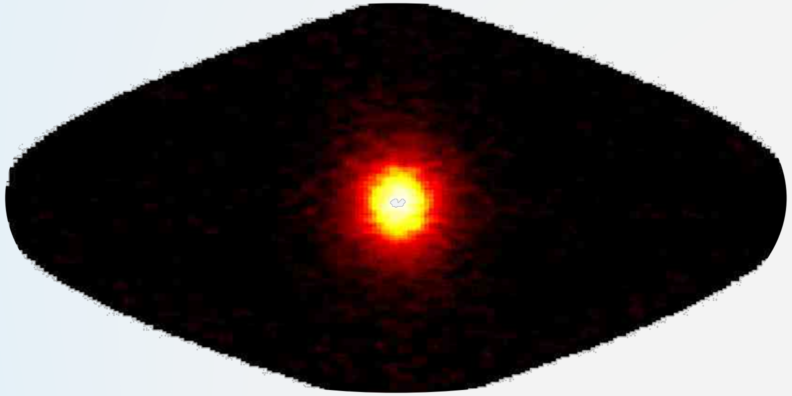
Updates on Super-Kamiokande

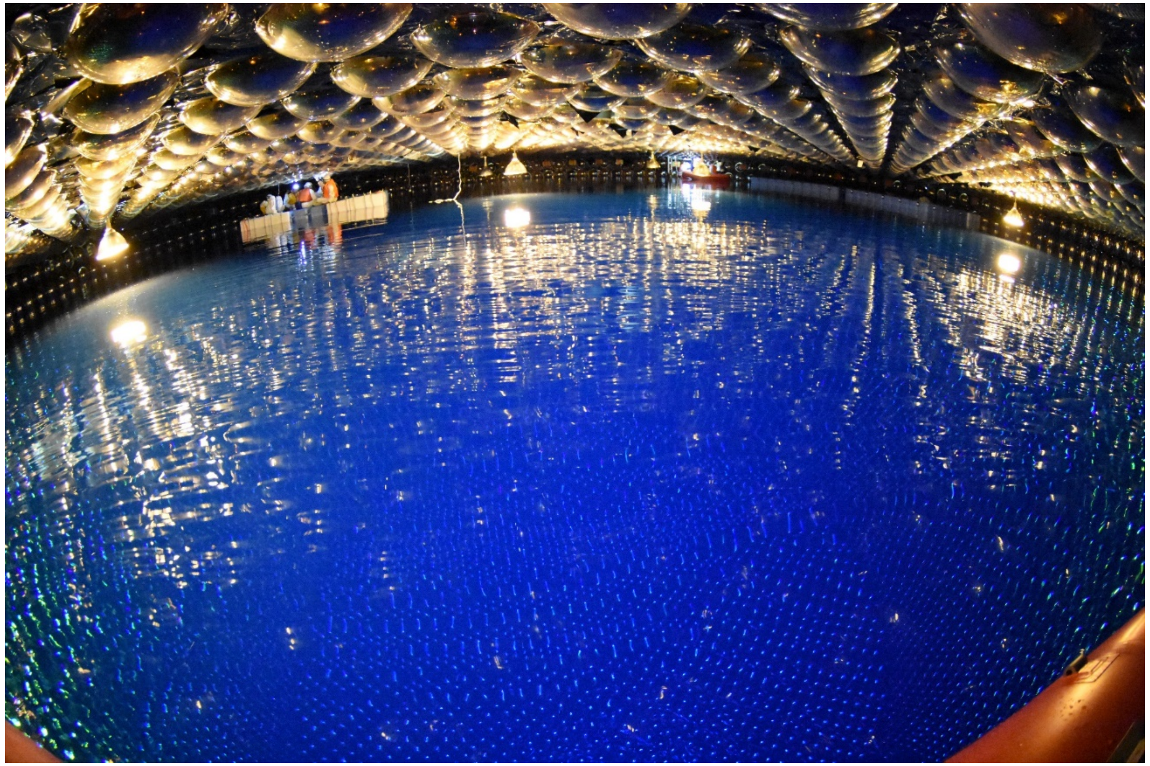
Solar neutrino results and the future of SK

NDM2018 @Daejeon
July 3 2018



Hiroyuki Sekiya
ICRR, University of Tokyo
for the Super-K Collaboration

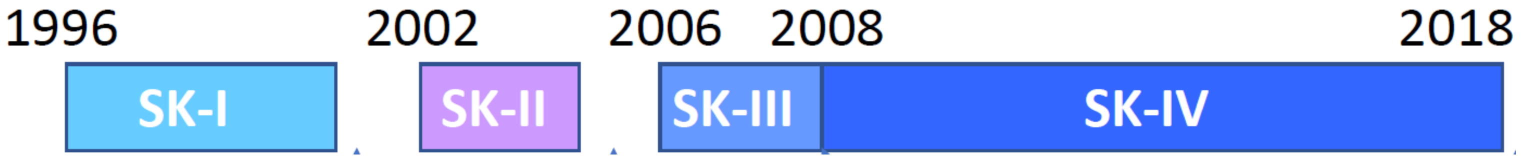
Outline

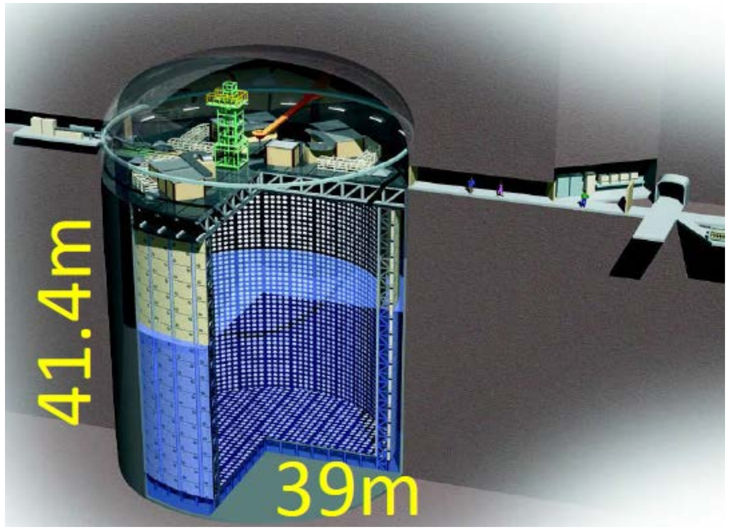


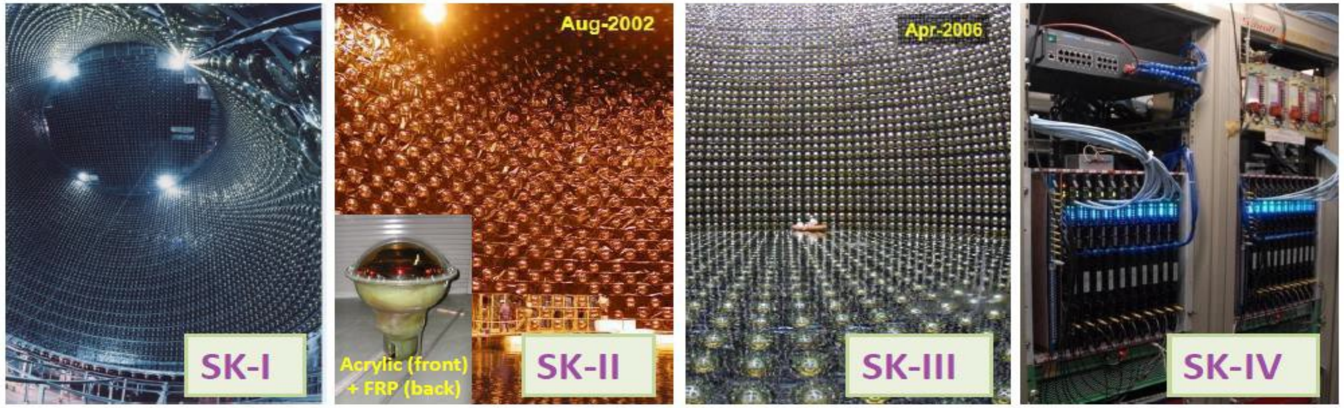
- Introduction
  - SK low energy analysis
  - Physics motivation
- Updated solar results
  - Flux and Spectrum
  - Oscillation analysis
  - NSI
- Future prospects
  - On-going analysis on 2.5MeV threshold data
  - SK-Gd status

Super-Kamiokande

- 50kton ring imaging pure water Cherenkov detector
- 1km (2700 mwe) underground in Kamioka







SK-III and later

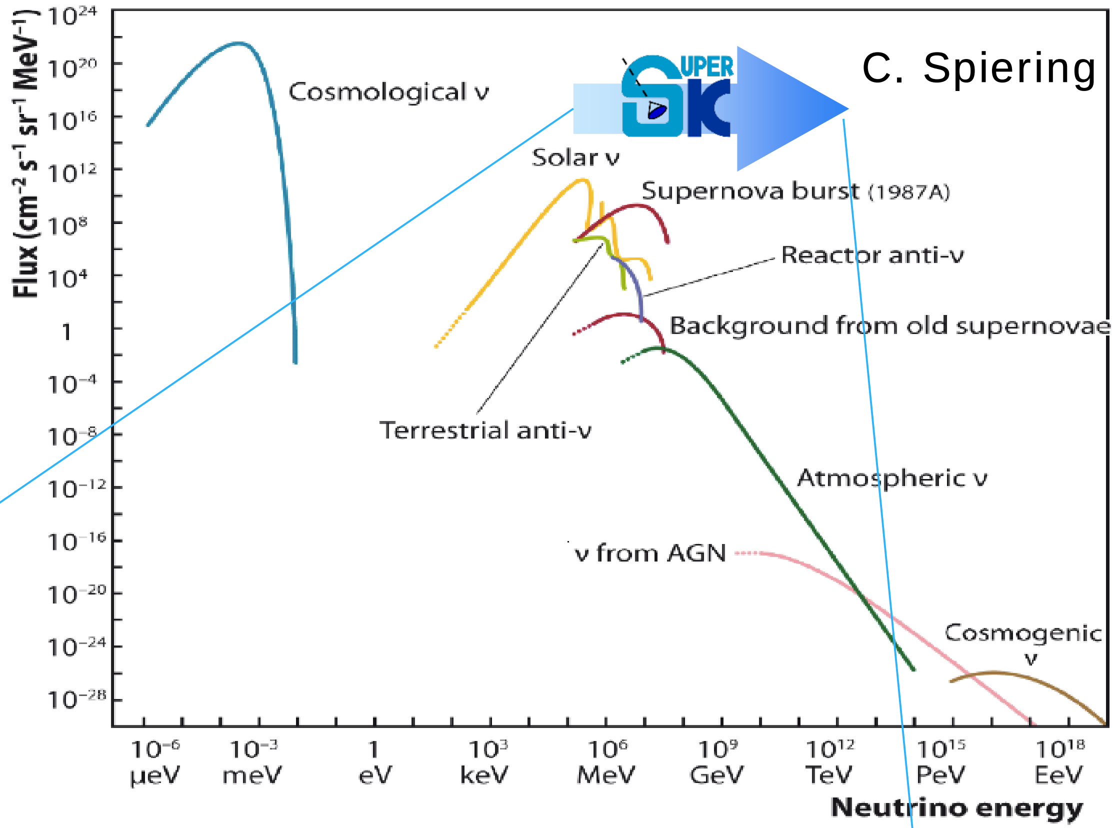
11129 50cm PMTs in Inner Detector

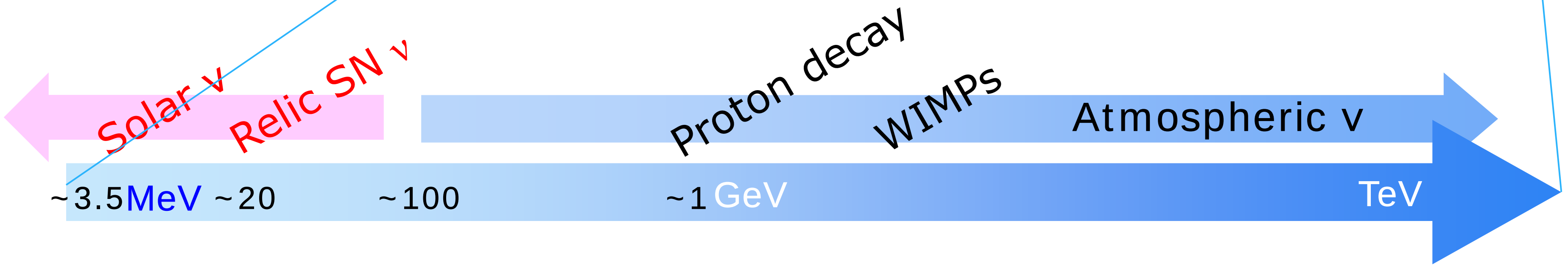
1885 20cm PMTs in Outer Detector

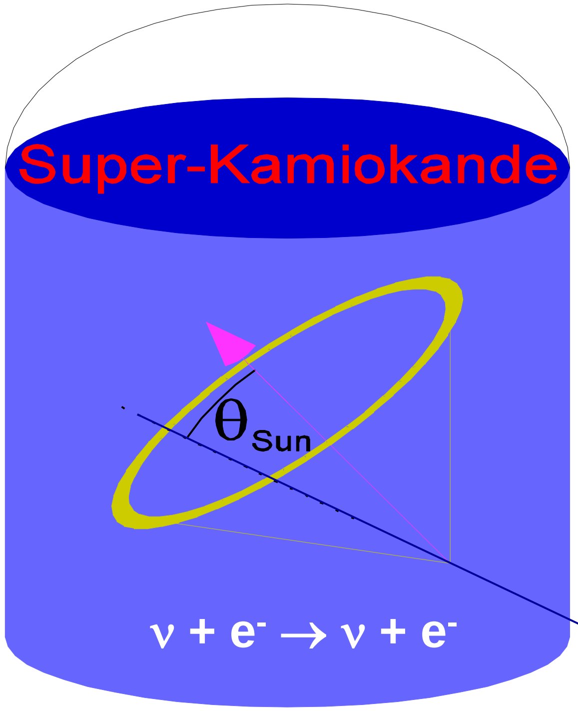
- SK-IV has just finished on May 31st 2018
  - For the preparation for SK-Gd
  - SK will be back online with pure water (as SK-V?) in January 2019

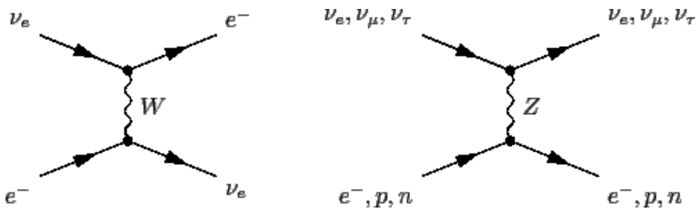
Super-Kamiokande's Physics targets

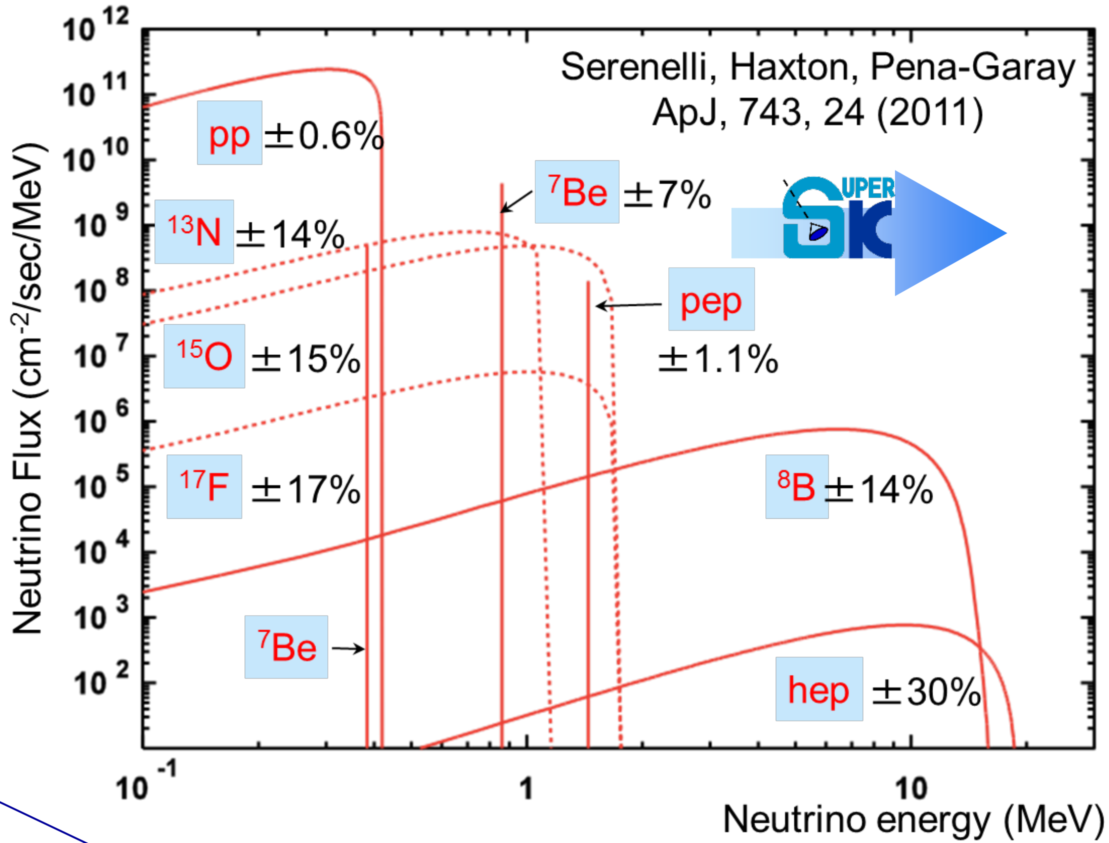
- This talk

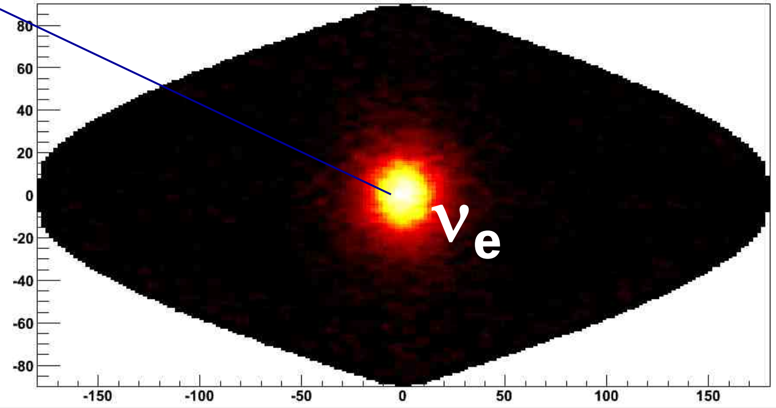












Solar neutrinos in SK

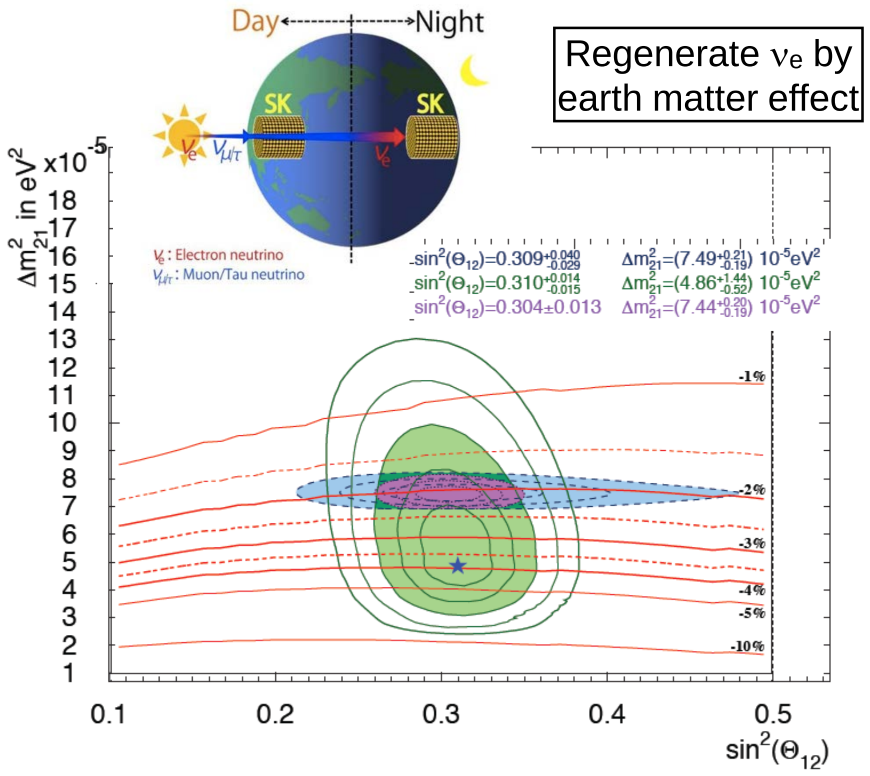
Physics motivation of ^{8}B neutrino measurements

- Search for the direct signals of the MSW effect

Earth matter effect

Flux day-night asymmetry

2.5σ @Phys. Rev. Lett. 112, 091805 (2014)

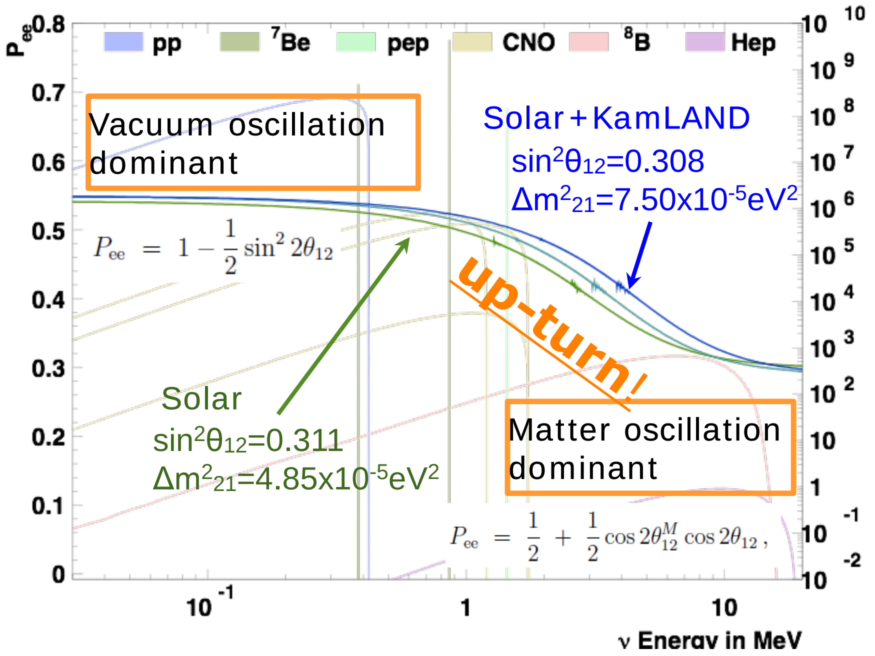


Solar matter effect

Energy spectrum distortion

Neutrino survival probability

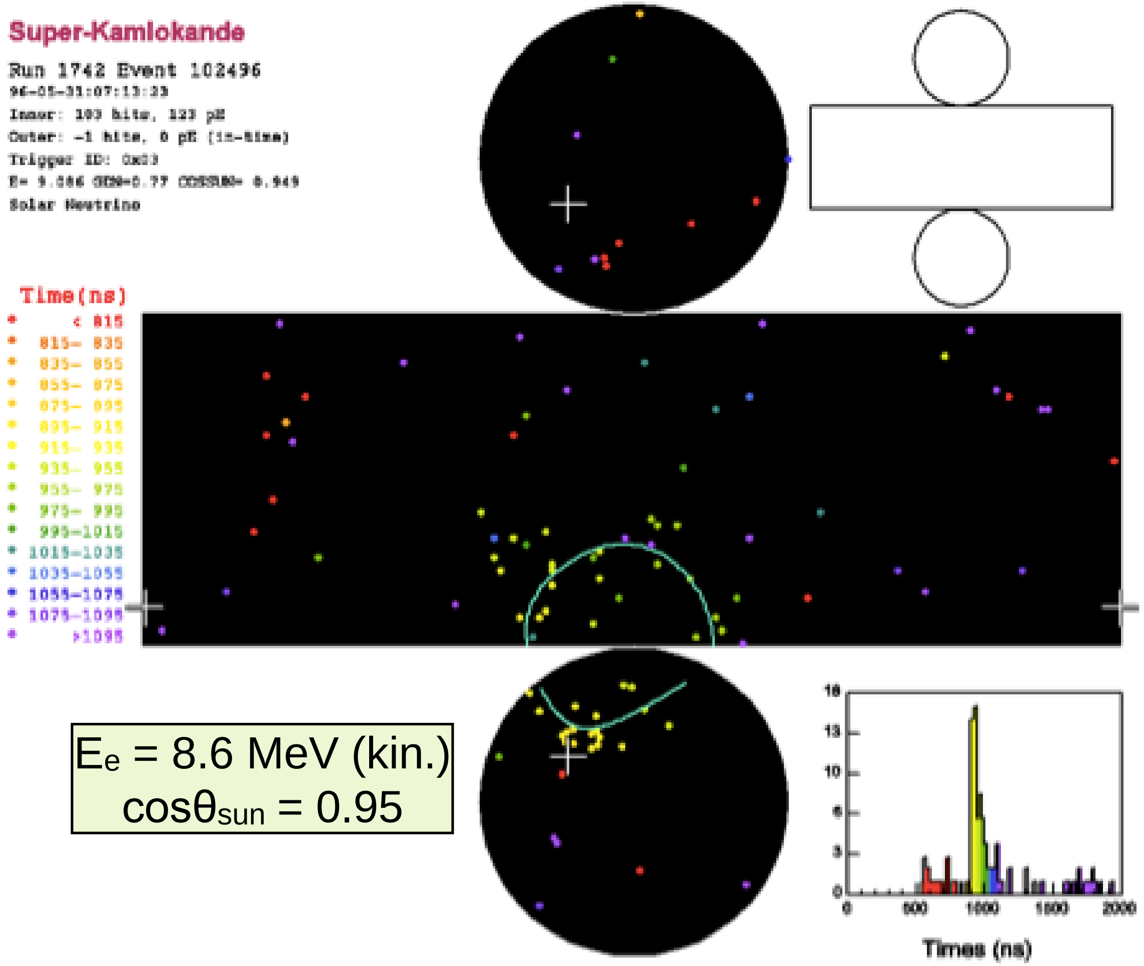
JHEP 0311:004(2003)



- Search for something unexpected NSI?

Solar neutrinos in SK

- Typical event



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

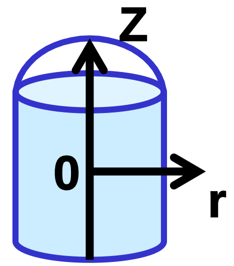
- Detector performance
  - Resolutions@10MeV

vertex	55cm	hit timing
direction	23deg.	hit pattern
energy	14%	# of hits.

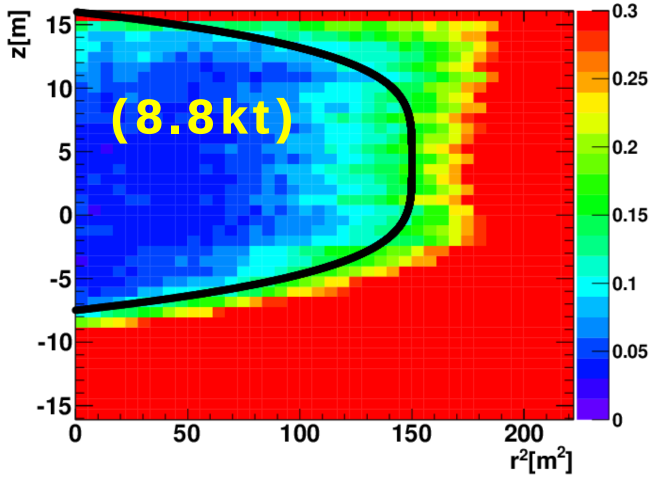
  - ~6hits/MeV
- Data used for analysis total 5695 days

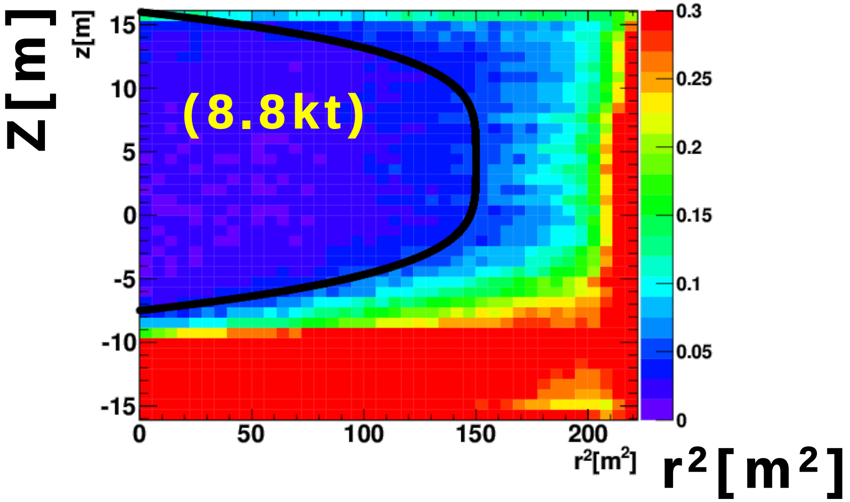
Phase	Period	Livetime (days)	Fiducial vol. (kton)	# of PMTs	Energy thr.(MeV)
SK-I	1996.4 ~ 2001.7	1496	22.5	11146 (40%)	4.5
SK-II	2002.10 ~ 2005.10	791		5182 (20%)	6.5
SK-III	2006.7 ~ 2008.8	548	22.5 (>5.5MeV) 13.3 (<5.5MeV)	11129 (40%)	4.5
SK-IV	2008.9 ~ 2018.1	2860	22.5 (>5.0MeV) 16.5 (4.5<E<5.0) 8.8 (<4.5MeV)		3.5

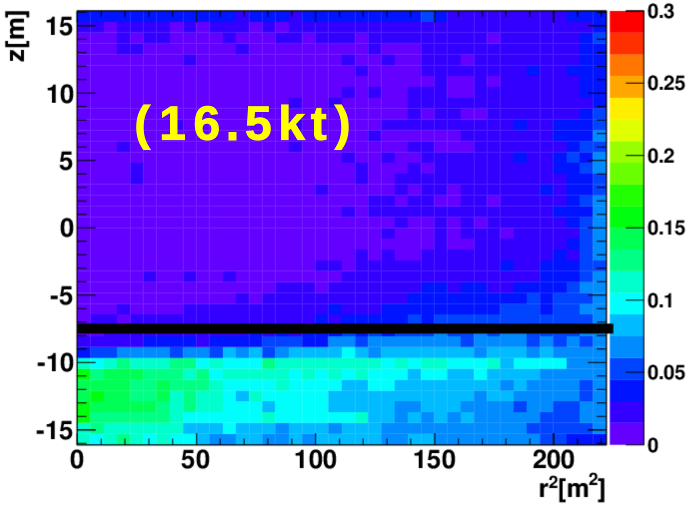
Stability of SK-IV



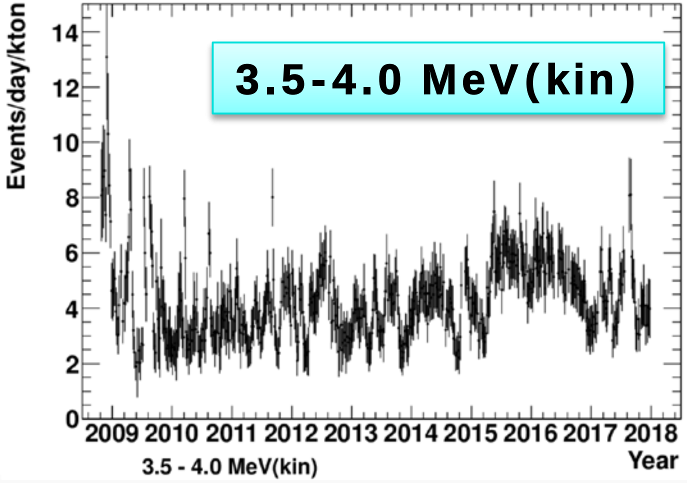
- Vertex distribution **SK-IV 2645 days**
  - Whole area in these plots corresponds to 22.5 kton

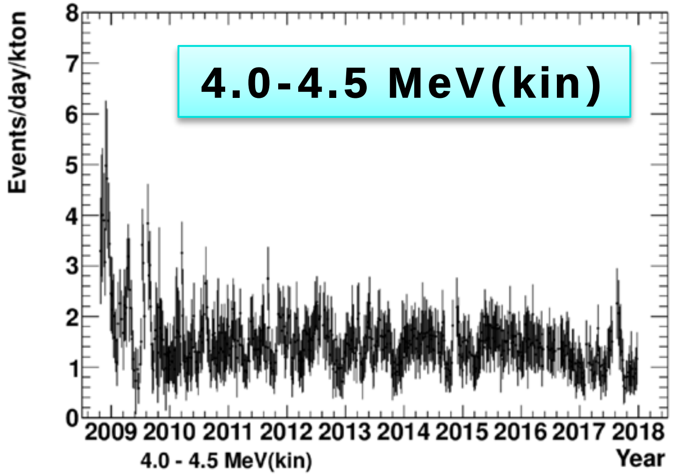


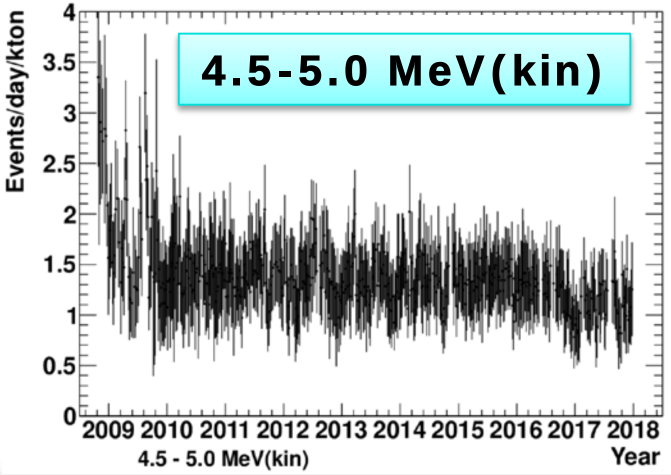




- Time variation



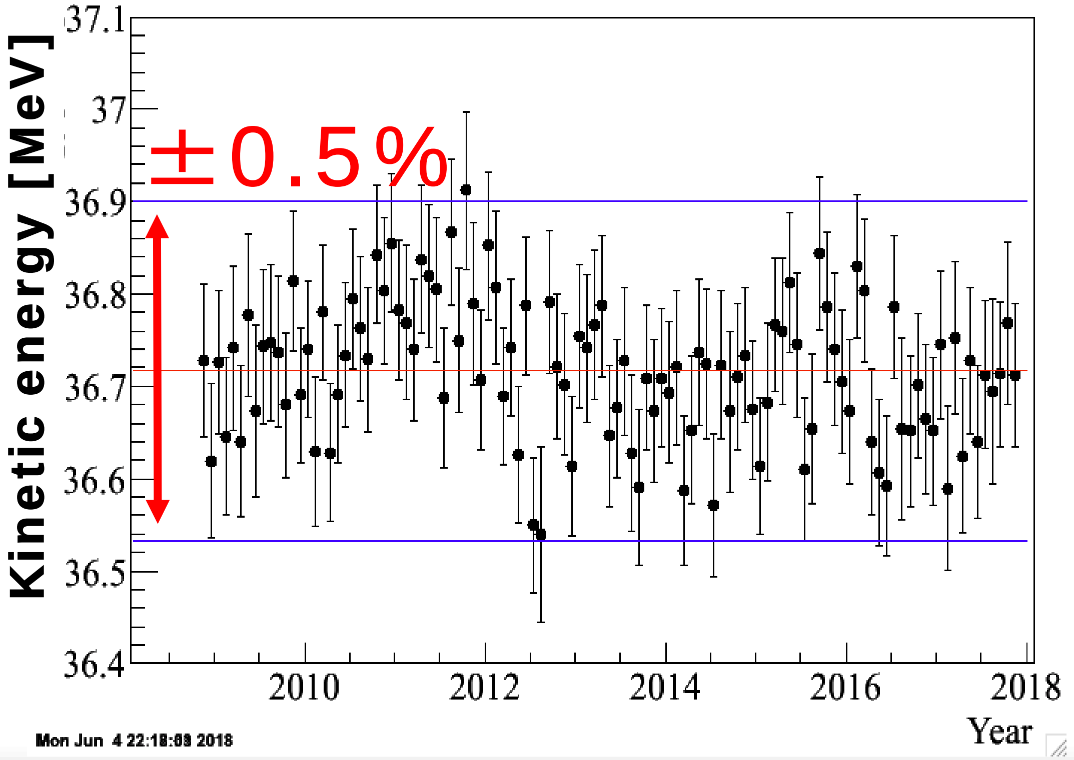


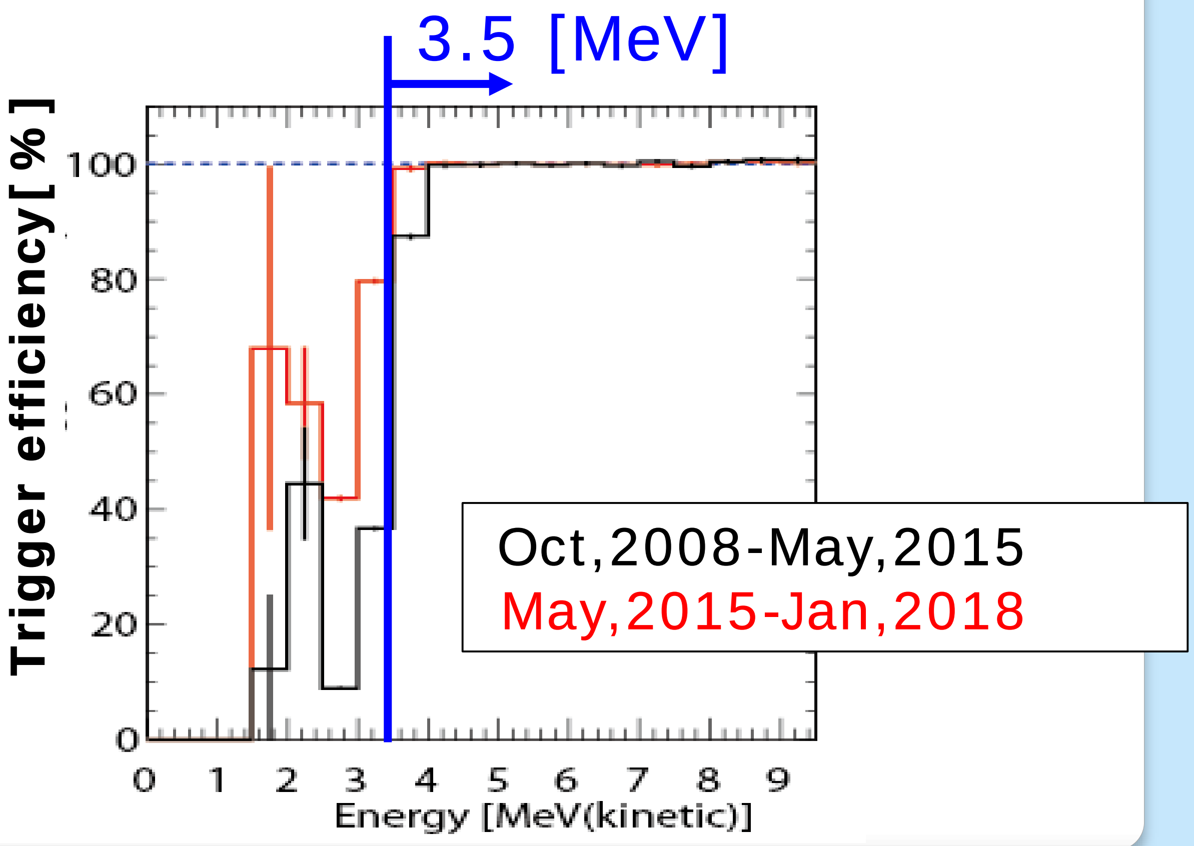


Stability of SK-IV

- Stability check of the water/energy scale by decay-e
  - Oct, 2008 – Jan 2018.
- Improved trigger efficiency at lowest energy bin since 2015

Decay electron average energy



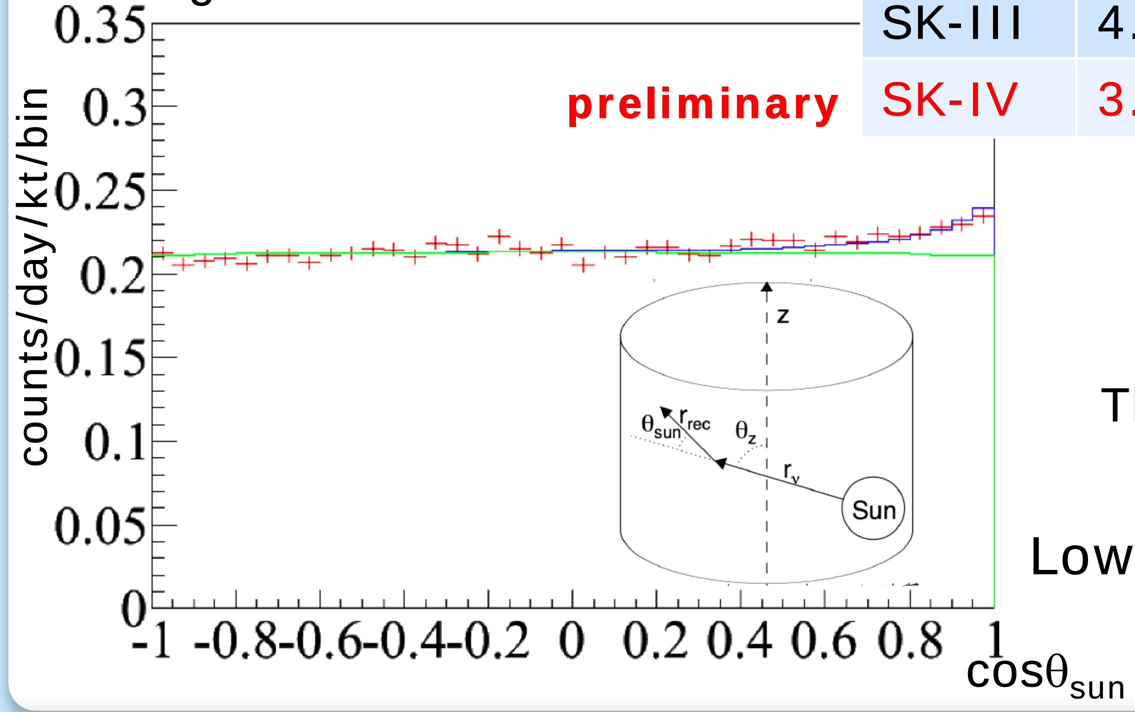


SK ^{8}B Solar neutrino observation

- SK has observed solar neutrino for 22 years(2 solar cycle!)
  - ~93000 solar ν

	Energy threshold	Livetime days	Extracted signal err. stat. only	8B Flux [×10^6 /cm^2/sec]
SK-I	4.5 keV	1496	22404 ±226	2.38±0.02±0.08
SK-II	6.5 keV	791	7213^{+153}_{-151}	$2.41\pm0.05^{+0.16}_{-0.15}$
SK-III	4.0 keV	548	8148^{+133}_{-131}	2.40±0.04±0.05
SK-IV	3.5 keV	2860	55729^{+363}_{-361}	2.29±0.02±0.04

SK-IV (2860days)
3.5MeV-4.0 MeV solar ν
signal extraction

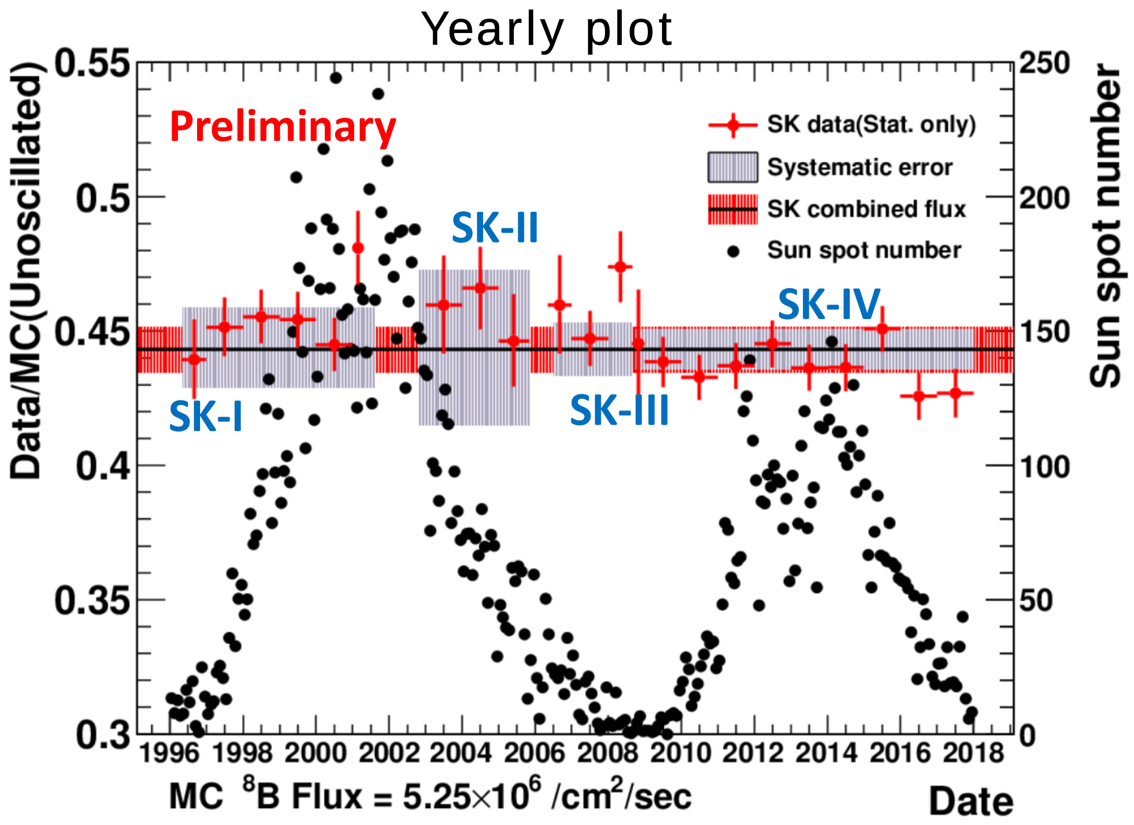


Average flux (SK-I~IV):
2.33±0.04(stat.+sys.) ×10^6 /cm^2/sec

The flux is consistent/stable all over the phases

Lowest energy bin: 3.5MeV-4.0MeV
1794^{+169}_{-166}(stat.) $^{+55}_{-54}$ (sys.) events

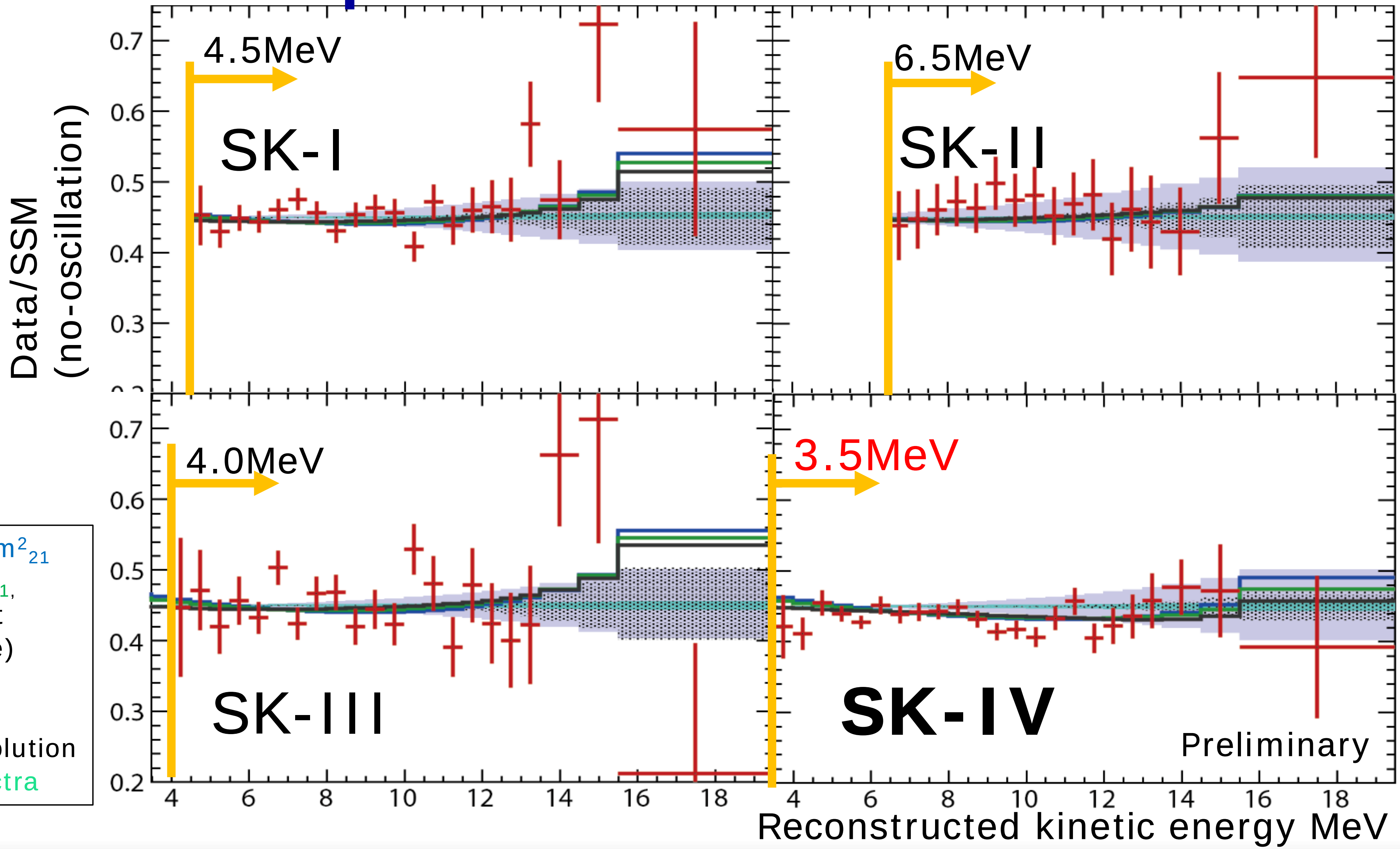
Time variation of ^{8}B solar neutrino flux



- No correlation with the 11 years solar activity is observed.
- Super-K solar rate measurements are fully consistent with a constant solar neutrino flux emitted by the Sun.
  - χ^2 = 21.57/21(dof)

Sun spot number was obtained by the web page of NASA
http://solarscience.msfc.nasa.gov/greenwch/spot_num.txt

Recoil electron spectra



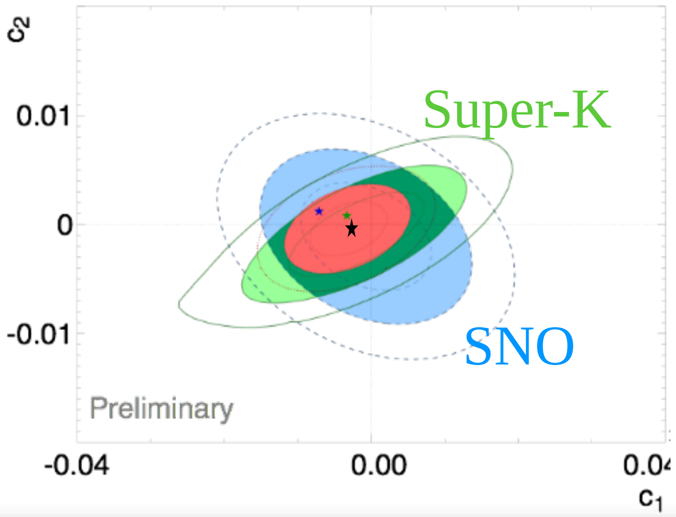
Blue: KamLAND Δm^2_{21}
Green; Solar Δm^2_{21},
Black; quadratic fit (next slide)
Sys errors;
gray; energy scale
mesh; energy resolution
turquoise; 8B spectra

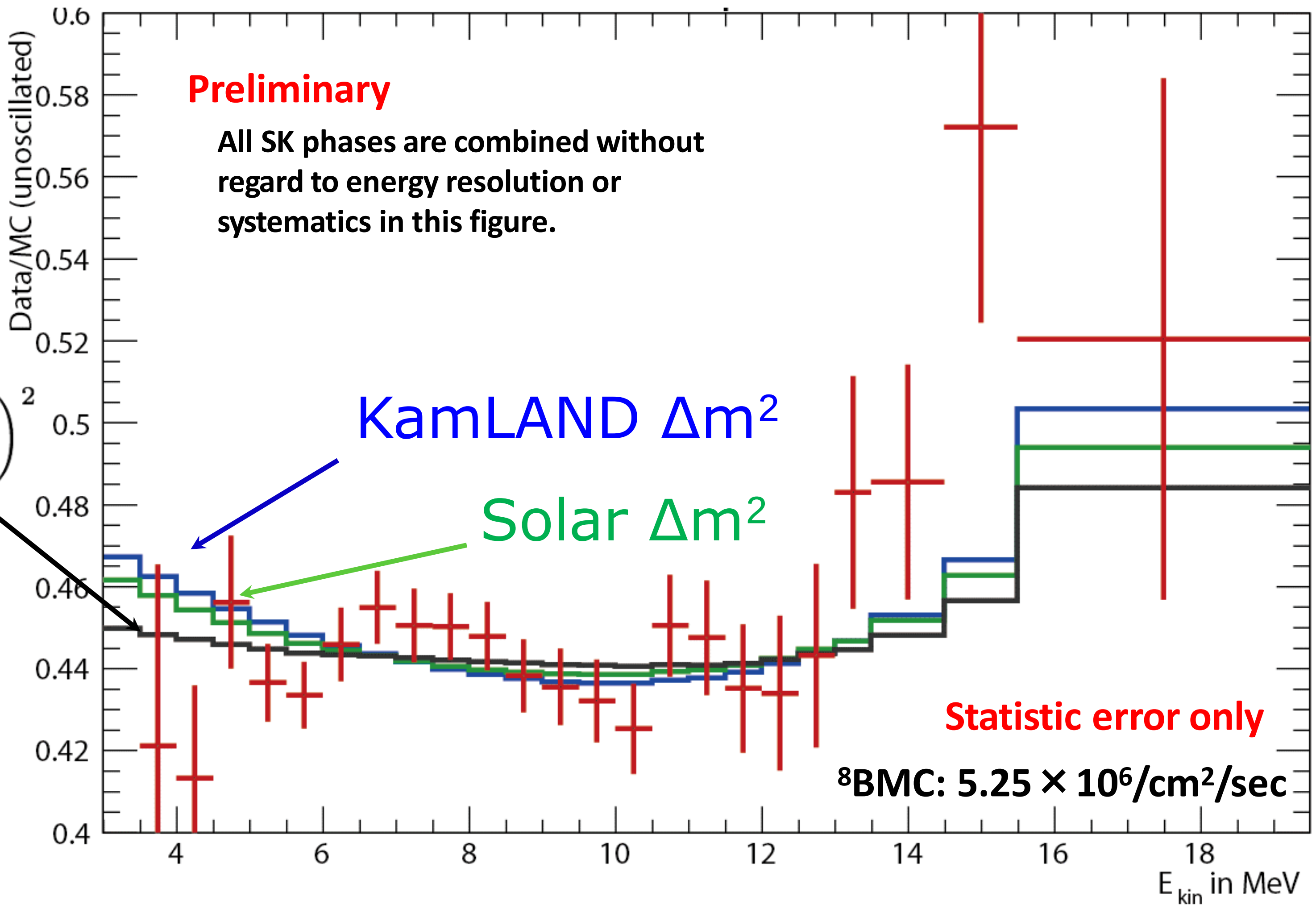
SK I-IV combined recoil spectrum

- To test of “spectrum upturn”

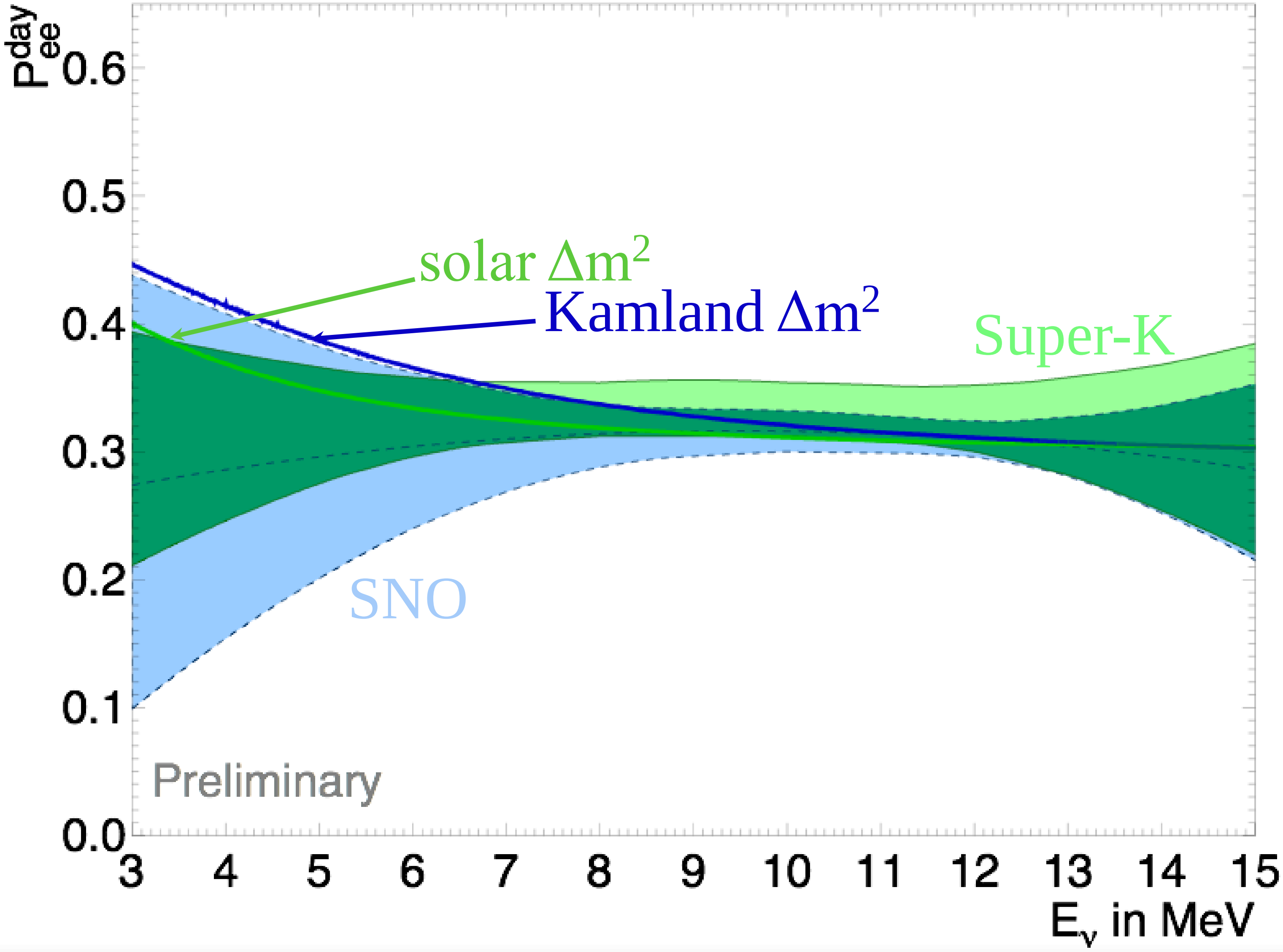
  Neutrino energy spectrum is convoluted in the electron recoil spectrum. For de-convolution, generic function is used as a survival probability and fitted to the data

$$P_{ee}(E_\nu) = c_0 + c_1\left(\frac{E_\nu}{MeV} - 10\right) + c_2\left(\frac{E_\nu}{MeV} - 10\right)^2$$

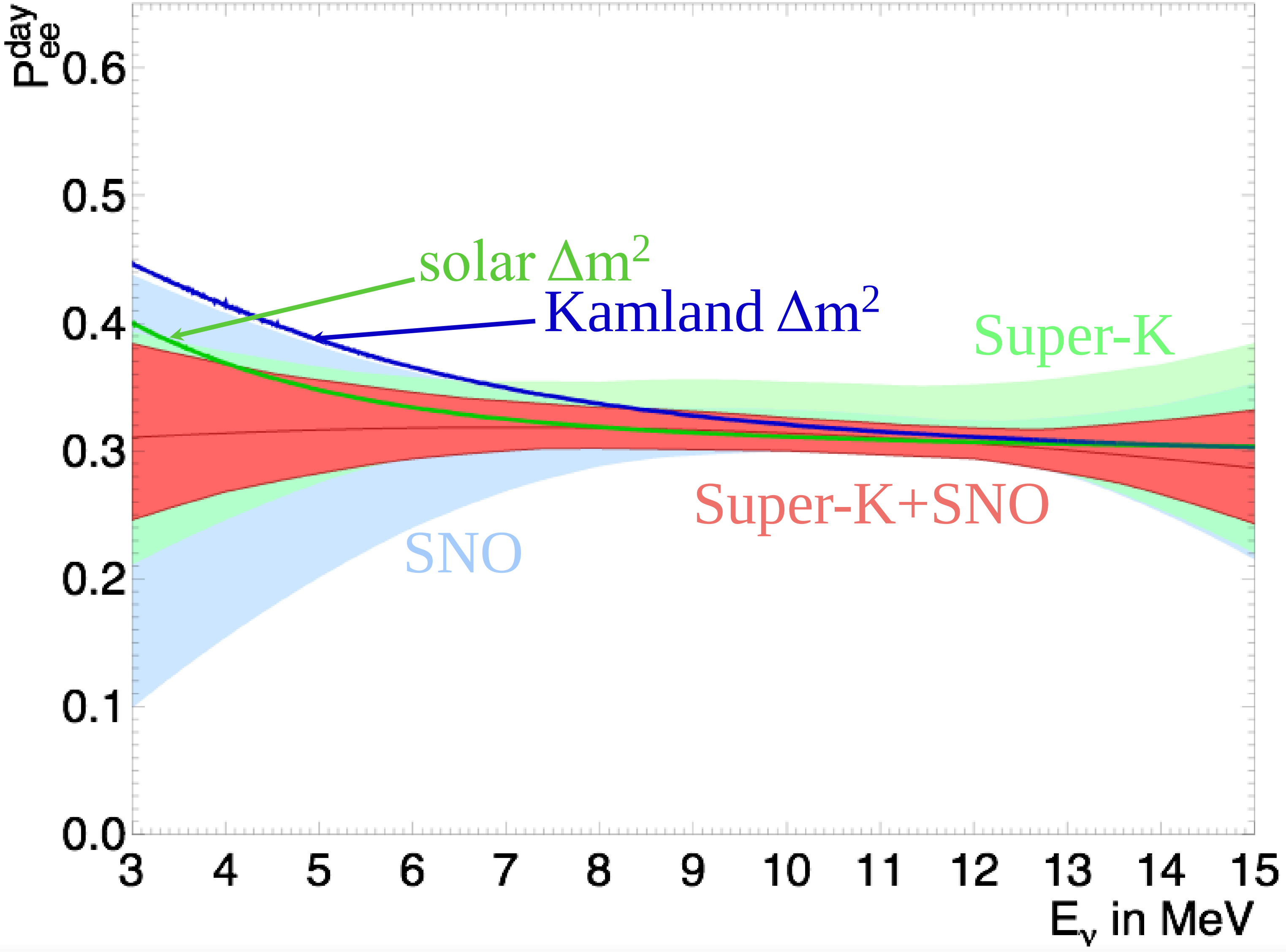




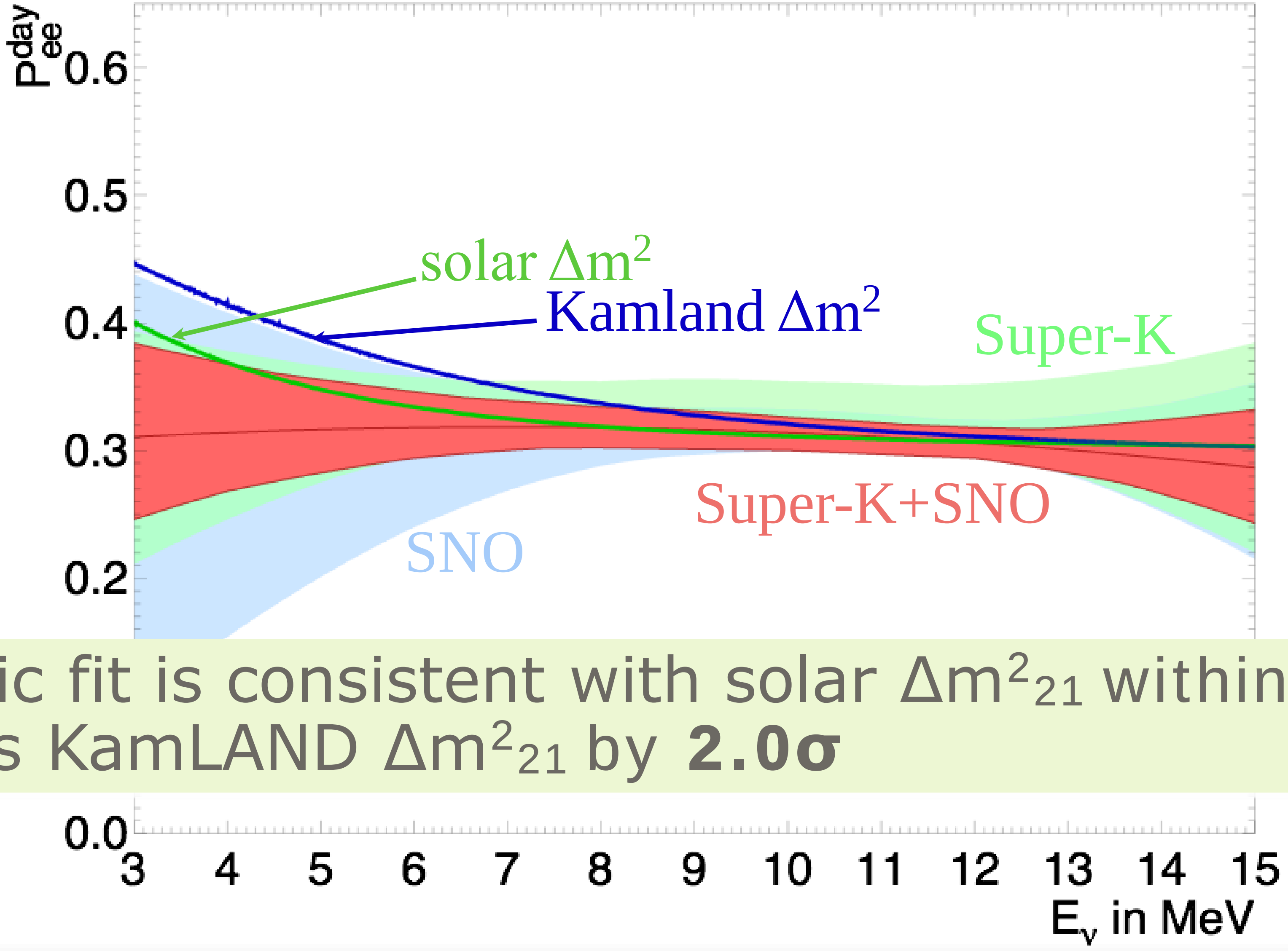
Survival probability $P_{ee}(E\nu)$



Survival probability $P_{ee}(E\nu)$

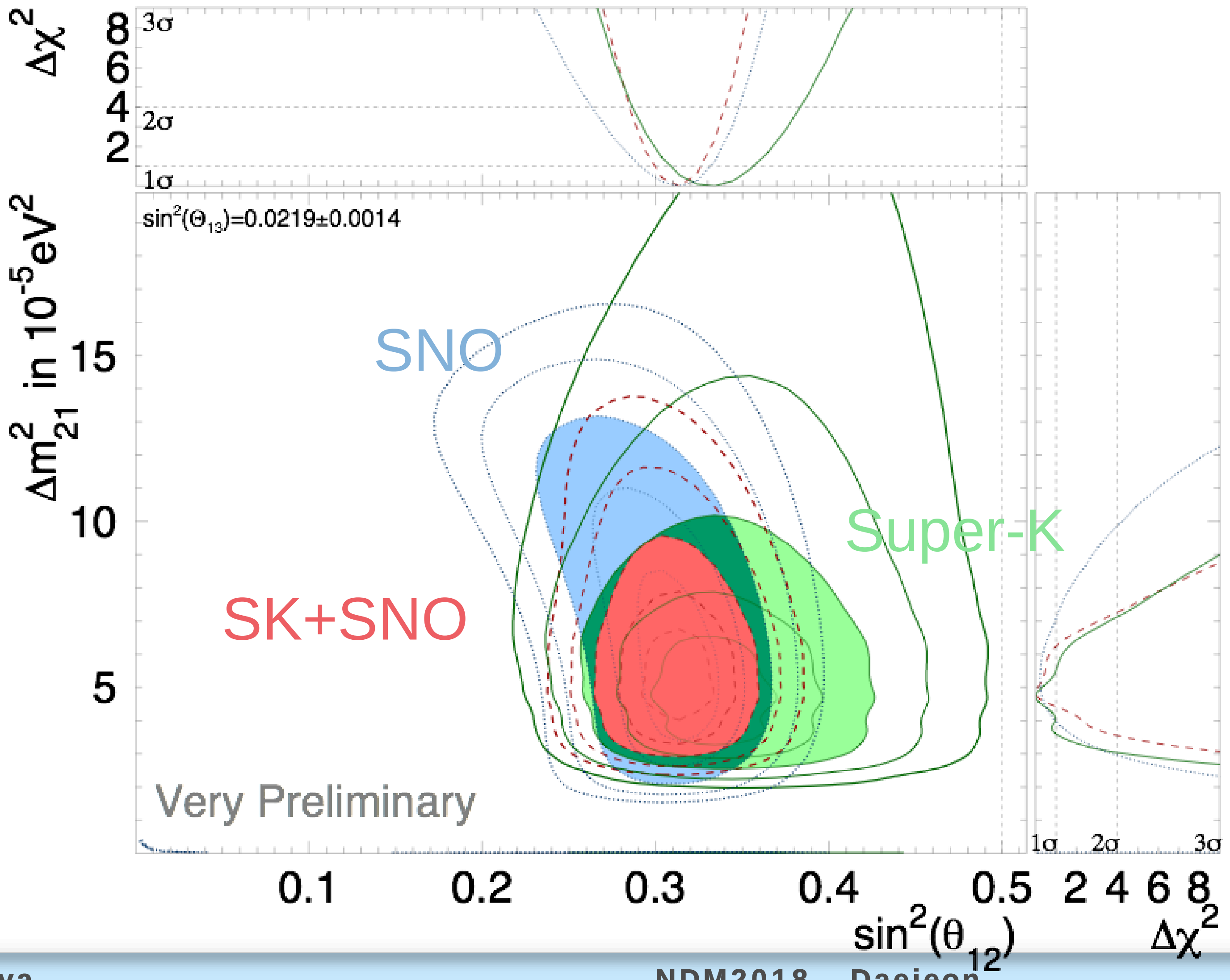


Survival probability $P_{ee}(E\nu)$



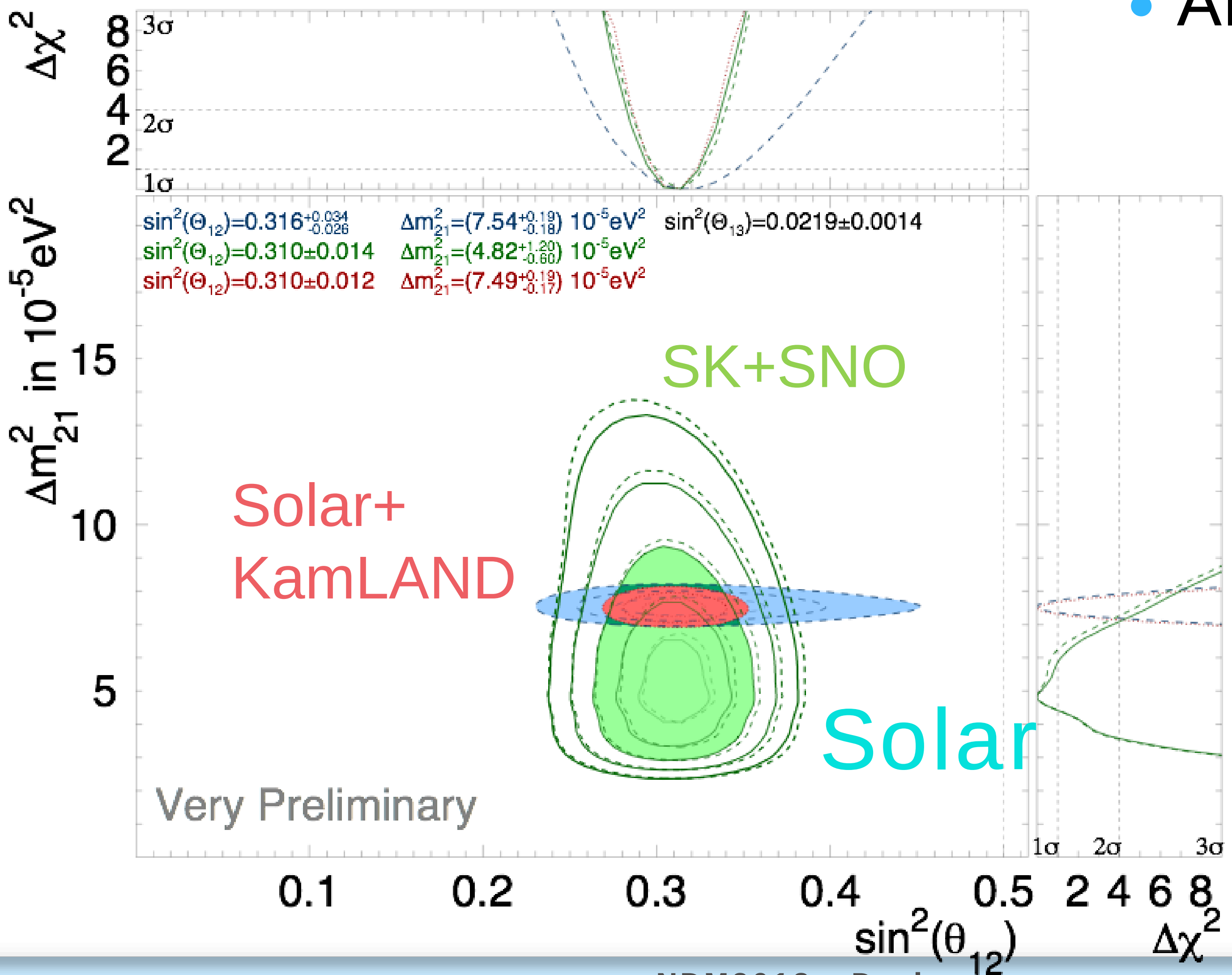
Quadratic fit is consistent with solar Δm^2_{21} within **1.2σ** and disfavors KamLAND Δm^2_{21} by **2.0σ**

Oscillation analysis θ_{12} & Δm^2_{21} SK+SNO



- Super-K data best constrains Δm^2_{21}
- SNO data best constrains $\sin^2\theta_{12}$
- complementarity makes combined fit beneficial

Oscillation analysis θ_{12} & Δm^2_{21} ALL Exp.



- All the solars + KamLAND

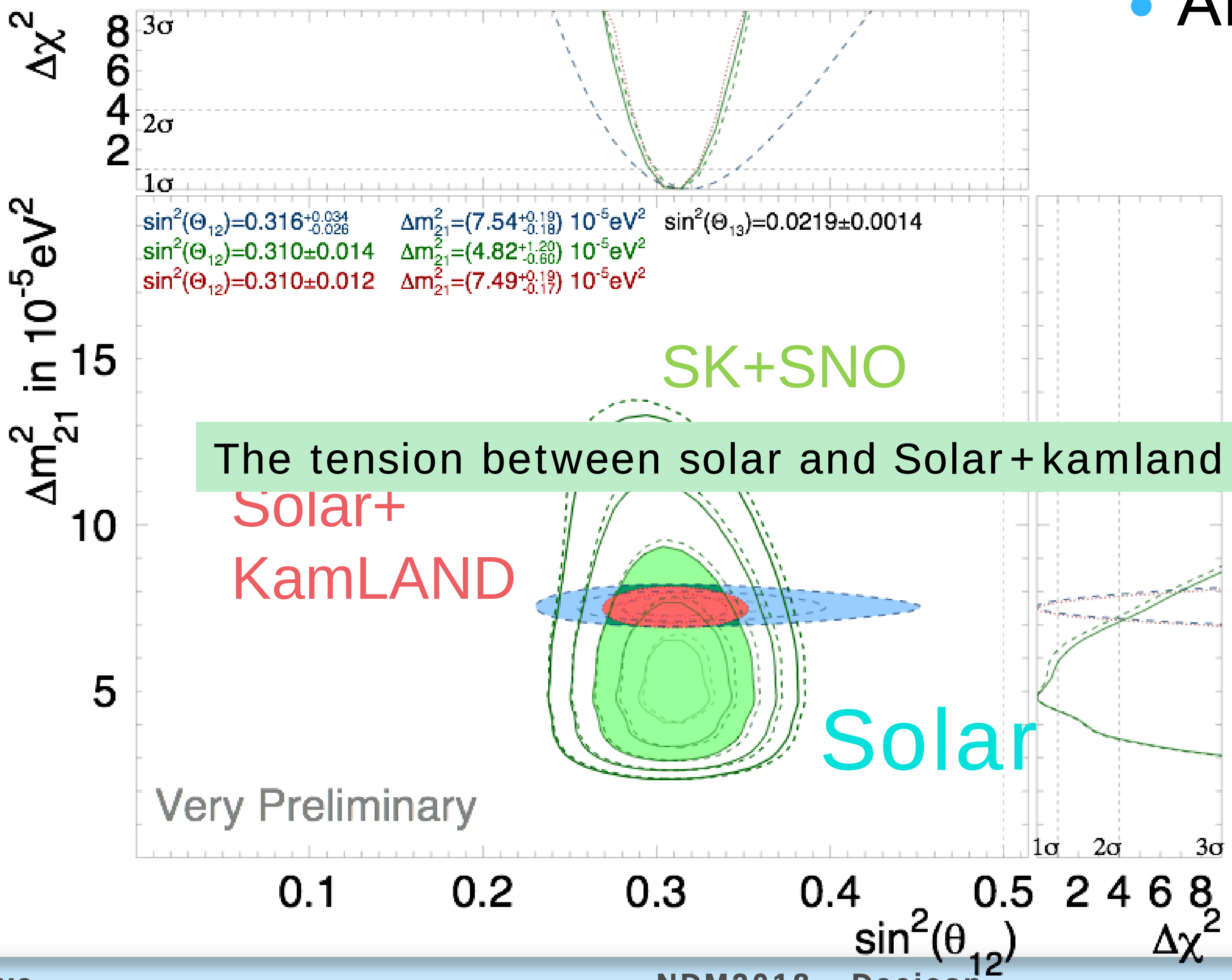
$\sin^2\theta_{12} = 0.310 \pm 0.014$
$\Delta m^2_{21} = 4.82^{+1.20}_{-0.60} \times 10^{-5} eV^2$

$\sin^2\theta_{12} = 0.316^{+0.034}_{-0.026}$
$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times 10^{-5} eV^2$

$\sin^2\theta_{12} = 0.310 \pm 0.012$
$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17} \times 10^{-5} eV^2$

Oscillation analysis θ_{12} & Δm^2_{21} ALL Exp.

- All the solars + KamLAND



The tension between solar and Solar+kamland is 2sigma level

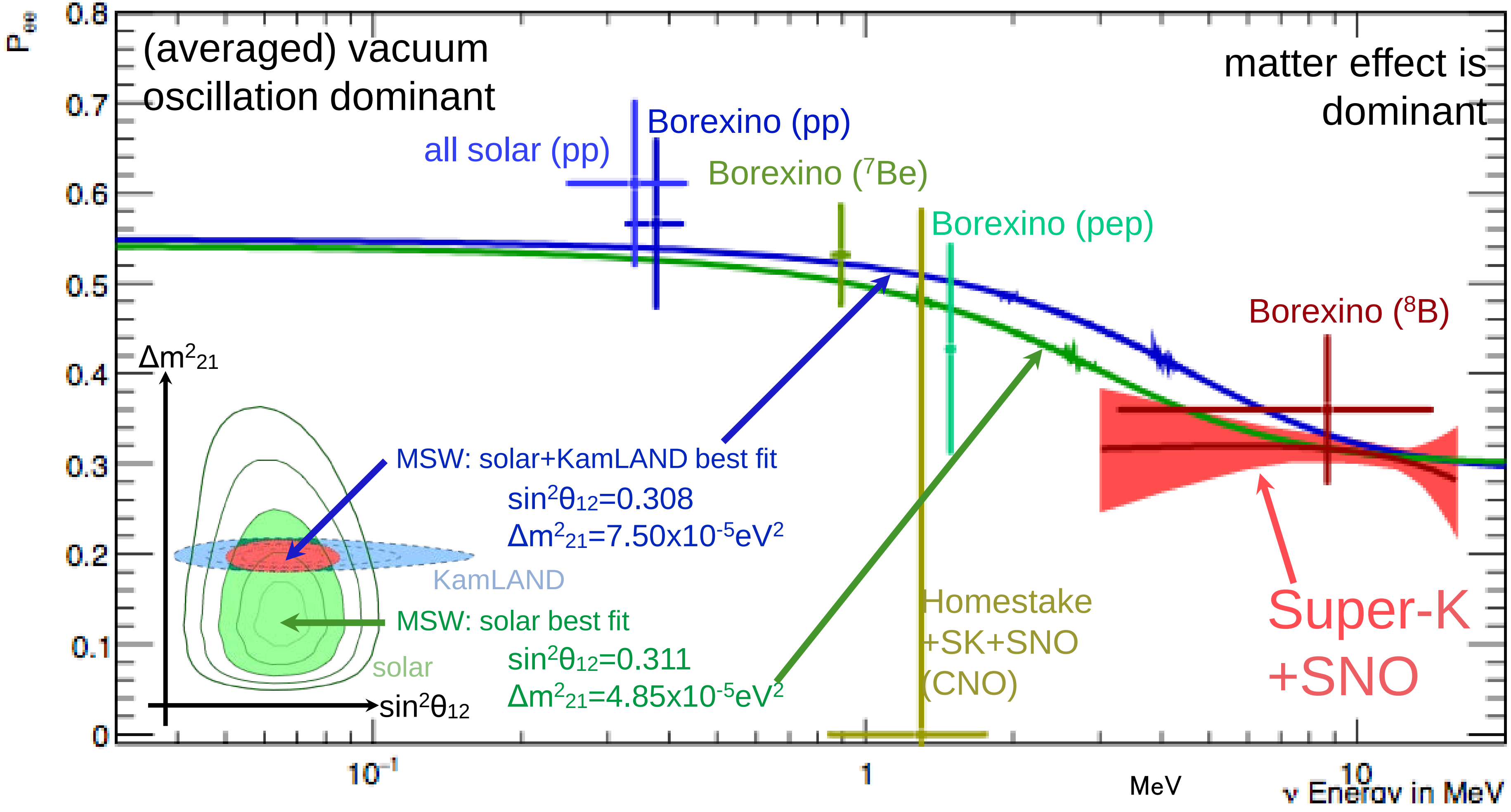
$\sin^2\theta_{12} = 0.310 \pm 0.014$
$\Delta m^2_{21} = 4.82^{+1.20}_{-0.60} \times 10^{-5}\mathrm{eV}^2$

${}^{+0.034}_{-0.026}$
$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times 10^{-5}\mathrm{eV}^2$

$\sin^2\theta_{12} = 0.310 \pm 0.012$
$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17} \times 10^{-5}\mathrm{eV}^2$

Survival probability $P_{ee}(E\nu)$ ALL Exp.

- Upturn" predicted by standard MSW is not seen yet.



Non standard interaction (NSI)

- To check the "NO upturn" possibility
  - Standard oscillation in matter

$$i\frac{d}{dt}\begin{pmatrix}\nu_e(t)\\ \nu_\mu(t)\\ \nu_\tau(t)\end{pmatrix} = \left(\frac{UM^2U^\dagger}{2E} + V\right)\begin{pmatrix}\nu_e(t)\\ \nu_\mu(t)\\ \nu_\tau(t)\end{pmatrix} \qquad V = \begin{pmatrix}\frac{a}{2E} & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{pmatrix}$$

$$a = 2\sqrt{2}G_F n_e E$$

  - NSI

$$H_{mat} = \sqrt{2}G_F n_e \begin{bmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu}^* & \epsilon_{e\tau}^* \\ \epsilon_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}^* \\ \epsilon_{e\tau} & \epsilon_{\mu\tau} & \epsilon_{\tau\tau} \end{bmatrix}$$

Strong constraint for muon nu related terms

Set at zero in this analysis

$$\Rightarrow \sqrt{2}G_F n_e \begin{bmatrix} 1+\epsilon_{ee} & 0 & \epsilon_{e\tau}^* \\ 0 & 0 & 0 \\ \epsilon_{e\tau} & 0 & \epsilon_{\tau\tau} \end{bmatrix}$$

Friedland, Lunardini, Pena-Garay,
"Solar neutrinos as probes of neutrino-matter interactions"
(2004) Phys.Lett.B594:347,2004

NSI: effective matter potential Hamiltonian

- Reduce full 3-flavor NSI matter potential to the 2x2 basis

$$H_{mat}^{eff} = \frac{G_F n_e}{\sqrt{2}} \begin{bmatrix} \{\cos^2(\theta_{13}) + \epsilon_{11}\} & \epsilon_{12}^* \\ \epsilon_{12} & -\{\cos^2(\theta_{13}) + \epsilon_{11}\} \end{bmatrix}$$

M.C. Gonzalez-Garcia, Michele Maltoni,
"Determination of matter potential from global analysis of neutrino oscillation data"
JHEP 1309:152, 2013

In this analysis, we tested two cases;

ν-up quark interaction

$$\epsilon_{11} = Y_u \epsilon_{11}^u \ \& \ \epsilon_{12} = Y_u \epsilon_{12}^u$$

ν-down quark interaction

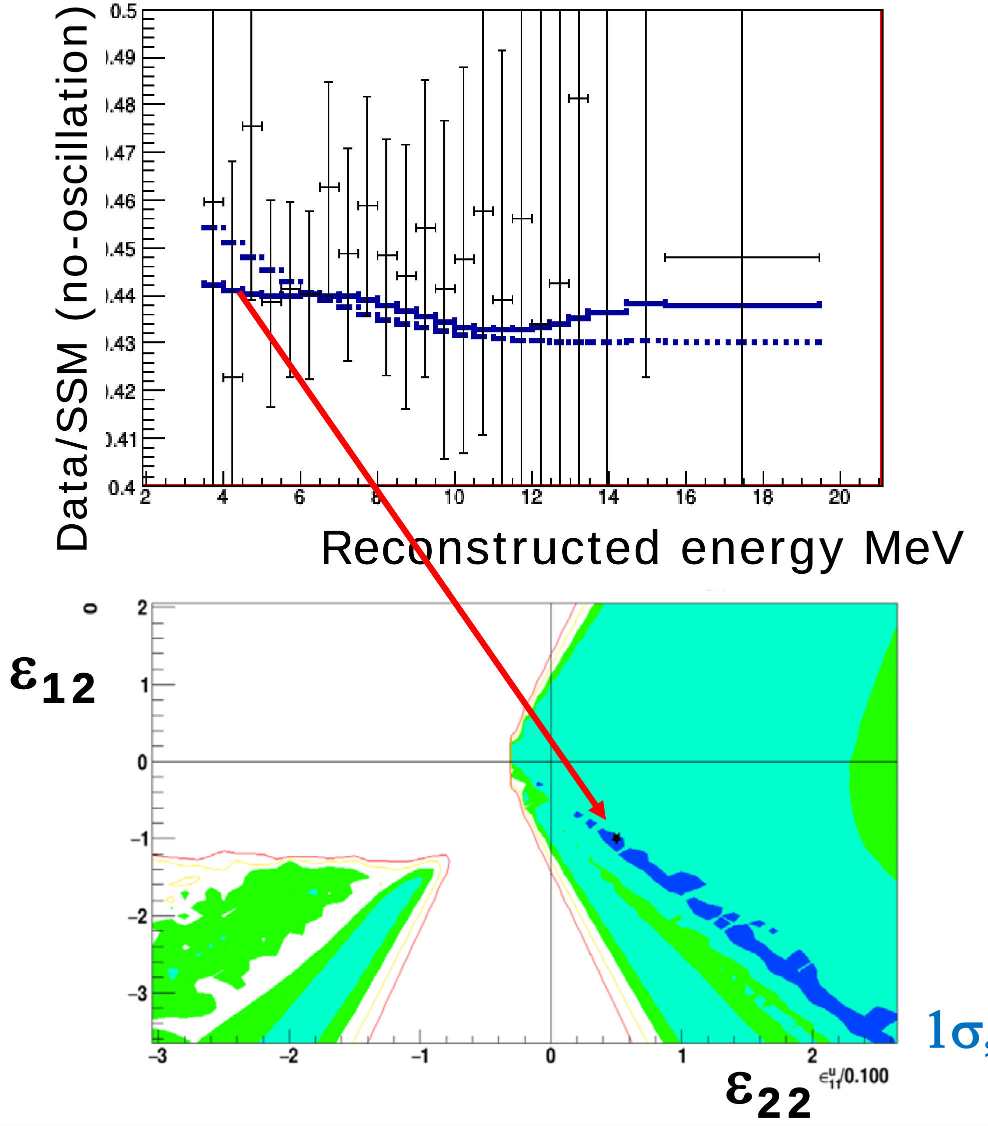
$$\epsilon_{11} = Y_d \epsilon_{11}^d \ \& \ \epsilon_{12} = Y_d \epsilon_{12}^d$$

Number density of quarks

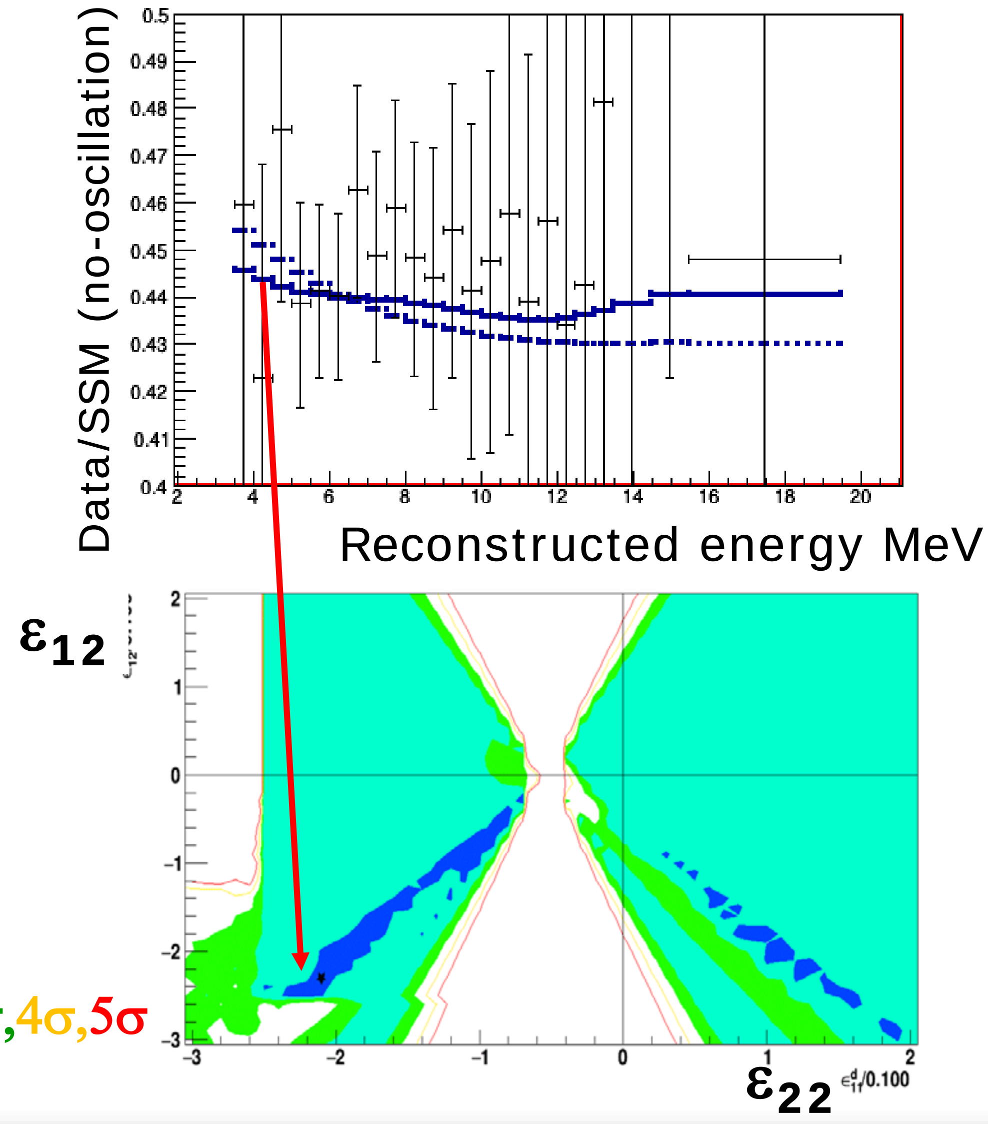
Constrains on ε_{12} and ε_{22}

- SK-I,II,III,IV(1670d)
  - with Day/Night asymmetry+SNO

Up quark interaction



Down quark interaction

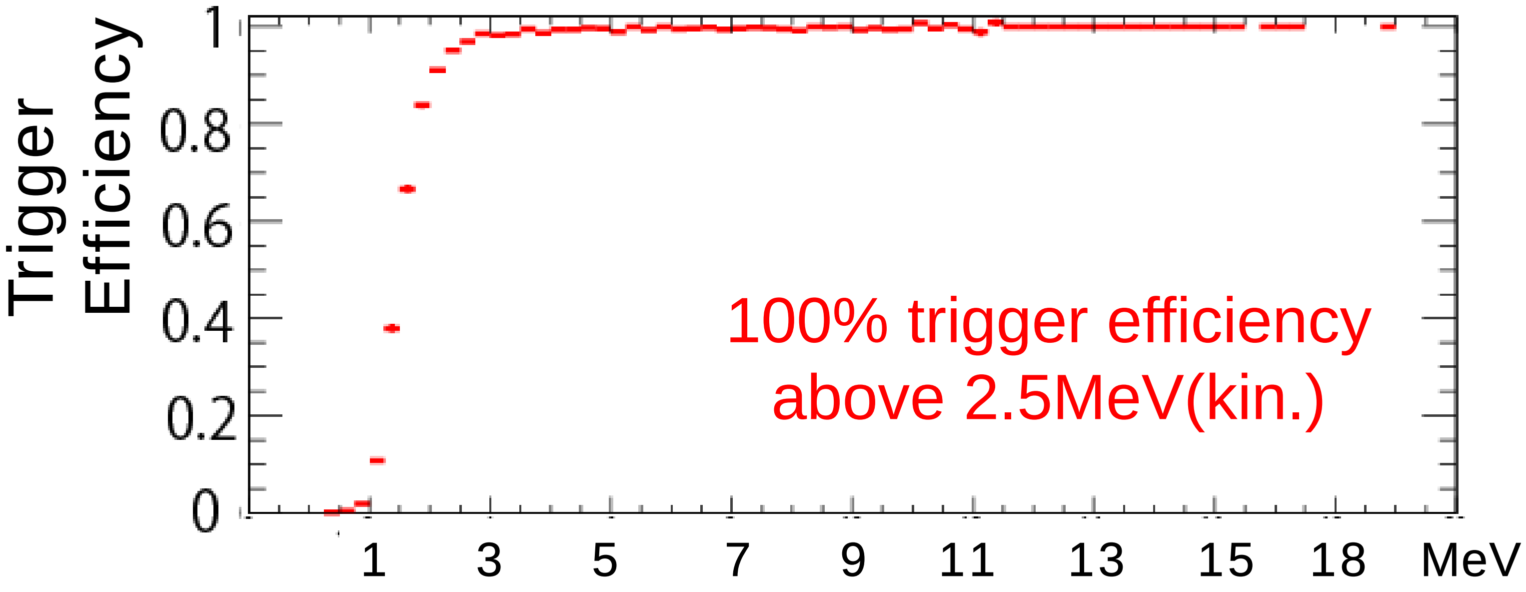


1σ,2σ,3σ,4σ,5σ

For future

2 years of 2.5MeV threshold data taking

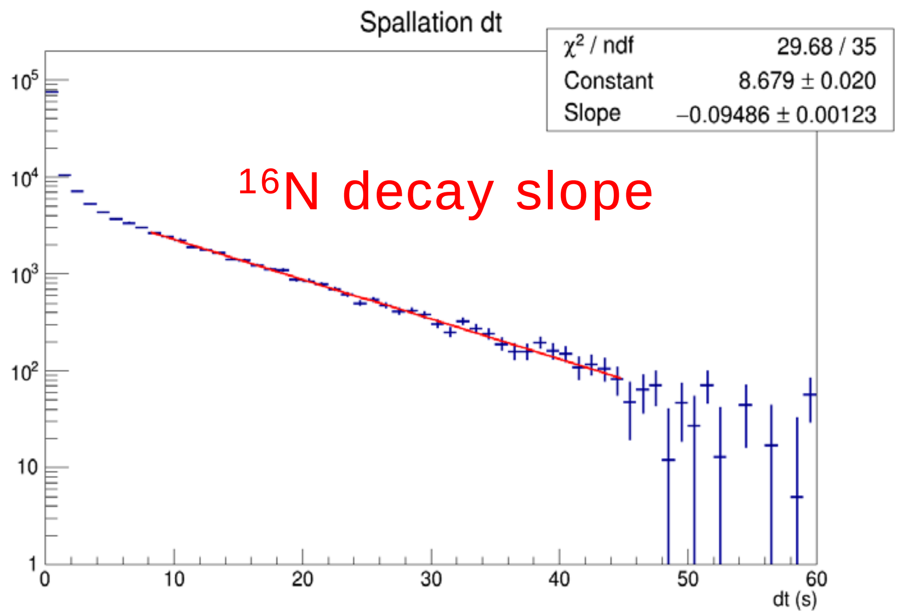
- Wide-band intelligent trigger (WIT)
  - Reconstruction and Reduction just after Front-end

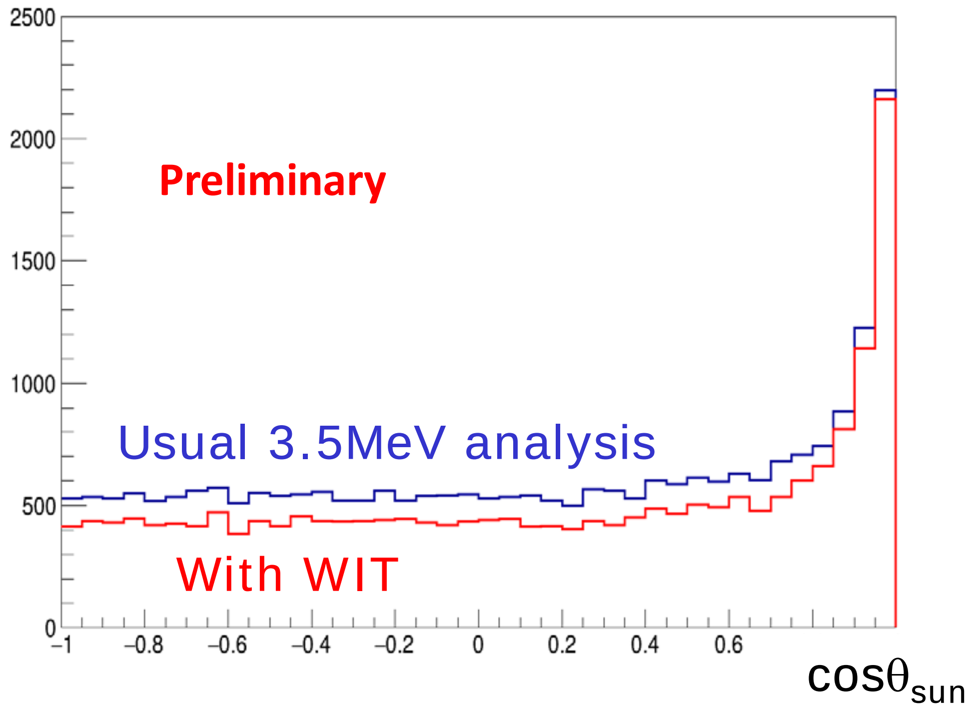


- For tagging spallation neutrons by capture on hydrogen.
- Although 2.2MeV detection efficiency is still low, if there is a big enough shower, it is possible.

Improvements of spallation BG cut

- Above 6 MeV, spallation ^{16}N (τ=10.3s) is the largest BG.
- With WIT, by tagging events within 1 min and 4m in vertex position of each other, ^{16}N is clearly observed!

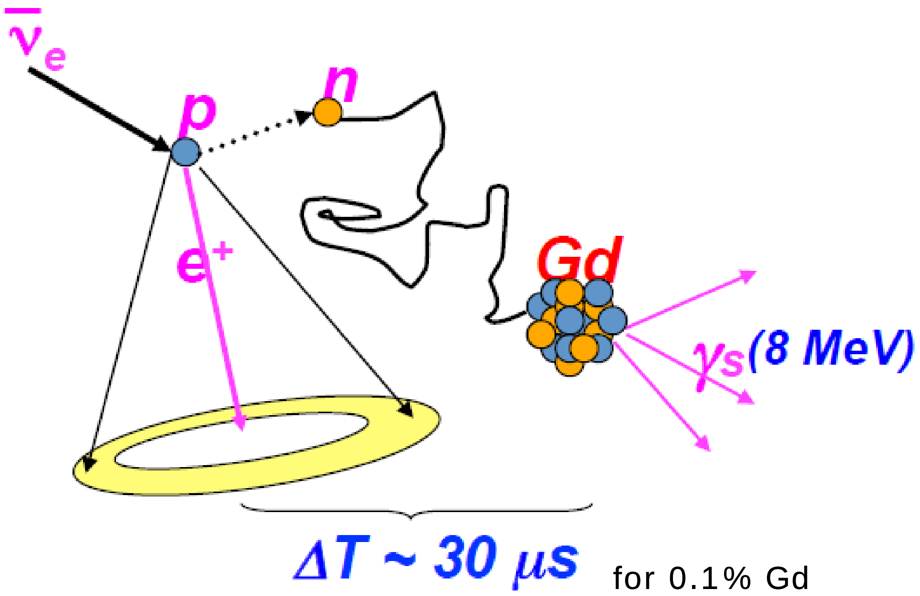




- Preliminary study; A tighter ^{16}N cut makes reduction of the total number of BG by 20% with few % loss of signals.

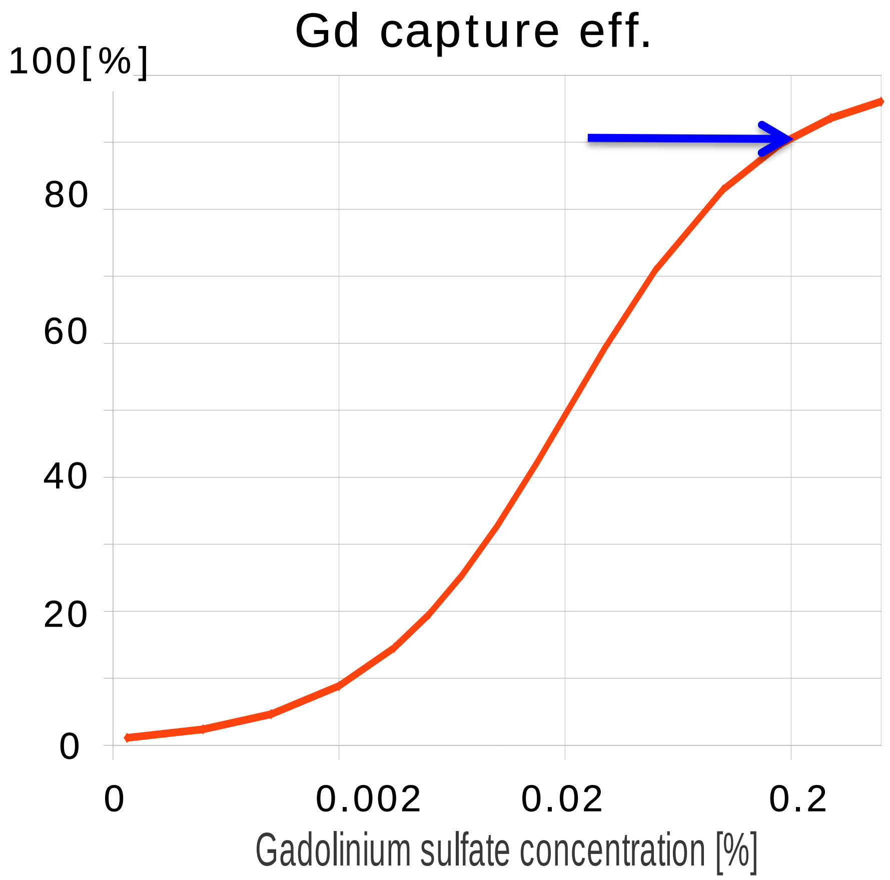
For further neutron tagging: SK-Gd

- To identify $\overline{\nu}_e p$ events by neutron tagging with Gadolinium.
- Large cross section for thermal neutron (48.89kb)
- Neutron captured Gd emits 3-4 γs in total 8 MeV
- 0.2% $Gd_2(SO_4)_3$ $8H_2O$ gives 90% neutron capture



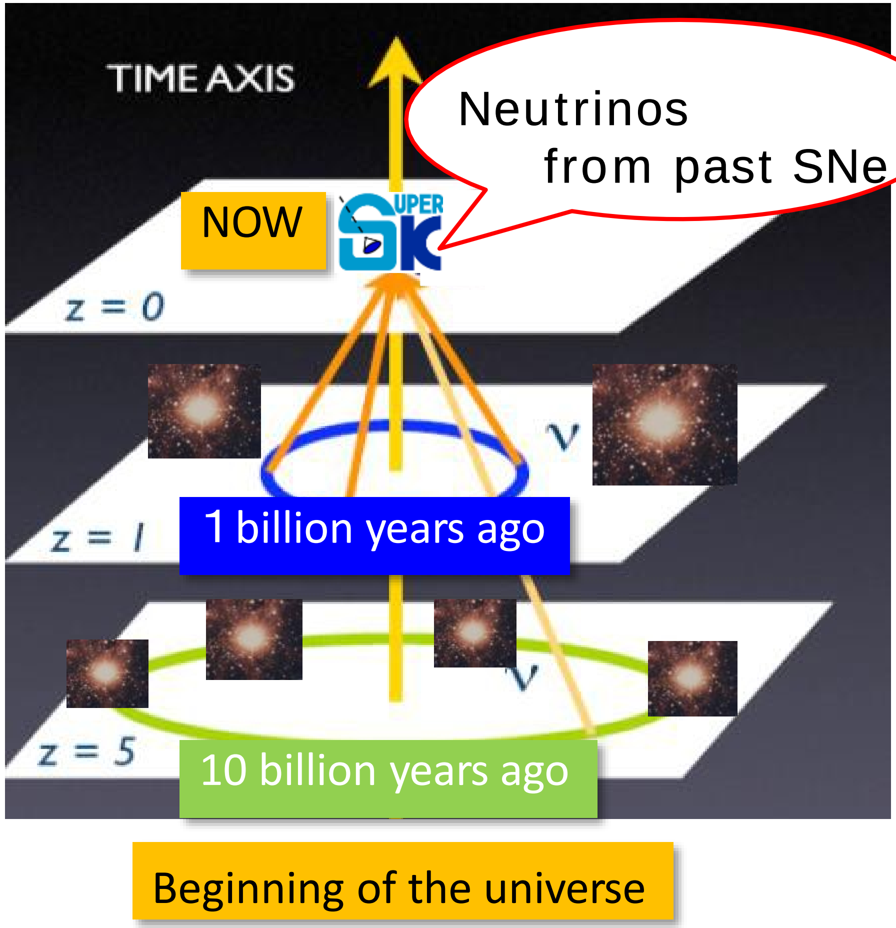
$Gd_2(SO_4)_3$ $8H_2O$

Beacom and Vagins PRL93,171101 (2004)

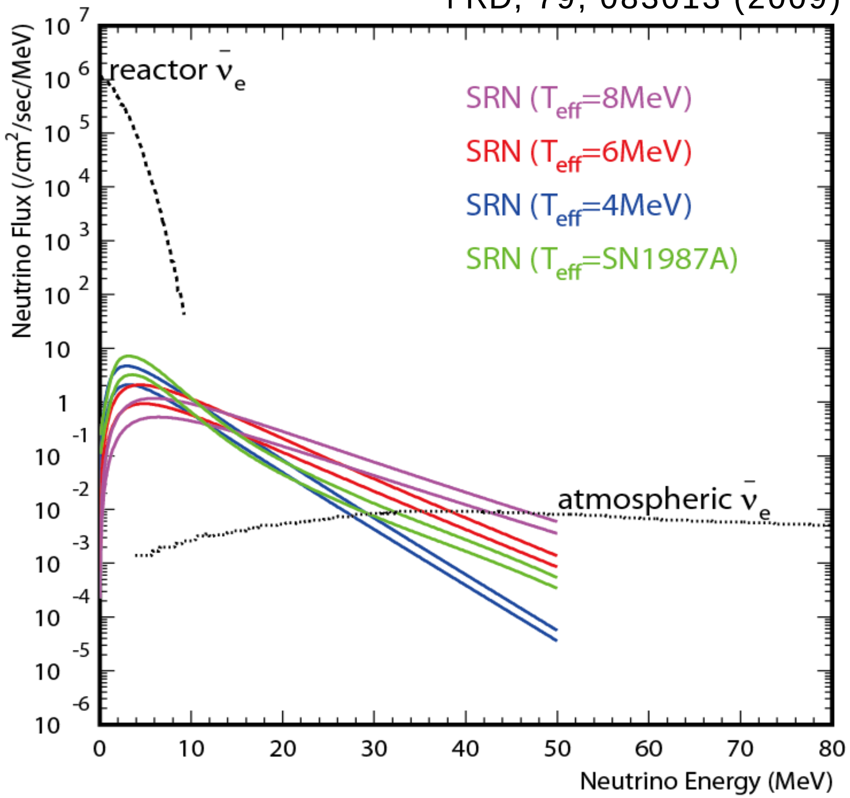


Diffuse Supernova Neutrino Background(DSNB)

- 10^{10} stellar/galaxy ×10^{10} galaxies ×0.3%(become SNe) ~$O(10^{17})$SNe



Horiuchi, Beacom and Dwek,
PRD, 79, 083013 (2009)

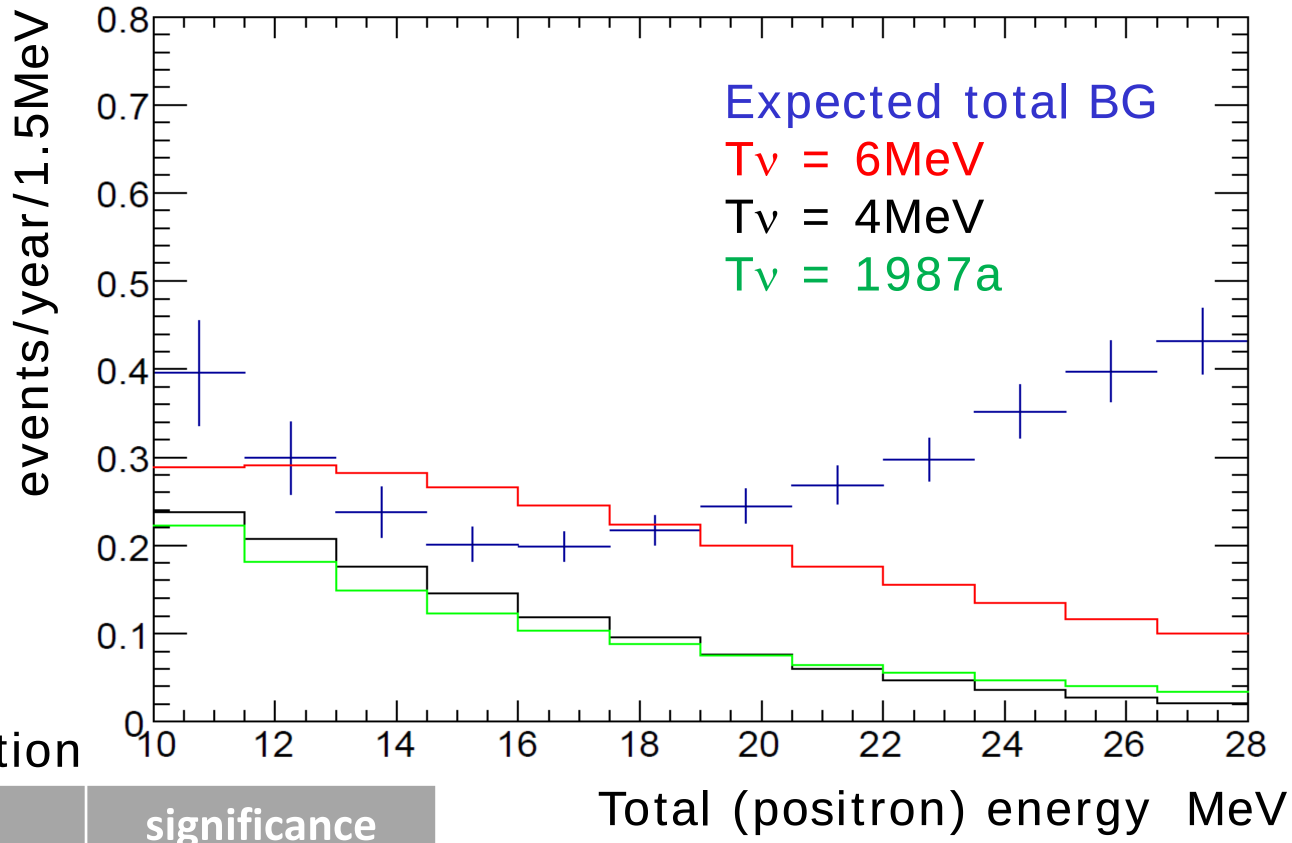


Search window for SK : From ~10MeV to ~30MeV

Expected signal

DSNB flux:
Horiuchi, Beacom and Dwek,
PRD, 79, 083013 (2009)

- It depends on typical/actual SN emission spectrum



DSNB events number with 10 years observation

HBD models	10-16MeV (evts/10yrs)	16-28MeV (evts/10yrs)	Total (10-28MeV)	significance (2 energy bin)
T_{eff} 8MeV	11.3	19.9	31.2	5.3 σ
T_{eff} 6MeV	11.3	13.5	24.8	4.3 σ
T_{eff} 4MeV	7.7	4.8	12.5	2.5 σ
T_{eff} SN1987a	5.1	6.8	11.9	2.1 σ
BG	10	24	34	----

- First observation is within SK-Gd's reach!
- Further BG reduction with topological cuts (NN,BDT,....) are expected.

The challenge to Solar ν
Radio isotopes in $Gd_2(SO_4)_3\,8H_2O$

Typical 99.999% purity $Gd_2(SO_4)_3$

Chain	Main sub-chain isotope	Radioactive concentration (*mBq/kg*)
^{238}U	^{238}U	50
	^{226}Ra	5
^{232}Th	^{228}Ra	10
	^{228}Th	100
^{235}U	^{235}U	32
	^{227}Ac/ ^{227}Th	300

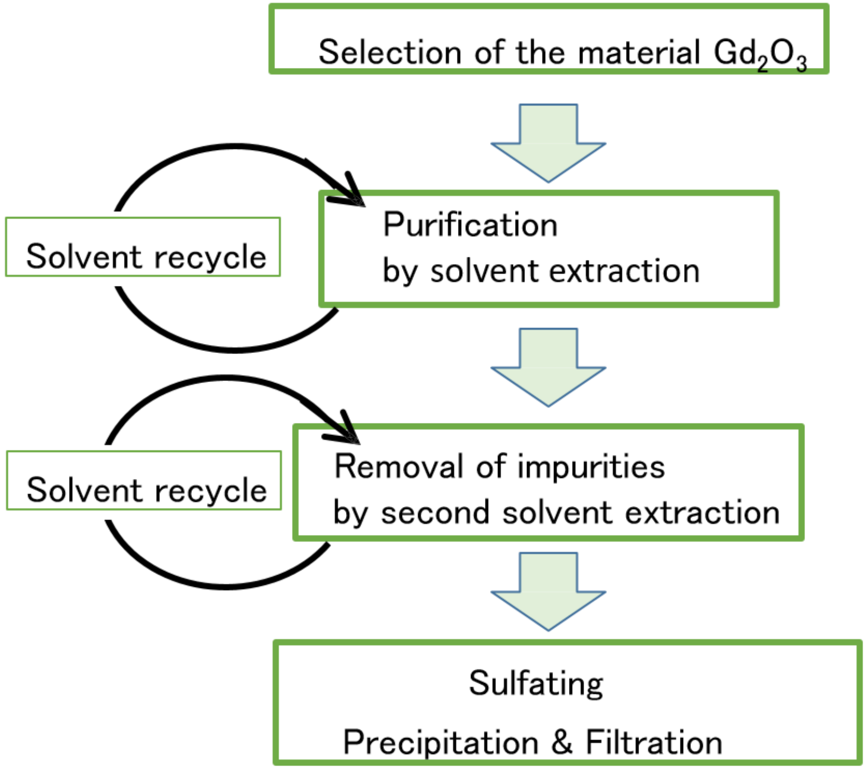
- SK 3.5MeV threshold data sample (~BG from Rn in FV)
  ~200events/day/FV
- neutron BG from U
  ~320events/day/ FV
- β,γ BG from Th/Ra
  ~3 x 10^5 events/day/FV

Requirements

1 order of U reduction
4 order of Th/Ra reduction

Pure $Gd_2(SO_4)_3$ development

- For more than 3 years, intensive development of pure $Gd_2(SO_4)_3$ has been conducted with several companies.



- Collaboration with Canfranc and Boulby Labs. for the evaluation and screening of $Gd_2(SO_4)_3$

Low RI $Gd_2(SO_4)_3$ evaluation

- Collaboration with underground Labs.

  ~1 mBq/kg : Ge detectors in Canfranc, Boulby, and Kamioka

  ~0.1mBq/kg : ICP-MS in Kamioka
- 3 companies had reached U goal, Company B has reached Th goal.

mBq/kg

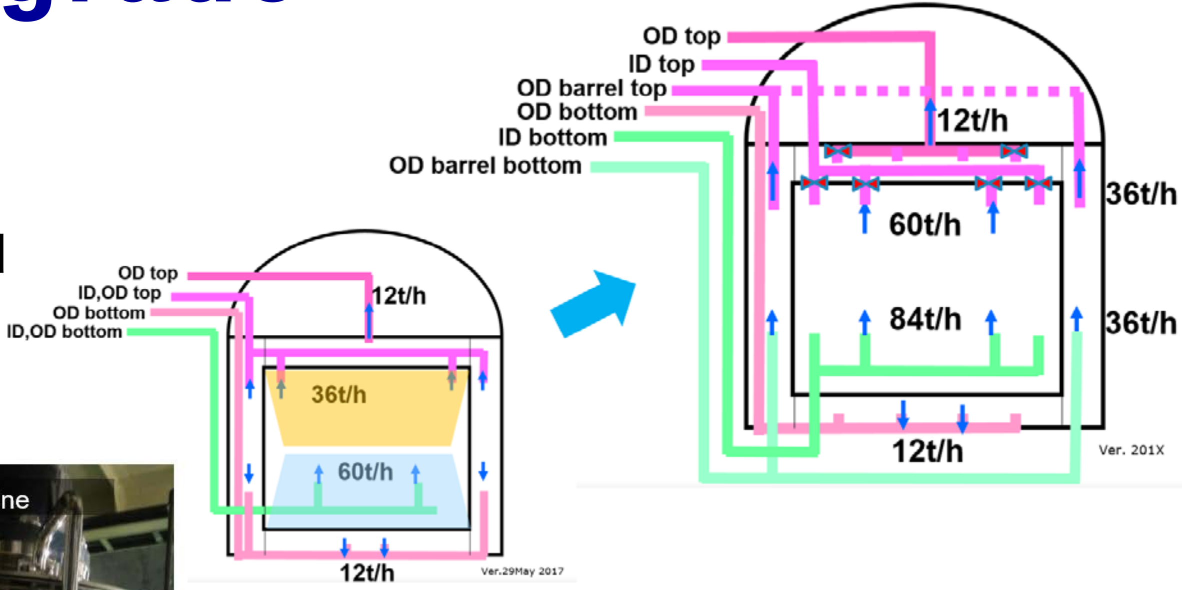
Chain	238U			232Th			235U	
Isotope	^{238}U		^{226}Ra	^{232}Th	^{228}Ra	^{228}Th	^{235}U	^{227}Ac/^{227}Th
Goal*	< 5		< 0.5	< 0.05	< 0.05	< 0.05	< 3	< 3
Detector	Ge	ICPMS	Ge	ICPMS	Ge	Ge	Ge	Ge
CompanyA	-	<0.04	-	0.09	-	-	-	-
CompanyB	<11	<0.04	<0.2	0.02		<0.3	<0.4	<1.7
CompanyC	< 10	<0.04	< 0.2	0.06	< 0.2	< 0.3	< 0.3	< 1.2

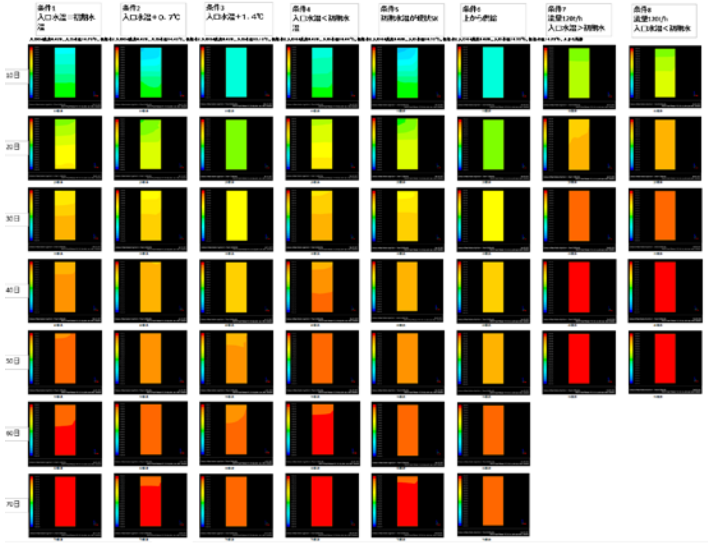
*Goal is for 0.2% solution

- Need to keep checking to see the batch/lot dependence
  - 1.5 tons $Gd_2(SO_4)_3$ will be delivered from this July.
  - 10 tons will come in 2019

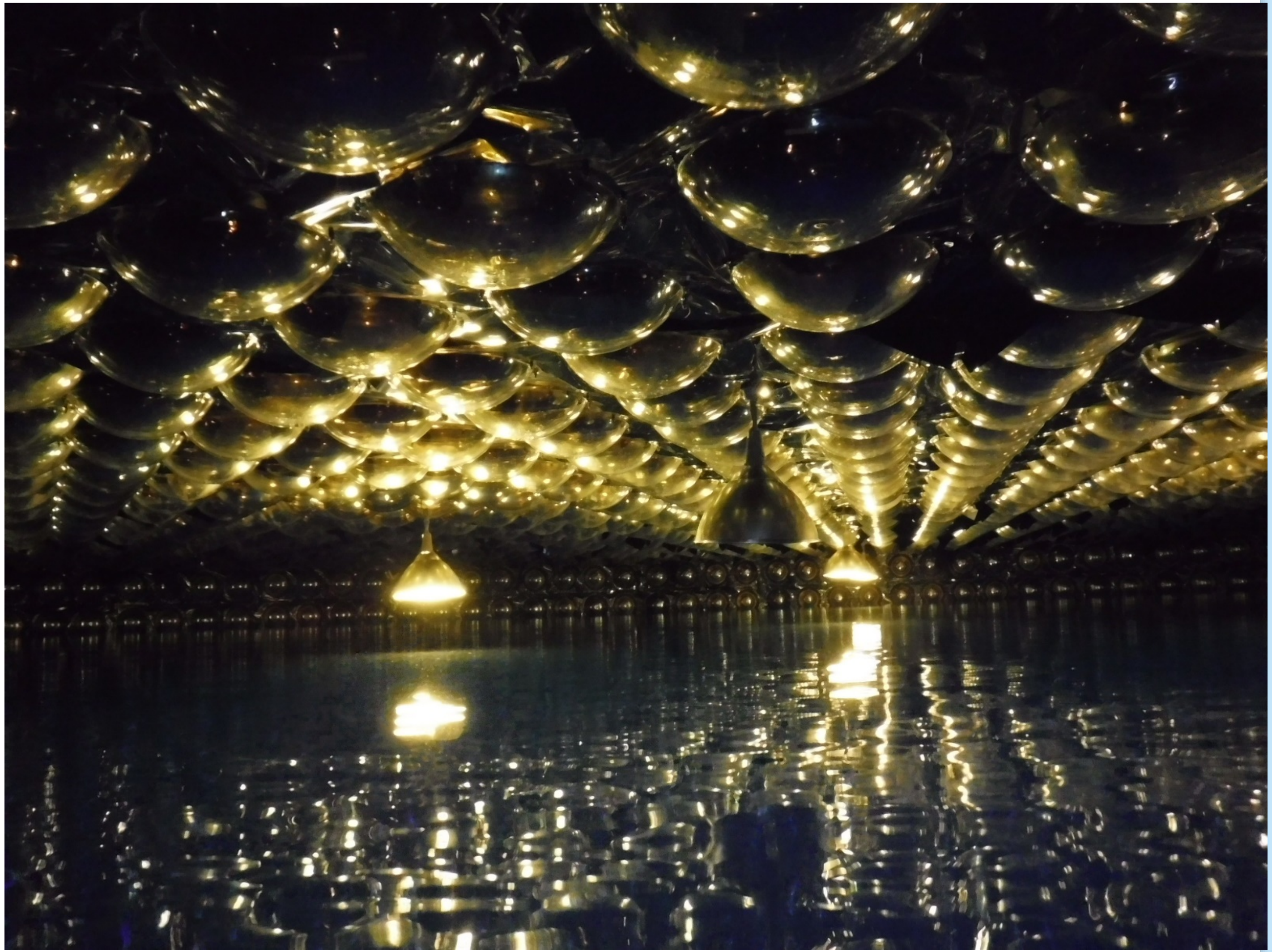
SK refurbishment / upgrade

- Fixing leakage
- For uniform Gd concentration
  - Brand new water system with doubled flow rate (120t/h)
  - New design of the pipes in tank

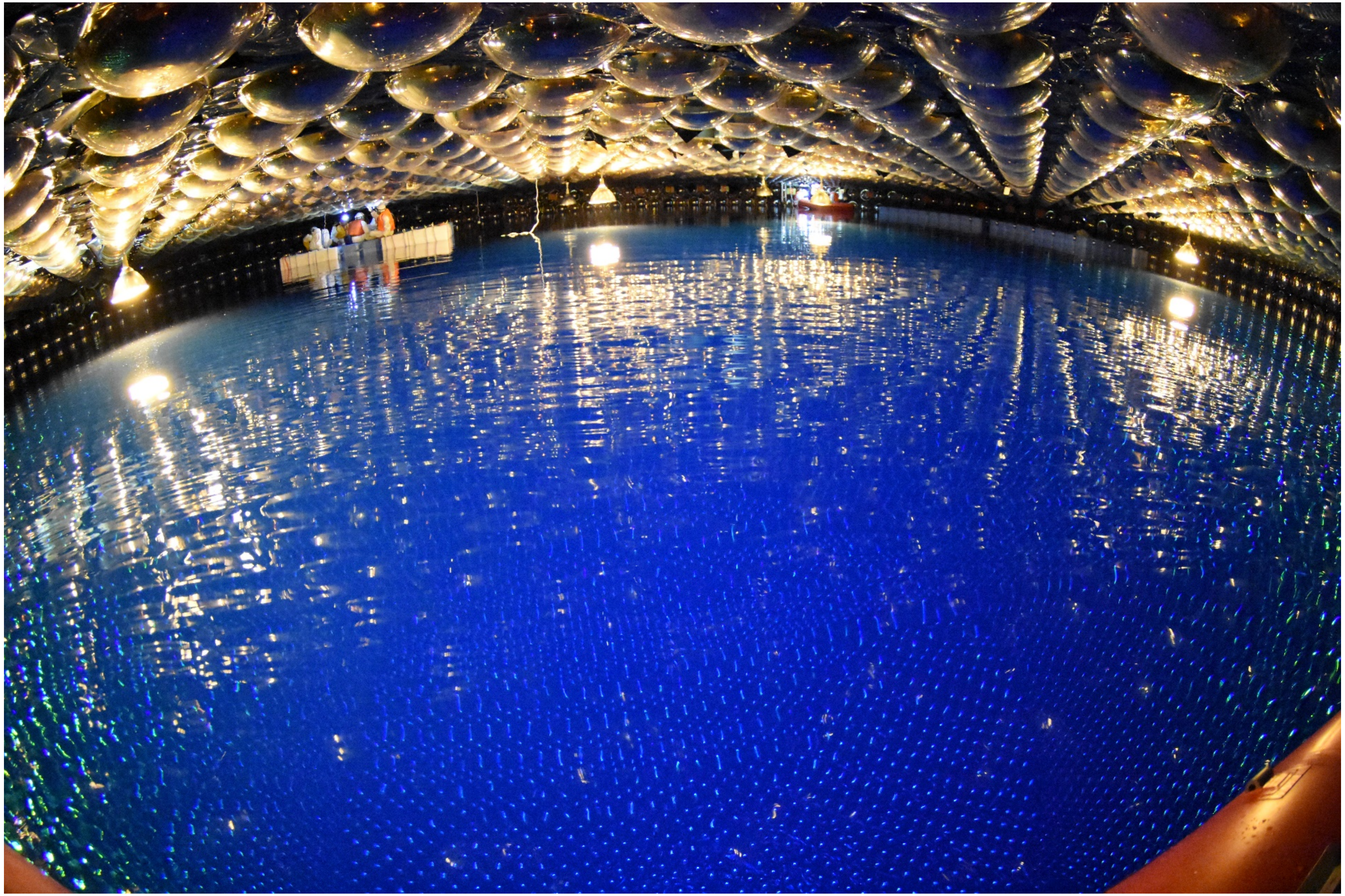




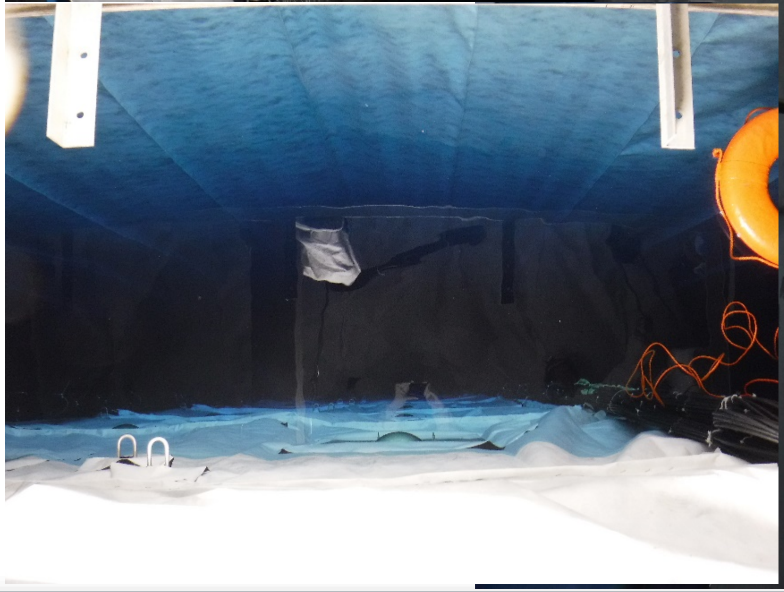
The work started from May 31 st.



The inner detector

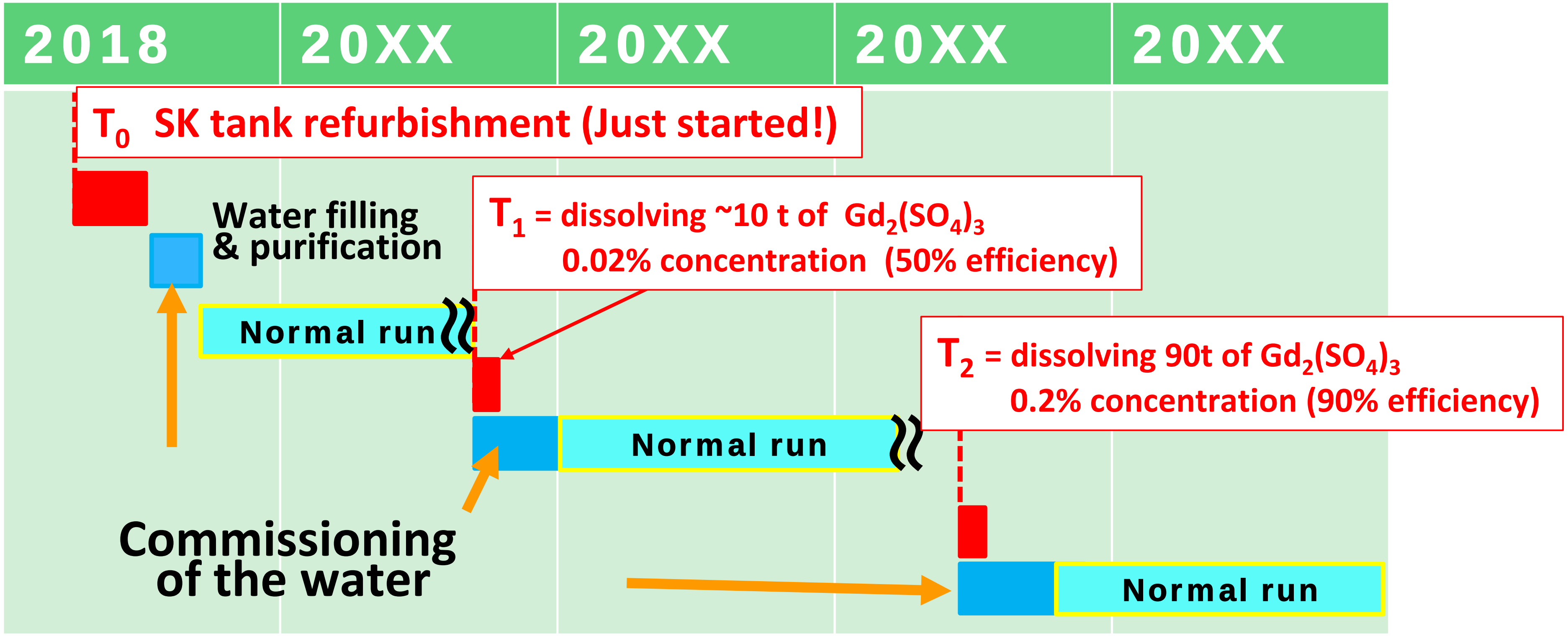


The outer detector



Plan

- 3 steps (T_0,T_1,T_2) to get 0.2% concentration
- T_1 and T_2 will be decided with T2K/J-Parc ν beam
  - First possible Gd loading in Super-K would be in late 2019.



Concluding remarks

- Stable data taking during whole SK-IV period.
- SK-IV ended on May 31.
  - Preliminary results are consistent with previous results.
  - Final results using all SK-IV period will come soon with various improvements.
- Now, working hard to start SK-Gd.
  - SK will be back in Jan. 2019 (SK-V, pure water)
  - After checking the performance of SK-V, Gd-loading and SK-Gd will start