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Investigation of solar g-mode oscillations search using solar neutrinos

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太陽模型構築と日震学理論に基づく
太陽ニュートリノを用いた太陽g-mode振動探索

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1. Introduction

◆ The Sun

- Energy generation via nuclear fusion reactions [1, 2].

$$4p \rightarrow \alpha + 2e^+ + 2\nu_e$$

- Electron density, temperature, and metallicity profiles affects the production of solar neutrinos [3].

◆ Solar oscillations (p-modes and g-modes)

- The Sun periodically oscillates

Name	Reason	Region	Frequency
p-mode	Pressure	Surface	5 minutes
g-mode	Gravity	Core	1-3 hours

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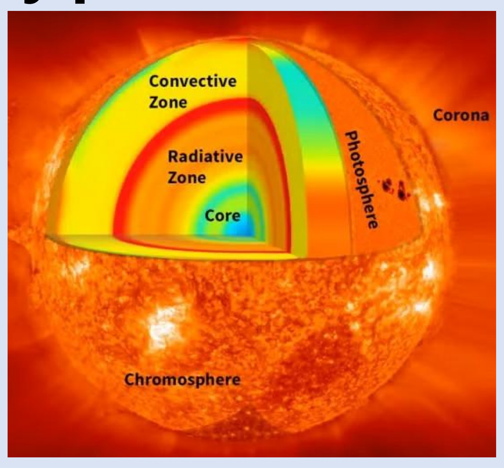
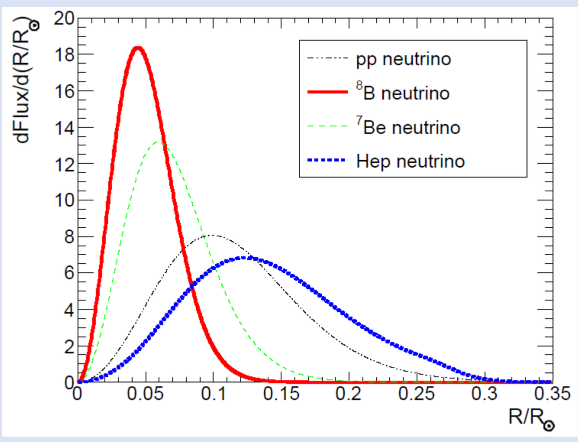
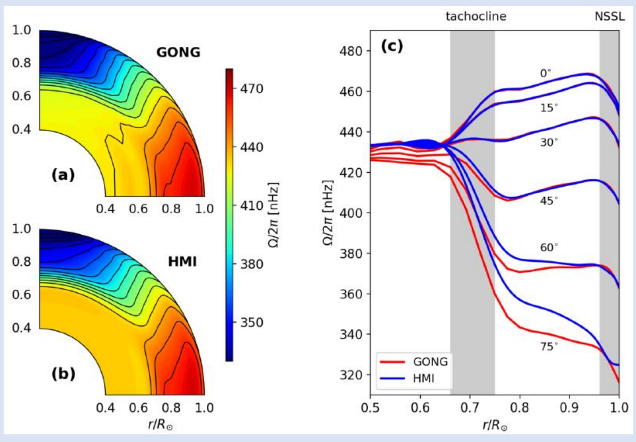


→ Frequency measurements of solar p-modes reveal the 1-d sound speed profile and 2-d rotational profile, etc.

- However, g-modes are not observed because its amplitude is small at the surface.





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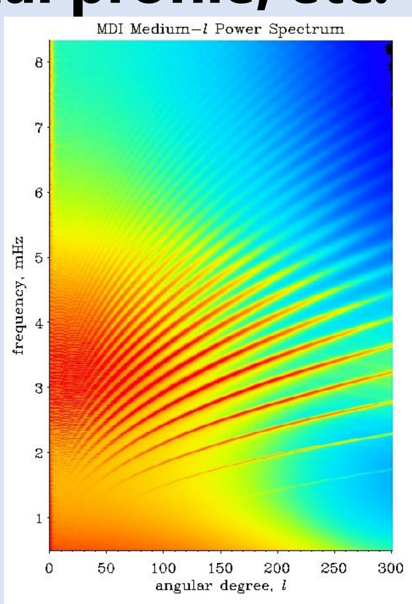
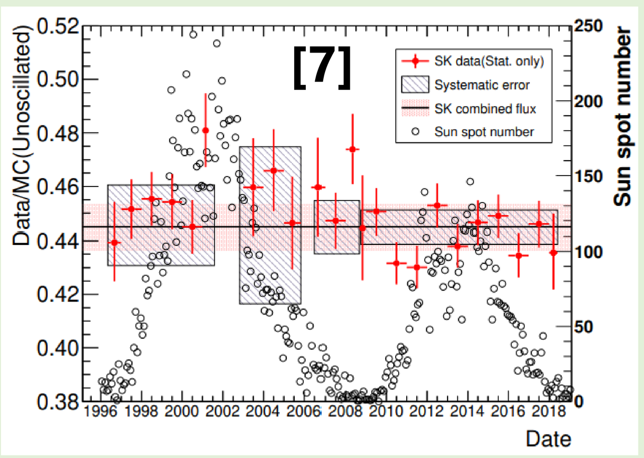


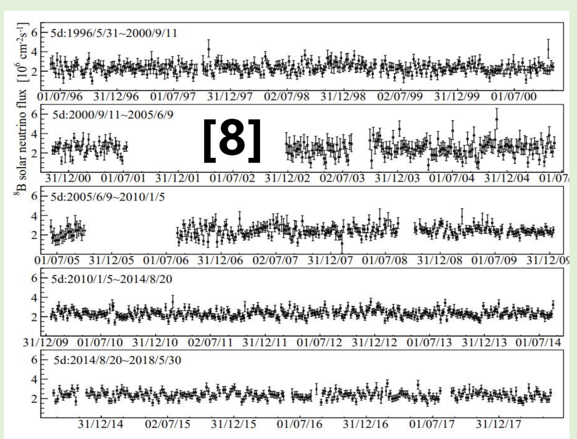
2. Periodic change of solar ν

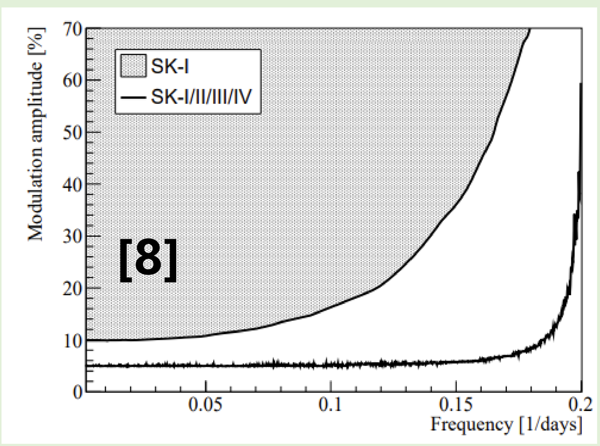
◆ Current situation of solar neutrino measurements

- The Super-Kamaiokande detector has measured the solar ^{8}B ν for more than 25 years [6, 7].

→ No periodic change is found except for annual modulation. (< 5 days, amplitude < 5.2% (90% C.L.) [8]).







◆ Periodic amplification of solar ^{8}B neutrinos

- G-modes have large amplitude in the core.

→ Periodic change of local temperature.

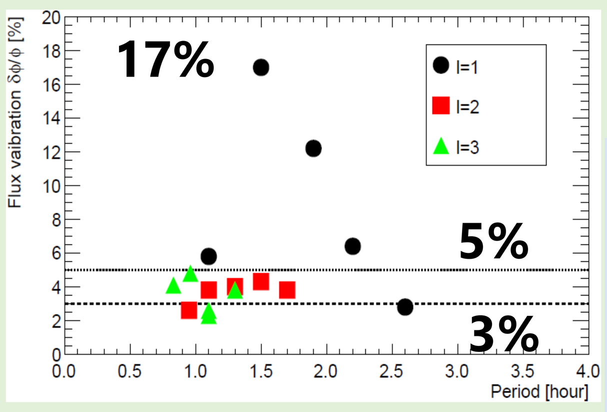
- The energy (production rate of ^{8}B ν) strongly depends on the temperature [9].

$$\frac{\delta\varepsilon}{\varepsilon} = \frac{\delta\rho}{\rho} + \mu\frac{\delta T}{T}$$

ε : Produced energy
ρ : Density
T : Temperature

Neutrino	Power Index (μ)
pp	[-1.1, -0.9]
pep	-1.4
^{7}Be	11
^{8}B	24~25
^{13}N, ^{15}O	20
^{17}F	23

- Lopes (2014) [10] suggests that at most ~17% fluctuation of solar ^{8}B ν due to g-modes propagating in the core.



- SNO experiment sets the upper limit of amplitude as 11% for 1-3 hours [11].

3. Motivation and strategy

◆ Goal

1) Search for solar g-mode oscillations using solar neutrinos by evaluating its amplitude and frequency,
2) Determine the density profile precisely in the core region.
3) Set an upper limit of temperature fluctuation in the core.
4) Improve the solar models by inputting g-mode results.

◆ Strategy

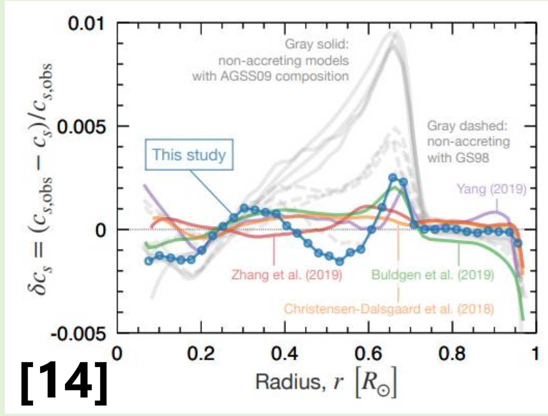
i) Reproduce Ref. [10] method by using the latest solar models.
ii) Make a catalog of amplitudes and frequencies of solar ν.
iii) Search for periodic change of solar ν by neutrino detectors, such as Super-Kamiokande and Hyper-Kamiokande detectors.

4. Solar models

◆ Model construction and assumption

- The Sun is well studied star observationally and theoretically.
- We will test four solar models with different assumptions.

Model	Assumption	Characteristic
SSM-GS98 [12]	Standard solar model High metallicity at the surface (old)	--
SSM-A09 [13]	Standard solar model Low metallicity at the surface (New)	--
K2-A2-12 [14]	Low metallicity abundances opacity increases by ~12% around the base of the convective zone	Sound speed profile inside the Sun is well reproduced.
K2-MZvarA2-12 [14]	Considering the accretion flow to protostars	High metallicity inside the Sun Neutrino fluxes are well re-produced



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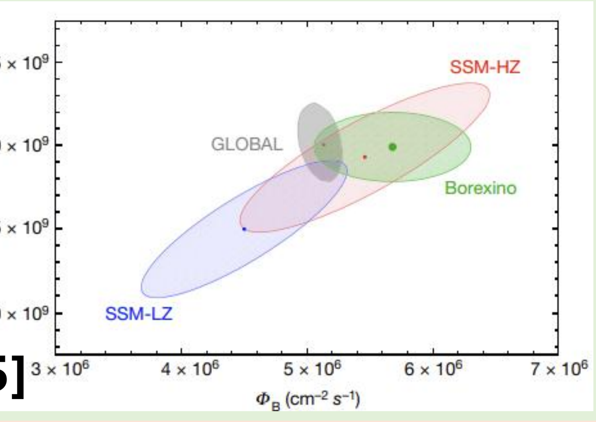

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5. Analysis and results

◆ Analysis scheme

a) Adding the g-modes effect into the constant solar ν flux under its equilibrium state based on the perturbation theory.

$$\Phi_0 = \int_0^{M_\odot} \varphi_0(m)dm \quad \xrightarrow{\delta T_{nl}(m,t)\ \ \delta\varphi_{nl}(m,t)} \quad \Delta\varphi_{nl} = \int_0^{M_\odot} \delta\varphi_{nl}(m,t)dm$$

b) Relating the neutrino production with temperature change.

$$\frac{\delta\varepsilon}{\varepsilon} = \frac{\delta\rho}{\rho} + \mu\frac{\delta T}{T} \quad \xrightarrow{\frac{\delta\varepsilon}{\varepsilon} = \frac{\delta\varphi}{\varphi} \quad \frac{\delta T}{T} = (\Gamma_3 - 1)\frac{\delta\rho}{\rho}} \quad \frac{\delta\varphi}{\varphi} = \left(\frac{1}{\Gamma_3 - 1} + \mu\right)\frac{\delta T}{T}$$

Adiabatic oscillation, ideal gas $\Gamma_3 = 5/3$ at the core.

c) Compute the neutrino flux fluctuations with δT_{nl} that are obtained by solving the eigenvalue problem.

$$\Delta\varphi_{nl}(t) = \Phi_0 \times \boxed{\mathcal{A}_{nl}} \times \int_0^{R_\odot} \Phi_0^{-1}(\mu)\left[\frac{\delta T}{T}(r)\right]_{\rm Norm} \varphi_0(r) \times 4\pi r^2 \rho dr \times e^{-i\omega_{nl}t}$$

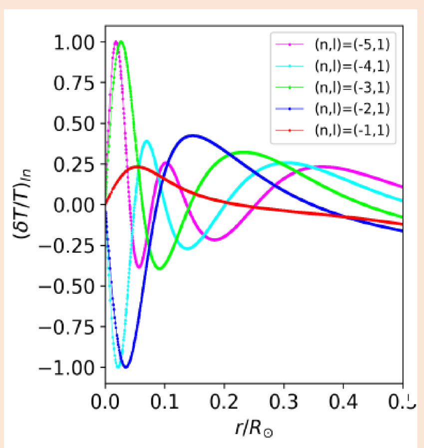
We assumed the constant amplitude of A_{nl} because g-modes are not observed. (one "free" parameter in this analysis)

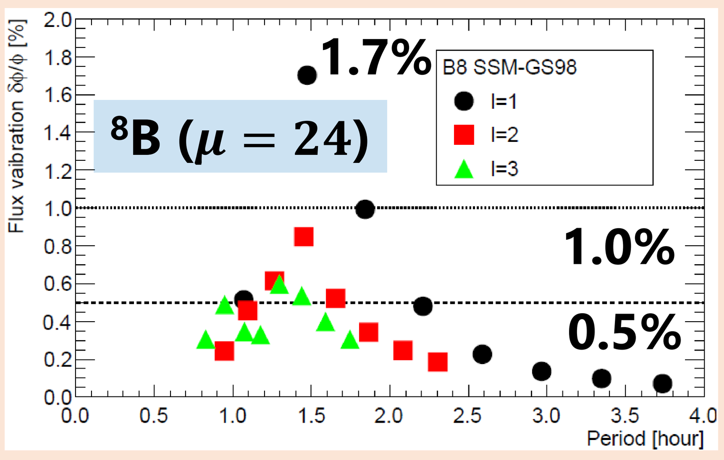
◆ Results and discussion

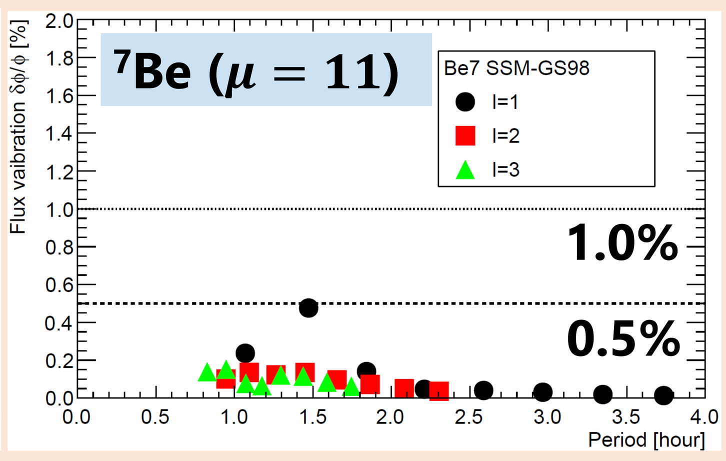
- We reproduced the solar ^{8}B ν fluctuations while its amplitude is 1/10 compared with the original method.

→ Less than 2% of accuracy is required to search for this effect.

- Hyper-Kamiokande can possibly detect?? (5-10 events/hour).







- Amplitude of solar ^{7}Be neutrino is quite small.

→ May be difficult by Borexino, KamLAND, and JUNO detectors.

6. Summary and future prospect

◆ Summary

- Solar g-modes propagating inside the Sun is not observed.

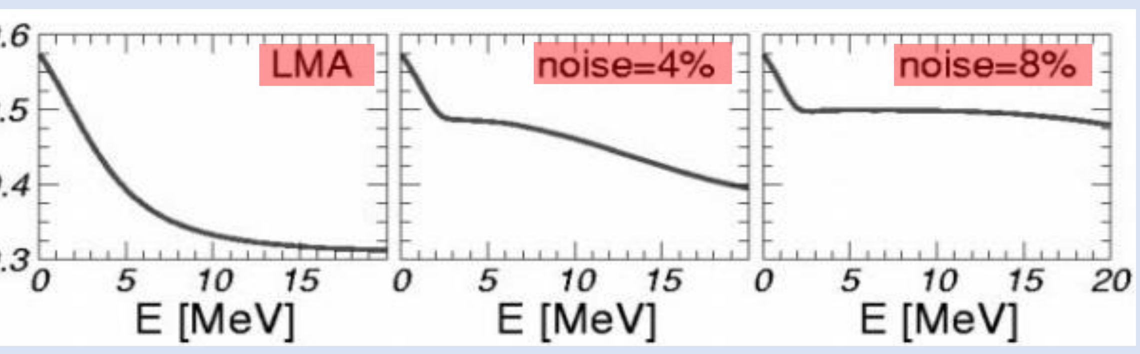
→ Search for this oscillation by solar neutrinos.

- Periodic amplification of solar neutrinos due to g-modes.

→ 1.7% of solar ^{8}B neutrinos (detectable in Hyper-K detector).

◆ Prospects

- G-mode may affect the survival probability by MSW effect [16].
- We are also discussing the second-order effect.



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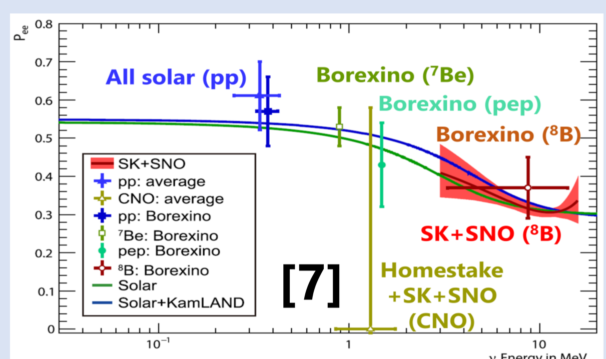

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Reference: [1] Phys. Rev. 54, 248 (1938) [2] Phys. Rev. 55, 434 (1939) [3] Mod. Phys. 54, 767 (1982) [4] SOHO (gallery) [5] Spa. Sci. Rev. 21, 77 (2023) [6] Phys. Rev. D 94, 052010 (2016) [7] Phys. Rev. D 109, 092001 (2024) [8] Phys. Rev. Lett. 132, 241803 (2024) [9] Phys. Rev. D 53, 4202 (1996) [10] Astrophys. J. Lett. 792, L35 (2014) [11] Astrophys. J. 710, 540 (2010) [12] Spa. Sci. Rev. 85, 161 (1998) [13] Annu. Rev. Astron. Astrophys. 47, 481 (2009) [14] A&A 655, A51 (2021) [15] Nature 562, 505 (2018) [16] Astrophys. J. 588, L65 (2003)