

Some recent developments of fast neutrino flavor conversion

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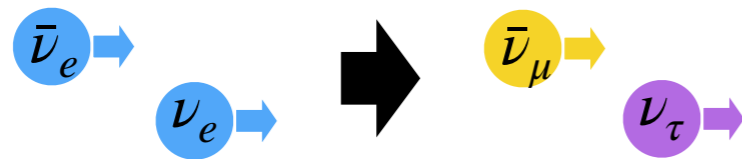
"Dark Matter and Neutrinos Workshop", Institut Henri Poincaré, Paris, France
May 14, 2025



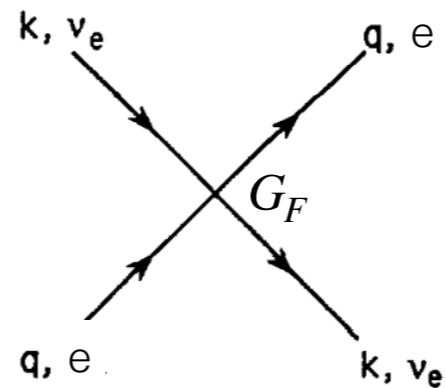
Neutrino oscillations & Fast flavor conversion (FFC)

Flavor mixing in vacuum

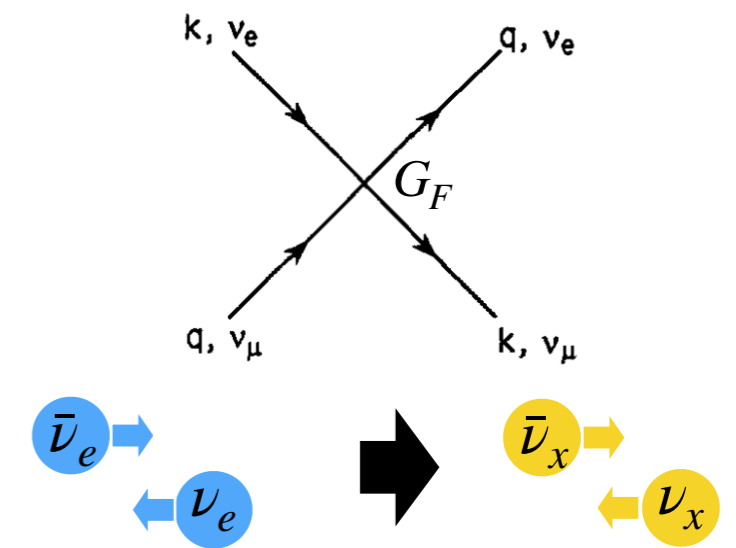
flavor eigenstate $\nu_\alpha = U_{\alpha l} \nu_l$ mass eigenstate



Mikheyev–Smirnov–Wolfenstein (MSW) matter effect



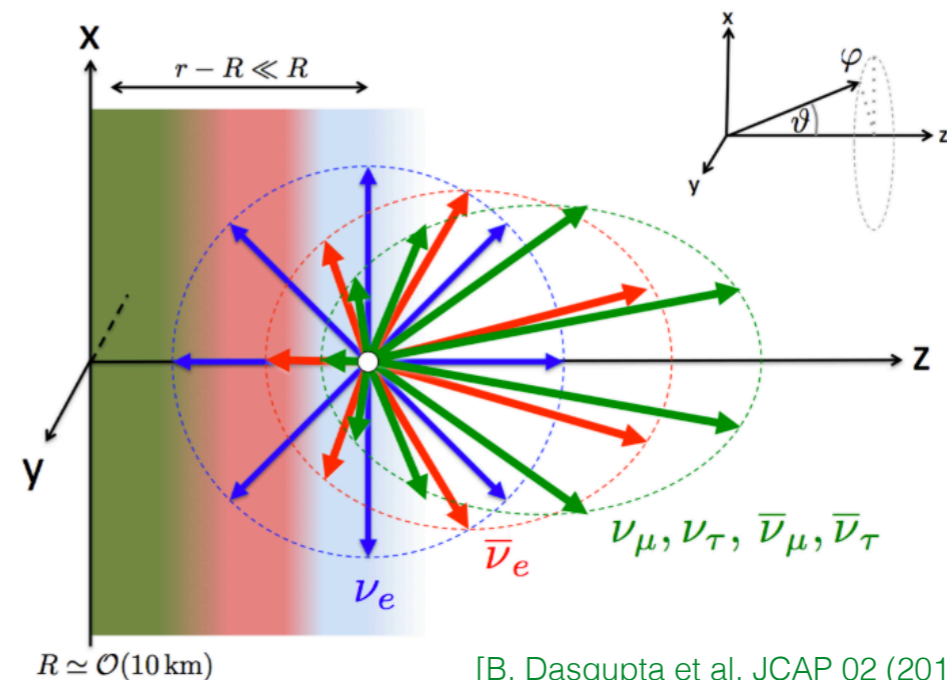
Neutrino-neutrino coherent forward scattering



The flavor conversion can be very **fast** in sub-nanosecond and centimeter, when **crossing** exists in the angular distributions of neutrino electron lepton number (ELN)

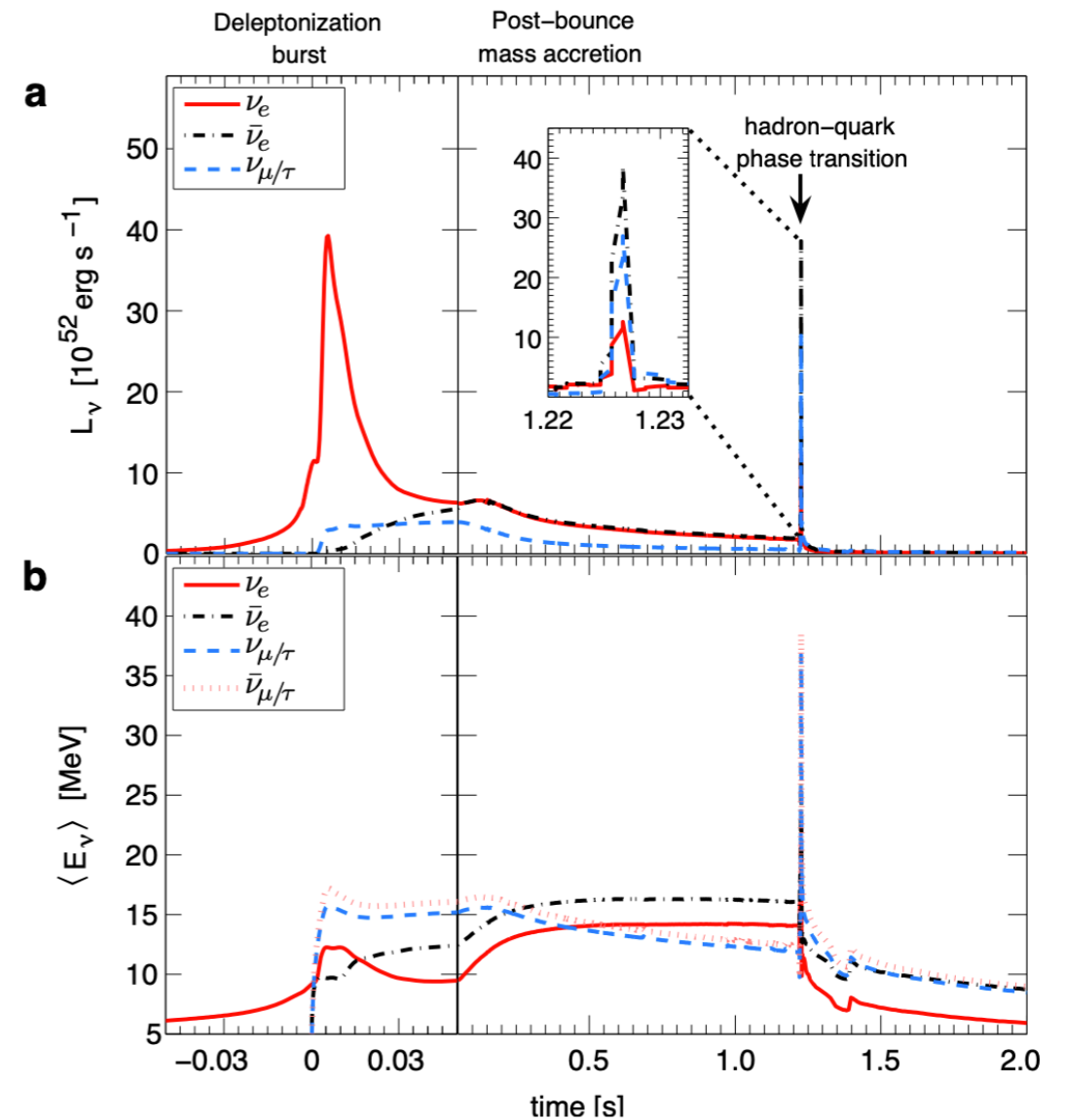
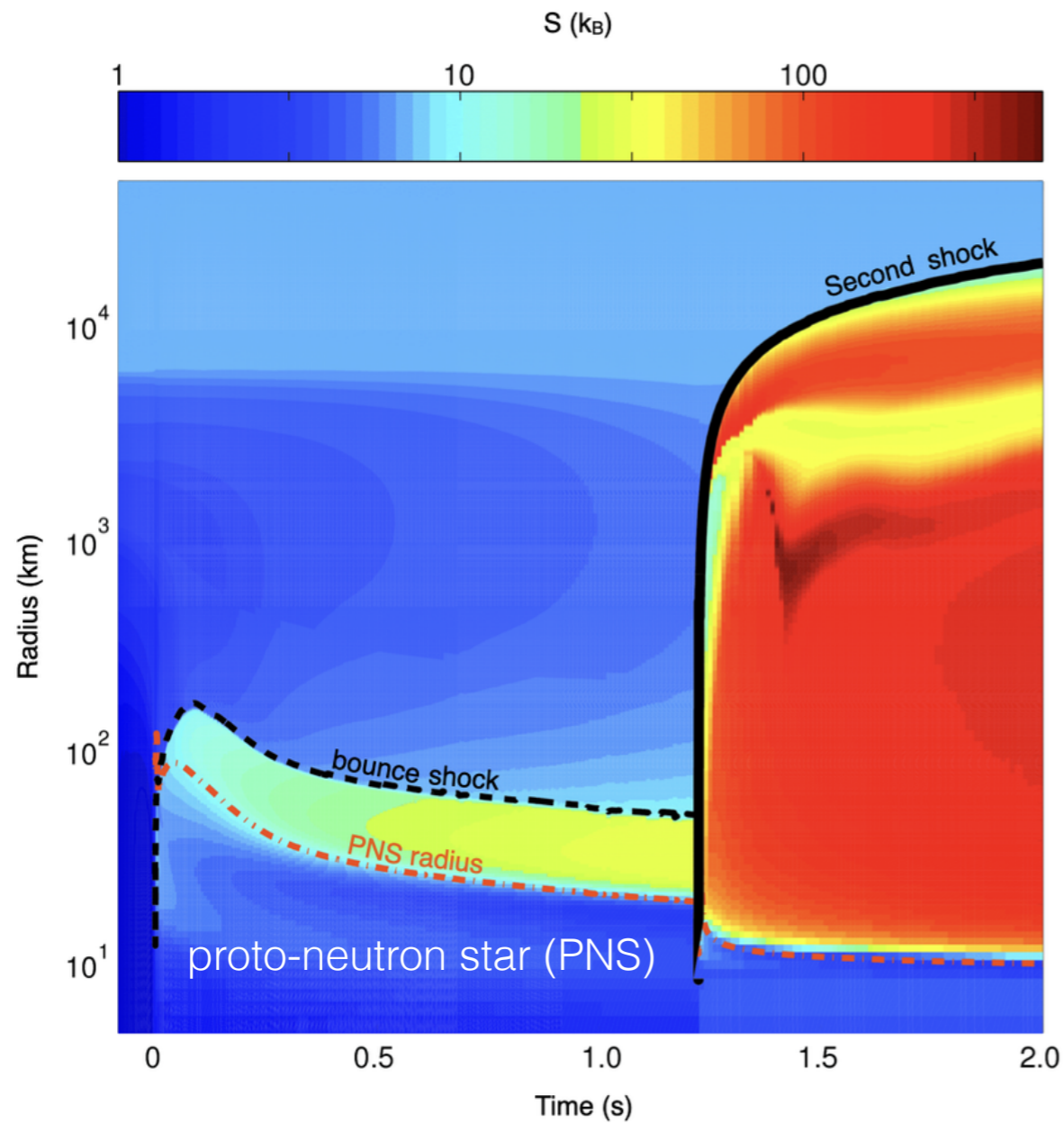
$$f_{\nu_e}(\mathbf{v}) - f_{\bar{\nu}_e}(\mathbf{v}) - f_{\nu_x}(\mathbf{v}) + f_{\bar{\nu}_x}(\mathbf{v})$$

[Sawyer, PRL 116, 081101 (2016); Izaguirre, Raffelt, Tamborra, PRL 118, 021101 (2017); ... T. Morinaga, PRD 105, L101301 (2022); ...]



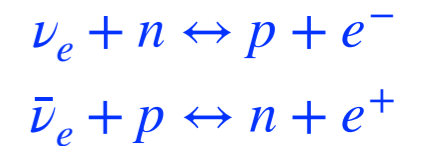
[B. Dasgupta et al, JCAP 02 (2017) 019]

QCD phase-transition supernovae

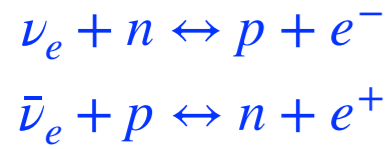


[Fischer, Bastian, et al, Nature Astron. 2, 980 (2018)]

- Neutrino signal is dominated by $\bar{\nu}_e$ in a galactic event.
- Possible site for rapid neutron capture (r process).

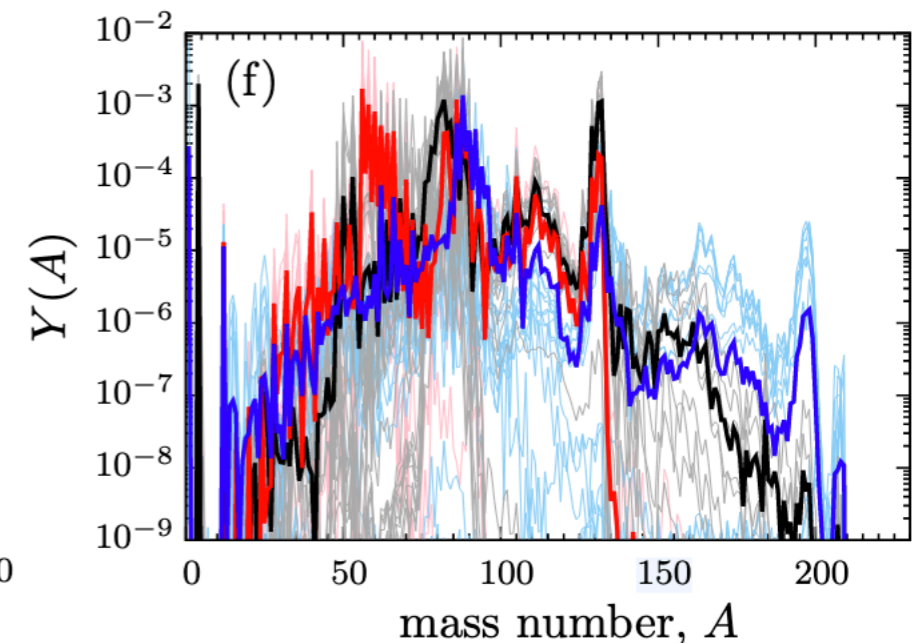
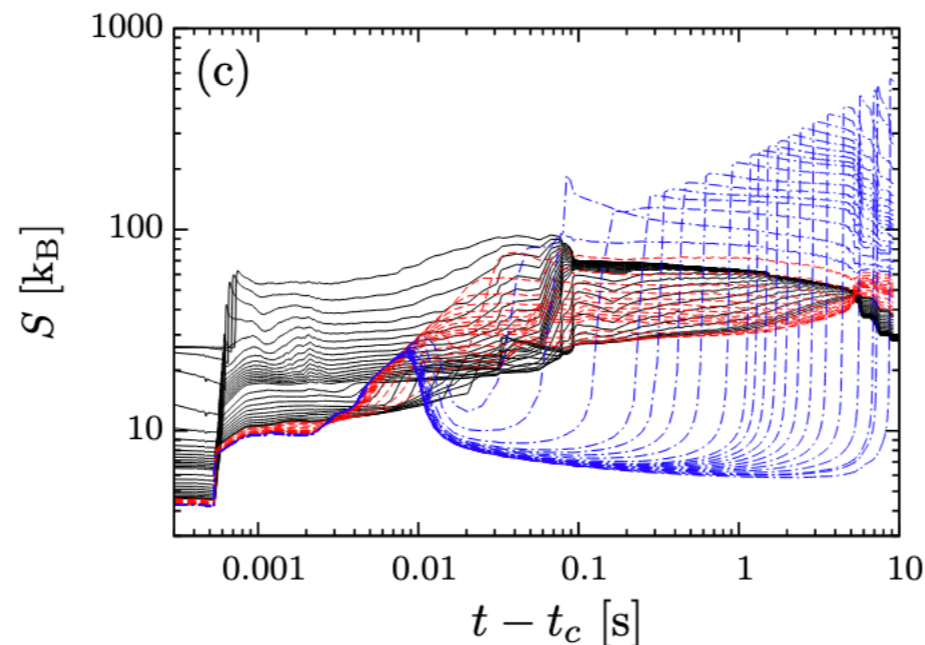
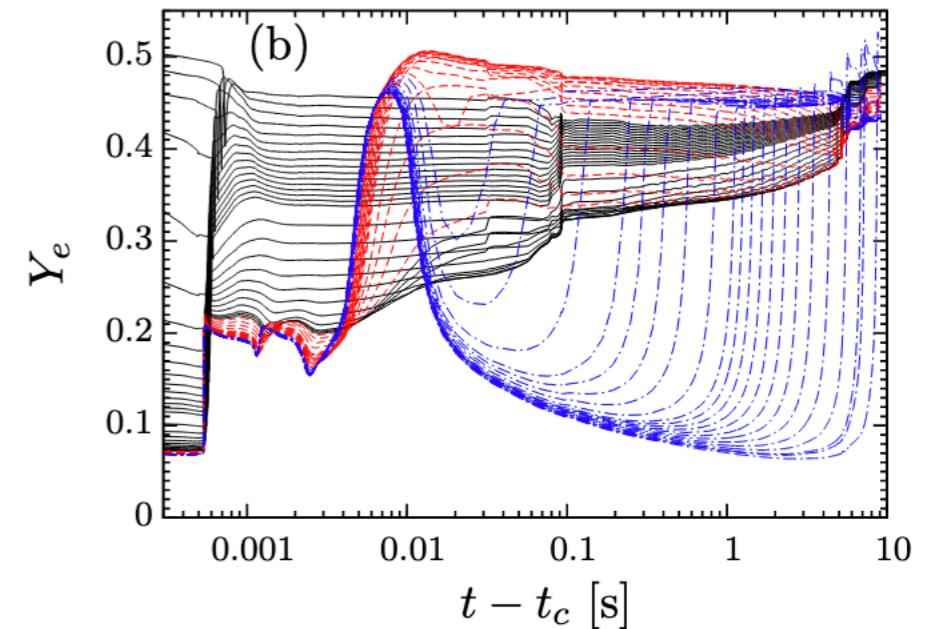
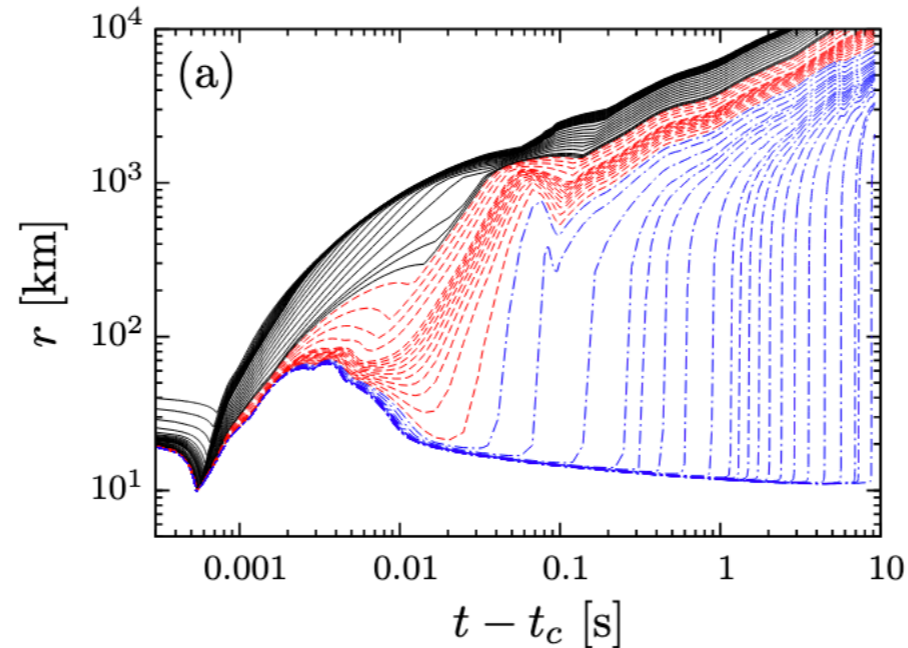


R-process in QCD supernova



electron fraction, $Y_e = \frac{Y_p}{Y_p + Y_n}$

- Direct ejecta: low/moderate entropy, low Y_e
- Intermediate ejecta: low entropy, high Y_e
- Neutrino-driven wind: high entropy, high Y_e

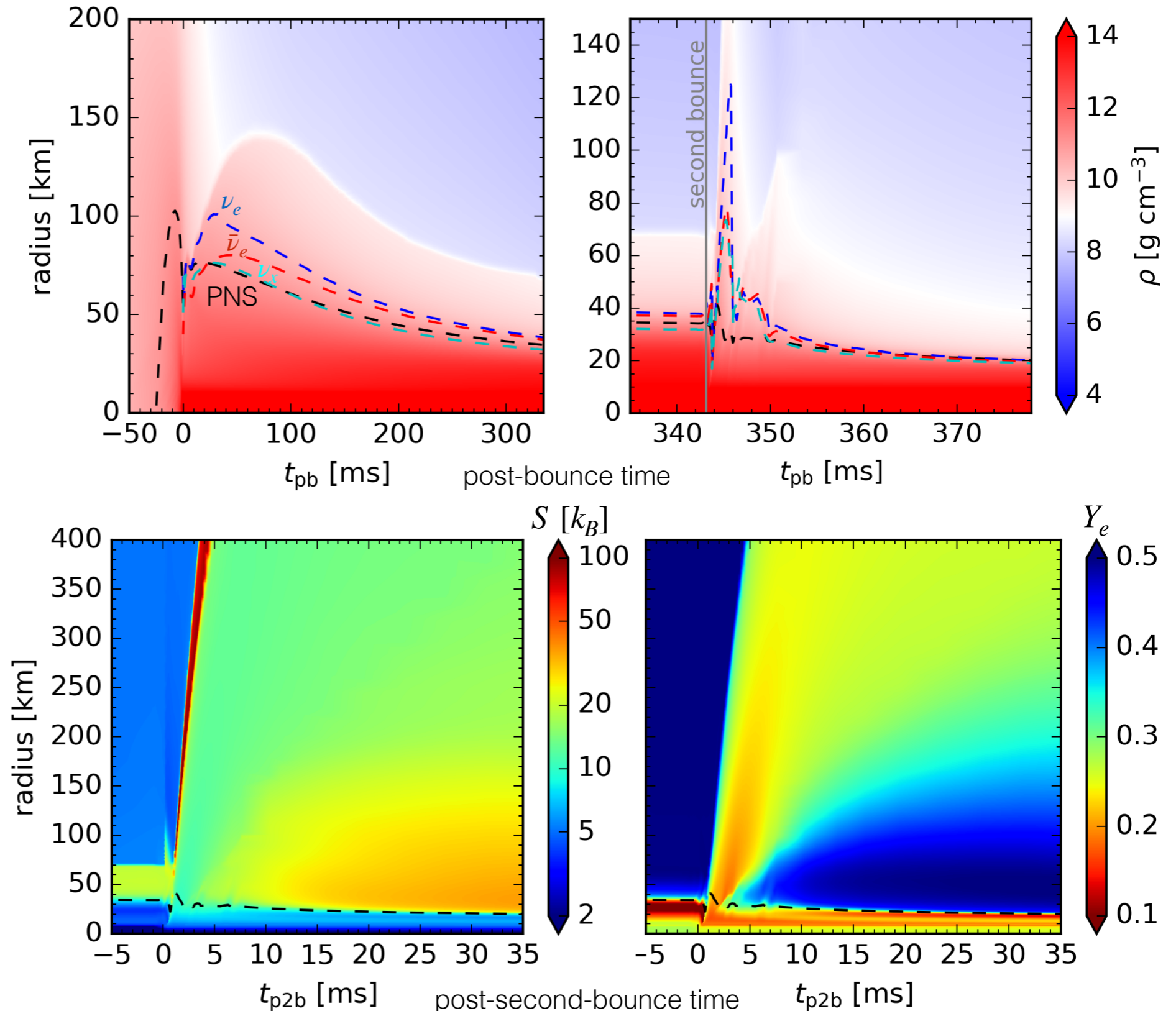


[Fischer, Wu, et al, APJ 894, 9 (2020)]

QCD phase-transition supernovae

- $25M_{\odot}$ progenitor
- Solar metallicity
- Hadronic EOS: DD2
- Quark EOS: relativistic density functional RDF-1.9 model
- AGILE-BOLTZTRAN

[Largani, Fischer, Bastian, APJ 964, 143 (2024)]



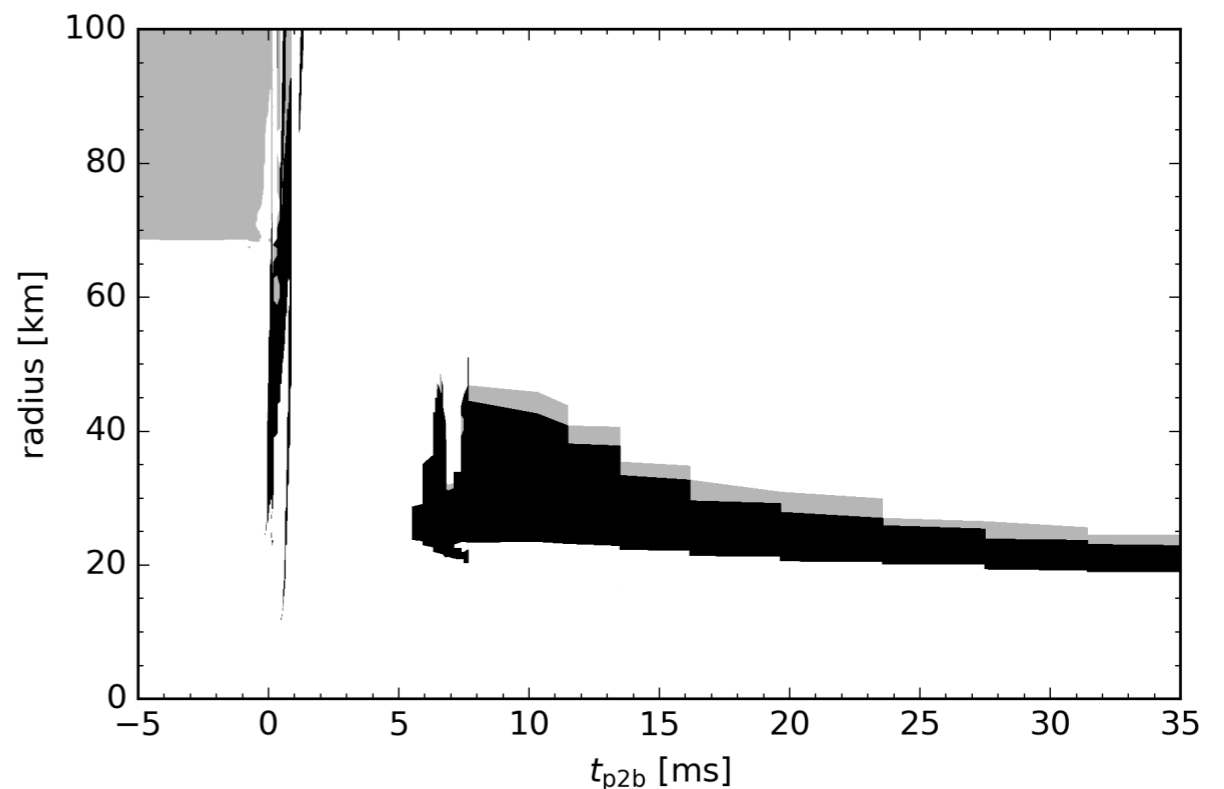
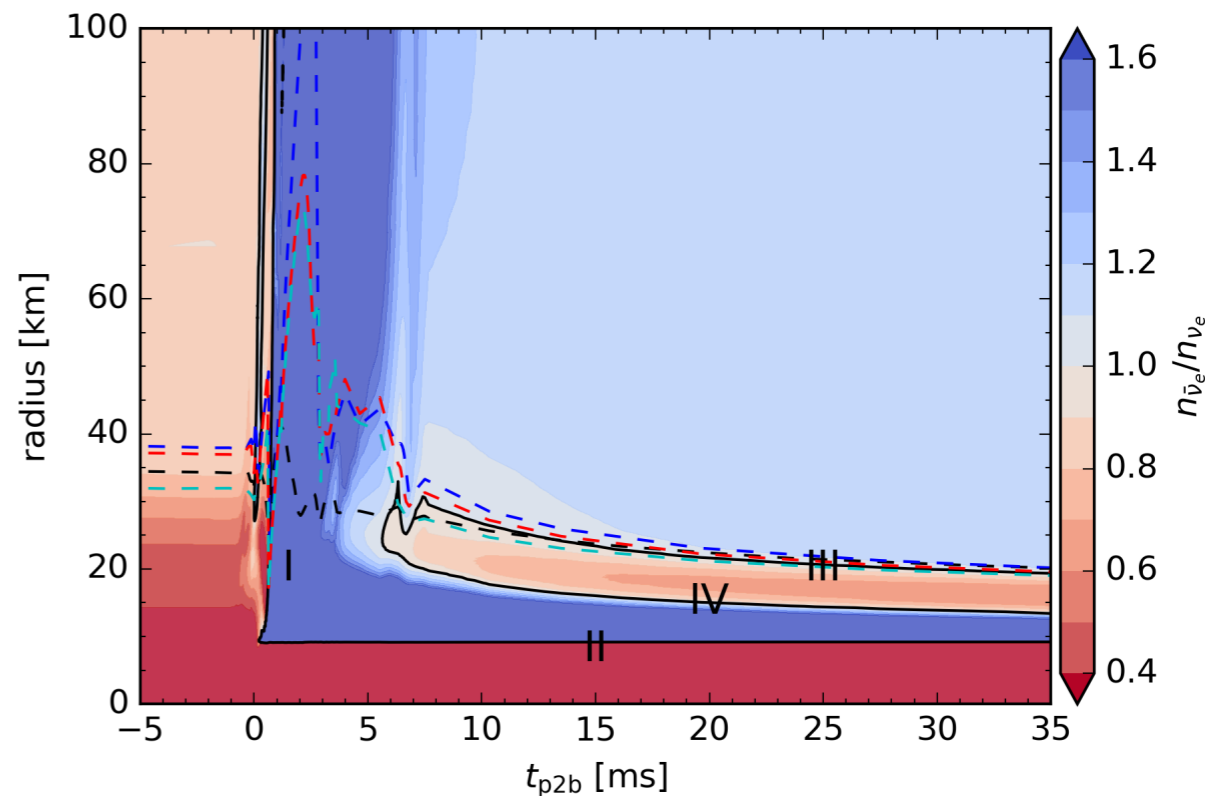
[ZX, Wu, et al., arXiv:2505.19592 (2025)]

Occurrence of fast flavor conversion



Two major phases:

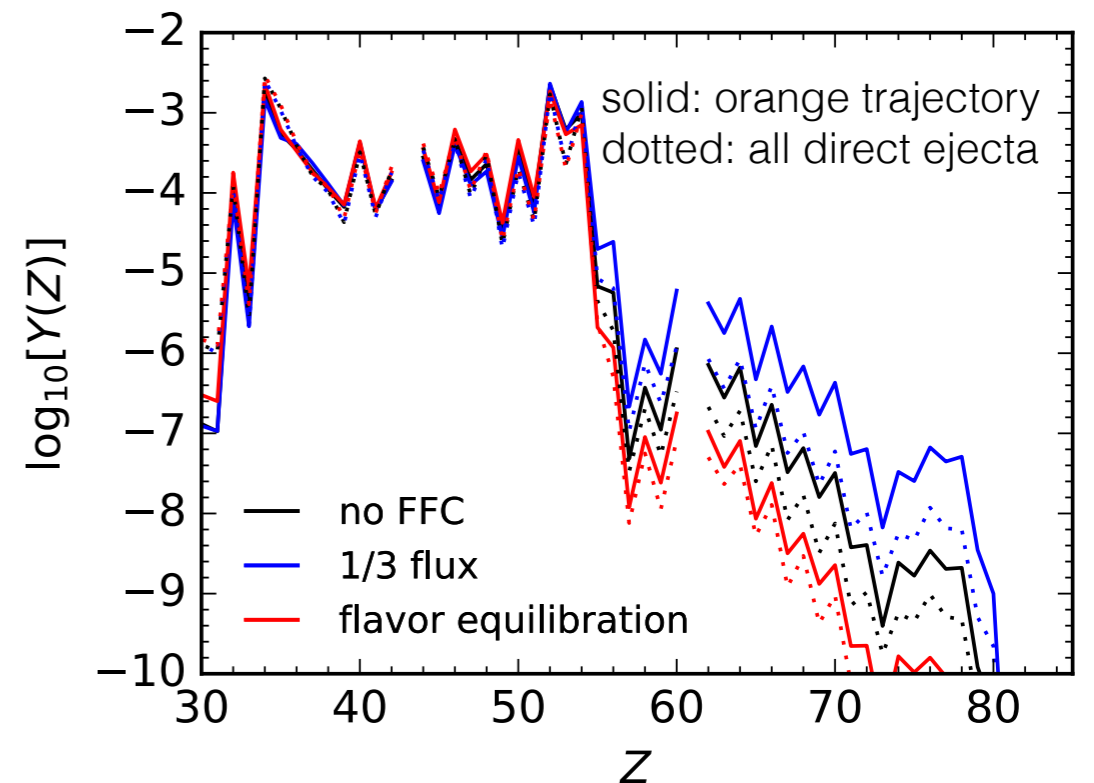
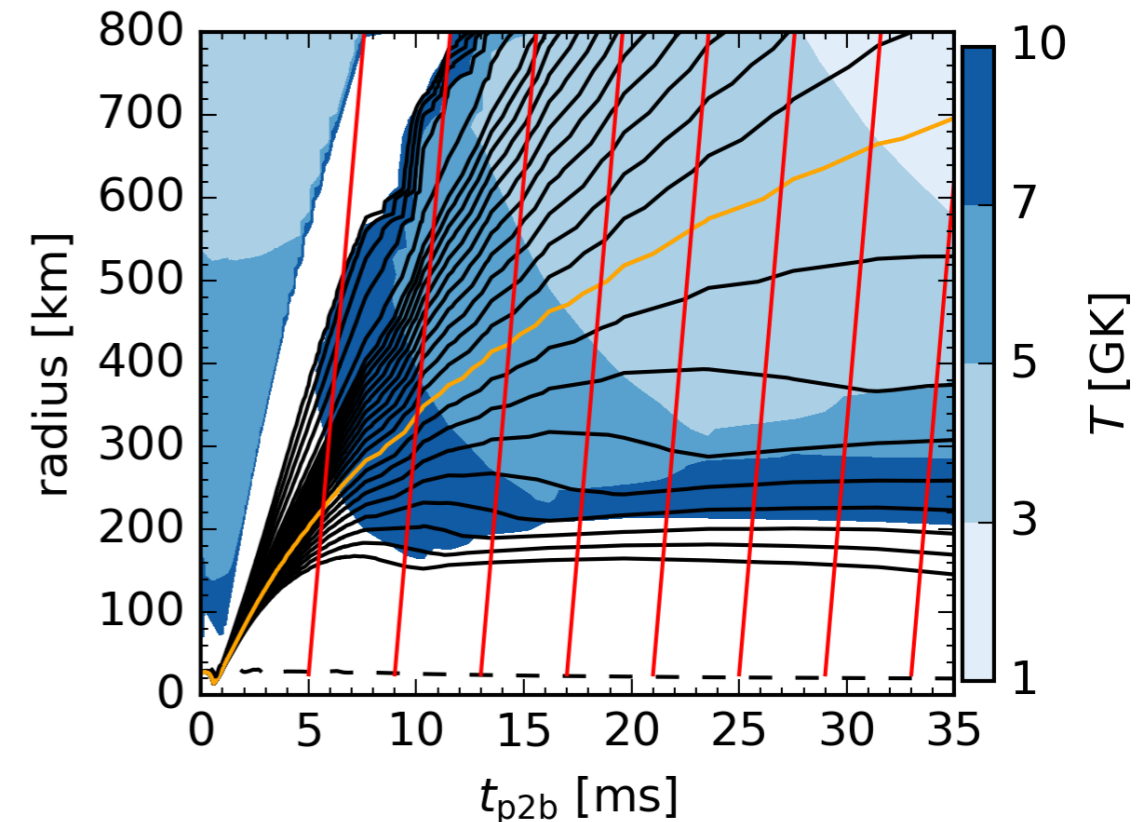
- along with the rapidly propagating shock
 - transition to $\bar{\nu}_e$ -dominated condition due to the protonization
- near the proto-neutron star surface after a few milliseconds
 - fast cooling on this shell to build up electron degeneracy again



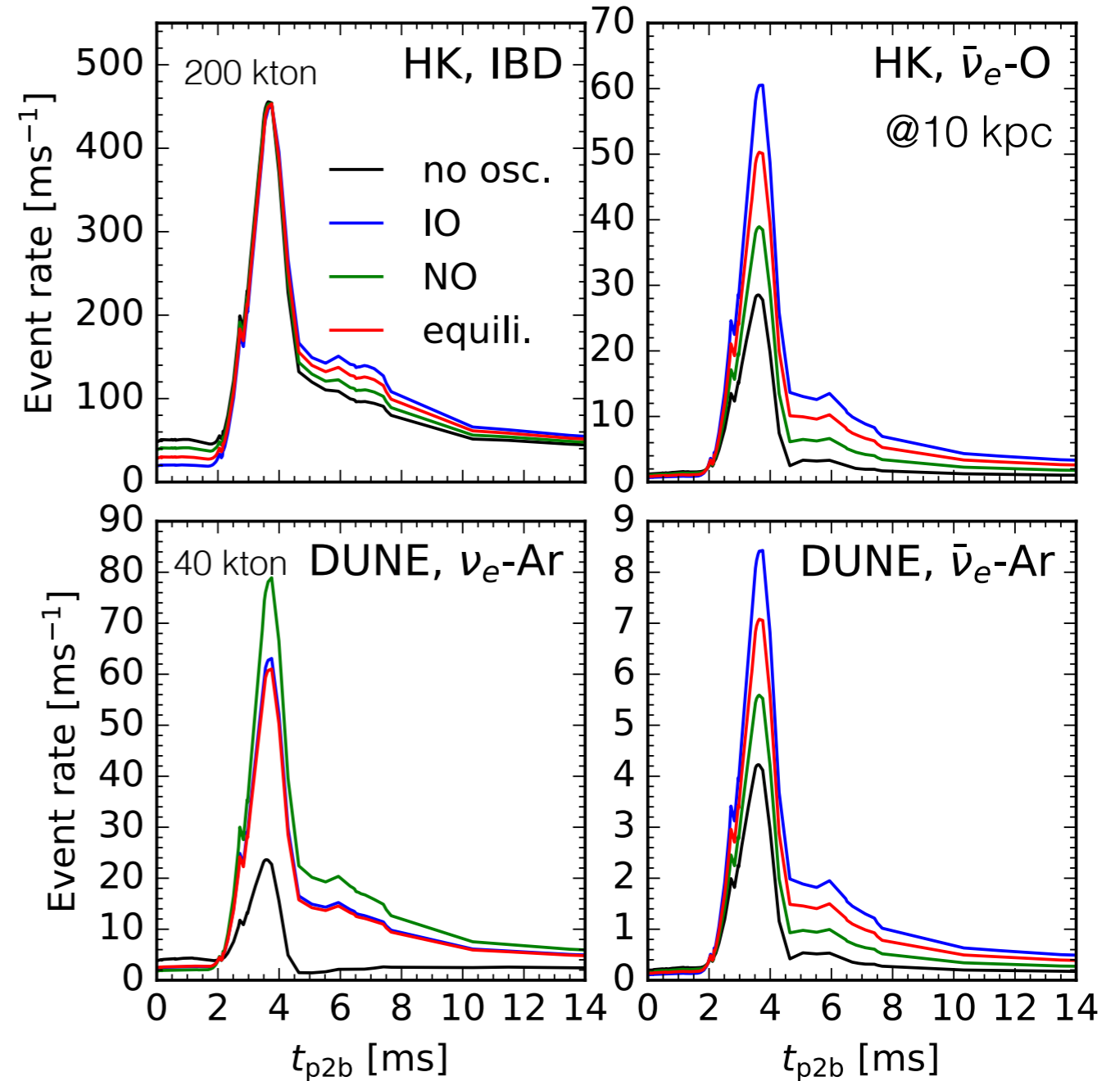
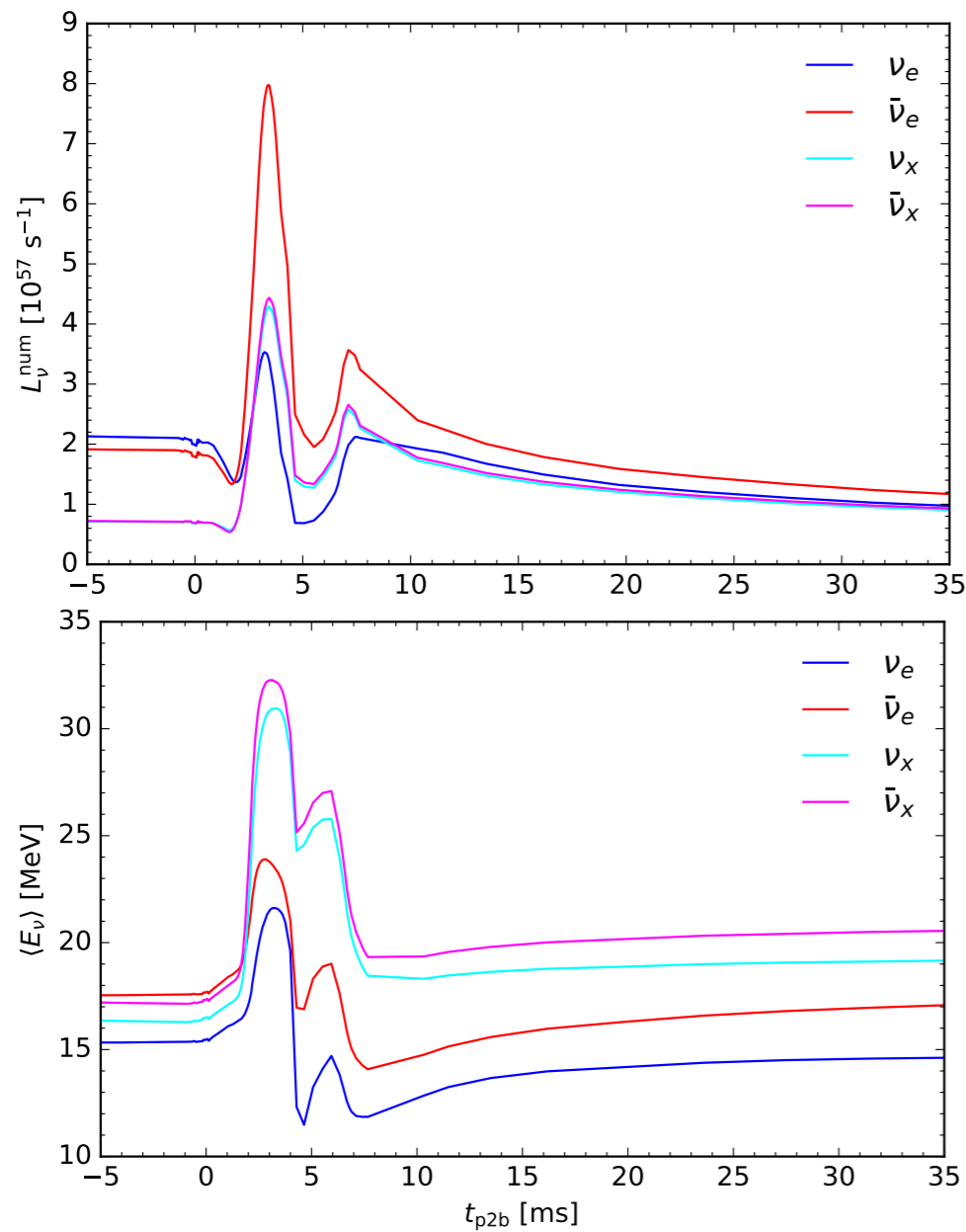
Potential effects on nucleosynthesis

Two scenarios for FFC:

- Fluxes in electron flavor reduced by a factor of 3
 - Y_e decreases by ~ 0.01
 - enhance the produced abundance for $Z \gtrsim 55$ within one order of magnitude
- Assuming flavor equilibration between electron and heavy-lepton flavors
 - enhancement on neutrino mean energy
 - Y_e increases by ~ 0.01
 - reduce the produced abundance



Neutrino signal



- Inverse beta decay (IBD) channel at the peak is nearly independent of the oscillation schemes, but difference in energy spectra is expected
- A jump between FFC and no-FC phases may be detectable [\[ZX, Wu, et al., arXiv:2505.19592 \(2025\)\]](#)

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

collisional weak
processes

matter

self-induced

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

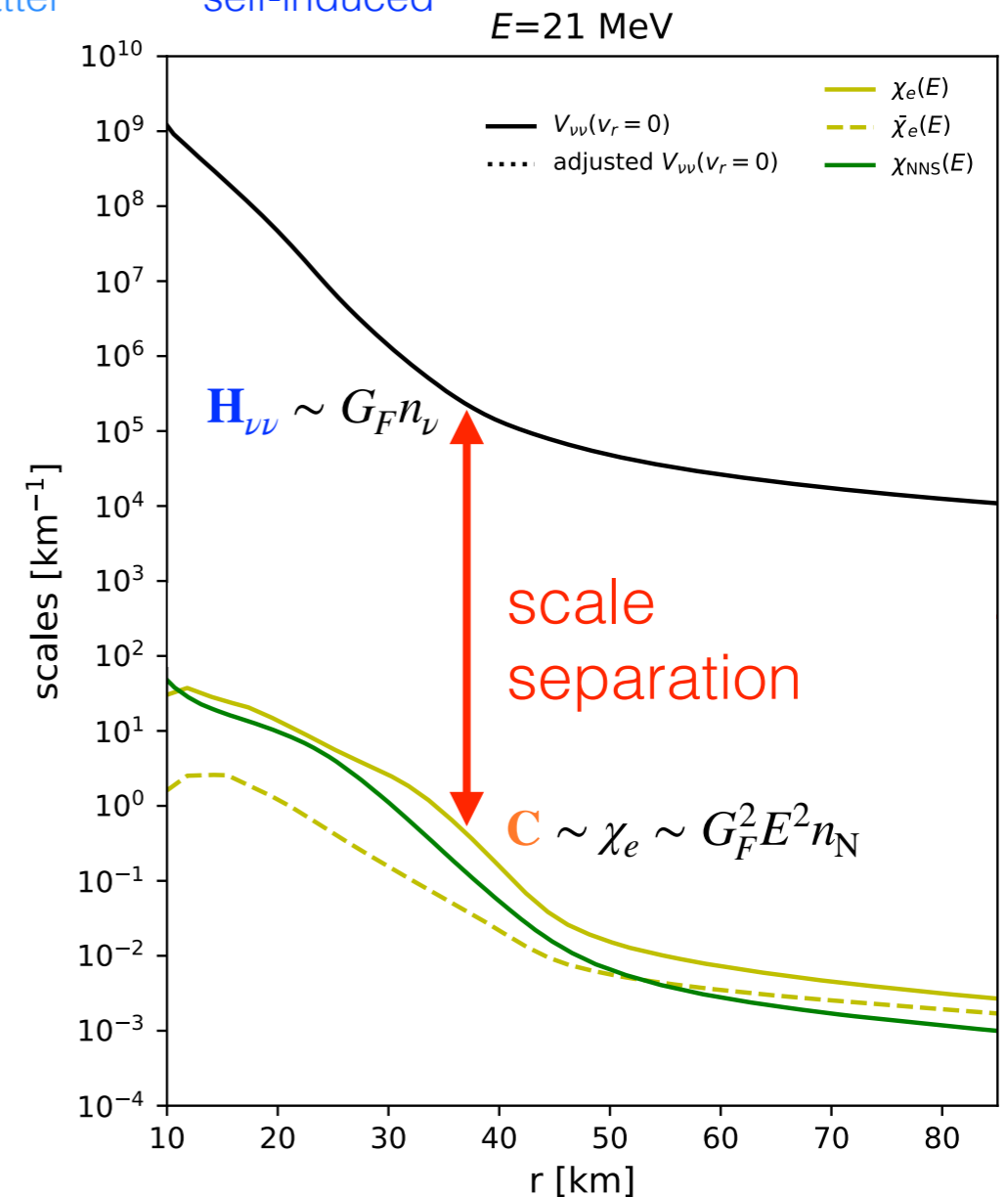
$$\mathbf{H}_{\text{vac}}(E) = \mathbf{U}\mathbf{M}^2\mathbf{U}^\dagger$$

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

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

$$df_{\nu_e}/dt = \underbrace{j_e(1 - f_{\nu_e})}_{\text{emissivity}} - \underbrace{\chi_e f_{\nu_e}}_{\text{opacity}}$$

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



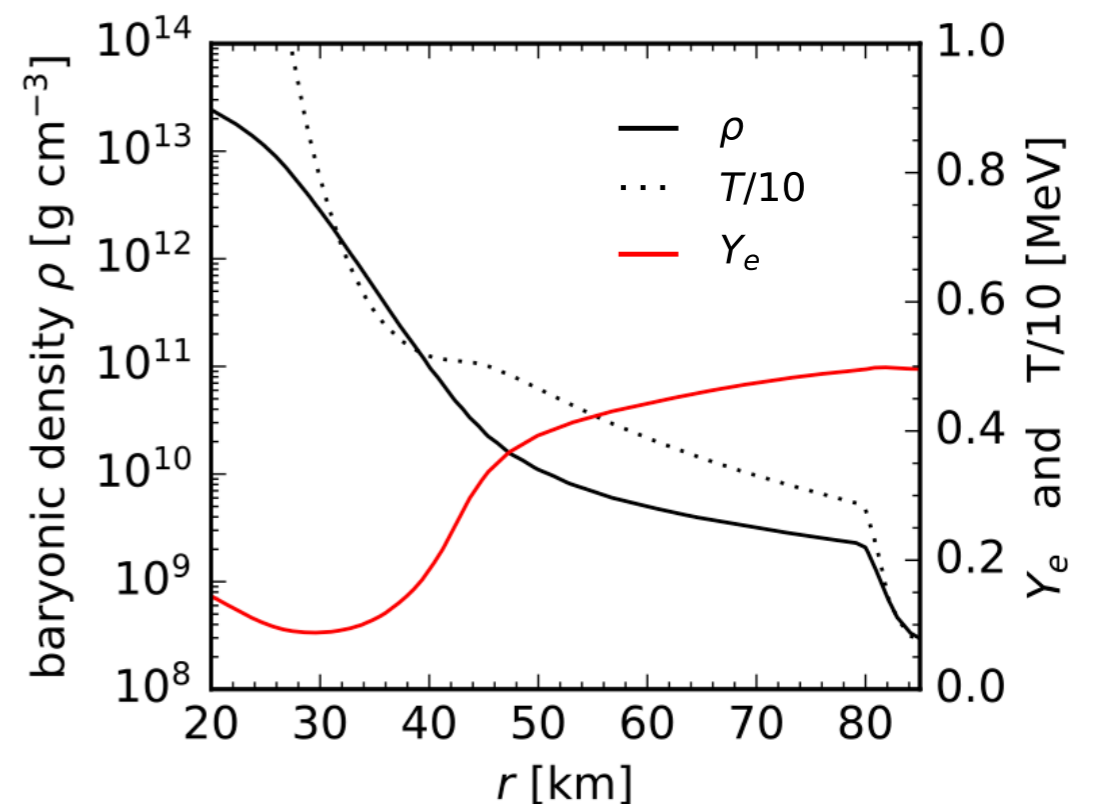
[ZX, M.-R. Wu, et al. PRD 107, 083016 (2023)]

Global ν QKE simulation set-up

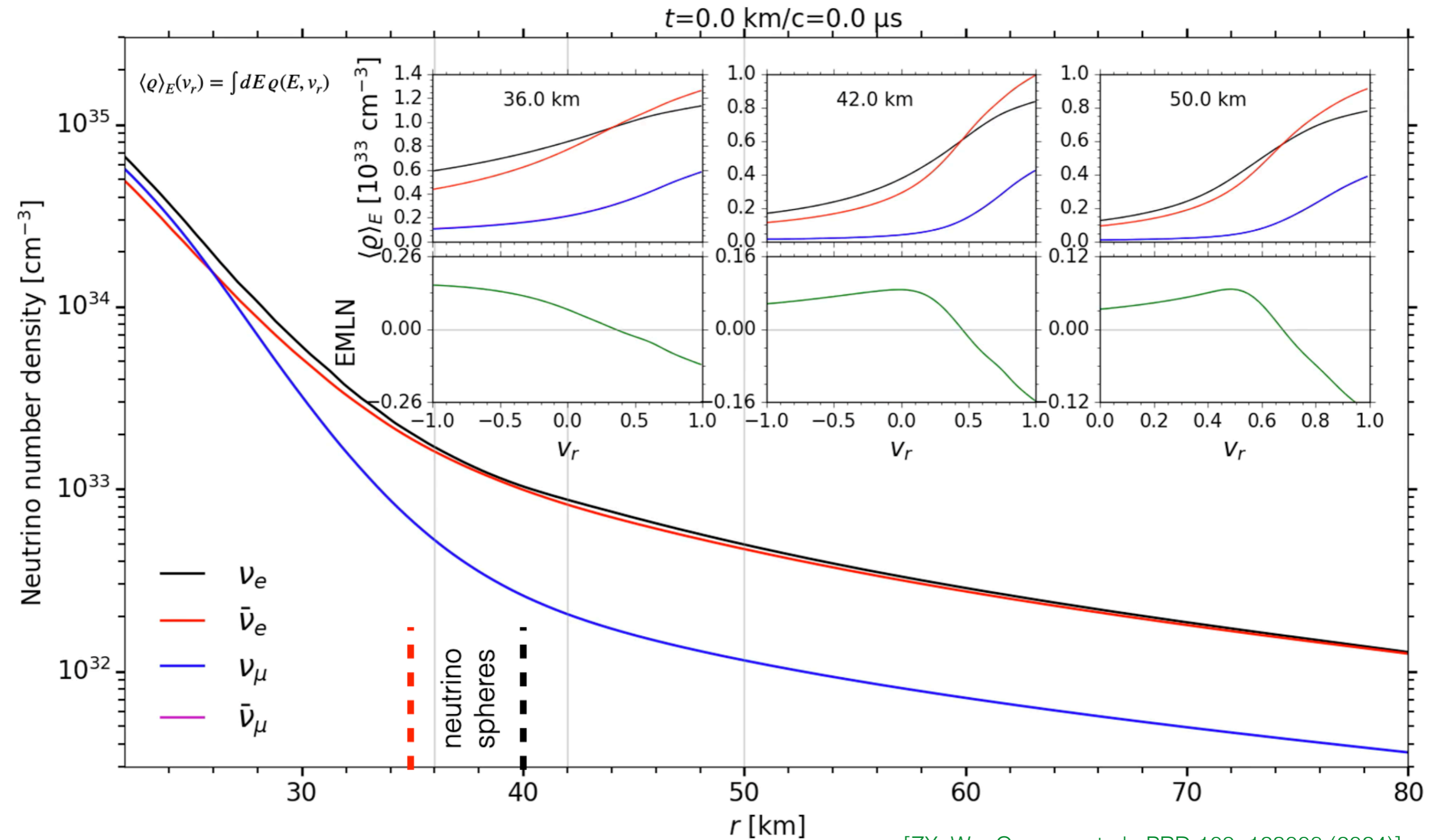
- Background matter profile (snapshot) in spherical symmetric supernova model from AGILE-BOLTZTRAN, $25M_{\odot}$ progenitor, post-bouncing time $t_{\text{pb}} \approx 250$ ms

$$(\partial_t + v_r \partial_r + \frac{1 - v_r^2}{r} \partial_{v_r}) \rho(E, v_r) = -i[\mathbf{H}_{\text{vac}} + a_{\nu\nu} \mathbf{H}_{\nu\nu}, \rho(E, v_r)] + \mathbf{C}$$

- Multi-energy & multi-angle
- Vacuum term generates flavor mixing seed
- *Inner boundary (20km)*: thermal equilibrium at the boundary
- *Outer boundary (80km)*: freely stream out, no injection for incoming neutrinos

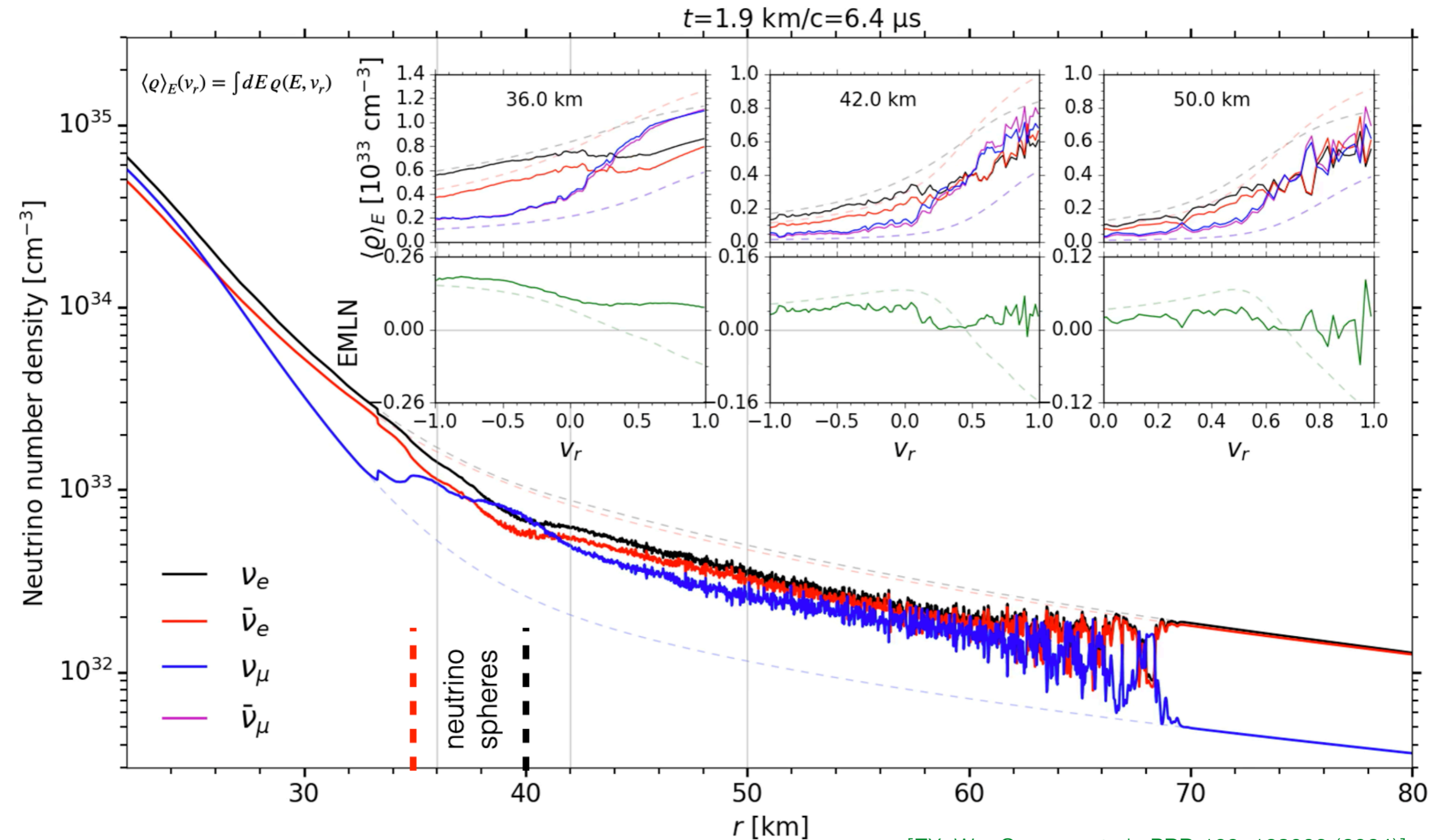


Global ν QKE simulation



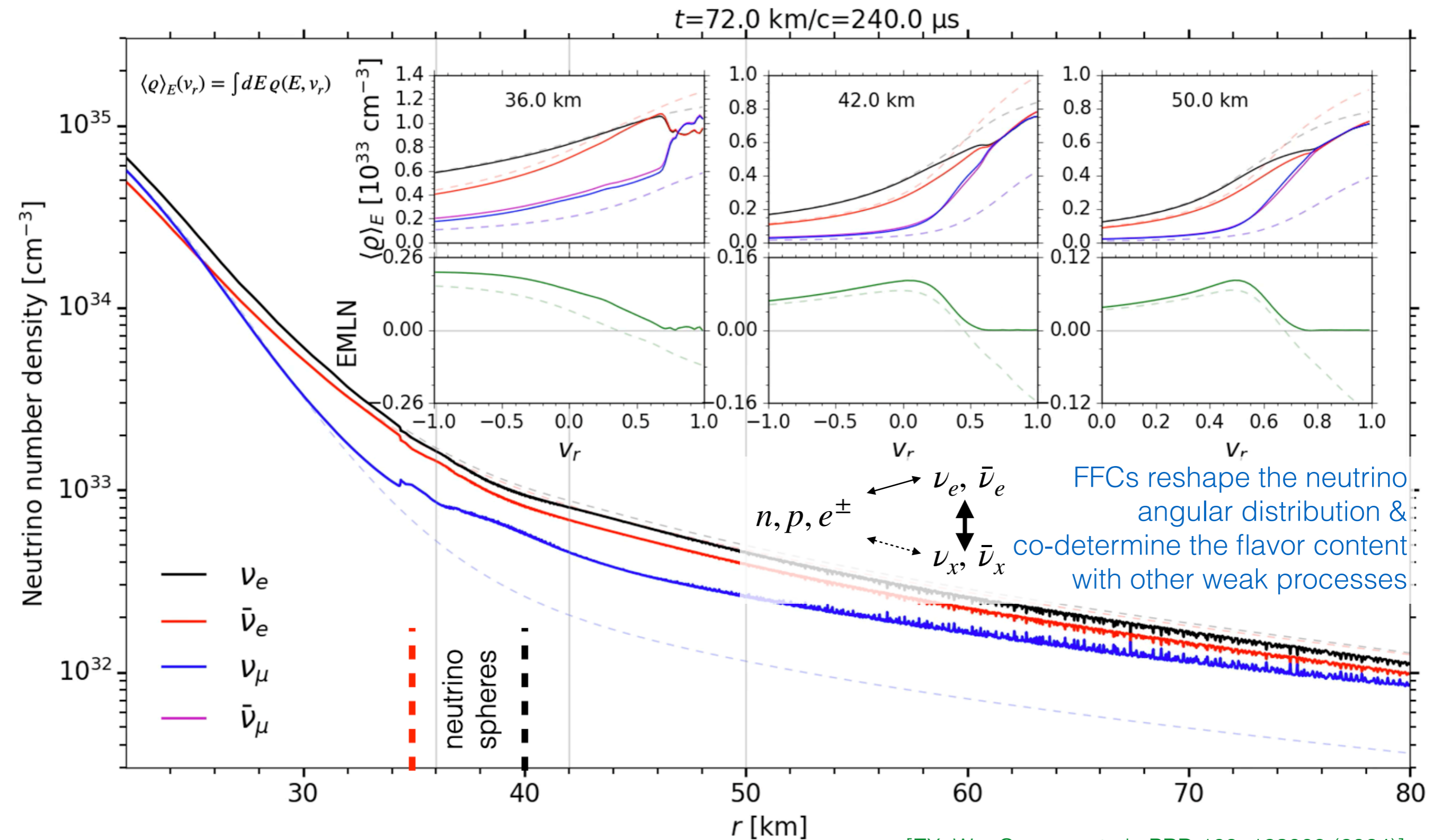
[ZX, Wu, George, et al., PRD 109, 123008 (2024)]

Global ν QKE simulation



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

Global ν QKE simulation

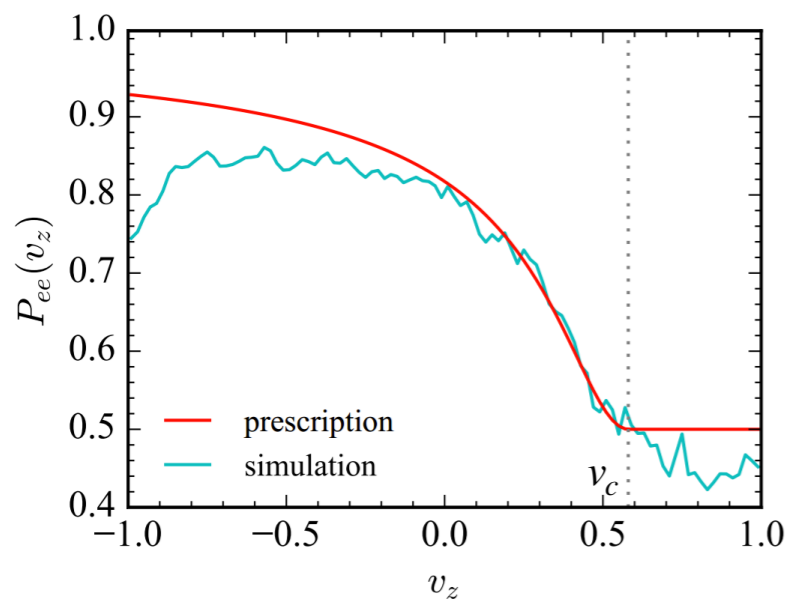


[ZX, Wu, George, et al., PRD 109, 123008 (2024)]

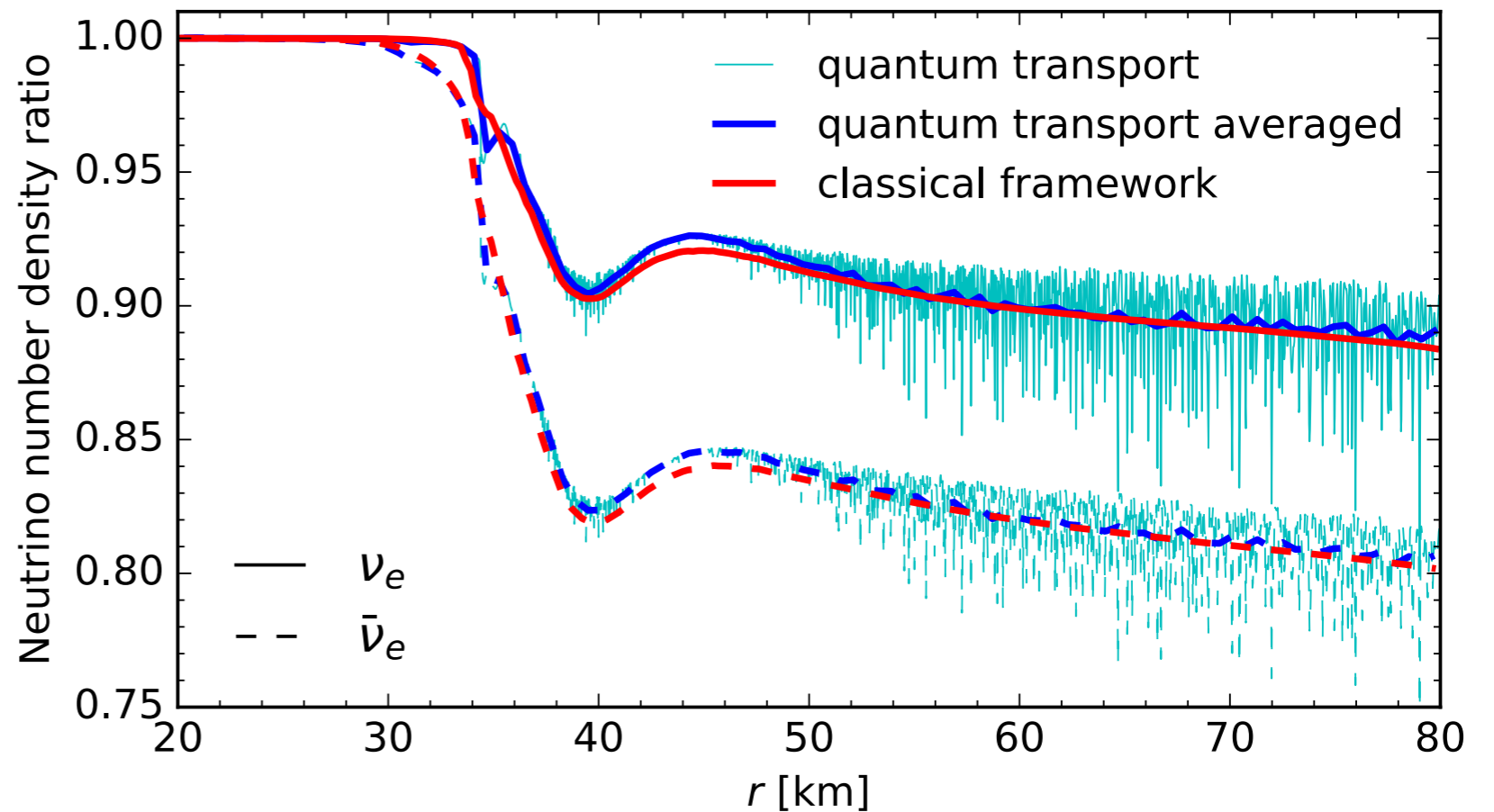
Effective prescription applicable for hydro simulations

$$(\partial_t + v_r \partial_r + \frac{1 - v_r^2}{r} \partial_{v_r}) \rho(E, v_r) = \cancel{i[\mathbf{H}_{\text{vac}} + a_{\nu\nu} \mathbf{H}_{\nu\nu}, \rho(E, v_r)]} + \mathbf{C}$$

- incorporate analytical prescriptions into classical framework of neutrino transport
 - **Prescription** excellently captures the flavor evolution of the solution from **vQKE**
 - feasible robust integration of fast flavor conversions



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



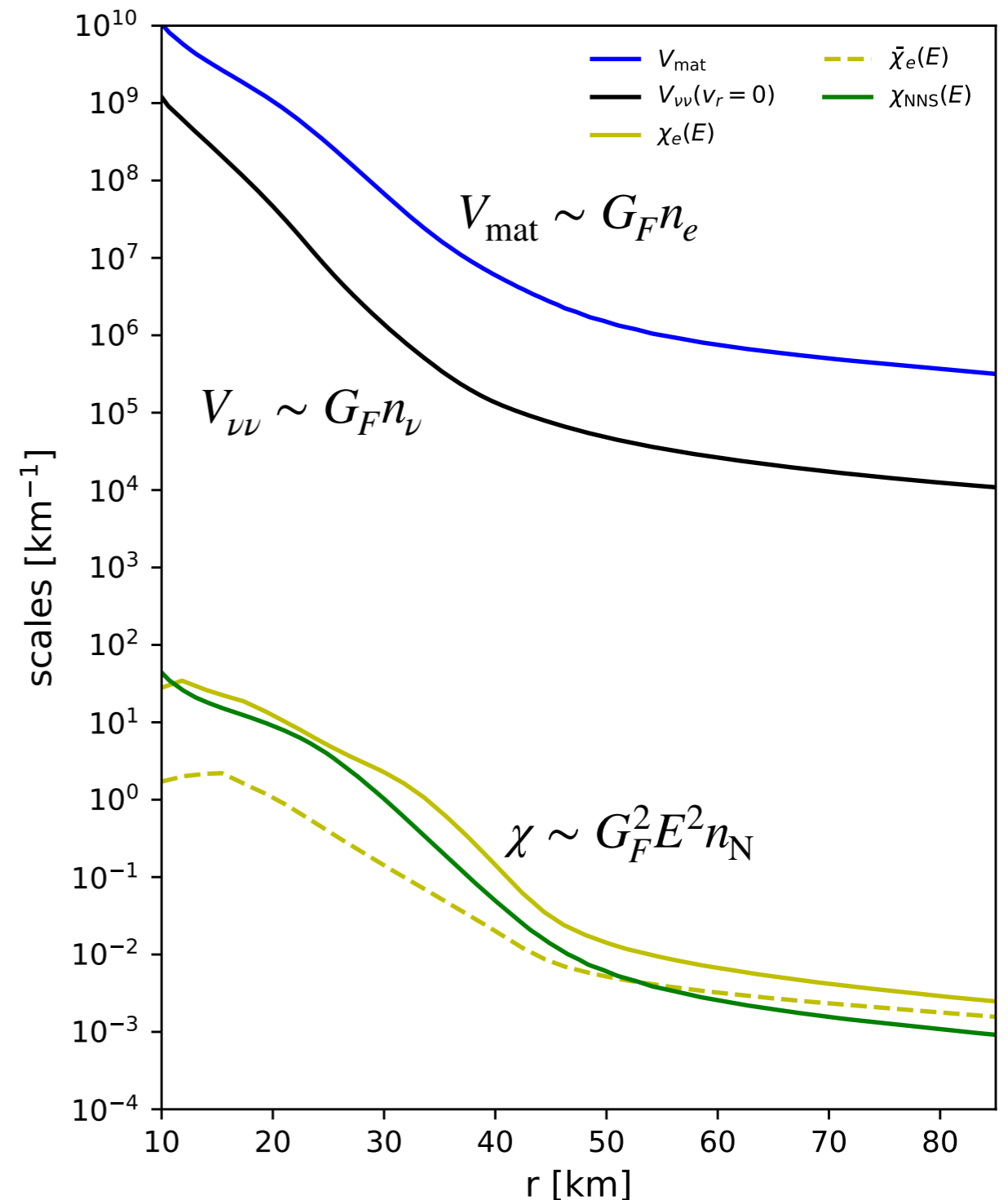
[ZX, Wu, et al. PRL 134, 051003 (2025)]

Role of matter inhomogeneity on fast flavor instability

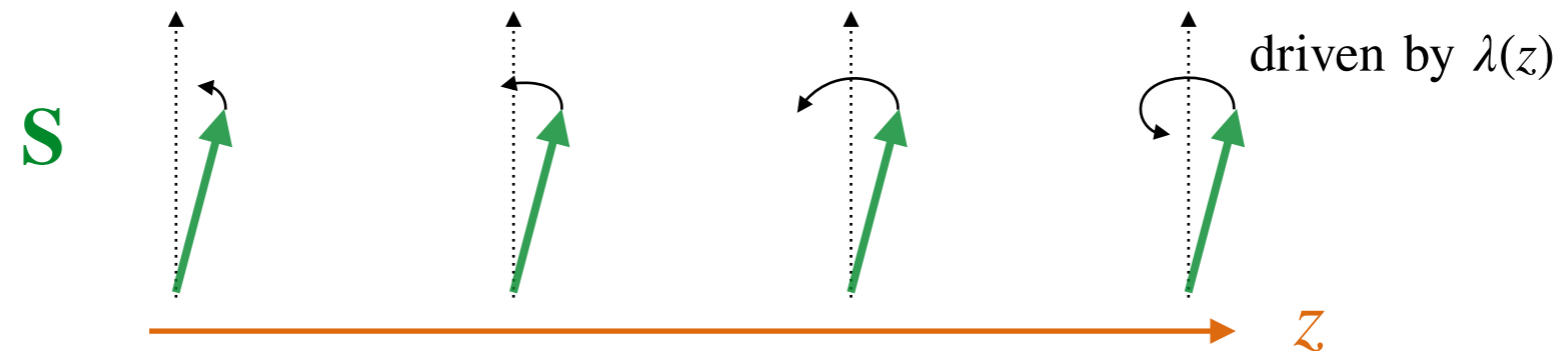
- Set-up:
 - a local box size $z \in (-30, 30)$ cm with $Nz=6000$
 - two beams labeled by + and -
 - periodic boundary for neutrino gas with $\mu = 1.5 \text{ cm}^{-1}$ and $\alpha = 1/3$
 - inhomogeneous background matter potential $\lambda(z) = m(z + 30) \text{ cm}^{-1}$
 - initial perturbation $\mathbf{S}_3(z) = 10^{-6} e^{-z^2/(50 \text{ cm}^2)}$
 - simulations end at $t \sim 1 \text{ ns}$

$$(\partial_t + \partial_z)\mathbf{S}_+ = [\lambda(z) - 2\mu\alpha\mathbf{S}_-] \times \mathbf{S}_+$$

$$(\partial_t - \partial_z)\mathbf{S}_- = [\lambda(z) + 2\mu\mathbf{S}_+] \times \mathbf{S}_-$$



Impact on dispersion relation



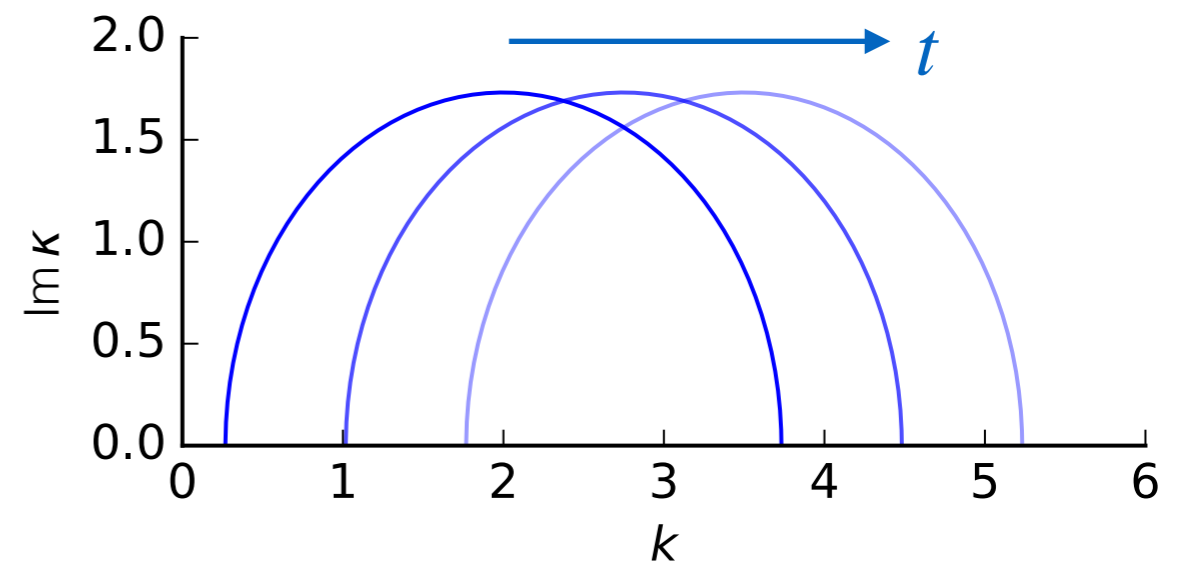
$$Q_{\pm}[k, t] = \int dz e^{i k_{\text{eff}}(k) z} \mathbf{S}_{\pm}^{\perp}(z, t), \quad \text{where } k_{\text{eff}} = k - mt$$

Effect of matter inhomogeneity manifests as the drifting of unstable modes in k-space:

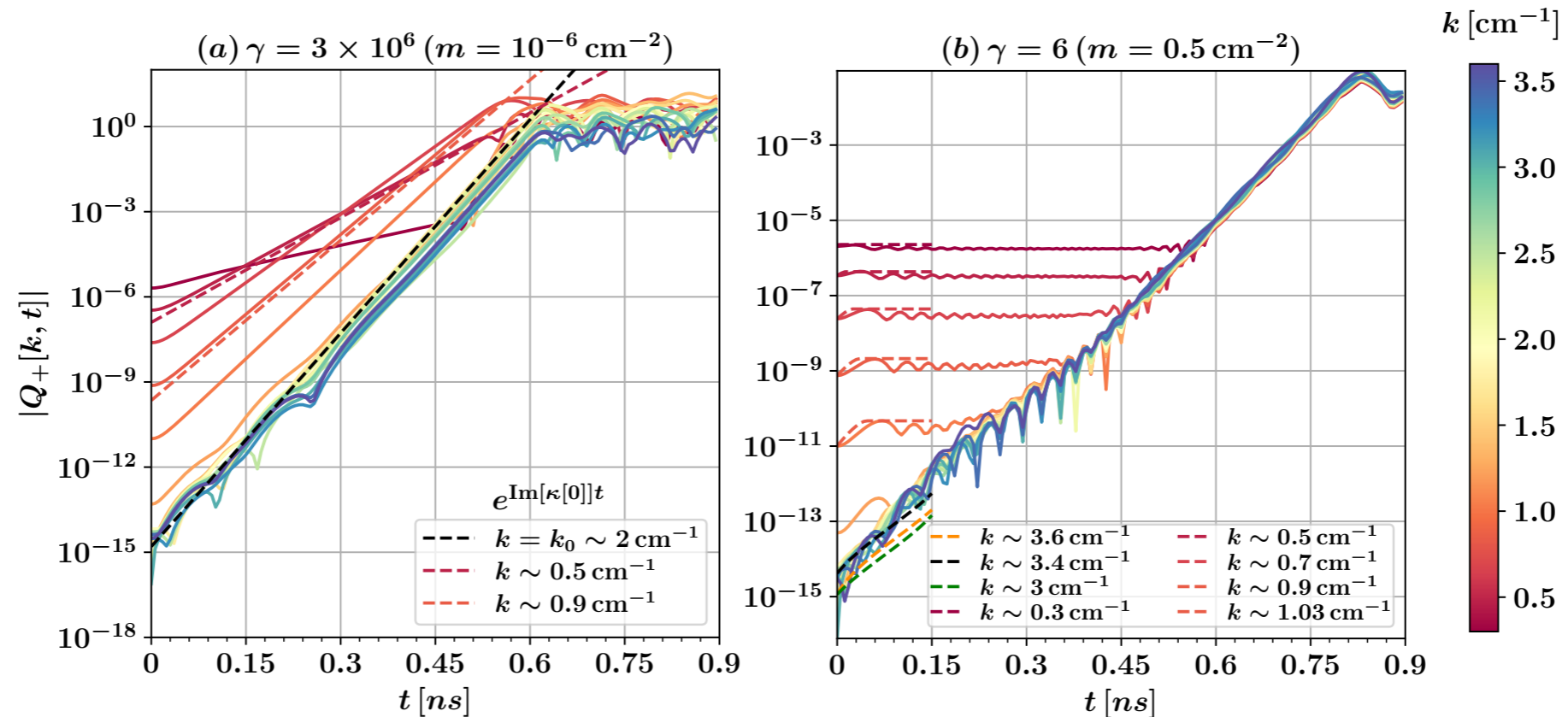
$$\partial_t \begin{pmatrix} Q_+ \\ Q_- \end{pmatrix} = \begin{pmatrix} -i(k - mt) + 2i\mu\alpha & -2i\mu\alpha \\ 2i\mu & i(k - mt) - 2i\mu \end{pmatrix} \begin{pmatrix} Q_+ \\ Q_- \end{pmatrix},$$

Eigenvalues:

$$\kappa_{\pm}[t] = \pm i \sqrt{|k_{\text{eff}}^2(t) - 2(1 + \alpha)\mu k_{\text{eff}}(t) + \mu^2(1 - \alpha)^2|}$$



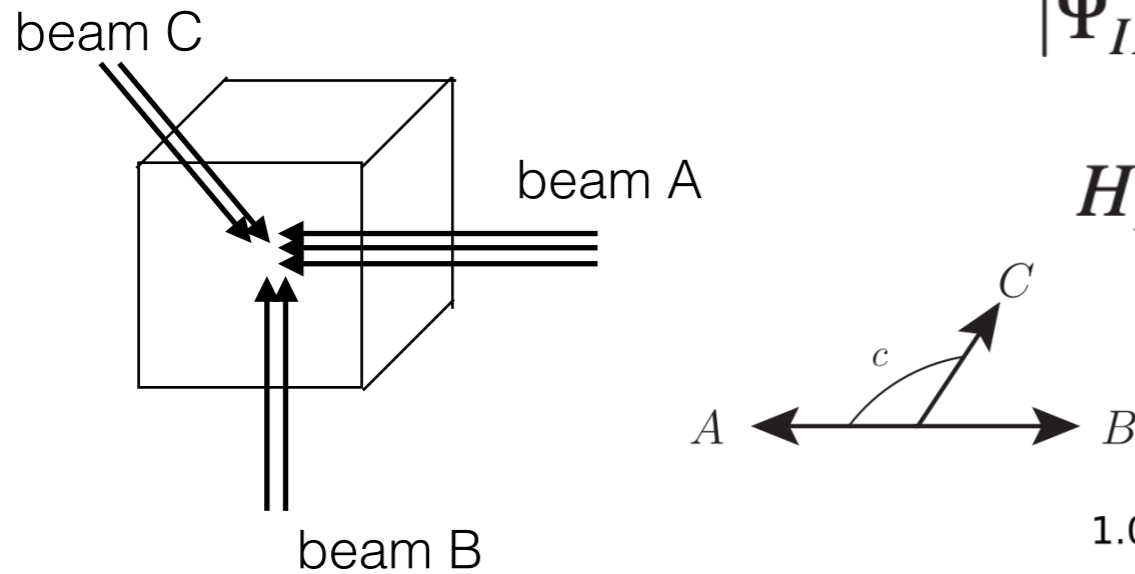
Behaviors in linear regime



[S. Bhattacharyya, M.-R. Wu, ZX, arXiv:2504.11316 (2025)]

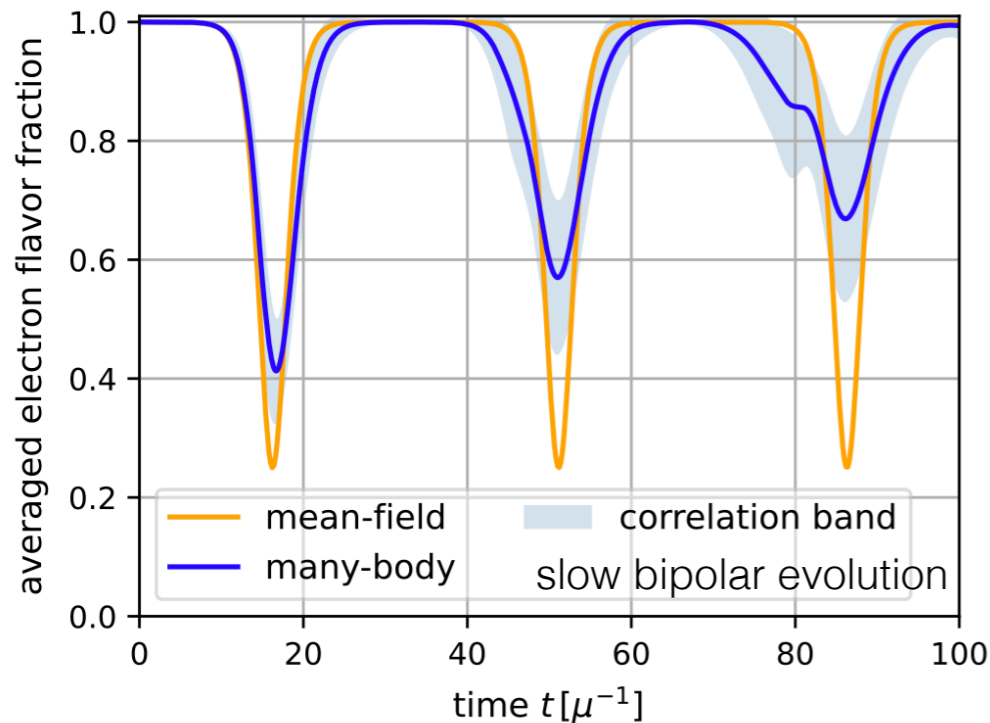
- "Adiabaticity": $\gamma = 4\alpha\mu^2/m \gtrsim 1$:
 - Competition between the drifting in k -space and the growth of unstable mode: $(k_{\text{max}} - k_{\text{min}})/m \gtrsim (\text{Im } \kappa_{\text{max}})^{-1}$
- Large gradient of inhomogeneous matter profile can delay the growth of fast flavor instability.

Fast flavor conversion in many-body picture

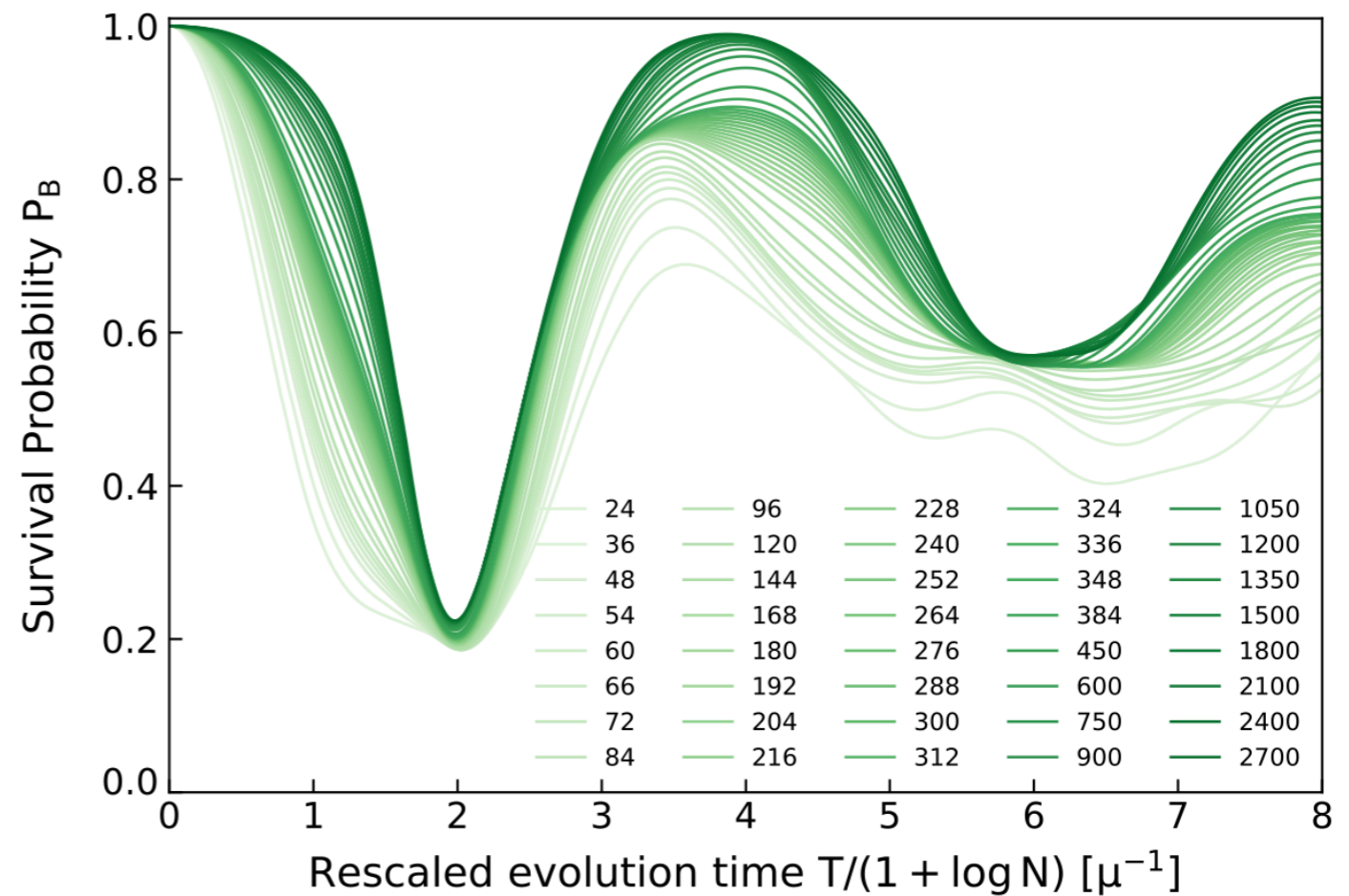


$$|\Psi_{II}(0)\rangle = |\uparrow\rangle^{\otimes N_A} \otimes |\downarrow\rangle^{\otimes N_B} \otimes |\uparrow\rangle^{\otimes N_C},$$

$$H_{ABC} = \frac{4\mu}{N} \mathbf{J}_A \cdot \mathbf{J}_B + \frac{2\mu}{N} (1 - c) \mathbf{J}_A \cdot \mathbf{J}_C + \frac{2\mu}{N} (1 + c) \mathbf{J}_B \cdot \mathbf{J}_C,$$



[ZX, PRD 105, 103002 (2022)]



[A. Roggero, E. Rrapaj, ZX, PRD 106, 043022 (2022)]

Summary & Outlook

- FFC occurs in QCD phase-transition supernovae
 - in two major phases;
 - can affect nucleosynthesis and neutrino signal.
- Global QKE simulation in a spherical symmetric supernova model
 - Asymptotic state at the coarse-grained level with EMLN crossing erased.
 - Collisional feedback.
 - Implication of prescriptions show excellent agreement with the vQKE solution.
- Large gradient of inhomogeneous matter potential can delay the growth of fast flavor instability.
- Many additional studies lie ahead:
 - spherical symmetry? time-dependent matter profiles & feedback on matter?
 - muon creations? many-body? ...?

Collaborators



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of Science
and Technology



Uniwersytet
Wrocławski

G. Martínez-Pinedo

S. Bhattacharyya, C.-Y. Lin, M. George, M.-R. Wu

T. Fischer, N. K. Largani

ERC Starting grant: NeuTrAE

- Scientific goals:
 - Understanding quantum kinetic evolution of dense neutrino gases
 - Assessing the impacts of collective neutrino oscillations on observational signatures

- **Actively hiring PhD and postdoc!**

Welcome to contact me: z.xiong@gsi.de



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