Fast neutrino flavor conversions in a supernova: Emergence, evolution, & effects

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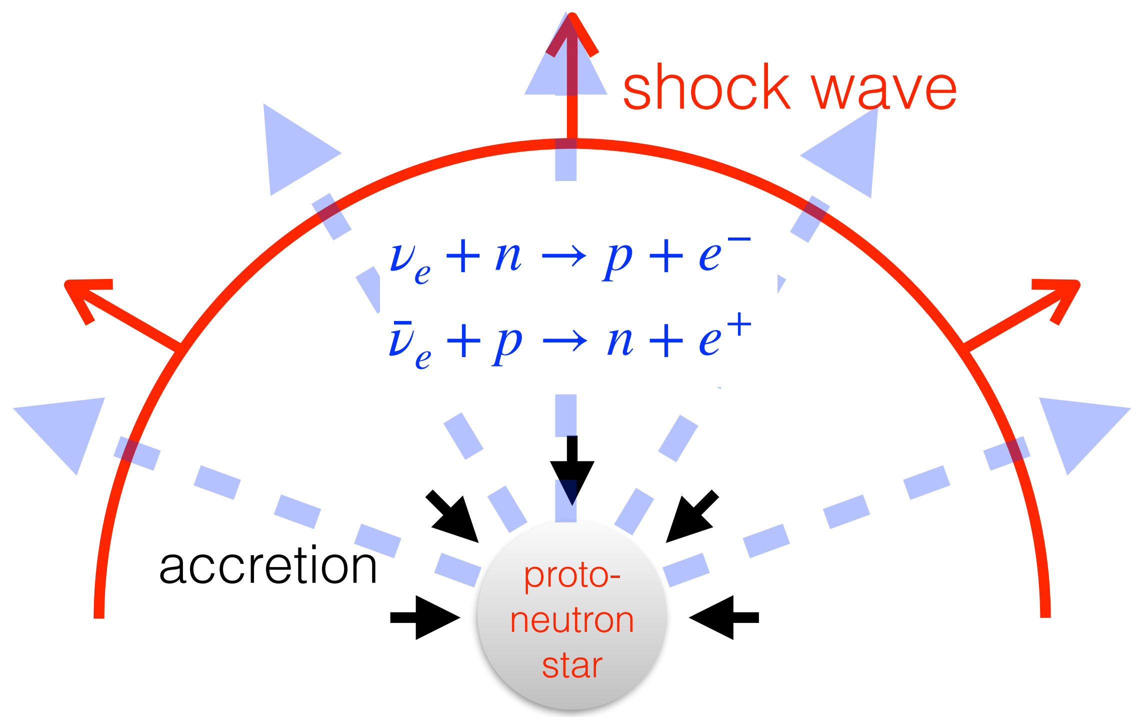
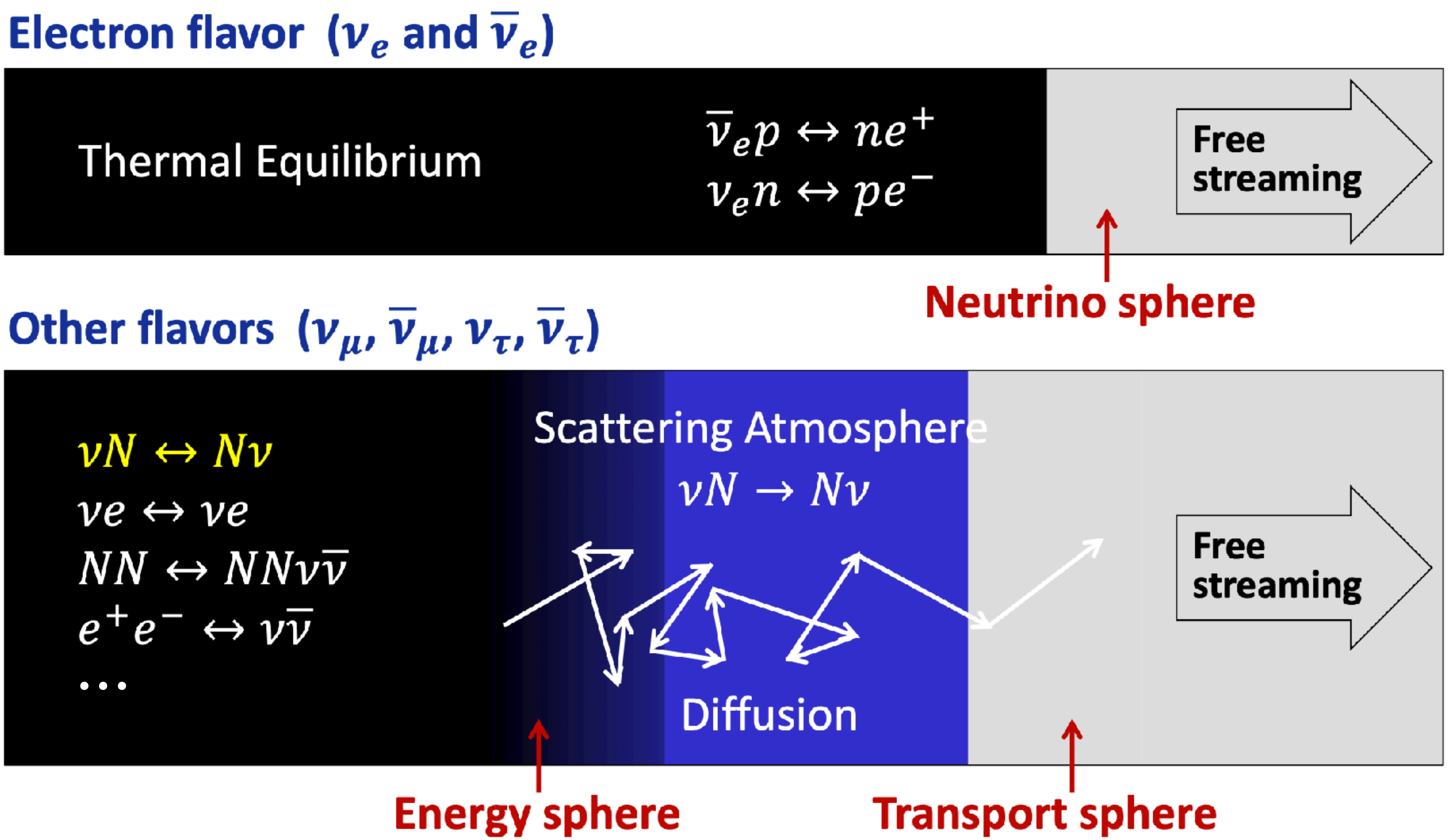
Neutrinos in core-collapse supernovae (CCSN)



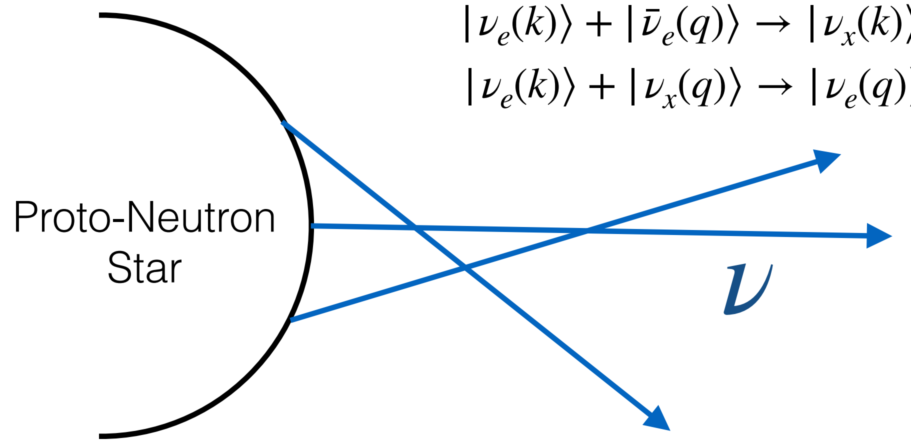
- Intense sources of MeV neutrinos in all flavors
- Neutrinos play important roles in dynamics and nucleosynthesis.

Collisional weak processes in classical neutrino transport

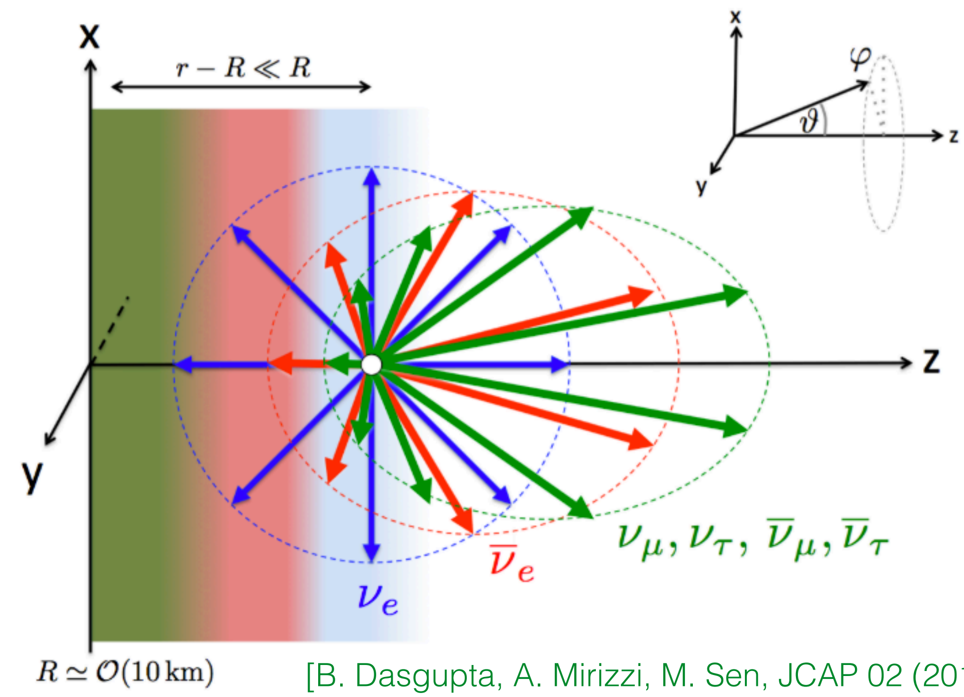


[G. G. Raffelt, ApJ 561, 890 (2001)]

Collective neutrino oscillations & Fast flavor instability (FFI)



$$|\nu_e(k)\rangle + |\bar{\nu}_e(q)\rangle \to |\nu_x(k)\rangle + |\bar{\nu}_x(q)\rangle$$
$$|\nu_e(k)\rangle + |\nu_x(q)\rangle \to |\nu_e(q)\rangle + |\nu_x(k)\rangle$$
$$(x = \mu, \tau)$$



[B. Dasgupta, A. Mirizzi, M. Sen, JCAP 02 (2017) 019]

non-trivial neutrino angular distributions

A "very fast" time scale $(G_F n_\nu)^{-1}$, where n_ν is the neutrino number density $n_e \sim T^3$. In our domain this time is of order 10^{-3} cm in units in which $c = 1$.

[redacted] the "very fast" rate mentioned in the introduction. This situation only arises when the angular distributions in the initial state are somewhat complex. [R. F. Sawyer, PRD 79, 105003 (2009)]

[R. F. Sawyer, PRL 116, 081101 (2016);
S. Chakraborty, R. Hansen, I. Izaguirre et al., JCAP 03 (2016) 042;
I. Izaguirre, G. Raffelt, I. Tamborra, PRL 118, 021101 (2017); ...]

Fast flavor instability is present if and only if the angular distributions of neutrino lepton number of 2 flavors cross each other. [T. Morinaga, PRD 105, L101301 (2022)]

$$G \equiv f_{\nu_e}(\mathbf{v}) - f_{\bar{\nu}_e}(\mathbf{v}) - f_{\nu_x}(\mathbf{v}) + f_{\bar{\nu}_x}(\mathbf{v}) \quad \text{(ELN, or E-XLN)}$$

Occurrence of fast flavor instability:

- ahead of the shock wave,
- near the neutrinosphere,
- deep inside neutrinosphere

[S. Abbar, H. Duan, et al., PRD 100, 043004 (2019);
M. Azari, S. Yamada et al. PRD 99 103011 (2019);
R. Glas, H.-T. Janka et al., PRD 101, 063001 (2020);
H. Nagakura, A. Burrows et al., PRD 104, 083025 (2021);
R. Akaho, A. Harad et al., APJ 944, 60 (2023);
...]

Neutrino quantum kinetic equation (νQKE)

[G. Sigl, G. Raffelt, 1993; A. Vlasenko, G. Fuller, V. Cirigliano, 2014; C. Volpe, 2015; S. Richers, G. McLaughlin et al., 2019 ...]

$$(\partial_t + \mathbf{v}\cdot\nabla_{\mathbf{r}})\varrho = -i[\mathbf{H}_{\text{vac}} + \mathbf{H}_{\text{mat}} + \mathbf{H}_{\nu\nu}, \varrho] + \mathbf{C}(\varrho)$$

advection — vacuum mixing — coherent forward scatterings (MSW, self-induced) — collisional weak processes

$$\varrho(t,\mathbf{r},\mathbf{p}) = \begin{pmatrix} f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho^*_{e\mu} & f_{\nu_\mu} & \varrho_{\mu\tau} \\ \varrho^*_{e\tau} & \varrho^*_{\mu\tau} & f_{\nu_\tau} \end{pmatrix}$$

$$\mathbf{H}_{\text{vac}}(E) = \mathbf{U}\mathbf{M}^2\mathbf{U}^\dagger$$

$$\mathbf{H}_{\text{mat}} = \sqrt{2}G_F\text{diag}[n_e, 0, 0]$$

$$\mathbf{H}_{\nu\nu}(\hat{\mathbf{p}}) = \sqrt{2}G_F\int d\mathbf{p}'(1-\hat{\mathbf{p}}\cdot\hat{\mathbf{p}}')[\varrho(\mathbf{p}') - \bar{\varrho}^*(\mathbf{p}')]$$

$$\mathrm{d}f_{\nu_e}/\mathrm{d}t = j_e(1-f_{\nu_e}) - \chi_e f_{\nu_e}$$

emissivity — opacity

$$\mathbf{C} \sim \begin{pmatrix} j_e(1-f_{\nu_e}) - \chi_e f_{\nu_e} & -(j_e+\chi_e)\varrho_{e\mu}/2 \\ -(j_e+\chi_e)\varrho^*_{e\mu}/2 & 0 \end{pmatrix}$$

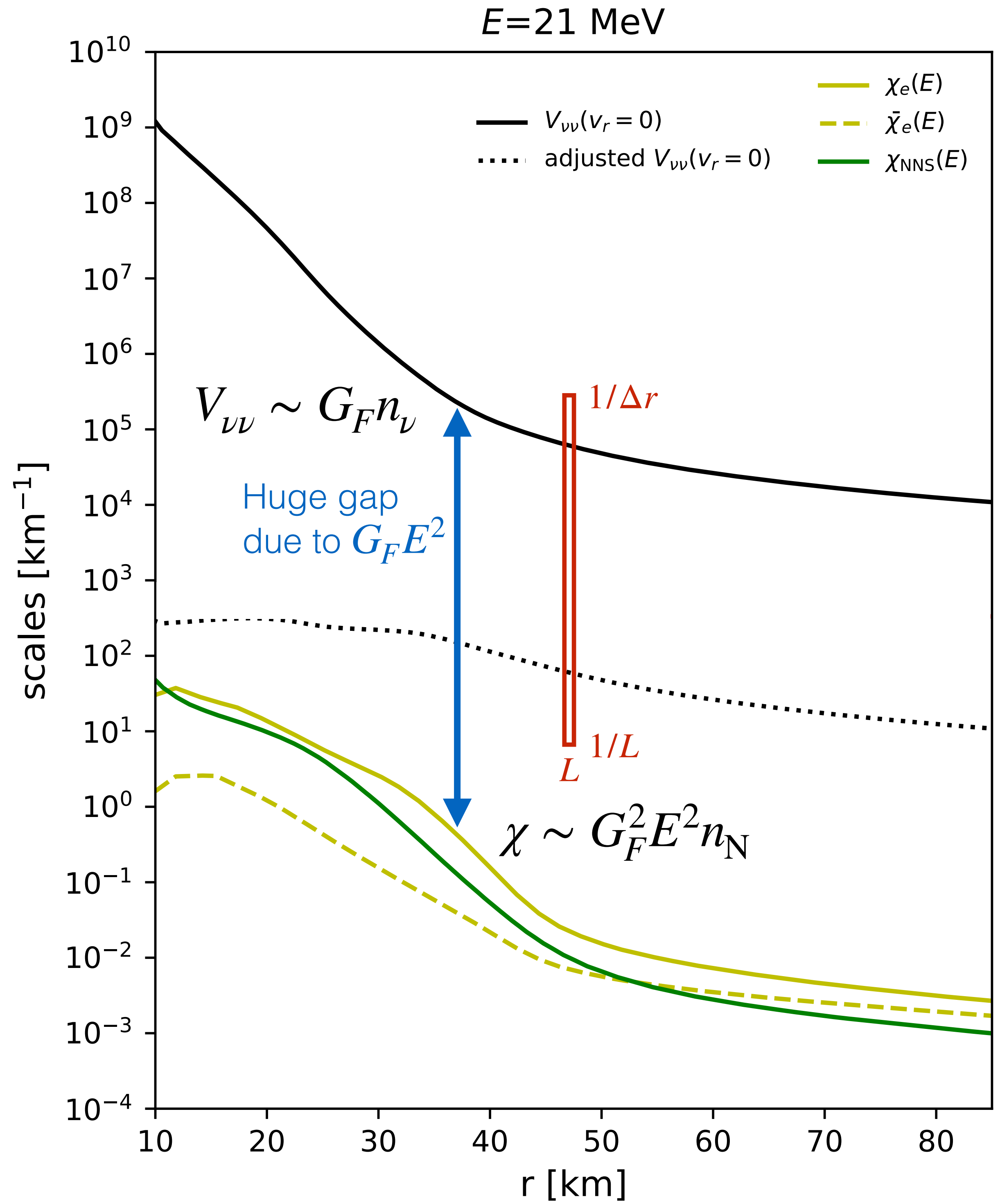
Challenging problem:

- Nonlinearity!
- High dimensions! $\varrho(t,\mathbf{r},\mathbf{p})$
- Scale separation! $\mathbf{H}_{\nu\nu} \sim G_F n_\nu$ $\quad \mathbf{C} \sim \chi_e \sim G_F^2 E^2 n_{\text{N}}$

Scenarios to simulate fast flavor conversions (FFCs)

$$(\partial_t + \mathbf{v}\cdot\nabla_{\mathbf{r}})\varrho = -i[\quad \mathbf{H}_{\nu\nu}, \varrho]$$

- Local box:
  periodic boundary condition
  without collisions
  [J. Martin, C. Yi, H. Duan, PLB 800, 135088 (2020);
  S. Bhattacharyya, B. Dasgupta, PRD 102, 063018 (2020); ...]



[ZX, M.-R. Wu, et al. PRD 107, 083016 (2023)]

Scenarios to simulate fast flavor conversions (FFCs)

$$(\partial_t + \mathbf{v} \cdot \nabla_{\mathbf{r}})\varrho = -i[a_{\nu\nu}\mathbf{H}_{\nu\nu}, \varrho] + \mathbf{C}(\varrho)$$

- Local box:
  periodic boundary condition
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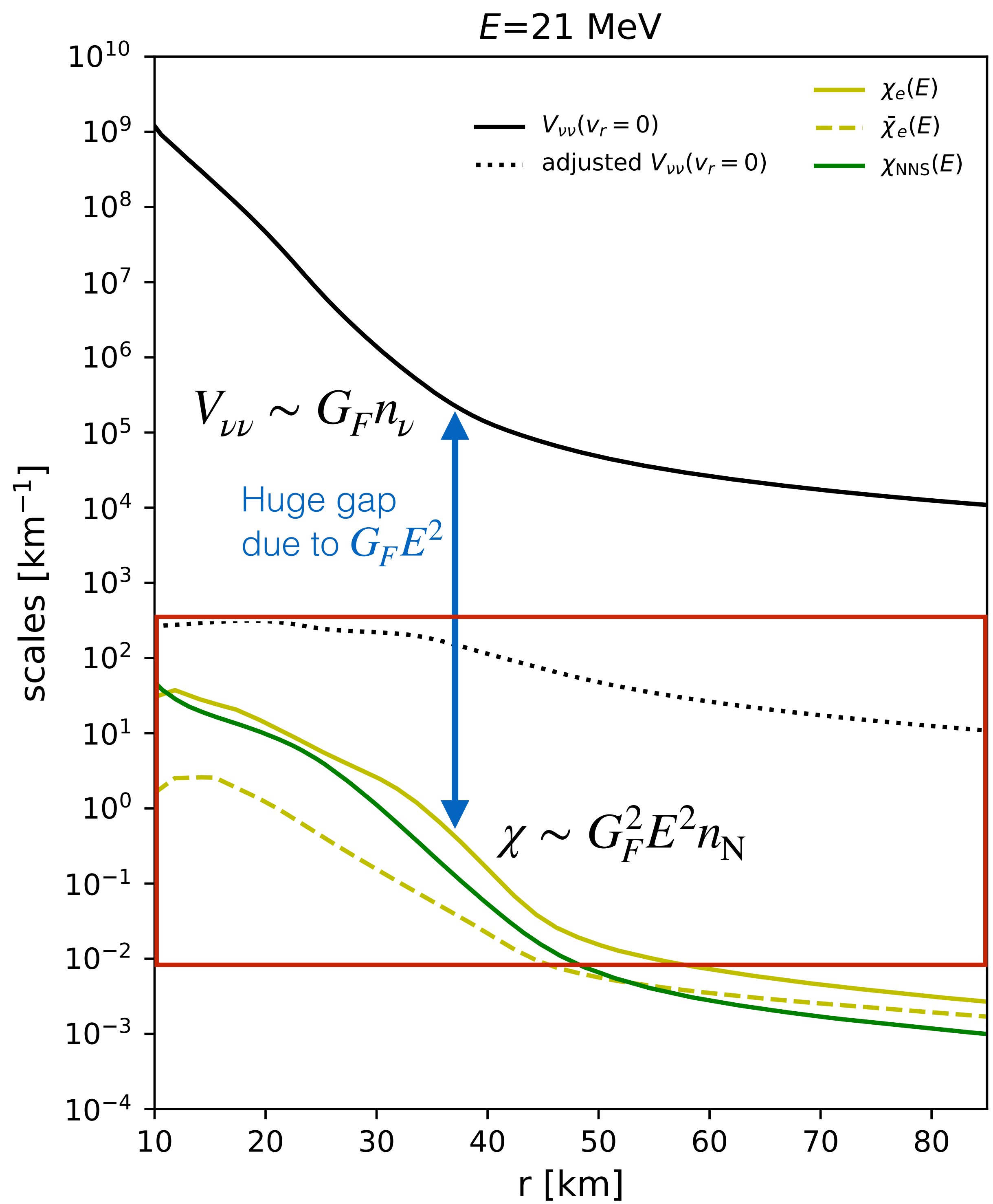
  [J. Martin, C. Yi, H. Duan, PLB 800, 135088 (2020);
  S. Bhattacharyya, B. Dasgupta, PRD 102, 063018 (2020); ...]

- Global advection:
  attenuation on $\mathbf{H}_{\nu\nu}$
  keeping the same hierarchy
  [H. Nagakura, M. Zaizen, PRL 129, 261101 (2022); ...]



[ZX, M.-R. Wu, et al. PRD 107, 083016 (2023)]

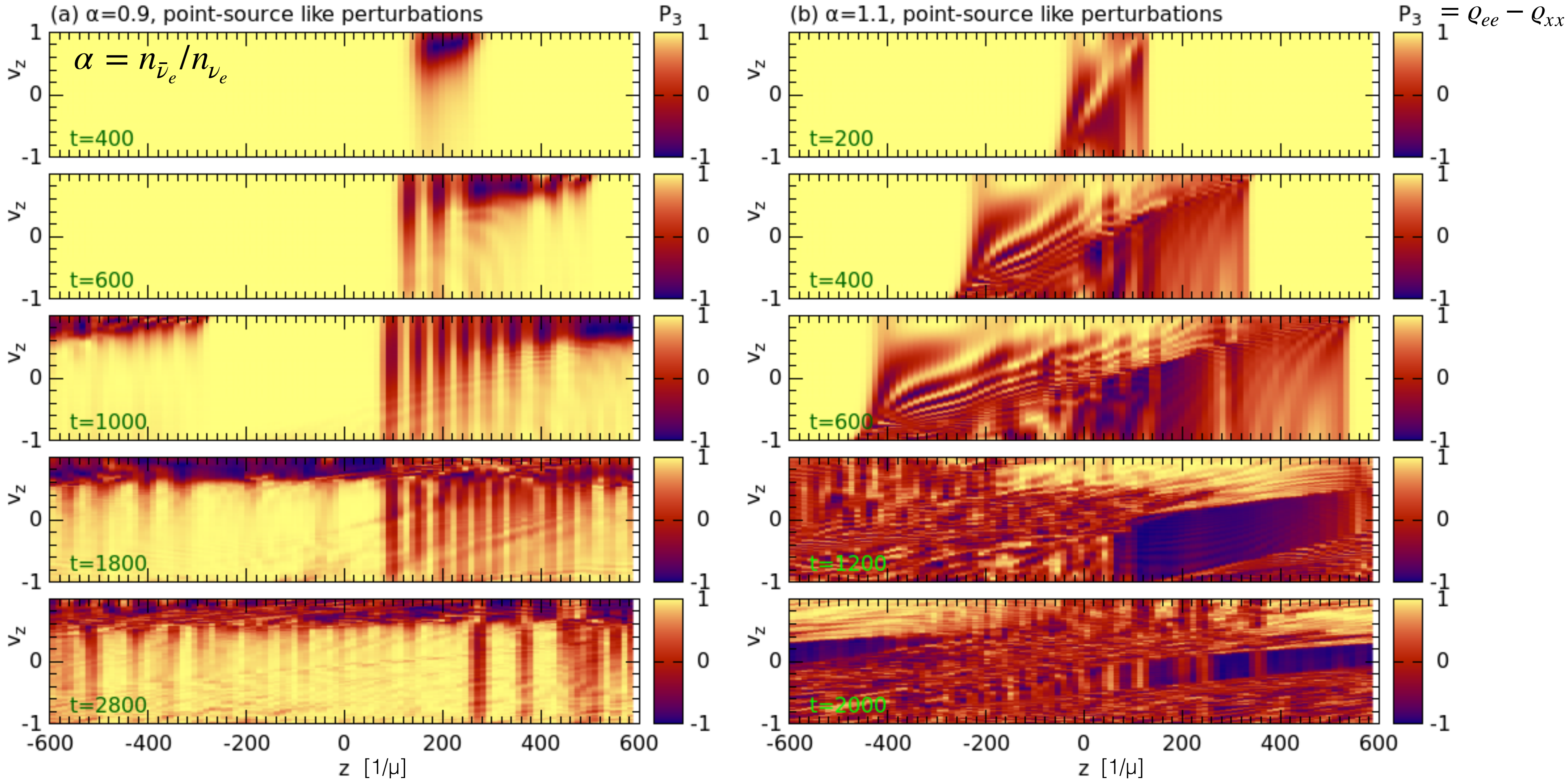
Local-box simulation

$$(\partial_t + v_z\partial_z)\varrho(v_z) = -i[\mathbf{H}_{\nu\nu}(v_z), \varrho(v_z)]$$

$$\mathbf{H}_{\nu\nu} = \mu\int_{-1}^{1} dv_z'(1 - v_z v_z')[g_\nu\varrho - g_{\bar{\nu}}\bar{\varrho}^*]$$

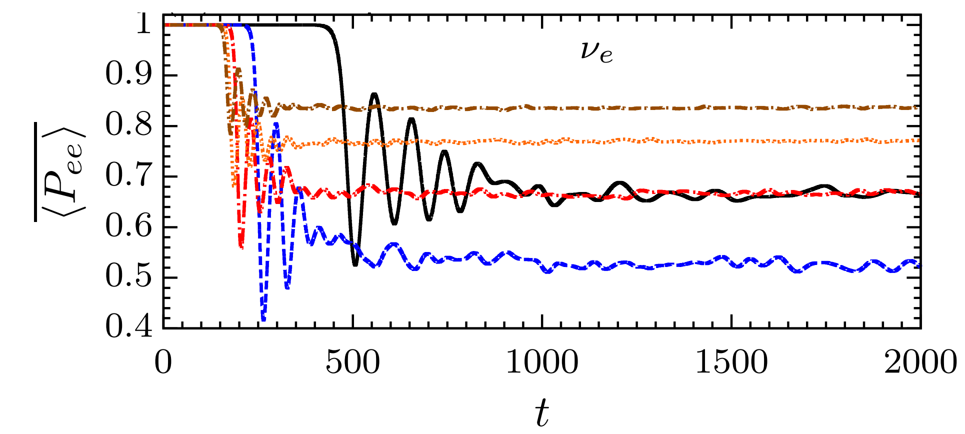
- translation symmetry along x & y
- azimuthal symmetry in v_x-v_y plane
- single energy, two flavors
- COSEν code (Collective Oscillation Simulation Engine for Neutrinos)

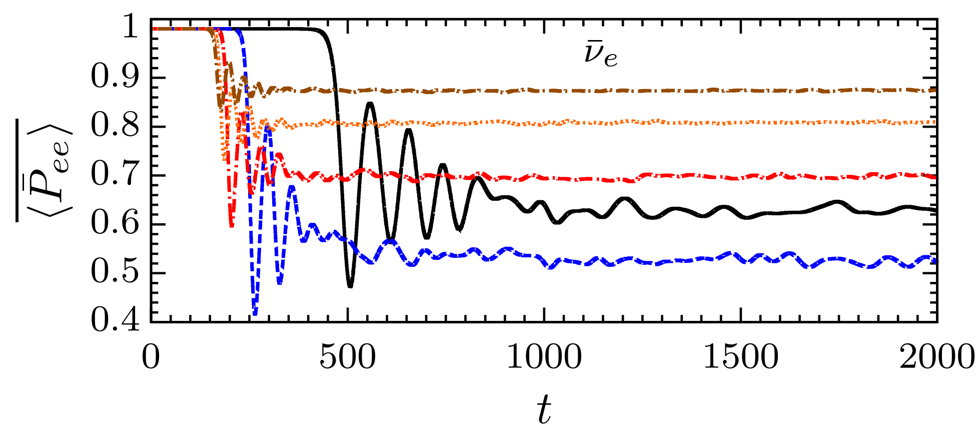
[M. George, M.-R. Wu et al., Comput. Phys. Commun. (2023)]

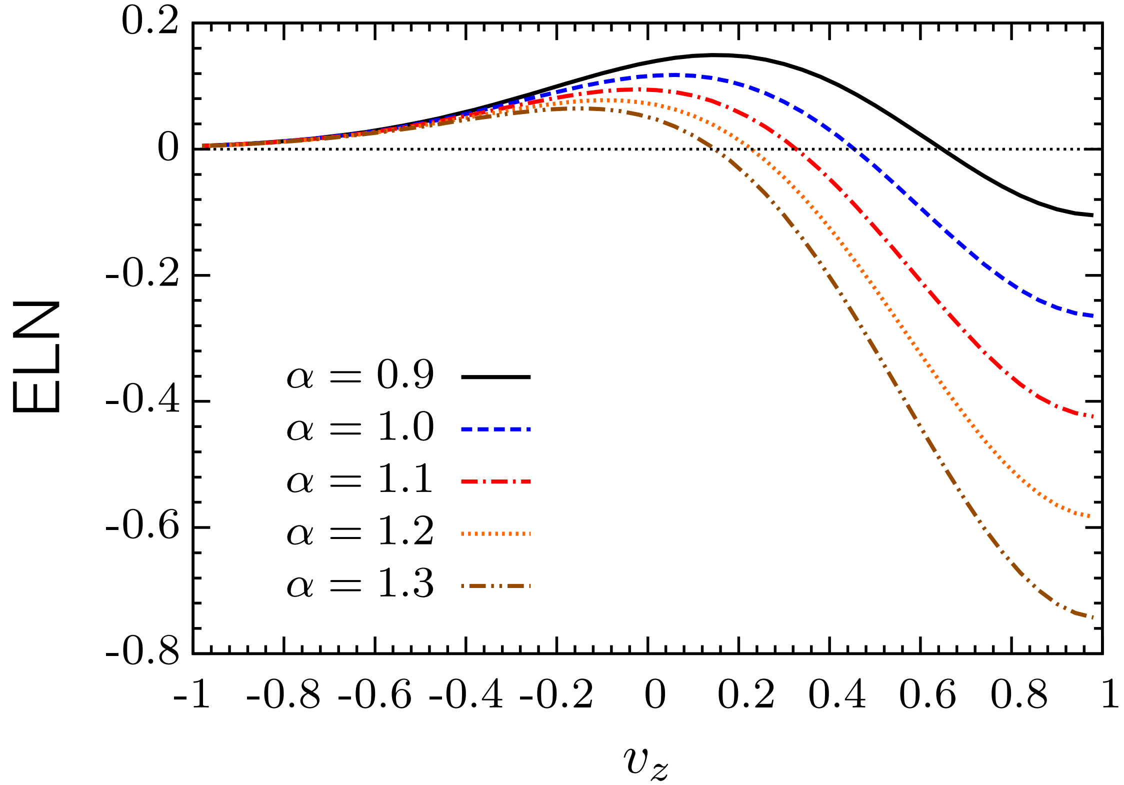


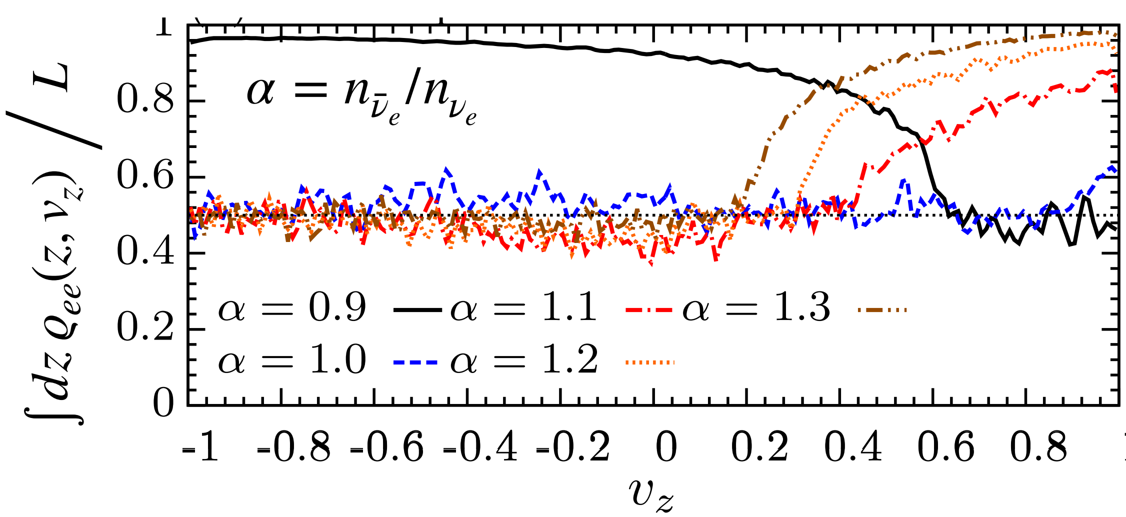
[M.-R. Wu, M. George, C.-Y. Lin, ZX, PRD 104, 103003 (2021)]

Asymptotic state







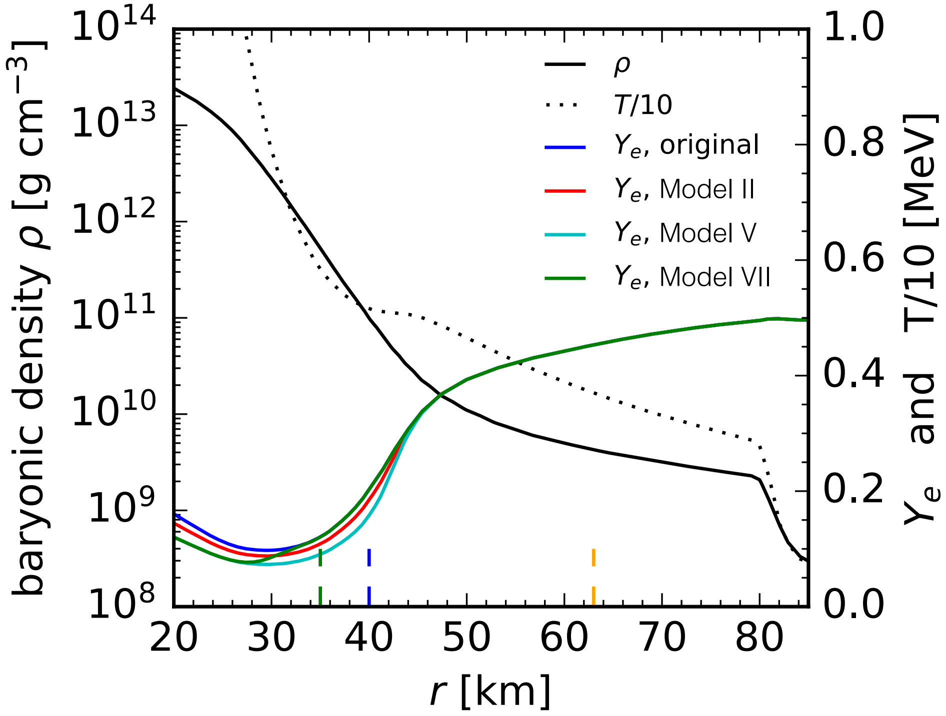


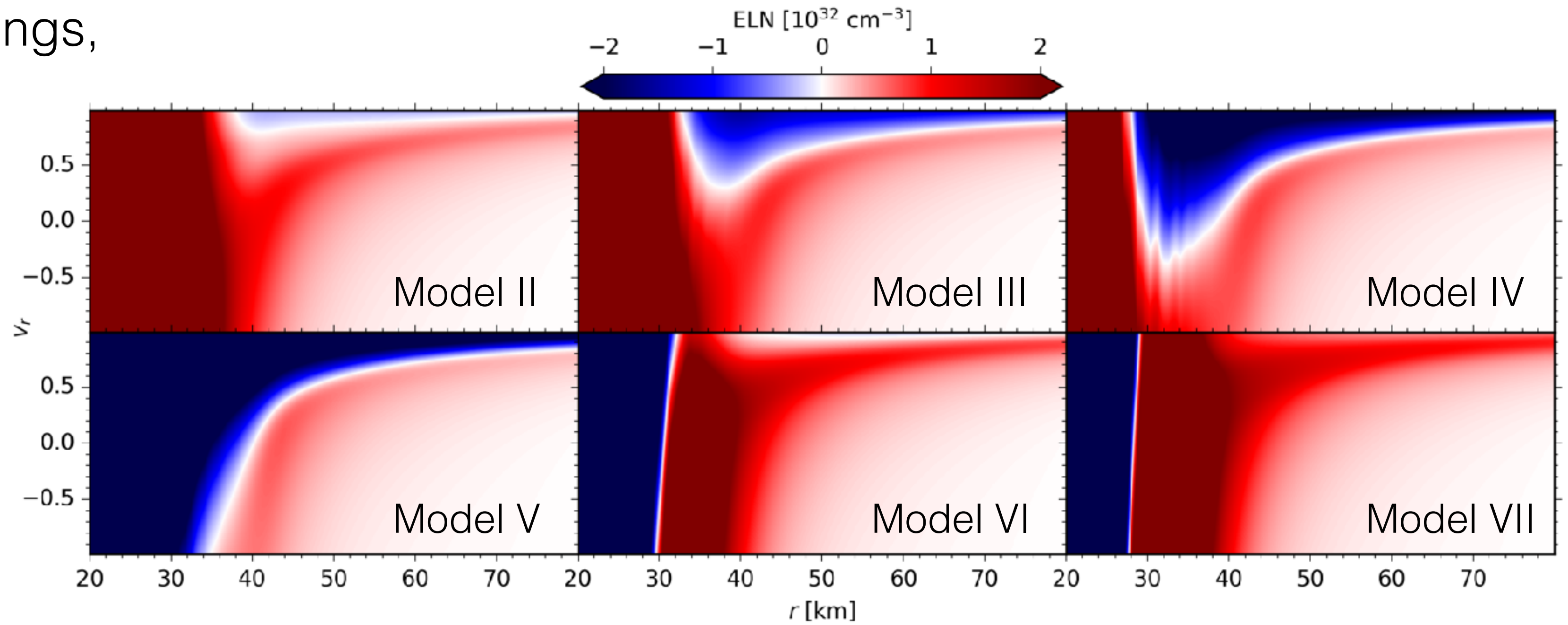
- Complete flavor equilibration for all neutrinos when α=1
- Strong angle-dependence when $\alpha \neq 1$: Flavor equilibration between e and x flavors is achieved only in one side of the vELN crossing, due to the conservation of vELN

[M.-R. Wu, M. George, C.-Y. Lin, ZX, PRD 104, 103003 (2021)]

Global simulation set-up

- Background matter profile from `AGILE-BOLTZTRAN`, $25M_\odot$ progenitor, & the post-bouncing time $t_{\rm pb} \approx 250$ ms
- $(\partial_t + v_r\partial_r + \frac{1-v_r^2}{r}\partial_{v_r})\varrho(E, v_r) = -i[\mathbf{H}_{\rm vac} + a_{\nu\nu}\mathbf{H}_{\nu\nu}, \varrho(E, v_r)] + \mathbf{C}$
  - Multi-energy & multi-angle
  - Two-flavor & three-flavor schemes
  - $a_{\nu\nu} \geq 10^{-3}$, $N_r \geq 25000$, $N_{v_r} = 100$, $N_E = 15$
  - Vacuum term generates flavor mixing seed
  - *Collisional weak processes:* emission & absorption, iso-energetic neutrino-nucleon scattering, inelastic neutrino-electron scatterings, & pair reactions
  - *Inner boundary (20km):* thermal equilibrium at the boundary, collisional weak processes determine neutrino spheres
  - *Outer boundary (80km):* freely stream out, no injection for incoming neutrinos

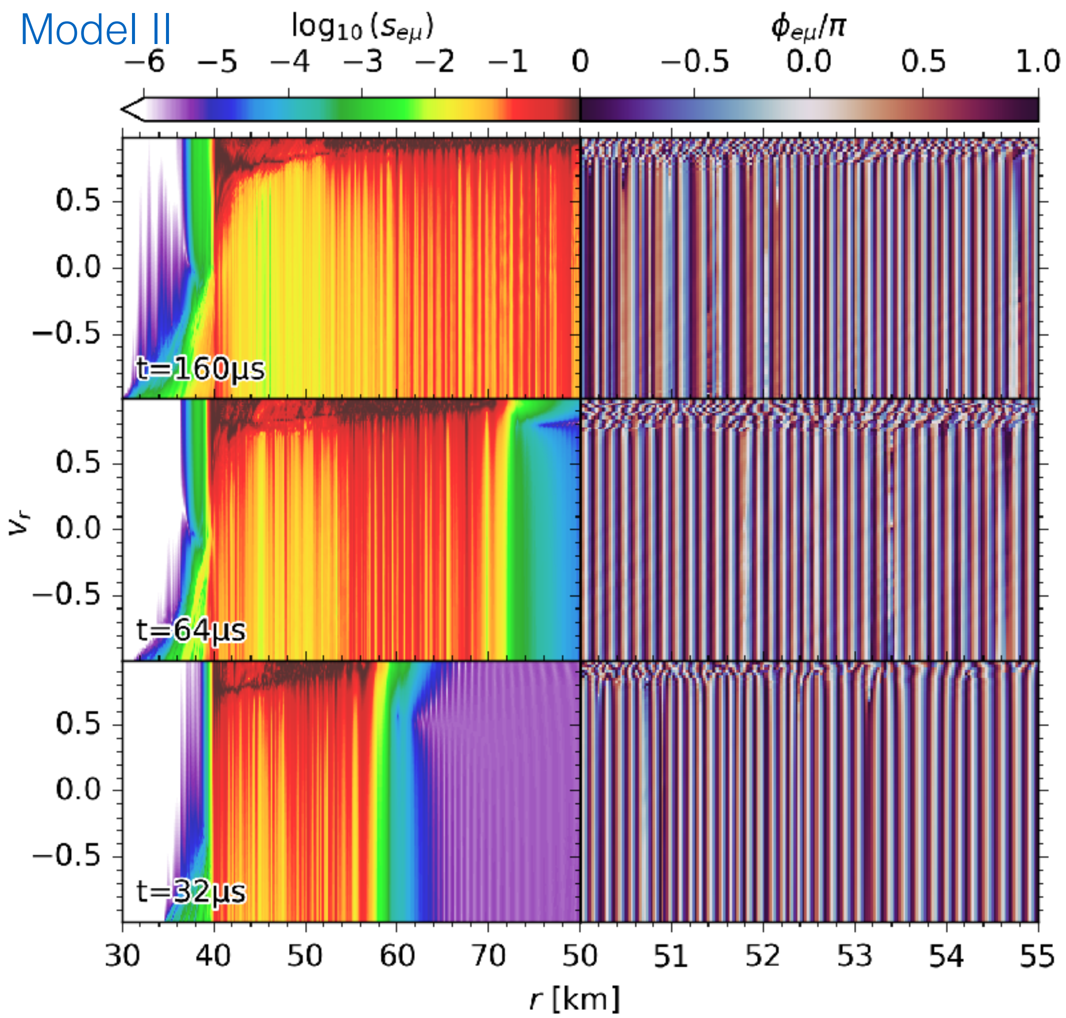


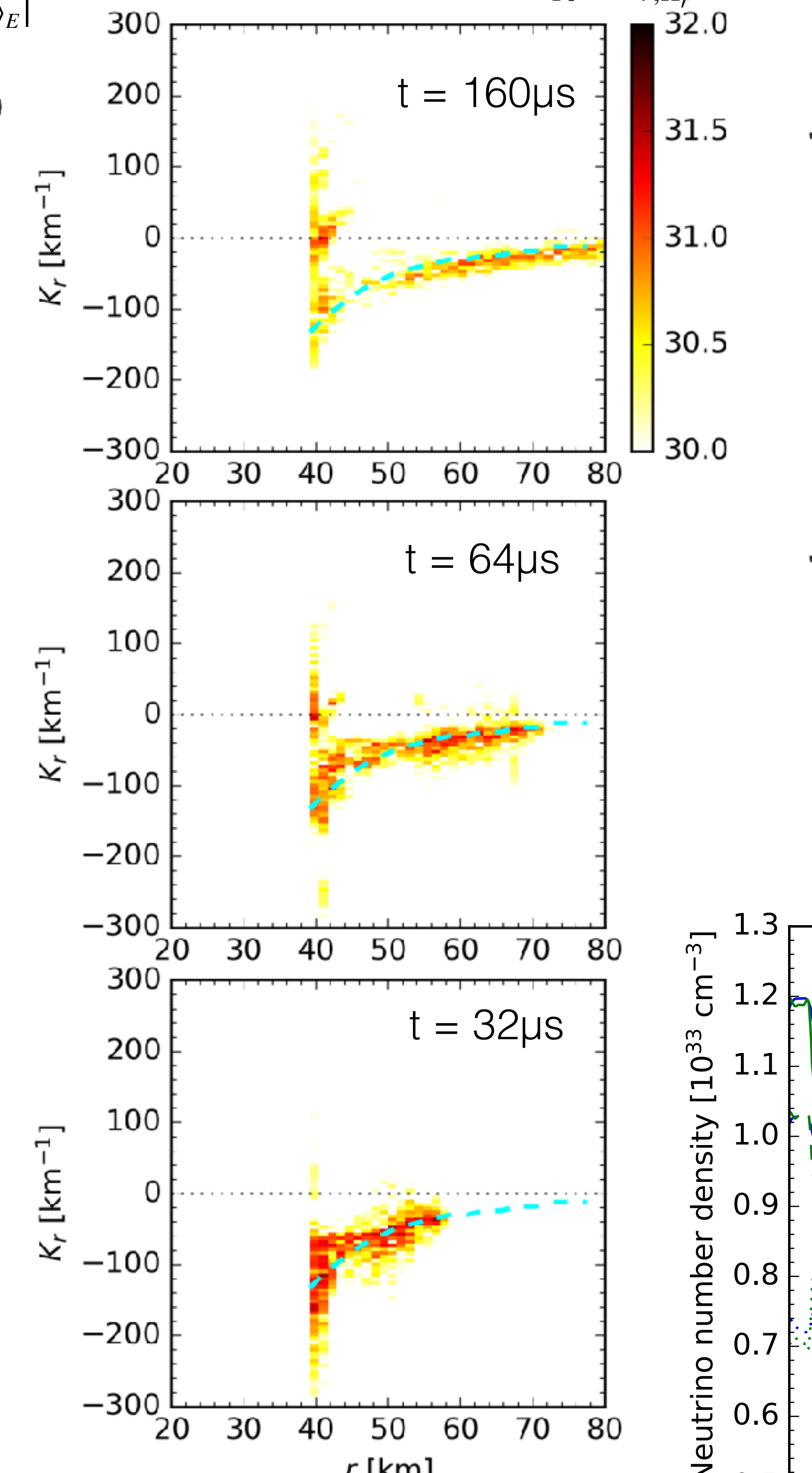


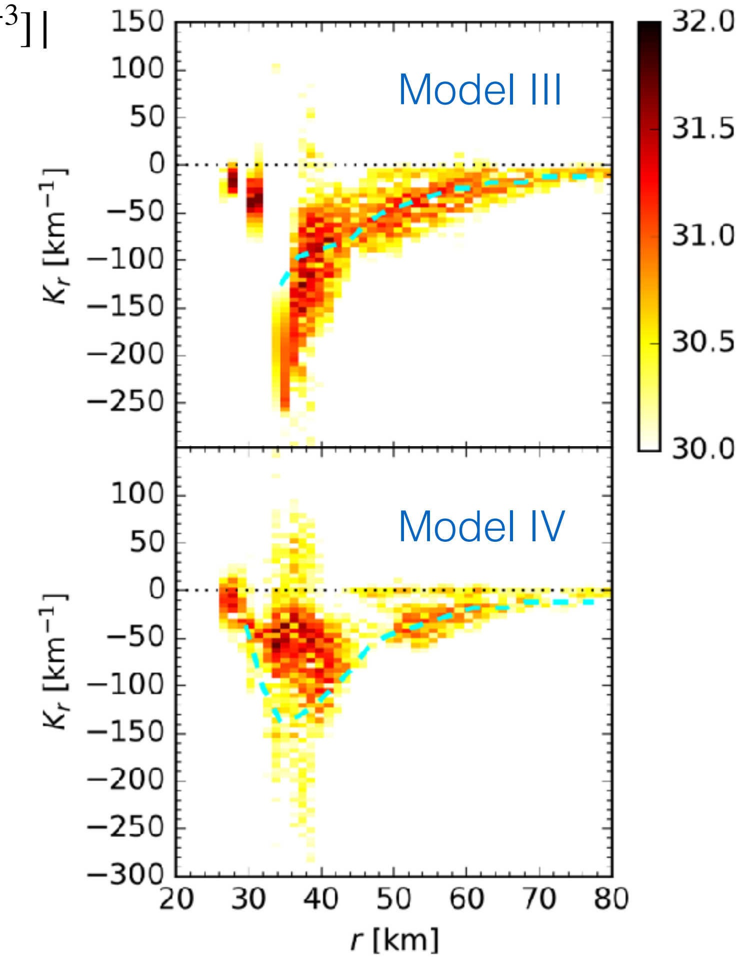
[ZX, M.-R. Wu, M. George, et al., PRD 109, 123008 (2024)]

Flavor waves in small scales

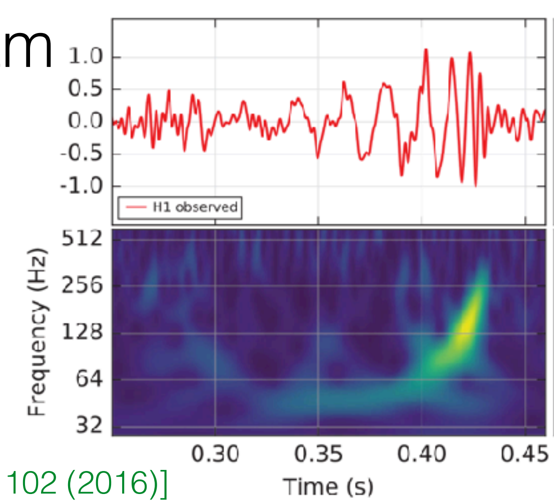
$\langle\varrho\rangle_E = \int dE\,\varrho(E, v_r)$, $\langle\varrho\rangle_A = \int dv_r\,\varrho(E, v_r)$, $s_{e\mu} = \frac{|\langle\varrho_{e\mu}\rangle_E|}{|\langle\varrho_{ee}\rangle_E - \langle\varrho_{\mu\mu}\rangle_E|}$



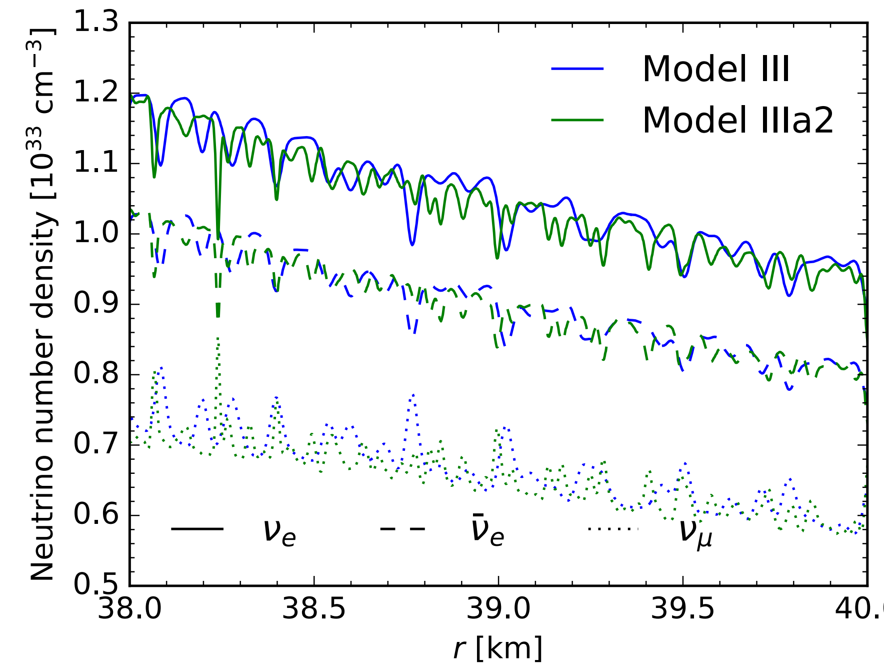




Spectrogram analysis:



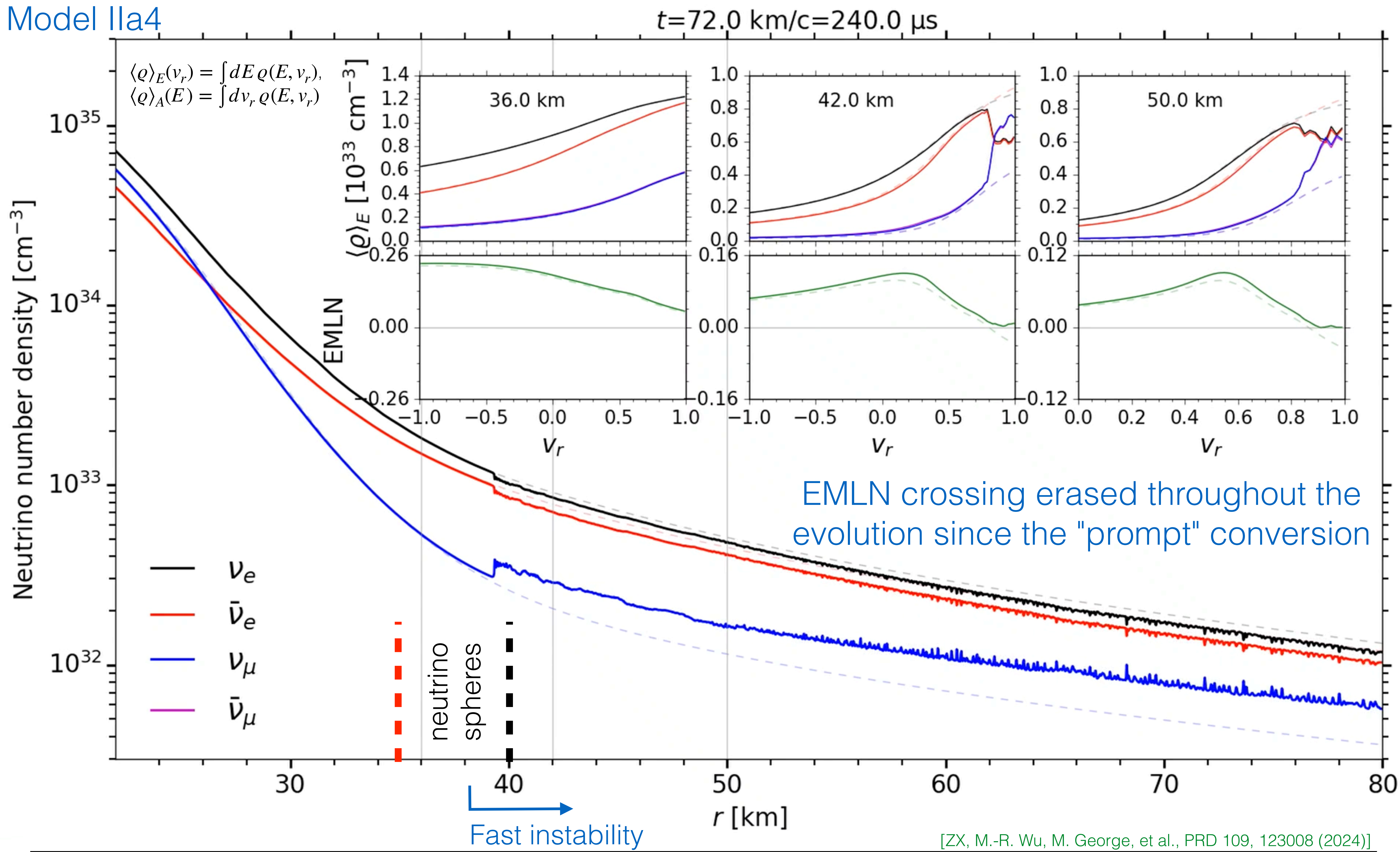
[LIGO, PRL 116, 061102 (2016)]



[ZX, M.-R. Wu, M. George, et al., PRD 109, 123008 (2024)]

Global simulation: instability beyond neutrino-sphere

Model IIa4



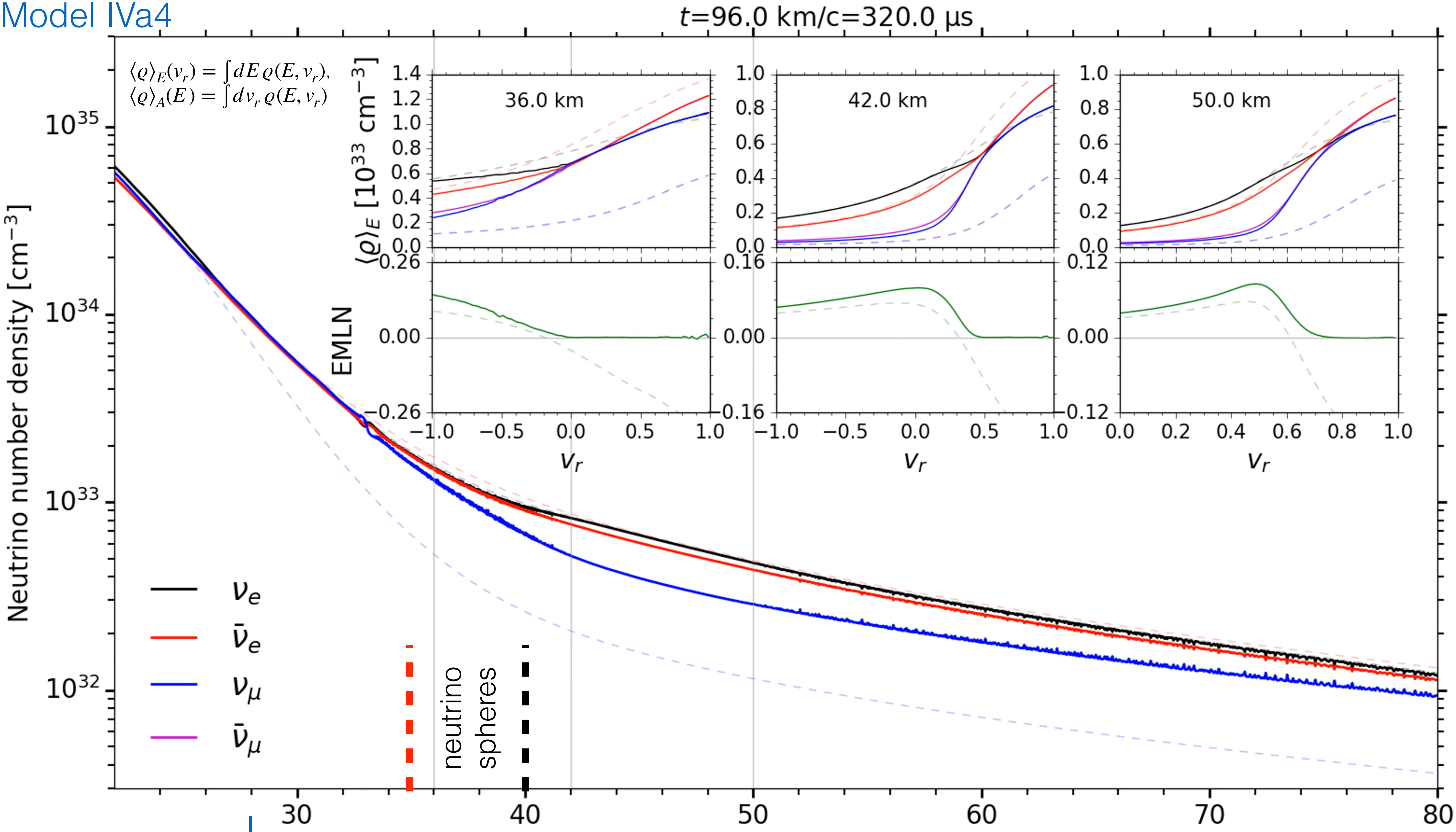
EMLN crossing erased throughout the evolution since the "prompt" conversion

Fast instability

[ZX, M.-R. Wu, M. George, et al., PRD 109, 123008 (2024)]

Global simulation: instability from inside neutrino-sphere

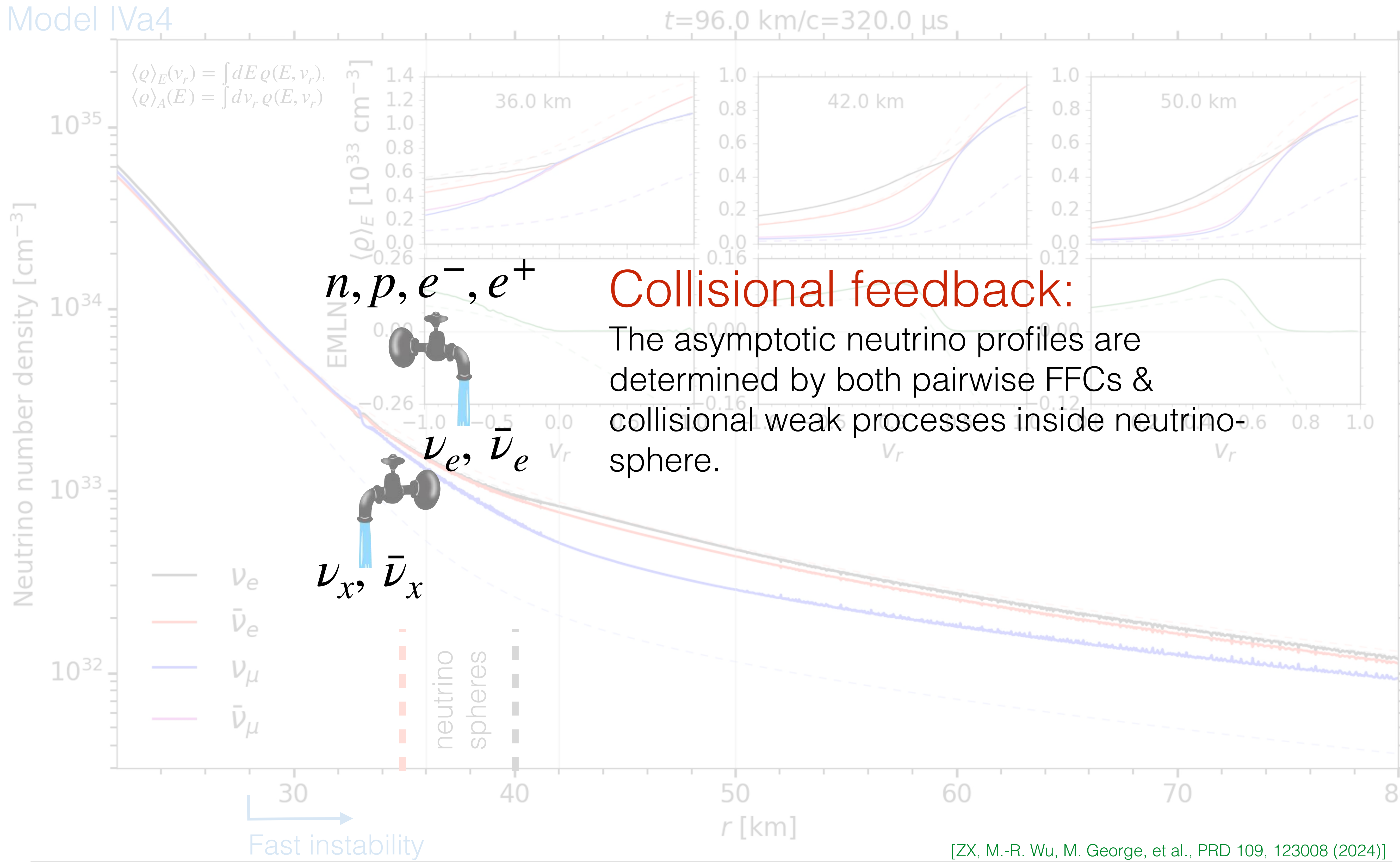
Model IVa4



Fast instability

[ZX, M.-R. Wu, M. George, et al., PRD 109, 123008 (2024)]

Global simulation: instability from inside neutrino-sphere

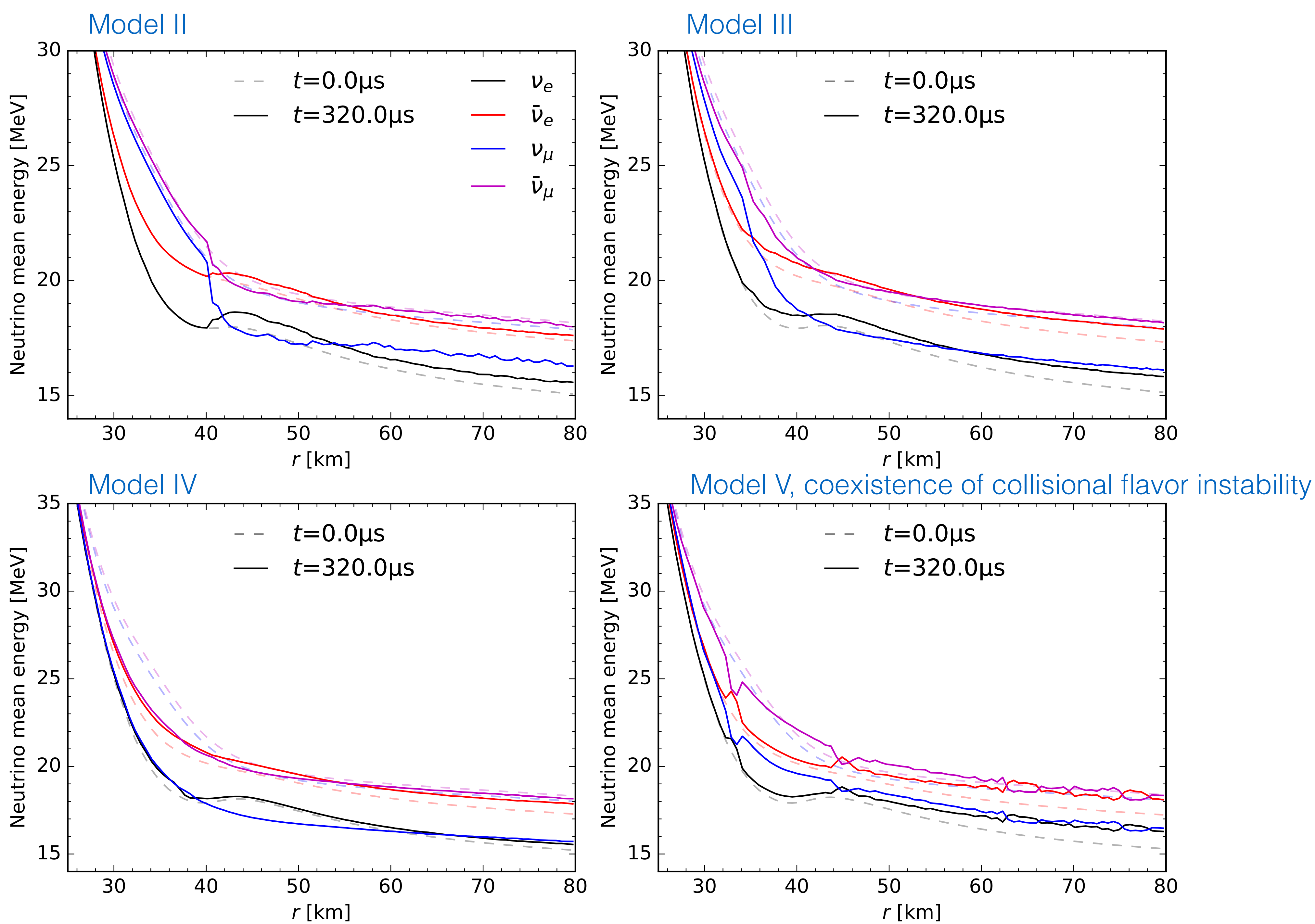


Collisional feedback:

The asymptotic neutrino profiles are determined by both pairwise FFCs & collisional weak processes inside neutrino-sphere.

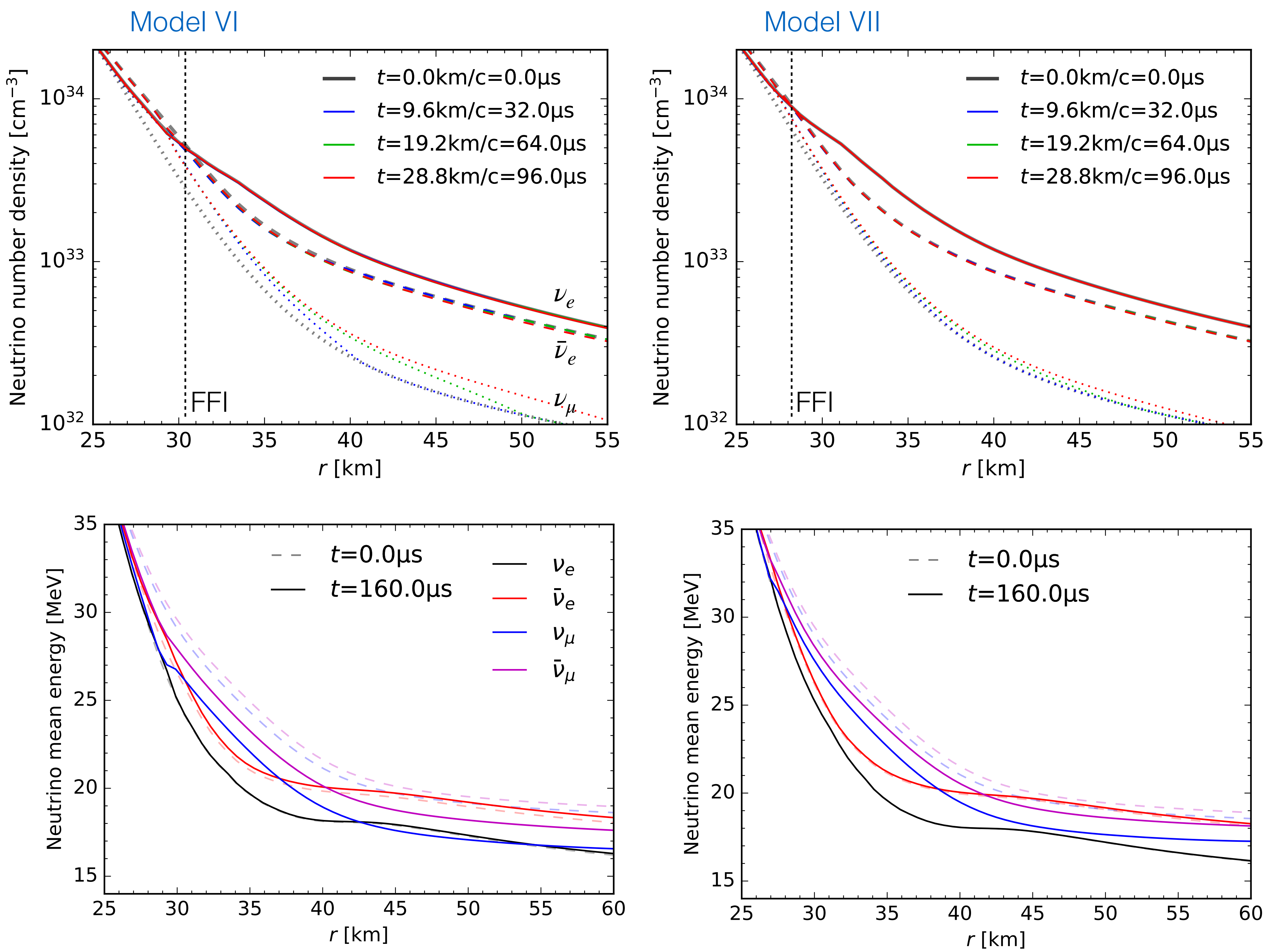
[ZX, M.-R. Wu, M. George, et al., PRD 109, 123008 (2024)]

Neutrino mean-energy profiles



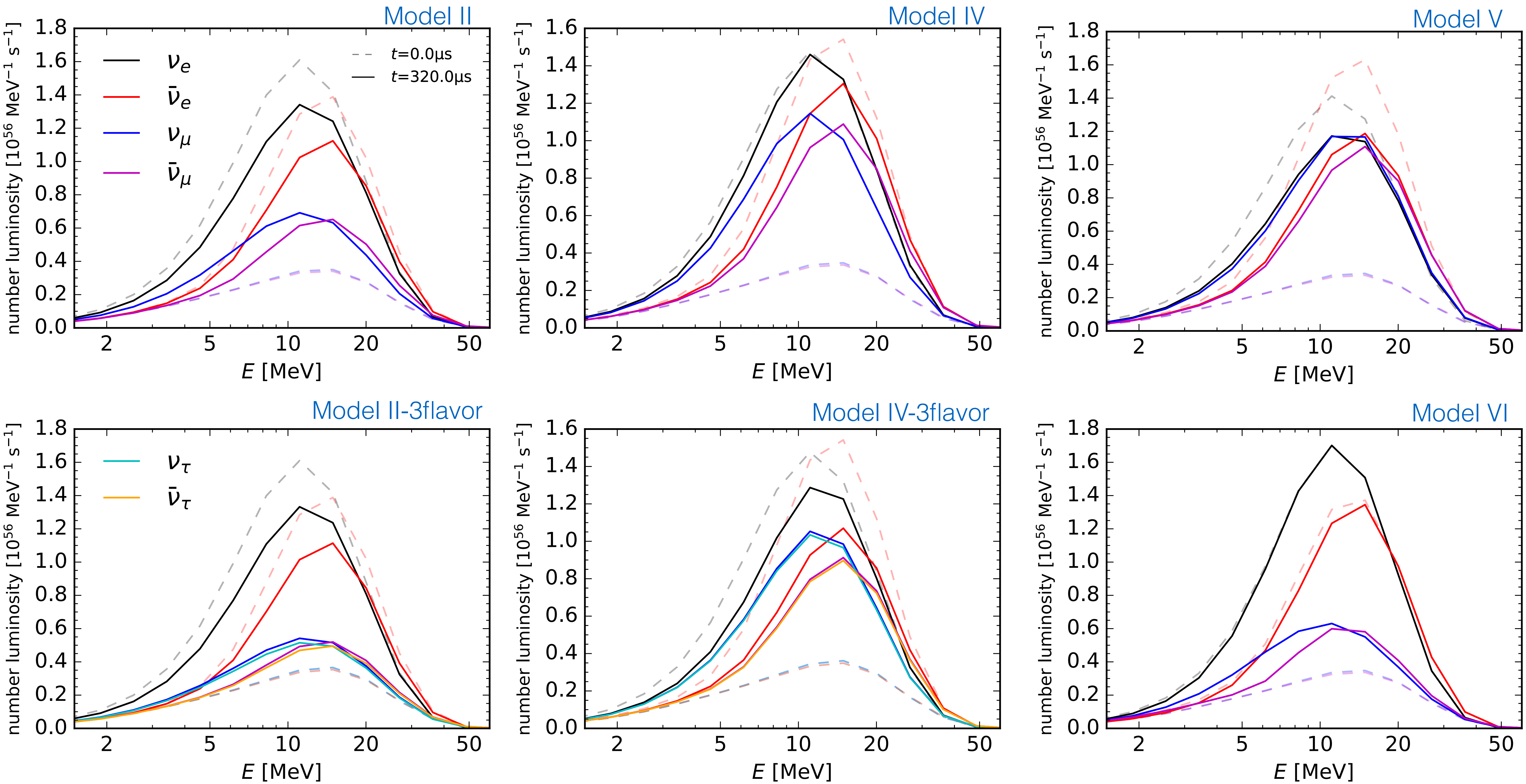
[ZX, M.-R. Wu, M. George, et al., PRD 109, 123008 (2024)]

Global simulation: instability only inside neutrino-sphere



[ZX, M.-R. Wu, M. George, et al., PRD 109, 123008 (2024)]

Free-streaming energy spectra



co-determined by both collisions and pairwise FFCs

[ZX, M.-R. Wu, M. George, et al., PRD 109, 123008 (2024)]

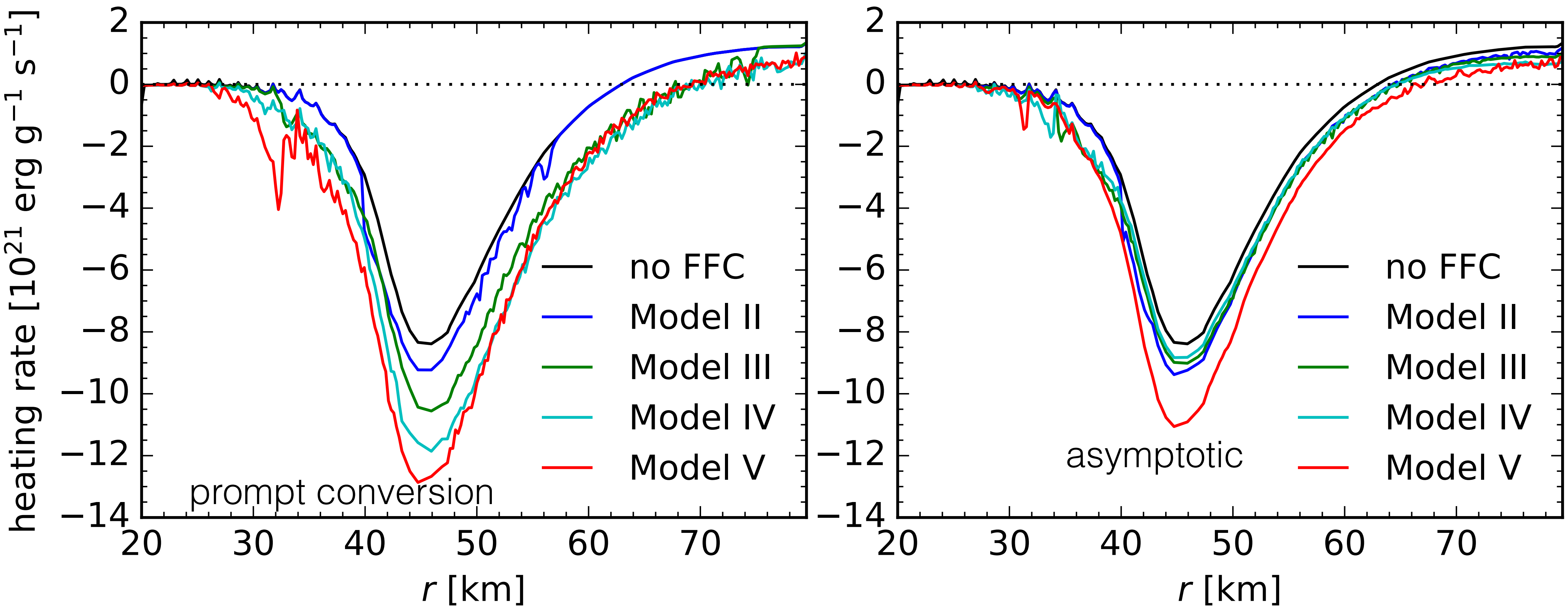
Effects of FFCs in neutrino heating

increase cooling & reduce heating

$\nu_e + n \leftrightarrows p + e^-$

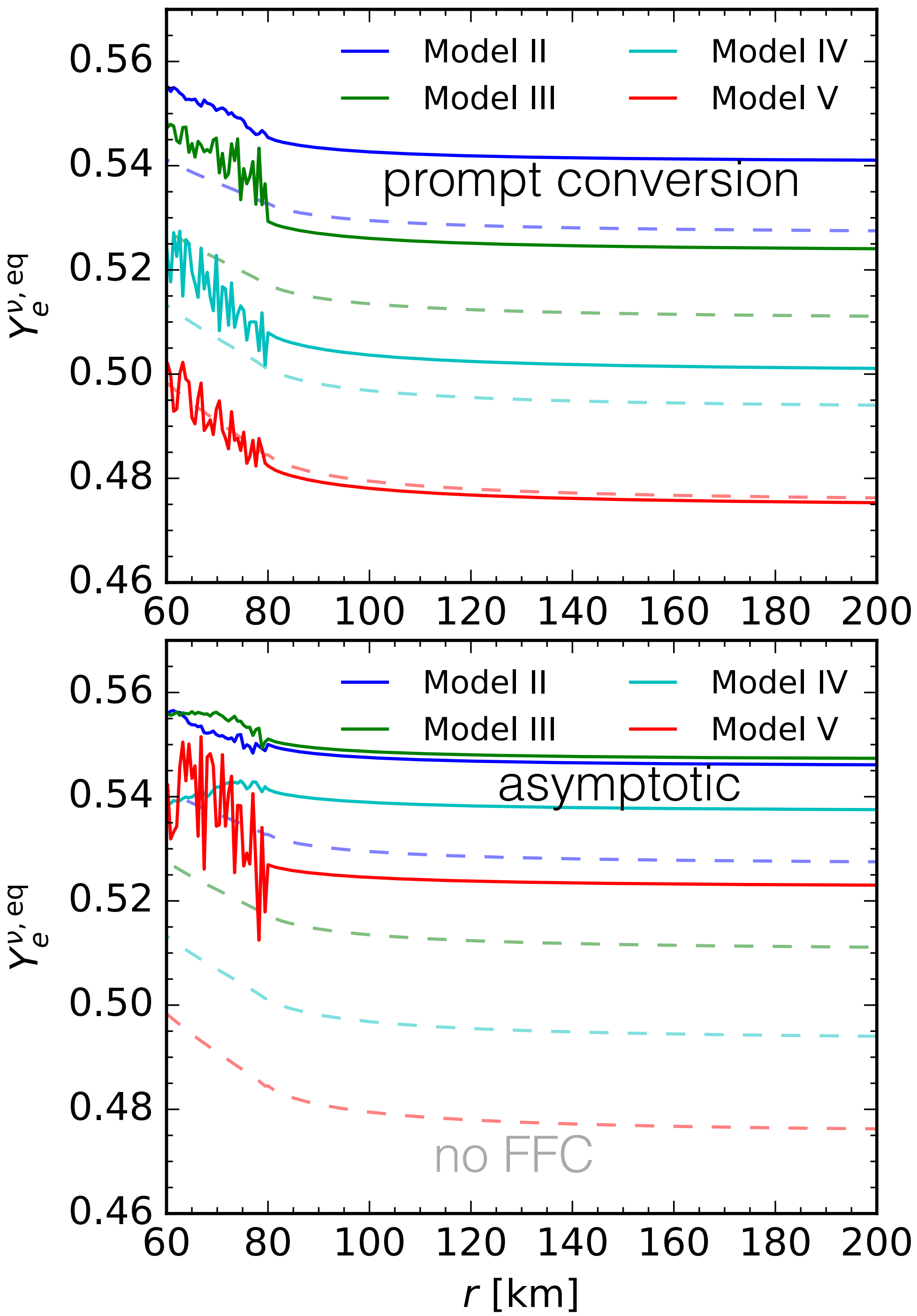
$\bar{\nu}_e + p \leftrightarrows n + e^+$

[see also H. Nagakura, PRL 130, 211401 (2023);
J. Ehring, S. Abbar, H.-T. Janka et al, PRL, (2023)]



[ZX, M.-R. Wu, M. George, et al., PRD 109, 123008 (2024)]

Effects of FFCs in nucleosynthesis

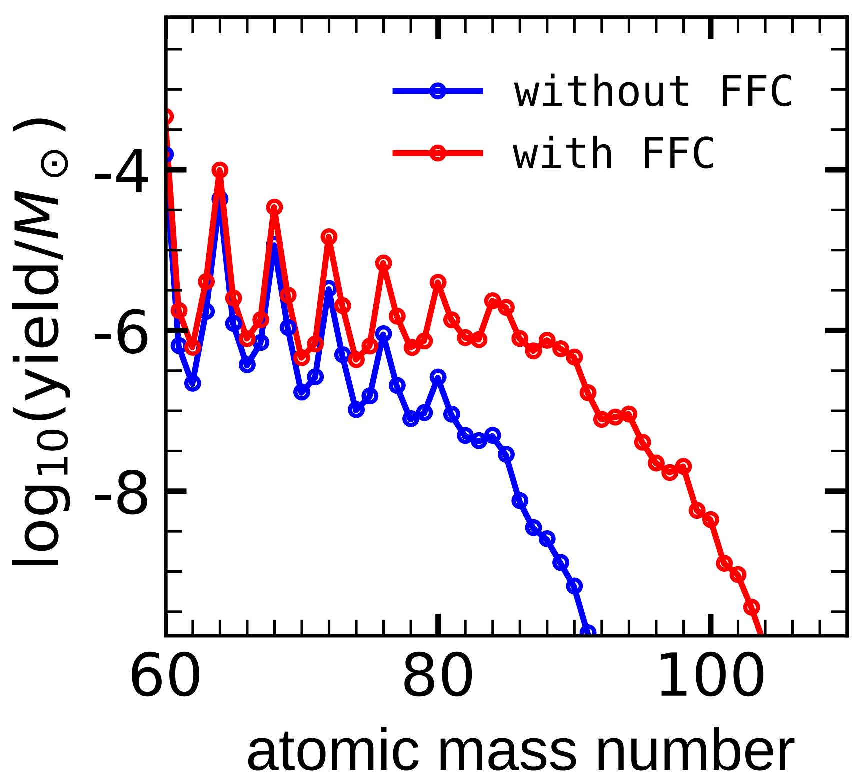


$$\nu_e + n \leftrightarrows p + e^-$$

$$\bar{\nu}_e + p \leftrightarrows n + e^+$$

$$Y_e^{\nu,\mathrm{eq}} \sim \left(1 + \frac{L_{\bar{\nu}_e}}{L_{\nu_e}} \frac{\langle E_{\nu_e} \rangle}{\langle E_{\bar{\nu}_e} \rangle}\right)^{-1}$$

enhance proton-rich nucleosynthesis

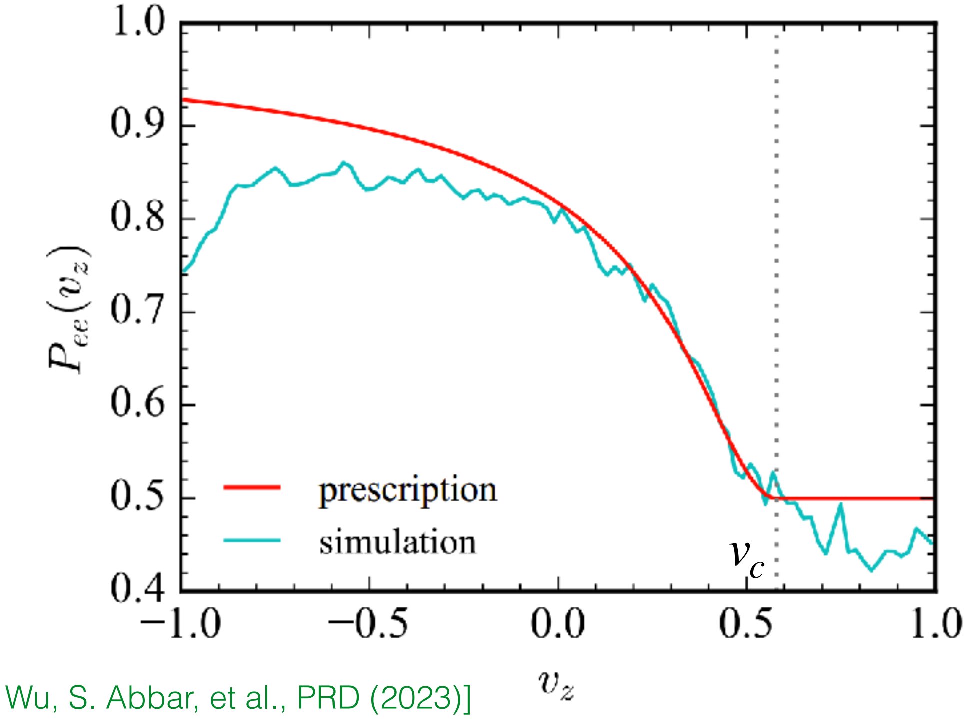


[ZX, A. Sieverding, M. Sen, Y.-Z. Qian, APJ (2020)]

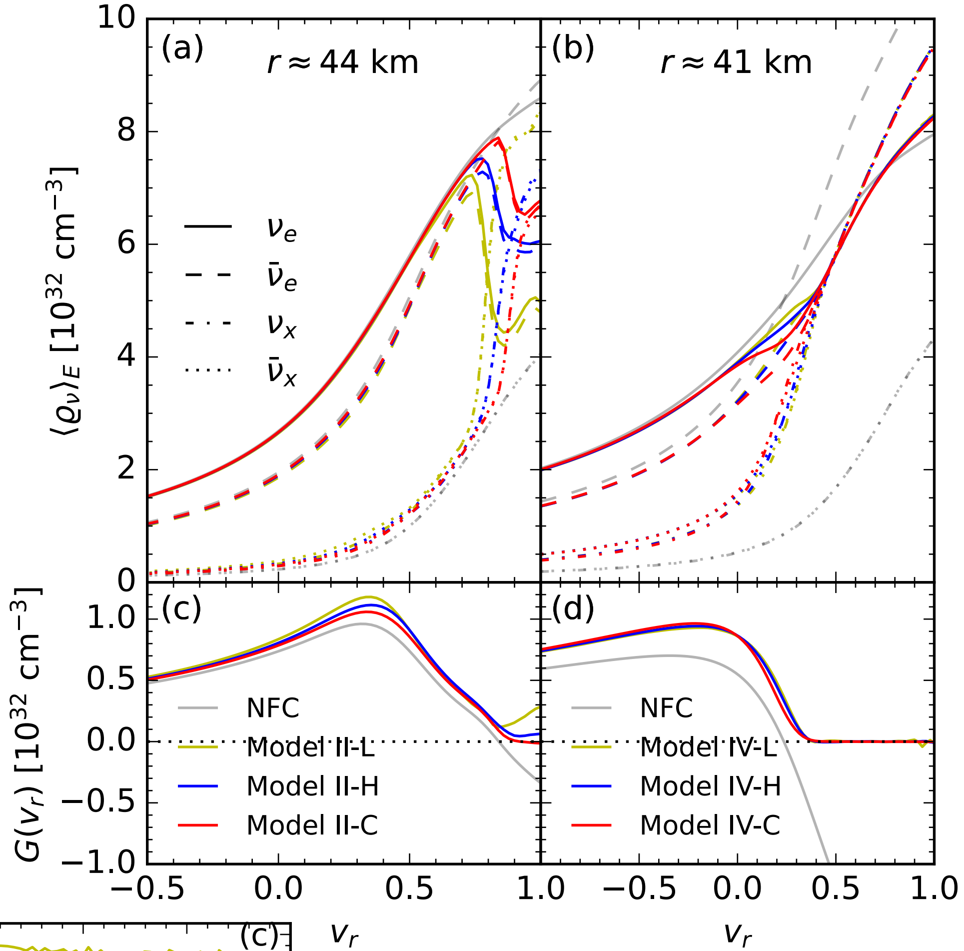
[ZX, M.-R. Wu, M. George, et al., PRD 109, 123008 (2024)]

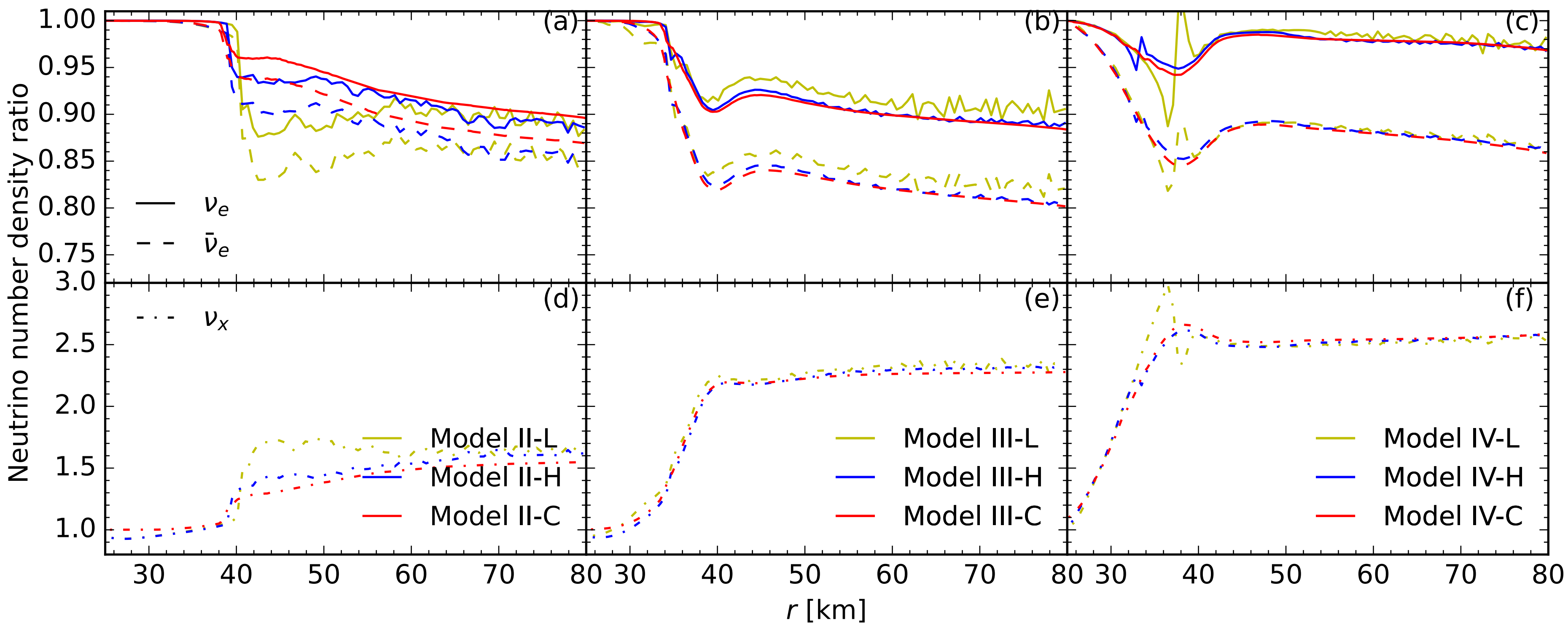
Analytical prescription

$P_{ee} = 1 - \frac{1}{2}h(|v_z - v_c|/a)$ with $h(x) = (x^2 + 1)^{-1/2}$



[ZX, M.-R. Wu, S. Abbar, et al., PRD (2023)]





[ZX, M.-R. Wu, et al., arXiv:2403.17269, submitted to PRL]

Prescription excellently captures the asymptotic solution from vQKE.

Summary & Outlook

- Local FFC simulation in a periodic 1D box
  - Flavor wave fluctuates in small scales; asymptotic state at the coarse-grained level
  - Complete flavor equilibration occurs for $\alpha \approx 1$; angular dependent flavor equilibration otherwise
- Global FFC simulation in spherically symmetric CCSN snapshots
  - Flavor wave fluctuates in small scales; asymptotic state at the coarse-grained level
  - EMLN crossing erased
  - Collisional feedback: asymptotic neutrino profiles are co-determined by both collisions & pairwise FFCs when FFIs are inside the neutrinosphere.
  - more production of neutrinos in total amount
  - can change the order of neutrino fluxes among species
  - affect the net neutrino heating rate & equilibrium Y_e
  - Implication of prescriptions show excellent agreement with the vQKE solution.
- Outlook:
  - spherical symmetry? time-dependent matter profiles? feedback on matter? muon creations? ...?