# Evidence for Sterile Neutrino Hot Dark Matter and Implications for Cold Dark Matter

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Sample of evidence for solar $\nu_e$ flux modulation

Modulations match known solar rates (e.g., rotation)

Explanation: sterile $\nu$, large transition magnetic moment

$\nu_s$ role as hot dark matter; possibilities for cold dark matter

# Solar $\nu_e$ Flux Modulation in Radiochemical Experiments

Work of Sturrock, Scargle, Walther, Weber, Wheatland

Homestake (Cl): constant flux rejected at $\gtrsim$99.9% C.L.

Two main frequencies (solar rotation rates)

Homestake: 12.88 $y^{-1}$ (28.4 d), above solar equator

SAGE, GALLEX (Ga): 13.59 $y^{-1}$ (26.9 d), equatorial

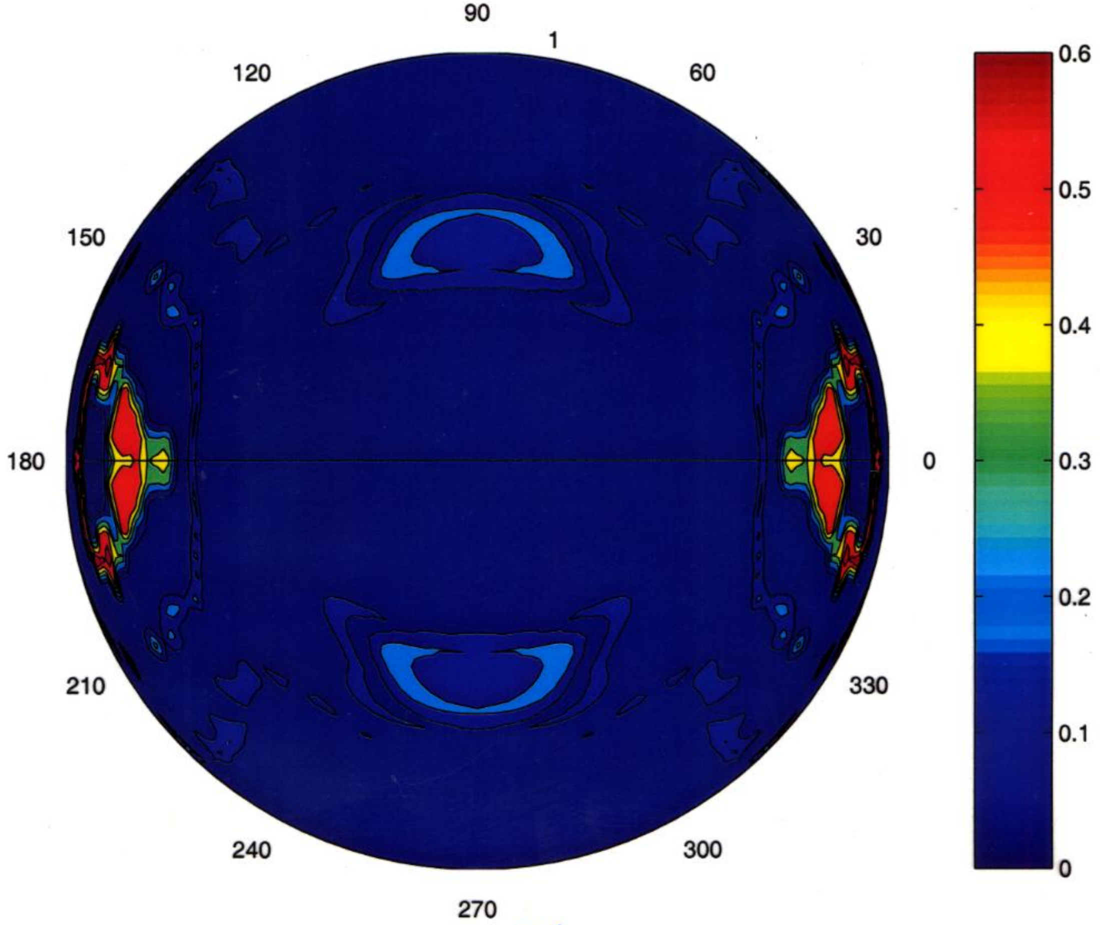
Same frequencies in coronal X-rays (SXT on Yohkoh)

12.86±0.02 $y^{-1}$ at high latitudes

13.55±0.02 $y^{-1}$ at the equator

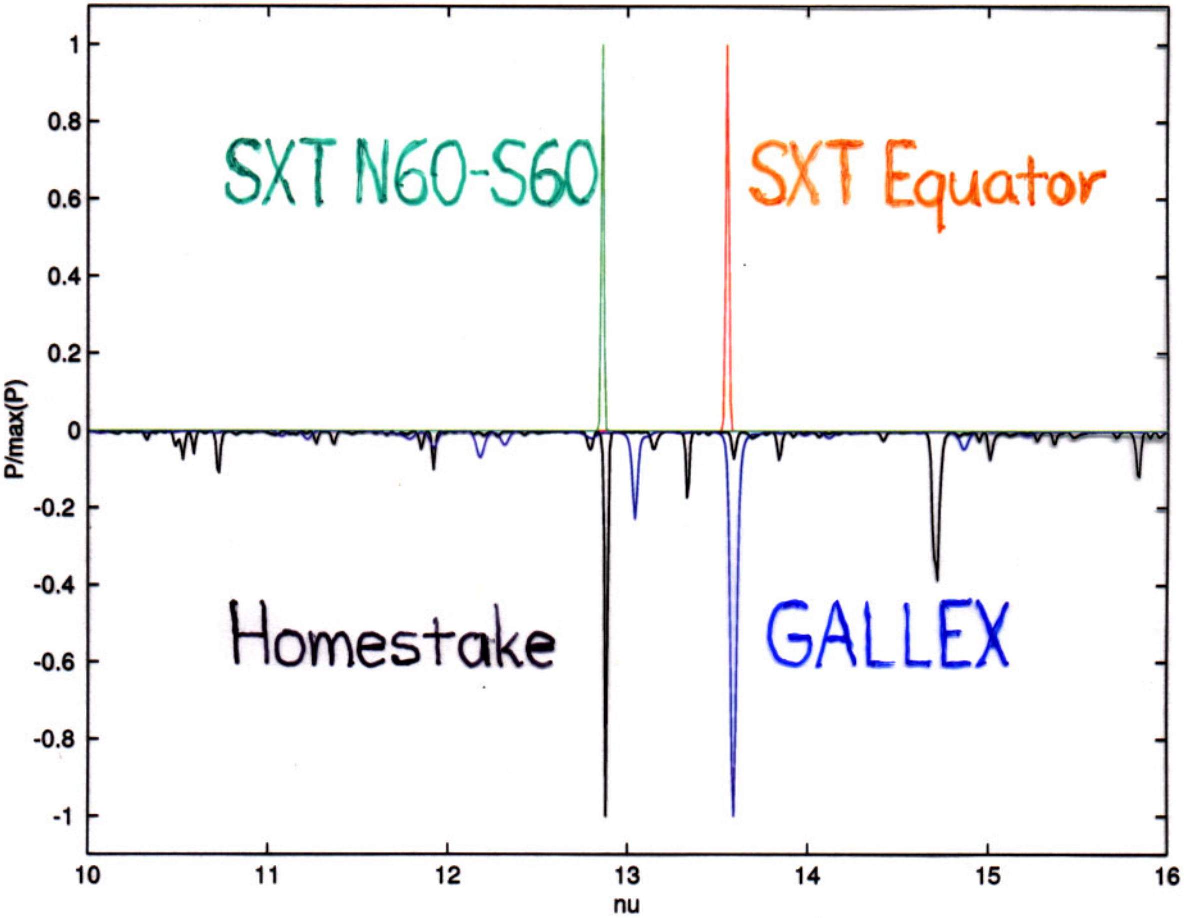
# Locating the 13.6 $y^{-1}$ Modulation in the Sun

Use GALLEX data with SOHO-MDI rotation profiles



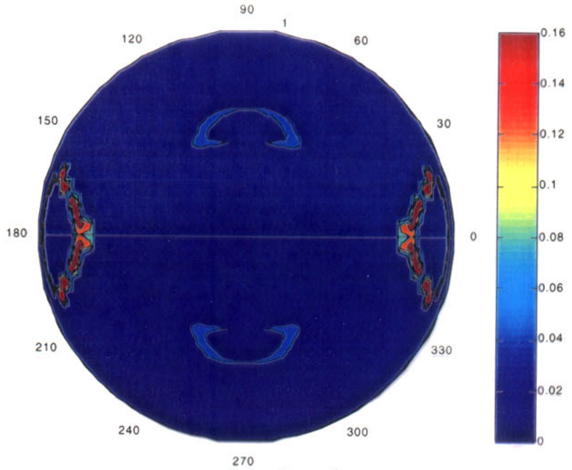
Resonance (red) in $\Xi(r,\lambda)=\int_{\nu_a}^{\nu_b} S(\nu)P(\nu|r,\lambda)\,d\nu$ gives location

# Time Spectra Normalized Probability Distribution Functions



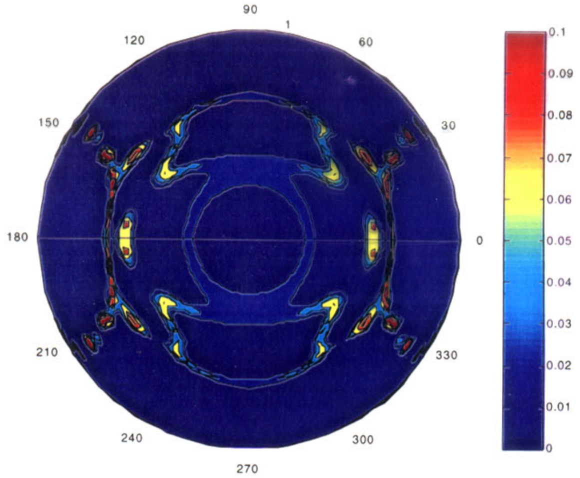
Frequency $y^{-1}$

# SXT+Helioseismology



$\nu=13.6y^{-1}$

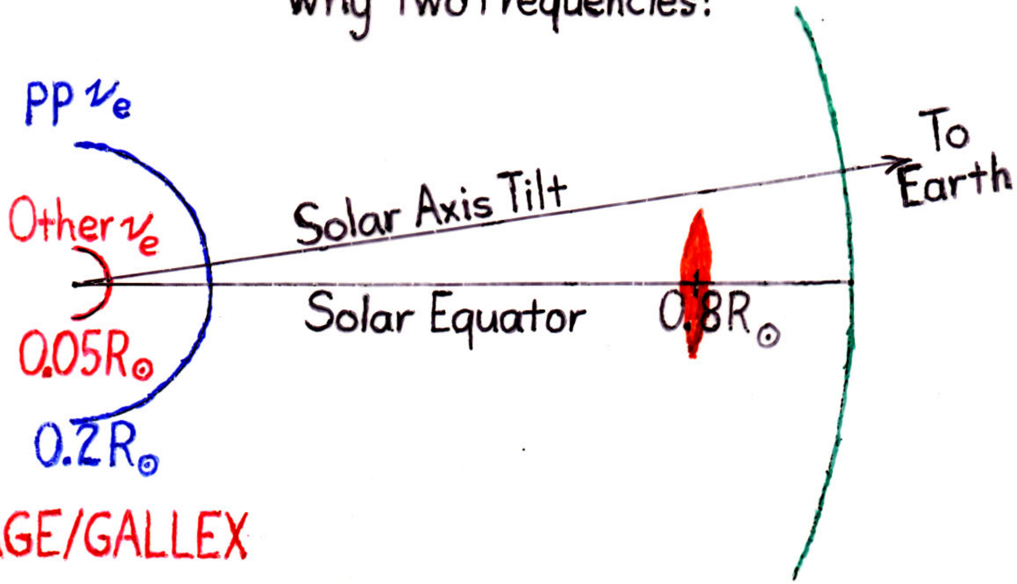
Rotational Modulation Statistic formed from the equatorial SXT data.



Rotational Modulation Statistic formed from spectra of the N60 and S60 SXT data.

$\nu=12.9y^{-1}$

# Why Two Frequencies?



## SAGE/GALLEX

Mainly pp $\nu_e$ ($^7$Be suppressed) produced at $\sim 0.2R_\odot$

Most $\nu_e$ modulated by equatorial field rotation ($13.6\,y^{-1}$)

## Homestake

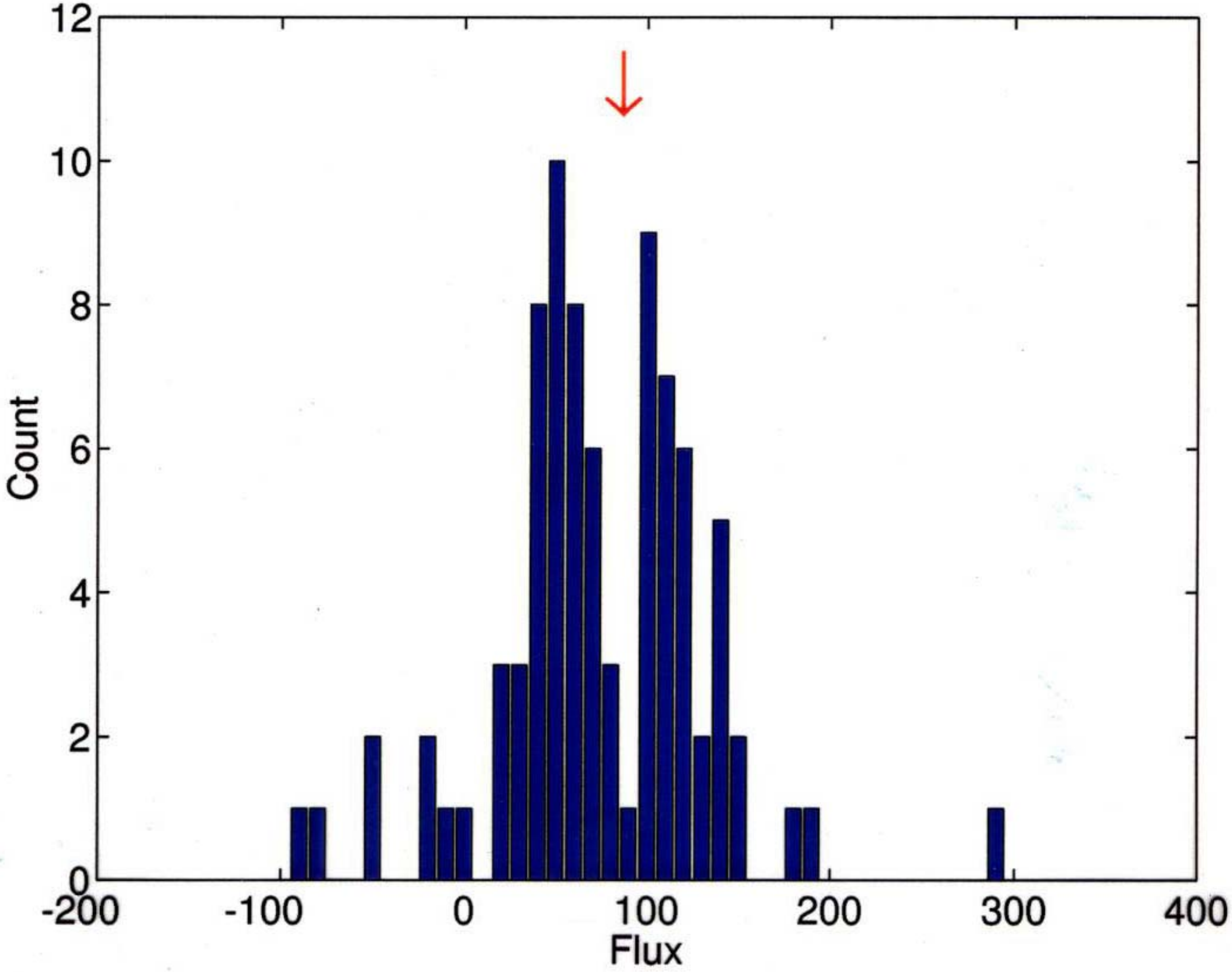
$\nu_e$ made near Sun's center at $\sim 0.05\,R_\odot$

7° axis tilt makes most $\nu_e$ miss equatorial field

Higher latitude field modulates most $\nu_e$ as it rotates

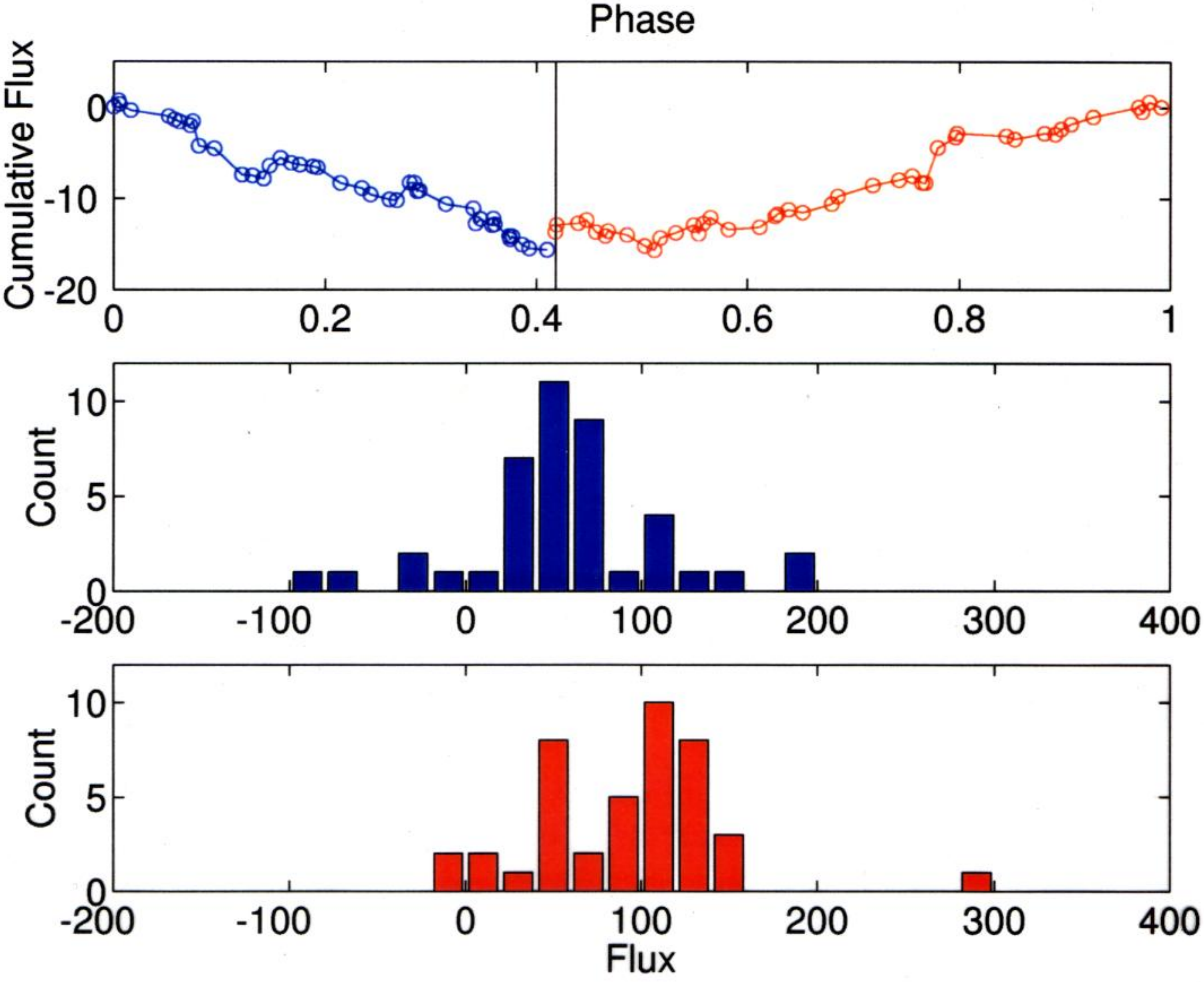
Get mainly $12.9\,y^{-1}$ rate

# GALLEX Event Distribution



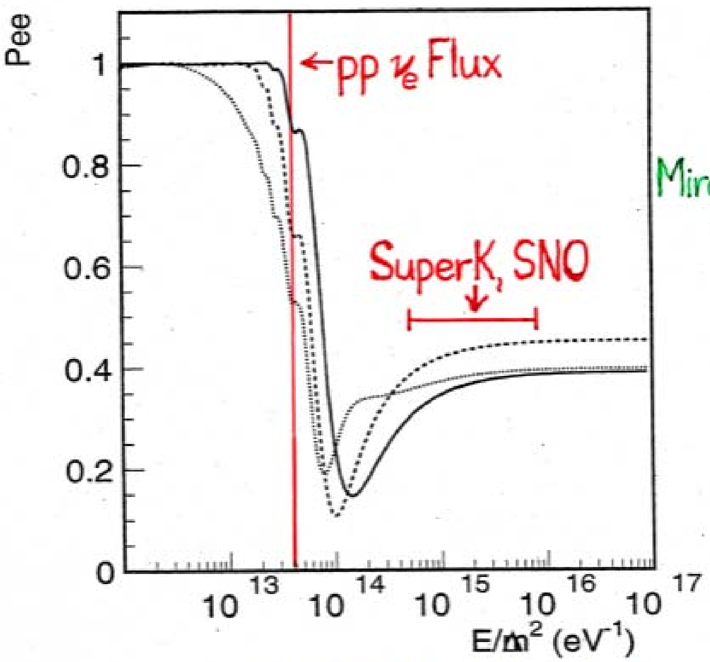
Bimodality by chance $<10^{-4}$

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



# Understanding a Bimodal $\nu$ Flux Distribution

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



Miranda et al.

Dip chosen near 0.86 MeV ($^7$Be) for data fit (pit at $\Delta m^2/E \sim 10^{-14}$)

GALLEX flux dominated by pp $\nu_e$ ($^7$Be suppressed)

Rate determined by spectrum-pit overlap

$B_\perp$ change can give factor of 2 drop in rate (lower peak~50)

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

# Understanding the Observations

Magnetic field effect, so Resonant-Spin-Flavor Precession

Subdominant to LMA MSW oscillation (in series with RSFP)

Two types of frequencies: field rotation, r-modes

$3\nu$ model (Friedland, Gruzinov; Balantekin, Volpe)

Effects are too small

RSFP in wrong location (small solar radius)

$4\nu$: $\nu_e \rightarrow \bar{\nu}_s$ with no mixing (DOC, used by Chauhan, Pulido)

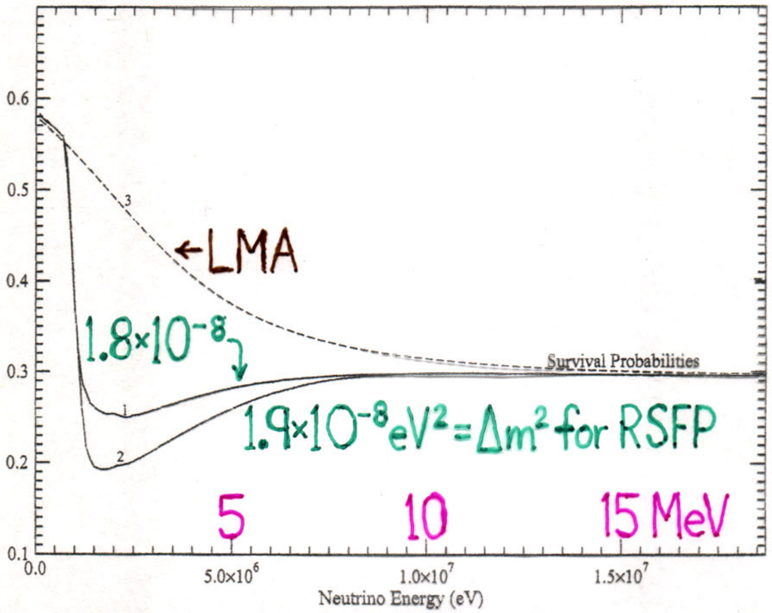
$\nu_s$ avoids constraints (unitarity, % of solar $\nu$, nucleosynthesis)

Size of flux modulation predicted correctly

Gives correct location of RSFP ($0.8 R_\odot$, convection zone)

Improves fit to time-averaged solar data

# $\nu_e$ Survival Probability vs. Energy



$\Delta m^2$ chosen to fit all time-averaged data using LMA+RSFP

Same $\Delta m^2$ gives RSFP at correct solar radius

RSFP survival probability dip improves fits

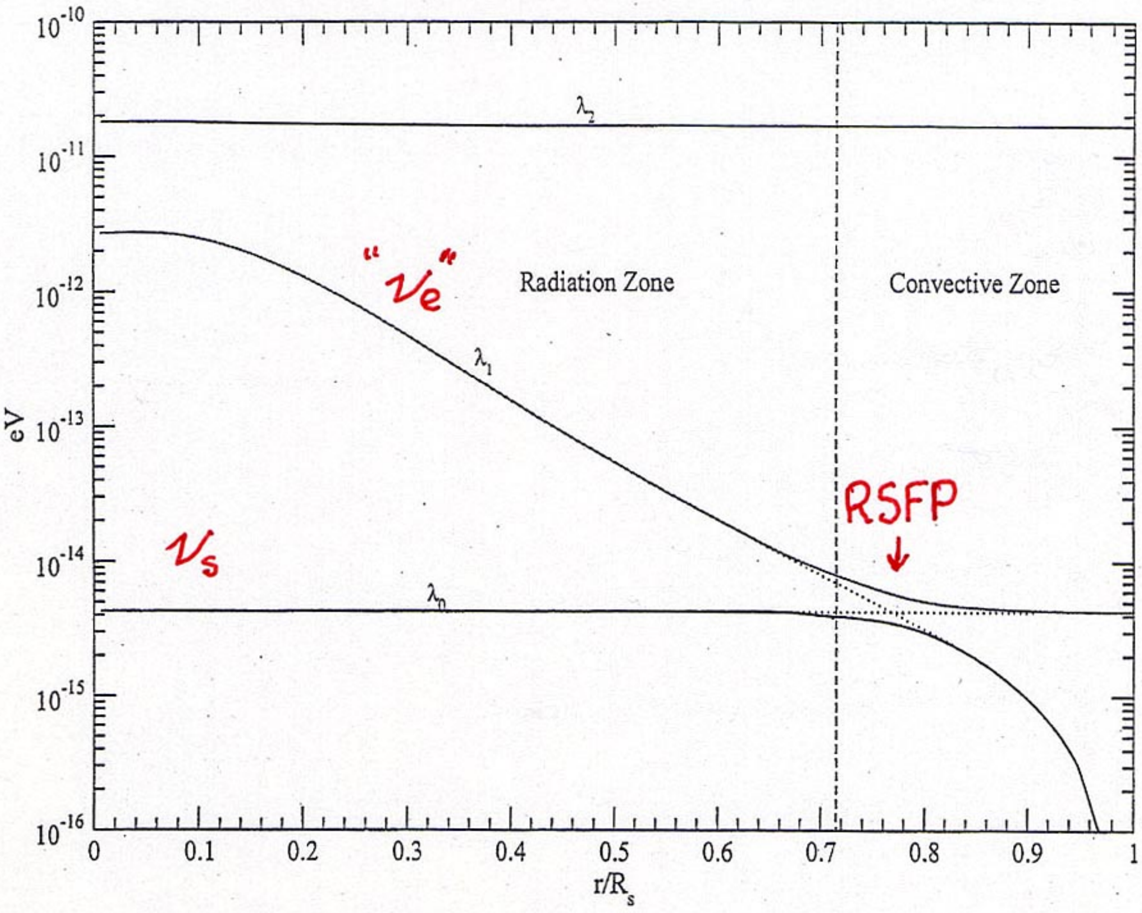
Super-K, SNO spectra are flat with energy

Lower energy: Cl result is $2.5\sigma$ too low for LMA

Different $\nu_s$ used by de Holanda, Smirnov for this

Modulation ~7% for Super-K; can be big for Ga (pp $\nu_e$)

# Mass Evolution with Solar Radius



Calculation by Chauhan and Pulido with $4\nu$ model

# Problems with Analyses

Small effect and very transient

Convection zone magnetic field changes with solar cycle

r-mode frequencies are even more episodic

Example: Pandola gets same peak ($13.6y^{-1}$) in GALLEX-GNO "but"

He sums the two experiments, but the solar cycles differ

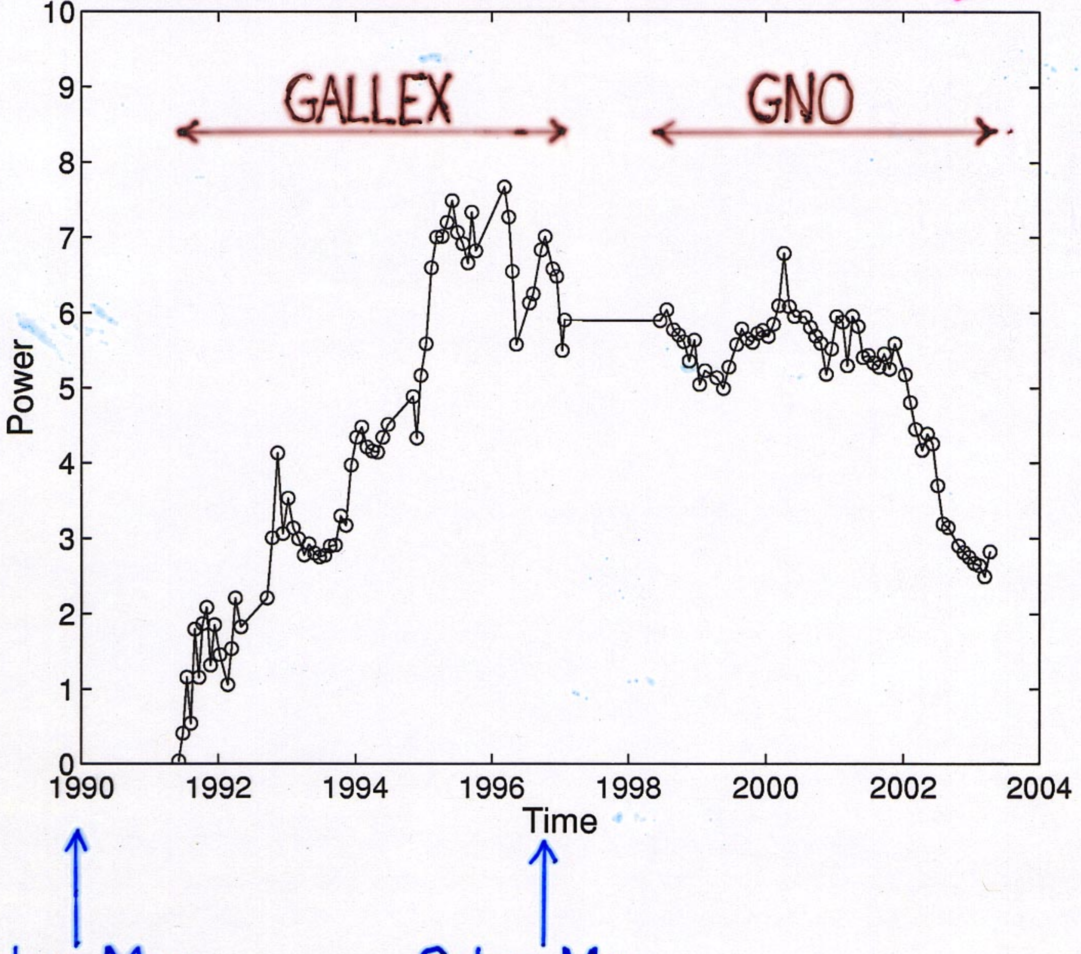
Looking for rotation effect ($12.5$-$13.8y^{-1}$) but uses $0$-$26y^{-1}$

Doesn't use all the information (stop times, not run length)

Doesn't consider harmonics (99.7% C.L. → 99.96%)

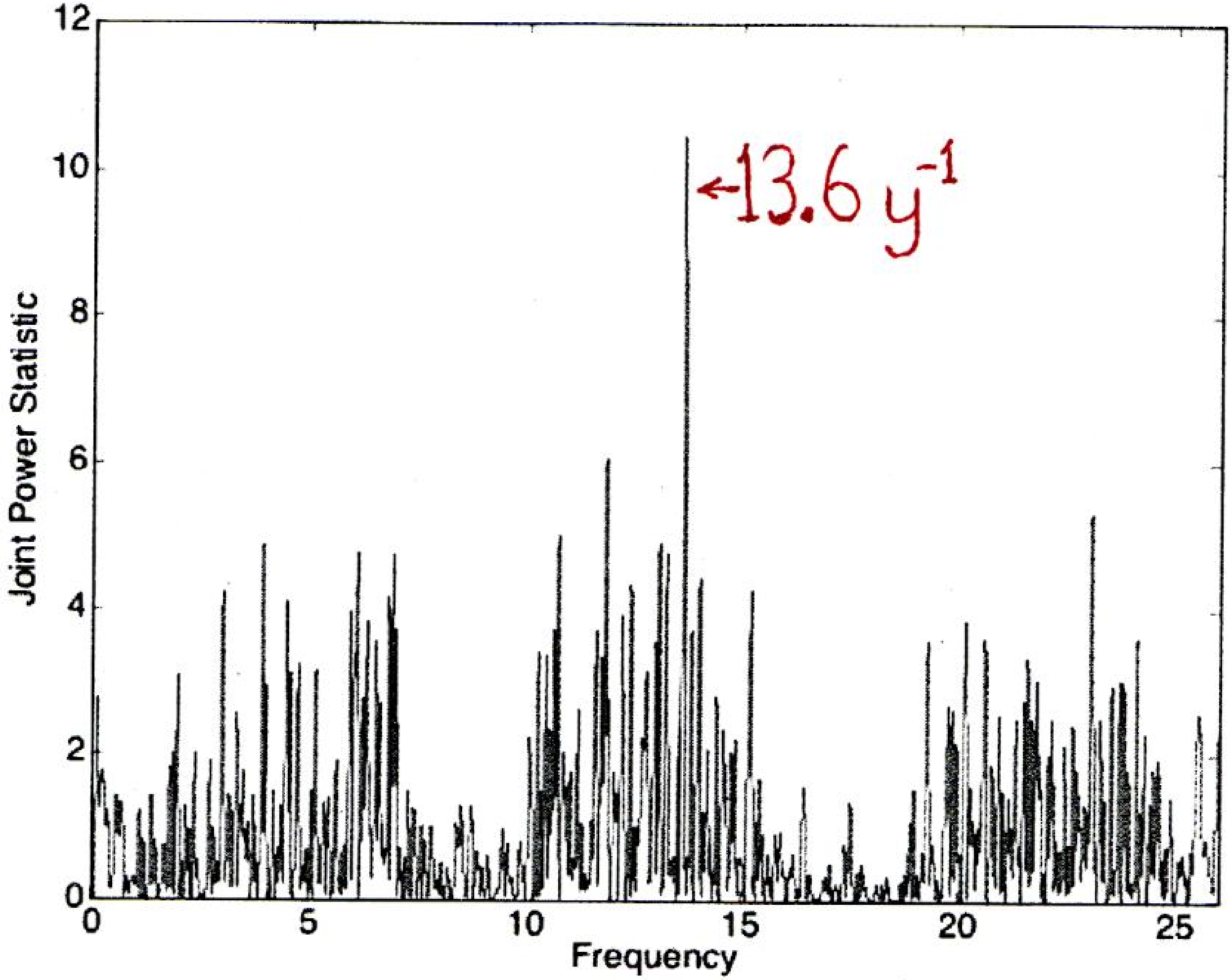
# Convection-zone field changes at solar maximum, minimum

GALLEX: Cumulative Power of $\nu = 13.59\ y^{-1}$



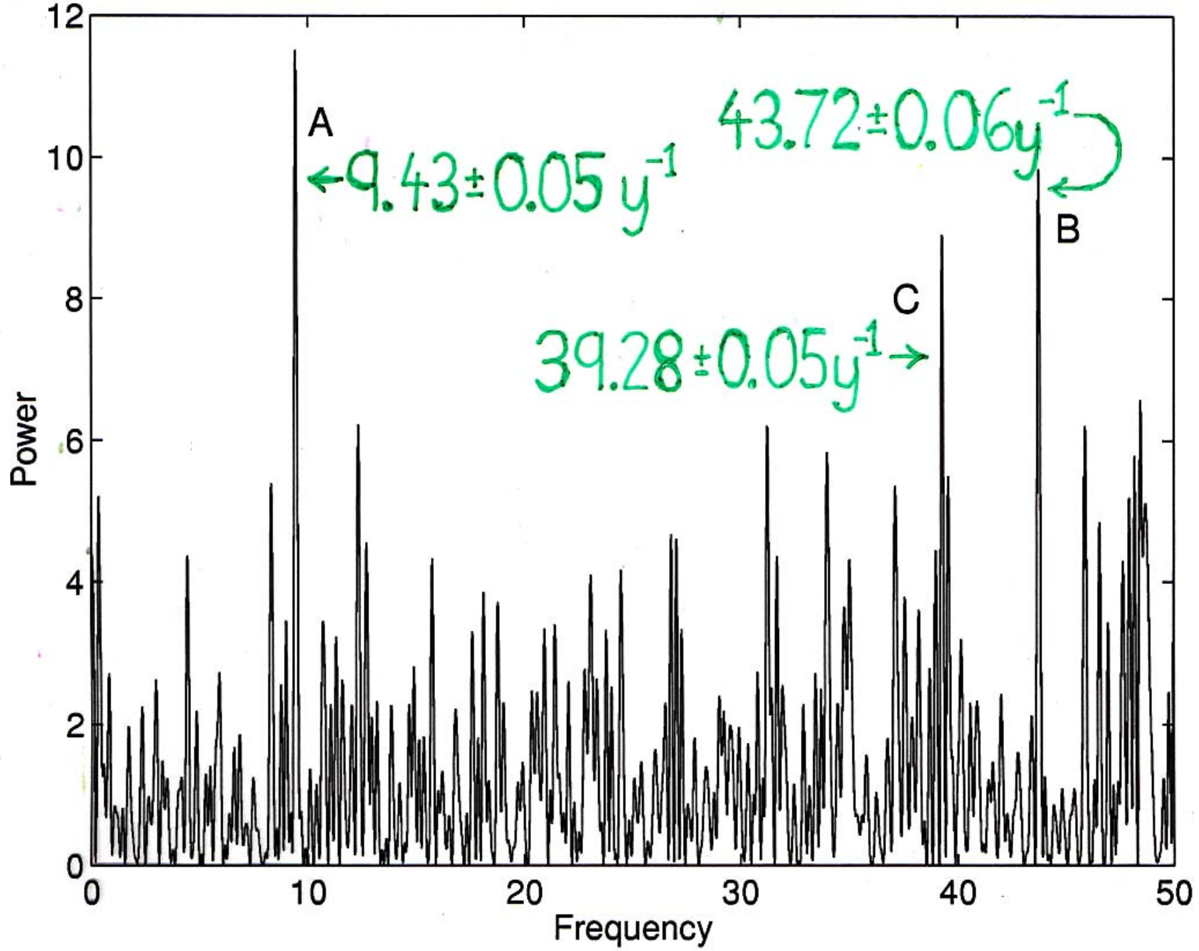
Solar Max.

Solar Min.



Pairs of peaks with frequencies 2:1 ratio

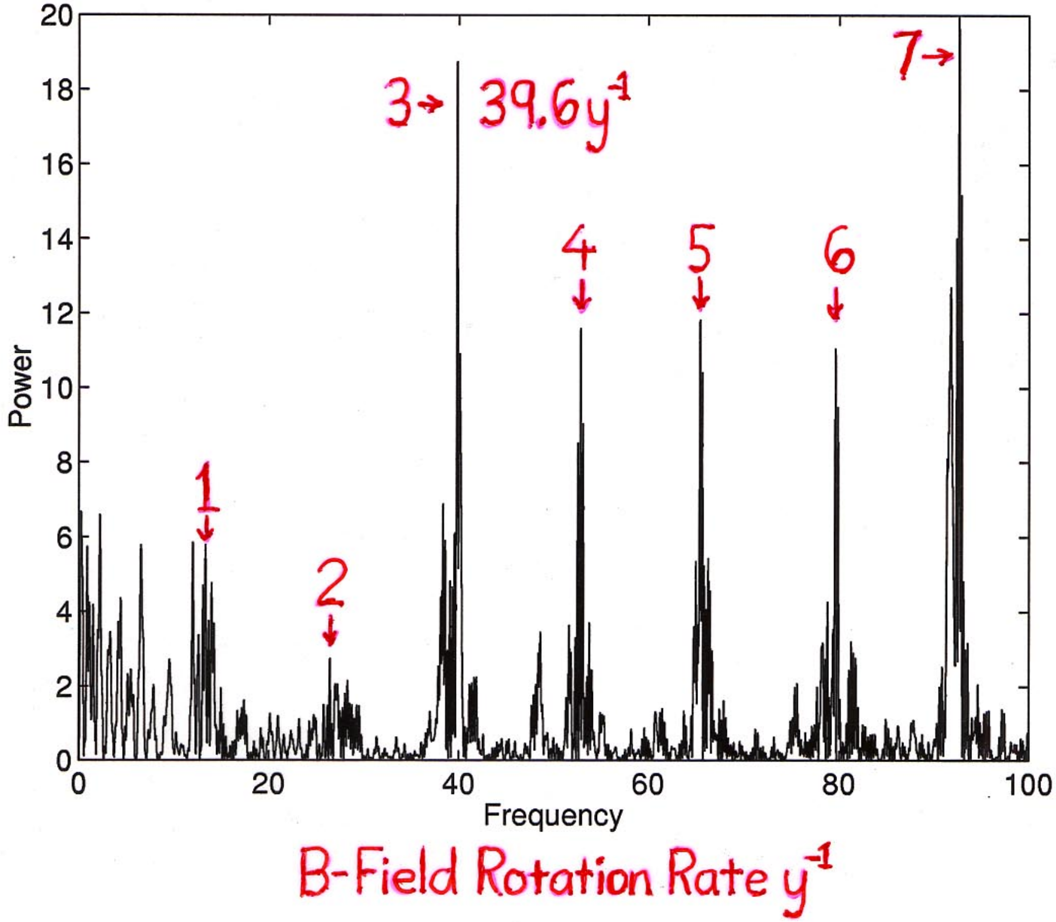
# Super-Kamiokande 5-day Data



Super-Kamiokande gets same peaks, but not significantly

Spectrum above uses much more experimental information

# Solar Magnetic Field in the Super-K Time Interval

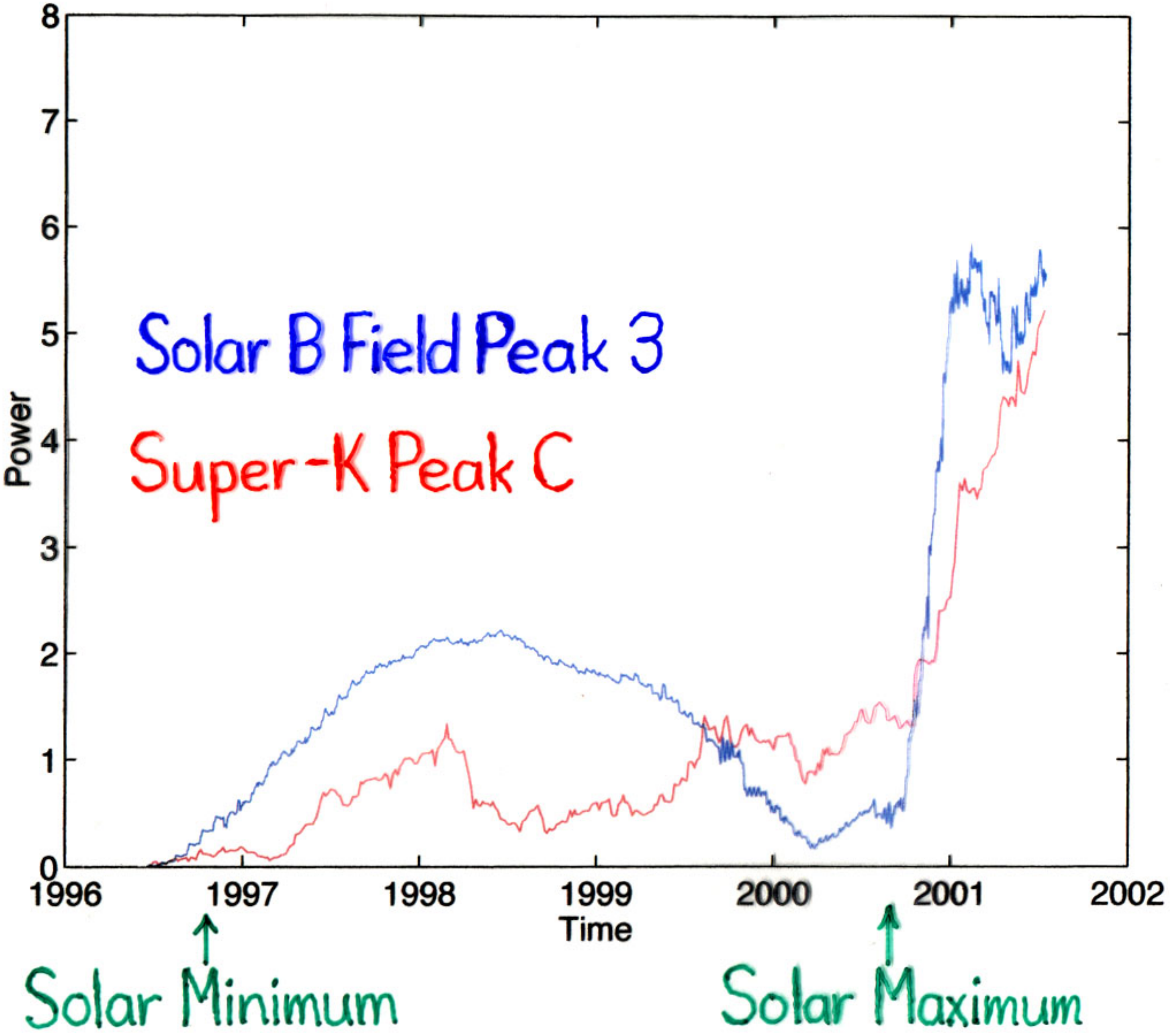


Only 39.6 $y^{-1}$ can be prominent in Super-K 5-day data

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

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

# Cumulative Power of $\nu = 39.6 y^{-1}$



# Origin of Peaks A and B

Retrograde waves (r-modes) move B regions in/out of $\nu_e$ path

Modulation: interference of r-mode frequency, B-field rotation

$\nu = |m\nu_R - \frac{2m}{\ell(\ell+1)}(\nu_R+1) \pm m\nu_R|$, where $\nu_R$ = synodic rotation frequency

+ sign: $\nu = \frac{2m}{\ell(\ell+1)}(\nu_R+1)$ seen Cl, Ga data at Rieger frequencies

$\ell=3$, $m=1,2,3$ and $\nu_R = 12.88\,y^{-1}$ gives $2.3, 4.6, 6.9\,y^{-1}$ (well-known)

− sign: $\nu = 2m\nu_R - \frac{2m}{\ell(\ell+1)}(\nu_R+1)$

From magnetic field: $\nu_R = 13.20 \pm 0.14\,y^{-1}$

This $\nu_R$ and $\ell=m=2$ gives $9.47 \pm 0.09$ 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

# Effect of Increased Information for 9.43 $y^{-1}$

Using run midtime only, power = 5.90

For run mean live time, power = 6.18 (Super-K's result)

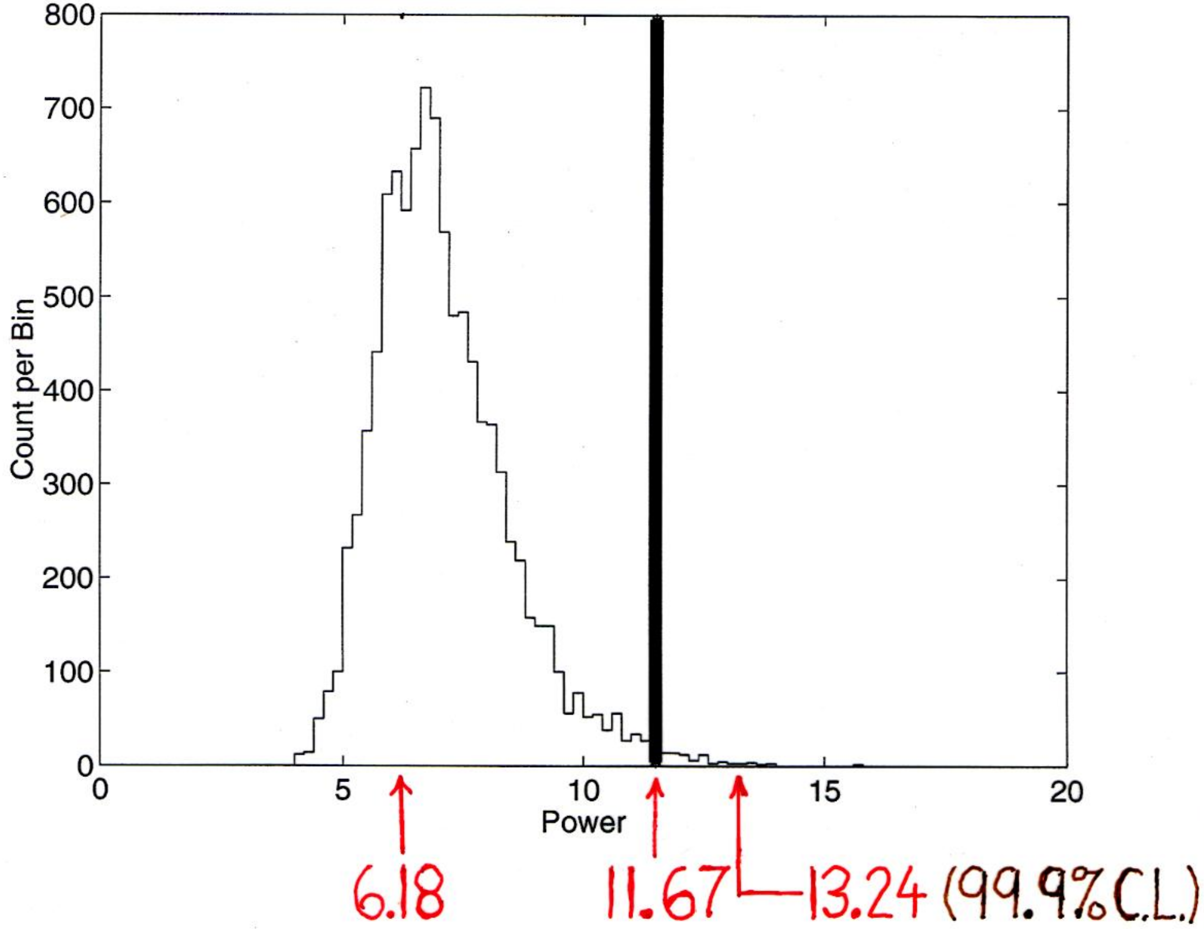
Run mean live time + experimental error, power = 9.56

Run start, end times + " " , " = 11.51

Start, end, mean times + " " , " = 11.67

In addition, taking account of error asymmetry = 13.24

# Significance of Power via Simulations



71% of simulations exceed power of 6.18 (SK result)

0.8% of simulations exceed power of 11.67 (likelihood)

# Comment on Recent SNO Results

- Problems which wash out the effects (≲7%)
  - Neutral-current events should not be included
  - Search band is too wide for solar frequencies
  - Assumes effects are constant in time (used $D_2O$, salt)
- Comparison of $9.4\,y^{-1}$ frequency in SNO and SuperK
  - In 1.6y overlap, power is small (~3) and equal for both
  - Rest of SuperK gives large power (13.2)
  - r-mode is very episodic, as for sunspots, solar flares
- Analysis in progress of $D_2O$ data (salt data hopeless)
  - One-day data, but big neutral-current "background"
  - Evidence for magnetic field rotation peaks 3, 7 (4-day)

# Possible Implications for Dark Matter

Solar $\nu_s$: only direct evidence for a sterile neutrino

No mixing with active neutrinos

Interactions via large transition magnetic moment

Solar $\nu_s'$ as hot dark matter

Non-thermal late production

Avoids usual limits on hot dark matter

May play a useful role for small-scale structure

Cold dark matter, if heavier, similar sterile $\nu$ exist

Advantages of keV $\nu_s$ given by Kusenko, Shaposhnikov

This type of sterile $\nu$ avoids the limits

Working on exciting consequences

# Conclusions

Evidence for flux modulation at 99.9% CL for SK, Ga, Cl

Modulations match known solar frequencies

Other analyses too insensitive for subdominant RSFP

Transition magnetic moment and sterile $\nu_s$ required

Opens new physics and astrophysics possibilities

D.O.C., P. Sturrock, Astropart. Phys. 23, 543 (2005); hep-ph/0309191

P. Sturrock, D.O.C., J. Scargle, M. Wheatland, Phys. Rev. D72, 113004 (2005);
hep-ph/0501205

P. Sturrock, D.O.C., J. Scargle, Astropart. Phys. 26, 174 (2006);
hep-ph/0409064