Low Energy Neutrinos in Super-Kamiokande

TAUP2015 @Torino
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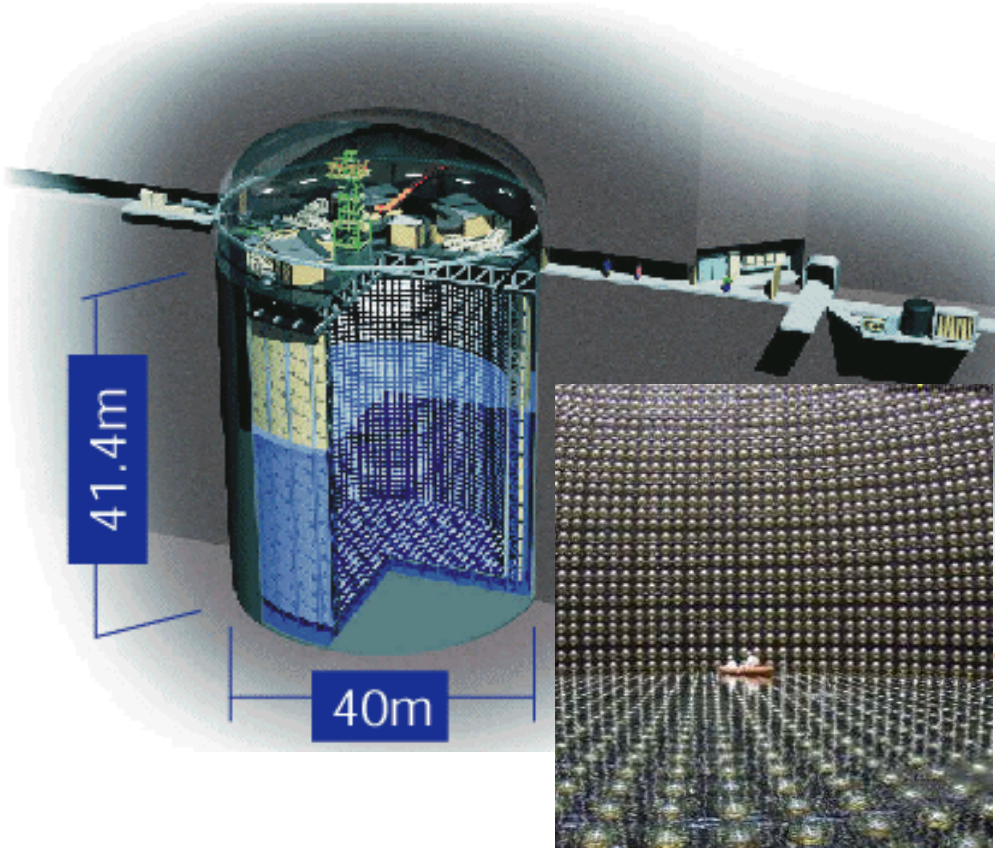
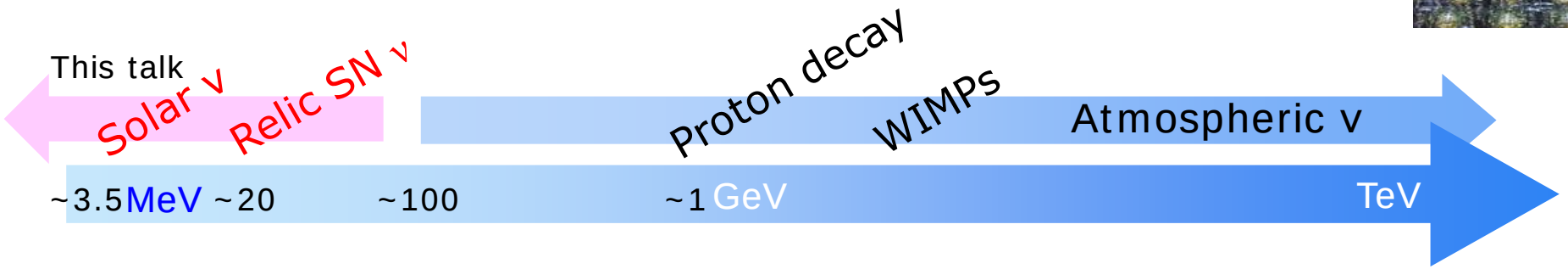
for the Super-K Collaboration

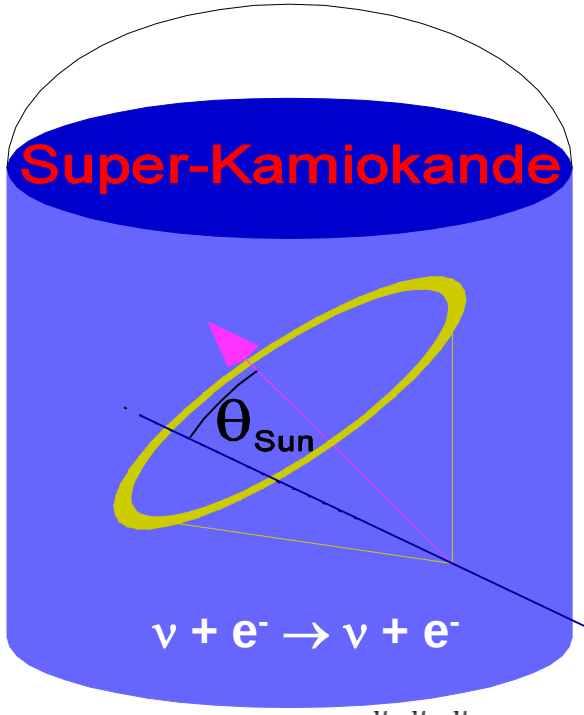
Super-Kamiokande

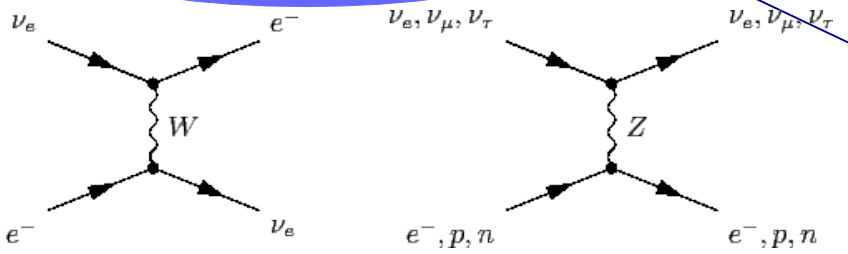
- 50kton pure water Cherenkov detector
- 1km (2.7km w.e) underground in Kamioka
- 11129 50cm PMTs
  in Inner Detector
- 1885 20cm PMTs
  in Outer Detector

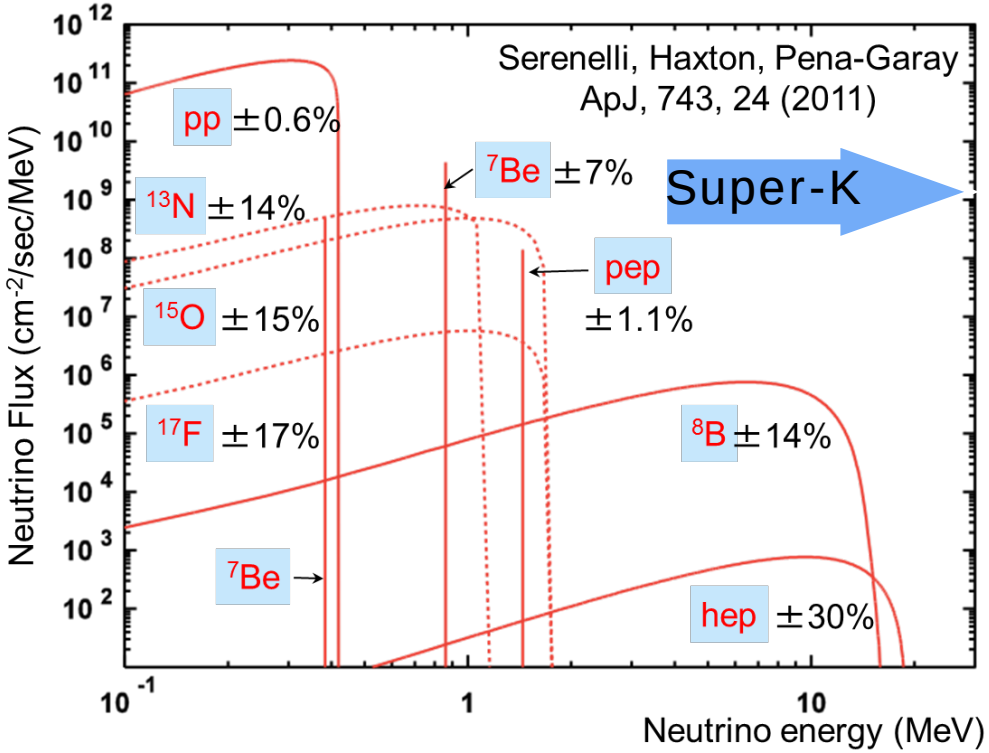


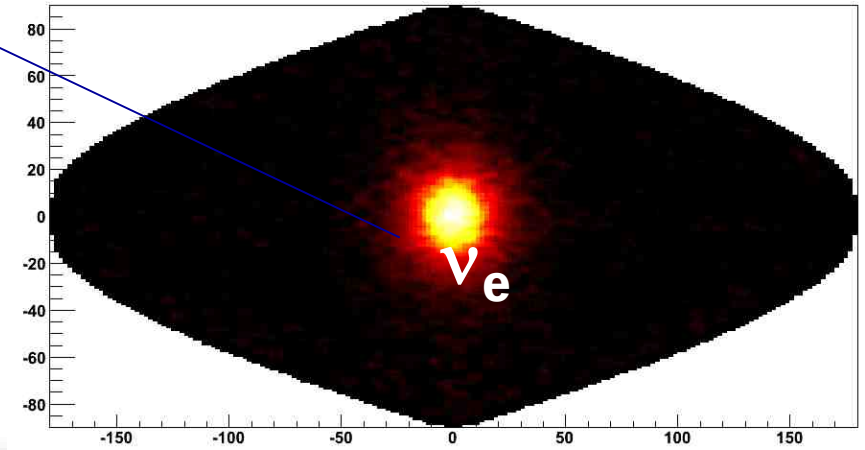
Physics targets of Super-Kamiokande







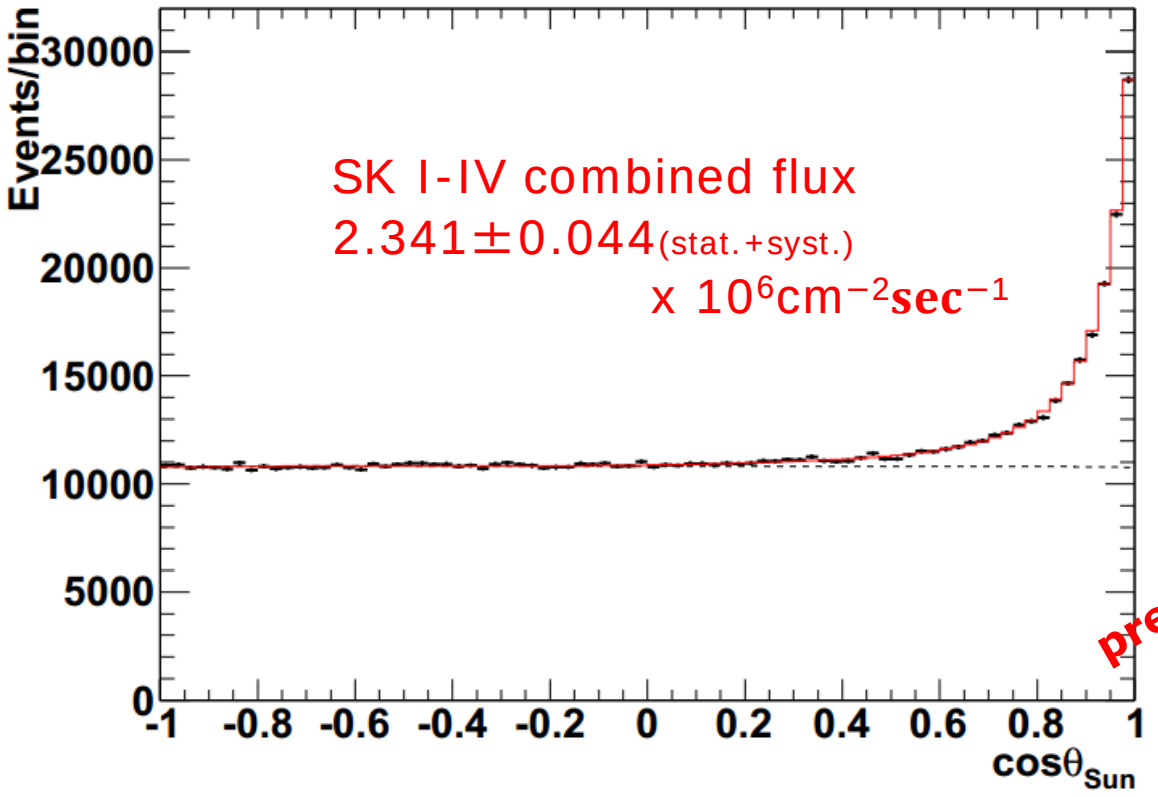




Solar neutrinos observation

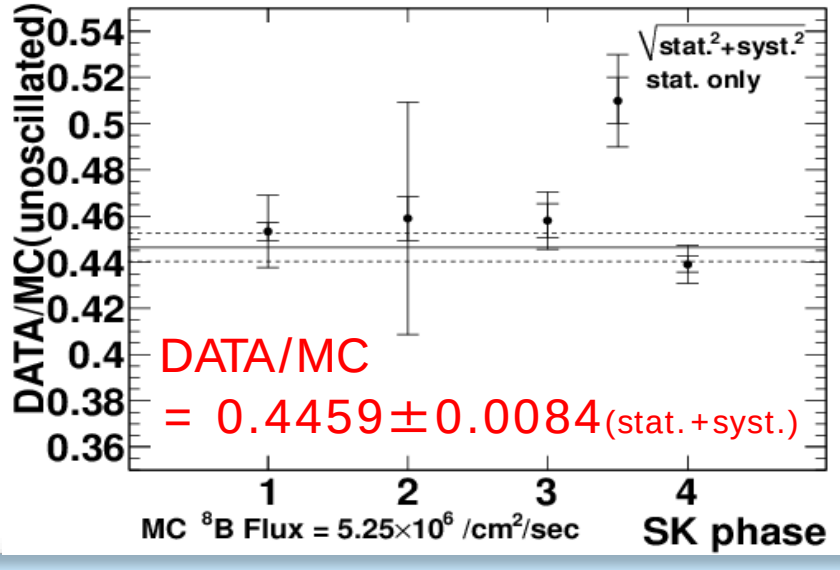
SK ^{8}B Solar neutrino observation

- SK has observed solar neutrino for 18 years(~ 1.5 solar cycle)
  - ~77000 solar ν interactions

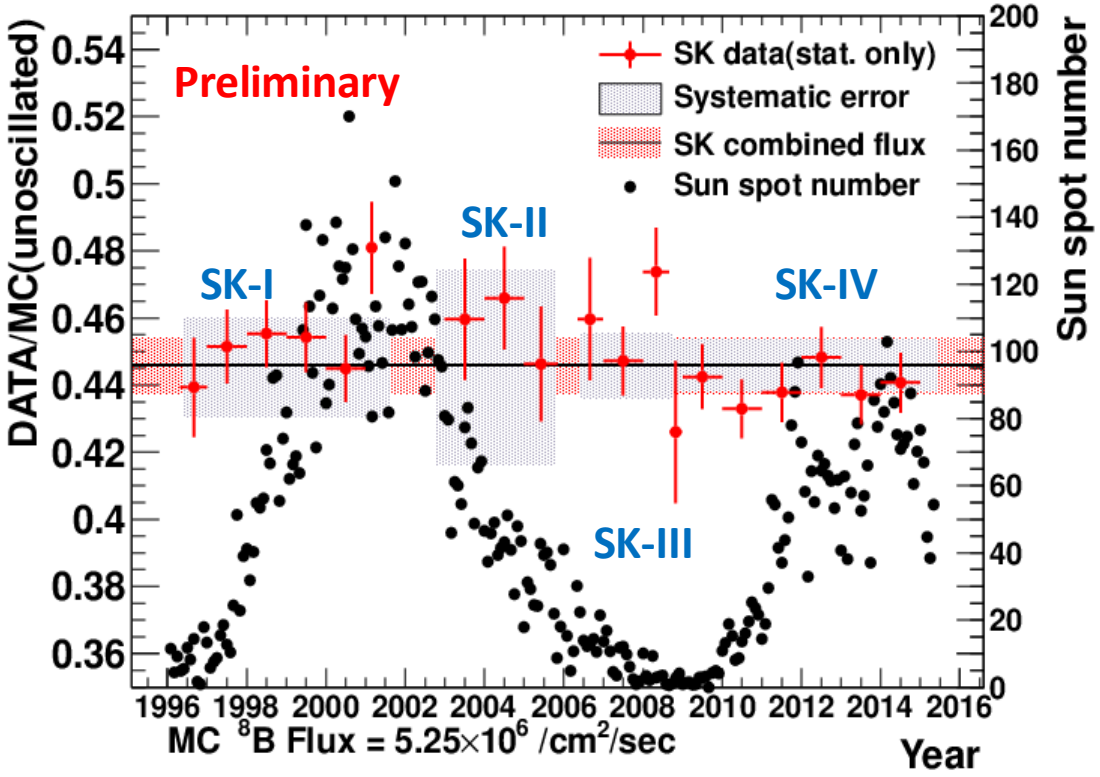


Phase	Energy threshold MeV(kin.)	Live time (say)	^{8}B Flux $\times 10^6$/cm^2/sec
SK-I	4.5	1496	2.38±0.02±0.08
SK-II	6.5	791	$2.41 \pm 0.05^{+0.16}_{-0.15}$
SK-III	4.0	548	2.40±0.04±0.05
SK-IV	3.5	2034	2.31±0.02±0.04

preliminary



Time variation of ^{8}B solar neutrino flux



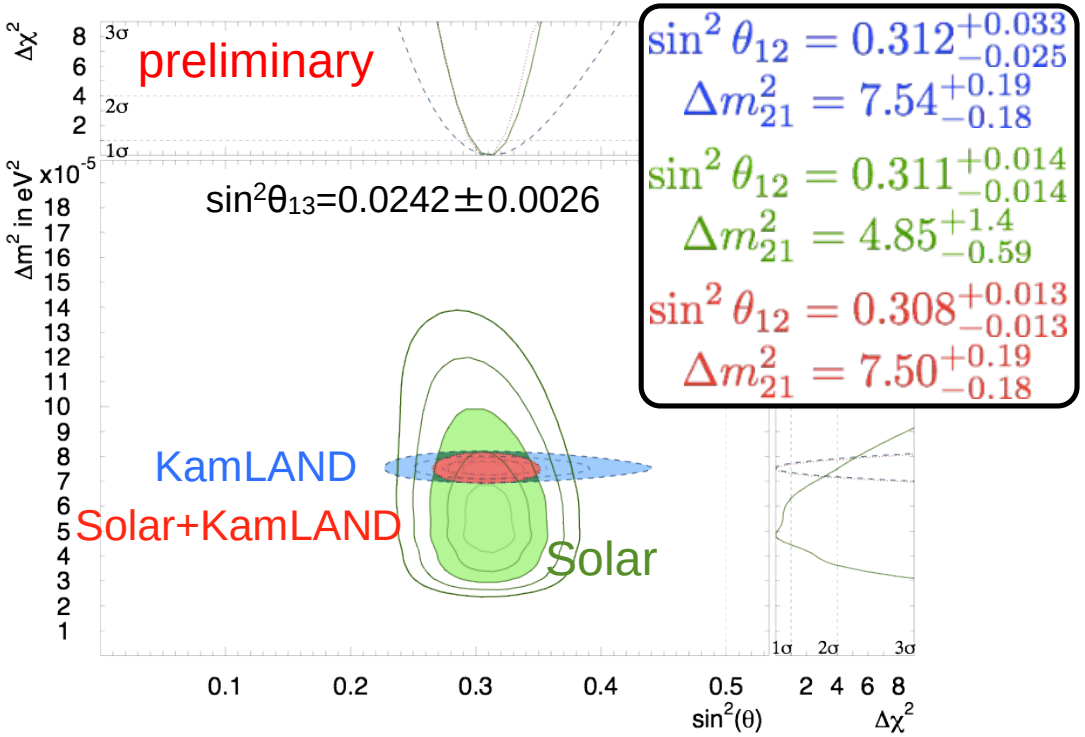
- No correlation with the 11 years solar activity is observed.
- Super-K solar rate measurements are fully consistent with a constant solar neutrino flux emitted by the Sun.
  - χ^2 = 13.10/18(dof)

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

Oscillation analysis: Solar global fit

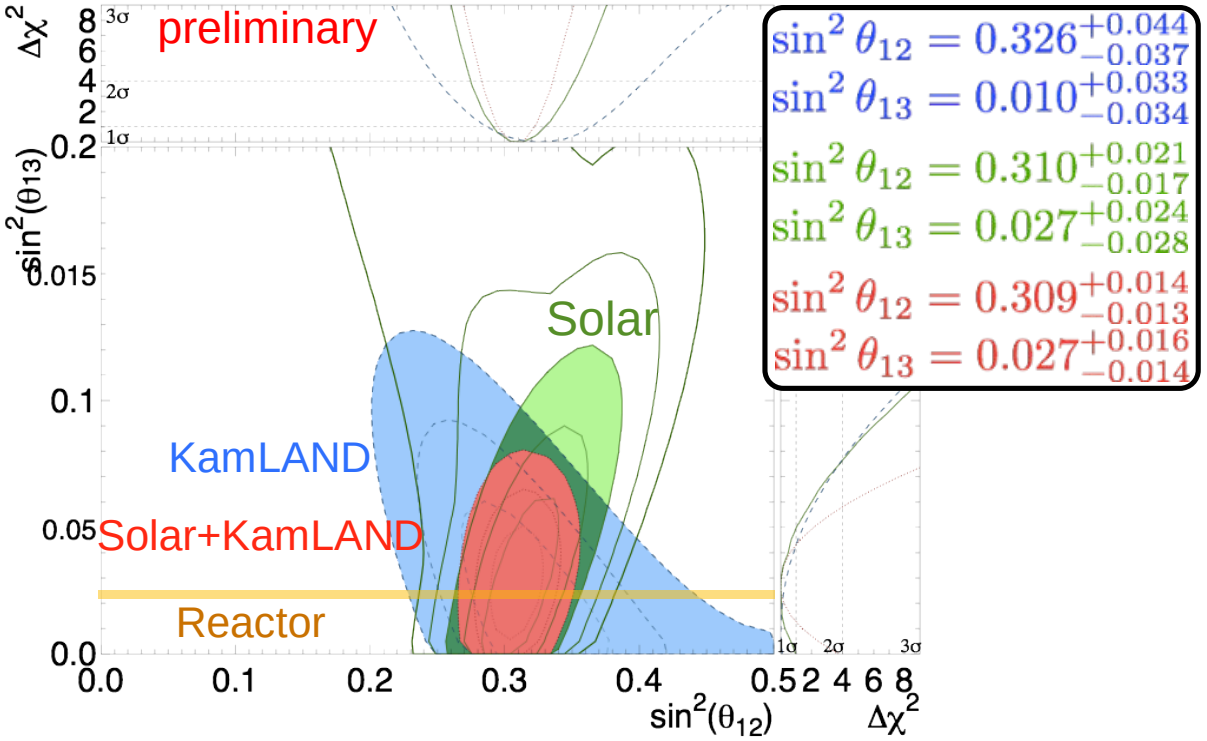
- This SK update and other latest results are combined.

Combined solar fit with KamLAND



~2σ tension in Δm^2_{21}
between solar and KamLAND

Without reactor θ_{13} constraint



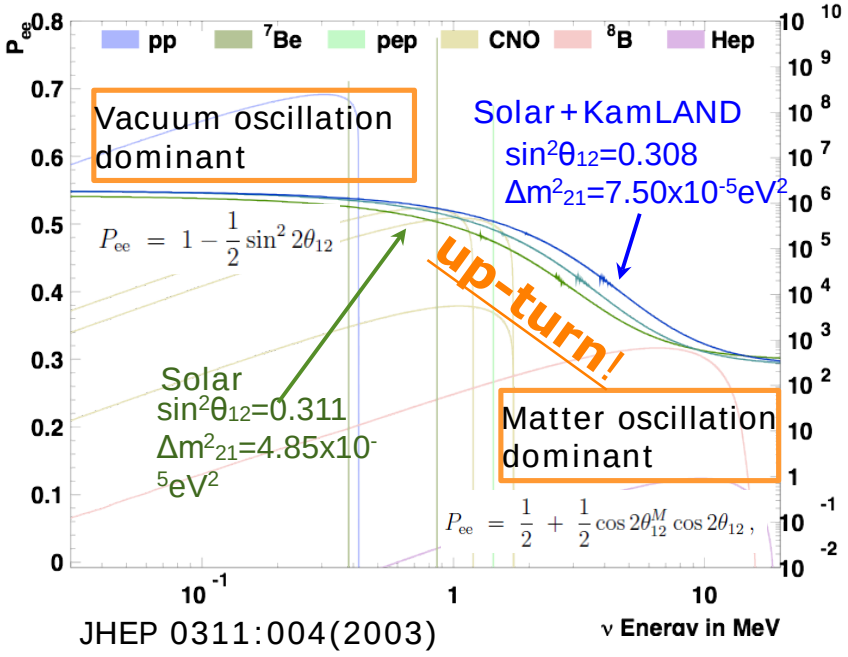
Non-zero θ_{13} at 2σ from solar+KamLAND
Good agreement with
Daya Bay, RENO & DC

Search for the direct MSW signal

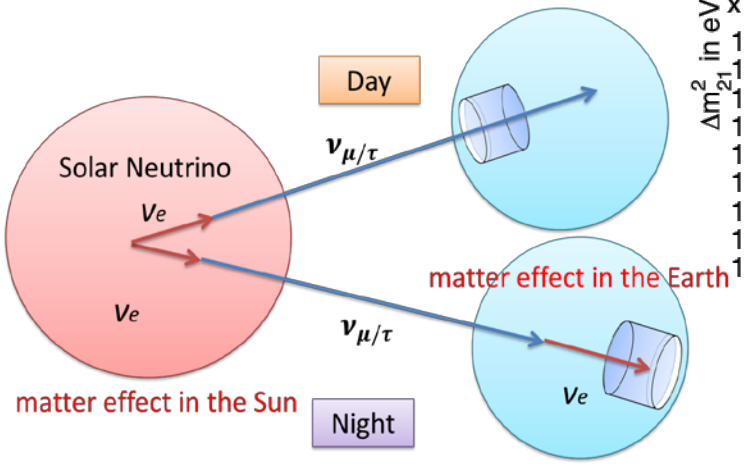
- Current main motivation of SK ^{8}B ν observation

Energy spectrum distortion

Neutrino survival probability

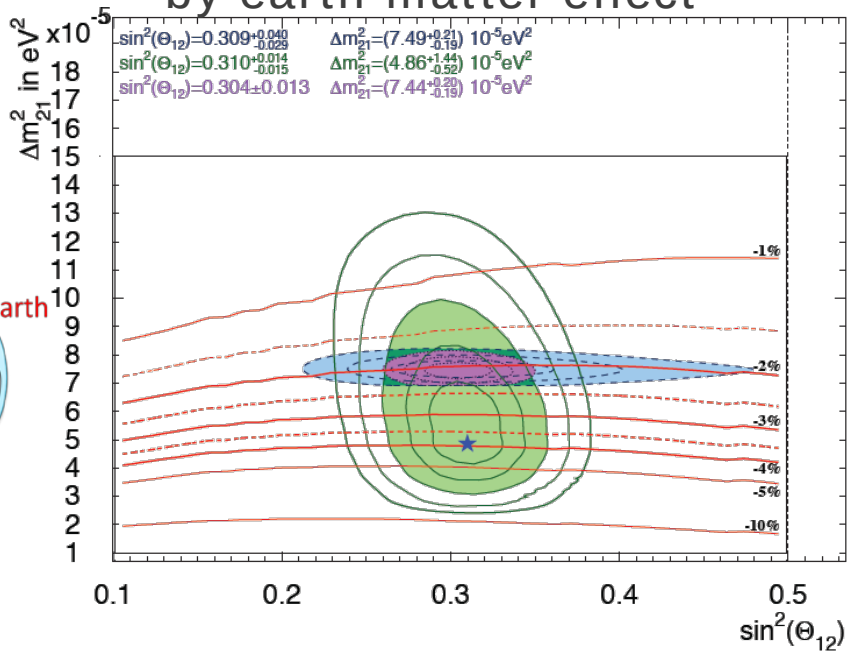


JHEP 0311:004(2003)



Flux day-night asymmetry

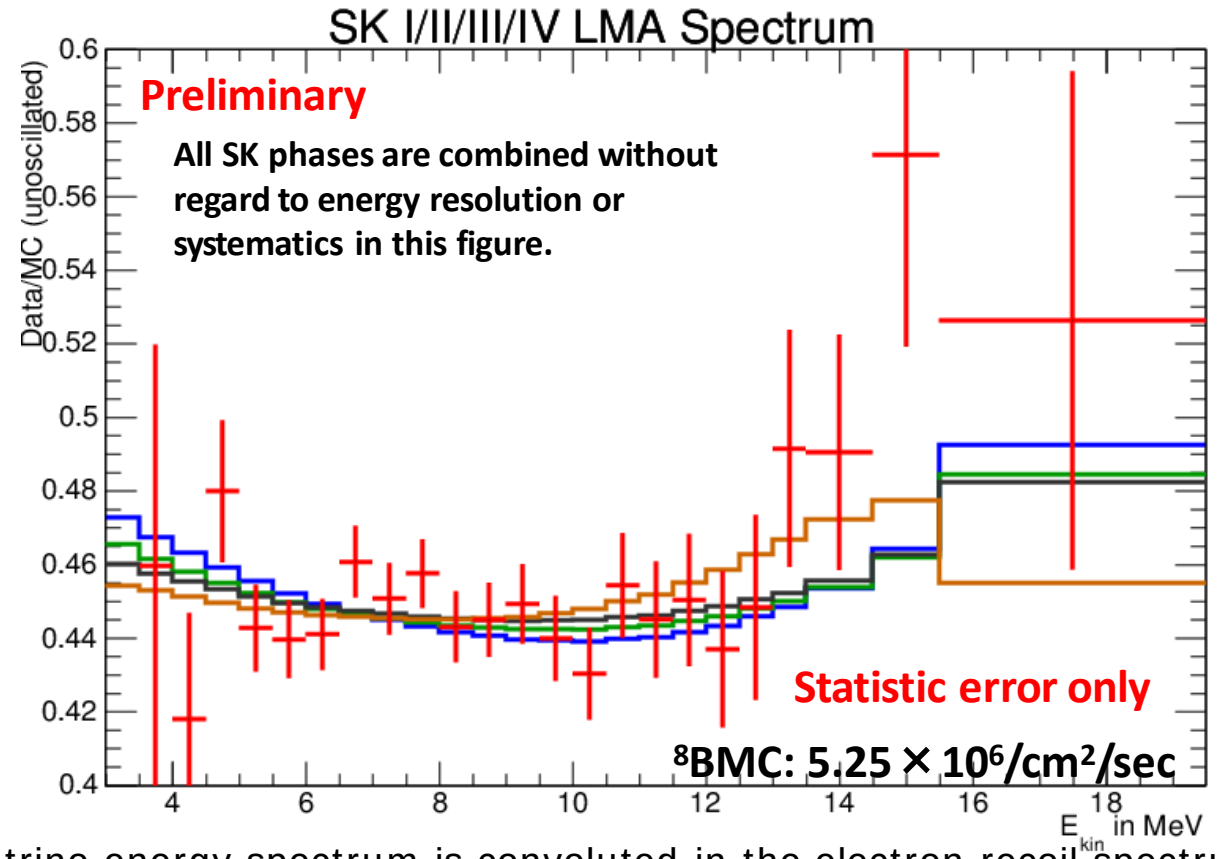
"Nighttime regeneration" of ν_e by earth matter effect



SK I-IV combined recoil spectrum

- Test of "spectrum upturn"
  - MSW is slightly disfavored by
    - ~1.7 σ using the Solar + KamLAND best fit parameters
    - ~1.0 σ using the Solar Global best fit parameters.

Total # of bins of SK I-IV is 83	χ^2
Solar + KamLAND	70.13
Solar global	68.14
Quadratic fit	67.67
Exponential	67.54

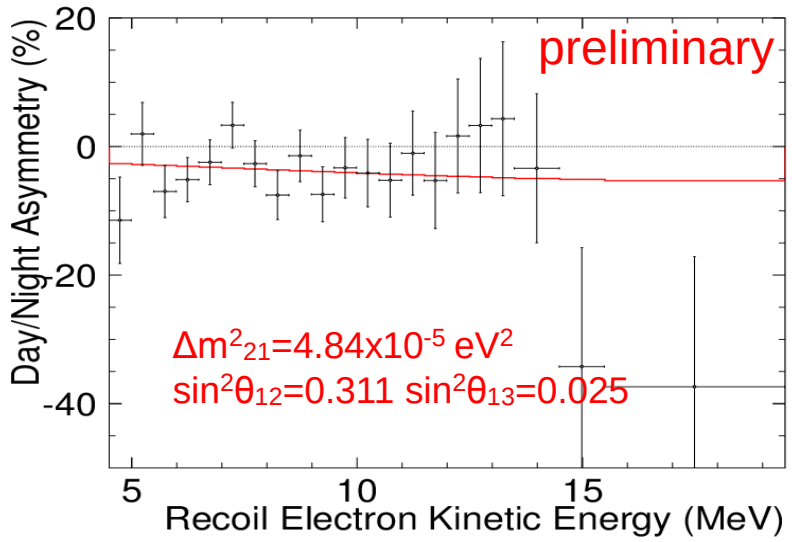


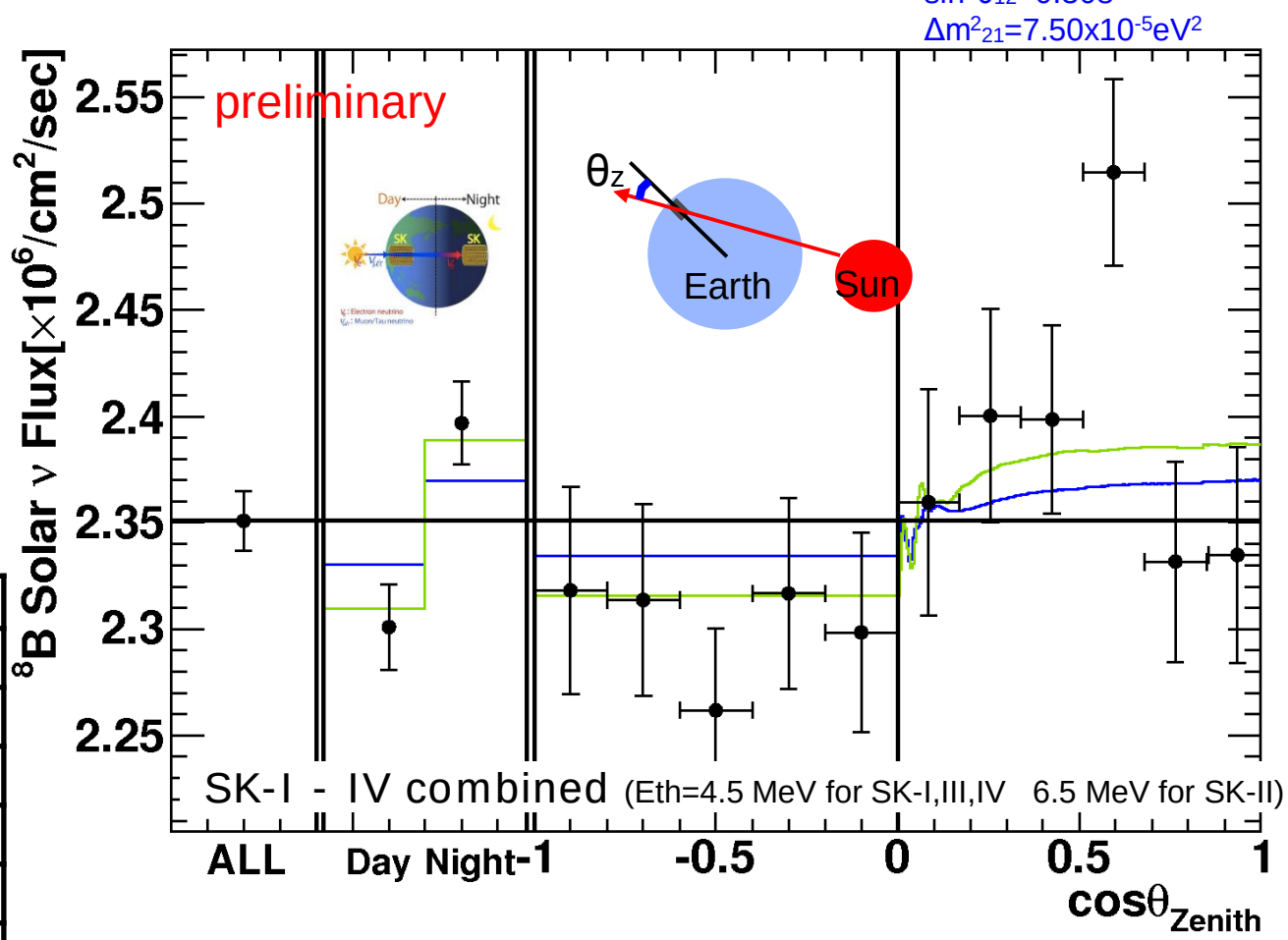
Neutrino energy spectrum is convoluted in the electron recoil spectrum. For de-convolution, generic functions are used as a survival probability;

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

$$P_{ee}(E_\nu) = e_0 + \frac{e_1}{e_2}\left(\exp\left(e_2\left(\frac{E_\nu}{MeV} - 10\right)\right) - 1\right) \text{ (exponential)}$$

Day-Night flux asymmetry



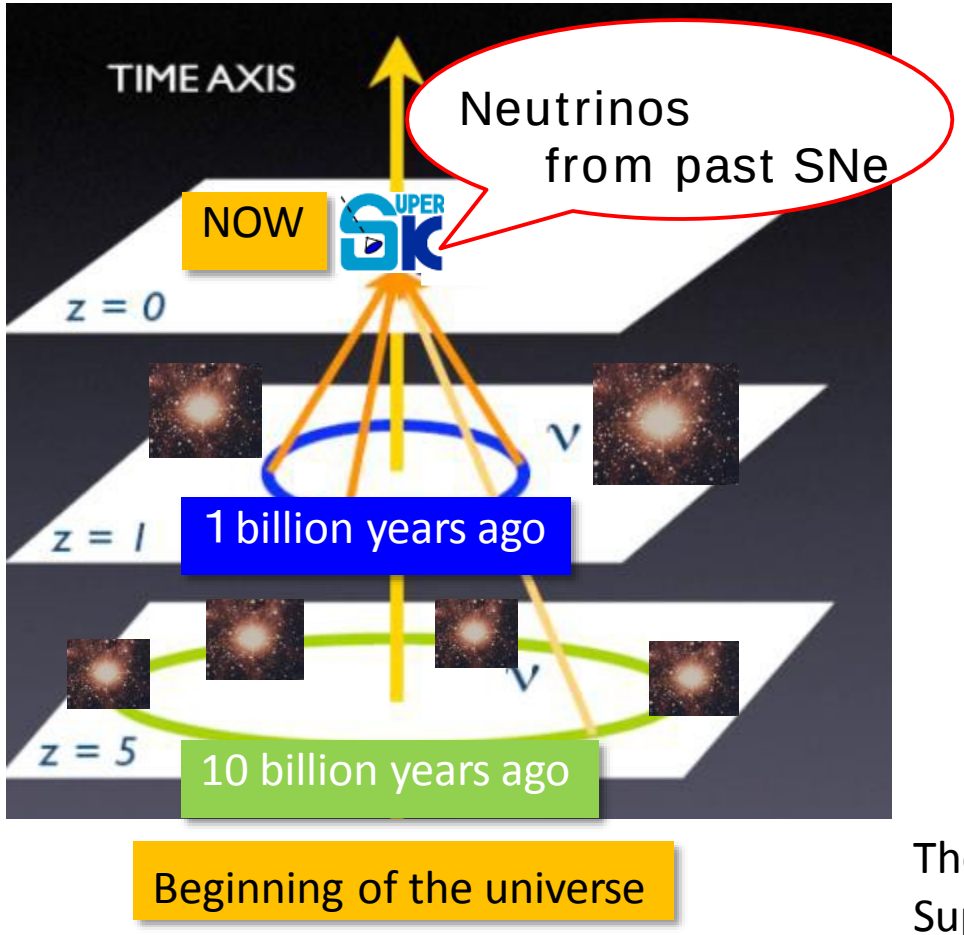


	Fitted asymmetry amplitude	
	Δm^2_{21}=4.84x10^{-5} eV^2	Δm^2_{21}=7.50x10^{-5} eV^2
SK-I	-2.0±1.8±1.0%	-1.9±1.7±1.0%
SK-II	-4.4±3.8±1.0%	-4.4±3.6±1.0%
SK-III	-4.2±2.7±0.7%	-3.8±2.6±0.7%
SK-IV	-3.6±1.6±0.6%	-3.3±1.5±0.6%
combined	-3.3±1.0±0.5%	-3.1±1.0±0.5%
non-zero significance	3.0σ	2.8σ

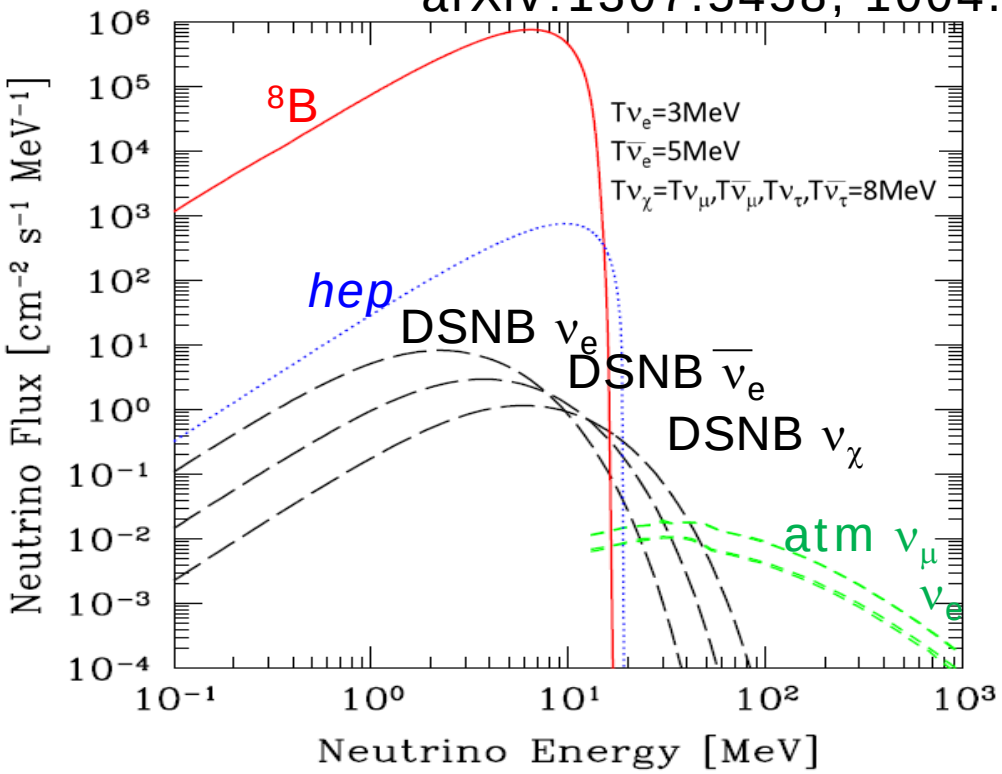
- This is the "direct" indication for matter enhanced neutrino oscillation

DSNB (SRN)

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



arXiv:1307.5458, 1004.3311

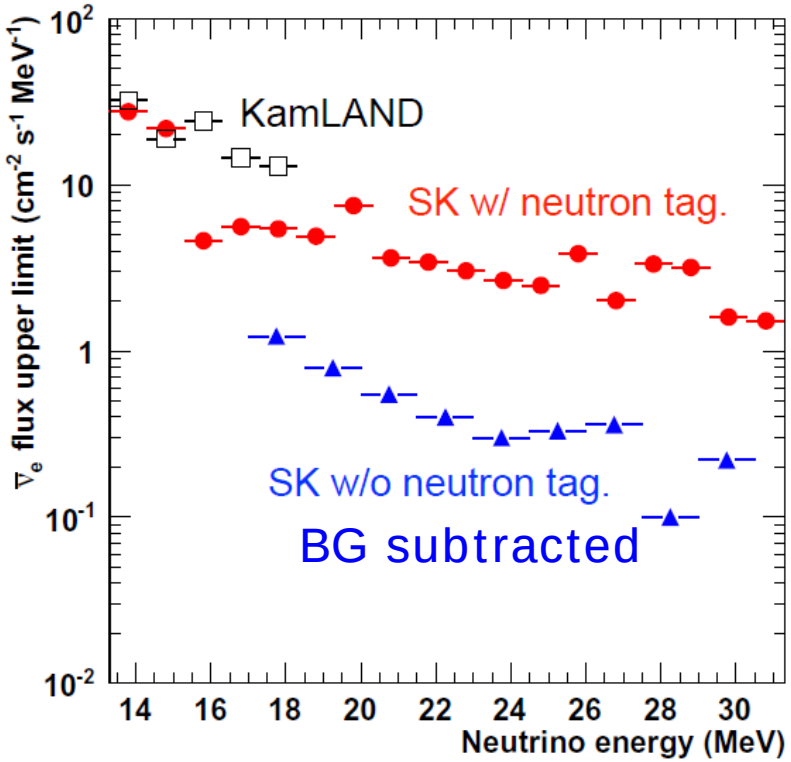


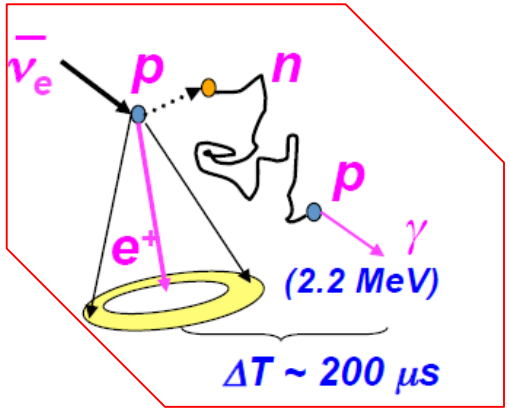
Theoretical flux prediction : 0.3~1.5 /cm²/s (17.3MeV threshold)
Super-K should be most sensitive to $\overline{\nu}_e$

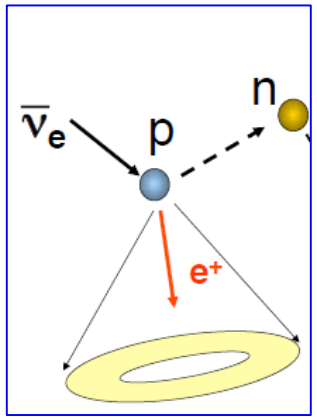
Status of DSNB search

- Search window for SRN at SK : From ~10MeV to ~30MeV
- Limited by BG. More than 1 order reduction is needed.
  - n tagging efficiency (by proton) is low…

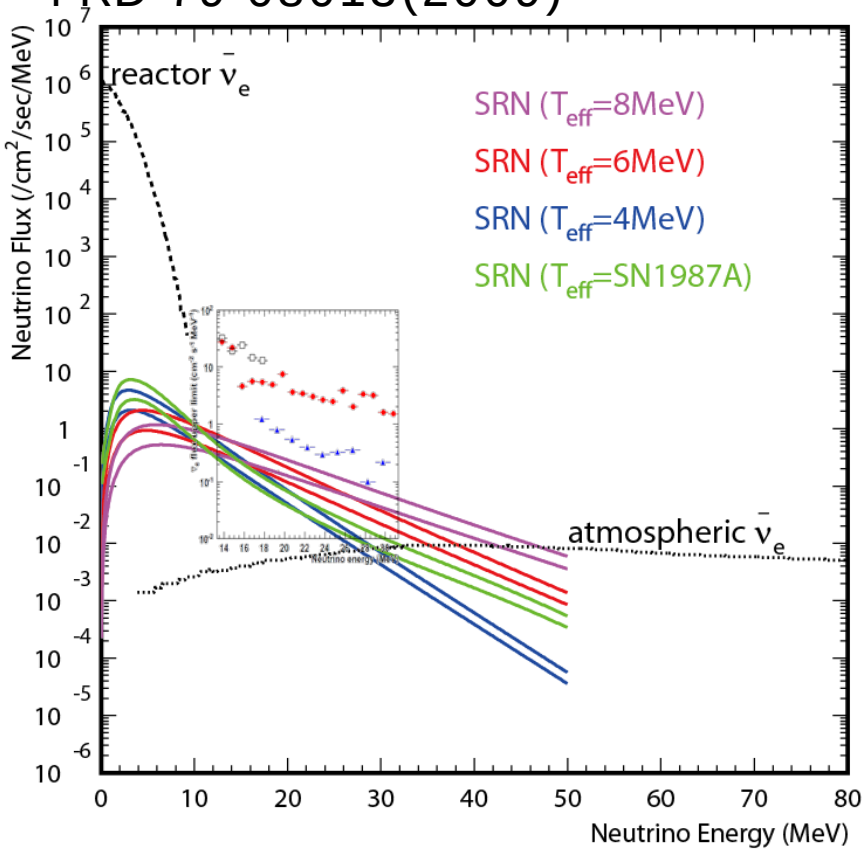
SK collaboration, Astropart. Phys. 60, 41-46 (2015)







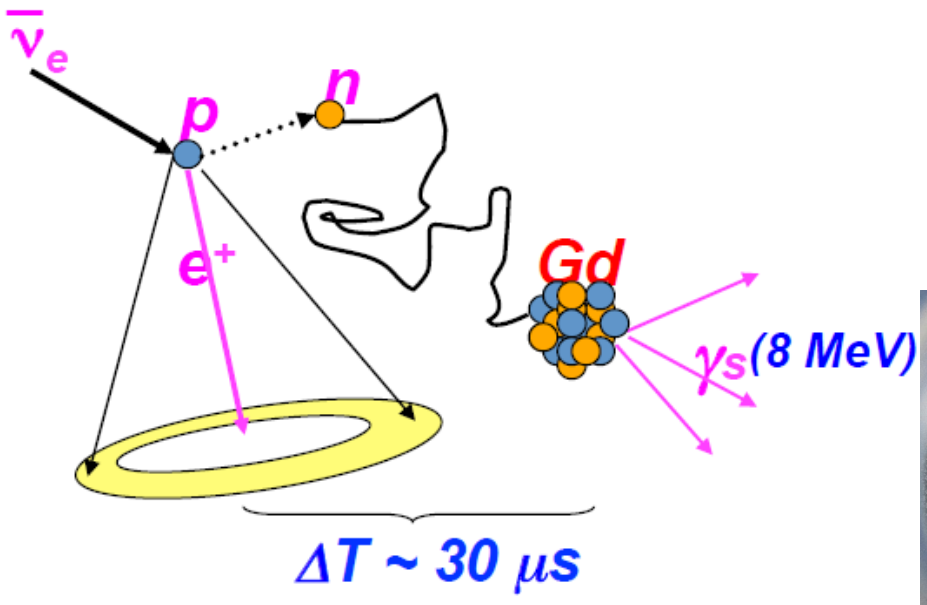
Comparison with Expected $\bar{\nu}_e$ spectra
PRD 79 08013(2009)

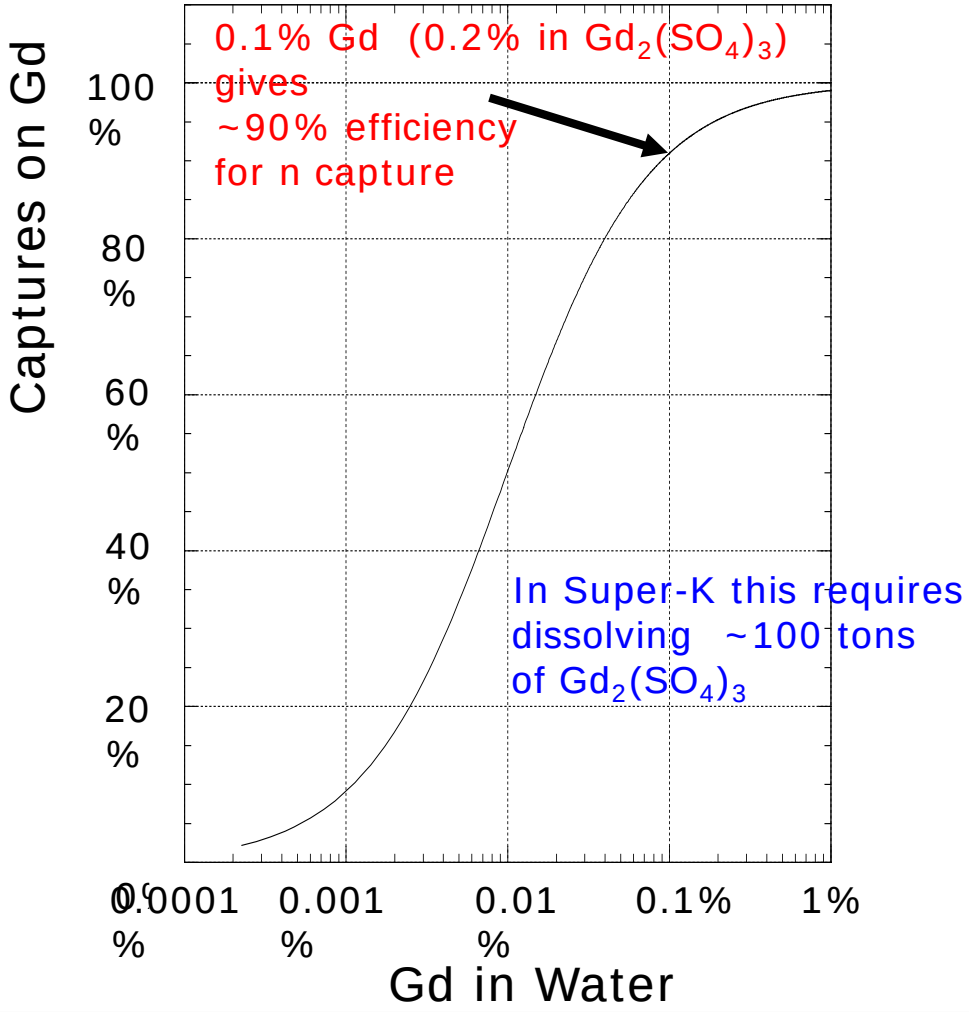


SK-Gd project

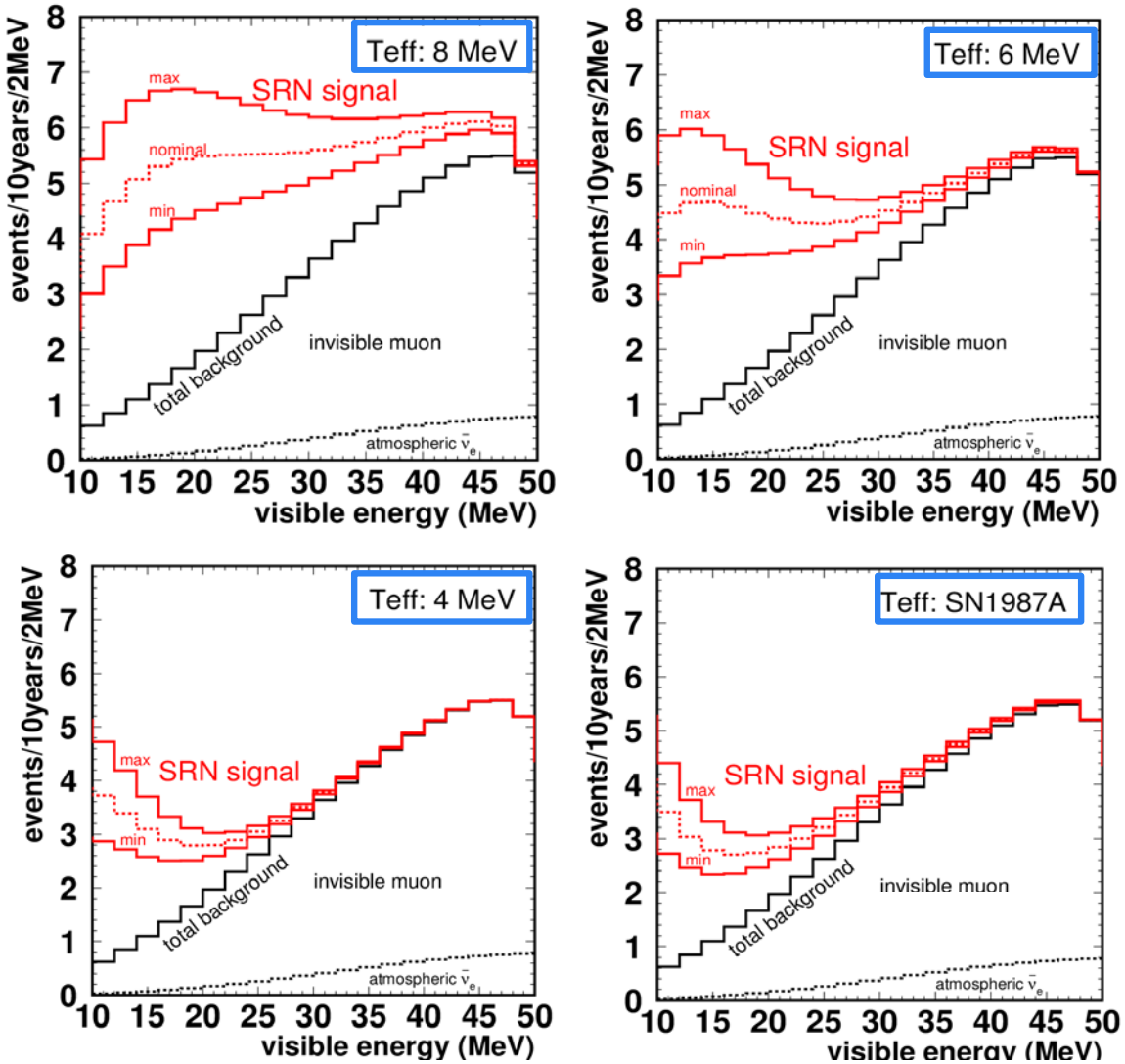
Beacom and Vagins PRL93,171101 (2004)

- Identify $\bar{\nu}_e p$ 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
- $Gd_2(SO_4)_3$ was selected to dissolve.





Expected signal with SK-Gd 10 years



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

Assumption

- n capture efficiency: 90%
- Gd γ detection efficiency: 74%.
- 35% of the SK-IV invisible muon BG
  - By n-tagging

Min/nominal/Max are due to uncertainties in astronomy.

Expect number of events in 10 years in E_{total} =10-30 MeV
Teff 6MeV case: 26-34 events
Teff 4MeV case: 13-16 events

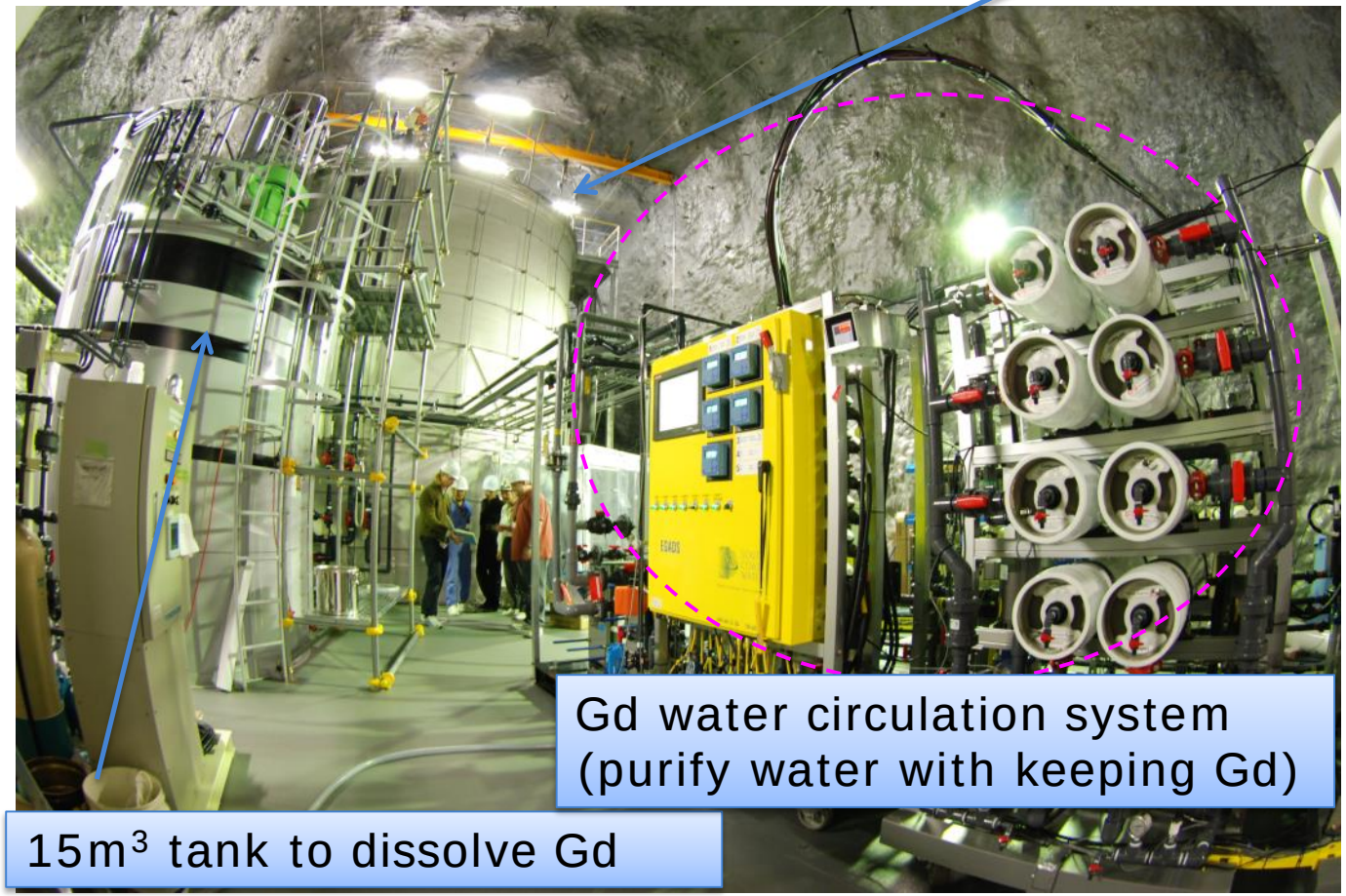
Background: ~18 events

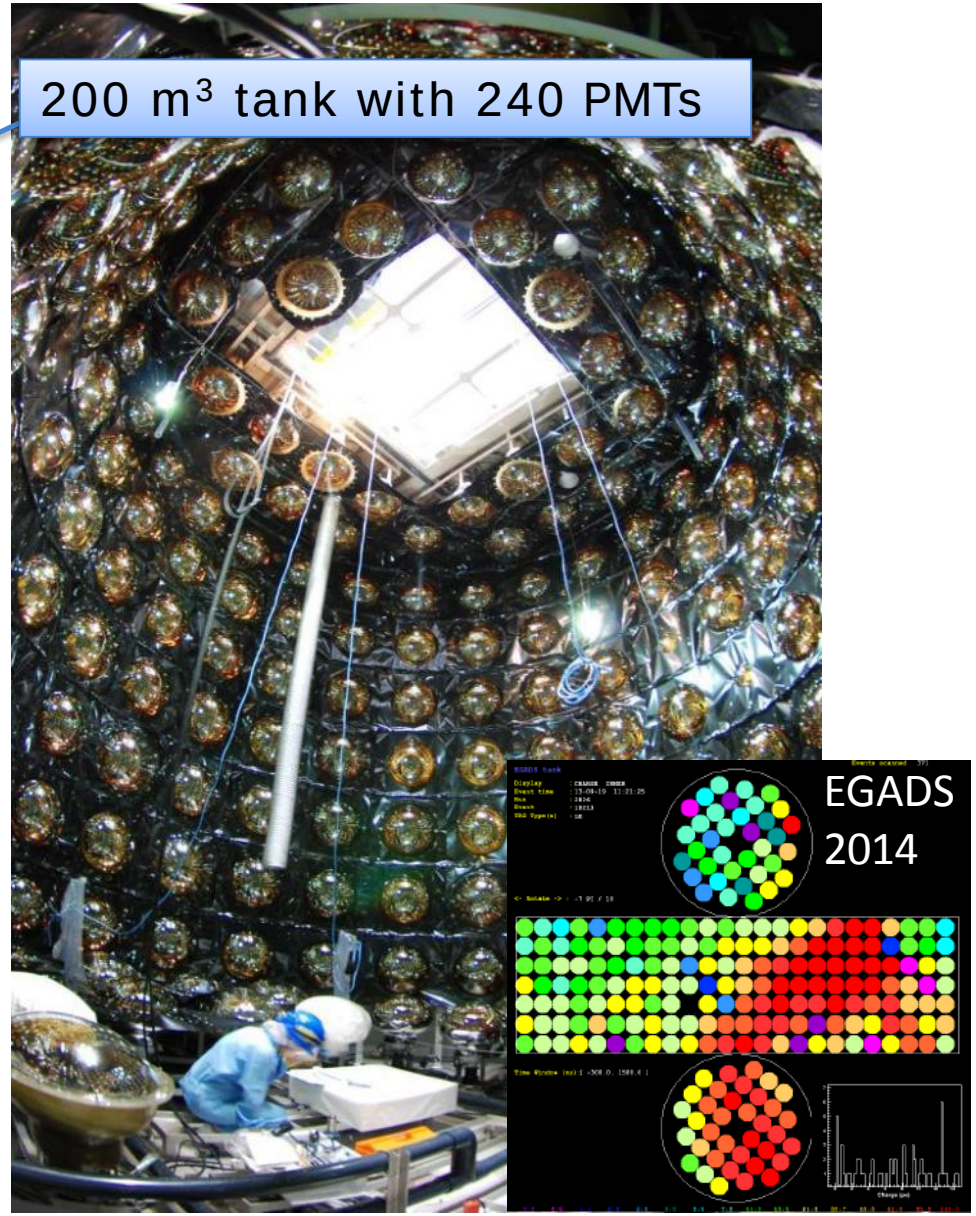
Aiming at "discovery" of SRN

EGADS

Evaluating Gadolinium's Action on Detector Systems

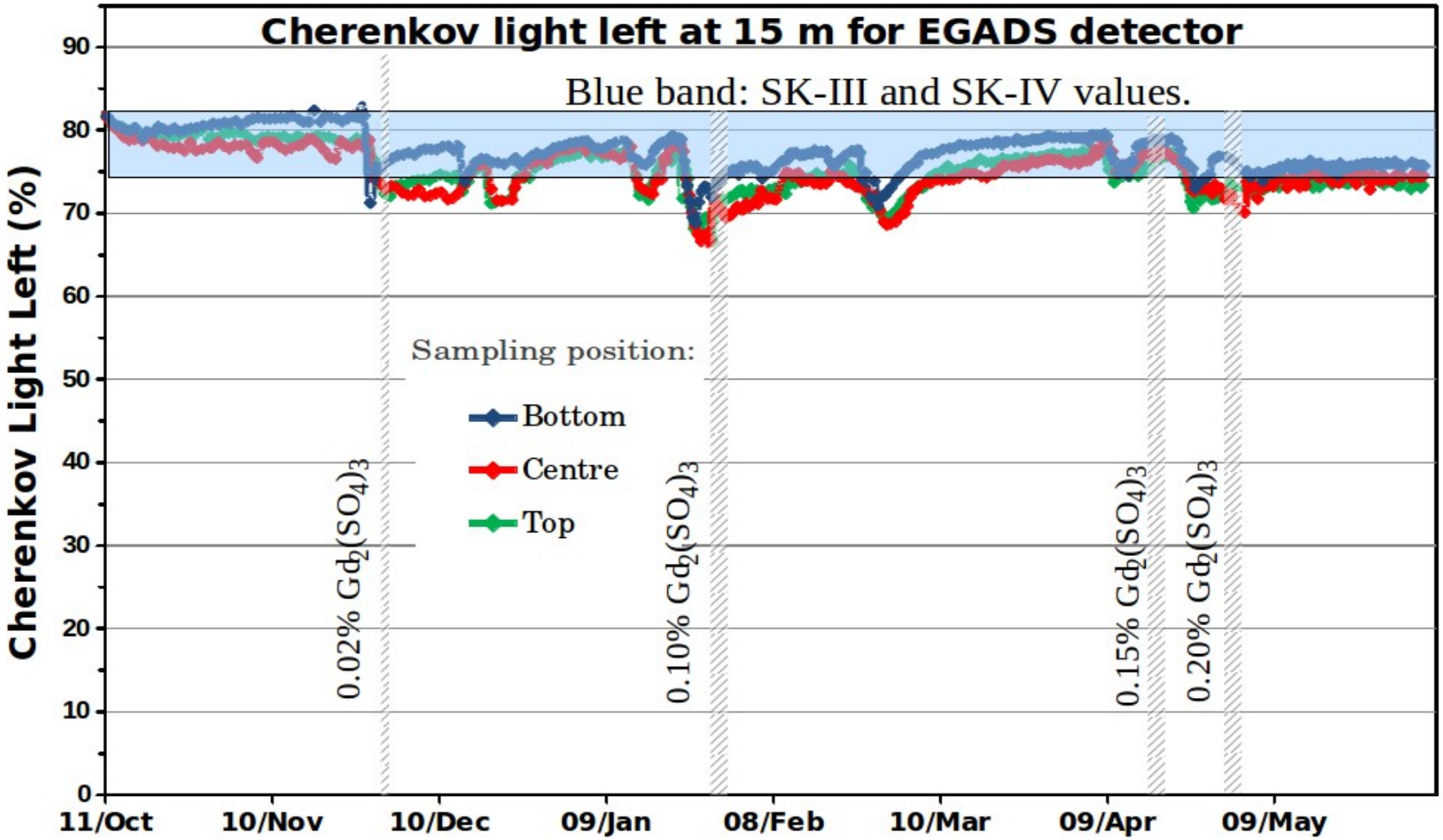
- To study the Gd water quality with actual detector materials.
- The detector fully mimic Super-K detector.
  : SUS frame, PMT and PMT case, black sheets, etc.



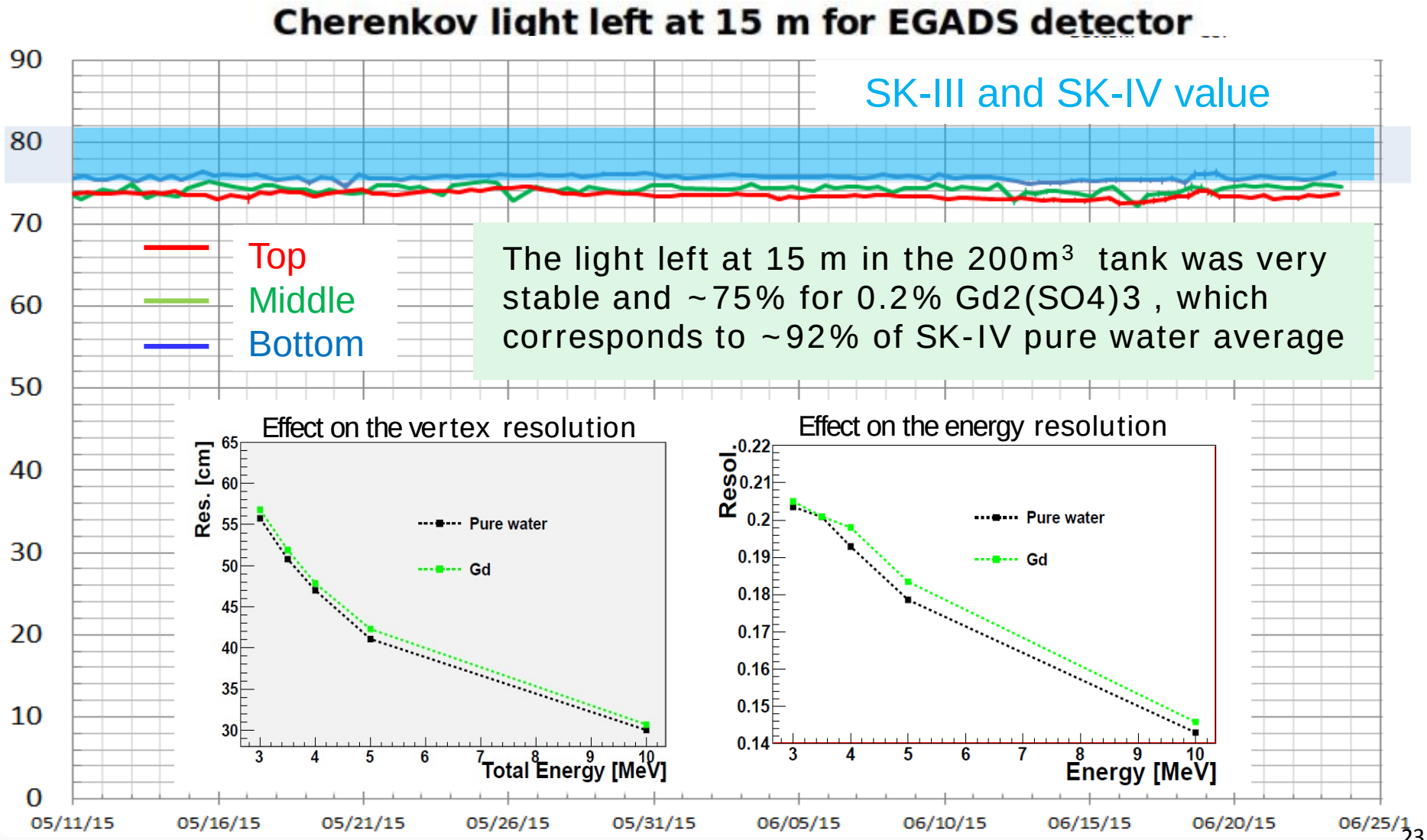


Water transparency during adding Gd

- Gd had been dissolved from Nov. 2014 to May. 2015



Water transparency after Gd conc. got 0.2%



The light left at 15 m in the 200m^3 tank was very stable and ~75% for 0.2% Gd2(SO4)3 , which corresponds to ~92% of SK-IV pure water average

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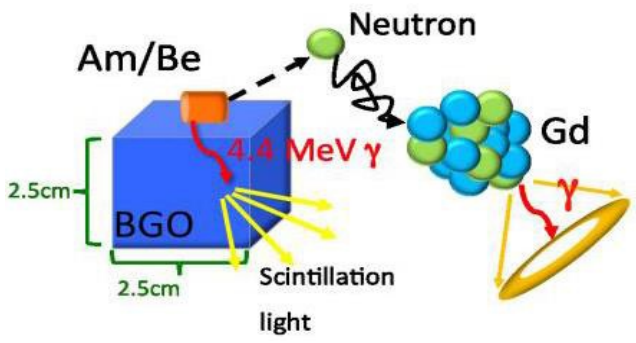
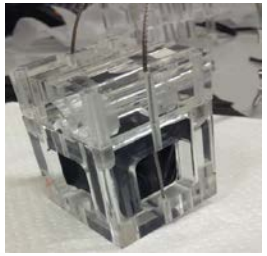
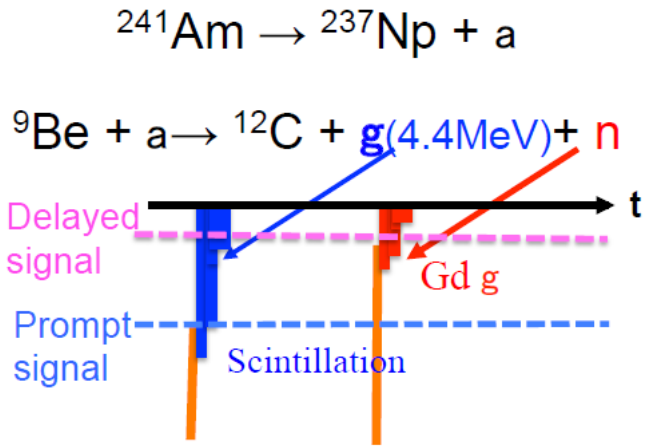
Neutron capture signal in EGADS

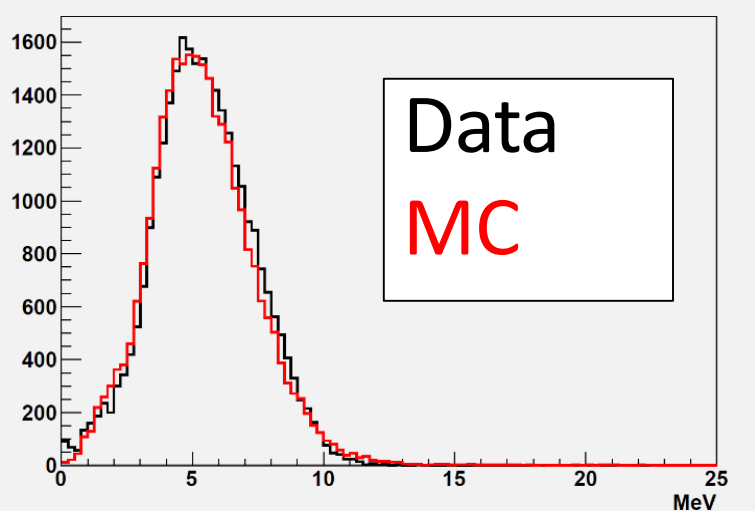
- Using Am/Be + BGO



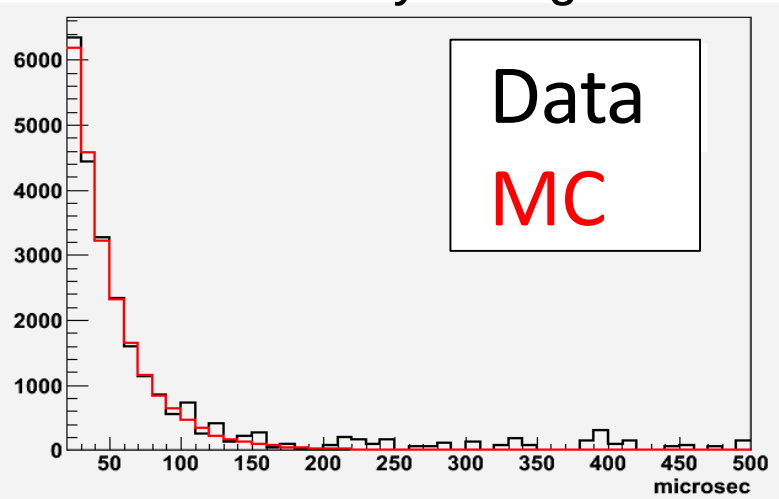




Delayed signal spectrum



Time to delayed signal



Gd concentration dependence was confirmed.

	2178±76ppm	1055±37ppm	225±8ppm
Data	29.89 ± 0.33	51.48 ± 0.52	130.1 ± 1.7
MC	30.05 ± 1.14	53.47 ± 1.77	126.2 ± 2.8

[μsec]

Official statement from SK collaboration

On June 27, 2015, the Super-Kamiokande collaboration approved the SuperK-Gd project which will enhance anti-neutrino detectability by dissolving gadolinium to the Super-K water.

The actual schedule of the project including refurbishment of the tank and Gd-loading time will be determined soon taking into account the T2K schedule.

Summary

Solar ν observation

- SK has observed ~77000 ^{8}B ν interactions over 18 years, by far the largest sample of solar neutrino events in the world.
  - No correlation with the solar activity cycle.
- SK recoil electron energy spectrum slightly disfavors "MSW upturn"
- SK data provide the first indication (at 2.8~3.0 σ) of terrestrial matter effects on ^{8}B solar ν oscillation.

For DSNB detection

- Gd project in SK (was known as GADZOOKS!) started in 2002.
- EGADS started in 2009 to evaluate Gd effect to SK.
- In 2015, 0.2% of Gd sulfate was dissolved in EGADS and it was confirmed that there is no showstopper for putting Gd into SK. SK-Gd was accepted by Super-K in June 2015.

Stay tuned for low energy SK neutrino

Extra Slides

History of Gd project in Super-K

2002 Nov. Started to discuss as "GADZOOKS!"

2006 May. Gd Advisory Committee was formed.
List up R&D items and specifications

2007 Nov. collaboration council
It was suggested to make a test tank and study feasibility.

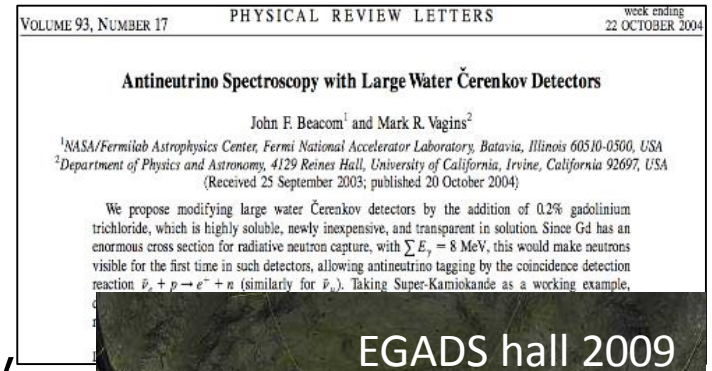
2009 "EGADS" was started.
A 200 ton test tank was constructed.

2013 0.2% $Gd_2(SO_4)_3$ was dissolved before mounting PMTs and transparency was measured.

2013 summer 240 PMTs were mounted in the EGADS tank.

2014 Oct. – 2015 May Dissolved 0.2% $Gd_2(SO_4)_3$ again and checked water transparency.

2015 Jun. collaboration council
GADZOOKS! was approved as
"Super Kamiokande Gd"


VOLUME 93, NUMBER 17 PHYSICAL REVIEW LETTERS week ending 22 OCTOBER 2004

Antineutrino Spectroscopy with Large Water Čerenkov Detectors

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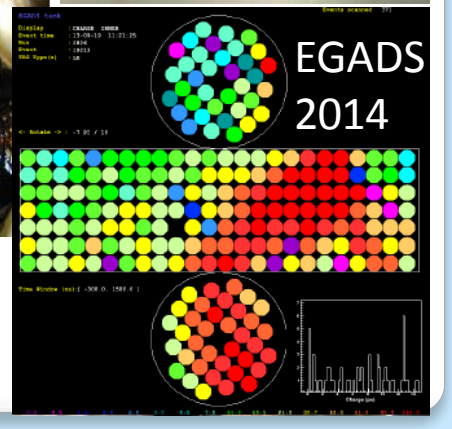
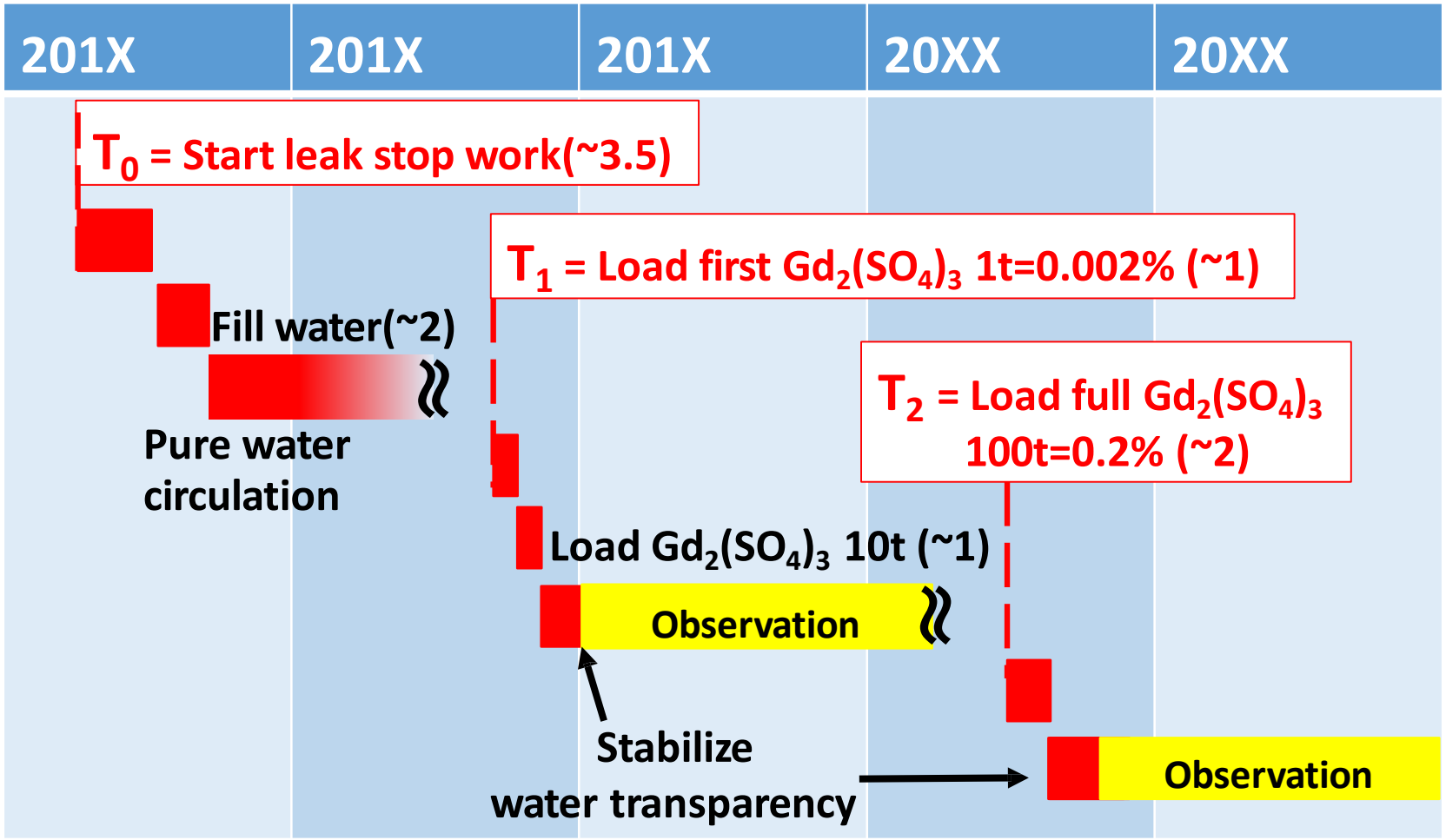
(Received 25 September 2003; published 20 October 2004)

We propose modifying large water Čerenkov detectors by the addition of 0.2% gadolinium trichloride, which is highly soluble, newly inexpensive, and transparent in solution. Since Gd has an enormous cross section for radiative neutron capture, with $\sum E_\gamma = 8$ MeV, this would make neutrons visible for the first time in such detectors, allowing antineutrino tagging by the coincidence detection reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ (similarly for $\bar{\nu}_\mu$). Taking Super-Kamiokande as a working example,



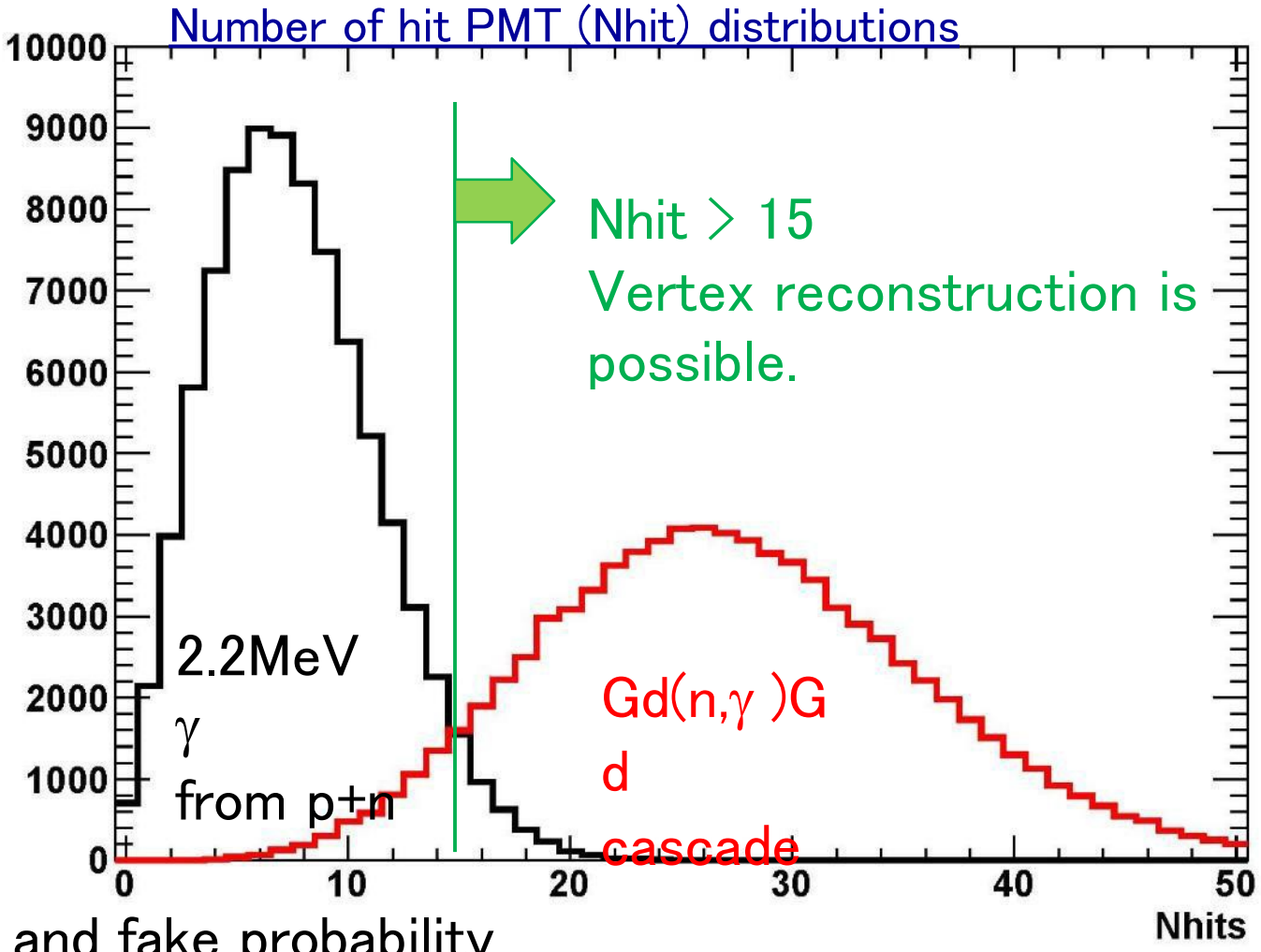
Timeline of SK-Gd

Numbers in parentheses are months to be taken for the work



- In order to set T_0, T_1,&T_2, T2K schedule will be also taken into account

Why Gd (not 2.2MeV γ) for neutron tagging



Efficiency and fake probability

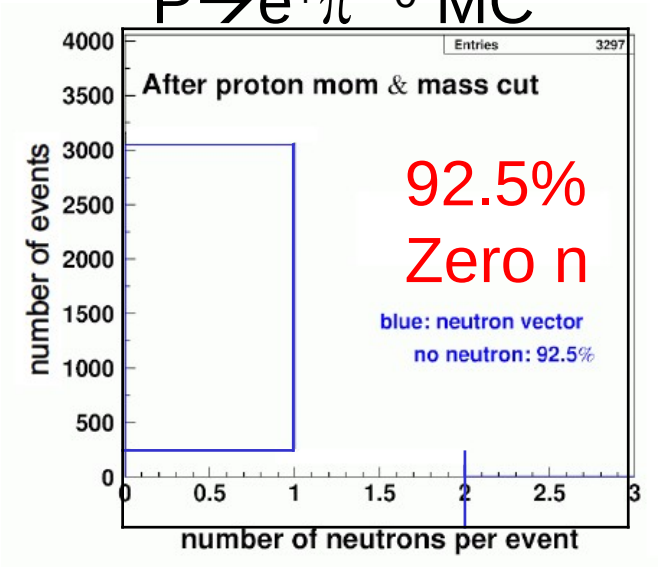
2.2MeV γ : Efficiency: 10～20%, fake probability: ～10^{-2}

Gd(n,γ)Gd: Efficiency: >80%, fake probability: <10^{-4}

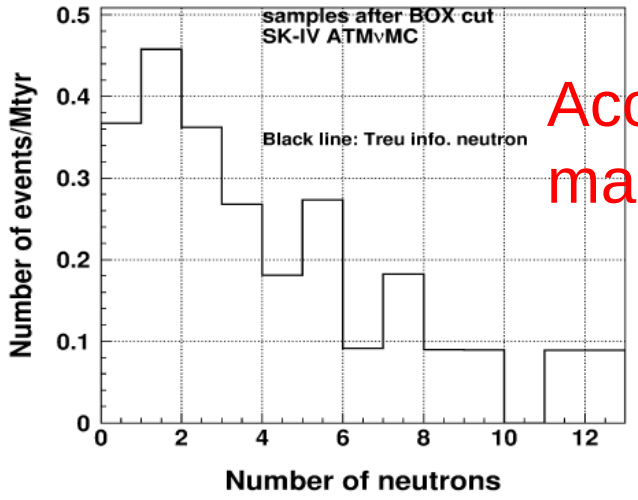
Improvement for Proton decay

Neutron multiplicity for

$P \rightarrow e^{+}\pi^{0}$ MC



Atmospheric ν BG



Accompany many n

<u>If one proton decay event is observed at Super-K after 10 years</u>

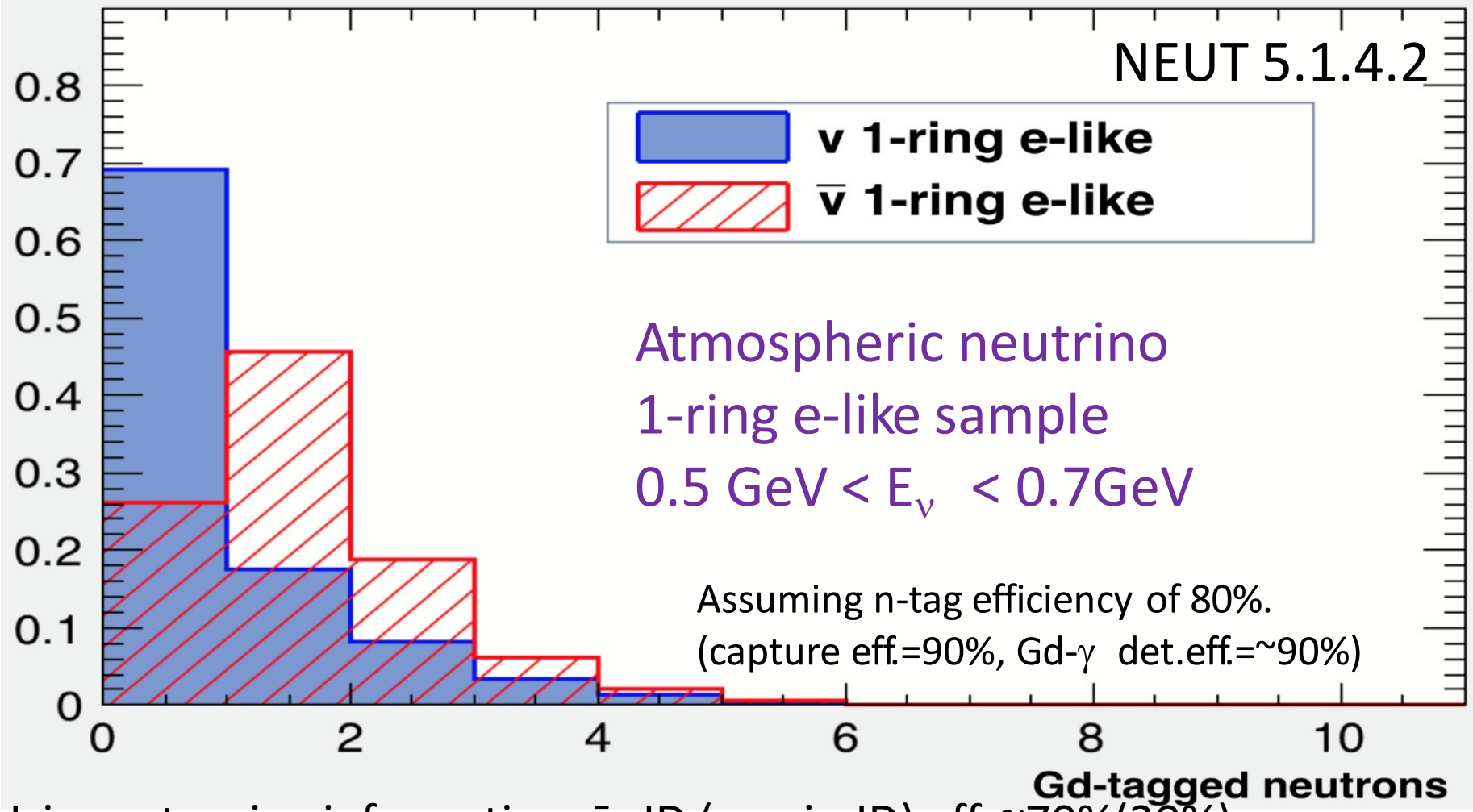
Current background level: 0.58 events/10 years

Background with neutron anti-tag: 0.098 events/10 years

Background probability will be decreased from 44%(w/o n) to 9%(w/ n).

Improvement for T2K

Number of tagged neutrons in T2K energy range

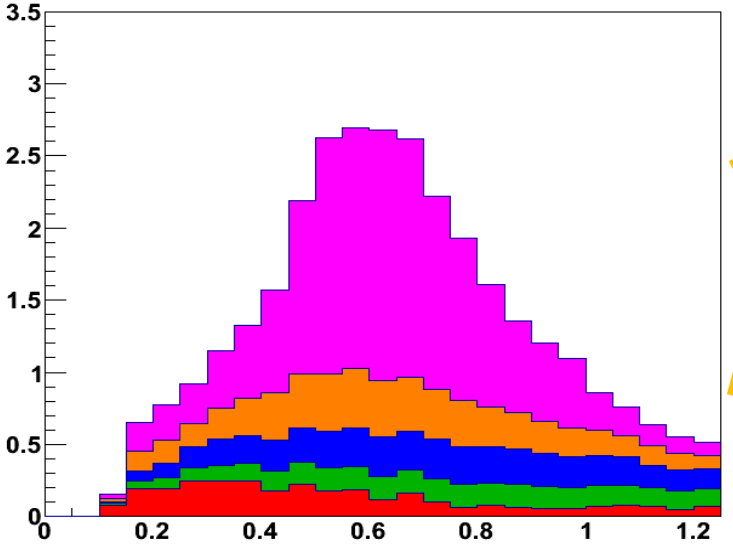


Using n-tagging information, $\bar{\nu}_e$ ID (ν_e missID) eff. ~70%(30%)

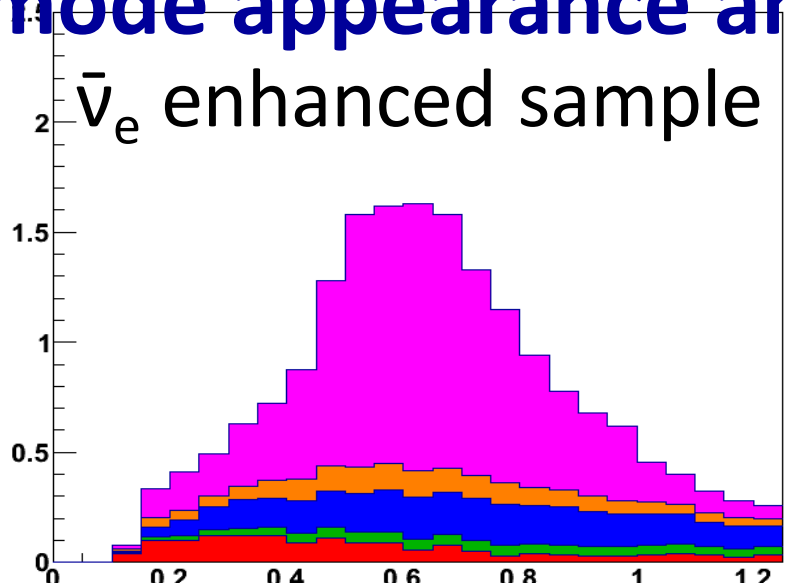
$\bar{\nu}_e$ enhanced sample in anti mode appearance analysis

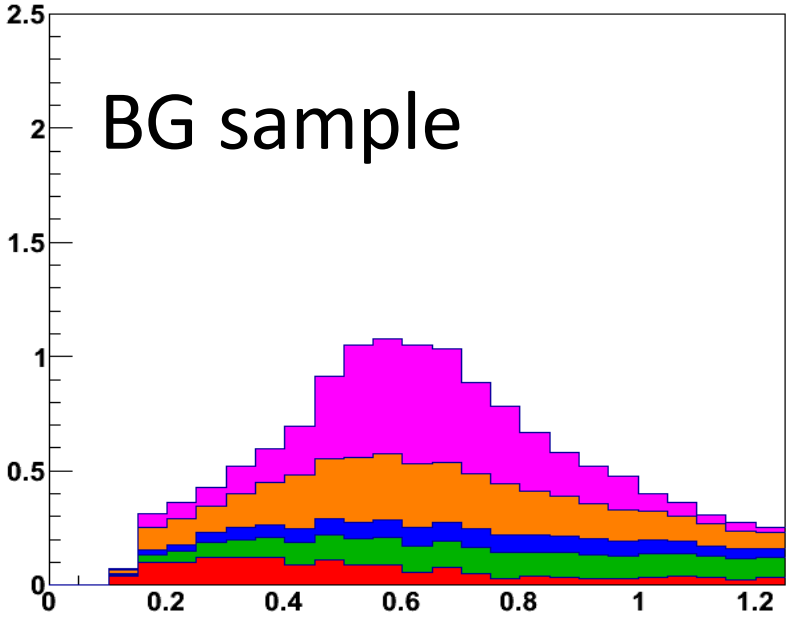
Signal $\bar{\nu}_e$, Signal ν_e

$\bar{\nu}_e$, ν_e, ν_μ and $\bar{\nu}_\mu$



Erec[GeV]





Erec[GeV]

Number of events @ 3.9×10^{21} POT

Osc parameters: $\sin^2 2\theta_{13}=0.1$, $\delta cp=-90^\circ$, $\Delta m^2_{32} = 0.0024 eV^2$, $\sin^2\theta_{23}=0.5$, NH

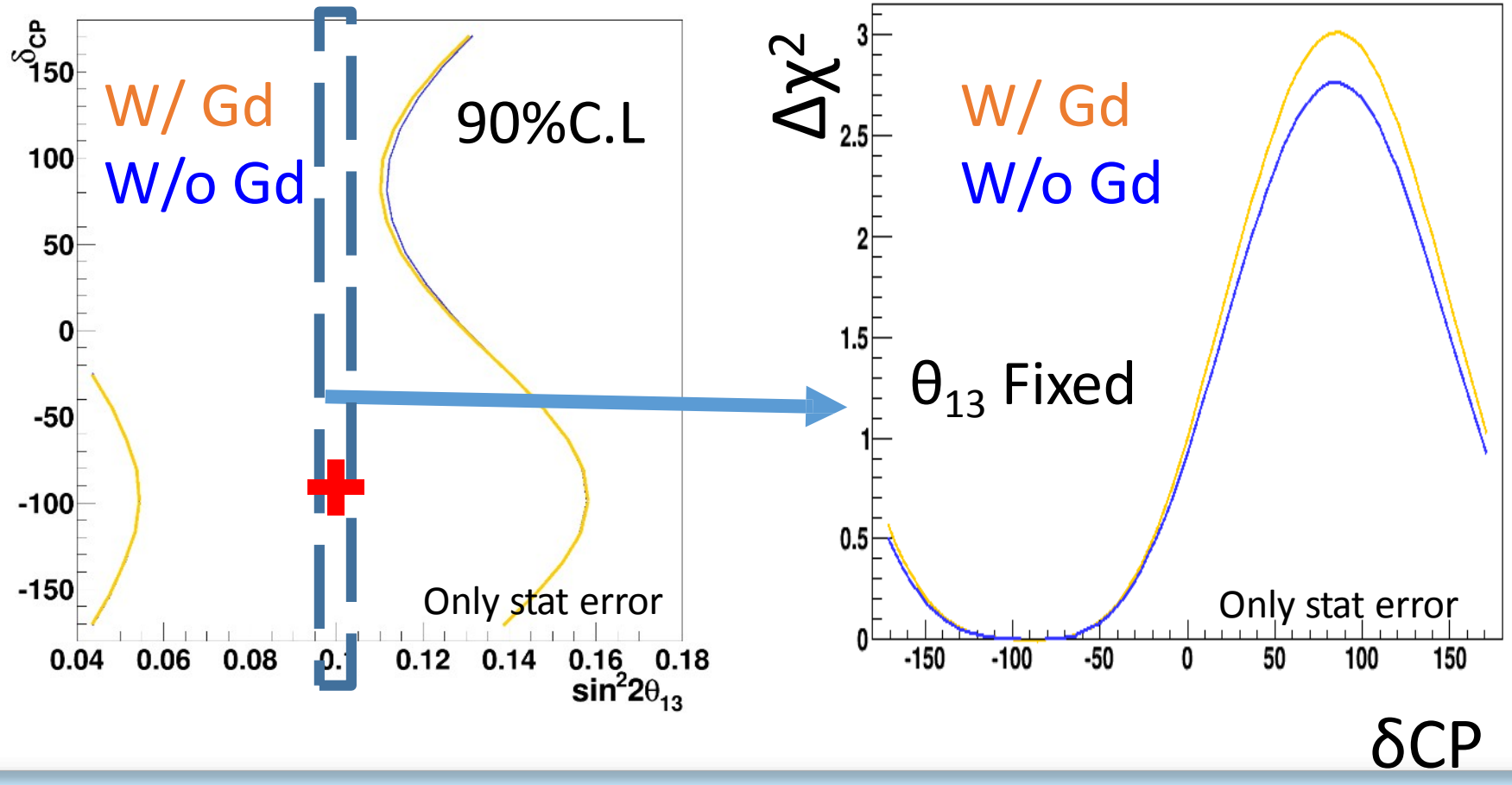
$\bar{\nu}_e$ ID (ν_e missID) eff. =70%(30%) is assumed w/o energy dependence

Note: Directional information of e/e+ is not used

Anti mode 3.9×10^{21} Appearance Contour

True parameters: $\sin^2 2\theta_{13}=0.1, \delta cp=-90^\circ$

$\Delta m^2_{32} = 0.0024 eV^2$ (Fixed), $\sin^2\theta_{23}=0.5$(Fixed), NH(Fixed)



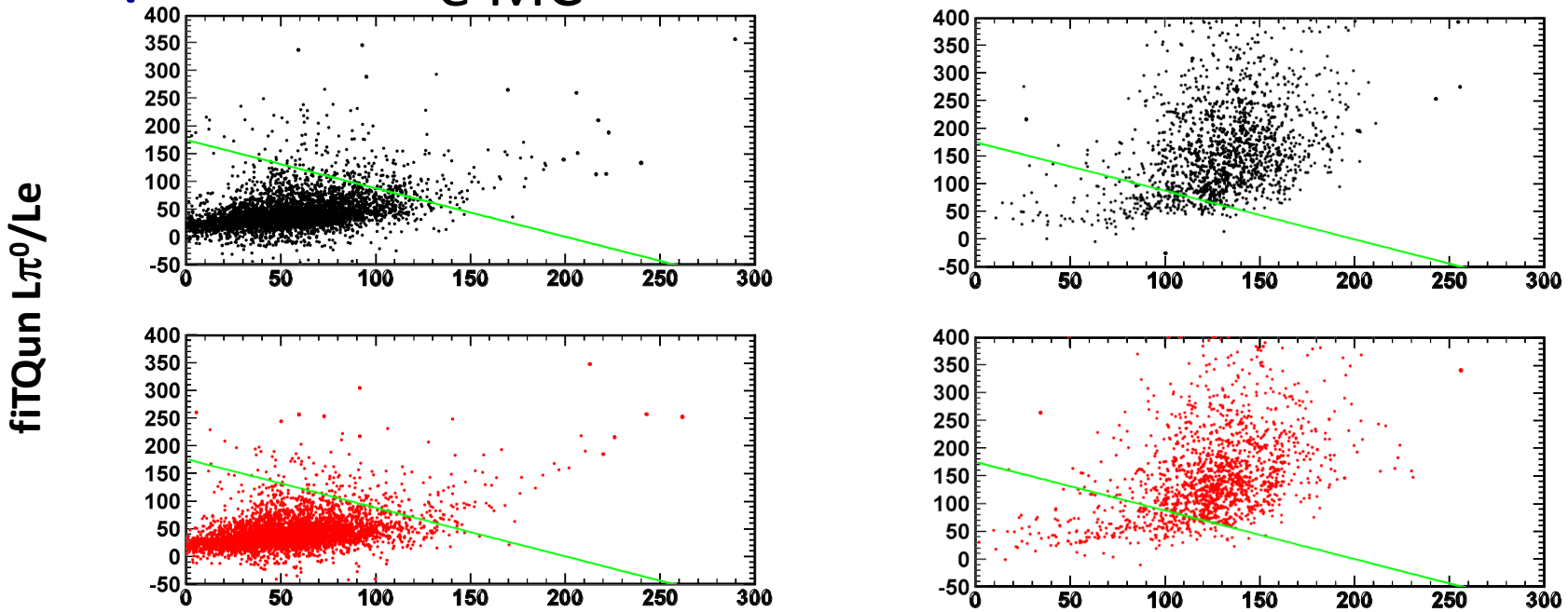
e/π ^{0} separation

(ex. 500MeV/c)

pure
Gd water

e MC

π ^{0} MC



e MC, det.

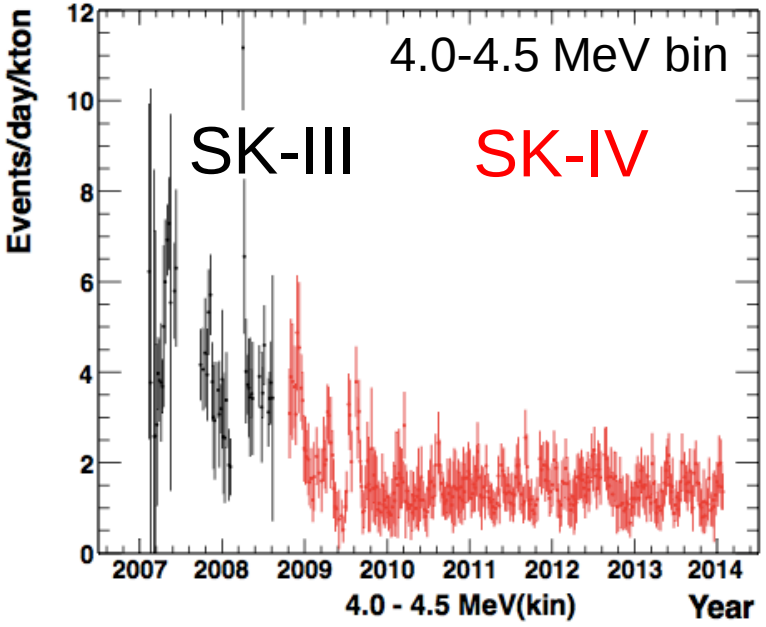
true (MeV/c)	pure	Gd water
250	92.9±2.1	91.9±2.1
500	89.3±2.0	88.4±2.0
1000	75.7±1.8	77.7±1.8

π ^{0} MC, remain ε (%)

true (MeV/c)	pure	Gd water
250	1.7±0.2	1.9±0.2
500	4.7±0.3	6.1±0.4
1000	15.8±0.7	16.7±0.7

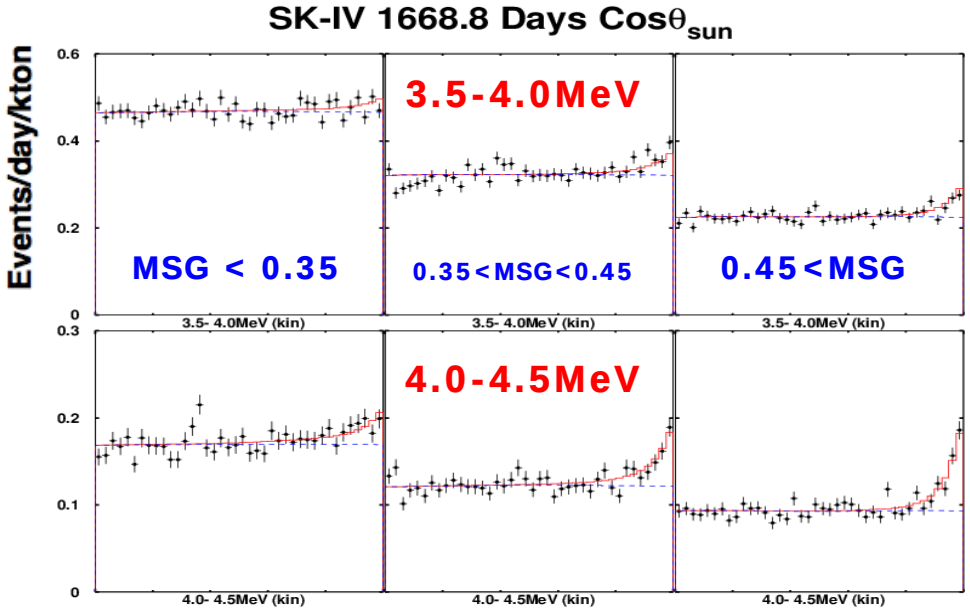
Improvements in SK-IV

- Reduced ^{222}Rn BG



- New analysis in low energy bins

Remaining BG-electrons from ^{214}Bi should have more multiple-scatterings than signal-electrons have: MSG



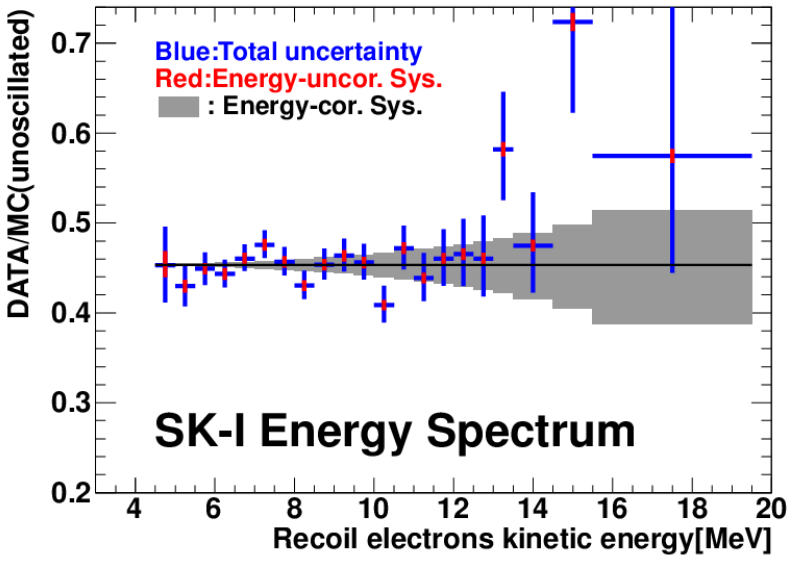
- Reduced systematic error

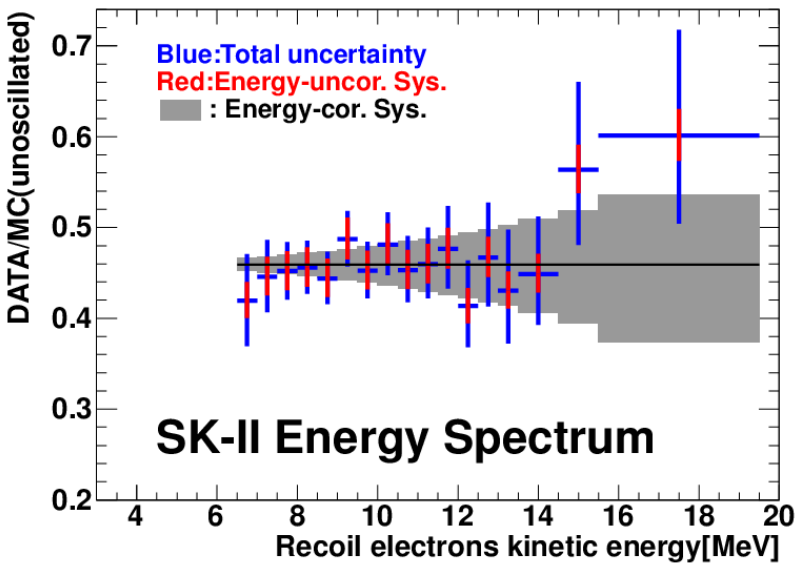
  1.7% for flux cf. SK-I: 3.2% SK-III: 2.1%

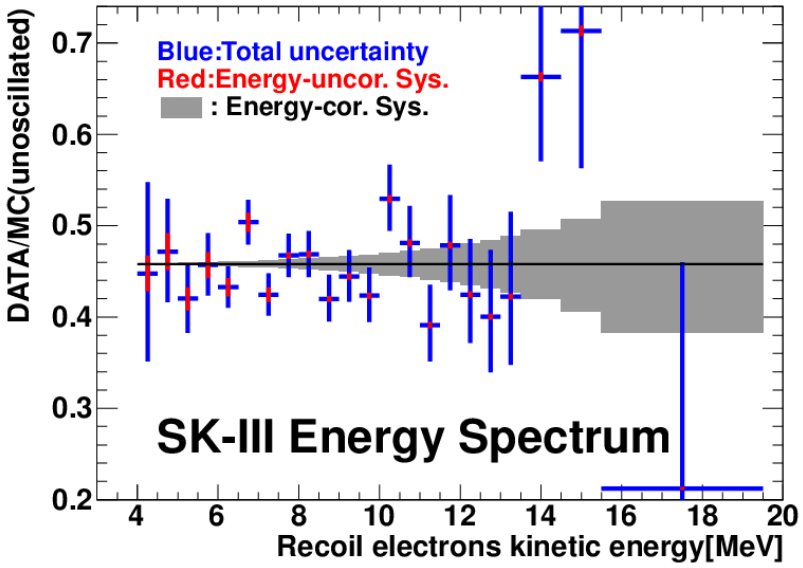
Achieved 3.5 MeV(kin.) energy threshold

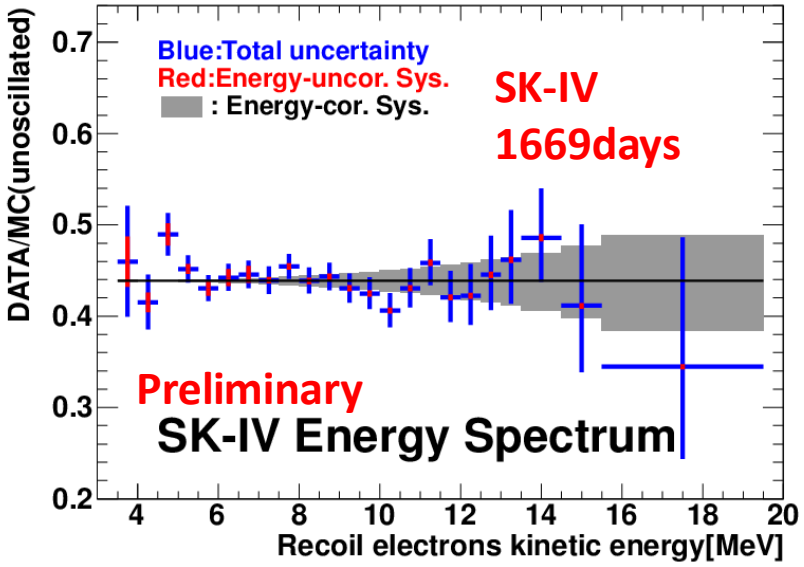
8.6σ signal is observed with MSG

Recoil electron spectra





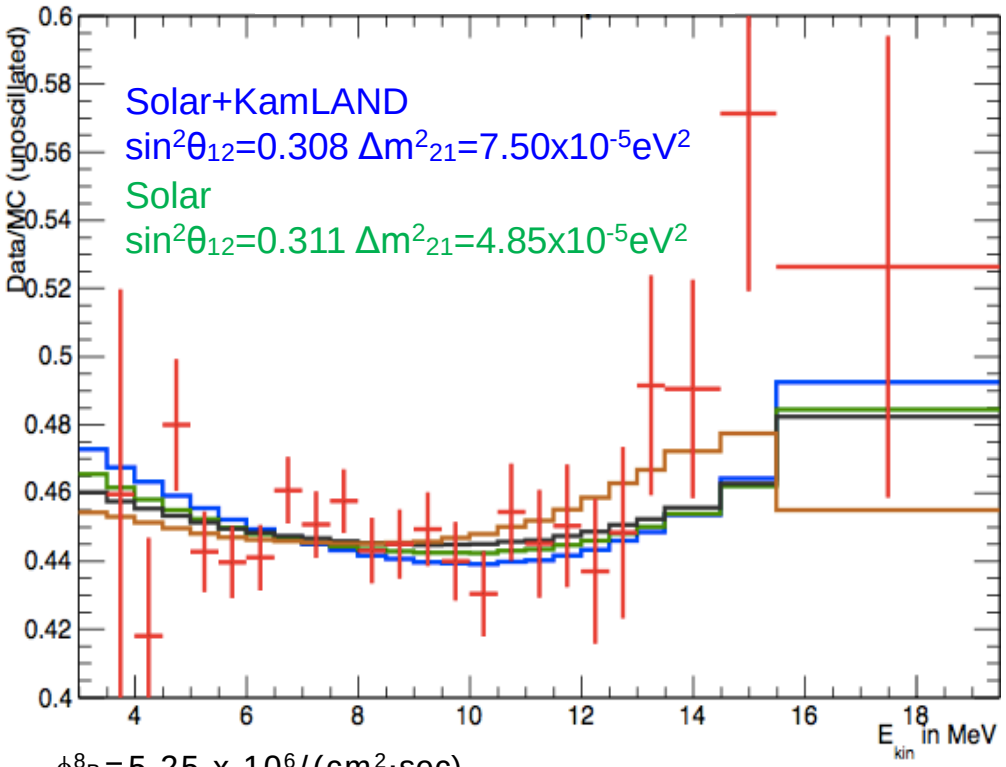




MC: $5.25 \times 10^6/cm^2/sec$

N.B. All SK phase are combined without regard to energy resolution or systematics in this figure

SK-I+II+III+IV spectrum



ϕ^8_B=5.25 x 10^6/(cm^2·sec)
ϕ_{hep}=7.88 x 10^3/(cm^2·sec)

(total # of bins of SKI - IV is 83)	χ^2
Solar+KamLAND	70.13
Solar	68.14
quadratic fit	67.67
exponential fit	66.54

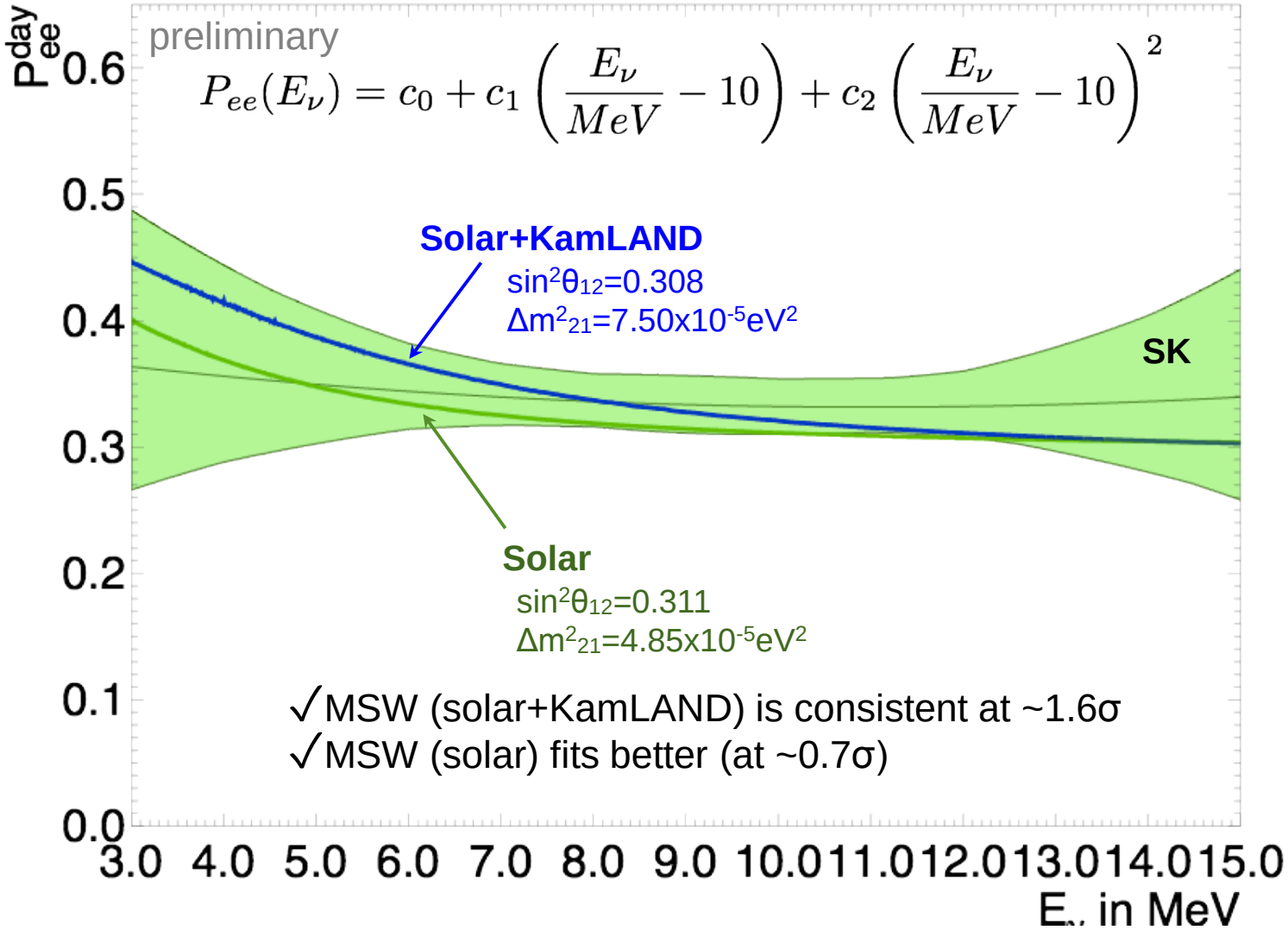
Neutrino energy spectrum is convoluted in the electron recoil spectrum. For de-convolution, generic functions are used as a survival probability;

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

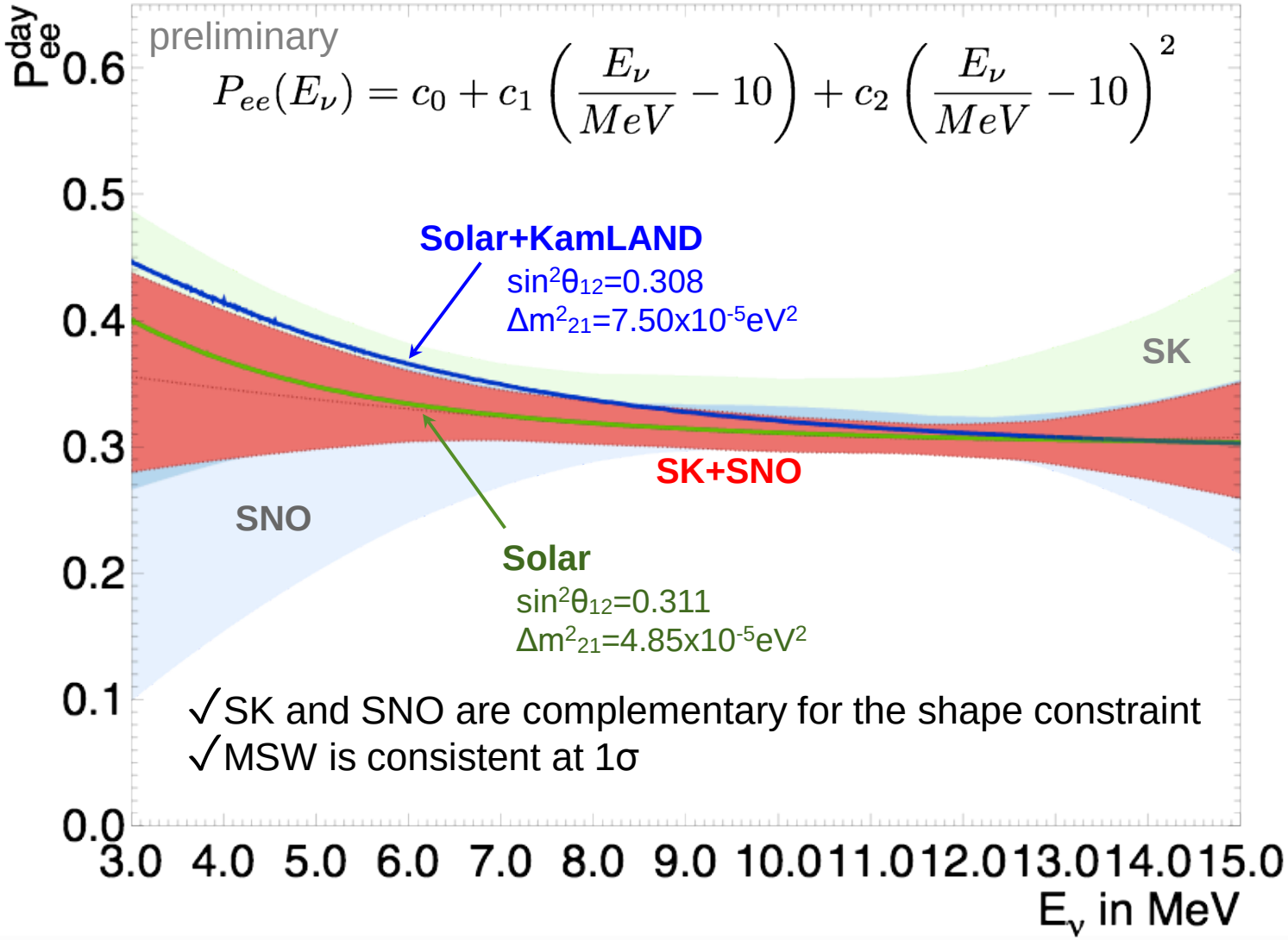
$$P_{ee}(E_\nu) = e_0 + \frac{e_1}{e_2}\left(\exp\left(e_2(\frac{E_\nu}{MeV} - 10)\right) - 1\right)$$

SK recoil electron spectrum constrain the fit parameters (c_i,e_i) of the function and the allowed $P_{ee}(E\nu)$ is derived using the allowed (c_i,e_i).

Allowed $P_{ee}(E\nu)$ for SK

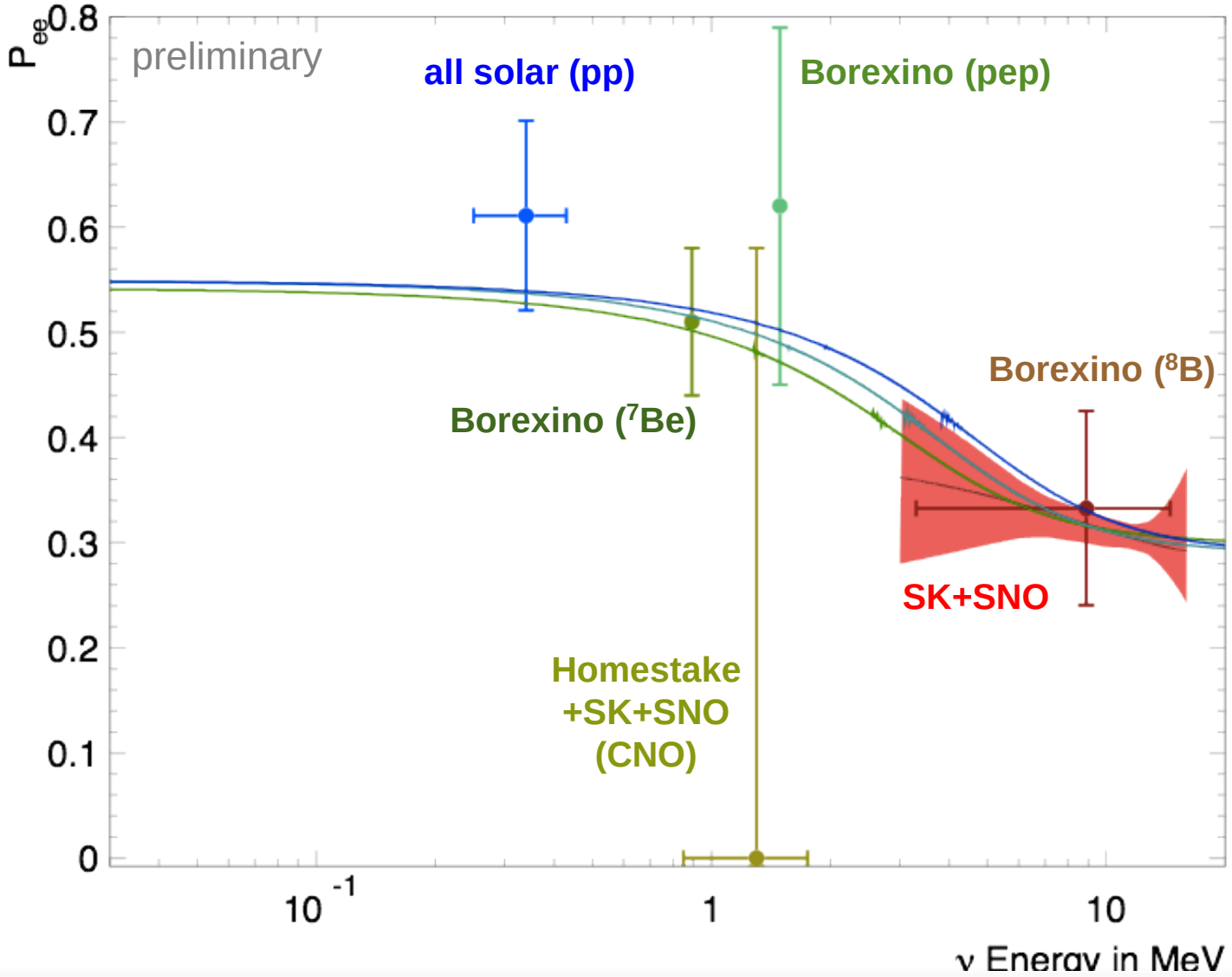


Allowed $P_{ee}(E\nu)$ for SK+SNO

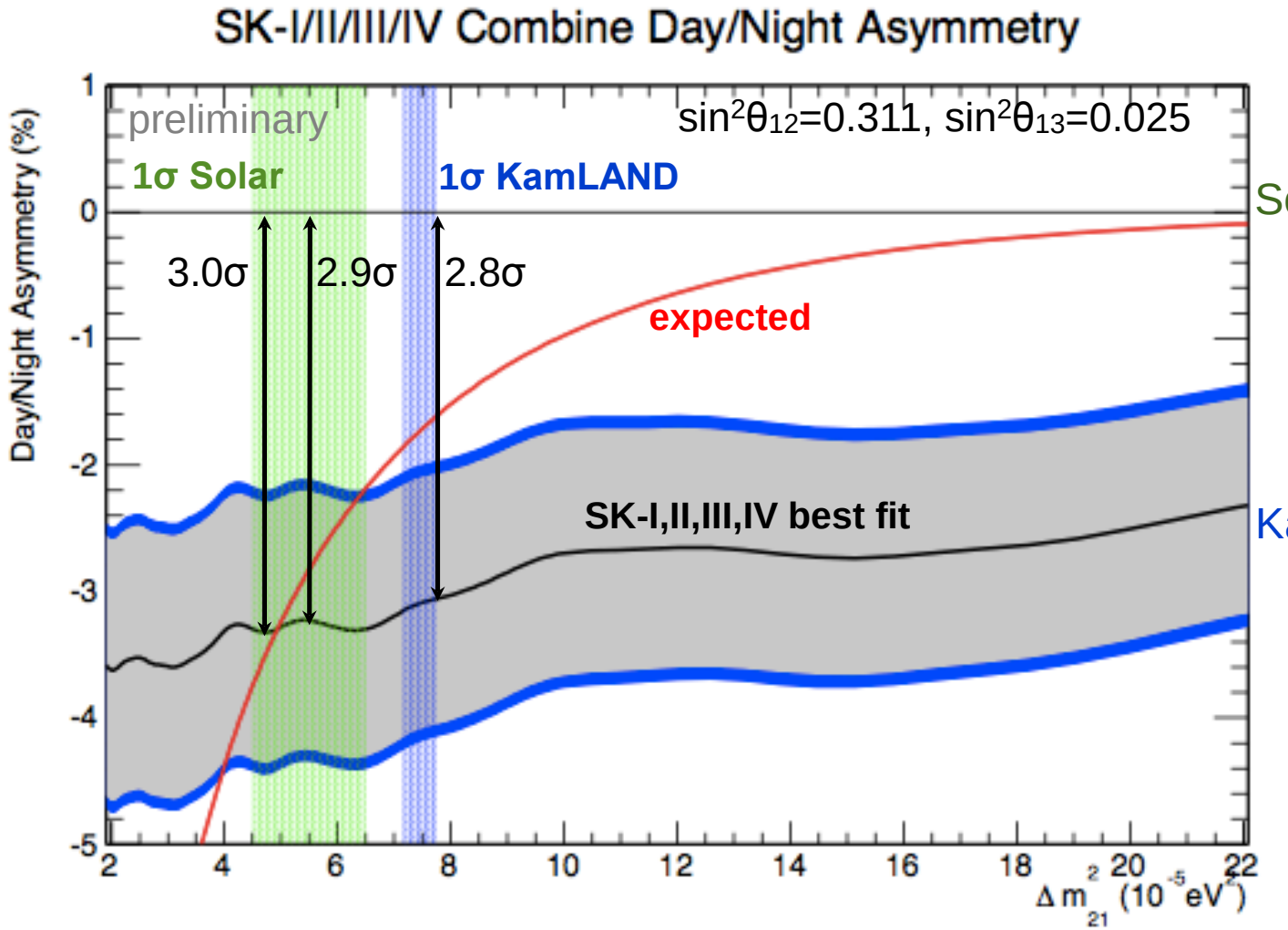


✓SK and SNO are complementary for the shape constraint
✓MSW is consistent at 1σ

Global view of $P_{ee}(E\nu)$



Δm^2_{21} dependence



Solar region

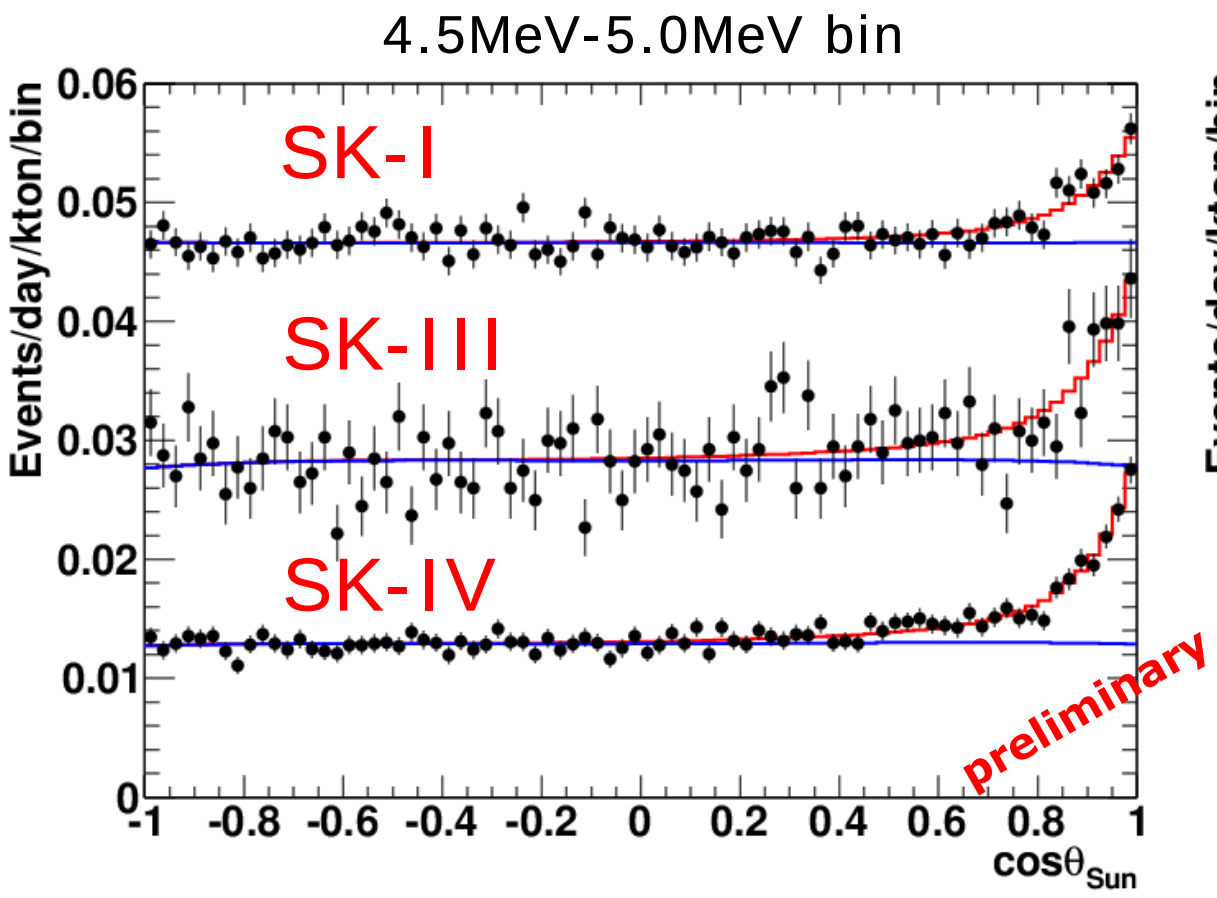
differ from zero
by 2.9~3.0σ
agree with expect
by 1.0σ

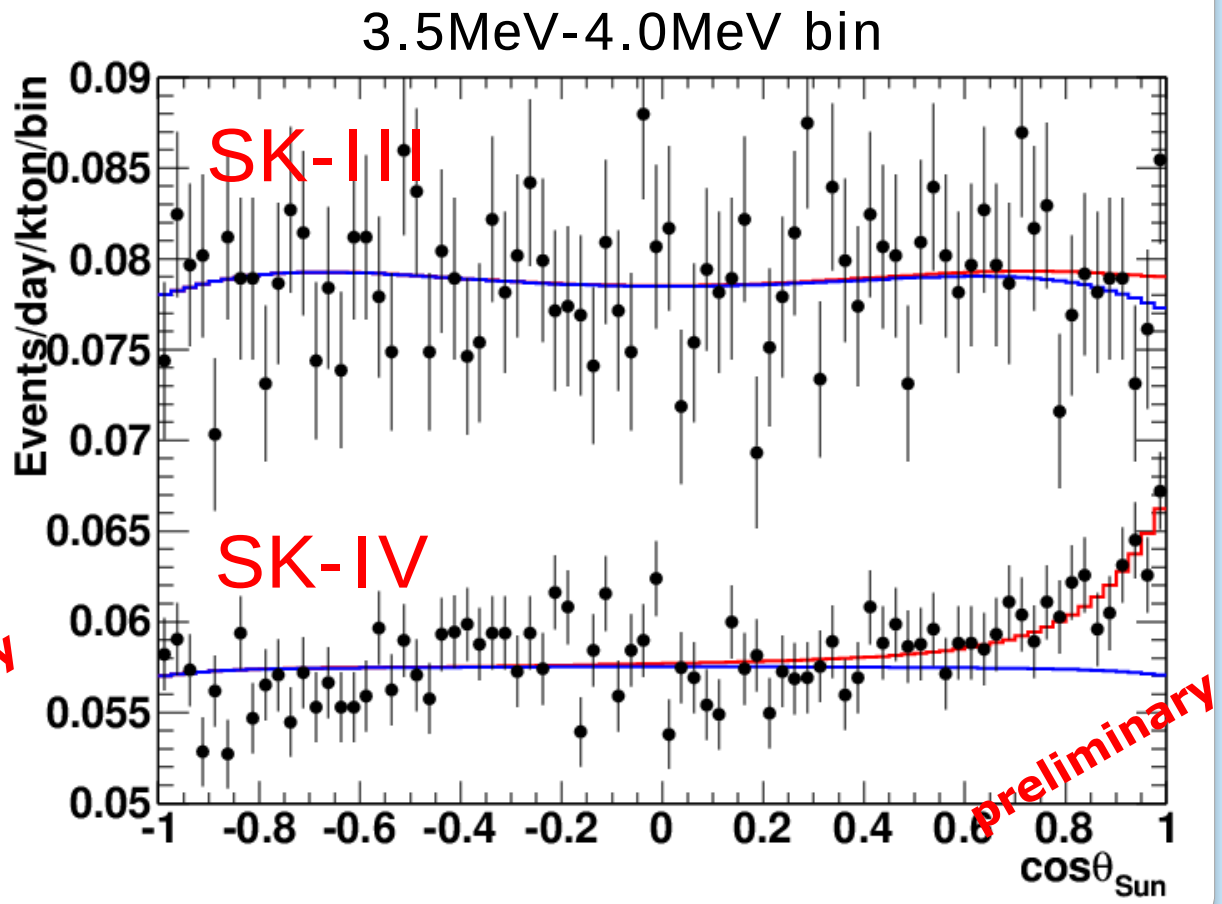
KamLAND region

differ from zero
by more than 2.8σ
agree with expect
by 1.3σ

History of lowered BG and threshold

- Solar angle distributions
  - BG SK-I/SK-IV=1/4, E_{th} SK-I – SK-IV = 1MeV

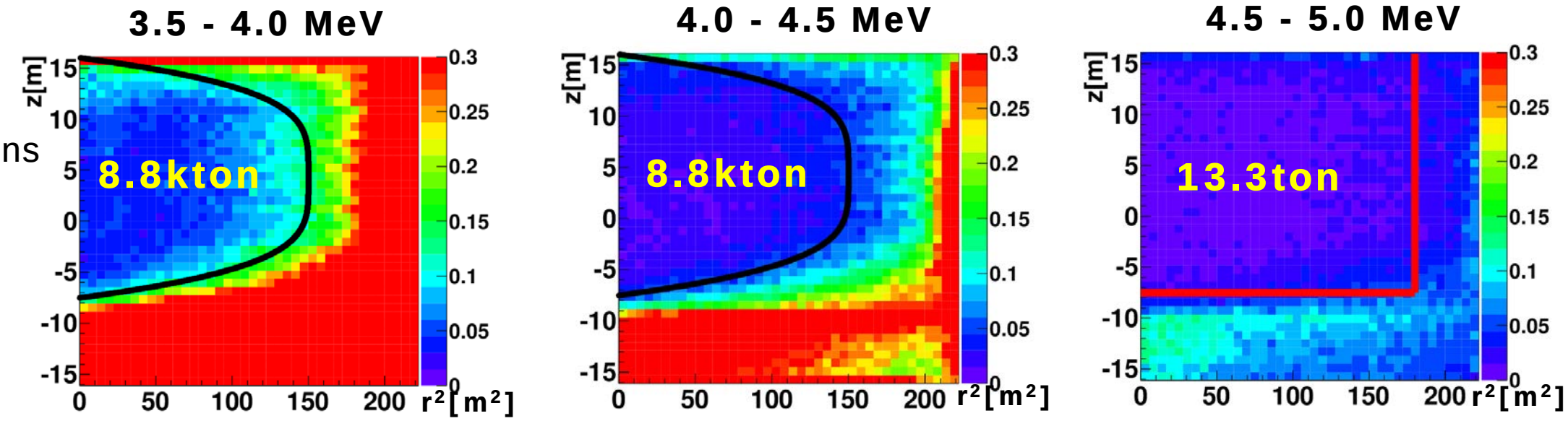




How it was achieved?

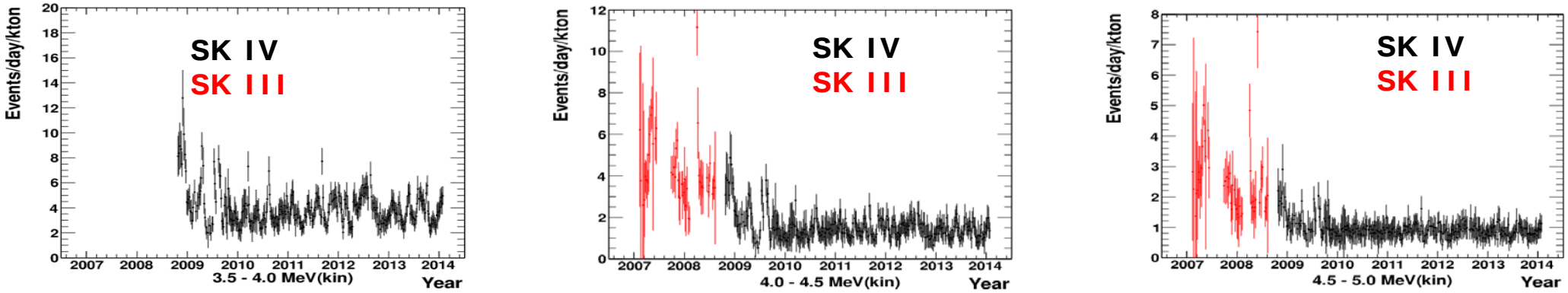
- It's easy! Just tightening the FV to reject Rn rich region.

SK-IV vertex distributions



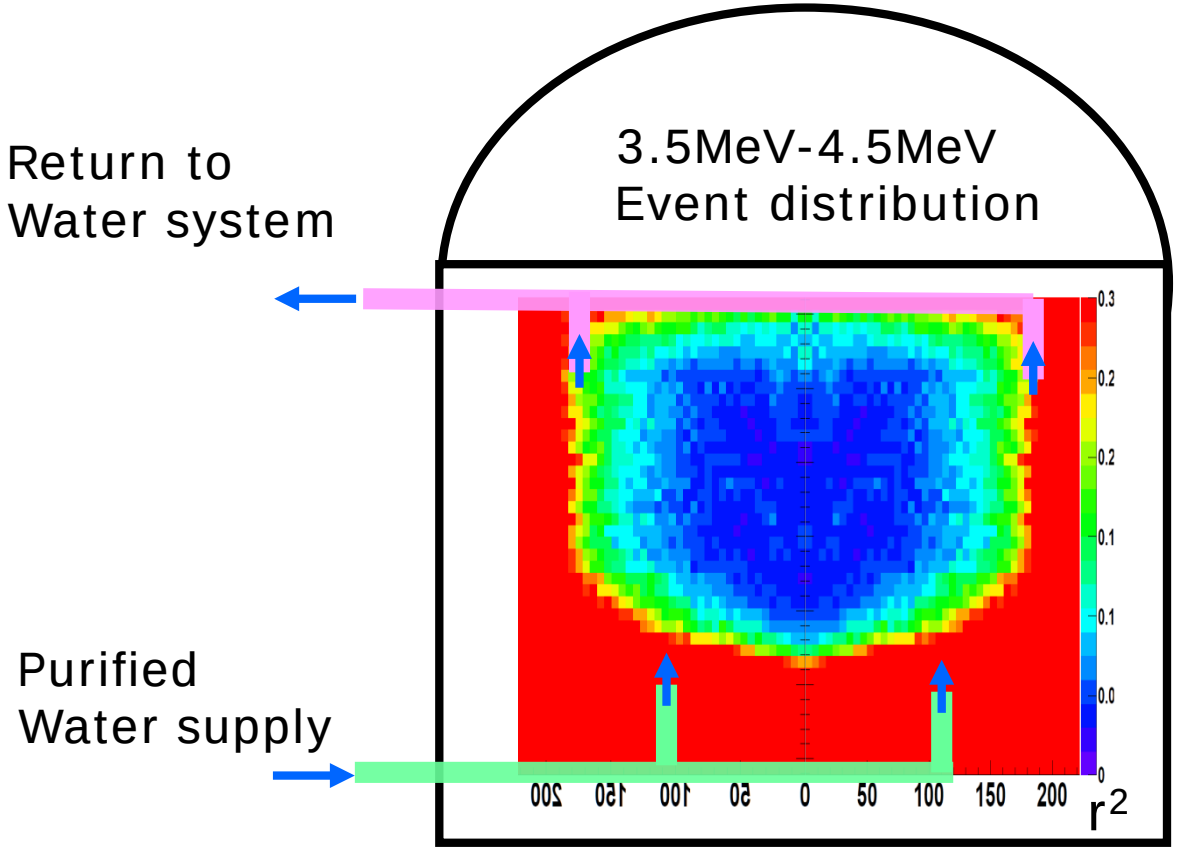
- Keeping the FV (boarder) is not easy at all!

Event rates



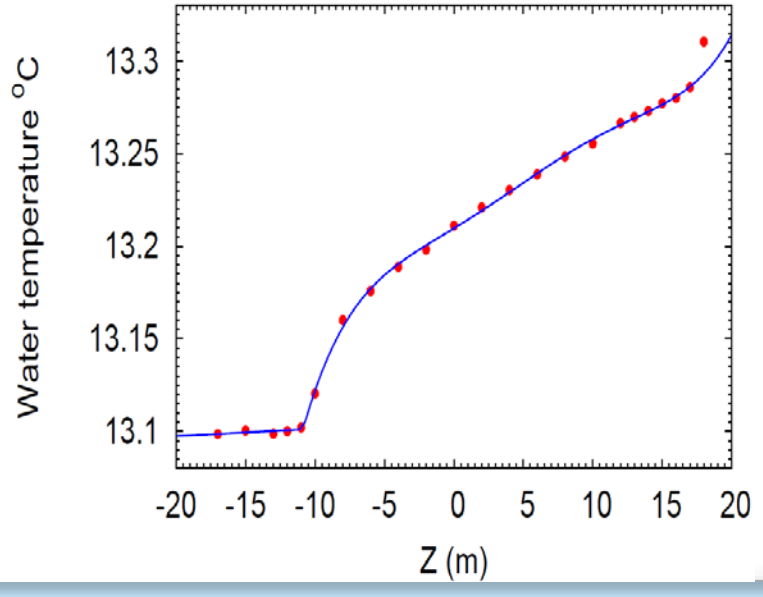
Convection suppression in SK-IV

- Very precisely temperature-controlled (±0.01ºC) water must be supplied to the bottom.



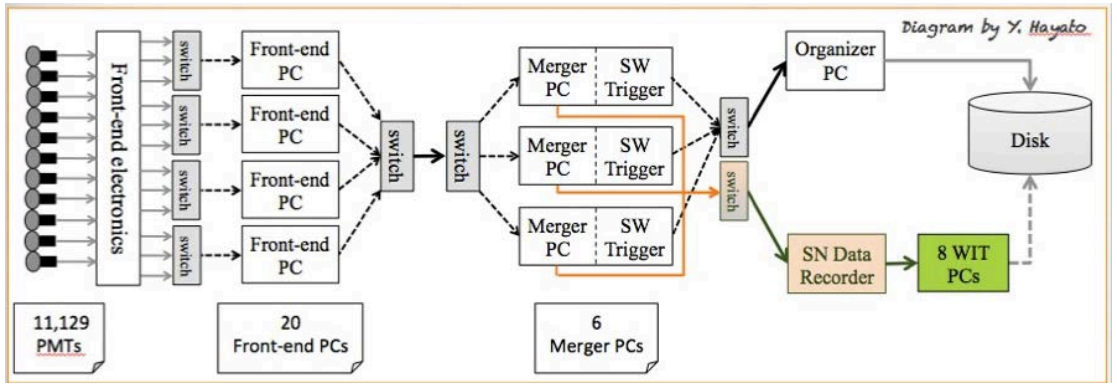
Temperature in Z derection

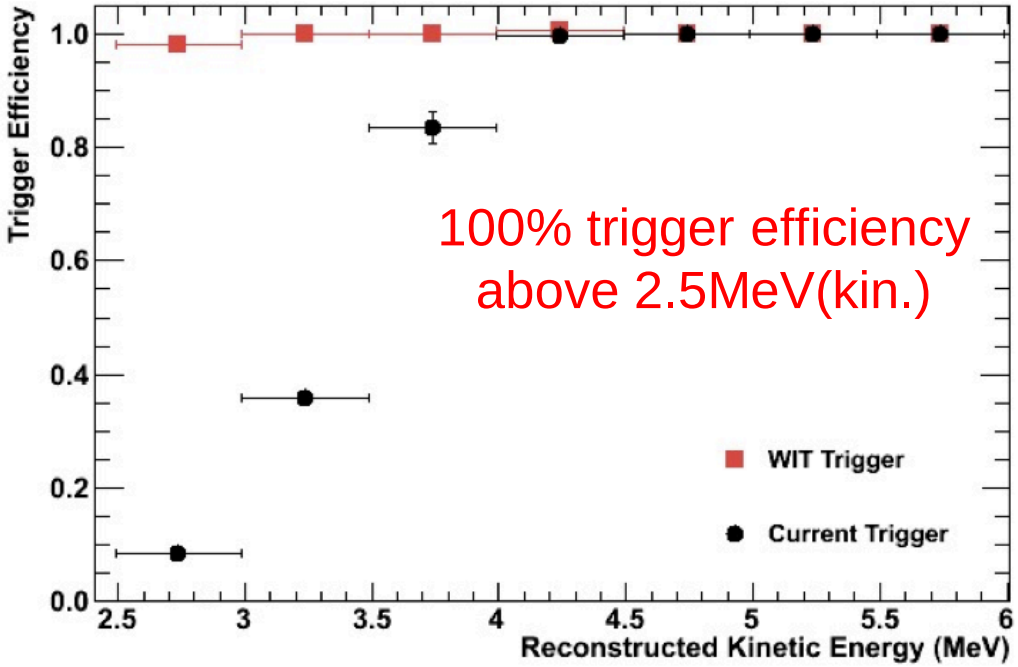
The difference is only 0.2 ºC



Wide-band Intelligent Trigger

- Reconstruction and Reduction just after Front-end

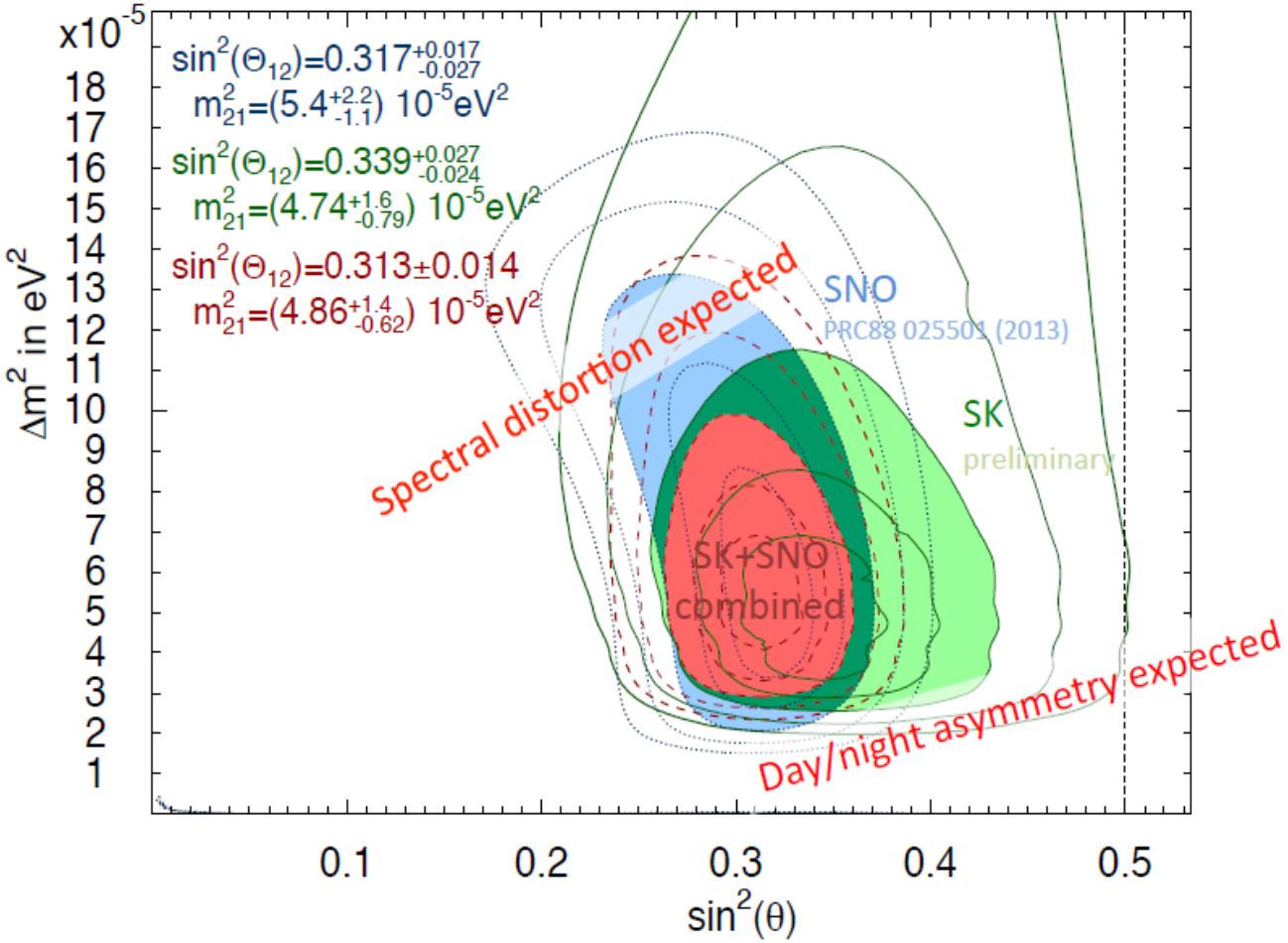




Just started

Oscillation parameter

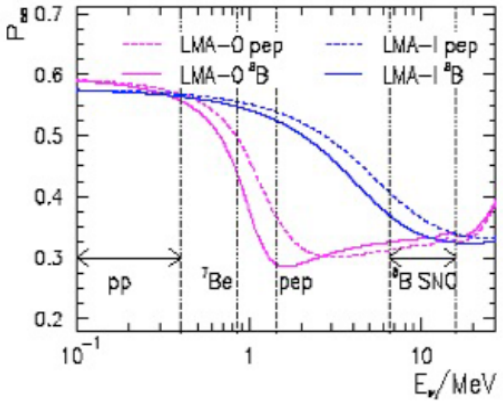
SK and SNO



Probing the Unknown

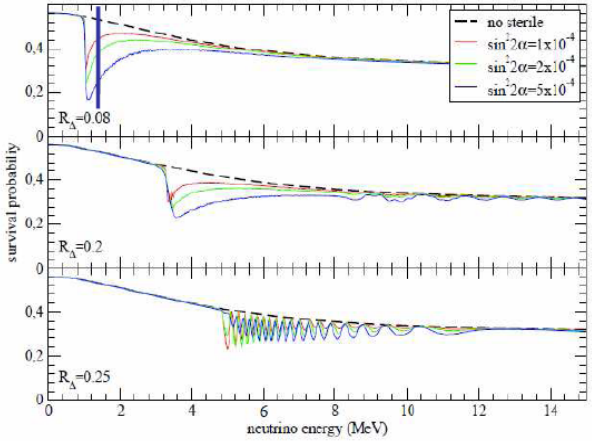
Non-standard physics effects can alter the shape / position of the "MSW rise"

Non-standard interactions (flavour changing NC)



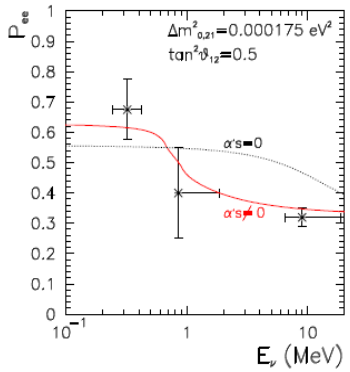
Friedland, Lunardini, Peña-Garay, PLB 594, (2004)

Sterile Neutrinos



Holanda & Smirnov PRD 83 (2011) 113011

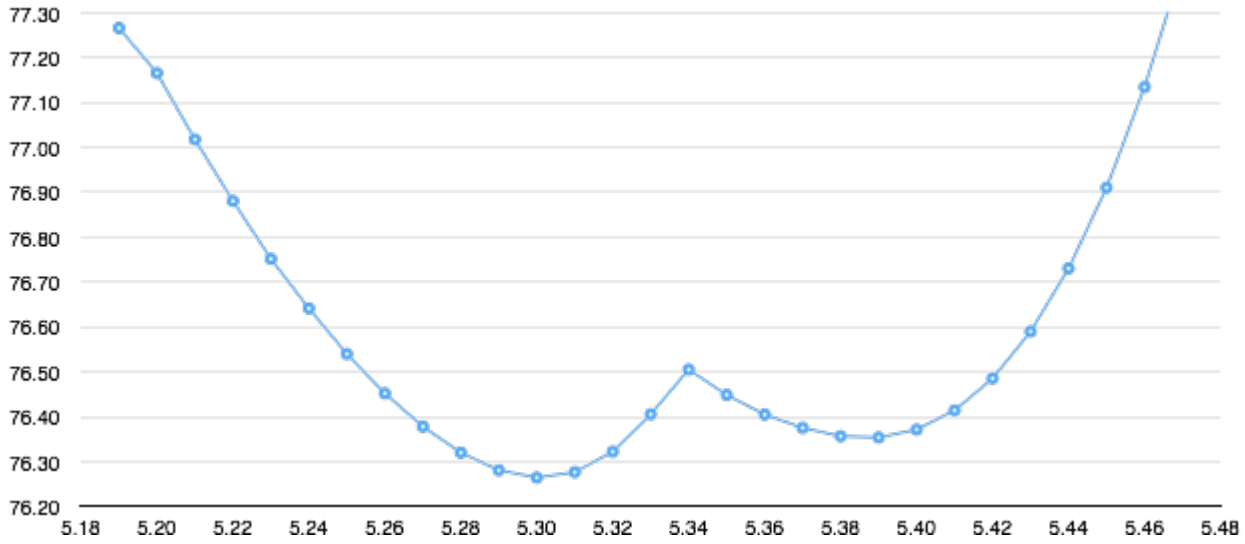
Mass varying neutrinos (MaVaNs)



M.C. Gonzalez-Garcia, M. Maltoni Phys Rept 460:1-129 (2008)

SK+SNO ^{8}B total flux

- For each oscillation parameter set there is a minimum chi2 and a 8B error term describing the parabolic increase of the chi2 with deviations from the best chi2. The reduced chi2 vs. 8B flux is below. The jump is due to the relatively coarse grid in theta12.
- 5.30+0.17-0.11x10^6/(cm2 sec), which is a (+3%,-2%) error on the total 8B for SK+SNO compared to the 1.5% error of SK's ES flux by itself.



Systematic errors

- Total 1.7 %

Source	SK-IV flux (3.5-19.5MeV)	SK-III flux (4.5-19.5MeV)
energy scale	+1.14, -1.16%	±1.4%
energy resolution	+0.14, -0.08%	±0.2%
B8 spectrum	+0.33, -0.37%	±0.2%
trigger efficiency	±0.1%	±0.5%
angular resolution	+0.32, -0.25%	±0.67%
vertex shift	±0.18%	±0.54%
BG event cut	±0.36%	±0.4%
hit pattern cut	±0.27%	±0.25%
another vertex cut	removed	±0.45%
spallation cut	±0.2%	±0.2%
gamma cut	±0.26%	±0.25%
cluster hit cut	+0.45, -0.44%	±0.5%
BG shape	±0.1%	±0.1%
signal extraction	±0.7%	±0.7%
cross section	±0.5%	±0.5%

Data set for global solar analysis

The most up-to-date data are used

- SK:
  - SK-I 1496 days, spectrum 4.5-19.5 MeV(kin.)+D/N:Ekin>4.5 MeV
  - SK-II 791 days, spectrum 6.5-19.5 MeV(kin.)+D/N: Ekin>7.0 MeV
  - SK-III 548 days, spectrum 4.0-19.5 MeV(kin.)+D/N: Ekin>4.5 MeV
  - SK-IV 1669 days, spectrum 3.5-19.5 MeV(kin.)+D/N: Ekin>4.5 MeV
- SNO:
  - Parameterized analysis (c0, c1, c2, a0, a1) of all SNO phased. (PRC88, 025501 (2013))
  - Same method is applied to both SK and SNO with a0 and a1 to LMA expectation
- Radiochemical: Cl, Ga
  - Ga rate: 66.1±3.1 SNU (All Ga global) (PRC80, 015807 (2009))
  - Cl rate: 2.56±0.23 SNU(Astrophys. J.496, 505 (1998))
- Borexino: Latest 7Be flux (PRL 107, 141302 (2011)) **Does NOT include Borexino pp 2014**
- KamLAND reactor : Latest (3-flavor) analysis (PRD88, 3, 033001 (2013))
- 8B spectrum: Winter 2006 (PRC73, 73, 025503 (2006))
- 8B and hep flux $\phi^{8}_{B}=5.25 \times 10^{6}/(cm^{2}\cdot sec)$
  $\phi_{hep}=7.88 \times 10^{3}/(cm^{2}\cdot sec)$

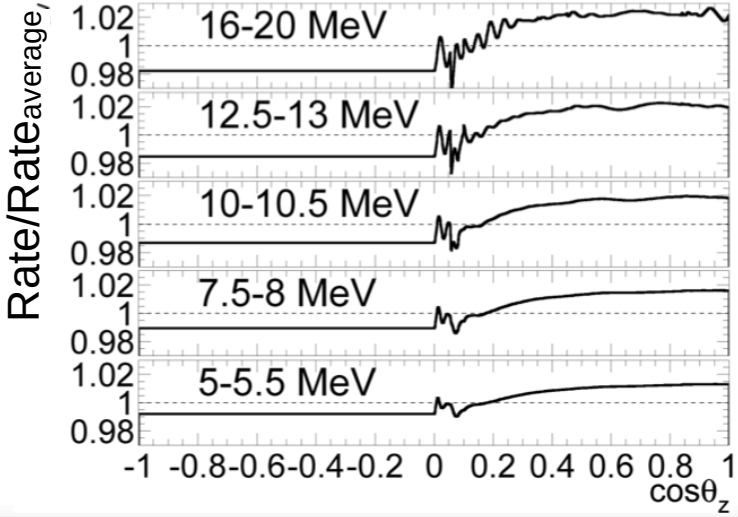
Day / Night

($\sin^2\theta_{12}$=0.311, $\sin^2\theta_{13}$=0.025)

	Amplitude fit		Straight calc. (D-N)/((D+N)/2)
	Δm^2_{21}=4.84x10^{-5} eV^2	Δm^2_{21}=7.50x10^{-5} eV^2	
SK-I	-2.0±1.8±1.0%	-1.9±1.7±1.0%	-2.1±2.0±1.3%
SK-II	-4.4±3.8±1.0%	-4.4±3.6±1.0%	-5.5±4.2±3.7%
SK-III	-4.2±2.7±0.7%	-3.8±2.6±0.7%	-5.9±3.2±1.3%
SK-IV	-3.6±1.6±0.6%	-3.3±1.5±0.6%	-4.9±1.8±1.4%
combined	-3.3±1.0±0.5%	-3.1±1.0±0.5%	-4.1±1.2±0.8%
non-zero significance	3.0σ	2.8σ	2.8σ

preliminary

expected time variation as a function of $\cos\theta_z$

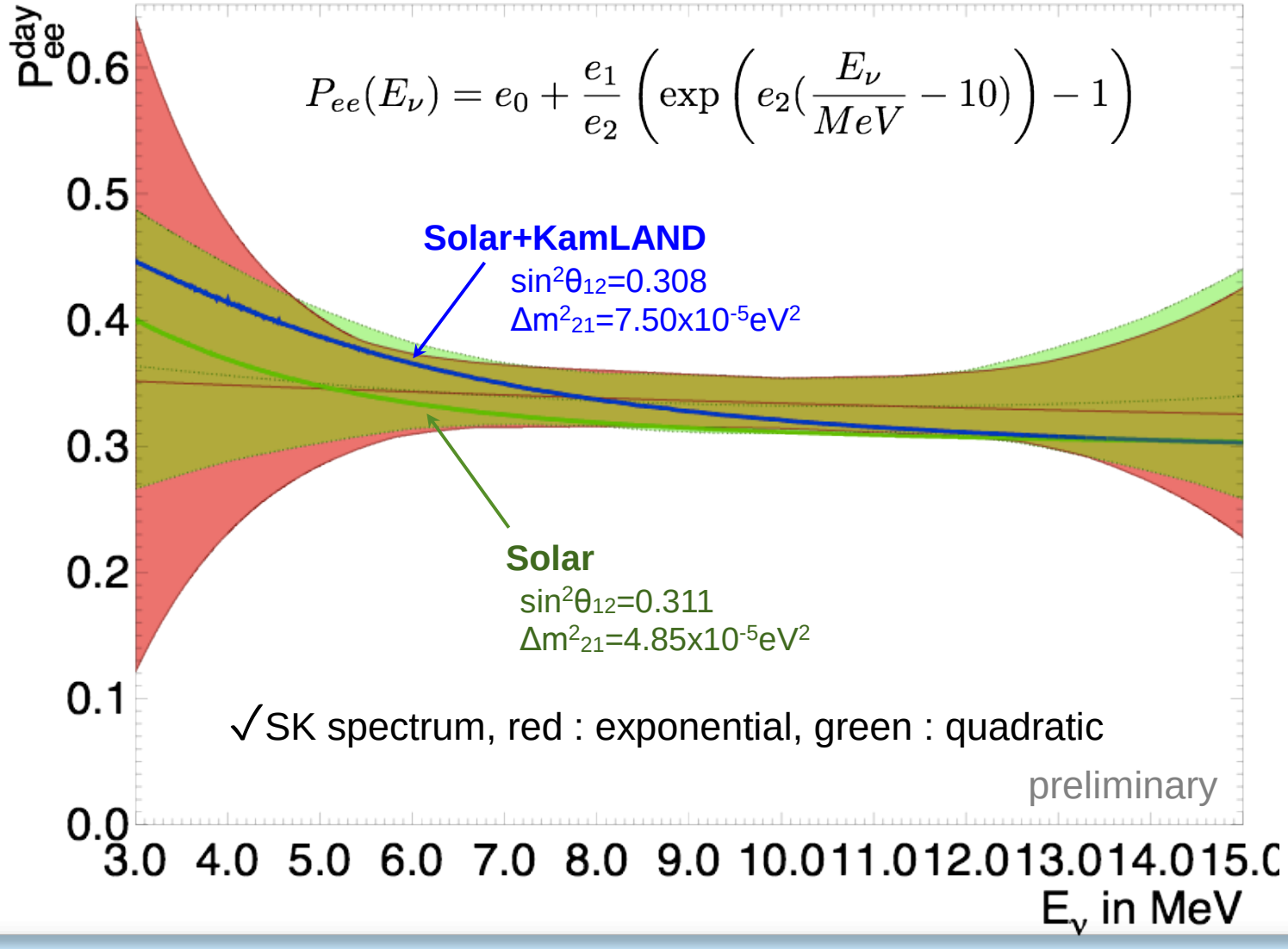


$$\mathcal{L} = e^{-\left(\sum_i B_i + S\right)} \prod_{i=1}^{N_{bin}} \prod_{\nu=1}^{n_i} \left(\beta_i(c_\nu) B_i + \sigma_i(c_\nu) \times z_i(t_\nu) m_i S\right)$$

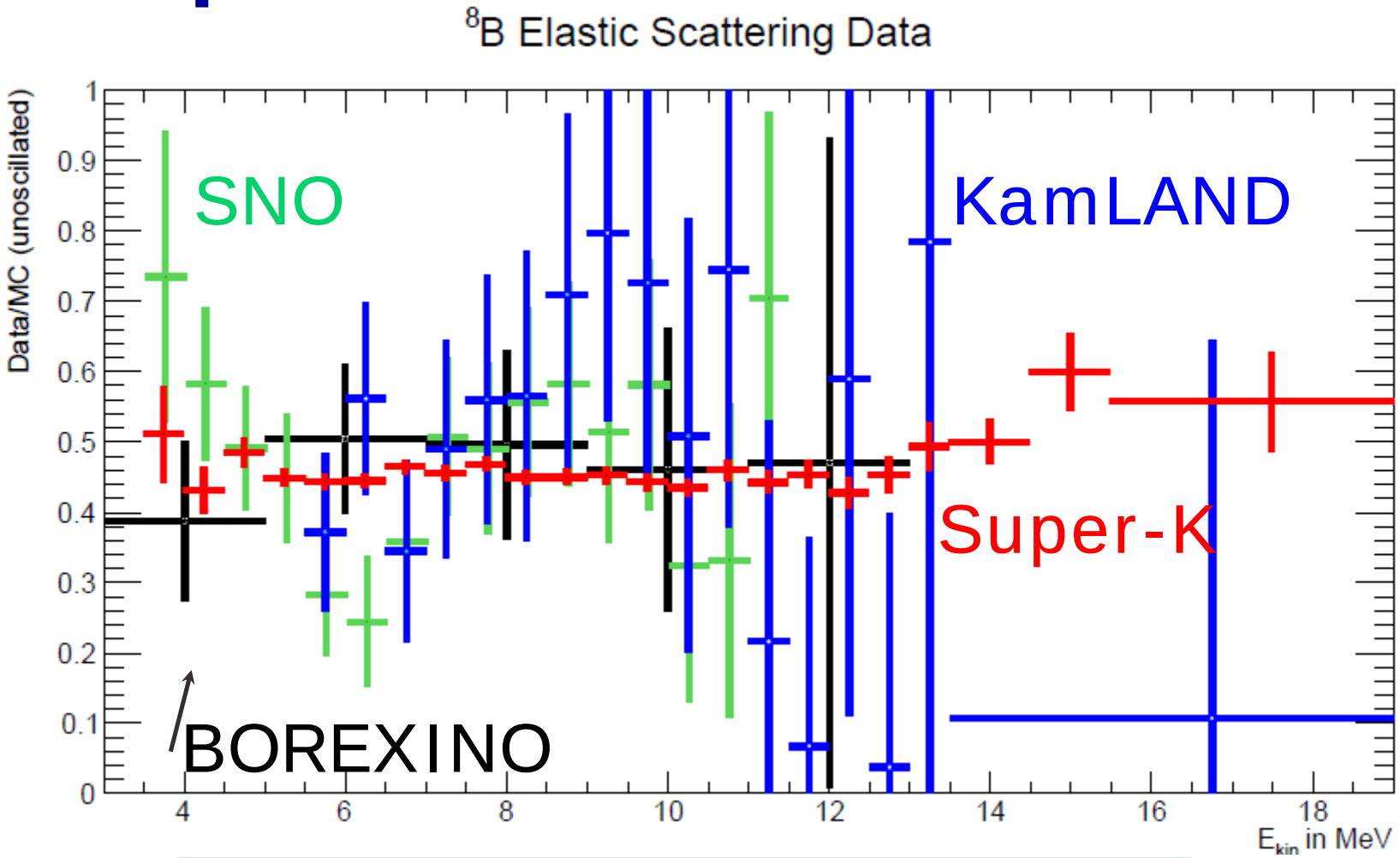
$$z_i(t_\upsilon) \Rightarrow z_i(\alpha, t) = \frac{1 + \alpha((1 + a_i) r_i(t) / r_i^{av} - 1)}{1 + \alpha a_i} \times z_{\exp}(t)$$

α : day-night asym. scaling factor

exponential parameterization



Comparison with others



Super-K spectrum is the most precise!