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Probing Late Neutrino Mass Properties with Supernova Neutrinos

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Outline

- **Late Time Neutrino Mass Models**
- **Supernova Relic Neutrinos (SRNs)**
- **Modifications of SRN spectrum due to new $\nu - \nu$ interactions**
- **Conclusions**

Late Time Neutrino Mass Models [*]

- **SuperK, K2K, SNO confirm that neutrinos have mass**
- **Theorists still need to construct a ν mass mechanism (Seesaw, hard to test)**
- **Introduce new symmetry to Lagrangian only for ν's (Example: U(1) flavor symmetry)**

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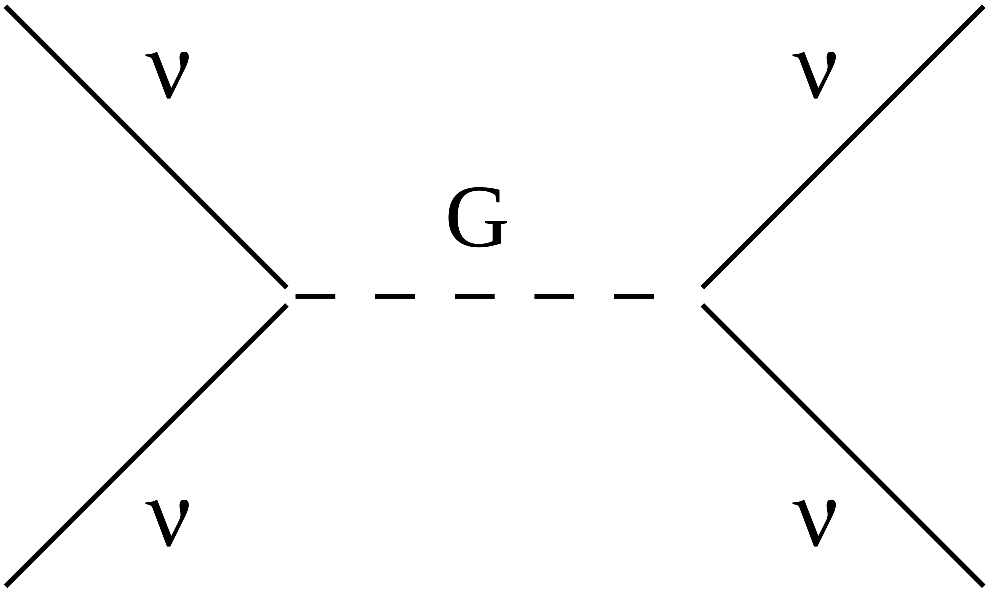
[*] Z. Chacko, L. J. Hall, T. Okui and S. J. Oliver, *Phys. Rev.* **D70**, 085008 (2004); L. J. Hall and S. J. Oliver, *Nucl. Phys. Proc. Suppl.* **137**, 269 (2004); Z. Chacko, L. J. Hall, S. J. Oliver and M. Perelstein, *Phys. Rev. Lett.* **94**, 111801 (2005); T. Okui, *JHEP* **09**, 017 (2005);H. Davoudiasl, R. Kitano, G. D. Kribs and H. Murayama, *Phys. Rev.* **D71**, 113004 (2005).

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

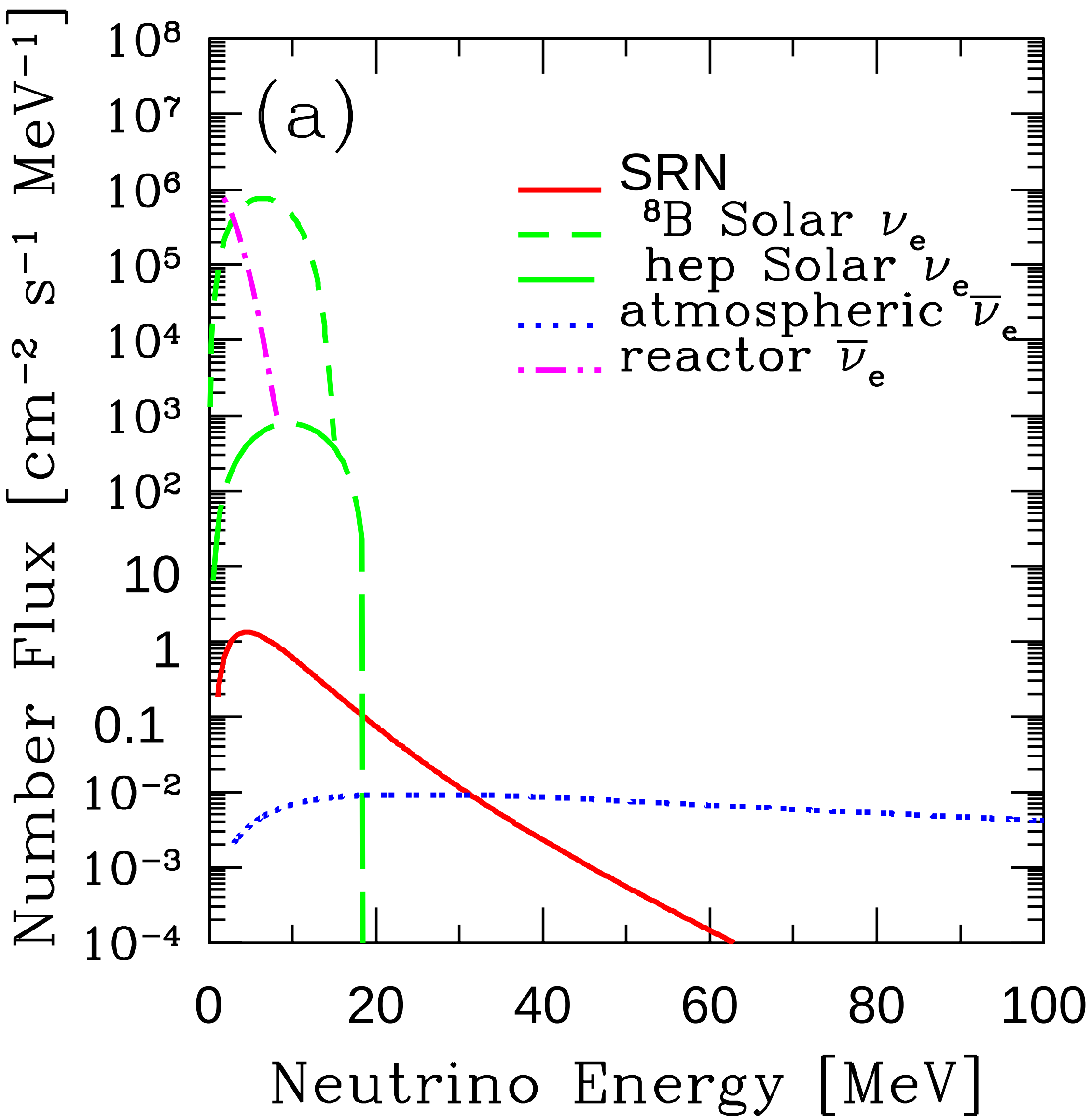
$$\mathcal{L}_\nu^D = \mathcal{L}_{kin} + y_\nu \phi \nu N + V(\phi) \quad \mathcal{L}_\nu^M = \mathcal{L}_{kin} + y_\nu \phi \nu \nu + V(\phi)$$

  - **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 $\nu - \nu$ Interactions in Late Time Neutrino Mass Models



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



(a)
SRN
^{8}B Solar ν_e
hep Solar ν_e
atmospheric $\overline{\nu}_e$
reactor $\overline{\nu}_e$
Number Flux [cm^{-2} s^{-1} MeV^{-1}]
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
0
20
40
60
80
100
Neutrino Energy [MeV]

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

- SRN neutrino energies will be redistributed at each redshift, z
- Can expect 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
- These modifications could be detected at large neutrino detectors

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**

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

What is the Flavor Composition of the Neutrino Flux that Emerges from Supernovae?

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

Normal Mass Hierarchy $(m_1 \simeq m_2 \ll m_3; \Delta m^2_{12} \sim \Delta m^2_{\odot}; \Delta m^2_{23} \sim \Delta m^2_{atm})$

$$\begin{aligned} F_{\nu_1} &= F^0_{\nu_\mu} & F_{\bar{\nu}_1} &= F^0_{\bar{\nu}_e} \\ F_{\nu_2} &= F^0_{\nu_\tau} & F_{\bar{\nu}_2} &= F^0_{\bar{\nu}_\mu} \\ F_{\nu_3} &= F^0_{\nu_e} & F_{\bar{\nu}_3} &= F^0_{\bar{\nu}_\tau} \end{aligned}$$

Inverted Mass Hierarchy $(m_1 \simeq m_2 \gg m_3)$

$$\begin{aligned} F_{\nu_1} &= F^0_{\nu_\mu} & F_{\bar{\nu}_1} &= F^0_{\bar{\nu}_\tau} \\ F_{\nu_2} &= F^0_{\nu_e} & F_{\bar{\nu}_2} &= F^0_{\bar{\nu}_\mu} \\ F_{\nu_3} &= F^0_{\nu_\tau} & F_{\bar{\nu}_3} &= F^0_{\bar{\nu}_e} \end{aligned}$$

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

SRN Flux at Earth

(No New Interactions)

$$F_{\nu_\alpha} = \sum_{i=1}^{3} |U_{\alpha i}|^2 F_{\nu_i} \text{ (SRN Flux at Earth)}$$

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

For electron antineutrinos

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

In terms of neutrino flavor eigenstates at production point

Normal Mass Hierarchy

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

Inverted Mass Hierarchy

$$F_{\bar{\nu}_e} = \cos^2\theta_\odot F^0_{\bar{\nu}_\tau} + \sin^2\theta_\odot F^0_{\bar{\nu}_\mu}$$

How Do Resonance Interactions Affect Neutrino Flux? [*]

- **Cross section for resonance in Breit-Wigner form is**

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

with Γ_ν, the boson decay width into two neutrinos, given by

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

- **For a SRN on resonance** $(E_\nu = E_\nu^{Res} = M_G^2/2m_\nu)$

$$\sigma_{Res} \simeq \frac{\pi}{M_G^2}$$

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[*] H. Goldberg, G. Perez and I. Sarcevic, hep-ph/0505221.

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

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

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

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

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

Acumulative Resonance Effect

- **Signal in SRN flux will be combination of absorption and replenishment from G decay**
- **For neutrinos emitted with energy greater than the resonance energy at redshift z, they can have resonant scattering at $\bar{z}$ if**

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

- **Neutrinos from G decay have flat energy distrubition, i.e. $E_\nu^G = f E_\nu^{Res}$, $0 \le f \le 1$**
- **Energy observed today is**

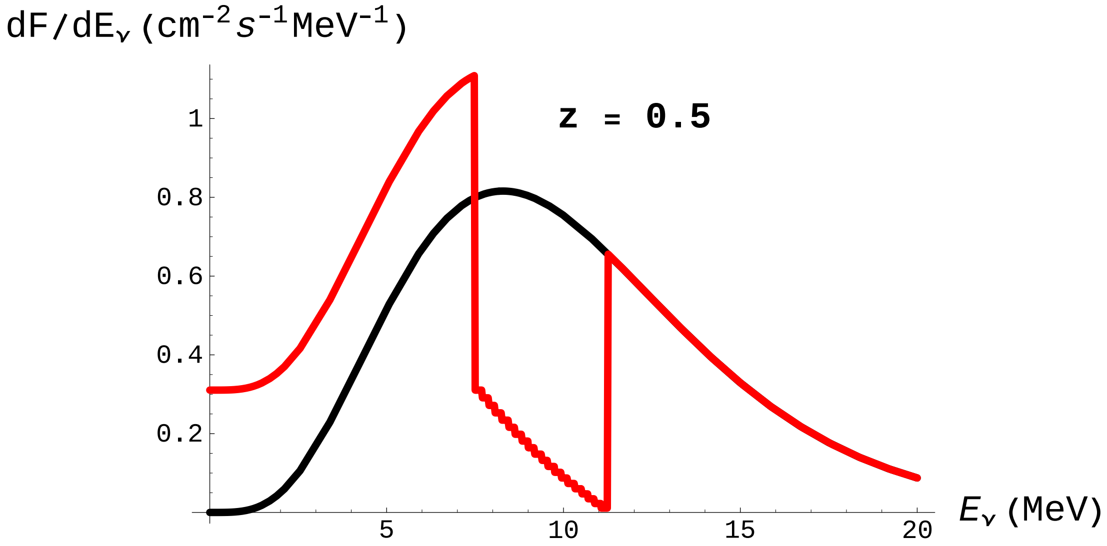
$$E_\nu^{Obs} = \frac{f E_\nu^{Res}}{1+\bar{z}} = \frac{f E_\nu^{SN}}{1+z} = f E_{unscattered}$$

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

SRN Flux with New Interactions

Example spectrum for neutrinos emitted from SN at redshift $z = 0.5$

- **Depletion of flux in region** $E_\nu^{Res}/(1+z) \leq E_\nu^{Obs} \leq E_\nu^{Res}$
- **Replenishment of flux from 0 energy back up to** $E_{unscattered}$ **for each neutrino energy in resonance region**



Final effect will be accumulative (range of redshift)

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** $(m_1 \simeq m_2 \ll m_3)$
  - **Inverted mass hierarchy** $(m_1 \simeq m_2 \gg m_3)$
  - **Quasi-degenerate neutrino masses** $(m_1 \simeq m_2 \simeq m_3)$
- **Dirac vs Majorana neutrinos?**
- **Absolute scale of neutrino masses?**

Modified SRN Flux

- **Consider specific values of parameters**
  - **Values of neutrino masses consistent with experimental constraints**
  - **Mass of G within allowable parameter space**
- **Position of dip cutoff for neutrino mass eigenstate i is** $E_i = M_G^2/2m_i$

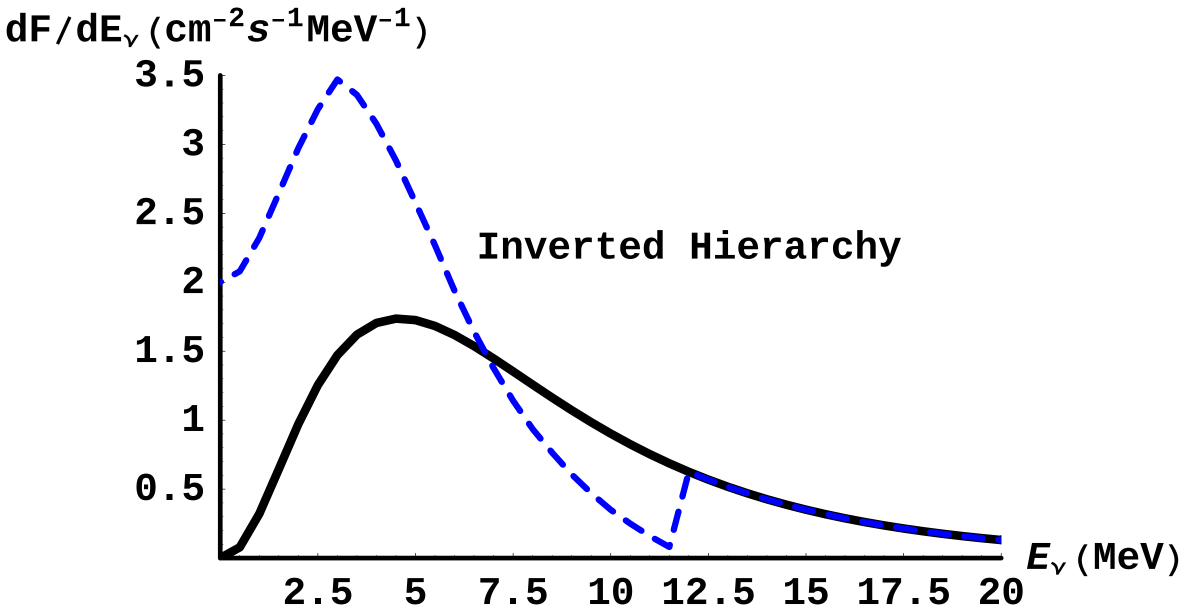
- **Resonance process is blind to the type of neutrino that produced resonance, i.e. scalar decays into all three neutrino mass eigenstates**
  - **Branching fractions given by** $P_j \approx m_j^2/\Sigma_{i=1}^3 m_i^2$
- **Modified flux of** j^{th} **mass eigenstate is given by**

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

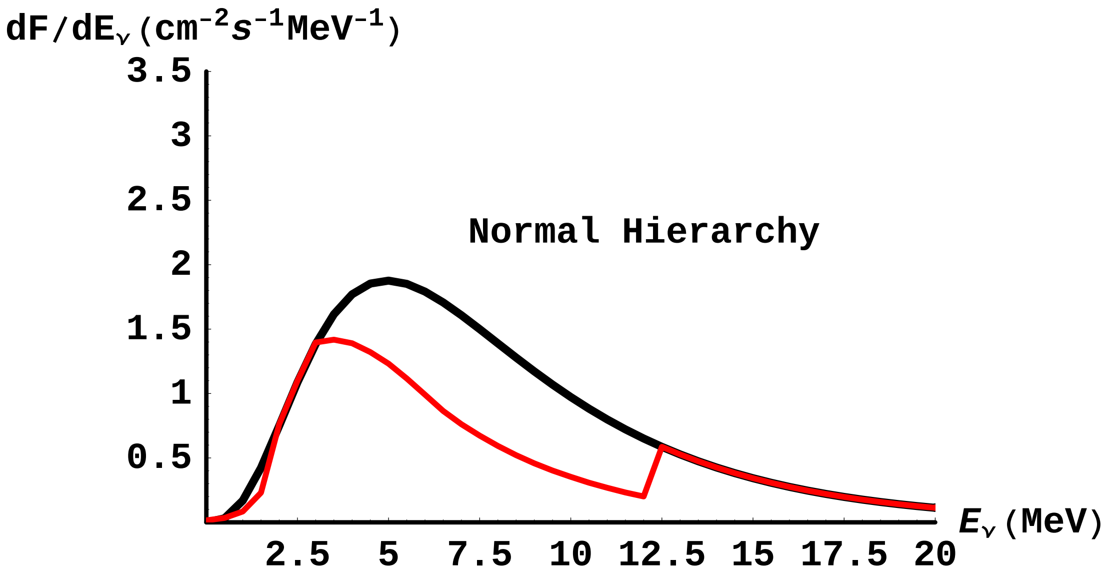
- **Observed electron antineutrino flux is then**

$$\widetilde{F_{\bar{\nu}_e}} = \cos^2\theta_{12}\widetilde{\bar{F}_{\nu_1}} + \sin^2\theta_{12}\widetilde{\bar{F}_{\nu_2}}$$

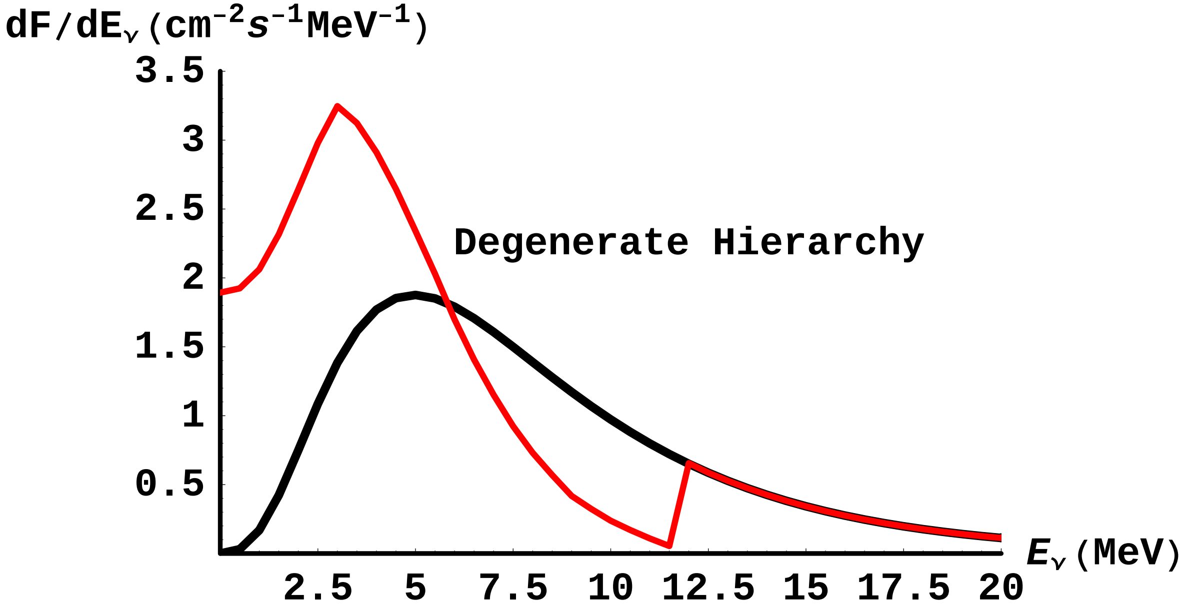
Neutrino Mass Hierarchy



- **Example:** $m_1 \simeq m_2 \simeq 0.05\ \mathrm{eV},\ m_3 \simeq 0.008\ \mathrm{eV}$
- **For 0.05 eV neutrino to have** $E_\nu^{Res} \approx 12\ \mathrm{MeV}$**,** $M_G \approx 1\ \mathrm{keV}$
- **Then 0.008 eV neutrinos have** $E_\nu^{Res} \approx 63\ \mathrm{MeV}$

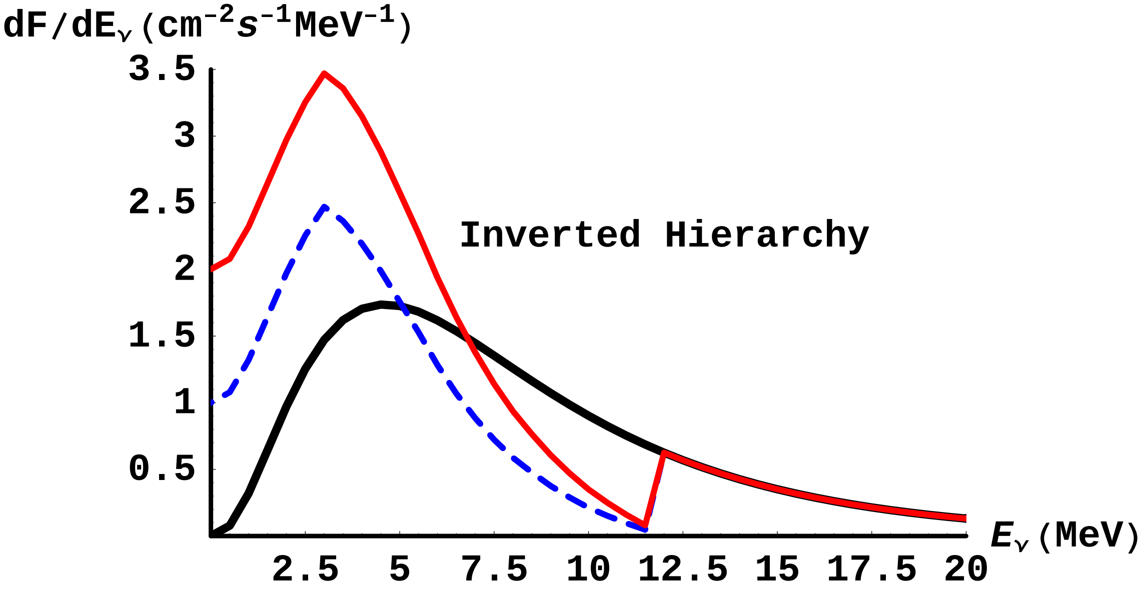


- **Example:** $m_1 \simeq 0.002 \text{ eV},\ m_2 \simeq 0.009 \text{ eV},\ m_3 \simeq 0.05 \text{ eV}$
- **For 0.002 eV neutrino to have** $E_\nu^{Res} \approx 12$ MeV**,** $M_G \approx 220$ eV
- **Other two neutrino mass eigenstates have dip at lower energies,** $E_2^{Res} \approx 3$ MeV **and** $E_3^{Res} \approx 0.5$ MeV
- **Overall depletion because G decays dominantly back into heaviest neutrino mass eigenstate, which does not contribute to electron antineutrino flux**



- **Possibility remains that neutrinos have nearly degenerate masses, i.e.** $m_1 \simeq m_2 \simeq 0.06$ eV, $m_3 \simeq 0.08$ eV
- **This case is difficult to distinguish from inverted hierarchy**

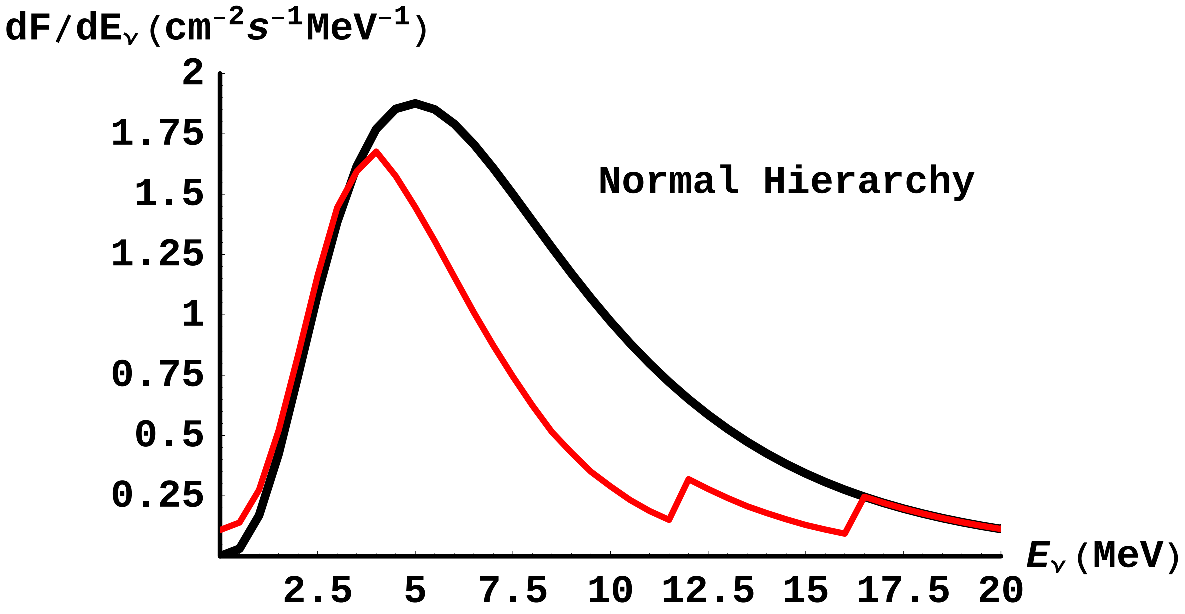
Dirac vs. Majorana Neutrinos?



- **If neutrinos are Majorana particles (red), each boson decay produces a $\nu\nu$ or $\bar{\nu}\bar{\nu}$**
- **If neutrinos are Dirac particles (blue) then the boson can decay to $\nu\bar{N}$ or to $N\bar{\nu}$**

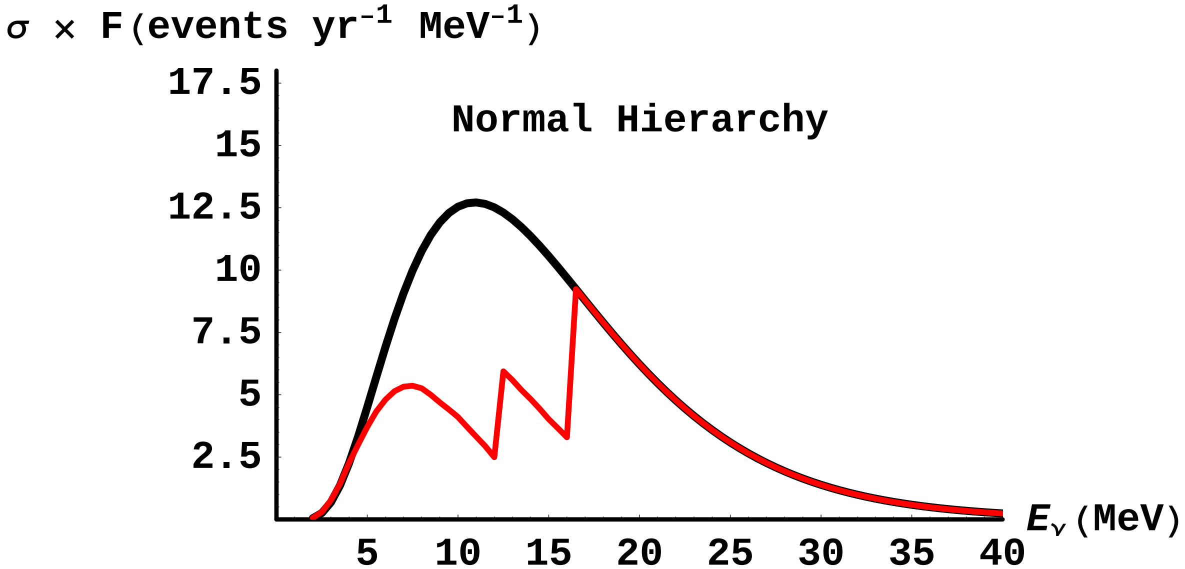
Overall factor of 1/2 for Dirac vs. Majorana particles

Determining Neutrino Masses



- **Two neutrinos could visibly go through resonance, i.e. two light nearly degenerate neutrino masses, one neutrino mass approximately** 0.05 eV
- **Ratio of peak positions leads to determination of neutrino masses,** $E_1^{Res} \approx 12$ MeV, $E_2^{Res} \approx 16$ MeV

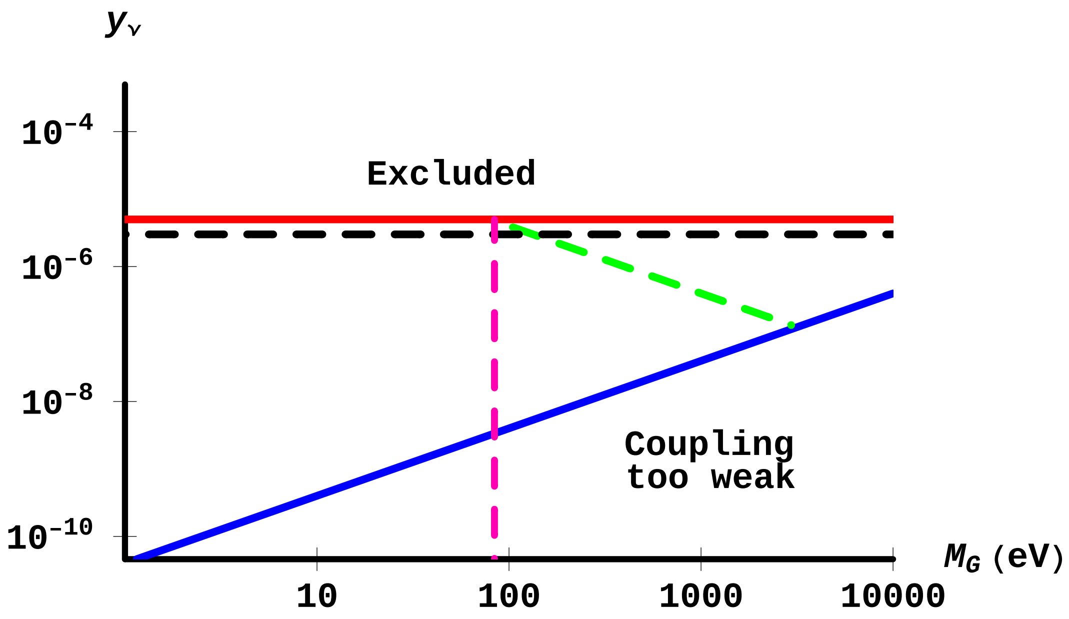
Folding dF/dE with $\bar{\nu}_e + p \rightarrow n + p^+$ Cross Section



- Differential flux folded with the detection cross section (inverse beta decay induced by antineutrino capture in the detector)

- Cross section for antineutrinos on protons is increasing function of the energy, leading to observed shape

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



- **Must satisfy BBN and supernova cooling constraints**
- **Coupling must be strong enough for effect to occur**
- **Off-resonance processes only important for very small region of parameter space ($\nu\nu \rightarrow 4\nu$'s)**
- **For experimental detection threshold of $E_{threshold} \approx 7$ MeV and lightest neutrino mass $m_{light} \approx 0.001$ eV, vertical line is lower M_G threshold**

Conclusions

- In late time neutrino mass models, additional light bosons are generically present
- Interactions between the SRN and CνB neutrinos can lead to dramatic changes of the SRN neutrino flux
- Measurements of these effects can lead to
  - A direct test for late time neutrino mass generation models
  - A clear indication of the presence of the CνB
  - Determination of the neutrino mass hierarchy
  - Possibility to distinguish between Dirac and Majorana neutrinos
  - Measurement of the absolute values of the neutrino masses
- Measurements of these effects are well within reach of future neutrino experiments (Gadzooks, HyperK, UNO, MEMPHYS)