Super-Kamiokande
― last 6 years ―

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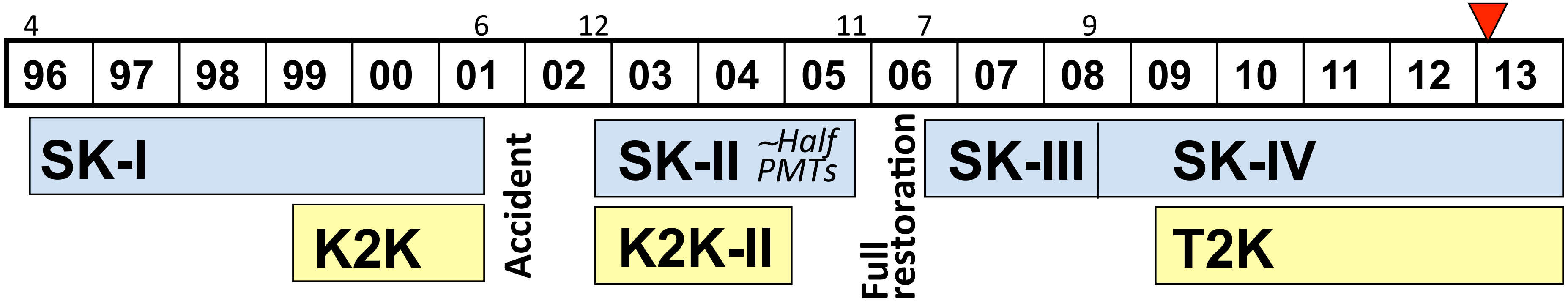
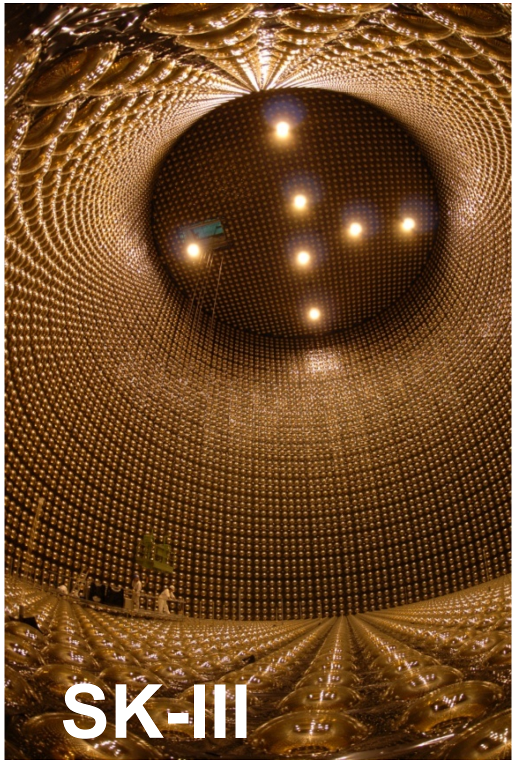
Jan-17-2013

@ICRR外部評価委員会

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
- 2006-2012: Today's presentation



Water Cherenkov

50,000 tons

11,129 PMTs

22.5 kt

fiducial mass

Protection case

SK Collaboration

	1998	2012
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***

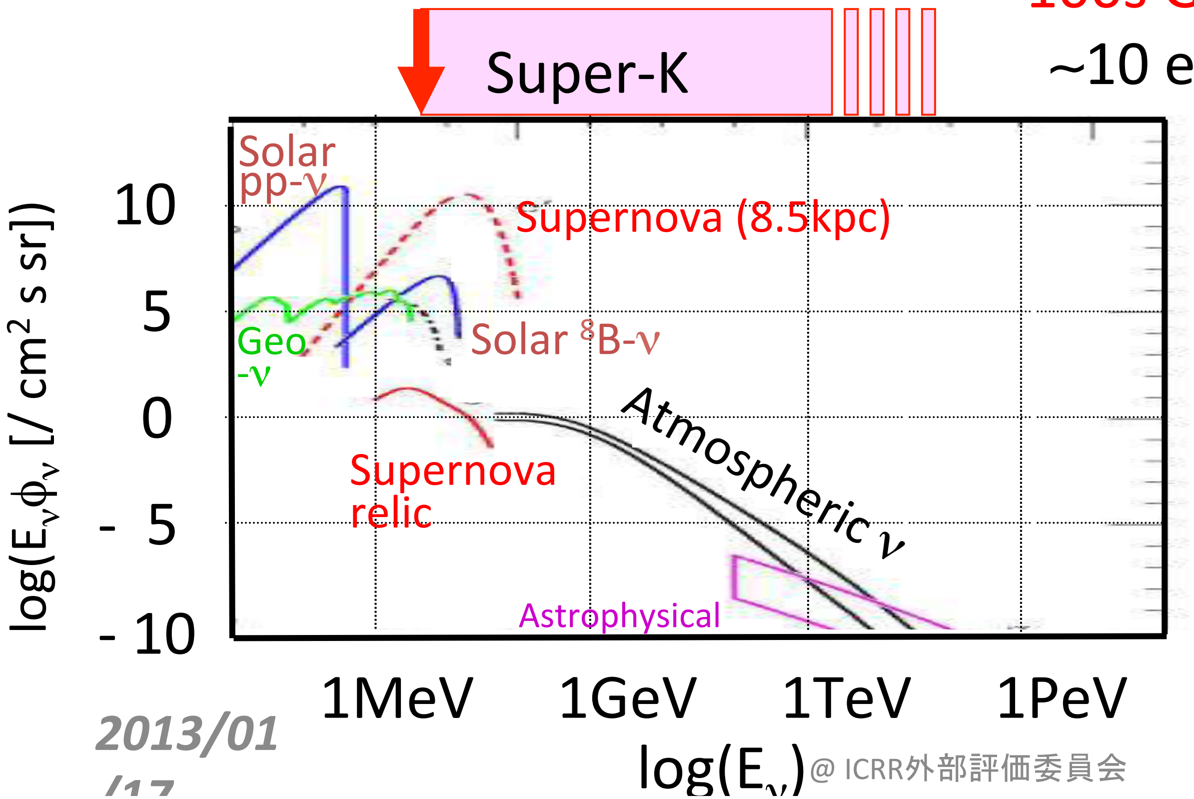
	1998	2012
Boston	14	4
BNL	1	1
Irvine	9	7
California State	2	3
Duke	--	5
George Mason	1	--
Hawaii	6	3
Los Alamos	1	--
Louisiana State	3	--
Maryland	4	--
Stony Brook	8	5
Washington	6	3
Warsaw(Poland)	1	1
UAM(Spain)	--	1
Chonnam(Korea)	--	3
Seoul National(Korea)	--	1
Sungkyunkwan(Korea)	--	1
Tsinghya(China)	--	4
Regina(Canada)	--	1
British C.(Canada)	--	3
Toront(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

Energy Range

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



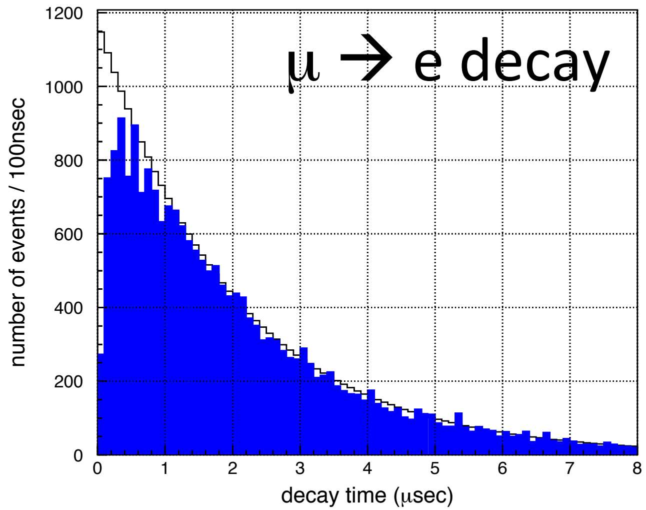
- 6 p.e. / MeV
- Resolution
  (solar/supernova ν)
  14.2% @10MeV
  (atmospheric ν)
  $1.7+0.7/\sqrt{E(GeV)}$ %
  (single ring μ)

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)	200 kt・yr

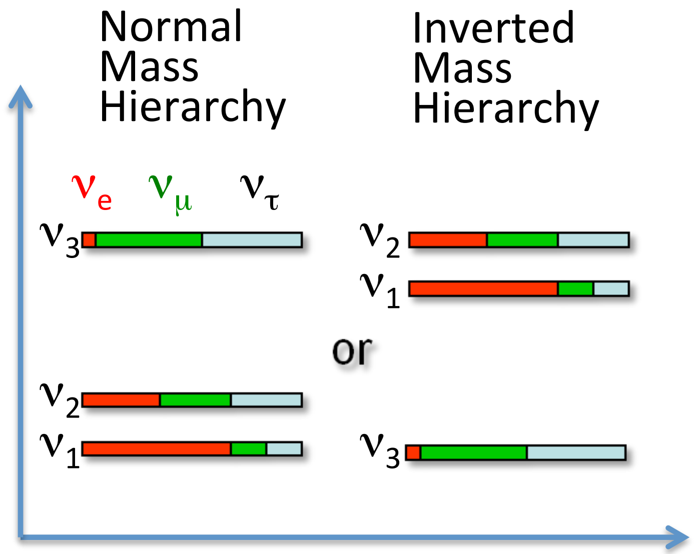
Electronics update (SK-IV)

- 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?)

SK /K2K

Reactor ShortBL
($\sin^2\theta_{13}$~0.025,
δ_{CP} ?)

SK /T2K

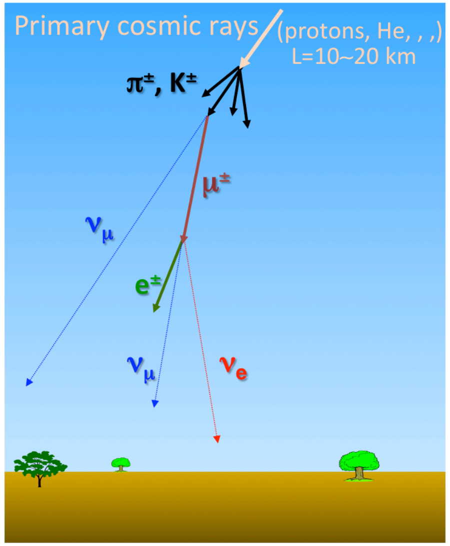
Solar ν
Reactor LBL
(θ_{12}: large)

SK

Remaining Issues

- Octant of θ_{23} : if $\theta_{23}\neq\pi/4$
- Mass hierarchy: sign of $\Delta m_{13}{}^2$
- CPV

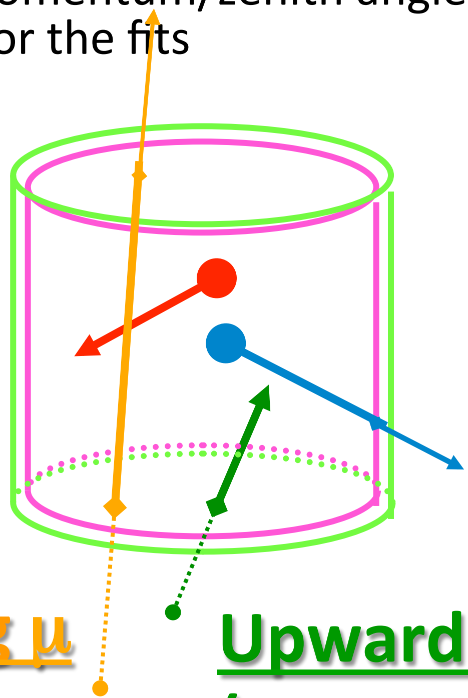
← SK atmospheric three flavor analysis



Atmospheric Neutrinos

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

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

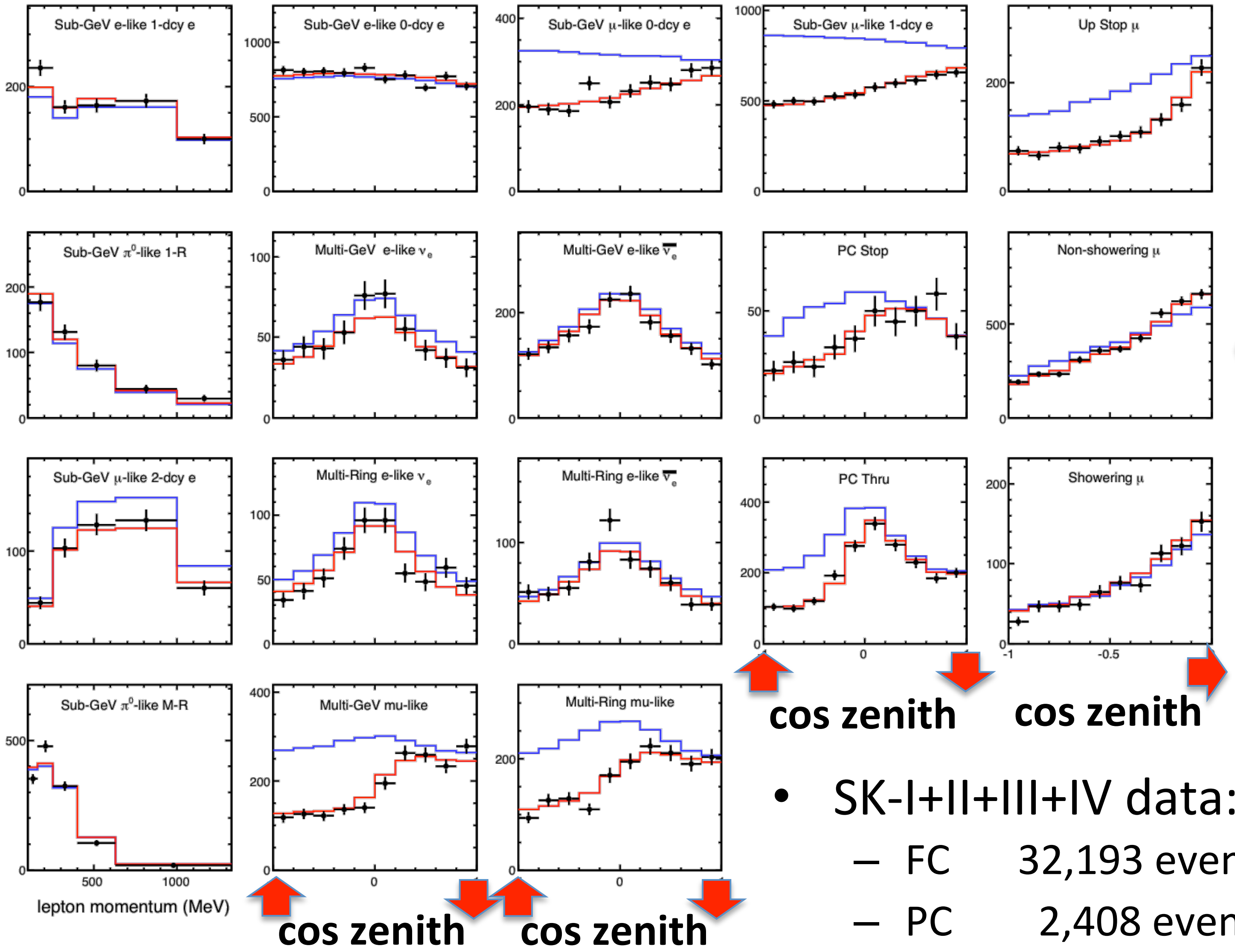


Partially Contained (PC)
($\langle E_{\nu} \rangle$ ~ 10GeV)
Through, stop

Upward Through-going μ
($\langle E_{\nu} \rangle$ ~ 100GeV)
Non-showering, showering

Upward Stopping μ
($\langle E_{\nu} \rangle$ ~ 10GeV)

Atmospheric Neutrinos



- 18 sub-samples
- All consistent with the oscillation

w/o oscillation

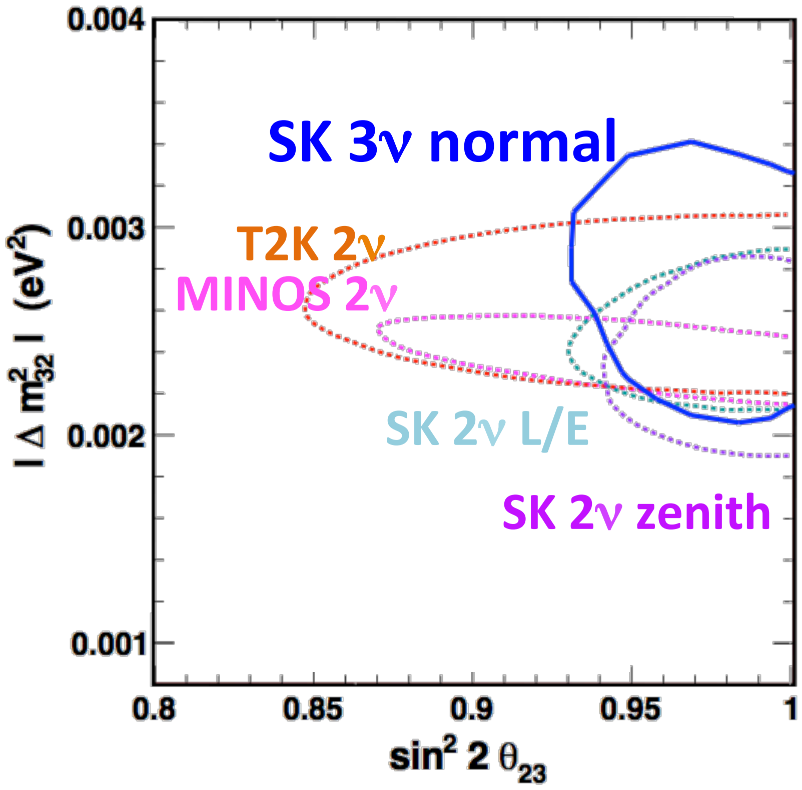
w/ oscillation

- SK-I+II+III+IV data:
  - FC 32,193 events (3903 days)
  - PC 2,408 events (3903 days)
  - Up-μ 6,018 events (4207 days)

Atmospheric Neutrinos

[SKI+II+II+IV Atm ν, zenith]

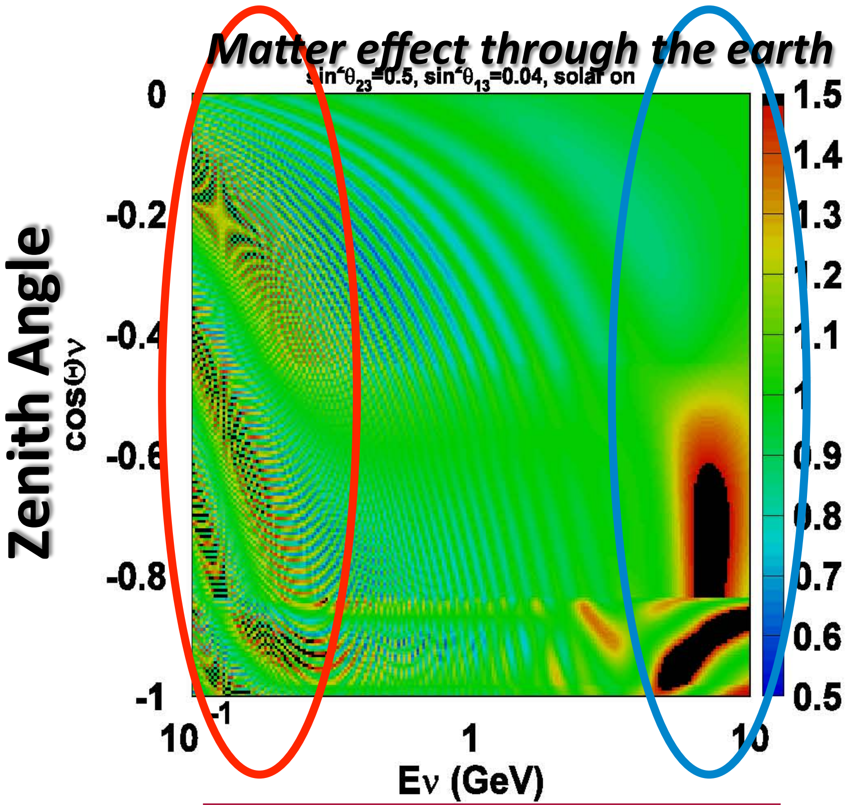
- Results of the fit
  for 2 flavor analysis
  - $\sin^2 2\theta_{23}$=1.00 > 0.96
    (1 parameter @90%)
  - $\Delta m_{23}{}^2 = 2.30^{+0.16}_{-0.22}\text{x}10^{-3}\ \text{eV}^2$
    (1σ)



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
$R_2 = \mathrm{Re}(A^*_{ee}A_{e\mu})$
$I_2 = \mathrm{Im}(A^*_{ee}A_{e\mu})$



$s^2 2\theta_{12}$=0.825, $s^2\theta_{23}$=0.4, $s^2\theta_{13}$=0.04
δ_{CP}=45°, Δm^2_{12}=8.3x10^{-5},Δm^2_{23}=2.5x10^{-3}

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
1~2% effect, sensitive to octant

3rd term: θ_{13} term, matter effect
> a few GeV (in multi-GeV data)
10~15% effect

2nd term: Interference
CP-Phase

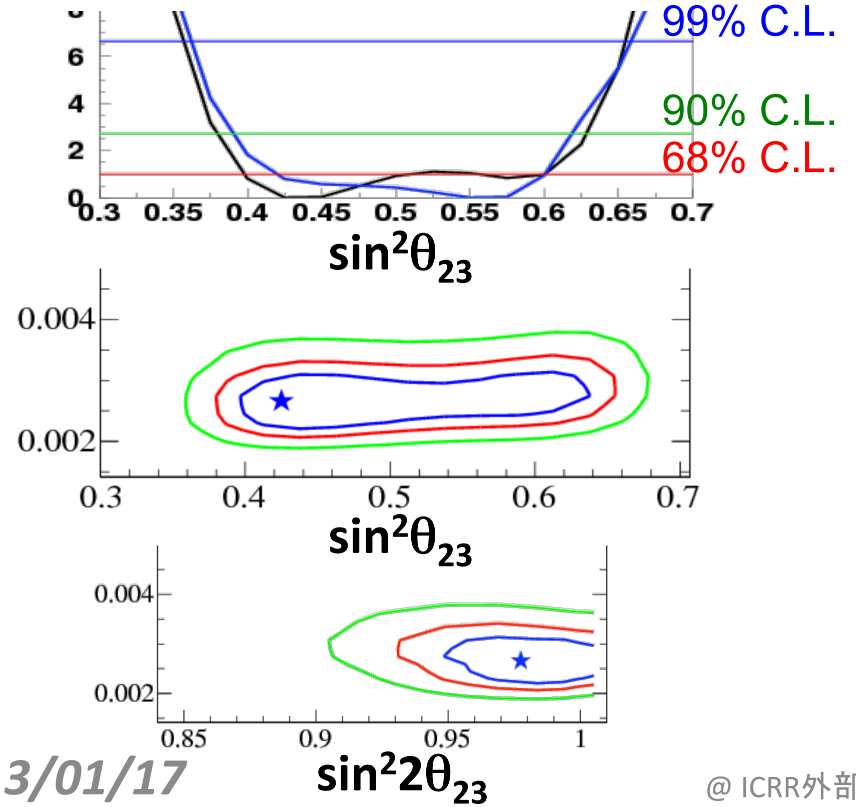
Sensitive to all the effects

Current situation of atmospheric ν
θ_{23} Octant

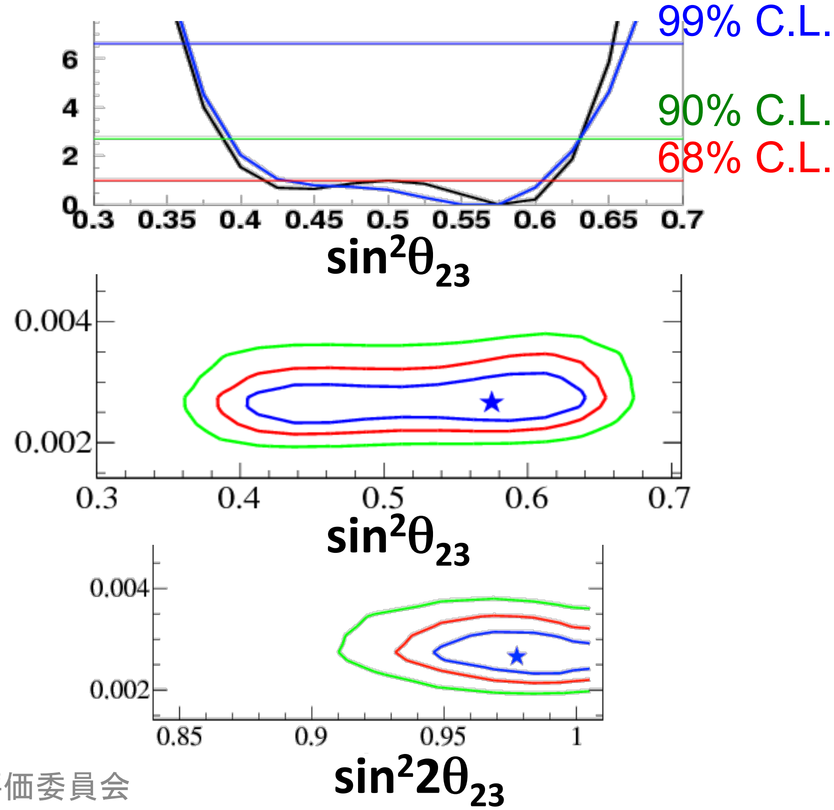
Super-Kamiokande atmospheric neutrino 3 flavor analysis
--- θ_{13} free in the fitting
--- θ_{13} fixed at the best value

We may start to see 1 σ level effect ??

- Normal Mass Hierarchy
- Best fit value: 0.425



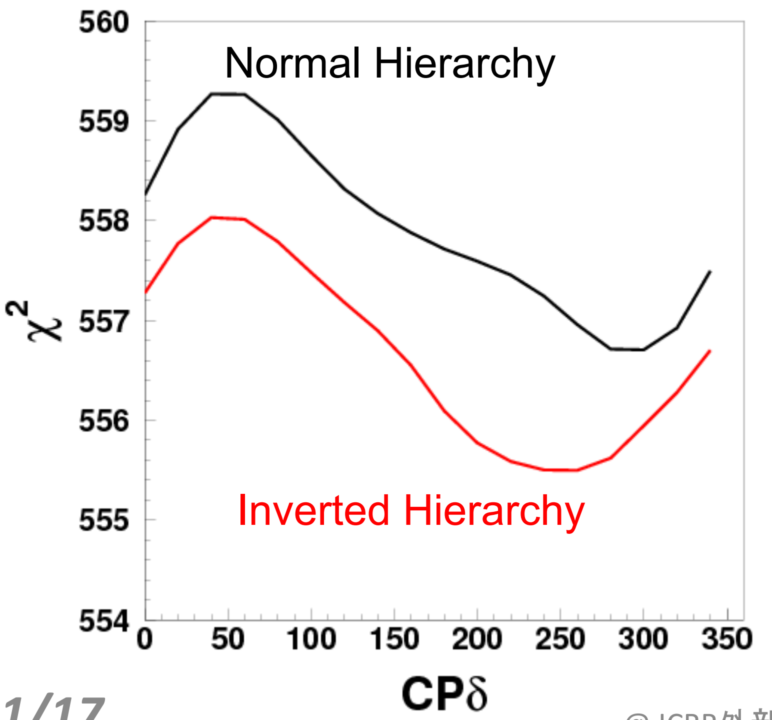
- Inverted Mass Hierarchy
- Best fit value: 0.575



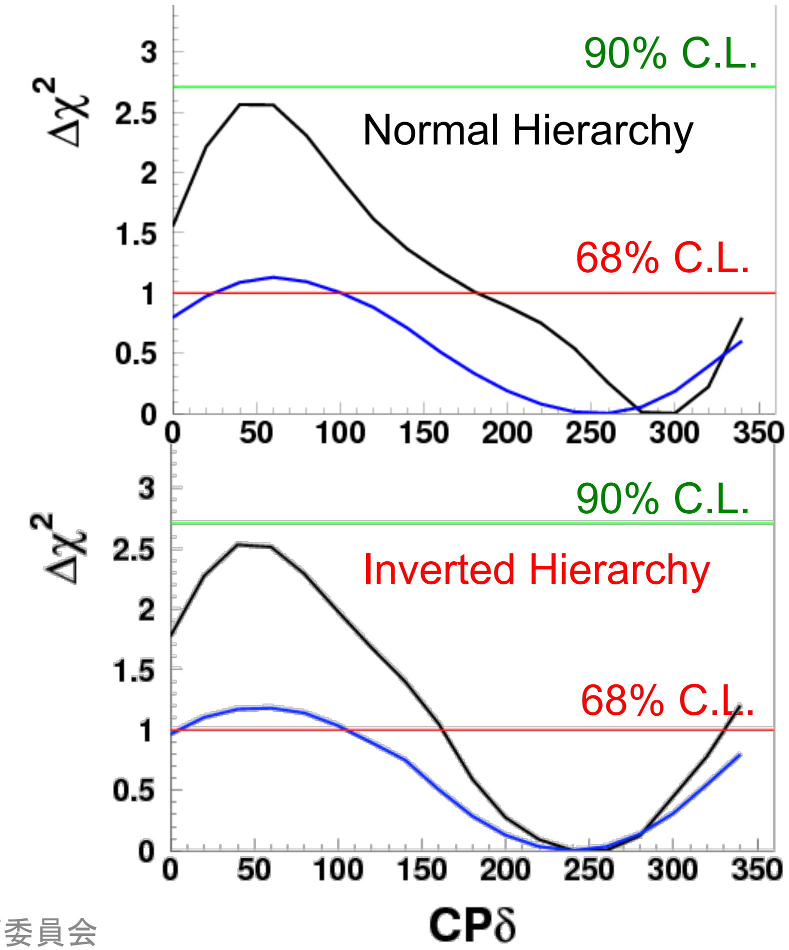
Current situation of atmospheric ν Mass Hierarchy and CP phase

- 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



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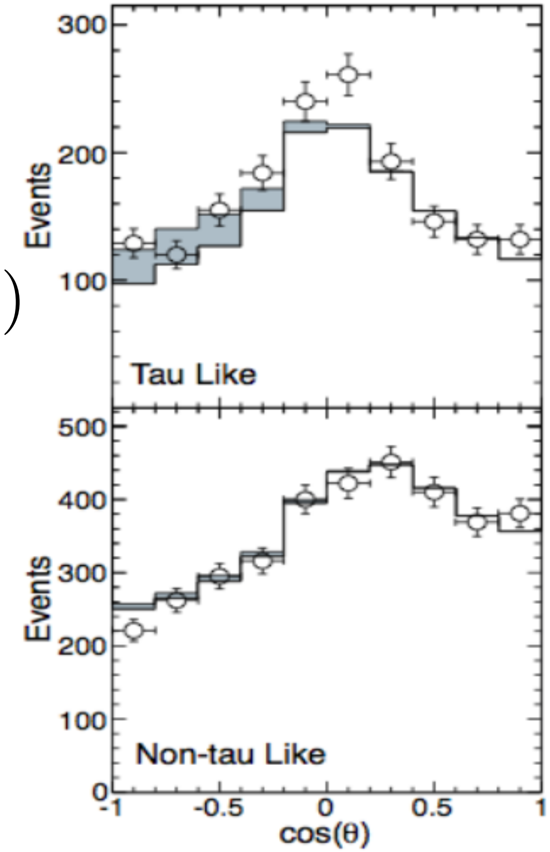
Tau Appearance

- Cannot: event-by-event analysis ➔ need statistical analysis
- Not easy: 🡐 E_{th}>3.5 GeV, low rate (S/BG~1/140)
- Need to produce tau enhanced sample🡐 likelihood and neural network
- Make zenith angle distribution



- SK results:
  - 2806 days of data
  - Found $180.1 \pm 44.3(stat)^{+17.8}_{-15.2}(syst)$
  - Expected $120.2^{+34.2}_{-34.8}(syst)$
  - Excluded no tau production at **3.8σ**

OPERA results:

Found 1 more candidate of ν_τ (total 2 ν_τ events)

expected events 2.1

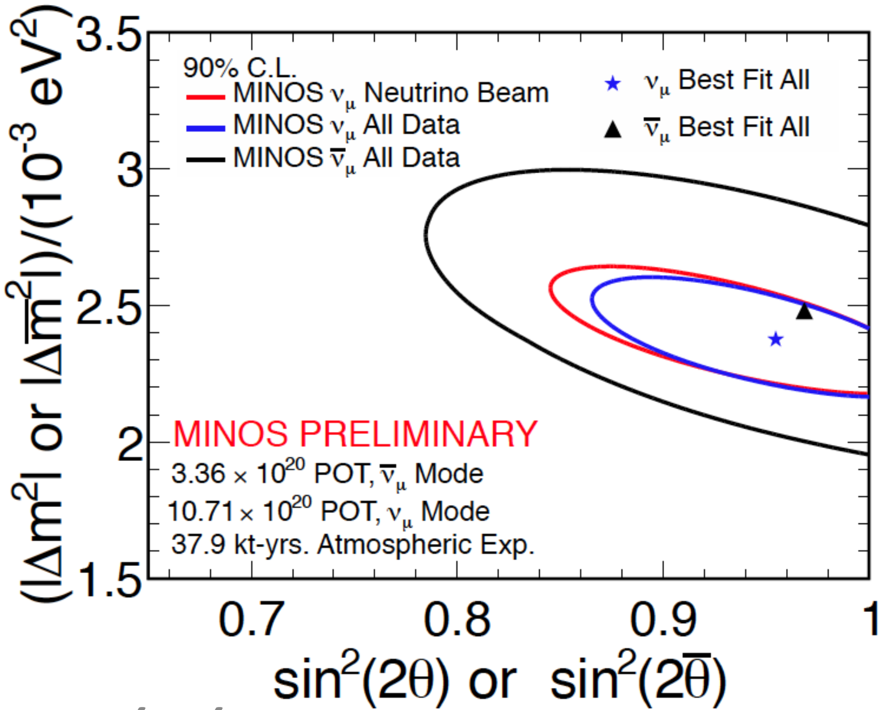
with 0.2 backgrounds

CPT

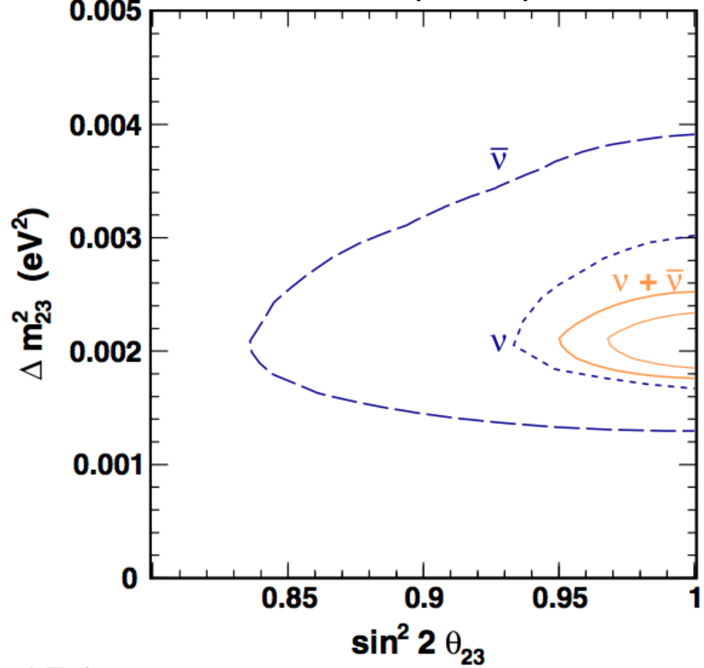
- MONOS in 2011 → CPT?
- MINOS: more data
  → no difference

Produce MC for ν (Δm_{23}^2, θ_{23}) and $\bar{\nu}$ (Δm_{23}^2, θ_{23}) separately, and look for best parameter sets, respectively

No evidence for CPT violating oscillations was found

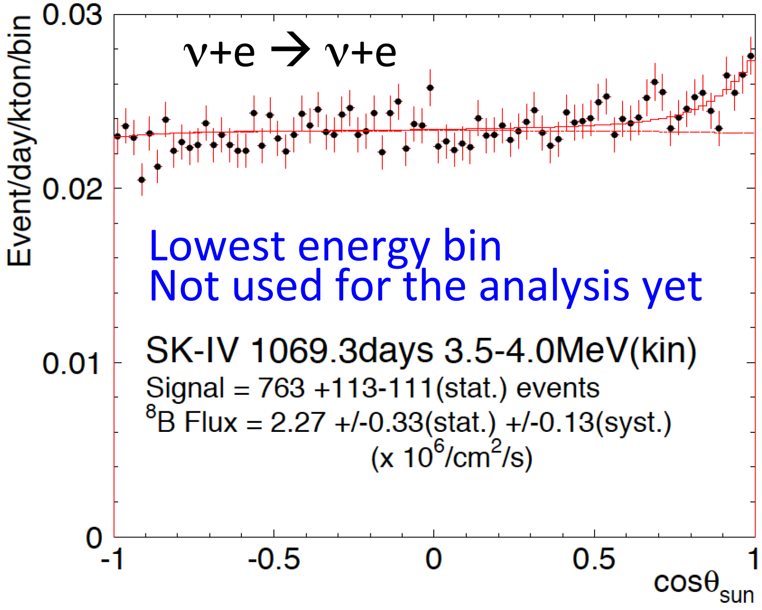


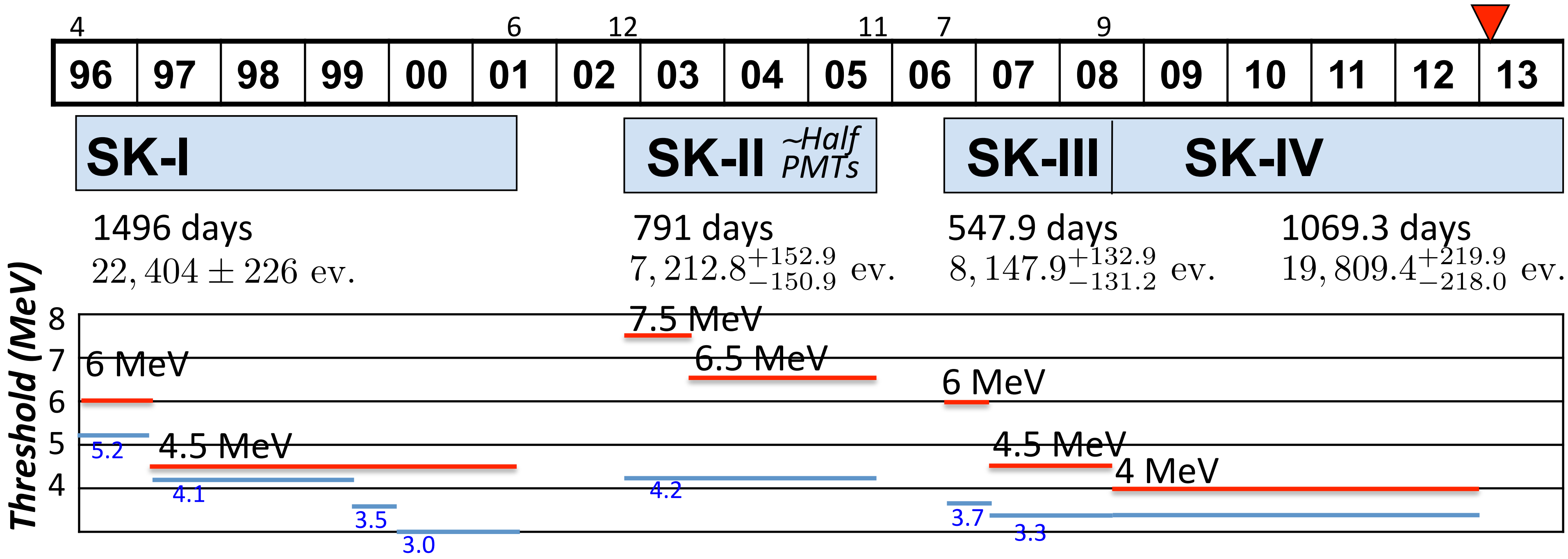
SK: PRL, 107(2011)241801



Solar neutrinos

- Total 3904 days
  - 57,574.1 solar neutrino events
- Analysis threshold: down to 4 MeV
  - Possible to 3.5 MeV in near future
- Fiducial volume
  - 22.5 kt (> 5.0 MeV)
  - 13.3 kt (4.5-5.0 MeV)
  - 8.8 kt (4.0-4.5 MeV)

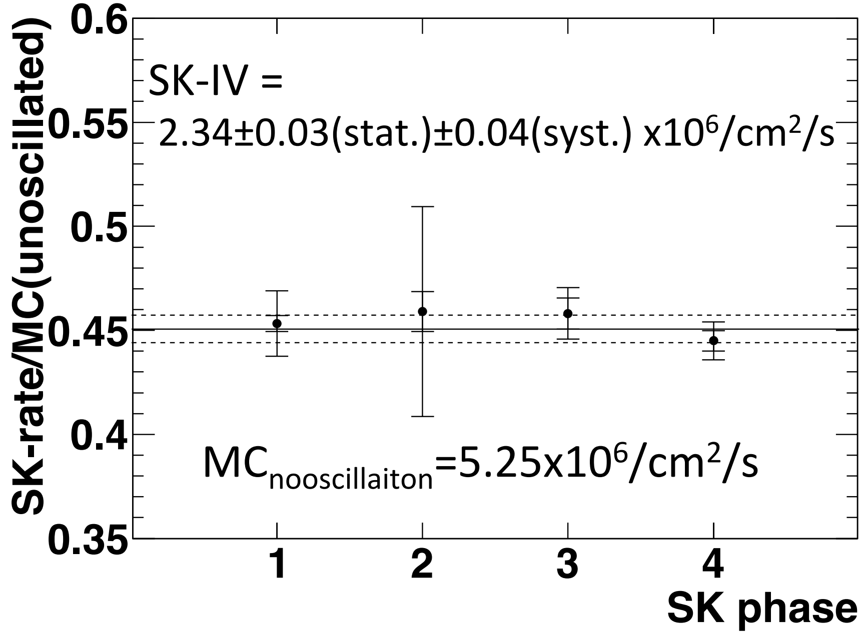




Solar neutrinos

Flux measurements

- Many Improvement for the last 6 yrs (systematic errors)
  - Total 3.5% → 1.7%
    - Fiducial volume: 1.3% → 0.17%
    - Energy scale: 0.64% → 0.54%
    - Others



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

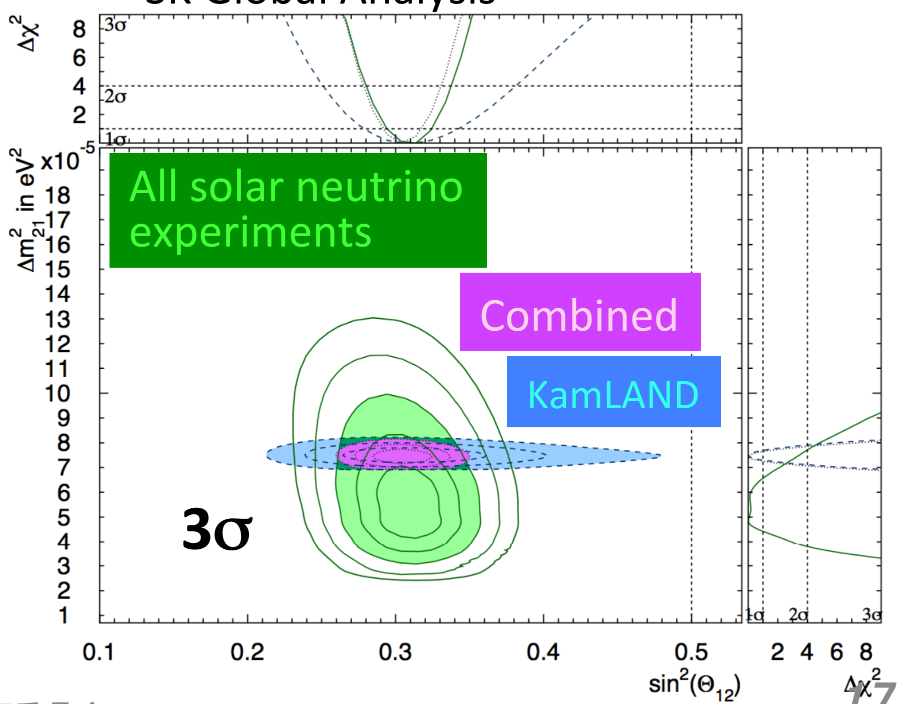
Solar Global

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

KamLAND

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

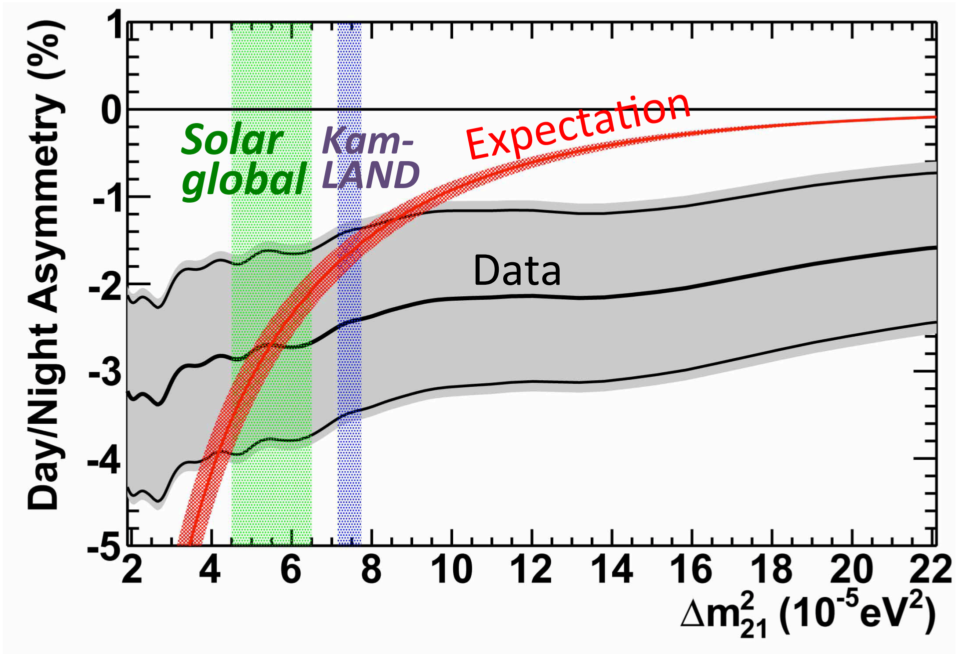
SK Global Analysis



- 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 depend on Δm_{12}

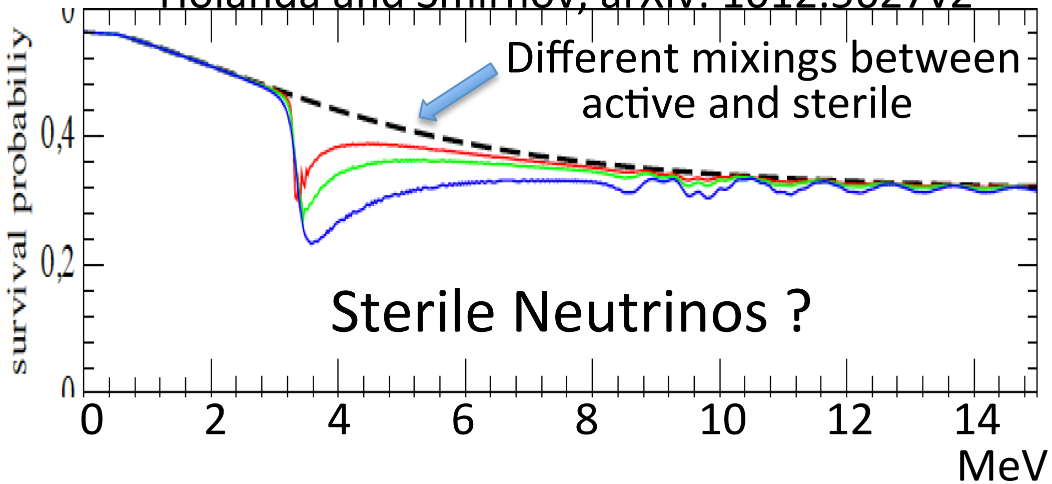


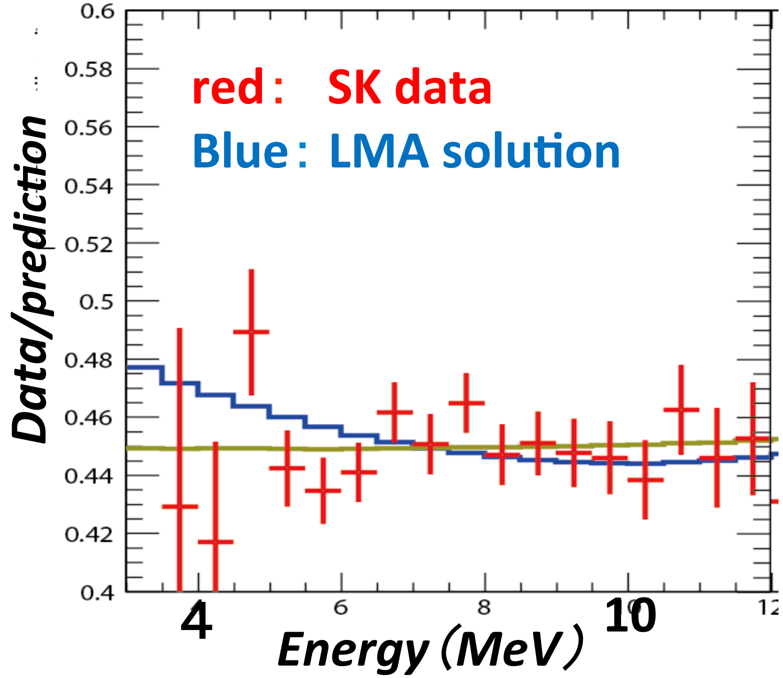
- SK-I, II, III, IV data
- A_{ND}=-2.8±1.1±0.5%
  – 2.3 σ

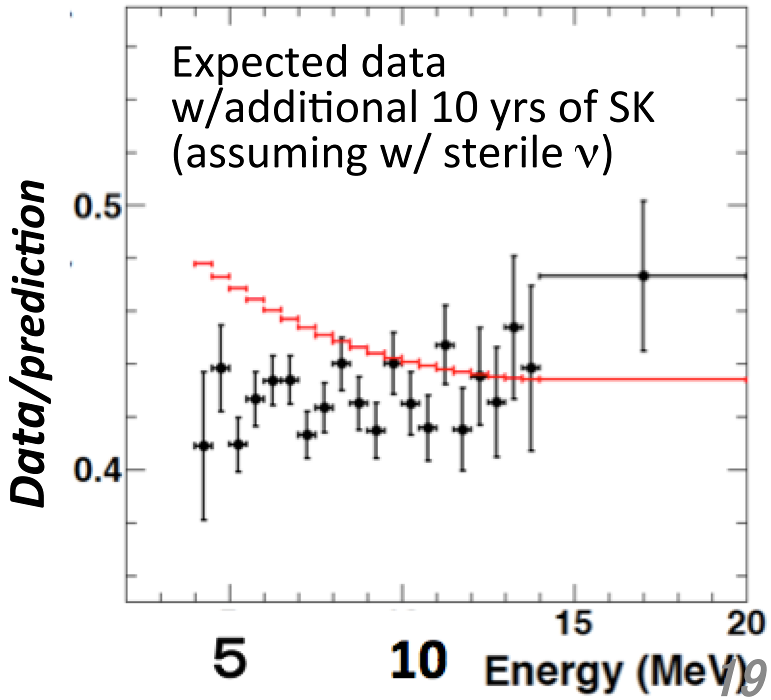
Solar neutrinos

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

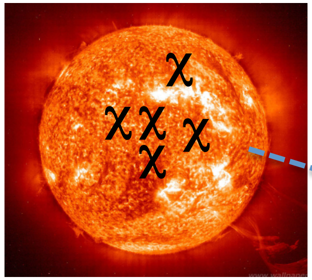
Holanda and Smirnov, arXiv: 1012.5627v2







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

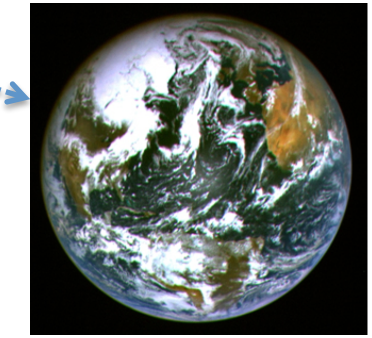


ν

Indirect search for Dark Matter

Neutrinos from the earth, the sun and the center of the Galaxy emanated by the annihilation of DM

ν



- Annihilation in the sun, the earth, the Galactic center and so on.
- Those neutrinos are detected as upward going muons
- The muon flux measured
  - ➔ Elastic scattering cross section (SI, SD)

In the sun, for example

- M_χ > 5 GeV → Evaporation can be neglected.
  - – Ref) Griest and Seckel, NPB, 283,681(87)
- Annihilation and capture ➔ in equilibrium: $\Gamma_A=(1/2)C_C$
  - – Solar age: $t_\odot$= 4.5x10^9 yr: $t_\odot/\tau$ >>1
- Annihilation rate depends only on the scattering cross section

$$\frac{dN}{dt} = C_C - C_A N^2 - C_E N$$

C_c: capture rate

C_A: annihilation rate

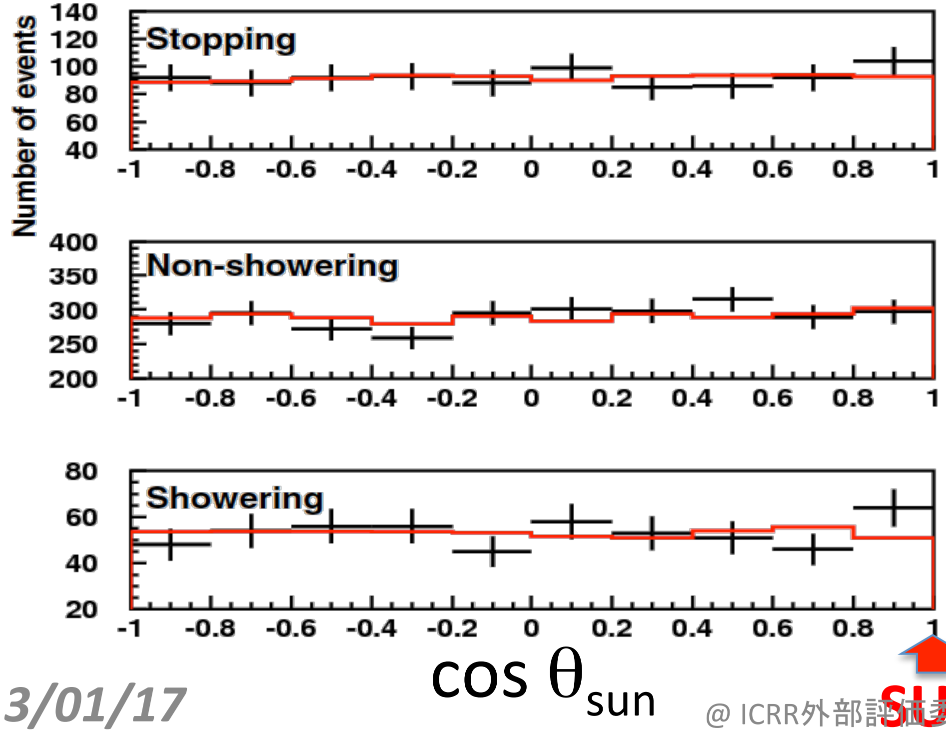
C_E: evaporation rate

Indirect search for Dark Matter

Neutrinos from the earth, the sun and the center of the Galaxy emanated by the annihilation of DM

Upward going muons

- 3109.6 days
  - SK-I, SK-II, SK-III
- Total 4351 events.



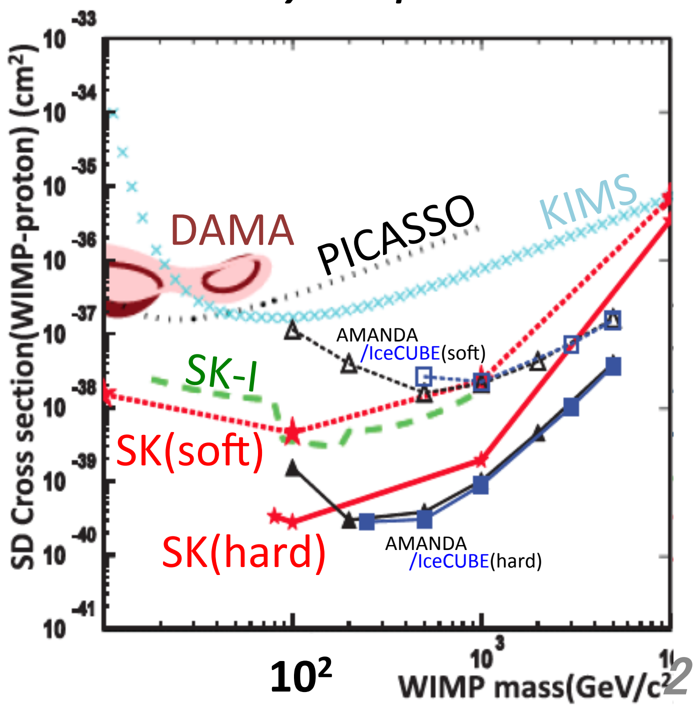
Annihilation

$$\chi\chi \rightarrow b\bar{b}$$ Soft channel

$$W^+W^-$$

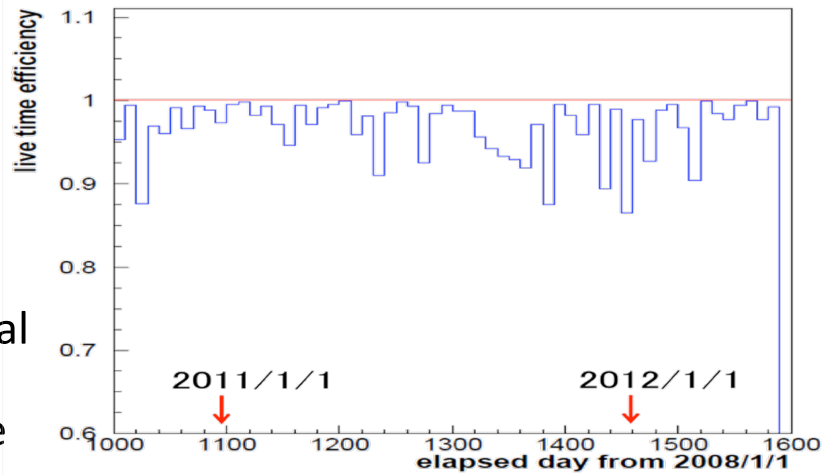
$$ZZ, ..etc.$$ Hard channel

decay to produce ν



Supernova Neutrinos

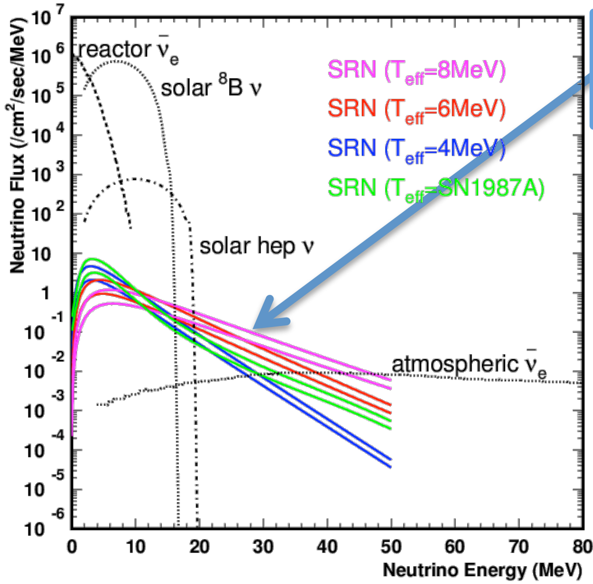
- Burst search
  - Near-by SN ➔ Detailed Explosion Mechanism
    ➔ Additional information for Neutrino Oscillation
  - Mostly ν_e + p → e^+ + n and ν_e e → ν_e e interactions
    - Event by event reconstruction, time, energy and directionality (only for ν_e e)
  - Expect 8000 neutrino events from the SN at 10 kpc
  - $2x10^7$ neutrinos for Betelgeuse (640 light years)
    - Currently updating 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)

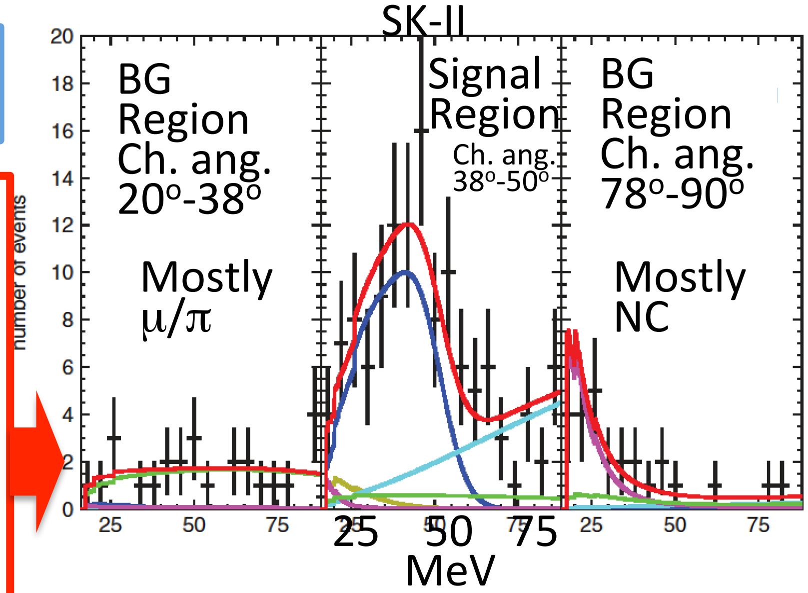
the diffuse supernova neutrino background from all the supernovae in the past

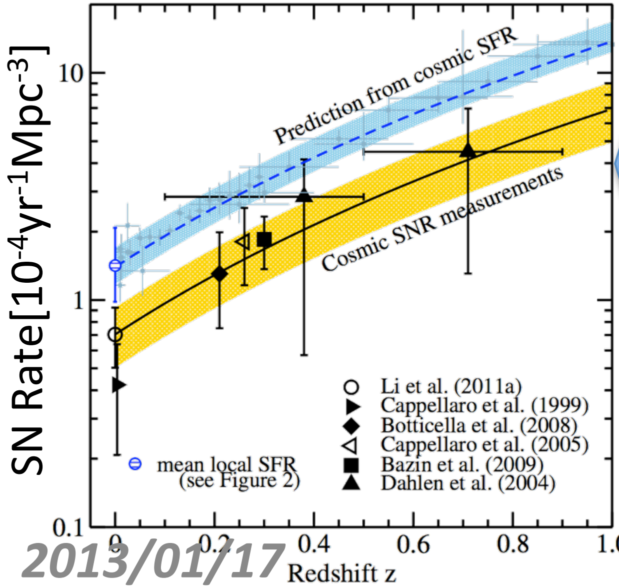


A gap between solar and atmospheric ν

BGs and fit:

- Relic Signal
- all Backgrounds
- ν_μ CC
- ν_e CC
- NC elastic
- μ/π

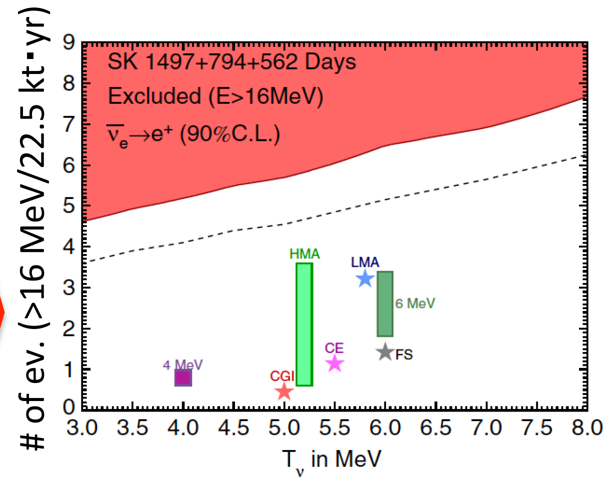


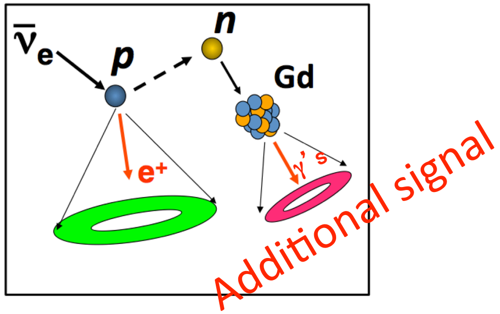


Carries information about Star Formation Rate, Initial Mass Functions and so on.

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

Flux limit: 2.8-3.1 ν_e/cm²/s² (>16 MeV)





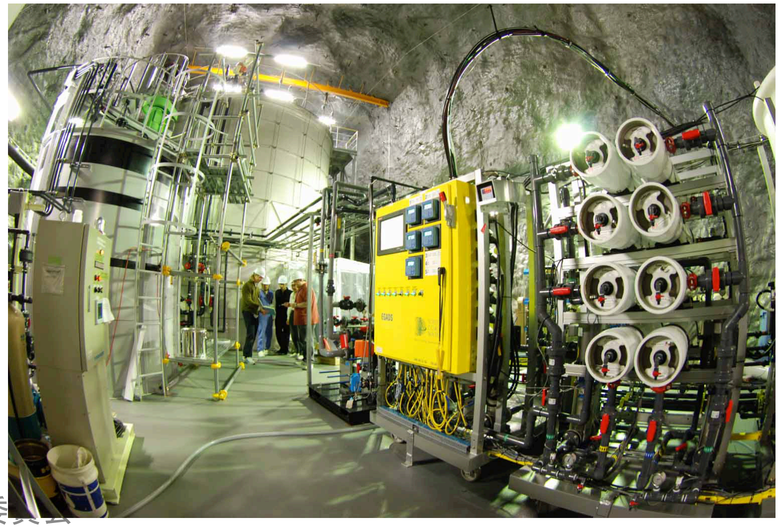
GadZOOKS

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

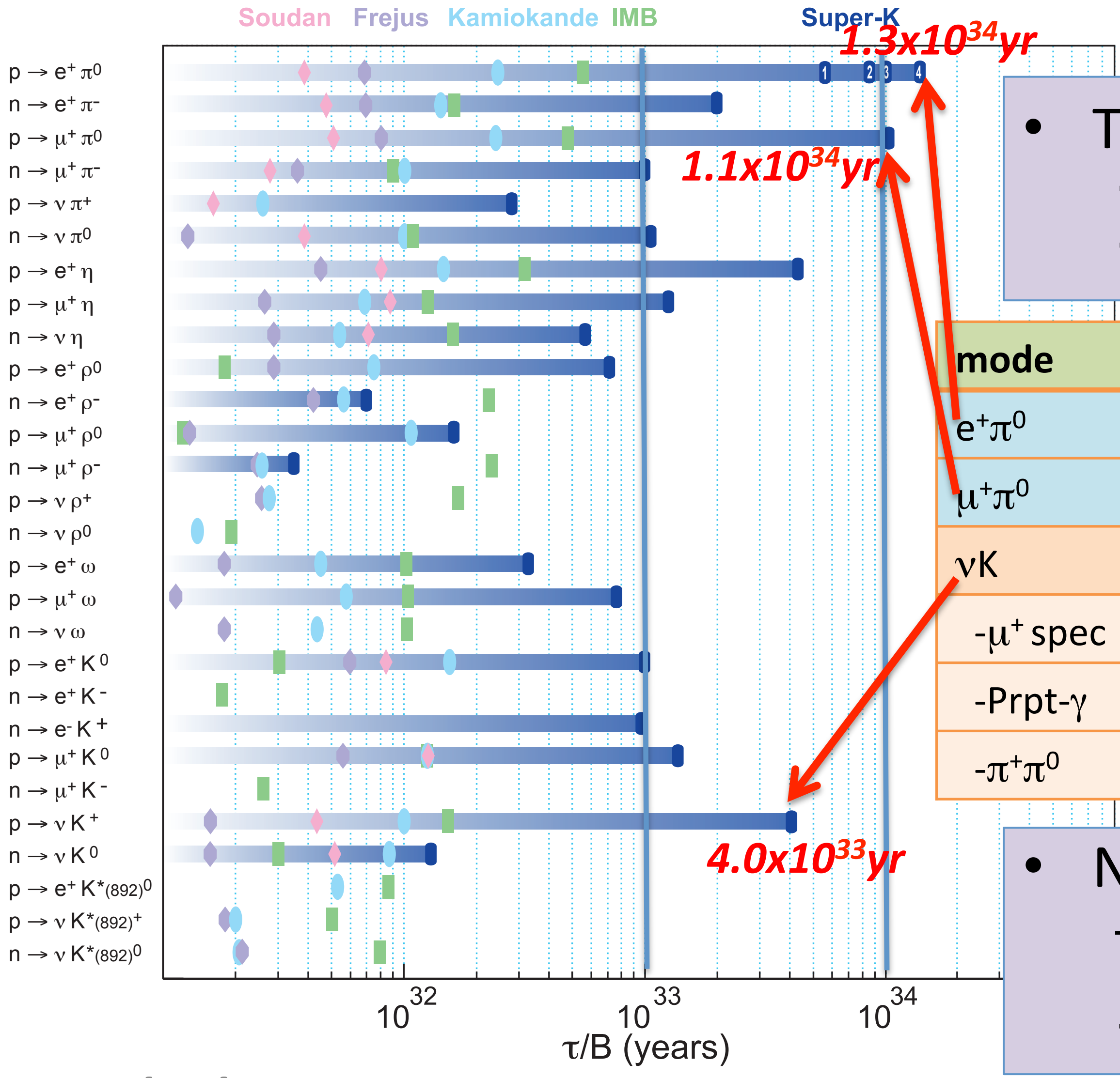
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

  - 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 ~)
  - 200 ton main tank
  - Selective filtration system
    - Cleaning unwanted impurities
    - Keep Gd in the water
  - Transparency measurement
- Full test w/ 240 PMT will be done in 2013.



Nucleon Decay

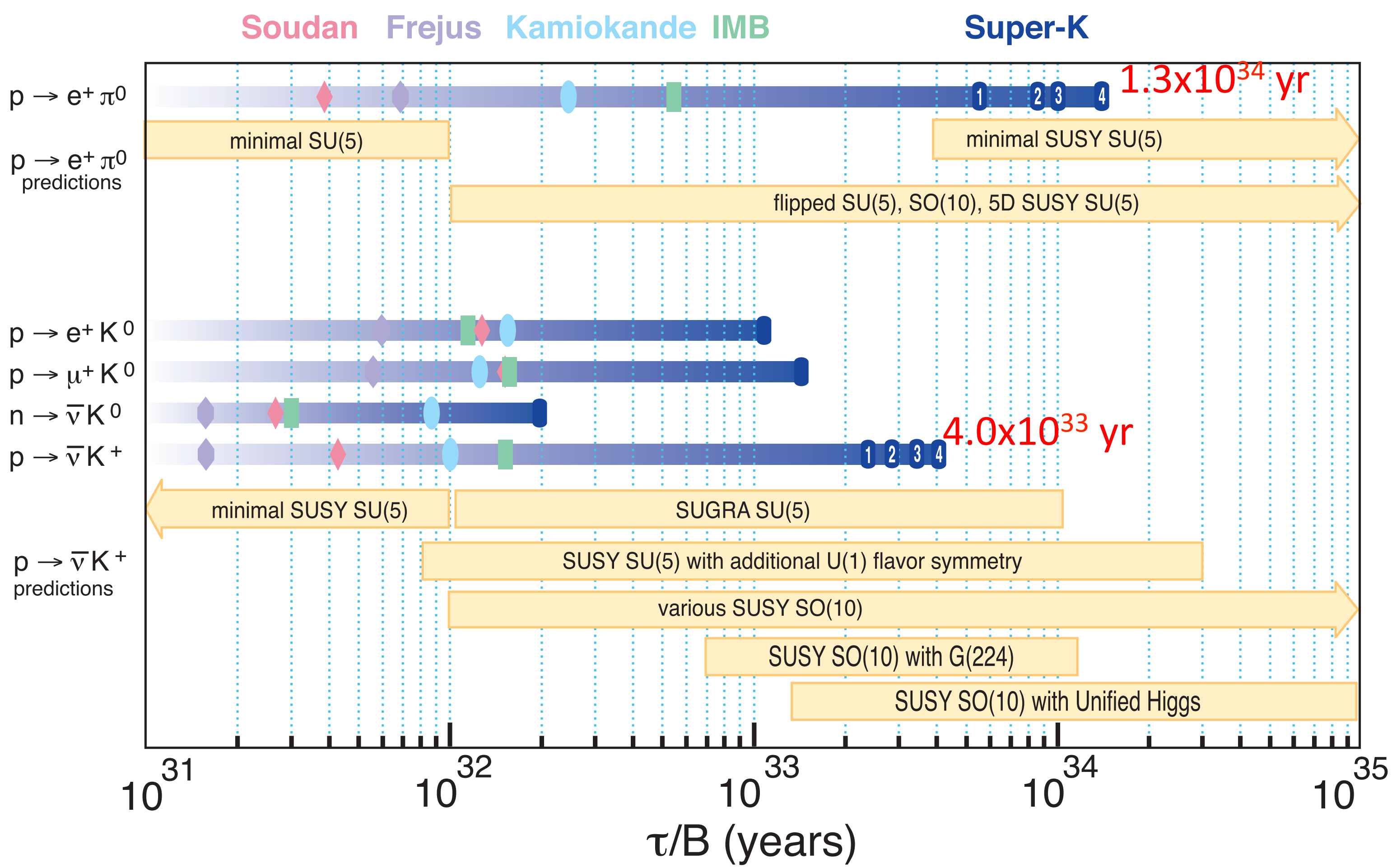


- The largest detector
  - → 220kt･yr maximum exposure
  - → No nucleon decay indications !

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, Eγ, Δt	6-8	0	0.4	
-$\pi^+\pi^0$	$E_{\pi 0}$, 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 our research in Super-K
  - Precisely determined oscillation parameters (atmospheric and solar neutrinos)
  - Studied MH and CPV and test of CPT (by using atmospheric)
  - Obtained positive indication of Day/Night effect (solar)
  - Studied upturn (solar)
  - Improved the machinery for detecting near-by SN burst
  - Studied the feasibility of GadZOOKs
  - Extended a search for proton decay to 10^{34} yrs
- We will continue data taking at least for the next ten years and hope that we will hand them to Hyper-Kamiokande
  - MH, CPV, upturn, SN burst and SN Relic neutrinos,……….

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*
Near by SN neutrino burst World highest sensitivity		Improve DAQ system	Continuous observation							
Mass hierarchy Precise measurement of atmospheric ν	sensitivity →			2.0σ →			2.3σ →	Identification of MH ?		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 sensitivity →			2.2σ →			2.7σ →	Indication of sterile neutrinos ?		3.0σ
Nucleon decay search World highest sensitivity			Test of grand unified theories				sensitivity		Discovery ? 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			