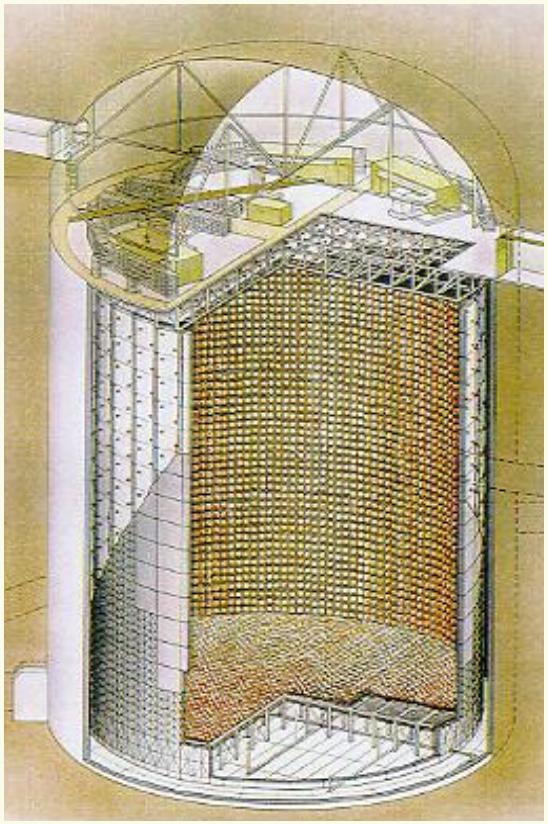
Recent experimental measurements of the Solar neutrinos with Cherenkov detectors



Yusuke Koshio

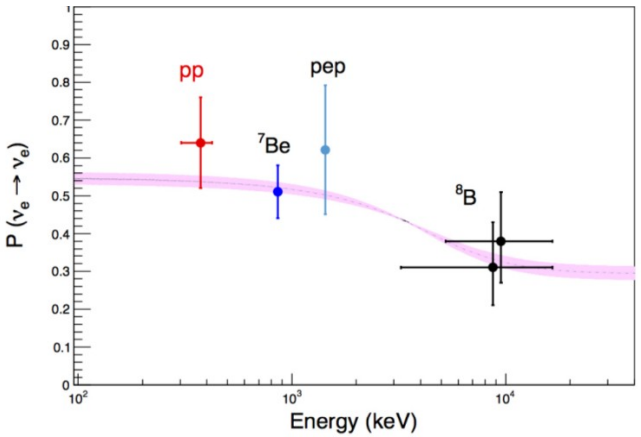
Okayama University

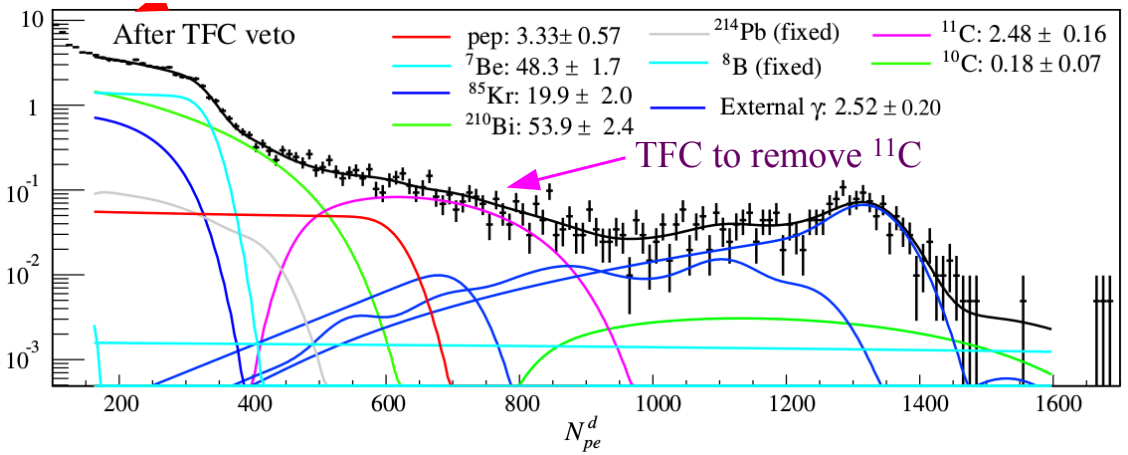
Recent developments in neutrino physics and astrophysics 5 Sep., 2017

Congratulations!

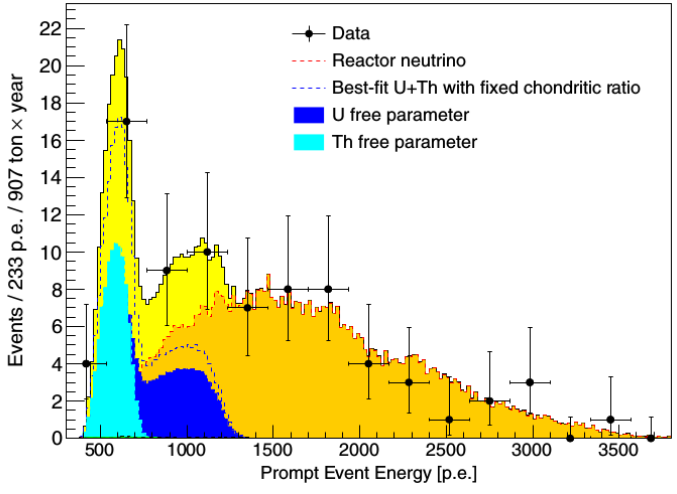
for 10th years anniversary of Borexino

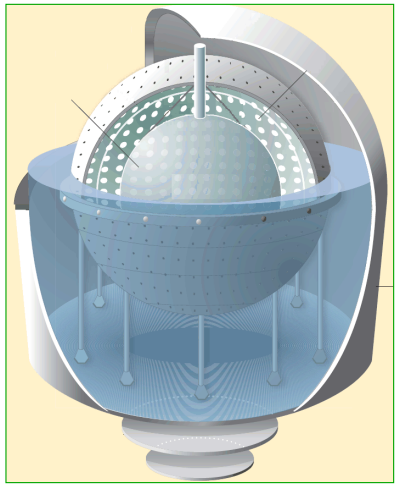
Lots of great results!

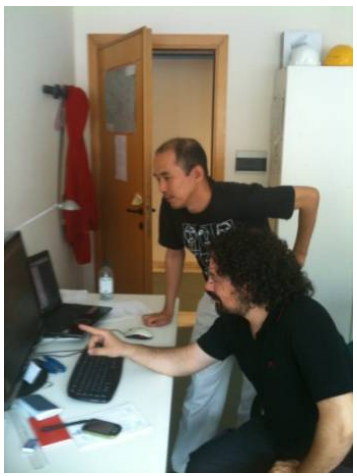




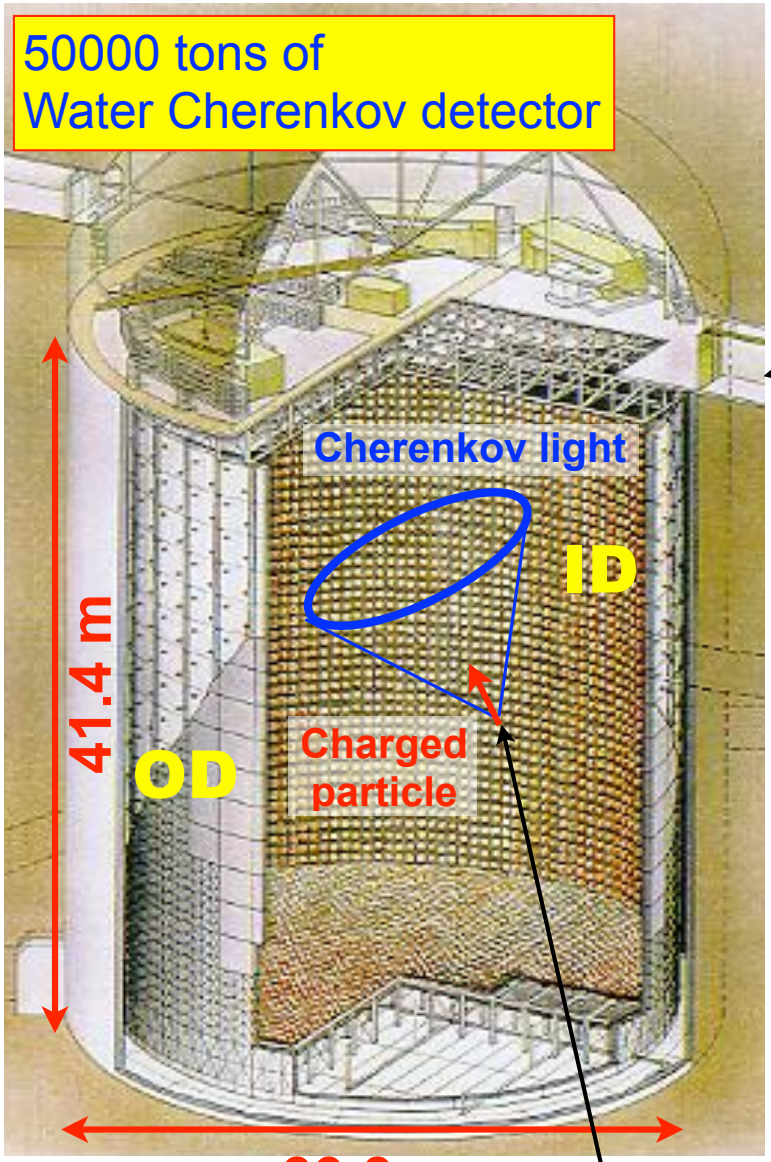
Beautiful memories for me!
(2009-2011)

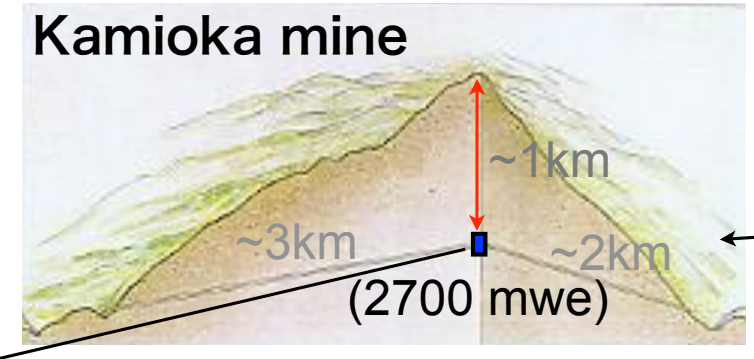


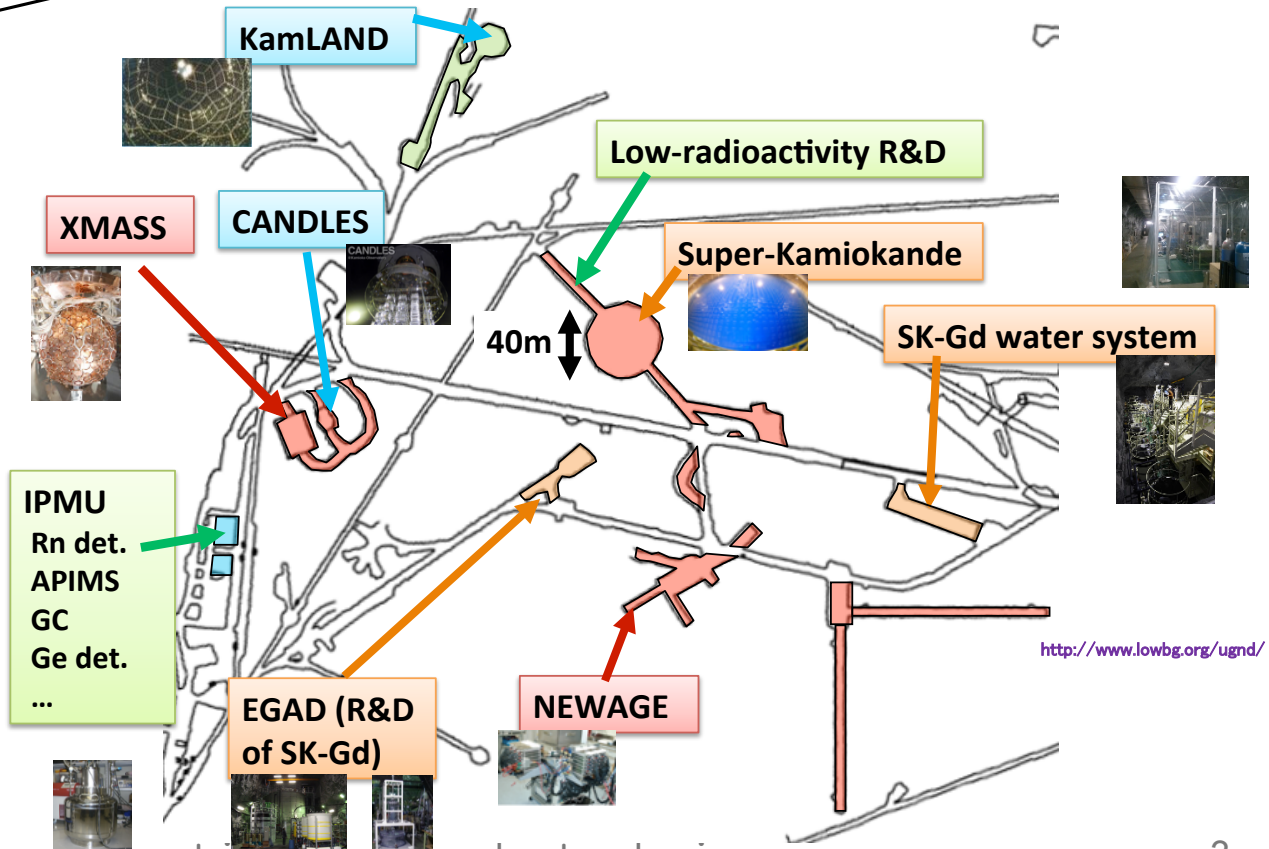




Super-Kamiokande



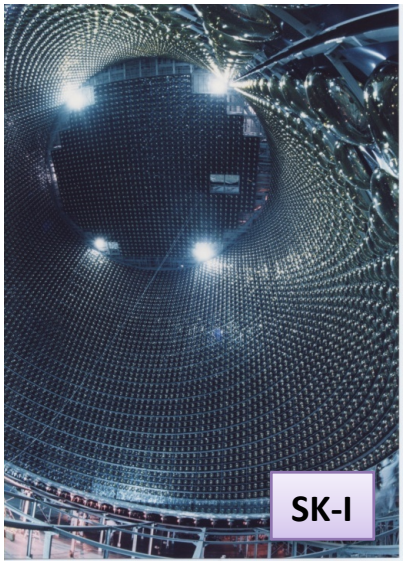


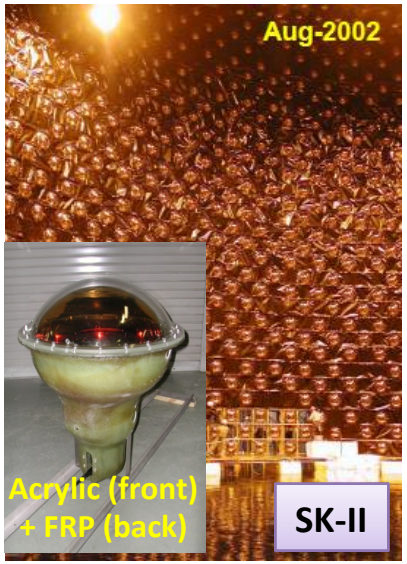


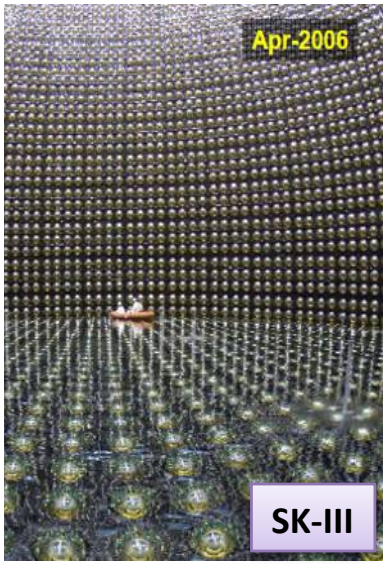
Super-Kamiokande

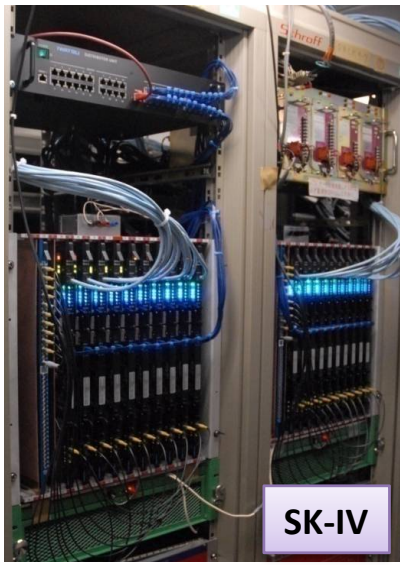
96 97 98 99 00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19

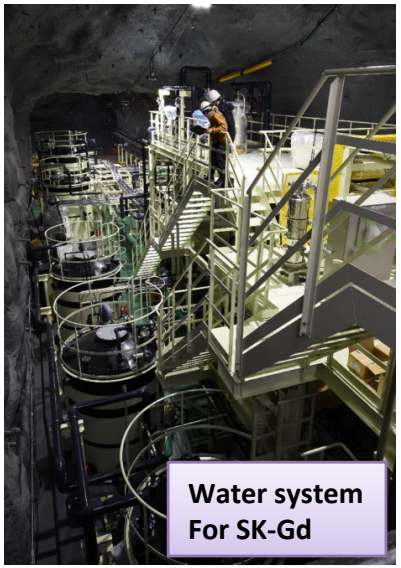
SK-I SK-II SK-III SK-IV SK-Gd











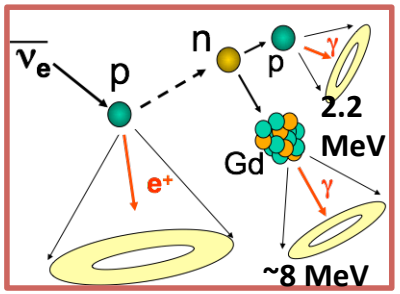
11146 ID PMTs (40% coverage)
4.5 MeV
1496 days

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

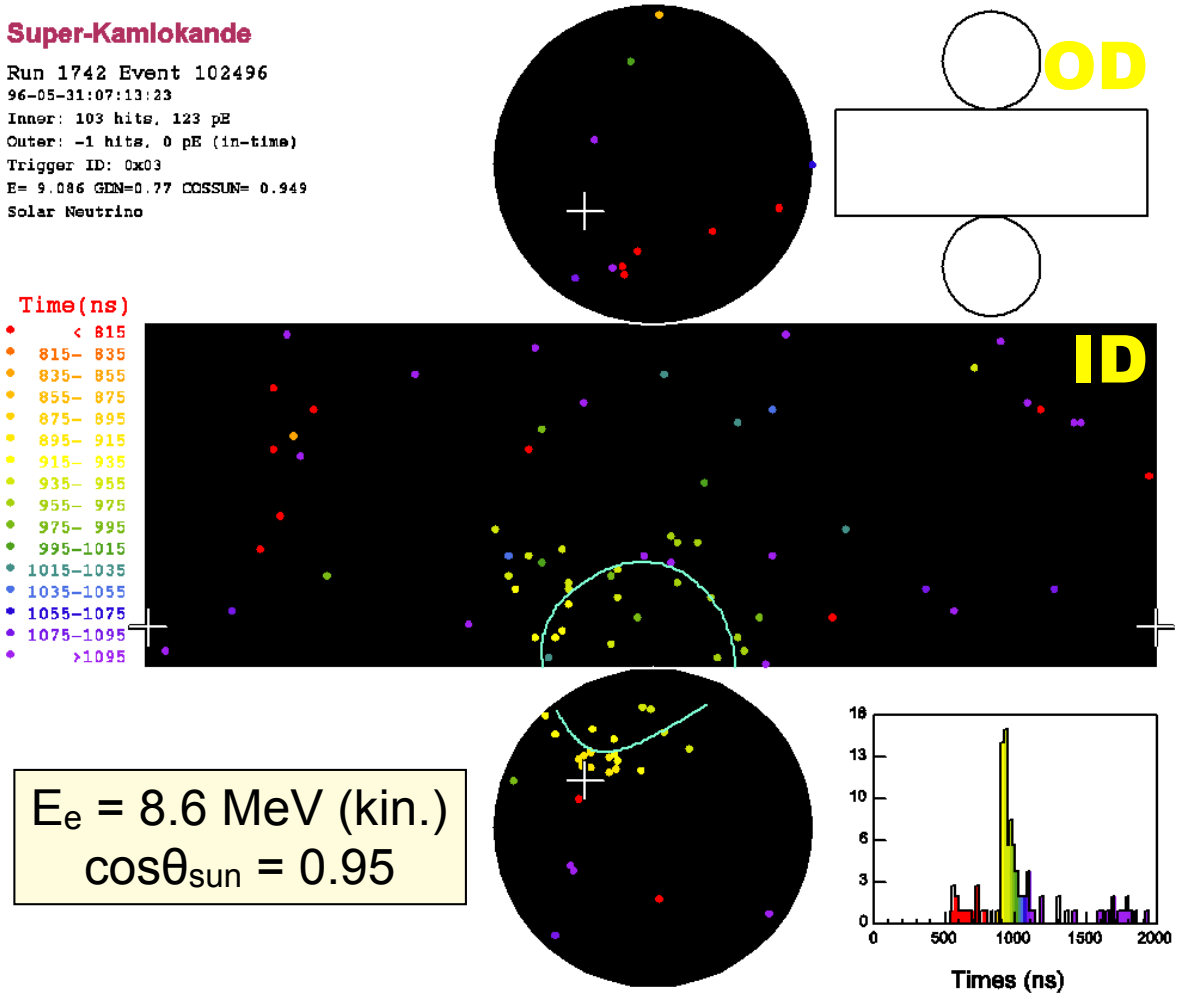


- Analysis energy threshold (recoil electron kinetic energy)
- Live time for solar neutrino analysis

Current total: 5480 days

Solar neutrino observation in SK

Typical event



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

neutrino-electron elastic scattering

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

- ✓Find solar direction
- ✓Realtime measurements
  - day-night flux differences
  - seasonal variation
- ✓Energy spectrum

Detector performance

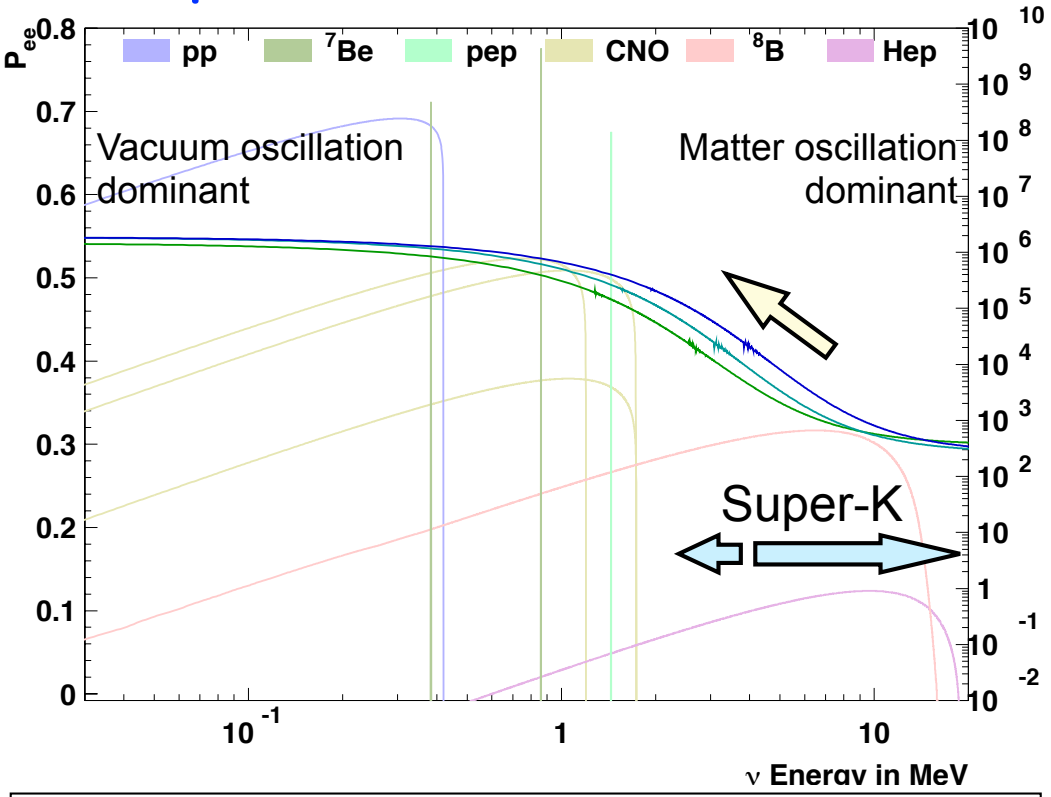
	resolution (10 MeV)	information
vertex	55cm	hit timing
direction	23deg.	hit pattern
energy	14%	# of hits.

~ 6 hits/MeV
well calibrated by LINAC and DT
within 0.5% precision

Motivation of the measurement

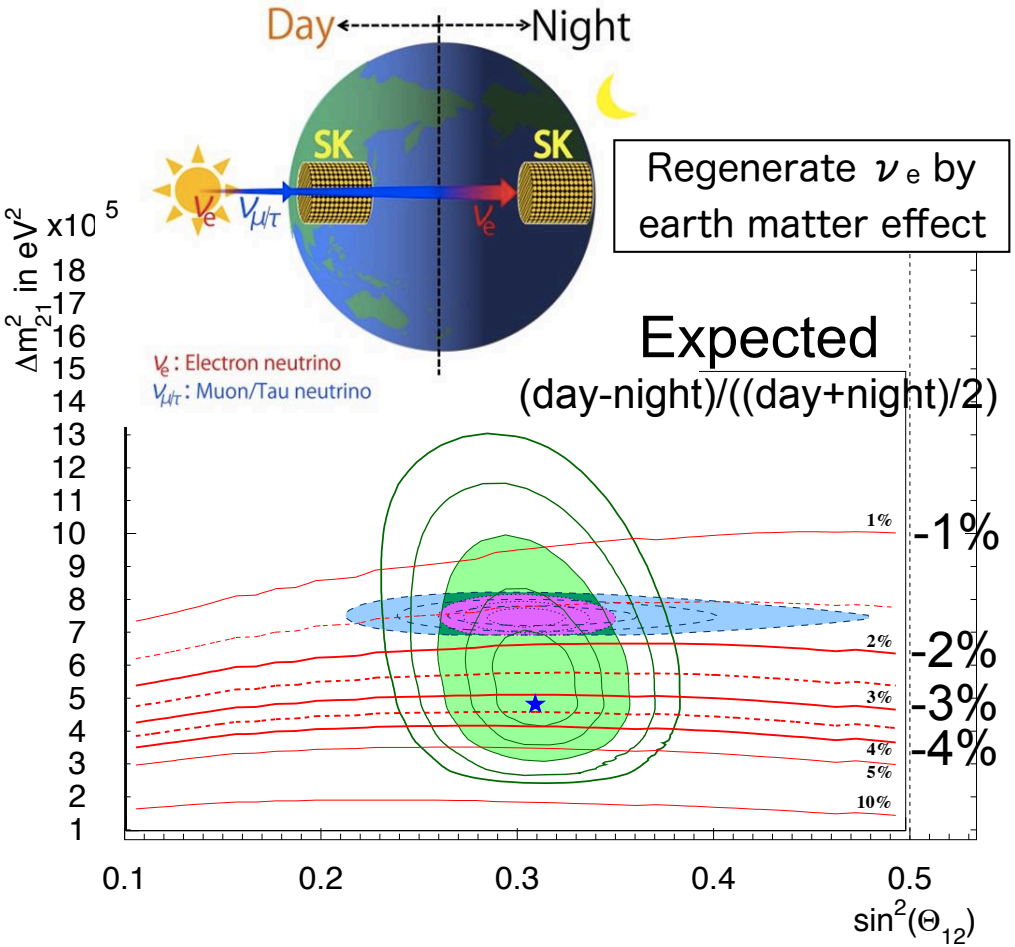
See the neutrino oscillation MSW effect directly

Spectrum distortion



Super-K can search for the spectrum "upturn" expected by neutrino oscillation MSW effect

Day-Night flux asymmetry



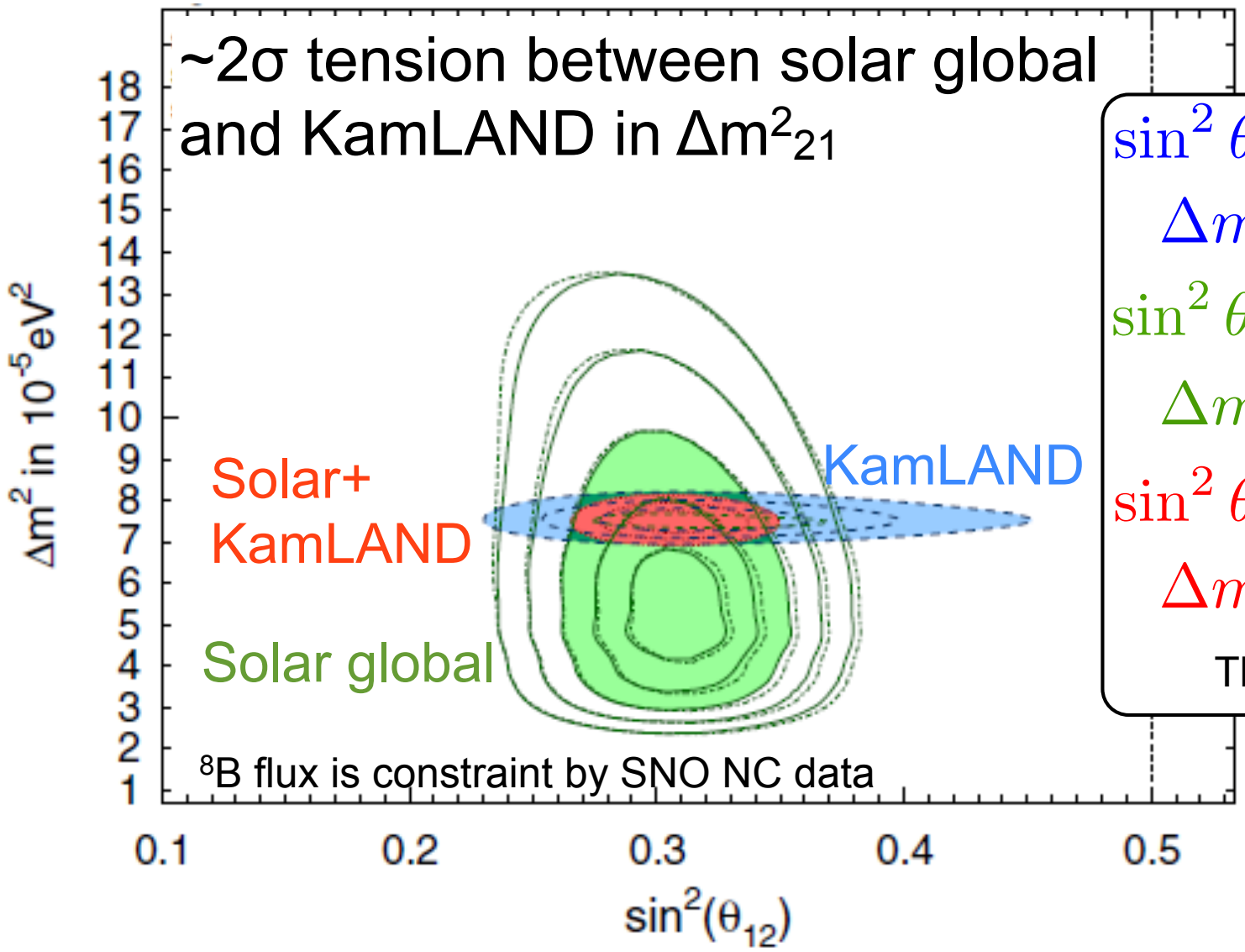
Published results

(PRD94, 052010, 2016)

Neutrino oscillation

PRD94, 052010 (2016)

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



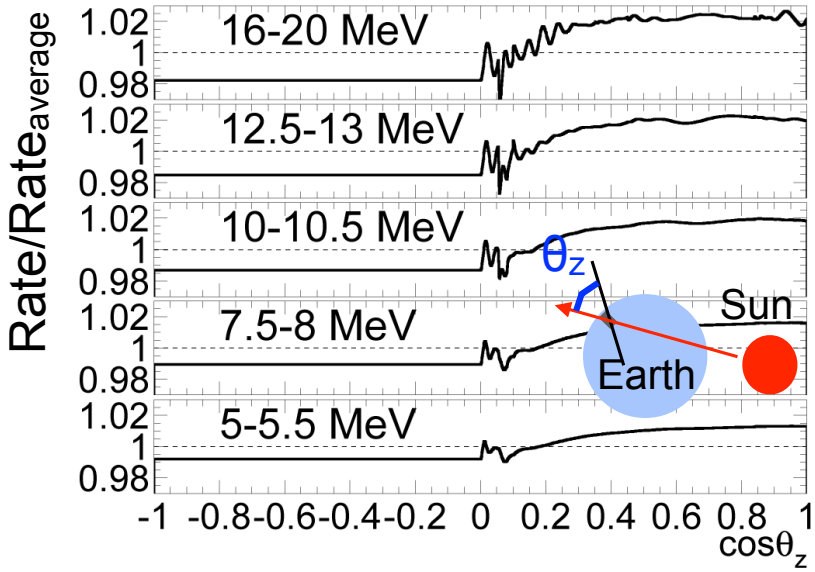
$$\sin^2\theta_{12} = 0.316^{+0.034}_{-0.026}$$
$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$$
$$\sin^2\theta_{12} = 0.308 \pm 0.014$$
$$\Delta m^2_{21} = 4.85^{+1.33}_{-0.59}$$
$$\sin^2\theta_{12} = 0.307^{+0.013}_{-0.012}$$
$$\Delta m^2_{21} = 7.49^{+0.19}_{-0.18}$$

The unit of Δm^2_{21} is 10^{-5} eV^2

$\sin^2\theta_{13}$=0.0219±0.0014

Day/Night asymmetry

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



PRD94, 052010 (2016)

Day/Night Amplitude was fitted to

-3.3±1.0±0.5%

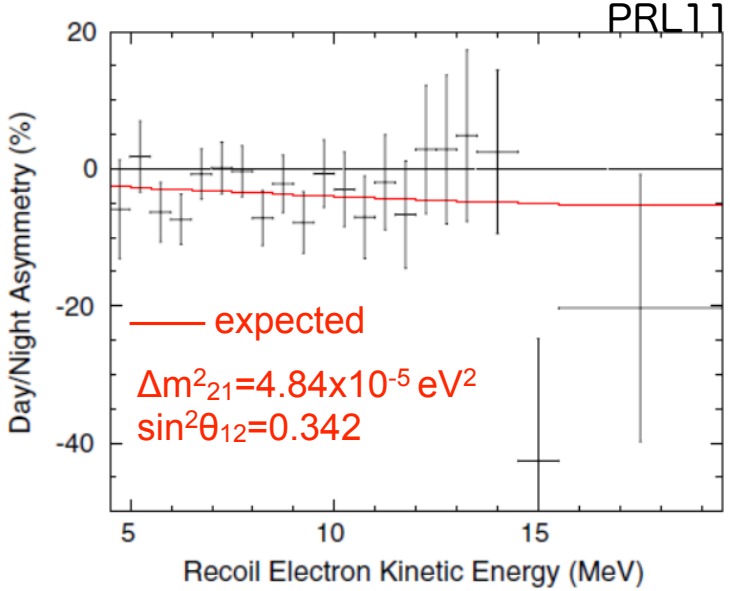
$\Delta m^2_{21}=4.84\times10^{-5}$ eV^2
$\sin^2\theta_{12}=0.311$
$\sin^2\theta_{13}=0.025$

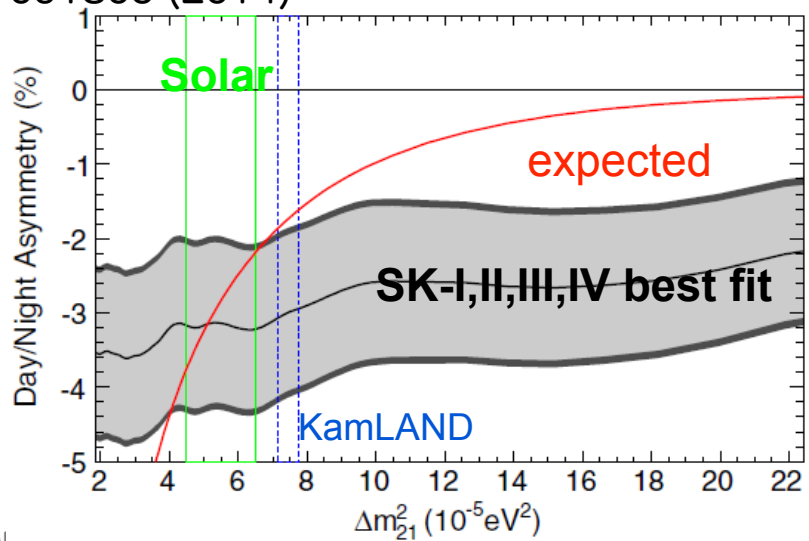
Non-zero significance was

2.9σ

in SK-I to IV (4499 days)

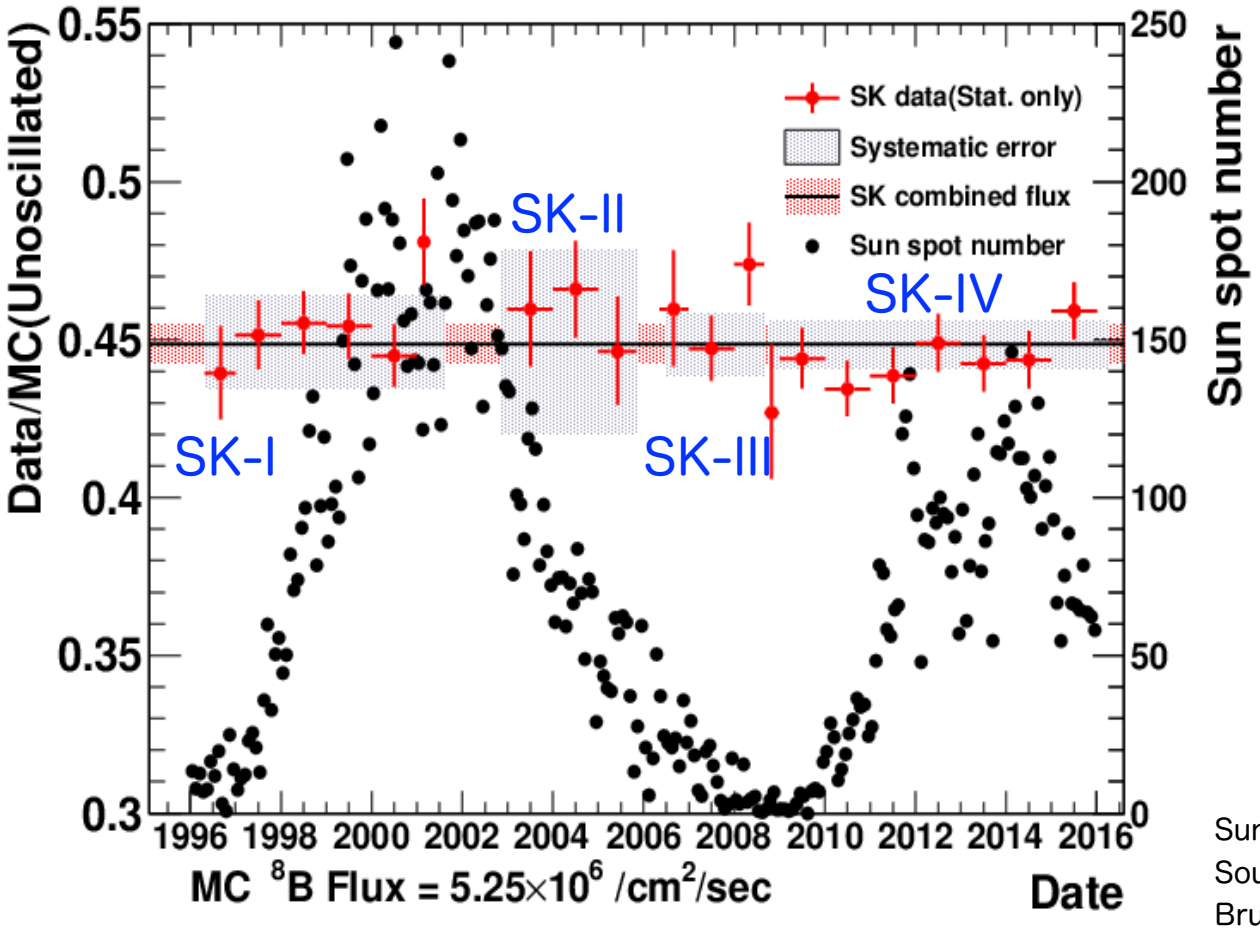
PRL112, 091805 (2014)





Preliminary

Yearly solar neutrino flux



^{8}B flux vs sun spot

No correlation with 11 years solar activity is observed

χ^2=15.52/19 (dof)

Prob. = 68.9%

Sun spot number : http://www.sidc.be/silso/datafiles
Source: WDC-SILSO, Royal Observatory of Belgium, Brussels

Solar neutrino rate measurement in SK is fully consistent with a constant solar neutrino flux emitted by the Sun

Latest results and progress

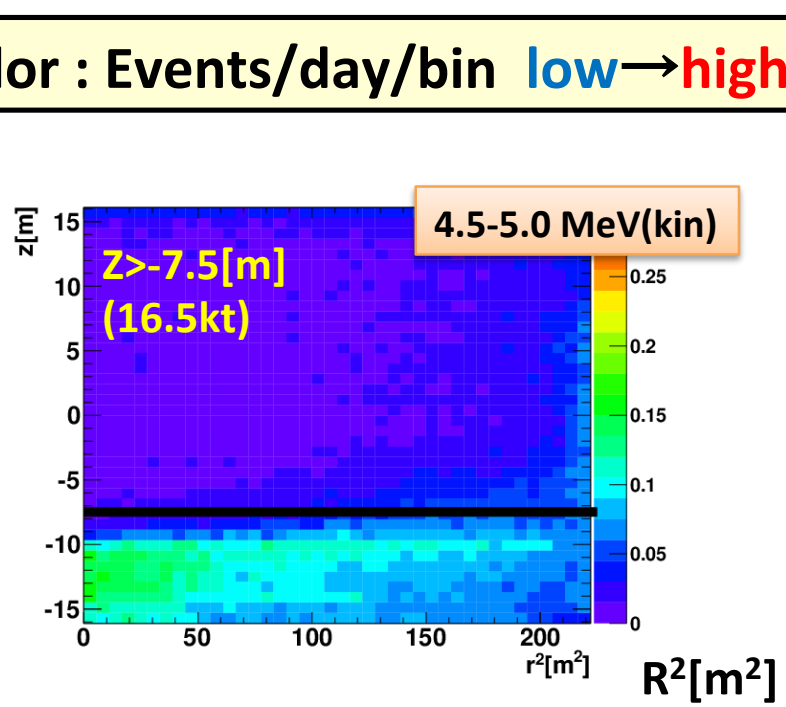
in June 2017

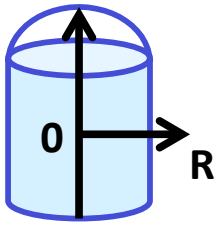
Contents

- 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)
- Periodic modulation analysis in SK-IV
  - Using same data set as PRD94, 052010
- Energy scale improvement
  - Take into account PMT gain & dark rate effects
- Study of spallation BG

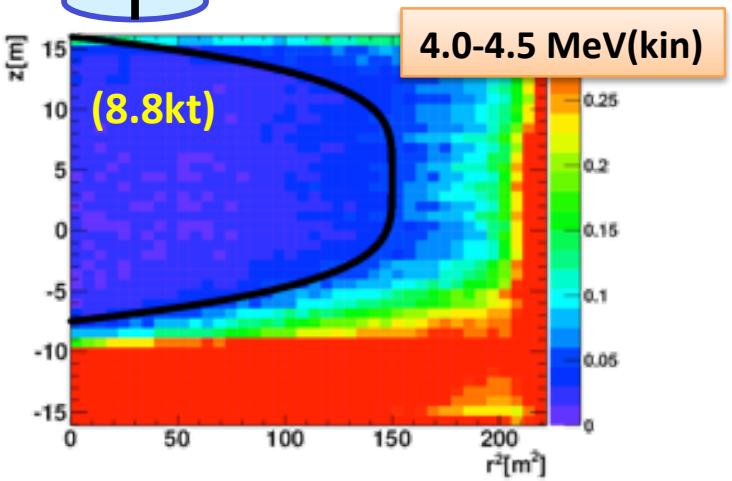
Event vertex distribution

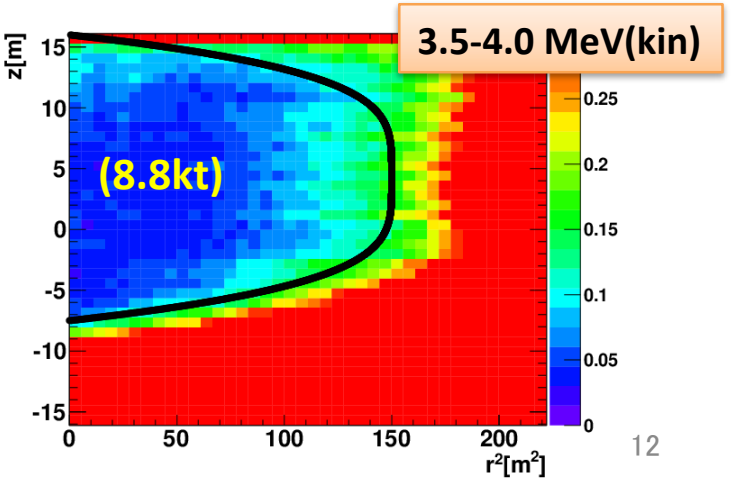
Color : Events/day/bin low→high





SK-IV (2645 days)

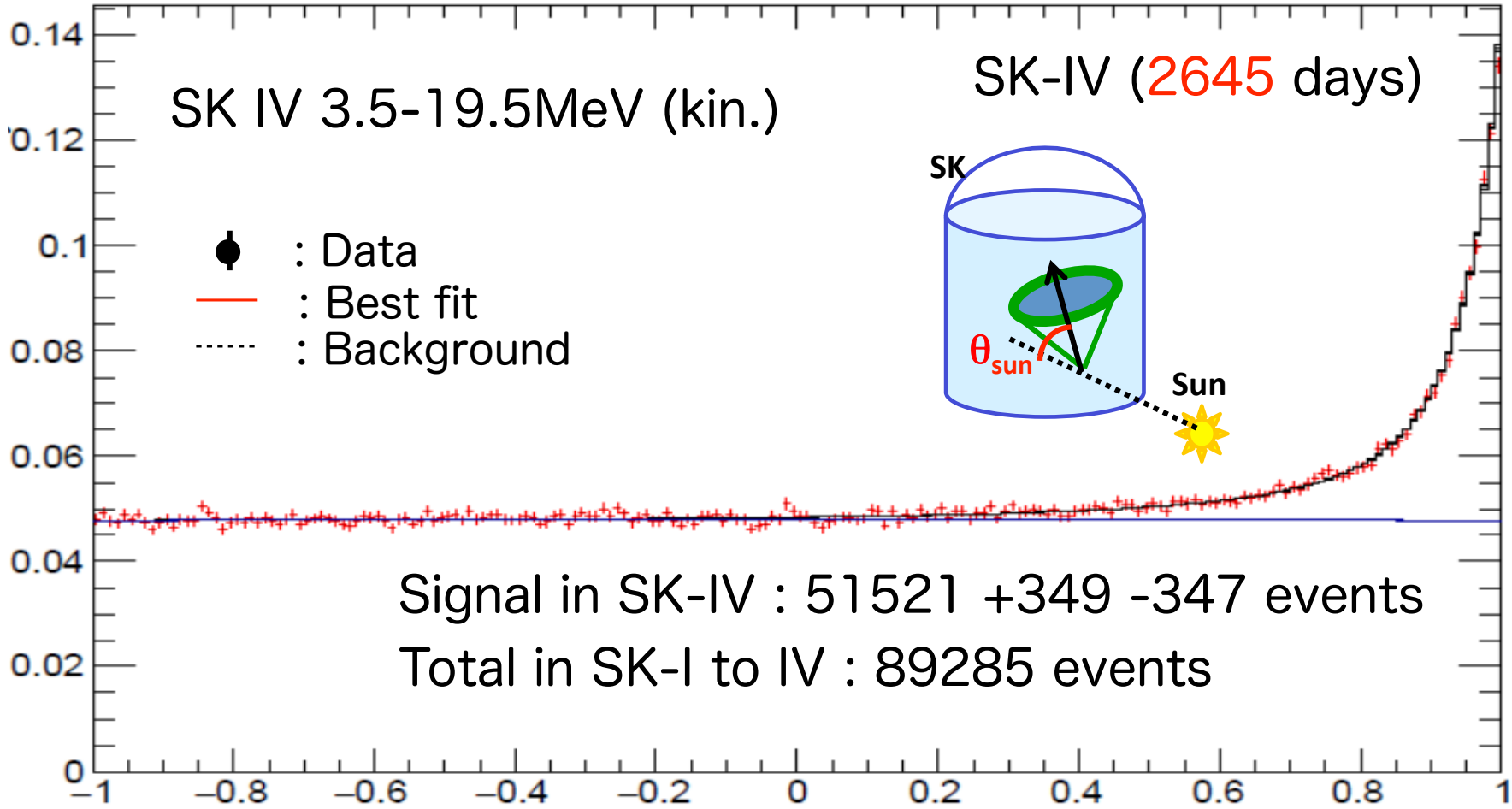




- Whole area in these plots corresponds to 22.5 kton.
- Above 5.0 MeV(kin), fiducial volume is 22.5kton.
- Below 5.0 MeV tight fiducial volume cut is applied.
- Water condition is controlled well

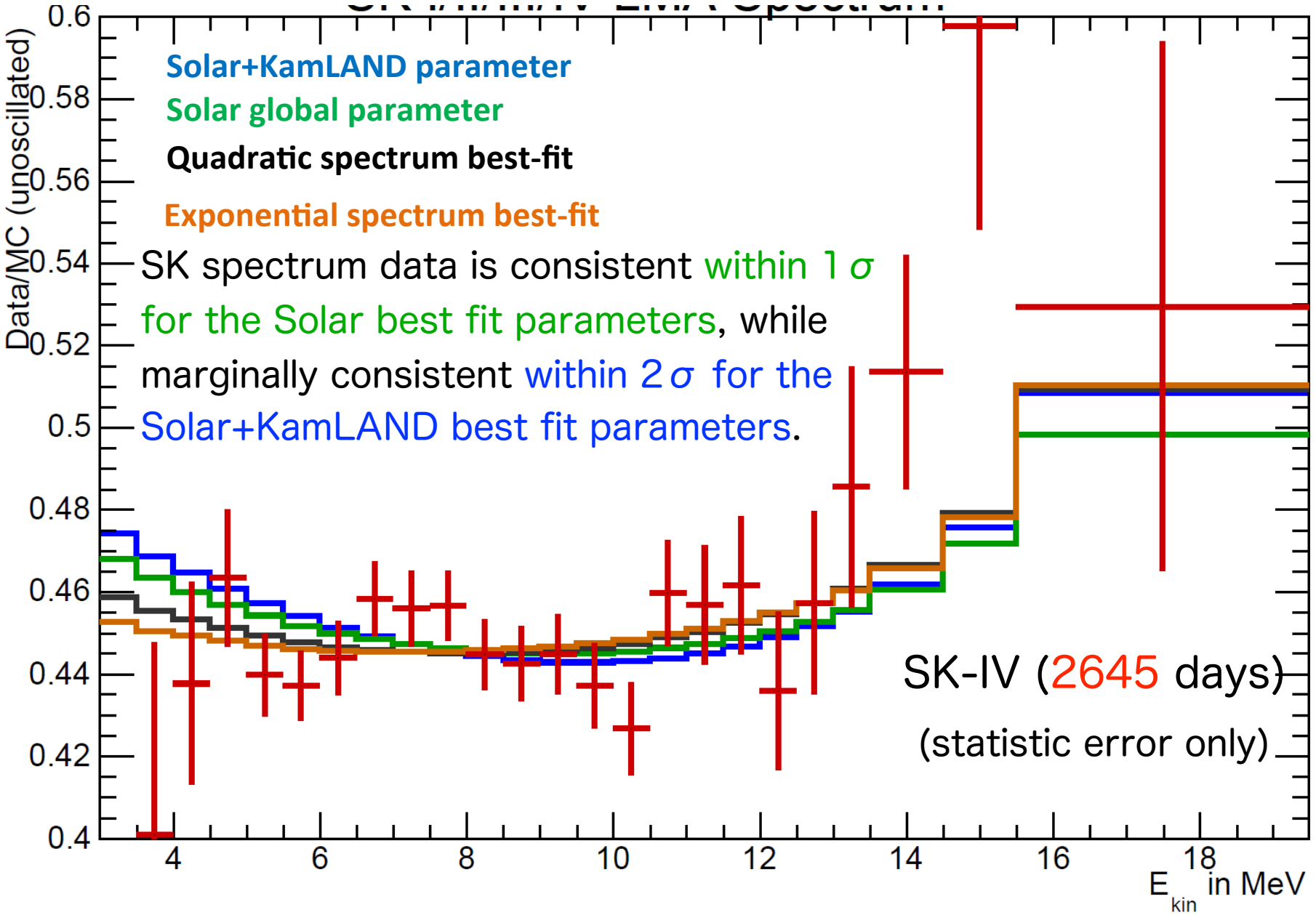
Preliminary

Observed solar neutrino signal



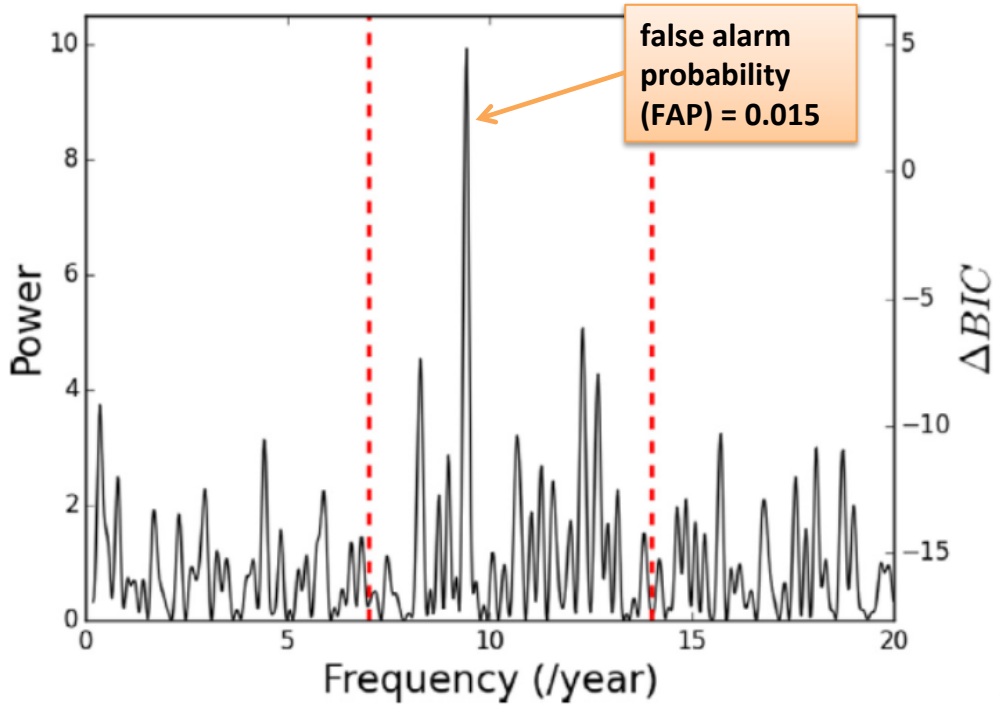
Preliminary

Recoil electron spectrum



Periodic modulation analysis

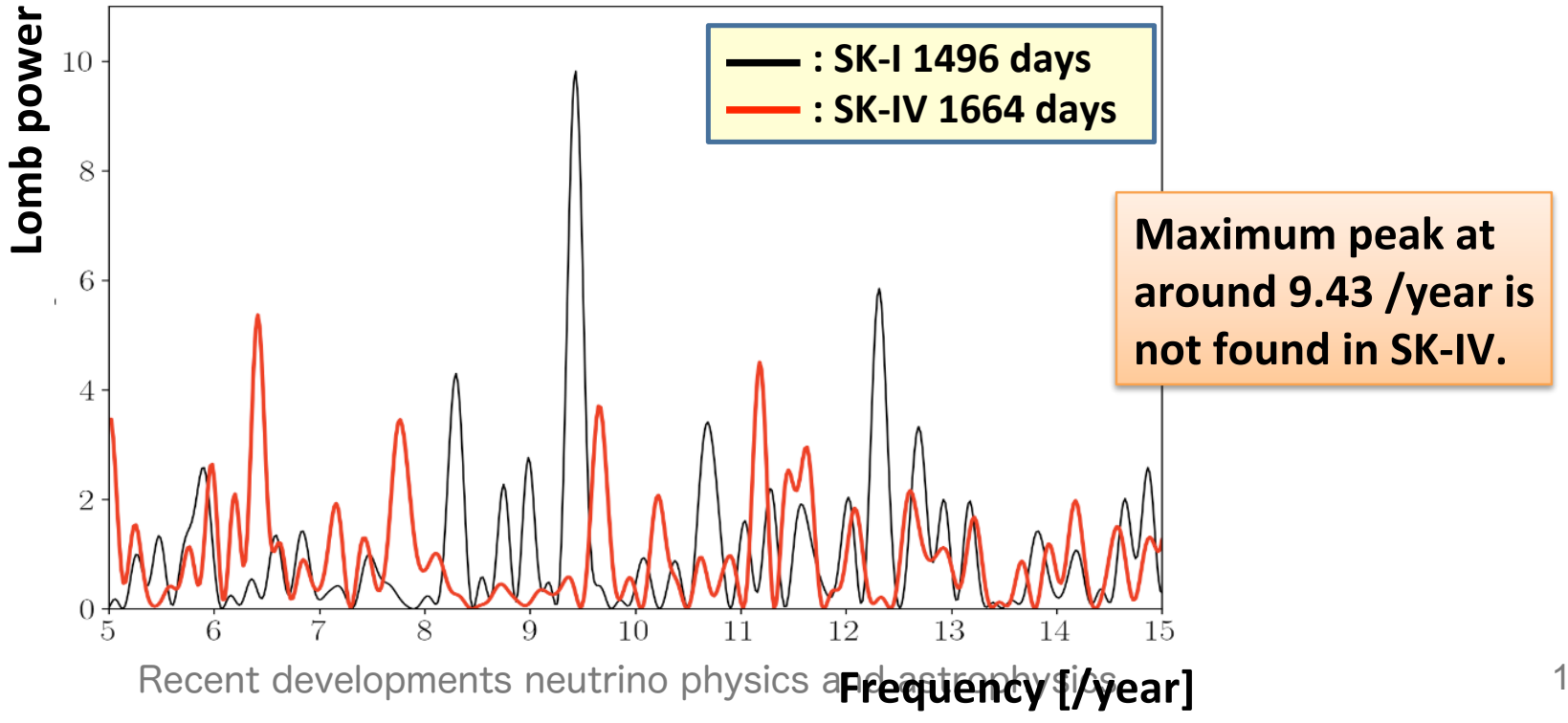
- Past publication : PRD68, 092002 (2003)
  - SK-I 1496 days, 4.5-19.5MeV (kin.)
  - Used Lomb-Scargle (LS) and 5-day long samples
- It was pointed out that a maximum peak was observed at around 9.43/year.
- A preliminary search in SK-IV in 5-15/year region is done.



Preliminary

Periodic modulation analysis

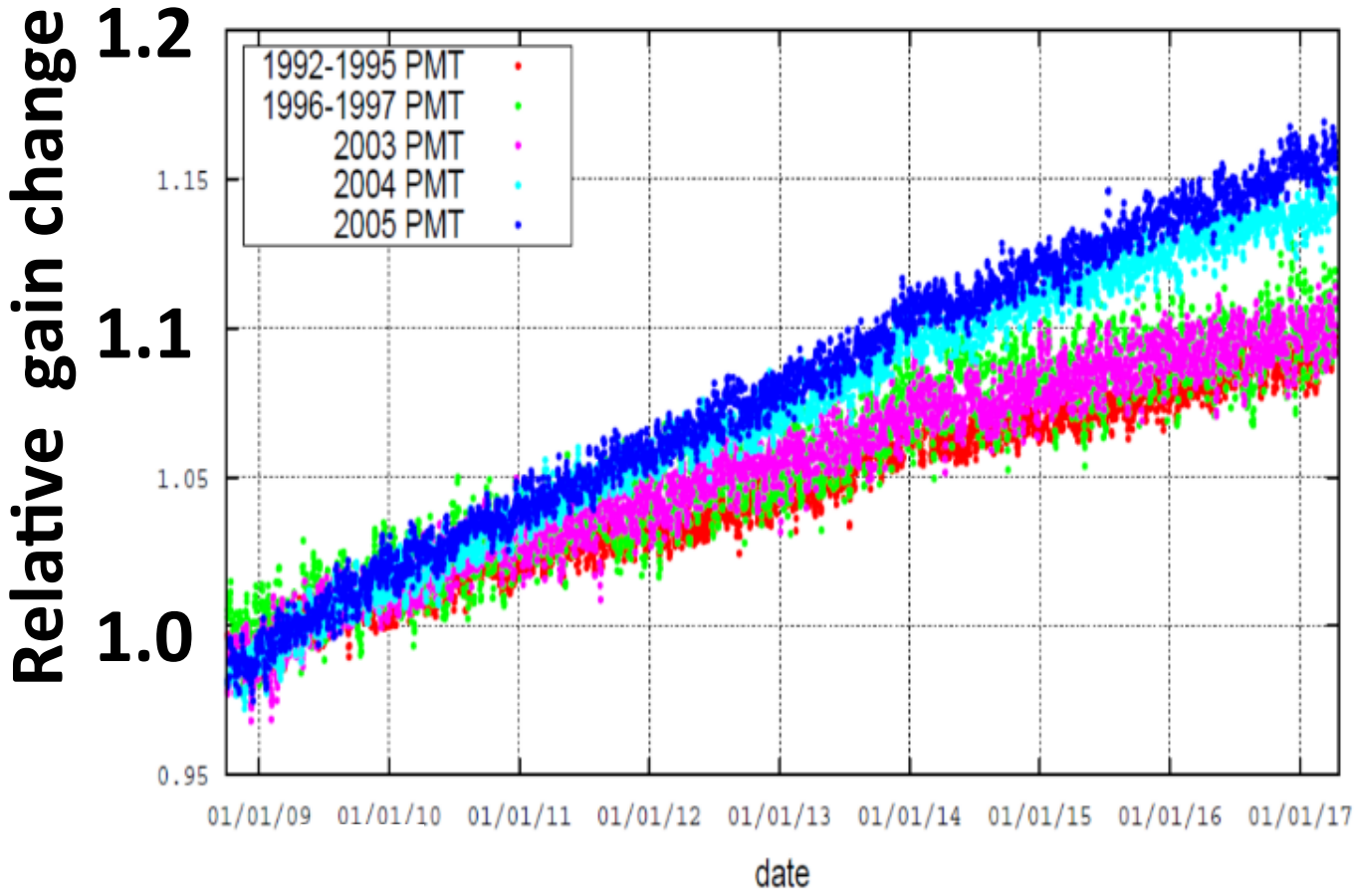
- Data set:
  - SK-I : 1496 days, 5-day long sample, 4.5-19.5 MeV (kin.)
  - SK-IV : 1664 days, 5-day long sample, 4.5-19.5 MeV (kin.)
  - Generalized LS method (with symmetric error)
  - Search region : 5-15 [/year]



Preliminary

Energy scale improvement

PMT gain is increasing

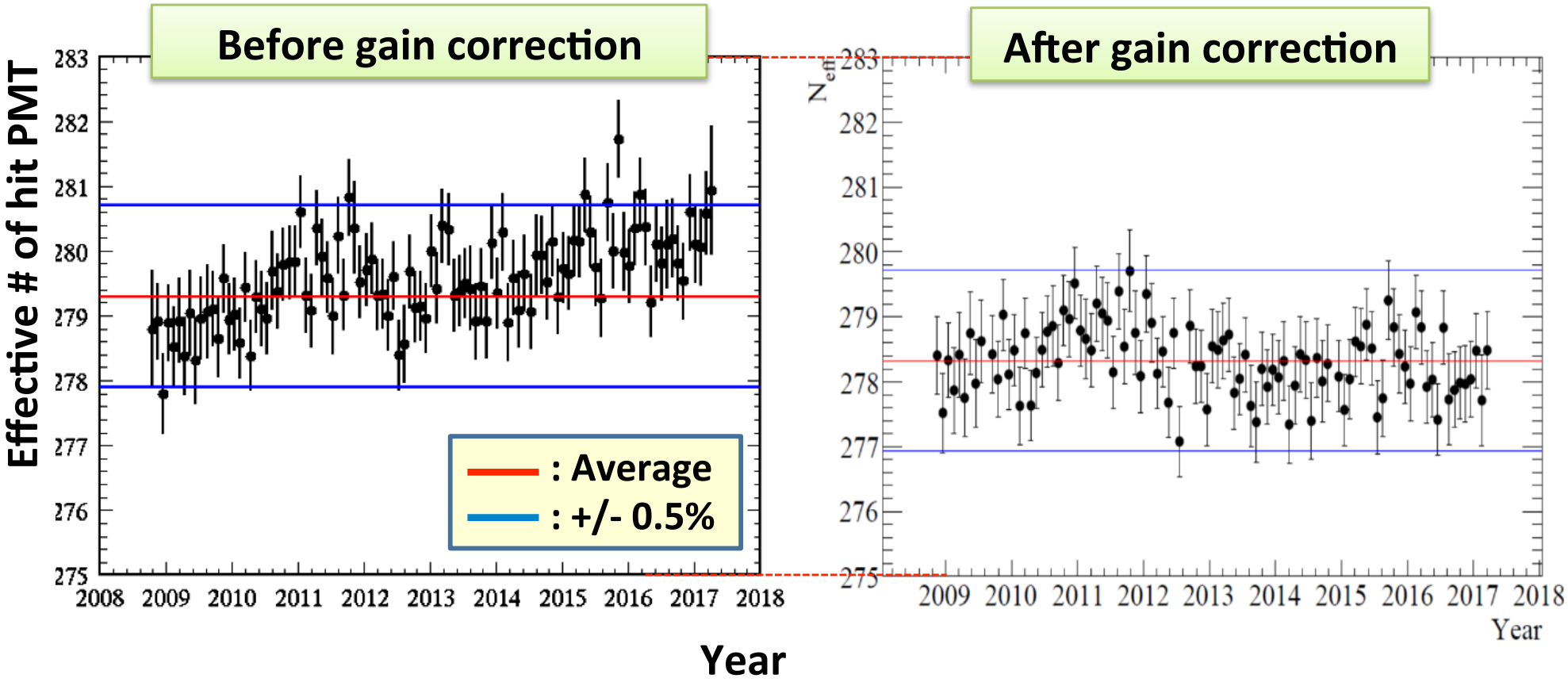


Try to implement the effect to detector simulation and energy reconstruction

Preliminary

Energy scale improvement

Energy scale of decay electron

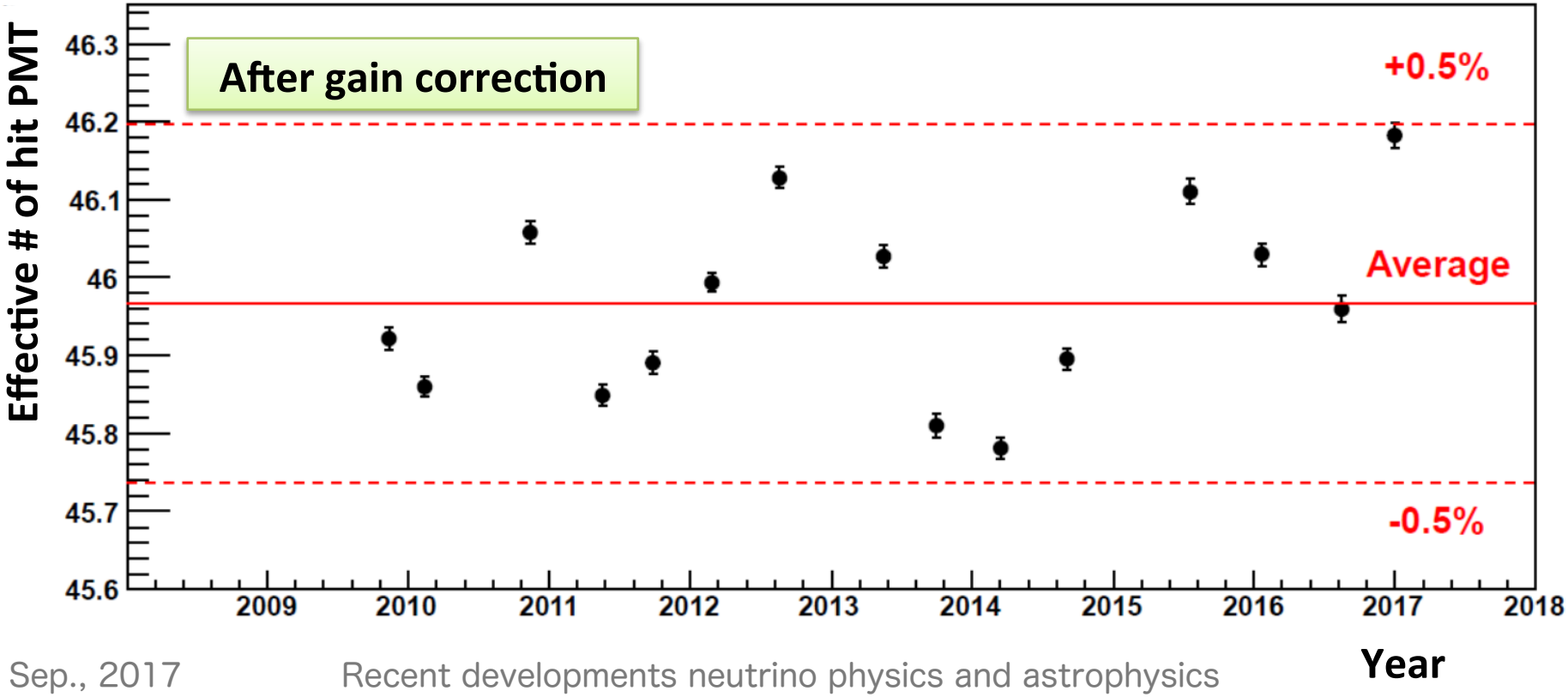


Looks stable after gain correction

Energy scale improvement

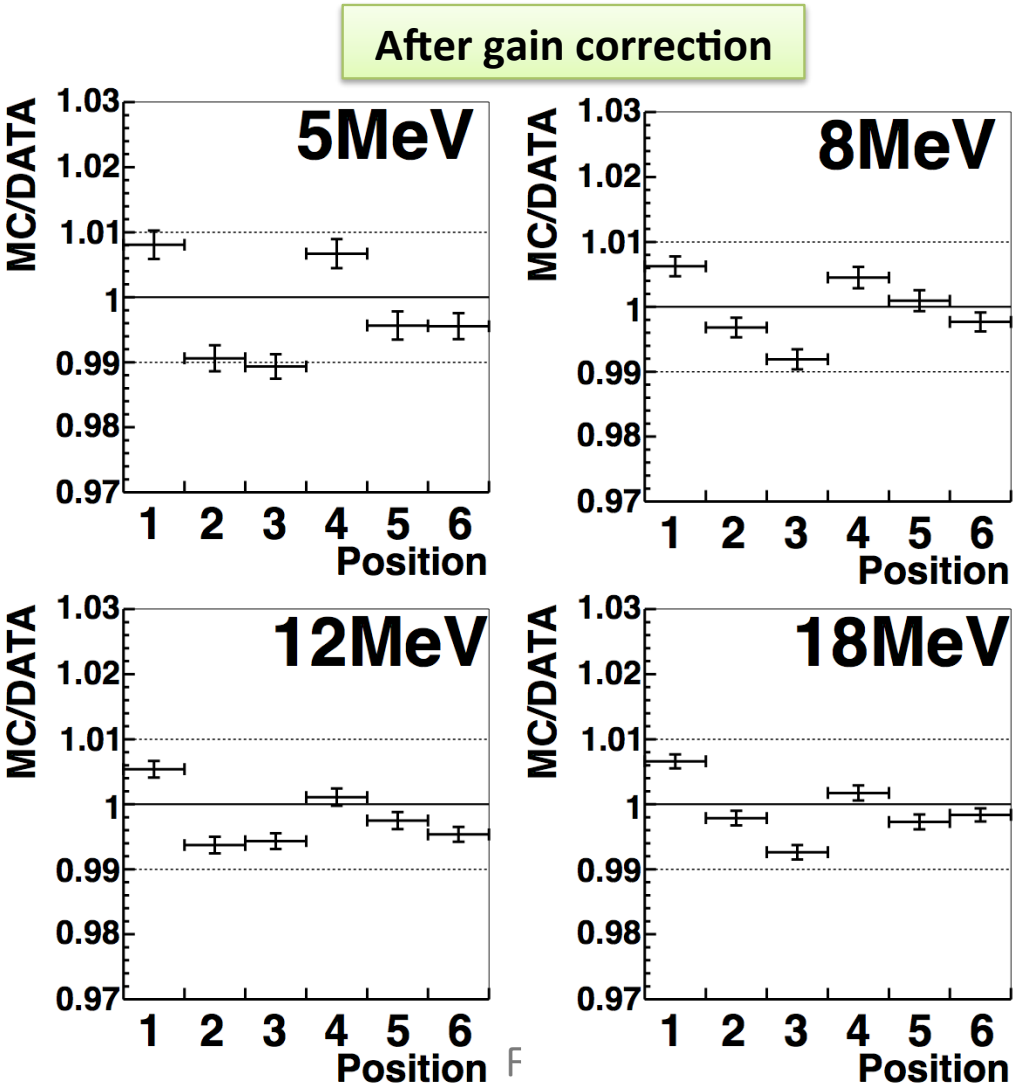
Look at the calibration data : DT generator

- Gamma rays from ^{16}N
- Center position in 2009-2017
- Looks stable



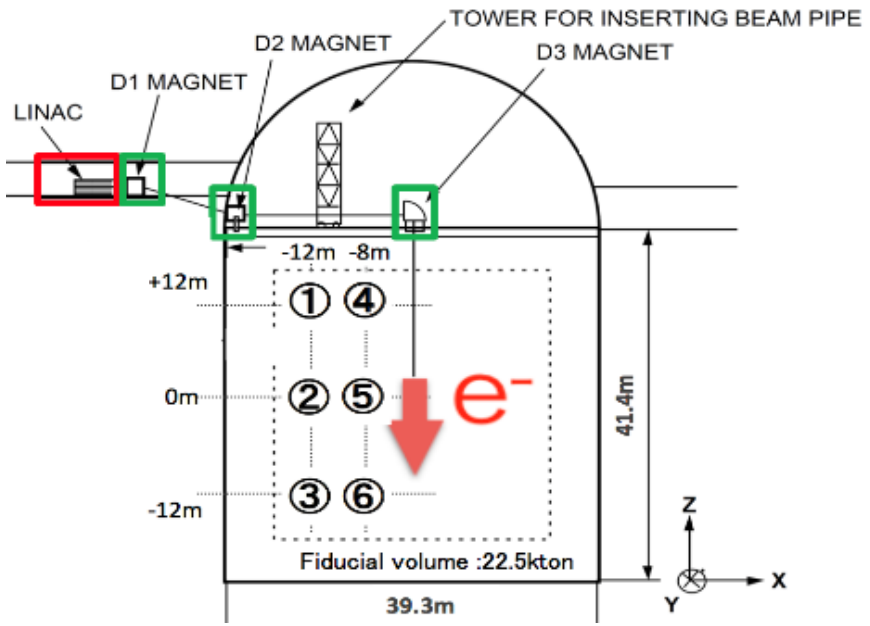
Energy scale improvement

Look at the calibration data : LINAC



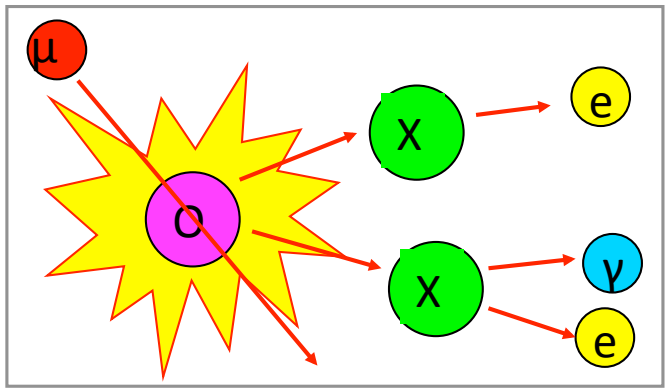
2016 LINAC campaign

Position dependence : ±0.5%

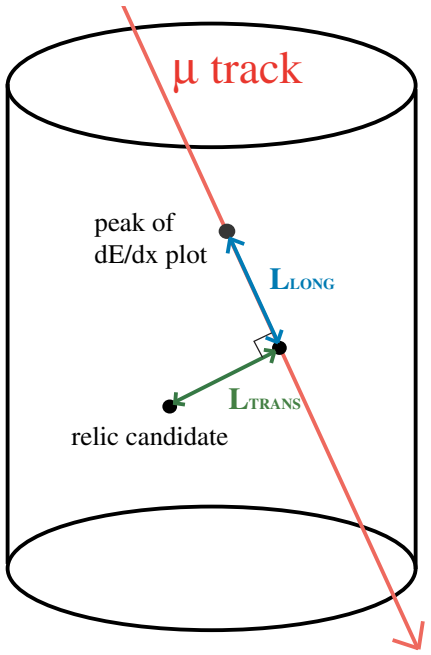


Study of the spallation event

- Neutrons production in the hadronic shower from a spallation causing muon was pointed out by J.Beacom and Shirley Li.



- They could be observed when the energy threshold is lowered via 2.2MeV gamma from n+p reaction
- Tried to use lowering threshold data (~2.5MeV (kin.) threshold.)



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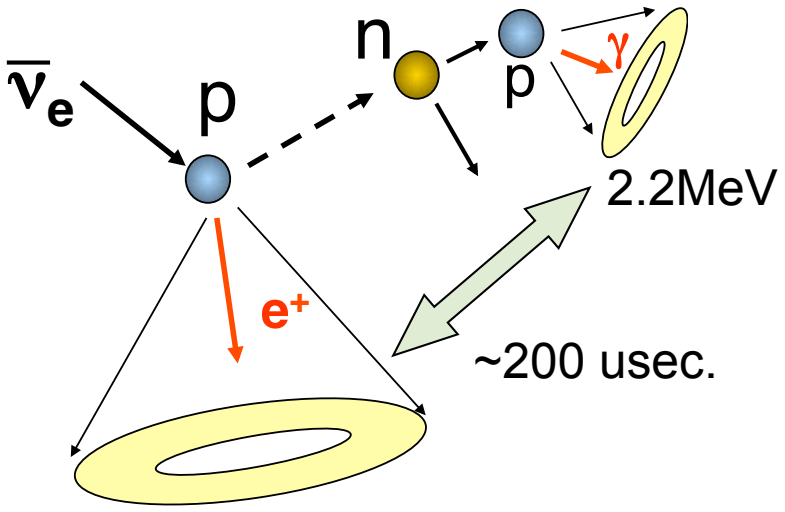
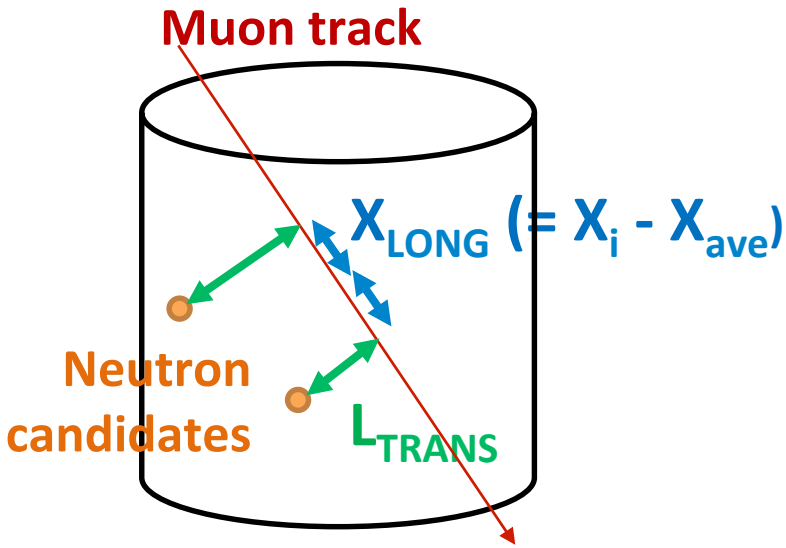
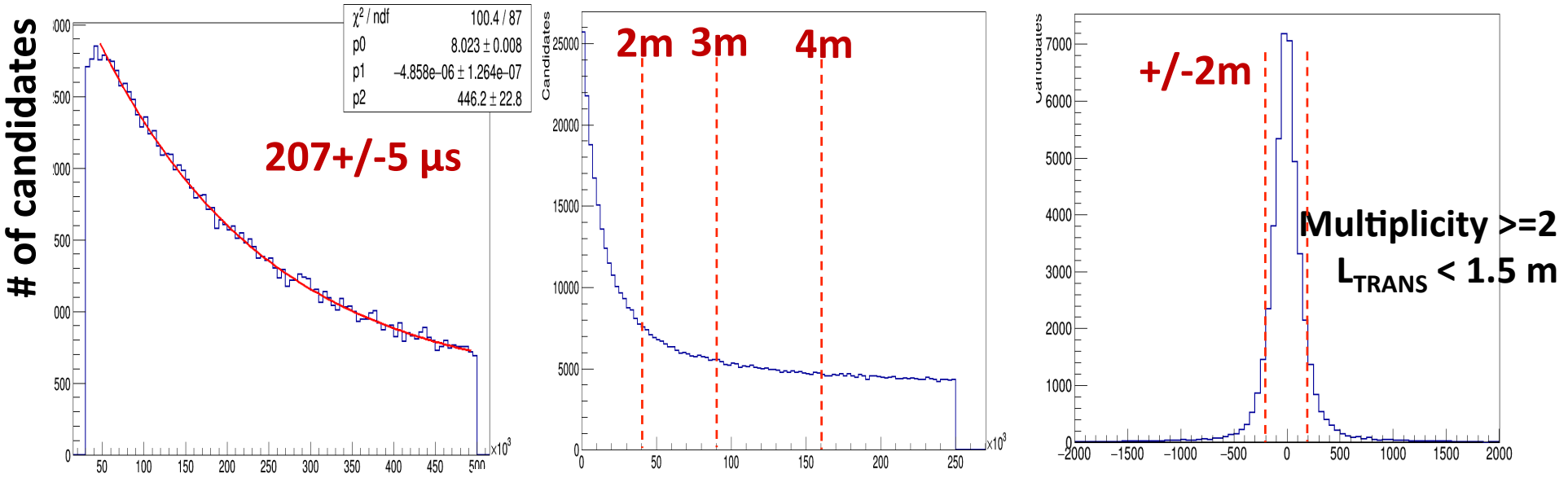


Preliminary

Study of the spallation event

- **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**

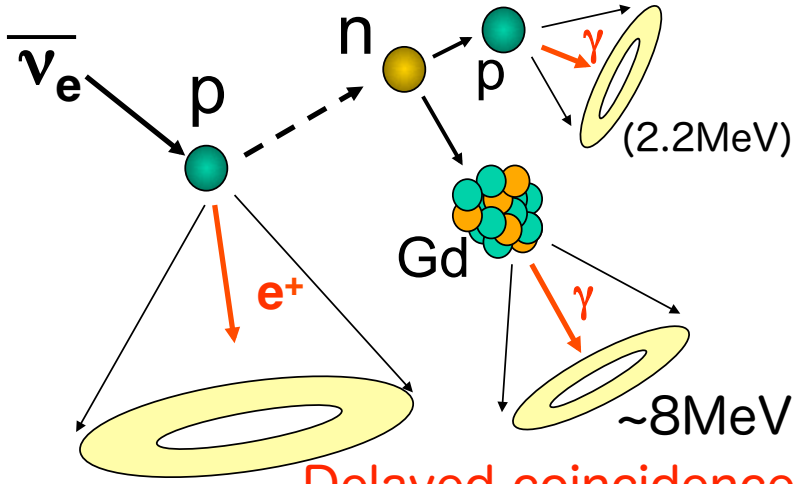




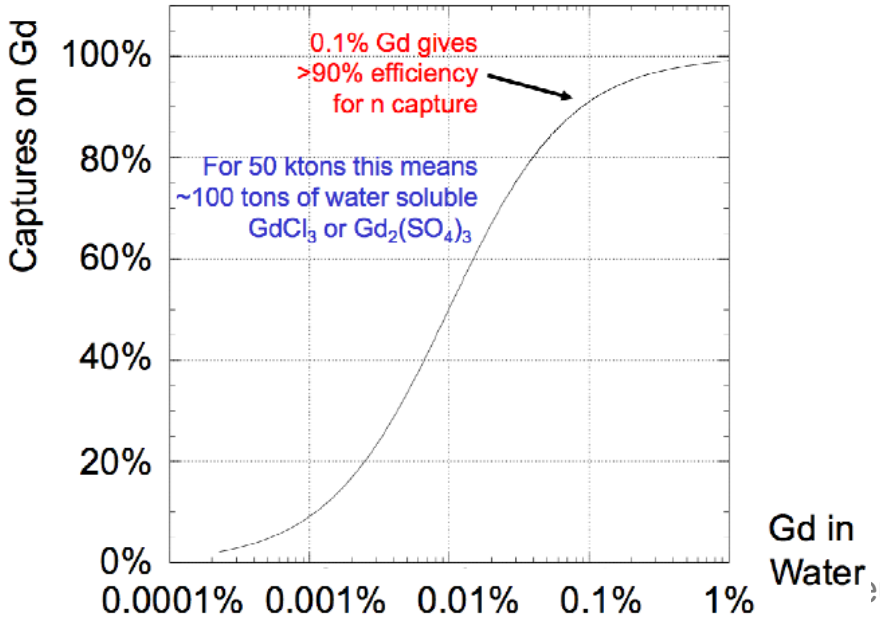
In future

Super-K Gd

Inverse beta decay

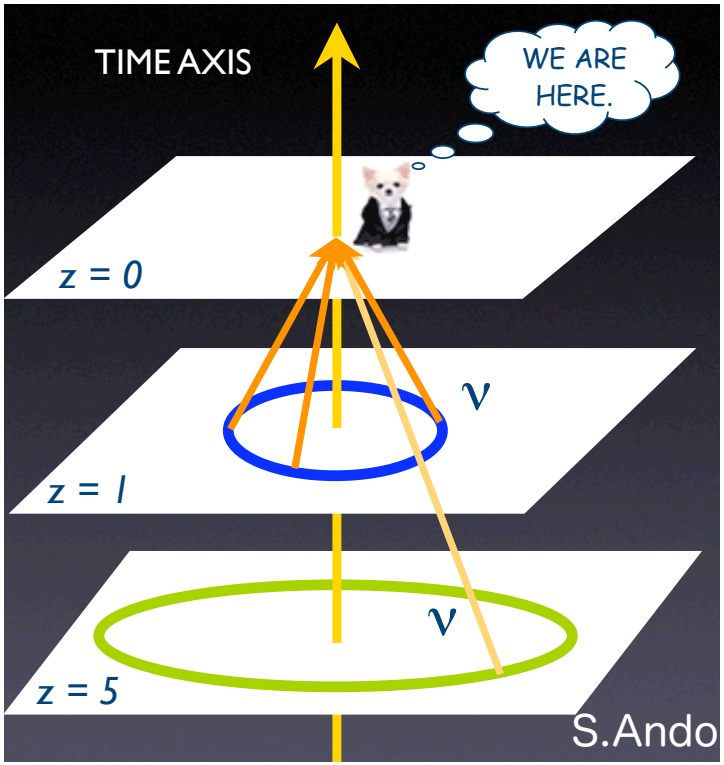


Delayed coincidence



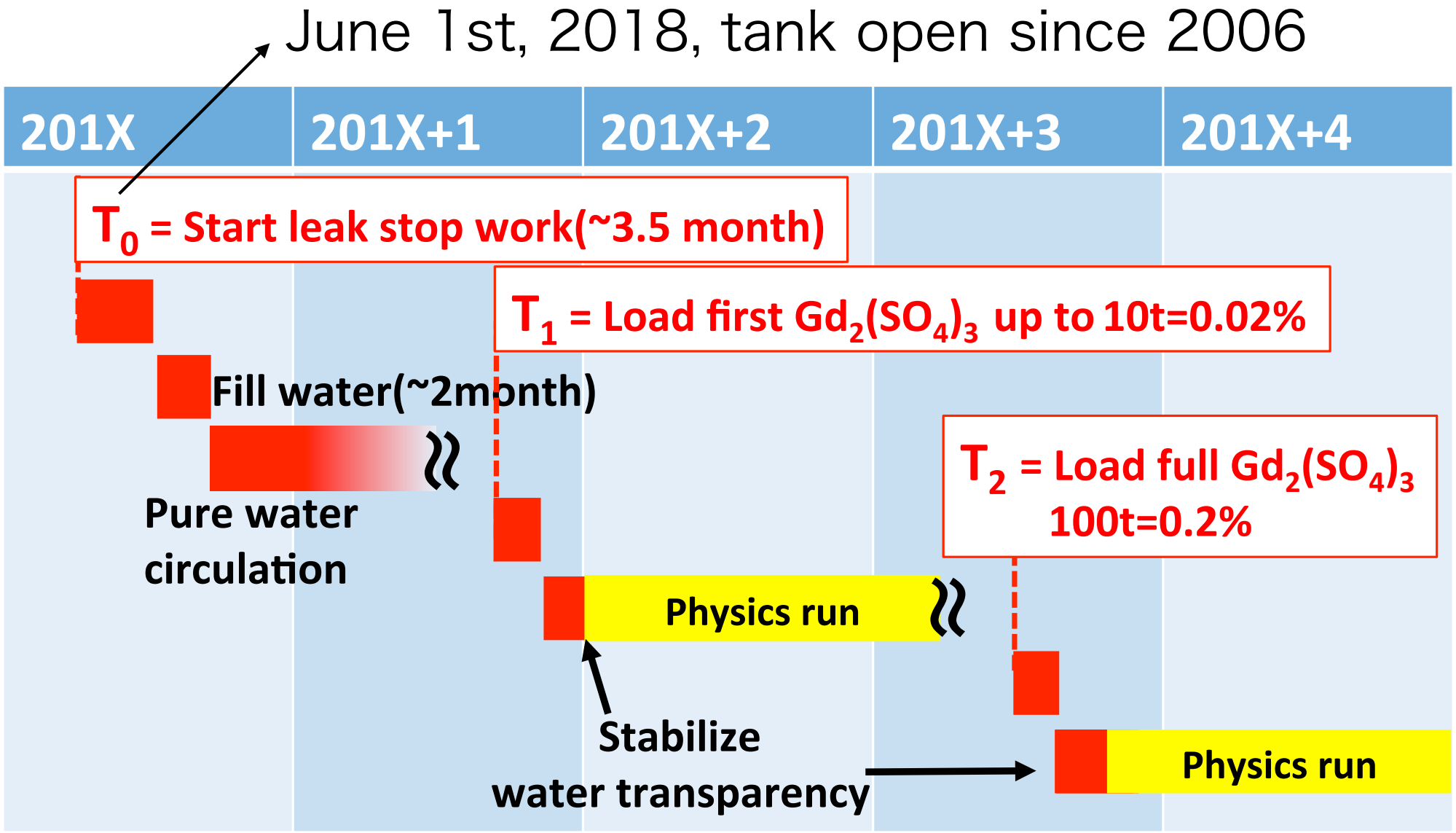
Dissolve Gadolinium into Super-K

J.Beacom and M.Vagins,
Phys.Rev.Lett.93(2004)171101



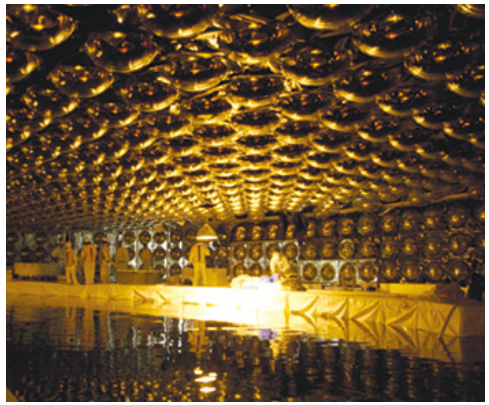
First observation of neutrinos emitted from past supernovae

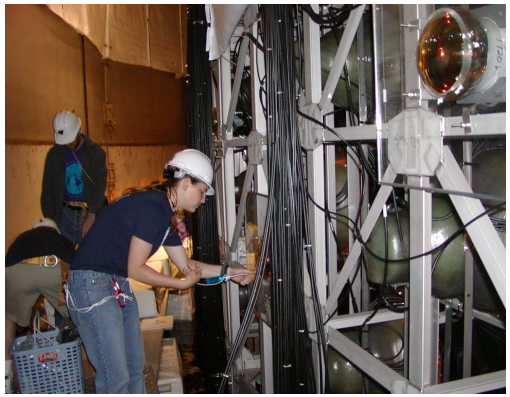
Super-K Gd

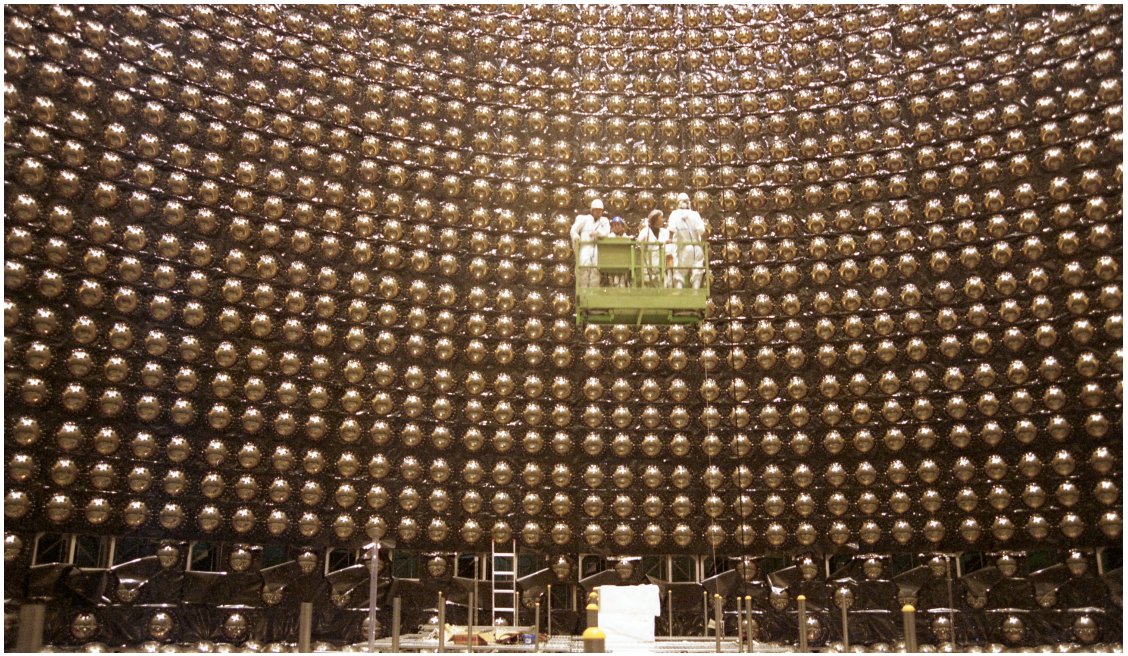

June 1st, 2018, tank open since 2006
201X
201X+1
201X+2
201X+3
201X+4
T0 = Start leak stop work(~3.5 month)
T1 = Load first Gd2(SO4)3 up to 10t=0.02%
Fill water(~2month)
Pure water circulation
T2 = Load full Gd2(SO4)3 100t=0.2%
Physics run
Stabilize water transparency
Physics run

Around this time next year

Open the Super-K tank since 2006



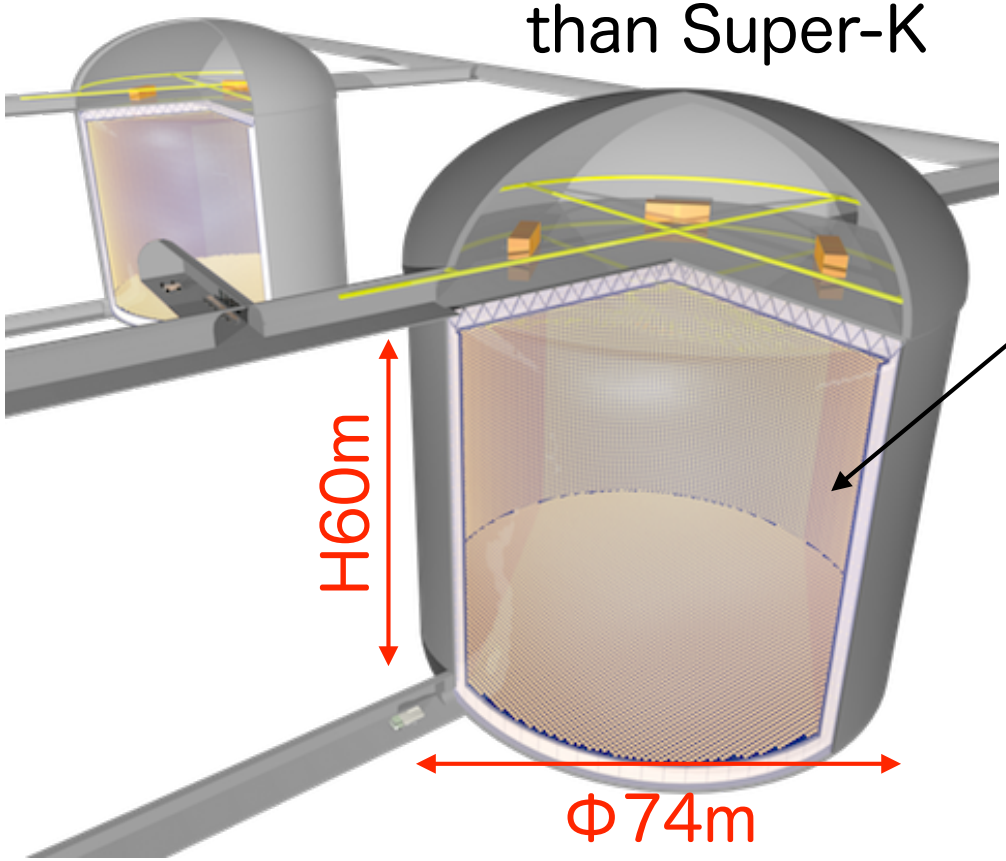




Hyper-Kamiokande

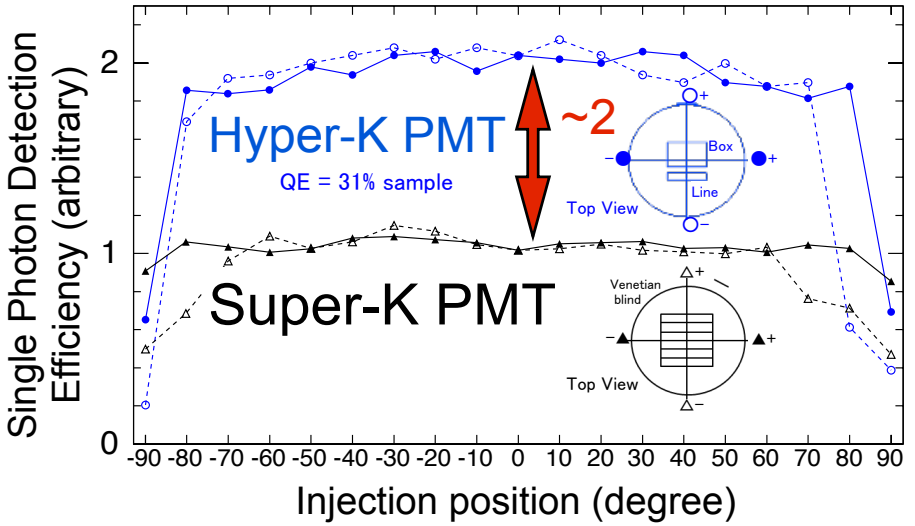
2 tanks x
with staging

~10 times larger volume
than Super-K

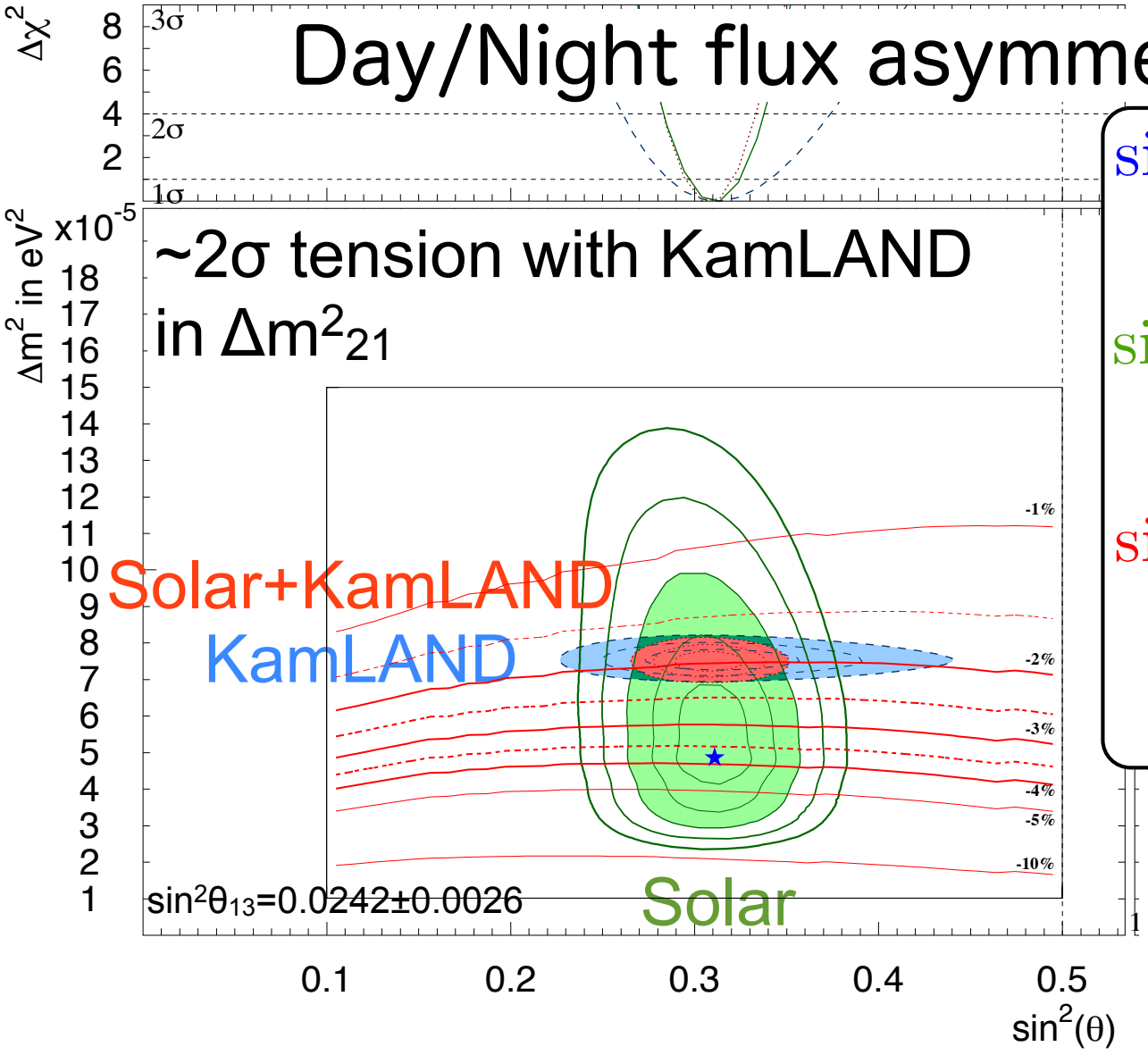


~40000 PMT / tank

New photo-censer which has
twice sensitivity than Super-K



Solar neutrinos in Hyper-K



$\sin^2\theta_{12} = 0.316^{+0.034}_{-0.026}$

$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$

$\sin^2\theta_{12} = 0.308 \pm 0.014$

$\Delta m^2_{21} = 4.85^{+1.33}_{-0.59}$

$\sin^2\theta_{12} = 0.307^{+0.013}_{-0.012}$

$\Delta m^2_{21} = 7.49^{+0.19}_{-0.18}$

The unit of Δm^2_{21} is 10^{-5} eV^2

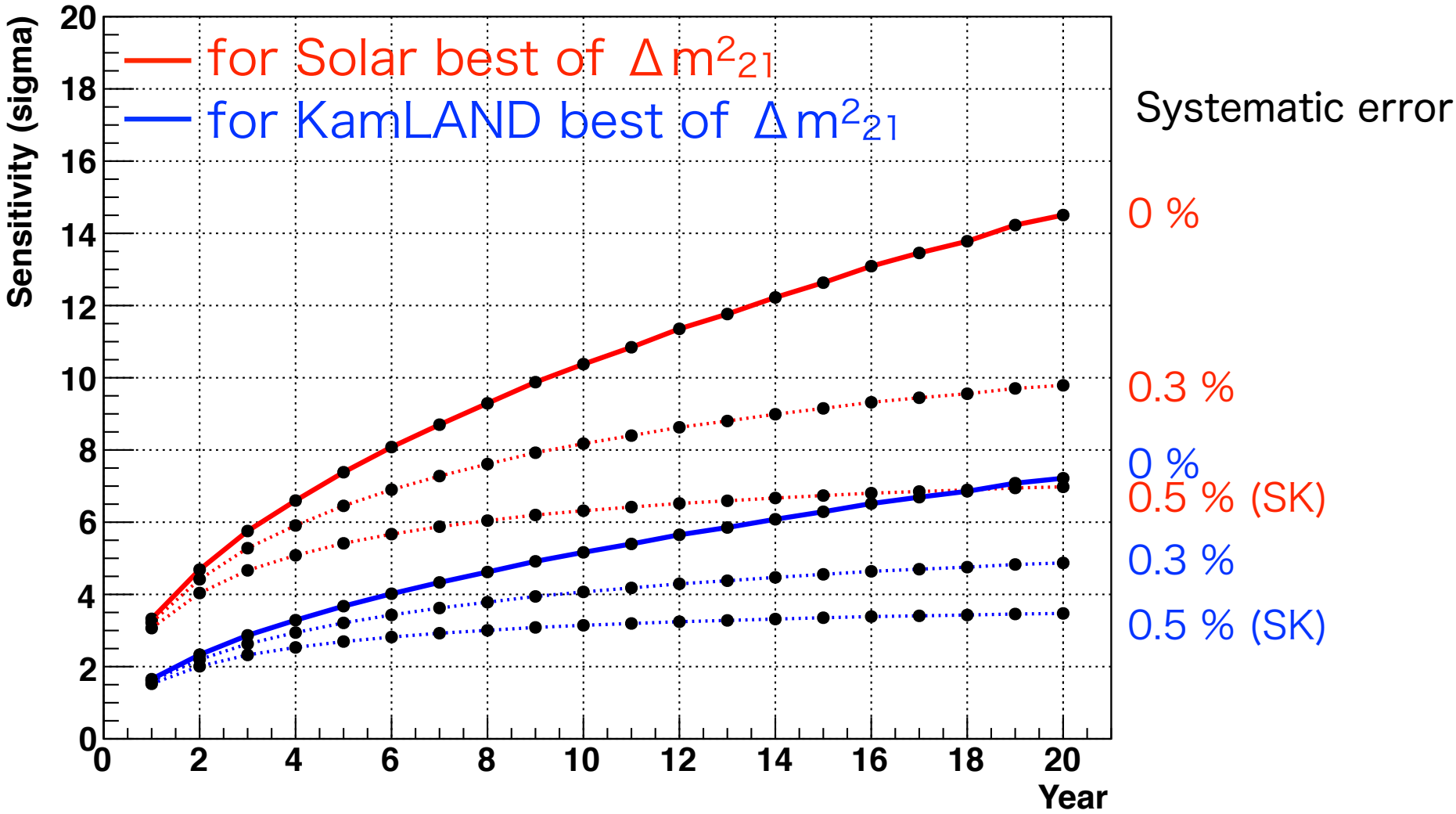
~4% at solar best

~2% at KamLAND

(E_{th} = 6.5MeV)

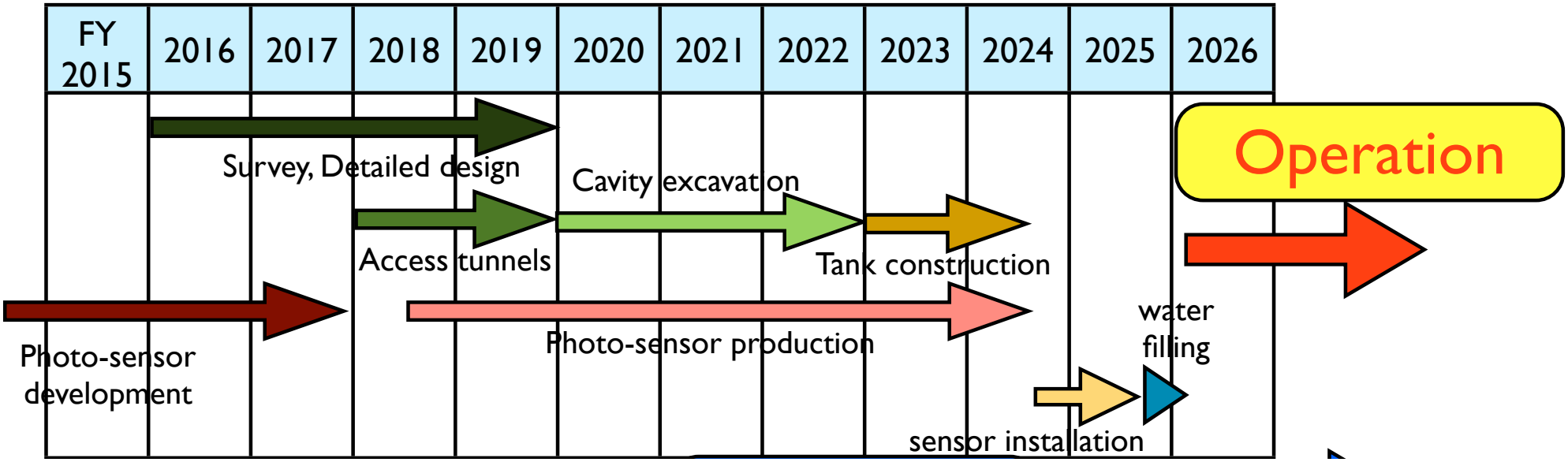
Solar neutrinos in Hyper-K

Sensitivity of Day/Night flux asymmetry



Hyper-Kamiokande

Notional timeline (1st tank)



Selected ‘Roadmap 2017’ in MEXT

Hope to realize as soon as possible!

Summary

- The current running detector of solar neutrino with Cherenkov detector is only Super-Kamiokande
  - Day/Night, oscillation analysis (PRD 94, 052010 (2016))
  - Yearly flux using SK-I~IV 5200 days sample
  - Spectrum using SK-IV 2645 days sample
  - Periodic modulation using 1664 days sample
  - Analysis improvements, (e.g. PMT gain correction, Neutron emission by muon spallation)
- In future
  - Super-K Gd will start from next year
  - Hope Hyper-Kamiokande is realized as soon as possible