

物質衝突がニュートリノ集団振動に 与える影響の調査

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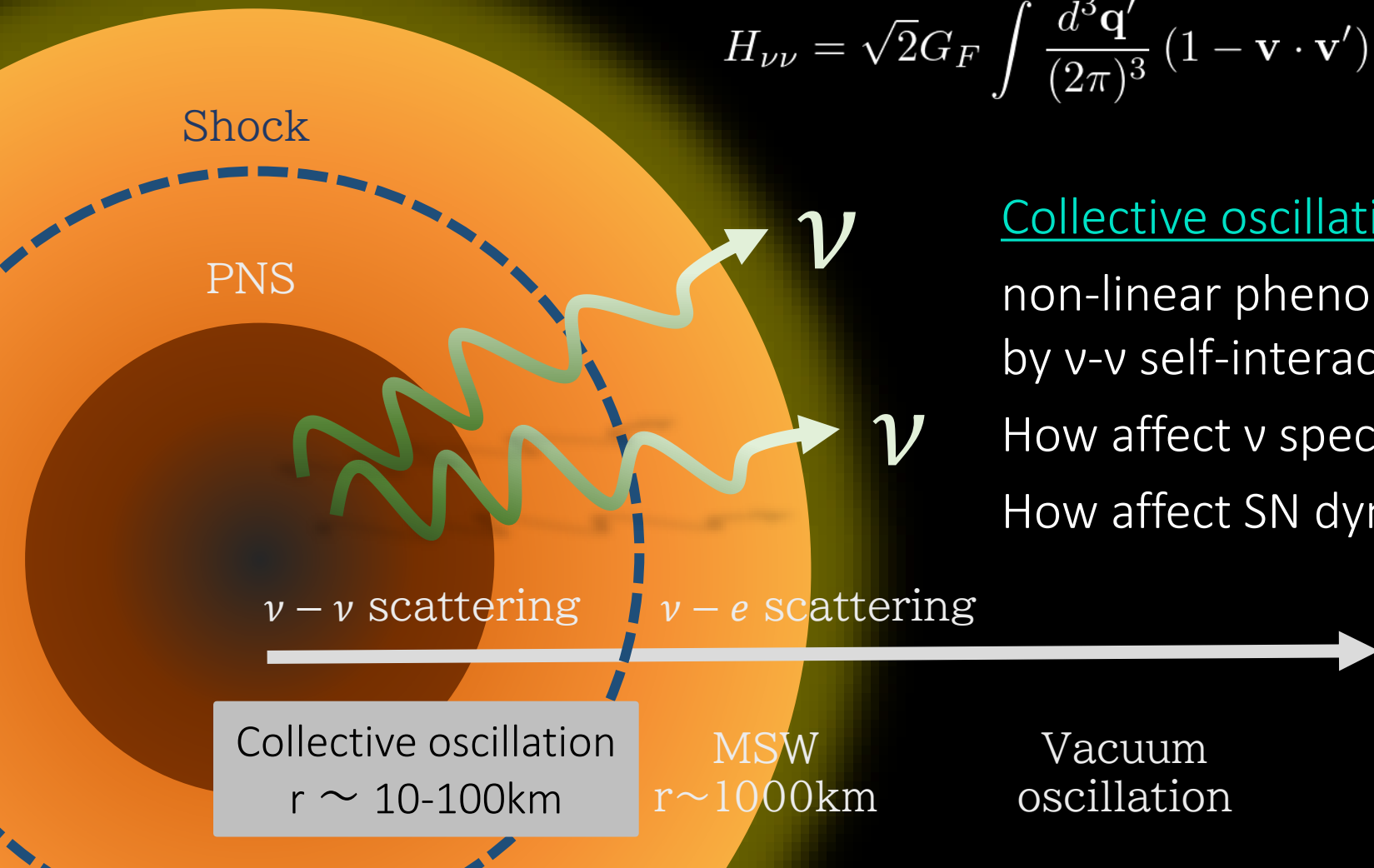
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Neutrino oscillation & ν transport

$$\text{QKE} \quad i \frac{\partial \rho}{\partial t} = [H_{\text{vac}} + H_{\text{mat}} + \underline{H_{\nu\nu}}, \rho] + iC$$

$$H_{\nu\nu} = \sqrt{2}G_F \int \frac{d^3\mathbf{q}'}{(2\pi)^3} (1 - \mathbf{v} \cdot \mathbf{v}') (\rho' - \bar{\rho}^{*'})$$



Collective oscillations

non-linear phenomena
by ν - ν self-interaction

How affect ν spectra?

How affect SN dynamics?

Properties of collective oscillations

- ✓ two distinct modes: fast mode & slow mode

fast mode : $\omega = E_\nu/2m \ll \mu = \sqrt{2}G_F n_\nu$

- ✓ fast conversions: small oscillation scales & fine angular structures

$O(1-100)\text{cm} \ll O(10)\text{km}, \cos \theta_\nu \sim O(10^{-3})$

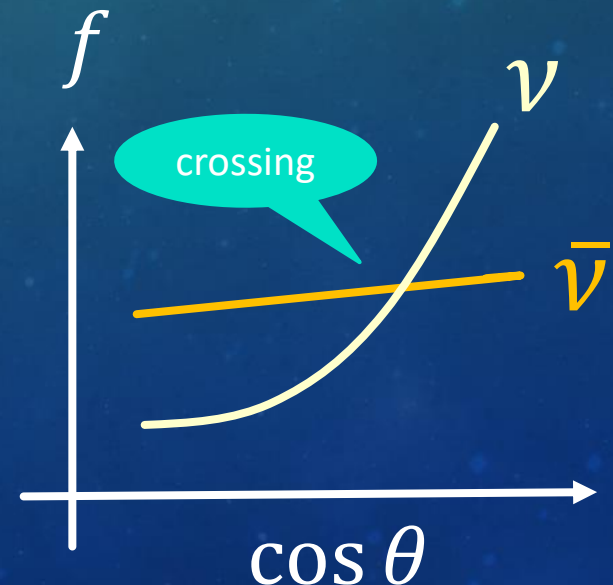
➔ high calculation costs

- ✓ local analysis of fast conversions

linear stability analysis, lepton number crossing

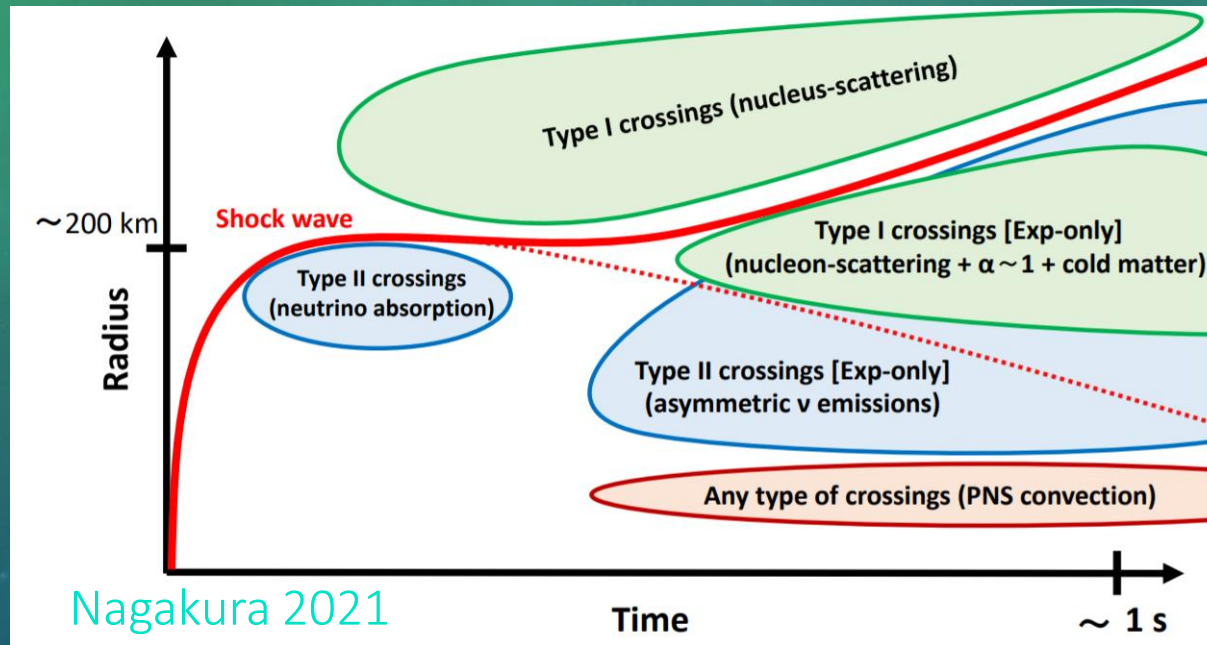
➔ the difference between ν & $\bar{\nu}$

$$G_{\mathbf{v}} = \sqrt{2}G_F \int_0^\infty \frac{dE E^2}{2\pi^2} [f_{\nu_e}(E, \mathbf{v}) - f_{\bar{\nu}_e}(E, \mathbf{v})]$$



ELN crossing in Supernovae

Local analysis suggests fast conversions surely occurs in SN matter!



- ✓ nucleus scattering in pre-shock region Morinaga 2020, Zaizen2021
- ✓ asymmetric neutrino emission associated with multi-D effects
Abbar 2018, Nagakura2019, Abbar 2020
- ✓ nucleon scattering in post-shock region Nagakura 2021
- ✓ PNS convection Milad 2020, Abbar2020, Glas 2020

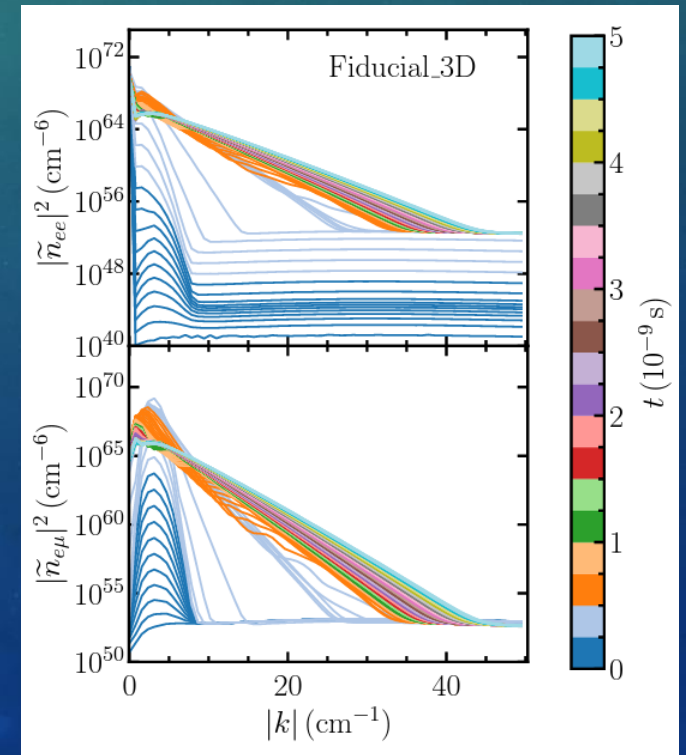
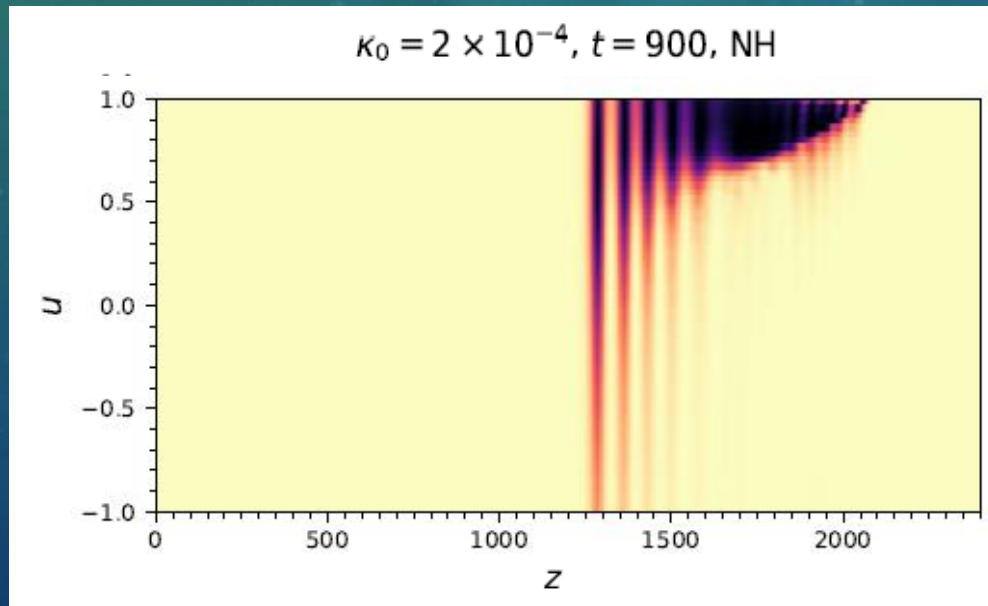
Non-linear evolution

✓ world trend : non-linear calculations with some simplifications

Abbar2019, Sherwood2019,2021, Martin2021, Shalgar2021, Zaizen2021, Sigle2021 etc

Sherwood2021

Martin2021



Fast conversion with matter collisions

Matter collisions affect fast conversion behaviors

- ✓ Collisions change ν distribution & make a new crossing
e.g., halo effects, ν -nuclei coherent scattering

Cherry2013, Capozzi2019, Morinaga2020, Zaizen2020

- ✓ Collisions affect the evolution of existing FCs
suppression? or enhancement?

Martin2021, Shalgar2020, Sigl2021

- ✓ Collisional instability = a new instability mode

Lucas2021, Dasgupta 2021

Conventional method VS MC method

- ✓ almost all calculations : deterministic method
this study : MC method (probabilistic)
- ✓ advantage of MC method
 - cross check of results
 - simple & low-cost reaction handling
 - high parallelization efficiency
- ✓ drawback of MC method
 - statistical errors via random numbers ➡ EMP method

Purpose

To investigate effects of fast conversions on observed ν spectra and supernova dynamics

In this talk

- ✓ To introduce a new MC ν transport code with both of collisions and neutrino oscillations
- ✓ To discuss non-linear behavior
- ✓ To discuss effects of collisions on fast conversions

Governing Equations & Assumptions

$$\begin{aligned}
 \nu \quad i \frac{\partial \rho}{\partial t} &= [H_{\text{vac}} + H_{\nu\nu}, \rho] + i \int_{-1}^1 \frac{d\mathbf{p}'^3}{(2\pi)^3} C \rho' - i \int_{-1}^1 \frac{d\mathbf{p}'^3}{(2\pi)^3} C \rho \\
 \bar{\nu} \quad i \frac{\partial \bar{\rho}}{\partial t} &= [H_{\text{vac}}^* - H_{\nu\nu}^*, \bar{\rho}] + i \int_{-1}^1 \frac{d\mathbf{p}'^3}{(2\pi)^3} C \rho' - i \int_{-1}^1 \frac{d\mathbf{p}'^3}{(2\pi)^3} C \rho
 \end{aligned}$$

Oscillation term

Collision term

$$\rho = \begin{pmatrix} \rho_{ee} & \rho_{ex} \\ \rho_{ex}^* & \rho_{xx} \end{pmatrix}, \bar{\rho} = \begin{pmatrix} \bar{\rho}_{ee} & \bar{\rho}_{ex} \\ \bar{\rho}_{ex}^* & \bar{\rho}_{xx} \end{pmatrix}$$

f_{ν_e} points to ρ_{ee} , f_{ν_x} points to ρ_{ex}

$$H_{\text{vac}} = U \frac{1}{2E} \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} U^\dagger$$

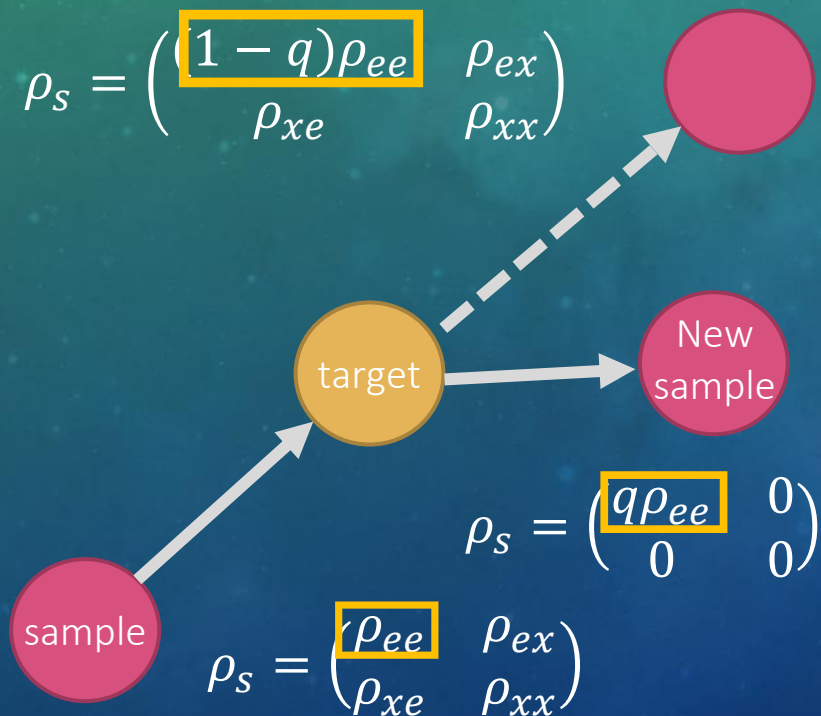
$$H_{\nu\nu} = \sqrt{2} G_F \int \frac{d^3 \mathbf{q}}{(2\pi)^3} (1 - \cos \theta) (\rho - \bar{\rho}^*)$$

- ✓ variables: 8 components in $\rho, \bar{\rho}$
- ✓ 2-flavor
 - monotonic ν energy
 - homogeneous in ρ
 - axial symmetry in phase space
- ✓ isotropic scattering
 - same reaction rates

ν transports with MC method

✓ Establish ν transport with MC method in the case of oscillation & collisions

Kato et al. 2021, ApJS, 257, 55



n step

Evolution of sample particles

Solving geodesic equation
Neutrino reactions
EMP method

Calculation of $H_{\nu\nu}$

Summing up MC samples

$$H_{\nu\nu} = \sqrt{2}G_F \int \frac{d^3\mathbf{q}}{(2\pi)^3} (1 - \cos\theta) (\rho - \bar{\rho}^*)$$

Evolution of $\rho, \bar{\rho}$

Solving QKE for each sample particle
4th-order Runge-Kutta method

n+1 step

Homogeneous fast conversion wo scattering

- ✓ initial: isotropic ν_e & anisotropic $\bar{\nu}_e$
- ✓ conversion occurs at crossing point
- ✓ periodic conversion
 - ➔ analyzed by pendulum like motion

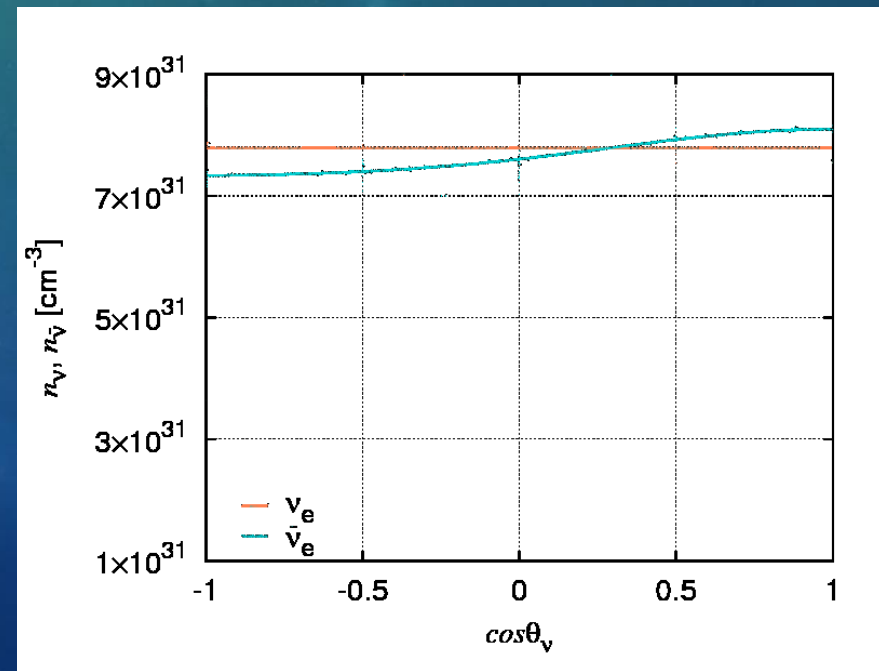
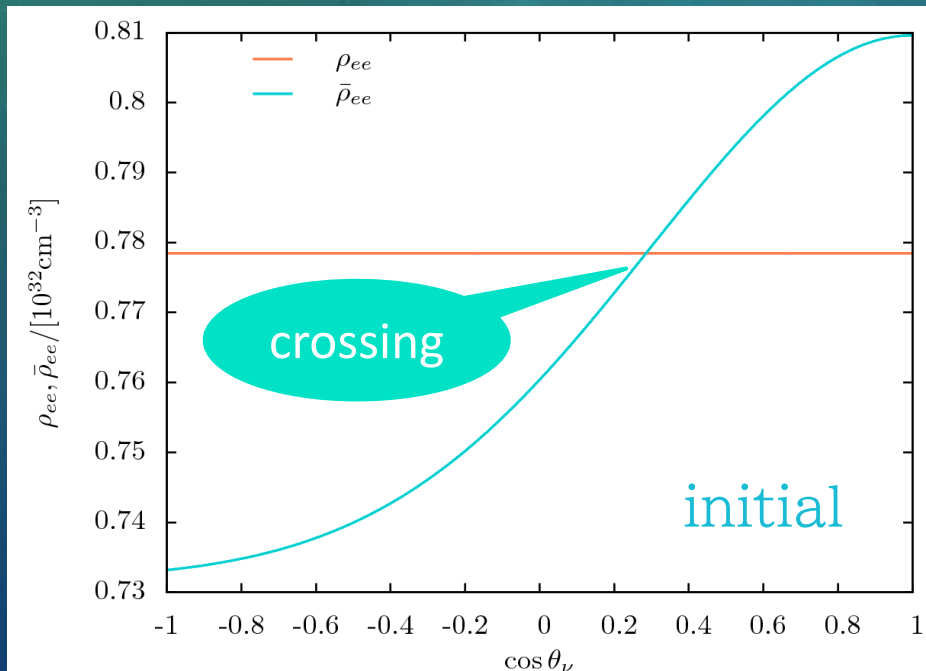
Shalgar 2020

$$\omega/\mu = 1.2 \times 10^{-9}$$

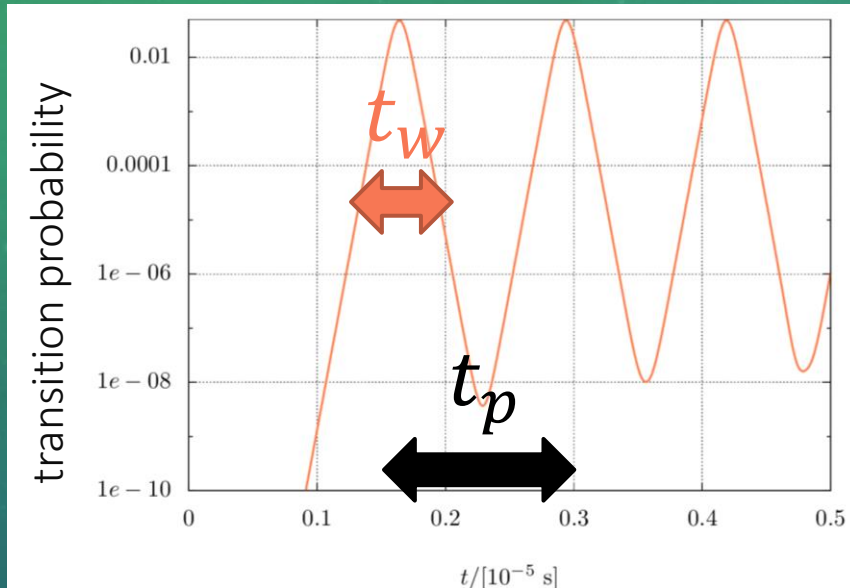
$$E_\nu = 50 \text{ MeV}$$

$$\Delta m^2 = 2.5 \times 10^{-6} \text{ eV}^2$$

$$\theta_\nu = 10^{-6}$$

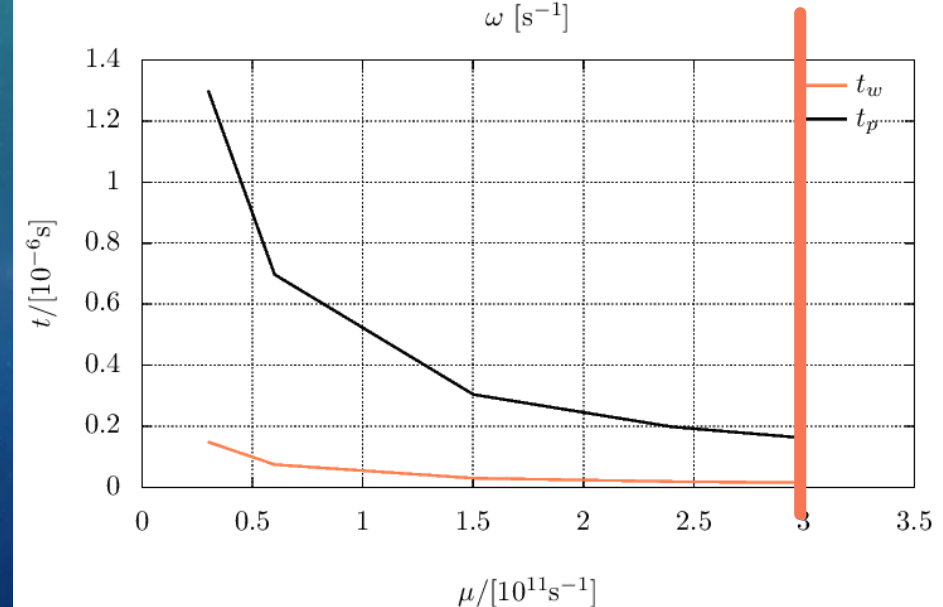
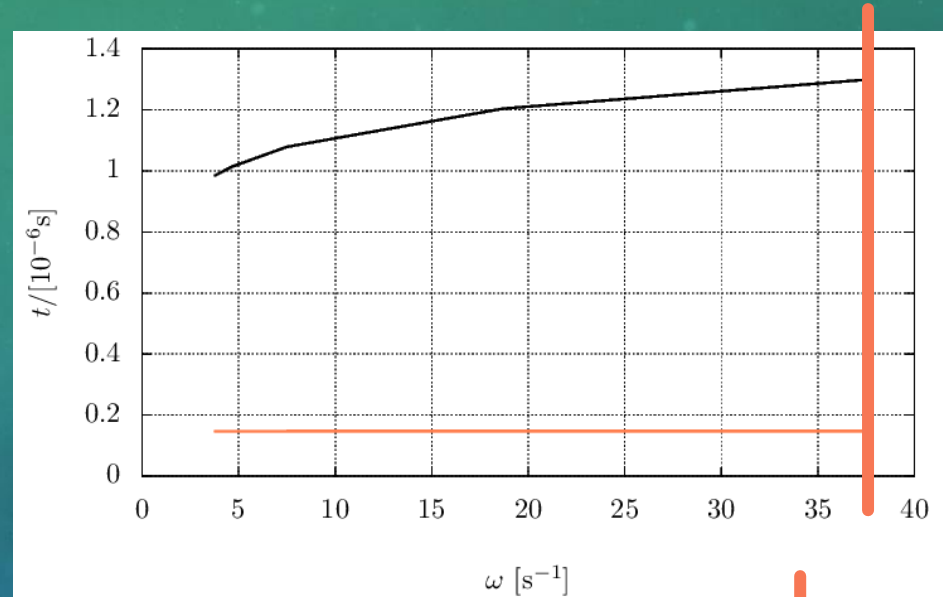


Fast conversion pendulum motions



✓ $t_w, t_p \propto \mu^{-1} \propto n_\nu^{-1}$

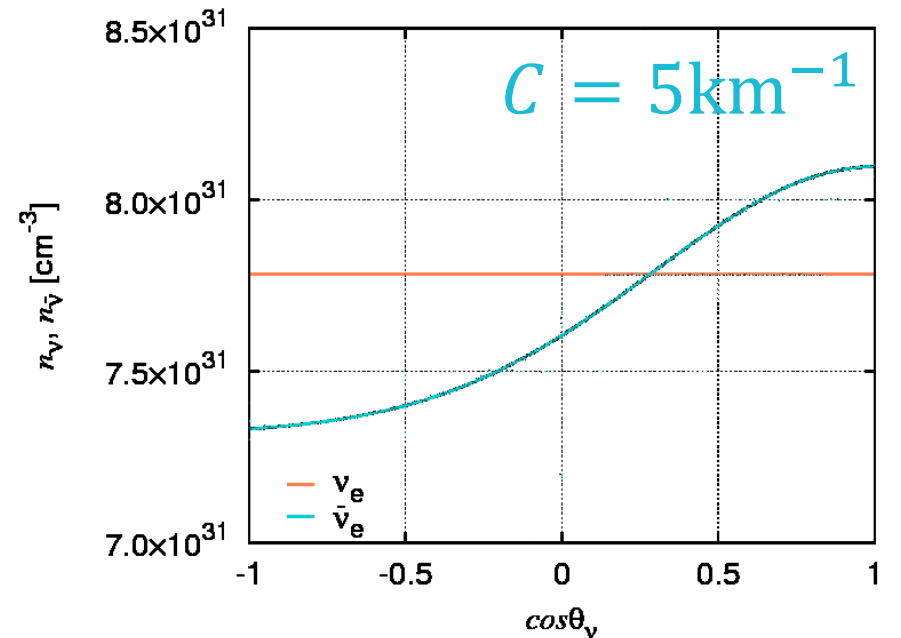
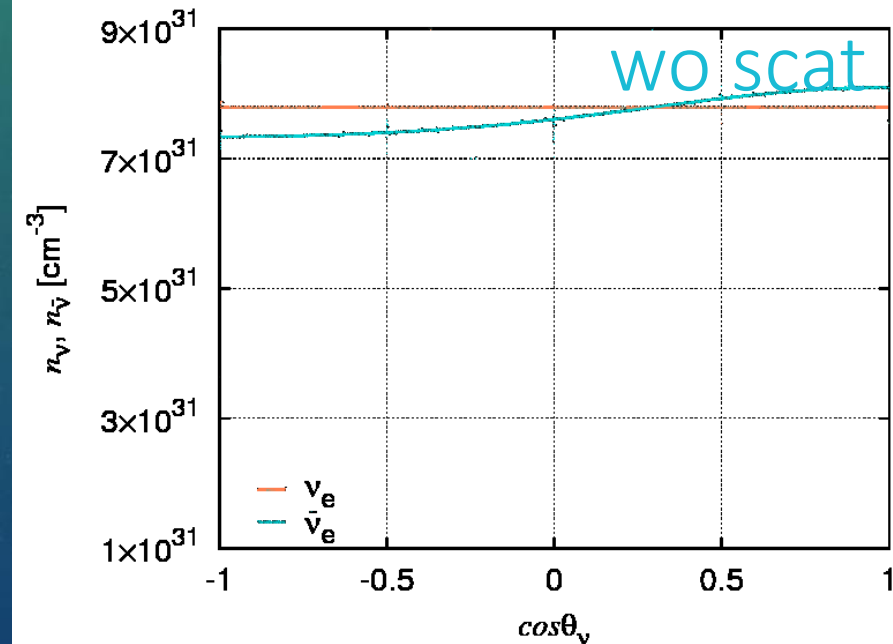
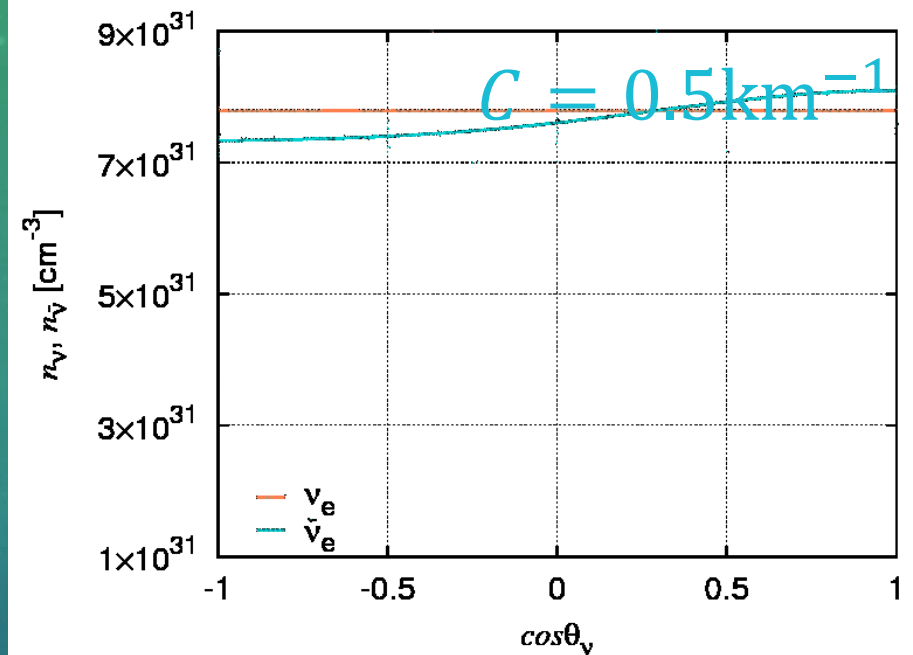
✓ $t_p \propto \omega^{-1} = 2E_\nu / \Delta m^2$



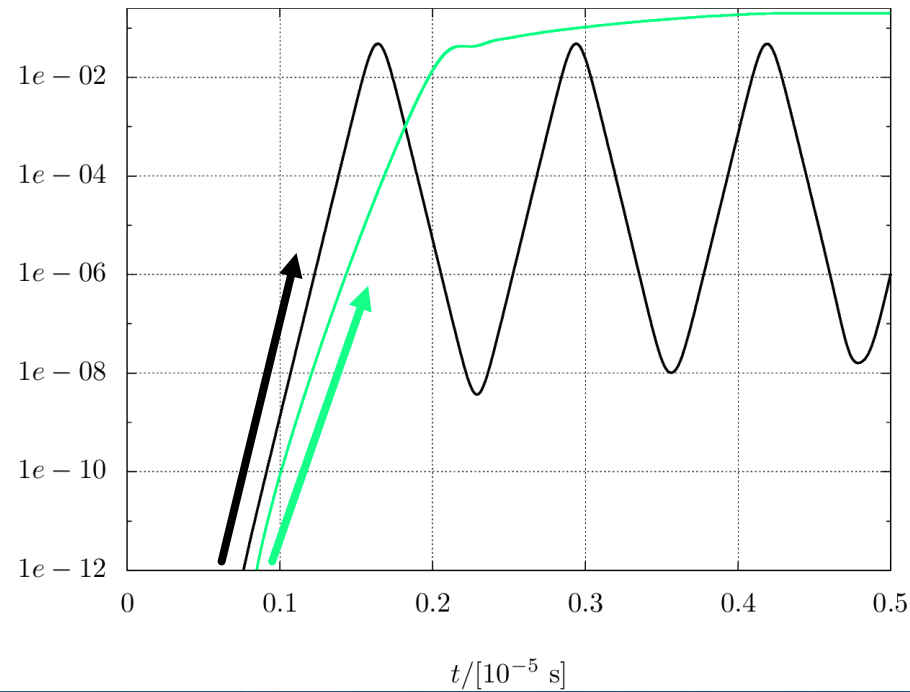
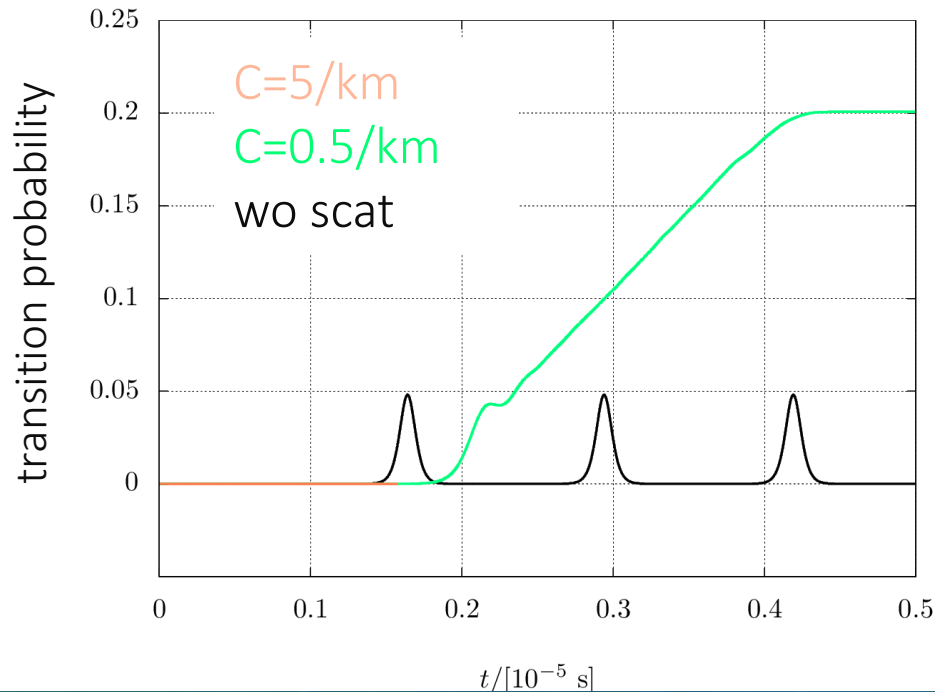
Scattering effects

- ✓ low rate : enhance wide angle range / large amplitude
- ✓ high rate : suppression isotropic distribution

32000 samples $\cdot q = 10^{-5} \cdot N_{\theta} = 256 \cdot 1\text{run}$



Linear & non-linear evolution



| | High rates | Low rates |
|-------------------|-------------|-------------|
| Linear regime | Suppression | Suppression |
| Non-linear regime | Suppression | enhancement |

What's the criterion?

What's the mechanism?

Summary & Future works

Summary

- ✓ collective oscillation may affect SN dynamics & observables
- ✓ new topic : fast conversions with matter collisions
- ✓ a new QKE-MC code with ν oscillations & matter collisions
- ✓ non-linear evolution : pendulum like evolution
- ✓ High scattering rates: suppression
low scattering rates: enhance

Future works

- ✓ What's the criterion for enhancement & suppression?
- ✓ What's the mechanism for enhancement by scatterings?
- ✓ How do assumptions affect FCs?
- ✓ How FCs affects SN dynamics & observables?