Super-Kamiokande

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Spokesperson of Super-Kamiokande

ICRR External Review, May 15th, 2019

Summary of achievements from 2012 to 2018 (1)

- [Atmospheric Neutrinos] Precision studies of three-flavor effects in neutrino oscillations were performed in atmospheric neutrino analysis. The SK data favor the NH with a significance of between 91.9% and 94.5% and show a weak indication for dCP~$3\pi/2$. The appearance of ν_τ events has been confirmed at 4.6σ significance.
- [Indirect dark matter search] Searches for dark matter-induced neutrino signals from the galactic center, the sun and the earth have performed. Limits have been placed on the WIMP self annihilation cross section as well as on its interaction cross sections with nucleons. SK's limits for masses below several tens GeV/c^2 are among the most stringent in the indirect searches in the world.
- [Solar Neutrinos] High accuracy solar neutrino measurements are carried out in SK-IV. There is about 2 σ level tension in Δm^2_{21} between solar global analysis and KamLAND measurement.

Summary of achievements from 2012 to 2018 (2)

- [Nucleon decay search] The nucleon decay lifetime reached more than or close to 10^{34} years for the major decay modes: $p \rightarrow e^+\pi^0$, $p \rightarrow \mu^+\pi^0$, and $p \rightarrow \bar{\nu} K^+$, with suppressing background by new technique of neutron tagging. Searches for other decay modes were also performed and we obtained the most stringent limits on nucleon lifetime in the world. ➡
- [Supernova neutrinos] SK has been searching for galactic supernovae with the efforts to minimize the dead time. A flux upper limit of supernova relic neutrinos(SRN) was obtained using all data from SK-I to III that has reached within a factor of model predictions. In SK-IV, SRN search by tagging neutron capture on hydrogen was performed. The result shows the world best limit down to 16 MeV. ➡

Summary of achievements from 2012 to 2018 (3)

- [Preparation for SK-Gd] Preparation for the next phase of SK with Gadolinium(Gd) loading (SK-Gd) is in progress. Feasibility of loading Gadolinium into SK has been demonstrated by the EGADS project. In addition, we succeeded to develop $Gd_2(SO_4)_3$ powder with low enough radio impurity. ➡
- [Tank open work in FY2018] A major refurbishment work on the SK tank, whose main purpose is to fix the leak for SK-Gd, was performed in FY2018. Currently we do not observe any water leakage from the SK tank within the accuracy of our measurement, which is less than 0.017 tons per day. We are aiming to start Gd loading within FY2019. ➡

The Super-Kamiokande Collaboration

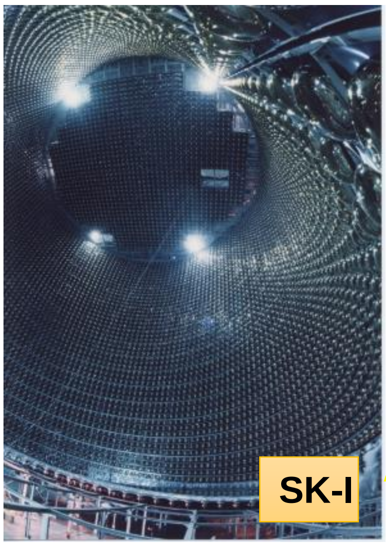
Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
University of British Columbia, Canada
Boston University, USA
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
Fukuoka Institute of Technology, Japan
Gifu University, Japan
GIST, Korea
University of Hawaii, USA
Imperial College London, UK
INFN Bari, Italy
INFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Kavli IPMU, The Univ. of Tokyo, Japan
KEK, Japan
Kobe University, Japan
Kyoto University, Japan
University of Liverpool, UK
LLR, Ecole polytechnique, France
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
Okayama University, Japan
Osaka University, Japan
University of Oxford, UK
Queen Mary University of London, UK
Seoul National University, Korea
University of Sheffield, UK
Shizuoka University of Welfare, Japan
Sungkyunkwan University, Korea
Stony Brook University, USA
Tokai University, Japan
The University of Tokyo, Japan
Tokyo Institute of Technology, Japan
Tokyo University of Science, japan
University of Toronto, Canada
TRIUMF, Canada
Tsinghua University, Korea
The University of Winnipeg, Canada
Yokohama National University, Japan

~175 collaborators from 44 institutes in 10 countries

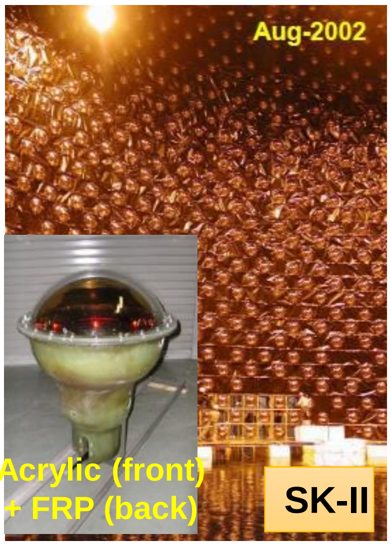
History & Plan of Super-Kamiokande

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

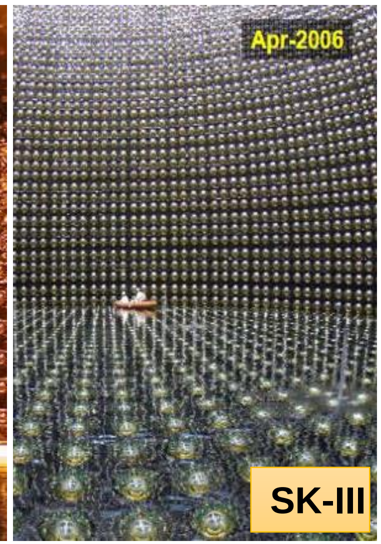
SK-I SK-II SK-III SK-IV SK-V
→SK-Gd



11146 ID PMTs
(40% coverage)
Apr.1996
~Jul. 2001
4.5 MeV

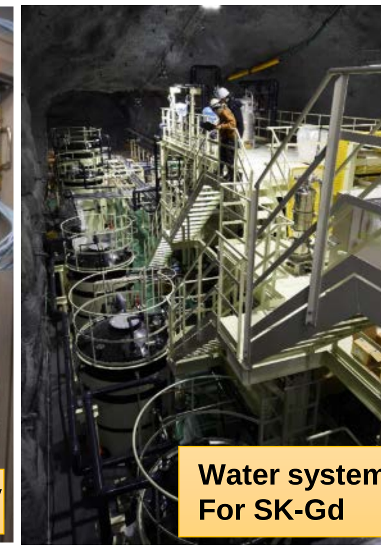


5182 ID PMTs
(19% coverage)
Sep.2002
~Oct.2005
6.5 MeV

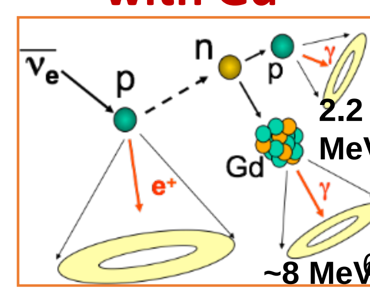


11129 ID PMTs
(40% coverage)
Jul.2006
~Aug.2008
4.5 MeV

Electronics
Upgrade
Sep.2008
~May 2018
3.5 MeV

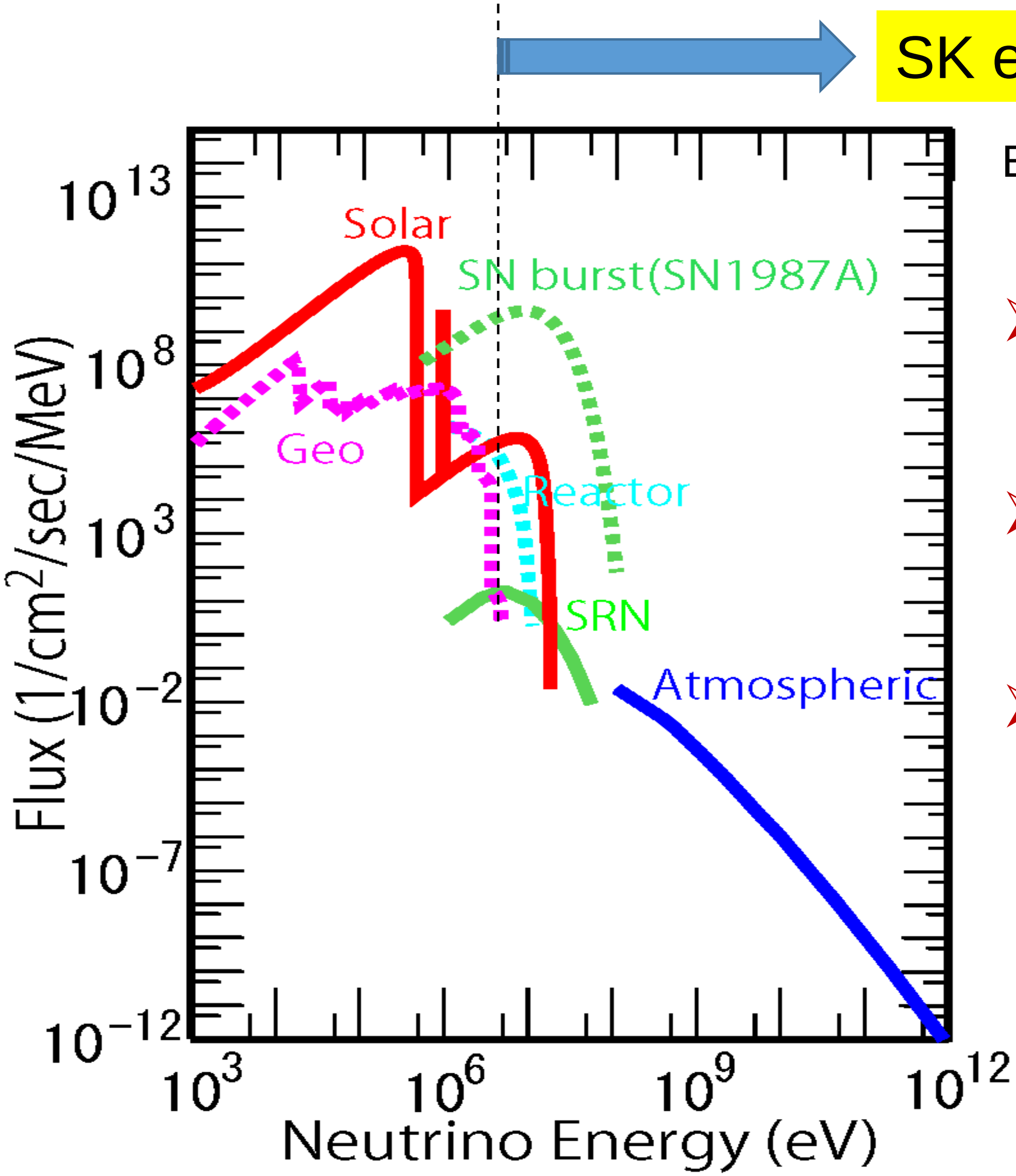


Neutron tagging
with Gd



■ Analysis energy threshold (recoil electron kinetic energy)

Neutrino energy range covered by SK

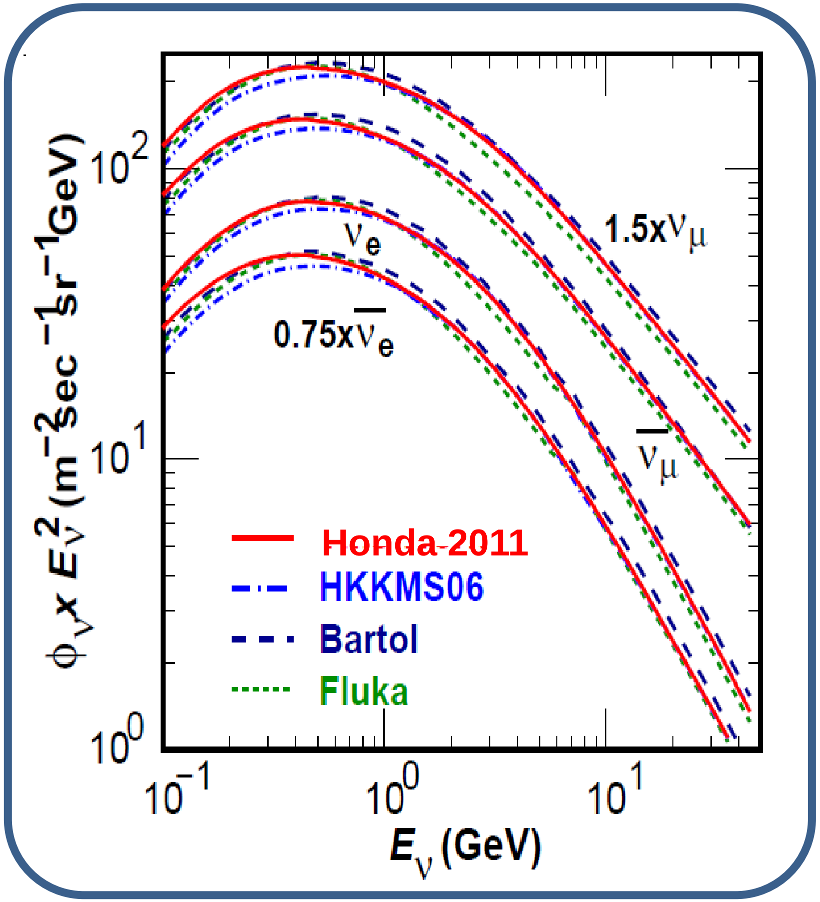


Energy threshold: 3.5 MeV in kinetic energy (SK-IV)

- Solar neutrinos
  - threshold ~ 3.5 MeV
  - ~15 events/day
- Super neutrinos
  - 5~20 MeV
  - ~8000 events for 10kpc
- Atmospheric neutrinos
  - < a few 100 GeV
  - ~ 10 events/day

Study neutrino oscillations by those sources.
Also, study astrophysics with those sources.

Atmospheric Neutrinos



Honda et al., Phys. Rev. D83, 123001 (2011).

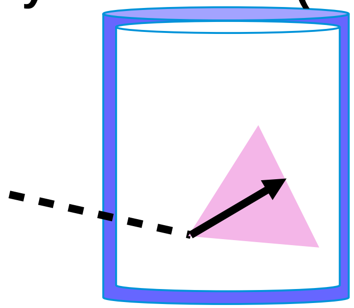
- Cosmic rays interact with air nuclei and the decay of pions and kaons produce neutrinos

$$P + A \rightarrow N + \pi^{\pm} + X$$
$$\pi^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_\mu$$
$$\mu^{\pm} \rightarrow e^{\pm} + \overset{(-)}{\nu}_e + \overset{(-)}{\nu}_\mu$$

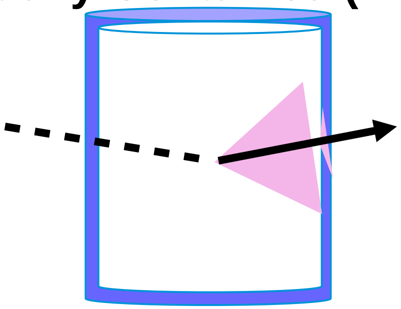
- νs travel 10 – 10,000 km before detection
- Both ν_μ and ν_e (ν_μ/ν_e = 2 at low energy)
- Both neutrinos and anti-neutrinos
  - ~ 30% of final analysis samples are antineutrinos
- Flux spans many decades in energy ~100 MeV – 100TeV
- Excellent tool for broad studies of neutrino oscillations

SK: Atmospheric ν Analysis Samples

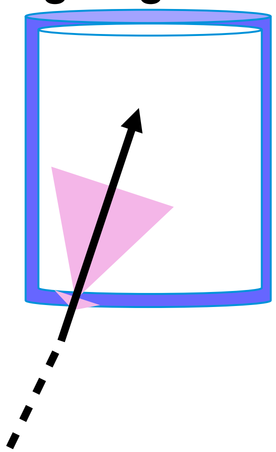
Fully Contained (FC)

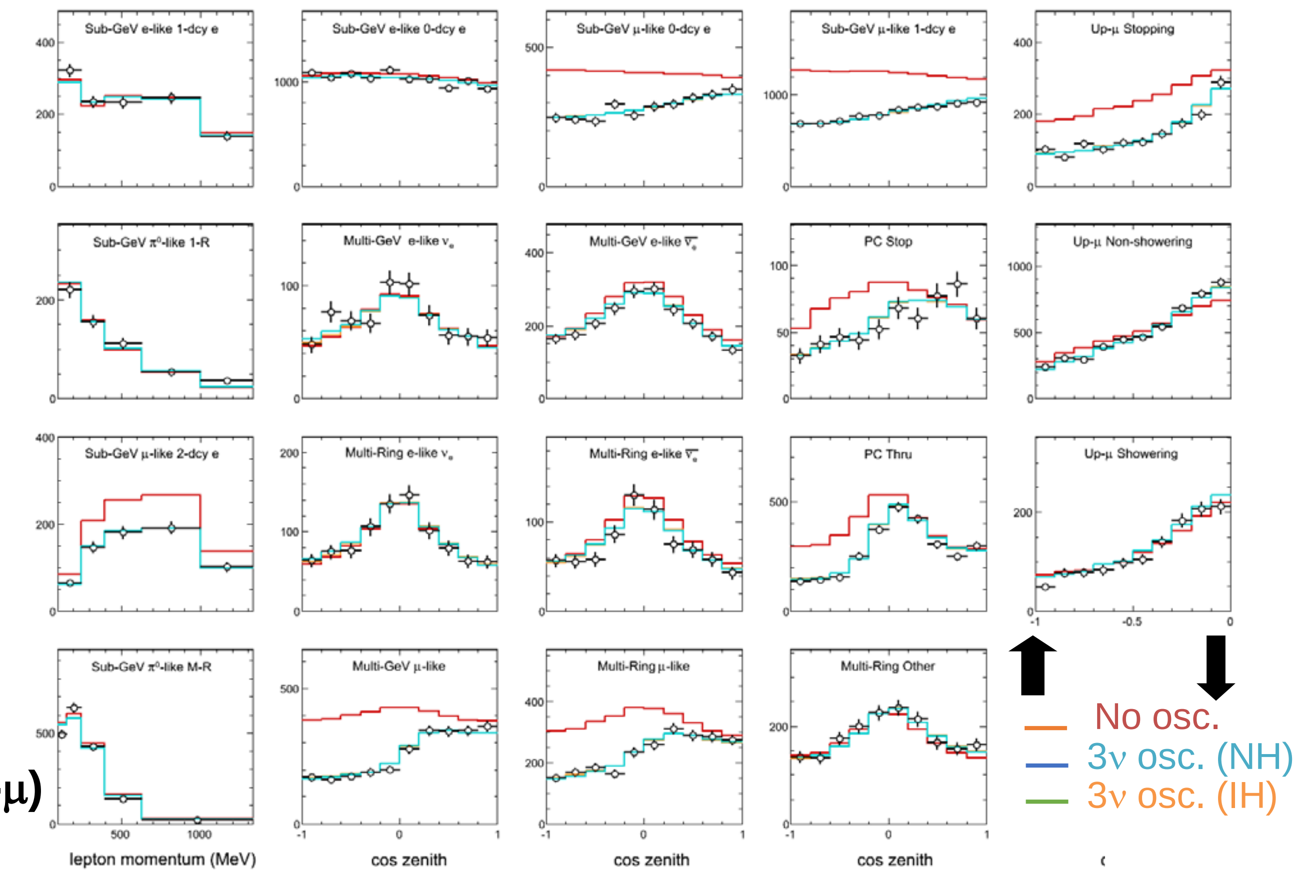


Partially Contained (PC)



Upward-going Muons (Up-μ)

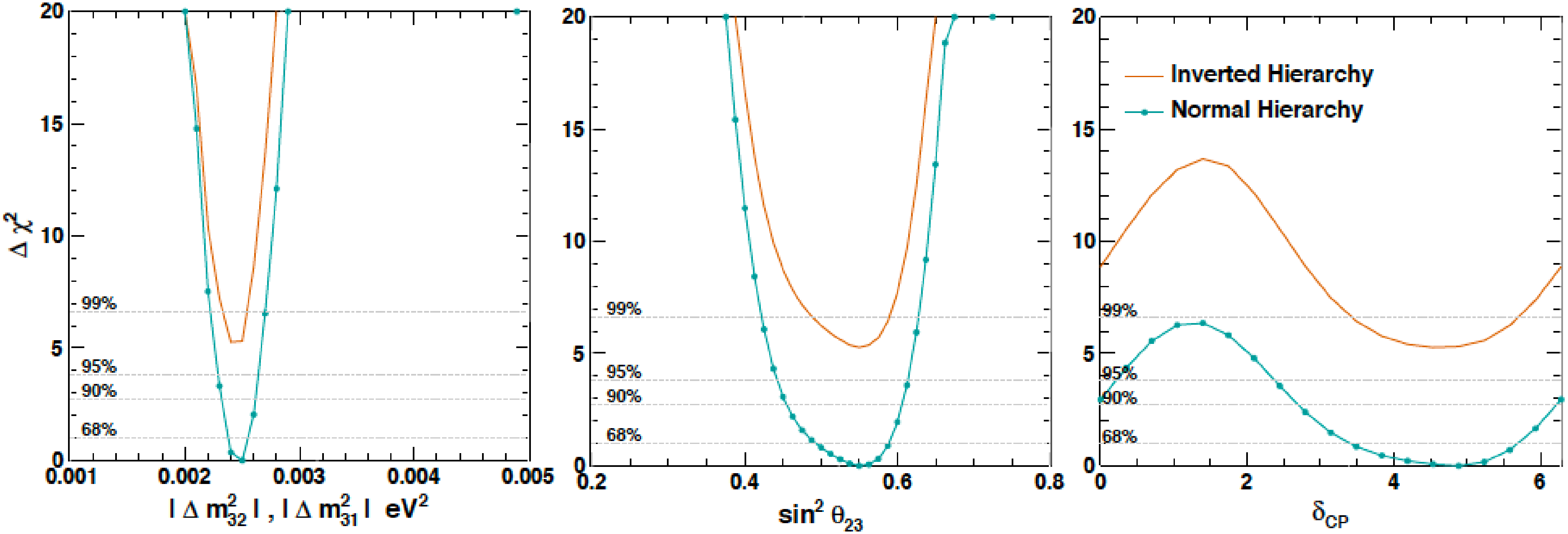




- **5,326 days** of atmospheric neutrino data (Through April 2016)
- **54,779 events** in total (43,476 FC, 3,367 PC, and 7,936 UP-μ)
- **19 analysis samples**: Sub-divided by event topology (FC/PC,UP-μ), energy range, e/μ–like, and # of rings. Multi-GeV e-like samples are divided into ν-like and $\overline{\nu}$–like samples in order to improve sensitivity for mass hierarchy.

SK Atmospheric Mixing + δ_{cp}: (with T2K constraint)

PHYSICAL REVIEW D **97,** 072001 (2018)



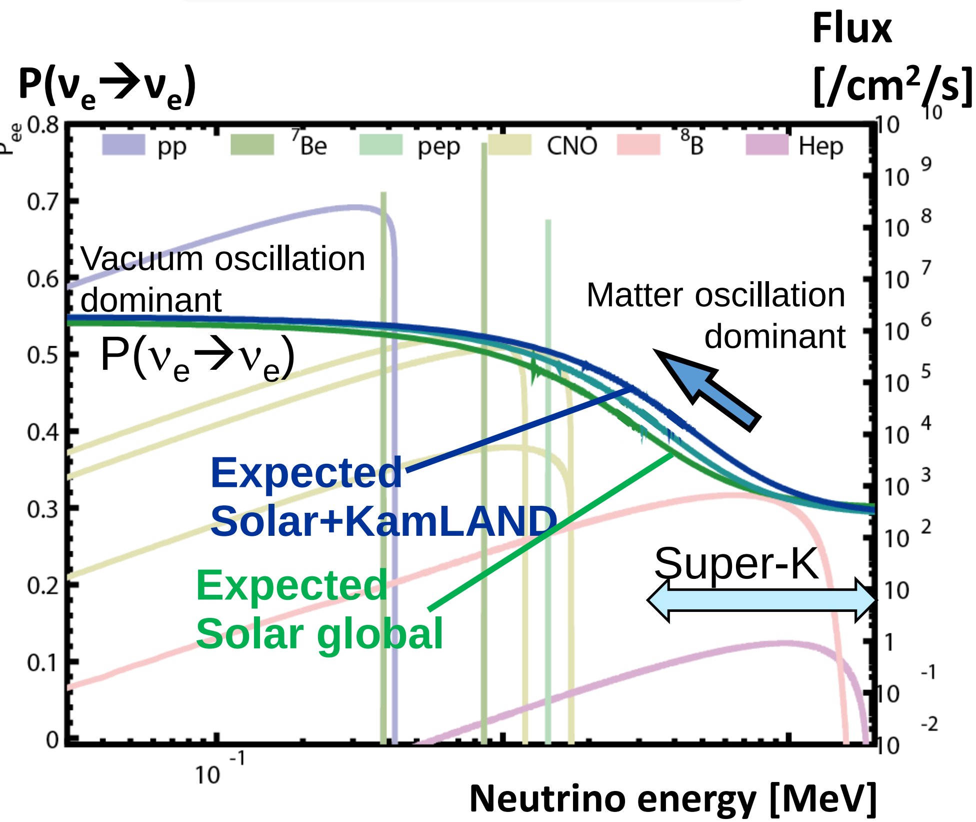
- Results of atmospheric neutrino data with a T2K constraint
  - Initial T2K data of 6.57×10^{20} POT (ν mode) is used.
    (cf. T2K has collected 3.16×10^{21} POT so far)
- *Normal hierarchy*(NH) is favored over *Inverted Hierarchy*(IH) :
  - $\Delta\chi^2$ (NH – IH) = -5.27 (SK only: -4.33)
  - IH is rejected by between 91.9% and 94.5%.
- Preference for δ_{cp} ~$3/2\pi$

Solar neutrinos

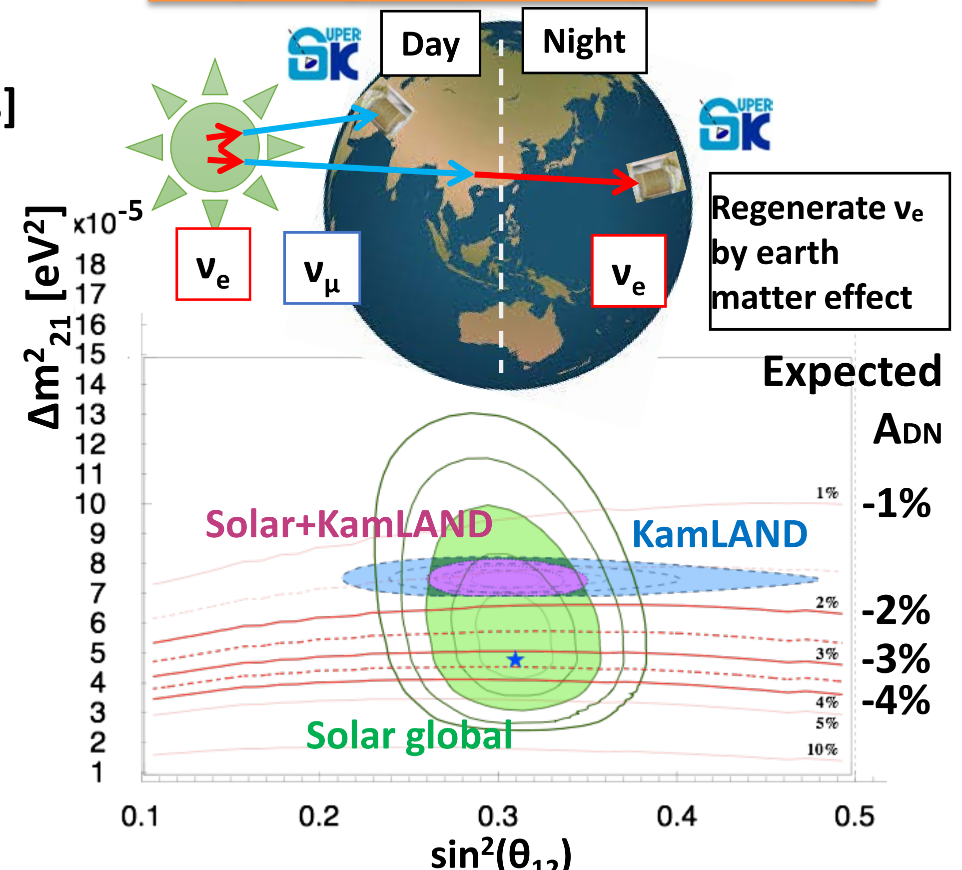
- High statistics measurement of ^{8}B solar neutrinos
  - Possible time variation of the flux
  - **Energy spectrum distortion** due to solar matter effect
  - **Day-night flux asymmetry** due to earth matter effect

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

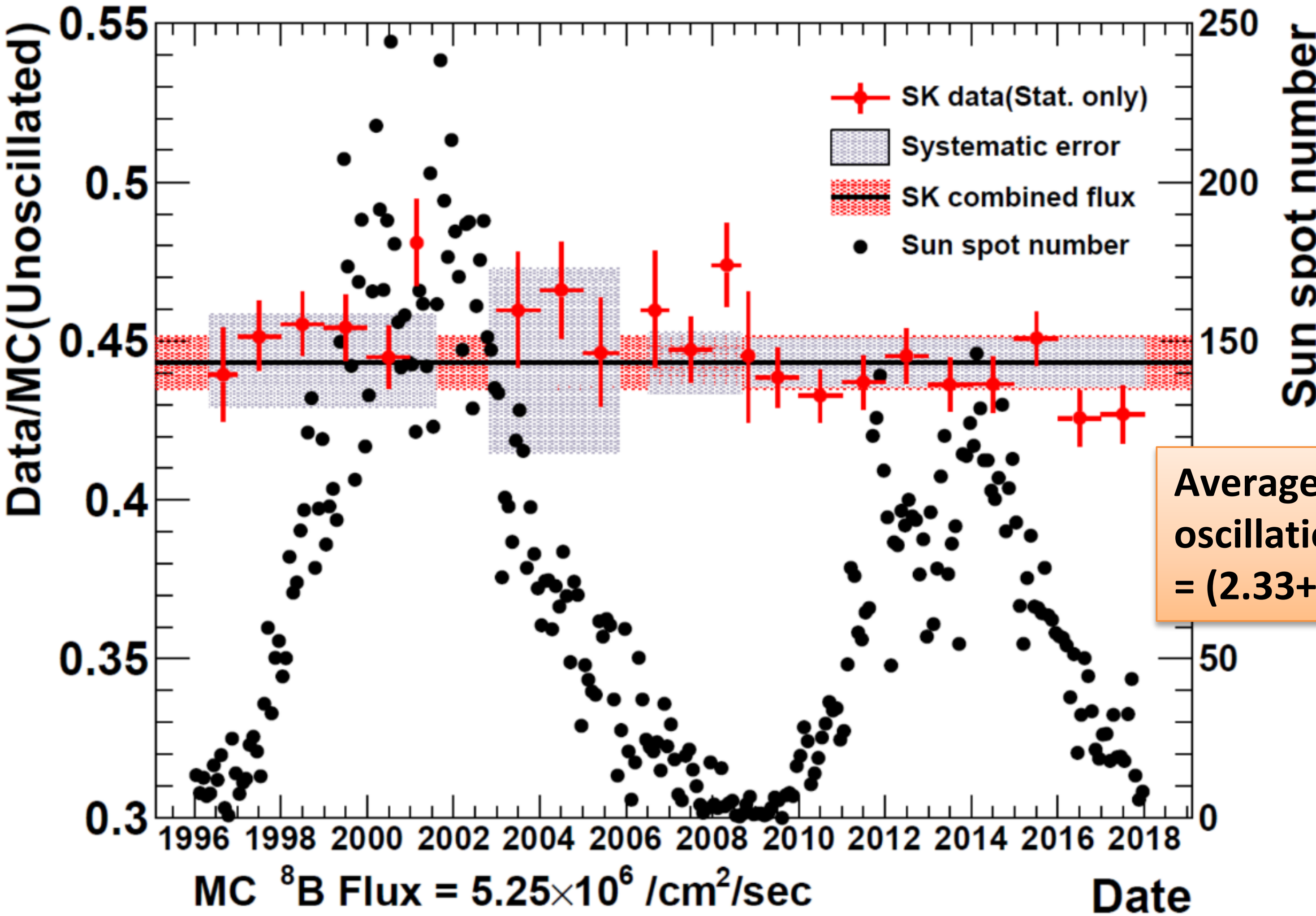
Spectrum distortion



Day-Night flux asymmetry



^{8}B solar neutrino flux: Yearly plot



Preliminary

SK 5695 days

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

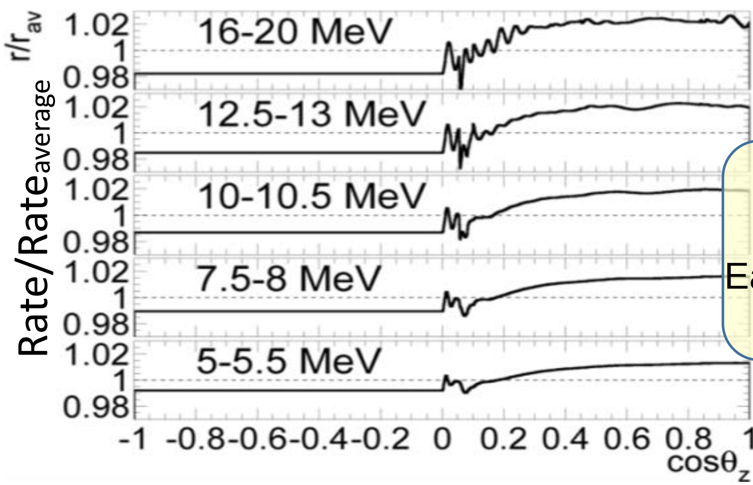
χ^2 = 21.57 / 21 d.o.f. → Confidence level = 41.4 %

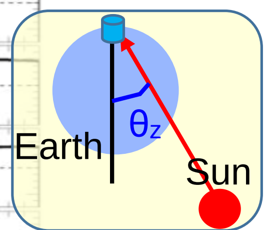
Super-K solar rate measurements are consistent with a constant solar neutrino flux emitted by the Sun.

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

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

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



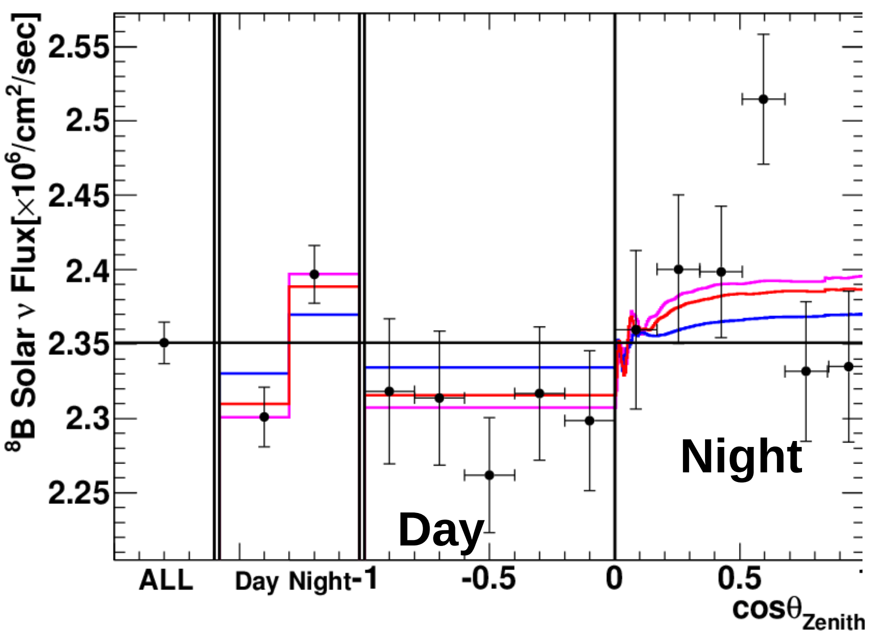


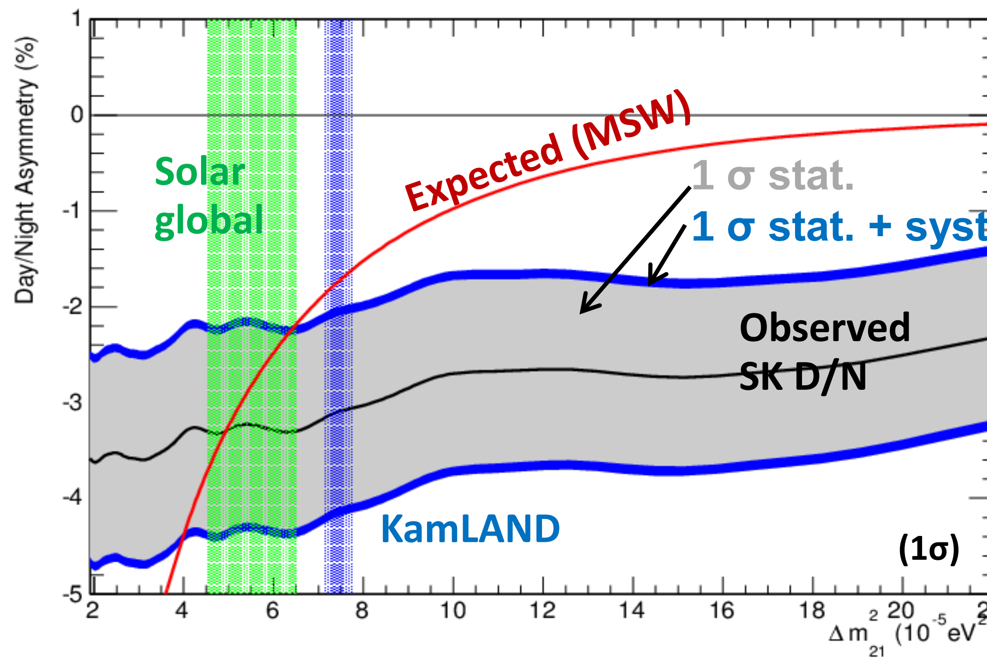
For solar global parameter:
Δm^2_{21}=4.84x10^{-5} eV^2
$\sin^2\theta_{12}$=0.311

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

	A_{DN}^{fit} (%)
SK-IV, 1664 days	-3.6+/-1.6+/-0.6
SK-I~IV, 4499 days	-3.3+/-1.0+/-0.5
Non-zero significance	3.0 σ

PRD94, 052010 (2016)





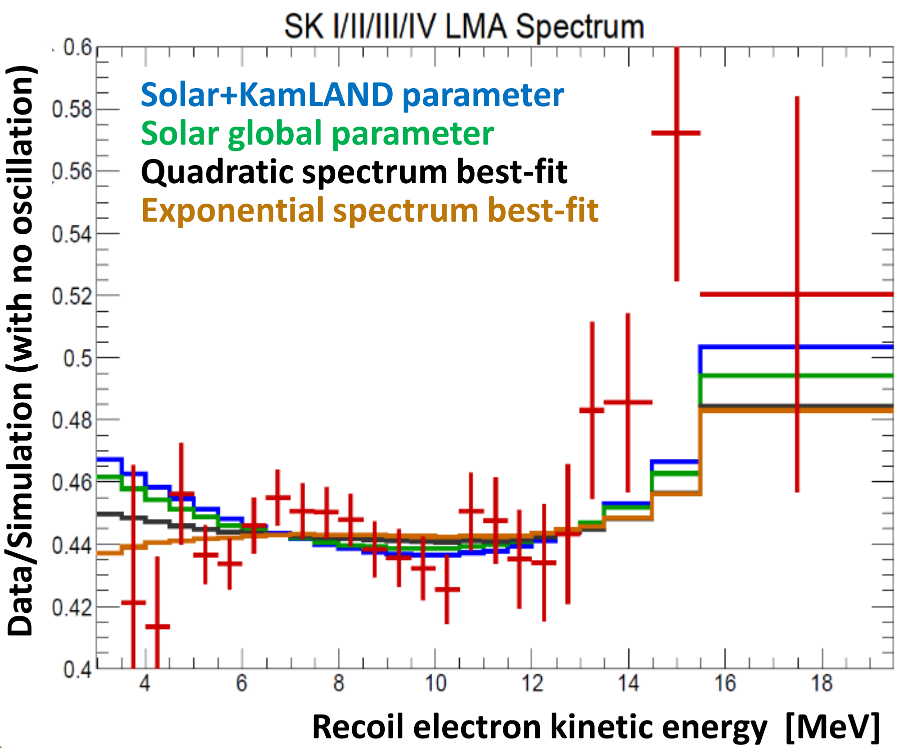
Solar ν oscillation results

- 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.

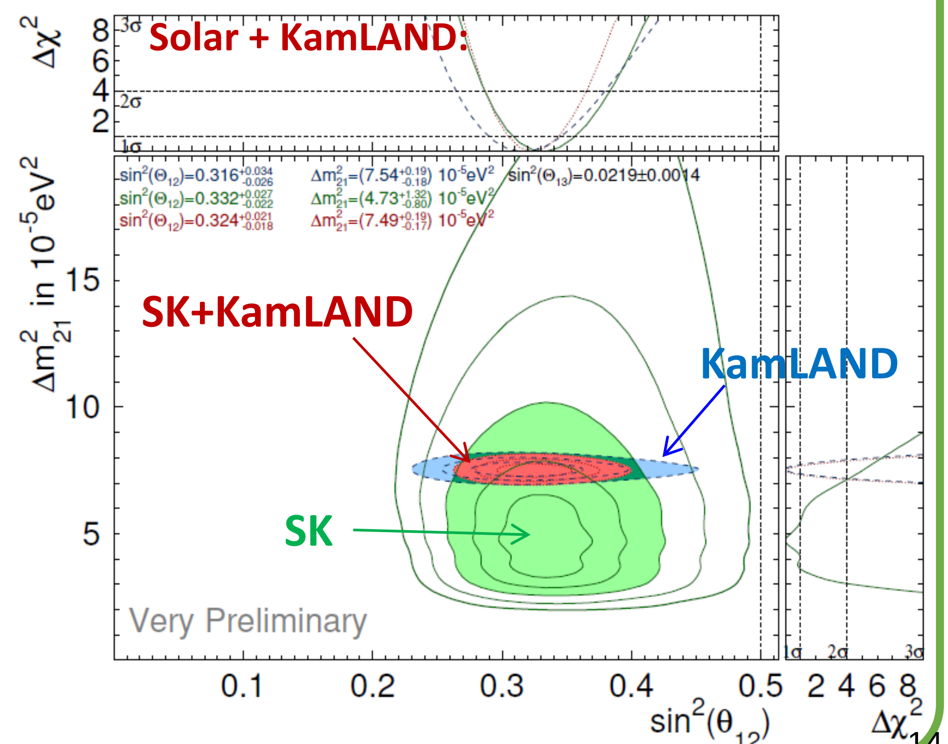
Preliminary

SK 5695 days

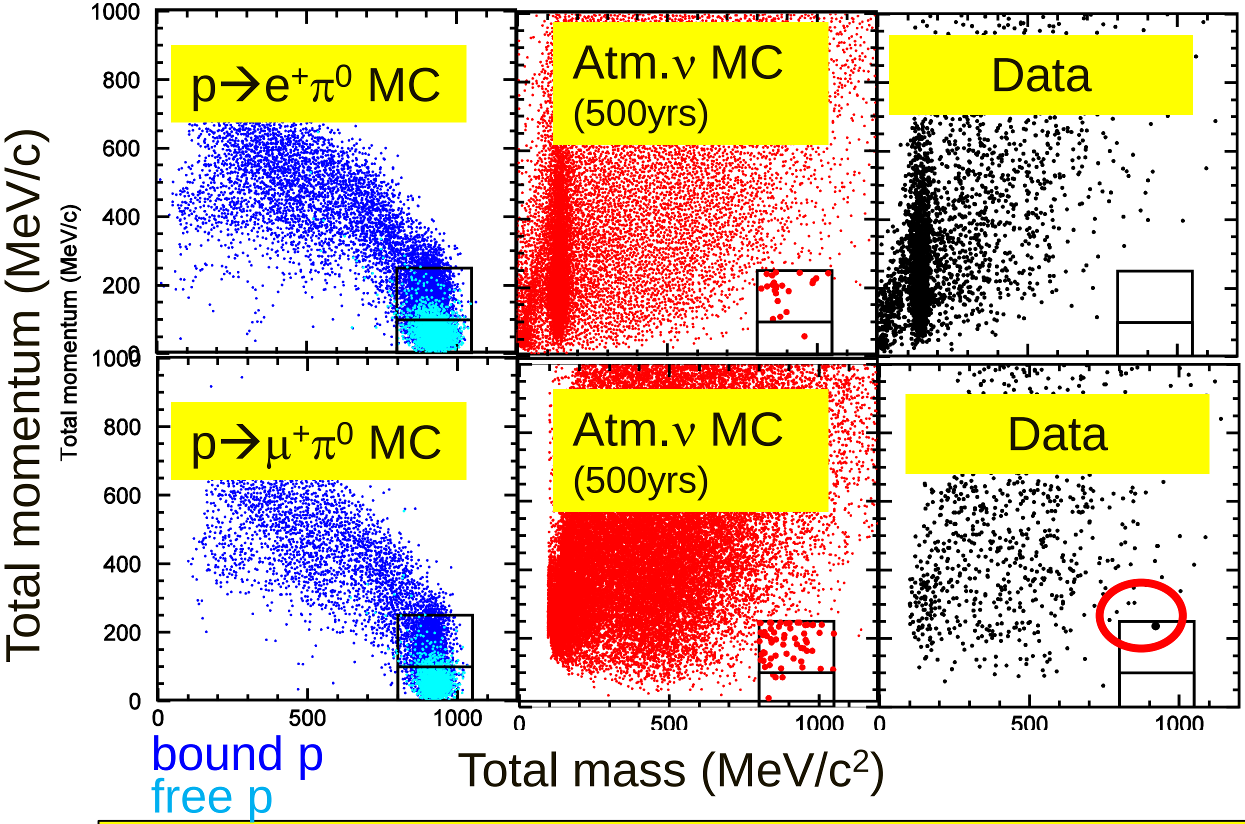
Solar ν energy spectrum



Solar ν oscillation parameters



Search for p→$e^+\pi^0$ and p→$\mu^+\pi^0$



p→$e^+\pi^0$

	Eff. (%)	BKG	OBS
Low P_{tot}	18.7	0.05	0
High P_{tot}	19.9	0.58	0
Total	38.6	0.63	0

p→$\mu^+\pi^0$

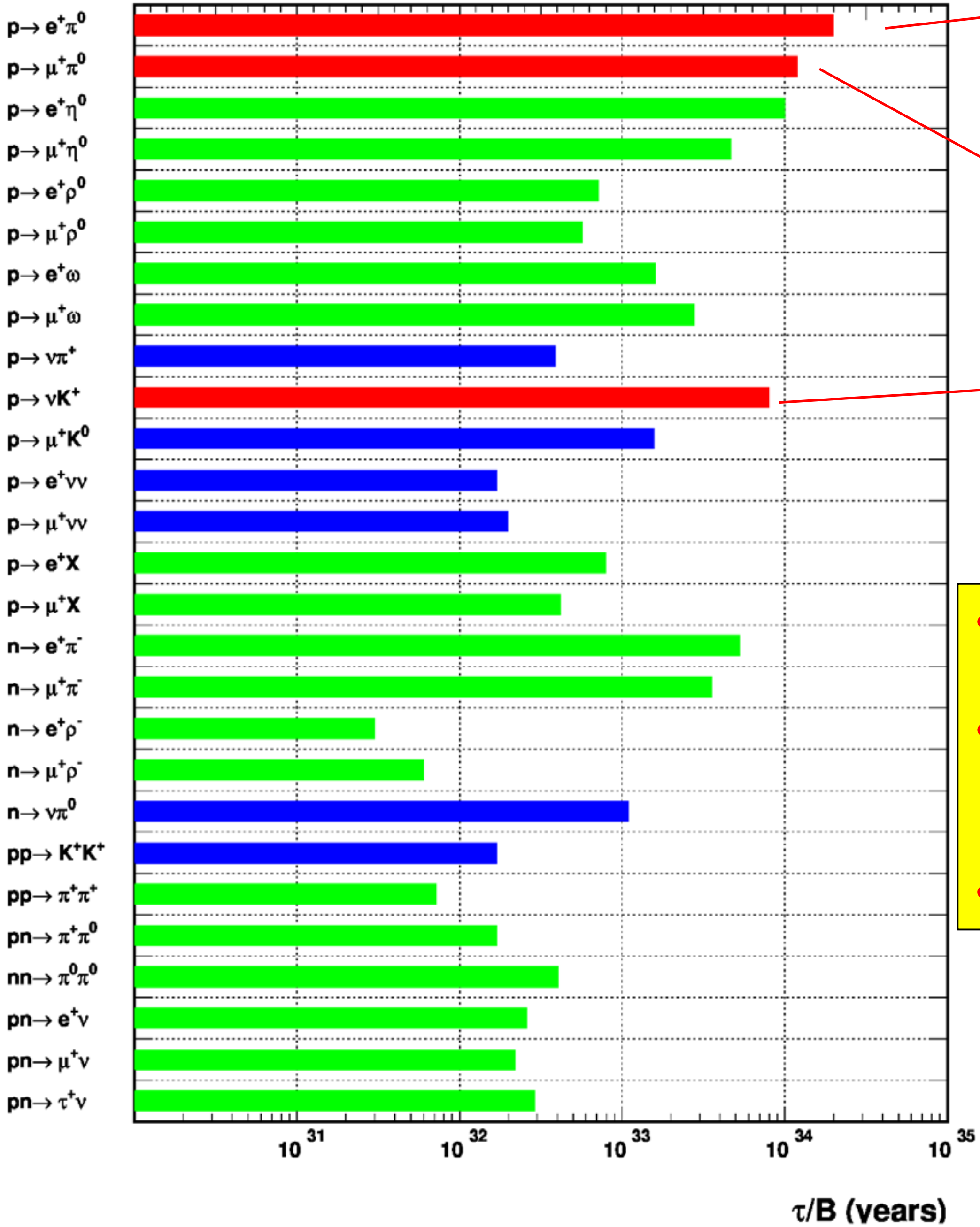
	Eff.(%)	BKG	OBS
Low P_{tot}	18.0	0.07	0
High P_{tot}	16.7	0.65	1
Total	34.7	0.72	1

Lifetime limit (90% CL,365kton･yrs data)

p→$e^+\pi^0$: > 2.0×10^{34} years

p→$\mu^+\pi^0$: > 1.2×10^{34} years

Nucleon decay limits for various decay modes



$p \to e^+\pi^0$
$\tau/Br > 2.0 \times 10^{34}$ years

$p \to \mu^+\pi^0$
$\tau/Br > 1.2 \times 10^{34}$ years

$p \to \bar{\nu}K^+$
$\tau/Br > 8.2 \times 10^{33}$ years

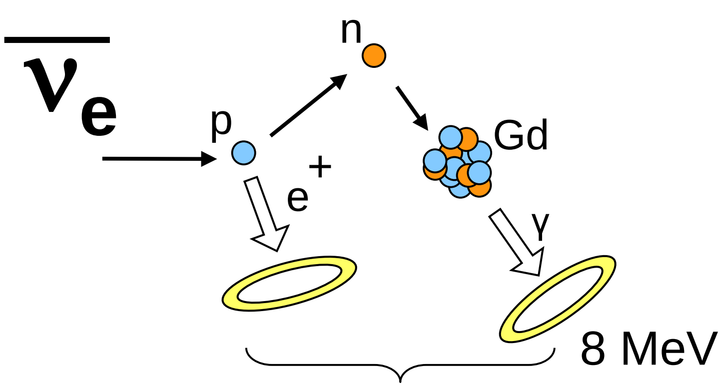
- Reached around 10^{34} years for favored decay modes.
- Searched systematically also for the other modes and reached 10^{32} - 10^{34} years.
- Most stringent limits in the world.

Red: analyzed with 365kt·yrs data
Green: analyzed with 350kt·yrs data
Blue: analyzed with SK I-III (173kt·yrs)

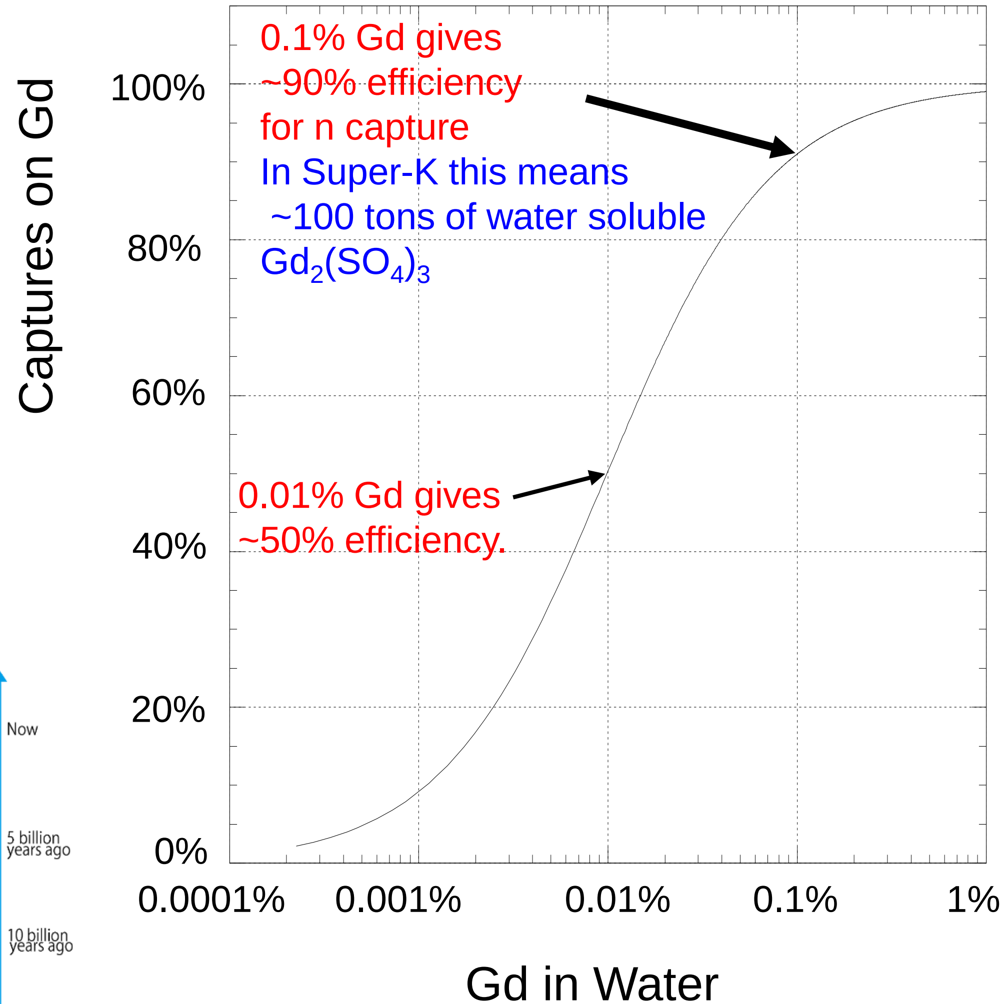
Gadolinium project at Super-K: SK-Gd

Identify $\bar{\nu}_e p$ events by neutron tagging with Gadolinium.

Gadolinium has large neutron capture cross section and emit 8MeV gamma cascade.

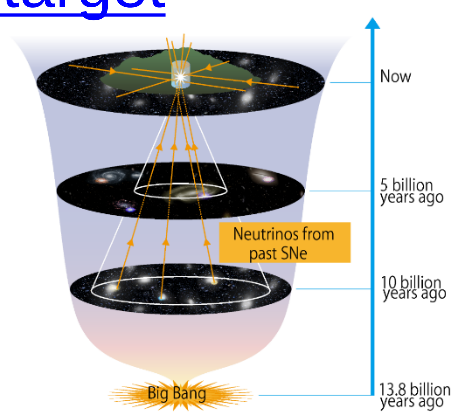


ΔT~30μs
Vertices within 50cm



Main physics target

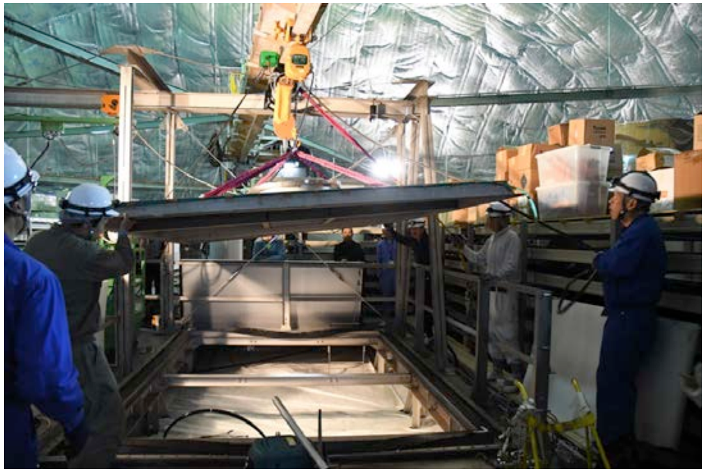
Observation of Supernova Relic Neutrinos.

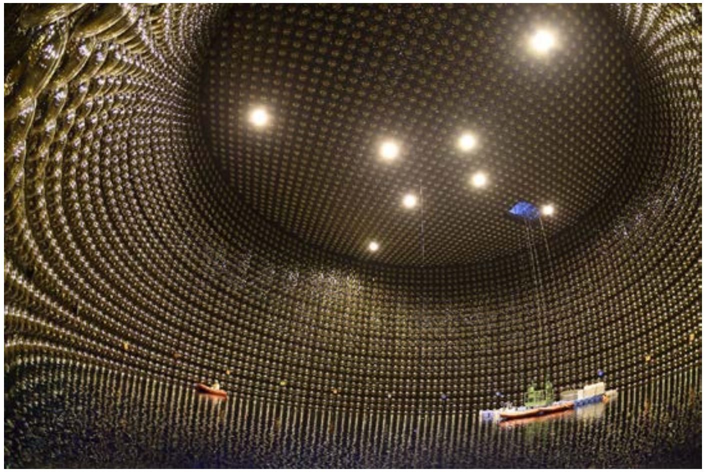


SK detector refurbishment in 2018

We started to refurbish the detector on May 31st, 2018.

The refurbishment was completed by January 2019.





Purpose of the refurbishiment

- **Fix water leak from the tank**

  About 1 ton per day of pure water leaked from the SK detector until 2018. We have sealed all welding joints of the stainless steel panels that make up the tank.

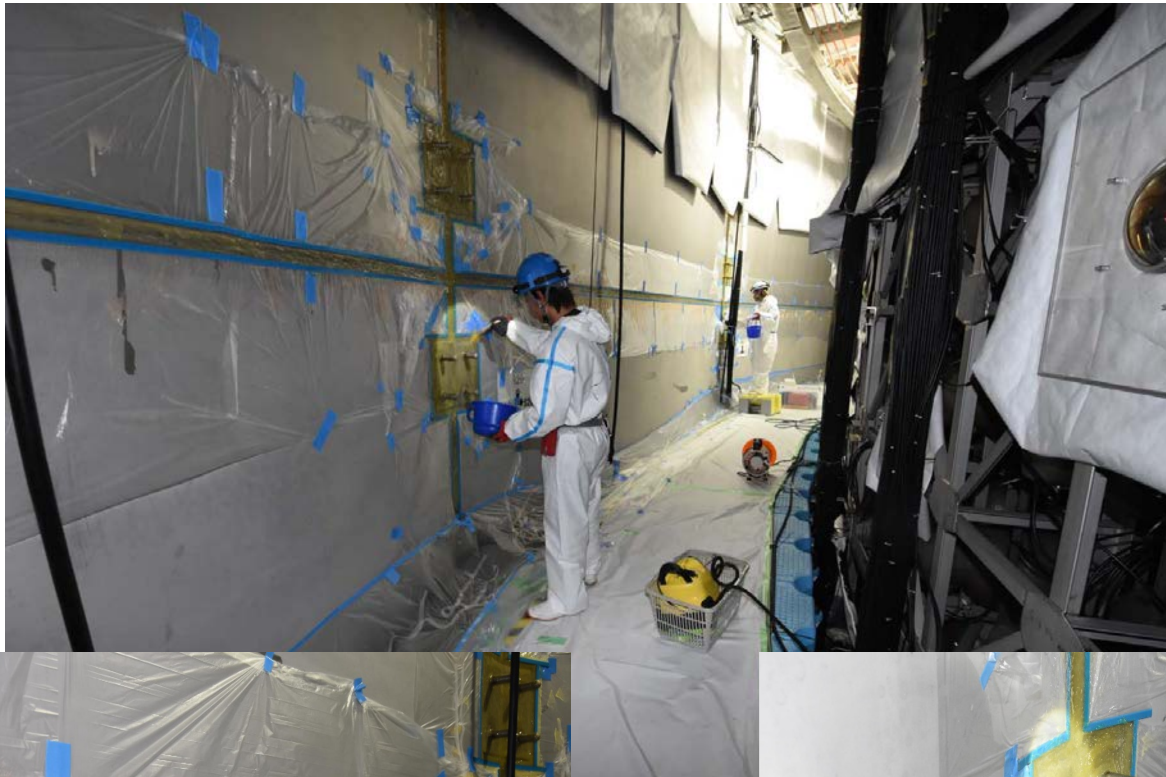
- **Improvement of tank piping**

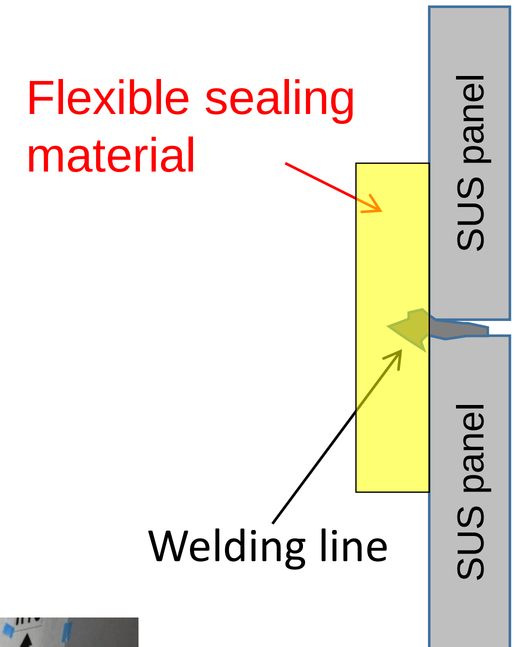
  Ultra-pure water in the tank was circulated at a flow rate of 60 tons per hour before. We improved the water piping and water systems so that they can process and circulate water at 120 tons per hour. (17days per one circulation).

- **Replacement of faulty photomultiplier tubes**

  Since the last in-tank SK maintenance during 2005-2006, some photomultipliers became faulty. We have replaced 136 ID and 217 OD PMTs.

Sealed all welding joints of the stainless steel panels



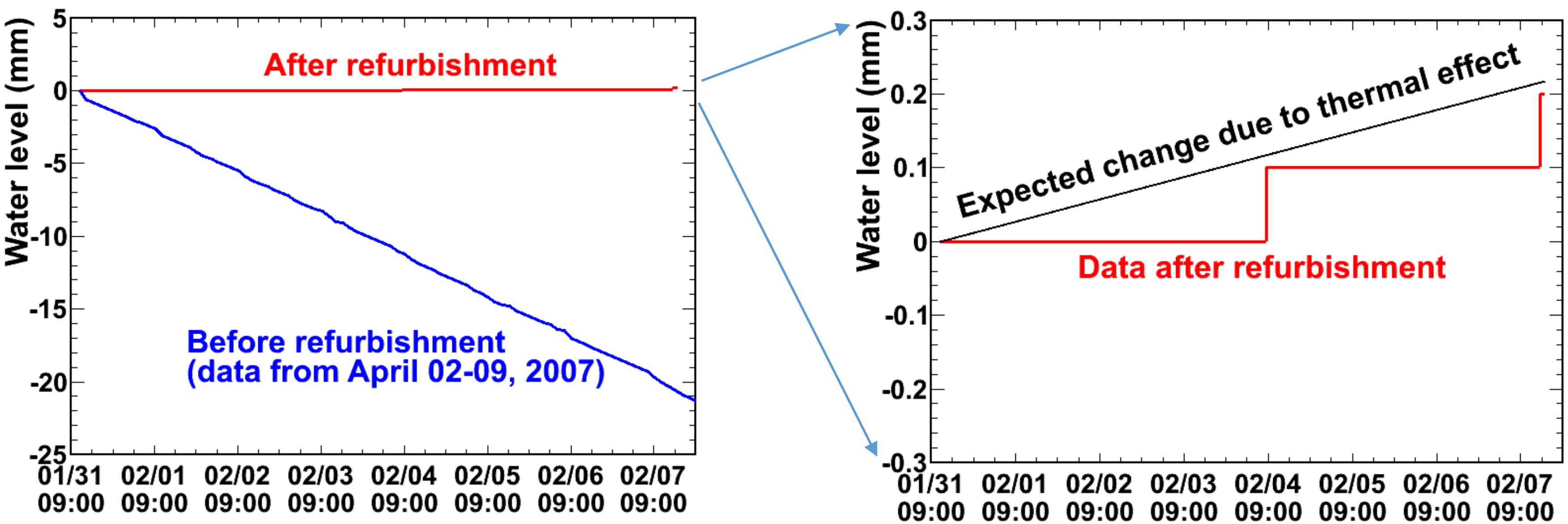


Developed the sealing material with a company

- Low emanation to pure and Gd-loaded water, i.e. keep good water transparency
- Low radon emanation, i.e. keep radio-purity of the tank water

Water Leakage check after refurbishment

After filling the tank completely with water, we started the water leakage measurement from 11:30 on 31st January to 15:52 on 7th February, 2019. (7 days 4 hours 22 minutes in total)

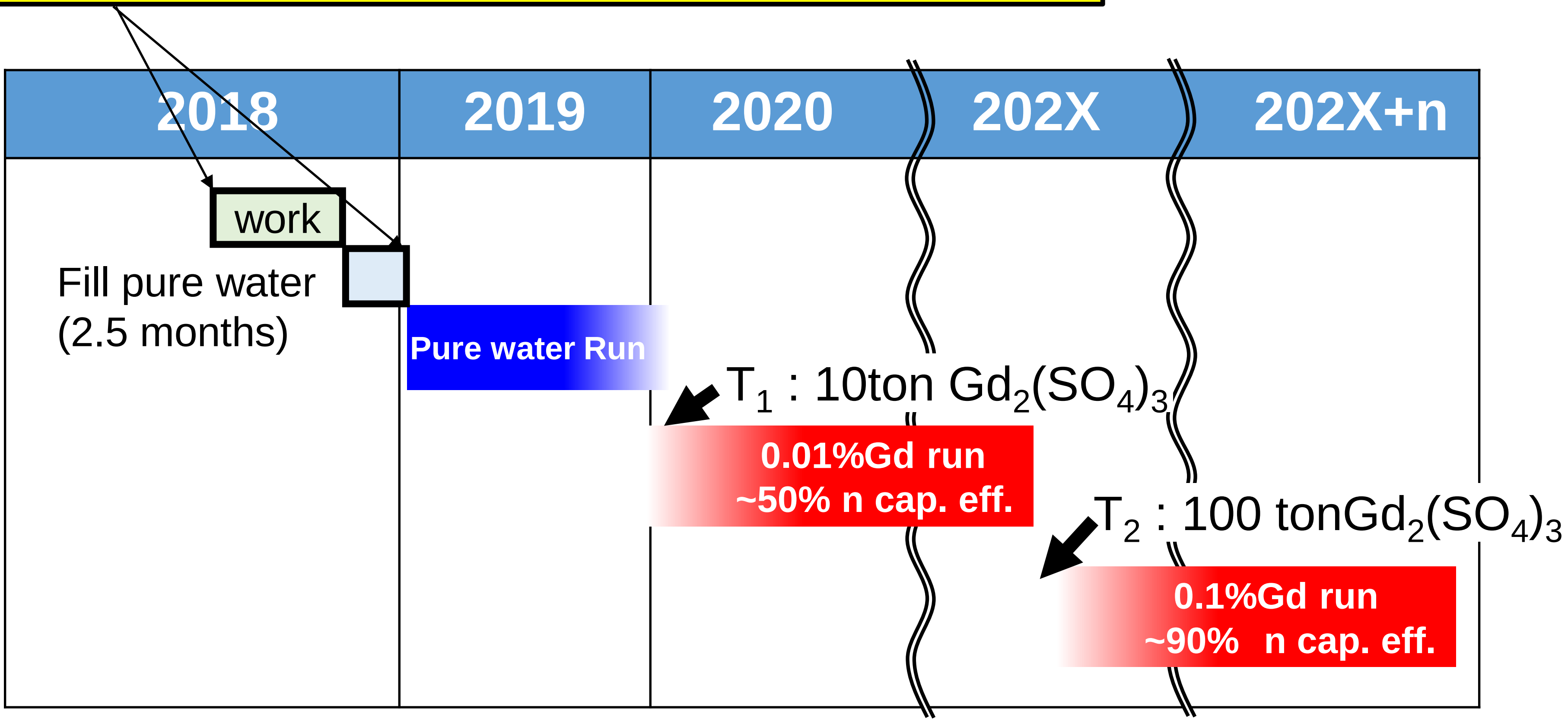


<u>Conclusion</u>

- Currently we do not observe any water leakage from the SK tank within the accuracy of our measurement, which is less than 0.017 tons per day.
- This is less than 1/200th of the leak rate observed before the 2018/2019 tank refurbishment.

Schedule of SK-Gd

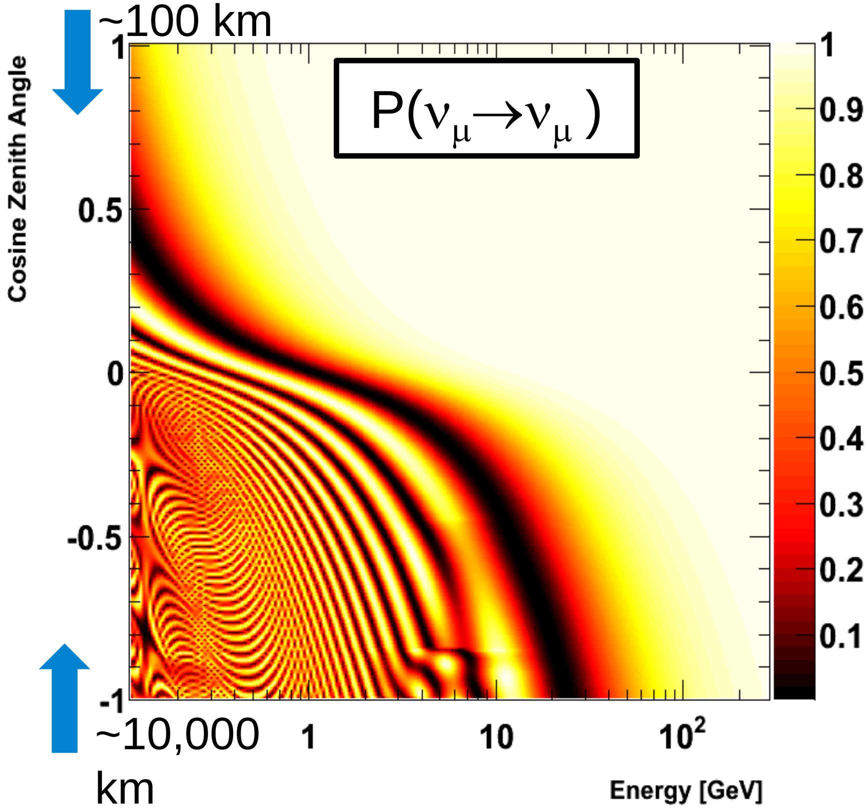
Refurbishment: Water filling was completed in January 2019.

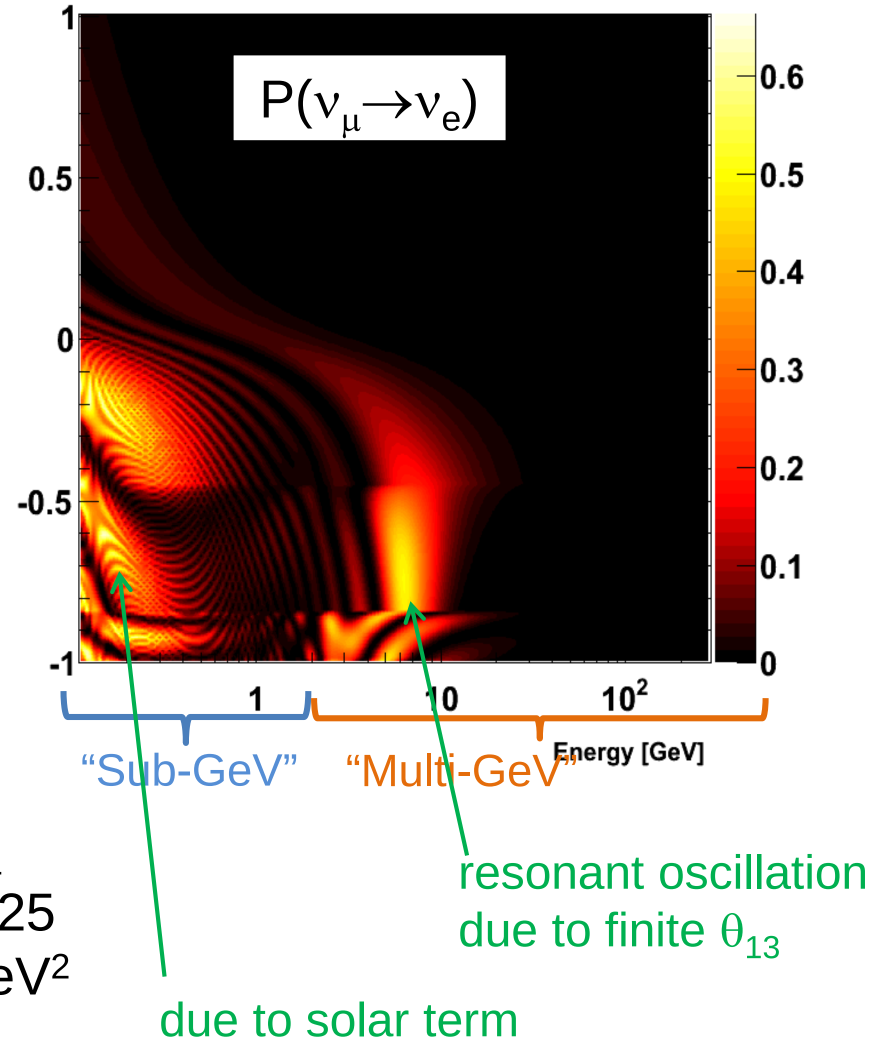


Plan to start 0.01% Gd run in early 2020.
(Adjusting schedule with T2K)

Backup

Oscillation probability maps





<u>Oscillation parameters used here are</u>

$\sin^2\theta_{12}$=0.31, $\sin^2\theta_{23}$=0.5, $\sin^2\theta_{13}$=0.025

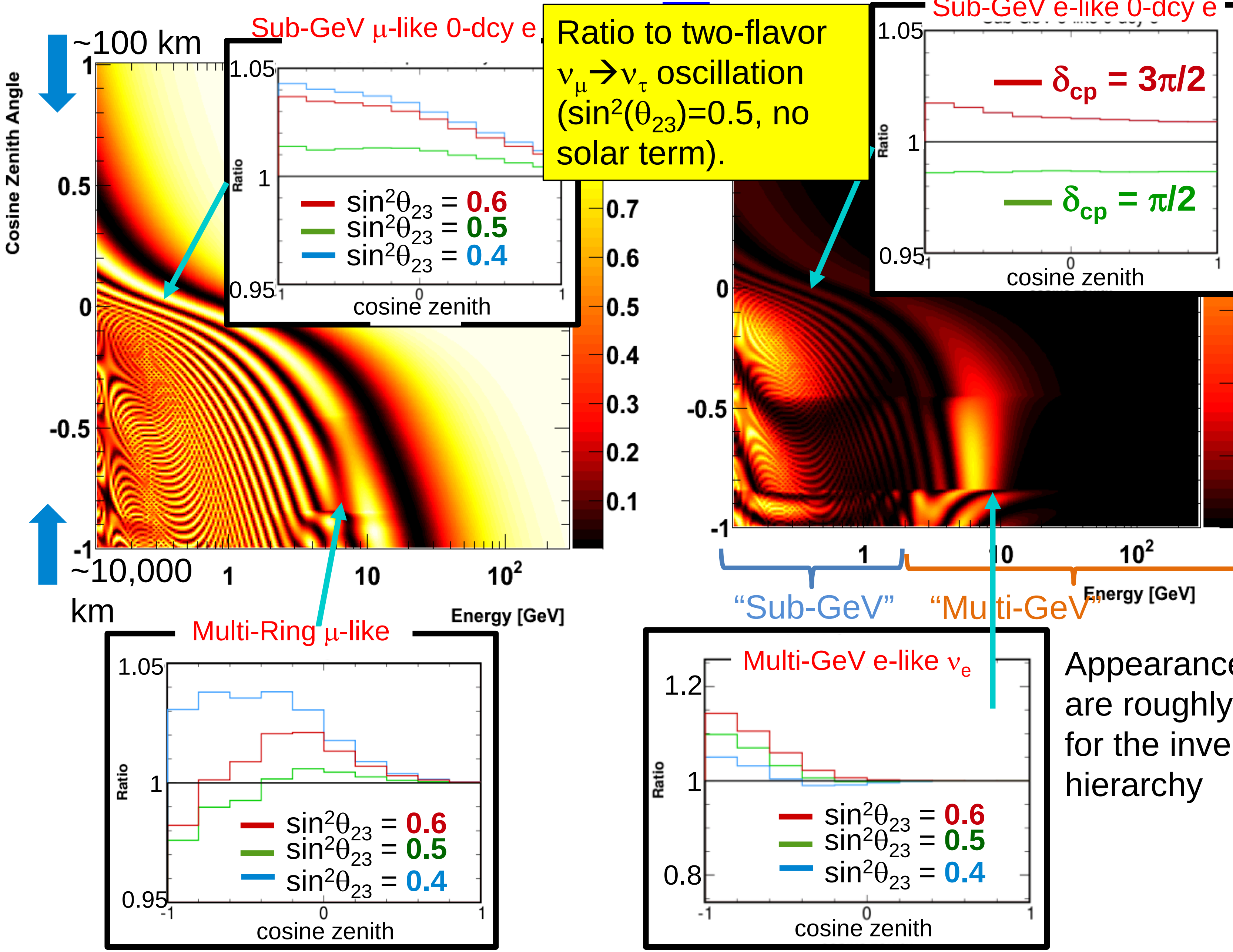
Δm^2_{12}=7.6x10^{-5} eV^2, Δm^2_{23}=2.5x10^{-3} eV^2

Normal Hierarchy (NH)

δCP=0.0

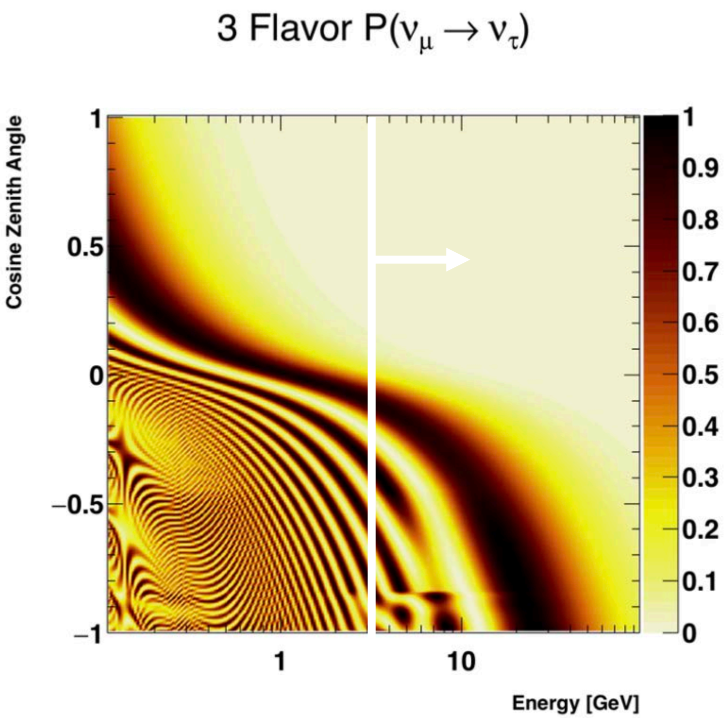
Effects of θ_{23} and δCP

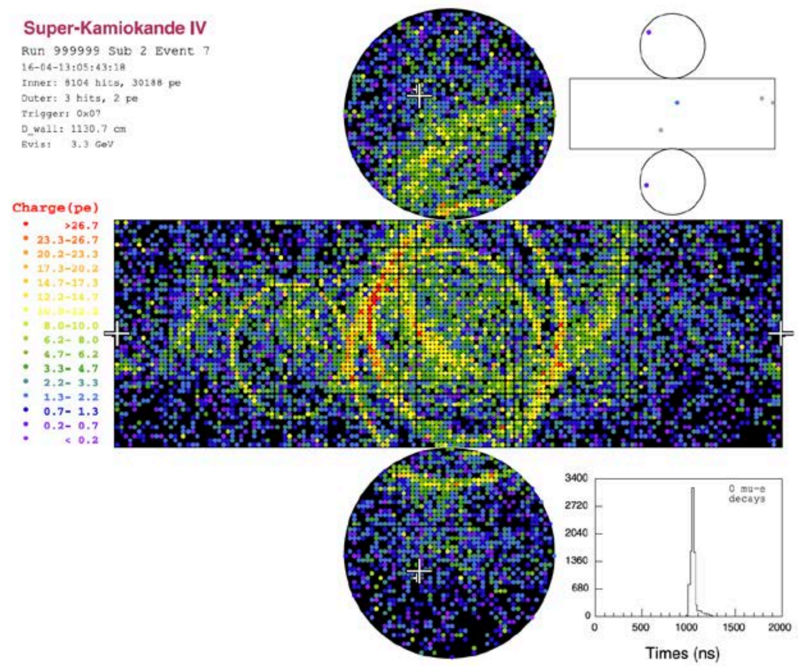
Ratio to two-flavor $\nu_\mu \rightarrow \nu_\tau$ oscillation ($\sin^2(\theta_{23})$=0.5, no solar term).



Appearance effects are roughly halved for the inverted hierarchy

Search for Tau Neutrinos at SK

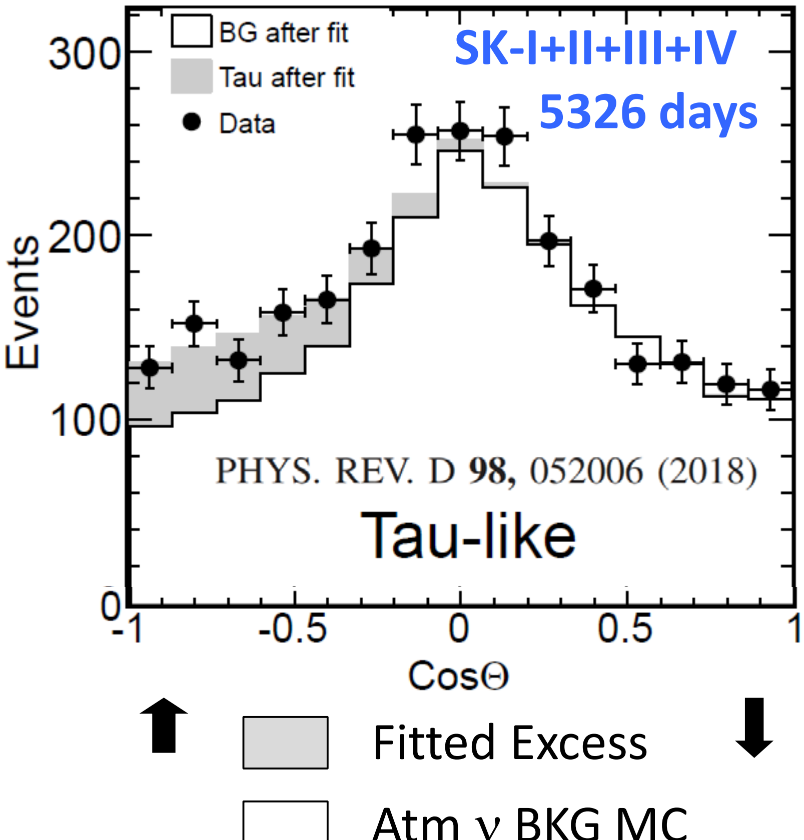




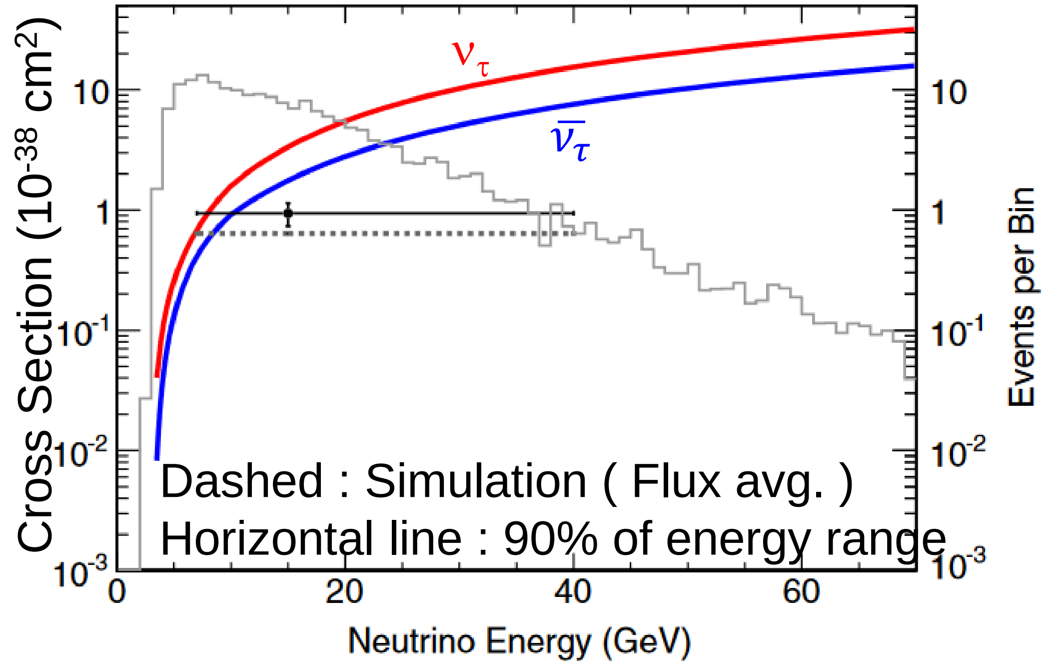
- Tau neutrinos are not in atmospheric flux below 10^5 GeV but can be induced by oscillations
  - Important for ν_τ cross section studies, tests of unitarity, background to mass hierarchy search, etc.
- Complicated event topologies due to hadronic tau decay, search using neural network-based method

Search for Tau Neutrinos at SK

Zenith angle distribution



Extracted CC ν_τ cross-section using atmospheric ν_τ sample



# of tau events

338.1 ± 72.7 (stat.+ sys.) events

Reject no-tau-appearance @ 4.6σ.

(Exp. significance is 3.3σ)

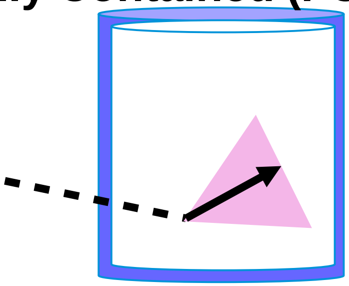
Average cross-section between 3.5 and 70 GeV

$$\sigma_{measured} = (1.47 \pm 0.32) \times \langle \sigma_{theory} \rangle$$

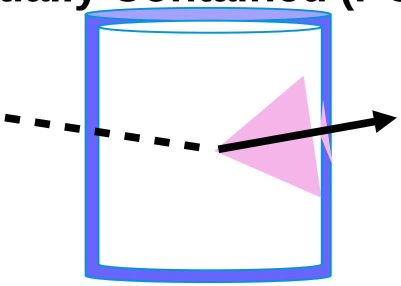
$$(0.94 \pm 0.20) \times 10^{-38}\ \text{cm}^2$$

Super-K Atmospheric ν Analysis Samples

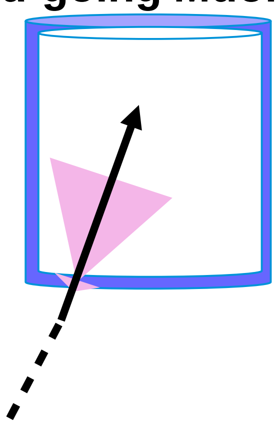
Fully Contained (FC)

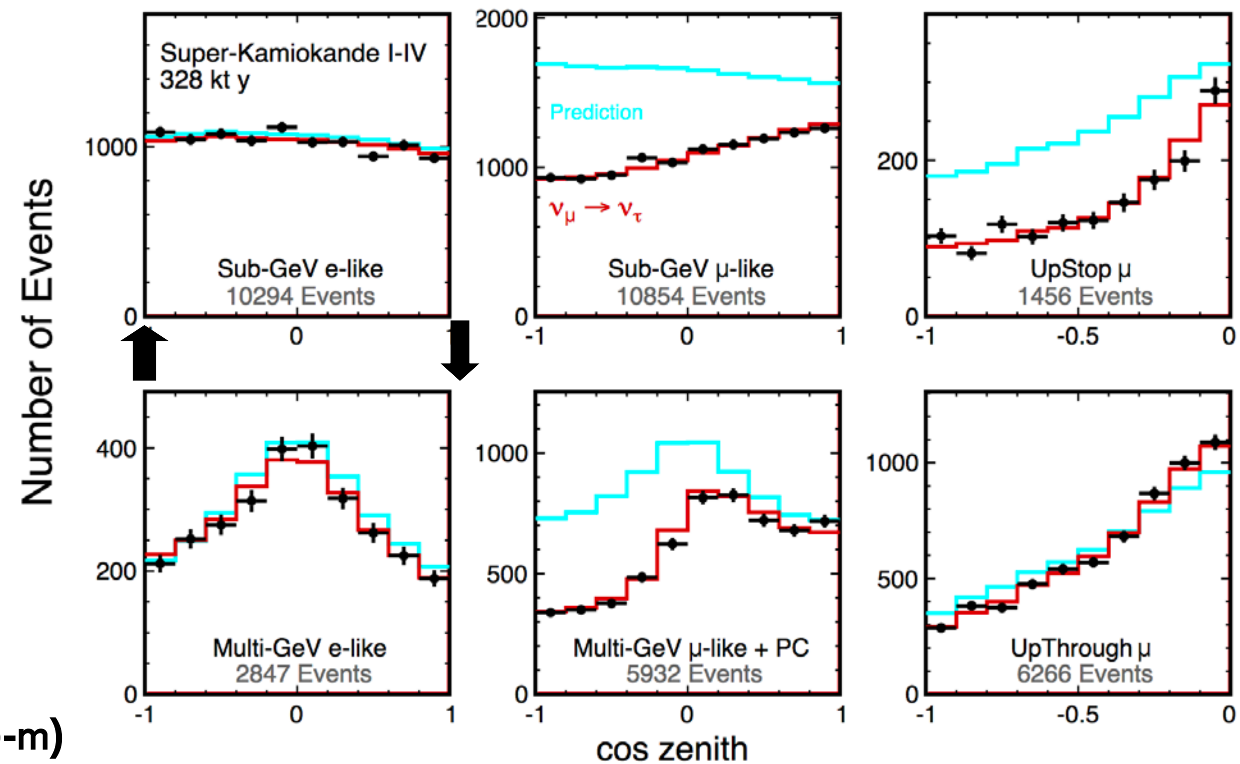


Partially Contained (PC)



Upward-going Muons (Up-m)





- In total **19** analysis samples: multi-GeV e-like samples are divided into ν-like and ν-bar-like subsamples (p, cos θ) binning
- 5,300 days (328 kton-yr) data set
- Dominated by $\nu_\mu \rightarrow \nu_\tau$ oscillations
- Interested in subdominant contributions to this picture
  - Ie three-flavor effects, Sterile Neutrinos, LIV, etc.

Test for Evidence of Matter Effects

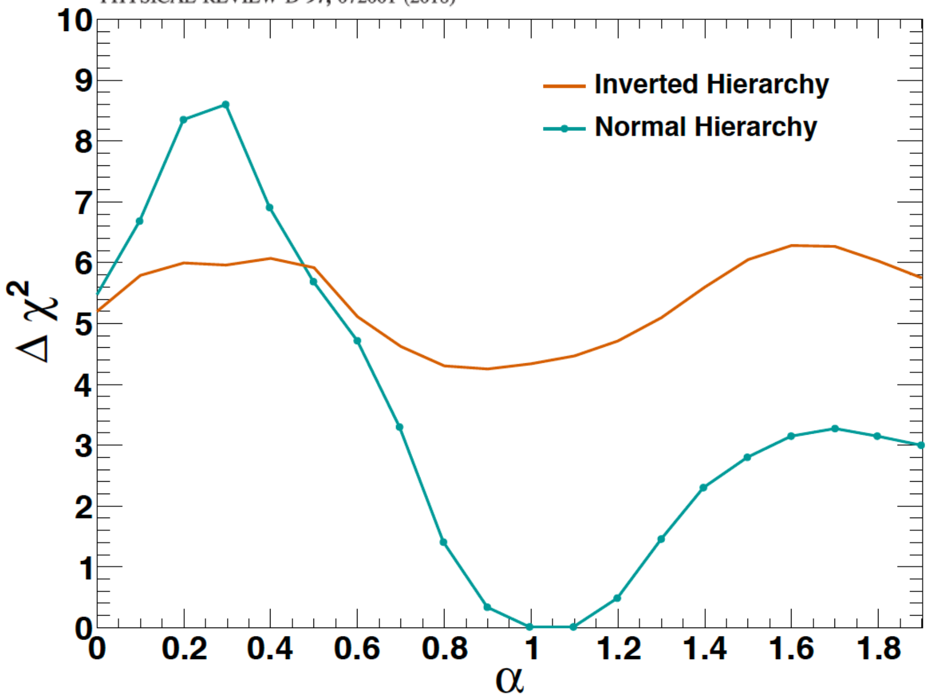
$$H_{\mathrm{matter}} = \begin{pmatrix} \frac{m_1^2}{2E} & 0 & 0 \\ 0 & \frac{m_2^2}{2E} & 0 \\ 0 & 0 & \frac{m_3^2}{2E} \end{pmatrix} + U^\dagger \begin{pmatrix} a & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} U$$

$$a = \pm\sqrt{2}\, G_F\, N_e$$

$$\downarrow$$

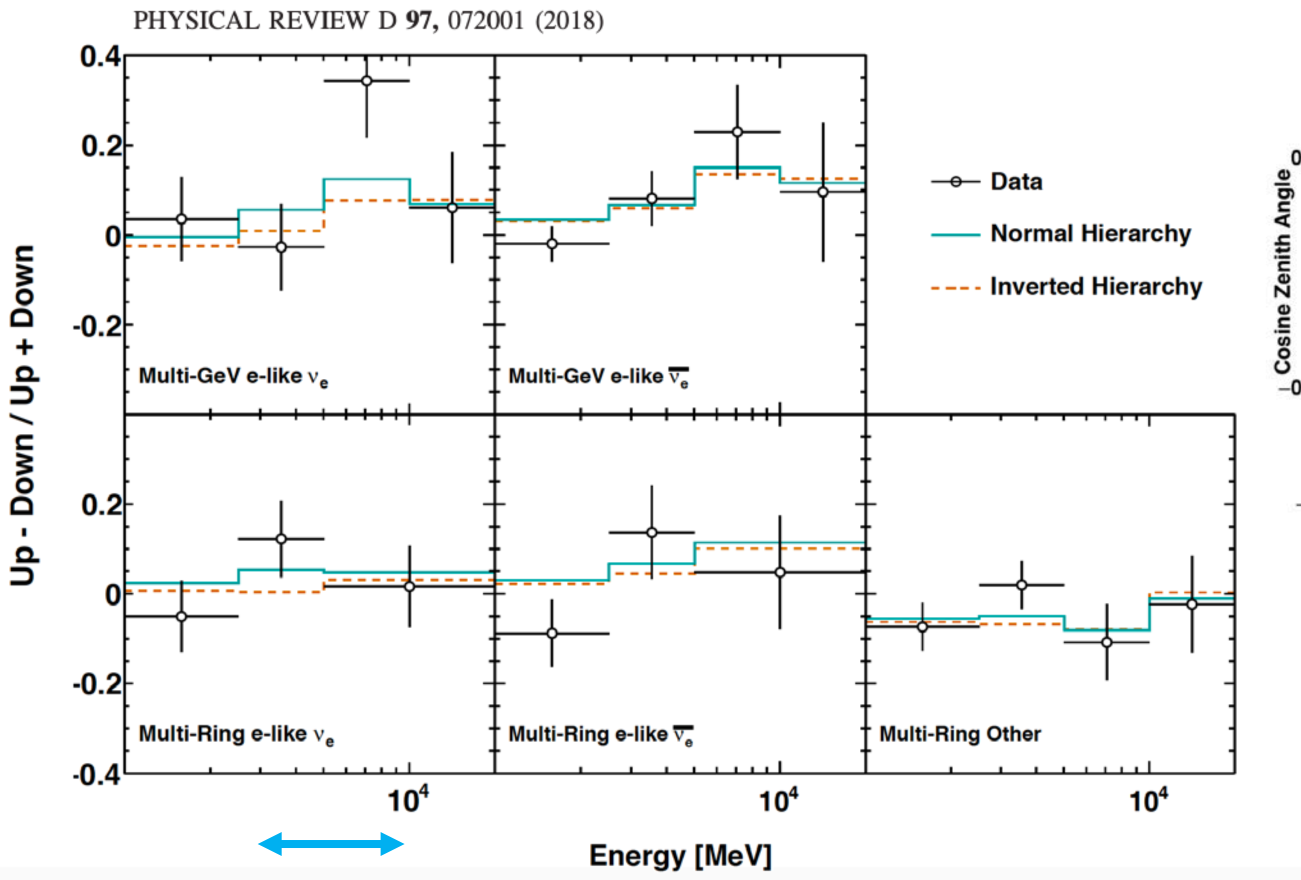
$$a = \pm\, \alpha \sqrt{2}\, G_F\, N_e$$

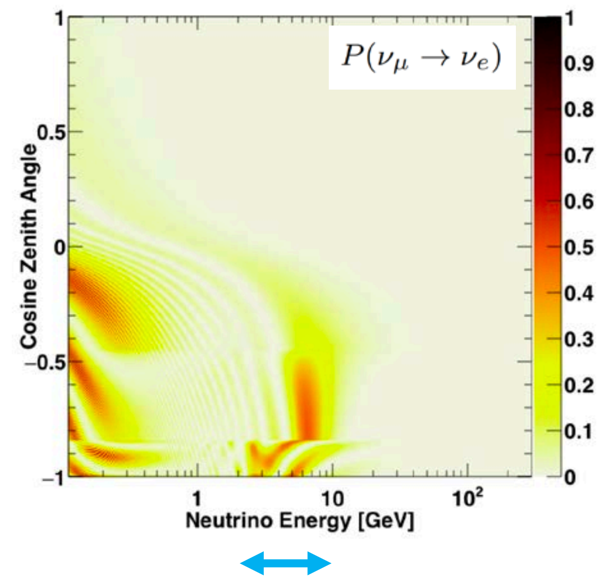
PHYSICAL REVIEW D 97, 072001 (2018)



- Best fit consistent with standard matter density and normal hierarchy ($\alpha = 1$)
- Vacuum oscillations ($\alpha = 0$) rejected at 1.6 σ

Atmospheric Mixing + δ_{cp}: Super-K (only)

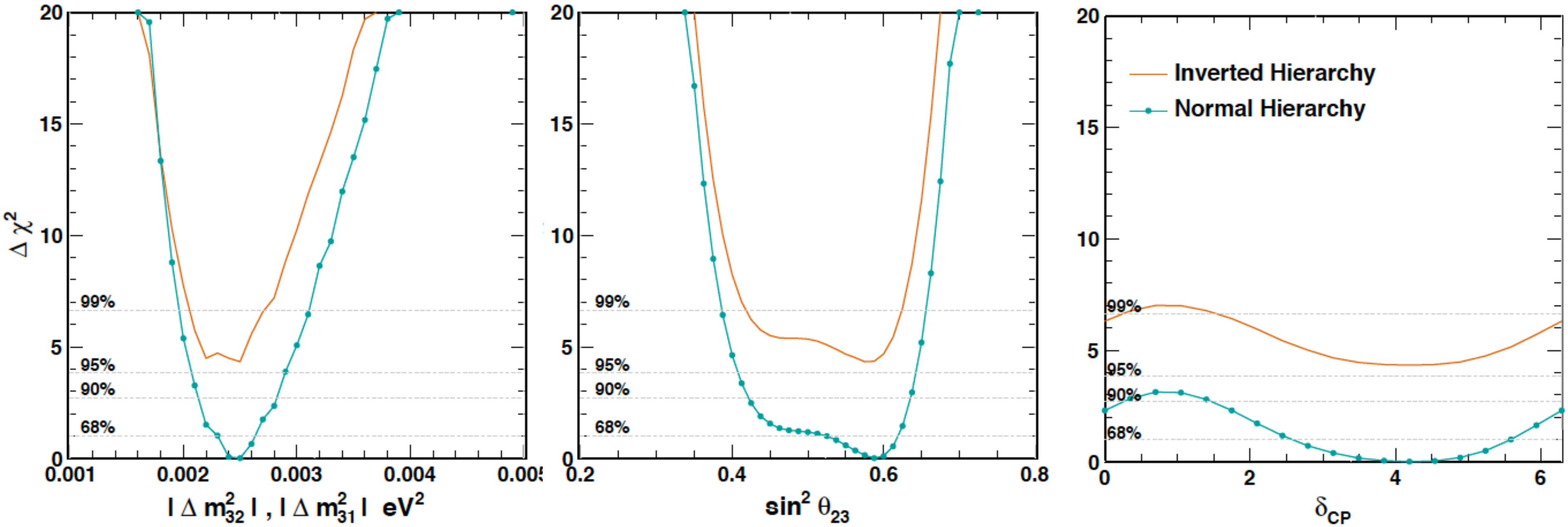




- Normal hierarchy favored by slight data excesses at energies consistent with resonantly-enhanced oscillations

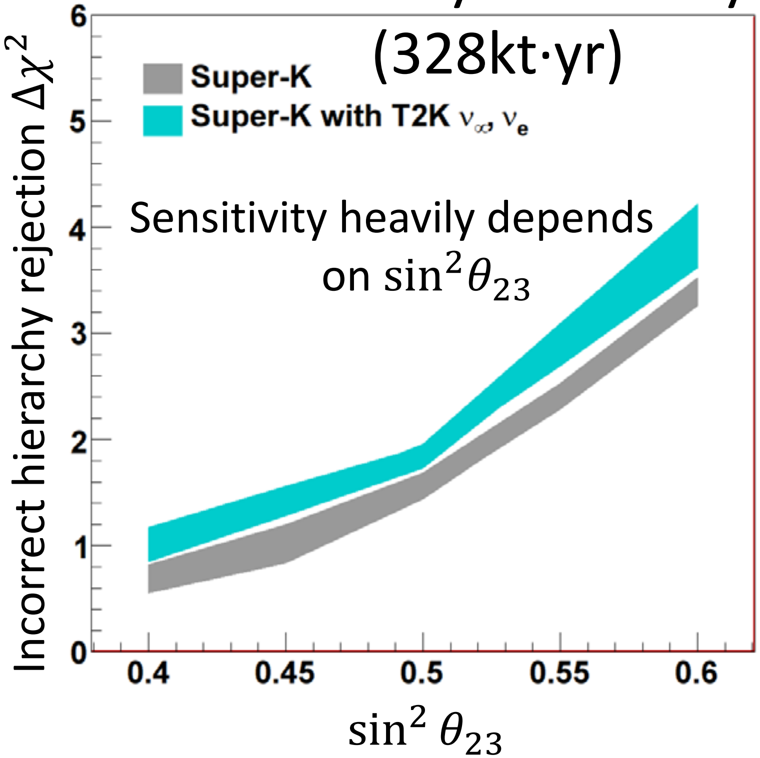
SK Atmospheric Mixing + δ_{cp}: (SK only)

PHYSICAL REVIEW D 97, 072001 (2018)

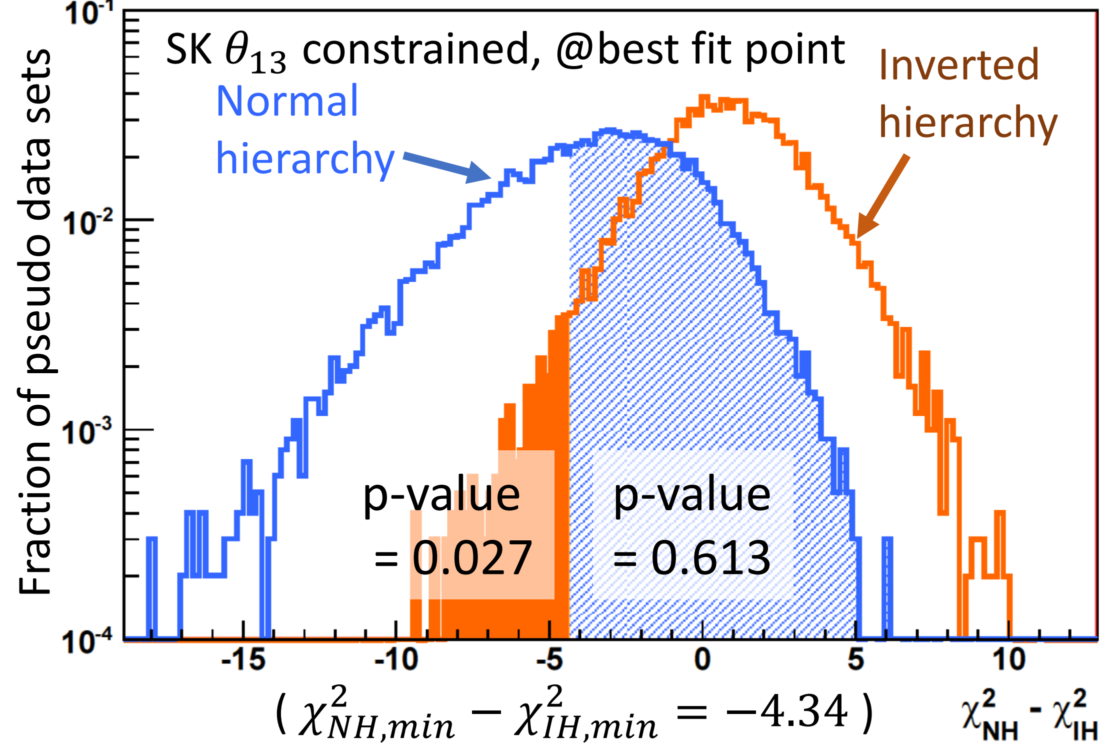


- Results of SK atmospheric neutrino data only, i.e. w/o T2K constraint
- *Normal hierarchy*(NH) is favored over *Inverted Hierarchy*(IH) :
  - $\Delta\chi^2$ (NH – IH) = -4.33
- Preference for δ_{cp} ~1.3π

Determination of hierarchy determination



Phys. Rev. D 97, 072001 (2018)



Estimate p-values using pseudo-data for the smallest and largest $\sin^2\theta_{23}$.

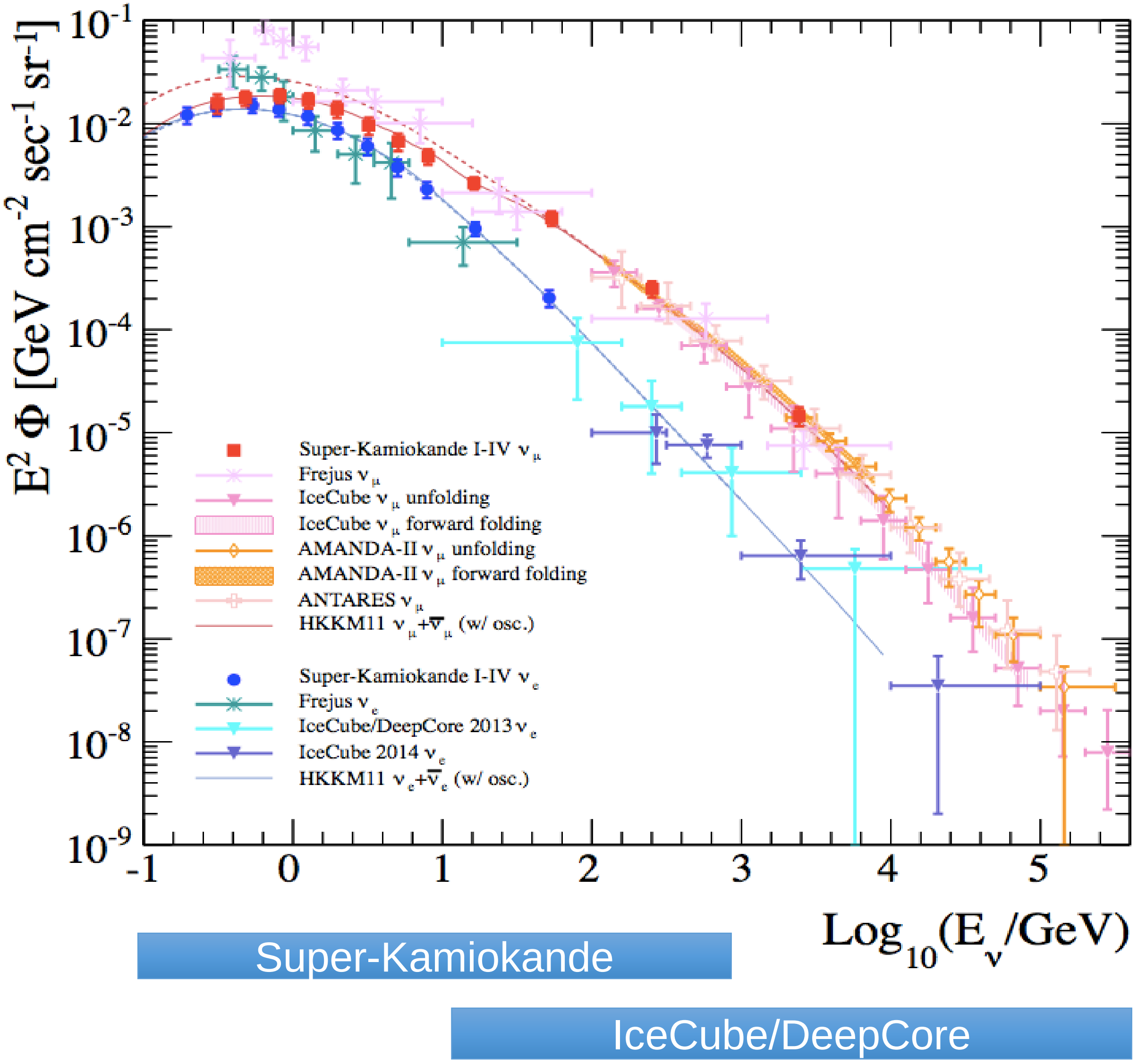
Hypothesis test ~ CL_s method : $CL_s(\text{IH rejection}) \equiv \frac{p_{0(IH)}}{1-p_0(NH)}$

Normal hierarchy is favored ➡

SK only	81.9 ~ 96.7%
SK + T2Kmodel	91.9 ~ 94.5%

Atmospheric Neutrino Flux:

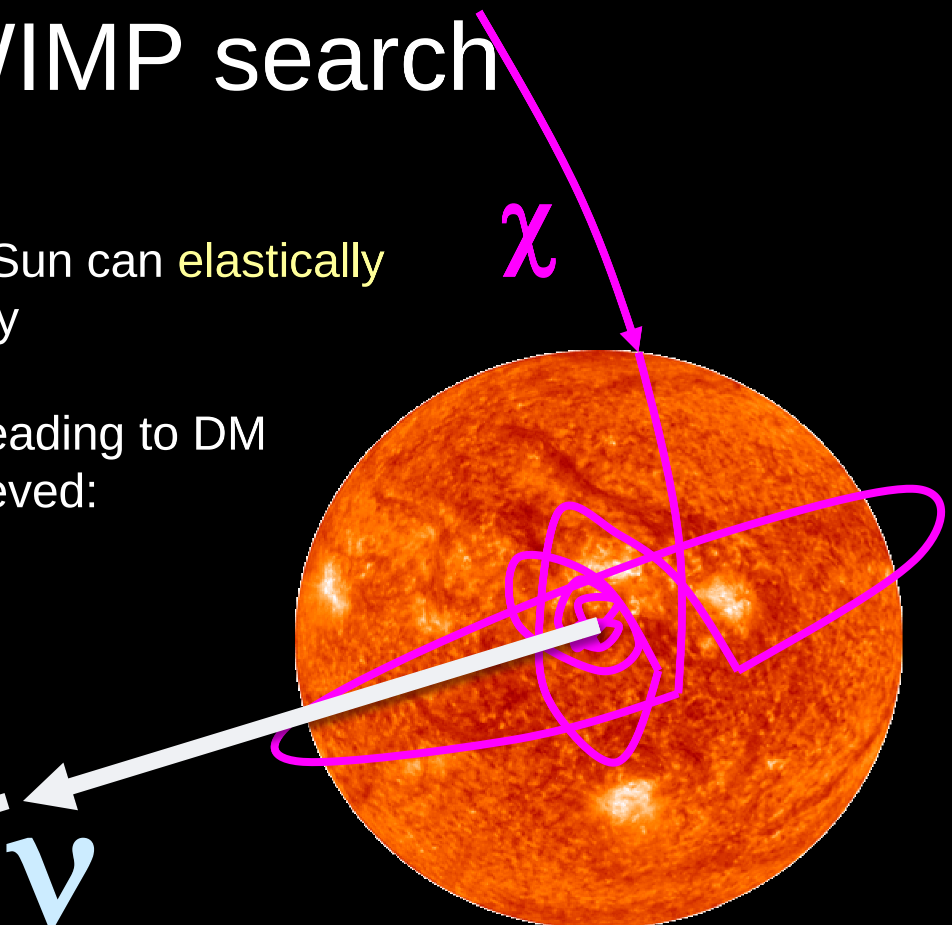
PHYSICAL REVIEW D 94, 052001 (2016)



Solar WIMP search

- DM particles passing through the Sun can elastically scatter with nuclei and loose energy

- WIMP density increases in core, leading to DM annihilation until equilibrium is achieved:
capture rate = annihilation rate



- Scattering cross section $\sigma_{\chi n}$ can be constrained and compared with results from direct DM detection

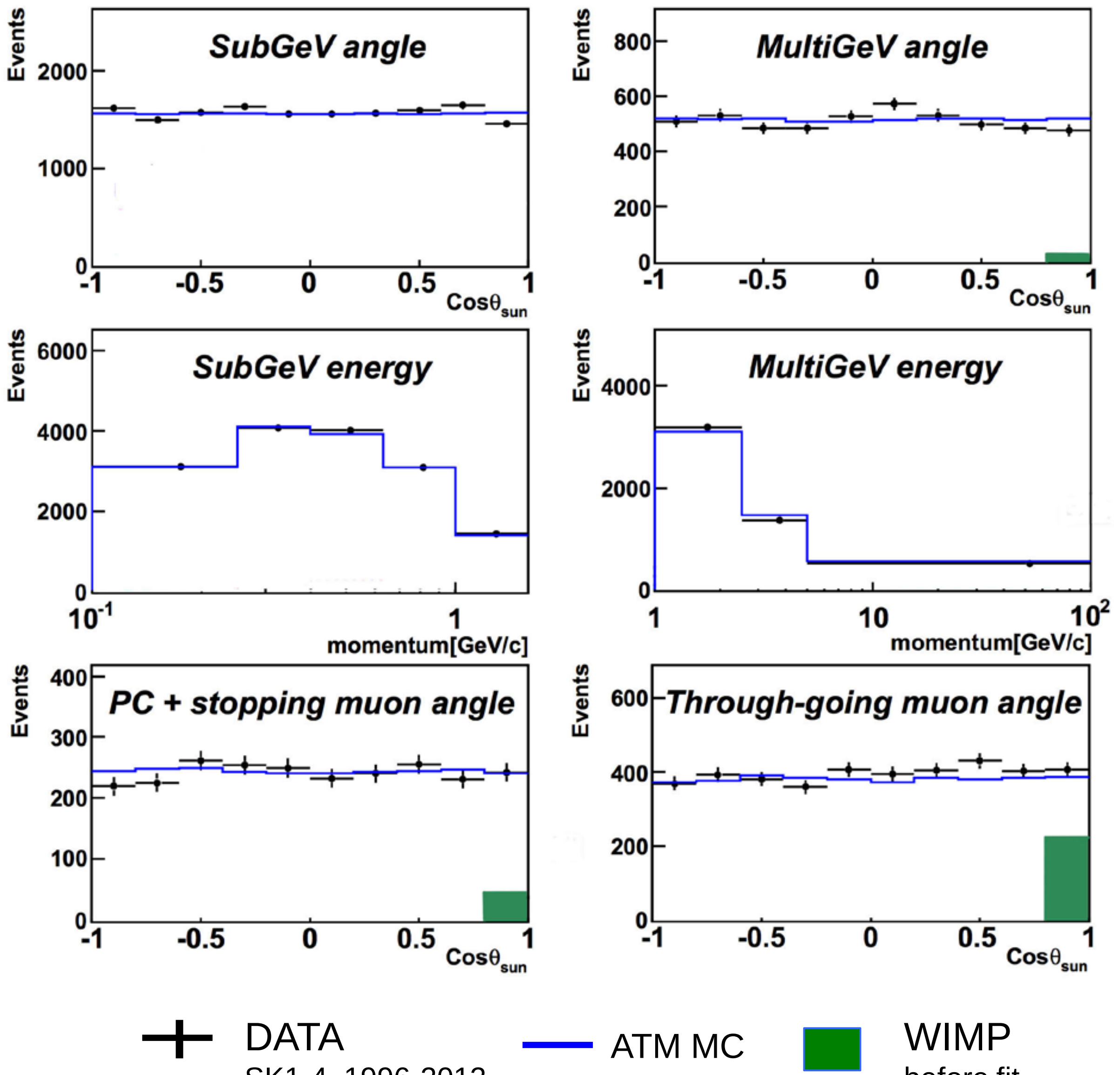
more: G.Wikström, J.Edsjö JCAP 04, 009 (2009)

Published analysis: K.Choi et al., Phys. Rev. Lett. 114, 141301 (2015)

Solar WIMP search

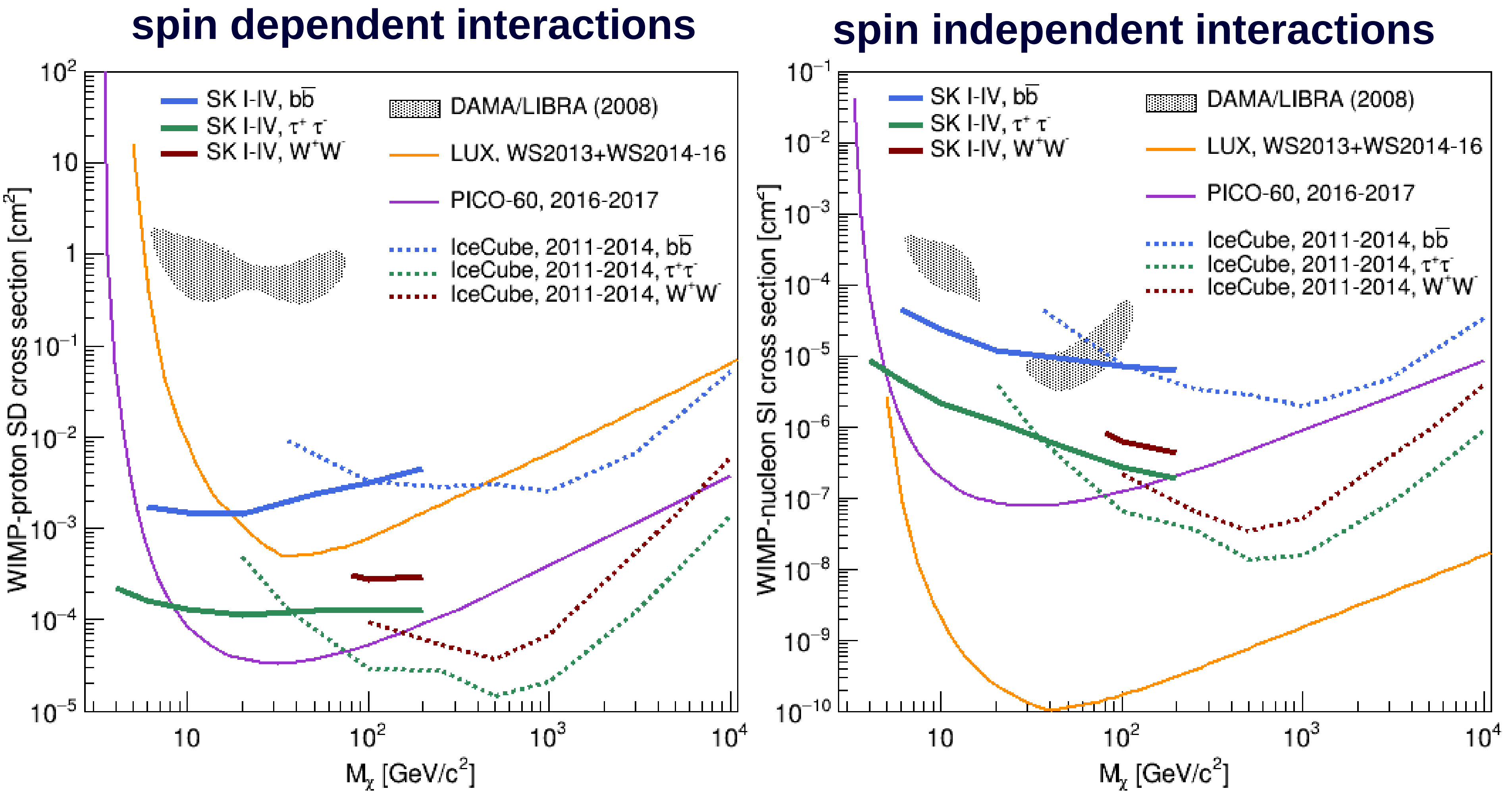
- FIT based on lepton mom. & $\cos\theta_{SUN}$ distributions, 3903 days of SK data (1996-2012)
- No excess of ν's from the SUN as compared to atm bkg is observed
- 90% CL upper limit on WIMP-nucleon scattering cross section $\sigma_{X}n$ for $\tau^+\tau^-$, $b\bar{b}$ and W^+W^- channels

example for: 200 GeV WIMPs, $\tau^+\tau^-$ ann. channel



Solar WIMP search: WIMP-nucleon SI & SD cross section limit

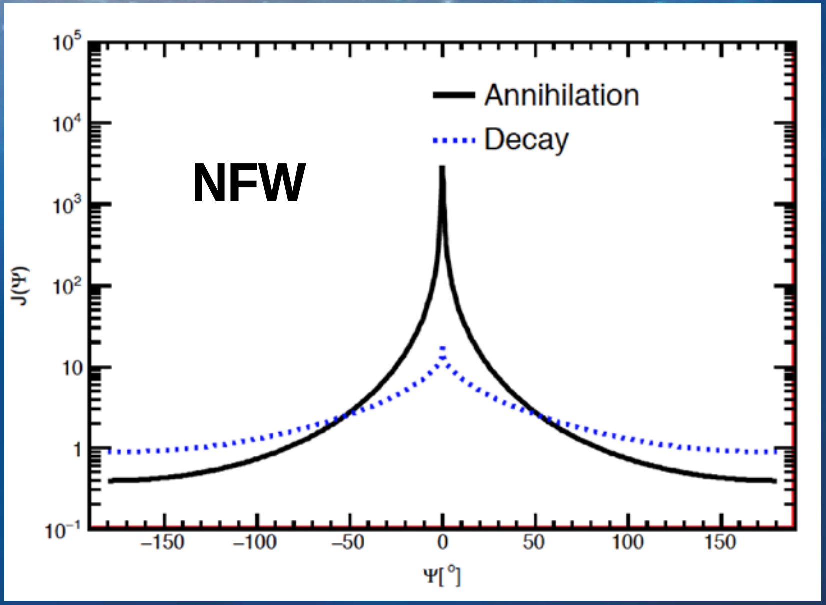
90% CL upper limit



published: K.Choi et al., Phys. Rev. Lett. 114, 141301 (2015)

Galactic WIMP search

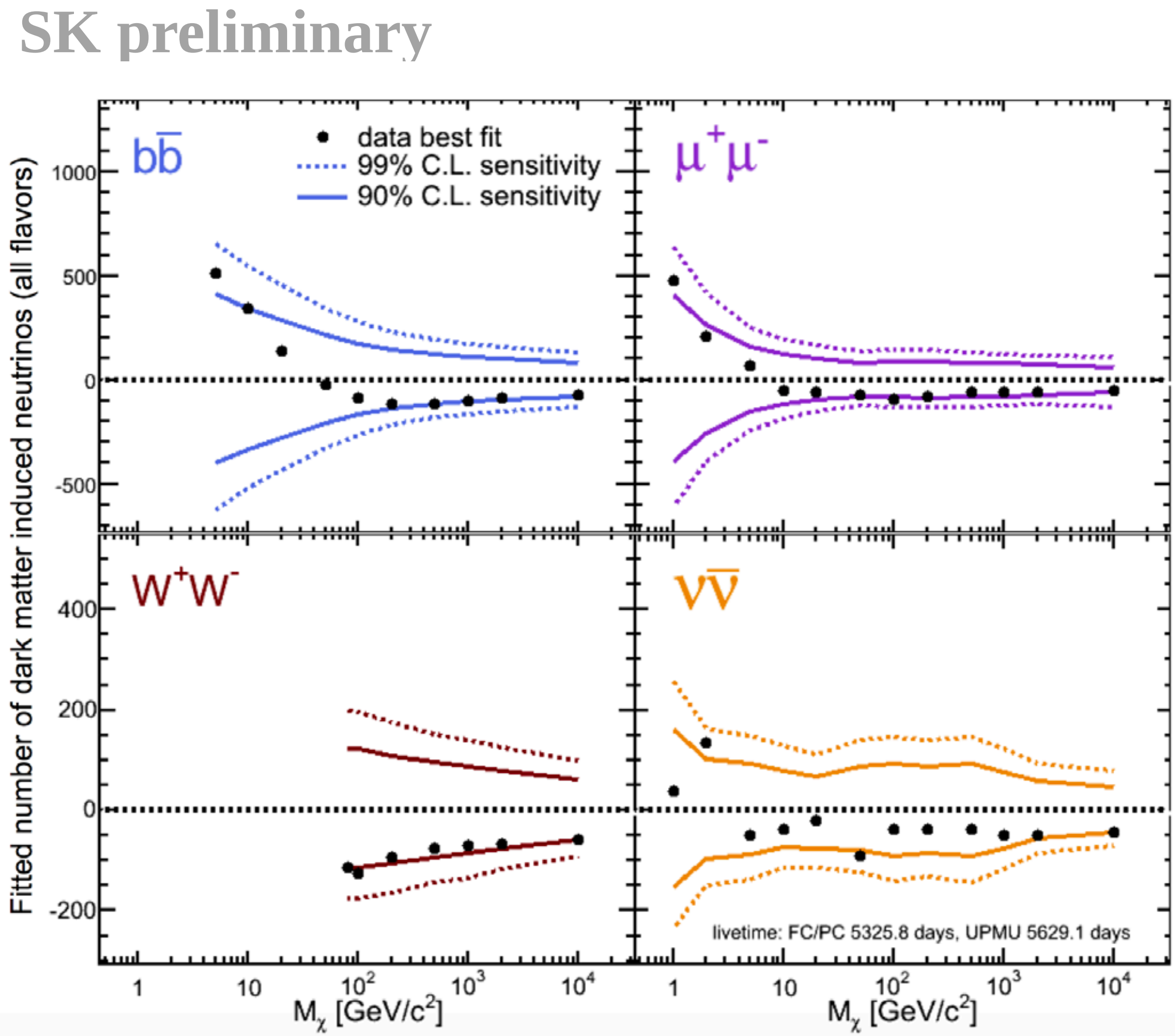
- diffuse signal from entire Galaxy, peaked from Galactic Center
- GC visibility with SK: ~71% with UPMU, 100% FC/PC
- search constrains DM self-annihilation cross section <σV>



Expected signal intensity strongly depends on halo model
NFW is considered as a benchmark model in this analysis

Galactic WIMP search: fitted number of DM-induced ν's

- FIT based on lepton mom. & $\cos\theta_{GC}$ distributions, 5326-5629 live-days,1996-2016
- NFW halo model assumed
- Fit results are consistent with null WIMP contribution
- 90% CL upper limit on DM self-annihilation cross section $<\sigma_A V>$



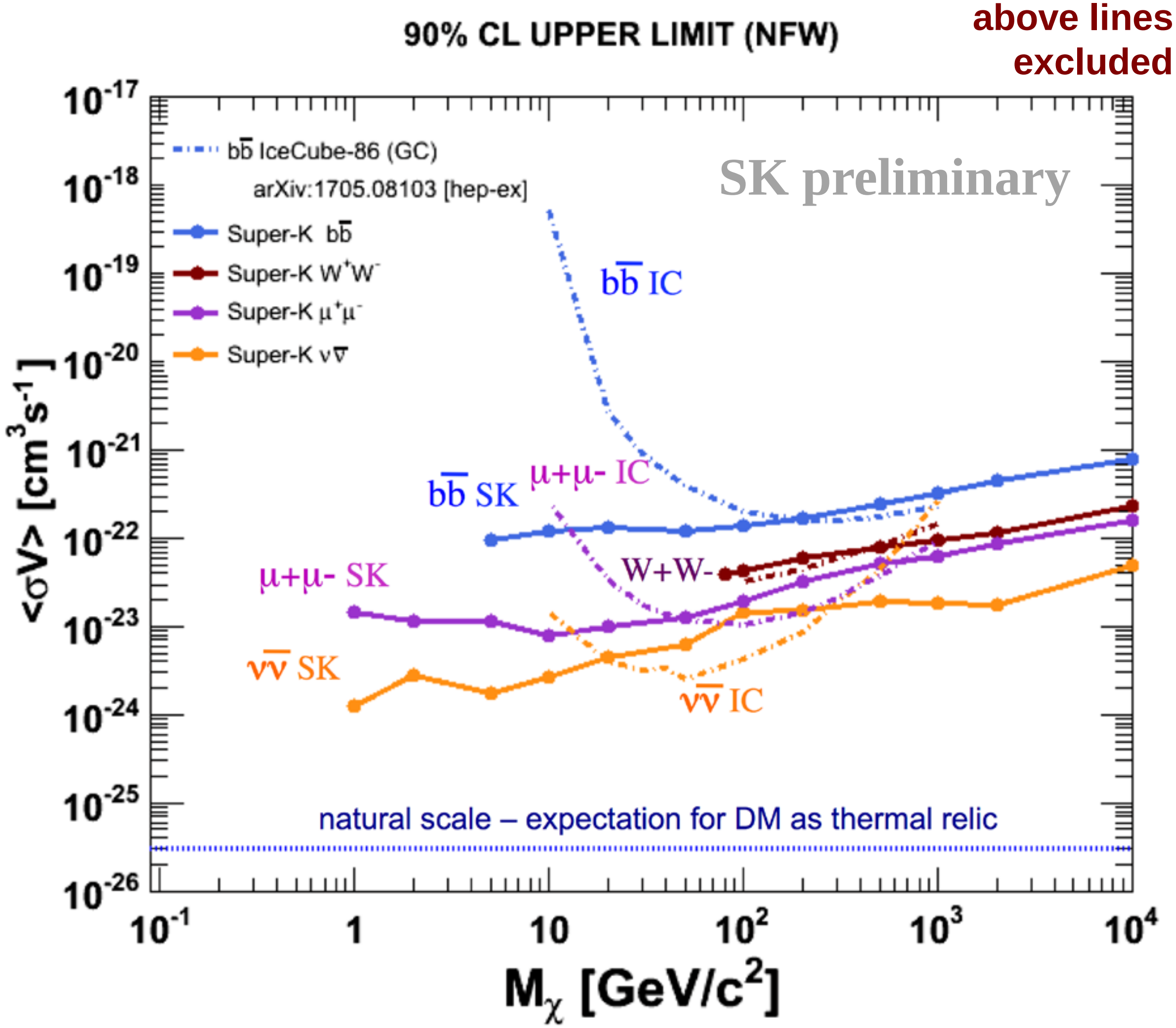
~150 systematic uncertainty terms included in the fit

p-values in backup

Galactic WIMP search: DM self-annihilation cross section

- FIT based on lepton mom. & $\cos\theta_{GC}$ distributions, 5326-5629 live-days,1996-2016
- NFW halo model assumed
- Fit results are consistent with null WIMP contribution
- 90% CL upper limit on DM self-annihilation cross section $\langle\sigma_A V\rangle$

above lines is excluded

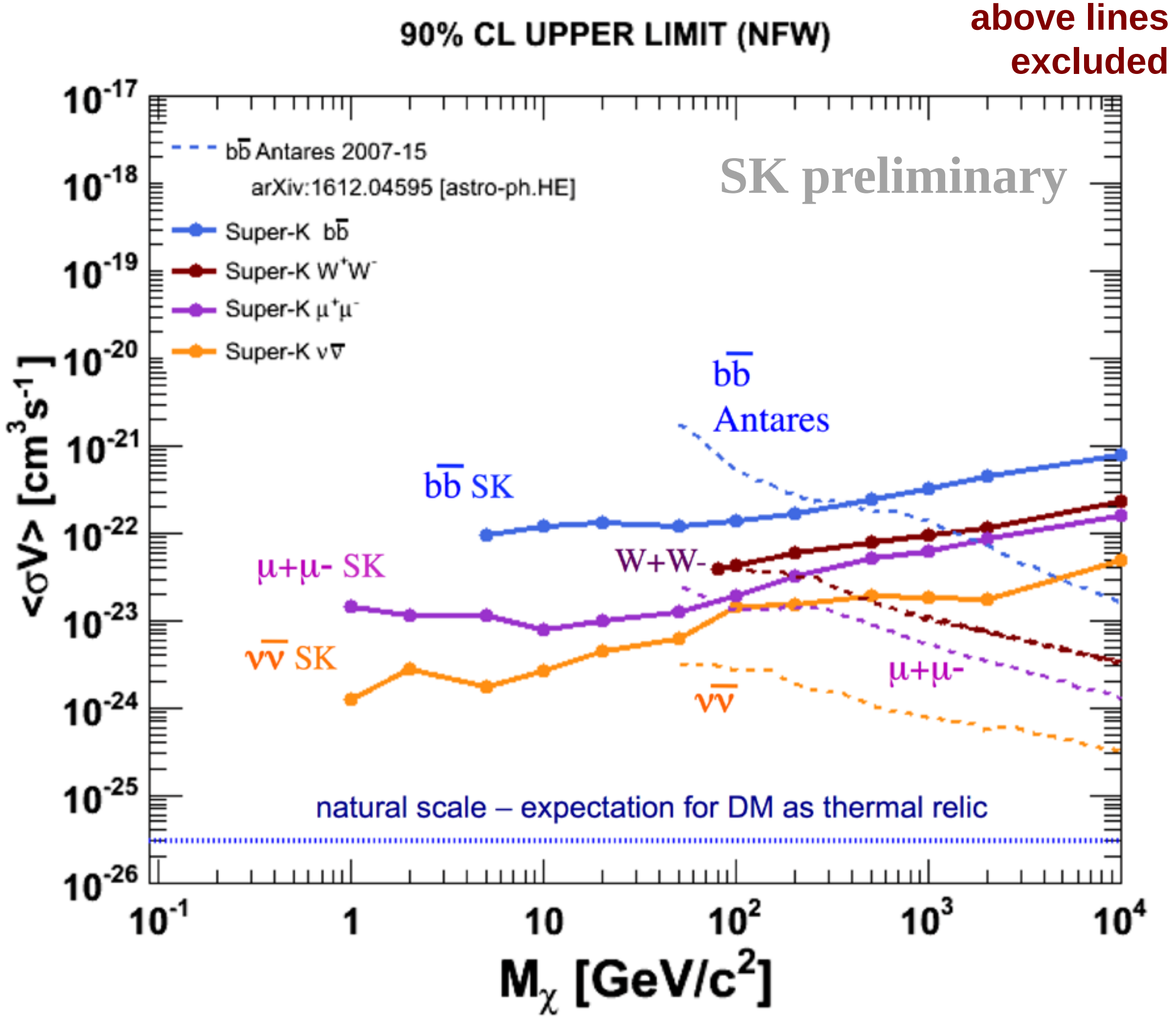


$$\frac{d\phi_{\Delta\Omega}}{dE} = \frac{\langle \sigma_A \cdot V \rangle}{2} J_{\Delta\Omega} \frac{R_{sc}\rho_{sc}^2}{4\pi \cdot M_\chi^2} \frac{dN}{dE}$$

Galactic WIMP search: DM self-annihilation cross section

- FIT based on lepton mom. & $\cos\theta_{GC}$ distributions, 5326-5629 live-days,1996-2016
- NFW halo model assumed
- Fit results are consistent with null WIMP contribution
- 90% CL upper limit on DM self-annihilation cross section $<\sigma_A V>$

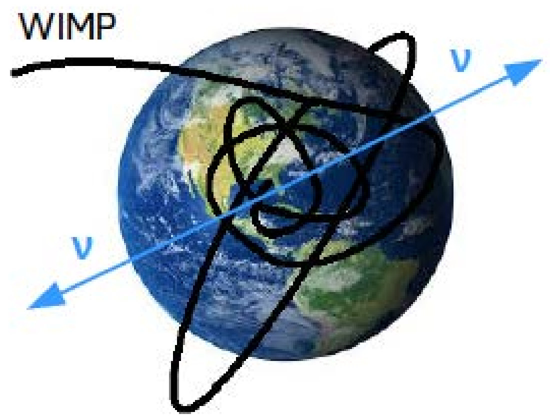
above lines is excluded

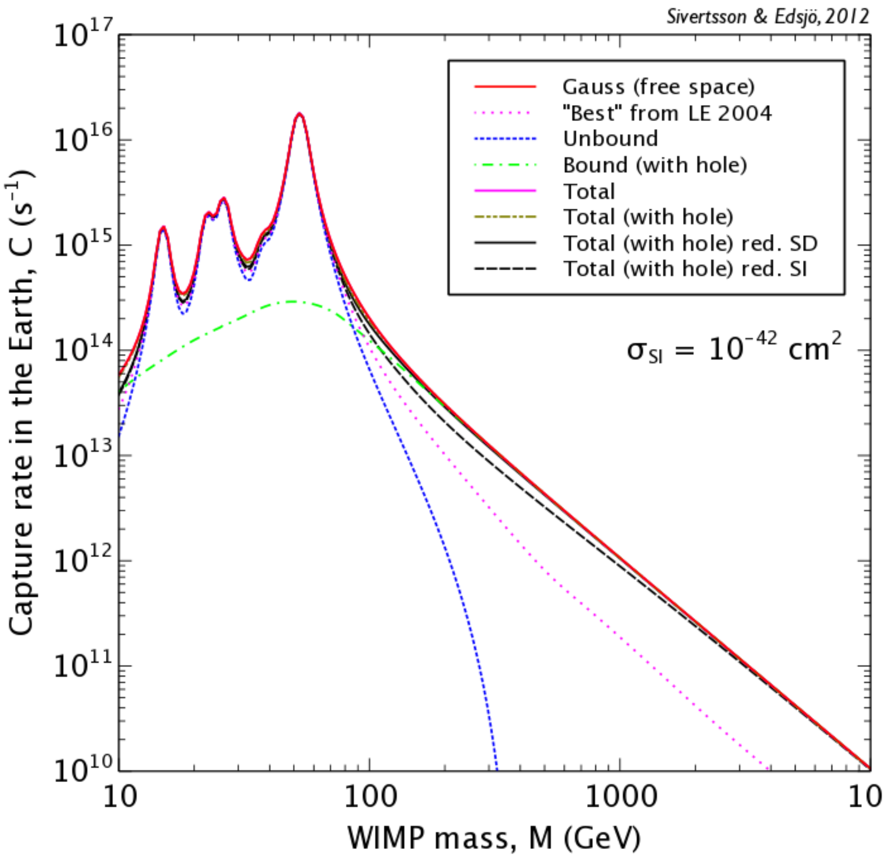


$$\frac{d\phi_{\Delta\Omega}}{dE} = \frac{\langle \sigma_A \cdot V \rangle}{2} J_{\Delta\Omega} \frac{R_{sc}\rho_{sc}^2}{4\pi \cdot M_\chi^2} \frac{dN}{dE}$$

Earth WIMP search

- Spin-independent interactions dominate in the capturing process → scalar interaction in which WIMPs couple to the nucleus mass
- If the mass of DM matches given heavy element, the capture rate increases considerably



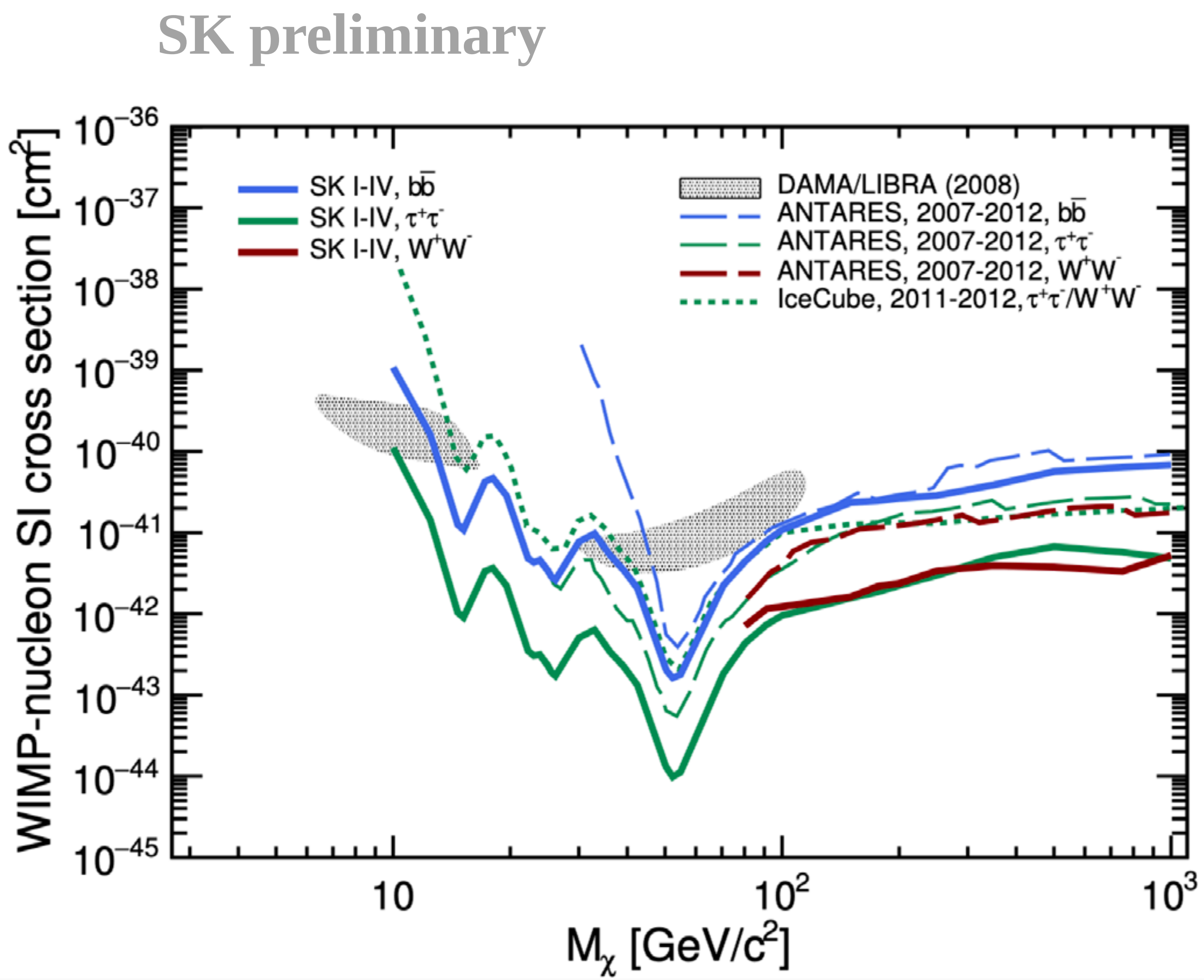


The peaks correspond to **resonant capture** on the most abundant elements **^{16}O**, **^{24}Mg**, **^{28}Si** and **^{56}Fe** and their isotopes

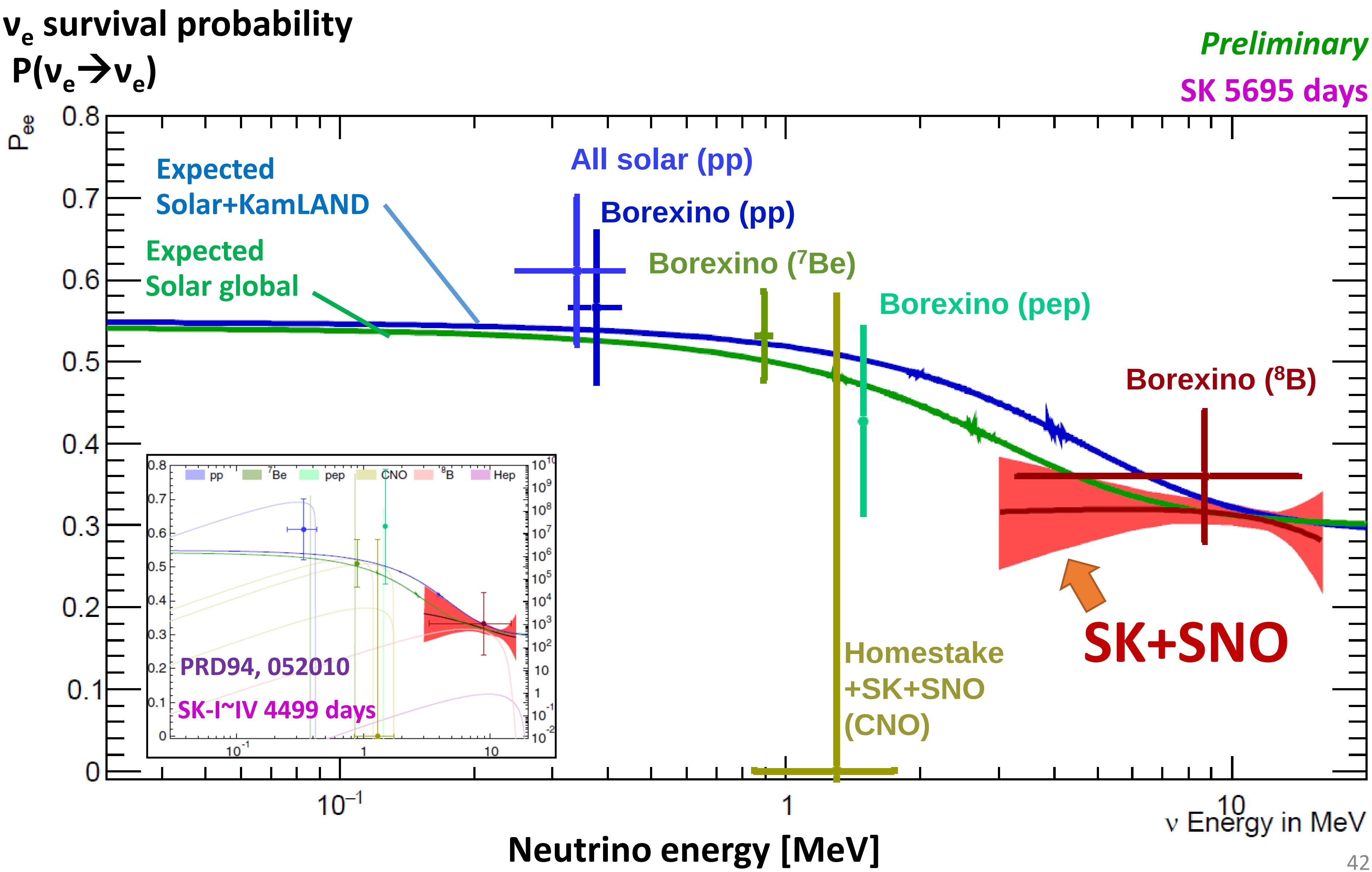
WIMP-nucleon SI scattering cross section $\sigma_{\chi n}$ can be constrained and compared with results from direct DM detection.

Earth WIMP search: WIMP-nucleon SI cross-section limit

- FIT based on lepton mom. & $\cos\theta_{GC}$ distributions, 5326-5629 live-days,1996-2016
- Fit results are consistent with null WIMP contribution
- 90 % upper limits on SI WIMP-nucleon scattering cross section $\sigma_{\chi\text{-}n}$

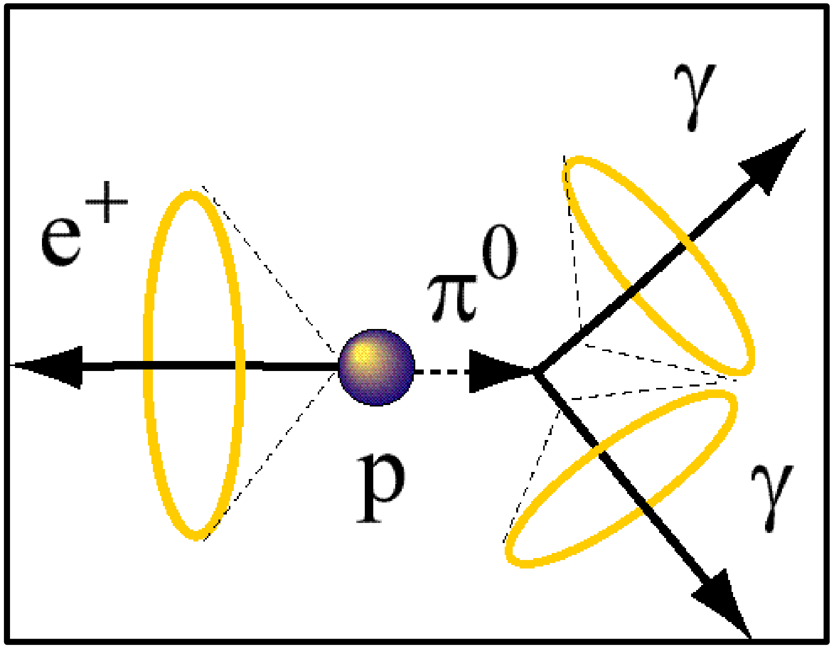


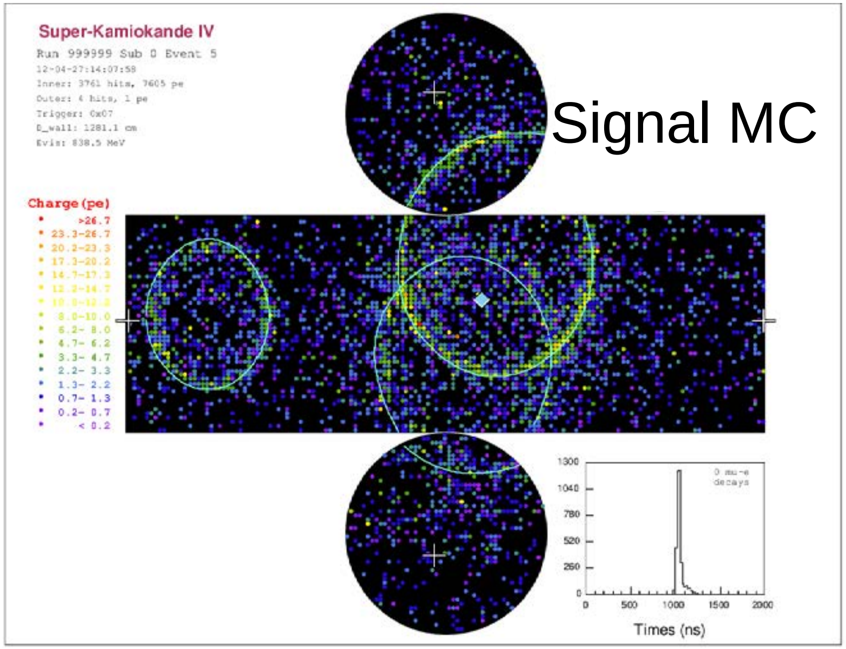
Super-K Spectral Data



Search for Proton decays

Search for $p \rightarrow e^{+}\pi^{0}$





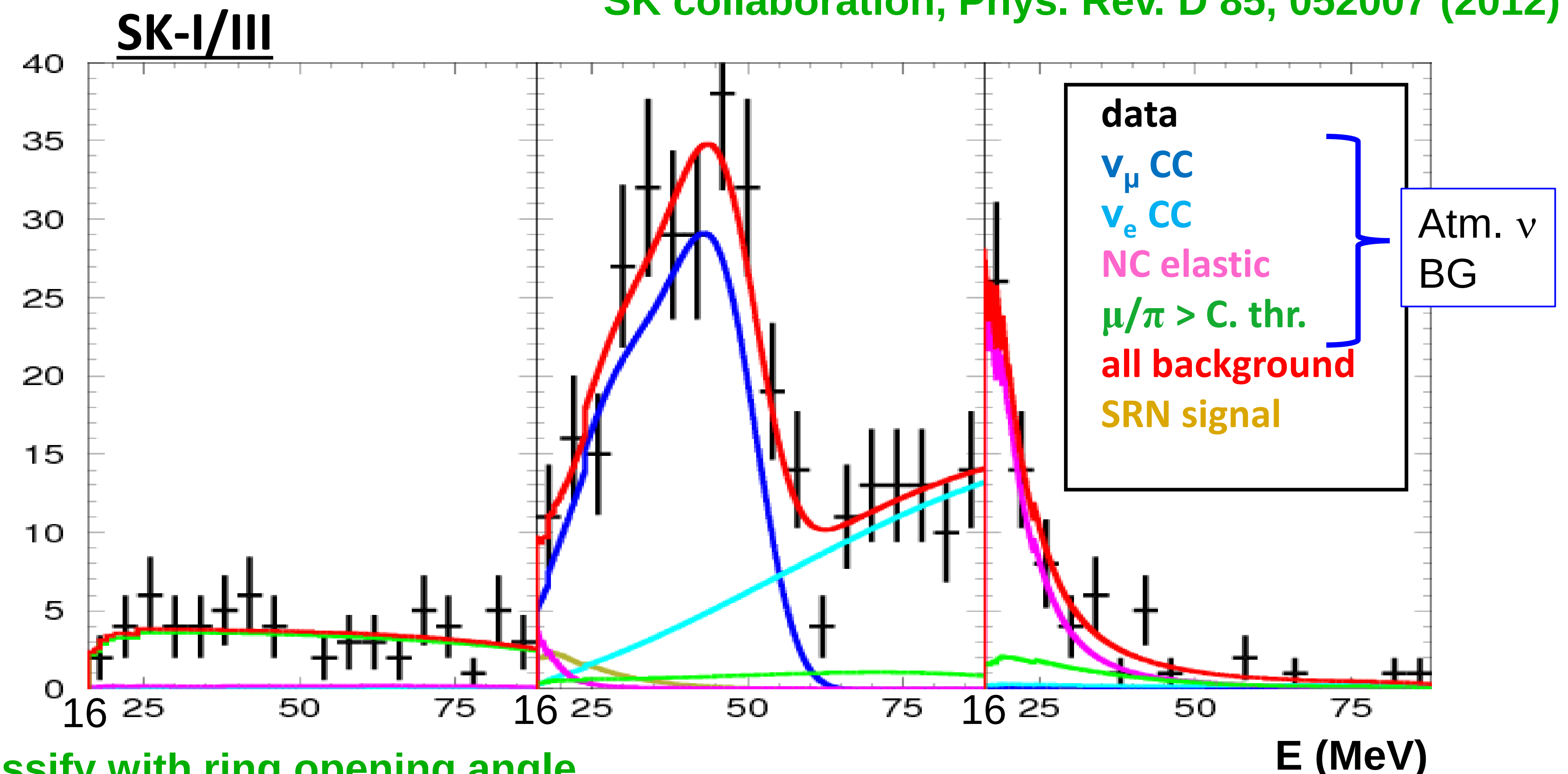
Signal MC

- **Positron and π^0 run back-to-back**
  - Momentum 459 MeV/c
- **All particles in the final stable are visible with Super-K**
  - **Able to reconstruct p mass and momentum**

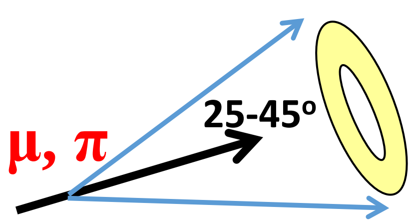
- Event selection:
  - All particles are fully contained in FV
  - 2 or 3 rings (two of them from π0)
  - All particles are e-like, w/o Michel-e
  - $85 < M_{\pi 0} < 185$ MeV/c^2
  - $800 < M_p < 1050$ MeV/c^2
  - $100 < P_{tot} < 250$ or $P_{tot} < 100$MeV/c
  - Neutron-tagging (SK-IV)
    - Further reduce bkg by ~50%

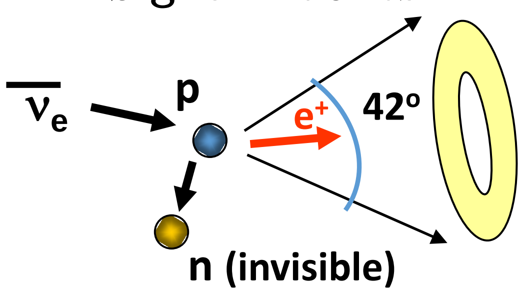
Current status of SRN search (results from SK-I, II, III)

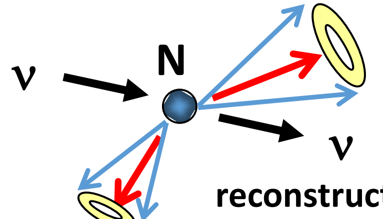
SK collaboration, Phys. Rev. D 85, 052007 (2012)



Classify with ring opening angle







Background types

Decay electron

"atm. muon neutrinos"

ν_e CC

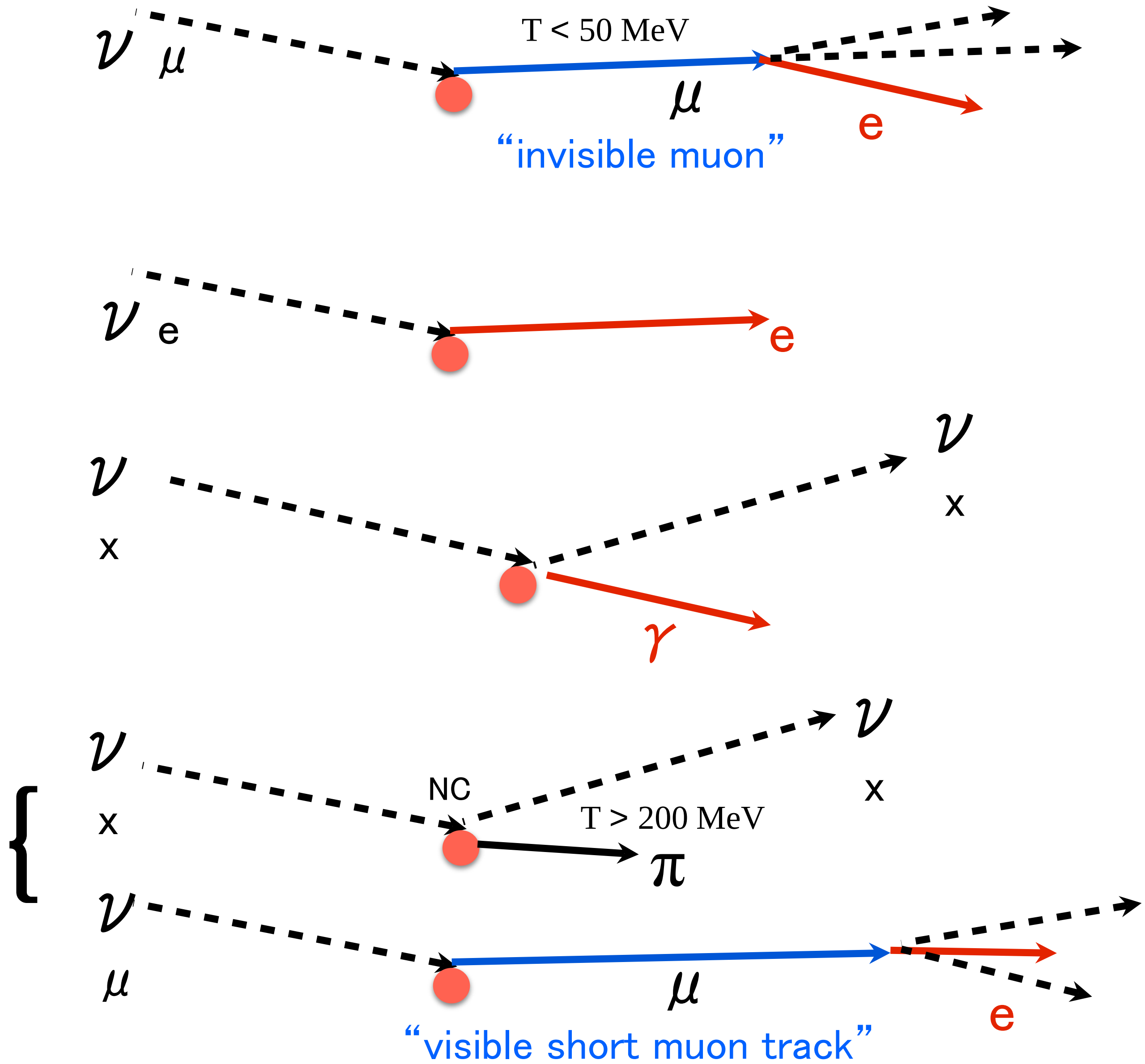
"atm. electron neutrinos"

NC Elastic

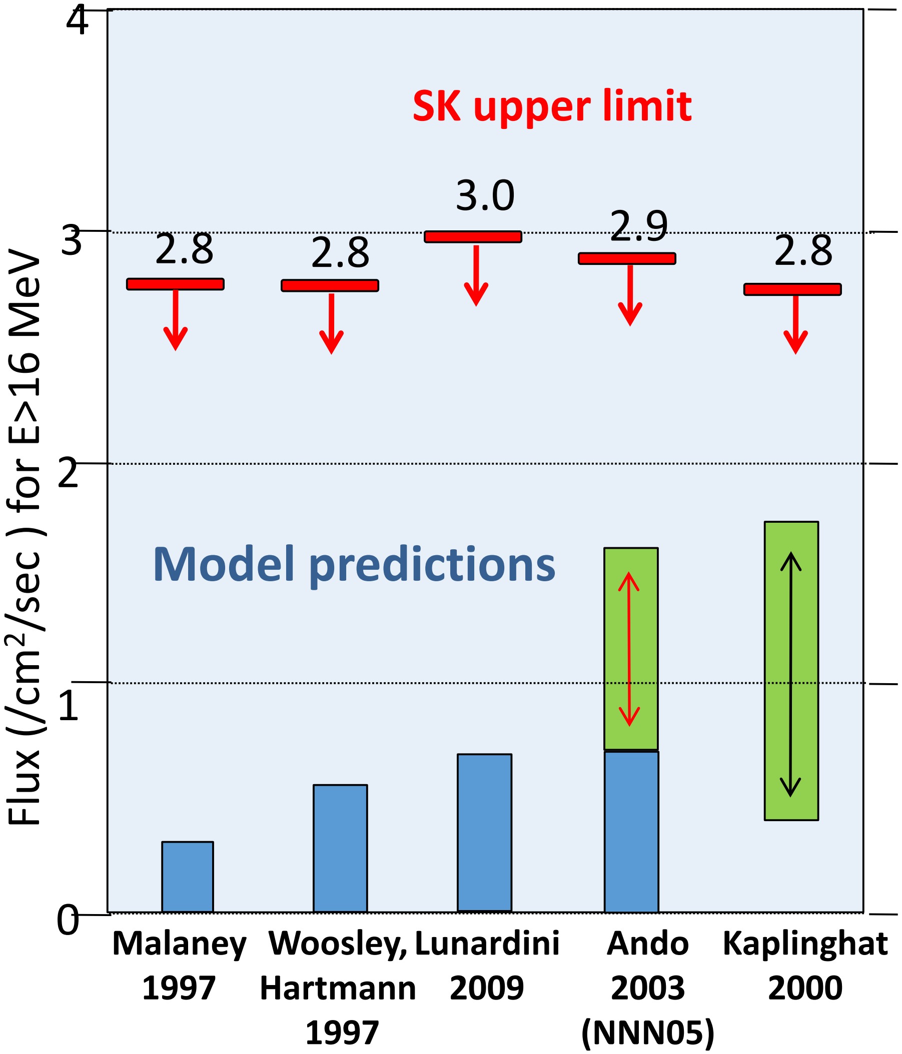
"atmospheric"

μ / π

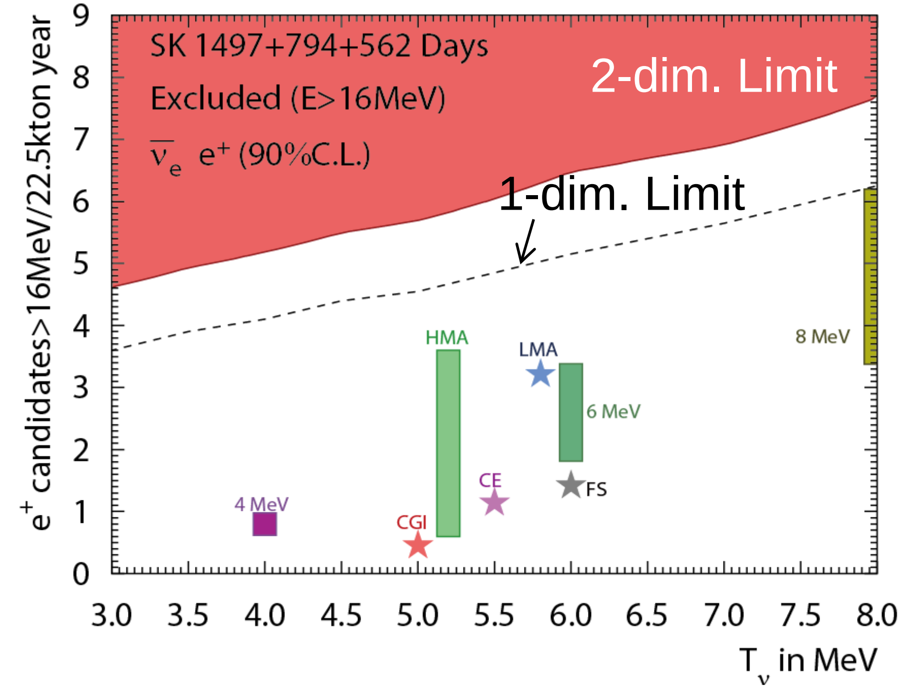
"μ / π production from atm. neutrinos"

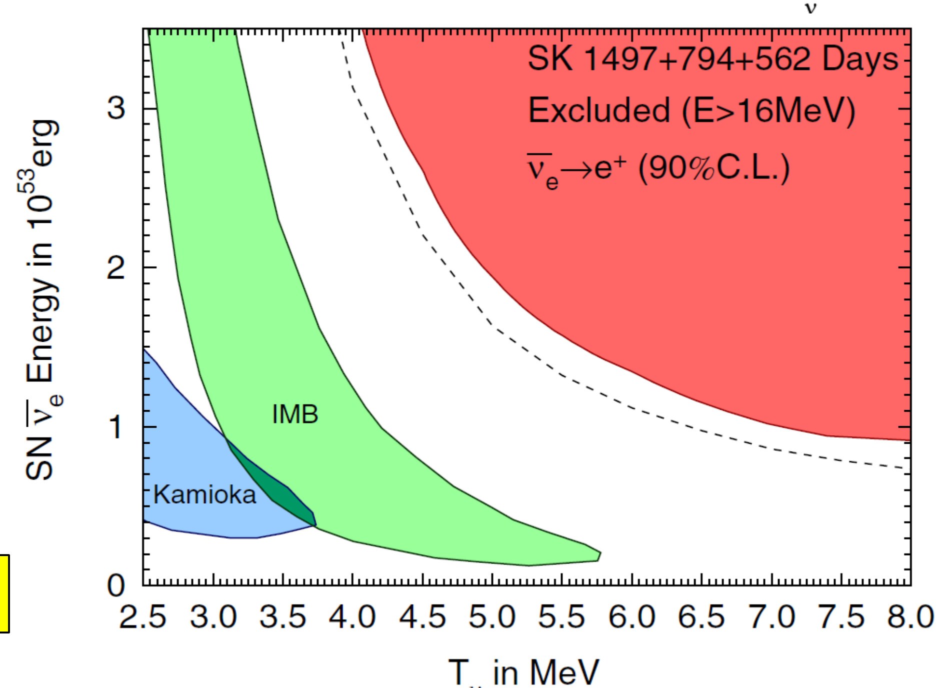


Upper limit from SK



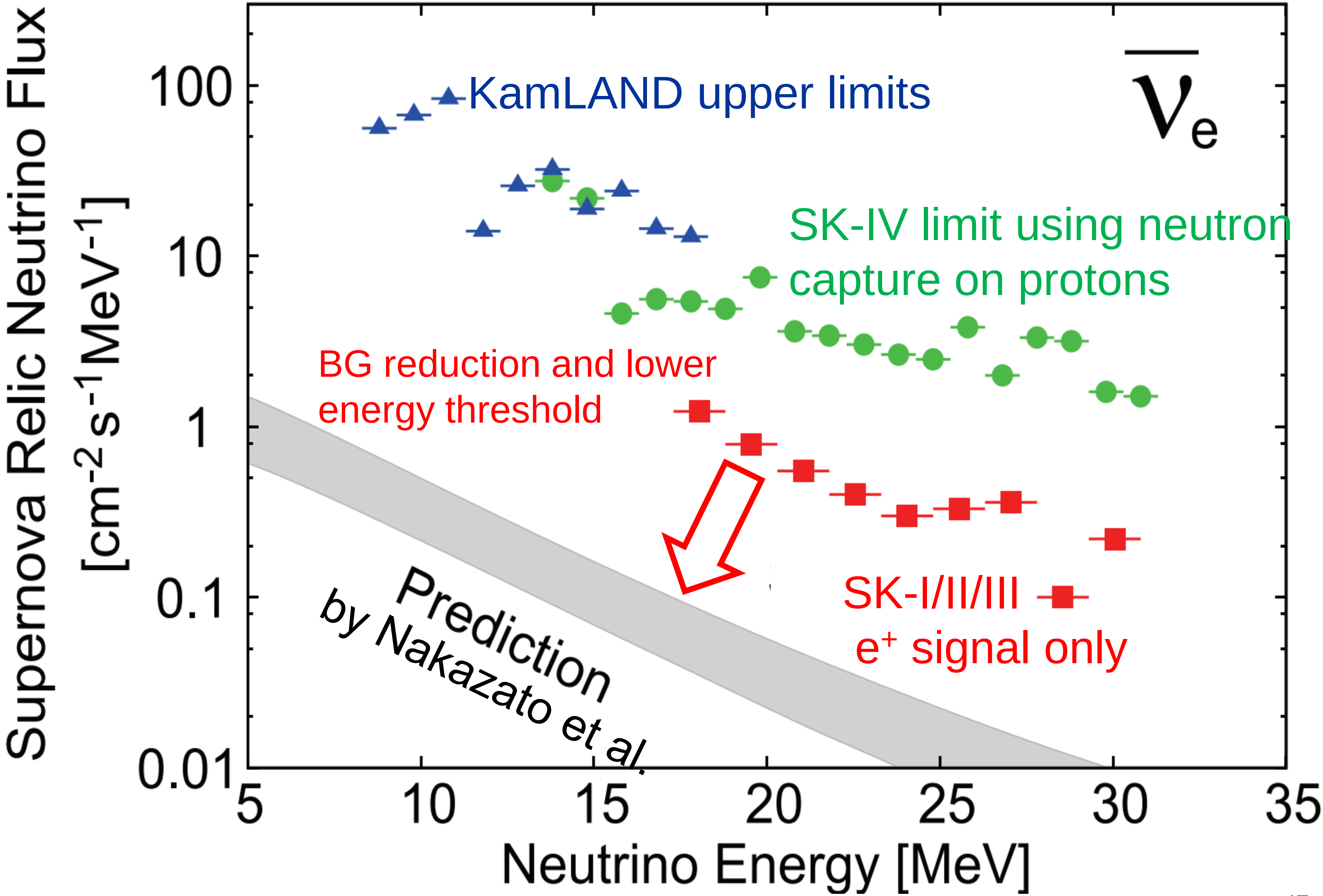
Limits on neutrino temperature and event rate



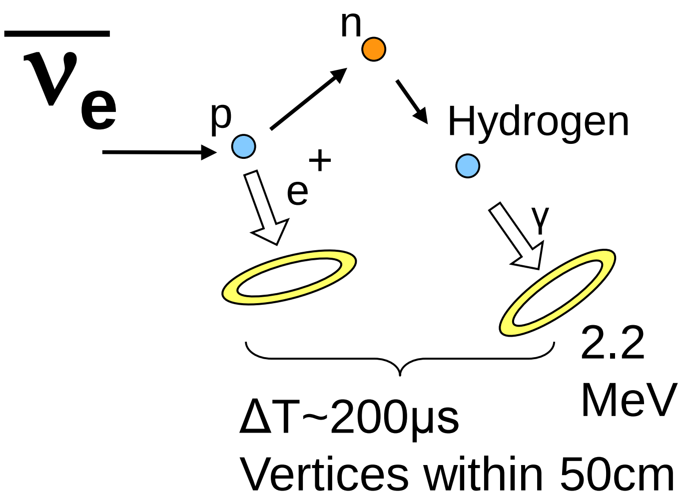


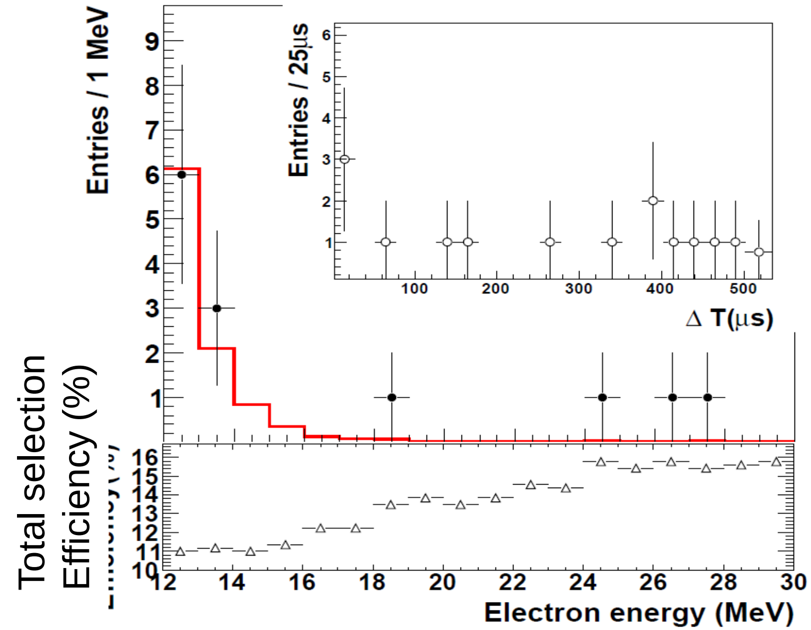
factor 2-4 to some model predictions

SRN flux limits



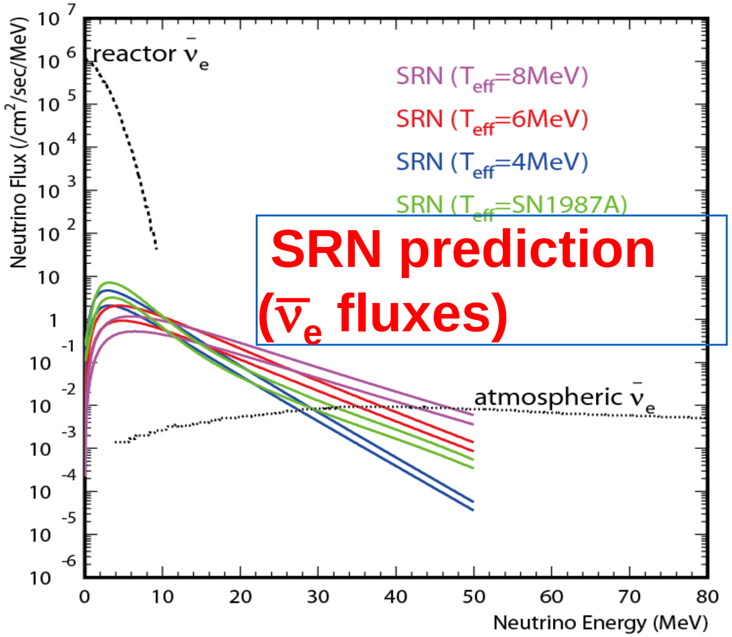
Netutron tagging by Hydrogen





- Published result using 960 live days of SK-IV data.
  - Finalizing result using full SK-IV data (3000 days)
- Search for delayed coincidence *hits* using the prompt vertex positon.
  - Event reconstruction for 2.2 MeV γ does not work
- The detection efficiency of 2.2 MeV γ is ~20%.
- Background probability is ~1%.

Physics with SK-Gd



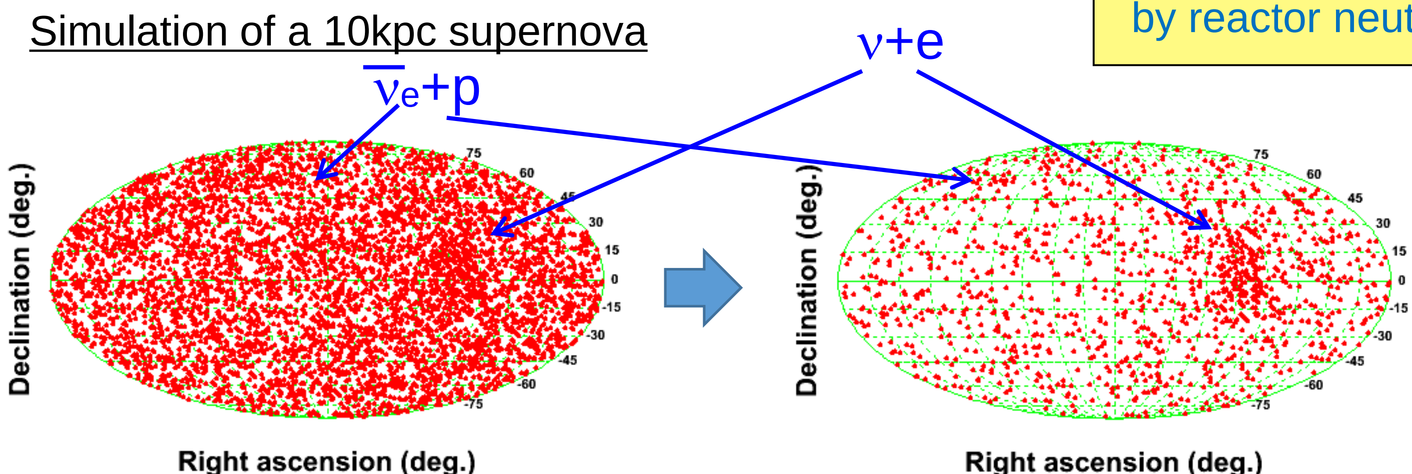
Supernova Relic Neutrinos (SRN)

- Open widow for SRN at 10-30MeV
- Expected event rate 1.3 -6.7 events/year/22.5kt(10-30MeV)
- Study supernova rate from the beginning of universe.
- Averaged energy spectrum.

- Discriminate proton decay (essentially no neutron) and atmospheric neutrino background(with neutrons).
- Neutrino/anti-neutrino identification.
- Precise measurement of θ_{12} and Δm^2_{21} by reactor neutrinos.

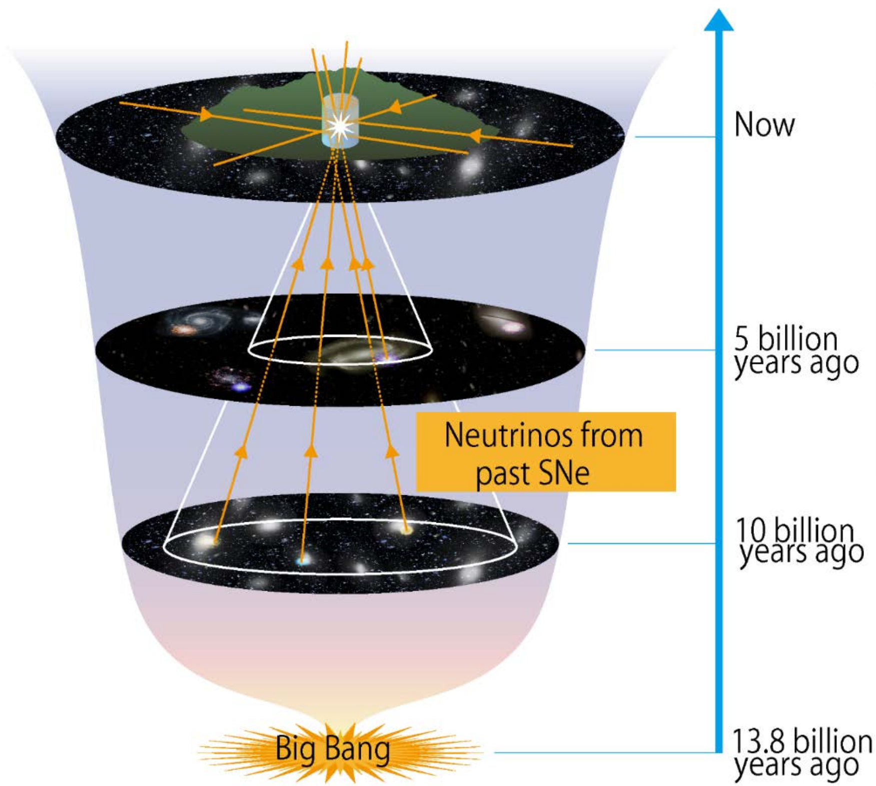
Improve pointing accuracy for supernova bursts, e.g. 4~5°→ 3°(90%C.L.) for 10kpc

Simulation of a 10kpc supernova



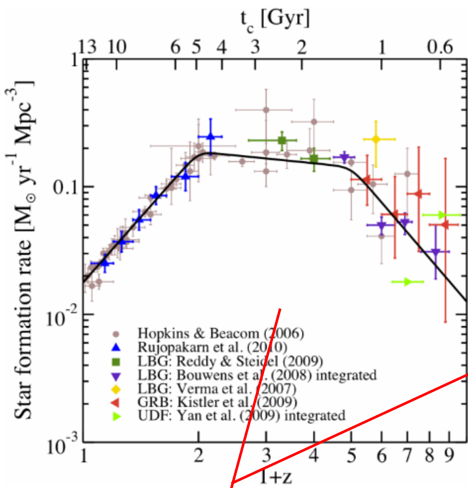
What is Supernova Relic Neutrinos（SRN）?

$10^{22\text{-}23}$ stars in the universe（～10^{11} galaxies, ~$10^{11\text{-}12}$ stars/galaxy）
At present, we are getting neutrinos from 10^8 supernovae every year.

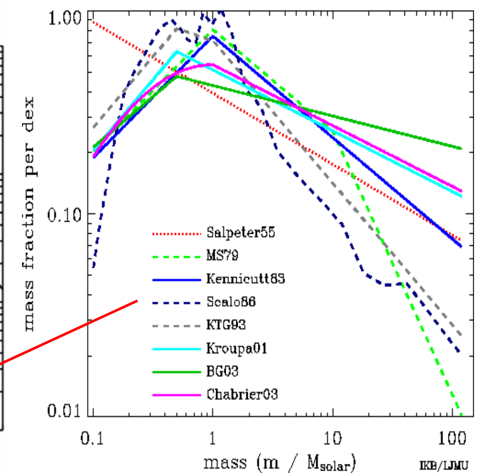


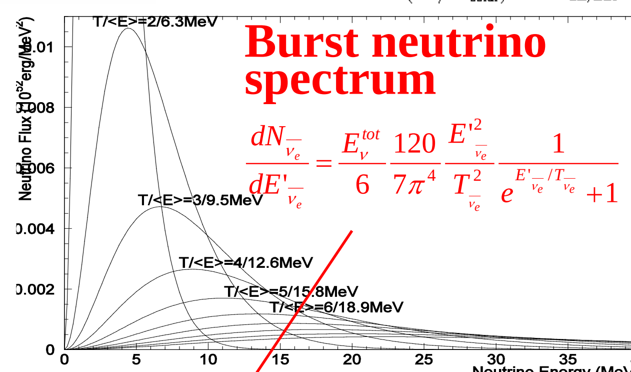
Horiuchi,Beacom(2010)

Star Formation Rate



Initial Mass Function





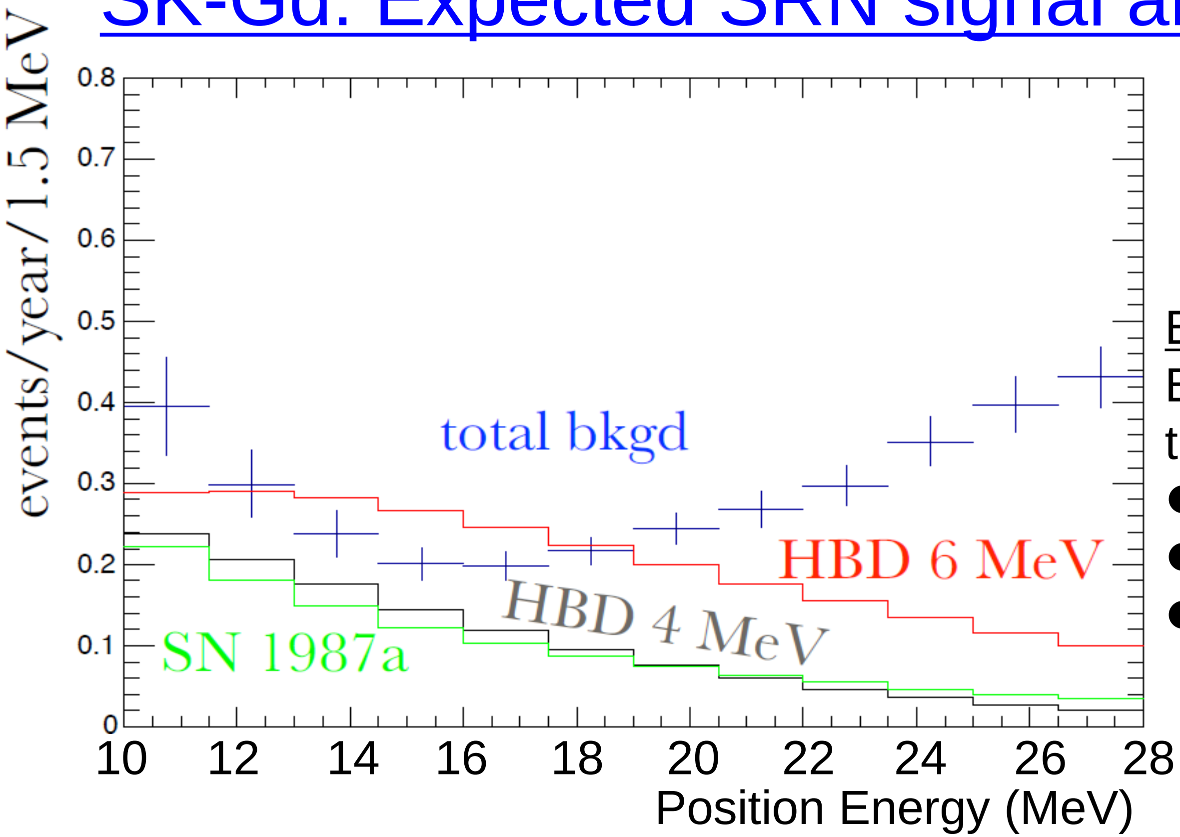
$$\frac{dN_{\bar{\nu}_e}}{dE'_{\bar{\nu}_e}} = \frac{E_\nu^{tot}}{6}\frac{120}{7\pi^4}\frac{E'^2_{\bar{\nu}_e}}{T^2_{\bar{\nu}_e}}\frac{1}{e^{E'_{\bar{\nu}_e}/T_{\bar{\nu}_e}}+1}$$

$$\frac{dF_\nu}{dE_\nu} = c\int_0^{z_{\rm max}} R_{\rm SN}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz}dz$$

We can study
star formation history and
averaged neutrino spectrum.

SK-Gd: Expected SRN signal and its significance

preliminary



SRN flux from
Horiuchi, Beacom and Dwek,
PRD, 79, 083013 (2009)

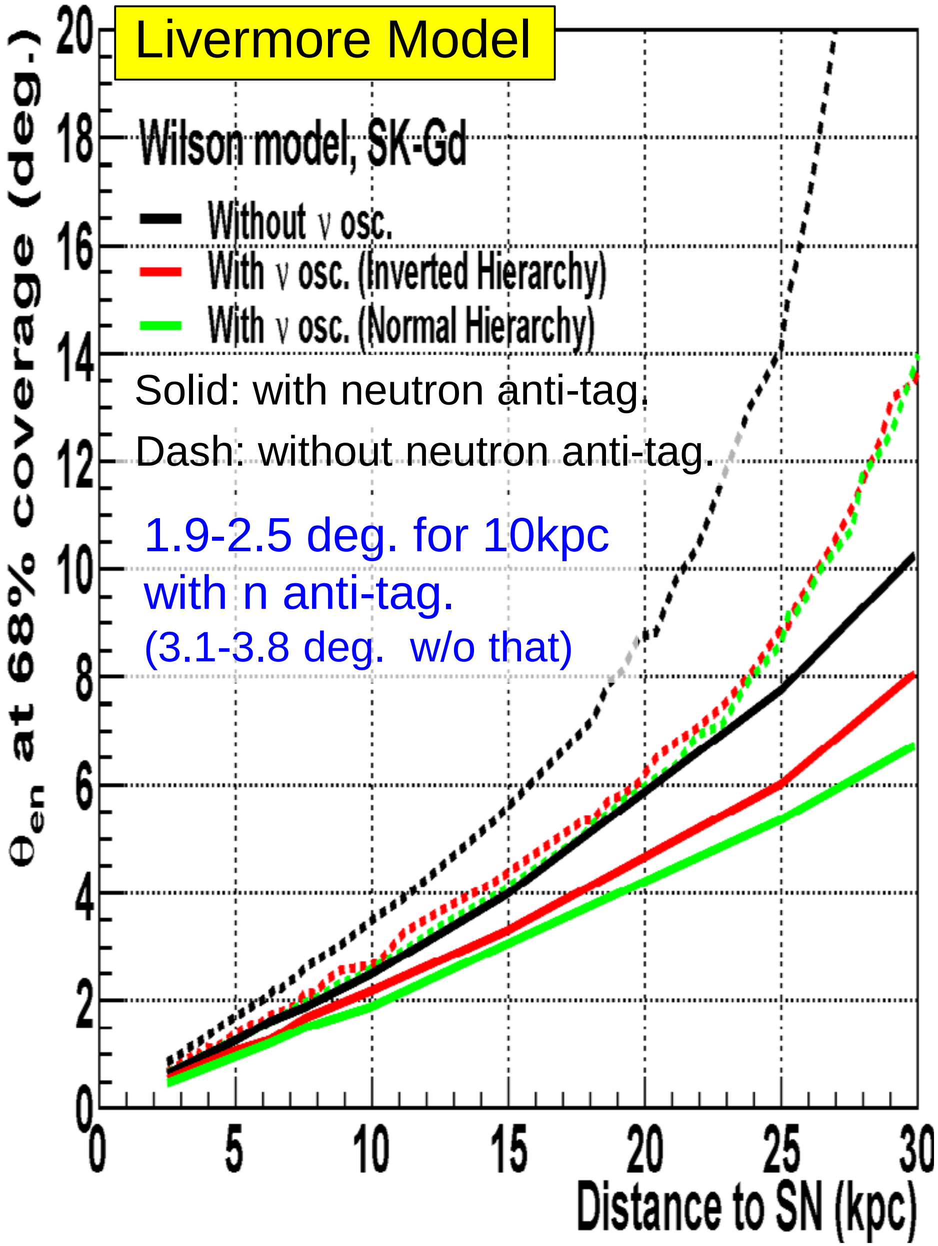
BG assumption

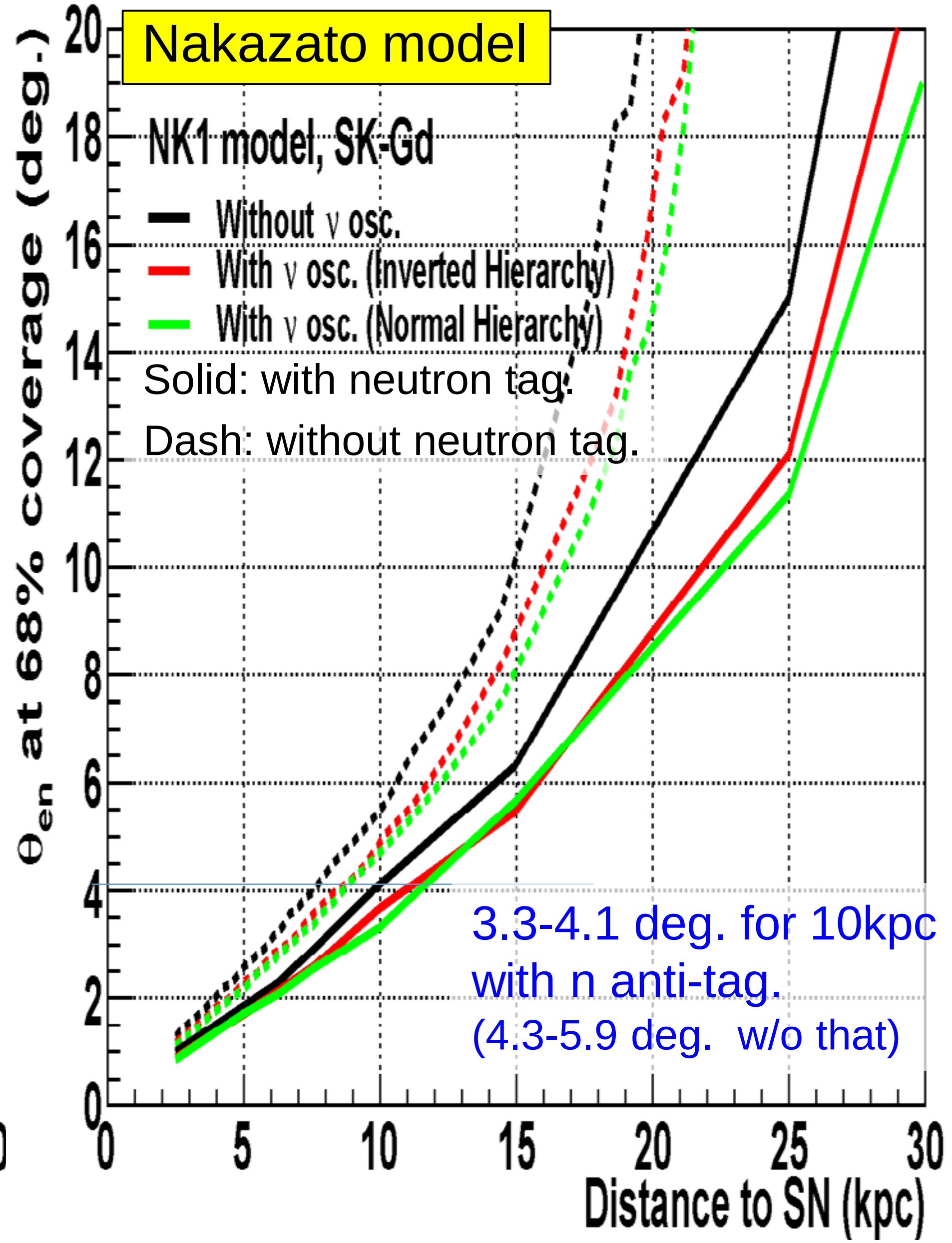
BG can be reduced by neutron tagging as follows

- ν_μ CC BG 1/4
- ν_e CC BG 2/3
- NC elastic BG 1/3（require only one neutron)

Model	10-16MeV (evts/10yrs)	16-28MeV (evts/10yrs)	Total (10-28MeV)	Significance (2 energy bin)
HBD 8MeV	11.3	19.9	31.2	5.3 σ
HBD 6MeV	11.3	13.5	24.8	4.3 σ
HBD 4MeV	7.7	4.8	12.5	2.5 σ
HBD SN1987a	5.1	6.8	11.9	2.1 σ
BG	10	24	34	----

Pointing accuracy with neutron information



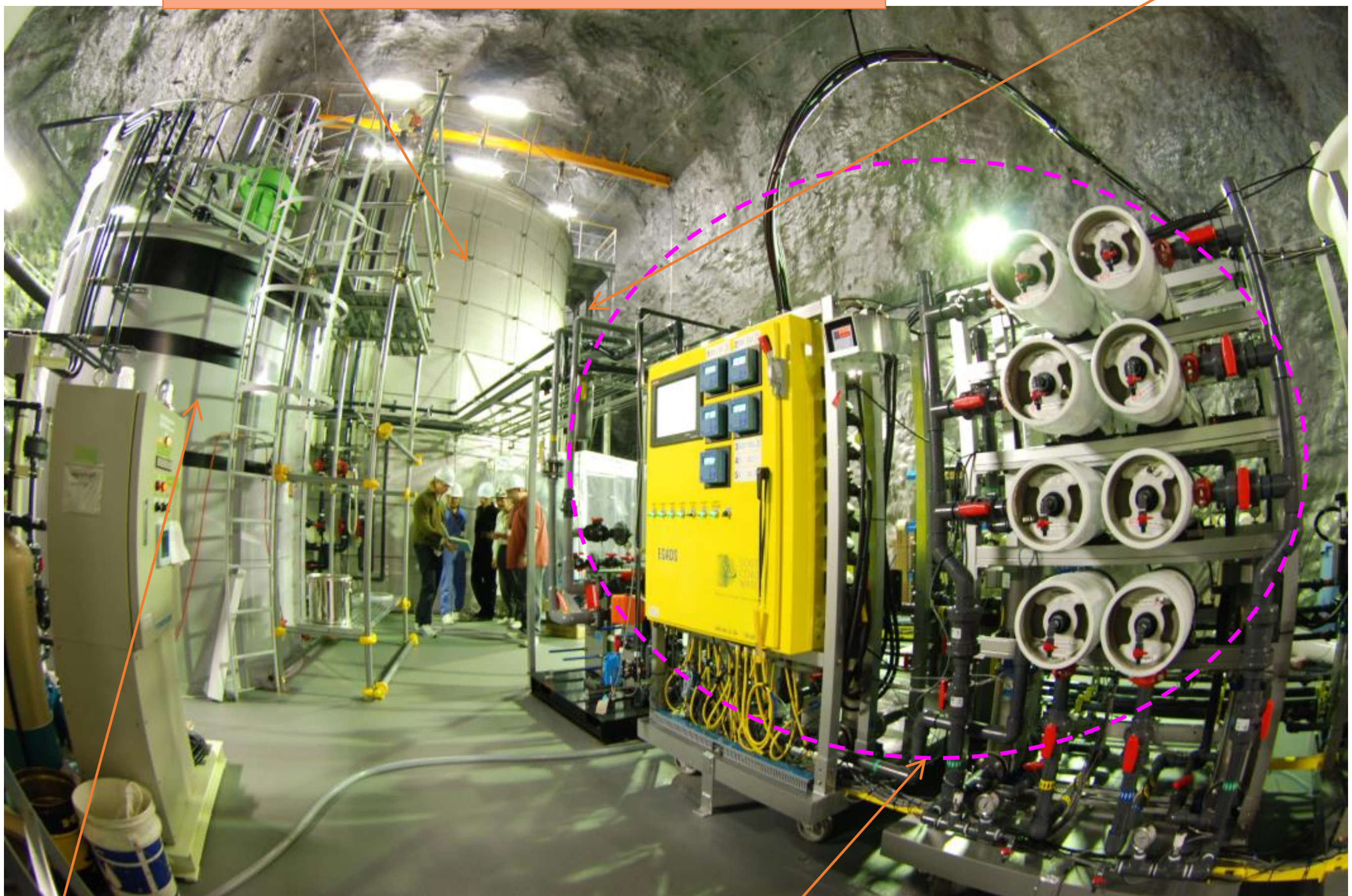


Pointing accuracy can be improved by neutron anti-tagging.

EGADS

Evaluating **G**adolinium's **A**ction on **D**etector **S**ystems

200 m³ test tank with 240 PMTs

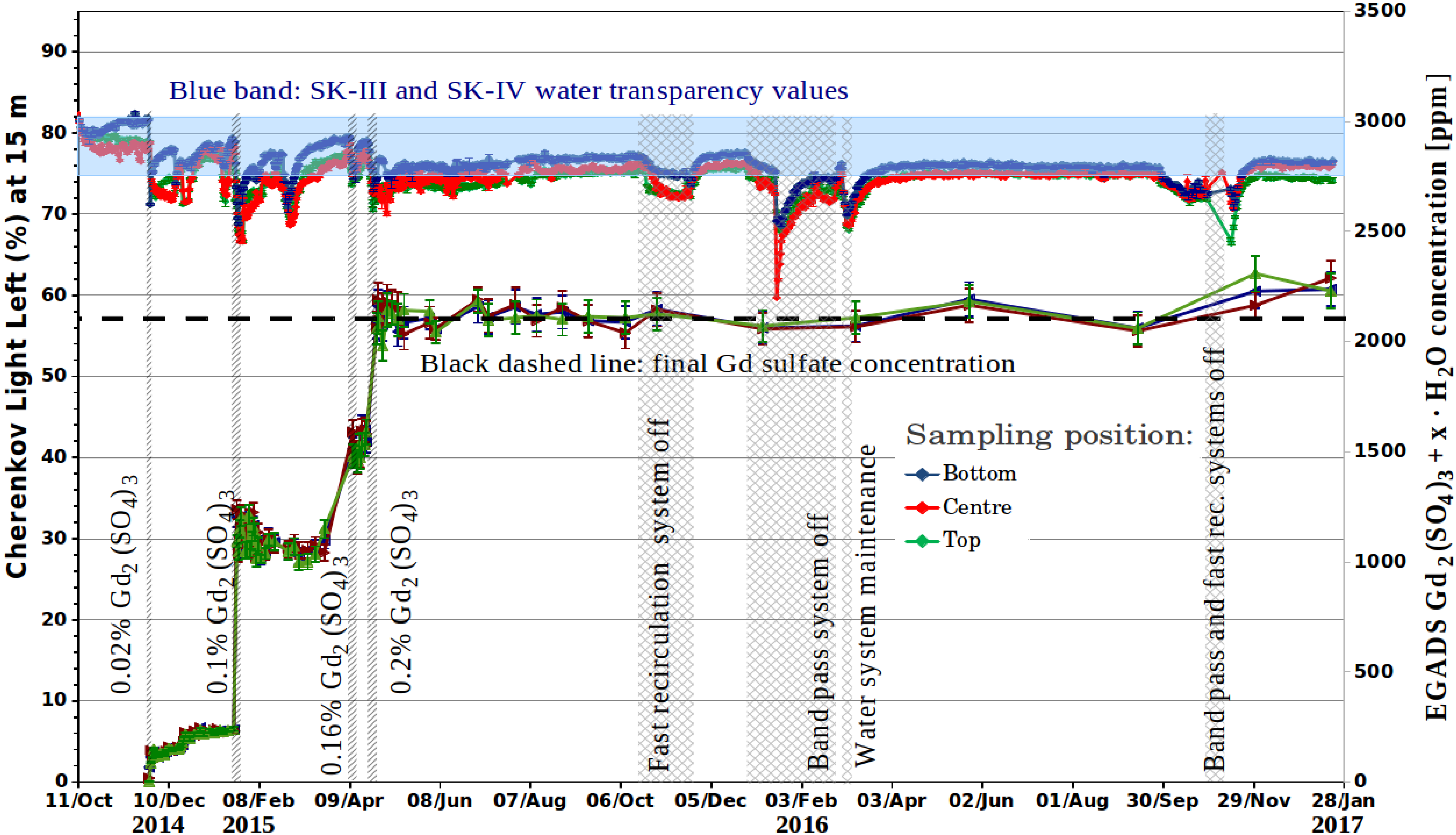


15m³ tank to dissolve Gd

Gd water circulation system
(purify water with Gd)

Transparency measurement
(UDEAL)

EGADS water quality



The light left at 15 m has been stable at ~75% for 0.2% $Gd_2(SO_4)_3$, corresponds to ~92% of SK-IV average.

No loss of Gd: >99.99% of Gd remains after circulating the water system for more than 350 times

Development of pure Gd powder

- U and Th/Ra contamination in Gd powder becomes backgrounds for solar neutrino measurements
- Intensively developing pure Gd powder with several companies
- Radio impurity measured w/ two methods:

Ge detector: Sensitive to almost 0.1 mBq/kg (Canfranc, Boulby and Kamioka)
ICPMS: For isotopes w/ long life (Kamioka)

* Goal for 0.2% Gd-sulfate loading

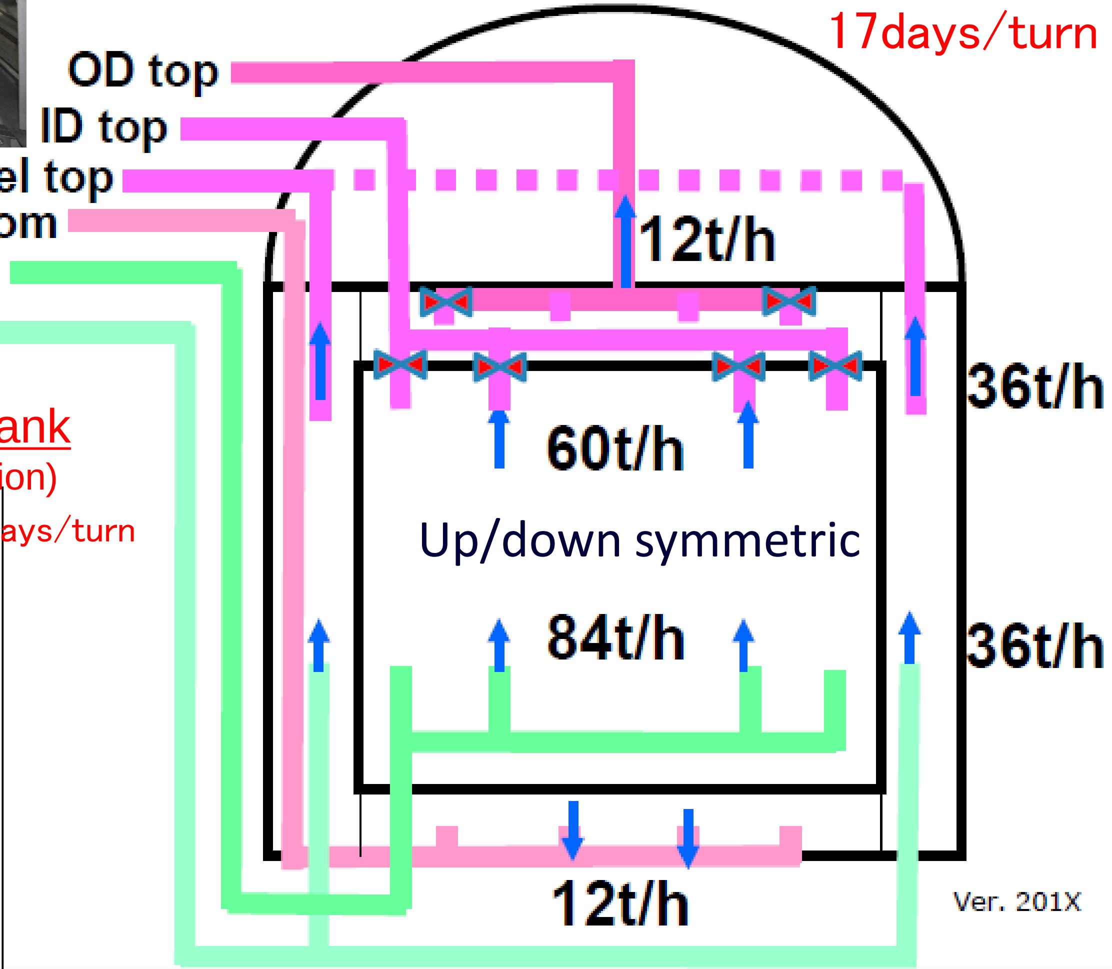
Chain	Isotope	Typical	Goal*	Company A		Company B		Company C	
				Ge	ICPMS	Ge	ICPMS	Ge	ICPMS
^{238}U	^{238}U	50	**< 5**	-	~ 0.04	< 11	< 0.04	< 10	< 0.04
	^{226}Ra	5	**< 0.5**	-	—	<0.2	—	< 0.2	—
^{232}Th	^{232}Th	100	**< 0.05**	-	~ 0.09		0.02	—	0.06
	^{228}Ra	10	**< 0.05**	-	—	< 0.3	—	< 0.2	—
	^{228}Th	100	**< 0.05**	-	—	< 0.3	—	< 0.3	—
^{235}U	^{235}U	30	**< 3**	-	—	< 0.4	—	< 0.3	—
	^{227}Ac/Th	300	**< 3**	-	—	< 1.7	—	< 1.2	—

Unit: [mBq/kg $(Gd_2SO_4)_3$]

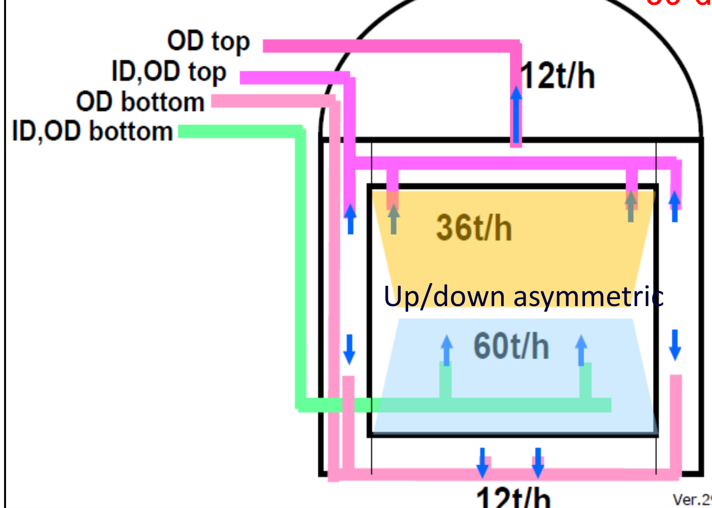
Company B achieved goals for U, 226Ra and 232Th

Improvement of tank piping

New piping in the tank
(120 tons/hour recirculation)

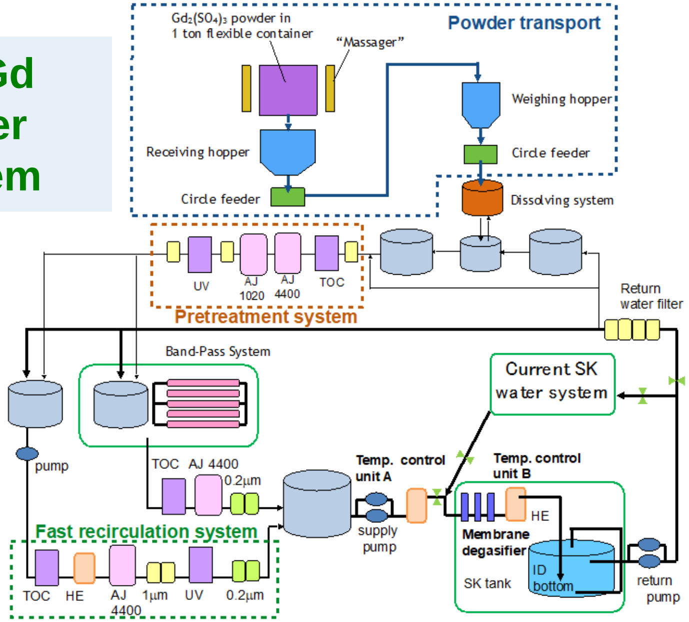


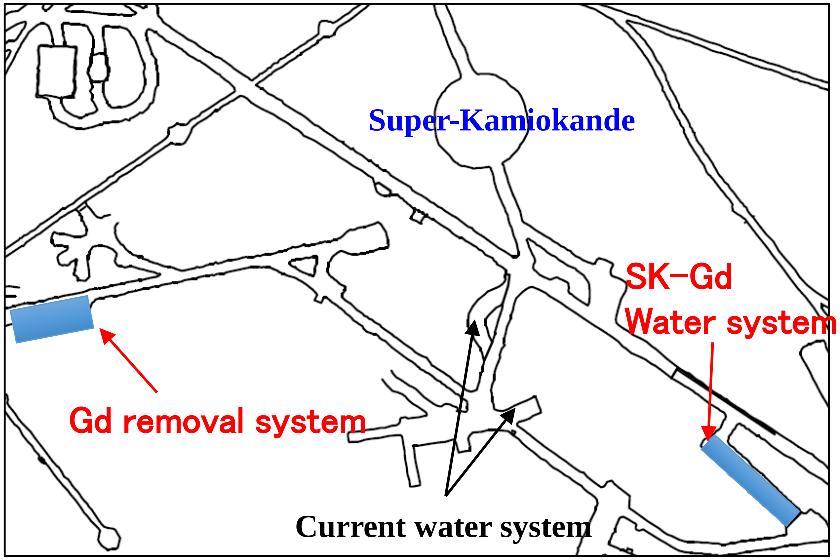
Old piping in the tank
(60 ton/hour recirculation)



SK-Gd water system based on EGADS experience

SK-Gd Water system





Gd removal system

Systems for SK-Gd have been installed