散乱過程に誘発される ニュートリノ集団振動

Collective Neutrino Oscillation Induced by Scattering Process

財前 真理

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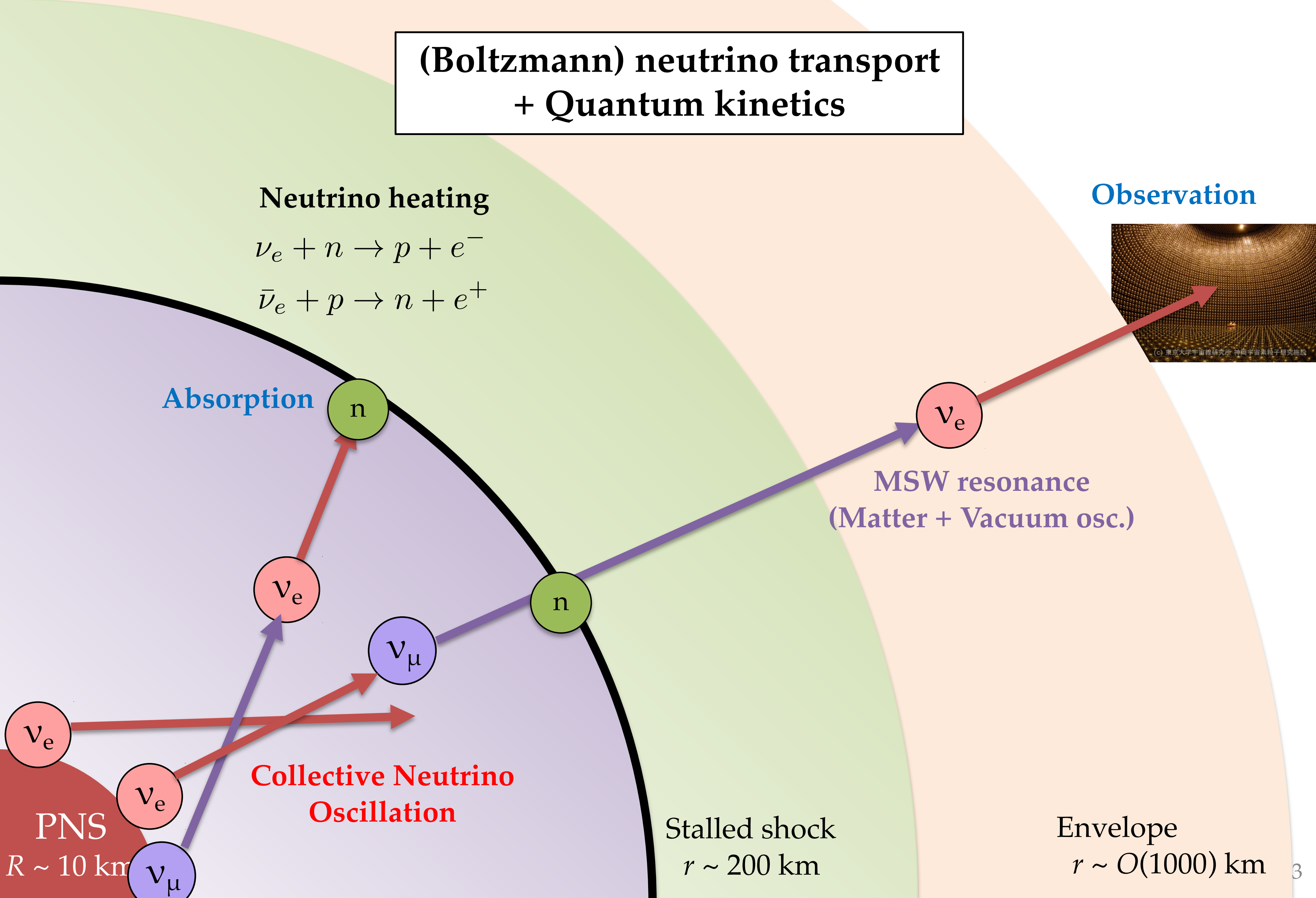
Outline

1. Introduction
    1. Collective oscillation & Flavor instability

2. Recent understandings (< 1 yr.)
    1. What do we know about flavor conversion in CCSNe?
    2. What's left to do?

3. My current task
    1. Flavor conversion induced by nucleon scattering
    2. Linear stability analysis

Neutrino Oscillation in CCSN



(Boltzmann) neutrino transport
+ Quantum kinetics

Neutrino heating

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

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

Observation

(c) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設

Absorption

n

ν_e

MSW resonance
(Matter + Vacuum osc.)

ν_e

n

ν_μ

ν_e

ν_e

Collective Neutrino
Oscillation

PNS
R ~ 10 km

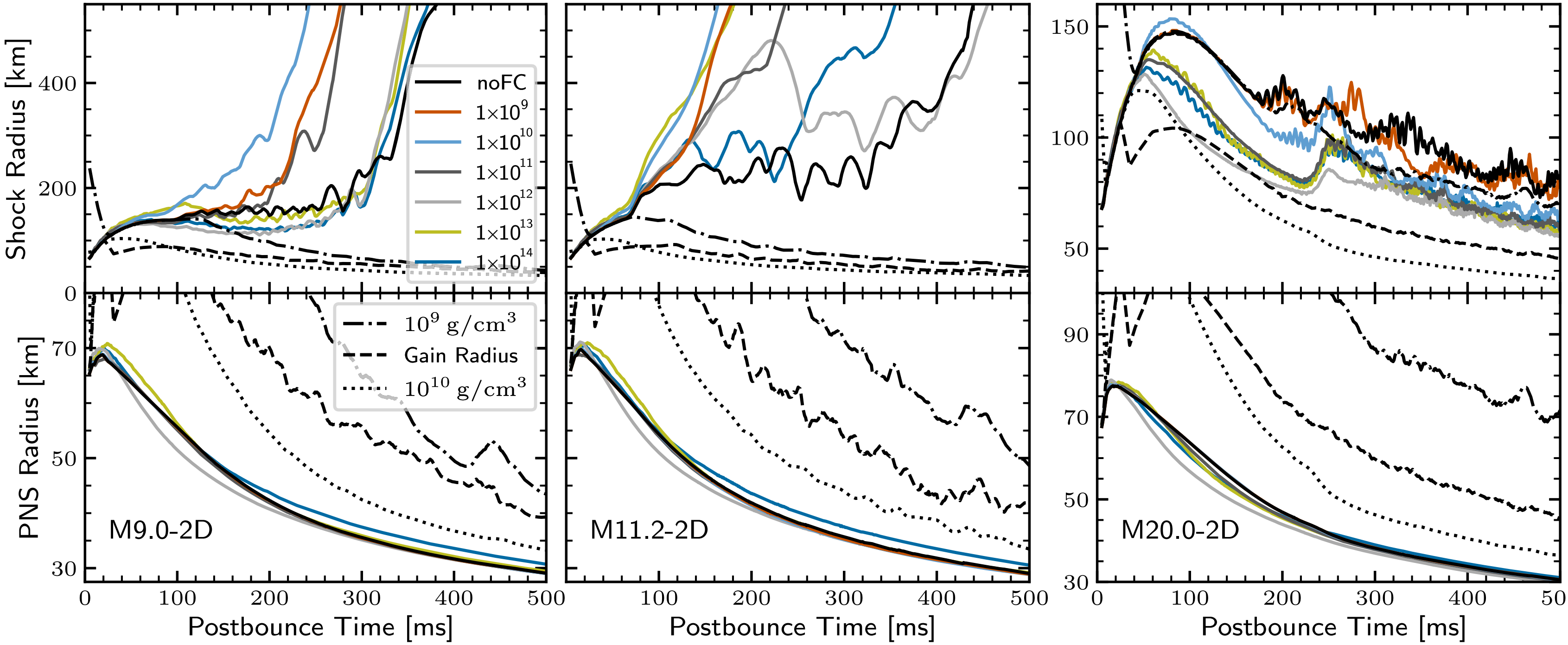
ν_μ

Stalled shock
r ~ 200 km

Envelope
r ~ O(1000) km

Impacts on CCSN

Ehring+ PRL '23



Assume that flavor conversion (flavor equilibrium) occurs at a critical matter density roughly.
Impact the explodability by changing heating & cooling at the location of the occurrence of flavor conversion.

Need more detailed analysis for flavor conversion!!

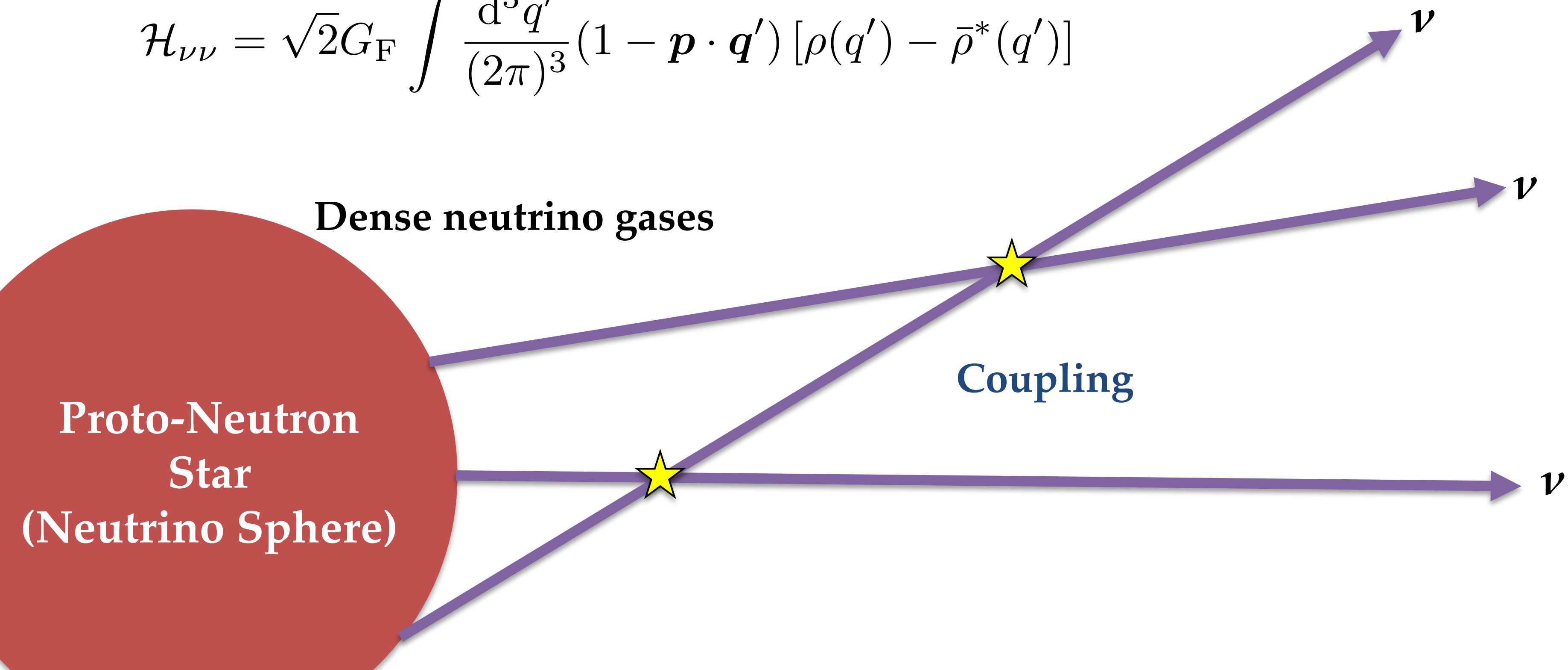
Quantum Kinetics

Quantum Kinetic Equation:

$$(\partial_t + \boldsymbol{v}\cdot\nabla)\rho = -\mathrm{i}\left[\mathcal{H}_{\mathrm{vac}} + \mathcal{H}_{\mathrm{mat}} + \mathcal{H}_{\nu\nu},\ \rho\right] + \mathcal{C}_{\mathrm{col}}$$

Neutrino self-interactions

$$\mathcal{H}_{\nu\nu} = \sqrt{2}G_{\mathrm{F}}\int\frac{\mathrm{d}^3q'}{(2\pi)^3}(1-\boldsymbol{p}\cdot\boldsymbol{q}')\left[\rho(q') - \bar{\rho}^*(q')\right]$$



Dense neutrino gases

ν

ν

Coupling

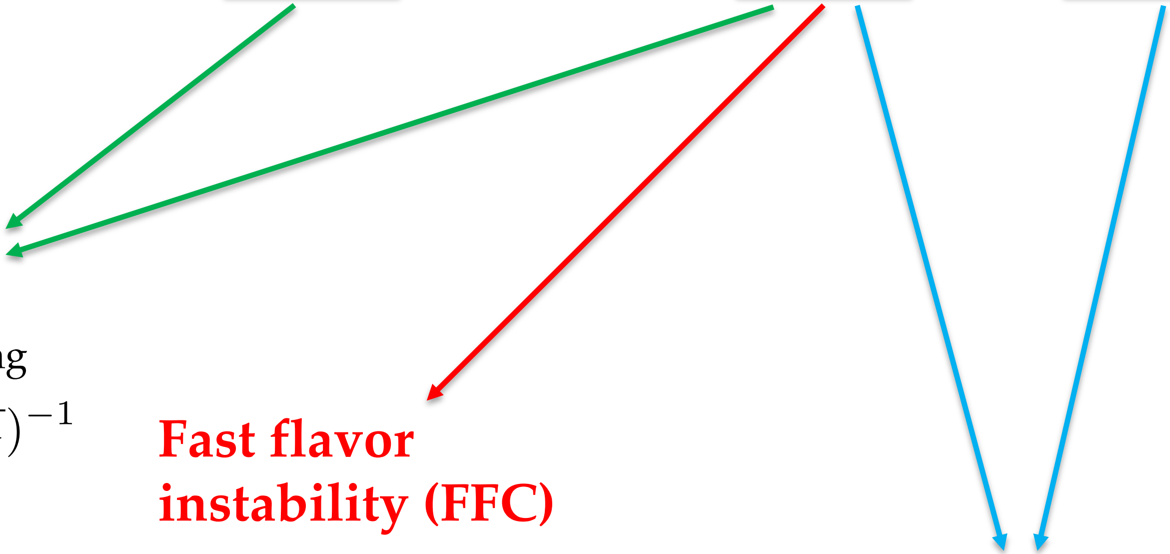
ν

Proto-Neutron Star (Neutrino Sphere)

Instability Modes

Quantum Kinetic Equation:

$$(\partial_t + \boldsymbol{v}\cdot\nabla)\rho = -\mathrm{i}\,[\underline{\mathcal{H}_{\mathrm{vac}}} + \mathcal{H}_{\mathrm{mat}} + \underline{\mathcal{H}_{\nu\nu},}\ \rho] + \underline{\mathcal{C}_{\mathrm{col}}}$$



Slow flavor instability

By energy crossing

$$\tau_{\mathrm{slow}} \sim \mathcal{O}(\sqrt{\mu\omega_{\mathrm{v}}})^{-1}$$

e.g.,
Duan+ '06,
Chakraborty+ '16

Fast flavor instability (FFC)

By angular crossing

$$\tau_{\mathrm{fast}} \sim \mathcal{O}(\mu^{-1}) \sim \mathcal{O}(G_{\mathrm{F}}n_{\nu})^{-1}$$

e.g.,
Sawyer '05 & '16, Izaguirre+ '17,
Wu+ '22, MZ+ '23 …

Collisional flavor instability (CFI)

By disparity in collision rates

$$\tau_{\mathrm{col}} \sim \mathcal{O}(\sqrt{\mu\Gamma})^{-1} - \mathcal{O}(\Gamma)^{-1}$$

e.g.,
Johns '23 & 22, Duan+ '22, Xiong+ '23,
Liu+ '23a & '23b, Kato+ '23, Akaho+ '23 …

Fast Flavor Conversion (FFC)

Fast Flavor Conversions (FFC)

- Short scale of **~ $(G_{\mathrm{F}}\, n_{\nu})^{-1} \lesssim O(\mathrm{cm})$ or $O(\mathrm{ns})$**. << stellar scale-height
- Triggered by ``**angular crossings**" in neutrino lepton number.

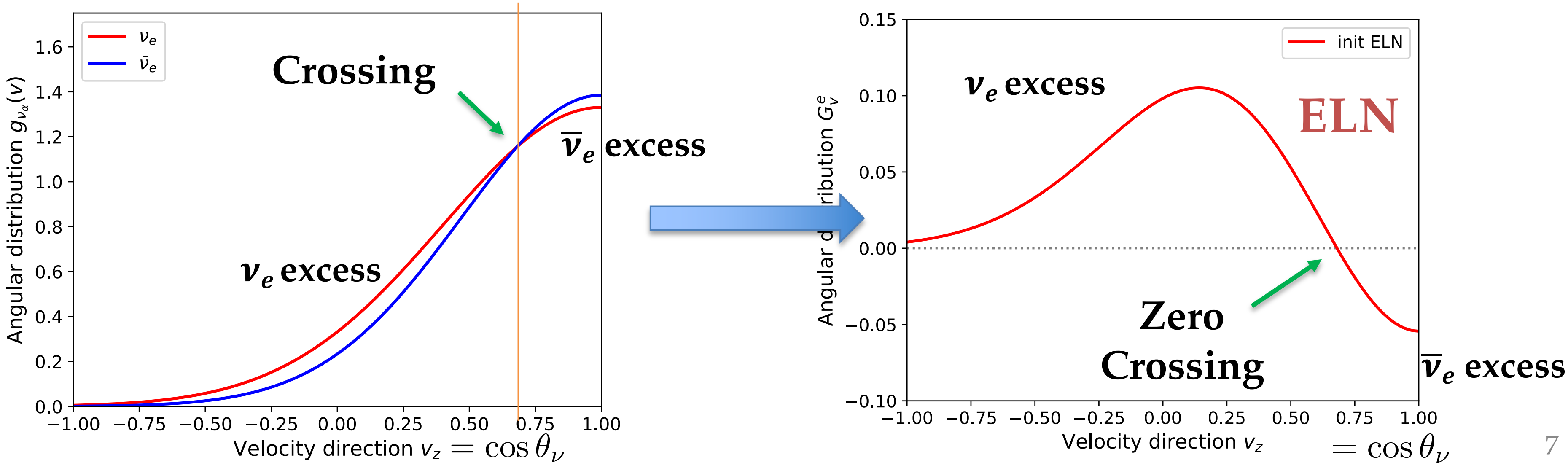
Izaguirre+ **'17**

Neutrino-flavor lepton number (NFLN) angular distribution.

$$G_{\boldsymbol{v}}^{ex} = \sqrt{2} G_{\mathrm{F}} \int \frac{E^2 \mathrm{d}E}{2\pi^2} \left[(f_{\nu_e} - f_{\bar{\nu}_e}) - (f_{\nu_x} - f_{\bar{\nu}_x}) \right]$$

= **ELN** − **XLN**

(Electron Lepton Number) **(Heavy-leptonic one)**



Collisional Flavor Instability (CFI)

Quantum Kinetic Equation:

$$(\partial_t + \boldsymbol{v}\cdot\nabla)\rho = -\mathrm{i}\left[\mathcal{H}_{\nu\nu},\ \rho\right] \boxed{+\,\mathcal{C}_{\mathrm{col}}[\rho]}$$

Collision decoheres neutrinos.

→ Usually suppress flavor instability

Shalgar+ '21, Kato+ '21, Sasaki+ '22
Martin+ '21, Sigl '22, Johns+ '22

$$\rho = \begin{pmatrix} f_{\nu_e} & S_{ex} \\ S^*_{ex} & f_{\nu_x} \end{pmatrix}$$

$$\mathcal{C}_{\mathrm{col}}[\rho] \sim \frac{1}{2}\{\mathrm{diag}(\Gamma_e, \Gamma_x), \rho_{\mathrm{eq}} - \rho\}$$

Off-diagonal components:

$$(\partial_t + \boldsymbol{v}\cdot\nabla)S_{ex} = -\sqrt{2}G_{\mathrm{F}}(f_{\nu_e} - f_{\nu_x})\int \mathrm{d}^3q'(1 - \hat{p}\cdot\hat{q}')S'_{ex} - \mathrm{i}\Gamma_{ex}S_{ex}$$

differential effect between ν and $\bar{\nu}$

$$\Gamma \neq \bar{\Gamma}$$

→ **Flavor instability**

(Relatively slower scale)

Johns '21 & PRL '23

Flavor Instability in CCSNe

CFI for emission & absorption occurs universally regardless of progenitor mass even for 1D model.

Liu+ PRD '23b

Liu, MZ, Yamada PRD '23a

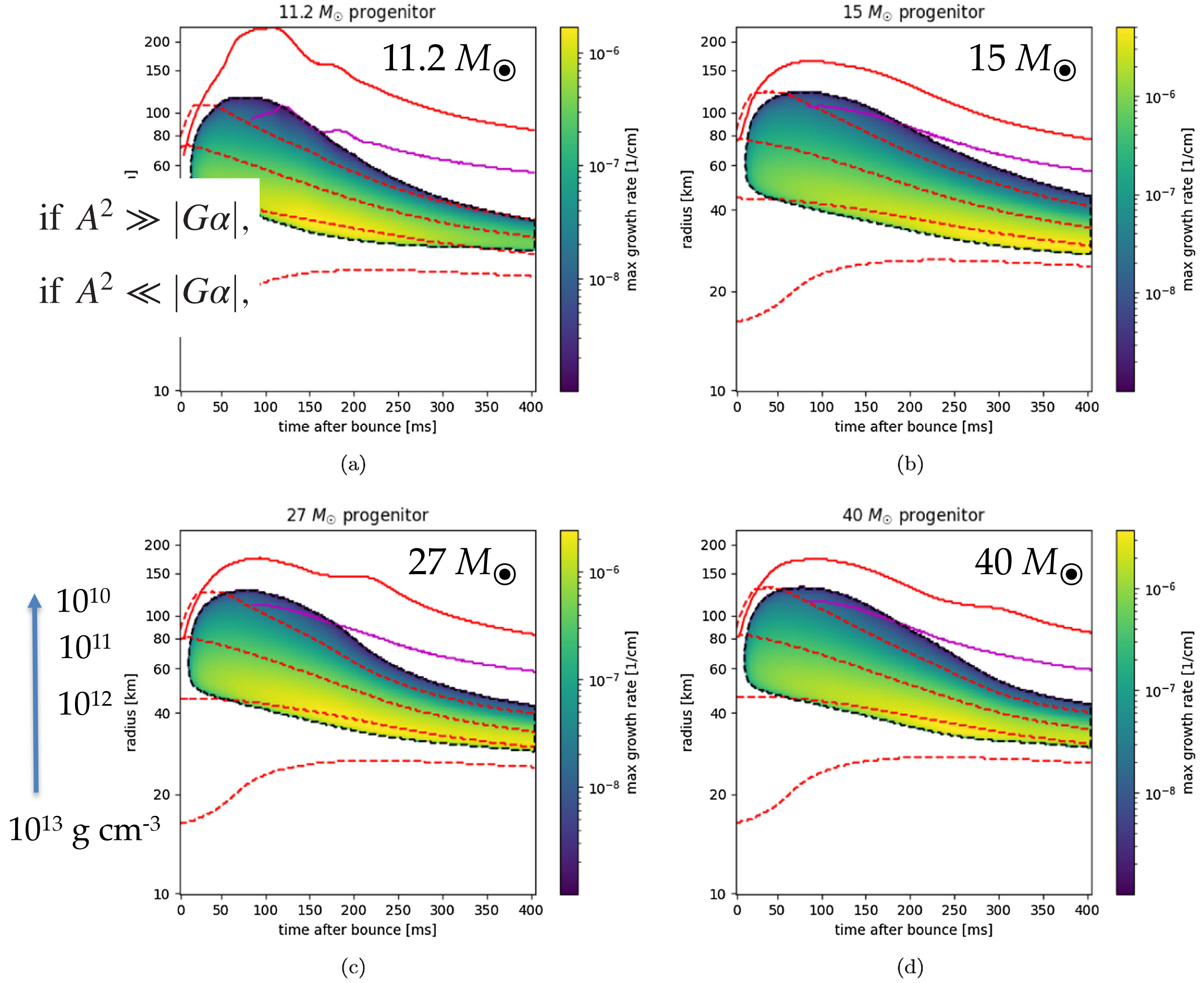
Approximate growth rate

$$\max[\operatorname{Im}\omega] = \begin{cases} -\gamma + \dfrac{|G\alpha|}{|A|}, & \text{if } A^2 \gg |G\alpha|, \\ -\gamma + \sqrt{|G\alpha|}, & \text{if } A^2 \ll |G\alpha|, \end{cases}$$

$$\gamma = \frac{\Gamma + \bar{\Gamma}}{2}, \quad \alpha = \frac{\Gamma - \bar{\Gamma}}{2},$$

$$G = \frac{\mathfrak{g} + \bar{\mathfrak{g}}}{2}, \quad A = \frac{\mathfrak{g} - \bar{\mathfrak{g}}}{2},$$

$$\mathfrak{g} = \sqrt{2} G_{\mathrm{F}} (n_{\nu_e} - n_{\nu_x})$$

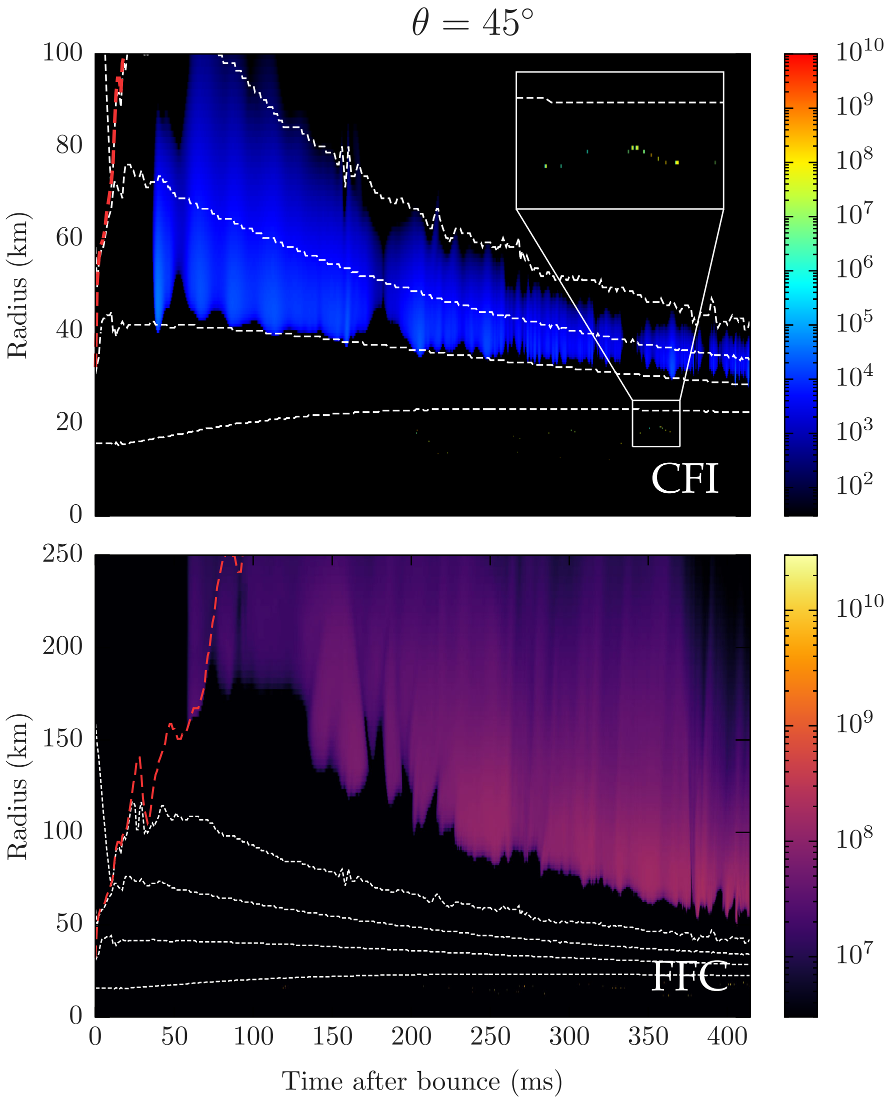


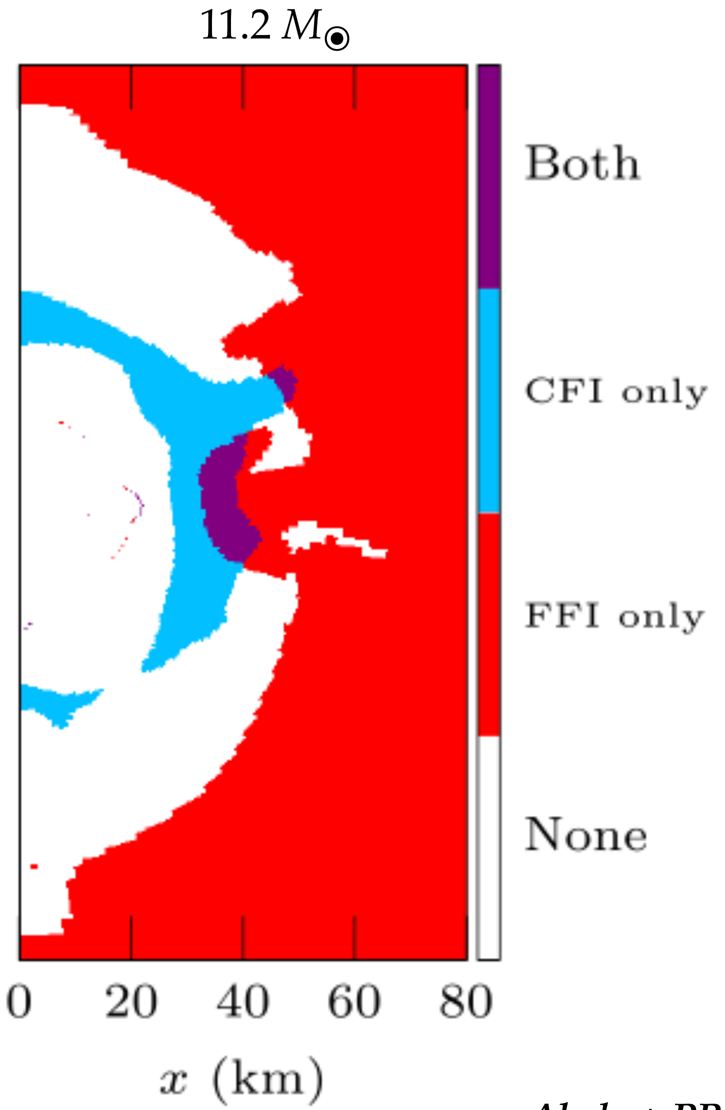
(a) (b) (c) (d)

Constant density surface

Flavor Instability in CCSNe

For 2D model, the regions of CFI and FFC are almost decoupled.





Akaho+ PRD '23

Sub-grid Model

Sub-grid model for neutrino oscillation term in QKE:

Bhatnagar-Gross-Krook (BGK) relaxation-time prescription

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

↓

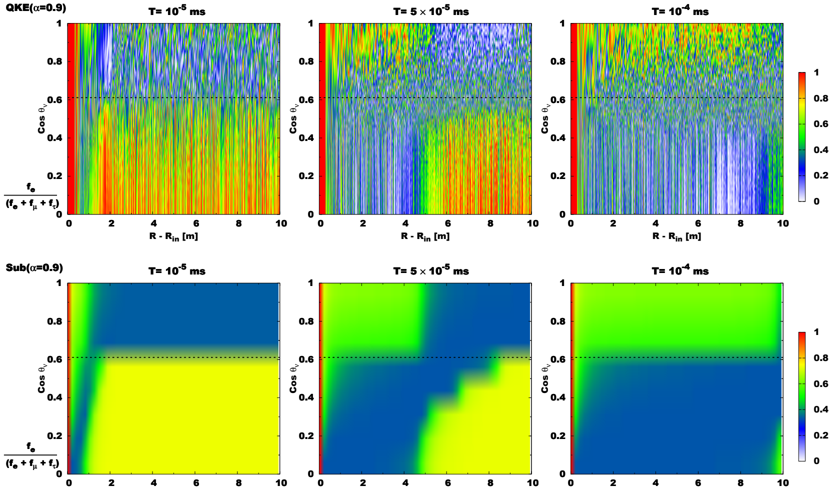
Nagakura, Johns, & MZ '23
BGK relaxation

$$p^{\mu}\frac{\partial f}{\partial x^{\mu}} + \frac{dp^{i}}{d\tau}\frac{\partial f}{\partial p^{i}} = -p^{\mu}u_{\mu}S + p^{\mu}n_{\mu}\frac{1}{\tau_a}(f - f^{a}).$$

τ_a : Growth rate corresponding to flavor instability

f_a : Asymptotic states for neutrino density matrix

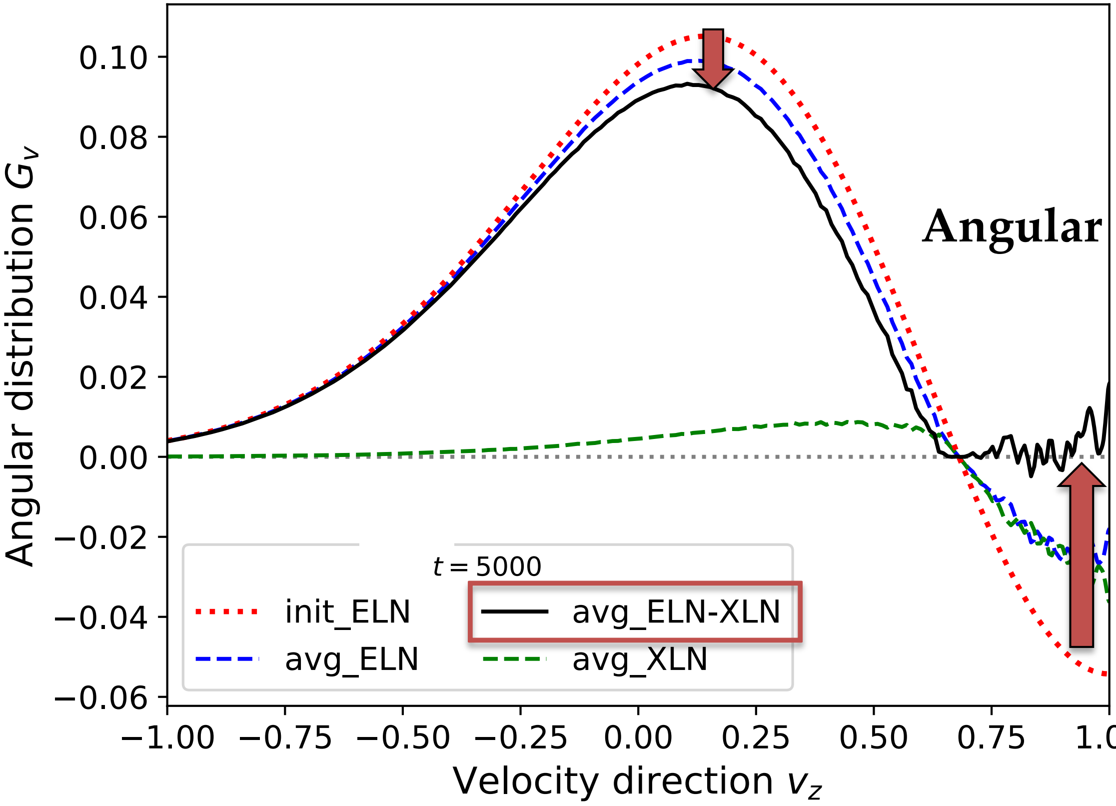
Flavor evolution can be reproduced on lower resolution with sub-grid model (for FFC) →



How are asymptotic states for each flavor instability determined?

Asymptotic States for FFC

MZ & Nagakura PRD '23



Angular dist. at final state.

ELN still has a crossing.

No Crossing **in ELN-XLN !!**

Stability at nonlinear saturation:

Disappearance of in ELN-XLN angular crossing ⇄ Establishment of quasi-steady state of FFC

(Reach a consensus in oscillation community.)

Asymptotic States for CFI

Angular crossing in ELN-XLN induces flavor instability,
and FFC stabilizes the system.
So simple.
(But we still have some questions in FFC.)

Then, what determines asymptotic states for CFI?
→ We haven't found it yet.

Maybe CFI proceeds until the system is stabilized?
→ What determines the stability of CFI?
→ CFI is more complicated than FFC.

FFC is driven only by neutrino self-interactions.
Therefore, the asymptotic states are also determined only by neutrino distributions.

Asymptotic States for CFI

CFI is more complicated than FFC.

$$(\partial_t + \boldsymbol{v} \cdot \nabla)\rho = -\mathrm{i}\,[\mathcal{H}_{\nu\nu},\ \rho] + \mathcal{C}_{\mathrm{col}}[\rho]$$

1. CFI is induced by both their self-interactions and collision term.

→ Need to consider the combination for asymptotic states.

2. Also, the growth rate is scaled by collision rates.

→ Neutrino distributions are relaxed during flavor evolution.

3. Also, collision term contains a variety of neutrino reactions.

e.g., emission & absorption,

scattering off nucleons & electrons,

(include recoil and weak-magnetism)

pair processes, …

→ Need to consider asymptotic states for each reaction.

CFI for scattering

Neutrino distributions are relaxed during flavor evolution.

Linear stability analysis assumes that background is stationary.

Scattering isotropizes neutrino angular distributions and the process is non-stationary.

→ Anisotropy = collisions + inhomogeneity (advection)

$$(\partial_t + \boldsymbol{v} \cdot \nabla)\rho = -\mathrm{i}\,\cancel{[\mathcal{H}_{\nu\nu},\, \rho]} + \mathcal{C}_{\mathrm{NNS}}$$

OFF = Classical transport

↓

$$(\partial_t + \boldsymbol{v} \cdot \nabla)\rho = -\mathrm{i}\,[\mathcal{H}_{\nu\nu},\, \rho] + \mathcal{C}_{\mathrm{NNS}}$$

ON = Quantum kinetic transport

Test Calculations

$$(\partial_t + \boldsymbol{v}\cdot\nabla)\rho = -\mathrm{i}\,[\mathcal{H}_{\nu\nu},\,\rho] + \mathcal{C}_{\mathrm{NNS}}$$

$$H_{\nu\nu} = \mu_{\nu_e}\int E'^2\mathrm{d}E'\mathrm{d}\Omega'(1-\boldsymbol{v}\cdot\boldsymbol{v}')(\rho'-\alpha\bar{\rho}')$$

Iso-energetic NNS = Flavor blind

$$\mathcal{C}_{\mathrm{NNS}} = \int \mathrm{d}v'(\kappa_0+\kappa_1 v v')(\rho'-\rho)$$

$$\mu_{\nu_e} \equiv \sqrt{2}G_{\mathrm{F}}n_{\nu_e} = 1$$

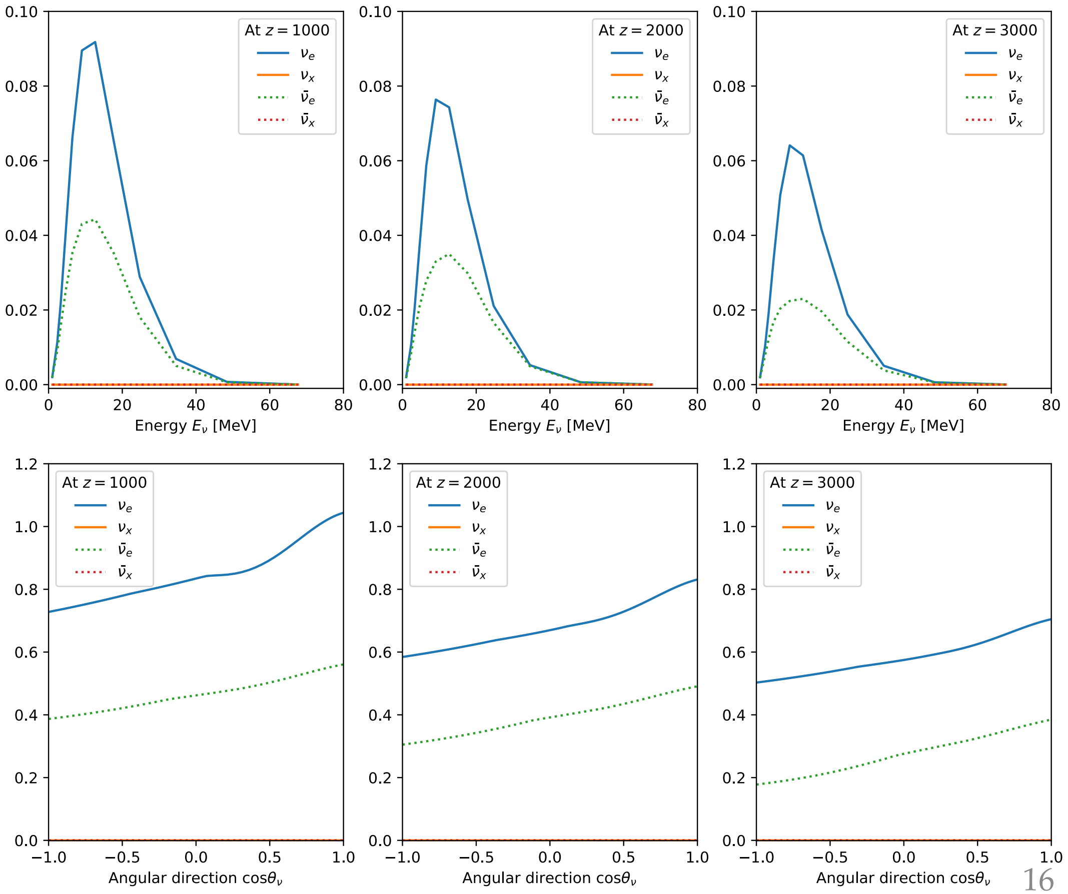
$$L_z = 4000/\mu_{\nu_e}$$

$$\kappa_0 = 10^{-3}\mu_{\nu_e}\left(\frac{E}{10\,\mathrm{MeV}}\right)^2$$

$$\alpha = n_{\bar{\nu}_e}/n_{\nu_e}$$

No angular crossing & vacuum term
= Only CFI

Initially electron-type only.



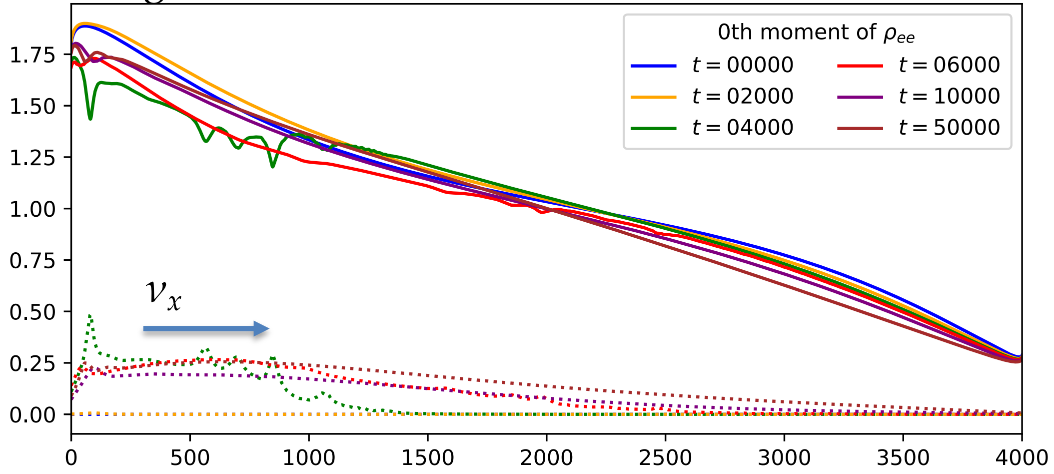
Evolution of CFI

$$M^0_{\alpha\beta} \equiv \int E^2 \mathrm{d}E \mathrm{d}\Omega\, \rho_{\alpha\beta}$$

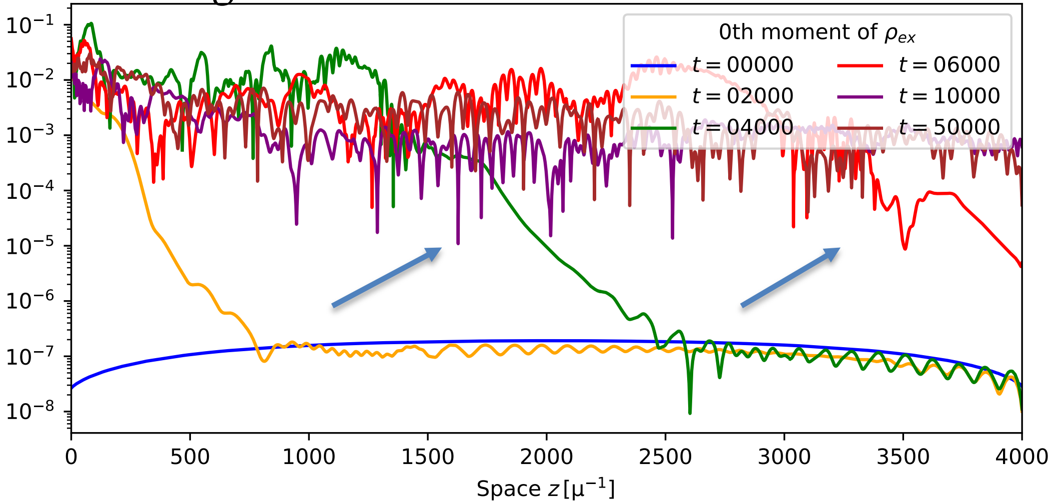
0th angular moment of density matrix:
diagonal. : number density
off-diagonal : flavor correlation.

Flavor instability grows with advection (see bottom panel).

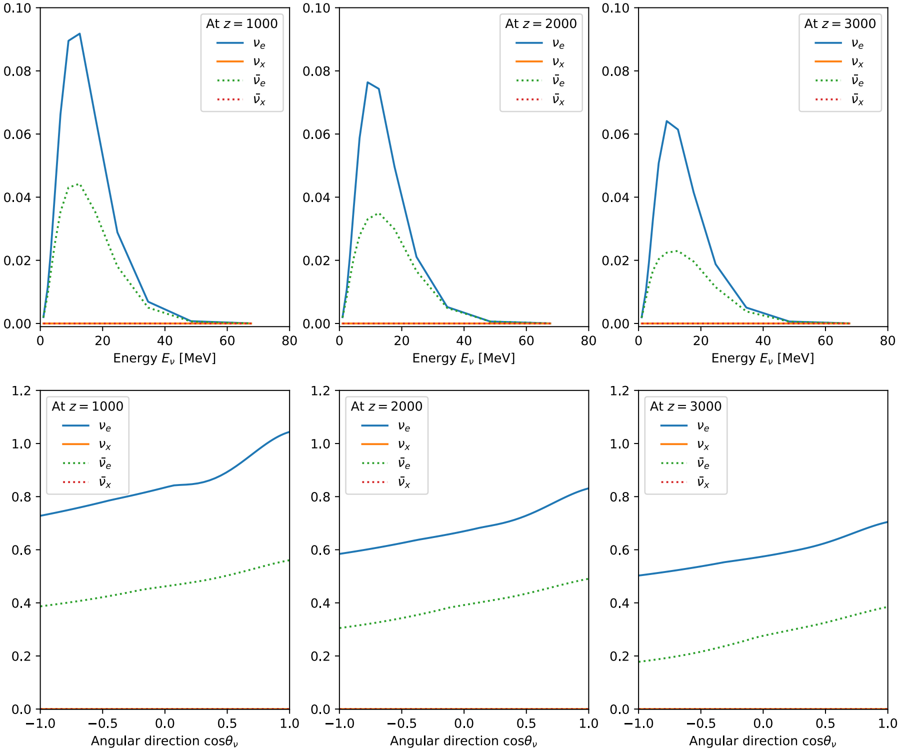
Diagonal



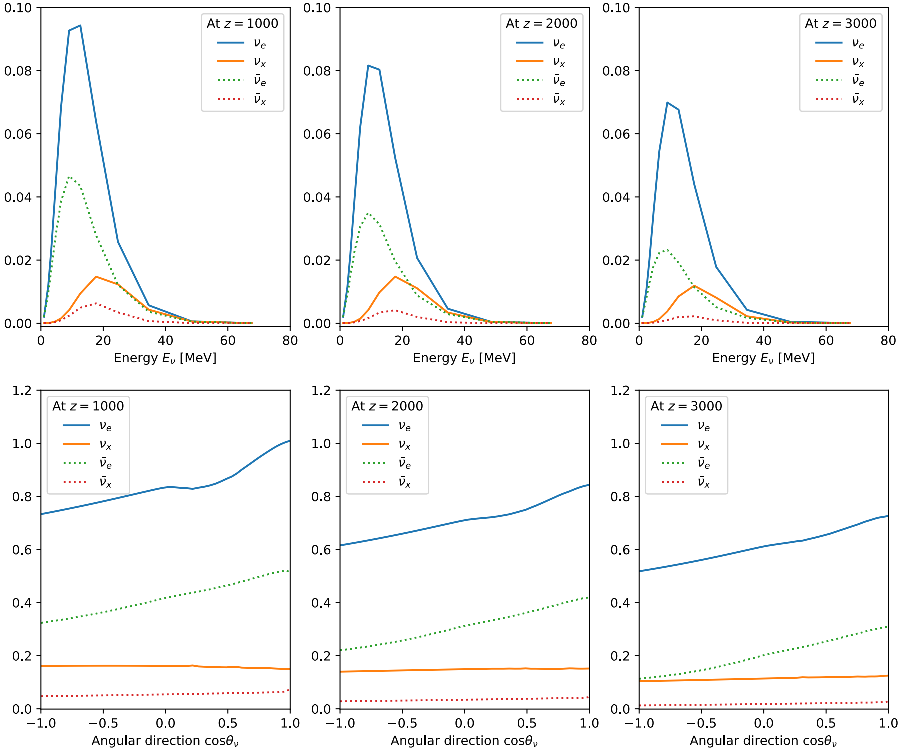
Off-diagonal



Asymptotic States for CFI



$t = 0$



$t = 50{,}000$

Heavy-leptonic neutrinos ν_x is generated by CFI.
Quantum kinetic neutrino transport works well.
→ Stability?

Summary

1. **Quantum kinetics for neutrinos dramatically changes the neutrino-radiation field.**

2. **Collective neutrino oscillation induced by their self-interactions, particularly fast & collisional flavor instability, emerges universally in CCSNe.**

3. **Approximate scheme as sub-grid model for neutrino flavor conversion has been developed.**
   1. **Need corresponding asymptotic state and growth rate.**
   2. **Preparation for fast flavor conversion (FFC) is ok.**
   3. **But that for collisional flavor instability (CFI) remains unexplored.**

4. **We investigate CFI driven by nucleon scatterings**
   1. **Flavor conversion for flavor-blind scattering process appears.**
   2. **Under the preparation of linear stability analysis for scattering.**