Focused workshop on collective oscillations and chiral transport of neutrinos @ Taiwan

Multi-energy handling of fast flavor conversions with matter collisions

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CK, Nagakura and Morinaga, ApJS, 257,55, 2021
CK & Nagakura, PRD, 106, 123012, 2022
CK, Nagakura and Zaizen, inprep, 2023

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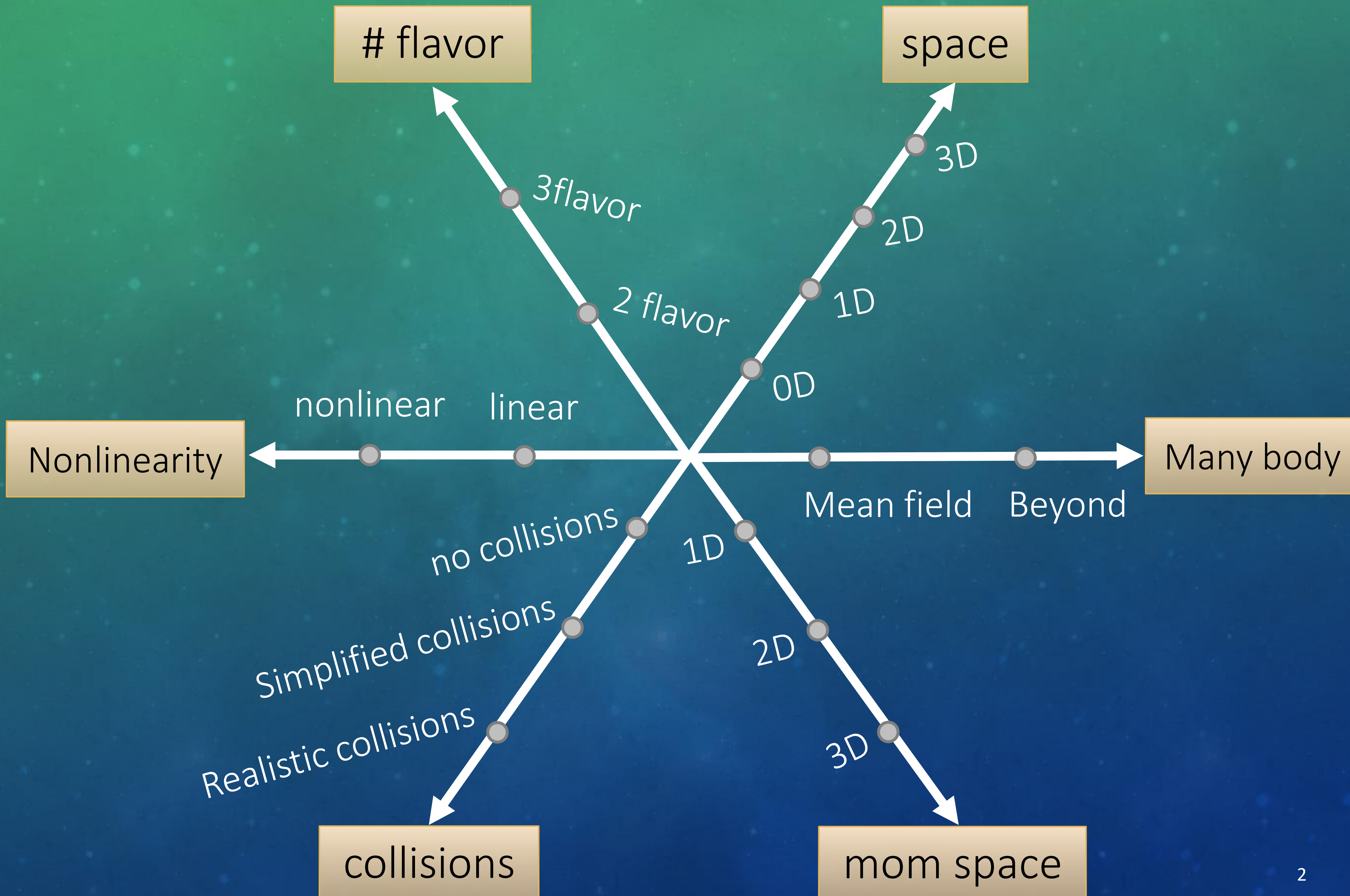
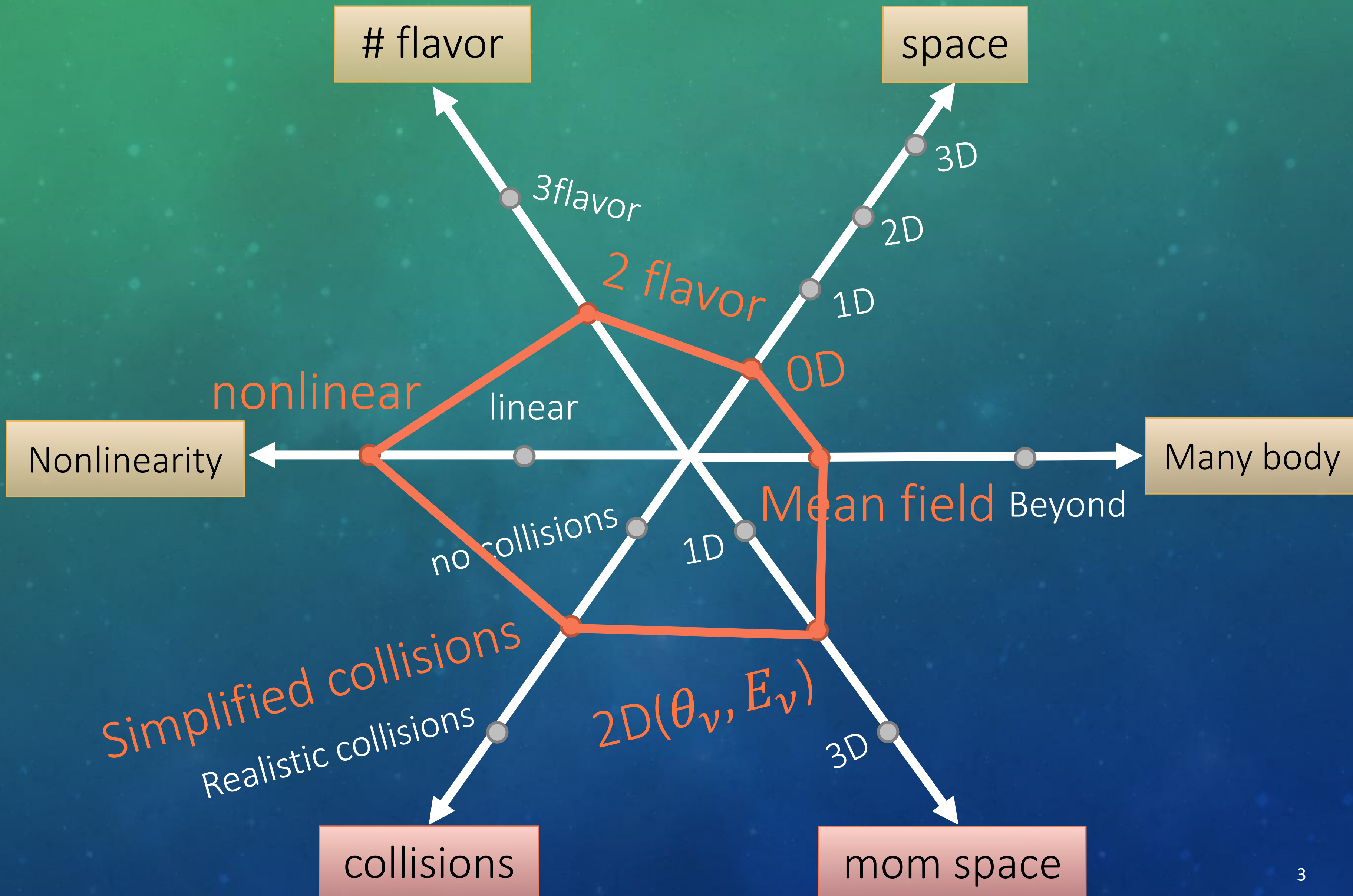
Variety of collective oscillation studies



Variety of collective oscillation studies



Flavor conversions & matter collisions

✓Collisions change neutrino distribution functions

➡ ex) ELN crossing, the difference between ν_e and ν_x

✓Nonlinear interplay between flavor conversions & matter collisions

➡ Change nonlinear asymptotic states

✓Collision-induced flavor instability (CFI)

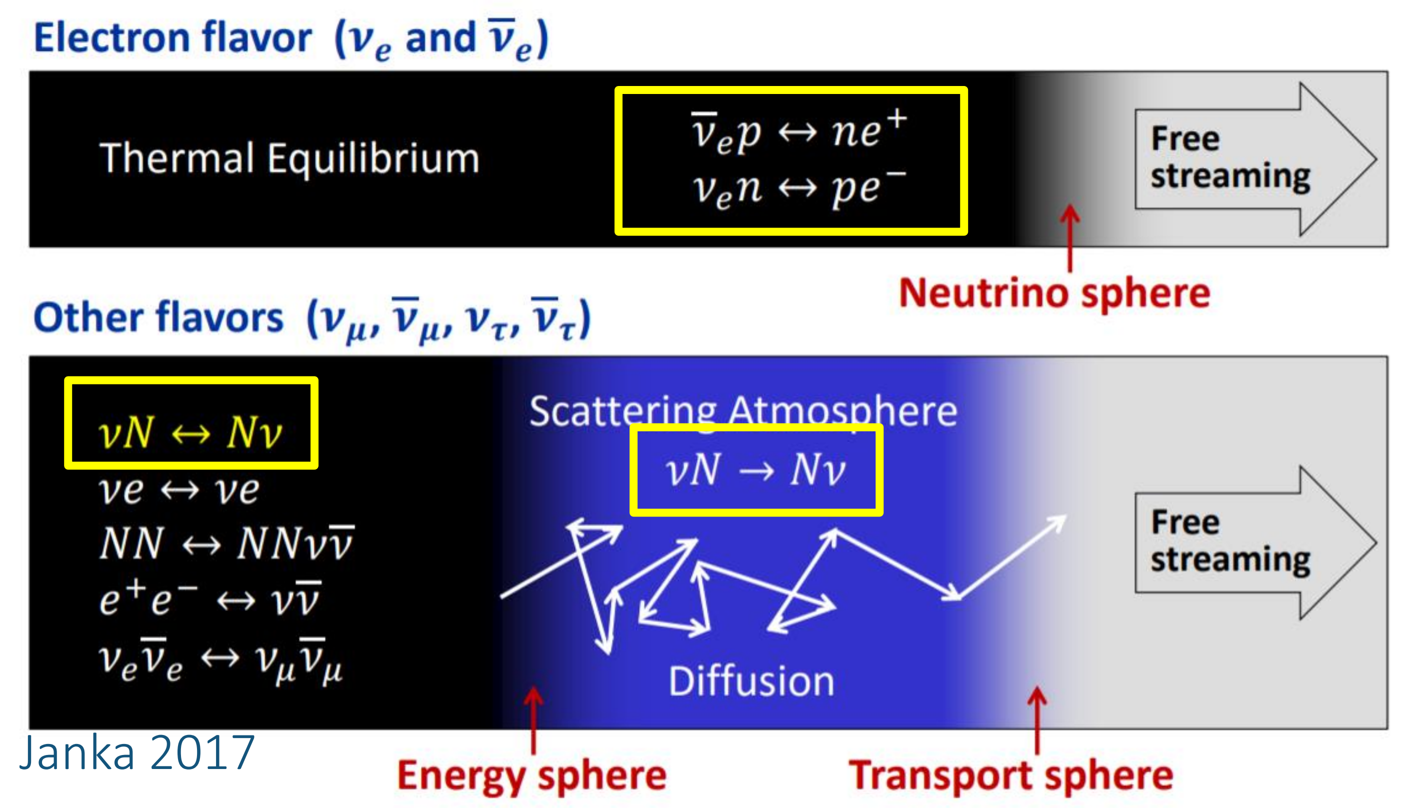
unstable modes induced by matter collisions

Neutrinos in SNe

✓ dominant reactions

- $\nu_e, \bar{\nu}_e$: charged current emis/abs
- $\nu_x, \bar{\nu}_x$: neutral current scatterings

✓ the position of neutrino sphere



Janka 2017

Multi-energy treatment

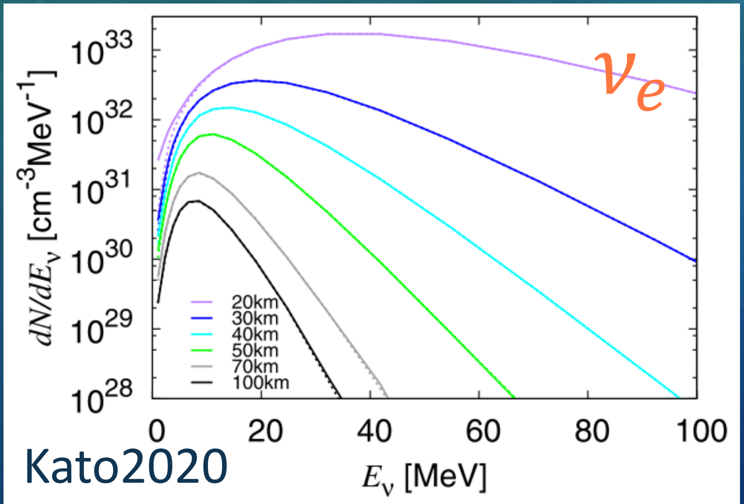
Considering the interplay between flavor conversions & matter collisions….

✓Neutrinos have energy spectrum

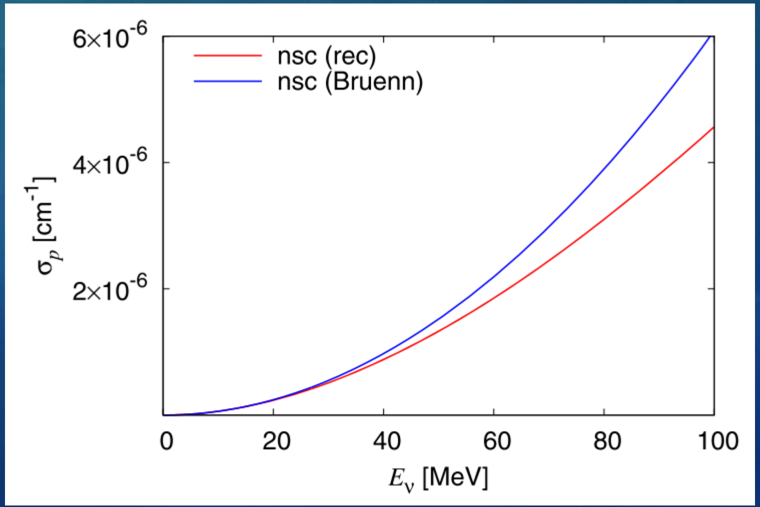
✓Reaction rates are energy-dependent

➡ The multi-energy treatment is natural !

at 100ms



Ex) proton scattering



Our standing and talk outline

<u>Our motivation</u>

Comprehensively understand the interplay between flavor conversions and matter collisions under simplified conditions

<u>Outline</u>

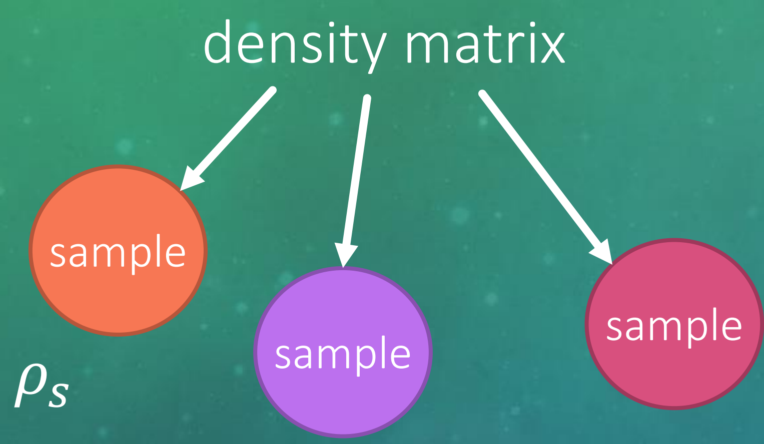
✓Brief introduction of our QKE-MC solver

✓Studies on isoenergetic scatterings (FFC)

✓Studies on charged-current emis/abs (FFC & CFIs)

QKE-MC solver

CK+2021

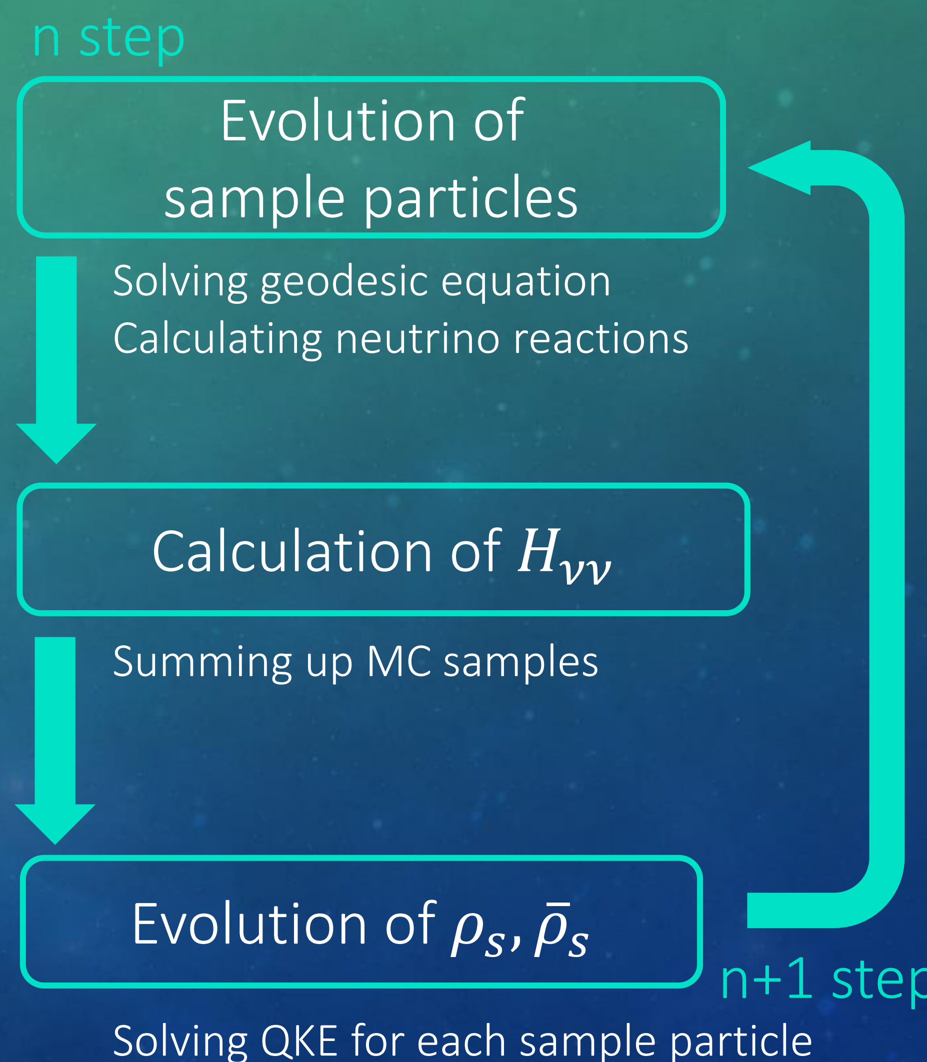


$$\rho_s = \begin{pmatrix} \rho_{ee} & \rho_{ex} \\ \rho_{xe} & \rho_{xx} \end{pmatrix}$$

$$\bar{\rho}_s = \begin{pmatrix} \bar{\rho}_{ee} & \bar{\rho}_{ex} \\ \bar{\rho}_{xe} & \bar{\rho}_{xx} \end{pmatrix}$$

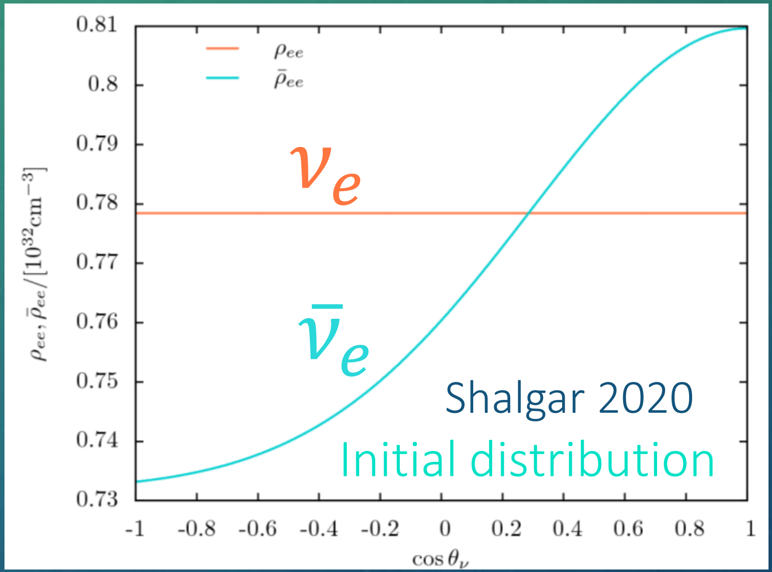
✓Advantage of MC

- simple and direct manner of reactions
- cross checking



FFC with Neutral current scattering CK+2022

$$i\frac{\partial \rho_a(E_\nu, \cos\theta_\nu, t)}{\partial t}$$
$$= [\mathcal{H}_{\nu\nu}, \rho_a(E_\nu, \cos\theta_\nu, t)]$$
$$+i\int_{-1}^{1} d\cos\theta'_\nu R(E_\nu)\rho_a(E_\nu, \cos\theta'_\nu, t)$$
$$-i\int_{-1}^{1} d\cos\theta'_\nu R(E_\nu)\rho_a(E_\nu, \cos\theta_\nu, t)$$



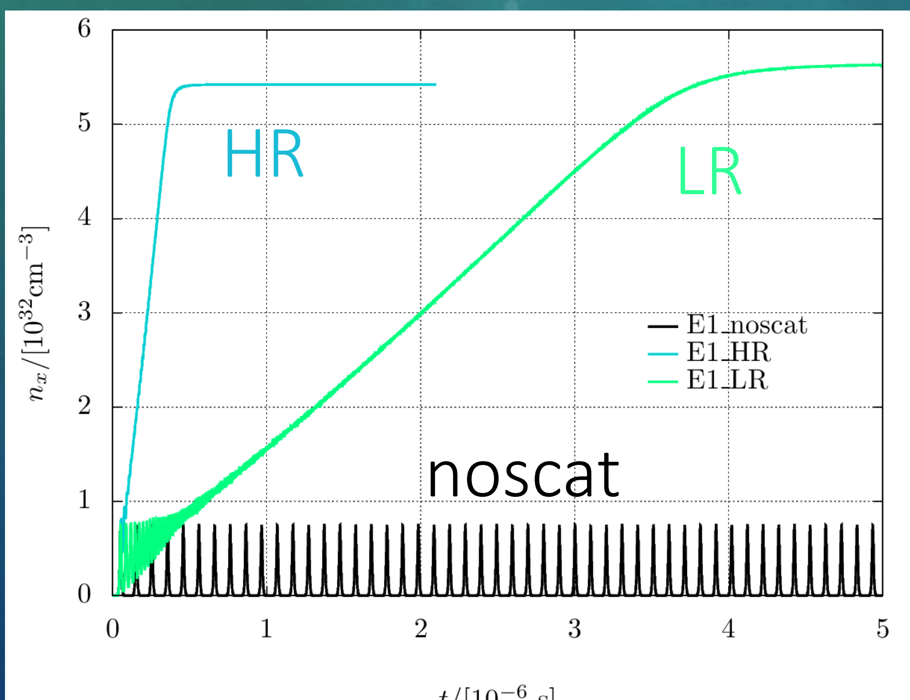
- ✓ reaction rates are independent of flavors
- ✓ isoenergetic and isotropic scattering e.g., nucleon scattering
  energy dependent rate : $R(E_\nu) = R_0 E_\nu^2$
- ✓ FFC-enhanced case
- ✓ no heavy leptonic (anti-)neutrinos

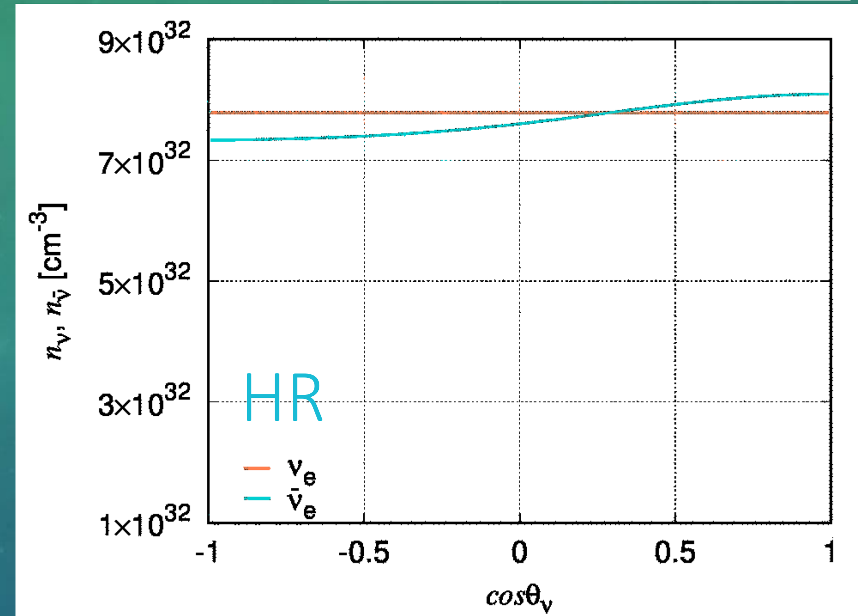
Single-energy results

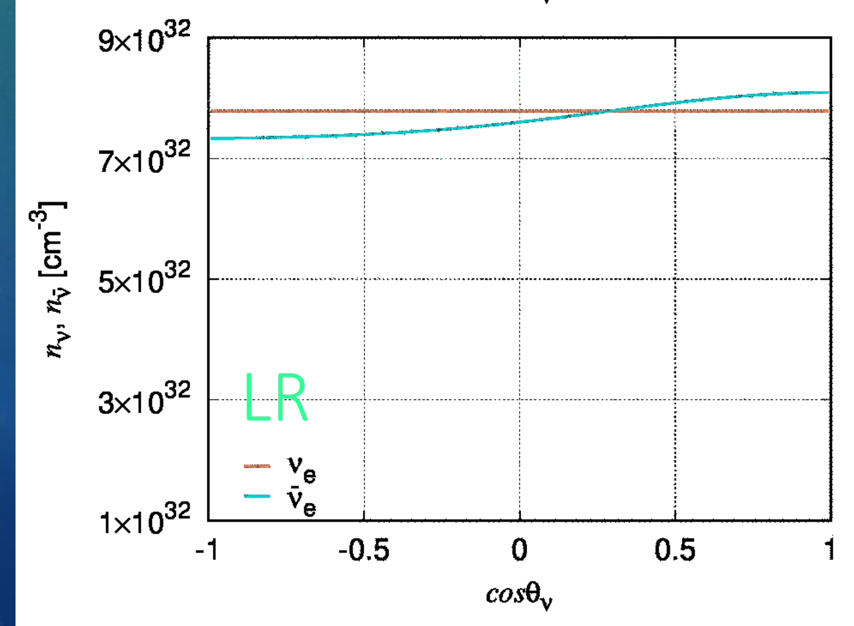
$$1.25 \times 10^{-5}\ \mathrm{cm}^{-1}\ \mathrm{(LR)}$$
$$1.25 \times 10^{-4}\ \mathrm{cm}^{-1}\ \mathrm{(HR)}$$

✓ low rate: more vigorous and longer-lived FFCs

✓ collisions spread conversions to wider angles







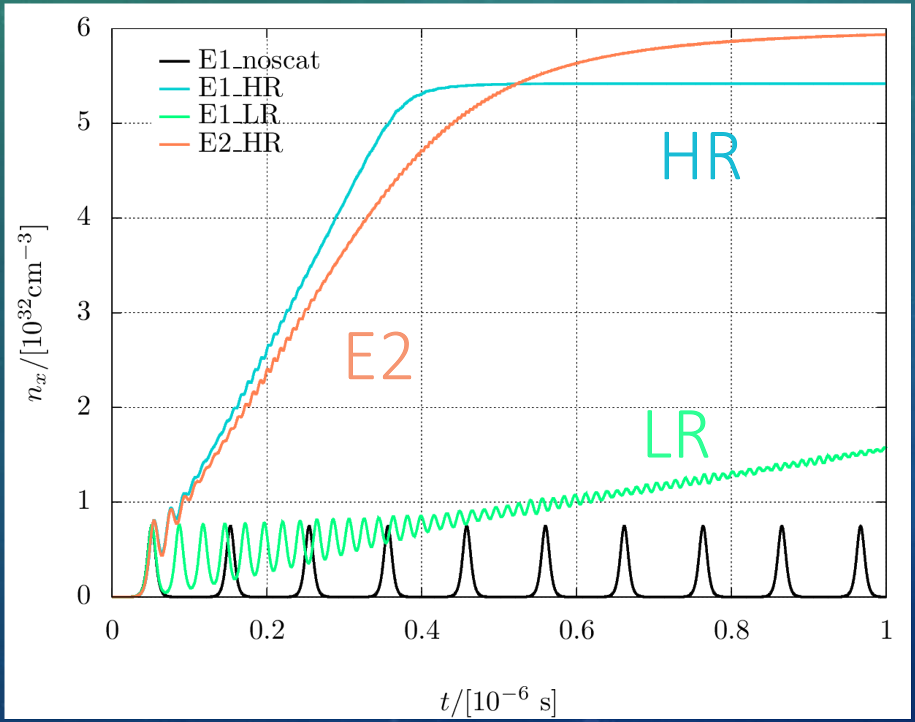
Multi-energy results

✓two neutrino energies (E_{low}=10MeV, E_{high}=30MeV)

✓flat energy spectrum

✓Energy dependent reaction rate $R(E_\nu) = R_0 E_\nu^2$

The average reaction rates are fixed to the single-HR case



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

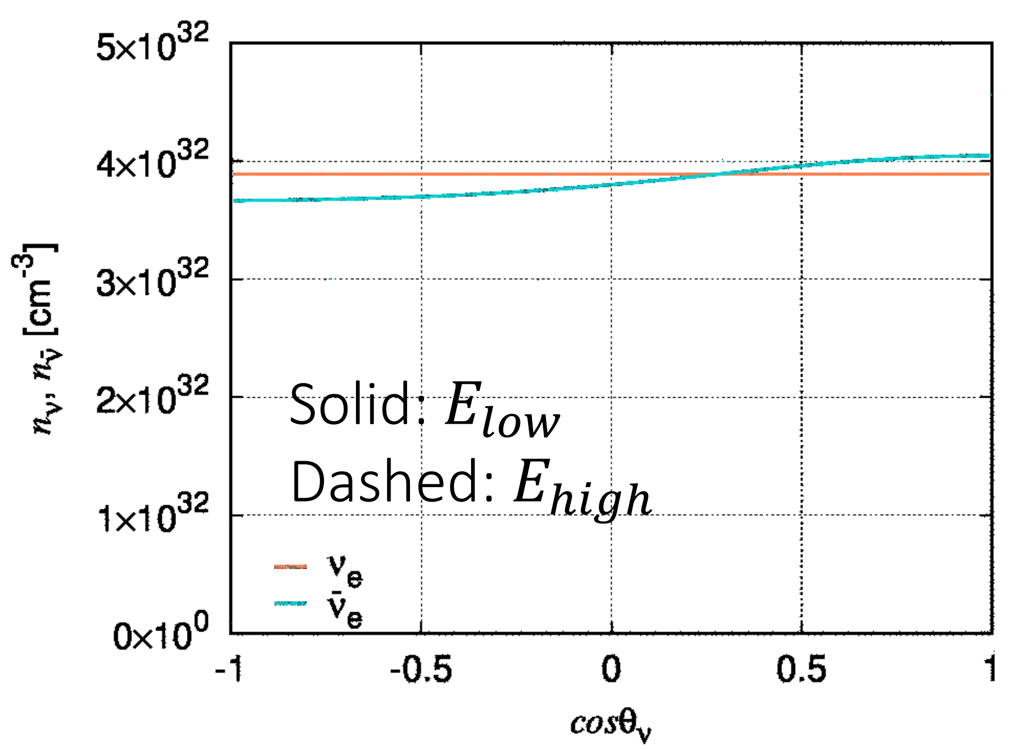
✓Energy dependence of reaction rate reduces the impact of collisions

Angular distribution

✓high energy neutrinos experience collisions more frequently

➡ detailed balance is achieved between two angles

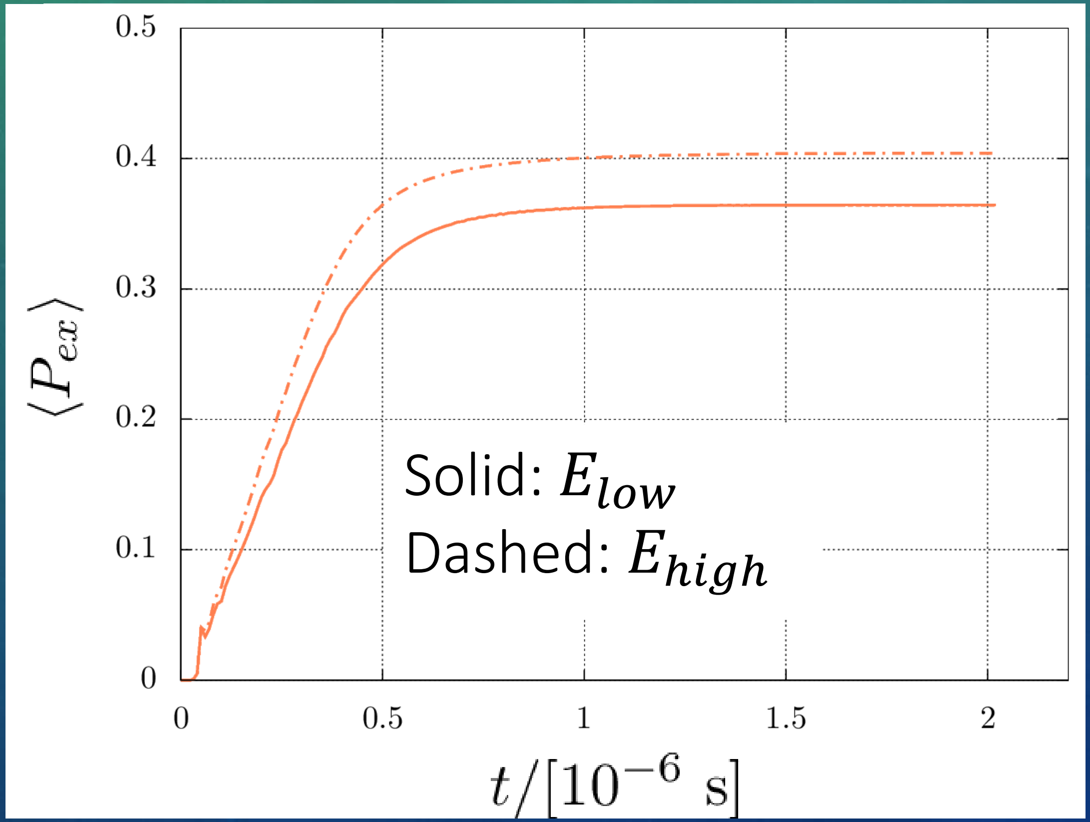
➡ the number of scatterings is effectively reduced



Energy dependent FFC

✓ The survival probabilities depend on ν energy !

➡ collisions induce energy-dependence in FFC dynamics



FFC, CFI with emis/abs

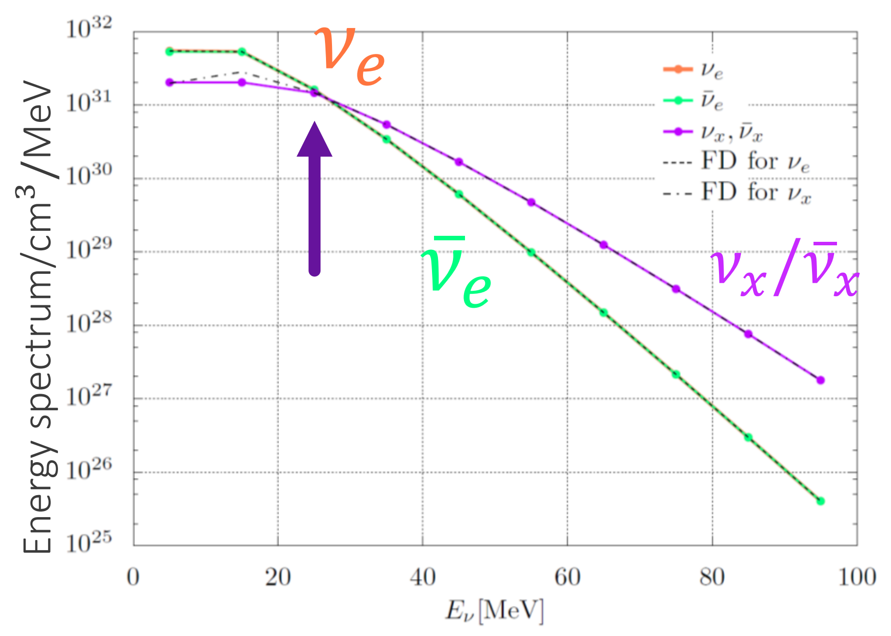
CK+2023 inprep

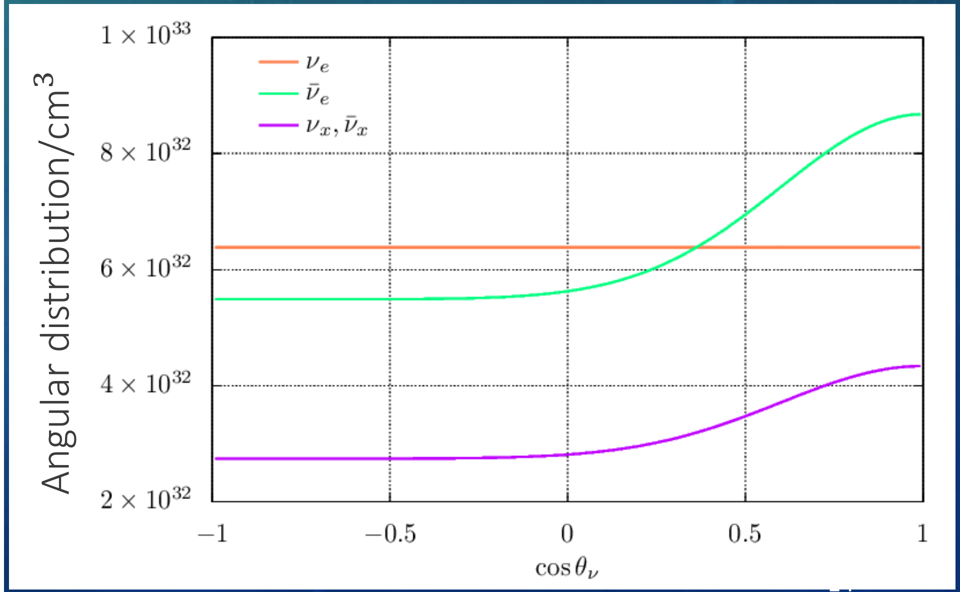
$$i\frac{\partial \rho_a}{\partial t} = [\mathcal{H}_{\nu\nu}, \rho_a] + i\begin{pmatrix} 2\pi R_e - [R_e + R_a]\,\rho_{ee,a} & -\frac{1}{2}[R_e + R_a]\,\rho_{ex,a} \\ -\frac{1}{2}[R_e + R_a]\,\rho_{xe,a} & 0 \end{pmatrix}$$

$$i\frac{\partial \bar{\rho}_a}{\partial t} = [\bar{\mathcal{H}}_{\nu\nu}, \bar{\rho}_a] + i\begin{pmatrix} 2\pi \bar{R}_e - [\bar{R}_e + \bar{R}_a]\,\bar{\rho}_{ee,a} & -\frac{1}{2}[\bar{R}_e + \bar{R}_a]\,\bar{\rho}_{ex,a} \\ -\frac{1}{2}[\bar{R}_e + \bar{R}_a]\,\bar{\rho}_{xe,a} & 0 \end{pmatrix}$$

✓Physically motivated numerical setup (SN ～50km at 100ms)

✓Spectral crossing between ν_e and ν_x at E=25MeV





Single-energy results

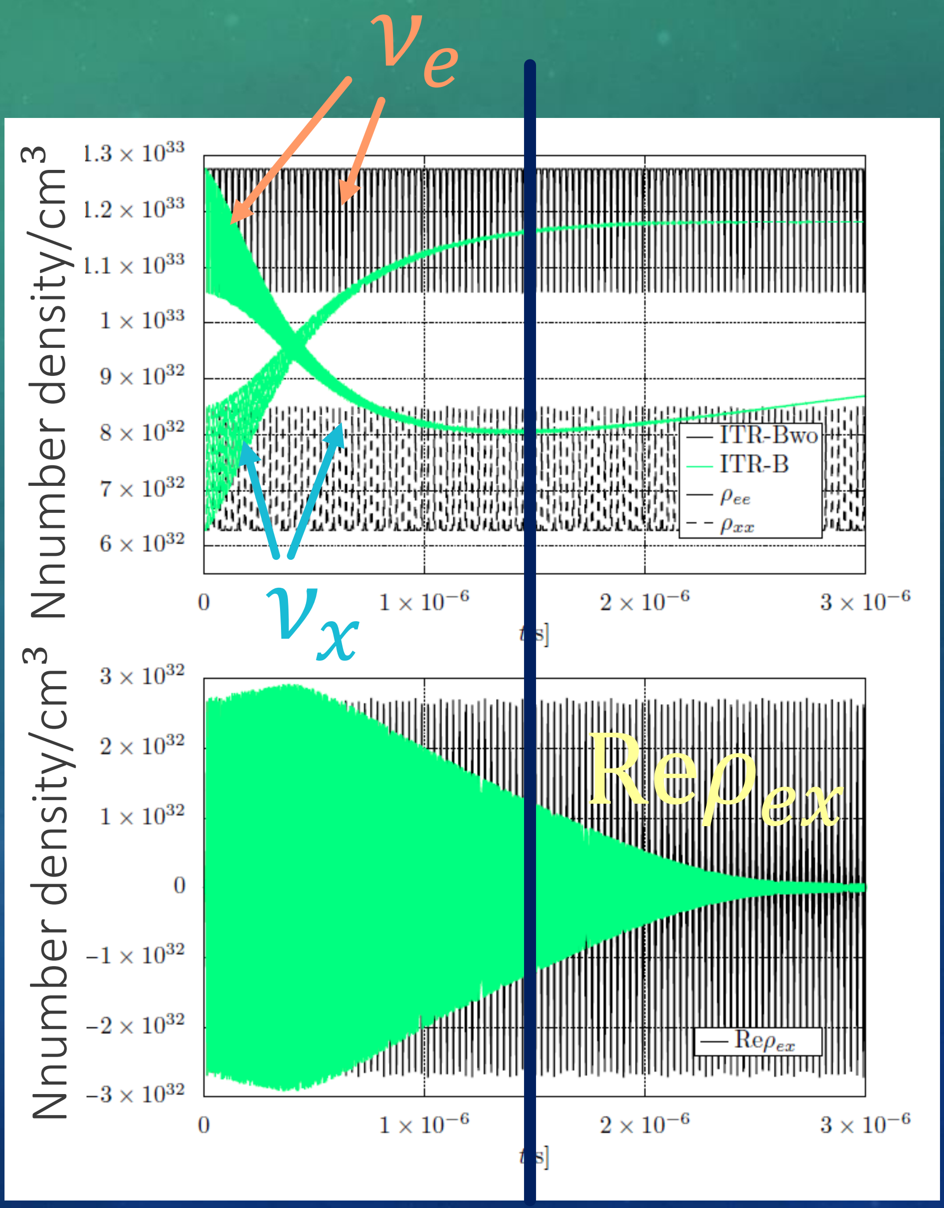
✓FFC timescale $\sim 10^{-12}$s << collision timescale $\sim 10^{-6}$s

➡ FFC & collision driven phases

✓ν_e: reduction by FFC

➡ thermalization by collisions

✓more vigorous but short-lived FFCs



Linear stability analysis

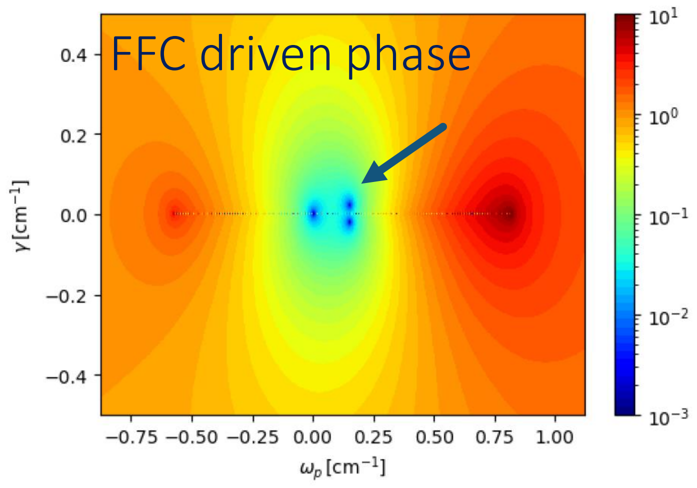
✓ Unstable modes in FFC & collision driven phases

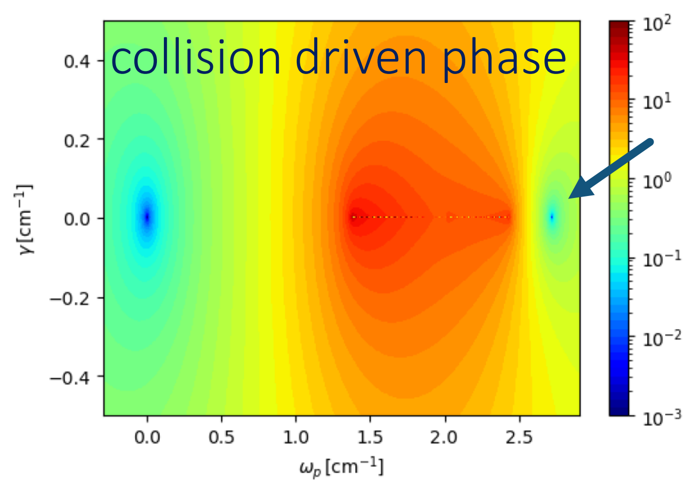
➡ FFC driven phase: FFC mode

collision driven phase: CFI mode

✓ After the sufficient attenuation of FFCs, CFIs occur weak flavor conversions

	$t = 0$ s		$t = 8 \times 10^{-6}$ s	
model	$\omega_p/[\mathrm{cm}^{-1}]$	$\gamma/[\mathrm{cm}^{-1}]$	$\omega_p/[\mathrm{cm}^{-1}]$	$\gamma/[\mathrm{cm}^{-1}]$
PTR-Bwo	0.150	2.11×10^{-2}	-	-
PTR-B	0.150	2.12×10^{-2}	2.72	2.12×10^{-6}





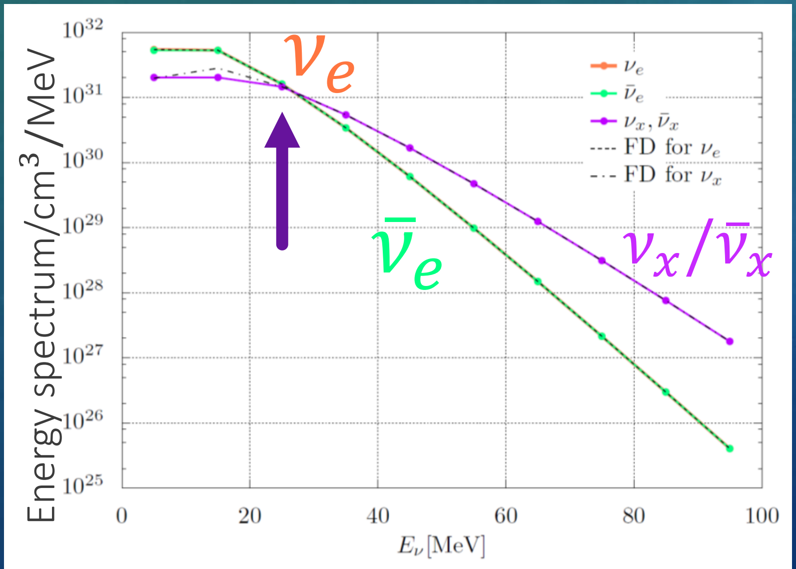
Multi-energy structures: energy-dependent FFC

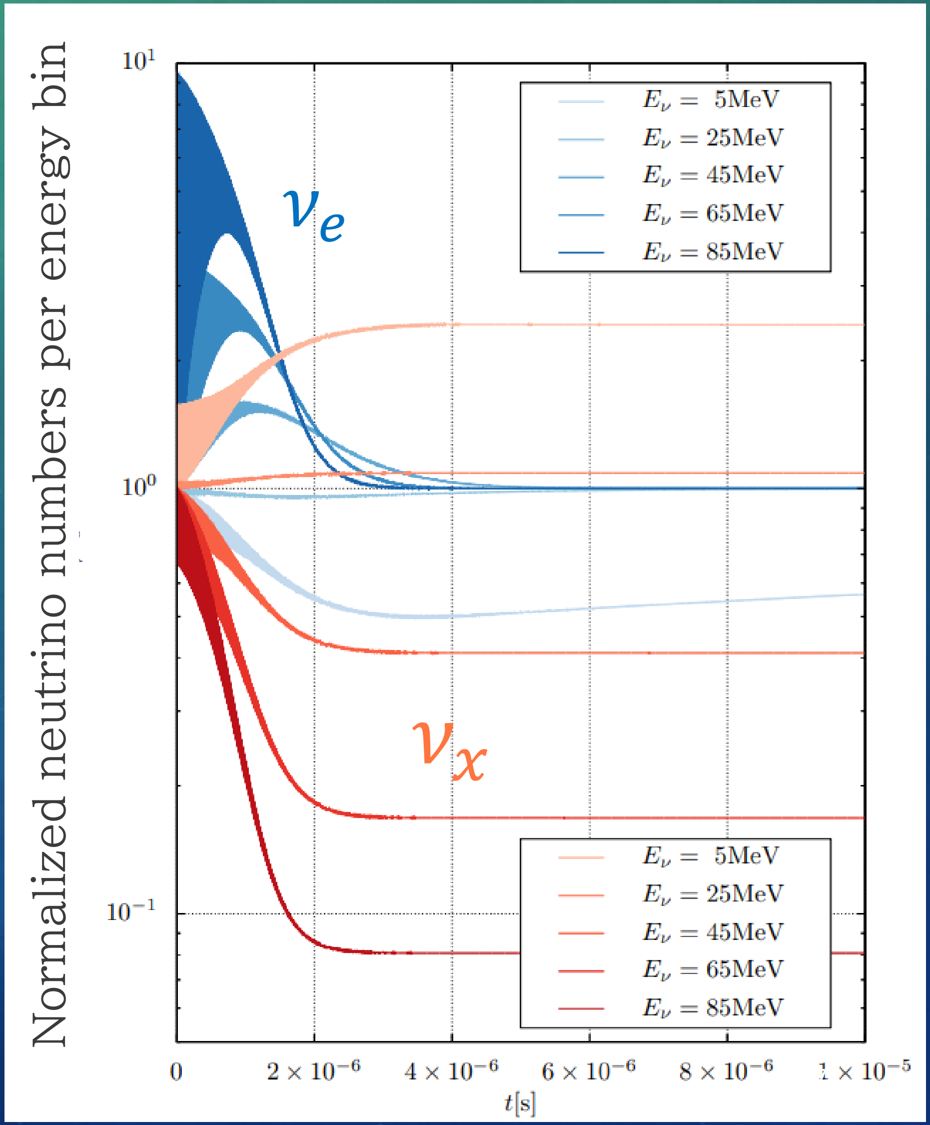
✓FFCs eliminate difference between ν_e & ν_x

✓larger difference between ν_e & ν_x in higher energy

➡ larger conversion

✓Energy-dependent FFCs





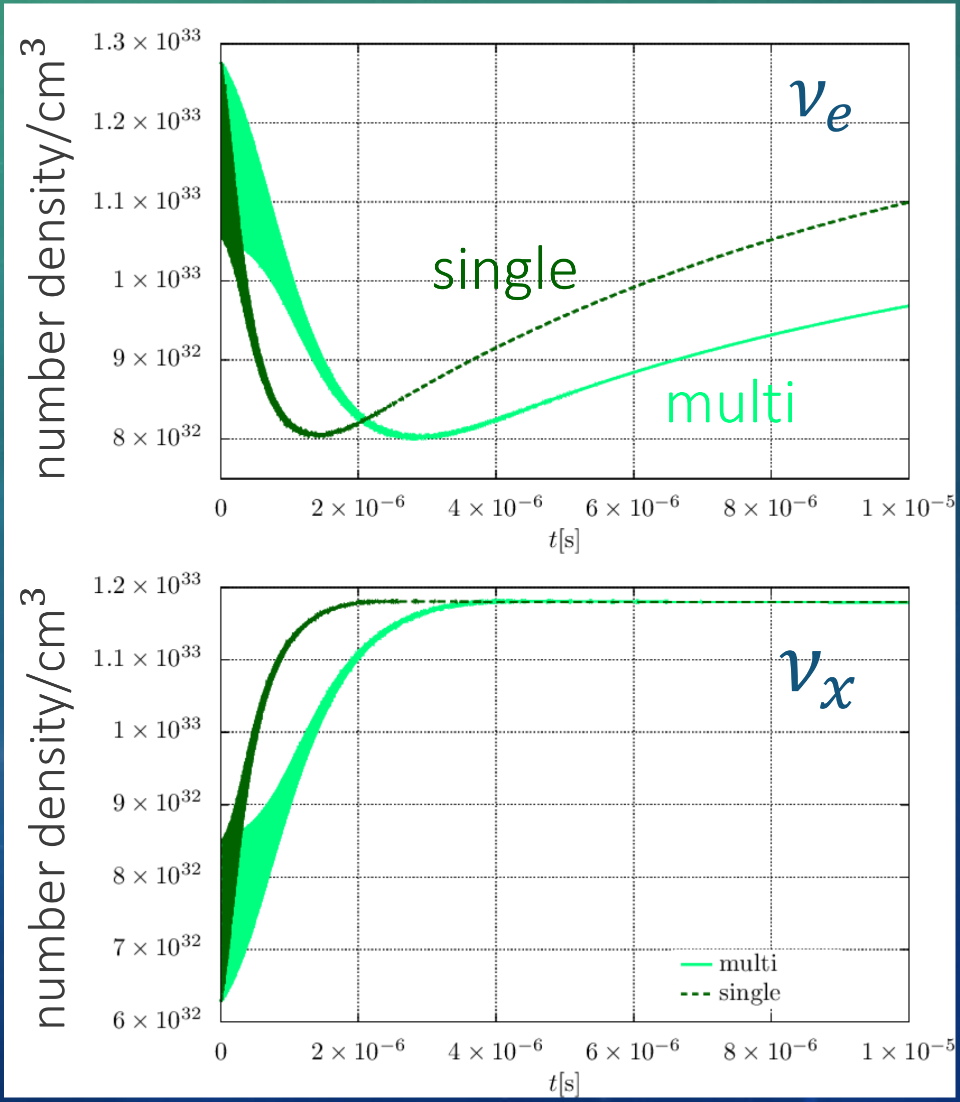
Multi-energy results

✓Large number of low energy neutrinos

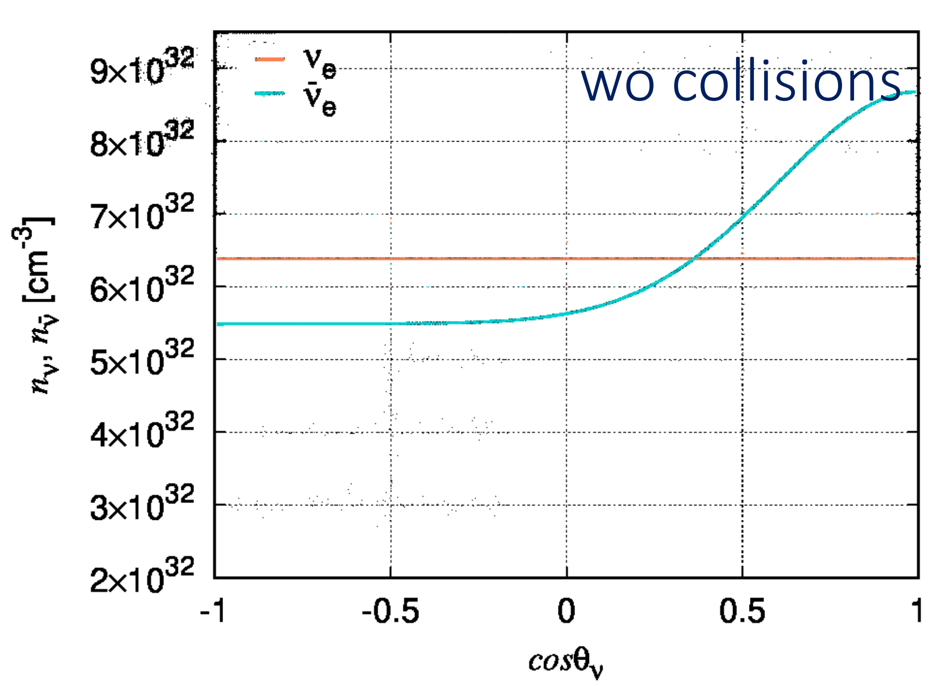
➡ Hamiltonian potential is determined by them

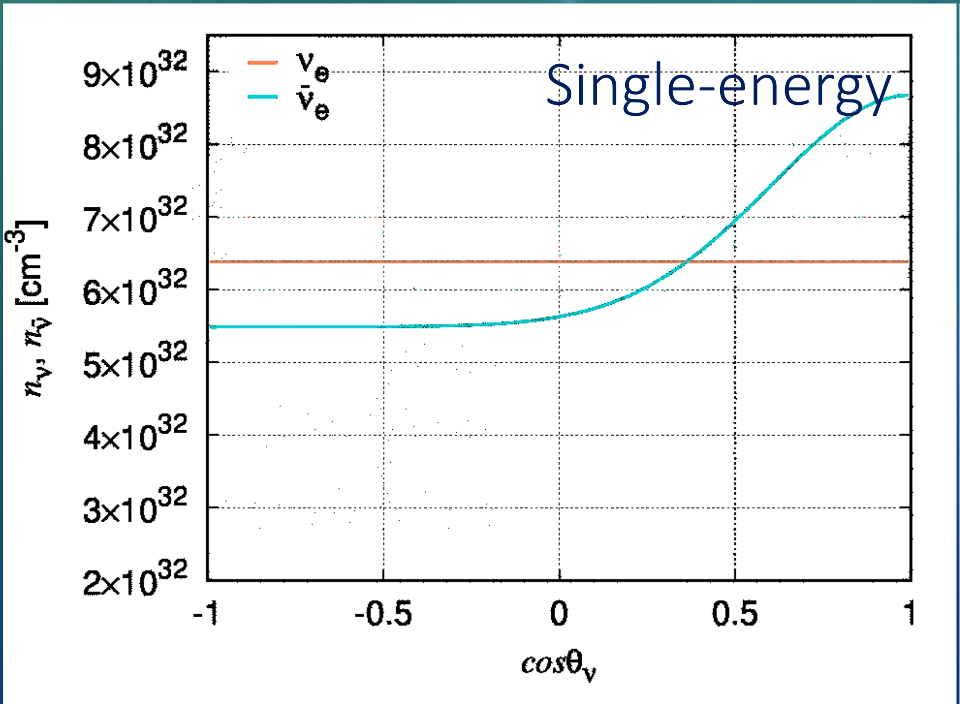
➡ weak matter damping

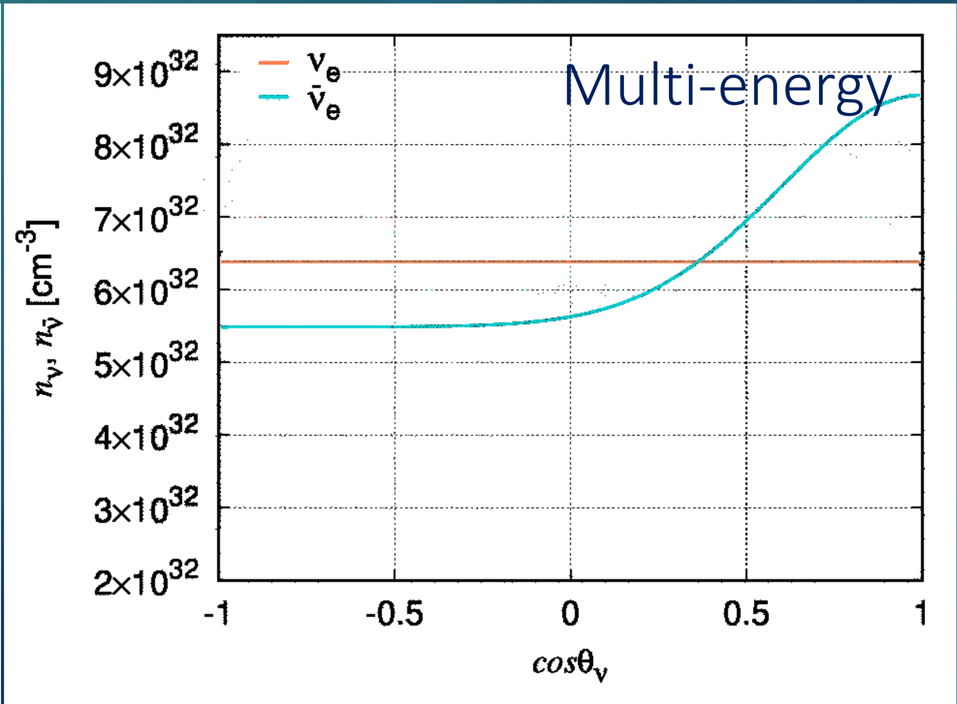
➡ long-lived FFCs



Angular distributions







Picture of local matter heating

✓ high-energy ν_x ➡ ν_e by FFCs

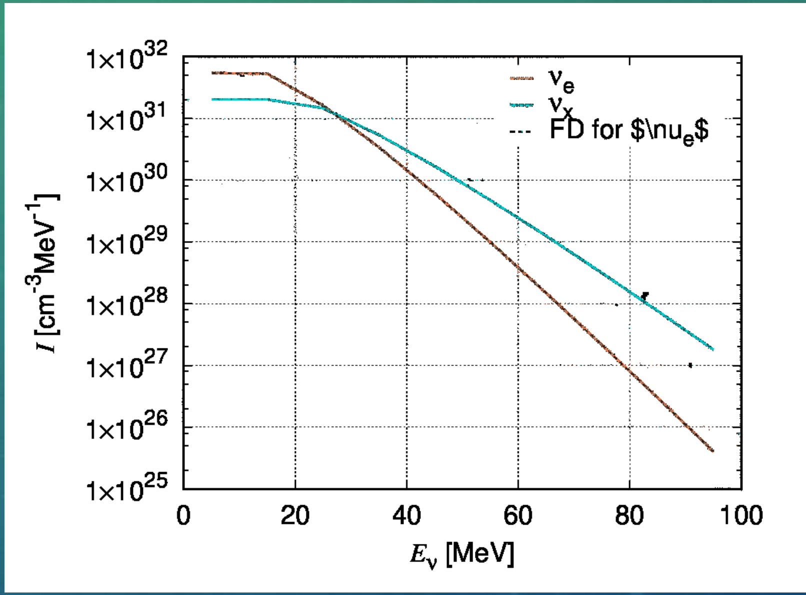
➡ ν_e are thermalized by absorption

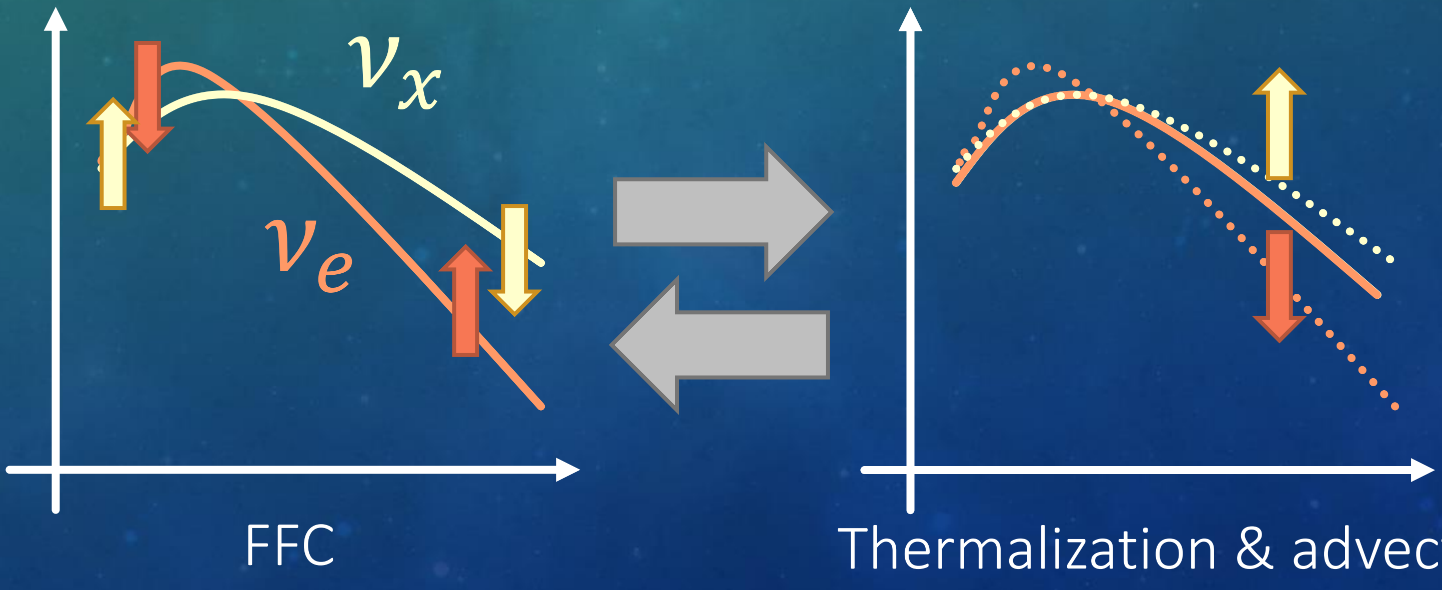
➡ local matter heating

✓ ν_x are replenished by advection

➡ $\nu_x \rightarrow \nu_e$

➡ .....





Summary

✓To comprehensively understand the interplay between flavor conversions & matter collisions

✓Dominant reactions in SNe

➡ nucleon scatterings / charged-current emis・abs

✓Multi-energetic treatment is natural in realistic situation

✓Collisions quantitatively change the nonlinear dynamics

➡ In our models, more vigorous and short-lived FFCs

✓Collisions make FFCs energy-dependent

✓In multi-energy treatment, low energy neutrinos drive oscillations and flavor conversions become longer-lived.