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強磁場天体におけるニュートリノー反ニュートリノ振動

Neutrino-antineutrino oscillations in magnetized astrophysical sites

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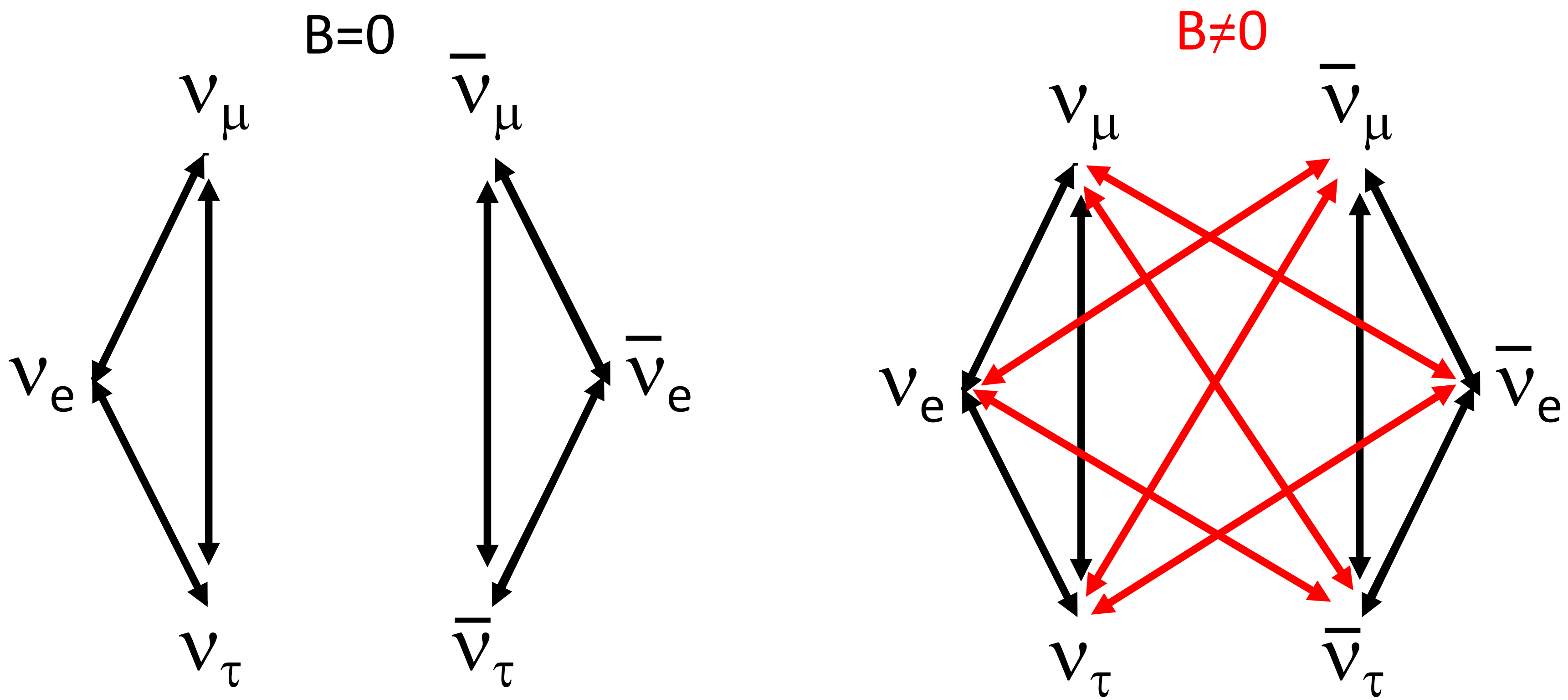
Neutrino oscillations in magnetic field



$\nu - \bar{\nu}$ oscillations may be possible in strong magnetic field

→ Information of particle physics

(ν magnetic moment, Dirac or Majorana..)

Ando and Sato, PRD**68** (2003) 023003

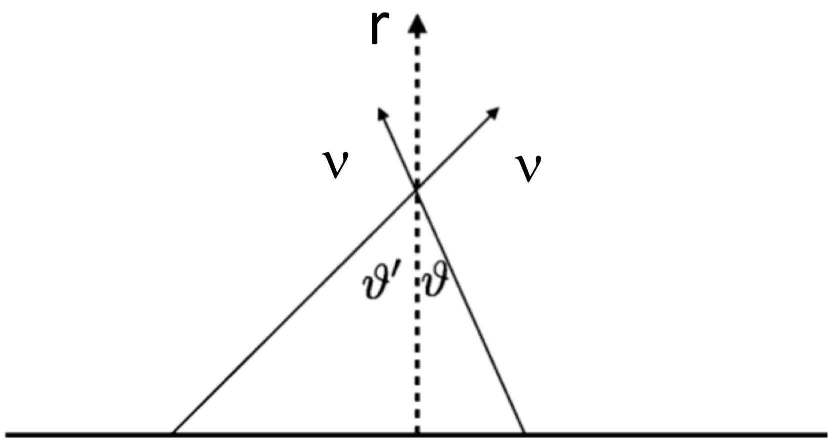
Yoshida et al., PRD**80** (2009) 125032

1. We demonstrate ν–$\bar{\nu}$ oscillations in various matter potentials
2. We check the possibility of ν–$\bar{\nu}$ oscillations in core-collapse supernovae

Equation of motion of neutrino oscillations

Sajad and Volpe, Phys.Lett.B**790**(2019)545-550

Sajad, PRD**101** (2020) 103032



- Liouville- von Neumann equation:

$$\cos\theta \frac{\partial}{\partial r} D(r,\theta) = -i[H(r,\theta), D(r,\theta)]$$

- Hamiltonian:

$$H(r,\theta) = H_{\mathrm{vac}} + H_{\mathrm{matter}} + H_{\mathrm{self}} + H_{\mathrm{mag}}$$

- Density matrix:

$$D(r,\theta) = \begin{pmatrix} \rho_\theta & X_\theta \\ X_\theta^\dagger & \bar{\rho}_\theta \end{pmatrix}$$

ρ_θ : 3 × 3 ν density matrix

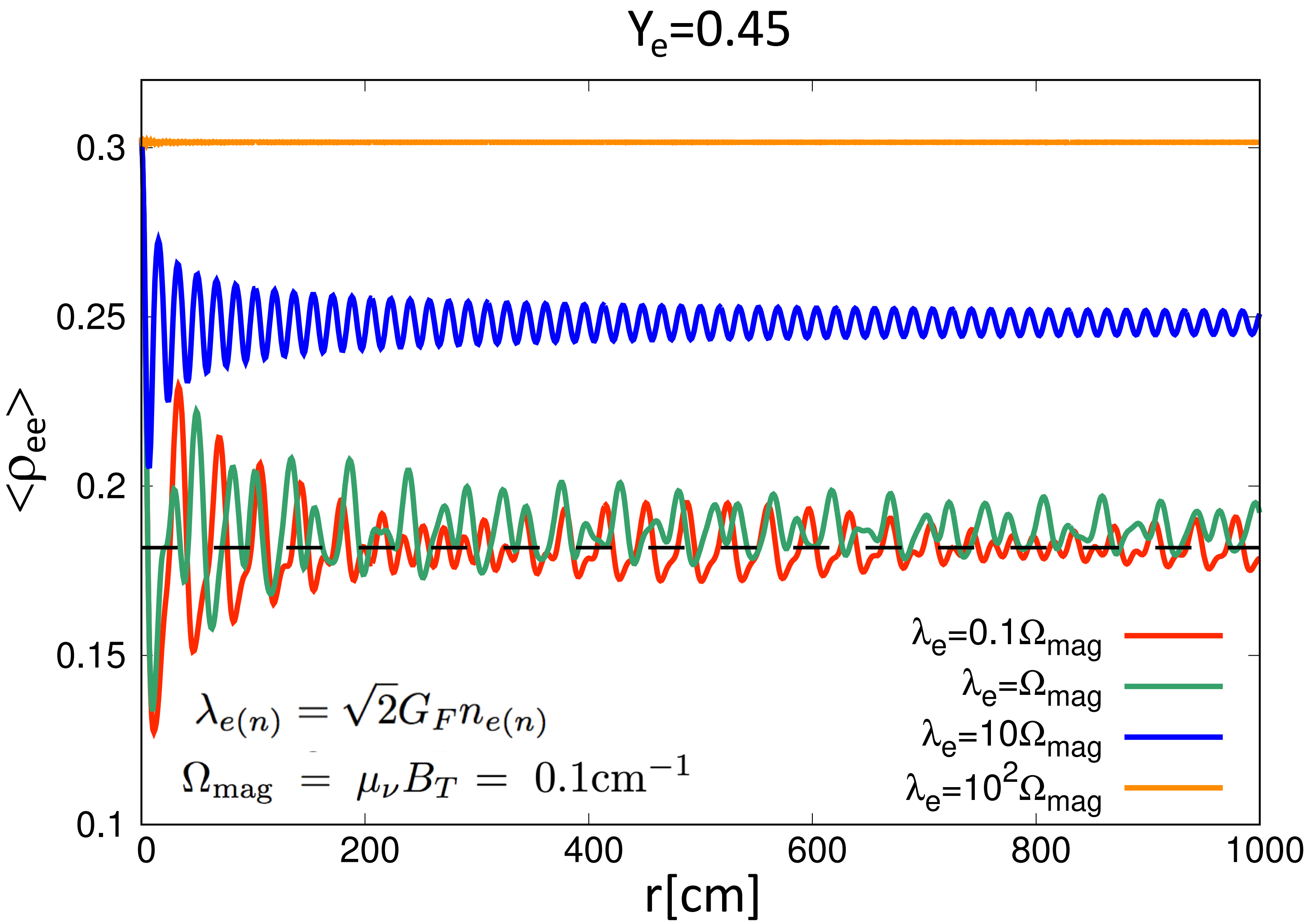
$\bar{\rho}_\theta$: 3 × 3 $\bar{\nu}$ density matrix

X_θ :Correlations between ν and $\bar{\nu}$

- Angle averaged ν_e number density:

$$\langle \rho_{ee} \rangle = \frac{3}{2\pi} \int_{-\frac{\pi}{3}}^{\frac{\pi}{3}} \mathrm{d}\theta \; \rho_{ee,\theta}$$

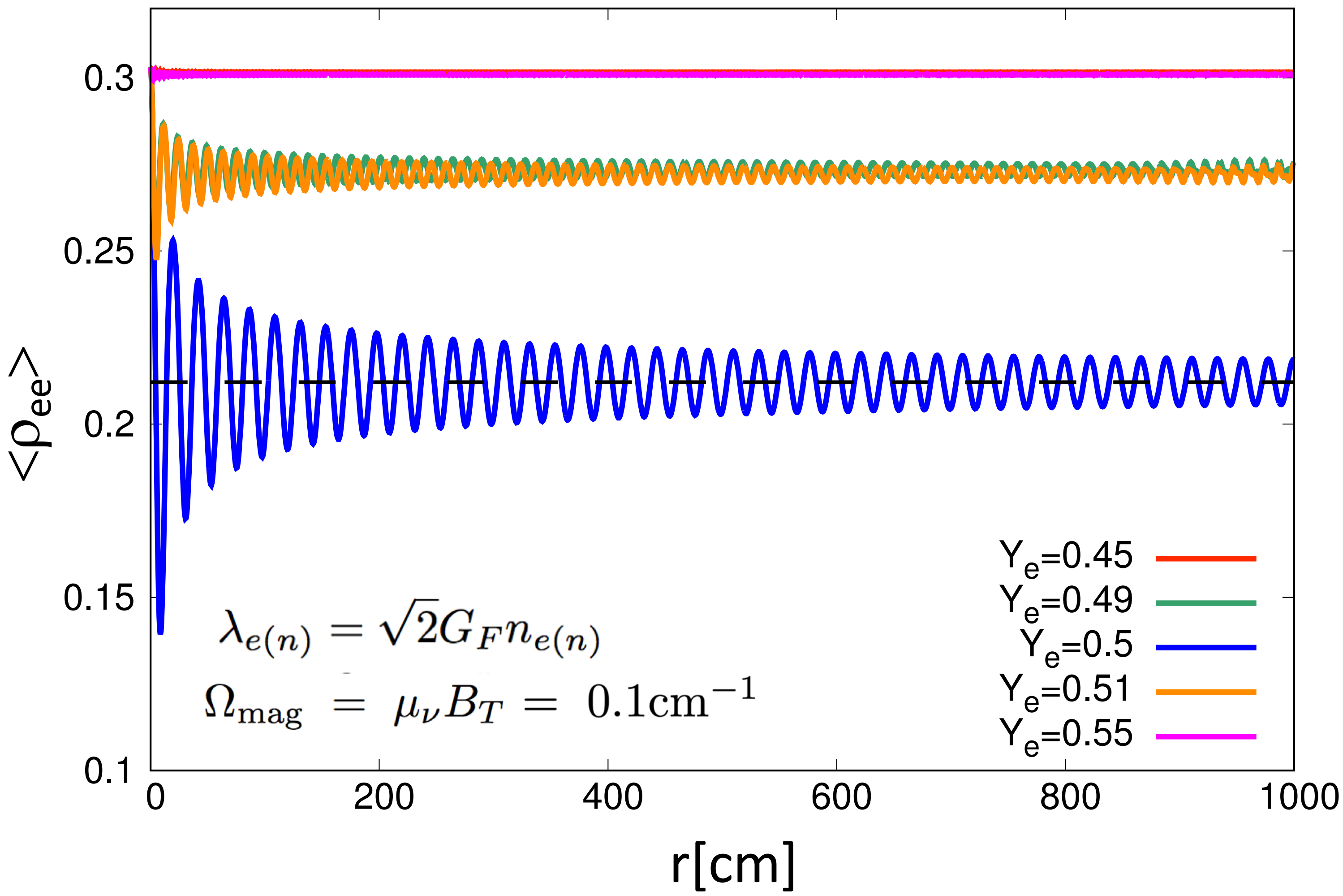
Results of $\nu-\bar{\nu}$ oscillations in different λ_e



Neutrino oscillations are suppressed in a dense matter ($\lambda_e = 10^2\Omega_{mag}$)

Results of $\nu - \bar{\nu}$ oscillations in different Y_e

$\lambda_e = 10^2 \Omega_{mag}$



Neutrino oscillations occur around $Y_e \sim 0.5$ even in dense matter

→ $\Omega_{mag} > |\lambda_e - \lambda_n| \propto |2Y_e - 1|$ is required for active $\nu - \bar{\nu}$ oscillations

Possibility of ν–$\bar{\nu}$ oscillations in core-collapse supernovae

The necessary condition for ν–$\bar{\nu}$ oscillations

$$\Omega_{\rm mag} \geq \eta,$$

$$\eta = \max\{\lambda, \zeta, \omega\}$$

・Strength of magnetic potential:

$$\Omega_{\rm mag} = \mu_\nu B_T$$

$$\mu_\nu = 10^{-12}\mu_B \qquad B_T = B_0\left(\frac{R_\nu}{r}\right)^3$$

Magnetic field on the surface of ν sphere

・Strength of vacuum potential:

$$\omega = |\Delta m^2_{32}|/2E$$

・Strength of matter potential:

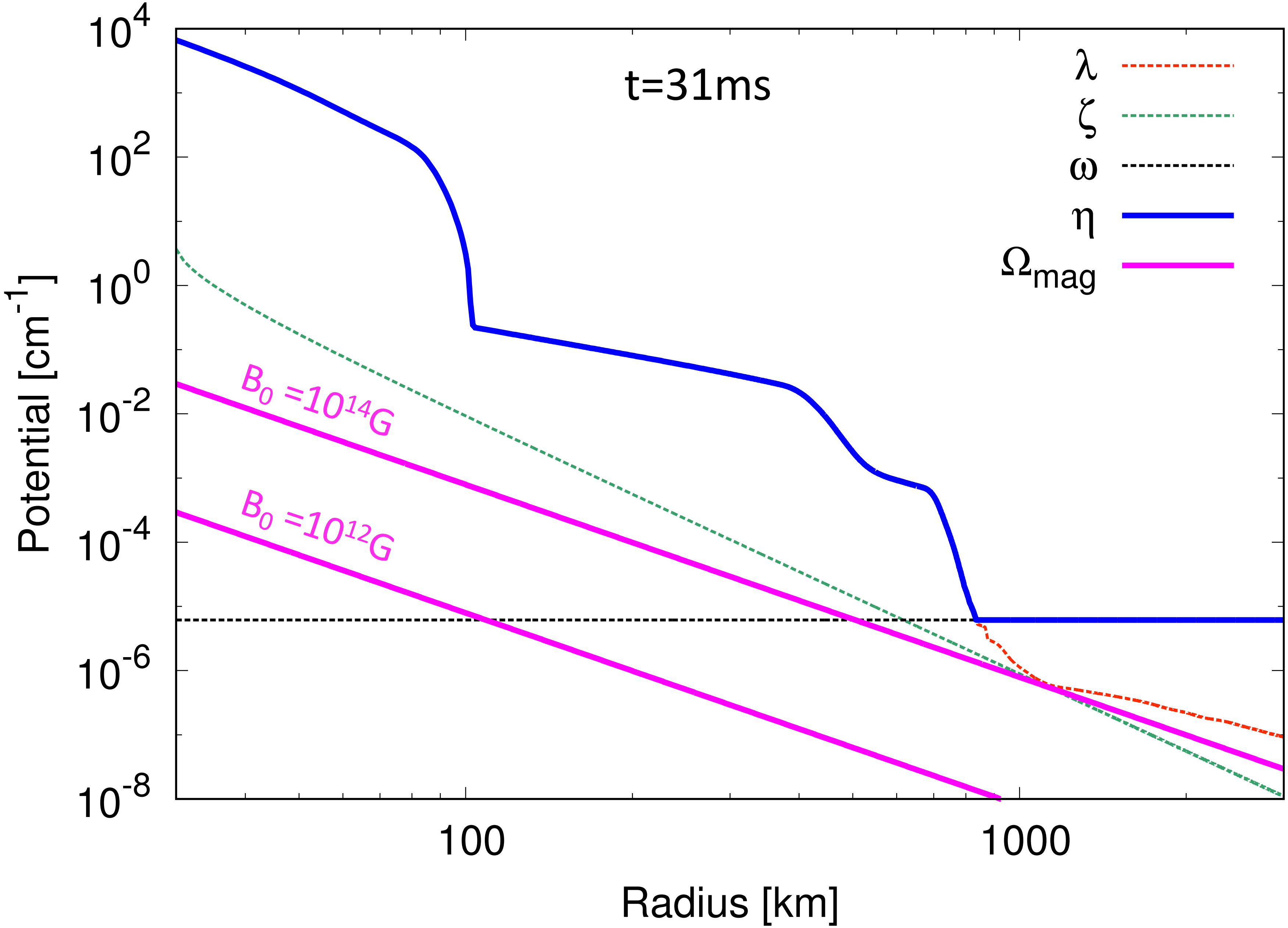
$$\lambda = |\lambda_e - \lambda_n| \;, \lambda_{e(n)} = \sqrt{2}G_F n_{e(n)}$$

・Strength of neutrino self interaction:

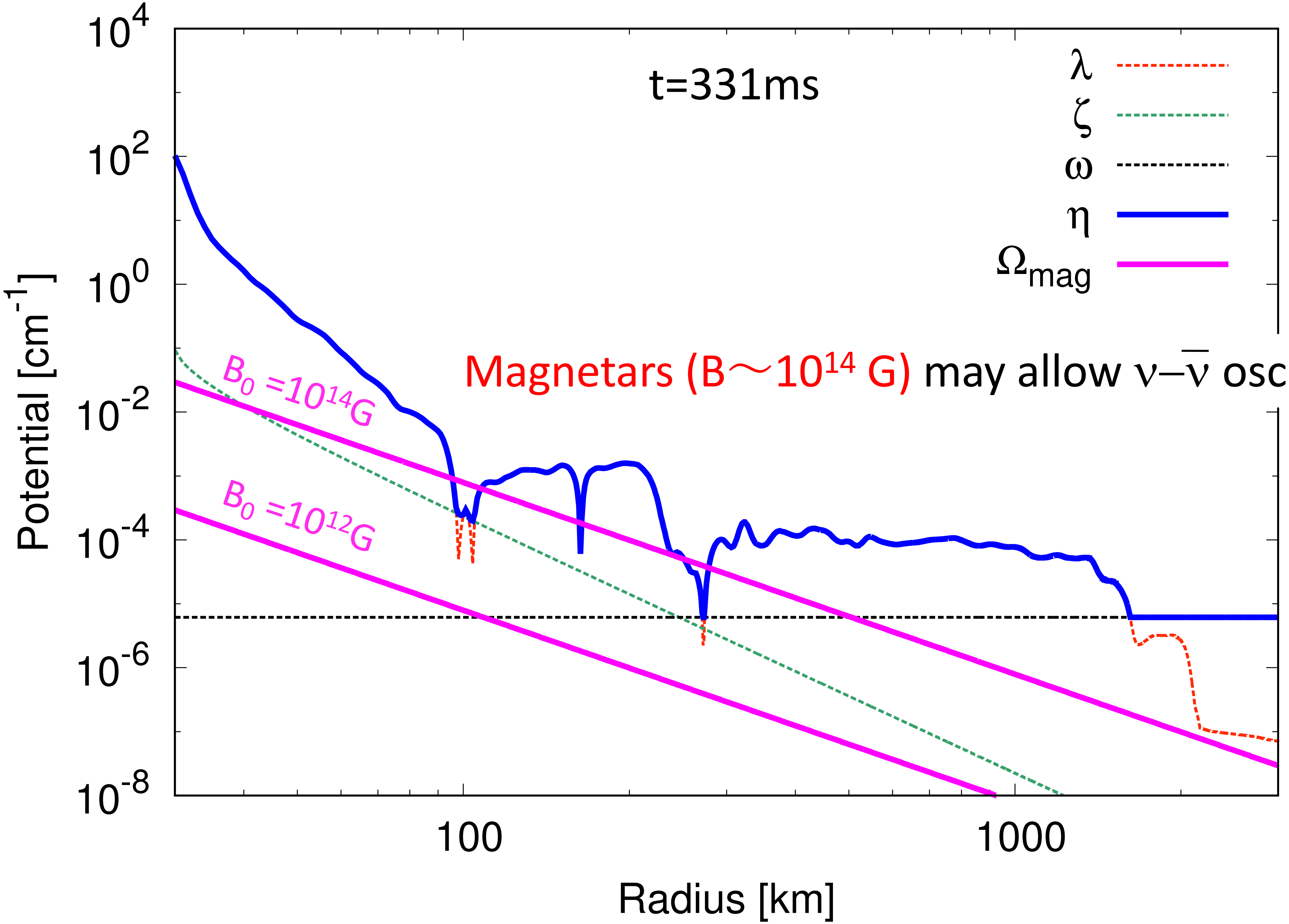
$$\zeta = \frac{\sqrt{2}G_F}{2\pi R_\nu^2}\left|\frac{L_{\nu_e}}{\langle E_{\nu_e}\rangle} - \frac{L_{\bar{\nu}_e}}{\langle E_{\bar{\nu}_e}\rangle}\right| \int_{\cos\theta_{\max}}^{1} {\rm d}\cos\theta \;\; (1-\cos\theta)$$

$$= \frac{\sqrt{2}G_F}{4\pi R_\nu^2}\left|\frac{L_{\nu_e}}{\langle E_{\nu_e}\rangle} - \frac{L_{\bar{\nu}_e}}{\langle E_{\bar{\nu}_e}\rangle}\right| \left(1 - \sqrt{1 - \left(\frac{R_\nu}{r}\right)^2}\right)^2,$$

Comparison of potentials in an early explosion phase



Comparison of potentials in a later explosion phase



Magnetars (B～10^{14} G) may allow $\nu - \bar{\nu}$ oscillations

Summary

- It is expected that properties of particle physics can be extracted from neutrino-antineutrino oscillations in strong magnetic field in astrophysical sites

- We carry out demonstration of neutrino-antineutrino oscillations in various parameter sets of matter potential. We find that neutrino-antineutrino oscillations are suppressed in dense matter. However, such matter suppression disappears around $Y_e \sim 0.5$

- We also investigate the possibility of neutrino-antineutrino oscillations in core-collapse supernovae by using matter profiles obtained in supernova simulations

- Our results imply that neutrino-antineutrino oscillations in magnetic field would be possible in a supernova explosion scenario which forms a magnetar ($B>10^{14}$G) when the value of neutrino magnetic moment is $10^{-12}\mu_B$