Global and asymptotic features of fast neutrino-flavor conversion in supernova and binary neutron star merger

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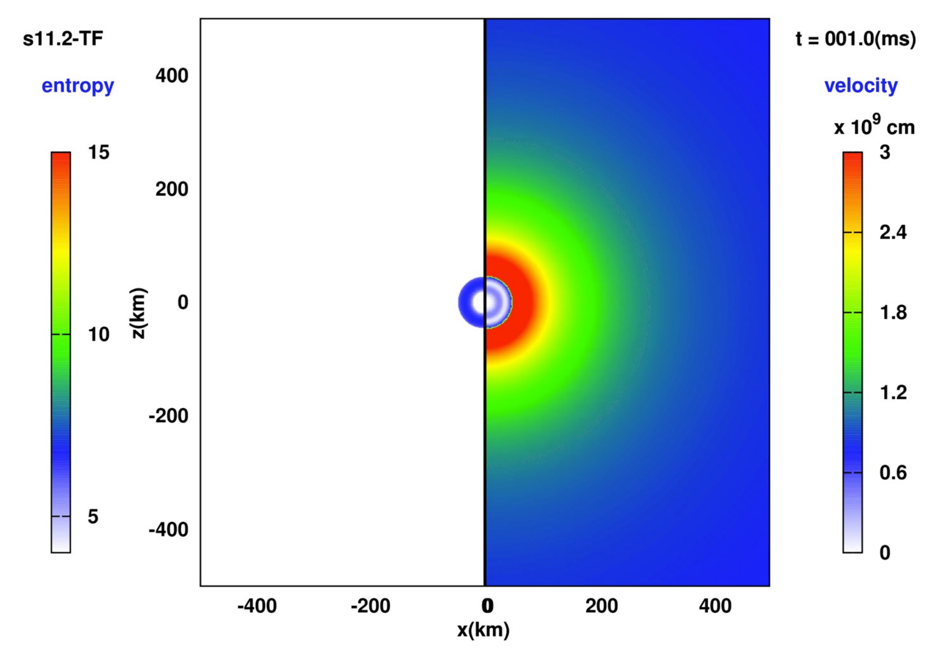
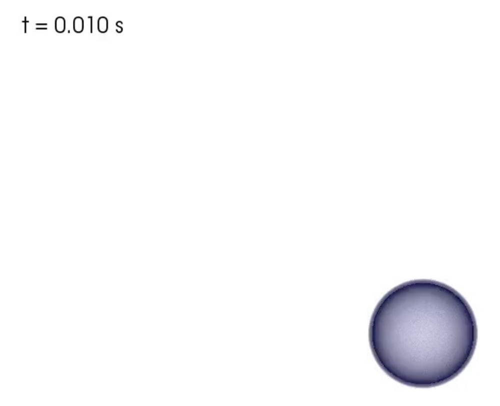
INT workshop at university of Washington in Seattle, July 17 - August 11, 2023

- Multi-dimensional core-collapse supernova (CCSN) simulations

CCSN simulations with full Boltzmann transport



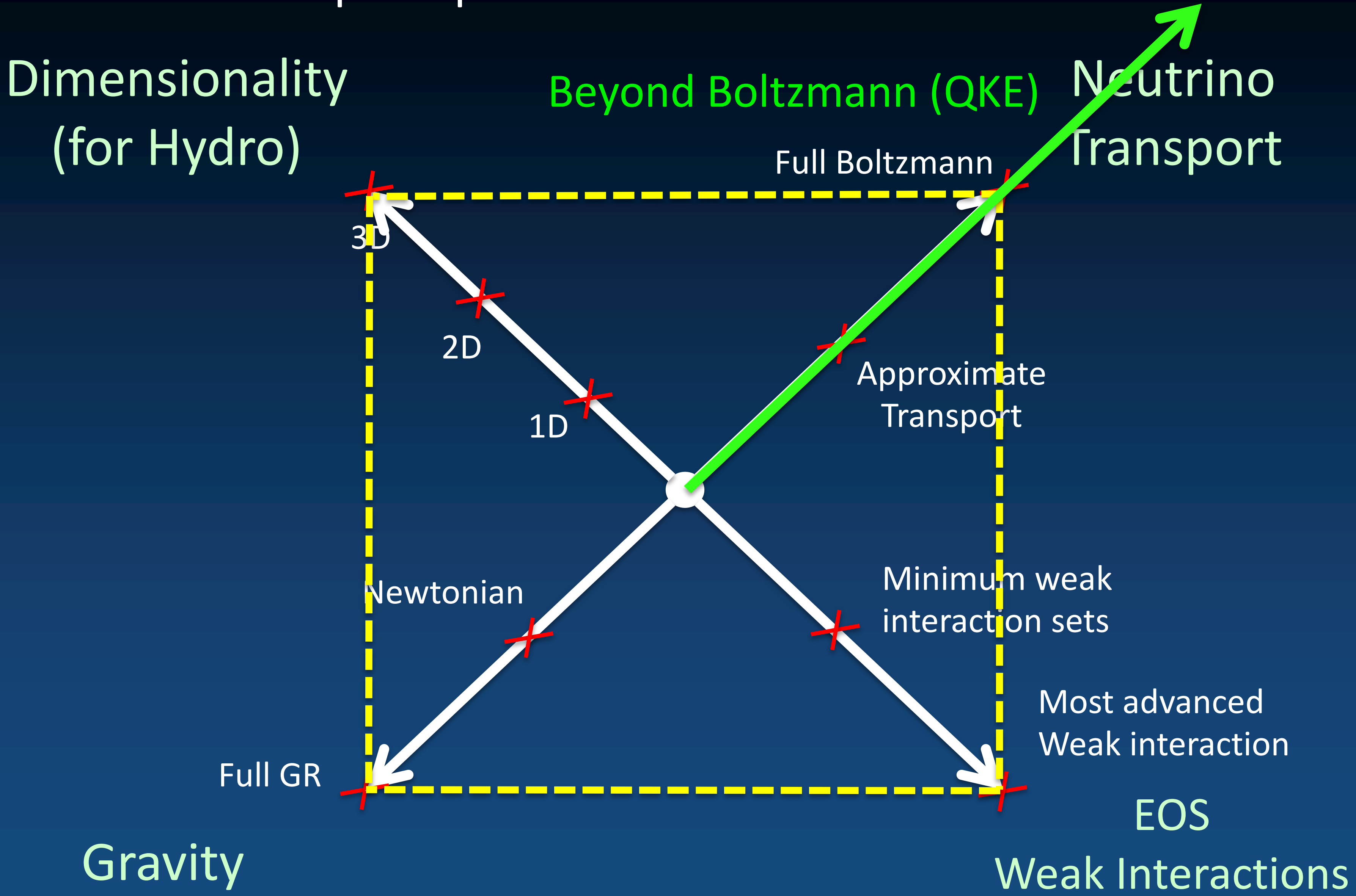
CCSN simulations with two-moment method



Neutrino transport plays key roles on CCSN dynamics

(Neutrino-heating mechanism for CCSN explosion)

- Towards first-principles CCSN simulations



Quantum Kinetics neutrino transport:

Vlasenko et al. 2014, Volpe 2015,
Blaschke et al. 2016, Richers et al. 2019

$$\underline{p^\mu \frac{\partial \overset{(-)}{f}}{\partial x^\mu} + \frac{dp^i}{d\tau}\frac{\partial \overset{(-)}{f}}{\partial p^i}} = \underline{-p^\mu u_\mu \overset{(-)}{S}_{\mathrm{col}}} + \underline{i p^\mu n_\mu [\overset{(-)}{H}, \overset{(-)}{f}],}$$

Advection terms
(Same as Boltz eq.)

Collision term

Oscillation term

f is not a
“distribution function”

Density matrix

$$\overset{(-)}{f} = \begin{bmatrix} \overset{(-)}{f}_{ee} & \overset{(-)}{f}_{e\mu} & \overset{(-)}{f}_{e\tau} \\ \overset{(-)}{f}_{\mu e} & \overset{(-)}{f}_{\mu\mu} & \overset{(-)}{f}_{\mu\tau} \\ \overset{(-)}{f}_{\tau e} & \overset{(-)}{f}_{\tau\mu} & \overset{(-)}{f}_{\tau\tau} \end{bmatrix}$$

Hamiltonian

$$\overset{(-)}{H} = \overset{(-)}{H}_{\mathrm{vac}} + \overset{(-)}{H}_{\mathrm{mat}} + \overset{(-)}{H}_{\nu\nu},$$

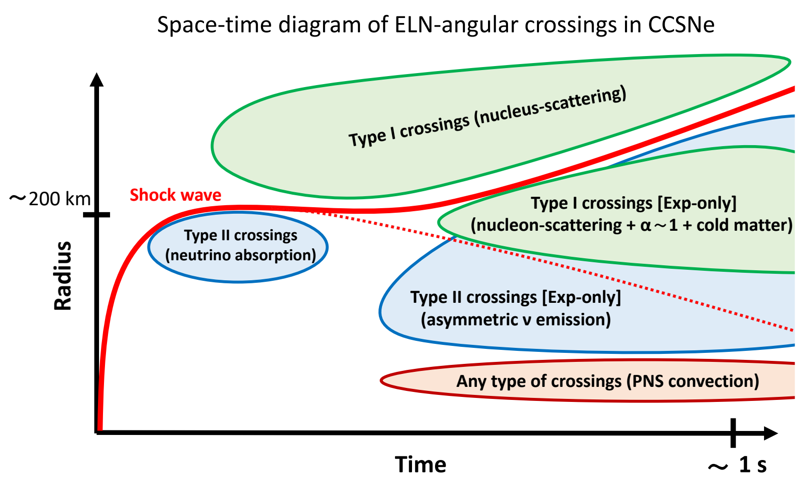
$$H_{\mathrm{vac}} = \frac{1}{2\nu} U \begin{bmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{bmatrix} U^\dagger,$$

$$H_{\mathrm{mat}} = D \begin{bmatrix} V_e & 0 & 0 \\ 0 & V_\mu & 0 \\ 0 & 0 & V_\tau + V_{\mu\tau} \end{bmatrix},$$

$$H_{\nu\nu} = \sqrt{2} G_F \int \frac{d^3 q'}{(2\pi)^3} \Big(1 - \sum_{i=1}^{3} \ell'_{(i)} \ell_{(i)}\Big)\big(f(q') - \bar{f}^*(q')\big),$$

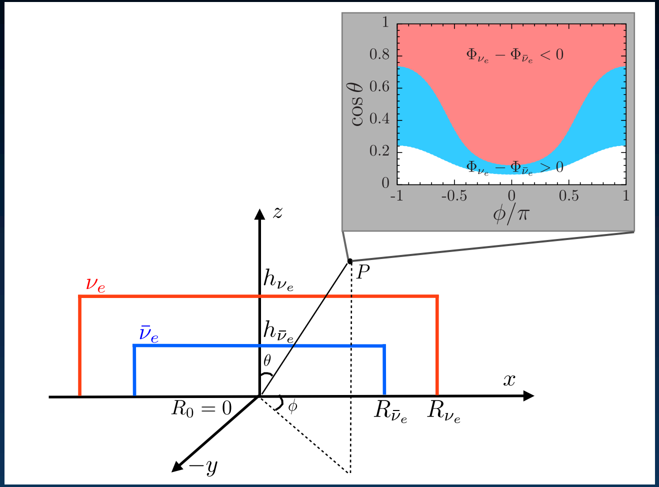
- Fast neutrino-flavor conversion (FFC)

CCSN



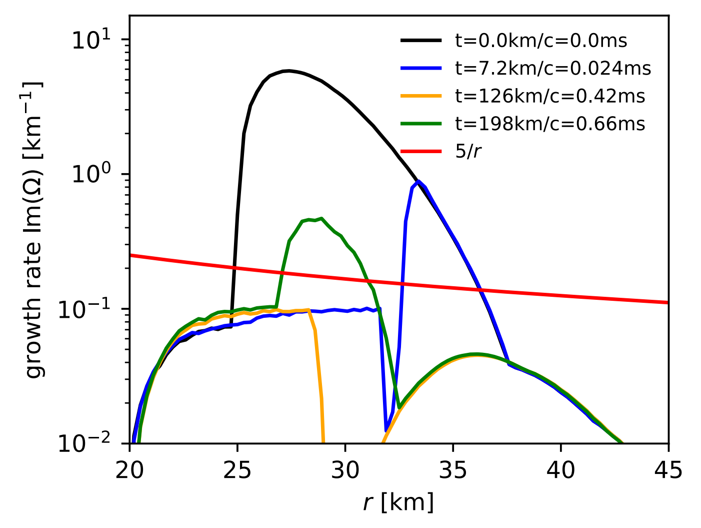
Nagakura et al. 2021

Binary neutron star merger (BNSM)

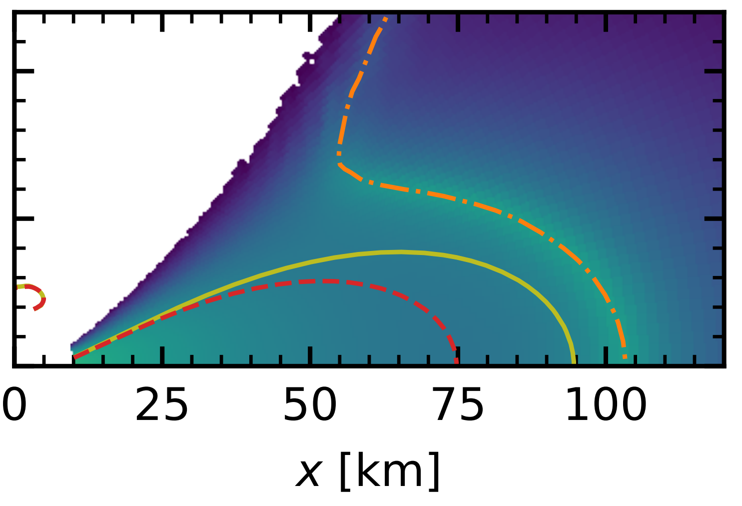


Wu and Tamborra 2017

- Collisional instability

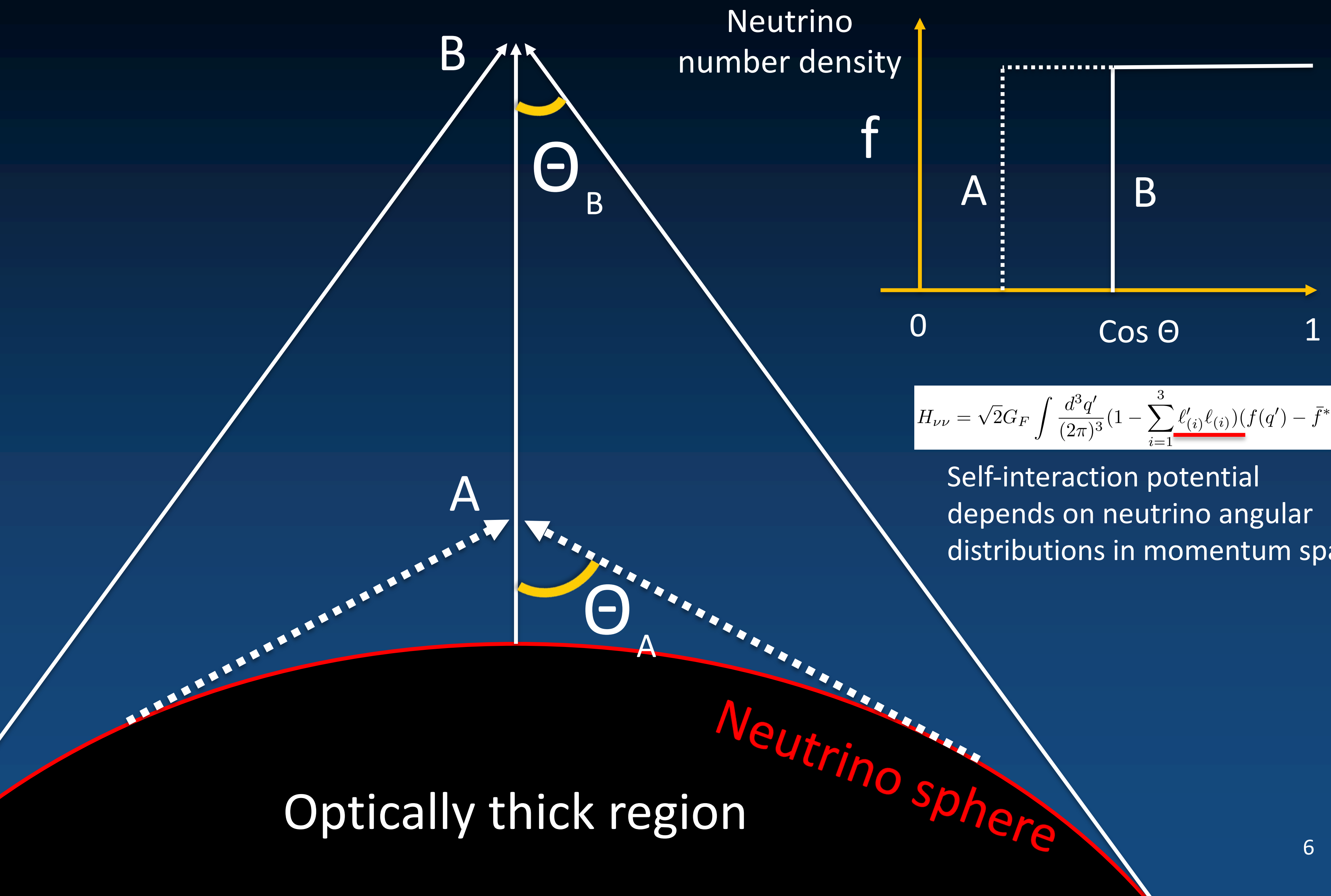


Xiong et al. 2023



Xiong et al. 2022

- Need of global simulations in the study of flavor conversions in CCSN/BNSM

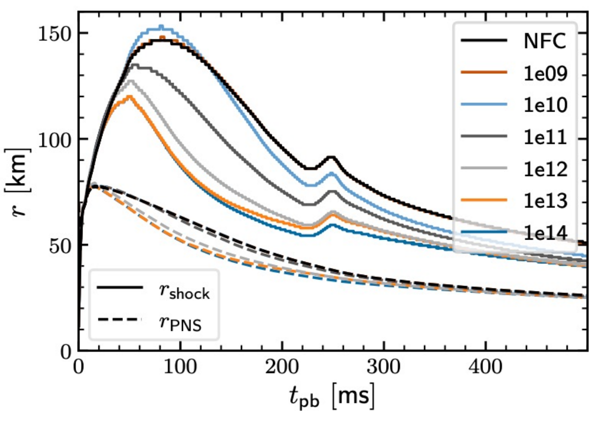


$$H_{\nu\nu} = \sqrt{2}G_F \int \frac{d^3q'}{(2\pi)^3}(1 - \sum_{i=1}^{3} \underline{\ell'_{(i)}\ell_{(i)}})(f(q') - \bar{f}^*(q')),$$

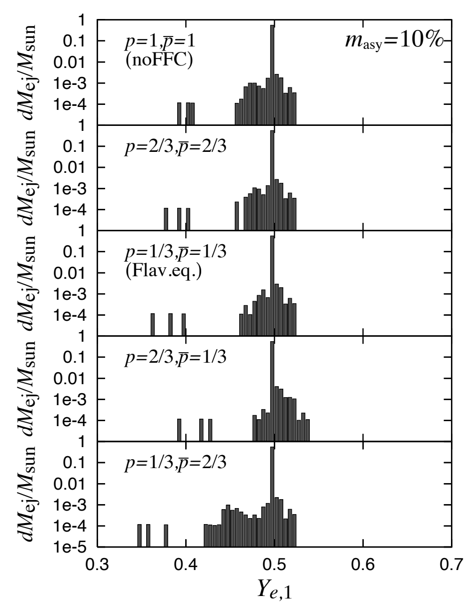
Self-interaction potential depends on neutrino angular distributions in momentum space

- Phenomenological approach: Examples

CCSN

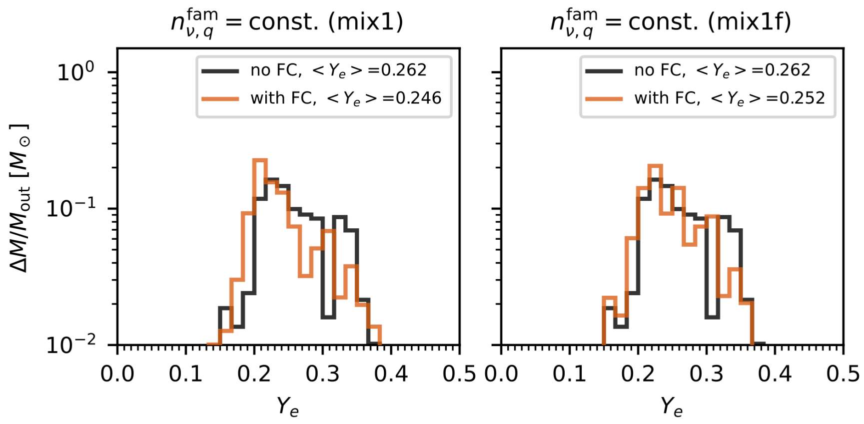


Jacob et al. 2023

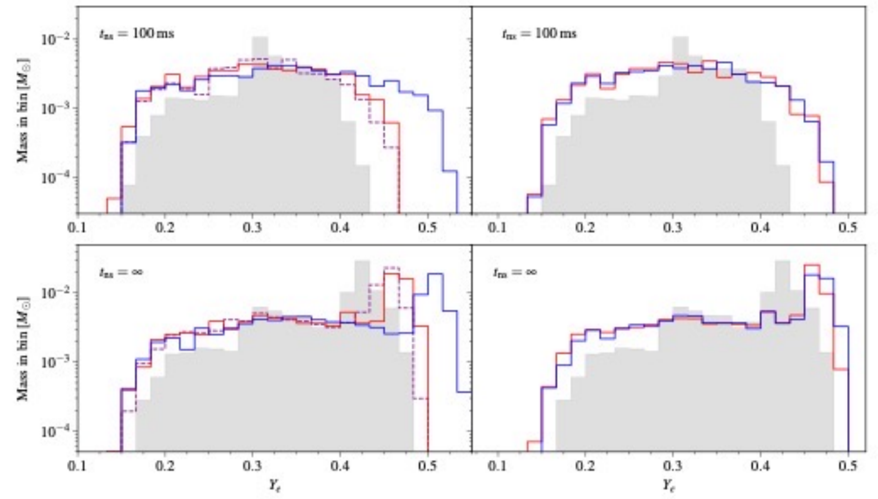


Fujimoto and H.N 2023

BNSM



Just et al. 2022



Fernandez et al. 2022

- Phenomenological approach: Uncertainties

- Degree of flavor mixing can not be determined.

  It is a parameter in phenomenological models

- No reliable approximate neutrino transport have been established.

  Requirements of quantum closure relations for angular moments

- Systematic errors are involved due to collision term (neutrino-matter interactions).

  Non-linear evolution of flavor conversions strongly hinge on collision term

⇩

These issues can be addressed only by solving quantum kinetic neutrino transport

- Global Simulations: code development

General-relativistic quantum-kinetic neutrino transport (GRQKNT)

Nagakura 2022

$$p^{\mu}\frac{\partial \overset{(-)}{f}}{\partial x^{\mu}} + \frac{dp^{i}}{d\tau}\frac{\partial \overset{(-)}{f}}{\partial p^{i}} = -p^{\mu}u_{\mu}\overset{(-)}{S}_{\mathrm{col}} + ip^{\mu}n_{\mu}[\overset{(-)}{H}, \overset{(-)}{f}],$$

- Fully general relativistic (3+1 formalism) neutrino transport
- Multi-Dimension (6-dimensional phase space)
- Neutrino matter interactions (emission, absorption, and scatterings)
- Neutrino Hamiltonian potential of vacuum, matter, and self-interaction
- 3 flavors + their anti-neutrinos
- Solving the equation with Sn method (explicit evolution: WENO-5th order)
- Hybrid OpenMP/MPI parallelization

- Time-dependent global simulations of FFC

Nagakura and Zaizen PRL 2022, PRD 2023

- Issue:

$$\ell_{\mathrm{n}_\nu} \equiv c\,\mathrm{T}_{\mathrm{n}_\nu} = 0.235\ \mathrm{cm} \left(\frac{L_\nu}{4\times 10^{52}\mathrm{erg/s}} \right)^{-1} \left(\frac{E_{\mathrm{ave}}}{12\mathrm{MeV}} \right) \left(\frac{R}{50\mathrm{km}} \right)^{2} \left(\frac{\kappa}{1/3} \right)$$

Oscillation wavelength is an order of sub-centimeter.

Too short !!!!

How can we make FFC simulations tractable???

- Strategy:

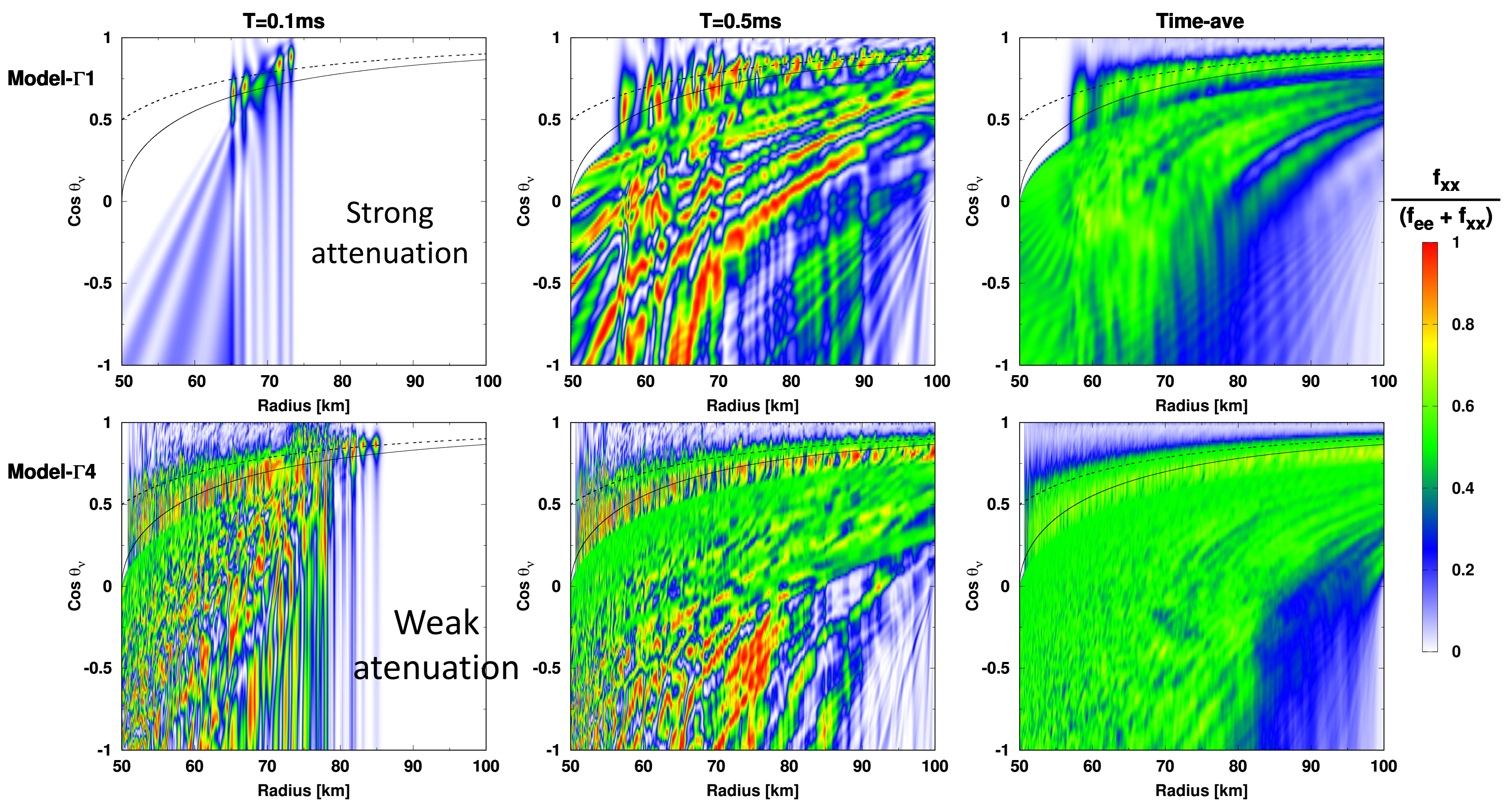
$$\frac{\partial \overset{(-)}{f}}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \cos\theta_\nu \overset{(-)}{f}\right) - \frac{1}{r\sin\theta_\nu}\frac{\partial}{\partial \theta_\nu}\left(\sin^2\theta_\nu \overset{(-)}{f}\right) = -i\,\xi\,[\overset{(-)}{H}, \overset{(-)}{f}],$$

Attenuation parameter (0 ≦ ξ ≦ 1)

V Attenuating Hamiltonian makes global QKE simulations tractable.

V Realistic features can be learned by a convergence study of ξ (→ 1).

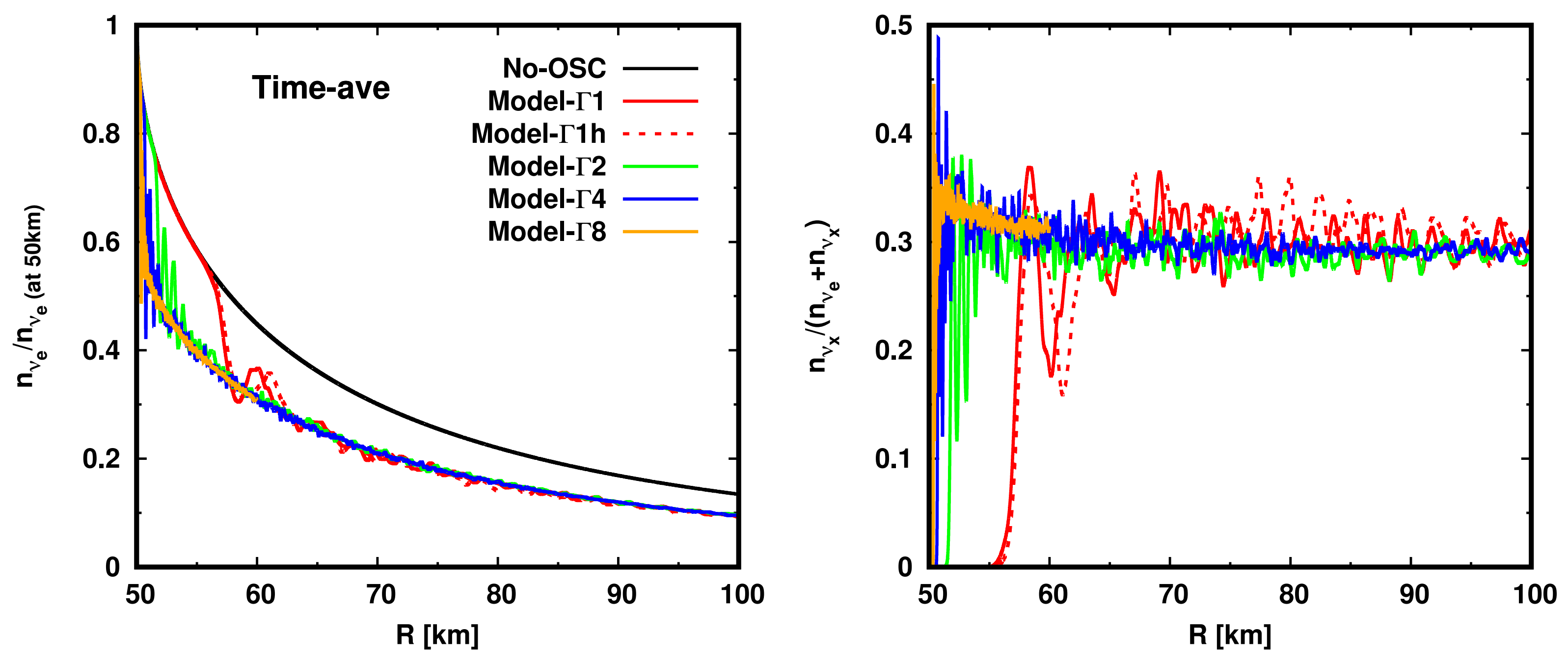
Temporal and quasi-steady features of FFC in global scale (1D in space + 1D angle in momentum space)



Strong attenuation

Weak atenuation

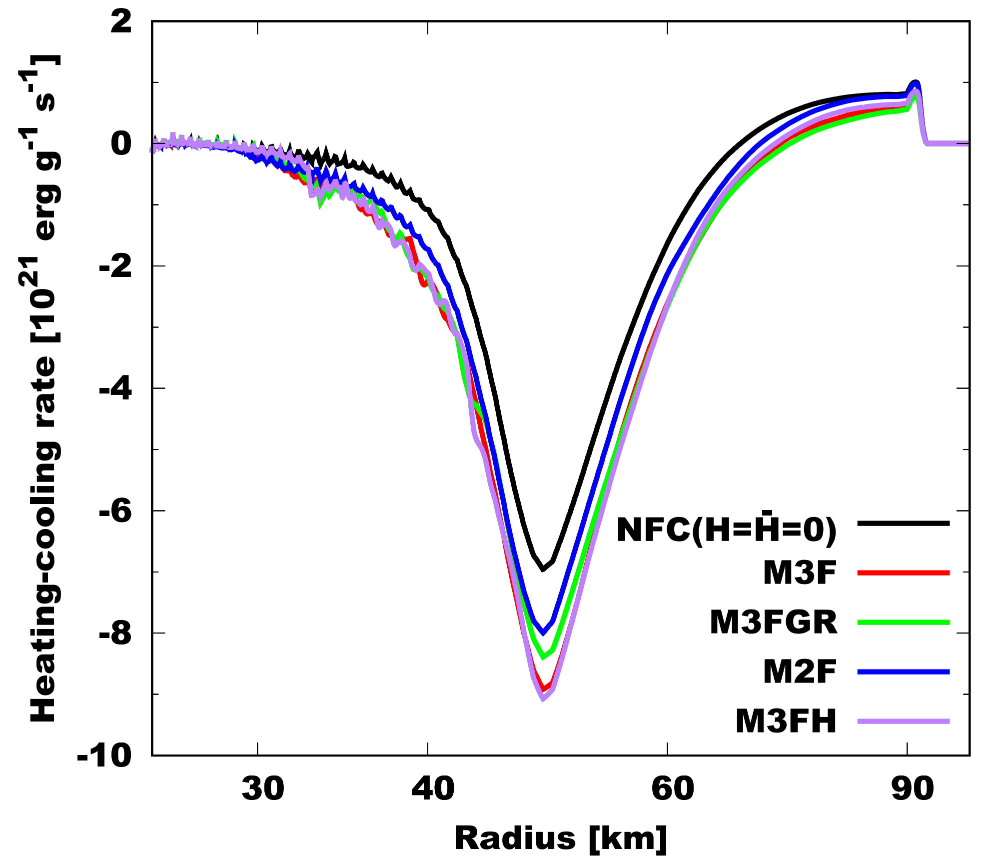
Attenuating Hamiltonian potential does not change degree of flavor conversion in asymptotic states.



Global simulations of FFC in a CCSN environment

Nagakura PRL 2023

Neutrino heating/cooling



Numerical setup:

Collision terms are switched on.

Fluid-profiles are taken from a CCSN simulation.

General relativistic effects are taken into account.

A wide spatial region is covered.

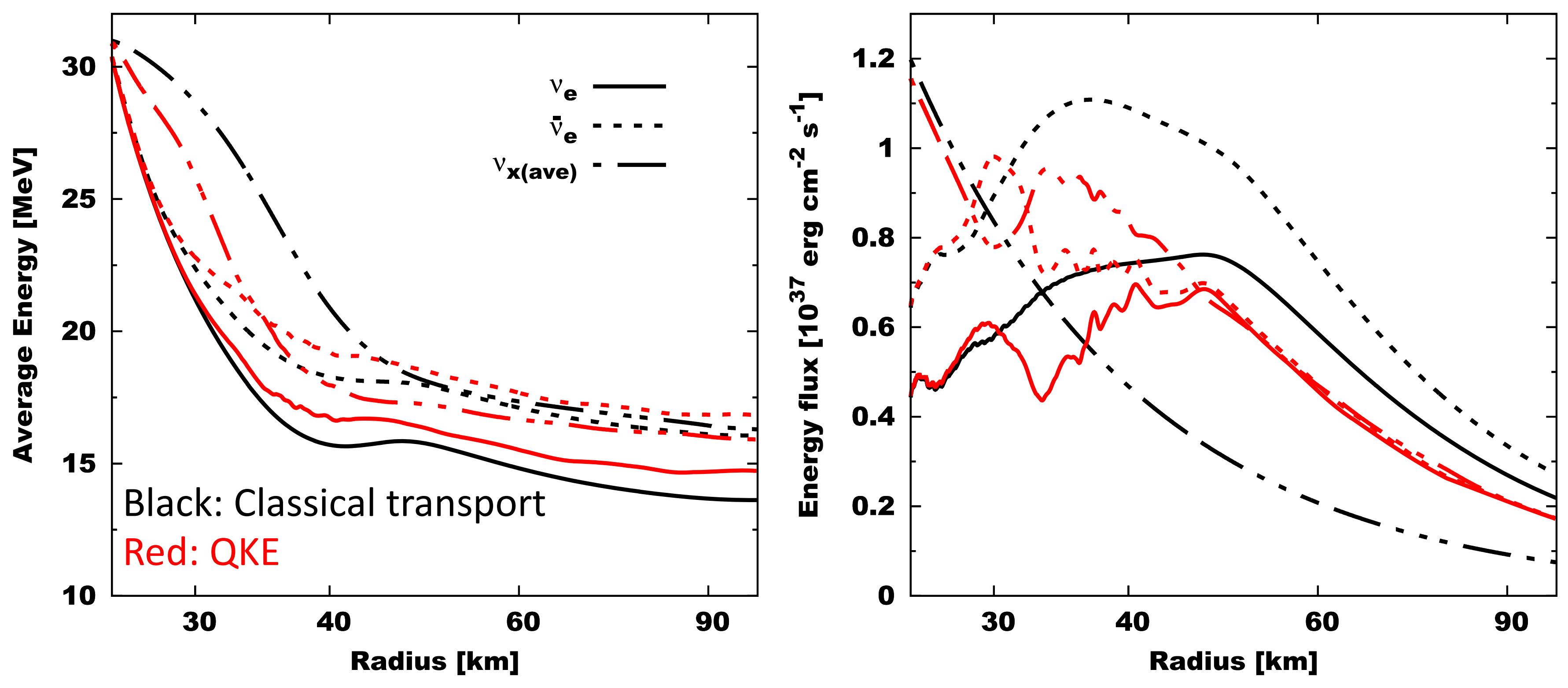
Three-flavor framework

Neutrino-cooling is enhanced by FFCs
Neutrino-heating is suppressed by FFCs

⇨ Impacts on CCSN explosion !!

Global simulations of FFC in a CCSN environment

Nagakura PRL 2023


Average energy

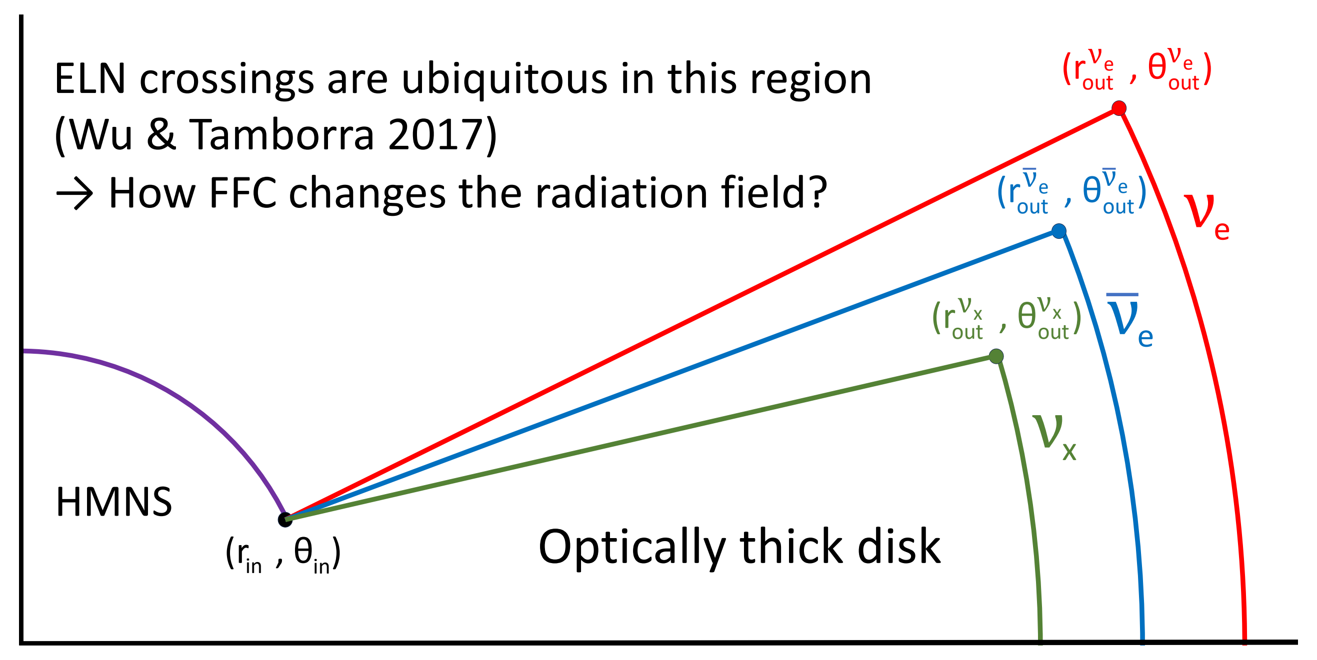
Energy flux

Global Simulations of FFC in a BNSM environment

Nagakura (arXiv:2306.10108)

ν Setup:

- Hypermassive neutron star (HMNS) + disk geometry
- Thermal emission on the neutrino sphere
- QKE (FFC) simulations in axisymmetry
- Resolutions: 1152 (r) × 384 (θ) × 98 (θ_ν) × 48 (ϕ_ν)



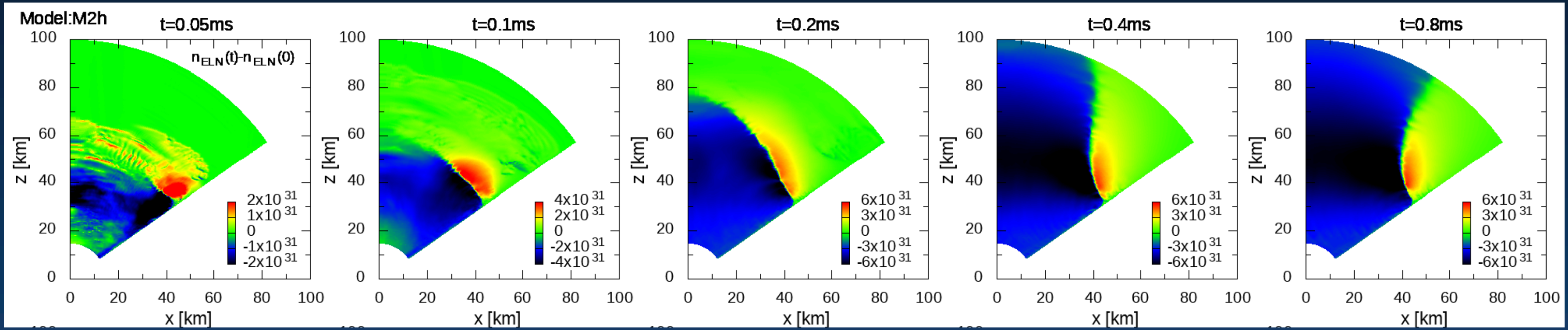
ELN crossings are ubiquitous in this region (Wu & Tamborra 2017)
→ How FFC changes the radiation field?

Global Simulations of FFC in a BNSM environment

Nagakura (arXiv:2306.10108)

- Temporal evolution of FFCs in global scale:

ELN(t) – ELN(0)



Time

Take-home message 1

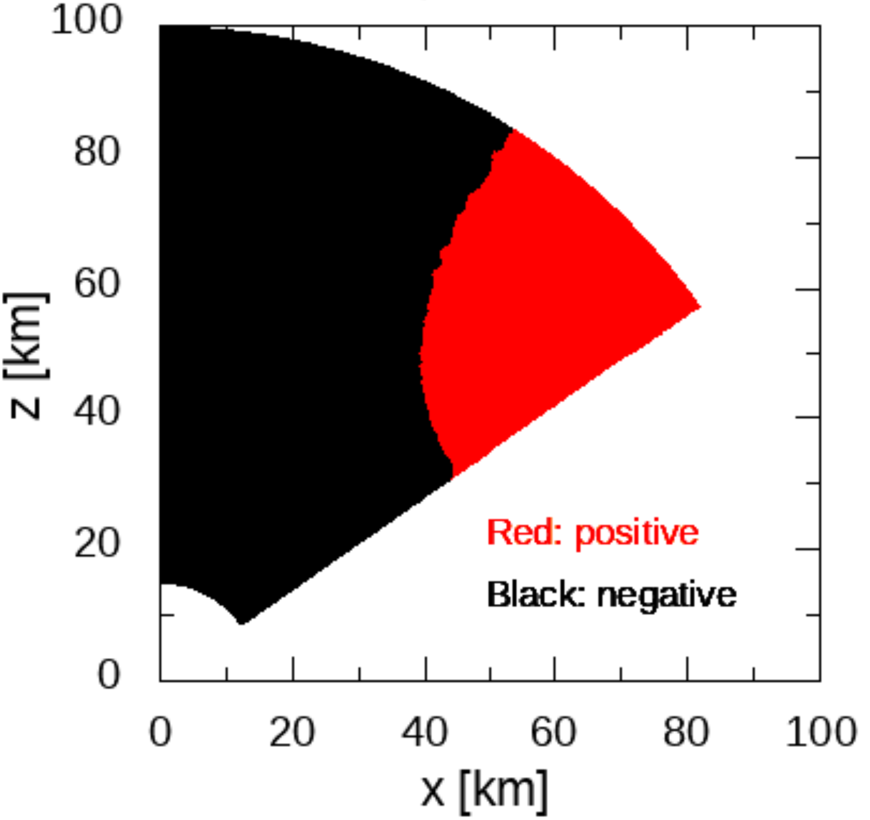
Non-conservations of ELN (and XLN) number density represent the importance of global advection of neutrinos in space!

Global Simulations of FFC in a BNSM environment

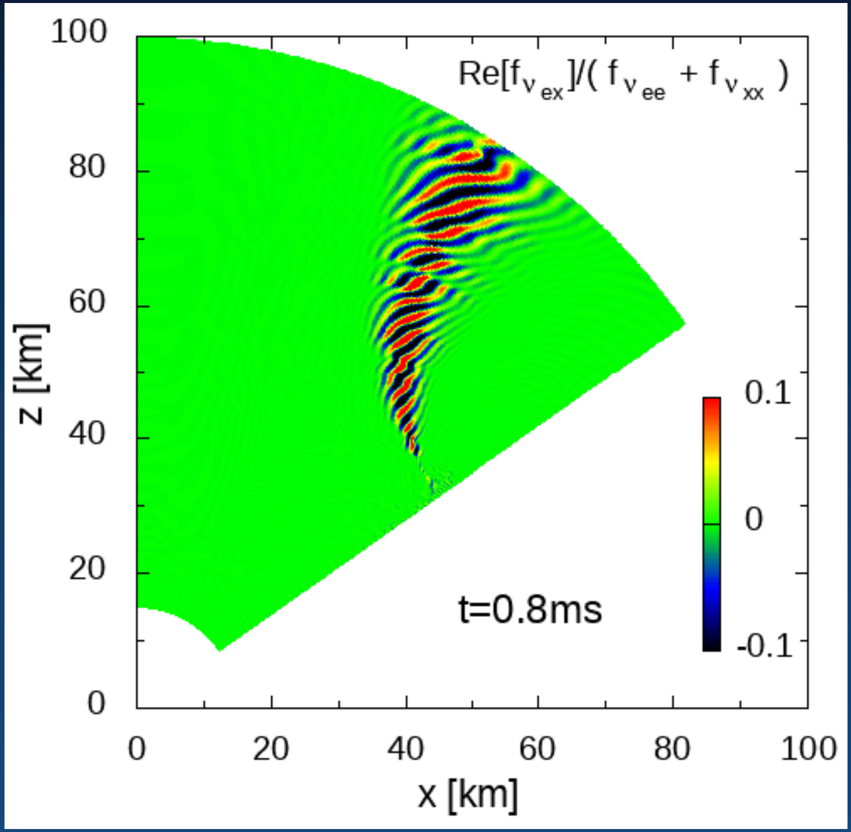
Nagakura (arXiv:2306.10108)

- EXZS (ELN-XLN Zero Surface):

ELN - XLN



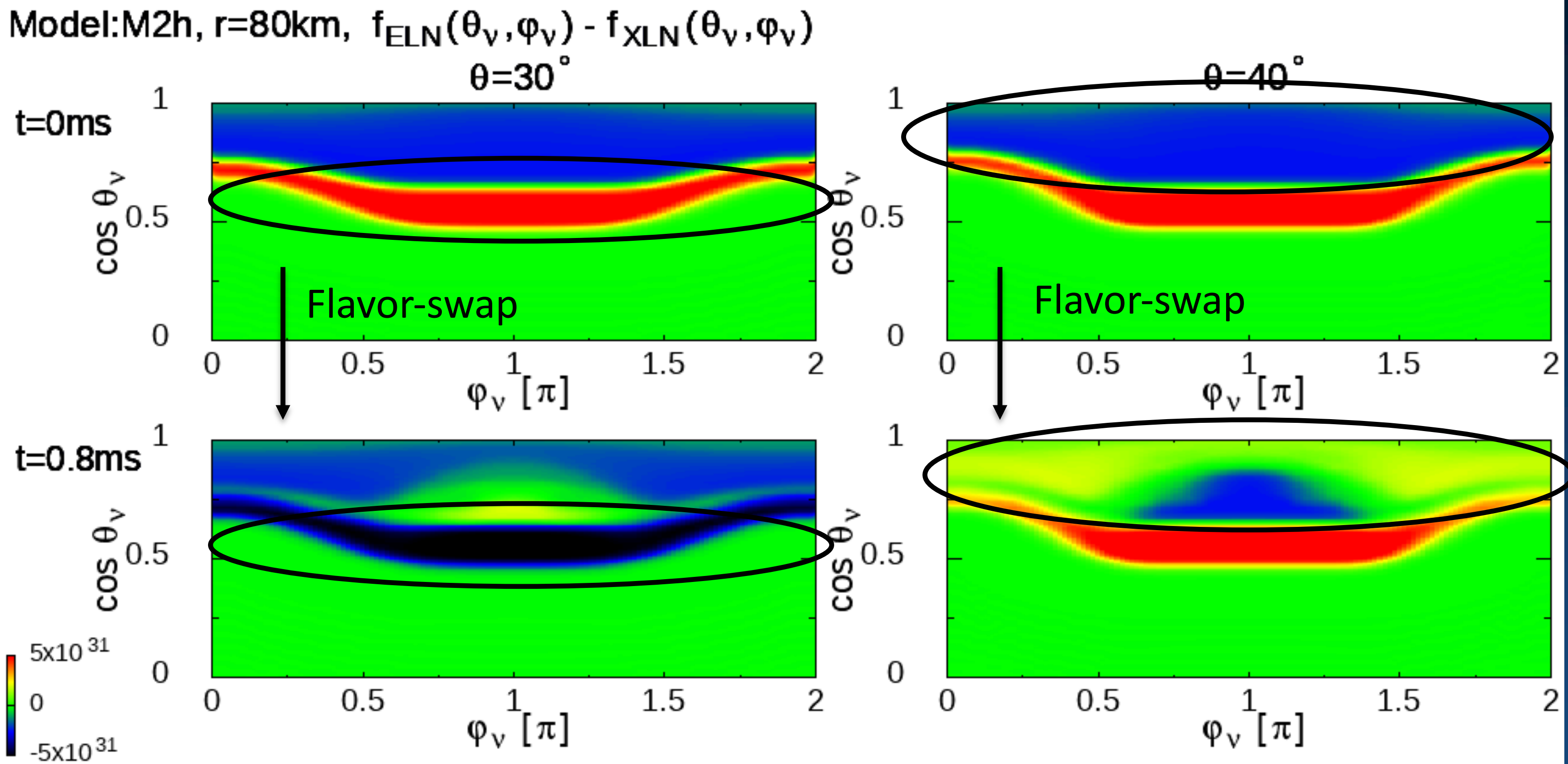
Flavor coherency



Global Simulations of FFC in a BNSM environment

Nagakura (arXiv:2306.10108)

- <u>Flavor swap between electron- and heavy-leptonic neutrinos:</u>



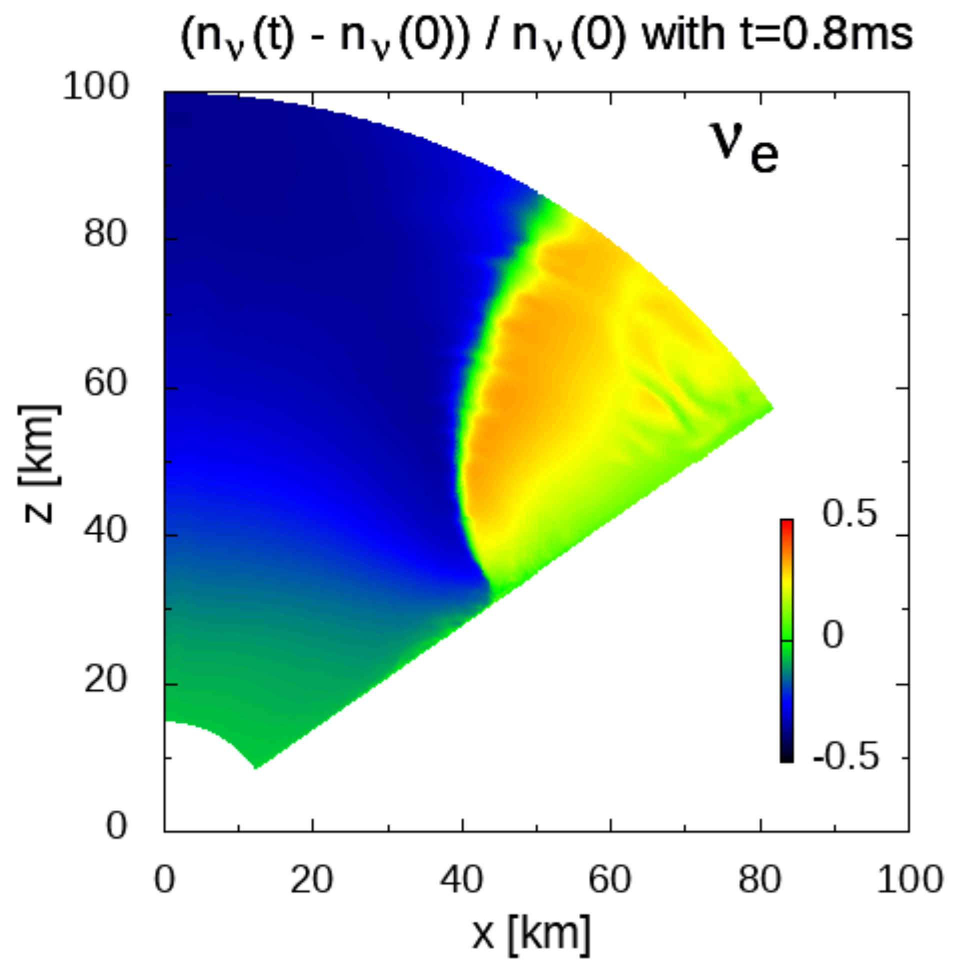
Flavor-swap

Flavor-swap

Global Simulations of FFC in a BNSM environment

Nagakura (arXiv:2306.10108)

- Substantial change of neutrino radiation field:



Note: Increase or decrease of electron-type neutrinos hinge on heavy-leptonic neutrinos

More detailed study is required!!

Summary

- Radiation-hydrodynamic simulations under classical treatments of neutrino kinetics have been matured in CCSN and BNSM community.
- Collective neutrino oscillations, one of the quantum kinetics features of neutrinos, ubiquitously occur in CCSN and BNSM environments.
- Fast neutrino-flavor conversion (FFC) potentially gives a huge impact on fluid-dynamics, nucleosynthesis, and neutrino signal.
- We developed a new GRQKNT code for time-dependent global simulations of neutrino quantum kinetics (QKE).
- QKE simulations are done in CCSN and BNSM environments with GRQKNT code.
- Global advection of neutrinos play important roles in FFC dynamics.