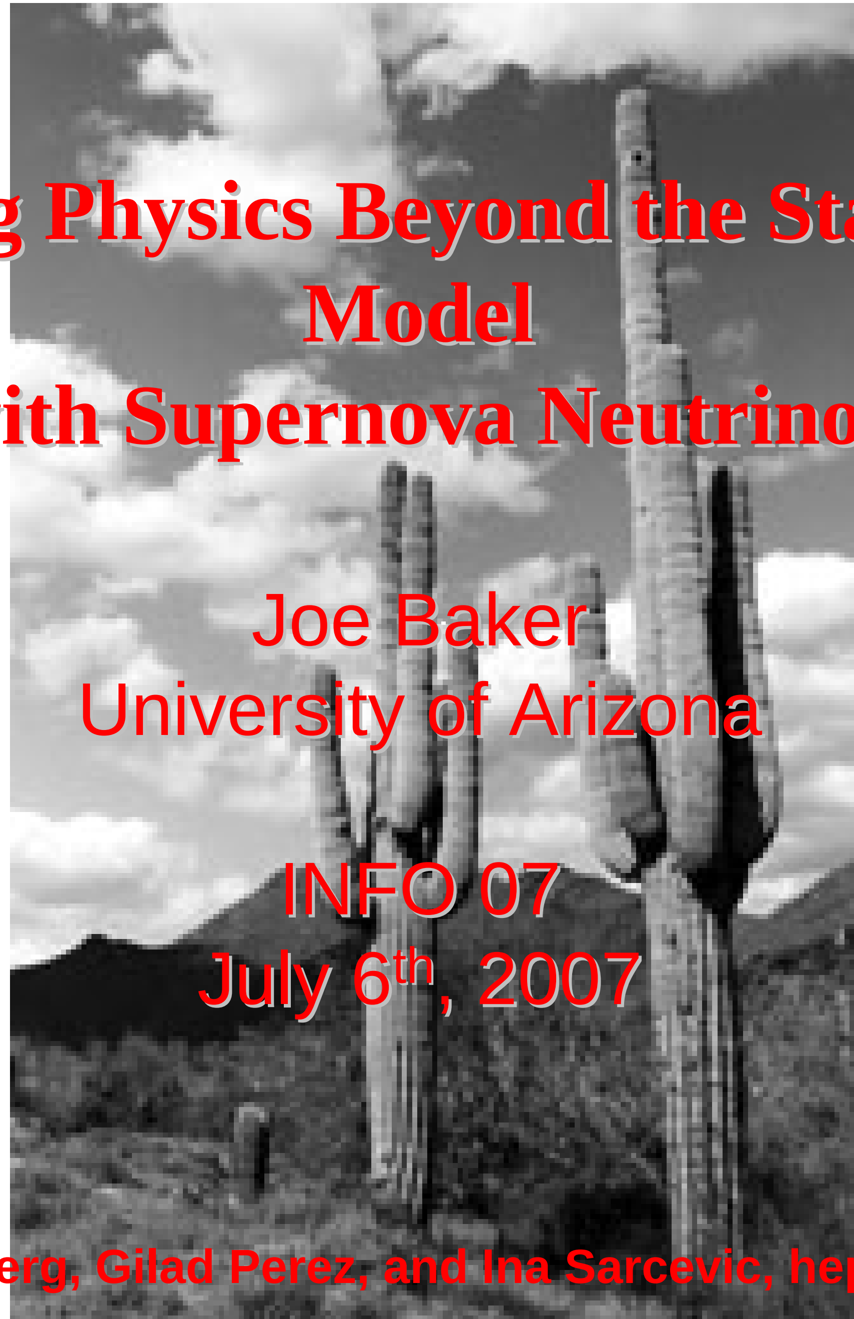

Probing Physics Beyond the Standard Model with Supernova Neutrinos

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INFO 07
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J.B., Haim Goldberg, Gilad Perez, and Ina Sarcevic, hep-ph/0607281

Late Time Neutrino Mass Models*

- Experimental confirmation that neutrinos have mass
- Theorists still have freedom to construct alternative ν mass mechanism (Seesaw, hard to test)
- Introduce new symmetry to Lagrangian only for ν's (Example: U(1) flavor symmetry)

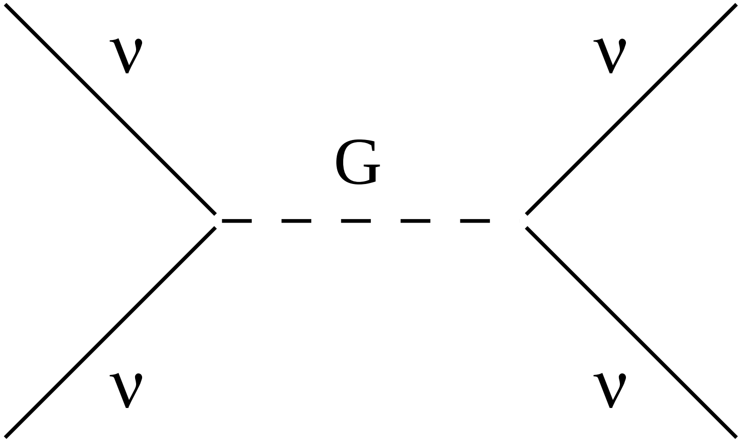
* Z. Chacko, et. al., *Phys. Rev.* **D70**, 085008 (2004); L.J. Hall and S.J. Oliver, *Nucl. Phys. Proc. Suppl.* **137**, 269 (2004); Z. Chacko, et. al., *Phys. Rev. Lett.* **94**, 111801 (2005); T. Okui, *JHEP* **09**, 017 (2005); H. Davoudiasl, *Phys. Rev.* **D71**, 113004 (2005).

- Effective Lagrangian below the electroweak symmetry breaking scale and close to the neutrino flavor symmetry breaking scale

$$\mathcal{L}_\nu^D = \mathcal{L}_{kin} + y_\nu \phi \nu N + V(\phi), \quad \mathcal{L}_\nu^M = \mathcal{L}_{kin} + y_\nu \phi \nu \nu + V(\phi),$$

  - Neutrinos acquire mass, $m_\nu = y_\nu \times f$, when symmetry is broken, where $<\phi> = f$, $f \gtrsim 10$ keV
  - Pseudo-Goldstone bosons produced with mass M_G (PGB's are light, $M_G << f$)
  - Neutrinos interact via the new scalar

New ν-ν Interactions in Late Time Neutrino Mass Models



$$E_\nu^{Res} = M_G^2/2m_\nu$$

July 6th, 2007

How Do Resonance Interactions Affect Neutrino Flux?

- Cross section for resonance in Breit-Wigner form is

$$\sigma_{\rm Res} \simeq \frac{y_\nu^4}{16\pi} \frac{s}{\left(M_G^2 - s\right)^2 + M_G^2 \Gamma_\nu^2}$$

  - Γ_ν, the boson decay width into two neutrinos is given by

$$\Gamma_\nu \sim \frac{y_\nu^2 M_G}{4\pi}$$

- For a SRN on resonance $\sigma_{Res} \simeq \dfrac{\pi}{M_G^2}$

- Mean free path for neutrino through the CνB is given by

$$\lambda_{Res} \approx \frac{1}{n_\nu \sigma_{Res}} \sim \frac{M_G^2}{\pi T_\nu^3} \sim \frac{2m_\nu E_\nu^{Res}}{\pi T_\nu^3}$$

- For $T_\nu \sim 9 \times 10^{-5}$ eV

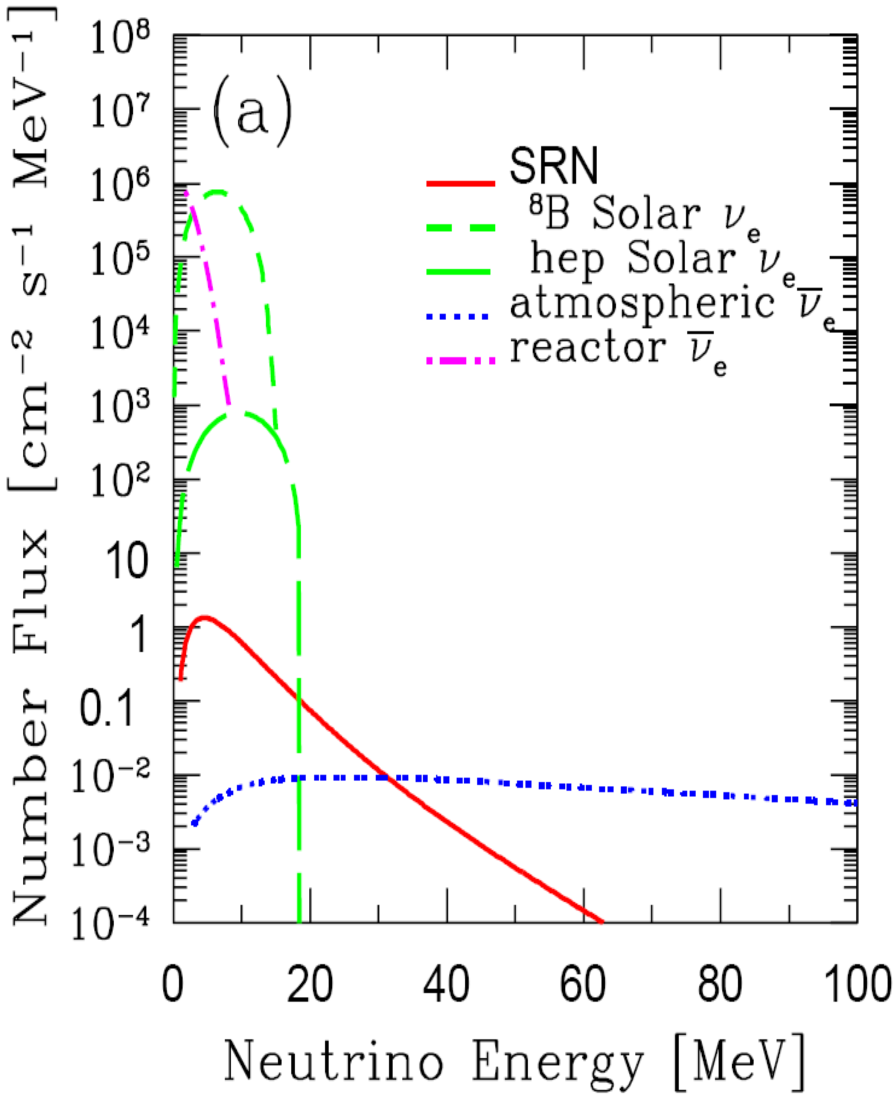
$$\lambda_{Res} \sim 5 \times\ 10^{-7} pc \frac{m_\nu}{5 \times\ 10^{-2} eV} \frac{E_\nu^{Res}}{10 MeV}$$

- For standard SRN neutrino energies and sub-eV neutrino masses, mean free path is very small

What is the Effect of New Interactions on SRN Neutrino Flux?

- SRN neutrino energies will be redistributed at each redshift, z
- Can expect a significant modification of the SRN flux as a result of redistribution
  - SRN flux can have regions of depletion relative to flux without new interactions
  - SRN flux can have regions of enhancement relative to flux without new interactions
- Can these modifications be detected at large neutrino detectors?

SRN and the Competition!



Supernova Relic Neutrino Flux

$$F(E_\nu) = \int_0^{z_{max}} R_{SN}(z) \frac{dN(E_\nu)}{dE_\nu} \ (1+z) \left| c \frac{dt}{dz} \right| dz$$

- R_{SN} is the comoving rate of supernova formation
- dN/dE is the energy spectrum for neutrinos emitted from supernova*
- dt/dz accounts for cosmological evolution

*M. Th. Keil, G. G. Raffelt and H. Th. Janka, *Astrophys. J.* **590**, 971 (2003).

Flavor Composition of Neutrino Flux that Emerges from a Supernova

- Matter oscillation effects lead to neutrinos emerging as mass eigenstates
- Relationship between emergent flux and production flux depends on neutrino mass hierarchy*

$$F_{\nu_e} = P_H|U_{e2}|^2 F^0_{\nu_e} + (1 - P_H|U_{e2}|^2) F^0_{\nu_x}$$
$$F_{\bar{\nu}_e} = |U_{e1}|^2 F^0_{\bar{\nu}_e} + |U_{e2}|^2 F^0_{\nu_x}$$

Normal Mass Hierarchy

$$F_{\nu_e} = |U_{e2}|^2 F^0_{\nu_e} + |U_{e1}|^2 F^0_{\nu_x}$$
$$F_{\bar{\nu}_e} = \bar{P}_H|U_{e1}|^2 F^0_{\bar{\nu}_e} + (1 - \bar{P}_H|U_{e1}|^2) F^0_{\nu_x}$$

Inverted Mass Hierarchy

$$P_H(\bar{P}_H) = 0 \ \text{adiabatic}$$
$$P_H(\bar{P}_H) = 1 \ \text{nonadiabatic}$$

*A. S. Dighe and A. Y. Smirnov, *Phys. Rev.* **D62**, 033007 (2000)

$$|U_{e1}|^2 = cos^2(\theta_{12}),\ |U_{e2}|^2 = sin^2(\theta_{12}),\ |U_{e3}|^2 \approx 0,\ \theta_{12} = \theta_\odot$$

Modified SRN Flux

- Position of dip cutoff for neutrino mass eigenstate i is

$$E_i = M_G^2/2m_i$$

- Resonance process is blind to the type of neutrino that produced resonance
  - Branching fractions given by

$$P_j \approx m_j^2/\Sigma_{i=1}^3 m_i^2$$

- Modified flux of j^th mass eigenstate is given by

$$\widetilde{F_j} = F_j - F_j^{Res} + P_j \times \sum_{i=1,2,3,\bar{1},\bar{2},\bar{3}} F_{i\to j}^{Res}$$

- Observed electron antineutrino flux is then

$$\widetilde{F_{\bar{\nu}_e}} = \cos^2\theta_{12}\widetilde{F_{\bar{\nu}_1}} + \sin^2\theta_{12}\widetilde{F_{\bar{\nu}_2}}$$

Accumulative Resonance Effect

- Signal in SRN flux will be combination of absorption and replenishment from G decay over range of z
- Which neutrinos will interact?
  - For neutrinos emitted with energy greater than the resonance energy at redshift z, they can produce G at resonance at z^* if

$$E_\nu^{Res} = E_\nu^{SN} \frac{1+z^*}{1+z}$$

  - Energy lower than resonance energy will never produce G.
- Neutrinos from G decay get redistributed, i.e. $E^G_\nu = f\, E^{Res}_\nu$, $0 \leq f \leq 1$
- Energy observed today is

$$E_\nu^{Obs} = \frac{f E_\nu^{Res}}{1+z^*} = \frac{f E_\nu^{SN}}{1+z} = f E_{unscattered}$$

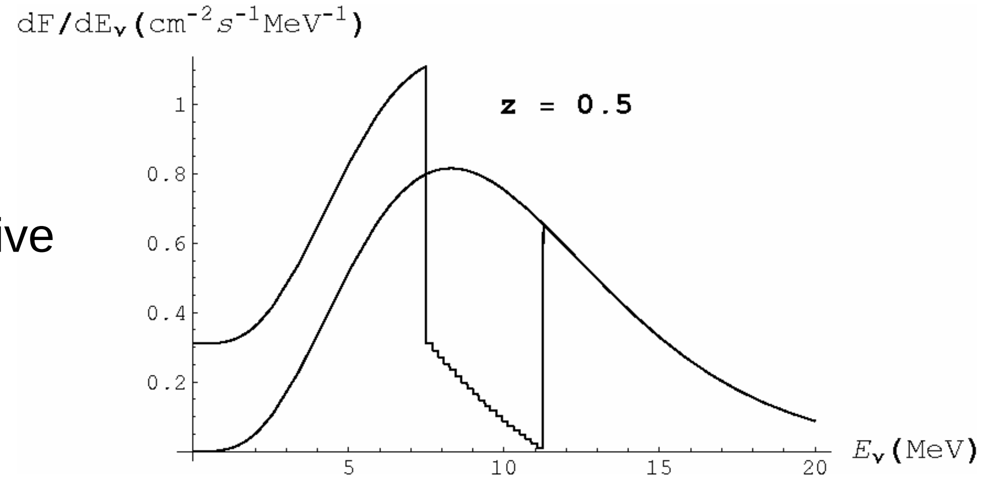
where $E_{unscattered} = E^{SN}_\nu/(1+z)$ would be observed energy of neutrinos without resonant process

SRN Flux with New Interactions

- Depletion of flux in region

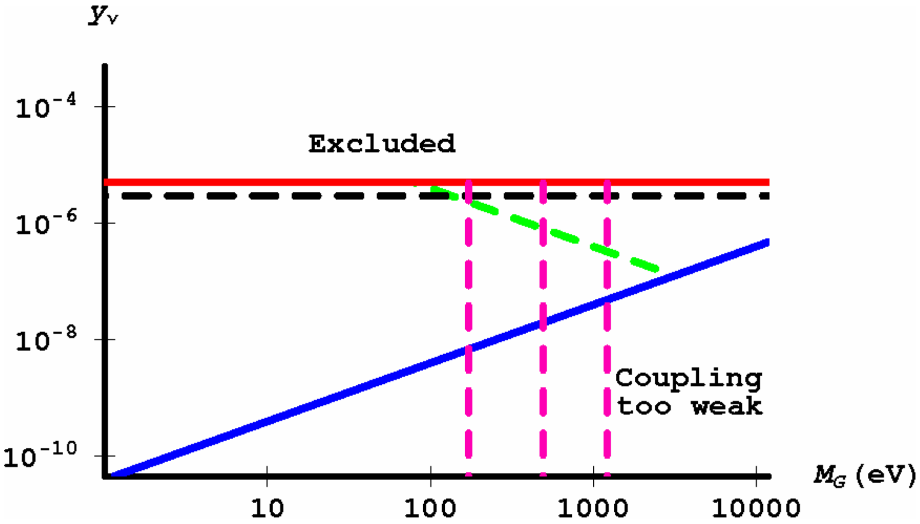
$$E_\nu^{Res}/(1+z) \leq E_\nu^{Obs} \leq E_\nu^{Res}$$

- Replenishment of flux from zero energy up to $E_{unscattered}$ for each neutrino energy in resonance region



Final effect will be accumulative (from a range of redshift)

Parameter Space



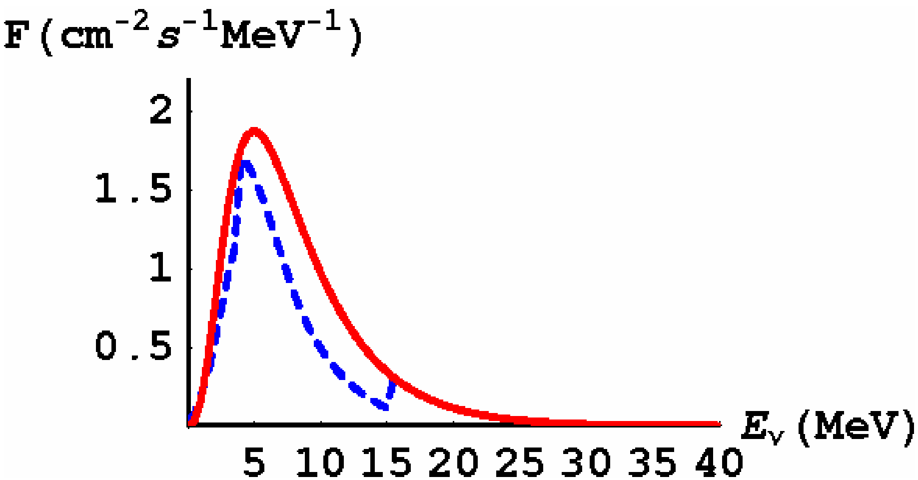
- Coupling must be strong enough for effect to occur (blue diagonal line)
- Red horizontal line from BBN (Dirac case) or SN cooling (Majorana case), green diagonal line for multiple scalars
- Off-resonance process important in very small window of parameter space, black horizontal line ($\nu\,\nu \rightarrow 4\,\nu$'s)
- For a 0.001 eV, 0.008 eV, or 0.05 eV neutrino, vertical lines are minimum values of M_G to give depletion signal above anti-ν_e reactor background

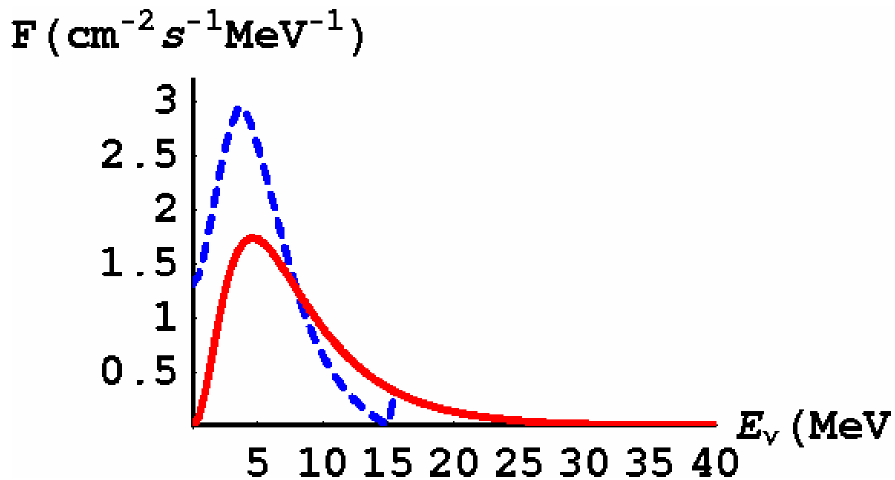
What can we Learn about ν's from Interactions?

Can neutrino-neutrino interactions through a new light scalar allow one to distinguish

- Neutrino mass hierarchy?
  - Normal mass hierarchy ($m_1 \simeq m_2 << m_3$)
  - Inverted mass hierarchy ($m_1 \simeq m_2 >> m_3$)
- Dirac vs Majorana neutrinos?
- Absolute scale of neutrino masses?

Normal vs. Inverted Neutrino Mass Hierarchy





Normal Hierarchy

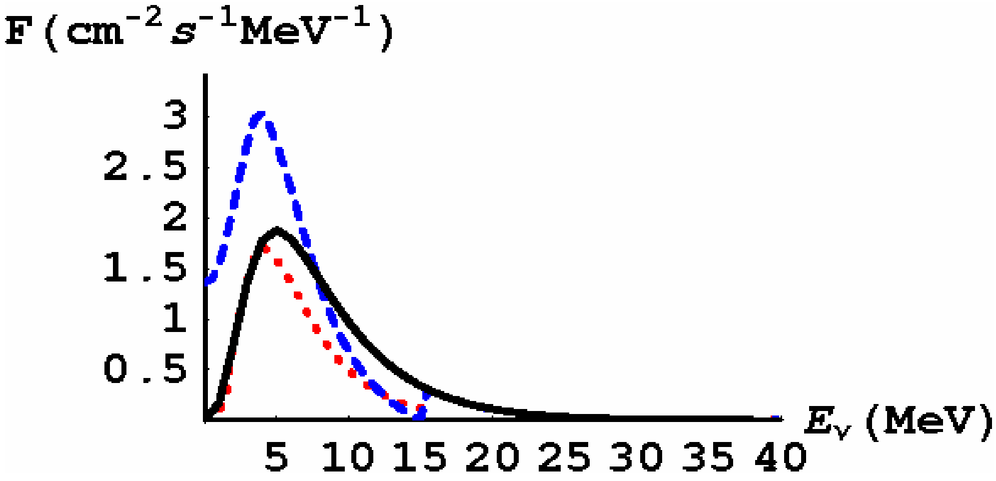
- $m_1 \simeq 0.002$ eV, $m_2 \simeq 0.009$ eV, $m_3 \simeq 0.05$ eV
- For 0.002 eV ν to have $E_{Res} \approx 15$ MeV, $M_G \approx 250$ eV
- G decays dominantly to ν_3 which does not contribute to anti-ν_e flux

Inverted Hierarchy

- $m_1 \simeq m_2 \simeq 0.05$ eV, $m_3 \simeq 0.008$ eV
- For 0.05 eV ν to have $E_{Res} \approx 15$ MeV, $M_G \approx 1.2$ keV
- G decays dominantly to ν_1 and ν_2 which do contribute to anti-ν_e flux

Adiabatic vs. Nonadiabatic?

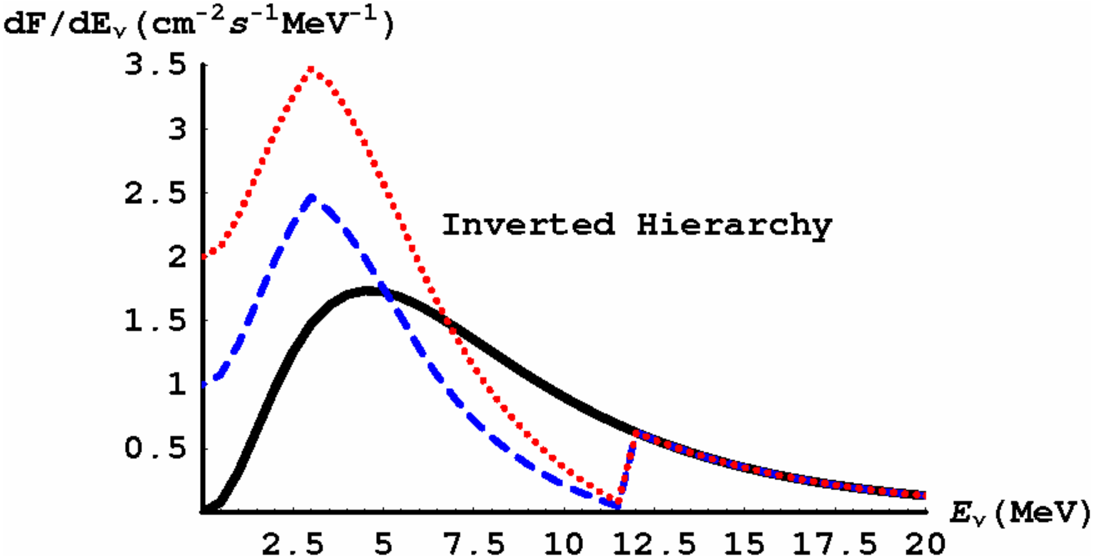
- For nonadiabatic flavor evolution, neutrino flux emerging from supernova is independent of neutrino mass hierarchy
- With new interactions, difference remains.
  - Normal hierarchy, G → m_3 state dominantly, depletion
  - Inverted hierarchy, G → m_1 and m_2 states dominantly, depletion and enhancement



$$F_{\nu_e} = sin^2(\theta_\odot)F^0_{\nu_e} + cos^2(\theta_\odot)F^0_{\nu_x}$$

$$F_{\bar{\nu}_e} = cos^2(\theta_\odot)F^0_{\bar{\nu}_e} + sin^2(\theta_\odot)F^0_{\nu_x}$$

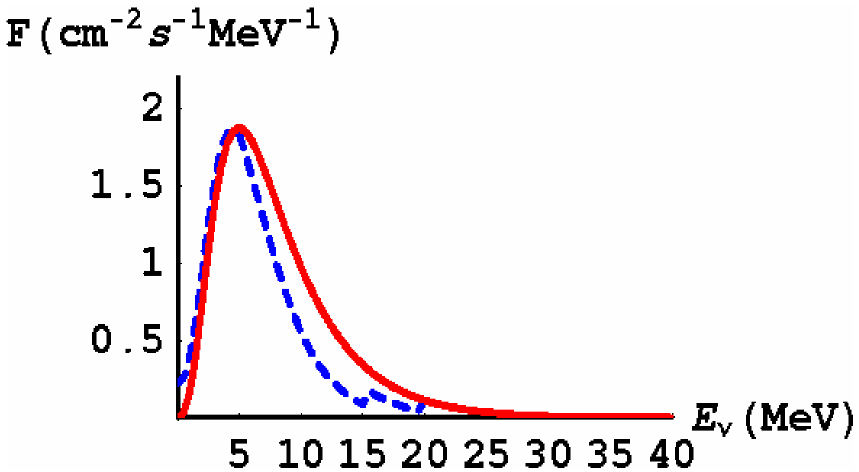
Dirac vs. Majorana Neutrinos

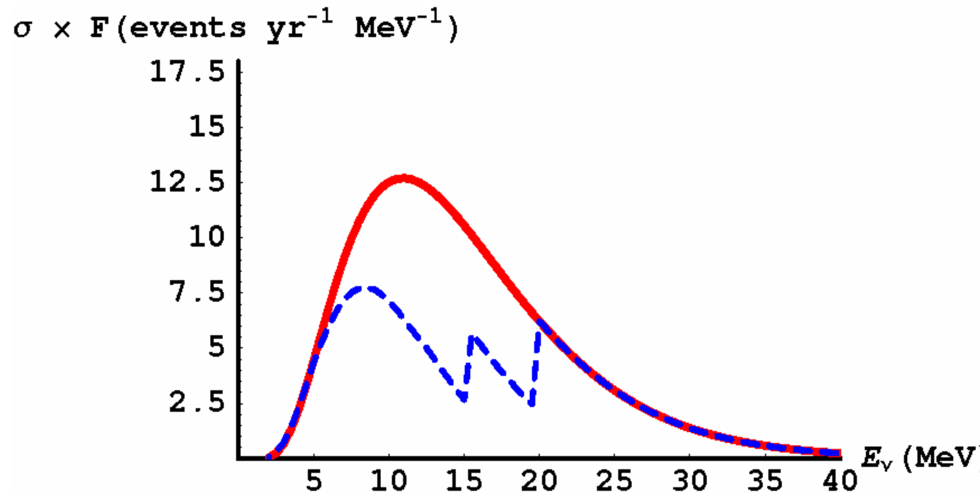


- If neutrinos are Majorana particles (red dotted curve), each G decay produces 2 active neutrinos
- If neutrinos are Dirac particles (blue dashed curve) then G decays to ν N-bar or to N ν –bar

Overall factor of ½ for Dirac vs. Majorana particles

Multiple Dips





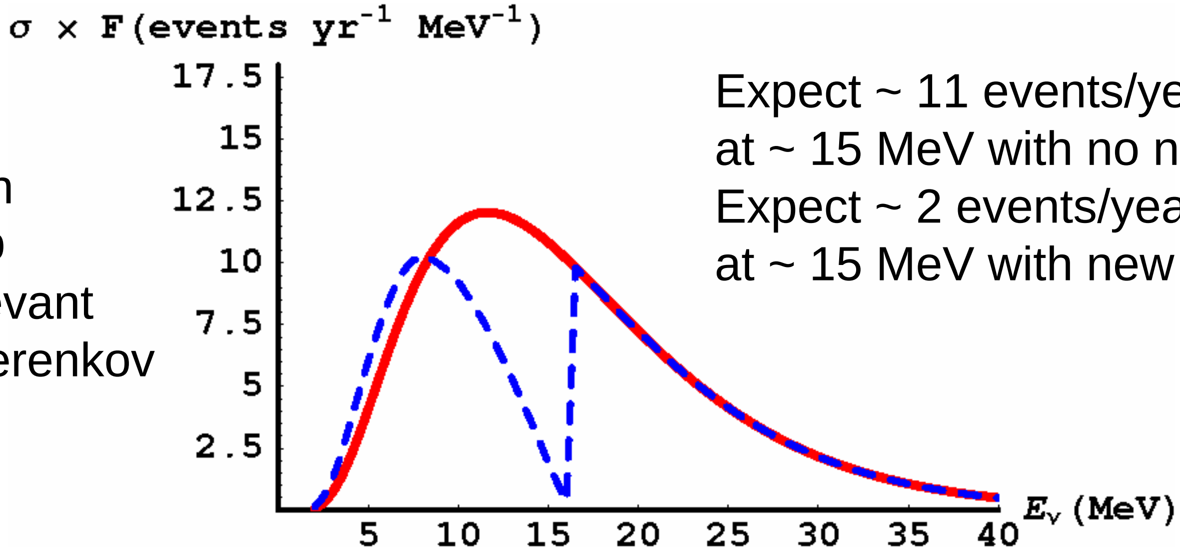
- Two neutrinos could visibly go through resonance, i.e. two light nearly degenerate neutrino masses ~ 0.01 eV, one neutrino mass approximately 0.05 eV ($M_G \approx$ 630 eV)
- Ratio of peak positions is ratio of the masses of the neutrinos
- Differential flux folded with cross section for

  anti-ν_e + p → n + e^+ is relevant for water Cerenkov detector
- Cross section for antineutrinos on protons is increasing function of the neutrino energy

  Main features, i.e. dip locations, remain unchanged

Signal Detection

Cross section for anti-ν_e + p →n + e^+, relevant for water Cherenkov detector

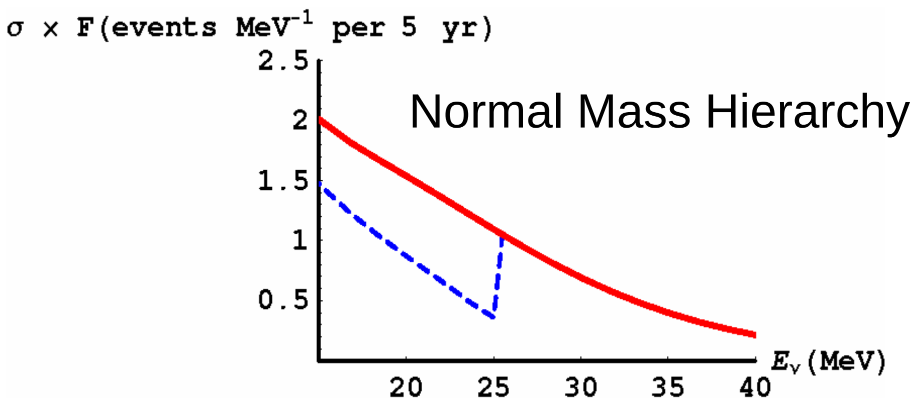


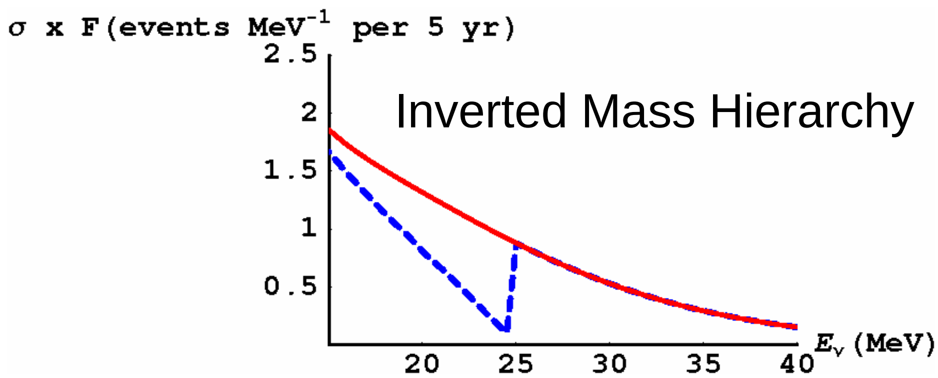
Expect ~ 11 events/year at ~ 15 MeV with no new interactions
Expect ~ 2 events/year at ~ 15 MeV with new interactions

- Depletion of flux at energies above ~ 8 MeV relative to no interactions
- In Gd-enhanced water Cherenkov detector, reactor antineutrinos main source of background (bg is small above ~ 12 MeV*)
- In 5 years with no new interactions, 55 events, σ ~ 7.5 events
- Signal is event deficit, 55 – 10 = 45 events, so 45/7.5 → approx. 6 σ effect

*L. J. Hall, H. Murayama and G. Perez, *Phys. Rev. Lett.* **95**, 111301 (2005); G. L. Fogli, E. Lisi, A. Mirizzi and D. Montanino, *JCAP* **0504**, 002 (2005)

Liquid Argon Detector





•LAr detectors can measure the electron neutrino flux by interaction with Argon nucleus

•Solar neutrinos provide large background below ~ 19 MeV, and atmospheric neutrinos provide background above ~ 40 MeV

•In window from 19 MeV to 40 MeV, could see ~ 25% reduction in expected integrated event rate (Normal: 0.001 eV with 250 eV for M_G, Inverted: 0.05 eV with 1.6 keV for M_G)

Summary

- In late time neutrino mass models, additional light bosons are generically present
- Interactions between the SRN and CνB can lead to dramatic changes of the SRN flux
- Measurements of these effects are well within reach of future neutrino experiments
  - Cannot distinguish between mass hierarchy, or Majorana vs. Dirac neutrinos because of reactor antineutrino/solar neutrino backgrounds
  - Indicates the presence of the cosmic neutrino background
  - Could see a multiple dip signal leading to ratio of neutrino masses
  - Can directly test some values of the parameters for late time neutrino mass generation models