Exploring the Effects of Neutrino Flavor Conversions in CCSN Explosions

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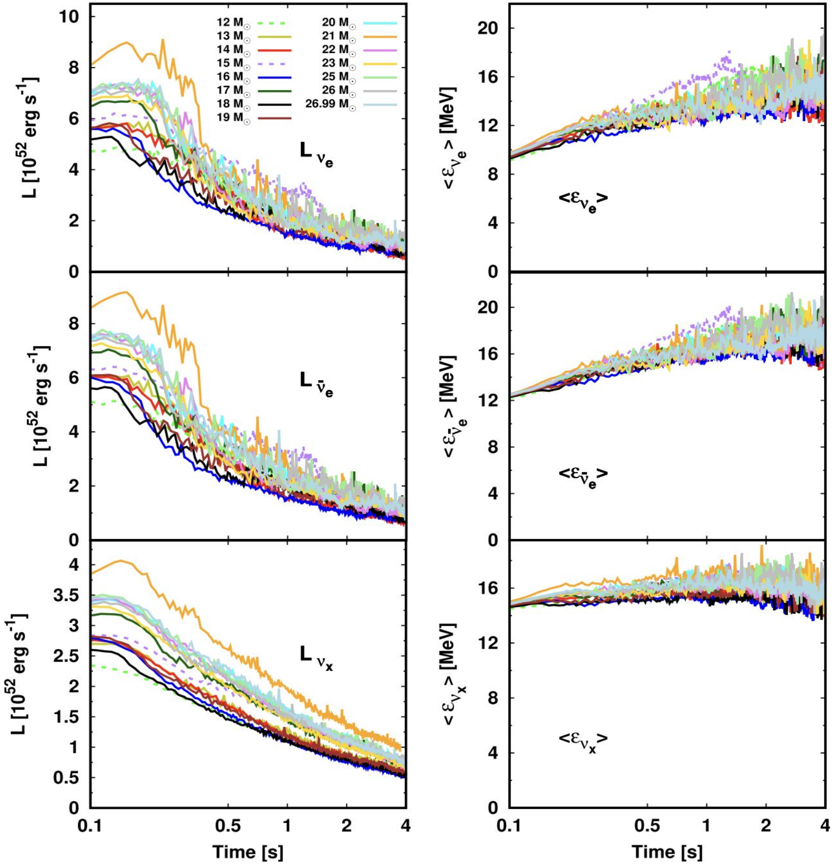
Nagakura+2021

CCSNe Without Neutrino Flavor Conversion

Neutrino mechanism explains the explosion of the majority of CCSNe, but this theory currently ignores neutrino flavor conversion.

Flavor instabilities induce flavor conversions, which may significantly change neutrino properties.

This is one of the largest uncertainty source in CCSN theory.



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General Flavor Instabilities in CCSNe

Quantum Kinetic Equation:

$$(\partial_t + \mathbf{v} \cdot \boldsymbol{\partial}_{\mathbf{r}})\rho(\mathbf{p}, \mathbf{r}, t) = -i\big[\mathsf{H}(\mathbf{p}, \mathbf{r}, t), \rho(\mathbf{p}, \mathbf{r}, t)\big] + \mathsf{C}(\rho, \overline{\rho})$$

$$\mathsf{H}(\mathbf{p}, \mathbf{r}, t) = \pm\frac{\mathsf{M}^2}{2E} + \sqrt{2}G_{\mathrm{F}}\mathsf{N} + \sqrt{2}G_{\mathrm{F}}\int \frac{d^3\mathbf{p}'}{(2\pi)^3}\left[\rho(\mathbf{p}', \mathbf{r}, t) - \overline{\rho}(\mathbf{p}', \mathbf{r}, t)\right](1 - \mathbf{v}' \cdot \mathbf{v})$$

Dispersion Relation: $\det(\varepsilon_{\mu\nu}) = 0$

ve-vx

$$\varepsilon_{\mu\nu} = g_{\mu\nu} - \mu\int \frac{d^3\mathbf{p}}{(2\pi)^3}\left[\frac{G_{\mathbf{p}}v_\mu v_\nu}{k \cdot v + \lambda - \tilde{\omega}_E + i\Gamma_E} - \frac{\overline{G}_{\mathbf{p}}v_\mu v_\nu}{k \cdot v + \lambda + \tilde{\omega}_E + i\overline{\Gamma}_E}\right]$$

wave 4-vector | vacuum oscillation | absorption rate

Solving the dispersion relation is very difficult → consider limiting cases

Limiting Cases

Fast Flavor Instability (FFI) Limit: $\varepsilon_{\mu\nu} = g_{\mu\nu} - \mu \int \frac{d^3v}{(2\pi)^3} \left[\frac{(f_e - f_x) v_\mu v_\nu}{\omega - \vec{k}\cdot\vec{v}} - \frac{(\bar{f}_e - \bar{f}_x) v_\mu v_\nu}{\omega - \vec{k}\cdot\vec{v}} \right]$

- No vacuum term. No absorption. Anisotropic neutrino distribution.

Collisional Instability (CFI) Limit: $\varepsilon_{\mu\nu} = g_{\mu\nu} - \mu \int \frac{E^2 dE}{2\pi^2} \left[\frac{f_e(E) - f_x(E)}{\omega + i\Gamma_E} - \frac{\bar{f}_e(E) - \bar{f}_x(E)}{\omega + i\bar{\Gamma}_E} \right] \int \frac{d\Omega}{4\pi} v_\mu v_\nu$

- No vacuum term. Vanishing wave vector. Isotropic neutrino distribution.

Slow Flavor Instability Limit:

- No absorption.

……

In these cases, growth rates can be computed more efficiently (even analytically).

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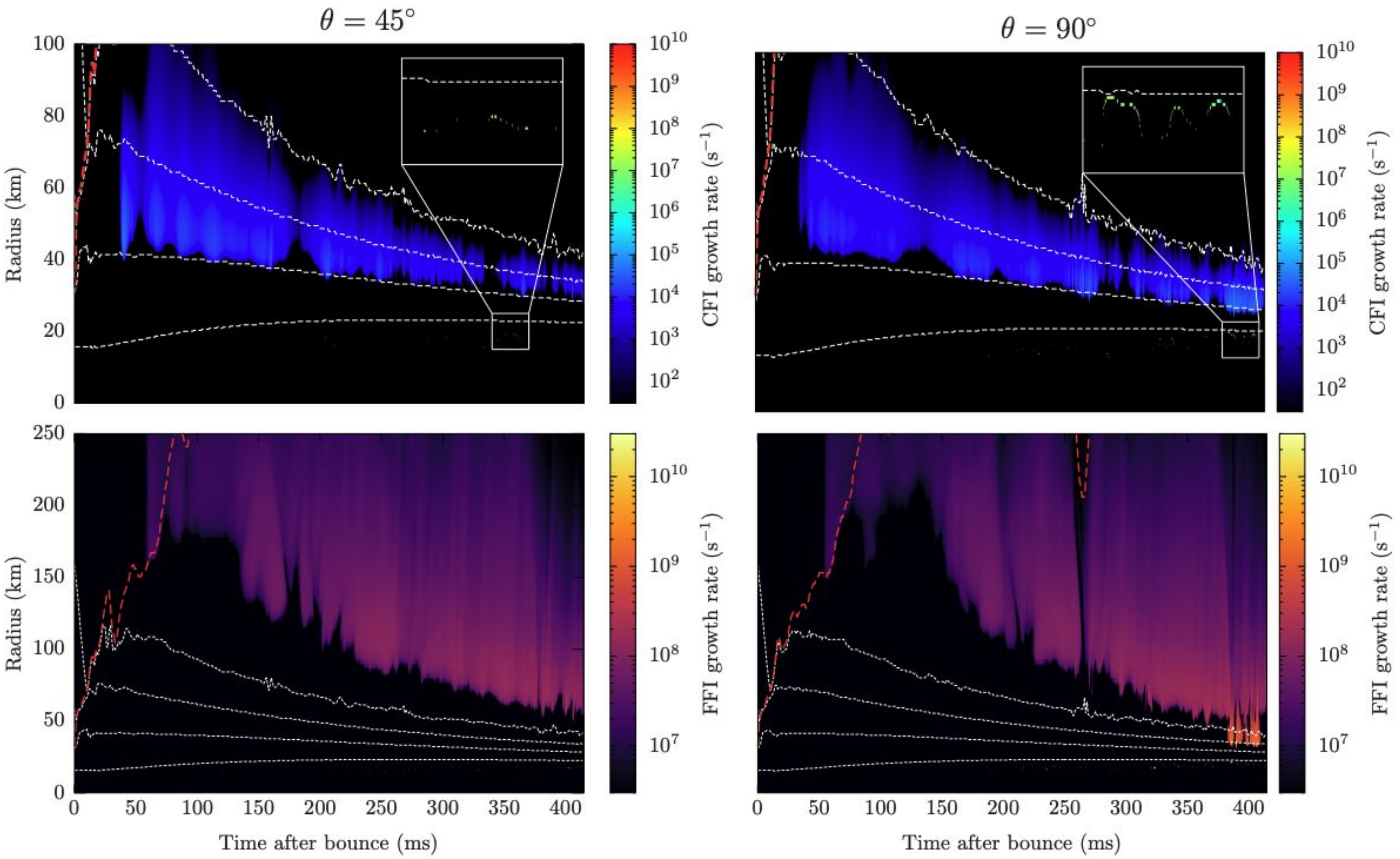
Previous Study: Instabilities in a 2D CCSN Model



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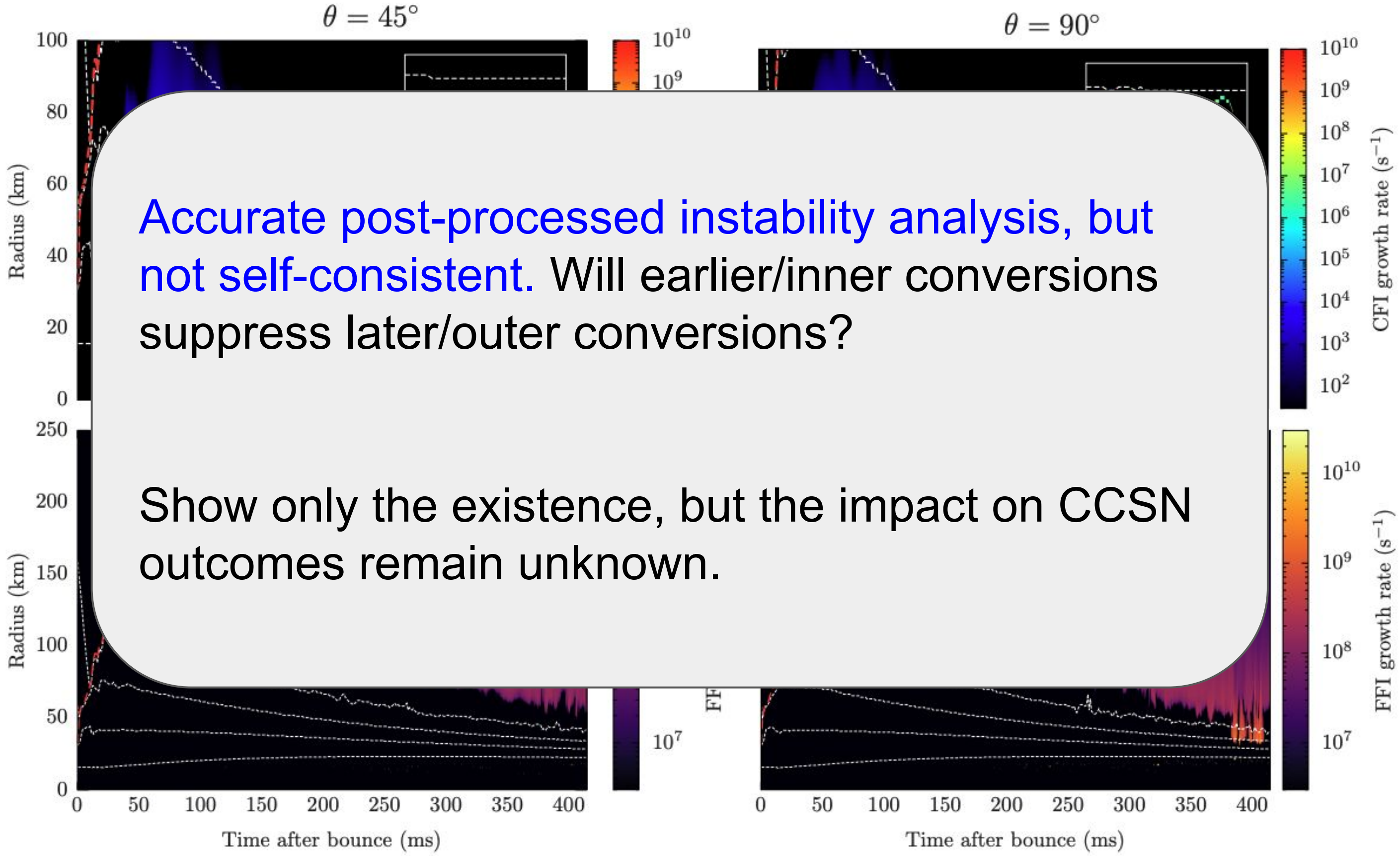
Previous Study: Instabilities in a 2D CCSN Model



Accurate post-processed instability analysis, but not self-consistent. Will earlier/inner conversions suppress later/outer conversions?

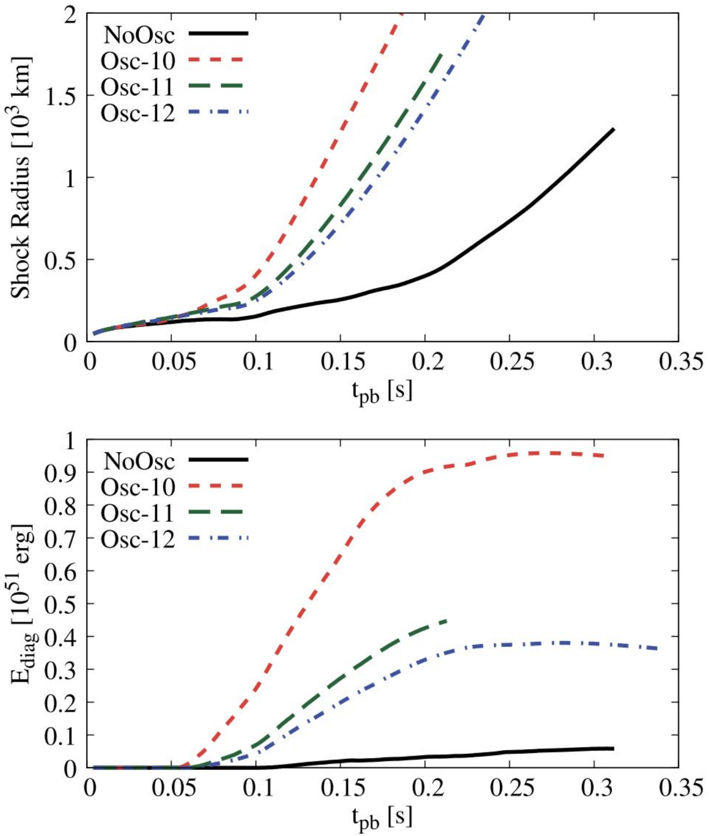
Show only the existence, but the impact on CCSN outcomes remain unknown.

Previous Study: Phenomenological Method

Fully mix different neutrino species if certain prescribed condition is satisfied, which requires free parameters.

Self-consistent, but results are sensitive to the free parameters and the inaccurate mixing condition.

How to combine the two types of previous studies?



Self-Consistent Flavor Conversion Treatment in CCSNe

Bhatnagar–Gross–Krook (BGK) Scheme:

- Step 1: Estimate the asymptotic flavor state: $f_{\rm a}$
- Step 2: Take the inverse growth rate as the relaxation timescale: τ
- Step 3: Calculate the new state as: $f_{\rm new} - f_{\rm a} = (f_{\rm old} - f_{\rm a})\exp(-\Delta t/\tau)$

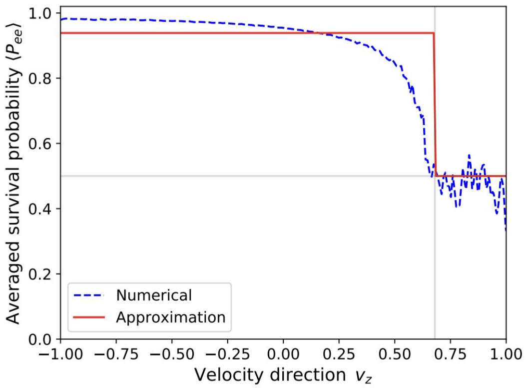
With this scheme, we can study the effects of neutrino flavor conversions in a self-consistent way.

Choice of Asymptotic States

Fast Flavor Instability

Box3D Method: Zaizen+2023, Richers+2024

$$P(\hat{n}) = \begin{cases} \frac{1}{3} & I_- < I_+, \hat{n} \in \Gamma_-, \\ 1 - \frac{2I_-}{3I_+} & I_- < I_+, \hat{n} \in \Gamma_+, \\ \frac{1}{3} & I_- > I_+, \hat{n} \in \Gamma_+, \\ 1 - \frac{2I_+}{3I_-} & I_- > I_+, \hat{n} \in \Gamma_-, \end{cases}$$



Collisional Flavor Instability

Flavor Equipartition:

$$f^a_{\nu_e}(E) = f^a_{\nu_x}(E) = \frac{f_{\nu_e}(E) + 2f_{\nu_x}(E)}{3},$$

$$f^a_{\bar{\nu}_e}(E) = f^a_{\bar{\nu}_x}(E) = \frac{f_{\bar{\nu}_e}(E) + 2f_{\bar{\nu}_x}(E)}{3}.$$

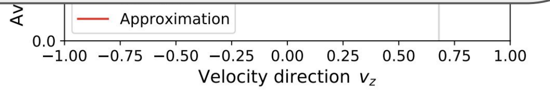
Choice of Asymptotic States

Fast Flavor Instability

Box3D Method: Zaizen+2023, Richers+2024

FFI has high growth rates, so we use a more accurate angle-dependent method.

Reconstruct neutrino angular distribution from M1 via closure relations.



Collisional Flavor Instability

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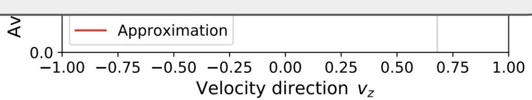
Choice of Asymptotic States

Fast Flavor Instability

Box3D Method: Zaizen+2023, Richers+2024



FFI has high growth rates, so we use a more accurate angle-dependent method.

Reconstruct neutrino angular distribution from M1 via closure relations.

Collisional Flavor Instability

Flavor Equipartition:

We use flavor equipartition because we haven't noticed any multi-group asymptotic state estimation for CFI yet.

Our results are insensitive to the choice of CFI asymptotic states.

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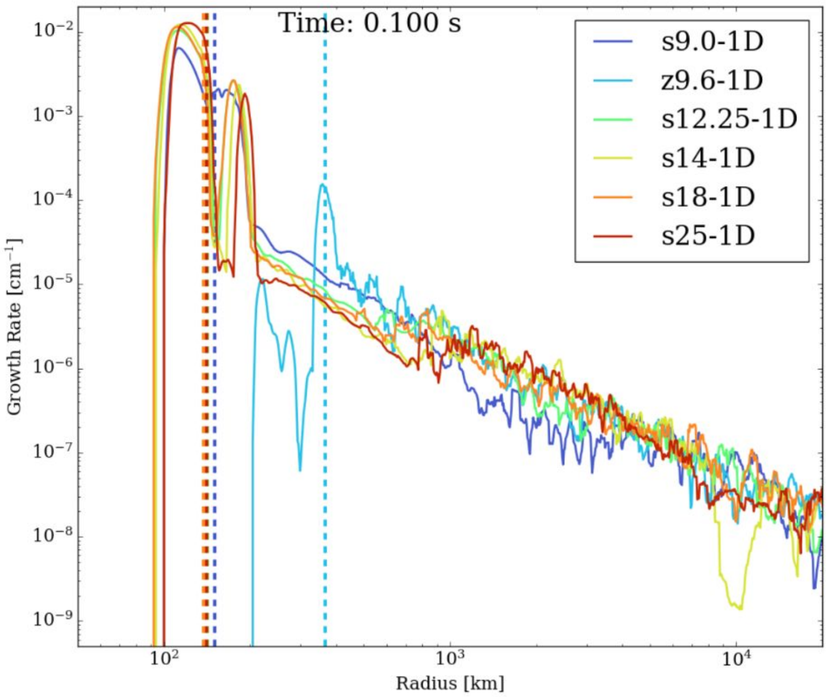
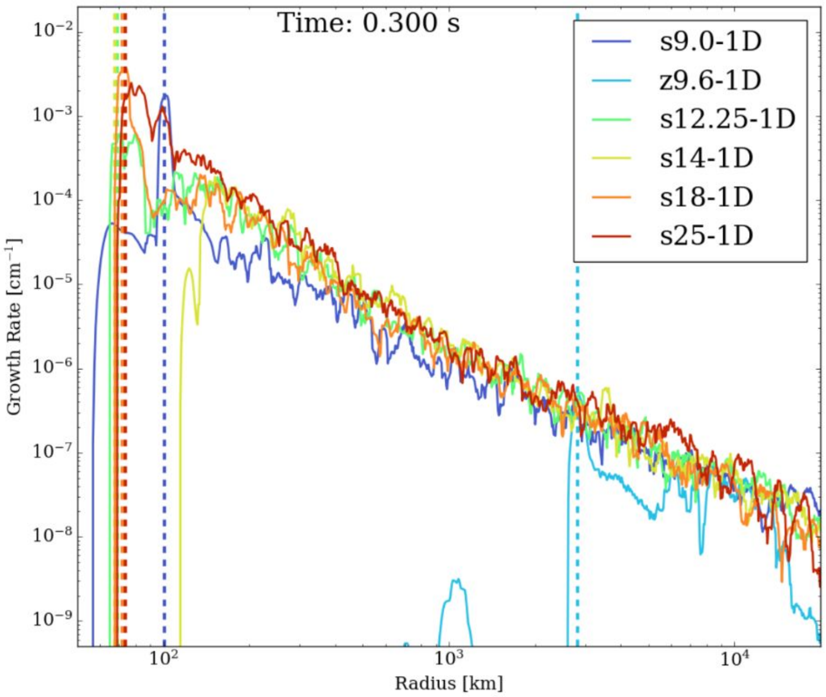
FFI: Growth Rates in Self-Consistent Models





Consistent pre-shock growth rates as previous works.
Post-shock unstable region shrinks with time.

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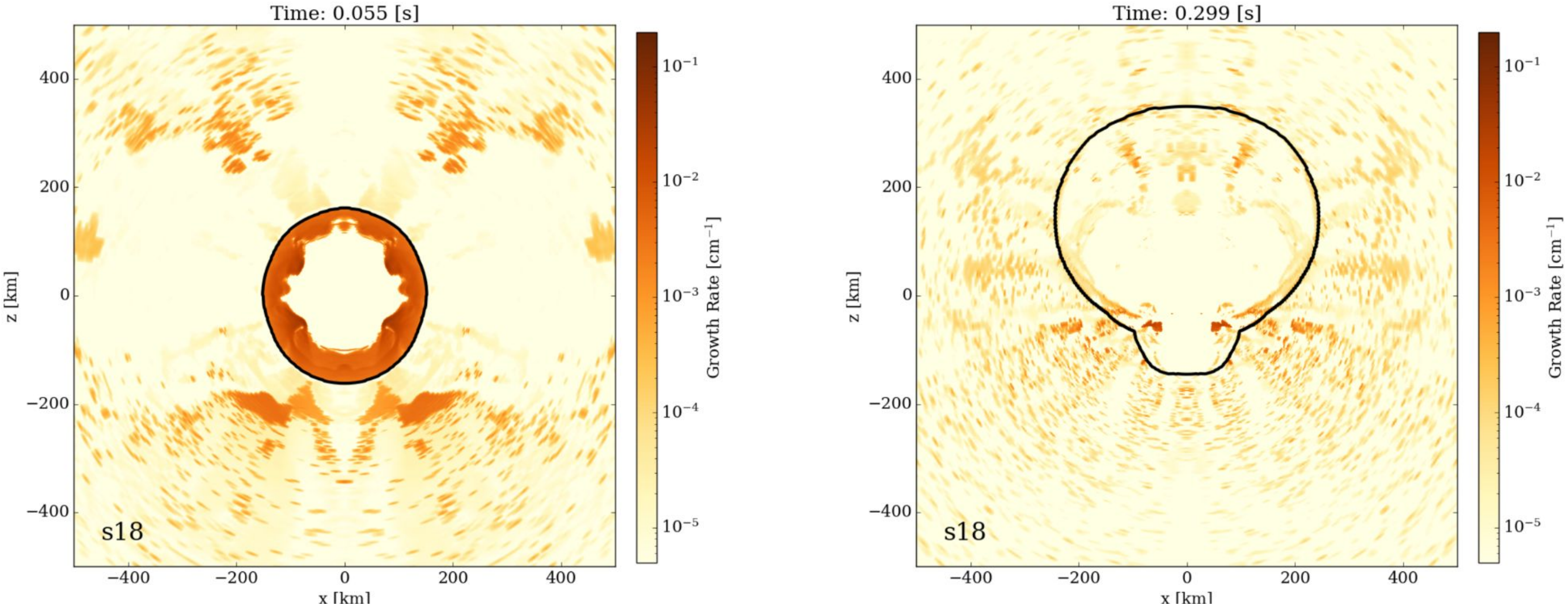
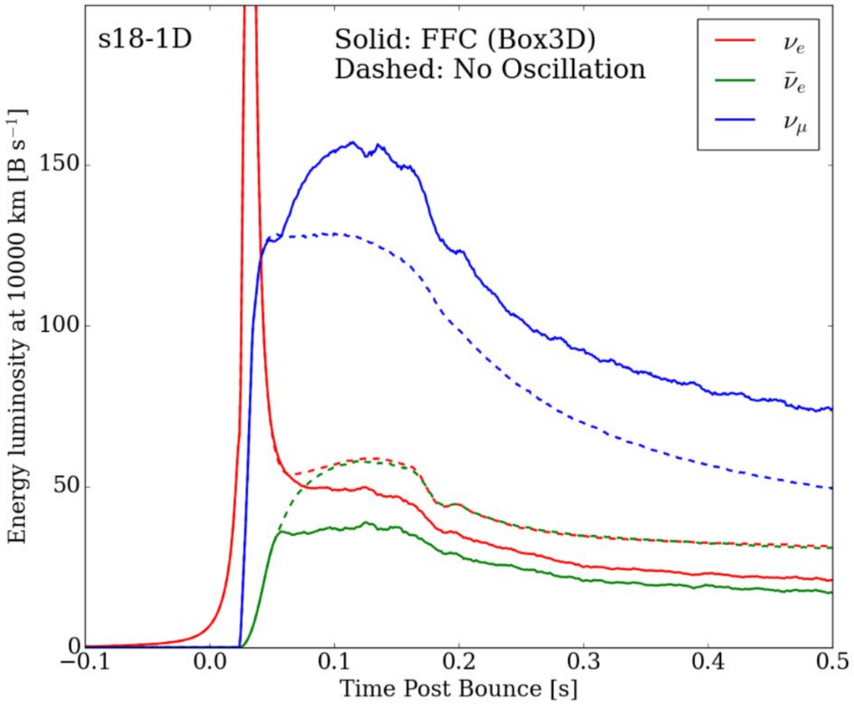
FFI: Growth Rates in Self-Consistent Models

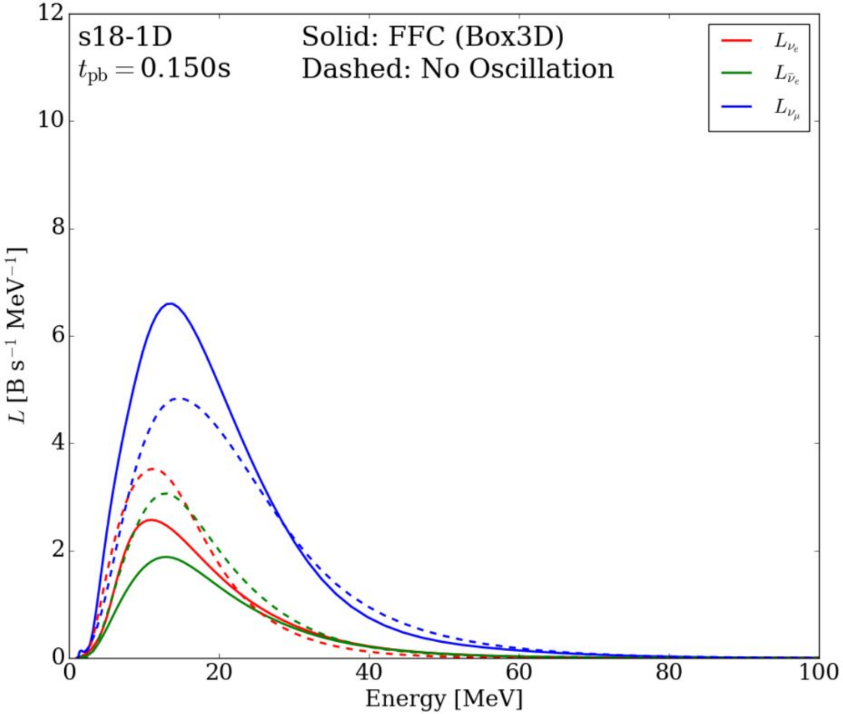


Consistent pre-shock growth rates as previous works.
Post-shock unstable region shrinks with time.

FFI: Neutrino Properties

“mu” = mu + tau + anti_mu + anti_tau





L↓, E↑: Competing Effects on CCSN dynamics

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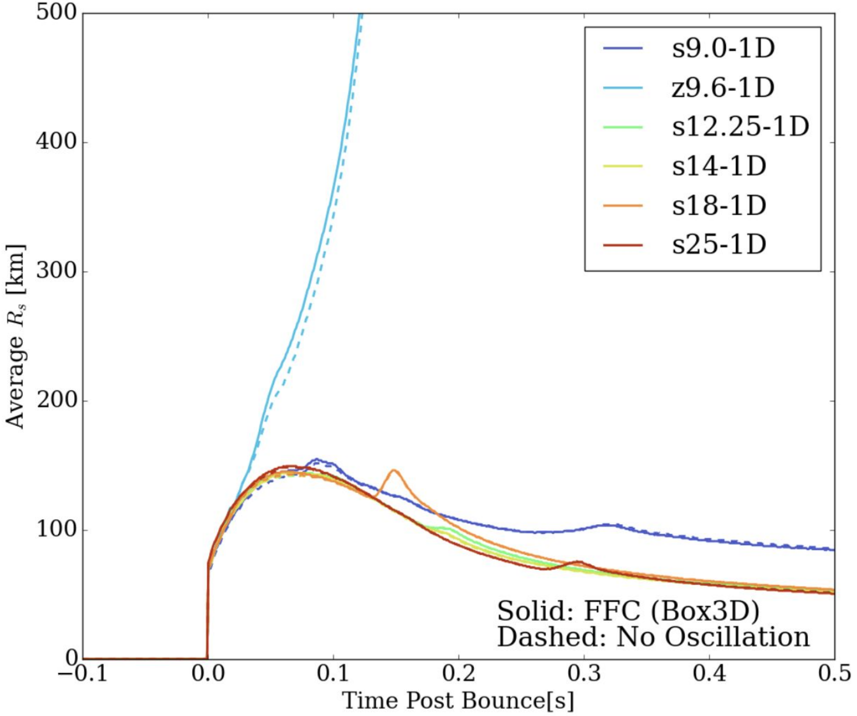
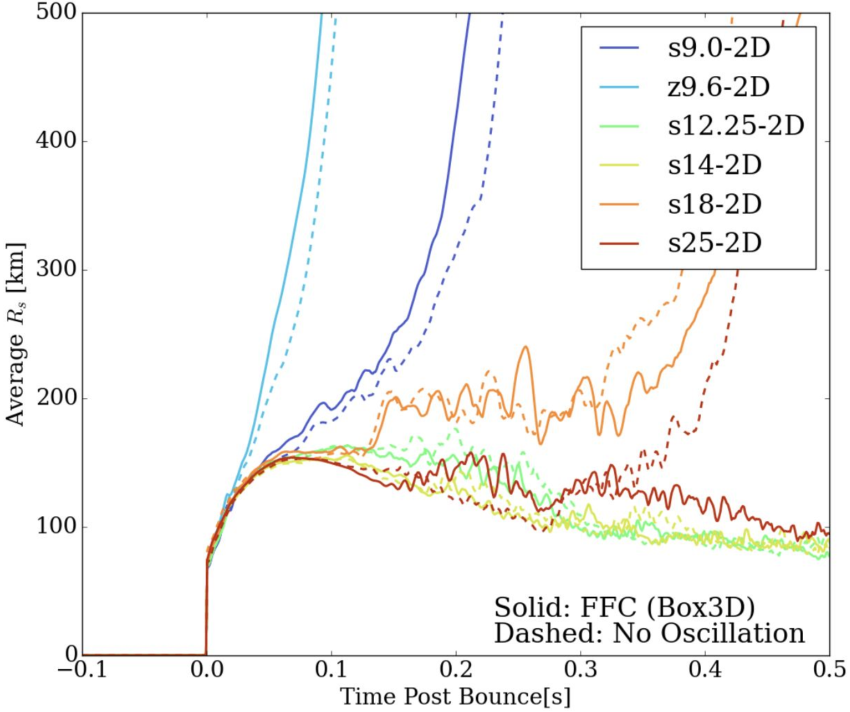
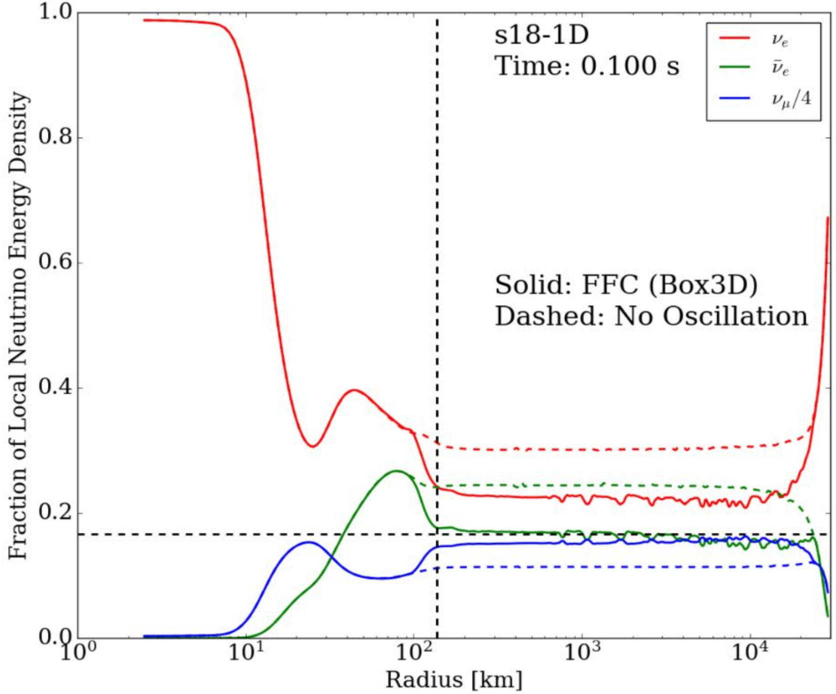
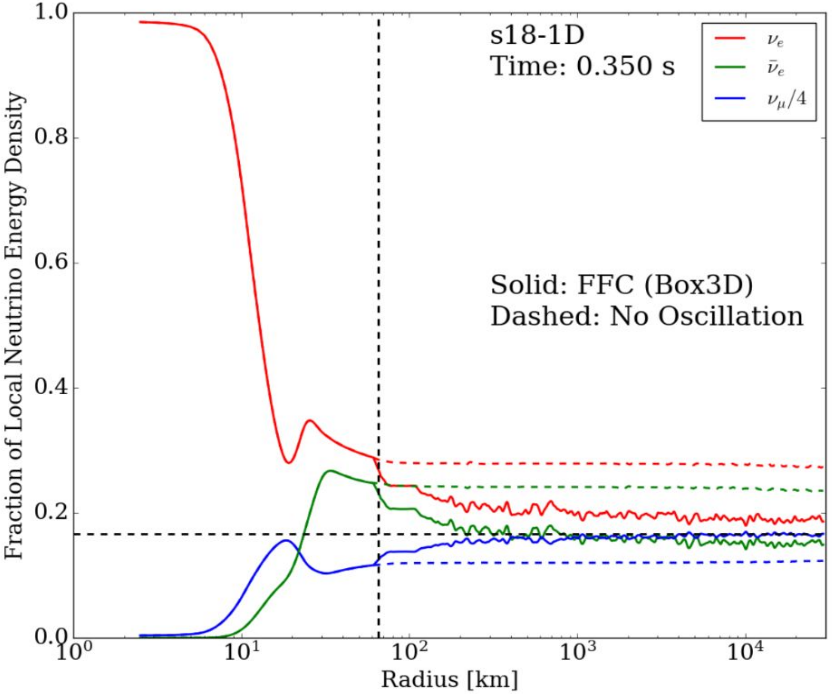
FFI: Shock Radii





FFI: Gradually Approached Equipartition





FFC shows strong impact on neutrino luminosities and spectra, but the conversion mostly happens in pre-shock region and have minor effects on hydrodynamics.

CFI: Incorrect Growth Rate Used in the Literature

$$\det(\varepsilon_{\mu\nu}) = 0 \qquad \varepsilon_{\mu\nu} = g_{\mu\nu} - \mu \int \frac{E^2 dE}{2\pi^2} \left[\frac{f_e(E) - f_x(E)}{\omega + i\Gamma_E} - \frac{\bar{f}_e(E) - \bar{f}_x(E)}{\omega + i\bar{\Gamma}_E} \right] \int \frac{d\Omega}{4\pi} v_\mu v_\nu$$

CFI assumes isotropic neutrino distribution and vanishing vacuum term. If neutrinos are also monochromatic, the growth rates can be analytically solved.

For non-monochromatic neutrinos, it has been argued that the monochromatic formula can still be applied, as long as physical quantities are averaged over the spectra. But this argument is problematic in the realistic multi-group context.

Previous CFI studies either do complex QKE simulations or use the monochromatic formula.

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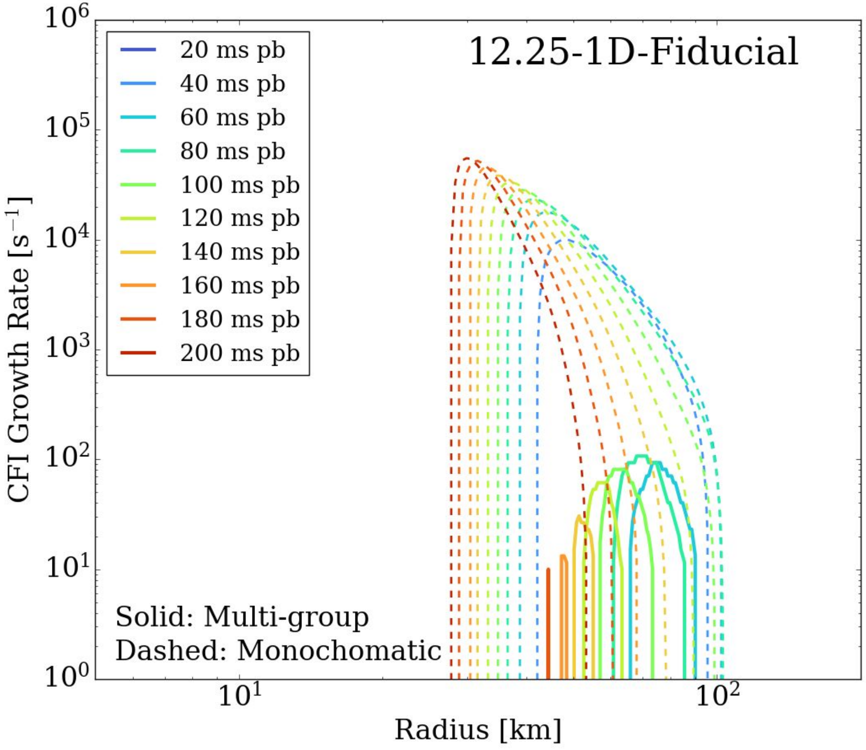
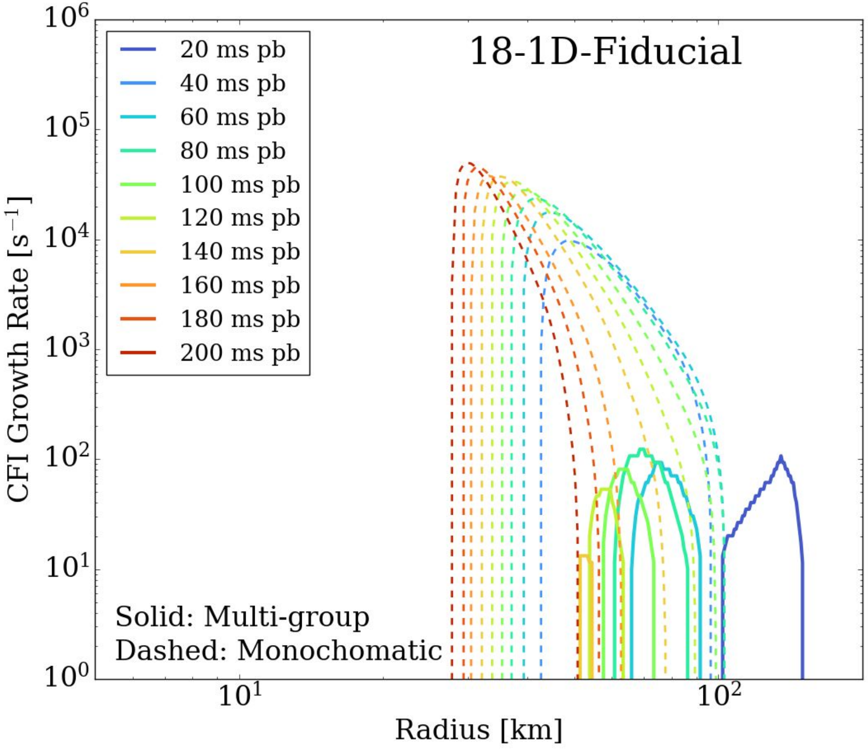
CFI: Monochromatic Formula vs Correct Growth Rate





Monochromatic formula overestimates the growth rates by ~3 orders of magnitudes!

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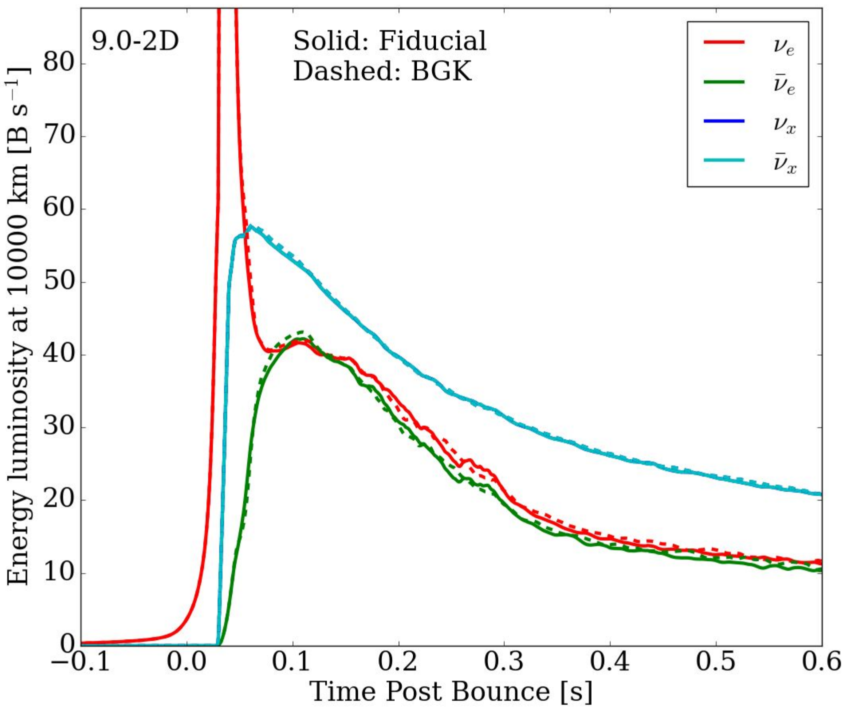
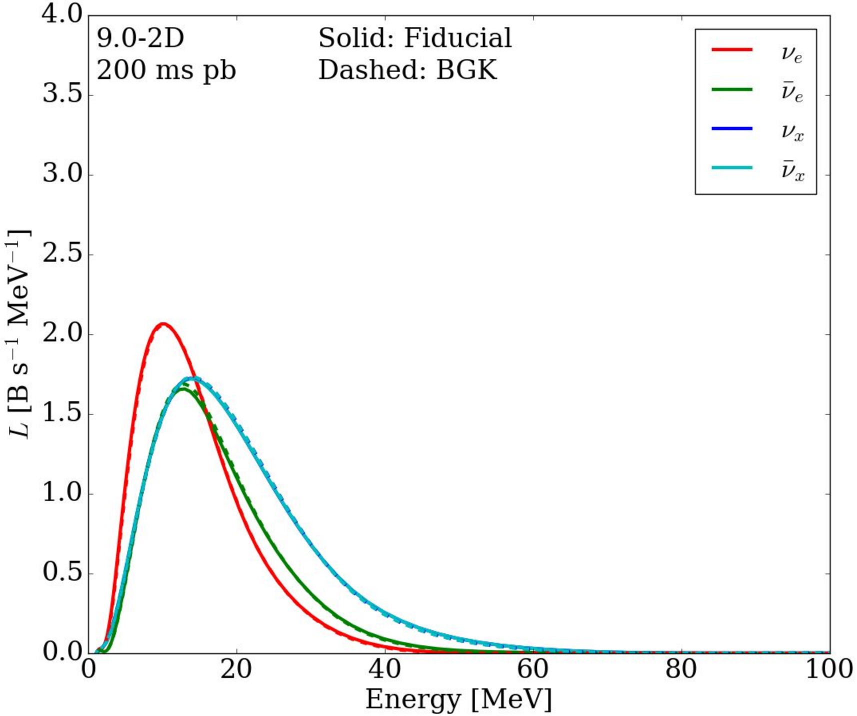
CFI: Neutrino Properties





Effects of CFI are negligible when the correct growth rates are used.

Conclusion:

We study the effects of neutrino flavor conversion induced by FFI and CFI on CCSN dynamics in a self-consistent way. We find that:

- The FFI impact on CCSN dynamics is significantly weaker than previously estimated by the phenomenological method. We see shrinking post-shock FFI region and slowly approached equipartition at ~1000km.
- The widely used monochromatic formula of CFI growth rate is incorrect. With the correct growth rates, the CFI impact becomes negligible.

In general, the effects of such flavor conversions on CCSN dynamics are weaker than expected in previous works.