Neutrino Flavor Changing Neutral Currents and Stellar Collapse

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Introduction

We know neutrino flavor changing occurs in nature

- Neutrinos have mass
- Flavor eigenstates are not mass eigenstates
- Flavor states oscillate
- Quantum mechanical effect

Another way neutrinos (or other particles) could change flavor is by flavor violating interactions

- Feature of some extensions to Standard Model
- Not discovered, constrained

If certain neutrino flavor changing scattering processes are included in Supernova model, the model is significantly changed!

Outline

- Interactions
- Scattering cross sections
- Supernova model (relevant parts)
- Effects of neutrino flavor changing scattering on model (qualitative)
- Quantitative results

Interactions

Low Energy Effective Theory:

$$\mathcal{L} = G_F \bar{\nu}^i \gamma^\mu (1-\gamma_5)\nu^j \bar{q}\gamma^\mu (\epsilon^q_{V_{ij}} + \epsilon^q_{A_{ij}}\gamma_5) q$$

Notice:

- neutral current
- neutrino flavor changing

$\Big\}$ FCNC's

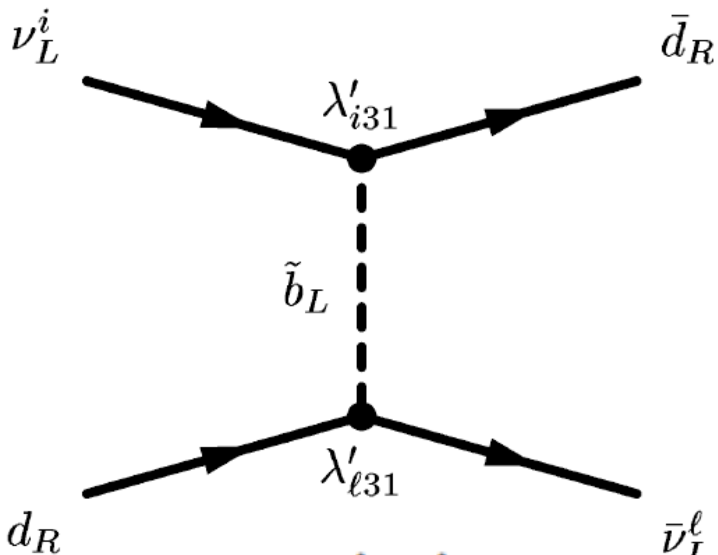
- epsilons - dimensionless parameter < 1
- could have other particles in place of quarks

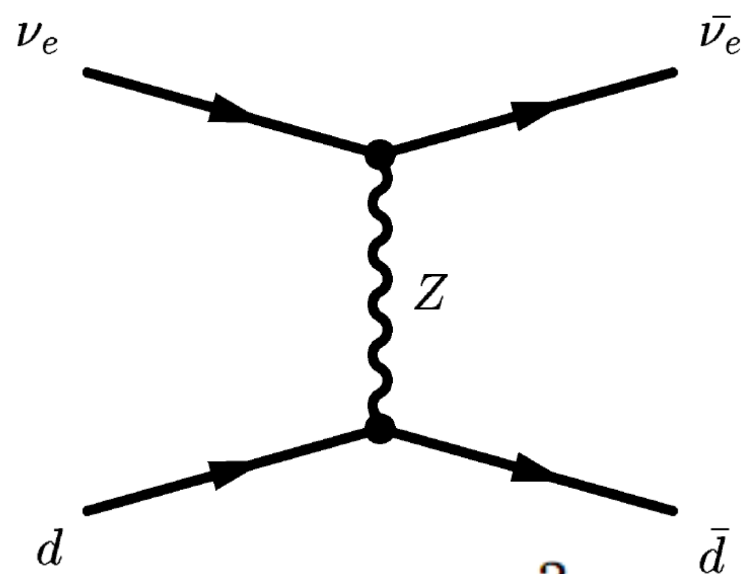
Examples:

- R_p violating SUSY
- Minimal Flavor Violation Hypothesis   hep-ph/0507001
- Lepto-Quark Models
- See talks from this meeting by Bell, Perelstein, Perez

Interactions

$$\mathcal{L} = G_F \bar{\nu}^i \gamma^\mu (1-\gamma_5) \nu^j \bar{q} \gamma^\mu (\epsilon^q_{V_{ij}} + \epsilon^q_{A_{ij}} \gamma_5) q$$





$$\frac{\lambda' \lambda'}{m^2_{\tilde{d}}}$$

$$\frac{G_F}{\sqrt{2}} \equiv \frac{g^2}{8 m_W^2}$$

Low energy effective theory: (Momentum transfer)^2 << M^2

Cross Sections

$$\mathcal{L} = G_F \bar{\nu}^i \gamma^\mu (1-\gamma_5)\nu^j \bar{q}\gamma^\mu(\epsilon^q_{V_{ij}} + \epsilon^q_{A_{ij}}\gamma_5)q$$

Nuclear matter in star…

Consider simplest case: Cross section for flavor changing elastic scattering with spin zero, Z=N, nucleus

Matrix Elements:

$$\begin{aligned}\langle (Z,N)p' \left| \bar{q}\gamma^\mu q \right| (Z,N)p\rangle &= f_q(t)(p+p')^\mu \\ \langle (Z,N)p' \left| \bar{q}\gamma^\mu \gamma_5 q \right| (Z,N)p\rangle &= 0\end{aligned}$$

$$Q_q = \int d^3x \bar{q}\gamma^0 q \quad \left\{ \begin{aligned} f_u(0) &= 2Z+N \\ f_d(0) &= Z+2N \end{aligned} \right.$$

Exact!

$$f_q(t) \simeq f_q(0)$$

$$\sigma_{ij} = \frac{G_F^2}{2\pi}\left|\epsilon^d_{V_{ij}} f_d(0) + \epsilon^u_{V_{ij}} f_u(0)\right|^2 \frac{4M^2E_\nu^2}{M^2+2ME_\nu}$$

Cross Sections

$$\sigma_{ij} \approx \frac{2G_F^2}{\pi}|\epsilon^d_{V_{ij}}(2N+Z)+\epsilon^u_{V_{ij}}(2Z+N)|^2 E_\nu^2$$

Compare to cross section for SM Neutral Current neutrino coherent scattering on a spin zero nucleus:

$$\sigma \approx \frac{2G_F^2}{\pi}(Z+N)^2 E_\nu^2$$

Notice For FCNC Cross Section:

- Coherent Amplification
- Factor of $(2N)^2$ becomes 16N for random walk number of scatterings [important as nuclei become neutron rich]

Approximations:

- vacuum cross sections, but nuclei are in hot dense medium
- other states of nuclear matter in core
- $f(q^2) = f(0)$

Supernova Model

Core Collapse Supernova

- Iron core of star about 1.5 solar masses
- Core supported by electron degeneracy pressure
- Core goes unstable, collapse of order 1 second
- Number of electrons determine evolution of core during collapse (again degeneracy pressure)
- Electron capture produces heavy neutron rich nuclei and electron neutrinos
- Neutrinos become trapped in core because of coherent scattering on heavy nuclei
- Net electron capture ceases when the sea of electron neutrinos reaches maximum level
- Inner region of core reaches nuclear density, outer region bounces off inner region and produces shockwave
- Somehow the star explodes

Supernova Model

Explosion:

- Shockwave forms and boundary between inner & outer core
- Mass of homologous inner core depends on Y_e
- Initial shock energy depends on mass of inner core and thus Y_e
- Amount of material in outer core (that shock must pass through) depends on mass of inner core
- Simulations show shock stalls, but then gets revived
- Do neutrinos participate in shock revival by depositing energy behind the shock???
- SN explosion energy about 10^{51} ergs (optical & kinetic)
- Energy released in neutrinos 10^{53} ergs (10% of stars rest mass)
- Explosion energy is 1% of neutrino energy

Supernova Model

$$Y_e = \frac{n_{e^-} - n_{e^+}}{n_b}$$

At onset of collapse: $Y_e = 0.42$

$$e^- + (Z, A) \leftrightarrow \nu_e + (Z-1, A)$$
$$e^- + p \leftrightarrow \nu_e + n$$

Neutrinos scatter (NC) off heavy (neutron rich) nuclei: $\sigma \sim (\frac{E_\nu}{m_e})^2 A^2$

Neutrinos become trapped in core; build up sea of neutrinos up to their Fermi Level ---> **net electron capture ceases** ---> $Y_e \sim 0.35$

$$M_{hc} \sim 5.8 Y_e^2 M_\odot$$
$$E_i \sim (Y_e^f)^{10/3}$$

Qualitative Effects

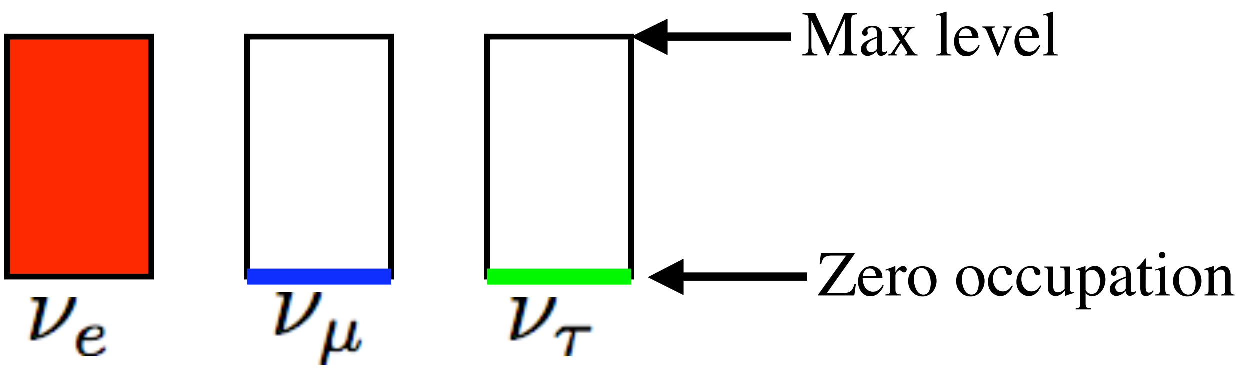
$$\nu_e \longrightarrow \nu_{\mu,\tau}$$

Open holes in neutrino sea, allow electron capture to proceed…

$$e^- + p \rightarrow \nu_e + n$$

Net reduction in Y_e

After trapping and before bounce, levels of the FD seas of neutrinos:



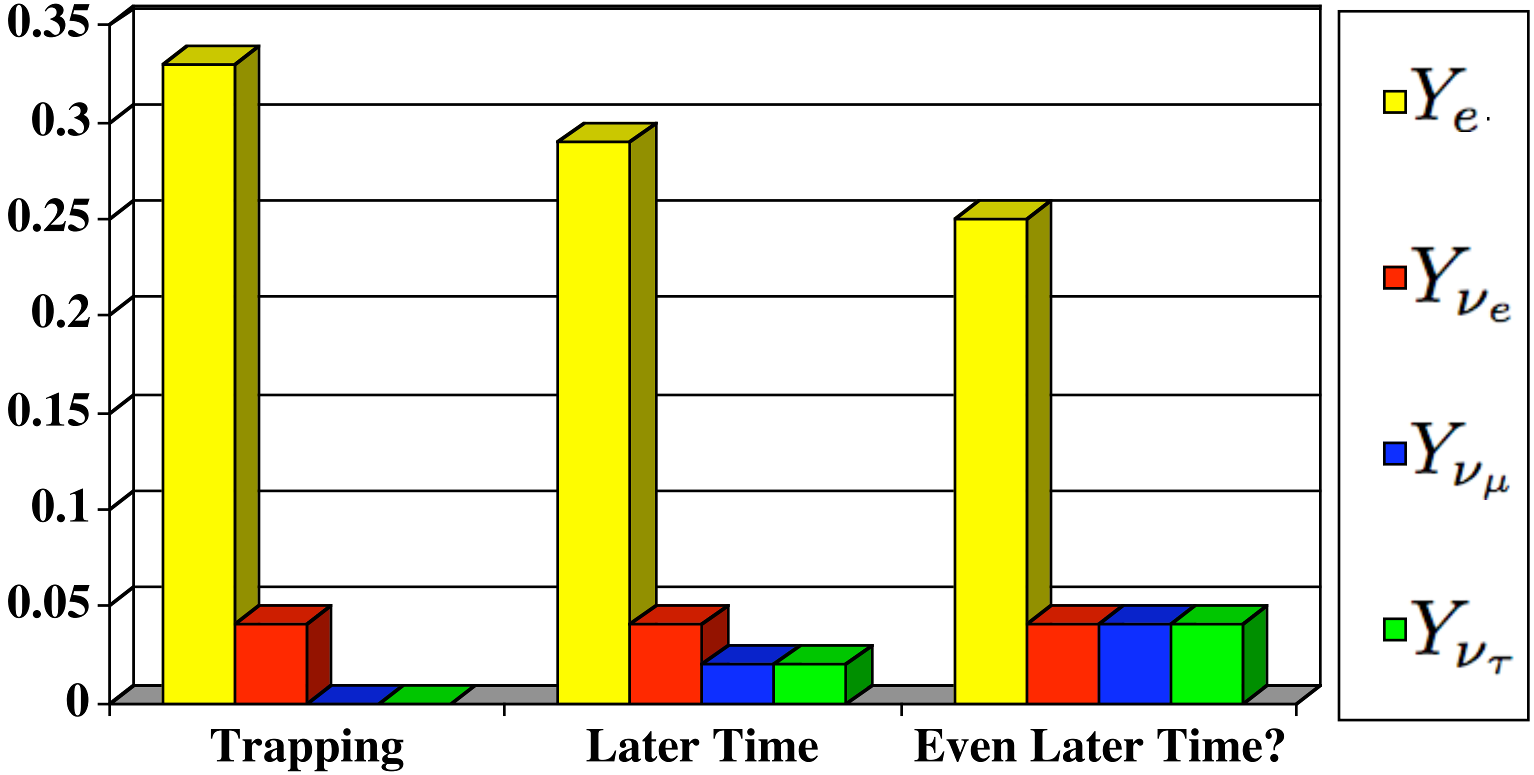
Cross sections for e^- capture > cross sections for FC scattering
so holes opened in ν_e sea are immediately replaced by electron capture

ν_e level remains the same ---> $\Delta Y_e = -(\Delta Y_{\nu_\mu} + \Delta Y_{\nu_\tau})$

Qualitative Effects

Possibilities between trapping and bounce

(time scale 100-200 milliseconds)



Qualitative Effects

Lower Y_e

$E_i \sim (Y_e^f)^{10/3}$ ⇒ Lower initial shock energy

$M_{hc} \sim 5.8 Y_e^2 M_\odot$ ⇒ More outer core material for shock to pass through

Disfavor getting explosion

Existance of ν_μ and ν_τ

More neutrinos participating in depositing energy behind shock

Favors getting explosion

Existence of mu and tau neutrinos in signal…

Model is significantly changed!

These effects exist for any model that gives sufficient neutrino flavor changing

Results

Extent of these effects for our case?

For neutrino FCNC scattering with **d quarks**:

$$\nu_e \leftrightarrow \nu_\mu \qquad\qquad \nu_e \leftrightarrow \nu_\tau$$

$$\epsilon < 10^{-3} \qquad\qquad \epsilon < 0.5$$

$$\sigma_{ij} = \frac{2G_F^2}{\pi}\epsilon^2(2N+Z)^2 E_\nu^2$$

Number of scatterings with targets T: $N_T = \left(\frac{R}{\lambda_T}\right)^2$

Mean free path between scatterings on target T: $\lambda_T^{-1} = n_T \sigma_T$

Results

For $Y_{\nu_e}^{\mathrm{trap}} = 0.05$, maximum possible $\Delta Y_e = 0.1$

Estimate numbers of flavor changing scatterings with R=50km:

ρ_{12} 10^{12}g/cm^3	$\epsilon = 10^{-1}$	$\epsilon = 10^{-2}$	$\epsilon = 10^{-3}$	$\epsilon = 10^{-4}$
1	10	10^{-3}	10^{-7}	10^{-11}
10	10^{5}	10	10^{-3}	10^{-7}
100	10^{8}	10^{4}	1	10^{-2}
1000	10^{11}	10^{7}	10^{3}	10^{-1}

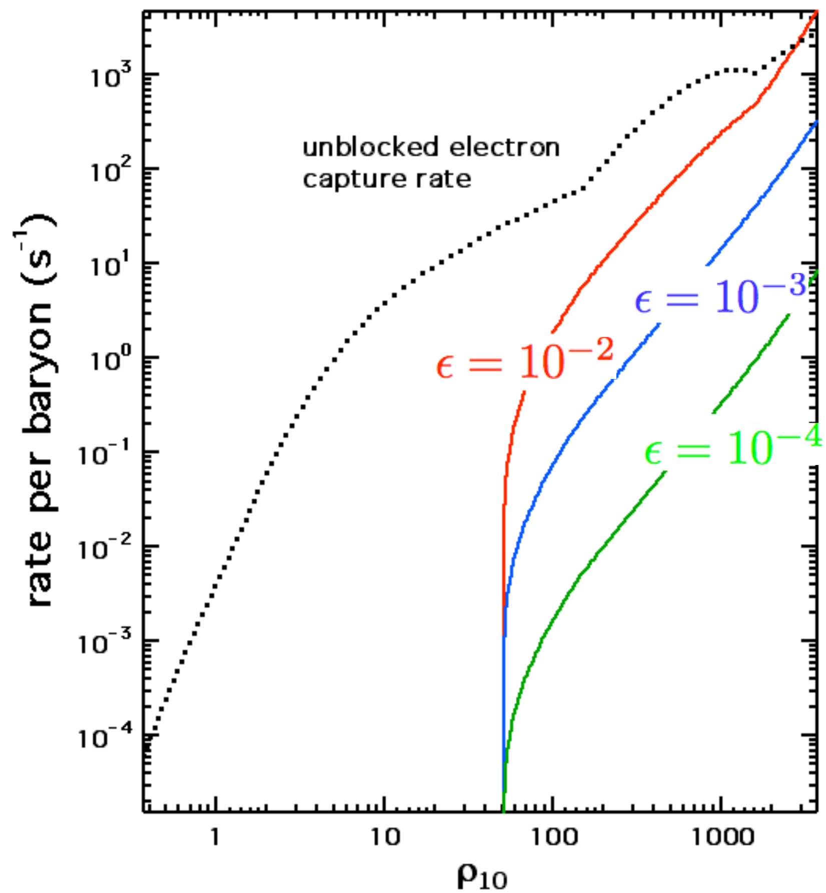
Results

1 Zone Calculation

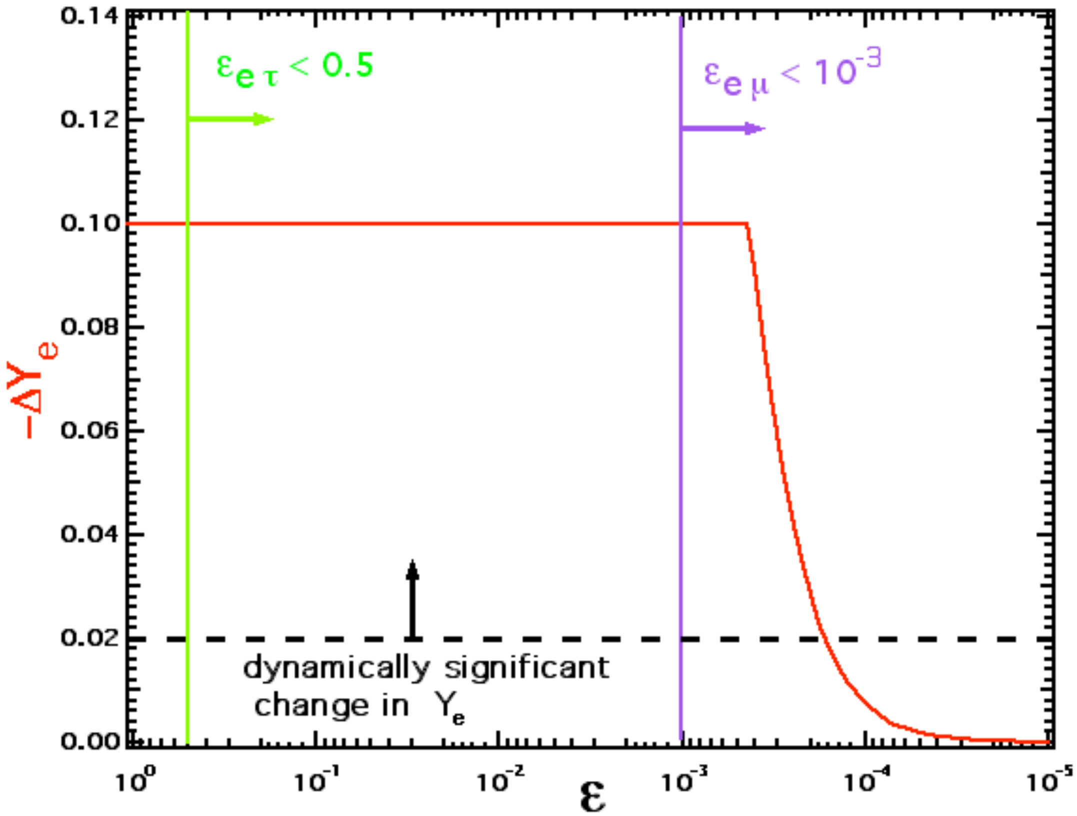
Neutrino flavor changing rates per nucleus and free nucleon:

$$\lambda_A = (\rho N_A Y_{\nu_e} c)\, \epsilon^2 G_F^2 E_\nu^2 (2N+Z)^2 \qquad \lambda_{\rm fn} = (\rho N_A Y_{\nu_e} c)\, \epsilon^2 G_F^2 E_\nu^2$$

- FCNC's turned on after trapping
- e^- capture fast compared to FCNC
- Y_e reduced for every FCNC



Results



Density range:

$$5 \times 10^{11} \text{ to } 1.5 \times 10^{12} \ \frac{\text{g}}{\text{cm}^3}$$

The total reduction in Y_e over this density range as a function of epsilon

Reducing Y_e by 0.1 reduced initial shock energy by about a factor of 3

Conclusions

- Neutrino FCNC's can cause more flavor transformation than matter enhanced oscillation
- Qualitative effects apply to any model for neutrino FCNC's
- Neutrino-quark FCNC's enhanced by coherence
- LHC may see new physics of this type - then it must be included in SN model
- Detection of SN neutrinos could give evidence for new physics of this type
- Need a more accurate simulation of this effect