20+5 min

Super-Kamiokande

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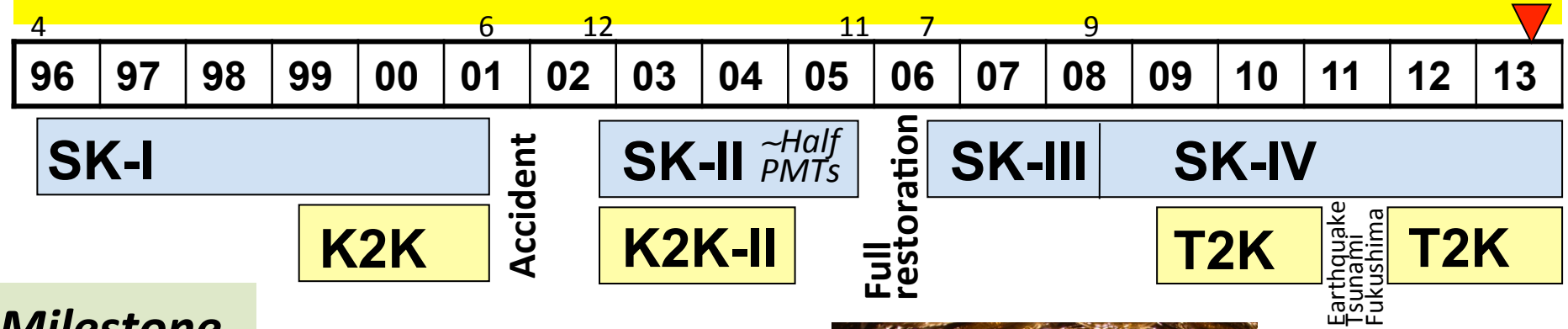
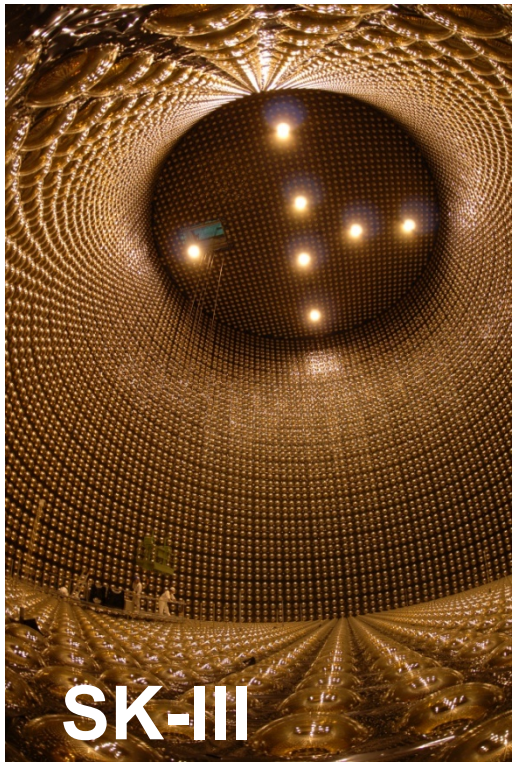
Super-K is 17 years old in the last April

Brief history of Super-Kamiokande



Milestone

- **1996: SK started**
- **1998: Discovery of Atmospheric Neutrino Oscillation (θ_{23}, Δm_{23}^2)**
- **2001: Discovery of Solar Neutrino Oscillation (w/SNO) (θ_{12}, Δm_{12}^2)**
- **2004: Confirmation of the atmospheric ν oscillation by K2K/SK**
- **2004: Discovery of the oscillatory behavior of the atmospheric ν**
- **2011: Indication of θ_{13} by T2K/SK**
- **2013: ν_τ appearance in atm-ν (3.8σ)**
- **2013: Day/Night effect sol-ν (2.7σ)**



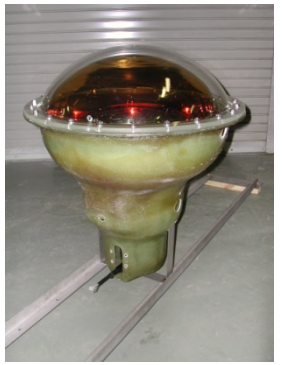
Water Cherenkov

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

	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

	1998	2013
Japan	75	62
USA	55	31
Poland	1	1
Spain	--	1
Korea	--	5
China	--	4
Canada	--	8
Total	***131***	***112***

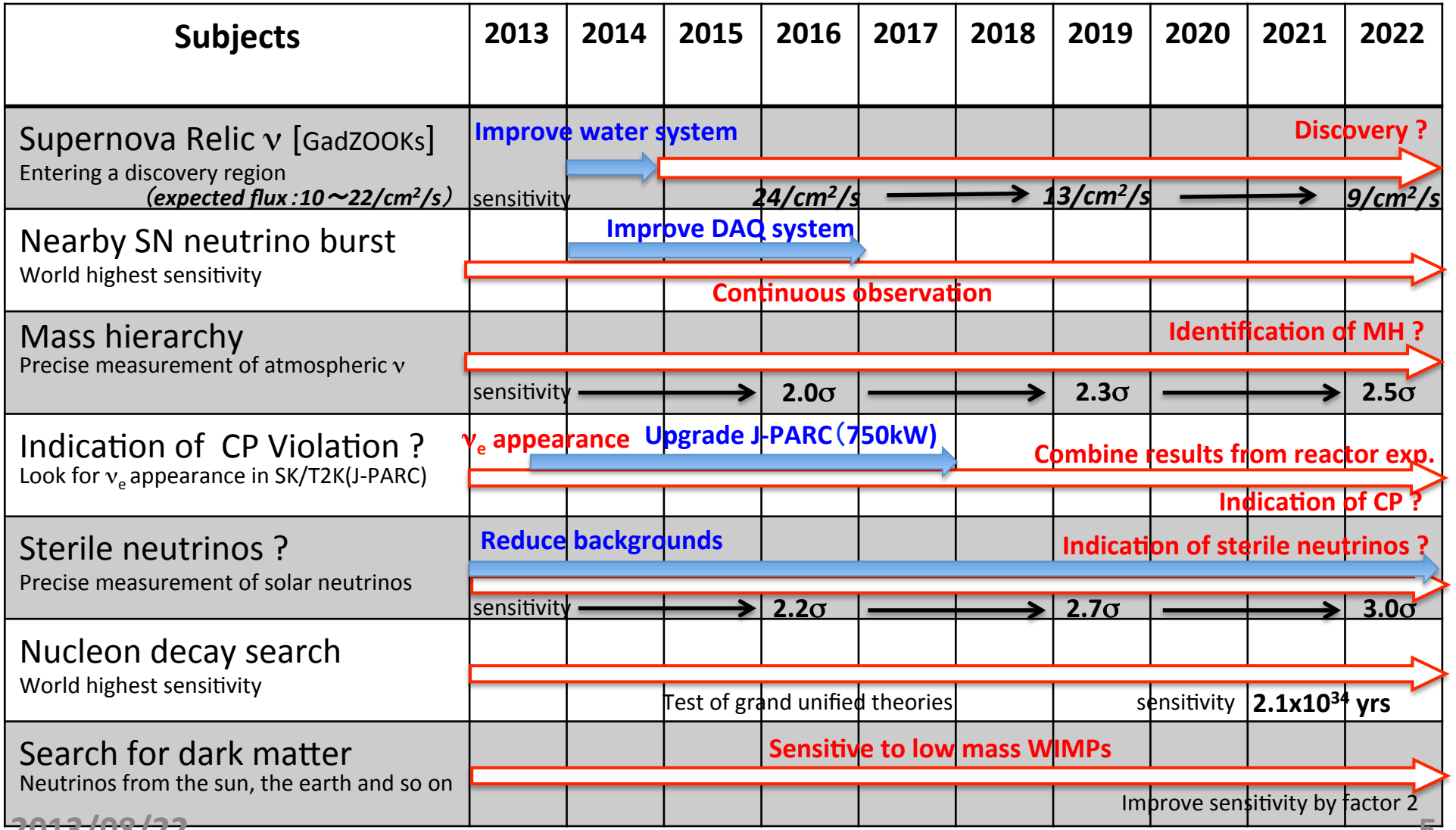
- T2K is a separated collaboration
  - Not all the SK collaborators are involved in T2K
- New countries (Spain, Korea, China, Canada) joined

Status of Super-K

- People might say that SK has finished the role.
- But not true
  - ***Last year our funding agency (MEXT) 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

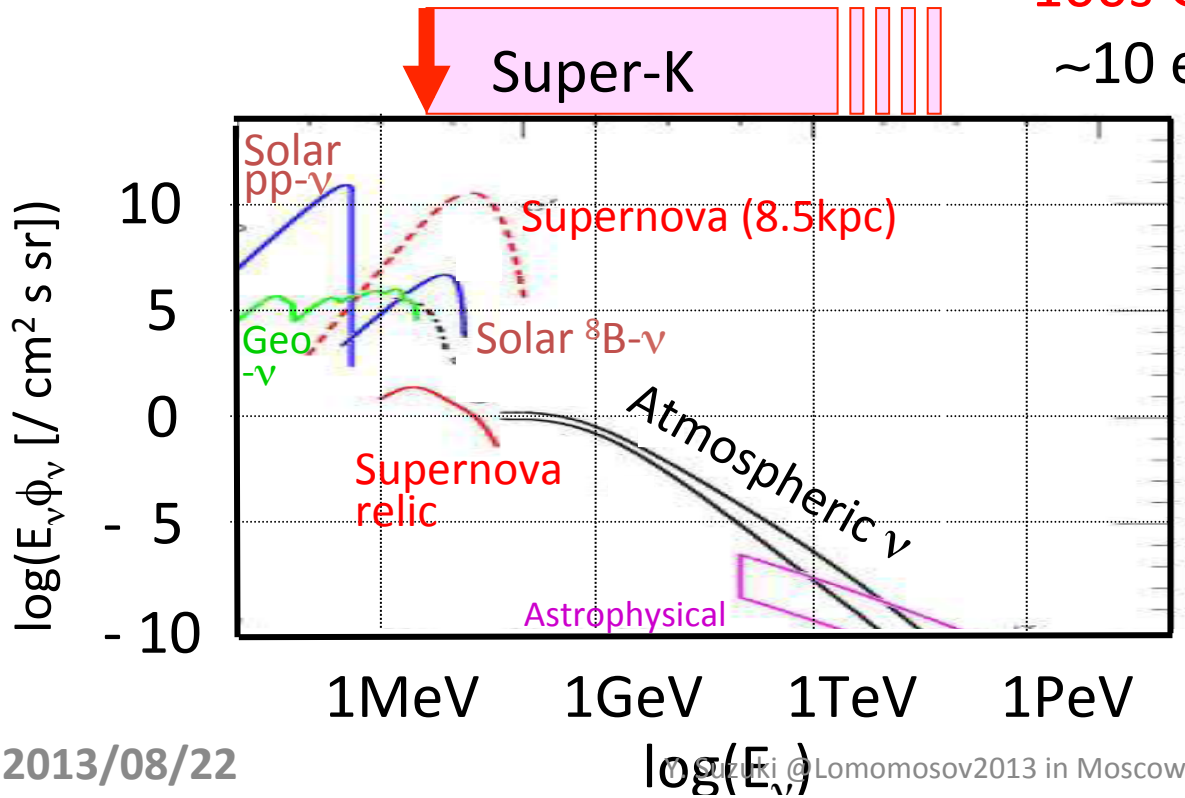
MEXT asked us to provide 10 years plan of Super-Kamiokande



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

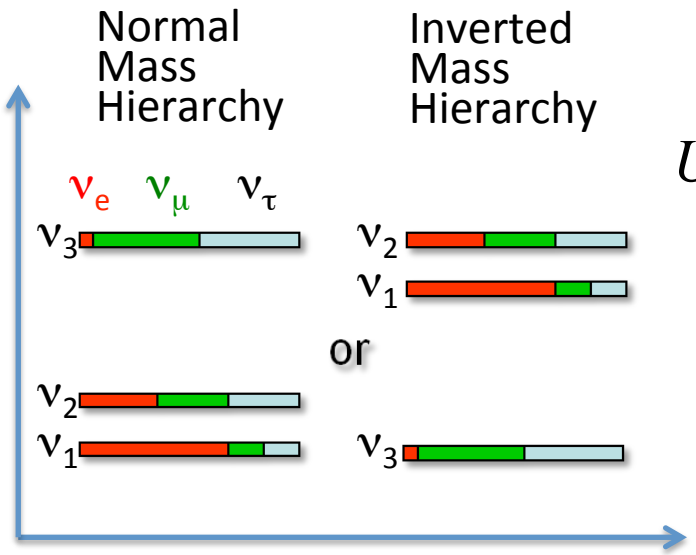
(atmospheric ν)
$1.7+0.7/\sqrt{E(GeV)}$ %
(single ring μ)

Data Accumulated

Before the last update

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

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 not only discovered the neutrino oscillation, but played also 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

ν_e appearance in 3 flavor oscillation

$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx P_2(r \cdot \cos^2\theta_{23} - 1)$$
$$-r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin^2\theta_{23}(\cos\delta_{CP} \cdot R_2 - \sin\delta_{CP} \cdot I_2)$$
$$-2\sin^2\tilde{\theta}_{13}(1 - r \cdot \sin^2\theta_{23})$$
$$-\sin^2\tilde{\theta}_{13}P_2(r - 2) + \sin^4\tilde{\theta}_{13}(1 - r\sin^2\theta_{23})(2 - P_2)$$

Solar term

Interference term; δ_{CP}

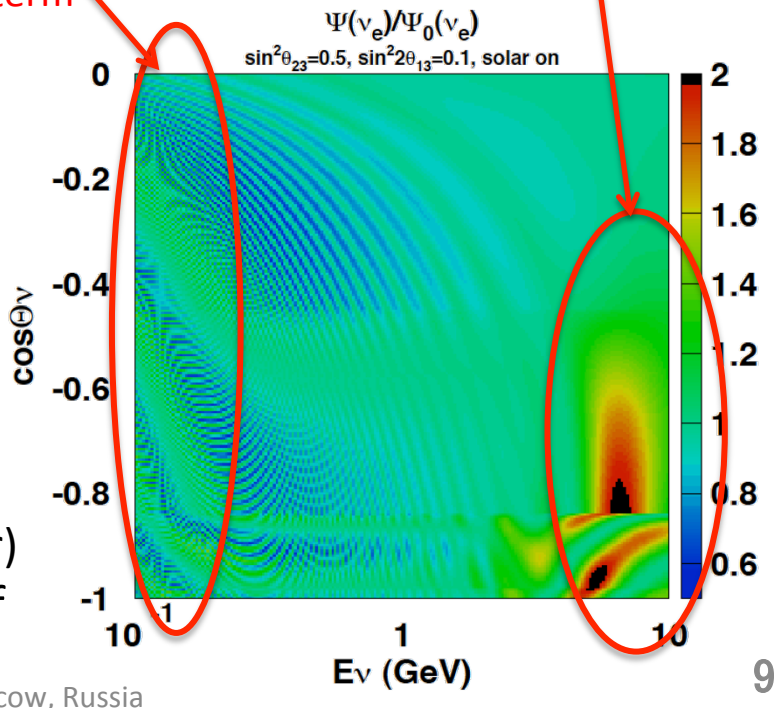
Ue3 term; matter enhancement

Negligible Ue3 term

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

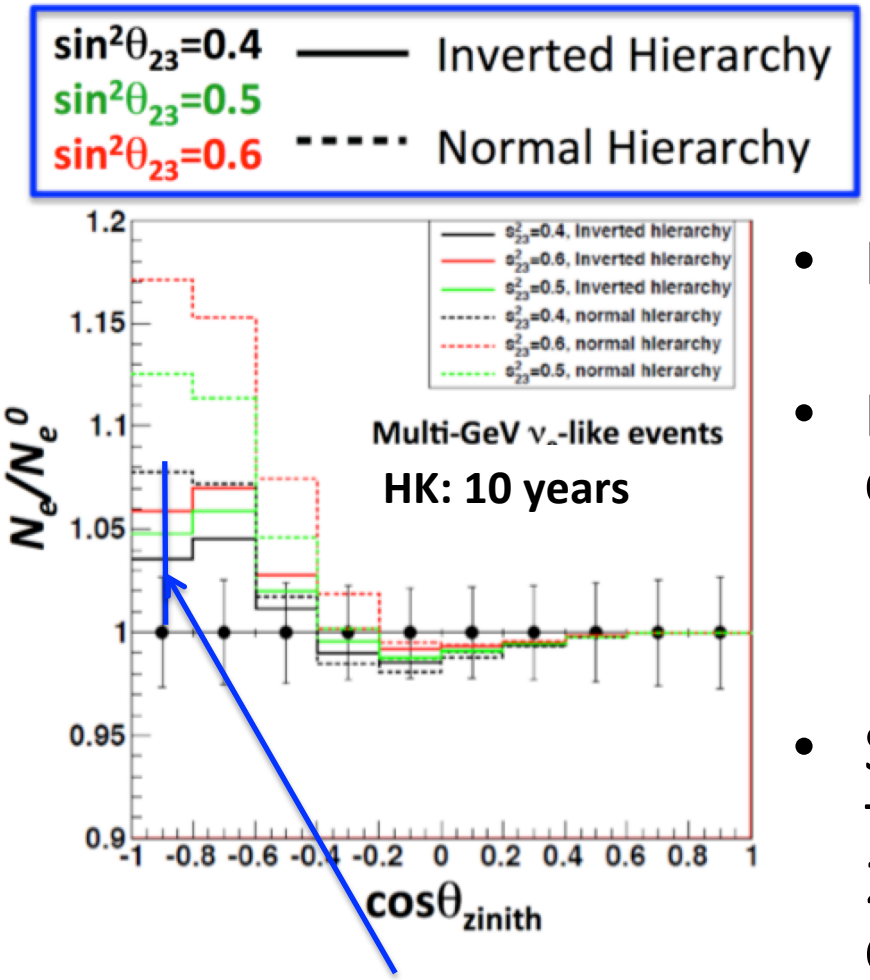
- **Mass hierarchy**
  - Ue3 matter enhancement
    - $\Delta m_{13}^2 = 2.4\times10^{-3}$ eV^2 ➔ ~10GeV
  - Resonance condition ($\pm V \sim \Delta m^2$)
    - NMH ➔ ν undergoes resonance, but not $\bar{\nu}$
    - IMH ➔ $\bar{\nu}$ undergoes resonance, but not ν
- **Octant of θ_{23}**
  - Many places: different ways to show up for different samples
- **CP-phase**
  - Interference term (Higher resonance eff is better)

➔ Atmospheric neutrinos have a clear signature of those effects if statistics is high enough.



Multi-GeV sample

R. Wendell for HK study

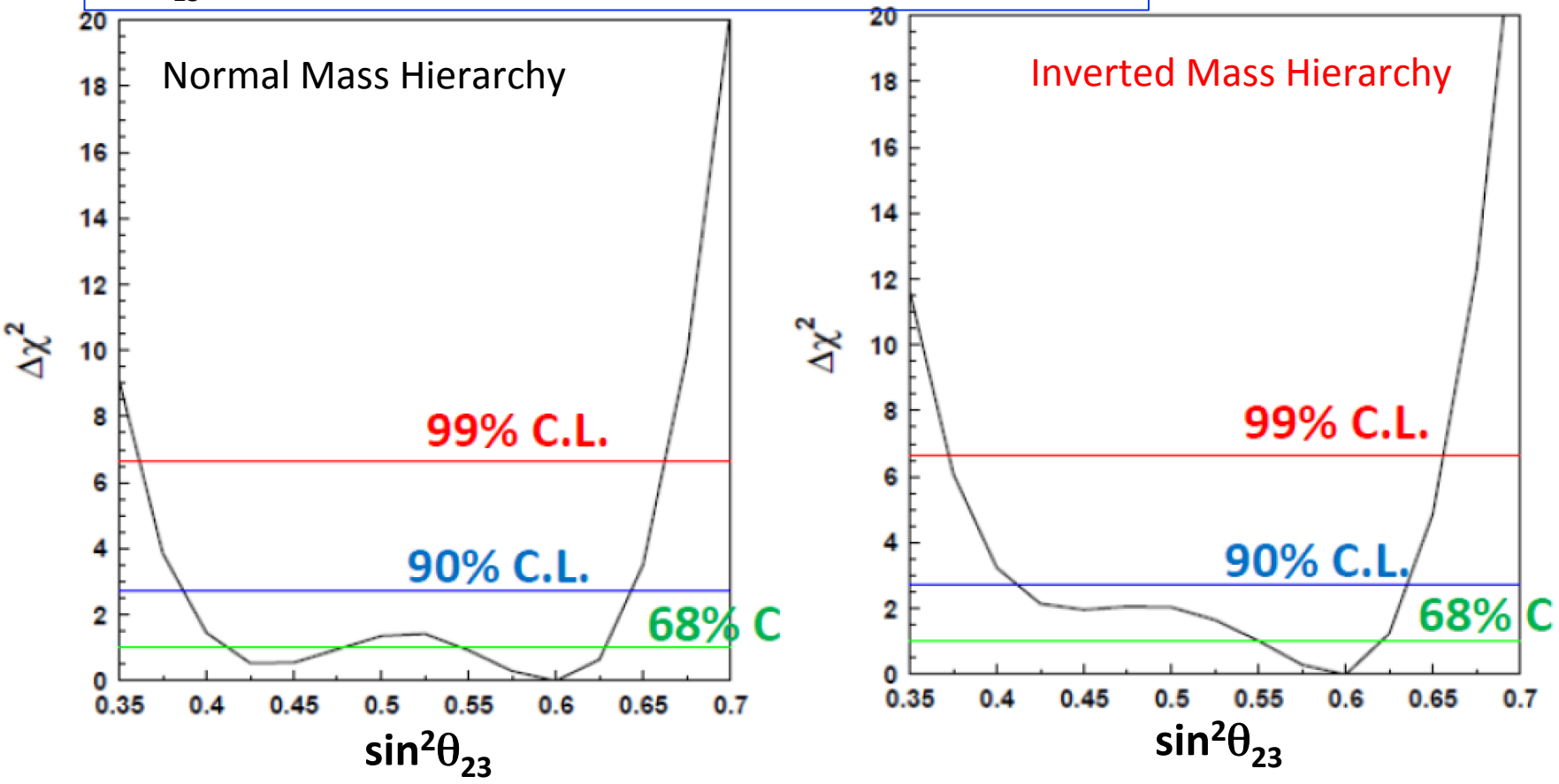


- Error bar size for SK: 20 years
- A few more years from now

- Resonance Effects: 5~15%,
  - Normal MH > Inverted MH
- Difference of MH is larger for $\cos^2\theta_{23} > 0.5$
  - → 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

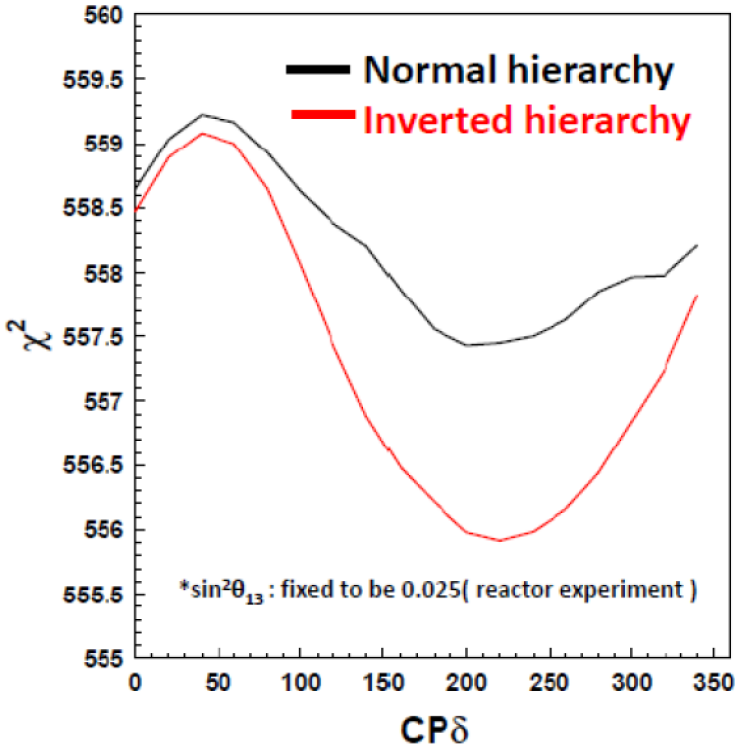
Current situation of atmospheric ν θ_{23} Octant

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

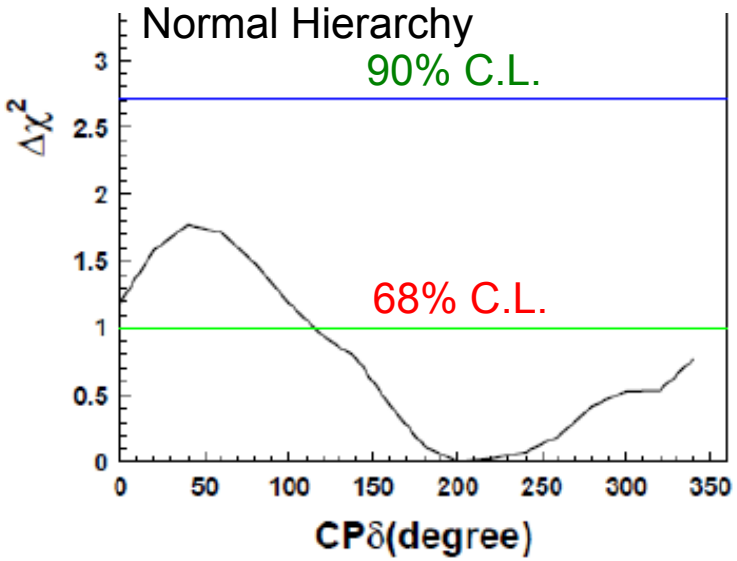


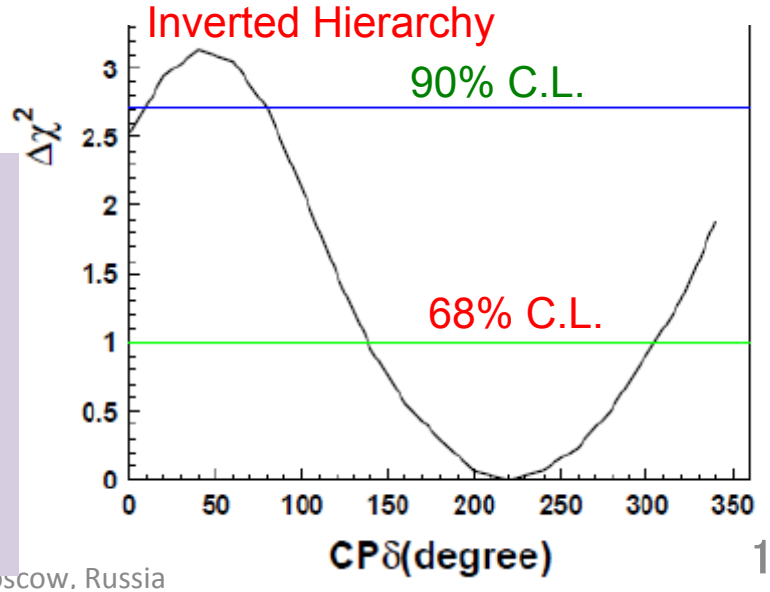
Super-K data favor the second octant of θ_{23} regardless of the assumed hierarchy

Mass Hierarchy and CP phase



--- θ_{13} fixed at the best value





NH: χ^2_{min} = 557.7 / 477 dof

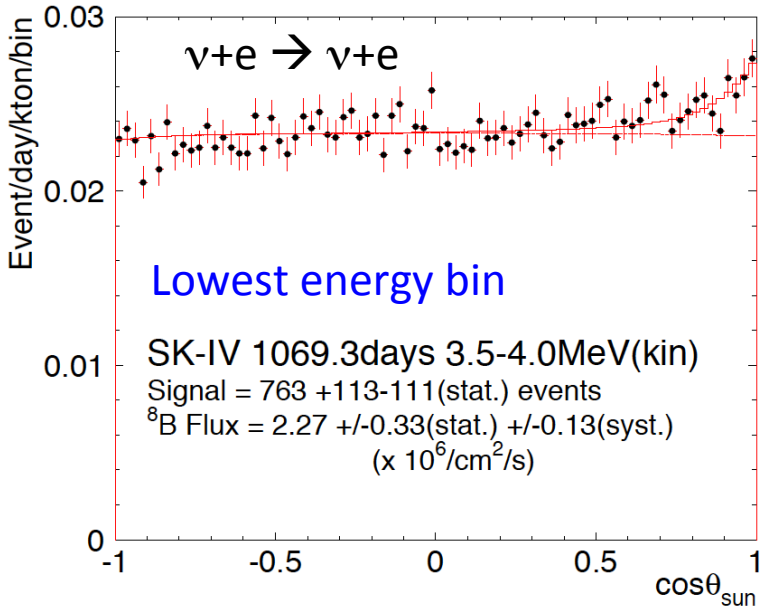
IH : χ^2_{min} = 556.2 / 477 dof

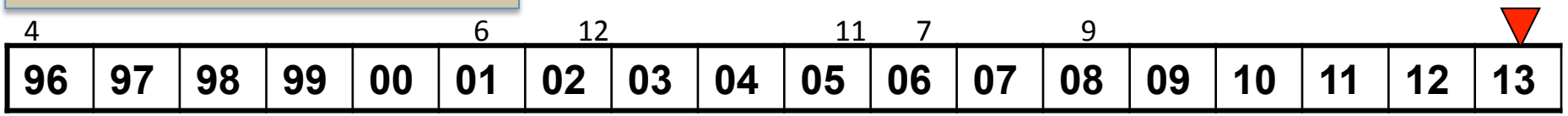
χ^2_{min} (NH) − χ^2_{min} (IH)= 1.51

- Small χ^2 for the inverted MH
- Super-K data favor δ_{cp} = 220 degrees over 40 degrees regardless of the assumed hierarchy
- Preference is stronger in the inverted hierarchy fit

Solar neutrinos

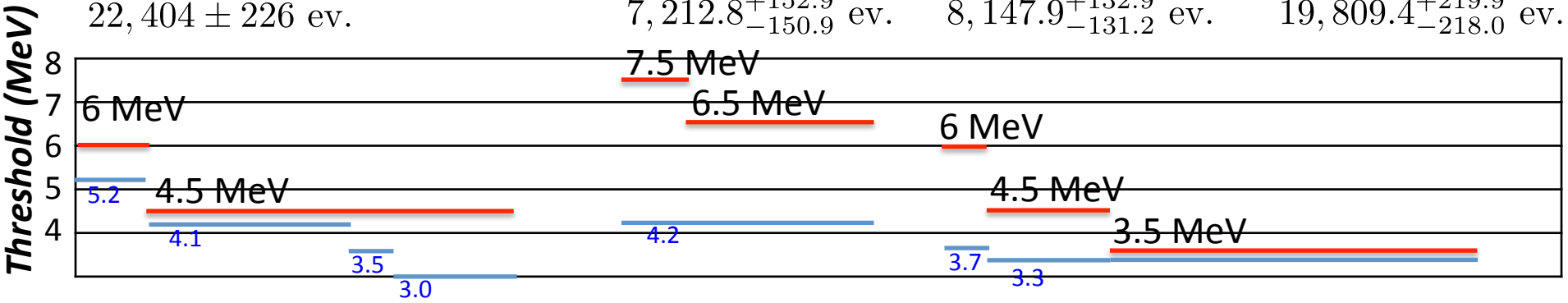
- Total 3904 days
  - 57,574.1 solar neutrino events
- Analysis threshold: down to 3.5 MeV
  - Possible to 3.0 MeV in near future
- Fiducial volume
  - 22.5 kt (> 5.0 MeV)
  - 13.3 kt (4.5-5.0 MeV)
  - 8.8 kt (3.5-4.5 MeV)





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.

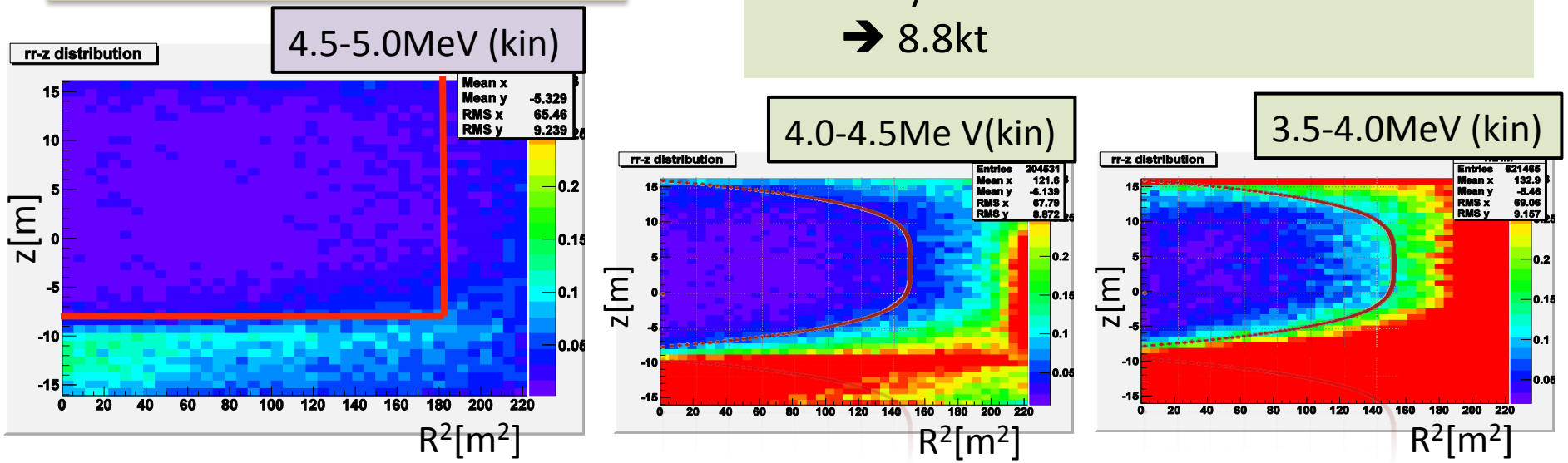


To reduce backgrounds
Tight fiducial volume cut

- 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

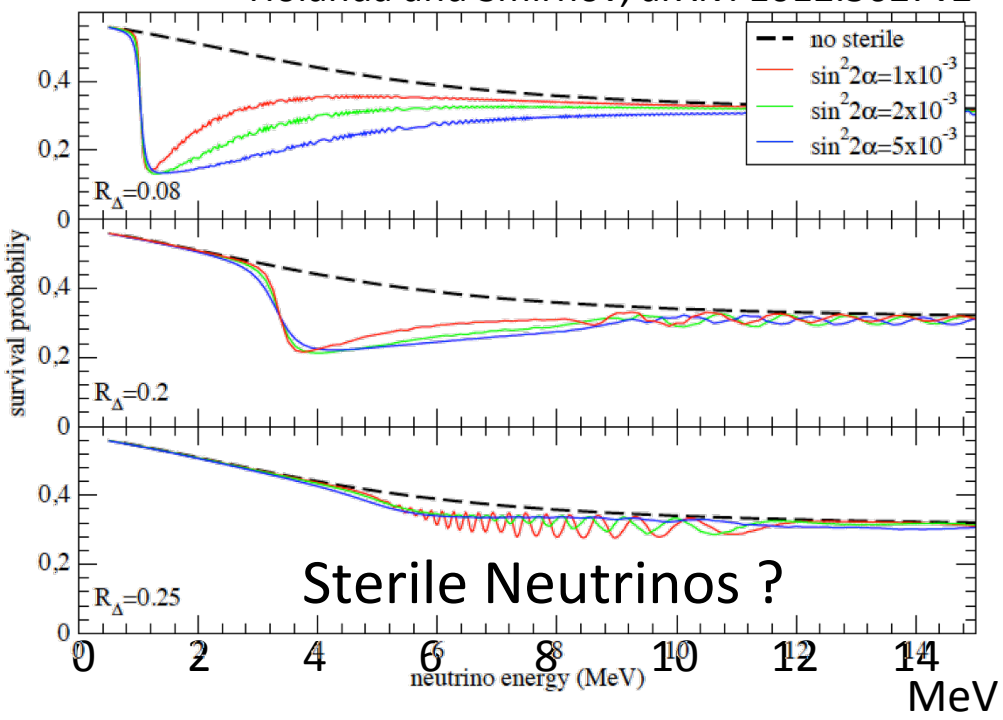


- Keep Rn lower at the lower level of the water tank
  - ➢ Need to avoid convection of the inner water
    - ✓ make laminar flow ← temperature control of input water is important
- **May make <u>Acrylic vessel</u> to prevent Rn to sneak into the fiducial volume in future**
  - ➢ **<u>Good and necessary also for the Gadzooks project</u>**

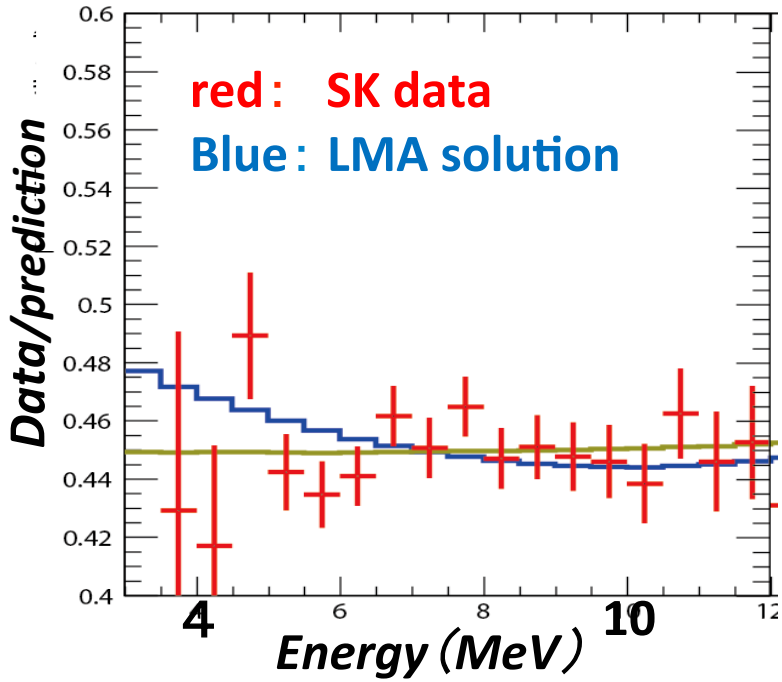
Solar neutrinos

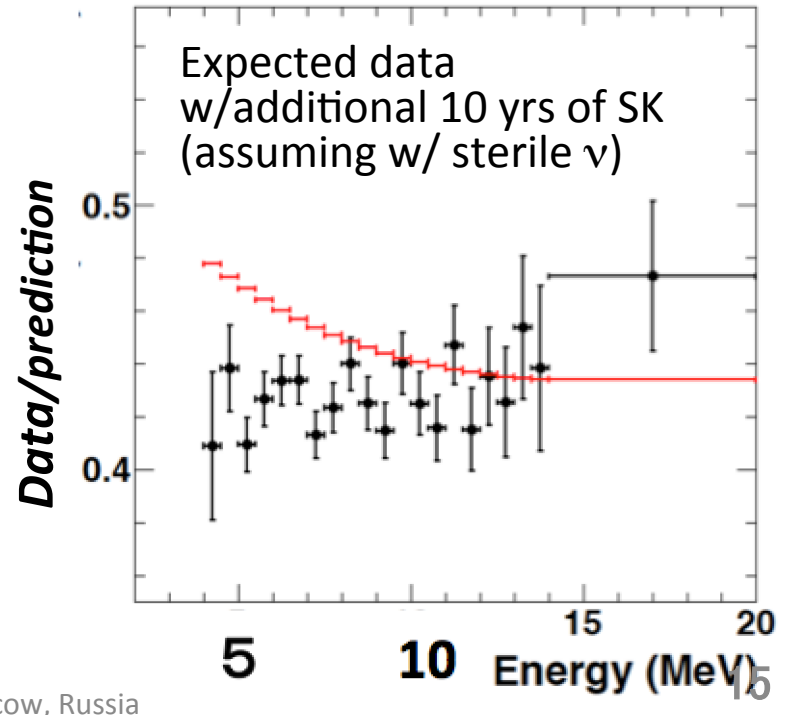
- ***No observation of up-turn yet***

Holanda and Smirnov, arXiv: 1012.5627v2



Sterile Neutrinos ?



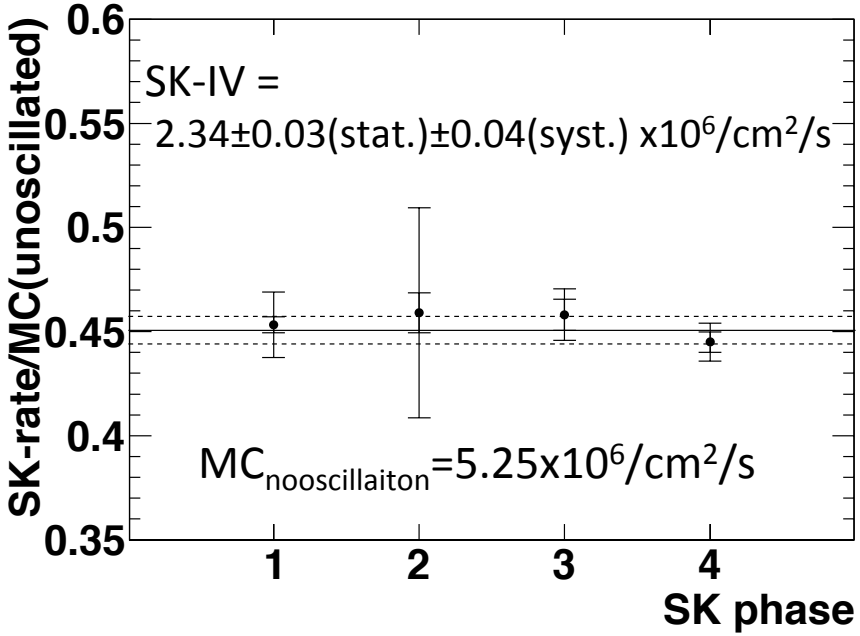


- Upturn [remaining problem]
  - Lower energy threshold
    - Remove BG
- Borexino threshold: 3.0 MeV
- SK threshold: 3.5 keV
  - aim to 3.0 MeV soon.

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: $\sin^2\theta_{13} = 0.025$)

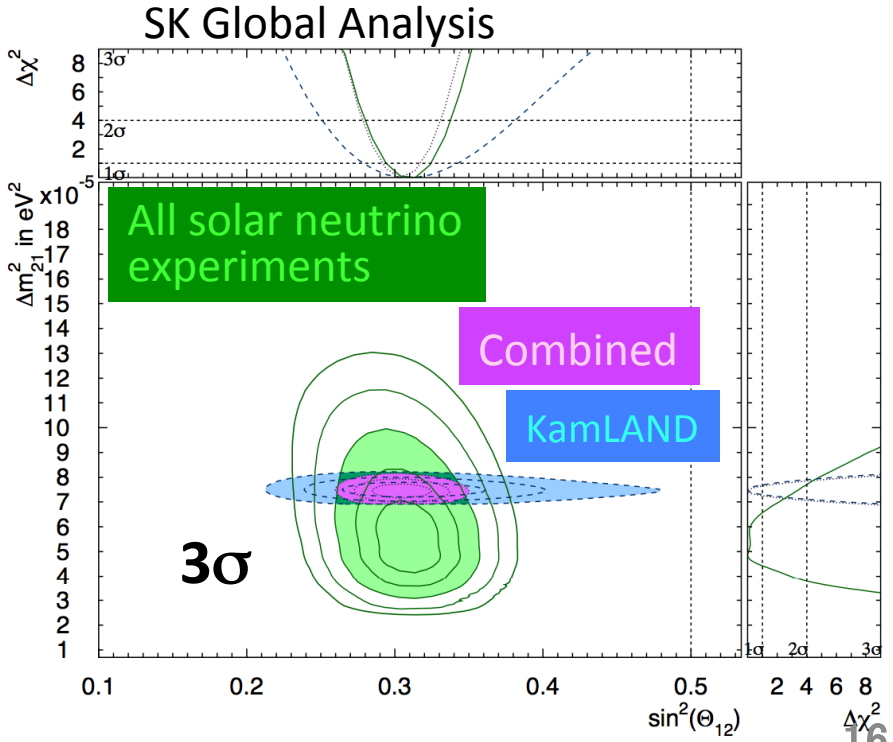
Solar Global (SK Analysis)

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

+KamLAND

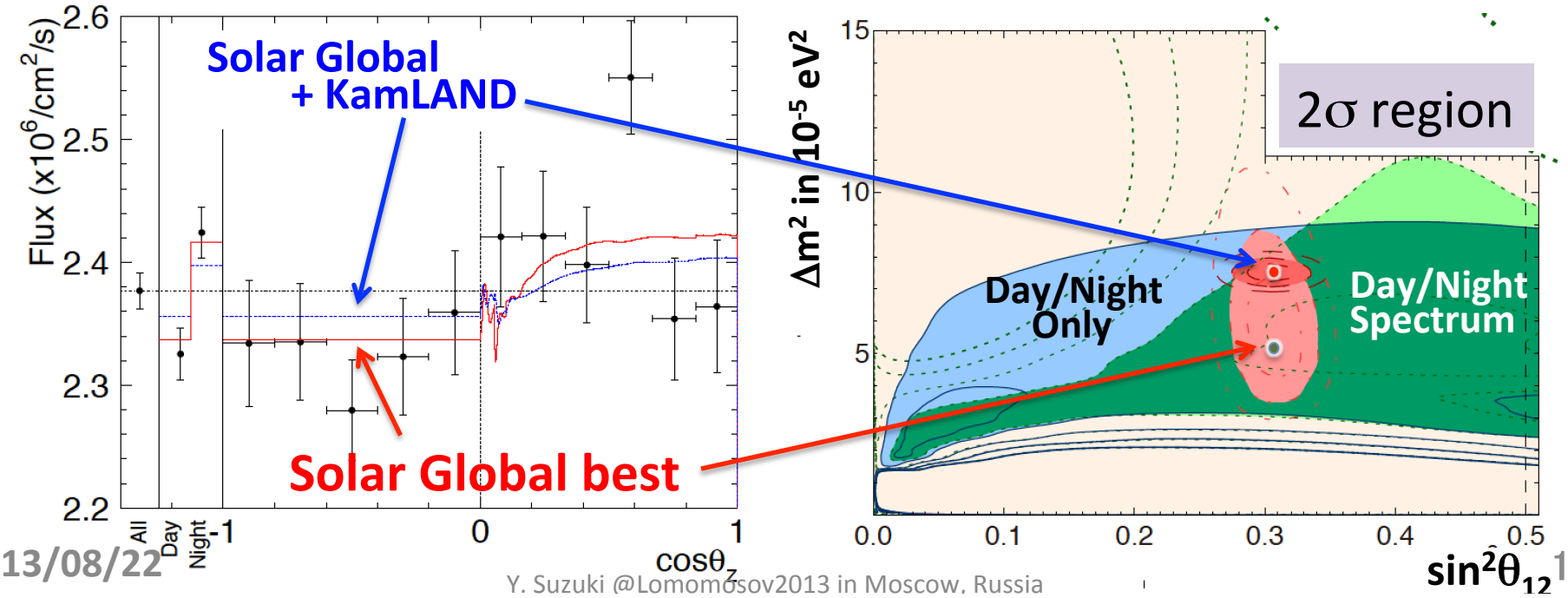
$$\sin^2\theta_{12} = 0.309^{+0.039}_{-0.029}$$
$$\Delta m_{12}{}^2 = 7.49^{+0.20}_{-0.19} \times 10^{-5} eV^2$$

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



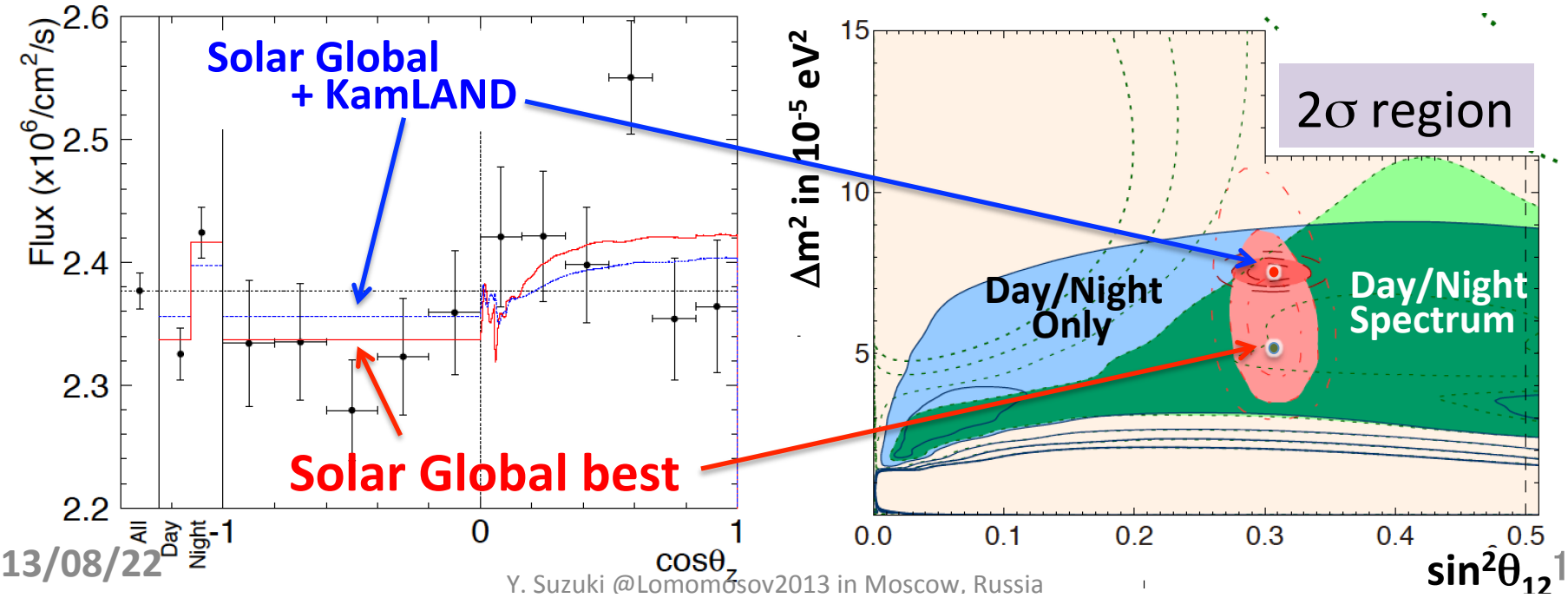
Day Night Flux difference
- Regeneration through the Earth's matter-

- First definitive evidence of matter effect through the earth:
  - $A_{DN}=2(D-N)/(D+N) = -3.2\pm1.1\pm0.5$ (2.7σ)
- Day/Night effect depends on Δm_{12} rather than $\sin^2\theta_{12}$
- Δm_{12} from D/N analysis agree better with that from the solar global analysis

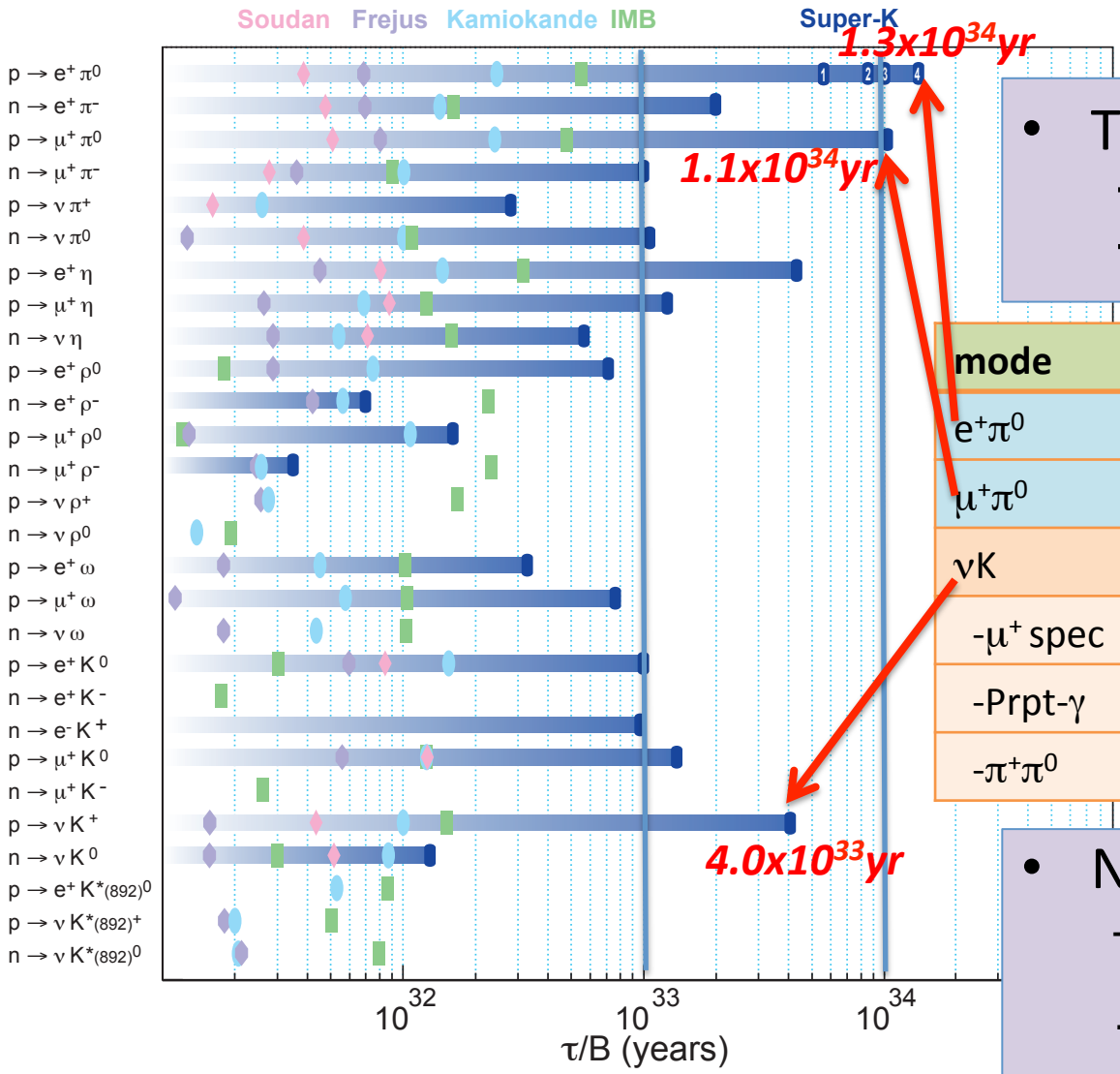


Day Night Flux difference
- Regeneration through the Earth's matter-

- The range of Δm_{21}^2 from SK D/N effect only (flux independent) is comparable to the results from solar global fit
- Well controlled study on matter effect
  - (Day ⇔No Matter effect, Night ⇔ Matter effect; scan cross the earth)
- ➔ **Future high statistic measurement will be very interesting**



Nucleon Decay

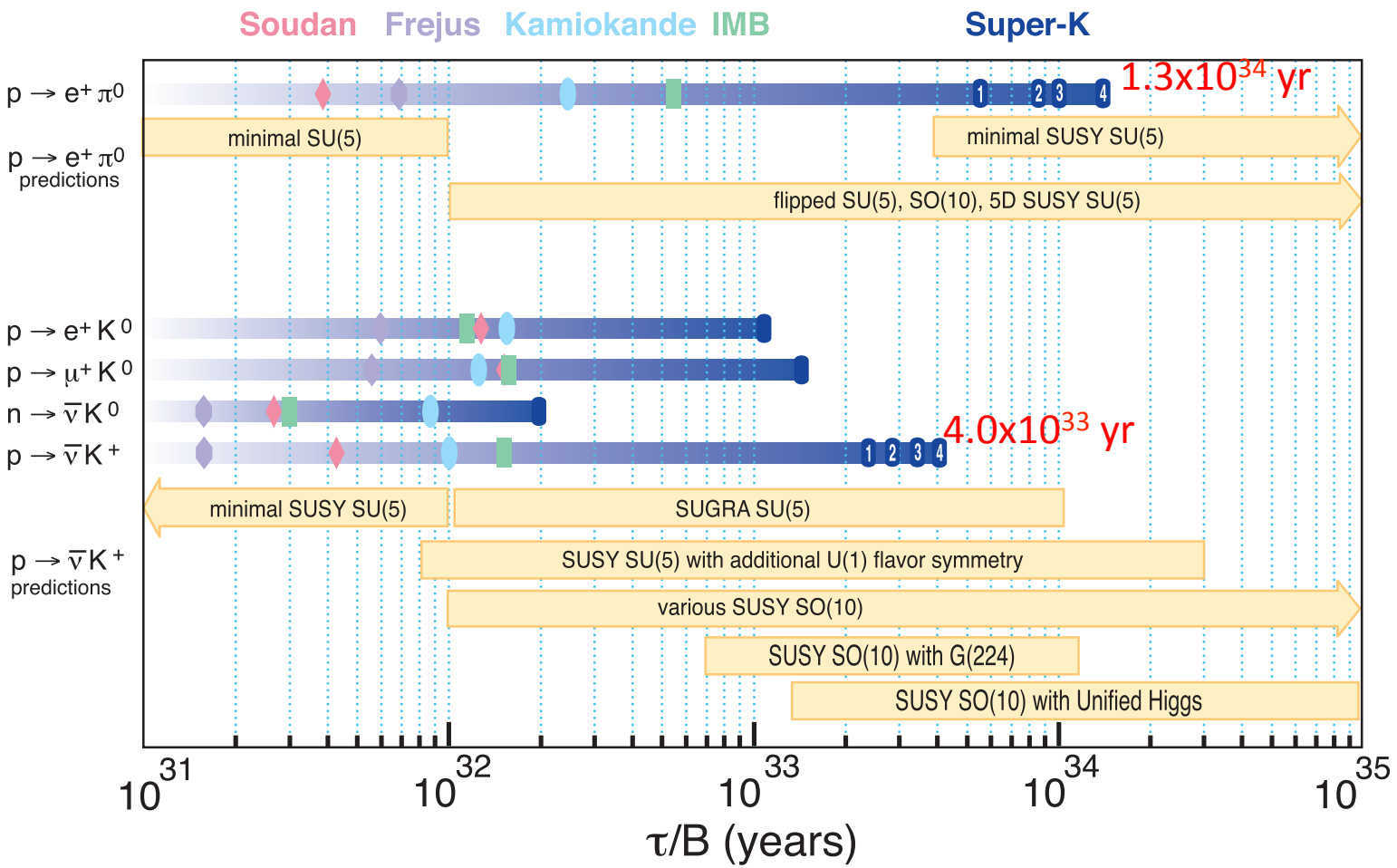


- The largest detector
  - → 220kt·yr maximum exposure
  - → No nucleon decay indications !

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

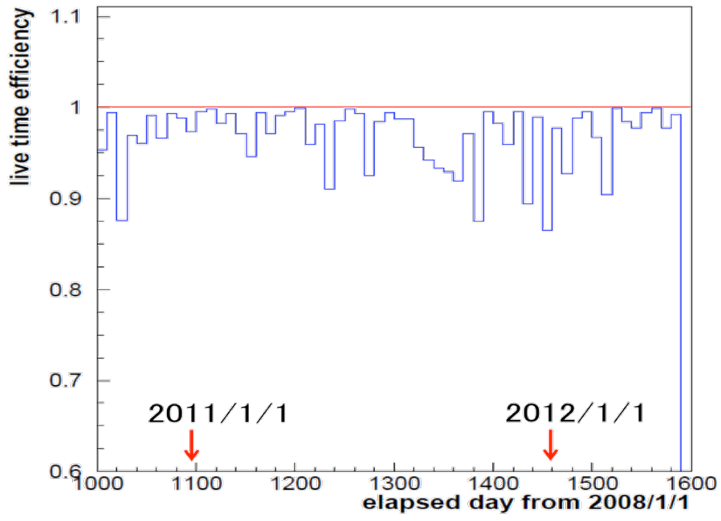


- ***Background level < 1 in many decay modes***
  - ***Sensitivity: proportional to the exposure in future***
- ***We continue to search for proton decay***

Supernova Neutrinos

- Burst search
  - Nearby SN ➔ Detailed Explosion Mechanism
    ➔ Study on SN explosion through ν 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) data taking sparsely, 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

Summary

- After the discovery of the neutrino oscillations we have further developed the oscillation study.
  - Precisely determined oscillation parameters (atm ν, solar ν)
  - Obtained evidence for tau appearance (atm ν)
  - Obtained positive indication of Day/Night effect (solar ν)
  - Achieved the 3.5 MeV analysis threshold (solar ν)
  - Being improved the DAQ system to detect nearby SN bursts
  - Mostly finished the the feasibility study of GadZOOKs

17 year old Super-K is still very active

- We will continue to take data 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