Status of Hot Dark Matter

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Conventional wisdom

LSND-KARMEN

Sterile neutrino (2+2 scheme)

Solar neutrino solution

Neutrino Scenarios

Conventional wisdom today

3 light active neutrinos only

Large-mixing-angle (LMA) solar neutrino solution

Total neutrino dark matter $\lesssim 2$ eV 2dF Galaxy Redshift Survey

Decade ago

2 ways to get HDM: 3ν ----0 eV (2+2) ν_s D.O.C. 1/93, D.O.C., Mohapatra

atm. sol.

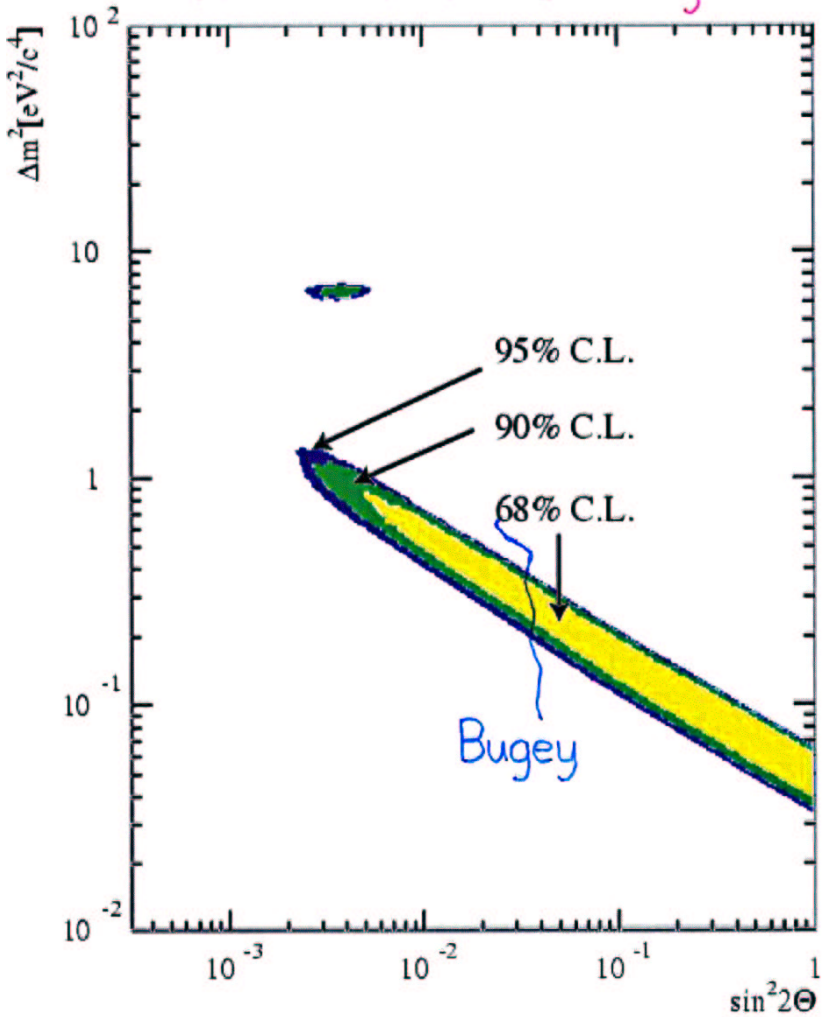
Also '93 ν_s Peltoniemi, Tommasini, Valle Peltoniemi, Valle

After LSND also 3+1 ν_s (better for WDM)

3ν HDM now a problem for Majorana neutrinos ($\beta\beta_{0\nu}$)

2+2 HDM enforced by LSND

Joint LSND-KARMEN Analysis



Church, Eitel, Mills, Steidl

Case Against 2+2?

Negative view of LSND, ν_s, and especially 2+2

Peres, Smirnov sum rule: $\eta^s_\odot + \eta^s_{atm} = 1$ (η^s=fraction of ν_s)

Gonzalez-Garcia, Maltoni, Peña-Garay

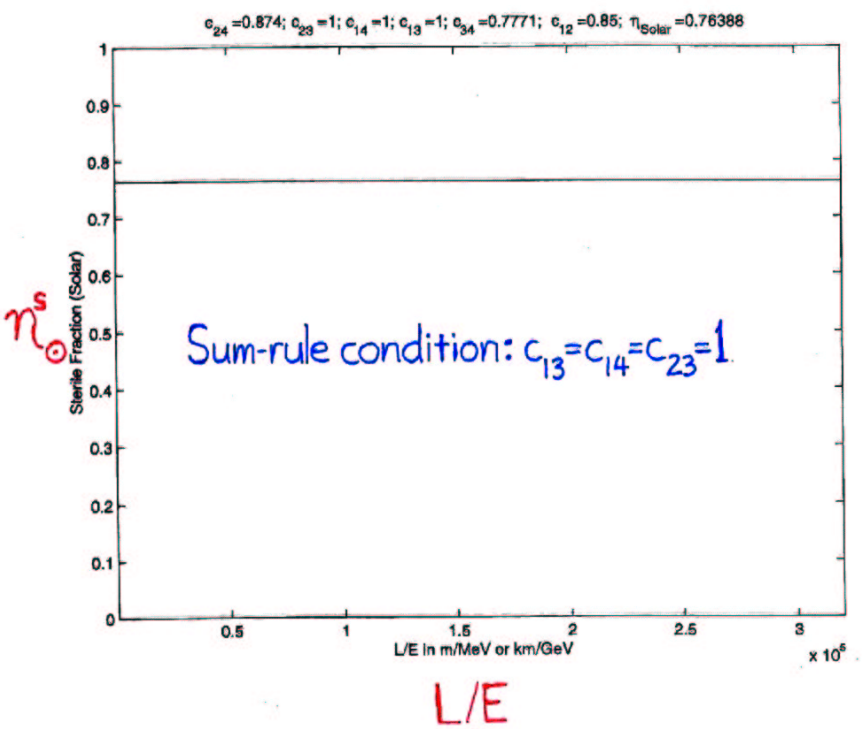
Maltoni, Schwetz, Tórtola, Valle

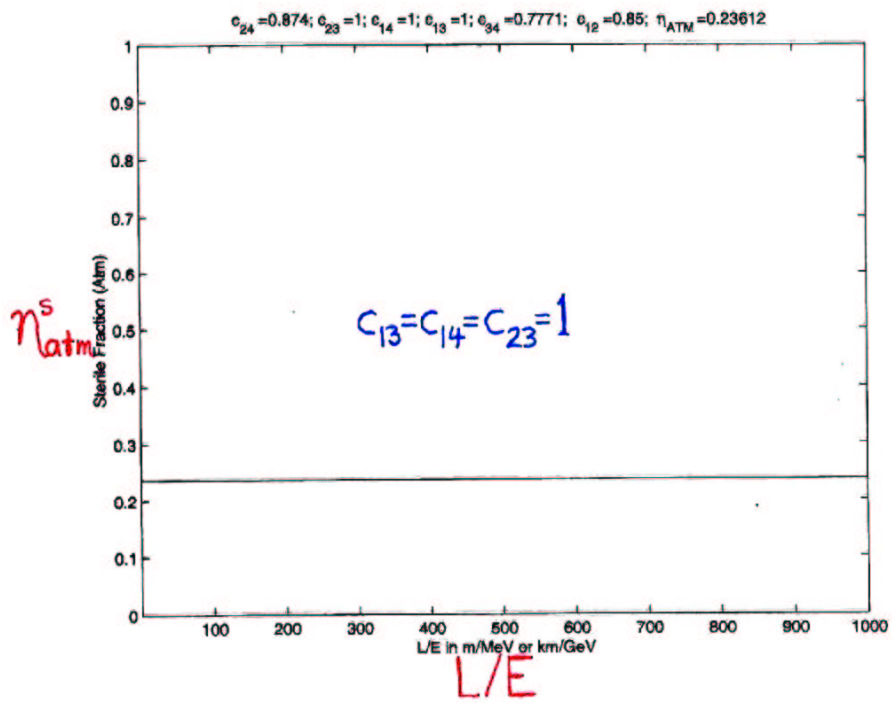
All put 4 zeros in mixing matrix; i.e., 3 angles are zero

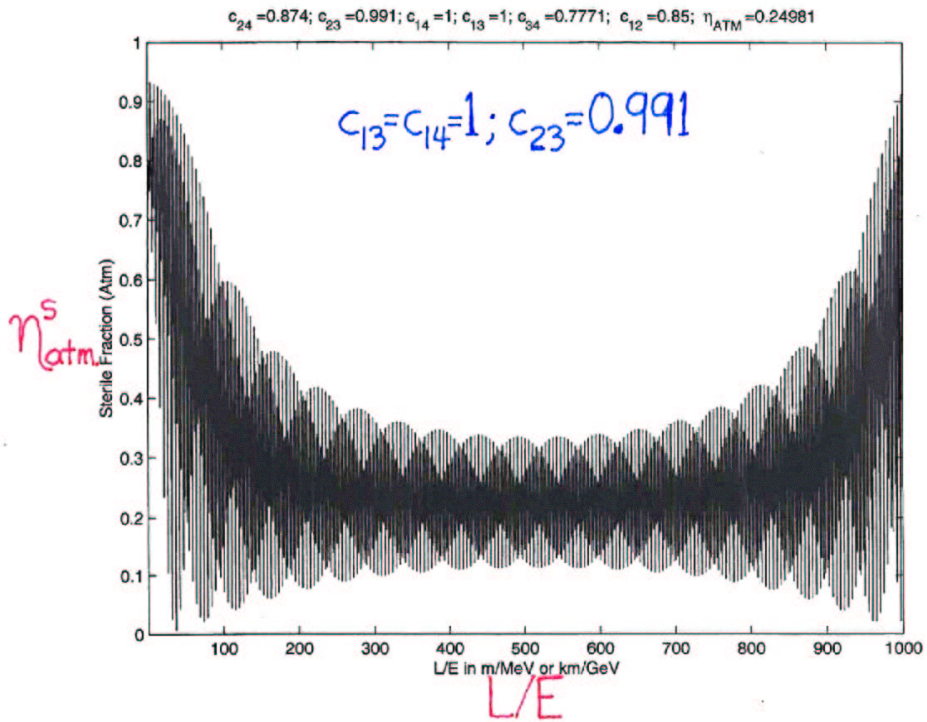
Consequence: ν_μ only in atmospheric pair; ν_e only in Θ pair

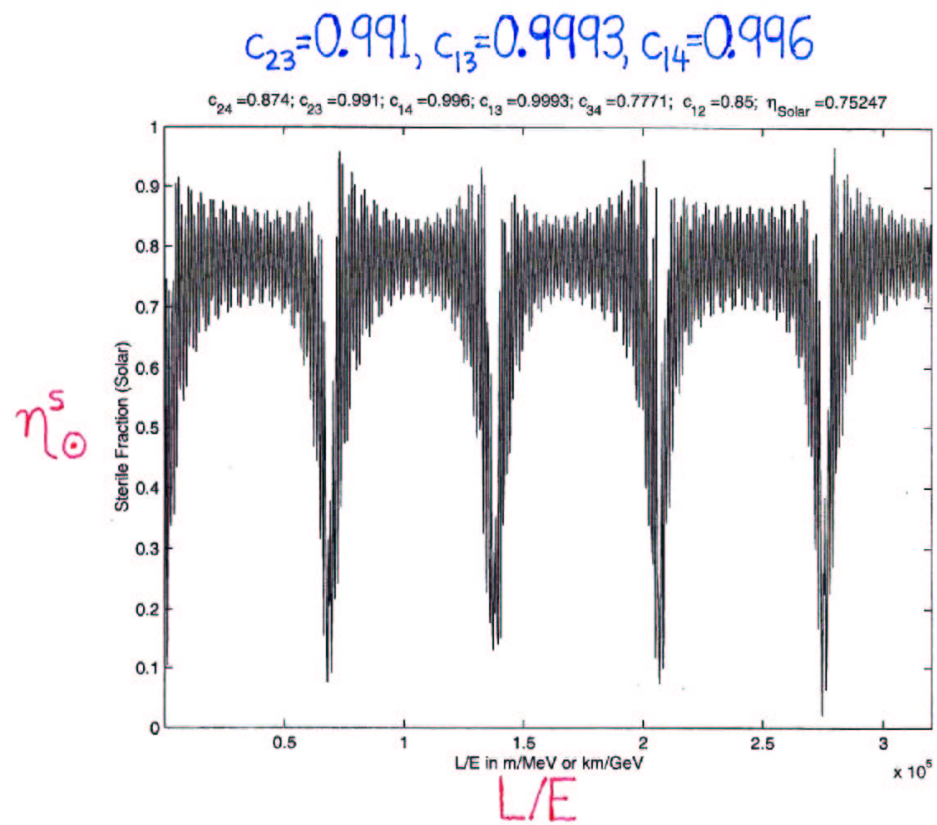
Limits show 4 terms small, but LSND needs ≥1 non-zero

Tiny terms destroy sum rule D.O.C., Mohapatra, Yellin


c_{24} =0.874; c_{23} =1; c_{14} =1; c_{13} =1; c_{34} =0.7771; c_{12} =0.85; η_{Solar} =0.76388
Sterile Fraction (Solar)
L/E in m/MeV or km/GeV
x 10^5
$n^s_\odot$
Sum-rule condition: $c_{13}=c_{14}=c_{23}=1$
L/E


c_{24} =0.874; c_{23} =1; c_{14} =1; c_{13} =1; c_{34} =0.7771; c_{12} =0.85; η_{ATM} =0.23612
Sterile Fraction (Atm)
L/E in m/MeV or km/GeV
n^s_{atm}
$c_{13}=c_{14}=c_{23}=1$
L/E


c_{24} =0.874; c_{23} =0.991; c_{14} =1; c_{13} =1; c_{34} =0.7771; c_{12} =0.85; η_{ATM} =0.24981
$c_{13}=c_{14}=1$; $c_{23}=0.991$
Sterile Fraction (Atm)
L/E in m/MeV or km/GeV
η^s_{atm}
L/E


$c_{23}=0.991$, $c_{13}=0.9993$, $c_{14}=0.996$
c_{24} =0.874; c_{23} =0.991; c_{14} =0.996; c_{13} =0.9993; c_{34} =0.7771; c_{12} =0.85; η_{Solar} =0.75247
Sterile Fraction (Solar)
L/E in m/MeV or km/GeV
x 10^5
$\eta^s_{\odot}$
L/E

LMA solar neutrino solution

Important for preceding anti-(2+2) arguments

SNO/Super-Kamiokande→LMA→3ν only

Widely believed, but is it right?

Solar neutrino flux variability

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

The Resonance-Spin-Flavor-Precession Solution

Invented ('88) for now-discredited solar-cycle dependence

RSFP needs neutrino magnetic moment for $\nu_e^L \to \nu_i^R$ ($i=\mu,\tau,s$)

Transition moment (likely for Majorana, possible for Dirac)

Models can give $\mu \sim 10^{-11}$-$10^{-12}\mu_B$ (Standard Model $\mu \sim \frac{m_\nu}{eV} 10^{-19}$)

Like MSW, resonance is a density effect: $\Delta m^2/E = 2\sqrt{2}G_F N_{eff}$

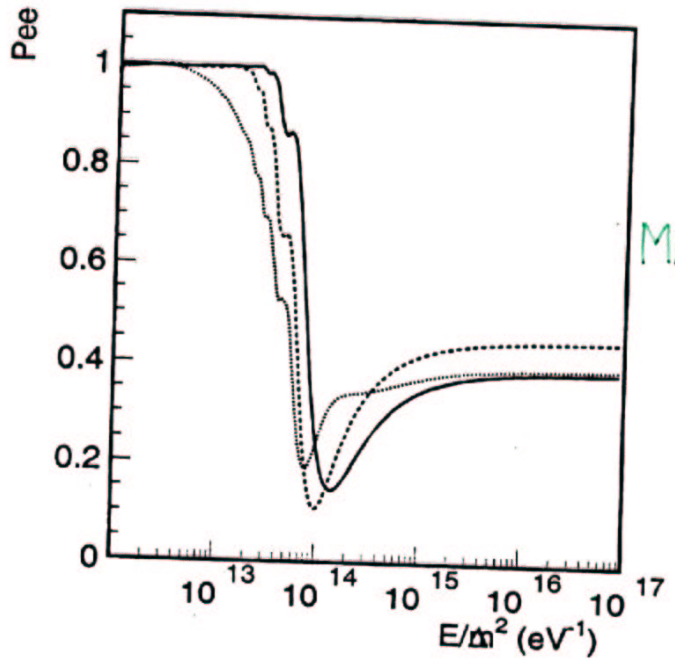
$N_{eff} = N_e - N_n$ (Majorana) or $N_e - N_n/2$ (Dirac); here $N_e \approx 6N_n$

Resonance adiabaticity: $\frac{2E}{\Delta m^2}(2\mu B_\perp)^2 [N_{eff}(\frac{dN_{eff}}{dr})^{-1}] > 1$

Cf. MSW: $N_{eff} = N_e/\cos 2\theta_0$ (∴ it is close but at larger r)

MSW, RSFP resonances can overlap

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



Miranda et al.

Choosing the dip at 0.86 MeV (^{7}Be) makes $\Delta m^2 \sim 10^{-8}\,eV^2$

Work of Sturrock and Collaborators

Homestake

Are Cl data compatible with a constant ν_e flux?

Compared 10^3 108-run simulated data sequences

Constant flux rejected at $\geq 99.9\%$ confidence

Time-power spectrum analysis—what frequencies?

12.88 y^{-1} (28.4 d) frequency dominant at 97% CL

10.88, 11.88, 13.88, 14.88 sidebands due to Sun's tilt adds conf.

∴ modulating field localized in latitude; seen directly at 98%CL

SAGE and GALLEX-GNO

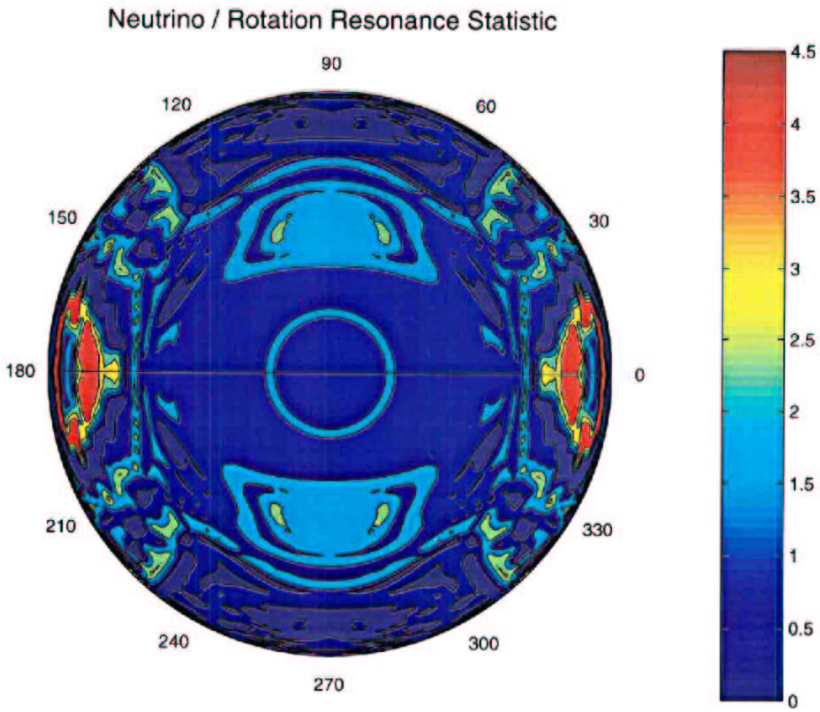
Also 12.88, but 13.59 y^{-1} (26.9 d) dominant and equatorial

Joint analysis with Homestake: stronger 13.59 evidence

Same frequencies seen in X-rays (SXT on Yohkoh spacecraft)

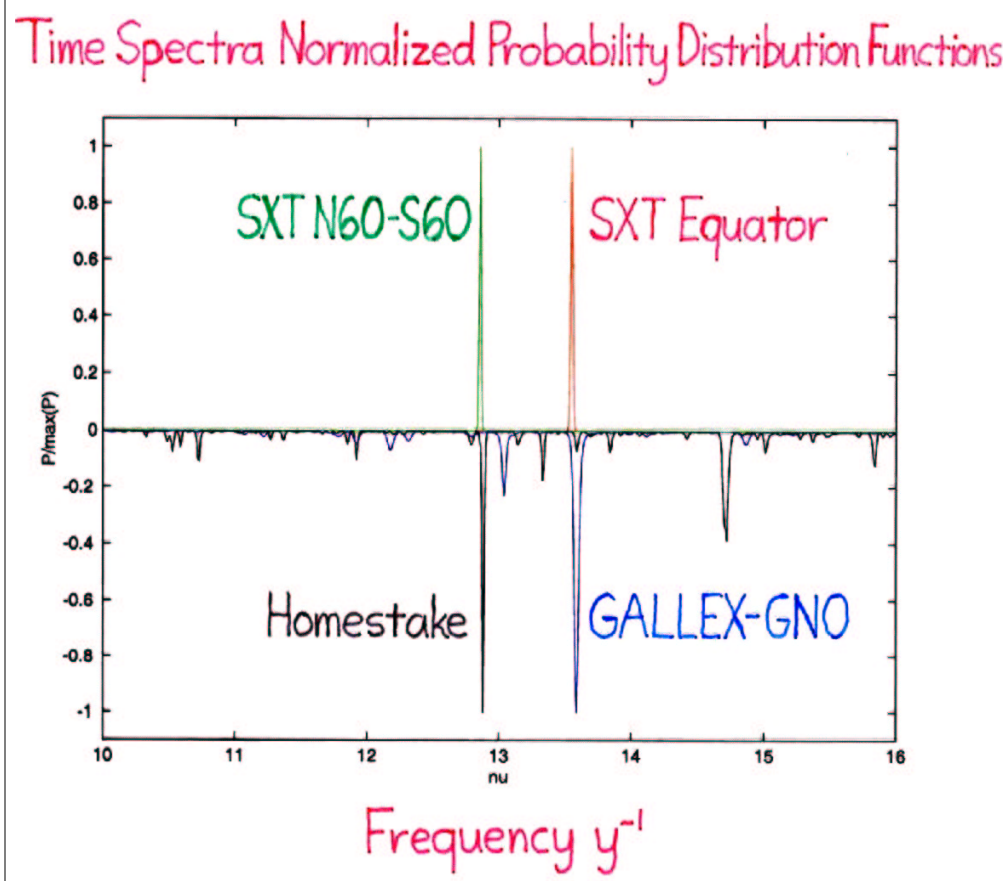
$12.86 \pm 0.02\ y^{-1}$ at high latitudes

$13.55 \pm 0.02\ y^{-1}$ at the equator

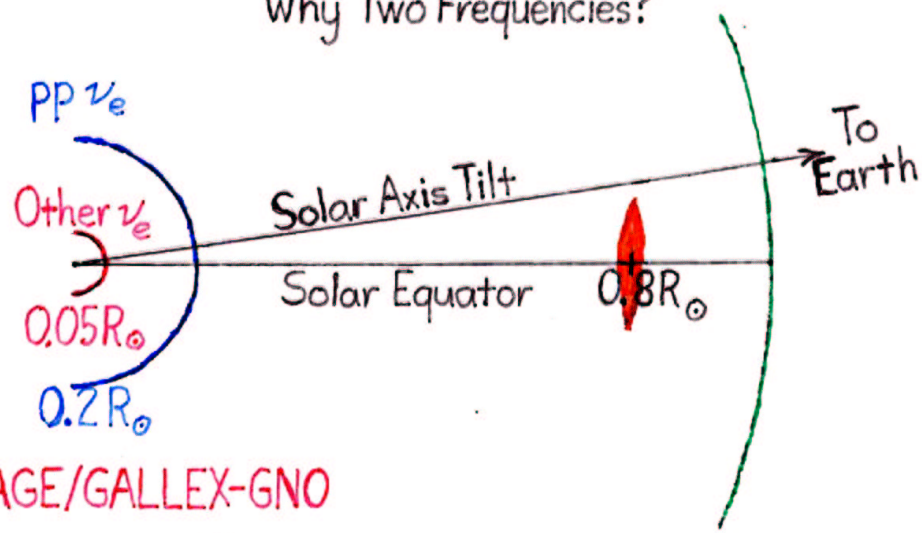


Map of the resonance statistic Ξ upon a meridional section of the solar interior. Red or yellow indicates a "resonance" between the neutrino flux and the local solar rotation, indicating that the two oscillations (flux variability and rotation) have the same frequency.

$$\Xi(r,\lambda) = \int_{\nu_a}^{\nu_b} \mathrm{d}\nu S(\nu) P(\nu|r,\lambda)$$



Why Two Frequencies?



SAGE/GALLEX-GNO

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

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

Homestake

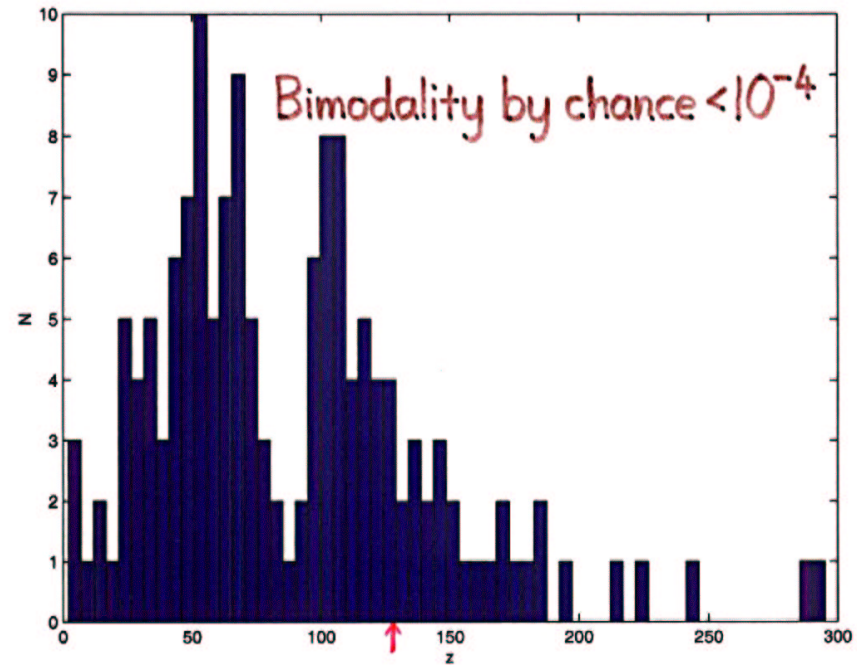
ν_e made near Sun's center at $\sim 0.05\,R_\odot$

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-GNO+SAGE Event Distribution

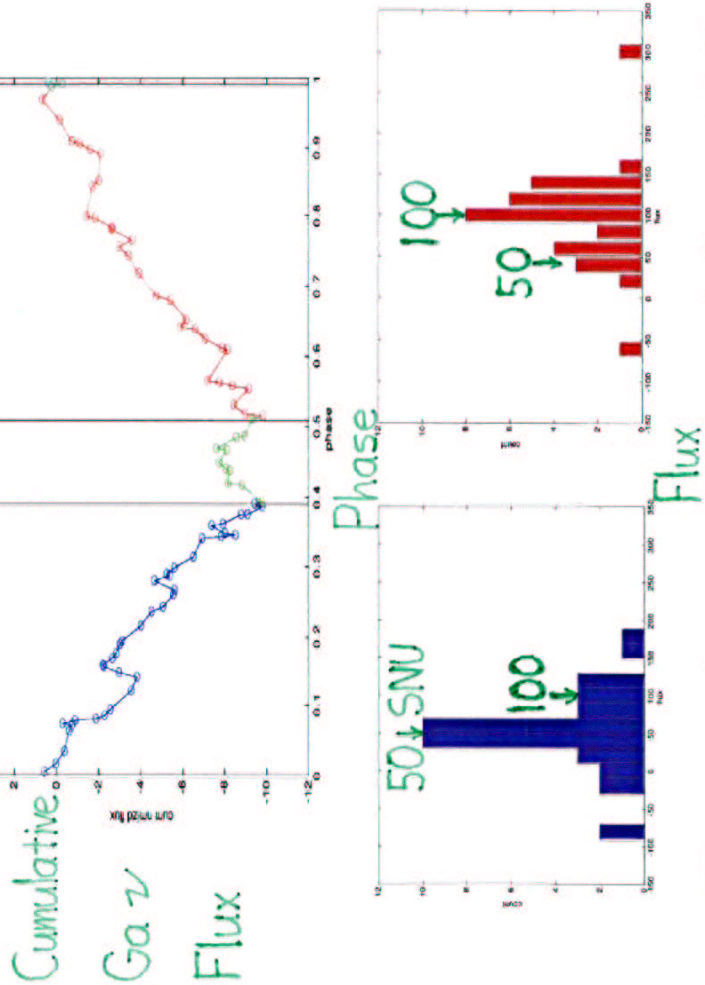


SNU

For no ν oscillations, expect 128^{+9}_{-7} SNU

Lower peak is half that; upper peak is 0.8-0.9

Ga SOLAR NEUTRINO FLUX VARIABILITY



- Histograms for two phase intervals for ν=13.59y^{-1}

Understanding a Bimodal ν Flux Distribution

If GALLEX-GNO is correct, can the model give two peaks?

Main effect: convection-zone field modulates pp ν at 13.6y^{-1}

Low $B_\perp$ half cycle (no RSFP; $\Delta m^2 \sim 10^{-8}$ eV^2 MSW only)

Little effect for small mixing angle ($\sin 2\theta \sim 0.1$)

^{7}Be, ^{8}B, CNO neutrinos reduced by radiative zone $B_\perp$

Overall flux reduced somewhat

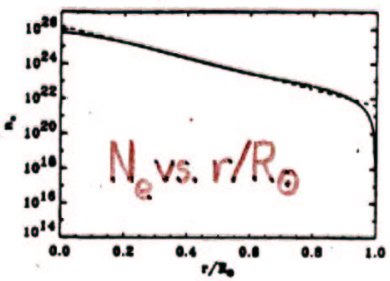
High $B_\perp$ half cycle

RSFP cuts into pp distribution below Ga threshold

Overall flux reduced by ~1/2

Location of the Resonance

- SOHO/MDI helioseismology convoluted with GALLEX-GNO data
  - 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 have given very diffent $\frac{\Delta m^2}{E}$
- RSFP resonance for $12.9\,y^{-1}$ must be at $r=0.8R_\odot$ also
  - Higher latitudes, however
  - Either radiative-zone field or latitudinal wave
  - Recall 12.9, $13.6\,y^{-1}$ frequencies seen out to corona