31-July-2018 @RICH2018

RECENT RESULTS AND FUTURE PROSPECTS OF SUPER-KAMIOKANDE

Yasuo Takeuchi
(Kobe University)

Inside of SK detector during refurbishment work (July 15, 2018)

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

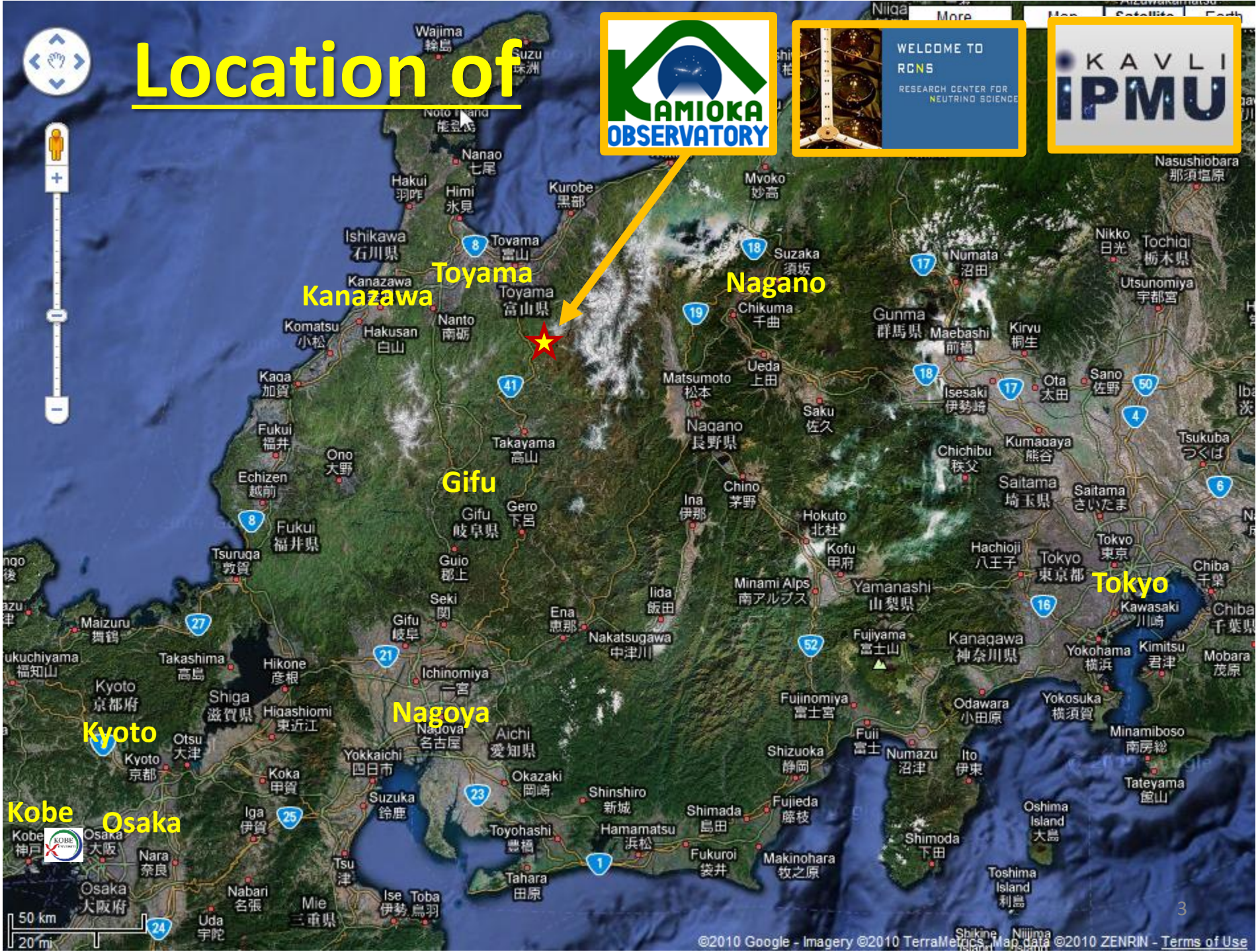
Duke University, USA
デューク大学

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

Chonnam National University, Korea
全南大学

10 nations, ~45 institutions, ~180 researchers (as of July 2018)

Location of

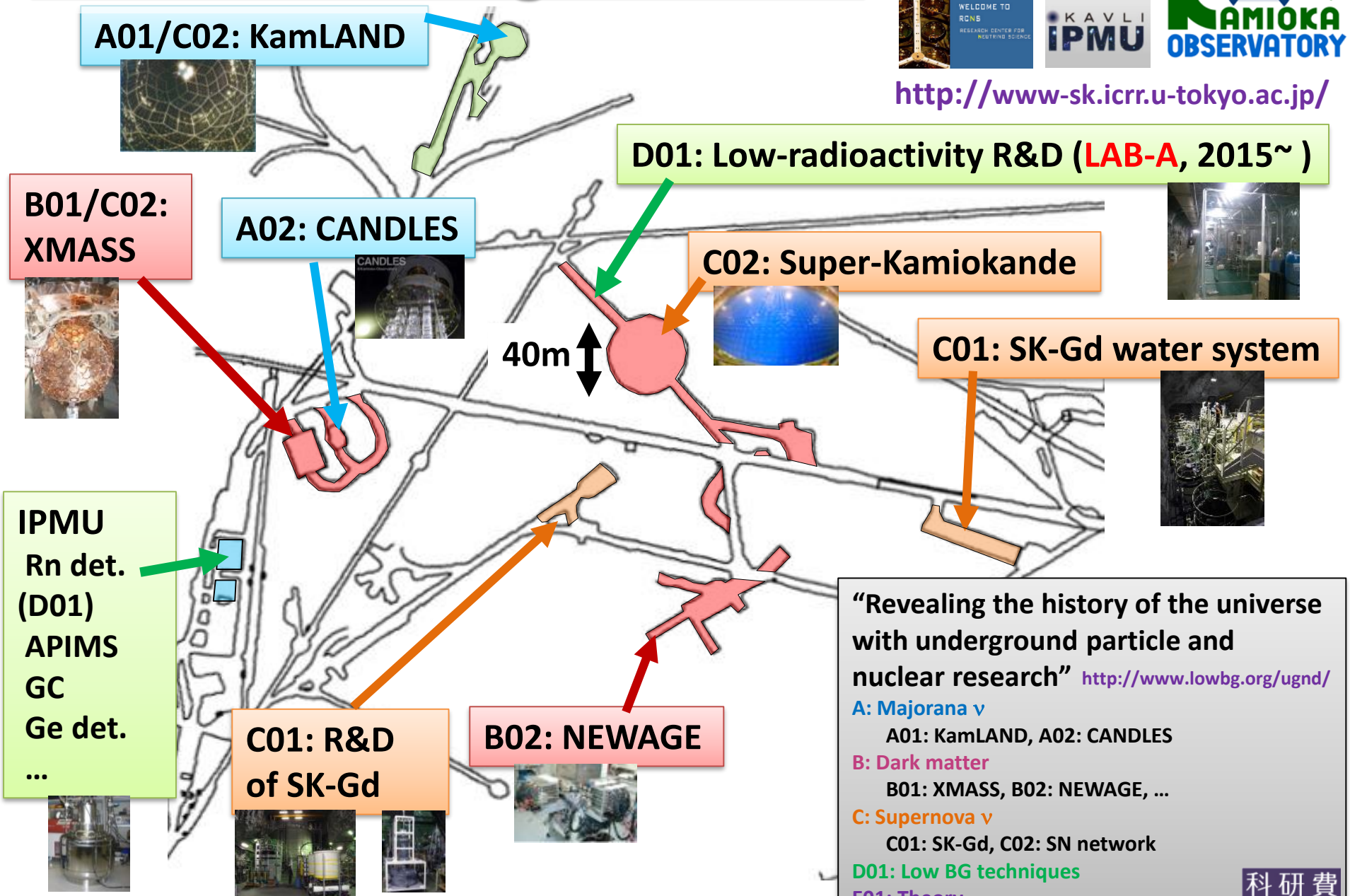

KAMIOKA OBSERVATORY
WELCOME TO RCNS
RESEARCH CENTER FOR NEUTRINO SCIENCE
KAVLI IPMU
Toyama
Kanazawa
Nagano
Gifu
Nagoya
Kyoto
Kobe
Osaka
Tokyo
Wajima
Nanao
Hakui
Himi
Kurobe
Toyama
Ishikawa
Kanazawa
Komatsu
Hakusan
Nanto
Kaga
Fukui
Ono
Echizen
Fukui
Tsuruga
Takayama
Gero
Gifu
Guio
Seki
Ena
Iida
Nakatsugawa
Ichinomiya
Nagoya
Aichi
Okazaki
Shinshiro
Toyohashi
Hamamatsu
Tahara
Ise
Toba
Mie
Tsu
Nabari
Uda
Nara
Osaka
Kyoto
Shiga
Higashiomi
Hikone
Takashima
Maizuru
Otsu
Koka
Iga
Suzuka
Kobe
Osaka
Mvoko
Suzaka
Chikuma
Matsumoto
Ueda
Nagano
Saku
Ina
Chino
Hokuto
Kofu
Minami Alps
Yamanashi
Fujiyama
Fujinomiya
Fuji
Shizuoka
Numazu
Ito
Shimada
Fujieda
Fukuroi
Makinohara
Shimoda
Oshima Island
Toshima Island
Tateyama
Minamiboso
Yokosuka
Odawara
Kanagawa
Yokohama
Kawasaki
Tokyo
Hachioji
Saitama
Chichibu
Kumagaya
Isesaki
Maebashi
Gunma
Numata
Nikko
Tochigi
Utsunomiya
Nasushiobara
Sano
Ota
Kiryu
Tsukuba
Chiba
Kimitsu
Mobara
50 km
20 mi
©2010 Google - Imagery ©2010 TerraMetrics - Map data ©2010 ZENRIN - Terms of Use


Toyama city
~30km
Office buildings
(~280m ASL)
Ikeno-yama
(1369m ASL)
Old Mozumi
entrance
3km
~1km overburden
Under ground
experimental area
(2700 m water
equivalent (m.w.e.))
2km
Atotsu entrance
41
© 2010 Europa Tec
© 2010 ZENRIN
Data © 2010 MIRC/JHA
Google
その他...
地図
航空写真
Earth
KAMIOKA OBSERVATORY
WELCOME TO RCNS
RESEARCH CENTER FOR NEUTRINO SCIENCE
KAVLI IPMU

Kamioka Underground site

2700 m.w.e.

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



"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, …

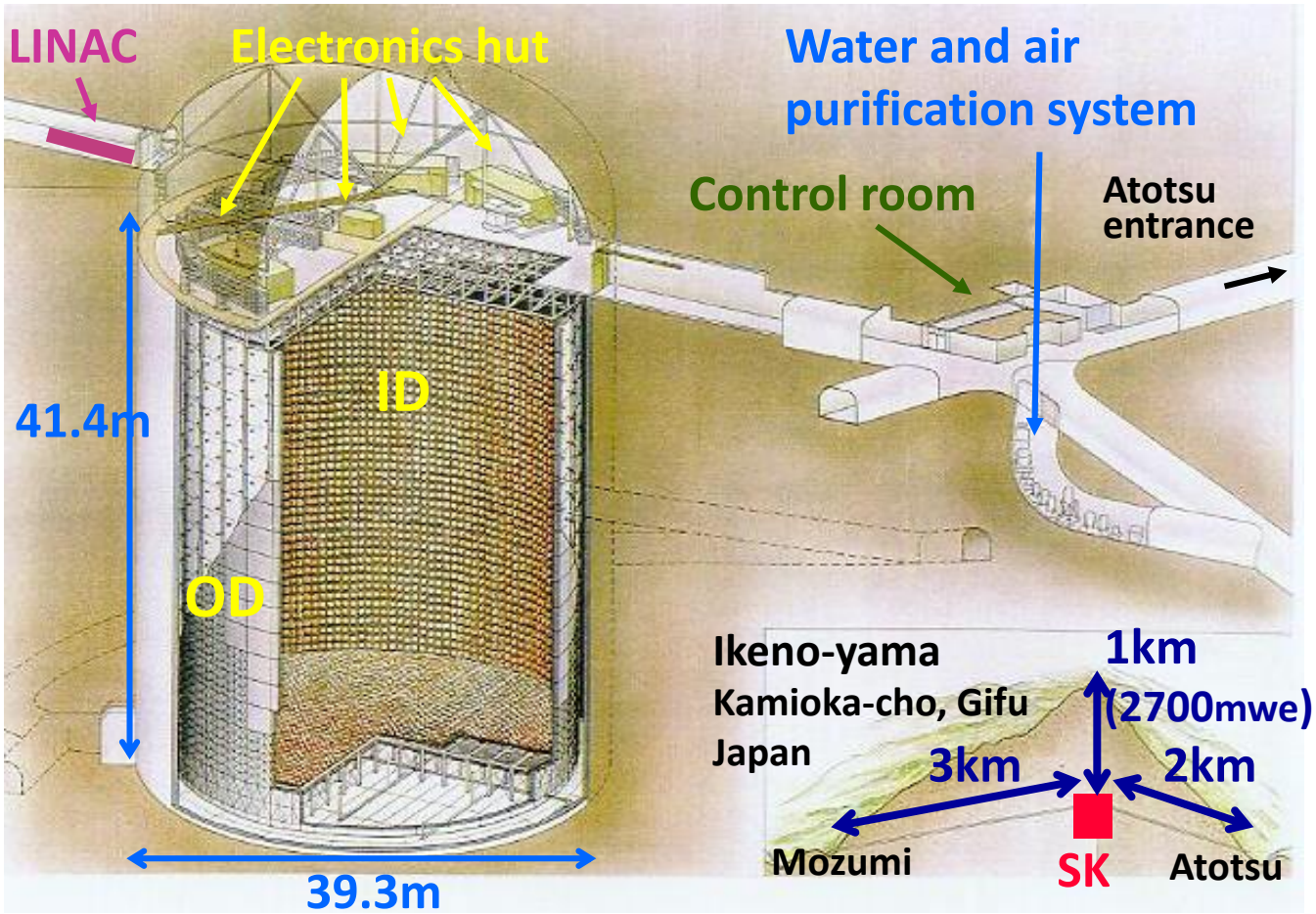
C: Supernova ν
- C01: SK-Gd, C02: SN network

D01: Low BG techniques

E01: Theory

Super-Kamiokande detector

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



- 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~
- Refurbishment work is ongoing

Physics targets:

- Nucleon decay search
- Neutrino oscillation study
- Astrophysical neutrino search

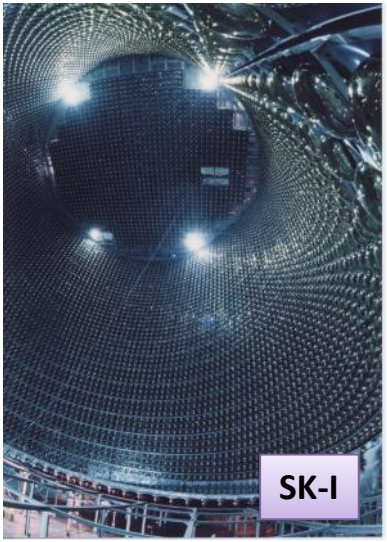
Inner Detector (ID) PMT: ~11100 (SK-I,III,IV), ~5200 (SK-II)
Outer Detector (OD) PMT: 1885

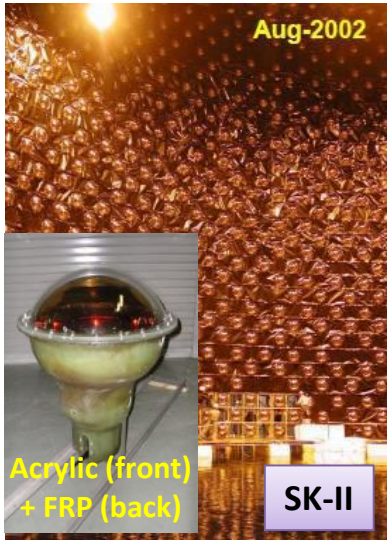
History & Plan of Super-Kamiokande

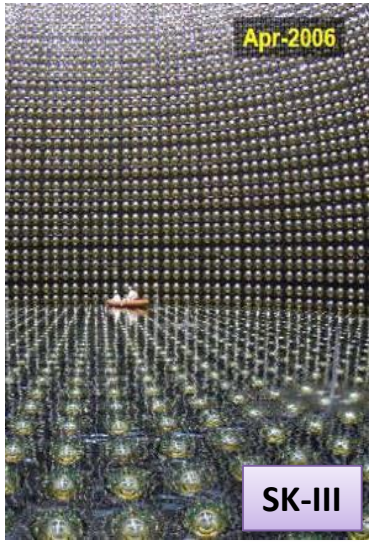
NOW

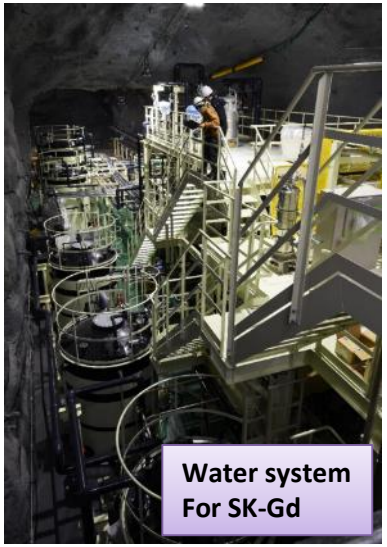
96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19

SK-I | SK-II | SK-III | SK-IV | Start upgrade for SK-Gd

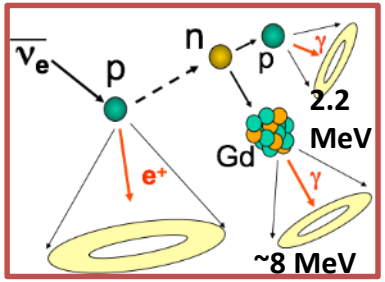








SK-I	SK-II	SK-III	SK-IV	Neutron tagging with Gd
11146 ID PMTs (40% coverage)	5182 ID PMTs (19% coverage)	11129 ID PMTs (40% coverage)	Electronics Upgrade	
4.5 MeV	6.5 MeV	4.5 MeV	3.5 MeV	
1496 days	791 days	548 days	2860 days	



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

Current total: 5695 days

Summary of recent results

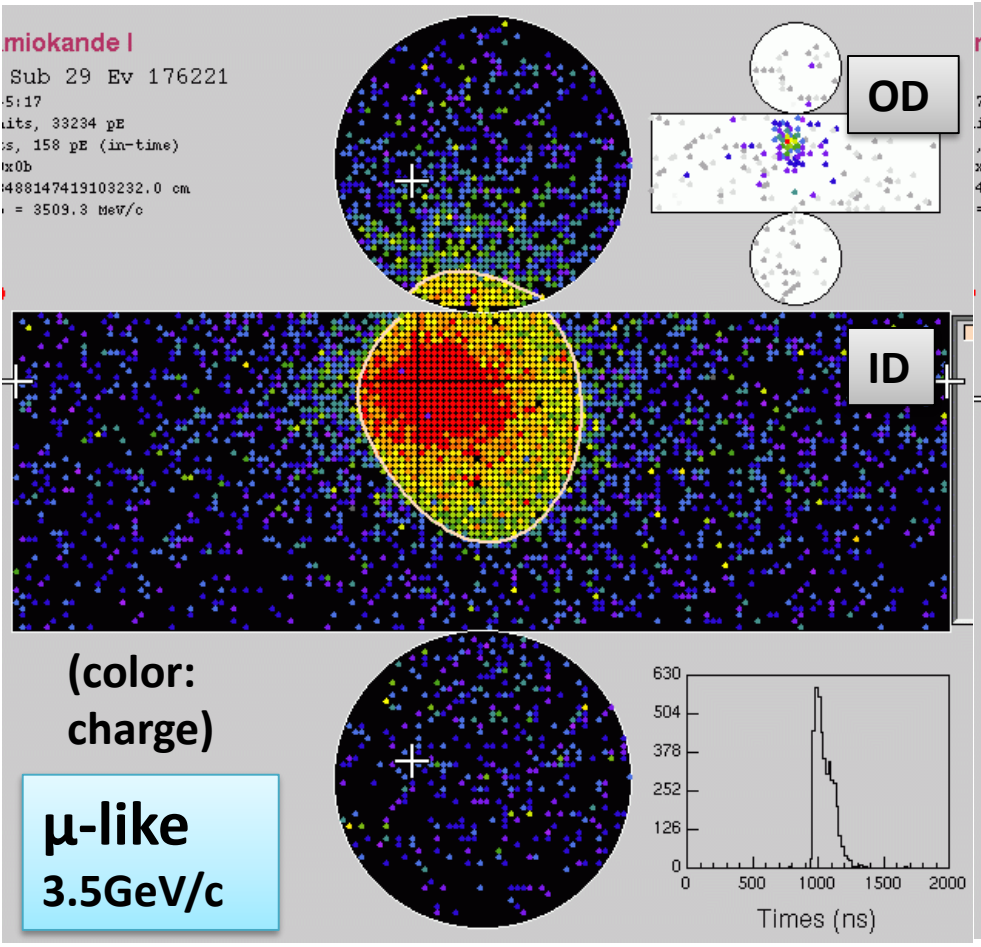
- **Nucleon decay search**
  - PRD96, 012003 (2017): SK 316 kt·yr
  - Current data set: SK 365 kt·yr (SK-IV: until Jan. 2018)
    - $\tau/B(p \rightarrow e^+ \pi^0)$ > 2.0×10^{34} years (90%CL, preliminary)
- **Atmospheric ν oscillation analysis**
  - PRD97, 072001 (2018): SK 5326 days, 328 kt·yr
  - arXiv: 1711.09436: ν_τ app. = 338.1 +/- 72.7 events (4.6 σ, 5326 d)
- **Solar ν oscillation analysis**
  - PRD94, 052010 (2016): (SK-IV: until Feb. 2014, 1664 d)
  - Current data set: SK 5695 days (SK-IV: until Dec. 2017, 2860 d)
- **Astrophysics**
  - Gravitational Wave source searches (GW170817)
  - WIMP searches (Sun, Earth, Galactic center)
  - Supernova neutrinos (burst, relic)

Atmospheric neutrino results

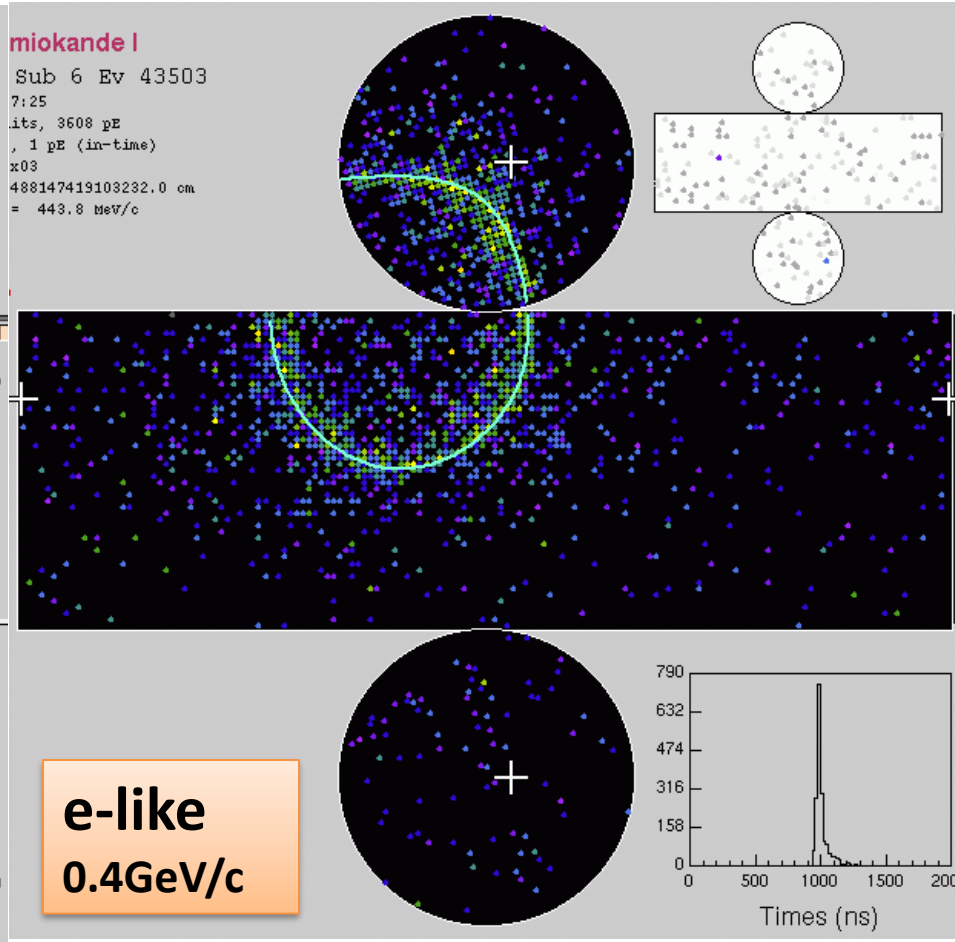
Typical high-energy events

Atmospheric ν: Partially contained (PC)

Atmospheric ν: Fully contained (FC)



μ-like
3.5GeV/c

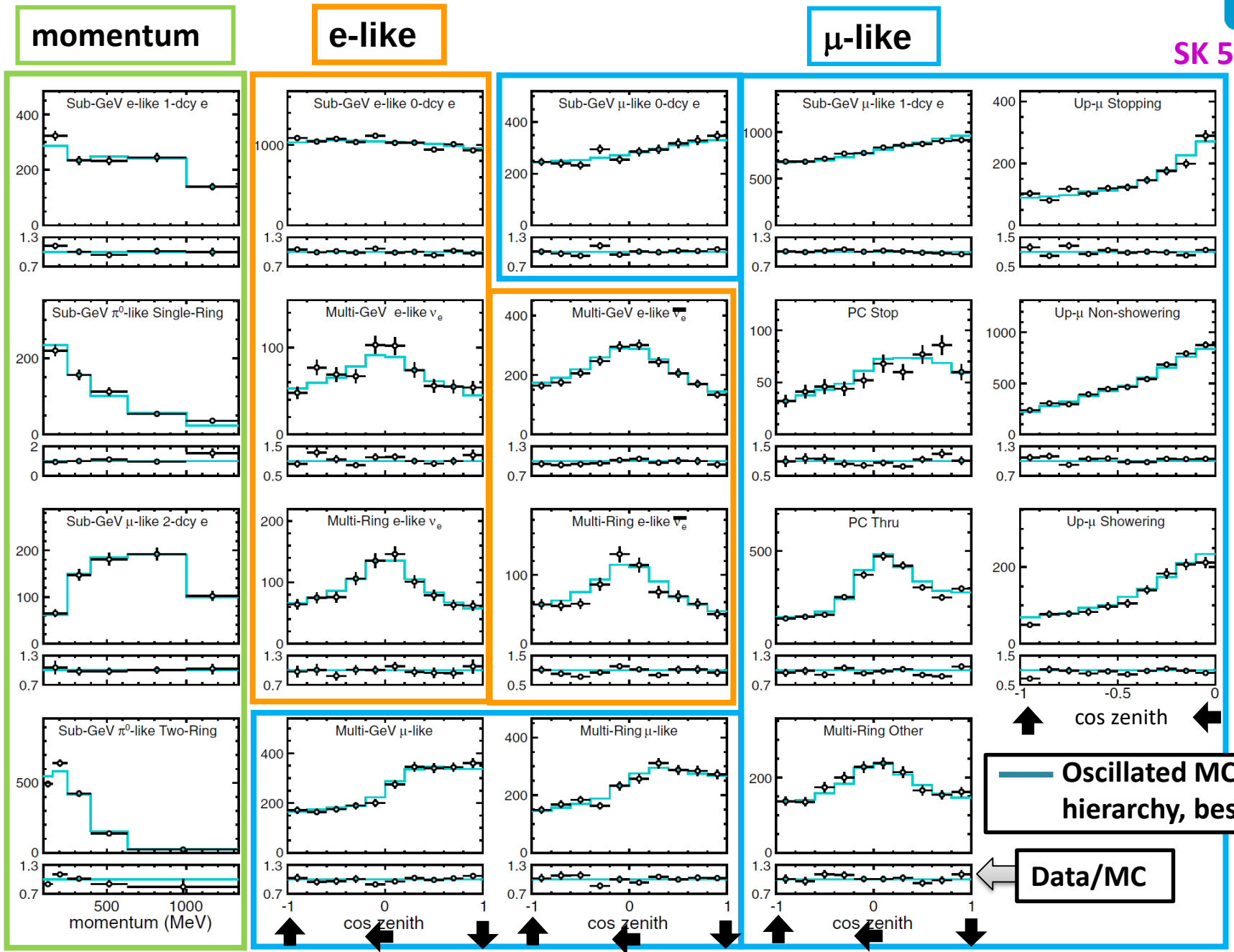


e-like
0.4GeV/c

Zenith angle & lepton momentum distributions

SK 5326 days

PRD97, 072001 (2018)



Atm. ν oscillation results: mass ordering

SK + T2K(model) with $\sin^2\theta_{13}$=0.0219+/-0.0012

SK 5326 days

PRD97, 072001 (2018)

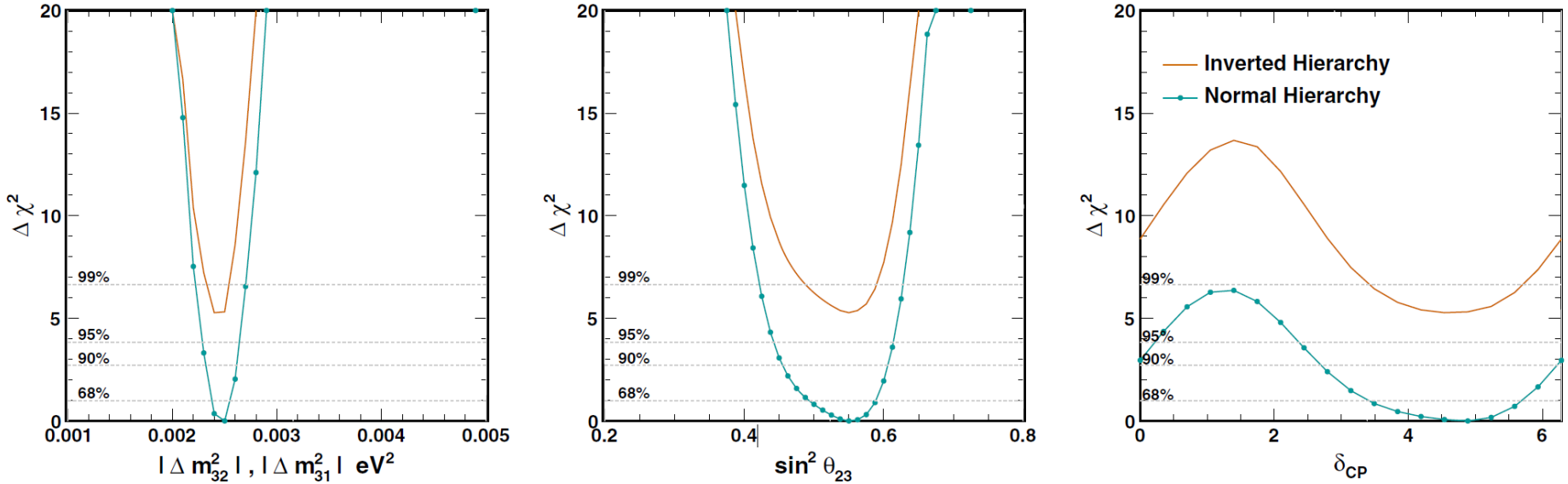


FIG. 16. Constraints on neutrino oscillation contours from a combined fit of Super-K atmospheric neutrino data and a model of the T2K experiment assuming $\sin^2\theta_{13} = 0.0219 \pm 0.0012$. Orange lines denote the inverted hierarchy result, which has been offset from the normal hierarchy result, shown in cyan, by the difference in their minimum χ^2 values.

$$\Delta\chi^2 = \chi^2_{NH,min} - \chi^2_{IH,min} = -5.27$$

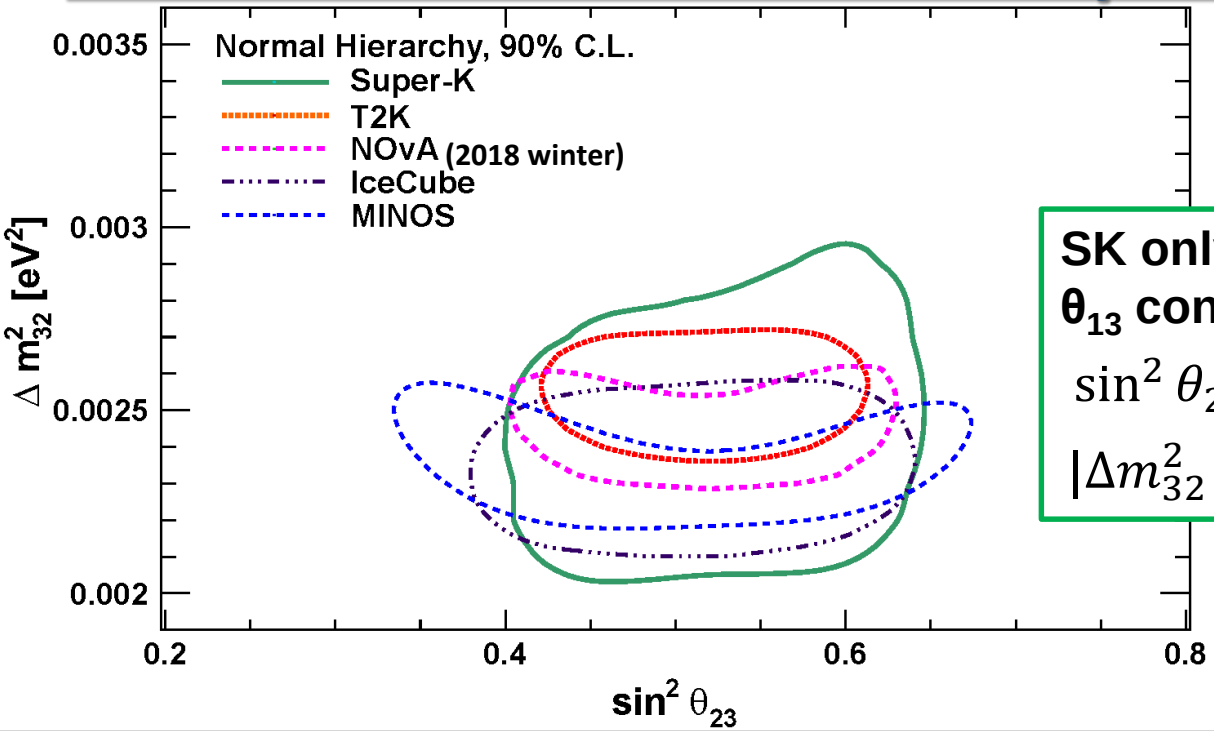
Over the range of parameters allowed at 90% confidence level, the normal mass hierarchy is favored by between 91.9% and 94.5% based on the combined Super-Kamiokande plus T2K result.

(*CL_s* technique [J. Phys. G 28, 2693 (2002)] is used)

Atm. ν oscillation results: parameters

SK 5326 days

PRD97, 072001 (2018)



SK only, normal hierarchy, θ_{13} constrained

$$\sin^2\theta_{23} = 0.588^{+0.031}_{-0.064}$$

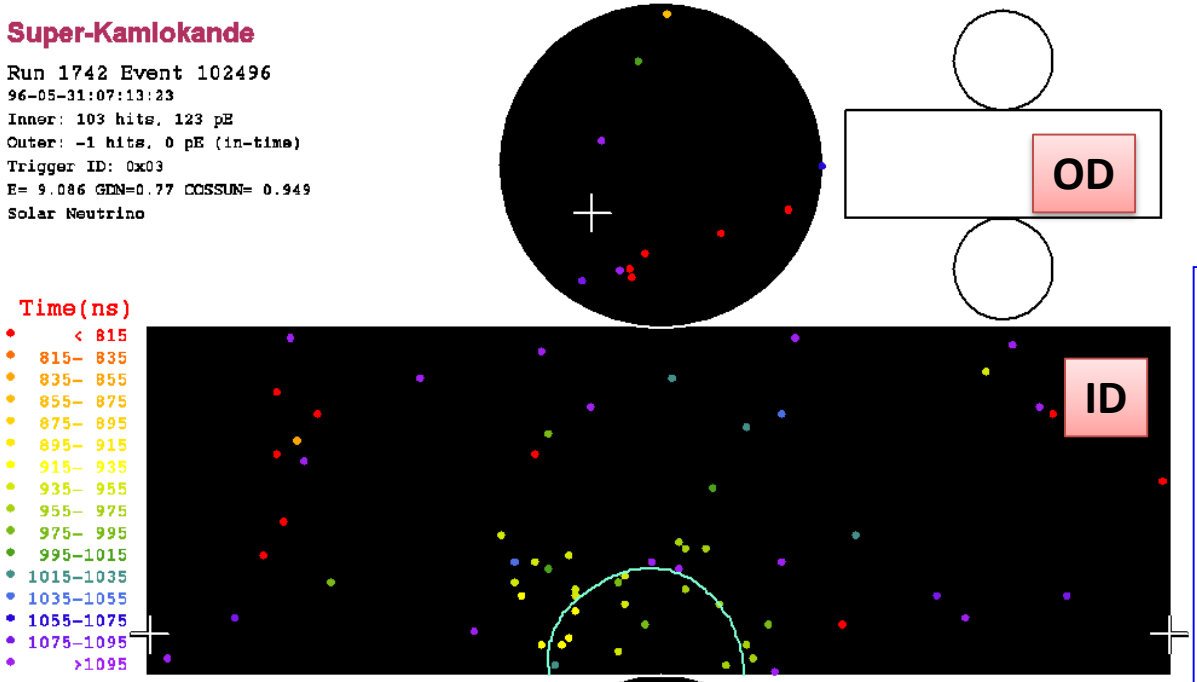
$$|\Delta m^2_{32}| = (2.50^{+0.13}_{-0.20}) \times 10^{-3}\,\mathrm{eV}^2$$

TABLE V. Summary of parameter estimates for each analysis and hierarchy hypothesis considered. Here NH (IH) refers to the normal (inverted) hierarchy fit. The terms "free" and "constrained" refer to fits without and with a constraint on $\sin^2\theta_{13}$, respectively, as described in the text. The expected absolute χ^2 value for the SK (SK + T2K) fits is 559.9 (636.2). The p-value for obtaining a smaller χ^2 than the data is 0.439 (0.482) in the NH θ_{13}-constrained fits.

Fit	Hierarchy	χ^2	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32,31}\rvert$ [$\times 10^{-3}$ eV^2]	δ_{CP}
SK θ_{13} Free	NH	571.29	$0.018^{+0.029}_{-0.013}$	$0.587^{+0.036}_{-0.069}$	$2.50^{+0.13}_{-0.31}$	$4.18^{+1.45}_{-1.66}$
	IH	574.77	$0.008^{+0.017}_{-0.007}$	$0.551^{+0.044}_{-0.075}$	$2.20^{+0.33}_{-0.13}$	$3.84^{+2.38}_{-2.12}$
SK θ_{13} Constrained	NH	571.33	–	$0.588^{+0.031}_{-0.064}$	$2.50^{+0.13}_{-0.20}$	$4.18^{+1.41}_{-1.61}$
	IH	575.66	–	$0.575^{+0.036}_{-0.073}$	$2.50^{+0.08}_{-0.37}$	$4.18^{+1.52}_{-1.66}$
SK + T2K θ_{13} Constrained	NH	639.43	–	$0.550^{+0.039}_{-0.057}$	$2.50^{+0.05}_{-0.12}$	$4.88^{+0.81}_{-1.48}$
	IH	644.70	–	$0.550^{+0.035}_{-0.051}$	$2.40^{+0.13}_{-0.05}$	$4.54^{+1.05}_{-0.97}$

Solar neutrino results

Typical low-energy event

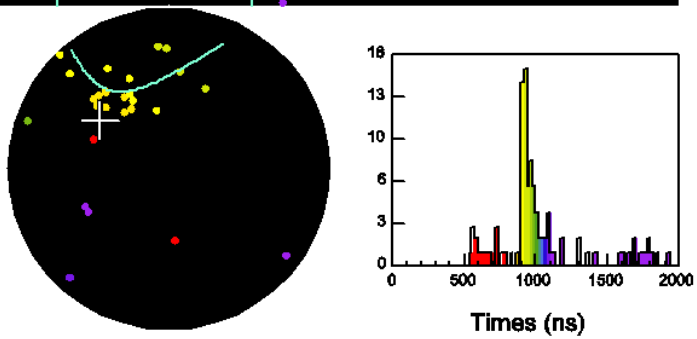


(color: time)

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

(for solar neutrinos)

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



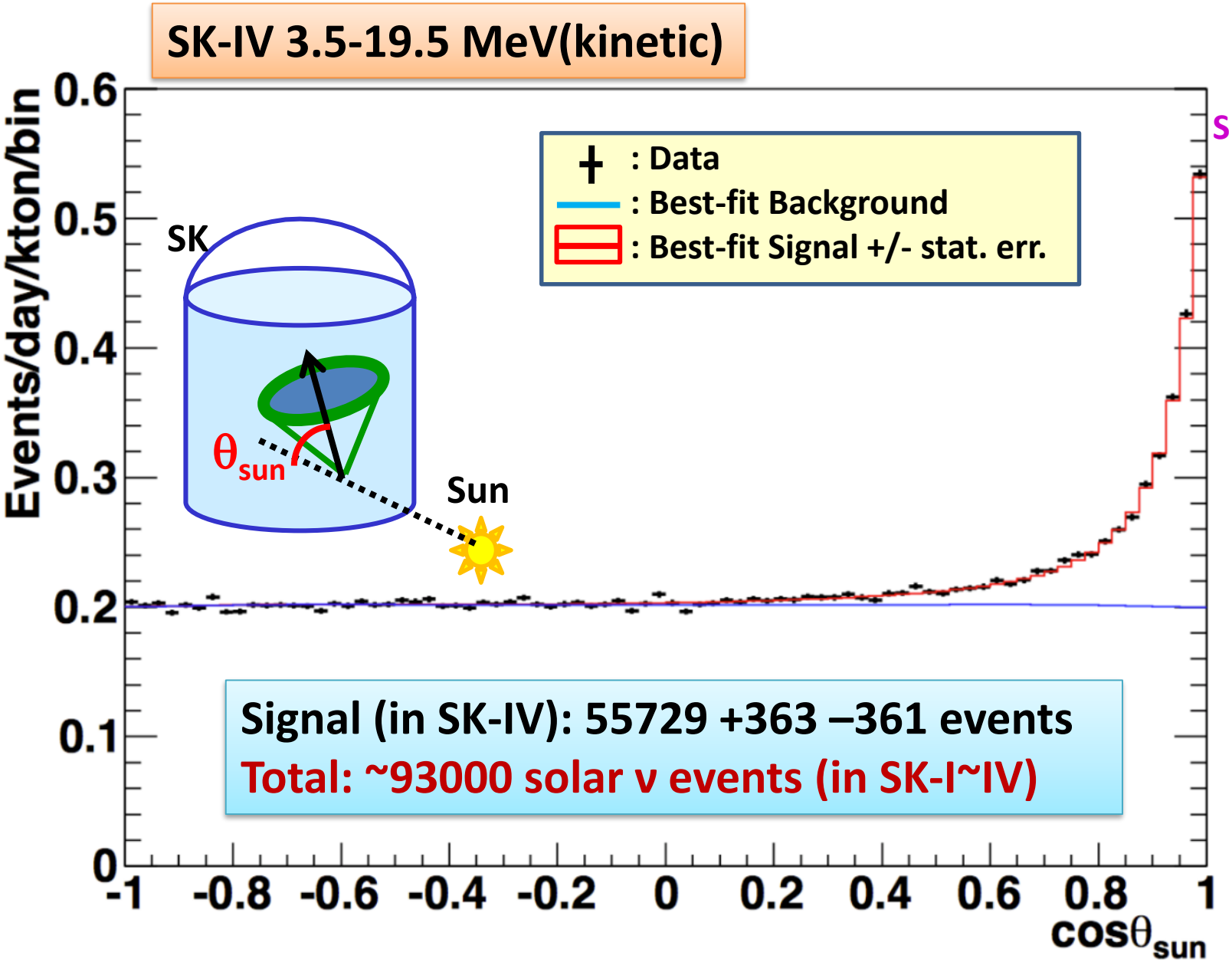
$E_{e,total}$ = 9.1 MeV
$\cos\theta_{sun}$ = 0.95

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

Resolutions (for 10 MeV electrons) (software improvement)

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

SK-IV solar neutrino signal

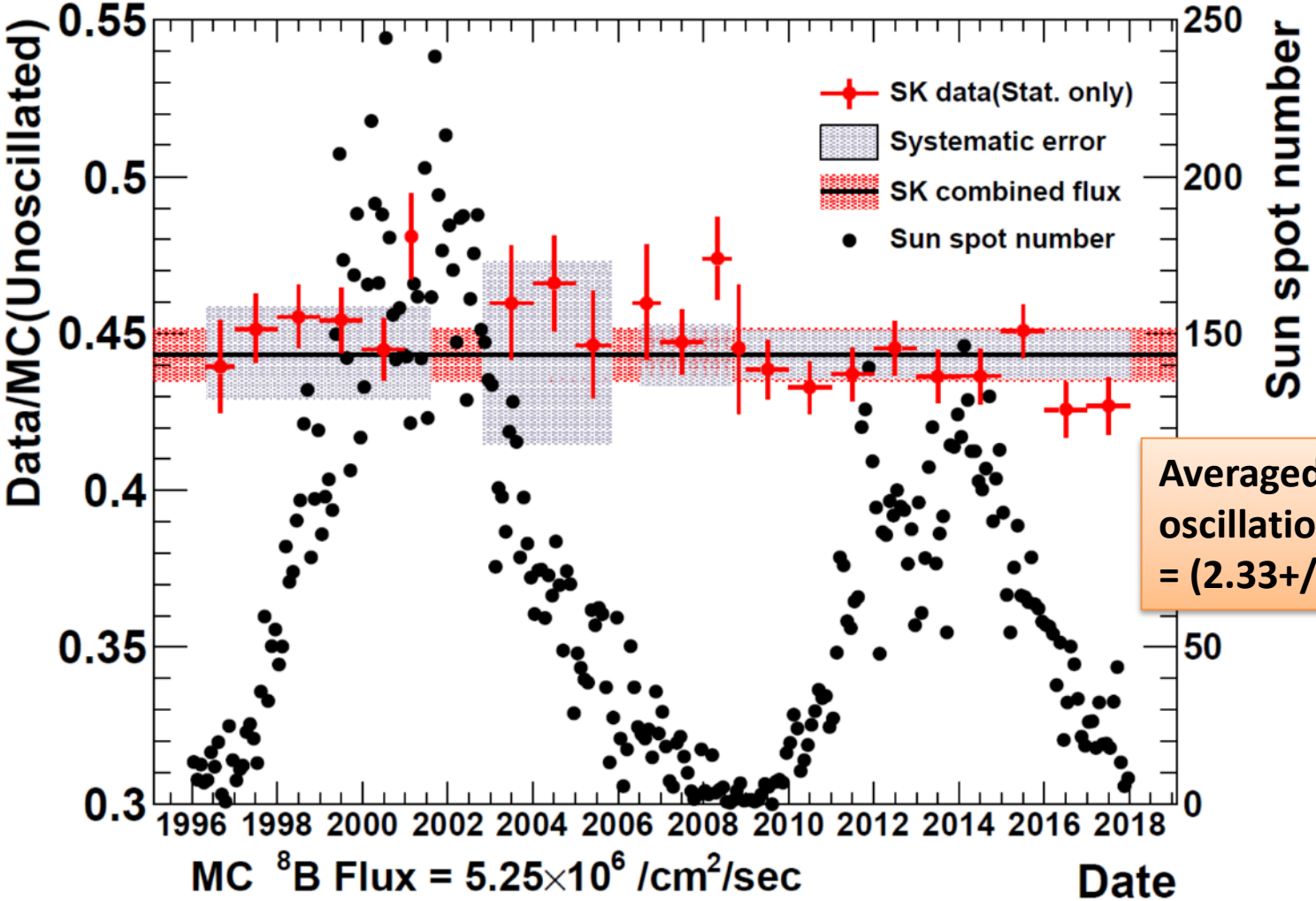


^{8}B solar neutrino flux: Yearly plot

Apr 2018

Preliminary

SK 5695 days



Averaged ^{8}B flux with no oscillation
= (2.33+/-0.04) x10^6/cm^2/s

χ^2 = 21.57 / 21 d.o.f. → Confidence level = 41.4 %

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

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

Solar ν oscillation results

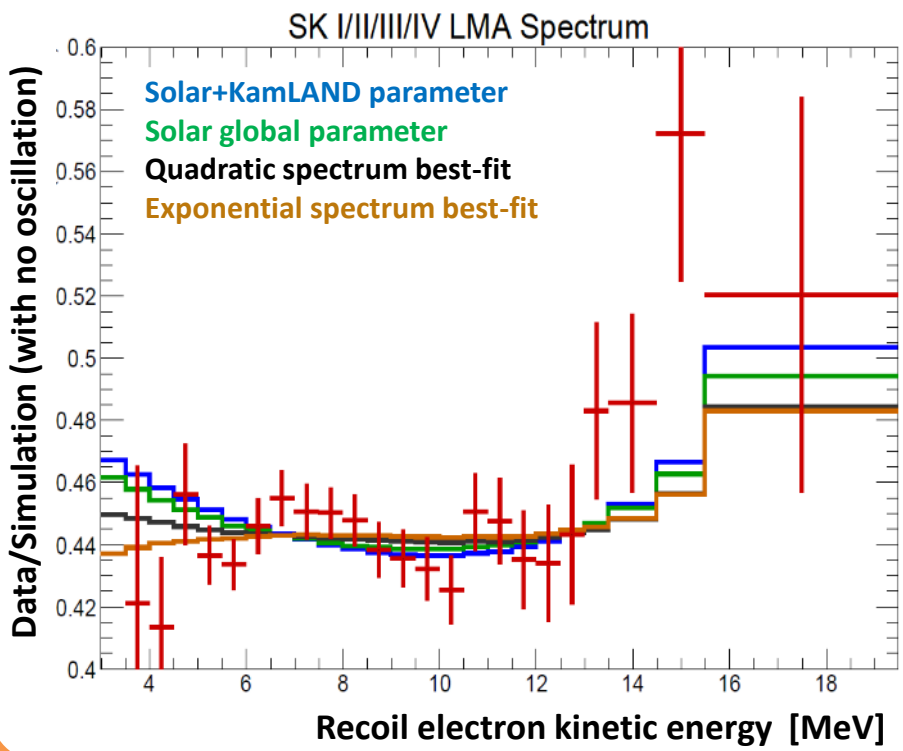
- Quadratic fit of SK spectrum is consistent with solar Δm^2_{21} within ~1.2 σ and disfavors KamLAND Δm^2_{21} by ~2.0 σ.
- ~2.0 σ level tension in Δm^2_{21} between solar global analysis and KamLAND is still remaining.

Apr 2018

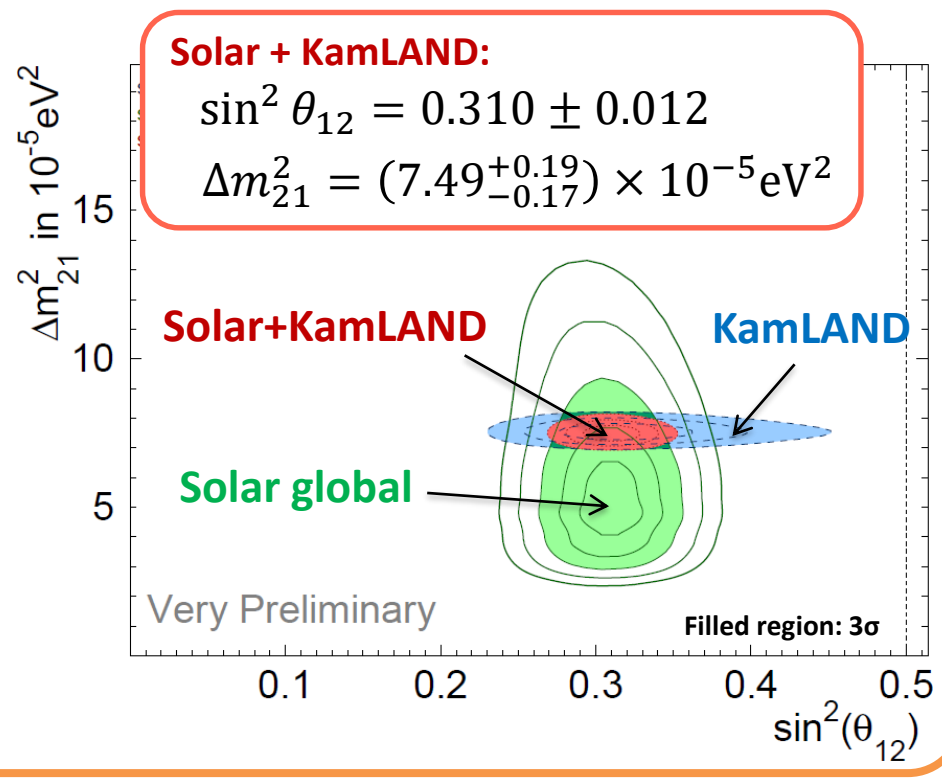
Preliminary

SK 5695 days

Solar ν energy spectrum



Solar ν oscillation parameters



Future prospects (SK-Gd)

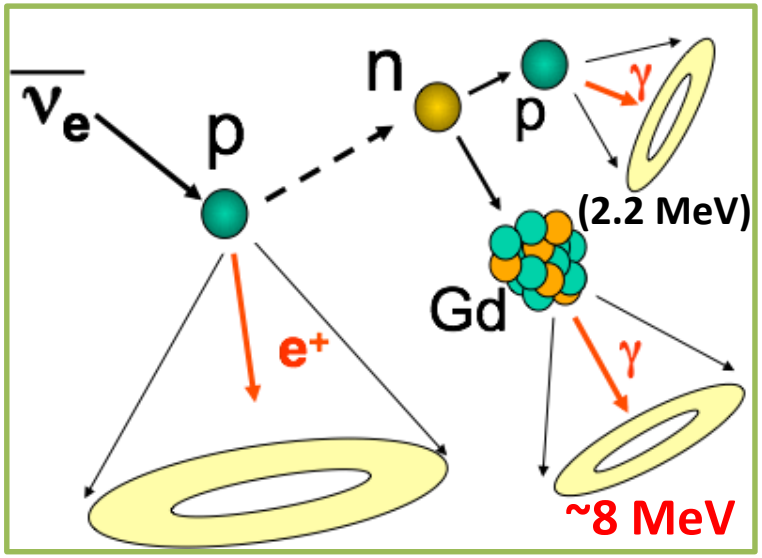
Next step: SK-Gd Phase

SK-Gd Phase:

Add gadolinium (Gd) to enhance neutron tagging efficiency of the SK detector.

Physics targets:

- **Detect the world's first Supernova Relic Neutrinos (SRN) (or Diffuse Supernova Neutrino Background, DSNB)**
- **Improve pointing accuracy for supernova**
- **Early warning of nearby supernova from pre-burst signal (silicon burning)**
- **Enhance ν or $\bar{\nu}$ discrimination in atmospheric ν & T2K analysis**
- **Reduce backgrounds in proton decay search**



- **Reduce BG of $\bar{\nu}_e$ signal**
  - **Delayed coincidence**
  - **ΔT ~ 30 μs**
  - **Vertices within ~ 50 cm**

SK refurbishment is ongoing since June 2018

- **Fix water leakage**
- **Replace dead PMTs**
- **Improve water piping in the SK detector**

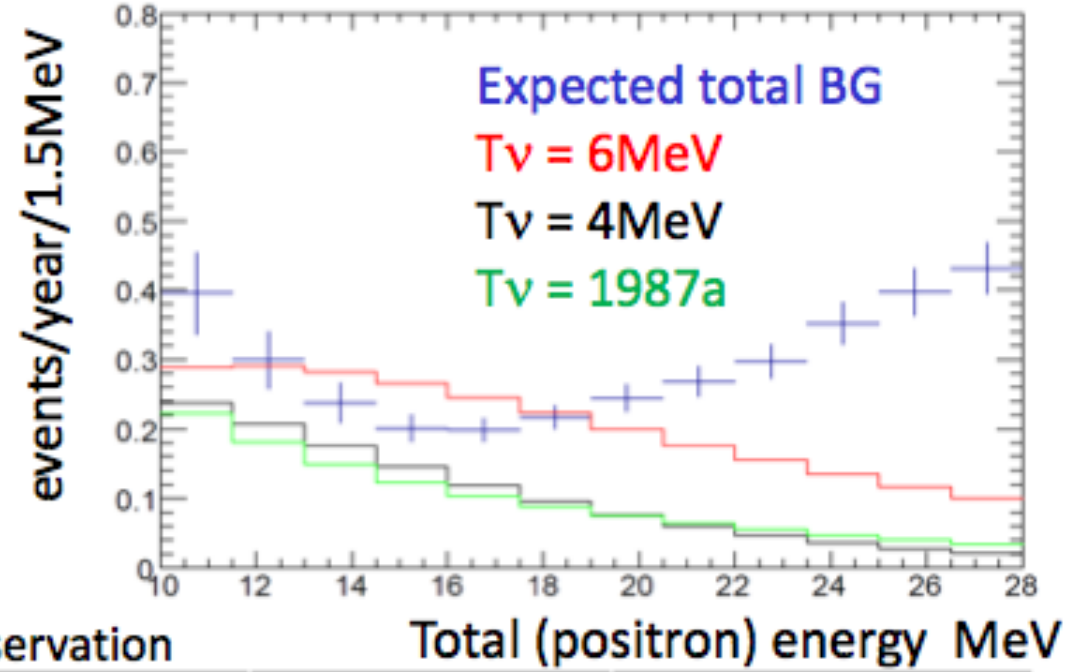
Capture efficiencies in water

- **0.01% Gd [$Gd_2(SO_4)_3$ 10t] : ~50%**
- **0.1% Gd [$Gd_2(SO_4)_3$ 100t] : ~90%**

SK-Gd: Expected sensitivity

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

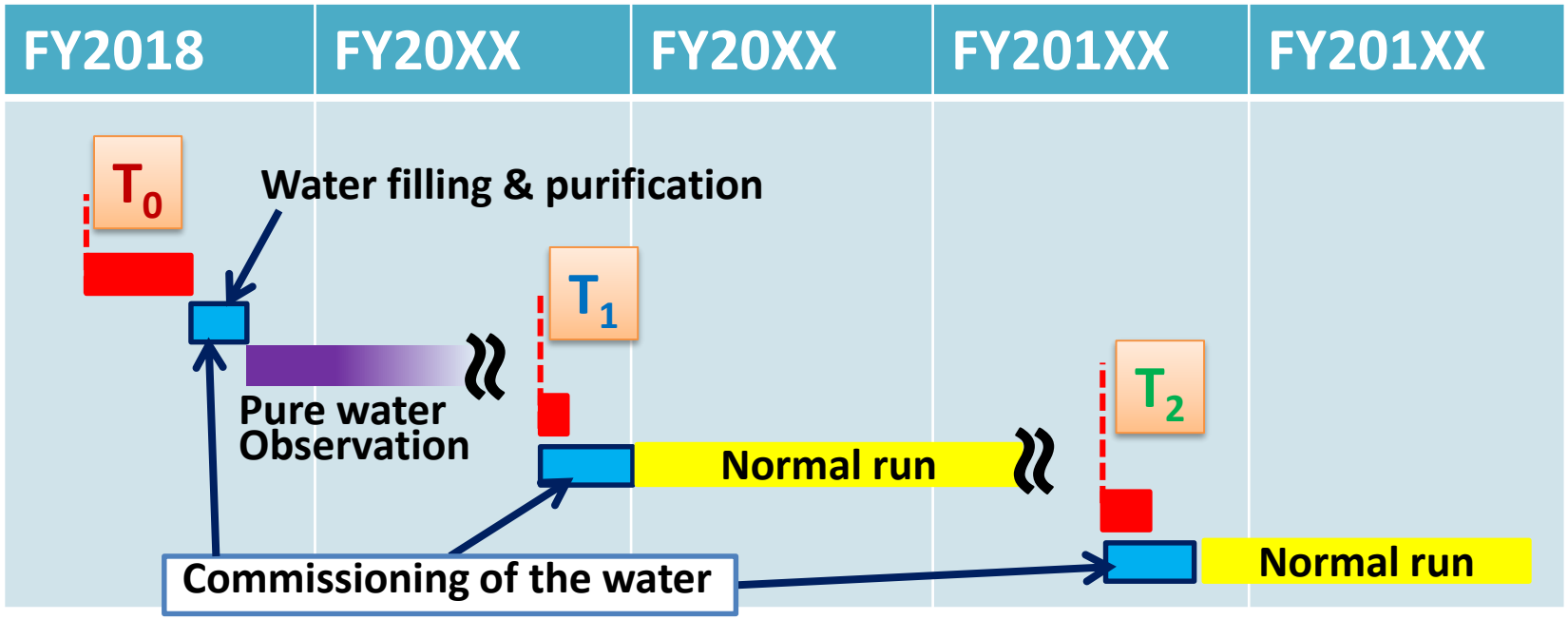
- It depends on typical/actual SN emission spectrum



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	----

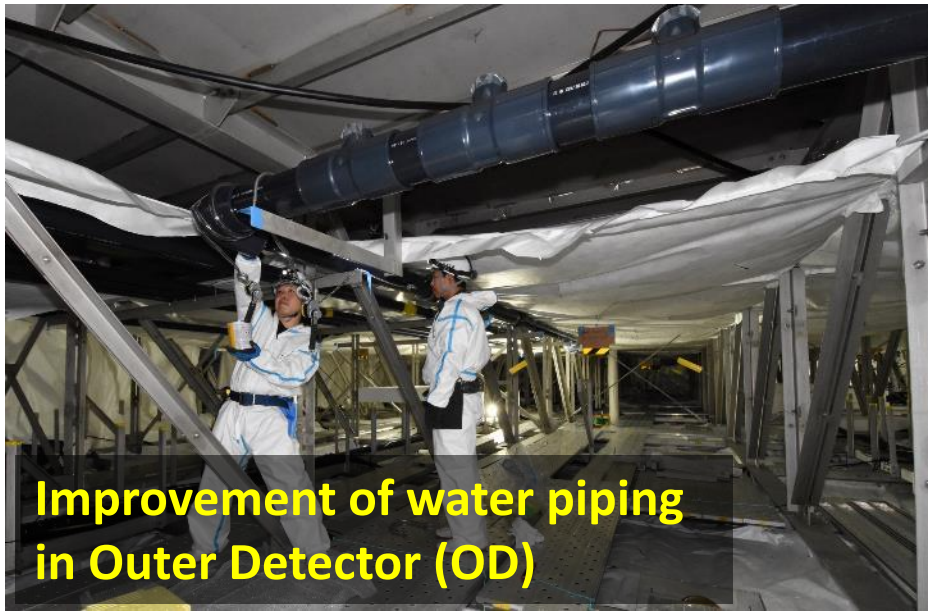
SK-Gd: Current plan



- T_0: Start SK detector refurbishment (May 31, 2018)
  - Jun. ~ Dec. 2018: refurbishment & water filling
  - Jan. 2019 ~: pure water run
- T_1: Load first 10 ton $Gd_2(SO_4)_3$ [0.01% Gd, 50% eff.]
  - First possible T_1 is late 2019 (will be decided with T2K/J-PARC ν beam)
- T_2: Load additional 90 ton $Gd_2(SO_4)_3$ [0.1% Gd, 90% eff.]

Refurbishment of SK detector: 1/2

Refurbishment of SK detector: 2/2



Summary

- Super-Kamiokande (SK) is a 50-kton water Cherenkov detector located 1,000 m underground in Japan.
- SK is providing various unique results since 1996, for more than 20 years.
  - neutrino oscillation parameters, nucleon decay searches, astrophysical neutrino searches, …
- The refurbishment of the SK detector for the next phase (SK-Gd) is started in June 2018.
- The main physics target in SK-Gd phase is the first observation of supernova relic neutrinos.