超新星爆発によるニュートリノ観測と重力波

小汐由介

岡山大学

日本物理学会／シンポジウム

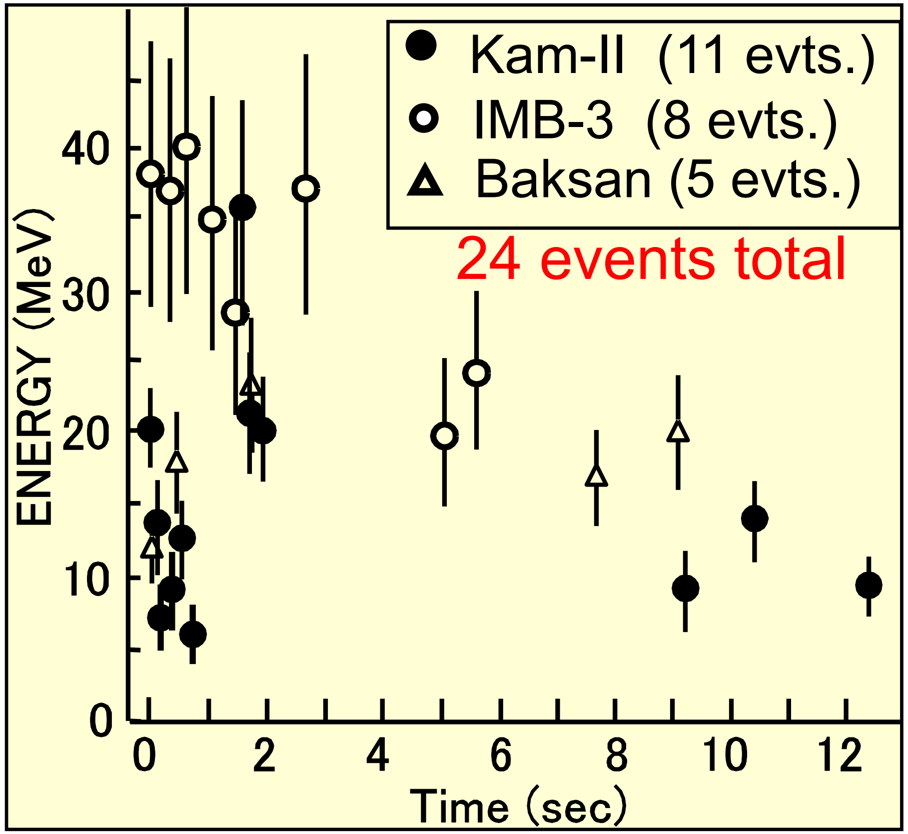
Outline

- ✓ Introduction
- ✓ Neutrino interaction for SN ν detection
- ✓ Current supernova neutrino detectors
  - Water Cherenkov detector
  - Scintillation detector
- ✓ Future prospects
  - Relation with gravitational wave
- ✓ Summary


Introduction

SN1987A in LMC

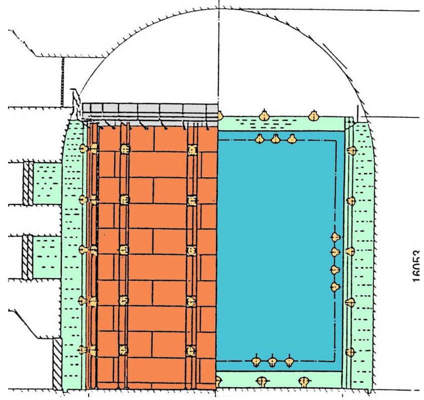
at 50kpc, ν's seen ~2.5 hours before first light



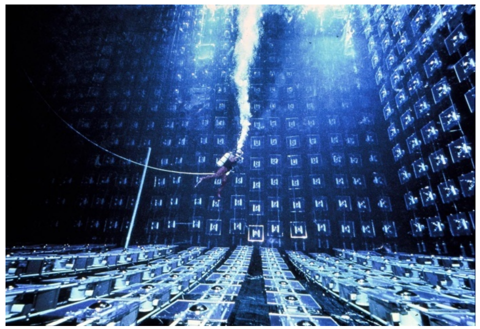
Most of them seems to $\overline{\nu}_e$ event

Water Cherenkov

Kamiokande-II



IMB-3

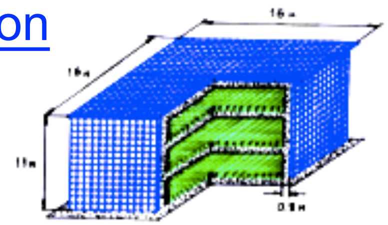


Strong directionality for ν_e event

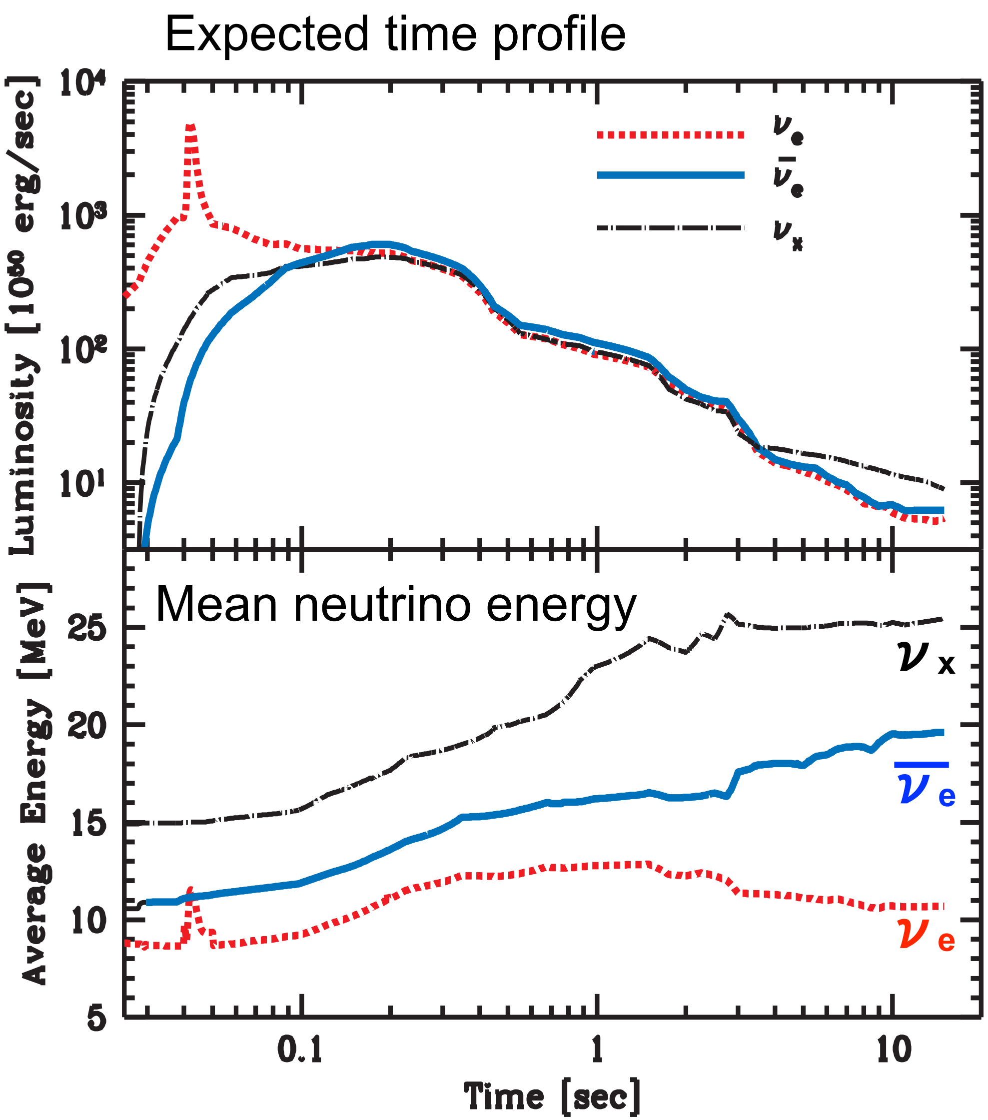
Liquid Scintillator

Baksan

Good $\overline{\nu}_e$ event identification



Neutrinos from supernova burst



What we can learn

✓Core collapse physics
- explosion mechanism
- proto-neutron star cooling
- black hole formation
- etc..

✓Neutrino physics
- neutrino oscillation
- etc..

Measurements of neutrino
flavor, energy, time profile
are the key points

Neutrinos from supernova burst

What we want for a detector

✓ Massive target
- Current : O(kton), sensitive for galactic center
- Future : O(Mton), sensitive for ~Mpc(?)

✓ Low background rate ~MeV energy region
- Underground detector

✓ No dead time

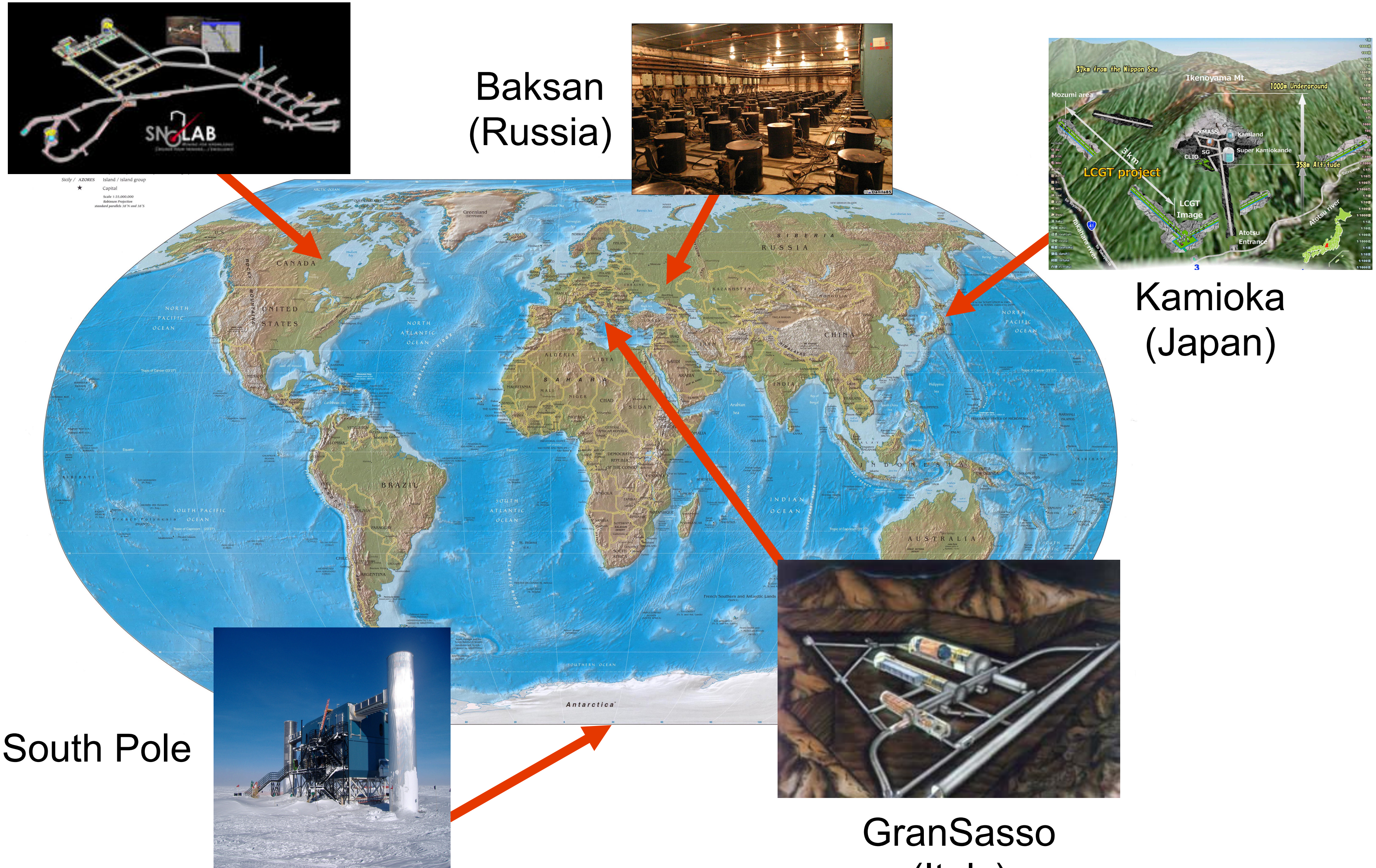
✓ Precise timing measurement

✓ Good energy resolution

✓ Measurable for direction, if possible

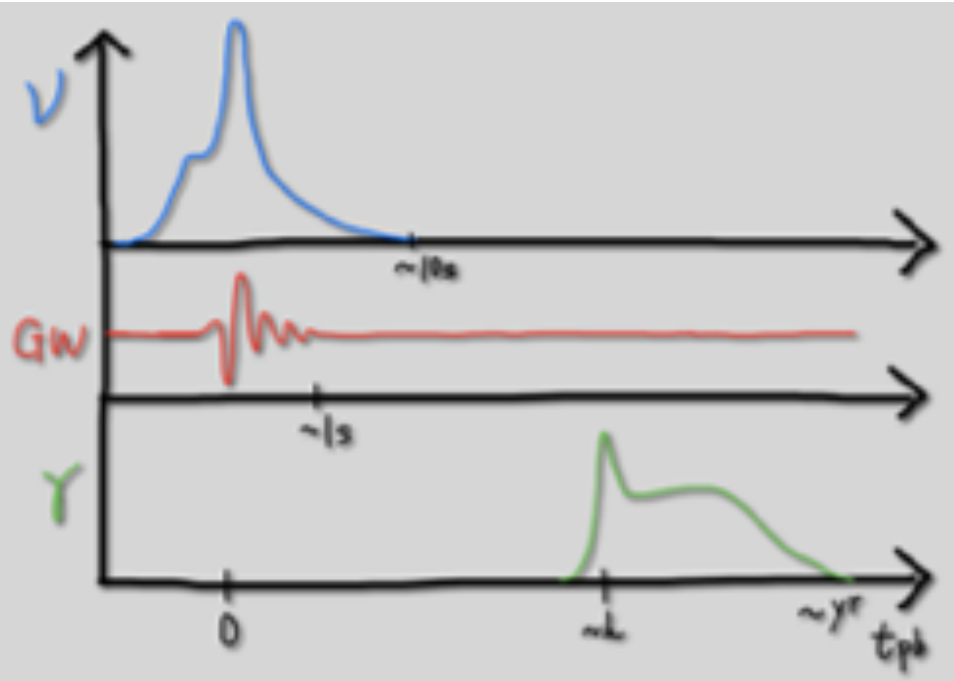
✓ Neutrino flavor sensitivity
- Use specific neutrino interactions

Underground facilities for SN ν



Gravitational wave and neutrinos

Only GW and Neutrino are released during the initial stellar collapse itself, and arrival at Earth through any obscures.



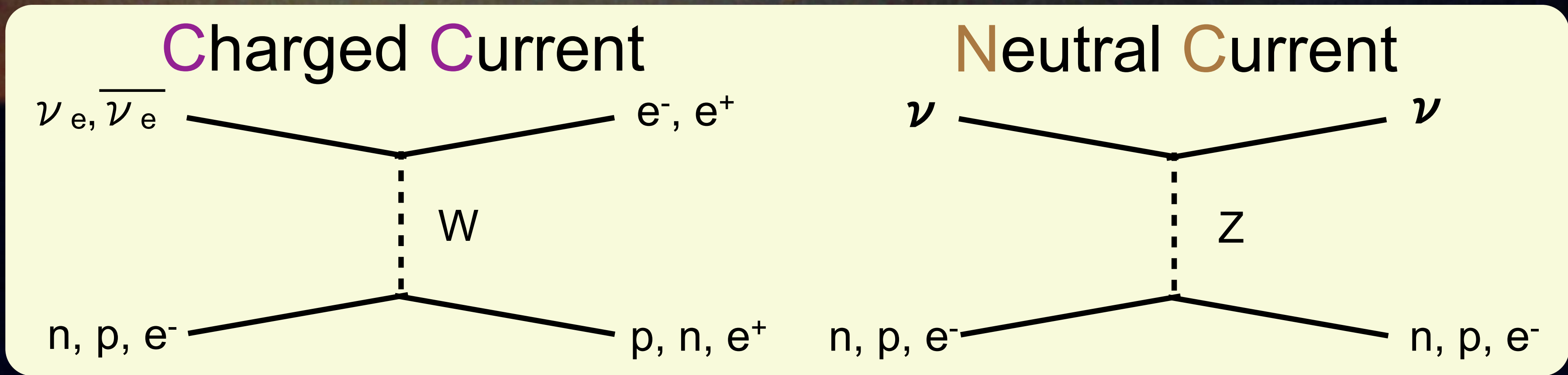
諏訪さん提供

<u>Coincidence analysis</u>

✓Status of progenitor core
- mass, mass density distribution, rotating ratio,...

✓Status of SASI, convection
✓27pTL-9 (横澤さん)

Neutrino interaction for supernova neutrino detection



Neutrino interaction for SN ν

Inverse beta decay

$$\boxed{\bar{\nu}_e + p \rightarrow e^+ + n}$$ (Charged Current interaction)

- ✓ Dominates for detectors with lots of free proton
  - Detect positron signal in water, scintillator, etc.
- ✓ $\bar{\nu}_e$ sensitive
- ✓ Large cross section
- ✓ Good energy resolution
  - $E_e \sim E_\nu - (m_n - m_p)$
- ✓ Poor directionality
- ✓ Neutron tagging using delayed coincidence
  - $n + p \rightarrow d + \gamma$

Neutrino interaction for SN ν

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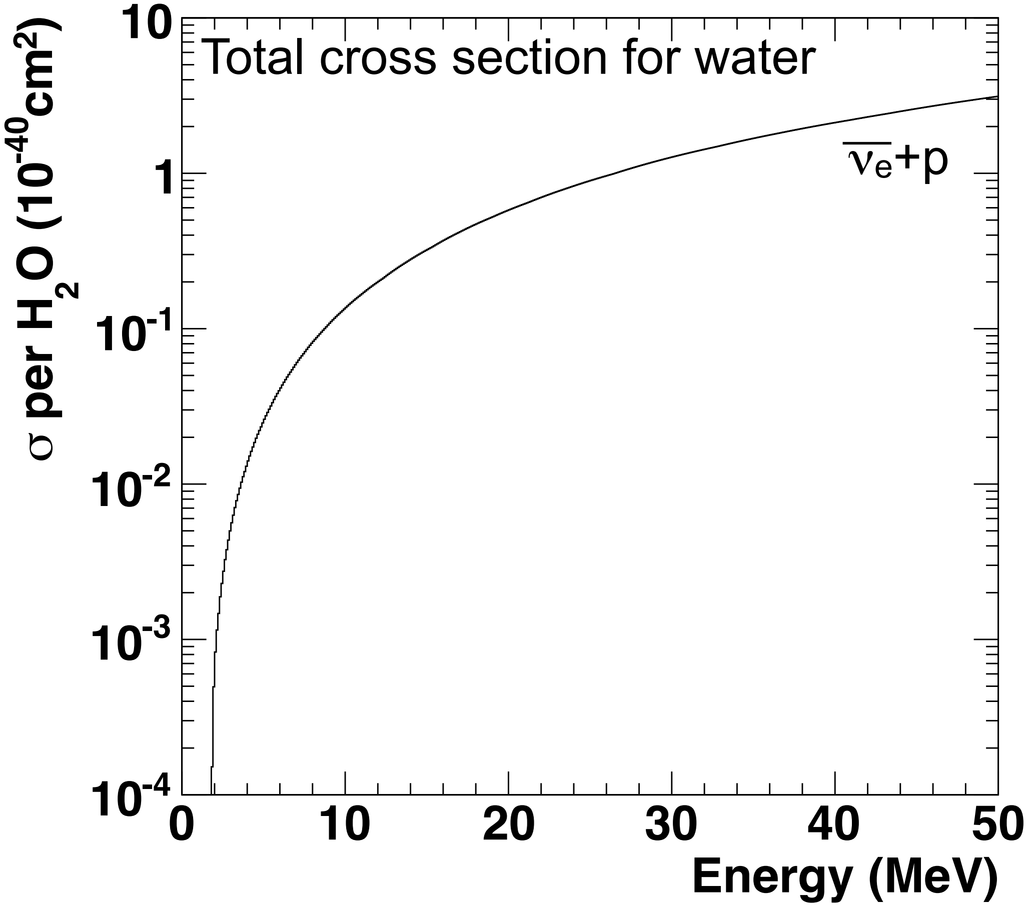
Strumia, Vissani
Phys. Lett. B564 (2003) 42



Neutrino interaction for SN ν

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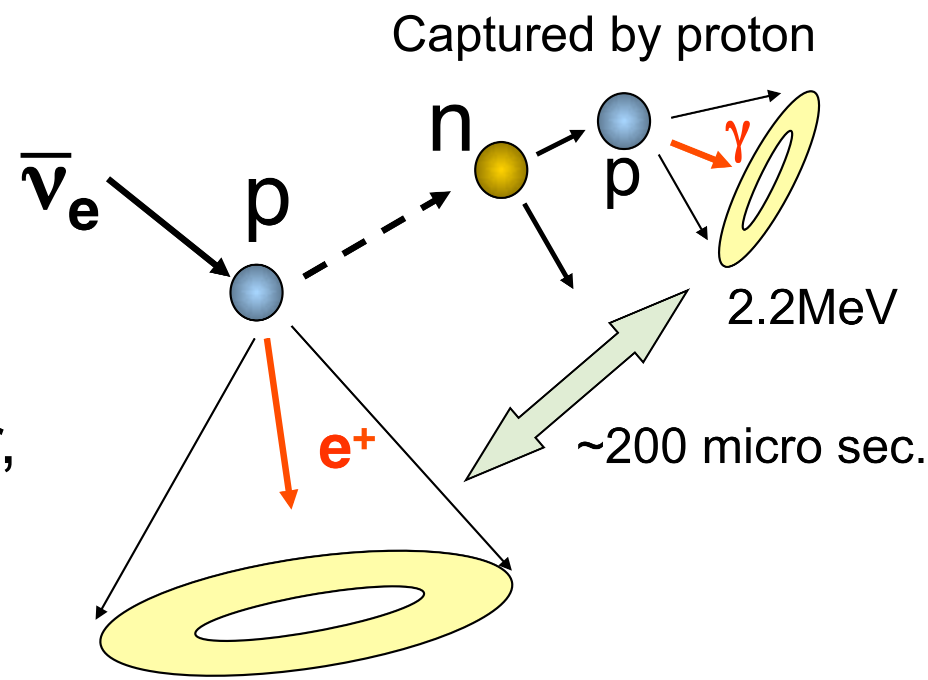

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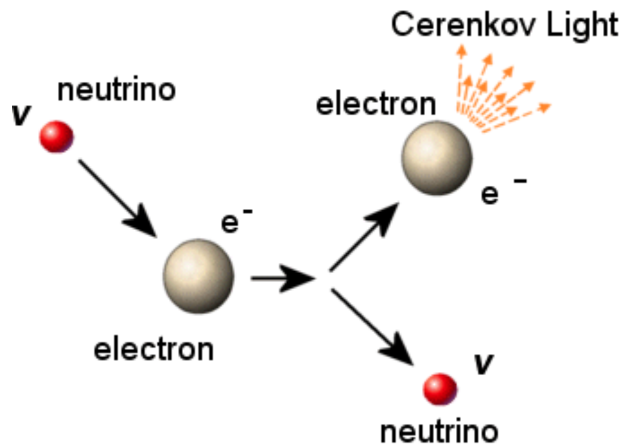
Possible to enhance this signal if Gd loaded
GADZOOKS!

Neutrino interaction for SN ν

Elastic scattering

$$\boxed{\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-}$$

(Both Charged Current and Neutral Current interaction)



✓ All neutrinos are sensitive

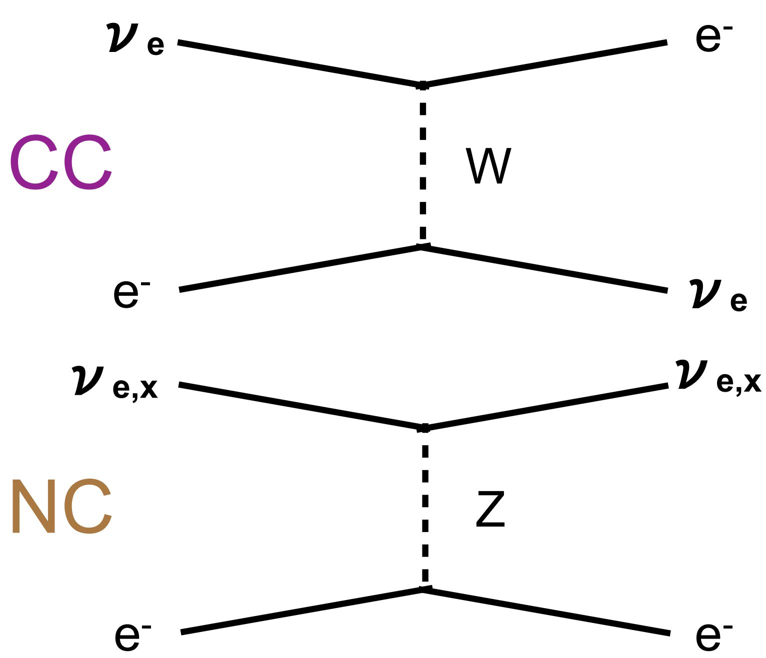
✓ The cross section for ν_e is larger than others because of CC effect.

✓ Well known cross section.

- few % of inverse beta decay

✓ Good directionality

✓ Measurable for only recoil electron energy, not neutrino energy



Neutrino interaction for SN ν

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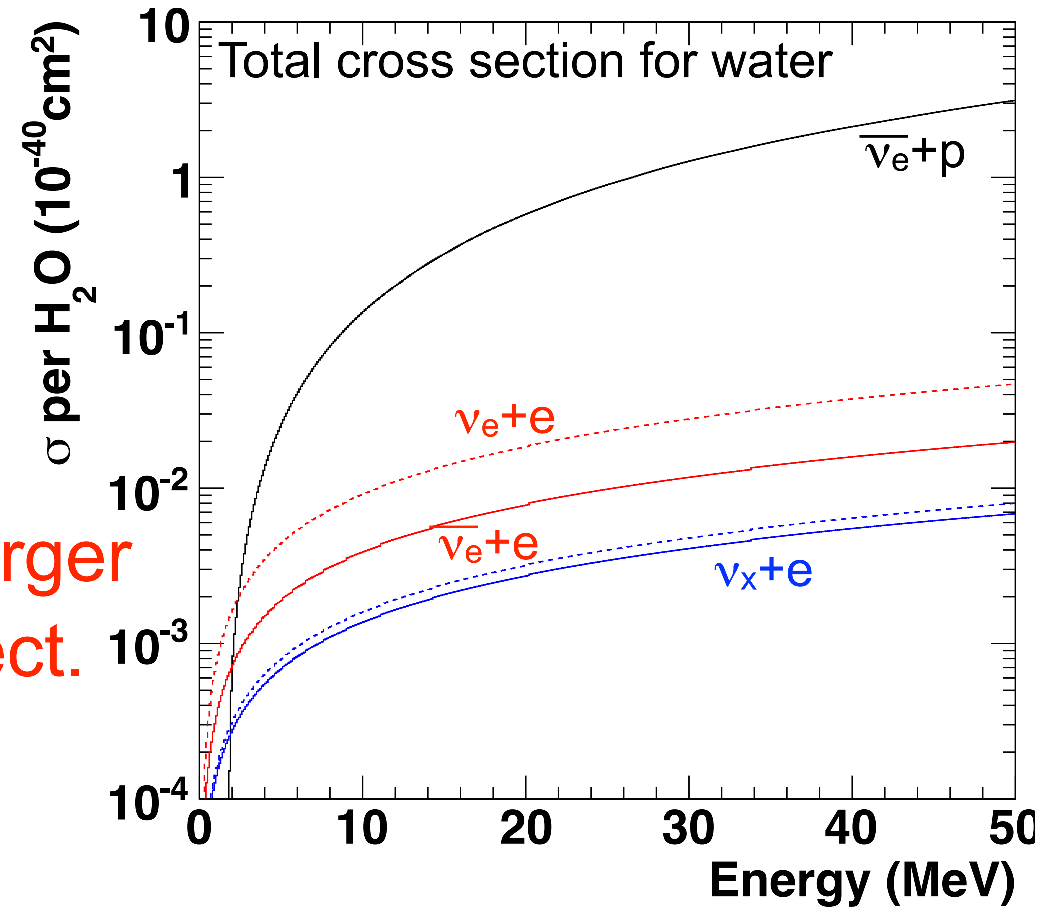

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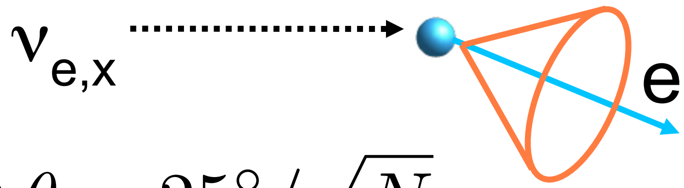
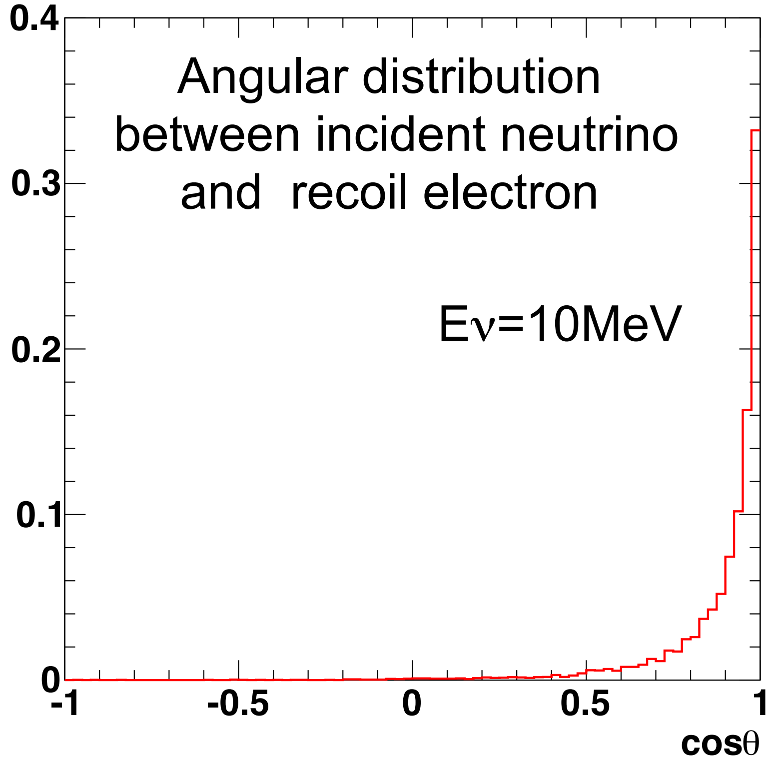
Water Cherenkov



$$\Delta\theta \sim 25^\circ/\sqrt{N}$$



Neutrino interaction for SN ν

CC interactions on nuclei

$$\nu_e + (N,Z) \rightarrow (N-1, Z+1) + e^-$$
$$\bar{\nu}_e + (N,Z) \rightarrow (N+1, Z-1) + e^+$$

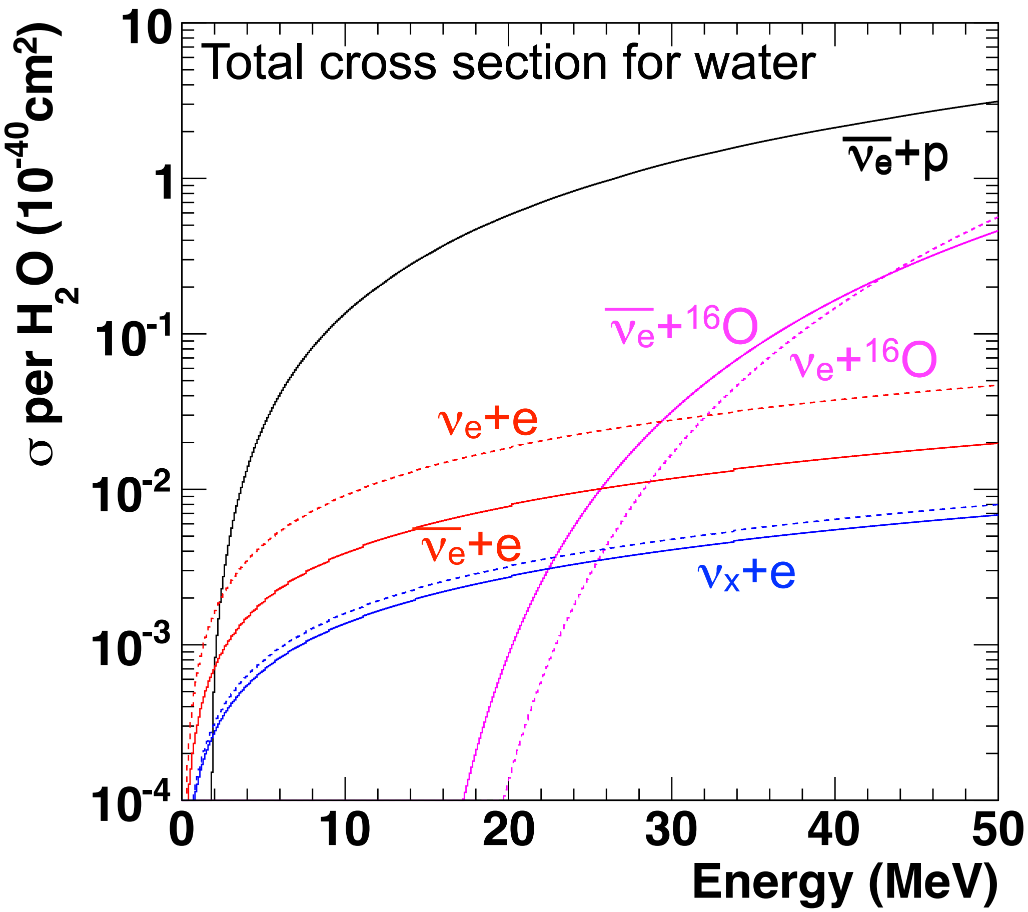
(for example)

oxygen in water

$$\nu_e + {}^{16,18}O \rightarrow {}^{16,18}F + e^-$$
$$\bar{\nu}_e + {}^{16}O \rightarrow {}^{16}N + e^+$$

carbon in scintillator

$$\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$$
$$\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+$$



Neutrino interaction for SN ν

NC interactions on nuclei

ν + (N,Z) → (N,Z) + ν
ν + (N,Z) → (N-1,Z) + n + ν
ν + (N,Z) → (N,Z-1) + p + ν

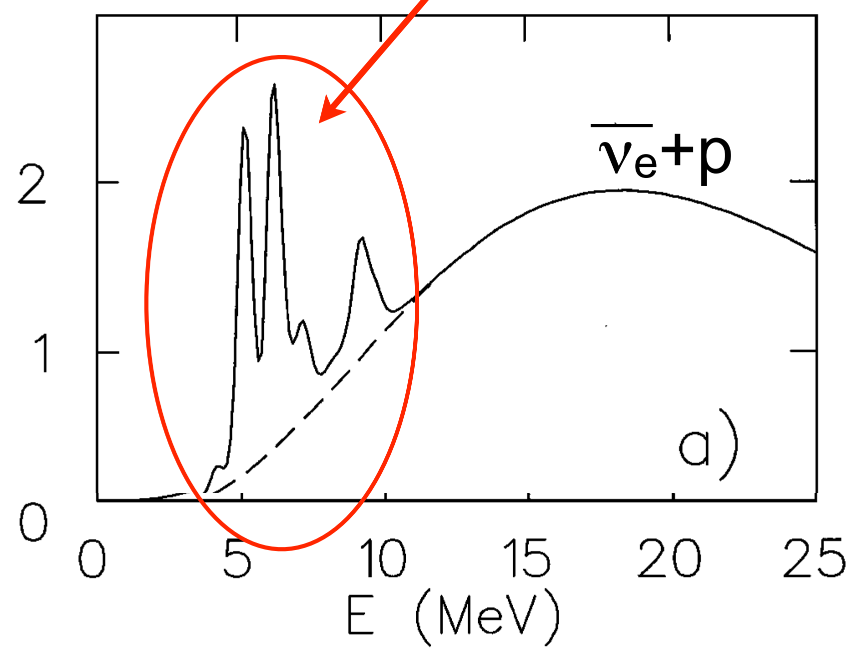
- ✓ Important to probe ν_μ, ν_τ flux
- ✓ Observables:
  - nuclear emission (p,n)
  - nuclear de-excitation γ's
- ✓ Need nuclear physics info.

carbon in scintillator

$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$
$\hookrightarrow {}^{12}C + \gamma$ (15.11MeV)

Langanke, Vogel, Kolbe
Phys. Rev. Lett. 76 (1996) 2629

de-excitation γ in oxygen



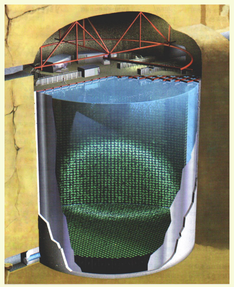
oxygen in water

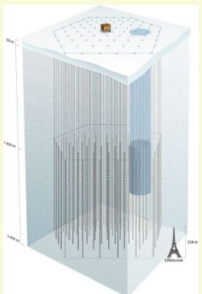
$\nu + {}^{16}O \rightarrow \nu + {}^{16}O^*$
$\hookrightarrow {}^{16}O + \gamma$

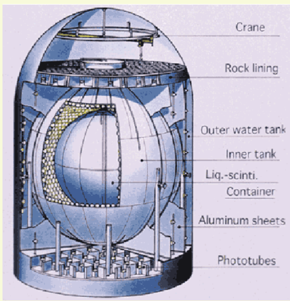
(Eν < ~150MeV)

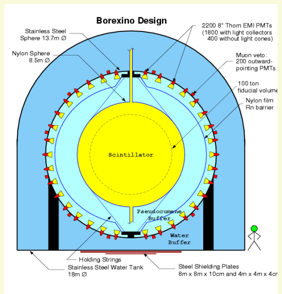
Supernova neutrino detectors

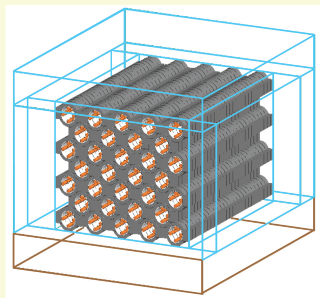
Water Cherenkov / Liquid scintillator / Others









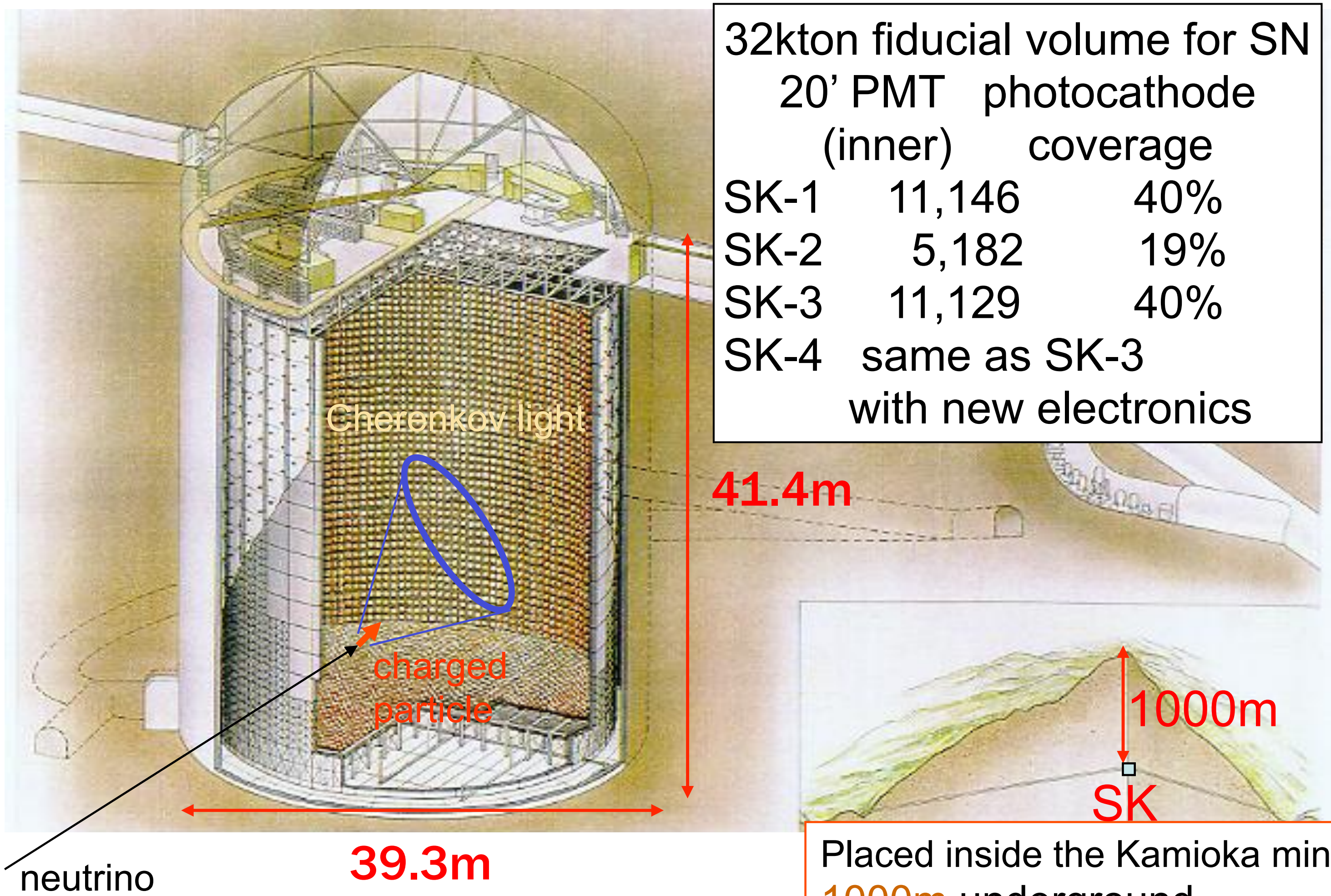


Current SN ν detectors

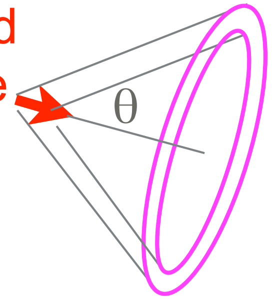
Super-Kamiokande

50kton Water Cherenkov detector

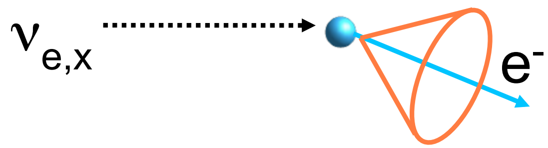
32kton fiducial volume for SN		
	20' PMT (inner)	photocathode coverage
SK-1	11,146	40%
SK-2	5,182	19%
SK-3	11,129	40%
SK-4	same as SK-3 with new electronics	



Placed inside the Kamioka mine
1000m underground

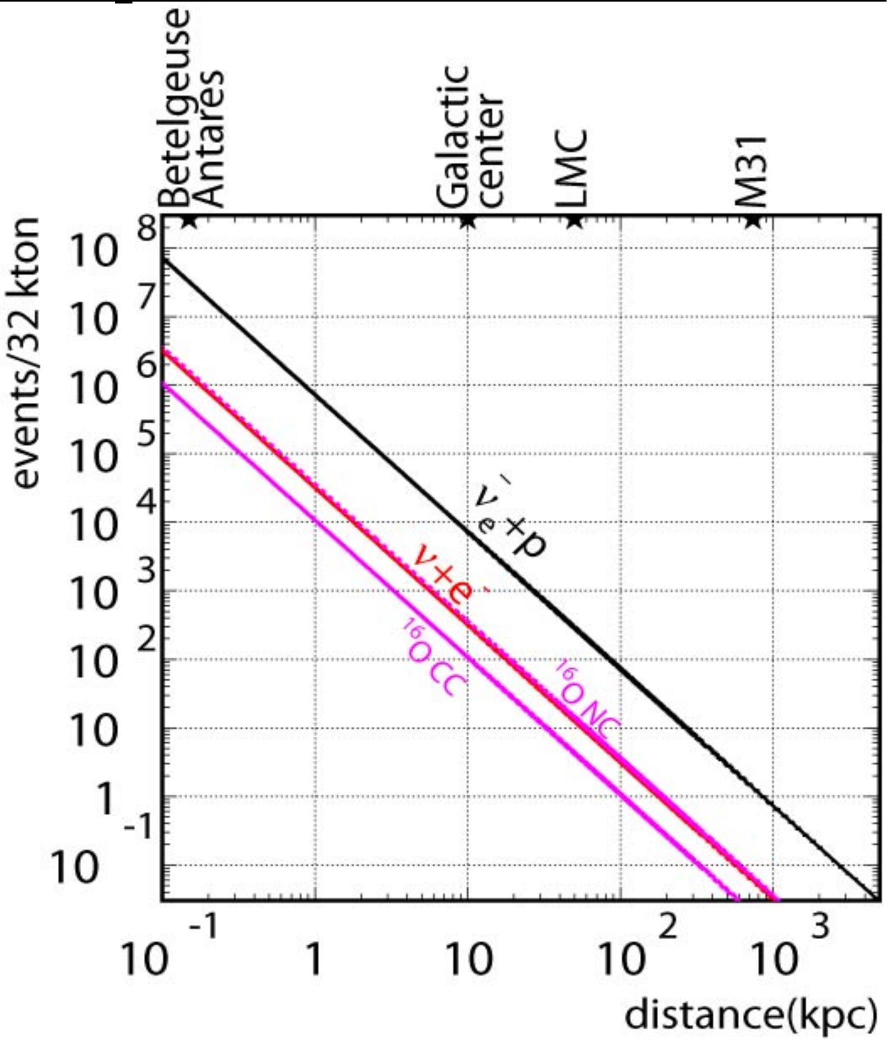


- ✓ Underground in Kamioka mine, (almost BG free)
- ✓ 3.5MeV energy threshold for recoil electron
- ✓ Dominant process is inverse beta decay
- ✓ Good directionality for νe elastic scattering

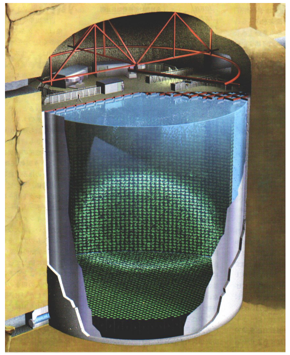


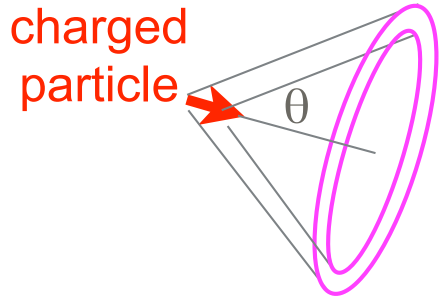
Current SN ν detectors

Super-Kamiokande



50kton Water Cherenkov detector





Expected number of event

~7300 ev (inverse beta decay)
~100 ev (^{16}O CC)
~300 ev (νe elastic scattering)
~360 ev (^{16}O NC γ)

at 10kpc, 4.5MeV energy threshold

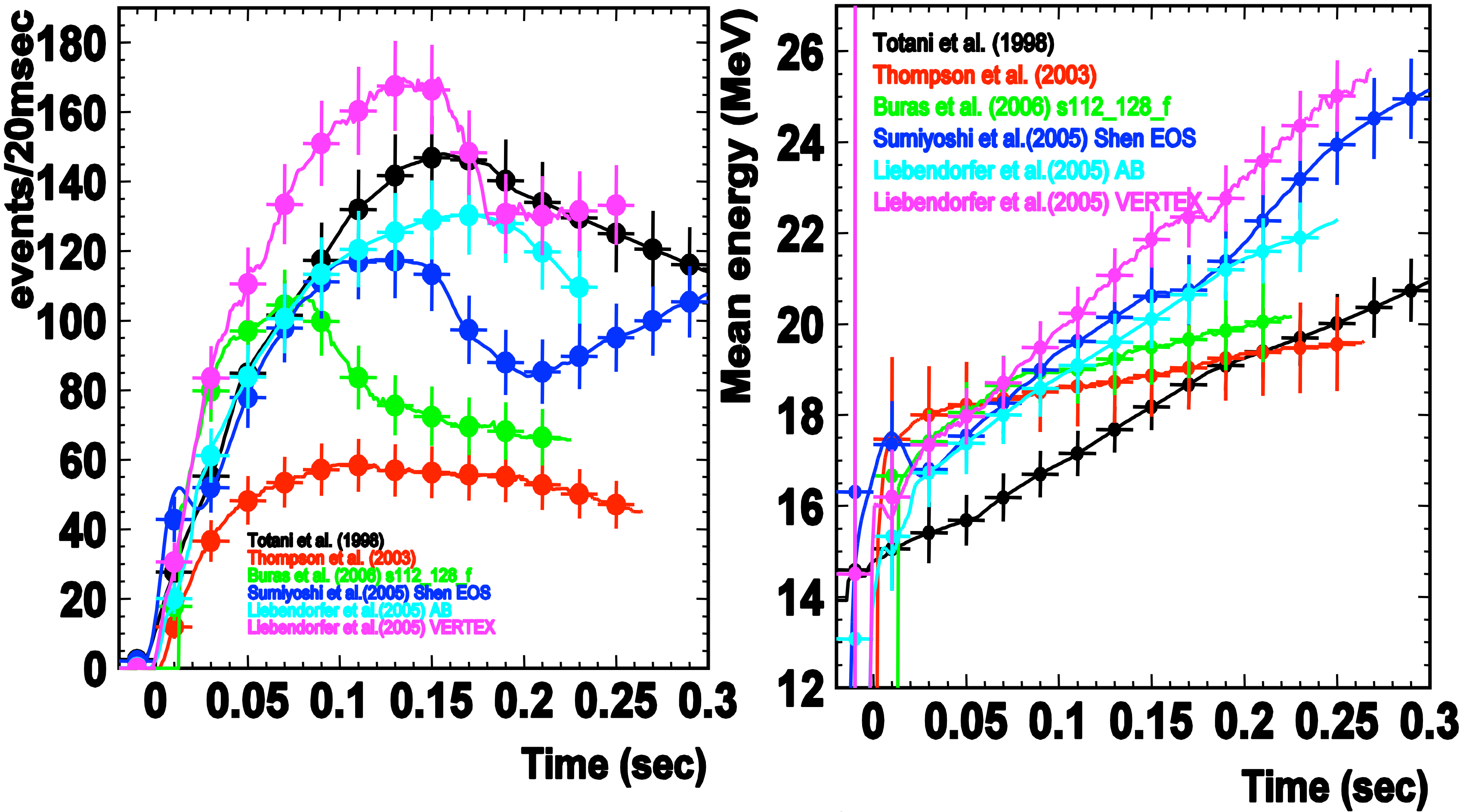
Livermore simulation
Totani, Sato, Dalhed, Wilson, ApJ. 496 (1998) 216

Current SN ν detectors

Super-Kamiokande

Time variation of $\overline{\nu_e}$+p at 10kpc

Time variation of event rate　　Time variation of mean energy

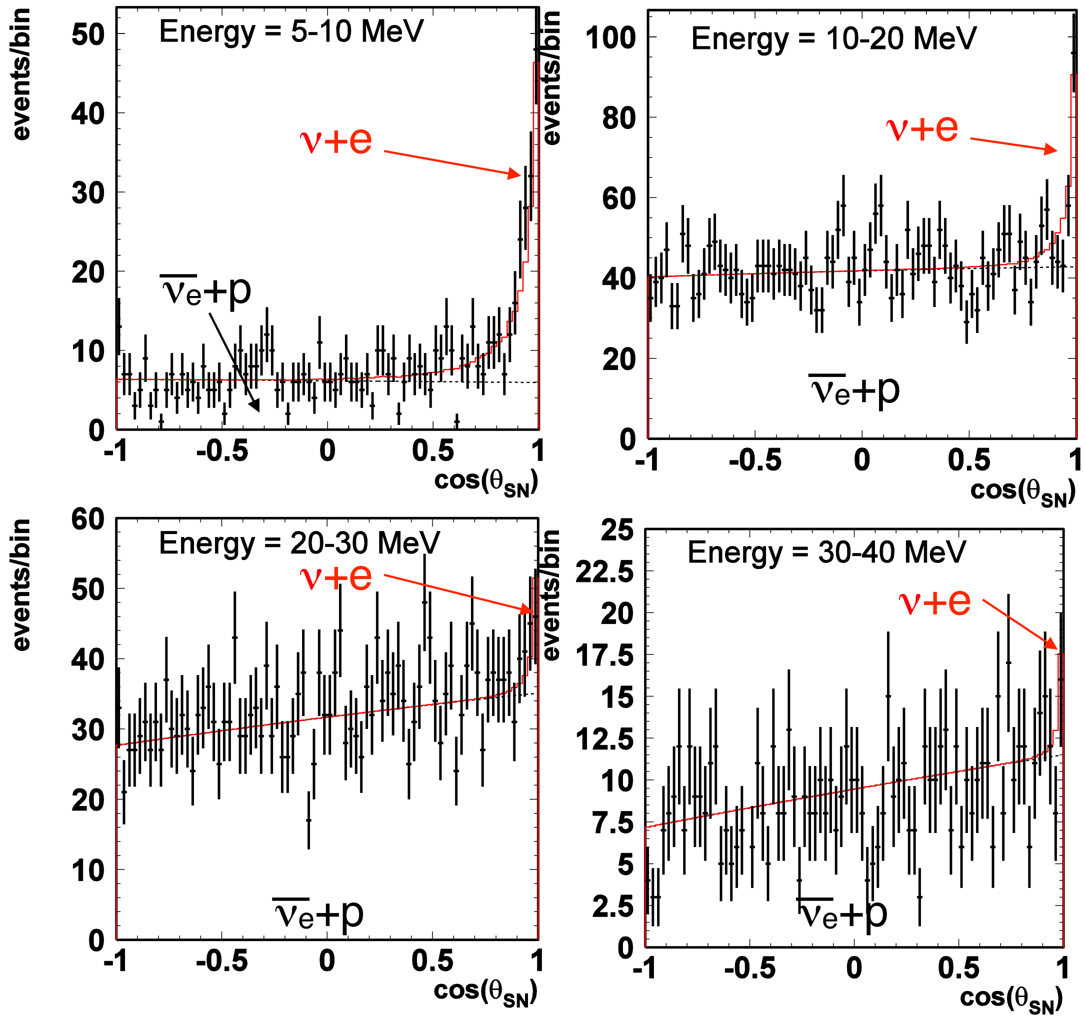


Current SN ν detectors

<u>Super-Kamiokande</u>

✓ ν-e elastic scattering has good directionality.
✓ Direction of supernova can be determined with an accuracy of ~5 degree.
✓ Spectrum of νe events can be statistically extracted using the direction to supernova.
✓ If Gd loaded, it will be more accurate since ν_e signal can be separated.

Simulation of angular distribution

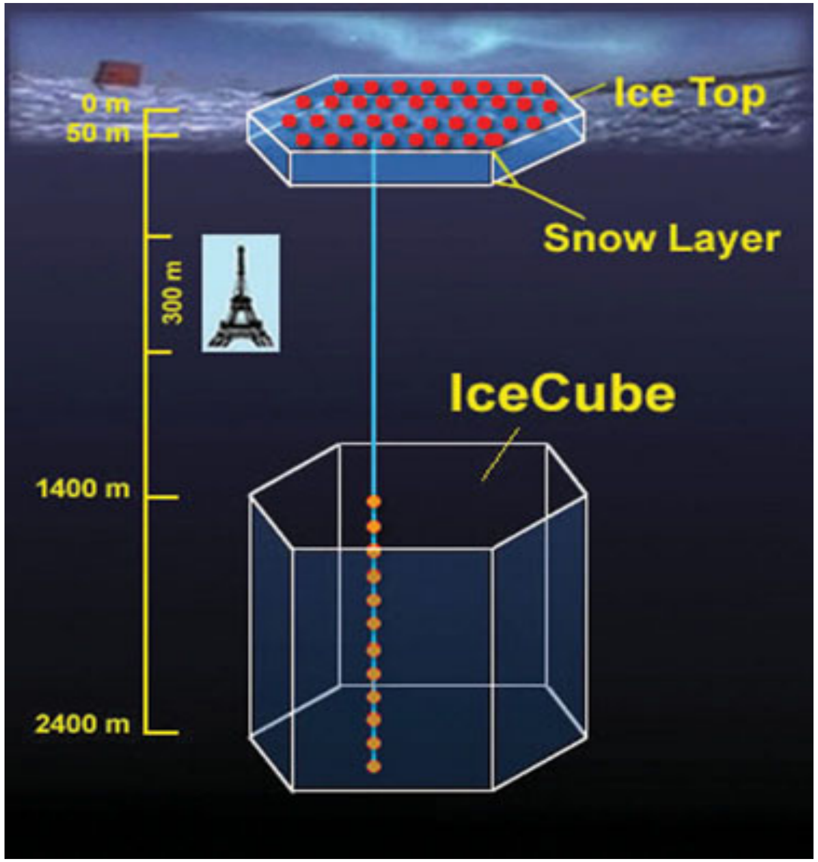


Current SN ν detectors

IceCUBE

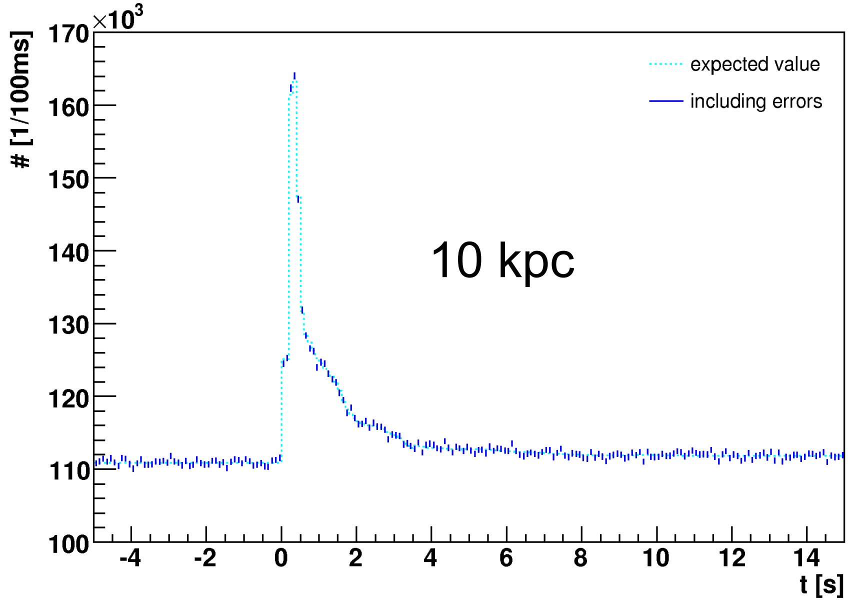
~km long string Water Cherenkov detector at the South Pole

Giga-ton detector



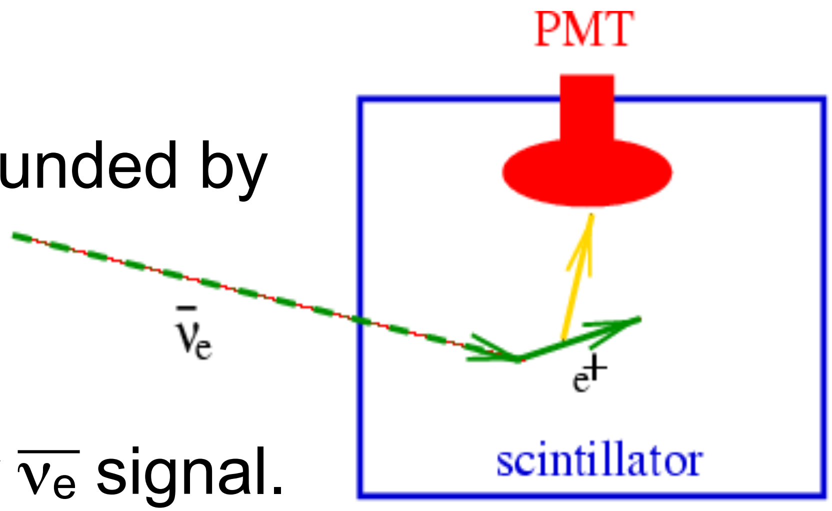
✓ Nominally multi-GeV energy threshold, but can see burst of low energy $\overline{\nu}_e$'s as increase in single PMT count rates.

✓ Cannot tag flavor, overall rate and fine time structure.

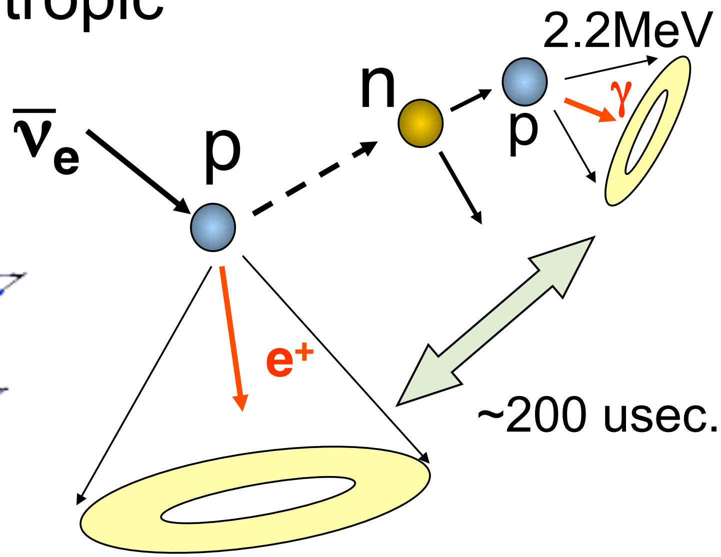


Current SN ν detectors

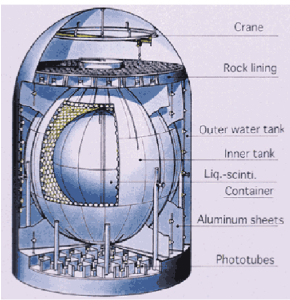
Scintillation detectors



✓ Liquid scintillator C_nH_{2n} volume surrounded by PMTs.
✓ Low energy threshold (O(100keV))
✓ Good neutron tagging using delayed coincidence technique → advantage for $\overline{\nu_e}$ signal.
✓ Poor directionality, since light is almost isotropic

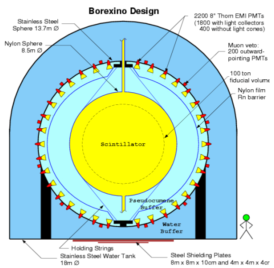


KamLAND (Japan)

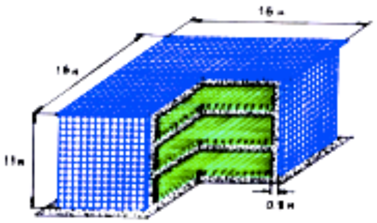


LVD (Italy)

Borexino (Italy)



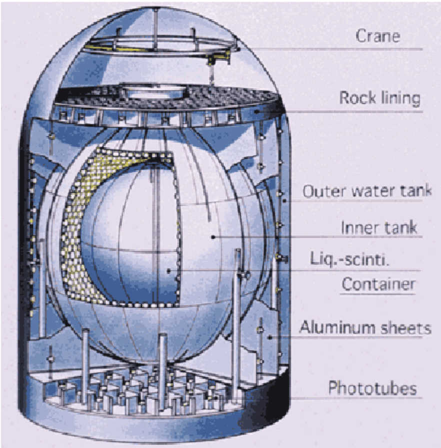
Baksan (Russia)



+Double Chooz, Daya Bay and RENO

Current SN ν detectors

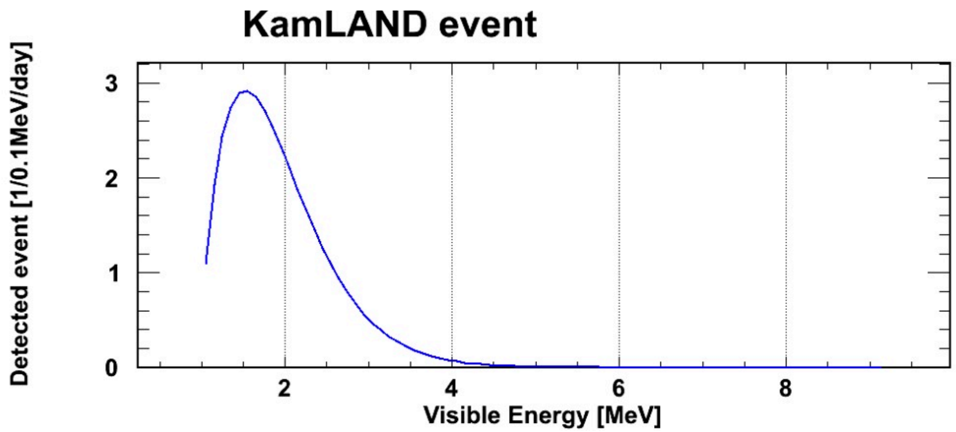
KamLAND 1000 ton Liquid scintillator at Kamioka



- ✓ Large volume
- ✓ Low energy threshold
- ✓ Good $\overline{\nu_e}$ sensitive
- ✓ Good energy resolution

$$7.25\%/\sqrt{E/(MeV)}$$

Prediction of SN by signal from Si burning



Expected number of event at 10kpc

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

~10 events/day for Betelgeuse

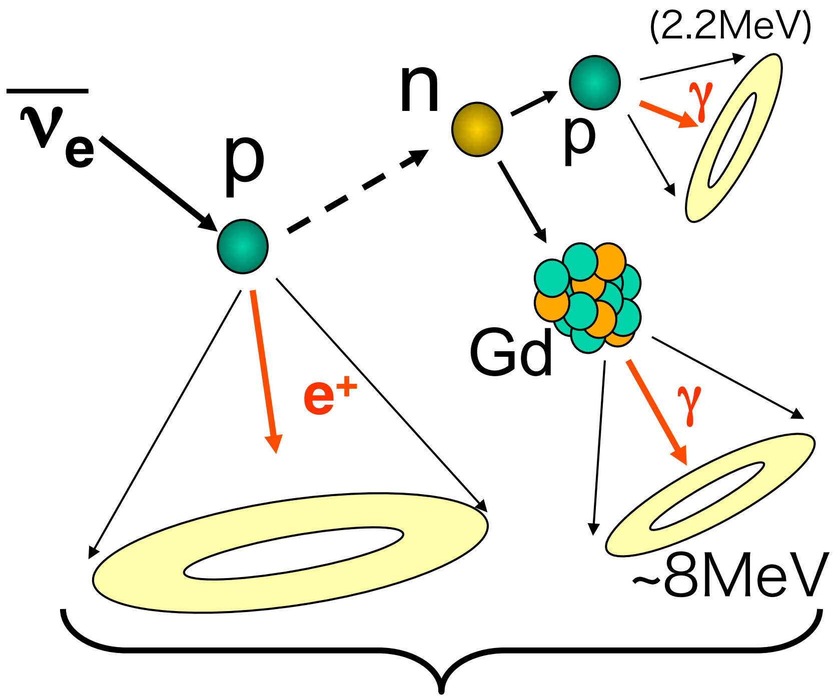
石徹白さん
2013年3月／日本物理学会


Future prospects

GADZOOKS!

(Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande Super!)

Inverse beta decay

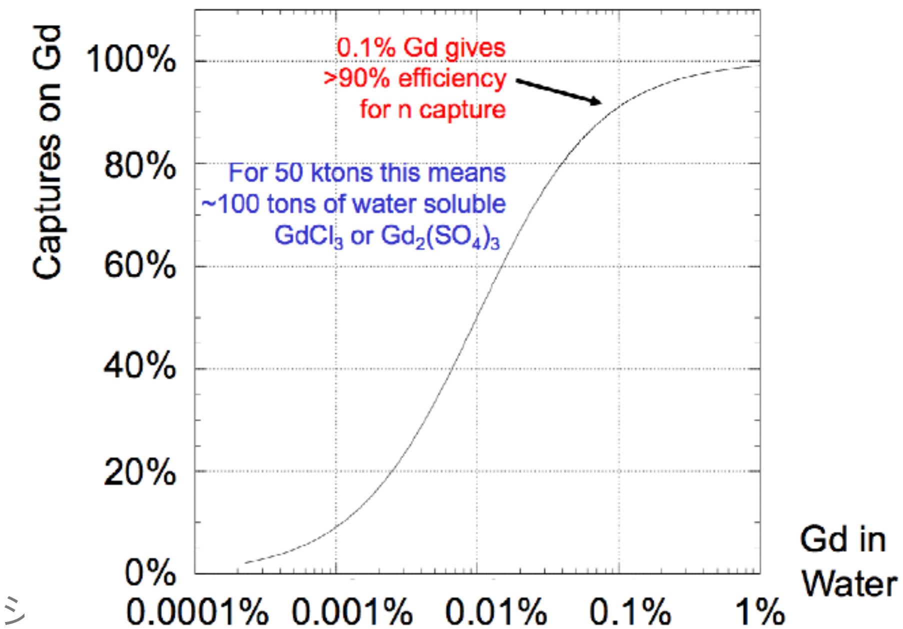


- ΔT~30μsec
- Vertices within~50cm

- Dissolve Gadolinium into Super-K

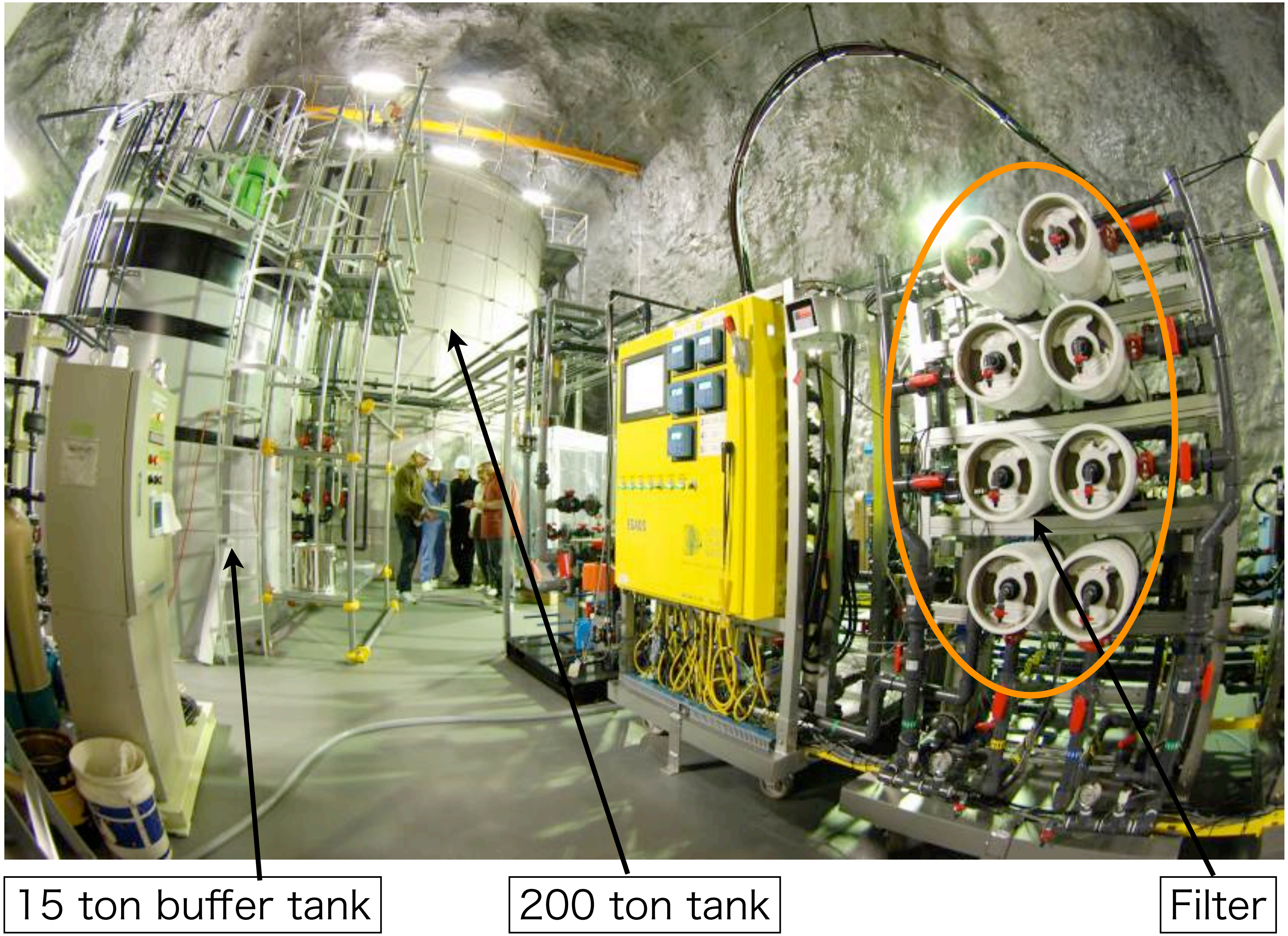
J.Beacom and M.Vagins, Phys.Rev.Lett.93(2004)171101

✓ First observation of SRN
✓ Also more precise detection of supernova burst neutrino



EGADS

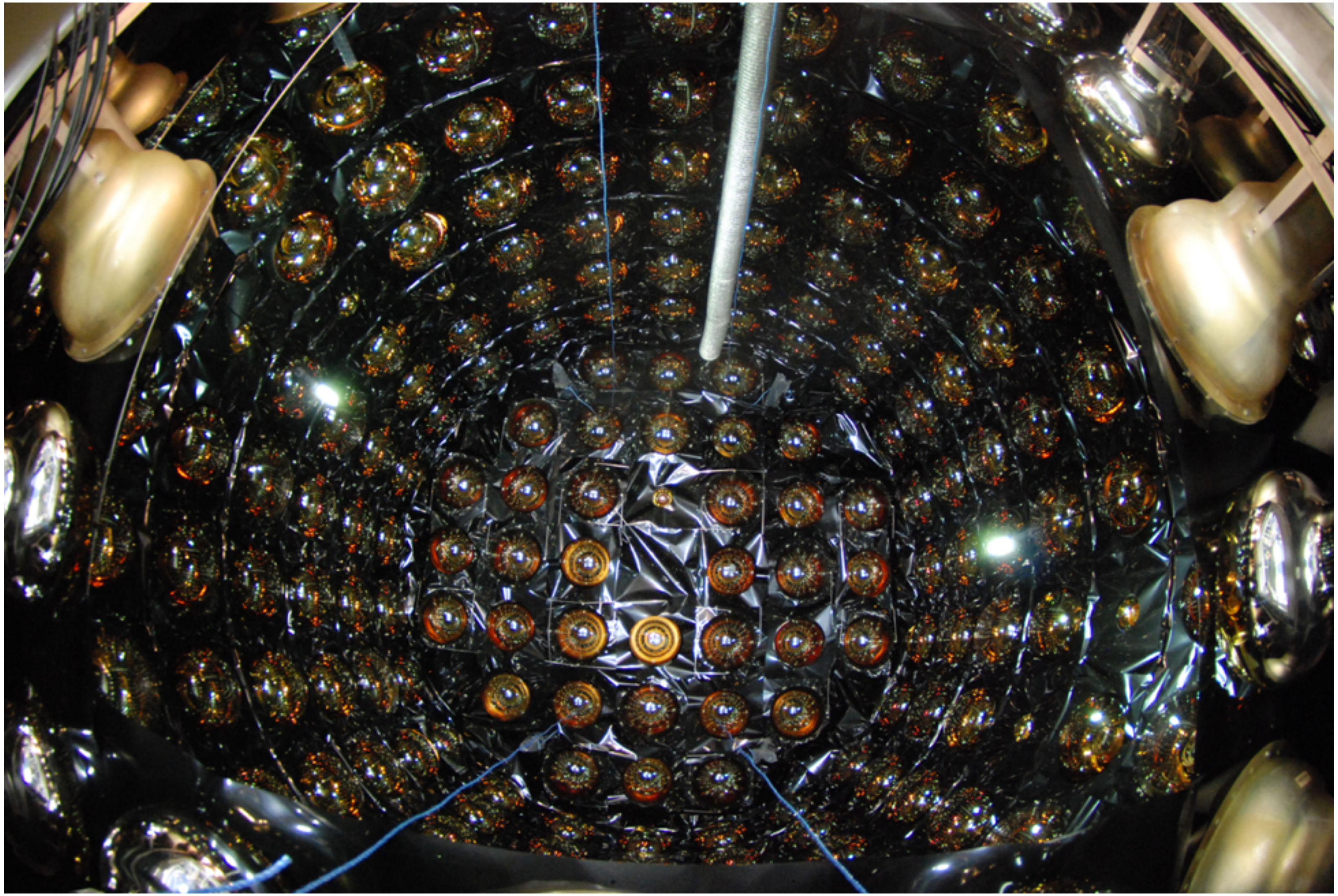
(Evaluating Gadolinium's Action on Detector Systems)



EGADS

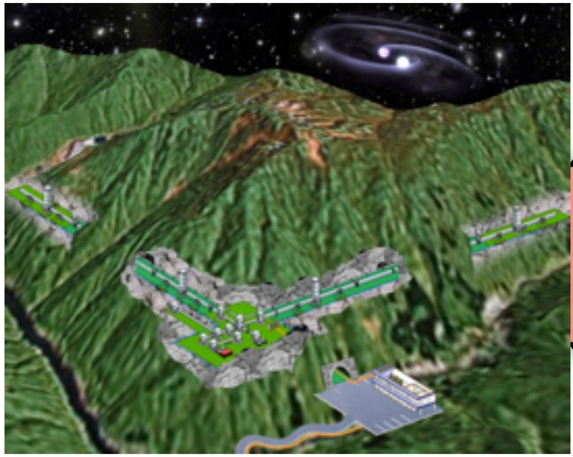
(Evaluating Gadolinium's Action on Detector Systems)

August, 2013



SKE (Supernova simulations with KAGRA and EGADS)

KAGRA



SNe Theory

Y. Suwa

- Provide time correlated data, GW and neutrino
- Suggest signature signals physical phenomenon

EGADS 27pTH-5-7

GW Analysis

T. Yokozawa, M. Asano
N. Kanda

- KAGRA detector simulations
- Develop/Optimize GW analysis tools
- Prepare for realtime observation

o-operat

ν Analysis

T. Kayano, Y. Koshio
M. Vagins

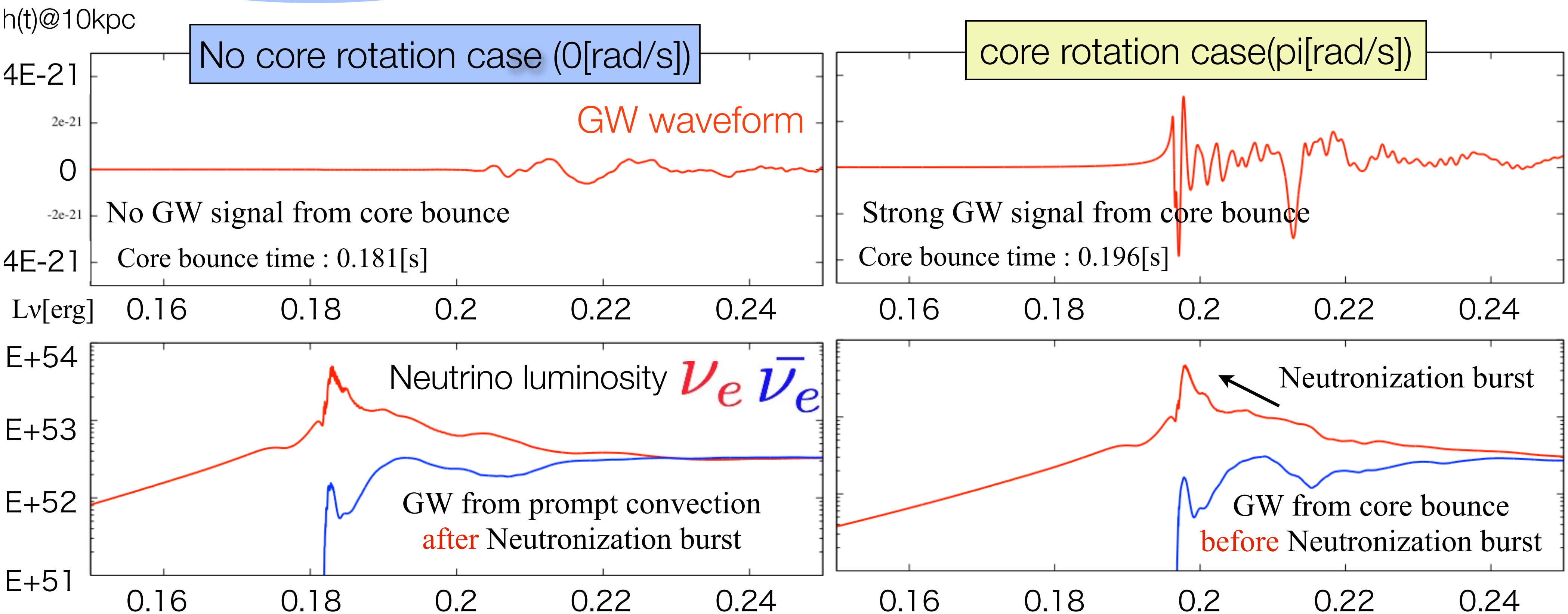
- R&D of EGADS detector
- Signal simulations with EGADS and SK

横澤さん提供

Progenitor core rotate or not?

No core rotation
No GW signal from core bounce
GW from prompt convection after
Neutronization burst

Strong core rotation
Strong GW signal from core bounce
GW from core bounce before
Neutronization burst



h(t) and Luminosity@10kpc for each model ; Time[s] : 0 is start time of gravitational collapse

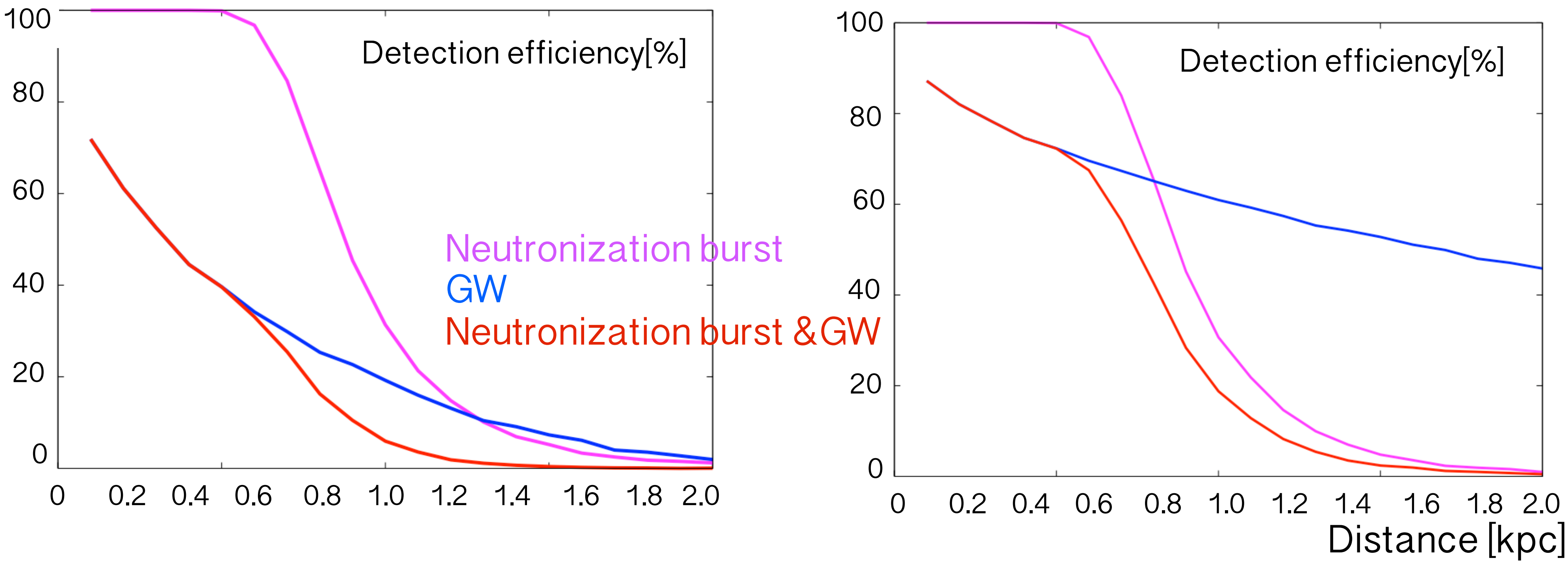
27pTL-8(浅野さん), 27pTL-9(横澤さん), 28aTK-11(茅野さん)

Progenitor core rotate or not?

No core rotation
No GW signal from core bounce
GW from prompt convection after
Neutronization burst

Strong core rotation
Strong GW signal from core bounce
GW from core bounce before
Neutronization burst

preliminary

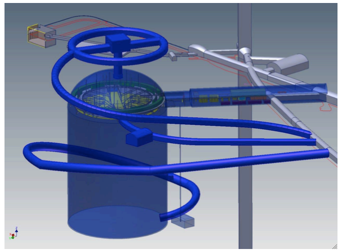


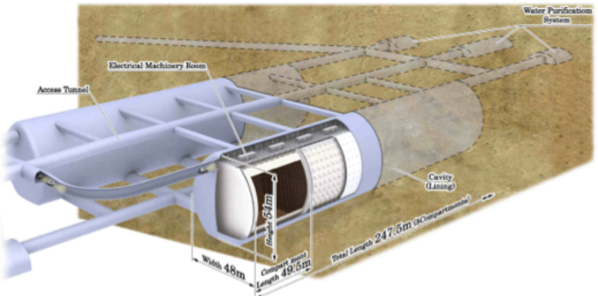
27pTL-8(浅野さん), 27pTL-9(横澤さん), 28aTK-11(茅野さん)

Future SN ν detectors

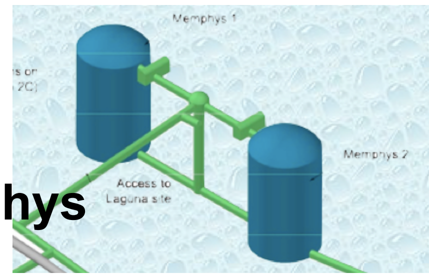
Large scale detectors

LBNE
WCh



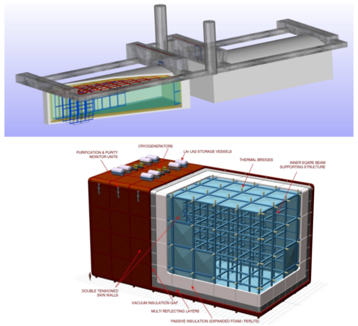


Hyper-K

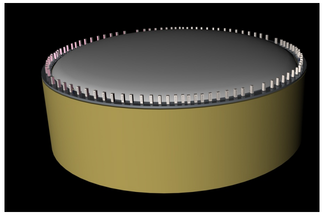


Memphys

Megaton-scale water detector concepts



5-100 kton-scale liquid argon concepts



LBNE LAr

GLACIER

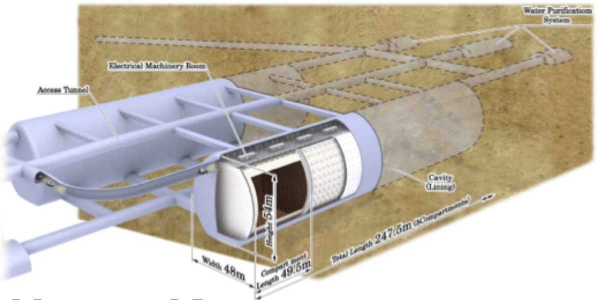
10-100 kton-scale scintillator detector concepts

LENA

Future SN ν detectors

Large scale detectors

LBNE
WCh



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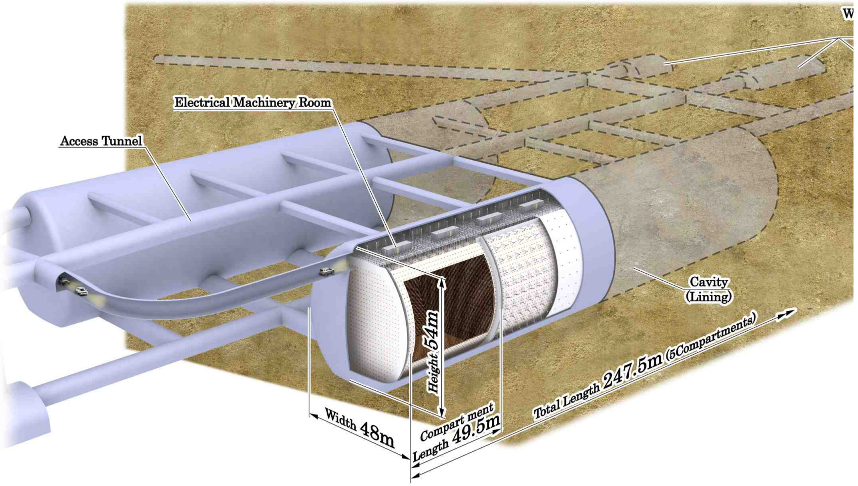
Future SN ν detectors

Hyper-Kamiokande

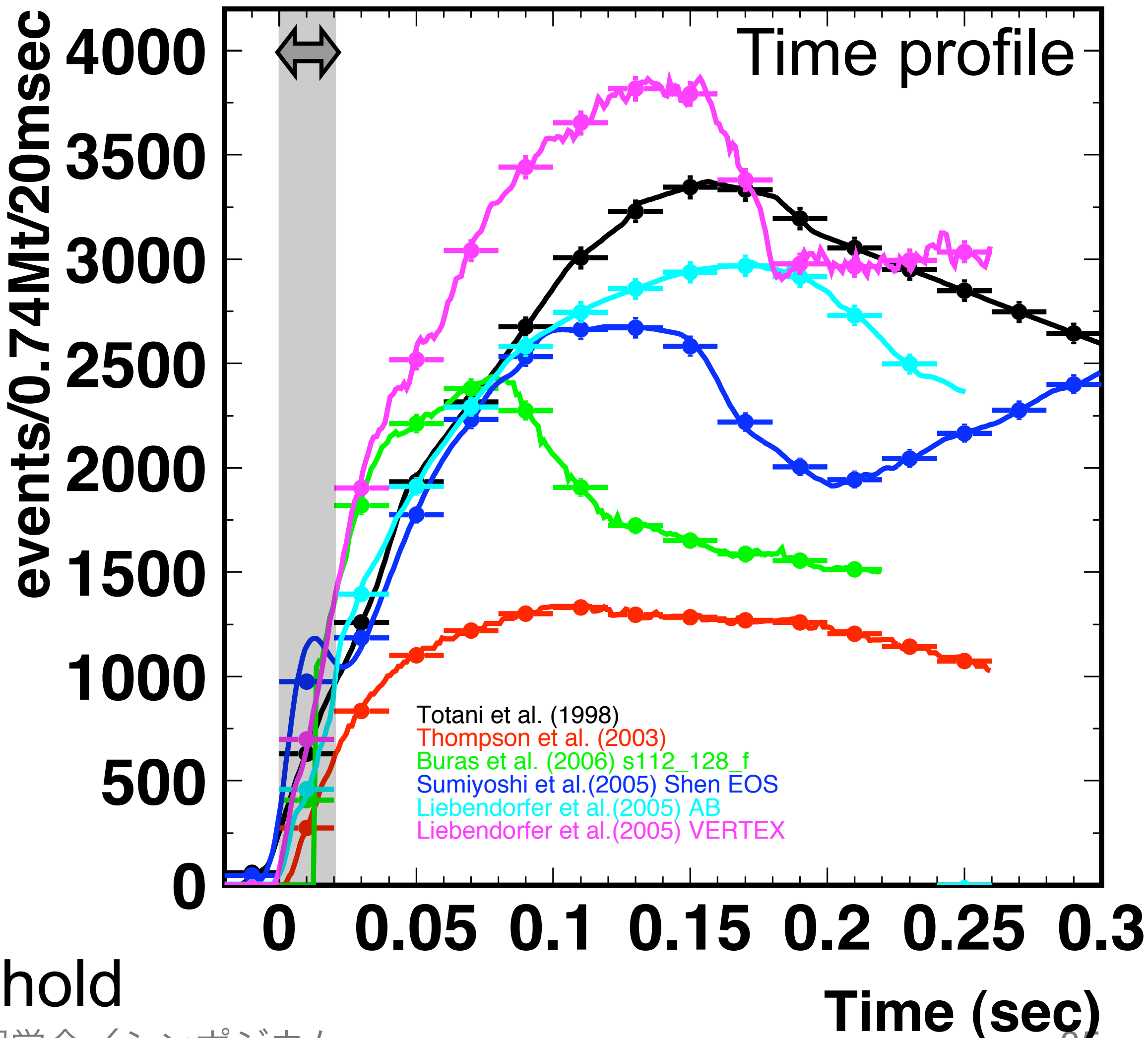


Expected number of event

~168000 ev (inverse beta d
~2300 ev (^{16}O CC)
~7000 ev (νe elastic scatte
~8300 ev (^{16}O NC γ)

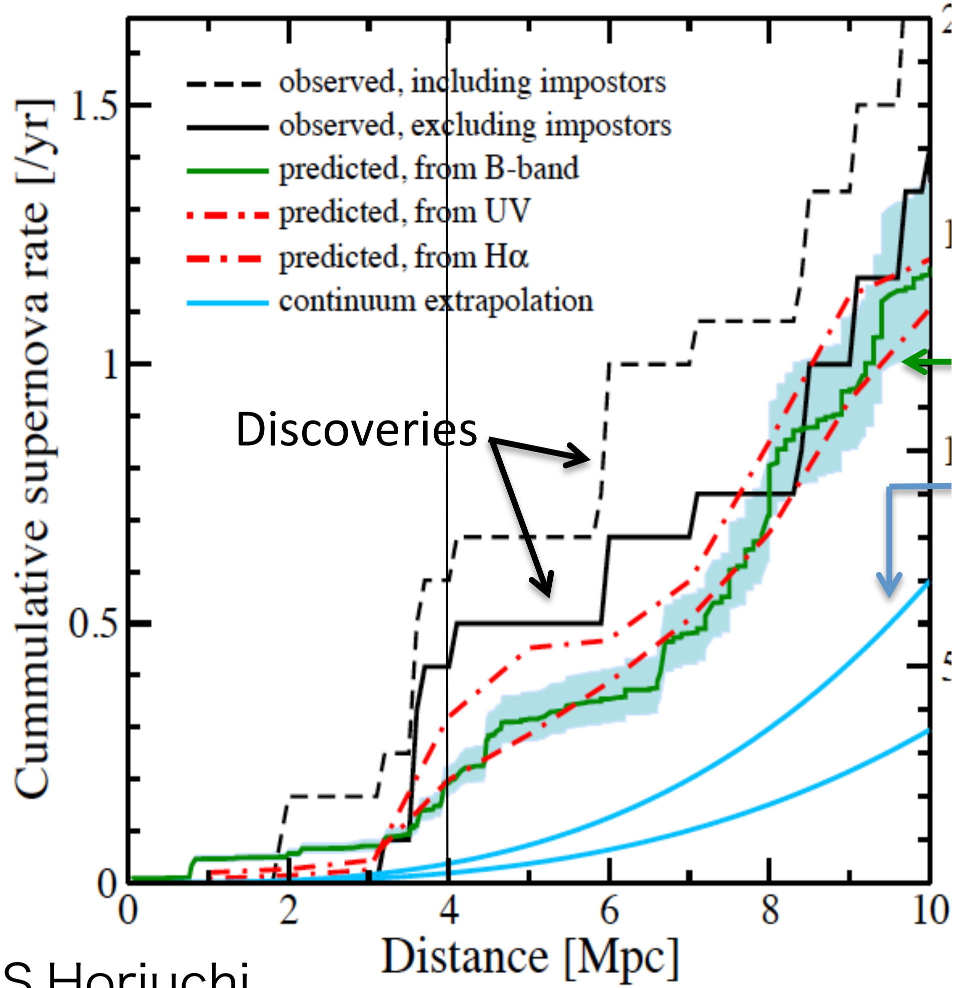
at 10kpc, 4.5MeV energy threshold

Determine starting time
with ~0.03 msec precision.



Future SN ν detectors

Hyper-Kamiokande



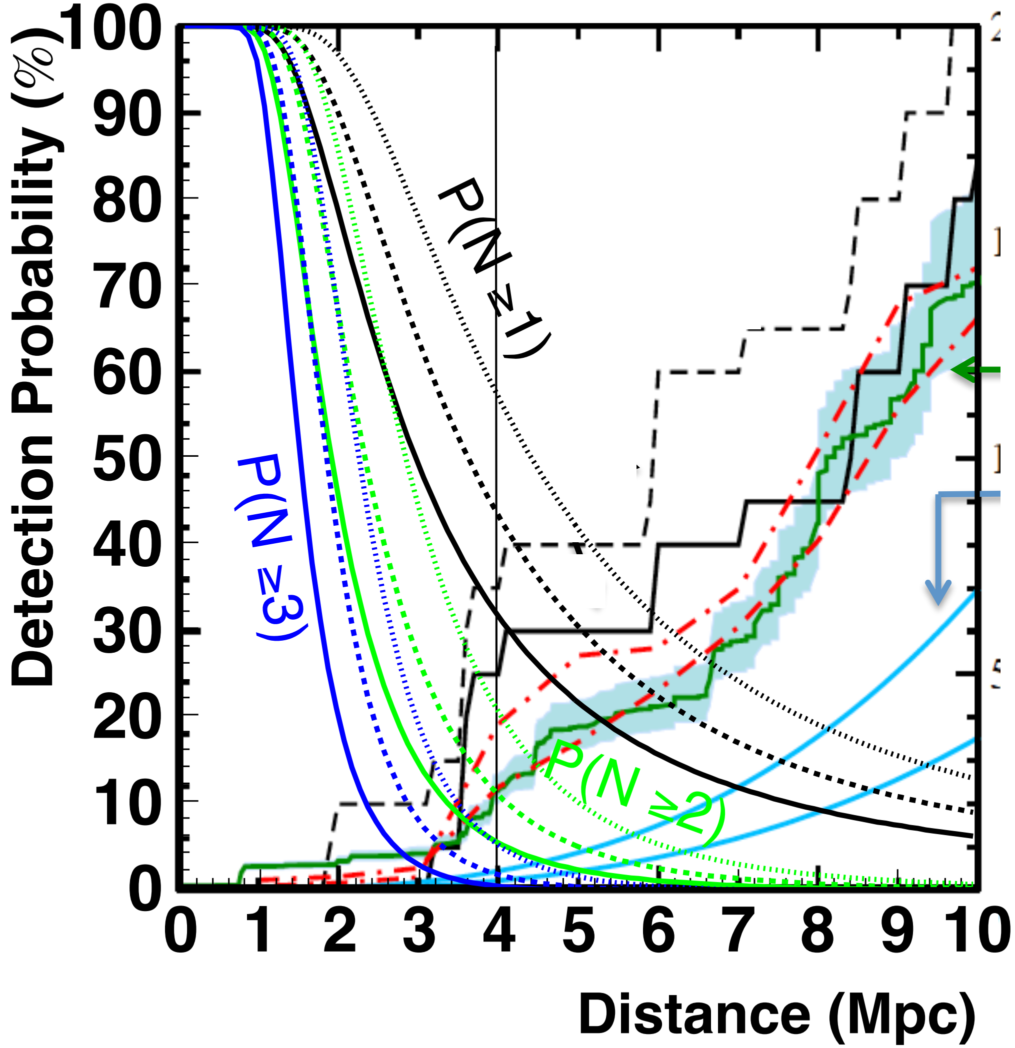
S.Horiuchi

Nearby galaxy

- ✓ 0.2~0.6 SN/year is expected at 4Mpc.
- ✓ The detection probability: 31~56% (N≧1) @4Mpc
- ✓ 1 event from SN@4Mpc (need another information e.g. GW) every 3~10 years is expected.

Future SN ν detectors

Hyper-Kamiokande



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Summary

Surprising recent theory improvement

Ready to observe by several neutrino detectors

Let's go supernova!

(but after advanced GW detectors are ready)

Thanks