

Neutrinos from the outer region of the Sun -- solar flare and solar atmospheric neutrinos --

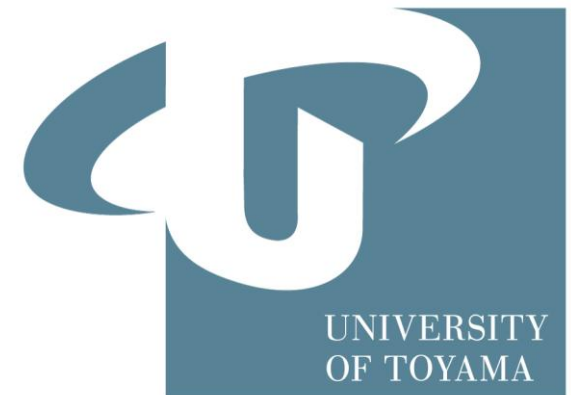
19th, September 2025

[II EU Workshop on Water Cherenkov Experiments
for Precision Physics](#)

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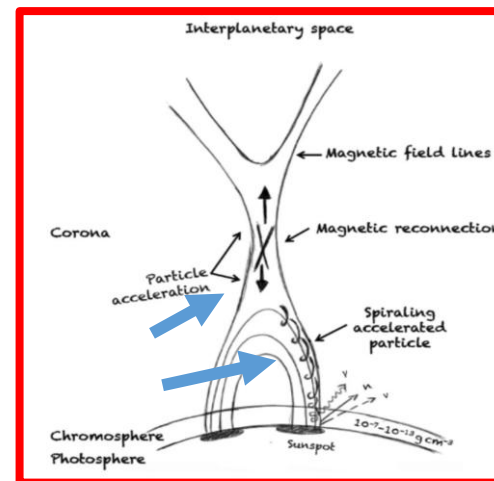
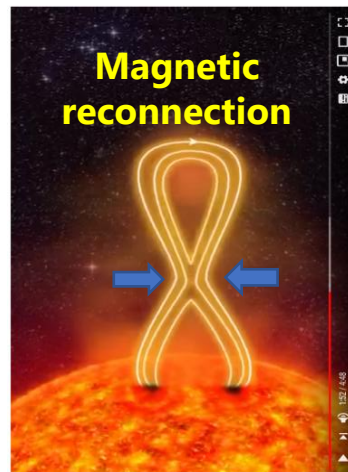
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- **Summary**

Motivation

■ Solar flare

- Solar flare accelerates charged particles and convert its magnetic energy into kinetic/thermal energies.
- Neutrinos from solar flares have not been detected so far.
- **Neutrino detection provides information about proton acceleration.**
- Neutral particles, such as γ -ray, X-ray, neutron, are useful to identify the time scale upto relativistic energies, astrophysical location of particle acceleration.



Particle acceleration occurs along with magnetic field line.

[Movie in youtube](#)

[Phys. Rev. D 103, 102001 \(2021\)](#)

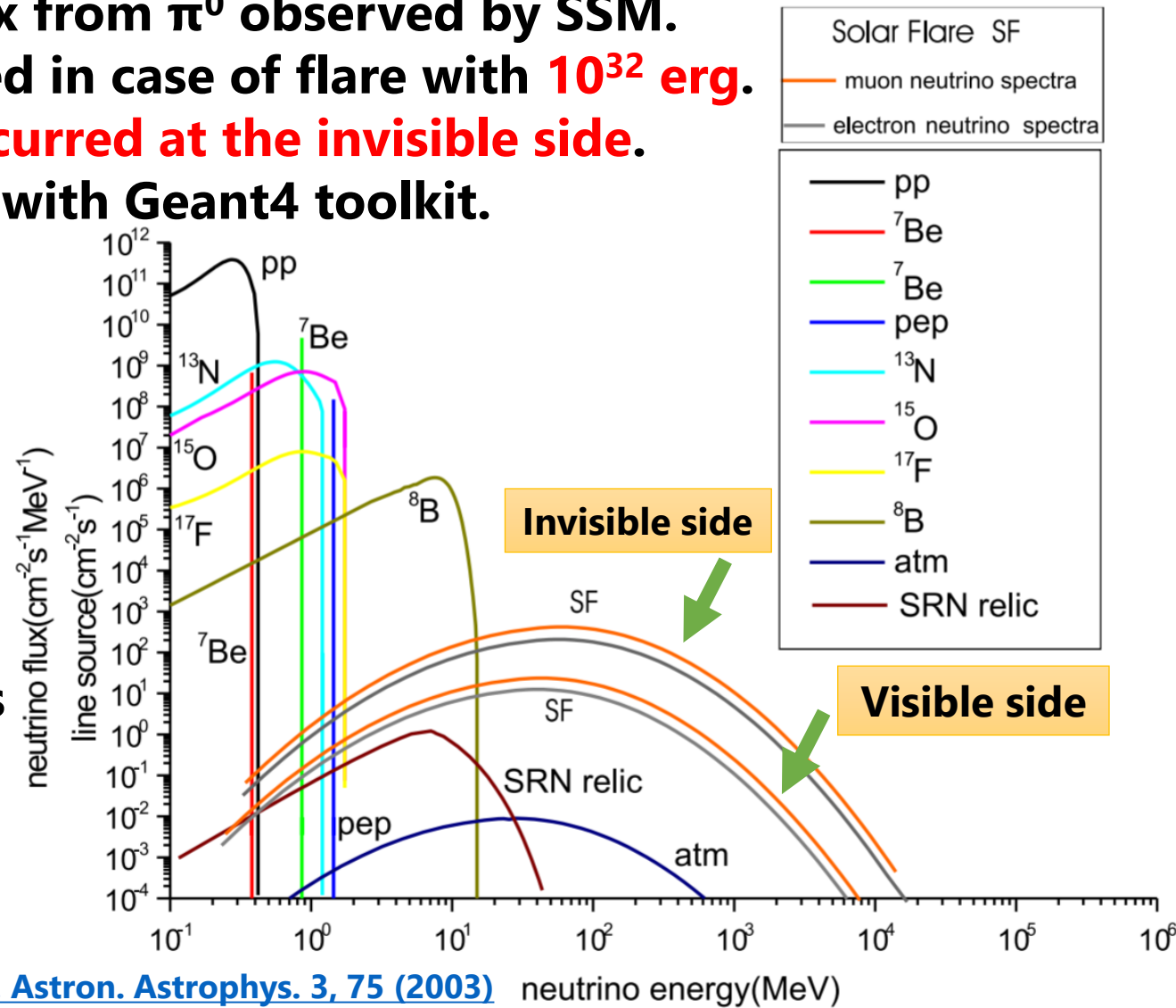
Expected neutrino flux

Theoretical models

- [Kocharov \(1991\)](#): Estimated neutrino flux from π^0 observed by SSM.
- [Fargion \(2004\)](#): Some events are expected in case of flare with 10^{32} erg.
Large flux when flare occurred at the invisible side.
- [Takeishi \(2013\)](#): Simulated neutrino flux with Geant4 toolkit.

Theoretical model (Reference)	Side of the Sun	Power index of proton	Directional feature of generated neutrino	Number of expected event in SK [flare ⁻¹]
Kocharov et al. (1991)	Visible side	3-4	isotropic	1.36×10^{-4}
Kocharov et al. (1991)	Invisible side	1	beam like	0.85
Fargion (2004)	Visible side	-	isotropic	0.75
Fargion (2004)	Invisible side	-	isotropic	7.5
Takeishi et al. (2013)	Invisible side	3	isotropic	9.0×10^{-5}
Takeishi et al. (2013)	Invisible side	1	beam like	3.8×10^{-6}

- Neutrino detectors with large target mass can **experimentally testify those models** by counting neutrino interactions during solar flare.



Search window for neutrino from solar flare^{p. 5}

■ Situation of neutrino search

- **Solar flare released neutrino only during time scale of particle acceleration.**
- **On the other hand, atmospheric neutrinos are constantly generated, and its energy range overlapped with neutrino from solar flares.**

■ Strategy

- **Search window** is required to improve the possibility of solar flare neutrino detection.
- **Proton acceleration results in neutrino production.**
 - π produced when protons are accelerated more than 300 MeV.
(Neutrinos are produced in the chain of π decays)
- **To identify the proton acceleration, we analyzed the satellites data by finding,**
 - (1) **Line γ -ray** (neutron capture)
 - (2) **De-excitation γ -ray** from nuclei, such as ^{12}C or ^{16}O .

Example of the search windows (visible side)

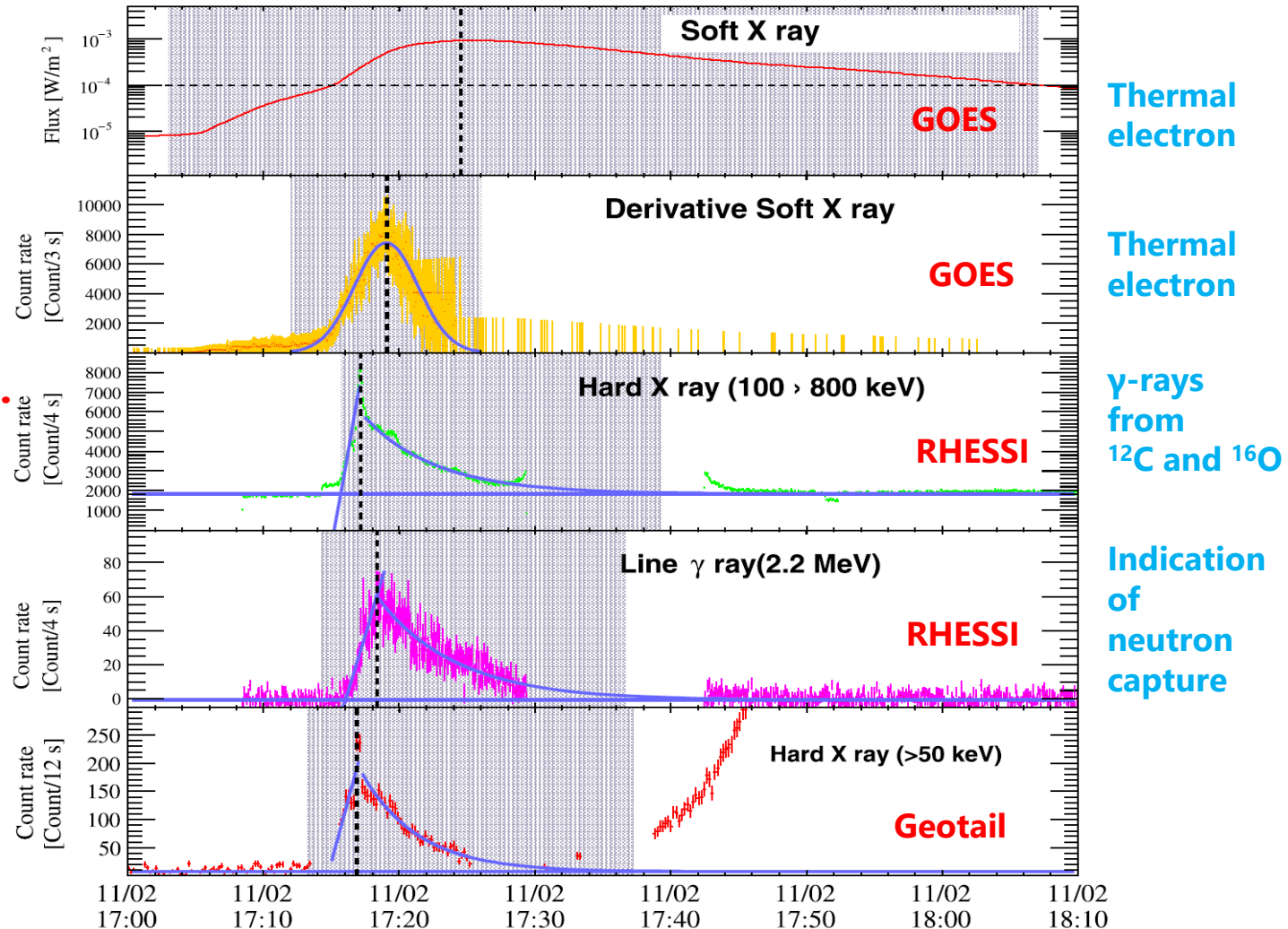
Example: November 2nd, 2003 (X9.2)

Satellite	Type
GOES	Soft X-ray (its derivative)
RHESSI	Hard X-ray, Line γ -ray
Geotail	Hard X-ray, soft γ -ray

They have finished data taking.

Type	Typical duration	# of flares
Soft X-ray	4178 sec	23
Derivative	700 sec	22
Hard X-ray	944 sec	5
Line γ -ray	1586 sec	3
Geotail	776 sec	7

Typically 10-15 minutes.



See detail
[Solar Physics 295, 133 \(2020\)](#)

Neutrino candidates (visible side)

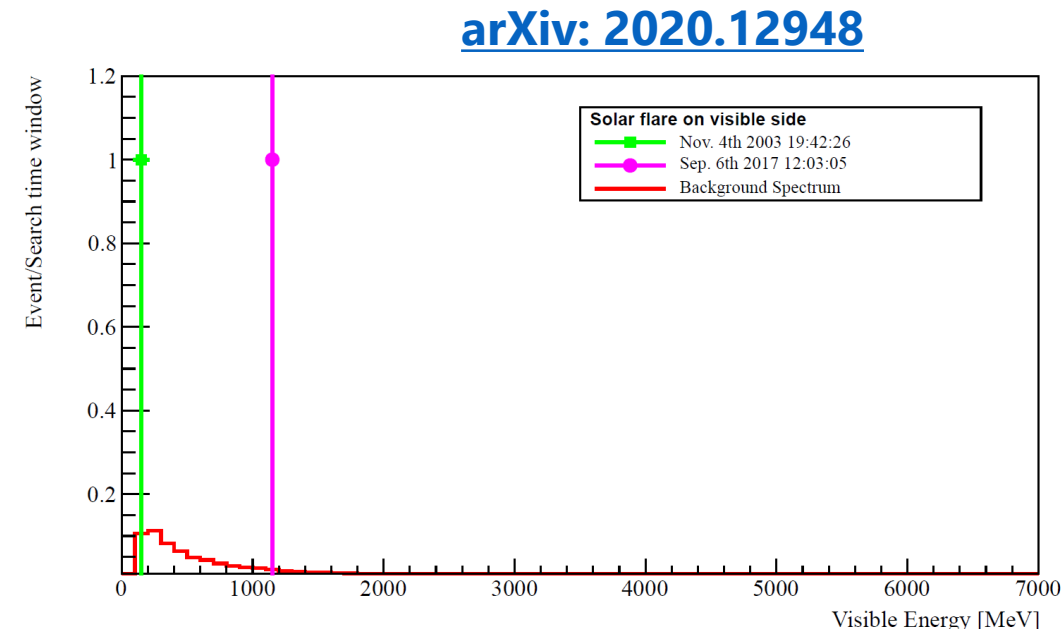
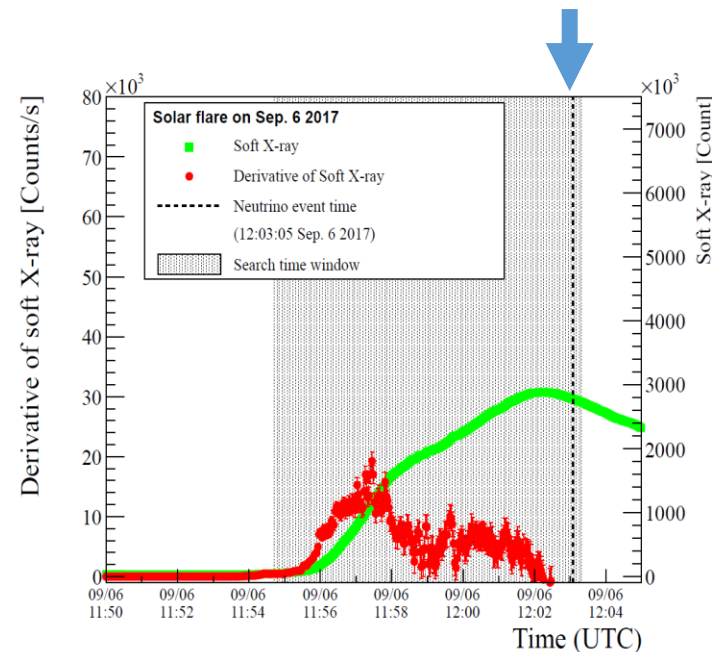
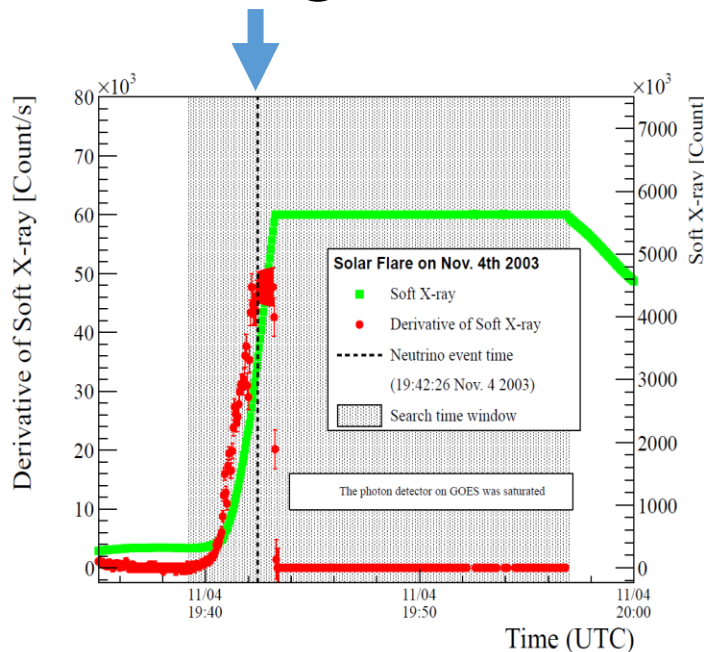
Below 100 MeV, no events

■ November 4th, 2003 (X28.0)

- One candidate is found in the search window (**impulsive phase of that flare**).
- 2-ring e-like, 178.3 MeV.

■ September 6th, 2017 (X9.4)

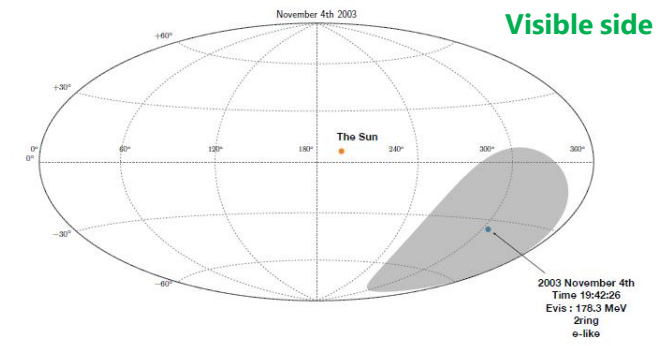
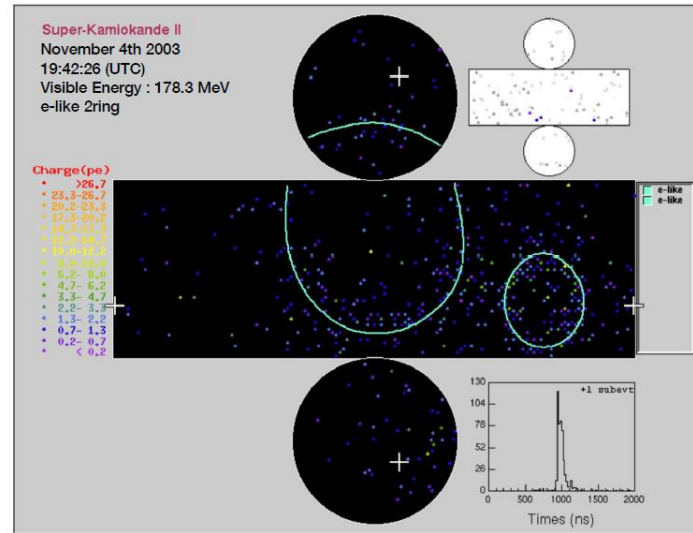
- One candidate is found in the search window (**after the peak of light curve**).
- 1-ring μ -like, 1.2 GeV.



Event candidates from visible side of the Sun

■ November 4th, 2003 (X28.0)

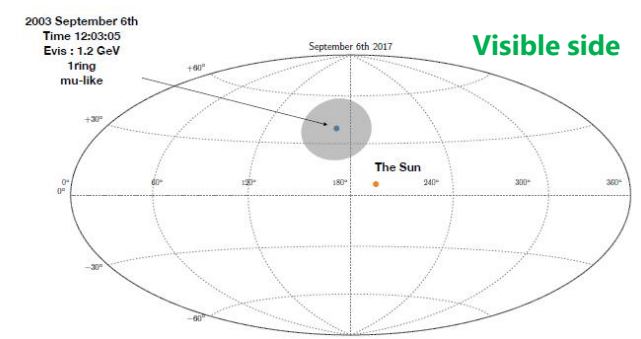
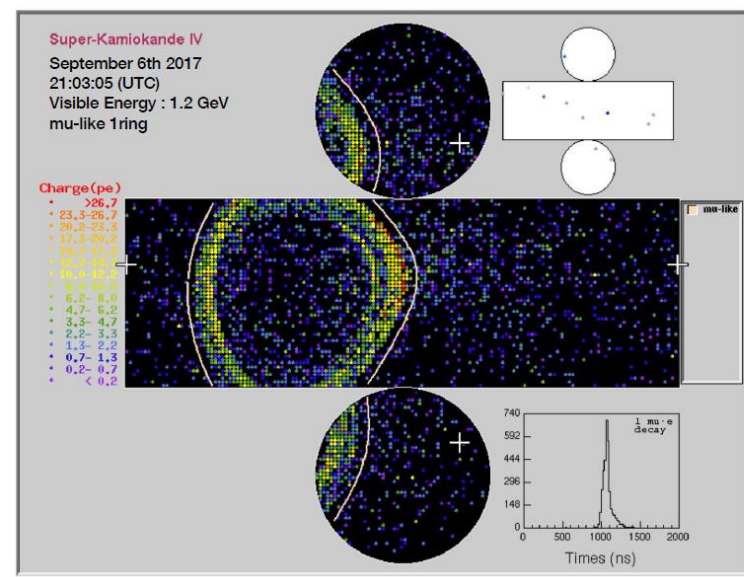
- One candidate is found in the search window (**impulsive phase of that flare**).
- 2-ring e-like, 178.3 MeV.



[arXiv: 2020.12948](https://arxiv.org/abs/2020.12948)

■ September 6th, 2017 (X9.4)

- One candidate is found in the search window (**after the peak of light curve**).
- 1-ring μ -like, 1.2 GeV.

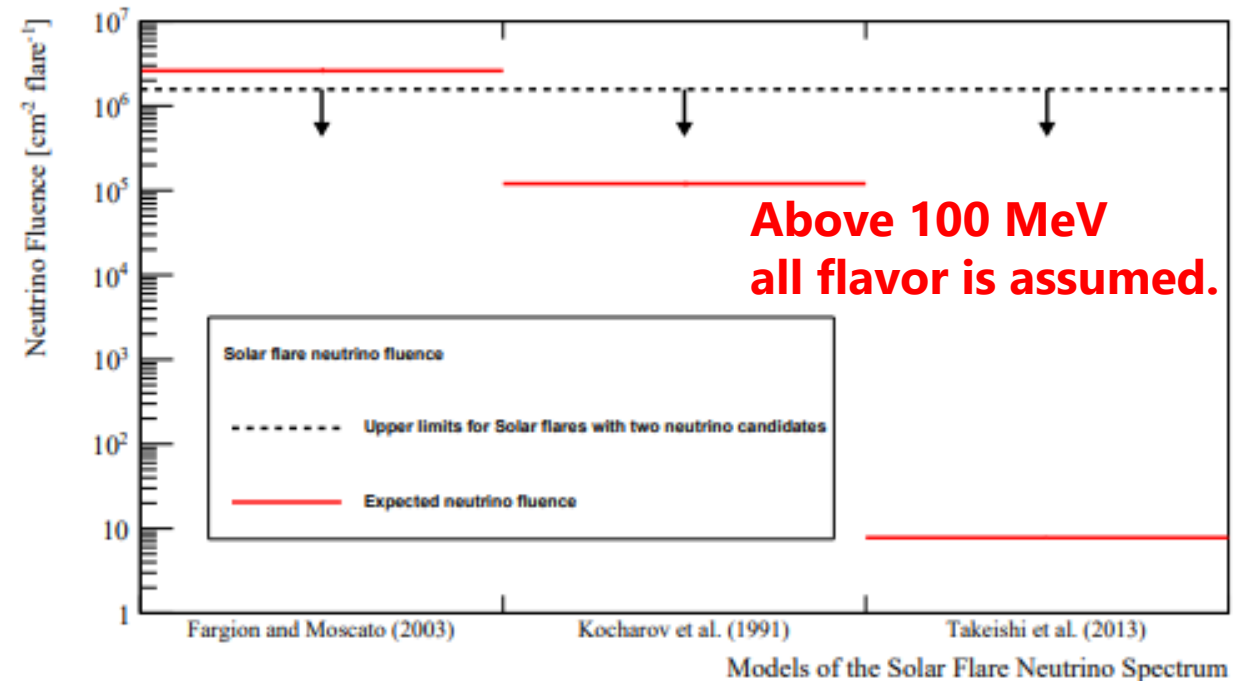
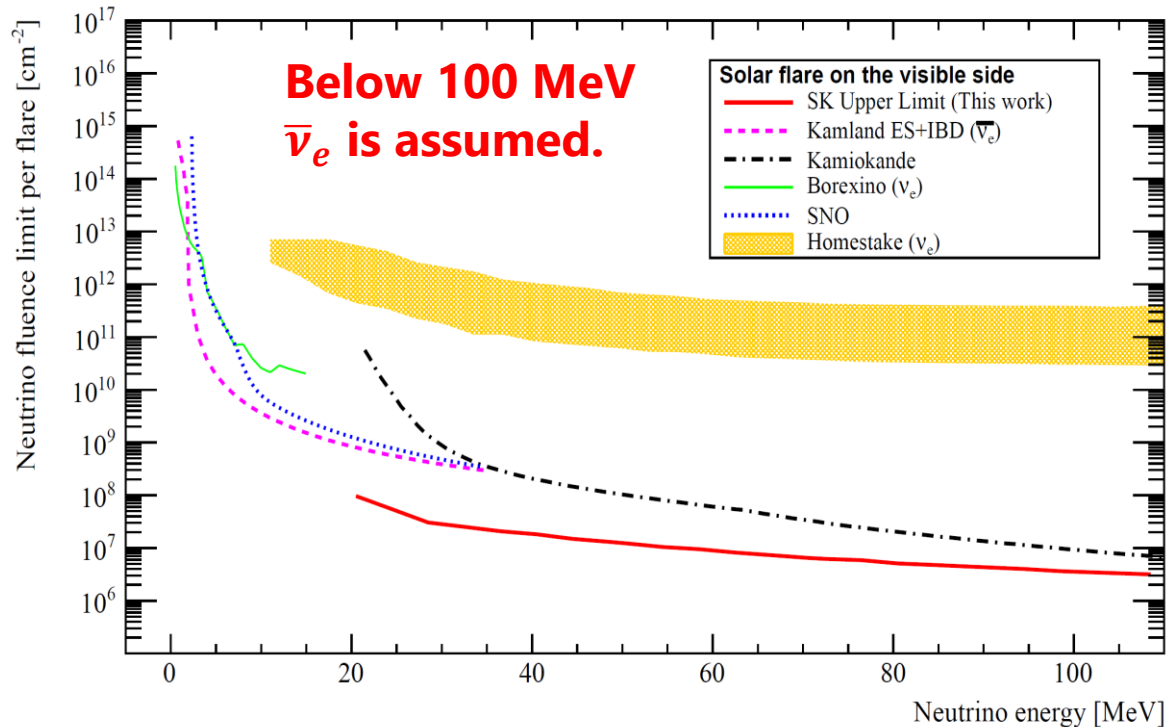


BG rate consistent in both cases.

Comparison among neutrino detectors

■ Testing theoretical models

- Set the upper limit for the solar flare neutrinos below 100 MeV, and excluded one theoretical model by [Fargion \(2004\)](#).
- Hyper-Kamiokande can test other theoretical models in sub-GeV region.

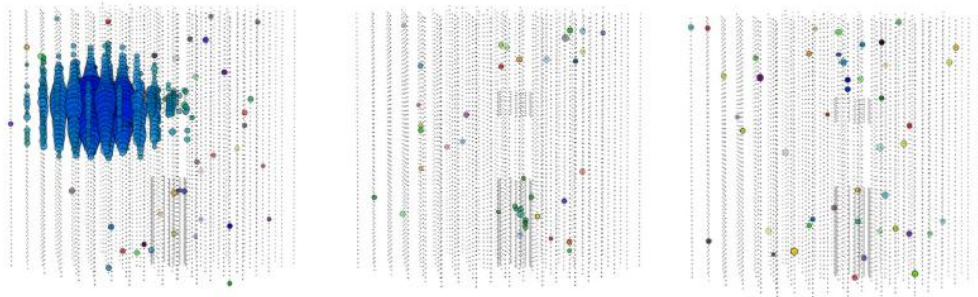


Solar flare neutrino search by IceCube

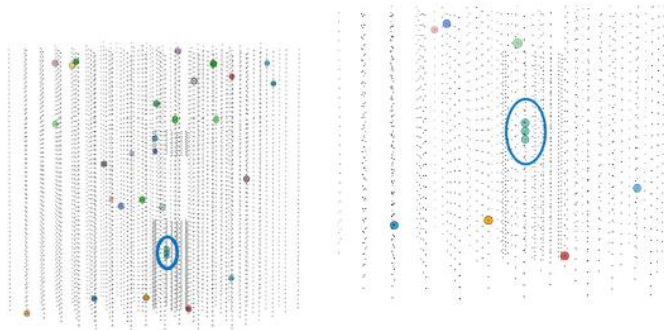
■ Constraint on the spectrum index of neutrinos

- IceCube also searched for solar flare neutrinos in **O (GeV)**.

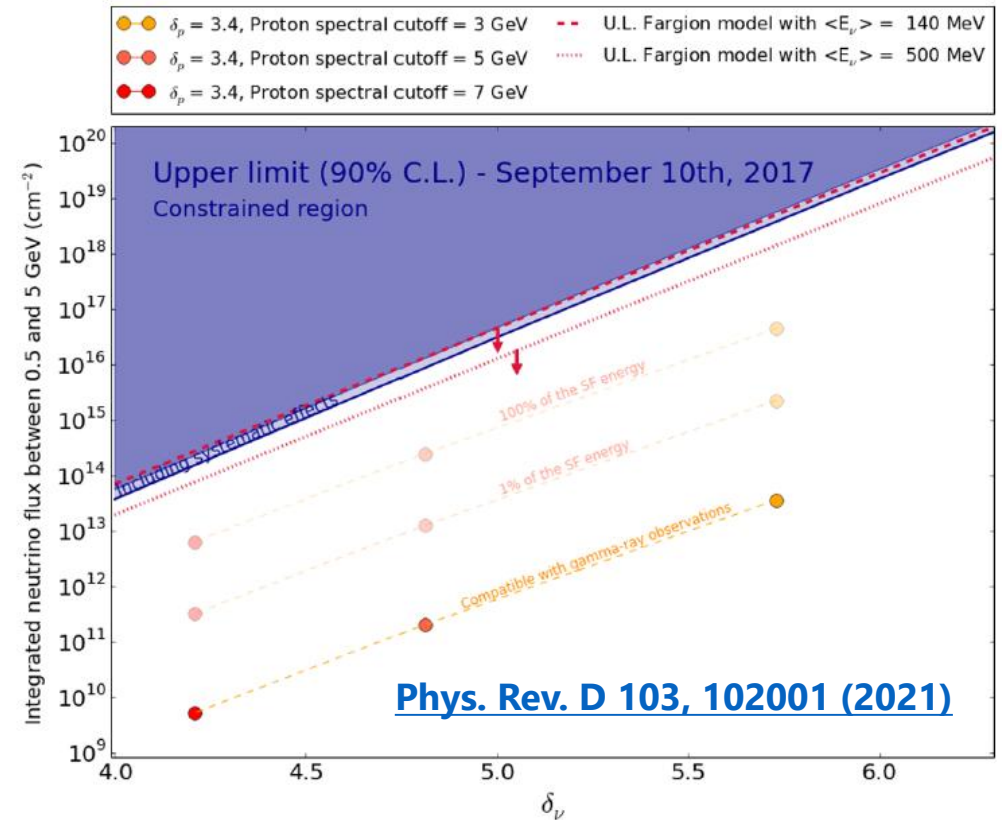
- 1) Time window: solar flare catalog from Fermi-LAT (γ -rays from π^0 decays).
- 2) Assuming the power-index of proton spectra are 4 or 6.



(a) PeV neutrino interaction (b) 10 GeV neutrino interaction (c) Detector noise event



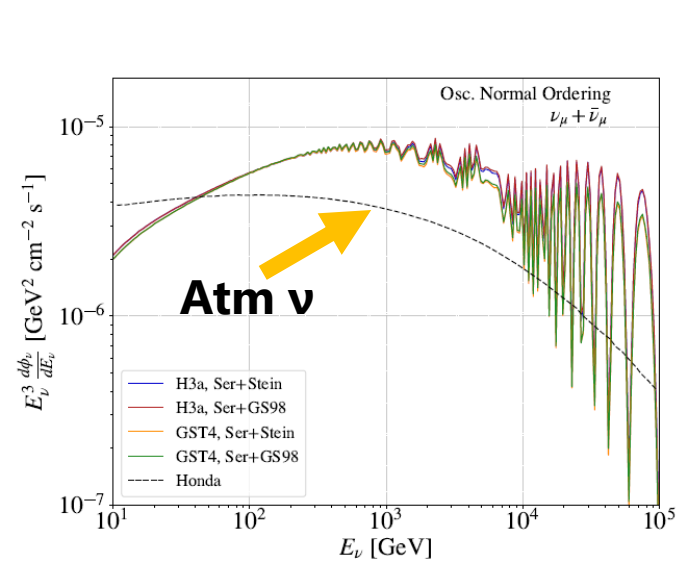
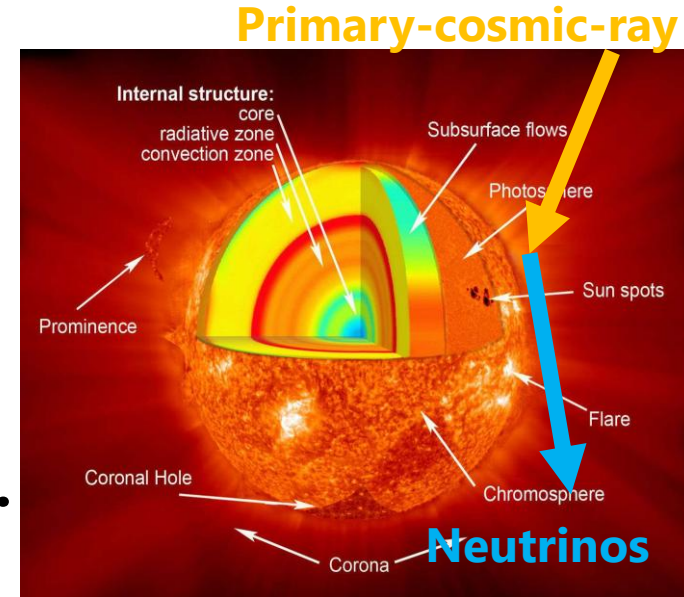
(d) GeV neutrino interaction (e) Focus on the GeV neutrino interaction



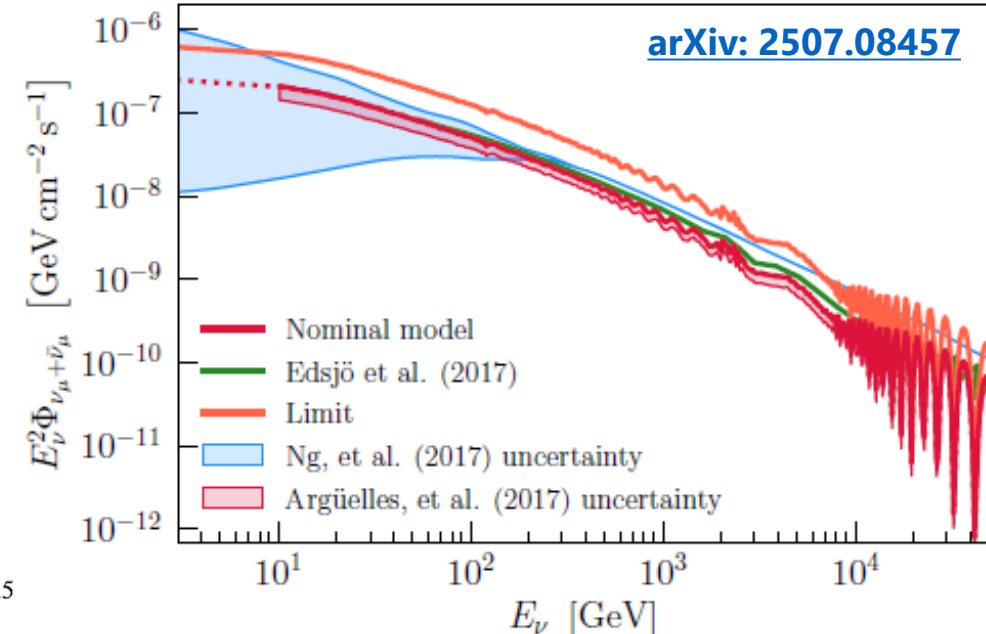
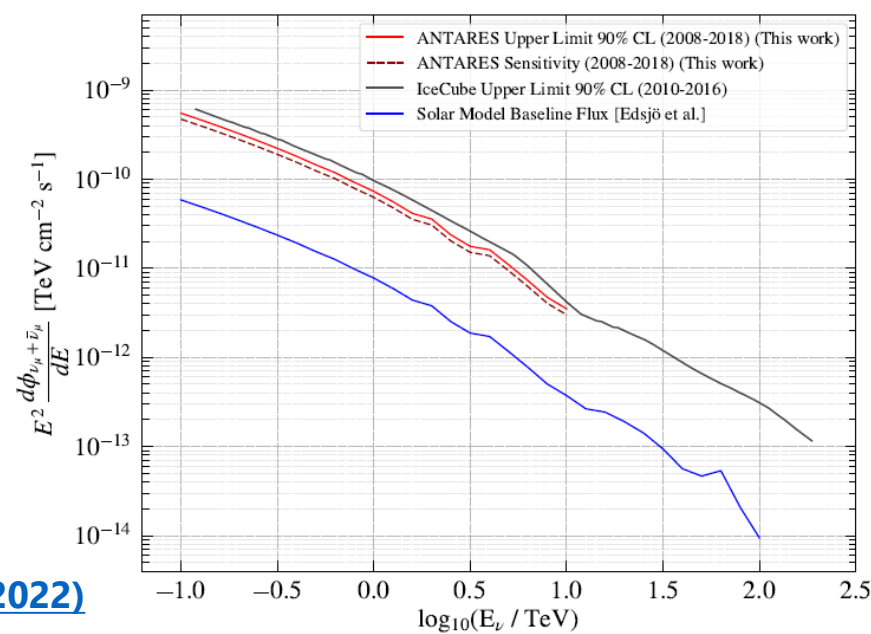
Solar “atmospheric” neutrinos

High energy neutrinos from the Sun

- Primary cosmic-ray collides with proton at the Sun’s atmosphere.
 - Such collision produce **very high energy neutrinos**.
- ANTARES and IceCube set the upper limits in TeV region. (used as the background rate of dark matter searches)



JCAP 06, 018 (2022)



arXiv: 2507.08457

Summary

- **Solar flare accelerates charged particle.**
 - 1) **Neutrinos are generated via π decay chain.**
 - 2) **Neutrino detection provides information of proton acceleration.**
 - 3) **Some theoretical models for neutrino emissions have been proposed.**

- **Determined the timing window by light curves observed by satellites.**
- **Water Cherenkov detectors have contributed to search for solar flare neutrinos.**
 - 1) **SK found two neutrino candidates in case of solar flare on the visible side.**
 - 2) **SK set world-leading constraint of neutrino fluence from solar flare.**
 - 3) **IceCube also constraint the power index of neutrino spectra.**

- **Solar atmospheric neutrinos attract attention for high energy neutrinos.**
- **Future detection is eagerly awaited by Water Cherenkov detectors.**

Back up slides

Time window in order to search for neutrinos

- We selected solar flares more than X5.0 class (to satisfy 10^{32} erg).

Time window for **visible side**

We analyzed the public data from CIDAS.

Satellite	Type
GOES	Soft X-ray (its derivative)
RHESSI	Hard X-ray, Line γ -ray
Geotail	Hard X-ray, soft γ -ray

We used GOES data since it is always available.

To tag neutron reactions, we analyzed the data including Line γ -ray, γ -rays from ^{12}C , ^{16}O . Therefore, we selected RHESSI and Geotail data.

*We know several satellites and data bases exist. To cover the Super-Kamiokande's data set (1996 April-2018 May), we selected satellites described above.

Time window for **invisible side**

We used the catalog of CMEs (LASCO). CMEs more than 2000 km/sec are selected.

This criteria allow to select at least X2.0 class.

1996 April-2018 May	Selected flares
Visible side	23
Invisible side	10 (but 2 of them are not used)

See detail
Solar Physics 295, 133 (2020)

Selected flares (solar cycle 23 and 24)

Our search windows for visible side

Time duration is determined by analyzing derivative of soft X-ray (GOES)

Date	Class X	t_{start}	t_{end}	Δt [s]	AR location
1997 Nov. 6	9.5	11:52:13	11:54:58	165	S18W63
2000 Jul. 14	5.7	10:08:44	10:28:31	1,187	N22W07
2001 Apr. 2	20.0	21:35:10	21:52:57	1,067	S21E83
2001 Apr. 6	5.6	19:12:32	19:21:31	539	S21E31
2001 Apr. 15	14.4	13:43:48	13:51:03	435	S20W85
2001 Aug. 25	5.8	16:28:36	16:33:38	302	S17E34
2001 Dec. 13	5.3	14:24:25	14:31:05	400	N16E09
2002 Jul. 23	5.1	00:25:08	00:31:36	388	S13E72
2003 Oct. 23	5.4	08:20:32	08:36:03	931	S21E88
2003 Oct. 28	17.2	10:59:30	11:10:57	687	S16W08
2003 Oct. 29	10.0	20:38:46	20:50:07	681	S15W02
2003 Nov. 2	9.2	17:12:01	17:26:03	842	S14W56
2003 Nov. 4	28.0	19:36:59	19:56:03	1,144	S19W83
2005 Jan. 20	7.1	06:39:22	06:57:12	1,070	N14W61
2005 Sep. 7	18.2	17:23:34	17:39:48	974	S11E77
2005 Sep. 8	5.4	21:00:27	21:08:05	458	S12E75
2005 Sep. 9	6.2	-	-	-	S12E67
2006 Dec. 5	9.0	10:24:18	10:35:43	685	S07E68
2006 Dec. 6	6.5	18:41:29	18:47:06	337	S05E64
2011 Aug. 9	7.4	08:00:50	08:05:40	290	N14W69
2012 Mar. 7	5.4	00:04:21	00:25:16	1,255	N22E12
2017 Sep. 6	9.4	11:54:39	12:03:20	521	S09W34
2017 Sep. 10	8.3	15:49:12	16:06:32	1,040	S08W88

Our search windows for invisible side

Time duration is determined from systematic studies of correlation between CMEs's speed and solar flare intensity.

3060 sec before CMEs emission (Yashiro & Gopalswamy(2009))
4178 sec after CMEs emission (Okamoto et al (2020)).

In total **7238 sec** for every search.

Date	Time [UTC]	t_{start}	t_{end}	AR location	Speed [km s^{-1}]
2001 Apr. 18	02:06:24	01:15:24	03:16:02	SW90b	2464.2
2002 Jul. 18	18:58:20	18:07:20	20:07:58	E90b	2191.3
2002 Jul. 19	16:04:34	15:13:34	17:14:12	S15E90	2046.6
2003 Nov. 2	09:00:23	15:13:34	17:14:12	SW90b	2036.0
2003 Nov. 7	15:32:19	14:41:19	16:41:57	W90b	2237.0
2003 Nov. 9	05:57:57	05:06:57	07:45:29	E90b	2008.1
2005 Jul. 24	13:35:51	12:44:51	14:45:29	E90b	2527.8
2011 Jun. 4	21:42:42	20:51:42	22:52:20	N16W153	2425.5
2012 Jul. 23	02:10:07	01:19:07	03:19:45	S17W132	2003.2
2014 Dec. 13	13:57:34	13:06:34	15:07:12	S20W143	2221.6

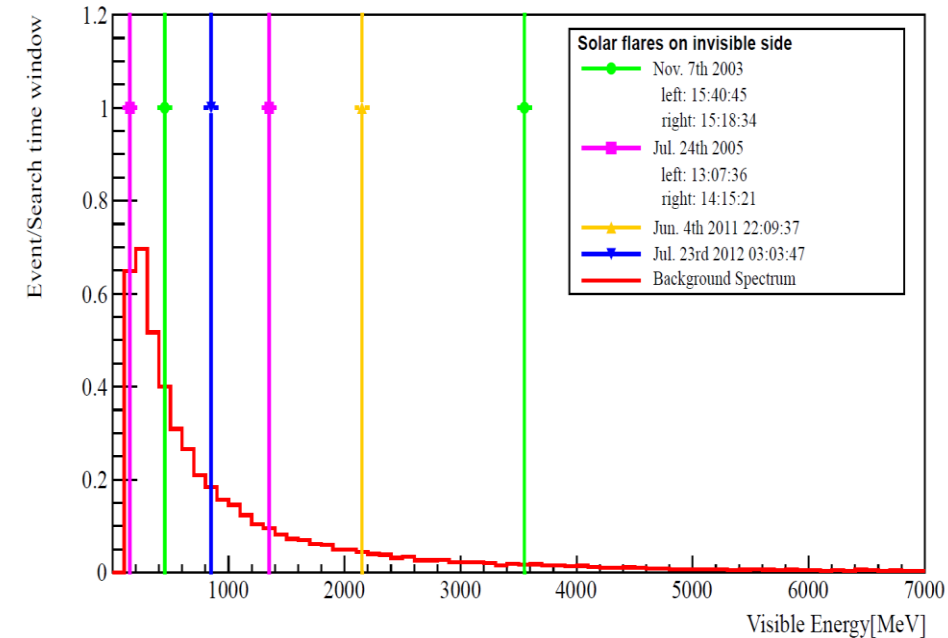
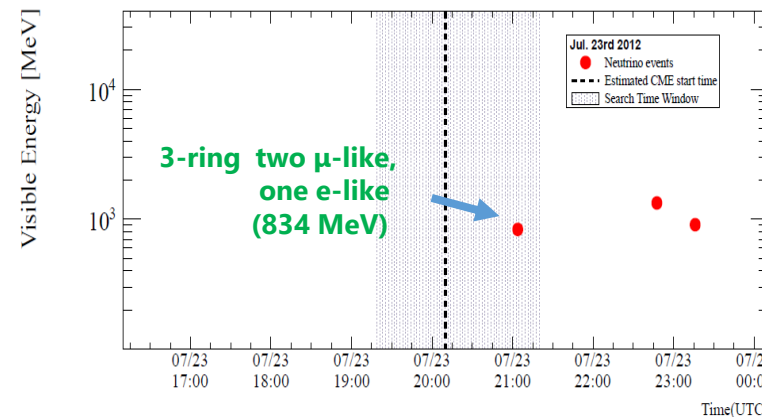
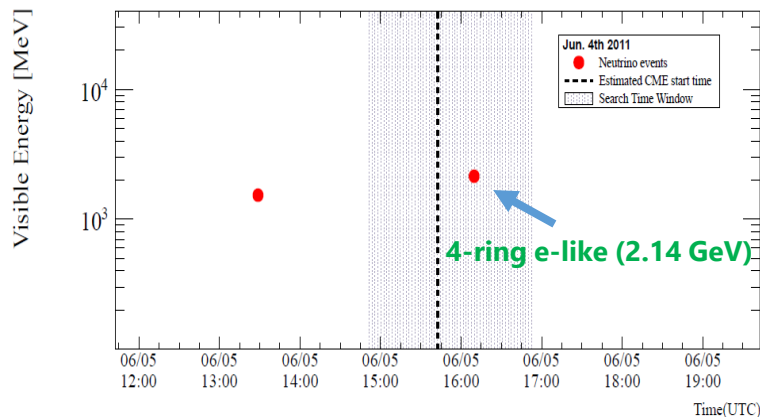
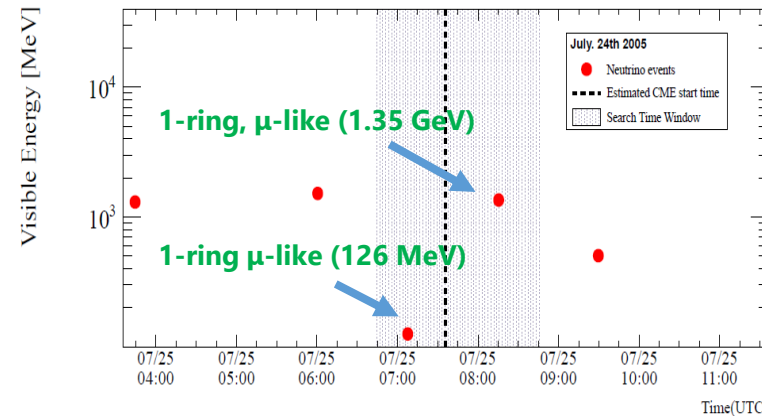
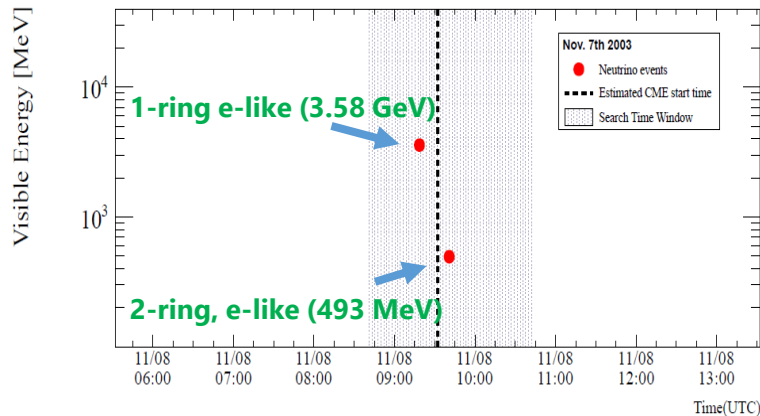
See detail
 Solar Physics 295, 133 (2020)

Neutrino candidates (invisible side)

Below 100 MeV, no events

■ Candidates

- **6 events** were found in the search windows (**7238 sec**).
- **Two consecutive events** in Nov. 7th, 2003 (**1131 sec**), Jul. 24th, 2005 (**4065 sec**).



Fluence limit assuming Fargion's spectrum

$$P_{\text{High}}(S + B | n_{\text{obs}}) = \frac{1}{A'} \iiint \frac{e^{-(S+B)} (S + B)^{n_{\text{obs}}}}{n_{\text{obs}}!} \times G(\Delta\sigma(E_\nu)) G(\Delta\varepsilon_{\text{High}}) G(\Delta B) d(\Delta\sigma(E_\nu)) d(\Delta\varepsilon_{\text{High}}) d(\Delta B)$$

$$S = N_T \int dE_\nu \sum_{i=e,\mu,\tau,\bar{e},\bar{\mu},\bar{\tau}} \left(\frac{F(E_{\nu_i}) \sigma(E_{\nu_i}) \varepsilon_{\text{High}}(E_{\nu_i})}{6} \right),$$

S: Expected signal

B: Background rate

N_T: Target of SK tank

F: Neutrino spectrum

σ: Cross section of neutrino

ε: Reduction efficiency

G: prior probabilities for fluctuation

Side	Selected flare	Observed event	Upper limits of energy conversion factor	Fluence limits [cm ⁻² flare ⁻¹]
Visible side	November 4th, 2003	1	< 0.004	< 8.5 × 10 ⁵
	September 6th, 2017	1	< 0.46	< 8.9 × 10 ⁵
	Other 22 flares	0	< 0.31	< 5.6 × 10 ⁵
Invisible side	November 7th, 2003	2	-	< 1.2 × 10 ⁶
	July 24th, 2005	2	-	< 1.2 × 10 ⁶
	June 4th, 2011	1	-	< 8.2 × 10 ⁵
	July 23rd, 2012	1	-	< 8.2 × 10 ⁵
	Other 6 flares	0	-	< 5.6 × 10 ⁵

Since no events were found below 100 MeV, neutrino fluence is calculated the sample above 100 MeV.

Fluence limits are shown in left table.