Solar Neutrino Flux Variability

David O. Caldwell

University of California Santa Barbara

Brief review of evidence from radiochemical experiments

New evidence from Super-Kamiokande

Framework

Solar neutrino flux variations

Quick sampling of evidence here

P. Sturrock, M. Weber, G. Walther, J. Scargle, M. Wheatland

Need ν transition magnetic moment: $\nu_e^L \to \nu_i^R$ ($i=\mu,\tau,s$)

If KamLAND is correct, this must be subdominant

Spin-Flavor-Precession (SFP)–Akhmedov, Pulido (now Pulido)

To near-LMA, add SFP transitions to ν_s (sterile mass state)

Like de Holanda, Smirnov for better data fit (mixing→SFP)

Resonant-Spin-Flavor-Precession (RSFP)–fits beat LMA

Sterile state has $\Delta m^2/E = 2\sqrt{2}G_F N_{eff} \cdot 10^{-14}$ eV for data fit

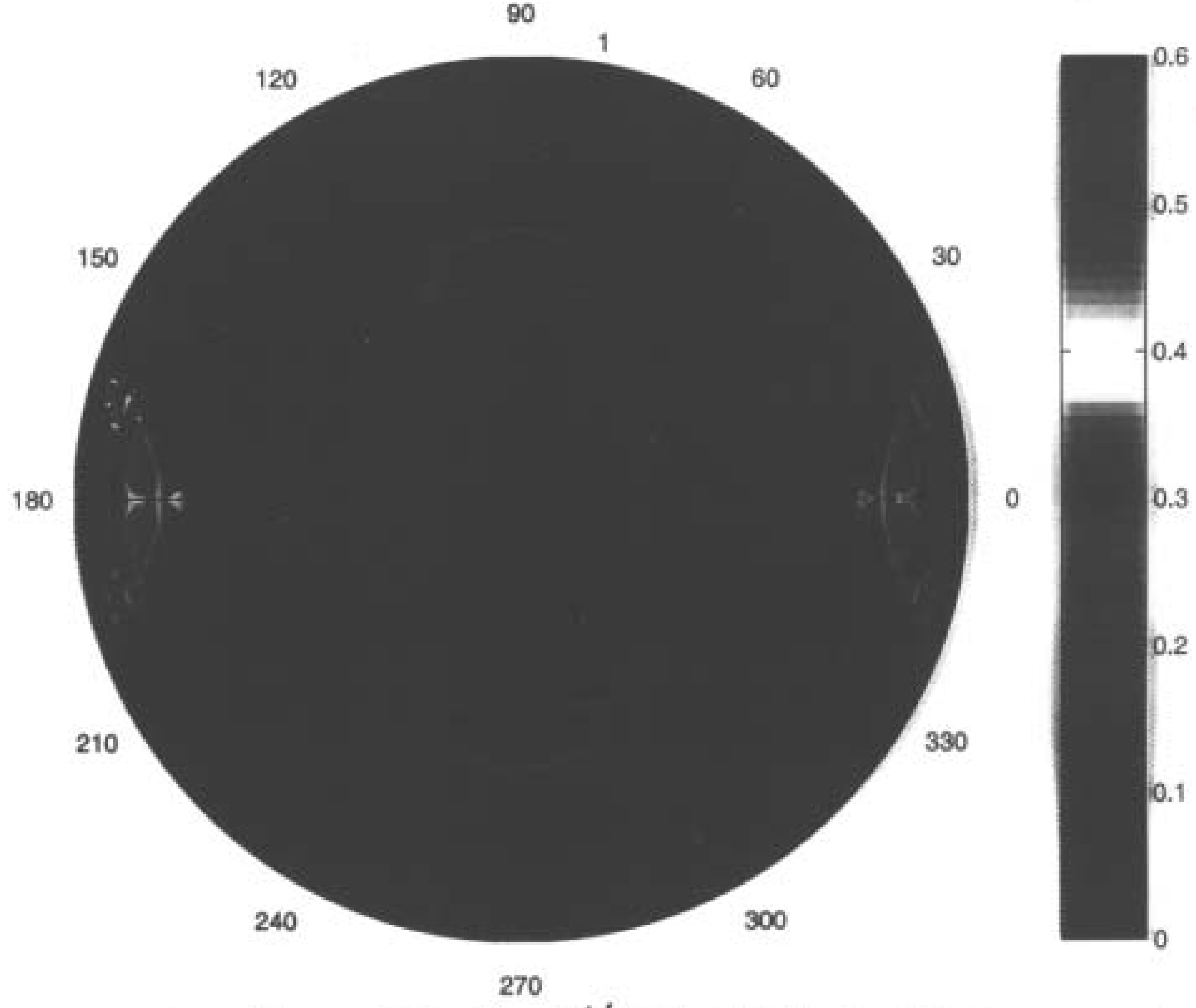
In series with near-LMA MSW, but farther out in the Sun

Favored over SFP by flux variability data

In either case, subdominance requires a sterile neutrino

Locating the 13.6 y^{-1} Modulation in the Sun

Use GALLEX data with SOHO-MDI rotation profile



Resonance (red) in $\Xi(r,\lambda)=\int_{\nu_a}^{\nu_b} S(\nu)P(\nu|r,\lambda)d\nu$ gives locc

Work of Sturrock and Collaborators

Homestake

Are Cl data compatible with a constant ν_e flux?

Compared [illegible]-run simulated [illegible]

Constant flux rejected at ≥ [illegible]% confidence [illegible]

Time-power spectrum analysis—what frequencies?

[illegible]

[illegible] 12.8[illegible] [illegible] to Sun's tilt [illegible]

[illegible]

SA[illegible]

Also 12.88, but 13.59 y^{-1} (26.9 d) dominant and equatoria

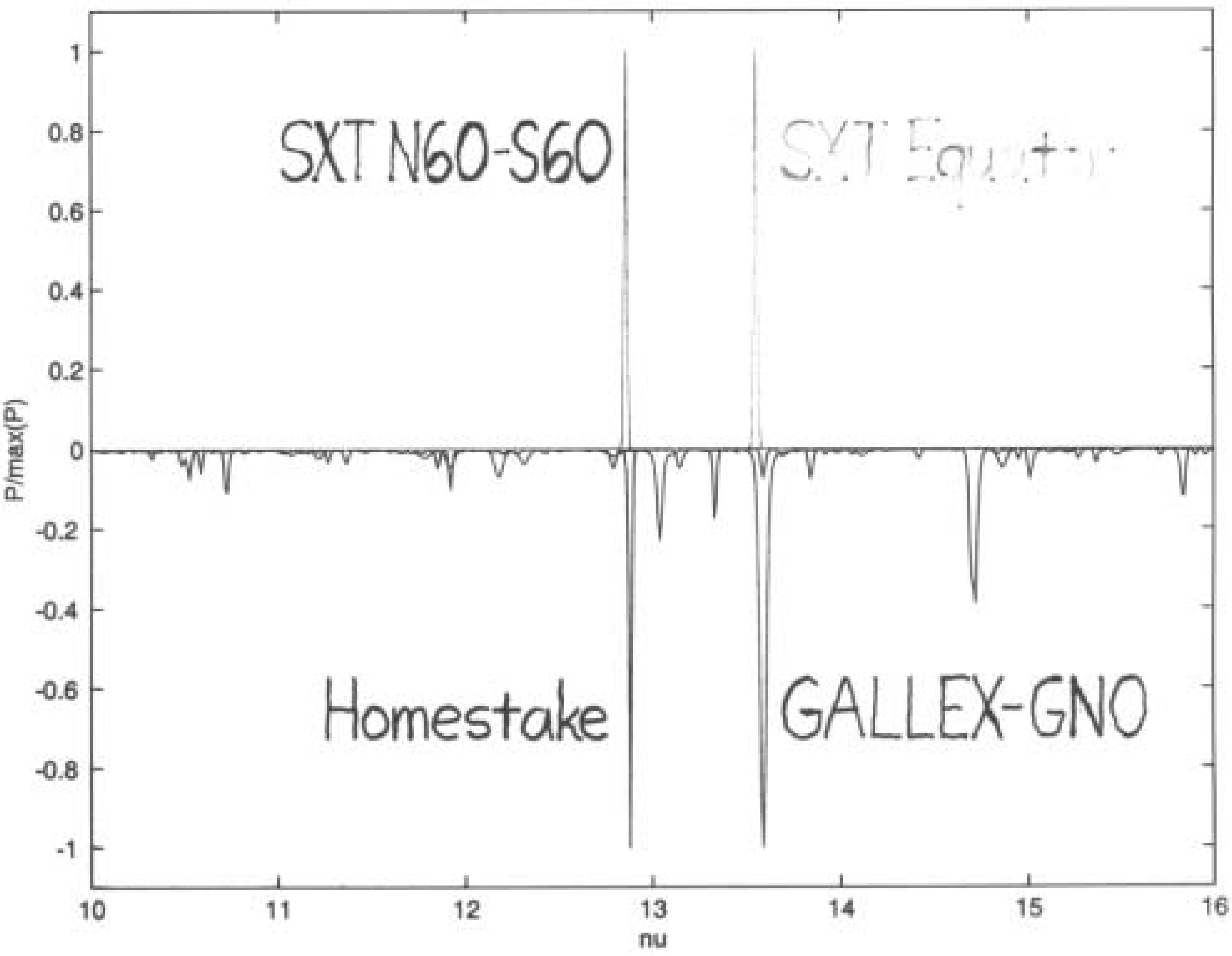
Joint analysis with Homestake: stronger 13.59 evidenc

Same frequencies seen in X-rays (SXT on Yohkoh spacec

12.86 ± 0.02 y^{-1} at high latitudes

13.55 ± 0.02 y^{-1} at the equator

Time Spectra Normalized Probability Distribution Function

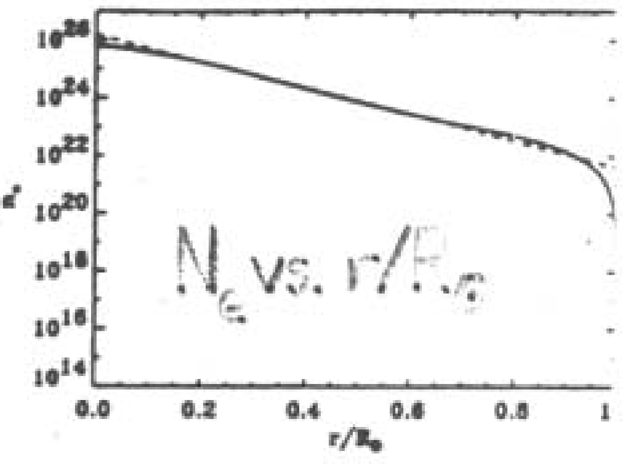


Frequency y^{-1}

Location of the Resonance

SOHO/MDI helioseismology convoluted with GALLEX-GNO d

SOHO/MDI(ν,λ) matching Ga(ν)



Near equator at $r=0.8R_\odot$

Locating $\nu=13.6\,y^{-1}$ determines $\frac{\Delta m^2}{E}$

$$\frac{\Delta m^2}{E}=2\sqrt{2}G_F(N_e-N_n)=1\times10^{-14}eV$$

Recall ν_e survival probability for RSFP fit

Exactly the $\Delta m^2/E$ needed

Exponential (N_e-N_n) vs. r could give very different $\Delta m^2/$

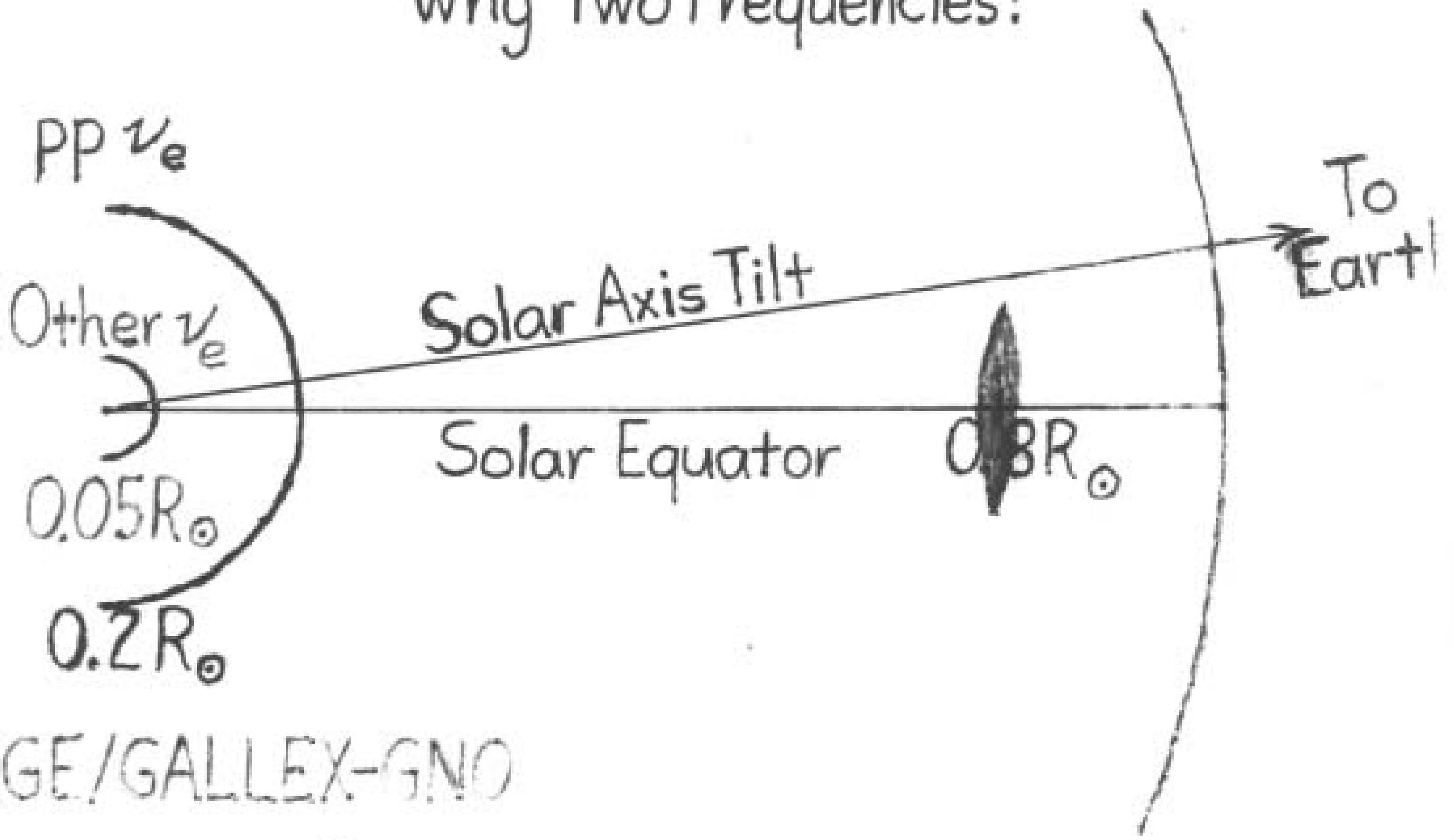
RSFP resonance for $12.9\,y^{-1}$ must be at $r>0.8R_\odot$

Higher latitudes

Either radiative-zone field or latitudinal wave

Recall 12.9, 13.6 y^{-1} frequencies seen out to corona

Why Two Frequencies?



SAGE/GALLEX-GNO

Mainly pp ν_e (^{7}Be suppressed) produced at ~0.2R$_\odot$

Most ν_e modulated by equatorial field rotation (13.6

Homestake

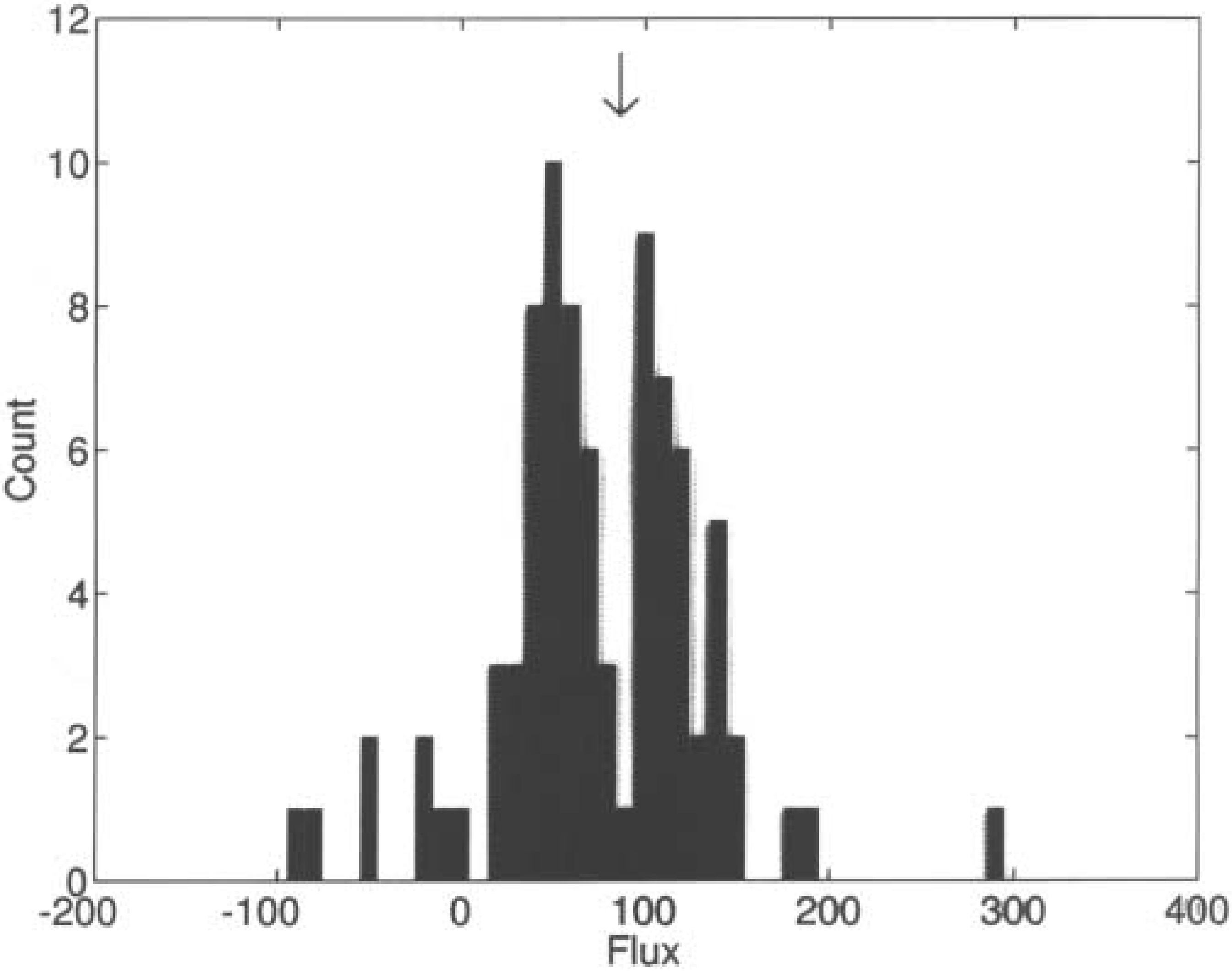
ν_e made near Sun's center at ~0.05 R$_\odot$

7° axis tilt makes most ν_e miss equatorial field

Higher latitude field modulates most ν_e as it rotate

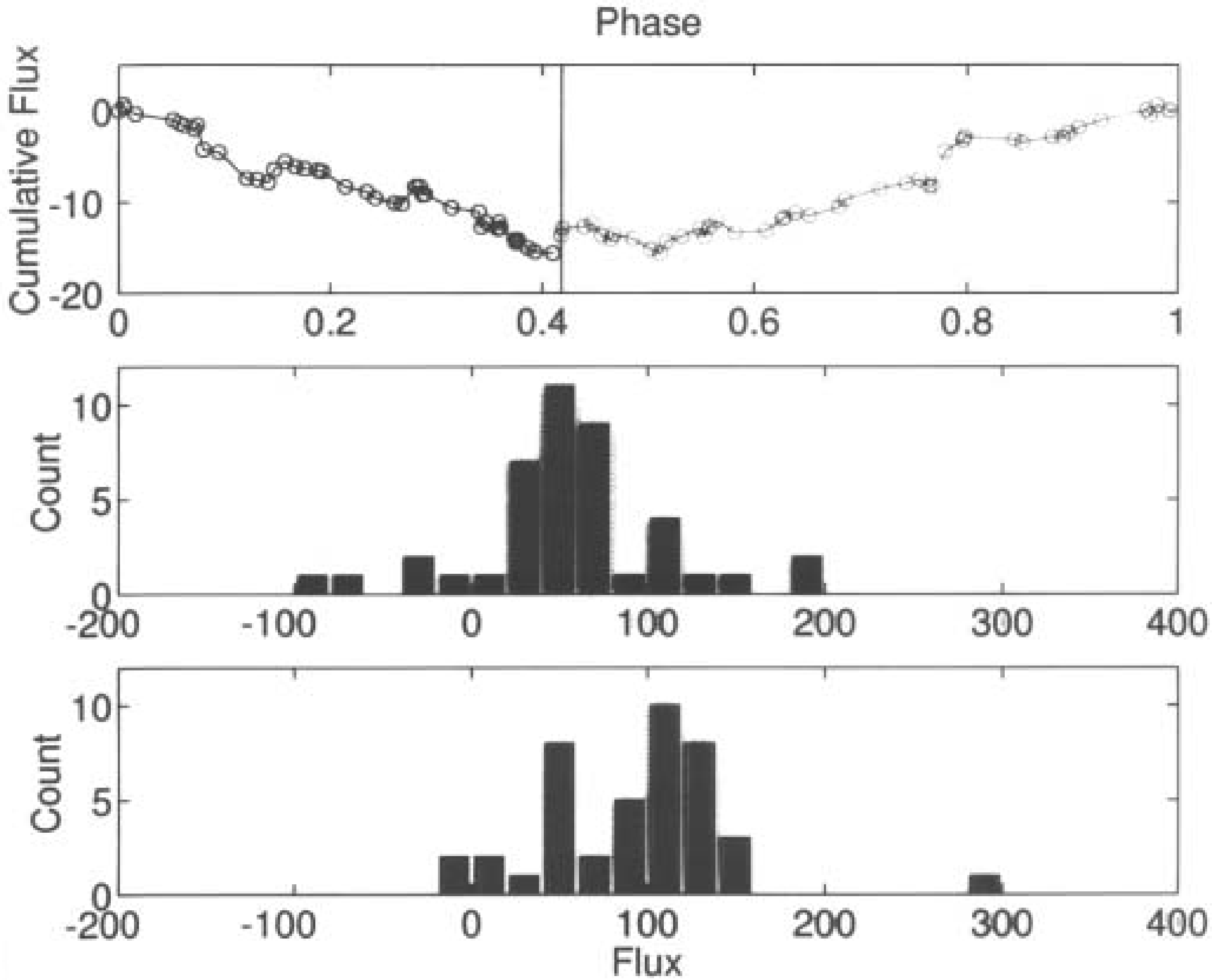
Get mainly 12.9 y^{-1} rate

GALLEX Event Distribution



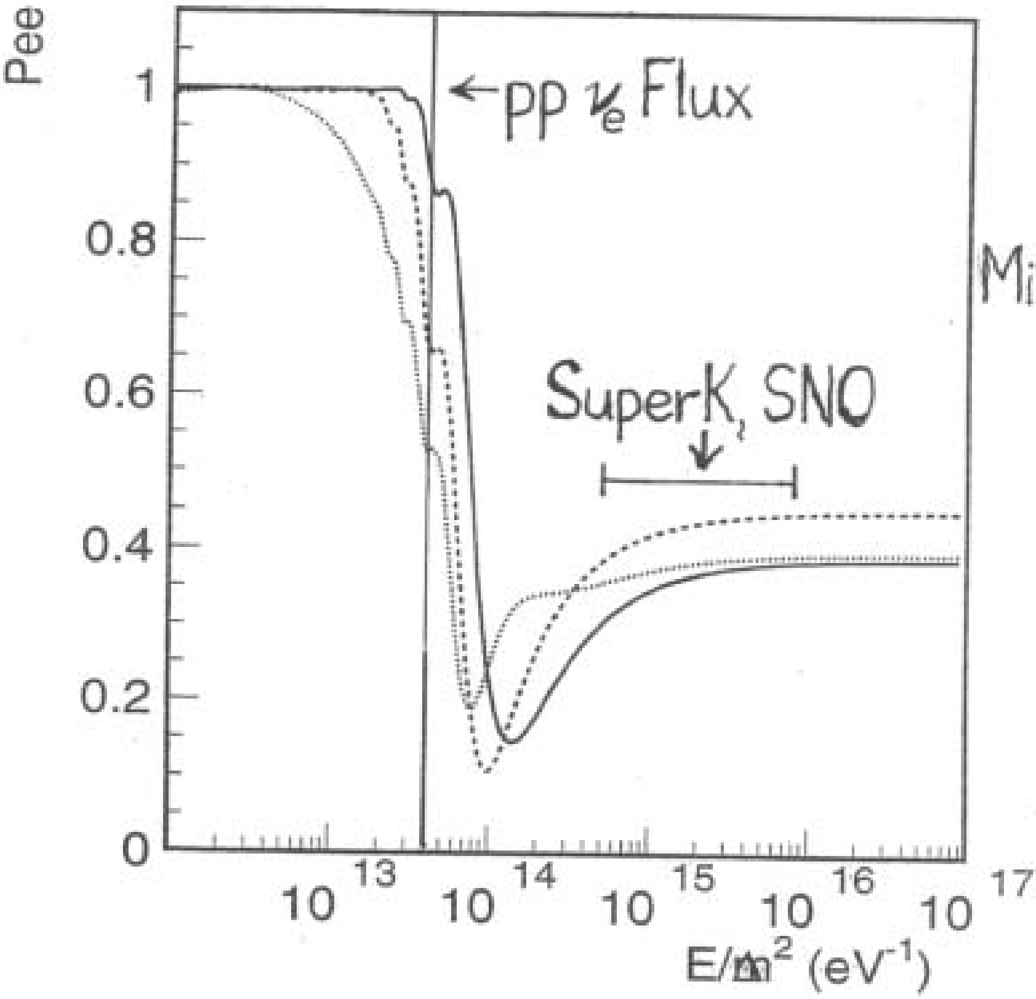
Bimodality by chance $< 10^{-4}$

GALLEX data reordered by phase for $\nu = 13.59\, y^{-1}$



Understanding a Bimodal ν Flux Distribution

ν_e^L Survival Probabilities for 3 $B_\perp$ Fields vs. $E_\nu/\Delta m^2$



Miranda et a

Dip chosen near 0.86 MeV (^{7}Be) for data fit (pit at $\Delta m^2/E \sim 10$

GALLEX flux dominated by pp ν_e (^{7}Be suppressed)

Rate determined by spectrum-pit overlap

$B_\perp$ change can give factor of 2 drop in rate (lower peak~.

Upper peak~100 (down from 128 by ^{8}B, ^{15}O, etc.)

Some Evidence for Rieger Frequencies

Known for 20 years in solar flares, sunspots, etc.

156-day period long known

78- and 52-day periods also seen

Identify with r-modes (**latitudinal motion**) seen on earth

$\nu(l,m) = \frac{2m\nu_R}{l(l+1)}$, for ν_R = sidereal frequency = synodic + 1

Rotating fluid sphere has $l \geq 2$

For $l=3$, expect to see $\nu_R - 1$, $\nu_R/6$, $\nu_R/3$, $\nu_R/2$ (periods ab

For $\nu_R = 12.88\ y^{-1} + 1$, get Rieger periods

Expected Convection-Zone Field Variation

Radiative-zone field can have spatial but not time variat

hep-ph/020209

Convection-zone field should change at solar max. and mi

How would neutrinos show this field change with time

If transitions stay adiabatic, field magnitude change uns

Shape of field can affect pp neutrino rate (Ga)

Most sensitive: resonance-pit edge (rate: $13.6 y^{-1}$ amou

Change of azimuthal symmetry of $B_\perp$ changes modulati

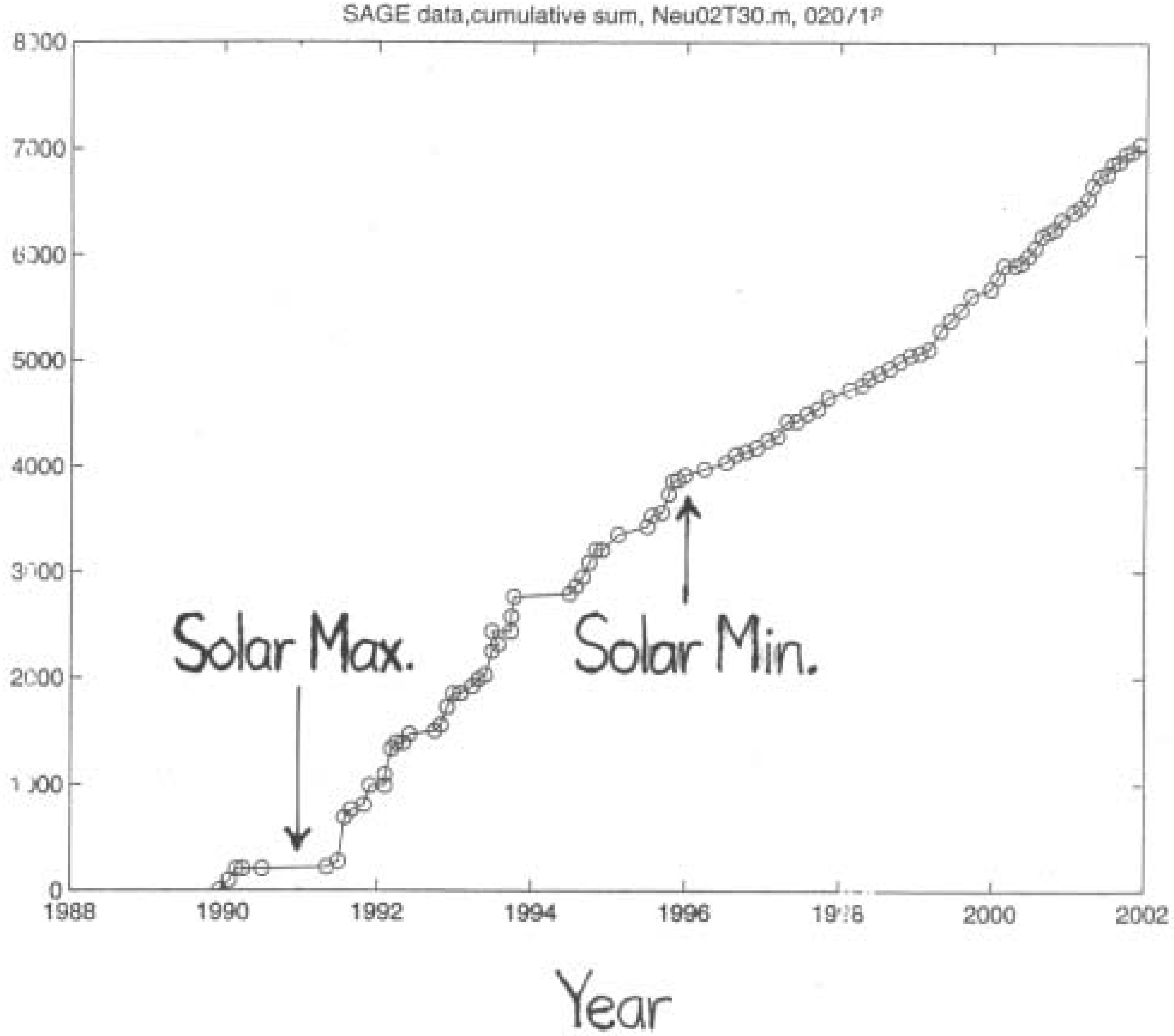
1989.6 solar maximum to the 1996.8 solar minimum

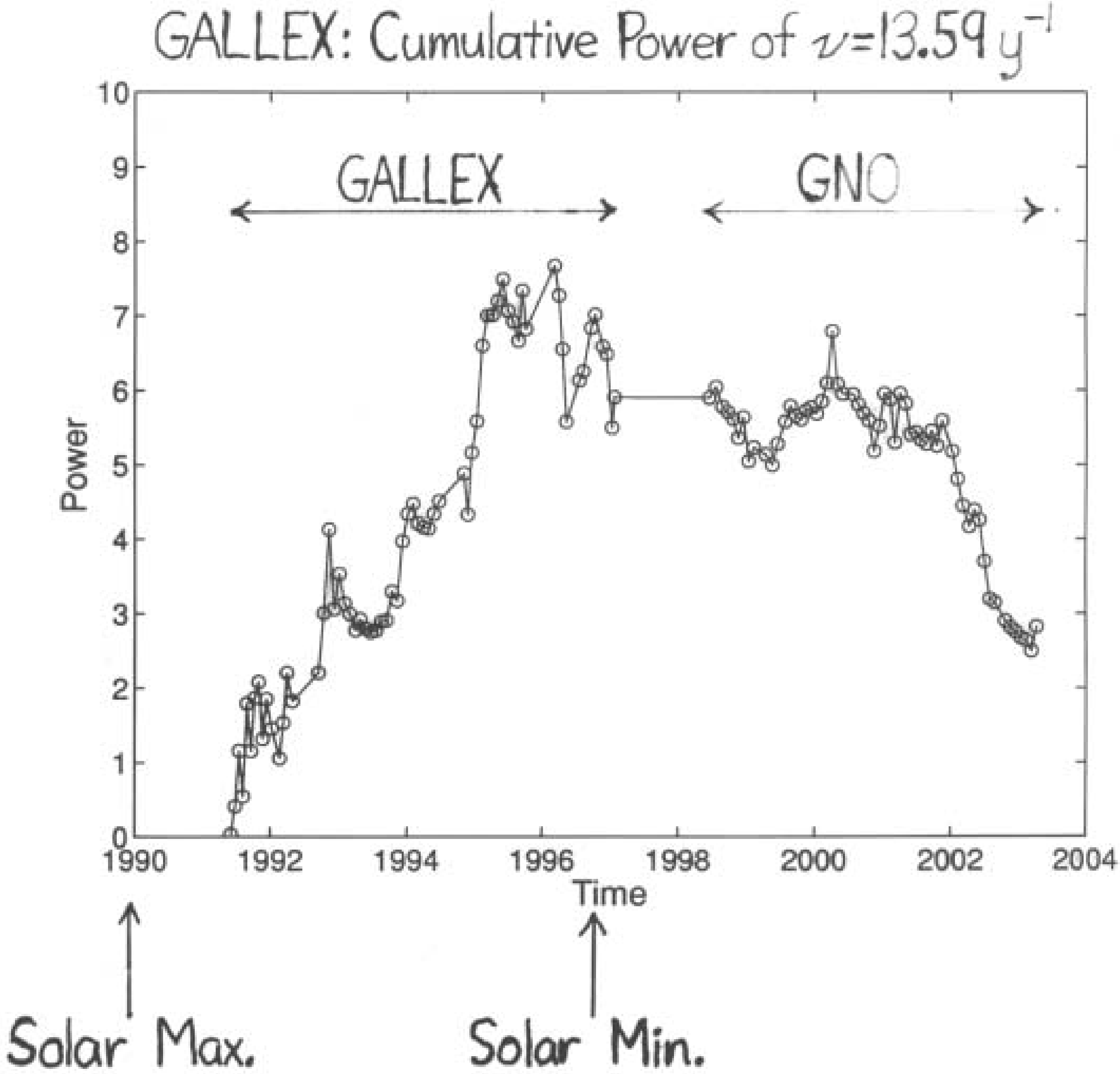
When $13.6 y^{-1}$ is observed in GALLEX

Also when main buildup of $12.9 y^{-1}$ in Homestake

And when those frequencies were seen in SXT X-ray

SAGE: Cumulative Neutrino Flux





GALLEX: Cumulative Power of ν=13.59 y⁻¹
GALLEX
GNO
Power
Time
0
1
2
3
4
5
6
7
8
9
10
1990
1992
1994
1996
1998
2000
2002
2004
Solar Max.
Solar Min.

Super-Kamiokande Time Data

Predicting the result

SK started at about the 1996.8 solar minimum

Homestake (like SK, saw mainly $^8B\ \nu$) stopped ther

SK ran from 5/96 to 7/01, just past solar maximu

No way from other data to predict SK time resu

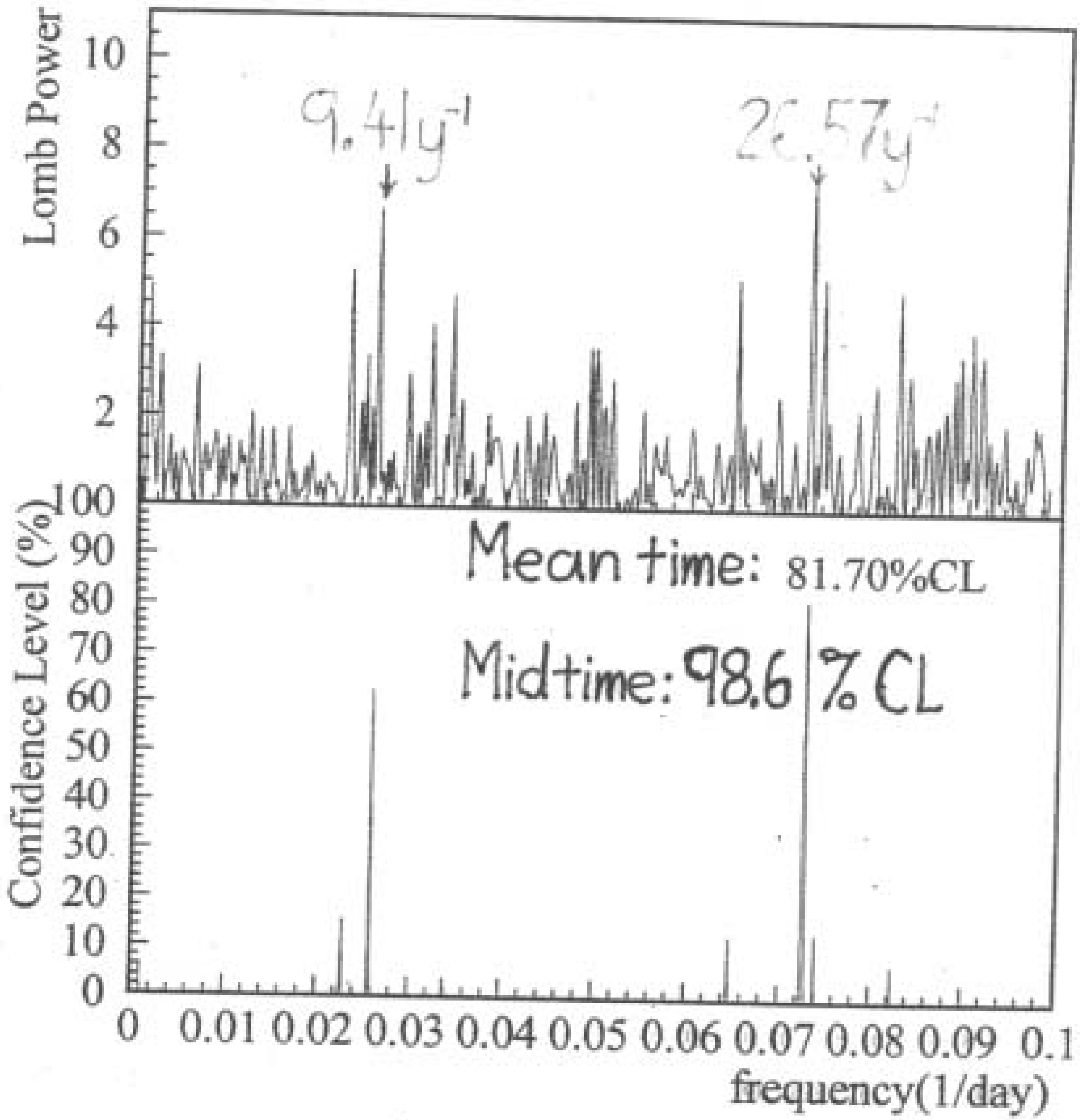
SK data

Too regular binning

10-day data originally; now 5-day data also

hep-ex/0307070

Super-Kamiokande Analysis (10d)



Lomb method

Really applies to irregularly-spaced data

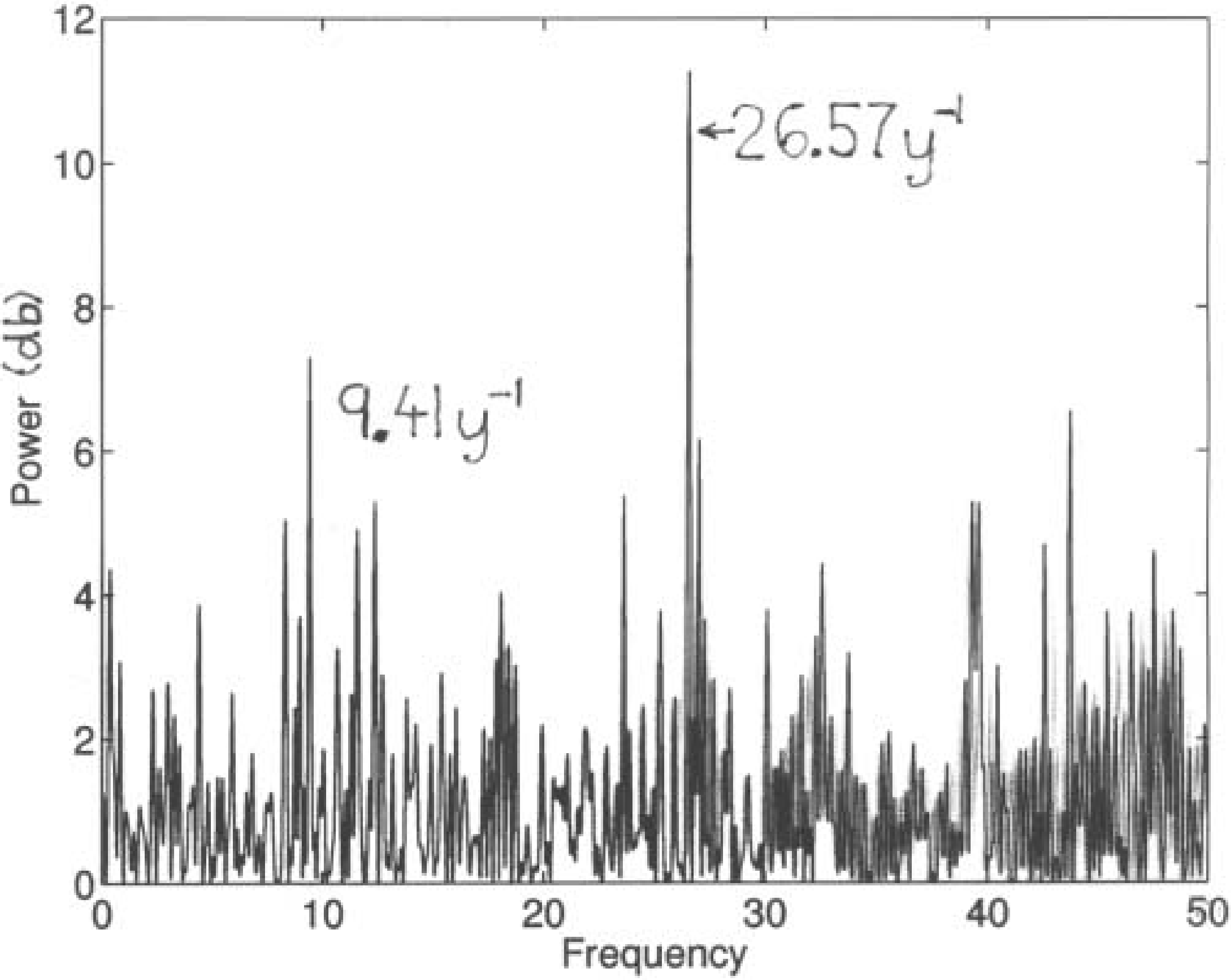
Places data as delta functions in time

Also used by Milsztajn

Does not include measurement errors

Likelihood Analysis

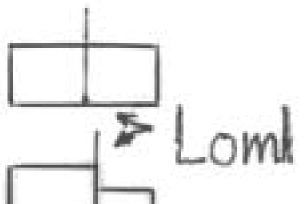
Super-Kamiokande 10-day Data



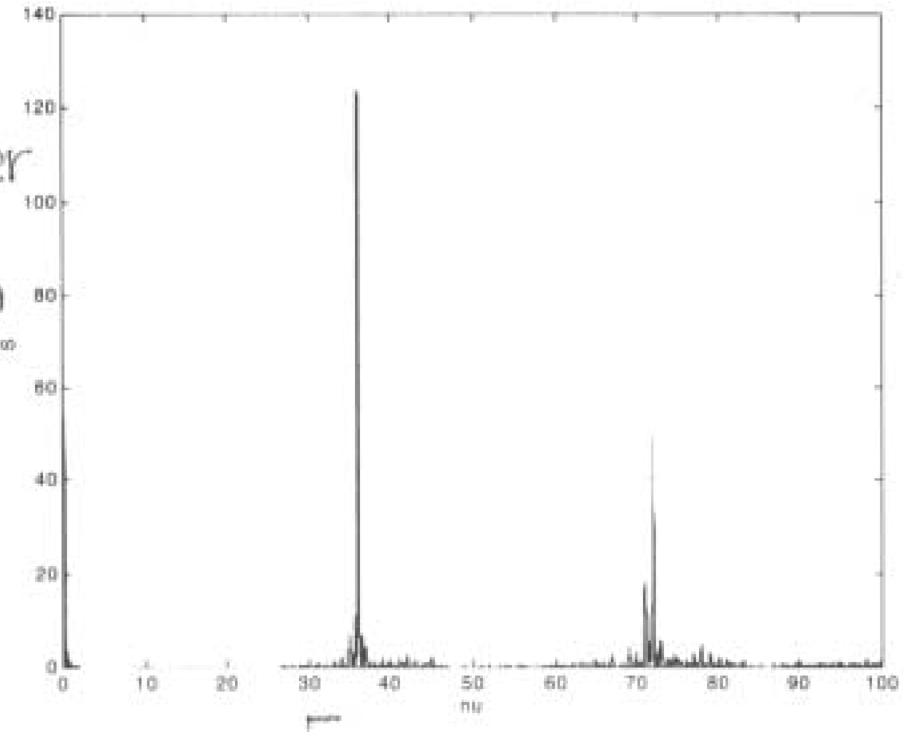
Includes measurent errors

Assumes data taken over whole interval

Later: used start, stop, and mean time



SUPER-KAMIOKANDE

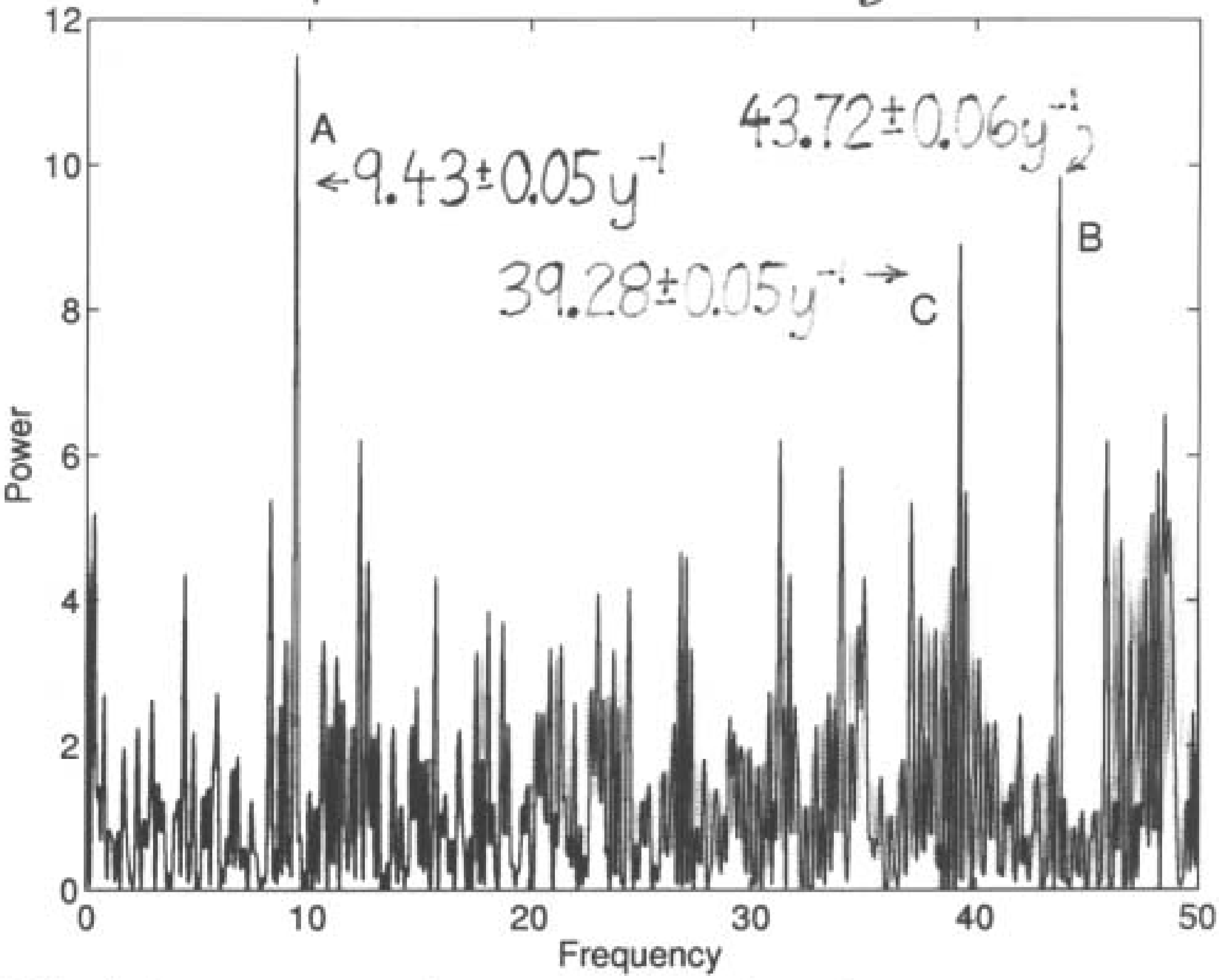


Power Spectrum formed from Timing of Data Bins
Strong Periodicity at 35.98 cpy (10.15 days)

9.41+26.57=35.98, so which is the alias?

S0209B05

Super-Kamiokande 5-day Data

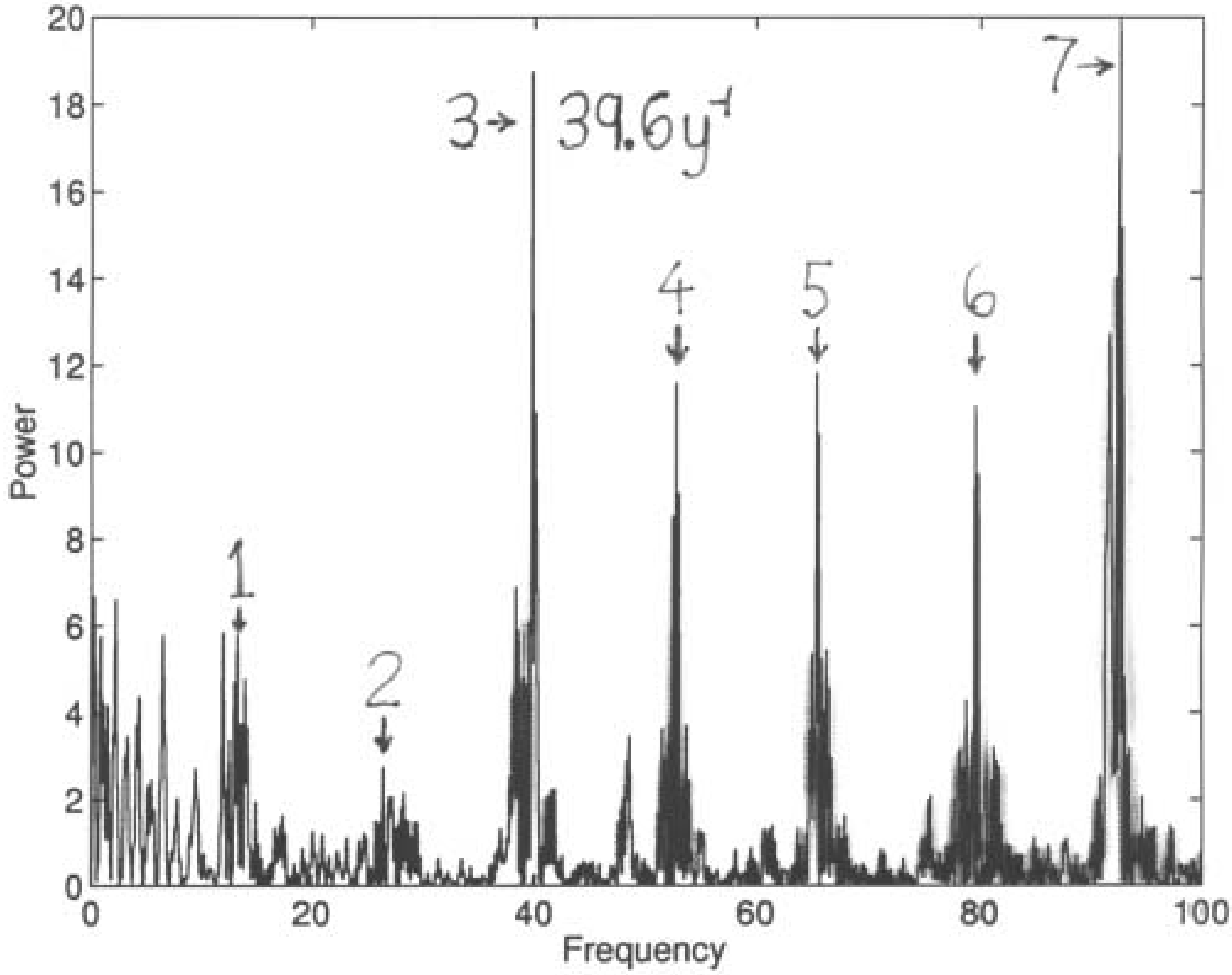


26.57 y^{-1} disappeared, so it was the alias

Timing peak at 72.01 y^{-1} (5.07 days), so expect 72.01−9.43

Alias expected = 62.58; peak at 62.56 ± 0.08 y^{-1} seen

Solar Magnetic Field in the Super-K Time Interval



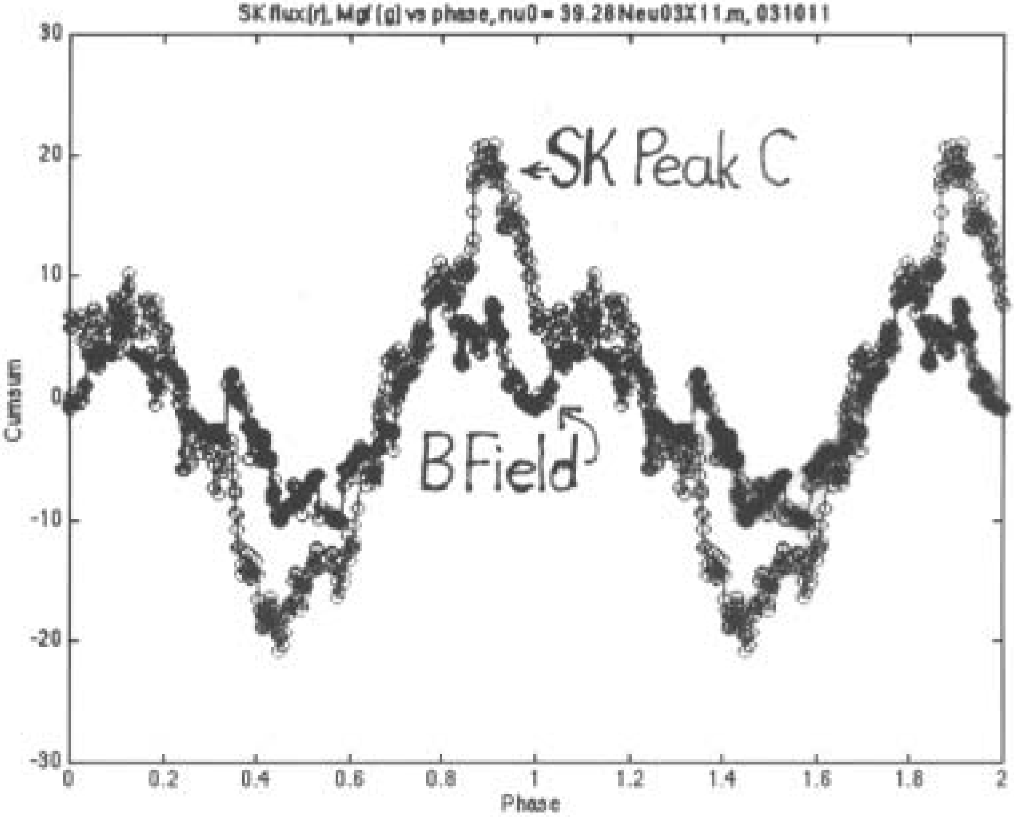
B-Field Rotation Rate y^{-1}

Only 39.6 y^{-1} can be prominent in Super-K 5-day data

$13.20 \pm 0.14\ y^{-1}$ rotation rate (peaks 3-7) gives $39.60 \pm 0.42\ y^{-1}$

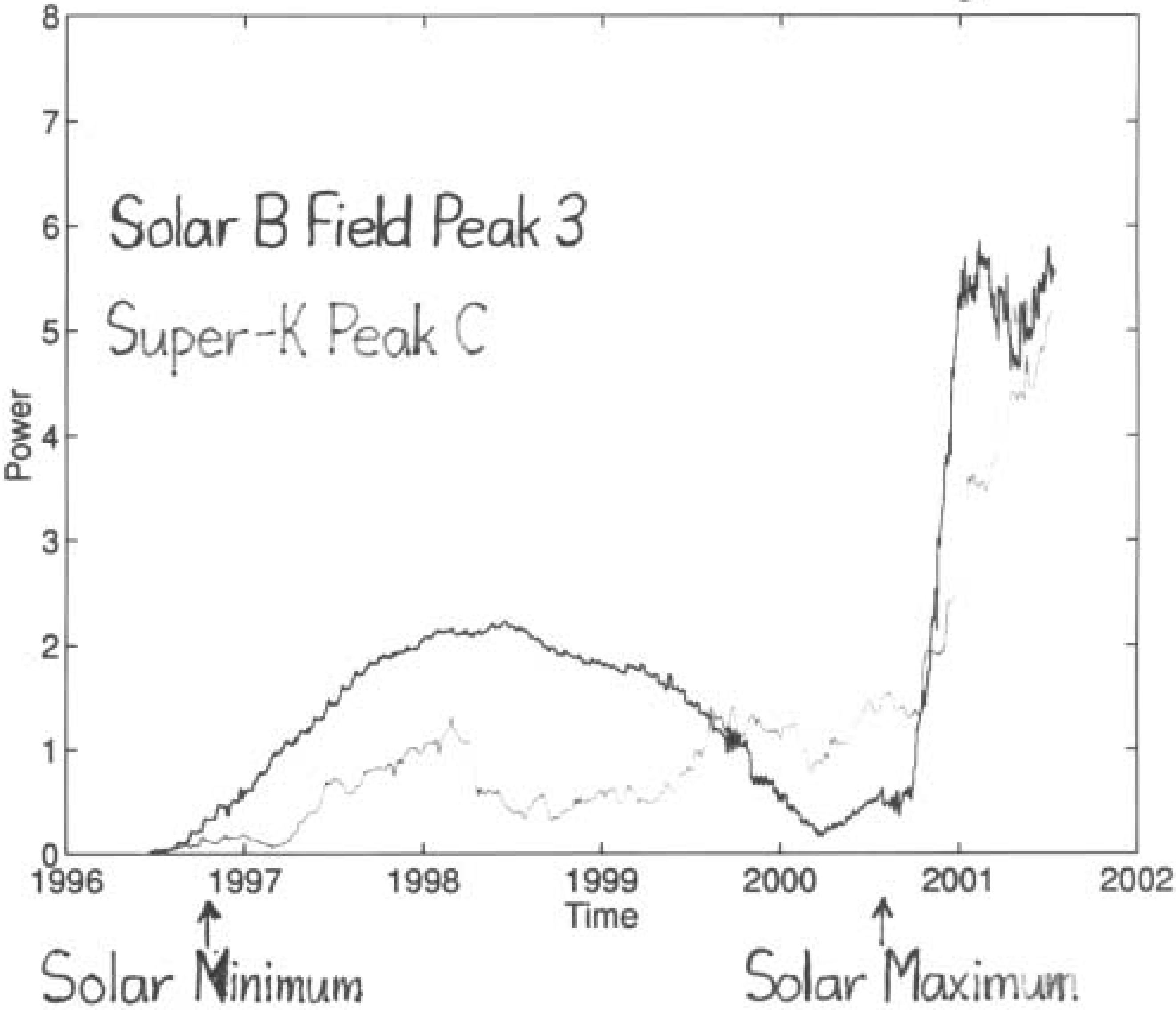
Peak C of power 8.91 in that band at 99.5% CL

SUPER-KAMIOKANDE, 5-day bins



Phase of 39.58 $y^{-1} = \nu$ 37

Cumulative Power of $\nu = 39.58\,y^{-1}$



Origin of Peaks A and B

Retrograde waves (r-modes) move B regions in/out of neutrino p

Oscillation: combination of r-mode frequency, B-field rotatic

$\nu = \left| m(\nu_R - 1) - \frac{2m\nu_R}{l(l+1)} \pm m'(\nu_R - 1) \right|$, where m′=azimuthal index of B field

For $m' = m$, + sign gives $\nu(l,m) = \frac{2m\nu_R}{l(l+1)}$ (used previously)

Alias-like frequency for − sign: $\nu(l,m) = 2m(\nu_R - 1) - \frac{2m\nu_R}{l(l+1)}$

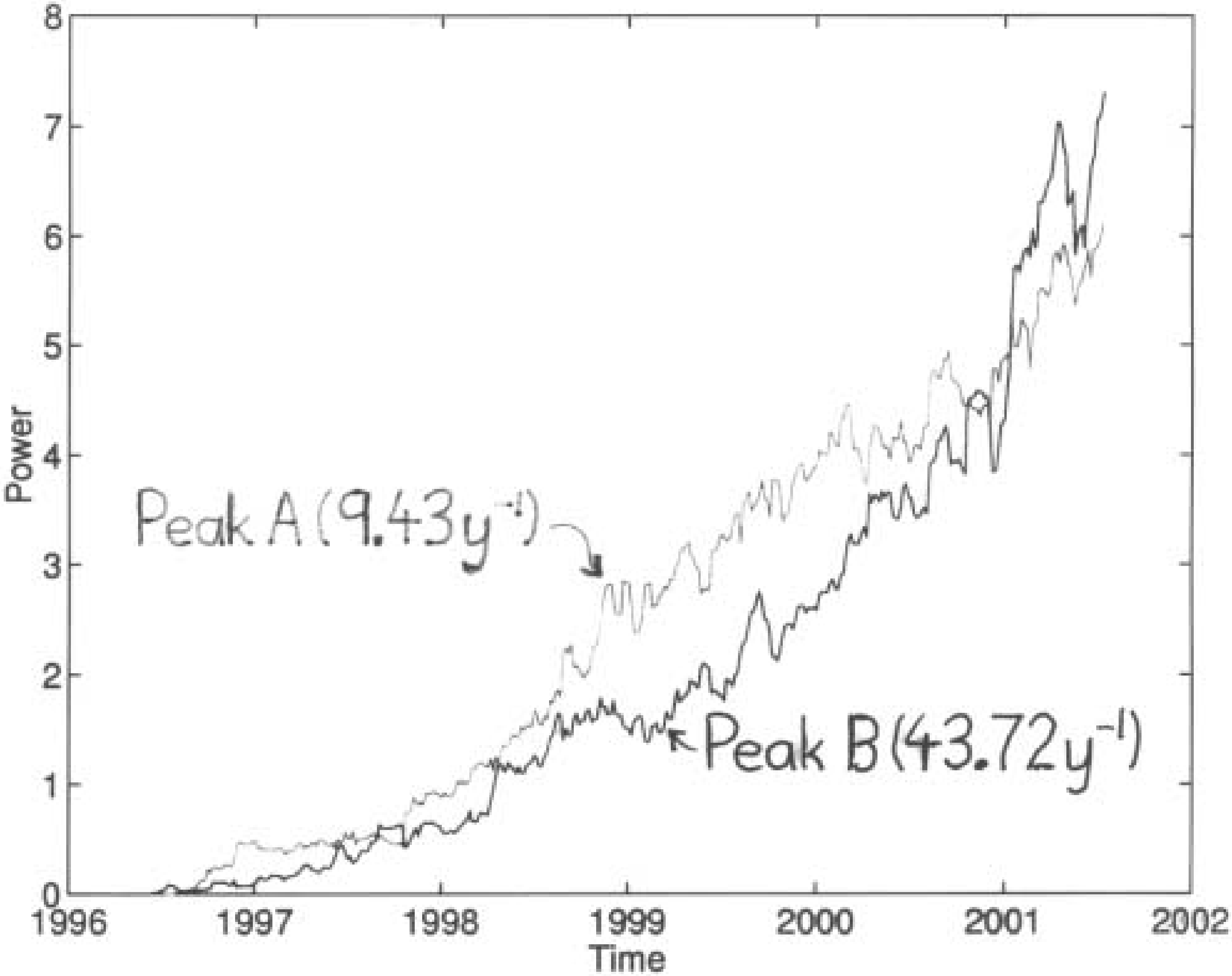
From magnetic field: $\nu_R = [(13.20 \pm 0.14) + 1]\ y^{-1}$

This ν_R and $l = m = 2$ gives 9.47 ± 0.09 and $43.33 \pm 0.47\ y^{-1}$

Peak A: 9.43 with power 11.51 matches at 99.98% CL

Peak B: 43.72 with power 9.83 matches at 99.7% CL

Cumulative Rayleigh Powers



Note difference from Peak C/B Field (different origin)

Conclusions

Very strong evidence for neutrino flux variations

Variations match known solar frequencies

Producing flux variations if KamLAND is correct

SFP with sterile ν_s ($\Delta m^2 \sim 10^{-5} eV^2$) could improve data fi

RSFP with ν_s of $\Delta m^2 \sim 10^{-8} eV^2$ improve fit, favored by data

SNO: provide check; possible identification of Majorana

New physics: large transition moment, sterile ν_s

More details: hep-ph/0309191v2