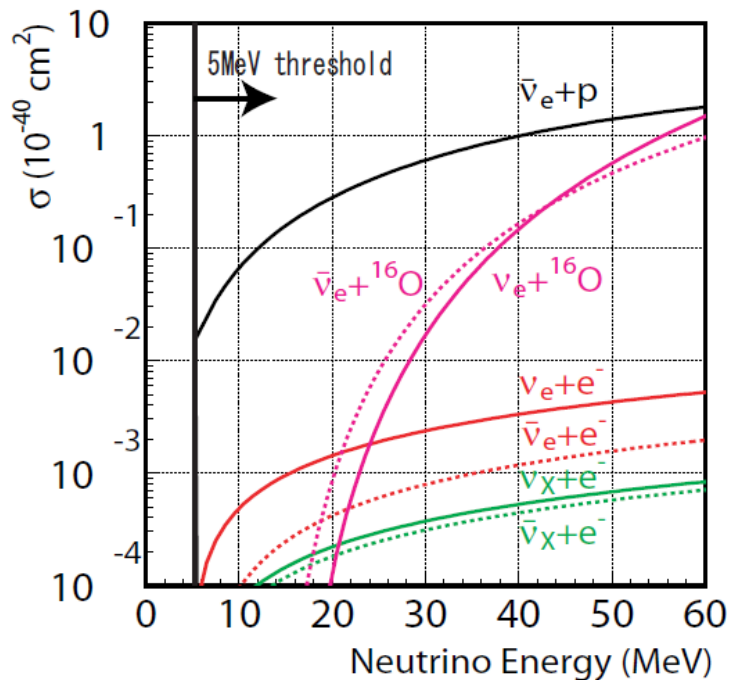
超新星爆発背景ニュートリノ (Supernova Relic Neutrinos, SRN)

宇宙に最初の星ができて以来、超新星爆発は約1秒に1回の頻度で絶えず起きており、その都度、ニュートリノや重元素物質が宇宙にまき散らされている。こういったニュートリノは、背景として現在の宇宙に大量に存在している。一方、ニュートリノは超新星の芯から外に直接出ることができる唯一の素粒子であるので、超新星爆発のメカニズムや中性子星・ブラックホール形成過程を「見る」**唯一(?)**の手段であると期待されている。また、超新星背景ニュートリノの観測は宇宙の歴史と大質量星の進化過程に繋がる。

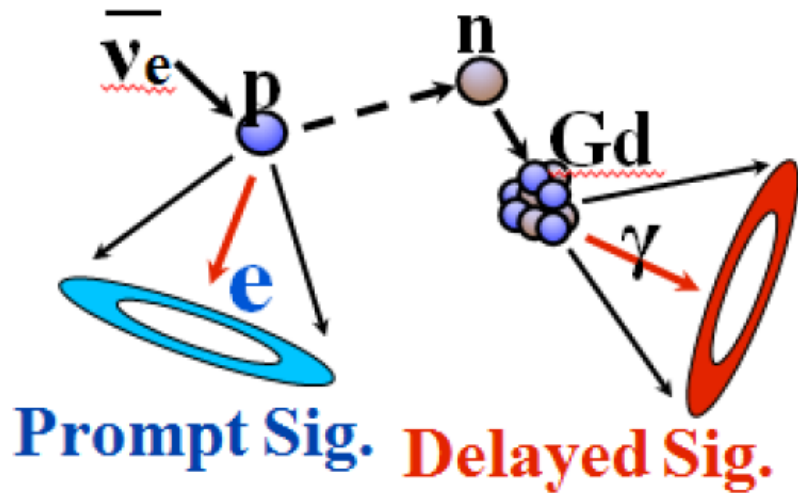
超新星爆発背景ニュートリノは未だに観測された事はありません。



SK-Gd



数MeV～数十MeVでは、逆ベータ崩壊 ($\bar{\nu}_e + p \rightarrow n + e^+$) が支配的。



ガドリニウムを入れると、逆ベータ崩壊は遅延信号ができて、他の反応と区別できる。

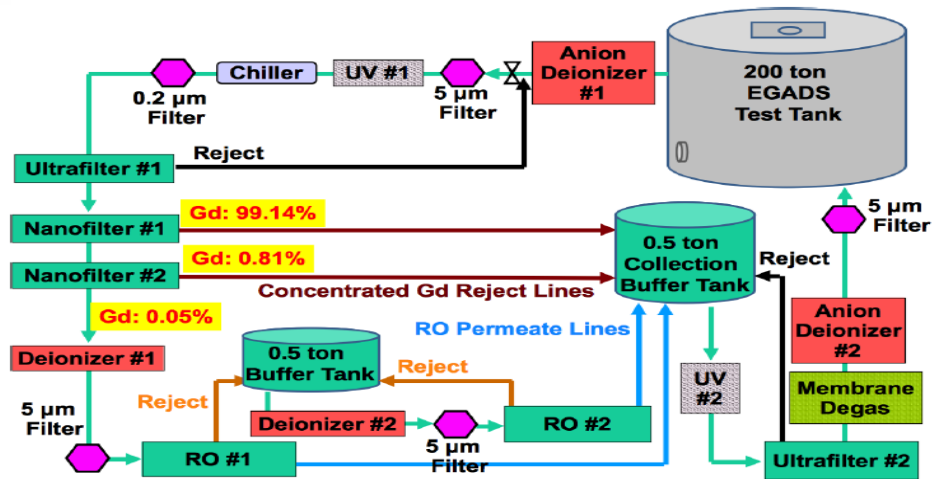
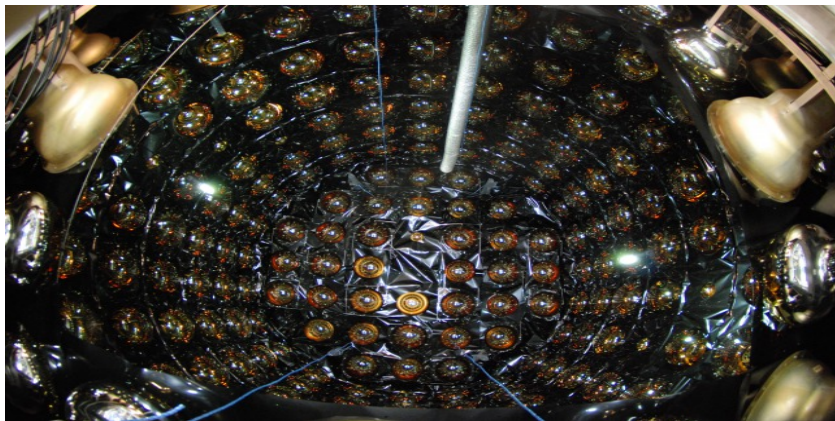
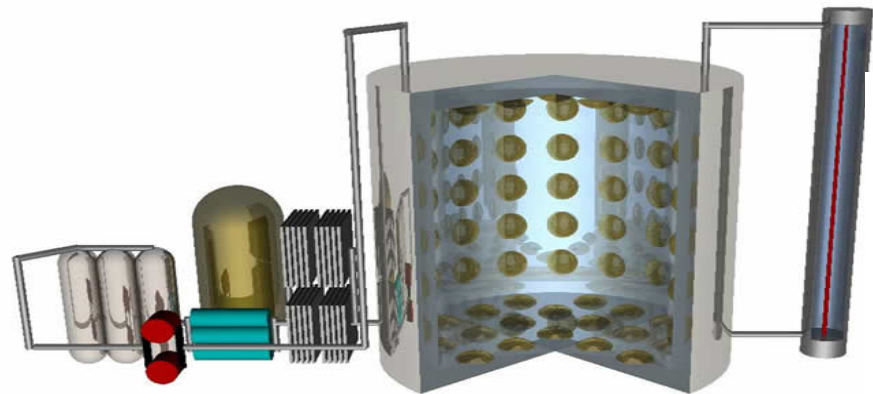
SK-Gd計画とEGADS実験

Kamioka鉱山内部のEGADS実験



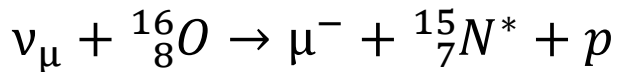
SKに0.2%Gdを導入するのが目標！

Evaluating Gadolinium Action on Detector Systems



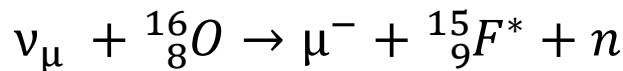
240本PMTを取り付けた200トン検出器

Atmospheric $\nu_\mu/\bar{\nu}_\mu$ CCQE interaction



$\downarrow$
 e^-

$\downarrow$
 $\gamma \sim 6 \text{ MeV}$



$\downarrow$
 e^-

$\downarrow$
 $\gamma \sim 6 \text{ MeV}$

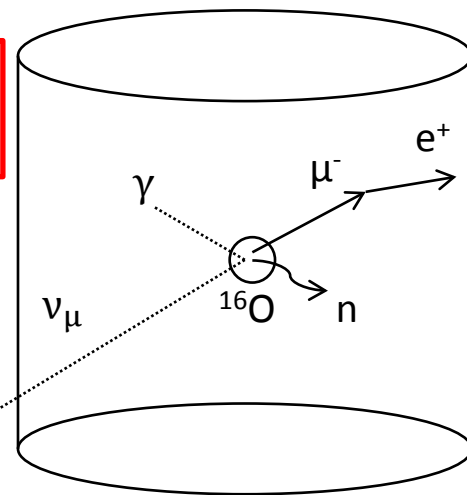
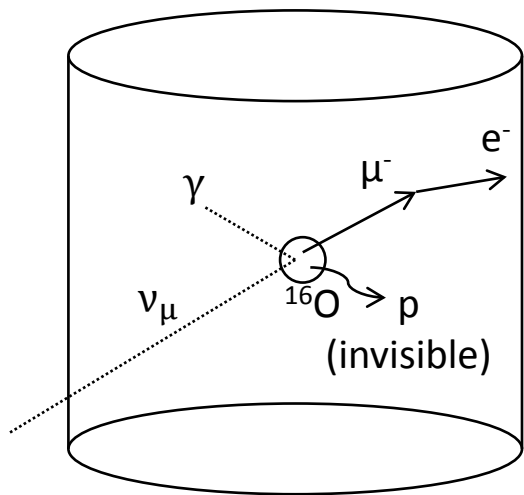
μ and γ at same
timing/position

μ and γ at same
timing/position

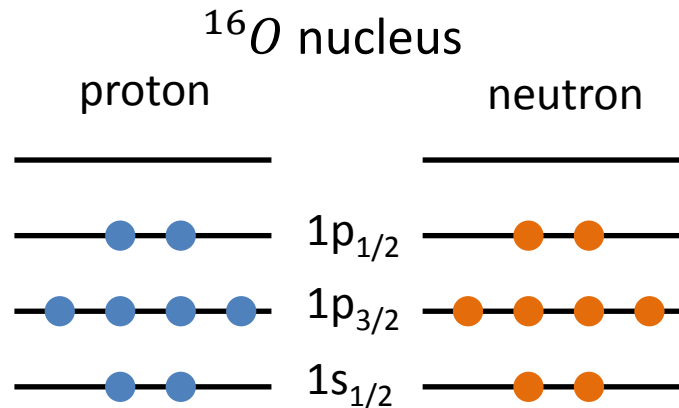
Decay e after
 $\sim 2.2 \mu\text{s}$

Decay e after
 $\sim 2.2 \mu\text{s}$

n signal after
 $\sim 200 \mu\text{s}$



Oxygen de-excitation γ



de-excitation occurs when 1p_{3/2} or 1s_{1/2} is knock out.

(1p_{1/2} case is stable)

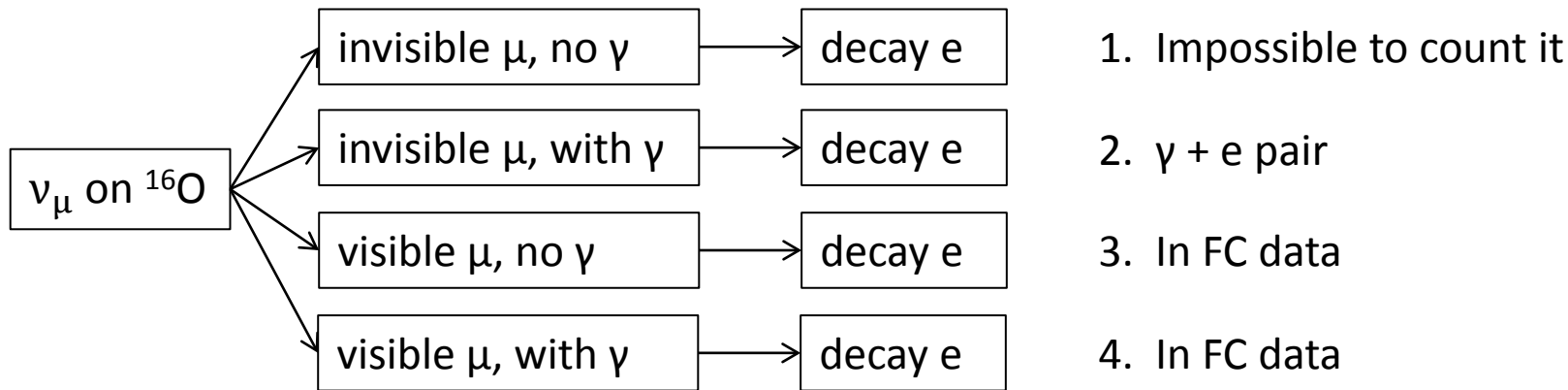
PHYSICAL REVIEW D 90, 072012 (2014)

	1p _{1/2}	1p _{3/2}	1s _{1/2}
Spectroscopic factors	0.632	0.703	0.422
γ -ray branching ratios:			
> 6 MeV from <i>p</i> hole	0%	91.8%	14.7%
> 6 MeV from <i>n</i> hole	0%	86.9%	14.7%
3–6 MeV from either	0%	0%	27.8%

SF is from calculation, branching ratio of each state is from electron/proton beam experiment.

$$\begin{aligned} \text{Br}(\gamma > 6\text{MeV}) &= 4/16 * 0.703 * 91.8\% + 4/16 * \\ &0.703 * 86.9\% + 2/16 * 0.422 * 14.7\% + 2/16 * \\ &0.422 * 14.7\% = 33\% \end{aligned}$$

CCQE cases and $\text{Br}(\gamma)$

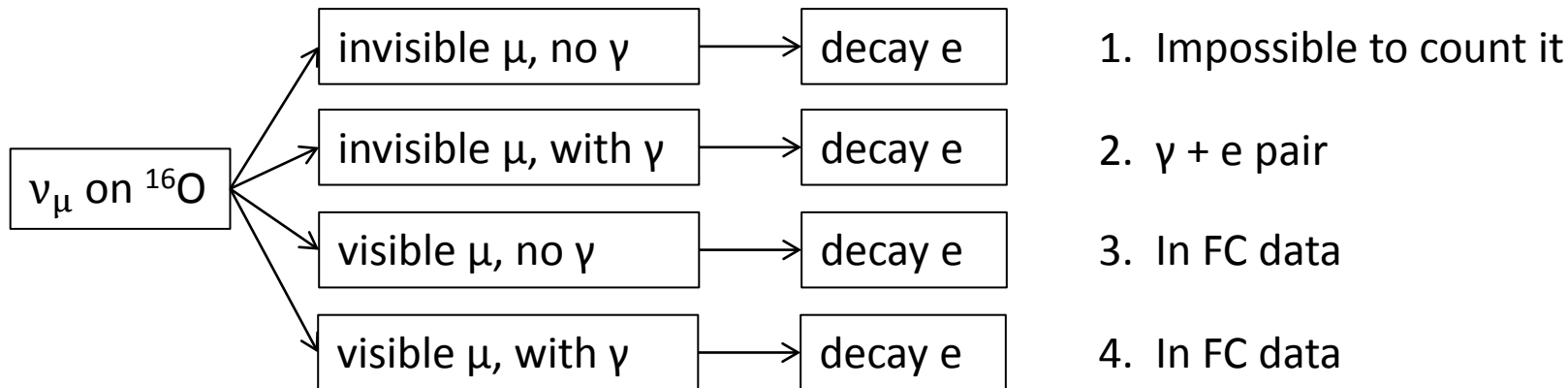


1で観測できるのはdecay eのみで、除去不可のバックグラウンドになる(主にSRN解析で)。さらに、中性子が弾き出される場合もあり、SK-Gdにおいても除去不可になる。

3&4を区別できれば、 $\text{Br}(\gamma)$ がわかる。(FC μ sampleを利用し、同一event内で6MeV γ を探す)

さらに2の数が分かれば、1を見積ることができる。

Plan



3&4を区別する可能性をSimulationで検討し、 μ 事象の中で γ を探す手法を確立する。

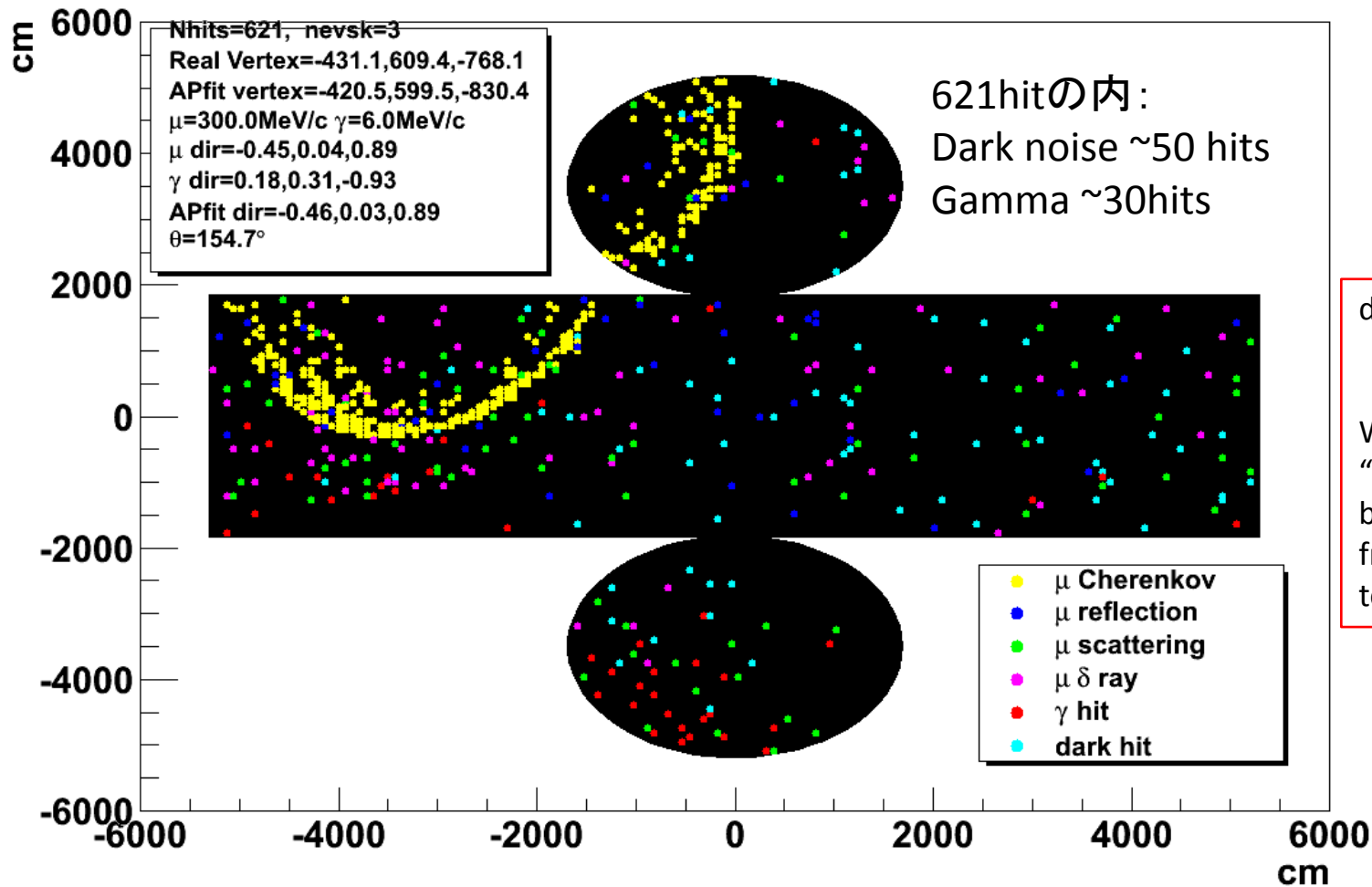
2の $\gamma + e$ pairを探して、脱励起ガンマ線のSampleを作る。

大気ニュートリノのFlux、CCQE反応のcross section理論値、SKの検出効率を考慮した上で、事象数の予想値を出して上記の結果と比較する。

脱励起ガンマ線のSampleを利用して、FC dataで $\text{Br}(\gamma)$ を出す。

SK EVENT DISPLAY

SK Simulation of 300MeV/c μ + 6MeV γ

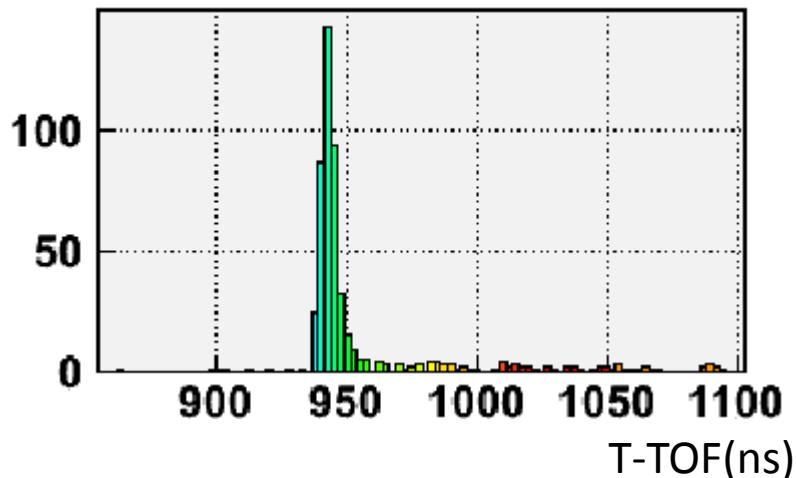
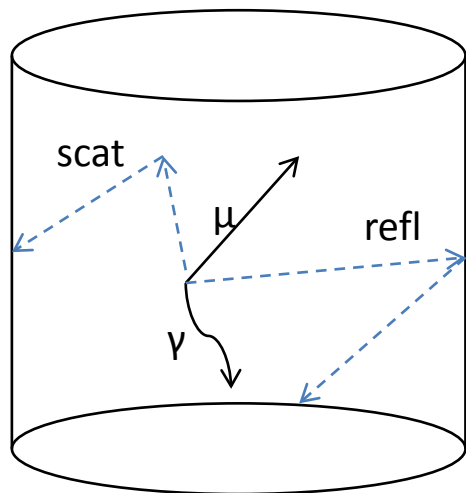


delta ray basic process:

$$\mu + e \rightarrow \mu + e$$

When μ loss energy by "ionization", it is really by scattering electrons from a few eV to a few tens MeV.

How to search for a γ inside a μ



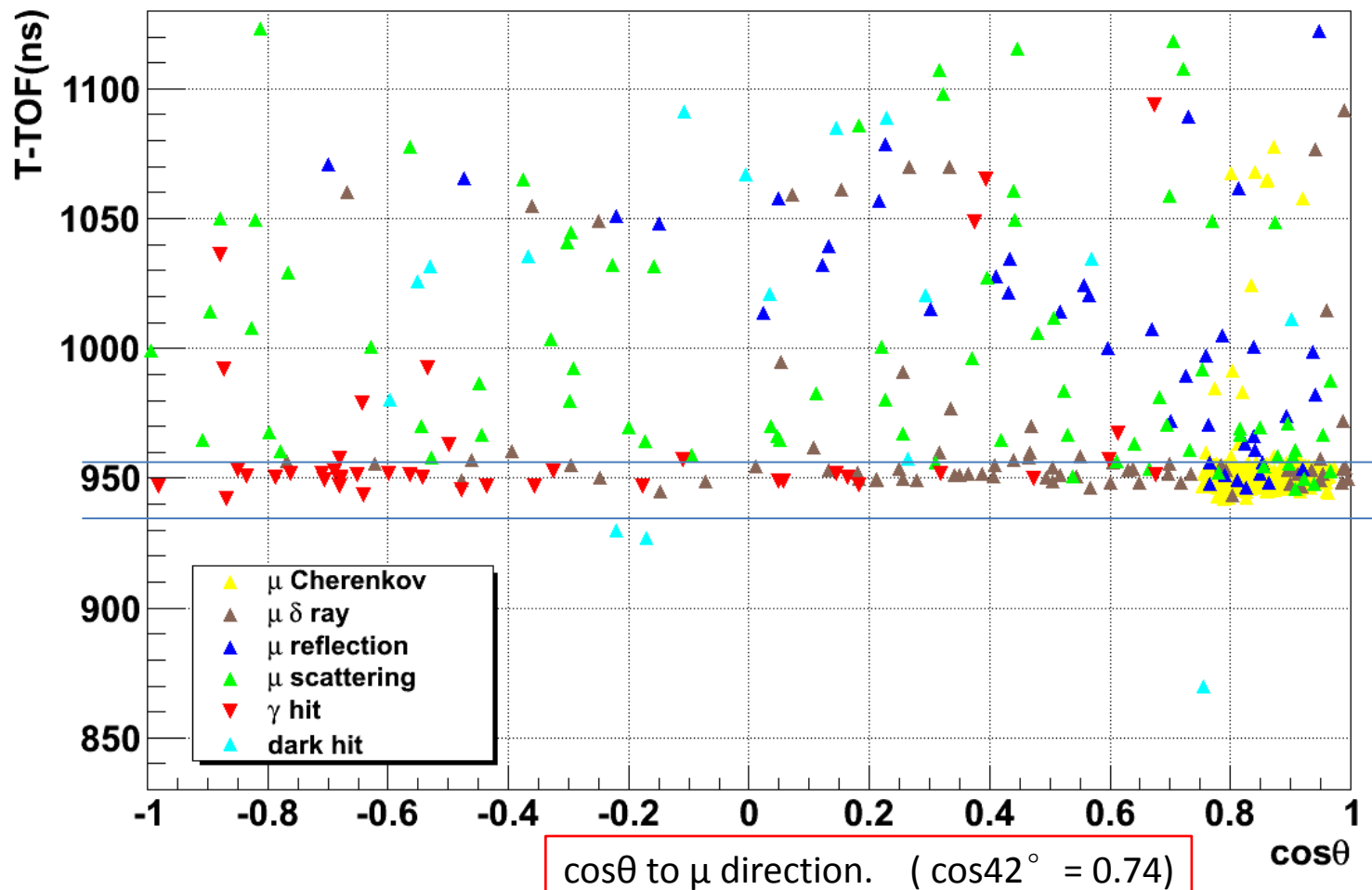
1. 散乱と反射は、Cherenkov光子より長い距離を走る為、hit時間が遅れる
2. Dark noiseはPMT自身の電気ノイズで、時間的にrandomに分布する
3. Cherenkov光子なら、vertex- $\rightarrow$ PMTのvectorと μ の進行方向は 42°
4. 脱励起 γ は全方向に出る
5. $\mu + \gamma$ の事象では、 μ の方向が再構成される

$\gamma[0.18,0.31,-0.93]6.0\text{MeV/c}$ $\mu[-0.45,0.04,0.89]300.0\text{MeV/c}$ $[-431.1\text{cm},609.4\text{cm},-768.1\text{cm}]$

Simulation

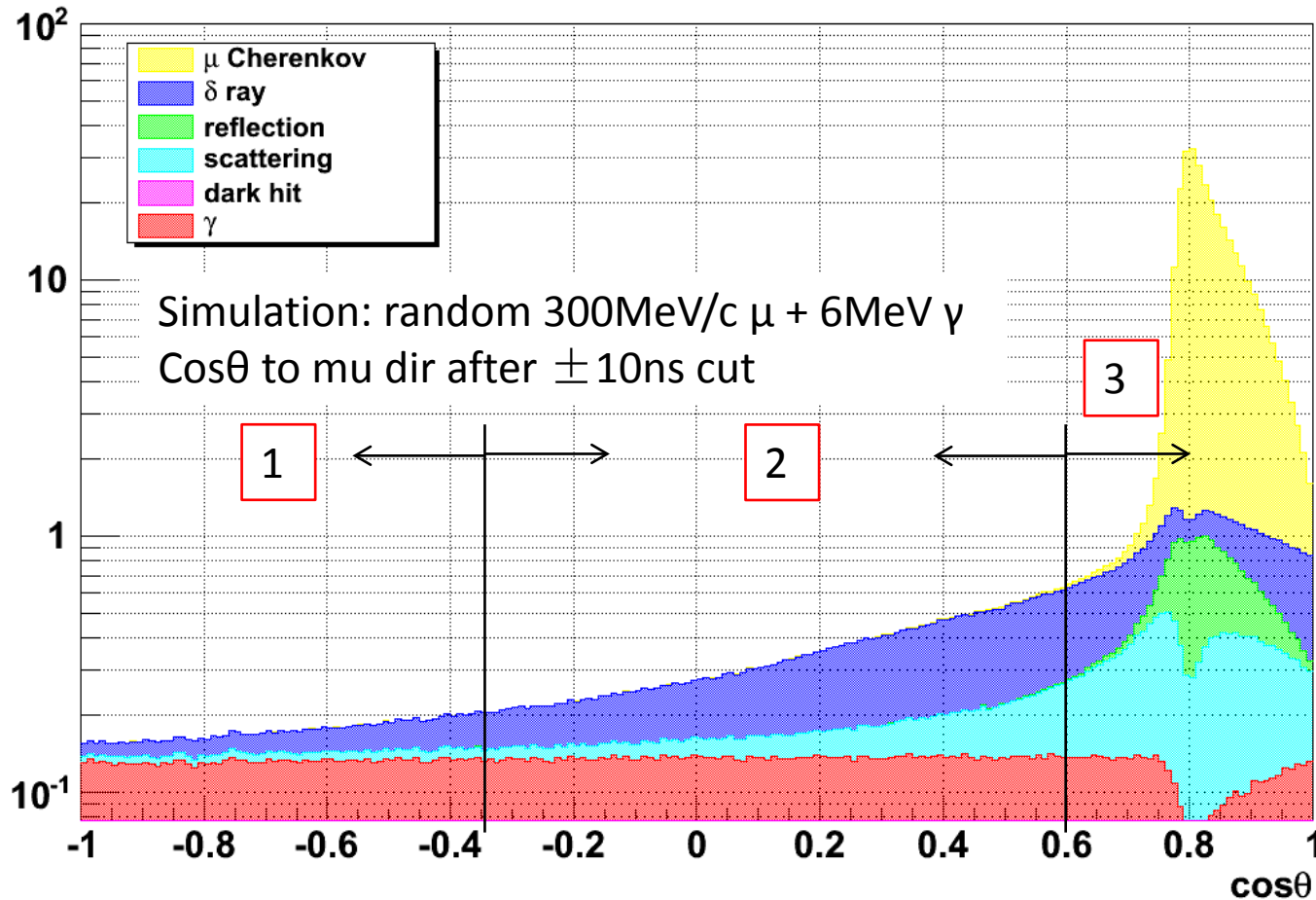
In this Fig :

$\pm 10\text{ns}$ T-Tof cut can
remove dark/refl/scat



300MeV/c μ and 6MeV γ

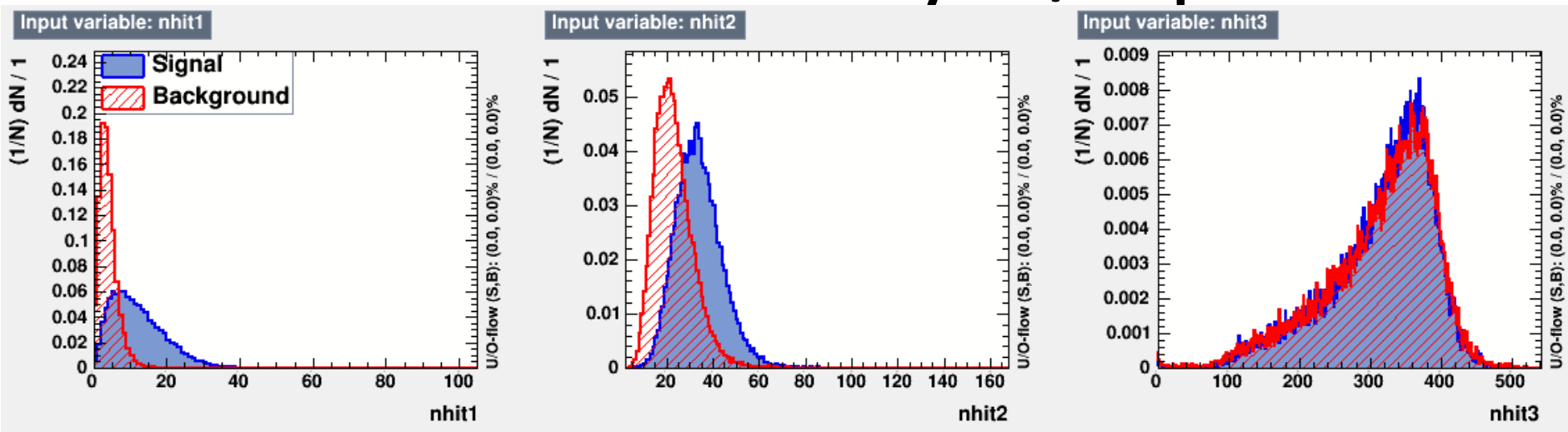
Build Likelihood from Hit Map



Hits in (T0-10ns, T0+10ns)
can be separated into 3
categories:

1. $-1 < \cos\theta < -0.34$
Mainly γ hits, with a little
delta ray hits
2. $-0.34 < \cos\theta < 0.6$
Mainly delta ray hits,
with a little possible γ
hits
3. $0.6 < \cos\theta < 1$
Mainly μ Cherenkov hits,
with a little delta ray hits
or a little possible γ hits

How to classify w/o γ



300MeV/c μ simulation, Signal is generated with uniform 6MeV/c γ , BG means no γ events

nhit1 : hits number in $-1 < \cos\theta < -0.34$

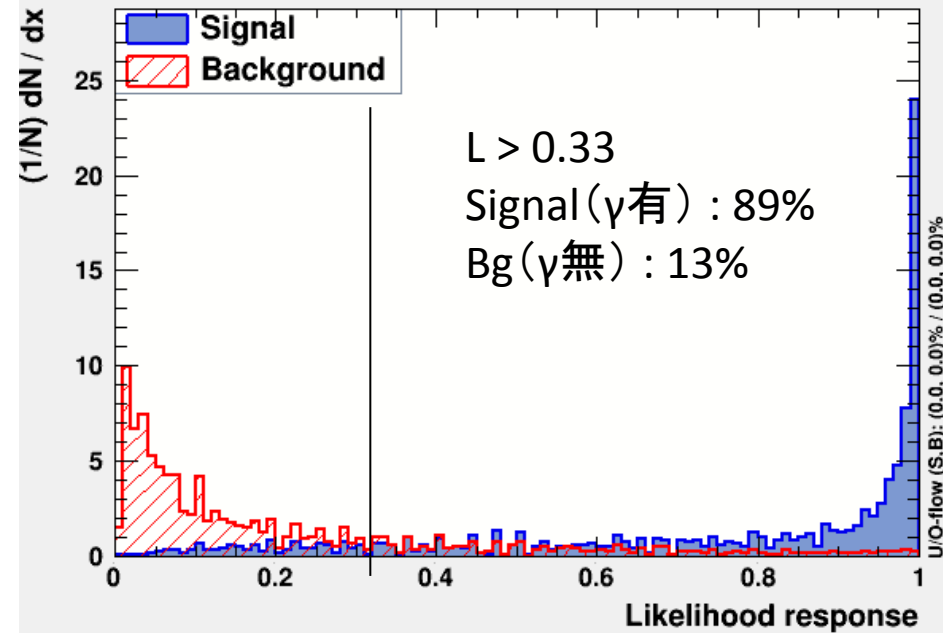
nhit2 : hits number in $-0.34 < \cos\theta < 0.6$

nhit3 : hits number in $0.6 < \cos\theta < 1$

Use 1 and 2 to make likelihood (3 is too similar)

300MeV/c μ + w/o γ

TMVA response for classifier: Likelihood



How to calculate $\text{Br}(\gamma)$

Signal : CCQE with γ

BG : CCQE without γ

Eff : Cut Efficiency when cut at max significance

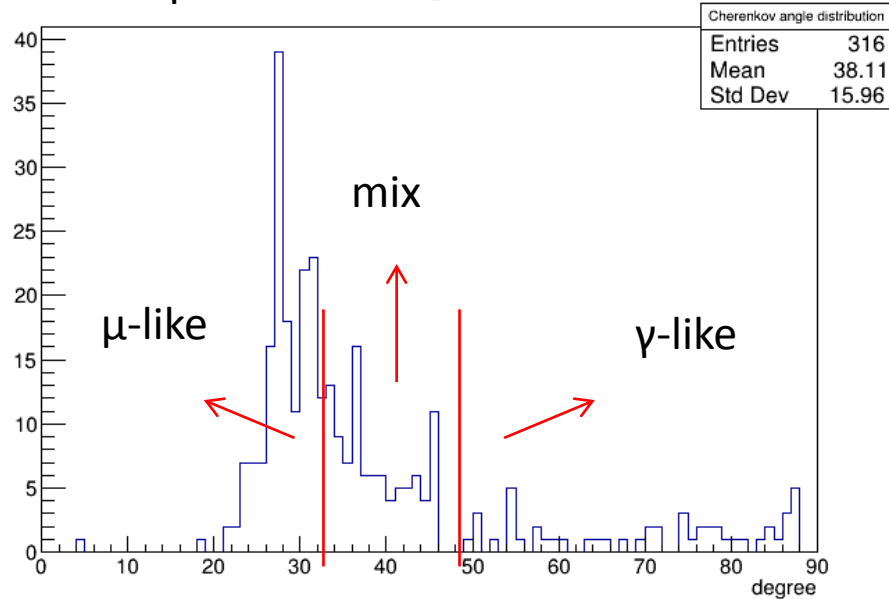
$$\text{Br}(\gamma) = N_s / (N_s + N_b)$$

We can observe N_{total} , but don't know N_s and N_b

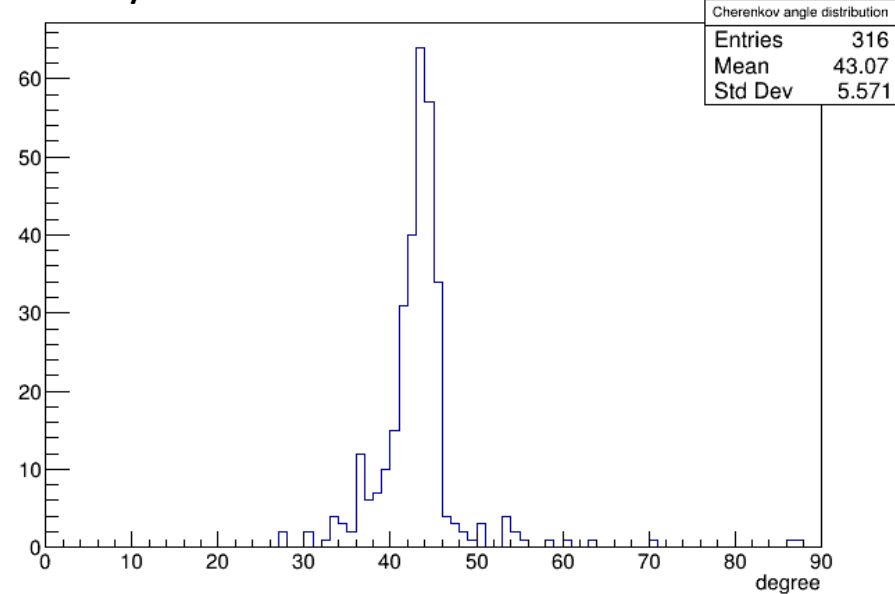
$$\begin{cases} N_s + N_b = N_{total} \\ N_s \times \text{Eff}_s + N_b \times \text{Eff}_b = N'_{total} \end{cases}$$

Gamma + Decay Electron(Data)

Parrent γ Cherenkov angle distribution



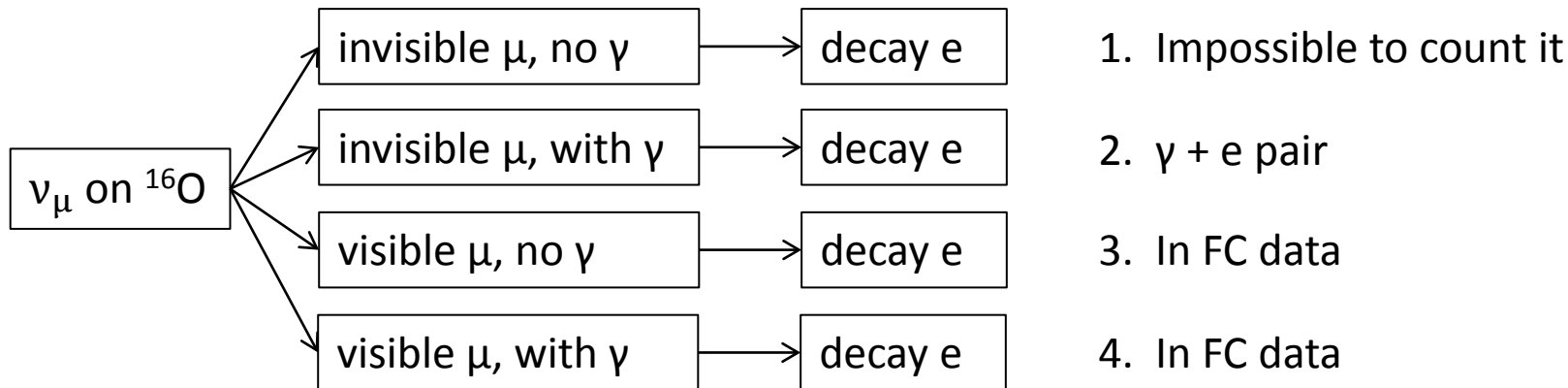
Decay e Cherenkov angle distribution



In SRN and T2K analysis, $[38^\circ, 50^\circ]$ is defined as electron region, $[50^\circ, 90^\circ]$ is defined as gamma region.

Most of them should be decay e

Still Need To do.....



3&4を区別する可能性を検討。 ○

2の $\gamma + e$ pairを探して、脱励起ガンマ線のSampleを作る。 ○

大気ニュートリノのFlux、CCQE反応のcross section理論値、SKの検出効率を考慮した上で、事象数の予想値を出して上記の結果と比較する。 ×

脱励起ガンマ線のSampleを利用して、FC dataで $\text{Br}(\gamma)$ を出す。 ×

SK phase

Phase	SK-I	SK-II	SK-III	SK-IV	SK-Gd
Start	Apr 1996	Oct 2002	Jul 2006	Sep 2008	Nov 2018
End	Jul 2001	Oct 2005	Aug 2008	Jun 2018	Running
ID PMT	11146	5182	11129	11129	11129
OD PMT	1885	1885	1885	1885	1885
PMT Coverage	40%	19%	40%	40%	40%
Electronics	ATM	ATM	ATM	QBEE	QBEE
Energy Thre.	4.5MeV	6.5MeV	4.0MeV	3.5MeV	-

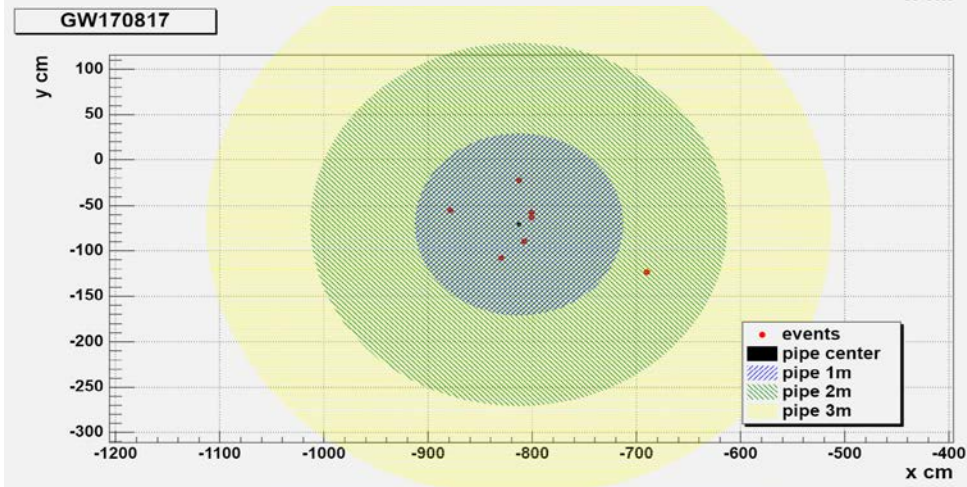
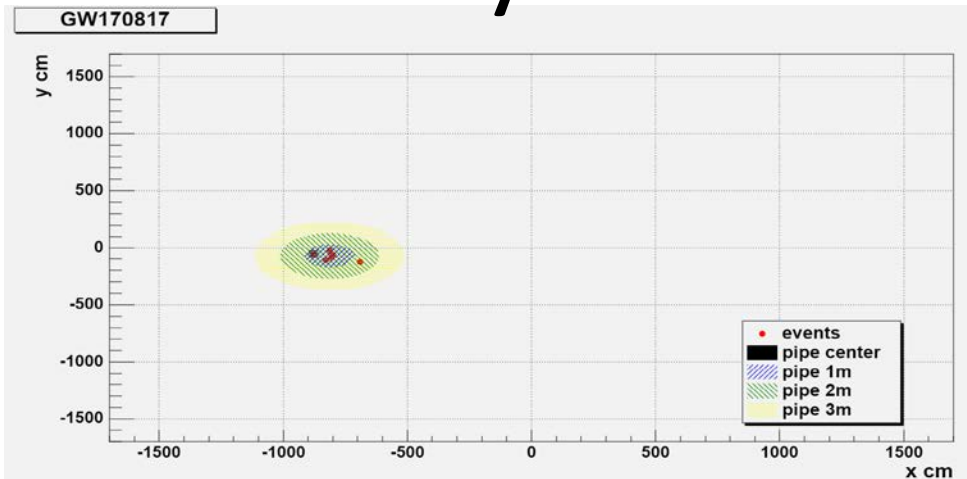
SKI -> SKII 事故により、PMTが半減

SKII -> SKIII PMTに衝撃波防止の為にAcrylic Coverを付けた上、11129本PMTが復帰

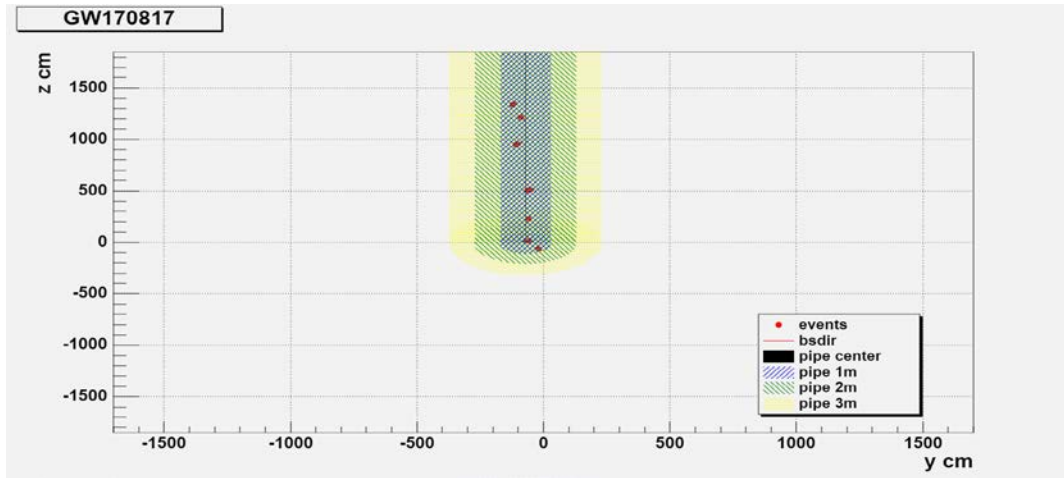
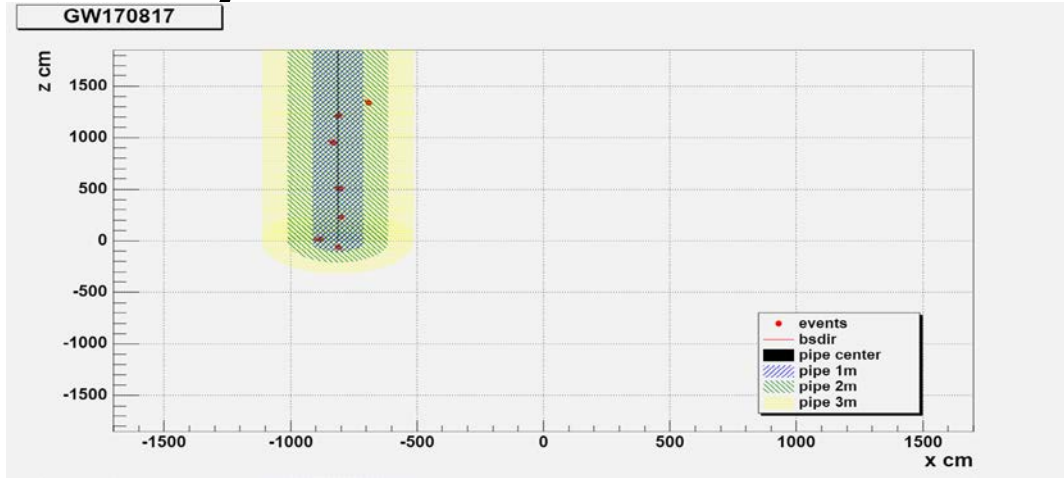
SKIII -> SKIV Electronicsのupgrade (ATM->QBEE, Hardware Trigger -> Software Trigger)

SKIV -> SK-Gd 硫酸ガドリニウム水和物($\text{Gd}_2(\text{SO}_4)_3 \cdot 15\text{H}_2\text{O}$)を超純水に溶かす

Vertex x-y of the 7 events

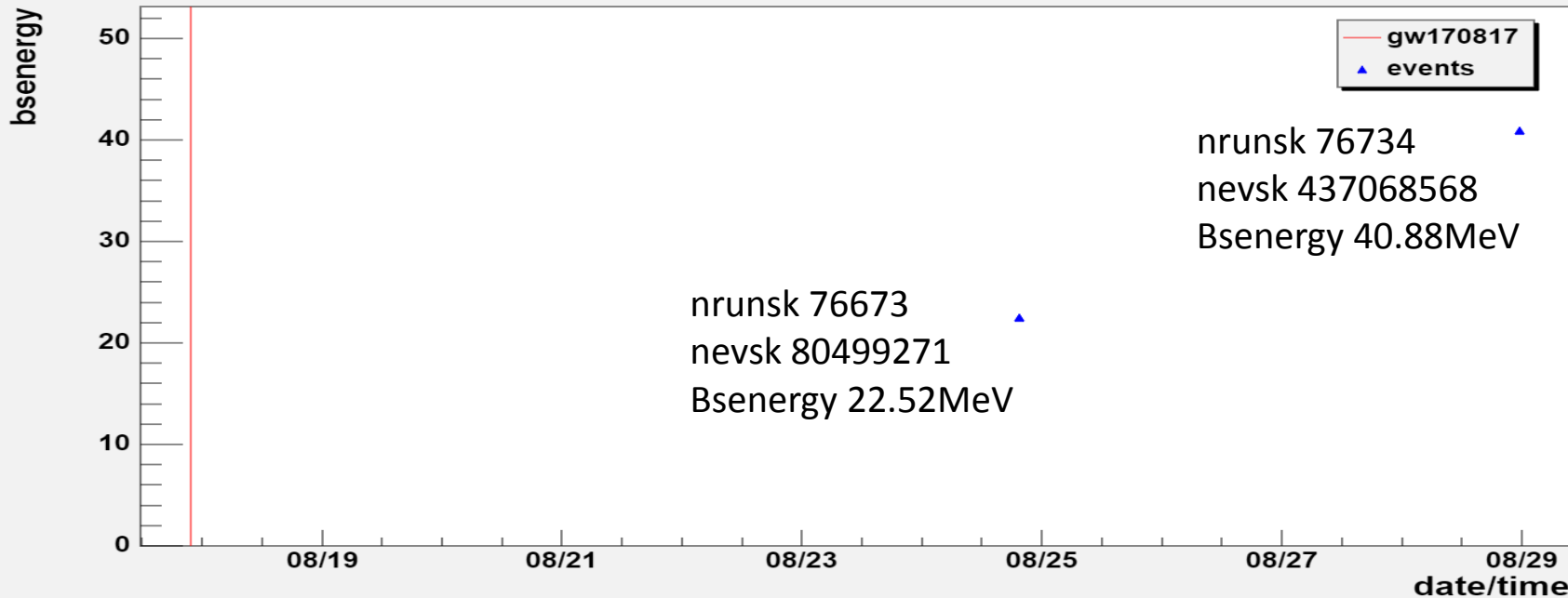


Vertex y-z and x-z of the 7 events

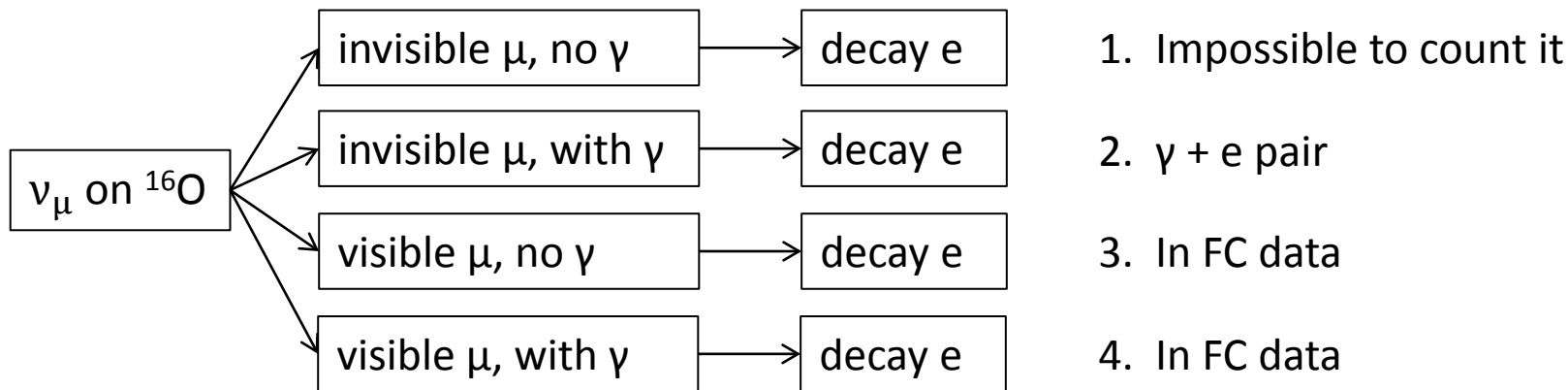


2 events left in relic sample in 14days after GW170817

cos to GW170817 0.0<bsenergy<999999.0 -1.00<cosgw<1.00 -1.000<tdiff_pre<999999999999999.000



CCQE cases and $\text{Br}(\gamma)$



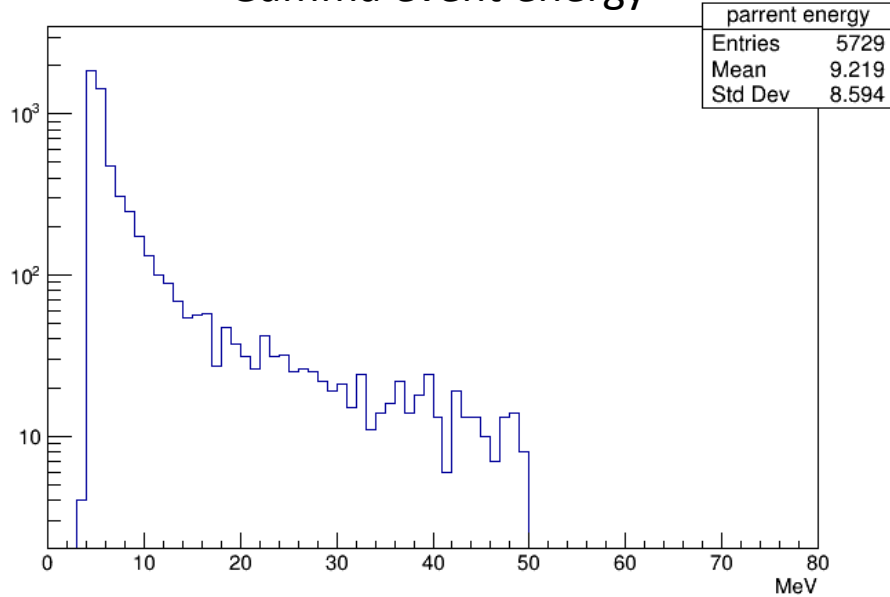
3&4を区別するのは可能。ただし、実際の場合、脱励起ガンマ線は単純の6MeVよりかなり複雑(6.18MeV、6.32MeV、9.93MeV)。

2の $\gamma + e$ pairを探して、脱励起ガンマ線のSampleを作る。

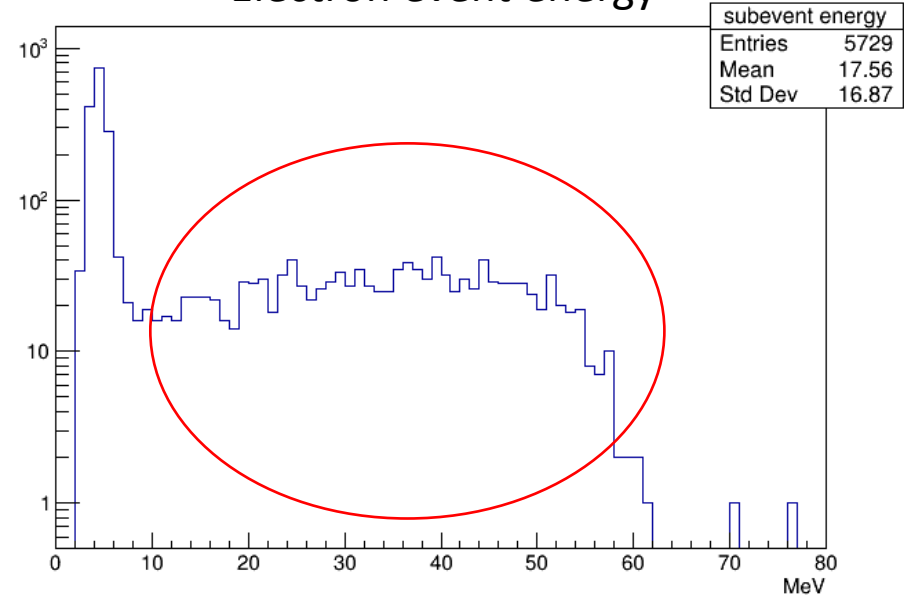
CCQE De-excitation γ in SK

1. γ が見付かれれば、後35 μ sのgateで全eventが記録される。
2. ただし、raw dataに戻るのは、計算機処理時間は現実的ではない(数ヶ月～半年程度)。
3. 6MeVはsolar neutrinoと同じenergy領域の為、この博士論文では、SK-IVの10年間のdataを利用し、solar reductionのfirst stepからstartした。

Gamma event energy



Electron event energy



Selections (all SKIV) :

Gamma event bsenergy < 50MeV

Electron event has and only has one sub-event in 35 μ s gate

very close to michel spectrum when > 15MeV

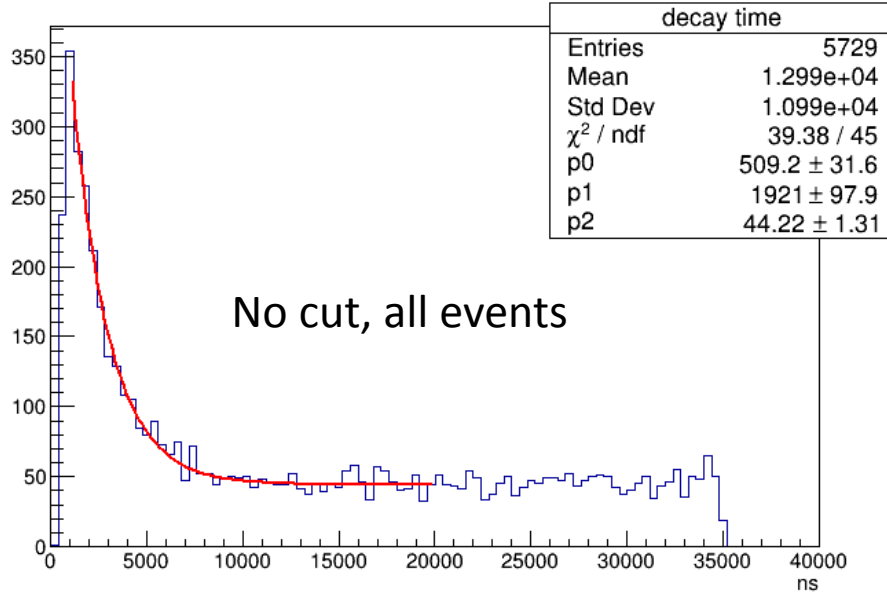
Other cuts included in solar reduction step:

bswallsk < 2m, ltimediff < 50 μ s, spalogleike < 4.517.....

Decay time

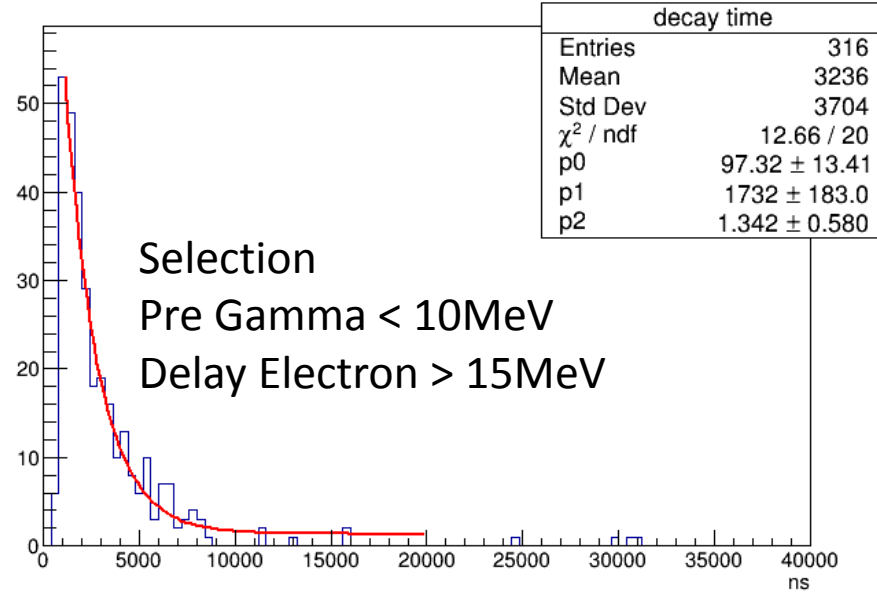
$$\text{Fit by : } f(x) = p0 \times e^{\frac{-x}{p1}} + p2$$

decay time



No cut, all events

decay time



Selection

Pre Gamma < 10MeV

Delay Electron > 15MeV

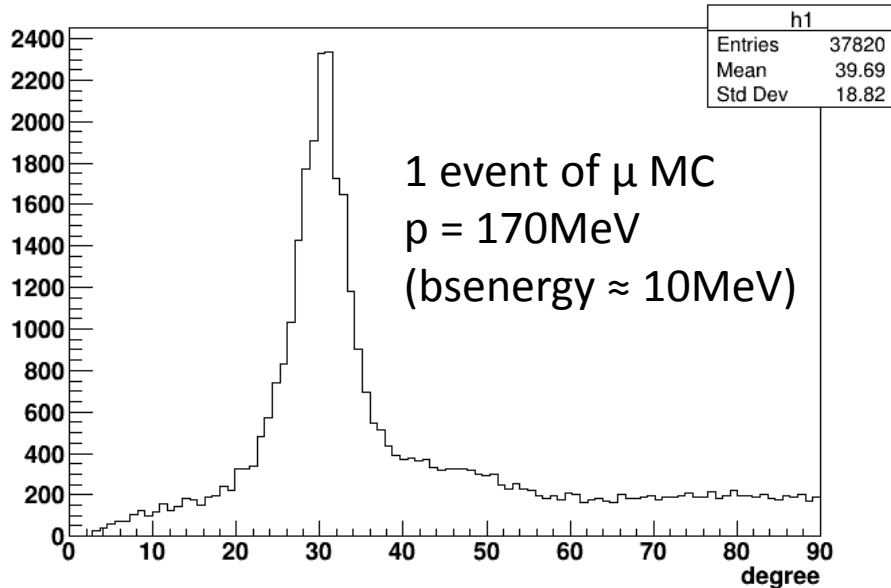
Most of the background are removed by energy selection.

New problem : The “Pre-Gamma” can be weak muons close to Cherenkov Threshold!

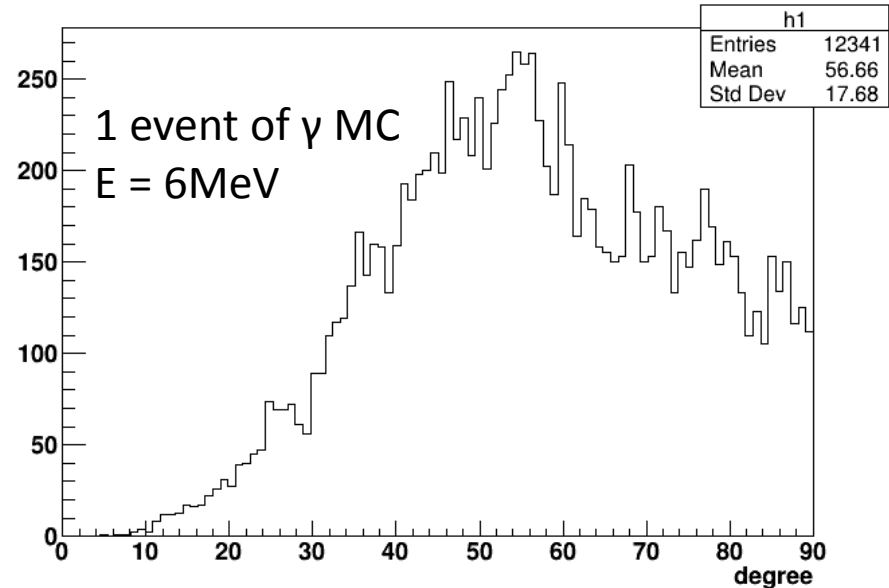
Cherenkov Angle Fit

1. Select PMT hits in 15ns time window by T-ToF
2. Calculate the angle from vertex to the triangle of all 3-PMT sets
3. Search for the highest position by taking the sum of near 7-bins

Opening Cherenkov Angle from 3-PMT combinations

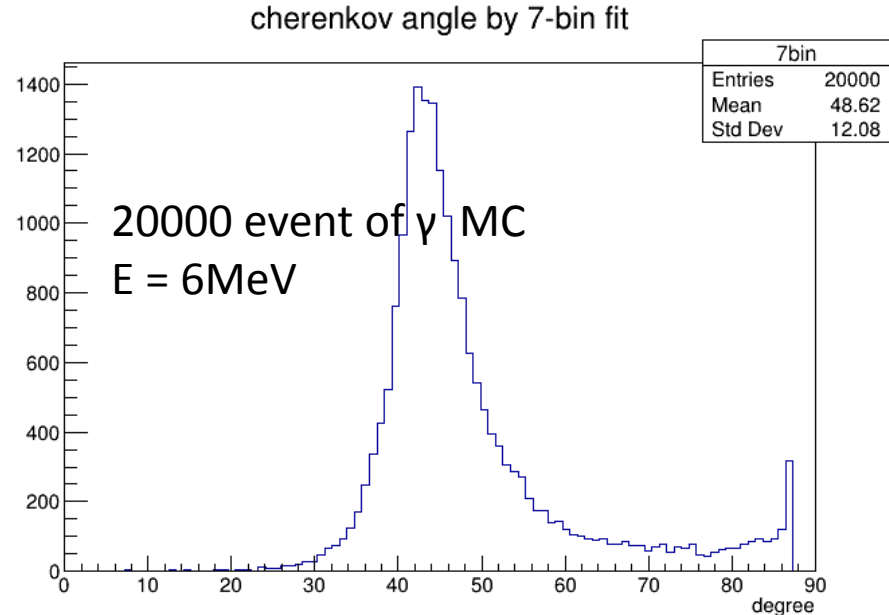
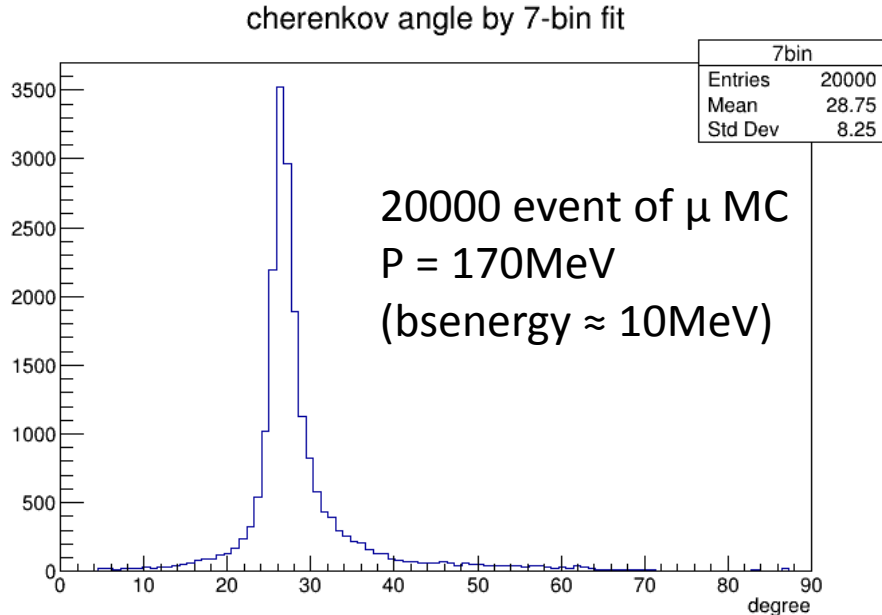


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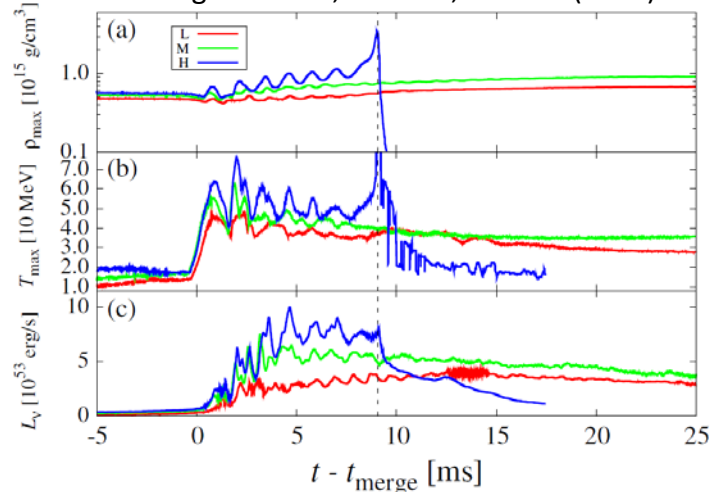


ν (MeV) Emission from NS-NS merger

Thermal ν from NS-NS merger

1. $e^- e^+$ production from thermal photon
2. $\nu_e/\bar{\nu}_e$ from e capture by nuclei :
 $e^- + p \rightarrow \nu_e + n$, $e^+ + n \rightarrow \bar{\nu}_e + p$
3. $\nu_x/\bar{\nu}_x$ from $e^- e^+$ annihilation
 $e^+ + e^- \rightarrow \nu_x + \bar{\nu}_x$
4. Spectrum can be approximated by Fermi-Dirac Dis.
5. Most of energy emitted in 10ms, by ν in 10~30MeV

Y. Sekiguchi et al., PRL 107, 051102 (2011)



K. Kyutoku, K. Kashiya, arXiv:1710.05922

