21-June-2017 @WIN2017

Astrophysical neutrinos at Super-Kamiokande

Yasuo Takeuchi
Kobe University

- Astrophysical neutrinos at SK (in Low-E)
- Recent progress in solar neutrino analysis
- Status of SK-Gd & supernova neutrinos in SK-Gd

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)

University Autonoma Madrid, Spain
マドリッド・オートノマ大学

岡山大学(日本)
Okayama University

Boston University, USA
ボストン大学

岐阜大学(日本)
Gifu University

University of British Columbia, Canada
ブリティッシュコロンビア大学

京都大学(日本)
Kyoto University

大阪大学(日本)
Osaka University

宮城教育大学(日本)
Miyagi University of Education

SEOUL NATIONAL UNIVERSITY
Seoul National University, Korea
ソウル大学

福岡工業大学短期大学部(日本)
Junior College, Fukuoka Institute of Technology

Sejong University, Korea
セジョン大学

University of California, Irvine, USA
カリフォルニア大学アーバイン校

University of Regina, Canada
レジャイナ大学

Stony Brook University, USA
ストニー・ブルック大学

横浜国立大学(日本)
Yokohama National University

KEK-JAPAN
高エネルギー加速器研究機構(KEK)(日本)
High Energy Accelerator Research Organization

ホスト研究機関 Host Institute

東京大学宇宙線研究所
Institute for Cosmic Ray Research University of Tokyo

ICRR
Institute for Cosmic Ray Research University of Tokyo

東海大学(日本)
Tokai University

名古屋大学(日本)
Nagoya University

SungKyunKwan University, Korea
成均館大学

California State University, Dominguez Hills, USA
カリフォルニア・ステート・ユニバーシティ・ドミングズ・ヒルズ

Korea Research Institute of Standards and Science, Korea
韓国標準科学研究院

University of Toronto, Canada
トロント大学

University of Washington, USA
ワシントン大学

National Centre for Nuclear Research (NCBJ), Poland
ポーランド国立原子力研究センター

Tsinghua University, China
清華大学

TRIUMF, Canada
カナダTRIUMF研究所

東京大学理学部(日本)
School of Science, The University of Tokyo

神戸大学(日本)
Kobe University

University of Hawaii, USA
ハワイ大学

東京大学国際高等研究所カブリ数物連携宇宙研究機構(日本)
Kavli Institute for the Physics and Mathematics of the Universe, The University of Tokyo

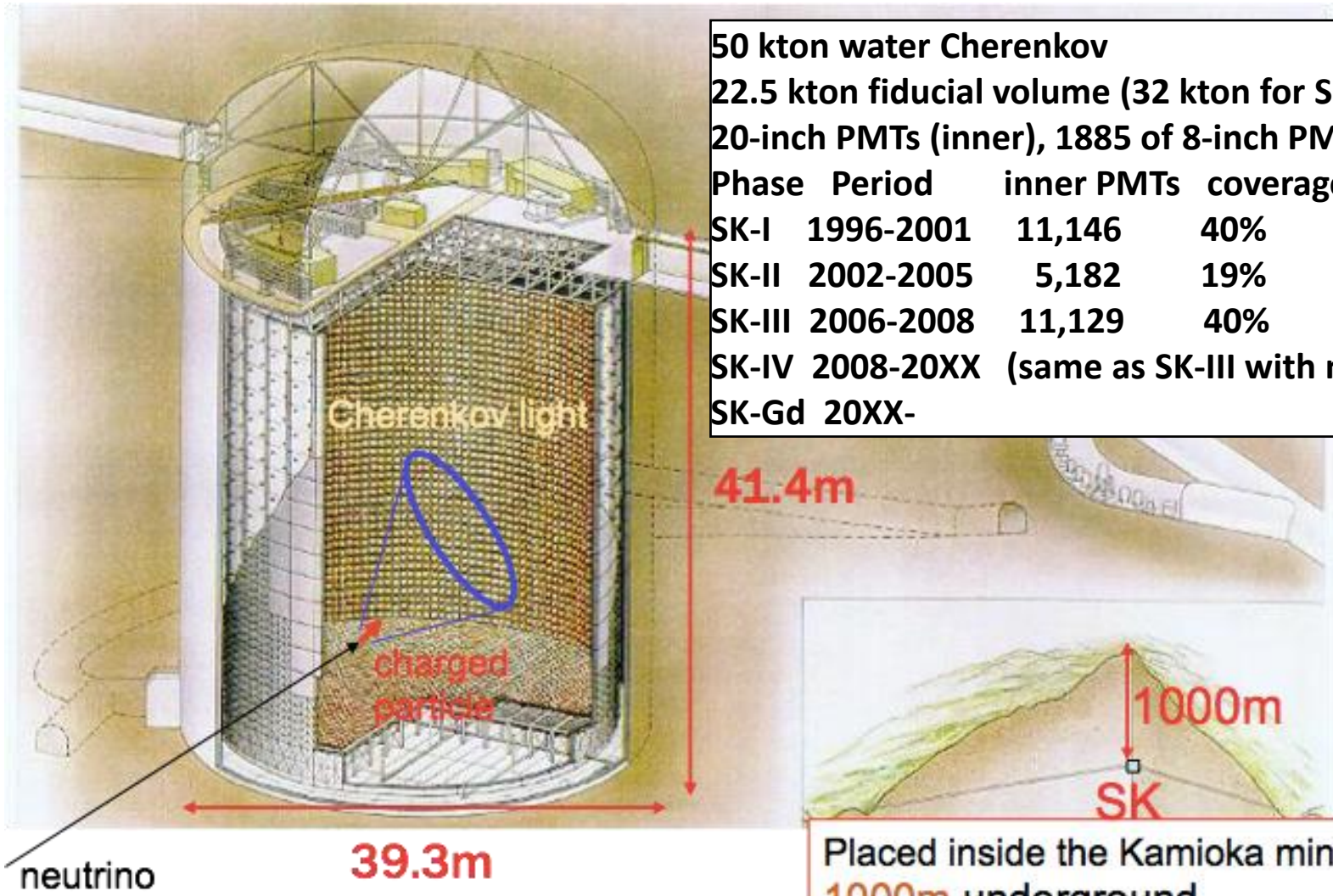
Duke University, USA
デューク大学

静岡福祉大学(日本)
Shizuoka University of Welfare

Chonnam National University, Korea
全南大学

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

Super-Kamiokande detector

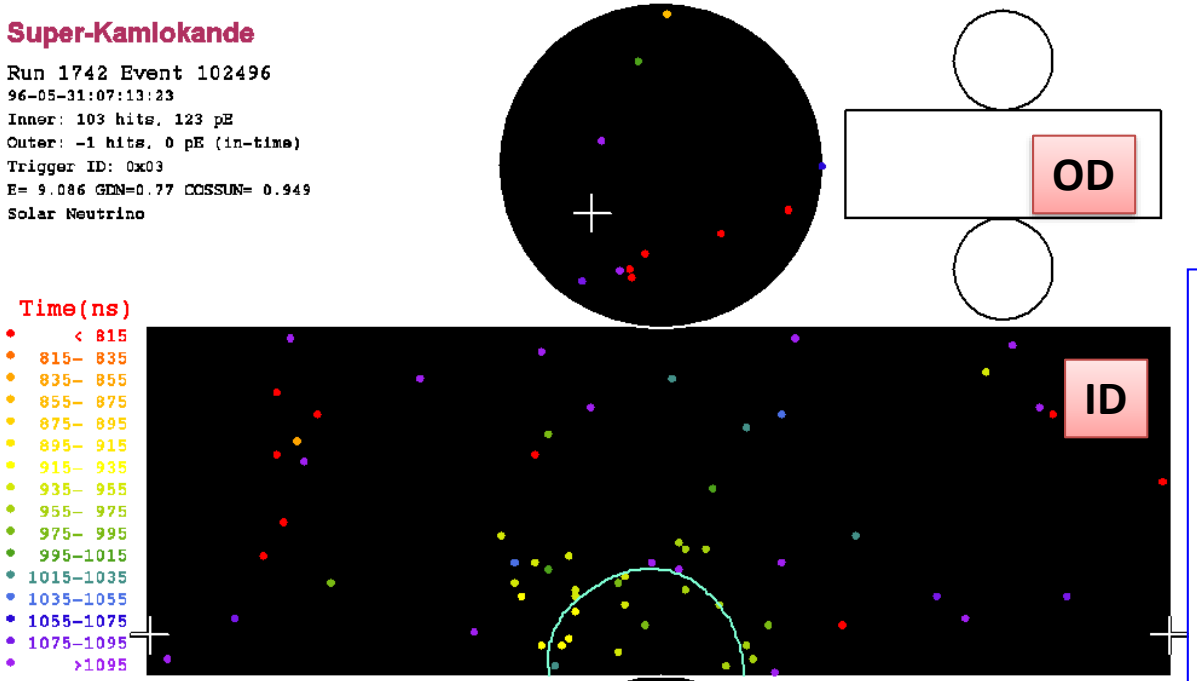


50 kton water Cherenkov
22.5 kton fiducial volume (32 kton for SN burst)
20-inch PMTs (inner), 1885 of 8-inch PMTs (outer)

Phase	Period	inner PMTs	coverage
SK-I	1996-2001	11,146	40%
SK-II	2002-2005	5,182	19%
SK-III	2006-2008	11,129	40%
SK-IV	2008-20XX	(same as SK-III with new electronics)	
SK-Gd	20XX-		

Placed inside the Kamioka mine
1000m underground

Typical low-energy event



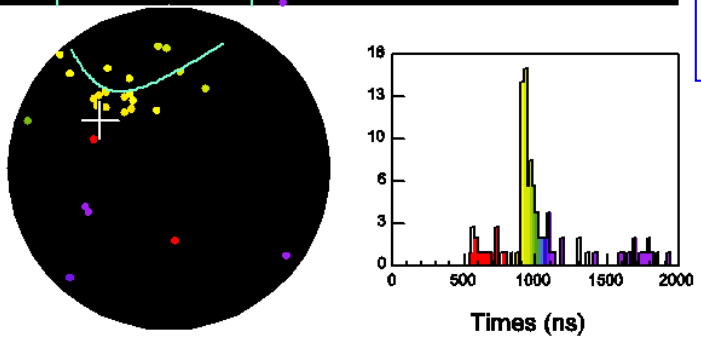
(color: time)

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

(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



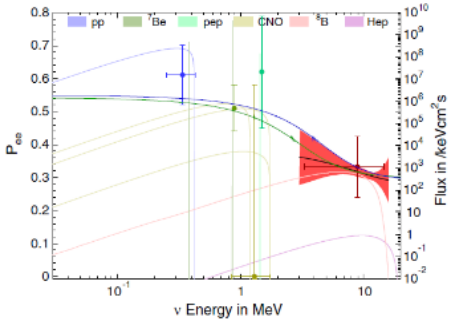
~6 hit / MeV
(SK-I, III, IV)

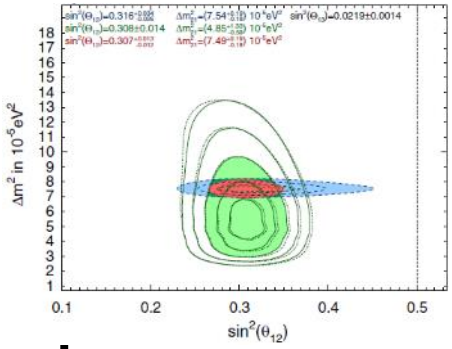
Resolutions (for 10MeV electrons) (software improvement)

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

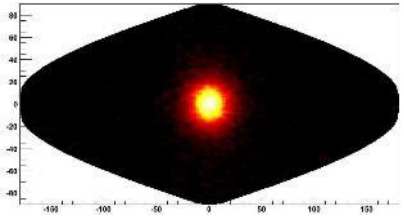
Astrophysical neutrinos at SK (in Low-E)

- **Solar neutrinos** — A. Sousa (Plenary session)
  - **Neutrino oscillation**
    - Solar MSW
    - Terrestrial MSW
      - Tension among solar nue and reactor nue-bar

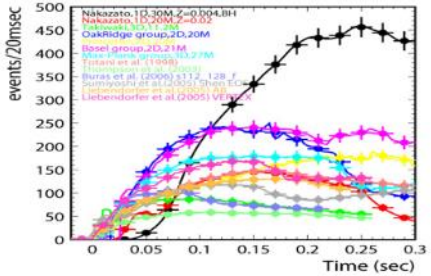


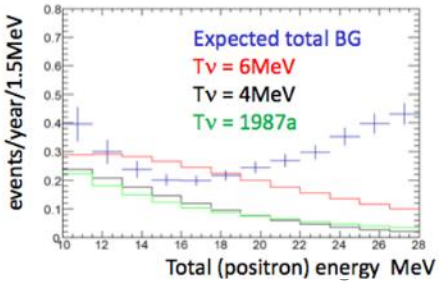


  - **Solar astrophysics**
    - Time variation

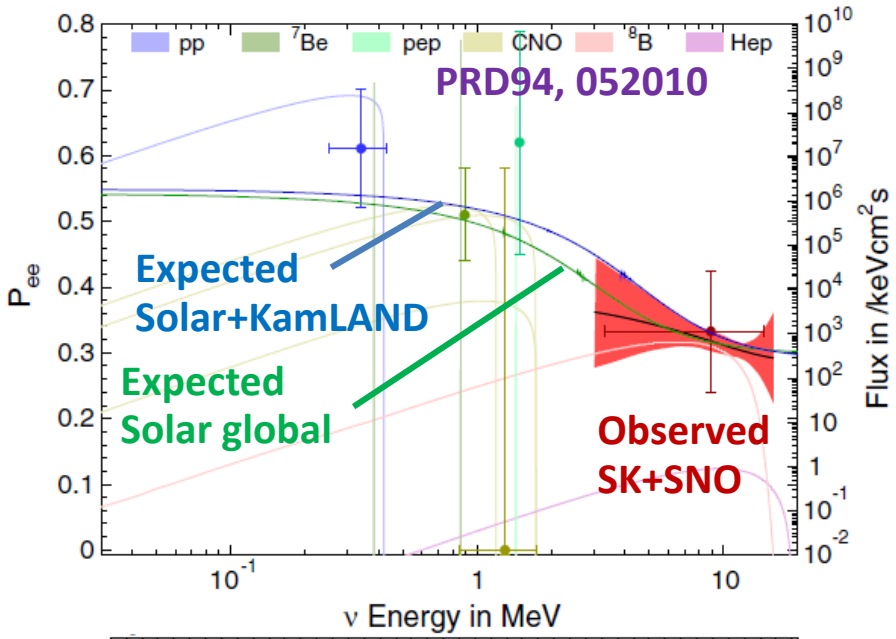


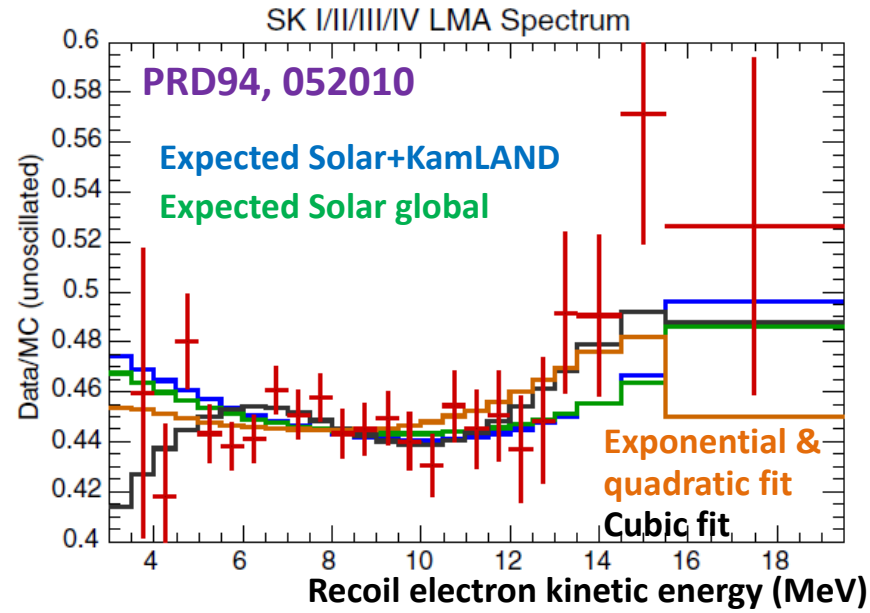
- **Supernova neutrinos** — M. Nakahata (Plenary session)
  - Burst
  - Relic (DSNB)

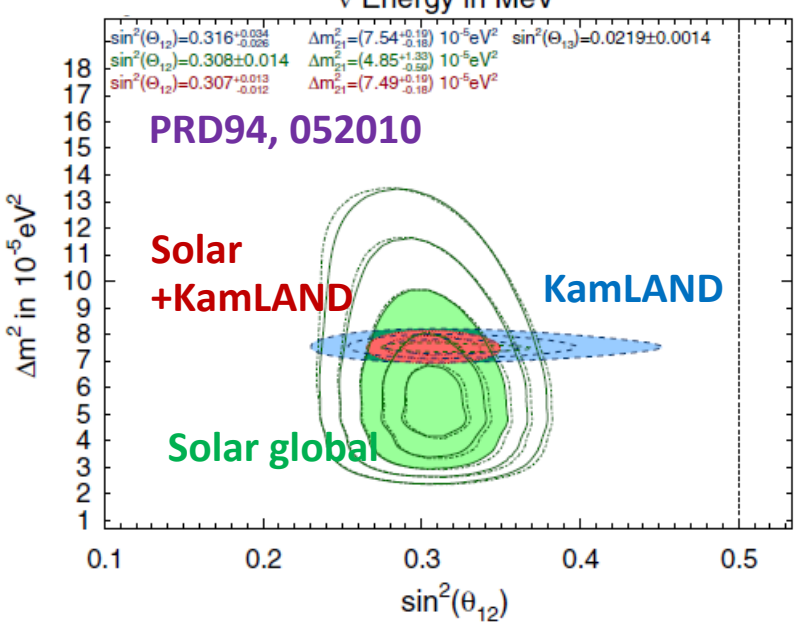


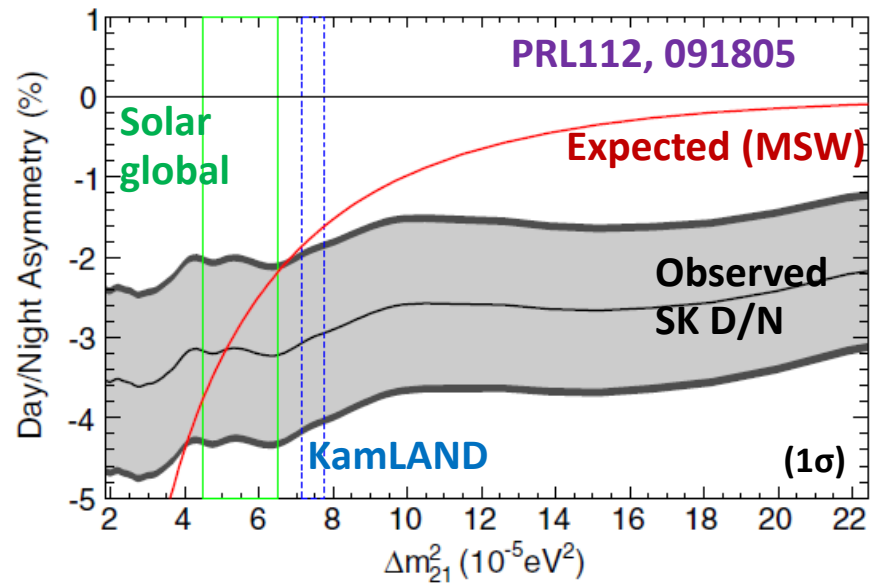


Solar neutrino measurements in SK

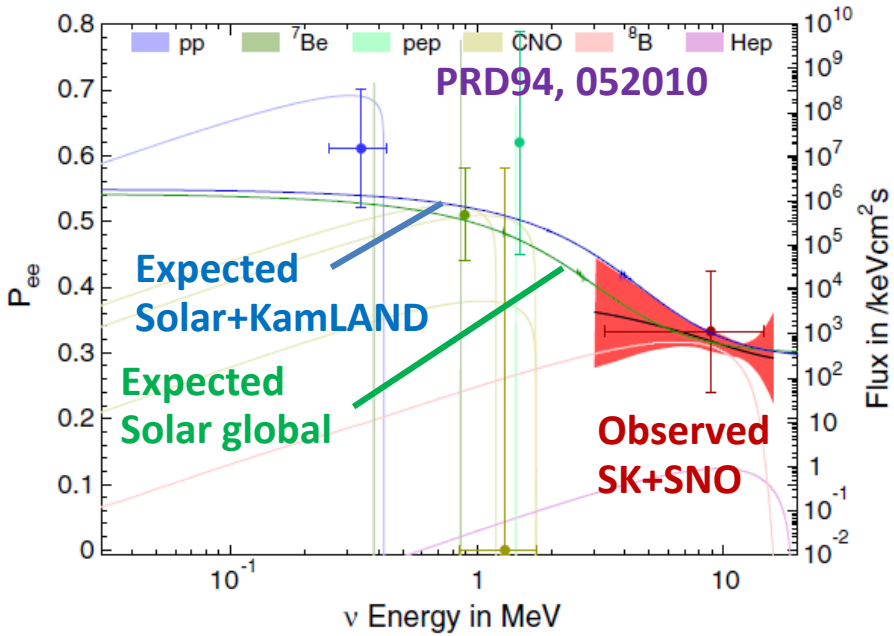


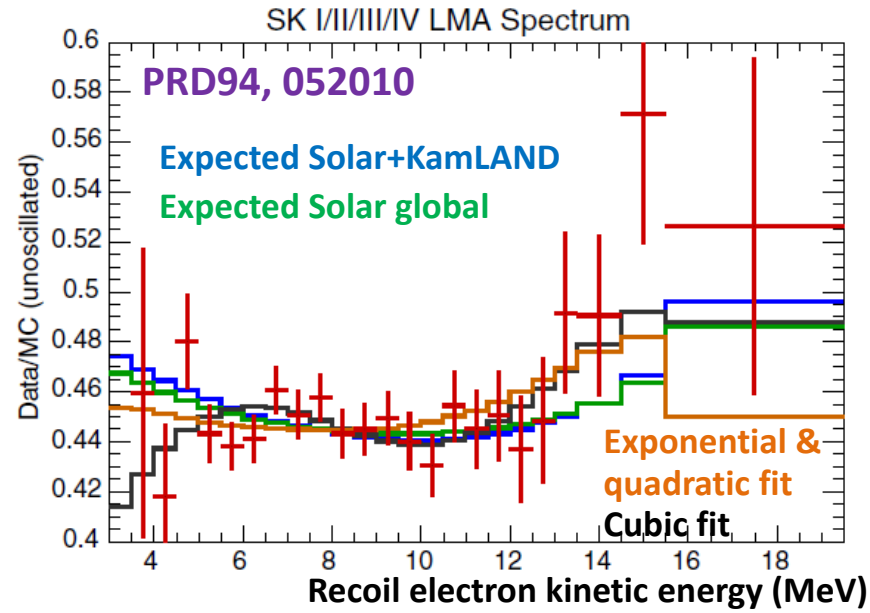


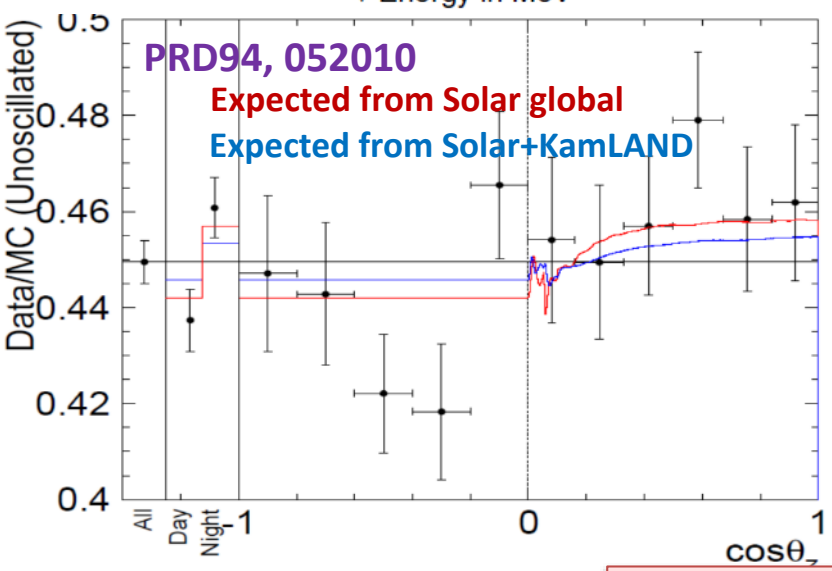


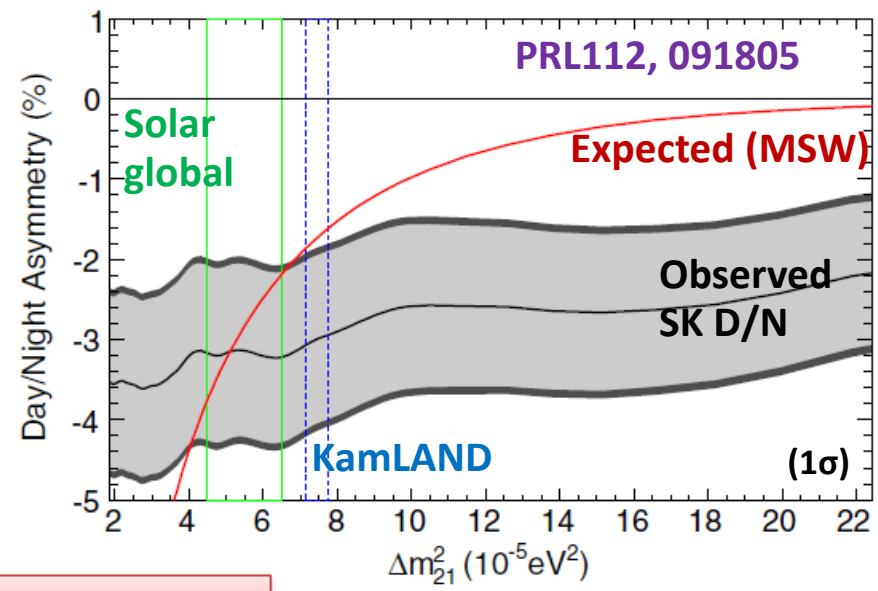


Solar neutrino measurements in SK









Statistical error dominates

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 A, in press (DOI: 10.1016/j.nima.2017.04.037) 科研費 KAKENHI

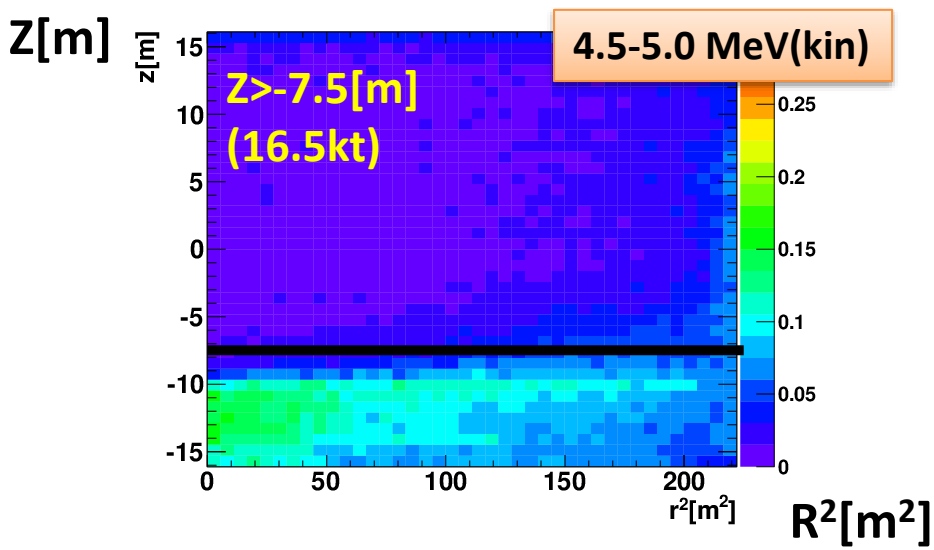
Vertex distribution in SK-IV

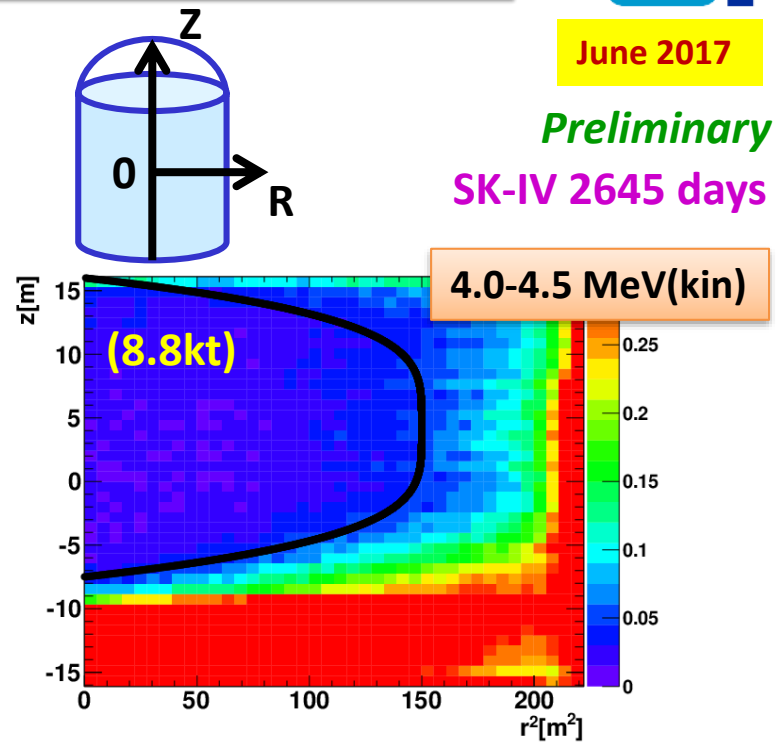
June 2017

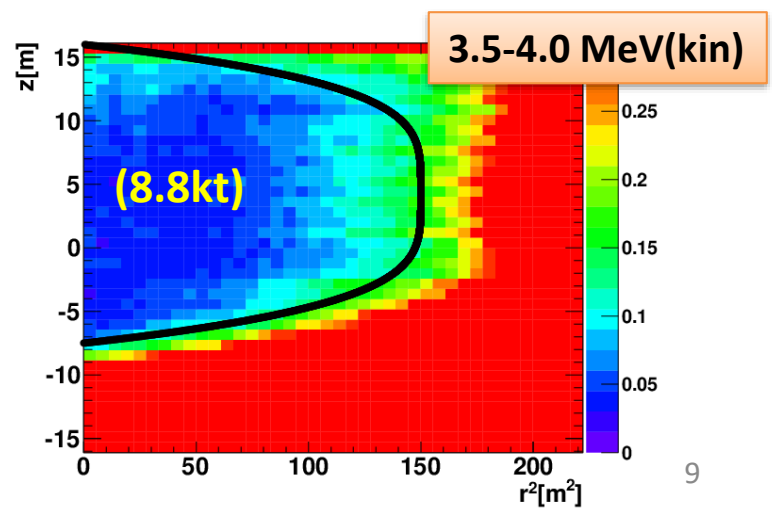
Preliminary

SK-IV 2645 days

Color : Events/day/bin low→high







- 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

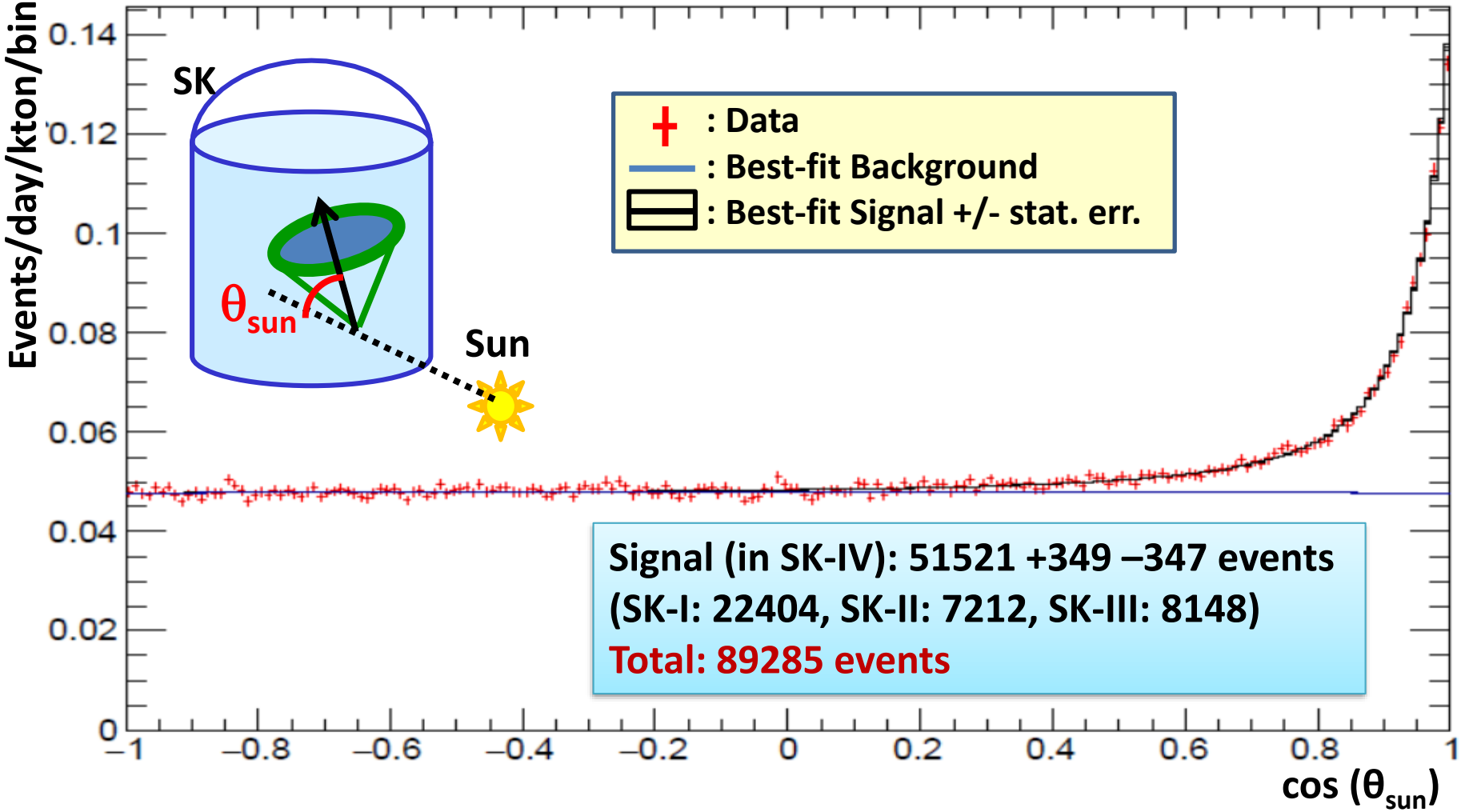
SK-IV solar neutrino signal

June 2017

SK-IV 3.5-19.5 MeV(kin)

Preliminary

SK-IV 2645 days

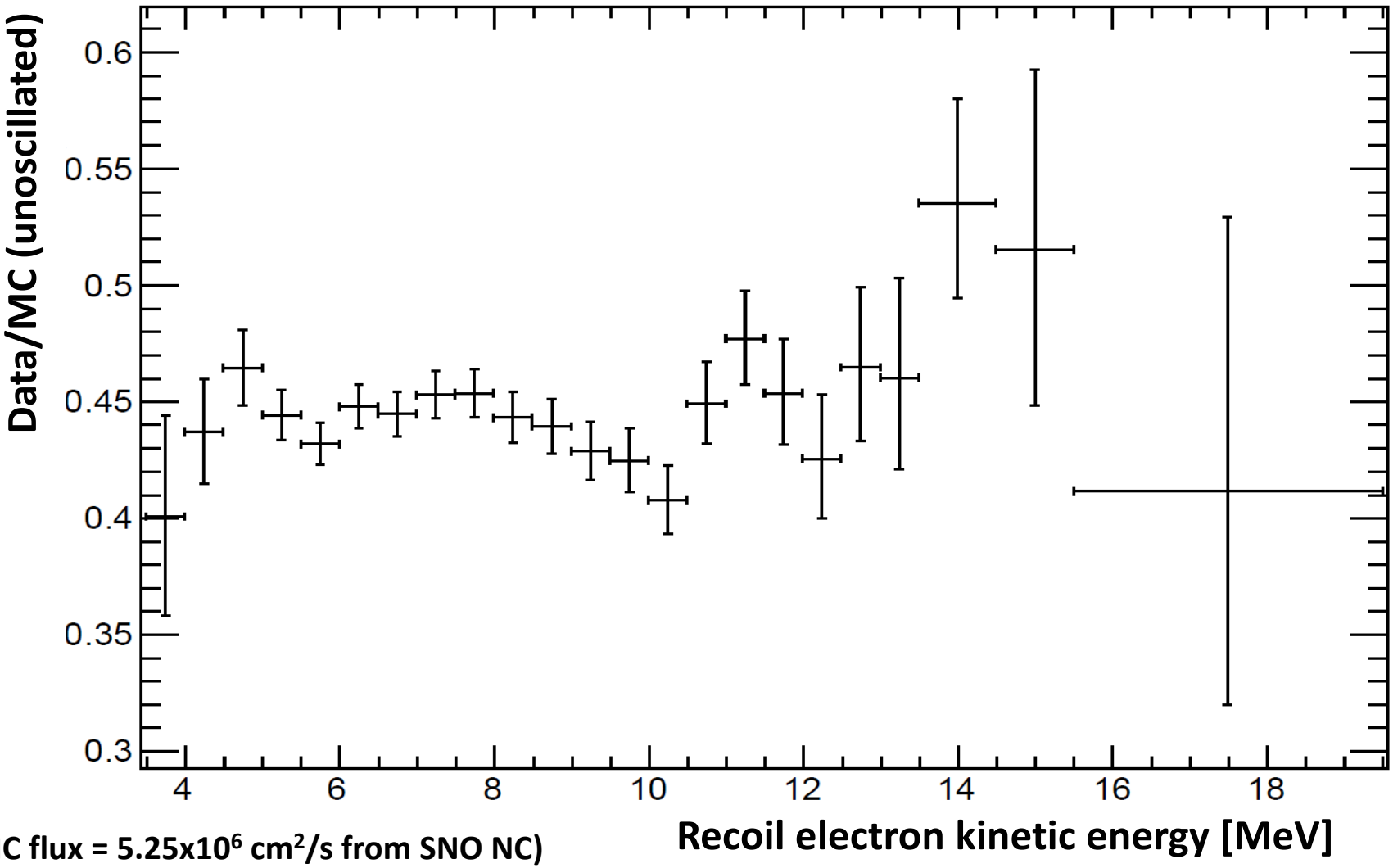


SK-IV solar neutrino energy spectrum

June 2017

Preliminary

SK-IV 2645 days



(MC flux = 5.25×10^6 cm^2/s from SNO NC)

Data set for oscillation analysis

June 2017

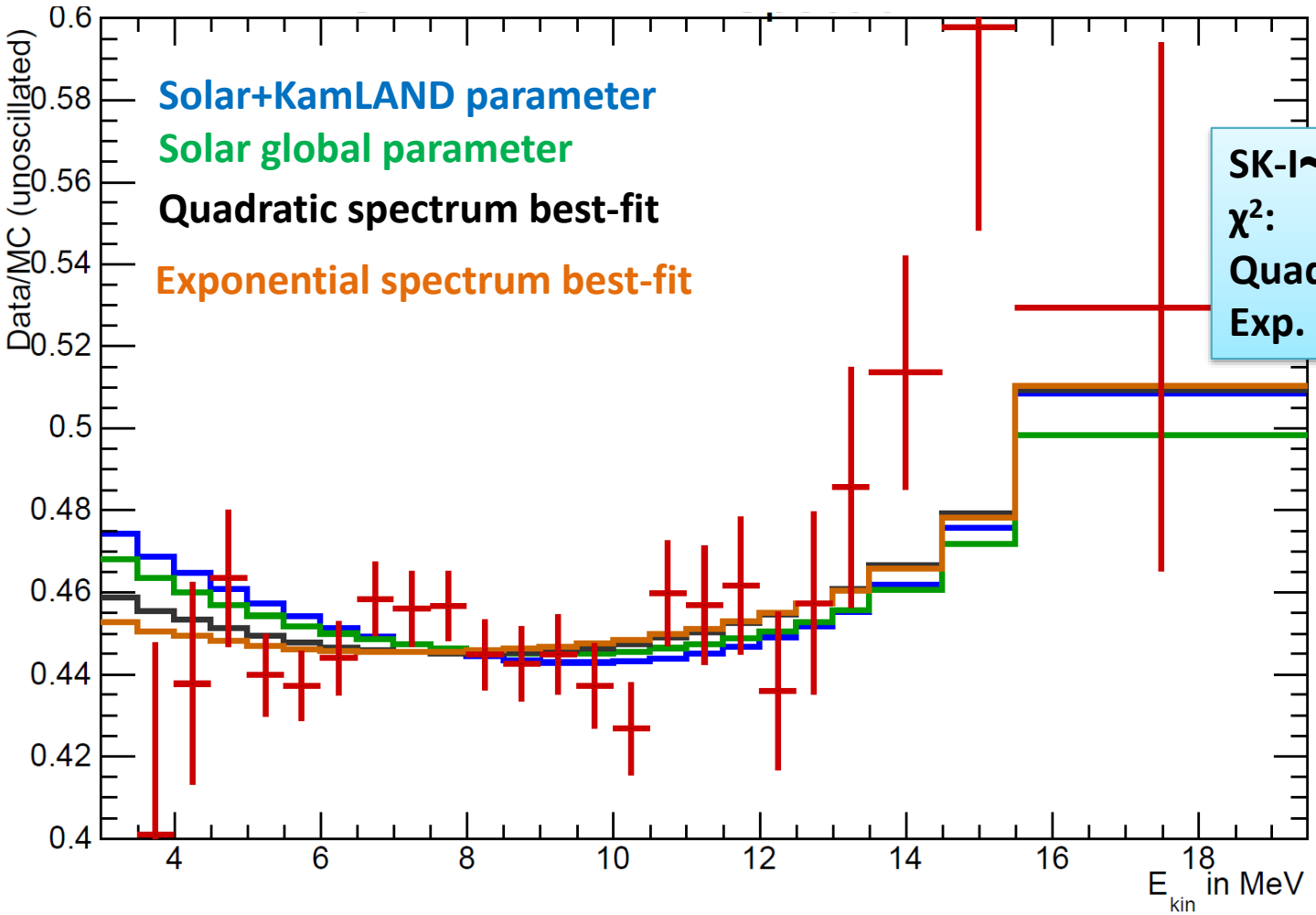
Preliminary

- 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



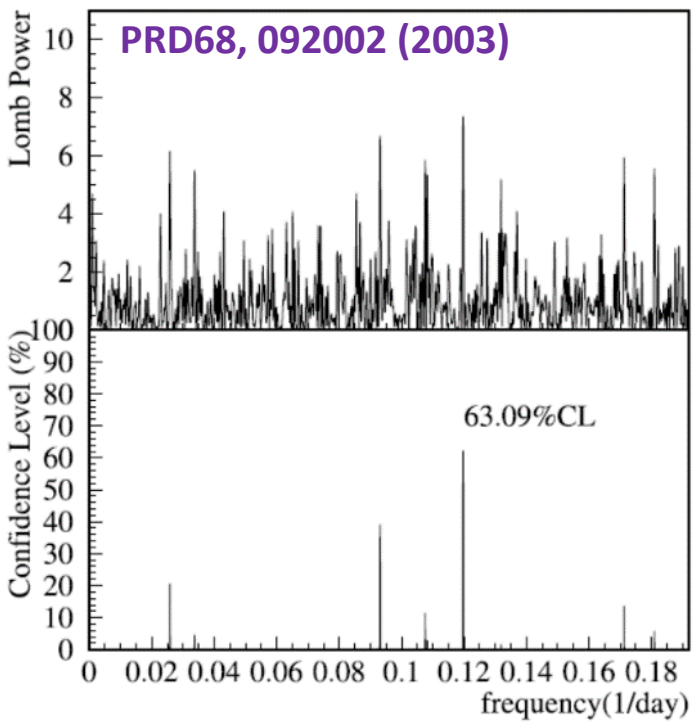
SK-I~IV: 83 bins
χ^2:
Quad. Fit: 75.5 /80 dof
Exp. Fit: 75.5 /80 dof

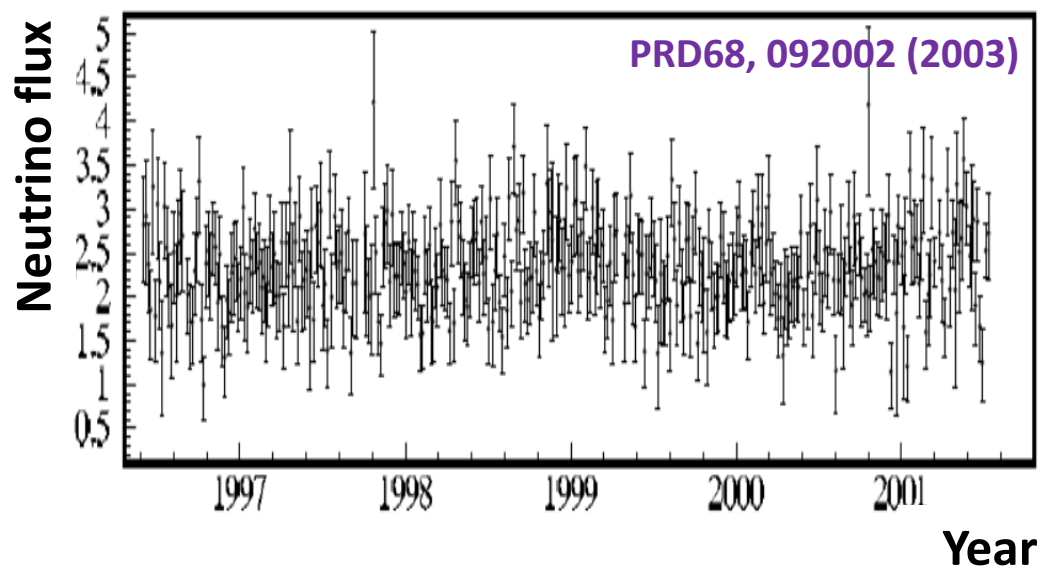
All SK phases are combined without regards to energy resolution or systematics in this figure

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

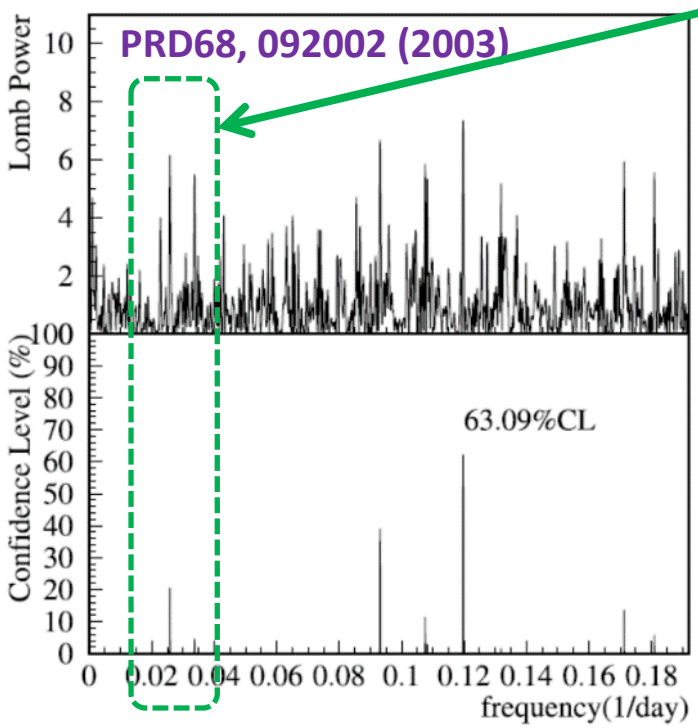
- **Past publication: PRD68, 092002 (2003)**
  - **SK-I 1496 days, 4.5-19.5 MeV(kin)**
  - **Used Lomb-Scargle (LS) and 5-day long samples**

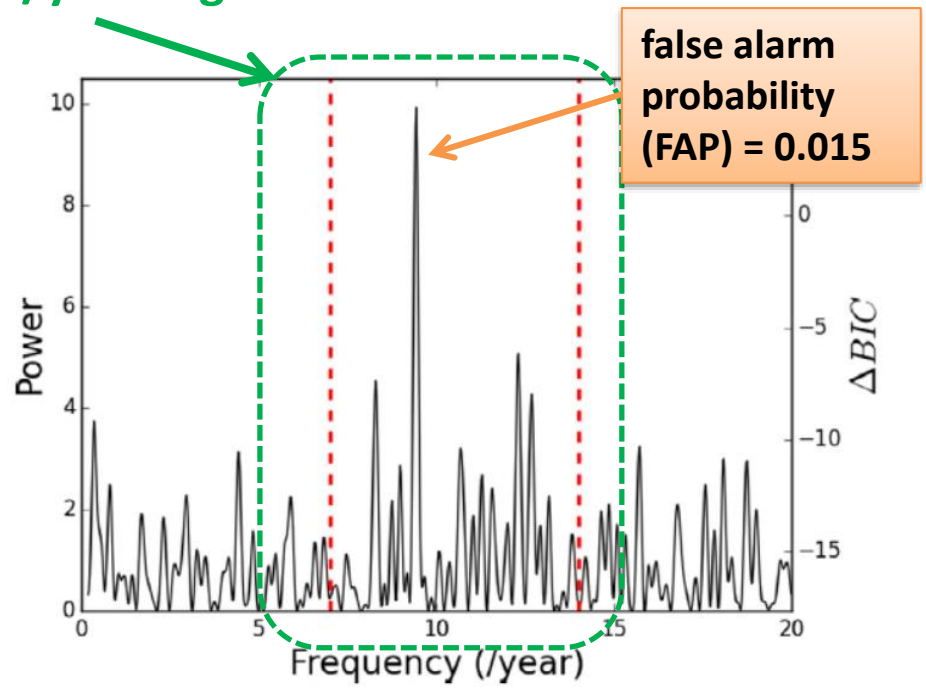




Periodic modulation analysis in SK-IV

- 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.





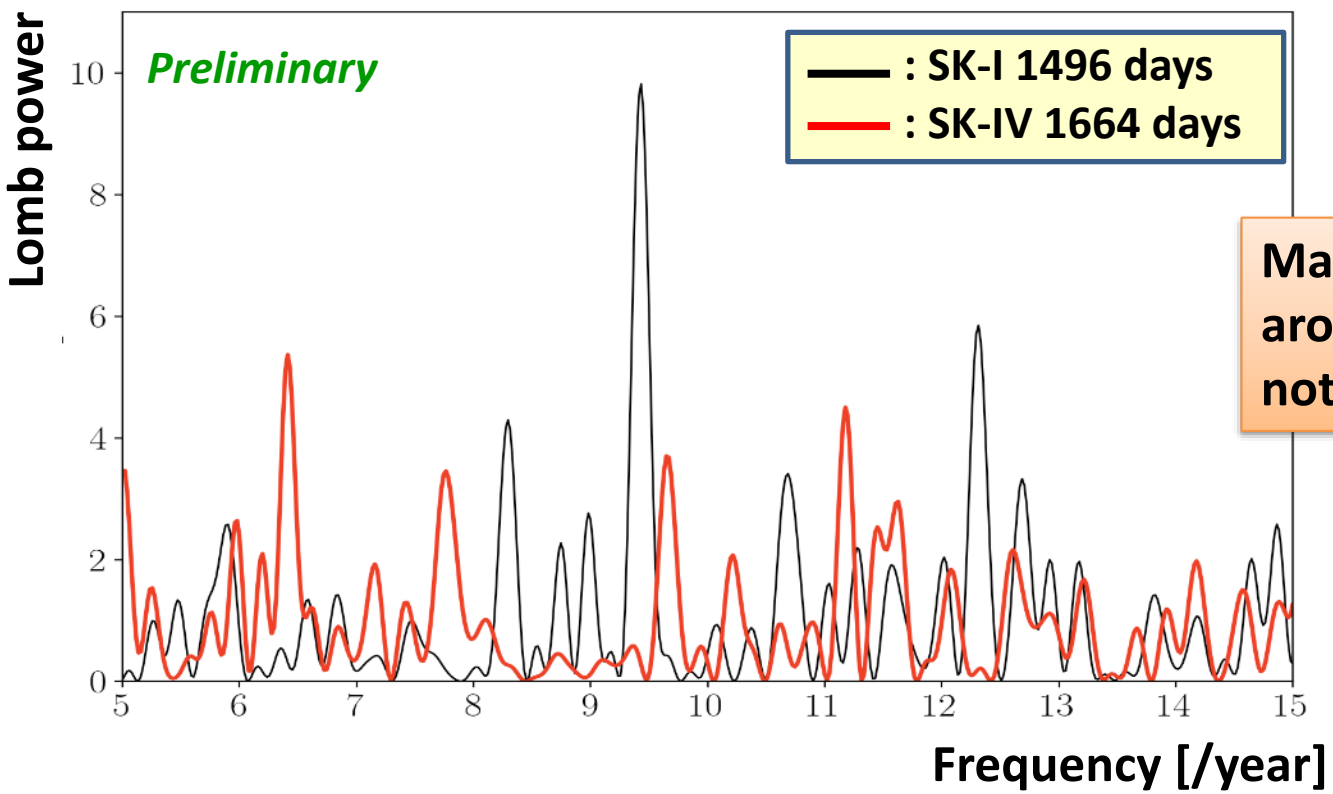
S. Desai, D.W. Liu / Astroparticle Physics 82 (2016) 86–92

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]**

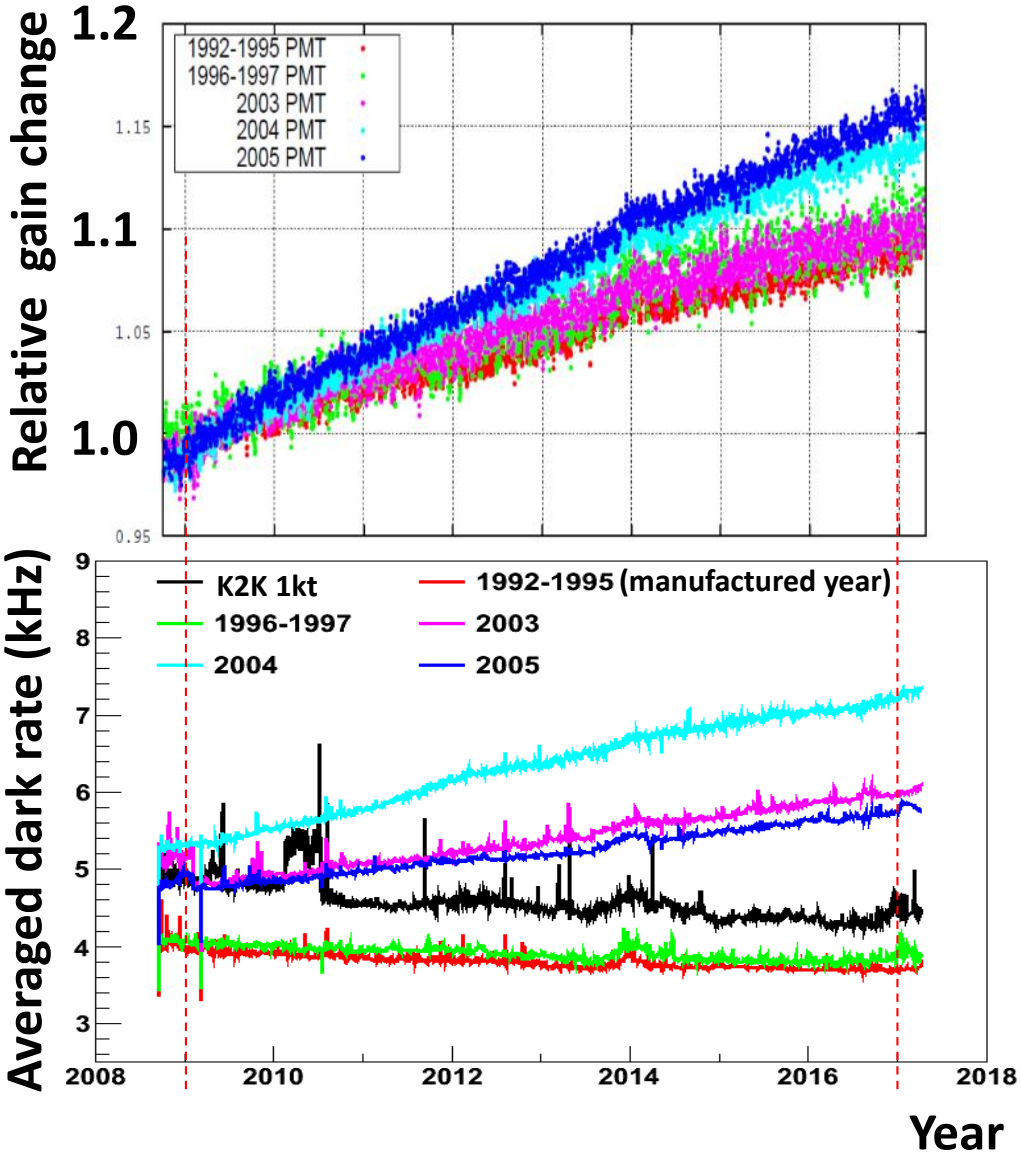


Maximum peak at around 9.43 /year is not found in SK-IV.

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.

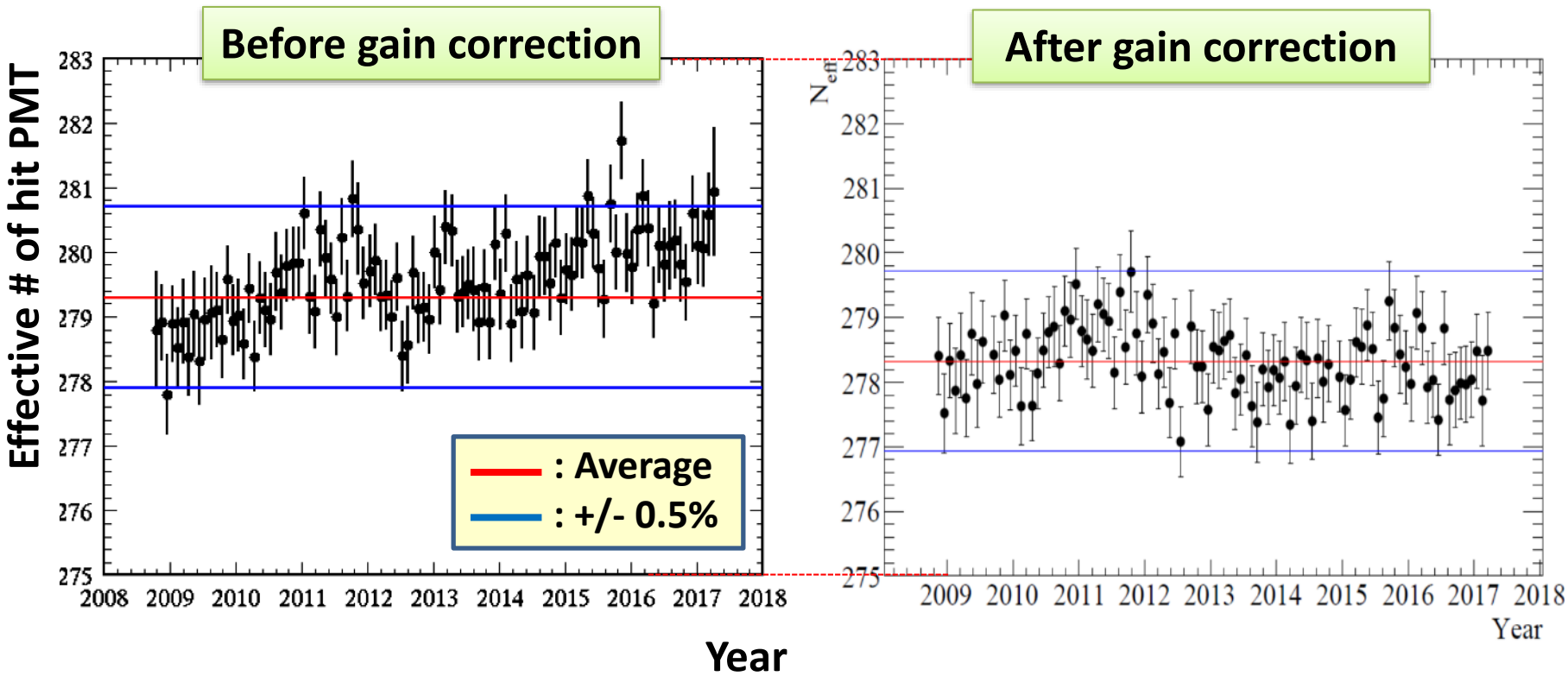
Energy scale improvement: 2/4

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.



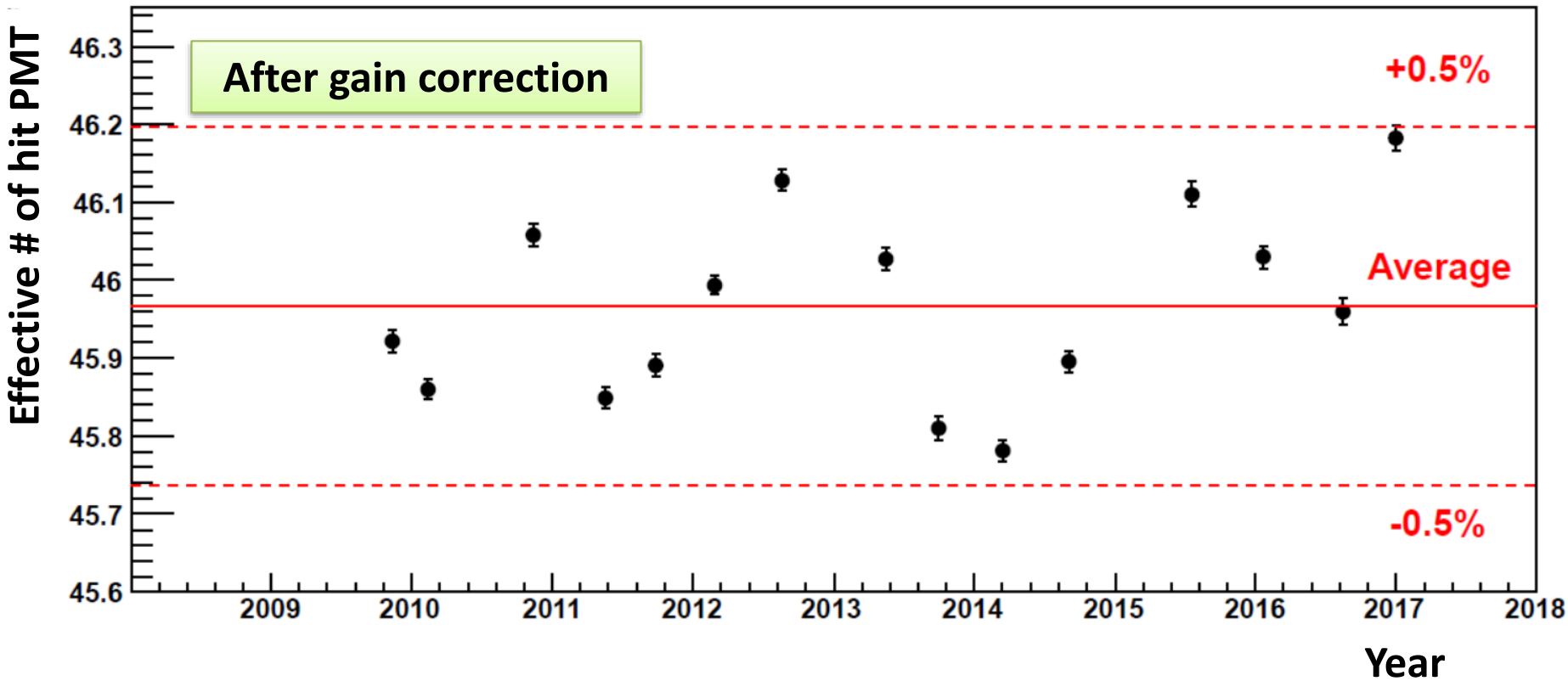
Energy scale improvement: 3/4

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

Maintained by

June 2017

Preliminary

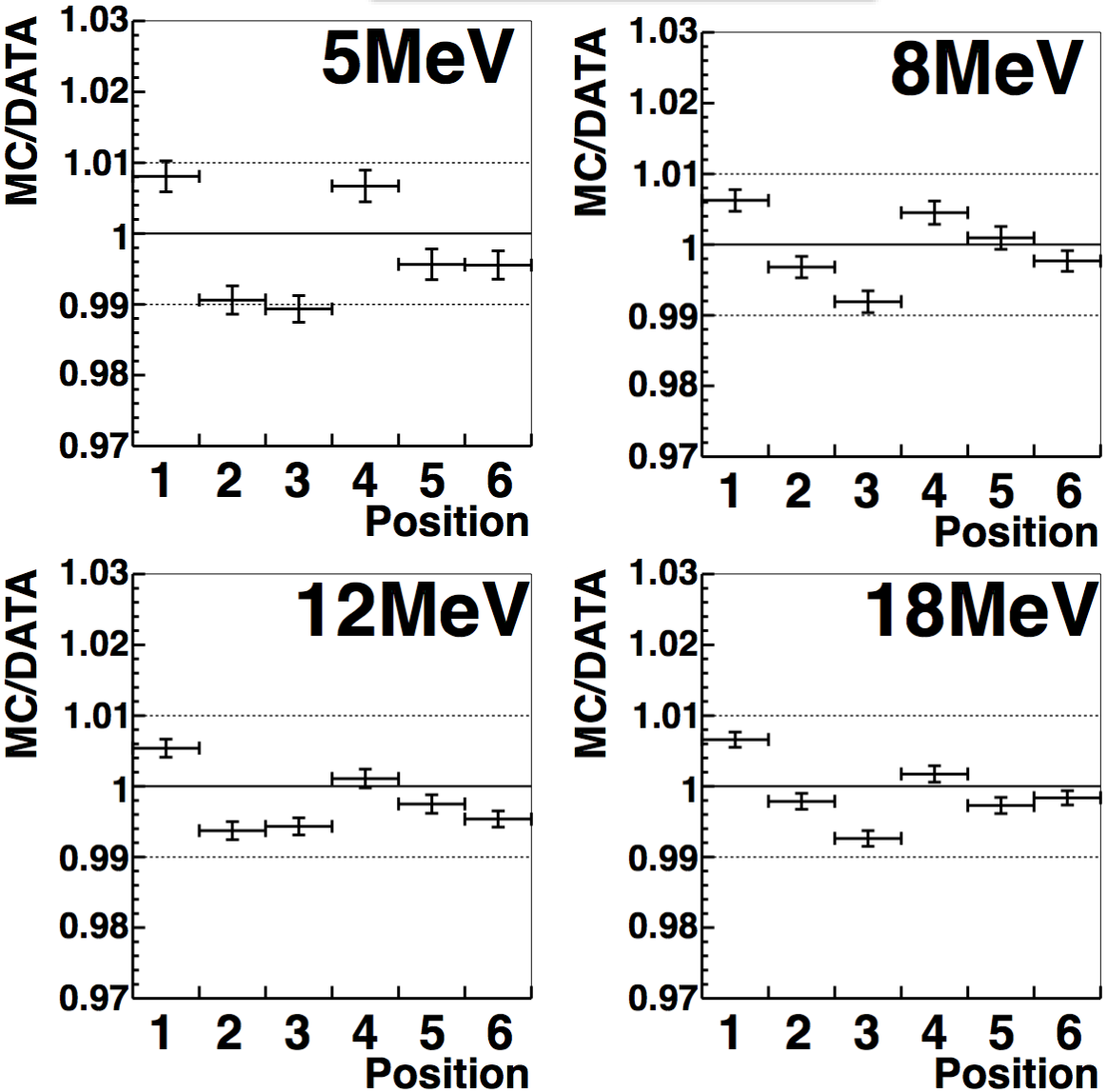


Energy scale improvement: 4/4

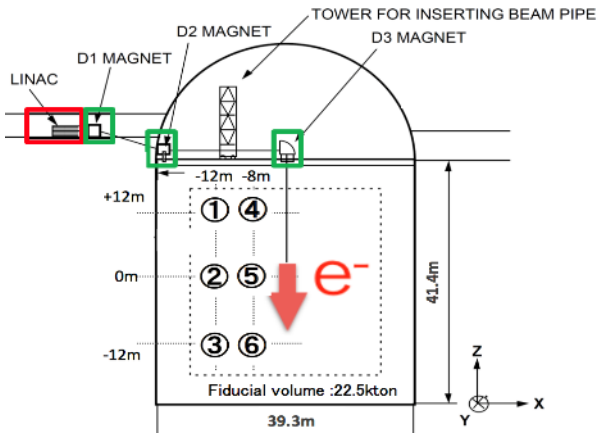
June 2017

Preliminary

After gain correction



- LINAC calibration in 2016
  - Monochromatic electrons
- looks stable

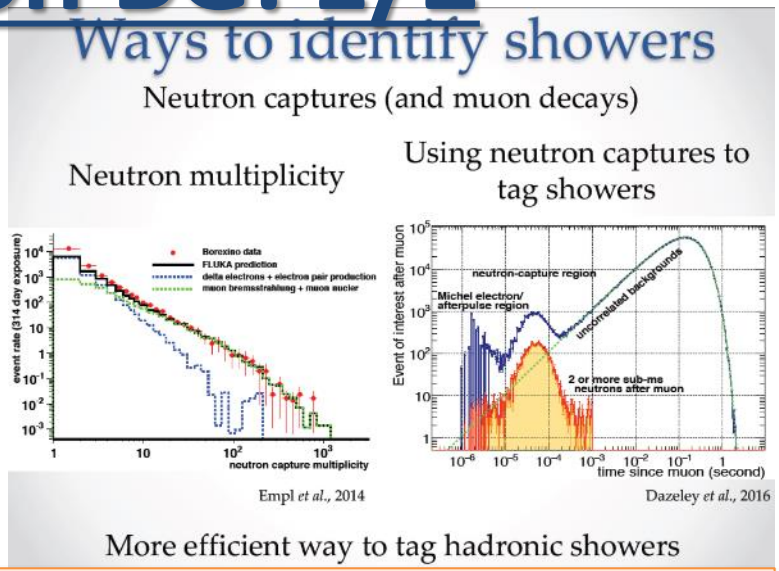


Study of spallation BG: 1/2

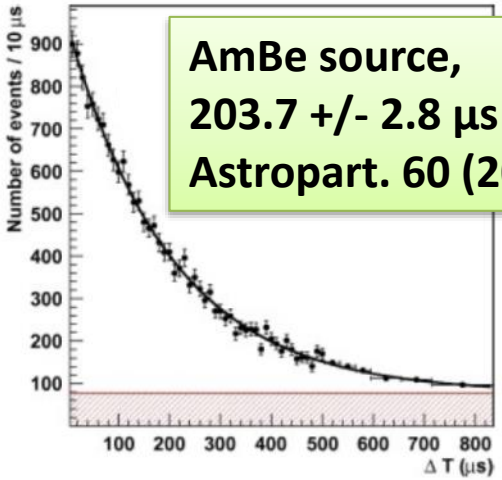
- **Motivation: More effective removal of spallation from SRN (DNSB) and solar neutrino data samples**

- **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)**

Developed by



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



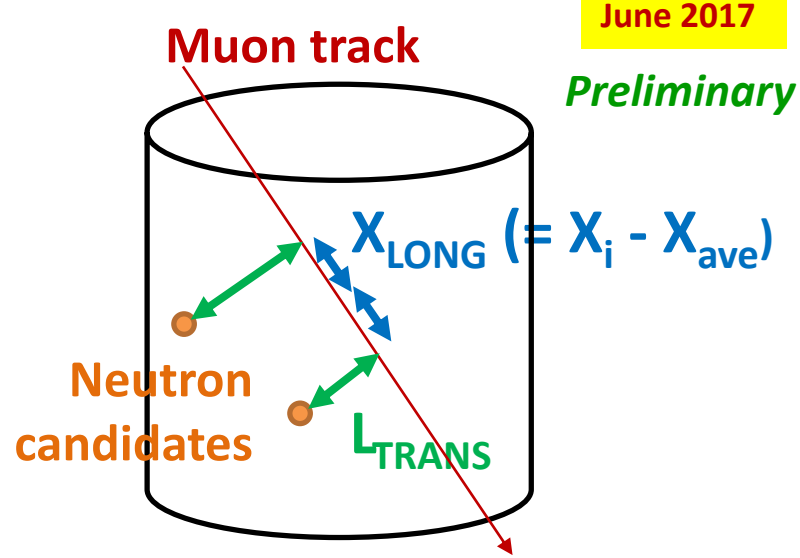
AmBe source,
203.7 +/- 2.8 μs
Astropart. 60 (2015) 41

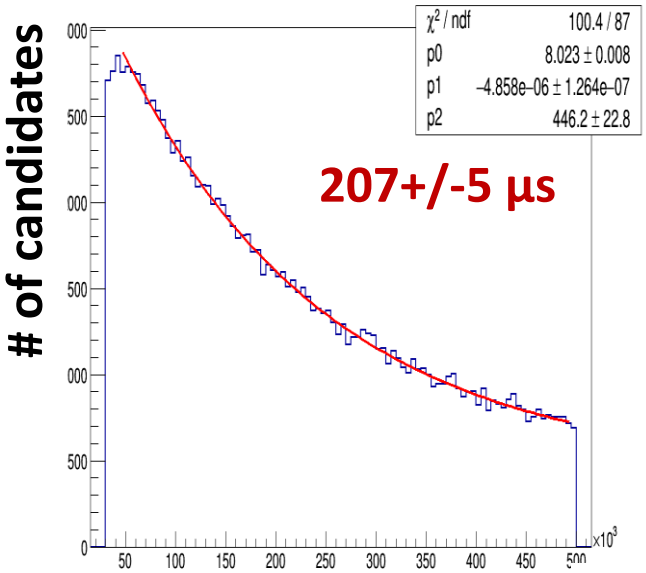
Study of spallation BG: 2/2

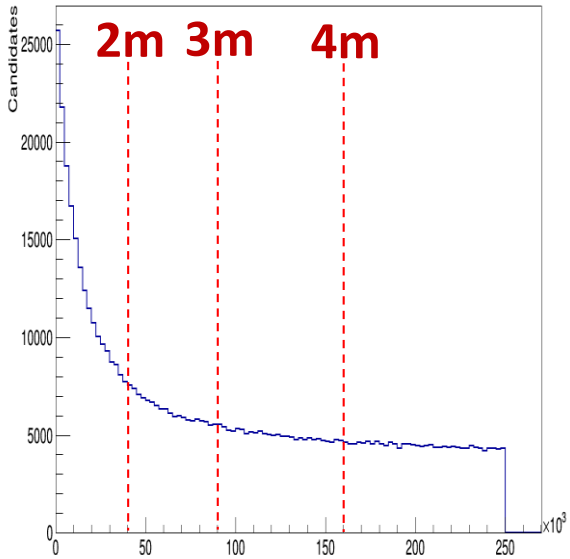
June 2017

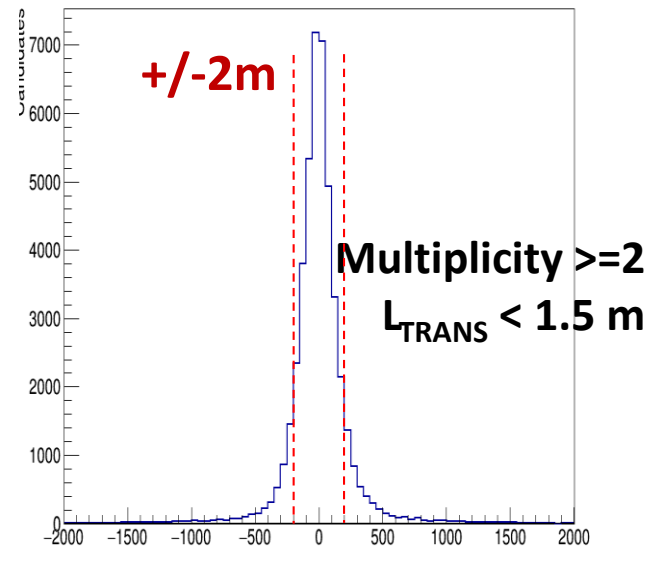
Preliminary

- **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**



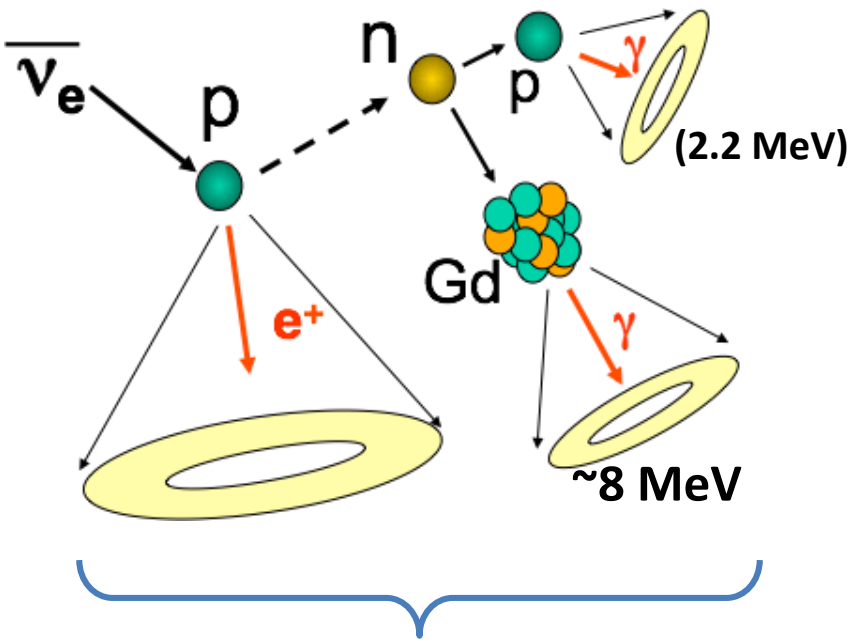




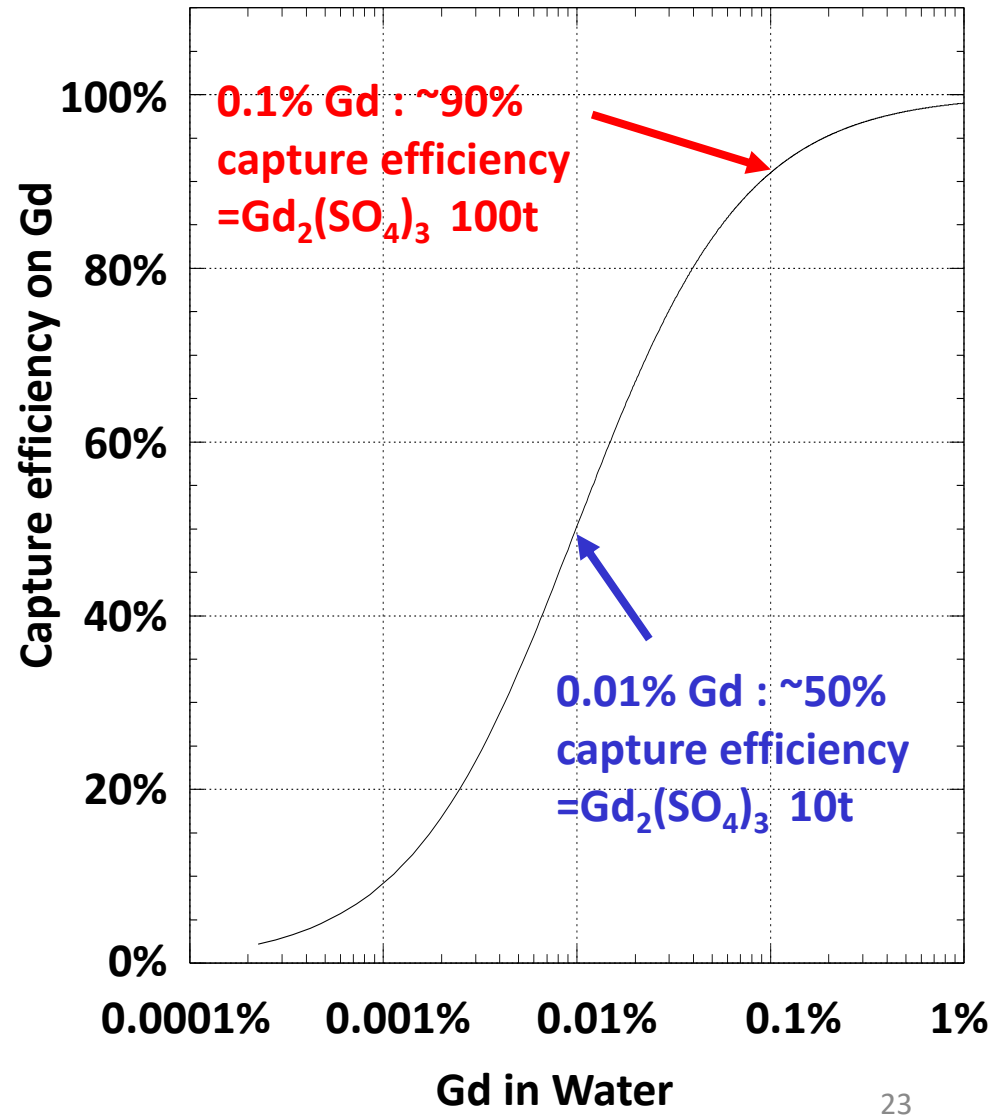


SK-Gd

Dissolve Gadolinium into SK
J. Beacom and M. Vagins, PRL93, 171101 (2004)



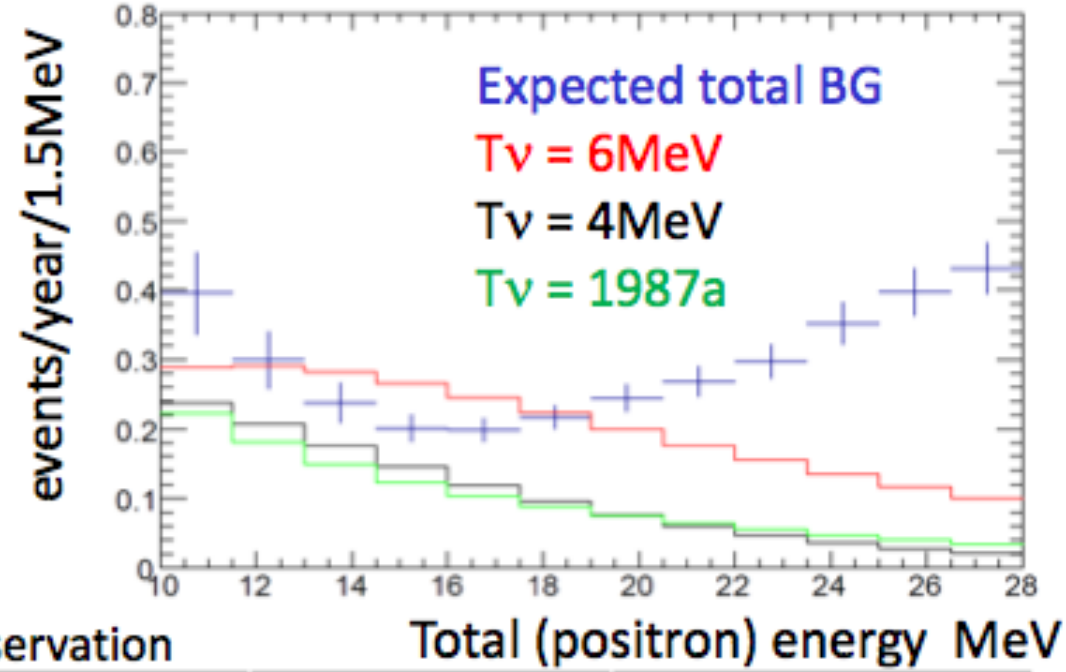
- Reduce BG of ν_e-bar signal
  - Delayed coincidence
  - ΔT ~ 30 μs
  - Vertices within ~ 50 cm



SK-Gd: Expected sensitivity

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

- It depends on typical/actual SN emission spectrum



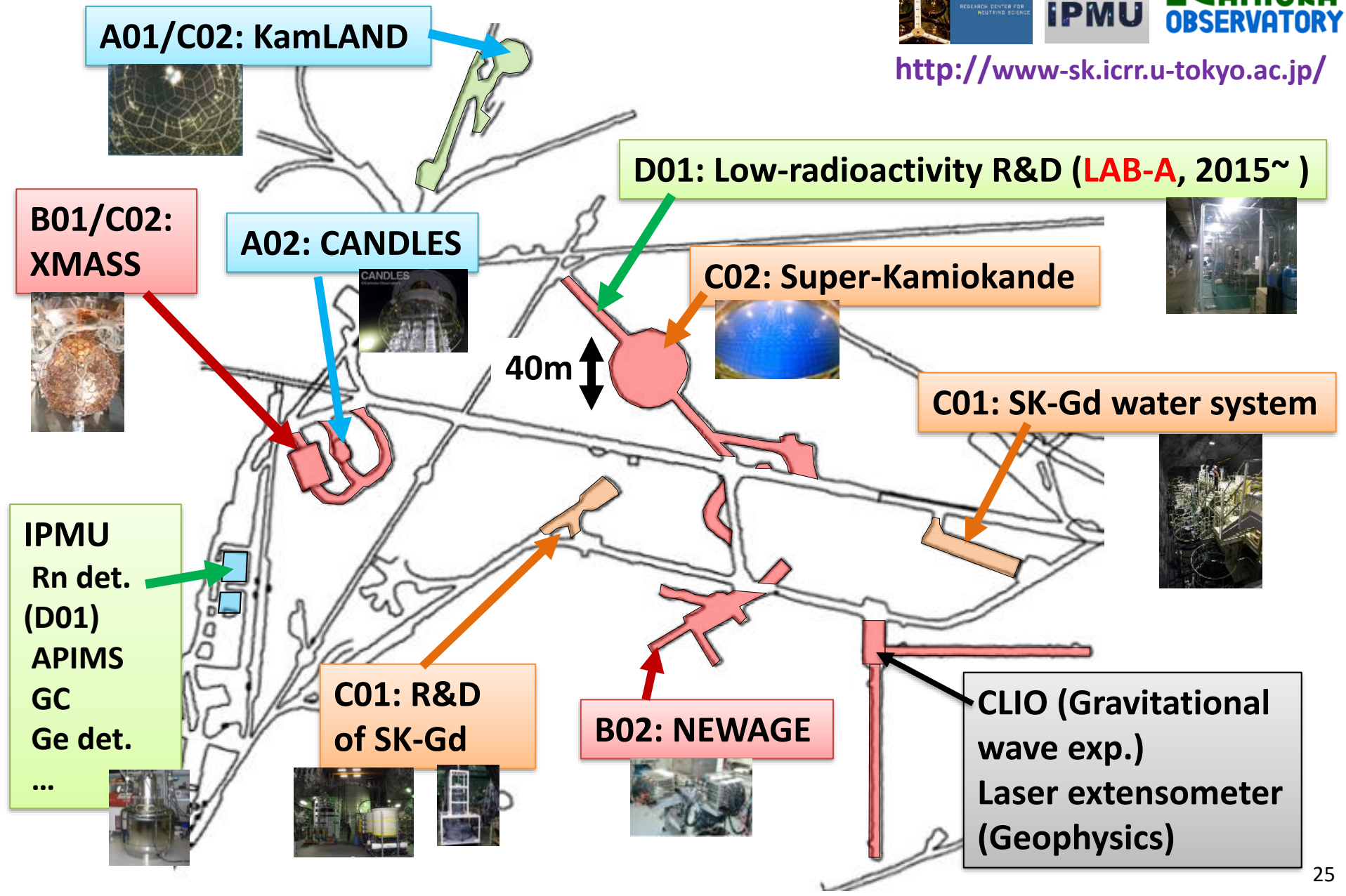
DSNB events number with 10 years observation

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	----

Kamioka Underground site

2700 m.w.e.

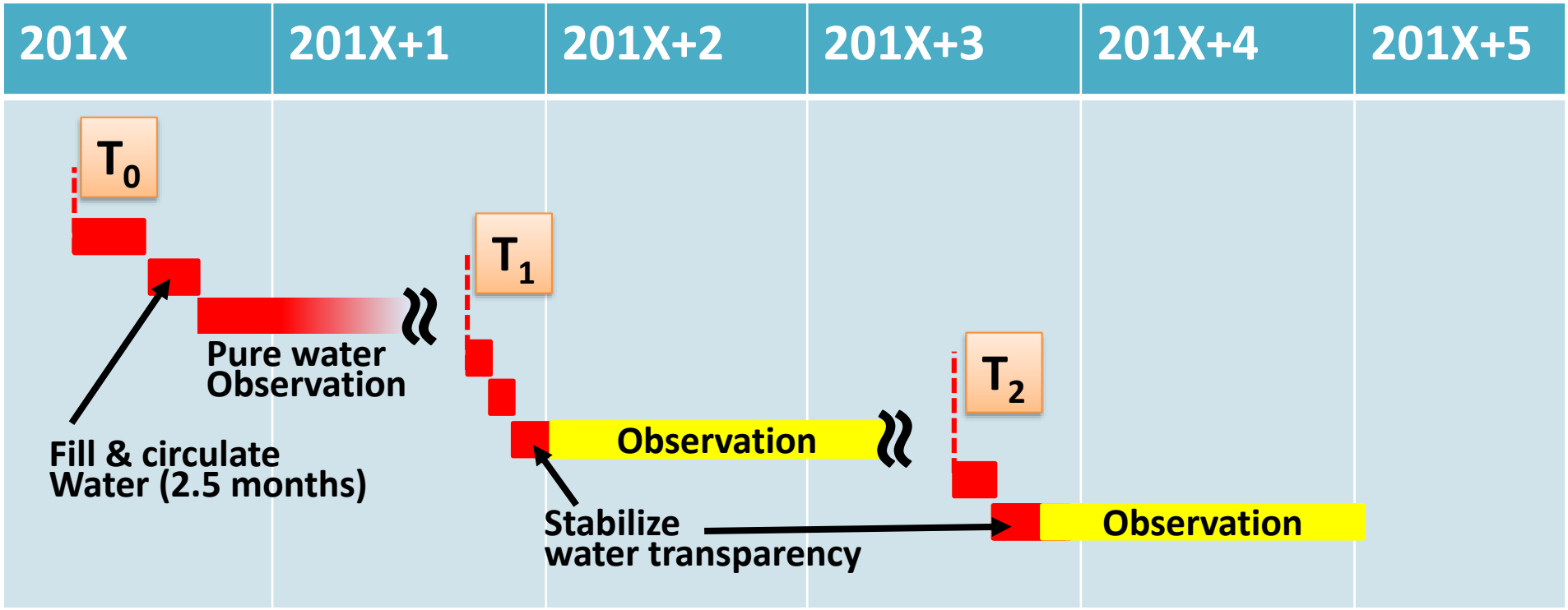
http://www-sk.icrr.u-tokyo.ac.jp/



SK-Gd: Water system extension

Gd-loading, pre-cleaning and Gd-water circulation systems were constructed.

SK-Gd: Current plan



T_0 is planned to be 2018 (next year).

T_0: Tank open work for leak tightening (~4 months)
T_1: Load first 10 ton $Gd_2(SO_4)_3$ [0.01% Gd]
T_2: Load full 100 ton $Gd_2(SO_4)_3$ [0.1% Gd]

Summary

- Solar and Supernova neutrinos are main astrophysical targets in low-energy region in SK.
- Partial preliminary results are reported.
  - 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 about to start.
  - T_0 will be 2018