物質衝突がニュートリノ集団振動に与える影響の調査

Chinami Kato (TUS)

Collaborators：Hiroki Nagakura (NAOJ)

Taiki Morinaga (Waseda Univ.)

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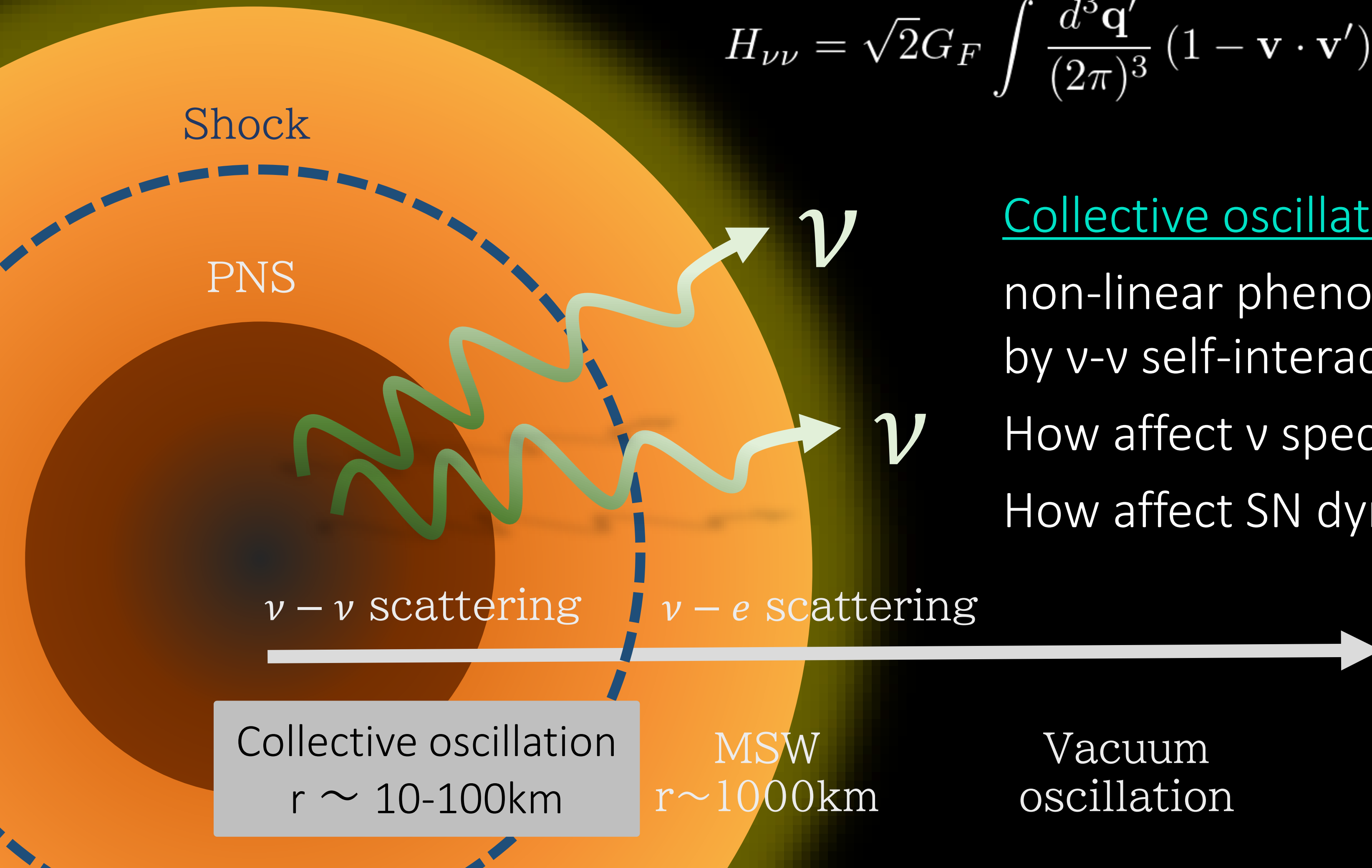
Neutrino oscillation & ν transport

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

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



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

✓fast conversions: small oscillation scales & fine angular structures

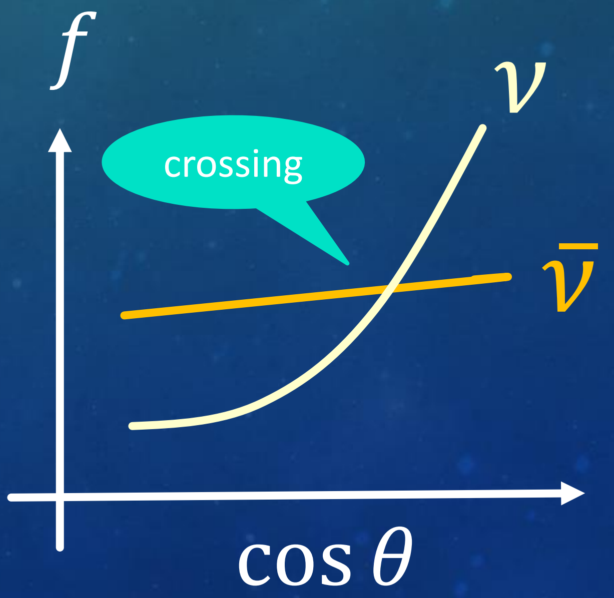
O(1-100)cm << O(10)km, $\cos\theta_\nu \sim$ O(10^{-3})

➡ high calculation costs

✓local analysis of fast conversions

linear stability analysis, lepton number crossing

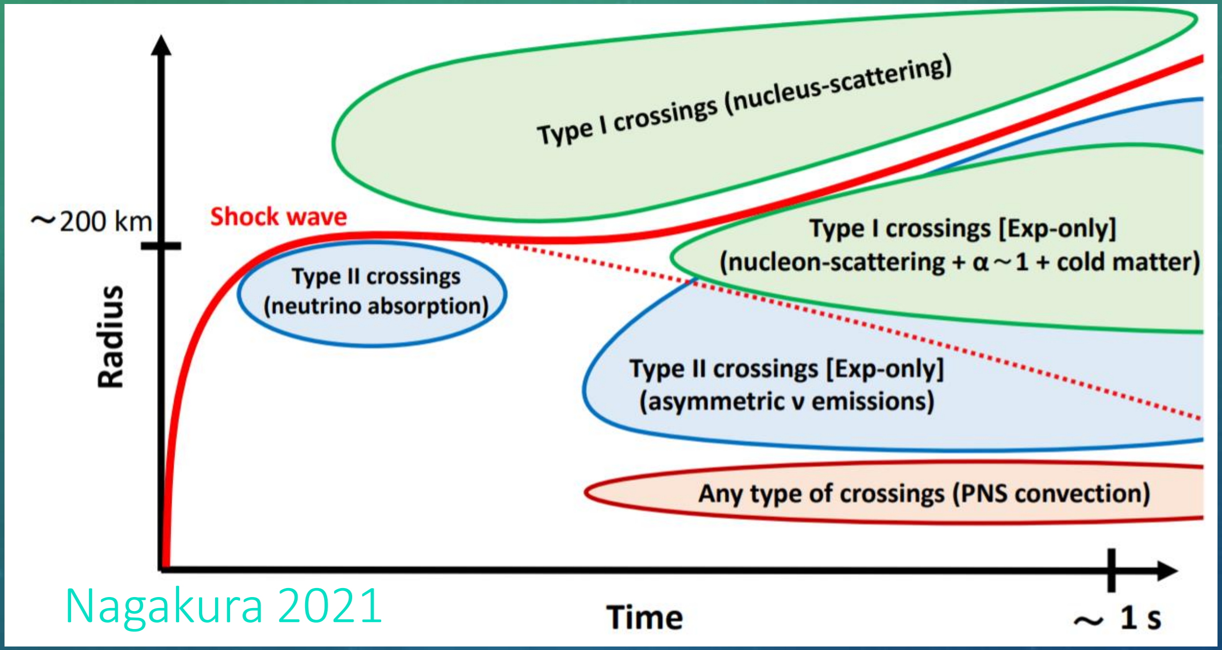
➡ the difference between ν & $\bar{\nu}$



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

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

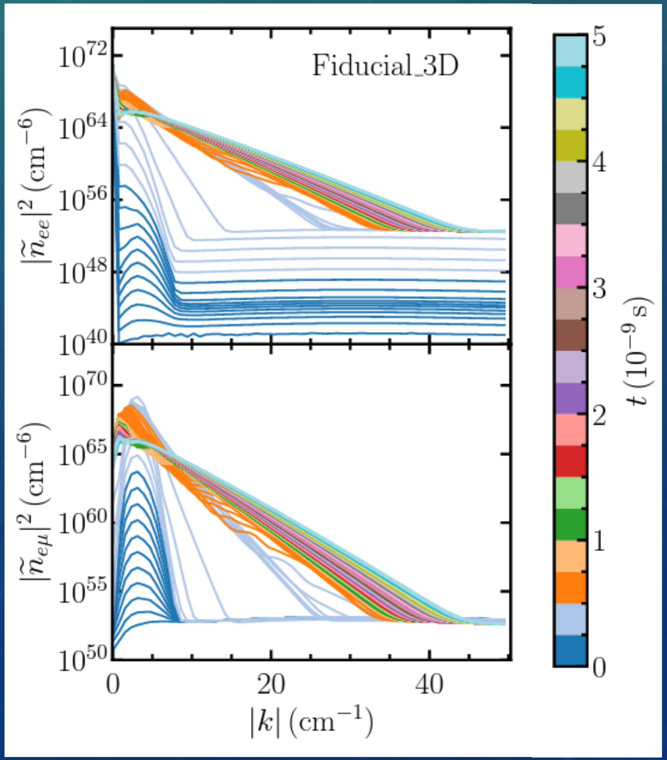
✓PNS convection Milad 2020, Abbar2020, Glas 2020

Non-linear evolution

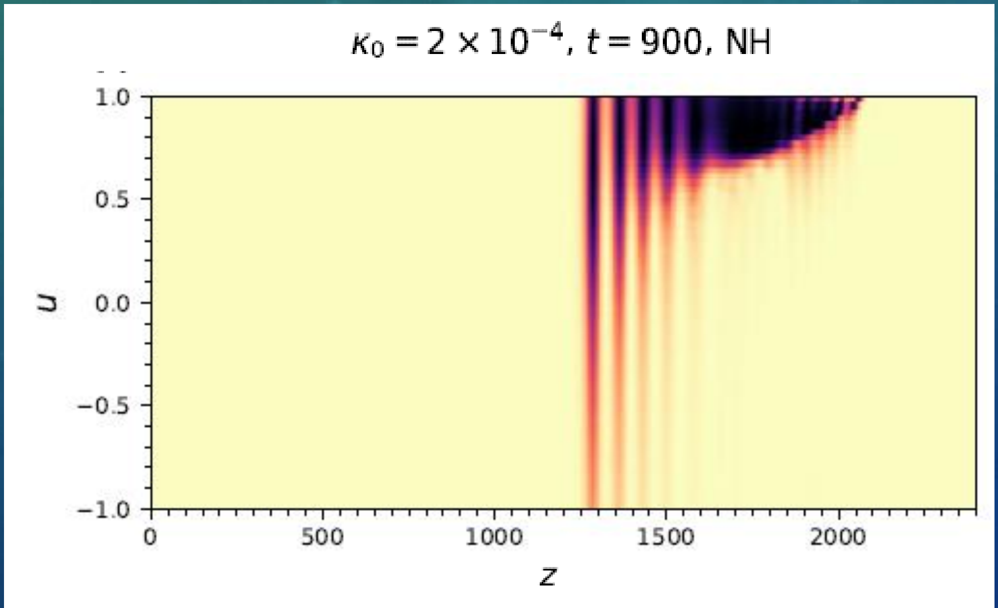
✓world trend : non-linear calculations with some simplifications

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

$$\nu \qquad i\frac{\partial \rho}{\partial t} = [H_{\rm vac} + H_{\nu\nu}, \rho] + i\int_{-1}^{1}\frac{d\mathbf{p}'^3}{(2\pi)^3}C\rho' - i\int_{-1}^{1}\frac{d\mathbf{p}'^3}{(2\pi)^3}C\rho$$

$$\bar{\nu} \qquad i\frac{\partial \bar{\rho}}{\partial t} = [H^*_{\rm vac} - H^*_{\nu\nu}, \bar{\rho}] + i\int_{-1}^{1}\frac{d\mathbf{p}'^3}{(2\pi)^3}C\rho' - i\int_{-1}^{1}\frac{d\mathbf{p}'^3}{(2\pi)^3}C\rho$$

Oscillation term

Collision term

f_{ν_e}

f_{ν_x}

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

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

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

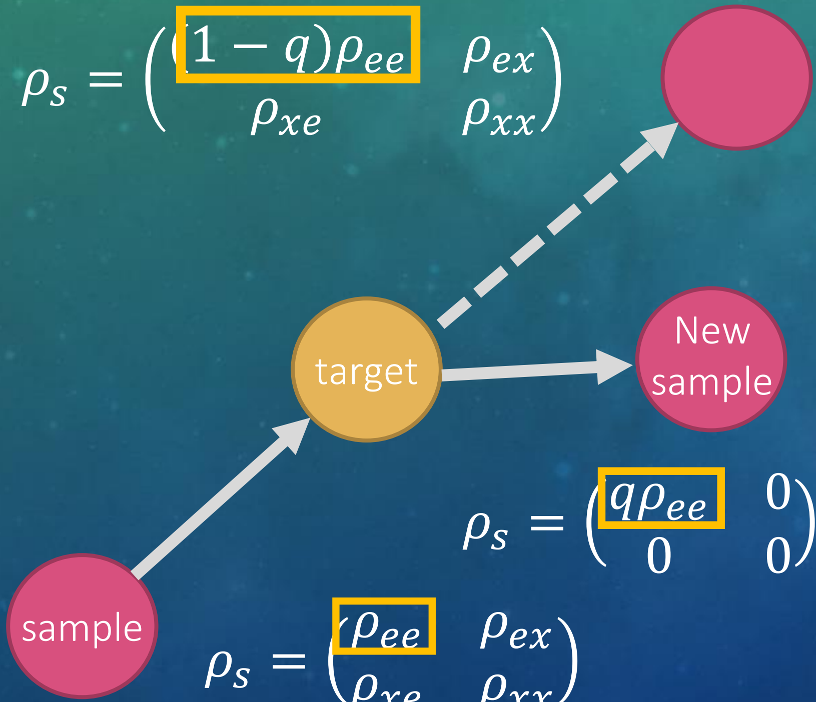
- ✓ variables: 8 components in $\rho, \bar{\rho}$
- ✓ 2-flavor
  - monotonic ν energy
  - homogeneous in ρ
  - axial symmetry in phase space
- ✓ isotropic scattering
  - same reaction rates

ν transports with MC method

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

Kato et al. 2021, ApJS, 257, 55

$$\rho_s = \begin{pmatrix} (1-q)\rho_{ee} & \rho_{ex} \\ \rho_{xe} & \rho_{xx} \end{pmatrix}$$



$$\rho_s = \begin{pmatrix} q\rho_{ee} & 0 \\ 0 & 0 \end{pmatrix}$$

$$\rho_s = \begin{pmatrix} \rho_{ee} & \rho_{ex} \\ \rho_{xe} & \rho_{xx} \end{pmatrix}$$

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 $\rho, \bar{\rho}$

n+1 step

Solving QKE for each sample particle

4th-order Runge-Kutta method

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

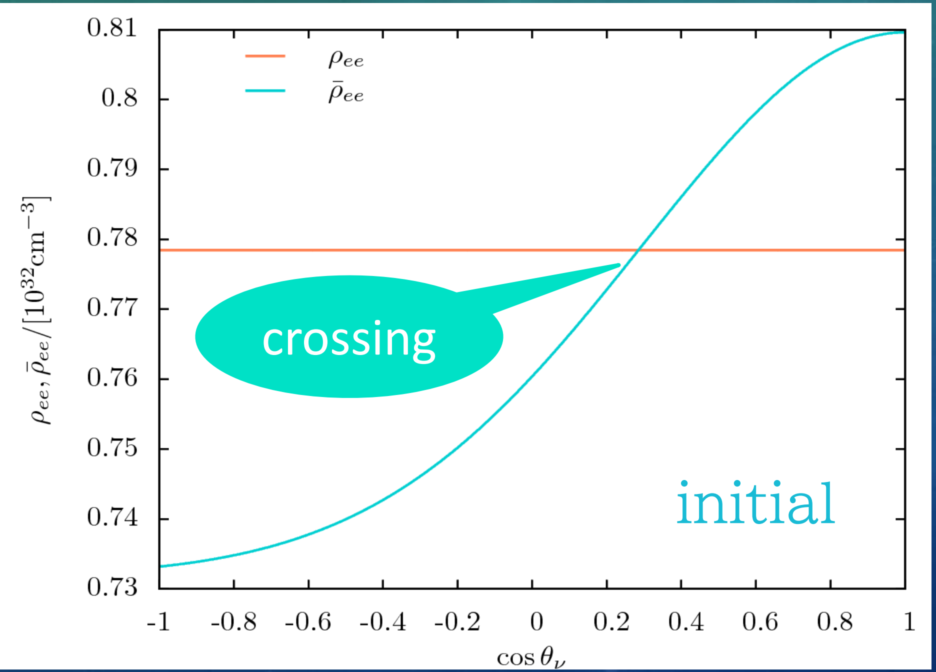
Shalgar 2020

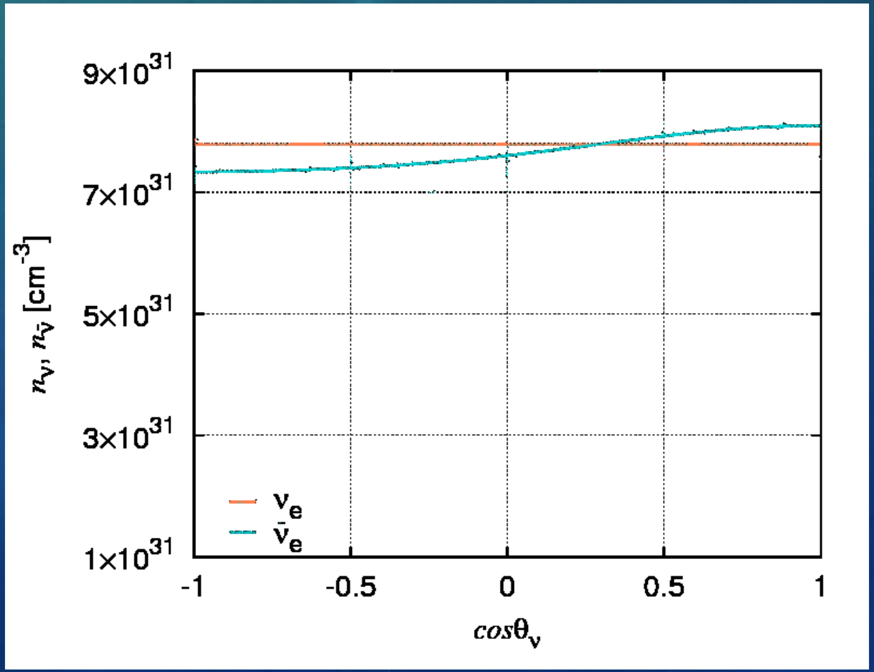
$\omega/\mu = 1.2 \times 10^{-9}$

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

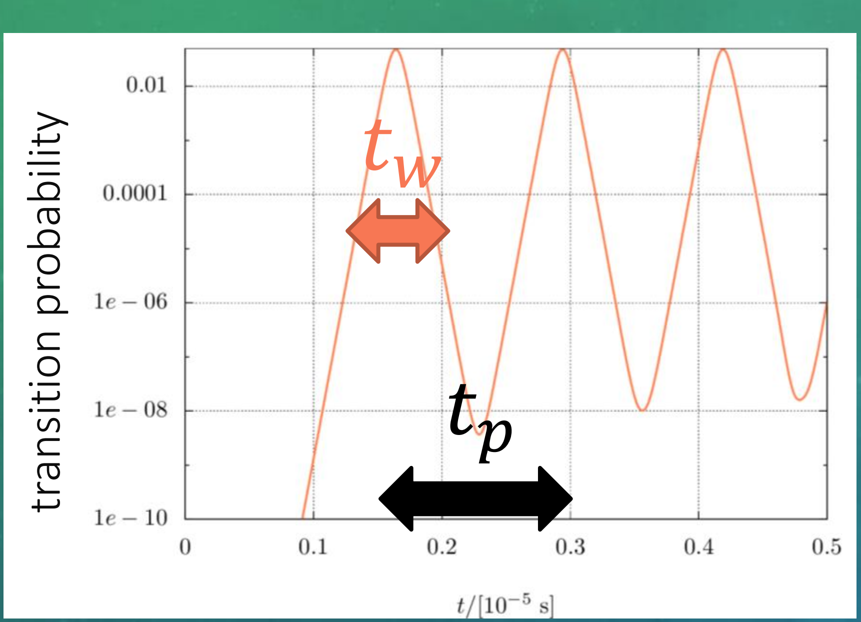
$\Delta m^2 = 2.5 \times 10^{-6}\text{eV}^2$

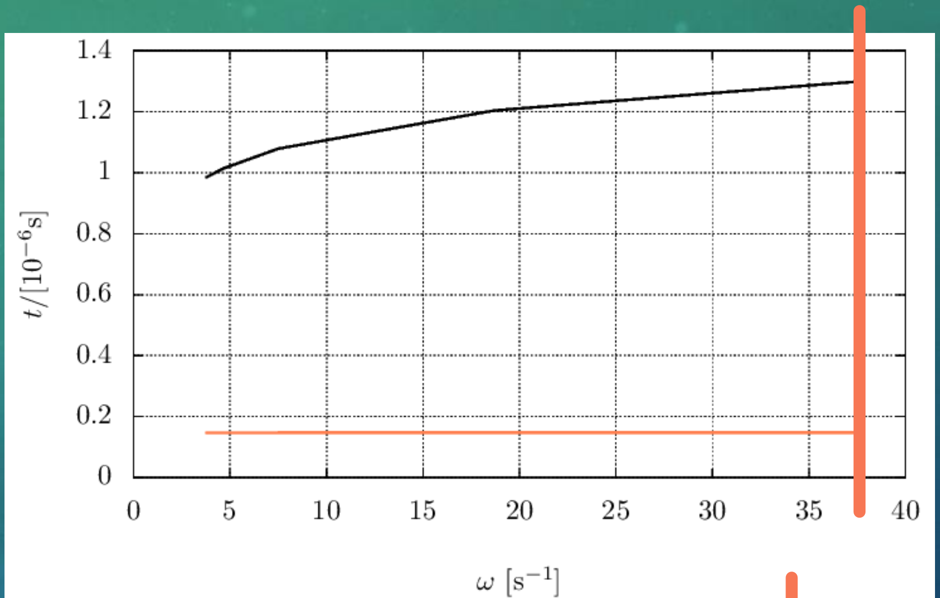
$\theta_\nu = 10^{-6}$

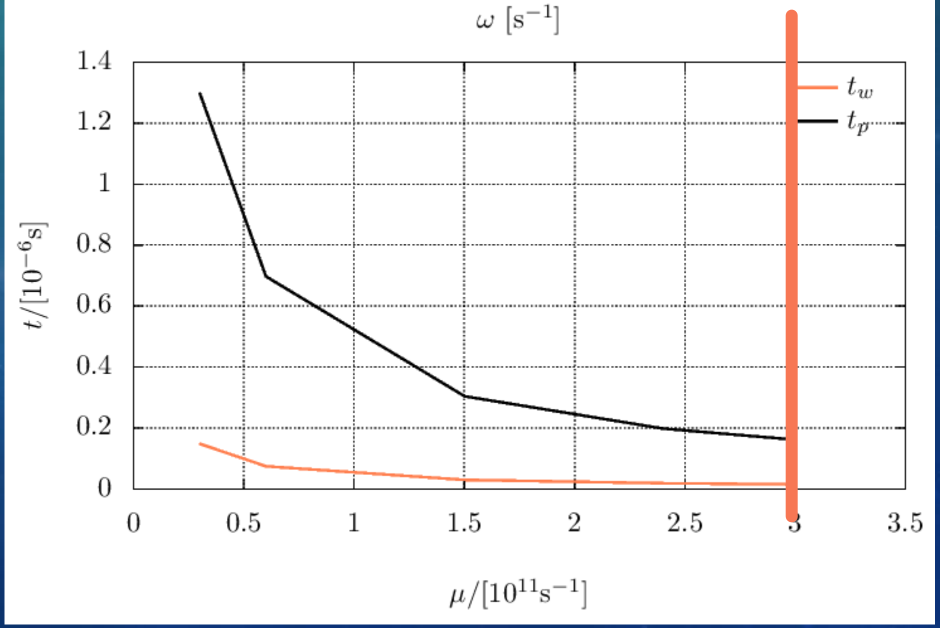




Fast conversion pendulum motions







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

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

Scattering effects

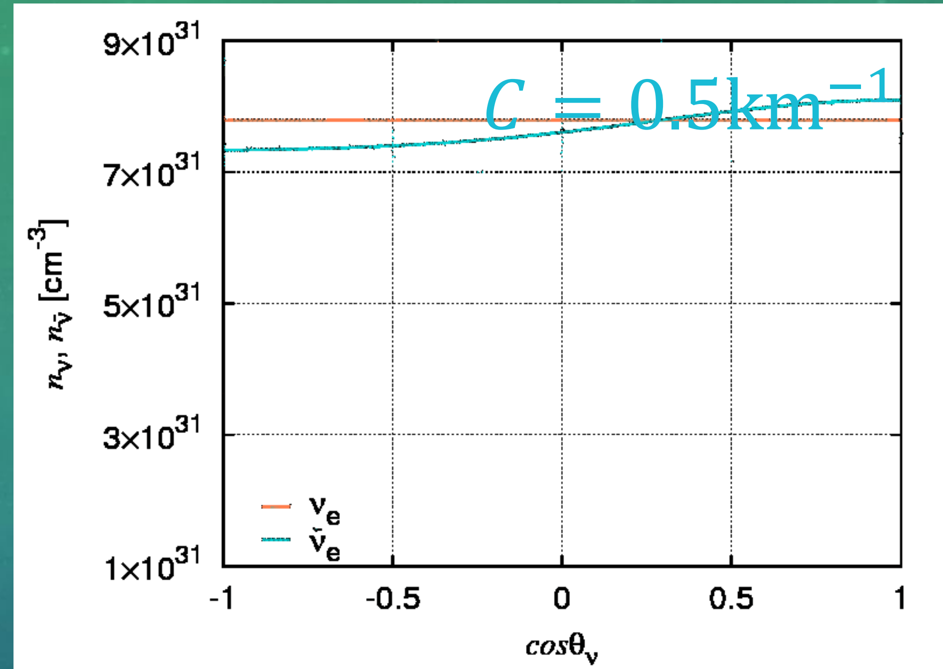
✓low rate : enhance

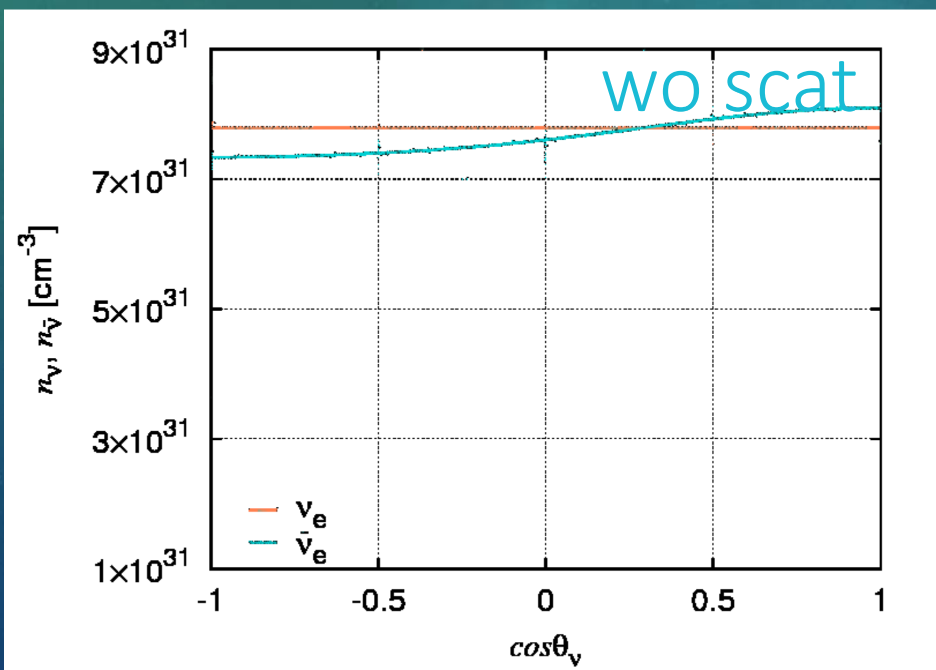
wide angle range/large amplitude

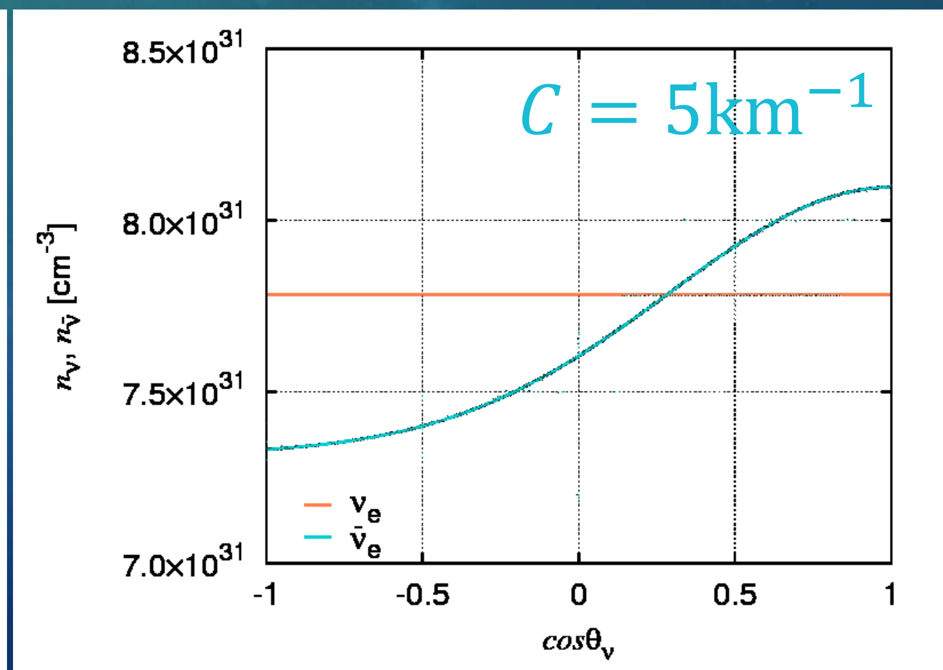
✓high rate : suppression

isotropic distribution

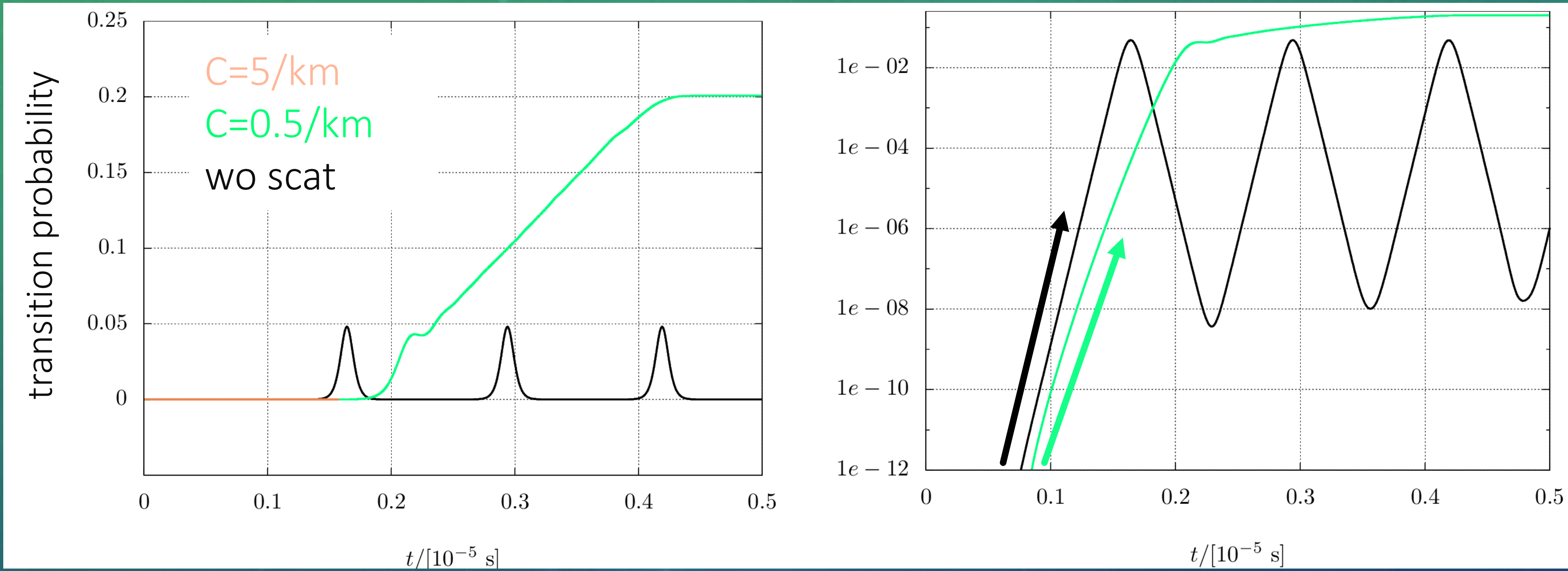
32000 samples・q = 10^{-5}・N_θ=256・1run







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?