

A05班合宿 超新星爆発ニュートリノ

2013年1月8日

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contents

- Supernova (SN) neutrino burst
 - introduction
 - detection studies at Super-Kamiokande
 - other experiments
- Latest result of a search for relic SN neutrinos at SK
- Neutron tagging studies at SK
 - Gd tests

SN neutrino burst

Importance of Supernova Neutrino Detection

How do core-collapse supernovae explode?

How do they form neutron stars and black holes?

What are the nucleosynthesis products of supernovae?

What are the actions and properties of neutrinos?

What is the cosmic rate of black hole formation?

Which supernova-like events make neutrinos?

What else is out there that makes neutrinos?

....

We cannot solve key problems without detecting supernova neutrinos

Only neutrinos can reveal the interior conditions of collapsing stars

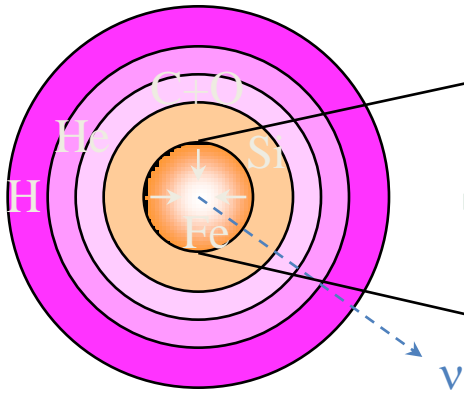
Detecting even a few neutrinos could often give decisive answers

Will open new frontiers in observational neutrino astrophysics

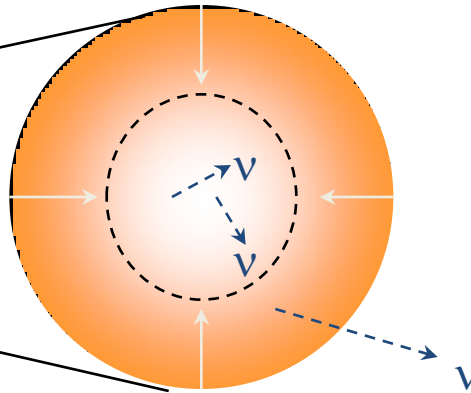
Core-collapse supernova

Standard scenario of the core-collapse supernova

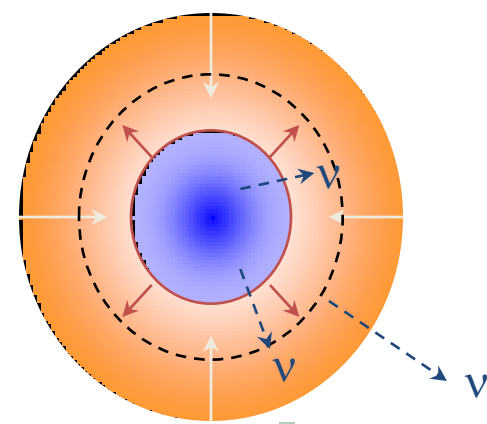
Core-collapse



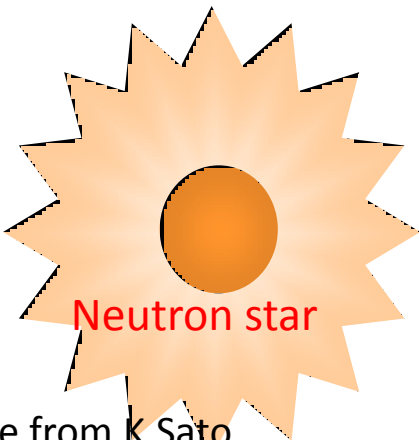
Neutrino trapping



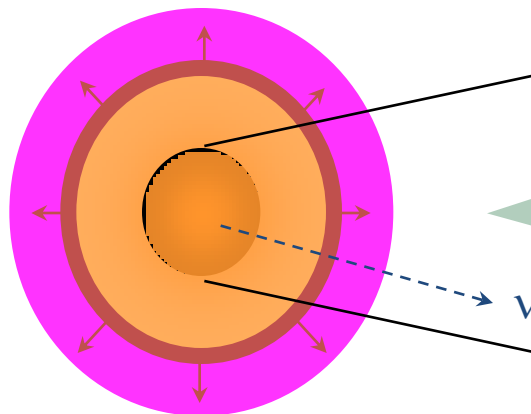
Core bounce



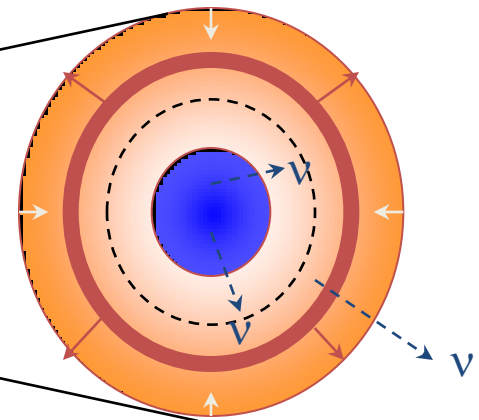
Supernova burst



Shock wave propagation

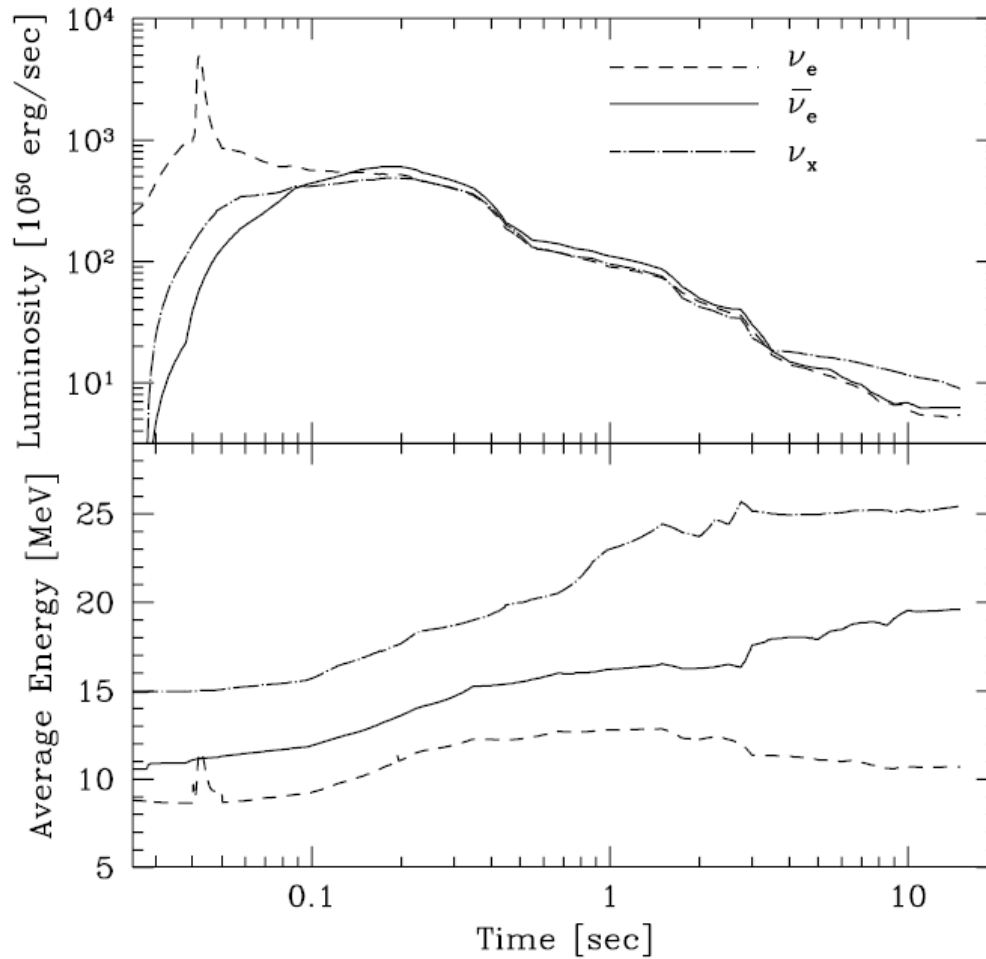


Shock wave at core



超新星爆発(SN)ニュートリノバースト

- 爆発のエネルギーの99%がニュートリノとして放出される。
 - $E_{\text{tot}} \sim 10^{53} \text{ erg} = 10^{46} \text{ J} = 6.2 \times 10^{58} \text{ MeV}$
 - 1つあたりのニュートリノエネルギーを10 MeVだとすると、 6.2×10^{57} 個のニュートリノ。
 - 太陽の核子(陽子+中性子)の数 $\sim 10^{57}$ 個
- ニュートリノバーストの時間は約10~20秒。
 - 銀河付近でSNがおきるのは~30年に一回。
 - 確率 $\sim 10^{-8}$
 - 宝くじ1等が当たる確率 $\sim 10^{-7}$
 - 日本の内閣総理大臣になる確率 $\sim 10^{-8}$



$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$

SN1987A

Sanduleak -69 202



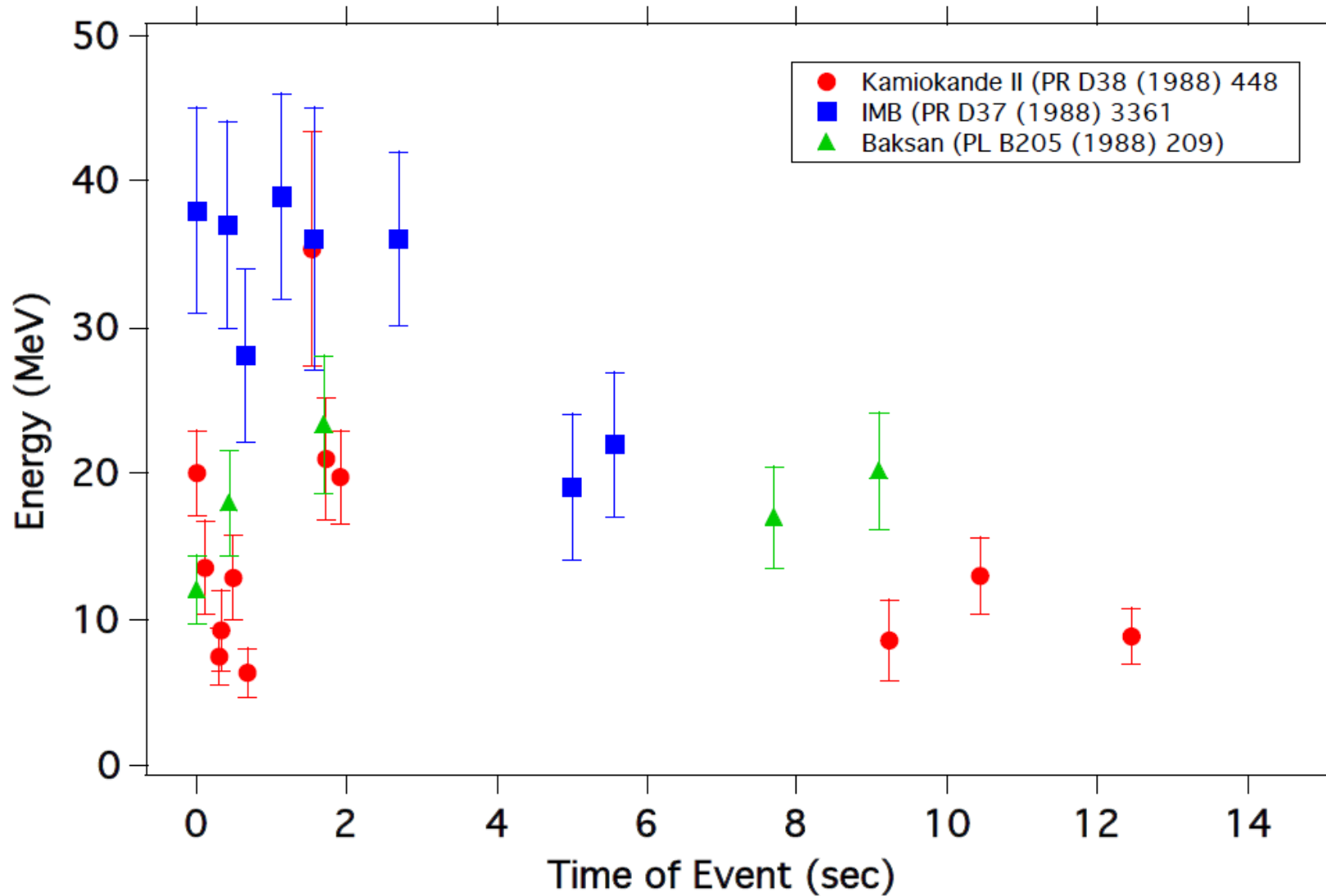
Supernova 1987A

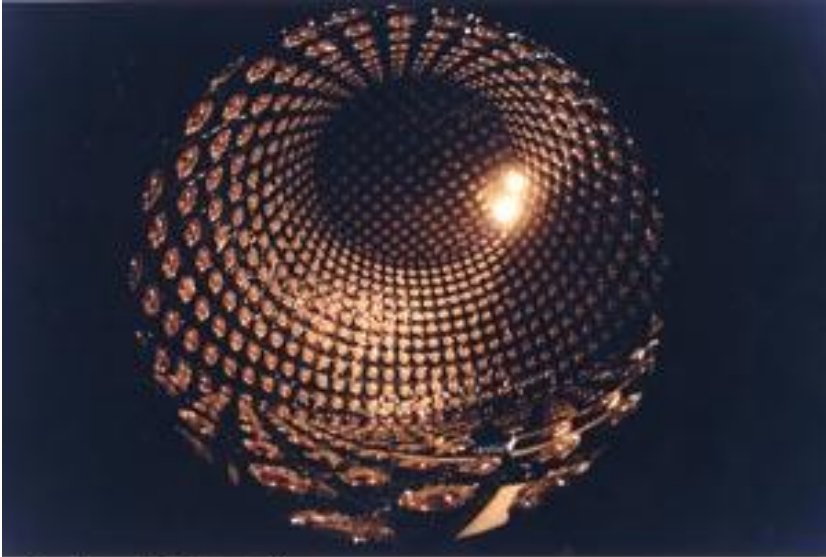
23 February 1987



George Herzberg, Alan Sandulek, and the University of Michigan

SN1987A





カミオカンデ

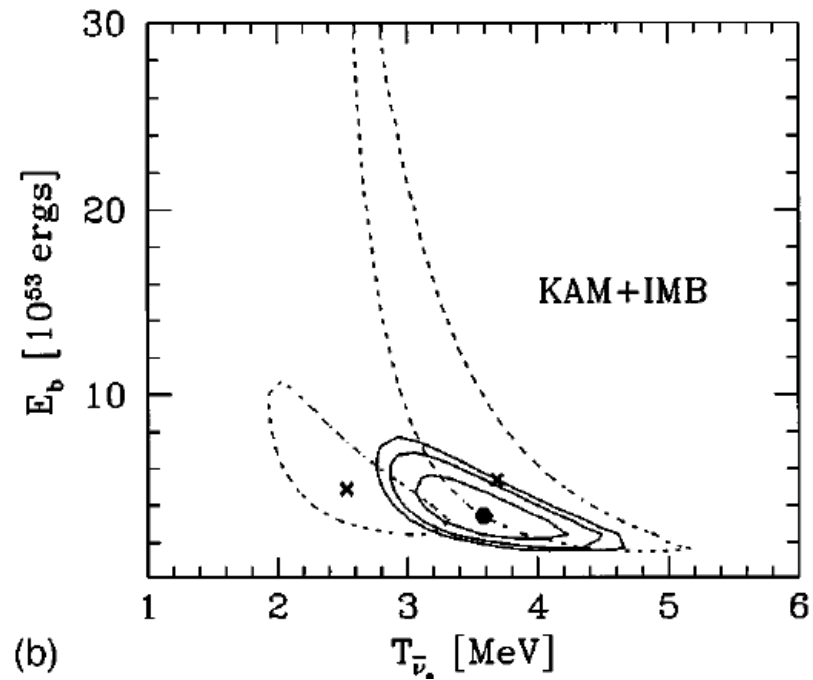
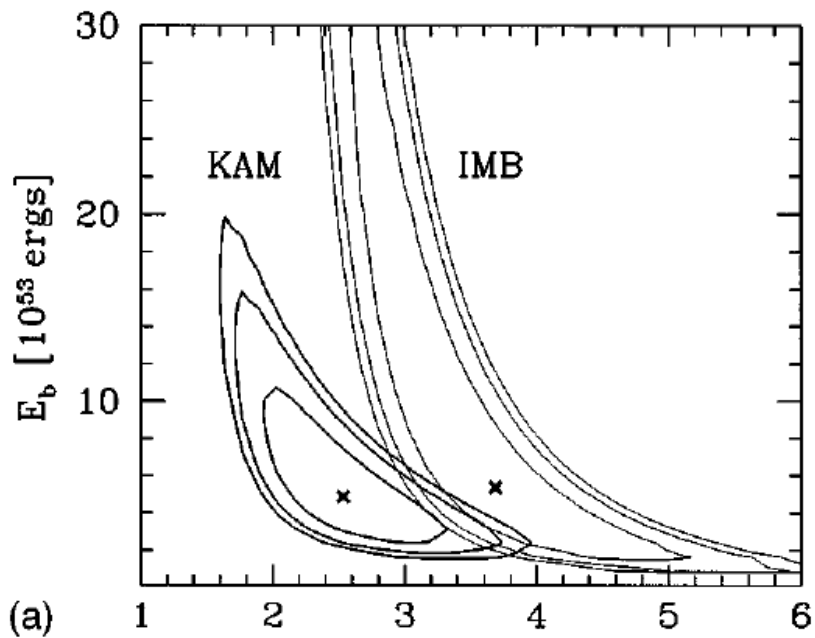


IMB

Irvine-Michigan-Brookhaven



Baksan



B. Jegerlehner, F. Neubig and G. Raffelt, Phys. Rev. D 54 (1996) 1194.

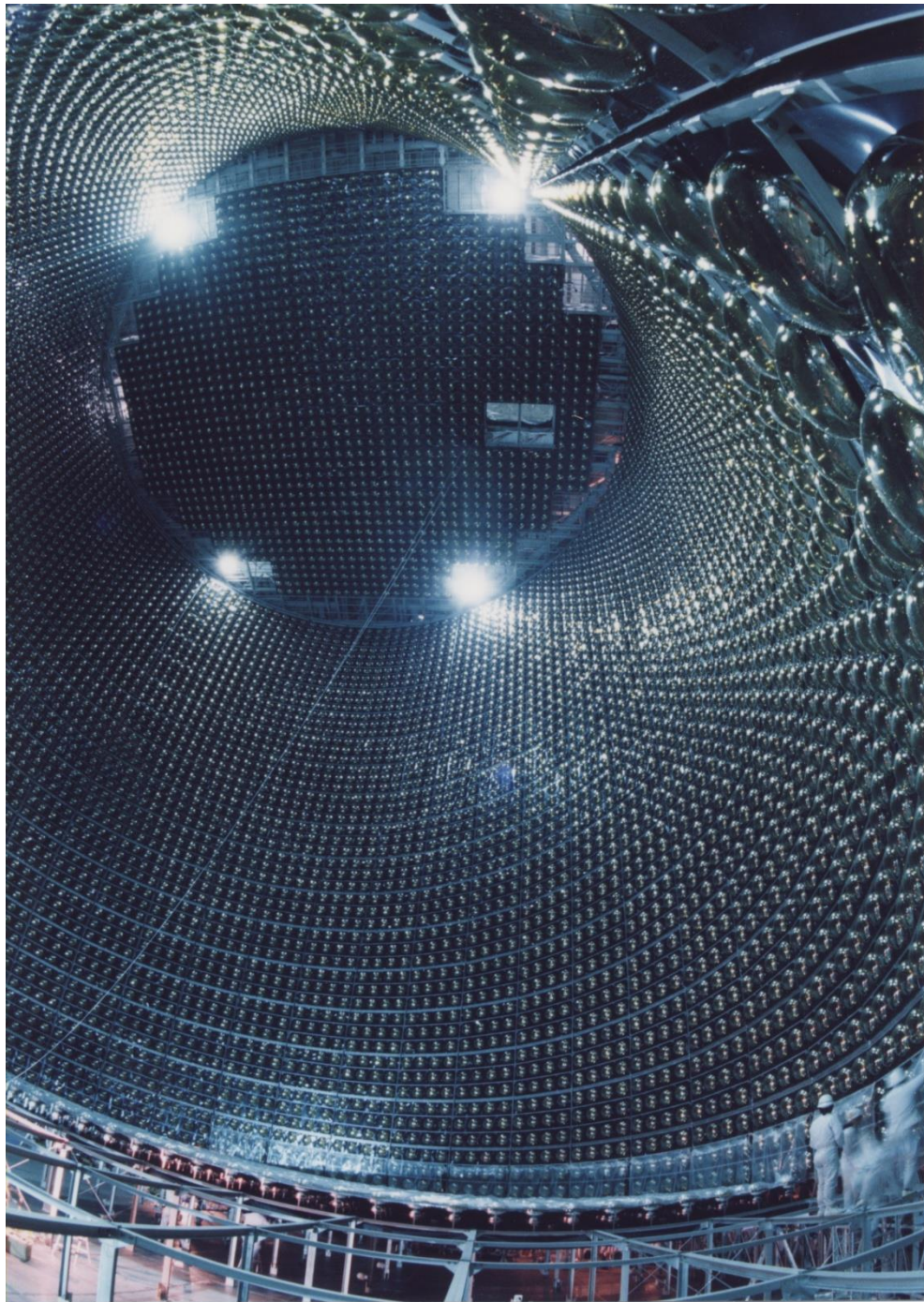
Summary of supernova neutrino detectors

| Detector | Type | Location | Mass (kton) | Events @ 8 kpc | Status |
|------------|--------------|------------|-------------|--------------------|----------------------|
| Super-K | Water | Japan | 32 | 8000 | Running (SK IV) |
| LVD | Scintillator | Italy | 1 | 300 | Running |
| KamLAND | Scintillator | Japan | 1 | 300 | Running |
| Borexino | Scintillator | Italy | 0.3 | 100 | Running |
| IceCube | Long string | South Pole | (600) | (10 ⁶) | Running |
| Baksan | Scintillator | Russia | 0.33 | 50 | Running |
| Mini-BOONE | Scintillator | USA | 0.7 | 200 | Running |
| Icarus | Liquid argon | Italy | 0.6 | 60 | Running |
| HALO | Lead | Canada | 0.079 | 20 | Under construction |
| NOvA | Scintillator | USA | 15 | 3000 | Construction started |
| SNO+ | Scintillator | Canada | 1 | 300 | Under construction |
| LBNE LAr | Liquid argon | USA | 34 | 3000 | Proposed |
| LBNE WC | Water | USA | 200 | 44,000 | Proposed |
| MEMPHYS | Water | Europe | 440 | 88,000 | Proposed |
| Hyper-K | Water | Japan | 540 | 110,000 | Proposed |
| LENA | Scintillator | Europe | 50 | 15,000 | Proposed |
| GLACIER | Liquid argon | Europe | 100 | 9000 | Proposed |

Galactic sensitivity

Extragalactic

plus reactor experiments, DM experiments...



スーパーカミオカンデ (SK)

- 岐阜県飛騨市神岡町池の山地下1000mに設置
- 純水50kton (有効体積22.5kton)、光電子増倍管約12000本からなる世界最大の検出器
- 超新星爆発ニュートリノに世界最高感度

SKの歴史

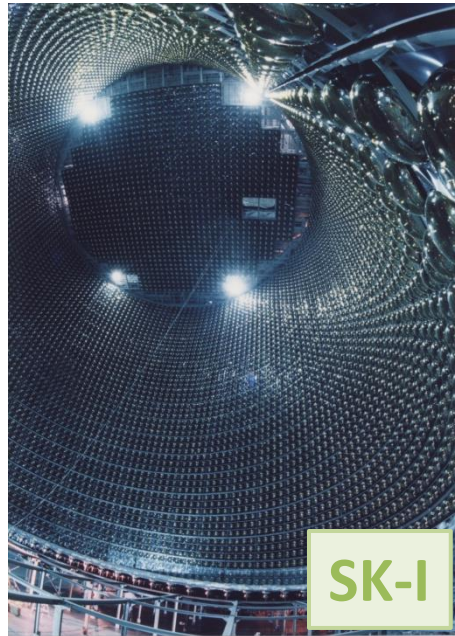
1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009

SK-I

SK-II

SK-III

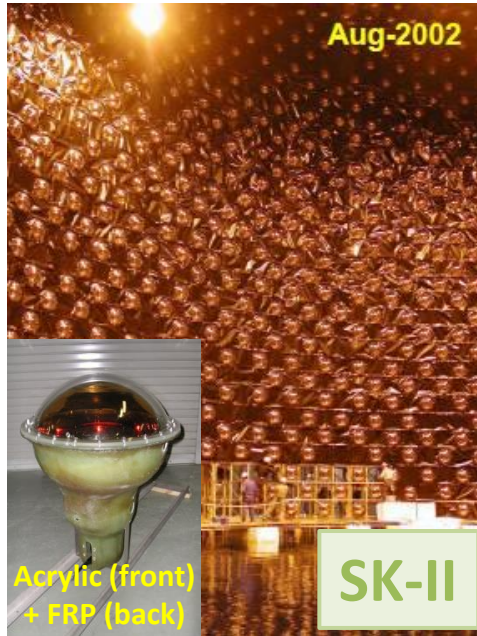
SK-IV



SK-I

11146 ID PMTs
(40% coverage)

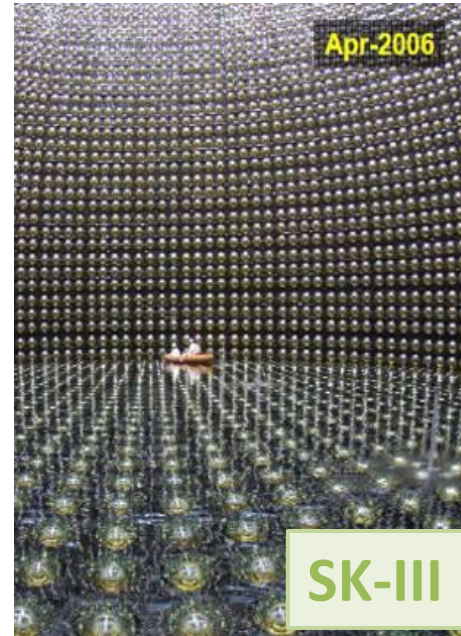
Energy
Threshold **5.0 MeV**
(total electron energy)



SK-II

5182 ID PMTs
(19% coverage)

7.0 MeV



SK-III

11129 ID PMTs
(40% coverage)

4.5 MeV
work in progress

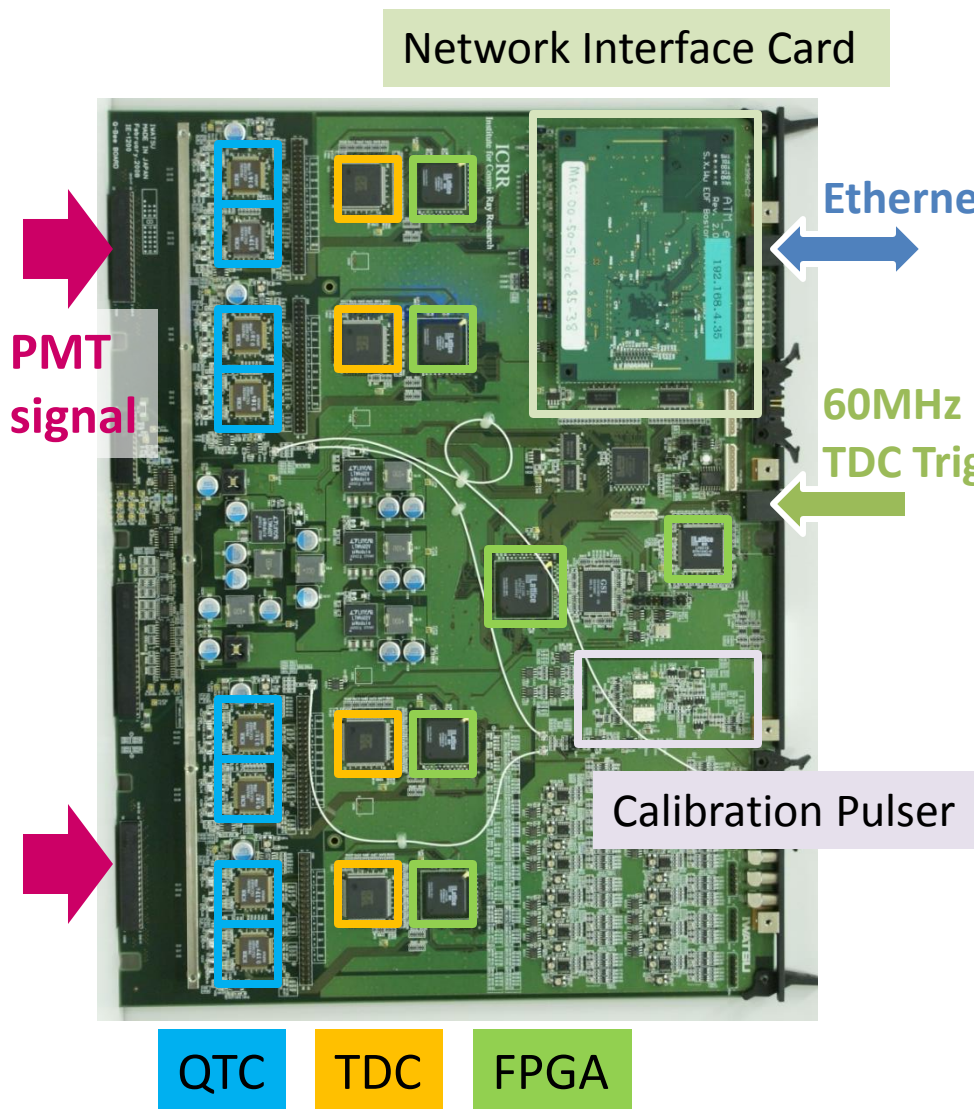


SK-IV

Electronics
Upgrade

< 4.0 MeV
target

SK IV の新電子回路(QBEE)



QTC-Based Electronics with Ethernet (QBEE)

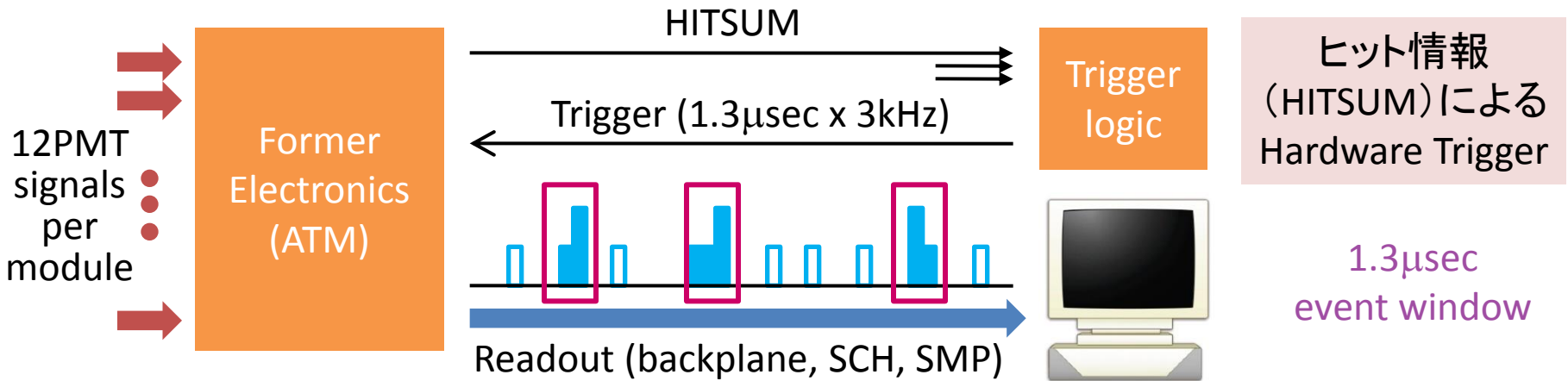
Ethernet Readout

- 24チャンネル入力
- QTC (custom ASIC)
- 60MHz Clock – 3段のゲインステージ
- TDC Trigger – 広いダイナミックレンジ (>2000pC)

H. Nishino *et al.*, NIMA 610, 710 (2009)

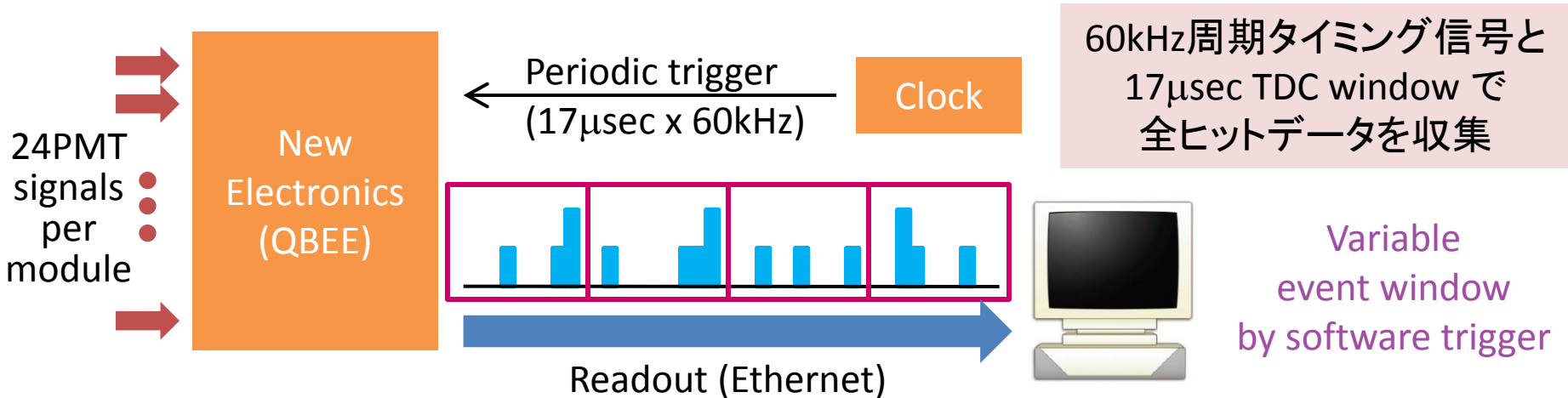
- パイプライン処理
 - multi-hit TDC (AMT3)
 - FPGA
- イーサネット読み出し
- 60MHzシステムクロック入力
- 内蔵キャリブレーションパルサー
- 低消費電力 (< 1W/ch)

SK-I, II, IIIでのデータ収集



SK-IVでのデータ収集

hardware triggerなし. all hitsを取得し、software triggersをかける。

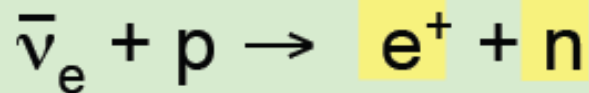


SKでのSN ニュートリノ観測

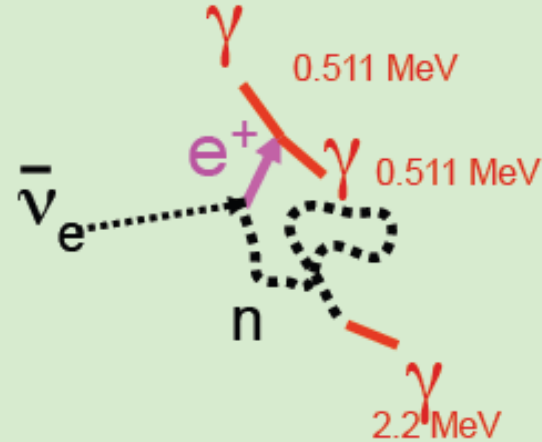
- 前もって応答を調べることは重要。
- シミュレーションによって応答を調べる。
 - Wilson model (Totani et al. ApJ 496, 216 (1998))を使用。
 - 事象数の特定
 - 逆ベータ崩壊
 - 電子弾性散乱
 - 方向の決定とその精度

Neutrino interactions in the few-tens-of-MeV range

Inverse Beta Decay (CC)



In any detector with lots of free protons (e.g. water, scint) this dominates

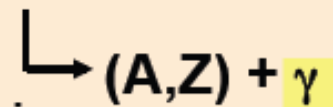
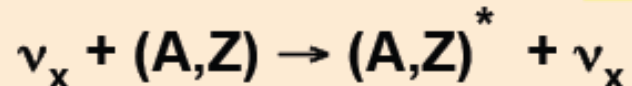
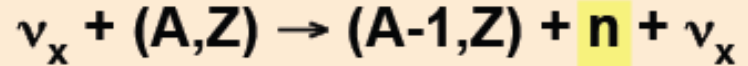


Elastic scattering on atomic electrons



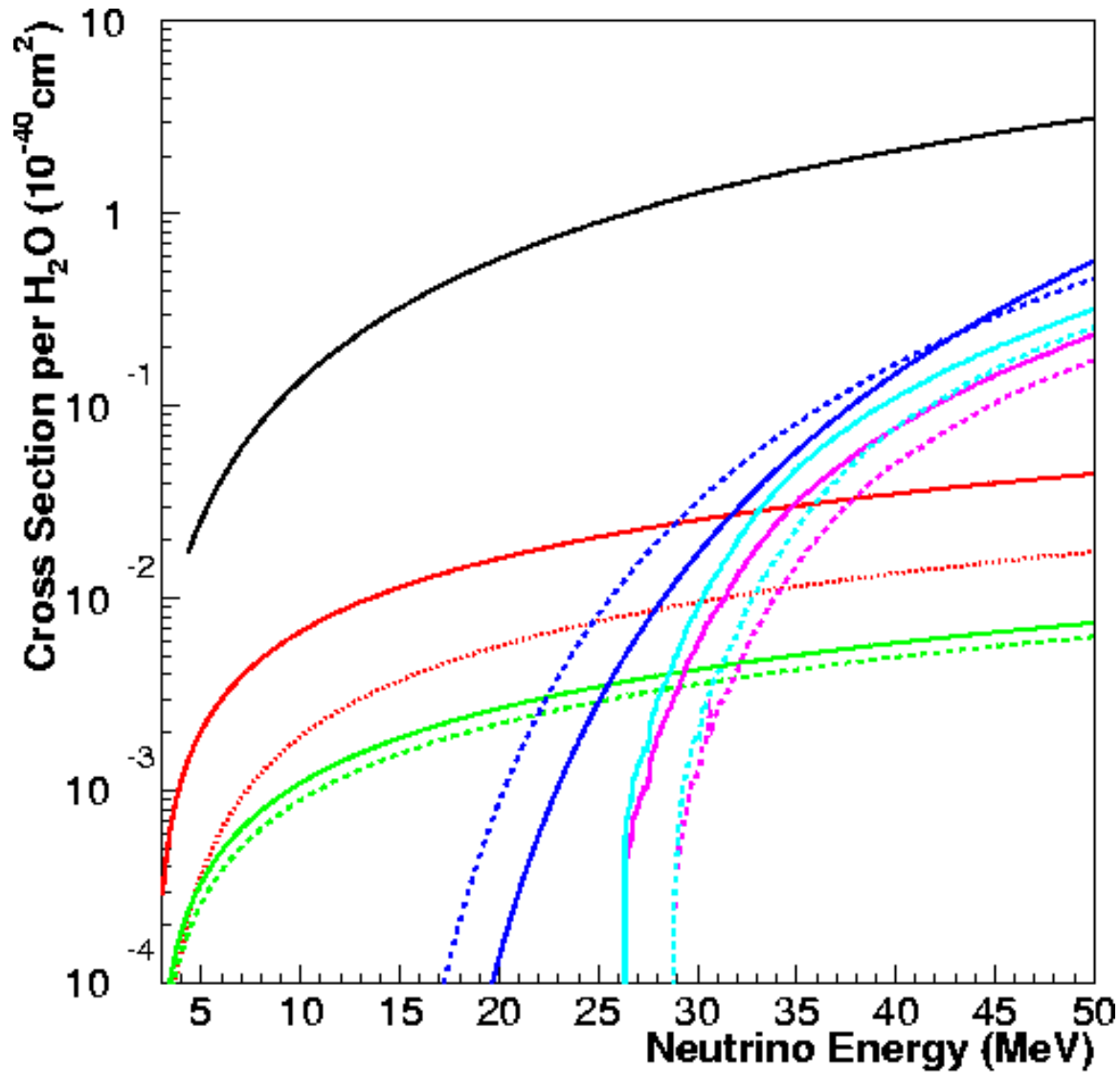
(useful for pointing)

CC and NC interactions on nuclei



+ NC coherent scattering

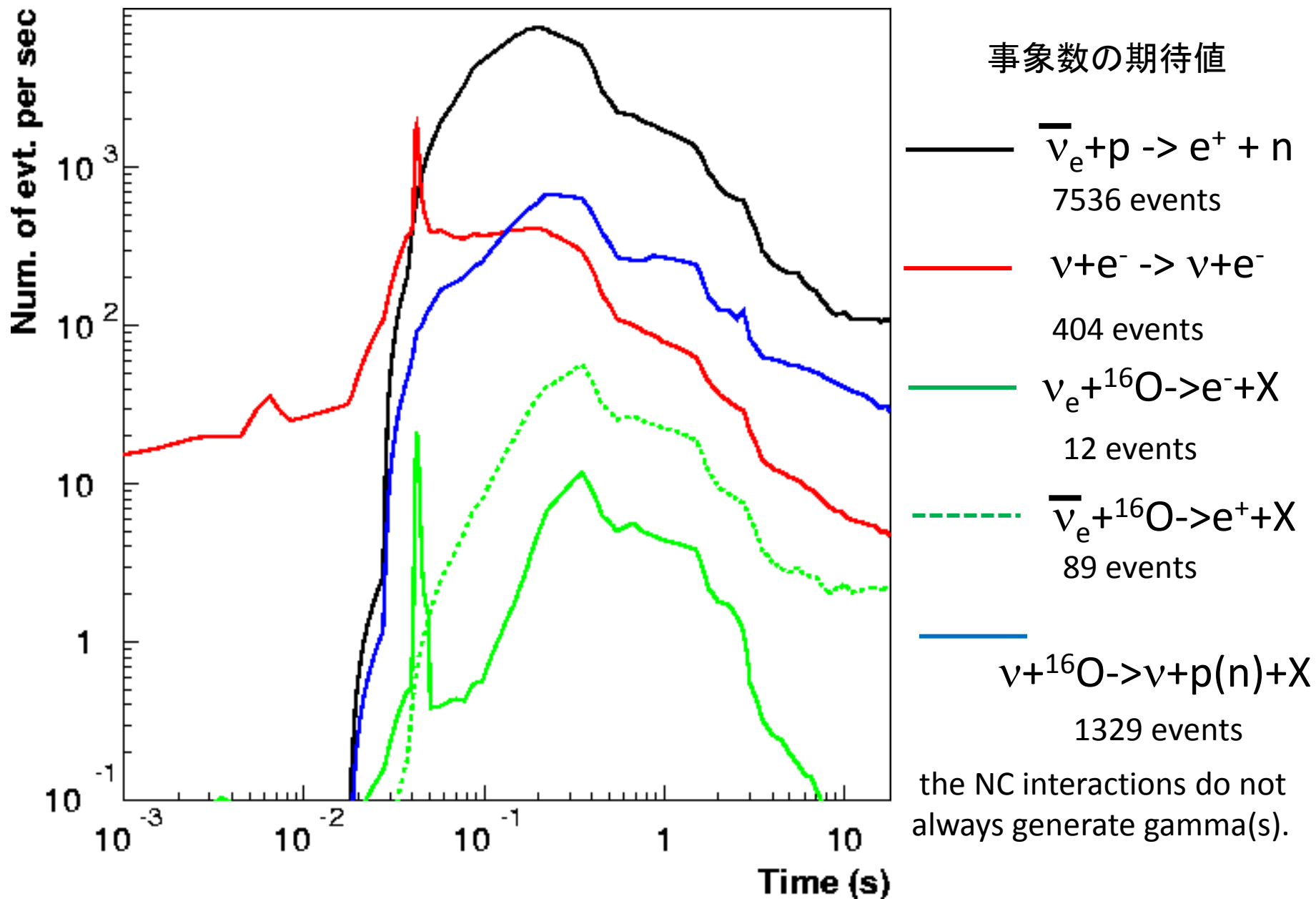
水との散乱断面積



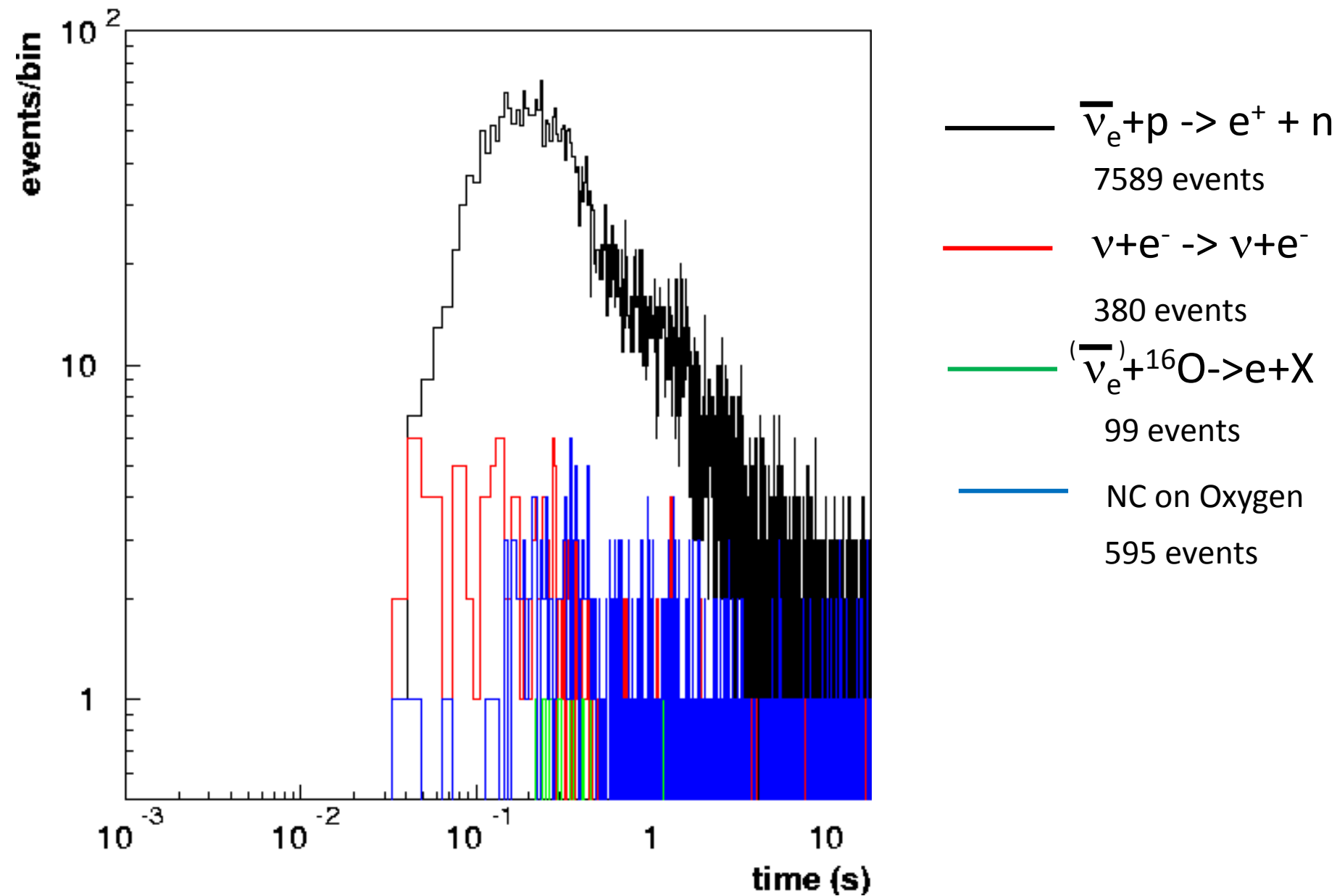
- $\bar{\nu}_e + p \rightarrow e^+ + n$
- $\nu_e + e^- \rightarrow \nu_e + e^-$
- - $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$
- $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$
- - $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$
- $\nu_e + {}^{16}\text{O} \rightarrow e^- + X$
- - $\bar{\nu}_e + {}^{16}\text{O} \rightarrow e^- + X$
- $\nu + {}^{16}\text{O} \rightarrow \nu + p + N'$
- - $\bar{\nu} + {}^{16}\text{O} \rightarrow \bar{\nu} + p + N'$
- $\nu + {}^{16}\text{O} \rightarrow \nu + n + O'$
- - $\bar{\nu} + {}^{16}\text{O} \rightarrow \bar{\nu} + n + O'$

NC cross sections are tentative.

10kpc SN でのニュートリノ事象数 (ニュートリノ振動無し)

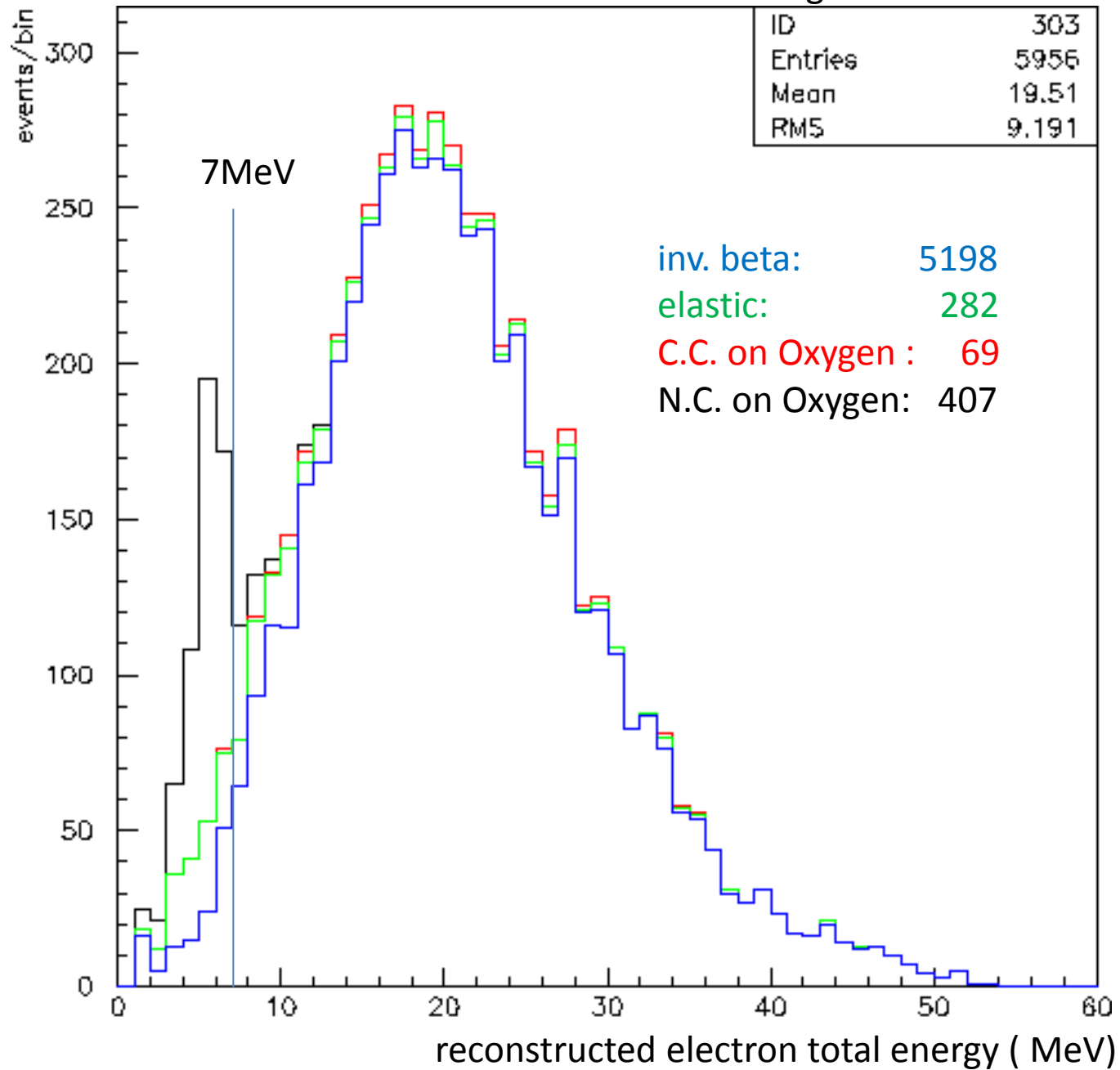


one SN MC sample for a 10kpc SN



d=10kpc w/o nu osc.

gdn>0.4 and fid. cuts are applied



method

a likelihood function is defined as $L = \exp\left(\sum_{k,r} N_r^k\right) \prod_i L_i$

where $L_i = \sum N_r^k p_r(E_i, \hat{d}_i; \hat{d}_{SN})$

$r = \bar{\nu}_e^r p, \nu e$, and $\bar{\nu}_e e$

$k = 1 \sim 5$ energy binning

$i =$ event index

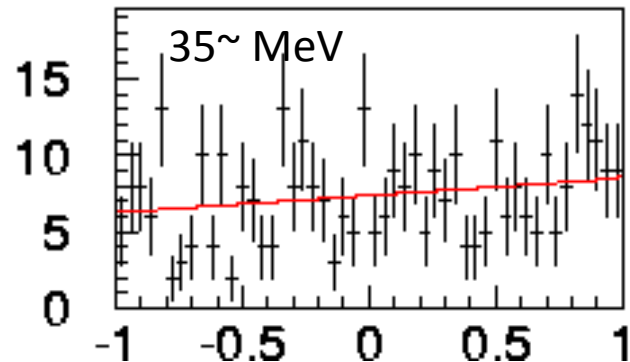
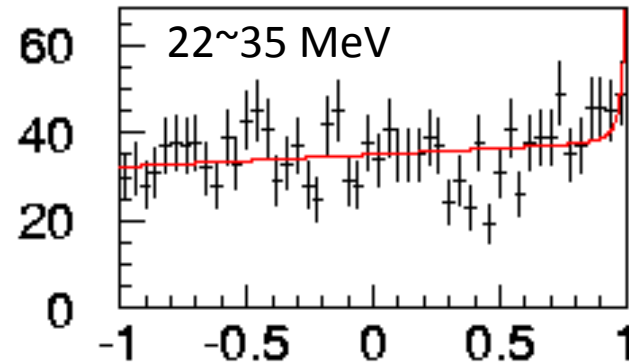
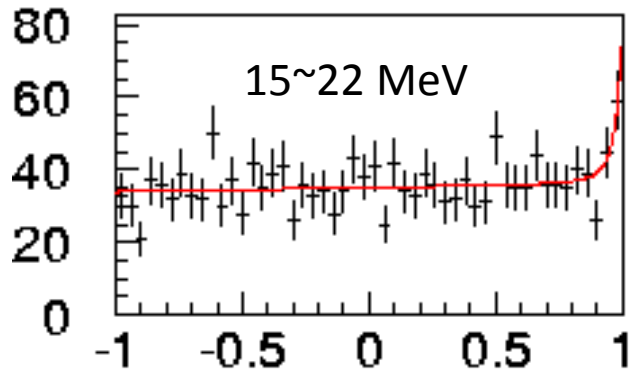
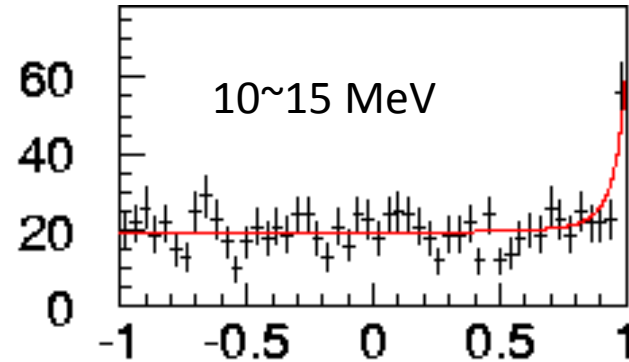
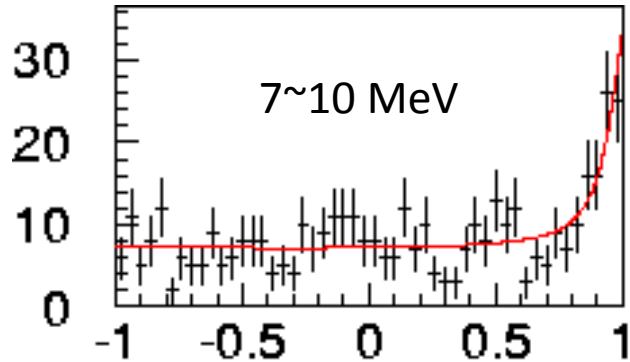
we impose a condition $N_{\bar{\nu}_e e}^k = \sum_m A^{km} N_{\bar{\nu}_e p}^m$

The matrix A and the p.d.f.s are obtained using a large SN MC sample. Note that this sample is NOT used for the pointing study.

We search for the values of N_r^k and d_{SN} that maximize the likelihood function, where the following condition is satisfied:

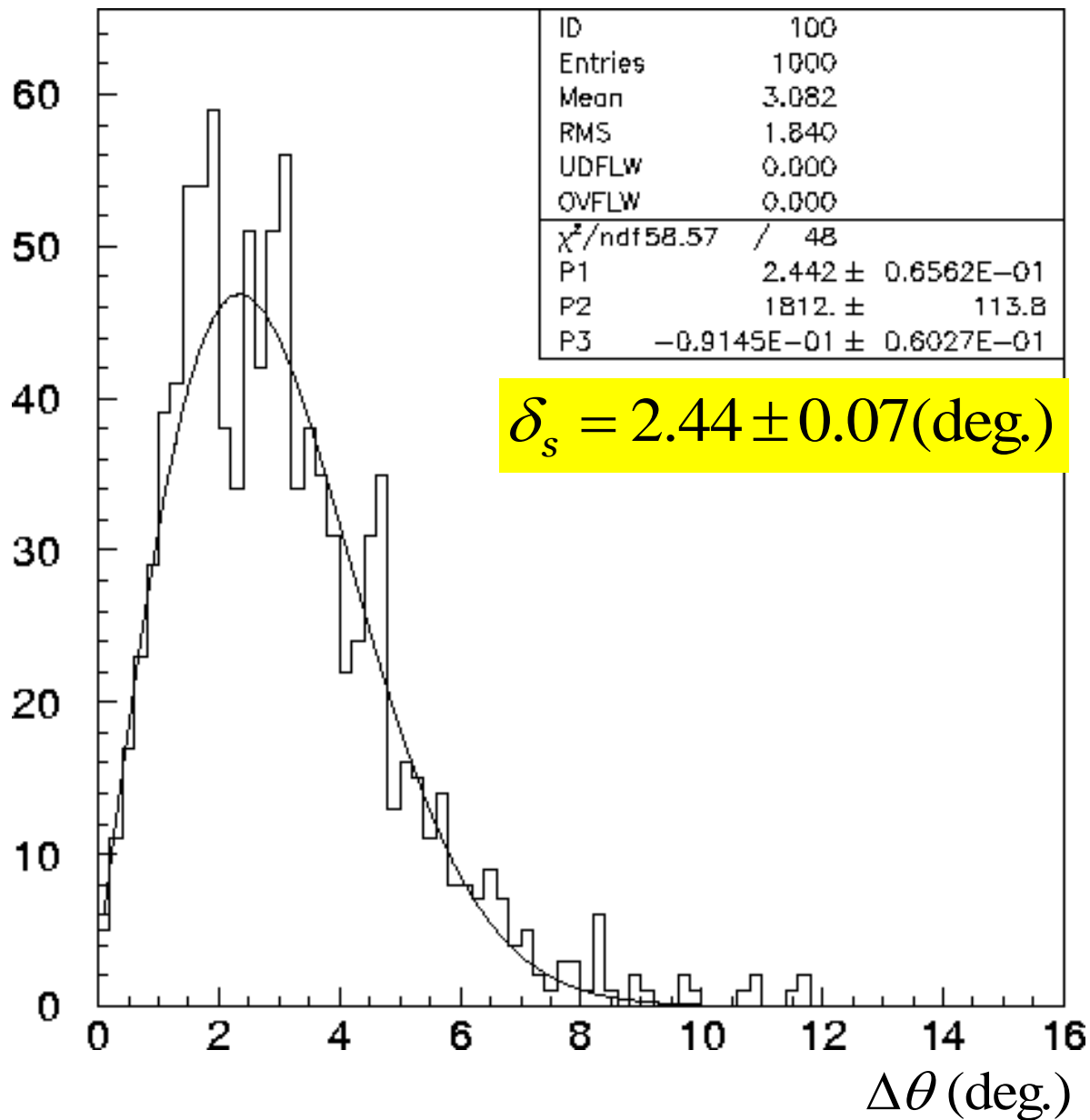
$$\frac{\partial L}{\partial N_r^k} = \frac{\partial L}{\partial \hat{d}_{SN}} = 0 \quad \text{In total, 12 parameters are varied.}$$

fit result for one sample of 10kpc SN MC w/o nu osc.

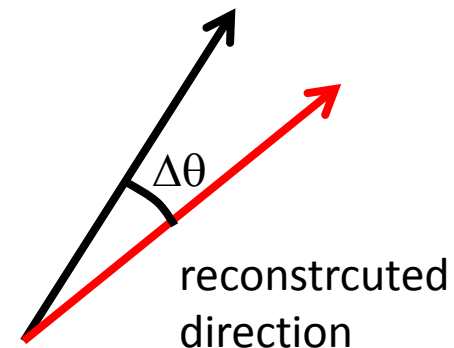


one minute to fit a one
MC sample (10kpc SN)
containing about 5000 events
in the fiducial volume.

fit results of 1000 MC samples w/o nu. osc.



true direction



a fit using a function

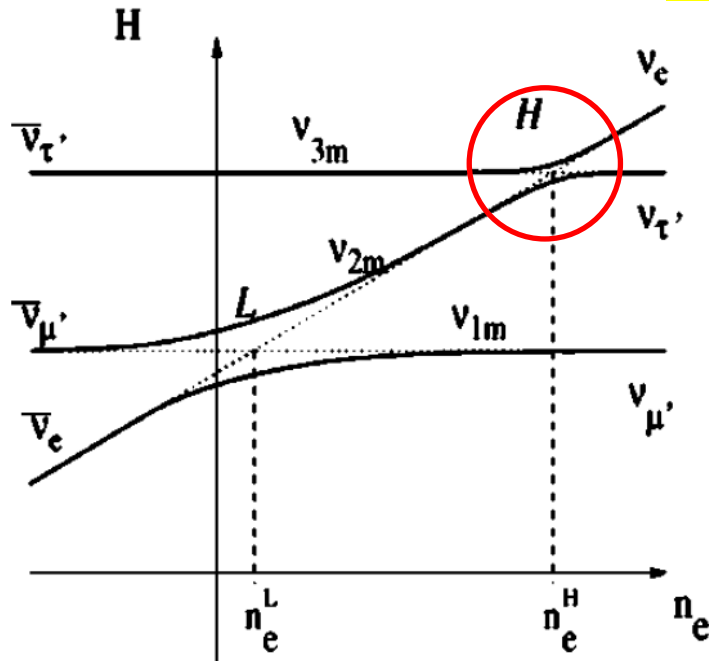
$$A \sin(\Delta\theta - \theta_b) \exp\left(-\frac{(\Delta\theta - \theta_b)^2}{2\delta_s^2}\right)$$

$$\theta_b = -0.09 \pm 0.06 \text{ deg.}$$

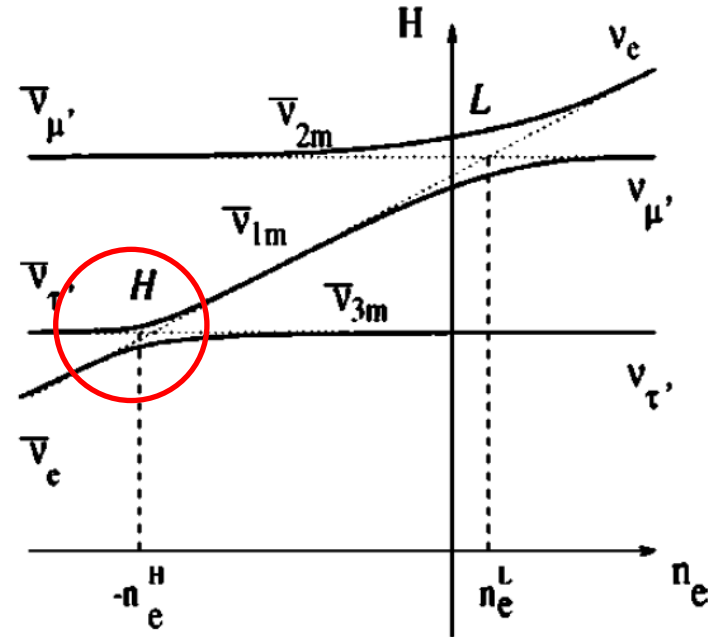
no bias in the direction

ニュートリノ振動を含めたシミュレーション

A. S. Dighe and A. Y. Smirnov PRD 62, 033007 (2000)



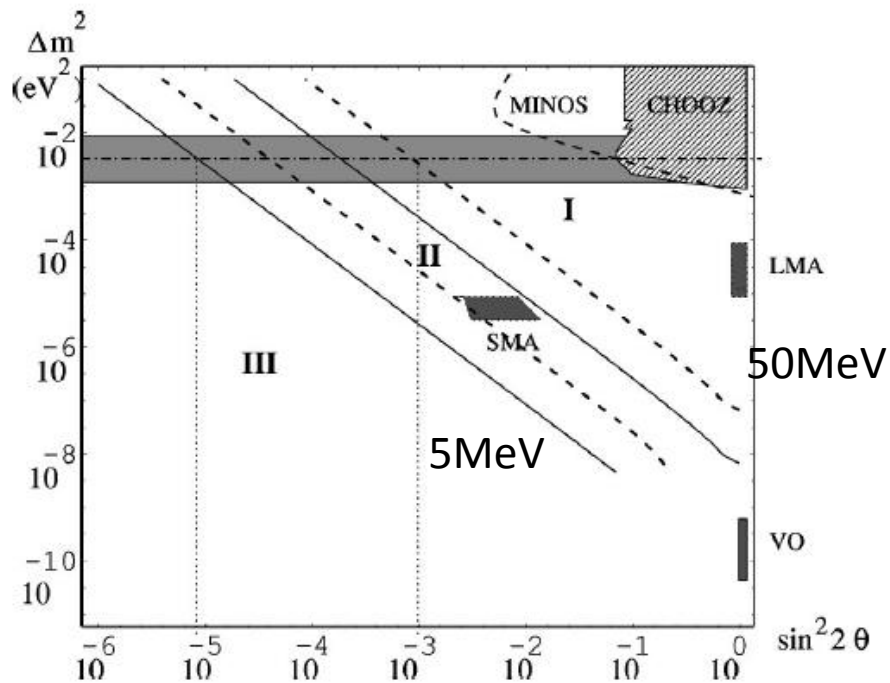
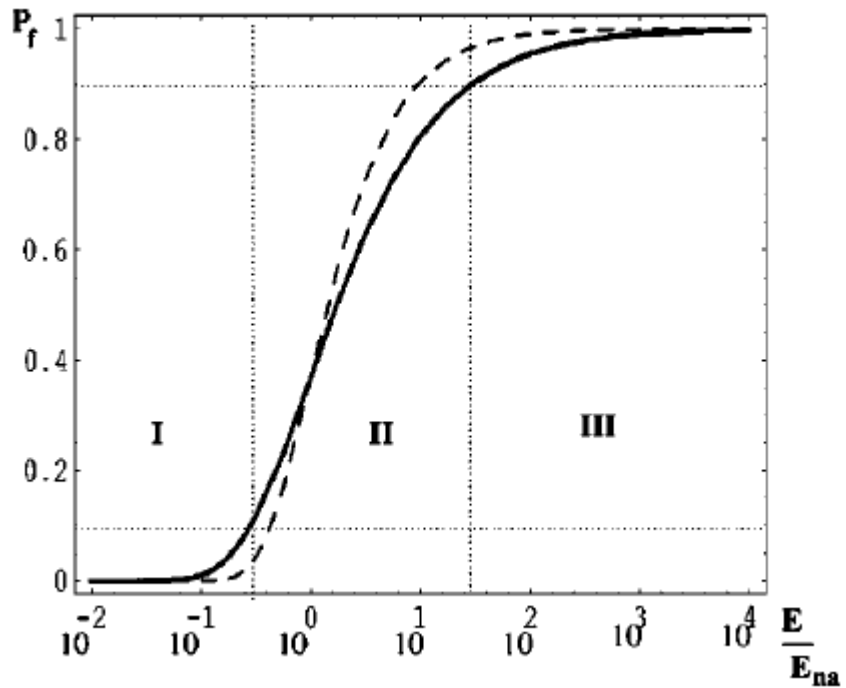
normal hierarchy



inverted hierarchy

$$P_f = \exp\left(-\frac{\pi}{2}\gamma\right) \quad \gamma \equiv \frac{\Delta m^2 \sin^2 2\theta}{2E \cos 2\theta} \frac{1}{(1/n_e)(dn_e/dr)}$$

P_H is related to $\sin 2\theta_{13}$



$$F_e = pF_e^0 + (1-p)F_x^0,$$

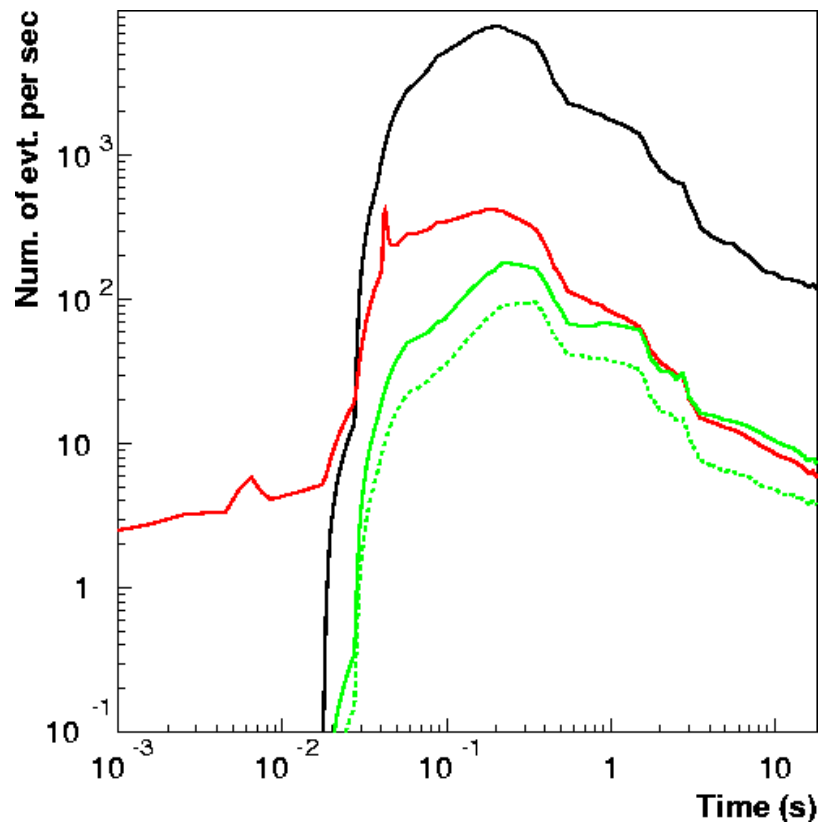
$$F_\mu + F_\tau = (1-p)F_e^0 + (1+p)F_x^0.$$

$$F_e^- = \bar{p}F_e^0 + (1-\bar{p})F_x^0,$$

$$F_\mu^- + F_\tau^- = (1-\bar{p})F_e^0 + (1+\bar{p})F_x^0$$

| | | p | \bar{p} |
|-----|----------|---------------------------|---------------------------------|
| LMA | Normal | $\sin^2 \theta_\odot P_H$ | $\cos^2 \theta_\odot$ |
| | Inverted | $\sin^2 \theta_\odot$ | $\cos^2 \theta_\odot \bar{P}_H$ |

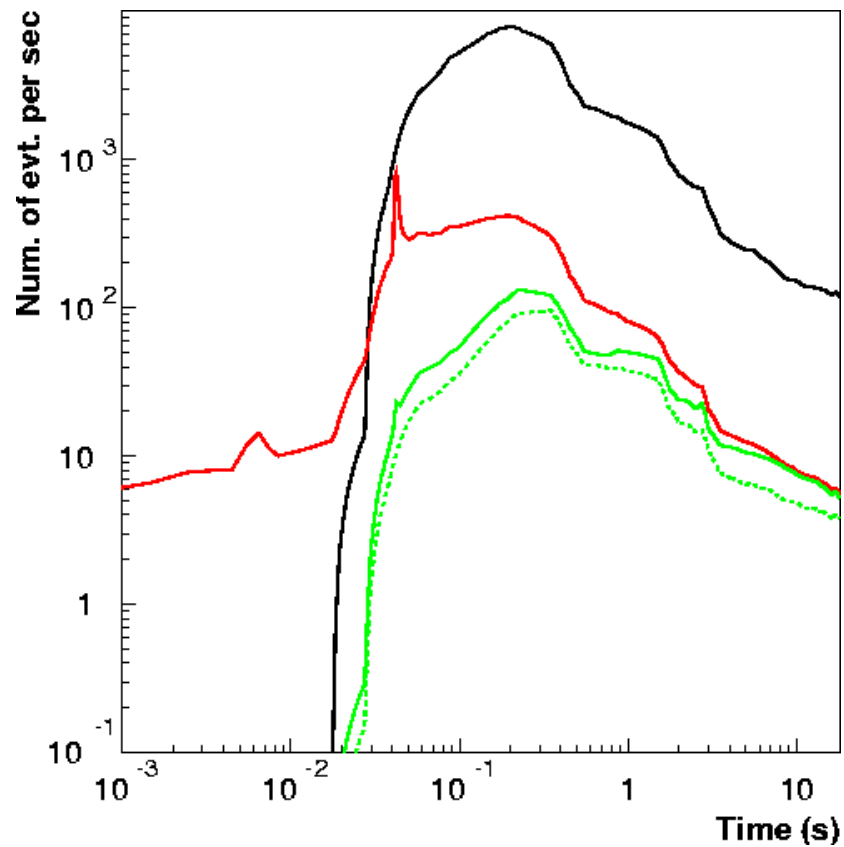
w/ neutrino oscillations
normal hierarchy $P_H=0$



— $\bar{\nu}_e + p \rightarrow e^+ + n$
8152 events

— $\nu + e^- \rightarrow \nu + e^-$
399 events

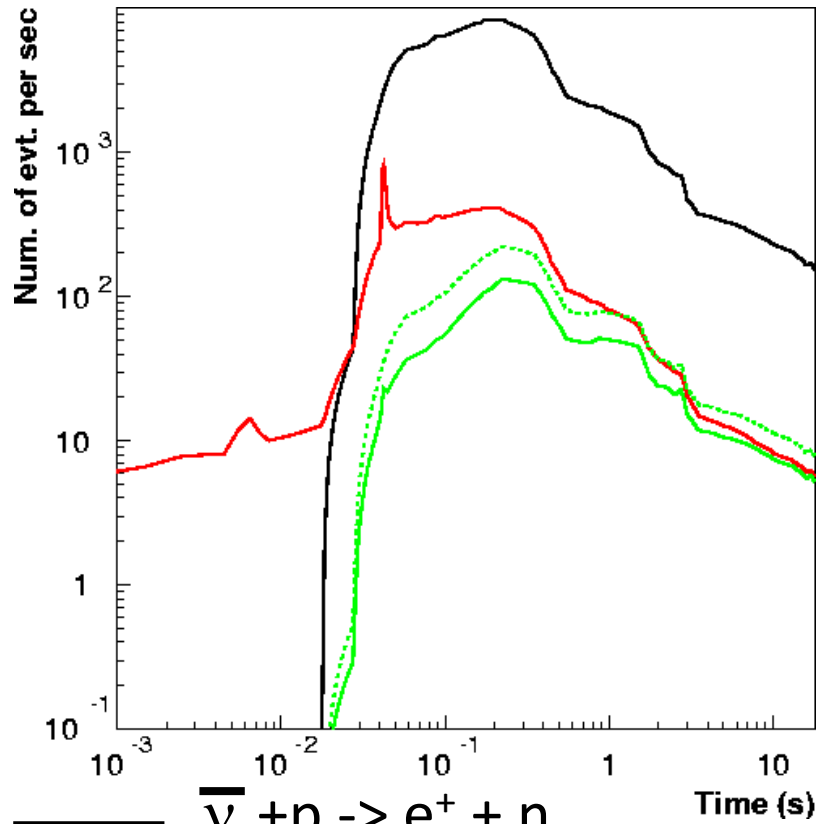
w/ neutrino oscillations
normal hierarchy $P_H=1$



— $\bar{\nu}_e + p \rightarrow e^+ + n$
8192 events

— $\nu + e^- \rightarrow \nu + e^-$
455 events

w/ neutrino oscillations
inverted hierarchy $P_H=0$

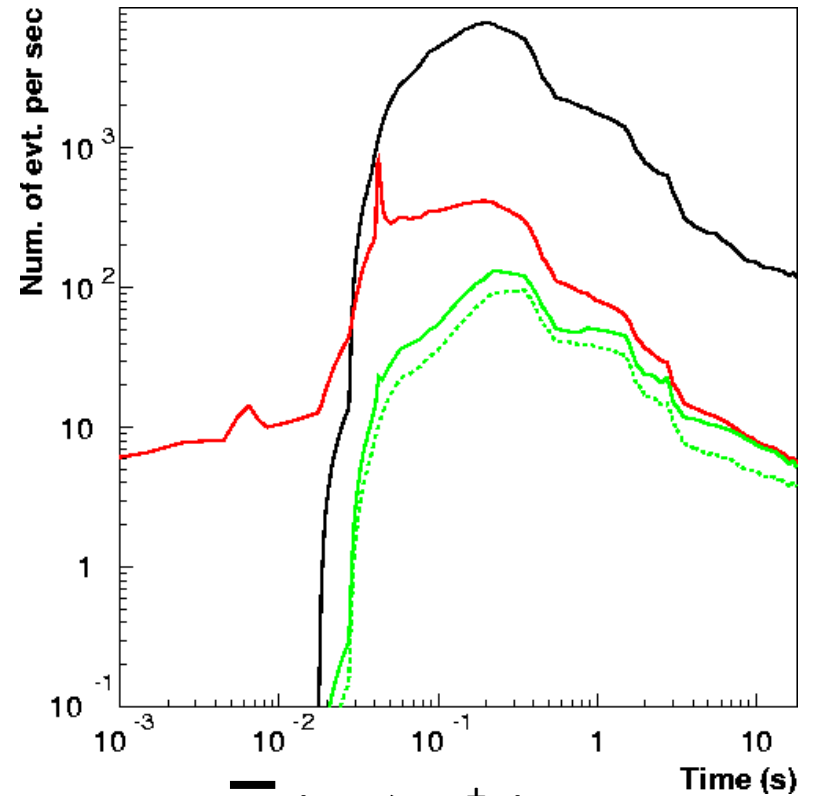


9754 events

$\nu + e^- \rightarrow \nu + e^-$

458 events

w/ neutrino oscillations
inverted hierarchy $P_H=1$

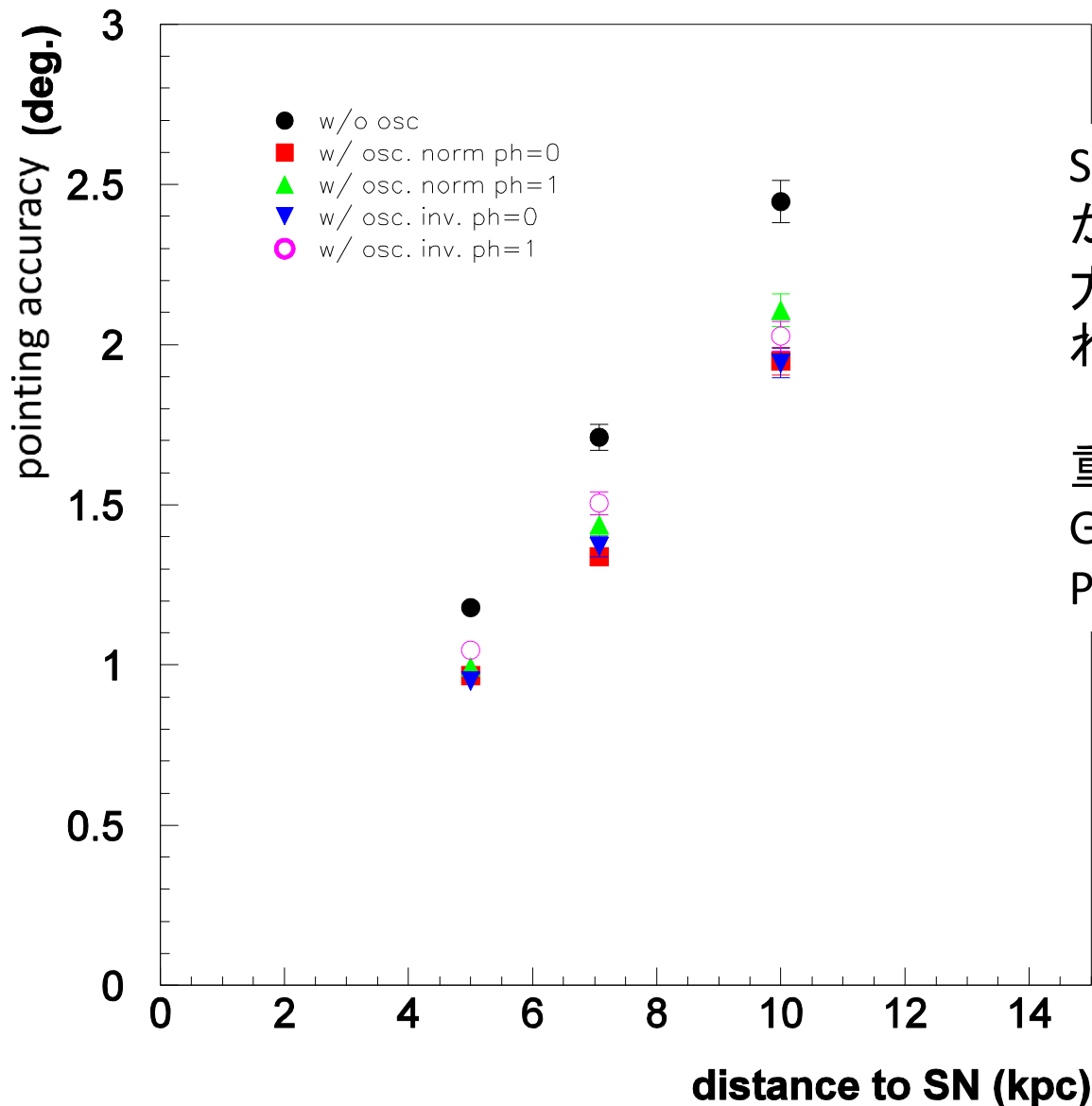


8214 events

$\nu + e^- \rightarrow \nu + e^-$

429 events

1000 SN MC simulations for each point



SKにおいて、ニュートリノのみから方向決定可能。
方向決定精度をさらにあげられるか検討中。

重力波検出においても重要：
G. Pagliaroli et al.
PRL 103, 031102 (2009).

Signal for Supernova ν_μ and ν_τ Neutrinos in Water Čerenkov Detectors

K. Langanke, P. Vogel and E. Kobe, Phys. Rev. Lett. 76 (1996) 2629

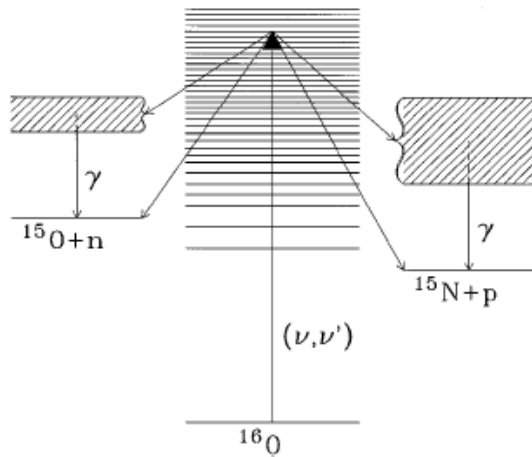
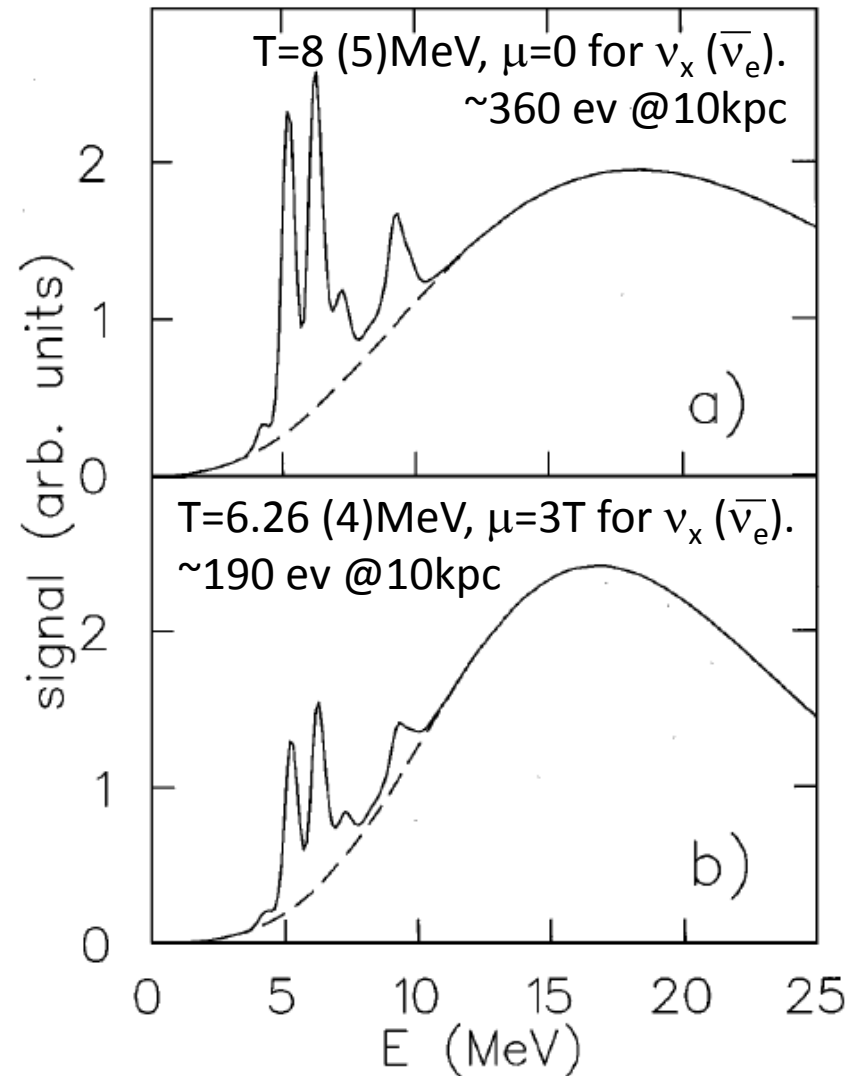
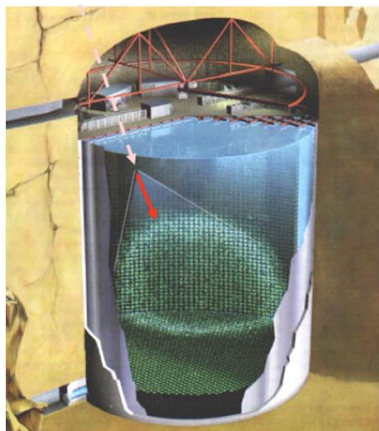


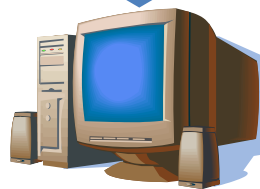
FIG. 1. Schematic illustration of the detection scheme for supernova ν_μ and ν_τ neutrinos in water Čerenkov detectors.



SKにおける超新星爆発即時モニター



生データ

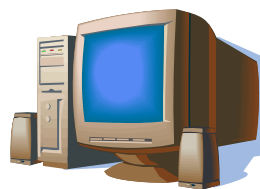


real time process

事象のフィットを行う。
データ取得後5~10分
後に完了。

SK実験シフトは365日24時間
これらのプロセスが動いている
かどうかモニターしている。

フィットされた
データ



Supernova watch

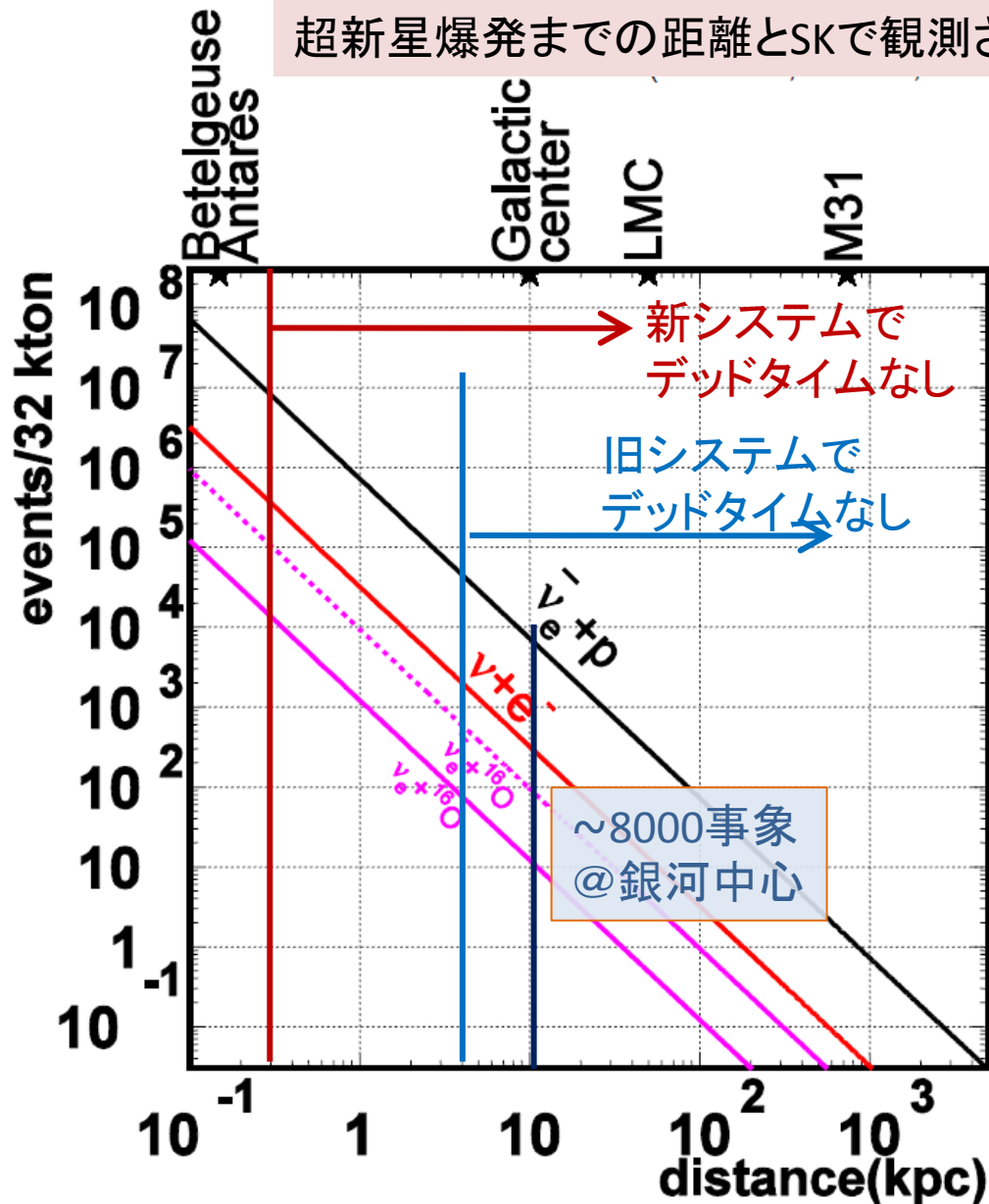
事象の時間的なクラスター
探す。フィットされてから約
20秒で完了。

もし、時間的なクラスターが
見つかったら、エキスパート
に電子メール(PCと携帯)を
自動的に配信。



新電子回路システム導入による検出器性能向上

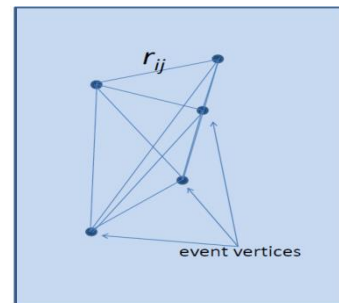
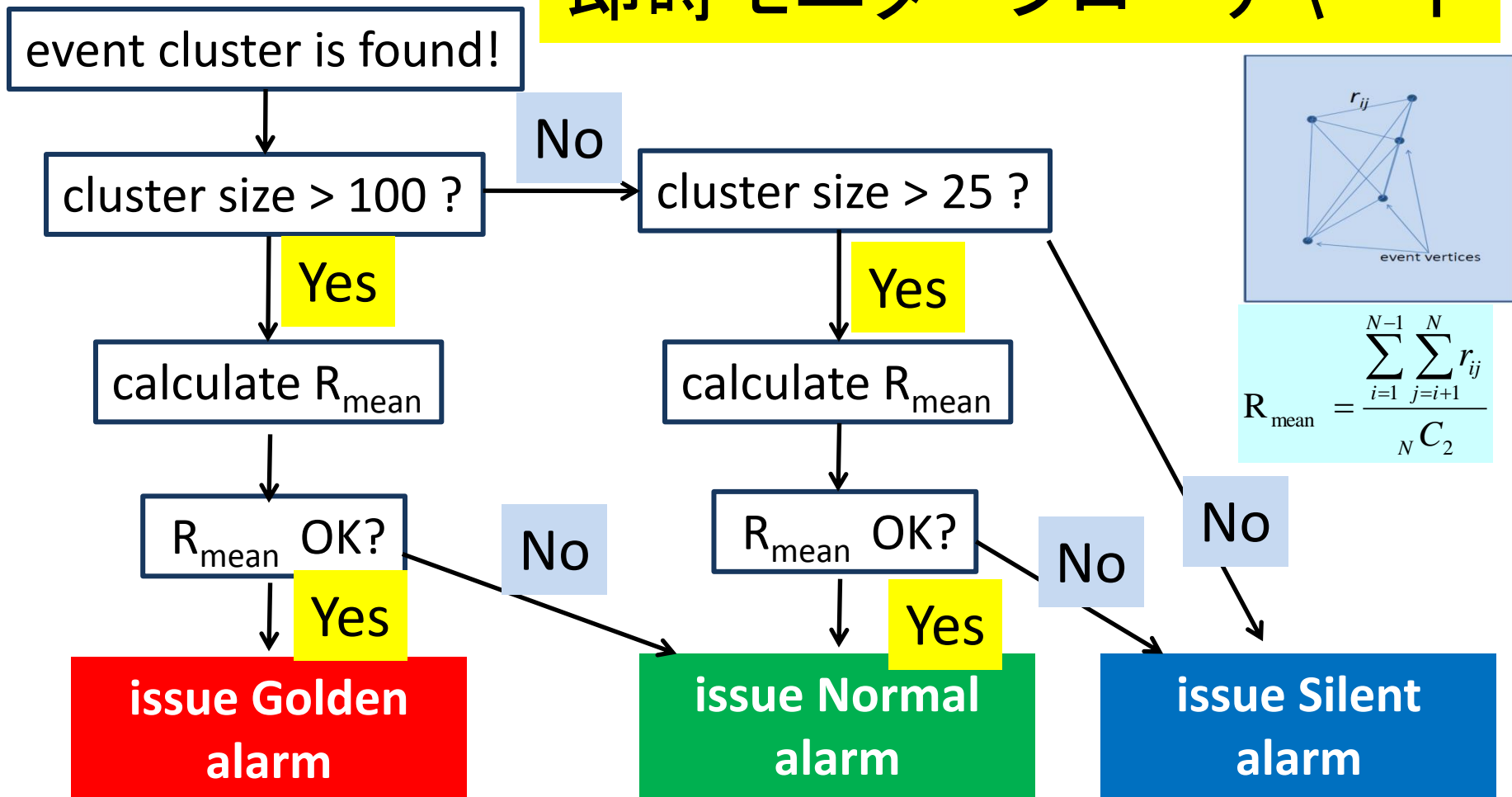
超新星爆発までの距離とSKで観測される事象数の関係



旧電子回路システムでは、4kpc以内の超新星爆発のニュートリノバーストでは、デッドタイムができた。

新電子回路システムでは、0.3kpc以内の超新星爆発のニュートリノバーストでもデッドタイムはできない。

即時モニターフローチャート

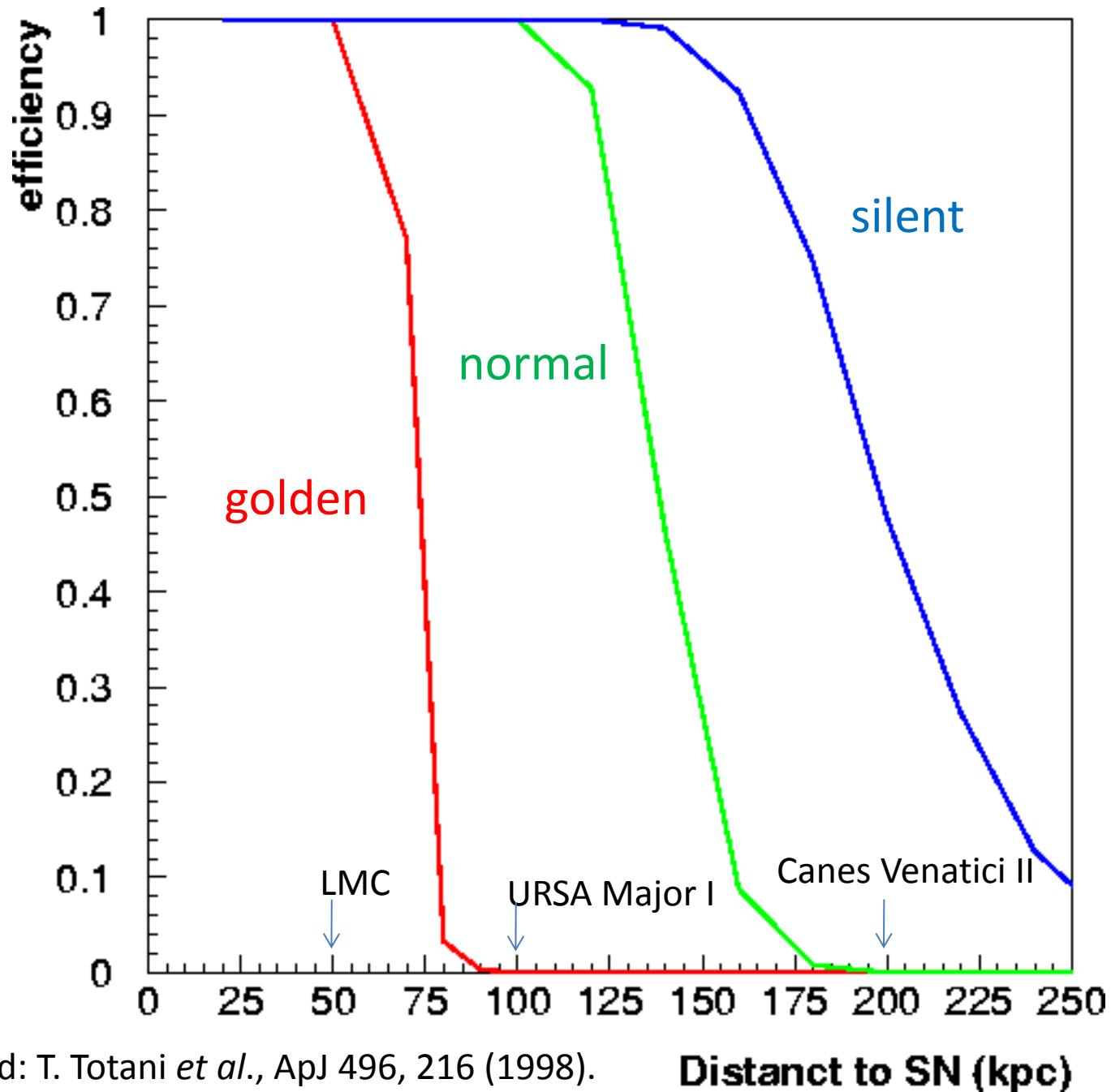


$$R_{\text{mean}} = \frac{\sum_{i=1}^{N-1} \sum_{j=i+1}^N r_{ij}}{N C_2}$$

すぐに関係者を招集し、TV会議を開き、議論。本物だと見なされれば全世界の発表。発生から1時間以内。

エキスパート内で議論。必要であればTV会議を開く。

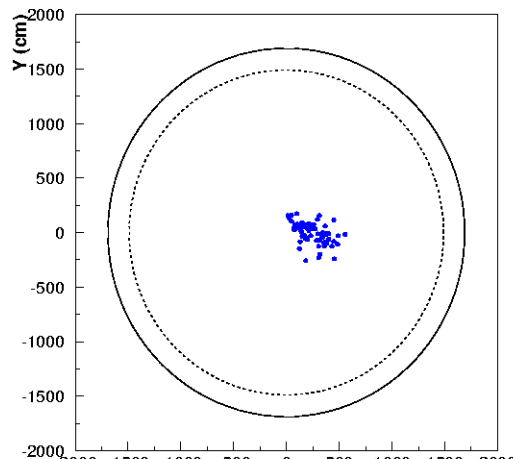
エキスパートにのみ電子メール。1日に平均2通。



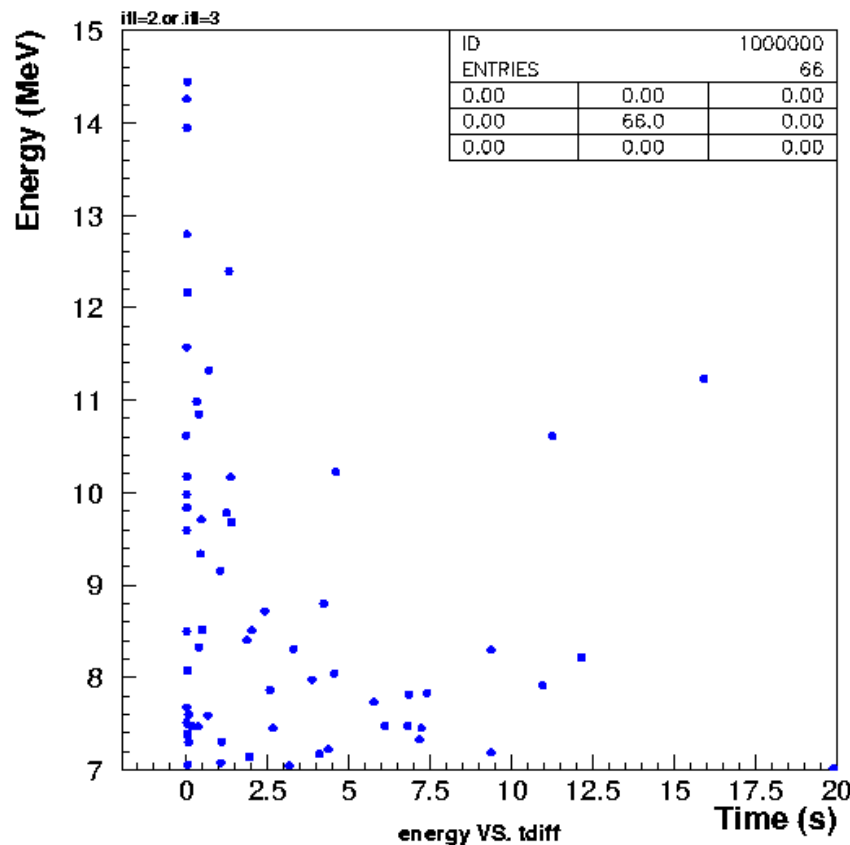
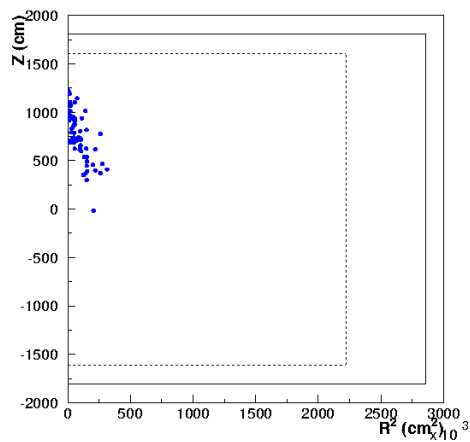
model used: T. Totani *et al.*, ApJ 496, 216 (1998).

Distanct to SN (kpc)

これまで発生したアラームのほとんど全てが宇宙線ミュオンによる spallation によるもの（～2アラーム/日）。



silent alarm の1例



事象の位置分布をみることによりspallationだと判断できる。
定量的には R_{mean} を用いる。

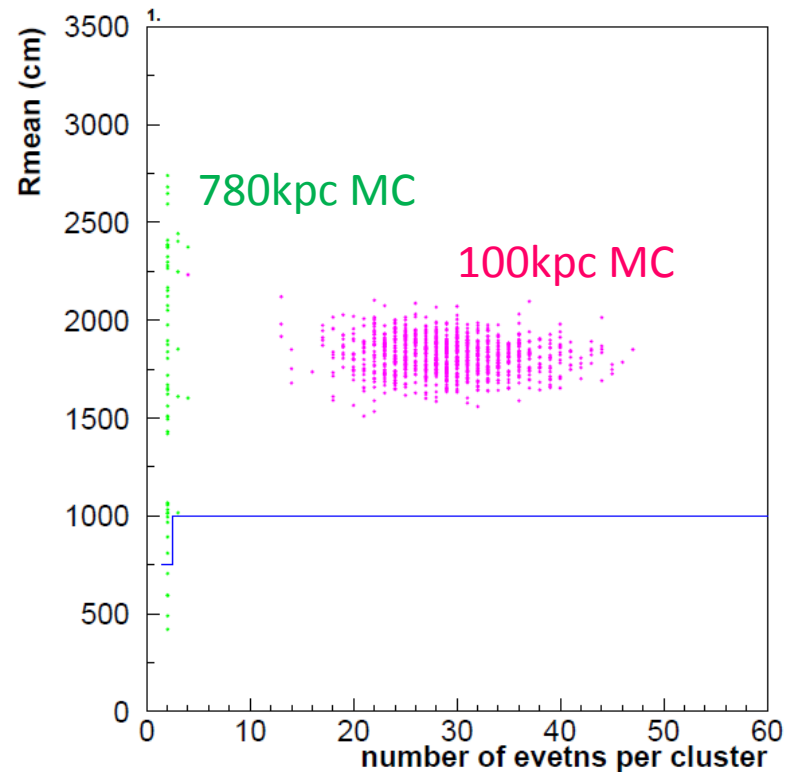
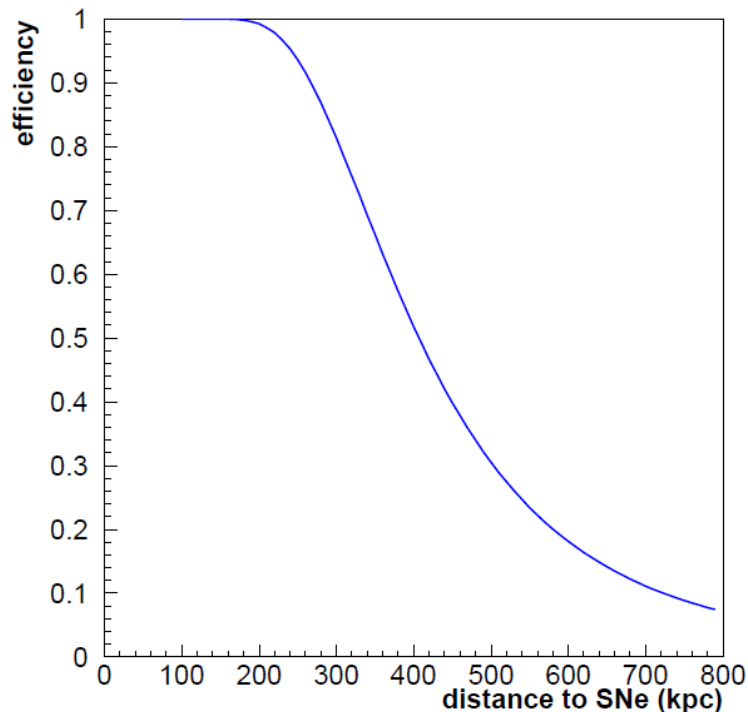
SKにおけるSNバースト探索

SK-I-IVの4206.4日のデータを用いた解析。

事象選択は太陽ニュートリノ解析と同様。

20秒時間幅で運動エネルギー15.5MeV以上の事象が2つあることを要求。

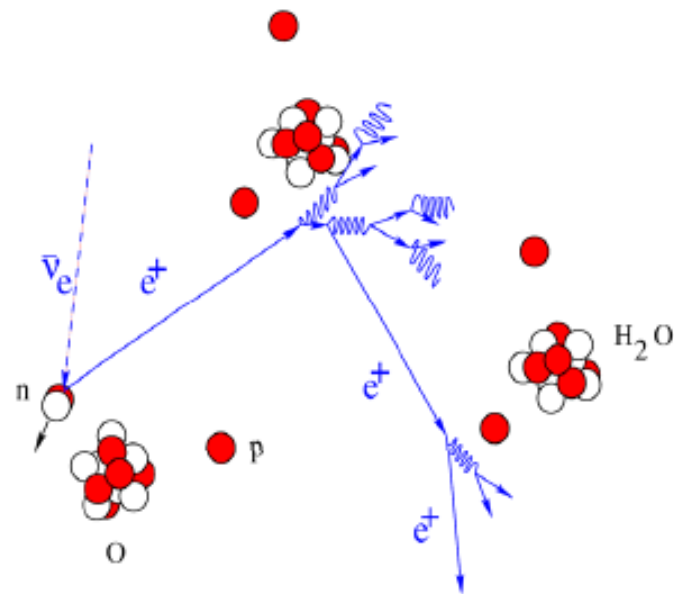
クラスターサイズが2より大きい(2)のとき、 $R_{\text{mean}} > 1000\text{cm}$ (750cm)を要求。



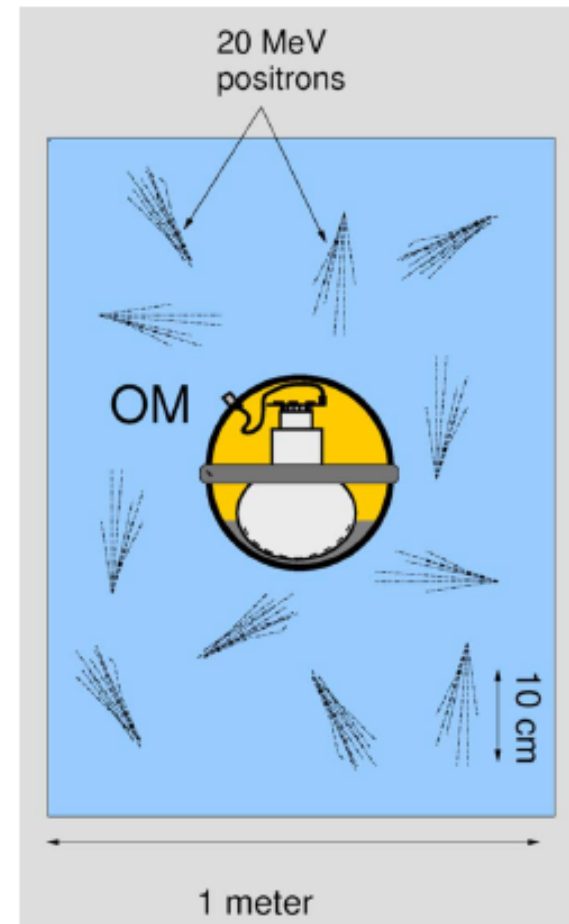
100kpc 以内で、90% C.L. で0.20 SN/yearの制限を与えた。

AMANDA/IceCube as MeV ν detector

...first proposed by Halzen, Jacobsen & Zas, astro-ph/9512080

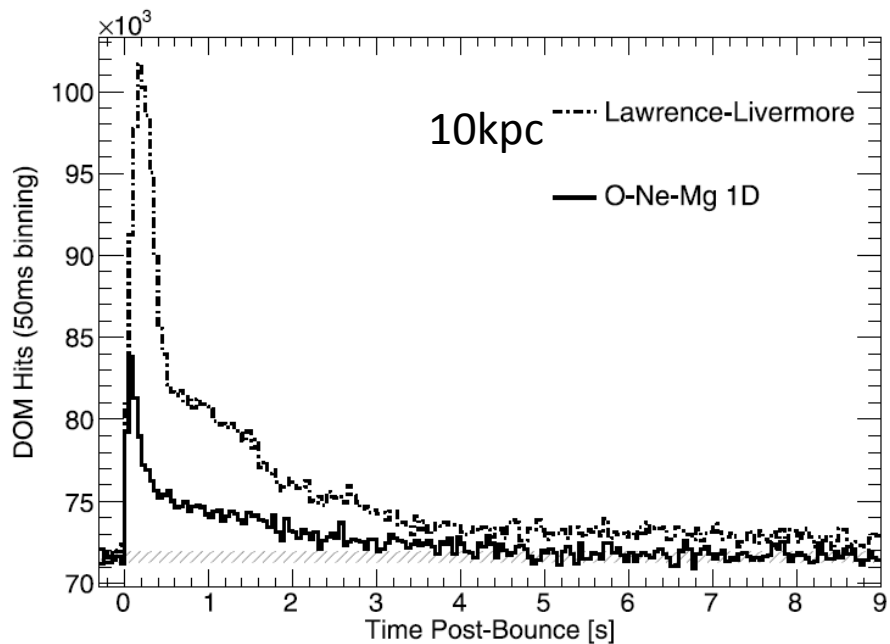


- ☞ ice uniformly illuminated
- ☞ detect correlated rate increase on top of PMT noise



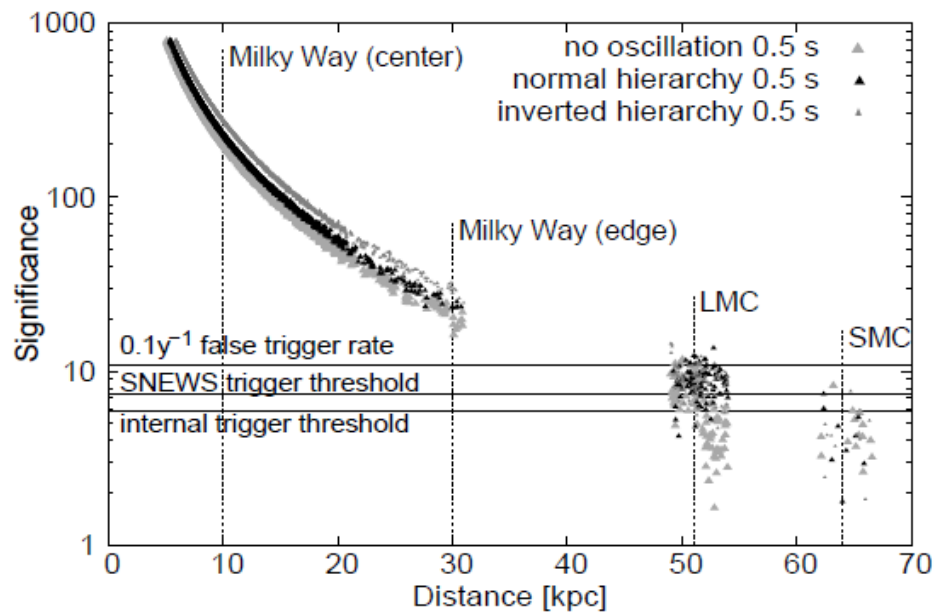
IceCube におけるSN検出シミュレーション

IceCube collaboration A&A 535, A109 (2011)

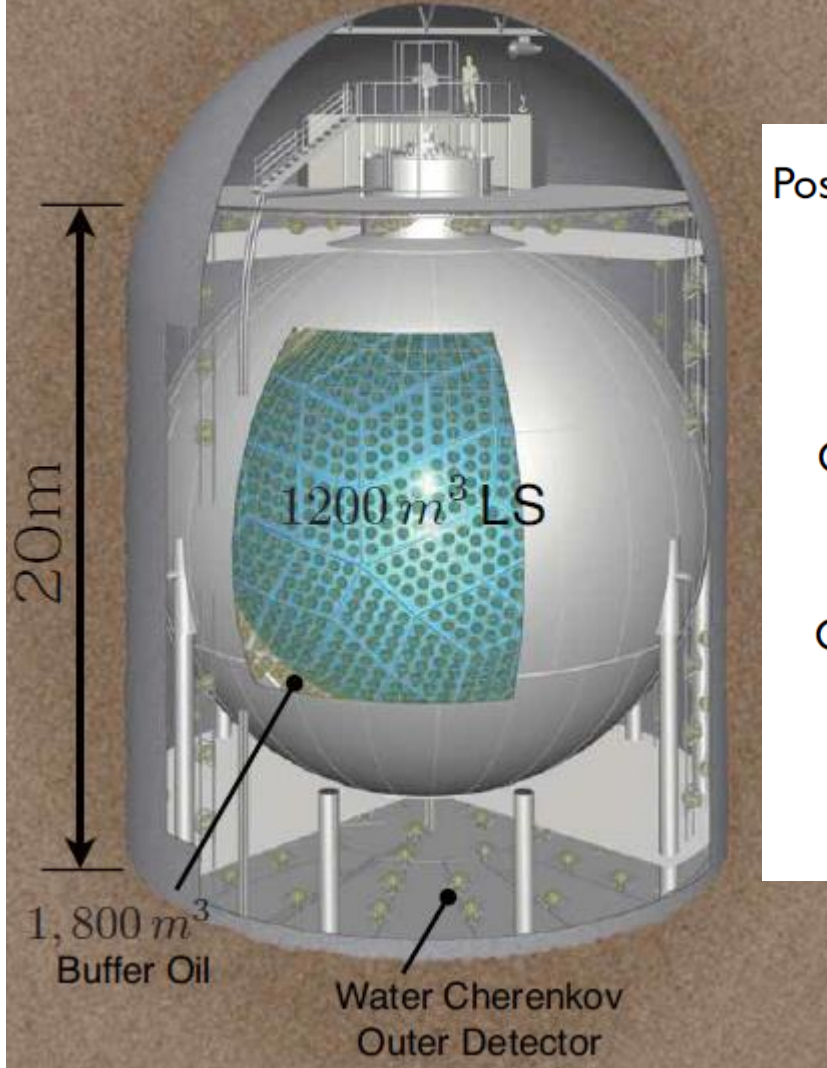


検出器のヒットレートからSNを検出する。

標的の大きさ $\sim 1 \text{ km}^3$



KamLAND



10kpc
Possible detection of supernova neutrinos with KamLAND

CC $\bar{\nu}_e + p \rightarrow e^+ + n$ ~300 events

CC/NC $\nu(\bar{\nu}) + {}^{12}\text{C} \rightarrow \underbrace{{}^{12}\text{N}, {}^{12}\text{B}, {}^{12}\text{C}^*}_{\text{a handful of events}}$ ~60 events

CC+NC $\nu + e^- \rightarrow \nu + e^-$ ~20 events

NC $\nu + p \rightarrow \nu + p$ ~300 events

Differential cross section

- proton recoil favors the maximum energy ($2E_\nu^2/M_p$). (good for E_ν measurement)

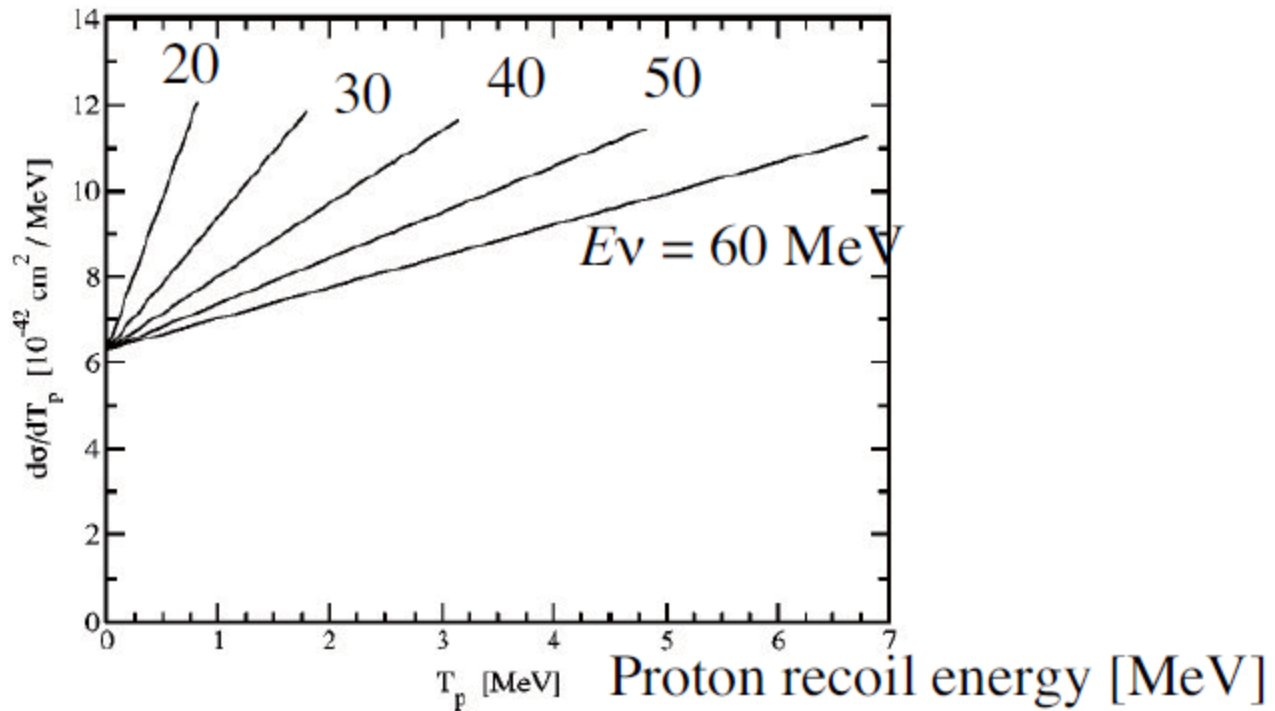
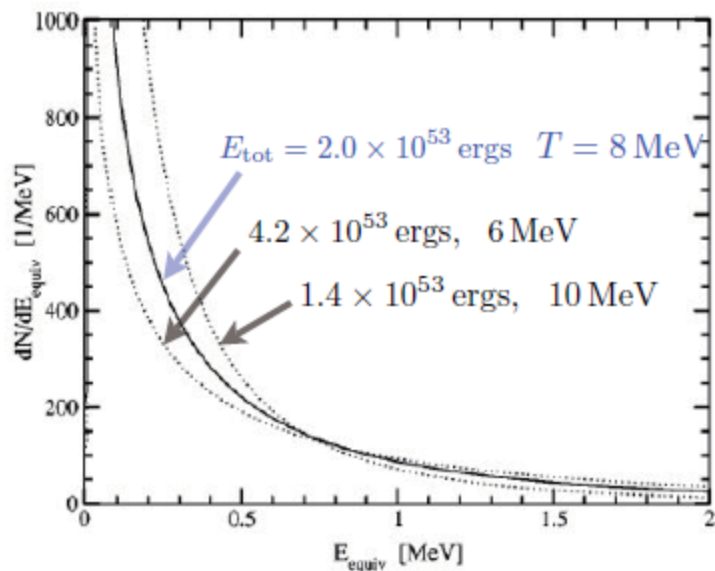
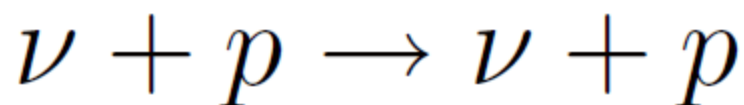
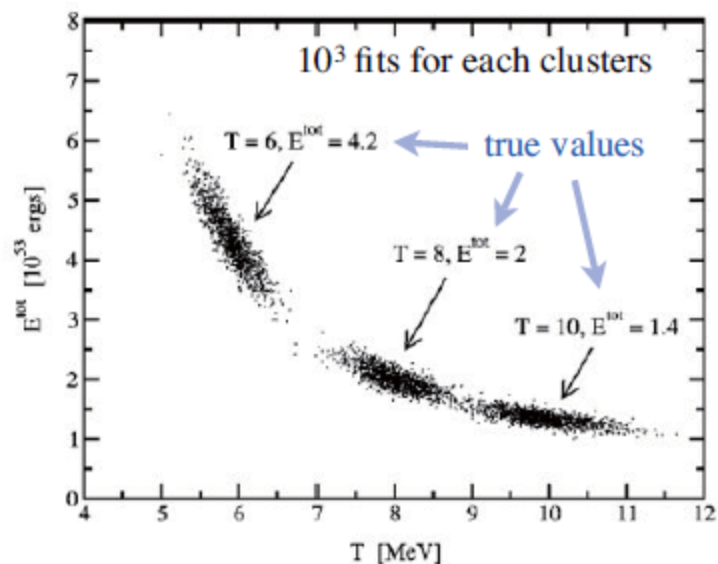


FIG. 1. The differential cross section as a function of T_p for fixed E_ν . Note the rise at large T_p , indicating that large kinetic energies are preferred. From left to right, the lines are for $E_\nu = 20, 30, 40, 50,$ and 60 MeV.

超新星観測でのカムランドの特徴



Visible energy [MeV]



スペクトルの違いから、全放出エネルギーと温度が同時に測定できる。

SNEWS: SuperNova Early Warning System



SNO
(until 2006)



LVD



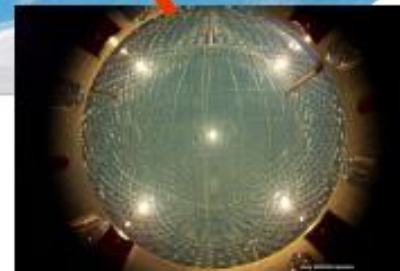
snews.bnl.gov



Super-K



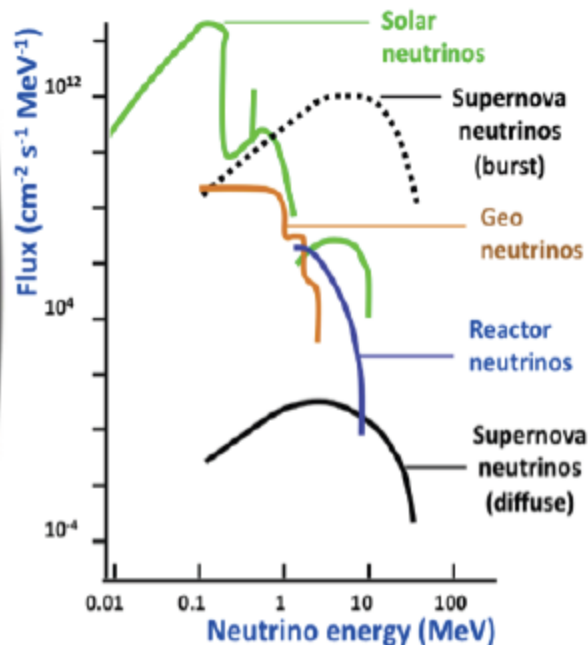
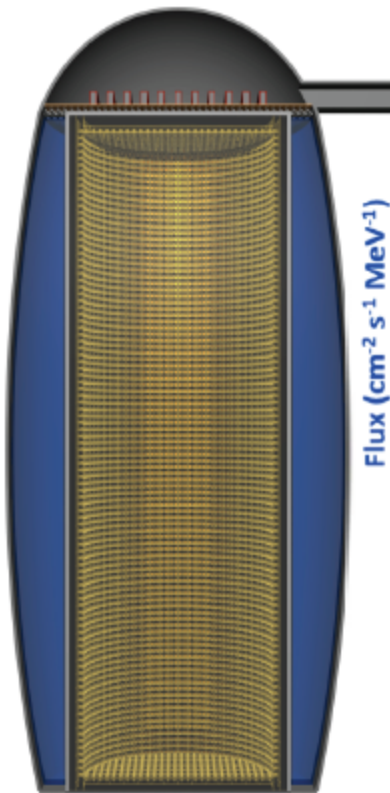
IceCube



Borexino

My topic: future ~ 50 kt liquid scintillator detector

Emphasize LENA (low energy neutrino astronomy) – scintillator detector of the European LAGUNA-LBNO consortium



Neutrino Sources

- | | Rates |
|--------------------------------|----------------------|
| ▪ Galactic Supernova neutrinos | $10^4/\text{SN}$ |
| ▪ Diffuse Supernova neutrinos | $10/\text{yr}$ |
| ▪ Solar neutrinos | $10^4/\text{d}$ |
| ▪ Geoneutrinos | $10^3/\text{yr}$ |
| ▪ Reactor neutrinos | $10^{3-4}/\text{yr}$ |
| ▪ Neutrino oscillometry | $10^4/\text{Mci}$ |
| ▪ Pion decay-at-rest beam | |
| ▪ Indirect dark matter search | |

LENA and a galactic supernova

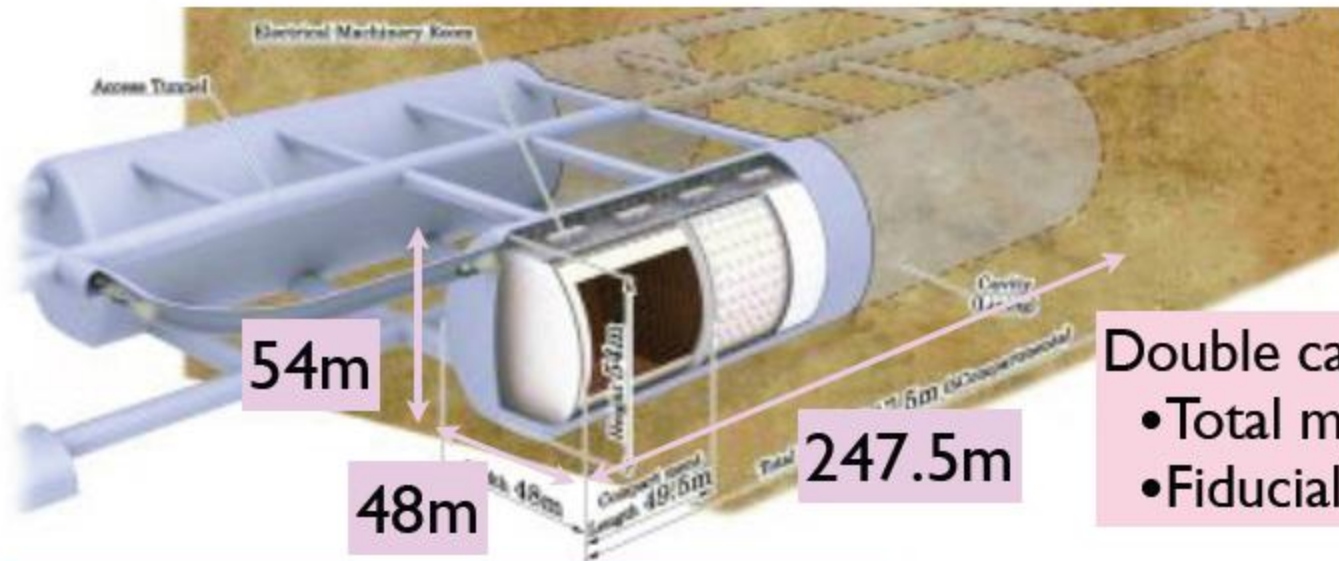
- $8 M_{\odot}$ ($3 \cdot 10^{53}$ erg) at $D = 10$ kpc (center of our galaxy)

In **LENA** detector: ~ 15000 events

Possible reactions in liquid scintillator

- $\bar{\nu}_e + p \rightarrow n + e^+$; $n + p \rightarrow d + \gamma$ $\sim 7000 - 13800$
- $\bar{\nu}_e + {}^{12}\text{C} \rightarrow {}^{12}\text{B} + e^+$; ${}^{12}\text{B} \rightarrow {}^{12}\text{C} + e^- + \bar{\nu}_e$ $\sim 150 - 610$
- $\nu_e + {}^{12}\text{C} \rightarrow e^- + {}^{12}\text{N}$; ${}^{12}\text{N} \rightarrow {}^{12}\text{C} + e^+ + \nu_e$ $\sim 200 - 690$
- $\nu_X + {}^{12}\text{C} \rightarrow {}^{12}\text{C}^* + \nu_X$; ${}^{12}\text{C}^* \rightarrow {}^{12}\text{C} + \gamma$ $\sim 680 - 2070$
- $\nu_X + e^- \rightarrow \nu_X + e^-$ (elastic scattering) ~ 700
- $\nu_X + p \rightarrow \nu_X + p$ (elastic scattering) $\sim 1500 - 5700$

Hyper-Kamiokande



Double caverns

- Total mass: 0.99 Mton
- Fiducial: 0.56Mton

Each cavity separated into five

- Each volume ~twice of Super-K
- Photo-sensors on separation walls

→ Performance equivalent to Super-K

x25 Super-K

Baseline design

- ID: 20% photo-coverage (=SK-II)
 - 99,000 20" PMT
- OD (2m) : 25,000 8" PMT

Technically feasible design established

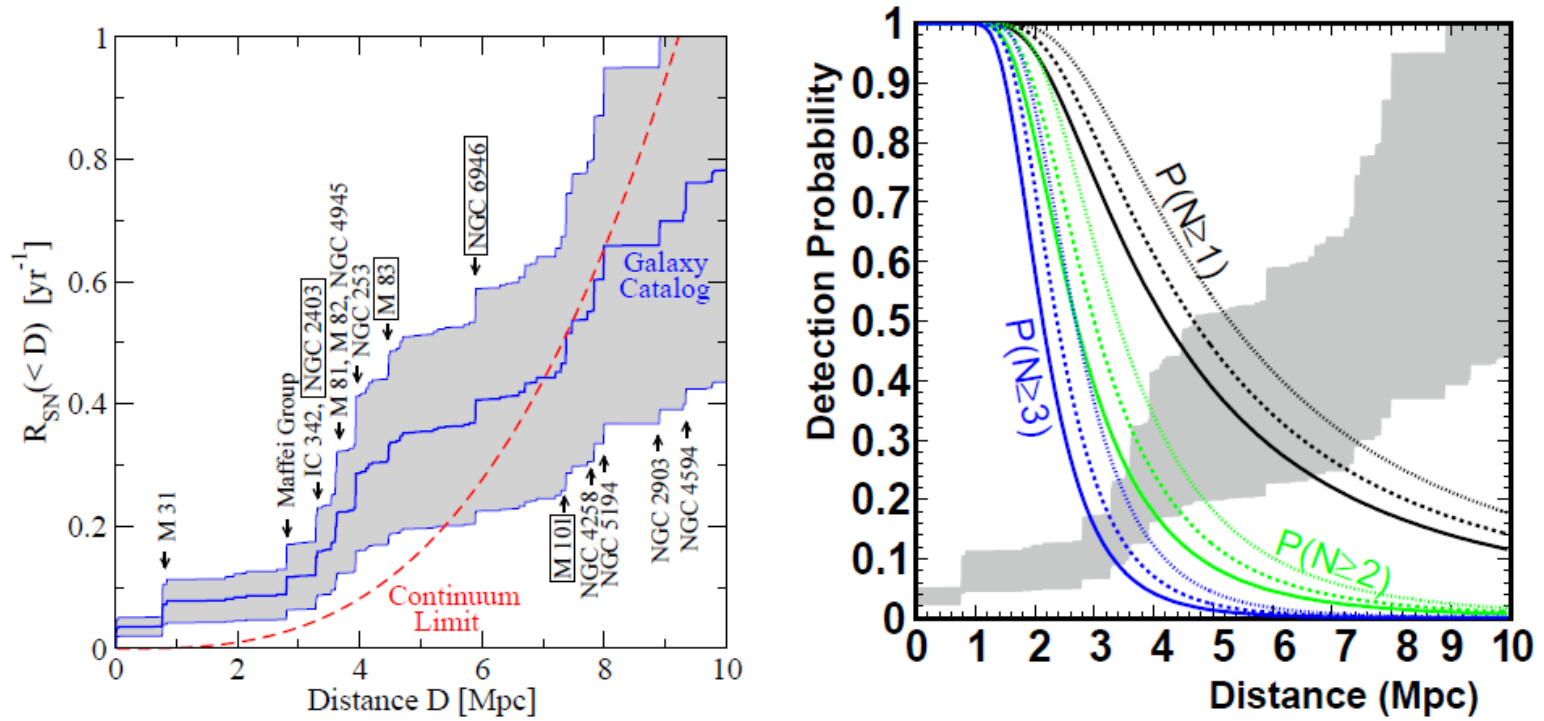
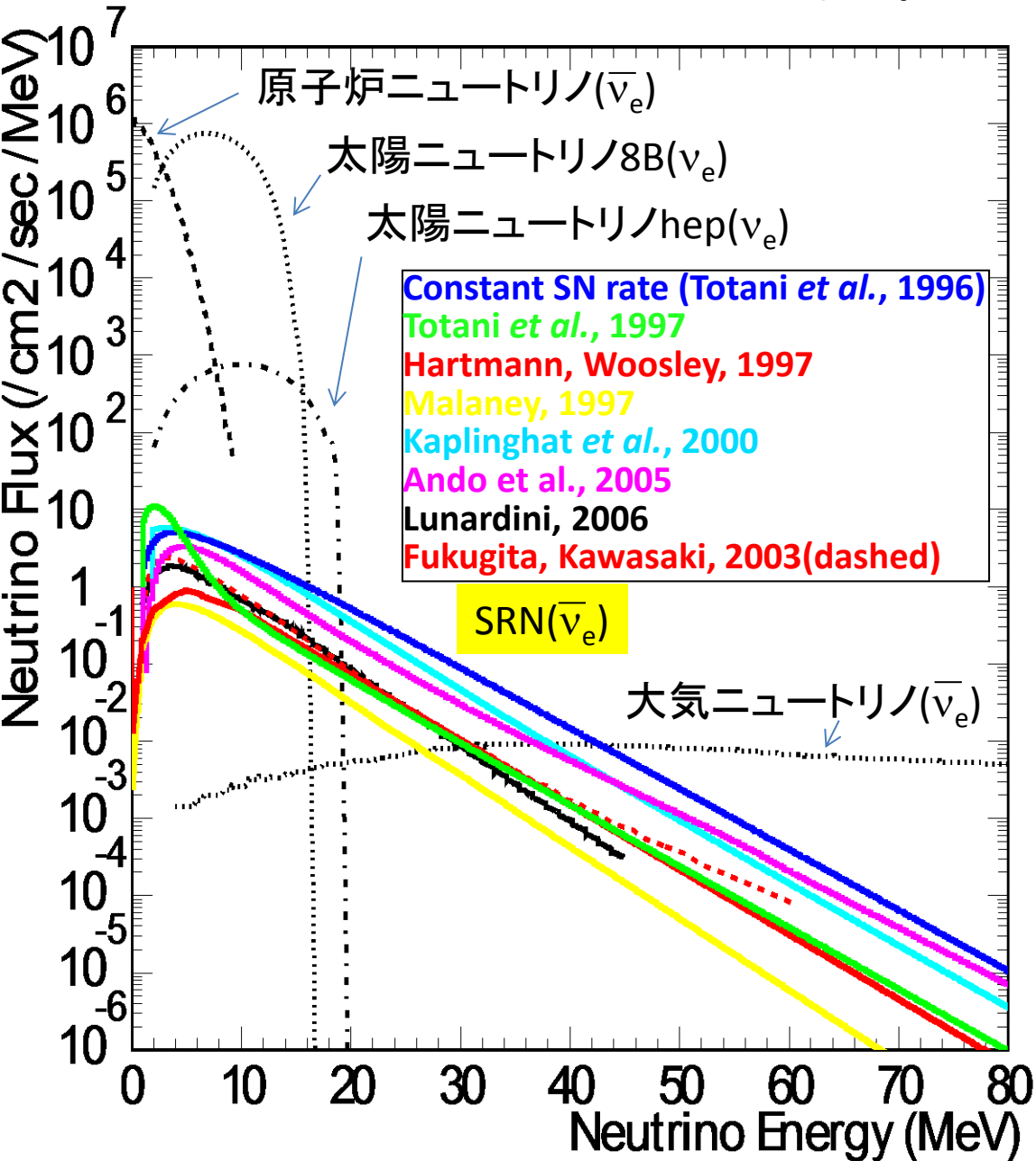


FIG. 59. (Left) cumulative calculated supernova rate versus distance for supernovae in nearby galaxies from ref.[100]. (Right) Detection probability of supernova neutrinos versus distance at Hyper-K assuming 0.56 Mton fiducial volume and 10 MeV threshold for this analysis. Black, green and blue curves show the detection efficiency requiring at least or equal to one, two and three events per burst, respectively. Solid, dotted and dashed curves are for neutrino oscillation scenarios of no oscillation, N.H. and I.H., respectively.

[100] S. Ando, J. F. Beacom, and H. Yüksel, Phys. Rev. Lett. **95**, 171101 (2005), arXiv:astro-ph/0503321.

SN relic neutrino search

超新星背景ニュートリノ (Supernova Relic Neutrinos)



- 期待されるSRN信号
事象の数

- 0.8-5.0 事象
/22.5kton/year (10-
30MeV)

- 0.3-1.9事象
/22.5kton/year(18-
30MeV)

- 低いエネルギー閾
値と大きな体積が
必要。

Theoretical Framework

Signal rate spectrum in detector in terms of measured energy

$$\frac{dN_e}{dE_e}(E_e) = N_p \sigma(E_\nu) \int_0^\infty [(1+z) \varphi[E_\nu(1+z)]] [R_{SN}(z)] \left[\left| \frac{c dt}{dz} \right| dz \right]$$

Third ingredient: Detector Capabilities
(well understood)

Second ingredient: Supernova Rate
(formerly very uncertain, but now
known with good precision)

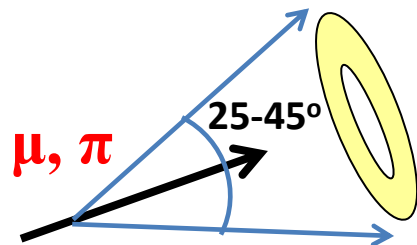
First ingredient: Neutrino spectrum
(this is now the unknown)

Cosmology? Solved. Oscillations? Included. Backgrounds? See below.

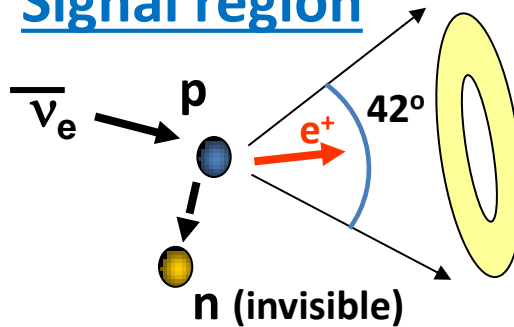
SKでのSRN探索

- SK I, II, IIIのデータを使用(2853日)
- エネルギー閾値は16MeV
 - それ以下のエネルギーでは、スパレーション事象によるバックグラウンドが多数
- その他のバックグラウンド
 - 大気ニュートリノCCによるmuon (visible)とpion, NCによるgamma
 - チェレンコフ角度をみることによって区別。
 - 大気ニュートリノCCによるmuon (invisible)が崩壊した電子と ν_e CC事象

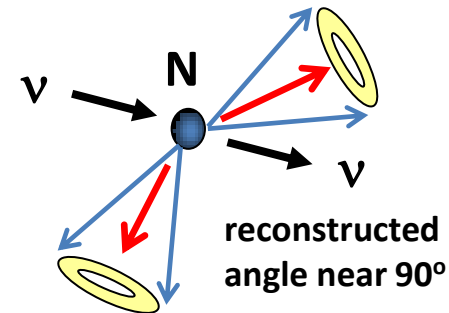
Low angle events



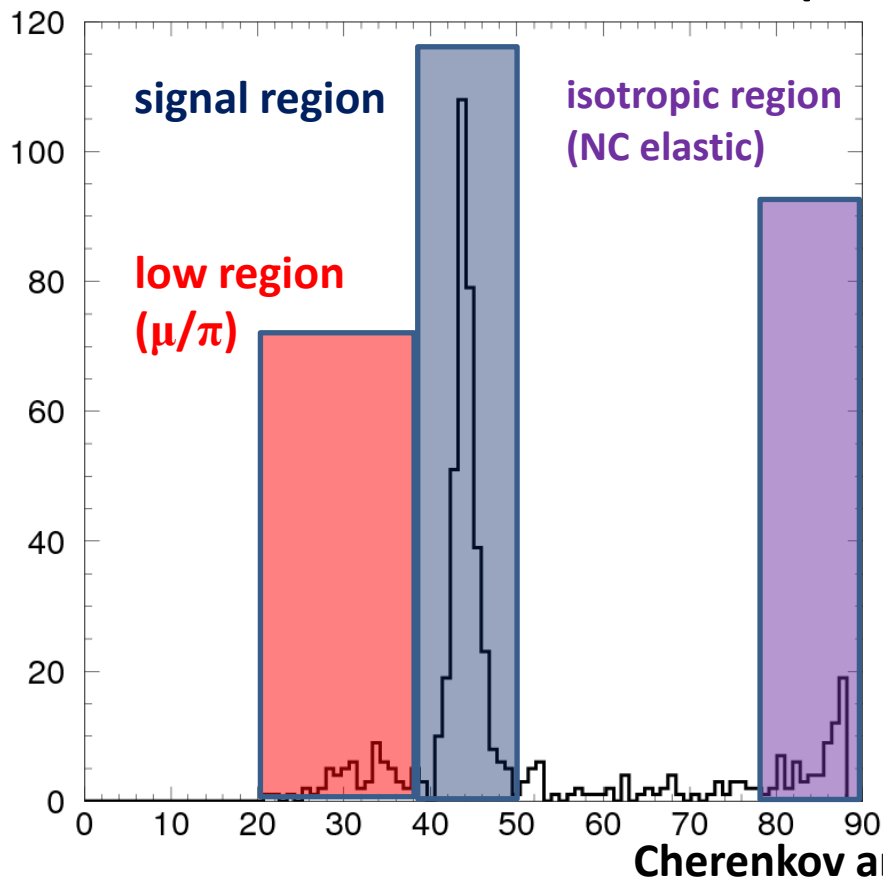
Signal region



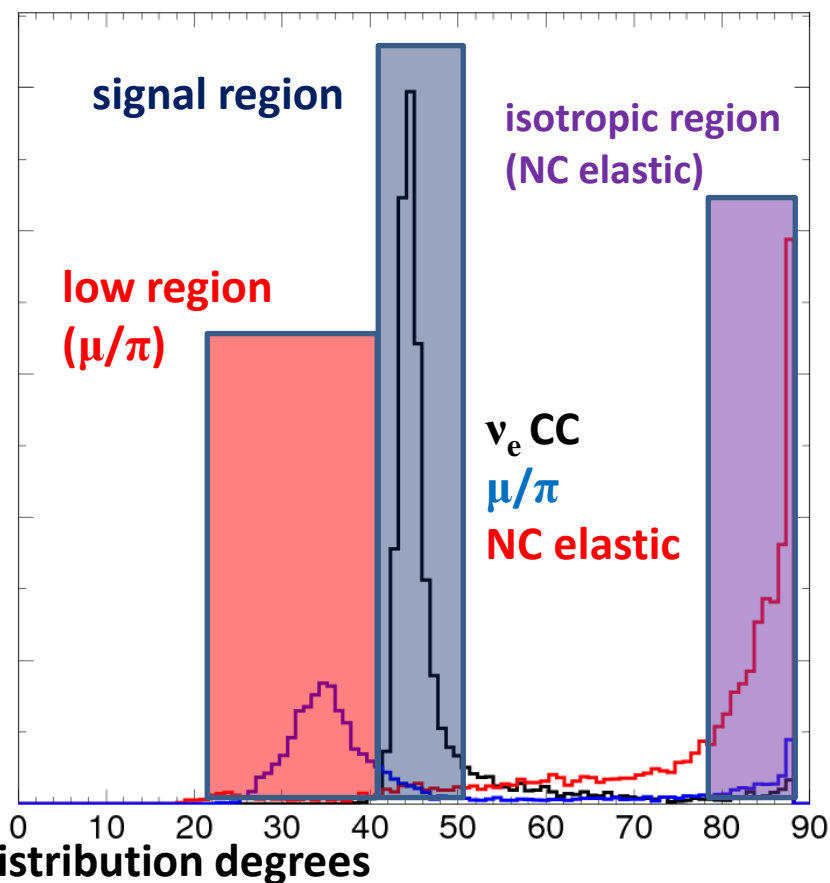
Isotropic region

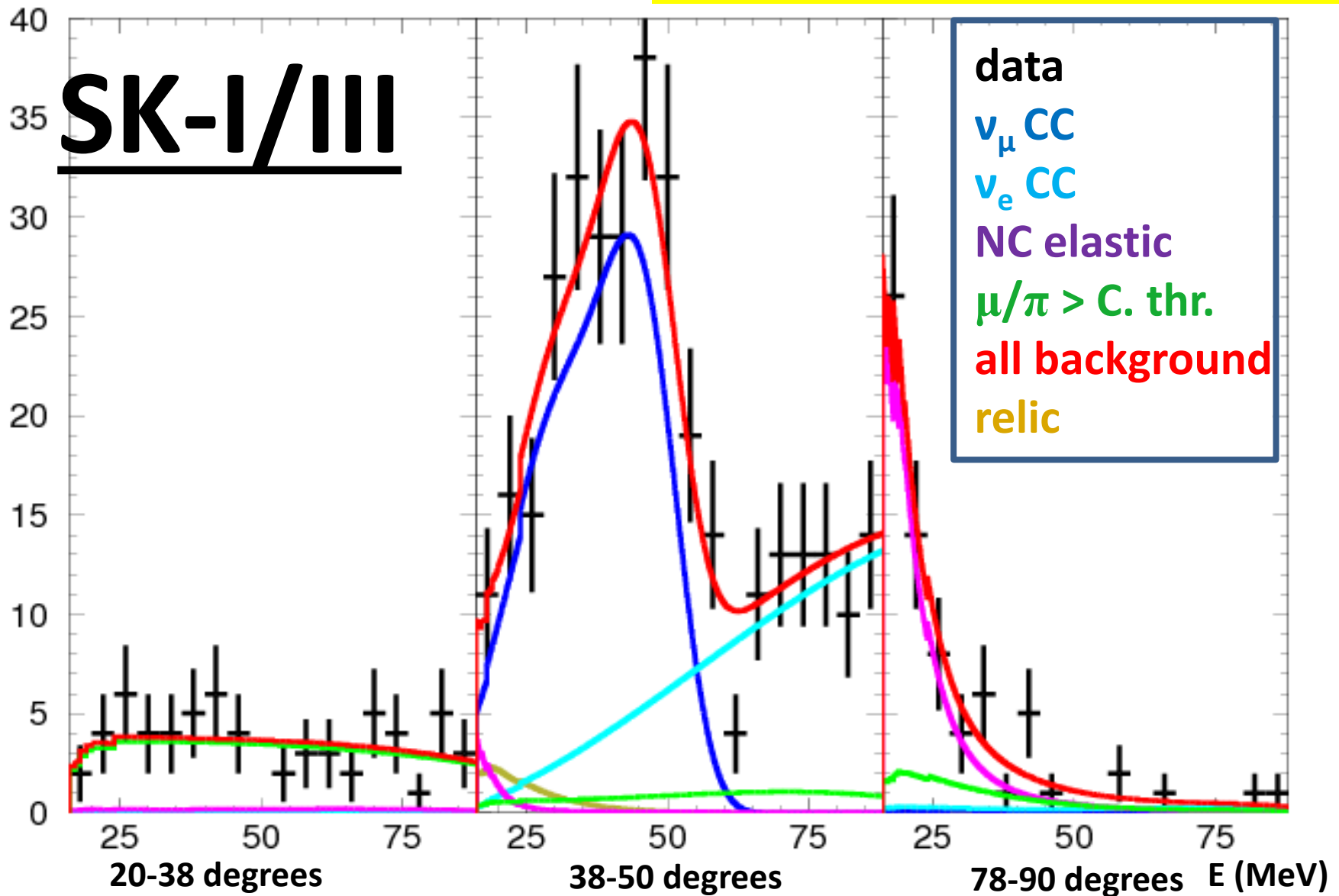


SK-I/III combined final data sample



MC (decay electron channel not shown)

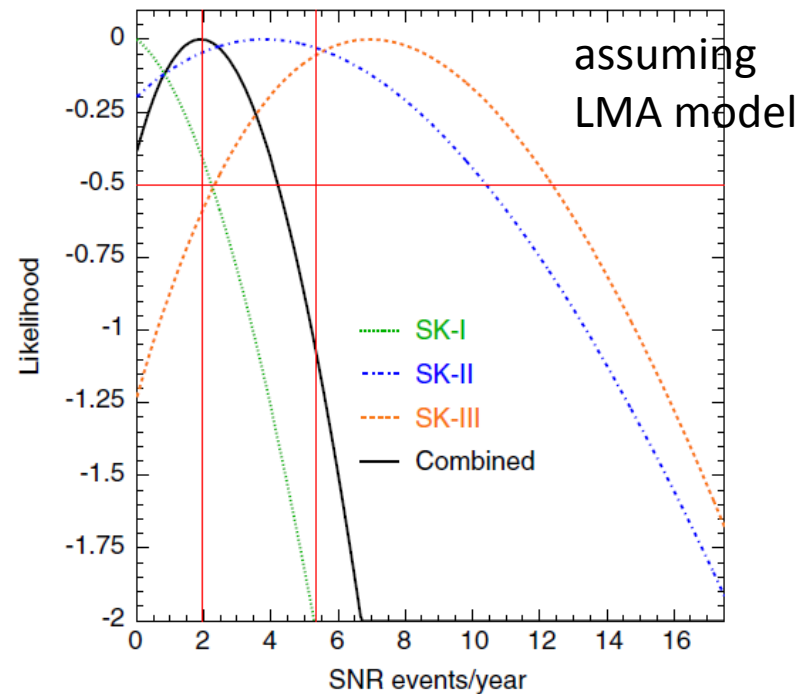
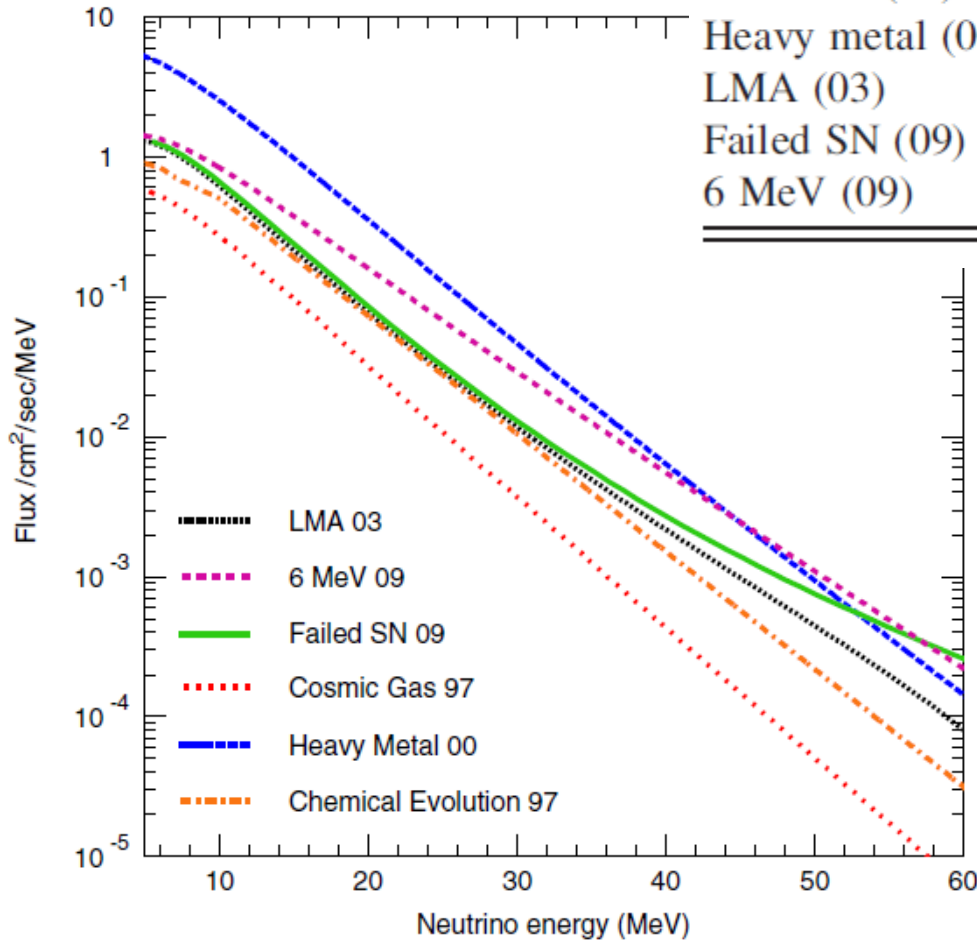


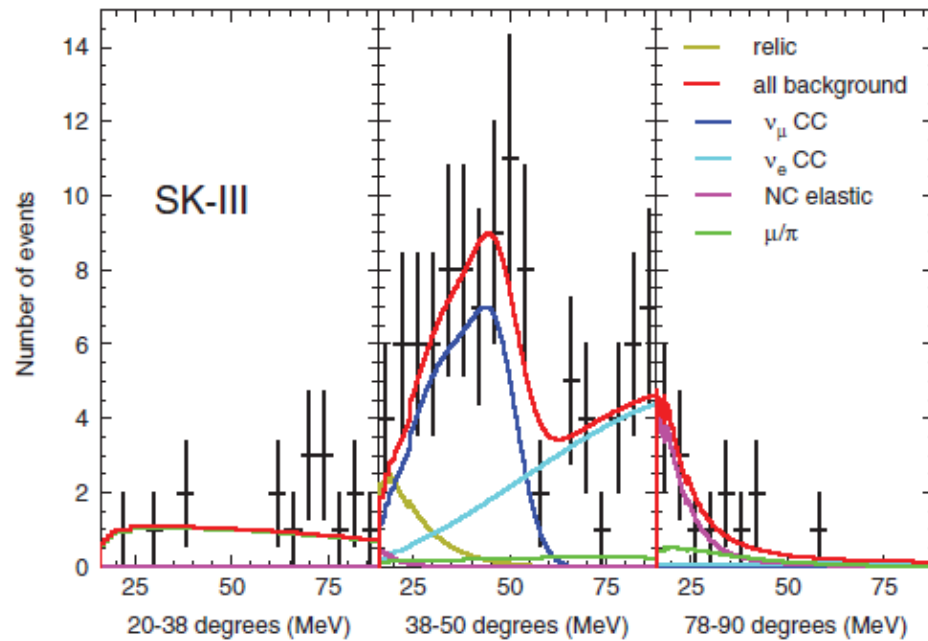
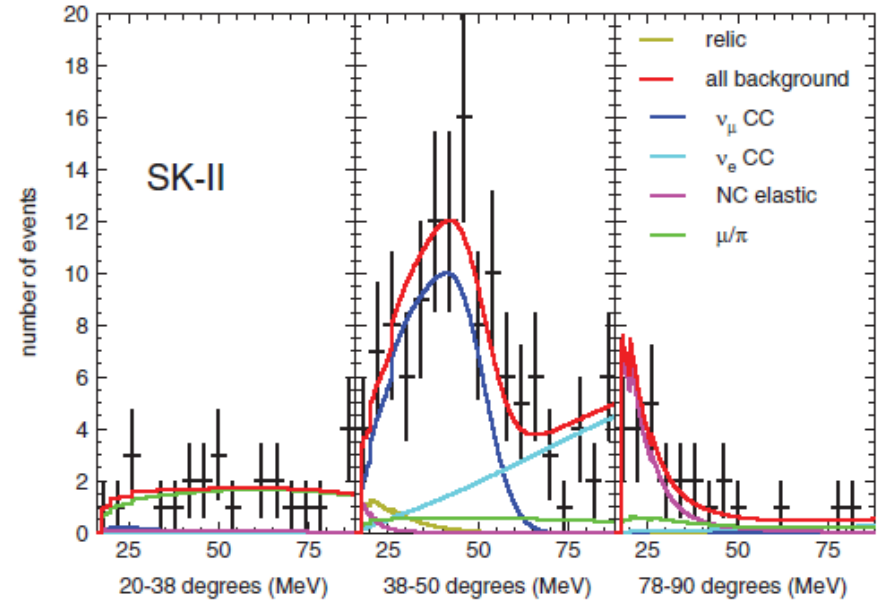
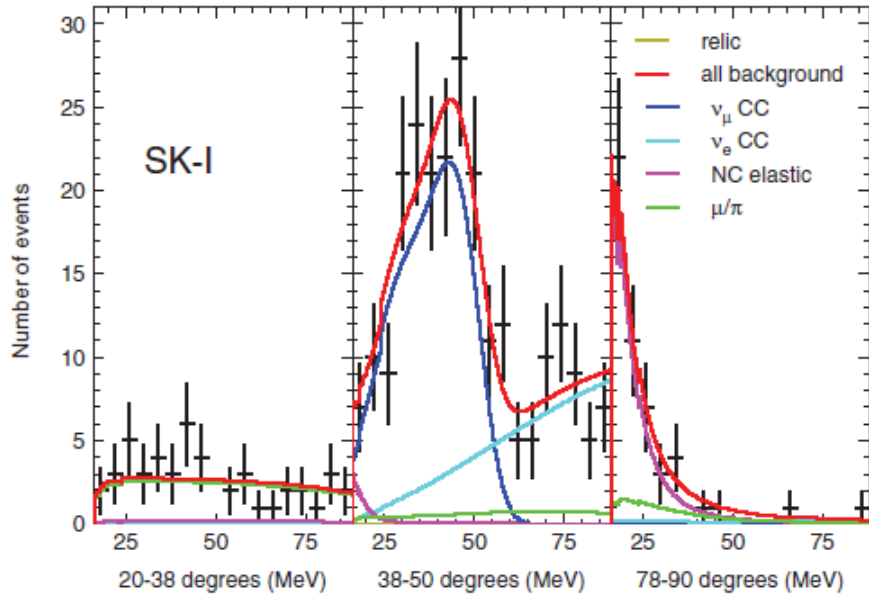


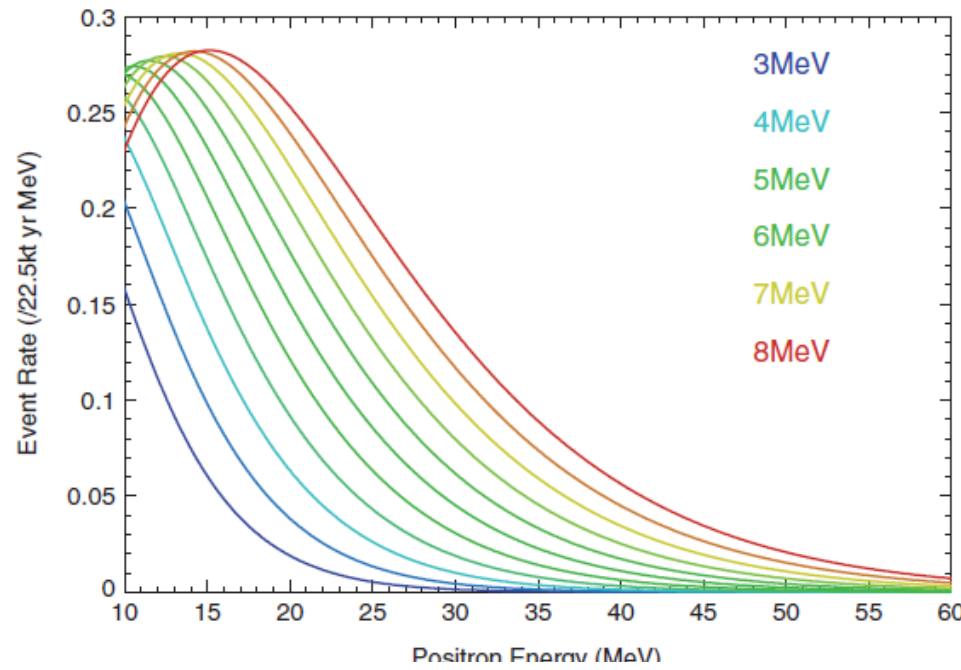
Electron total energy threshold: 16 MeV

TABLE V. 90% C.L. flux limit ($\bar{\nu}$ cm⁻² s⁻¹), $E_\nu > 17.3$ MeV.

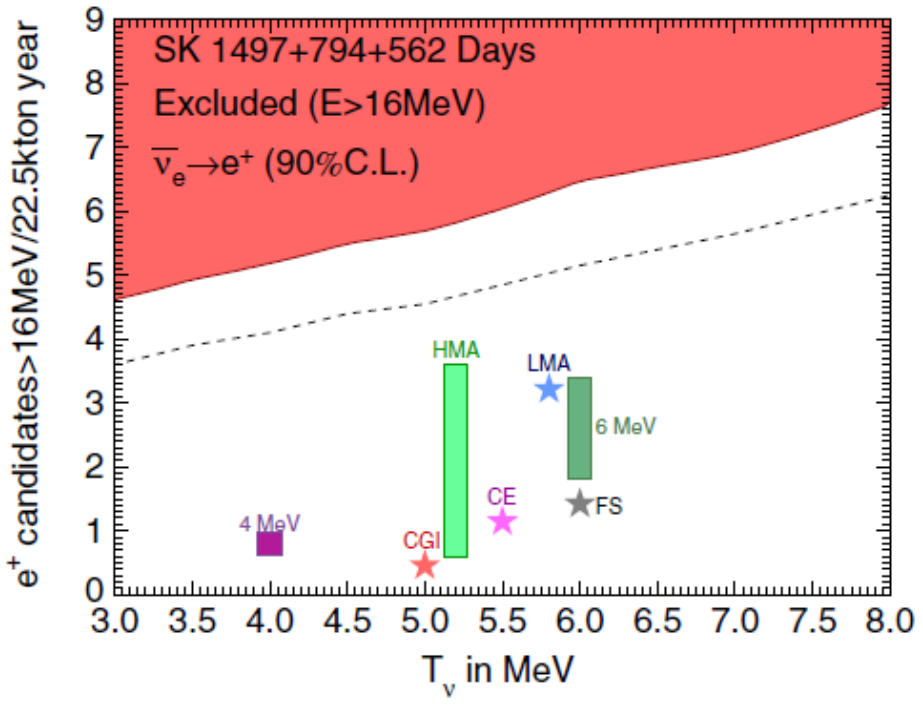
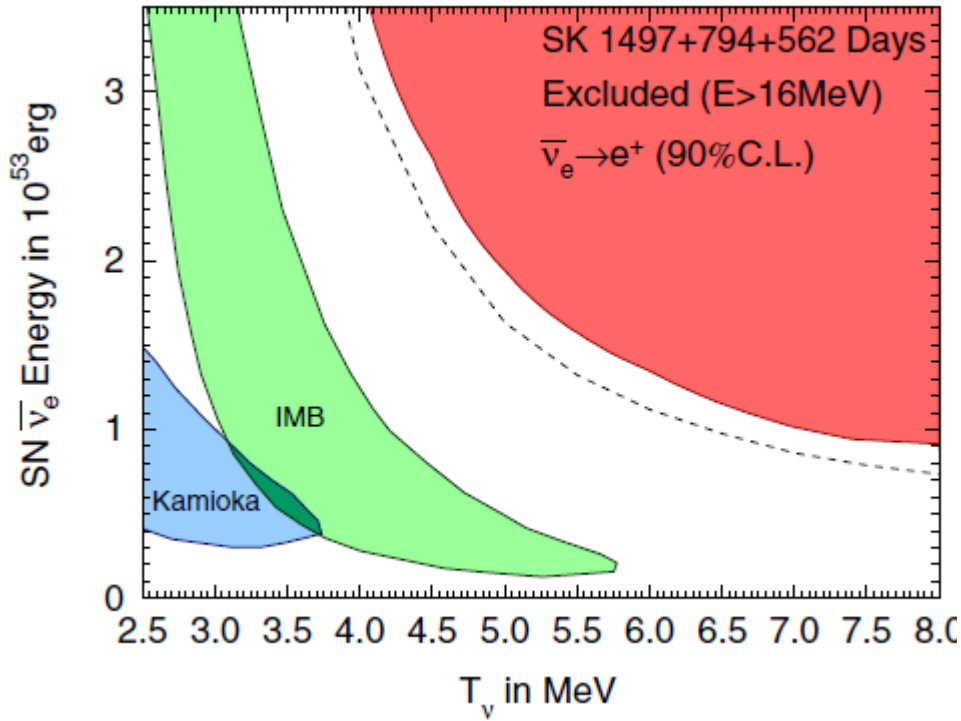
| Model | SK-I | SK-II | SK-III | All | Predicted |
|------------------|------|-------|--------|------|-----------|
| Gas infall (97) | <2.1 | <7.5 | <7.8 | <2.8 | 0.3 |
| Chemical (97) | <2.2 | <7.2 | <7.8 | <2.8 | 0.6 |
| Heavy metal (00) | <2.2 | <7.4 | <7.8 | <2.8 | <1.8 |
| LMA (03) | <2.5 | <7.7 | <8.0 | <2.9 | 1.7 |
| Failed SN (09) | <2.4 | <8.0 | <8.4 | <3.0 | 0.7 |
| 6 MeV (09) | <2.7 | <7.4 | <8.7 | <3.1 | 1.5 |







$$\varphi(E_\nu) = E_{\bar{\nu}_e, tot} \frac{120 E_\nu^2}{7\pi^4 T^4} \frac{1}{e^{E_\nu/T} + 1}$$



neutron tagging with Gd

Antineutrino Spectroscopy with Large Water Čerenkov Detectors

John F. Beacom¹ and Mark R. Vagins²

¹*NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500, USA*

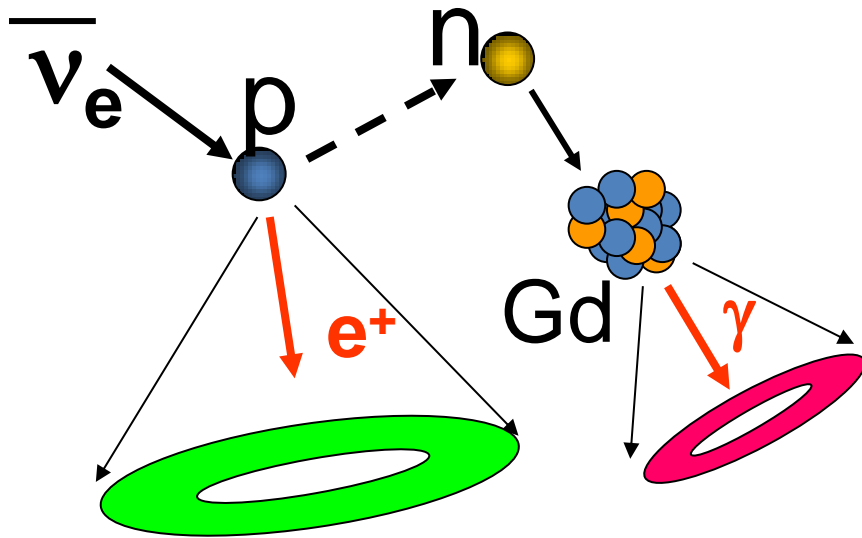
²*Department of Physics and Astronomy, 4129 Reines Hall, University of California, Irvine, California 92697, USA*

(Received 25 September 2003; published 20 October 2004)

We propose modifying large water Čerenkov detectors by the addition of 0.2% gadolinium trichloride, which is highly soluble, newly inexpensive, and transparent in solution. Since Gd has an enormous cross section for radiative neutron capture, with $\sum E_\gamma = 8$ MeV, this would make neutrons visible for the first time in such detectors, allowing antineutrino tagging by the coincidence detection reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ (similarly for $\bar{\nu}_\mu$). Taking Super-Kamiokande as a working example, dramatic consequences for reactor neutrino measurements, first observation of the diffuse supernova neutrino background, galactic supernova detection, and other topics are discussed.

large water Čerenkov detectors by the addition of 0.2% gadolinium

Gd入りSK (GADZOOKS!)



- SKでGdを使って、陽電子と遅延ガンマ線によるコインシデンス
 - J.F. Beacom and M.R. Vagins, PRL 93, 171101 (2004).
 - $\sigma \sim 49000 \text{ barn}$ (0.3 barn for p).
- Gdが中性子を吸収すると、3-4個計8MeVのガンマ線を放出。
- SKでGdを入れることにより、5年間でSRNの理論的予言に到達可能。
 - spallation事象の抑制により、10MeVに閾値を下げる事が可能。
 - 「見えないミューオン」事象を1/5にすることが可能。

Gd 化合物

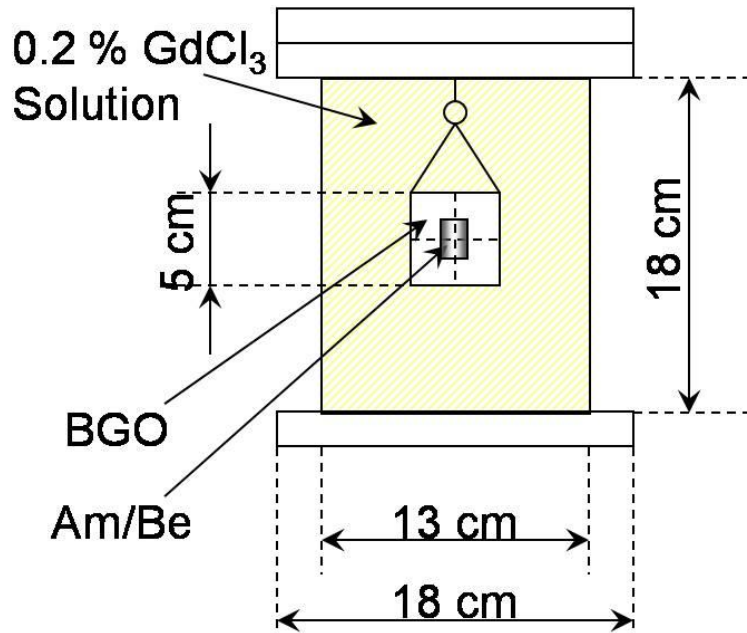
| Gd compound | corrosion | light attenuation |
|------------------------------|-----------|-------------------|
| GdCl_3 | X | O |
| $\text{Gd}(\text{NO}_3)_3$ | O | X |
| $\text{Gd}_2(\text{SO}_4)_3$ | O | O |

- 硫酸ガドリニウムが現在考えられている候補。
- SKの構成物質の腐食テストを実施。
 - ステンレス、ガラス、ゴム等、SKで使用される物質37種類について、 $\text{Gd}_2(\text{SO}_4)_3$ 溶液による浸水試験。
 - 温度が13度以下に保たれるSKにおいては、水質に問題はない。

SKでの中性子検出効率の測定

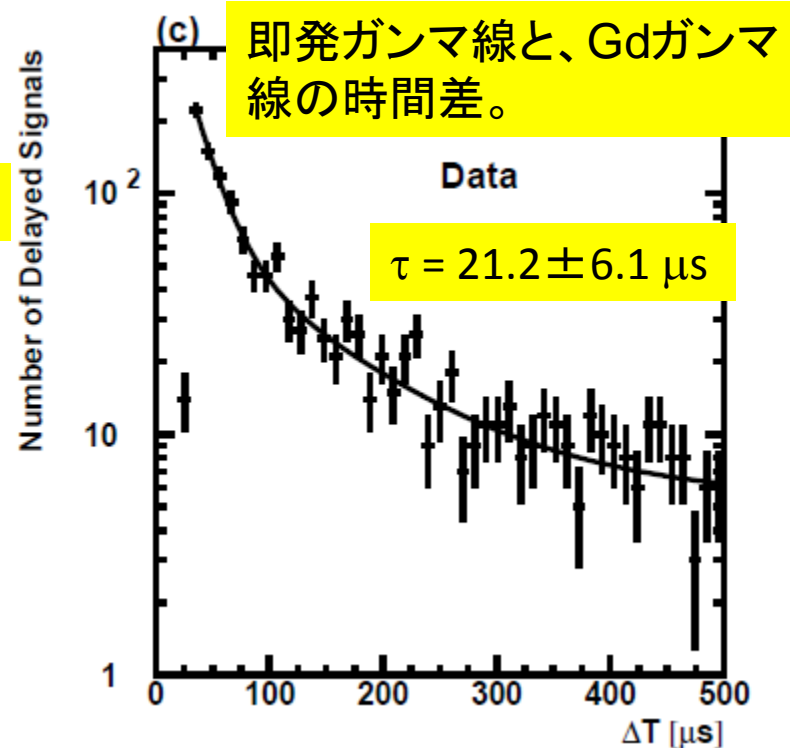
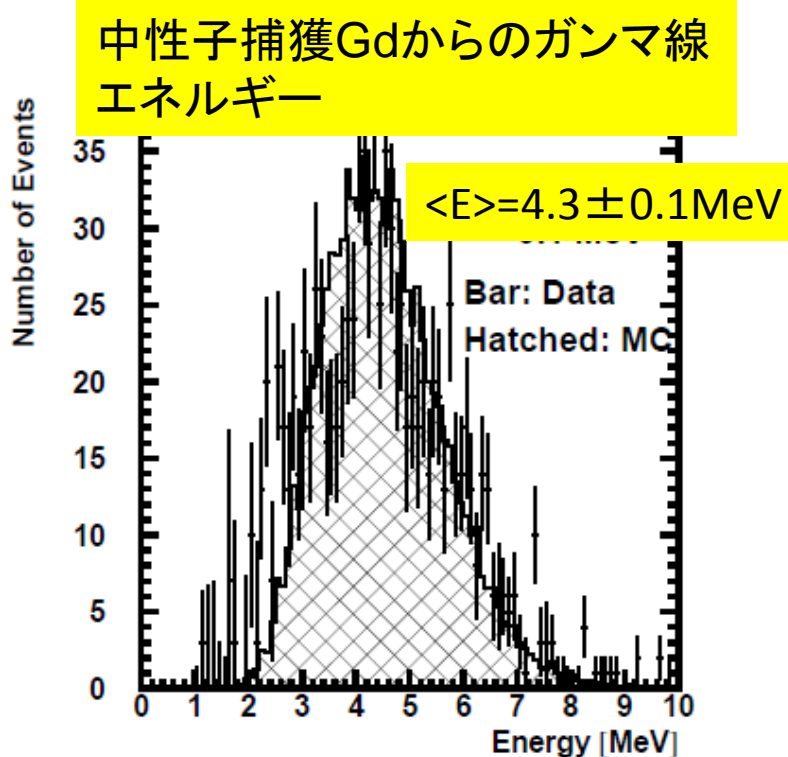
H. Watanabe et al., Astropart., Phys. 31, 320 (2009)

GdCl₃ test vessel



- Am/Be ソースは 4.43MeV のガンマ線と中性子を放出。
 - 4.43MeVガンマ線は、BGOによって検出。
 - 中性子は、容器の中のGd水溶液で吸収され、エネルギーが計8MeVガンマ線を放出。
- この容器をSKの中に配置して、SKでデータ収集。

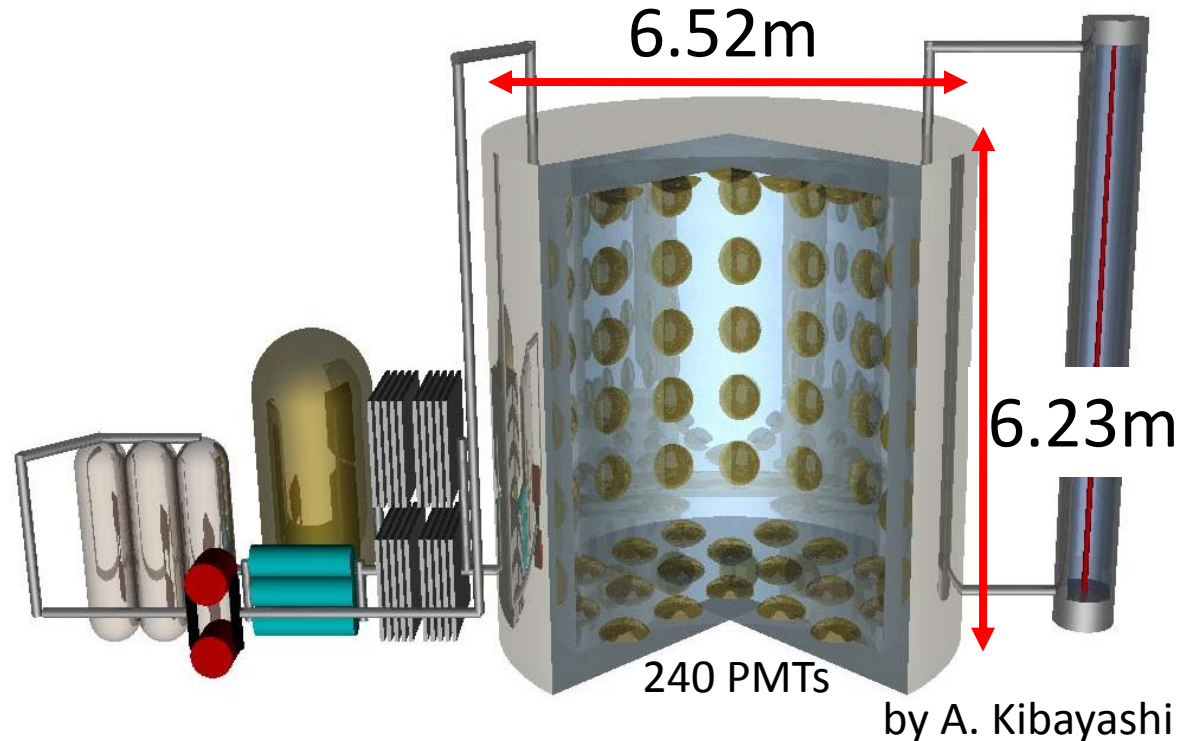
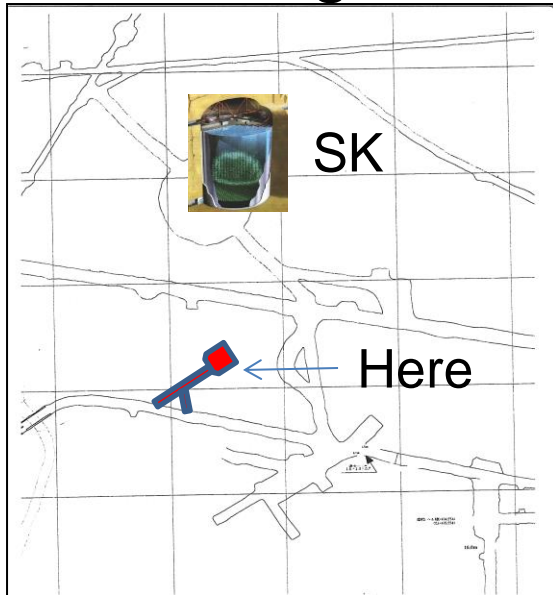
SKでの中性子検出効率の測定



- エネルギー分布はMCと一致。
- 遅延時間分布は、Gd溶液中での中性子の自由行程時間と一致。
- 中性子タグの効率 66.7%.
 - 偶発バックグラウンドは、即発事象のエネルギーが10MeV以上で、 2×10^{-4} 以下。

EGADS

Evaluating Gadolinium's Action on Detector Systems



- 評価用200トンGd溶液チェレンコフ装置
 - 水の透過率、腐食、環境中性子線、純化装置の試験等
- 平成21年度に予算が認められた。

200トン水チェレンコフ装置

溶液透過率測定装置



ガドリニウム溶解タンク

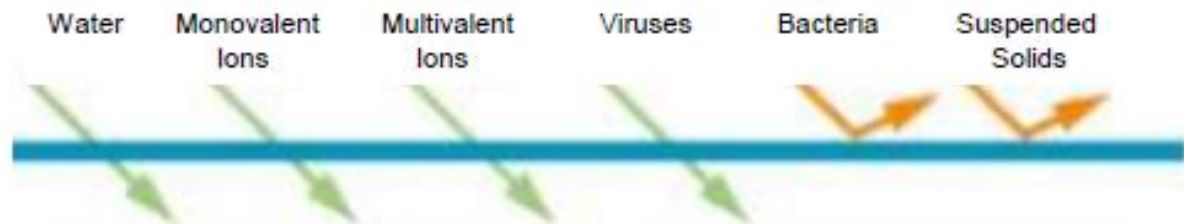
水純化装置群

2011.2.16



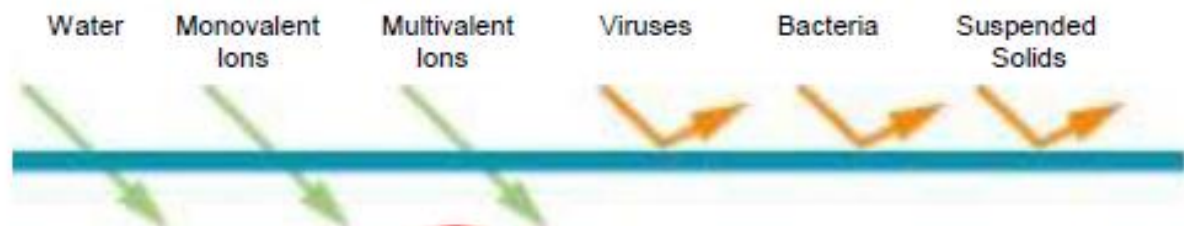
Microfiltration

1,000 – 100,000 angstroms
membrane pore size



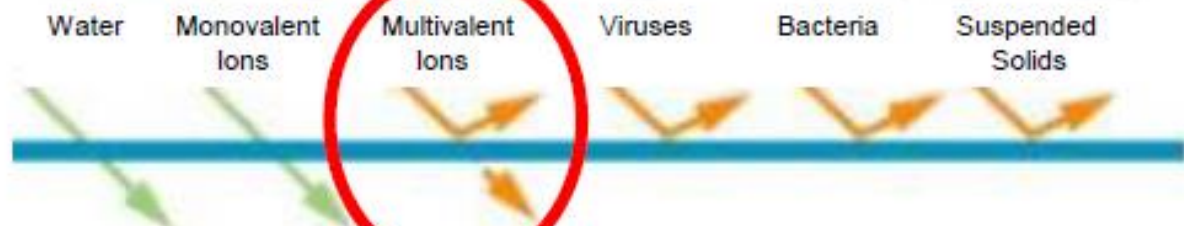
Ultrafiltration

100 – 1,000 angstroms
membrane pore size



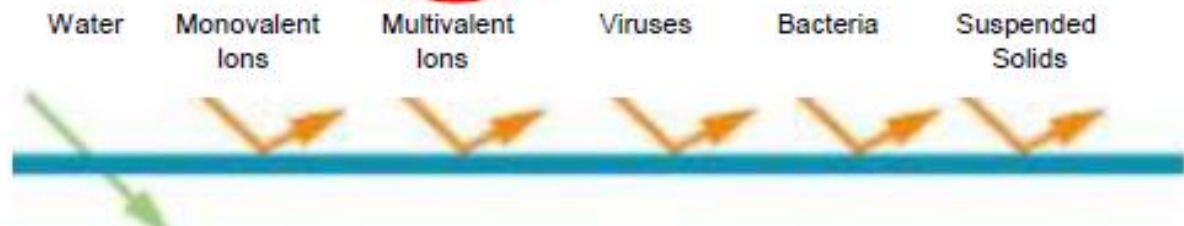
Nanofiltration

10 – 100 angstroms
membrane pore size

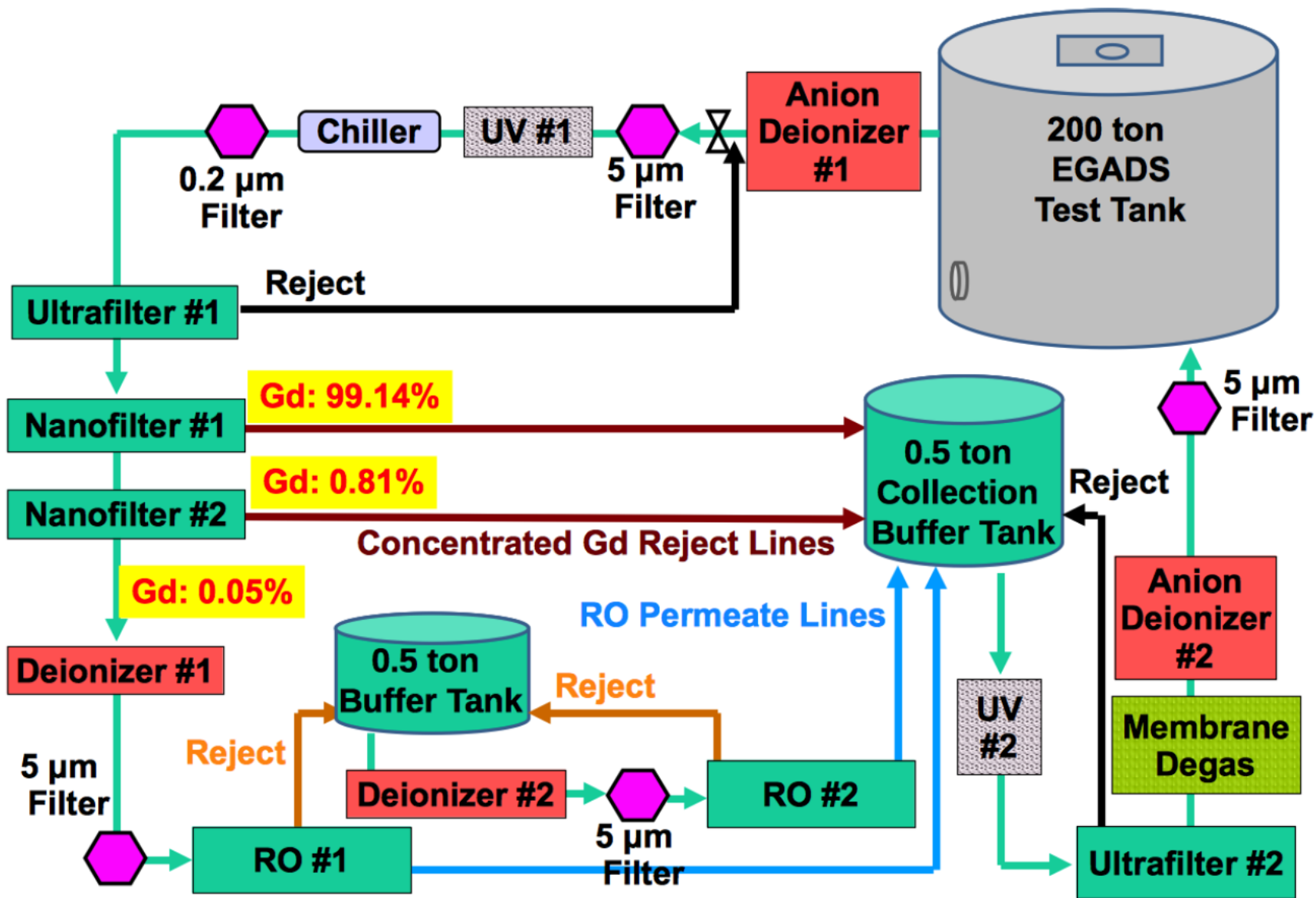


Reverse Osmosis

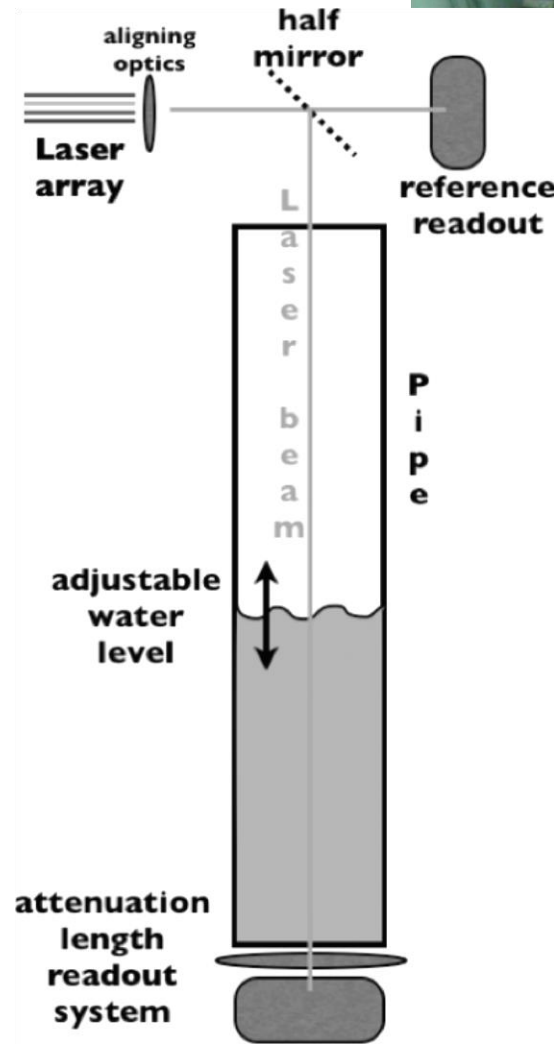
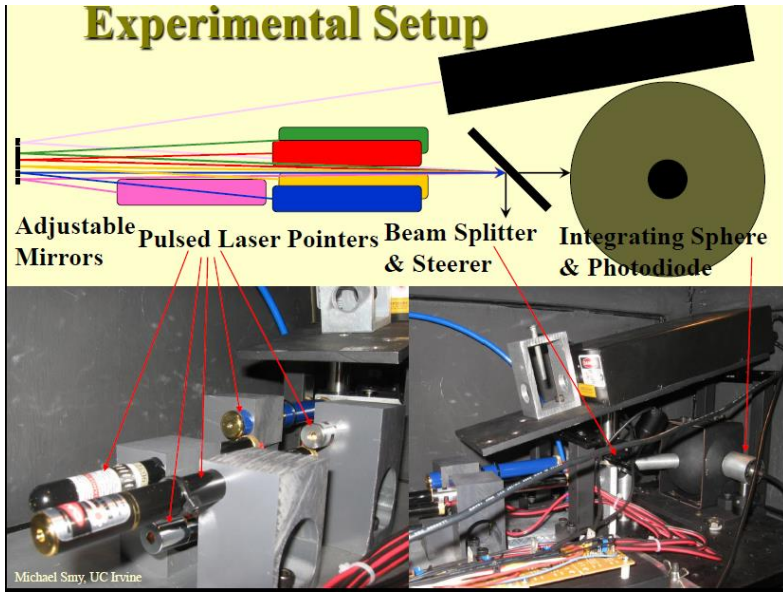
5 – 15 angstroms
membrane pore size



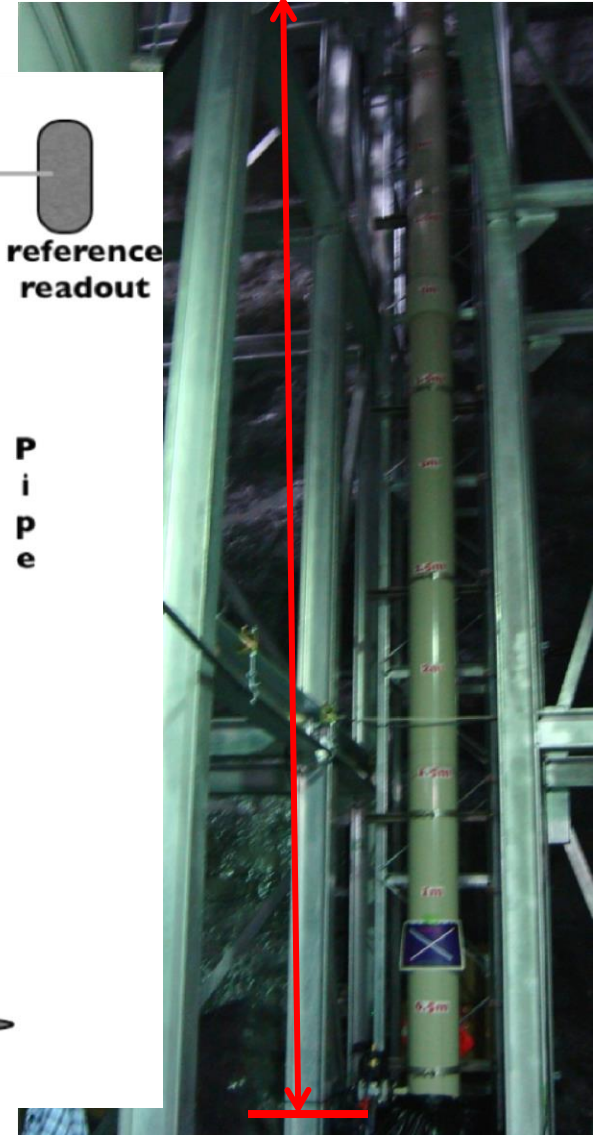
EGADS 純化装置



透過率の測定装置

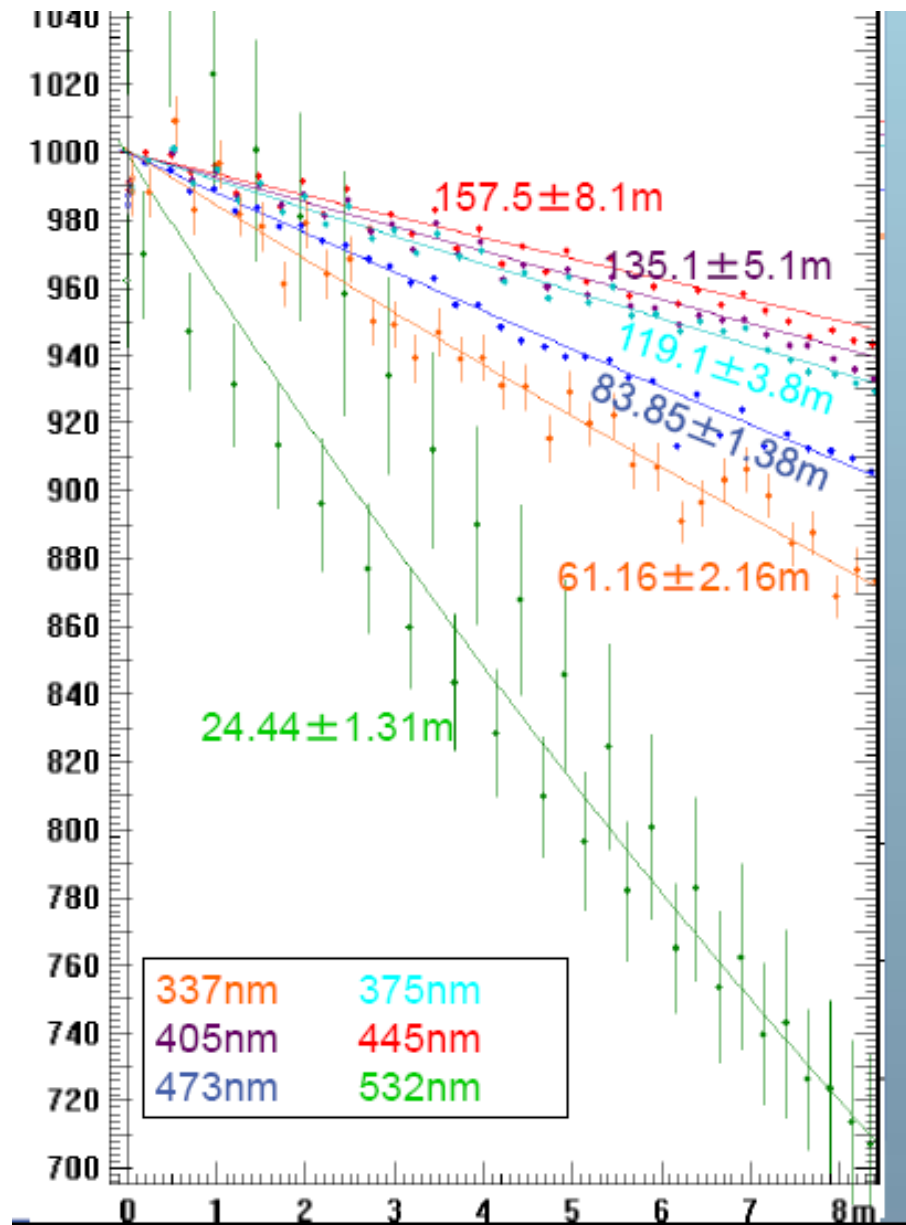


6.3m



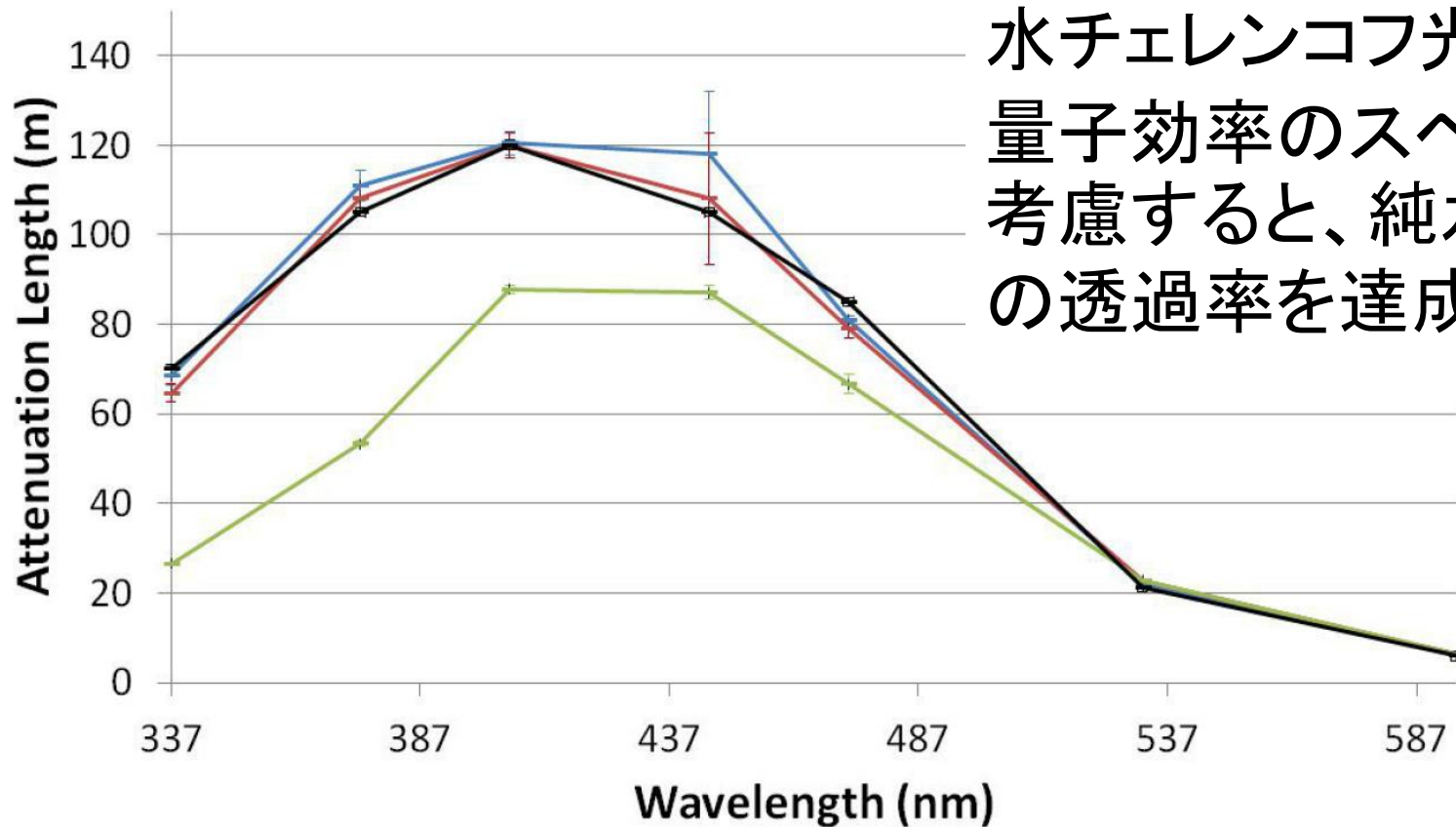
- 上部からレーザー光を入射
 - 波長:337~650nm
- 水位を変えることにより、光の減衰長を測定。

最初の透過率の測定結果



Gd 溶液透過率測定

— Pure Water in 200 Ton Tank — Pure Water in 15 m3 Tank
— Gd Water on Feb. 1st — SK Water



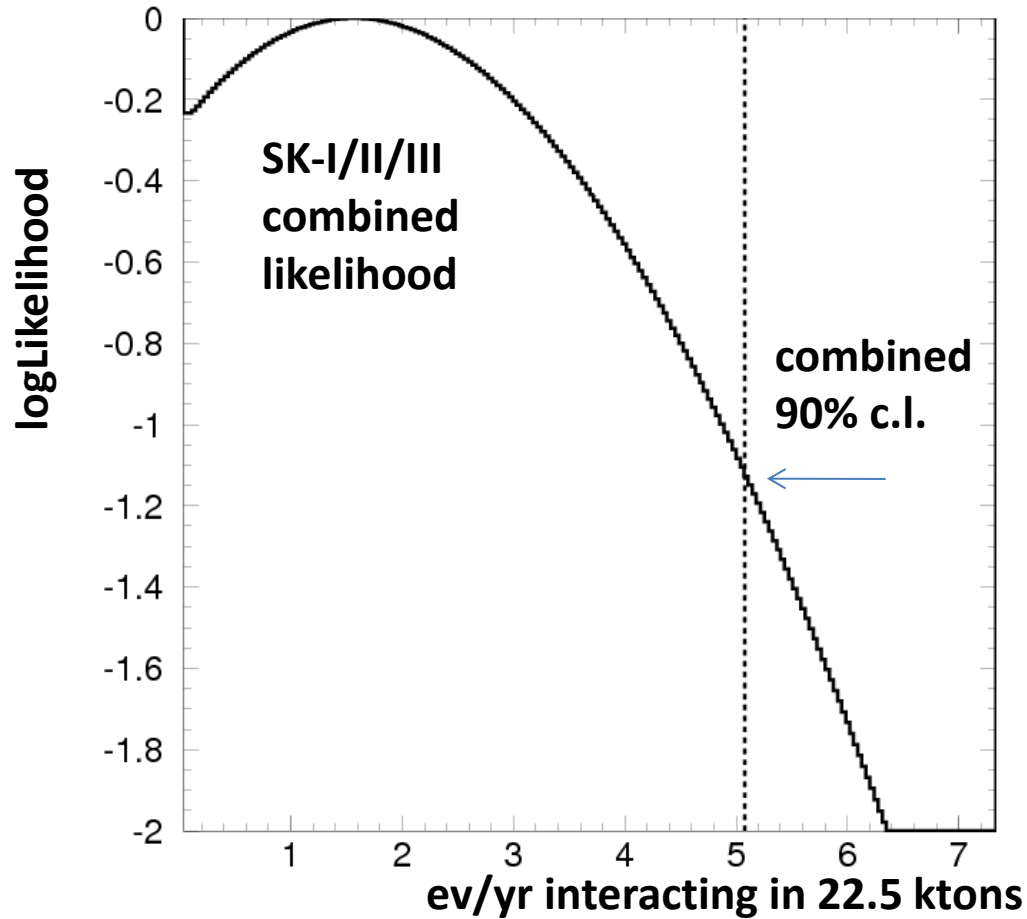
水チェレンコフ光 + PMT
量子効率のスペクトルを
考慮すると、純水の85%
の透過率を達成。

まとめ

- SN burst 探索
 - 世界中でSN burst のモニターをしている。
 - SKはニュートリノのみから方向を決定可能。
 - SN burst が起きたら1時間以内にアナウンスするシステム起動中。
 - SN方向は重力波検出にも有用な情報
- SKでのSRN探索
 - モデルの数倍程度まで上限値が与えられた。
- 中性子タグ
 - バックグラウンド事象を除くのに有用。
 - SKにおいて、陽子・ガドリニウムを用いた中性子タグのR&Dが進んでいる。

backup slides

Combined Fit

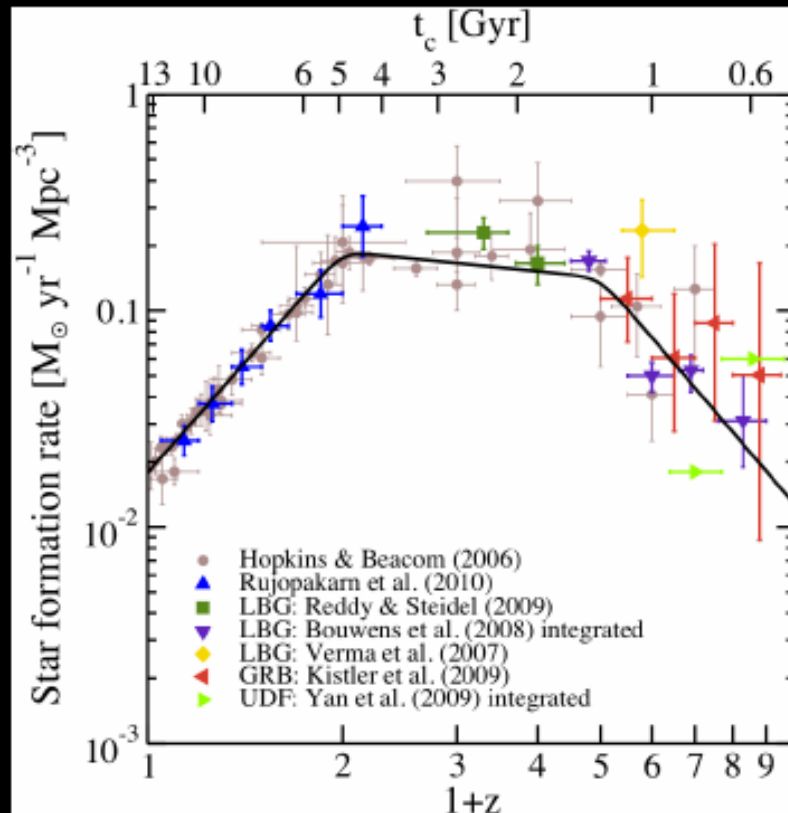


combined 90% c.l.:

- < 5.1 ev / yr / 22.5 ktons interacting
- < 2.7 /cm²/s (>16 MeV)
- < 1.9 /cm²/s (scaled to >18 MeV)

| <u>Comparison to Published</u> | /cm ² /s >18 MeV |
|---|--------------------------------|
| Published limit | 1.2 |
| cross section update to Strumia-Vissani | 1.2 → 1.4 |
| Gaussian statistics → Poissonian statistics in fit | 1.4 → 1.9 |
| <u>New SK-I Analysis:</u> E _{THRESH} 18 → 16 MeV ε = 52% → 78 % (small statistical correlation in samples) improved fitting method takes into account NC | 1.9 → 1.6 |
| New SK-I/II/III combined fit | 1.6 → 1.9 |

Predictions from Cosmic Star Formation Rate



Horiuchi, Beacom (2010);
see also Hopkins, Beacom (2006)

Total star formation rate
deduced from massive stars
using initial mass function (IMF)

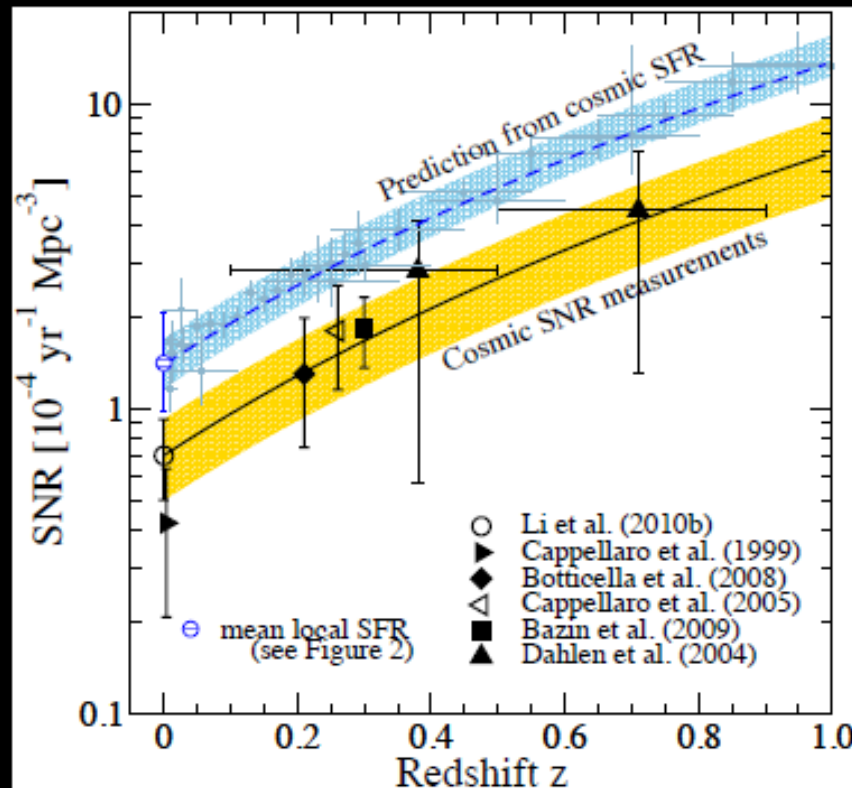
Impressive agreement among
results from different groups,
techniques, and wavelengths

Integral of R_{SF} agrees with EBL

$$R_{\text{SN}}(z) \simeq \frac{R_{\text{SF}}(z)}{143 M_{\odot}}$$

IMF uncertainty on R_{SN} small

Measured Cosmic Supernova Rate



Horiuchi et al. (2011);
see also Hopkins, Beacom (2006),
Botticella et al. (2008),
Mattila et al. (2012)

Measured cosmic supernova rate is **half as big as expected**, a greater deviation than allowed by uncertainties

Why?

There must be missing supernovae – are they faint, obscured, or truly dark?

Preliminary Dahlen (2010) points near solid line, below preliminary Dahlen (2008)

(Horiuchi poster)