Super-Kamiokande

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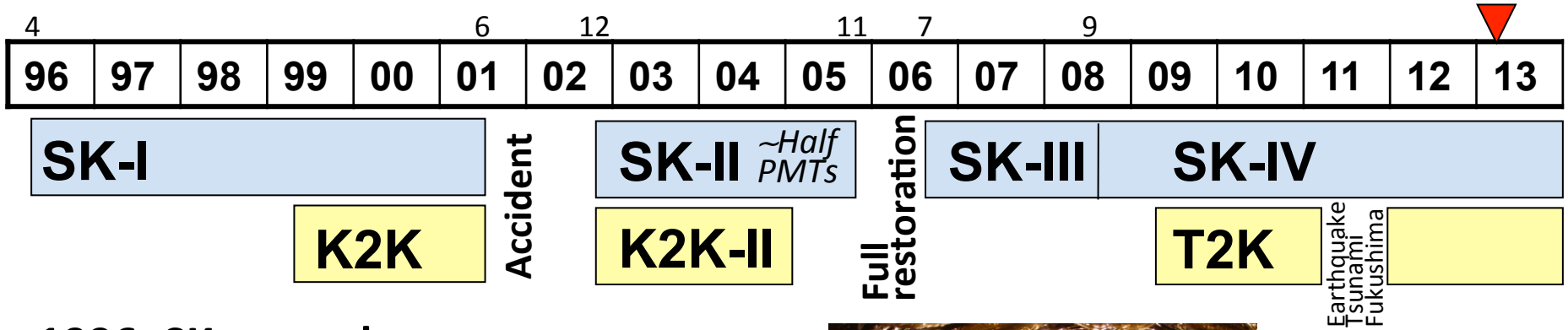
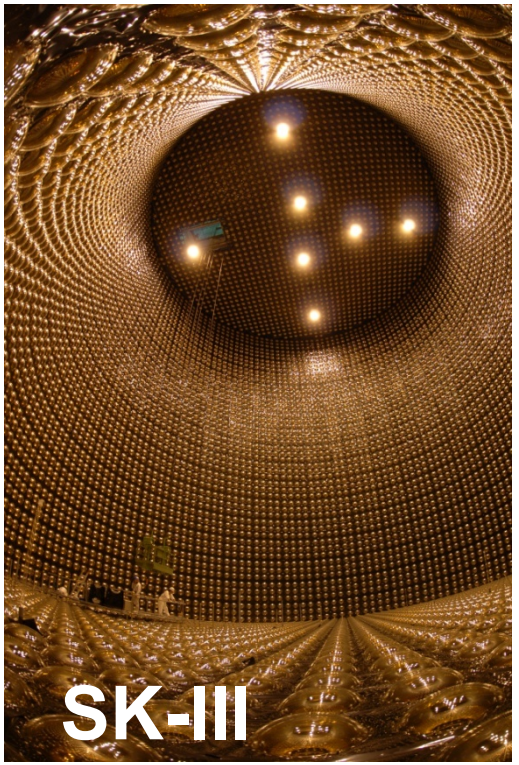
Super-K will be 17 years old in this April

Brief history of Super-Kamiokande



- **1996: SK started**
- **1998: Discovery of Atmospheric Neutrino Oscillation**
- **2001: Discovery of Solar Neutrino Oscillation (w/SNO)**
- **2004: Confirmation of the atmospheric neutrino oscillation by K2K.**
- **2004: Discovery of the oscillatory behavior of the atmospheric neutrinos**
- **2011: Indication of θ_{13} by T2K**



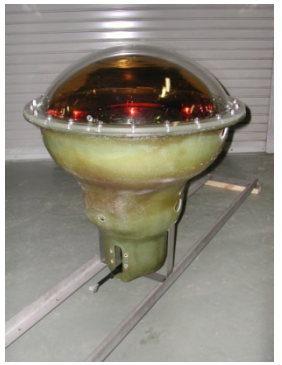
Water Cherenkov

50,000 tons

11,129 PMTs

22.5 kt

fiducial mass



Protection case

SK Collaboration

	1998	2013
ICRR	27	23
IPMU	--	2
Fukuoka Tech	--	1
Gifu	1	1
KEK	9	11
Kobe	3	2
Kyoto	--	6
Miyagi	1	1
Nagoya	--	4
Niigata	8	--
Okayama	--	5
Osaka	5	1
Tohoku	13	--
SW Shizuoka	--	1
Tokyo	1	3
Tokyo Tech	5	--
Tokai	2	1

Japan	75	62
USA	55	31
Poland	1	1
Spain	--	1
Korea	--	5
China	--	4
Canada	--	8
Total	***131***	***112***

	1998	2013
Boston	14	4
BNL	1	1
Irvine	9	7
California State	2	3
Duke	--	5
George Mason	1	--
Hawaii	6	3
Los Alamos	1	--
Louisiana State	3	--
Maryland	4	--
Stony Brook	8	5
Washington	6	3
Warsaw(Poland)	1	1
UAM(Spain)	--	1
Chonnam(Korea)	--	3
Seoul National(Korea)	--	1
Sungkyunkwan(Korea)	--	1
Tsinghya(China)	--	4
Regina(Canada)	--	1
British C.(Canada)	--	3
Toronto(Canada)	--	2
TRIUMF(Canada)	--	2

- T2K is a separated collaboration
  - Not all the SK collaborators are involved in T2K
- New countries (Spain, Korea, China, Canada) joined

Status of Super-K

- People might say that SK has finished the role.
- But not true
  - ***Last year our funding agency asked us to provide a plan of SK for the next 10 years***
    - Many interesting subjects still to be solved
  - ***the number of collaborating institutions have increased for the last few years***
    - Good to learn Water Cherenkov technology for future

10 years plan

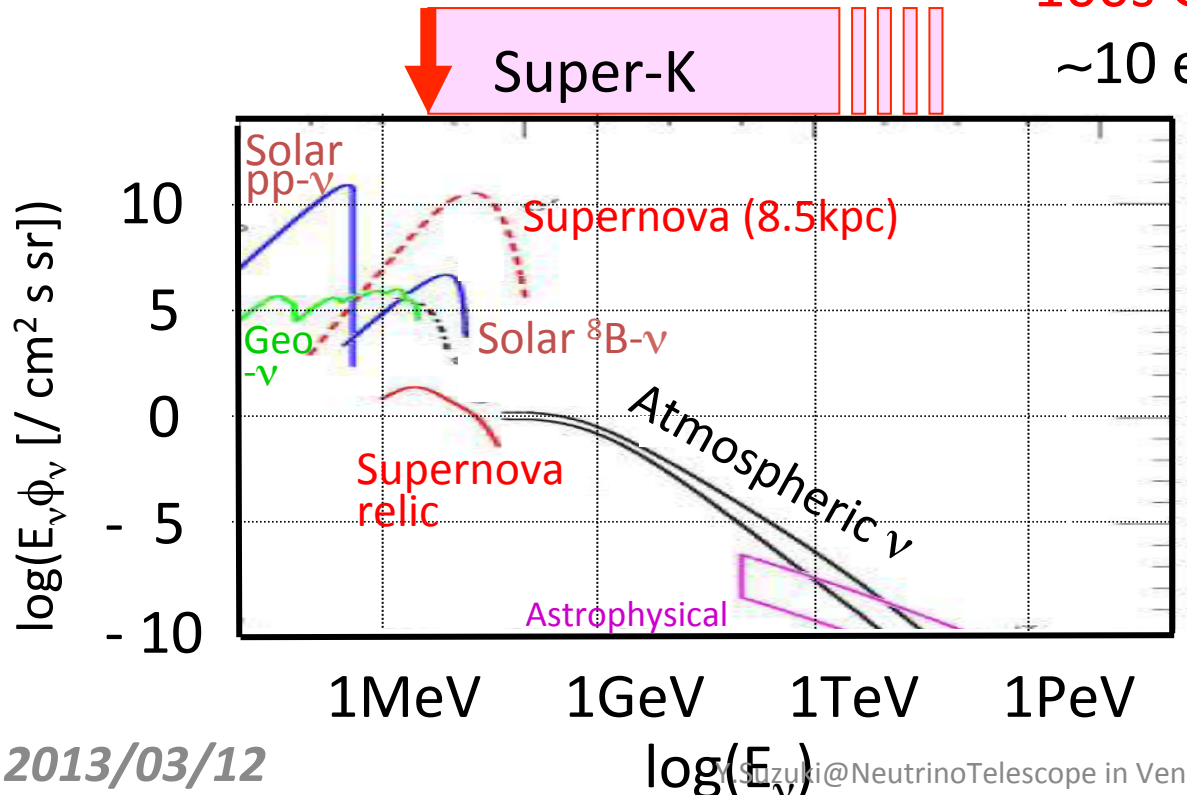
MEXT asked us to provide 10 years plan of Super-Kamiokande

Subjects	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Supernova Relic ν Entering a discovery region *(expected flux : 10～22/cm²/s)*	Improve water system sensitivity			*24/cm²/s*			*13/cm²/s*			Discovery ? *9/cm²/s*
Nearby SN neutrino burst World highest sensitivity		Improve DAQ system								
			Continuous observation							
Mass hierarchy Precise measurement of atmospheric ν										Identification of MH ?
	sensitivity			2.0σ			2.3σ			2.5σ
Indication of CP Violation ? Look for ν_e appearance in SK/T2K(J-PARC)	ν_e appearance	Upgrade J-PARC（750kW）								Combine results from reactor exp.
										Indication of CP ?
Sterile neutrinos ? Precise measurement of solar neutrinos	Reduce backgrounds									Indication of sterile neutrinos ?
	sensitivity			2.2σ			2.7σ			3.0σ
Nucleon decay search World highest sensitivity										
			Test of grand unified theories						sensitivity	2.1×10^{34} yrs
Search for dark matter Neutrinos from the sun, the earth and so on				Sensitive to low mass WIMPs						
										Improve sensitivity by factor 2

Energy Range

- Trigger (Software):
  - 50% efficiency @ 3.3MeV
  - 100% eff. for E_{kin} > 4.0 MeV
- Trigger Rate
  - 3.5 kHz

- Solar neutrinos (< 15 MeV):
  ~15 events /day
- Supernova ν's (10~20 MeV):
  ~8000 events @10 kpc
- Atmospheric Neutrinos (< a few 100s GeV):
  ~10 events /day



- 6 p.e. / MeV
- Resolution

(solar/supernova ν)
14.2% @10MeV

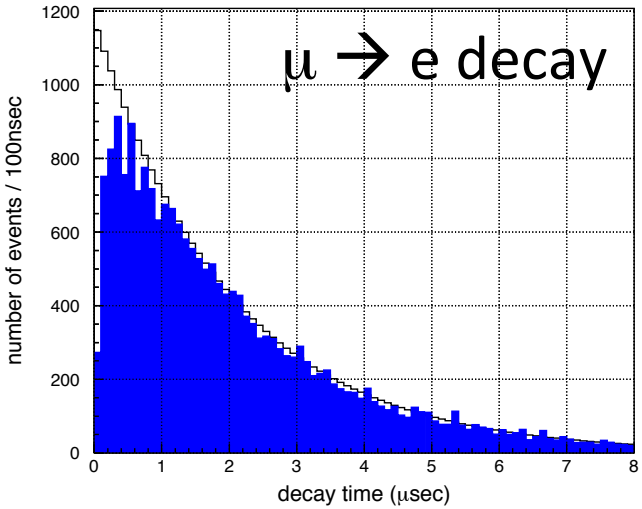
(atmospheric ν)
$1.7+0.7/\sqrt{E(GeV)}$ %
(single ring μ)

Data Accumulated

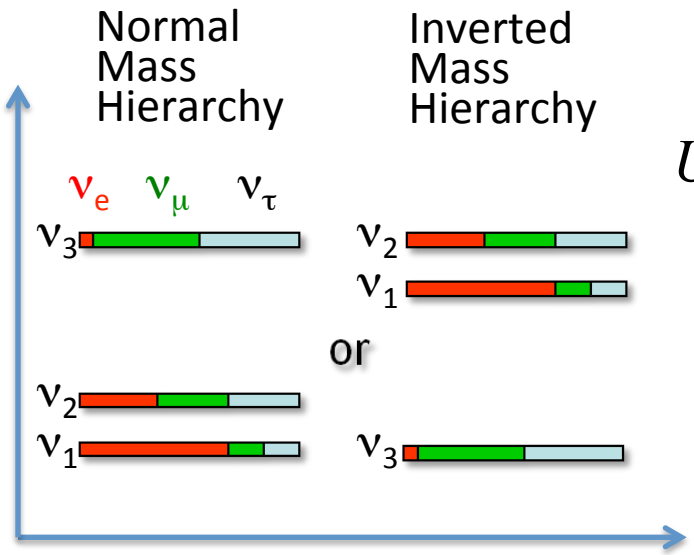
Phase	SK-I	SK-II	SK-III	SK-IV	Total
Periods	96-Apr ～01-Jun	02-Dec ～05-Nov	06-Jul ～08-Sep	08-Sep ～running	
ID PMTs	11,146 (40%)	5,182 (19%)	11,129 (40%)	11,129 (40%)	
Electronics	ATM	ATM	ATM	***QBEE***	
Trigger	Hardware	Hardware	Hardware	***Software***	
Atm ν FC+PC (days)	1489 days	799 days	518 days	1097 days (< '12 Mar)	3903 days (< '12 Mar)
(# of ev.)	12,299+902	6,610+427	4,355+344	8,929+735	32,193+2,408
Atm ν up-μ (days)	1646 days	828 days	636 days	1097 days (< '12 Mar)	4207 days (< '12 Mar)
(# of ev.)	2,328	1,094	945	1,651	6,018
Solar ν (days)	1496 days	791 days	547.9 days	1069.3 days (< '12 Mar)	3904 days (< '12 Mar)
(# of ev.)	22,404 ev.	7,212.8 ev.	8,147.9 ev.	19,809.4 ev.	57,574.1 ev.
Proton decay	91.7 kt･yr	49.2 kt･yr	31.9 kt･yr	46.5 kt･yr (< '11 Mar)	220 kt･yr

Electronics update (SK-IV)

- QBEE(QTC-Based Electronics with Ethernet)
  - width of the output time pulse represent the integrated charge
  - Dynamic range: 0.2 – 2500 pC
    - 5 times better than the previous one
- Record every hit + software trigger
  - Higher efficiency for μ → e decay
  - Detection of delayed 2.2 MeV γ-rays after neutron captures
- High event process:
  - Up to 6 Million events /sec without any event loss.
  - 100 times better than the previous one



Neutrino Oscillation



$$U_{\alpha i} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

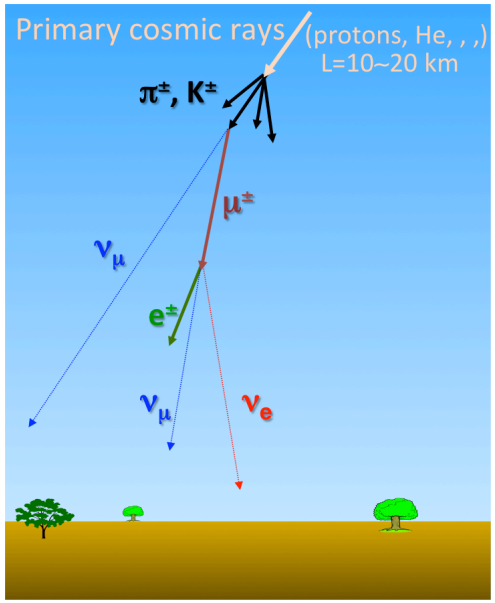
Atmospheric ν Long baseline Acc (θ_{23}: maximal?)	Reactor ShortBL ($\sin^2\theta_{13}$~0.025, δ_{CP} ?)	Solar ν Reactor LBL (θ_{12}: large)
SK /K2K(SK)	**T2K(SK)**	**SNO+SK /KL**

Super-K have not only discovered the neutrino oscillation, but also played the essential roles in discovering all the mixing angles.

Remaining Issues

- Octant of θ_{23} (if $\theta_{23} \neq \pi/4$); Mass hierarchy (sign of Δm_{13}^2), CPV

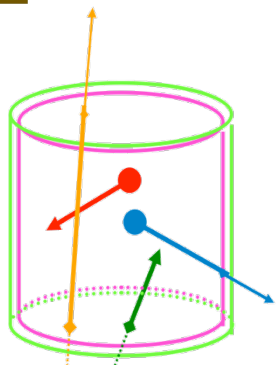
← SK atmospheric three flavor analysis may give some hints in near future



Atmospheric Neutrinos

- Wide range of baseline: 10 km ~ 13,000 km
- 5 orders of magnitude of energy range: 0.1 GeV ~ 10 TeV
- Variety of Matter Effect
- Four neutrino sources: $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$

Fully Contained (FC)
(<E_ν> ~ 1GeV)
Sub-GeV: Evis<1.33GeV
Multi-GeV: >1.33GeV
1R, MR, e-like, μ-like
ν_e-like, $\bar{\nu}_e$-like, ...



Partially Contained (PC)
(<E_ν> ~ 10GeV)
Through, stop

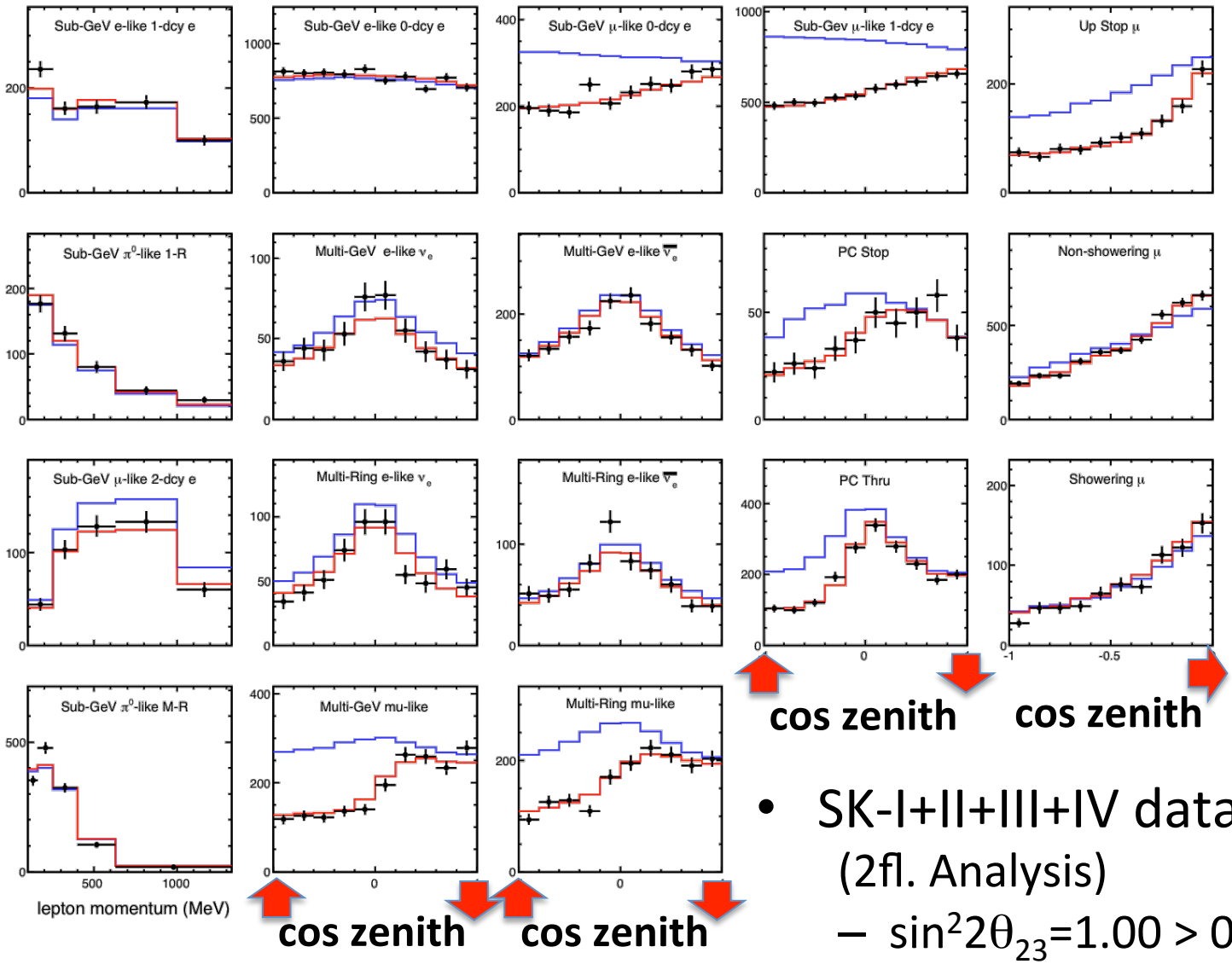
Upward Through-going μ
(<E_ν> ~ 100GeV)
Non-showering, showering

Upward Stopping μ
(<E_ν> ~ 10GeV)

- *Many Event Categories*
  - ← Energy, topology, # of Rings, # of decay electrons, e-like, μ-like, …
- 18 Categories
  - 480 momentum/zenith angle bins (as of March, 2012) are used for the fits

→ Good to identify best suitable events for different kinds of oscillation studies

Atmospheric Neutrinos



- 18 Categories
- All consistent with the oscillation

w/o oscillation
w/ oscillation

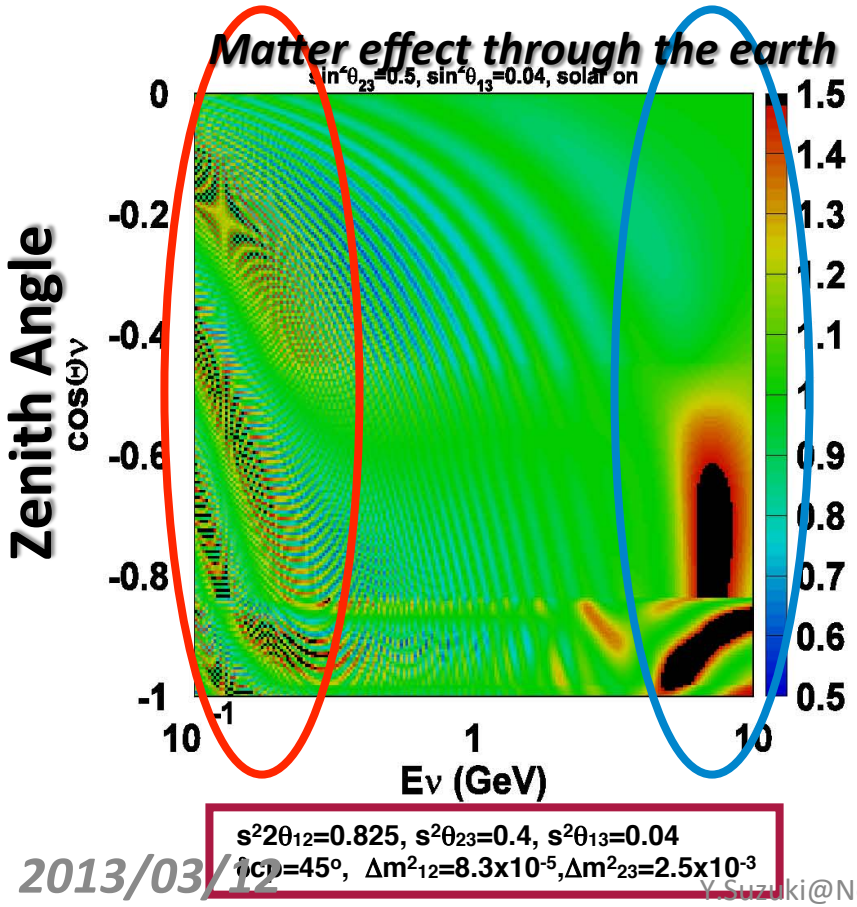
- SK-I+II+III+IV data
  (2fl. Analysis)
  - $\sin^2 2\theta_{23} = 1.00 > 0.96$ (90%, 1par)
  - $\Delta m_{23}^2 = 2.30^{+0.16}_{-0.22} \times 10^{-3}$ eV^2 (1σ)

Three flavor analysis

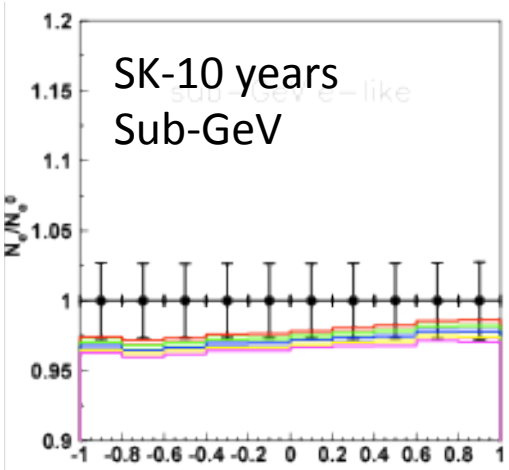
ν_e appearance in atmospheric-ν

$$\frac{\Psi(\nu_e)}{\Psi_0(\nu_e)} - 1 \cong P_2(r \cdot c_{23}^2 - 1) - r \cdot \tilde{s}_{13} \cdot \tilde{c}_{13}^2 \cdot \sin 2\vartheta_{23} (\cos\delta_{CP} \cdot R_2 - \sin\delta_{CP} \cdot I_2) + 2\tilde{s}_{13}^2 (r \cdot s_{23}^2 - 1)$$

~ : mixing angle in matter
$P_2 = |A_{e\mu}|^2 : \nu_e \rightarrow \nu_{\mu\tau}$ in matter
$R_2 = \mathrm{Re}(A^*_{ee}A_{e\mu})$
$I_2 = \mathrm{Im}(A^*_{ee}A_{e\mu})$



1st term: solar term (θ_{12}, Δm_{12})
mostly in low energy
cancellation effect
if c^2_{23}=0.5, r=ν_μ/ν_e=2@LE
a few %; octant may be seen



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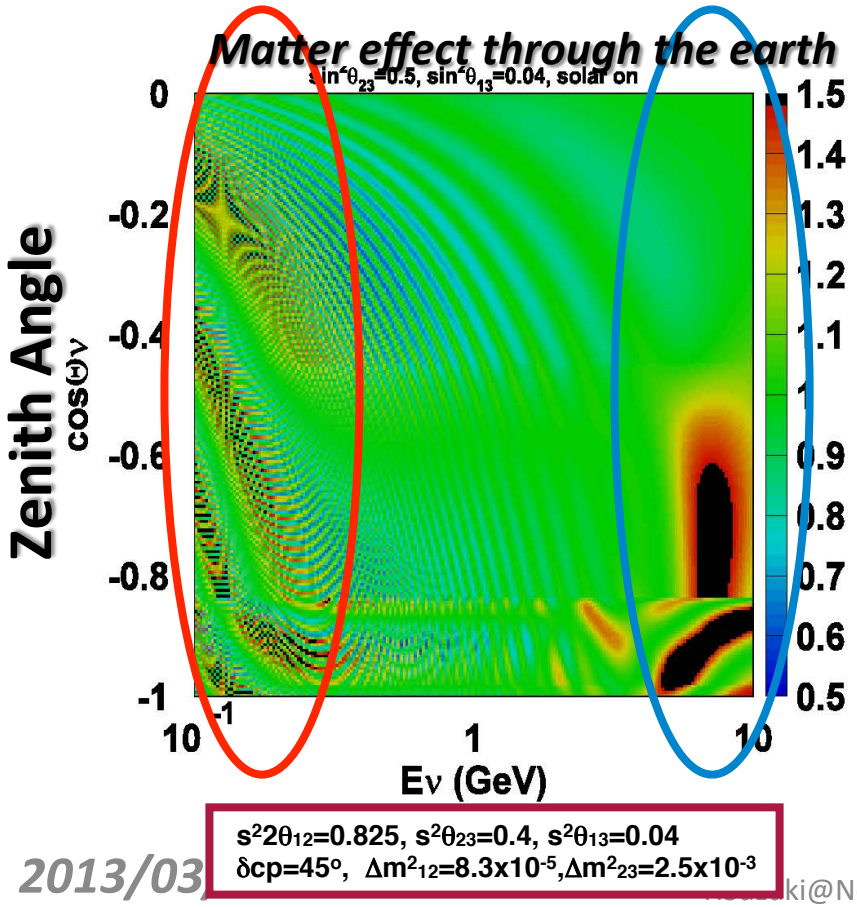
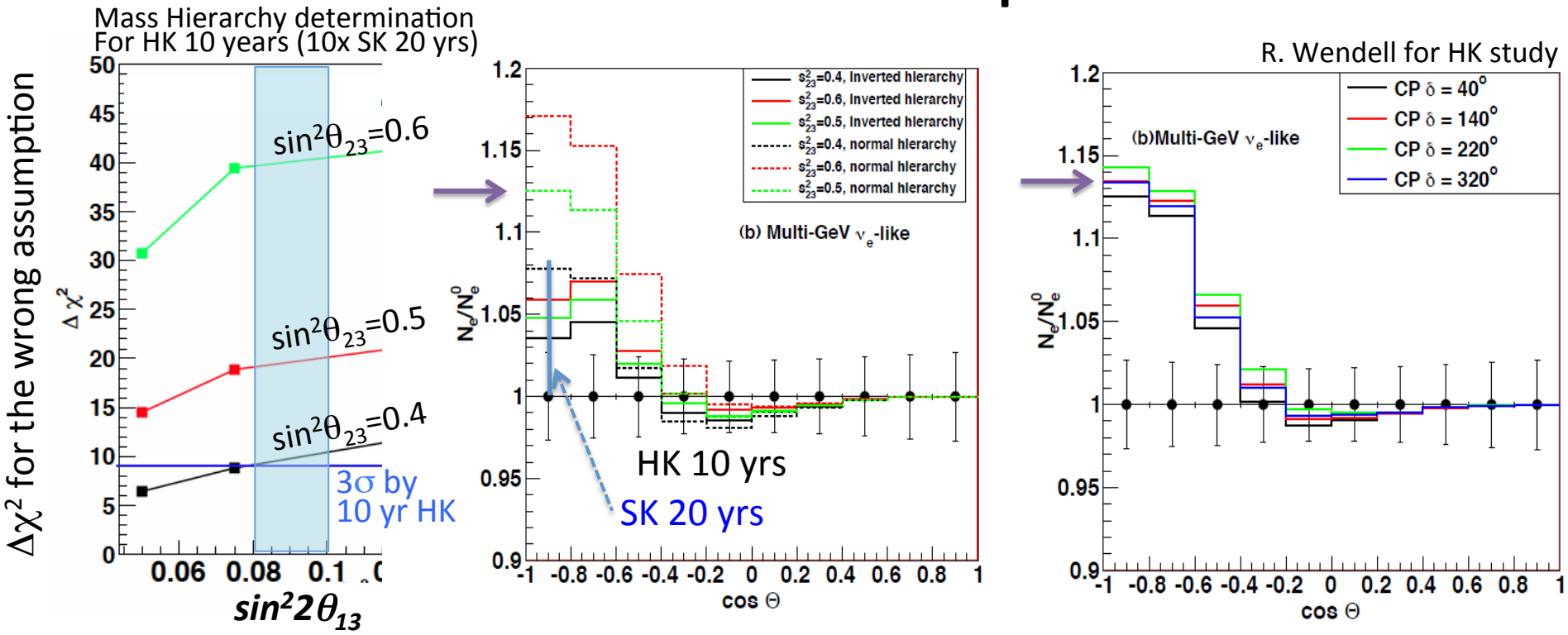


3rd term: θ_{13} term, Matter Effect Resonance for
neutrinos + Normal MH
antineutrinos + Inverted MH
5~15% effect

2nd term: Interference: CP-Phase

➔ **Multi-GeV sample**

Multi-GeV sample



- Resonance Effects: 5~15%, Normal MH > Inverted MH
- Difference for MH is larger for $\cos^2\theta_{23} > 0.5$
- CP difference is ~1~2 % for SK → difficult to measure
- For MH ➔ SK may indicate ~2σ level effect in a few more years if 'the parameters are lucky for us'
- Since MH is a kind of on/off, therefore 2~3 experiments showing 2~3σ effect may be enough to determine!

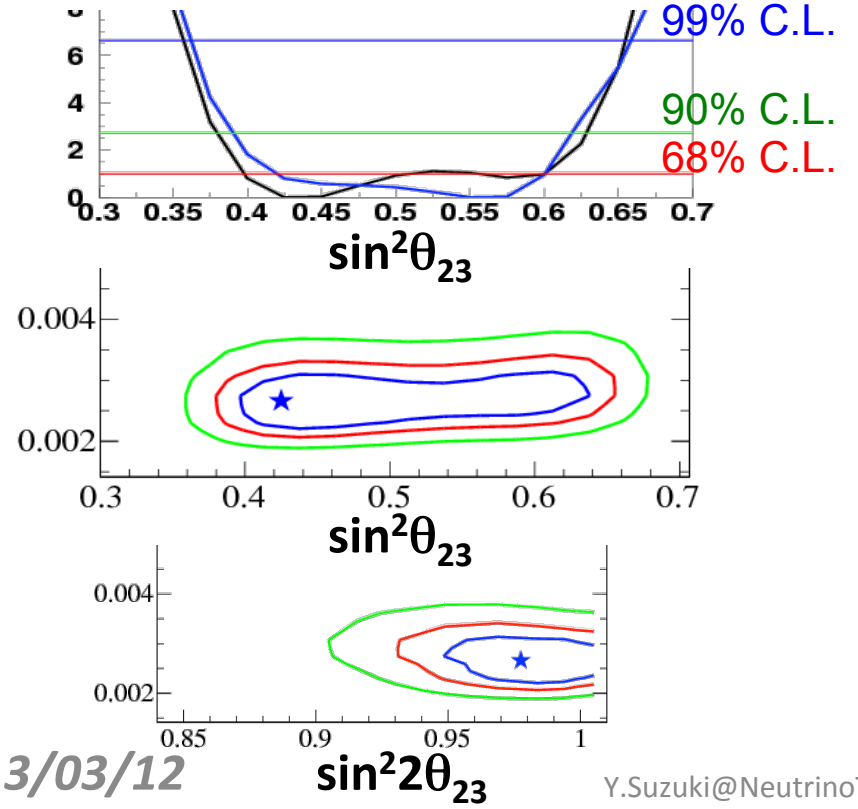
We have made ν_e ($\overline{\nu}_e$) enhanced samples
ν_e → larger y=(E-E')/E
→ larger # of π
→ diff. # of decay-e

Current situation of atmospheric ν θ_{23} Octant

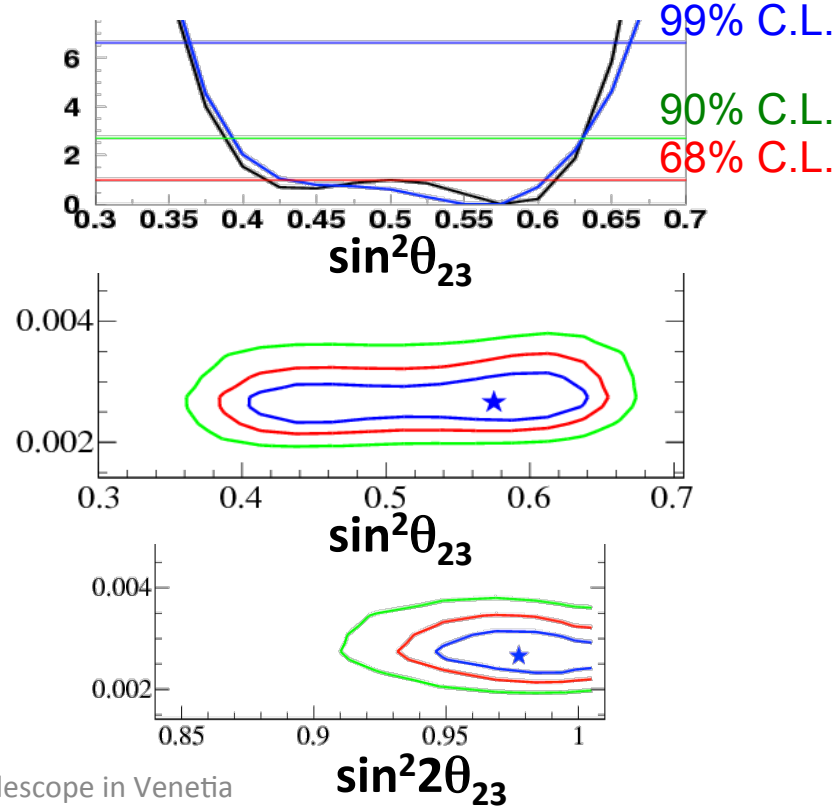
Super-Kamiokande atmospheric neutrino 3 flavor analysis
--- θ_{13} free in the fitting
--- θ_{13} fixed at the best value

We may start to see 1 σ level effect ??

- Normal Mass Hierarchy
- Best fit value: 0.425



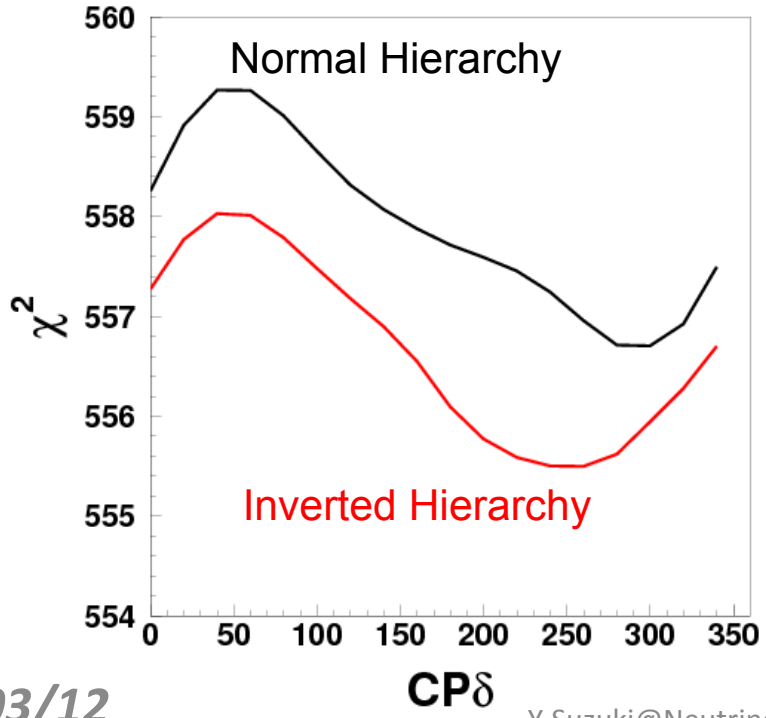
- Inverted Mass Hierarchy
- Best fit value: 0.575



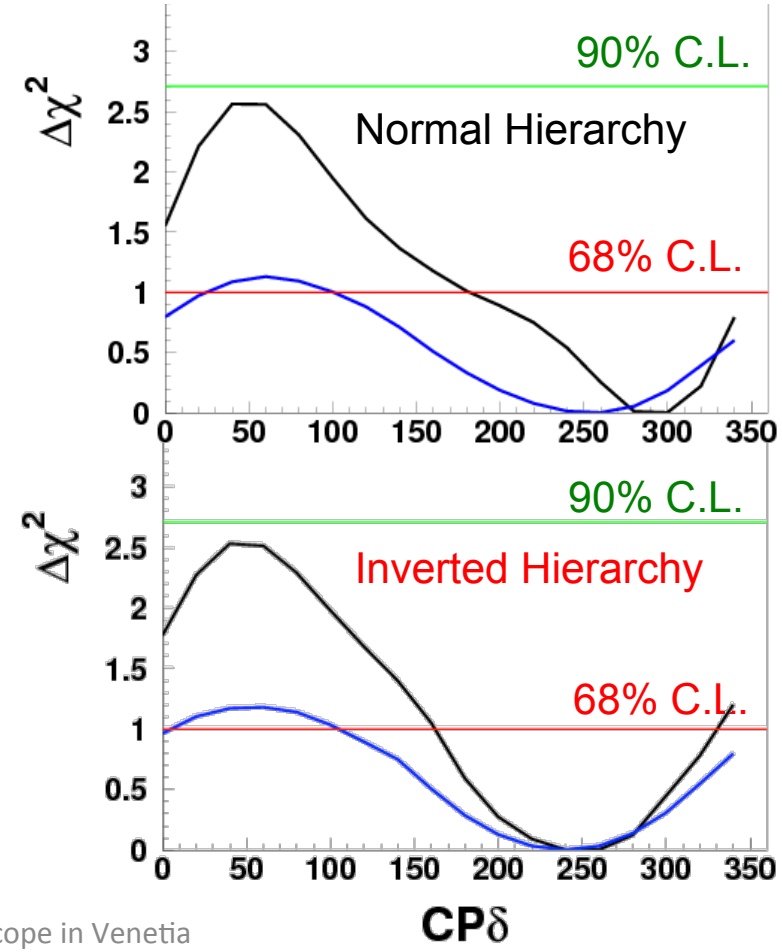
Current situation of atmospheric ν Mass Hierarchy and CP phase

- There may be a hint in Atm ν (SK)
  - NH: χ^2_{min} = 556.7 / 477 dof
  - IH : χ^2_{min} = 555.5 / 477 dof

χ^2_{min} (NH) − χ^2_{min} (IH)= 1.2



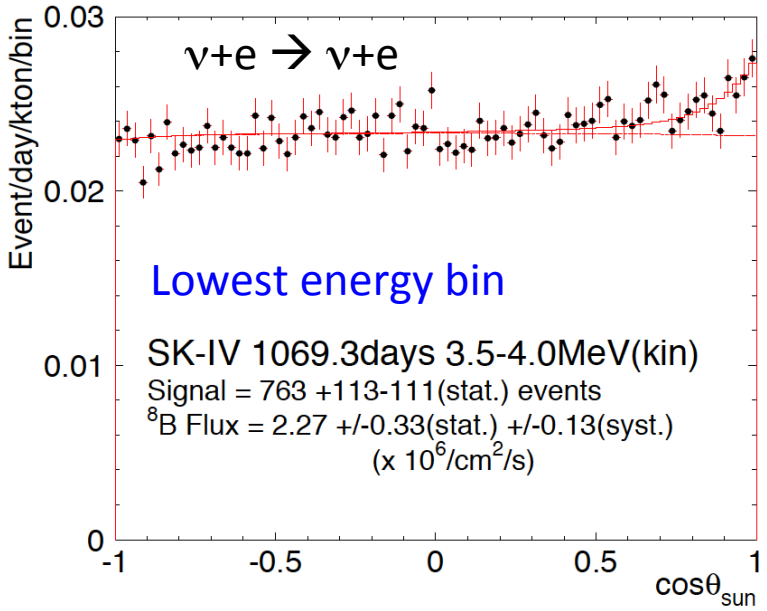
--- θ_{13} free in the fitting
--- θ_{13} fixed at the best value

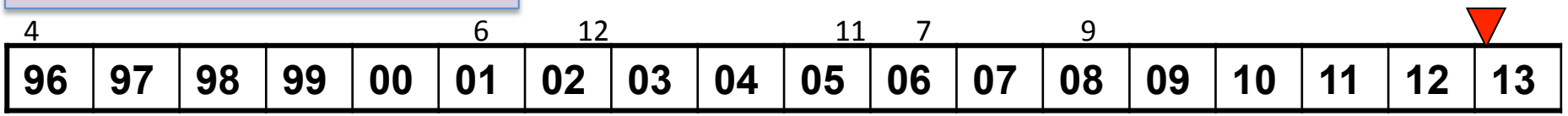


- Details and other subjects of atmospheric neutrinos will be discussed by Chris in this afternoon

Solar neutrinos

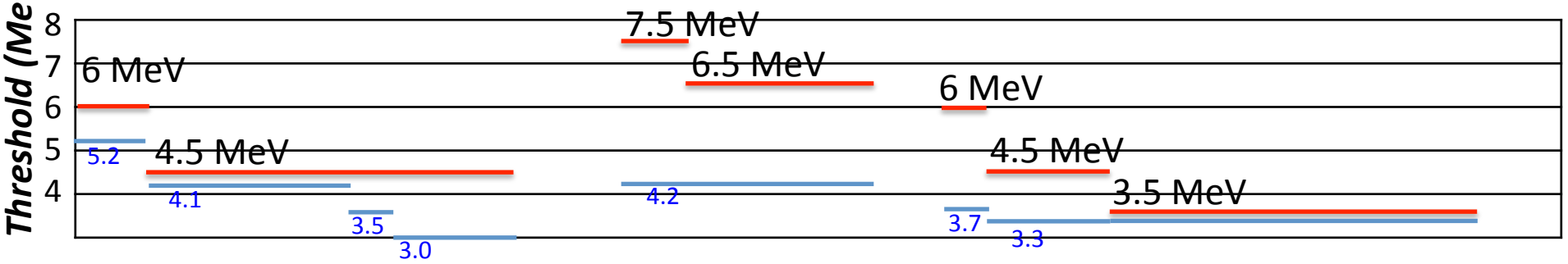
- Total 3904 days
  - 57,574.1 solar neutrino events
- Analysis threshold: down to 3.5 MeV
  - Possible to 3.0 MeV in near future
- Fiducial volume
  - 22.5 kt (> 5.0 MeV)
  - 13.3 kt (4.5-5.0 MeV)
  - 8.8 kt (3.5-4.5 MeV)





SK-I | **SK-II** *~Half PMTs* | **SK-III** | **SK-IV**

SK-I	SK-II	SK-III	SK-IV
1496 days	791 days	547.9 days	1069.3 days
$22,404 \pm 226$ ev.	$7,212.8^{+152.9}_{-150.9}$ ev.	$8,147.9^{+132.9}_{-131.2}$ ev.	$19,809.4^{+219.9}_{-218.0}$ ev.

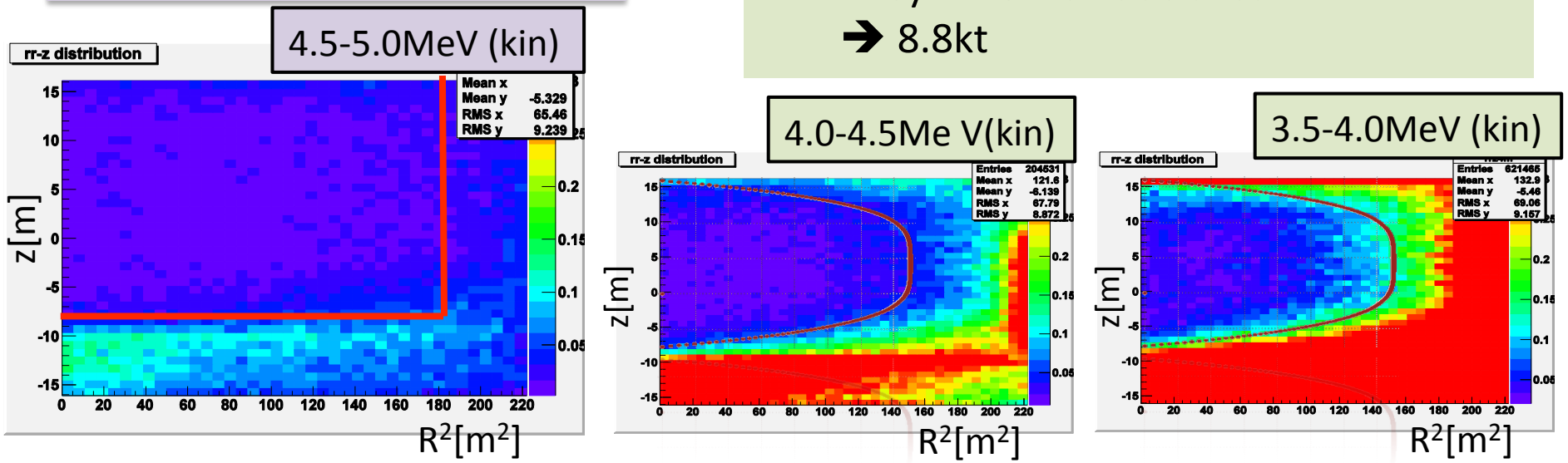


To reduce backgrounds
Tight fiducial volume cut

- Usual fiducial volume (> 5.0 MeV): 22.5 kt
- Need a limited fiducial volume for low energy to reduce backgrounds

- 4.5-5.0MeV(kin)
  - $z > -7.5$[m], $R^2<180$[m^2]
  - ➔ 13.3 kt

- 3.5-4.5MeV(kin)
  - Use z dependent, but vertically symmetric fiducial cut
  - ➔ 8.8kt

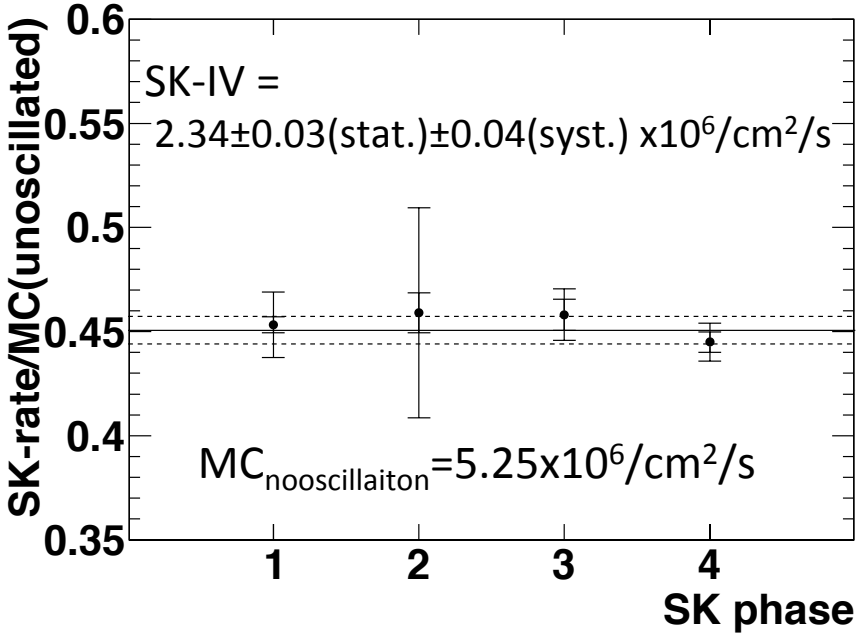


- Keep Rn at the lower level of the water tank
  - ➢ Need to avoid convection of the inner water
    - ✓ make laminar flow ← temperature control of input water is important
- **Make Acrylic vessel to prevent Rn from sneaking into the fiducial volume**
  - ➢ **Good and necessary also for the Gadzooks project**

Solar neutrinos

Flux measurements

- Many Improvement for the last few years (systematic errors)
  - Total 3.5% → 1.7%
    - Fiducial volume: 1.3% → 0.17%
    - Energy scale: 0.64% → 0.54%
    - Others



Global Analysis (fixed: $\sin^2\theta_{13} = 0.025$)

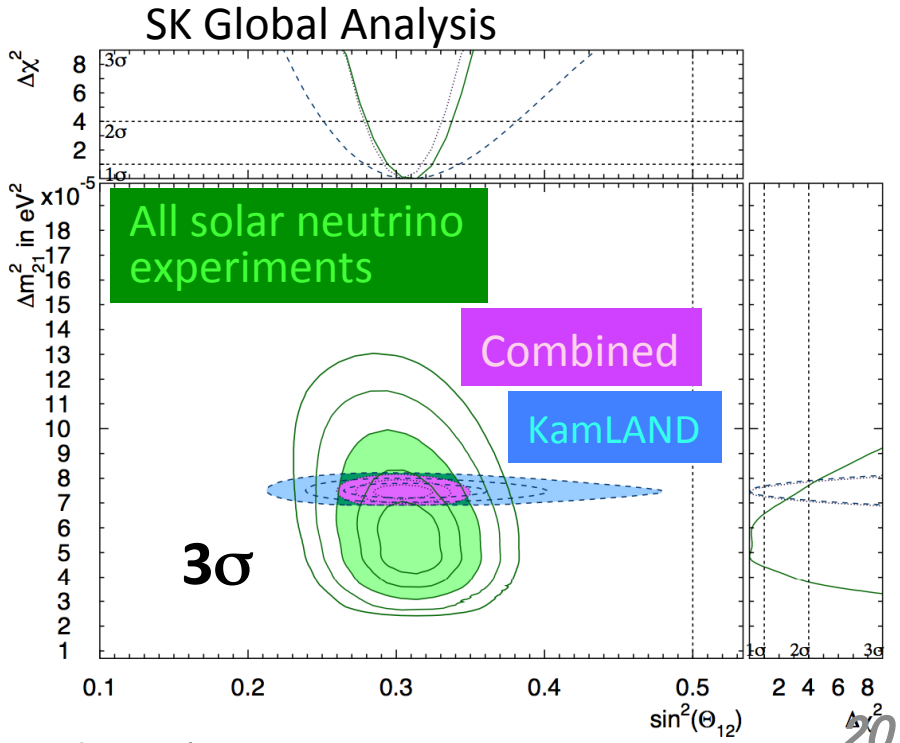
Solar Global (SK Analysis)

$$\sin^2\theta_{12} = 0.310^{+0.014}_{-0.015}$$
$$\Delta m_{12}{}^2 = 4.86^{+1.44}_{-0.52} \times 10^{-5} eV^2$$

KamLAND

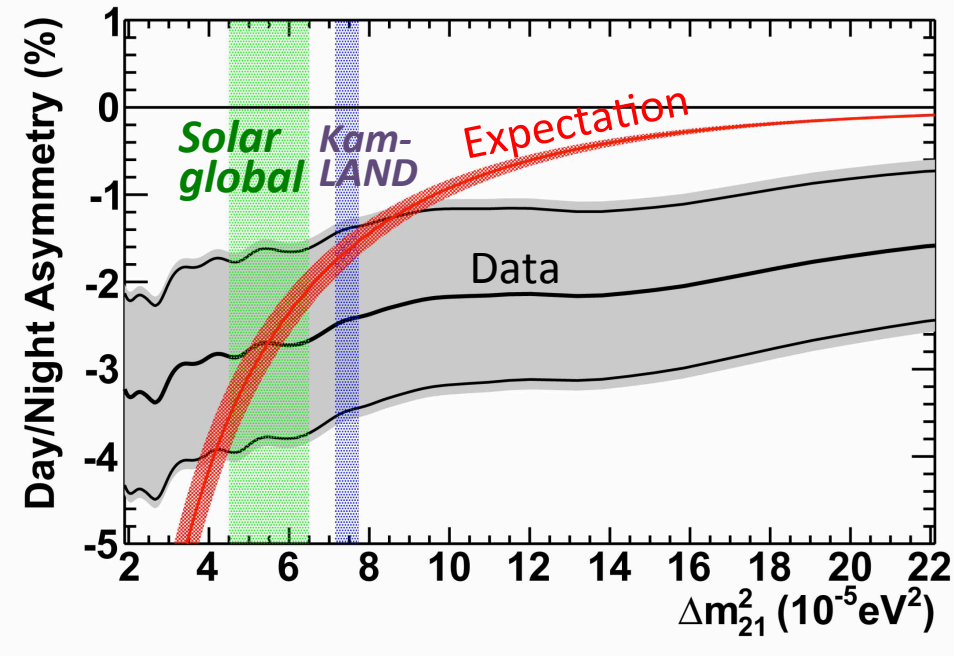
$$\sin^2\theta_{12} = 0.309^{+0.039}_{-0.029}$$
$$\Delta m_{12}{}^2 = 7.49^{+0.20}_{-0.19} \times 10^{-5} eV^2$$

- 1.5 σ difference between **KamLAND** and **solar neutrino experiments** in $\Delta m_{12}{}^2$



Day/Night Asymmetry

- Regeneration of ν_e through the earth:
- $A_{DN}=2(D-N)/(D+N)$
  ~2~3% effect
- Night-time spectrum variation depends on Δm_{12} ➔ Results (data) depend on Δm_{12}
- Δm_{12} from D/N analysis agree better with that from the solar global analysis

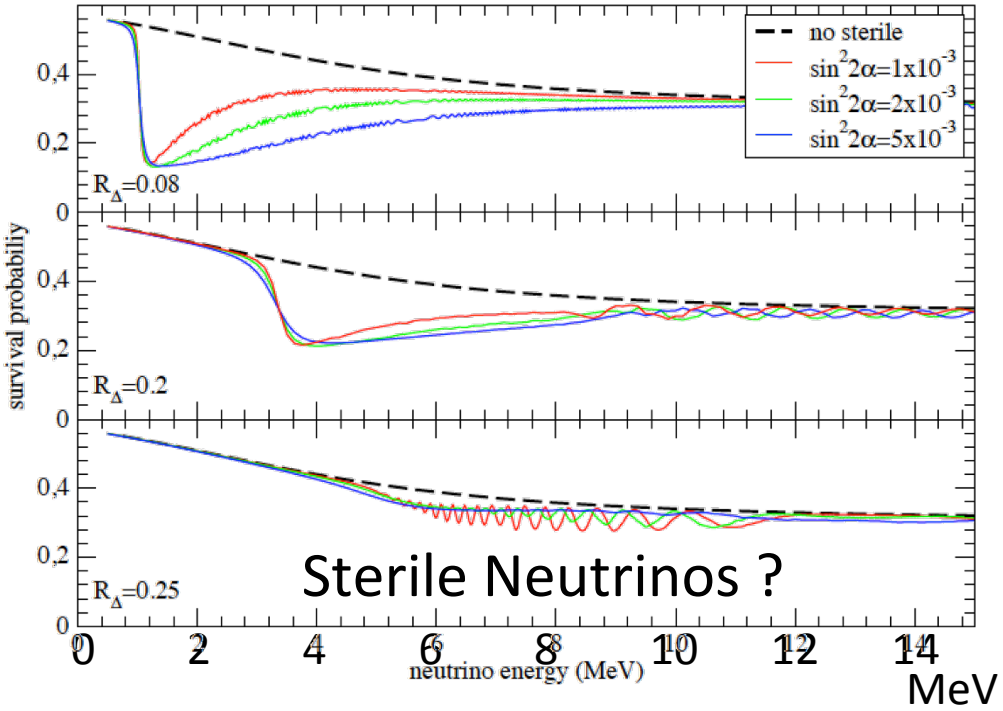


- SK-I, II, III, IV data
- $A_{ND}= -2.8\pm1.1\pm0.5\%$
  → 2.3 σ

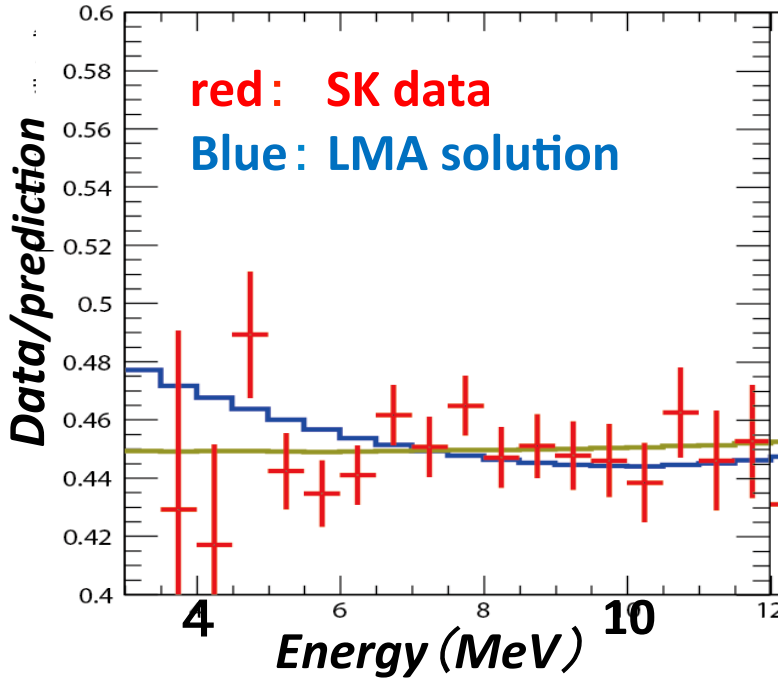
Solar neutrinos

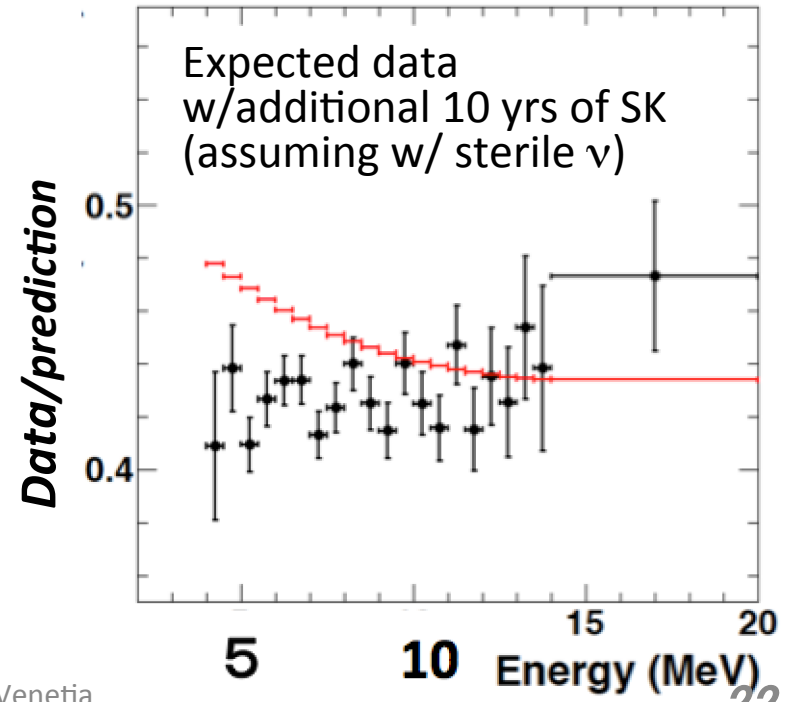
- ***No observation of up-turn yet***

Holanda and Smirnov, arXiv: 1012.5627v2



MeV

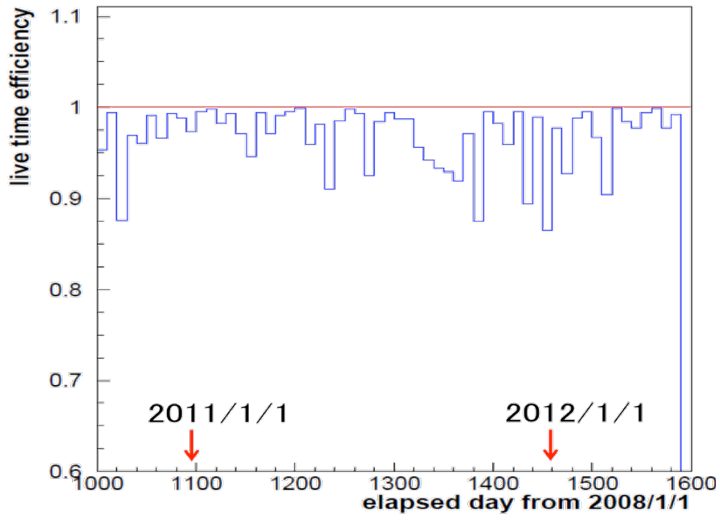




- Upturn [remaining problem]
  - Lower energy threshold
    - Remove BG
- Borexino threshold: 3.0 MeV
- SK threshold: 3.5 keV
  - aim to 3.0 MeV soon.

Supernova Neutrinos

- Burst search
  - Nearby SN ➔ Detailed Explosion Mechanism
    ➔ Additional information for Neutrino Oscillation
  - Mostly $\bar{\nu}_e + p \rightarrow e^+ + n$ and $\nu_x e \rightarrow \nu_x e$ interactions
    - Event by event reconstruction, time, energy and directionality(only for $\nu_x e$)
  - Expect 8000 neutrino events from the SN at 10 kpc
  - 2×10^7 neutrinos for Betelgeuse (640 light years)
    - Currently upgrading the electronics; 1) Sparse data taking, 2) energy flow
- SNWATCH: Continuous data taking
  - Minimizing dead time
  - Less down time for calibration
- SNEWS (Supernova Early Warning System)
  - Neutrino arrives 20-40 hours before the optical observation for Betelgeuse
  - Early warning to the observatories world wide

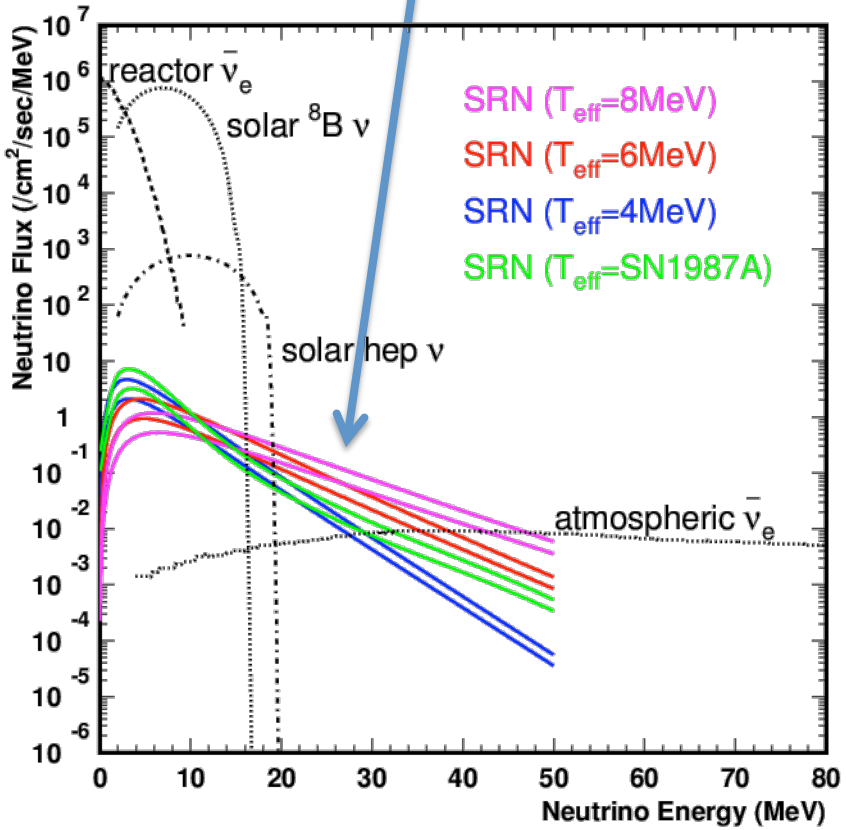


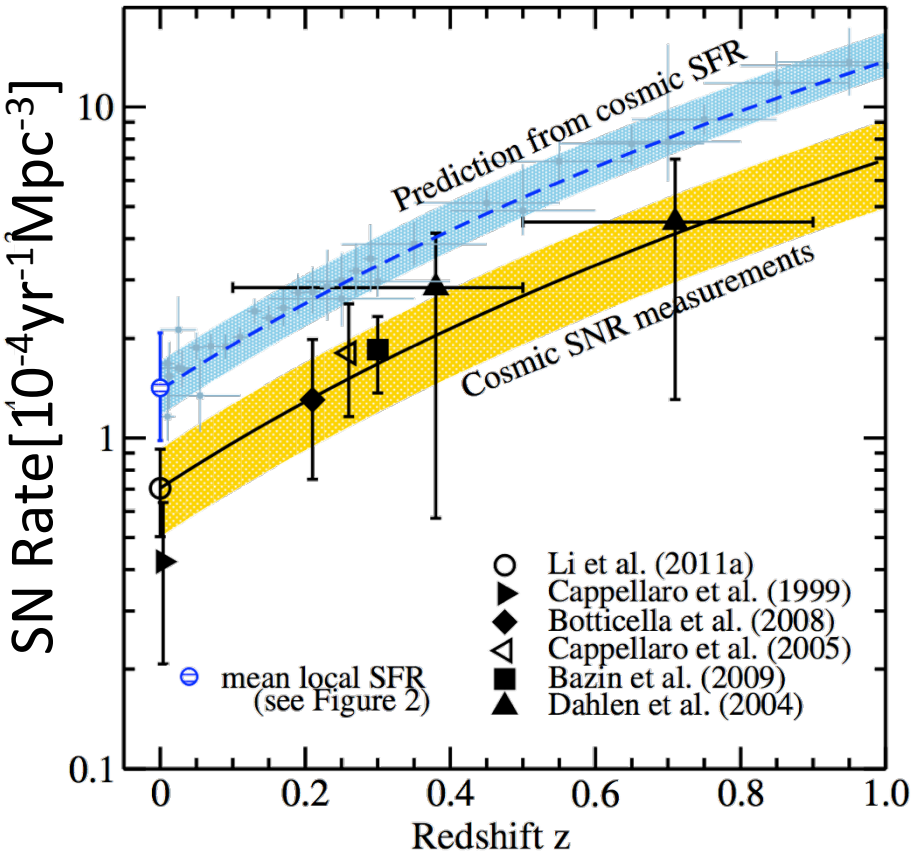
- We are preparing for the next Galactic Supernova

SRN(Supernova Relic Neutrinos)

the diffuse supernova neutrino background from all the supernovae in the past

A gap between solar and atmospheric ν

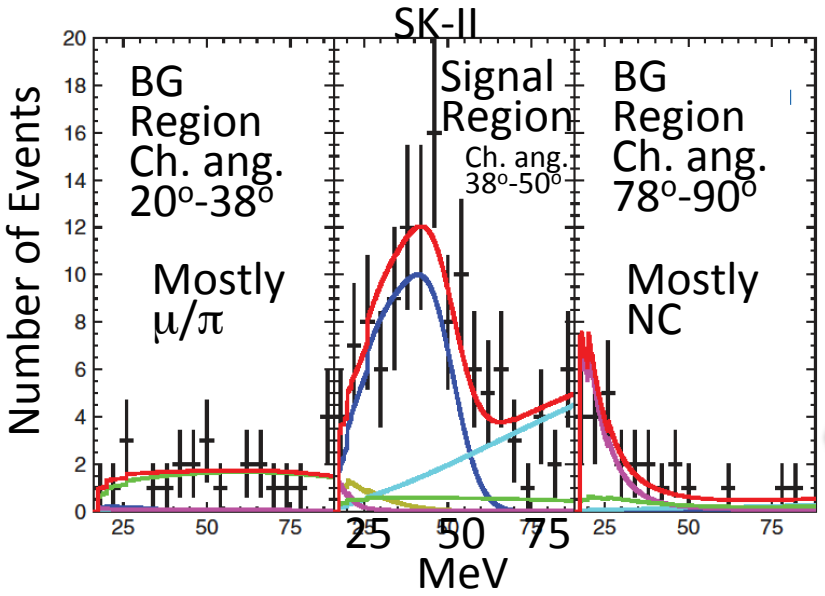




SRN carries information about Star Formation Rate (SFR), Initial Mass Functions (IMF) and so on.

SNRate: factor 2 mismatch
pred. SFR ⇔ meas. SNRate

SK result on SRN

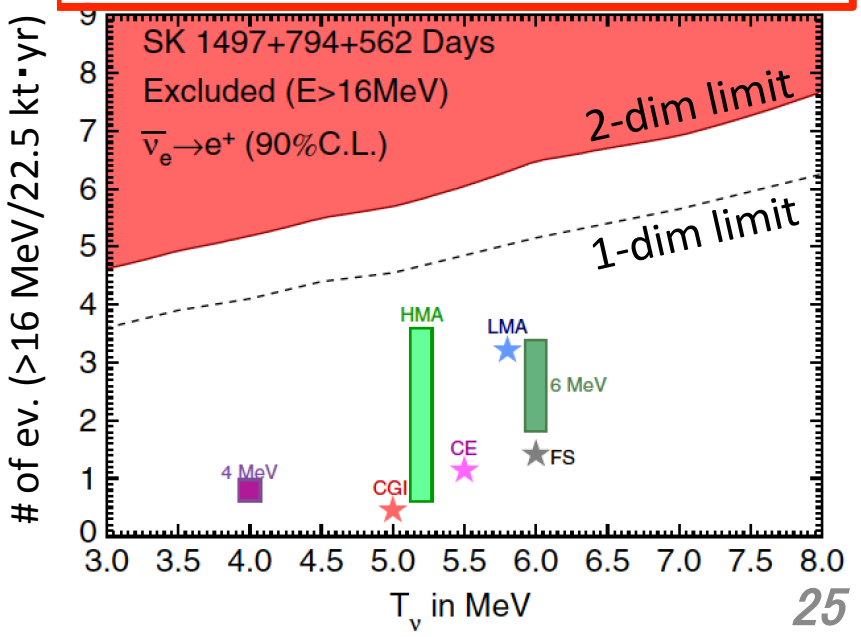


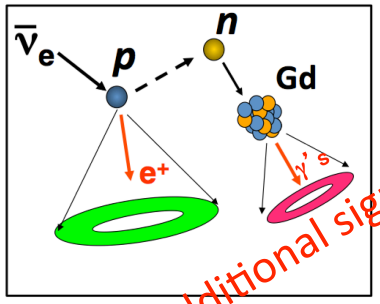
BGs and fit:
- Relic Signal
- all Backgrounds
- ν_μ CC
- ν_e CC
- NC elastic
- μ/π

- μ/π: heavier and low energy
  → small Cherenkov angle events.
- NC elastic: multiple γ's (Isotropic events).
  → 'Large Ch.' angle

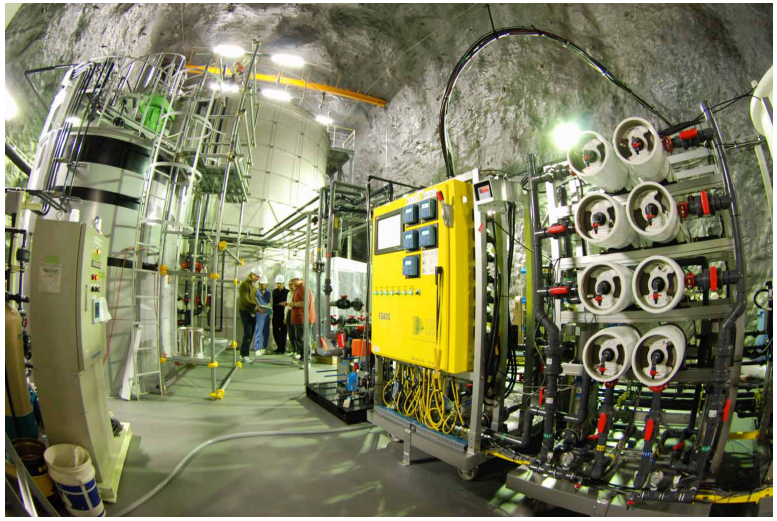
- Improvement
  - Reduce spallation BG
    - Improved the muon/spallation correlation
  - Select 16-30MeV Interval
    - Lower energy threshold by 2 MeV
  - Increase efficiency by 20%
- Two new BG channels are taken
  - Multiple region of Cherenkov angle distributions for the evaluation

Flux limit: 2.8-3.1 ν_e/cm^2/s^2 (>16 MeV)





Future Project GadZOOKs!



- To detect SRN
  - Need to reduce BG
- Gadzooks: to identify neutrons in

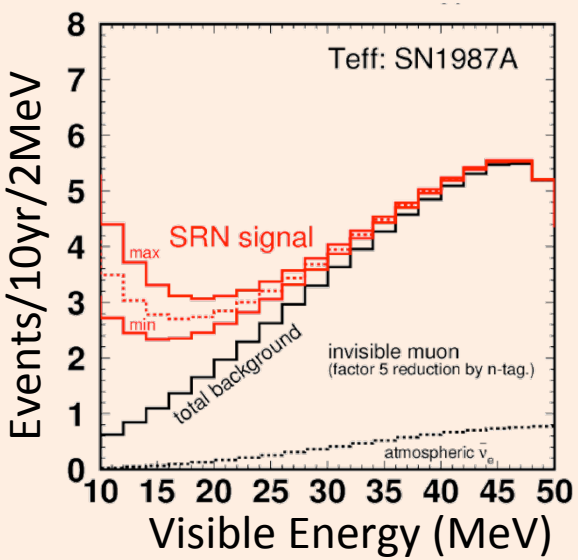
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

  - Coincidence of e^+ and n
- 0.2% Gd sulfate
  - 49,000 barns (5 order larger than *p*) for thermal cap.
  - γ cascade of 8 MeV
  - $\Delta t \sim 20\ \mu s$

- R&D: EGADS (2009 ~): Test Facility
  - 200 ton main tank
  - Selective filtration system
    - Cleaning unwanted impurities
    - Keep Gd in the water
  - Transparency measurement
- Currently Gd doped water is circulated by increasing the Gd concentration gradually

- In summer, the 240 PMTs will be mounted
- Full test w/ the PMT will be done in Fall, 2013.

Merits of GadZOOKs



Supernova Relic Neutrinos

- Assume 1/5 reduction of the backgrounds (efficiency for neutron capture: 90% and cut efficiency 74%)

➔We expect 20~40 SRN events between 10 and 30 MeV for T_{eff} = SN1987A

➔More events for larger T_{eff}

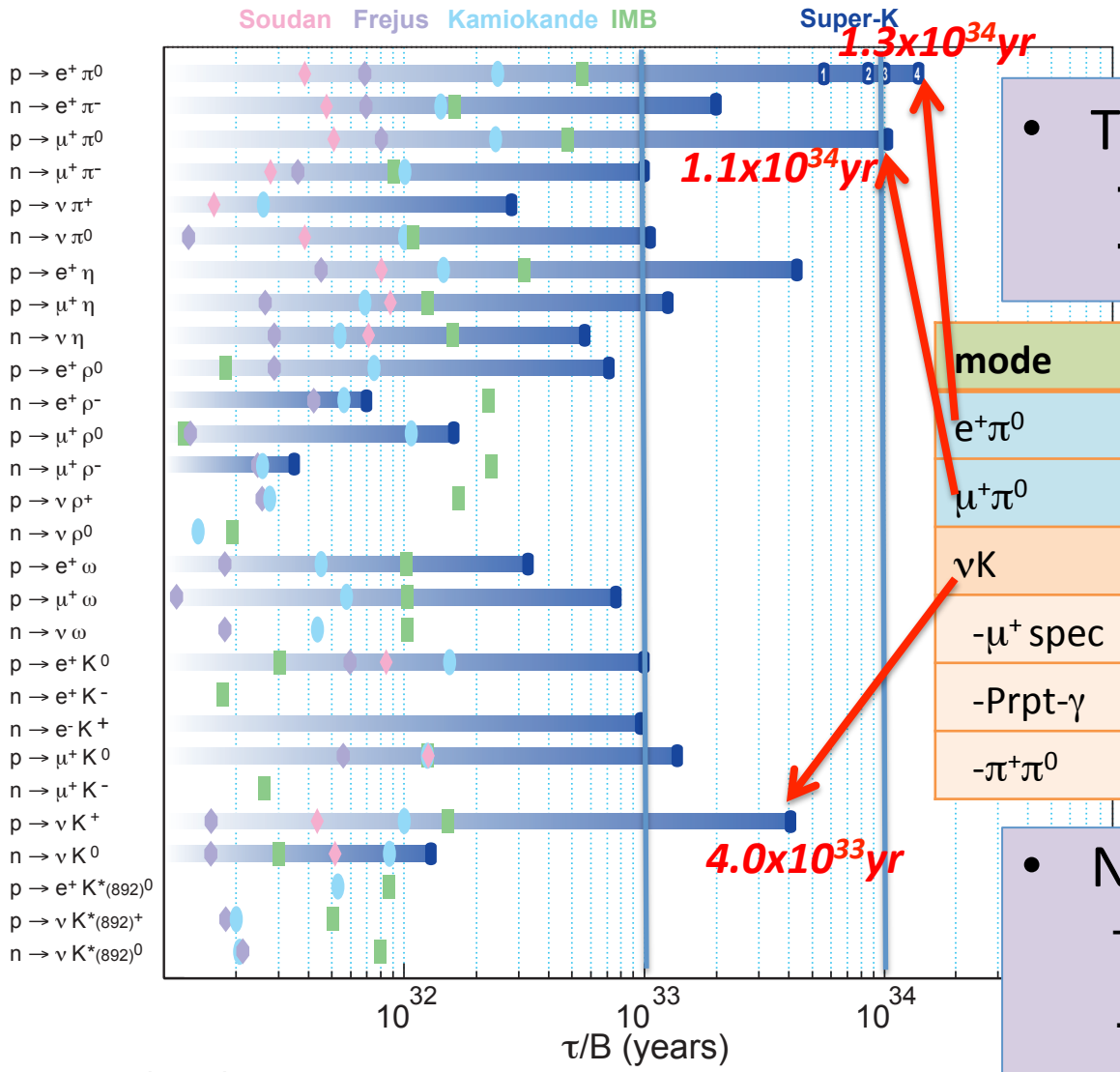
A. Odrzywolek et al., astro-ph/0311012

Si-burning for 20x $M_\odot$

Burnig Phase	T_c [MeV]	L_ν [erg/s]	Duration	Total energy [erg]	Average ν energy [MeV]	Ev. Rate for SK day-1
C	0.07	7.4×10^{39}	300 yrs	7×10^{49}	0.71	
Ne	0.146	1.2×10^{43}	140 days	1.4×10^{50}	0.99	
O	0.181	7.4×10^{43}	180 days	1.2×10^{51}	1.13	
Si	0.319	3.1×10^{45}	2 days	5.4×10^{50}	1.85	41 at 1 kpc

- For Betelgeuse (0.2 kpc), expect 1000 events / day
  - difficult to detect e^+ from $\bar{\nu}_e + p \rightarrow e^+ + n$, but
  - easy to observe 8 MeV γ's from neutron capture

Nucleon Decay

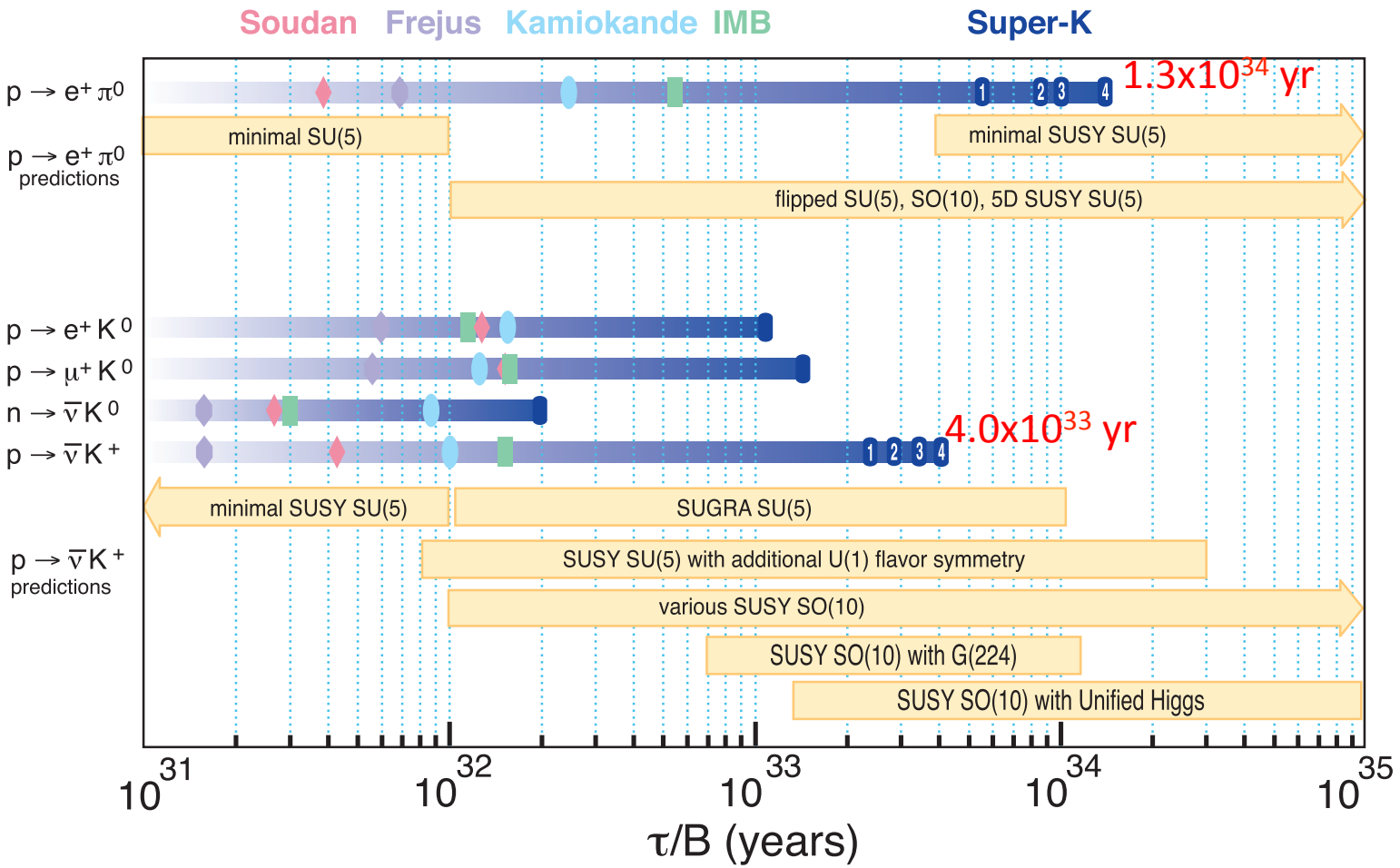


- The largest detector
  - → 220kt·yr maximum exposure
  - → No nucleon decay indications !

mode	selection	εBr (%)	obs	BG	physics
$e^+\pi^0$	P_{tot}, m_p	44-45	0	0.5	$\tau \sim M_x^4$
$\mu^+\pi^0$	P_{tot}, m_p	35-44	0	0.6	$\tau \sim M_x^4$
νK					SUSY-G
-μ^+ spec	p_μ	36-44	*	*	
-Prpt-γ	p_μ, $E\gamma$, Δt	6-8	0	0.4	
-$\pi^+\pi^0$	E_{π^0}, π^+ id.	5-8	0	1.2	

- New electronics (SK-IV)
  - Increase the efficiency for Michel electrons
  - → Improved efficiency for $\mu^+\pi^0$, νK^+

Nucleon Decay



- ***Background level < 1 in many decay modes***
  - ***Sensitivity: proportional to the exposure in future***
- ***We continue to search for proton decay***

Summary

- After the discovery of the neutrino oscillations we have further developed the oscillation study.
  - Precisely determined oscillation parameters (atmospheric and solar neutrinos)
  - Obtained evidence for tau appearance and tested CPT in atmospheric ν
  - Obtained positive indication of Day/Night effect (solar ν)
  - Made many efforts to reduce low energy backgrounds
  - Improved the machinery for detecting nearby SN burst
  - Mostly finished the the feasibility study of GadZOOKs

17 year old Super-K is still very active

- We will continue data taking at least for the next ten years
  - to study MH, CPV, upturn
  - to observe SN Relic neutrinos
  - to look for neutrino bursts from SNe and protons to decay
- We hope that we will hand them to Hyper-Kamiokande in very near future