Search for neutrinos associated with solar flare

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1.Introduction

Neutrinos associated with solar flares (solar flare neutrinos)

- Solar Flare is a release of magnetic energy on the sun surface[1].
  Typical Total energy: $10^{29} \sim 10^{32}$ erg   Typical Time scale: 100 ~ 1000 sec
- The flux of solar flare neutrinos are estimated by solar flare models [2-4].
  The predicted neutrino flux originated from the solar flares occurred on the opposite side of solar surface from the earth (invisible side) would be larger than that of the other side (visible side).
- Solar flare neutrinos have been experimentally sought by several neutrino detectors but not observed yet [5-12].

Table 1: Summary of the predicted solar flare models.

Models	Solar flare location	Proton acceleration condition	The number of expected events in SK [event/flare]
Kocharov [2]	Visible	Isotropic	1.36×10^{-4}
	invisible	Beam-like	0.85
Takeishi [3]	Visible	Isotropic	9.0×10^{-5}
	invisible	Beam-like	3.6×10^{-6}
Fargion [4]	Visible	Isotropic	0.75
	invisible	Isotropic	7.5

The Super-Kamiokande detector (SK) [13]

- SK is a water Cherenkov detector with 50 kton pure water and ~11,000 PMTs for inner detector located at 1000 m (2700 m water equivalent) below the top of Mt. Ikenoyama in Gifu prefecture, Japan.
- SK has 6 data taking periods up to date, called SK-I ··· SK-VI.
- In this analysis, the date sets from SK-I to SK-IV were used.

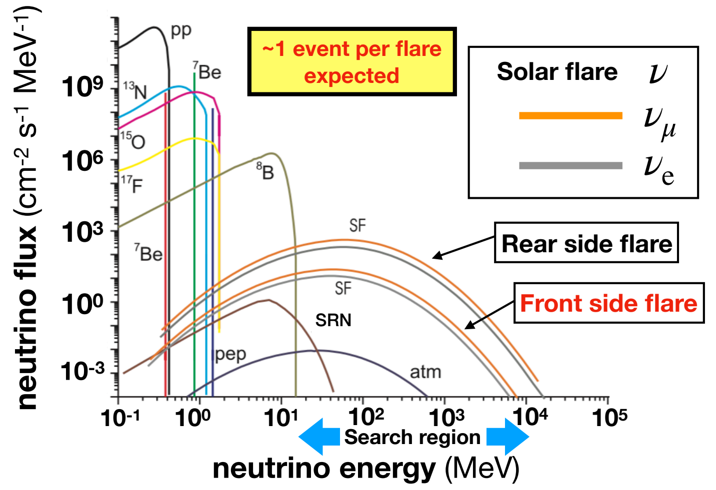

Figure 1: An expected neutrino flux [4]

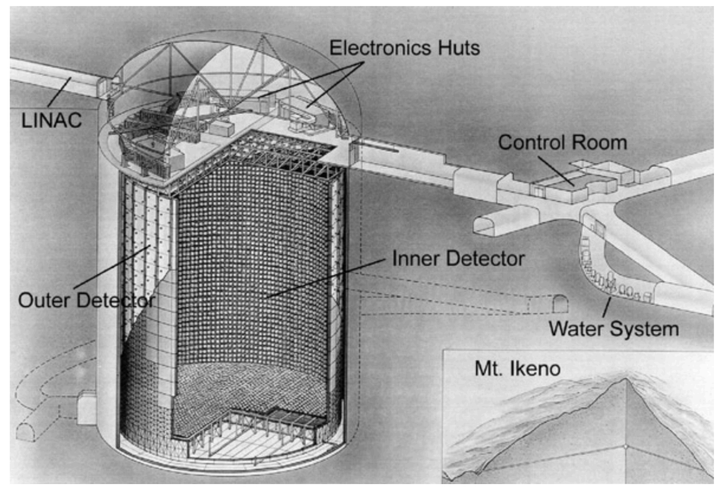

Figure 2: schematic view of SK [5]

Reference
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[18]]Phys. Rev. D 97, 072001 (2018)

2. Search time window

The separation between solar flare neutrinos and atmospheric neutrinos is technically difficult. To enhance the S/N, solar flare events are selected with appropriate time window.

Solar flares on the visible side of the Sun

- To get large signal, 23 largest class flare events (> X5) were selected as summarized in Table 2(Apr. 1996~ May. 2018).
- Data used for determining time windows for solar flares on visible side[14];
  Soft X-ray (1-8 Å) from GOES[15], Hard X-ray (100 keV -800 keV) and
  γ-ray(2.223 MeV) from RHESSI[16], Soft γ-ray (>50 keV) from GEOTAIL[17].

Table 2: Summary of the target solar flares on visible side

	Date	Class	start	End	Visible energy of signal	Event time	Fluence limit [cm^{-2}]
1	1997/Nov/06	X9.5	11:52:13	11:54:58	No signal	-	5.6×10^5
2	2000/Jul/14	X5.7	10:08:44	10:28:31	No signal	-	5.6×10^5
3	2001/Apr/02	X20.0	21:35:10	21:52:57	No signal	-	5.6×10^5
4	2001/Apr/06	X5.6	19:12:32	19:21:31	No signal	-	5.6×10^5
5	2001/Apr/15	X14.4	13:43:48	13:51:03	No signal	-	5.6×10^5
6	2001/Aug/25	X5.8	16:28:36	16:33:38	No signal	-	5.6×10^5
7	2001/Dec/13	X5.3	14:24:25	14:31:05	No signal	-	5.6×10^5
8	2002/Jul/23	X5.1	00:25:08	00:31:36	No SK data	-	5.6×10^5
9	2003/Oct/23	X5.4	08:20:32	08:36:03	No signal	-	5.6×10^5
10	2003/Oct/28	X17.2	10:59:30	11:10:57	No signal	-	5.6×10^5
11	2003/Oct/29	X10.0	20:38:46	20:50:07	No signal	-	5.6×10^5
12	2003/Nov/02	X9.2	17:12:01	17:26:03	No signal	-	5.6×10^5
13	2003/Nov/04	X28.0	19:36:59	19:56:03	181.9 MeV	19:42:26	8.5×10^5
14	2005/Jan/20	X7.1	06:39:22	06:57:12	No signal	-	5.6×10^5
15	2005/Sep/07	X18.2	17:23:34	17:39:48	No signal	-	5.6×10^5
16	2005/Sep/08	X5.4	21:00:27	21:08:05	No signal	-	5.6×10^5
17	2005/Sep/09	X6.2	19:13:00	21:20:36	No signal	-	5.6×10^5
18	2006/Dec/05	X9.0	10:24:18	10:35:43	No signal	-	5.6×10^5
19	2006/Dec/06	X6.5	18:41:29	18:47:06	No signal	-	5.6×10^5
20	2011/Dec/09	X7.4	08:00:50	08:05:40	No signal	-	5.6×10^5
21	2012/Mar/07	X5.4	00:04:21	00:25:16	No signal	-	5.6×10^5
22	2017/Sep/06	X9.4	11:54:39	12:03:20	1186.8 MeV	12:03:05	8.9×10^5
23	2017/Sep/10	X8.3	15:49:12	16:06:32	No signal	-	5.6×10^5

Solar flares on the invisible side of the Sun

- For solar flares on the invisible side, Coronal Mass Ejection (CME) data was used.
- 10 CMEs occurred on the invisible side of the Sun, whose speed exceeds 2000 km/sec, were selected as target Solar flares as shown in Table 3.
- The start time of solar flares can be estimated with CME data recorded by LASCO[18]. For end time, we conservatively set the start and end time of search time window as before 3060 seconds and after 4178 seconds from estimated CME emission start time.

Table 3: Summary of the target solar flares on invisible side

	Date	start	End	Visible energy of signal	Event time	Fluence limit [cm^{-2}]
1	2001/Apr/18th	01:15:24	03:16:02	No signal	-	5.6×10^5
2	2002/Jul/19th	18:07:20	20:07:58	No SK data	-	5.6×10^5
3	2002/Jul/20th	15:13:34	17:14:12	No SK data	-	5.6×10^5
4	2003/Nov/2nd	08:09:23	10:10:01	No signal	-	5.6×10^5
5	2003/Nov/7th	14:41:19	16:41:57	3555.9 MeV, 493.1 MeV	15:18:34, 15:40:45	1.2×10^5
6	2003/Nov/9th	05:06:57	07:07:35	No signal	-	5.6×10^5
7	2005/Jul/24th	12:44:51	14:45:29	125.5 MeV, 1351.3 MeV	13:07:36, 14:15:21	1.2×10^6
8	2011/Jun/4th	20:51:42	22:52:20	2135.6 MeV	22:09:37	8.2×10^5
9	2012/Jul/23rd	01:19:07	03:19:45	834.8 MeV	03:03:47	8.2×10^5
10	2014/Dec/13th	13:06:34	15:07:12	No signal	-	5.6×10^5

3. Result of Searching for neutrinos in SK

- Search for solar flare neutrinos was performed with the analysis tools in SK.
  Atmospheric neutrino analysis [19] : 100 MeV ~ 10 GeV (high-energy sample)
  Supernova relic neutrino analysis [18] :16 MeV ~ 100 MeV (low-energy sample)

Table 4: Summary of background rate and

Period	Date	Background rate (100MeV ~10 GeV)	Background rate (16 MeV ~ 100MeV)
SK I	Apr. 1996 – Jun. 2001	7.45 ± 0.07 event/day	0.20 ± 0.01 event/day
SK II	Oct. 2002 – Oct. 2005	7.33 ± 0.09 event/day	0.19 ± 0.01 event/day
SK III	Jul. 2006 – Sep. 2008	7.53 ± 0.12 event/day	0.20 ± 0.01 event/day
SK IV	Sep. 2008 – May 2018	7.48 ± 0.05 event/day	0.19 ± 0.01 event/day

Solar flares on the visible side of the Sun

- There were two events in high-energy sample while no event in low-energy sample.
- Probabilities that the events are background for the most extreme cases;

Sep. 6th 2017 : Po(1,0.25) = 21.8 % ⟶ Background consistent

Solar flares on the invisible side of the Sun

- There were six events in high-energy sample while no event in low-energy sample.
- Probabilities that the events are background for the most extreme cases;

Nov. 7th 2003 : Po(2,0.63) = 10.2 % ⟶ Background consistent

- The limits of the solar flare neutrinos were calculated using the Fagion's prediction. The 90% Confidence Level (C.L.) limits on the fluence of solar neutrinos can be calculated using the following equation

$$\Phi_{90} = \frac{N_{90}}{N_T \int dE_\nu \sum_{i=e,\mu,\tau,\bar{e},\bar{\mu},\bar{\tau}} 1/6(F(E_\nu)\bar{\sigma}(E_{\nu_i})\epsilon(E_{\nu_i}))}$$

- To compare the results of this work with the other experimental results, the model independent fluence upper limit was also calculated for low energy data sample.

$$\Phi_{90}(E) = \frac{N90(E)}{N_p \int dE_\nu \delta(E_\nu - E)\bar{\sigma}(E_\nu)\epsilon(E_\nu)}$$

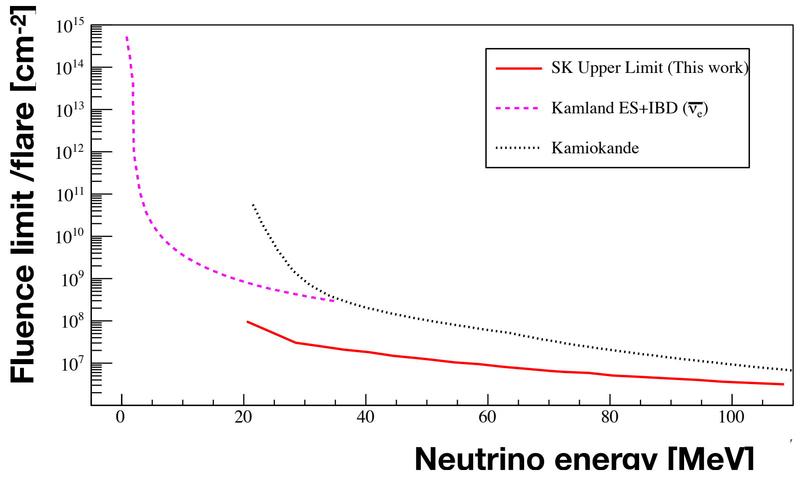

Figure 3: Model independent upper limit (20-110 MeV)

Conclusion

- Searching for solar flare neutrino was done in SK.
- The 90% C.L. limits on the solar flare neutrino fluence were calculated for solar flares on visible side and invisible side.
- The obtained result is the strong constraint of the fluence of solar flare neutrinos in MeV region up to date.