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
  \[ H = H_{\text{vac}} + H_{\text{mat}} + H_\nu + H_B + H_{\nu\nu} \]

  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:

\[
H^D_B = \begin{pmatrix}
\left(\frac{\mu}{\gamma}\right)_{ee} B || \\
\left(\frac{\mu}{\gamma}\right)_{ex} B || \\
\left(\frac{\mu}{\gamma}\right)_{xx} B || \\
-\mu_{ee} B_\perp e^{-i\phi} \\
-\mu_{ex} B_\perp e^{-i\phi} \\
-\mu_{xx} B_\perp e^{-i\phi} \\
-\mu_{ee} B_\perp e^{i\phi} \\
-\mu_{ex} B_\perp e^{i\phi} \\
-\mu_{xx} B_\perp e^{i\phi}
\end{pmatrix}
\]

- Transversal matter current:

\[
\begin{pmatrix}
\left(\frac{\eta}{\gamma}\right)_{ee} = \frac{\cos^2 \theta}{\gamma_{11}} + \frac{\sin^2 \theta}{\gamma_{22}}, \\
\left(\frac{\eta}{\gamma}\right)_{xx} = \frac{\sin^2 \theta}{\gamma_{11}} + \frac{\cos^2 \theta}{\gamma_{22}}, \\
\left(\frac{\eta}{\gamma}\right)_{ex} = \frac{\sin 2\theta}{\gamma_{21}},
\end{pmatrix}
\]

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*

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

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