Perspectives in Japan for CP violation in the neutrino sector, proton decay and supernova neutrinos

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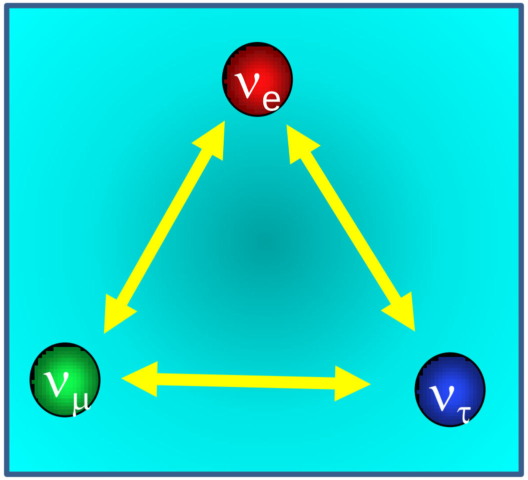
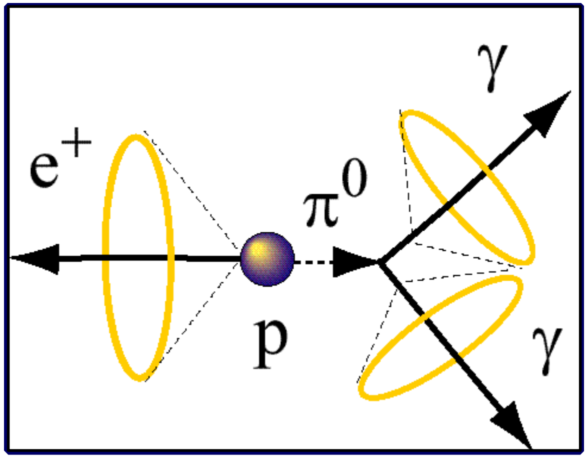
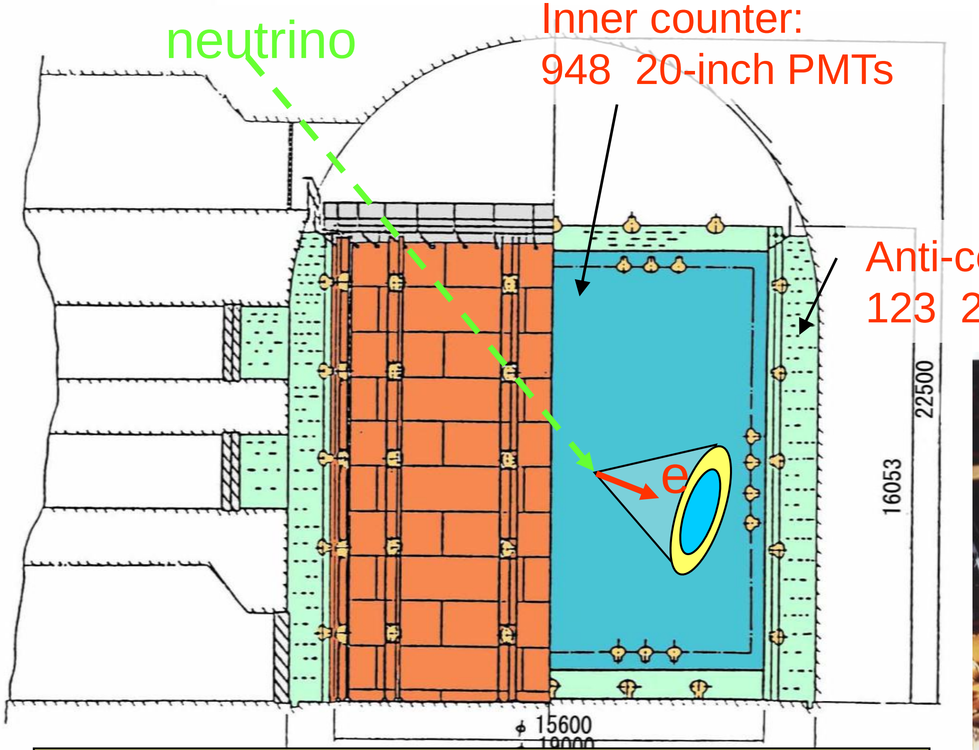




Neutrinos at the forefront of elementary particle physics and astrophysics, 22-24 Oct. 2012, Lyon (France)

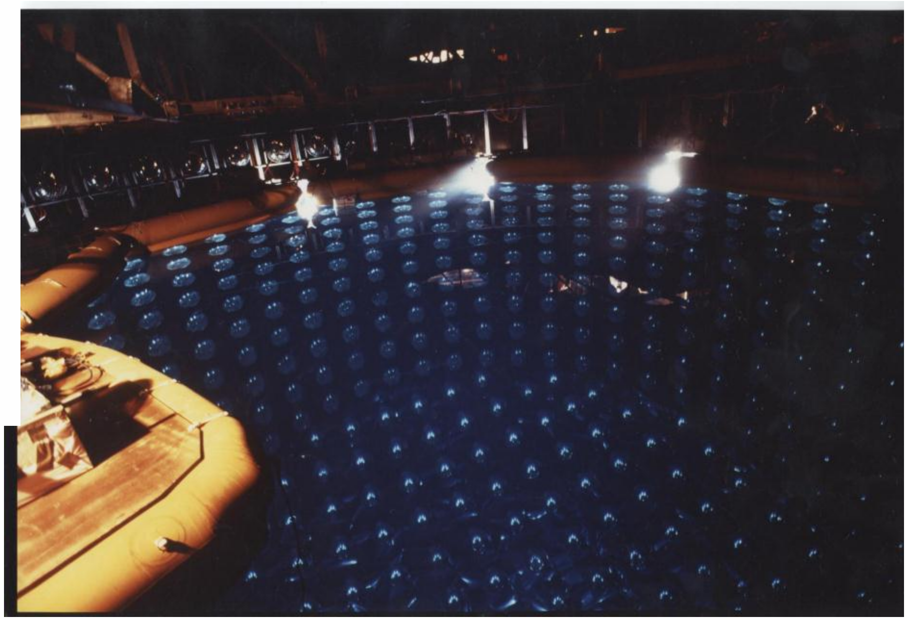
A little history

Kamiokande experiment (1983 – 1996)



Inner counter:
948 20-inch PMTs

Anti-counter
123 20-inch PMTs



3000 ton water Cherenkov detector

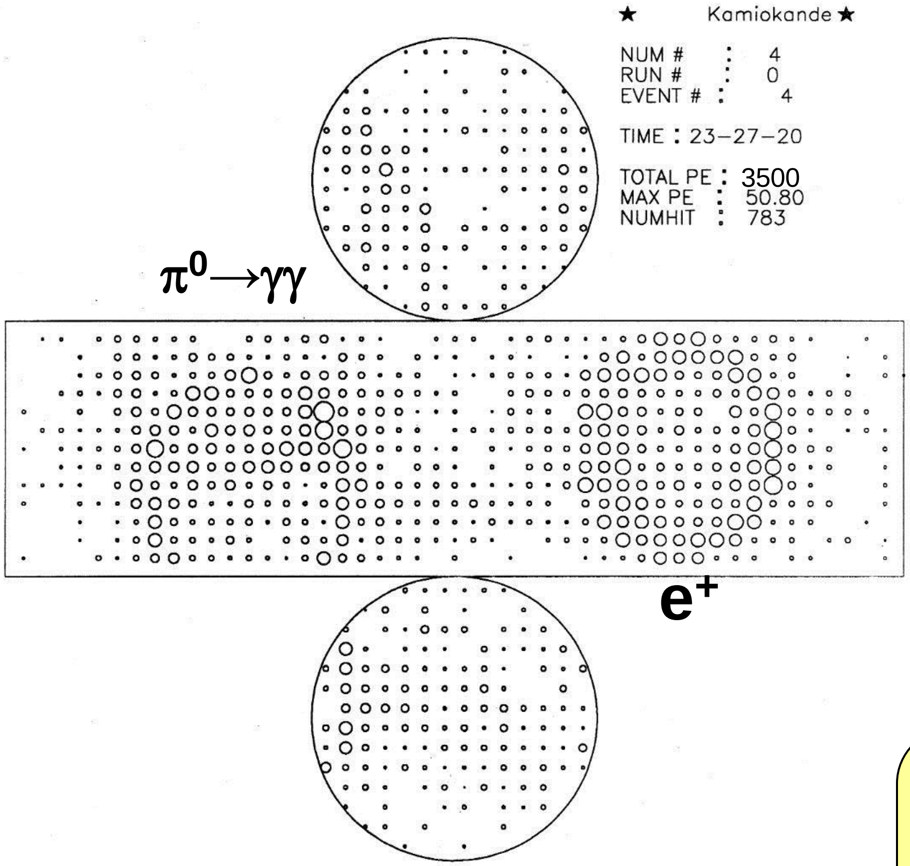
Photo-sensitive: 2140 t

Fiducial volume: 780 t

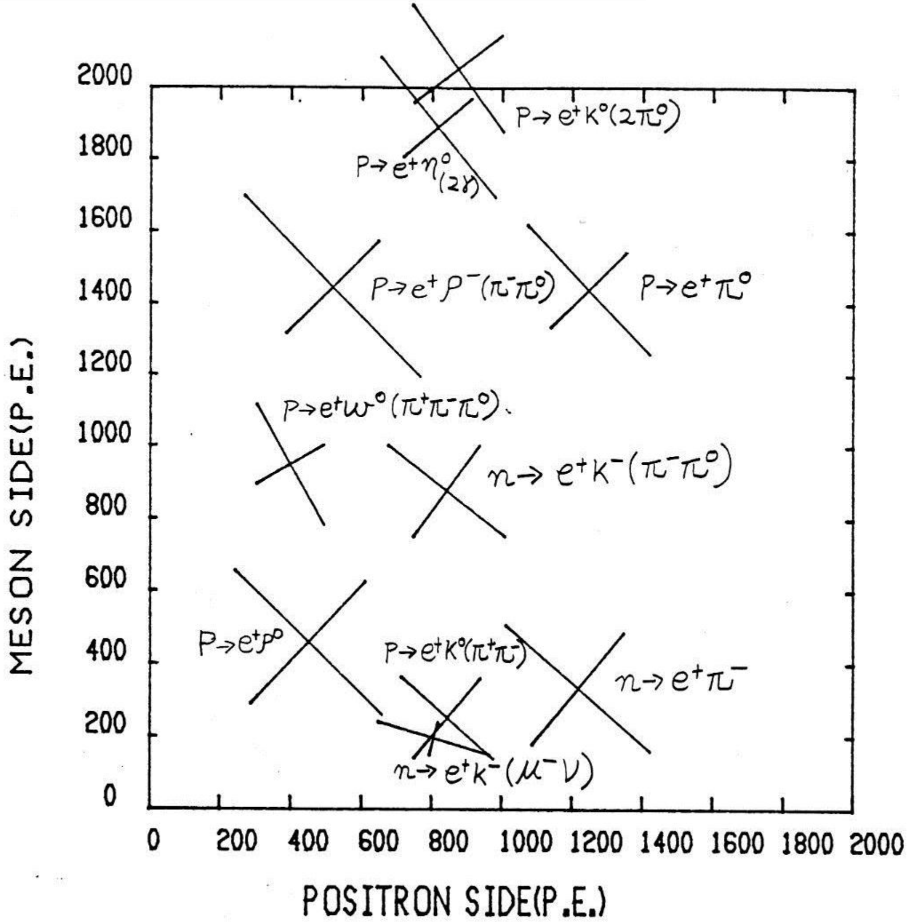
Photo-coverage: 20 % ⟷ 1.25% in IMB-1 (7000ton detector, 1982 start)

Original purpose of Kamiokande

Search for proton decay



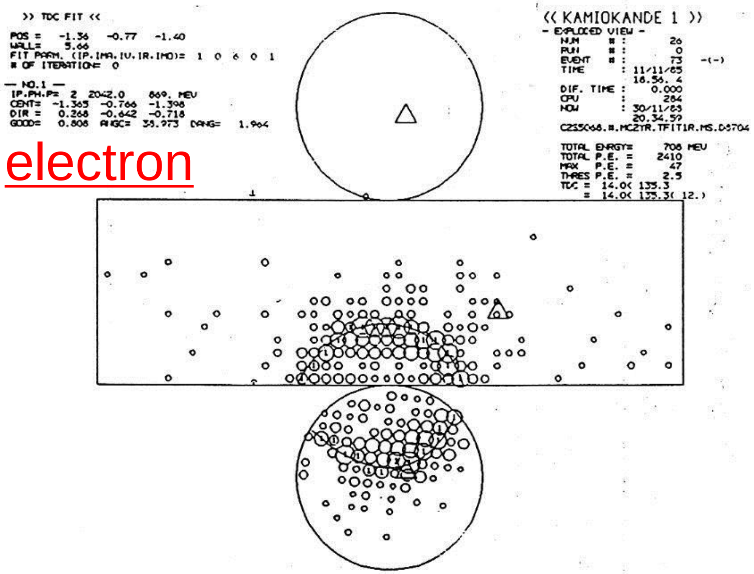
p→e+π0 Monte Carlo simulation



High resolution detector for measuring the branching ratio of proton decay.

It should be useful to pin down the true GUT model.

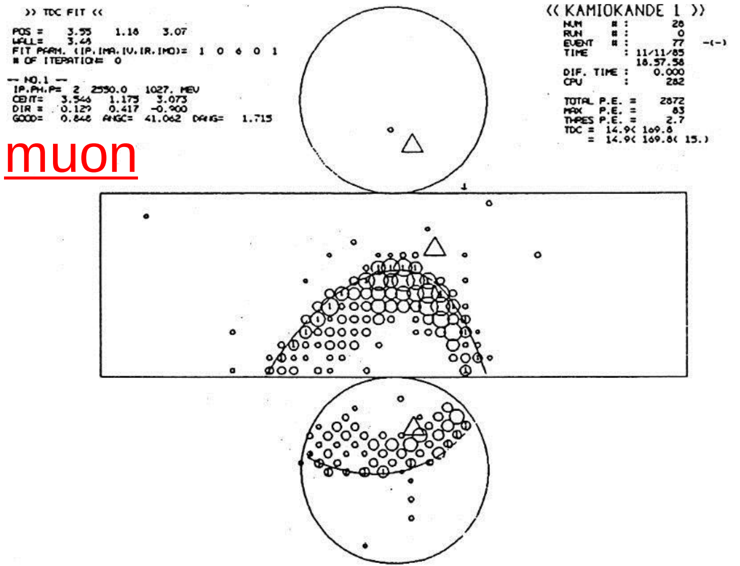
Thanks to large photo-coverage, Particle identification(PID) was possible.



```
>> TDC FIT <<

POS =   -1.36   -0.77   -1.40
WALL=    5.66
FIT PARM. (IP.IMA.IV.IR.IMO)=  1  0  6  0  1
# OF ITERATION=  0

-- NO.1 --
IP.PH.P=  2  2042.0    869. MEV
CENT=  -1.365  -0.766  -1.398
DIR =   0.268  -0.642  -0.718
GOOD=   0.808  ANGC=  35.973  DANG=   1.964
```

```
<< KAMIOKANDE 1 >>
- EXPLODED VIEW -
  NUM      # :          26
  RUN      # :           0
  EVENT    # :          73    -(-)
  TIME       :    11/11/85
                  18.56. 4
  DIF. TIME  :       0.000
  CPU        :         284
  NOW        :    30/11/85
                  20.34.59
  C235068.#.MC2YR.TFIT1R.MS.D5704

  TOTAL ENRGY=      708 MEV
  TOTAL P.E. =     2410
  MAX   P.E. =       47
  THRES P.E. =      2.5
  TDC =  14.0( 135.3
      =  14.0( 135.3( 12.)
```

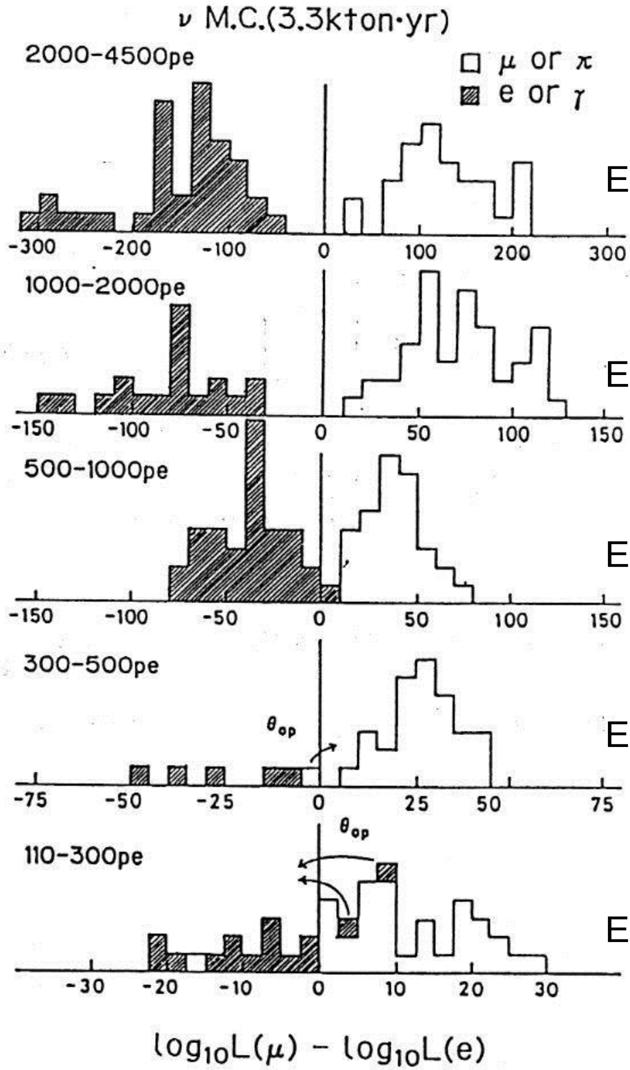
electron



```
>> TDC FIT <<

POS =    3.55    1.18    3.07
WALL=    3.48
FIT PARM. (IP.IMA.IV.IR.IMO)=  1  0  6  0  1
# OF ITERATION=  0

-- NO.1 --
IP.PH.P=  2  2550.0   1027. MEV
CENT=   3.546   1.175   3.073
DIR =   0.129   0.417  -0.900
GOOD=   0.848  ANGC=  41.062  DANG=   1.715
```

```
<< KAMIOKANDE 1 >>
  NUM      # :          28
  RUN      # :           0
  EVENT    # :          77    -(-)
  TIME       :    11/11/85
                  18.57.58
  DIF. TIME  :       0.000
  CPU        :         282

  TOTAL P.E. =     2872
  MAX   P.E. =       83
  THRES P.E. =      2.7
  TDC =  14.9( 169.8
      =  14.9( 169.8( 15.)
```

muon



E_{vis}=540 - 1200 MeV

E_{vis}=270 - 540 MeV

E_{vis}=130 - 270 MeV

E_{vis}=80 - 130 MeV

E_{vis}=30 - 80 MeV

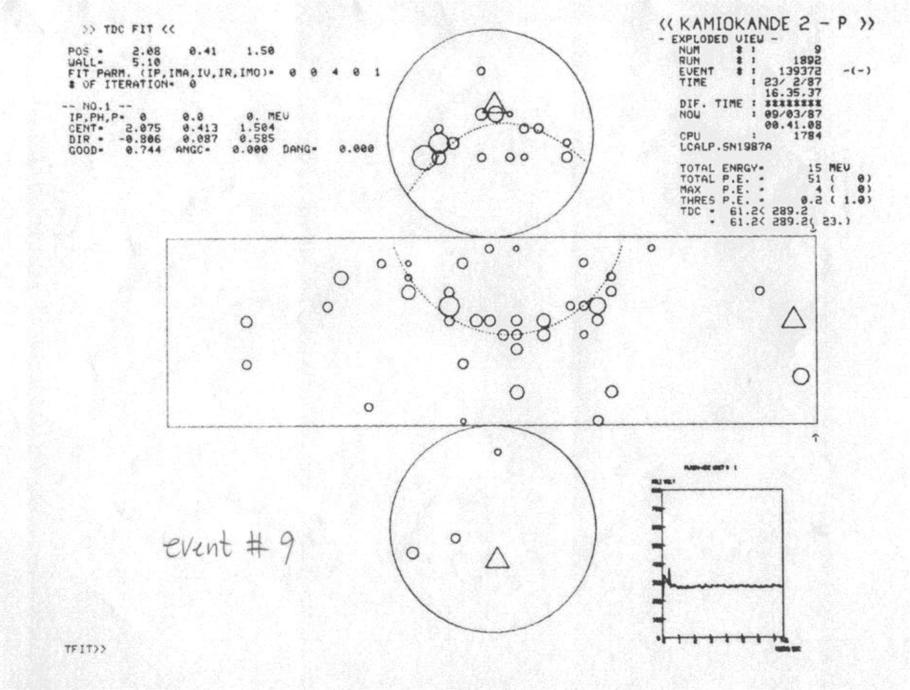
Mis-identification is less than 1%.

PID was very important for the study of atmospheric neutrinos.

Also, low energy neutrino detection

It was found that the large photo-coverage is effective also for detection of low energy neutrinos.
So, the detector was upgraded for solar neutrinos in 1985.

A low energy event at Kamiokande

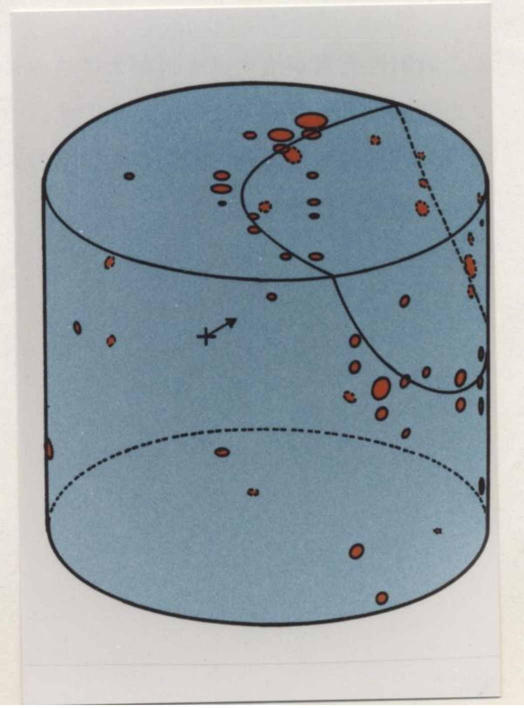


```
 >> TDC FIT <<

POS =     2.08     0.41     1.50
WALL=     5.10
FIT PARM. (IP,IMA,IV,IR,IMO)=  0  0  4  0  1
# OF ITERATION=  0

-- NO.1 --
IP,PH,P=  0       0.0       0. MEV
CENT=    2.075   0.413   1.504
DIR =   -0.806   0.087   0.585
GOOD=    0.744  ANGC=    0.000  DANG=    0.000
```

```
<< KAMIOKANDE 2 - P >>
- EXPLODED VIEW -
   NUM      # :         9
   RUN      # :      1892
   EVENT    # :    139372    -(-)
   TIME       : 23/ 2/87
                16.35.37
   DIF. TIME  : ********
   NOW        : 09/03/87
                00.41.08
   CPU        :      1784
   LCALP.SN1987A

   TOTAL ENRGY=        15 MEV
   TOTAL P.E. =        51 (    0)
   MAX   P.E. =         4 (    0)
   THRES P.E. =       0.2 ( 1.0)
   TDC =  61.2< 289.2
       =  61.2< 289.2( 23.)
```

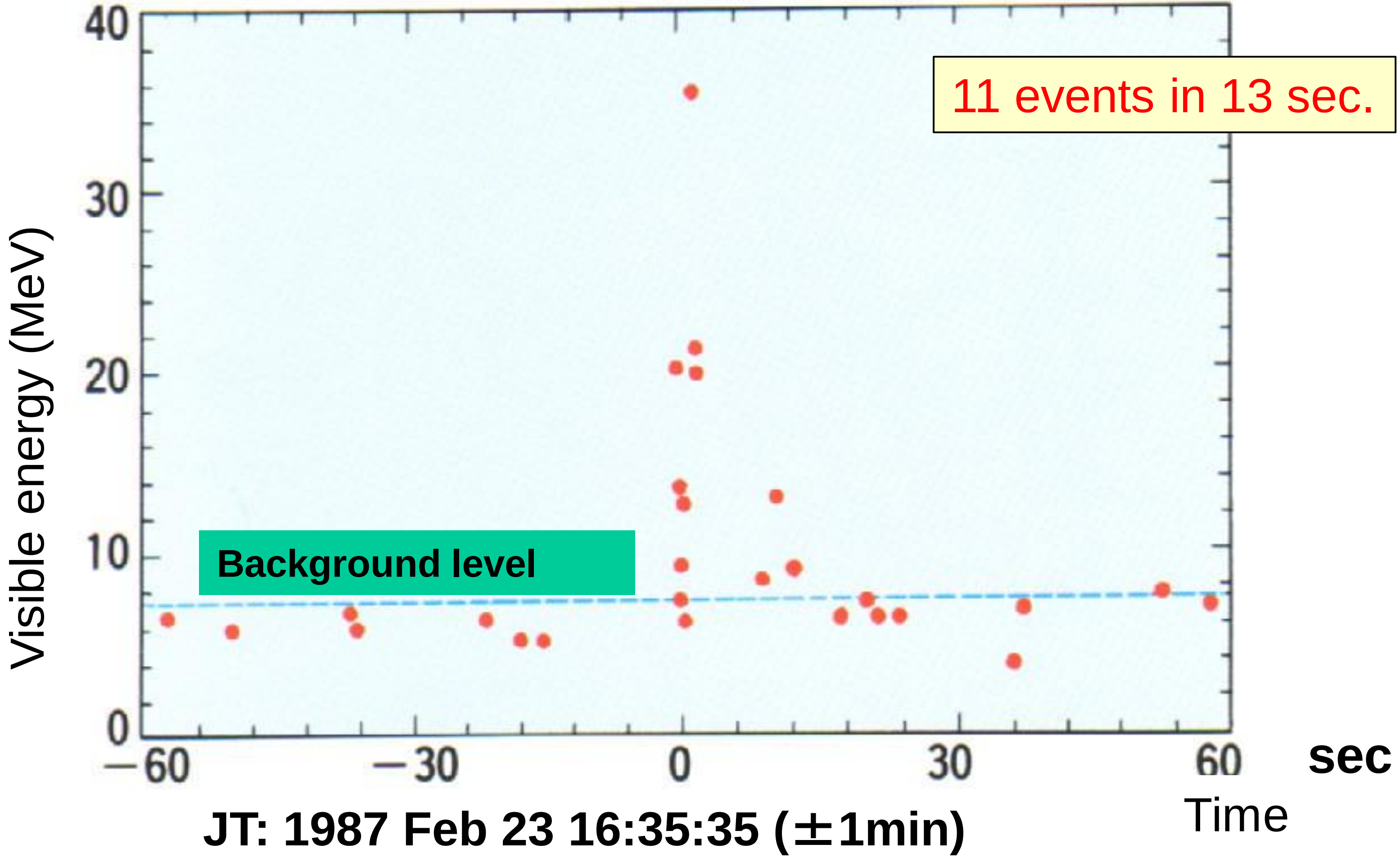
event #9

TFIT>>



SN1987A signal by Kamiokande

It happened when the Kamiokande detector was almost ready for solar neutrino detection.

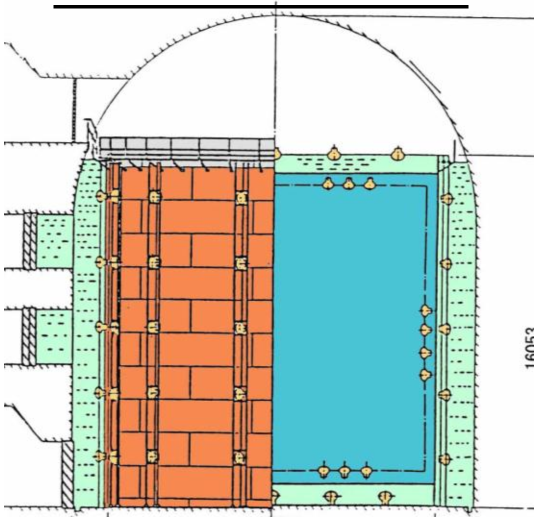


11 events in 13 sec.

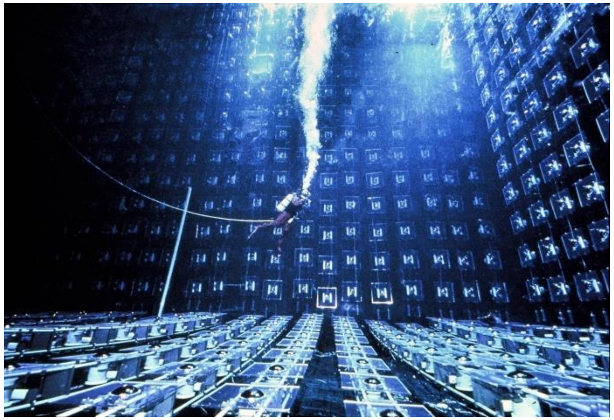
JT: 1987 Feb 23 16:35:35 (±1min)
UT: 7:35:35

SN1987A: supernova at LMC(50kpc)

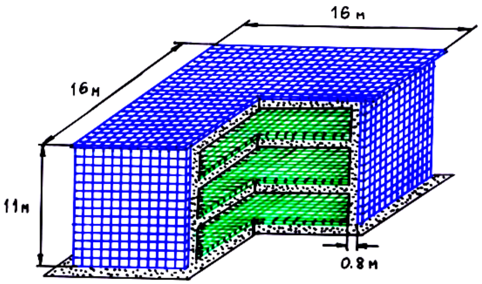
Kamiokande-II



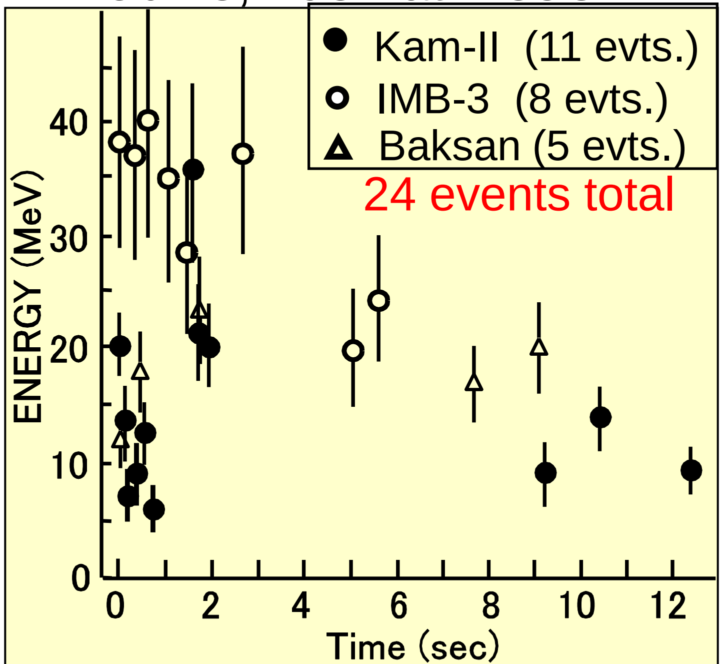
IMB-3

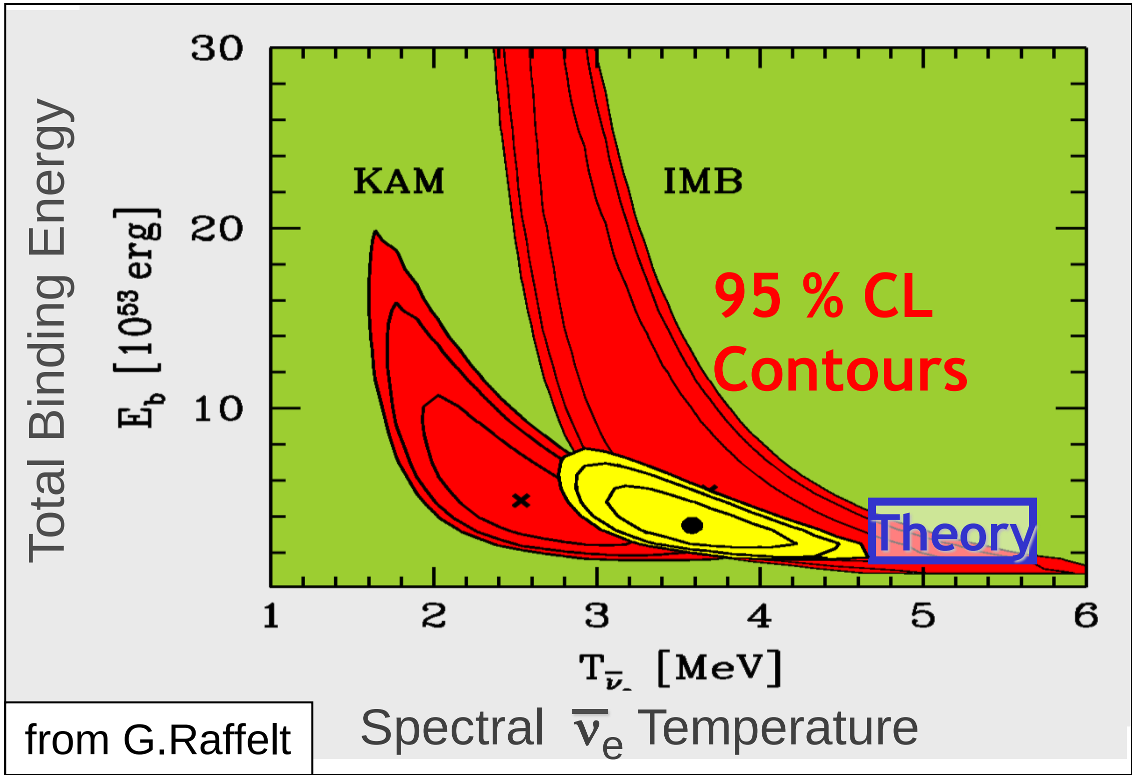


BAKSAN



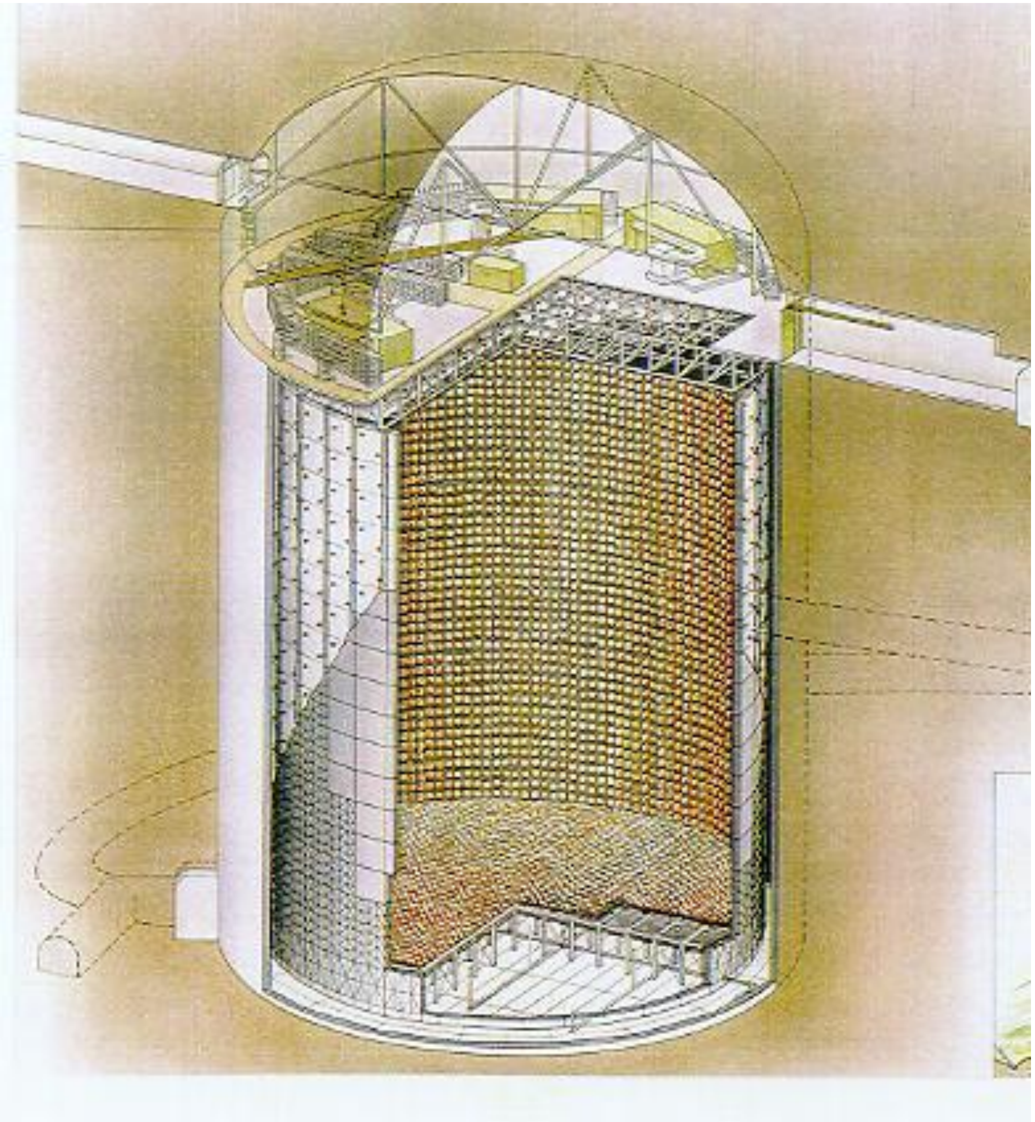
Feb.23, 1987 at 7:35UT





from G.Raffelt

Super-Kamiokande detector (1996 –)

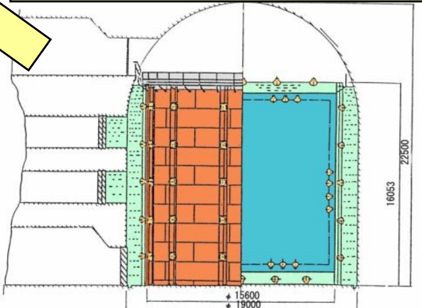


- 50,000 t water tank
  (42m high, 40m diameter)

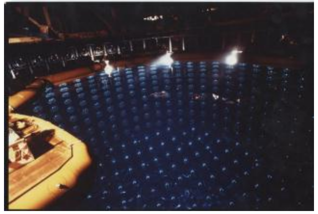
  32,000 t photo-sensitive volume

  22,000 t fiducial volume
- 11,146 20-inch PMTs
- Photo-coverage: 40%
  (x2 of Kamiokande in order to lower energy threshold)
- 1000m underground in Kamioka mine

X 30 fiducial volume than Kamiokande

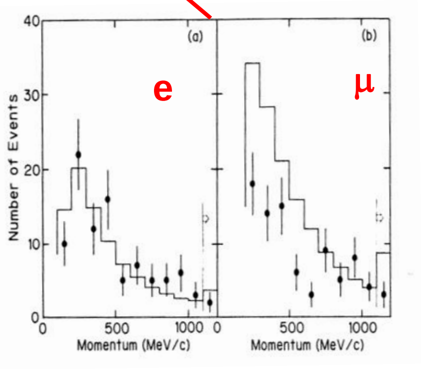


1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997

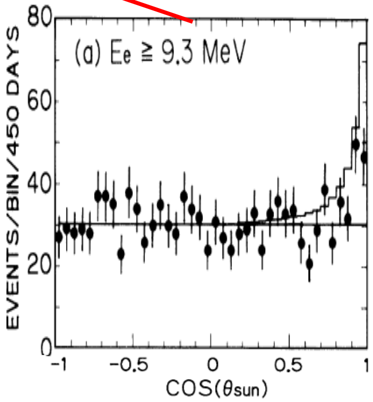


Kamiokande start

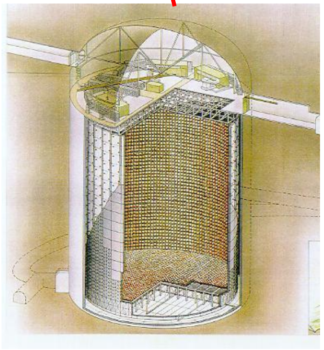
SN1987a



First atmospheric ν anomaly paper

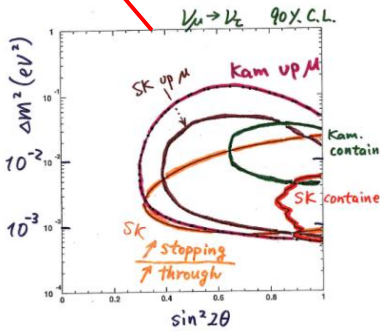


First solar ν observation (flux=0.5xSSM)

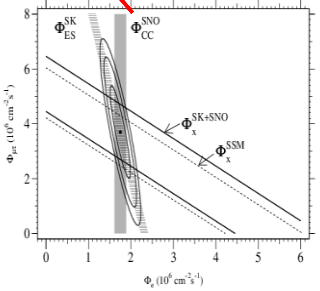


Super-K start

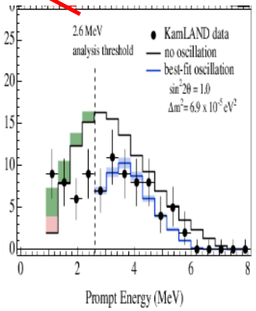
1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012



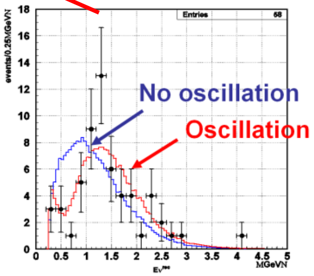
Atmospheric ν oscillations



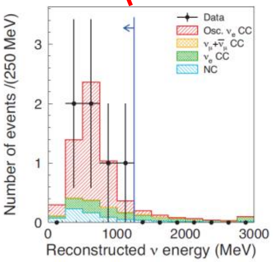
Solar ν oscillations (SK vs. SNO CC)



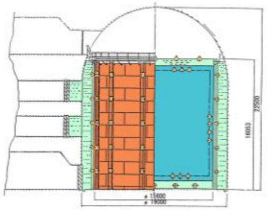
Reactor ν oscillations by KamLAND



K2K confirmed atmospheric osc. by long baseline ν

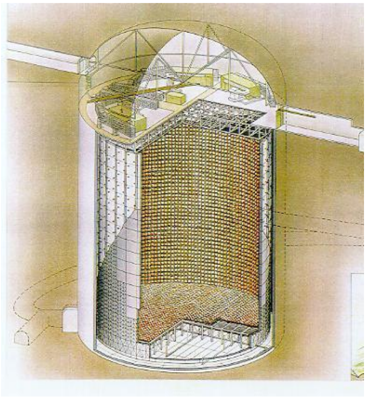


θ13 by T2K



Kamiokande 780 ton fiducial / 3000 ton total water Cherenkov detector

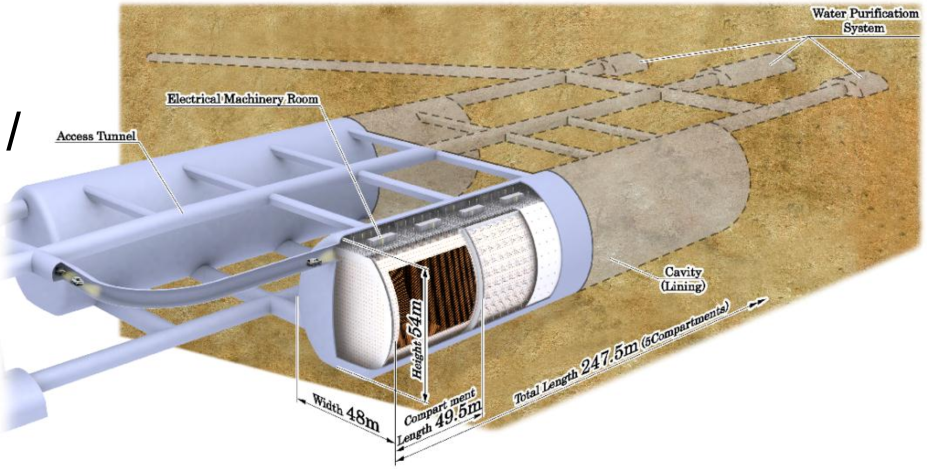
X ~30 times



Super-Kamiokande 22,500 ton fiducial / 50,000 total water Cherenkov detector

X ~25 times

Hyper-Kamiokande 560,000 ton fiducial / 990,000 total water Cherenkov detector



Japanese saying: 3度目の正直.

The third time’s the charm.

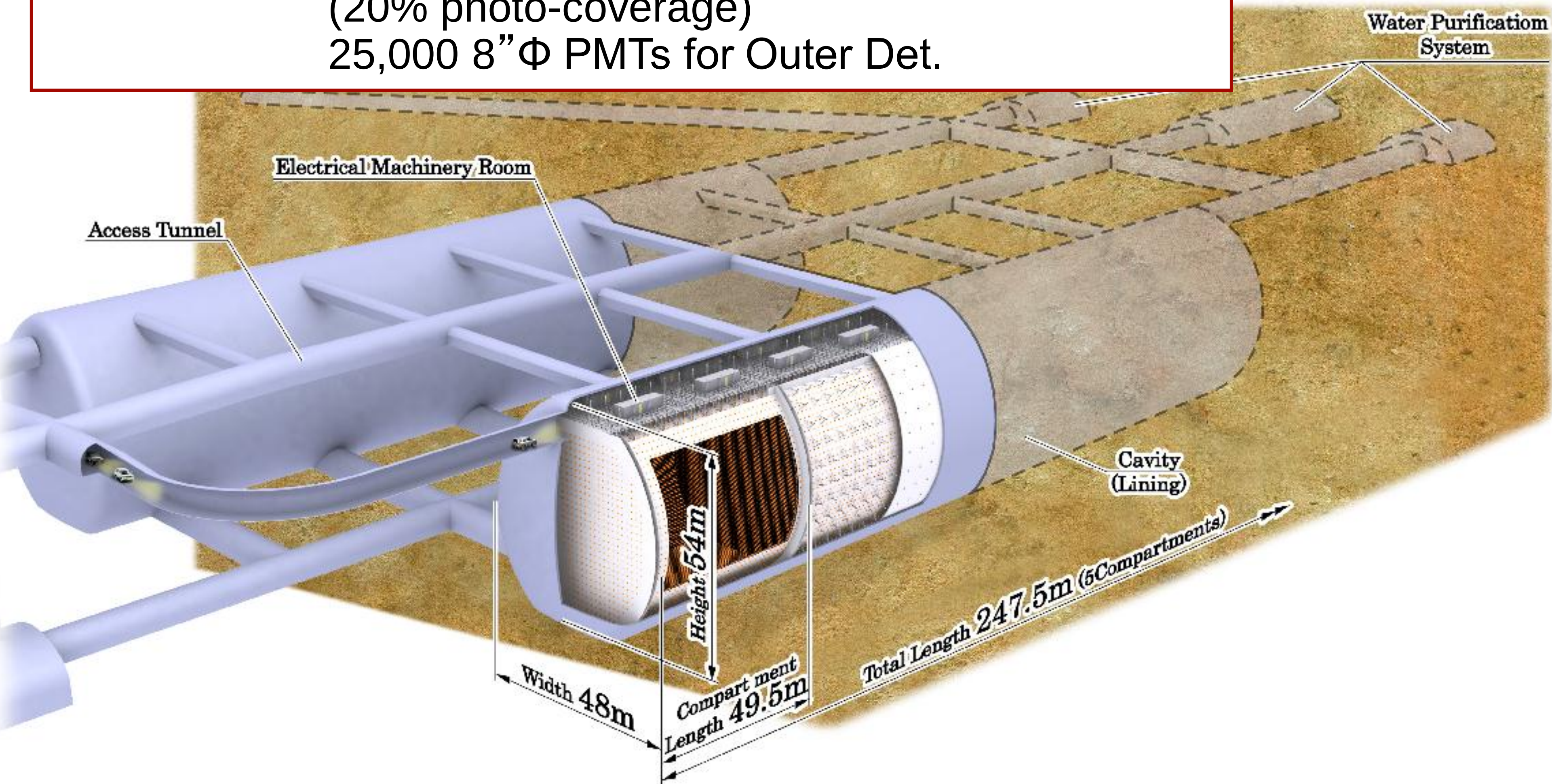
La troisième fois sera la bonne.

My translation

Proton decay will be observed in the third generation experiment.

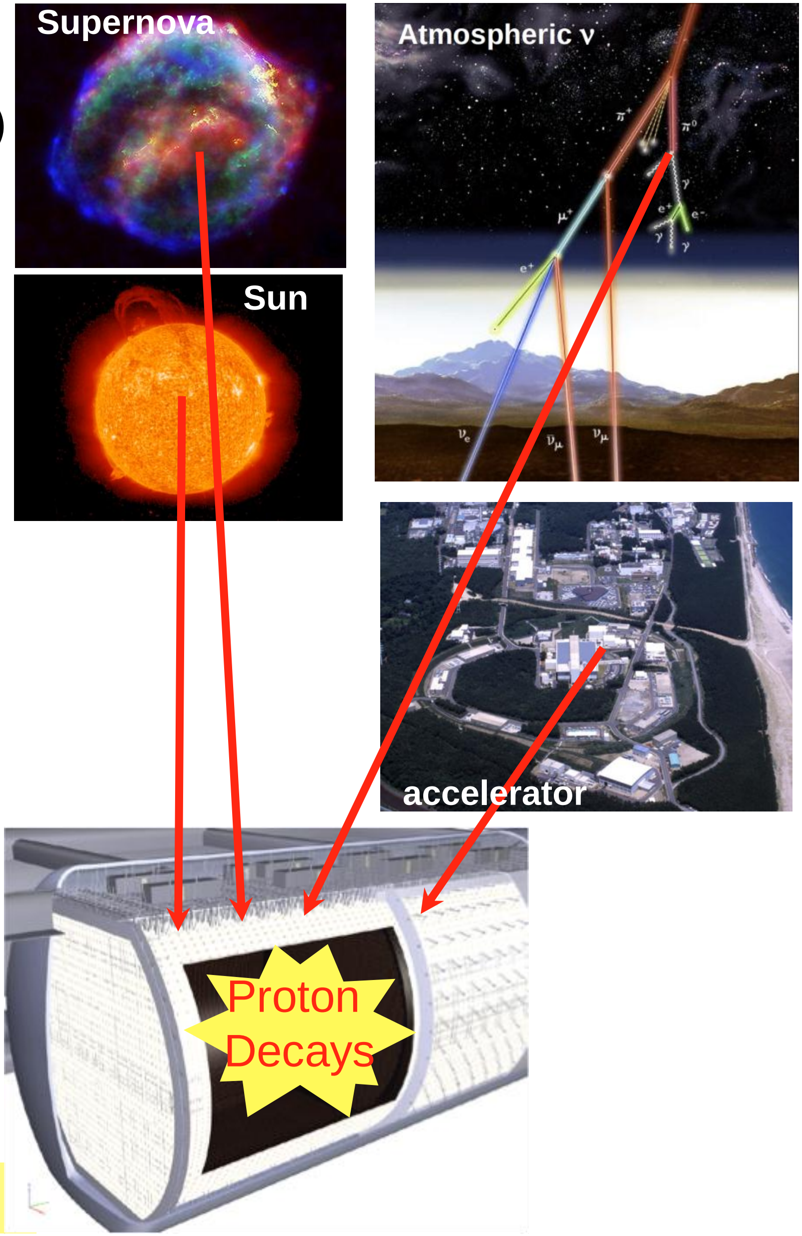
Schematic view of Hyper-Kamiokande

Total Volume	0.99 Megaton
Inner Volume	0.74 Mton
Fiducial Volume	0.56 Mton (0.056 Mton × 10 compartments)
Outer Volume	0.2 Megaton
Photo-sensors	99,000 20”Φ PMTs for Inner Det. (20% photo-coverage) 25,000 8”Φ PMTs for Outer Det.



Multi-purpose detector, Hyper-K

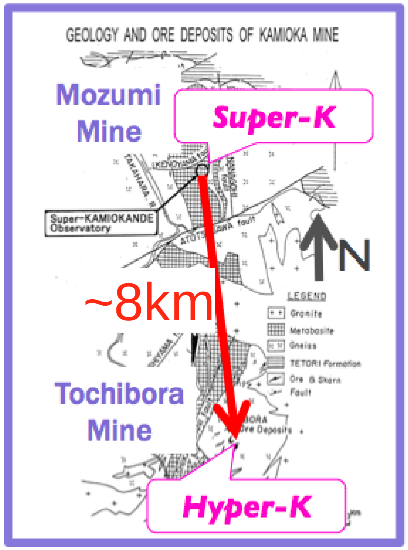
- Explore full picture of neutrino oscillation parameters.
  - Discovery of leptonic CP violation (Dirac δ)
  - ν mass hierarchy determination($\Delta m^2_{32}>0$ or <0)
  - θ_{23} octant determination ($\theta_{23}<\pi/4$ or $>\pi/4$)
- Extend nucleon decay search sensitivity
  - $\tau_{proton}=10^{34}\sim10^{35}$ years
- Neutrinos from astrophysical objects
  - 200 ν's / day from Sun
    - possible time variation, day/night matter effect.
  - 250,000 (50) ν's from Supernova @Galactic-center (Andromeda)
  - ~800 ν's / 10 years (>10MeV) SN relic ν
  - WIMP ν, solar flare ν, etc

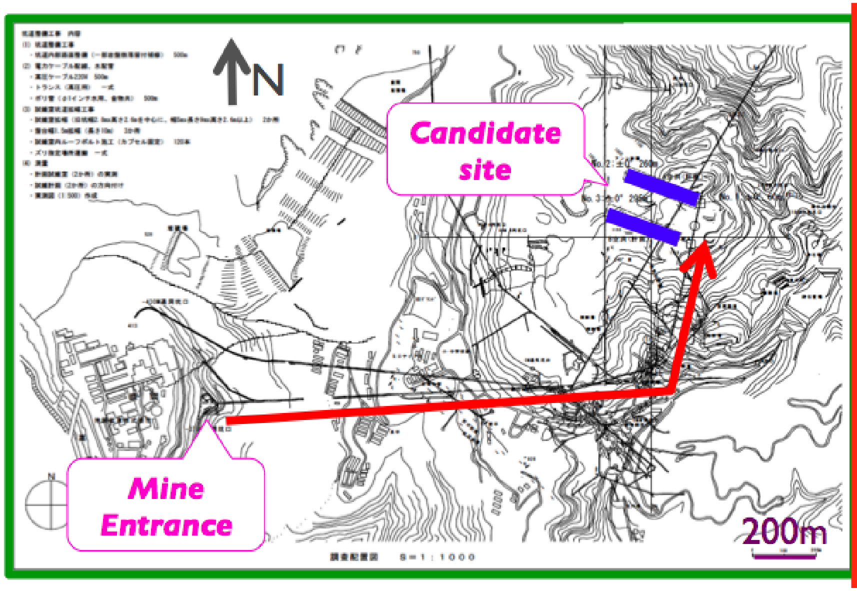


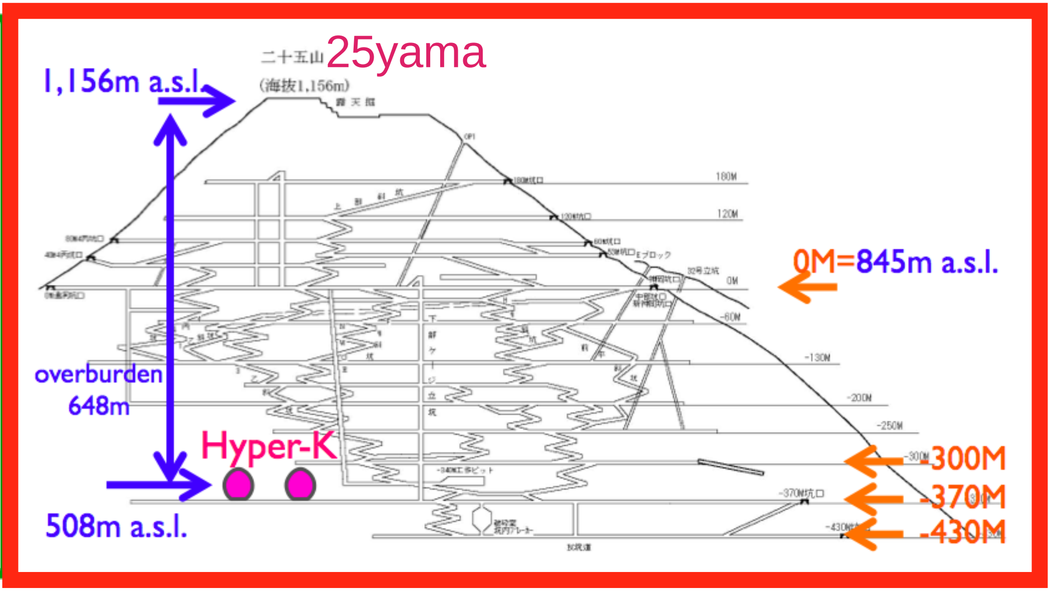
Letter of Intent, Hyper-K WG, arXiv:1109.3262 [hep-ex]

Hyper-Kamiokande candidate site

- 8km south from Super-K
  - same T2K beam off-axis angle (2.5 degree)
  - same baseline length (295km)
- 2.6km horizontal drive from entrance
- under the peak of Nijuugo-yama
  - 648m of rock or 1,750 m.w.e. overburden
- 13,000 m^3/day or 1megaton/80days natural water







Accelerator ν

Hyper-K

~0.6GeV νμ

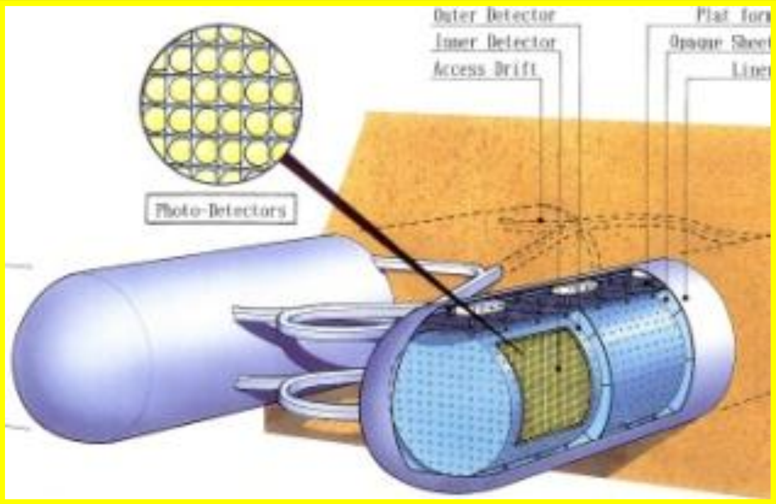
295km baseline

Future LBL plans using J-PARC

Current: T2K
J-PARC ~0.75MW
+ 50kt WC @ 295km 2.5°

J-PARC+HK @ Kamioka

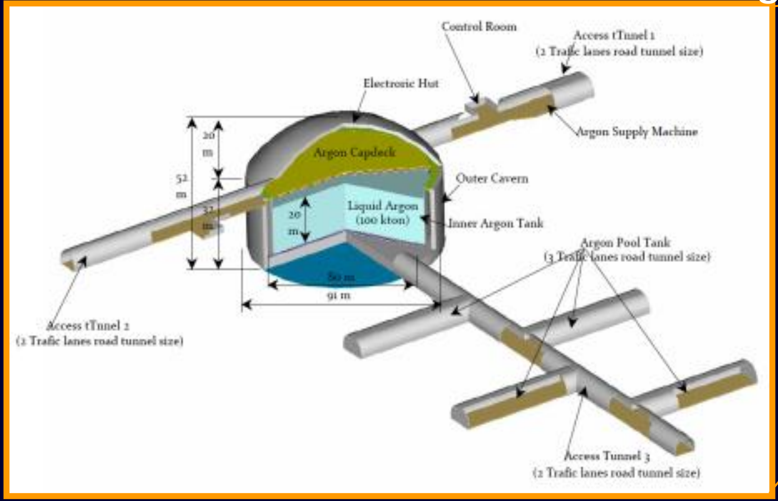
L=295km OA=2.5deg



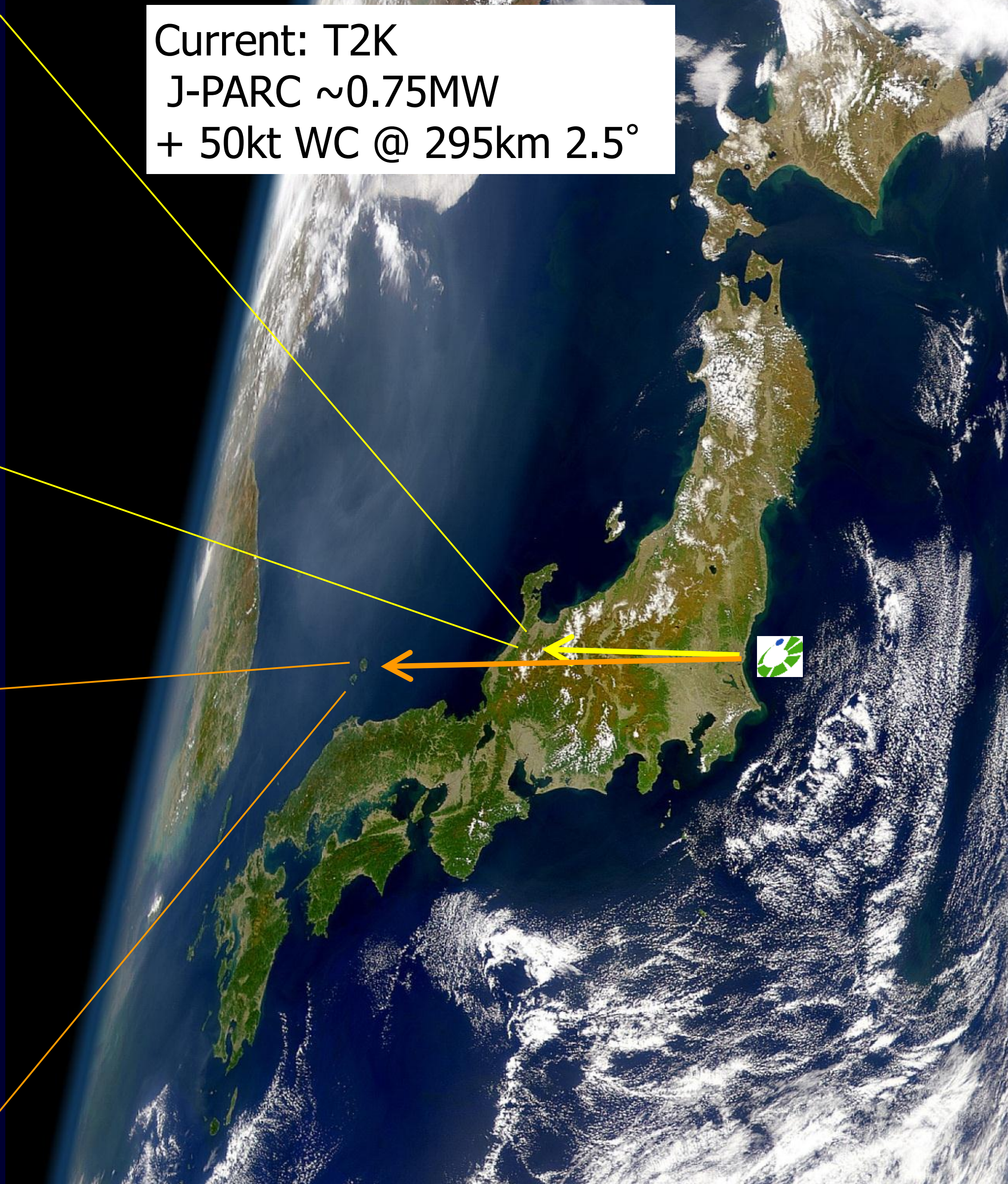
LoI: The Hyper-Kamiokande Experiment
arXiv:1109.3262v1

J-PARC+LAr @ Okinoshima

L=658km OA=0.78deg



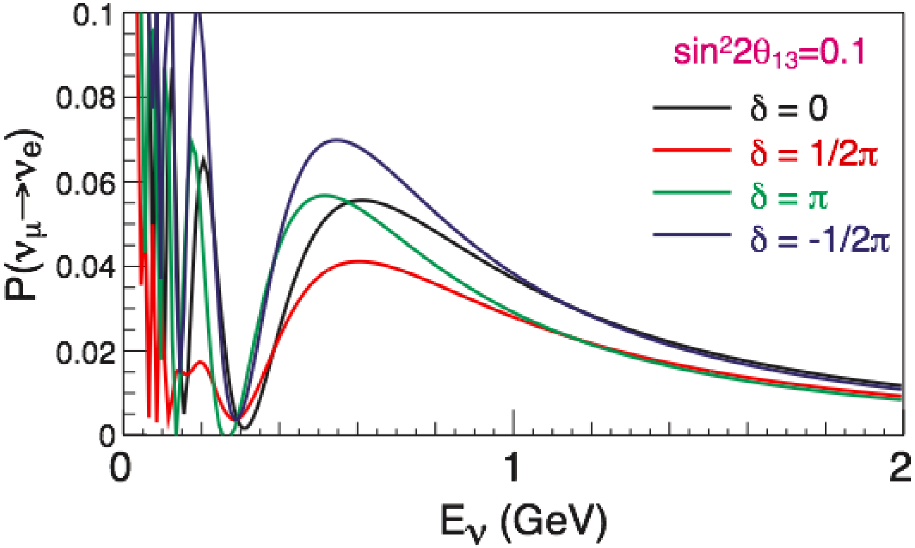
J-PARC P32 (LAr TPC R&D), arXiv:0804.2111



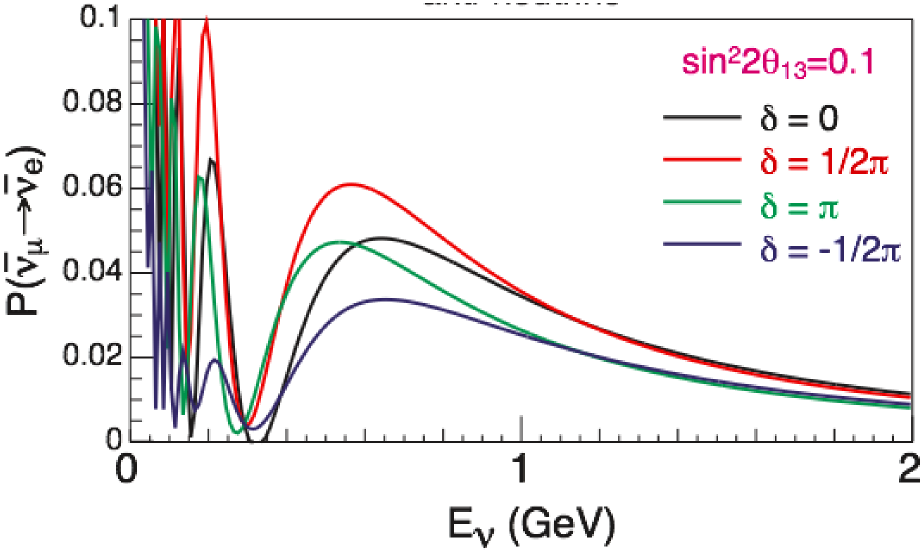
$\nu_\mu \rightarrow \nu_e$ probability (L=295km)

Normal hierarchy

Neutrino case



Anti-neutrino case



- Comparison between $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - As large ±25% from nominal.

Expected ν_e CC candidates

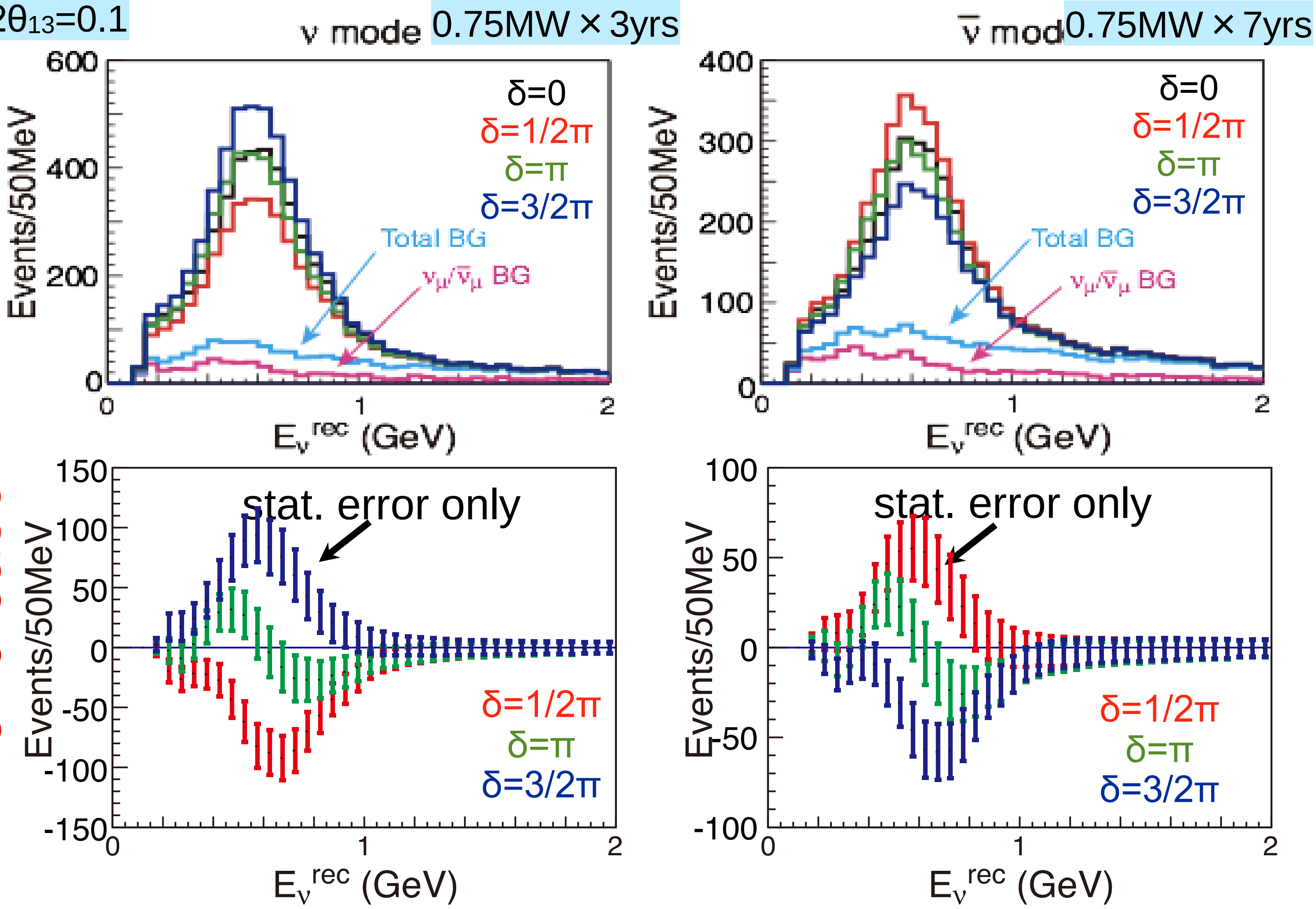
$\sin^2 2\theta_{13}=0.1$

0.75MW × 3yrs

0.75MW × 7yrs

ν_e candidates

diff. from $\delta=0$ case



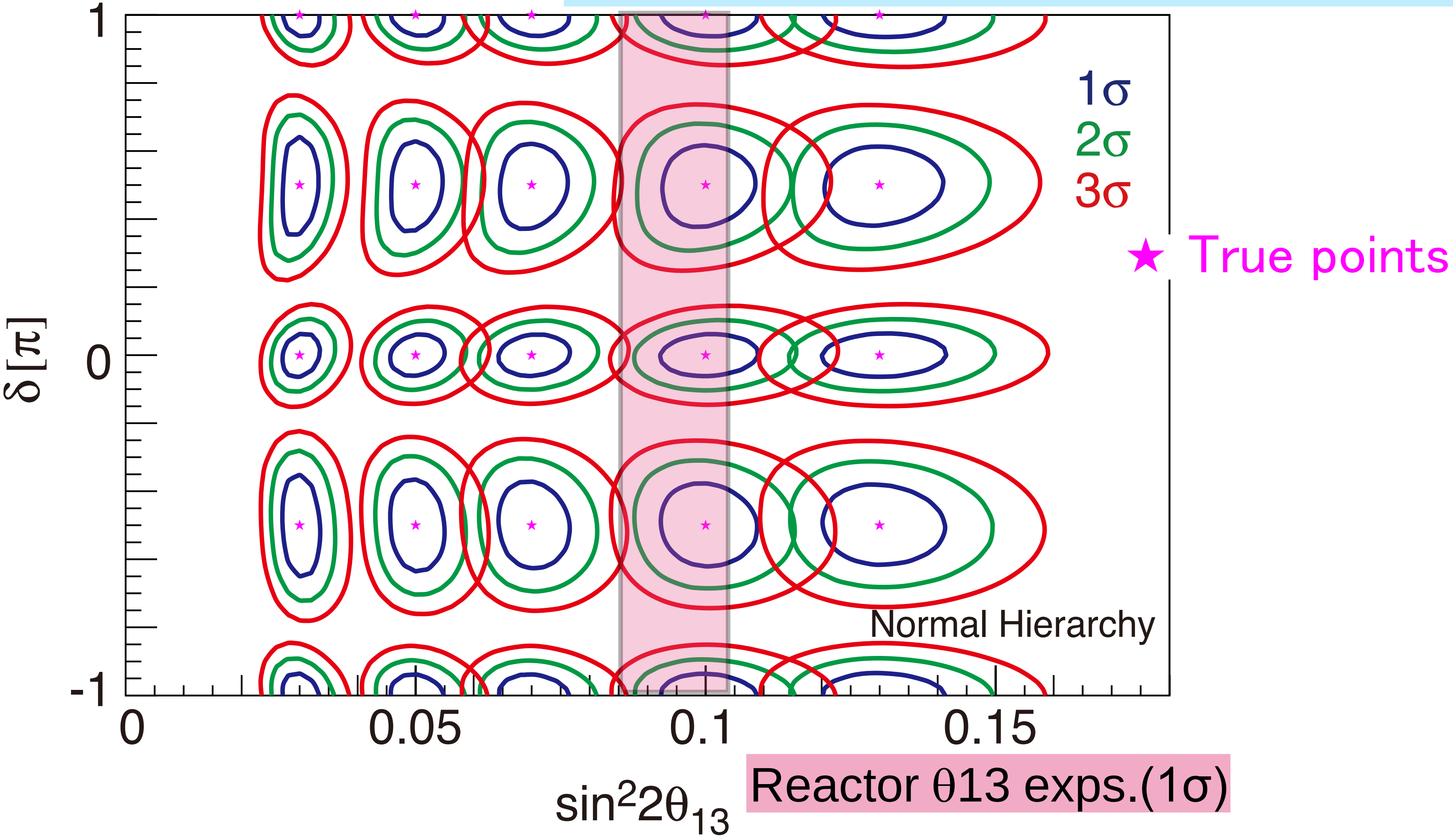
Numbers and shape for CP measurement

Expected Contours

7.5MW・years

Normal mass hierarchy (known)

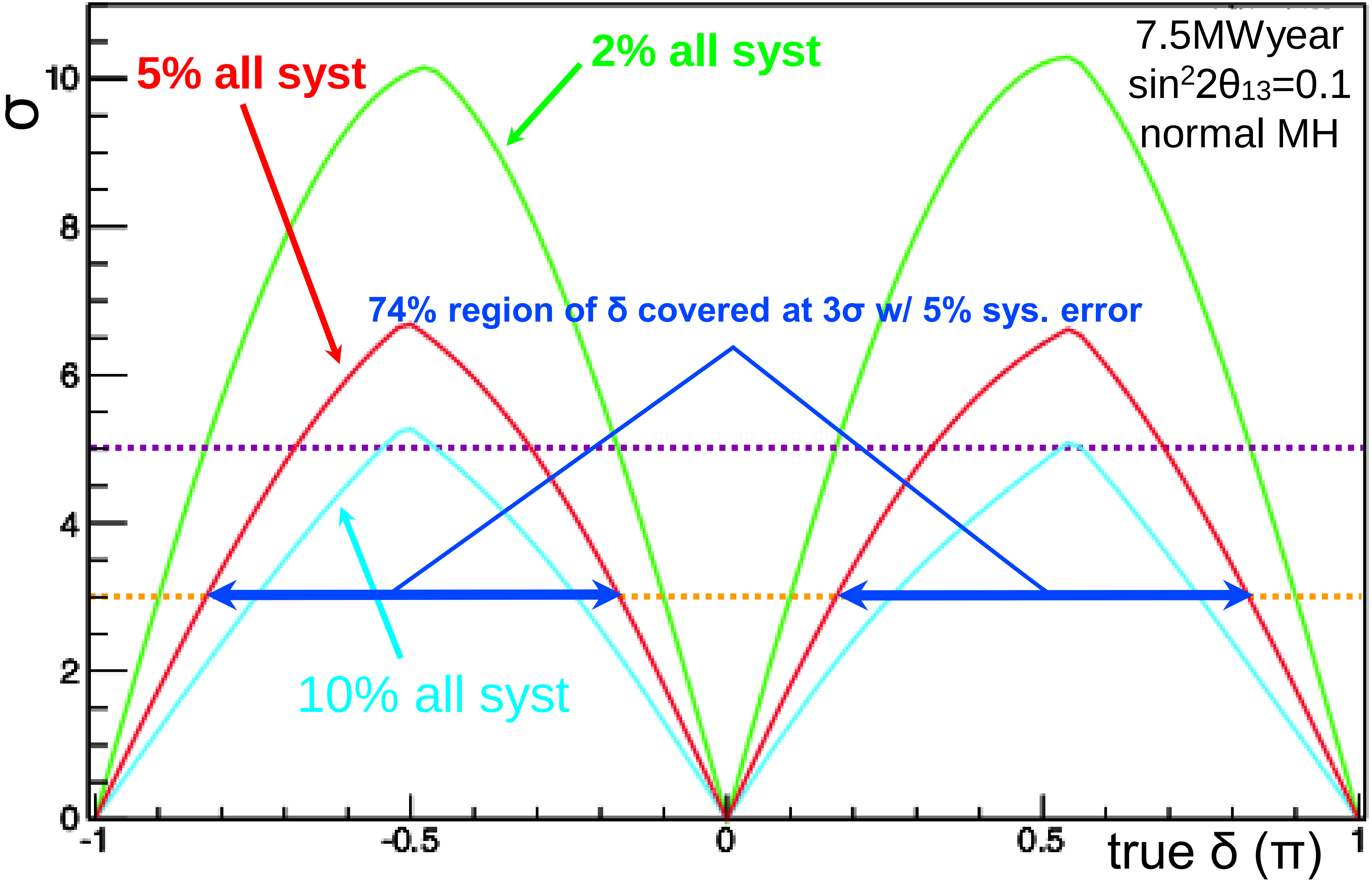
5% systematics on signal, ν_μ BG, ν_e BG, $\nu/\bar{\nu}$



- Good sensitivity for CPV

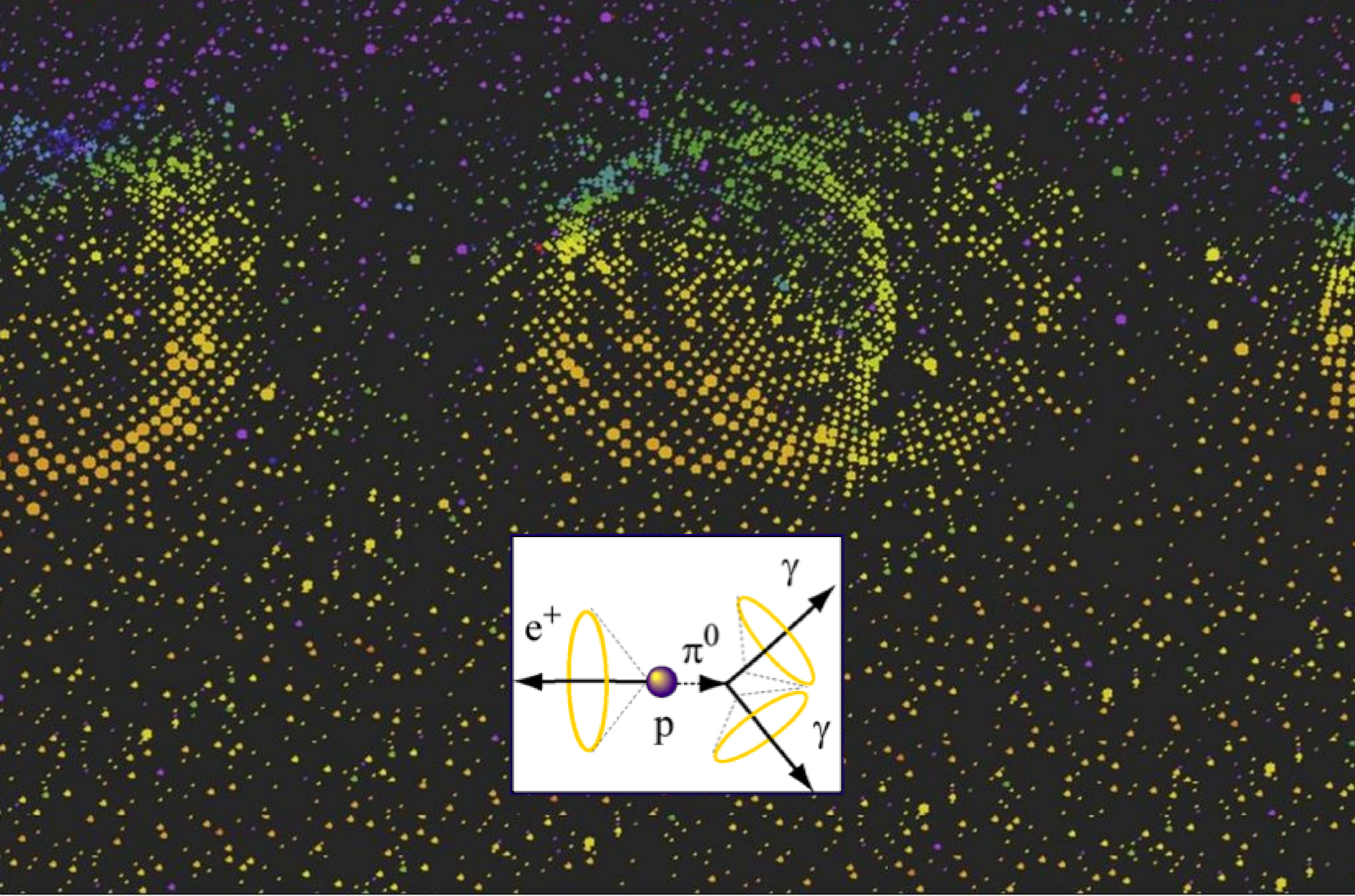
CPV Discovery Sensitivity

(w/ Mass Hierarchy known)

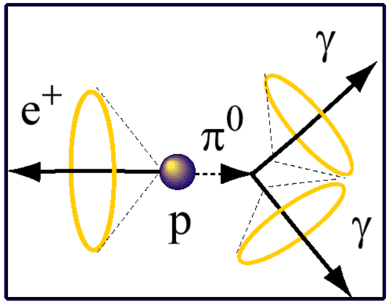


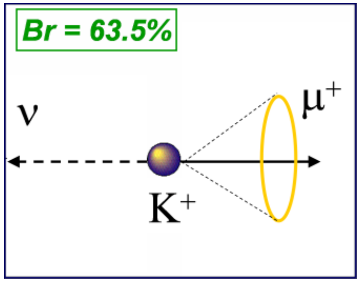
High Sensitivity to CPV w/ <~5% sys. error

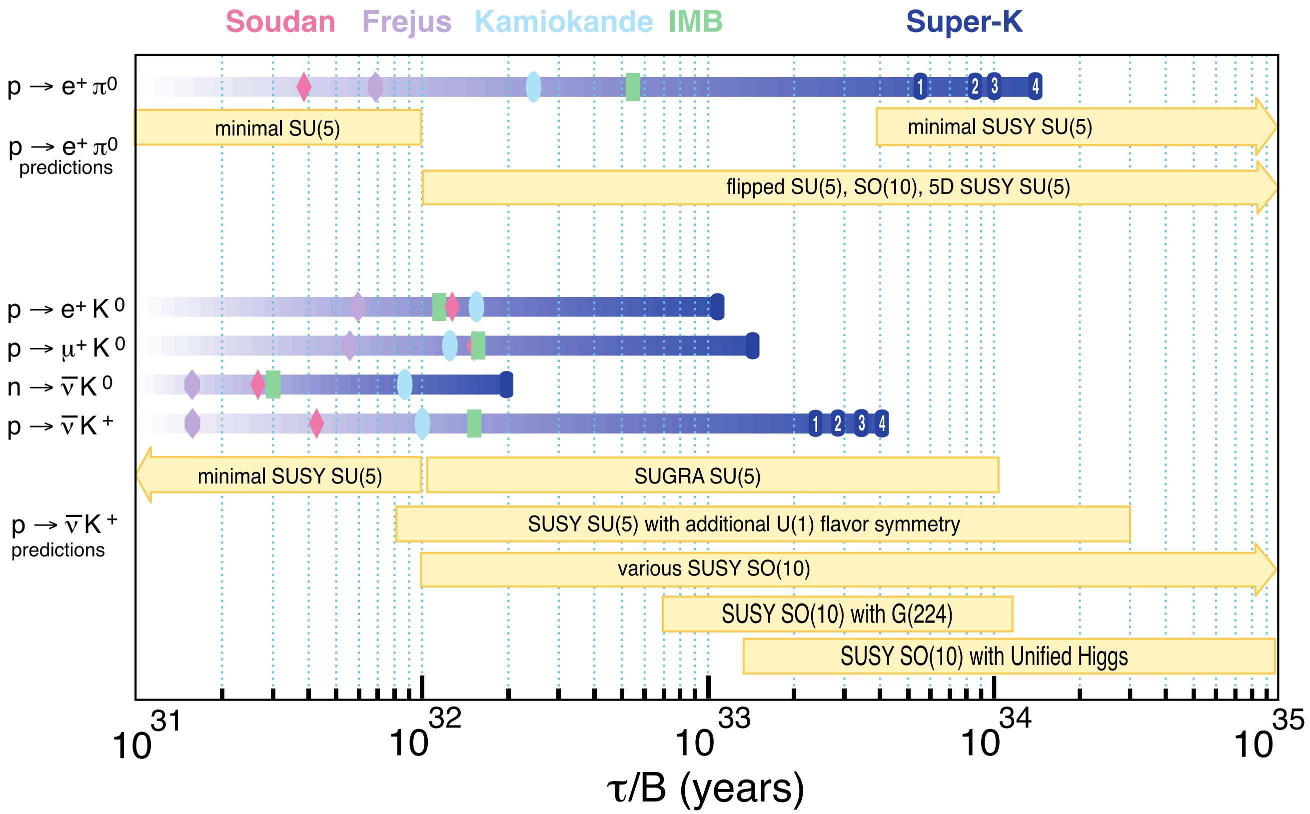
Proton Decays



Current Experimental Limits

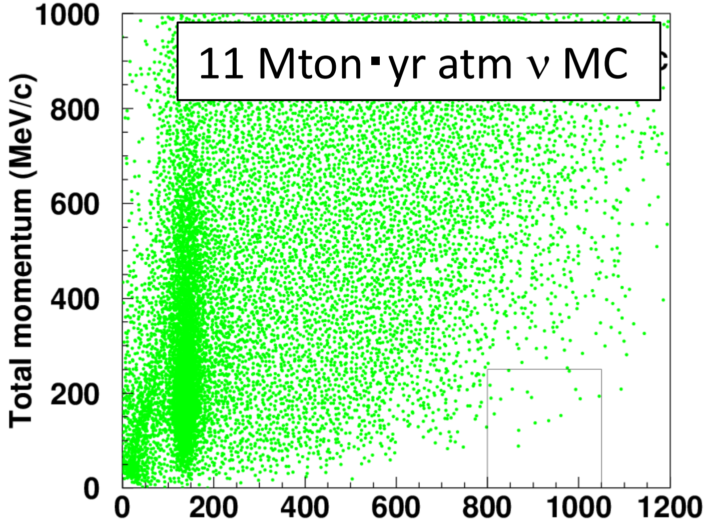


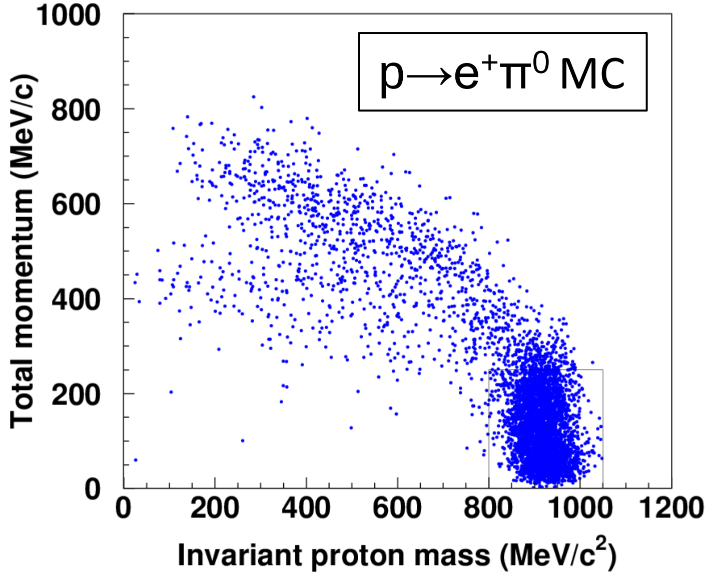




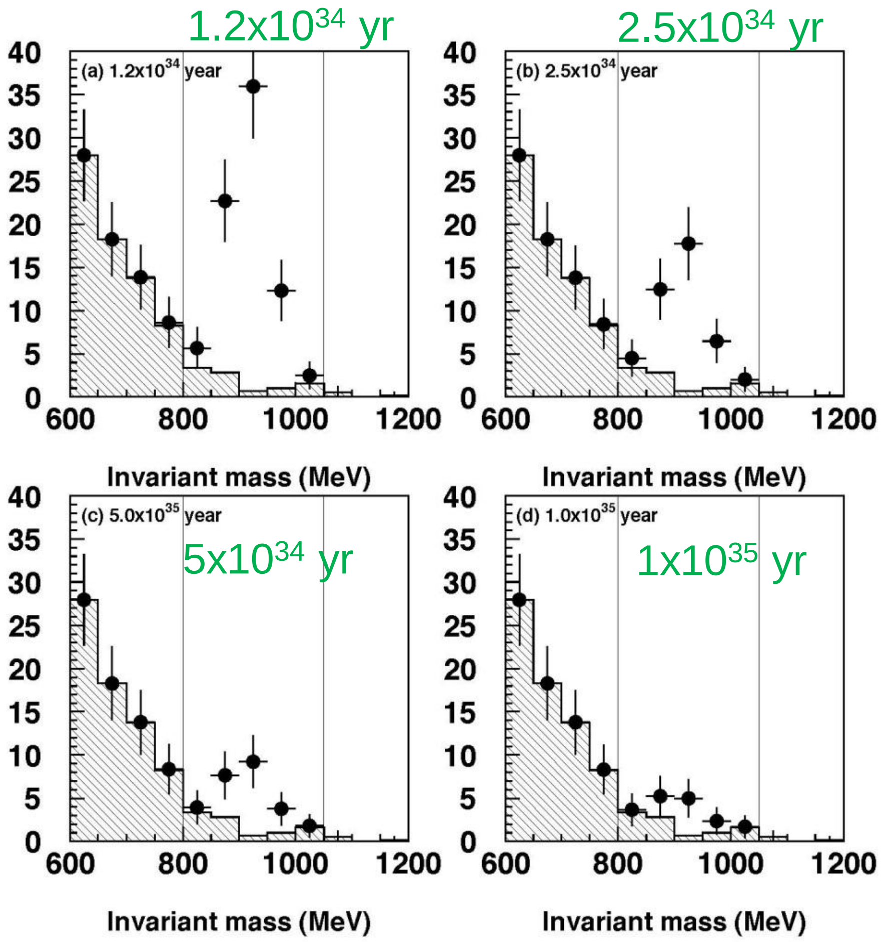
- Super-K gives most stringent limits for many decay modes.
- $\tau(p \to e^+\pi^0) > 1.3 \times 10^{34}$ years (90%C.L. by 220kton・yrs data)
- $\tau(p \to \nu K^+) > 4.0 \times 10^{33}$ years (90%C.L. by 220kton・yrs)
- No signal evidence has been found ➡ giving constraints on models (GUTs)
- Constraints on SUSY models (ex: R-parity conservation)
- Exclude minimal *SU(5)* and minimal SUSY *SU(5) models.*

$p \rightarrow e^+ + \pi^0$ mode at Hyper-K





Reconstructed proton mass(10 years)
(Total p < 250 MeV/c)

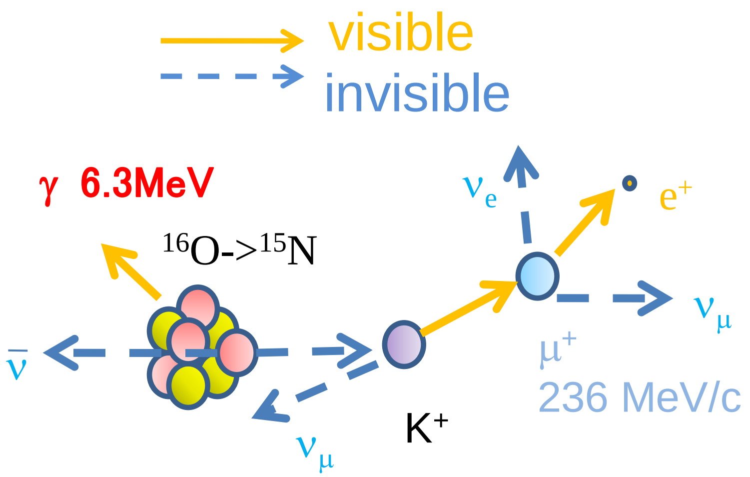


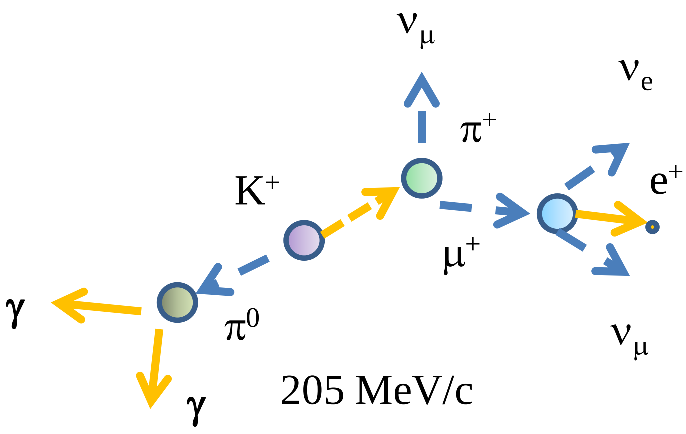
Discovery potential (3σ): 5.7×10^{34} years

Sensitivity (90%C.L.): 1.3×10^{35} years

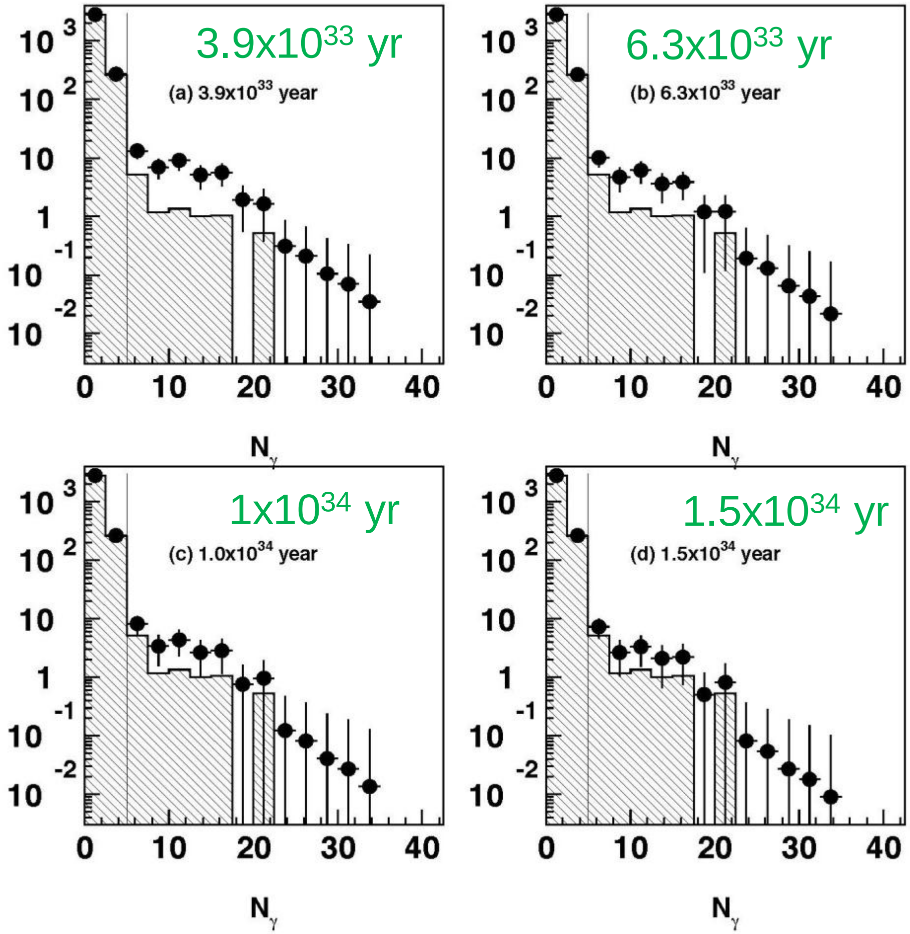
with 10 years run (5.6 Mton·yrs)

$p \rightarrow \nu K^+$ mode at Hyper-K





Number of hits of the prompt gamma signal (10 years)



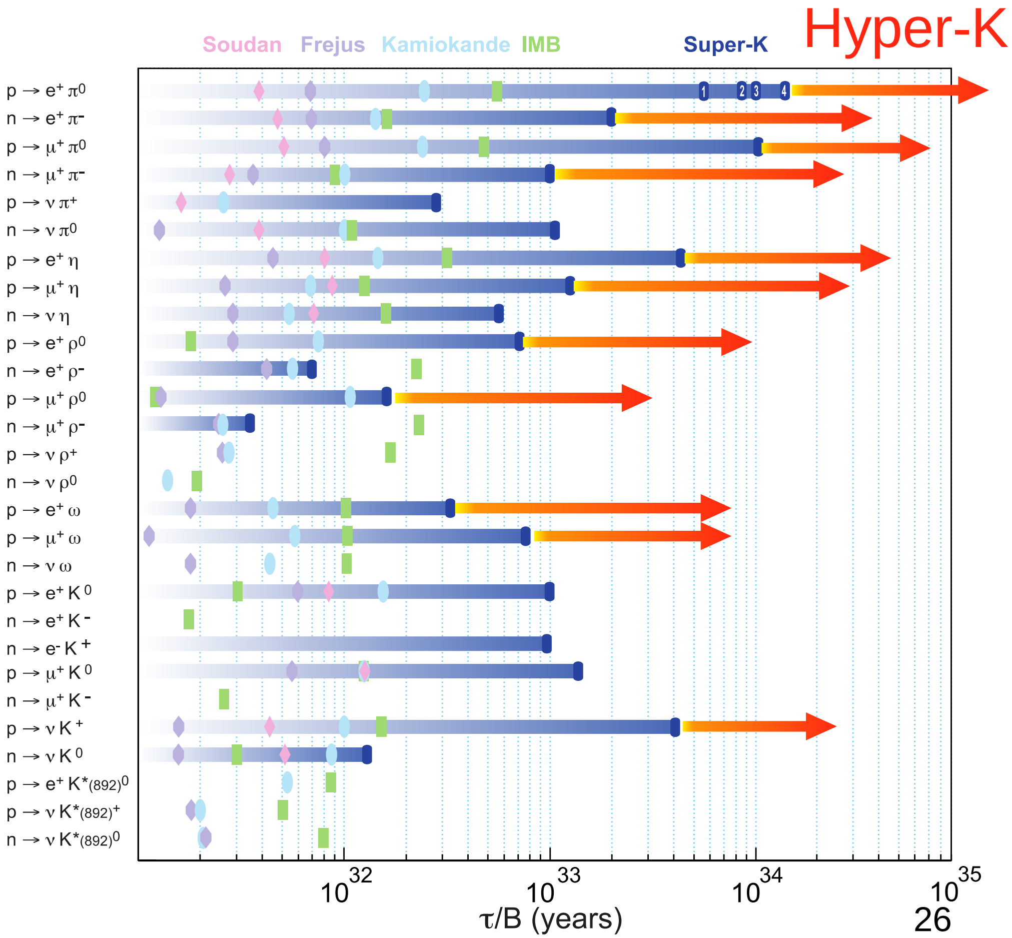
Discovery potential (3σ): 1.0x10^{34} years

Sensitivity (90%C.L.): 2.5x10^{34} years

with 10 years run (5.6 Mton･yrs)

Sensitivity for various decay modes

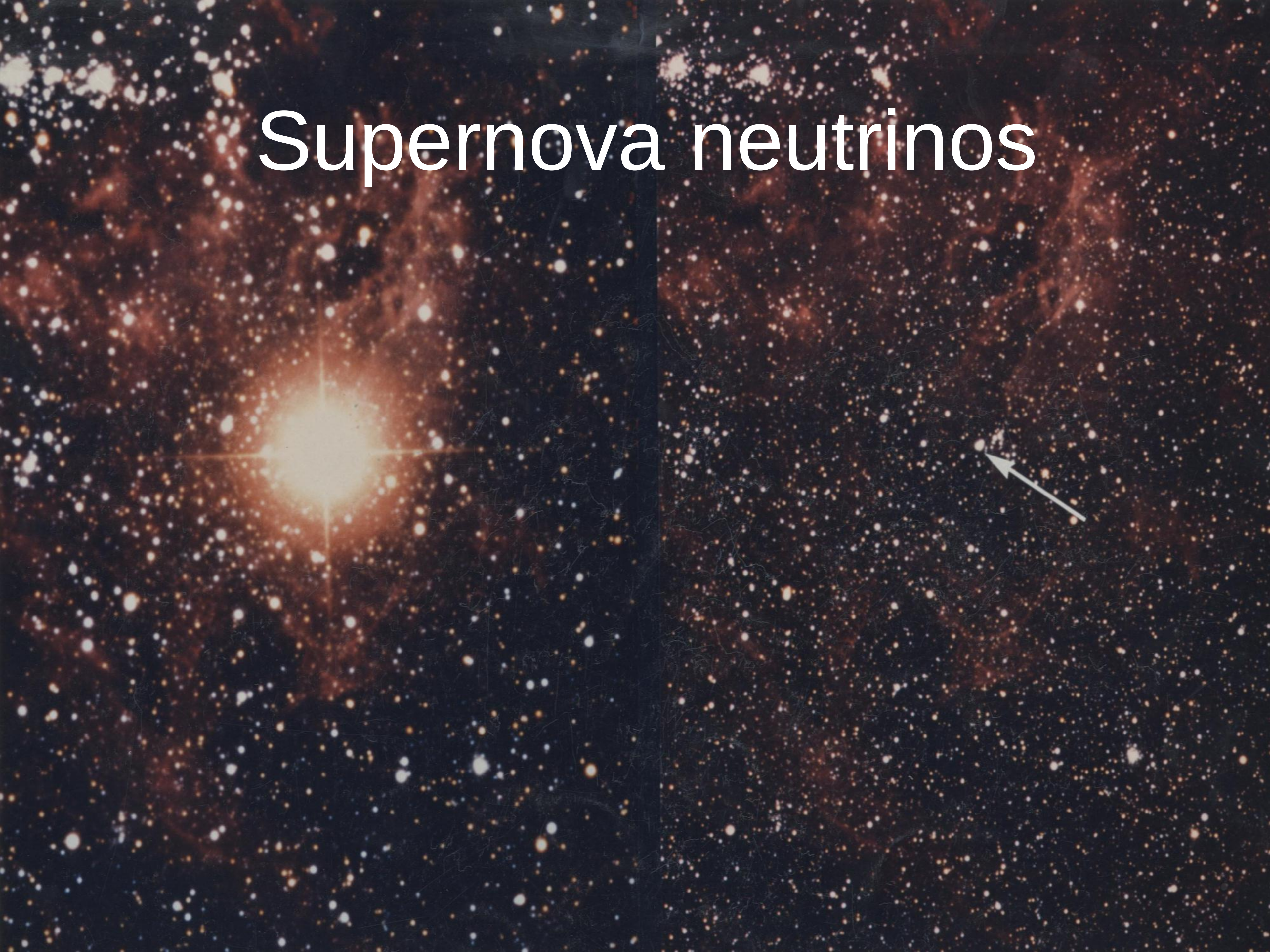
- 10 times better sensitivity than Super-K.
- go beyond 10^{35} years for $p \rightarrow e^{+}+\pi^{0}$
- >3σ discovery is possible for lifetime beyond Super-K limits.



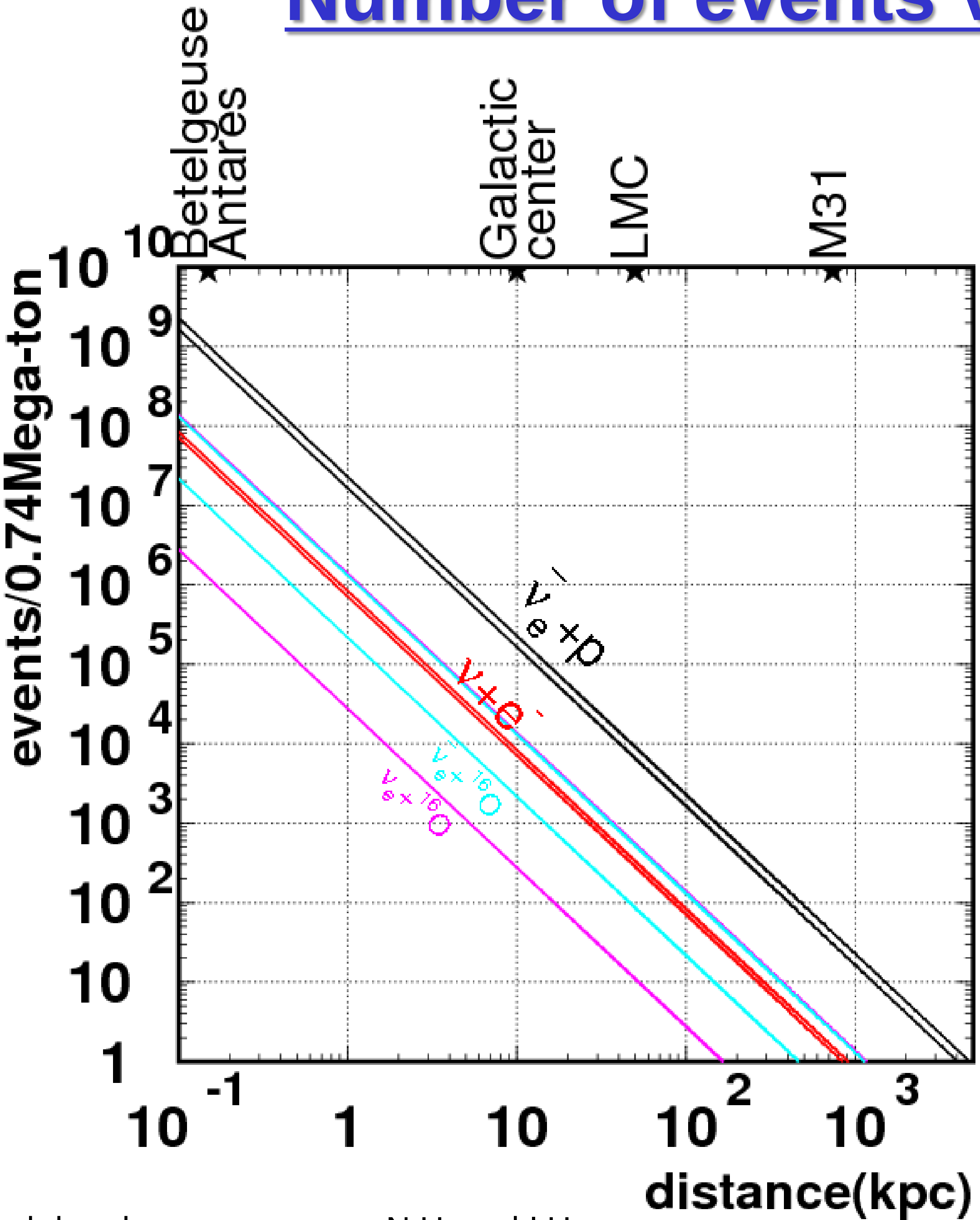
__Hyper-K sensitivities__

- *$p \rightarrow e^{+}+\pi^{0}$*
  - $\tau_{proton}/Br > 1.3 \times 10^{35}$ years @90%CL
  - 5.6Mton × years (10 Hyper-K years)
  - *$p,n \rightarrow (e^{+},\mu^{+})+(\pi,\rho,\omega,\eta)$*
  - $O(10^{34\sim35})$years
  - *SUSY favored $p \rightarrow \nu+K^{+}$*
  - 2.5×10^{34} years
  - K^{0} modes, $\nu\pi^{0}$, $\nu\pi^{+}$ possible
  - Other various decay modes.
  - (B-L) violated modes
  - radiative decays *$p \rightarrow e^{+}\gamma$, $\mu^{+}\gamma$*
  - neutron-antineutron振動 (|ΔB|=2)
  - di-nucleon decays (|ΔB|=2)
  - pp→XX..., nn→XX...

Supernova neutrinos



Number of events vs. distance



Expected number of events

~200,000 $\bar{\nu}_e + p \rightarrow e^+ + n$

~7,500 $\nu + e \rightarrow \nu + e$

~10,000 $\nu_e + {}^{16}O \rightarrow e + N/F$

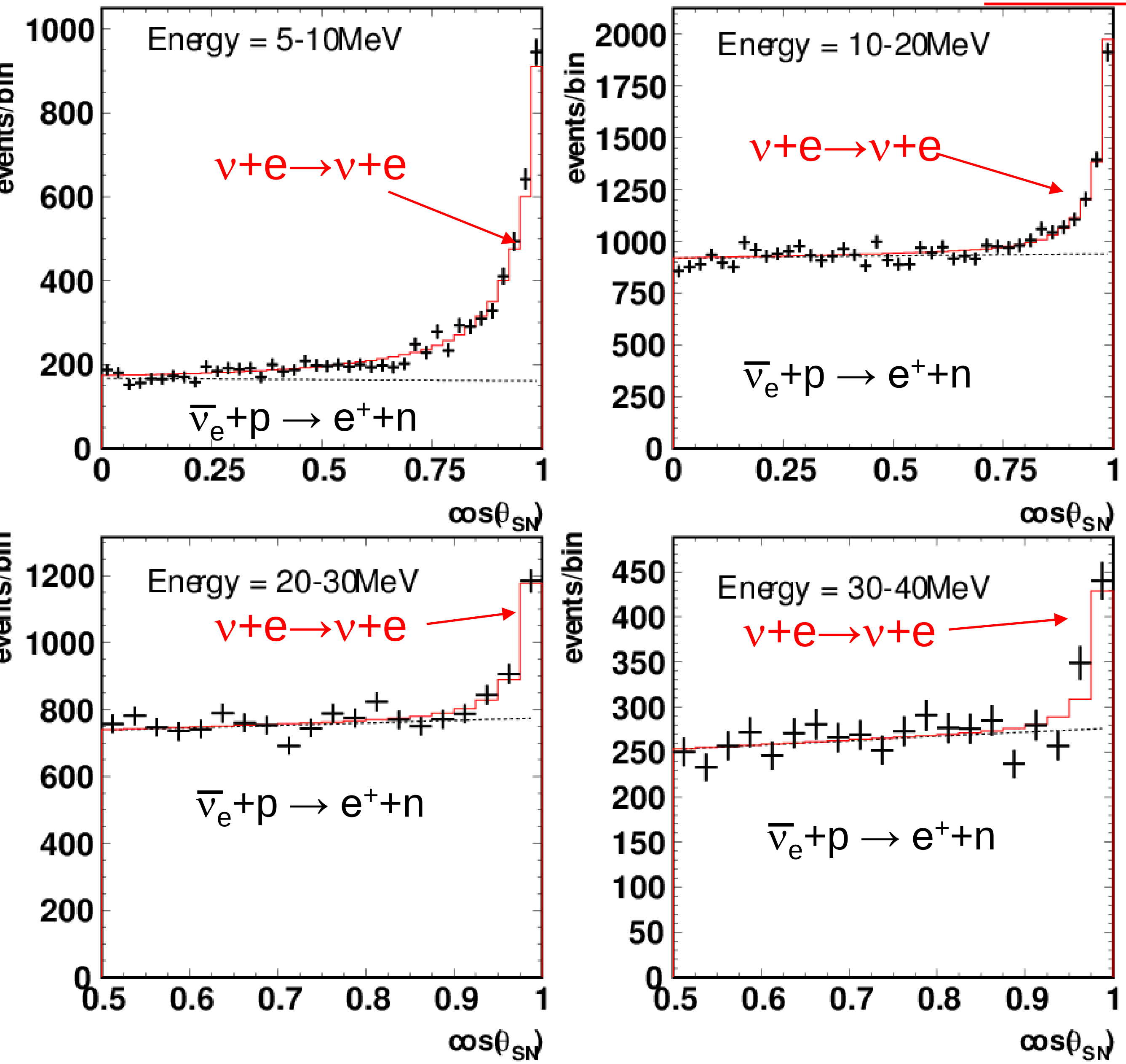
for 10 kpc supernova

Even for a supernova at M31 (Andromeda Galaxy), about 30~50 events are expected.

Each band covers, no osc., N.H. and I.H. cases

Event direction to supernova

SN at 10kpc, Hyper-K



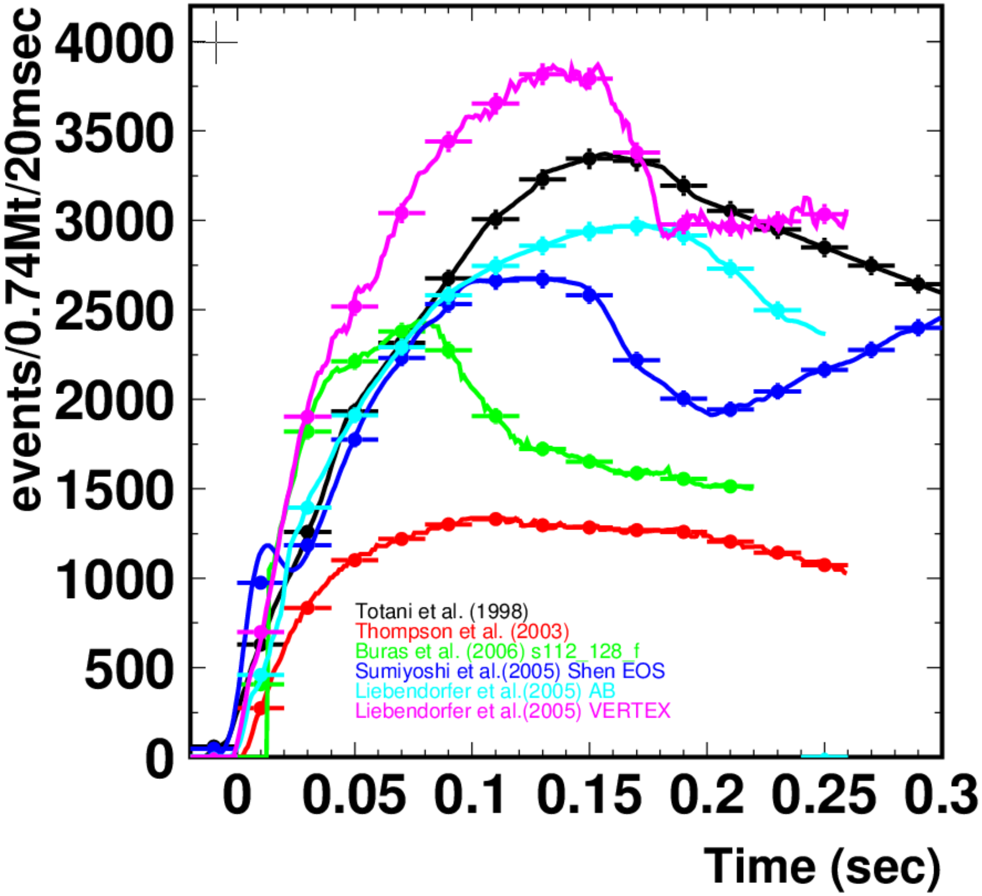
Angular resolution to supernova ~2°

It is possible to extract ν+e events and discuss their energy spectrum.

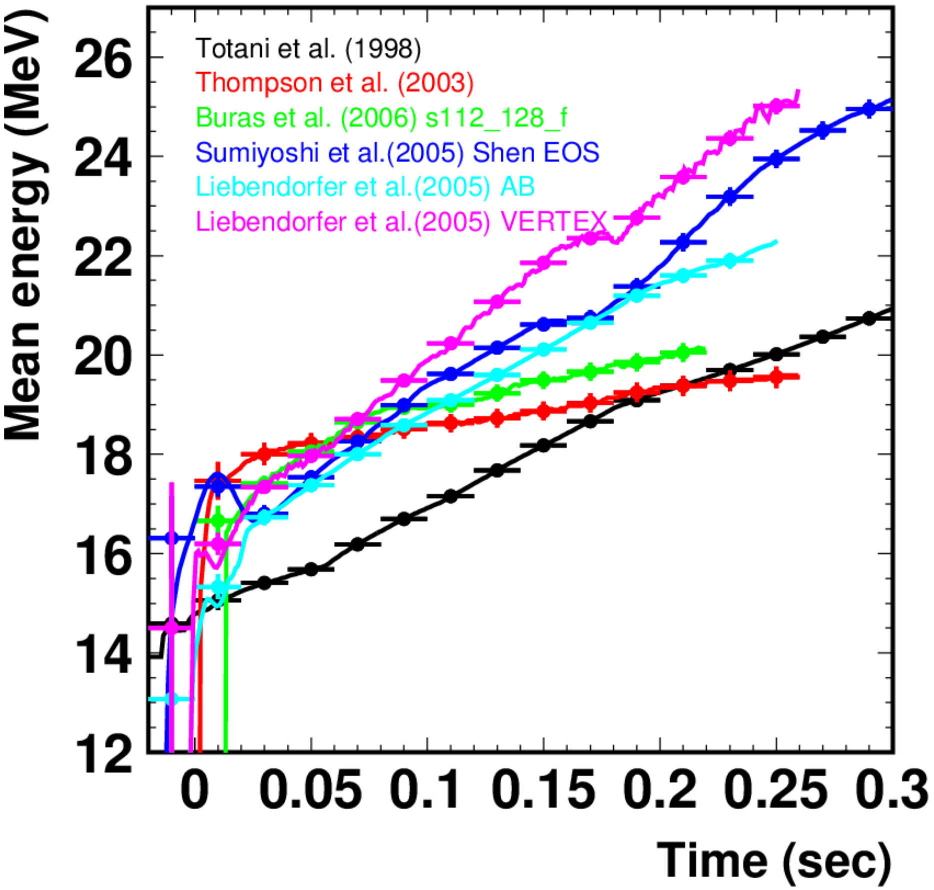
Time variation measurement by $\bar{\nu}_e$+p

Assuming a supernova at 10kpc.
$\bar{\nu}_e p \rightarrow e^+ n$ events give direct energy information ($E_e = E_\nu - 1.3$MeV).

Time variation of event rate



Time variation of mean energy



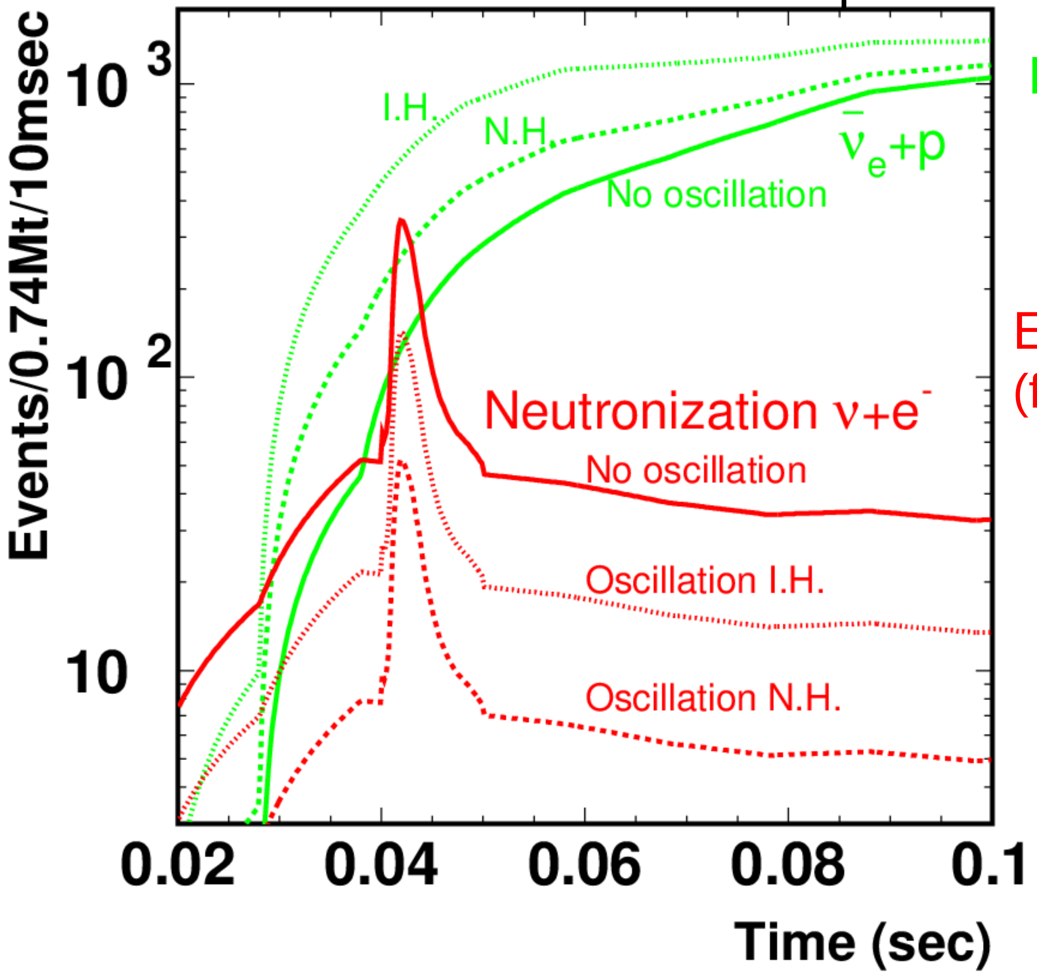
High statistics to discuss model predictions.
Determine onset time with an accuracy of ~ 1msec.

Neutronization burst

($e^- + p \rightarrow n + \nu_e$)

SN at 10kpc

Neutrino flux and spectrum from Livermore simulation



Event rate of $\bar{\nu}_e$+p events

Event rate of neutronization burst
(forward peaked ν+e scattering events)

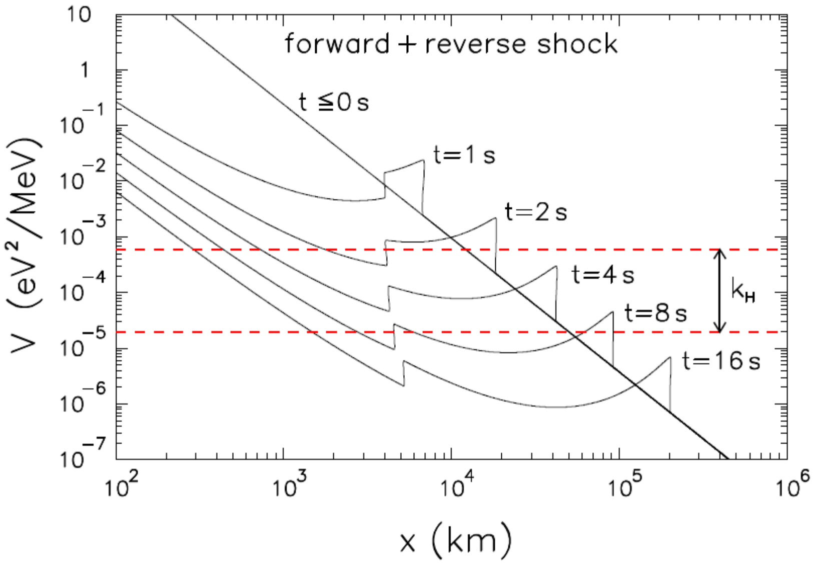
Number of events from neutronization burst is ~20(NH), ~56(IH) and ~130(no osc.)

$\bar{\nu}_e$p events during this 10msec is ~350(NH), 700 (IH) and 190(no osc.) .

Limiting the direction to SN, event execess of neutronization can be seen.

How Mass hierarchy affect to supernova Neutrinos

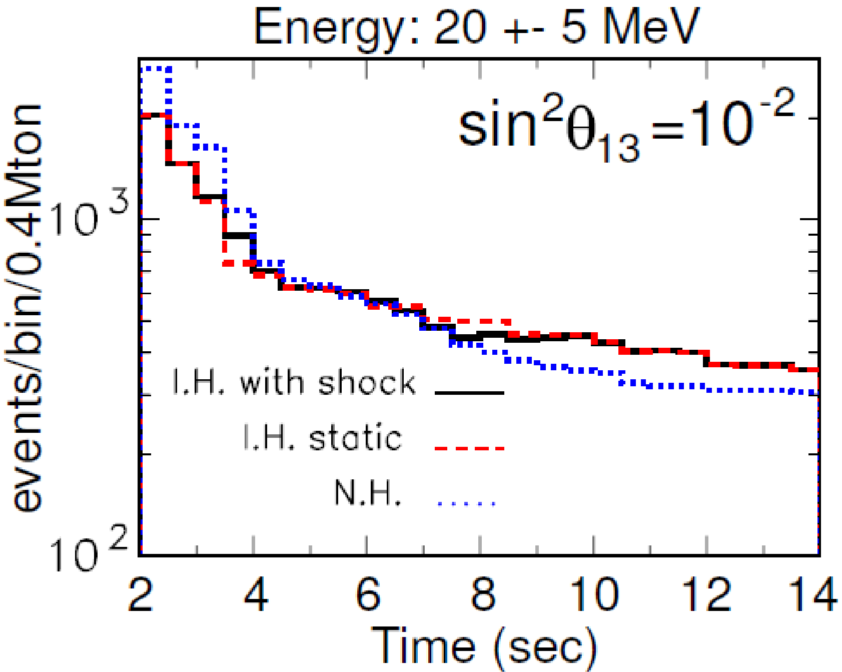
G. L. Fogli, E. Lisi, A. Mirizzi, and D. Montanino, JCAP 0504, 002 (2005), arXiv:hepph/0412046.

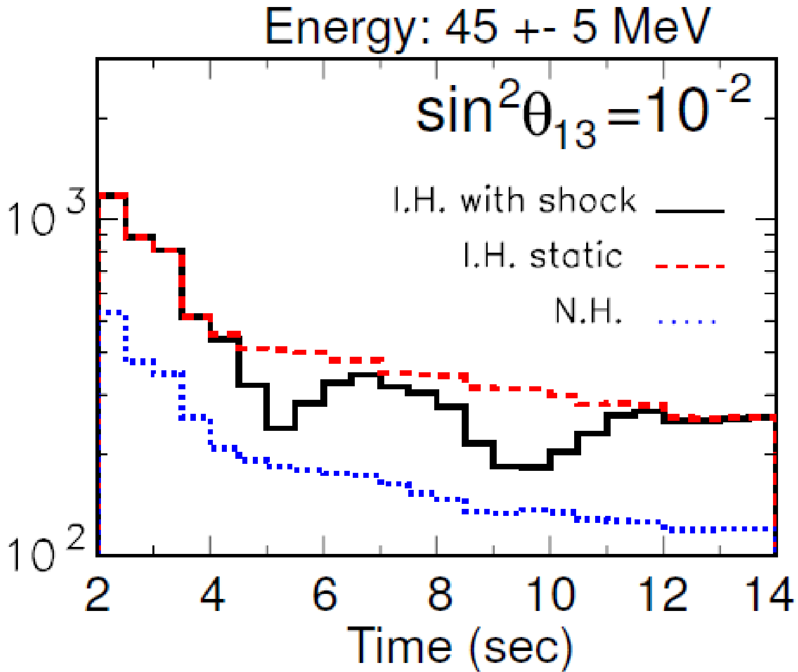


Time variation of the electron density N_e, i.e. matter potential V,

$$V(x,t) = \sqrt{2}\, G_F\, N_e(x,t)$$

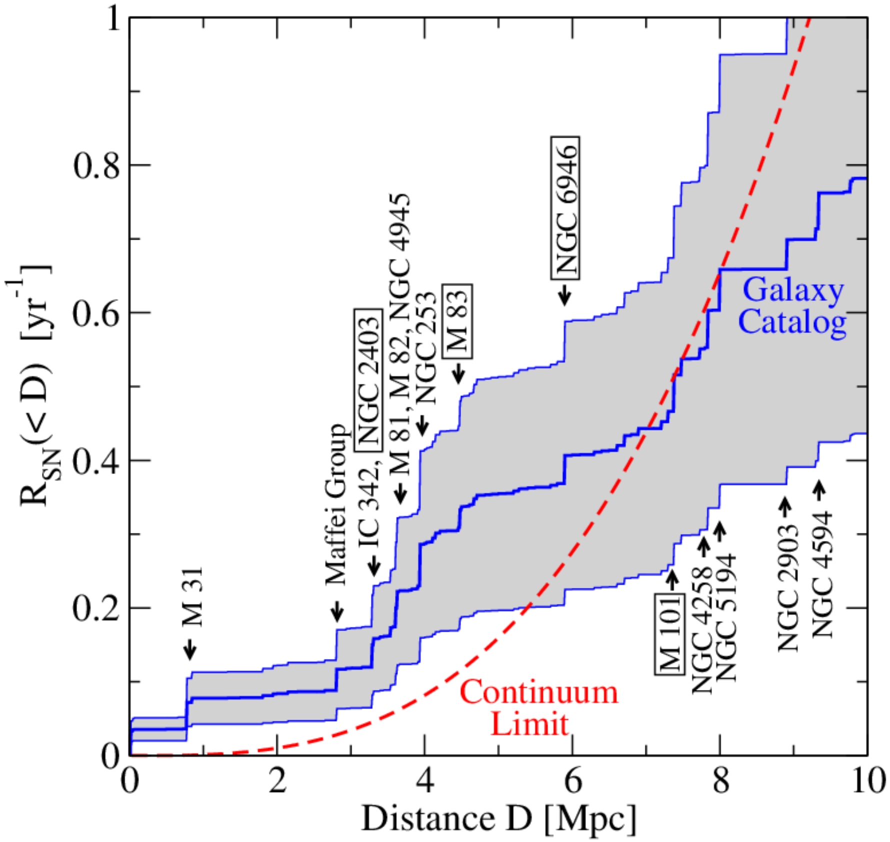
may cause oscillatory event rate change in higher energy range if mass hierarchy is I.H.



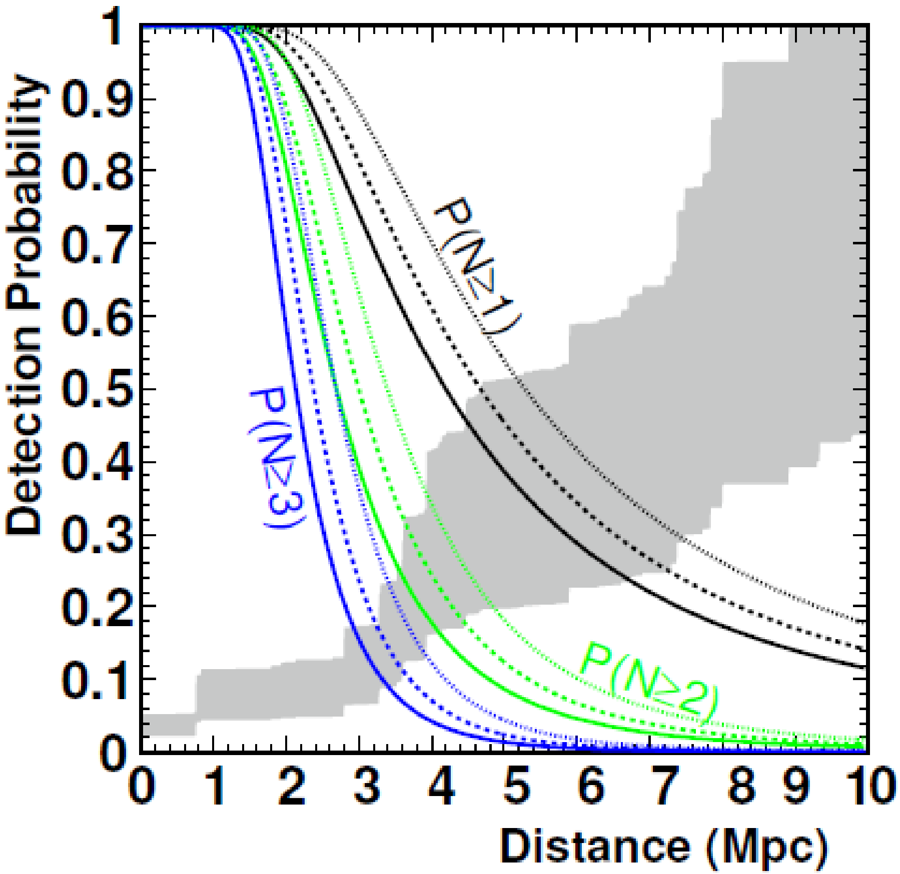


Nearby supernova

Supernova bursts happen once every few years within ~4 Mpc.
Hyper-K is able to detect a few events for each supernova.



Ando, Beacom, Yusel (2005)

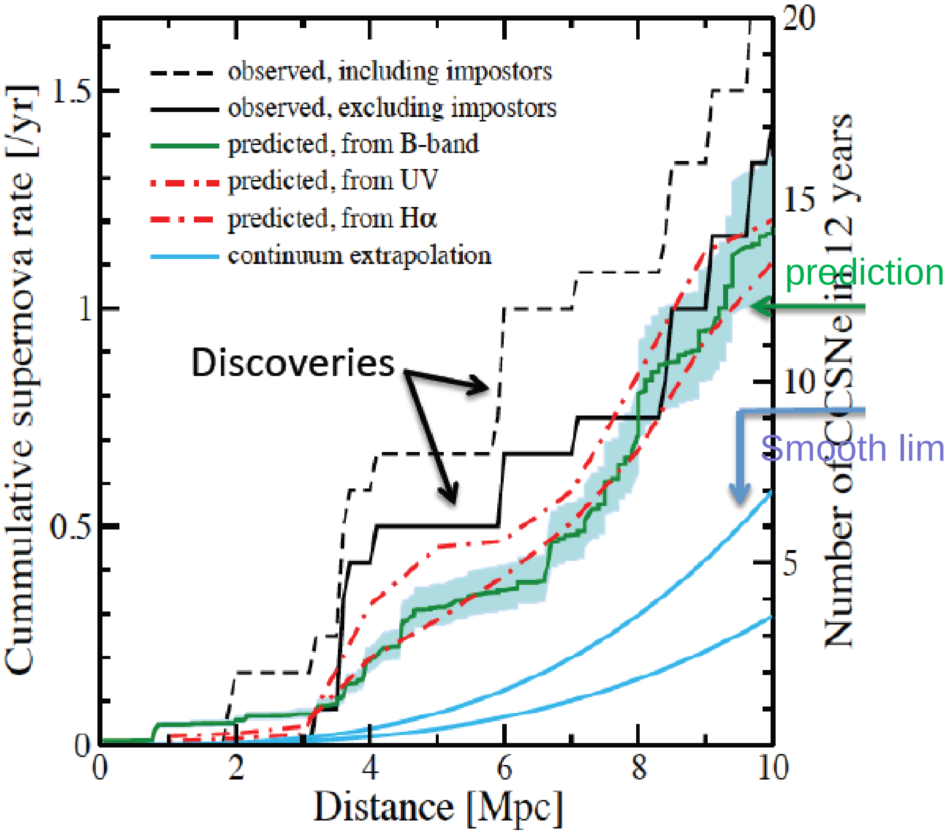


Soid:no osc., dot:N.H., dash:I.H.

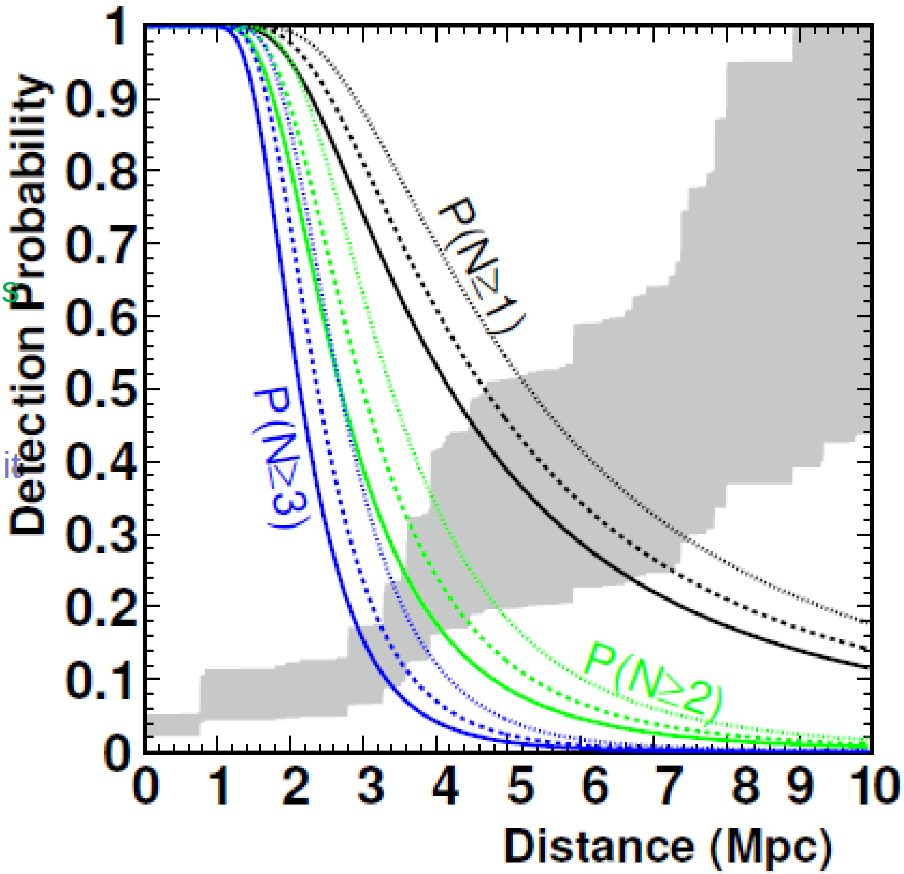
Coincidence with prompt information such as gravitational wave signal could extract such supernova signals.

Nearby supernova

Supernova bursts happen once every few years within ~4 Mpc.
Hyper-K is able to detect a few events for each supernova.



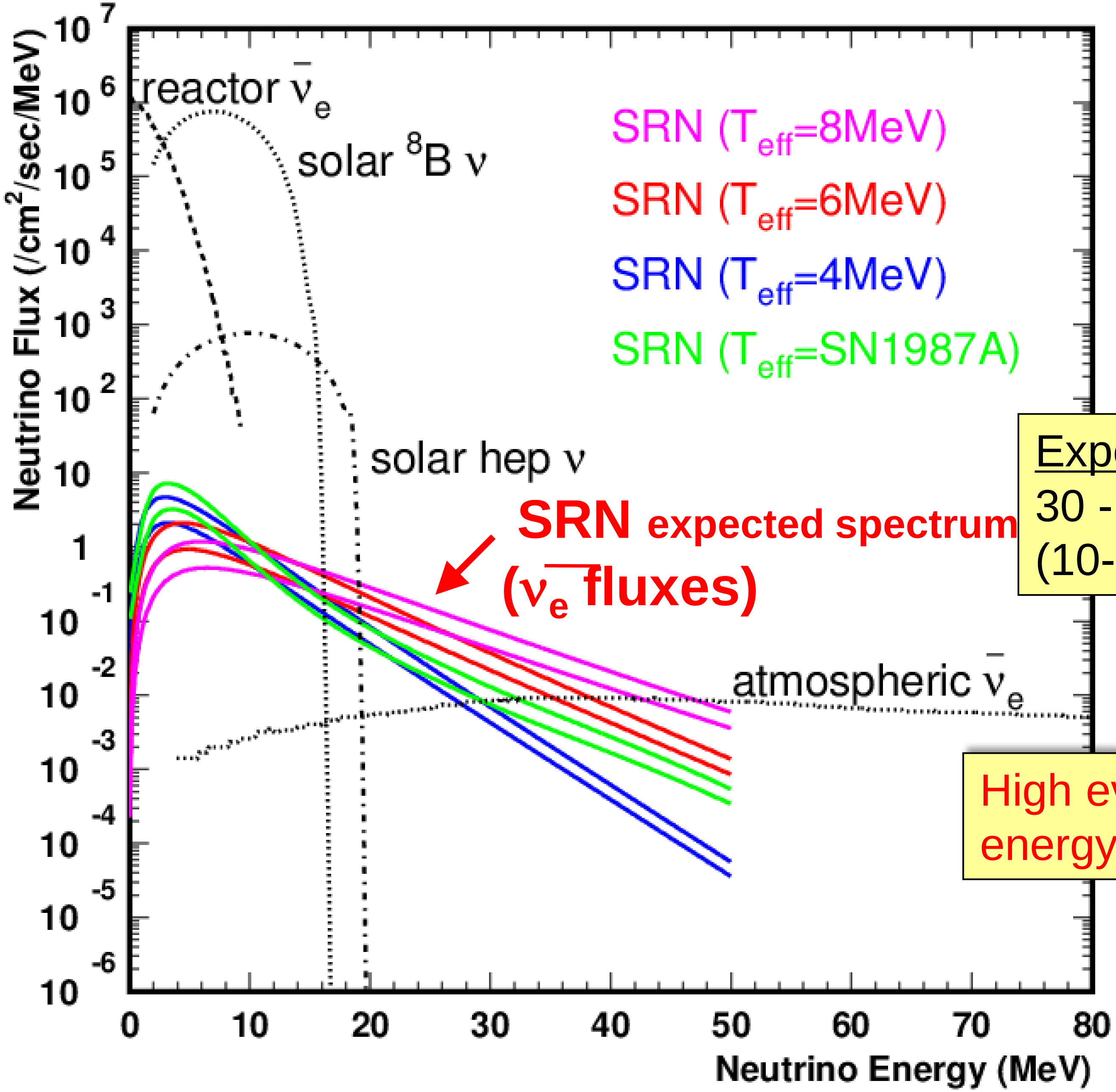
Horiuchi et al. (in prep.)



Soid:no osc., dot:N.H., dash:I.H.

Coincidence with prompt information such as gravitational wave signal could extract such supernova signals.

Supernova Relic Neutrino (SRN)



SRN expected spectrum ($\bar{\nu}_e$ fluxes)

SRN flux from Horiuchi et al.
PRD, 79, 083013 (2009)

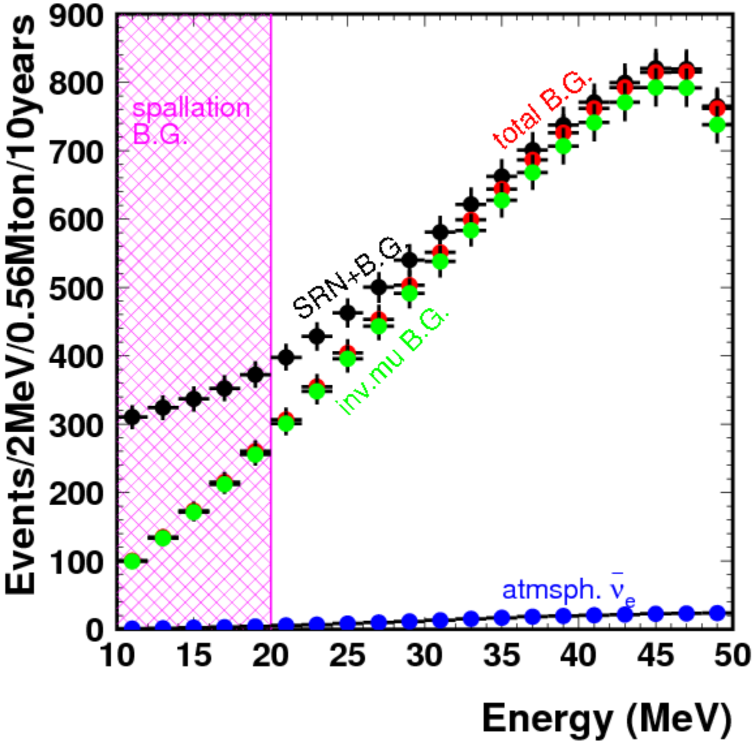
Expected number of events
30 -170 events/year/0.56Mt
(10-30MeV)

HK fiducial volume

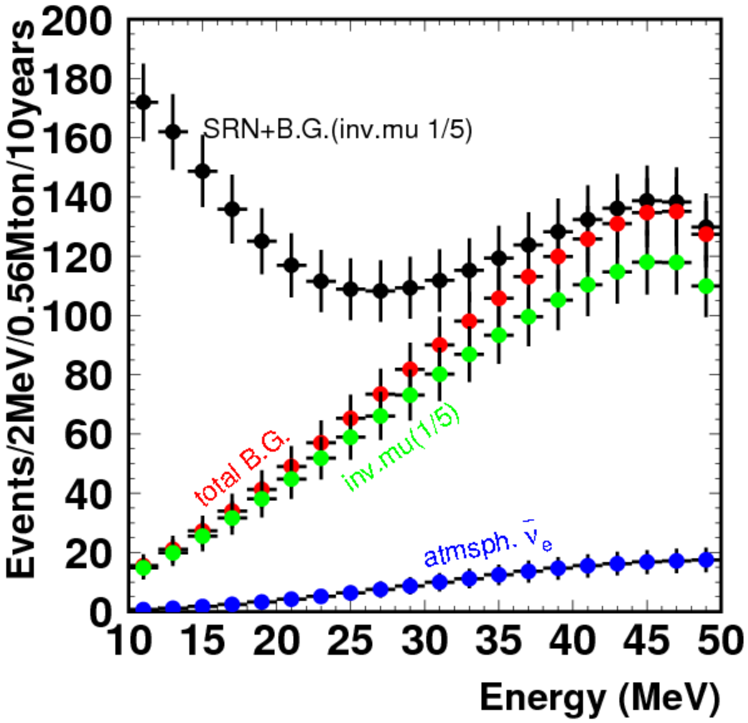
High event rate to discuss energy spectrum of SRN.

Expected signals of SRN

W/O neutron tagging



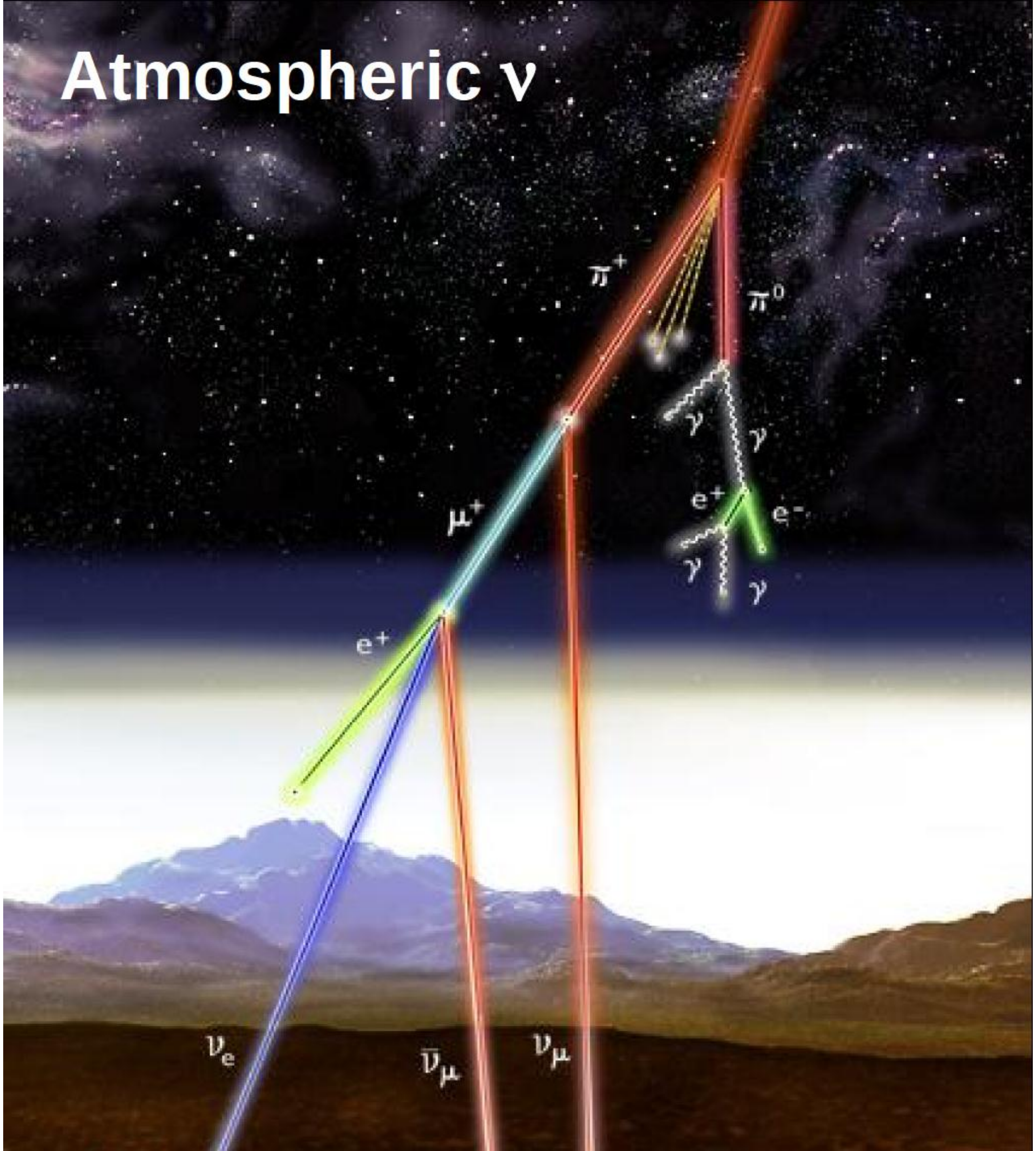
W/ neutron tagging



The expected number of SRN events in E = 20-30MeV is ~300/10yrs assuming a flux prediction of Ando et al. (2005). Large background below 20 MeV.

The expected number of SRN events in the energy range of 10-30 MeV is ~800 with 10 years of live time. Backgrounds of spallation and invisible muons are highly reduced by neutron tagging.

Atmospheric ν



3-flavor oscillations in atmospheric ν

NuclPhysB669,255(2003)

NuclPhysB680,479(2004)

$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx P_2(r \cdot \cos^2\theta_{23} - 1)$$

Solar term

$$-r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin 2\theta_{23}(\cos\delta \cdot R_2 - \sin\delta \cdot I_2)$$

Interference term (δCP)

$$+2\sin^2\tilde{\theta}_{13}(r \cdot \sin^2\theta_{23} - 1) \qquad (3)$$

θ_{13} resonance term

r : μ/e flux ratio (~2 at low energy)

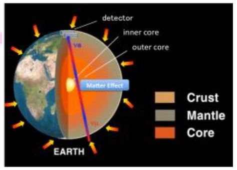
$P_2 = |A_{e\mu}|^2$: 2ν transition probability ν_e → $\nu_{\mu\tau}$ in matter

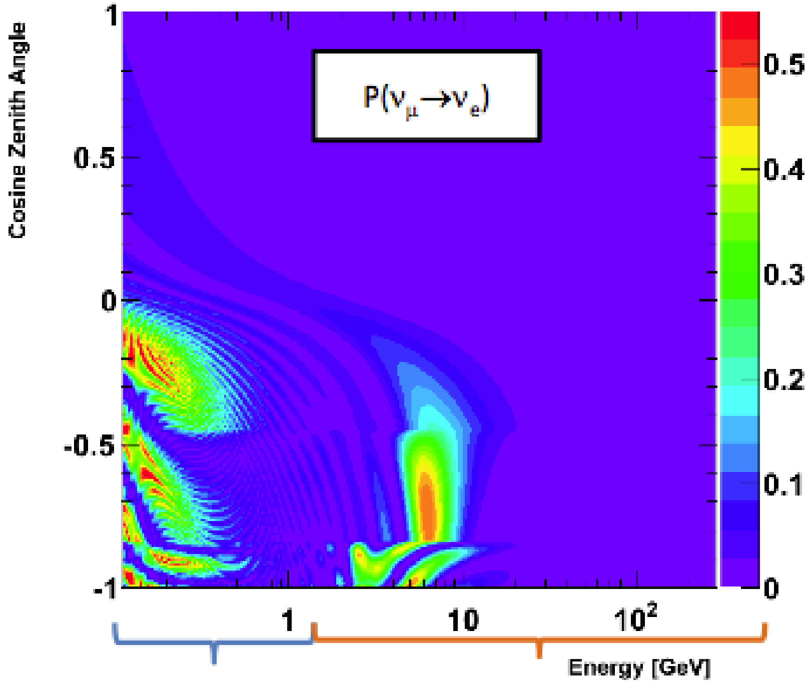
$R_2 = \mathrm{Re}(A^*_{ee}A_{e\mu})$

$I_2 = \mathrm{Im}(A^*_{ee}A_{e\mu})$

A_{ee} : survival amplitude of the 2ν system

$A_{e\mu}$: transition amplitude of the 2ν system

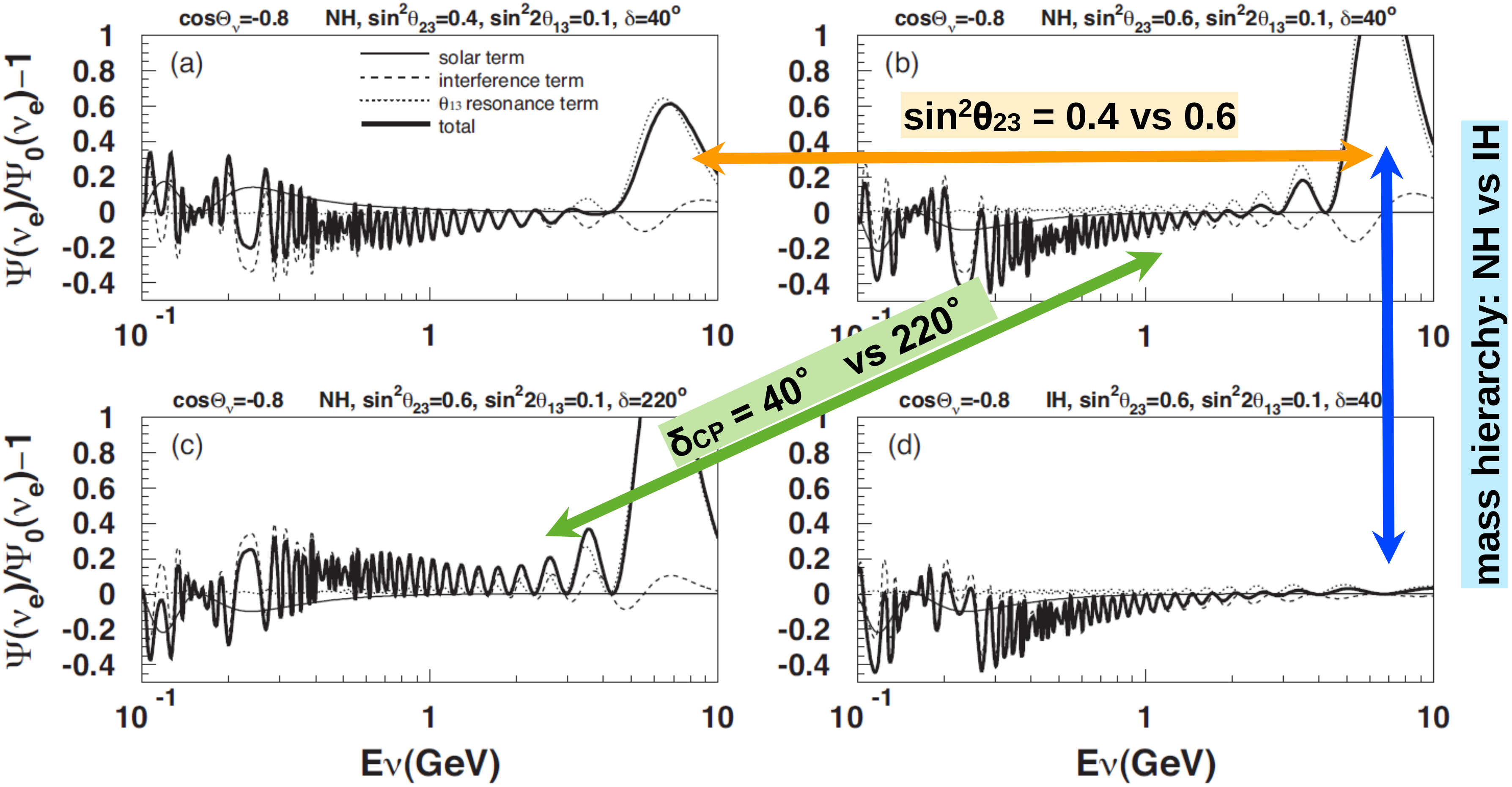




"Sub-GeV" "Multi-GeV"

ν_e appearance (and ν_μ distortion) is expected due to MSW effect in the Earth's matter
- happens in ν in the case of normal mass hierarchy
- in anti-ν in inverted mass hierarchy

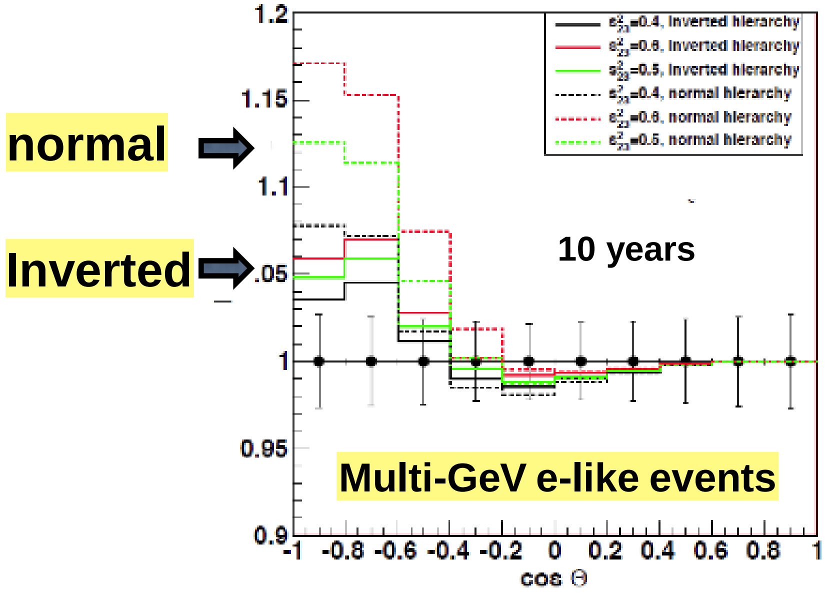
Large θ_{13} value gives us a good chance to discriminate mass hierarchy.

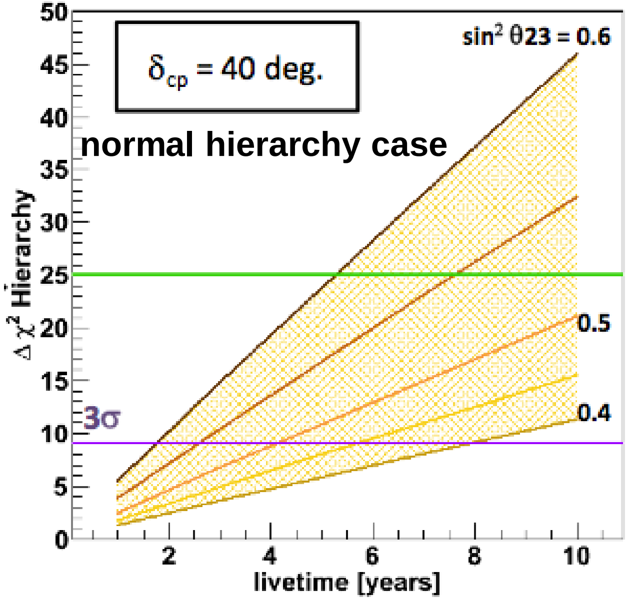


- Trough matter effect (MSW), we study
  - Mass hierarchy ⇨ Asymmetry between neutrinos and antineutrinos.
  - Octant of θ_{23} ⇨ Appearance (and $\nu_\mu \rightarrow \nu_\mu$ disappearance) interplay
  - δ_{CP} ⇨ Magnitude of the interference

Mass Hierarchy Sensitivity

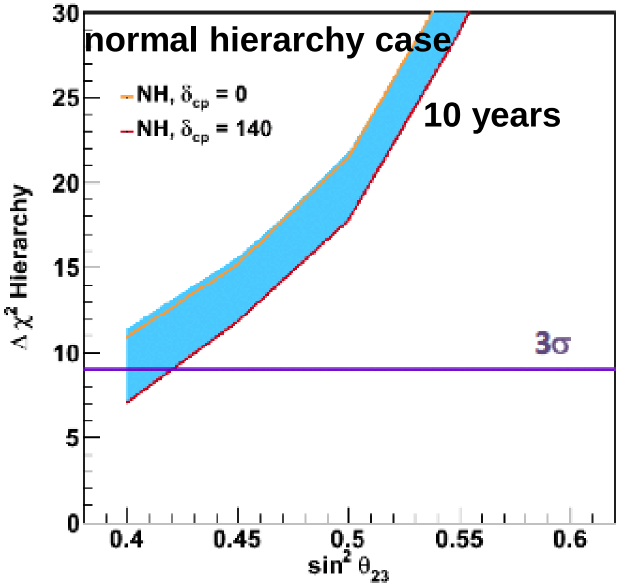
$N_{e\text{-like}} / N_{e\text{-like}}$(no osc.)





Sensitivity depends on θ_{23}, δ and mass hierarch (a little).

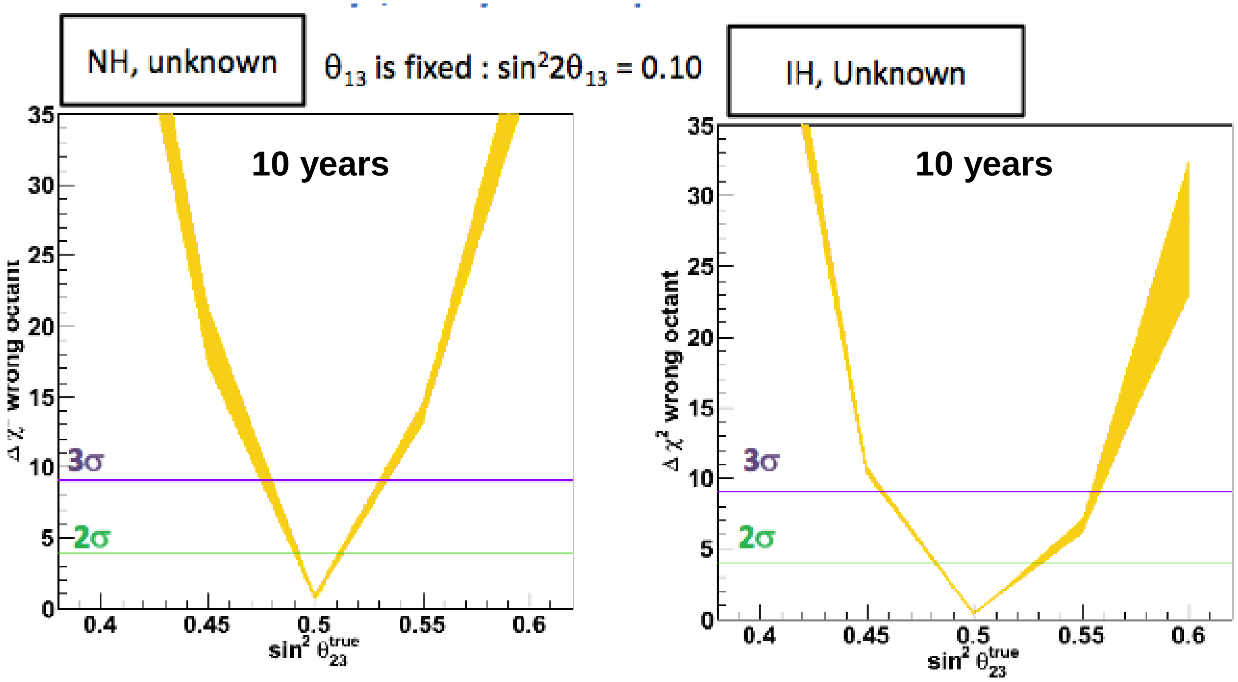
3σ mass hierarchy determination for $\sin^2\theta_{23}>0.42$ (0.43) in the case of normal (inverted) hierarchy.



Sensitivity for θ_{23} octant

θ_{23} octant sensitivity

- (band depends on δ)



Bands correspond to δ_{CP} uncertainty

If $\sin^2 2\theta_{23} < 0.99$ ($\sin^2\theta_{23} < 0.45$ or $\sin^2\theta_{23} > 0.55$), θ_{23} octant can be determined at >3σ.

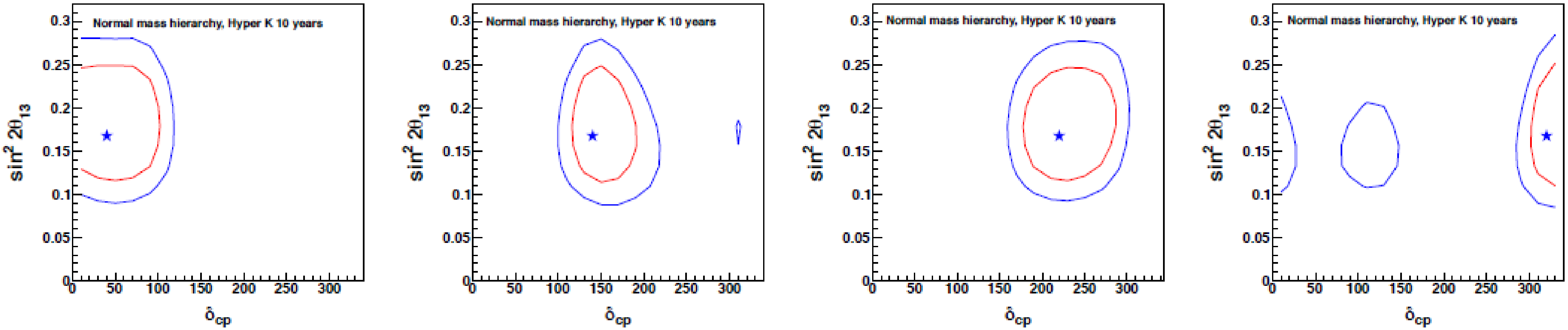
Sensitivity for CPV

Hyper-K 10 years

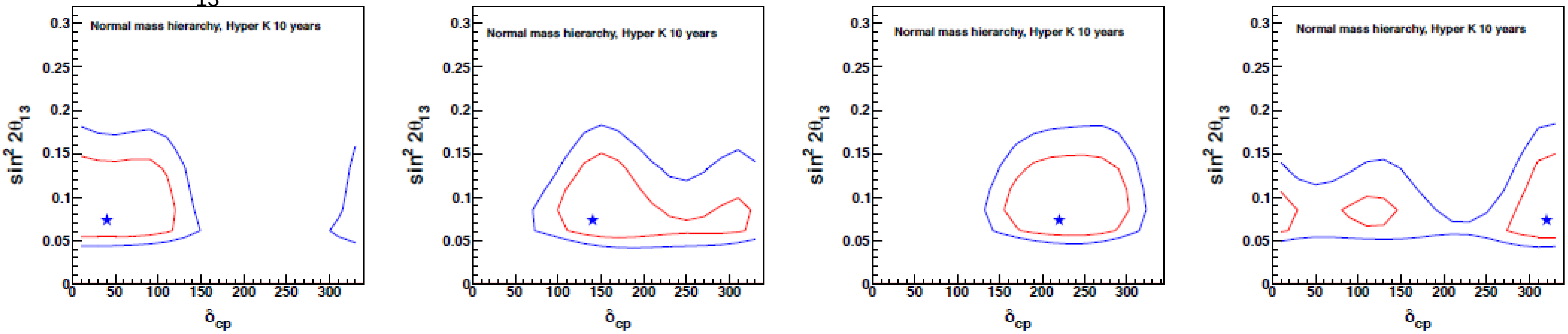
— 90% CL
— 99% CL

δCP vs. $\sin^2 2\theta_{13}$ contours

$\sin^2 2\theta_{13}$=0.16



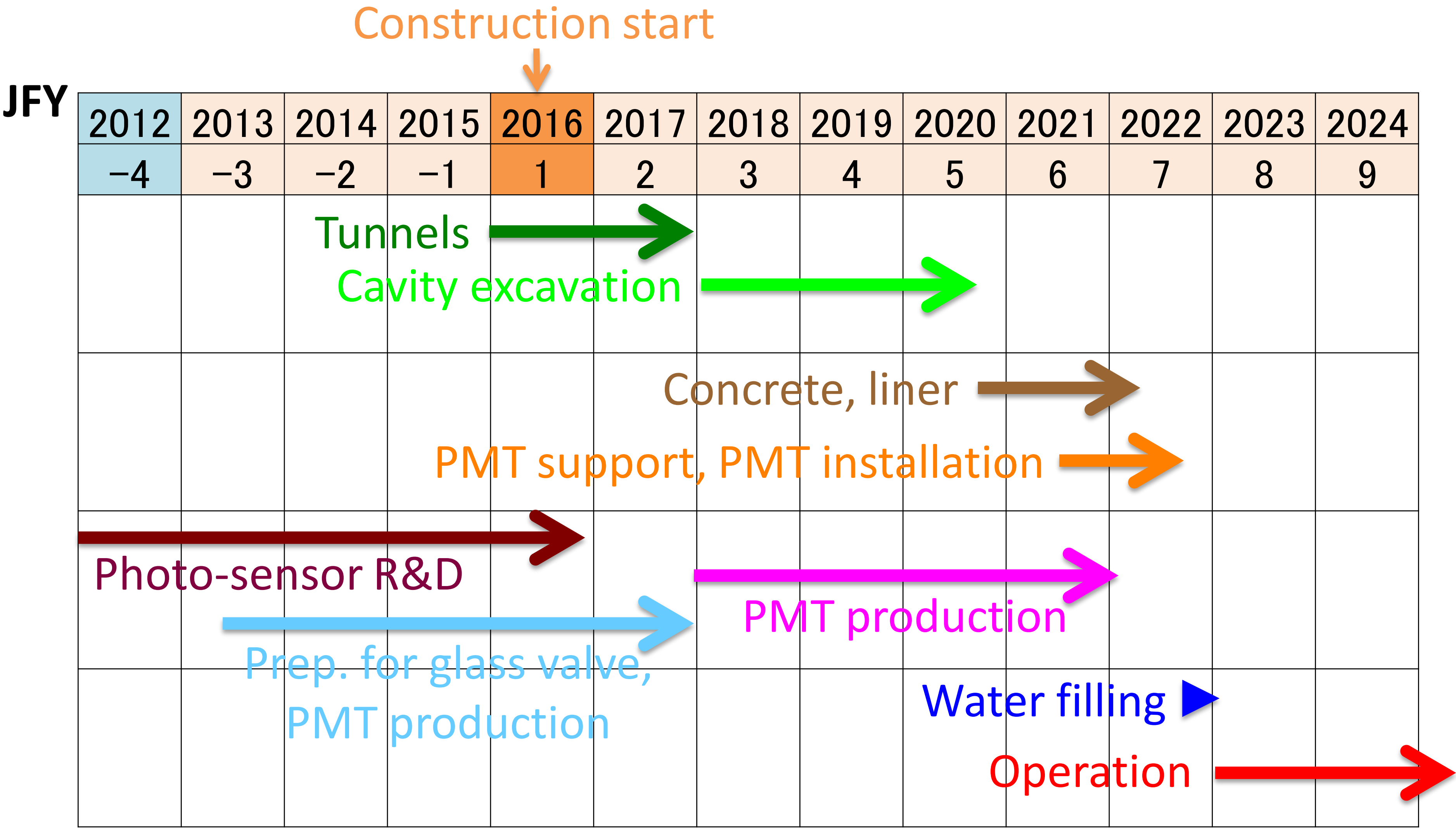
$\sin^2 2\theta_{13}$=0.08



Give supplemental information for the CP study conducted by the J-PARC beam

Schedule

assuming budget being approved from JPY2016



Construction start

JFY	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
	−4	−3	−2	−1	1	2	3	4	5	6	7	8	9

Tunnels

Cavity excavation

Concrete, liner

PMT support, PMT installation

Photo-sensor R&D

PMT production

Prep. for glass valve,
PMT production

Water filling

Operation

Summary

- The neutrino program in Japan started from Kamiokande with the observation of supernova neutrinos from SN1987A.
- It was followed by solar neutrino observation, atmospheric anomaly, discoveries of neutrino oscillations.
- On the other hand, proton decay, which was the primary motivation of Kamiokande, has not been observed yet.
- Thanks to large theta13, further progress of the neutrino program is expected.
- Hyper-Kamiokande covers rich fundamental physics topics:
  - discovery reach for leptonic CP violation of CPV >3σ for 74% of δ with J-PARC neutrino beam.
  - Discovery potential of nucleon decays up to (3σ) 5.7×10^{34} for $e^+\pi^0$, 1.0×10^{34} for vK^+ with 10 yrs.
  - Detailed study of supernova bursts.
  - Mass hierarchy, octant of theta23 and etc. with high statistics atmospheric neutrinos.
  - …
- R&D for Hyper-Kamiokande has started.