

超新星ニュートリノ検出

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@早稲田大学 2015年3月24日

もくじ

- 超新星爆発ニュートリノバースト
 - 主な超新星爆発ニュートリノ検出器
- 超新星爆発背景ニュートリノ
 - SuperKにおけるガドリニウム導入計画
- 将来の超新星爆発ニュートリノ検出器
 - 次世代ニュートリノ検出器

参考資料:

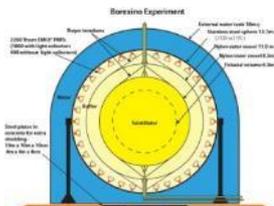
新学術「地下素核研究」 第一回超新星ニュートリノ研究会

@東京理科大3月16-17日

<http://www.lowbg.org/ugnd/workshop/groupC/sn20150316/agenda.html>

世界の超新星ニュートリノ検出器

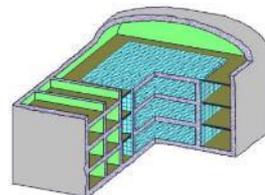
Borexino



LVD



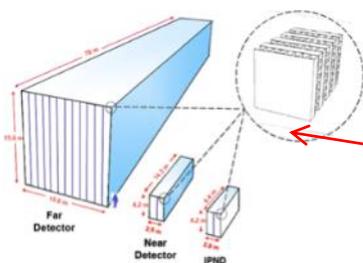
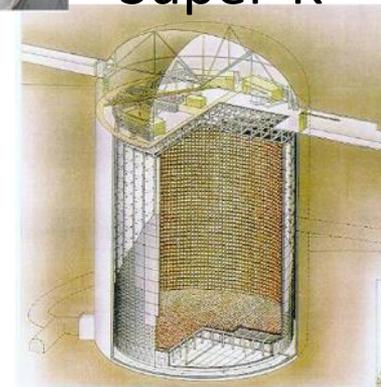
Baksan



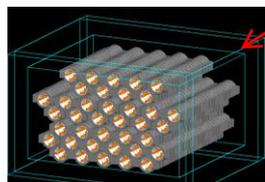
RENO



Super-K



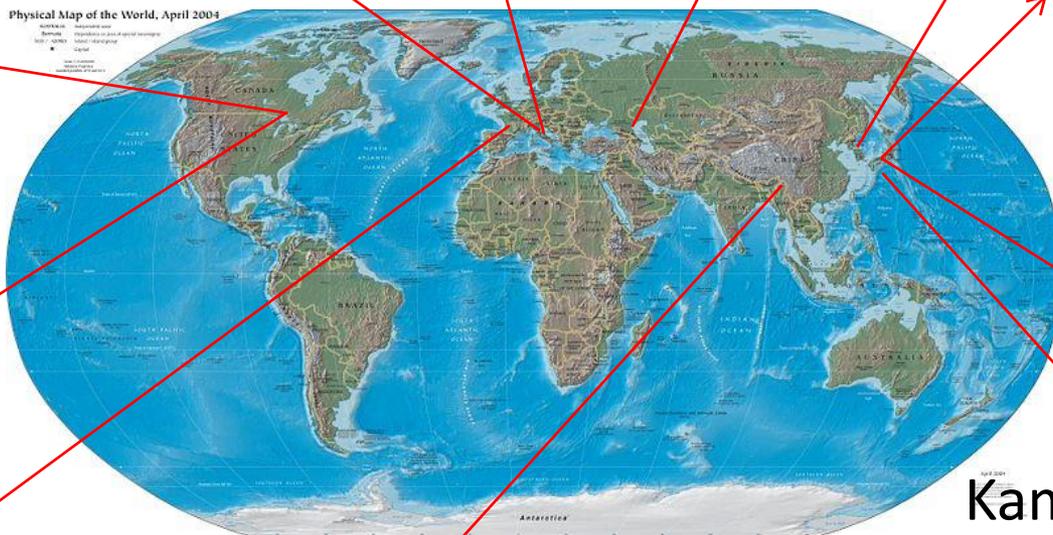
HALO



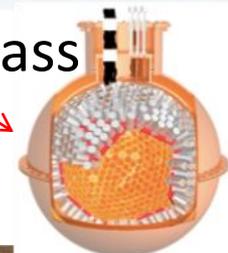
Double Chooz



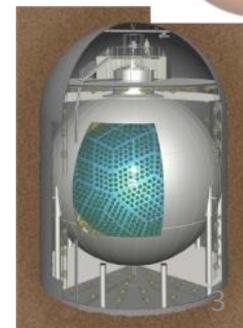
Daya bay



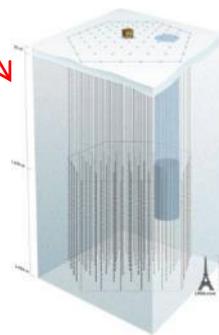
Xmass



KamLAND

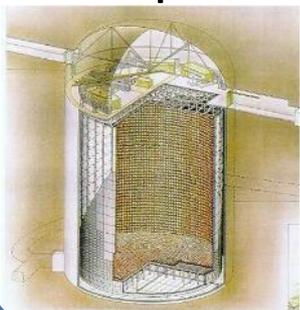


IceCube



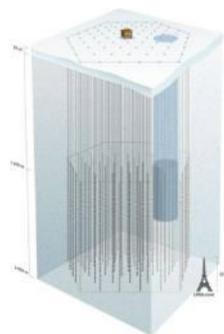
検出原理

Super-K



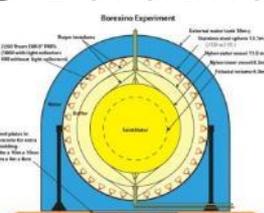
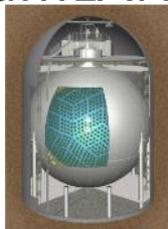
水チェレンコフ
SNの方向！

IceCube

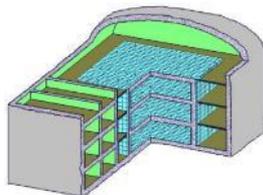


氷チェレンコフ

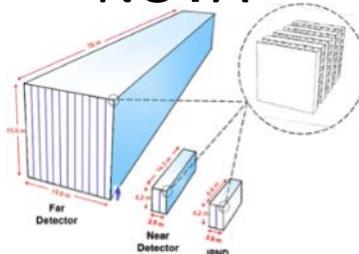
KamLAND Borexino



Baksan



NOvA



液体
シンチ

Double Chooz



Daya Bay



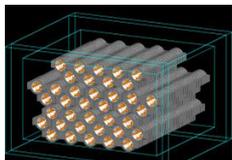
RENO



LVD



+ Gd



HALO

鉛+3He比例管



XMASS

液体Xeのシンチレーション光

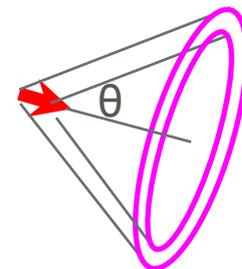
Super-Kamiokande

50kton 水チェレンコフ検出器

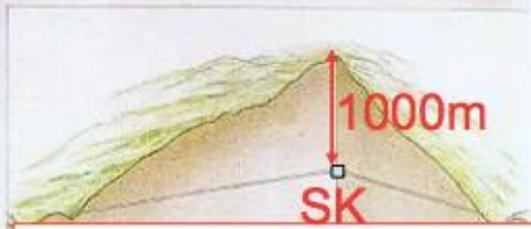


| | | |
|---------------------------------------|--------------|-----|
| 32kton fiducial volume for SN | | |
| 20' PMT photocathode (inner) coverage | | |
| SK-1 | 11,146 | 40% |
| SK-2 | 5,182 | 19% |
| SK-3 | 11,129 | 40% |
| SK-4 | same as SK-3 | |
| with new electronics | | |

charged particle



- ✓ 反跳電子のエネルギー閾値: 3.5MeV
- ✓ Inverse Bete Decay (IBD)
 - $\bar{\nu}_e + p \rightarrow n + e^+$
 - が主な反応
- ✓ 電子散乱反応から、方向がわかる。

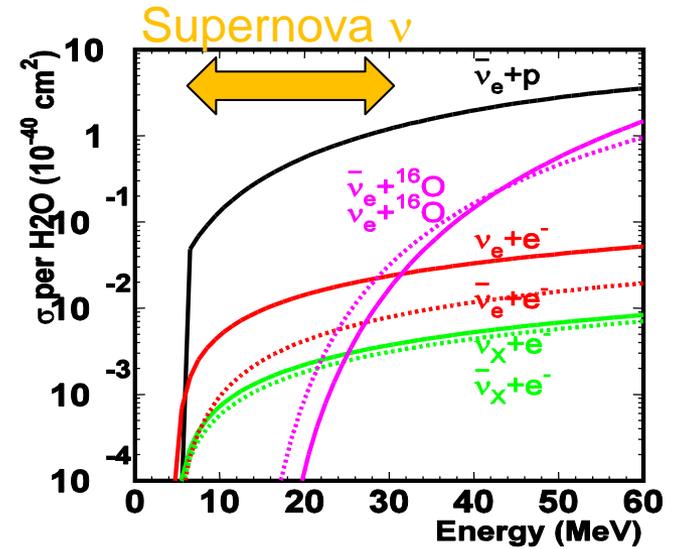
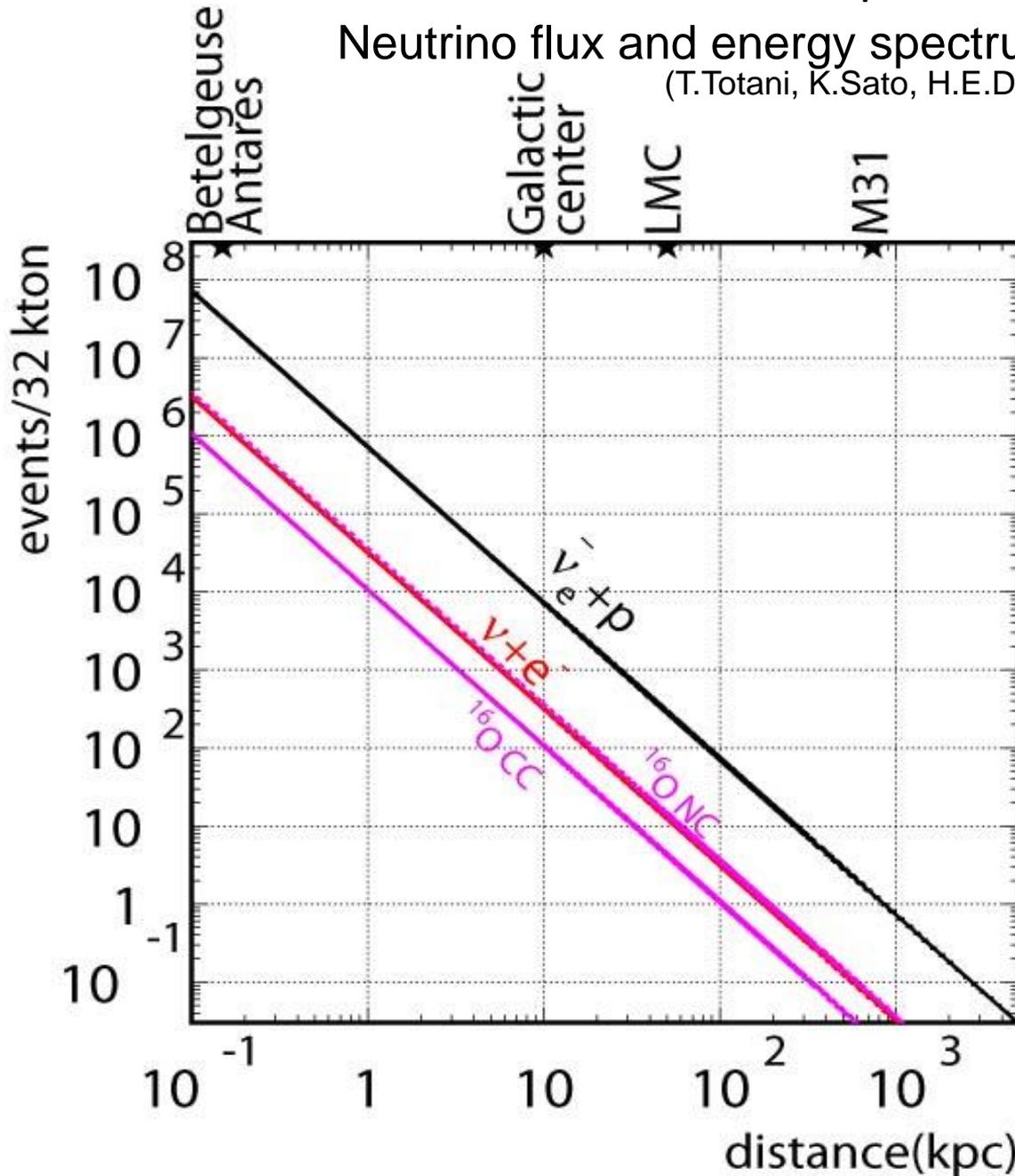


Placed inside the Kamioka mine 1000m underground



超新星爆発バースト @ Super-K

Neutrino flux and energy spectrum from Livermore simulation
 (T.Totani, K.Sato, H.E.Dalhed and J.R.Wilson, ApJ.496,216(1998))



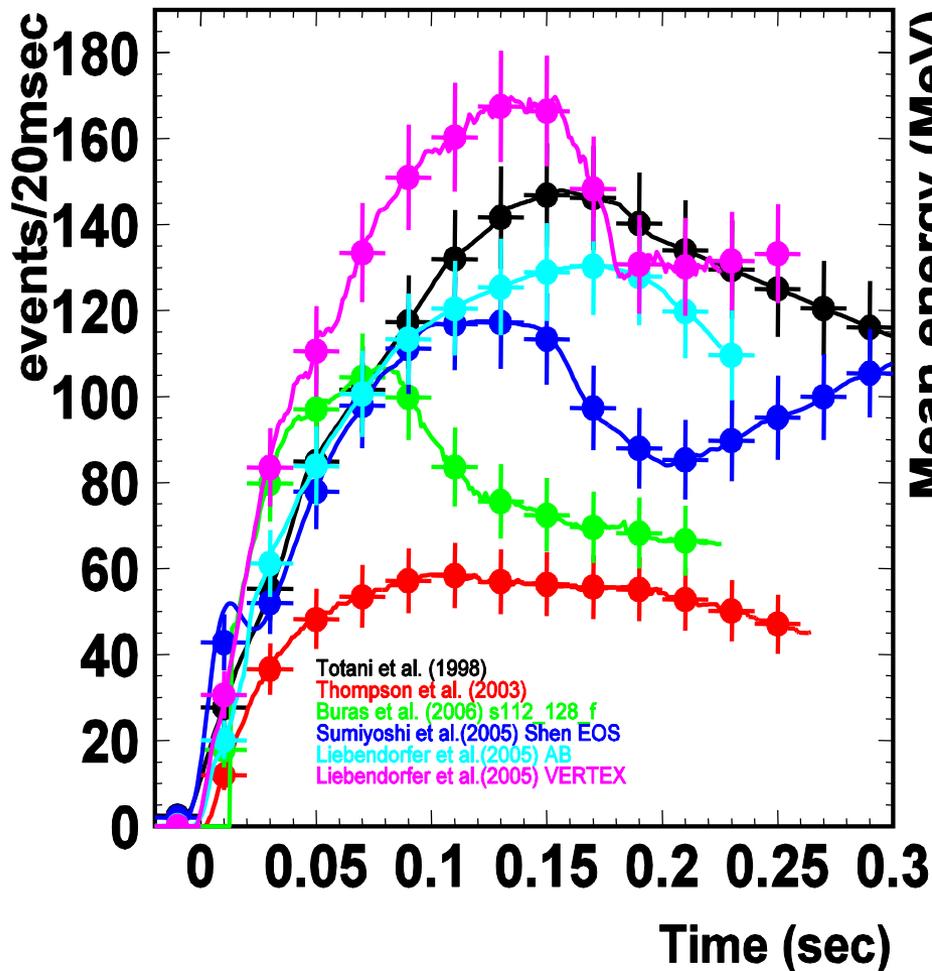
~7,300 $\bar{\nu}_e + p$ events
 ~300 $\nu + e$ events
 ~360 $^{16}\text{O NC } \gamma$ events
 ~100 $^{16}\text{O CC}$ events
 (with 5MeV thr.)
 for 10 kpc supernova

Super-K:高統計の観測が期待

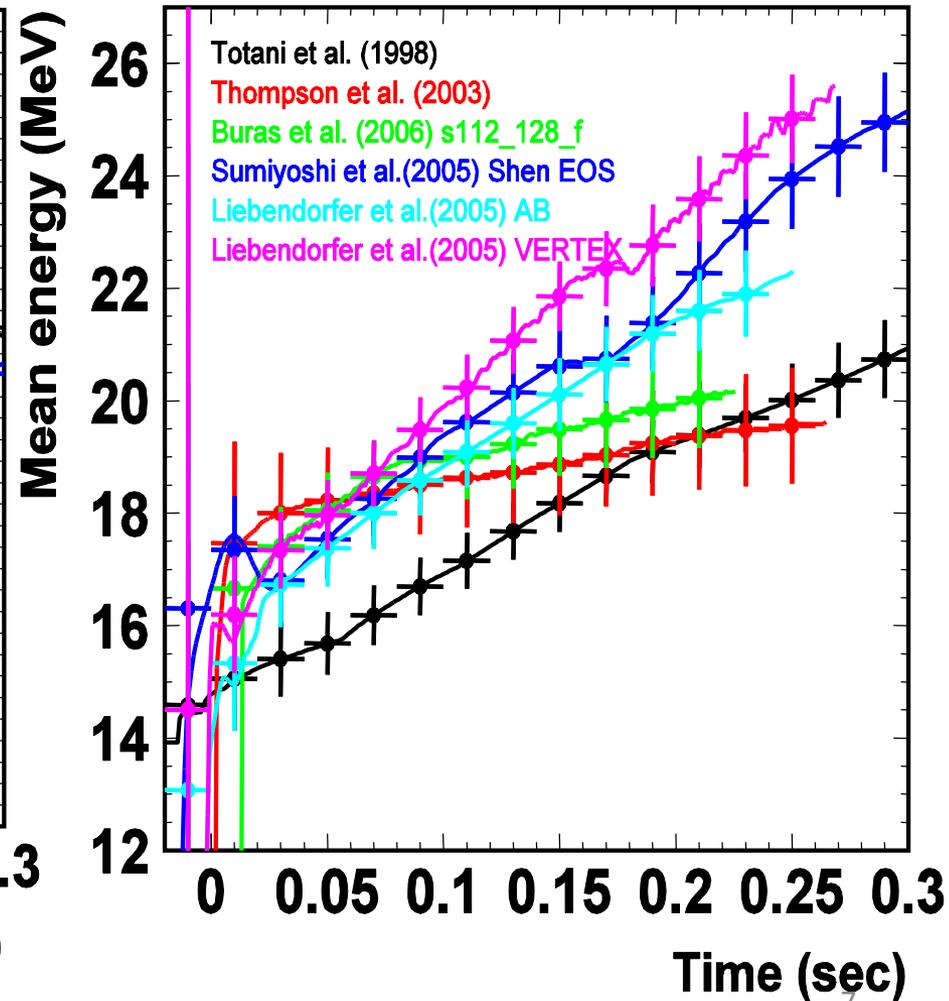
Assuming a supernova at 10kpc.

$\bar{\nu}_e p \rightarrow e^+ n$ events give direct energy information ($E_e = E_\nu - 1.3\text{MeV}$).

Time variation of event rate

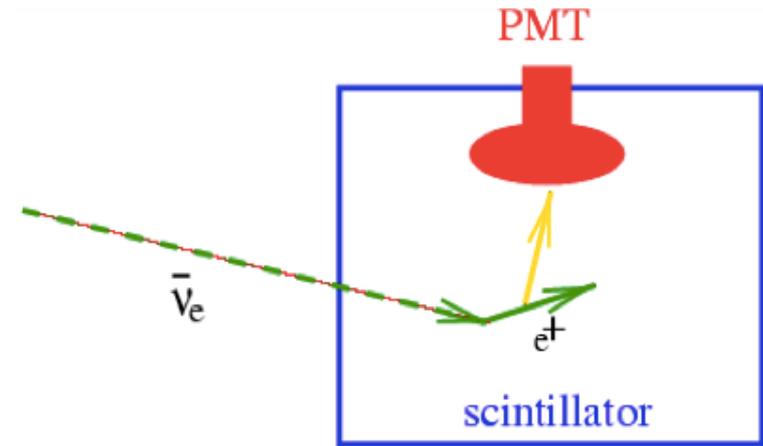


Time variation of mean energy

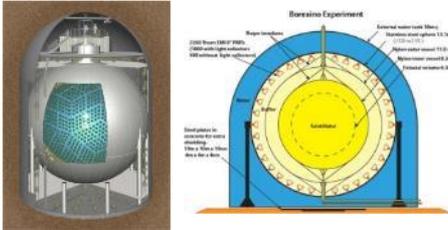


シンチレーション検出器

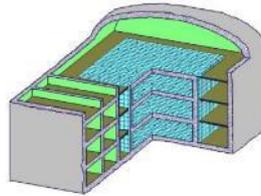
- ✓ 液シン(C_nH_{2n}) の発光を PMTs で観測.
- ✓ 低エネルギー閾値 (O(100keV))
- ✓ 遅延同時計測で低バックを実現
- ✓ 超新星の方向を決めるのは難しい



KamLAND Borexino



Baksan



LVD



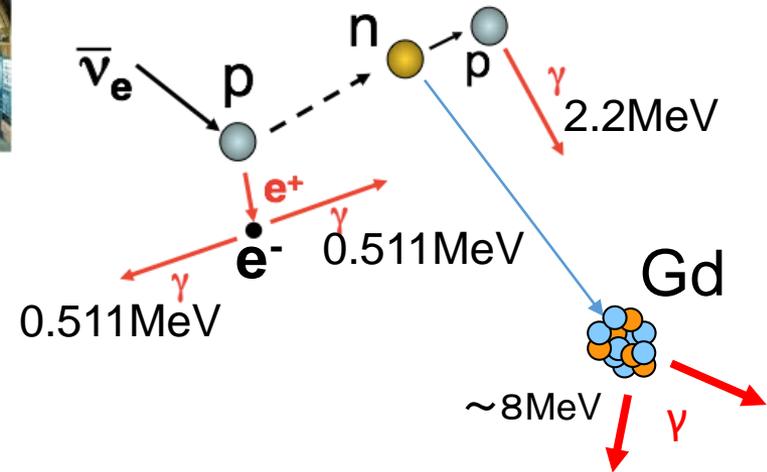
Double Chooz



Daya Bay



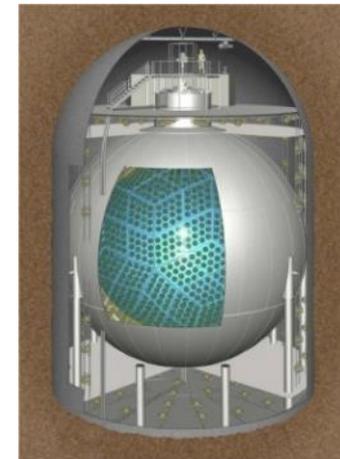
RENO



KamLAND

1000 ton Liquid scintillator at Kamioka

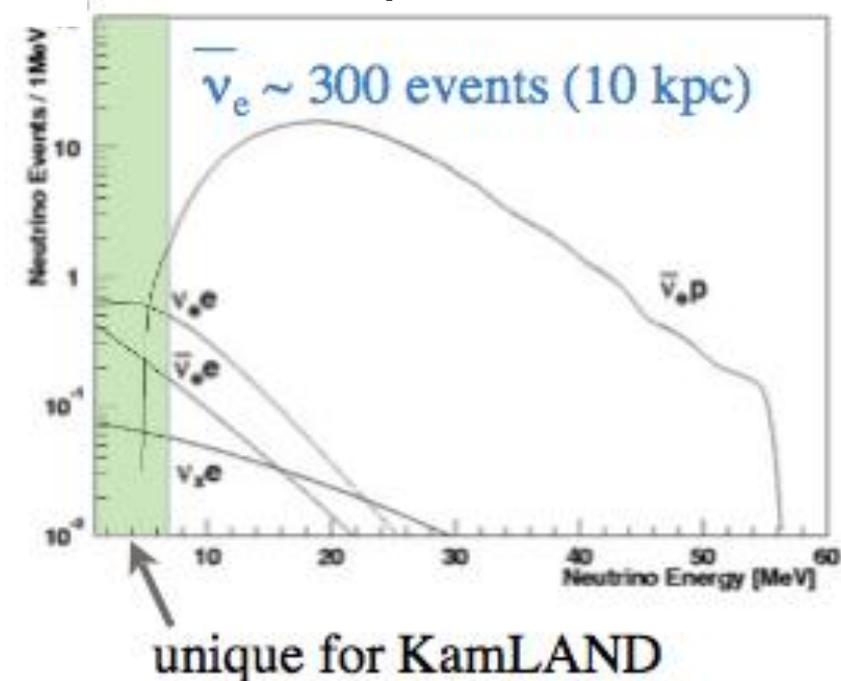
- ✓ 液シンで世界最大
- ✓ 低エネルギー閾値: 400keV
- ✓ エネルギー分解能 $7.25\% / \sqrt{E/(MeV)}$
- ✓ 前兆ニュートリノ(超近傍)



Spectrum

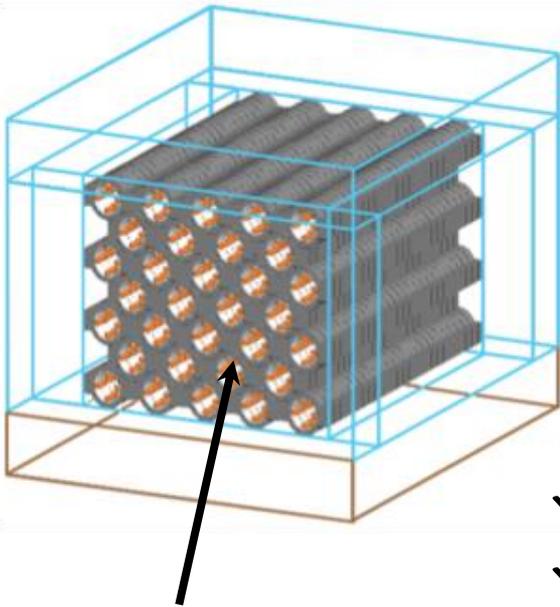
予想されるSN事象数(10kpc)

- ~300 ev (inverse beta decay)
- ~60 ev (^{12}C CC)
- ~20 ev (ν_e elastic scattering)
- ~300 ev ($\nu+p \rightarrow \nu+p$)



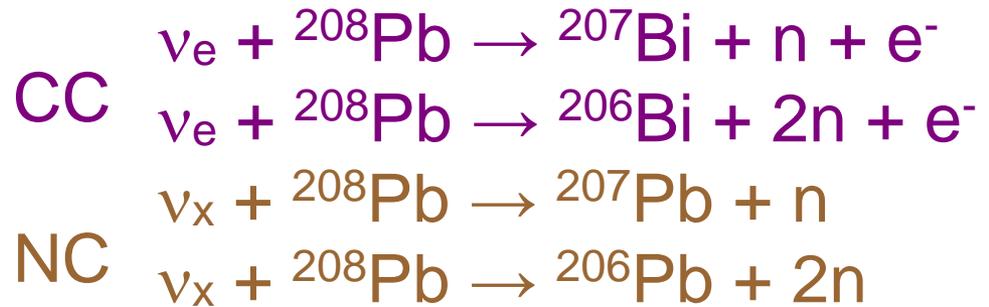
HALO

Helium and Lead Observatory at SNO lab. (Canada)



^3He 中性子検出器
+ 鉛ターゲット

$^3\text{He} + n \rightarrow p + T$
陽子 (573keV)
トリチウム(191keV)
を比例計数管で検出



- ✓ HALO-1 : 76 tons of Pb
- ✓ 85中性子 from SN@10kpc
 - 65 neutrons through CC
 - 20 neutrons through NC
- ✓ 中性子検出効率 ~50%
- ✓ ~40 events from SN@10kpc
- ✓ HALO-2 : kton スケールの将来計画進行中

XMASS 800kg Liquid Xenon detector

主な反応: NCコヒーレント散乱

$$\nu_x + (N, Z) \rightarrow \nu_x + (N, Z)$$

↑
13.5MeV 以上

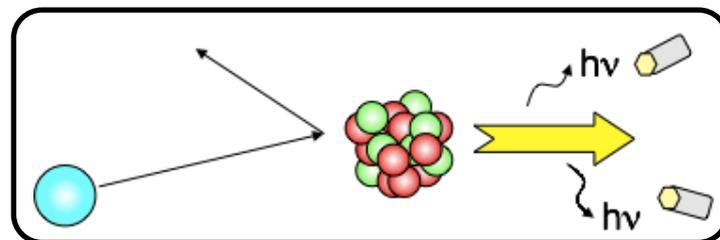
原子核
反跳が見える

XMASS(832kg)で期待されるイベント数

| Supernova model | d=10kpc |
|-------------------------------|------------|
| Livermore | 15 events |
| Nakazato (20M, Z=0.02, 100ms) | 3.5 events |
| Nakazato (30M, Z=0.02, 300ms) | 8.7 events |
| Nakazato (blackhole) | 21 events |

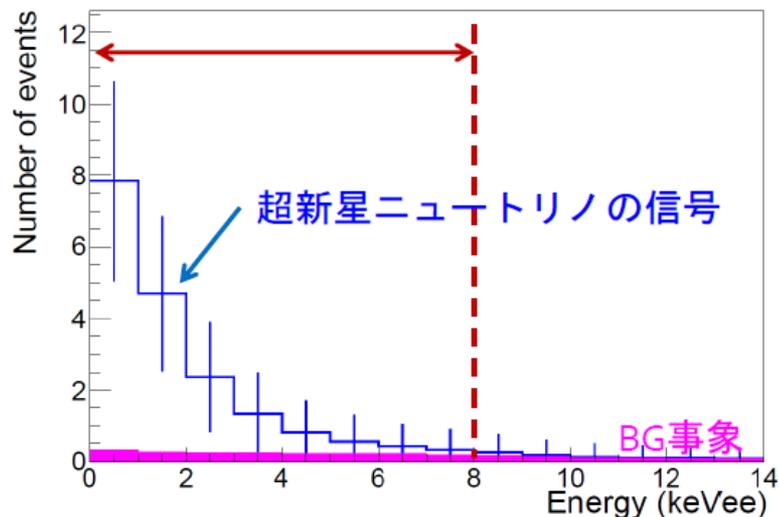
NCコヒーレント反応は
これまで誰も見たことがない!

Direct dark matter search



nuclear recoil interaction

Livermoreモデル (d=10kpc)
10秒間で観測される事象



超新星ニュートリノバースト観測

| | SN1987A | 次の銀河内SN (10kpc) |
|-------------|-------------------|--------------------|
| 実験数 | 3(KM,IMB,Baksan) | >10 |
| ニュートリノ数 | 24(KM11,IMB5,Bs8) | 5000~10000 |
| 発見までにかかった時間 | ~1日 | 1時間以内 |
| 爆発したSNモデル | 1? | 多数 |
| 重力波観測 | × | ○ |
| マンパワー | ~few NH | <10NH? |

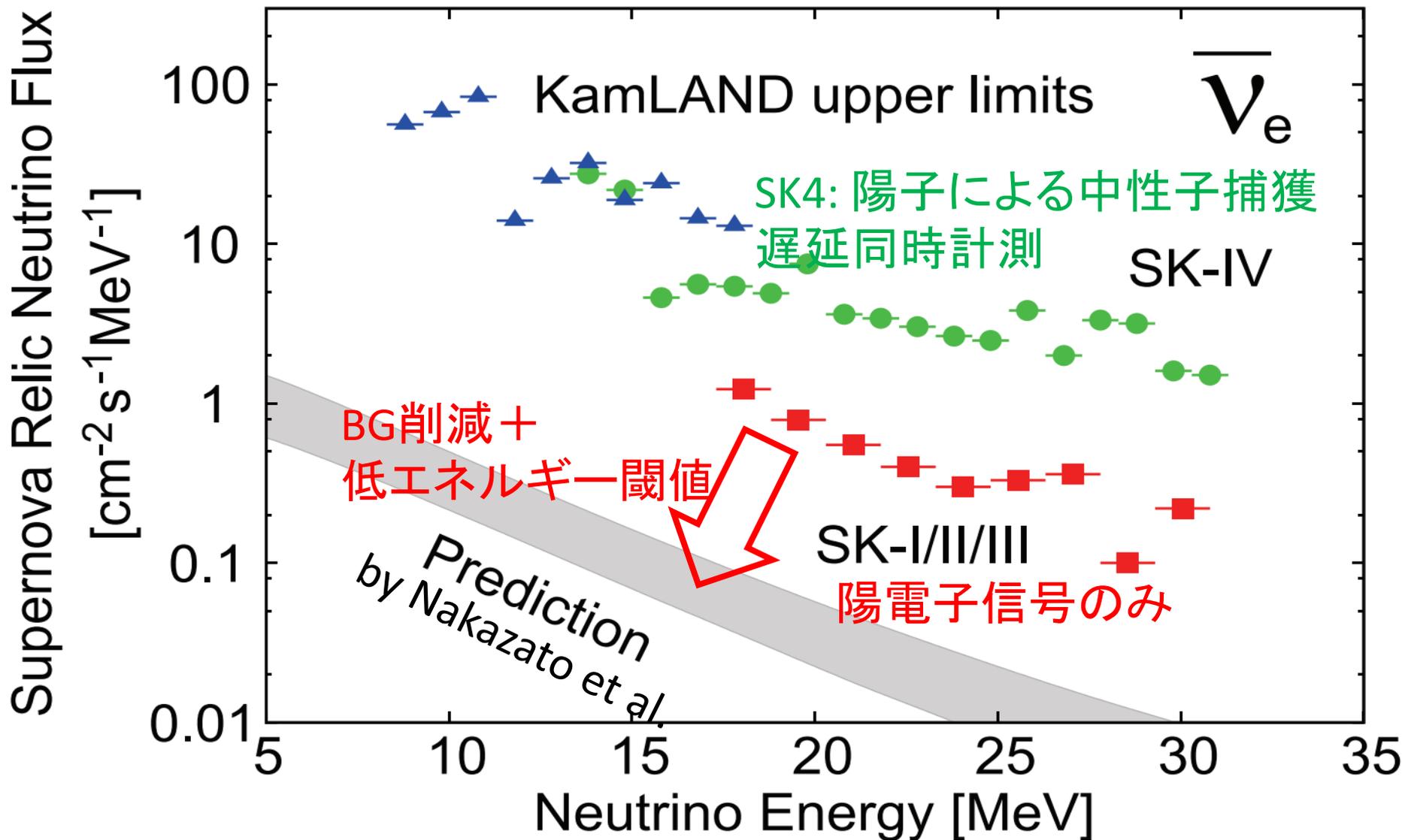
1NH = 3人*24時間

超新星ニュートリノバースト観測

| | SN1987A | 次の銀河内SN (10kpc) |
|-------------|-------------------|--------------------|
| 実験数 | 3(KM,IMB,Baksan) | >10 |
| ニュートリノ数 | 24(KM11,IMB5,Bs8) | 5000~10000 |
| 発見までにかかった時間 | ~1日 | 1時間以内 |
| 爆発したSNモデル | 1? | 多数 |
| 重力波観測 | × | ○ |
| マンパワー | ~few NH | <10NH? |

みなさん(特に学生さん)大歓迎! 1NH = 3人*24時間

超新星背景ニュートリノ (SRN)



SKのSRN探索におけるバックグラウンド

NC Elastic

“reactor + solar”

Decay electron

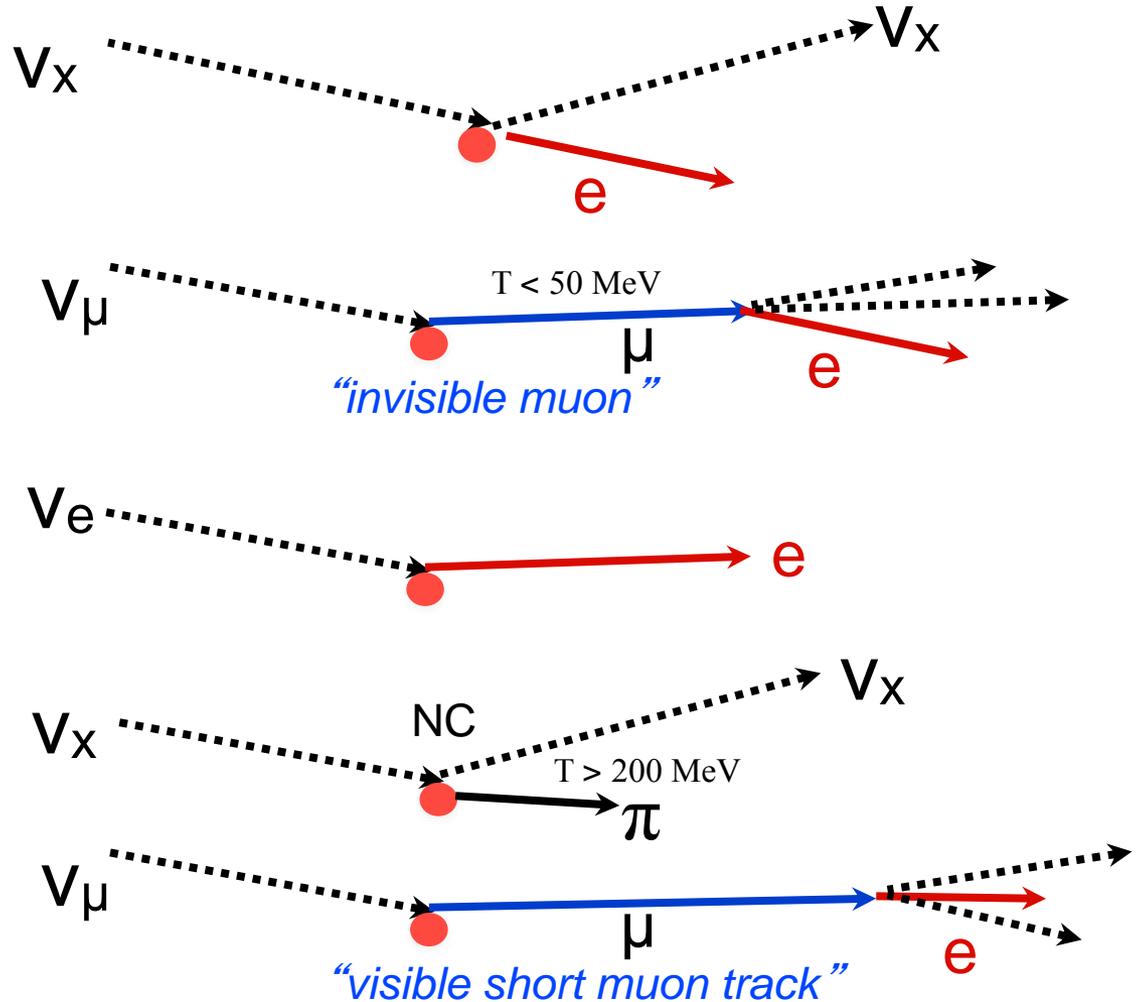
“atm. muon neutrinos”

ν_e CC

“atm. electron neutrinos”

μ/π

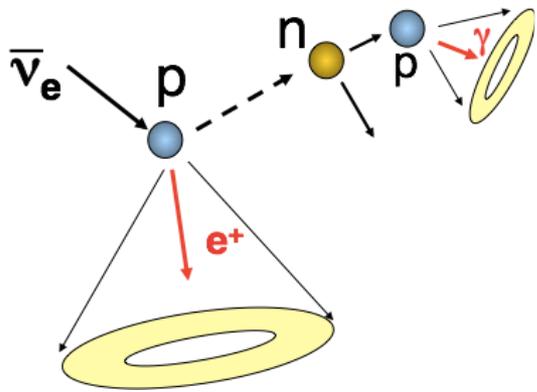
“ μ/π production from atm. neutrinos”



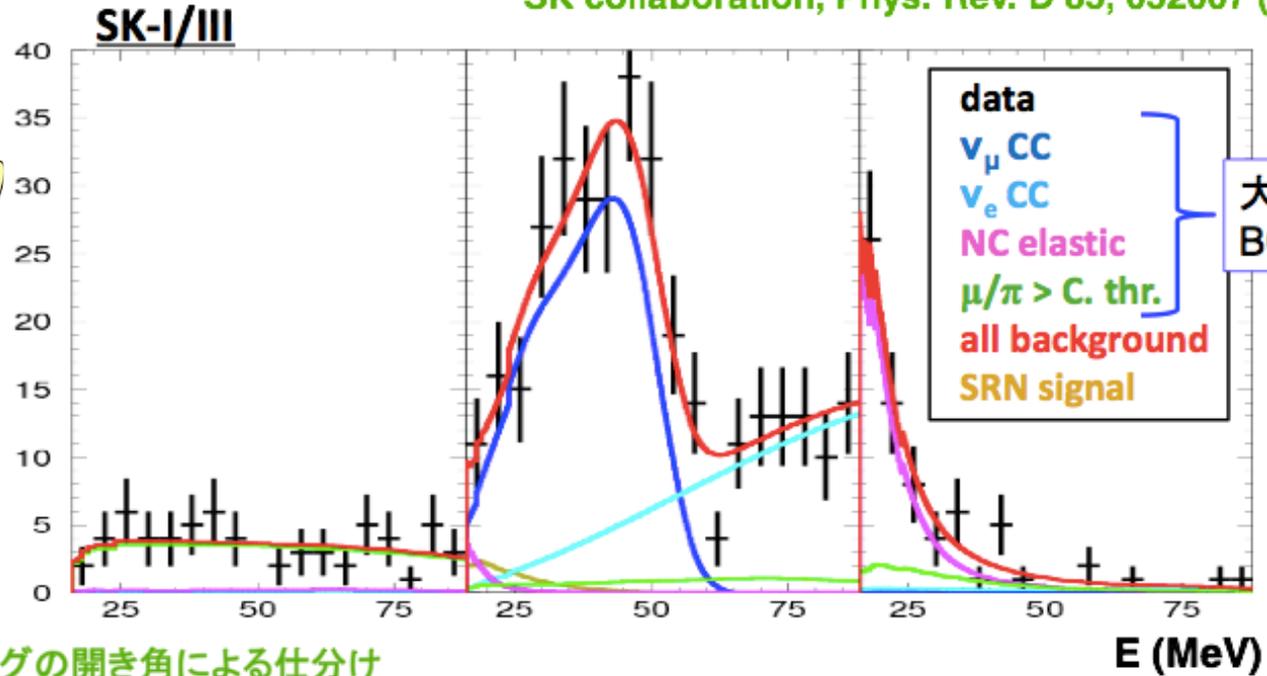
SRN探索@SK

現在のベストリミットは中性子タグ無し
 サイドバンドサンプルよりBG量に制限をかけている。

SK collaboration, Phys. Rev. D 85, 052007 (2012)

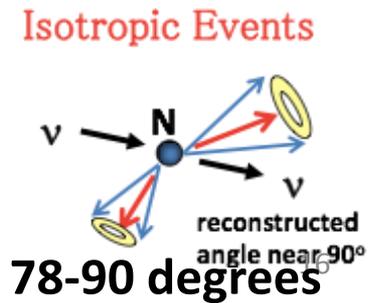
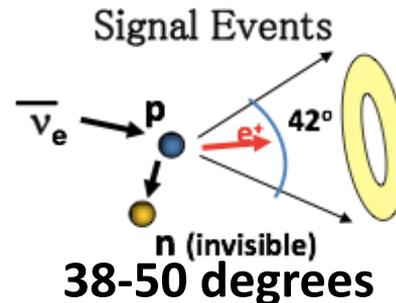
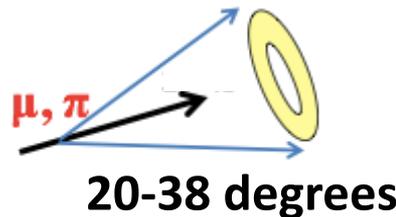


Only this signal

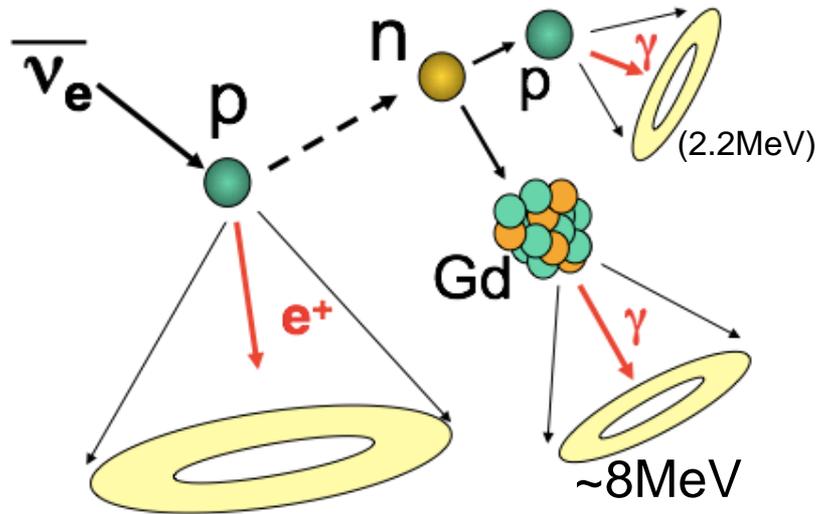


リングの開き角による仕分け

Low angle events



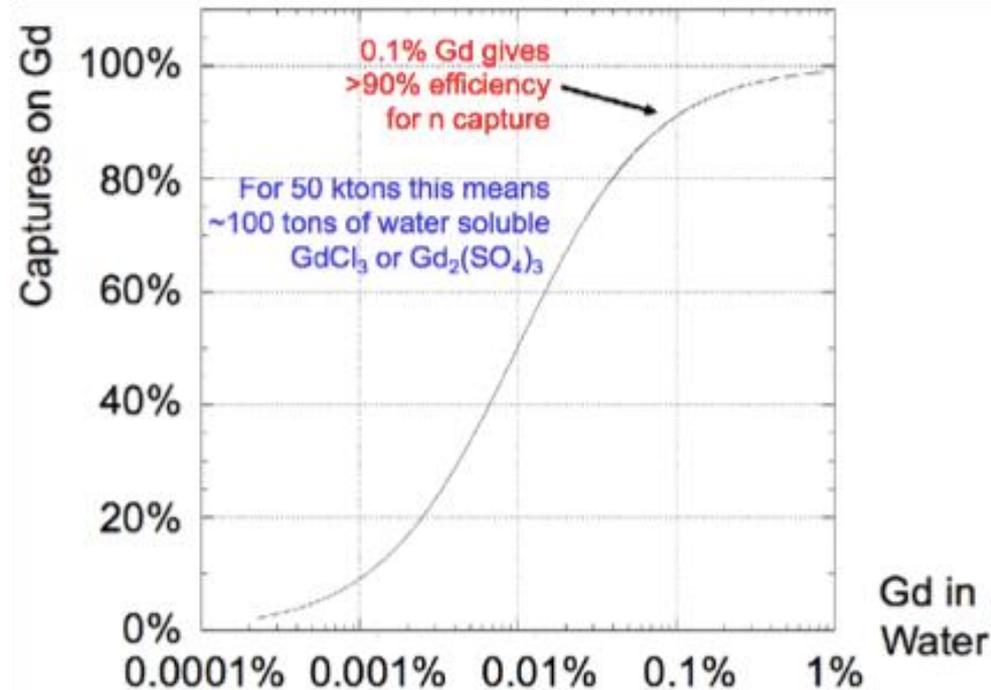
Gd導入計画@Super-K



- 液シン検出器同様に遅延同時計測が可能
- 中性子を伴わない大気ν起源BGを削減
- $\Delta T \sim 20 \mu\text{sec}$
- 発生点分解能 $\sim 50\text{cm}$

GADZOOKS!

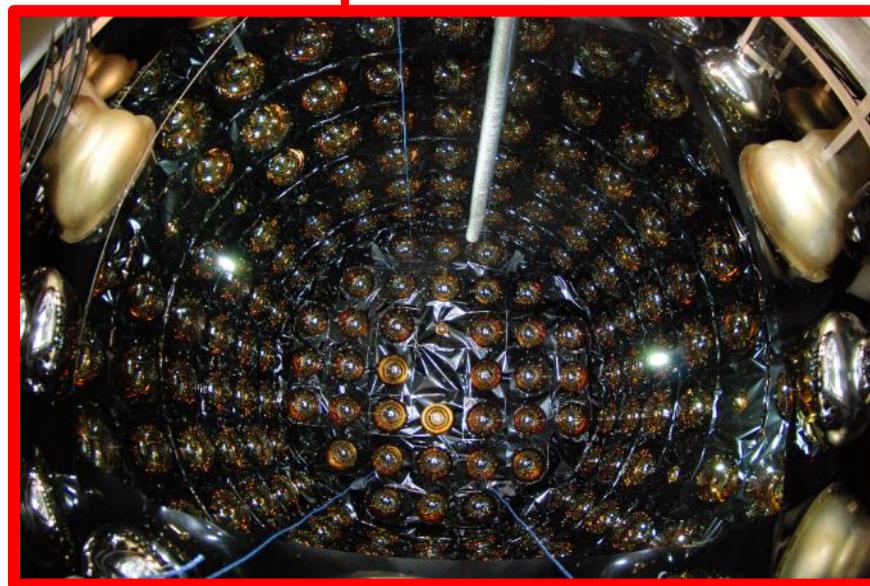
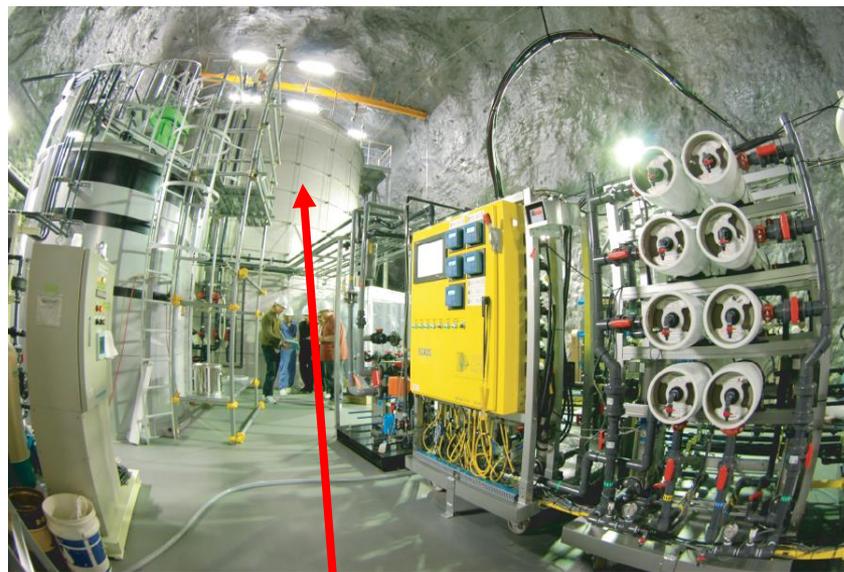
Dissolve Gadolinium into Super-K
J.Beacom and M.Vagins,
Phys.Rev.Lett.93(2004)171101



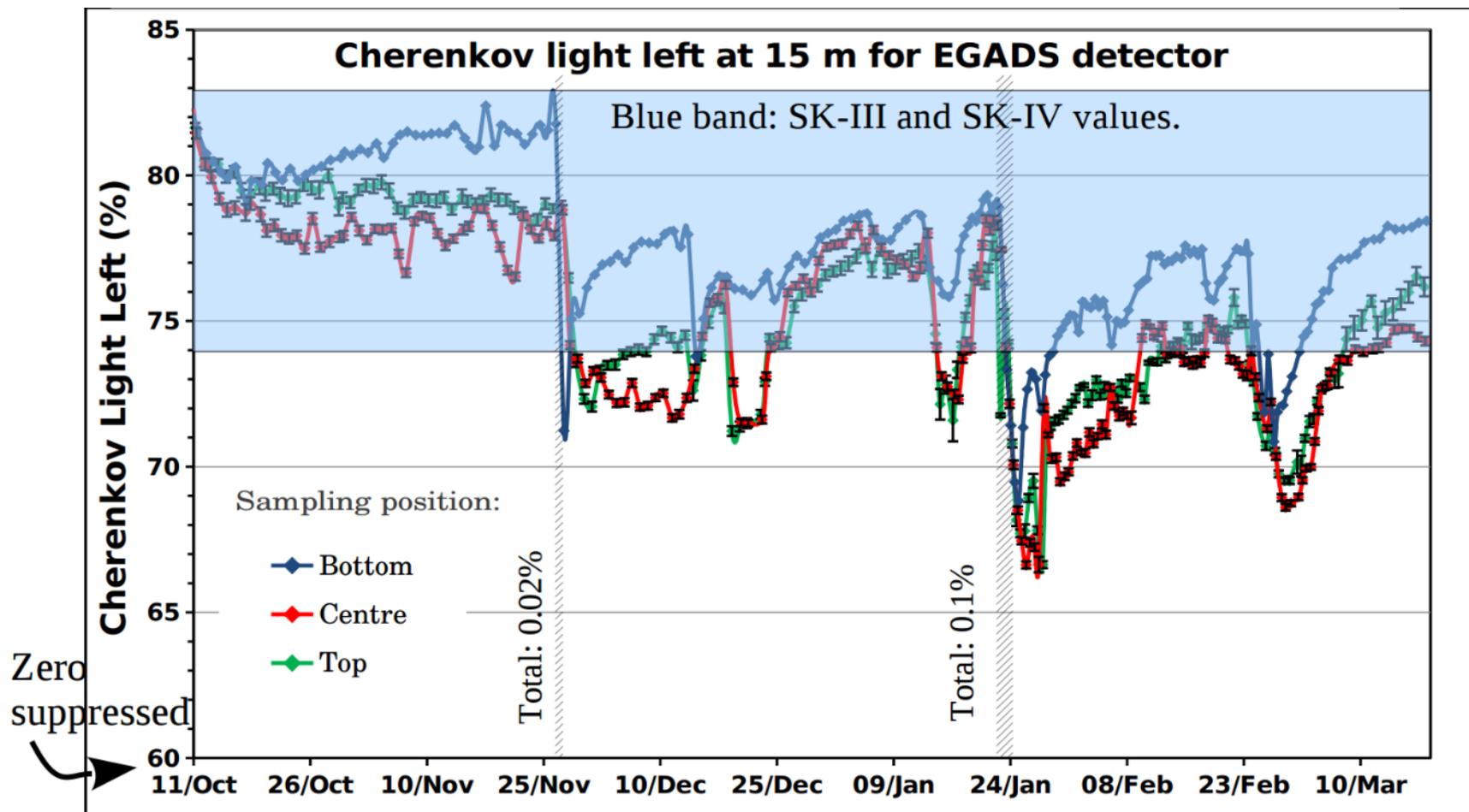
SKにおけるGdの効果を検証する実験: EGADS

(Evaluating Gadolinium's Action on Detector Systems)

- 水循環システム
 - EGADS用のシステムは順調に稼働中。
- 水透過率への影響
 - 現在目標の半分の濃度SKと同等の透過率をキープ
- 検出器への影響
 - PMTの応答をモニター
- Gd中性子タグ方法確認
 - Am/Be 中性子線源で確認



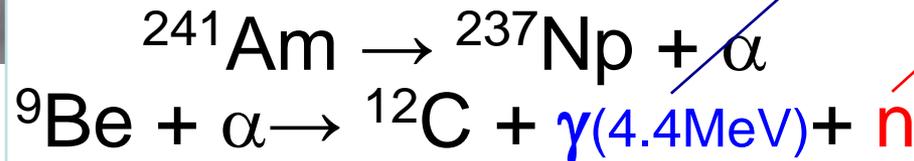
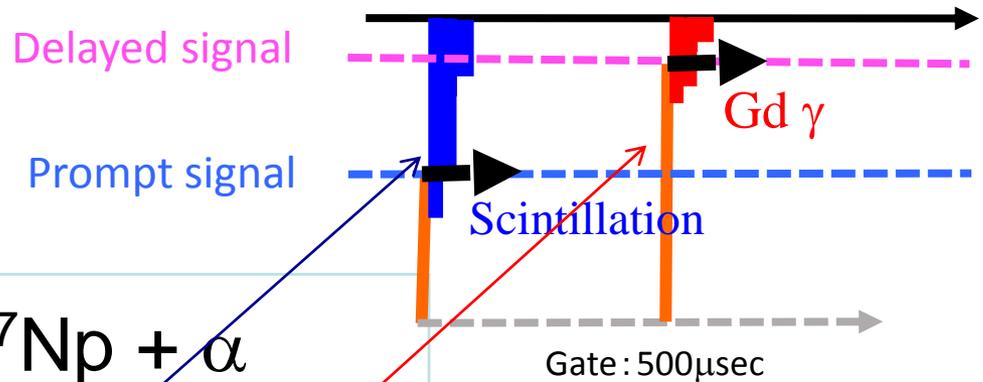
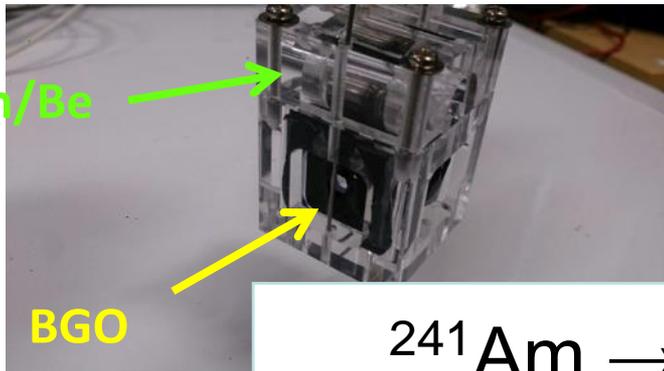
EGADSで測定された透過率



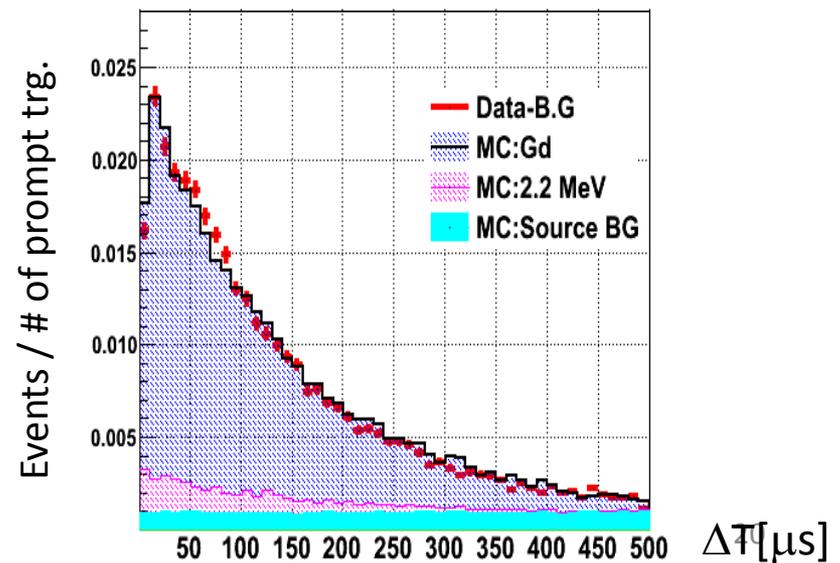
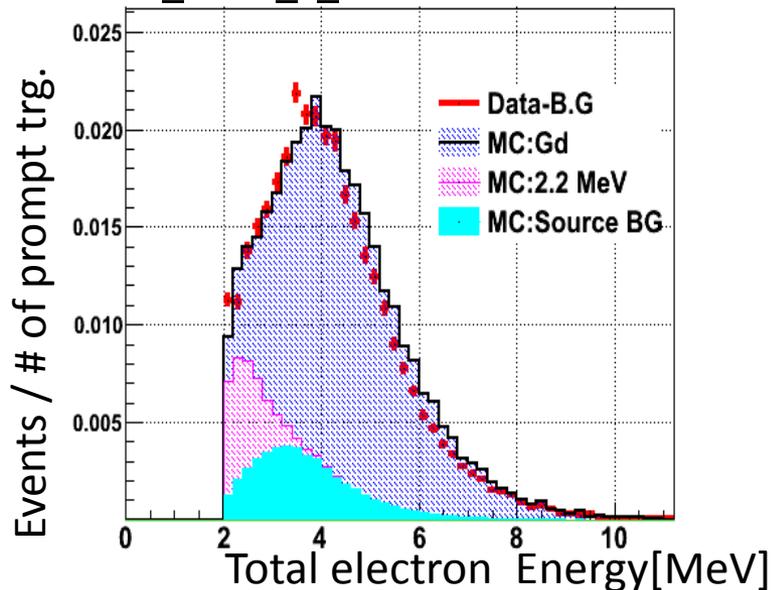
After loading 0.1% of $Gd_2(SO_4)_3$, the Cherenkov light left after traveling 15 m in the EGADS tank is still within the typical SK values:

まだ目標の半分の濃度だが、SKの透過率をキープできている¹⁹

EGADSでの中性子捕獲信号



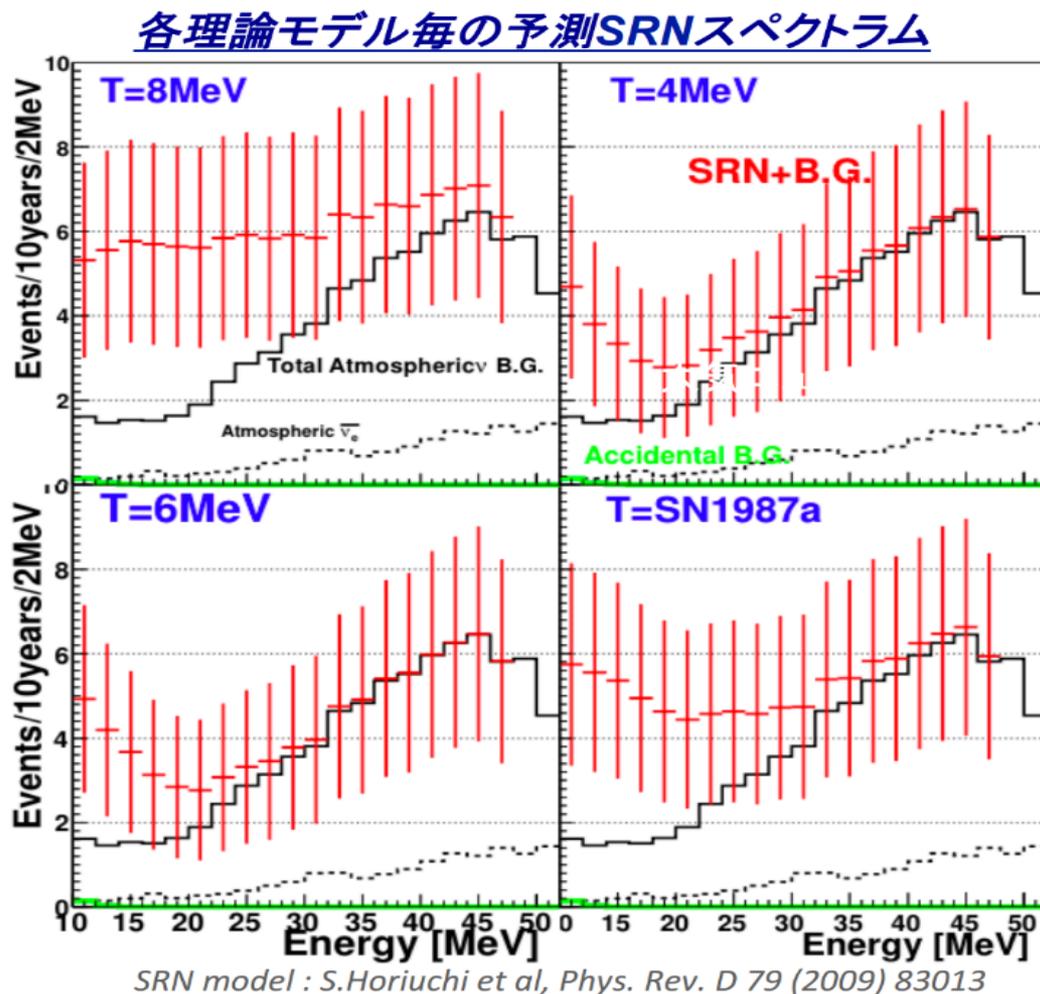
Gd₂(SO₄)₃ concentration: 200 ppm (目標の10分の1)



SK+GdにおけるSRN信号

硫酸Gd 0.2% (Gd 0.1%) で
10年観測のSRN事象数:
16~30事象 : Horiuchi et al
4~9事象 (10~18MeV)
: Nakazato et al
モデル識別が可能。

~2年後には
観測開始(したい)

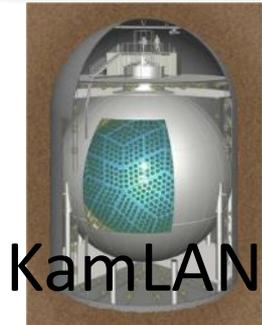
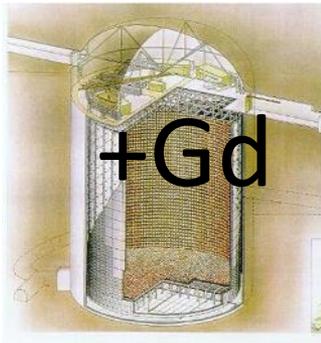
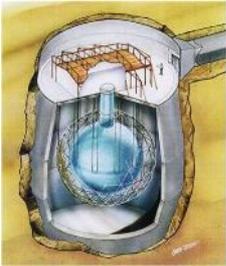


将来の超新星ν検出器

アップグレード

新しい大型検出器

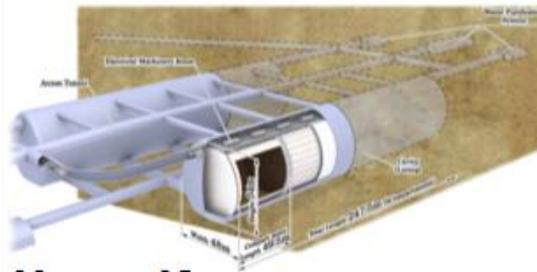
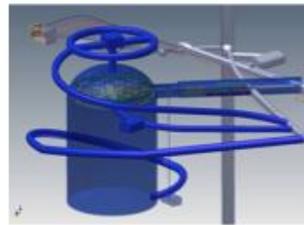
SNO+



KamLAND2

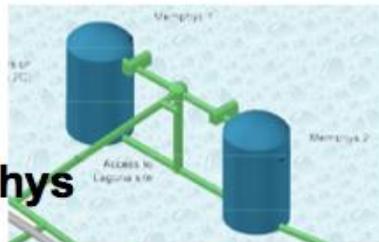
水チェレンコフ

LBNE
WCh



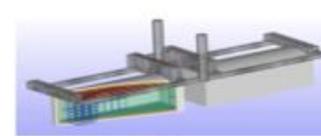
Hyper-K

Memphys



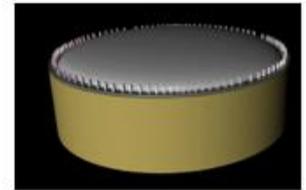
Megaton-scale water
detector concepts

液体アルゴン



LBNE LAr

5-100 kton-scale
liquid argon
concepts



GLACIER

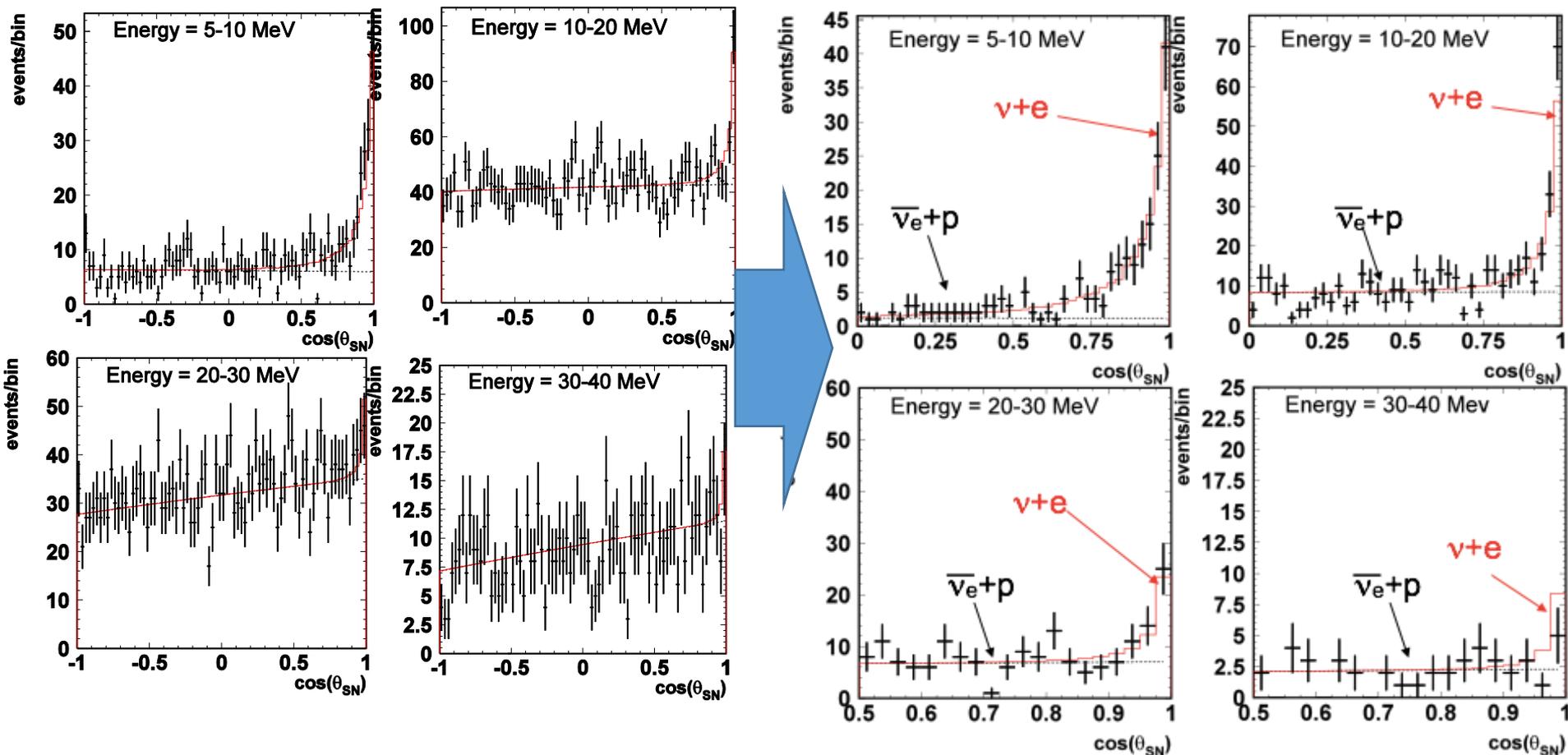
10-100
kton-scale
scintillator
detector
concepts



LENA
液体シン

GADZOOKS!と超新星νバースト

- ✓ ν -e 散乱事象から ν の方向を観測できる。
- ✓ Gd導入で νe , $\bar{\nu} e$ の分離がよくなる。

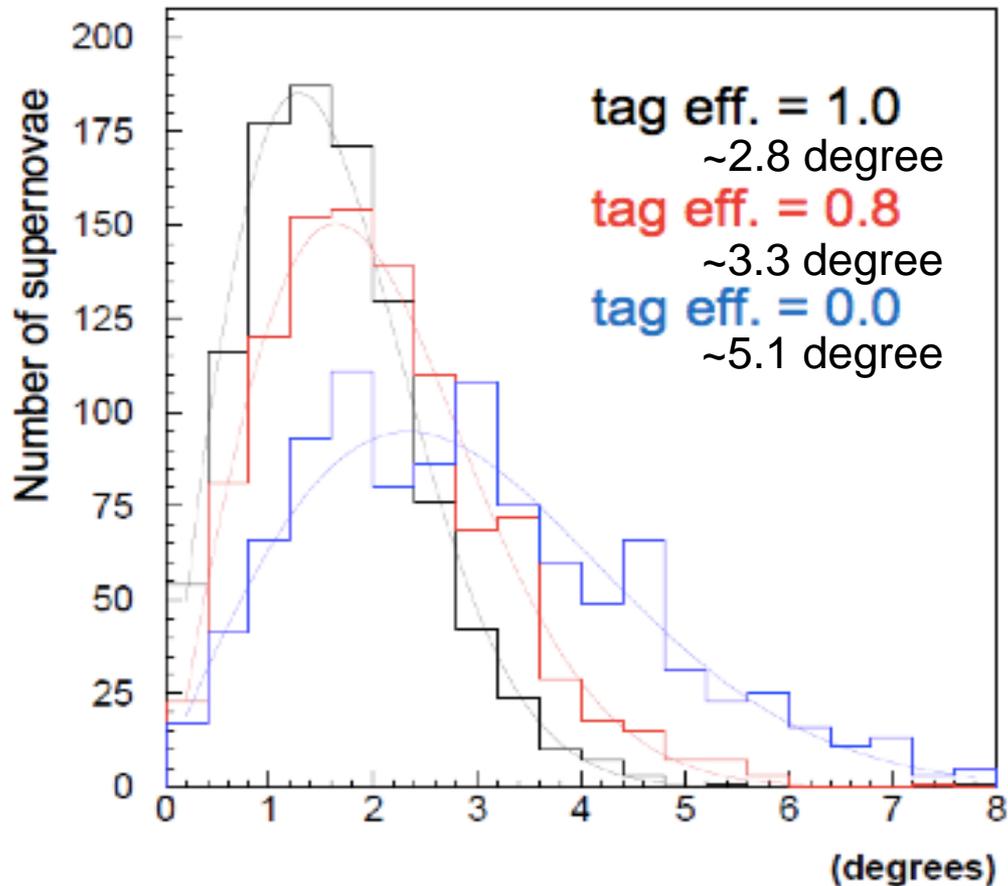


Syper-Kの超新星角度分解能

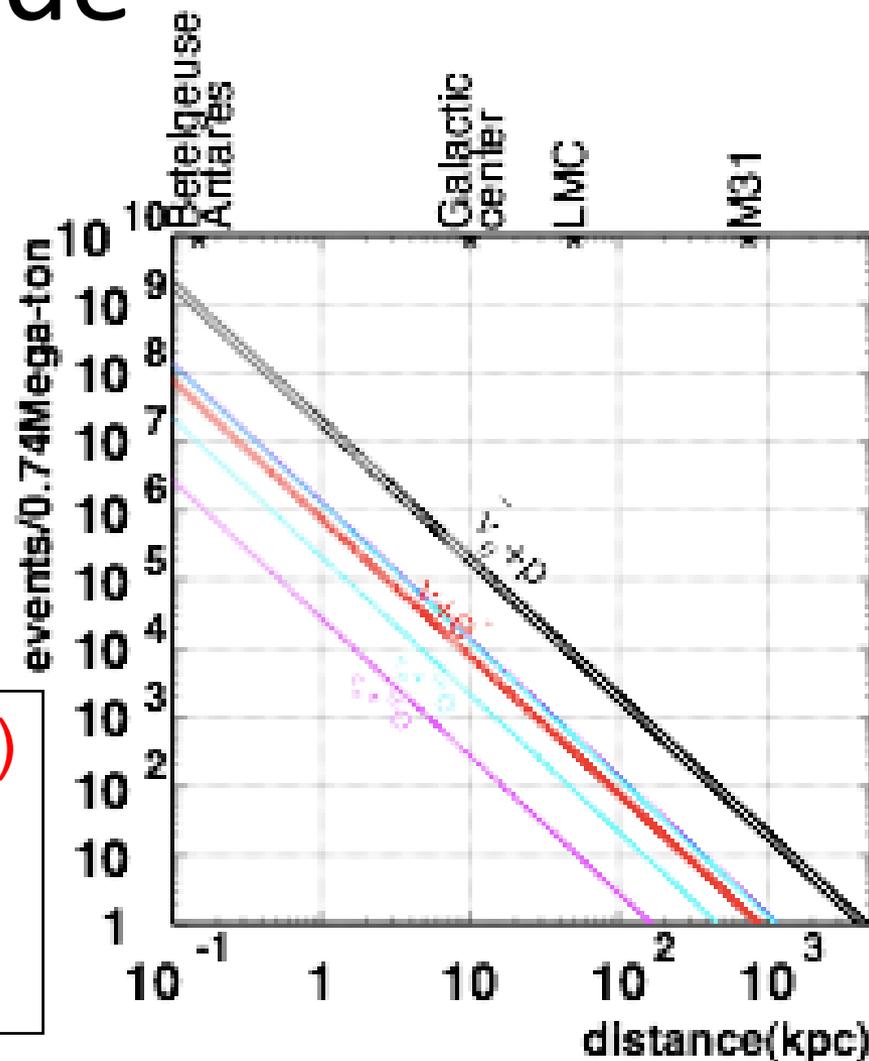
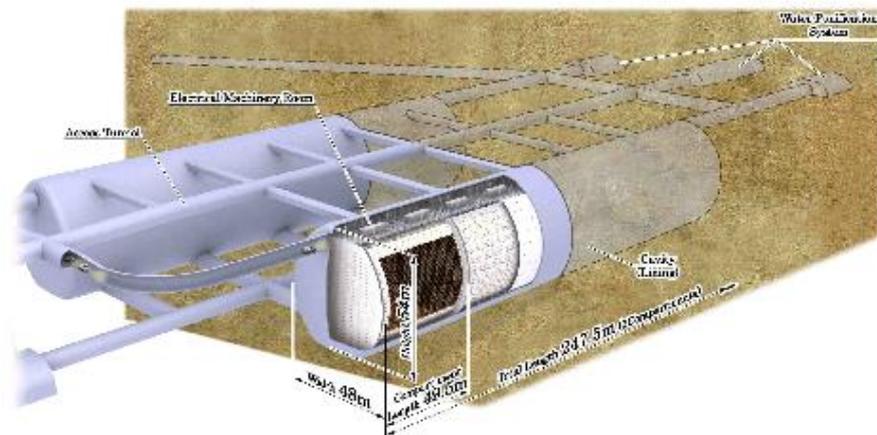
Gdによる V 、 \bar{V} の分離で、
角度分解能(SN@10kpc)
は倍近く向上する。

V 、 \bar{V} 識別能力が向上することにより、
中性化バーストの
検出や、 \bar{V}_e のスペクトル測定
もより正確になる。

Determination of the SN direction



Hyper — Kamiokande



Expected number of event

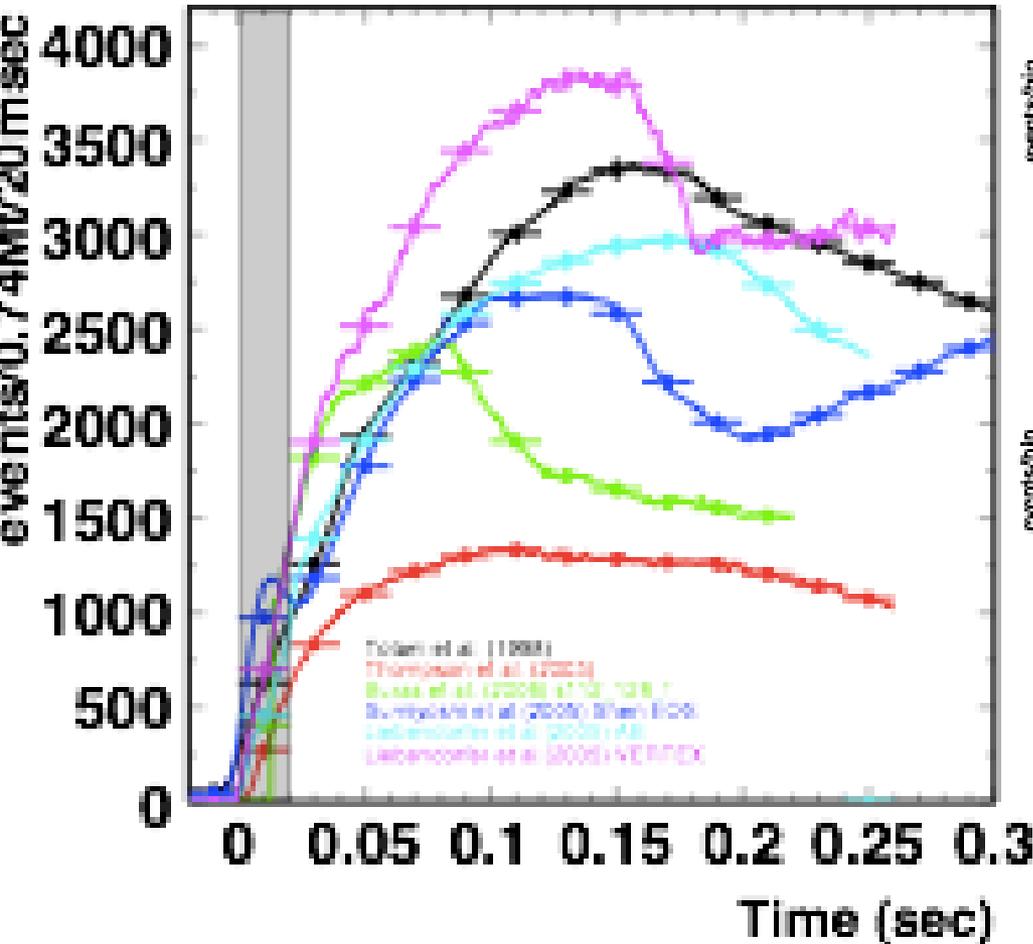
- ~168000 ev (inverse beta decay)
- ~2300 ev (^{16}O CC)
- ~7000 ev (νe elastic scattering)
- ~8300 ev (^{16}O NC)

at 10kpc, 4.5MeV energy threshold

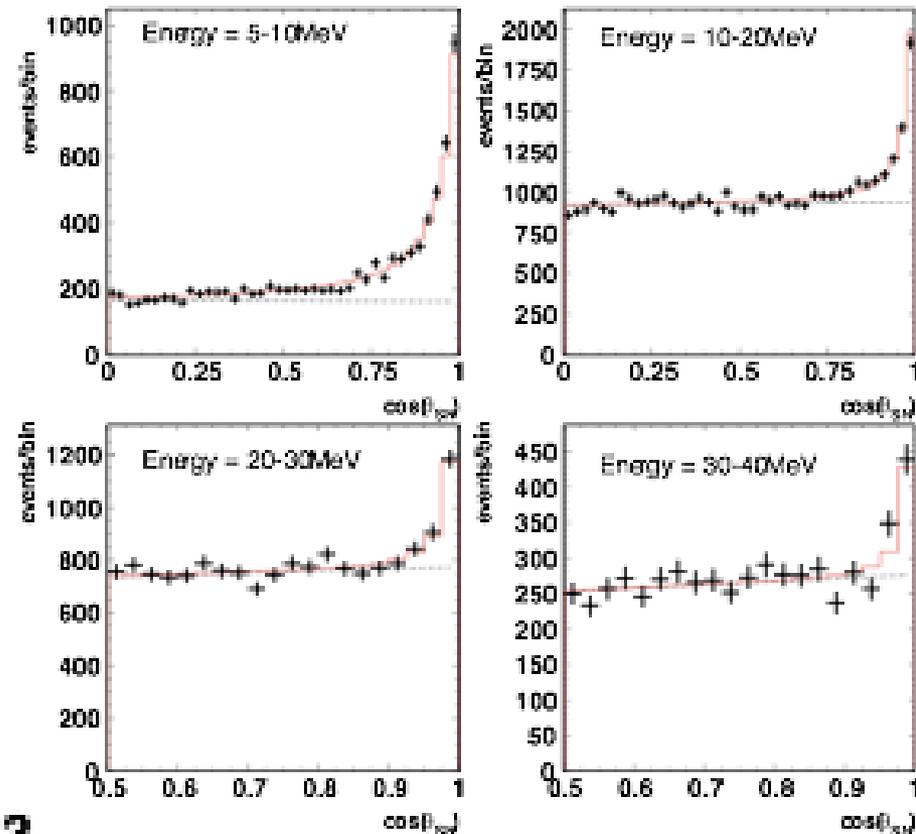
SKと比べて~20倍の統計量

Hyper — Kamiokande

Determine starting time with
~0.03 msec precision.



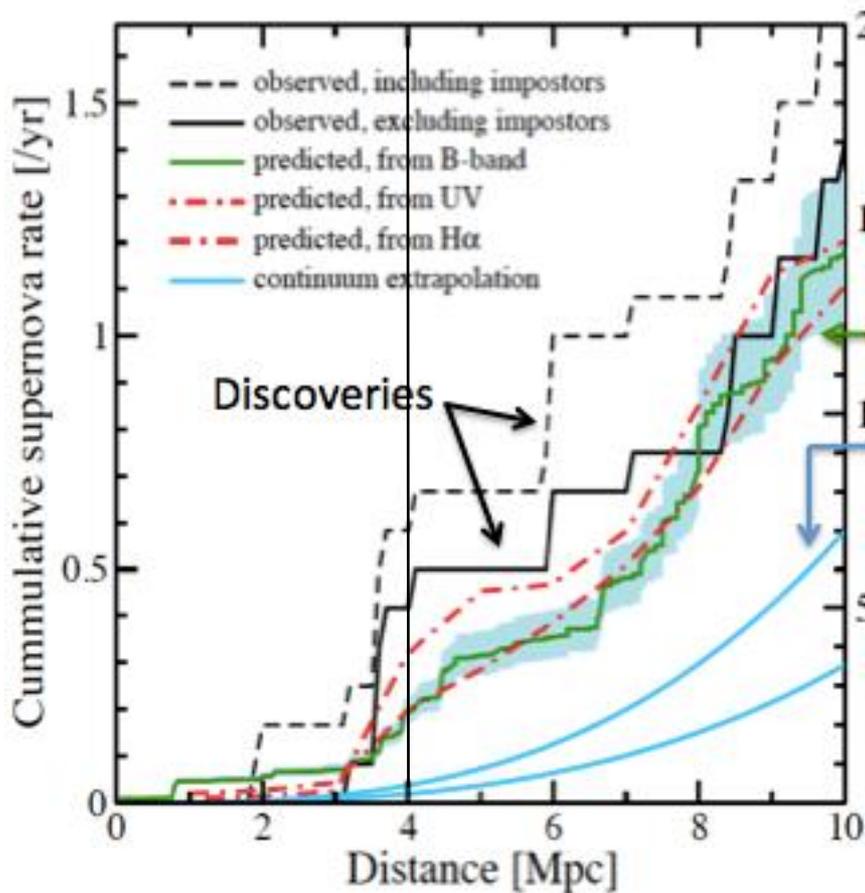
Angular distribution



direction determination is with ~2
degree.

近傍銀河超新星

Hyper-Kamiokande

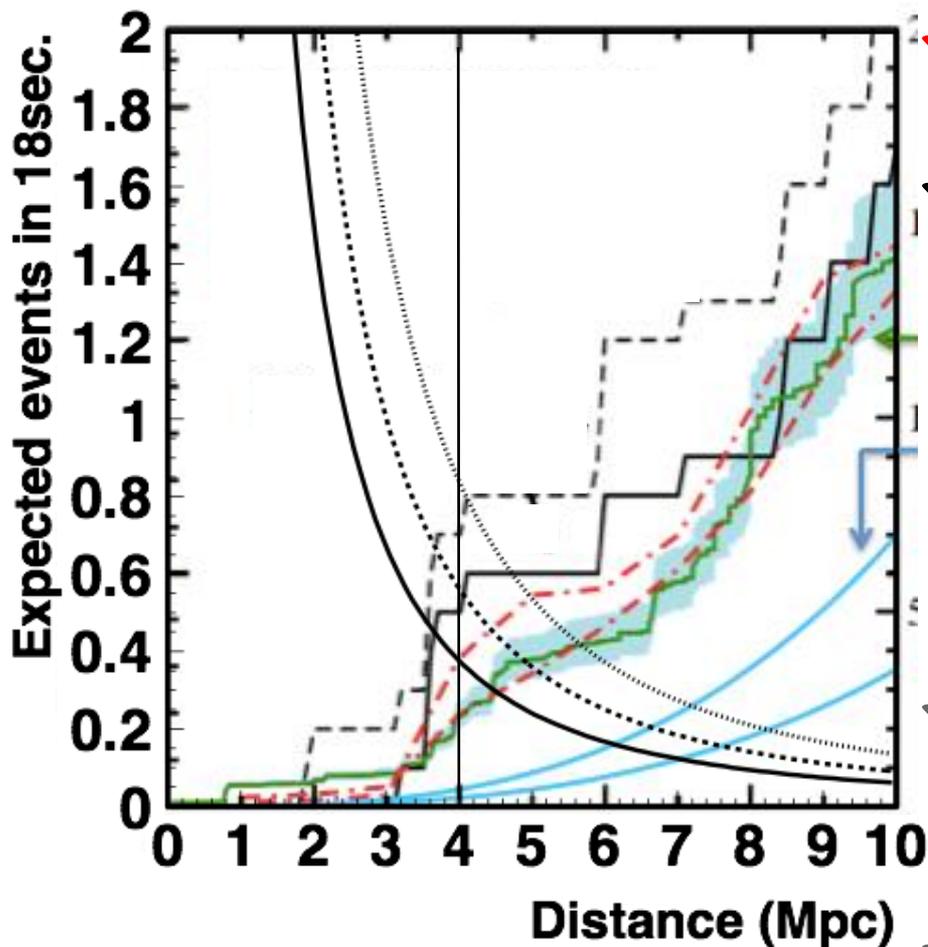


S.Horiuchi

- ✓ 0.2~0.6 SN/yr @ 4Mpc.
- ✓ 18MeV閾値（核破碎BGを除く）での事象数：
0.37~0.83 @4Mpc.
accidental BG:
0.00656
- ✓ 観測確率：31~56%
($N \geq 1$) @4Mpc
- ✓ 1事象/3-10年 from
SN@4Mpc

近傍銀河超新星

Hyper-Kamiokande



✓ 0.2~0.6 SN/yr @ 4Mpc.

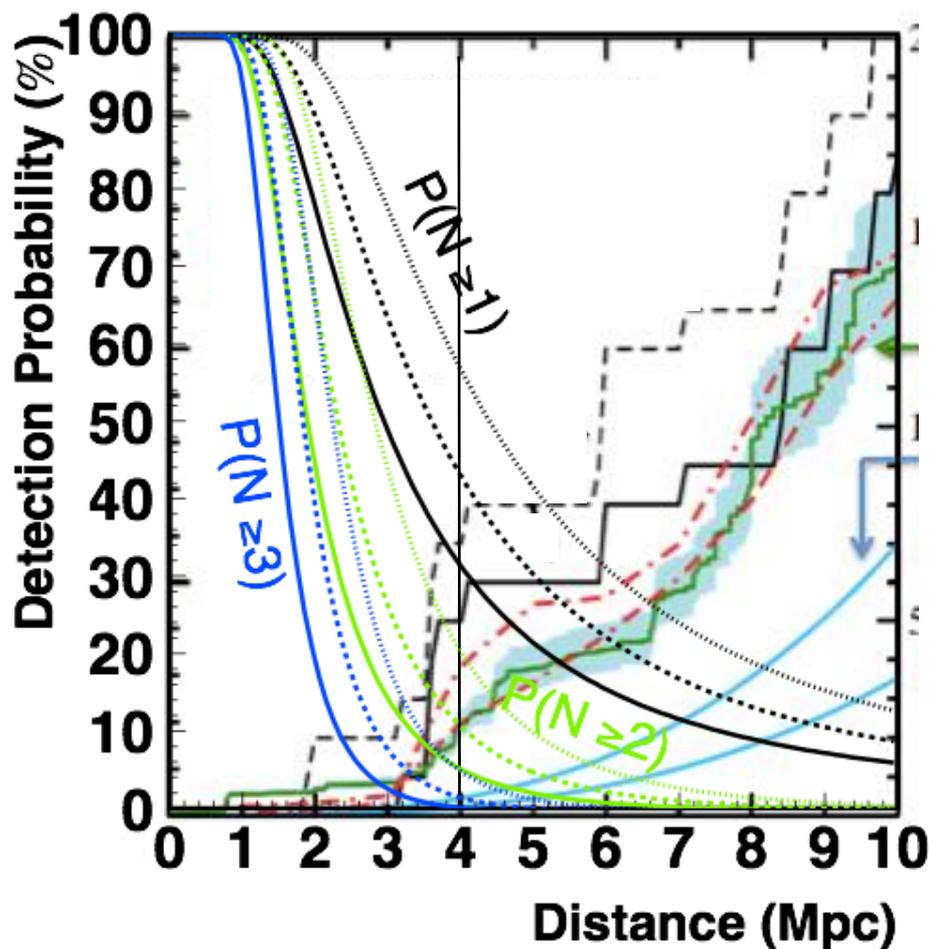
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近傍銀河超新星

Hyper-Kamiokande



✓ 0.2~0.6 SN/yr @ 4Mpc.

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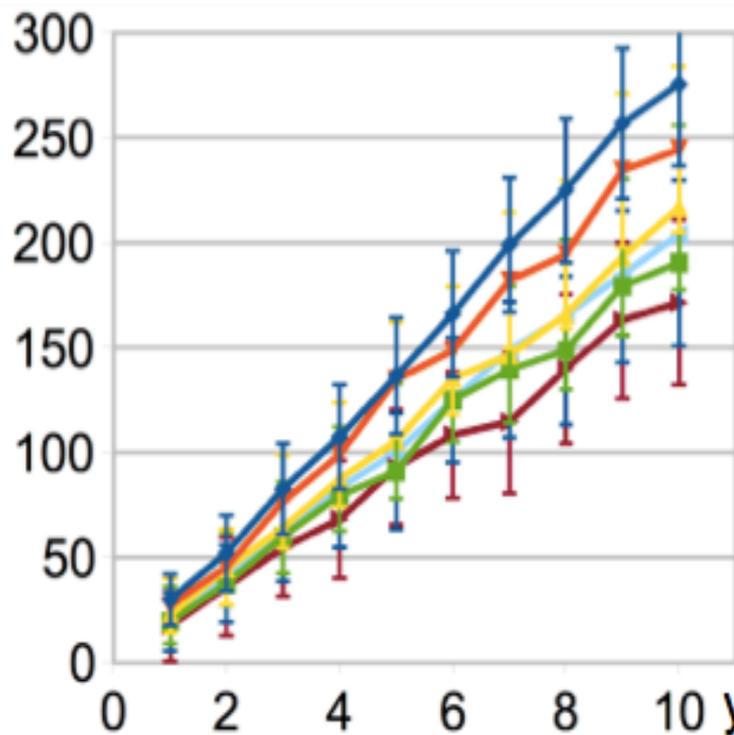
✓ 観測確率：31~56%
($N \geq 1$) @4Mpc

✓ 1事象/3-10年 from
SN@4Mpc

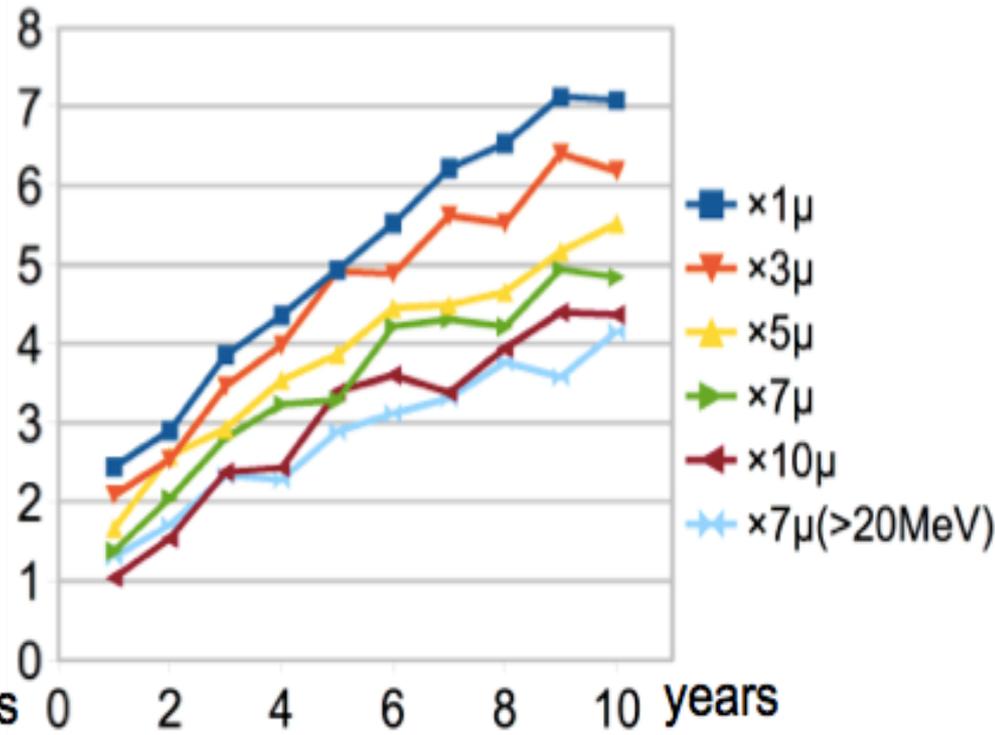
Hyper-KのSRNに対する感度

w/o neutron tagging, w/ spectrum information

$N_{\text{obs}}(20\text{-}30\text{MeV})$



$n\sigma$ LMA SRN model, 100 trials are averaged.

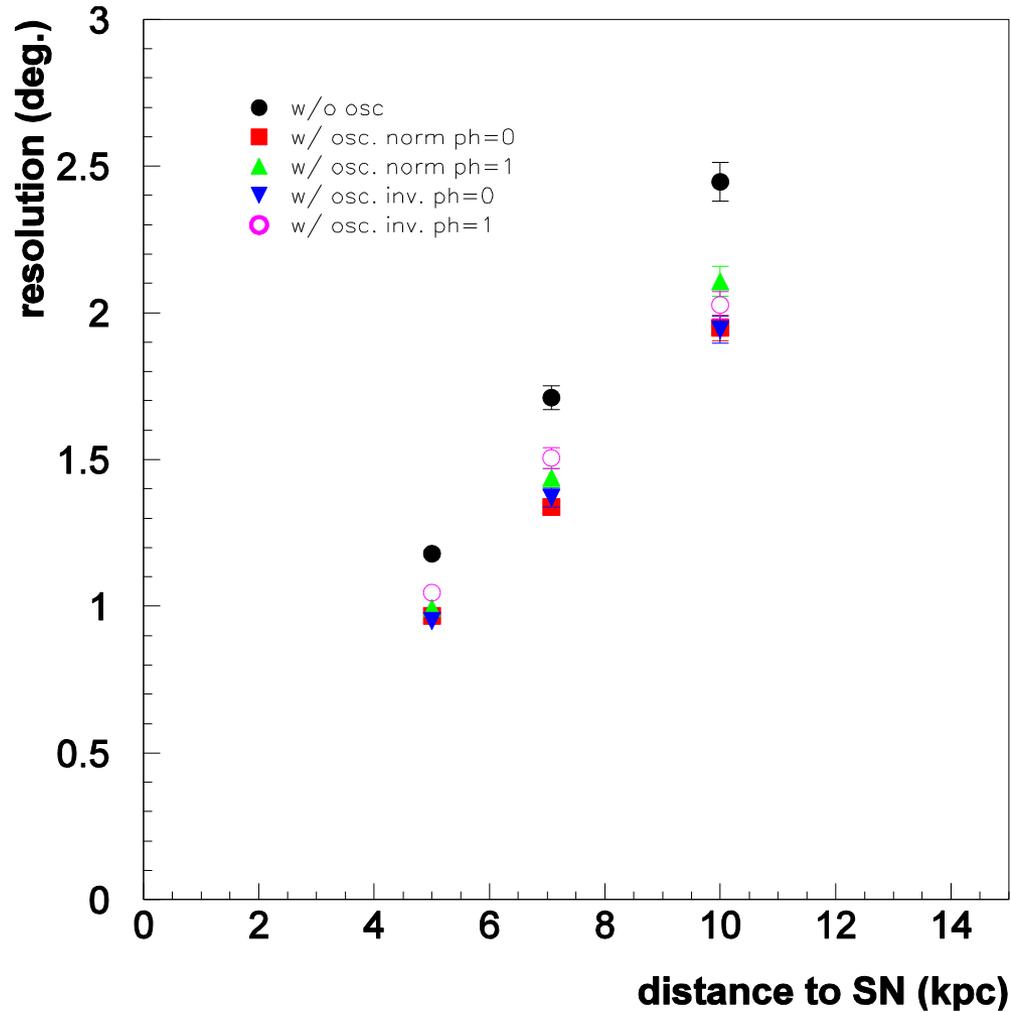


まとめ

- 次の銀河系内超新星爆発では
 - $O(1000)$ のニュートリノが観測
 - 10以上の実験がその瞬間を待っている
 - いろいろな実験結果を複合してより多くの情報を引き出す
- 超新星背景ニュートリノ
 - SK+Gdで中性子タグを使うと発見の可能性大
 - R&Dは順調に進められている
- 将来の超新星ニュートリノ検出
 - Hyper-K:SKの20倍！
 - 近傍銀河超新星爆発ニュートリノ観測も可能

一緒に次の超新星爆発を観測したい人、大歓迎

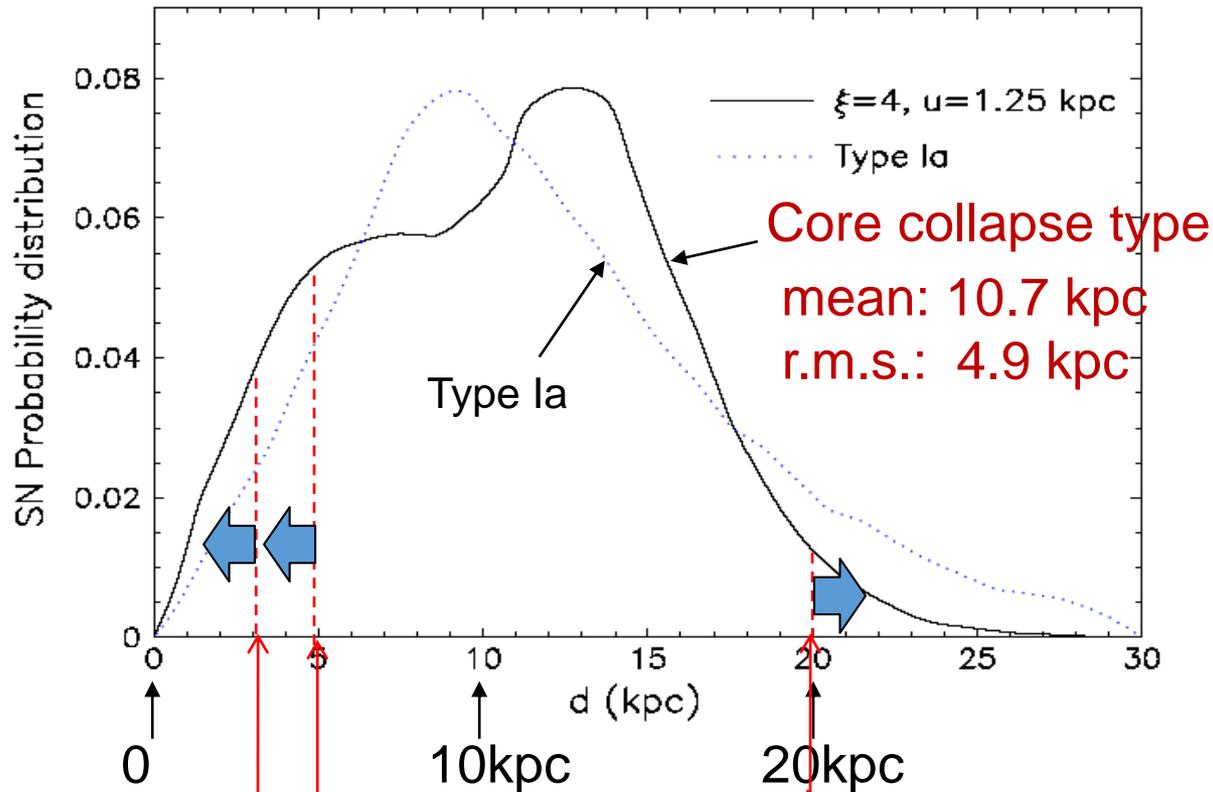
Angular resolution vs. distance



Distance to Galactic supernova

Mirizzi, Raffelt and Serpico, JCAP 0605,012(2006),
astro-ph/0604300

Based on birth location of neutron stars

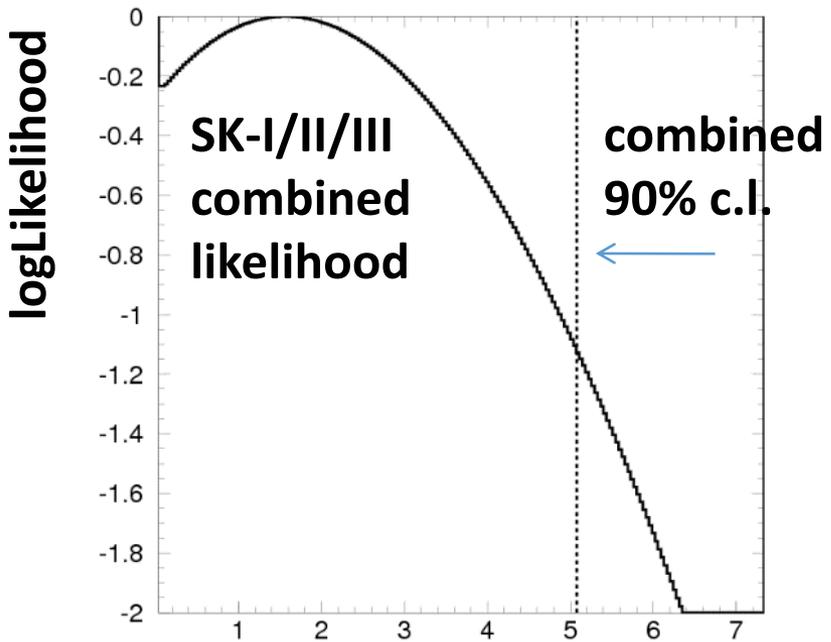


7% probability
< 3.16 kpc
> x10 statistics

16% probability
< 5 kpc
> x 4 statistics

3% probability
> 20 kpc
< 1/4 statistics

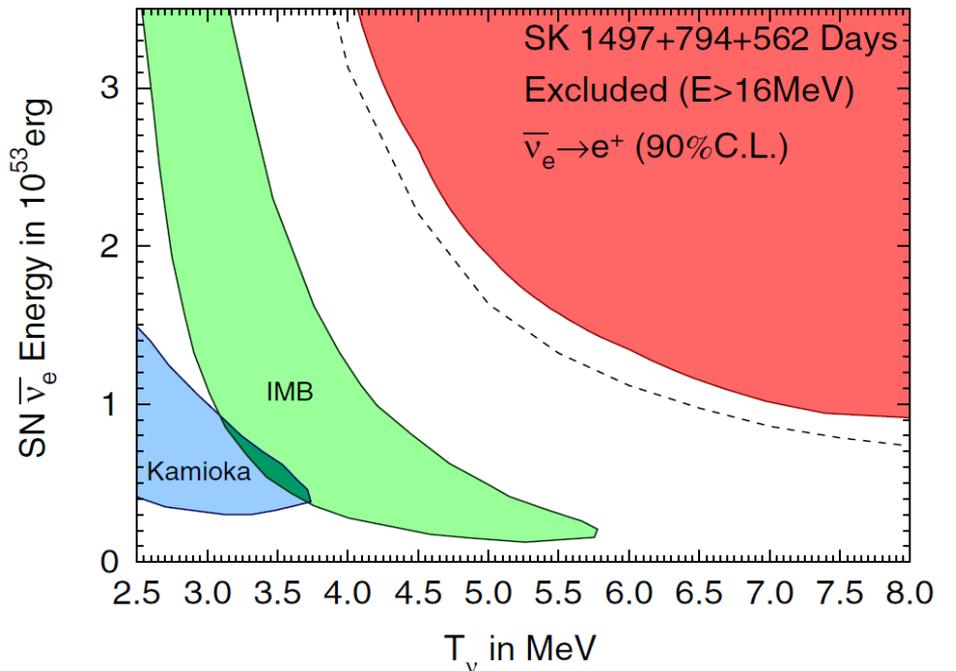
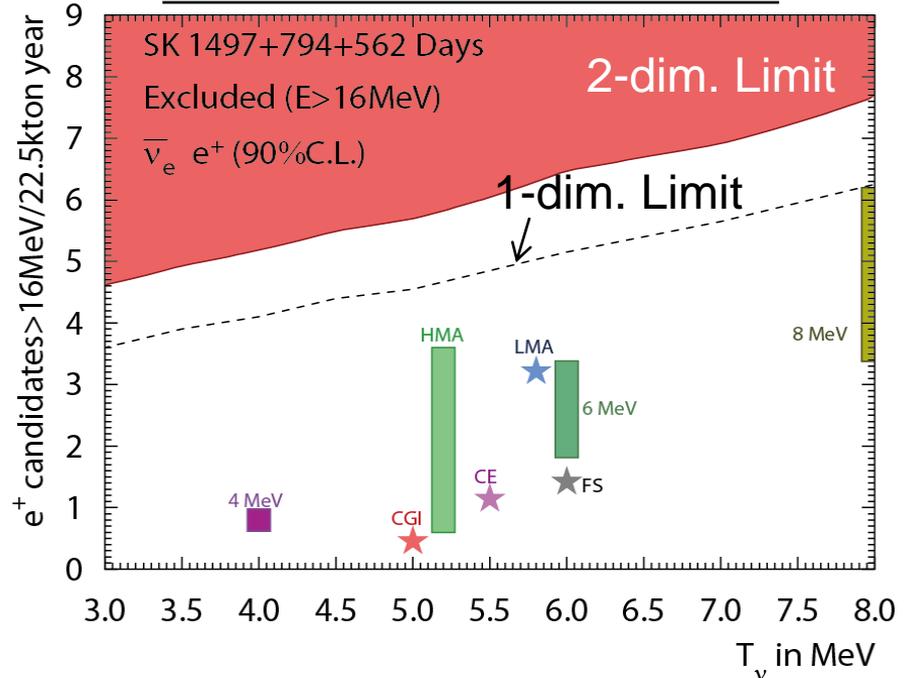
Upper limit from SK



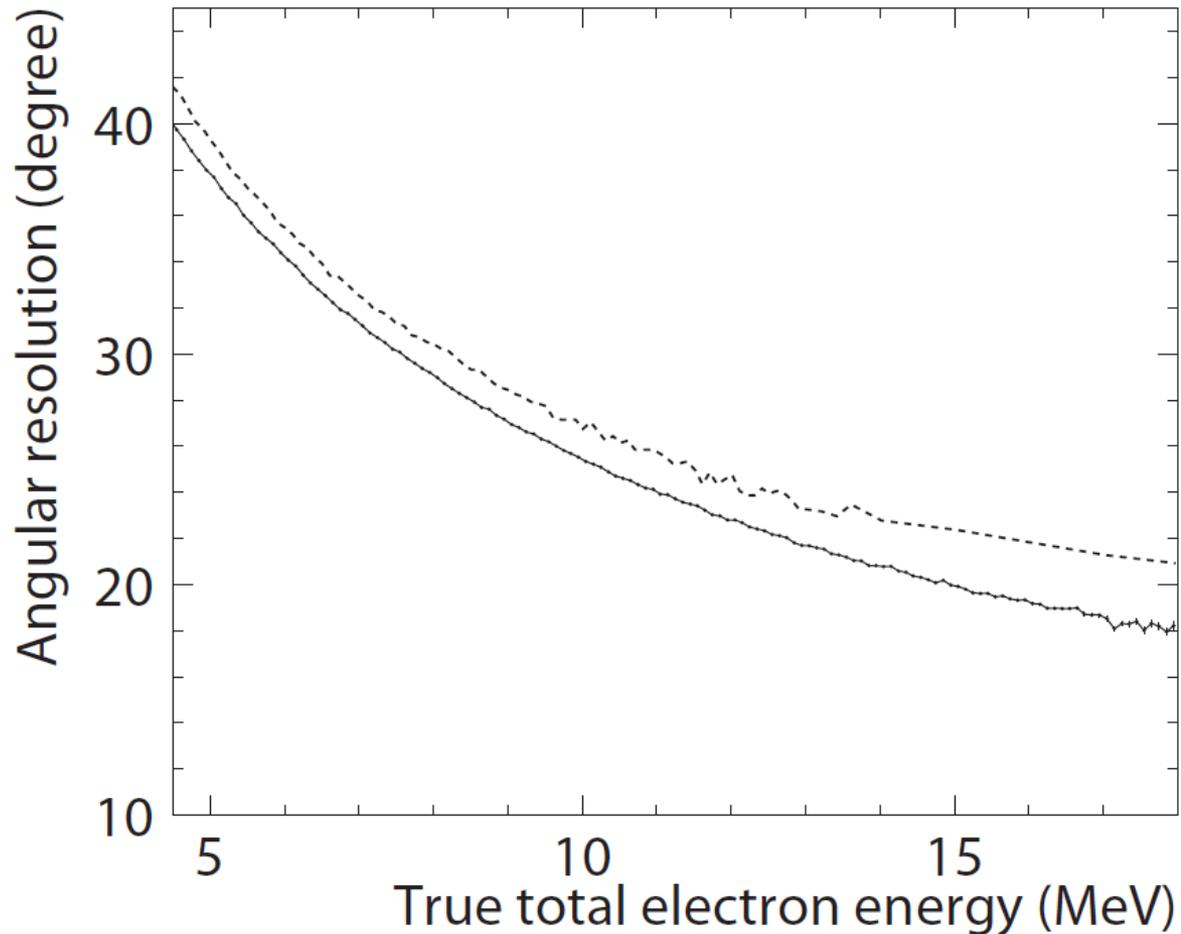
ev/yr interacting in 22.5 kttons

combined 90% c.l.:
< 5.1 ev / yr / 22.5 kttons
< 2.7 /cm²/s (>16 MeV)
 (using LMA model prediction (Ando et.al, 2005))

Limit on number of events

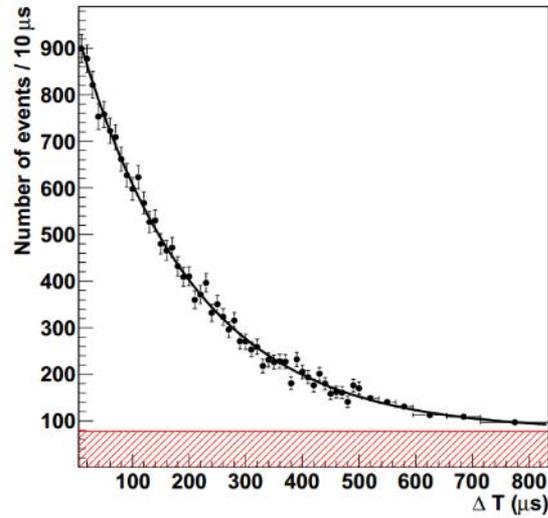


Angular resolution of SK (e-scat.)

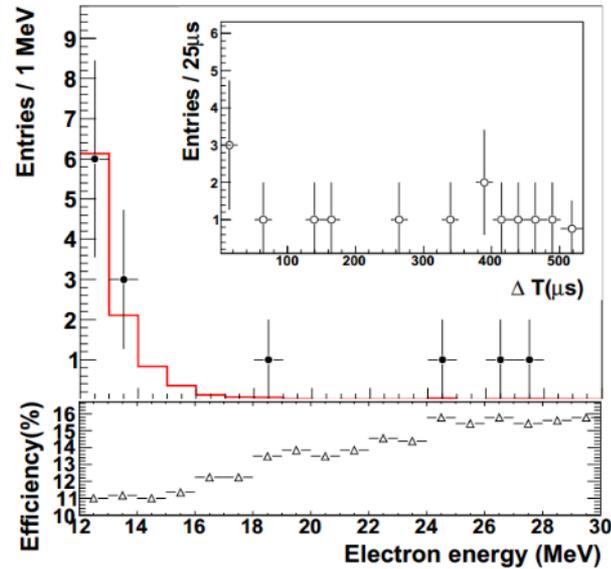


SRN with n capture by p

SK-4 960 days

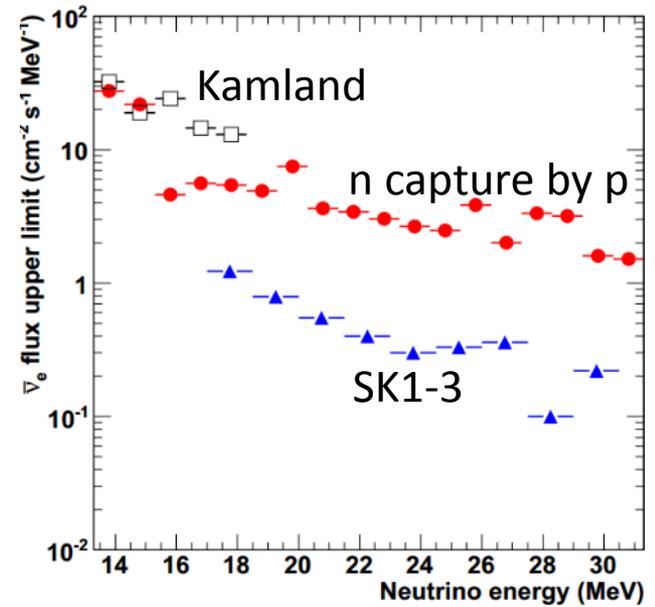


Am/Be calibration



Physics run

Flux upper limit

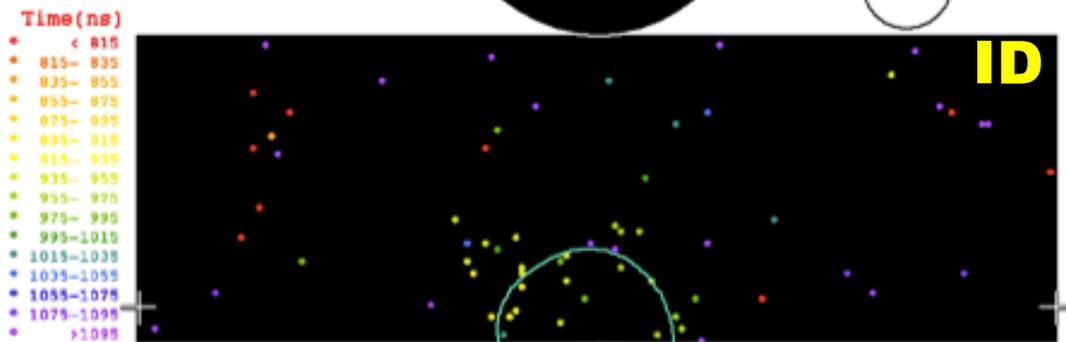
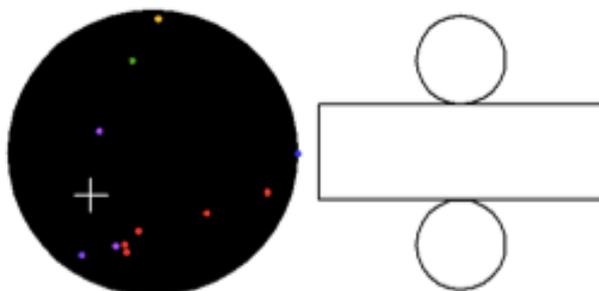


Super-Kamiokande

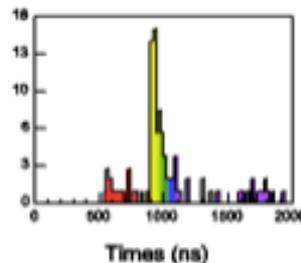
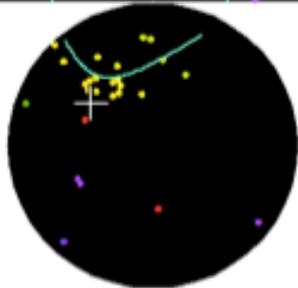
~ 6 hits/MeVなのでリングはきれいに見えません。
 エネルギースケールは、LINAC / DT を使って 0.5% の精度で決定

Super-Kamiokande

Run 1742 Event 102496
 96-05-31:07:13:25
 Inner: 103 hits, 123 pE
 Outer: -1 hits, 0 pE (in-time)
 Trigger ID: 0x03
 $E = 8.066 \text{ GeV} \pm 0.77 \text{ GeV}$ COSMOS = 0.943
 Solar Neutrino



$E_e = 8.6 \text{ MeV (kin.)}$
 $\cos\theta_{\text{sun}} = 0.95$



Detector performance

Resolution@
 10MeV 電子事象 情報

| | | |
|-----------|--------|-------------|
| vertex | 55cm | hit timing |
| direction | 23deg. | hit pattern |
| energy | 14% | # of hits. |

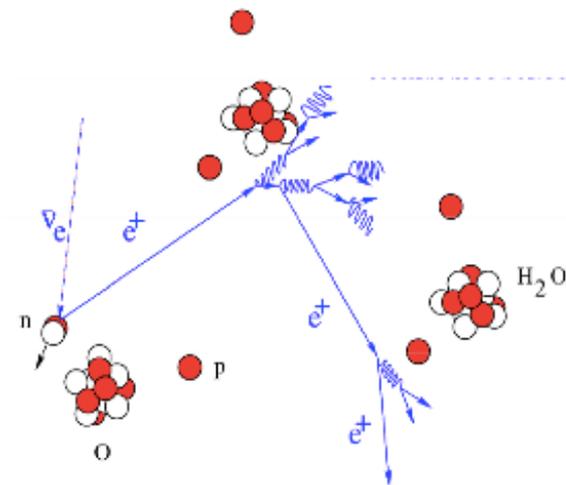
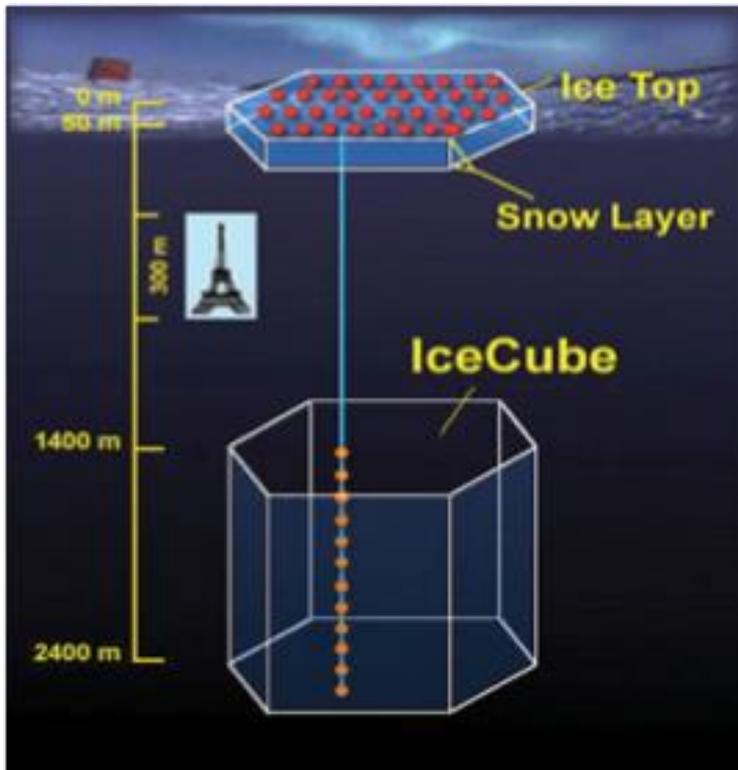
Current SNv detectors

IceCUBE

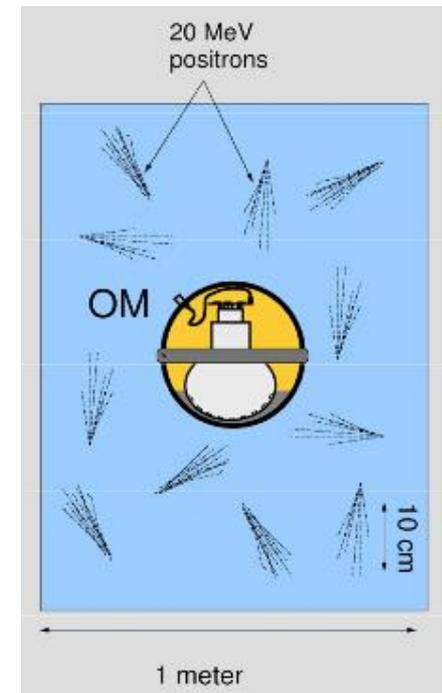
Giga-ton detector

~km long string **Water Cherenkov** detector at the South Pole

✓ **Nominally multi-GeV energy threshold, but can see burst of low energy $\bar{\nu}_e$'s as increase in single PMT count rates.**



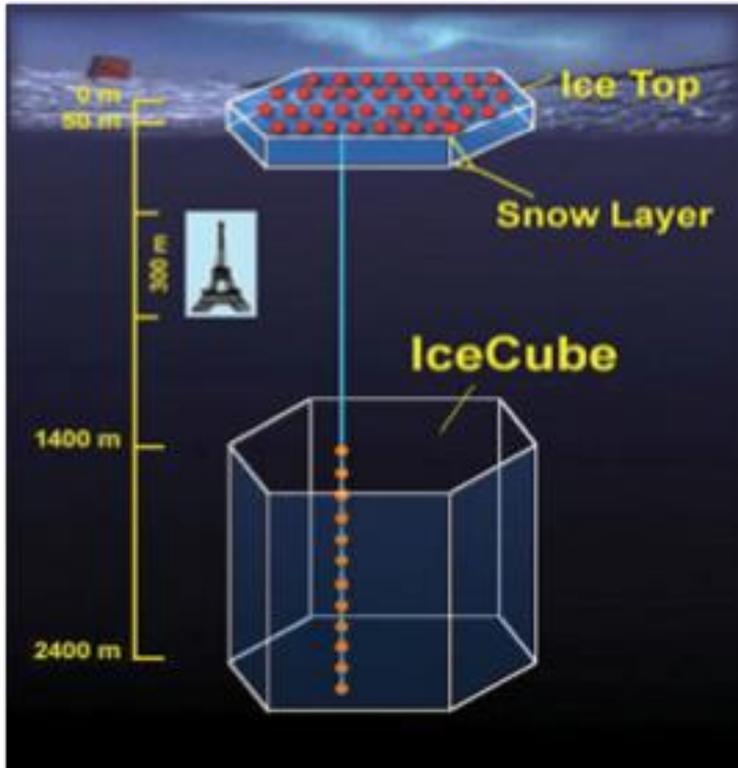
- ☞ ice uniformly illuminated
- ☞ detect correlated rate increase on top of PMT noise



Current SNvdetectors

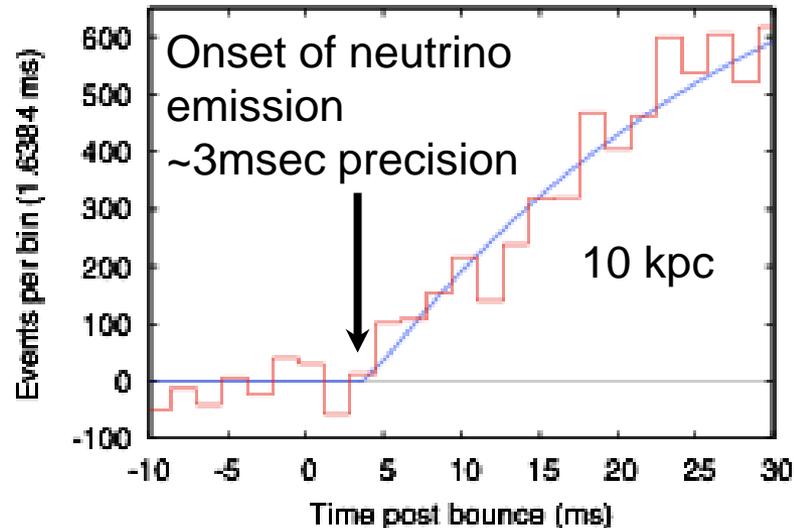
IceCUBE

Giga-ton detector



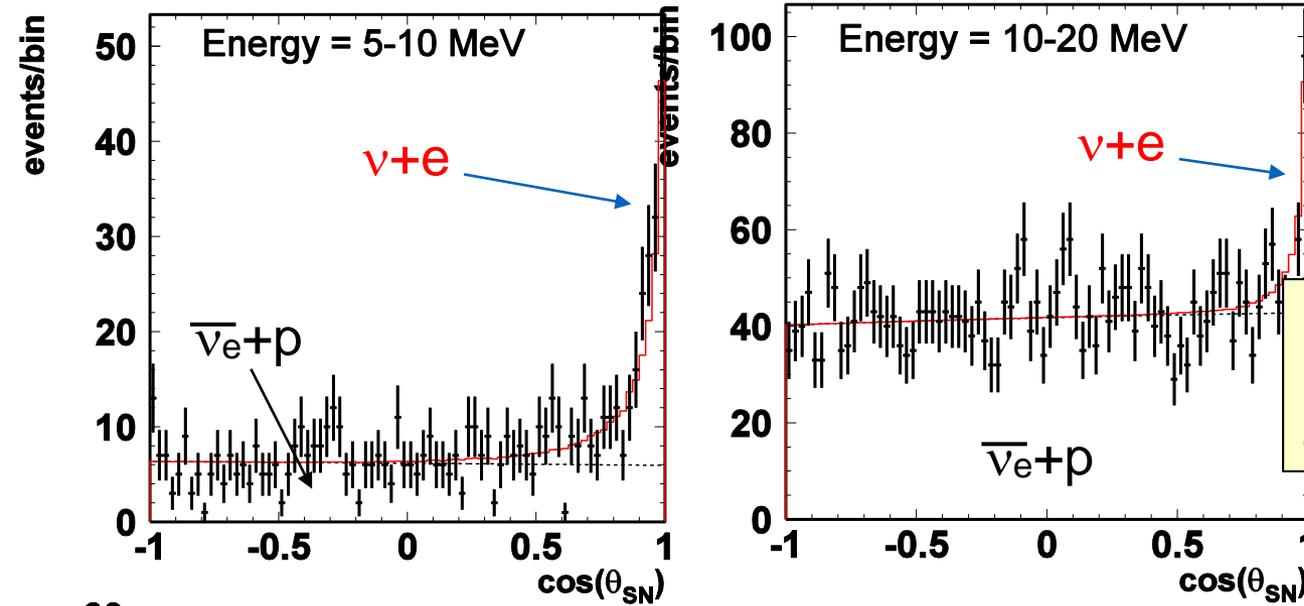
~km long string **Water Cherenkov** detector at the South Pole

- ✓ Nominally multi-GeV energy threshold, but can see burst of low energy $\bar{\nu}_e$'s as increase in single PMT count rates.
- ✓ **Cannot tag flavor, or other interaction info., overall rate and fine time structure.**



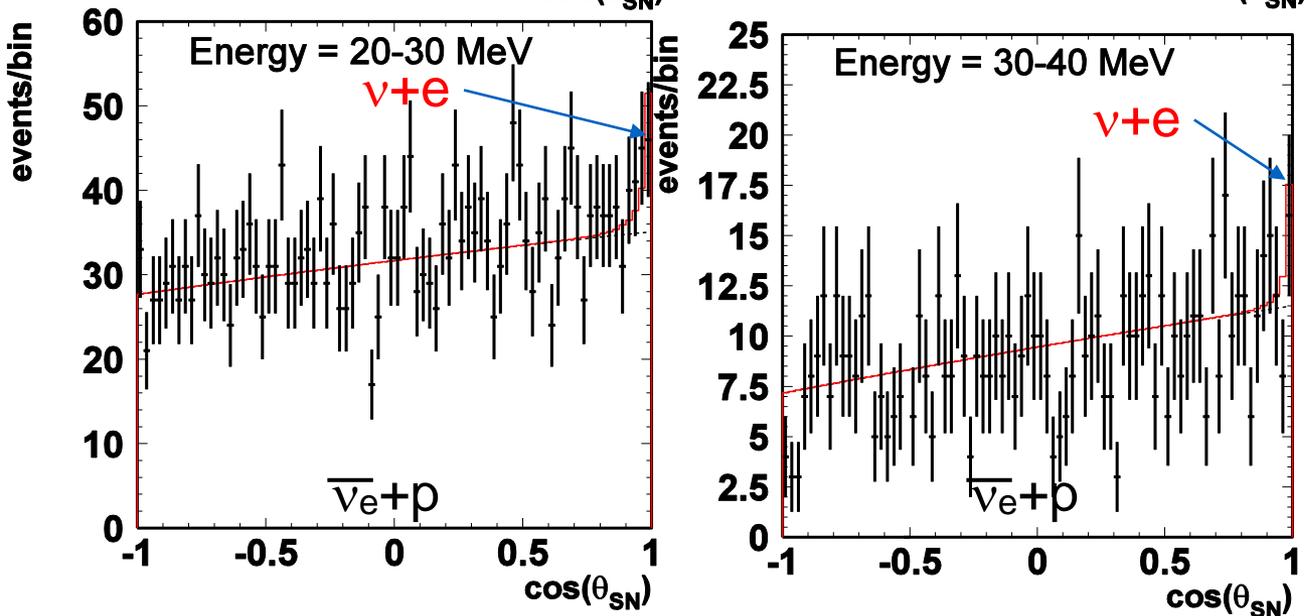
Halzen, Raffelt
arXiv : 0908.2317

Super-K: simulation of angular distribution



SN at 10kpc

Direction of supernova can be determined with an accuracy of ~ 5 degree.



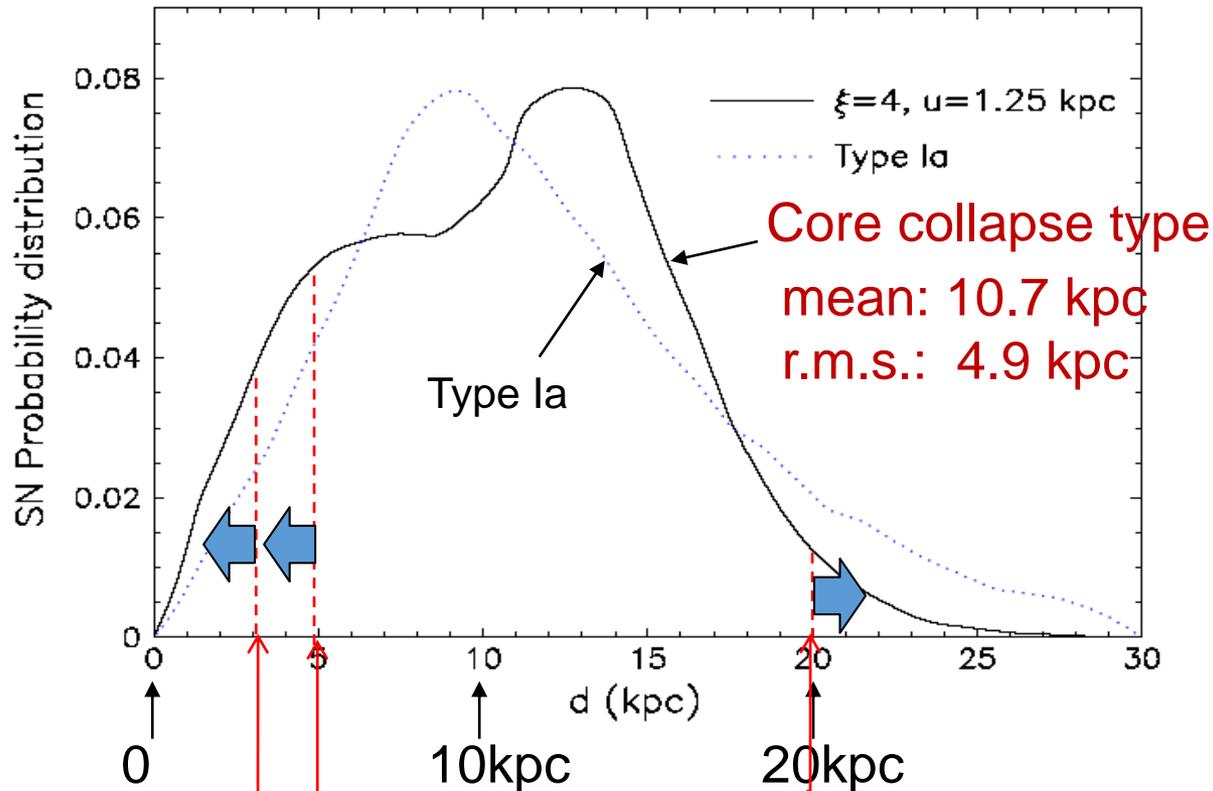
Spectrum of $\nu+e$ events can be statistically extracted using the direction to supernova.

Neutrino flux and spectrum from Livermore simulation

Distance to Galactic supernova

Mirizzi, Raffelt and Serpico, JCAP 0605,012(2006),
astro-ph/0604300

Based on birth location of neutron stars



7% probability
< 3.16 kpc
> x10 statistics

16% probability
< 5 kpc
> x 4 statistics

3% probability
> 20 kpc
< 1/4 statistics

次の超新星ニュートリノへ向けて

前兆ニュートリノ (シリコン燃焼フェーズ)

