Status and Implications of Solar Neutrino Flux Modulation Requiring a Particular Sterile Neutrino

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Sample of flux variation evidence from all experiments

Flux changes match solar rates (rotation, r-modes)

Explanation: sterile ν, large transition magnetic moment

Problems with other analyses (Super-Kamiokande, SNO)

Possible implications for this type of sterile neutrino

Solar ν_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

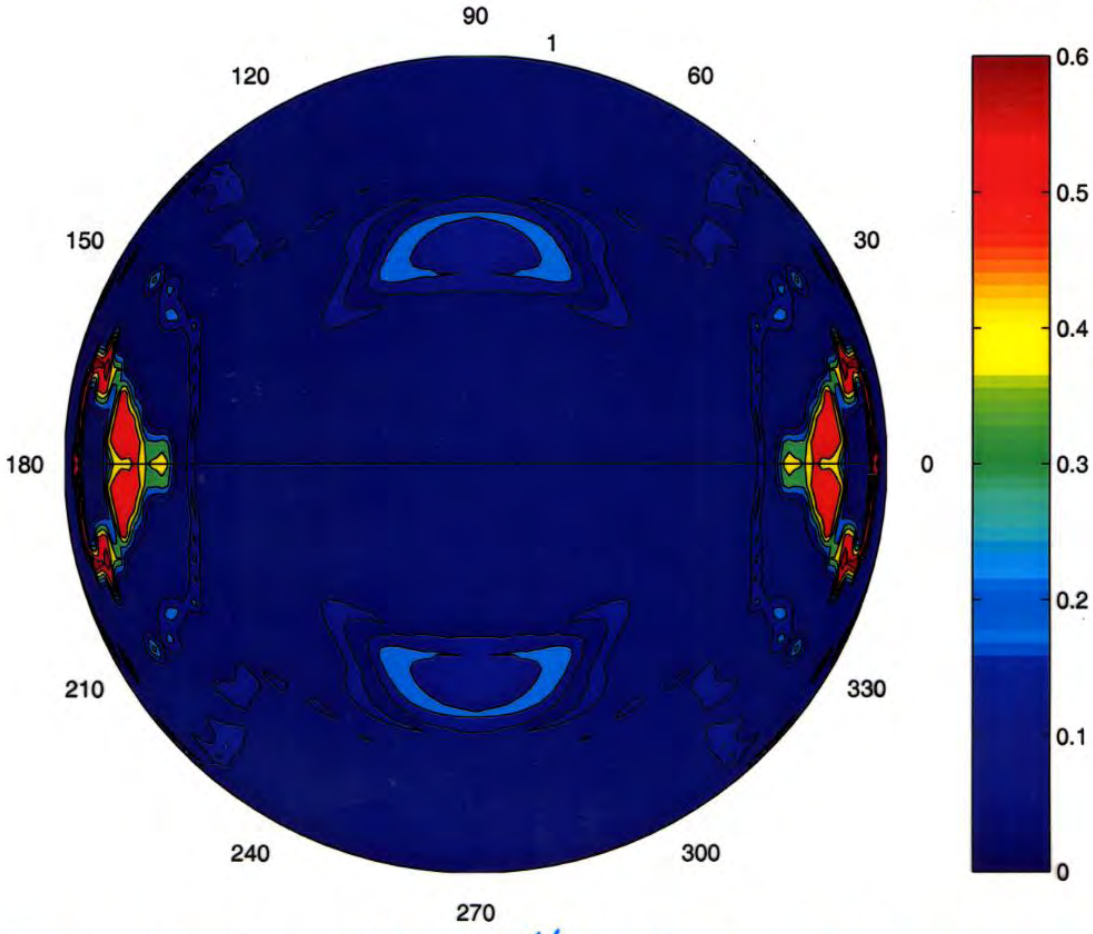
Same frequencies in coronal X-rays (SXT on Yohkoh)

12.86±0.02 y^{-1} at high latitudes

13.55±0.02 y^{-1} at the equator

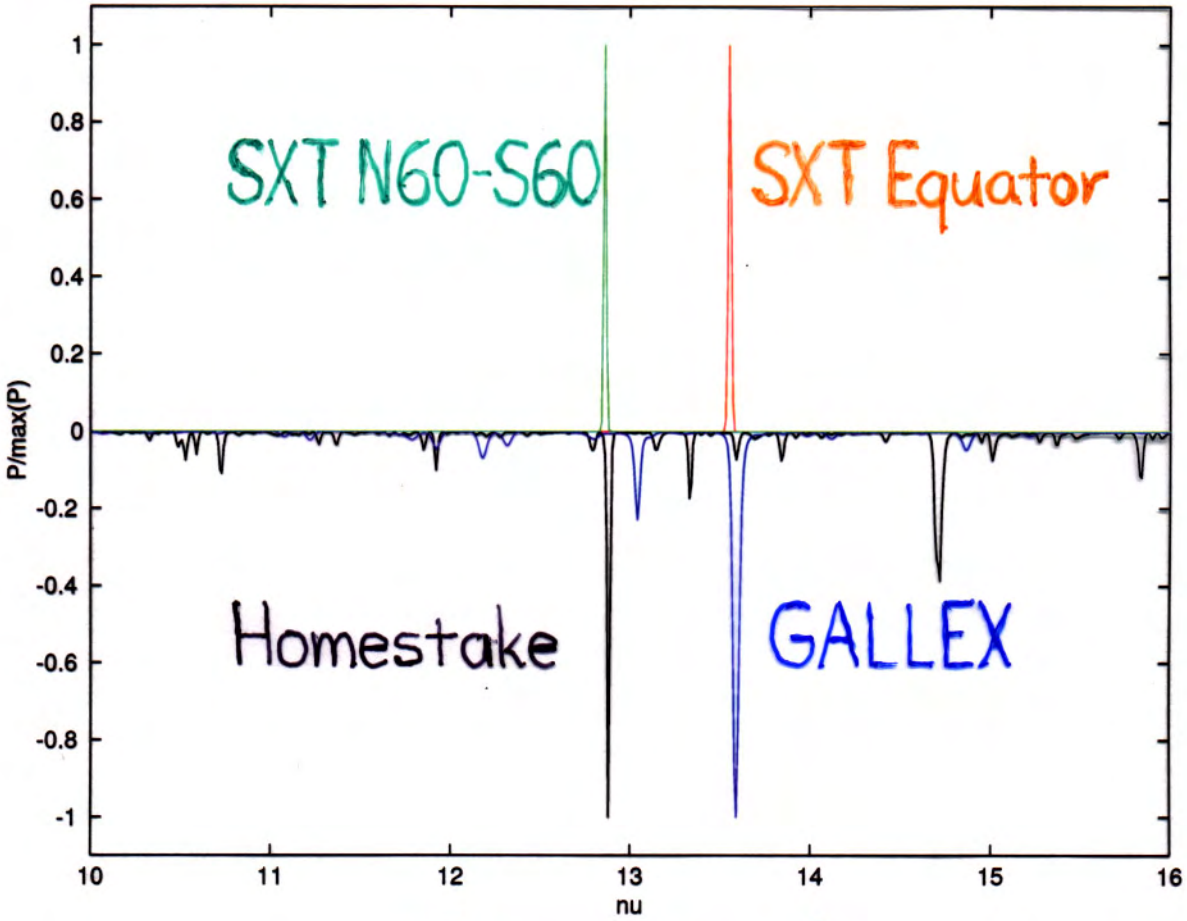
Locating the 13.6 y^{-1} Modulation in the Sun

Use GALLEX data with SOHO-MDI rotation profiles



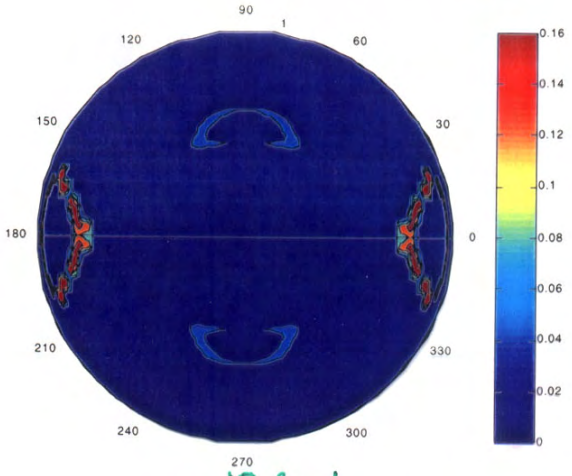
Resonance (red) in $\Xi(r,\lambda)=\int_{\nu_a}^{\nu_b} S(\nu)\,P(\nu|r,\lambda)\,d\nu$ gives location

Time Spectra Normalized Probability Distribution Functions



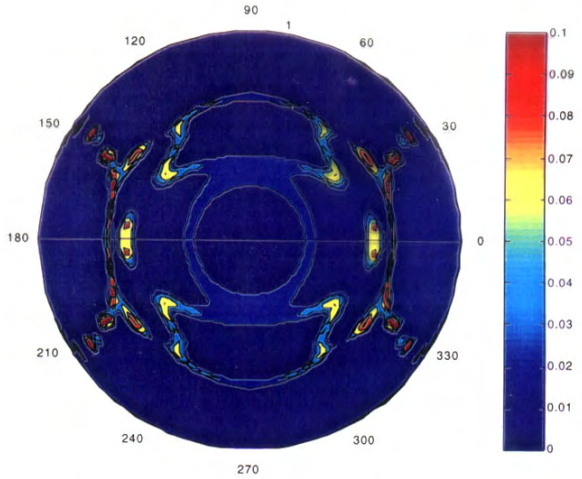
Frequency y^{-1}

SXT+Helioseismology



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

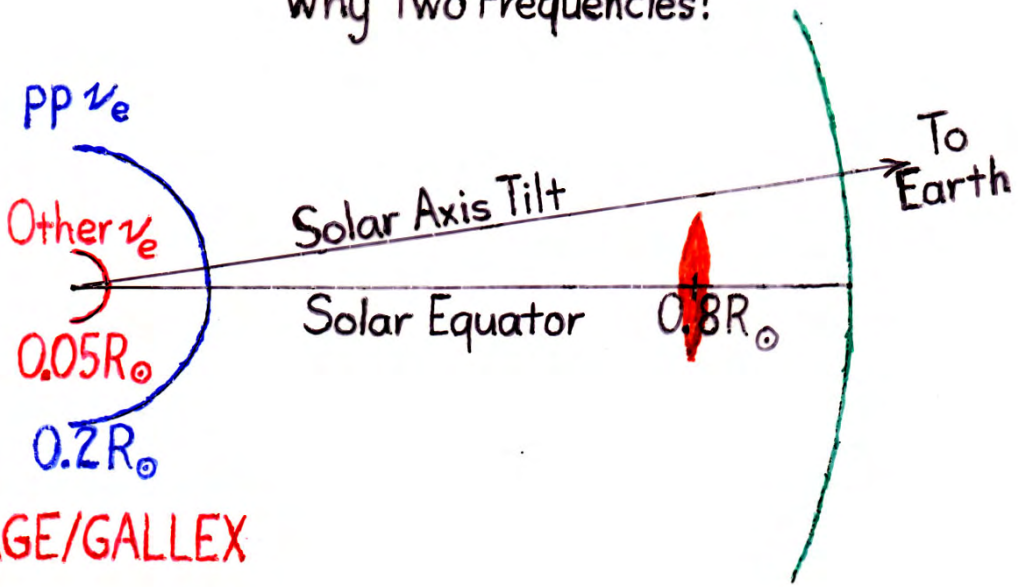
Rotational Modulation Statistic formed from the equatorial SXT data.



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

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

Why Two Frequencies?



SAGE/GALLEX

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

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

Homestake

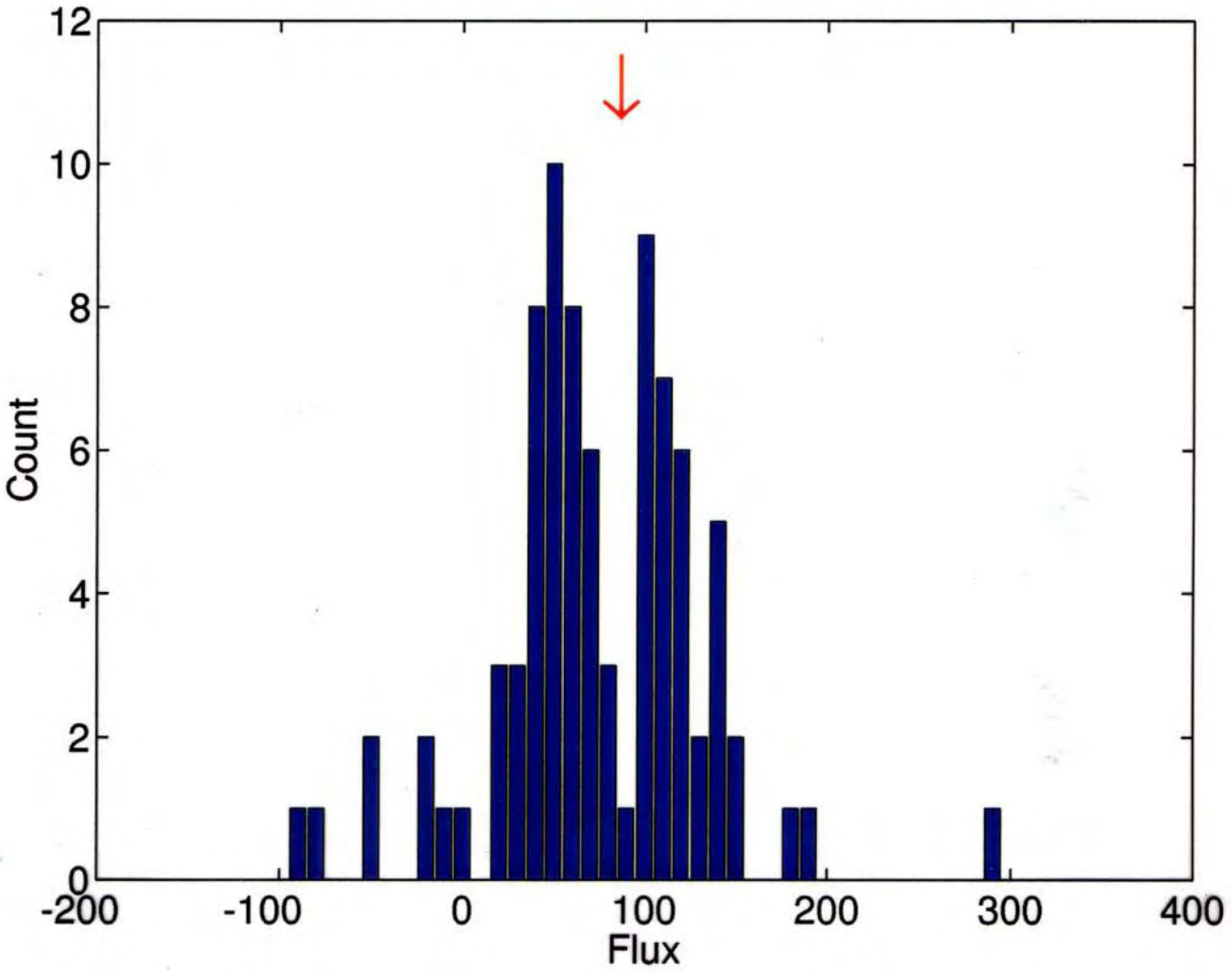
ν_e made near Sun's center at ~$0.05\,R_\odot$

7° axis tilt makes most ν_e miss equatorial field

Higher latitude field modulates most ν_e as it rotates

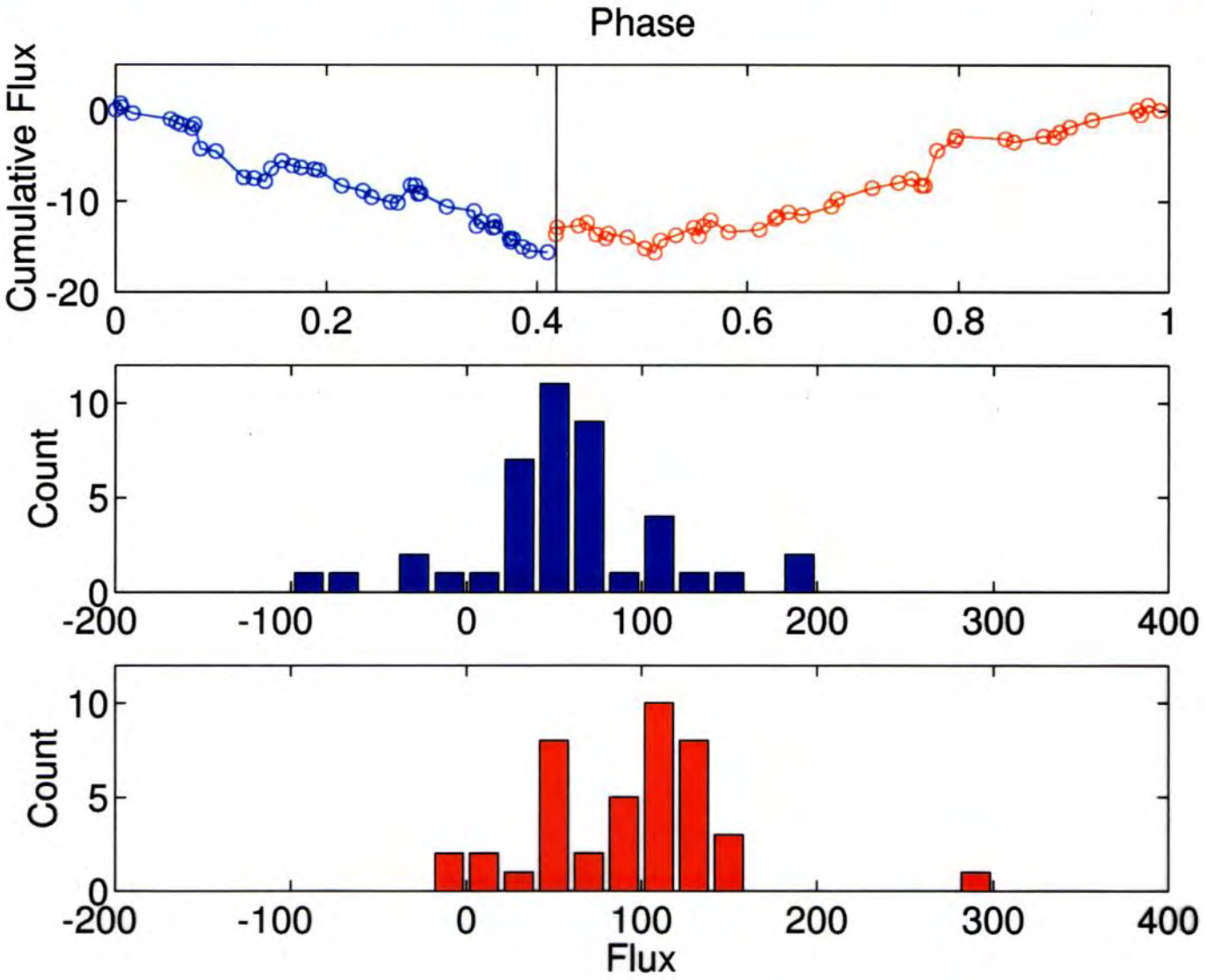
Get mainly $12.9\,y^{-1}$ rate

GALLEX Event Distribution



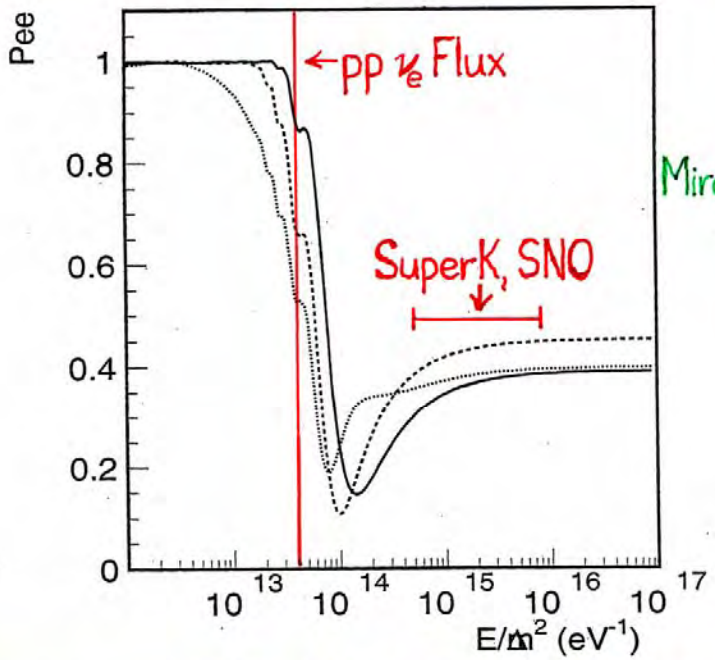
Bimodality by chance $< 10^{-4}$

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



Understanding a Bimodal ν Flux Distribution

$\nu_e^{\perp}$ 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 ν_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

3ν model (Friedland, Gruzinov; Balantekin, Volpe)

Effects are too small

RSFP in wrong location (small solar radius)

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

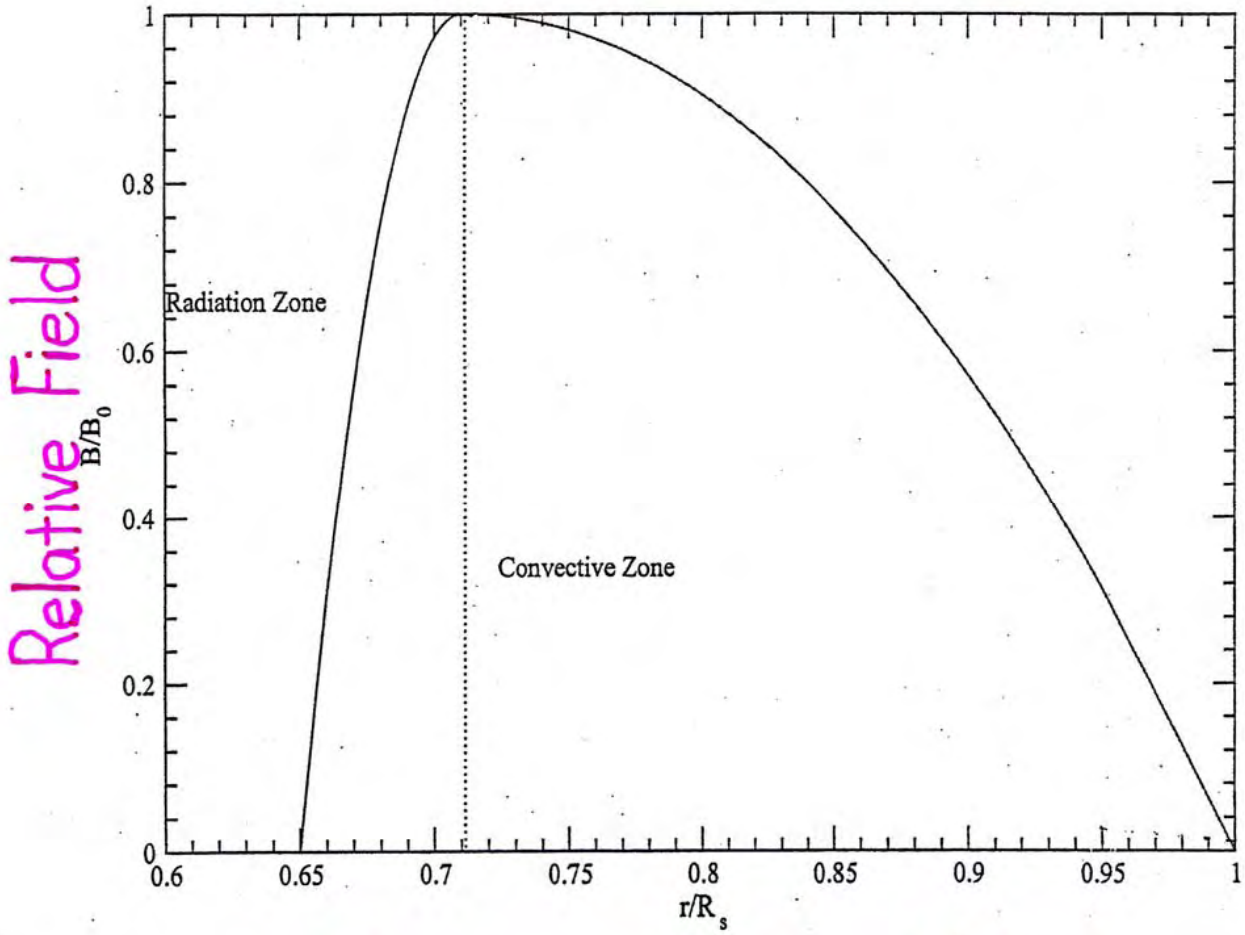
ν_s avoids constraints (unitarity, % of solar ν, nucleosynthesis)

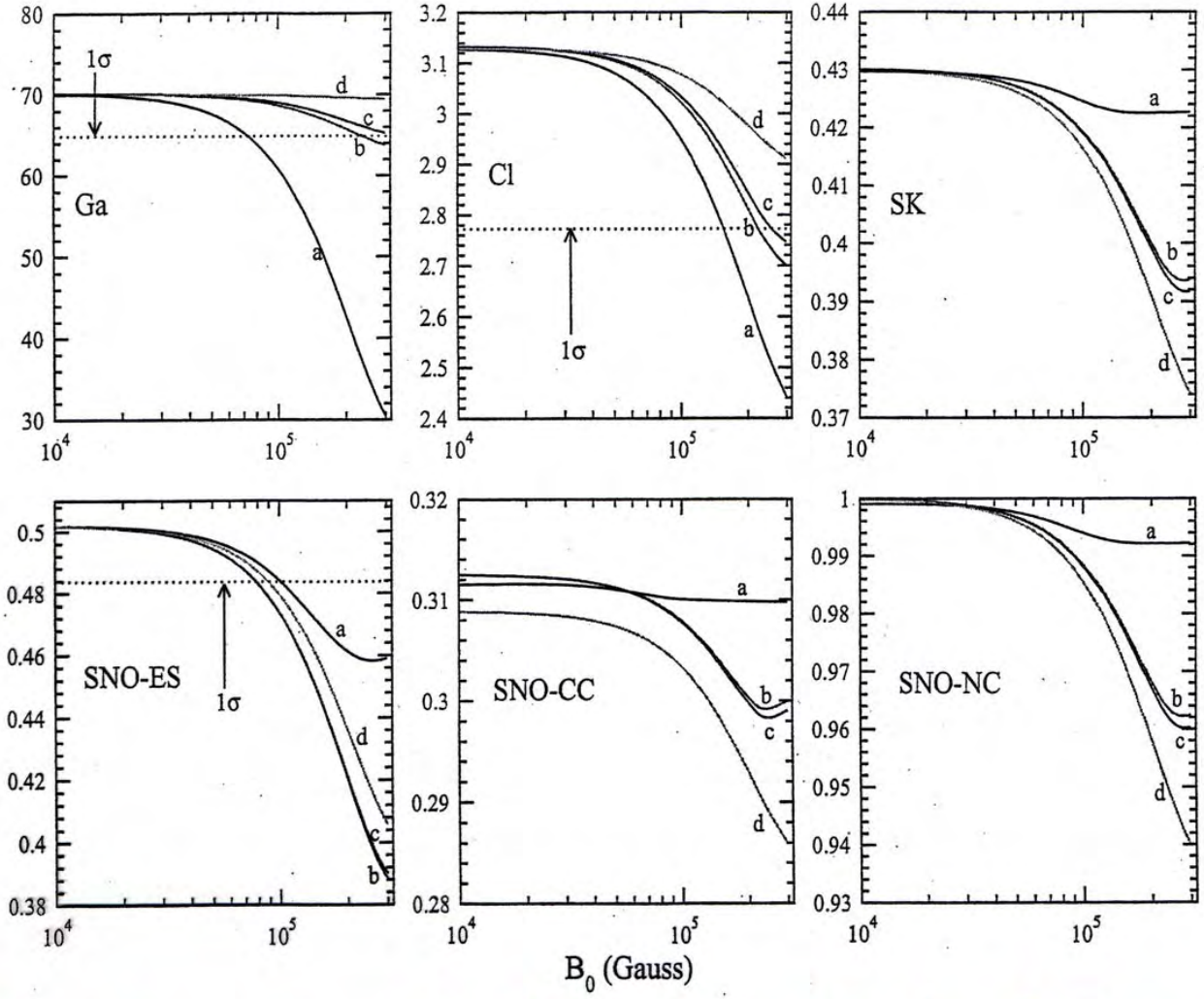
Size of flux modulation predicted correctly

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

Improves fit to time-averaged solar data

Solar Magnetic Field Shape

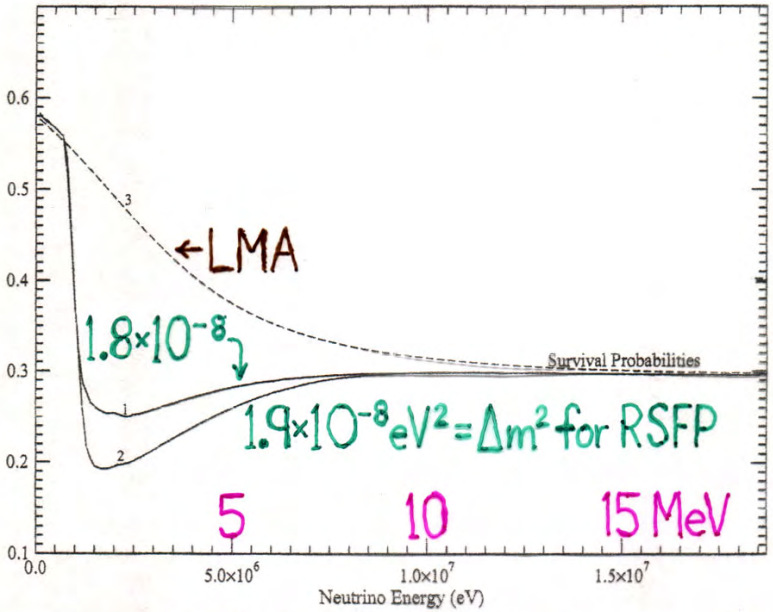




For wide range of Δm^2 can stay within 1σ of all varying B

$a=0.5\times10^{-8}$, $b=1.8\times10^{-8}$, $c=1.9\times10^{-8}$, $d=5\times10^{-8}$

ν_e Survival Probability vs. Energy



Δm^2 chosen to fit all time-averaged data using LMA+RSFP

Same Δm^2 gives RSFP at correct solar radius

RSFP survival probability dip improves fits

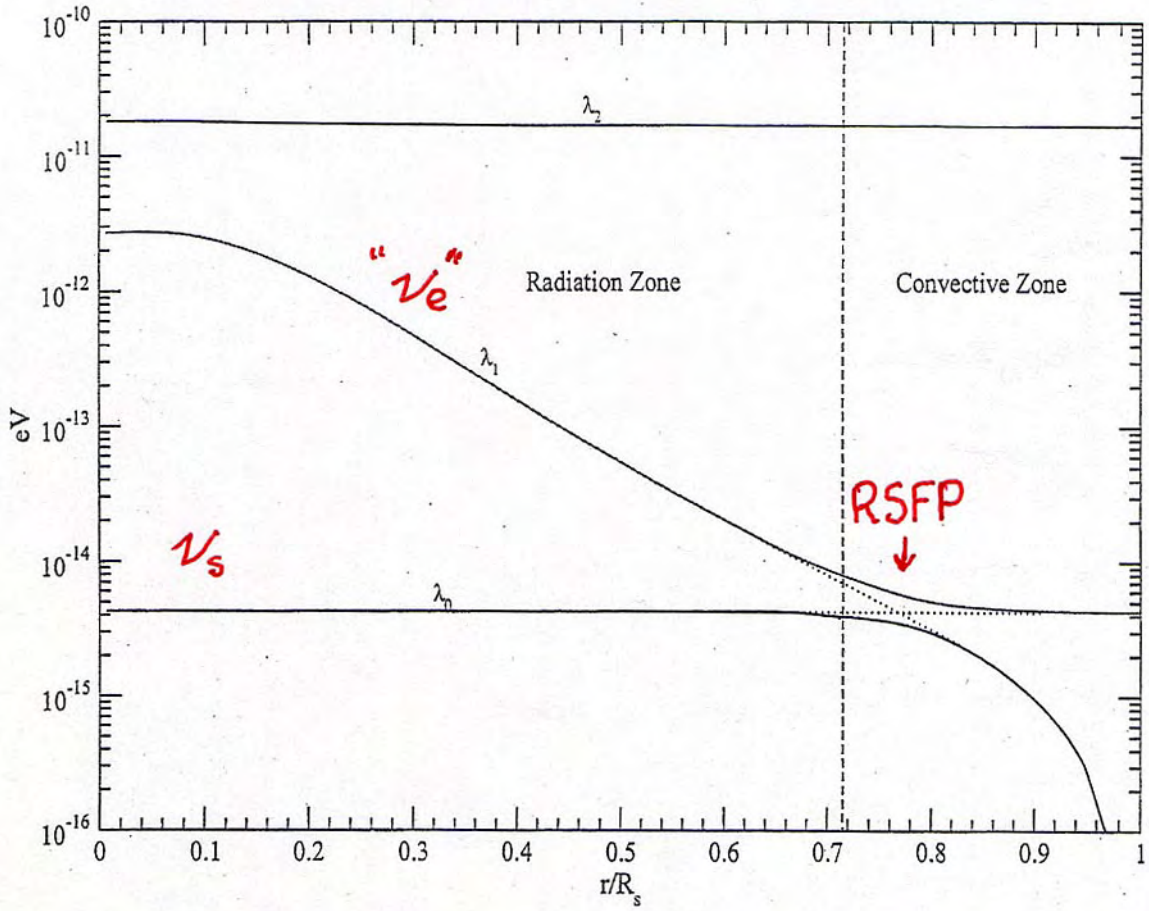
Super-K, SNO spectra are flat with energy

Lower energy: Cl result is 2.5σ too low for LMA

Different ν_s used by de Holanda, Smirnov for this

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

Mass Evolution with Solar Radius



Calculation by Chauhan and Pulido with 4ν 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 ($13.6\,y^{-1}$) in GALLEX-GNO "but"

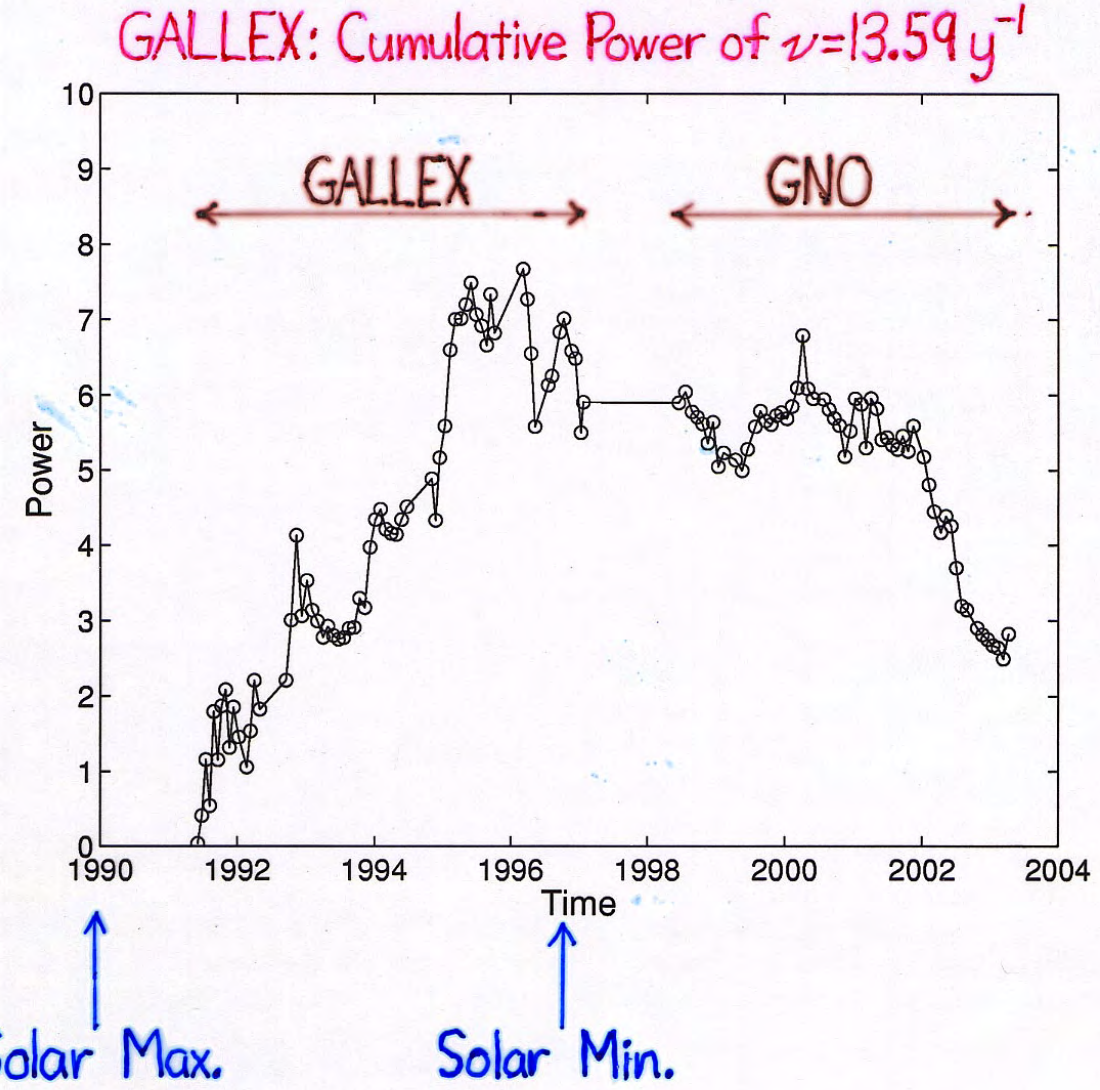
He sums the two experiments, but the solar cycles differ

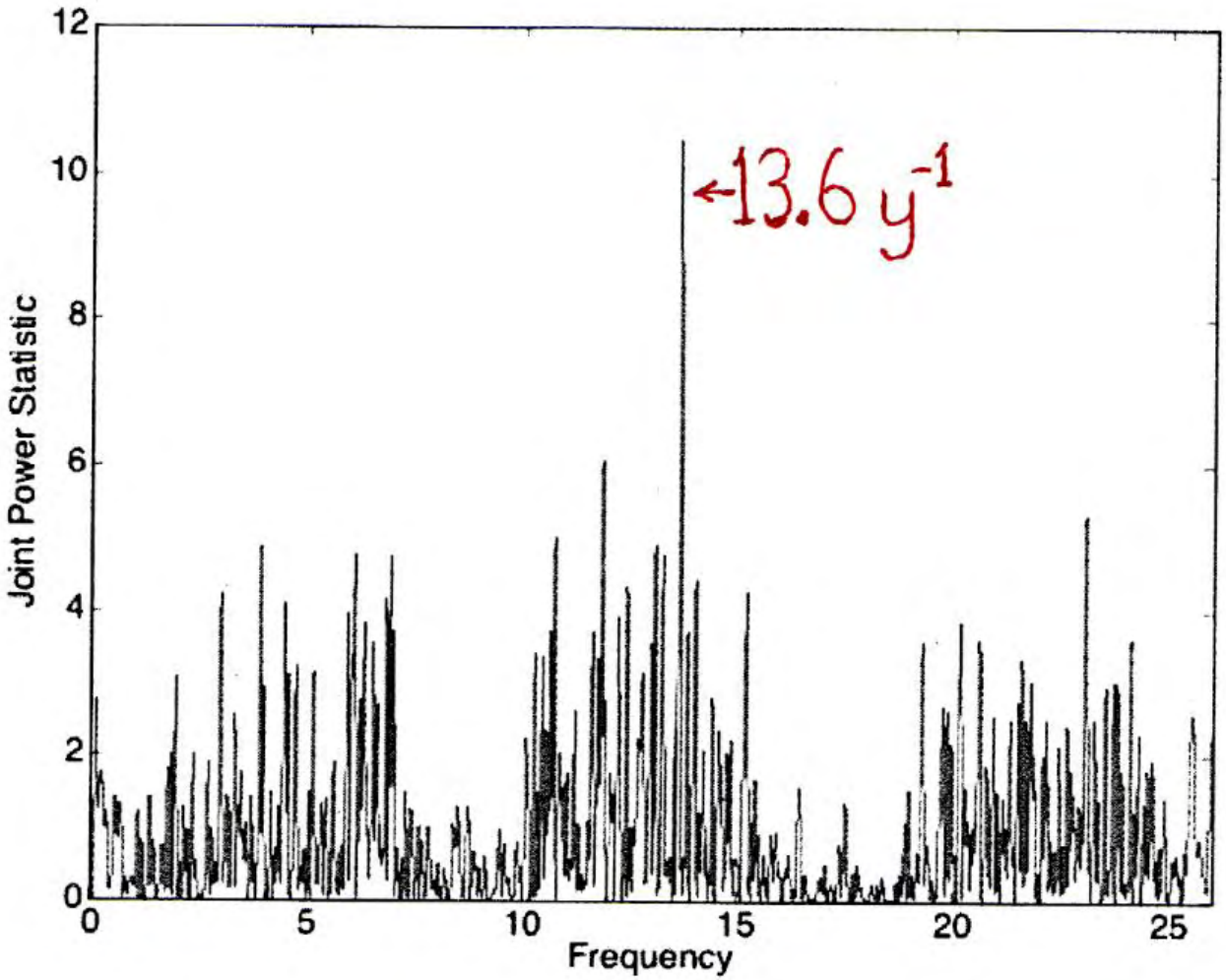
Looking for rotation effect (12.5-$13.8\,y^{-1}$) but uses 0-$26\,y^{-1}$

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

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

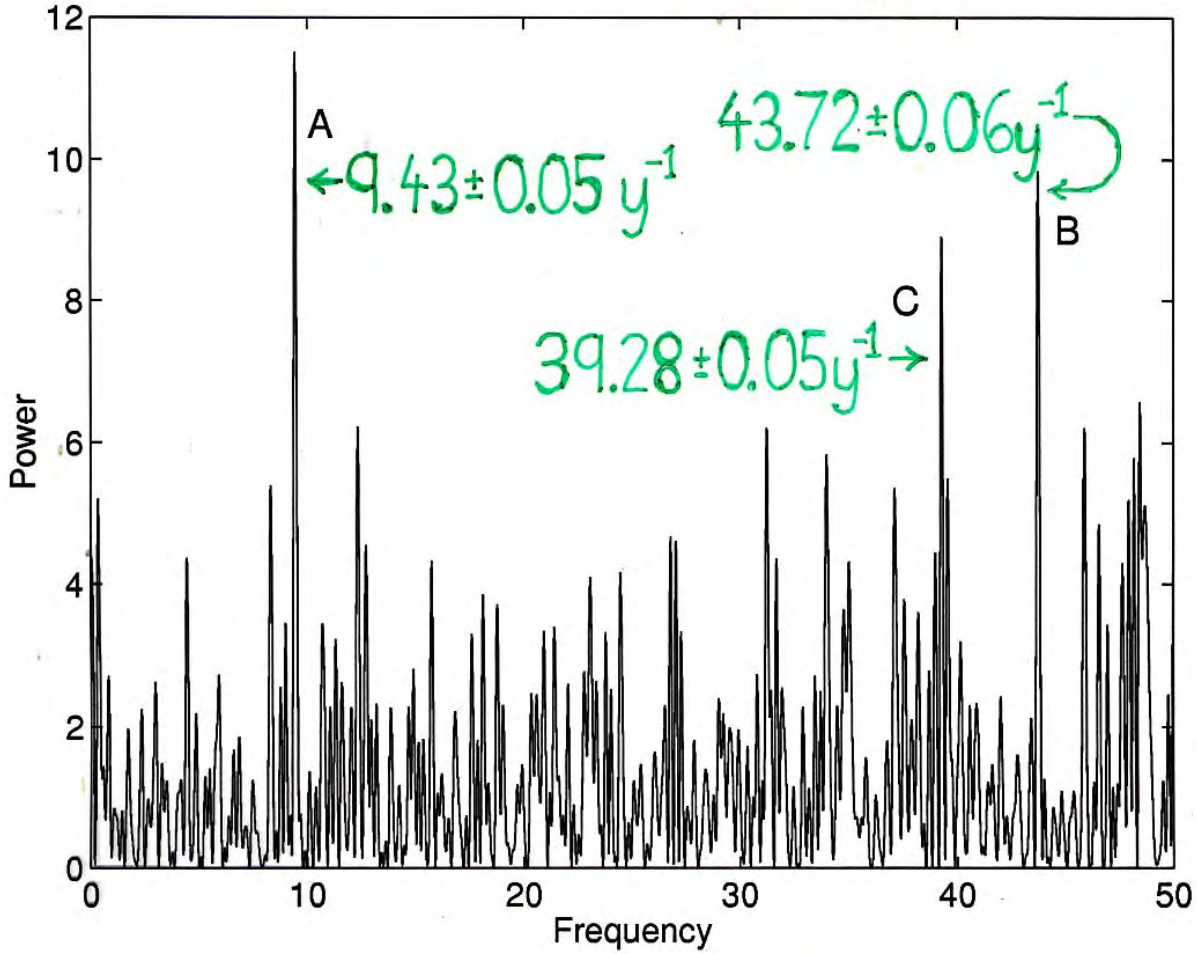
Convection-zone field changes at solar maximum, minimum





Pairs of peaks with frequencies 2:1 ratio

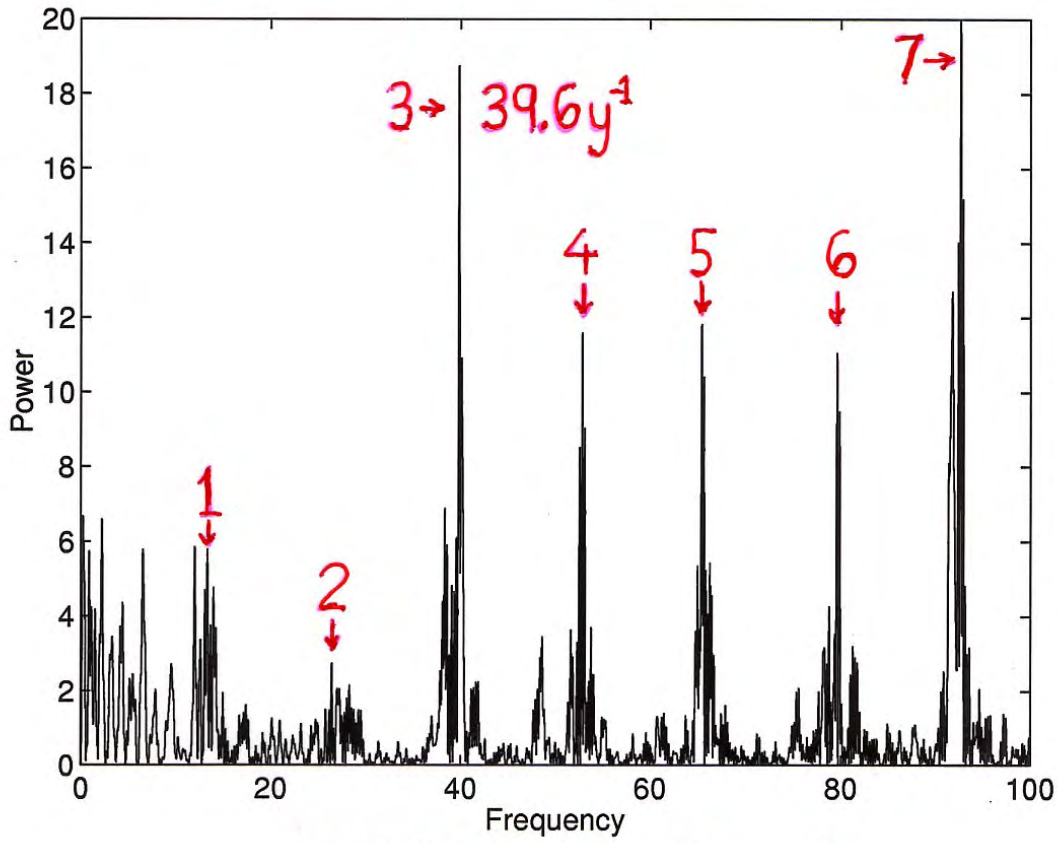
Super-Kamiokande 5-day Data



Super-Kamiokande gets same peaks, but not significantly

Spectrum above uses much more experimental information

Solar Magnetic Field in the Super-K Time Interval



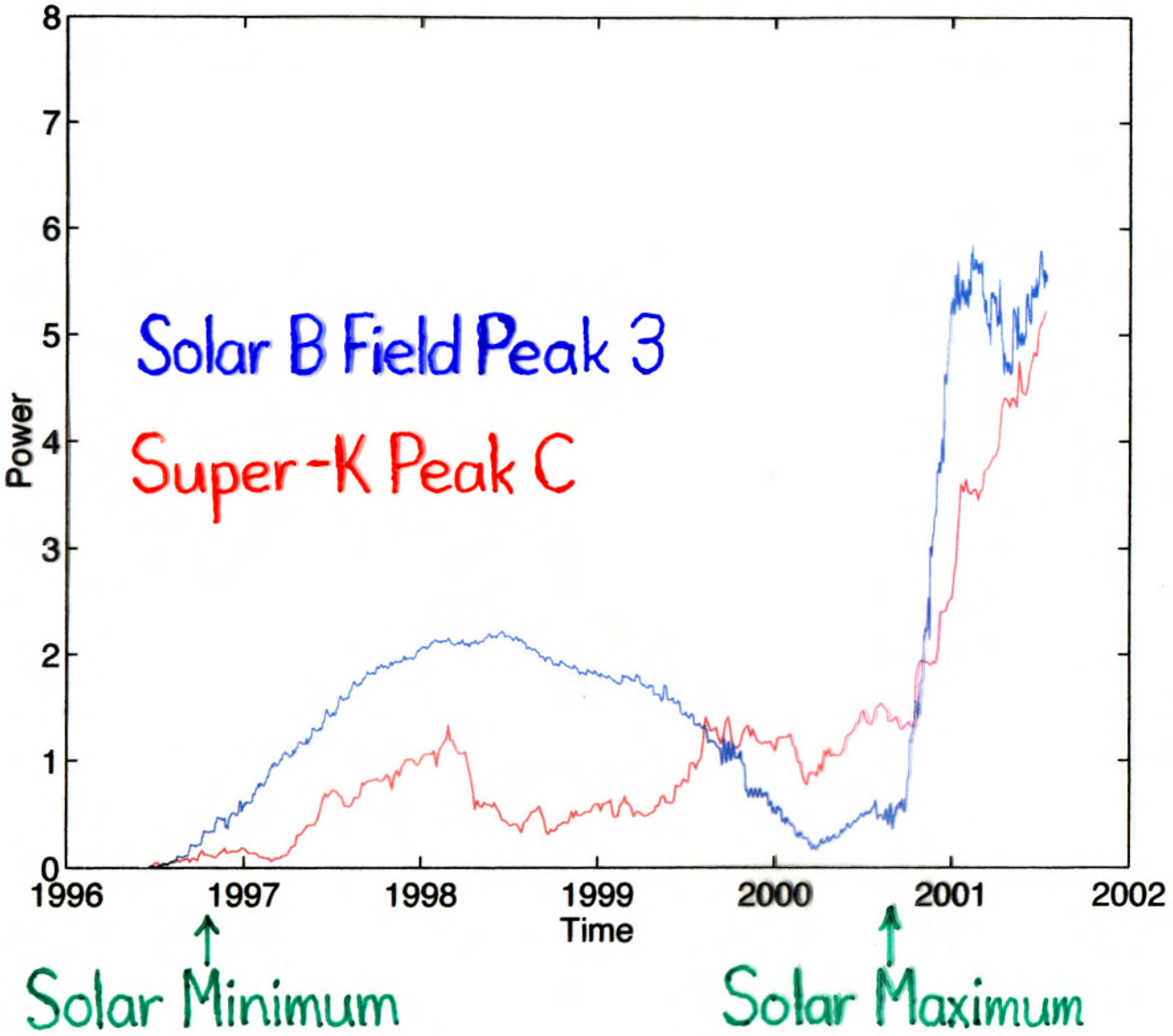
B-Field Rotation Rate y^{-1}

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 ν_e path

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

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

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

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

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

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

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

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)

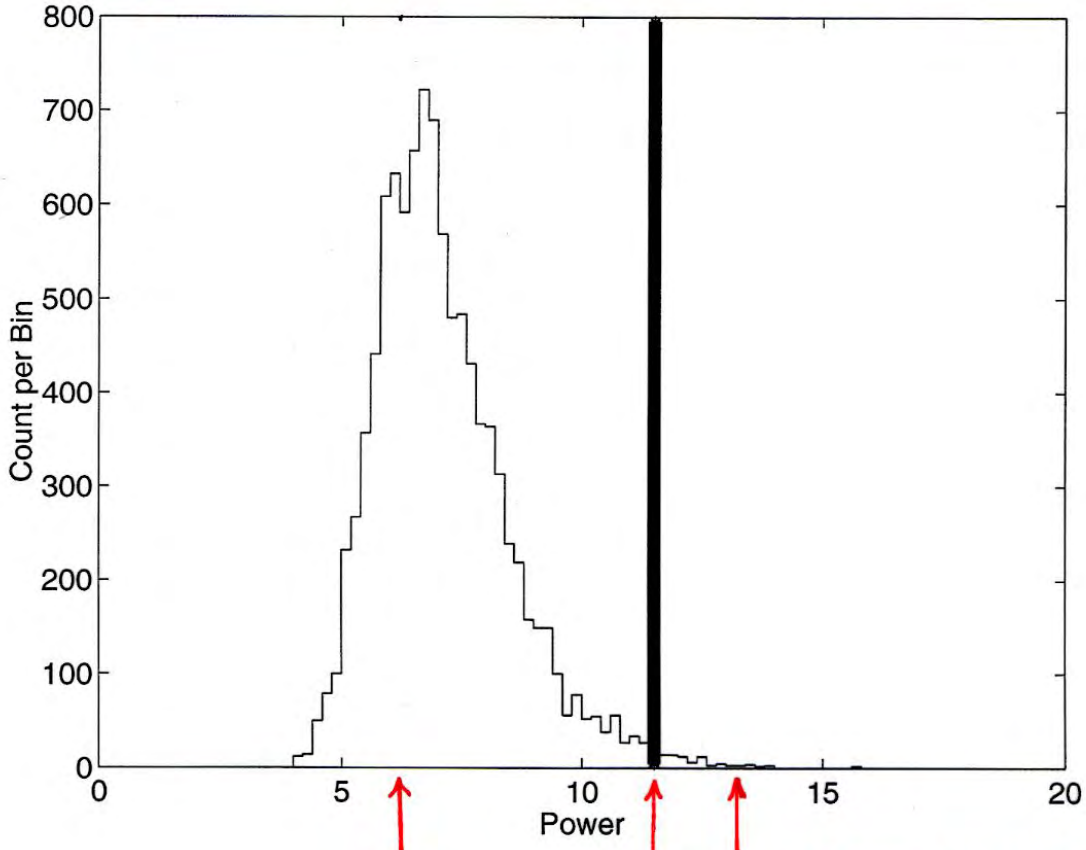
Run mean live time + experimental error, power = 9.56

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)

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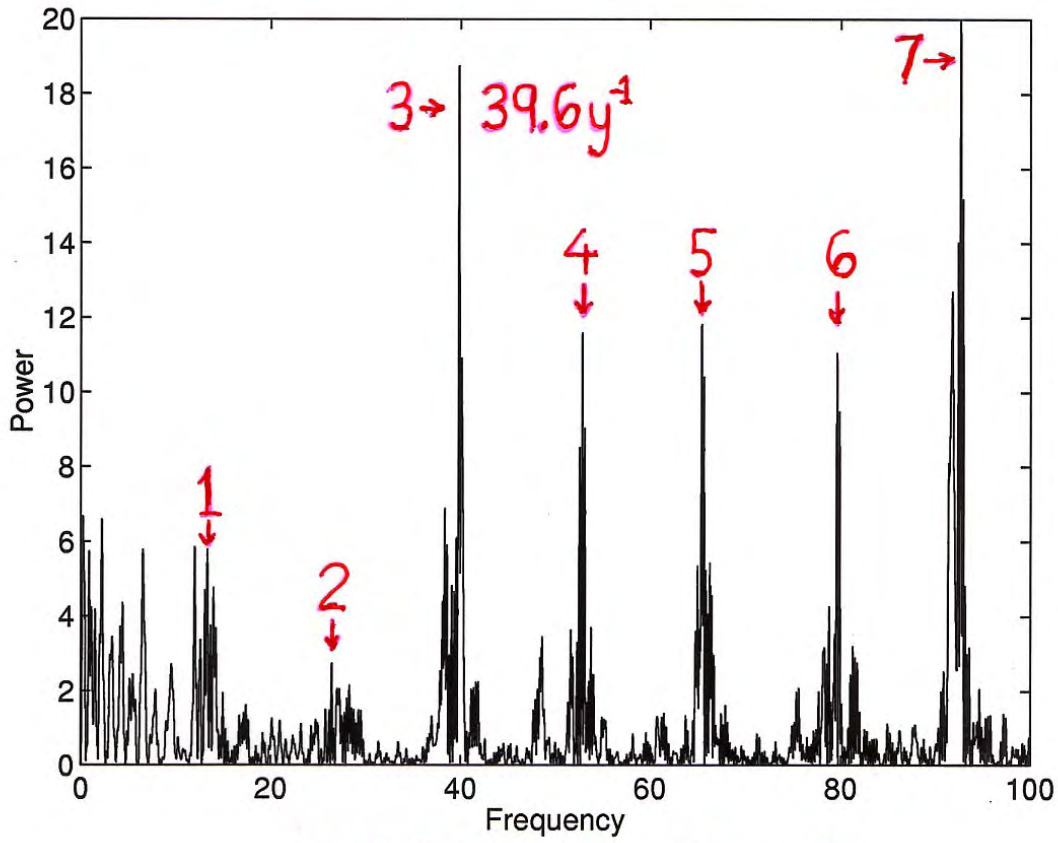

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Magnetic Moment Experiment

RFNC making 40 MCi (4kg) ^3H source

More flux than a reactor ($6\times10^{14}\ \bar{\nu}_e\ cm^{-2}s^{-1}$)

Cylinder of ^3H in Ti, so detectors go inside

Need to go to low energies (~10 eV) in a low background

EM interaction exceeds the EW

Neganov-Luke effect (large E) in cryogenic detectors

Tests started at Case Western (Stanford involved)

Aim: 10^2 improvement over present limits

400 days, reach $\mu_\nu < 2\times10^{-12}\ \mu_B$

Exceeds even problematic astrophysical limits

Exceeds our expected requirement

Possible Implications for this Type of Sterile Neutrino

Unmixed ν_s interacts via transition magnetic moment

Possible supernova role

- Off-diagonal $\mu B_\perp$ dominance transfers energy from core
- Reconversion issue

Avoids limitations as hot dark matter (production, mass)

Heavier partner (~10 keV) as warm/cold dark matter

- Avoids present X-ray 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 ν_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