

Probing the Origin of Neutrino Mass and Neutrino Properties with Supernova Neutrinos [†]

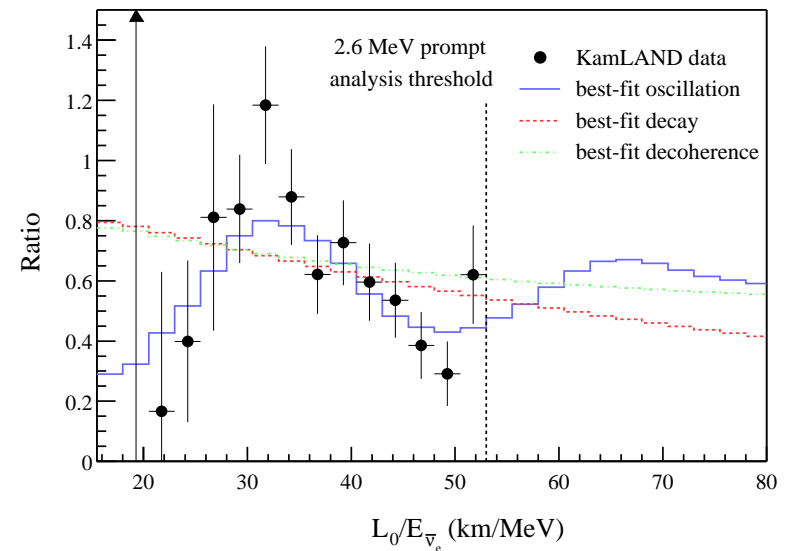
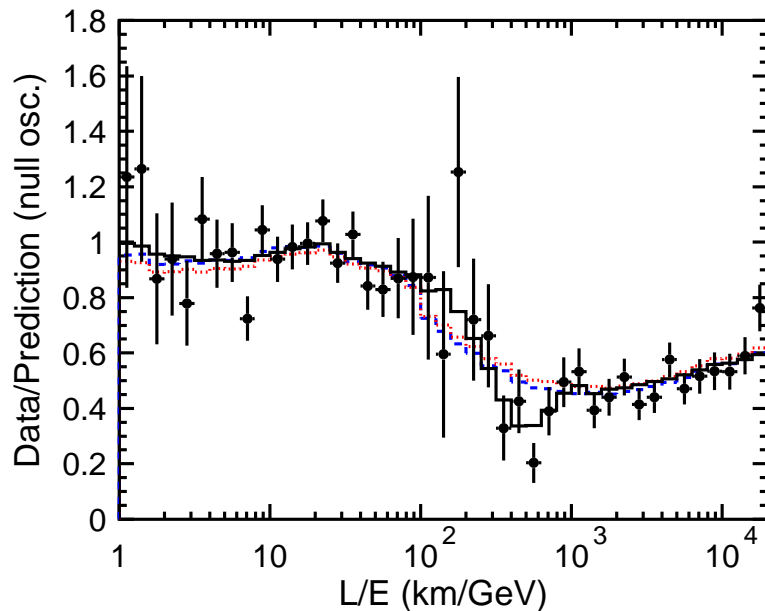
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- Models of Neutrino Mass with a Low Scale Symmetry Breaking
- New Interactions of Supernova Relic Neutrinos
- Probing Neutrino Properties with Supernova Neutrinos
- Experimental Detection of the New Interactions via Light Scalar (HyperK, GADZOOKS, UNO, MEMPHYS)
- BBN and SN1987A Constraints on the Parameter Space of the Neutrino Mass Models

[†] H. Goldberg, G. Perez and I. Sarcevic, JHEP **11**, 023 (2006); J. Baker, H. Goldberg, G. Perez and I. Sarcevic, hep-ph/0630218.

- **Observation of neutrino flavor conversion from solar (SuperK, SNO), atmospheric (SuperK) and terrestrial (KamLand, K2K) neutrino data has provided firm evidence for neutrino flavor conversion.**
- Recent SuperK data on the L/E -dependence of atmospheric neutrino events and the new spectrum data from terrestrial experiments (KamLand, K2K) is the first time evidence of the expected oscillatory behavior. This strongly favors **non-vanishing sub-eV neutrino masses.**



Neutrino Mass Models with Low Scale of Symmetry Breaking

Chacko, Hall, Okui and Oliver, **PR D70** (2004)

Chacko, Hall, Oliver and Perelstein, **PRL 94** (2005)

Davoudiasl, Kitano, Kribs and Murayama, **PR D71**(2005)

- Consider the effective Lagrangian below EWB scale and close to the neutrino flavor symmetry breaking scale:

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

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

ν is an active neutrino, $V(\phi)$ is the scalar potential (for the global case this contains interaction between ϕ and the additional Goldstone bosons).

- After the symmetry breaking, neutrino gets the mass $\implies m_\nu = y_\nu f$, where $f = \langle \phi \rangle$ and $f \ll M_W$.

- Strongest limits on f come from cosmology and astrophysics: light scalars not to be in thermal equilibrium during big bang nucleosynthesis (BBN) gives a limit on f of approximately $f \geq 10$ keV.

Chacko et al., PRL 94 (2005)

Davoudiasl et al., PRD 71 (2005)

- Similar bound is obtained by demanding that SN cooling not be modified in the presence of these additional fields.

Y. Farzan, PRD 67 (2003)

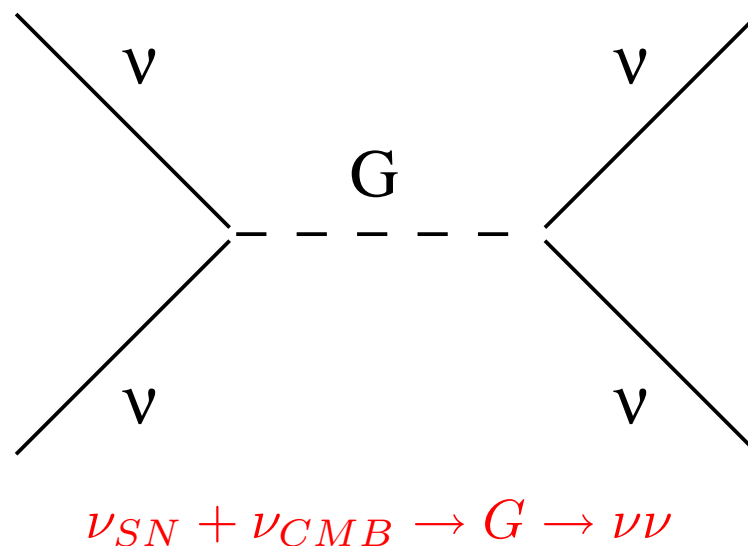
- Combining BBN bound and assuming that the heaviest neutrino mass, $m_\nu^h \sim 4 \times 10^{-2}$ eV, we find that the strength of the interaction between the scalar and the neutrinos y_ν is rather weak,

$$y_\nu \leq 10^{-5},$$

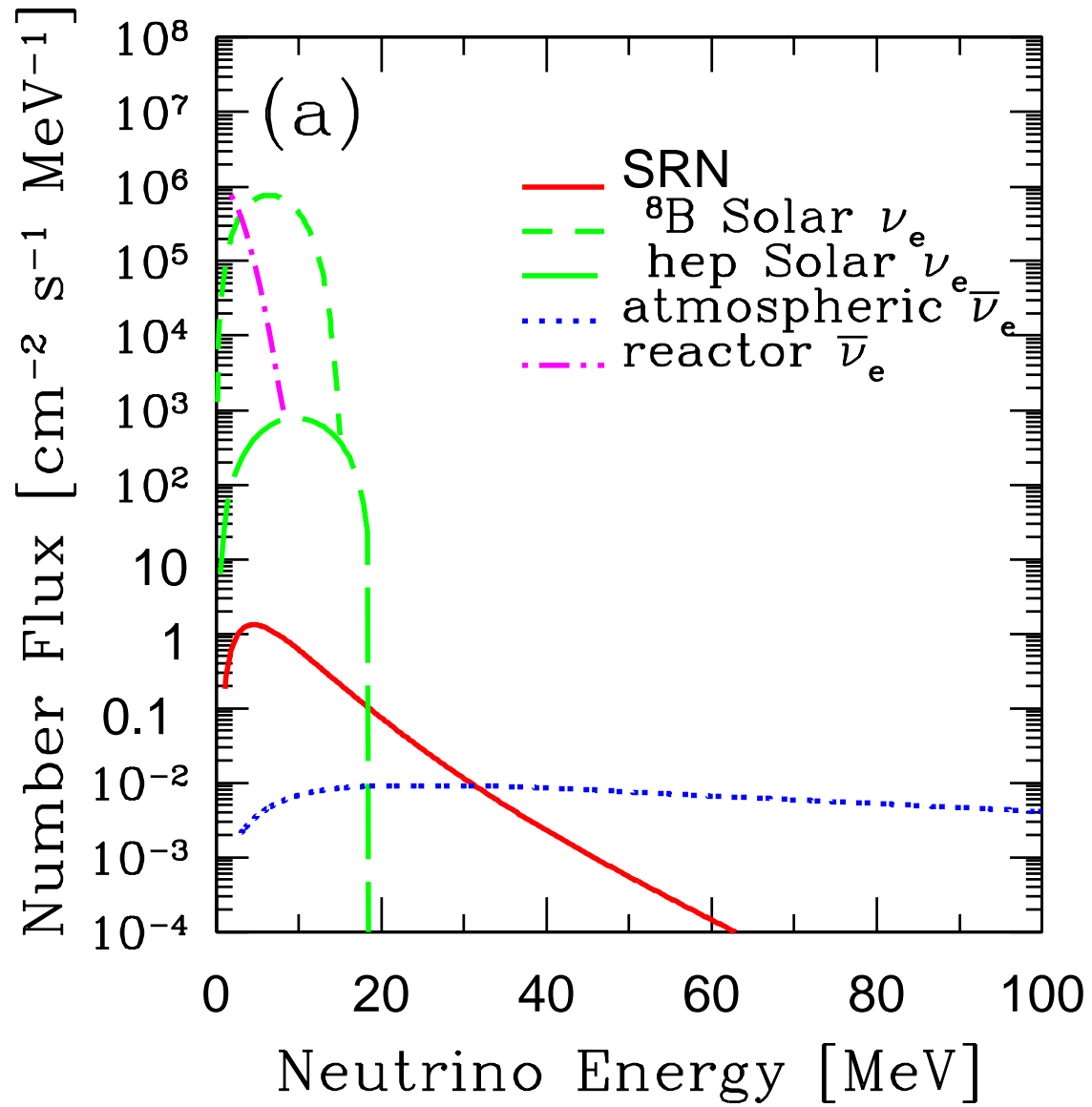
New Interactions of Supernova Relic Neutrinos

H. Goldberg, G. Perez and I.S.,
JHEP **11**, 023 (2006).

- **Dramatic modification of the supernova neutrino flux (diffuse or burst) through interactions between SN neutrinos and the cosmic background neutrinos:**



- Typical SRN energies are above solar neutrino energies and below the atmospheric ones \Rightarrow likely to be observed by SuperK, GAZOOKS, HyperK, KamLand, UNO and MEMPHYS.
- **Unique possibility of detecting the extra light degrees of freedom as well as cosmic background neutrinos!**

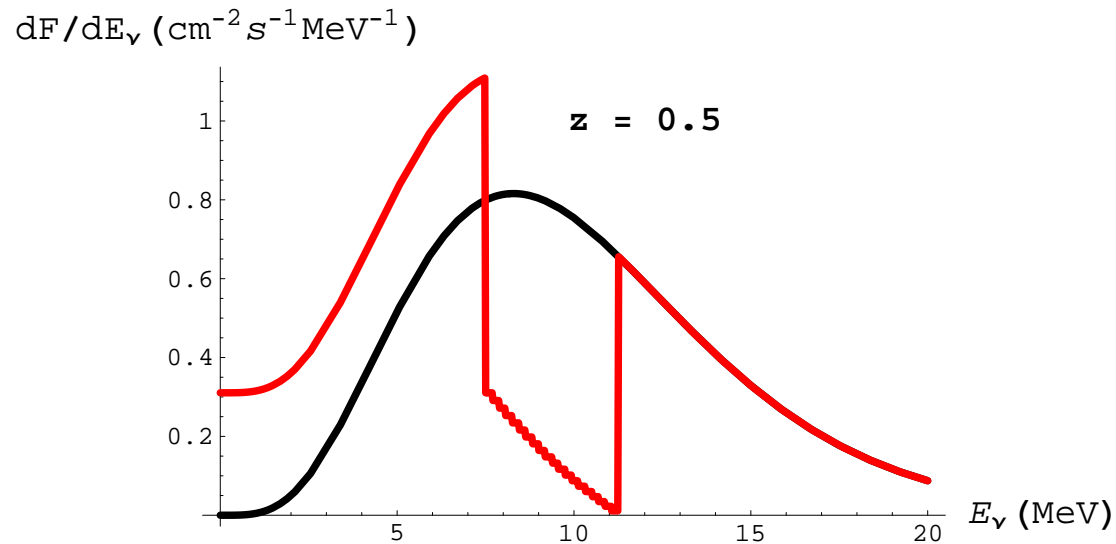


The Effect of New Interactions on SRN Flux

- SRN neutrino energies will be redistributed after the interaction
- Significant distortion 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

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 0 energy back up to $E_{unscattered}$ for each neutrino energy in resonance region



Resonance Including Cosmological Expansion

- Consider the conditions on the coupling for which there is sizable resonant degradation of the *original* flux of supernova neutrinos.
- Probability that a neutrino, created at red shift z , with energy $(1+z)E$ arrives unscattered at the detector with energy E is given by:

$$P(E, z) = \exp \left(- \int_0^z \frac{d\bar{z}}{H(\bar{z})(1+\bar{z})} n(\bar{z}) \sigma_{\nu\nu \rightarrow \phi}(2m_\nu(1+\bar{z})E) \right),$$

where $n(\bar{z}) = (1+\bar{z})^3 n_0$ is the background neutrino density at redshift \bar{z} and $n_0 \simeq 56 \text{ cm}^{-3}$.

- Large depletion of the initial SRN flux if

$$y_\nu \gtrsim 4 \times 10^{-8} \frac{M_G}{1 \text{ keV}}$$

Accumulative Resonance

- There will be resonant absorption of the original neutrino flux as well as replenishment from neutrinos re-emitted in the decay of a G .
- A neutrino emitted with energy $E_i \geq E^*$ from a source at redshift z undergoes resonant scattering at redshift $\bar{z} < z$, so that

$$E^* = E_i \frac{1 + \bar{z}}{1 + z}$$

- Neutrinos from the decay have flat energy distribution, $E' = fE^*$, $0 \leq f \leq 1$, where f varies uniformly over the region $[0,1]$.
- The spectrum with absorption has a dip at $E = E^*$, and is shifted downward from the spectrum absent resonant absorption. The complete effect of neutrinos emitted with non-resonant energies, passing through resonance, and then replenishing the flux at lower energies, is what we call **accumulative resonance**.

Event Rates

- Consider the effect of the accumulative resonance on the total SRN differential flux. The differential flux of Supernova Relic Neutrinos is given by

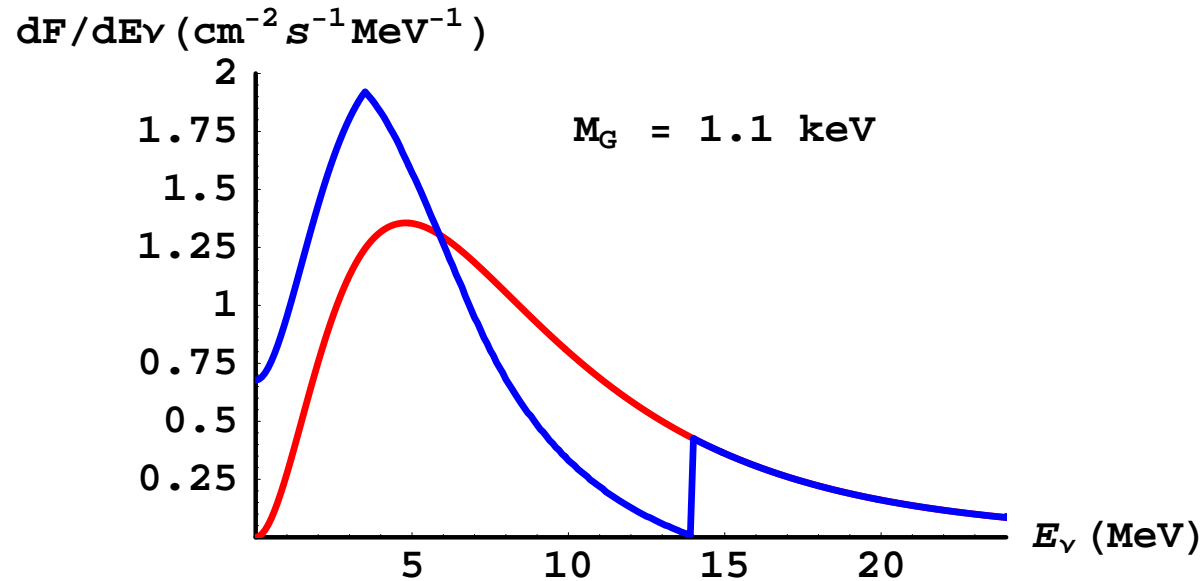
$$\frac{dF}{dE} = \int_0^{z_{max}} R_{SN}(z) \left\langle \frac{dN(\epsilon)}{d\epsilon} \right\rangle_{\epsilon=(1+z)E} (1+z) \left| \frac{dt}{dz} \right| dz ,$$

- where $\frac{dN(\epsilon)}{d\epsilon}$ is the neutrino energy spectrum, R_{SN} is the (comoving) rate of supernova formation and $\frac{dt}{dz}$ is the Jacobian given by

$$\frac{dt}{dz} = - \left[100 \frac{\text{km}}{\text{s Mpc}} h (1+z) \sqrt{\Omega_M (1+z)^3 + \Omega_\Lambda} \right]^{-1}$$

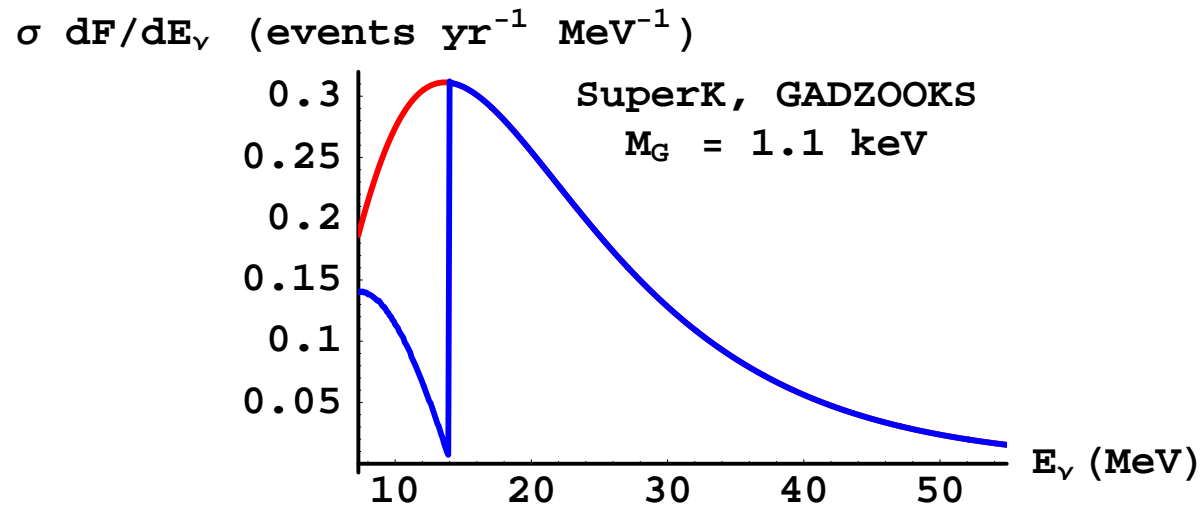
with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ and $h = 0.7$.

- The resulting differential flux, showing depletion in the incoming SRN flux due to the accumulative resonance effect (**blue curve**) and without resonance (**red curve**), integrated over redshift up to $z = 4$.



- There is a sharp dip at $E_\nu = E^* \equiv M_G^2/2m_\nu$ for all values of z .

- Differential neutrino flux folded with the detection cross section (the inverse beta decay induced by $\bar{\nu}_e$ capture in the detector):



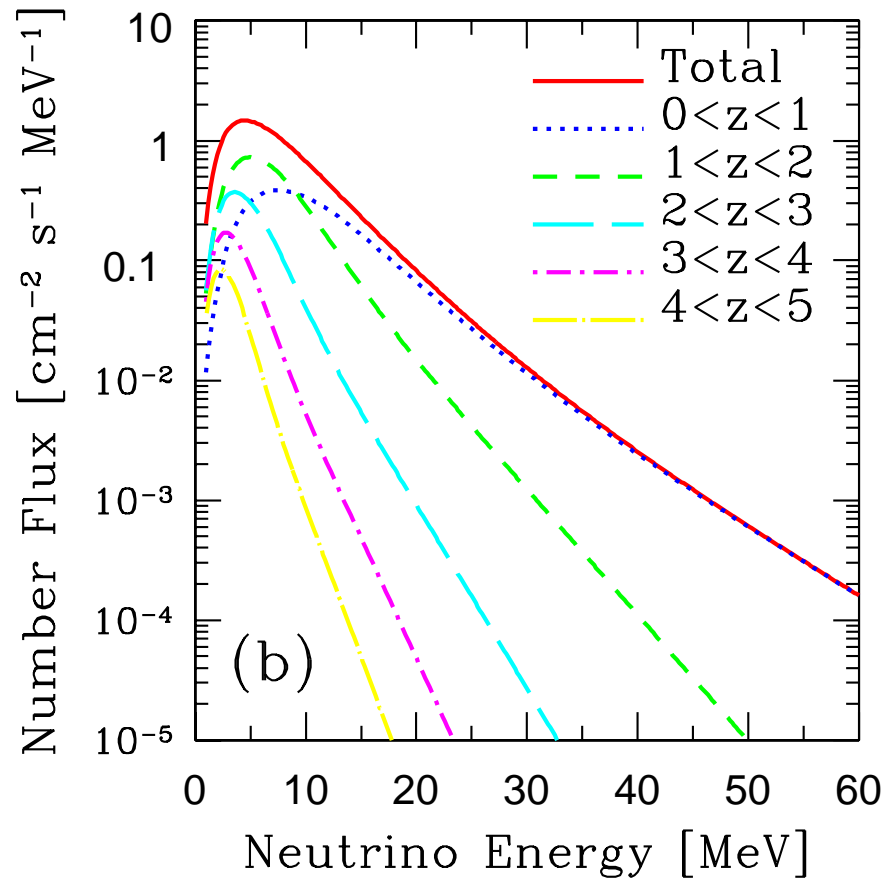
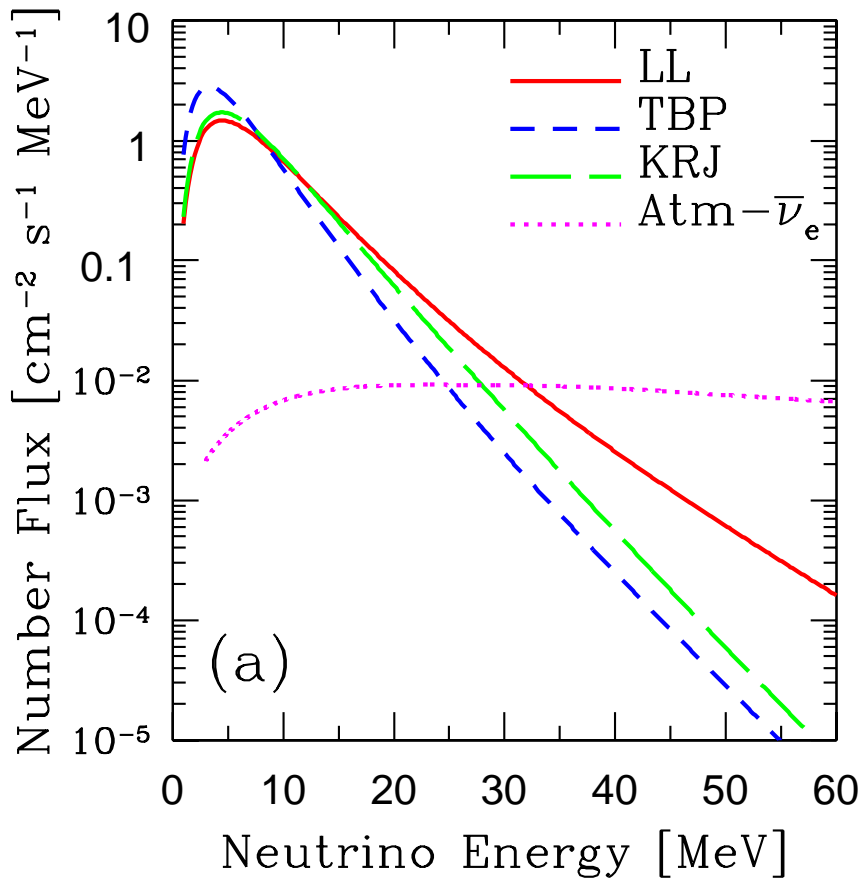
- The shape of the differential rate is modified due to the energy dependence of the cross section, i.e. $\sigma_{\bar{\nu}_e + p \rightarrow e^+ + n} \approx 0.0952 \left(\frac{E_{e^+} p_{e^+}}{1 \text{ MeV}^2} \right) \times 10^{-42} \text{ cm}^2$.
- **The main features of the effect due to the accumulation resonance such as the location of the dip and its width remain unmodified.**

Theoretical Models for Neutrino Spectrum from Supernova Explosion

- The neutrino spectrum is well fitted by a simple formula:

$$\frac{dN_\nu}{dE_\nu} = \frac{(1 + \beta_\nu)^{1+\beta_\nu} L_\nu}{\Gamma(1 + \beta_\nu) \bar{E}_\nu^2} \left(\frac{E_\nu}{\bar{E}_\nu} \right)^{\beta_\nu} e^{-(1+\beta_\nu)E_\nu/\bar{E}_\nu}$$

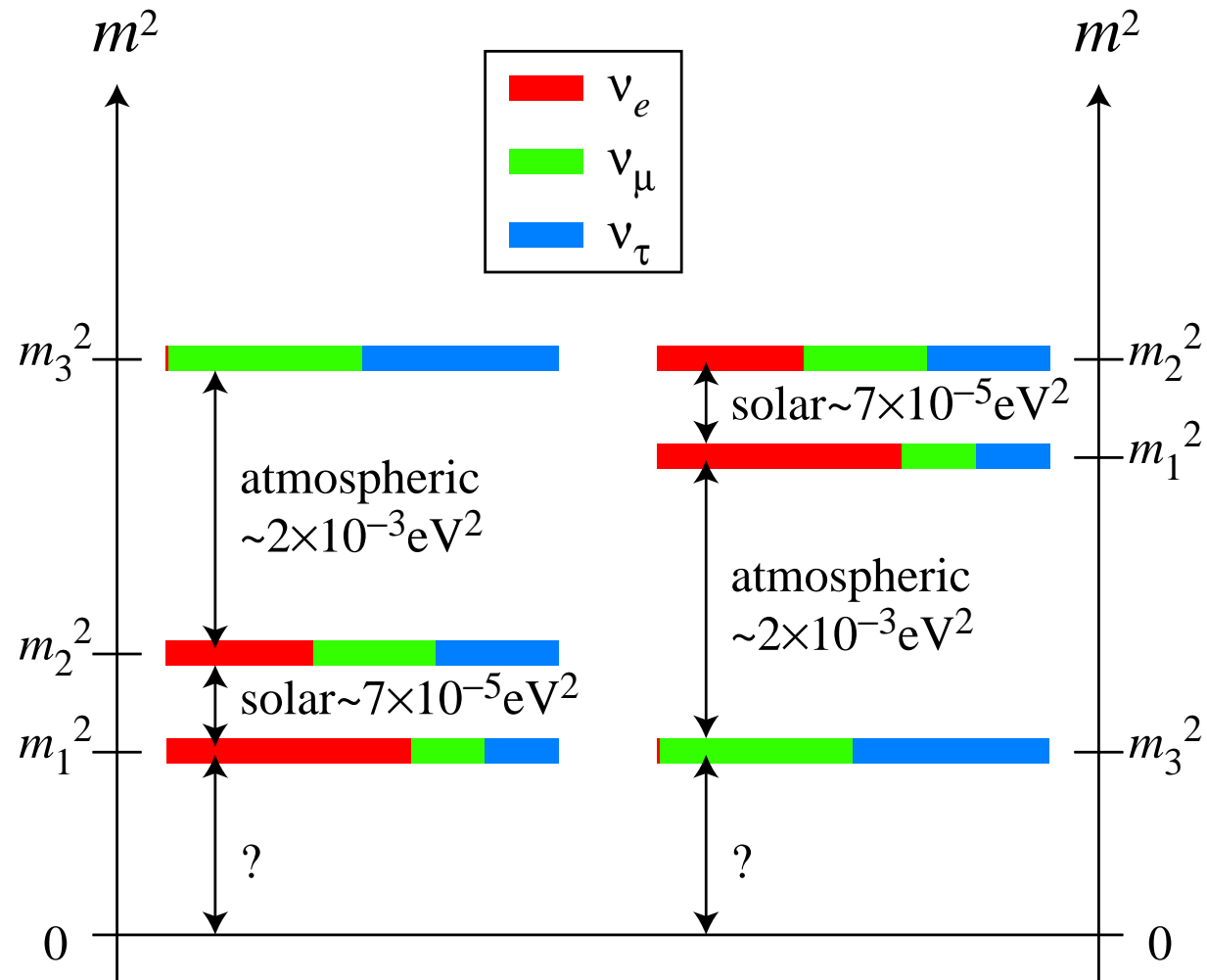
Model	Mass (M_\odot)	$\bar{E}_{\bar{\nu}_e}$ (MeV)	\bar{E}_{ν_x} (MeV)	$\beta_{\bar{\nu}_e}$	β_{ν_e}	$L_{\bar{\nu}_e}$ (erg)	L_{ν_e} (erg)
LL	20	15.4	21.6	3.8	1.8	4.9×10^{52}	5.0×10^{52}
TBP	11	11.4	14.1	3.7	2.2	—	—
	15	11.4	14.1	3.7	2.2	—	—
	20	11.9	14.4	3.6	2.2	—	—
KRJ	—	15.4	15.7	4.2	2.5	—	—



Supernova Relic Neutrino Flux

Probing Neutrino Mass Hierarchy

- Consider three flavor neutrino mixing



Flavor Composition of the Neutrino Flux that Emerges from a Supernova

- Because of the matter oscillation effects, neutrinos emerge from a supernova as coherent fluxes of mass eigenstates (F_{ν_i})

Dighe and Smirnov, PR D62, 033007 (2000)

- If neutrino evolution inside of the collapsing star is either adiabatic or fully non-adiabatic then the energy spectrum of each neutrino mass eigenstates that leaves the surface of the star corresponds to the original energy spectrum of some particular neutrino flavor eigenstate at emission from the neutrino sphere

Dighe and Smirnov, PR D62, 033007 (2000)

F_{ν_e} and $F_{\bar{\nu}_e}$ Fluxes

- For normal hierarchy:

$$F_e = P_h U_{e2}^2 F_e^0 + (1 - P_h U_{e2}^2) F_x^0$$

$$F_{\bar{e}} = U_{e1}^2 F_{\bar{e}}^0 + U_{e2}^2 F_{\bar{x}}^0$$

- For inverted hierarchy:

$$F_e = U_{e2}^2 F_e^0 + U_{e1}^2 F_x^0$$

$$F_{\bar{e}} = P_h U_{e1}^2 F_{\bar{e}}^0 + (1 - P_h U_{e1}^2) F_{\bar{x}}^0$$

$$U_{e1}^2 = \cos^2 \theta_{12}, \quad U_{e2}^2 = \sin^2 \theta_{12}; \quad \theta_{12} = \theta_{\odot}$$

$P_h = 0$ for the adiabatic case

$P_h = 1$ for non-adiabatic case.

$$\sin^2 \theta_{13} \gtrsim 10^{-3} \text{ (adiabatic, } P_h = 0)$$

$$\sin^2 \theta_{13} \lesssim 10^{-5} \text{ (non adiabatic, } P_h = 1)$$

Normal Hierarchy

$$F_{\nu_e} = F_{\nu_x}^0$$
$$F_{\bar{\nu}_e} = \cos^2 \theta_{\odot} F_{\bar{\nu}_e}^0 + \sin^2 \theta_{\odot} F_{\nu_x}^0$$

Inverted Hierarchy

$$F_{\nu_e} = \sin^2 \theta_{\odot} F_{\nu_e}^0 + \cos^2 \theta_{\odot} F_{\nu_x}^0$$
$$F_{\bar{\nu}_e} = F_{\nu_x}^0$$

Normal & Inverted Hierarchies

$$F_{\nu_e} = \sin^2 \theta_{\odot} F_{\nu_e}^0 + \cos^2 \theta_{\odot} F_{\nu_x}^0$$
$$F_{\bar{\nu}_e} = \cos^2 \theta_{\odot} F_{\bar{\nu}_e}^0 + \sin^2 \theta_{\odot} F_{\nu_x}^0$$

Normal Hierarchy

- In the case of the normal hierarchy the neutrinos emerge from the supernova in mass eigenstates and carry information with them about the original fluxes of different neutrino flavors according to

$$\begin{aligned} F_1 &= F_{\nu_\mu}^0 & F_{\bar{1}} &= F_{\bar{\nu}_e}^0 \\ F_2 &= F_{\nu_\tau}^0 & F_{\bar{2}} &= F_{\bar{\nu}_\mu}^0 \\ F_3 &= F_{\nu_e}^0 & F_{\bar{3}} &= F_{\bar{\nu}_\tau}^0 \end{aligned}$$

- $F_{\bar{\nu}_e}$ flux seen at Earth is a mixture of the one-bar and two-bar mass eigenstates (the mixing of the mass three eigenstate in electron type neutrinos is small),

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

Inverted Hierarchy

- In the case of the inverted hierarchy the neutrino mass eigenstates carry information about the original fluxes of the different types of neutrinos according to

$$\begin{aligned} F_1 &= F_{\nu_\mu}^0 & F_{\bar{1}} &= F_{\bar{\nu}_\tau}^0 \\ F_2 &= F_{\nu_e}^0 & F_{\bar{2}} &= F_{\bar{\nu}_\mu}^0 \\ F_3 &= F_{\nu_\tau}^0 & F_{\bar{3}} &= F_{\bar{\nu}_e}^0 \end{aligned}$$

- In this case the final electron antineutrino flux is given by

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

- The observed SRN spectrum depends on the **neutrino mass hierarchy**, whether neutrinos are **Majorana or Dirac** and whether there is a **heavy sterile neutrino**. It also depends on how many of the mass eigenstates go through the resonance on their way to the earth.
- After the interaction, the modified flux is given by

$$\widetilde{F}_{\bar{1}} = F_{\bar{1}} - F_{\bar{1}}^{res} + P_1 \times (F_{1 \rightarrow \bar{1}}^{res} + F_{\bar{1} \rightarrow \bar{1}}^{res} + F_{2 \rightarrow \bar{1}}^{res} + F_{\bar{2} \rightarrow \bar{1}}^{res} + F_{3 \rightarrow \bar{1}}^{res} + F_{\bar{3} \rightarrow \bar{1}}^{res})$$

where $F_{\bar{1}}$ is the original flux, $F_{\bar{1}}^{res}$ is the flux of one-bar neutrinos that go through resonance, and the $F_{i \rightarrow \bar{1}}^{res}$ are the contribution from the state i to the final one-bar flux after going through the resonance. P_1 is the probability that a boson will decay into the one-bar mass eigenstate neutrino.

- For Dirac case a factor of 1/2 multiplies the third term.
- Different eigenstates, i , that give contribution to $F_{\bar{1}}$ go through the resonance at different energies for a given boson mass.

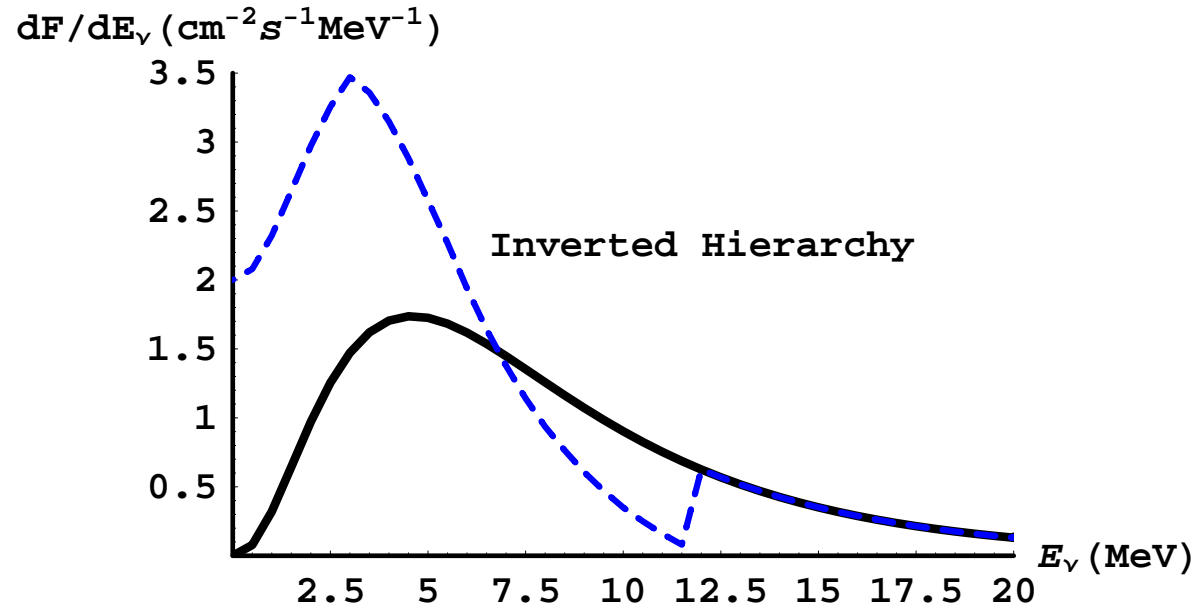
- Similarly,

$$\widetilde{F}_2 = F_2 - F_2^{res} + P_2 \times (F_{2 \rightarrow 2}^{res} + F_{2 \rightarrow 2}^{res} + F_{1 \rightarrow 2}^{res} + F_{1 \rightarrow 2}^{res} + F_{3 \rightarrow 2}^{res} + F_{3 \rightarrow 2}^{res})$$

- Mixing with the third eigenstate is small, thus the combination of these modified fluxes, \widetilde{F}_1 and \widetilde{F}_2 determines the observed spectra.
- The modified flux of electron antineutrinos can then be written as

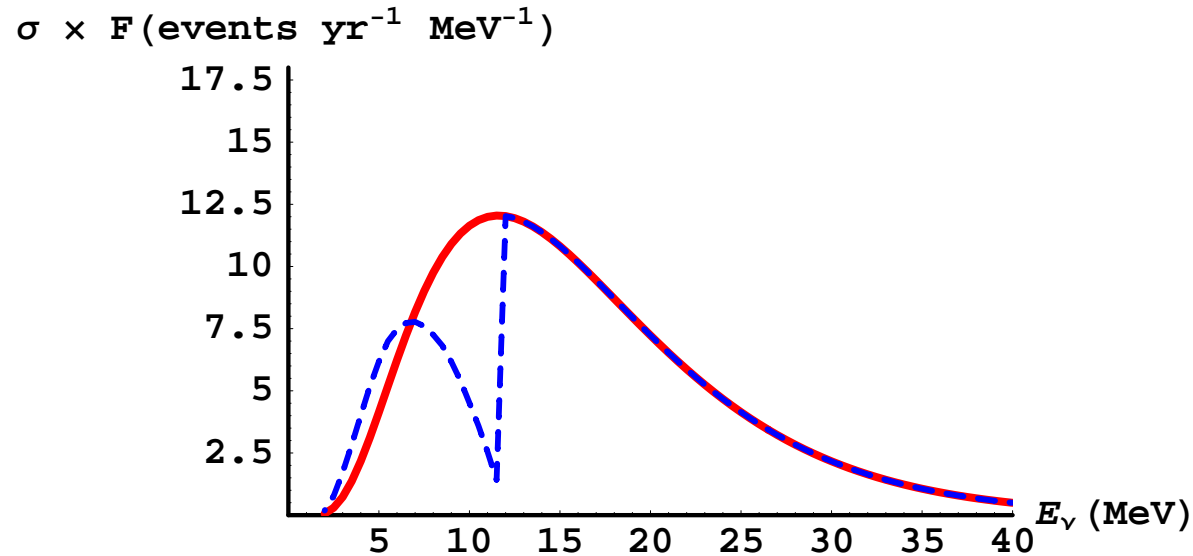
$$\widetilde{F}_{\bar{\nu}_e} = \cos^2 \theta_{12} \widetilde{F}_1 + \sin^2 \theta_{12} \widetilde{F}_2.$$

Neutrino Mass Hierarchy

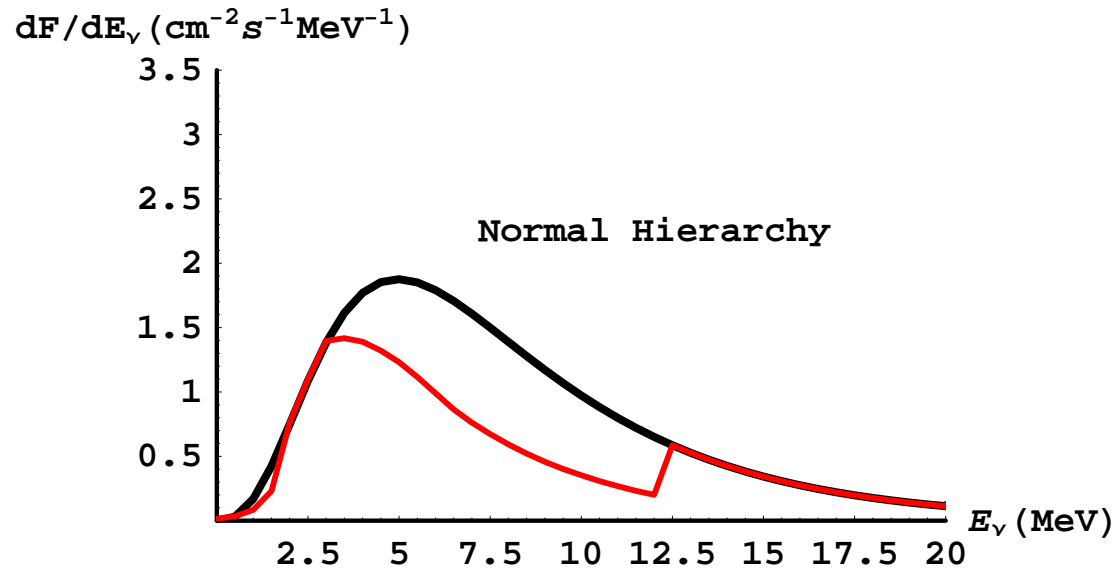


- $m_1 \simeq m_2 \simeq 0.05$ eV, $m_3 \simeq 0.008$ eV
- m_1 and m_2 neutrinos go through resonance at $E_\nu^{Res} \approx 12$ MeV ($M_G \approx 1$ keV); m_3 neutrino goes through resonance at $E_\nu^{Res} \approx 63$ MeV
- The decay probabilities are $P_1 \approx 0.49$, $P_2 \approx 0.49$ and $P_3 \approx 0.02$.

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

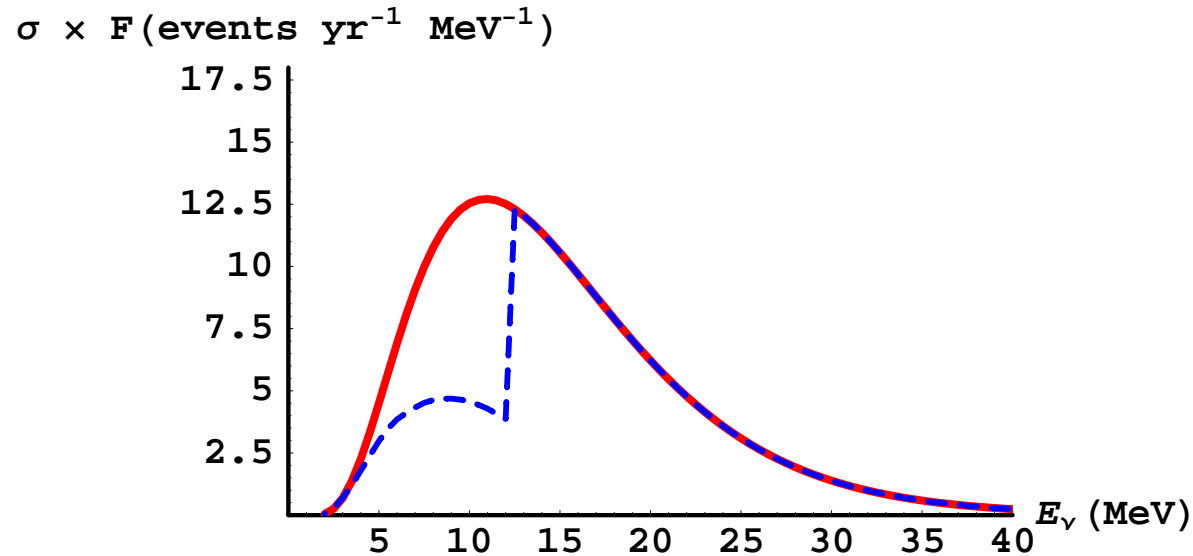


- Differential flux folded with the detection cross section (inverse beta decay induced by antineutrino capture in the detector)
 - Cross section for antineutrinos on protons is increasing function of the energy, leading to observed shape
- Main features, i.e. dip location, remain unchanged



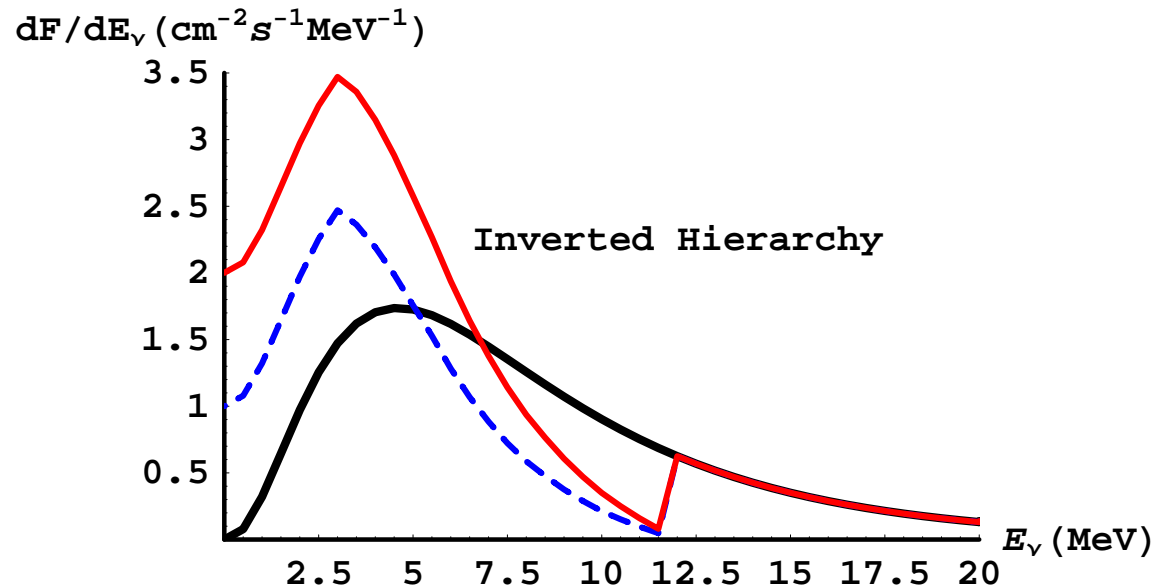
- $m_1 \simeq 0.002$ eV, $m_2 \simeq 0.009$ eV, $m_3 \simeq 0.05$ eV
- Two heavier neutrino mass eigenstates have dip at lower energies, $E_2^{Res} \approx 3$ MeV and $E_3^{Res} \approx 0.5$ MeV
- The probabilities are: $P_1 \approx 0.005$, $P_2 \approx 0.025$ and $P_3 \approx 0.97$.
- Overall depletion because G decays with P_3 into heaviest neutrino mass eigenstate, which does not contribute to electron antineutrino flux.

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

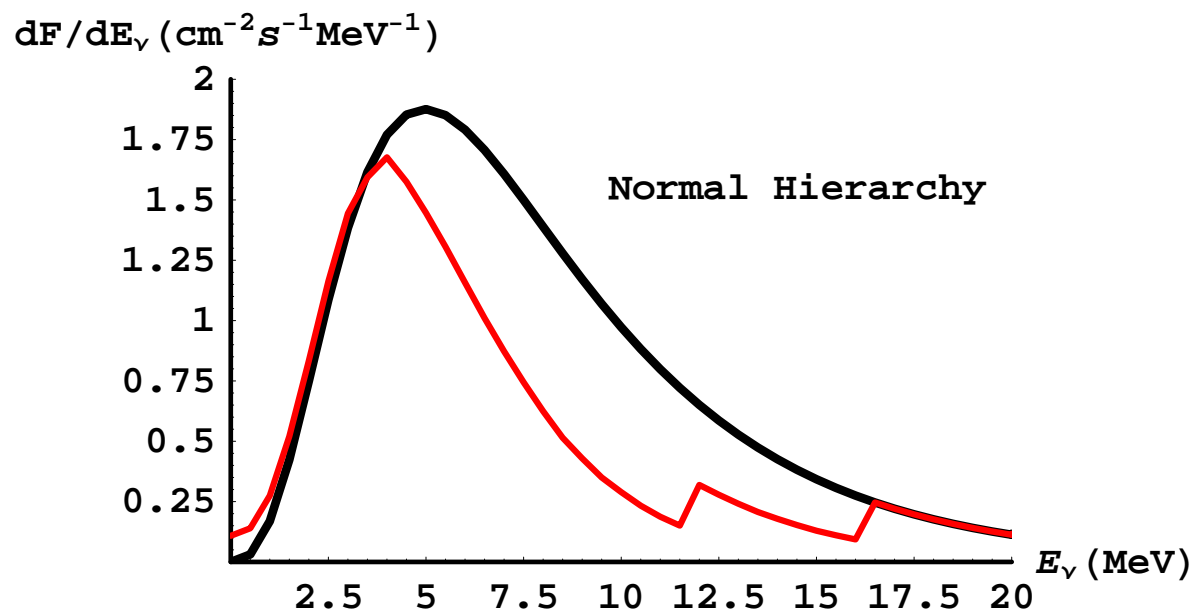
Dirac vs. Majorana Neutrinos?



- 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 $N\bar{\nu}$

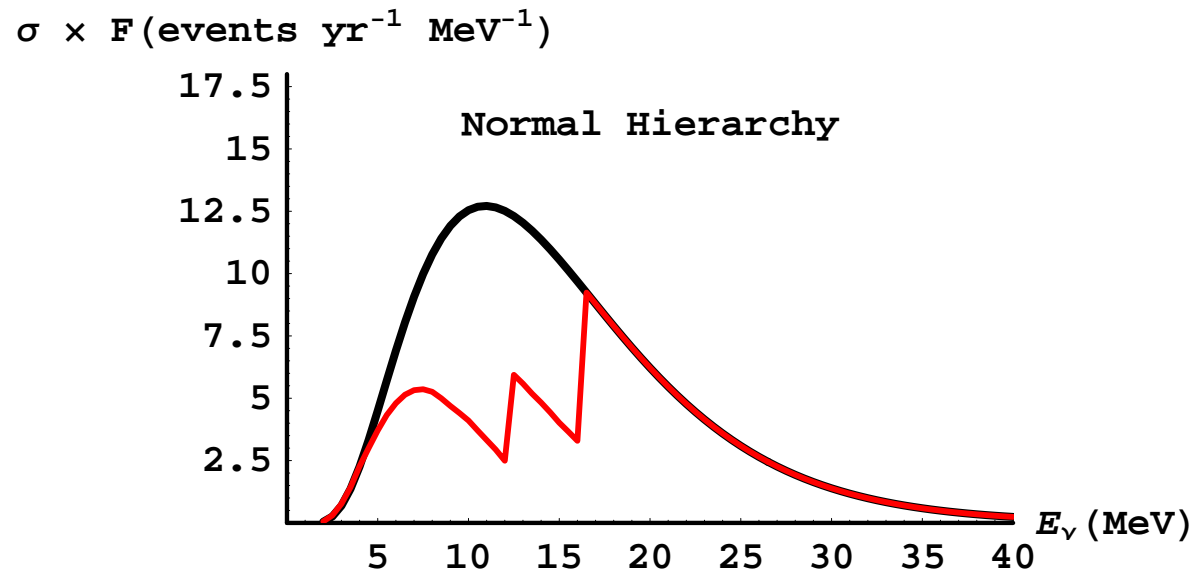
Overall factor of 1/2 for Dirac vs. Majorana particles

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

Bounds on Neutrino Mass Models from BBN Constraints

- **The minimal model:** Majorana neutrinos with Abelian symmetry. The symmetry breaking scale, f , is below the BBN temperature of about 1 MeV. During the BBN epoch we cannot separate the Goldstone and the scalar (higgs) as they are a single entity, a complex scalar field. The BBN bound on the number of neutrinos is $N = 3.24 \pm 1.2$ at 95%. The complex scalar adds $8/7$ (neutrino) degrees of freedom, so this additional degree of freedom can be accommodated with the BBN bound above.
- **In the non-Abelian Majorana models, typically several complex scalars are present, which are not permitted to be by BBN considerations. Thus, in this case y_ν must be bounded from above to ensure decoupling. We have considered all the processes that would produce G's. Recoupling via the $2 \rightarrow 1$ process $\nu\nu \rightarrow G$ takes place as the temperature falls to some value T_{rec} determined**

by equating the decay rate at T_{rec} to the Hubble expansion rate:

$$\frac{M_G}{3T_{\text{rec}}} \frac{y_\nu^2 M_G}{16\pi} = \sqrt{\frac{8\pi^5 g}{45}} \frac{T_{\text{rec}}^2}{M_{Pl}^2} ,$$

where g is the number of degrees of freedom at T_{rec} . By requiring $T_{\text{rec}} < T_{\text{BBN}}$ we find

$$y_\nu \lesssim 6 \times 10^{-7} (\text{keV}/M_G)$$

- For the Dirac case, the absence of a negligible population of right-handed (sterile) neutrinos (N) in the bath disallows the reaction $\nu N \rightarrow G$, so that G 's can only be produced via $\nu_L \nu_L \rightarrow G G$ (via t channel N exchange). Requiring that this process be out of equilibrium at T_{BBN} yields a BBN bound of

$$y_\nu \lesssim 1 \times 10^{-5} .$$

The s -channel process requires a chirality flip which makes the bound weaker. Note that this bound is independent of the Goldstone mass.

Non-Resonance Processes

- Two Goldstones production through scalar exchange, the off-resonance process.

- For $s \ll M_\phi^2$, $\sigma_{\text{GG}} \sim \frac{y_\nu^2 f^2}{m_\phi^4} \sim \frac{y_\nu^2}{f^2} \sim \frac{y_\nu^4}{m_\nu^2}$.

- To have a substantial scattering, $\lambda_{\text{non-res}} H \simeq \frac{H m_\nu^2}{T_\nu^3 y_\nu^4} \ll 1$.

\Rightarrow This yields a lower bound on y_ν (independent of M_G):

$$y_\nu > \left(\frac{H m_\nu^2}{T_\nu^3} \right)^{1/4} \sim 10^{-6} \left(\frac{m_\nu}{0.05 \text{ eV}} \right)^{1/2}$$

- Dramatic effect on the SRN flux: **If $M_G < 2m_\nu$ and there is sufficient optical depth, all the SRN will be transformed into invisible Goldstones and the signal is lost.** **If $M_G > 2m_\nu$ then the process can effectively be characterized as $\nu \rightarrow 4\nu$, implying a substantial shifting of the entire SRN spectrum to lower energies.**

Bounds from SN1987A

- For a point source at distance ℓ , the condition for sufficient optical depth is

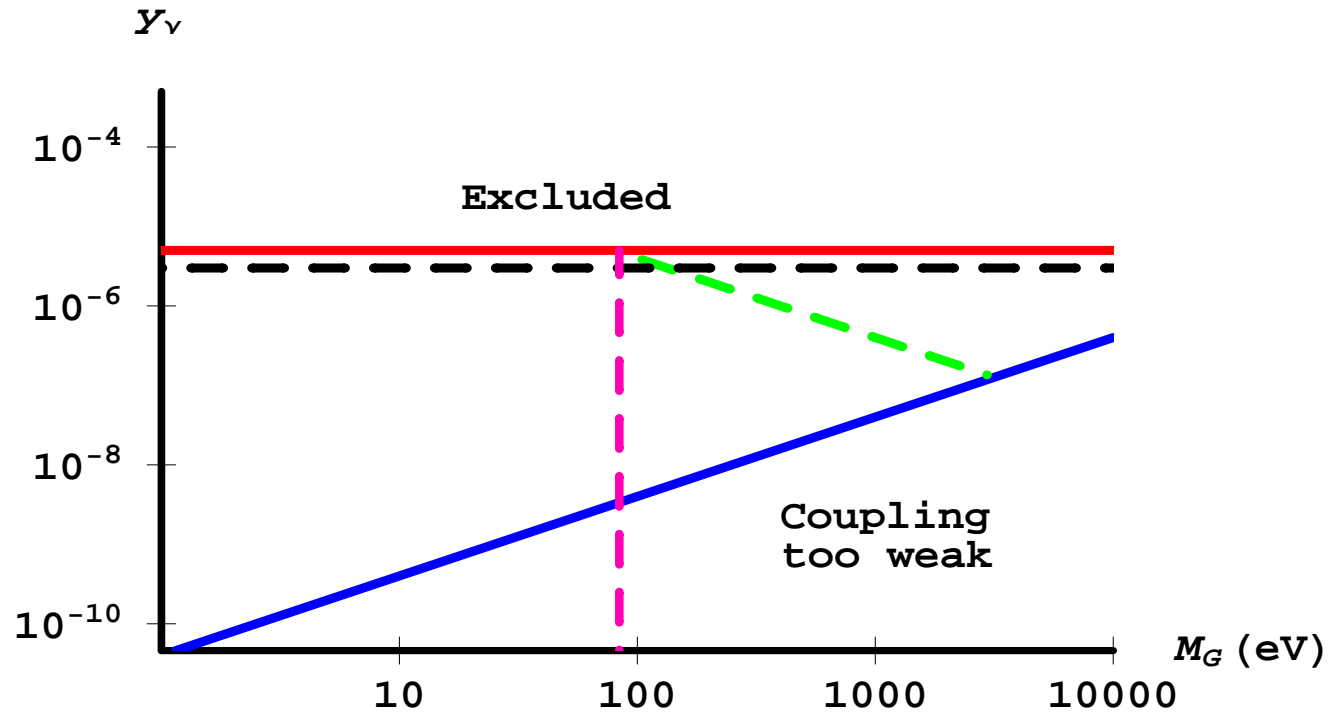
$$y_\nu \geq 3.3 \times 10^{-6} \left(\frac{3000 \text{ Mpc}}{\ell} \right)^{1/4}$$

where l is the distance travelled by the SRN. For SN1987A, $\ell = 50 \text{ kpc}$.

- SN1987A neutrinos observed with undegraded energy, implying an independent upper bound on y_ν

$$y_\nu \leq 5.5 \times 10^{-5}$$

which is comparable to the cosmological one.



The region above the red line is excluded by the BBN constraint (for the Dirac case), SN cooling (for Majorana case) and due to the observation of (undegraded) SN1987A neutrinos. In the region below the blue line the mean free path is too long for the resonance to occur. The region above the green line, which is relevant only for the non abelian Majorana case, is the region excluded by the BBN constraint. The region above the black dashed line is the region of the future experimental sensitivity to the observation/non-observation of the SRN neutrinos due to the the non-resonant processes.

Summary

- Interactions between the SRN and $C\nu B$ neutrinos via light bosons can result in a dramatic change of the SRN neutrino flux
- Measurements of these effects could shed light on
 - ★ Symmetry structure of neutrino mass generation
 - ★ Presence of the $C\nu B$
 - ★ Neutrino mass hierarchy
 - ★ Possibility to distinguish between Dirac and Majorana neutrinos
 - ★ Absolute values of the neutrino masses
- Measurements of these effects are well within reach of future neutrino experiments (GADZOOKS, HyperK, UNO, MEMPHYS)