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太陽内部を伝搬する太陽g-mode振動への実験的な制限

論文そろそろ投稿します

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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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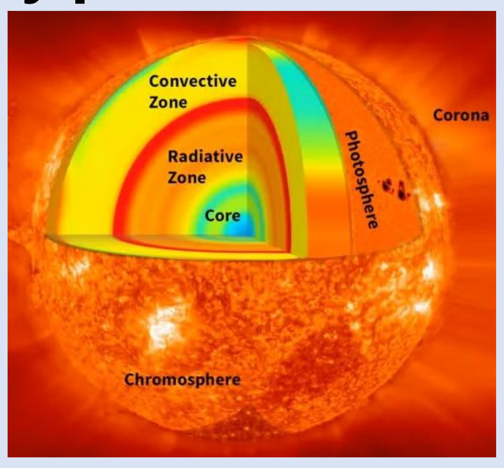
1. Introduction

◆ 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].



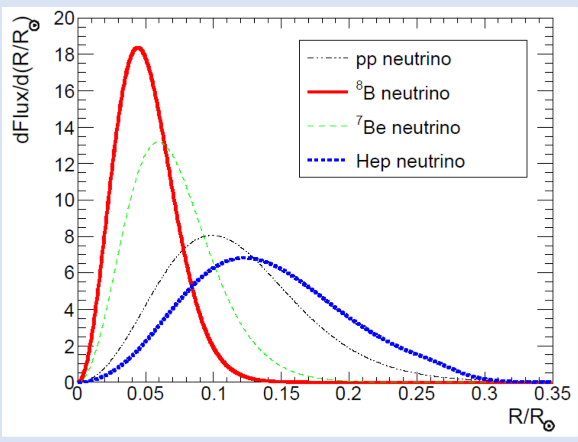
◆ Solar oscillations (p-modes and g-modes)

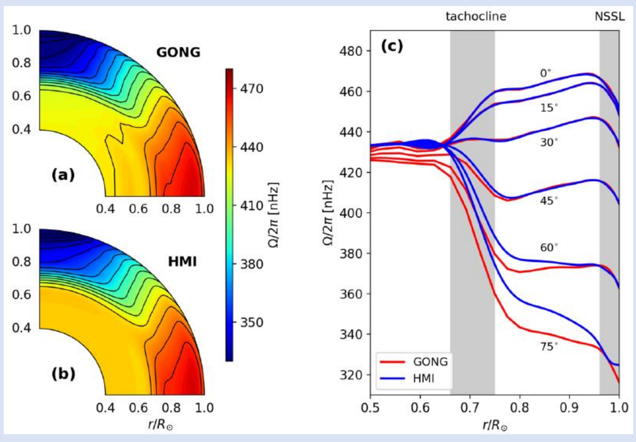
- The Sun periodically oscillates [4] →

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

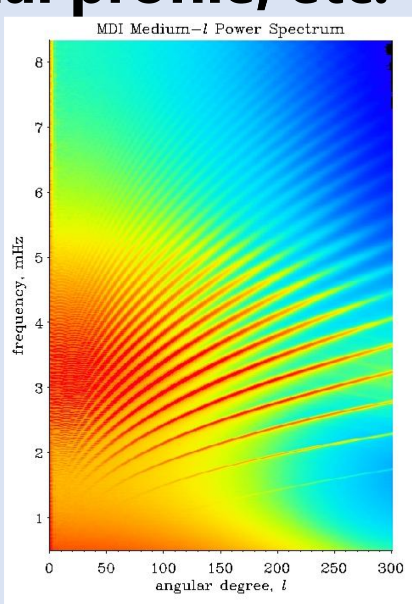
→ Frequency measurements of solar p-modes reveal the 1-d sound speed profile and 2-d rotational profile, etc.

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





← [5]

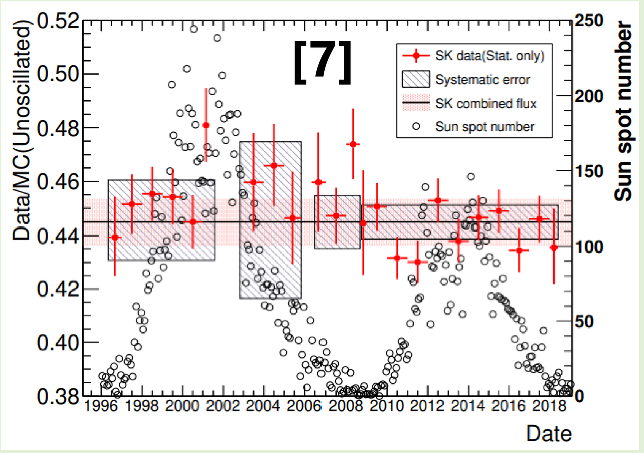


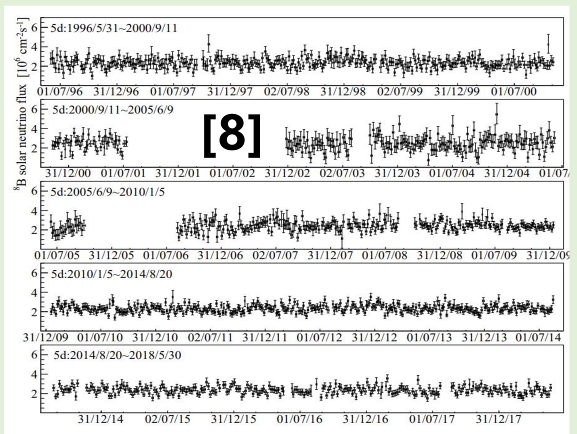
[4] →

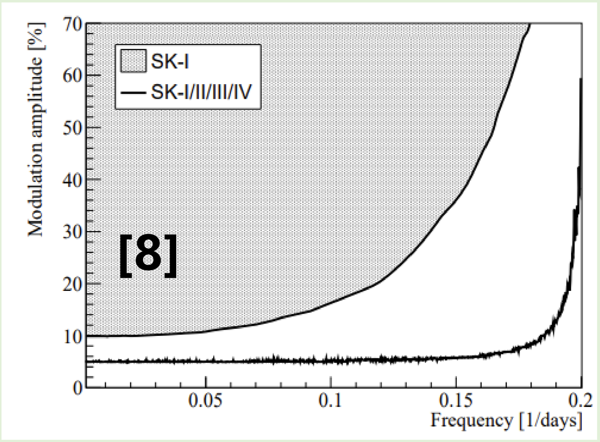
2. Periodic change of solar ν

◆ 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.

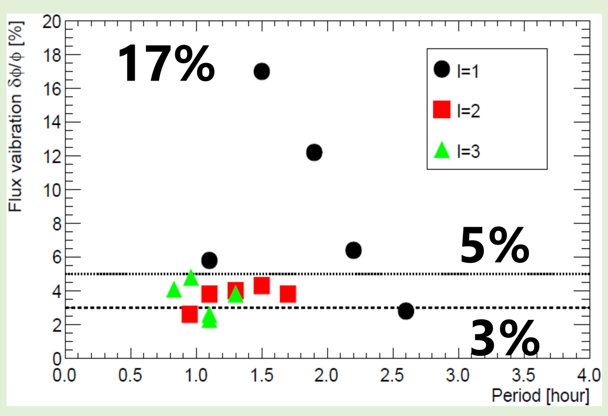
- The energy (production rate of ^{8}B ν) strongly depends on the temperature [9].

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

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) Detect 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) Consider 2nd order effect to further study the g-modes.
iii) Compare theoretical predictions with the experimental results and test our theory based on linear adiabatic oscillation.

4. Analysis

◆ 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.

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

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.

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

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

5. Results

◆ Results and discussion

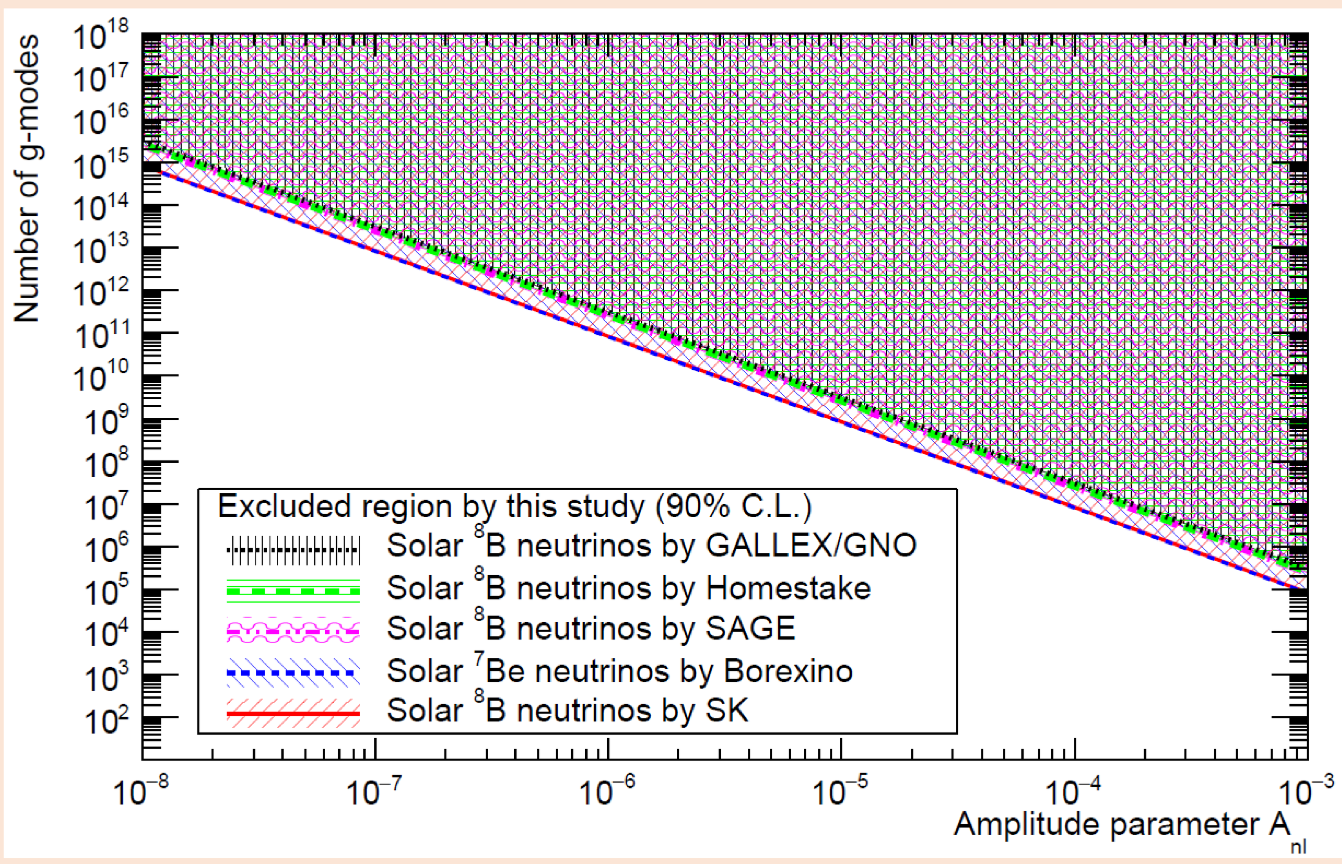
- First order calculation predicts no periodic change because of geometrical cancellation.
 → We suspect Lopes (2014) [10] may not consider this effect.

- Second order calculation predicts the change of neutrino flux with the 11-year solar cycle.
 → Possibly caused by the change in how g-modes are excited/damped by turbulent convection.

- We analyzed the solar neutrino results by SK [8], Borexino [12], Homestake [13], SAGE [14] and GALLEX/GNO [15, 16].

- Set an experimental constraint on the # of g-mode oscillations.
 → SK result gives the strongest limit: $< 7.8 \times 10^7$ at $A_{nl} = 10^{-5}$.

- Long term operation of the neutrino detector is important to search for the g-mode oscillations propagating in the Sun.



6. Summary and future prospect

- Solar g-modes propagating inside the Sun is not observed.
 → Search for this oscillation by solar neutrinos.

- No periodic amplification of solar neutrinos due to g-modes is expected by our 1st order calculation.

- Long term measurement with small fluctuation of background is important to search for the g-mode oscillations.

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