ニュートリノ集団振動が超新星ダイナミクスに及ぼす影響

arXiv:2506.07017

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概要

- 近年、ニュートリノ自己相互作用に起因する集団振動、中でも**高速フレーバー変換**(fast flavor instability, FFC)が超新星にどのような影響を及ぼすか、注目が集まっている。
- FFCの発生はニュートリノ**運動量空間角度分布**に依存するため、その影響は近似的ニュートリノ輸送手法では正確に取り扱うことができない。
- 本研究では**ボルツマン輻射流体シミュレーションに、FFCのBhatnagar-Gross-Krook (BGK) サブグリッドモデルを実装**し、空間一次元超新星シミュレーションを行った。
- FFCの効果を調べるほか、先行研究で用いられてきた簡易的手法との違いも調べた。

Boltzmann neutrino radiation-hydrodynamics

Boltzmann eq.

$$\frac{1}{\alpha}\frac{\partial f}{\partial t}+\frac{\cos\theta_\nu}{\alpha r^2\sqrt{\gamma_{rr}}}\frac{\partial}{\partial r}\left(\alpha r^2 f\right)-\frac{1}{\epsilon^2}\frac{\partial}{\partial \epsilon}\left(\epsilon^3 f\omega_{(t)}\right)$$
$$+\frac{1}{\sin\theta_\nu}\frac{\partial}{\partial\theta_\nu}\left(\sin\theta_\nu f\omega_{(\theta_\nu)}\right)=S_{\mathrm{rad}}\boxed{-\frac{1}{\tau_{\mathrm{as}}}(f-f^{\mathrm{as}})}$$

FFC subgrid term with BGK method

Hydrodynamics eq.

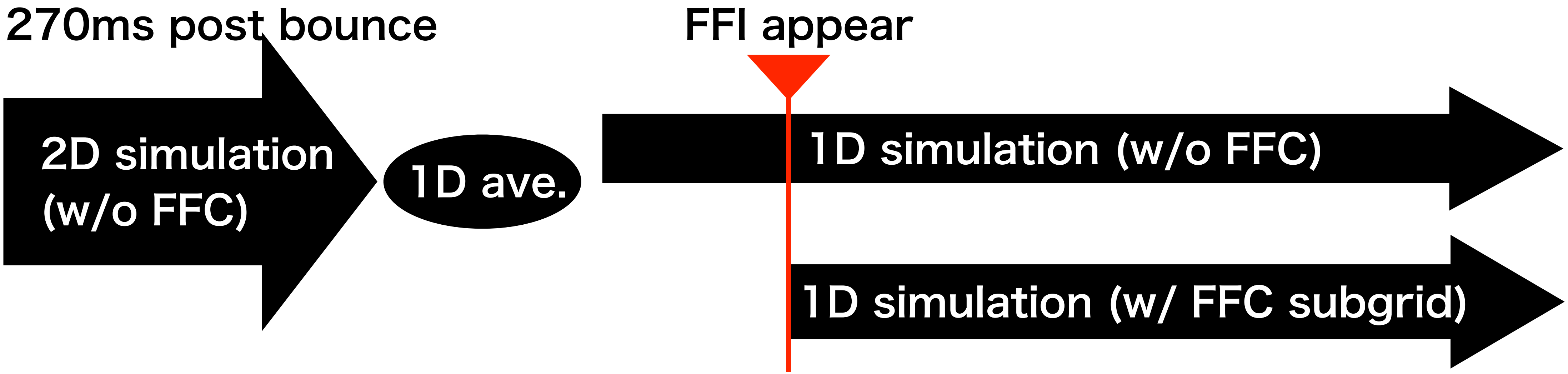
$$\partial_t\rho_*+\partial_r(\rho_* v^r)=0,$$

$$\partial_t S_r+\partial_r(S_r v^r+\alpha\sqrt{\gamma}P)$$
$$=-S_0\partial_r\alpha-\frac{1}{2}\alpha\sqrt{\gamma}S_{jk}\partial_r\gamma^{jk}-\alpha\sqrt{\gamma}\gamma_r{}^{\mu}G_\mu,$$

$$\partial_t(S_0-\rho_*)+\partial_r((S_0-\rho_*)v^r+\sqrt{\gamma}Pv^k)$$
$$=\alpha\sqrt{\gamma}S^{ij}K_{ij}-S_rD^r\alpha+\alpha\sqrt{\gamma}n^\mu G_\mu,$$

Setup

- Progenitor: $M_{\rm ZAMS} = 11.2 M_{\odot}$
- Nuclear matter: Furusawa-Togashi EOS
- 2D simulation => 1D relaxation run => 1D simulation w/ and w/o FFC



Comparison of Mixing Methods

4spBGK (most robust)

$$f_e^{\mathrm{as}} = \eta f_e + (1-\eta) f_x,$$
$$\bar{f}_e^{\mathrm{as}} = \eta \bar{f}_e + (1-\eta) \bar{f}_x,$$
$$f_x^{\mathrm{as}} = \frac{1-\eta}{2} f_e + \frac{1+\eta}{2} f_x,$$
$$\bar{f}_x^{\mathrm{as}} = \frac{1-\eta}{2} \bar{f}_e + \frac{1+\eta}{2} \bar{f}_x,$$

$B > A$

$$\eta = \begin{cases} 1/3 & (\Delta G < 0) \\ 1 - 2A/(3B) & (\Delta G \geq 0) \end{cases}$$

$B < A$

$$\eta = \begin{cases} 1/3 & (\Delta G > 0) \\ 1 - 2B/(3A) & (\Delta G \leq 0) \end{cases}$$

$$A \equiv \left| \frac{1}{8\pi^3} \int_{\Delta G < 0} d(\cos\theta_\nu) d\phi_\nu \Delta G \right|,$$
$$B \equiv \frac{1}{8\pi^3} \int_{\Delta G > 0} d(\cos\theta_\nu) d\phi_\nu \Delta G,$$
$$\Delta G \equiv \int (f_e - \bar{f}_e - f_x + \bar{f}_x) \epsilon^2 d\epsilon.$$

3spBGK

3-species
assumption ($\nu_x = \bar{\nu}_x$)

$$f_e^{\mathrm{as}} = \eta f_e + (1-\eta) f_x,$$
$$\bar{f}_e^{\mathrm{as}} = \eta \bar{f}_e + (1-\eta) f_x,$$
$$f_x^{\mathrm{as}} = \frac{1-\eta}{4} f_e + \frac{1-\eta}{4} \bar{f}_e + \frac{1+\eta}{2} f_x.$$

Lepton number violated!

3sp$\rho 11$

Simple equipartition with
density threshold $\rho < 10^{11}$g/cc

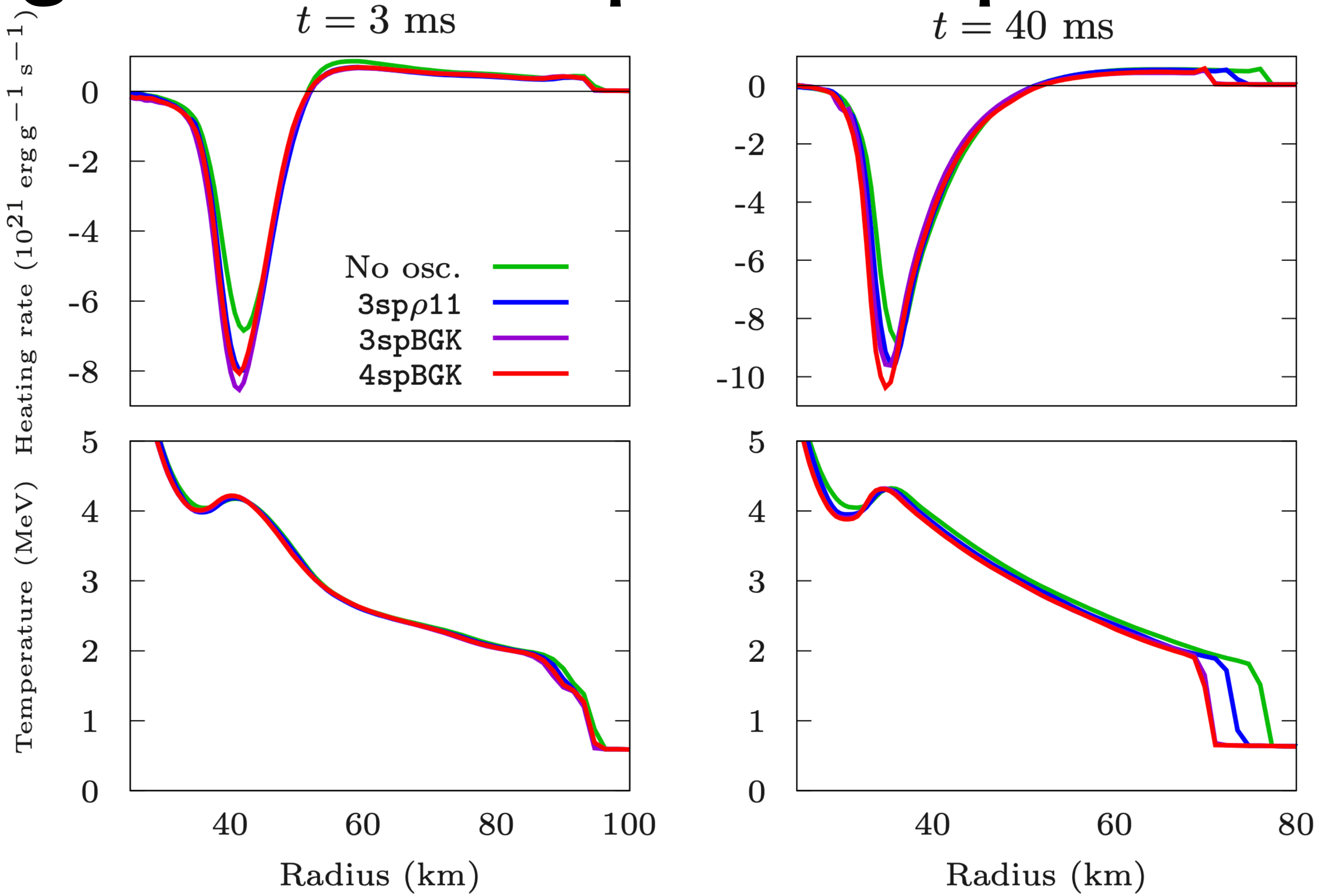
$n_{\nu_e} > n_{\bar{\nu}_e}$

$$f_e^{\mathrm{as}} = f_e + \frac{2}{3}(f_x - \bar{f}_e),$$
$$\bar{f}_e^{\mathrm{as}} = \frac{\bar{f}_e + 2 f_x}{3},$$
$$f_x^{\mathrm{as}} = \frac{\bar{f}_e + 2 f_x}{3}.$$

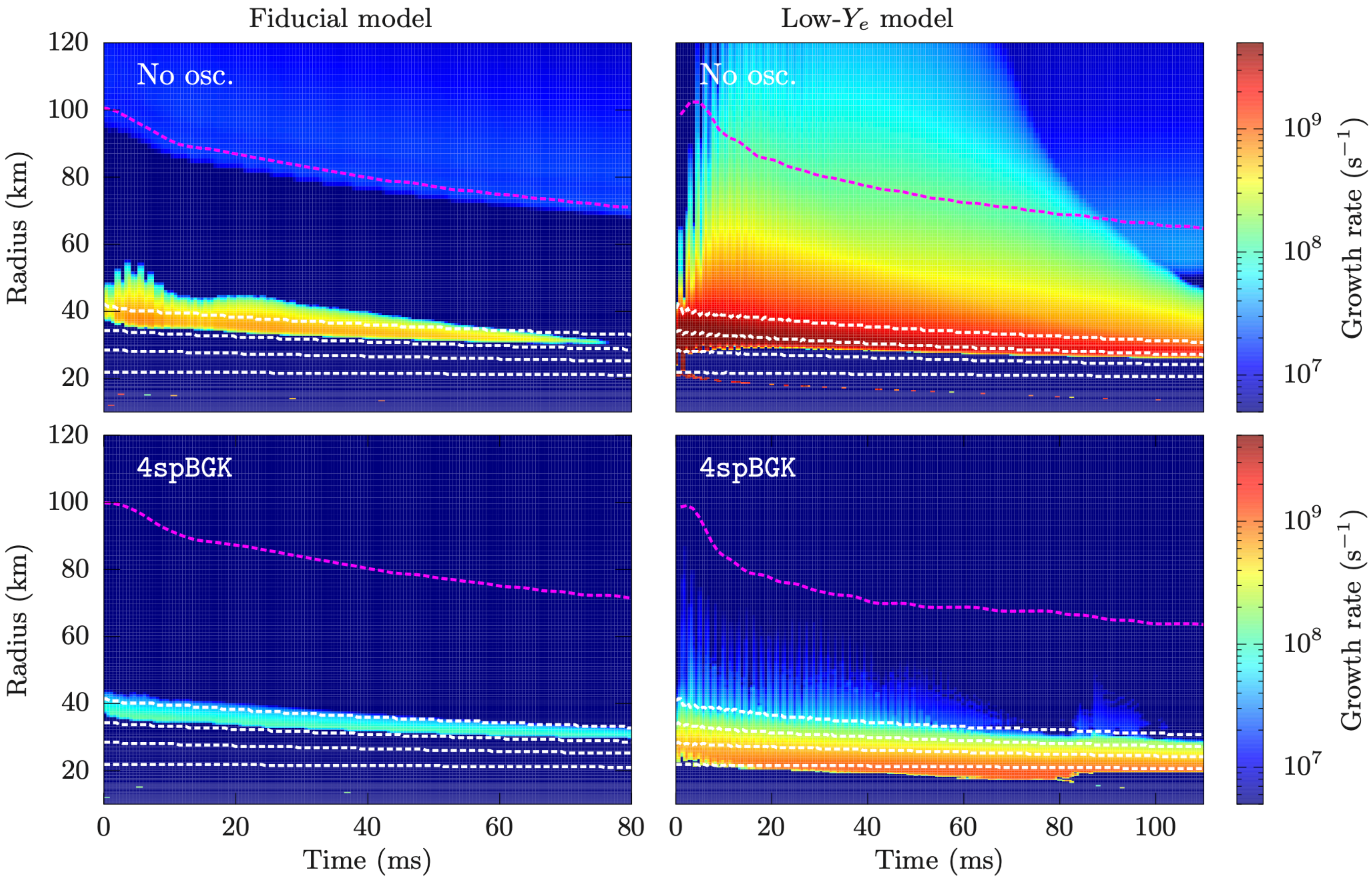
$n_{\nu_e} < n_{\bar{\nu}_e}$

$$f_e^{\mathrm{as}} = \frac{f_e + 2 f_x}{3},$$
$$\bar{f}_e^{\mathrm{as}} = \bar{f}_e + \frac{2}{3}(f_x - f_e),$$
$$f_x^{\mathrm{as}} = \frac{f_e + 2 f_x}{3}.$$

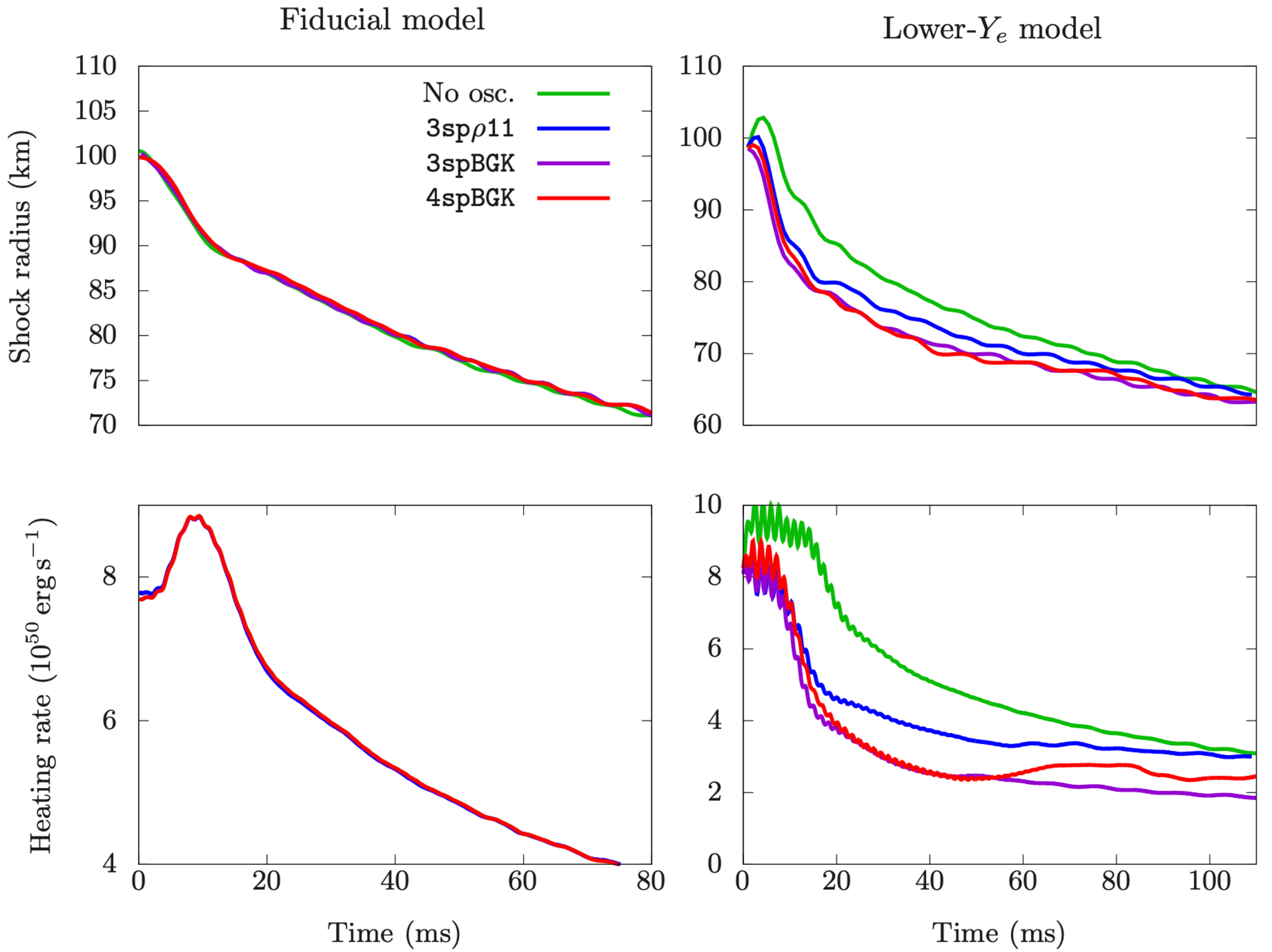
Heating rate and temperature profiles



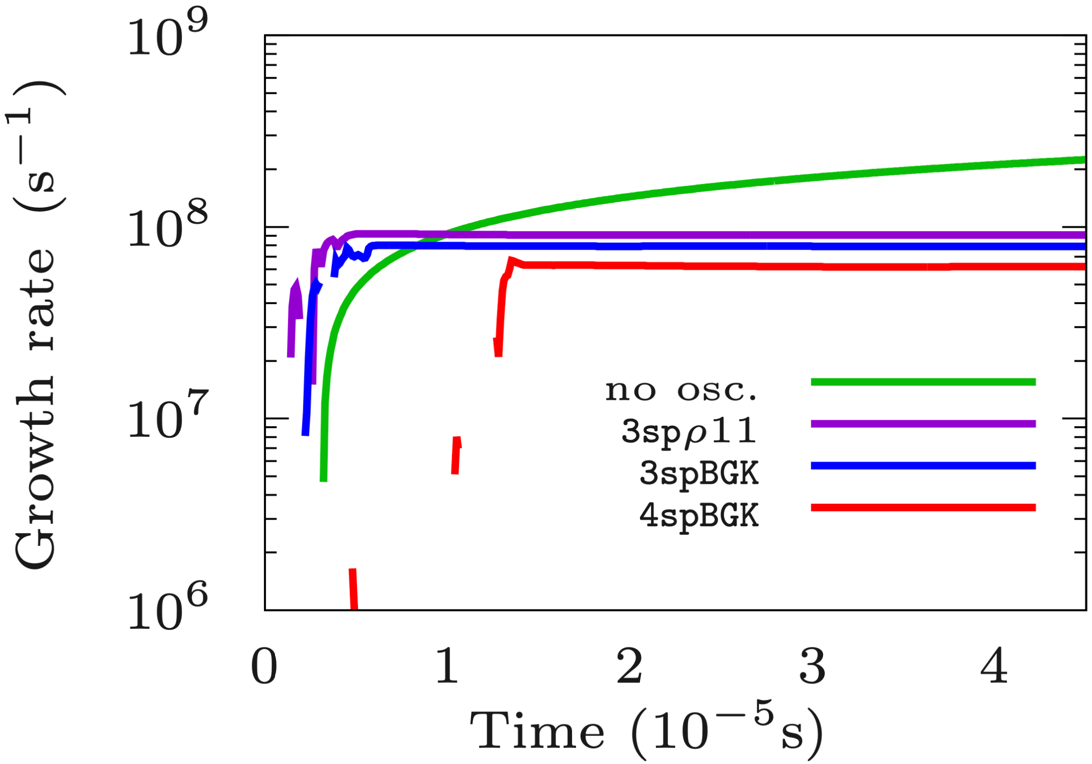
FFI growth rates

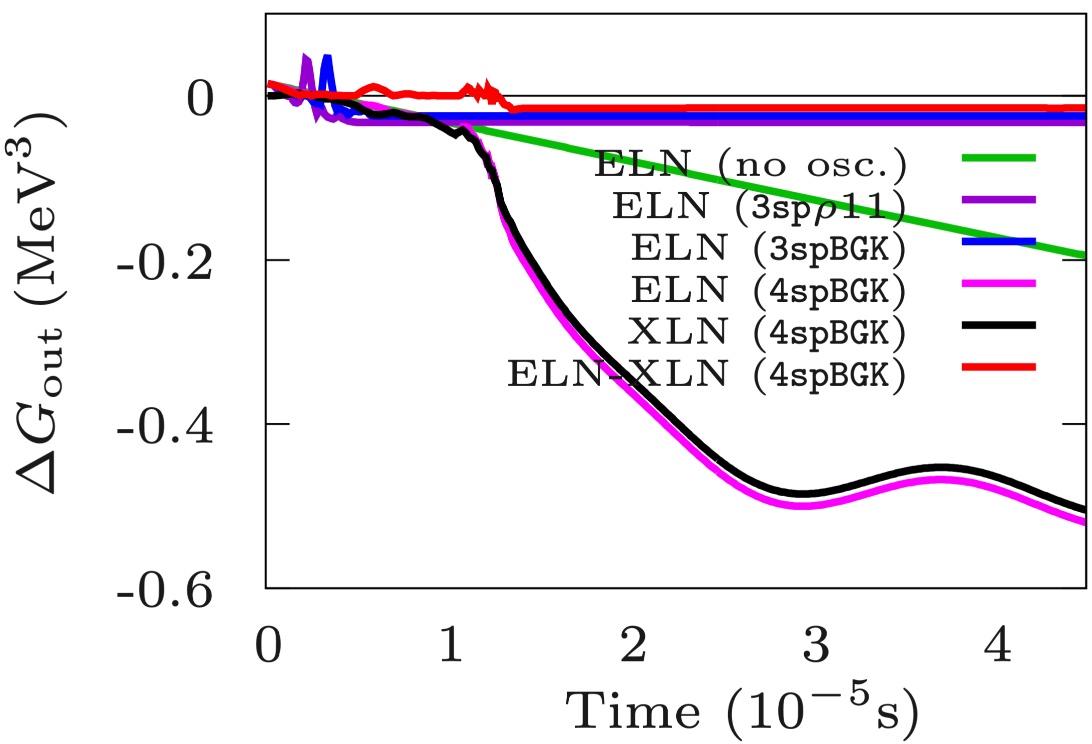


Shock evolution

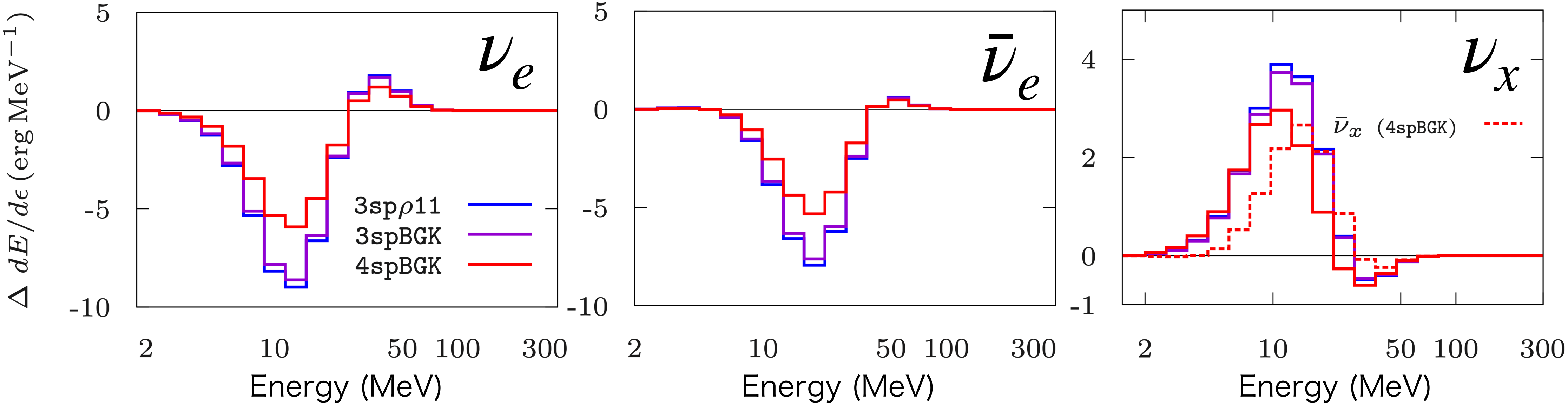


Flavor evolution at the appearance of FFI

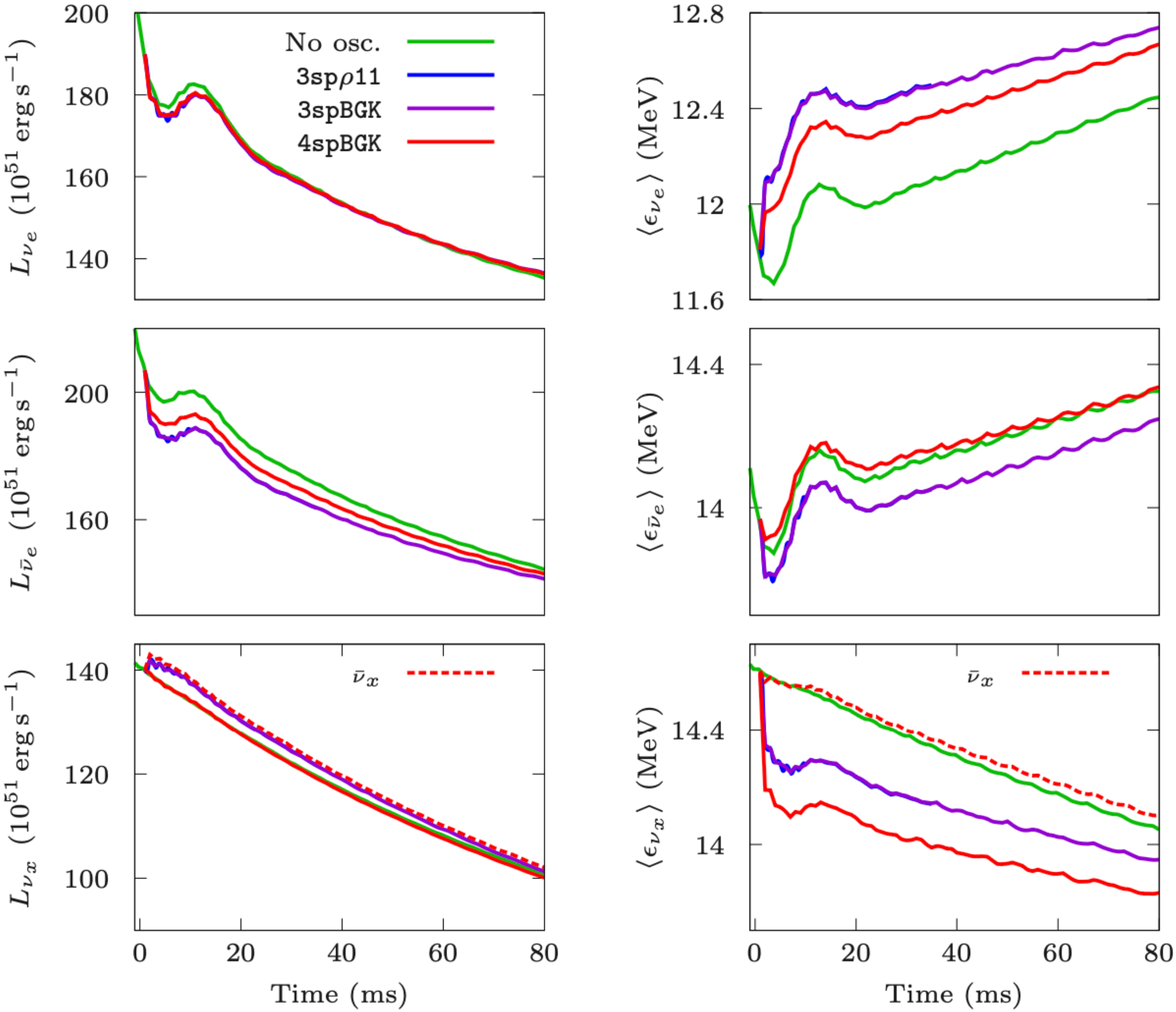




Difference of energy spectra w.r.t no FFC model



Neutrino emission properties (Fiducial)



Neutrino emission properties (lower-Y_e model)