Multiple Splits in Supernova Neutrino Spectra And r-Process Nucleosynthesis

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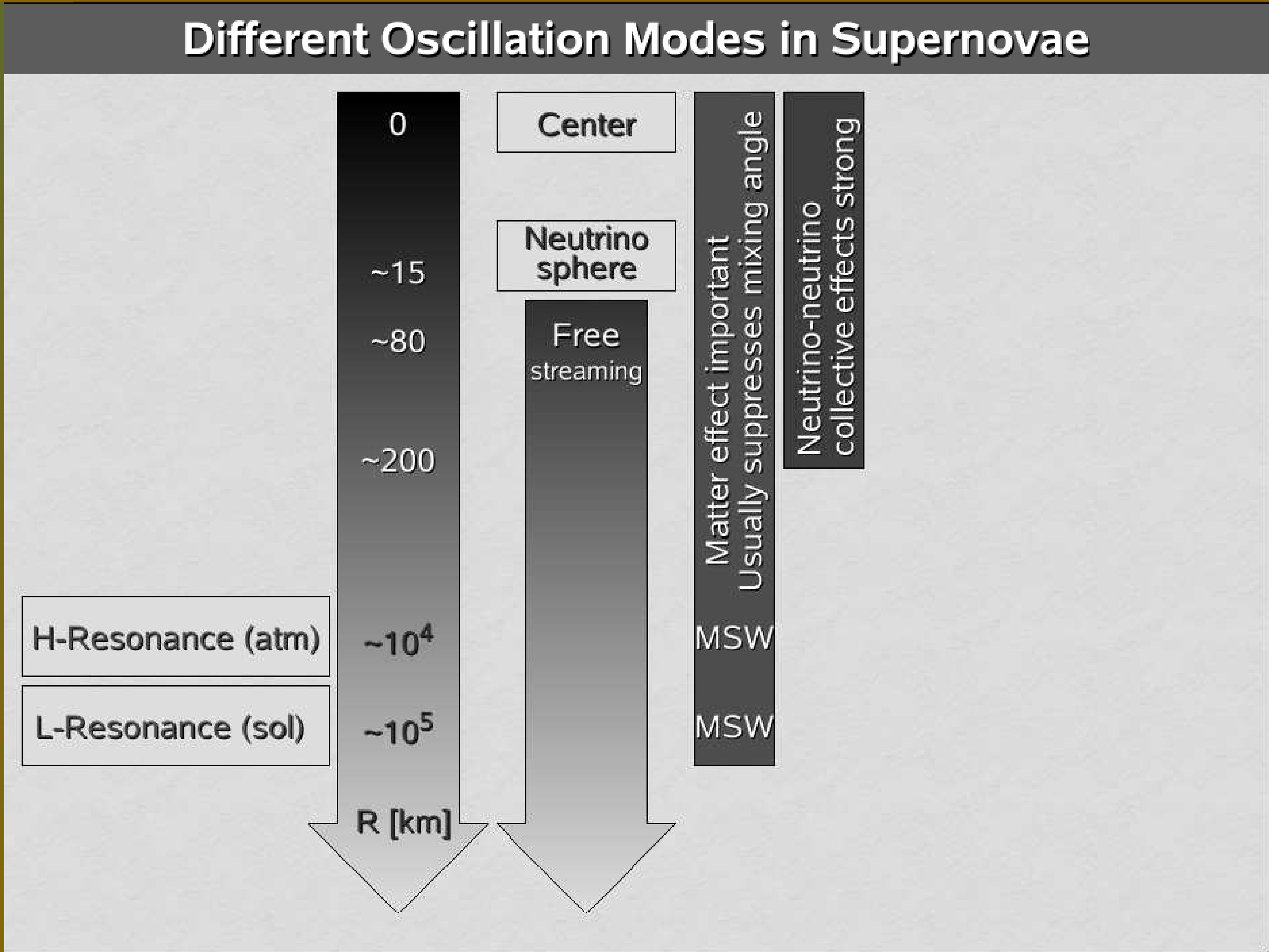
Plan of the Talk:

- Collective Effect and Luminosity Variation
- r-Process Nucleosynthesis and Collective Effect
- Remarks .

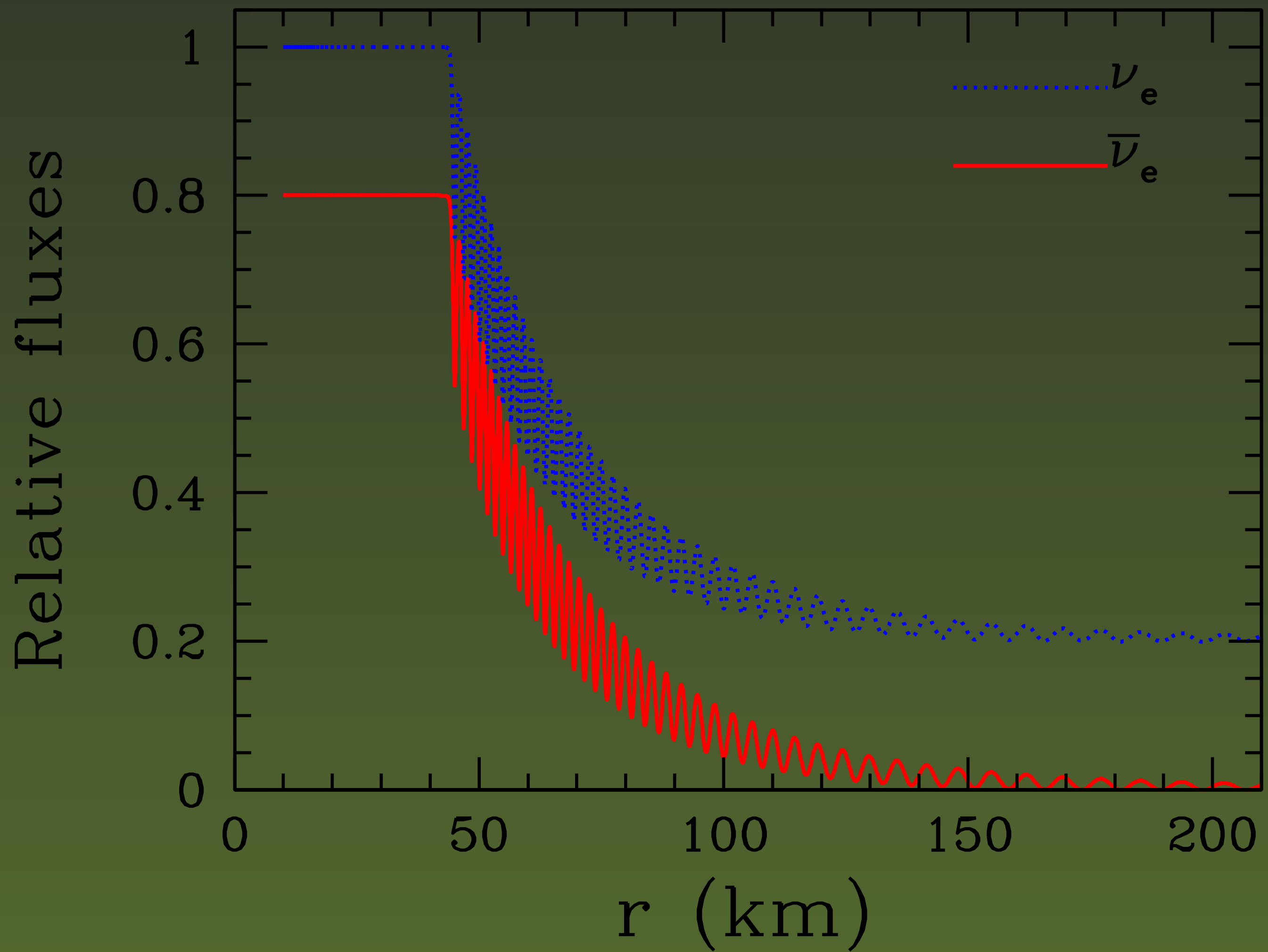
- Collective Effect and Luminosity Variation

SN and Neutrino (Raffelt's slide JIGSAW'07)



Collective effect

Hannestad et al 2006



Evolution Equation :

Ensemble of relativistic neutrinos and Antineutrinos.

Evolution equations are

$$\partial_t \rho = -i[H, \rho] \ , \ \ \partial_t \bar{\rho} = -i[H, \bar{\rho}]$$

Hamiltonian of a neutrino/antineutrino in the ensemble.

$$H = H_{vacuum} + H_{MSW} + H_{\nu\nu}$$

Bloch vector and E.O.M:

For a 2×2 Hermetian Matrix M

$$M = \frac{1}{2}(1 + \mathbf{m}.\bar{\sigma})$$

Where σ Pauli spin Matrices and **m** (m_x, m_y, m_z) is called the Bloch Vector.

Bloch vectors corresponding to ρ , $\bar{\rho}$, H_{vacuum} , H_{MSW} , $H_{\nu\nu}$ are **P** , $\mathbf{P}'$, **B** , **L** , **D** respectively.

E.O.M:

E.O.M for neutrino and antineutrino polarization vector P and P'

$$\dot{\mathbf{P}} = (\omega\mathbf{B} + \lambda\hat{\mathbf{L}} + \mu\mathbf{D}) \times \mathbf{P}$$

$$\dot{\mathbf{P}}' = (-\omega\mathbf{B} + \lambda\hat{\mathbf{L}} + \mu\mathbf{D}) \times \mathbf{P}'$$

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$$\mathbf{B} = (sin2\theta, 0, -cos2\theta)^T \quad ; \quad \omega = \frac{\Delta^2}{2E}$$

E.O.M:

E.O.M for neutrino and antineutrino polarization vector P and P'

$$\dot{\mathbf{P}} = (\omega\mathbf{B} + \lambda\hat{\mathbf{L}} + \mu\mathbf{D}) \times \mathbf{P}$$

$$\dot{\mathbf{P}}' = (-\omega\mathbf{B} + \lambda\hat{\mathbf{L}} + \mu\mathbf{D}) \times \mathbf{P}'$$

$$\hat{\mathbf{L}} = (0,0,1)^T \quad ; \quad \lambda = \sqrt{2}G_F N_e$$

E.O.M:

E.O.M for neutrino and antineutrino polarization vector P and P'

$$\dot{\mathbf{P}} = (\omega \mathbf{B} + \lambda \hat{\mathbf{L}} + \mu \mathbf{D}) \times \mathbf{P}$$

$$\dot{\mathbf{P}}' = (-\omega \mathbf{B} + \lambda \hat{\mathbf{L}} + \mu \mathbf{D}) \times \mathbf{P}'$$

$$\mathbf{D} = \frac{1}{(N_{\nu_e} + N_{\nu_x} + N_{\bar{\nu}_e} + N_{\bar{\nu}_x})} \int dE (n\mathbf{P} - \bar{n}\mathbf{P}')$$

$$\mu = \sqrt{2} G_F (N_{\nu_e} + N_{\nu_x} + N_{\bar{\nu}_e} + N_{\bar{\nu}_x})$$

E.O.M:

$$n = n_{\nu_e} + n_{\nu_x} \quad ; \quad \bar{n} = n_{\bar{\nu}_e} + n_{\nu_x}$$

where n_α's are the effective number per unit volume per unit energy and given by

$$n_\alpha(r, E) = \frac{D(r)}{2\pi R_\alpha^2} \frac{L_\alpha}{\langle E_\alpha \rangle} \Psi(E)_\alpha$$

N_α's represent the total effective number density of the αth species.

$$N_\alpha = \int dE \, n_\alpha$$

Initial Energy Distribution :

Effective number density for the αth species per unit energy

$$n_\alpha(r,E) = \frac{D(r)}{2\pi R_\alpha^2}\frac{L_\alpha}{\langle E_\alpha\rangle}\psi(E)_\alpha$$

Fermi-Dirac

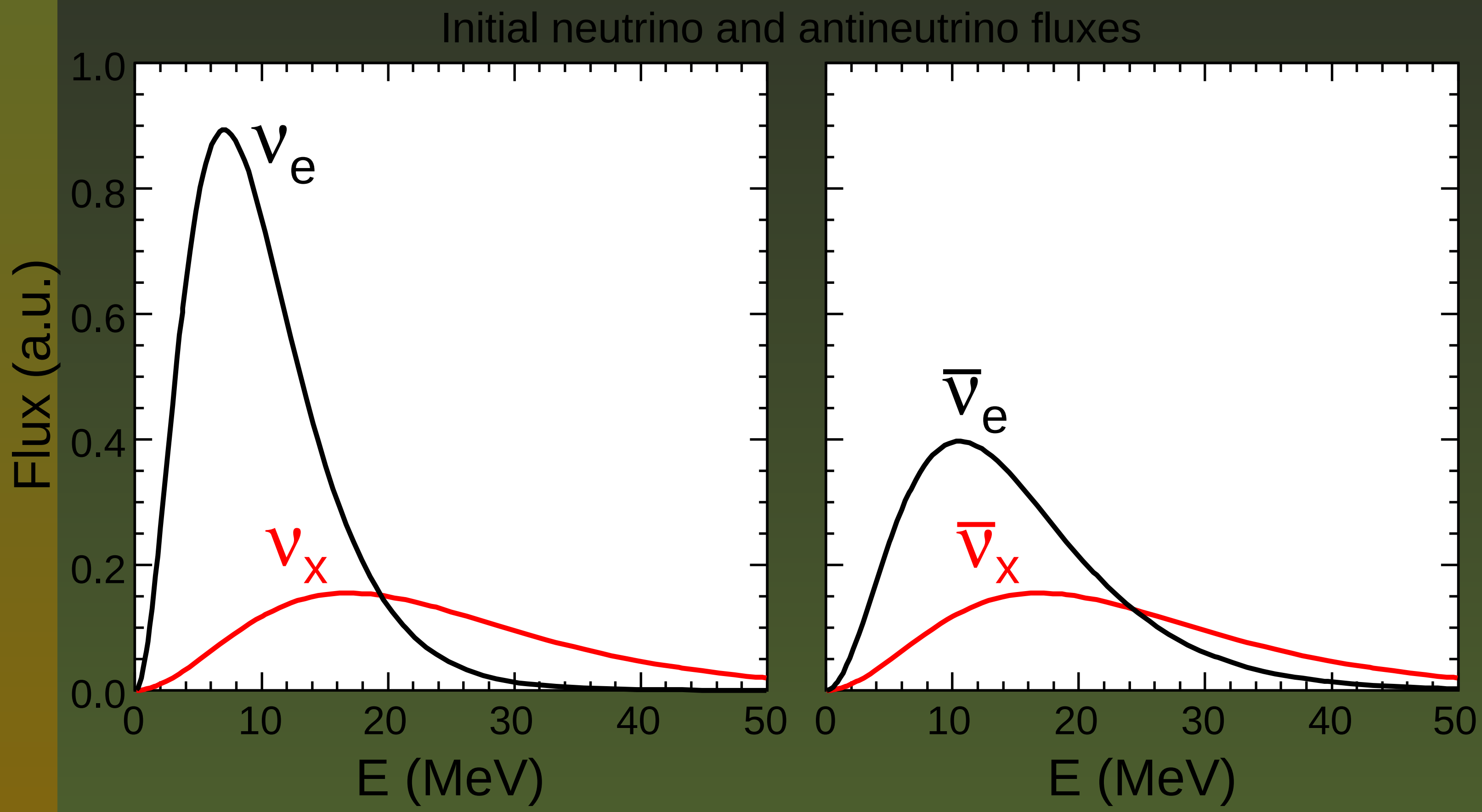
$$\Psi_\alpha^{FD}(E) \propto \frac{\beta_\alpha \ (\beta_\alpha E)^2}{e^{\beta_\alpha E}+1}$$

where the inverse temperature parameters are

$$\beta_{\nu_e} = 0.315 \ MeV^{-1}; \ \ \beta_{\bar{\nu}_e} = 0.210 \ MeV^{-1}$$

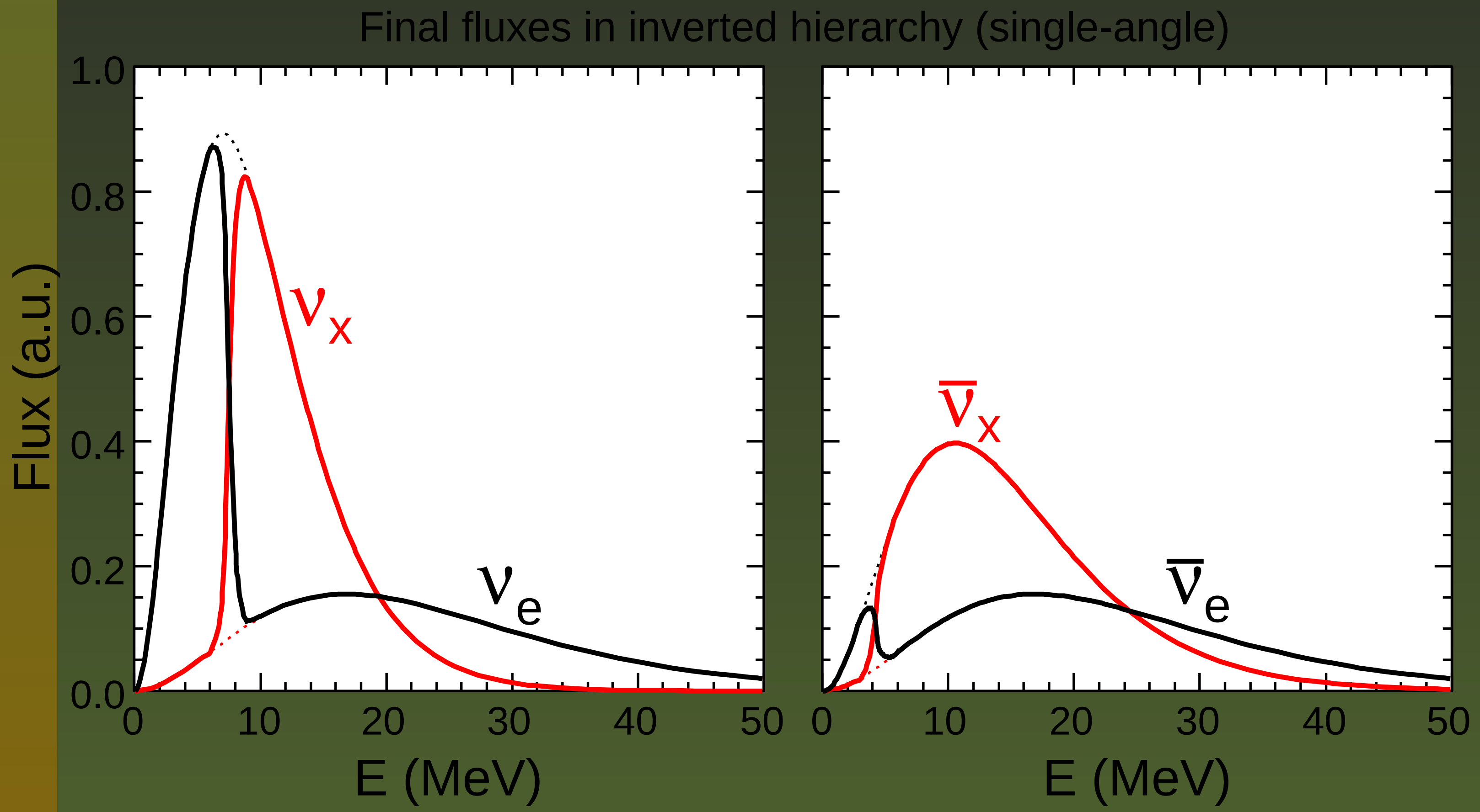
$$\beta_{\nu_x} = \beta_{\bar{\nu}_x} = 0.131 MeV^{-1}.$$

Initial Flux (FD)



Fogli et al. JCAP(2007)

Flux Collective Effect



Fogli et al. JCAP(2007)

Pinched Energy Distribution :

Effective number density for the αth species per unit energy

$$n_\alpha(r,E) = \frac{D(r)}{2\pi R_\alpha^2}\frac{L_\alpha}{\langle E_\alpha\rangle}\psi(E)_\alpha$$

Pinched spectra for different simulations are parameterized as

$$\Psi_\alpha(E) = \frac{(1+\zeta_\alpha)^{1+\zeta_\alpha}}{\Gamma(1+\zeta_\alpha)}\left(\frac{E_\alpha}{\langle E_\alpha\rangle}\right)^{\zeta_\alpha}\frac{\exp\left(-(1+\zeta_\alpha)\frac{E_\alpha}{\langle E_\alpha\rangle}\right)}{\langle E_\alpha\rangle}\,,$$

Keil et al. ApJ(2003)

where ζ_α is the pinching parameter

Different simulation models have different ζ_α and $\langle E_\alpha\rangle$

Initial Neutrino Flux:

The initial flux ($\phi^0_{\nu_\alpha} = \frac{L_\alpha}{\langle E_\alpha \rangle}$) is another important input parameter.

Total emitted SN energy ($E_B = 3 \times 10^{53}$ erg) puts a constraint on flavor luminosities.

$$L_{\nu_e} + L_{\bar{\nu}_e} + 4L_{\nu_x} = \frac{E_B}{\tau}$$

where τ is the luminosity decay timescale.We took $\tau = 10$ seconds. Thus the initial fluxes of different flavors are also constrained

$$\phi^0_{\nu_e}\langle E_{\nu_e}\rangle + \phi^0_{\bar{\nu}_e}\langle E_{\bar{\nu}_e}\rangle + 4\phi^0_{\nu_x}\langle E_{\nu_x}\rangle = 3 \times 10^{52}$$

Initial Neutrino Fluxes

If the ratio between the initial fluxes of different flavors are

$$\phi^0_{\nu_e} : \phi^0_{\bar{\nu}_e} : \phi^0_{\nu_x} = \phi^r_{\nu_e} : \phi^r_{\bar{\nu}_e} : 1 \ ,$$

where $\phi^r_{\nu_e}$, $\phi^r_{\bar{\nu}_e}$ are positive numbers.

$$\phi^0_{\nu_x}(\phi^r_{\nu_e}\langle E_{\nu_e}\rangle + \phi^r_{\bar{\nu}_e}\langle E_{\bar{\nu}_e}\rangle + 4\langle E_{\nu_x}\rangle) = 3 \times 10^{52} \ .$$

The parameters are initial relative fluxes

$$\phi^r_{\nu_e} = \frac{\phi^0_{\nu_e}}{\phi^0_{\nu_x}} \ , \quad \phi^r_{\bar{\nu}_e} = \frac{\phi^0_{\bar{\nu}_e}}{\phi^0_{\nu_x}}$$

SN Neutrino Parameters

Three representative models motivated by SN simulations.

2 Garching simulations (G1, G2) and 1 Lawrence Livermore (LL).

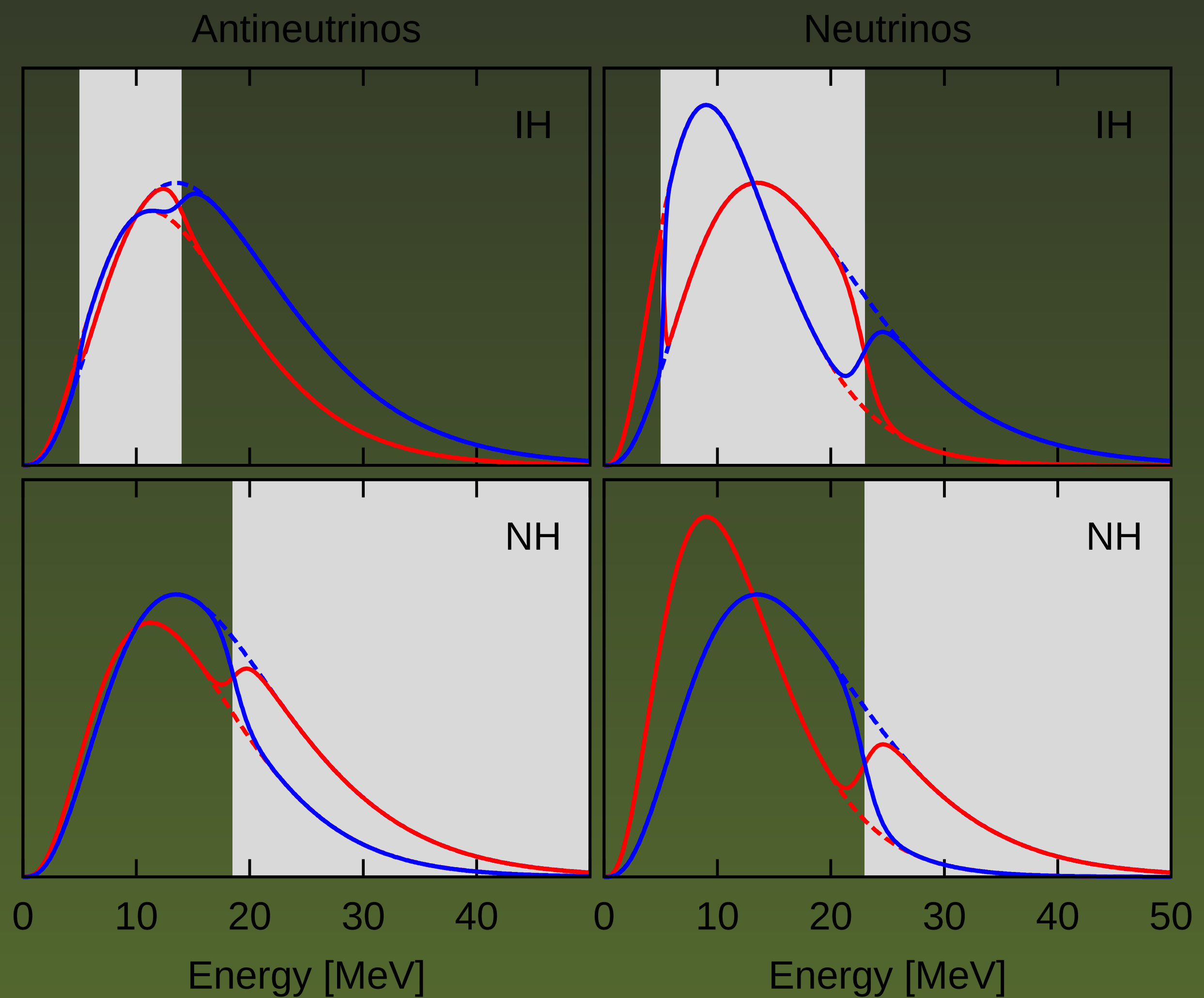
Another ‘plausible’ choice, say ‘G3’. Dasgupta et al. PRL (2009)

Fitting Parameters

Model	$\langle E_{\nu_e} \rangle$ (MeV)	$\langle E_{\bar{\nu}_e} \rangle$ (MeV)	$\langle E_{\nu_x} \rangle$ (MeV)	$\zeta_{\nu_e} = \zeta_{\bar{\nu}_e}$	$\zeta_{\bar{\nu}_x}$	$\phi^r_{\nu_e} = \frac{\phi^0_{\nu_e}}{\phi^0_{\nu_x}}$	$\phi^r_{\bar{\nu}_e} = \frac{\phi^0_{\bar{\nu}_e}}{\phi^0_{\nu_x}}$
LL	12	15	24	3	4	2.00	1.60
G1	12	15	18	3	4	0.80	0.80
G2	12	15	15	3	4	0.50	0.50
G3	12	15	18	3	3	0.85	0.75

Multiple Split Spectra ‘G3’

Dasgupta et al. PRL (2009)



Luminosity Variation

$$\frac{1}{2} \le \frac{L_{\nu_e}}{L_{\nu_x}} \le 2 \;\; ; \;\; \frac{1}{2} \le \frac{L_{\bar{\nu}_e}}{L_{\nu_x}} \le 2$$

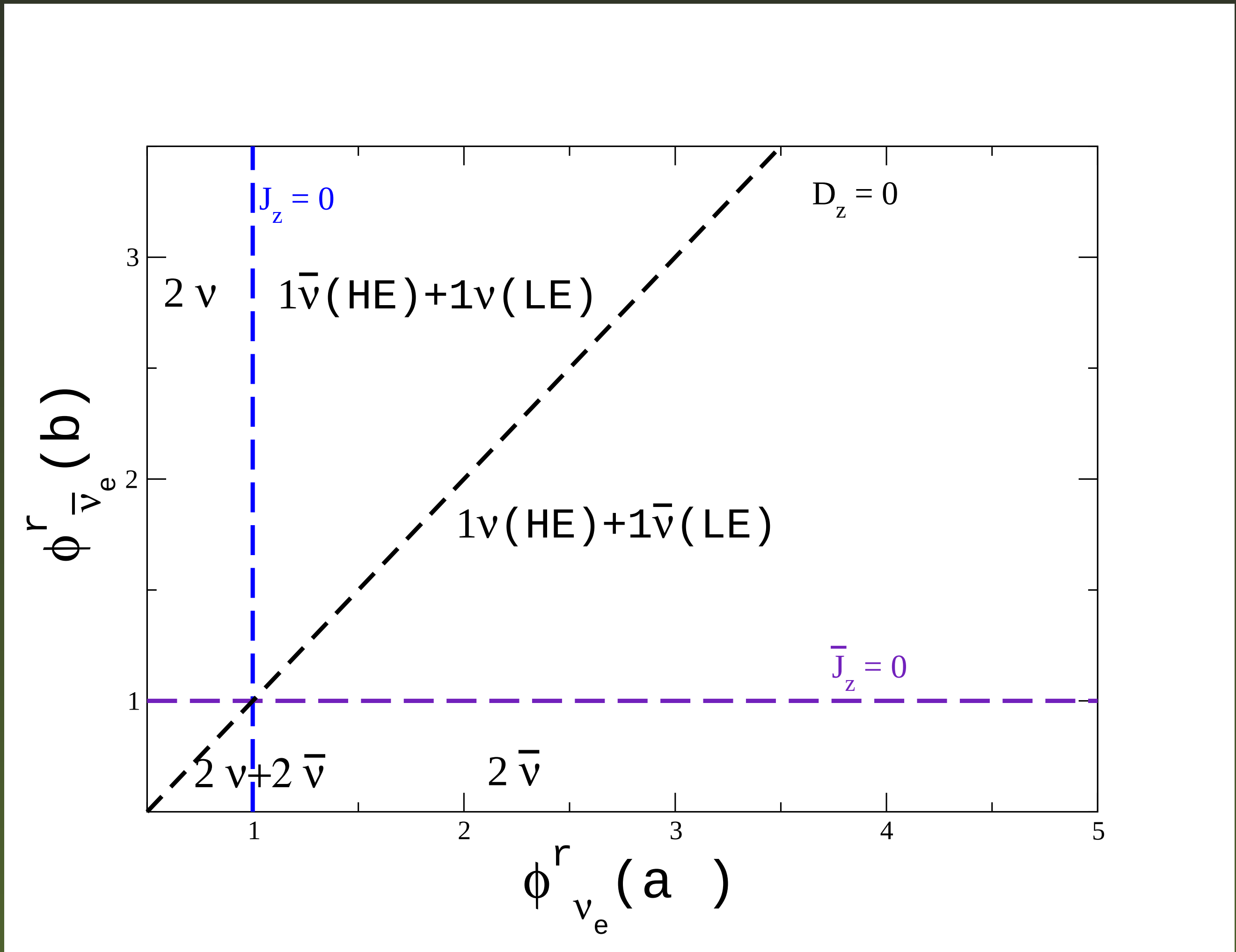
$$\frac{1}{2}\frac{\langle E_{\nu_x}\rangle}{\langle E_{\nu_e}\rangle} \le \phi^r_{\nu_e} \le 2\frac{\langle E_{\nu_x}\rangle}{\langle E_{\nu_e}\rangle} \;\; ; \;\; \frac{1}{2}\frac{\langle E_{\nu_x}\rangle}{\langle E_{\bar{\nu}_e}\rangle} \le \phi^r_{\bar{\nu}_e} \le 2\frac{\langle E_{\nu_x}\rangle}{\langle E_{\bar{\nu}_e}\rangle} \; .$$

Model	$\langle E_{\nu_e}\rangle$	$\langle E_{\bar{\nu}_e}\rangle$	$\langle E_{\nu_x,\bar{\nu}_x}\rangle$	$\phi^r_{\nu_{e;ll}}$	$\phi^r_{\nu_{e;ul}}$	$\phi^r_{\bar{\nu}_{e;ll}}$	$\phi^r_{\bar{\nu}_{e;ul}}$
LL	10	15	24	1.20	4.80	0.80	3.2
G1/G3	12	15	18	0.75	3.00	0.60	2.4

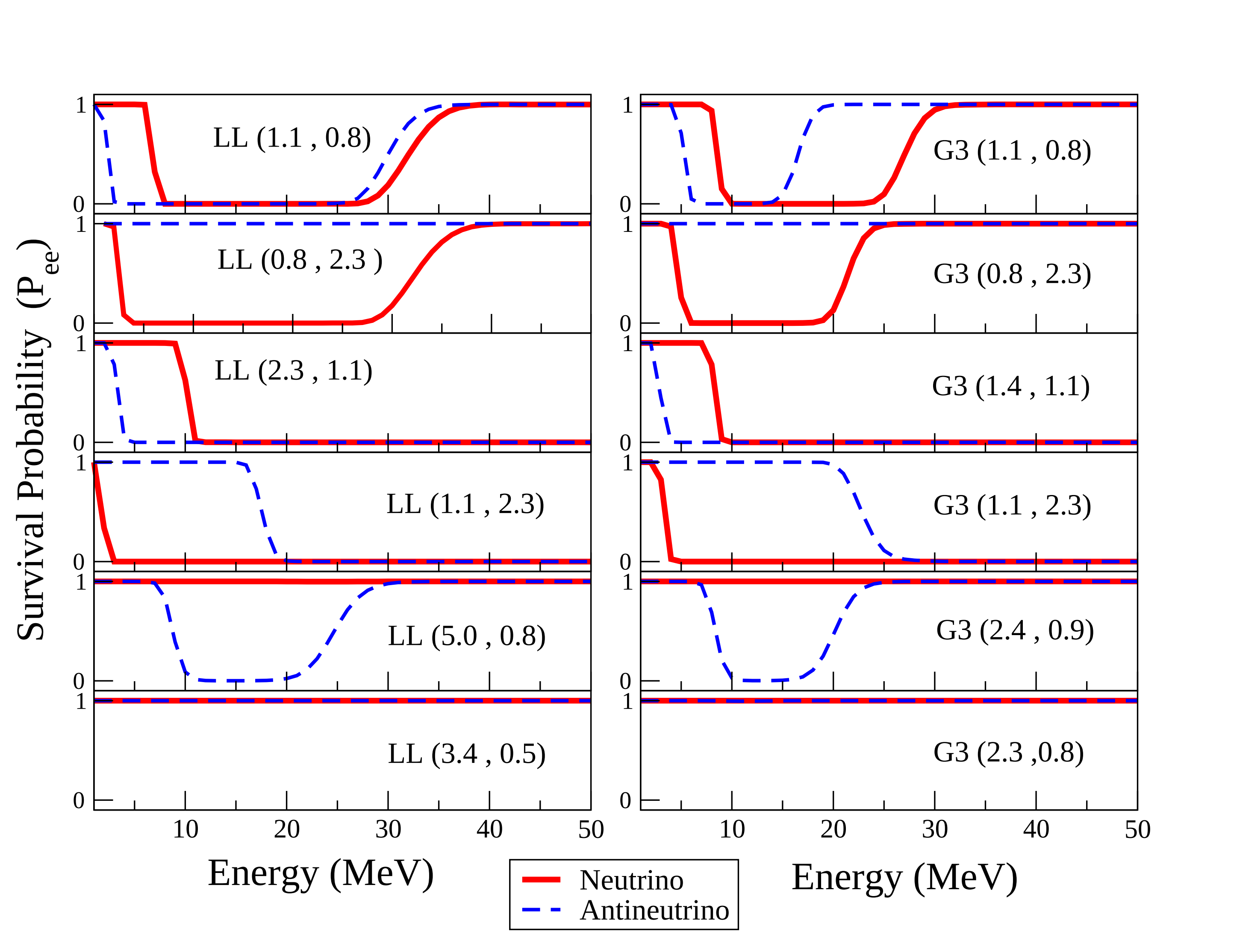
We Study in the range

$$0.5 \le \phi^r_{\nu_e} \le 5.0 \;\; ; \;\; 0.5 \le \phi^r_{\bar{\nu}_e} \le 3.5 \; .$$

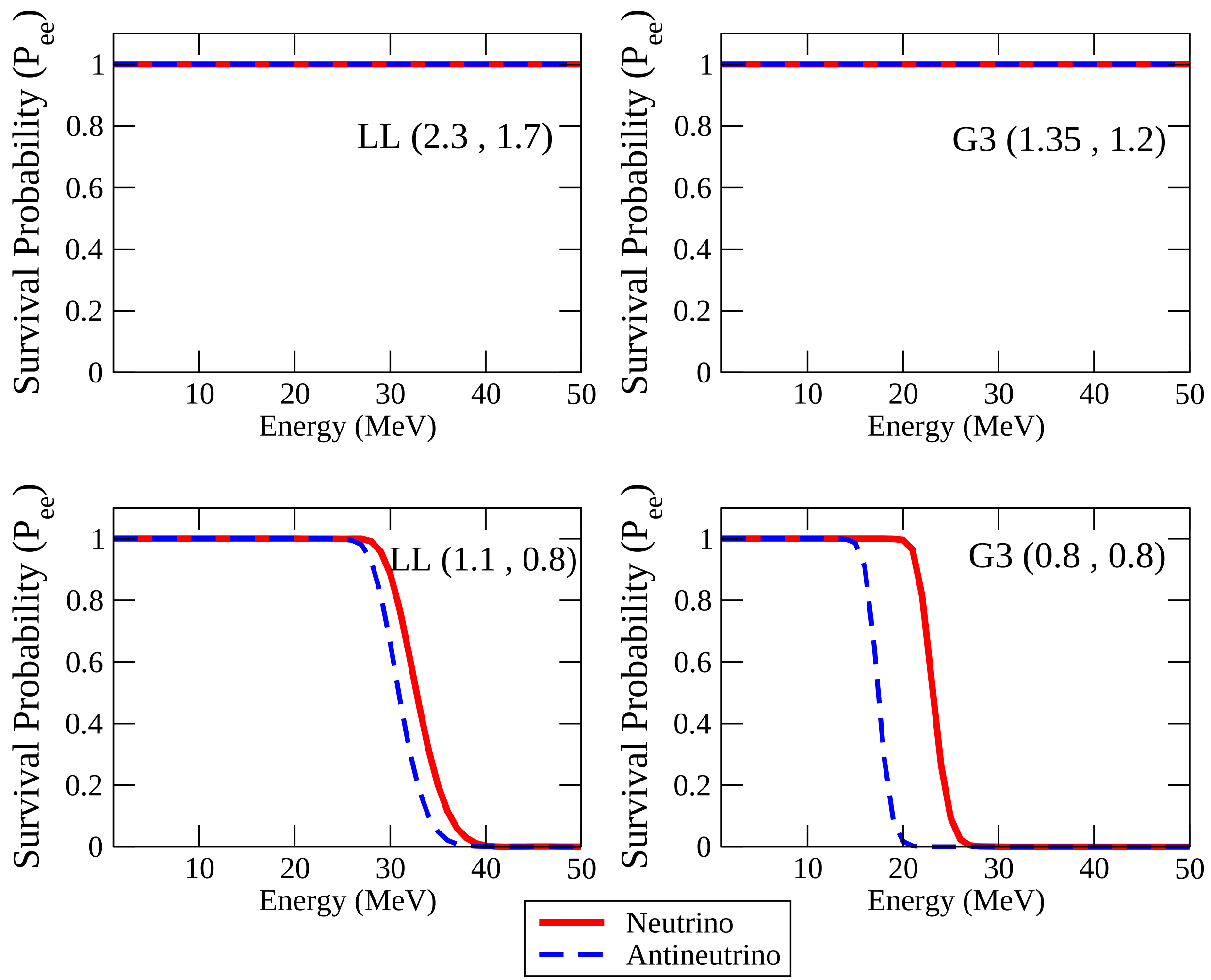
Spectral Split Regions



Spectral Split Patterns (IH)



Spectral Split Patterns (NH)



- r-Process and Collective Effect :

r-Process Nucleosynthesis

- Heavy Neutron (n) rich nuclei (beyond Iron group) are synthesized by rapid neutron capture,

$$n + Y(Z, A-1) \rightarrow Y(Z, A)$$

- r-Process $\Rightarrow$ Rapid process of neutron capture $t(n, \gamma) \ll$beta decay life time (t_β).

- r-process requires high neutron(n) number density ($> 10^{20} cm^{-3}$)

- Possible site $\Rightarrow$ "ν driven wind" ahead of "hot bubble" in SN.

r-Process Nucleosynthesis

- Heating by neutrino driven wind coming from neutrino-sphere

$$\nu_e + n \leftrightharpoons e^- + p \;\; ; \;\; \bar{\nu}_e + p \leftrightharpoons e^+ + n$$

- Important quantity whose evolution should be studied is Electron fraction (Y_e) = $\frac{No\ of\ electrons}{No\ of\ Baryons}$

- For Neutron rich conditions Y_e < 0.5 (Preferably < 0.45).

- This is minimal requirement, other constraint on Entropy, Temparature.

r-Process Nucleosynthesis

The expression for Y_e involves reaction rates

$$Y_e \simeq \frac{\lambda_{\nu_e n}}{\lambda_{\nu_e n} + \lambda_{\bar{\nu}_e p}} = \frac{1}{1 + \frac{\lambda_{\bar{\nu}_e p}}{\lambda_{\nu_e n}}}$$

Qian et al PRL(1993)

where,

$$\lambda_{\nu N} \simeq \frac{L_\nu}{4\pi R_\nu^2} \frac{\int dE\, \sigma_{\nu N}\, f_\nu(E)}{\int dE\, E\, f_\nu(E)}$$

N can be either p or n.

r-Process Nucleosynthesis

Electronfraction

$$Y_e \simeq \frac{1}{1+\frac{\lambda_{\bar{\nu}_e p}}{\lambda_{\nu_e n}}}$$

In terms of the initial relative flux $\phi^r_{\nu_e}$ and $\phi^r_{\bar{\nu}_e}$

$$\frac{\lambda_{\bar{\nu}_e p}}{\lambda_{\nu_e n}}(r) = \frac{\int_0^\infty \sigma_{\bar{\nu}_e p}(E)(P^c_{\bar{\nu}_e}(r,E)\phi^r_{\bar{\nu}_e}\Psi_{\bar{\nu}_e}(E) + (1-P^c_{\bar{\nu}_e}(r,E))\Psi_{\nu_x}(E))dE}{\int_0^\infty \sigma_{\nu_e n}(E)(P^c_{\nu_e}(r,E)\phi^r_{\nu_e}\Psi_{\nu_e}(E) + (1-P^c_{\nu_e}(r,E))\Psi_{\nu_x}(E))dE}$$

r-Process Nucleosynthesis

$$\frac{\lambda_{\bar{\nu}_e p}}{\lambda_{\nu_e n}}(r) = \frac{\int_0^\infty \sigma_{\bar{\nu}_e p}(E)(P^c_{\bar{\nu}_e}(r,E)\phi^r_{\bar{\nu}_e}\Psi_{\bar{\nu}_e}(E) + (1 - P^c_{\bar{\nu}_e}(r,E))\Psi_{\nu_x}(E))dE}{\int_0^\infty \sigma_{\nu_e n}(E)(P^c_{\nu_e}(r,E)\phi^r_{\nu_e}\Psi_{\nu_e}(E) + (1 - P^c_{\nu_e}(r,E))\Psi_{\nu_x}(E))dE}$$

The cross section used are

$$\sigma_{\nu_e n}(E_{\nu_e}) \approx 9.6 \times 10^{-44} \left(\frac{E_{\nu_e} + \triangle_{np}}{MeV}\right)^2 \mathrm{cm}^2 ,$$

$$\sigma_{\bar{\nu}_e p}(E_{\bar{\nu}_e}) \approx 9.6 \times 10^{-44} \left(\frac{E_{\bar{\nu}_e} - \triangle_{np}}{MeV}\right)^2 \mathrm{cm}^2 ,$$

$\triangle_{np}$(1.293 MeV) is mass difference between neutron and proton.

r-Process Nucleosynthesis

$$\frac{\lambda_{\bar{\nu}_e p}}{\lambda_{\nu_e n}}(r) = \frac{\int_0^\infty \sigma_{\bar{\nu}_e p}(E)(P^c_{\bar{\nu}_e}(r,E)\phi^r_{\bar{\nu}_e}\Psi_{\bar{\nu}_e}(E) + (1 - P^c_{\bar{\nu}_e}(r,E))\Psi_{\nu_x}(E))dE}{\int_0^\infty \sigma_{\nu_e n}(E)(P^c_{\nu_e}(r,E)\phi^r_{\nu_e}\Psi_{\nu_e}(E) + (1 - P^c_{\nu_e}(r,E))\Psi_{\nu_x}(E))dE}$$

$$P^c_{\bar{\nu}_e/\nu_e}(r_s, E) = 0$$

$$\frac{\lambda_{\bar{\nu}_e p}}{\lambda_{\nu_e n}}(r) = \frac{\int_0^\infty \sigma_{\bar{\nu}_e p}(E)\Psi_{\nu_x}(E)dE}{\int_0^\infty \sigma_{\nu_e n}(E)\Psi_{\nu_x}(E)dE},$$

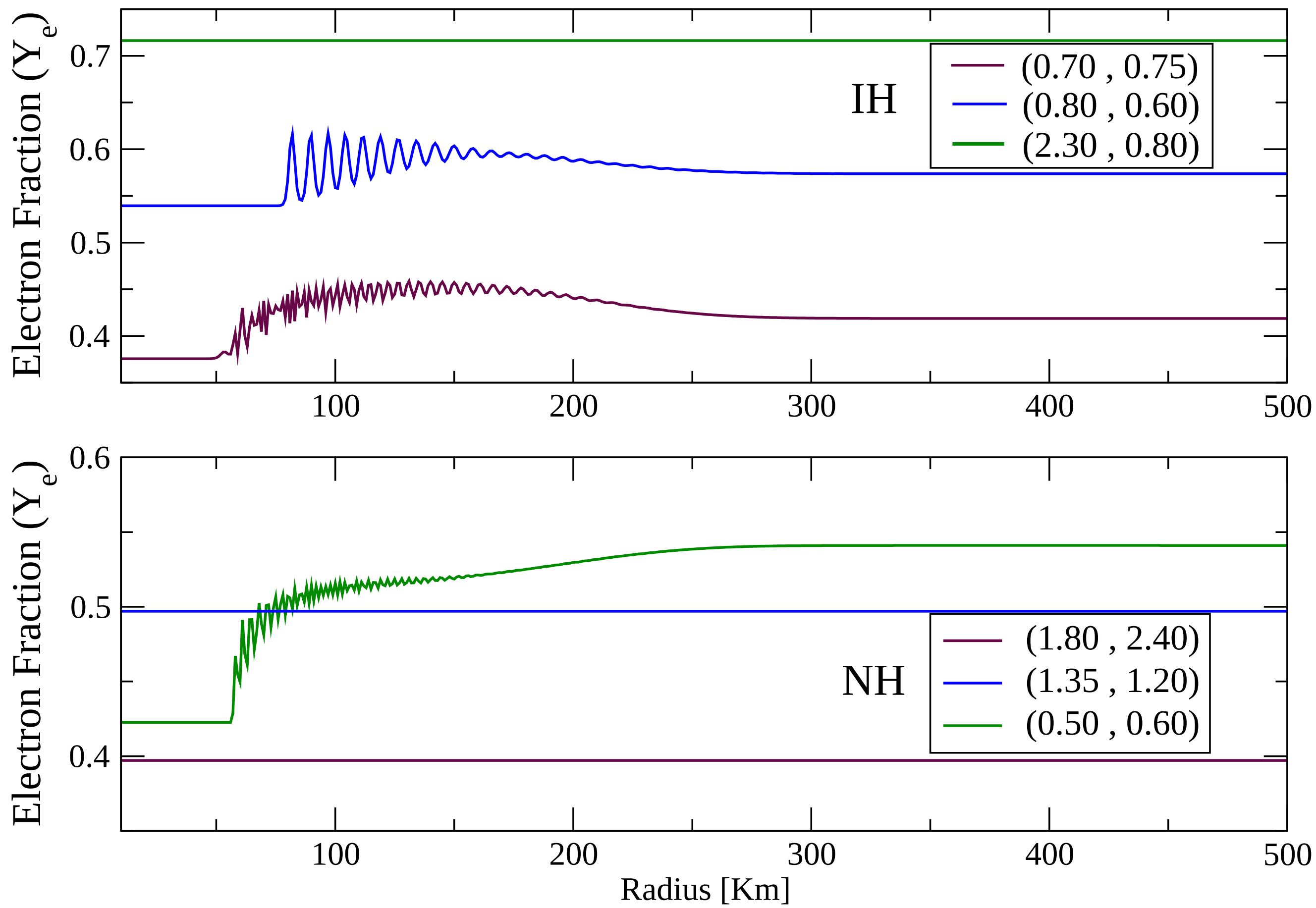
r-Process Nucleosynthesis

$$\frac{\lambda_{\bar{\nu}_e p}}{\lambda_{\nu_e n}}(r) = \frac{\int_0^\infty \sigma_{\bar{\nu}_e p}(E)(P^c_{\bar{\nu}_e}(r,E)\phi^r_{\bar{\nu}_e}\Psi_{\bar{\nu}_e}(E) + (1 - P^c_{\bar{\nu}_e}(r,E))\Psi_{\nu_x}(E))dE}{\int_0^\infty \sigma_{\nu_e n}(E)(P^c_{\nu_e}(r,E)\phi^r_{\nu_e}\Psi_{\nu_e}(E) + (1 - P^c_{\nu_e}(r,E))\Psi_{\nu_x}(E))dE}$$

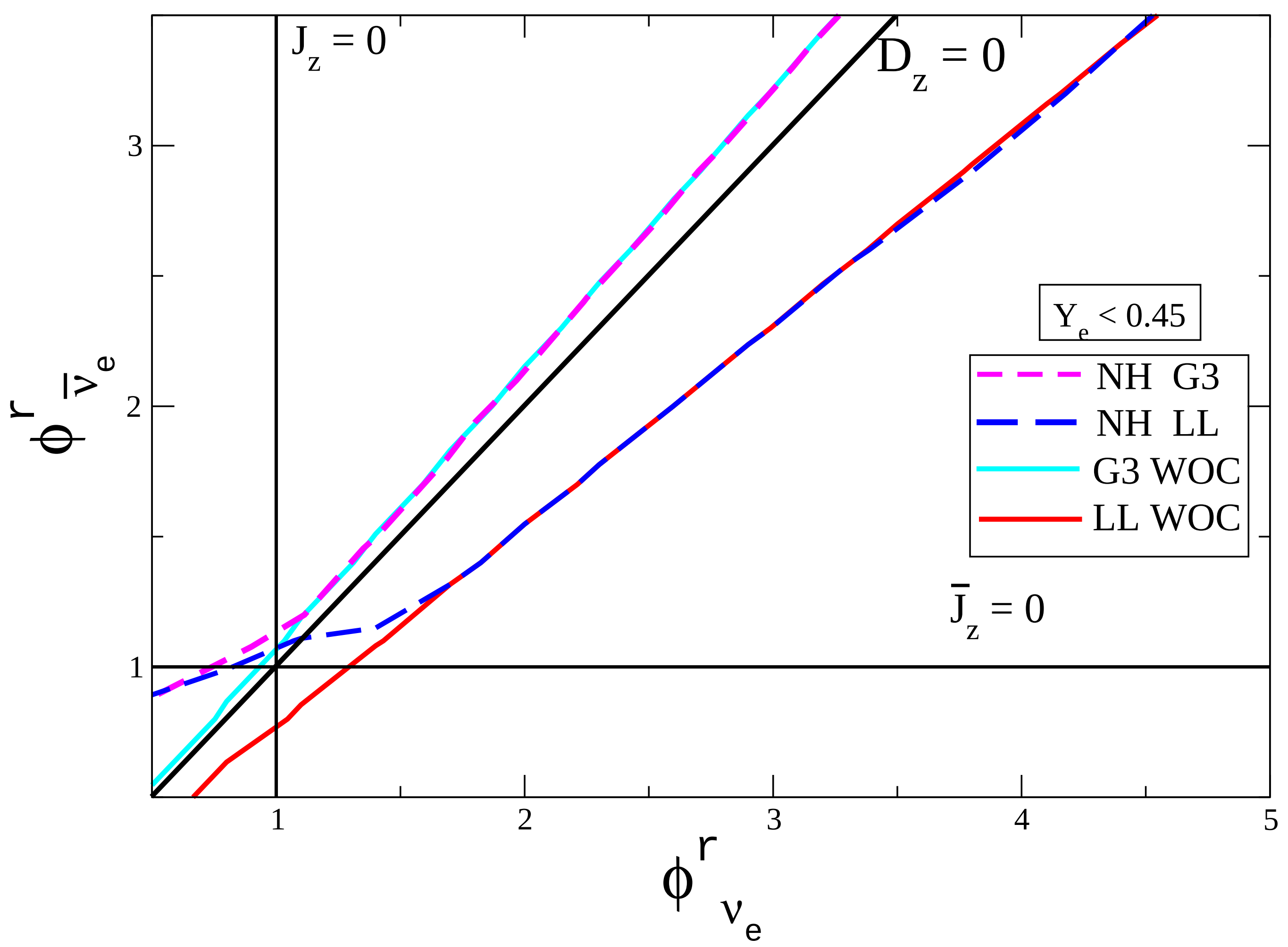
$$P^c_{\bar{\nu}_e/\nu_e}(r_s, E) = 1$$

$$\frac{\lambda_{\bar{\nu}_e p}}{\lambda_{\nu_e n}}(r) = \frac{\int_0^\infty \sigma_{\bar{\nu}_e p}(E)\phi^r_{\bar{\nu}_e}\Psi_{\bar{\nu}_e}(E)dE}{\int_0^\infty \sigma_{\nu_e n}(E)\phi^r_{\nu_e}\Psi_{\nu_e}(E)dE},$$

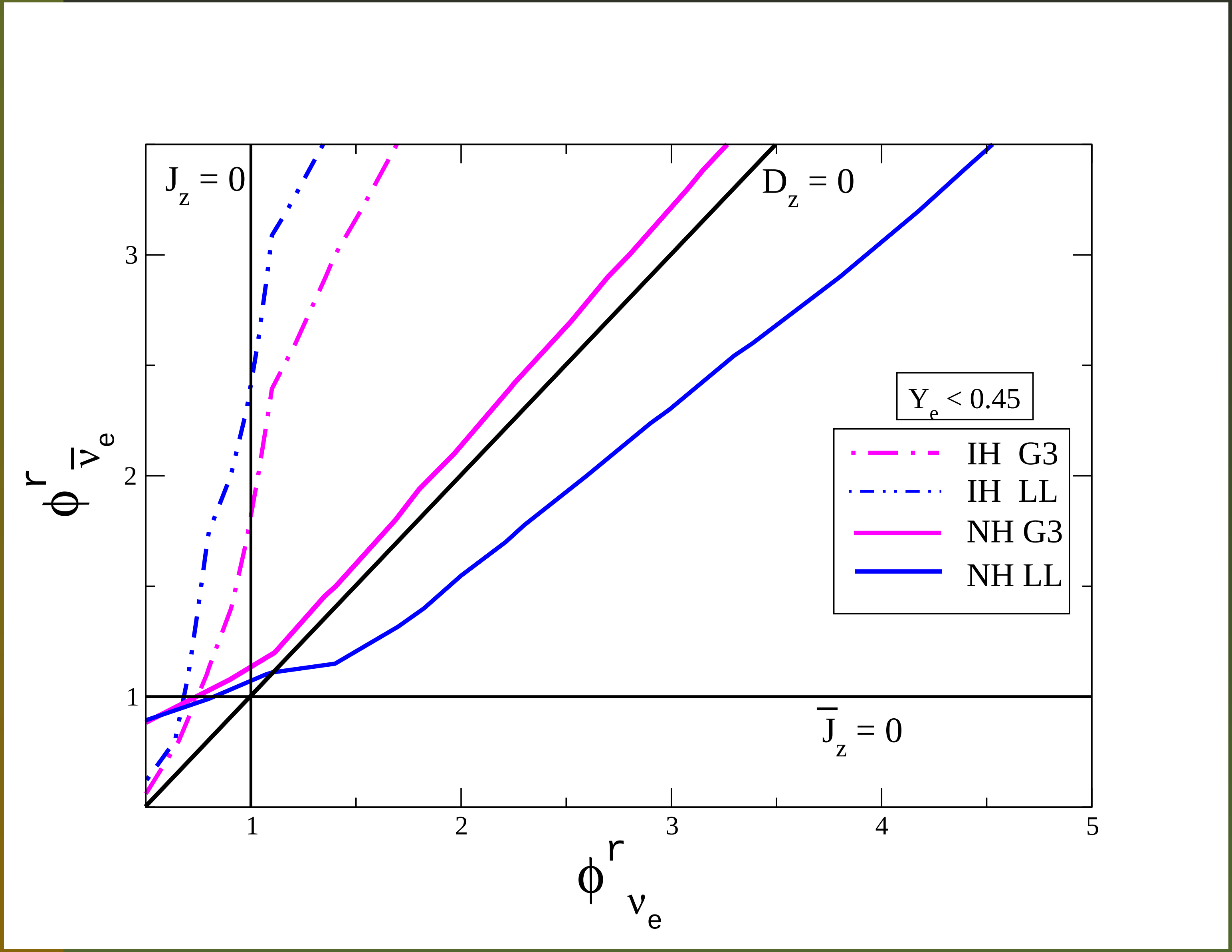
Y_e Vs Radius


Electron Fraction (Y_e)
0.7
0.6
0.5
0.4
IH
(0.70 , 0.75)
(0.80 , 0.60)
(2.30 , 0.80)
100
200
300
400
500
Electron Fraction (Y_e)
0.6
0.5
0.4
NH
(1.80 , 2.40)
(1.35 , 1.20)
(0.50 , 0.60)
100
200
300
400
500
Radius [Km]

Exclusion Plot Y_e <0.45 : NH



Exclusion Plot Y_e <0.45



Conclusion

- Different than active-sterile oscillation.
- IH the parameter space is more constrained than NH.
- For successful r-process all initial relative fluxes are not allowed.

THANK YOU !