Solar neutrinos with Super-Kamiokande

Yasuo Takeuchi
Kobe University

- Super-Kamiokande detector
- Solar neutrino observation at SK
- Recent progress in solar neutrino analysis

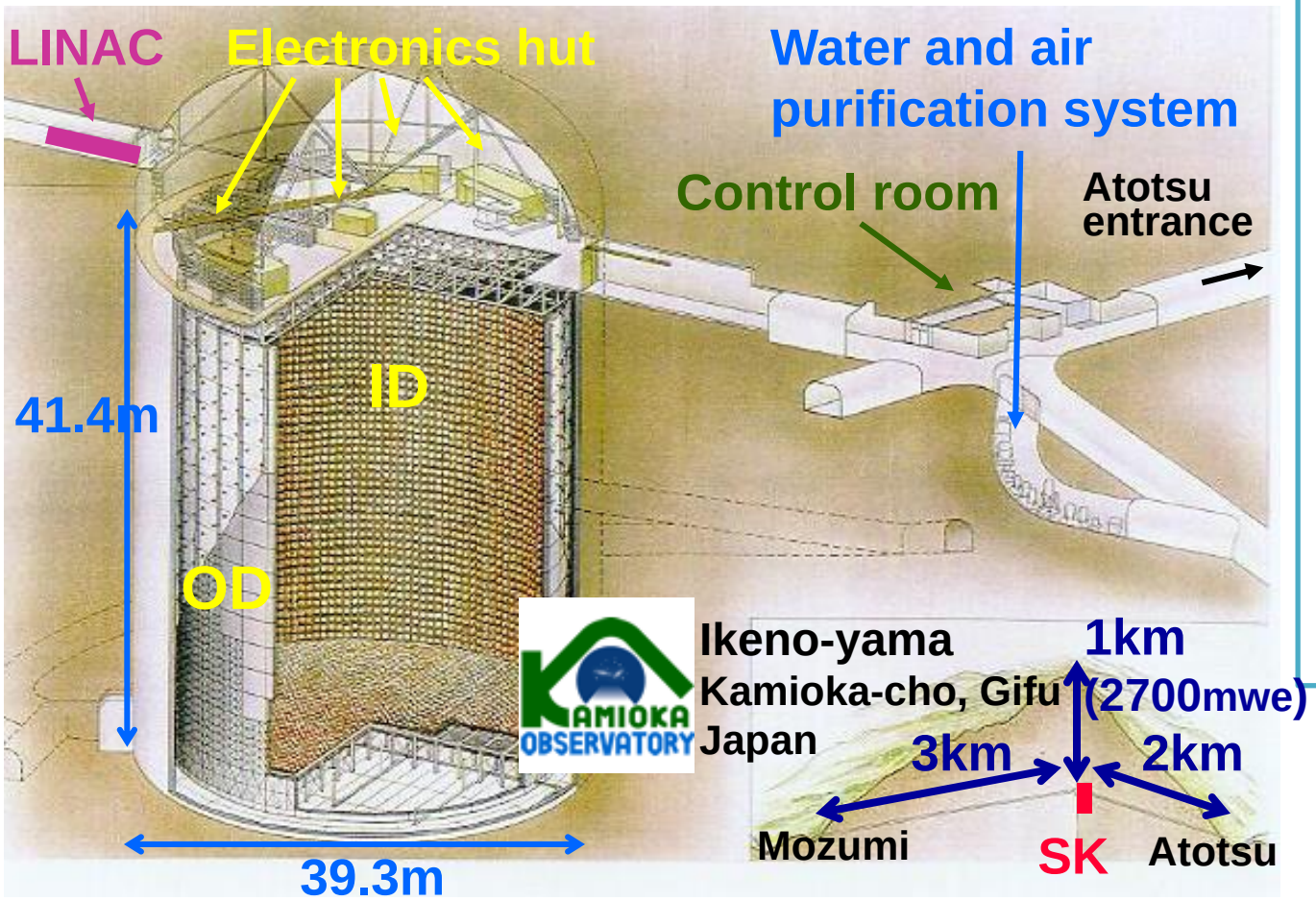
Super-Kamiokande collaboration

主要共同研究機関
Collaborating Institutes

http://www-sk.icrr.u-tokyo.ac.jp/library/pamphlet.html (as of June 2016)

10 nations, ~42 institutions, ~160 researchers (as of June 2017)

Super-Kamiokande detector



- 50 kton water
- ~2m OD viewed by 8-inch PMTs
- 32kt ID viewed by 20-inch PMTs
- 22.5kt fid. vol. (2m from wall)
- SK-I: April 1996~
- SK-IV is running

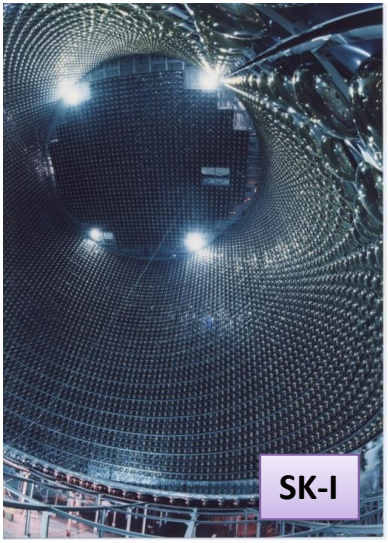
Inner Detector (ID) PMT: ~11100 (SK-I,III,IV), ~5200 (SK-II)
Outer Detector (OD) PMT: 1885

History & Plan of Super-Kamiokande

96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19

SK-I | SK-II | SK-III | SK-IV

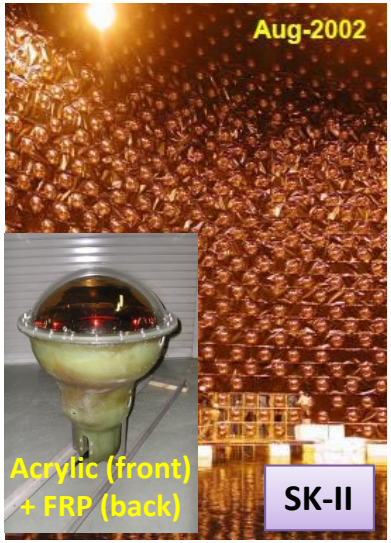
Start upgrade for **SK-Gd** (current plan)



11146 ID PMTs (40% coverage)

4.5 MeV

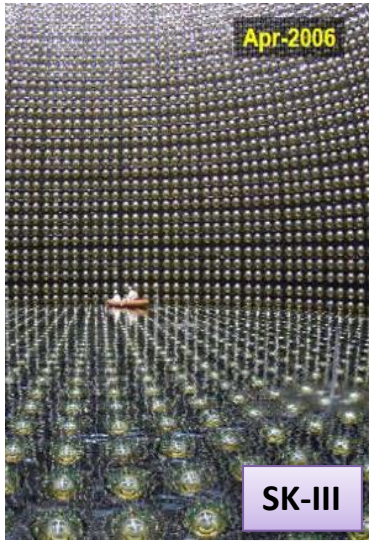
1496 days



5182 ID PMTs (19% coverage)

6.5 MeV

791 days



11129 ID PMTs (40% coverage)

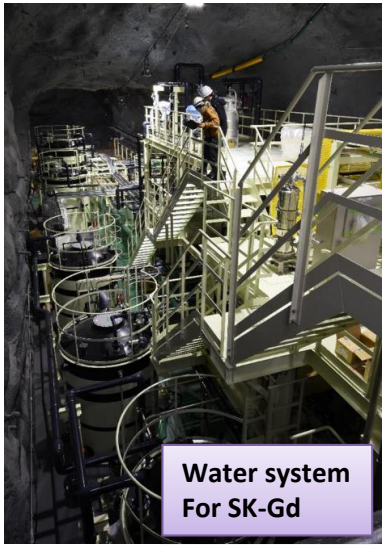
4.5 MeV

548 days

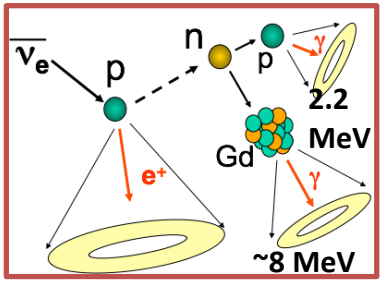
Electronics Upgrade

3.5 MeV

2645 days (~March 2017)



Neutron tagging with Gd



Current total: 5480 days

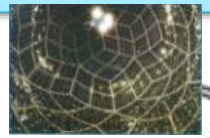
- Analysis energy threshold (recoil electron kinetic energy)
- Live time for solar neutrino analysis

Kamioka Underground site

2700 m.w.e.

http://www-sk.icrr.u-tokyo.ac.jp/

A01/C02: KamLAND



B01/C02: XMASS

A02: CANDLES

D01: Low-radioactivity R&D (LAB-A, 2015~)

C02: Super-Kamiokande

40m

C01: SK-Gd water system

IPMU
Rn det.
(D01)
APIMS
GC
Ge det.
…

C01: R&D of SK-Gd

B02: NEWAGE

"Revealing the history of the universe with underground particle and nuclear research" http://www.lowbg.org/ugnd/

A: Majorana ν
A01: KamLAND, A02: CANDLES

B: Dark matter
B01: XMASS, B02: NEWAGE, …

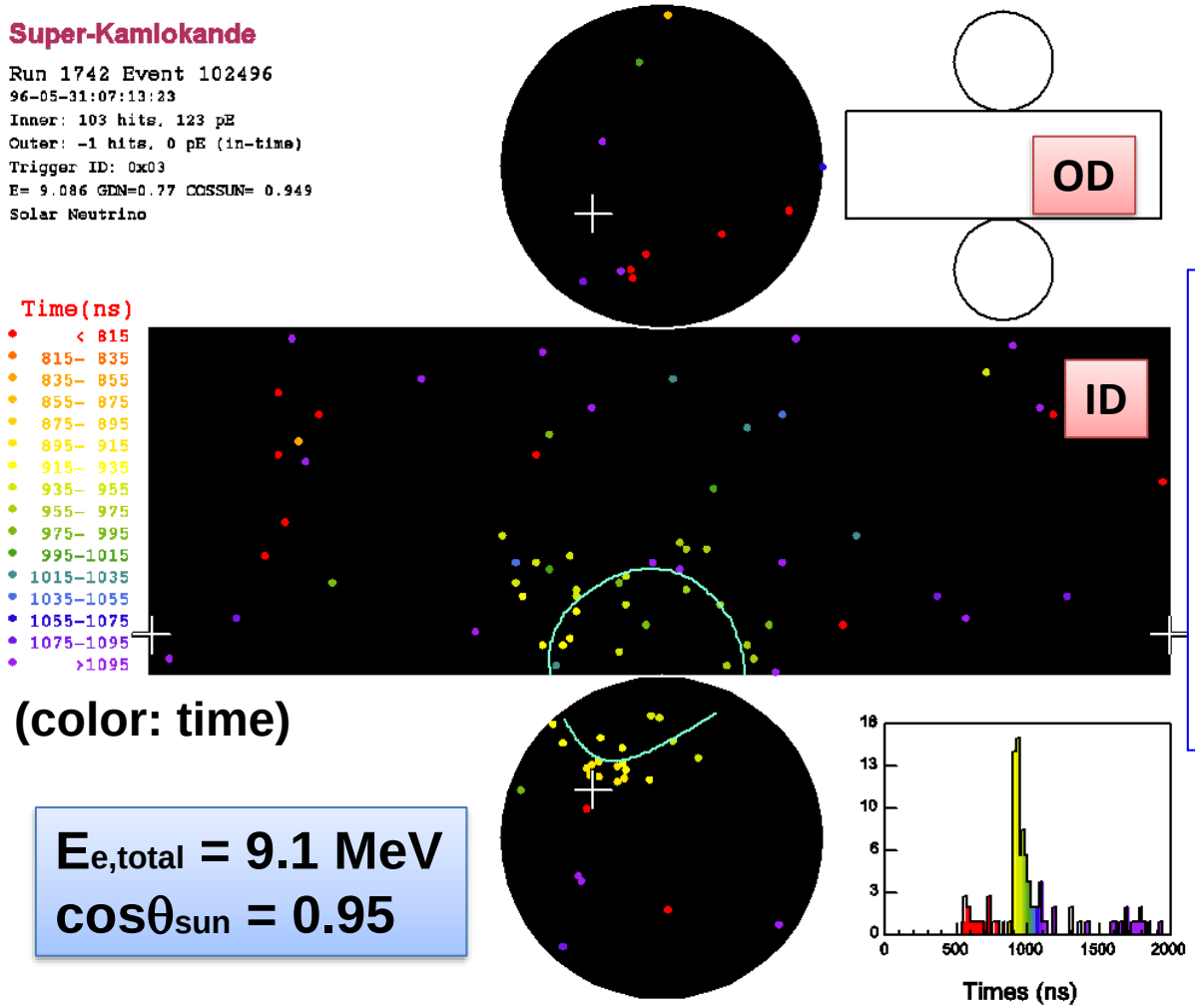
C: Supernova ν
C01: SK-Gd, C02: SN network

D01: Low BG techniques

E01: Theory

科研費 KAKENHI

Typical low-energy event



(color: time)

$\nu + e^- \rightarrow \nu + e^-$

(for solar neutrinos)

- Timing information
  - ➡ vertex position
- Ring pattern
  - ➡ direction
- Number of hit PMTs
  - ➡ energy

$E_{e,total}$ = 9.1 MeV
$\cos\theta_{sun}$ = 0.95

~6 hit / MeV
(SK-I, III, IV)

Resolutions (for 10MeV electrons)

(software improvement)

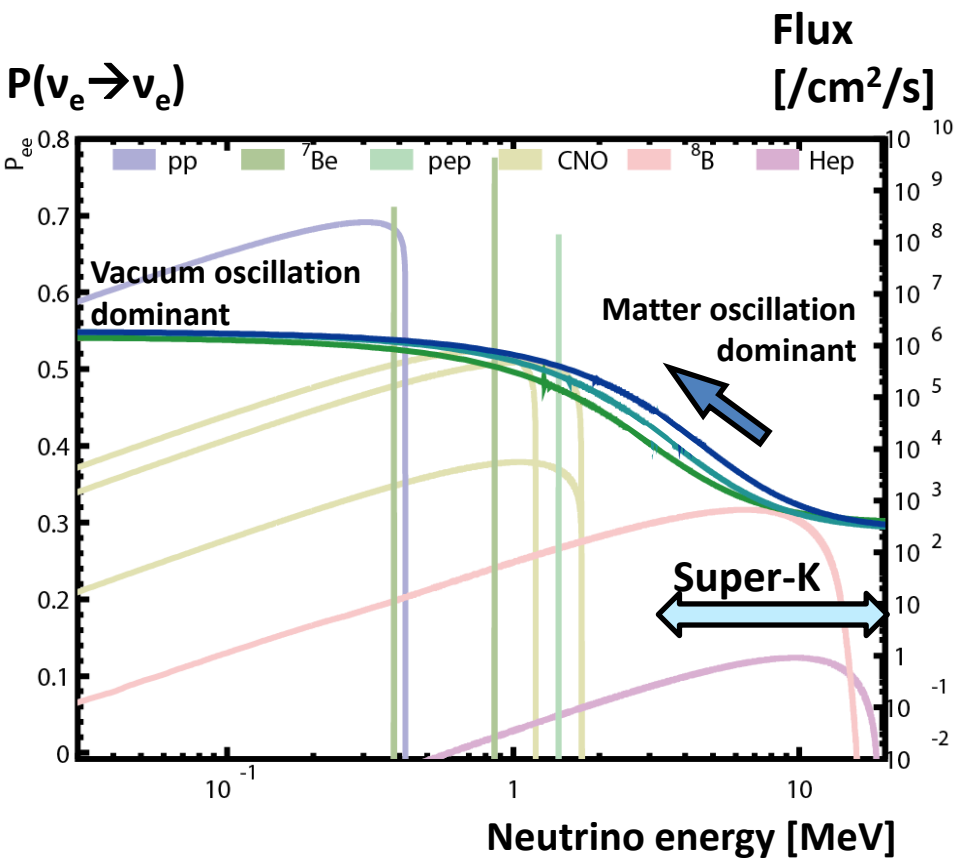
Energy: 14%	Vertex: 87cm	Direction: 26º SK-I
Energy: 14%	Vertex: 55cm	Direction: 23º SK-III

^{8}B solar neutrino measurement

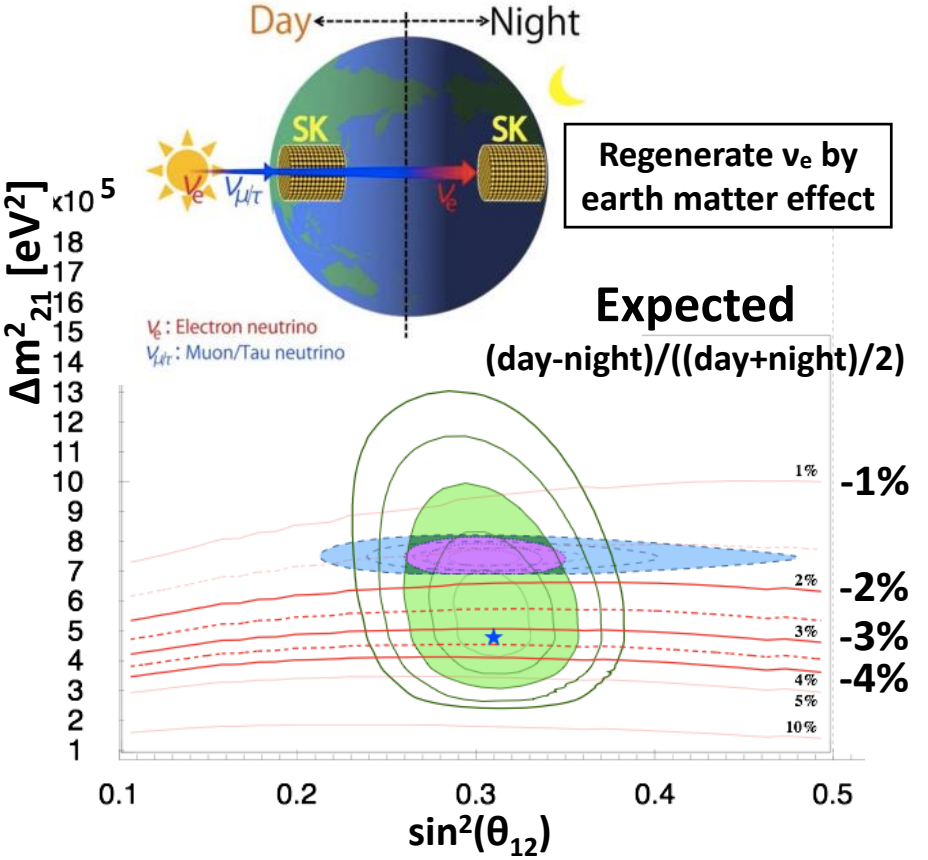
- High statistics (~20events/day) measurement of ^{8}B solar neutrinos
  - Possible time variation of the flux
  - **Energy spectrum distortion** due to solar matter effect
  - **Day-night flux asymmetry** due to earth matter effect

$$A_{DN} = \frac{(Day - Night)}{(Day + Night)/2}$$

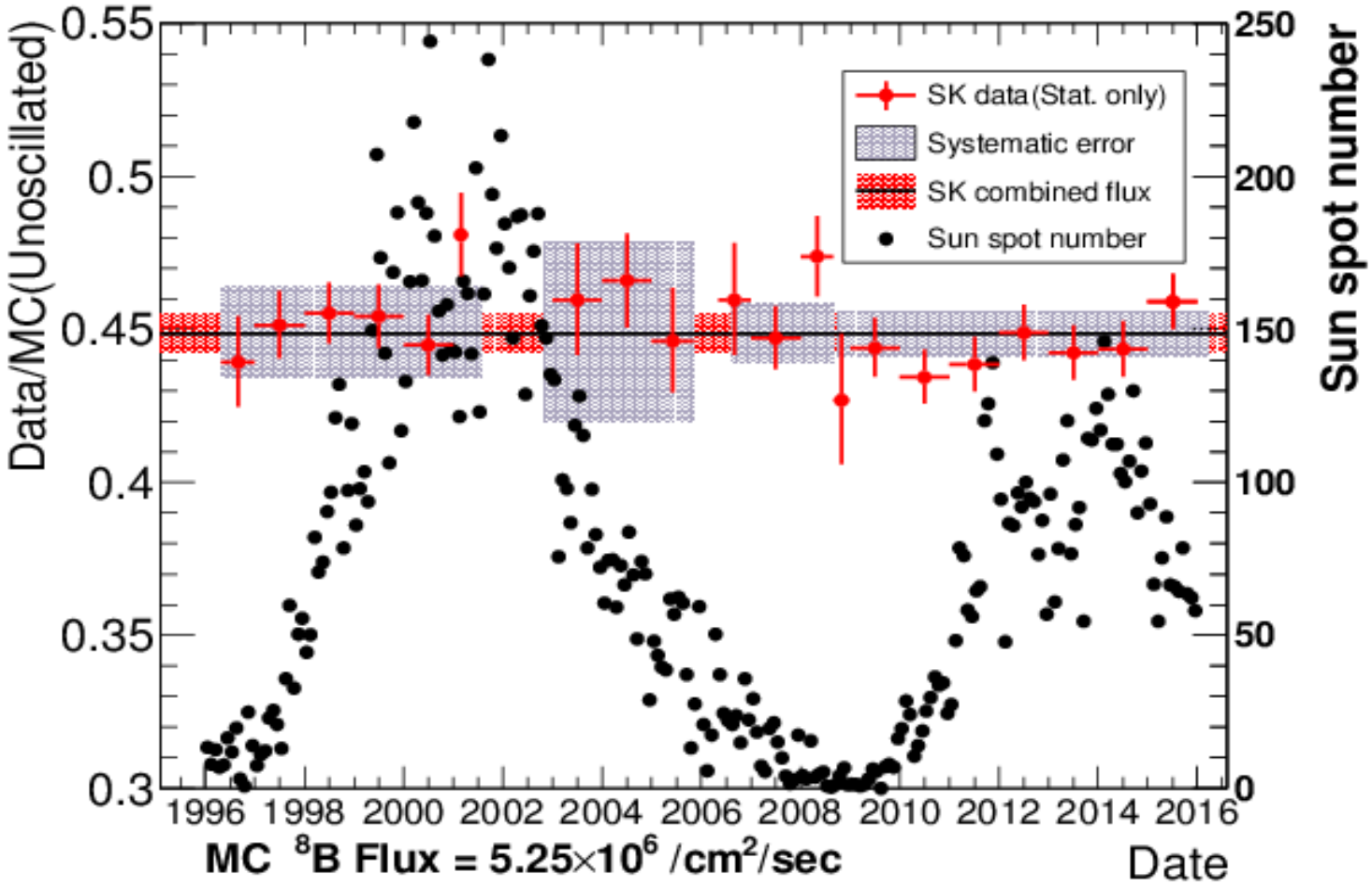
Spectrum distortion



Day-Night flux asymmetry



^{8}B solar neutrino flux: Yearly plot



Preliminary

SK-I~IV 5200 days

Sun spot number: WDC-SILSO, Royal Observatory of Belgium, Brussels

χ^2 = 15.52 / 19 d.o.f. → Confidence level = 69 %

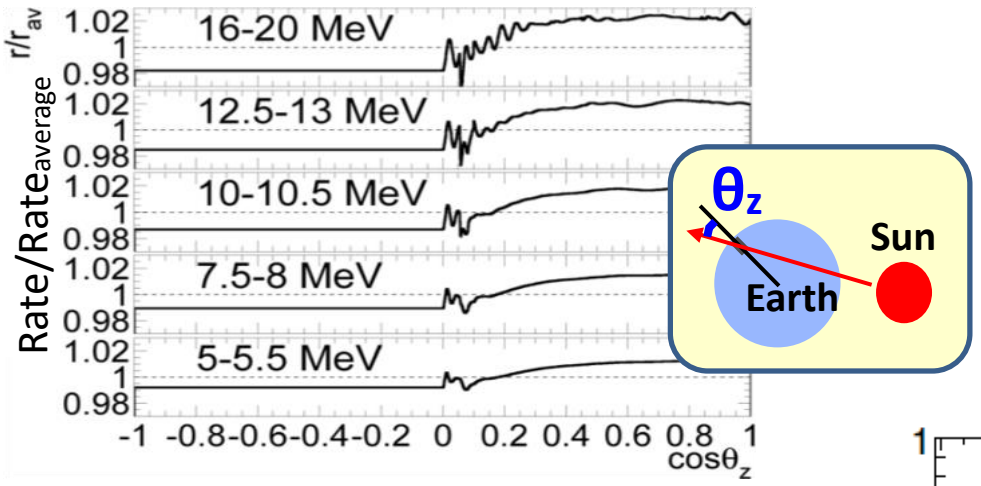
Super-K solar rate measurements are fully consistent with a constant solar neutrino flux emitted by the Sun.

Day/Night asymmetry (A_{DN}^{fit})

Assuming the expected time variation as a function of $\cos\theta_z$ like below, amplitude of A_{DN} was fitted.

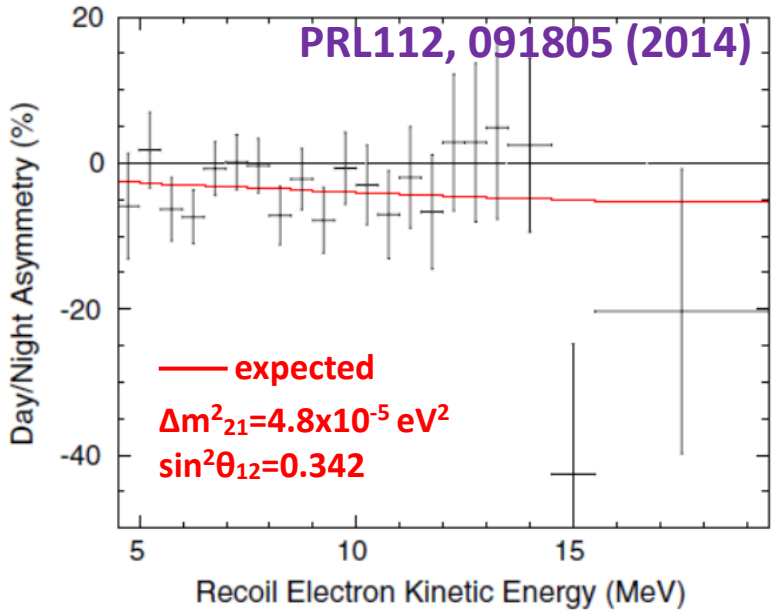
For solar global parameter:
$\Delta m^2_{21}=4.84\times10^{-5}$ eV^2
$\sin^2\theta_{12}=0.311$

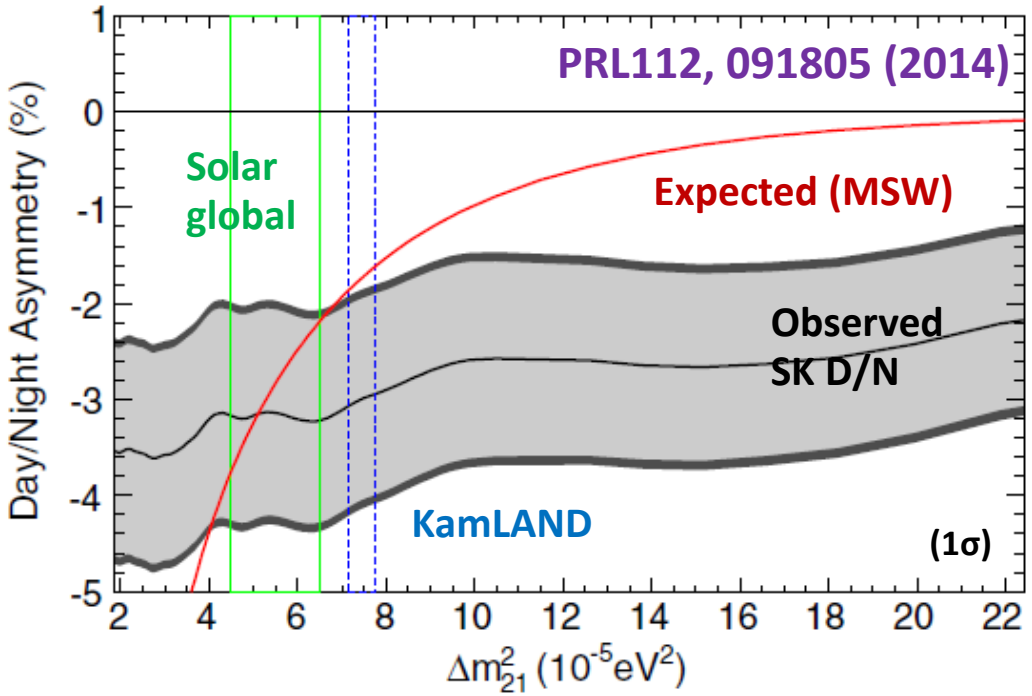
$$A_{DN} = \frac{(Day - Night)}{(Day + Night)/2}$$



	A_{DN}^{fit} (%)
SK-IV, 1664 days	-3.3+/-1.5+/-0.6
SK-I~IV, 4499 days	-3.3+/-1.0+/-0.5
Non-zero significance	2.9 σ

PRD94, 052010 (2016)

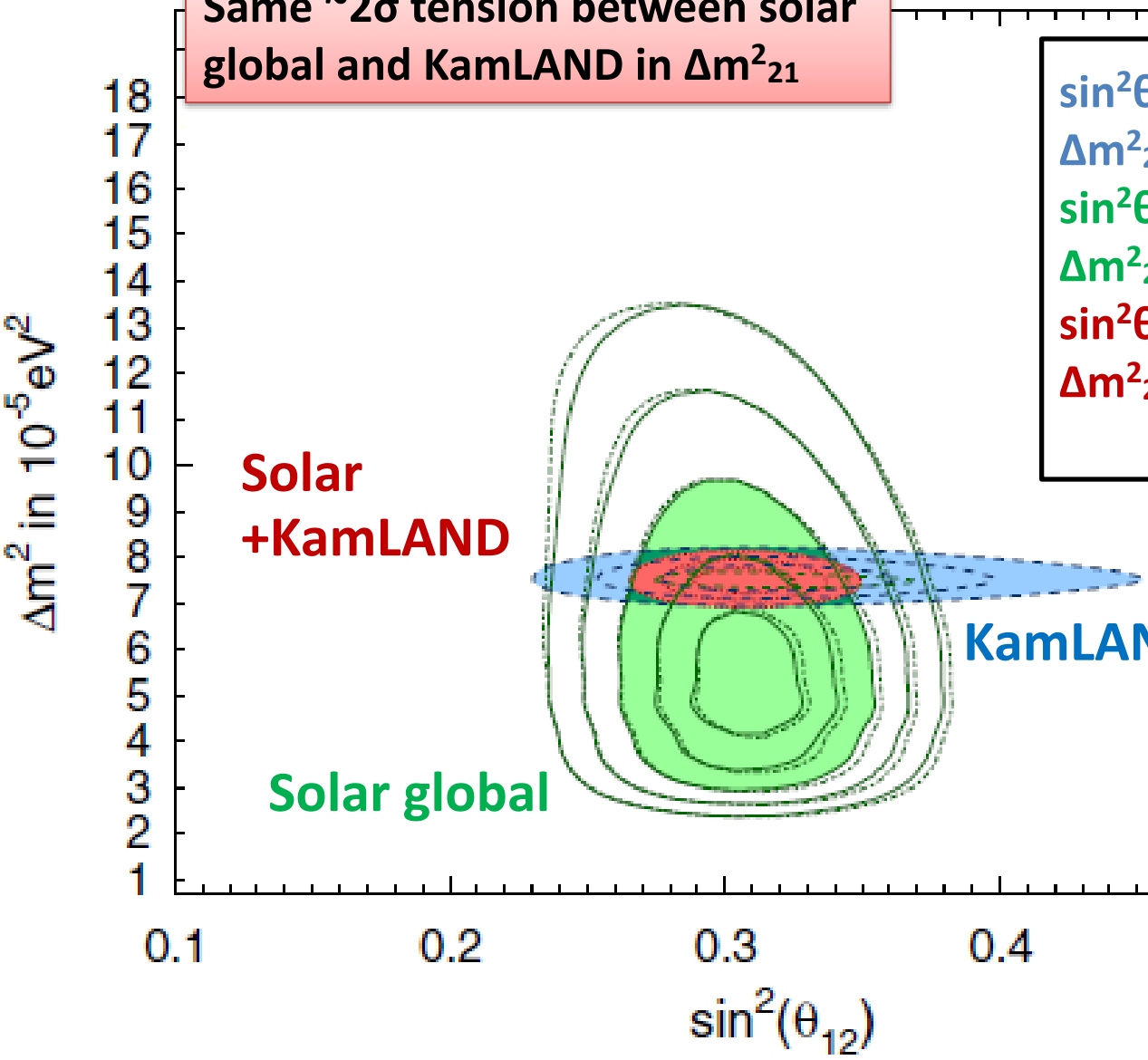




θ_{12} and Δm^2_{21} from Solar global vs. KamLAND

PRD94, 052010 (2016)

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



$\sin^2\theta_{12}$= 0.316+0.034/-0.026
Δm^2_{21}= 7.54+0.19/-0.18
$\sin^2\theta_{12}$= 0.308+/-0.014
Δm^2_{21}= 4.85+1.33/-0.59
$\sin^2\theta_{12}$= 0.307+0.013/-0.012
Δm^2_{21}= 7.49+0.19/-0.18

(The unit of Δm^2_{21} is 10^{-5} eV^2)

Constrained with $\sin^2\theta_{13}$=0.0219+/-0.0014 (from short baseline exp.)

Recent progress in solar ν analysis

June 2017

- **Updated spectrum analysis**
  - Total live time 5480 days (May 1996 - March 2017)
  - SK-I (1496 days), SK-II (791 days), SK-III (548 days), SK-IV (2645 days, PRD94, 052010: 1664 days)
- **Preliminary periodic modulation analysis in SK-IV**
  - Using same data set as PRD94, 052010
- **Energy scale improvement**
  - Taking into account PMT gain & dark rate effects
- **Study of spallation BG**
  - Start looking neutron data in SK-IV
- **Study of radon BG**
  - "Measurement of Radon Concentration in Super-Kamiokande's Buffer Gas", NIM A867 (2017) 108-114 (DOI: 10.1016/j.nima.2017.04.037)

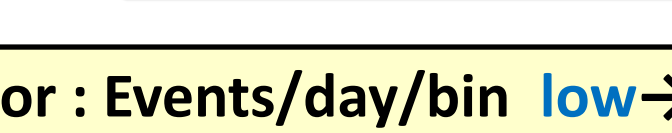
Vertex distribution in SK-IV

June 2017

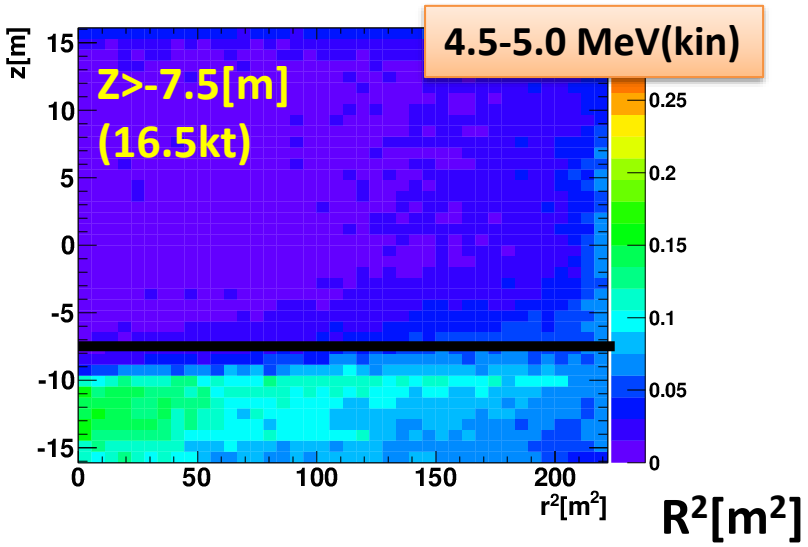
Preliminary

SK-IV 2645 days

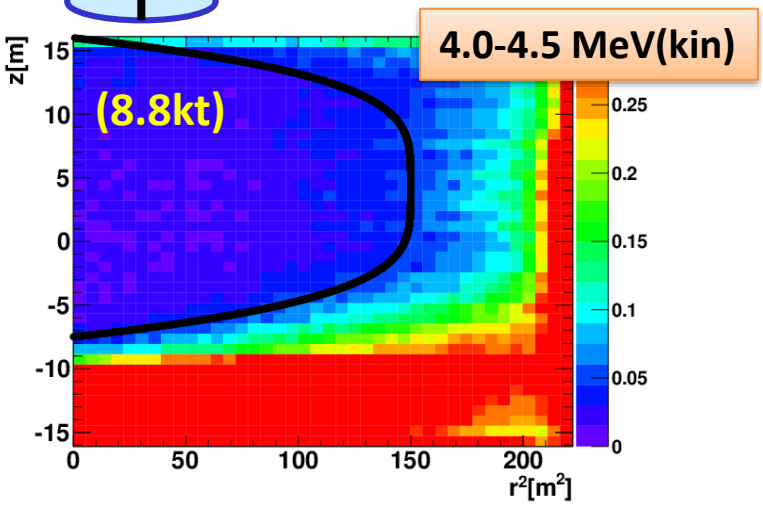
Color : Events/day/bin low→high

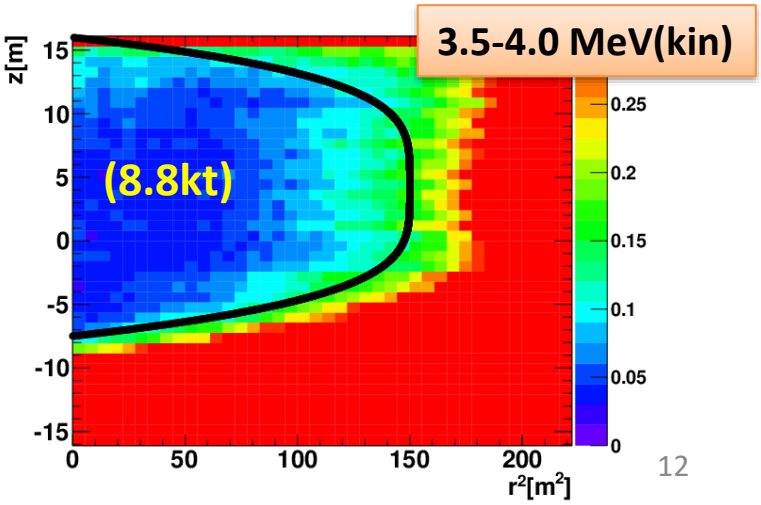


Z[m]



R²[m²]





- Whole area in these plots corresponds to 22.5 kton.
- Above 5.0 MeV(kin), fiducial volume is 22.5kton.
- Below 5.0 MeV tight fiducial volume cut is applied.
- Water condition is controlled well

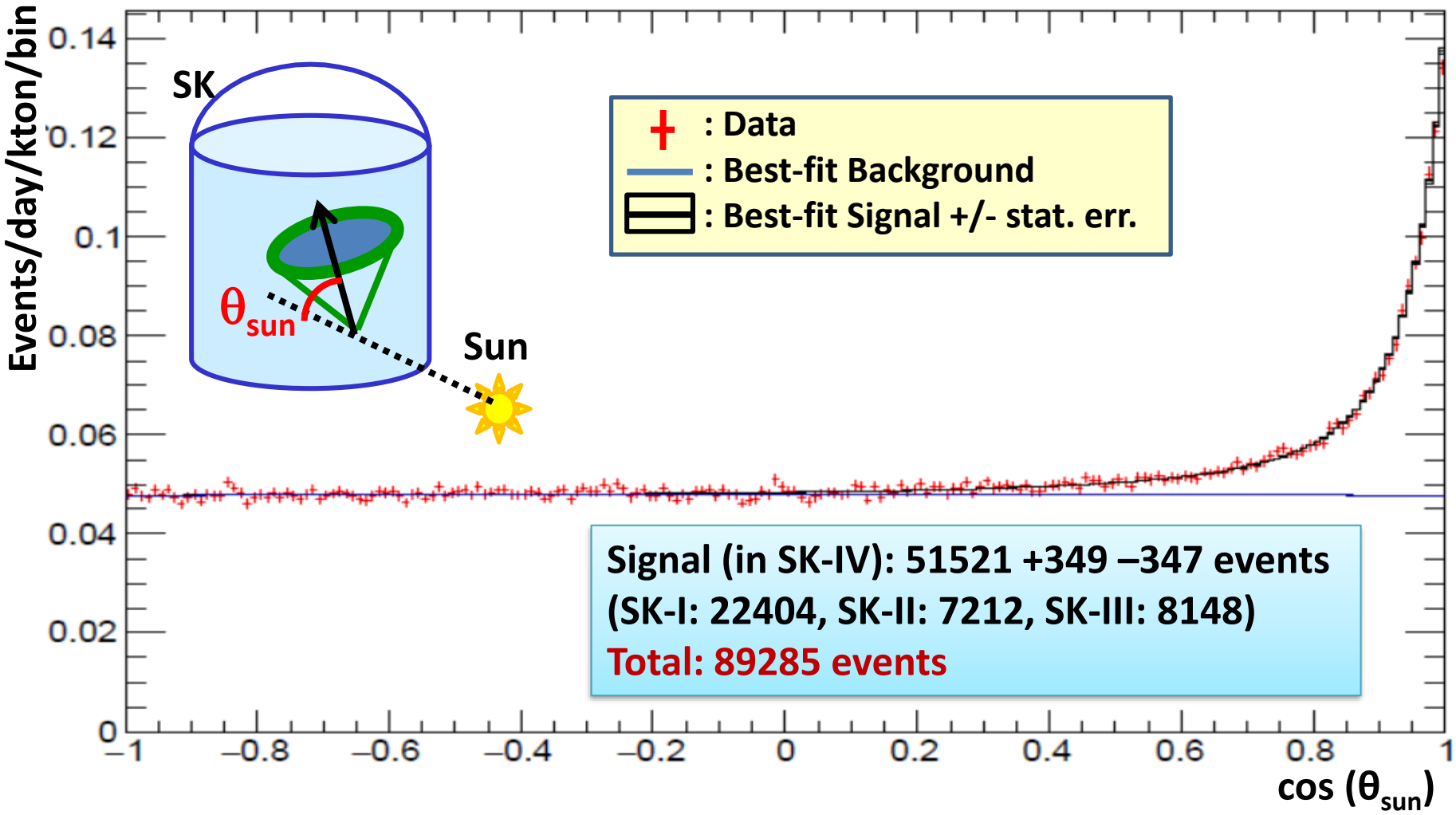
SK-IV solar neutrino signal

June 2017

Preliminary

SK-IV 2645 days

SK-IV 3.5-19.5 MeV(kin)

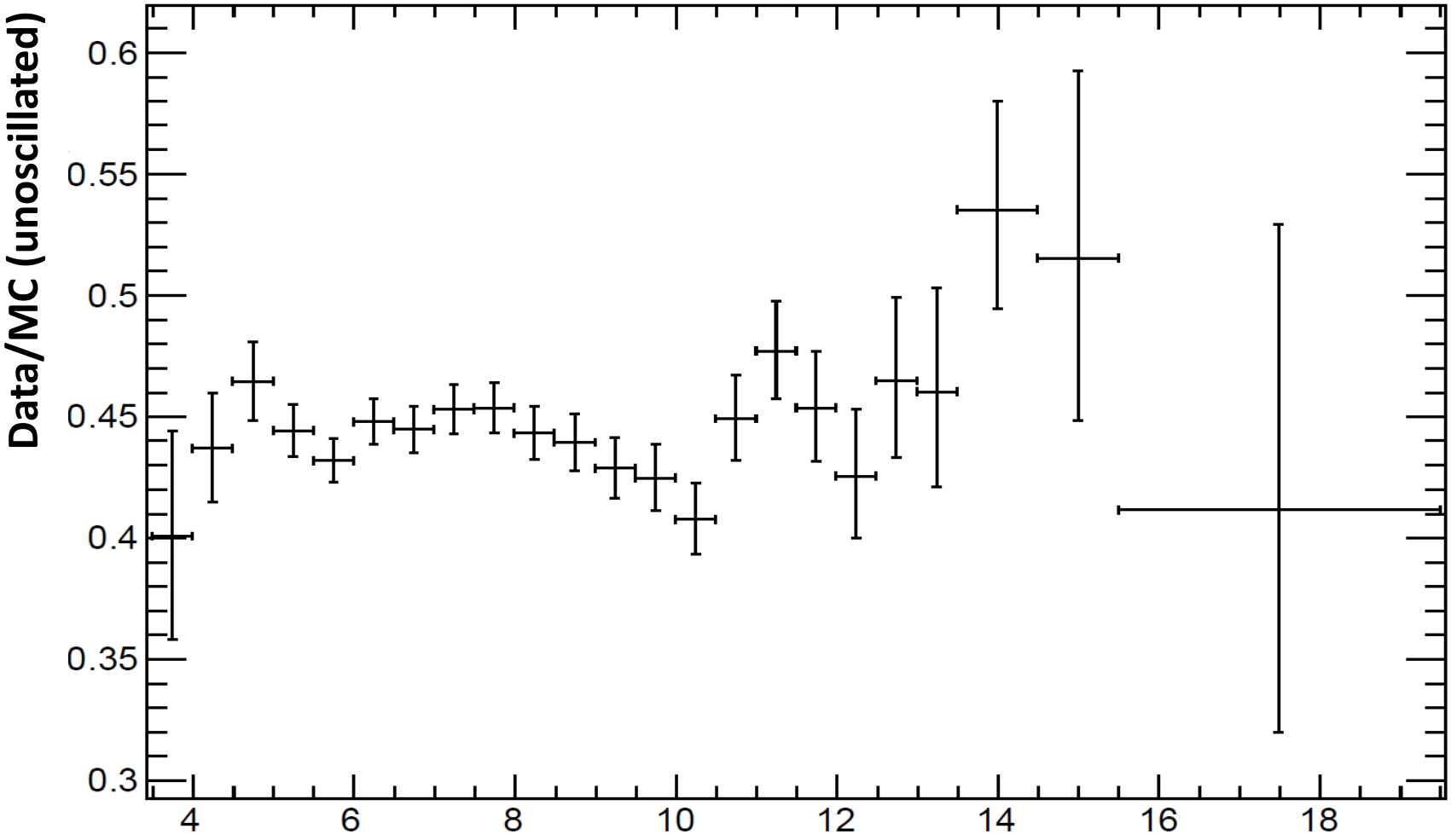


SK-IV solar neutrino energy spectrum

June 2017

Preliminary

SK-IV 2645 days



(MC flux = 5.25x10^6 cm^2/s from SNO NC)

Data set for oscillation analysis

June 2017

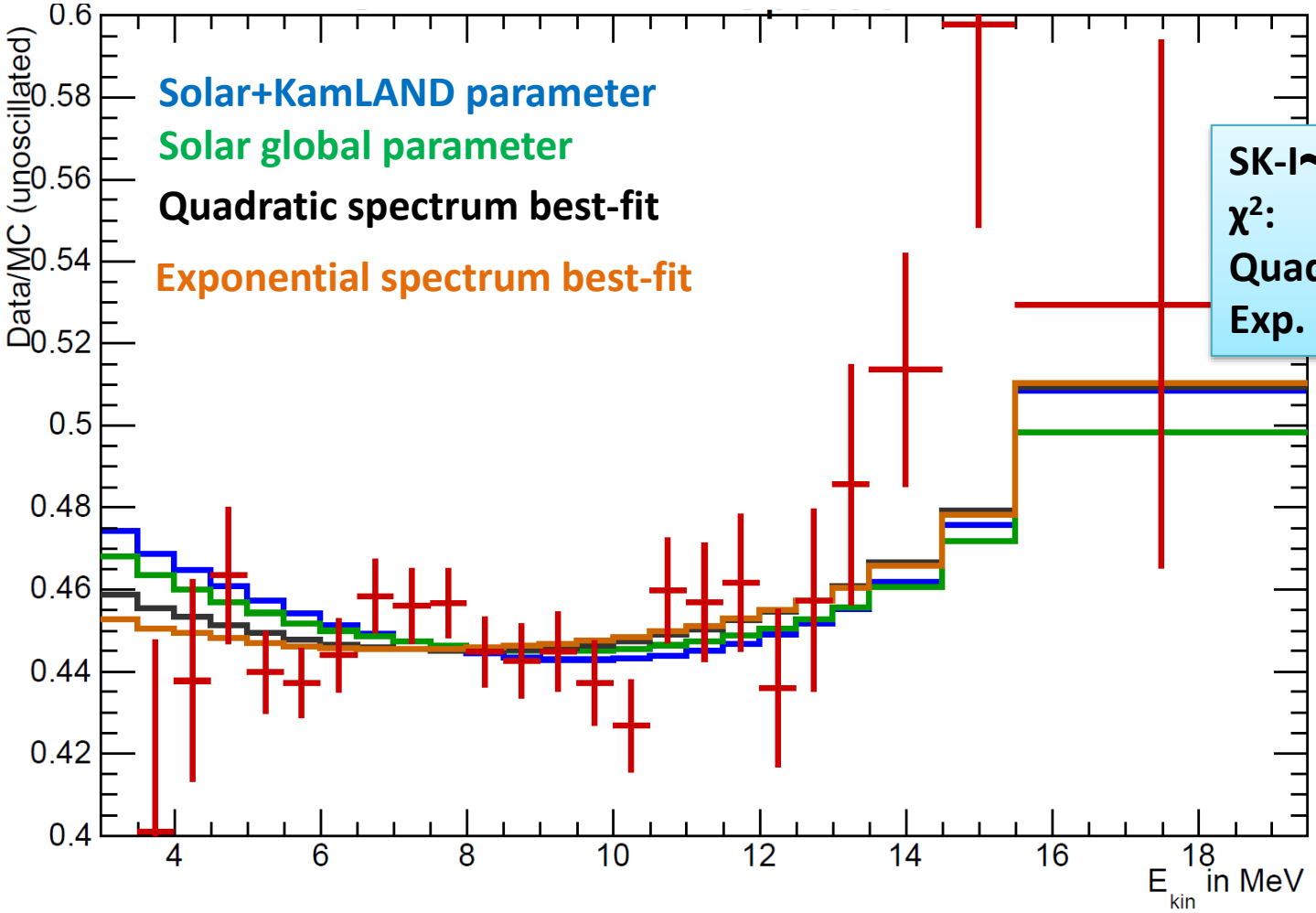
Preliminary

- SK: PRD94,052010(2016) + preliminary SK-IV spectrum data
  - SK-I 1496 days, spectrum 4.5-19.5MeV(kin) + D/N : E ≥ 4.5MeV(kin)
  - SK-II 791 days, spectrum 6.5-19.5MeV(kin) + D/N : E ≥ 7.0MeV(kin)
  - SK-III 548 days, spectrum 4.0-19.5MeV(kin) + D/N : E ≥ 4.5MeV(kin)
  - SK-IV 2645 days, spectrum 3.5-19.5MeV(kin)
    + D/N (1664days) : E ≥ 4.5MeV(kin)
- SNO: PRC88,025501 (2013)
- 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 : ^{7}Be flux (PRL107, 141302 (2011))
- KamLAND : reactor measurement (PRD88, 033001 (2013))
- ^{8}B spectrum : Winter 2006 (PRC73, 025503 (2006))
- ^{8}B and *hep* flux free, if not mentioned.

Super-K Spectral Data

June 2017

Preliminary



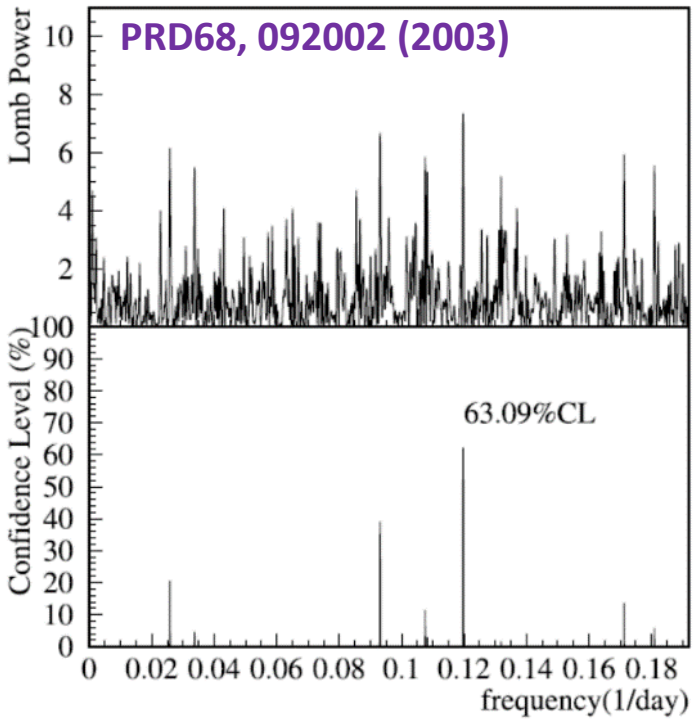
SK-I~IV: 83 bins
χ^2:
Quad. Fit: 75.5 /80 dof
Exp. Fit: 75.5 /80 dof

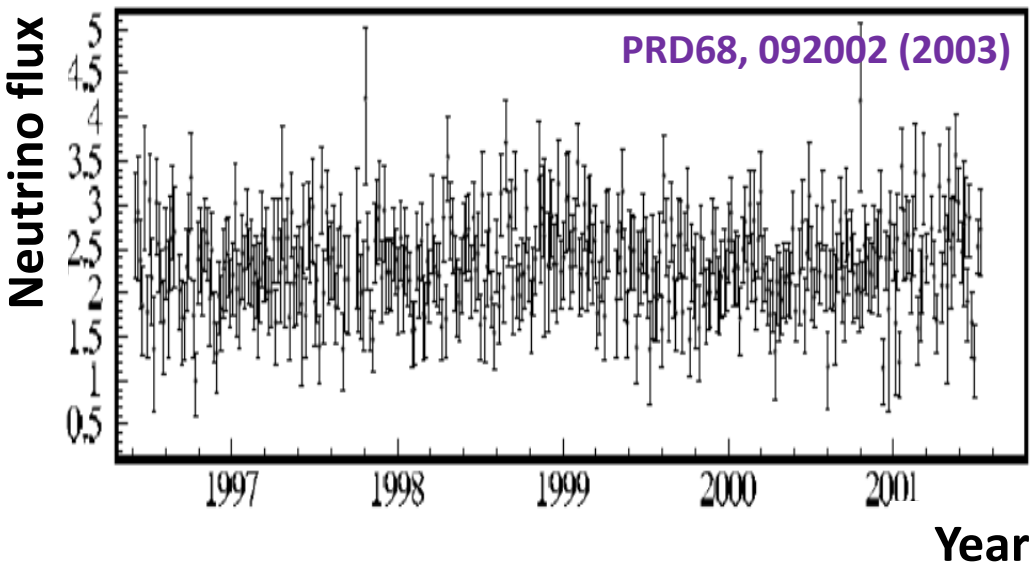
All SK phases are combined without regards to energy resolution or systematics in this figure

SK spectrum is consistent within ~1 sigma with the MSW upturn for the solar best fit parameters, and marginally consistent within ~2 sigma with the MSW upturn for the solar+KamLAND best fit parameters.

Periodic modulation analysis in SK-IV

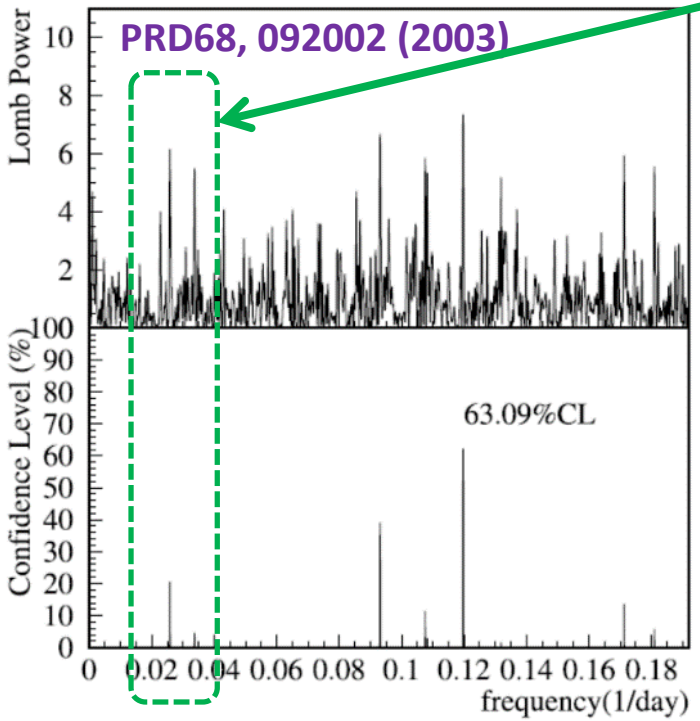
- **Past publication: PRD68, 092002 (2003)**
  - **SK-I 1496 days, 4.5-19.5 MeV(kin)**
  - **Used Lomb-Scargle (LS) and 5-day long samples**

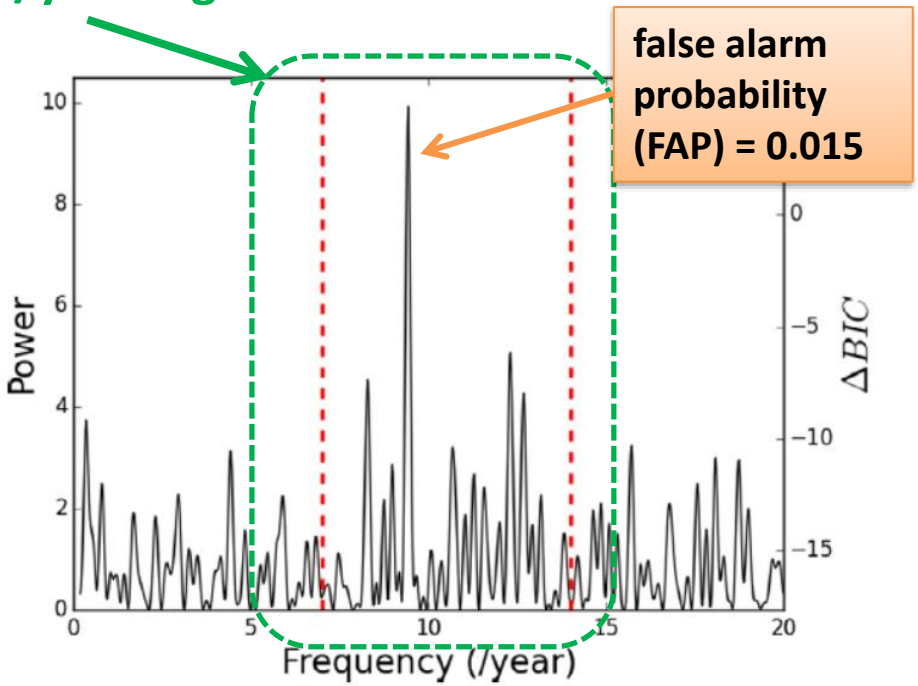




Periodic modulation analysis in SK-IV

- **Past publication: PRD68, 092002 (2003)**
  - **SK-I 1496 days, 4.5-19.5 MeV(kin)**
  - **Used Lomb-Scargle (LS) and 5-day long samples**
- **It is pointed out that a maximum peak is observed at around 9.43/year from several researchers.**
  - **Analysis techniques are improved**
- **We have reanalyzed SK-I data with Generalized LS method in astroML.**
- **A preliminary search in SK-IV in 5~15/year region is also done.**





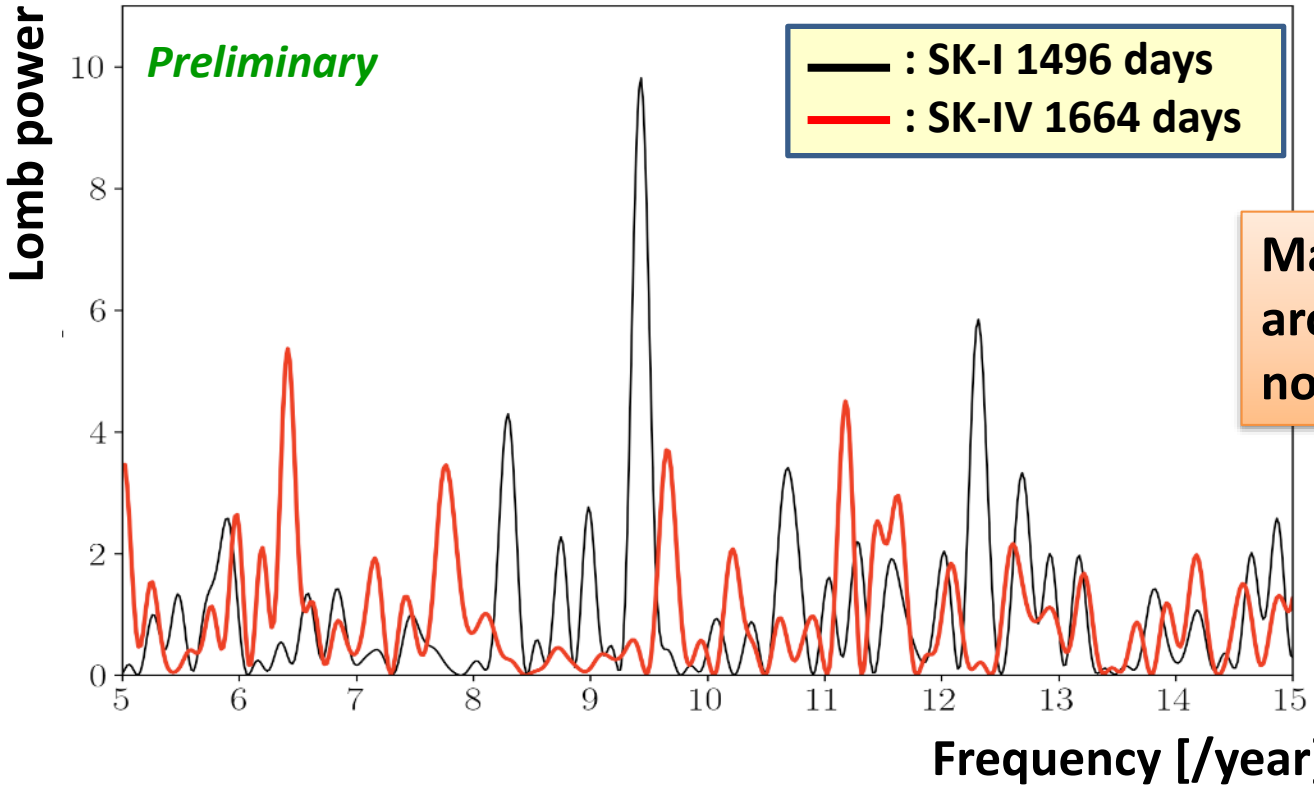
S. Desai, D.W. Liu / Astroparticle Physics 82 (2016) 86–92

Periodic modulation analysis in SK-IV

June 2017

Preliminary

- **Data set:**
  - SK-I: 1496days, 5-day long sample, 4.5-19.5 MeV(kin)
  - SK-IV: 1664 days, 5-day long sample, 4.5-19.5 MeV(kin)
  - Generalized LS method (with symmetric error)
  - Search region: 5 – 15 [/year]

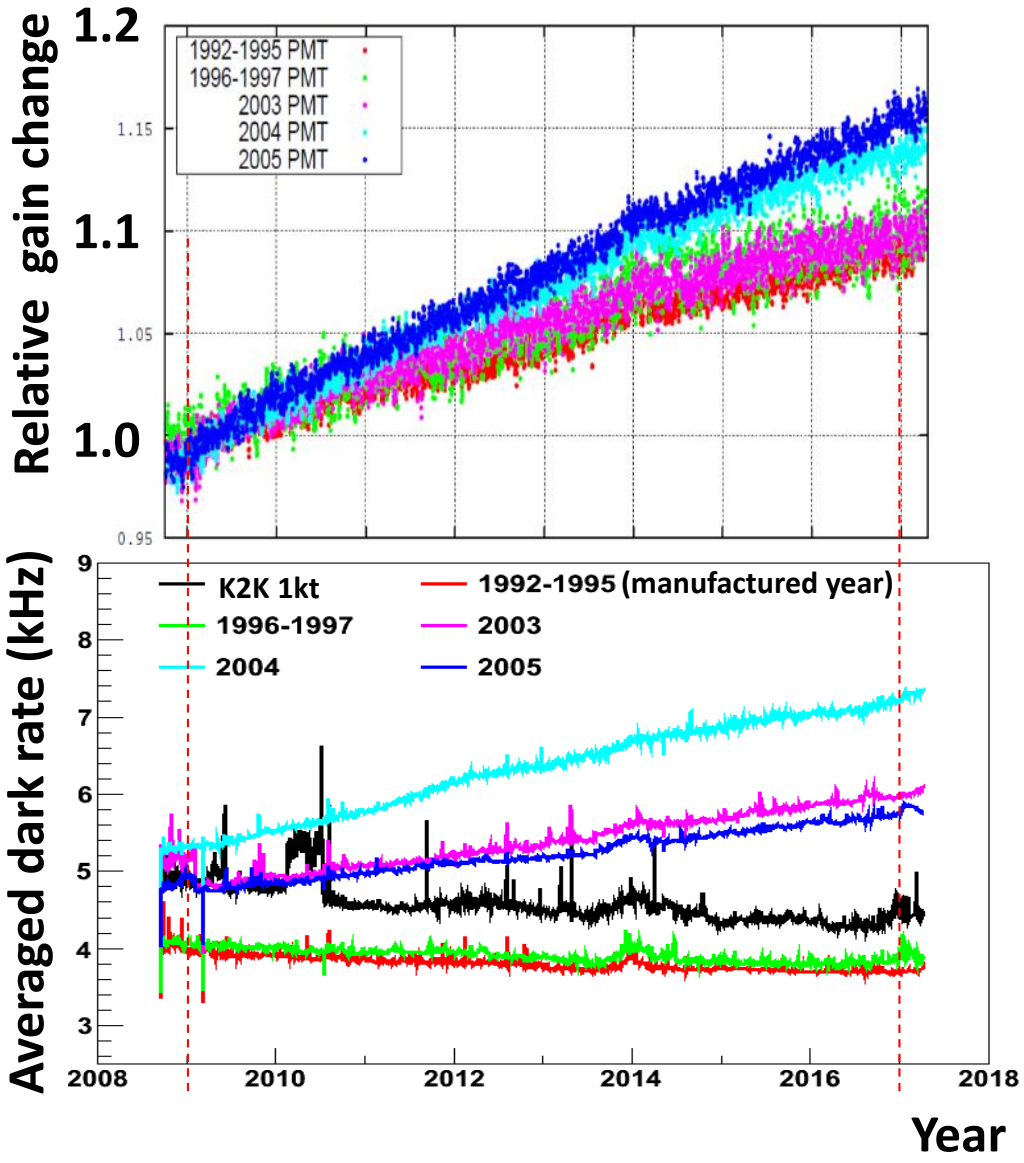


Maximum peak at around 9.43 /year is not found in SK-IV.

Energy scale improvement: 1/4

June 2017

Preliminary



- PMT gain and PMT dark rate are changing.
- So far, these variation are not considered in energy scale calculation for low-energy events.
- We are currently implementing theses effect in our detector simulation and energy reconstruction codes to reduce energy scale uncertainty in future.

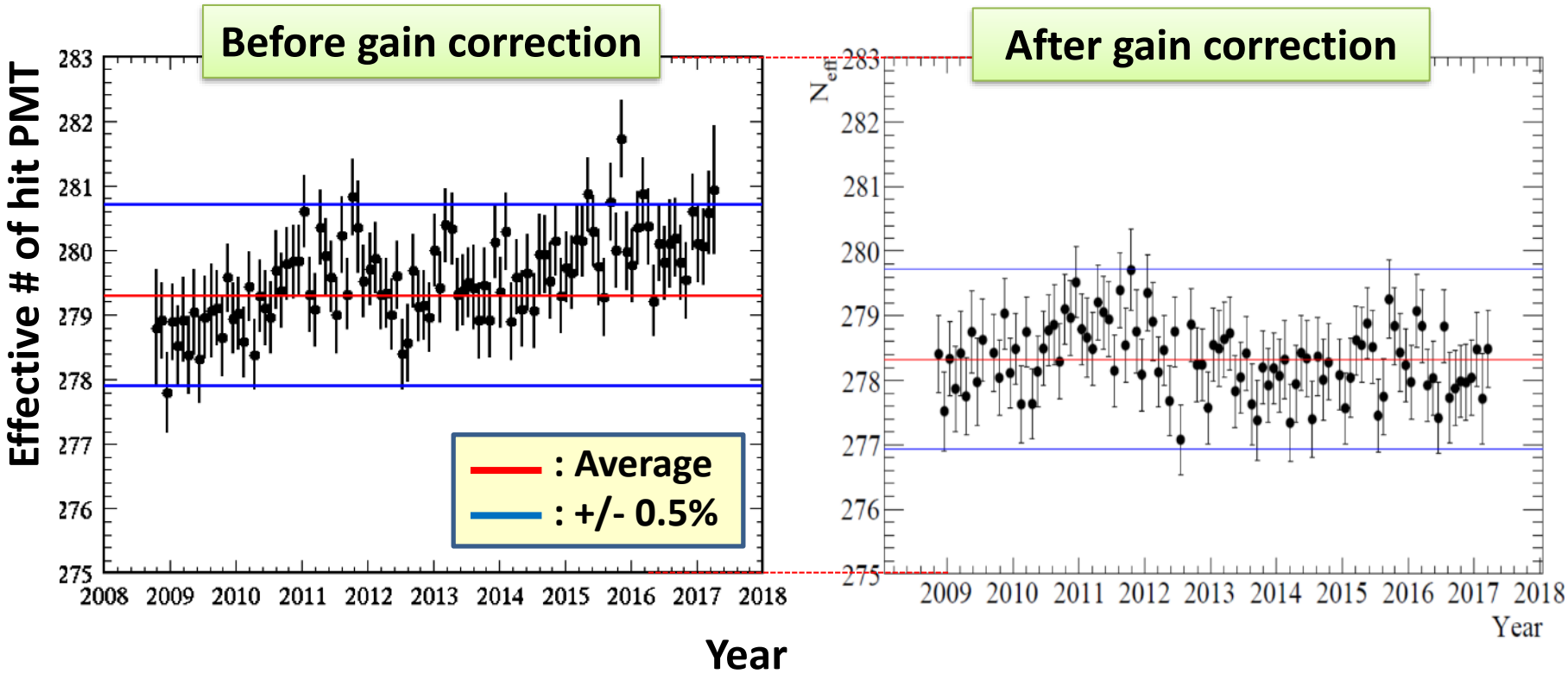
Energy scale improvement: 2/4

June 2017

Preliminary

- Peak of decay electron energy from stopping cosmic-ray muons
- Distribution looks stable after the gain correction

Effective number of hit PMT (with various corrections) is used in the energy scale for low-energy events.

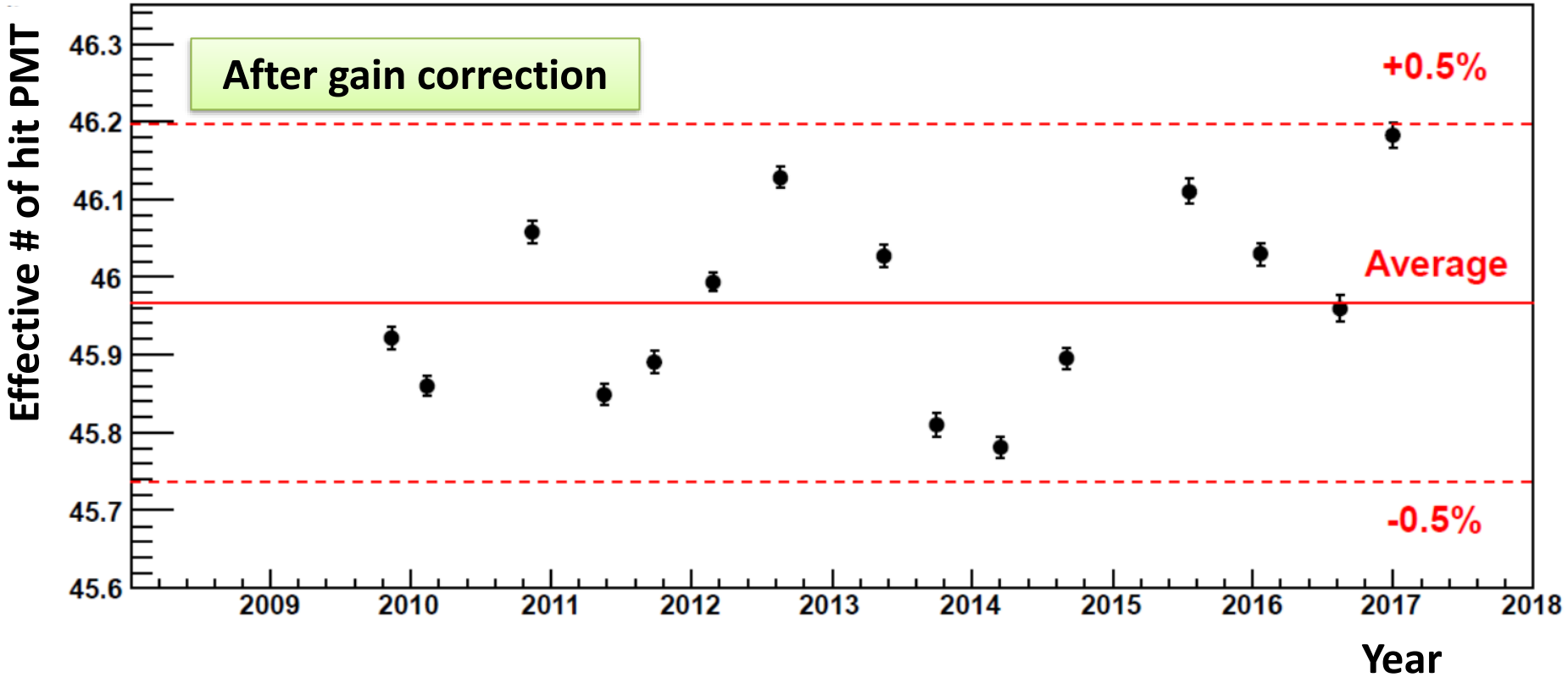


Energy scale improvement: 3/4

- DT neutron generator calibration
  - Gamma rays from ^{16}N
- Center position data in 2009-2017
- Looks stable

June 2017

Preliminary

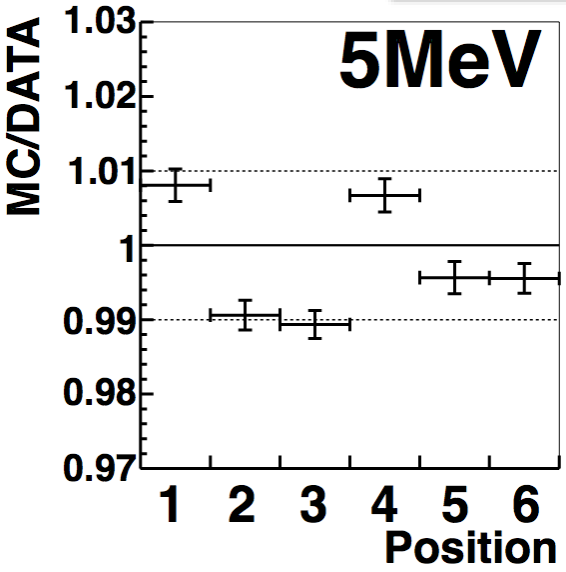


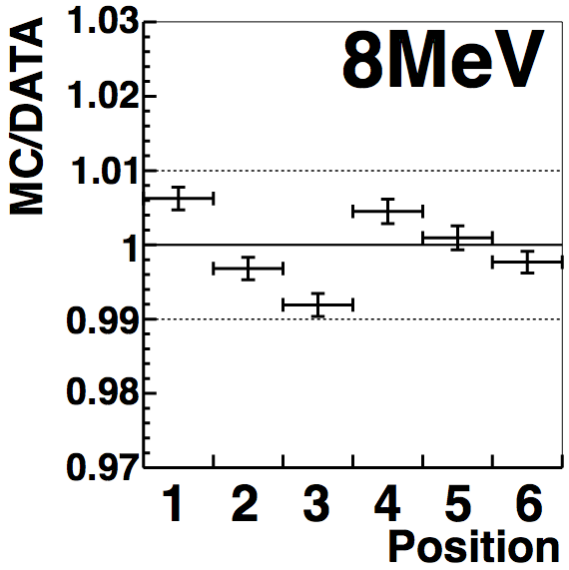
Energy scale improvement: 4/4

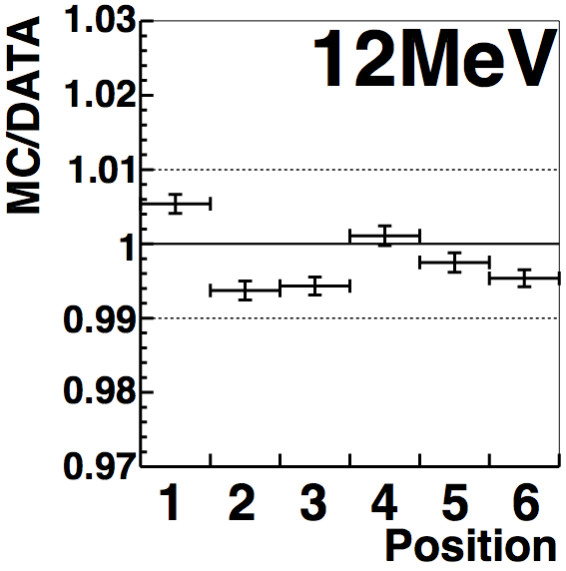
After gain correction

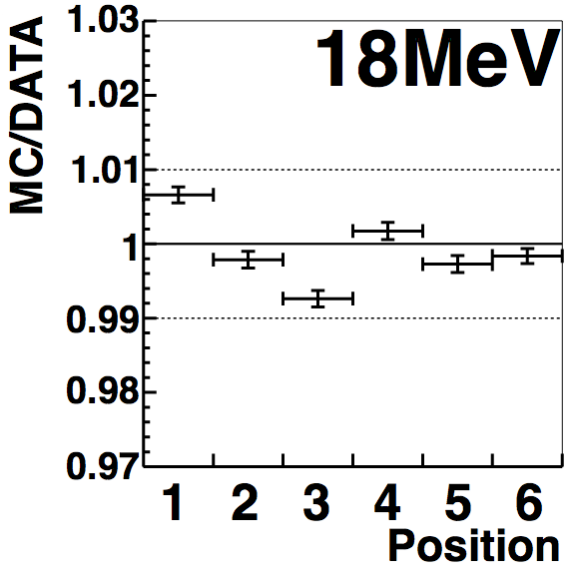
June 2017

Preliminary

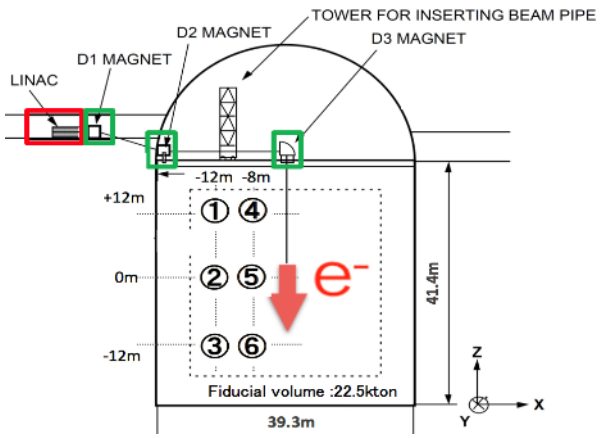








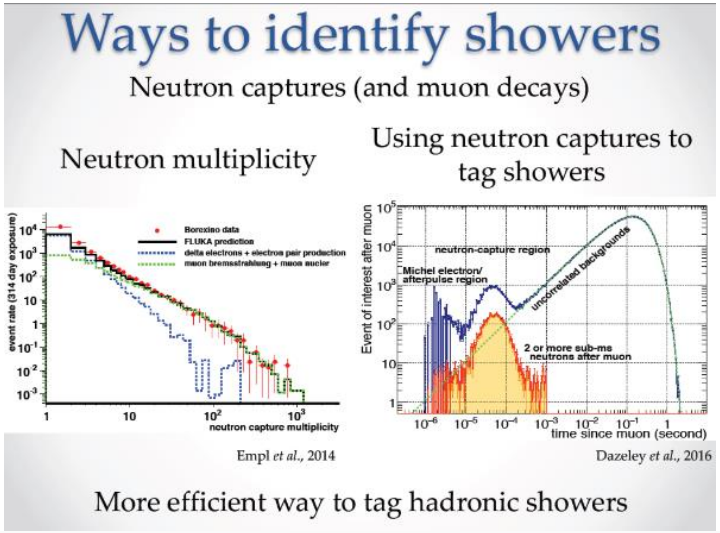
- LINAC calibration in 2016
  - Monochromatic electrons
- looks stable



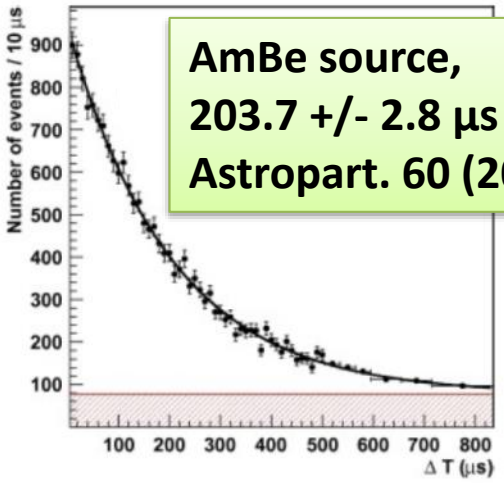
Study of spallation BG: 1/2

- **Motivation: More effective removal of spallation from SRN (DNSB) and solar neutrino data samples**

- **John Beacom and Shirley Li predict many neutrons would be produced in the hadronic shower from a spallation causing muon.**
- **Neutrons could be observed when energy threshold is lowered via 2.2 MeV gamma from n + p reaction (Astropart. 60 (2015) 41)**
- **Tried to use Wide-band Intelligent Trigger (WIT) data stream (~2.5 MeV(kin) threshold)**



Shirley Li (Workshop on Supernova at Hyper-Kamiokande)
http://www-sk.icrr.u-tokyo.ac.jp/indico/conferenceDisplay.py?confId=2935



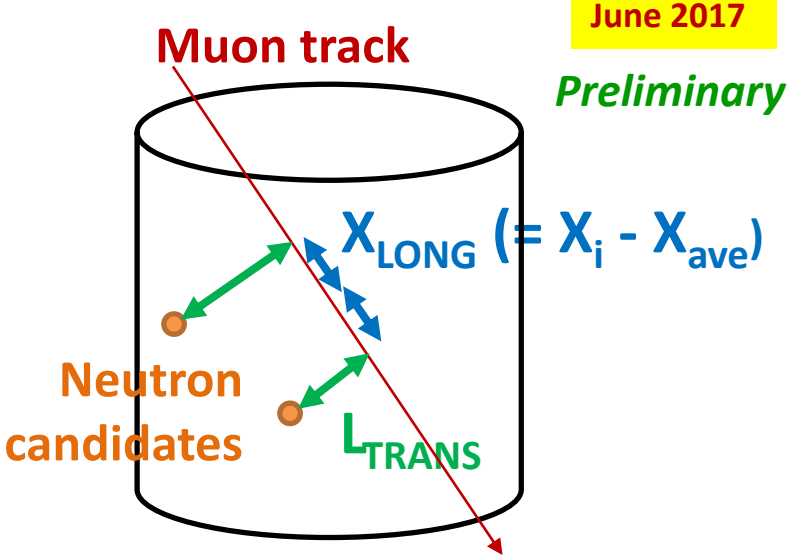
AmBe source,
203.7 +/- 2.8 µs
Astropart. 60 (2015) 41

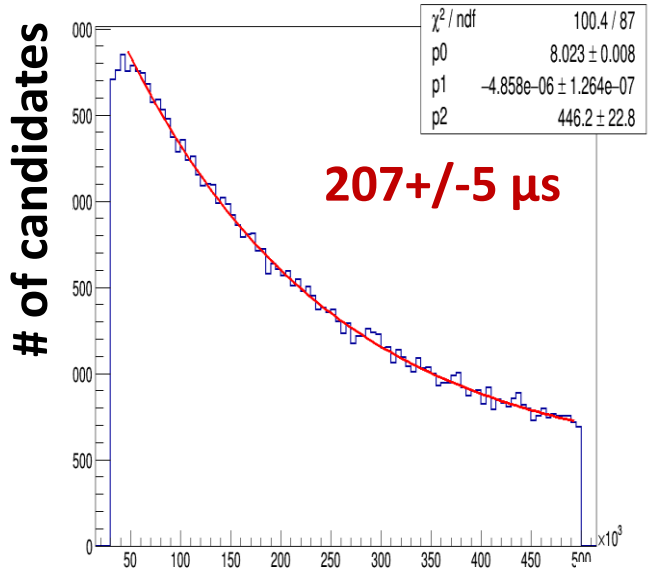
Study of spallation BG: 2/2

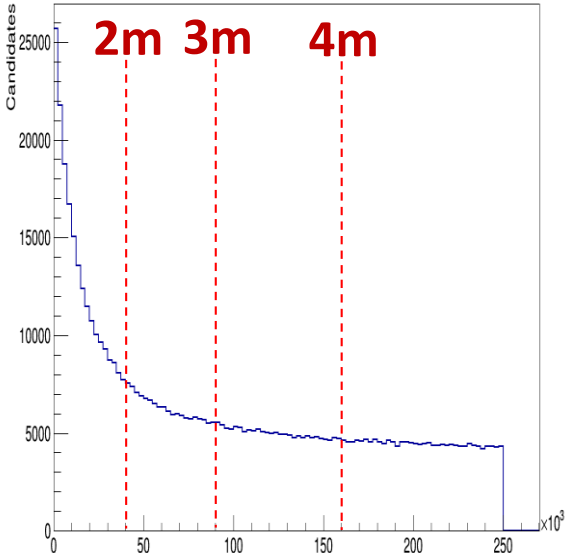
June 2017

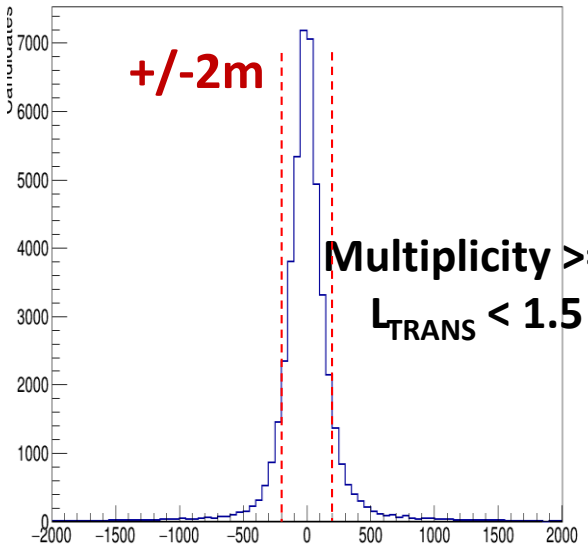
Preliminary

- **Data set:**
  - ~6 week data from WIT
  - 20 ~ 500 μsec. after muons
  - Energy < 5.5 MeV(kin)
  - Transverse distance (L_{TRANS}) < 5 m
  - Applied a simple event quality cut
- **We observed neutron candidates**
- **Further study is on going**









Summary

- Precise measurement of solar neutrinos are on going
- Latest (preliminary) results are reported.
  - Day/Night, Oscillation analysis (PRD94, 052010 (2016))
  - SK-I~IV 5200 days yearly flux
  - SK-IV 2645 days spectrum
  - SK-IV 1664 days periodic modulation analysis
- Improvements of analysis are on going.
  - Gain correction in energy scale
  - Spallation BG
- Detector upgrade work for SK-Gd is planned to start in 2018