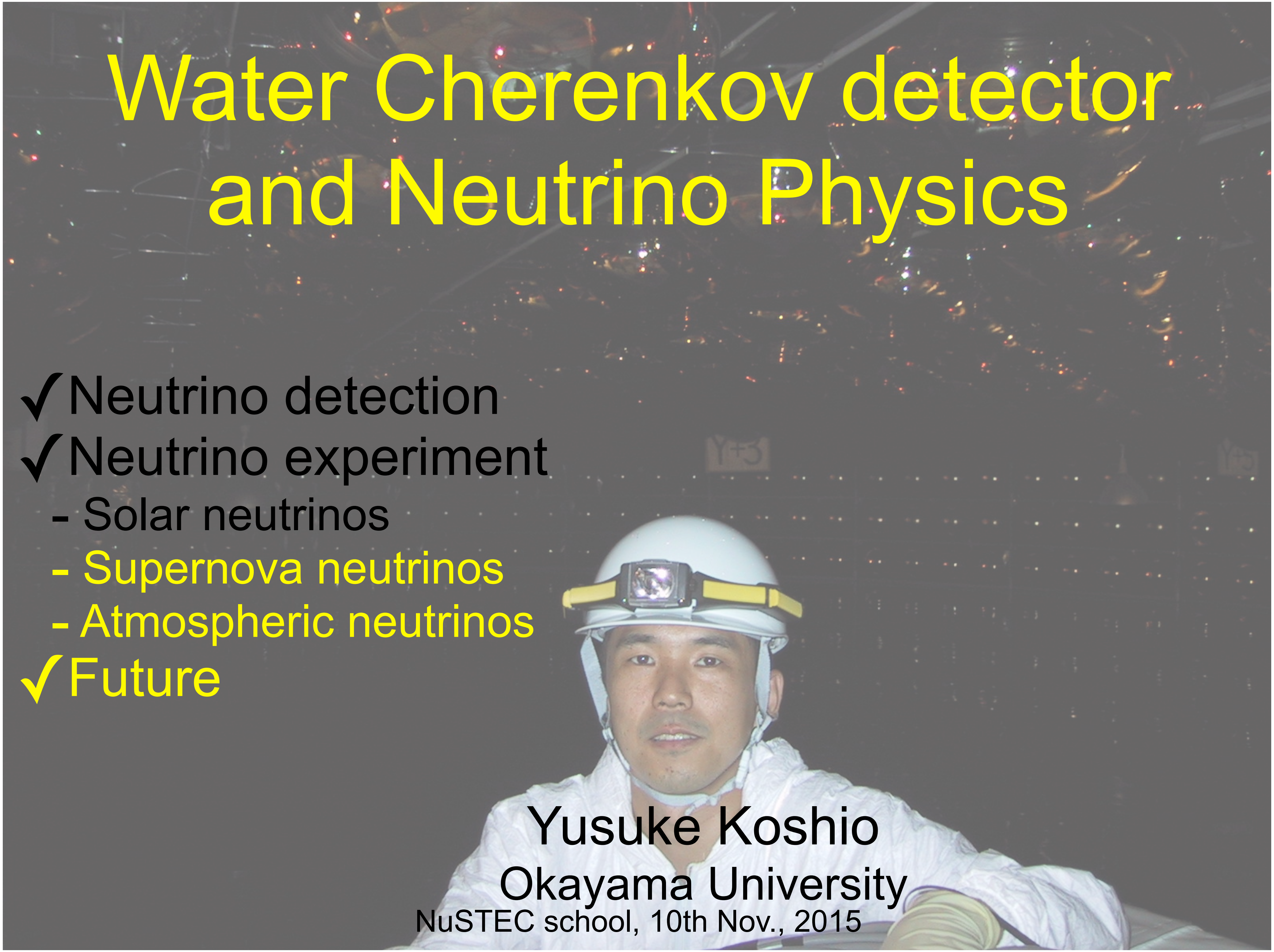


Water Cherenkov detector and Neutrino Physics

✓Neutrino detection

✓Neutrino experiment

- Solar neutrinos
- Supernova neutrinos
- Atmospheric neutrinos

✓Future

Yusuke Koshio

Okayama University

NuSTEC school, 10th Nov., 2015

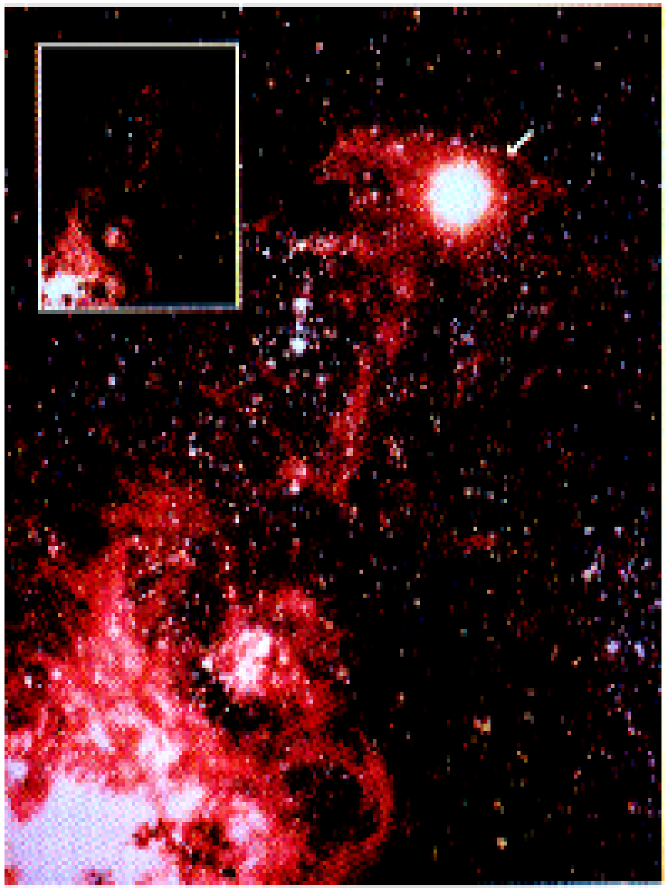
Supernova neutrino


SN1987A

Review of the SN1987A in LMC

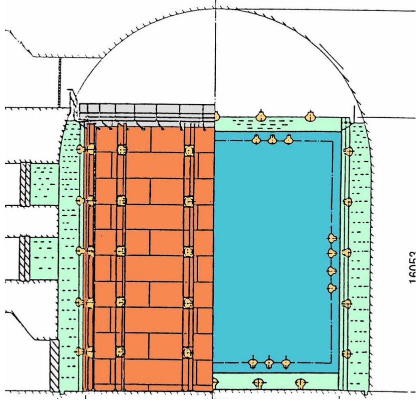
at 50kpc, ν's seen ~2.5 hours before first light

Large Magellanic Cloud
SN1987A

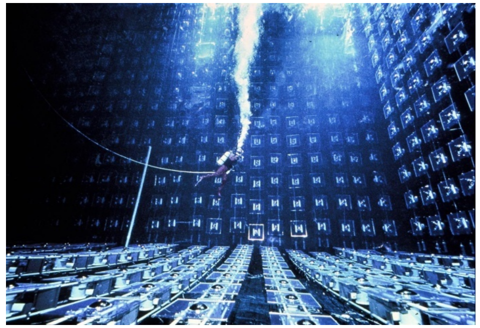


Water Cherenkov

Kamiokande-II



IMB-3

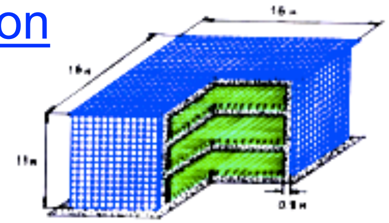


Strong directionality for ν_e event

Liquid Scintillator

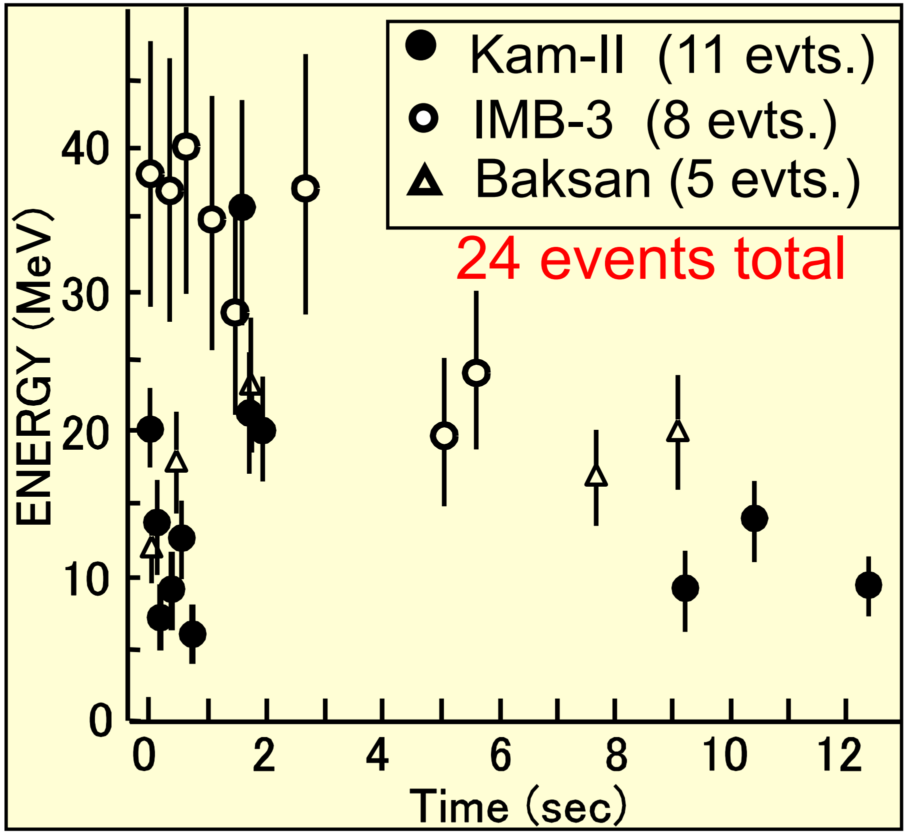
Good $\overline{\nu}_e$ event identification

Baksan



Review of the SN1987A in LMC

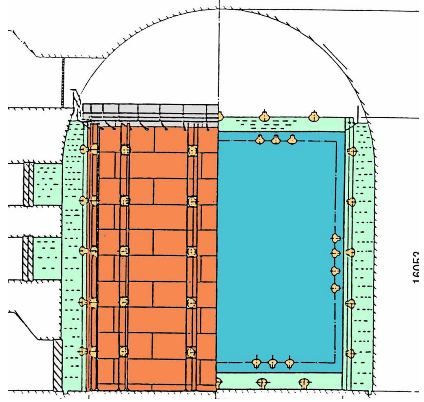
at 50kpc, ν's seen ~2.5 hours before first light



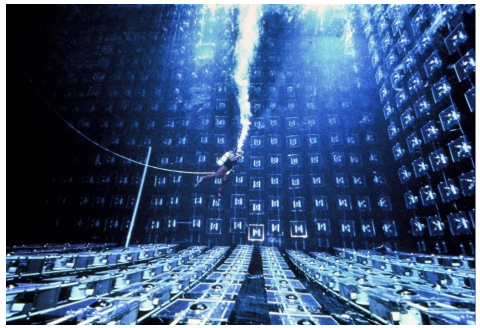
Most of them seems to $\overline{\nu_e}$ event

Water Cherenkov

Kamiokande-II



IMB-3



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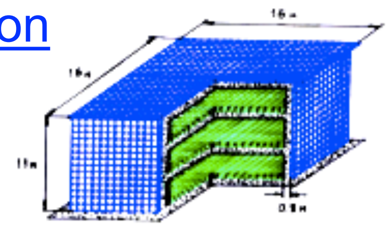
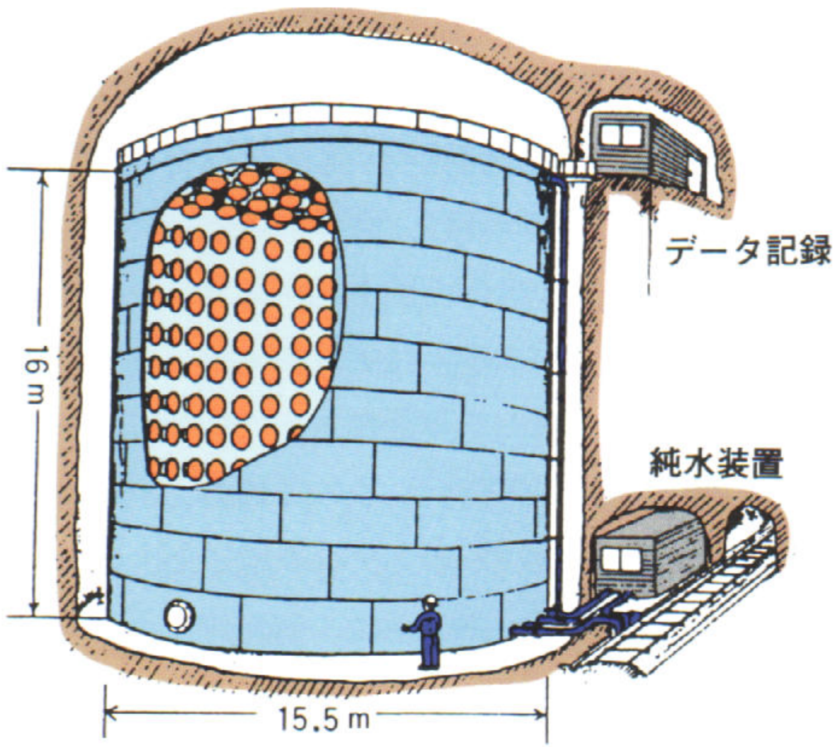


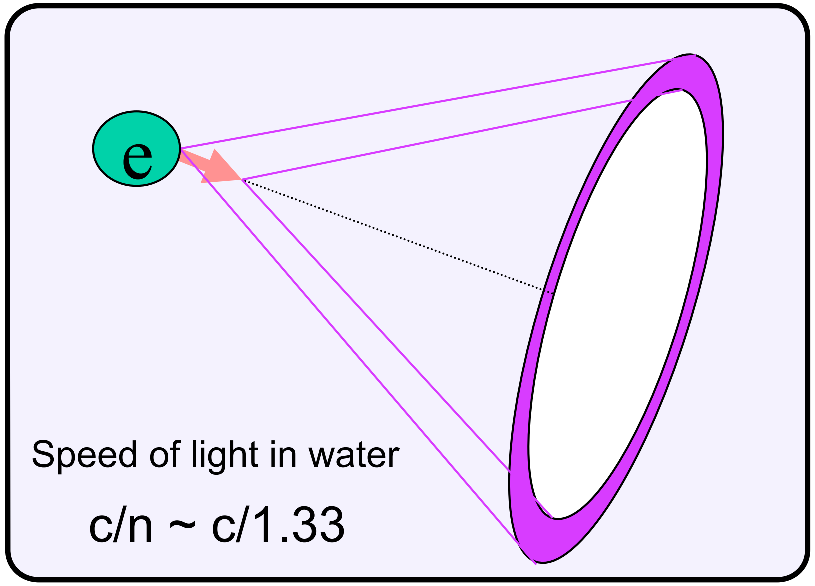
Review of the SN1987A in LMC

Kamiokande (1983-1995)

kamioka mine (2700mwe)



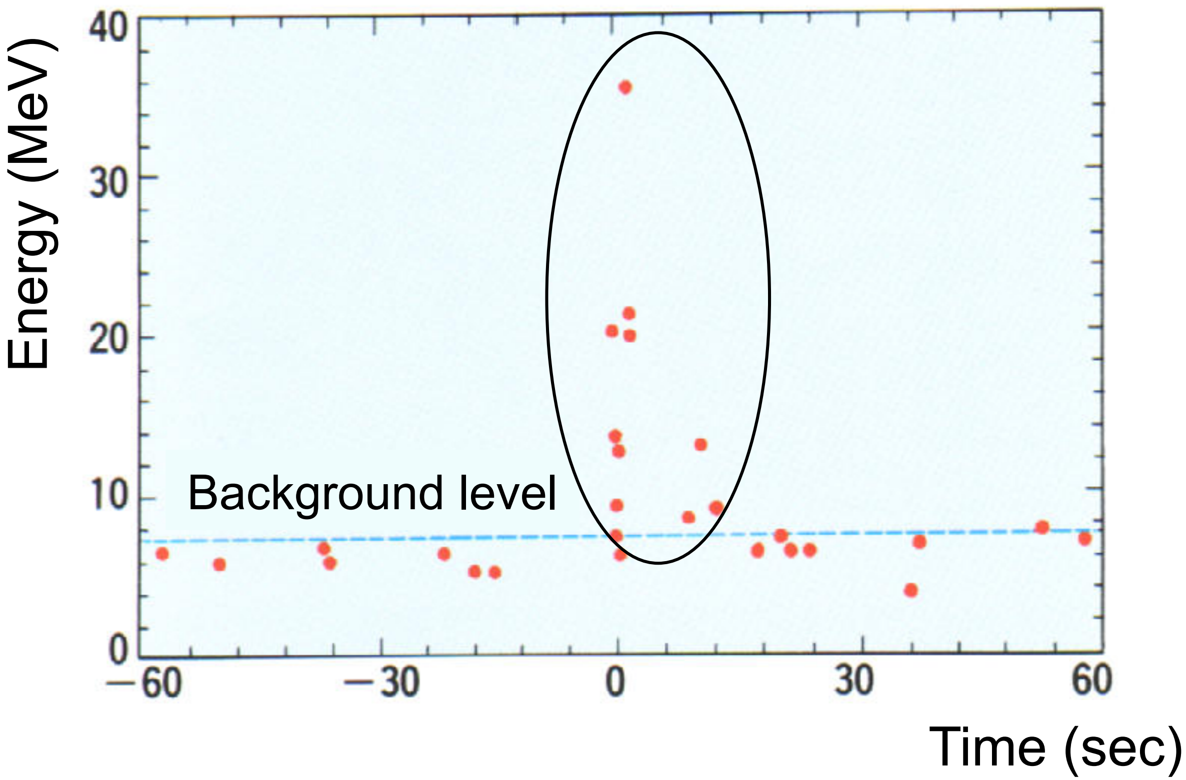
3000トン水タンク、約1000本の光電子増倍管



Review of the SN1987A in LMC

$\overline{\nu}_e + p \rightarrow e^+ + n$ (CC)

Kamiokande



Realtime detector

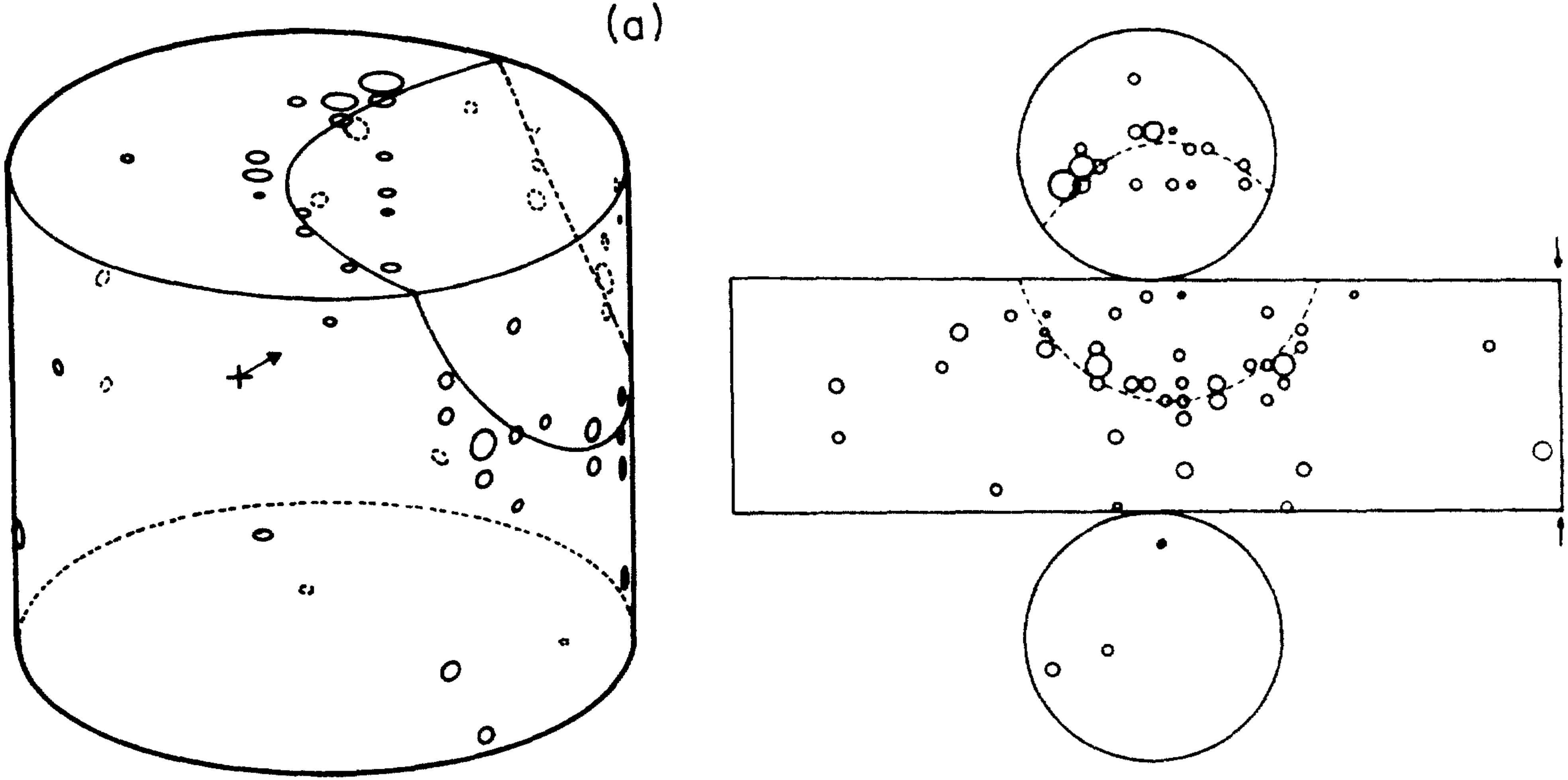
- Date : 23 Feb. 1987
- Time : 07:35:35 (UT)
- 11 events in 13 sec.

Energy is determined by the number of hit PMTs for which the residual time (T-Tof) is ± 15nsec

Trigger if 20 hits within 100 nsec ~ 7.5 MeV (@50% eff.)

Review of the SN1987A in LMC

Kamiokande



Review of the SN1987A in LMC

IMB (Irvine-Michigan-Brookhaven)

Einstein LoSecco

Smith Wuest Sinclair Learned Cortez

Bratton Sobel Vander Velde Goldhaber Reines Sulak

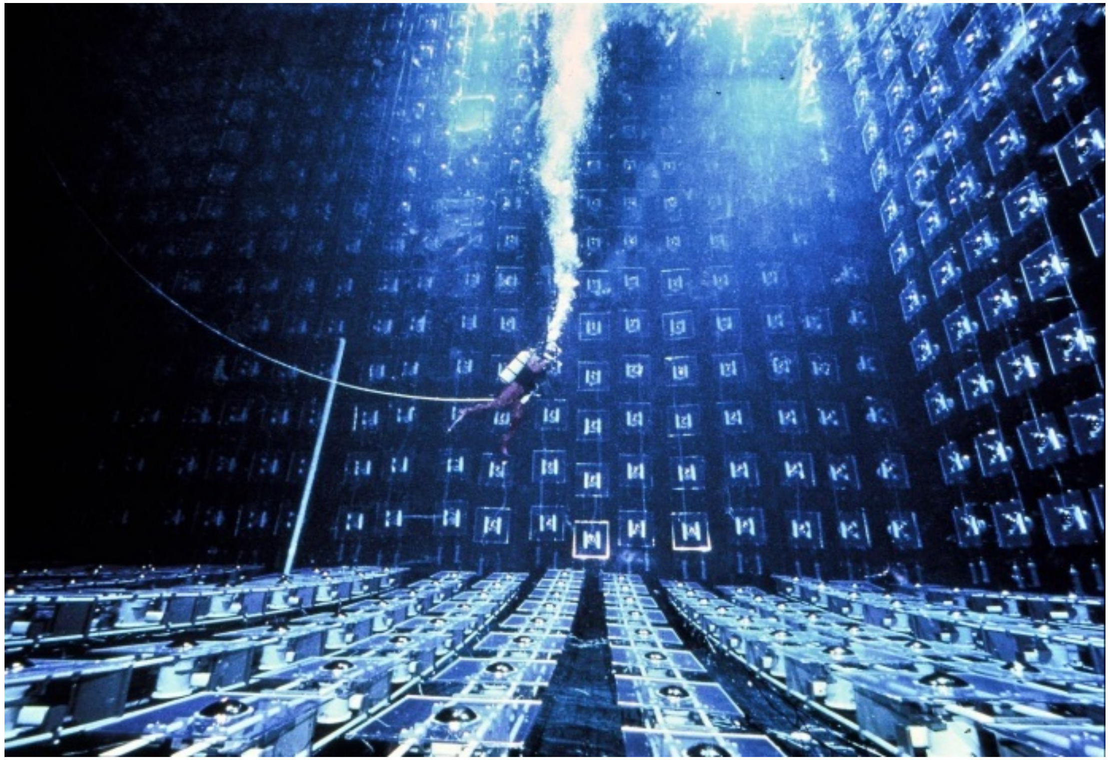
Review of the SN1987A in LMC

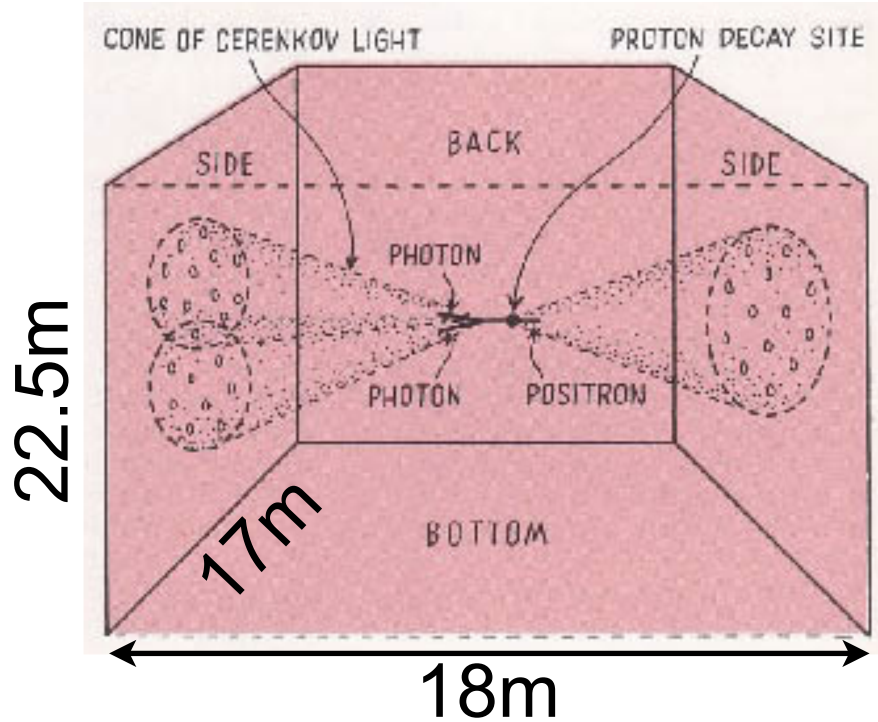
IMB (1979-1989)

Morton salt mine in Mentor, Ohio, USA (1570mwe)

(close to the Lake Erie)

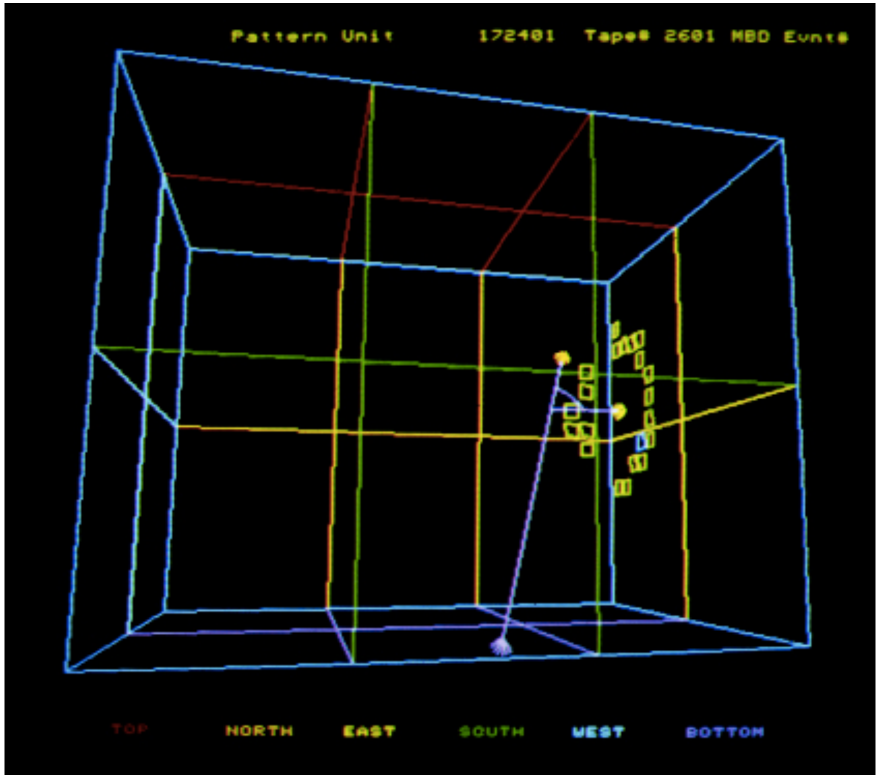
8 kton water (3.3kton F.V.) with 2048 8' PMTs





Review of the SN1987A in LMC

SN1987A in IMB



Realtime detector

- Date : 23 Feb. 1987
- Time : 07:35:41 (UT)
- 8 events in 6 sec.

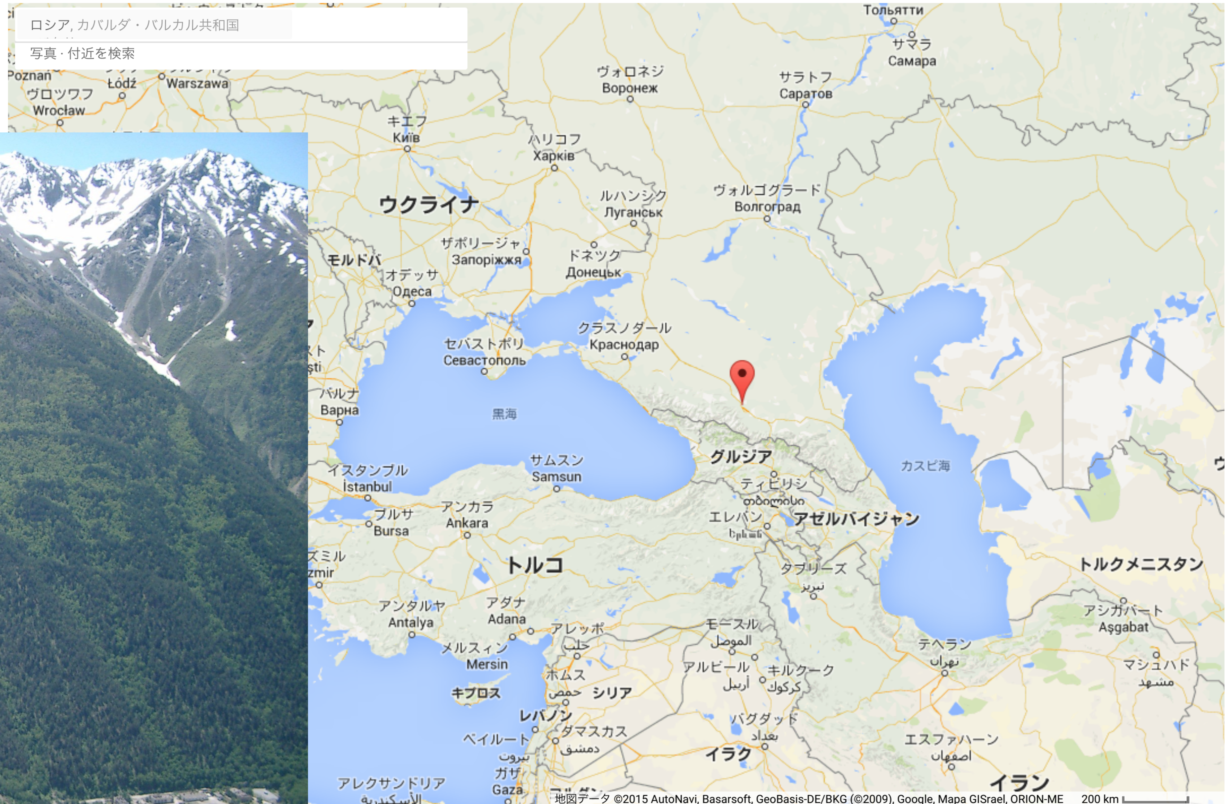
Energy is determined by the number of hit PMTs for which the residual time is within 50nsec

Trigger if 25 hits within 50 nsec ~ 35 MeV (@50% eff.)

Review of the SN1987A in LMC

Baksan underground scintillator telescope

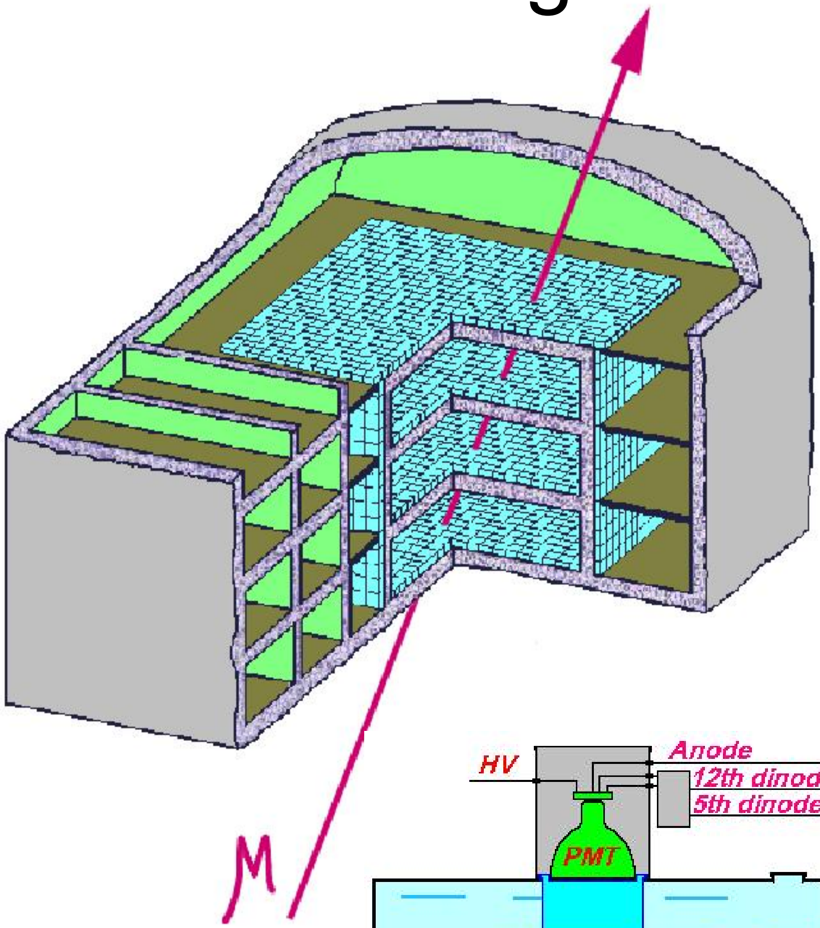
(2700mwe)

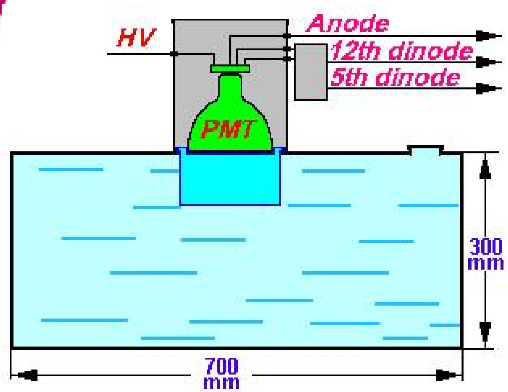


ロシア／コーカサス

Review of the SN1987A in LMC

Baksan underground scintillator telescope (1978~)





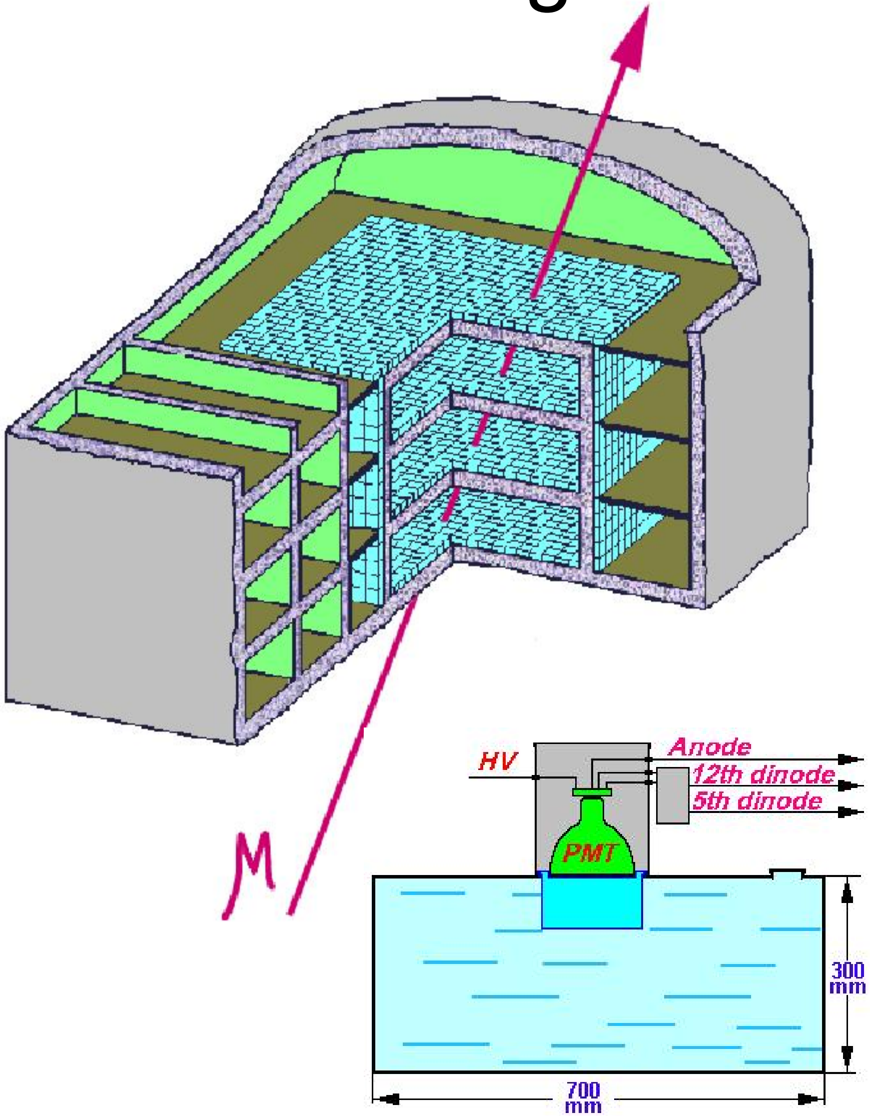
3156 tanks filled with liquid scintillator and one 15cm PMT

Total target mass : 330 ton

Detection eff. 10MeV @ 50%

Review of the SN1987A in LMC

Baksan underground scintillator telescope (1978~)



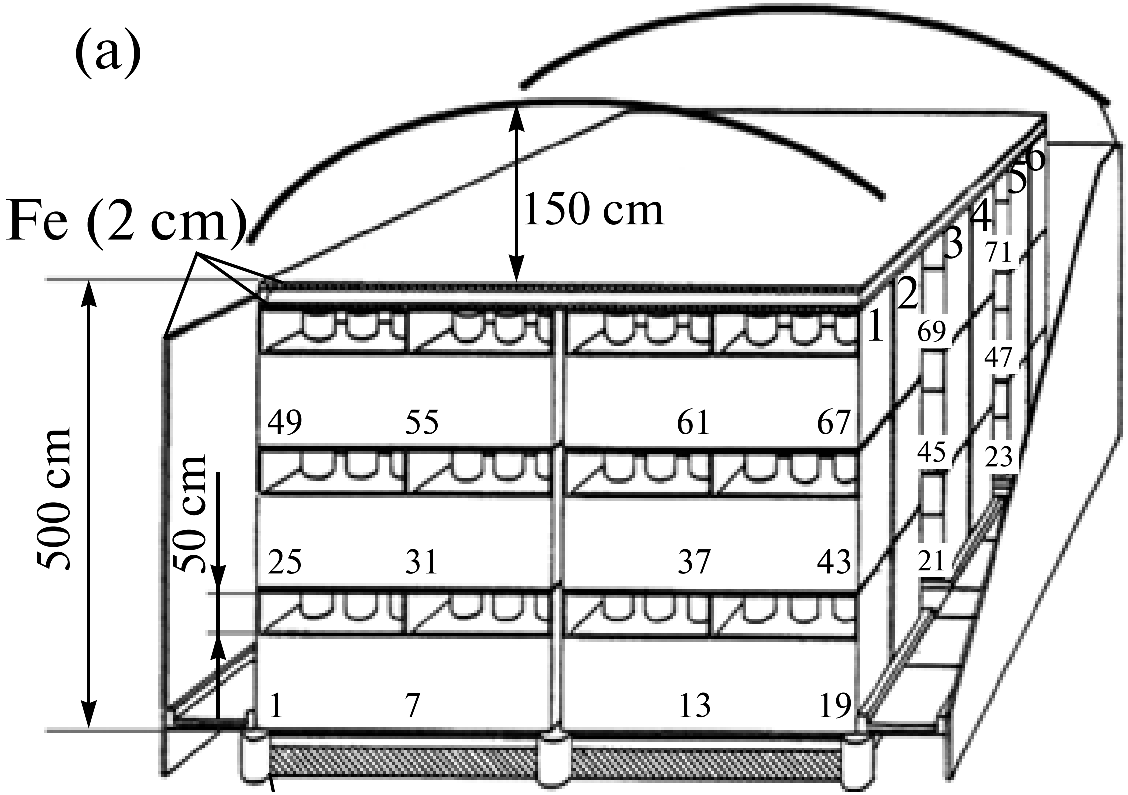
Realtime detector

- Date : 23 Feb. 1987
- Time : 07:36:11 (UT)
- 5 events in 9 sec.

Review of the SN1987A in LMC

Soviet-Italian LSD (Liquid Scintillation Detector) under Mont Blanc (5200mwq, 1985~1999)

72 scintillation counters (1.5m^3, 1.2ton) with three PMTs



Total target mass : 90 tons

Energy threshold > 5MeV

Realtime detector

- Date : 23 Feb. 1987
- Time : 02:52:32 (UT)
- 5 events in 7 sec.

  (7~11MeV,
  one has delayed coincidence)

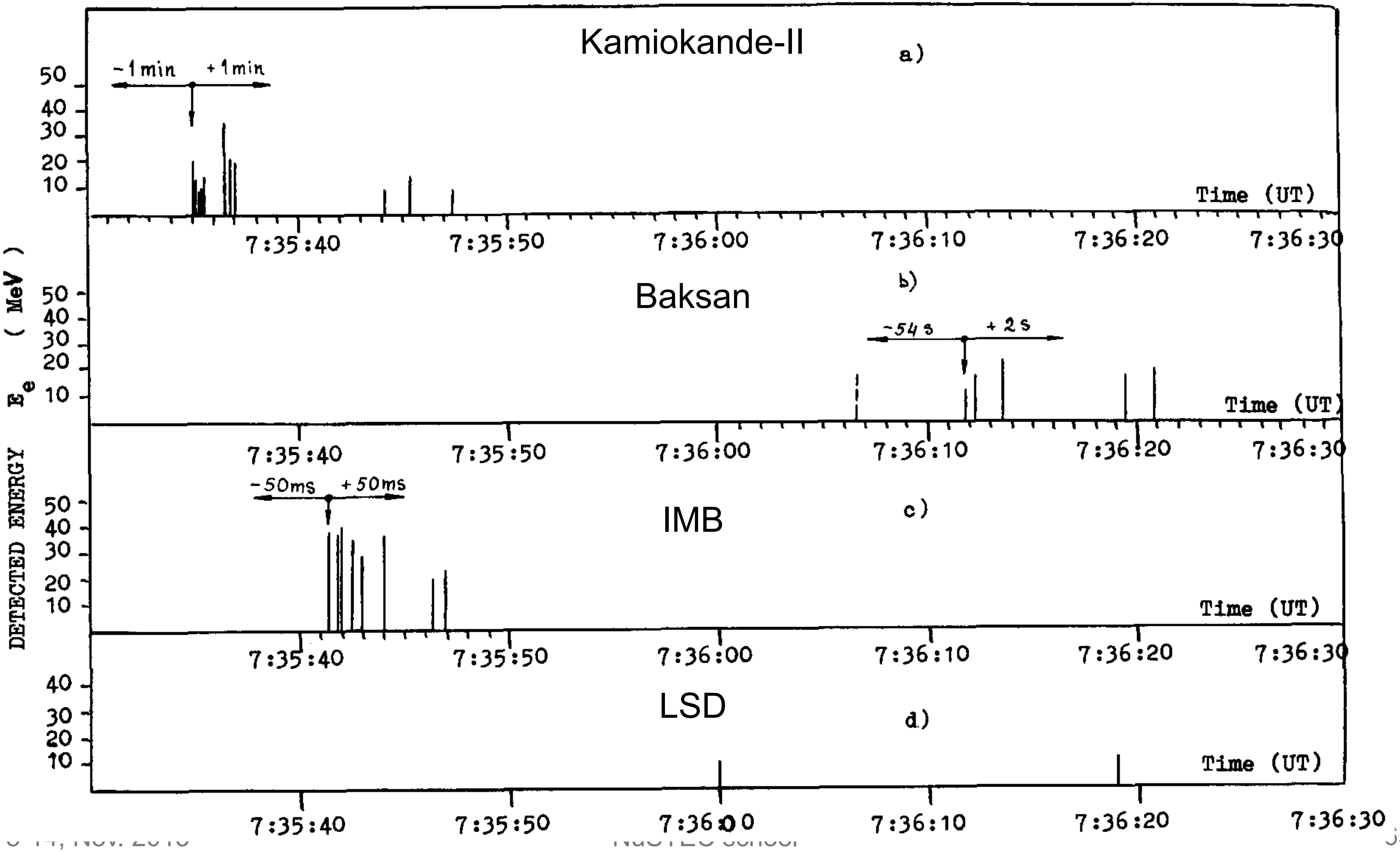
Review of the SN1987A in LMC

LSD vs Others ?

Annu. Rev. Astron. Astrophys. 1989, 27 : 629-700

Our reasons for this belief are as follows: (*a*) No neutrino events (which were clearly different from background) were observed in the much larger Kamiokande II and IMB detectors at the earlier time reported by the scintillator detectors [(55, 179) and especially (180)]. The number of free protons in the Mont Blanc telescope (0.08×10^{32}) is more than an order of magnitude less than in the Kamiokande II detector (1.4×10^{32} protons) and the IMB detector (4.5×10^{32} protons). (*b*) The expected number of events in the Mont Blanc detector for a standard stellar collapse (see Table 3) is only ~ 1 event, assuming a 100% detection efficiency (40). The satisfactory agreement between the a priori model predictions and the observations made with the Kamiokande II and IMB detectors strengthens this argument. (*c*) The reported events have energies that are close to the threshold energy for the detection, which is between 5 and 7 MeV [depending upon which counters were excited; see (2)]. The measured energies are (in MeV) 7, 8, 11, 7, and 9. Theoretically, one expects a greater spread in energy, since the absorption cross section increases with the square of the neutrino energy for charged-current absorption, and the numerical models predict an average antineutrino energy of more than 10 MeV. (*d*) No plausible astrophysical scenario has been suggested for two distinct neutrino bursts [cf. (126)]. (*e*) It is difficult to obtain a satisfactory light curve for the visual supernova if the earlier time indicated by the scintillation experiments is adopted as the time at which the star collapsed [cf. (22–25, 353) and Figure 1].

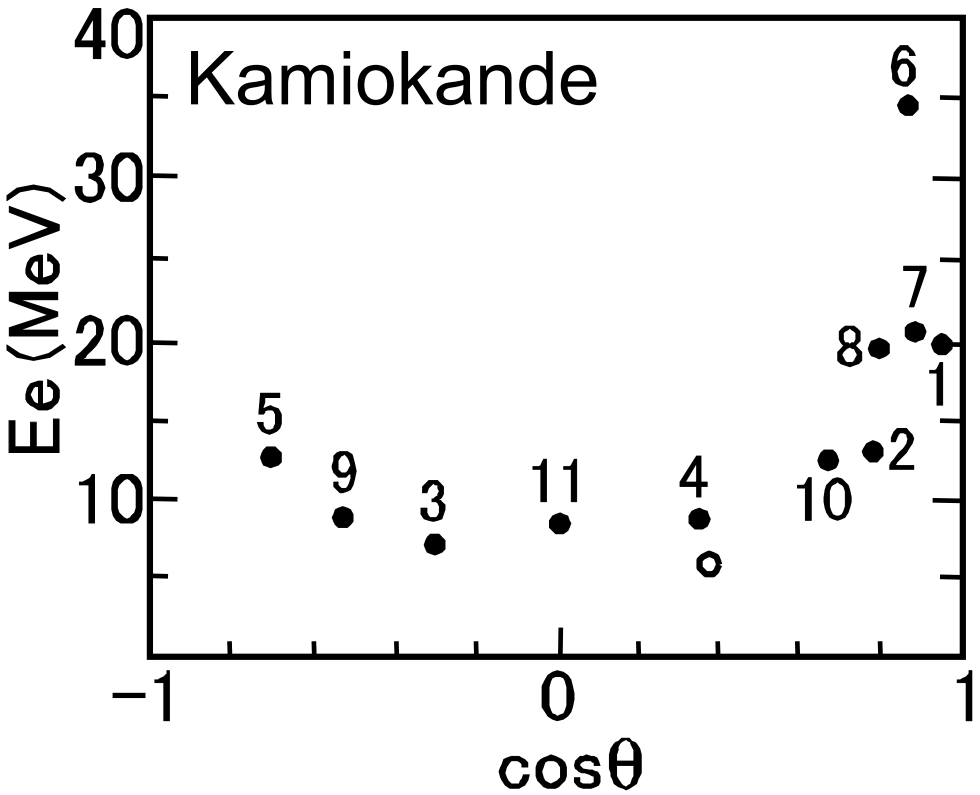
Review of the SN1987A in LMC

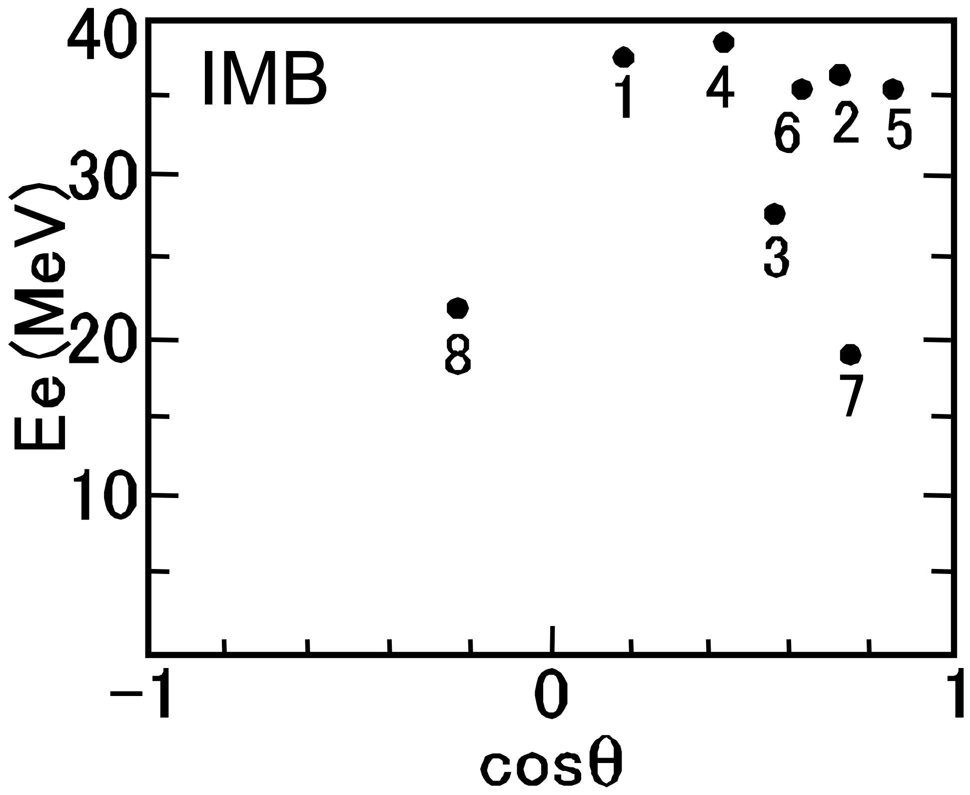


Review of the SN1987A in LMC

Angular distribution

ν_e event ?

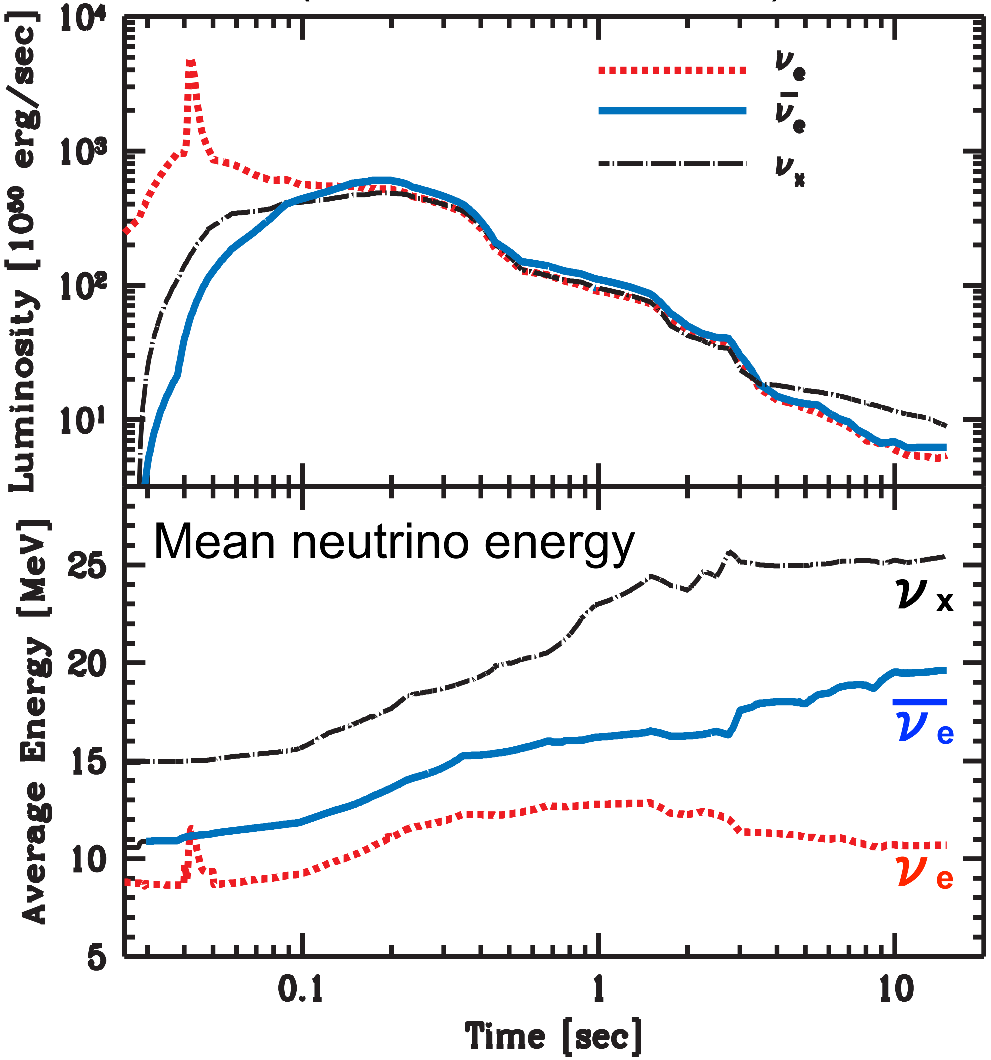




Hard to say anything...

Neutrinos from supernova burst

Expected time profile
(Livermore simulation)



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
- Now : O(kton), sensitive for galactic center
- Future : O(Mton), sensitive for ~Mpc(?)

✓ Low background rate ~MeV energy region
- Easy for underground detector

✓ Precise timing measurement

✓ Good energy resolution
- Energy spectrum measurement is crucial for all the physics

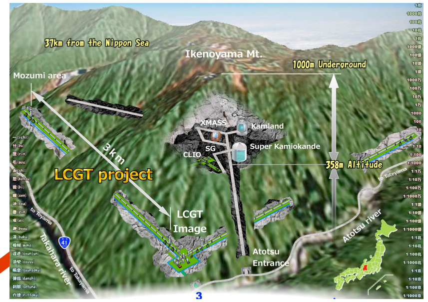
✓ Measurable for direction, if possible

✓ Neutrino flavor sensitivity
- Use specific neutrino interactions

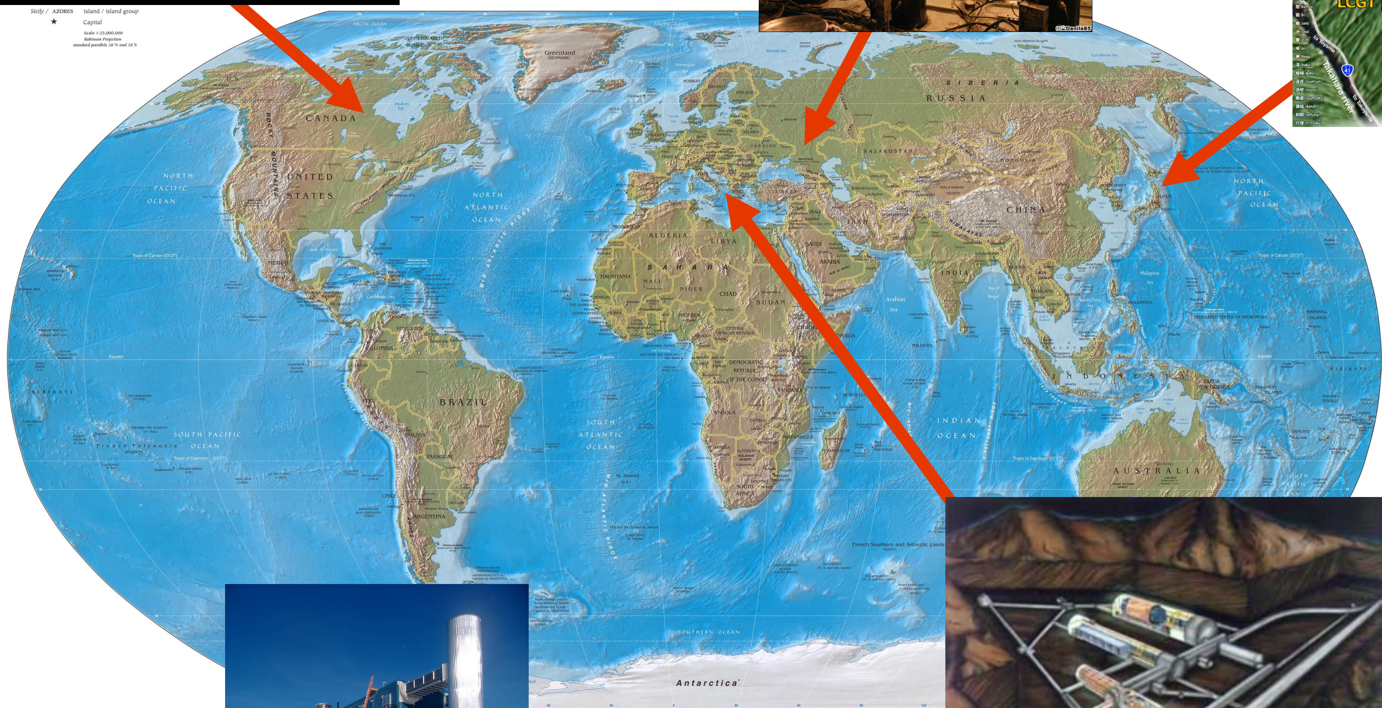
Underground facilities for SN ν

Sudbery (Canada)

Baksan (Russia)



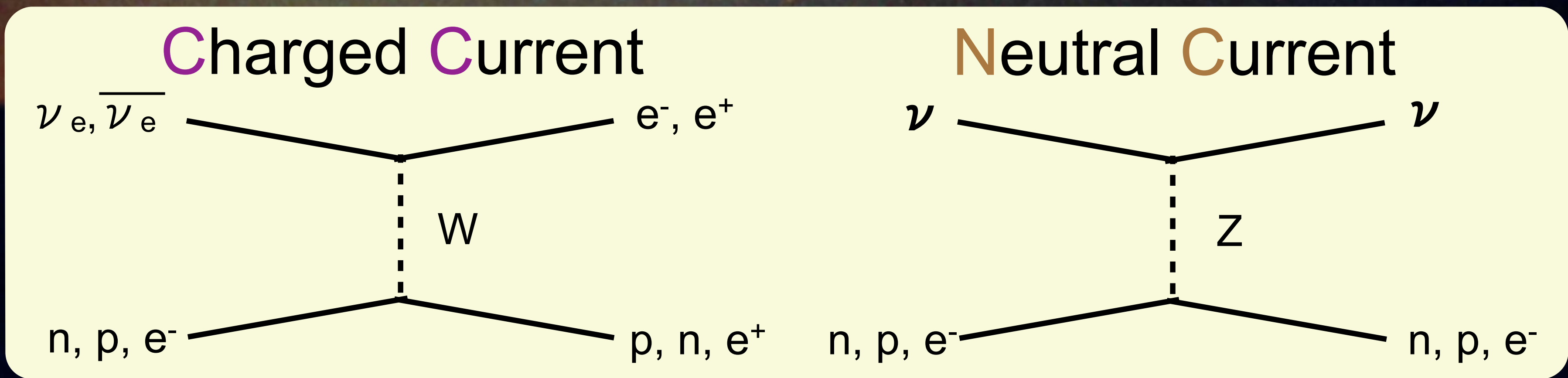
Kamioka (Japan)



GranSasso (Italy)

South Pole

Neutrino interaction for supernova neutrino detection



Neutrino interaction for SN ν

<u>Inverse beta decay</u>

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

- ✓ Dominates for detectors with lots of free proton
  - Detect positron signal in water, scintillator, etc.
- ✓ $\overline{\nu_e}$ sensitive
- ✓ Obtain the neutrino energy from the positron energy
  - $E_e \sim E_\nu - (m_n - m_p)$, $E_\nu > 1.86$MeV
- ✓ Well known cross section
- ✓ Poor directionality
- ✓ Neutron tagging using delayed coincidence
  - $n + p \rightarrow d + \gamma$

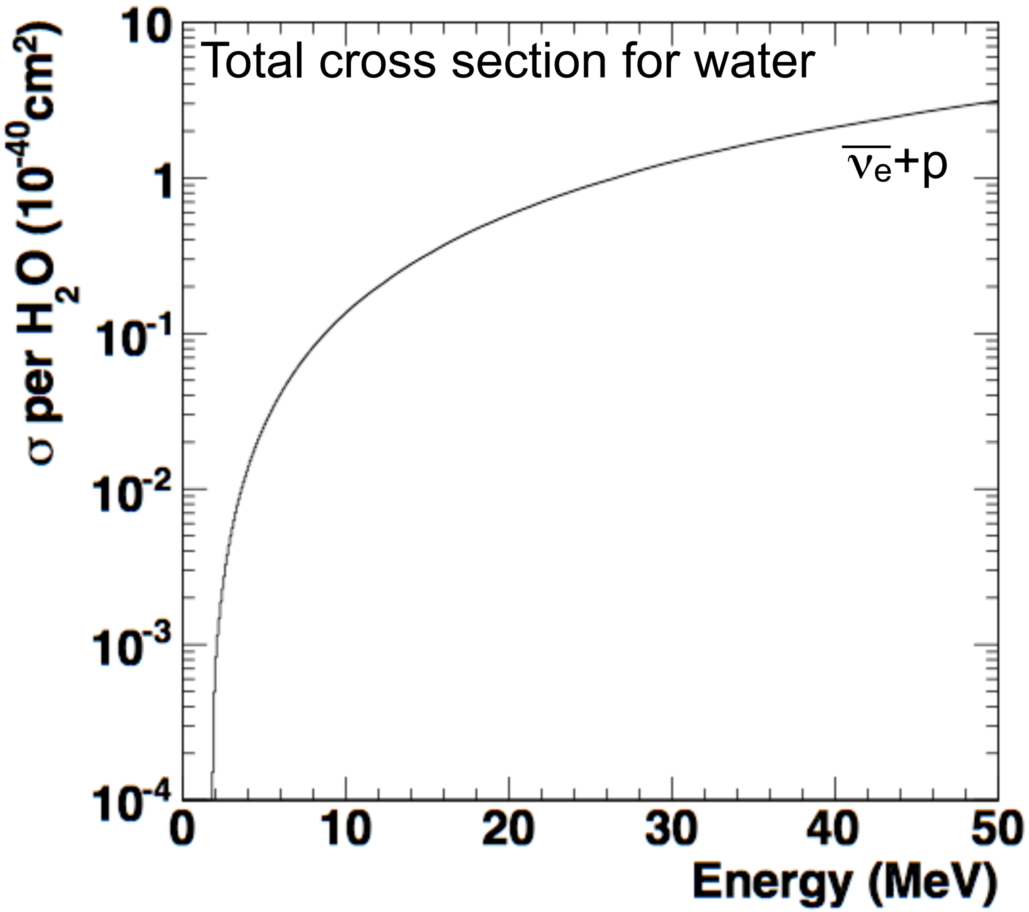
Neutrino interaction for SN ν

Inverse beta decay

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

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

- ✓ Dominates for detectors w
  - Detect positron signal in w
- ✓ $\overline{\nu}_e$ sensitive
- ✓ Obtain the neutrino energ
  - $E_e \sim E_\nu - (m_n - m_p)$, $E_\nu > 1.$
- ✓ Well known cross section
- ✓ Poor directionality
- ✓ Neutron tagging using de
  - $n + p \rightarrow d + \gamma$



Neutrino interaction for SN ν

Inverse beta decay

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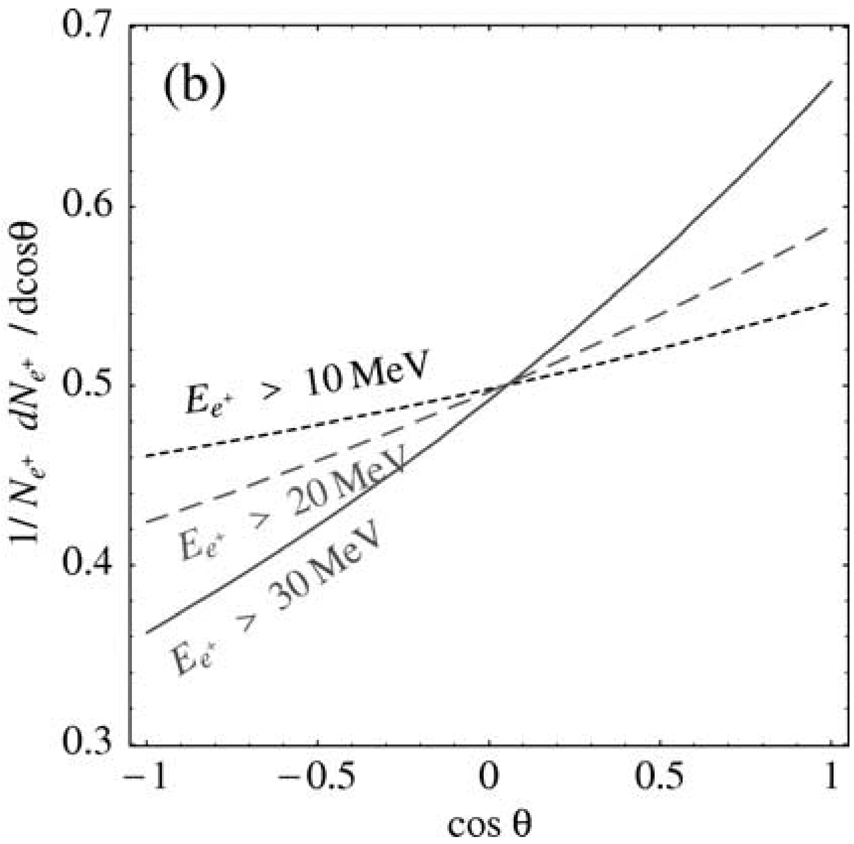
Strumia, Vissani
Phys. Lett. B564 (2003) 42



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Neutrino interaction for SN ν

Inverse beta decay

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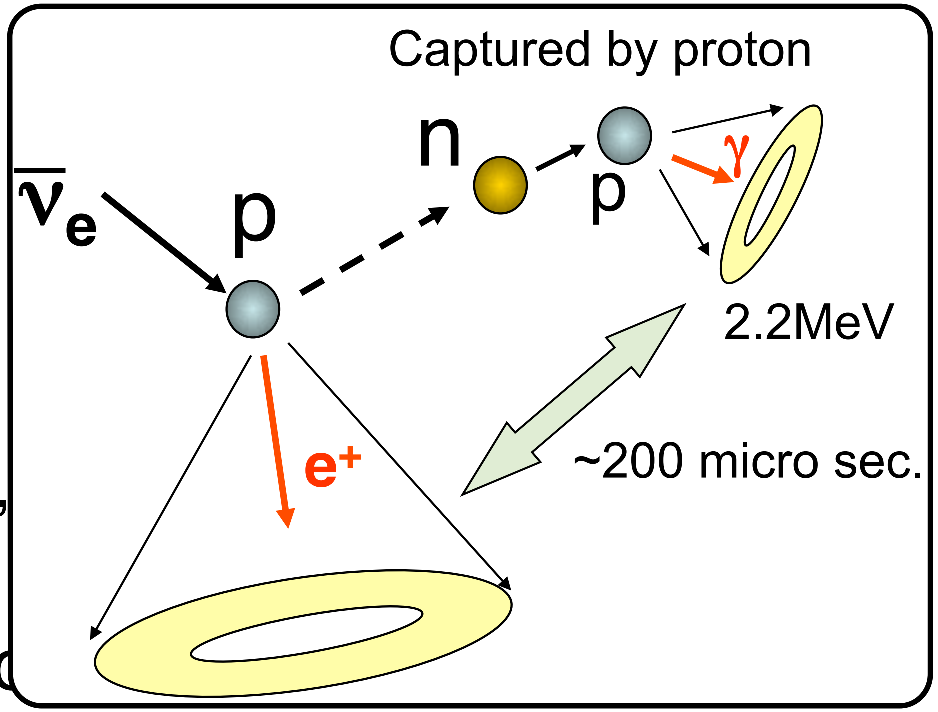

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  - $n + p \rightarrow d + \gamma$

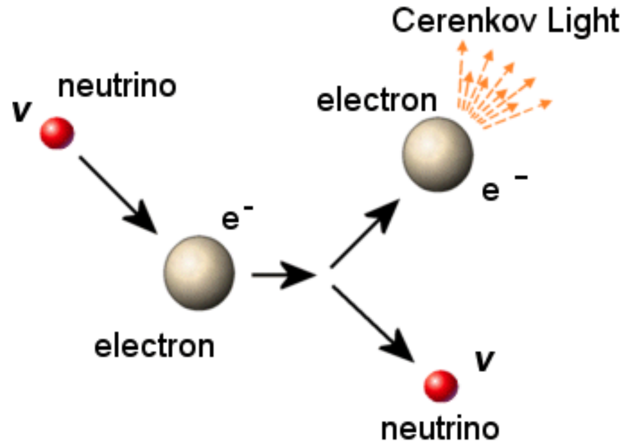
Possible to enhance this signal if Gd loaded
(→ M.Ikeda's presentation)

Neutrino interaction for SN ν

Elastic scattering

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

(Both Charged Current and Neutral Current interaction)



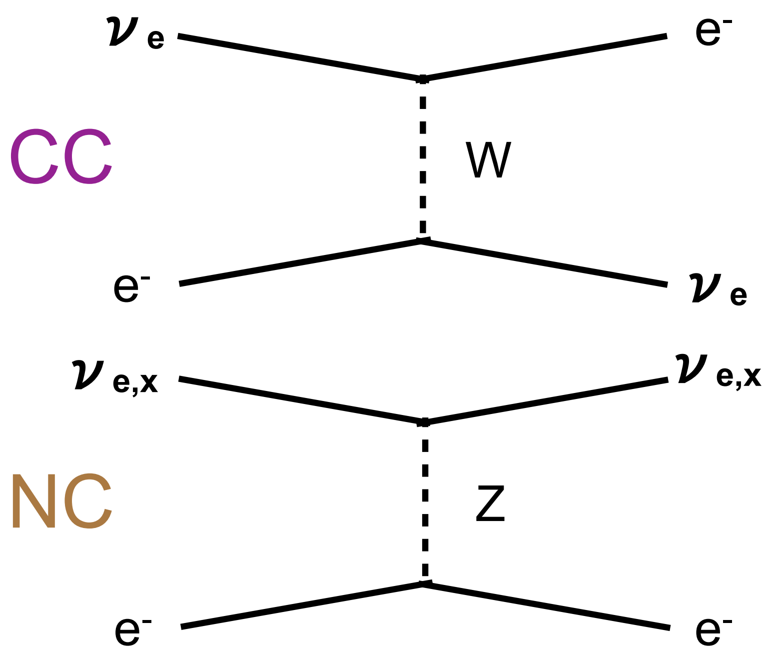
✓ All neutrinos are sensitive

✓ 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



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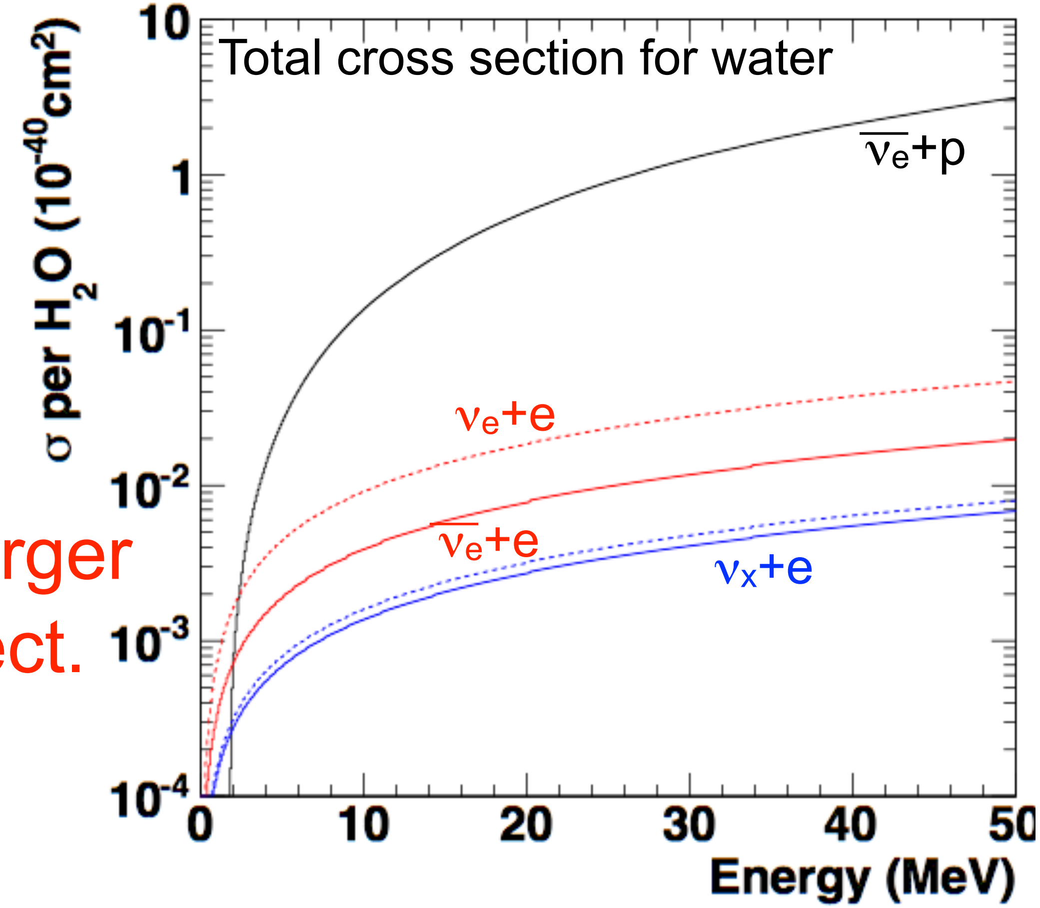

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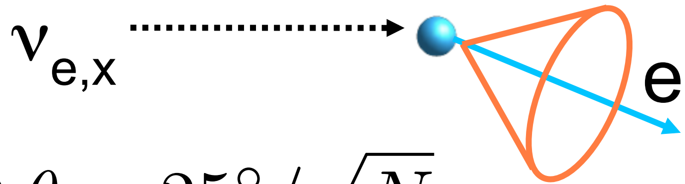
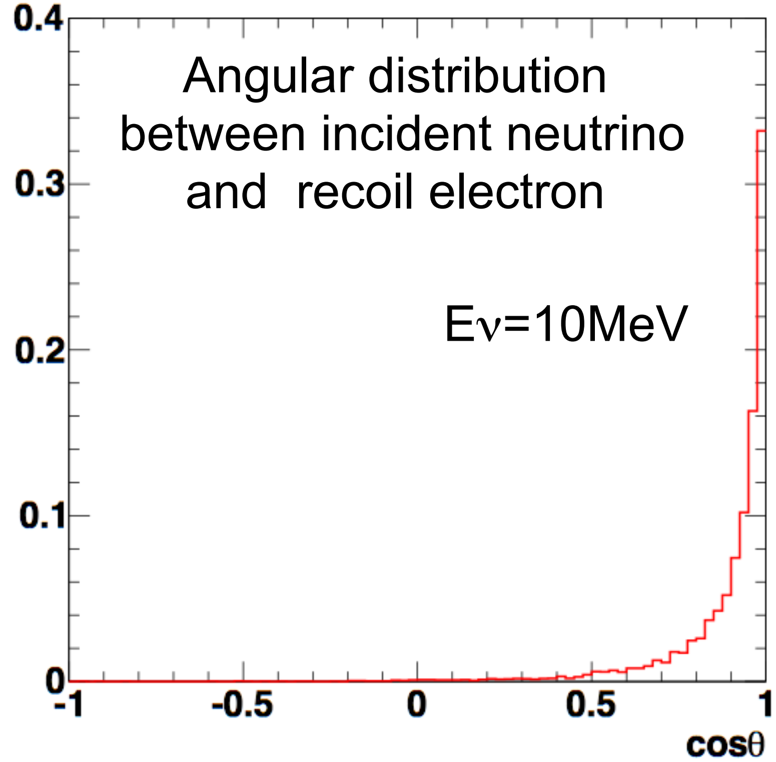
Water Cherenkov



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



Neutrino interaction for SN ν

Elastic scattering

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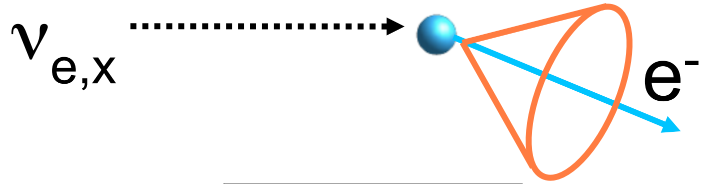
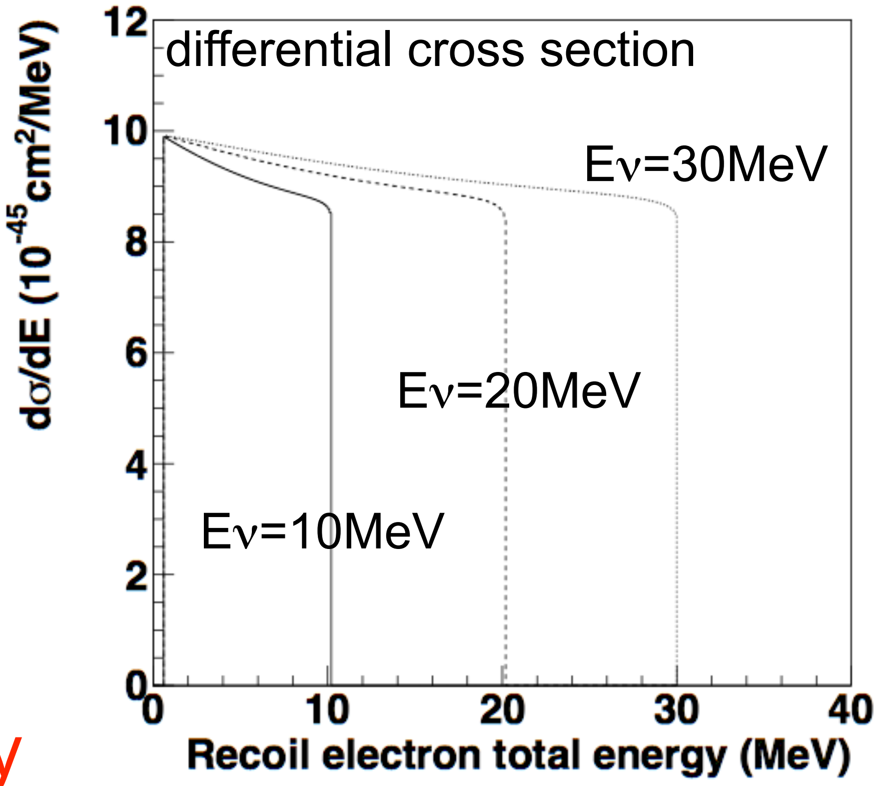
Water Cherenkov



$$\Delta E \sim 15\%/\sqrt{E/10MeV}$$



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✓ Measurable for only recoil electron energy, not neutrino energy

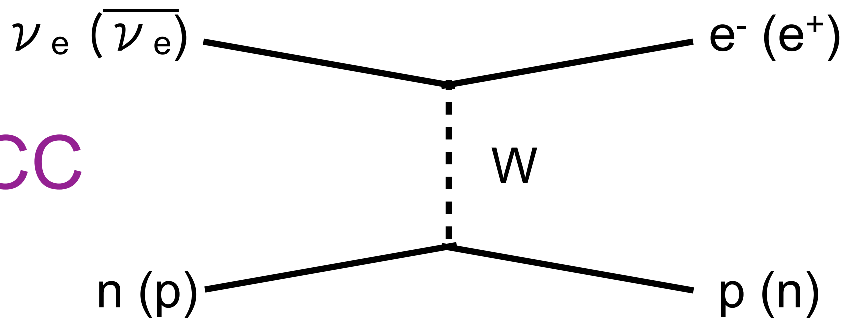
Neutrino interaction for SN ν

CC interactions on nuclei

$\nu_e + n \rightarrow p + e^-$: $\nu_e + (N,Z) \rightarrow (N-1, Z+1) + e^-$

$\overline{\nu}_e + p \rightarrow n + e^+$: $\overline{\nu}_e + (N,Z) \rightarrow (N+1, Z-1) + e^+$

CC



✓Observables:

- charged lepton $e^{+/-}$
- possibly ejected nucleons
- possibly nuclear γ's

(for example)

oxygen in water

$\nu_e + {}^{16,18}O \rightarrow {}^{16,18}F + e^-$

$\overline{\nu}_e + {}^{16}O \rightarrow {}^{16}N + e^+$

carbon in scintillator

$\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$

$\overline{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+$

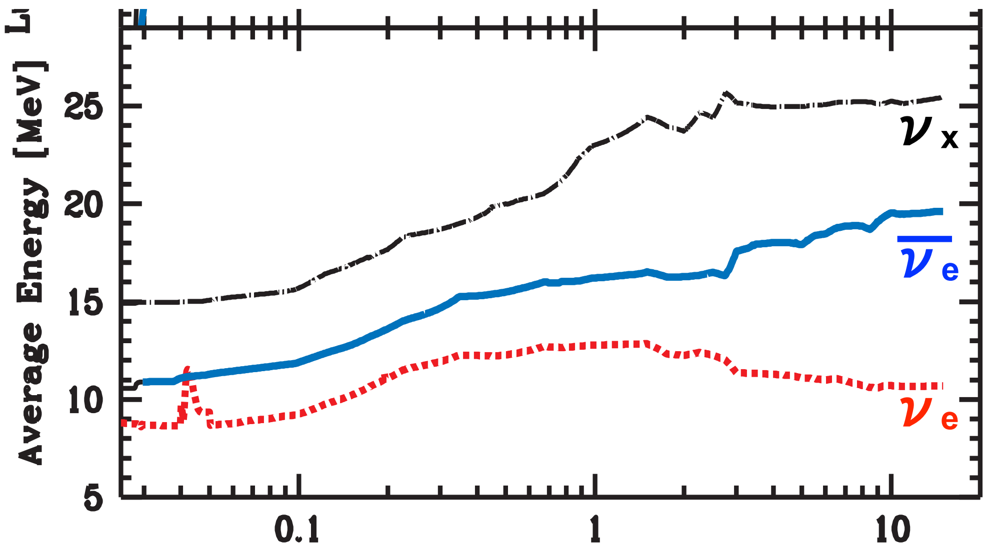
Neutrino interaction for SN ν

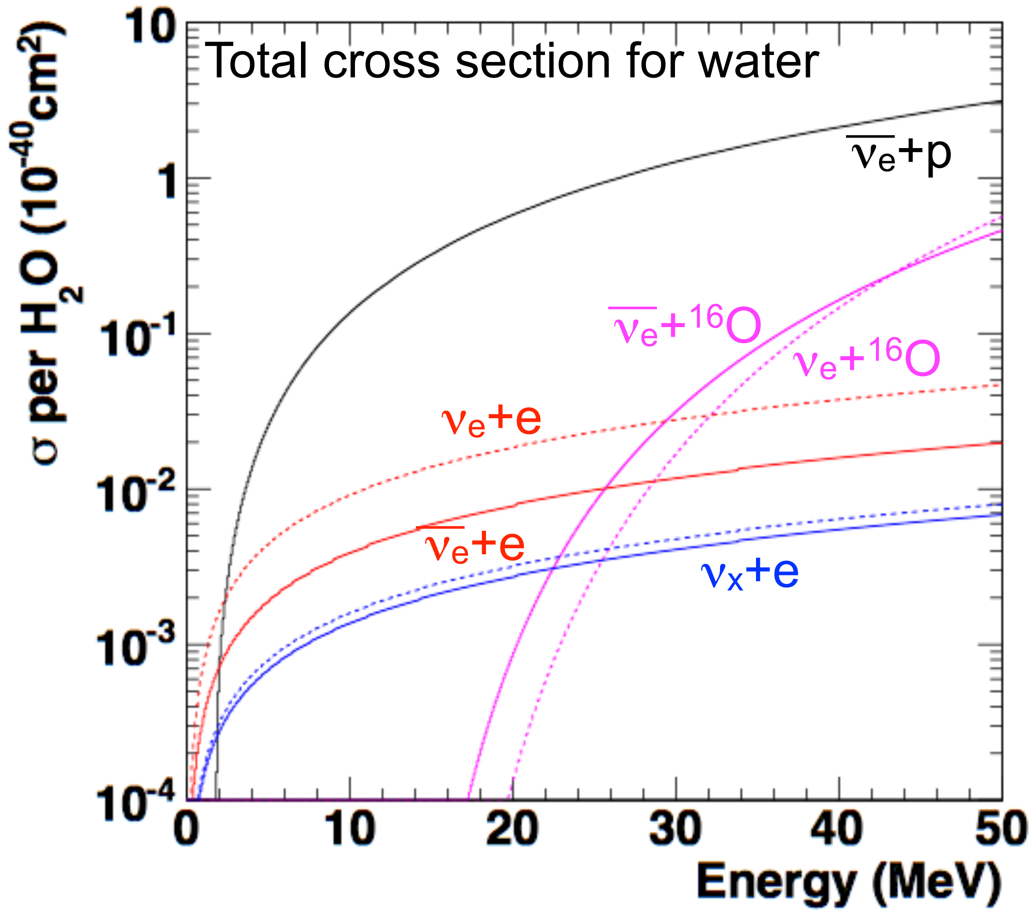
CC interactions on nuclei

✓ Small cross section by bound nucleons

✓ Also has large uncertainties

- Nuclear physics is important





This signal is small portion, but may access neutrino oscillation effect

Neutrino interaction for SN ν

NC interactions on nuclei

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

$\nu + (N,Z) \rightarrow (N,Z) + \nu$
$\nu + (N,Z) \rightarrow (N-1,Z) + n + \nu$
$\nu + (N,Z) \rightarrow (N,Z-1) + p + \nu$

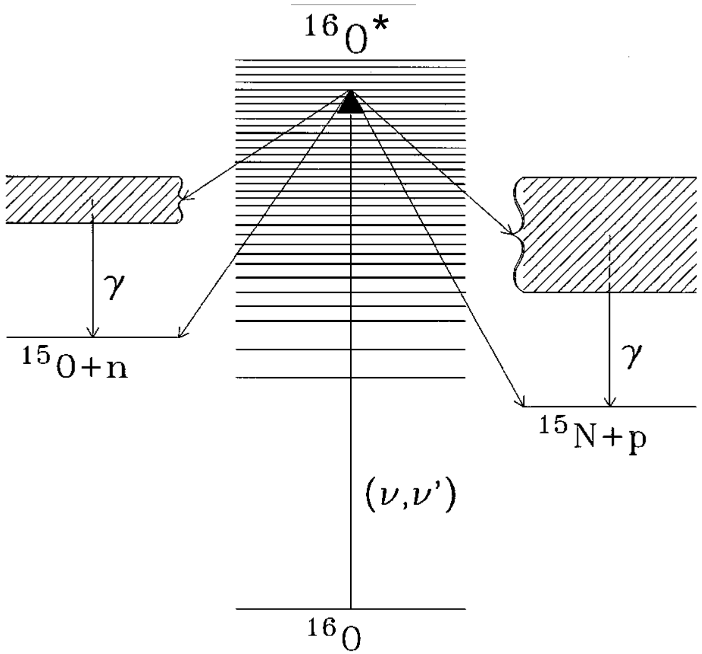
✓ Important to probe ν_μ, ν_τ flux
✓ Observables:
- nuclear emission (p,n)
- γ's by giant resonance

✓Need nuclear physics info.

carbon in scintillator

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

giant resonance



oxygen in water

$\nu + {}^{16}O \rightarrow \nu + {}^{16}O^*$
$\hookrightarrow {}^{16}O + \gamma$
($E\nu$ < ~150MeV)

Neutrino interaction for SN ν

NC interactions on nuclei

$\nu + (N,Z) \rightarrow (N,Z) + \nu$
$\nu + (N,Z) \rightarrow (N-1,Z) + n + \nu$
$\nu + (N,Z) \rightarrow (N,Z-1) + p + \nu$

✓ Important to probe ν_μ, ν_τ flux

✓ Observables:

- nuclear emission (p,n)
- γ's by giant resonance

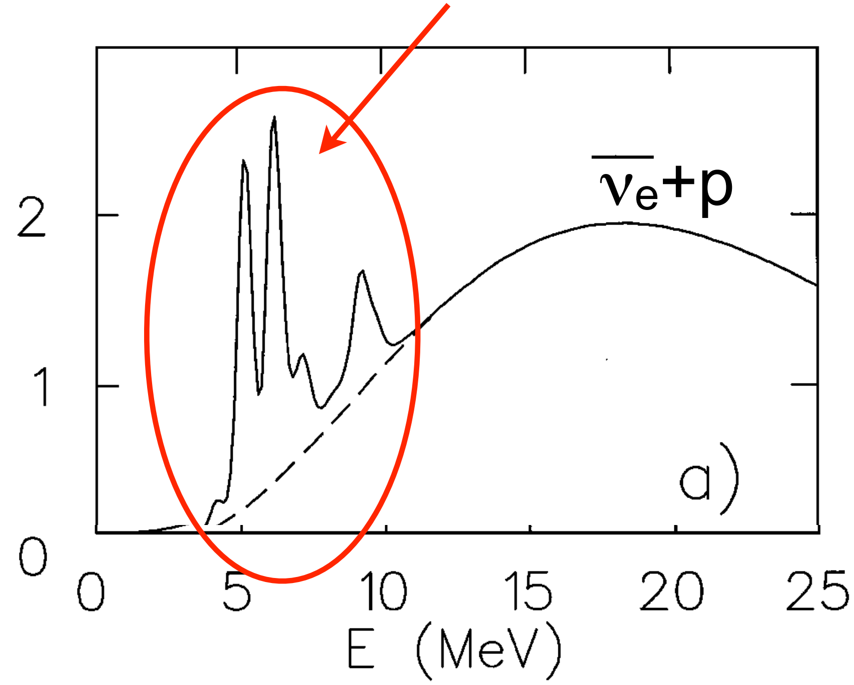
✓ Need nuclear physics info.

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

γ by giant resonance

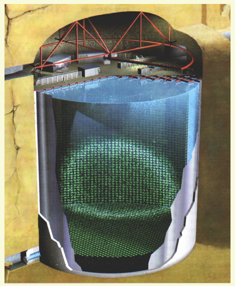


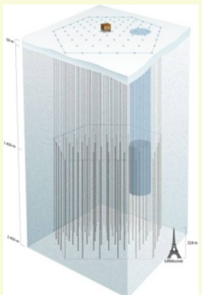
oxygen in water

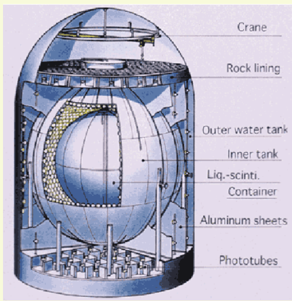
$\nu + {}^{16}O \rightarrow \nu + {}^{16}O^*$
$\hookrightarrow {}^{16}O + \gamma$
($E\nu$ < ~150MeV)

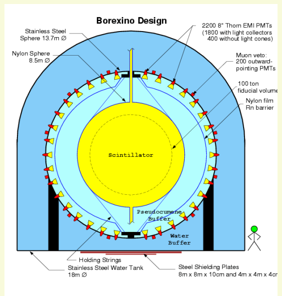
Supernova neutrino detectors

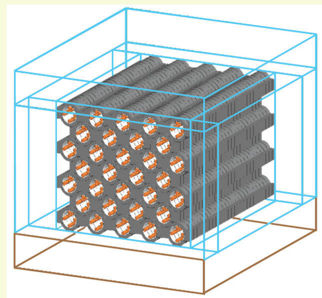
Water Cherenkov / Liquid scintillator / Others





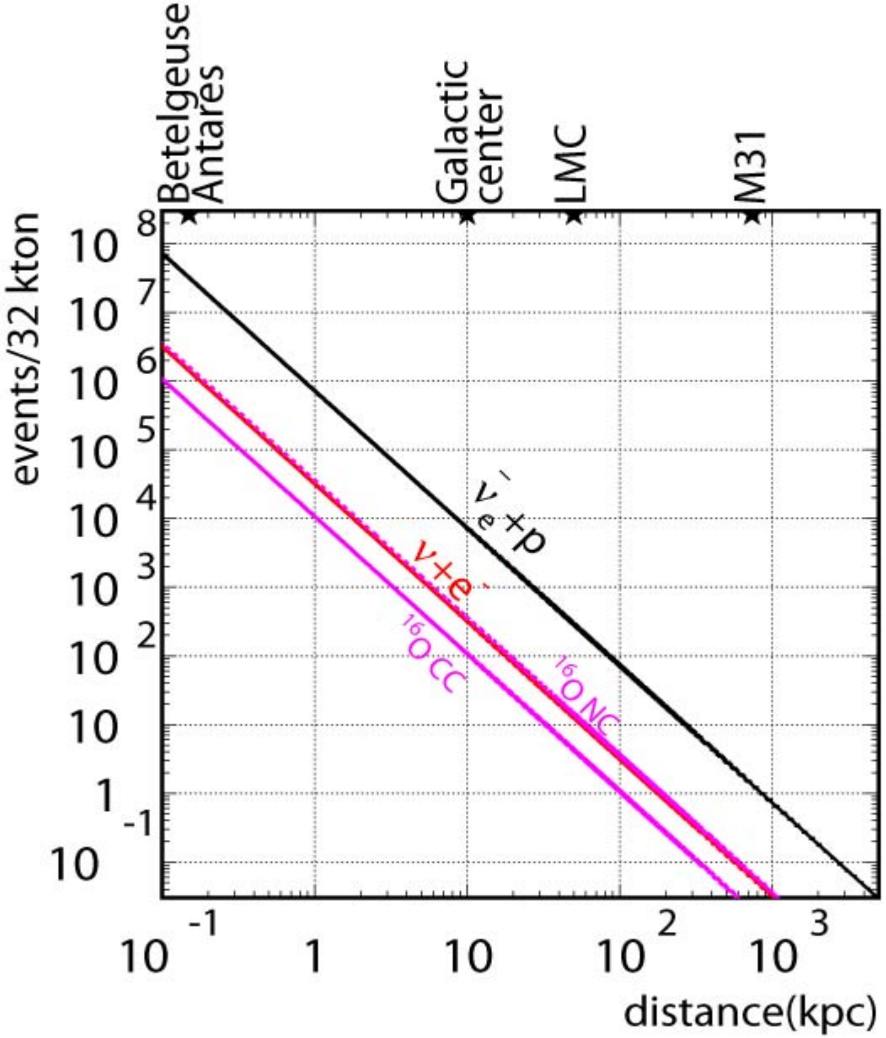




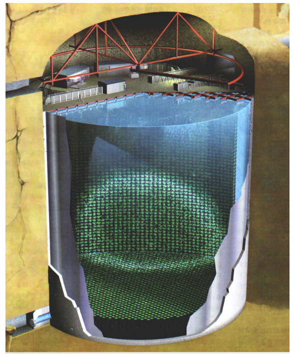


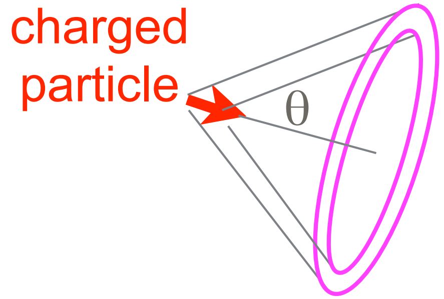
Current SN ν detectors

Super-Kamiokande



50kton Water Cherenkov detector





<u>Expected number of event</u>

~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

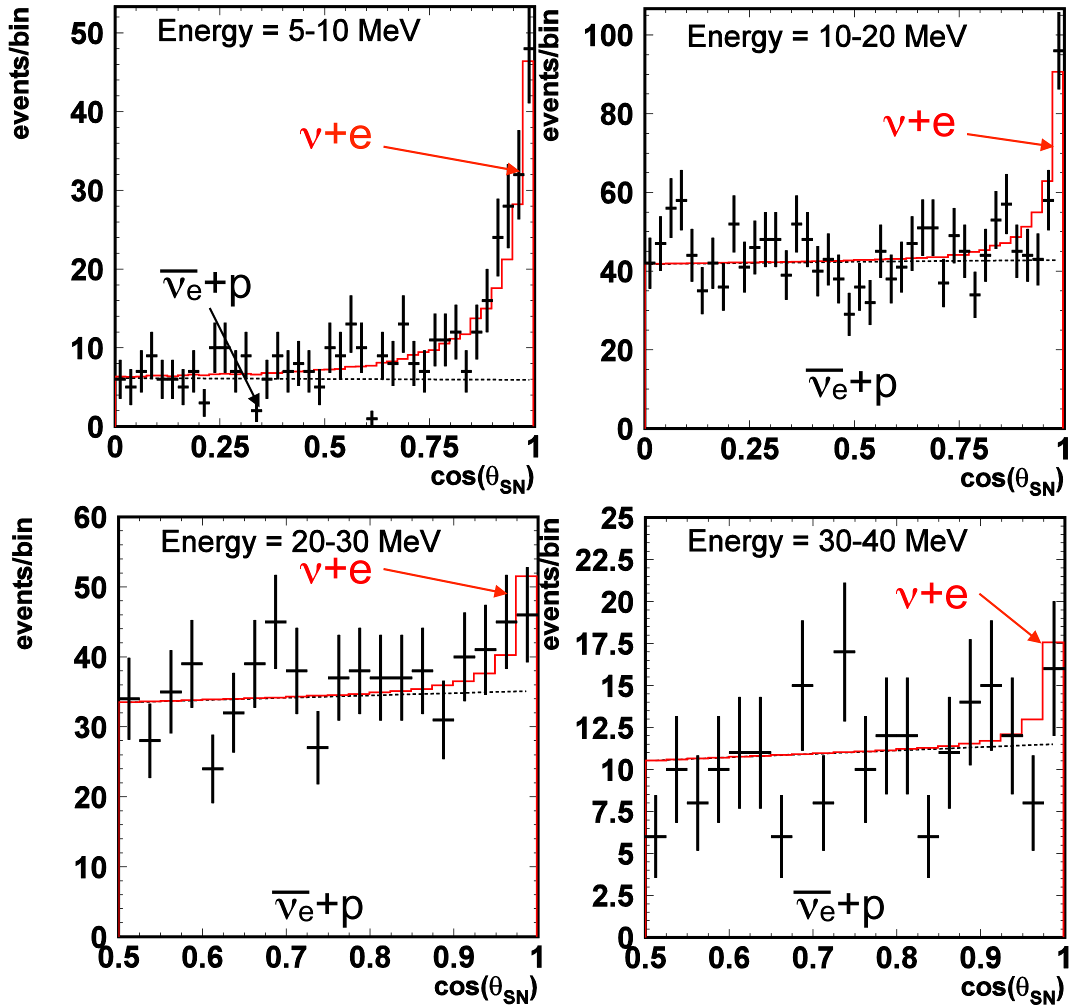
Livermore simulation
Totani, Sato, Dalhed, Wilson, ApJ. 496 (1998) 216

Current SN ν detectors

Super-Kamiokande

✓ ν-e elastic scattering has good directionality.
✓ Direction of supernova can be determined with an accuracy of 4~5 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. (later)

Simulation of angular distribution

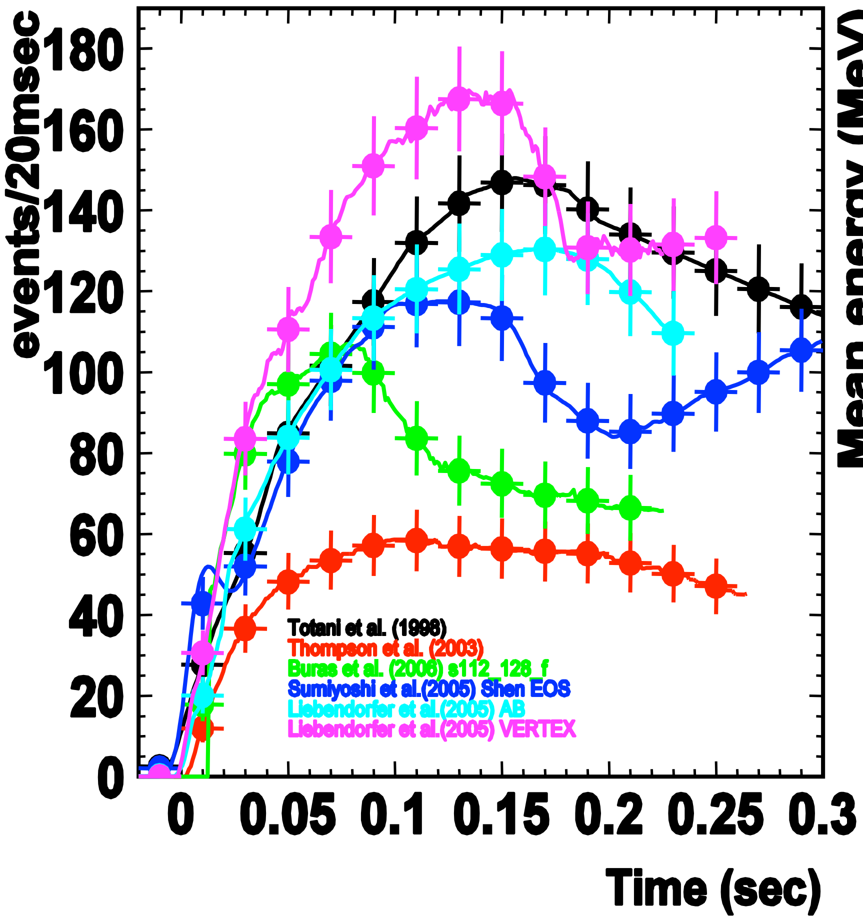


Current SN ν detectors

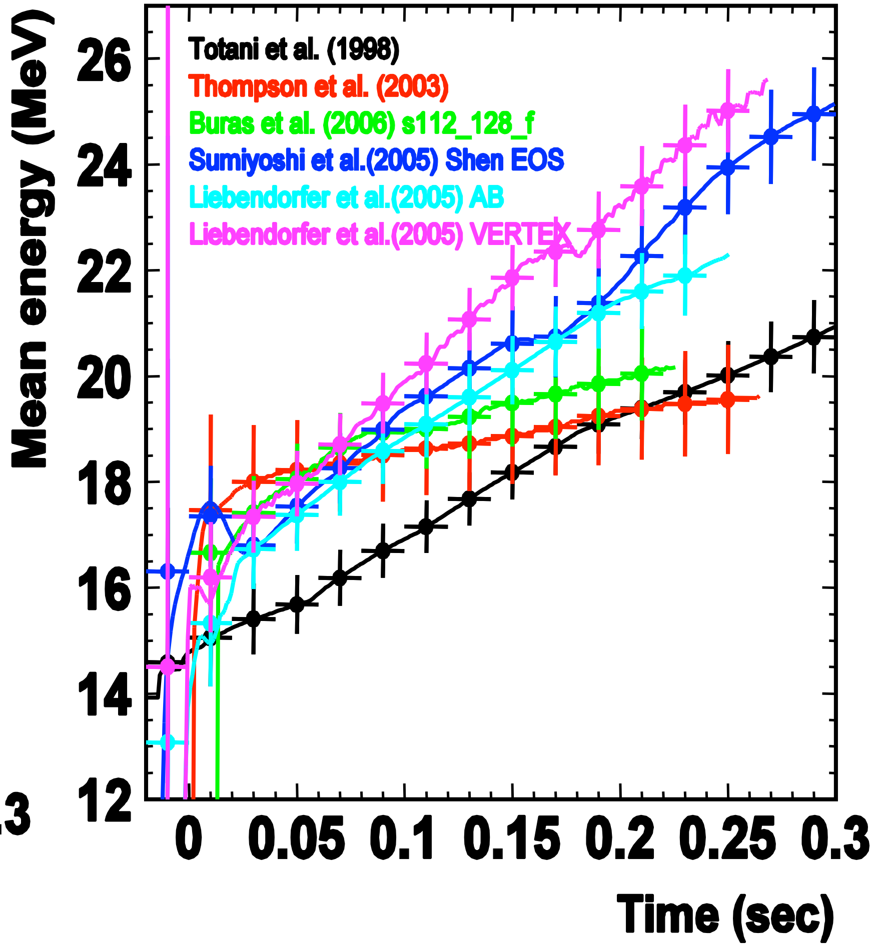
Super-Kamiokande

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

Time variation of event rate



Time variation of mean energy

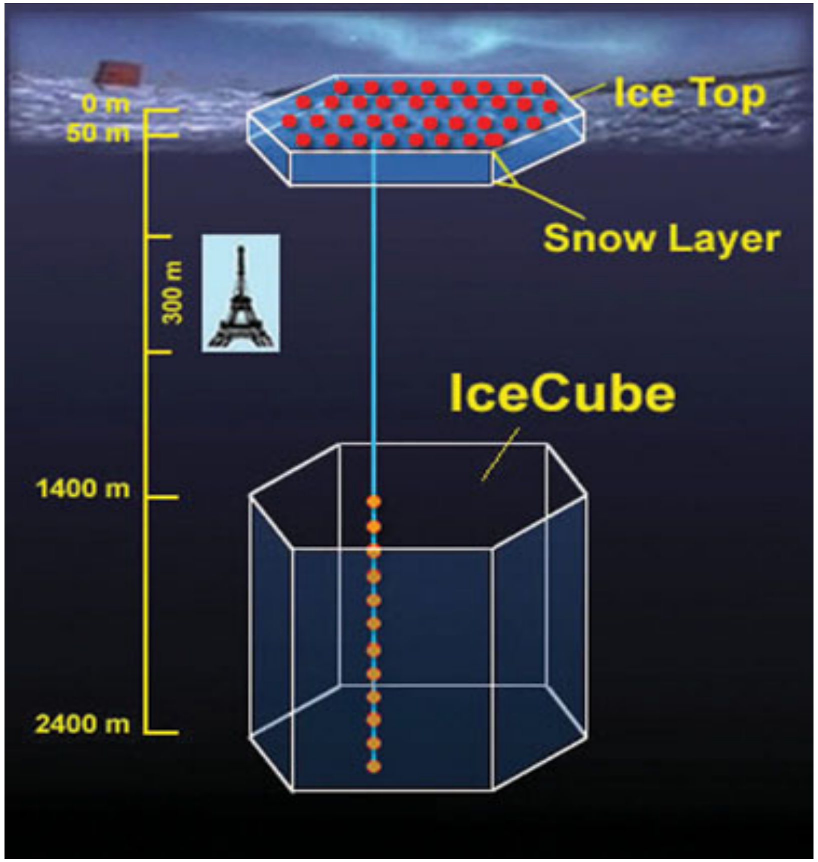


Current SN ν detectors

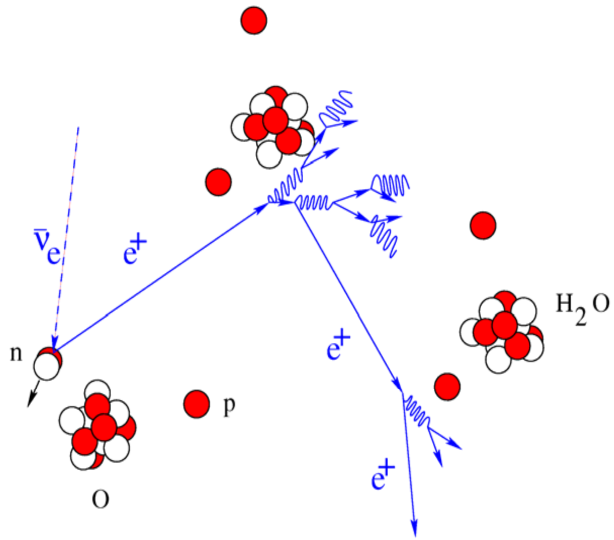
<u>IceCUBE</u>

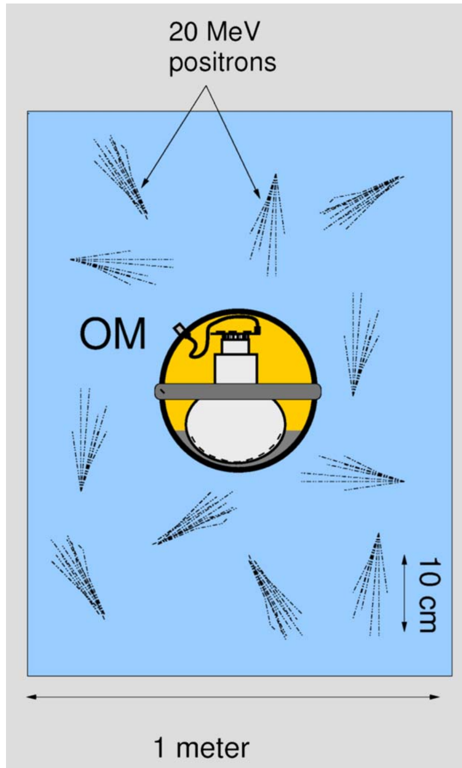
~km long string Water Cherenkov detector at the South Pole

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.





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

Current SN ν detectors

IceCUBE

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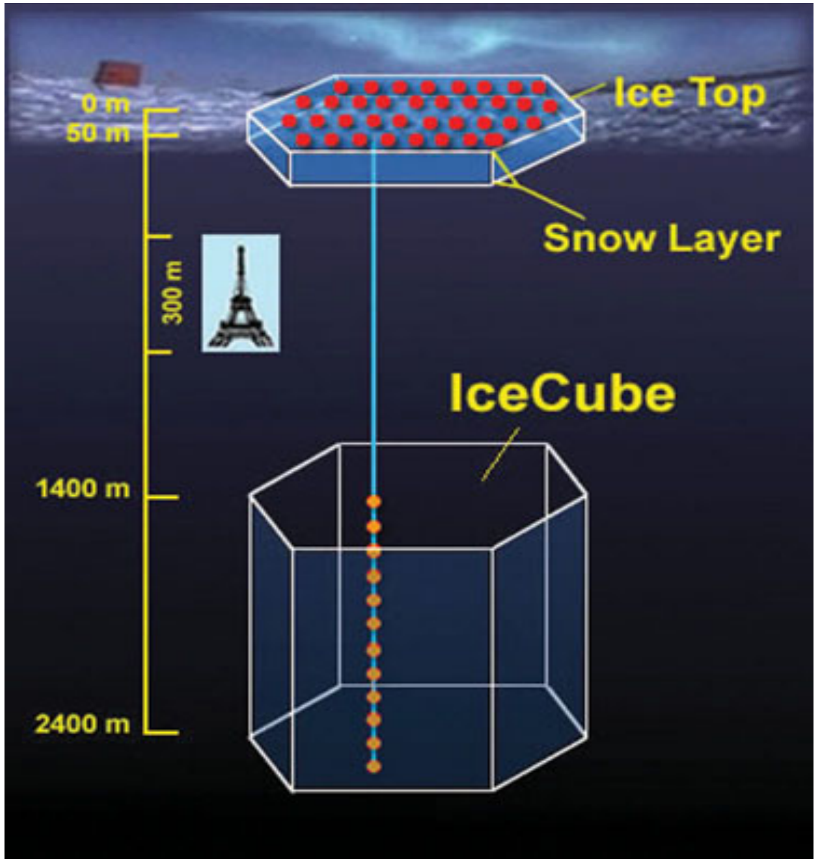
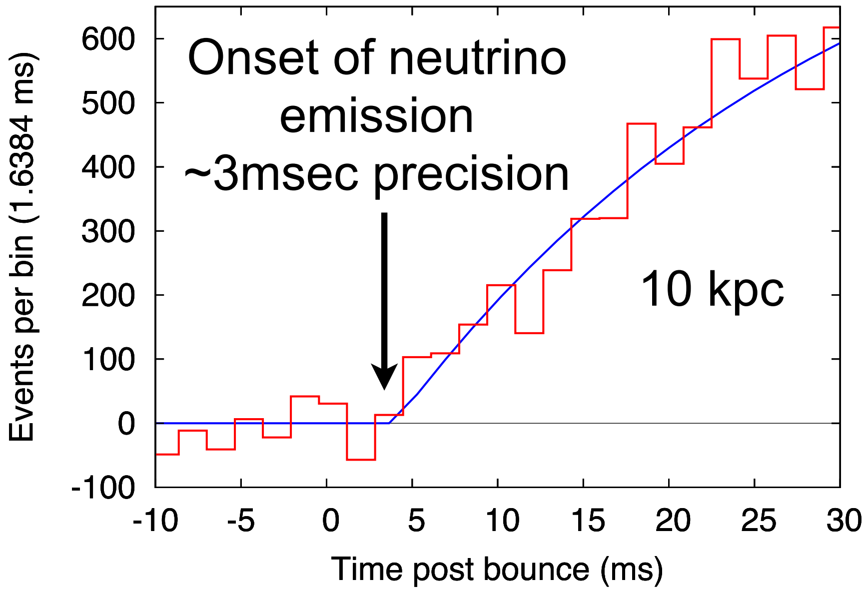
Giga-ton detector



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

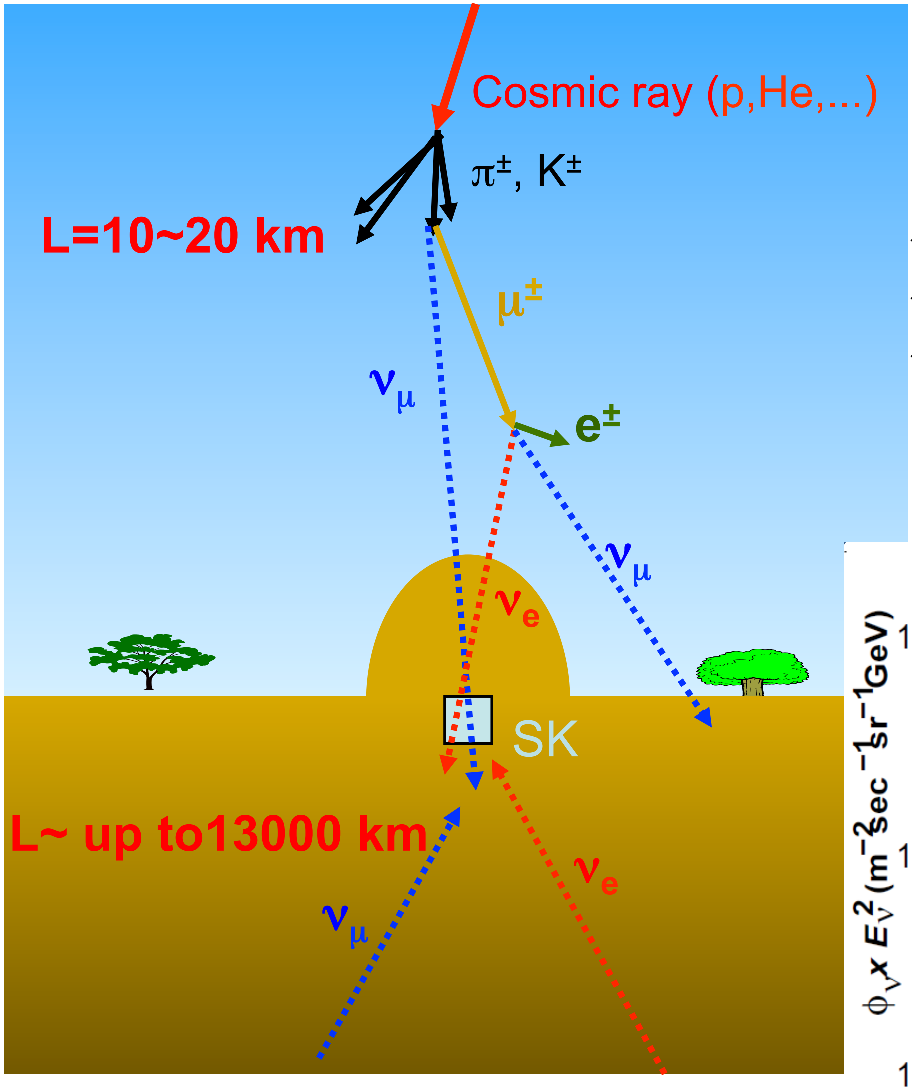
✓ Cannot tag flavor, or other interaction info., overall rate and fine time structure.



Halzen, Raffelt
arXiv : 0908.2317

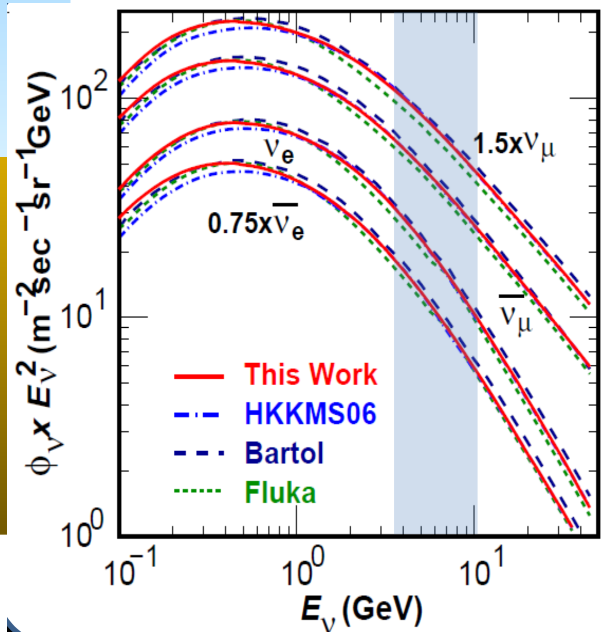
Atmospheric neutrino

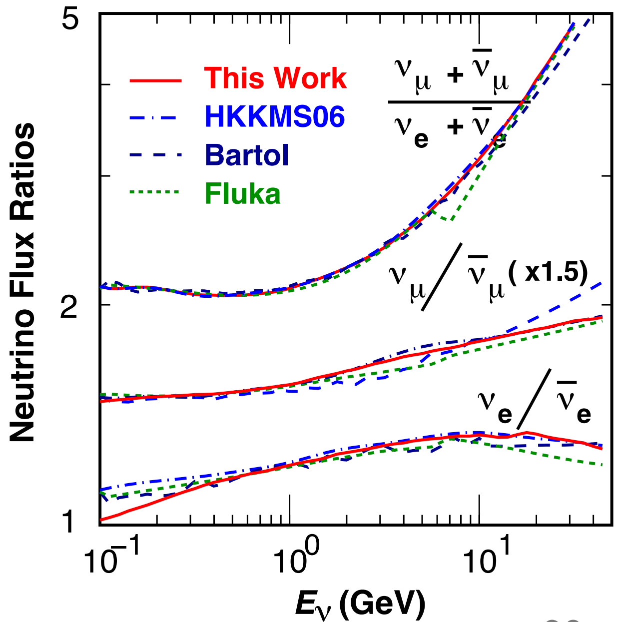
Atmospheric neutrino



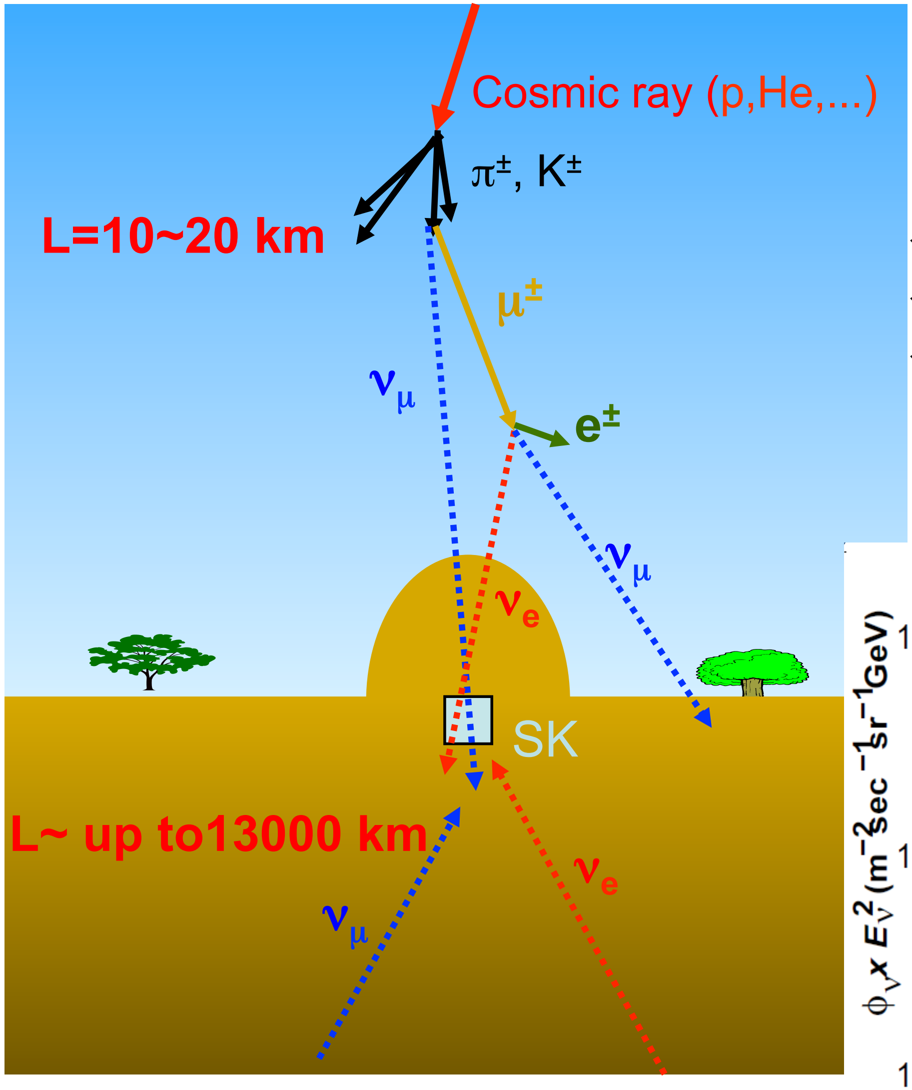
Cosmic rays strike air nuclei and the decay of the out-going hadrons gives neutrinos.

✓Primary cosmic rays isotropic about Earth
✓ν's travel 10-10,000km before detection
✓Both neutrinos and antineutrinos in the flux
- ~30% of final analysis samples are antineutrinos





Atmospheric neutrino



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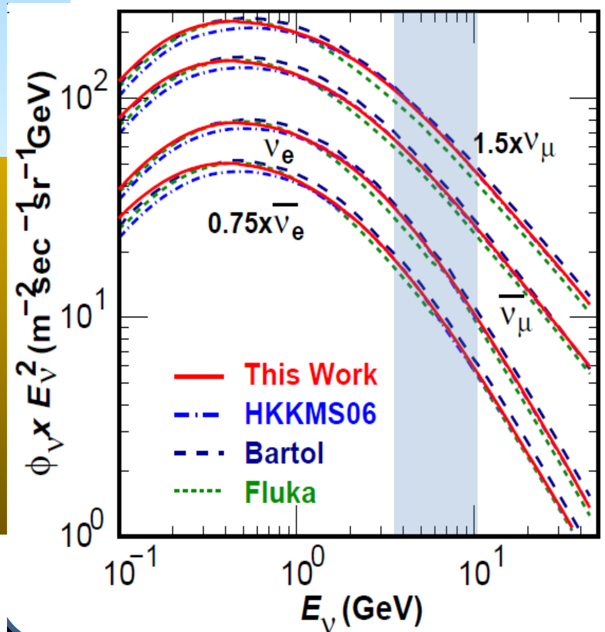
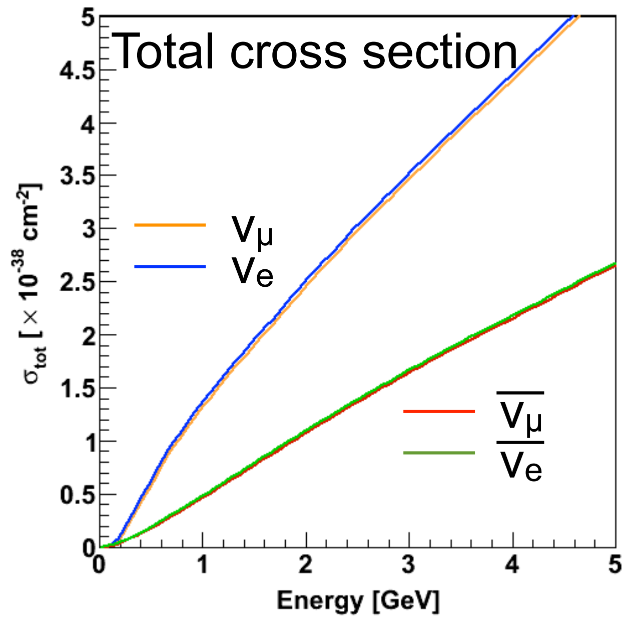




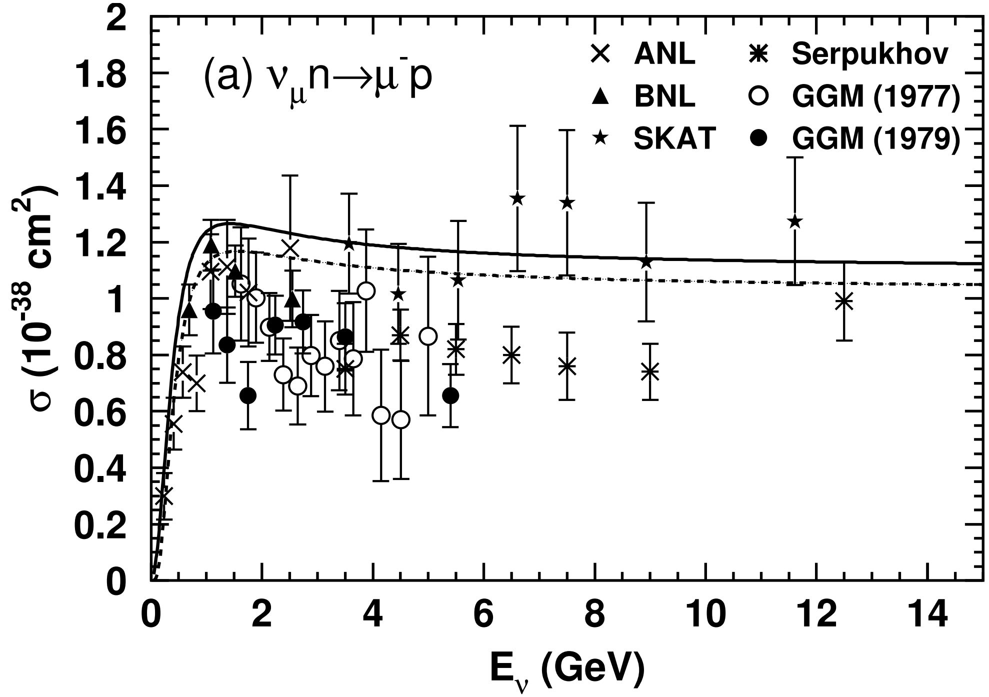
Atmospheric neutrino interaction

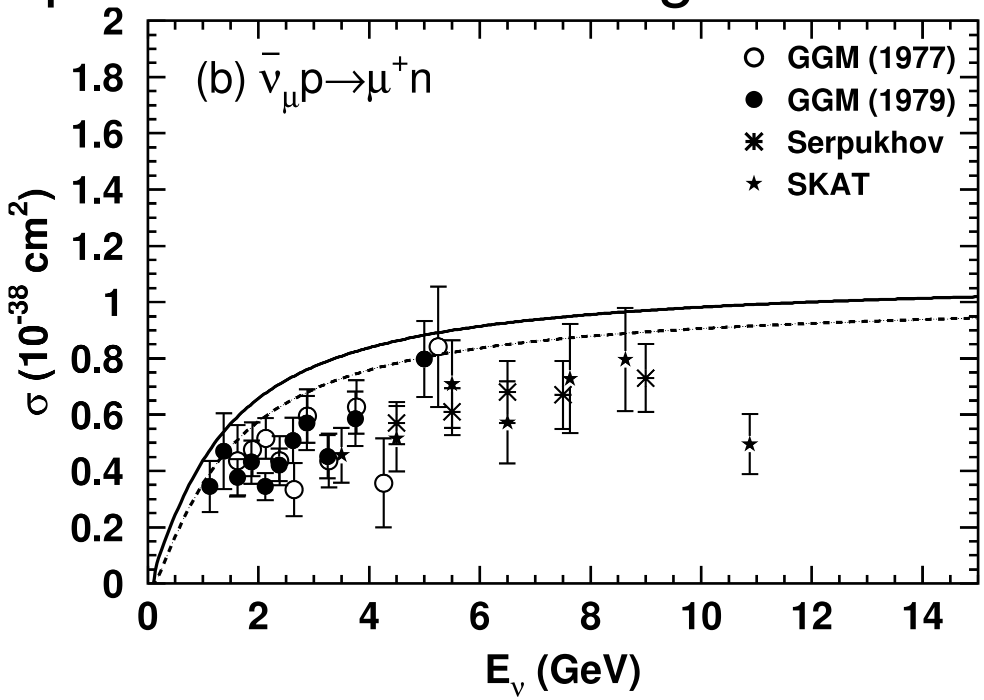
Neutrino interactions

Lepton : conserve the original neutrino flavor
electron / muon (hard to identify tau in SK)

- (quasi-)elastic scattering : $\nu + N \rightarrow l + N'$
- single meson production : $\nu + N \rightarrow l + N' + \text{meson}$
- deep inelastic interaction : $\nu + N \rightarrow l + N' + \text{hadrons}$
- coherent pion production : $\nu + {}^{16}O \rightarrow l + {}^{16}O + \pi$

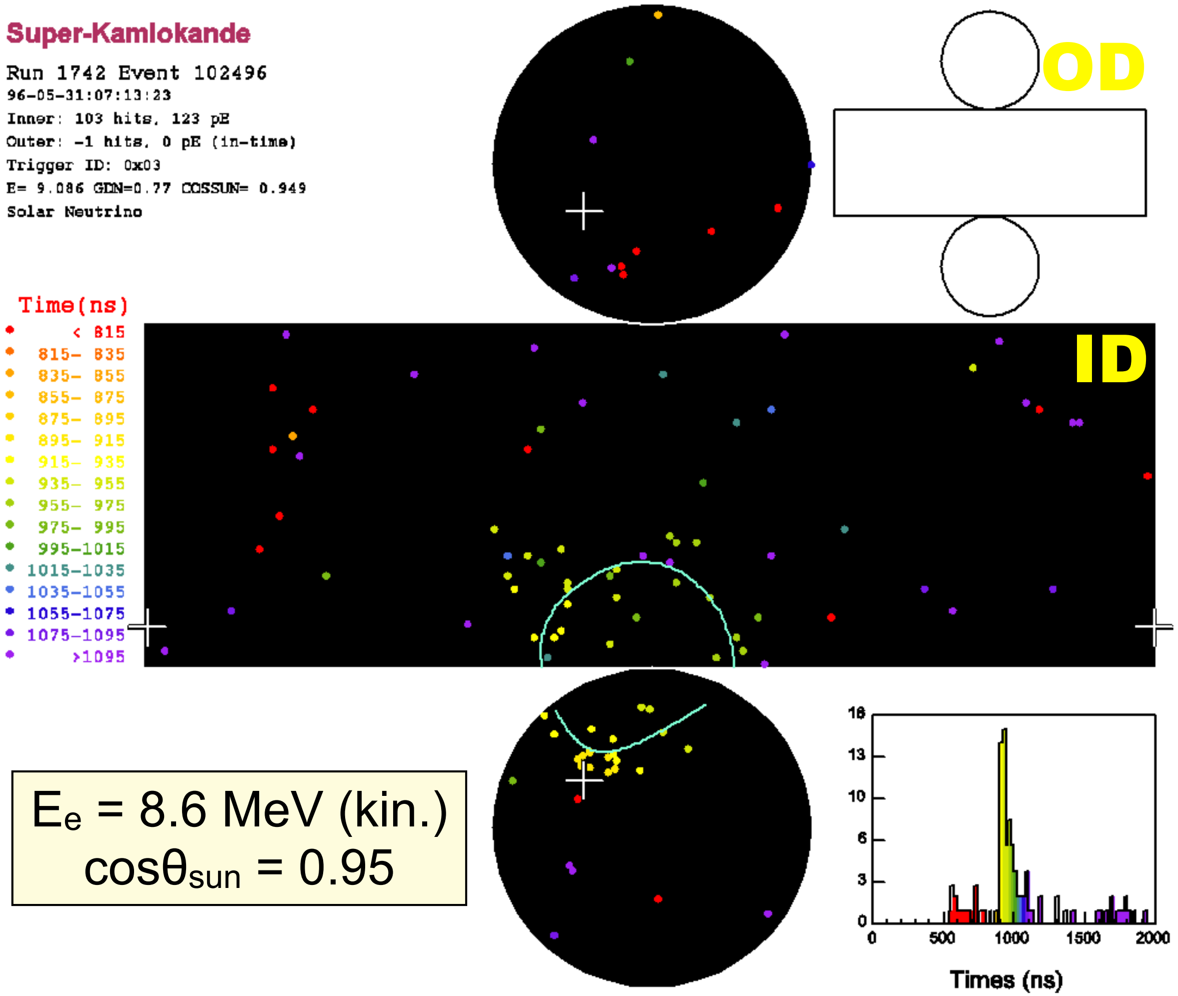
Total cross section of quasi-elastic scattering





Solar neutrino measurement in SK

Typical event



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

electron elastic scattering (ES)

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

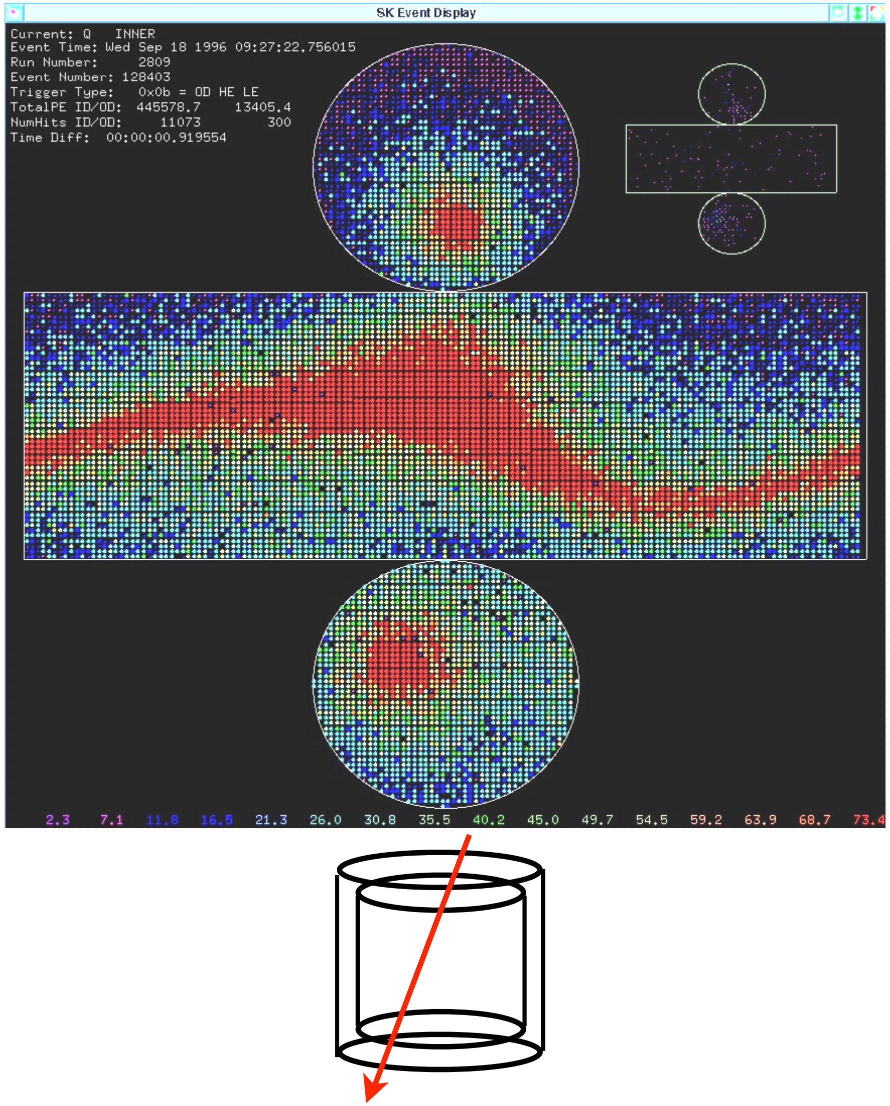
- ✓Find solar direction
- ✓Realtime measurement
  - day/night flux differences
  - seasonal variation
- ✓Energy spectrum

Interaction with all flavors of neutrino

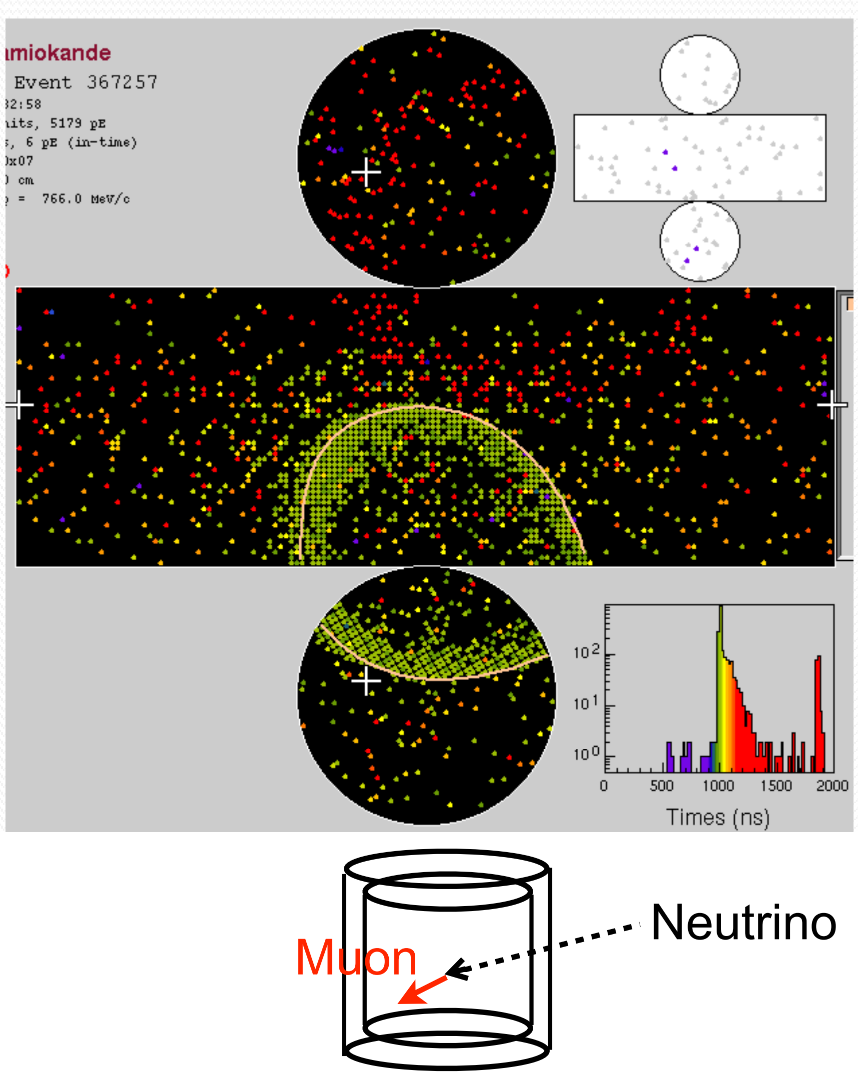
$$\nu_e + 0.154(\nu_\mu + \nu_\tau)$$

Super-Kamiokande

Cosmic ray muon

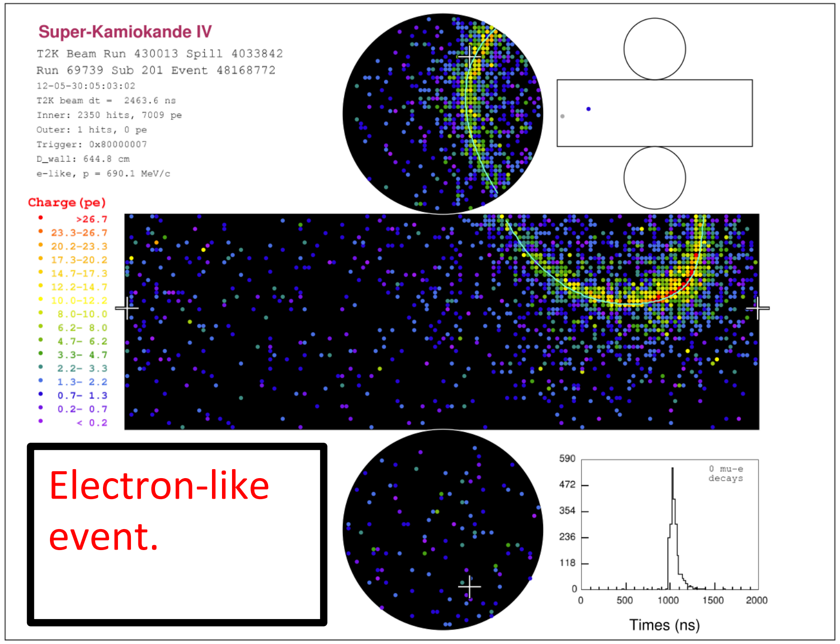


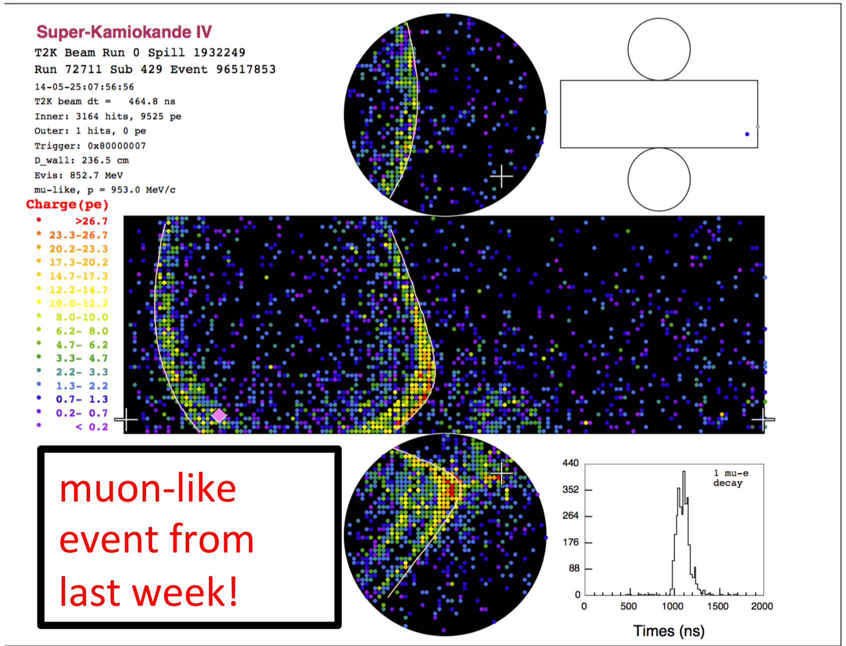
Neutrino signal



Event pattern (T2K)

Examples of far detector events

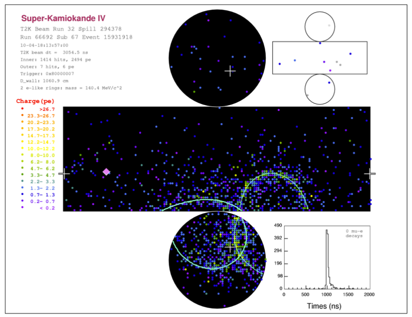




P_e = 690 MeV/c 0 decay-e

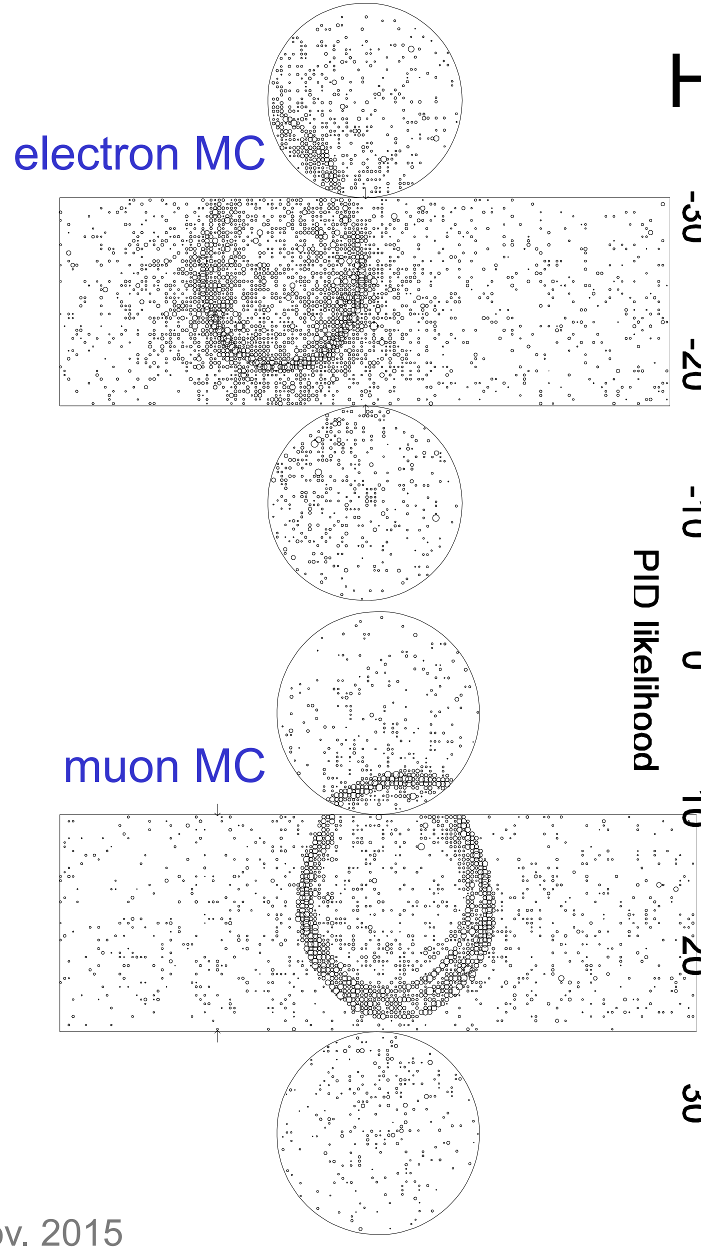
P_μ = 953 MeV/c 1 decay-e

<u>Super-K has excellent particle ID</u>
These events are split into three selected streams: ν_μ, ν_e and low energy events.

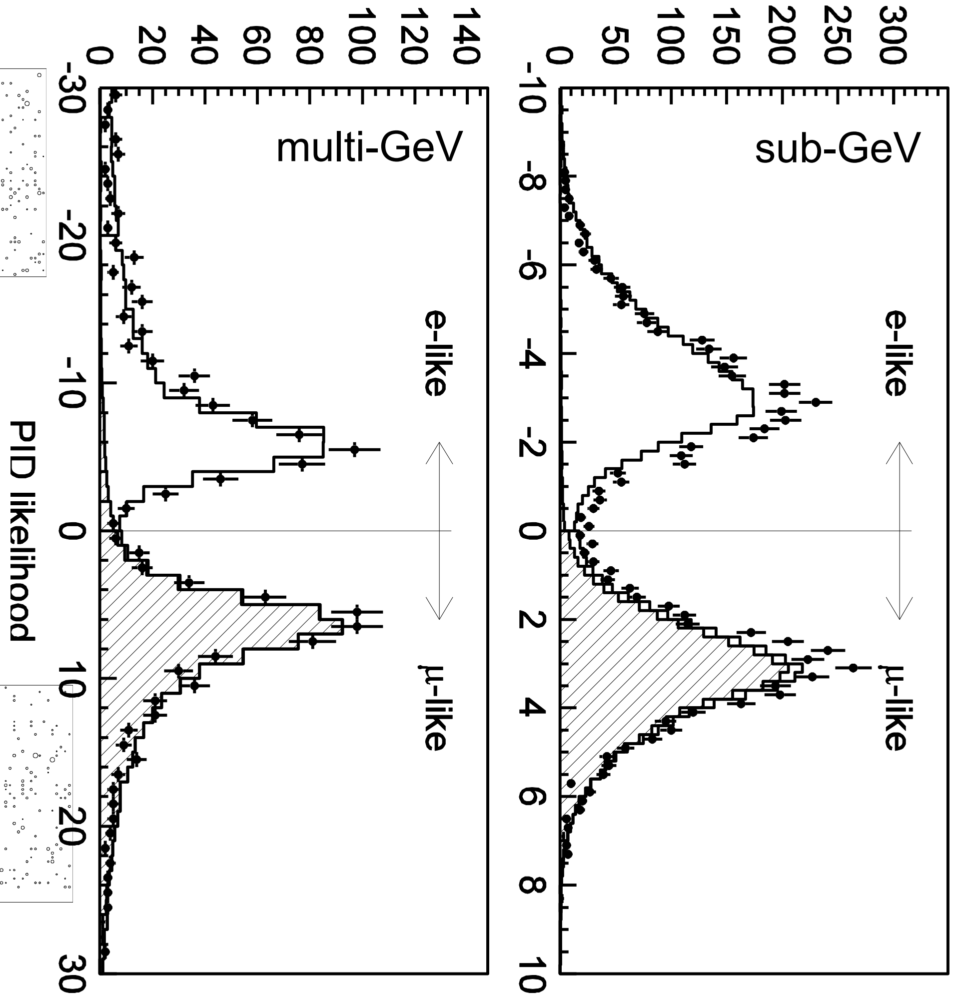


π^0 candidate.
M_{inv}=104 MeV/c^2

Atmospheric neutrino in SK

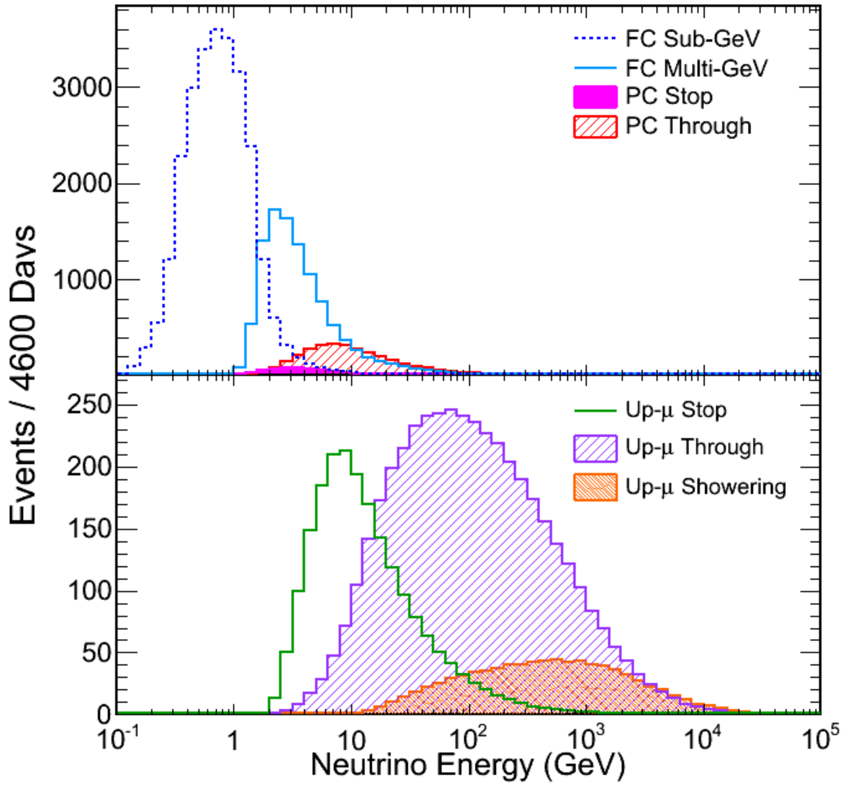


How to identify electron and muon

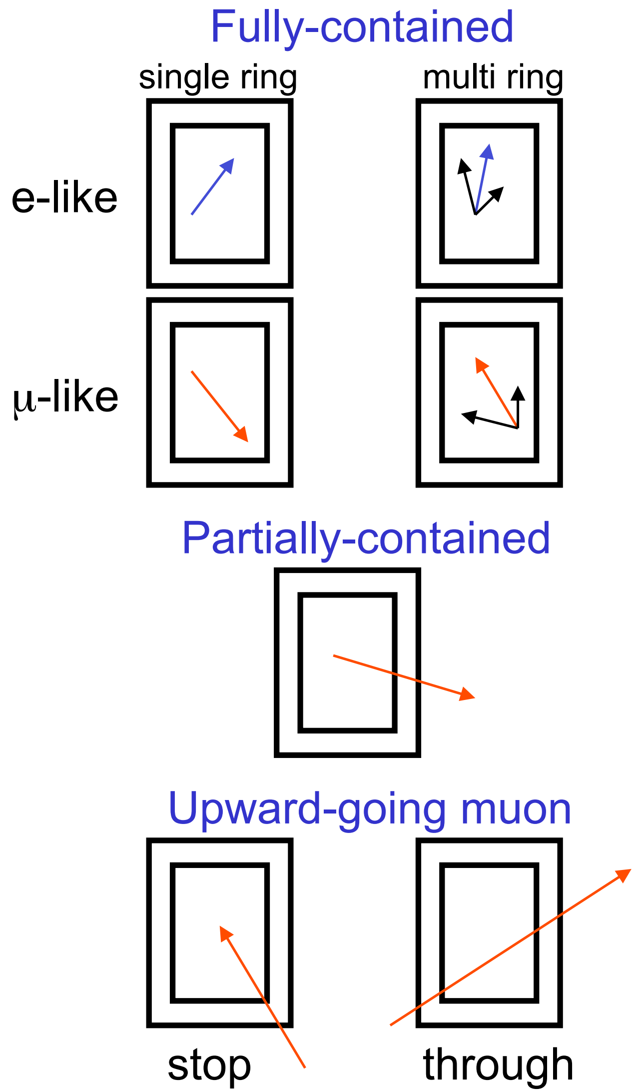


Atmospheric neutrino in SK

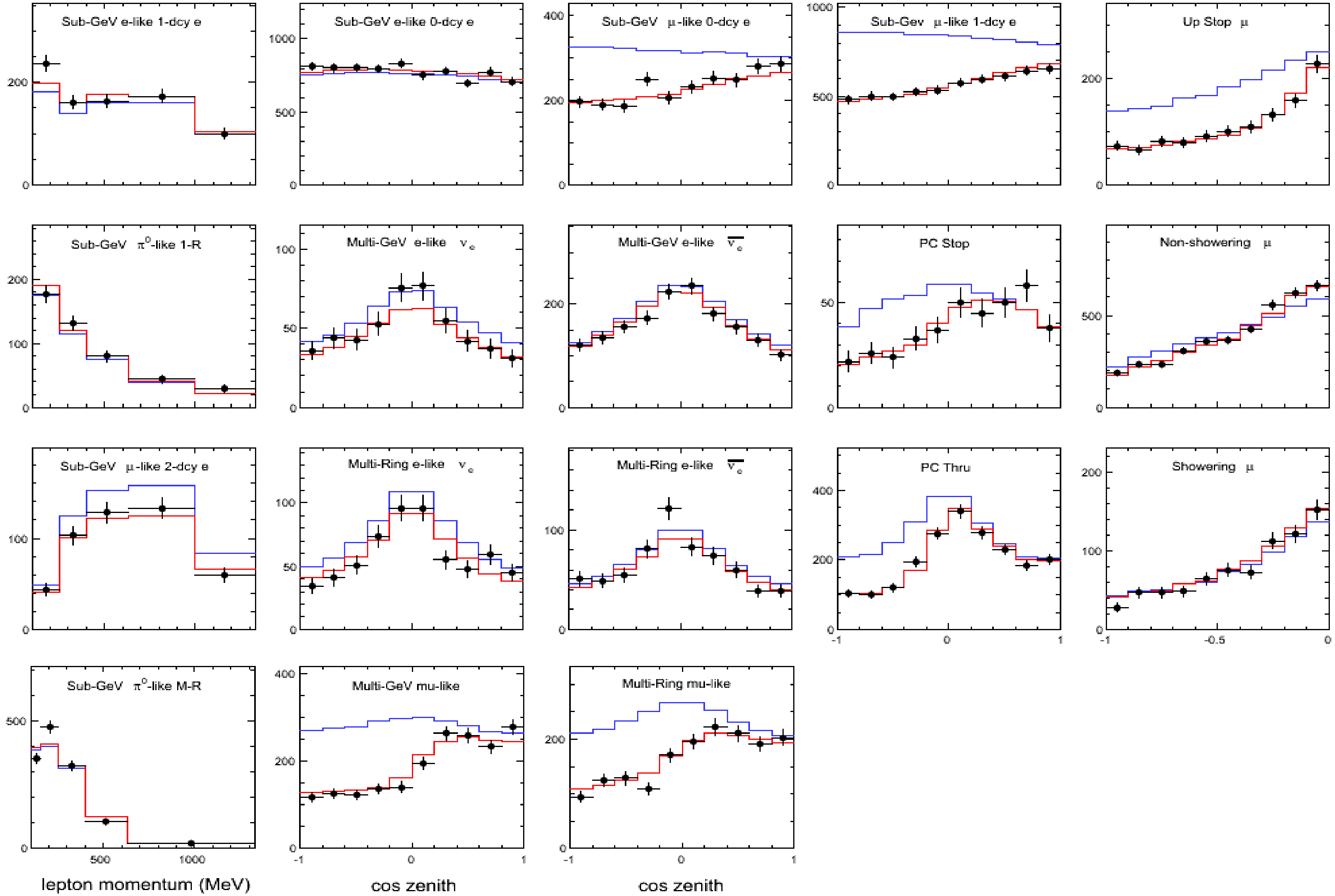
Parent neutrino spectrum in SK



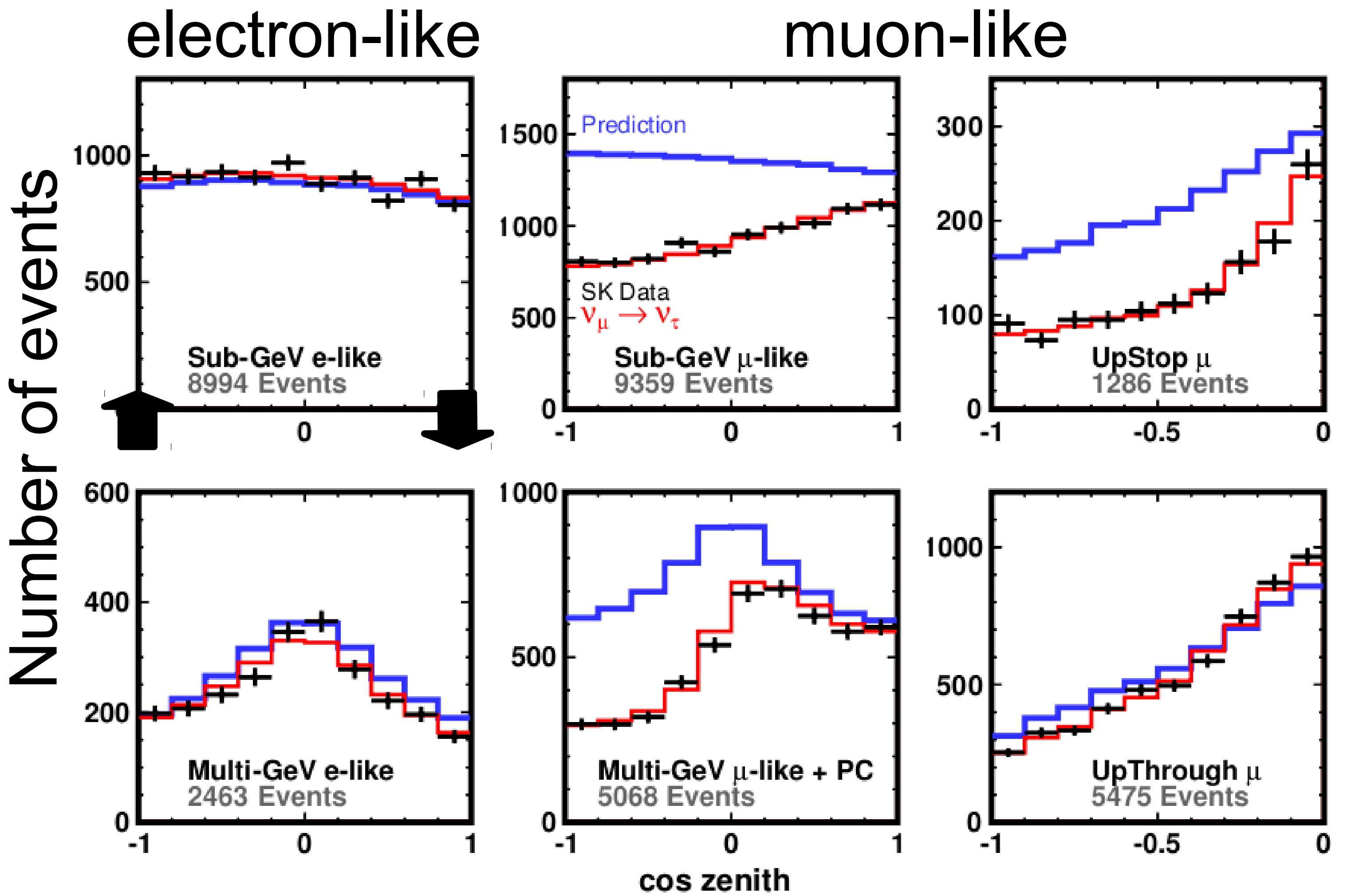
Event topologies



Atmospheric neutrino in SK



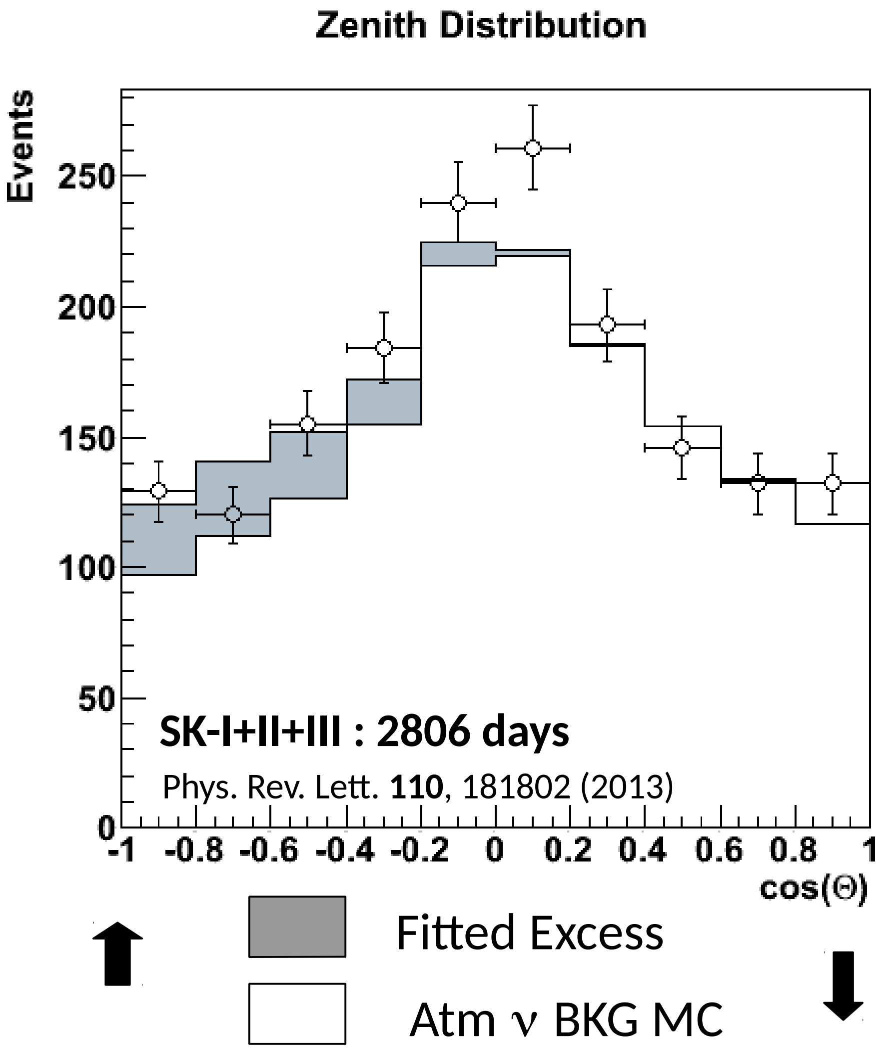
Atmospheric neutrino in SK



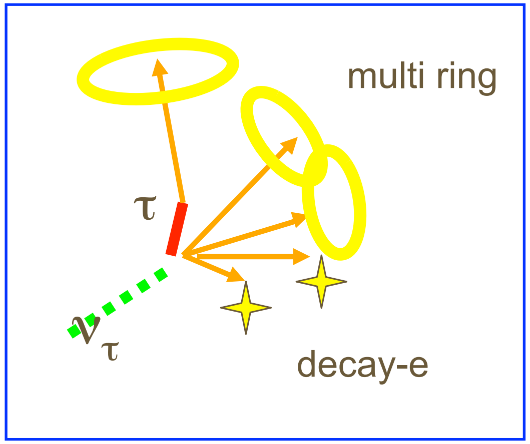
First evidence of neutrino oscillation in 1998

Atmospheric neutrino in SK

Tau appearance?



hard to identify event by event
but can be statistically seen

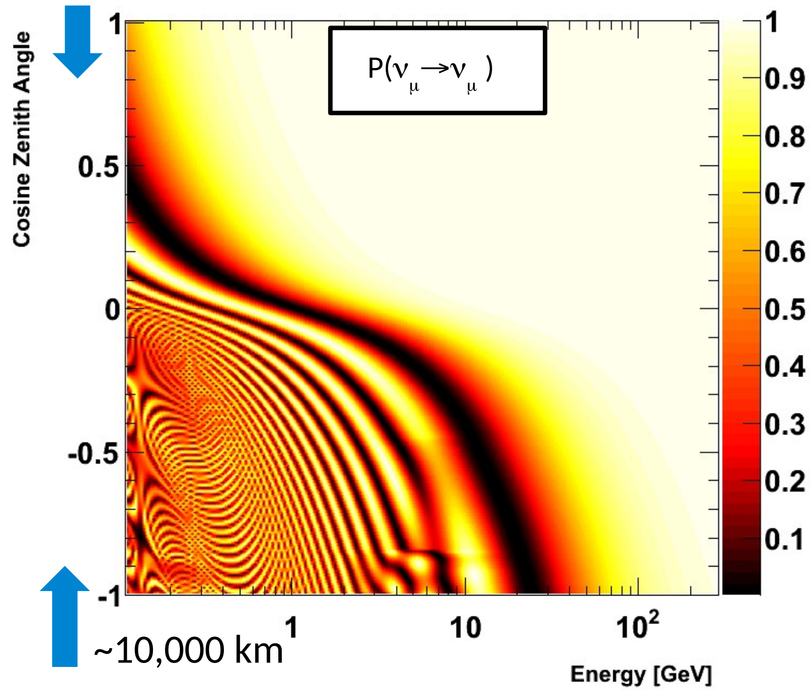


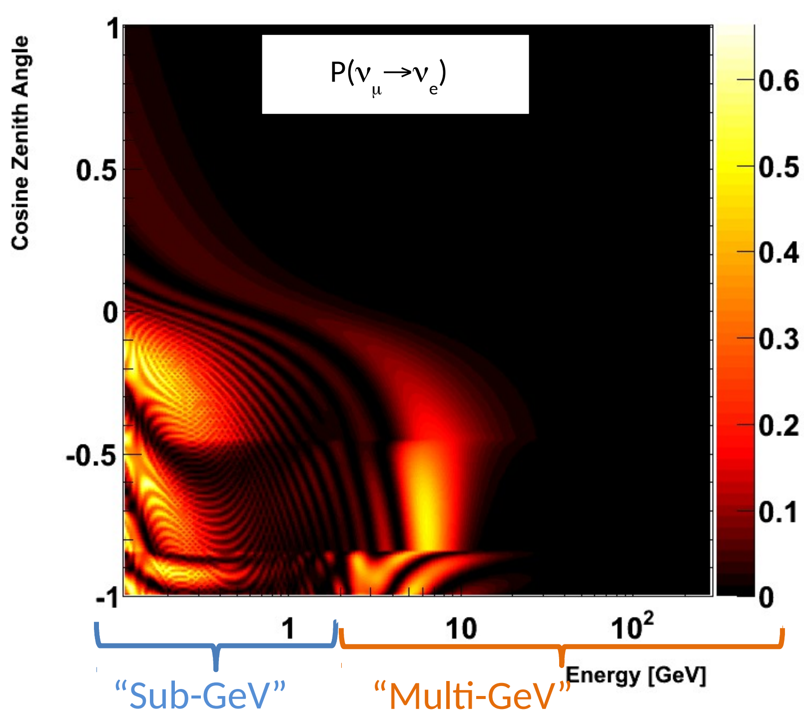
Search for events consistent with hadronic decays of tau lepton

180.1 ±44.3 (stat) +17.8-15.2 (sys) events, a **3.8 σ** excess (Expected 2.7 σ significance)

Atmospheric neutrino in SK

Searching for three-flavor effects





Earth matter effect

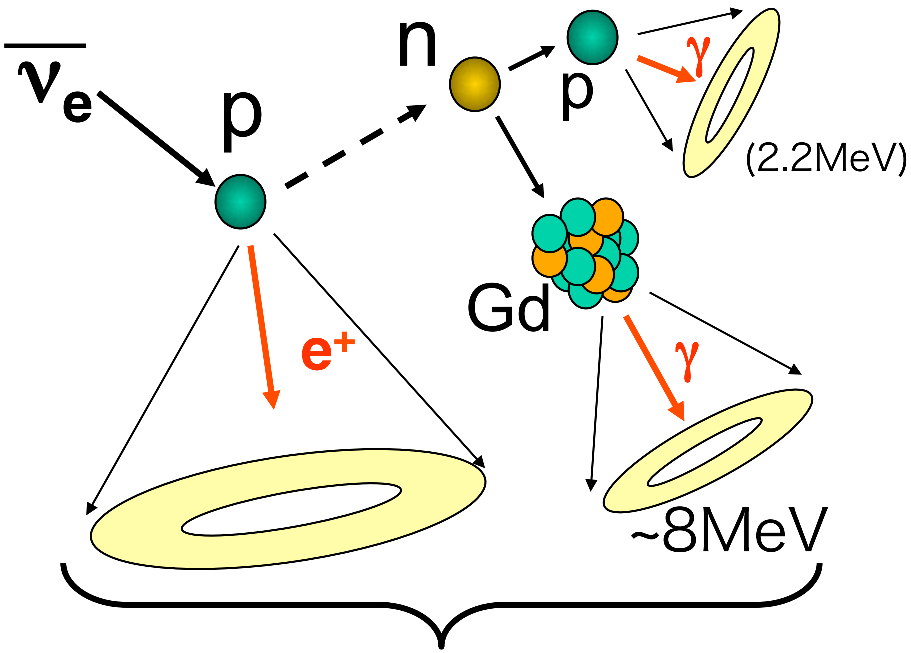
	neutrino	anti-neutrino
normal	enhanced	suppressed
inverted	suppressed	enhanced

In future

Super-Kamiokande with Gadolinium

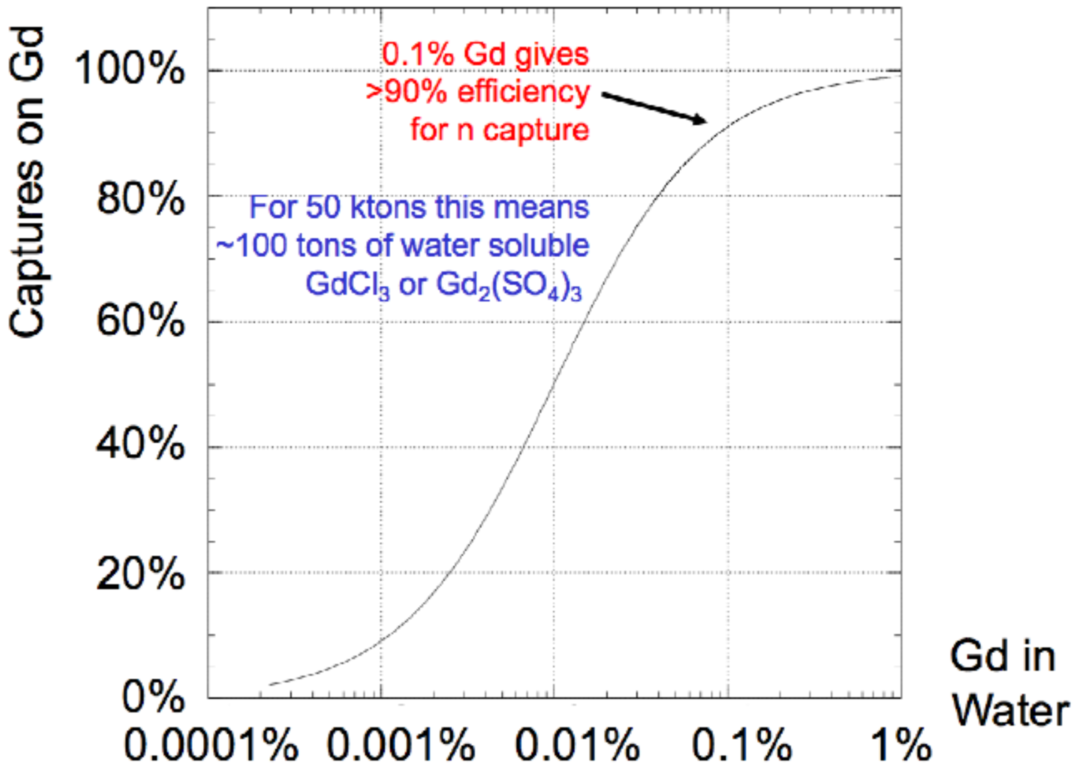
SuperK-Gd

Inverse beta decay

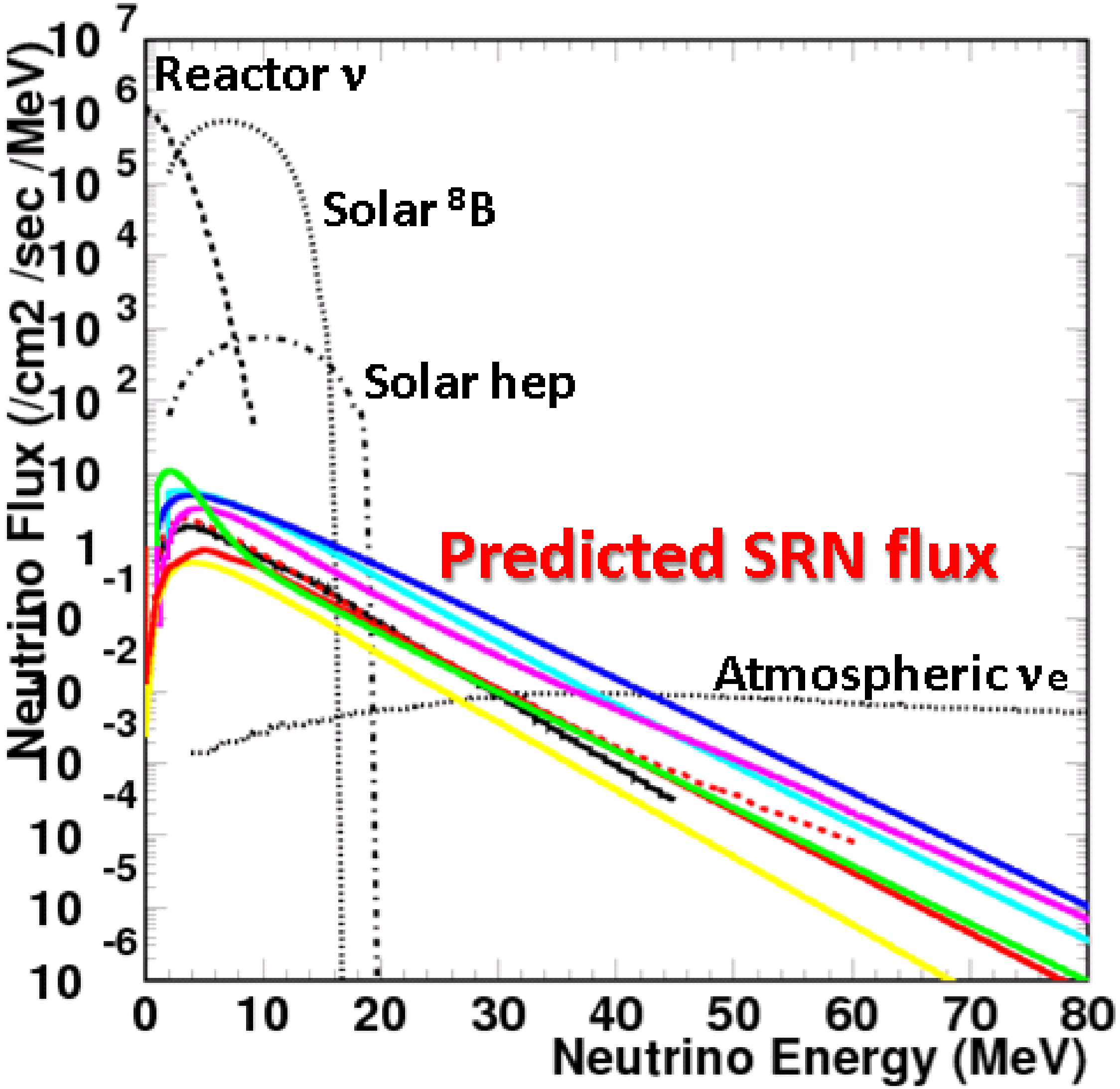


- Delayed coincidence
  - Suppress B.G. drastically for $\overline{\nu}_e$ signal
  - ΔT~20μsec
  - Vertices within ~50cm

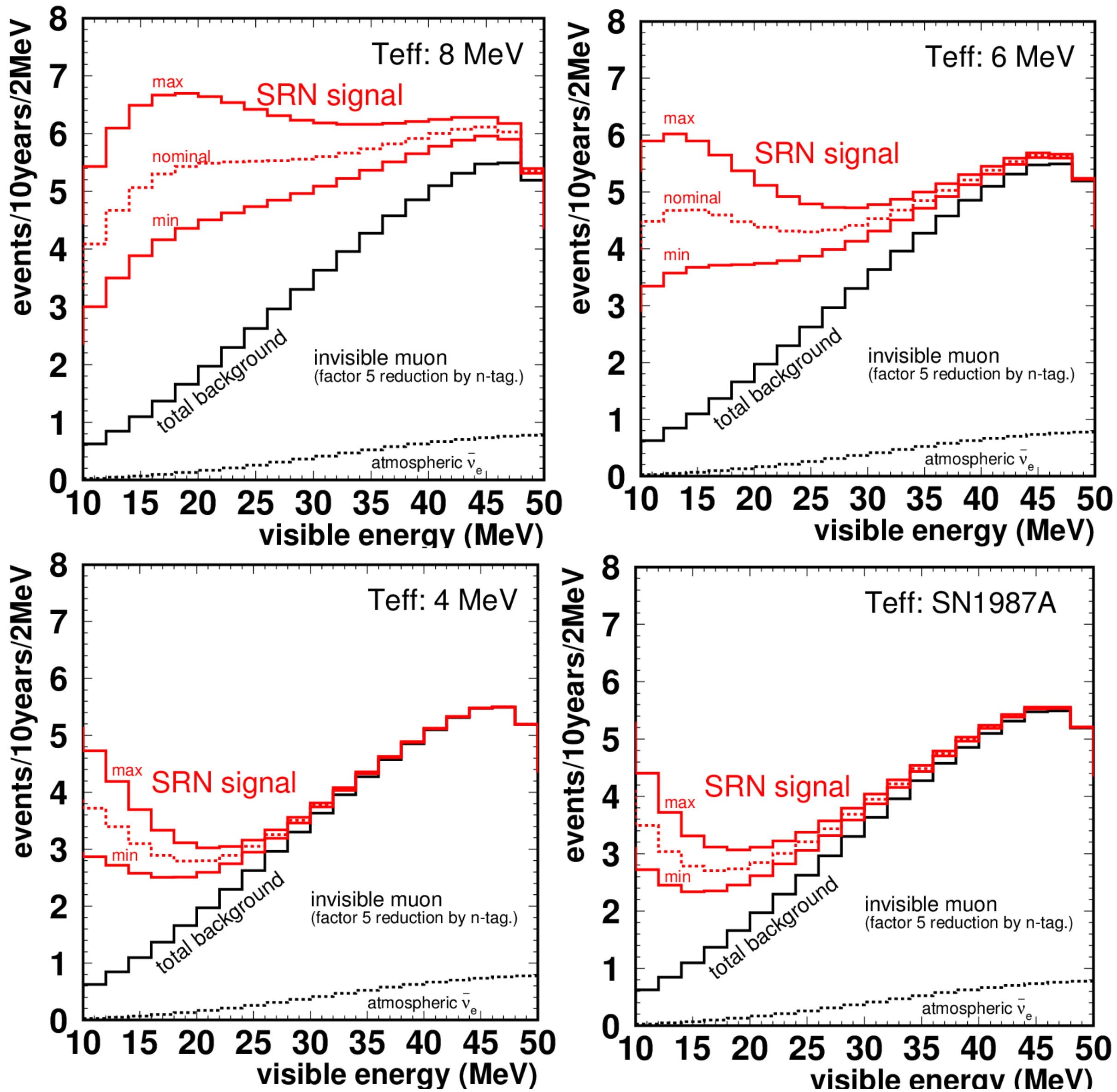
Dissolve Gadolinium into Super-K
J.Beacom and M.Vagins,
Phys.Rev.Lett.93(2004)171101



Supernova Relic Neutrinos



Expected signal



Assumption:
- 90% neutron capture efficiency
- 74% Gd γ detection efficiency
- invisible muon B.G. is 35% of ones in the SK-IV

10~45 SRN events in 10 years data taking (E_{vis}=10-30MeV)

Hyper-Kamiokande

Neutrino oscillation parameters

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&\cos\theta_{23}&\sin\theta_{23}\\0&-\sin\theta_{23}&\cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13}&0&\sin\theta_{13}e^{-i\delta}\\0&1&0\\-\sin\theta_{13}e^{-i\delta}&0&\cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12}&\sin\theta_{12}&0\\-\sin\theta_{12}&\cos\theta_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atm. ν + Acc. ν
$\theta_{23} = 45 \pm 6°$
Really 45°, <45° or >45° ?

Reactor ν + Acc. ν
$\theta_{13} = 9.1 \pm 0.6°$
δ =0 or not?

Solar ν + KamLAND
$\theta_{12} = 33.7 \pm 0.8°$

LBL with J-PARC and Hyper-K

$\nu_\mu \rightarrow \nu_e$ appearance

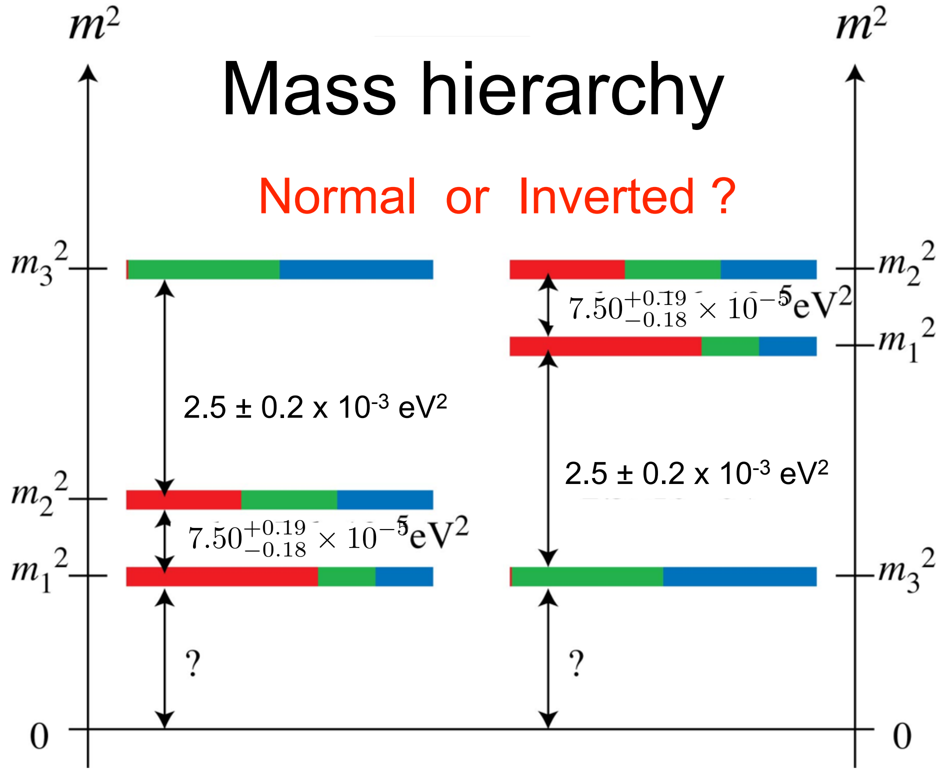
$$\begin{aligned}
&4C_{13}^2S_{13}^2S_{23}^2\sin^2\Delta_{31}\\
&+8C_{13}^2S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cdot\cos\Delta_{32}\cdot\sin\Delta_{31}\cdot\sin\Delta_{21}\\
&-8C_{13}^2C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\cdot\sin\Delta_{32}\cdot\sin\Delta_{31}\cdot\sin\Delta_{21}\\
&+4S_{12}^2C_{13}^2(C_{12}^2C_{23}^2+S_{12}^2S_{23}^2S_{13}^2-2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta)\cdot\sin^2\Delta_{21}\\
&-8C_{13}^2S_{13}^2S_{23}^2\cdot\frac{aL}{4E_\nu}(1-2S_{13}^2)\cdot\cos\Delta_{32}\cdot\sin\Delta_{31}\\
&+8C_{13}^2S_{13}^2S_{23}^2\cdot\frac{a}{\Delta m_{31}^2}(1-2S_{13}^2)\cdot\sin^2\Delta_{31}
\end{aligned}$$

ν_μ disappearance

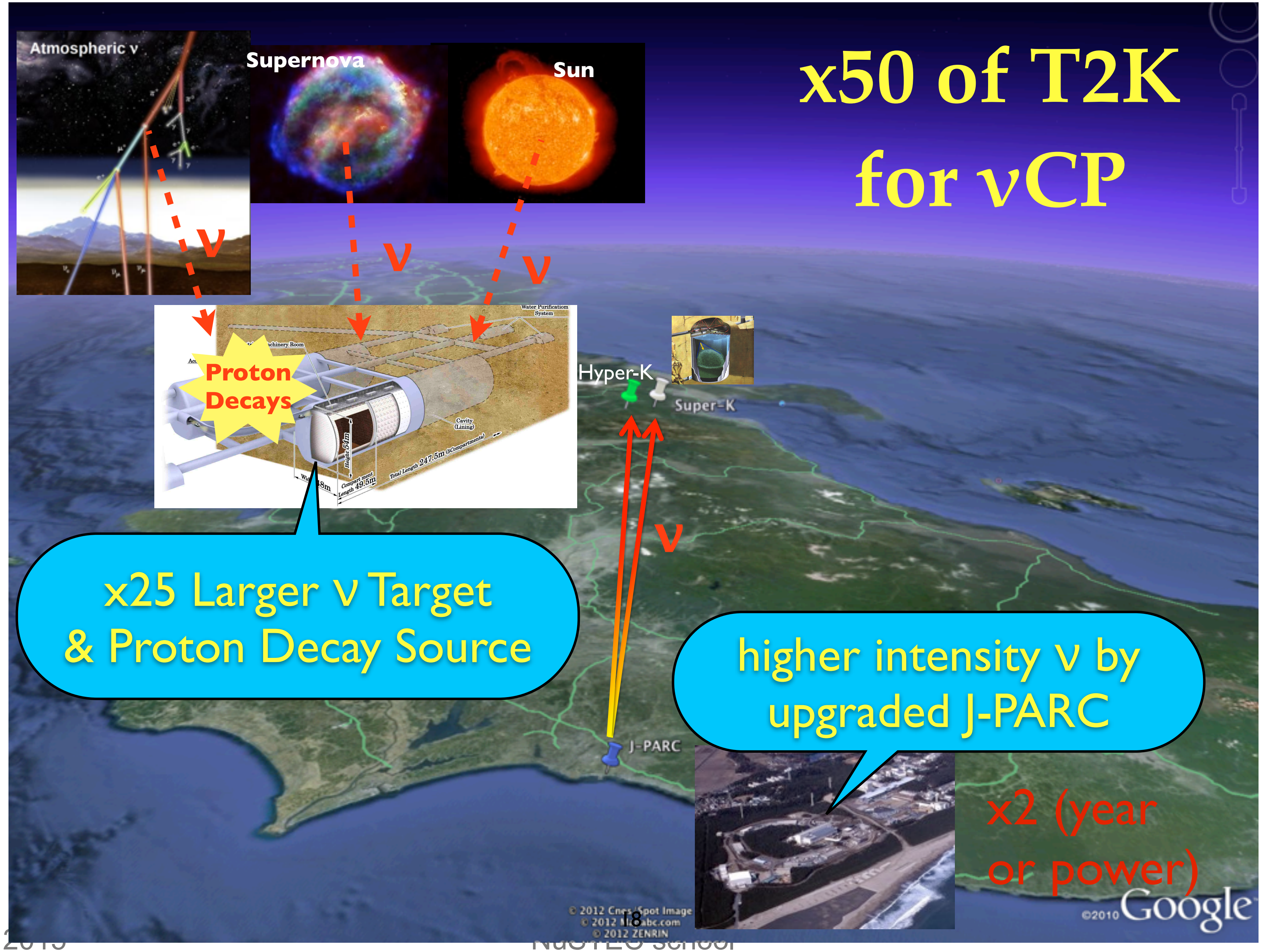
$$1-4C_{13}^2S_{23}^2(1-C_{13}^2S_{23}^2)\sin^2\Delta_{32}$$

Mass hierarchy

Normal or Inverted ?

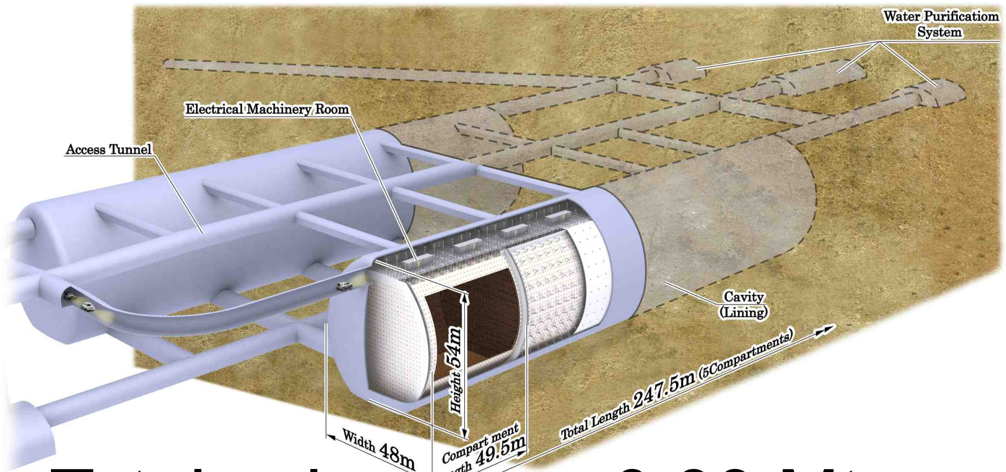


J-PARC and Hyper-Kamiokande



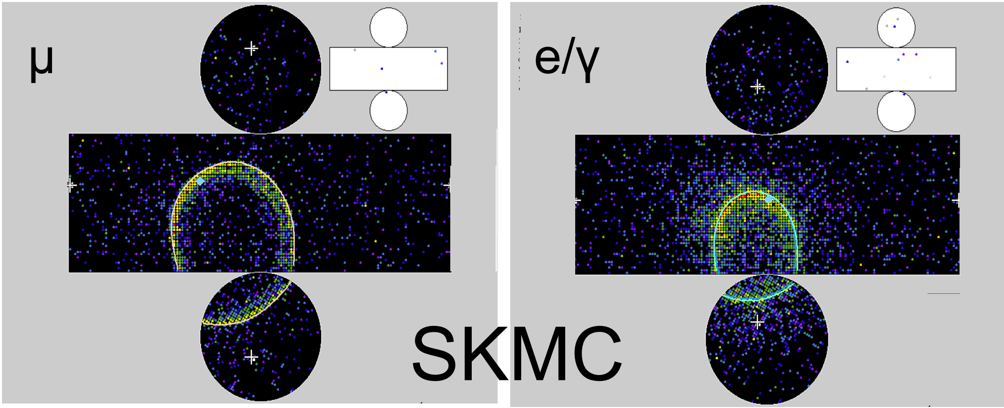
Hyper-Kamiokande

Water Cherenkov detector



Total volume : 0.99 Mton
Inner : 0.74 Mton
Outer : 0.2 Mton
Fiducial volume: 0.56 Mton

99,000 20" PMT for inner (20% coverage)
25,000 8" PMT for outer



- Signal (CCQE):

$$\nu_l + N \rightarrow l + N'$$

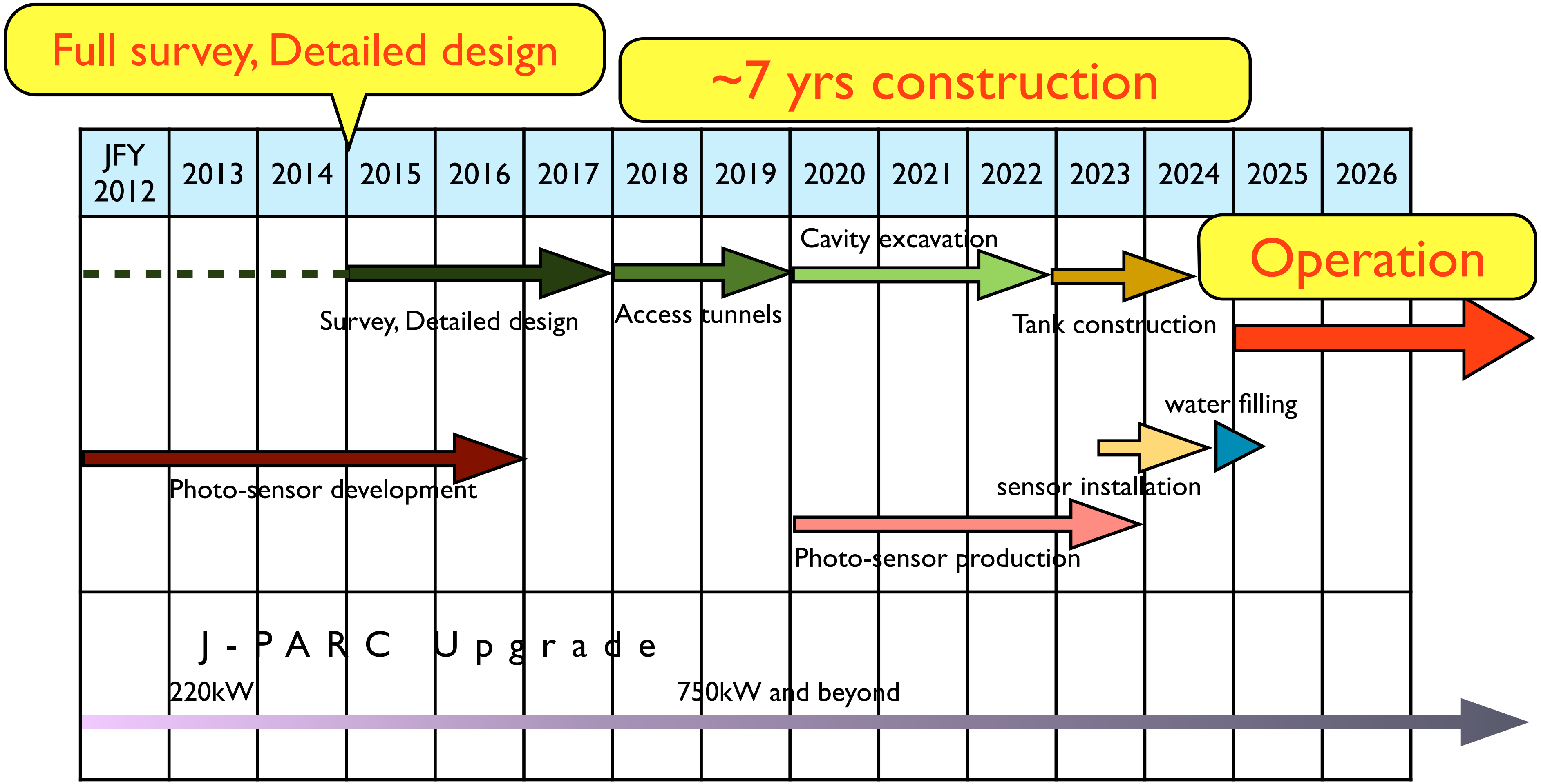
✓Appears as single μ/e-like event. Excellent particle ID capability > 99%.
✓E^{rec}_{ν} can be reconstructed by energy and direction of ring relative to beam.

- Backgrounds:

✓π0 : ring counting, 2-ring invariant mass
✓μ/π : ring counting, decay electron
✓intrinsic ν_e present in beam

Technique is established

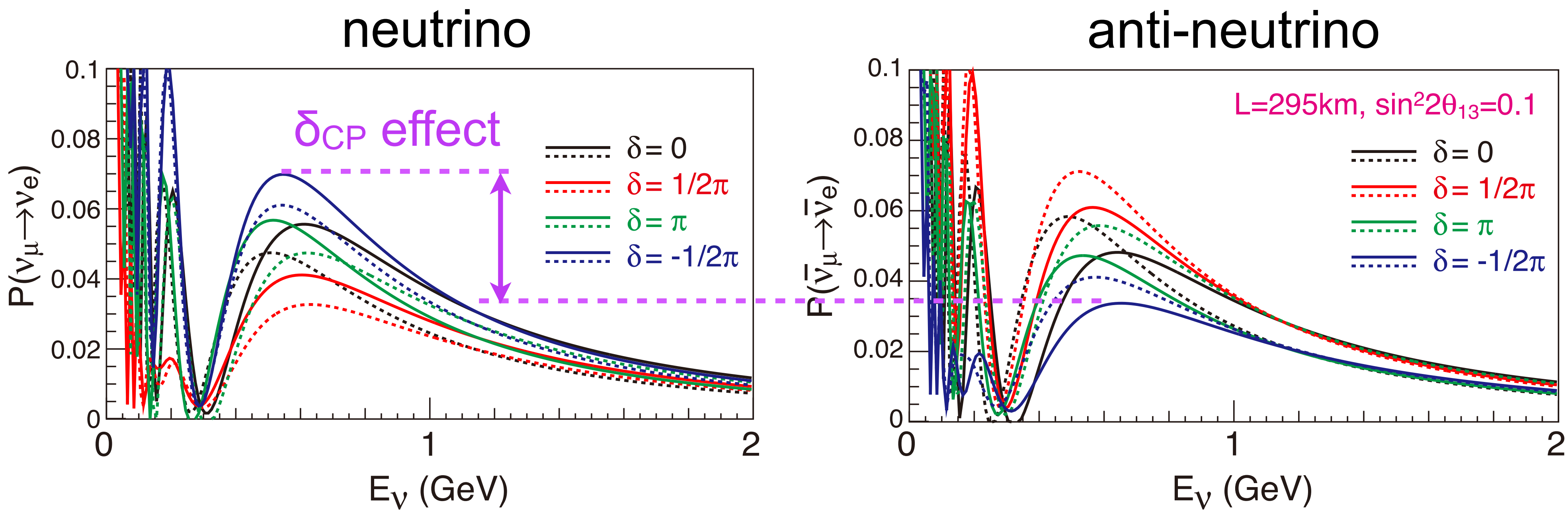
Notional timeline



-2015 Full survey, Detailed design (3 years)
-2018 Excavation start (7 years)
-2025 Start operation

Measurement of CP asymmetry

$\nu_\mu \rightarrow \nu_e$ Appearance probability w/ J-PARC and HK



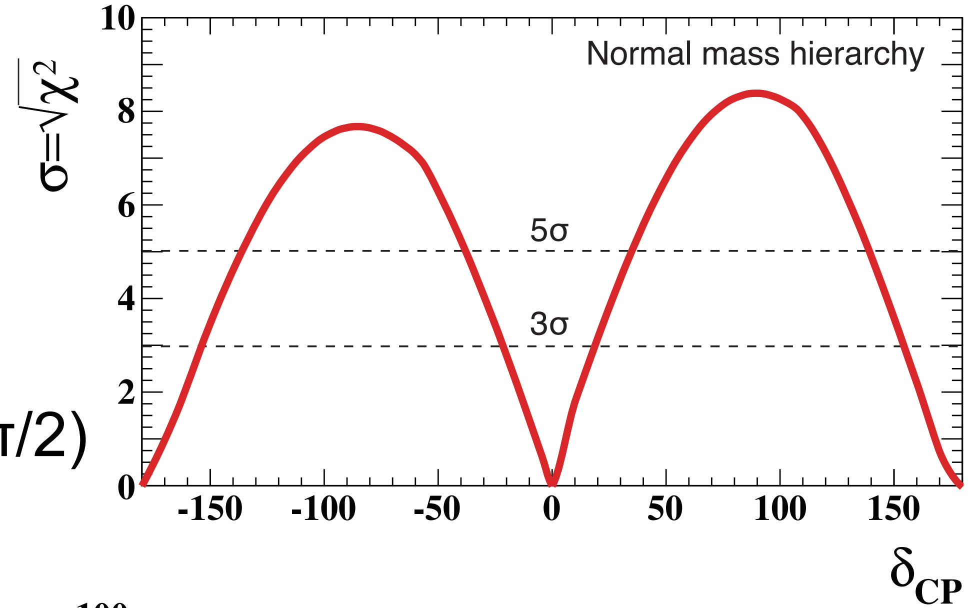
Direct CPV test by comparing between $P(\nu_\mu \rightarrow \nu_e)$ and $P(\overline{\nu_\mu} \rightarrow \overline{\nu_e})$

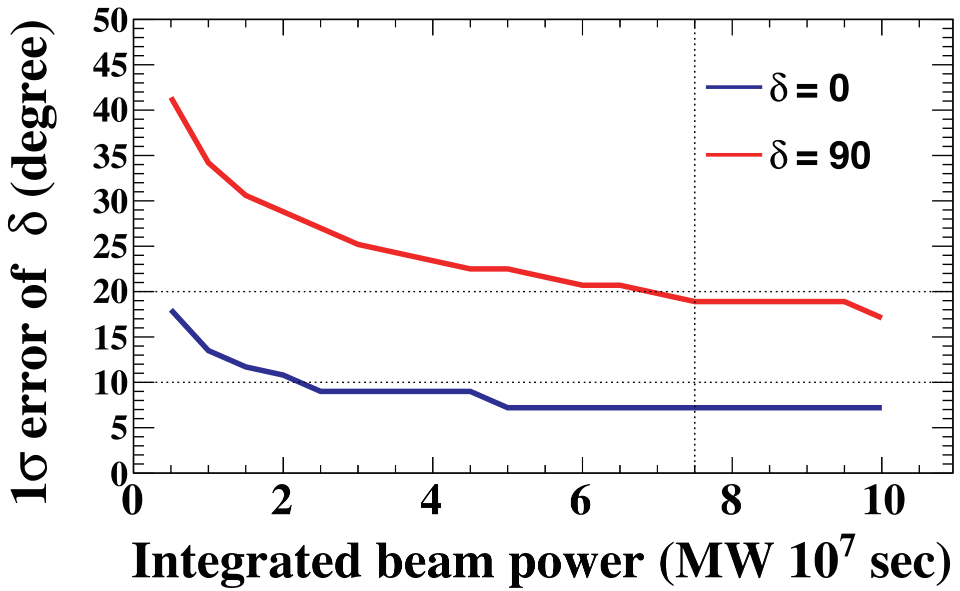
- CPV term in probability is proportional to $\sin\theta_{13} \sin\delta_{cp}$
- At maximum CPV ~±25% change.
- Test an exotic (non-MNS) CPV sources.

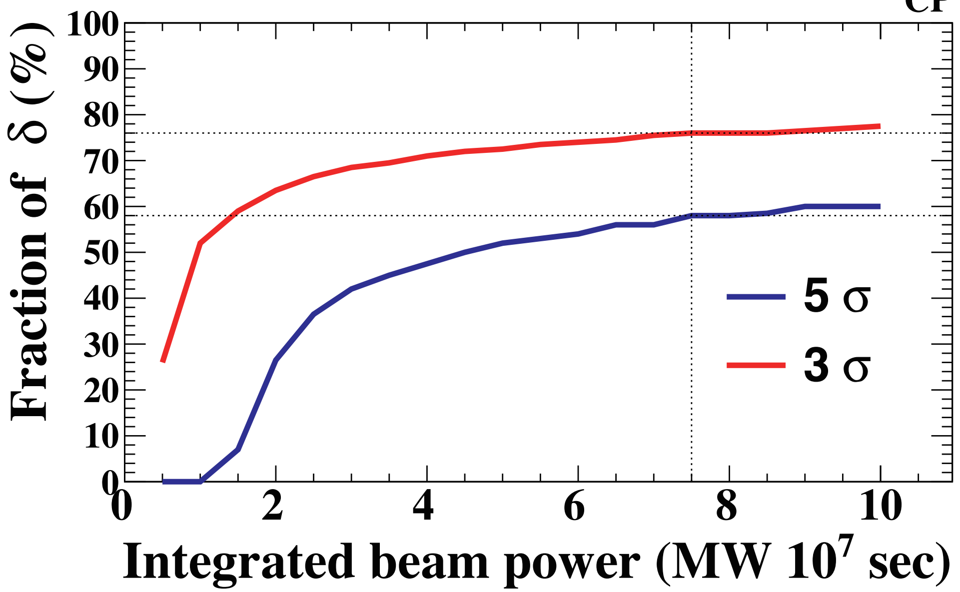
Sensitivity of CP violation

At 7.5×10^7 MW sec,

- CP violation can be observed at
  - ✓ 3σ for 76% values of δ
  - ✓ 5σ for 58% values of δ
- δ_{cp} can be measured with
  - ✓ 8 degree (δ=0) ~ 19 degree (δ=π/2) depending on the true value of δ







Thanks a lot!