Interplay of neutrino flavor, spin and collective oscillations in supernovae

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Neutrino evolution in astrophysical environment

- **Density matrix formalism for the neutrino evolution:**

$$i\frac{d\rho}{dt} = [H, \rho]$$

with

$$H = H_{vac} + H_{mat} + H_{v} + H_{B} + H_{\nu\nu}$$

where the density matrix is for both left- and right- handed (Dirac or Majorana) neutrinos:

$$\rho = \begin{pmatrix} \rho_{\nu} & X \\ X^{\dagger} & \rho_{\bar{\nu}} \end{pmatrix}$$

and

$$X = \begin{pmatrix} \rho_{\nu_e \bar{\nu}_e} & \rho_{\nu_e \bar{\nu}_x} \\ \rho_{\nu_x \bar{\nu}_e} & \rho_{\nu_x \bar{\nu}_x} \end{pmatrix}$$

- **The Hamiltonian H includes:**

a) vacuum oscillation term; b) isotropic matter potential

c) matter potential of moving matter; d) magnetic field term

e) neutrino self interaction potential

- **Supernova neutrino flavor conversion with a), b), e) has been intensively studied.** ***See reviews: 1001.2799, 1508.00785, etc.***

Connecting different spin components

- **Magnetic field:**

$$\gamma_\alpha^{-1} = \frac{m_\alpha}{E_\alpha}, \quad \gamma_{\alpha\beta}^{-1} = \frac{1}{2}\left(\gamma_\alpha^{-1} + \gamma_\beta^{-1}\right), \quad \tilde{\gamma}_{\alpha\beta}^{-1} = \frac{1}{2}\left(\gamma_\alpha^{-1} - \gamma_\beta^{-1}\right)$$

$$H_B^D = \begin{pmatrix} \left(\frac{\mu}{\gamma}\right)_{ee} B_{||} & \left(\frac{\mu}{\gamma}\right)_{ex} B_{||} & -\mu_{ee} B_\perp e^{i\phi} & -\mu_{ex} B_\perp e^{i\phi} \\ \left(\frac{\mu}{\gamma}\right)_{ex} B_{||} & \left(\frac{\mu}{\gamma}\right)_{xx} B_{||} & -\mu_{ex} B_\perp e^{i\phi} & -\mu_{xx} B_\perp e^{i\phi} \\ -\mu_{ee} B_\perp e^{-i\phi} & -\mu_{ex} B_\perp e^{-i\phi} & -\left(\frac{\mu}{\gamma}\right)_{ee} B_{||} & -\left(\frac{\mu}{\gamma}\right)_{ex} B_{||} \\ -\mu_{ex} B_\perp e^{-i\phi} & -\mu_{xx} B_\perp e^{-i\phi} & -\left(\frac{\mu}{\gamma}\right)_{ex} B_{||} & -\left(\frac{\mu}{\gamma}\right)_{xx} B_{||} \end{pmatrix},$$

- **Transversal matter current:**

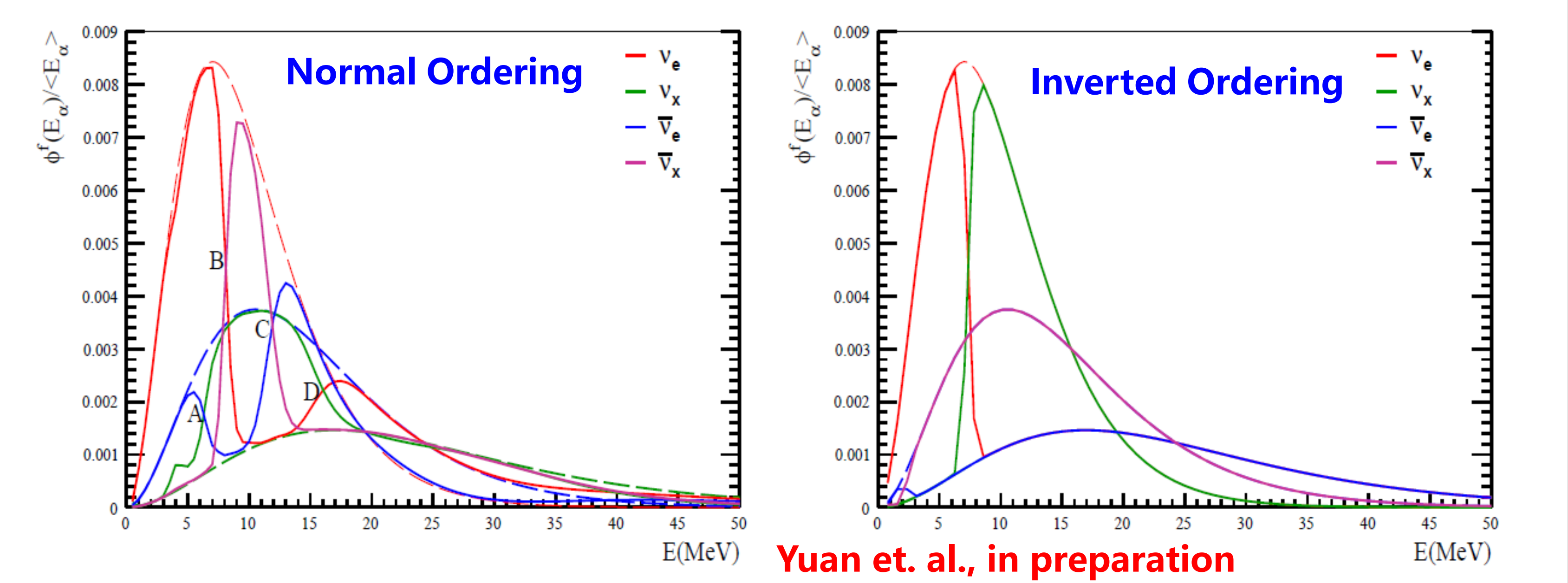
$$\left(\frac{\eta}{\gamma}\right)_{ee} = \frac{\cos^2\theta}{\gamma_{11}} + \frac{\sin^2\theta}{\gamma_{22}}, \quad \left(\frac{\eta}{\gamma}\right)_{xx} = \frac{\sin^2\theta}{\gamma_{11}} + \frac{\cos^2\theta}{\gamma_{22}}, \quad \left(\frac{\eta}{\gamma}\right)_{ex} = \frac{\sin 2\theta}{\tilde{\gamma}_{21}}.$$

$$H_{mat}^D = \frac{G_F}{2\sqrt{2}} \begin{pmatrix} 2(2n_e - n_n)\left(1 - v_{||}\right) & 0 & (2n_e - n_n) v_\perp \left(\frac{\eta}{\gamma}\right)_{ee} & (2n_e - n_n) v_\perp \left(\frac{\eta}{\gamma}\right)_{ex} \\ 0 & -2n_n\left(1 - v_{||}\right) & -n_n v_\perp \left(\frac{\eta}{\gamma}\right)_{ex} & -n_n v_\perp \left(\frac{\eta}{\gamma}\right)_{xx} \\ (2n_e - n_n) v_\perp \left(\frac{\eta}{\gamma}\right)_{ee} & -n_n v_\perp \left(\frac{\eta}{\gamma}\right)_{ex} & 0 & 0 \\ (2n_e - n_n) v_\perp \left(\frac{\eta}{\gamma}\right)_{ex} & -n_n v_\perp \left(\frac{\eta}{\gamma}\right)_{xx} & 0 & 0 \end{pmatrix}$$

- **For the case of Majorana neutrinos, see our poster, and more discussions in** *Phys. Atom. Nucl. 67 (2004) 993, Phys. Rev. D 98 (2018) 113009.*

Spectral splits of spin-flavor components

- **Using the neutrino bulb model and single angle approximation, the model of transversal matter current (v_T=0.067c) is from** *Phys. Rev. D 98 (2018) 113009*



Yuan et. al., in preparation

- **Magnetic field and neutrino magnetic moment can also have similar effects, see** JCAP 10 (2012) 027, JCAP 04 (2013) 018

- **Please join our Poster for more information and discussion!**