XXX International Conference
on Neutrino Physics and Astrophysics
May 30 (Mon) - June 4 (Sat), 2022 | Virtual Seoul, Korea

NEUTRINO 2022
XXX International Conference on Neutrino Physics and Astrophysics
May 30 - June 4, 2022 Virtual Seoul

Overview of the solar neutrino observation

(Super-K, Borexino, SNO+)

OKAYAMA
UNIVERSITY

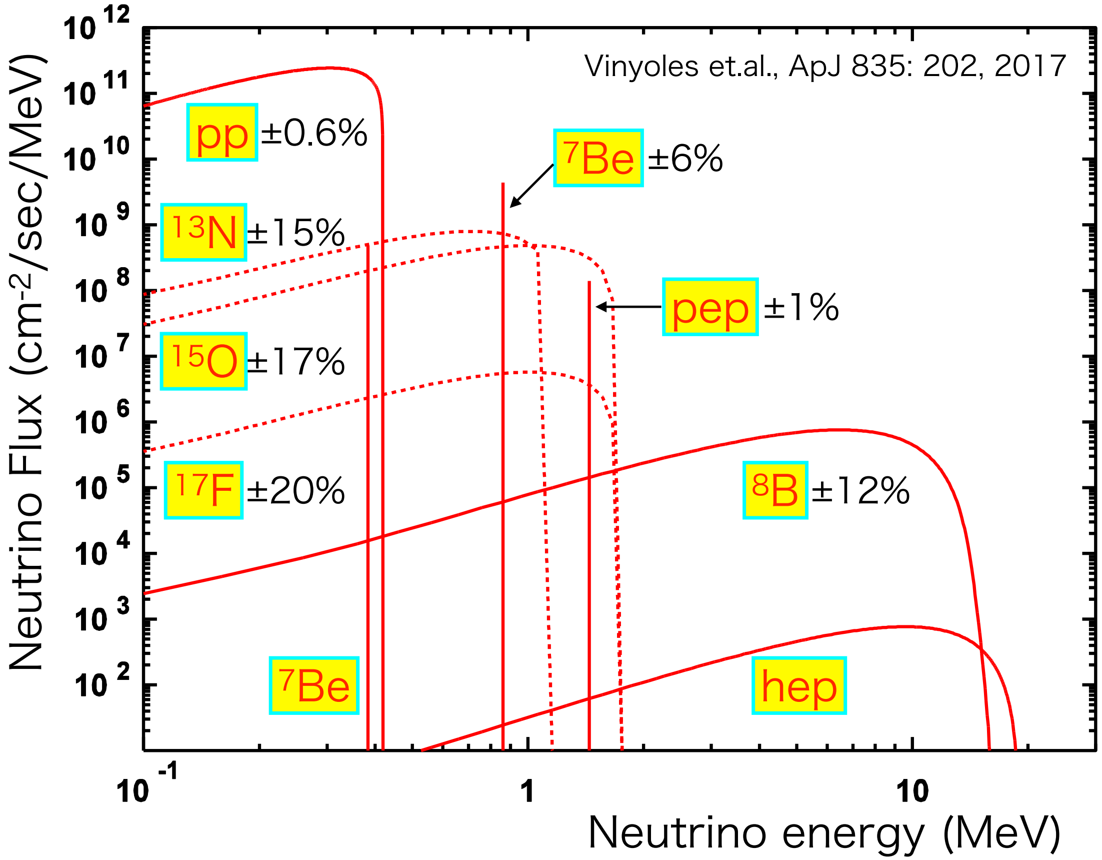
Yusuke Koshio
(Okayama university)

2nd June, 2022

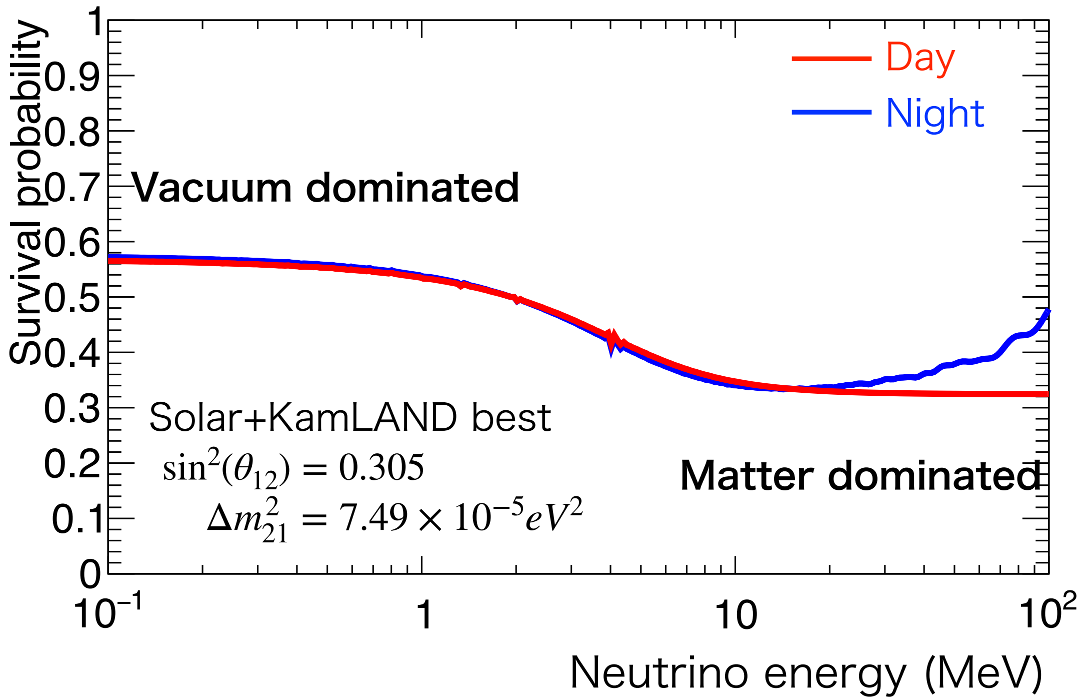
Introduction

Solar neutrino
Standard scenario

Standard Solar Model (SSM)



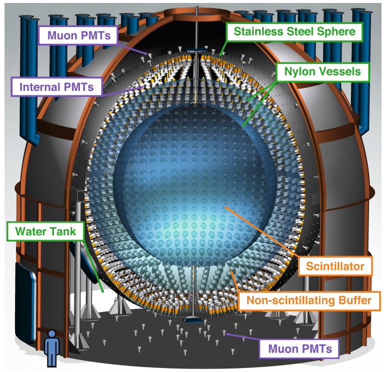
Neutrino oscillation (MSW-LMA)



Solar neutrino

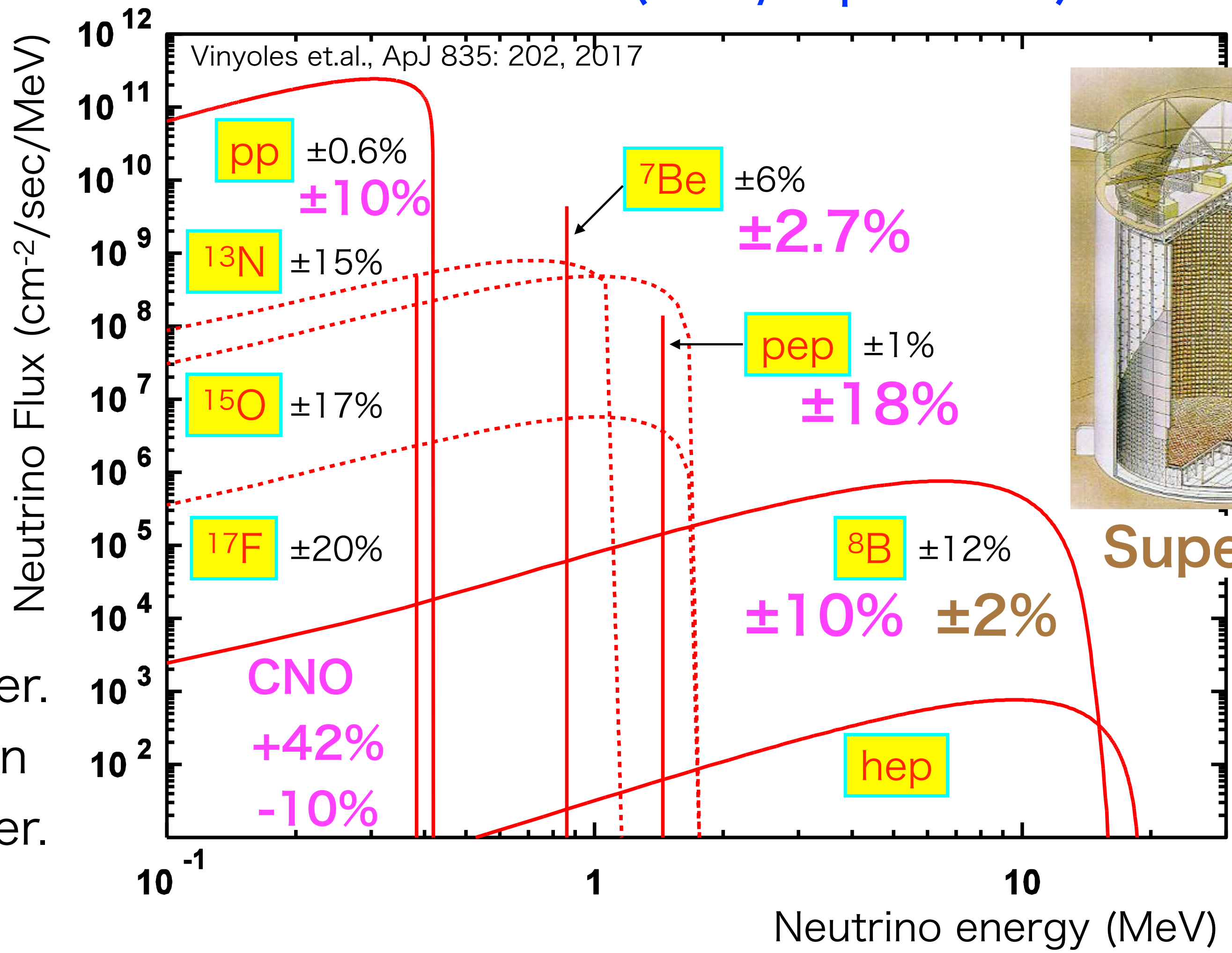
Recent results

Borexino



New observations were reported one after another. Its measurement precision becomes better and better.

Uncertainties (SSM / experiments)



Super-K

Solar neutrino

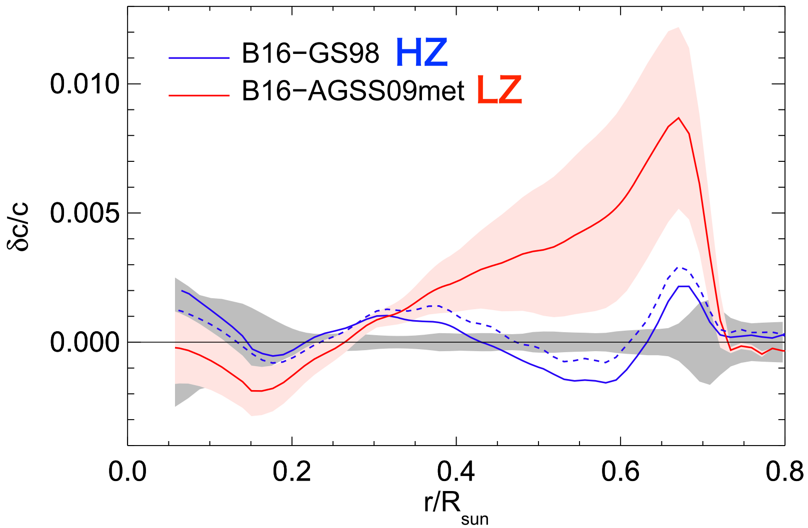
Metallicity problem

Heavy element abundance:

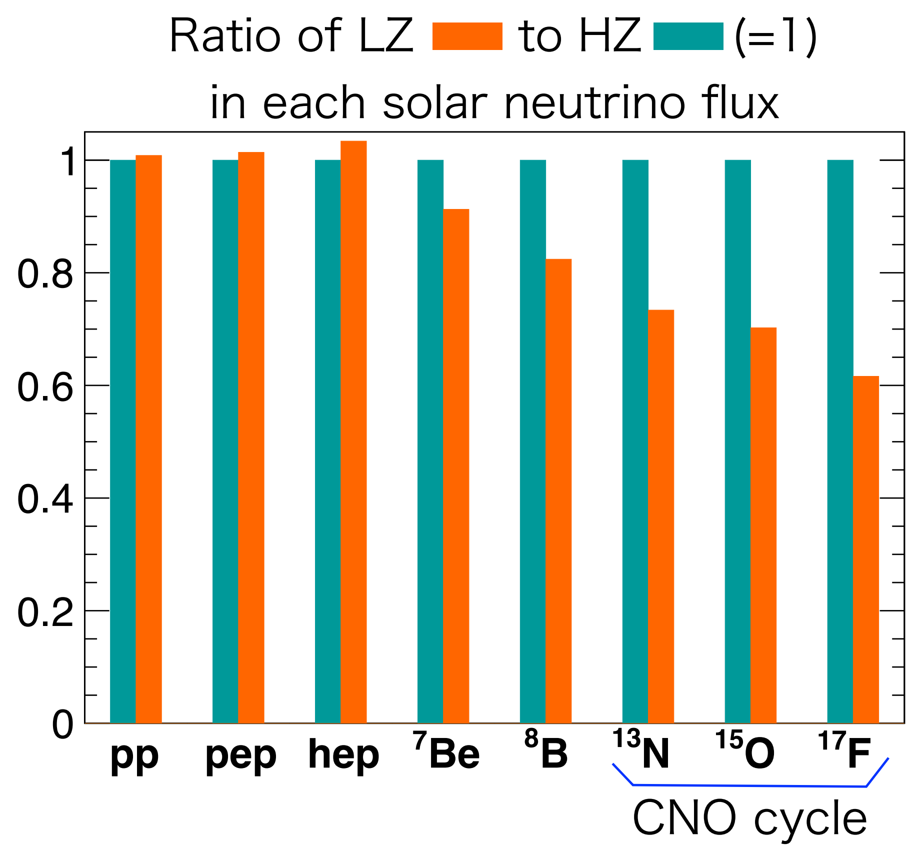
Z/X=0.02292 (GS98) -> HZ model

Z/X=0.01780 (AGSS09) -> LZ model

Corresponding abundances by mass of H, He, more than He are traditionally denoted by X, Y, Z, respectively.



Vinyoles et.al., ApJ 835: 202, 2017

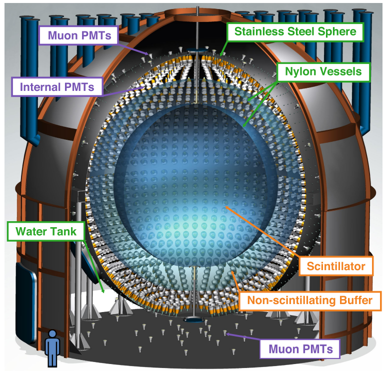


Solar neutrino measurements might solve the problem.

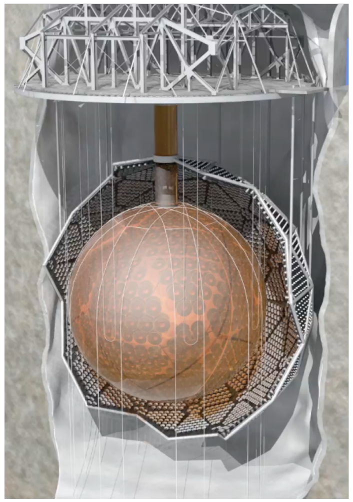
Solar neutrino

In this talk

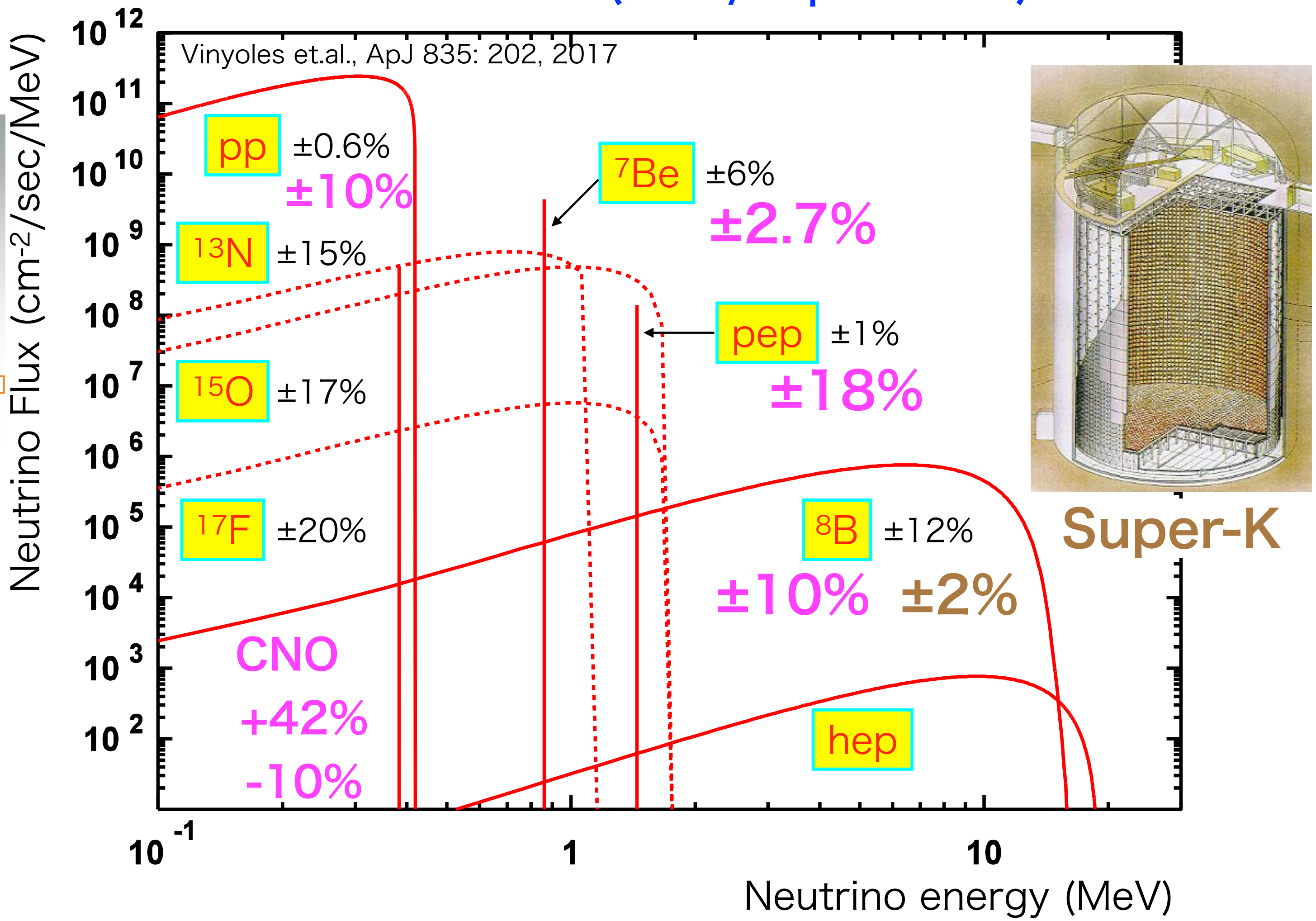
Borexino



SNO+



Uncertainties (SSM / experiments)



Super-K

Super-Kamiokande

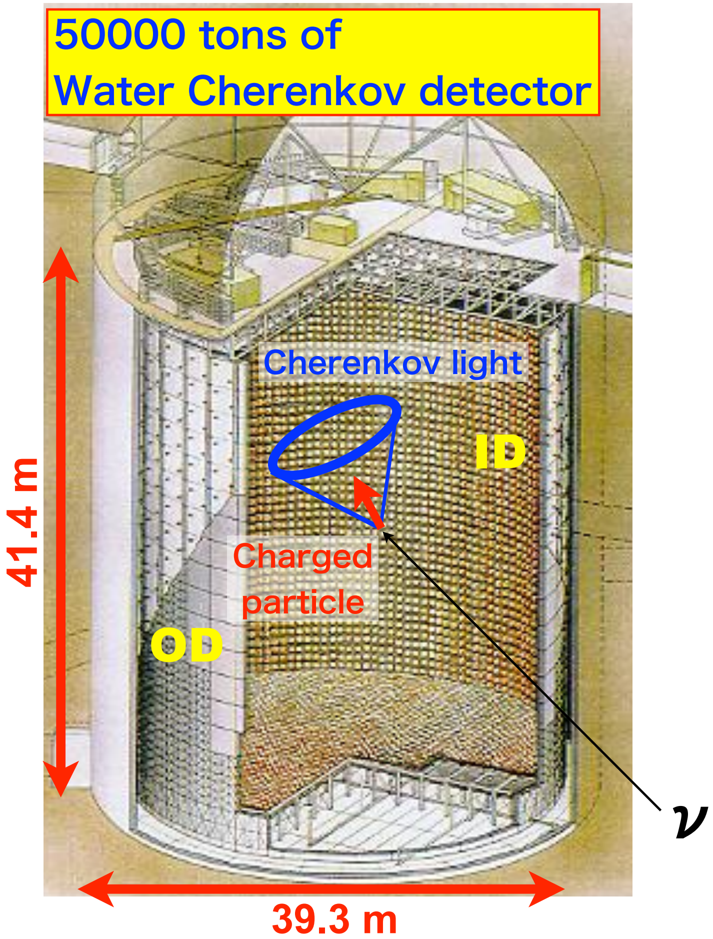
Poster presentation (ZEP location : 3F. Majorana)

MT10-097 Alejandro Yankelevich
MT10-380 Hiroshi Ito
MT10-583 Yuuki Nakano

Many thanks to Super-K collaboration!

Super-Kamiokande

As a solar neutrino detector

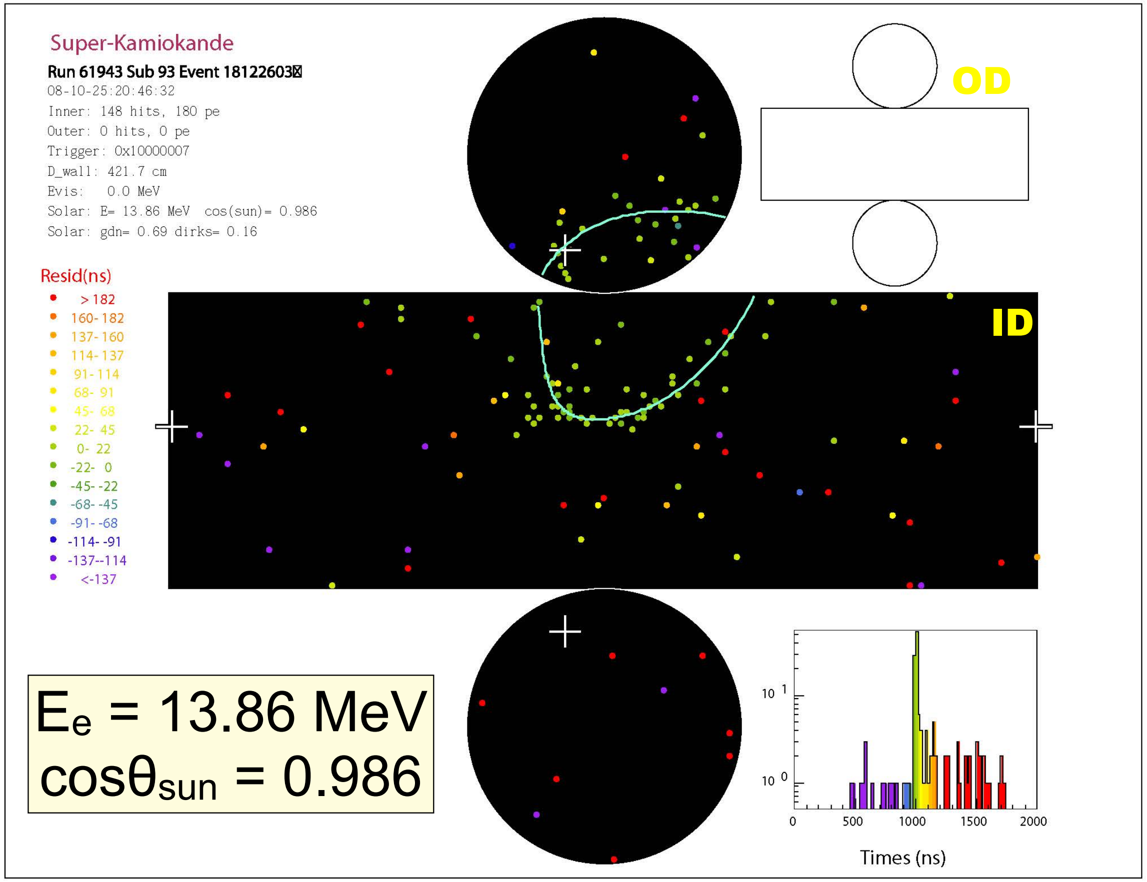


Phase	Period	# of PMTs	Fiducial volume for solar neutrino	Energy thr.(MeV)
SK-I	1996.4 2001.7	11146 (40%)	22.5 kton	4.5
SK-II	2002.10 2005.10	5182 (20%)		6.5
SK-III	2006.7 2008.8	11129 (40%)	22.5 (>5.5MeV) 13.3 (<5.5MeV)	4.0
SK-IV	2008.9 2018.5		22.5 (>5.5MeV) 16.5 (4.5<E<5.5) 8.9 (<4.5MeV)	3.5
SK-V	2019.1 ~ 2020.8		Analysis is on going	
SK-VI	2020.8 ~ 2022.6			
SK-VII	2022.6 ~			

} with Gadolinium -> Mark's talk (SK-VI, SK-VII)

Solar neutrino observation in Super-K

Detection principle



neutrino-electron elastic scattering

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

- ✓ Large volume
- ✓ Find solar direction
- ✓ Realtime measurements
- ✓ Precise energy determination

Verify neutrino oscillation scenario

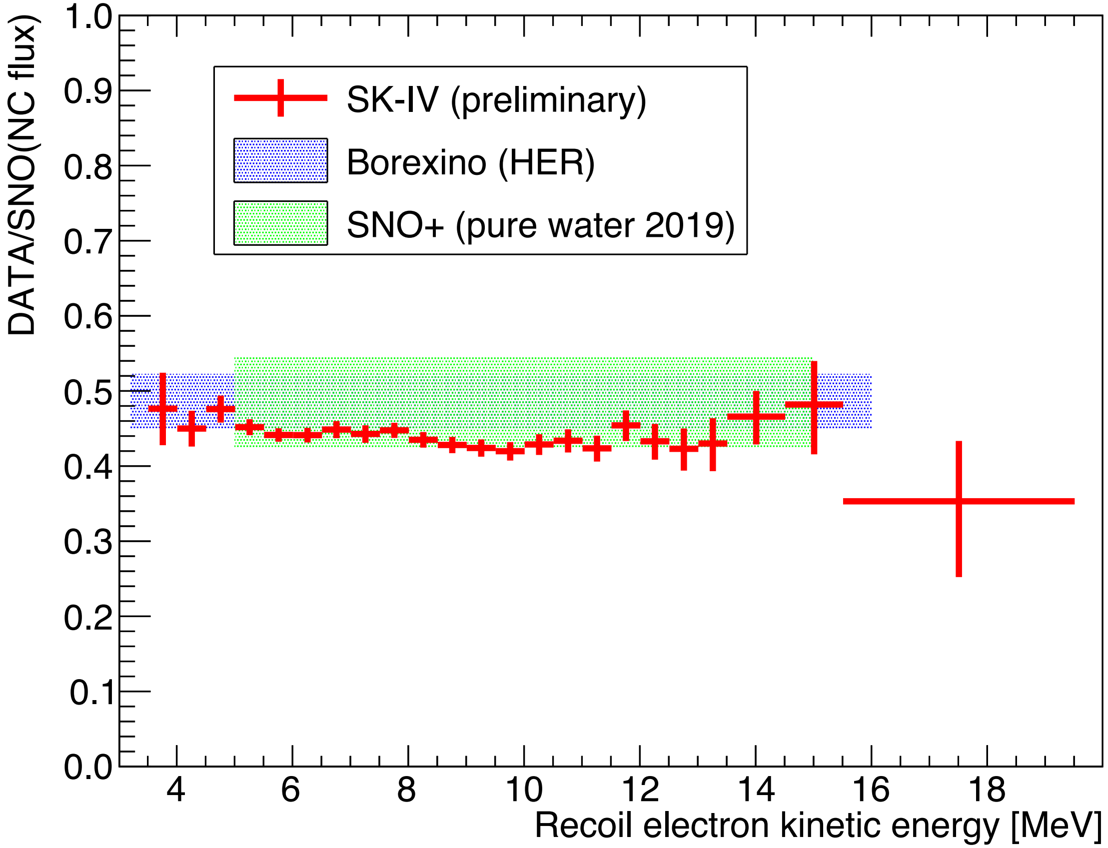
- **Oscillation parameter determination**
- **Day/Night and seasonal flux variation, spectrum distortion.**
- **Investigate exotic senario**

Precise ^8B flux measurement is important for solar metallicity problem

Solar neutrino observation in Super-K

Huge statistics and precise measurement

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



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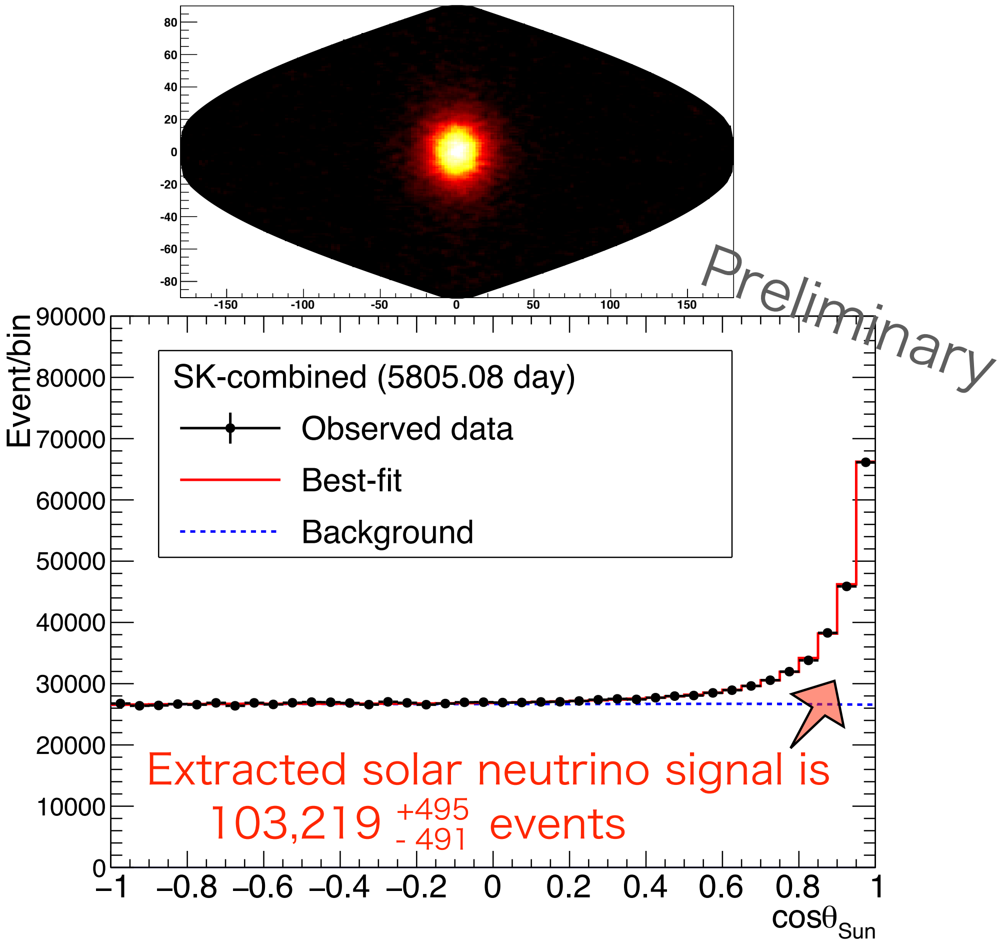
Precise ^{8}B flux measurement is important for solar metallicity problem

Solar neutrino observation in Super-K

Can "see" the sun from underground



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

✓ Large volume

✓ **Find solar direction**

✓ Realtime measurements

✓ Precise energy determination

Verify neutrino oscillation scenario

- **Oscillation parameter determination**
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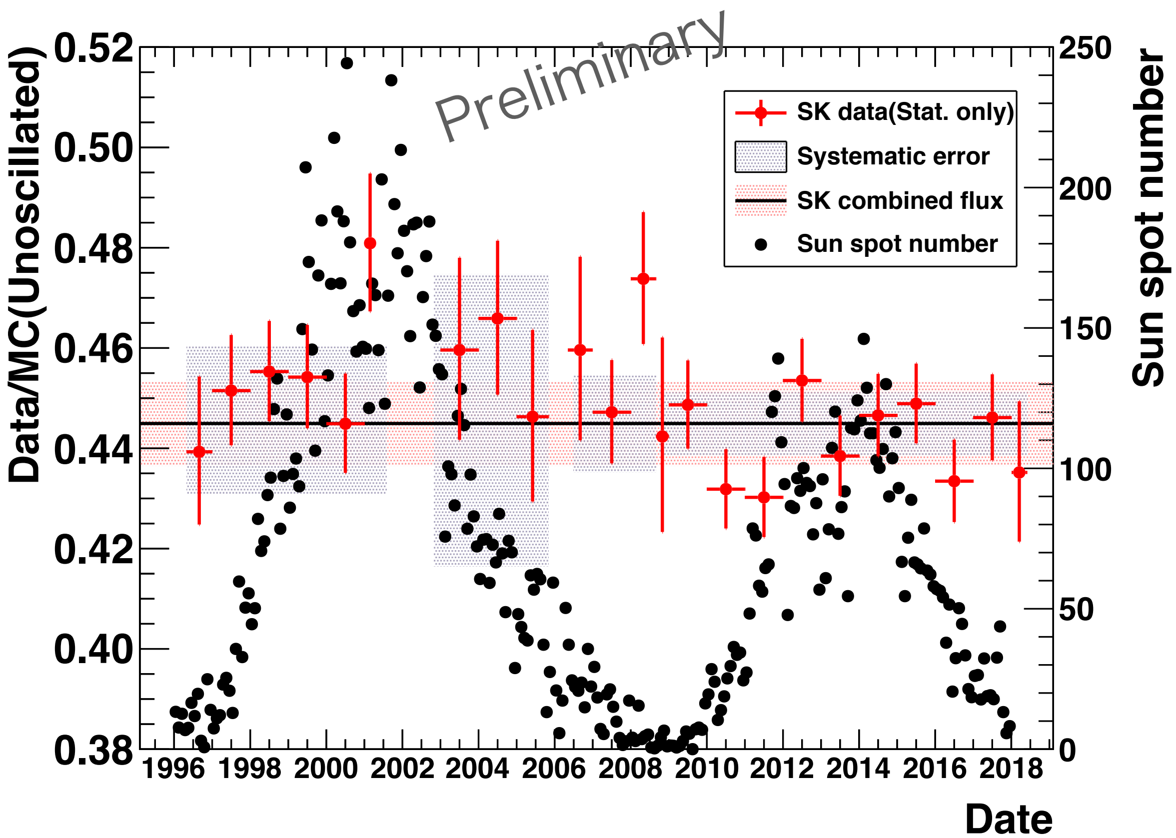
Precise ^{8}B flux measurement is important for solar metallicity problem

Solar neutrino observation in Super-K

Time variation of flux measurement

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



✓Large volume

✓Find solar direction

✓**Realtime measurements**

✓Precise energy determination

Verify neutrino oscillation scenario

- Oscillation parameter determination
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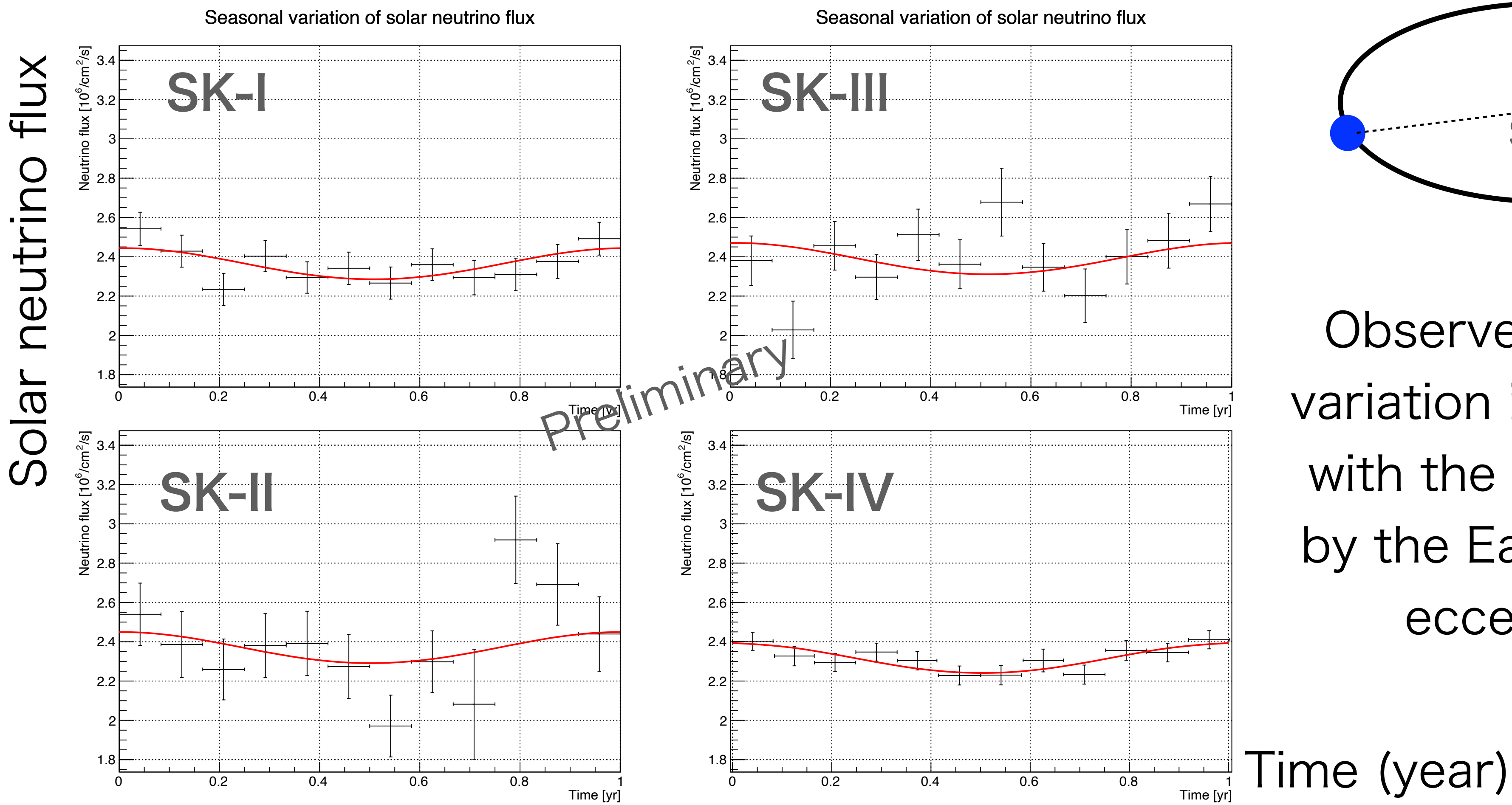
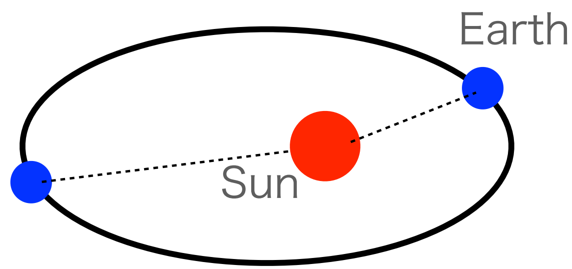
- Investigate exotic senario

Precise ^{8}B flux measurement is important for solar metallicity problem

Seasonal variation

Earth's orbital eccentricity, and more?

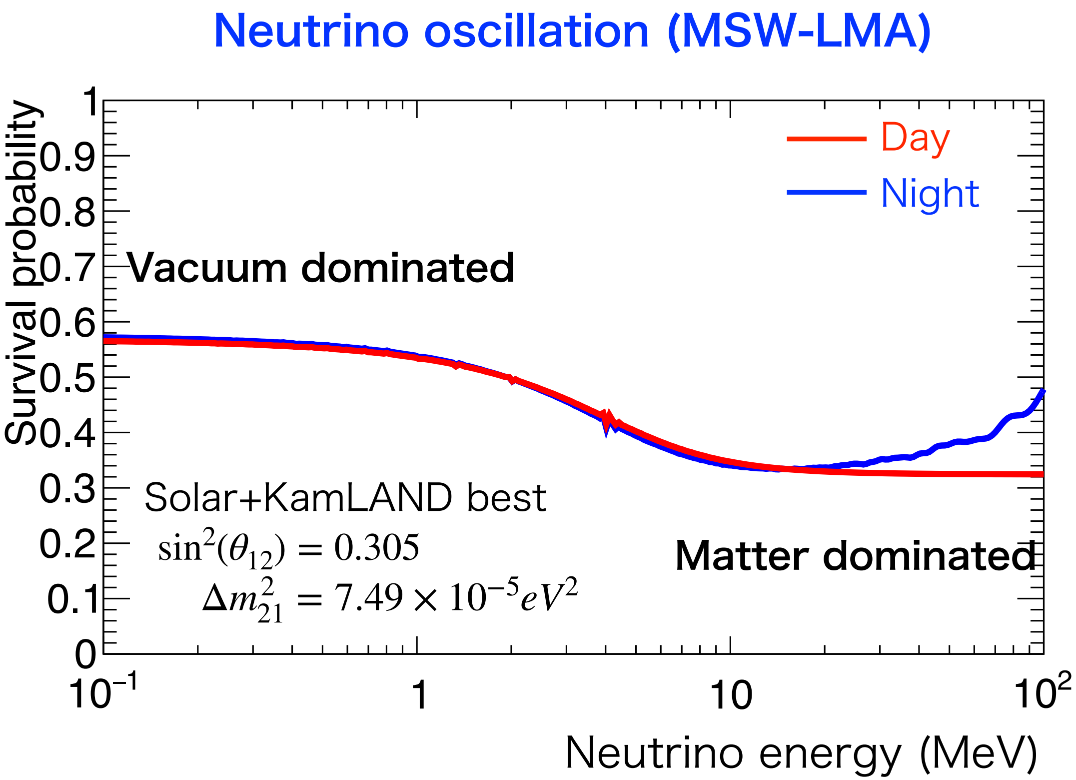


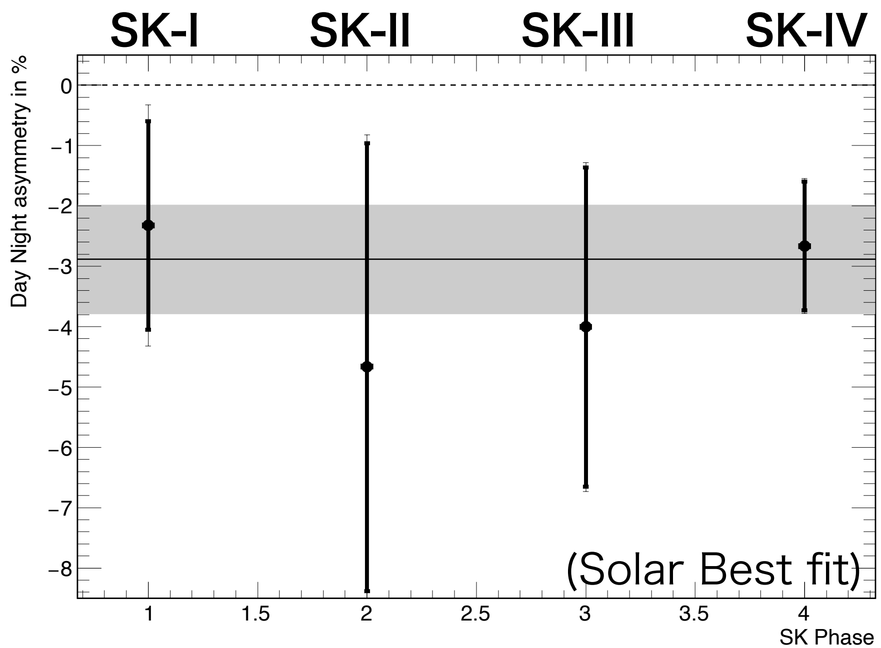


Observed seasonal variation is consistent with the expectation by the Earth's orbital eccentricity.

Day-Night flux difference

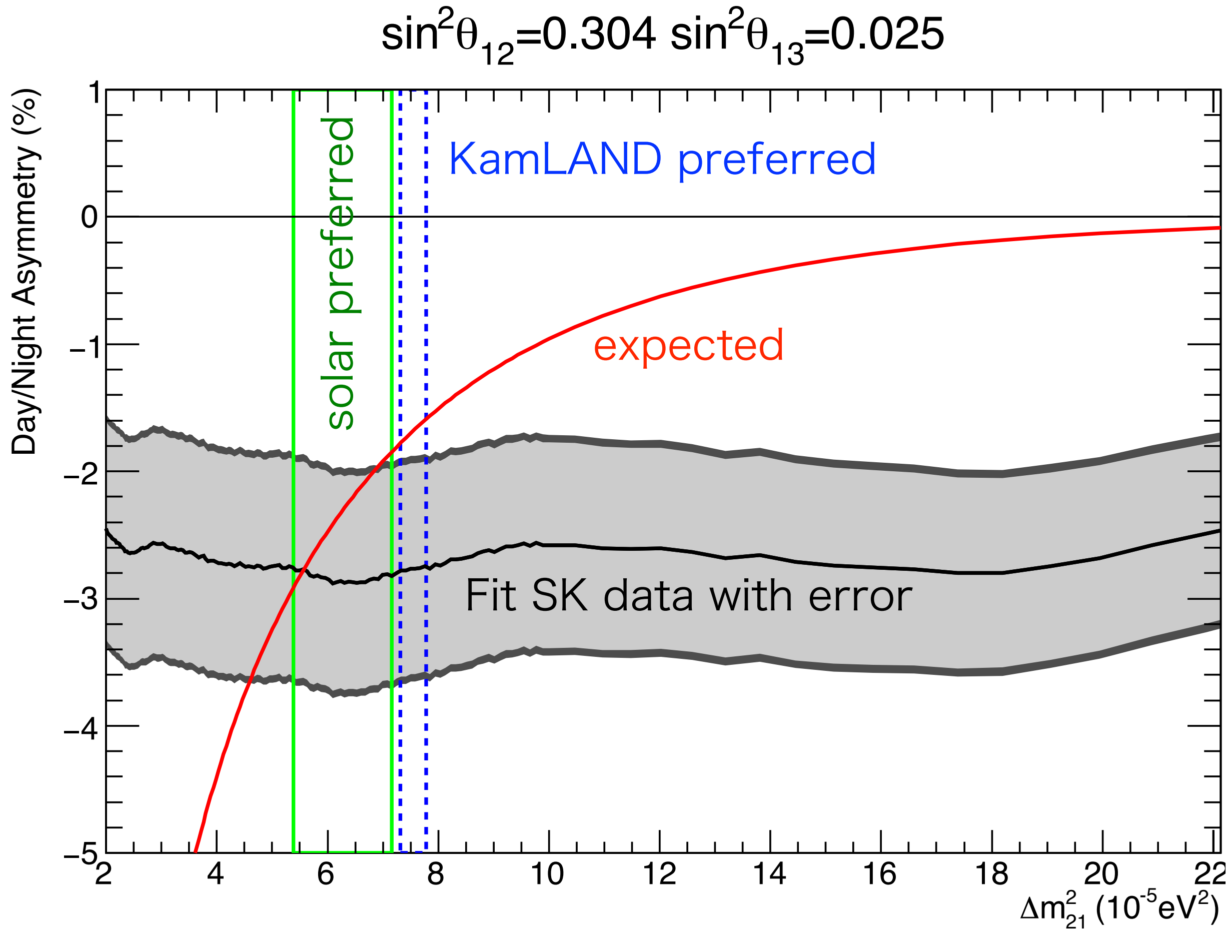
Direct MSW effect





Day-Night flux difference

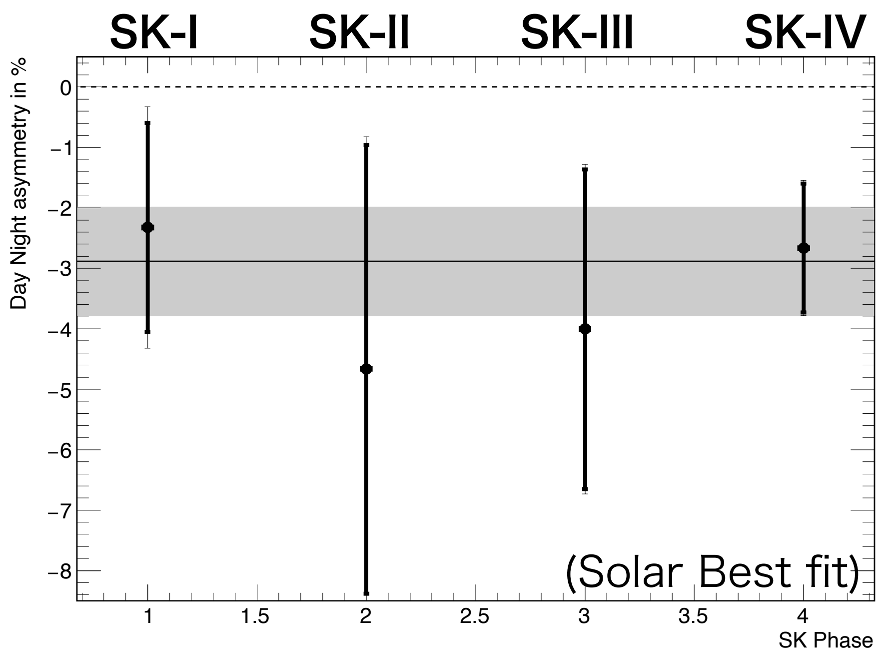
Direct MSW effect



Significance of D/N asymmetry:

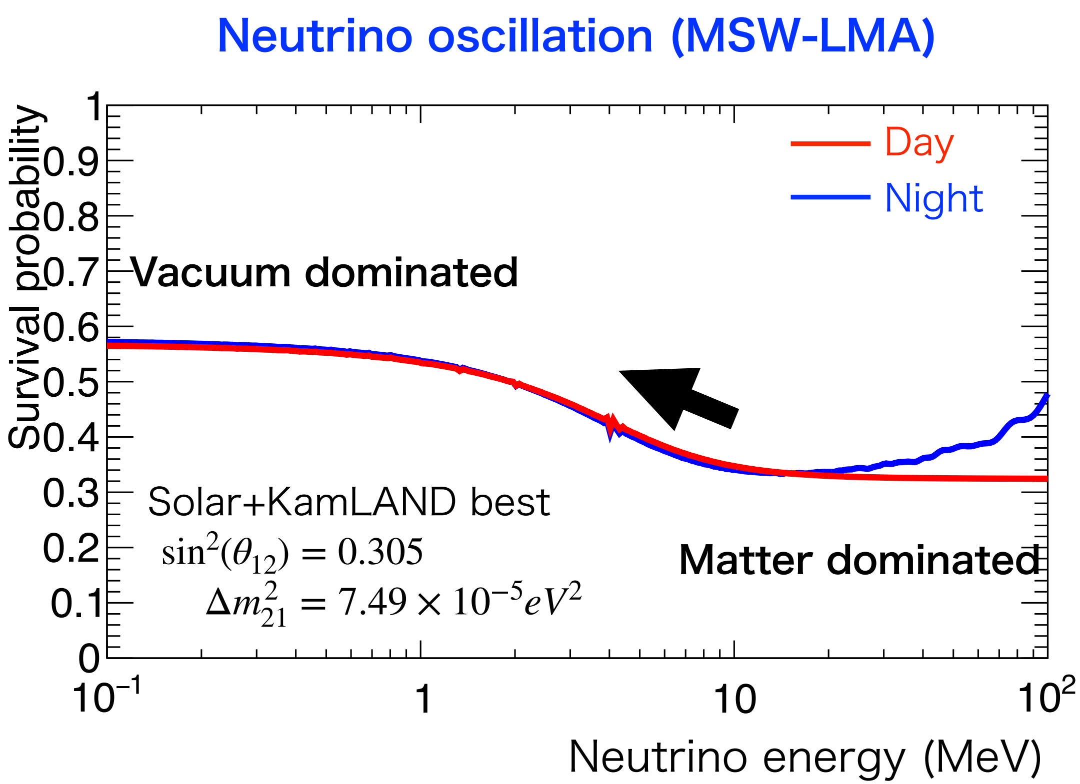
3.2σ for Solar Best fit

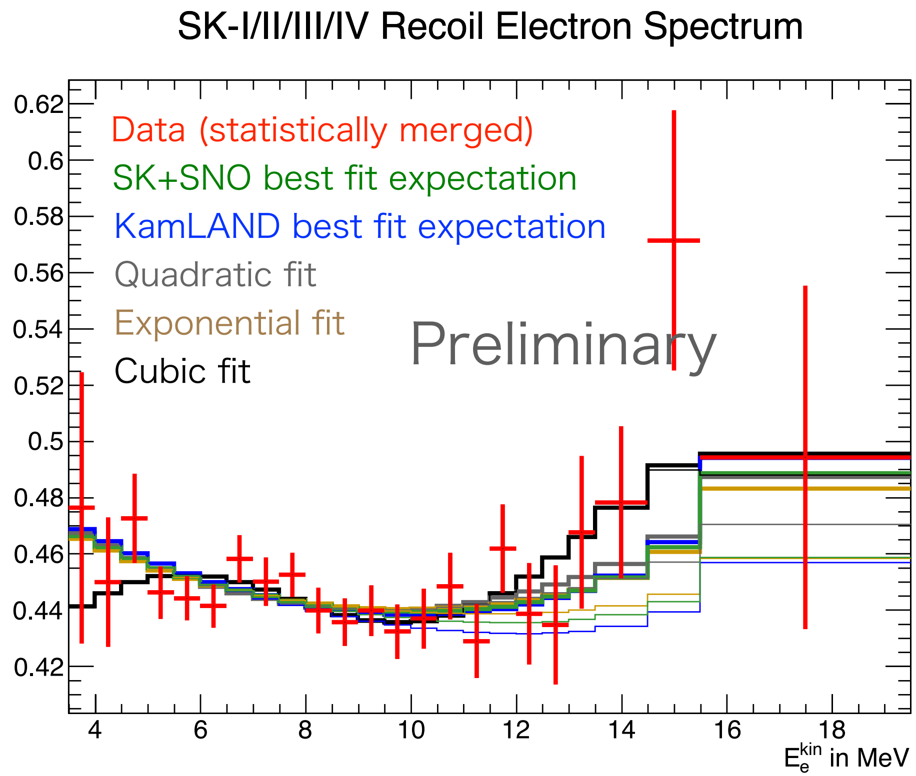
3.1σ for Global Best fit



Energy spectrum

Upturn toward the lower energy?

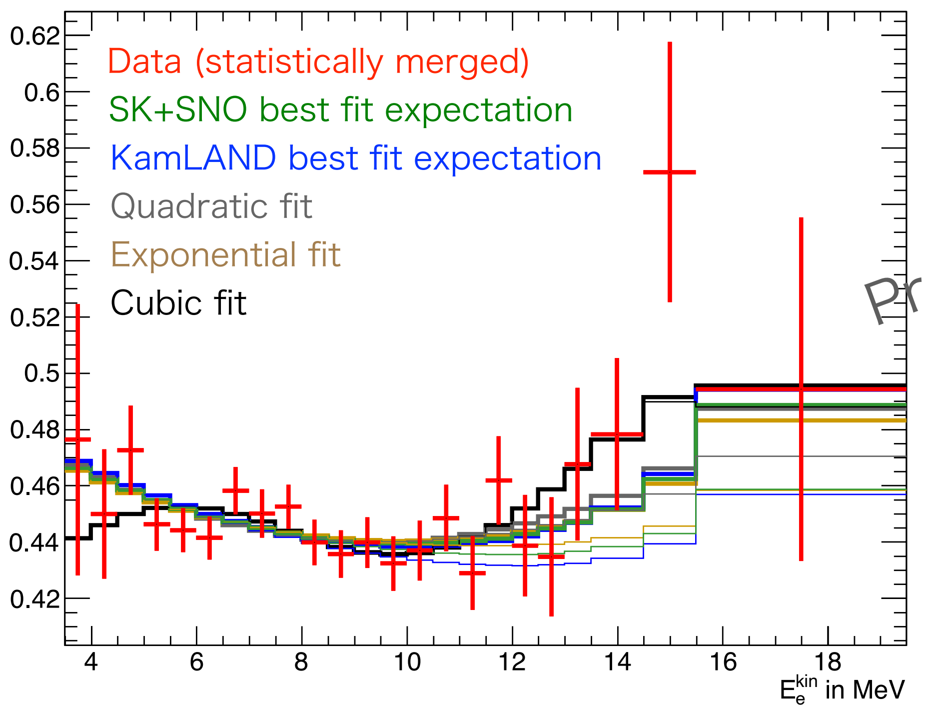




Slightly favors up-turn, though need more data

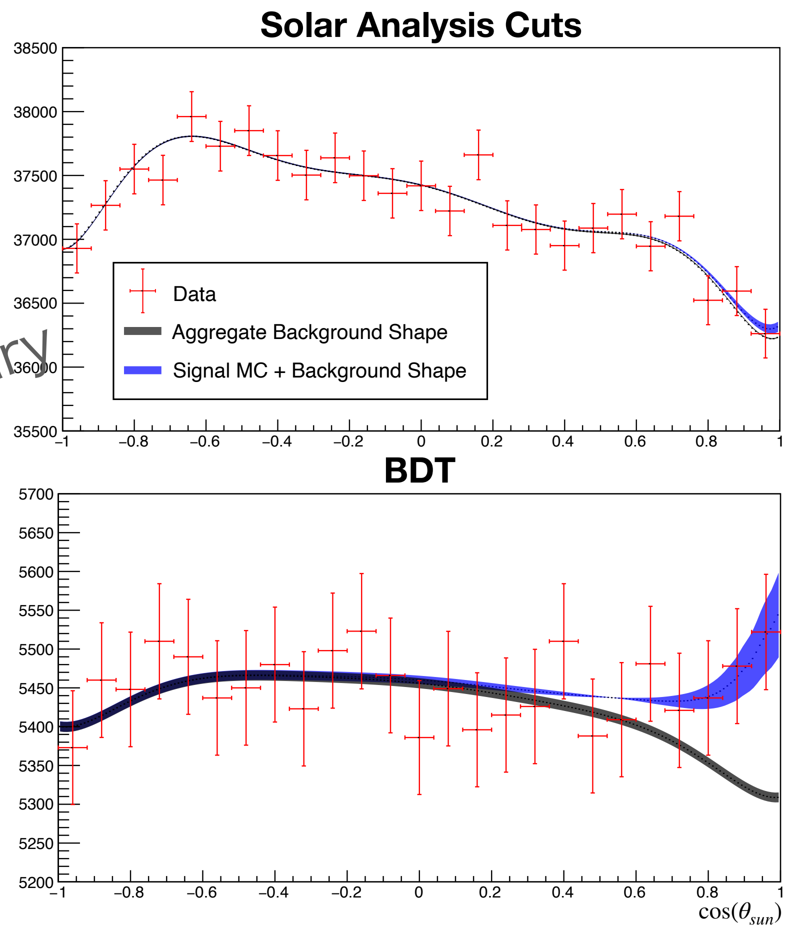
Energy spectrum

Upturn toward the lower energy?



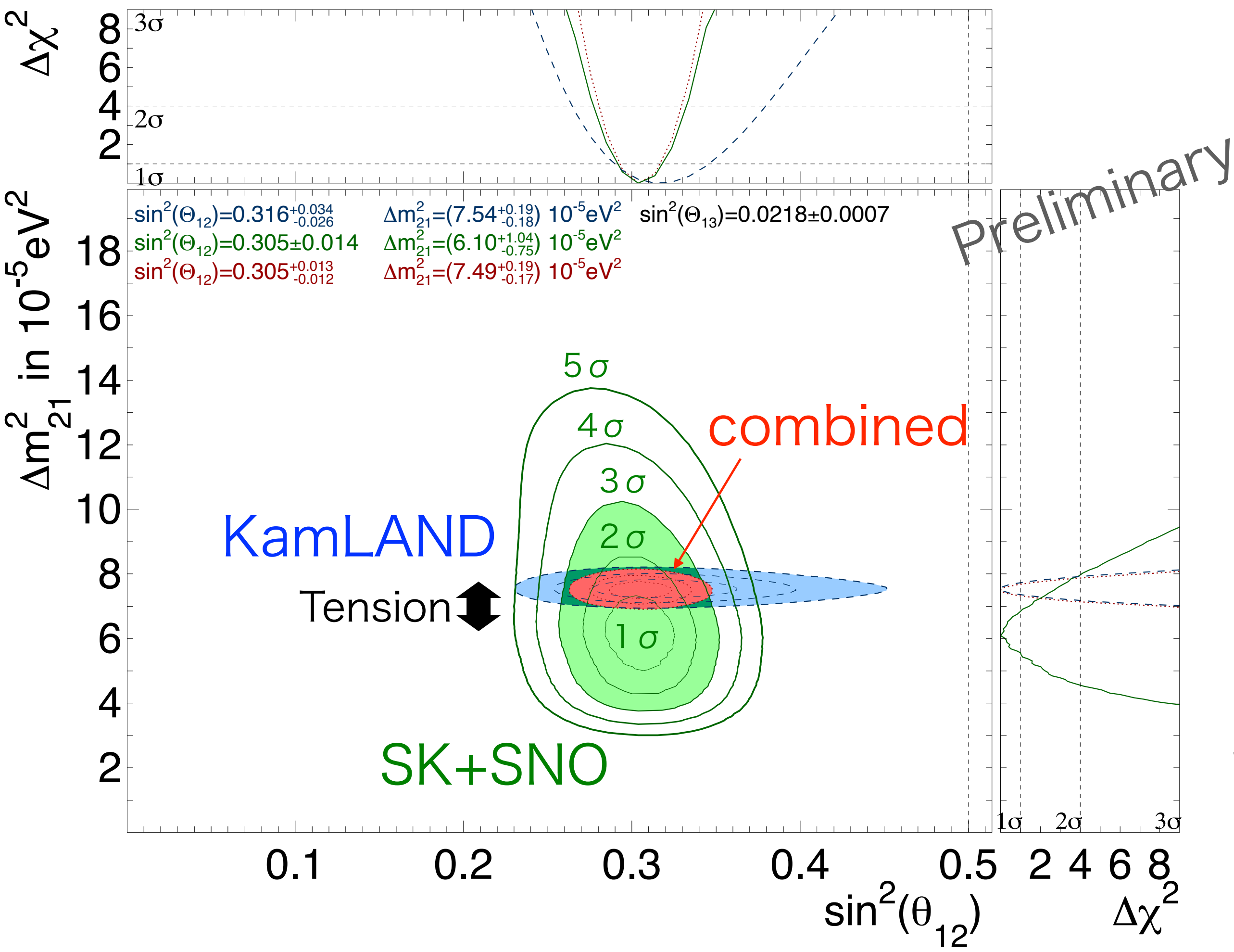
Slightly favors up-turn, though need more data

2.49 MeV < Ekin < 3.49 MeV



See also the poster MT10-097 by A.Yankelevich

Oscillation analysis



Best fit oscillation parameters

$$\sin^2(\theta_{12}) = 0.316^{+0.034}_{-0.026}$$

$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times 10^{-5} eV^2$$

$$\sin^2(\theta_{12}) = 0.305 \pm 0.014$$

$$\Delta m^2_{21} = 6.10^{+1.04}_{-0.75} \times 10^{-5} eV^2$$

$$\sin^2(\theta_{12}) = 0.305^{+0.013}_{-0.012}$$

$$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17} \times 10^{-5} eV^2$$

There is ~1.5σ tension between SK+SNO and KamLAND in Δm^2_{21}

See also the poster MT10-583 by Y.Nakano

Borexino

Poster presentation (ZEP location : 3F. Majorana)

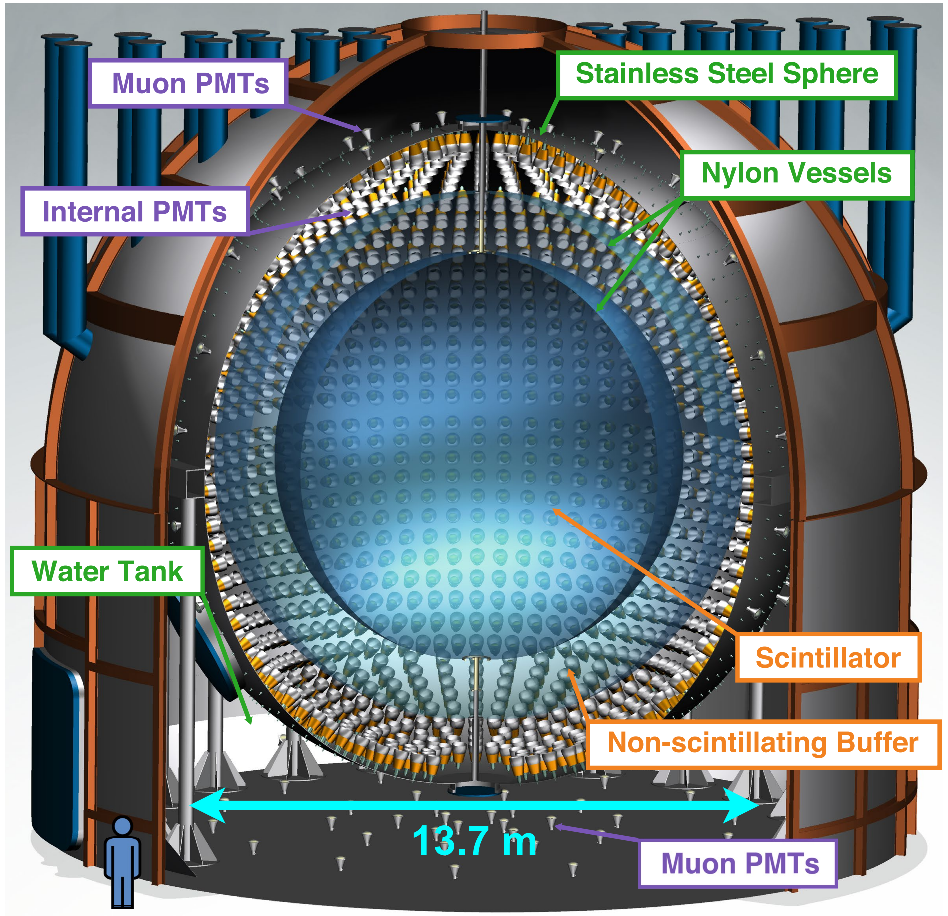
MT10-083 Riccardo Biondi
MT10-142 Apeksha Singhal
MT10-612 Davide Basilico
MT10-659 Daniele Guffanti

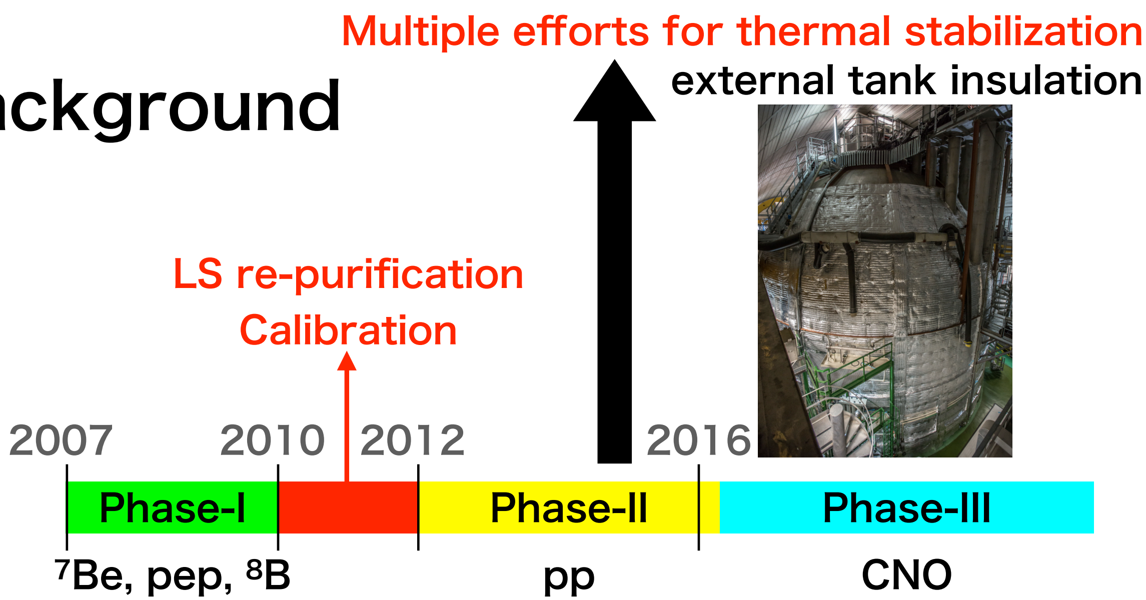
Many suggestions by Borexino friends, Thanks!

Borexino

Ultimate low radioactive background

Nature, 496 (2018) 505





- Active volume 280 tons of liquid scintillator (PC+PPO, 1.5g/l in a nylon vessel R=4.25m)
- ^{232}Th < 5.7x10^{-19} g/g, ^{238}U < 9.4x10^{-20} g/g
- R(^{210}Bi) < 11.5±1.3 cpd/100ton(upper limit)! which is the background of CNO neutrino search (3~5 cpd/100ton is expected).

Borexino

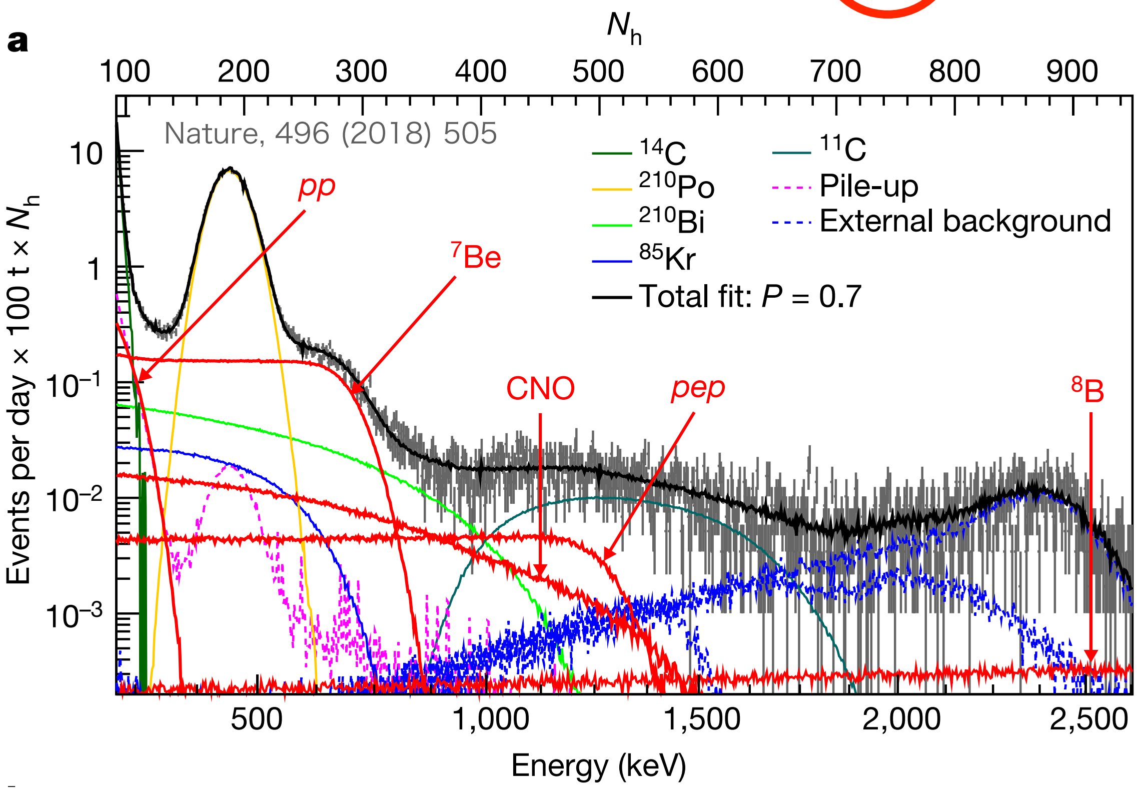
As a solar neutrino detector

neutrino-electron elastic scattering

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

Possible to access multiple solar neutrino sources by single detector thanks to its high light yield and low background.

a



- First direct measurements of ^{7}Be, pep, pp, CNO, also first measurement of ^{8}B by LS.
- Verify neutrino oscillation scenario. Possible to simultaneously test neutrino flavor conversion both in the vacuum and the matter dominated region.
- Astrophysical point of view:
  - Solar luminosity confirmation.
  - Solar metallicity problem investigation.

Results in pp-chain

	Flux observed by Borexino ($cm^{-2}s^{-1}$)	Flux SSM prediction ($cm^{-2}s^{-1}$)
pp	$(6.1 \pm 0.5^{+0.3}_{-0.5}) \times 10^{10}$	$5.98(1.0 \pm 0.006) \times 10^{10}$ (HZ) $6.03(1.0 \pm 0.005) \times 10^{10}$ (LZ)
^{7}Be	$(4.99 \pm 0.11^{+0.06}_{-0.08}) \times 10^{9}$	$4.93(1.0 \pm 0.06) \times 10^{9}$ (HZ) $4.50(1.0 \pm 0.06) \times 10^{9}$ (LZ)
pep (HZ)	$(1.27 \pm 0.19^{+0.08}_{-0.12}) \times 10^{8}$	$1.44(1.0 \pm 0.01) \times 10^{8}$ (HZ) $1.46(1.0 \pm 0.009) \times 10^{8}$ (LZ)
pep (LZ)	$(1.39 \pm 0.19^{+0.08}_{-0.13}) \times 10^{8}$	$1.44(1.0 \pm 0.01) \times 10^{8}$ (HZ) $1.46(1.0 \pm 0.009) \times 10^{8}$ (LZ)
$^{8}B_{HER-I}$	$(5.77^{+0.56+0.15}_{-0.56-0.15}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
$^{8}B_{HER-II}$	$(5.56^{+0.52+0.33}_{-0.64-0.33}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
$^{8}B_{HER}$	$(5.68^{+0.39+0.03}_{-0.41-0.03}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)

Low Energy Region (LER)

Dec. 2011 - May 2016

1291.51days x 71.3 tons

(0.19-2.93) MeV

High Energy Region (HER)

Jan. 2008 - Dec. 2016

2062.4 days x 227.8 tons (HER-I)

x 266.0 tons (HER-II)

(3.2-16) MeV

(5.7MeV is the boundary of I/II)

Calculate the solar luminosity

$(3.89^{+0.35}_{-0.42}) \times 10^{33}$ erg/s

$(3.846 \pm 0.015) \times 10^{33}$

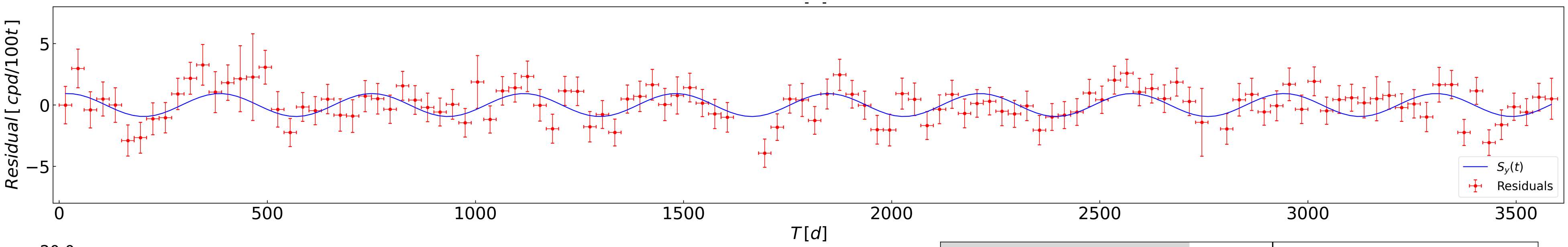
by photon output

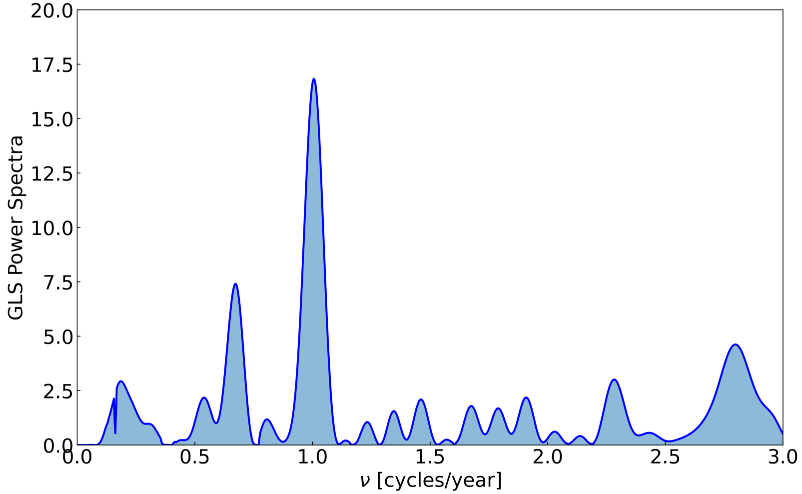
Time variation of ^{7}Be flux

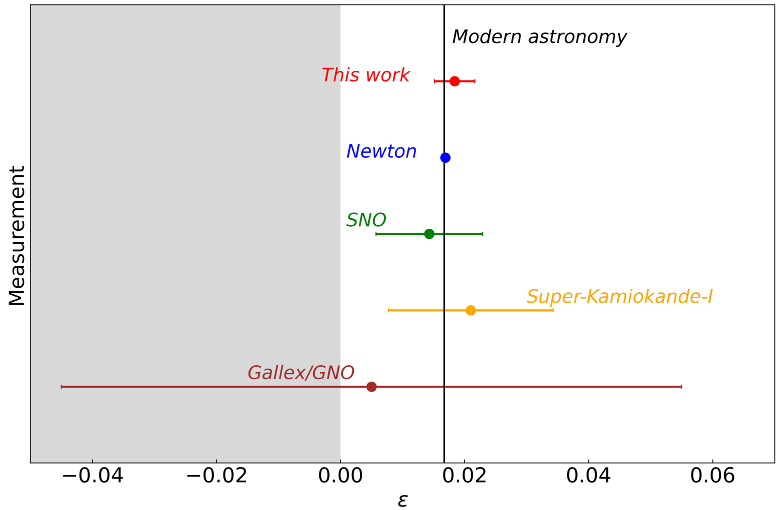
Earth's orbital eccentricity, and more?

See the poster
MT10-083 by R.Biondi

arXiv : 2204.07029







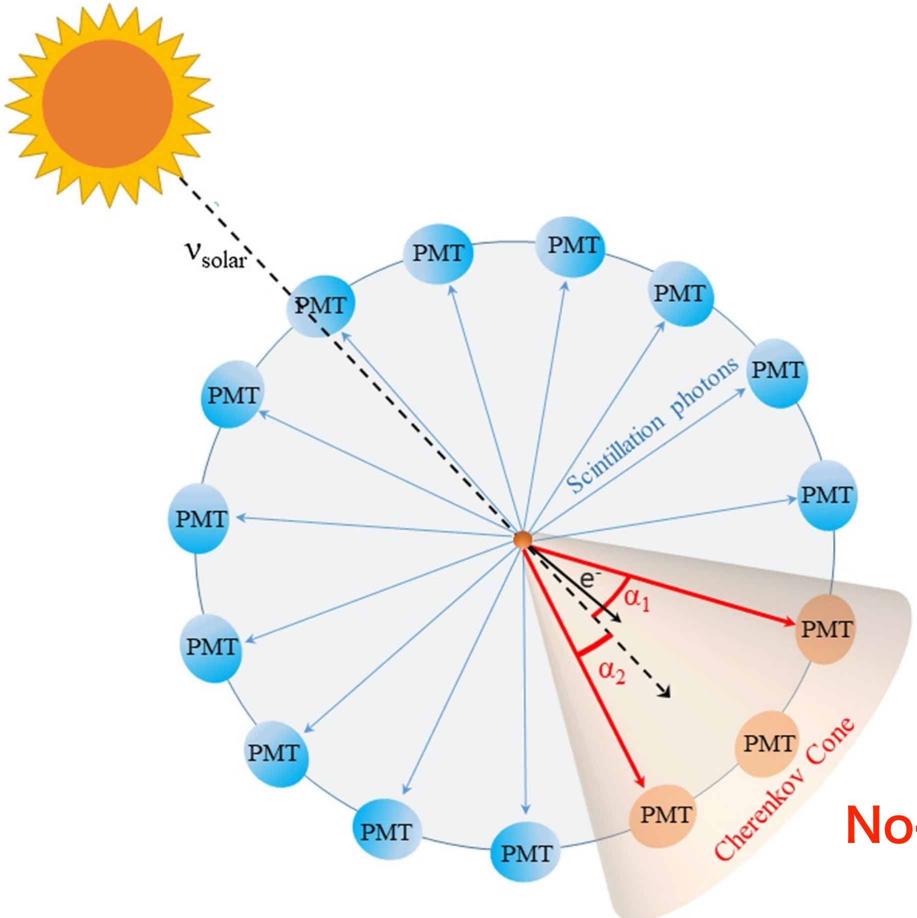
Clear annual periodicity can be seen.

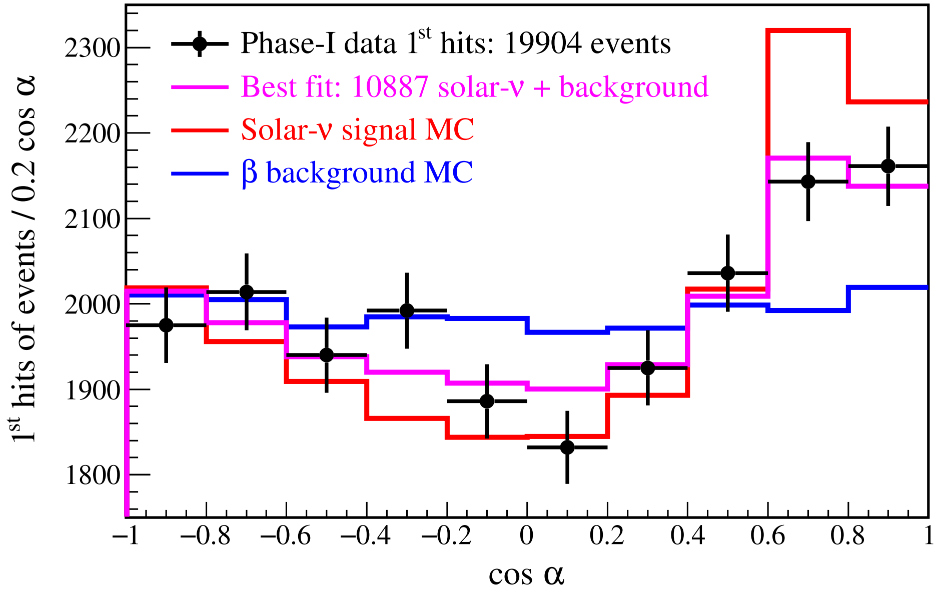
Precise measurements of eccentricity!

Find the solar direction in LS

First directional measurement of Sub-MeV solar neutrinos

PRL, 128 (2022) 091803





Best fit for the number of solar neutrino events:

$10887 \ ^{+2386}_{-2103} \ \pm 947$ (0.54-0.74MeV, phase I)

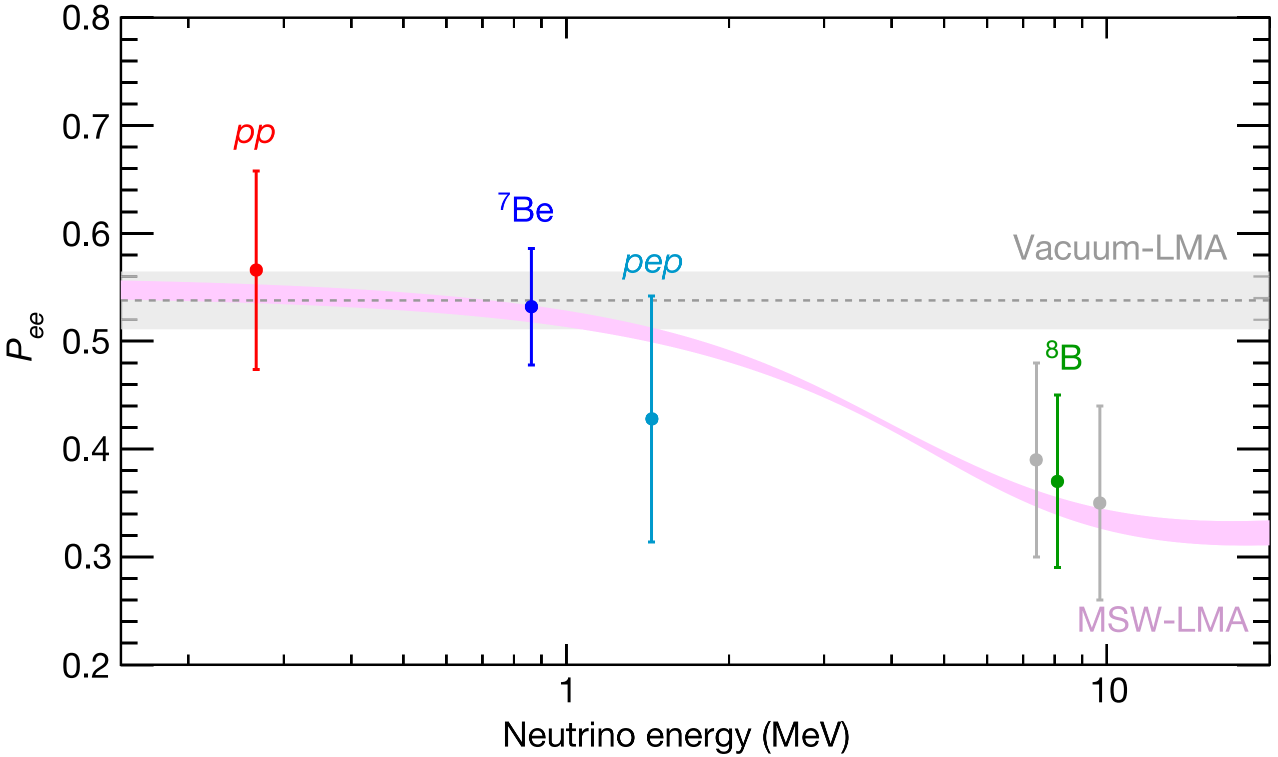
No-neutrino hypothesis can be excluded with > 5σ!

See the poster MT10-142 A.Singhal

Neutrino oscillation

Electron neutrino survival probability

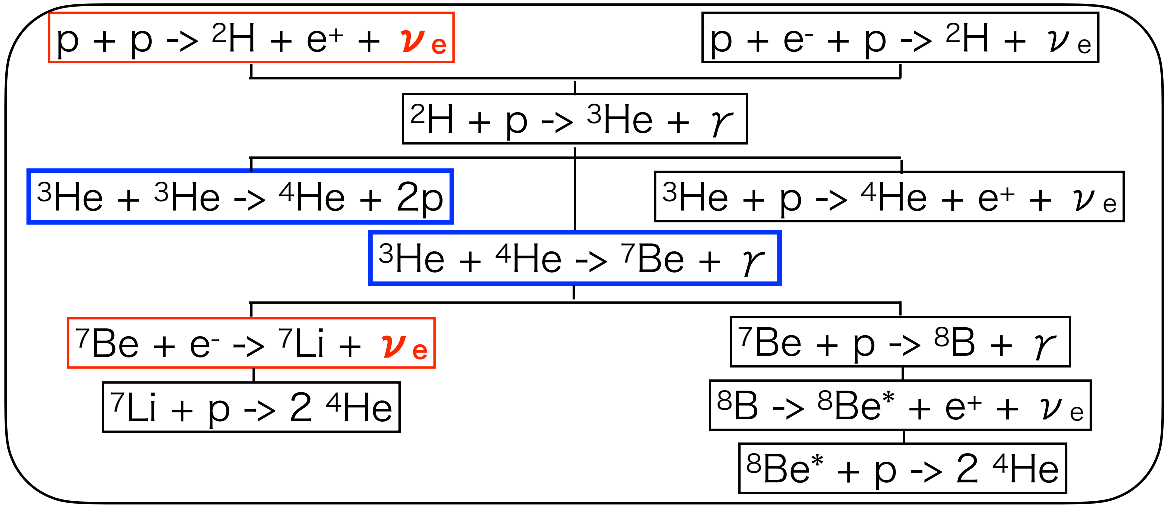
Nature, 496 (2018) 505



- ✓Most precise observation of P_{ee} in the LER.
- ✓Simultaneously test the neutrino flavor conversion both in the vacuum and in the matter dominated region.
- ✓Agreement with the expectations from MSW-LMA scenario.

Solar metallicity problem

HZ or LZ, that is the question

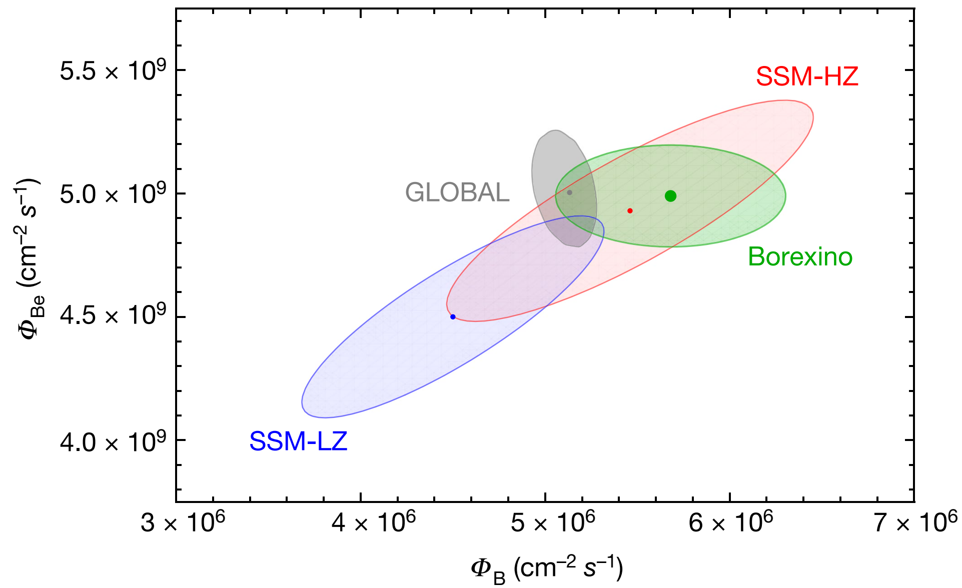


$$R \equiv \frac{<^3He + ^4He>}{<^3He + ^3He>} = 2\Phi(^7Be)/[\Phi(pp) - \Phi(^7Be)]$$

$R_{Borexino} = 0.178^{+0.027}_{-0.023}$

0.180 ± 0.011 (HZ) and 0.161 ± 0.010 (LZ)

Nature, 496 (2018) 505



✓Hint in favor of HZ from Borexino results, while it weakens from global fit.

✓Theoretical uncertainties are dominated.

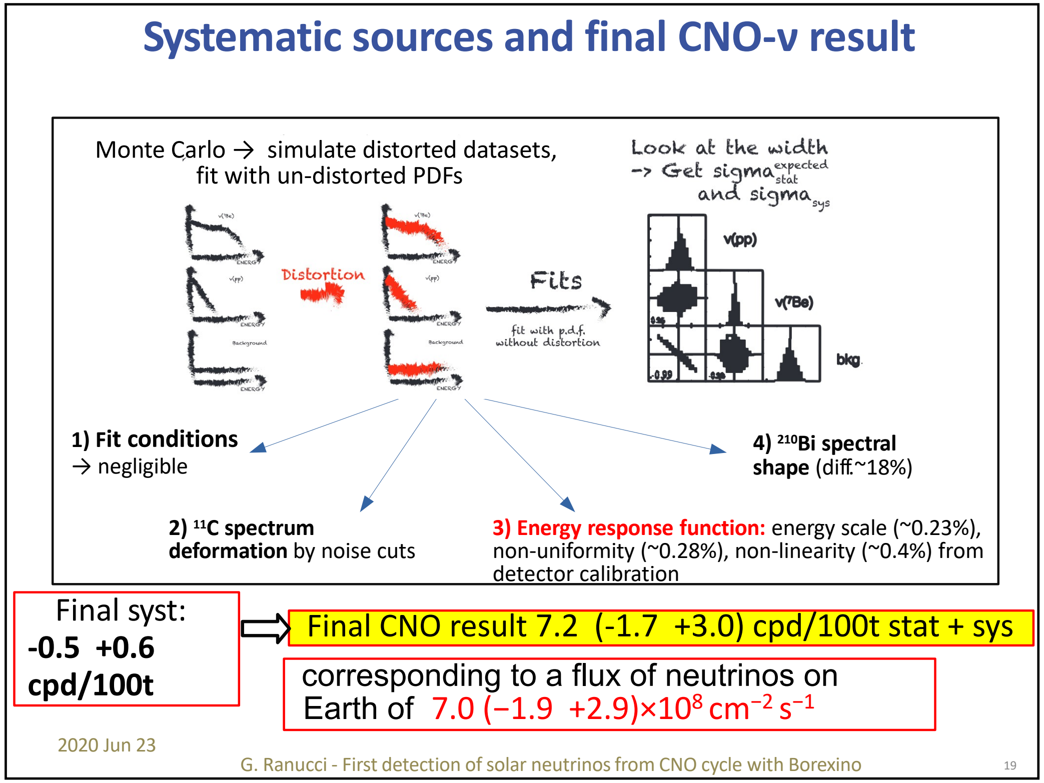
See the poster MT10-659 D.Guffanti

CNO measurement will be the key of the solution

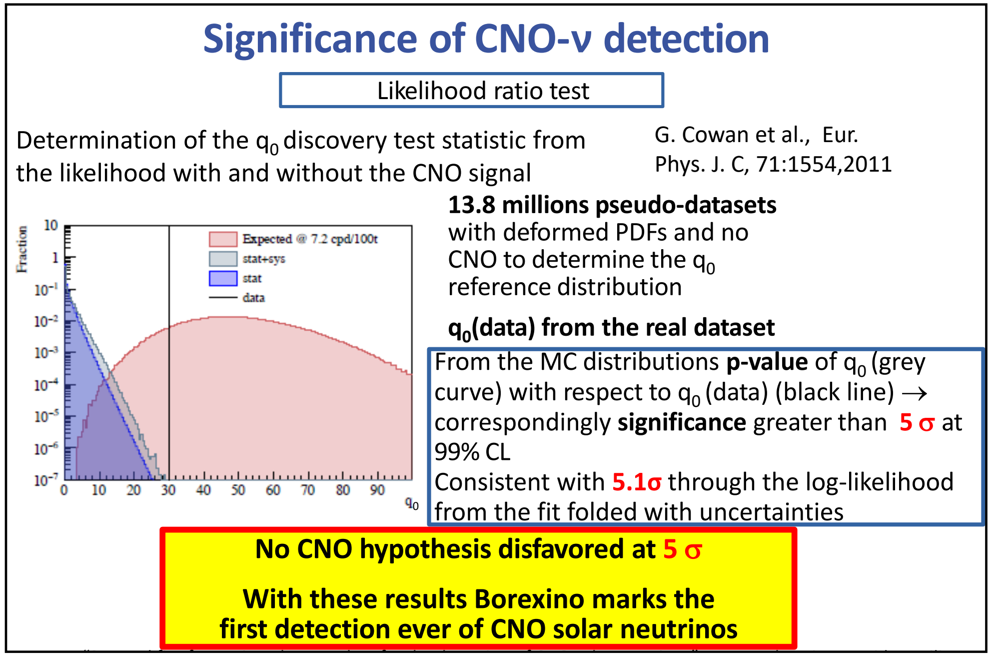
~5 (HZ) / ~3 (LZ) [cpd/100 tons] expected in Borexino

CNO neutrinos

First observation presented in NEUTRINO 2020



Gioacchino Ranucci



Pay attention to Barbara’s next presentation!

SNO+

Poster presentation (ZEP location : 3F. Majorana)

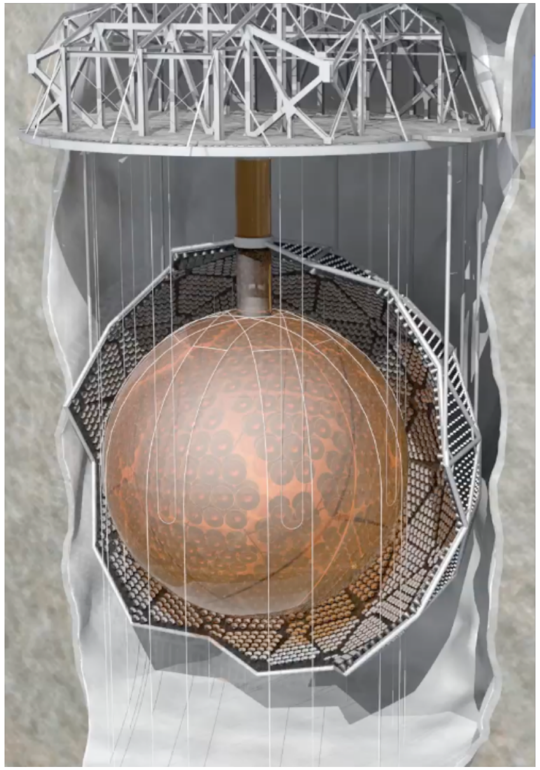
MT10-060 Max Smiley
MT10-078 Josephine Paton
MT10-353 Lorna Nolan

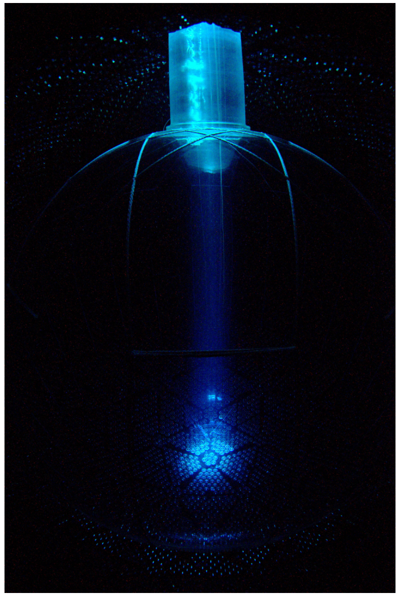
Materials were provided by M. Chen, Thanks!

SNO+

SNO+

Deep underground multi-purpose detector





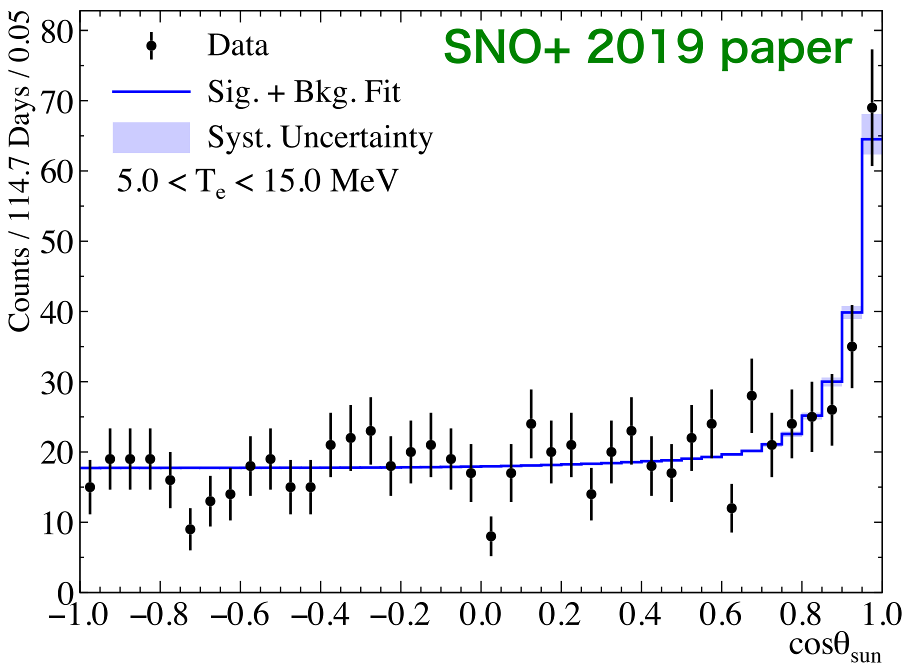
Neutrinoless double beta decay, Geo- and Reactor antineutrinos, supernova, as well as solar neutrinos

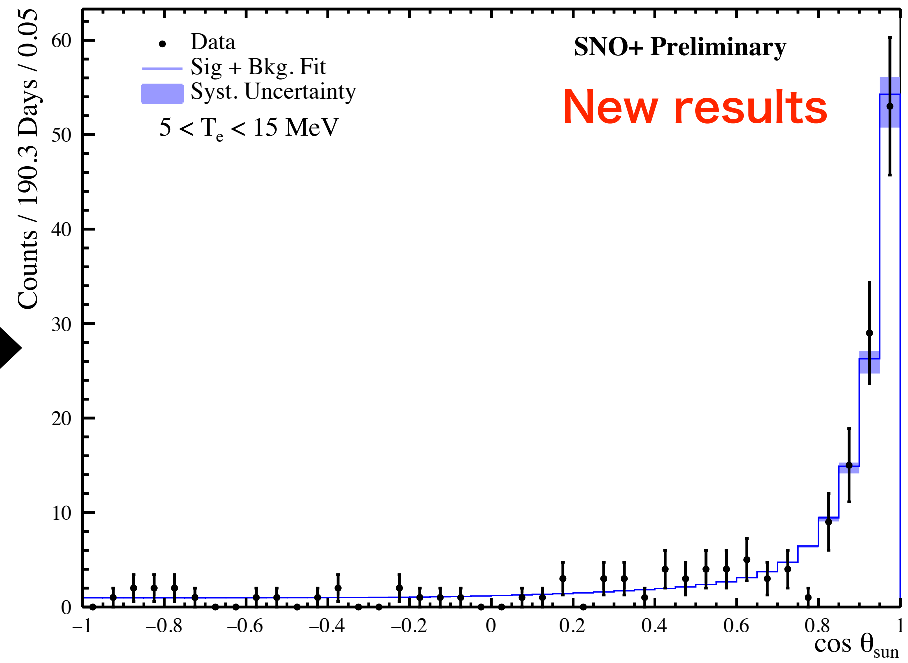
- Deep underground location, 6010 m.w.e., greatly suppresses cosmogenic backgrounds. (Kamioka: 2700m.w.e., GranSasso: 3800 m.w.e.)
- Pure water phase is May 2017 to July 2019 as a water Cherenkov detector filled with 905 tonnes of ultra pure water.
- Scintillator phase, which uses 780 tonnes of newly developed organic LS, is just started.
- Tellurium phase will use tellurium-loaded liquid scintillator for experiment

Pure water phase

^{8}B solar neutrinos: solar peak

Same energy range (5.0 < T_e < 15.0MeV)



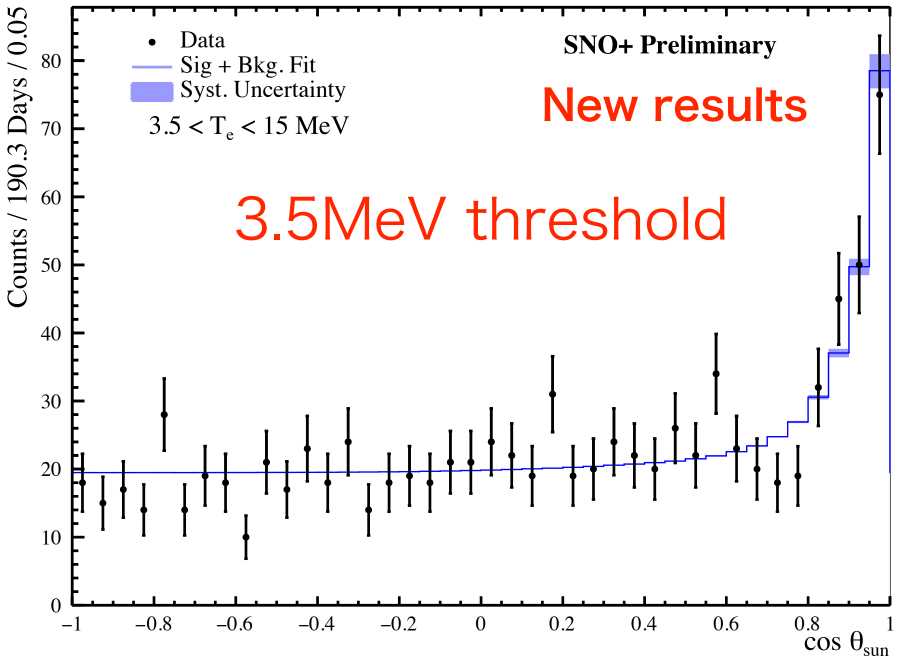


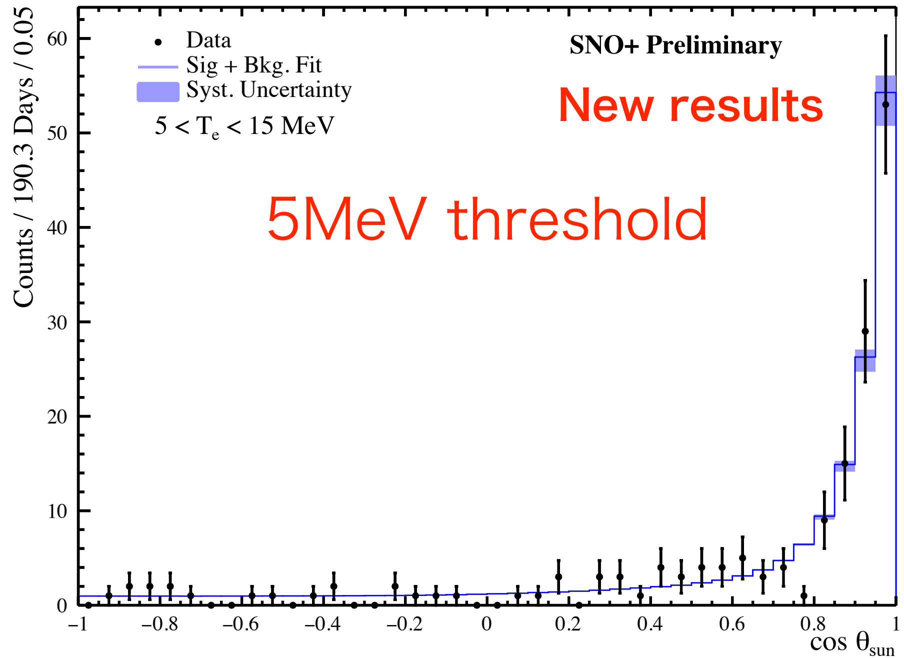
Latest results with ~1/10 Radon level (new SNO+ cover gas system) make apparent lower backgrounds in solar neutrino measurement!

Pure water phase

^{8}B solar neutrinos: solar peak

Also 3.5 MeV threshold



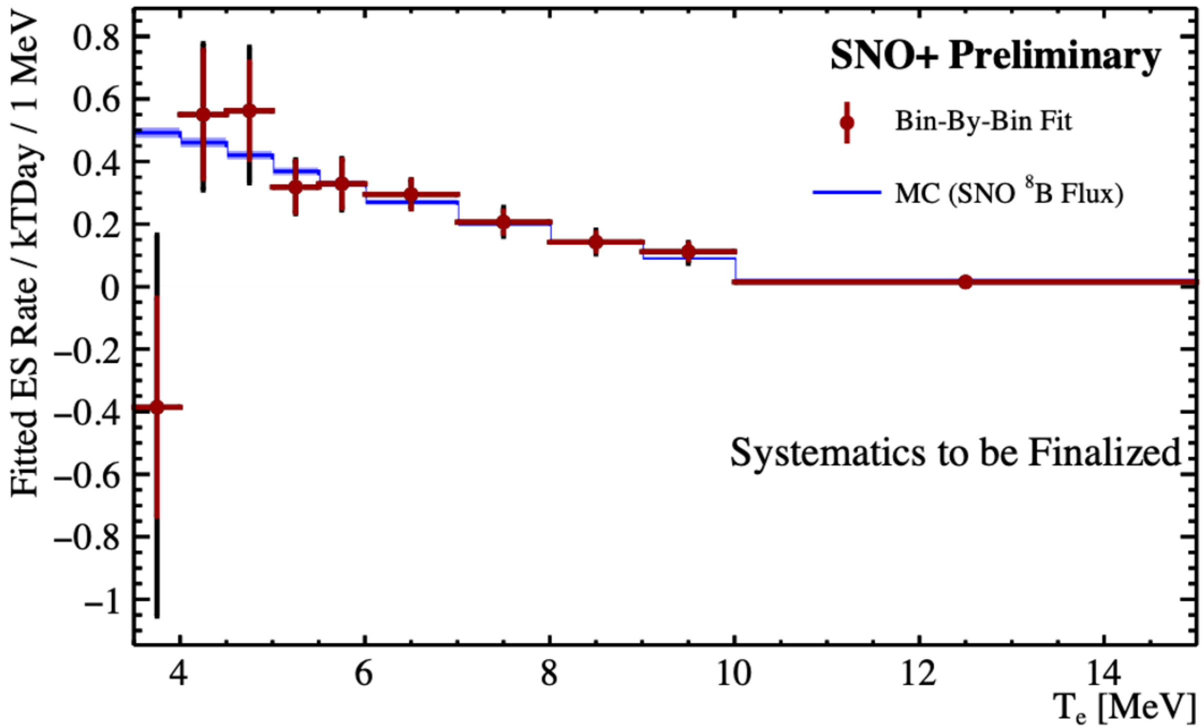


Latest results with ~1/10 Radon level (new SNO+ cover gas system) make lower energy threshold possible in solar neutrino measurements!

Pure water phase

^{8}B solar neutrinos: Energy spectrum

new result

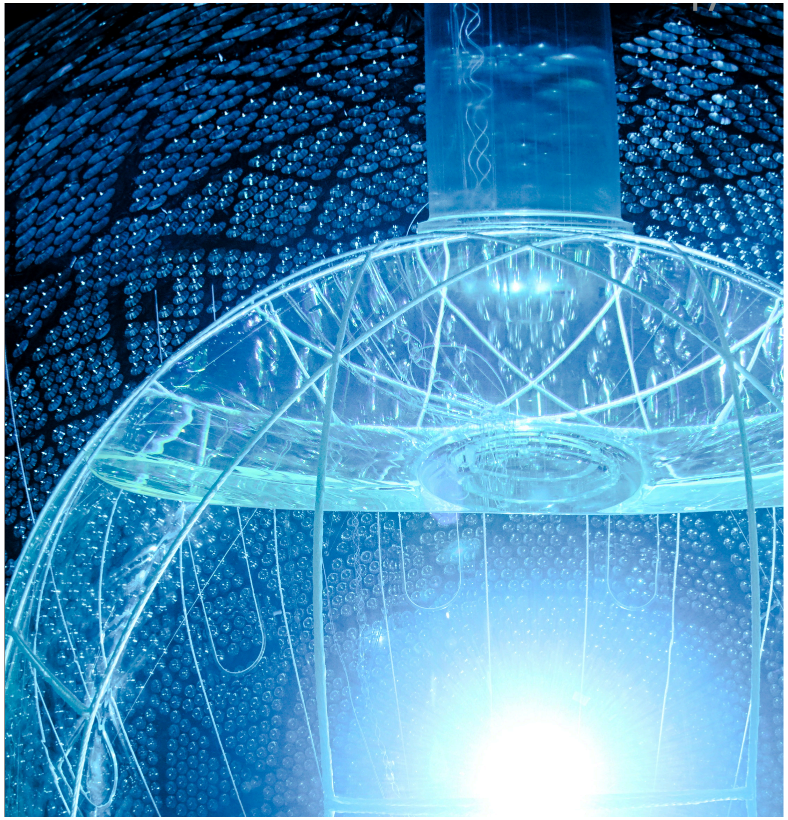


Good agreement with expectation

SNO+

Scintillator phase

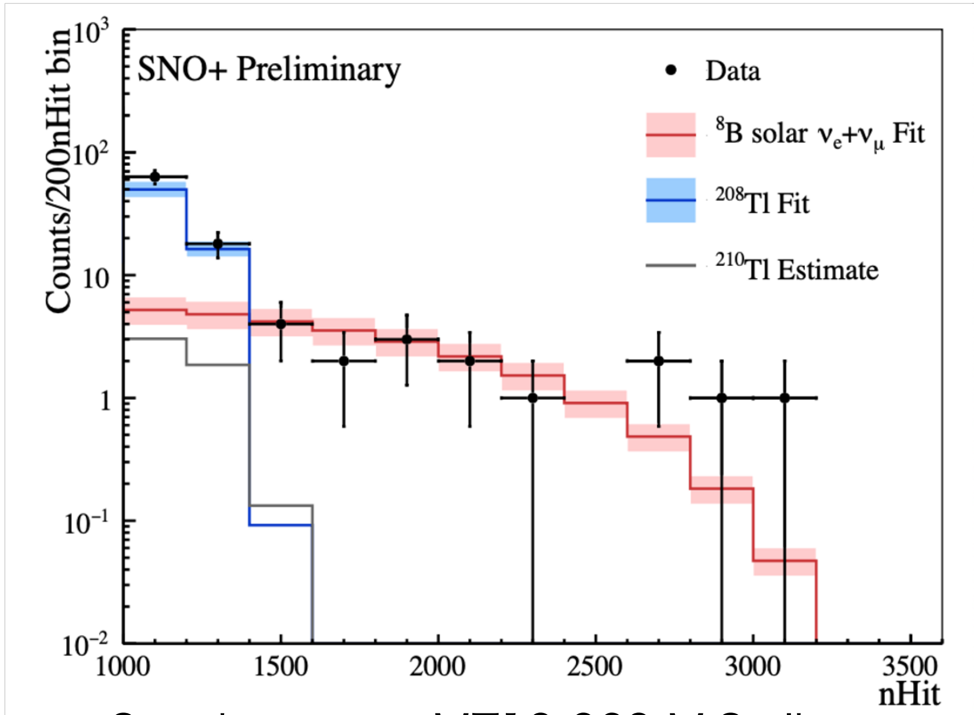
Partial fill



- Filling operations were paused in 2020 by COVID pandemic.
- Partial fill: quiet period of low background data:
  After Radon decayed, before filling resumed
- Measured liquid Scintillator backgrounds:
  ^{214}Bi-Po decayed coincidences
  for U chain: $(4.7\pm1.2)\times10^{-17}$ g_{U}/g_{LAB}
  for Th chain: $(5.3\pm1.5)\times10^{-17}$ g_{Th}/g_{LAB}
  reaches SNO+ target for double beta decay.
- Optical properties of liquid scintillator is Good!
- Also physics from SNO+ partial fill period.

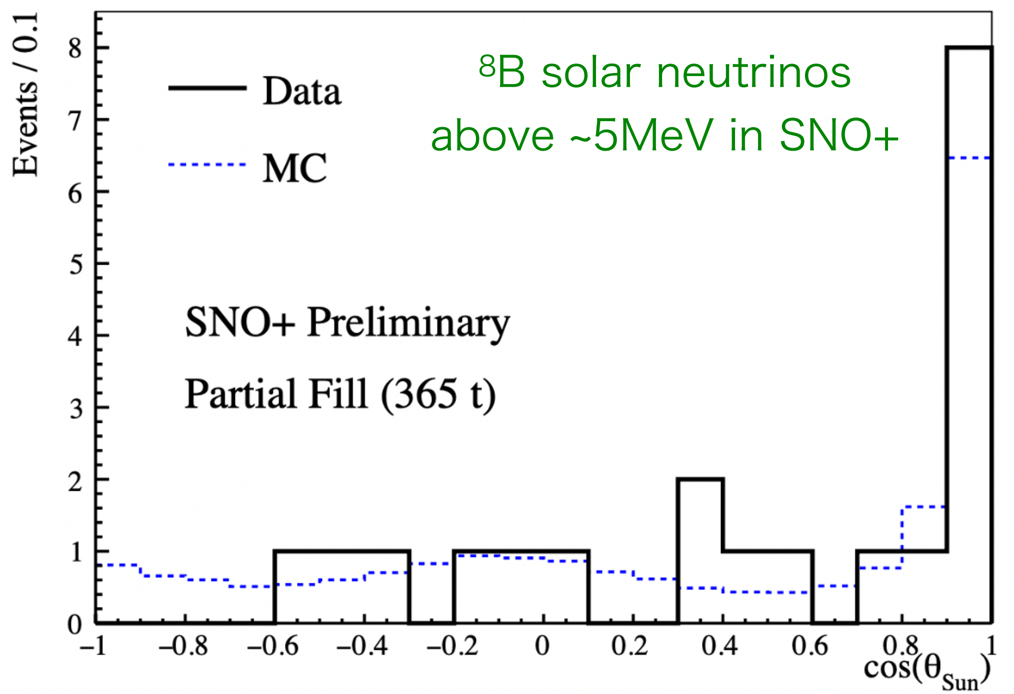
Scintillator phase

Partial fill



See the poster MT10-060 M.Smiley

Reconstructed by fitting using Cherenkov+Scintillation light combined pdf.



See the poster MT10-078 J.Paton

This is the first event-by-event direction reconstruction of MeV events in liquid scintillator!

SNO+

Scintillator phase

Fill completed

Completely filled with 2.2 g/L PPO in LAB

Truly a monumental effort to complete this during the pandemic!

- receiving shipments of LAB
- transport from surface to underground through the mine, coordinating with mine operations logistics (during COVID)
- distillation of LAB
- water extraction and distillation of PPO
- nitrogen stripping
- nearly 5,000 QA shifts to verify optical properties of purified LS before sending it to the Acrylic Vessel

Rn backgrounds in the detecter are decaying; quiet physics data taking is underway in SNO+ scintillator phase

Looking forward to seeing next results!

Summary

Conclusion and outlook

- The standard solar model and the MSW neutrino oscillation scenario has been established in solar neutrinos.
- Lots of precise solar neutrino observation results are appeared from Super-K and Borexino. Recently, SNO+ has also started.
- Still have several issues to be solved in future:
  - Δm2 tension between solar and KamLAND?
  - Solar metallicity problem, High-Z or Low-Z?
- Next generation experiments are constructed and planed. I future, hope to understand more about solar neutrino both from neutrino physics and astrophysics

Thank you for your attention!