Search for Periodic Time Variations of the Solar $^{8}\mathrm{B}$ Neutrino Flux Between 1996 and 2018 in Super-Kamiokande

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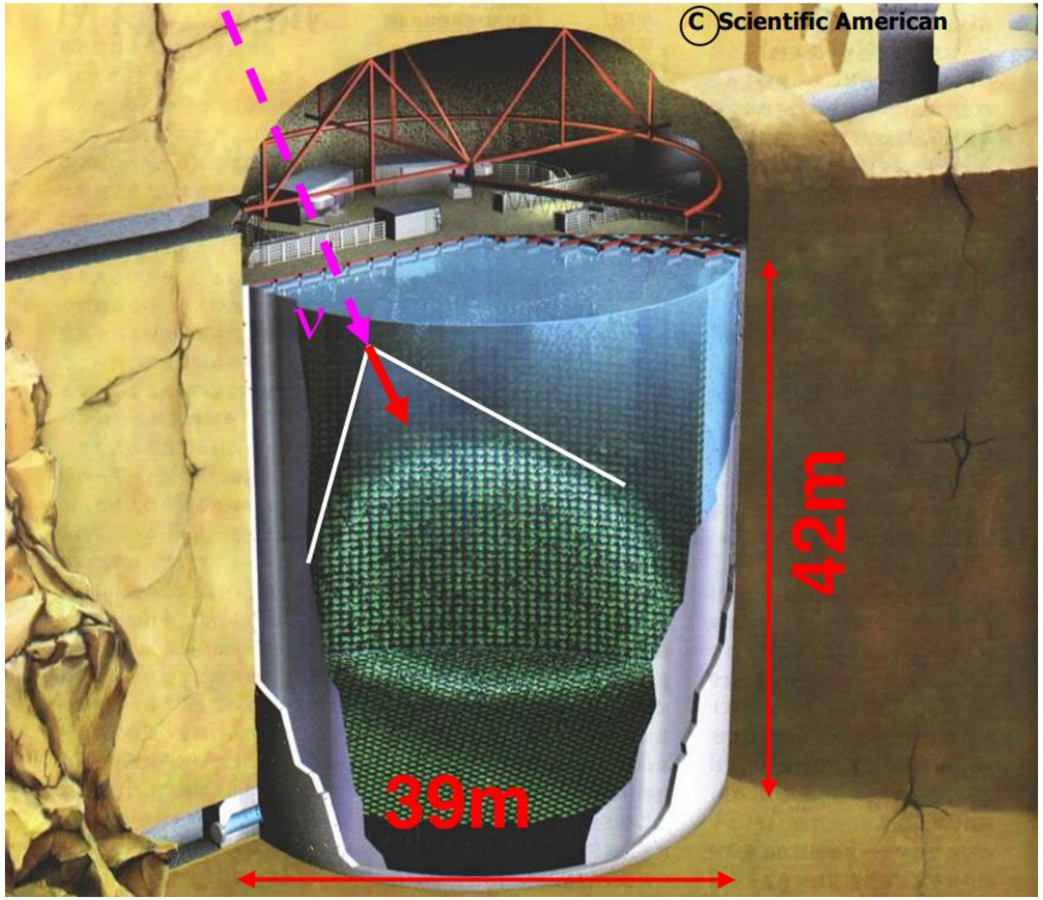
WIN2023

Introduction – SuperKamiokaNDE

- Water cherenkov detector for neutrino
- Water 50ktons (22.5ktons fid.)
- 1,000m underground
- Inner-Detector (ID) : 11,146 50cm PMTs (40%)
- Outer-Detector (OD) : 1,885 20cm PMTs

SK Phase	start ~ end date
SK1	1996-04-01 ~ 2001-09-01
SK2	2002-12-10 ~ 2005-10-06
SK3	2006-05-23 ~ 2008-08-17
SK4	2008-09-15 ~ 2018-05-30

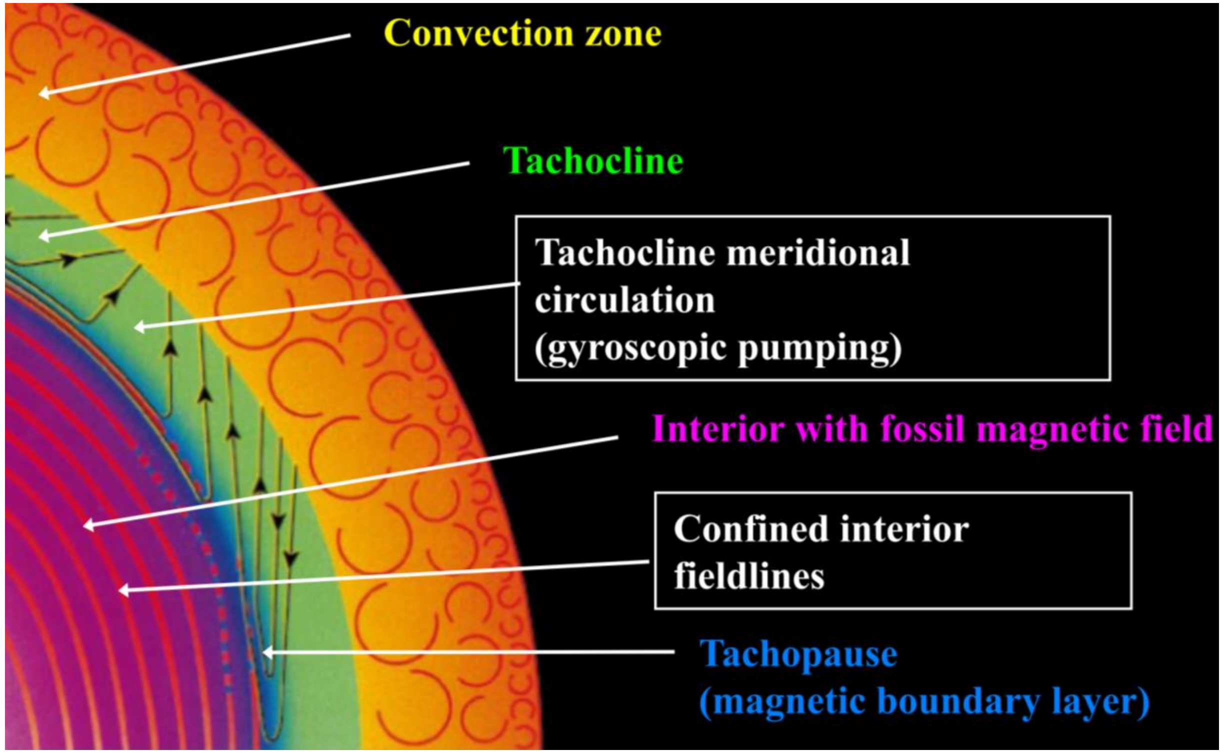


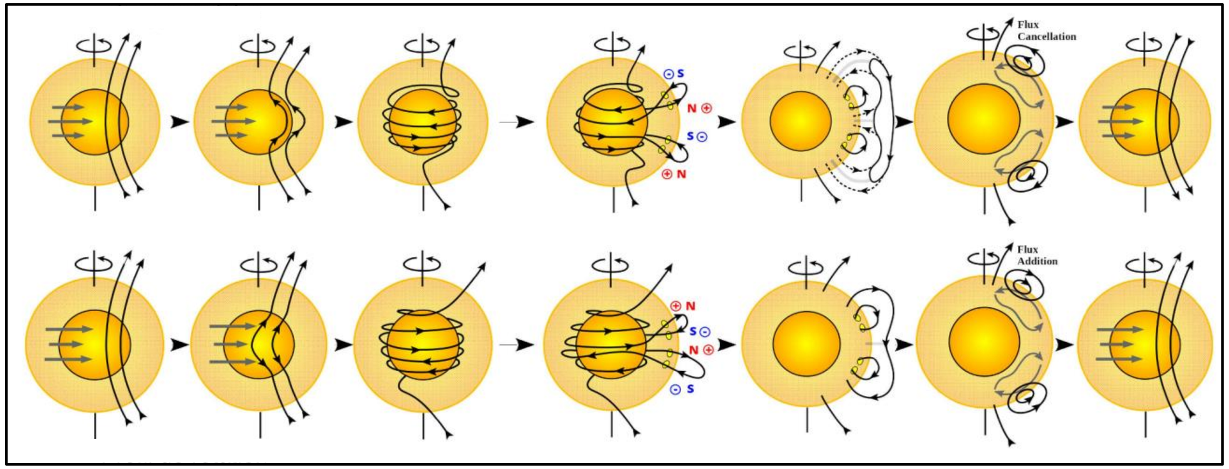
Motivation

- LMA solution – $1/r^2$ annual modulation
- Flux dependence of core temperature

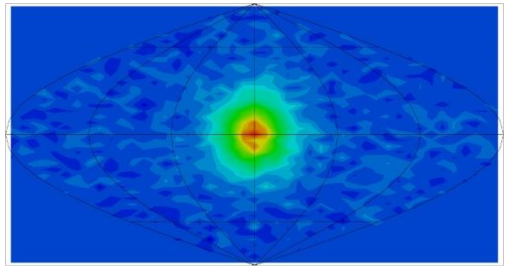
  $\Phi_{solar\ 8B\ \nu} \propto T^{25}$ (PRD, 53:4202, 1996)
- Friction in tachocline

  - Related with the sunspot
  - Strong magnetic field
- Magnetic field flips flavor and spin of ν called resonant spin flavor precession
  - Additional disappearance
  - Periodicity of flux modulation

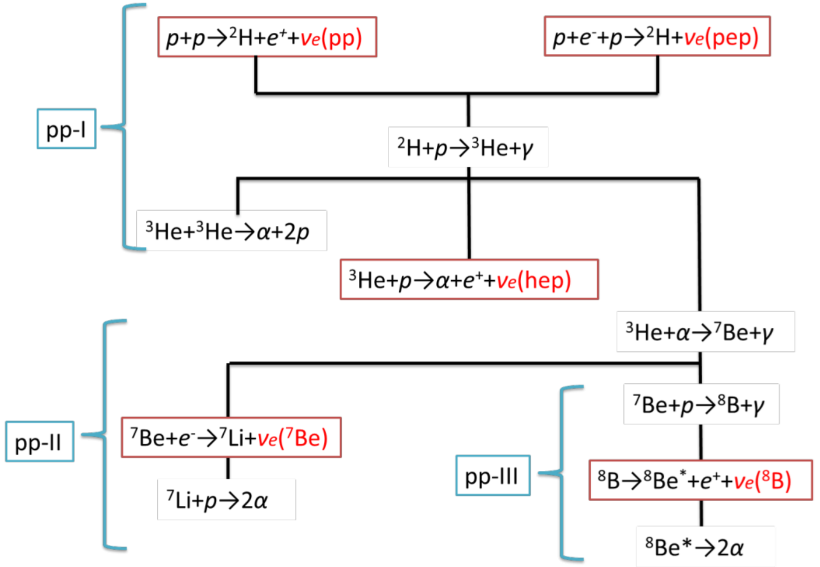




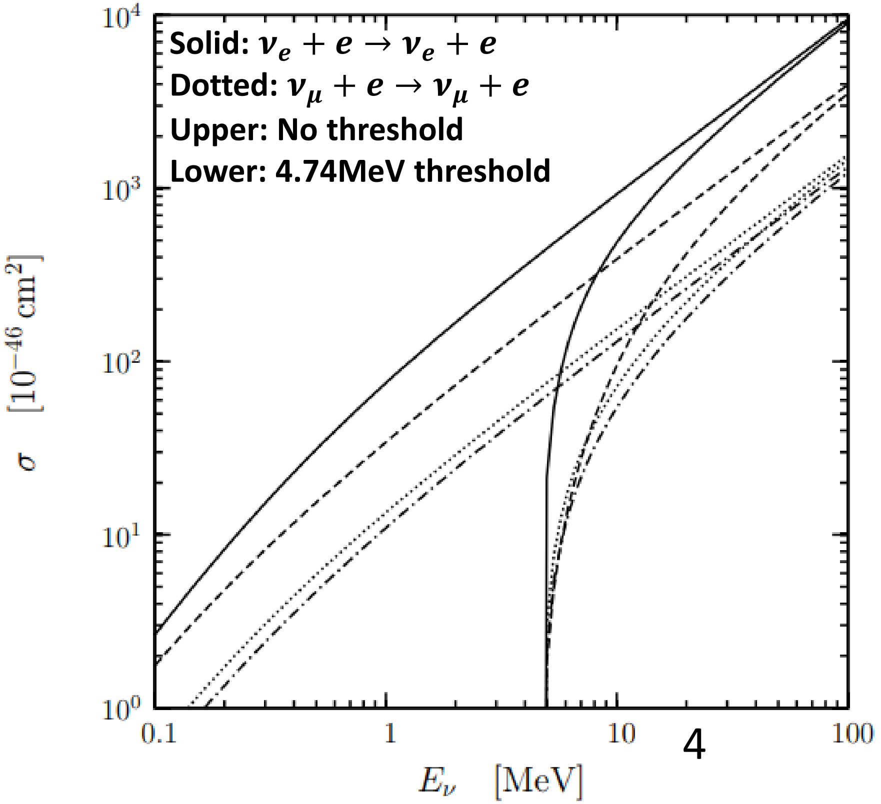
Impact of anti-solar differential rotation in mean-field solar-type dynamos (Q. Noraz et al. 2021 Nov 11, Solar Physics)

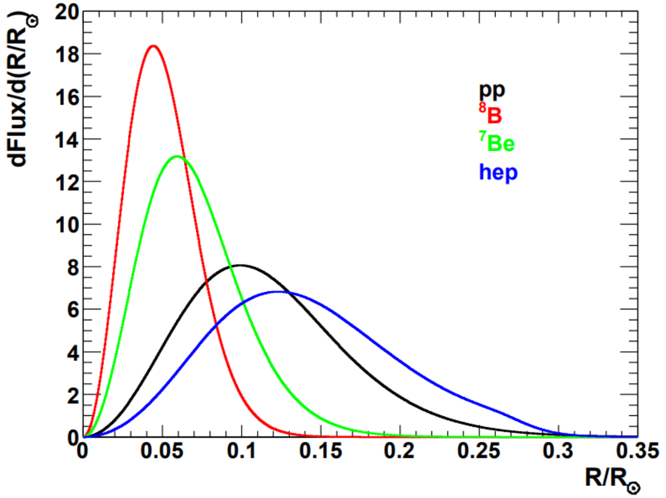


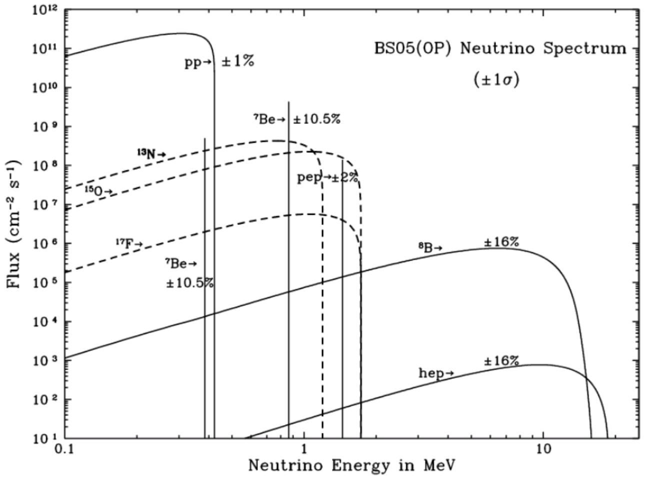
Solar neutrino at SK



- Neutrino from ⁸**B(99.8%)** and hep(0.2%)
- Most neutrino made in core($< 0.3R_{sun}$)
- When escaping the Sun, the neutrino coincide 2nd mass eigenstate after undergoing MSW effect inside of the Sun.
- Measure electron/muon neutrino event at SK
  $\nu_e + e \rightarrow \nu_e + e\ (Z, W)$ / $\nu_\mu + e \rightarrow \nu_\mu + e\ (Z)$

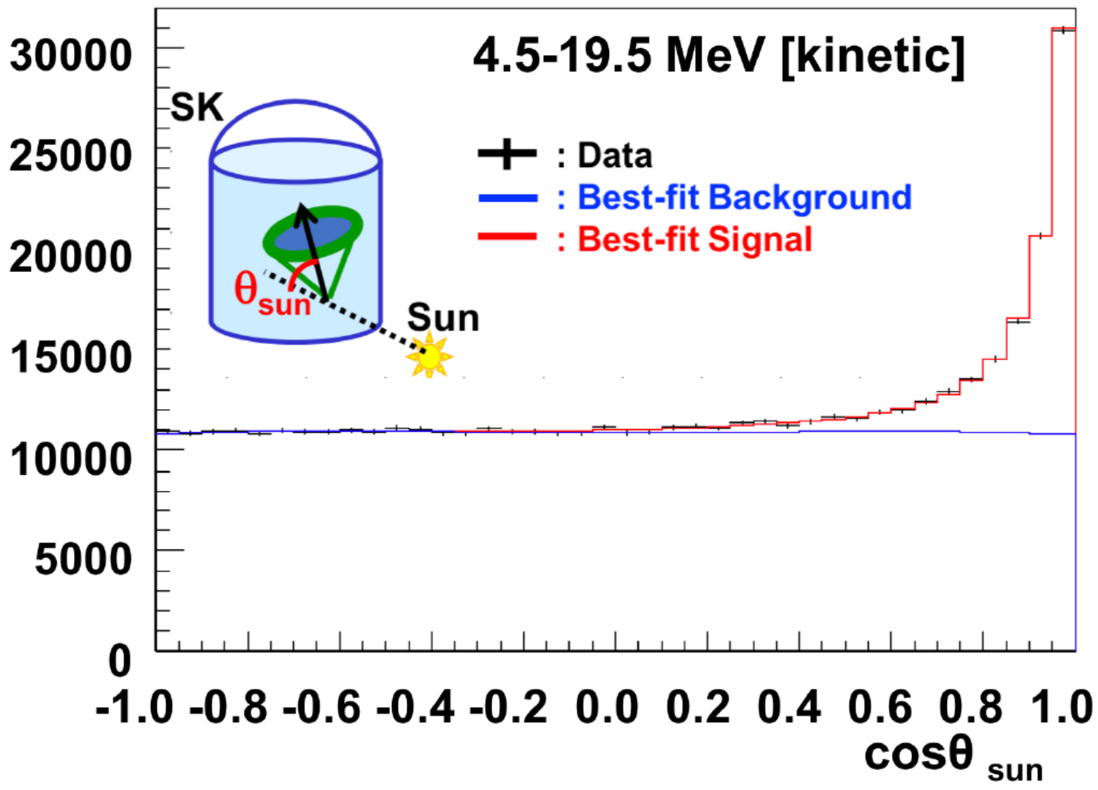




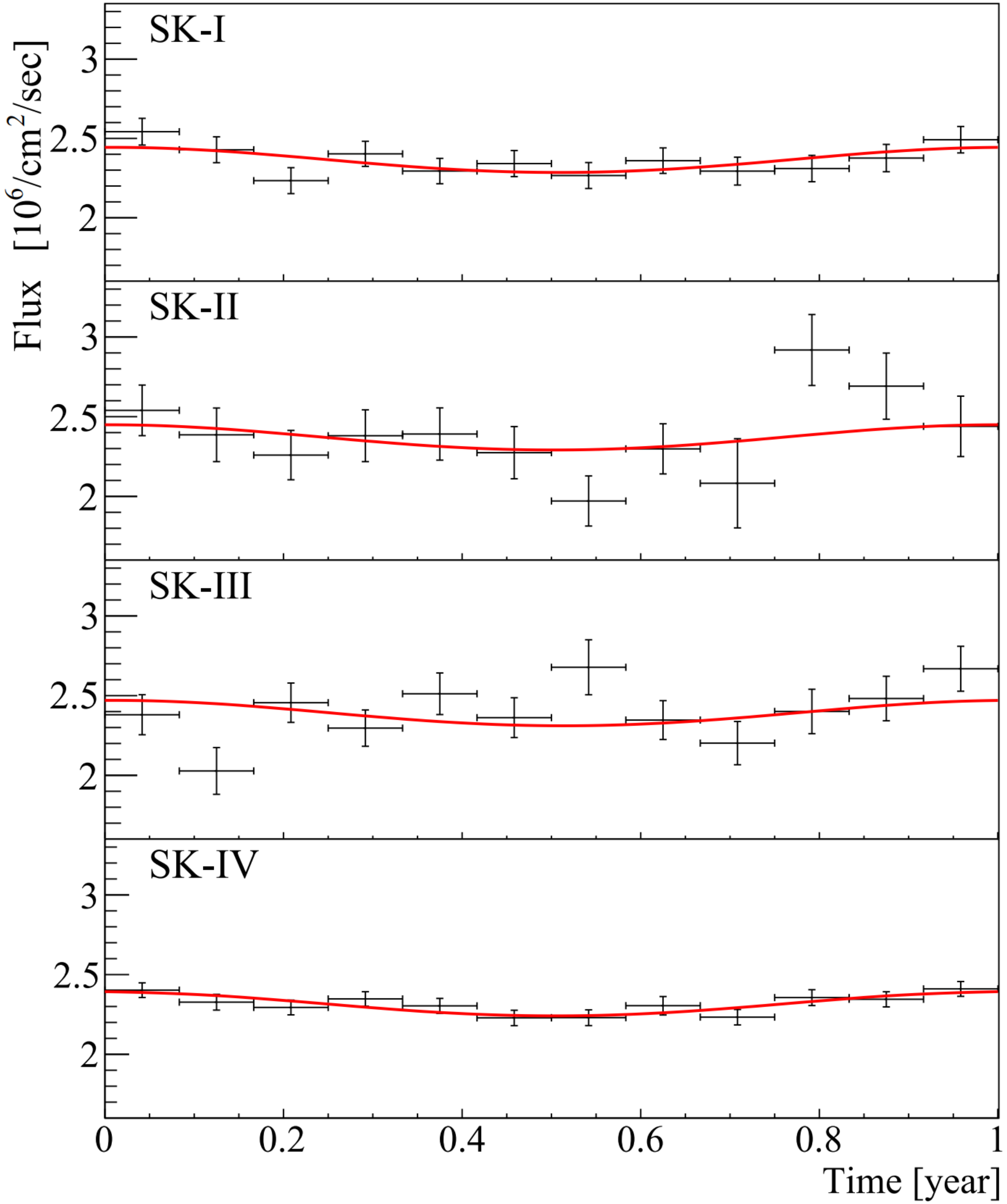


Angular distribution of recoiled electron event

$$\mathcal{L} = e^{-(\sum_i B_i + S)} \prod_{i=1}^{N_{\text{bin}}} \prod_{j=1}^{n_i} (B_i \cdot b_{ij} + S \cdot Y_i \cdot s_{ij})$$



- Maximize binned extended likelihood (event by event)
- Use background(b_{ij}) and signal(s_{ij}) shape
- The fraction of signal events(Y_i) expected in the i^{th} energy bin from MC
- Find number of background(B_i) for each i^{th} energy bin and total number of signal(S)
- Signal and background shape for each SK period
- Measure solar ν for monthly merged bin, i.e. 12 seasons
- Finally, calculate ratio : Signal / Expected



Preliminary

Annual modulation of solar ν flux

- Measure 16 ~ 20 events/day
- Accumulated monthly bin

e.g) SK-IV : 1bin = 10 months statistics

- Flux = Measured/Expected x SNO NC ($5.25\ cm^{-2}\ sec^{-1}$)

SK Phase	Start date ∼ End date	Live days	Energy range [MeV]
SK-I	1996-03-31 ∼ 2001-09-01	1495.7	4.49∼19.5
SK-II	2002-12-10 ∼ 2005-10-06	791.9	6.49∼19.5
SK-III	2006-05-23 ∼ 2008-08-17	548.5	4.49∼19.5
SK-IV	2008-09-15 ∼ 2018-05-30	2967.7	4.49∼19.5

Chi2 for Annual modulation of solar ν flux

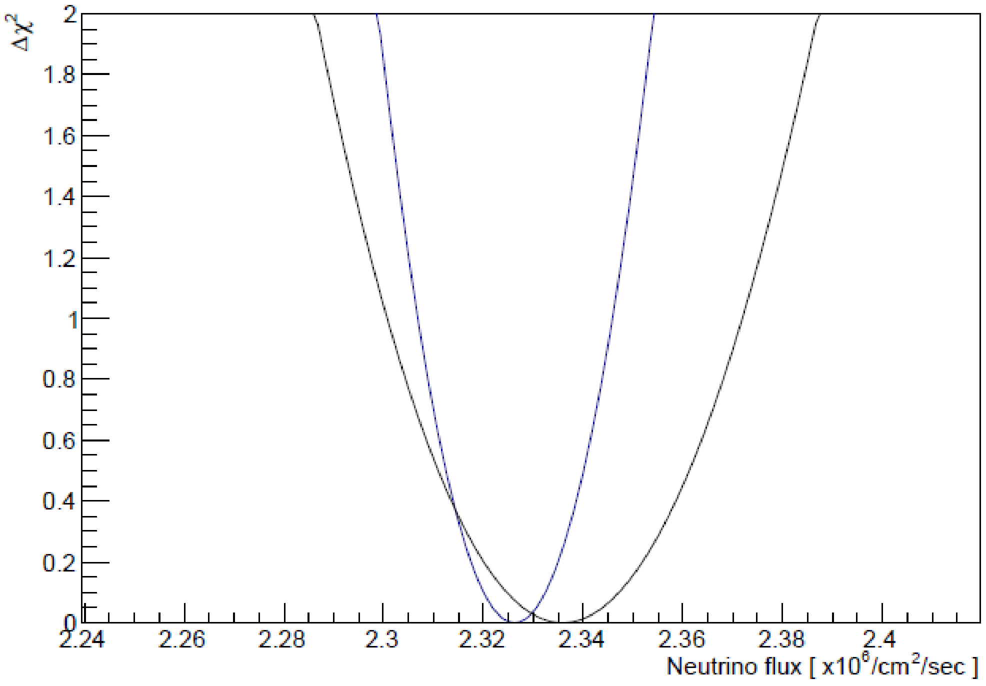
- Measure flux(f), eccentricity(ε) and perihelion days(t_p)
  NDF = 48 bins – 3 parameters, 4 nuisance parameters
- Use SK1-4 flux systematic uncertainty

  $\sigma_{p=1\sim4,b}^{flux\ syst.}$: 3.35%, 6.55%, 2.1%, 1.67%

$$\chi^2 = \sum_{p=1}^{4}\left[\sum_{b=1}^{12}\left(\frac{D_{p,b} - E_{p,b}(f,\varepsilon,\delta t_p,\delta_p)}{\sigma_{p,b}^{stat.}}\right)^2 + \delta_p^2\right]$$

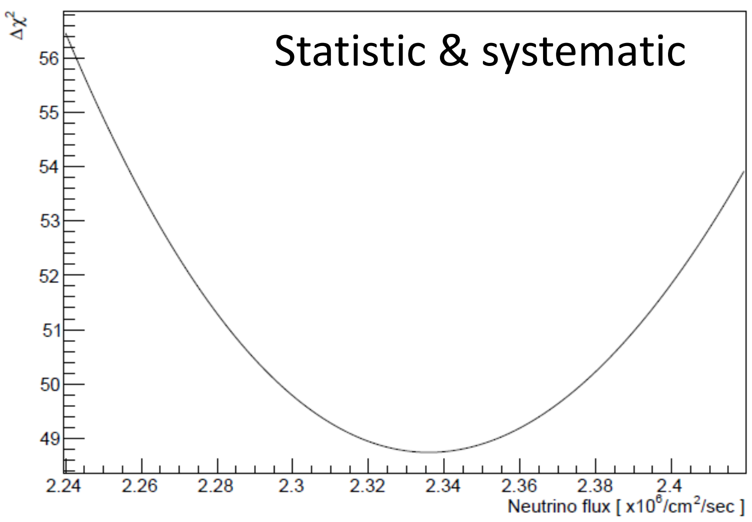
$$E_{p,b} = f\left(1 - \delta_p\sigma_{p,b}^{flux\ syst.}\right) \times r\left(\varepsilon, t_{peri} + \delta t_{peri}\right)^{-2}$$ (Only syst. error for flux)

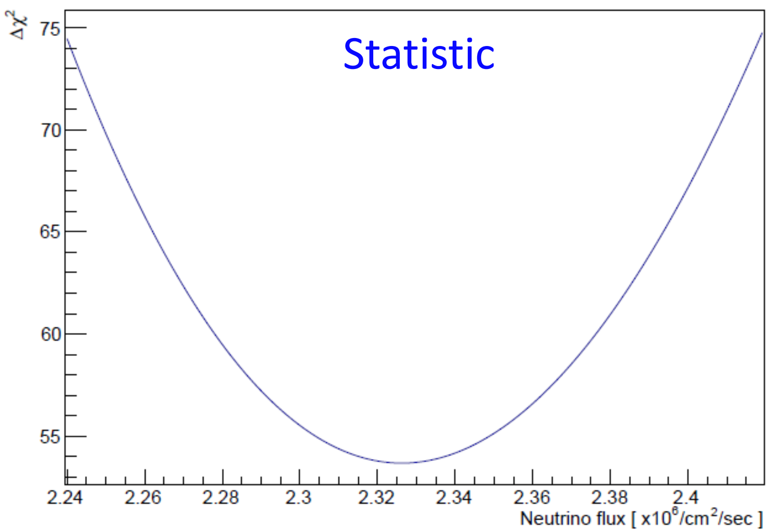
Measurement of solar neutrino flux at 1 A.U.



$$f = 2.335^{+0.0198(stat.)+0.0311(syst.)}_{-0.0198(stat.)+0.0290(syst.)}$$

- Assume total flux from SNO $= 5.25 \times 10^6/cm^2/sec$
- Minimum $\chi^2/NDF = 48.74/(48-3)$
- Flux (error) = $2.335 \times 10^6/cm^2/sec$ (1.54%)

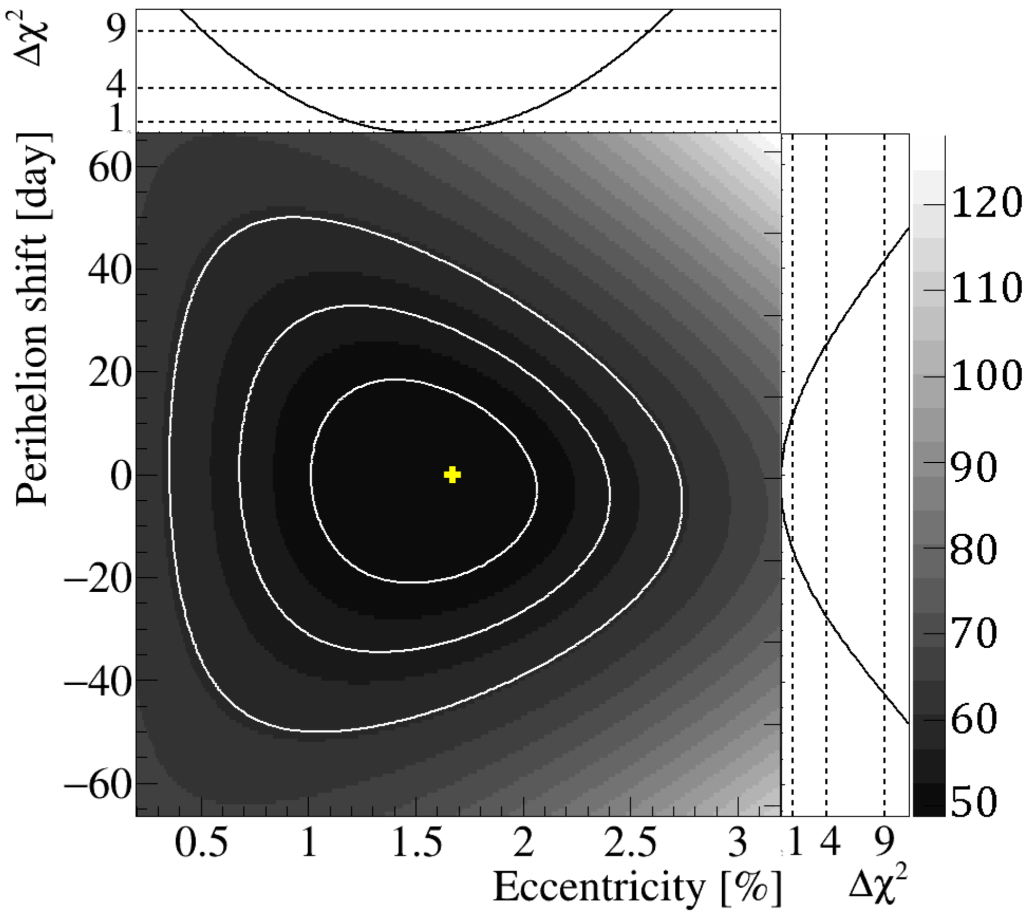




Preliminary

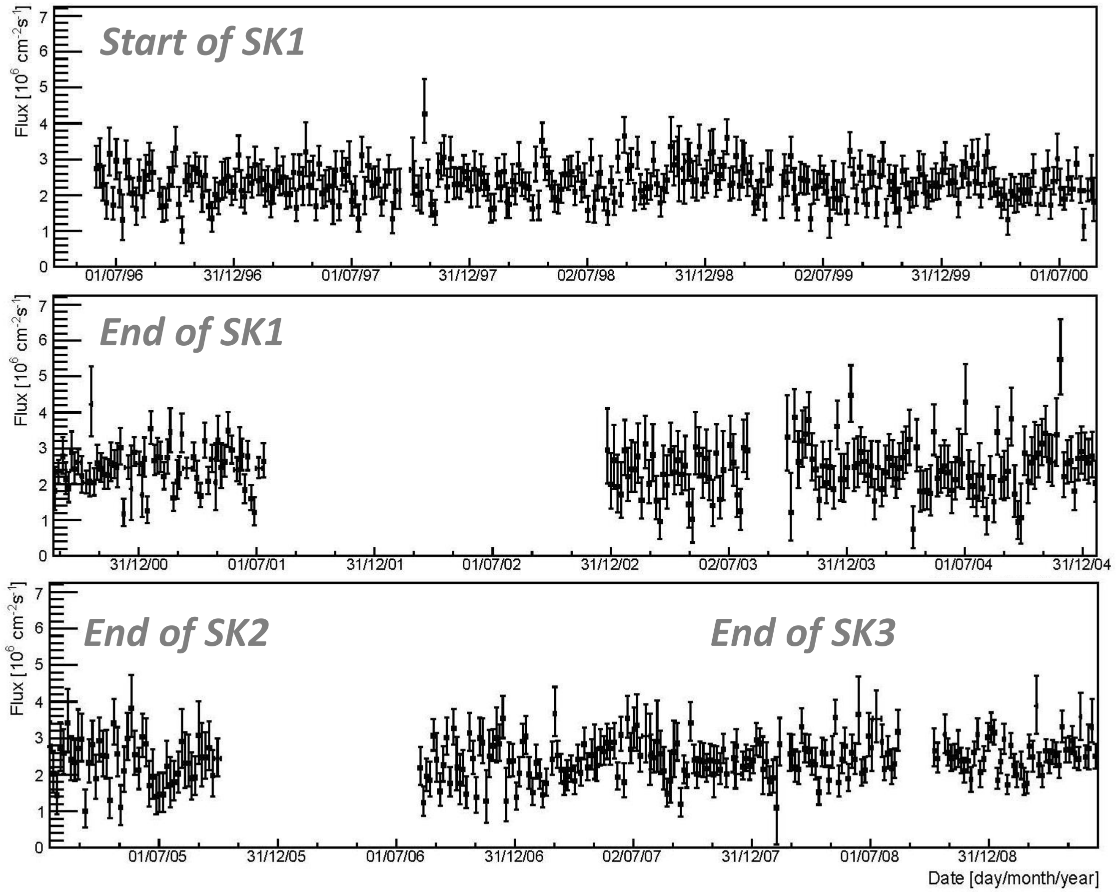
Kepler orbit constant (eccentricity, perihelion)

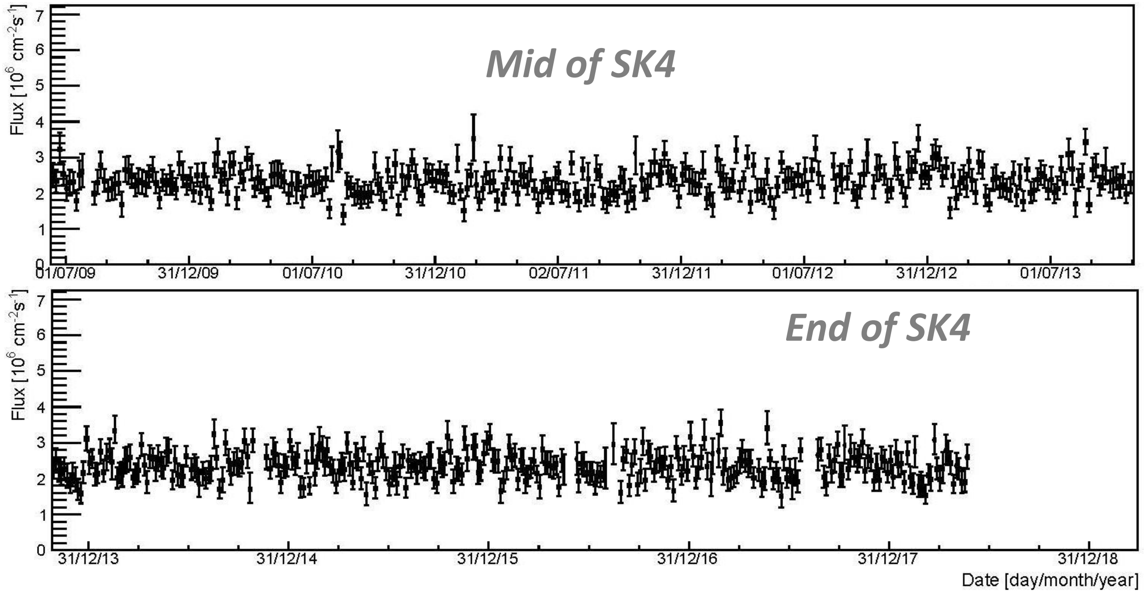
$\Delta\chi^2 = 2.3, 6.18, 11.83, 19.33$



- Find minimum of χ^2 in variation of eccentricity and perihelion days
- Expected values : $\varepsilon = 1.67\%, \quad \delta t_p = 0$
- $\varepsilon = 1.53 \pm 0.35\ \%\ (expected\ 1.67\%)$
- $\delta t_p = 1.5 \pm 13.5\ day$
- systematic error is propagated only to the solar neutrino flux at 1 A.U..

Time variation of ^{8}B solar ν flux variation for 5days interval



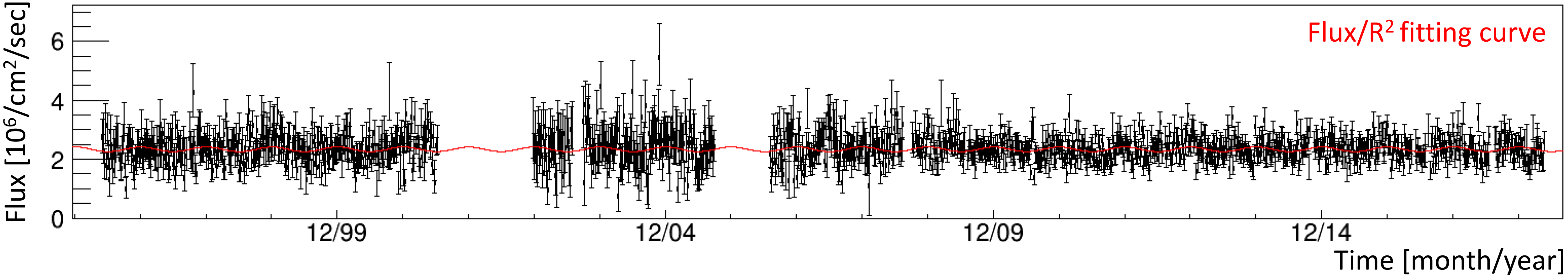


- Use the published SK-I result (PRD 68:092002)
- Use B8/HEP MC for expectation
- Mean time of actual data-taking
- 5 days statistics : approx. 90 events

Preliminary

Comparison of average flux

Flux = 2.335 x 10^6/cm^2/sec (best-fit)
R: distance between the Sun and earth



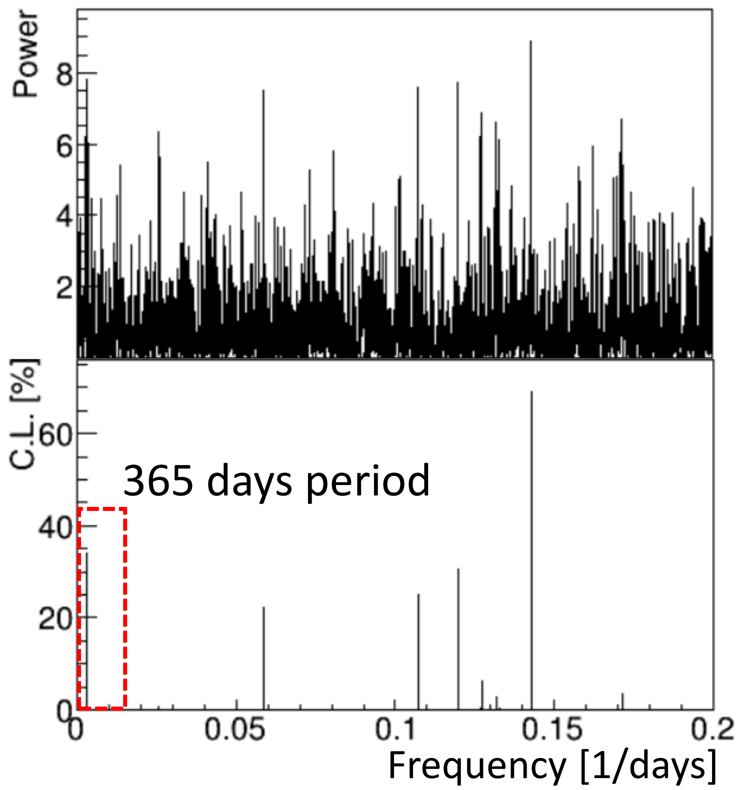
SK phase	Flux (Paper) of whole period [/cm²/sec]	Average of 5d flux $(\pm stat.)$ [/cm²/sec]	χ^2/NDF for *Flux/R²* fitting
1	$2.35 \pm 0.024(stat)^{+0.084}_{-0.076}(syst)$	2.345 ± 0.024	$407.8/(358-1)$
2	$2.38 \pm 0.05(stat)^{+0.16}_{-0.15}(syst)$	2.388 ± 0.05	$176.5/(175-1)$
3	$2.32 \pm 0.039(stat) \pm 0.053(syst)$	2.383 ± 0.038	$182.8/(141-1)$
4	$2.31 \pm 0.014(stat) \pm 0.04\ (syst)$ (Preliminary)	2.327 ± 0.013	$854.5/(669-1)$
Combined	$2.336 \pm 0.011(stat) \pm 0.043\ (syst)$ (draft)	2.338 ± 0.011	$1261.6/(1343-1)$

Preliminary

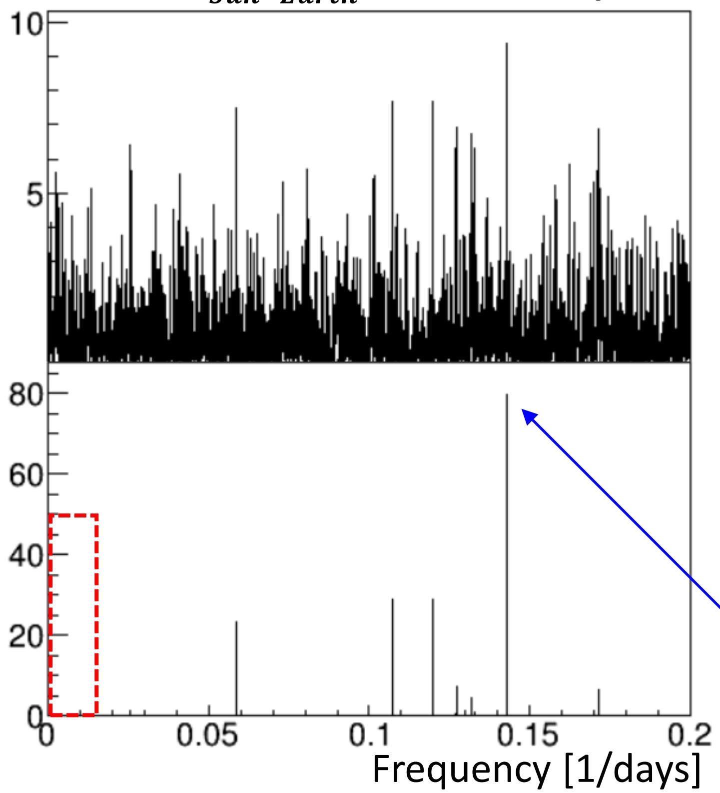
Frequency analysis – Lomb-Scargle

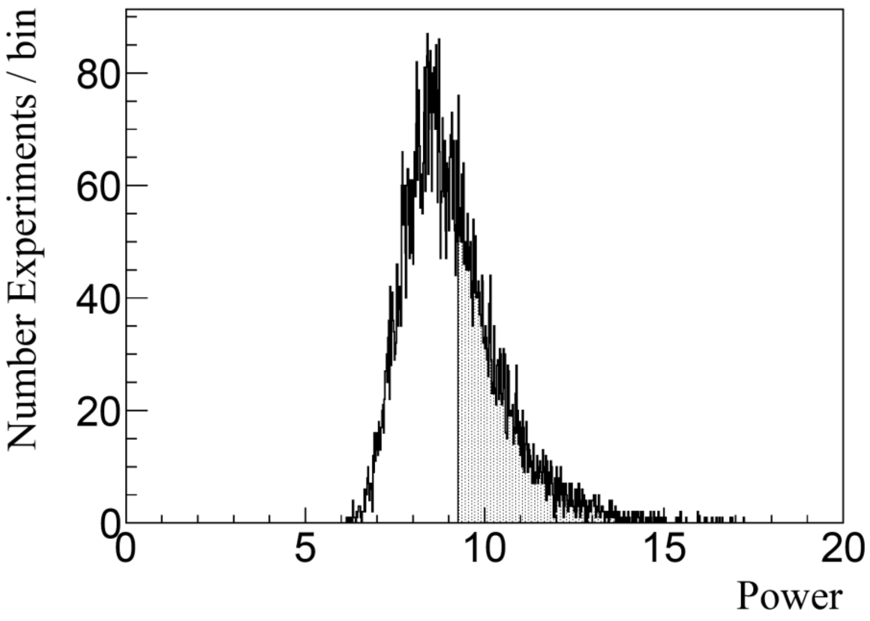
- Lomb-Scargle periodogram: quick search for periodicity
- Assume all errors are the same
  → Statistical consistency check (10,000 MC samples).

For 5-day data



For $R^2_{Sun\sim Earth}$ corrected 5-day data





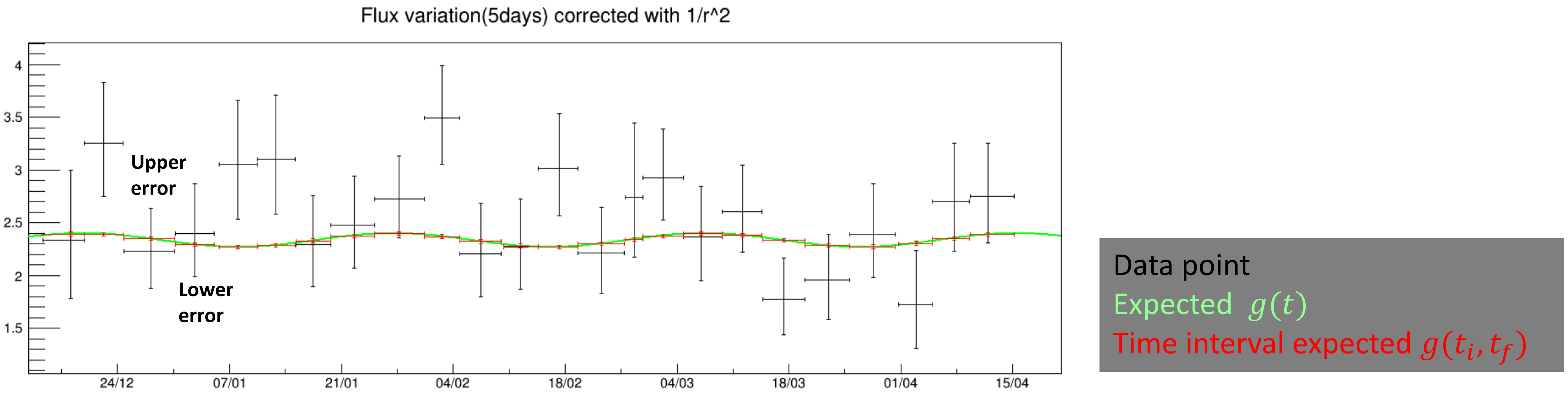
If maximum power is 9.39, statistically the maximum power can be larger than 9.39 in 34.3%
cf) C.L.= 79.8% vs 65.7%(=100−34.3%)

Sinusoidal likelihood test

- Find flux average value (g_0) with minimization(L_0) of chi2, $-lnL(r;A,B) = \frac{1}{2}\Sigma_r\left(\frac{D_r - g(r)}{\sigma_r}\right)^2$
- Apply asymmetric error(σ_r). If below data then error is lower, vice versa.
- Fit for each frequency ($\omega = 2\pi f$)
- Find A, B in $g(t_i, t_f)$ with minimization(L) of chi2.

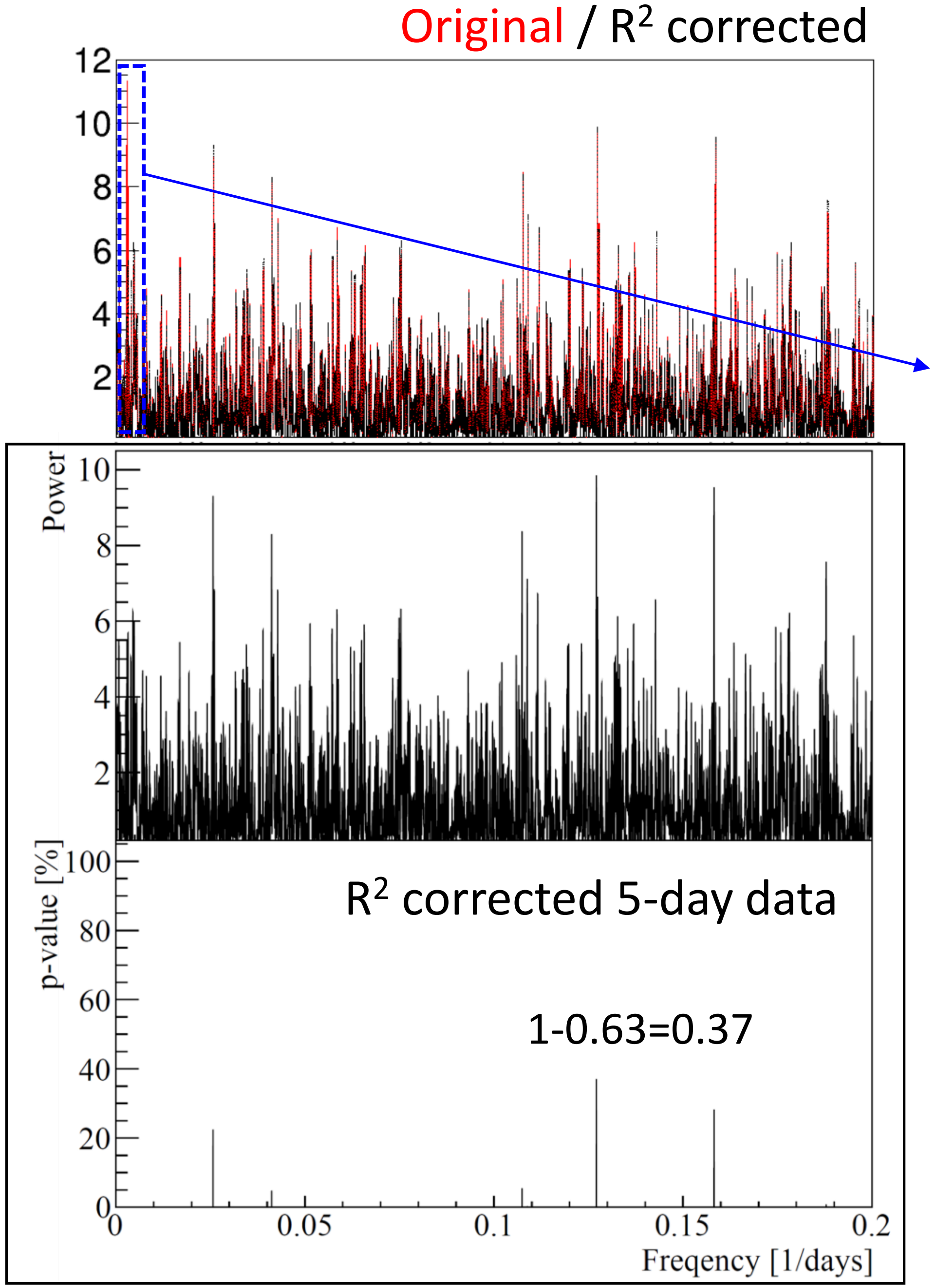
$$g(t_i, t_f) = g_0(t_i, t_f) + \frac{1}{\Delta t}\int_{t_i}^{t_f} Acos(\omega t) + Bsin(\omega t)\, dt$$

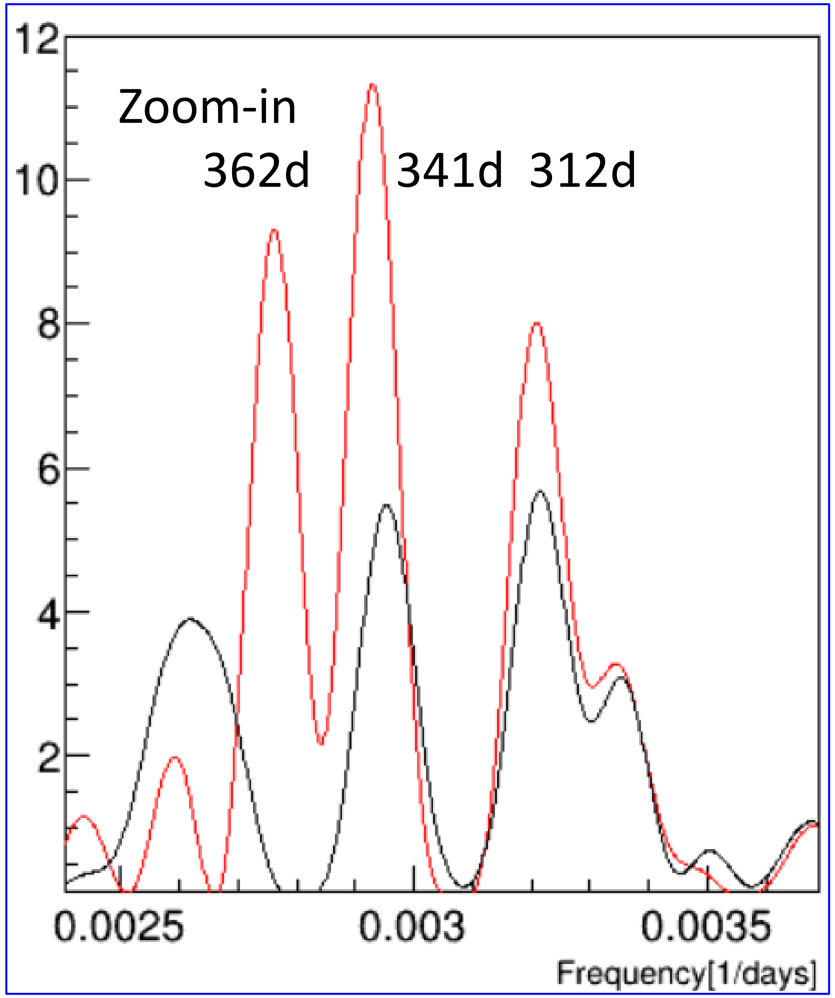
- Draw fitting-power plot ($f, \Delta L = lnL_0 - lnL$)
- For interpretation, generate 10,000 MC samples for g_0 with statistical error

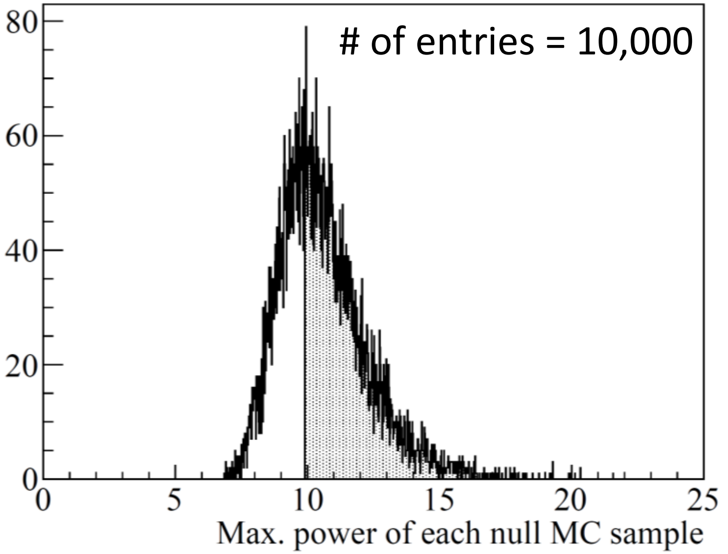


Preliminary

Fitting-power distribution







If maximum power is 9.9, statistically the maximum power can be larger than 9.9 in 63%

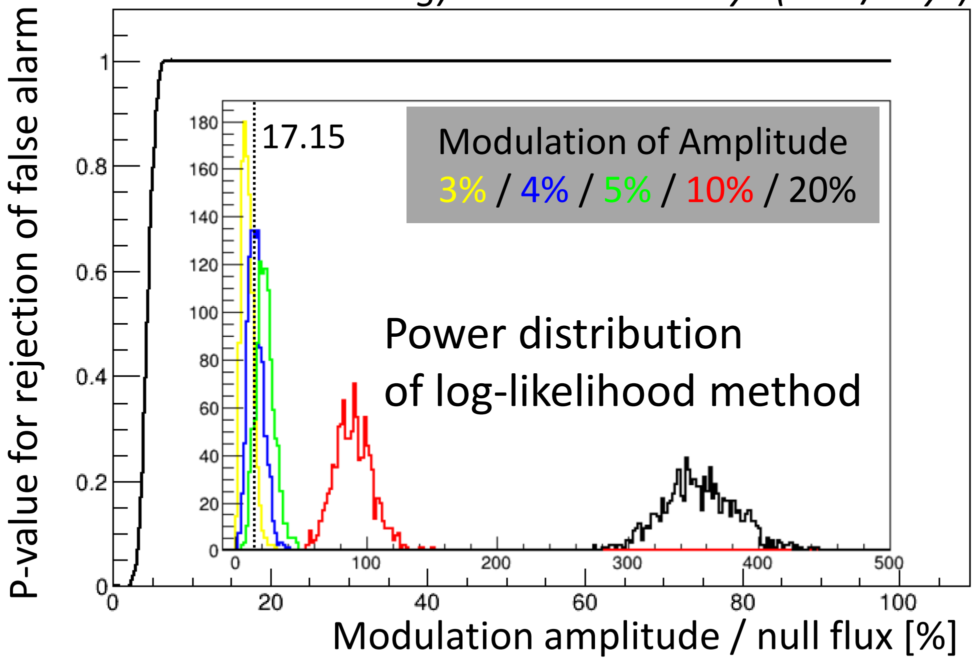
98% at power = 17.15

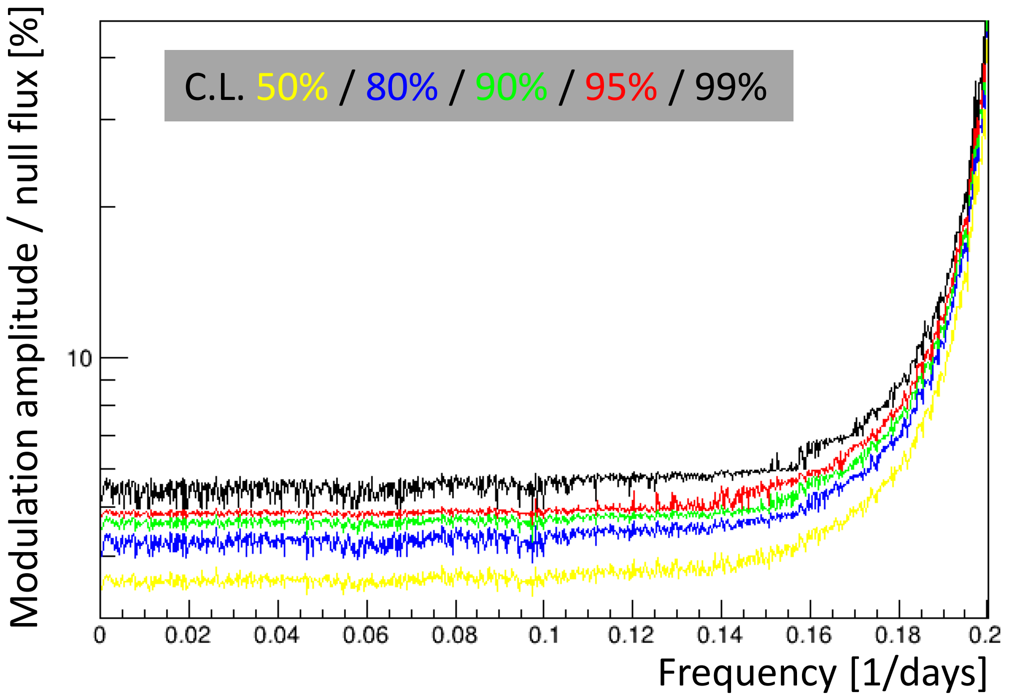
Preliminary

Sensitivity

- Simulated 1,000 MC signals for various amplitudes and frequencies
- Use statistical error for **$1/R^2$ corrected** 5-day samples
- Amplitude / null flux = 1-99% & frequency = 1000 cases in [0/day,0.2/day]
- 98% false alarm criteria : power>17.15 (previous slide, the same as SK1 paper)

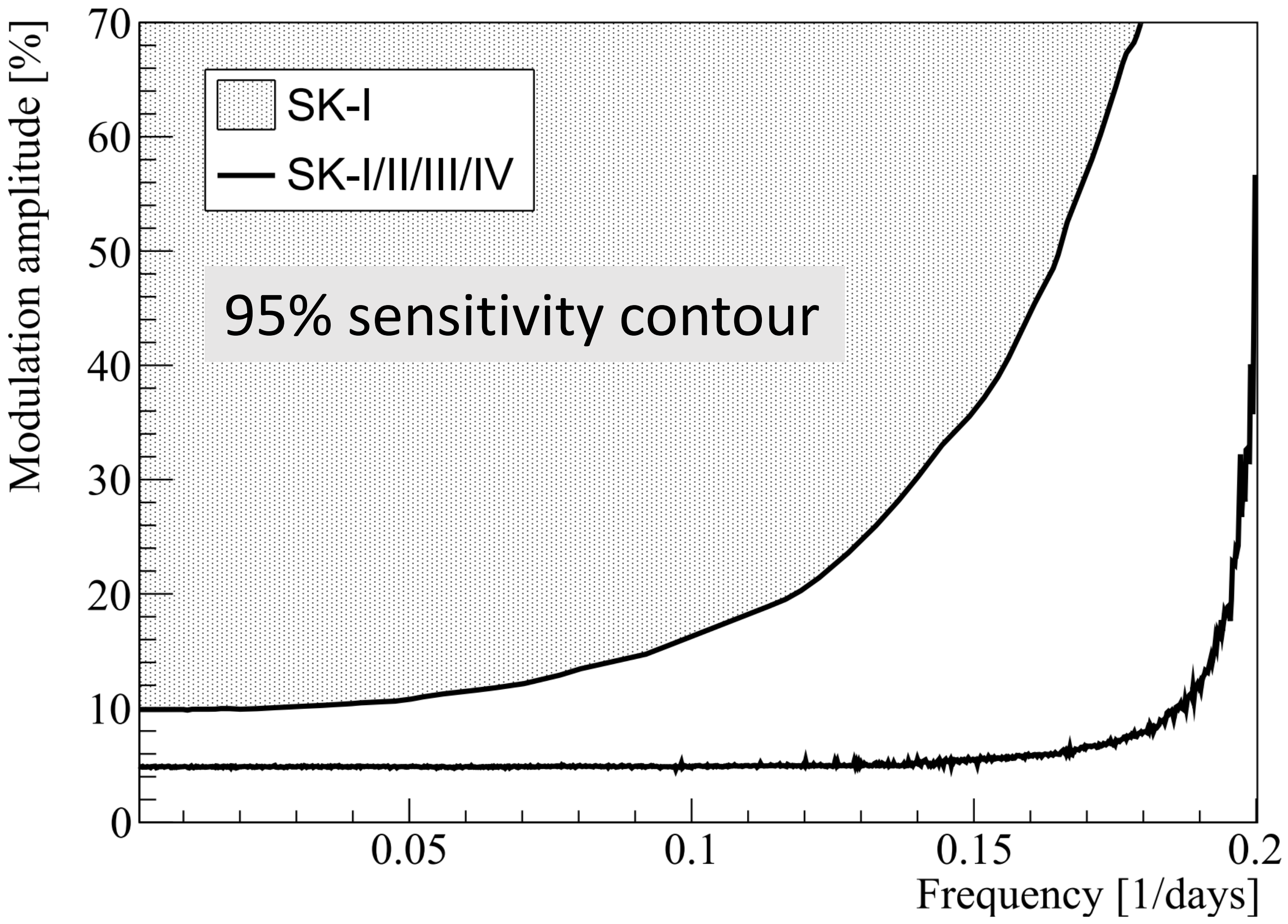
e.g) Period = 6.25days (0.16/days)





Preliminary

Summary



- Observe annual modulation
- 5-day interval ^{8}B solar ν flux
- No significant modulation was found.
- Exclude 4.9% of solar modulation amplitude

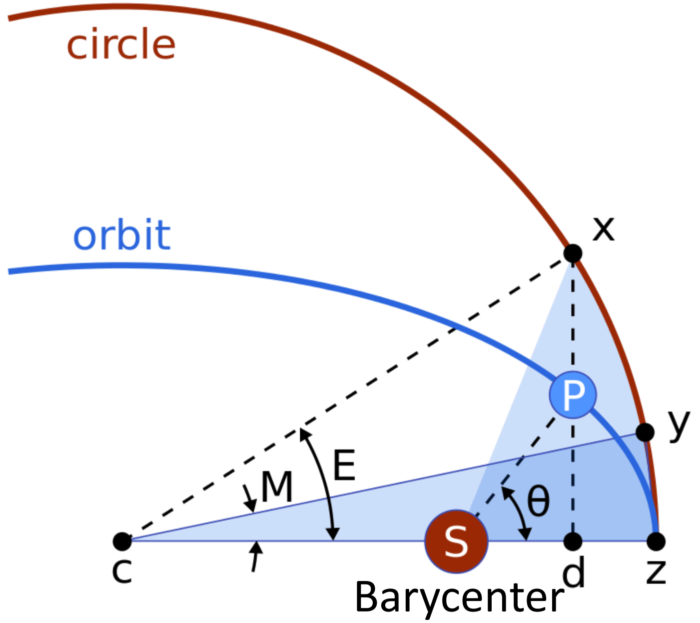
cf.) SK1 flux : $2.345 \pm 0.024\ (stat.)$

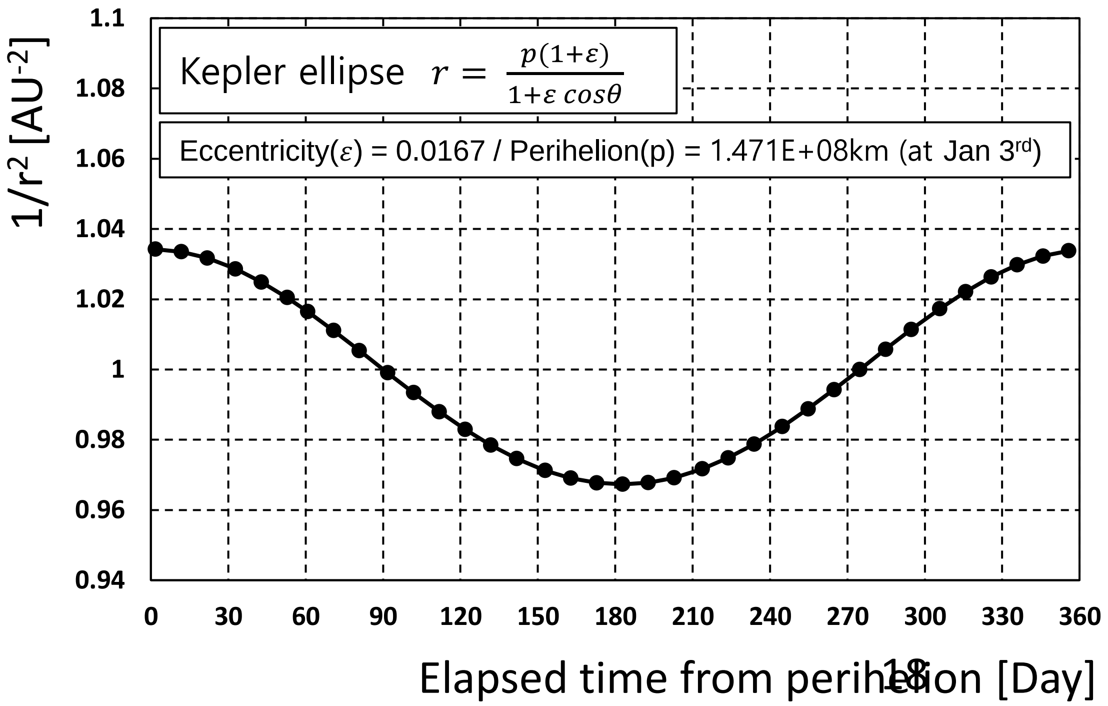
SK1-4 flux : $2.338 \pm 0.011\ (stat.)$

backup

Distance calculation

- Distance r is not closed form of time.
- Mean anomaly, M
- $M = \frac{2\pi}{T}(t - t_p)$, $t_p = time\ at\ perihelion,$
- Eccentric anomaly, E satistfies below
- $M = E - \varepsilon \sin E$, $\varepsilon = eccentricity$
- Distance $r = a(1 - \varepsilon \cos E)$
- Calculate : $M \rightarrow E \rightarrow r$
- *T = 365.2425* days, $\varepsilon = 0.0167$
- $t_p = Jan\ 3^{rd}\ 19{:}43, 2007$
  (https://wgc.jpl.nasa.gov:8443/webgeocalc/#NewCalculation)
- If necessary, make a shift(δ) for $\varepsilon + \delta\varepsilon, t_p + \delta t_p$





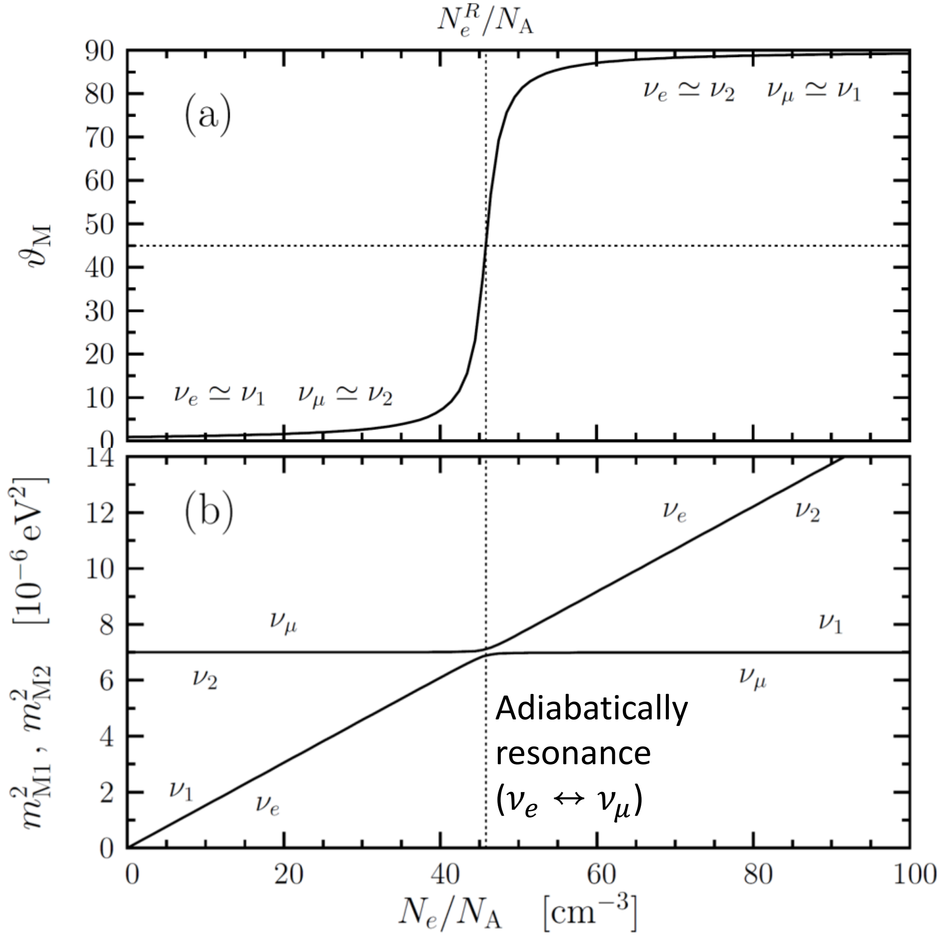
Motivation – Solar Model (SSM)

- MSW effect in the Sun
  : 1) dense electron ~ θ_M 2) variation of density $d\theta_M(x)/dx \neq 0$
- $i\frac{d}{dx}\begin{pmatrix}\phi_{e1}\\ \phi_{e2}\end{pmatrix} = \frac{1}{4E}\begin{pmatrix}-\Delta m_M^2 & -4Eid\theta_M/dx\\ 4Eid\theta_M/dx & \Delta m_M^2\end{pmatrix}\begin{pmatrix}\phi_{e1}\\ \phi_{e2}\end{pmatrix}$

  $\Delta m_M^2,\ \theta_M = effective\ squated\ MSW\ mass\ difference, angle$
- Dense electron: mass state (ν_1, ν_2) → MSW state $(\nu_1^m(x), \nu_2^m(x))$
- Variation of electron density
  → Also, state varies, $\nu_i^m(x) \neq \nu_i^m(x+\delta x)$
- In the Sun, adiabatic condition (off diag. ≪ diag.)
  : no transition between $\nu_1^m(x)$ and $\nu_2^m(x)$
- At the solar surface, neutrino state coincide to ν_2, even small mixing θ.

$$\Delta m^2 = 7\times 10^{-6} eV^2, \sin^2 2\theta = 10^{-3}, E = 1MeV$$

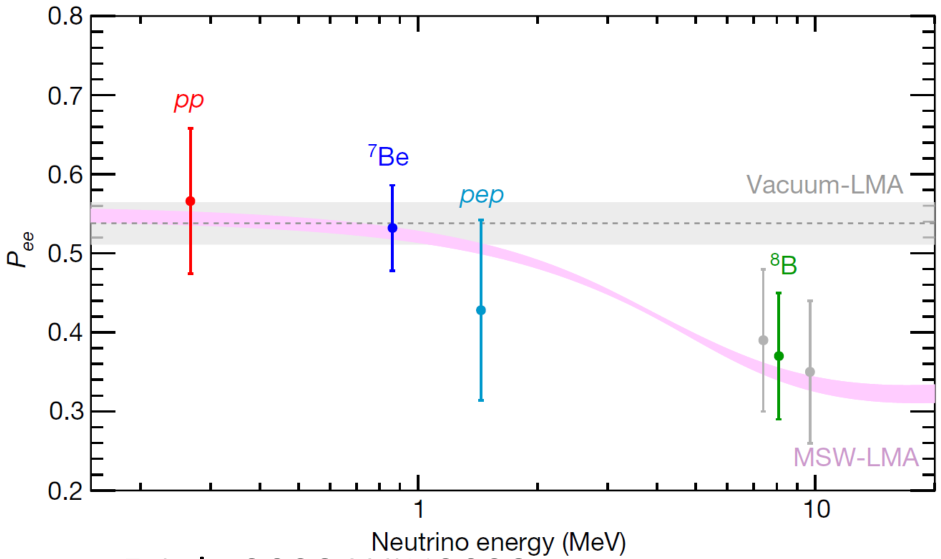
$$m_{M2,1}^2 = \frac{1}{2}(m_1^2 + m_2^2 + 2\sqrt{2}G_F E N_e\ + \Delta m_M^2)$$

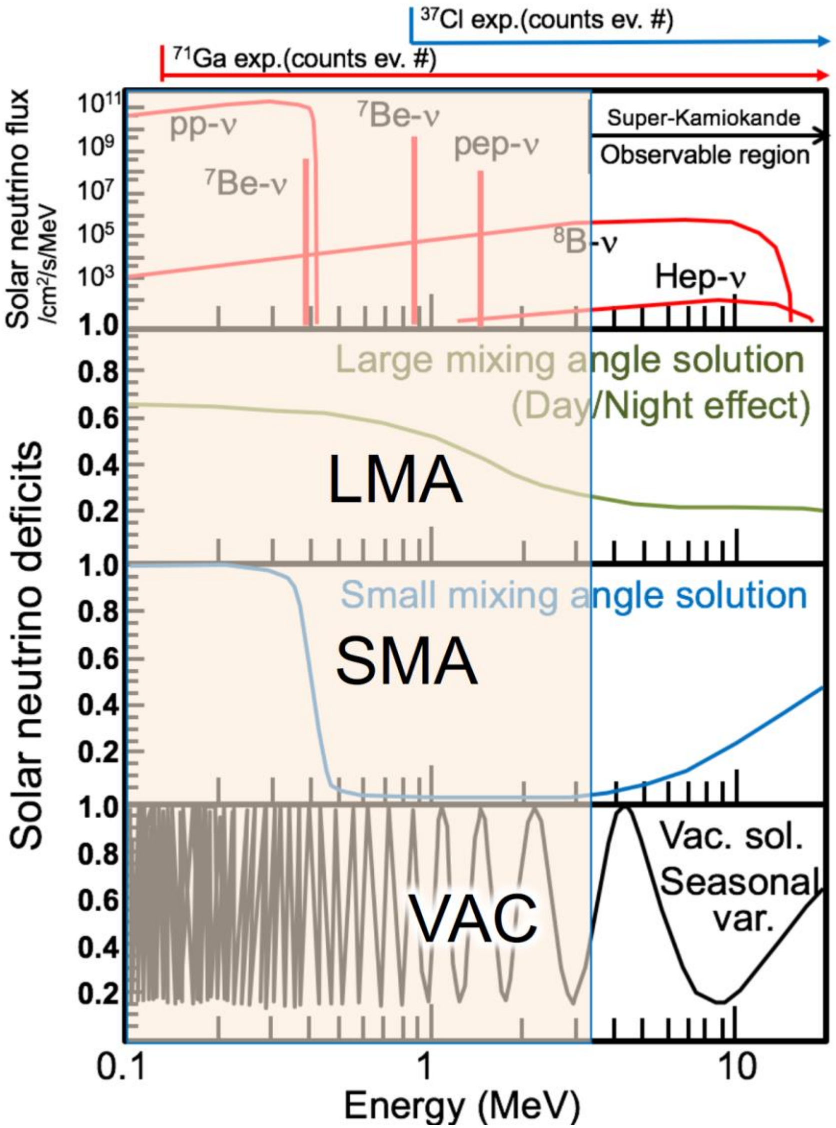


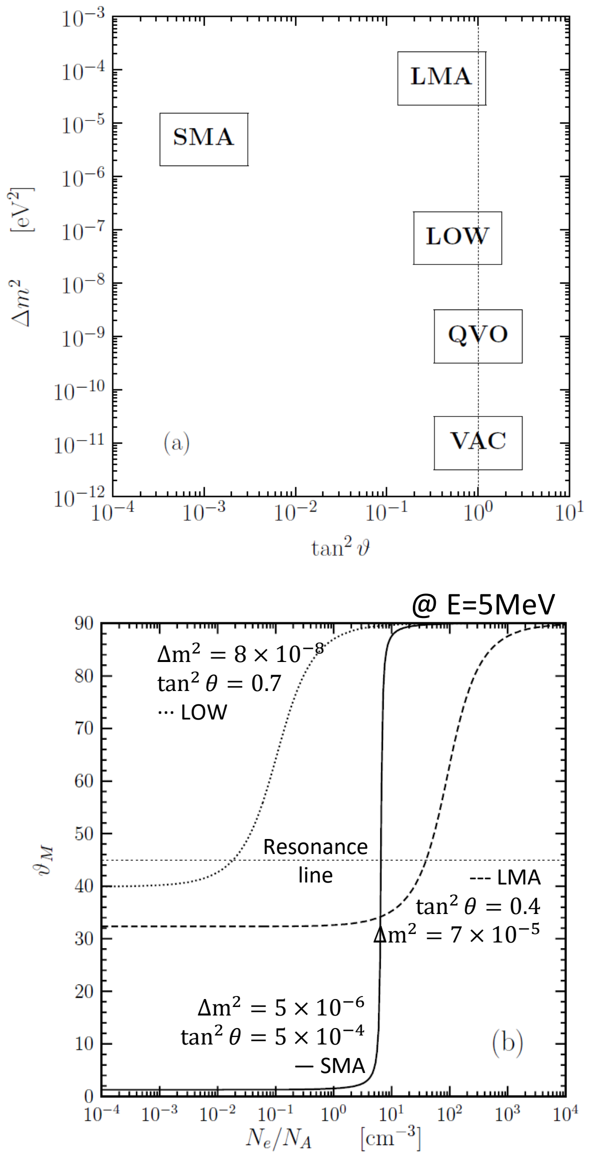
Motivation – Oscillation parameter

Consider both Solar & earth MSW effect

- LMA : no energy distortion, **day/night flux difference**
- SMA : energy distortion
- VAC : energy distortion, **seasonal variation**
- Recent result solidify LMA

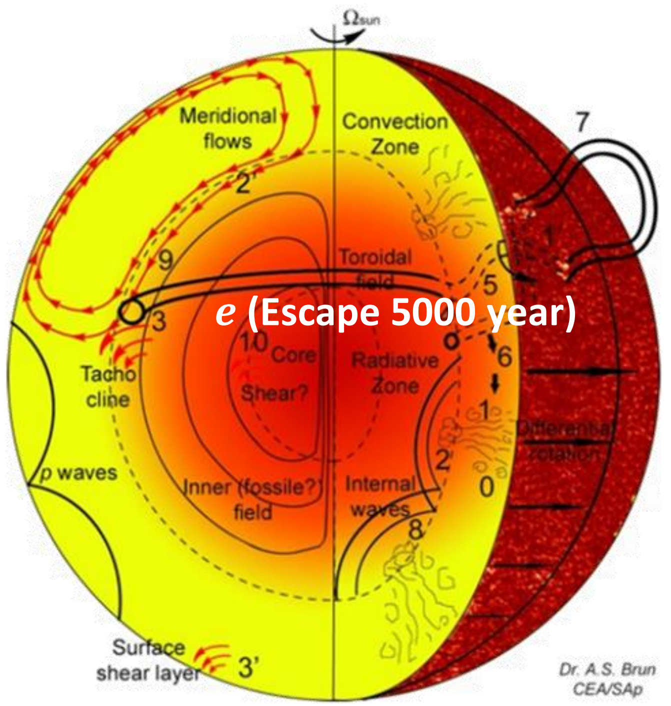


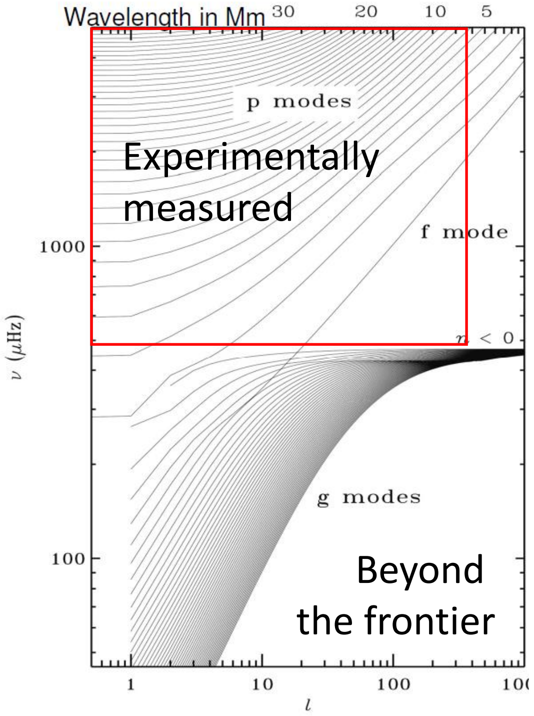


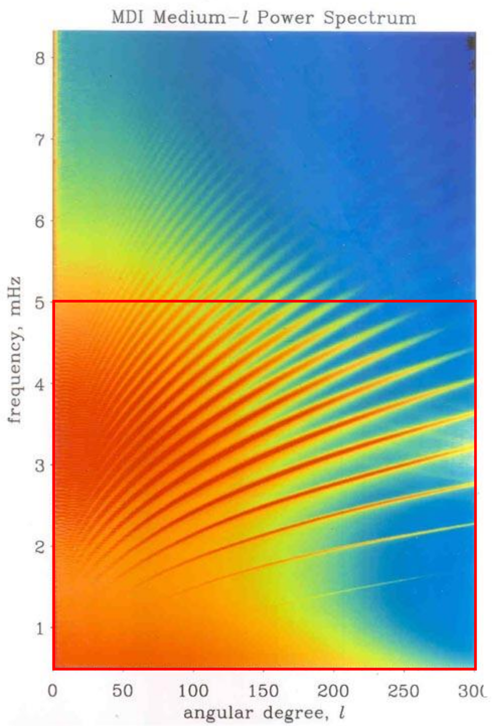


Motivation – Solar structure

- Seismic Solar Model (SeSM)
- Hydraulic & thermal equilibrium state
- but Fluctuating → Change temperature → Core burning rate $\sim T^{25}$ → e, ν_e, He rate
- Solution: acoustic mode & **gravity mode**(core, can measure by fluctuation of ν_e)







Propagation diagram of solar oscillations

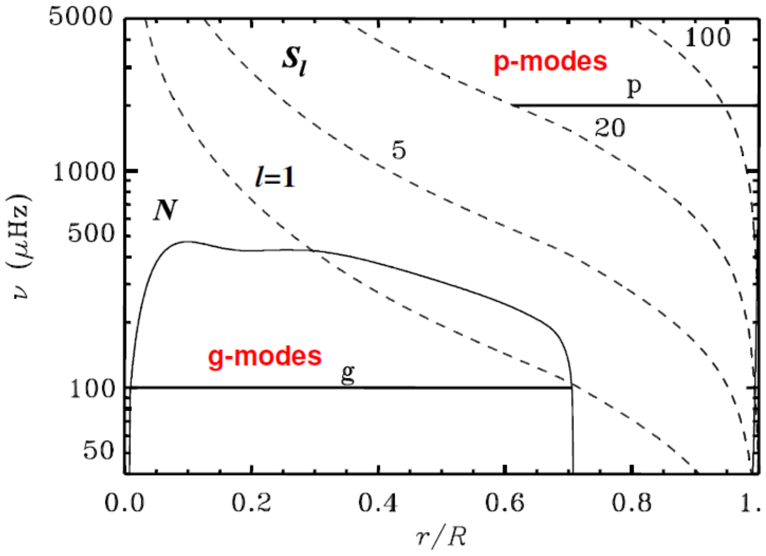
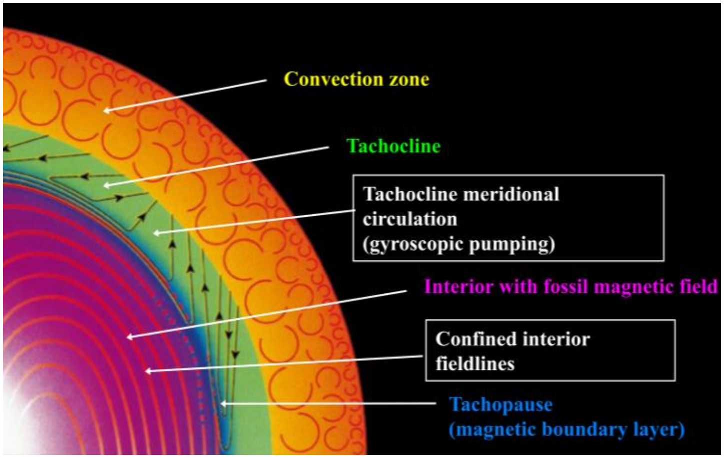


TABLE 1
^8B NEUTRINO FLUX VARIATIONS
CAUSED BY g-MODES FOR A FLUCTUATION OF $|\frac{\Delta T}{T}| = 0.001$.

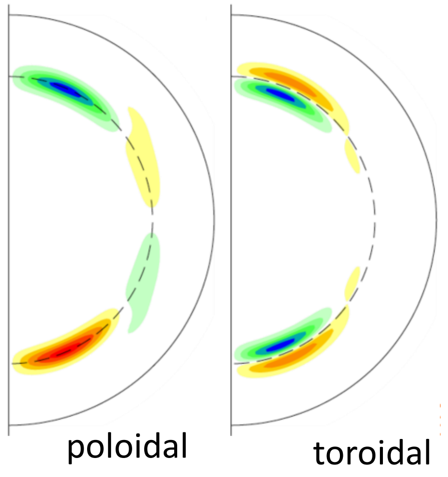
Degree l	Order n	Freq. SSM	(μHz) SeSM	Period (hr)	B_{ln} (−)	$\lvert\Delta\phi/\phi\rvert_{ln,\max}$ (%)
1	-1	254.7	262.7	1.1	2.3	5.8
—	-2	185.5	191.1	1.5	6.7	17.0
—	-3	148.6	153.2	1.9	4.8	12.2
—	-4	123.6	127.8	2.2	2.5	6.4
—	-5	105.6	109.3	2.6	1.1	2.8
2	-1	291.5	296.4	0.95	1.0	2.6
—	-2	250.3	256.1	1.1	1.5	3.8
—	-3	216.8	222.0	1.3	1.6	4.0
—	-4	188.6	194.1	1.5	1.7	4.3
—	-5	165.3	151.3	1.7	1.5	3.8
3	-1	333.6	340.1	0.83	1.6	4.1
—	-2	288.8	296.6	0.96	1.9	4.8
—	-3	255.9	261.3	1.1	1.0	2.6
—	-4	233.6	238.3	1.2	0.9	2.3
—	-5	211.2	217. 1	1.3	1.5	3.8

Motivation – Solar Dynamo

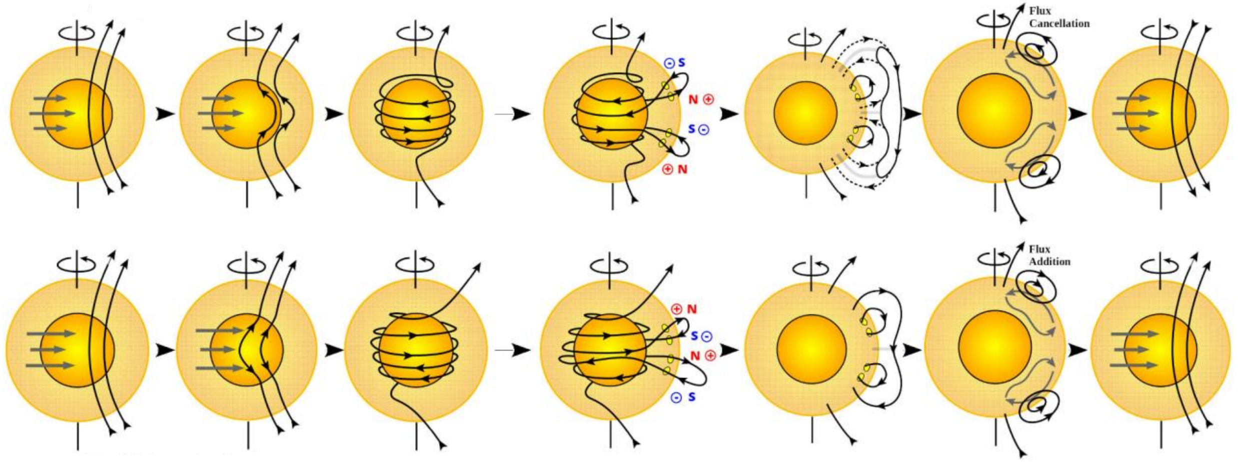


- SeSM+**M**agneto-**H**ydro**D**ynamics (Rotation&Magnetism, MHD)
- Velocity difference → alpha & omega effect
- Meridional Flow → periodic Sunspot
- Magnetic field (fossil field generated in the proto-star) is **strong** between convection and radiation zone : tachocline
- Q. thinkness&frequency of tachocline → **Interaction with ν_e**
- E.g) Simulation: $0.05R_{sun}$, $24days$ (arXiv:1009.0852v2, 52p, 7.1.1)
- E.g) $49.1,\ 43.3, 38.7days$ (Space Science Reviews volume 218, 23 (2022))

https://cpaess.ucar.edu/sites/default/files/heliophysics/resources/presentations/2014_Charboneau.pdf



Shearing by axisymmetric differential rotation



Impact of anti-solar differential rotation in mean-field solar-type dynamos (Q. Noraz et al. 2021 Nov 11, Solar Physics)

- fast equator and slow poles(grey arrow), the poloidal field(black arrow) have reversed, AC dynamo

- fast poles and slow equator, the poloidal remains in the same direction, DC dynamo

Motivation – RSFP

- In matter and magnetic field (Dirac and Majorana)

$$L_{int}^{D\ or\ M} = \Sigma_{i,k}\frac{1}{2}\mu_{ik}^{D\ or\ M}\left[(\bar{\nu}_{kR}\ or\ \bar{\nu}_{kR}^{C})\sigma_{\alpha\beta}\nu_{iL}\right]F^{\alpha\beta} + h.c$$

$\mu_{ik}^{D,M}$: magnetic moment, M $(i,k = e,\mu)$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e^{(L)}\\ \nu_\mu^{(L)}\\ \nu_e^{(R)}\\ \nu_\mu^{(R)}\end{pmatrix} = \begin{pmatrix}H^L & BM^\dagger\\ BM & H^R\end{pmatrix}\begin{pmatrix}\nu_e^{(L)}\\ \nu_\mu^{(L)}\\ \nu_e^{(R)}\\ \nu_\mu^{(R)}\end{pmatrix} \qquad H^{L(,R)} = \begin{pmatrix}\frac{\delta m^2}{2E}s + V_e(,V_\mu) & \frac{\delta m^2}{4E\sin 2\theta}\\ \frac{\delta m^2}{4E\sin 2\theta} & \frac{\delta m^2}{2E}\cos^2\theta + V_\mu(,V_e)\end{pmatrix}$$

$$s = 0\ (Majorana), \sin^2\theta\ \ (Dirac), V_e = \frac{G_F(2N_e - N_n)}{\sqrt{2}}, V_\mu = -\frac{G_F N_n}{\sqrt{2}},$$

$$\{i\gamma^\mu\partial_\mu - m - \frac{\mu}{2}\sigma^{\mu\nu}(G_{\mu\nu} + F_{\mu\nu})\}\Psi(x) = 0$$

$F_{\mu\nu}$: External electromagnetic fields
$G_{\mu\nu}$: Weak interaction with matter

- Like MSW resonance, **resonant** spin flavor precession can be induced.

→ RSFP change flavor of neutrino passing through magnetized plasma

→ The resonance leads additional oscillation effect.

→ Magnetic field frequency results in **time variation of neutrino flux.**

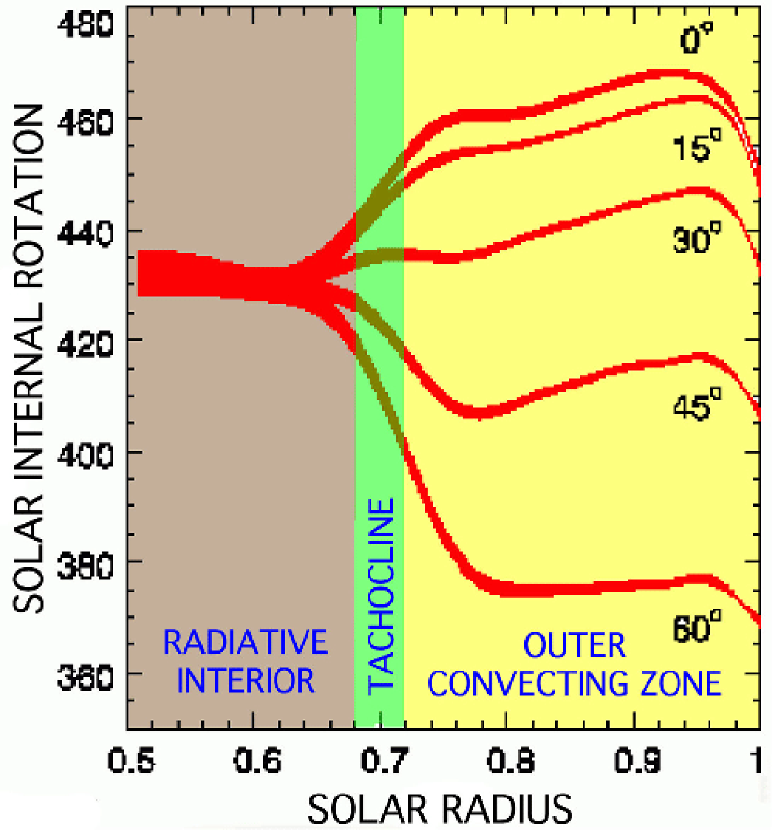


TABLE I. The location of the MSW and spin-flavor precession resonances for Majorana neutrinos. Neutrino energies are given in MeV. The $r/R_\odot$ value for the location of the resonances is shown.

E_ν	SFP	MSW
2.50	0	0.07
3.35	0.05	0.10
5.00	0.10	0.13
8.00	0.15	0.18
13.00	0.20	0.22

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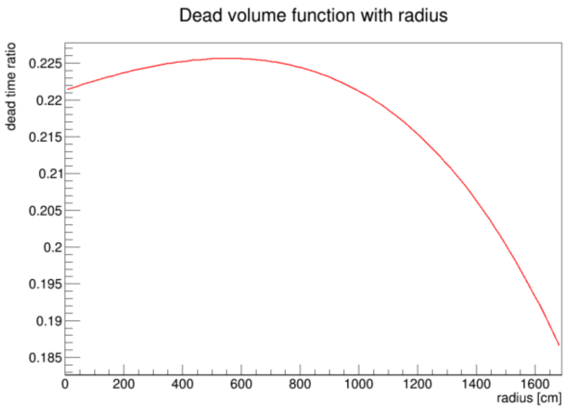
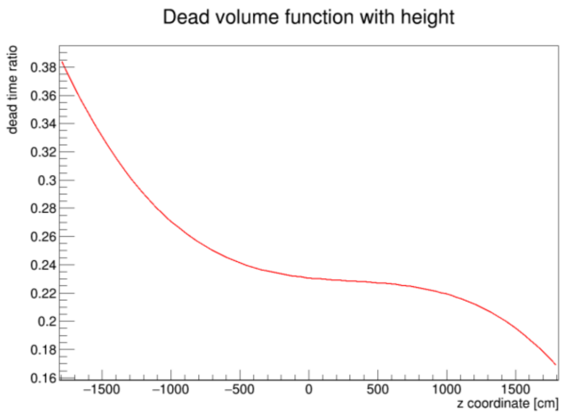
Expected flux – MC sample

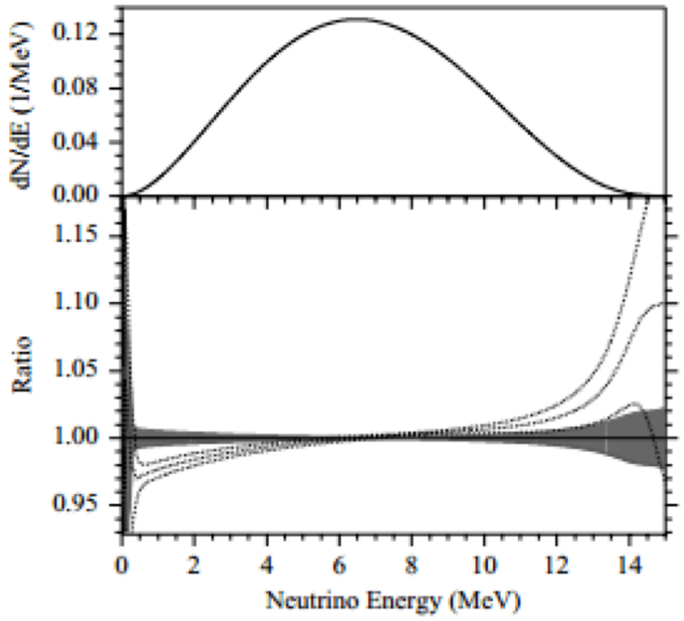
- Generate total number of flux for ^8B (HEP) based on
  1. the theoretical calculation – SK1/2 (SK1/2/3/4)
  2. the experimental measurement – SK3/4

events/day	B8(ref.)	HEP(ref.)
SK1/2	326.107366($BP2004+Ortiz$)	0.637463489($BP2004+NU98$)
SK3/4	294.735496($SNO\ NC$)	0.637463489($BP2004+NU98$)

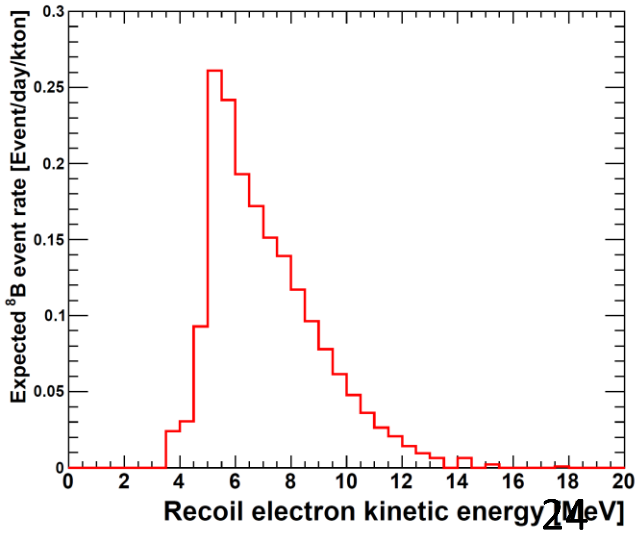
- Identical cuts for data are applied to MC sample except for spallation & ^{16}N cut → Compensated by dead volume(~20%)



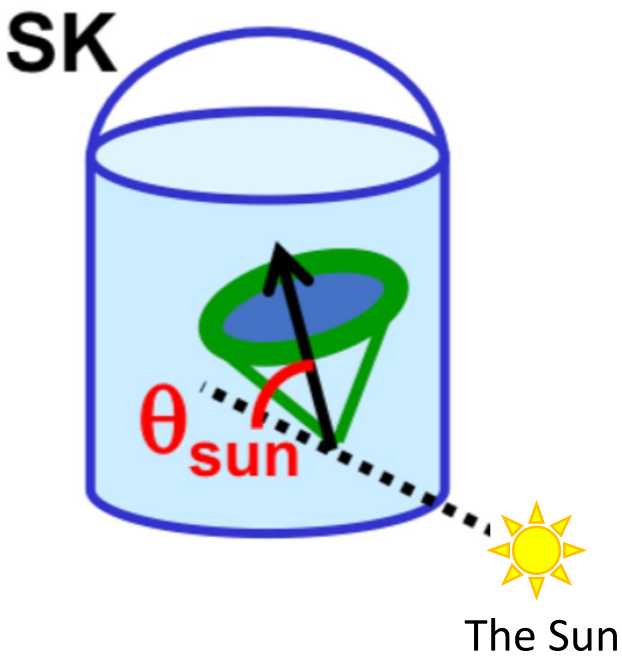




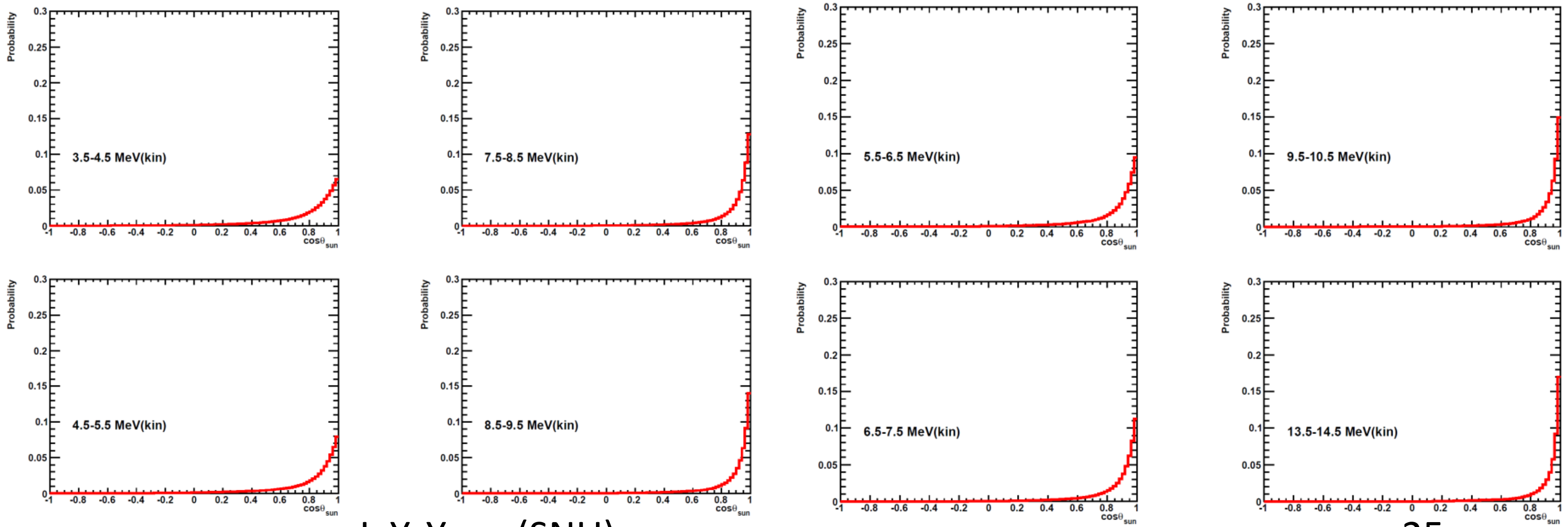
^8B spectrum(Winter, upper) and comparison of other 3 spectra (lower)



Signal modeling



- Angular distribution($cos\theta_{sun}$) of MC samples
- Assume: Neutrino events along with the Sun
- For each energy and zenith angle bin, $s(cos\theta_{sun}, E, cos\theta_{zenith})$
- Fit with 3 exponentials and 1 Gaussian
- Will be used as input for fitting.



Background modeling

- Angular distribution($cos\theta_{sun}$) from Data
- For each energy and zenith angle bin
- Assume: background should not be related with the solar angle ($cos\theta_{sun} > 0.75$, signal range).

1. Extract distribution of $(cos\phi, cos\theta_z)$ for $cos\theta_{sun} < 0.75$, background range
2. Build $cos\theta_{sun}$ for background range sample and smooth the distribution
3. Fitting $cos\theta_{sun}$ distribution with 8th polynomial. Estimate entries in signal range.
4. Generate Toy MC using distribution of $(cos\phi, cos\theta_z)$ in background range.
   :The number of events are background range event + estimated events in signal range
5. Iterate 1-4, until 8th polynomial converges.