Non-linear evolution of fast conversions in dense medium

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Unraveling the History of the Universe and Matter Evolution with Underground Physics

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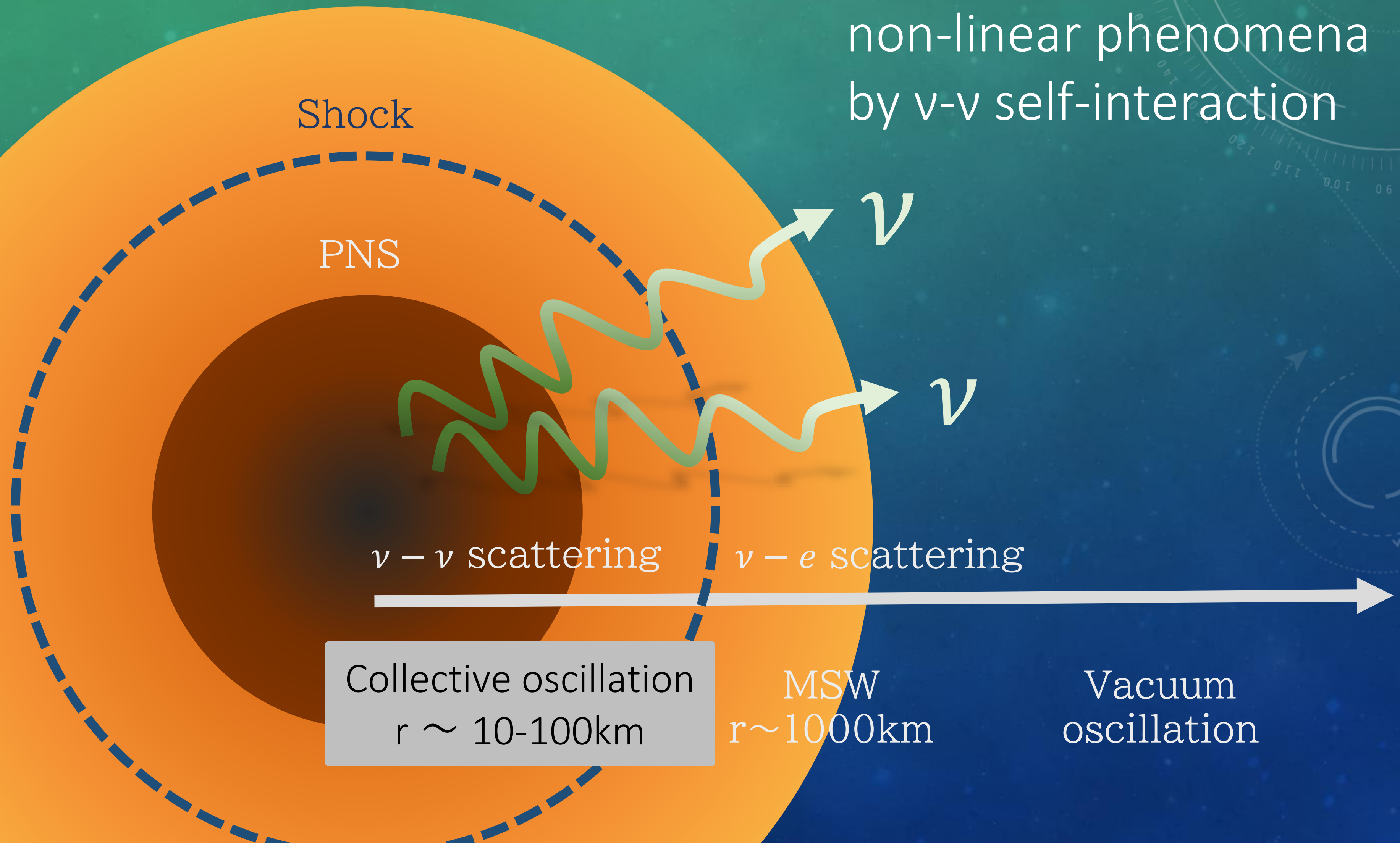
Neutrino oscillation in supernovae

Collective oscillations

non-linear phenomena by ν-ν self-interaction



Quantum Kinetic Equations

ν $$i\left(\frac{\partial}{\partial t}+\vec{v}\cdot\nabla\right)\rho(\vec{x},\vec{p},t)=[\mathcal{H},\rho(\vec{x},\vec{p},t)]+i\mathcal{C}[\rho]$$

$\bar{\nu}$ $$i\left(\frac{\partial}{\partial t}+\vec{v}\cdot\nabla\right)\bar{\rho}(\vec{x},\vec{p},t)=[\bar{\mathcal{H}},\bar{\rho}(\vec{x},\vec{p},t)]+i\bar{\mathcal{C}}[\bar{\rho}]$$

Oscillation term Collision term

3×3 density matrix

$$\rho=\begin{pmatrix}\rho_{ee} & \rho_{e\mu} & \rho_{e\tau}\\ \rho_{\mu e} & \rho_{\mu\mu} & \rho_{\mu\tau}\\ \rho_{\tau e} & \rho_{\tau\mu} & \rho_{\tau\tau}\end{pmatrix}$$

distribution function of active neutrinos

Hamiltonians

$$\mathcal{H}=\mathcal{H}_{\text{vac}}+\mathcal{H}_{\text{mat}}+\mathcal{H}_{\nu\nu}$$
$$\bar{\mathcal{H}}=\mathcal{H}^*_{\text{vac}}-\mathcal{H}^*_{\text{mat}}-\mathcal{H}^*_{\nu\nu}$$

$$\mathcal{H}_{\text{vac}}=U\frac{M^2}{2E_\nu}U^\dagger$$
$$\mathcal{H}_{\text{mat}}=\sqrt{2}G_F diag[n_l-\bar{n}_l]$$
$$\mathcal{H}_{\nu\nu}=\sqrt{2}G_F\int\frac{d^3\vec{p}'}{(2\pi)^3}\left(1-\vec{v}\cdot\vec{v}'\right)\left(\rho'-\bar{\rho}^{*\prime}\right)$$

Properties of collective oscillations

✓two distinct modes: fast mode & slow mode

slow mode : self-interaction $\lesssim$ vacuum

fast mode : self-interaction << vacuum

$$l_{\rm fast} \sim (\hbar c)^{-2} G_{\rm F}^{-1} n_\nu^{-1}$$

✓small oscillation scales & fine angular structures

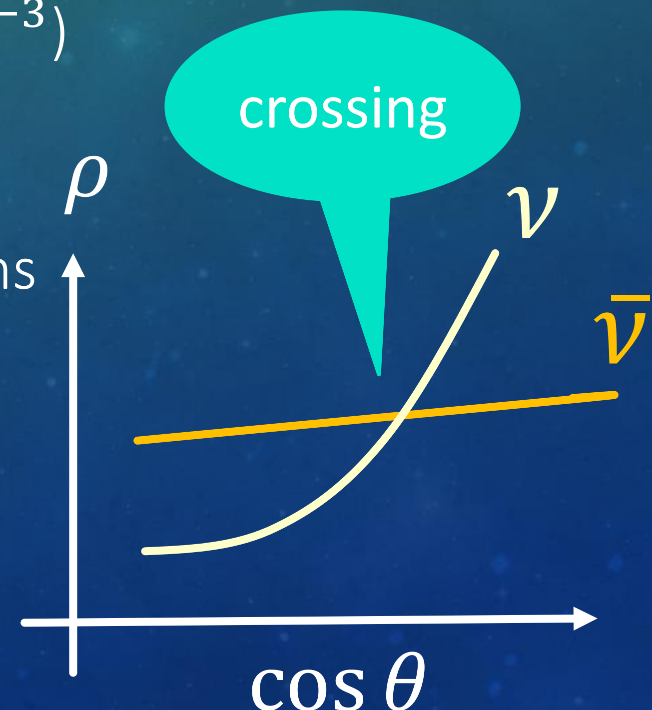
O(1-100)cm << O(10)km, $\cos\theta_\nu \sim$O(10^{-3})

✓linear regime study

search for the criterion of fast conversions

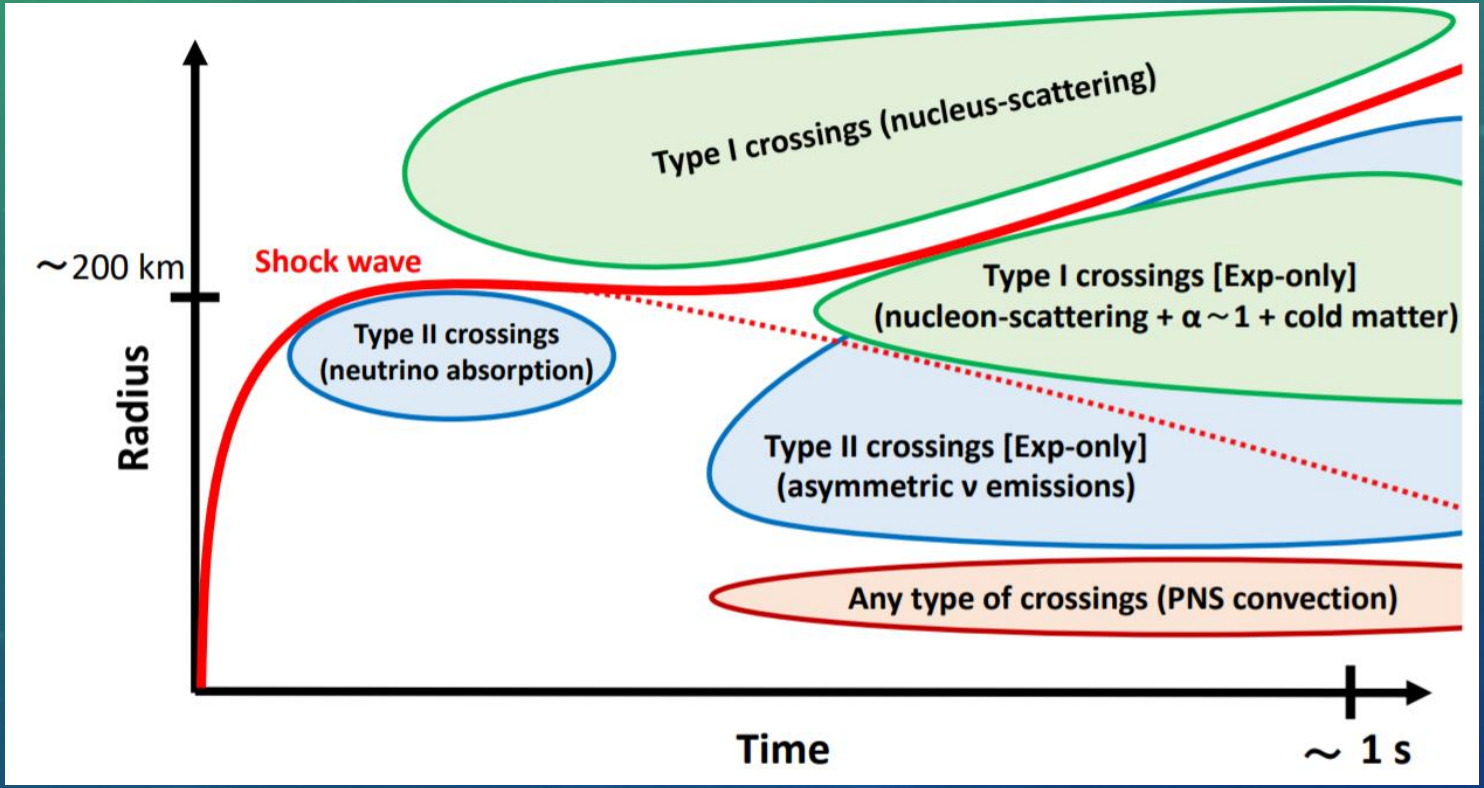
e.g., linear stability analysis, LN crossing

$$L_{\vec{v}} = \sqrt{2} G_F \int \frac{E_\nu^2 dE_\nu}{2\pi^2} (\rho - \bar{\rho})$$



ELN crossing in Supernovae

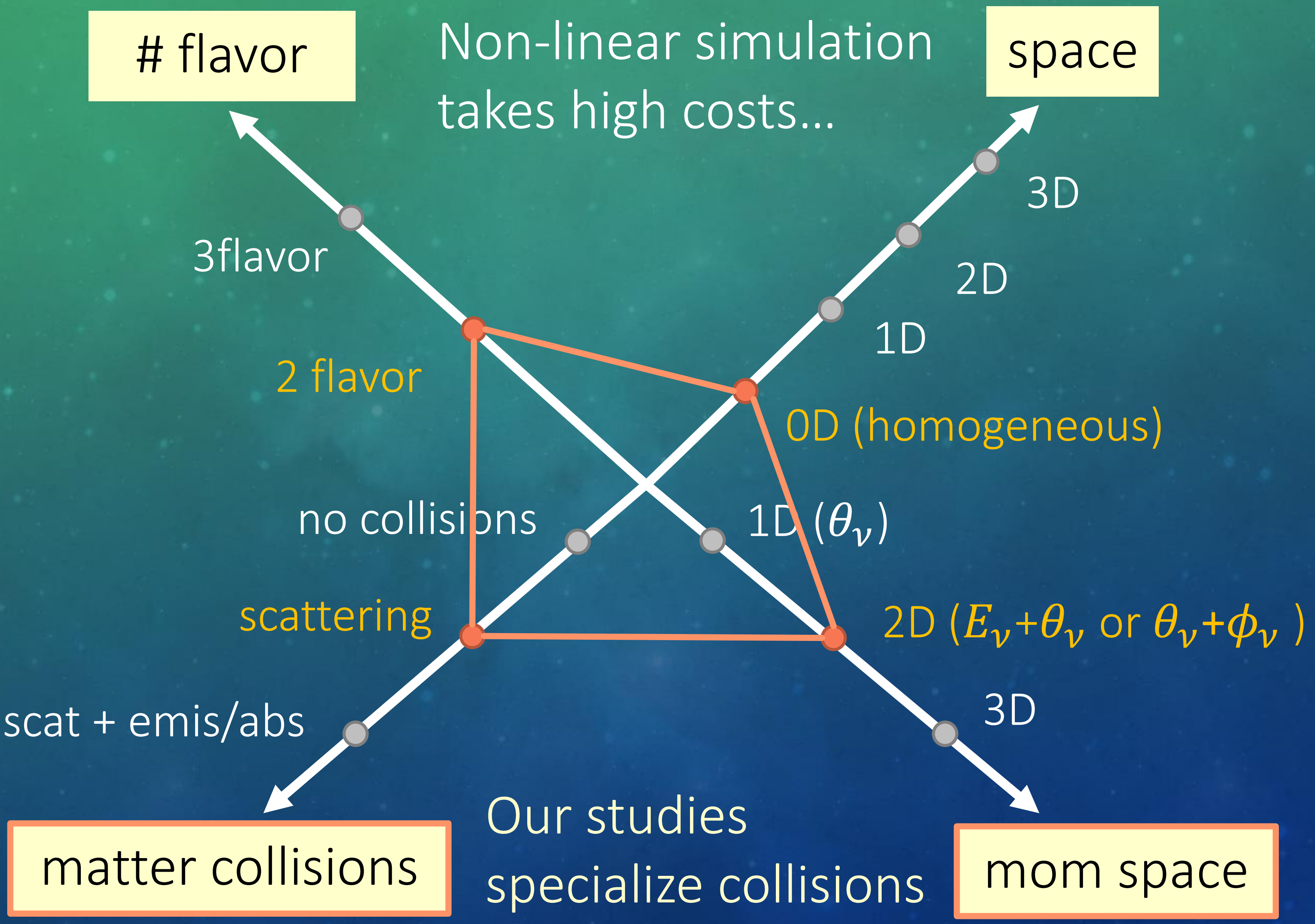
Fast conversions occur everywhere and every time in SN!
➡ affect the SN dynamics? or observables?



Nagakura 2021

After triggering, how do fast conversions evolve?

Non-linear simulations of fast conversions



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

Depending on reaction rate and angular distributions,
FCs are enhanced or suppressed

Martin2021, Shalgar2020, Sigl2021, Shalgar2022

✓ Collisional instability = a new instability mode

Lucas2021, Dasgupta 2021

Energy dependence of fast conversions

- ✓ Fast conversion itself does not depend on ν energy

  ➡ integrate over ν energy

  choose representative ν energy

$$\mathcal{H}_{\nu\nu} = \sqrt{2} G_F \int \frac{d^3\vec{p}'}{(2\pi)^3} \left(1 - \vec{v}\cdot\vec{v}'\right)\left(\rho' - \bar{\rho}^{*\prime}\right)$$

- ✓ However…

  Neutrinos have energy spectrum in SN

  Reaction rates have ν energy dependence

  ➡ If we consider energy-dependent reaction rates, how are the dynamics of fast conversions changed?

Our goal & today's targets

<u>Our ambitious goal</u>

To investigate the effects of fast conversions on SN dynamics & observables ?

neutrino spectra, heavy elements etc…

<u>Today's targets</u>

✓ Effects of isotropic & isoenergetic collisions
✓ Effects of energy-dependent collisions

Simulation setups

$$i\frac{\partial \rho_a(E_\nu, \cos\theta_\nu, t)}{\partial t}$$

Oscillation term

$$= [\mathcal{H}_{\nu\nu}, \rho_a(E_\nu, \cos\theta_\nu, t)]$$

$$+ i\int_{-1}^{1} d\cos\theta'_\nu R(E_\nu)\rho_a(E_\nu, \cos\theta'_\nu, t)$$

$$- i\int_{-1}^{1} d\cos\theta'_\nu R(E_\nu)\rho_a(E_\nu, \cos\theta_\nu, t)$$

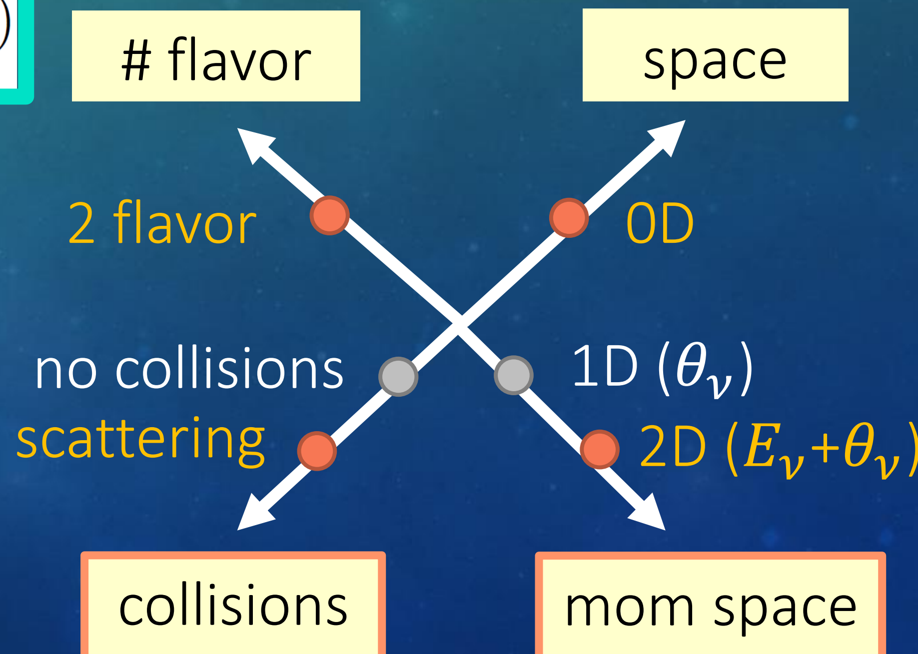
Collision term

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

$$\rho_a \equiv \int \rho d\phi_\nu$$

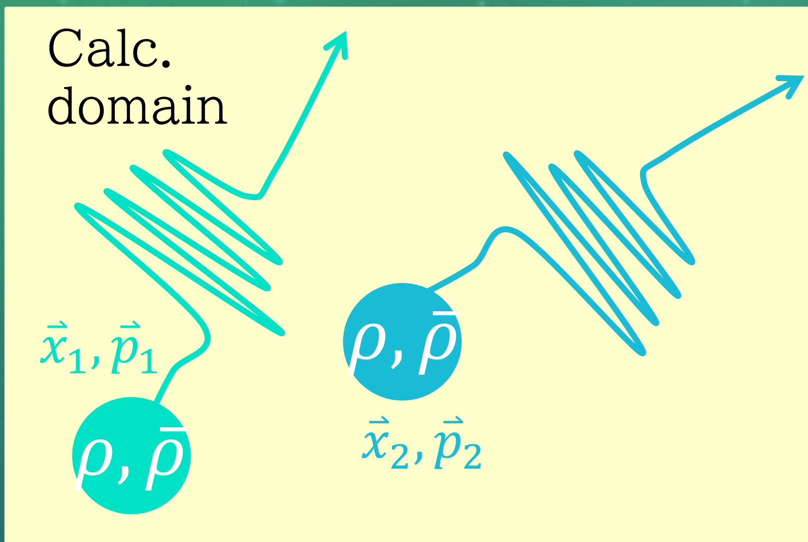
isotropic, isoenergetic scat.
equivalent reaction rates

1. w/o scattering, 1Dps
2. w scattering, 1Dps
3. w scattering, 2Dps



QKE-MC ν transports

CK et al,ApJS,257,55,2021



n step

Evolution of sample particles

Solving geodesic equation
Neutrino reactions

Calculation of $H_{\nu\nu}$

Summing up MC samples

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

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

n+1 step

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

✓Almost the same as the normal MC method

✓8 degrees of freedom in each particle

w/o scattering, 1D phase space

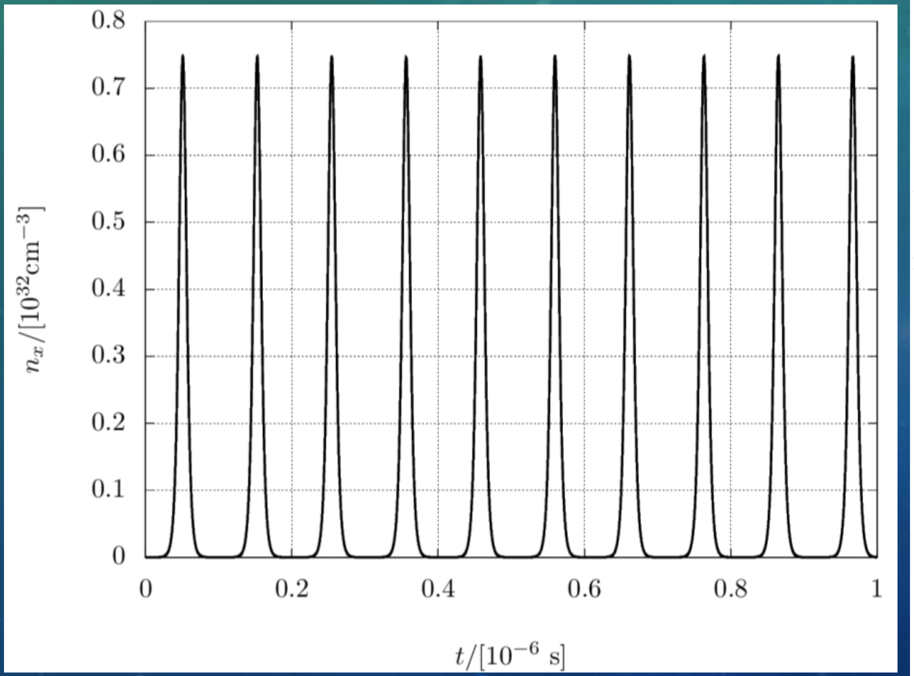
✓ $n_{\nu_e} + n_{\nu_x}$ = constant

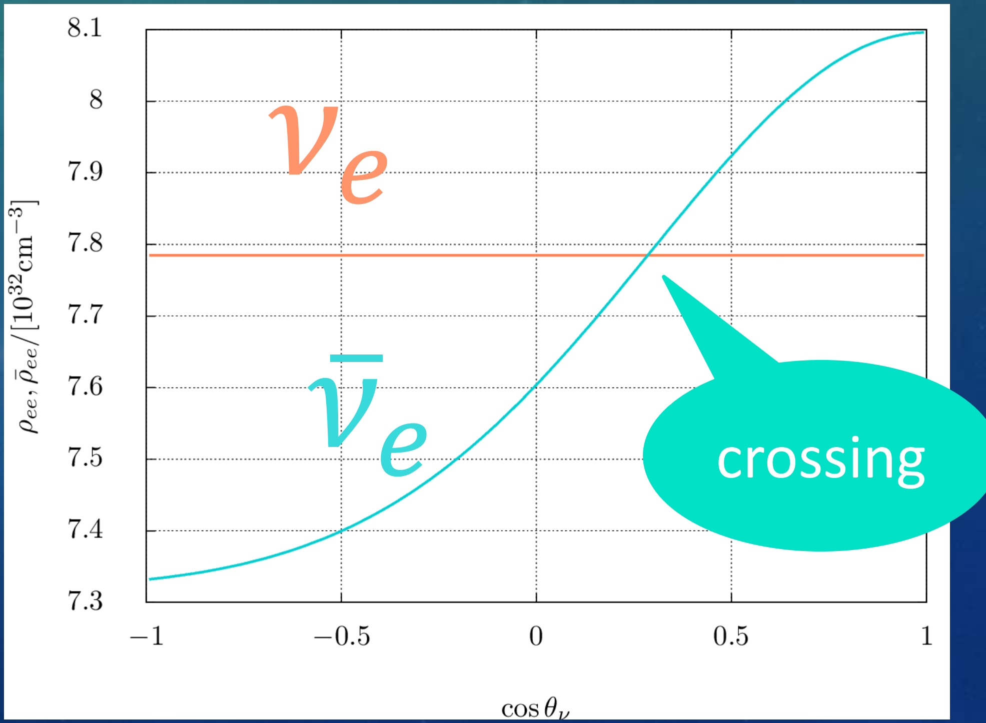
✓ periodic conversion

✓ conversion occurs at crossing point

$$n_{\nu_e} = 1.56 \times 10^{33}\mathrm{cm}^{-3}$$
$$\bar{n}_{\nu_e} = 1.53 \times 10^{33}\mathrm{cm}^{-3}$$
$$n_{\nu_x} = \bar{n}_{\nu_x} = 0$$

$$\mathrm{Im} n_{ex} = -\mathrm{Re} n_{xe} = 10^{-6} n_{\nu_e}$$
$$\mathrm{Im} \bar{n}_{ex} = -\mathrm{Re} \bar{n}_{xe} = 10^{-6} \bar{n}_{\nu_e}$$





w scattering, 1D phase space

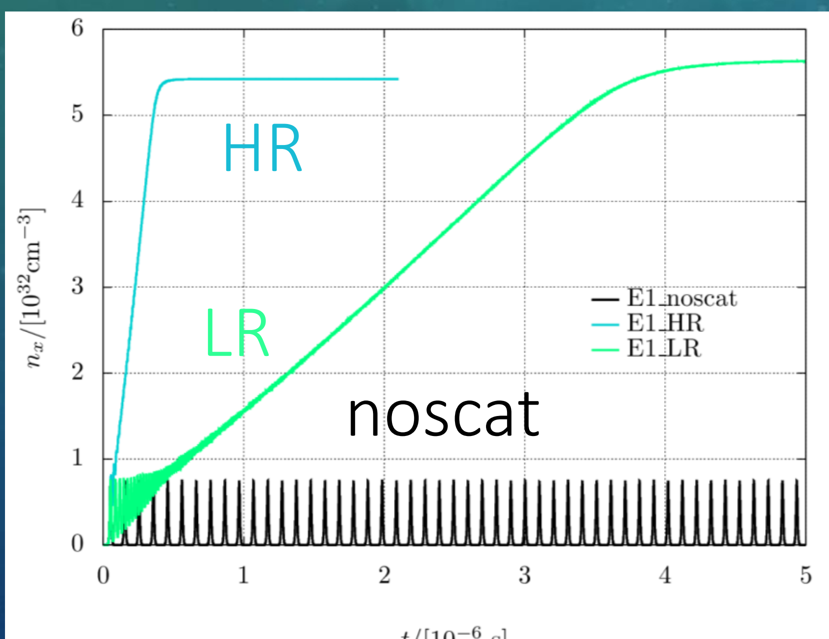
$1.25 \times 10^{-5}\ \mathrm{cm}^{-1}$ (LR)
$1.25 \times 10^{-4}\ \mathrm{cm}^{-1}$ (HR)

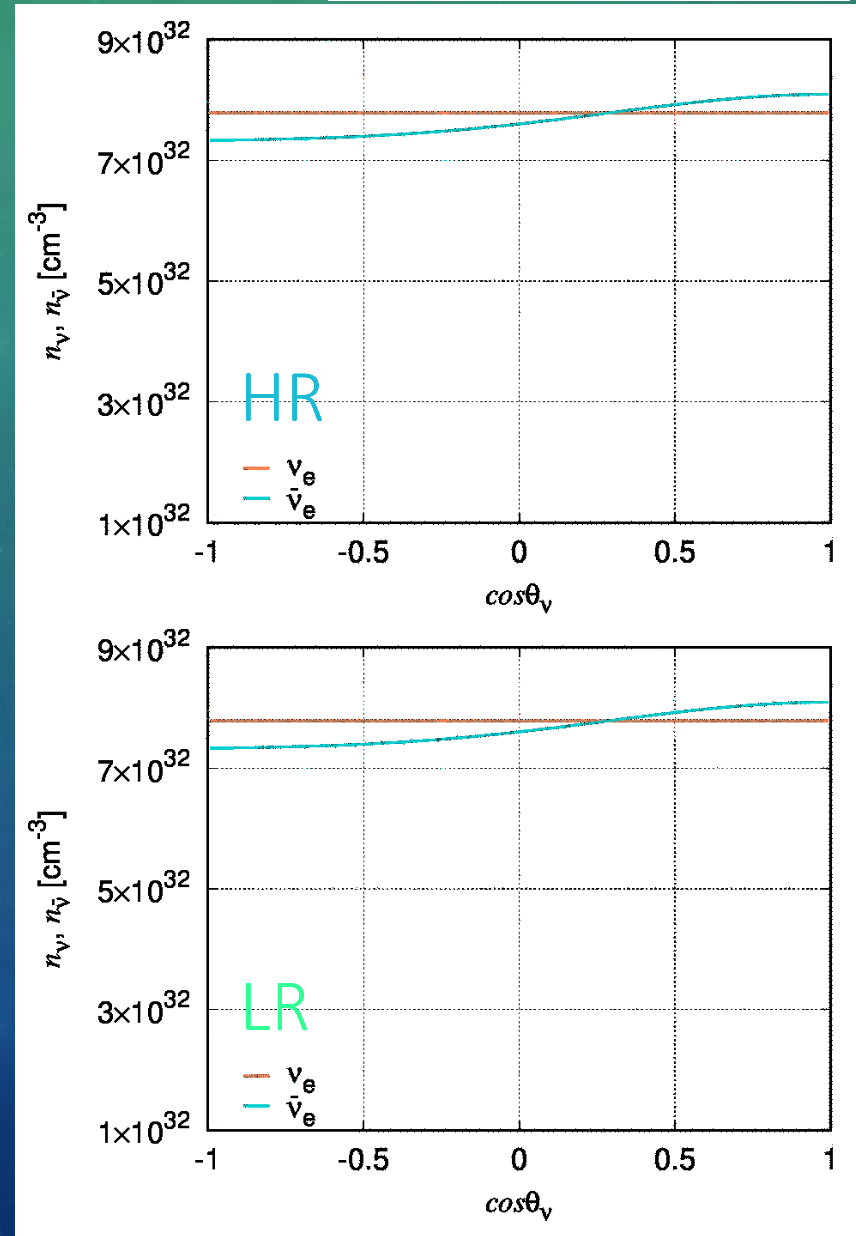
✓collisions enhance conversions

✓low rate ➡ slower growth

larger number of n_x

✓conversions occur at wide range





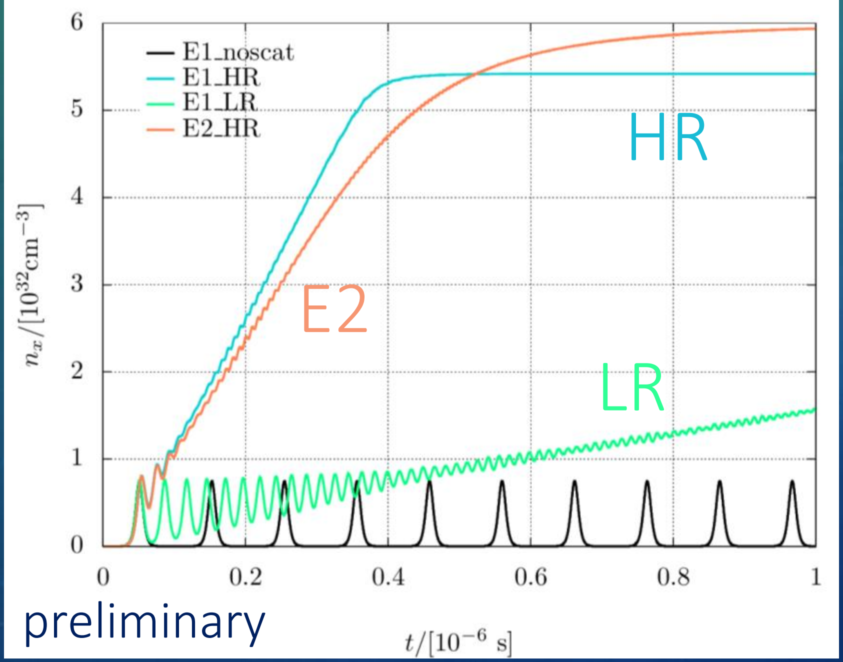
w scattering, 2D phase space

- ✓two neutrino energies

  E_{low}=10MeV, E_{high}=30MeV
- ✓$n_{low} = n_{high}$ for ν_e & $\bar{\nu}_e$
- ✓Energy dependent reaction rate $R(E_\nu) = R_0 E_\nu^2$

  $\langle R_{ee} \rangle = 1.25\times10^{-4} cm^{-1}$

$$\langle R_{ee} \rangle = \frac{R(E_{\rm low})n_{\rm low} + R(E_{\rm high})n_{\rm high}}{n_\nu}$$



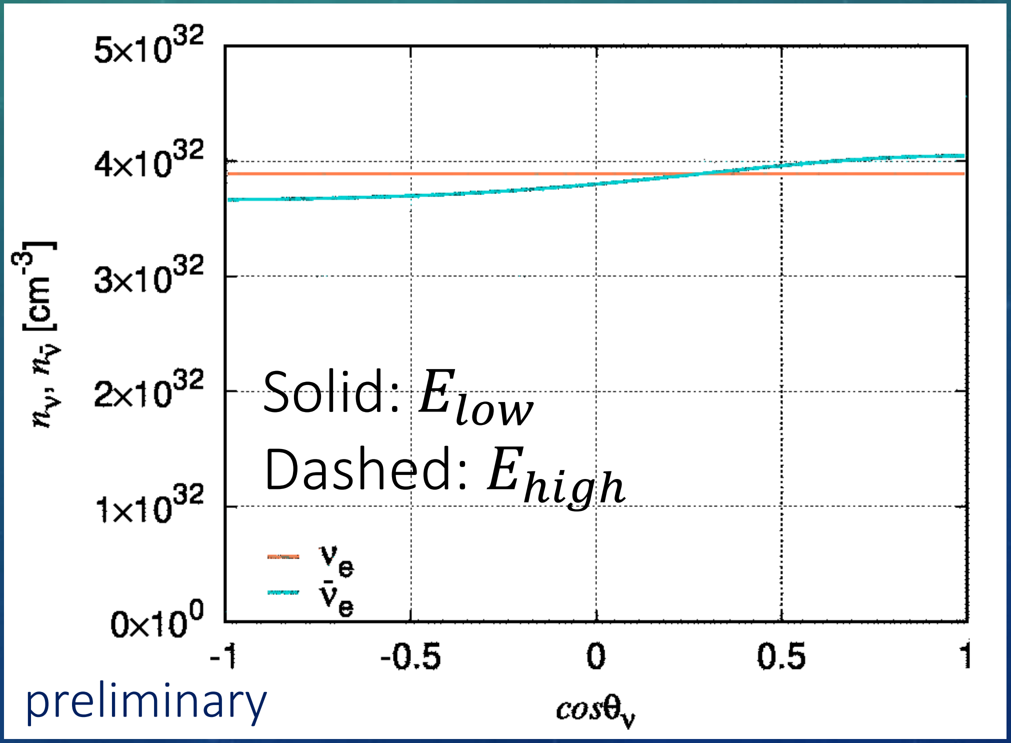
✓Energy dependence of reaction rate reduces the impact of collisions from the single energy case

Angular distribution

✓high energy neutrinos experience collisions more frequently

➡ detailed balance is achieved between two angles

➡ the number of scatterings is effectively reduced

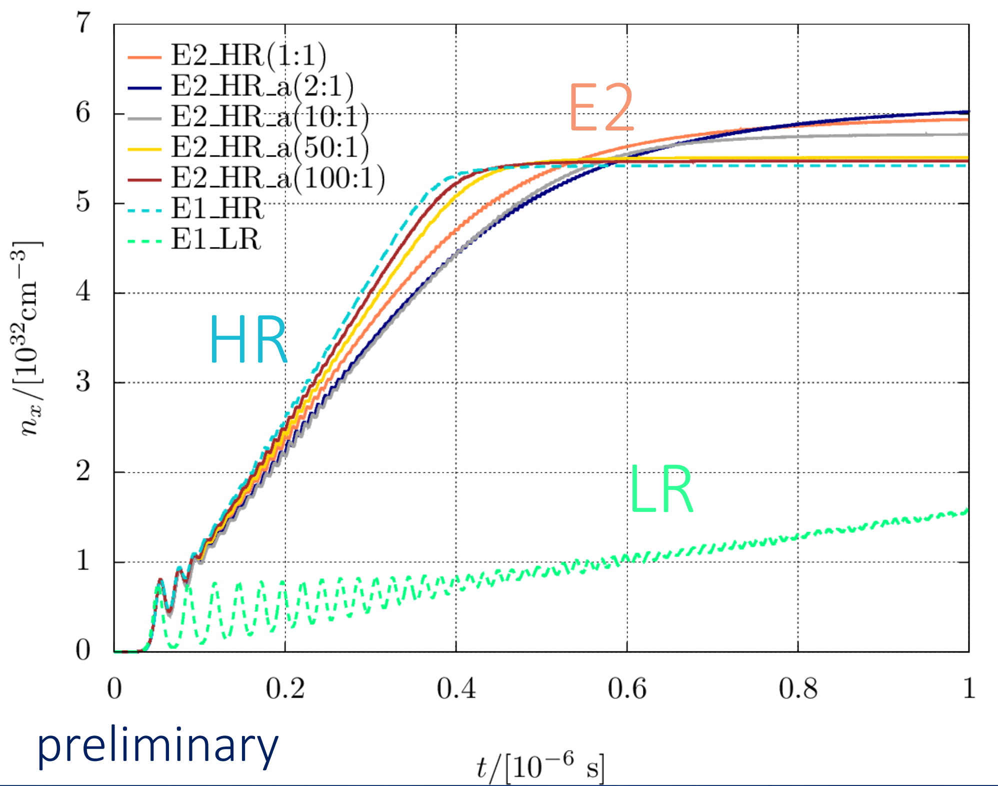


Number asymmetric case ($n_{low} \neq n_{high}$)

✓we change the number ratio between two ν energies

✓In all the models, the impact of collisions is reduced

✓But some models have very close results



$$\langle R_{ee} \rangle = 1.25 \times 10^{-4} cm^{-1}$$

$$\langle R_{ee} \rangle = \frac{R(E_{\mathrm{low}})n_{\mathrm{low}} + R(E_{\mathrm{high}})n_{\mathrm{high}}}{n_\nu}$$

	$R_0/[10^{-4}\mathrm{cm}^{-1}]$	n_{low}/n_ν	n_{high}/n_ν	β
E2_HR(1:1)	1.00	1/2	1/2	1
E2_HR_a(2:1)	1.36	2/3	1/3	2
E2_HR_a(10:1)	2.89	10/11	1/11	10
E2_HR_a(50:1)	4.32	50/51	1/51	50
E2_HR_a(100:1)	4.63	100/101	1/101	100

Validity of monochromatic assumption

✓ monochromatic assumption in two ν energies

= $R_{low} n_{low} \gg R_{high} n_{high}$

= $R_{low} n_{low} \ll R_{high} n_{high}$

✓ monochromatic assumption in general

= collisions in a specific ν energy dominate others

✓ a versatile index for measuring multi-energy effects

χ → 0 ⇔ monochromatic

$$\chi = \left| \frac{\langle E_\nu \rangle - \langle R E_\nu \rangle}{\langle E_\nu \rangle + \langle R E_\nu \rangle} \right|$$

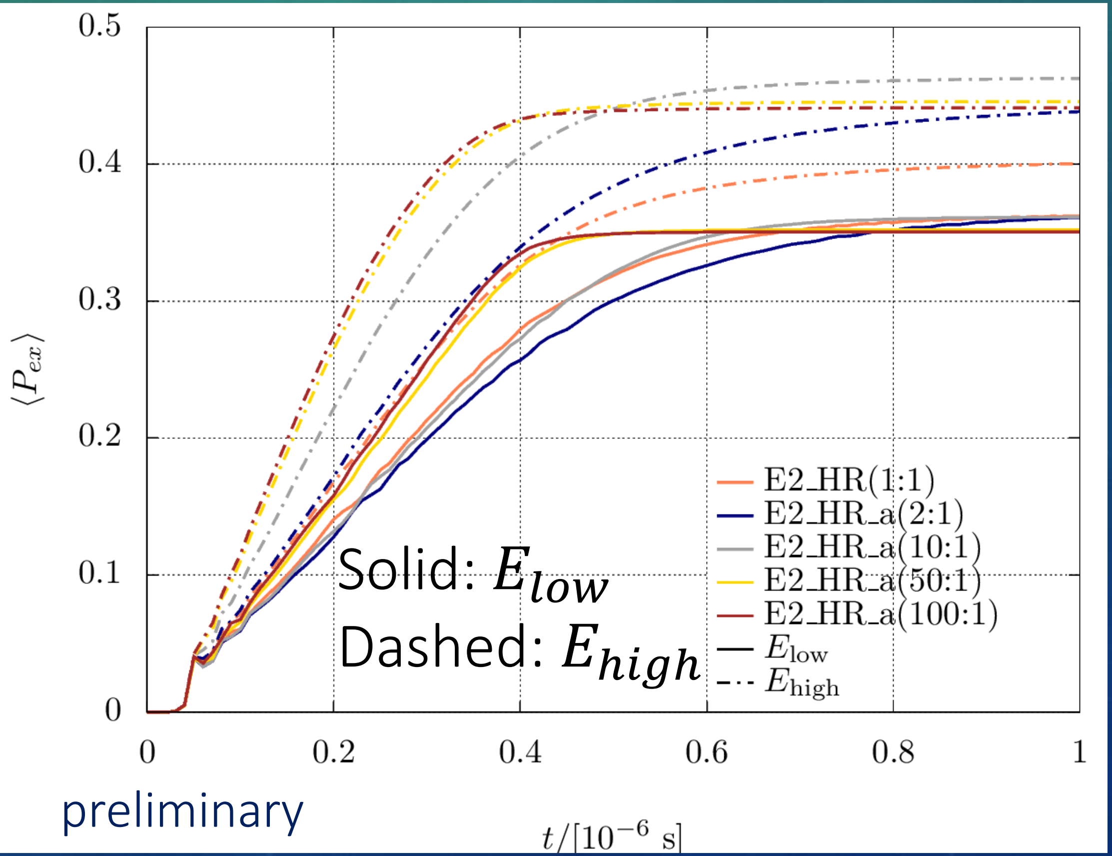
$$\langle E_\nu \rangle = \frac{\int d^3\vec{p} E_\nu \rho}{\int d^3\vec{p} \rho}$$

$$\langle R E_\nu \rangle = \frac{\int d^3\vec{p} R E_\nu \rho}{\int d^3\vec{p} R \rho}$$

Energy dependence of fast conversions

✓ fast conversion itself does not depend on ν energy

➡ energy-dependent collisions introduce dependence!



Summary & Future works

Summary

✓collective oscillation will affect SN dynamics & observables

✓Homogeneous fast conversions have periodic feature

✓Collisions break this feature and larger number of n_x is produced

✓If we introduce energy-dependence into reaction rates, the results deviate from the monochromatic results.

✓If collisions are localized in a certain energy, the monochromatic assumption is valid

Future works

✓Emission & absorption, realistic scatterings (non-isoenergetic, non-isotropic)

✓Realistic neutrino energy spectrum & angular distributions

✓How FCs affects SN dynamics & observables?