Update on Solar Oscillations at Super-Kamiokande

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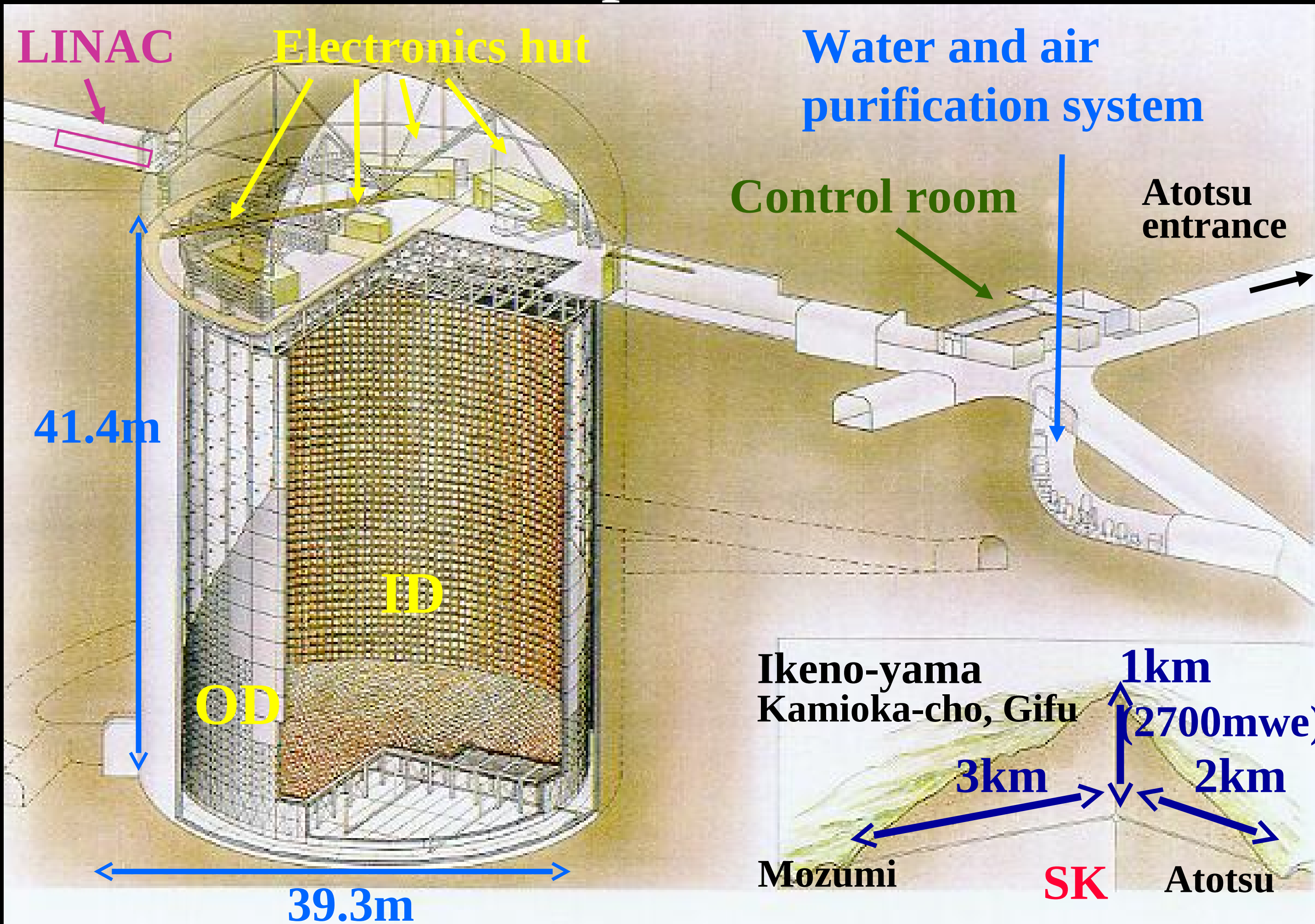
NuFact (WG 1), Seoul (Korea)
August 25th, 2023.

Super-Kamiokande Detector



- **50 kton water**
- **13+26 tons of Gd sulfate octahydrate**
- **~2 m OD viewed by 8-inch PMTs**
- **32 kt ID viewed by 20-inch PMTs**

		SK-I	SK-II	SK-III	SK-IV	SK-V	SK-VI	SK-VII
	Start - end	1996 Apr - 2001 Jul	2002 Oct - 2005 Oct	2006 Jul - 2008 Sep	2008 Sep - 2018 Mar	2019 Jan-2020 Jul	2020 Jul-2022 Jun	2022 July -
Captures on Gd							50%	75%
Number of PMTs	ID (coverage)	11146 **(40 %)**	5182 **(19 %)**	11129 **(40 %)**	11129 **(40 %)**	11129 **(40%)**	11129 **(40%)**	11129 **(40%)**
	OD	**1885**						

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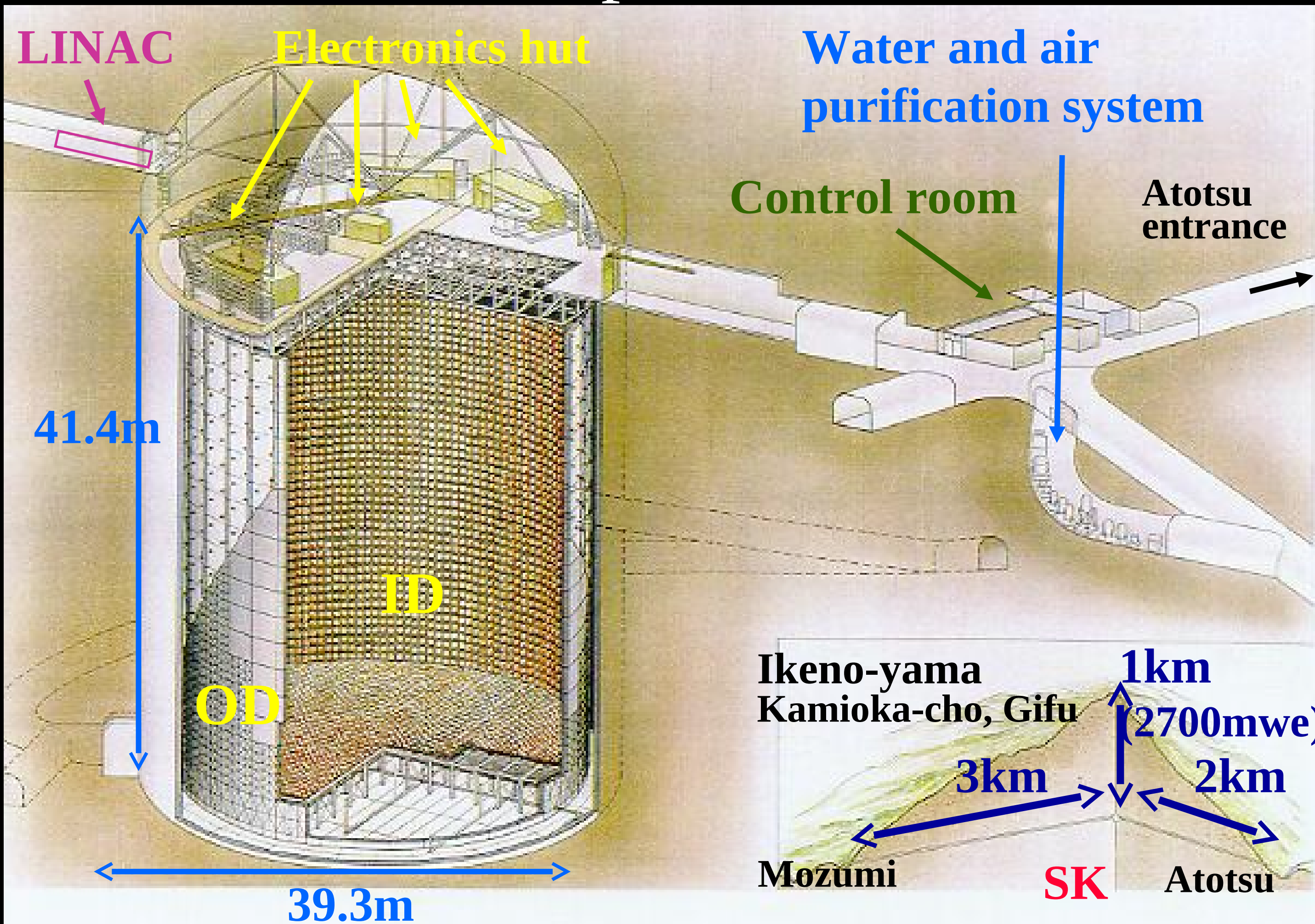

Versatile detector:

Solar neutrinos,
Atmospheric neutrinos,
Proton decay,
Supernovae,
Supernova Relic Neutrinos,
Indirect search for DM and more

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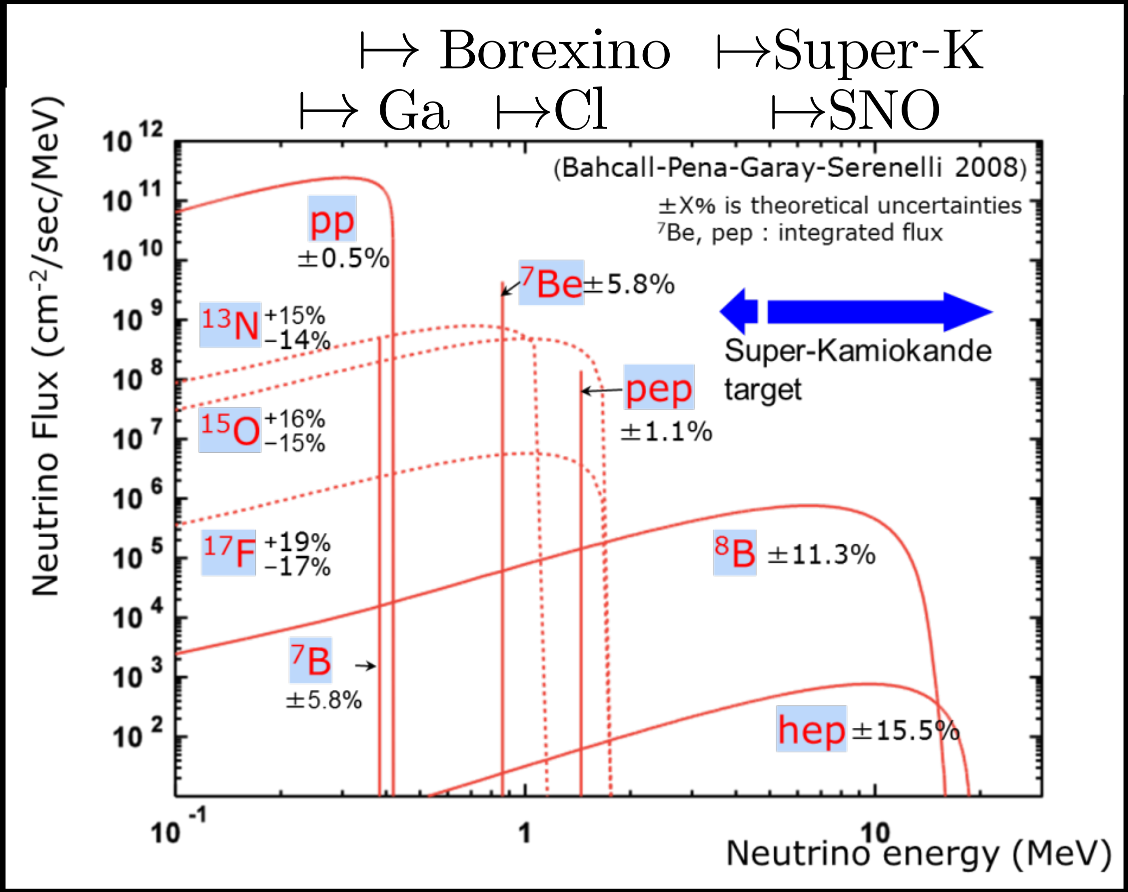
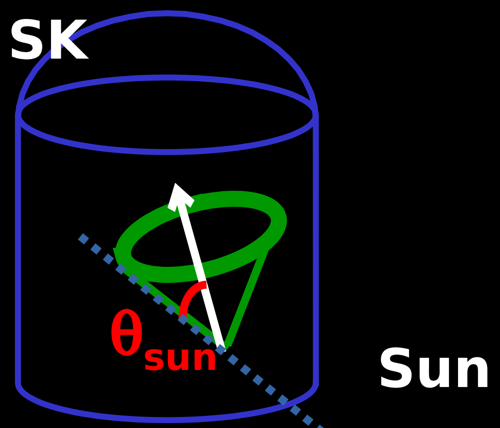
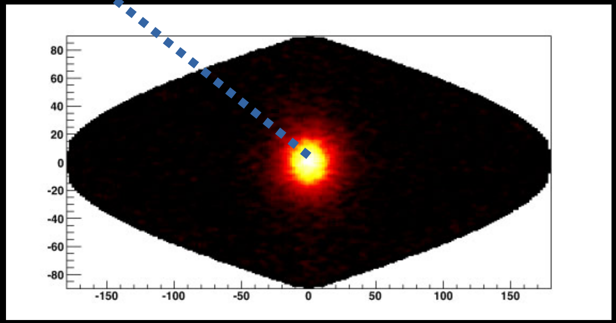
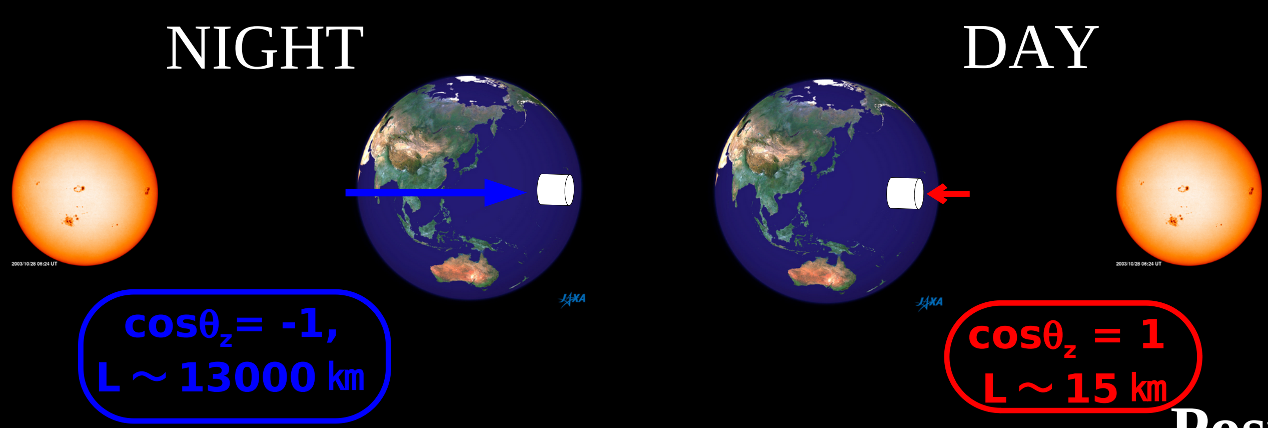
Solar neutrinos observation at SK



- Neutrino Flux
- Energy spectrum
- Day/night asymmetry
- Global analysis







Poster #5 by Jeong Yeol Yang

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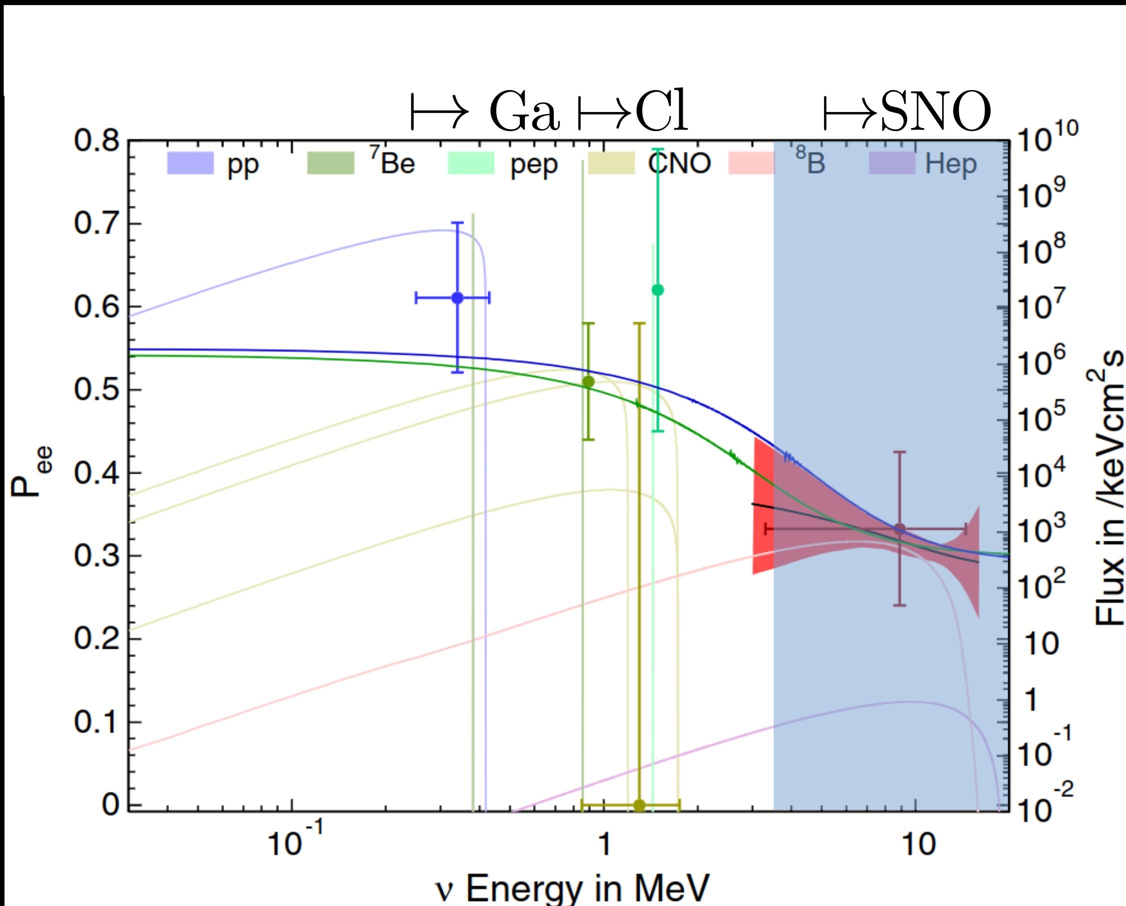

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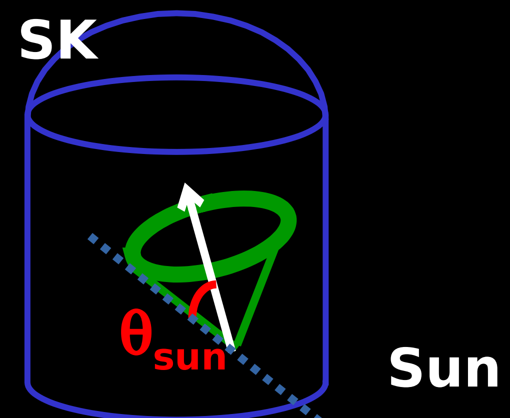
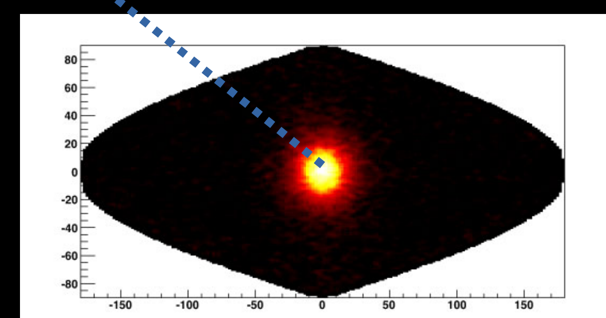
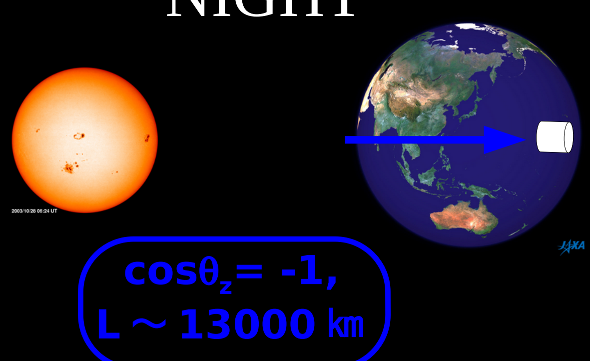
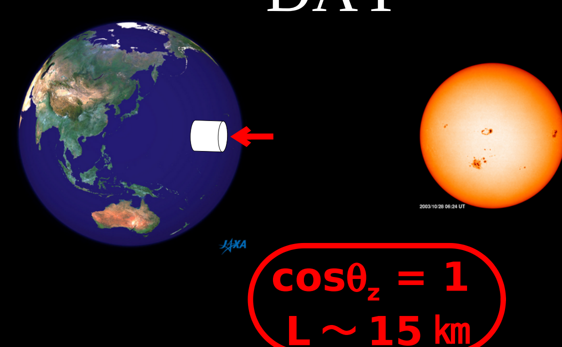




NIGHT



DAY



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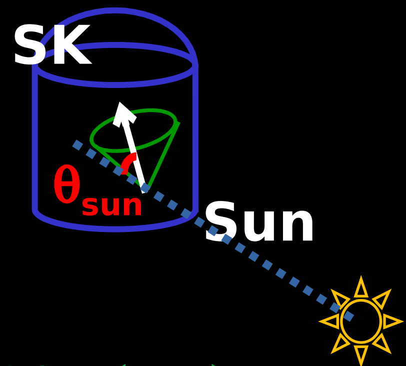


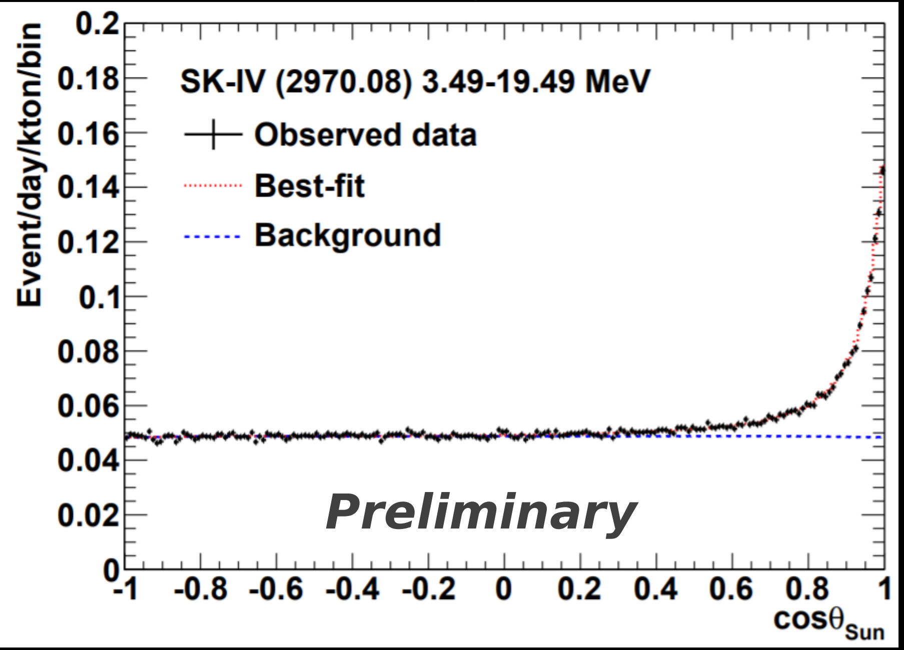
SK-IV:

Good water quality control

Lower threshold: **3.5 MeV** (kin).

Largest statistics among all phases: 2970 days and

63890 $^{+381}_{-379}$ (stat) ± 907 (sys) events.



New electronics

High speed signal processing.

All PMT signal digitized. No deadtime.

Better timing determination.

Better MC model for trigger efficiency.

Analysis

Multiple Scattering Goodness (MSG).

New spallation cut.

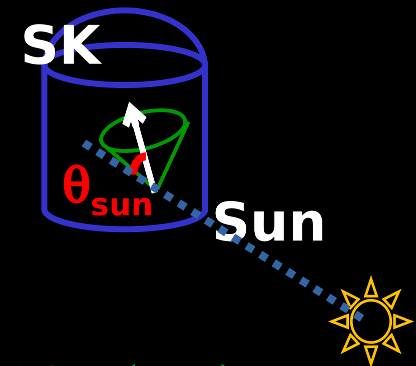
Improvement in MC, energy reconstruction, etc.

Reduced systematics

^{8}B flux: **2.33 ± 0.01(stat) ± 0.03(sys) x 10^6/cm^2/sec**

→ this is: 1.3% cf. SK-I 3.2% SK-III 2.1%

SK-IV:



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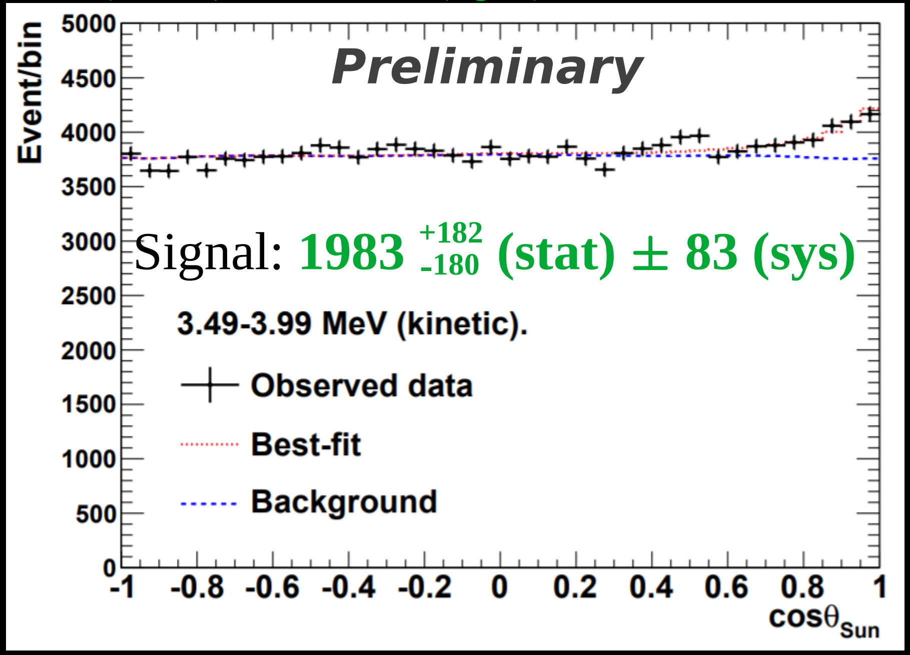

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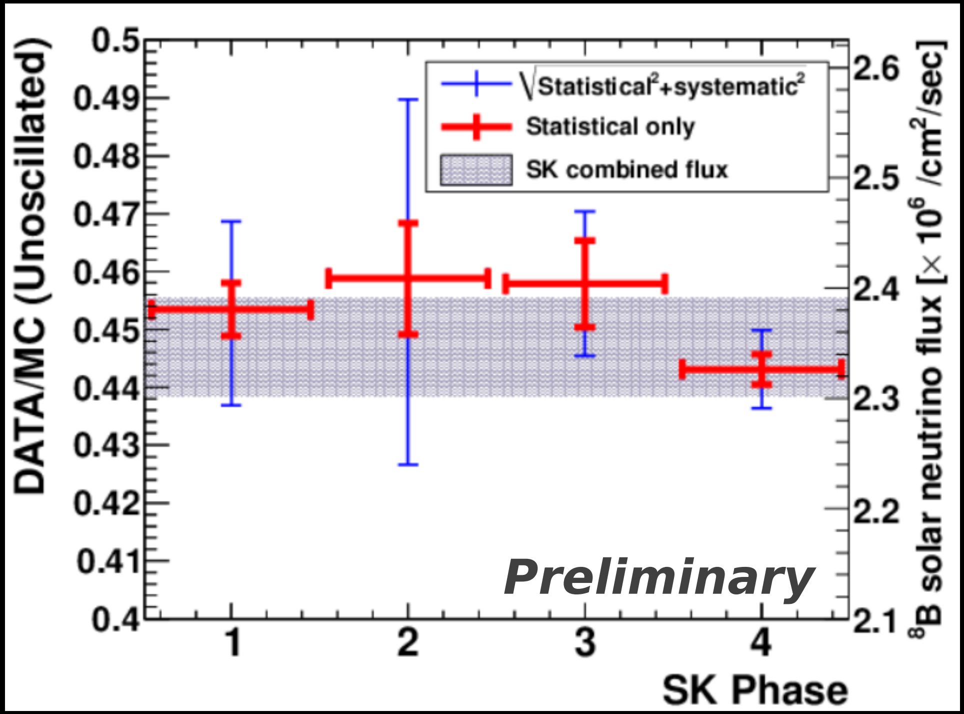
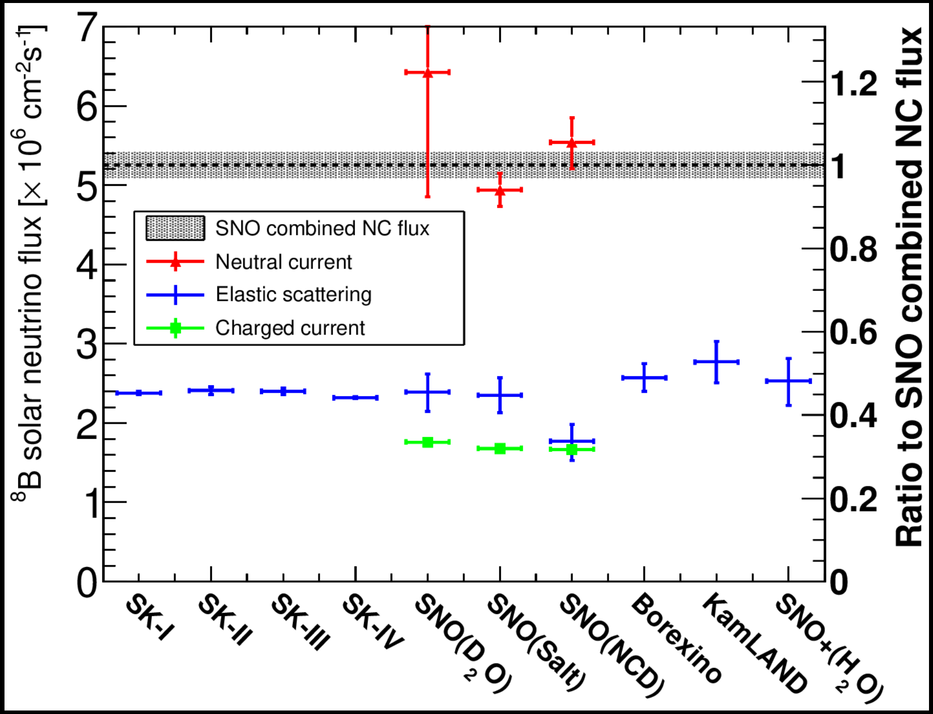
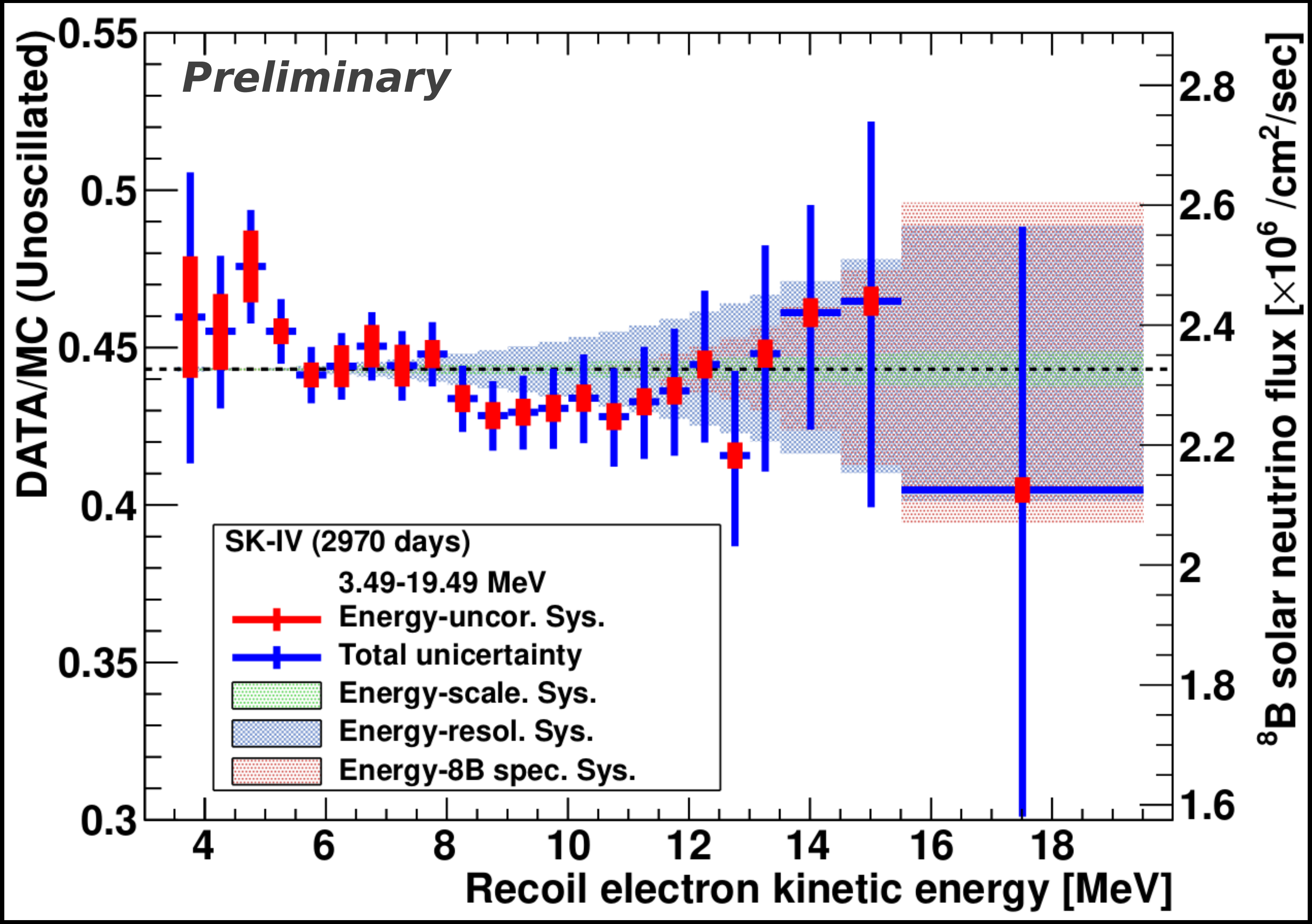
Solar neutrinos at SK: Flux





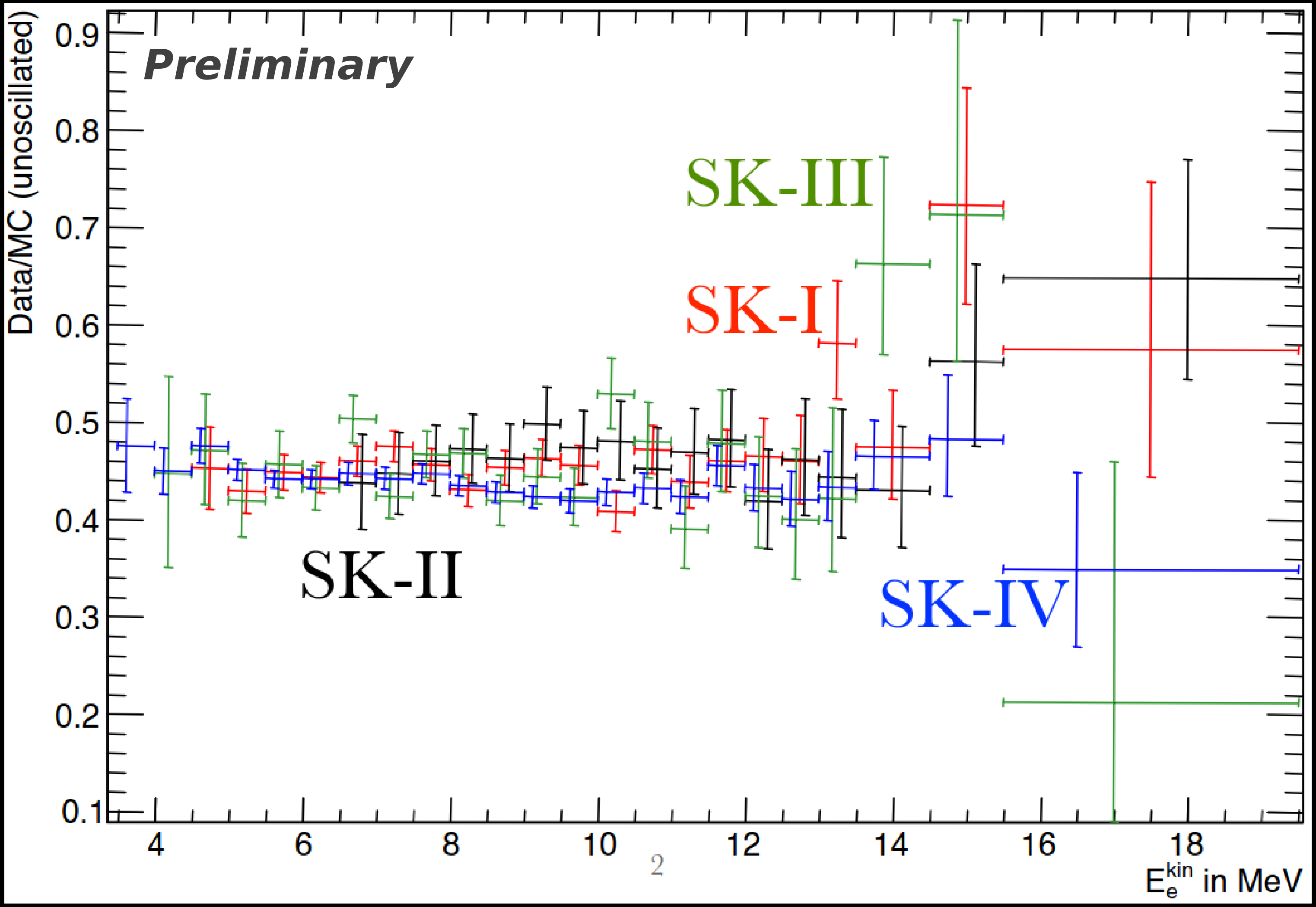
Phase	Livetime [days]	DATA/MC	Flux ± (stat) ± (sys) x10^6/cm^2/sec
SK-I	1496	$0.453\pm0.005^{+0.016}_{-0.014}$	$2.38\pm0.02\pm0.08$
SK-II	791	$0.459\pm0.010\pm0.030$	$2.41\pm0.05^{+0.16}_{-0.15}$
SK-III	548	$0.458\pm0.008\pm0.010$	$2.40\pm0.04\pm0.05$
SK-IV	2970	$0.443\pm0.003\pm0.006$	$2.33\pm0.01\pm0.03$
Total	5805	$0.447\pm0.002\pm0.008$	$2.346\pm0.011\pm0.043$

SK-IV Energy Spectrum



SK-IV data analyzed, the largest phase for SK
Adds a big new data set in the already reach SK solar data sample

SK Energy Spectrum (stat. only)



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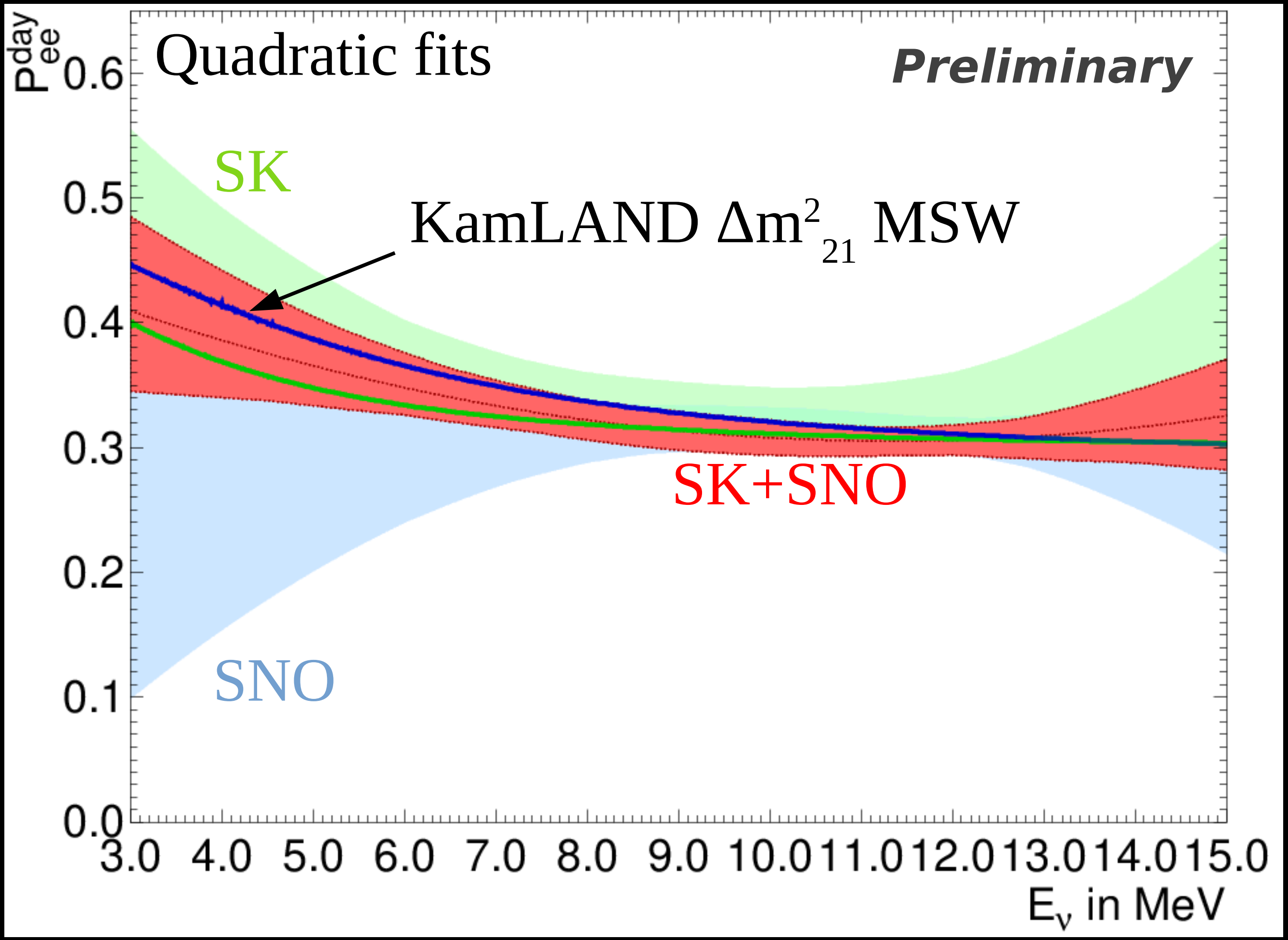
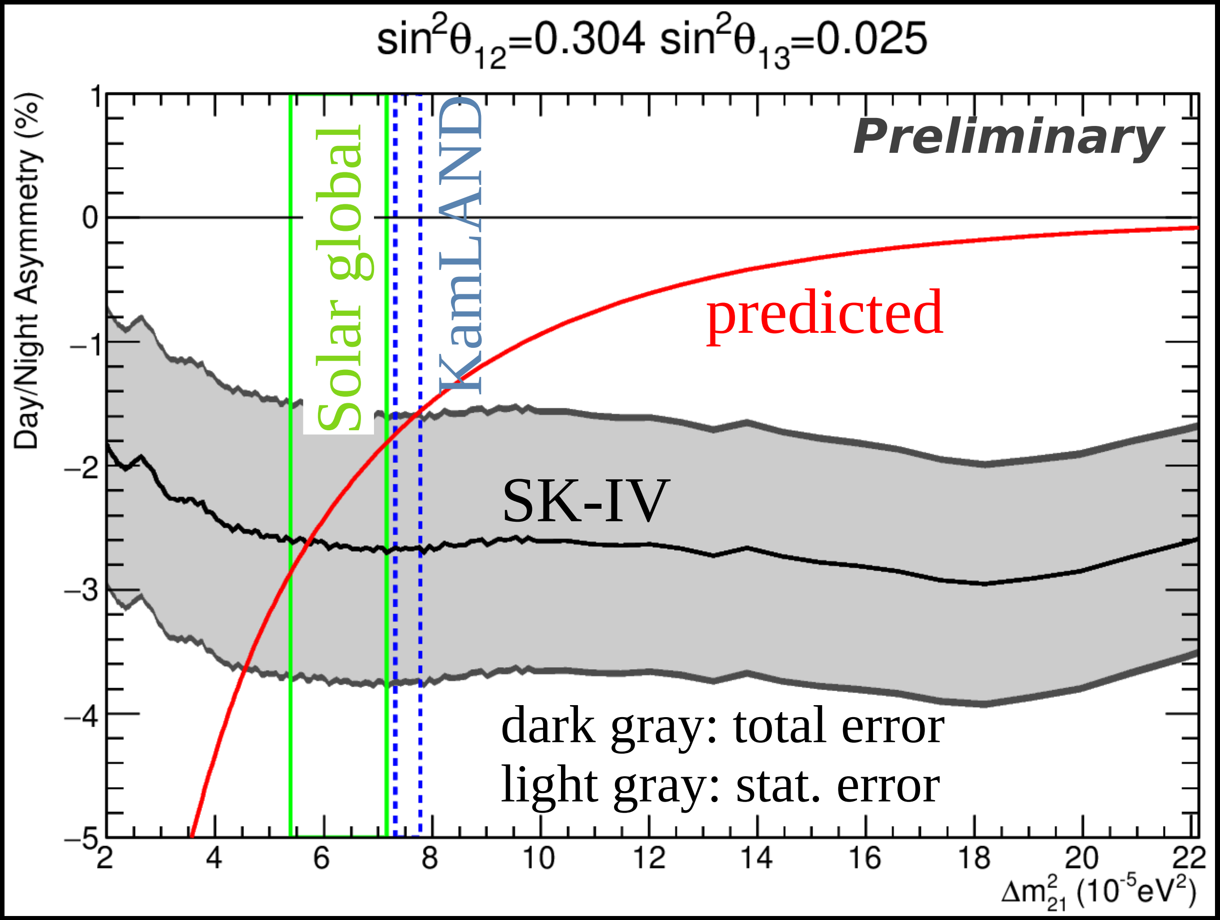
ν_e Survival Probability（P_{ee}）



- SK data prefers a slight “upturn” while SNO’s a “downturn”
- SK constrains tighter at low energy while SNO constrains more at higher energy
- Combined fit favours an “upturn” more strongly than SK data only.

Day/Night asymmetry (Δm^2_{21})



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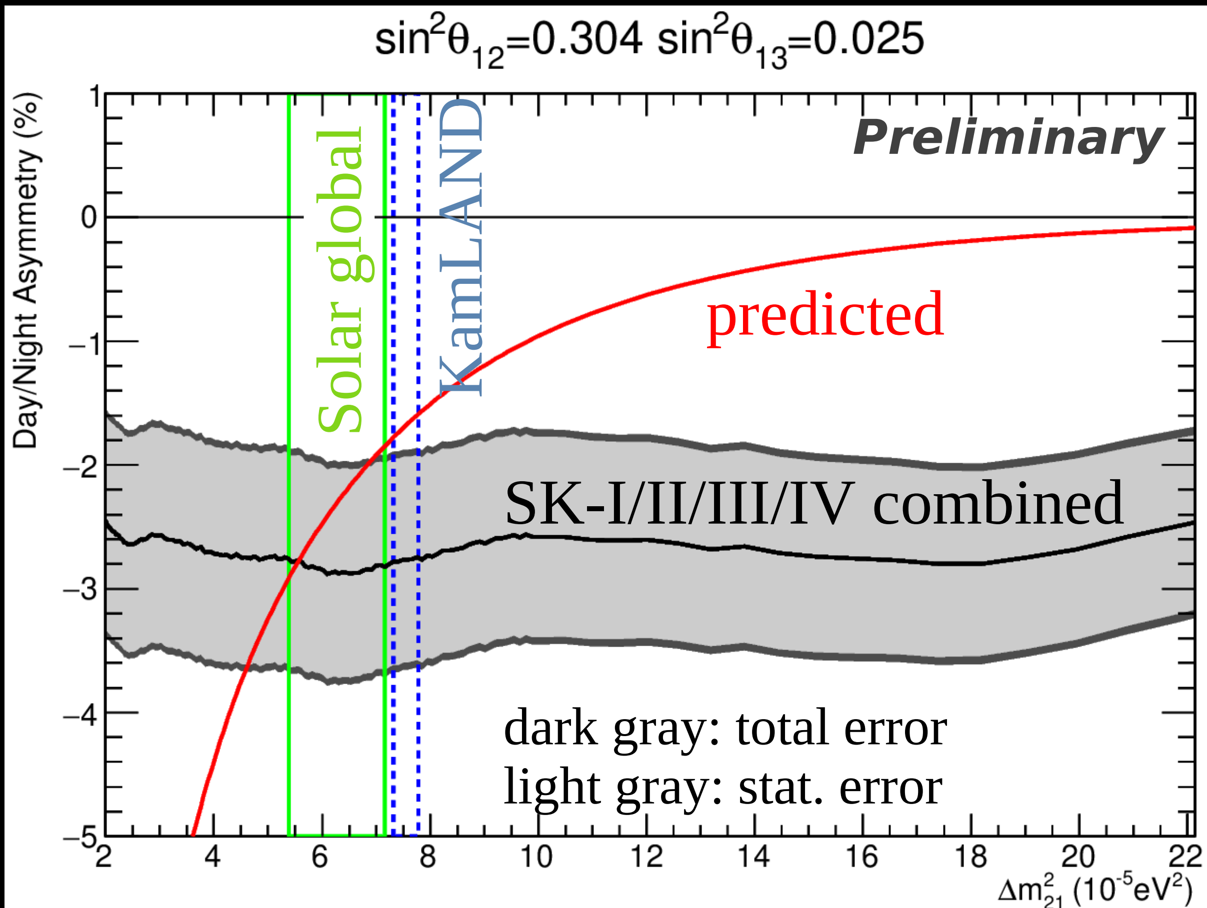
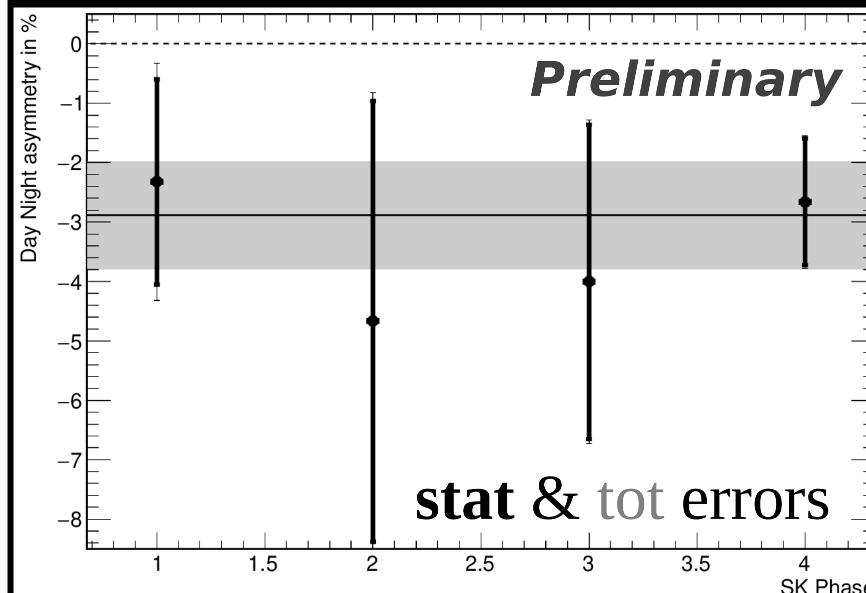


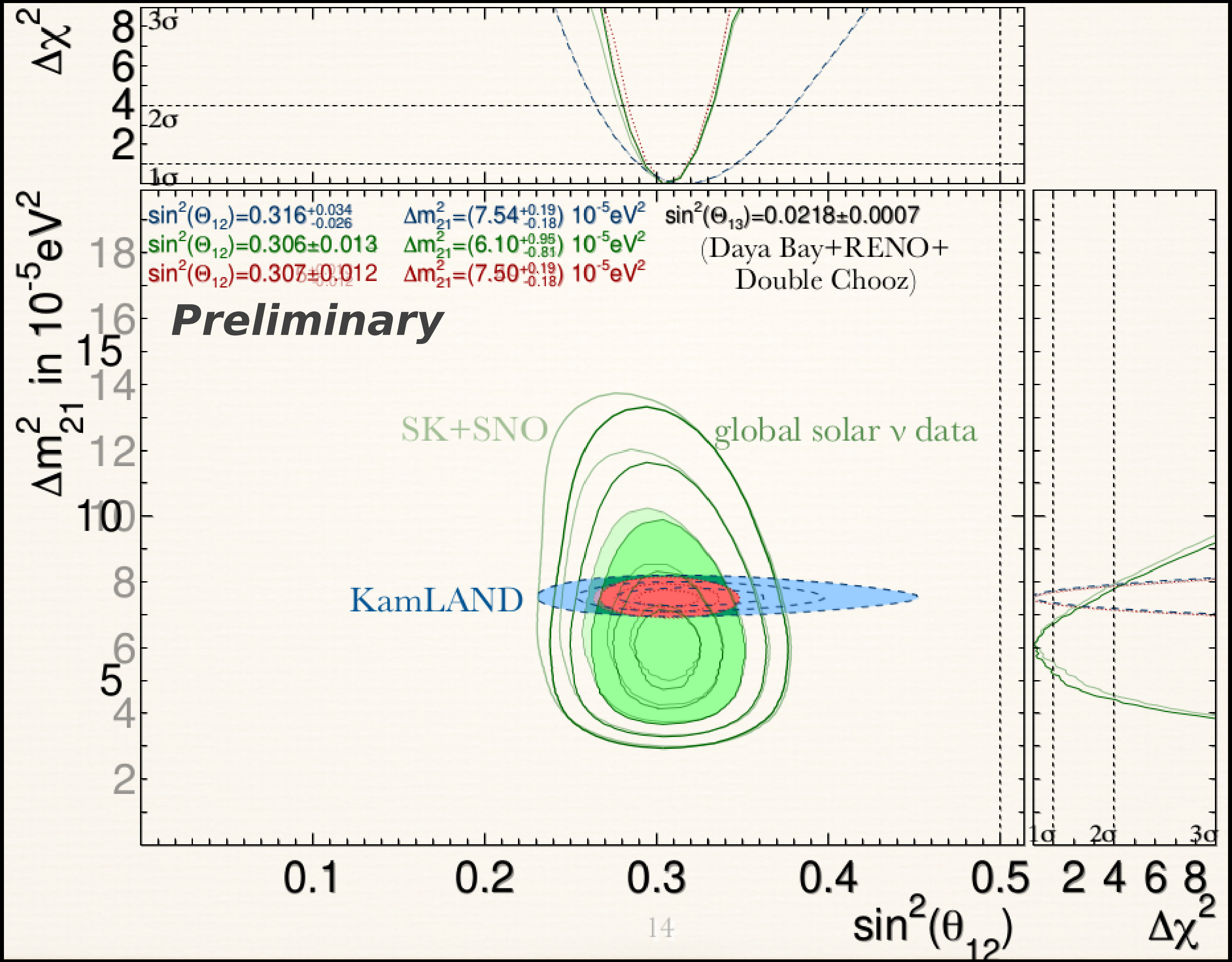
$\Delta m^2_{21} = 6.1\text{x}10^{-5}\,\text{eV}^2$



[%]	Asymmetry	stat	sys	total
SK-I	-2.32	±1.73	±1.00	±2.00
SK-II	-4.66	+3.71 -3.72	±0.92	+3.84 -3.85
SK-III	-4.01	+2.64 -2.65	±0.70	+2.72 -2.73
SK-IV	-2.67	±1.07	±0.34	±1.12
combined	-2.88	±0.85	±0.32	±0.90

3.2 σ significance
(solar best fit)

Global neutrino oscillation



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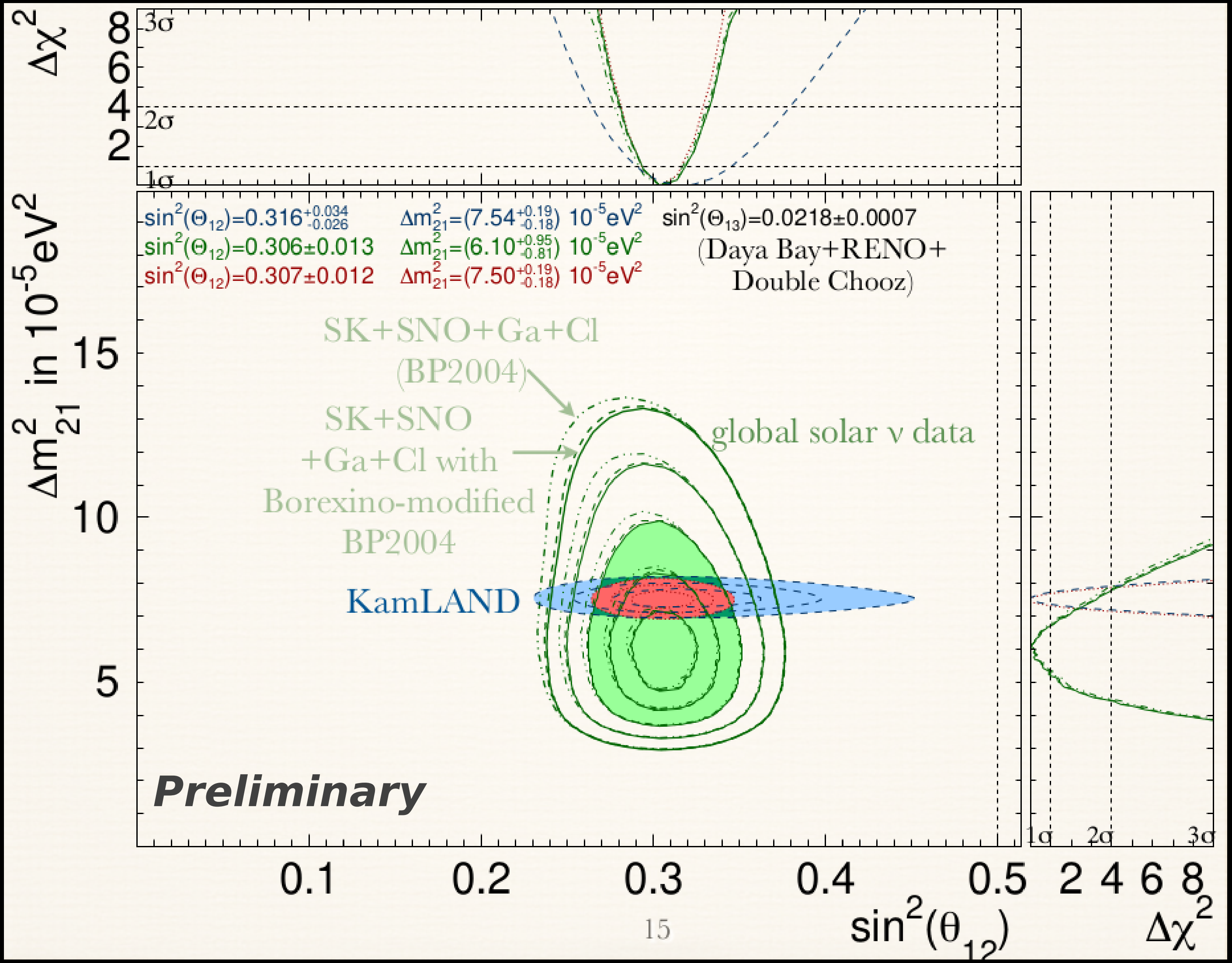


Summary

- Super-Kamiokande's SK-IV (the longest phase and largest data set ~3k days) analysis has been finished.

- For SK-IV, many improvements have been made, ranging from hardware to software.
    - Almost 64k solar events collected (total more than 101k)
    - Almost 2k events in the lowest energy bin (3.5 – 4 MeV)
    - New Flux: $2.346 \pm 0.011 \pm 0.043$
    - Slight preference for "upturn" in SK/SNO combined fit.
    - 3.2 **σ** significance for Day/Night asymmetry.
    - New oscillation parameters estimation from a global fit:

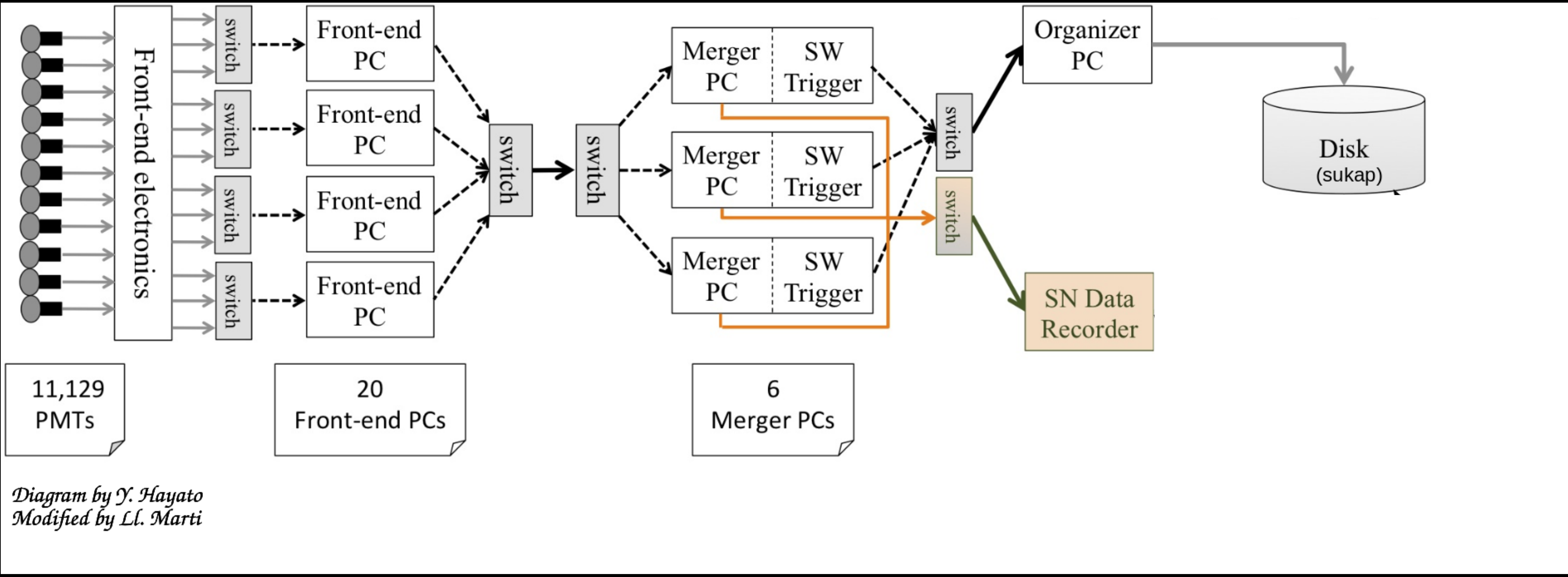
$$\sin^2\theta_{12} = 0.306 \pm 0.013$$

$$\Delta m^2_{12} = 6.10^{+0.95}_{-0.81} \times 10^5 \text{ eV}^2$$

<u>A new paper is coming. Stay tuned!</u>

WIT System

SK's standard DAQ system:

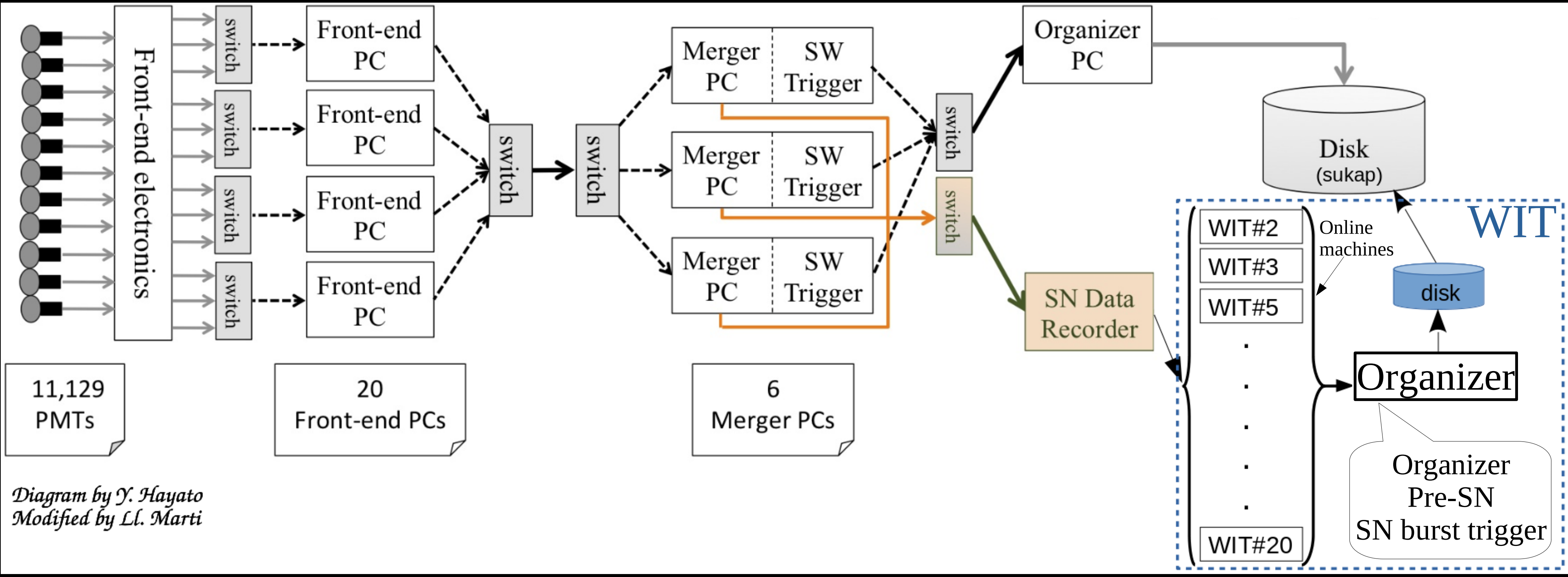


WIT System

Computer cluster running parallel software trigger:

<u>Online machines:</u> WIT#[2-20]
Receive 23 ms data blocks
+
Event reconstruction

<u>Organizer</u>
Sorts the data blocks



<u>WIT hosts:</u>
- Triggers low energy events (electrons of E_{kin} > 2.5 MeV).
- Online pre-supernova alarm.
- Online SN burst alarm and SN-triggered raw data saving system.

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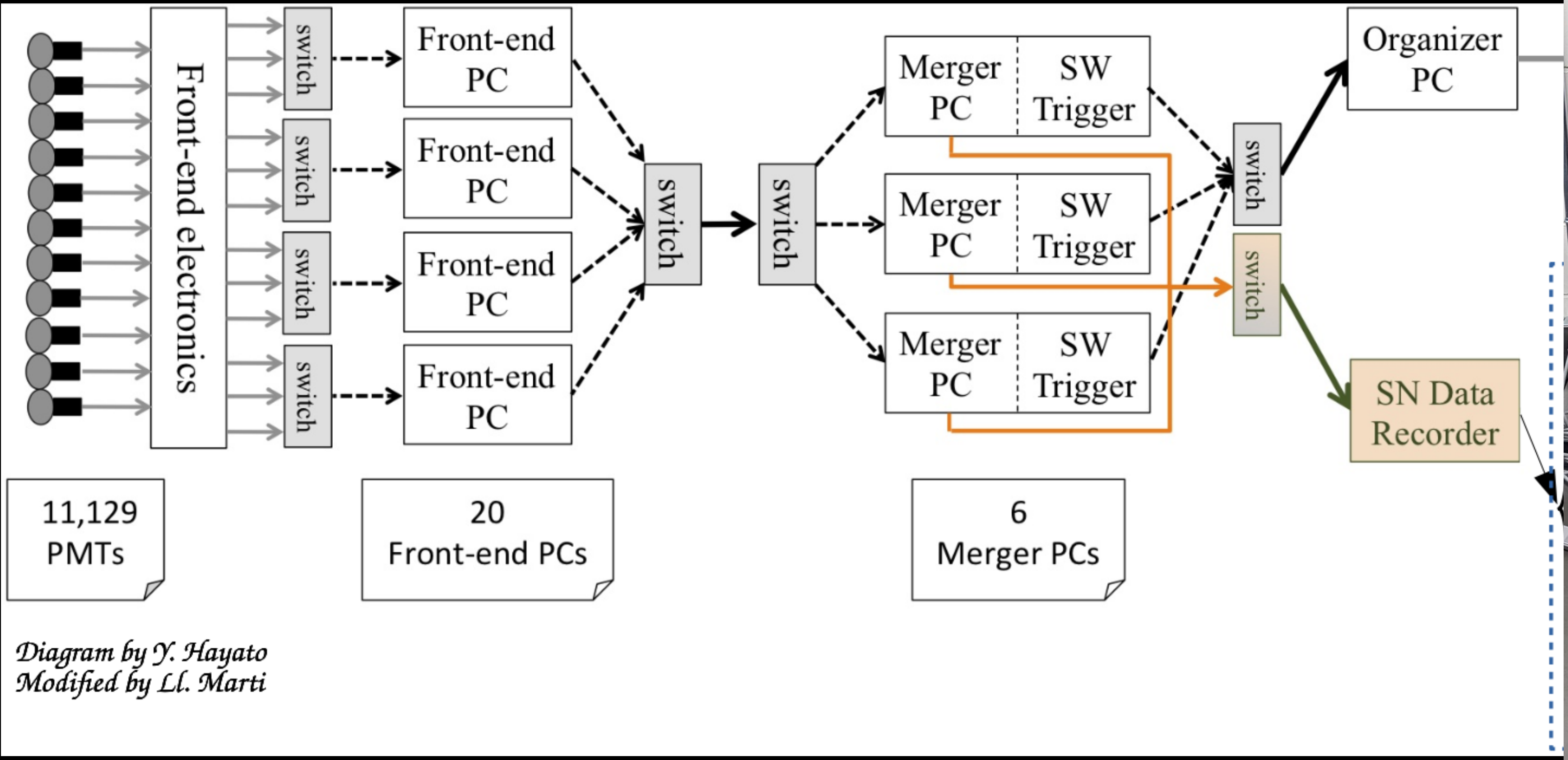

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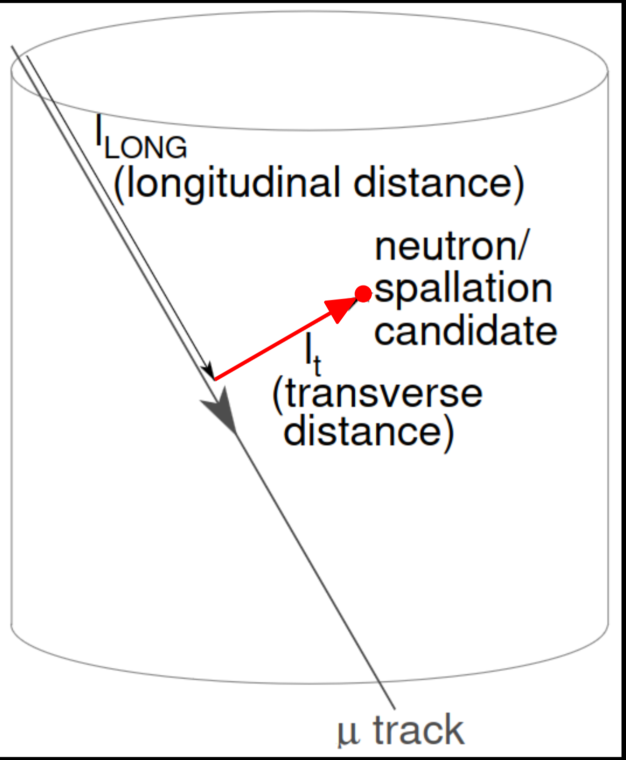
Removing Spallation Background



Variables: Δ_t, l_t and Q_{res} where:

Δ_t = time diff. between candidate and muon

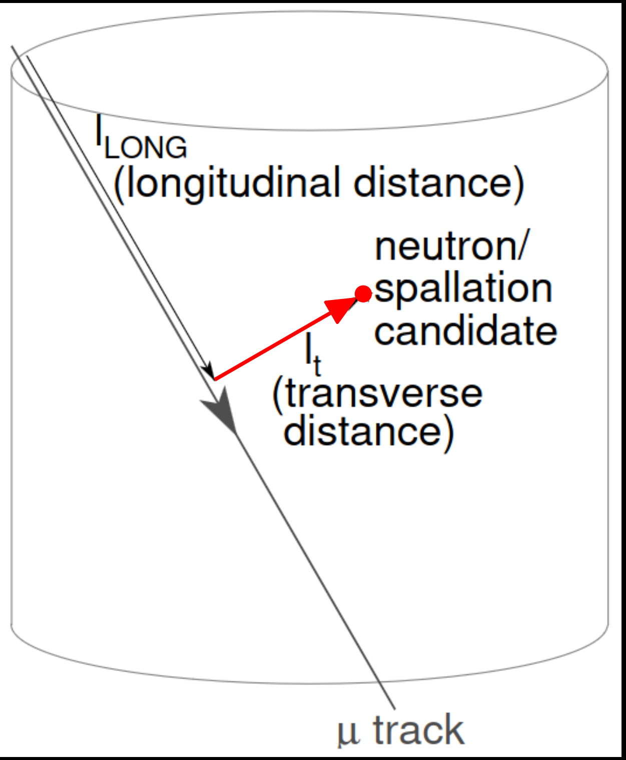
Q_{res}= (Charge deposited) - (min. ionization)

→ Define PDFs
→ Define log likelihood

Resulted in:
90% spallation events removed
20% deadtime

More details in:
arXiv:1606.07538 [hep-ex]
arXiv:0508053 [hep-ex]

Removing Spallation Background with WIT



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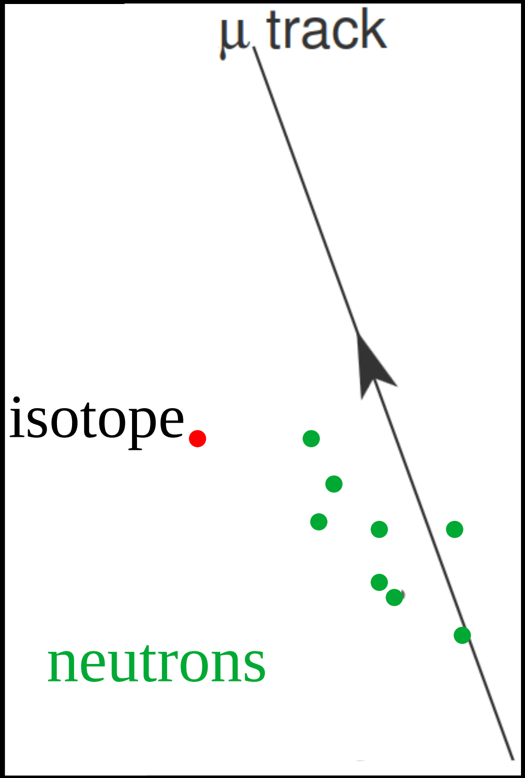

Tag neutrons with WIT:

→ neutron clouds

→ 388/2970 days in SK-IV

More details in (paper in preparation):
New Methods and Simulations for Cosmogenic Induced Spallation Removal in Super-Kamiokande-IV

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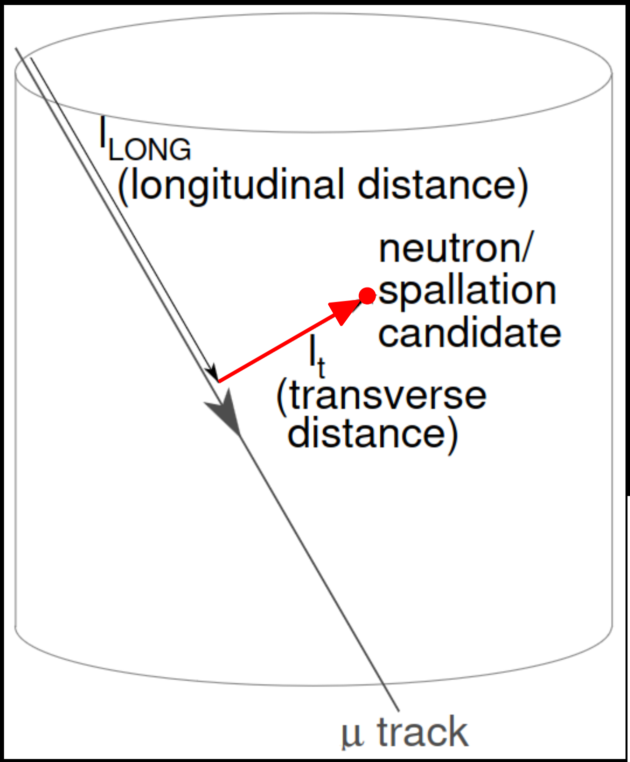

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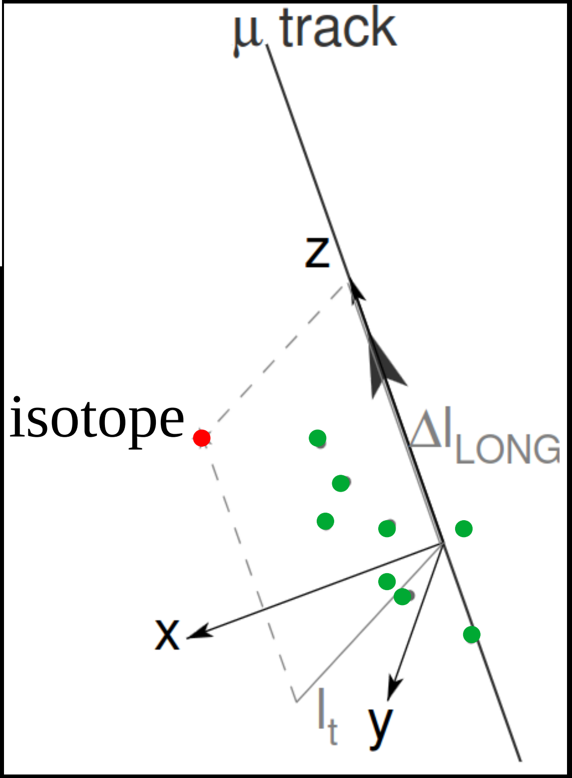

New variables:

Δl_{LONG}

Neutron multiplicity

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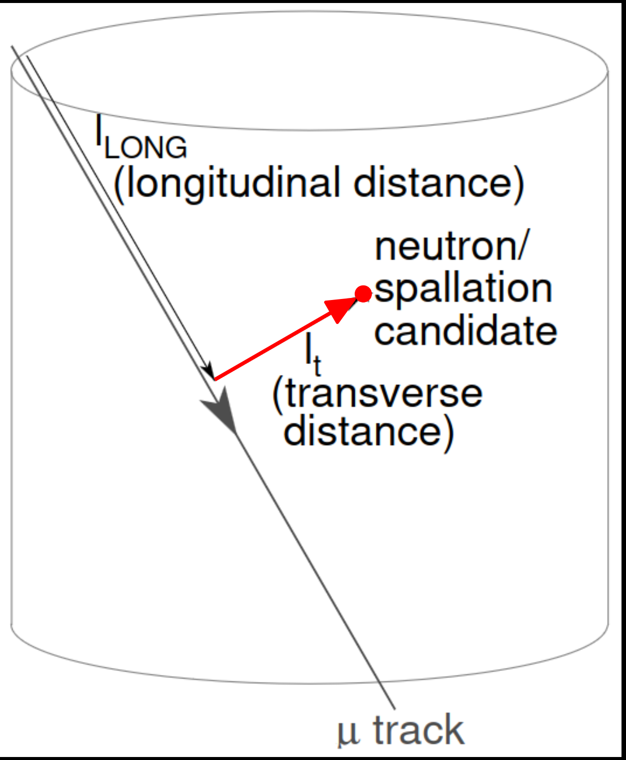

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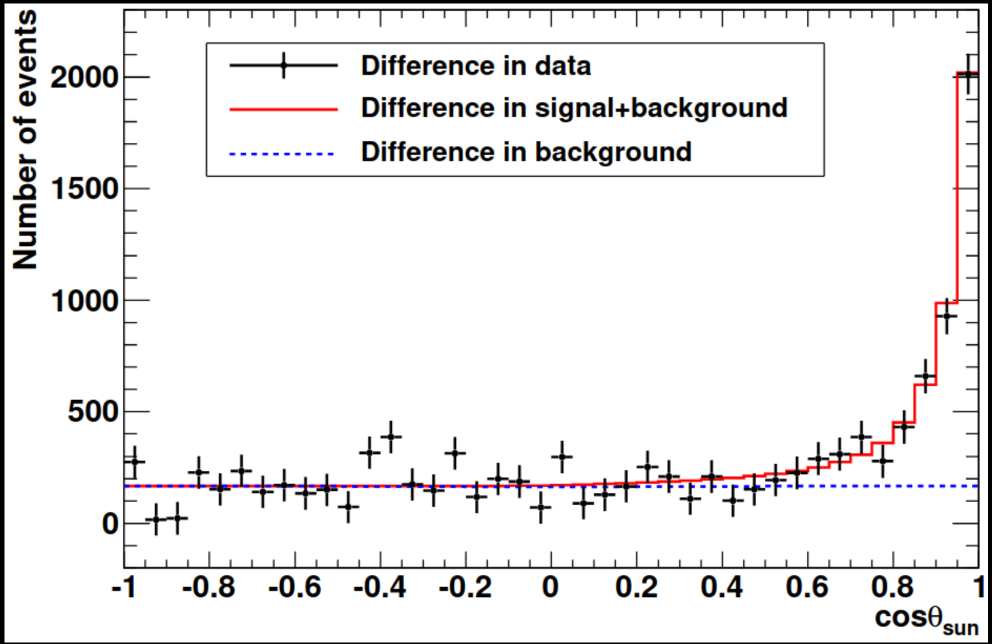
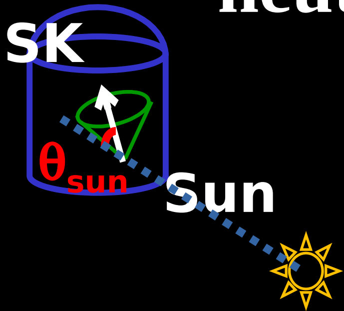


Define new cuts:

→ 47% spallation events removed

→ 1.3% effective deadtime

12% Increase in solar neutrino events (~7000)



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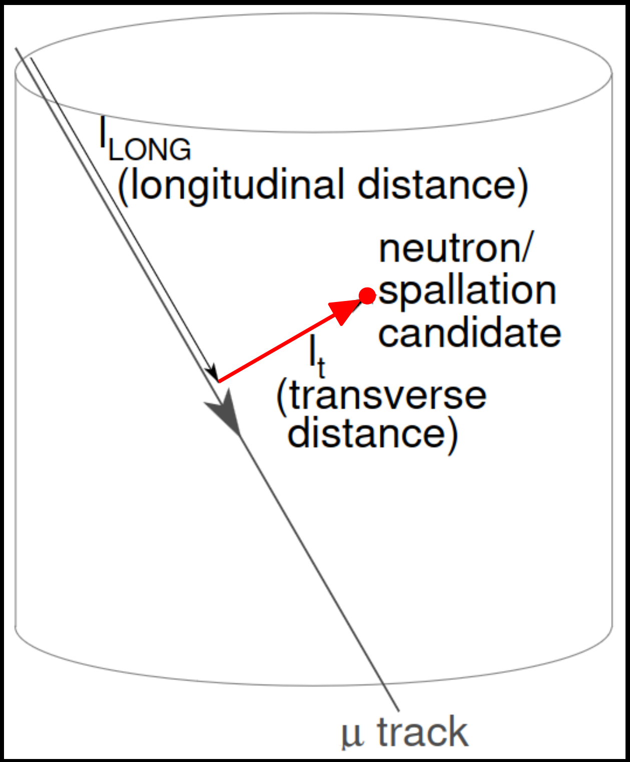

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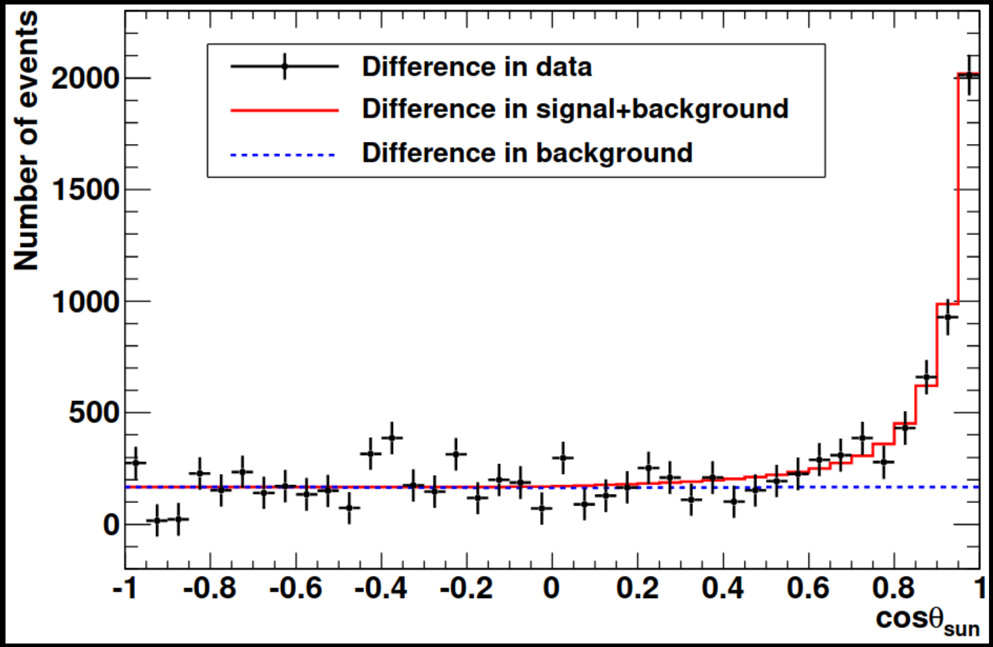

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Improvement expected for Gd phases

Systematics

	SK-I	SK-II	SK-III	SK-IV
Threshold [MeV]	4.49	6.49	3.99	3.49
Trigger efficiency	±0.4%	±0.5%	±0.5%	±0.1%
Angular resolution	±1.2%	±3.0%	±0.7%	±0.1%
Reconstruction goodness	$^{+1.9}_{-1.3}$%	±3.0%	±0.4%	±0.5%
Hit pattern	±0.8%	–	±0.3%	±0.4%
Small hit cluster	–	–	±0.5%	±0.1%
External event cut	±0.5%	±1.0%	±0.3%	±0.1%
Vertex shift	±1.3%	±1.1%	±0.5%	±0.2%
Second vertex fit	±0.5%	±1.0%	±0.5%	–
Background shape	±0.1%	±0.4%	±0.1%	±0.1%
Multiple scattering goodness	–	±0.4%	±0.4%	±0.4%
Livetime	±0.1%	±0.1%	±0.1%	±0.1%
Spallation cut	±0.2%	±0.4%	±0.2%	±0.2%
Signal extraction	±0.7%	±0.7%	±0.7%	±0.7%
Cross section	±0.5%	±0.5%	±0.5%	±0.5%
Subtotal	±2.8%	±4.8%	±1.6%	±1.1%
Energy scale	±1.6%	$^{+4.2}_{-3.9}$%	±1.2%	±0.8%
Energy resolution	±0.3%	±0.3%	±0.2%	±0.1%
^{8}B spectrum	$^{+1.1}_{-1.0}$%	±1.9%	$^{+0.3}_{-0.4}$%	$^{+0.3}_{-0.4}$%
Total	$^{+3.5}_{-3.2}$%	$^{+6.7}_{-6.4}$%	±2.2%	±1.4%

Systematics

Energy [MeV]	3.49–3.99	3.99–4.49	4.49–4.99	4.99–5.49	5.49–5.99	5.99–6.49	6.49–6.99	6.99–7.49	7.49–19.49
Trigger efficiency	$^{+3.5}_{-3.2}$%	±0.7%	–	–	–	–	–	–	–
Angular resolution	±0.2%	±0.2%	±0.2%	±0.1%	±0.1%	±0.1%	±0.1%	±0.1%	±0.1%
Reconstruction goodness	±0.1%	±0.2%	±0.1%	±0.1%	±0.1%	±0.3%	±0.5%	±0.7%	±0.4%
Hit pattern	–	–	–	–	–	±0.5%	±0.5%	±0.4%	±0.4%
Small hit cluster	±0.1%	±0.1%	±0.1%	–	–	–	–	–	–
External event cut	±0.1%	±0.1%	±0.1%	±0.1%	±0.1%	±0.1%	±0.1%	±0.1%	±0.2%
Vertex shift	±0.4%	±0.4%	±0.4%	±0.7%	±0.4%	±0.4%	±0.4%	±0.4%	±0.1%
Background shape	±2.7%	±0.6%	±0.6%	±0.2%	±0.2%	±0.2%	±0.2%	±0.2%	±0.1%
Signal extraction	±2.1%	±2.1%	±2.1%	±0.7%	±0.7%	±0.7%	±0.7%	±0.7%	±0.7%
Cross section	±0.2%	±0.2%	±0.2%	±0.2%	±0.2%	±0.2%	±0.2%	±0.2%	±0.2%
Multiple scattering goodness	±0.4%	±0.2%	±0.3%	±0.3%	±0.3%	±0.6%	±1.3%	±1.3%	–
Total	$^{+4.9}_{-4.8}$%	±2.4%	±2.3%	±1.1%	±0.9%	±1.2%	±1.7%	$^{+1.8}_{-1.7}$%	±0.9%

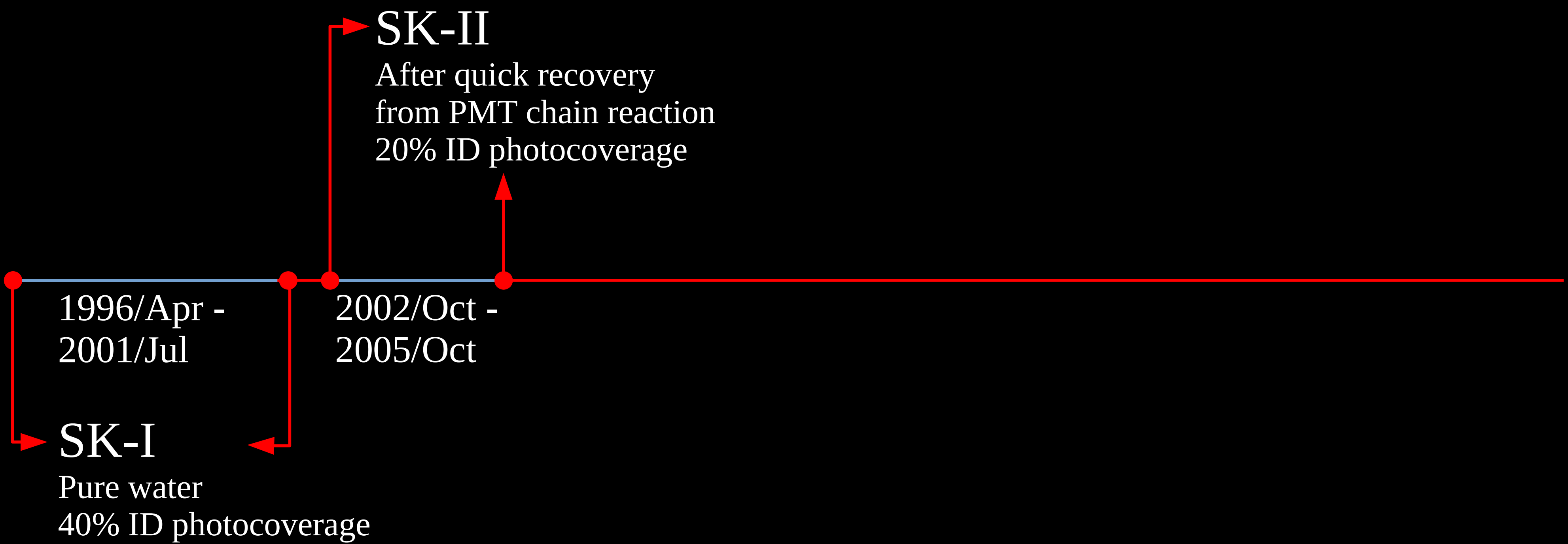
Super-Kamiokande Detector Timeline

1996/Apr -
2001/Jul

SK-I

Pure water
40% ID photocoverage

Super-Kamiokande Detector Timeline



Super-Kamiokande Detector Timeline

SK-II
After quick recovery
from PMT chain reaction
20% ID photocoverage

1996/Apr -
2001/Jul

2002/Oct -
2005/Oct

2006/Jul -
2008/Sep

SK-I
Pure water
40% ID photocoverage

SK-III
Full recovery
40% ID photocoverage

Super-Kamiokande Detector Timeline

SK-I
Pure water
40% ID photocoverage

1996/Apr -
2001/Jul

SK-II
After quick recovery
from PMT chain reaction
20% ID photocoverage

2002/Oct -
2005/Oct

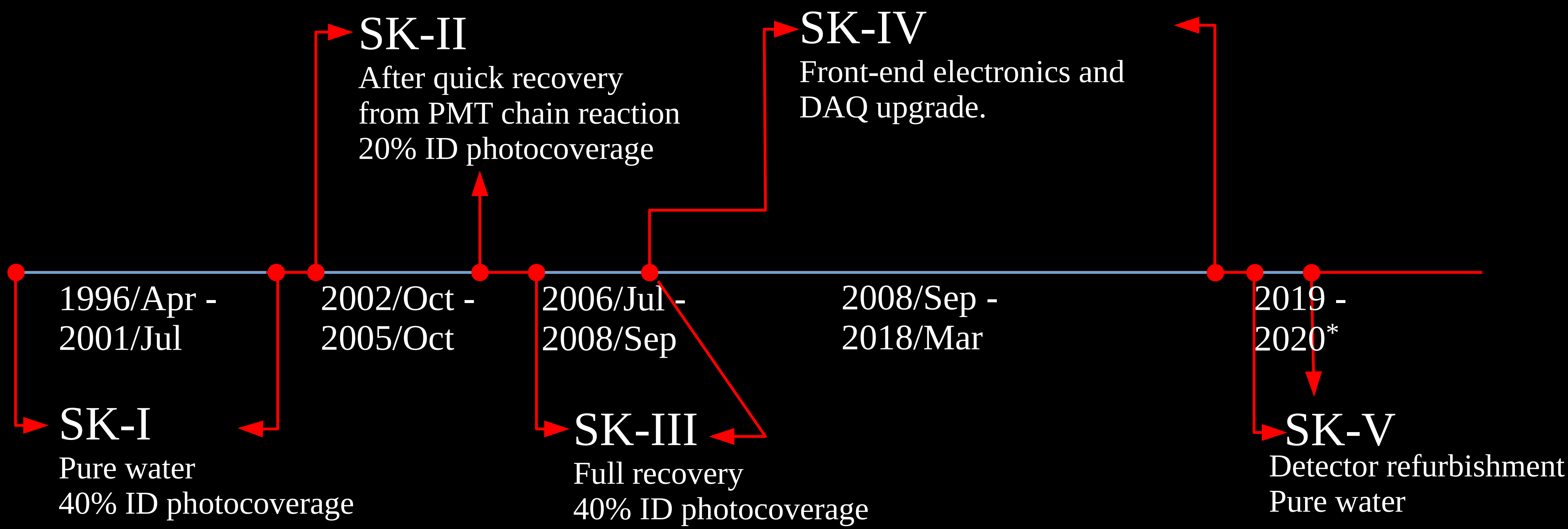
SK-III
Full recovery
40% ID photocoverage

2006/Jul -
2008/Sep

SK-IV
Front-end electronics and
DAQ upgrade.

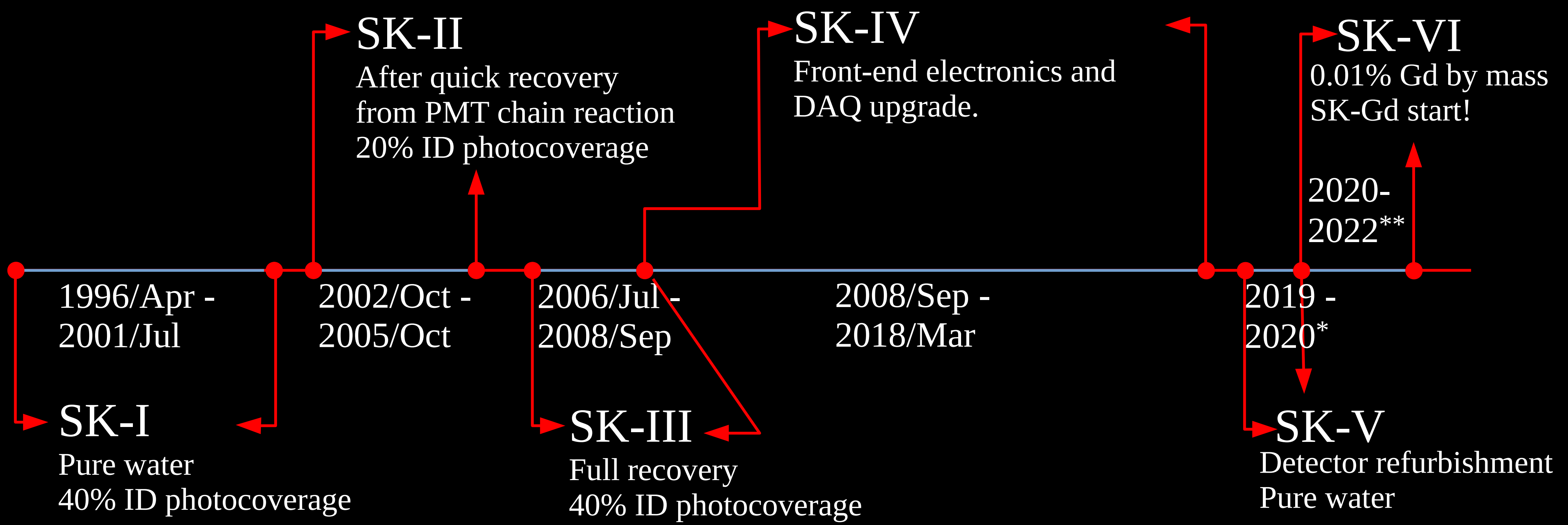
2008/Sep -
2018/Mar

Super-Kamiokande Detector Timeline



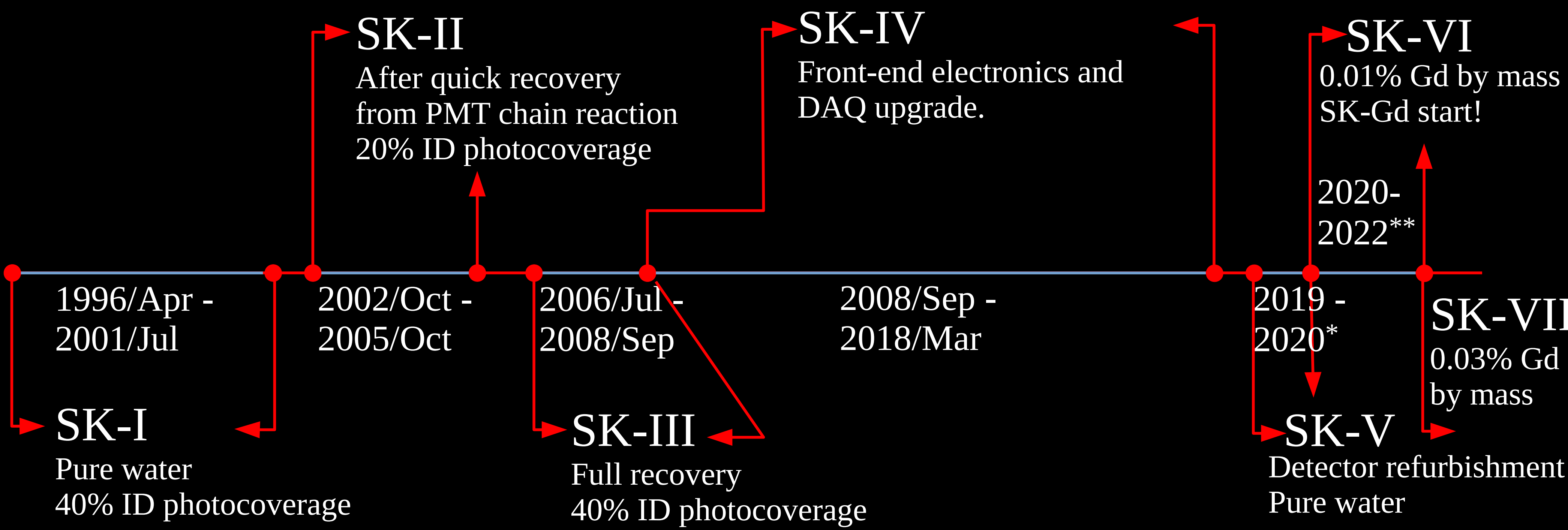
* 2019/Feb – 2020/Jul

Super-Kamiokande Detector Timeline



* 2019/Feb – 2020/Jul
** 2020/Jul - 2022/Jun

Super-Kamiokande Detector Timeline



* 2019/Feb – 2020/Jul
** 2020/Jul - 2022/Jun

Super-Kamiokande Detector Timeline

1996/Apr - 2001/Jul

SK-I
Pure water
40% ID photocoverage

2002/Oct - 2005/Oct

SK-II
After quick recovery from PMT chain reaction
20% ID photocoverage

2006/Jul - 2008/Sep

SK-III
Full recovery
40% ID photocoverage

2008/Sep - 2018/Mar

SK-IV
Front-end electronics and DAQ upgrade.

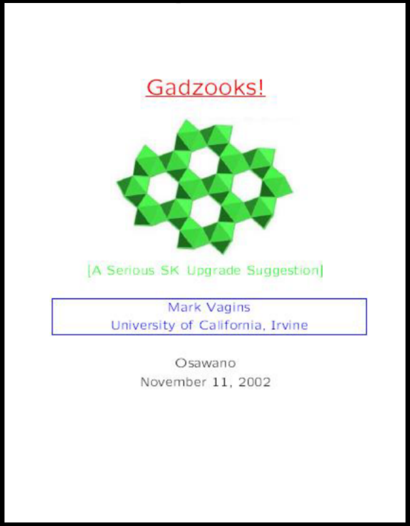
2019 - 2020*

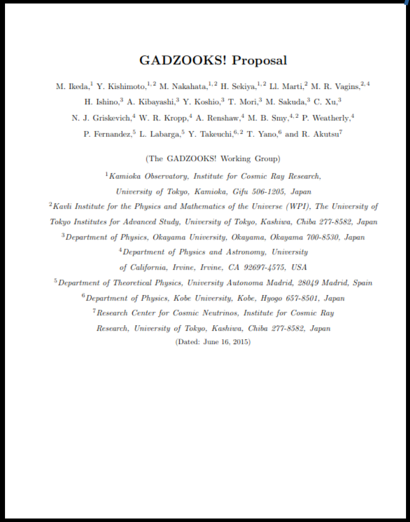
SK-V
Detector refurbishment
Pure water

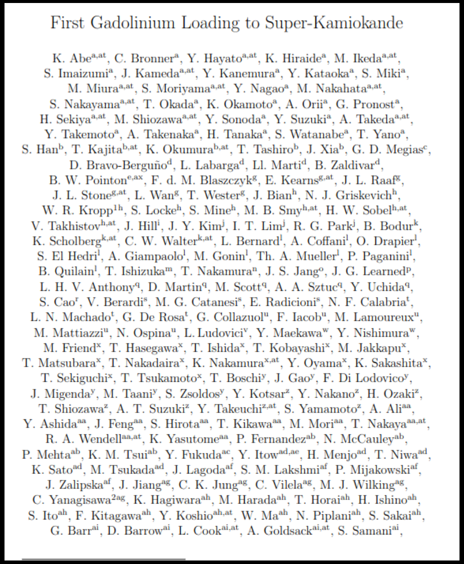
2020- 2022**

SK-VI
0.01% Gd by mass
SK-Gd start!

SK-VII
0.03% Gd by mass







* 2019/Feb – 2020/Jul
** 2020/Jul - 2022/Jun