集団振動を伴うニュートリノ輸送に対して背景物質の密度勾配がもたらす影響

Quantum Kinetic Neutrino Transport with Global Matter Gradient

in prep.

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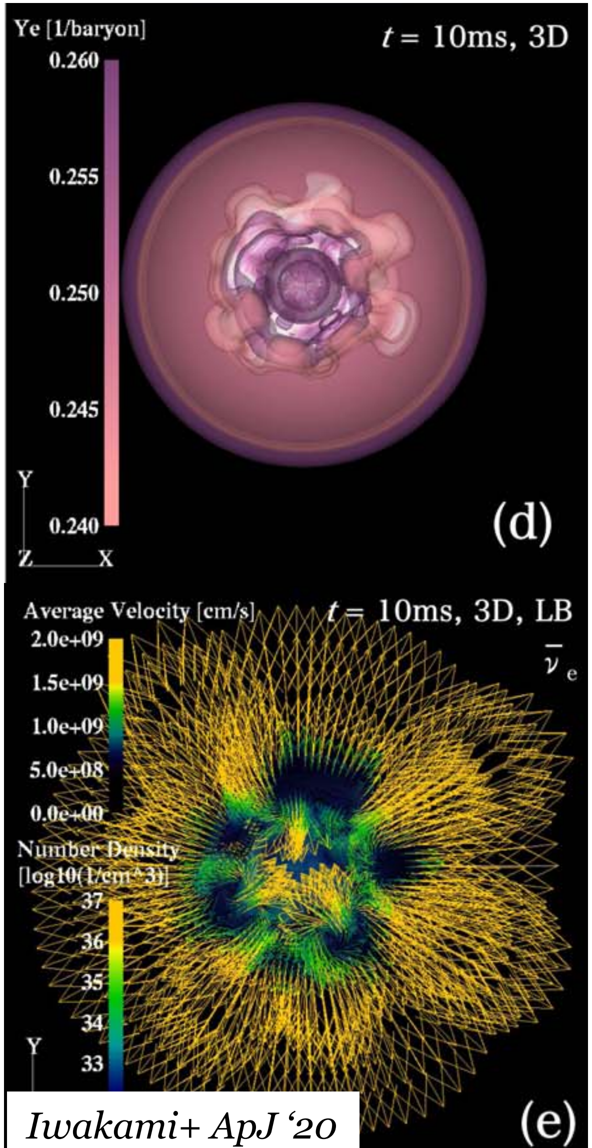
Mar. 10, 2026

第12回超新星ニュートリノ研究会 @沼津

Neutrino Physics in CCSN

Core-collapse supernova (CCSN)



Iwakami+ ApJ '20

CCSN: forming an extreme environment in the center.

e.g., Nuclear density

Neutrinos: coupling weakly with matters

→ As a ***mediator*** for thermal energy

→ Affect the dynamics and the observables.

e.g., Neutrino heating mechanism

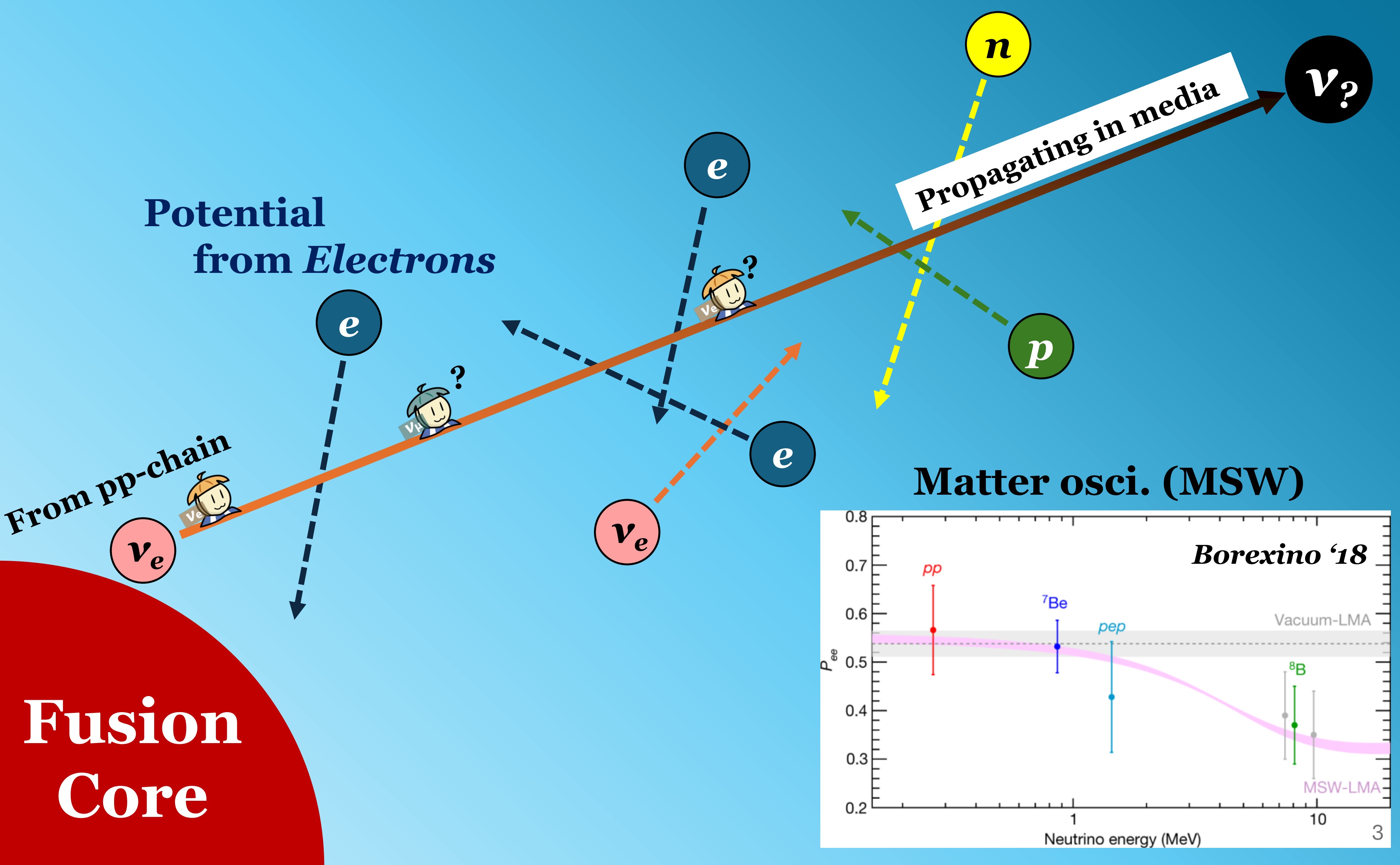
Need numerical modeling.

→ Incorporation of all physics.

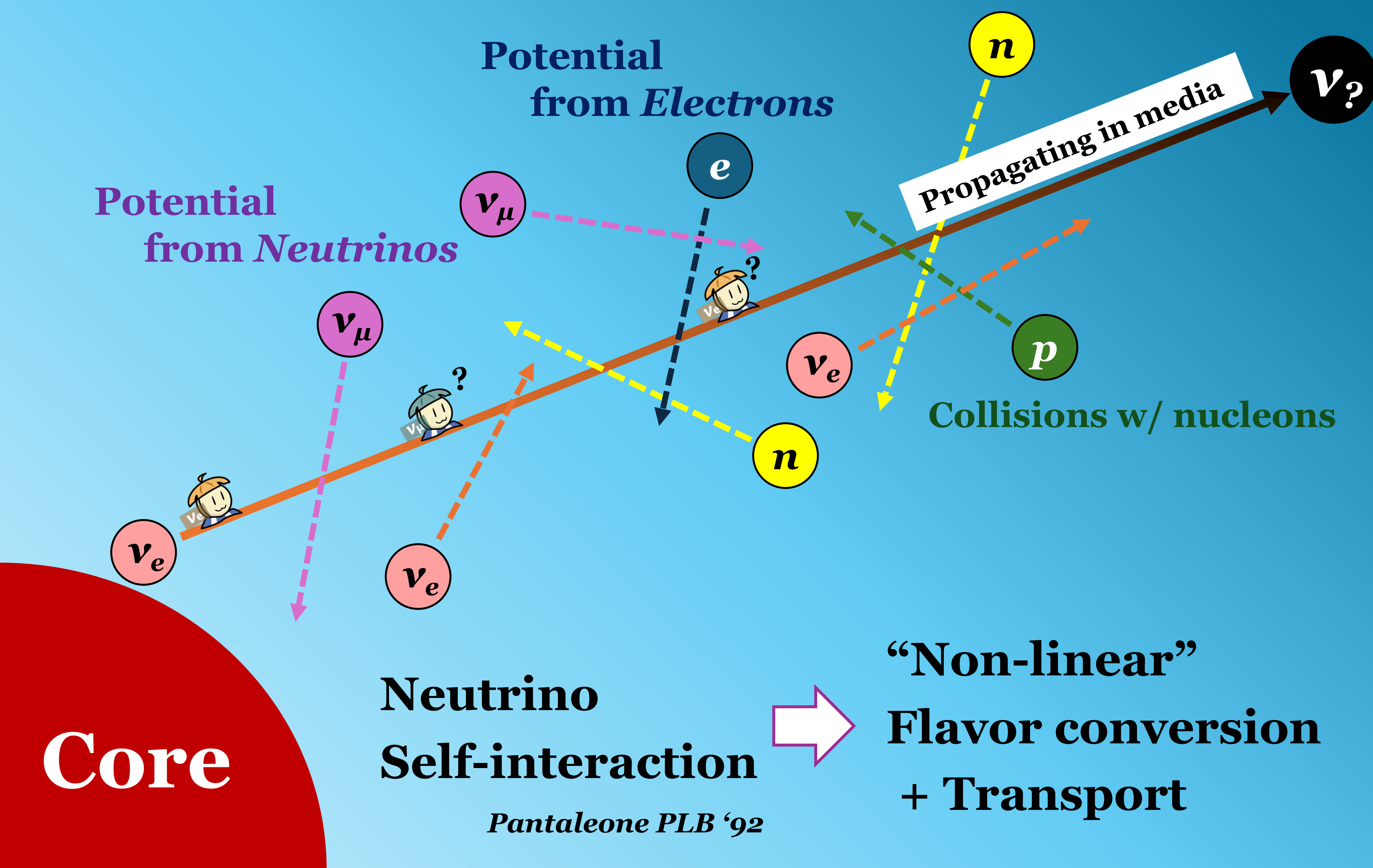
→ *One of the uncertainties is* ***"Neutrino Oscillation"***

higgstan.com

Solar Neutrino Problem



Sea of Leptons & Nucleons



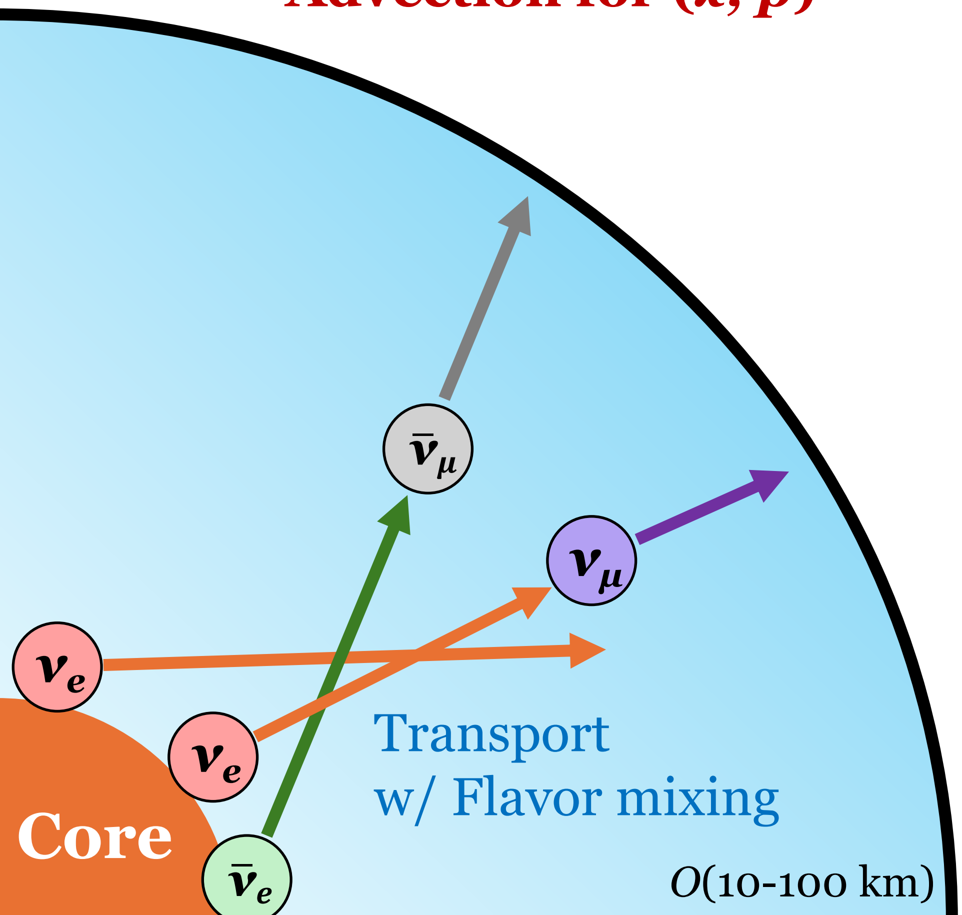
Neutrino Self-interaction ⇒ **"Non-linear" Flavor conversion + Transport**

Pantaleone PLB '92

Quantum Kinetic Neutrino Transport

Beyond Boltzmann eq.:

$$\underbrace{\left(p^\mu \frac{\partial}{\partial x^\mu} - \Gamma^j_{\mu\nu} p^\mu p^\nu \frac{\partial}{\partial p^j}\right)\rho}_{\text{Advection for }(x,\,p)} = -\mathrm{i}\left[\mathcal{H}_{\mathrm{osc}},\ \rho\right] + \underbrace{\mathcal{C}[\rho]}_{\text{Collisions}}$$



Quantum Kinetic Neutrino Transport

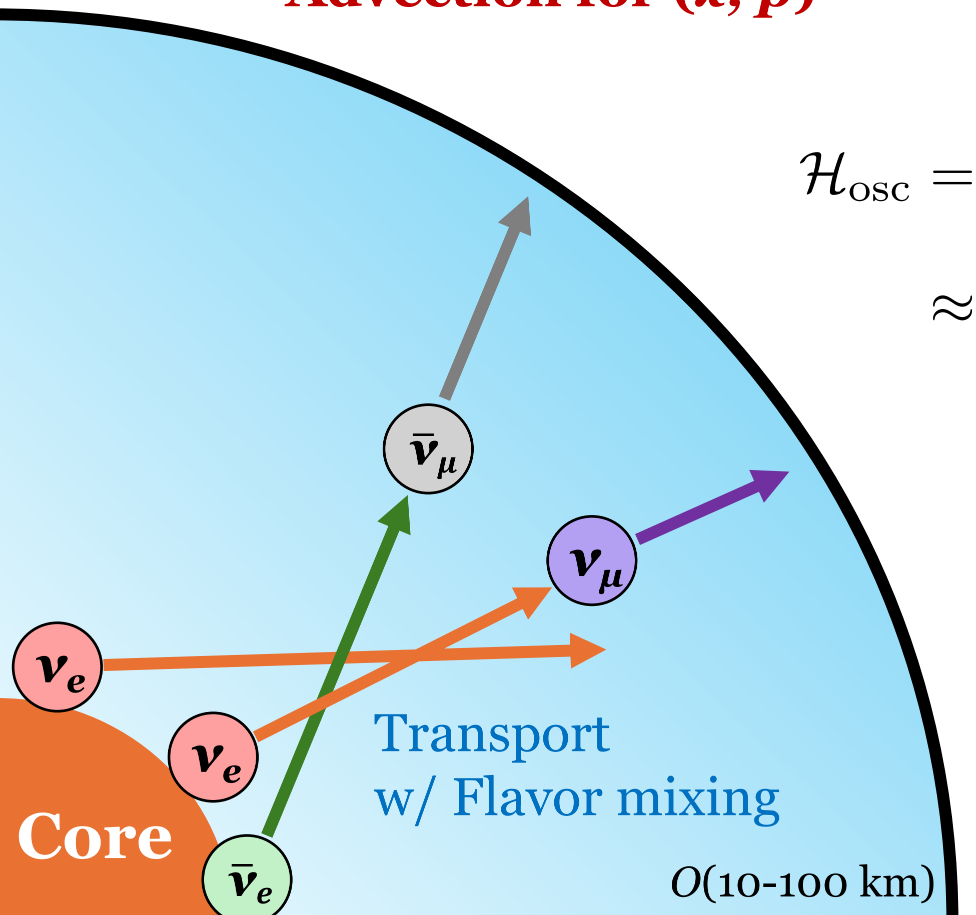
Beyond Boltzmann eq.:

$$\underbrace{\left(p^\mu \frac{\partial}{\partial x^\mu} - \Gamma^j_{\mu\nu} p^\mu p^\nu \frac{\partial}{\partial p^j}\right)\rho}_{\textbf{Advection for } (\boldsymbol{x}, \boldsymbol{p})} = \underbrace{-\mathrm{i}\left[\mathcal{H}_{\mathrm{osc}},\ \rho\right]}_{\textit{Neutrino oscillation}} + \mathcal{C}[\rho]$$

$$\begin{aligned}\mathcal{H}_{\mathrm{osc}} &= \mathcal{H}_{\mathrm{vac}} + \mathcal{H}_{\mathrm{mat}} + \mathcal{H}_{\nu\nu} \\ &\approx \frac{M^2}{2E_\nu} + \underbrace{\sqrt{2}G_{\mathrm{F}}\, n_e}_{\textit{Electrons}} + \underbrace{\sqrt{2}G_{\mathrm{F}}\, n_\nu}_{\textit{Neutrinos}}\end{aligned}$$

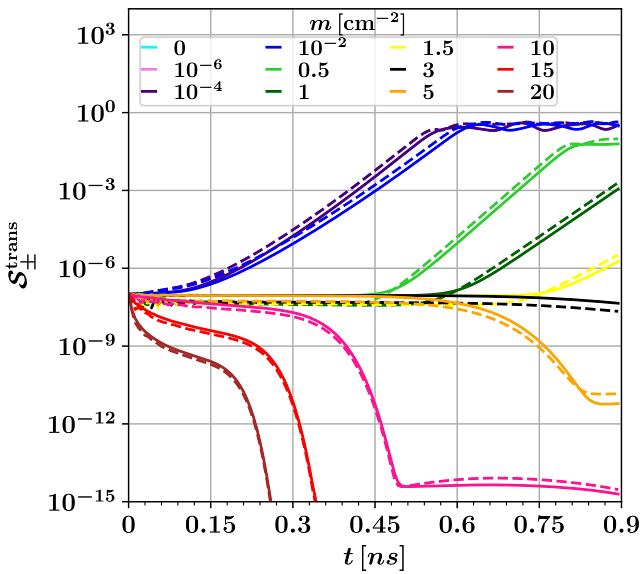
Radial profile

(Background)



Matter Gradient (Advection)

Bhattacharyya+ '25



$$\mathcal{H}_{\rm osc} = \mathcal{H}_{\rm vac} + \mathcal{H}_{\rm mat} + \mathcal{H}_{\nu\nu}$$

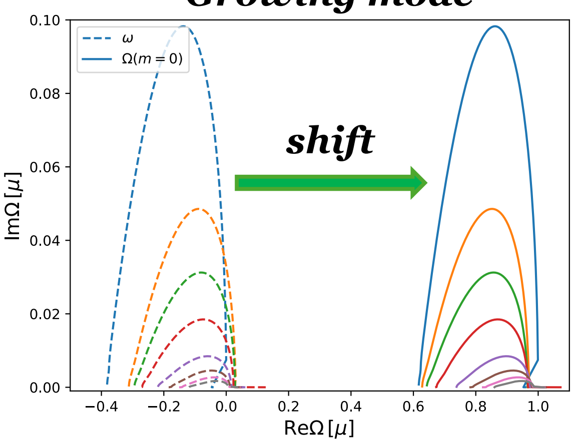
$$\approx \frac{M^2}{2E_\nu} + \underbrace{\sqrt{2}G_{\rm F}\, n_e}_{\text{Electrons}} + \underbrace{\sqrt{2}G_{\rm F}\, n_\nu}_{\text{Neutrinos}}$$

Electrons ***Neutrinos***

Bhattacharyya+ (2504.11316) says

"Inhomogeneous matter can suppress the flavor conversion."

Growing mode



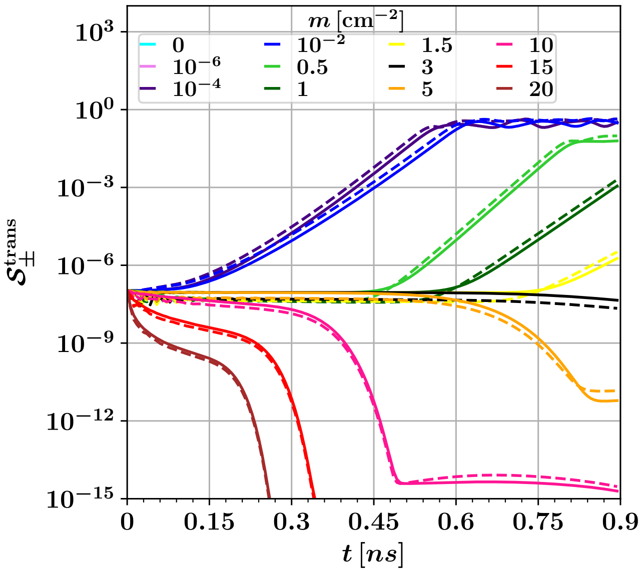
Dominant unstable mode is shifted due to background matter.

-- It prevents it from evolving sufficiently?

Competition between growth time scale vs. matter inhomogeneity

Matter Gradient (Advection)

Bhattacharyya+ '25



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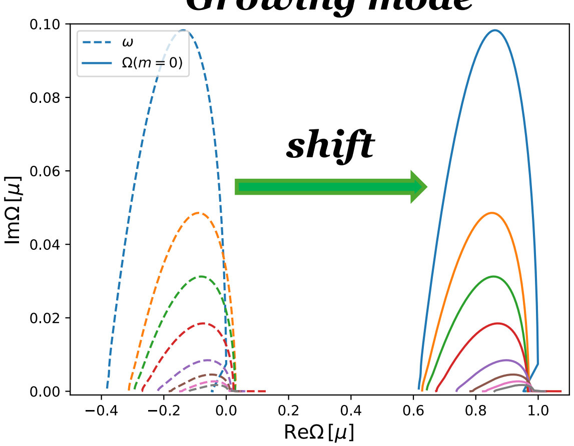


But, investigated for
- ***local*** & ***periodic*** sim.
- ***constant*** ν number density in space.

→ ***For global geometry?***
Gradient as a global geometry.

Attenuation Technology for Global

Quantum Kinetic Equation in 1D spherical symmetry (*r; E*$_\nu$*, θ*$_\nu$):

$$\left(p^\mu \frac{\partial}{\partial x^\mu} - \Gamma^j_{\mu\nu} p^\mu p^\nu \frac{\partial}{\partial p^j}\right)\rho = -\mathrm{i}\xi[\mathcal{H}_{\mathrm{osc}},\ \rho] + \mathcal{C}[\rho]$$

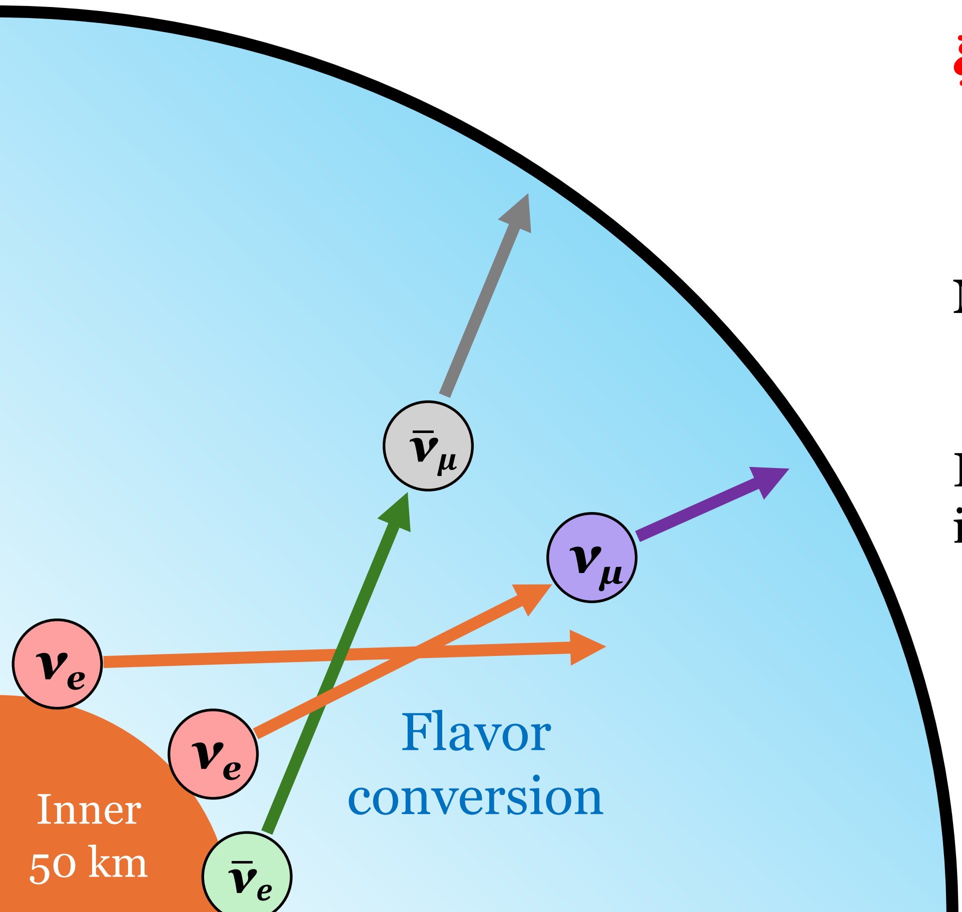
$$0 \le \xi \le 1$$

ξ is an ***attenuation*** parameter handling oscillation scales.

Nagakura & MZ PRL '22

No attenuation:
osci. scale 1 cm vs. O(10-100 km)

If the attenuated scale remains dominant, it is acceptable.



Outer boundary
r ~ 100 km

Attenuation Technology for Global

Quantum Kinetic Equation in 1D spherical symmetry (*r; E_ν, θ_ν*):

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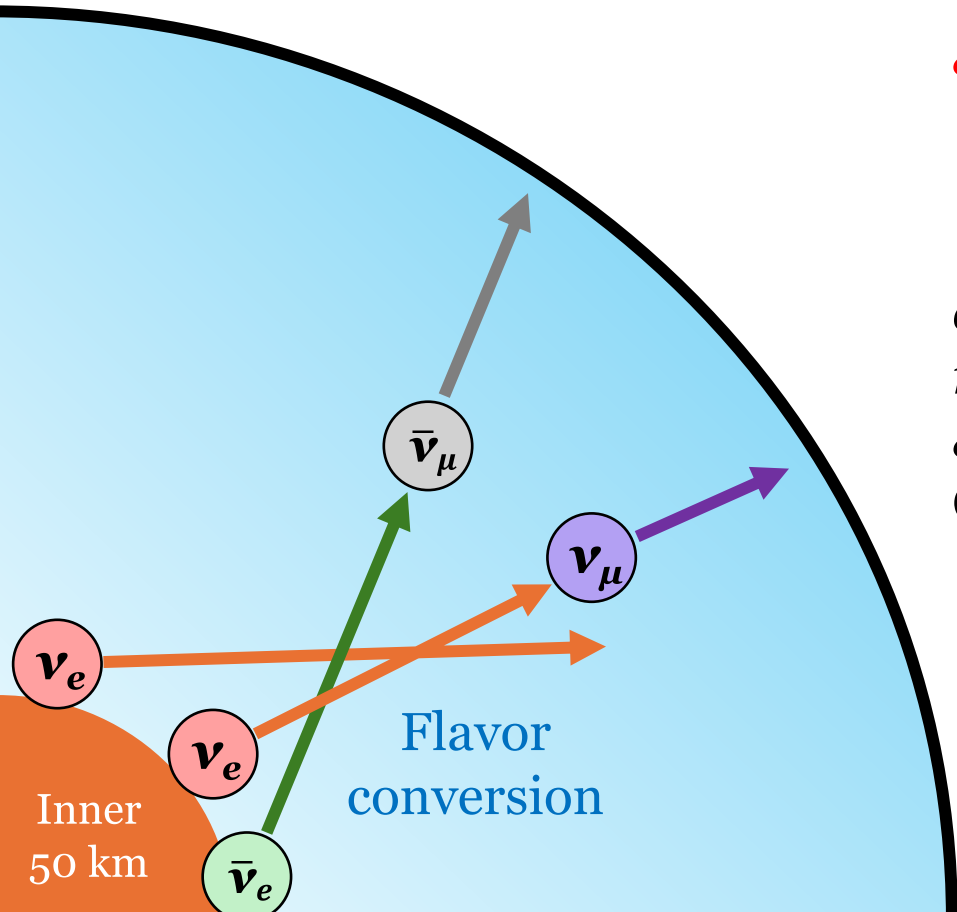


ex.)

n_ν = 10^{33} cm^{-3}

ξ = 10^{-4} $\qquad \mu \to \xi\mu$

Osci. scale ~ $2\pi/\mu$ ~ **1 cm** → **100 m**

Treatable?

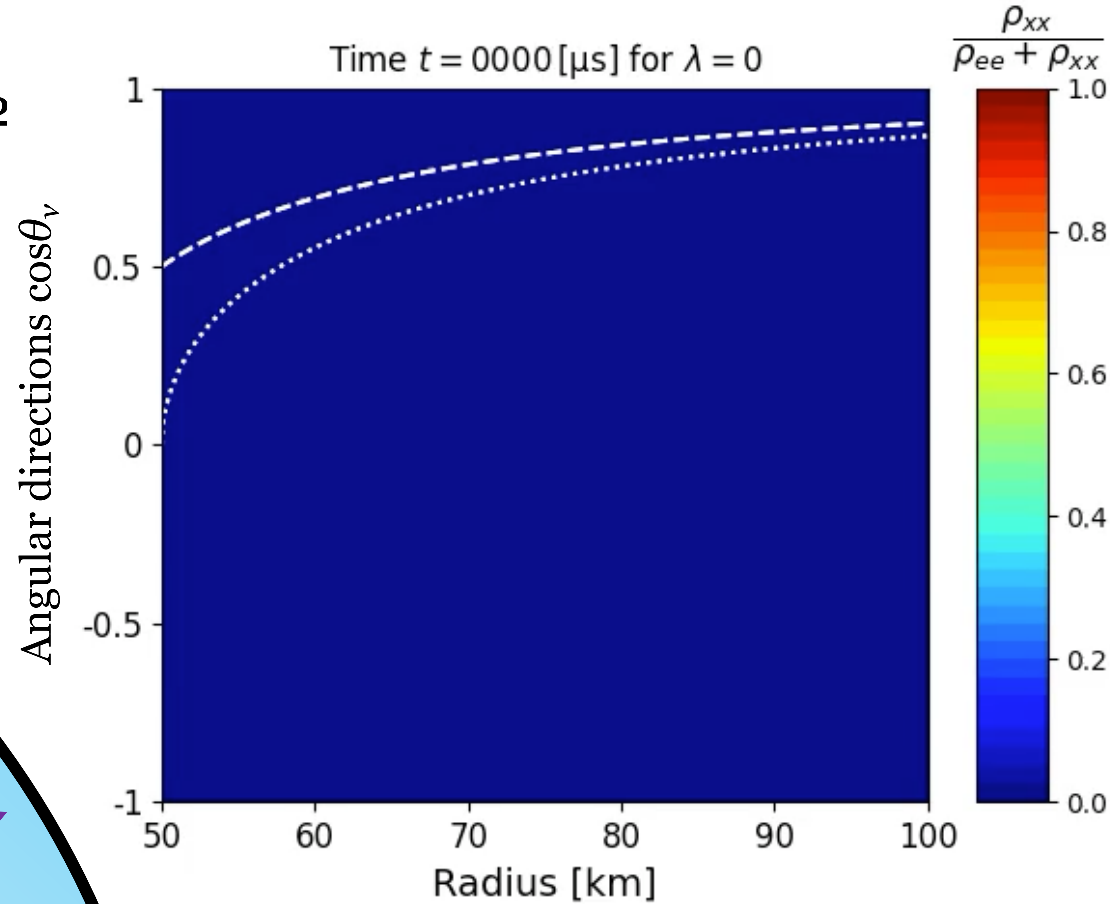
Global Simulation w/ Attenuation

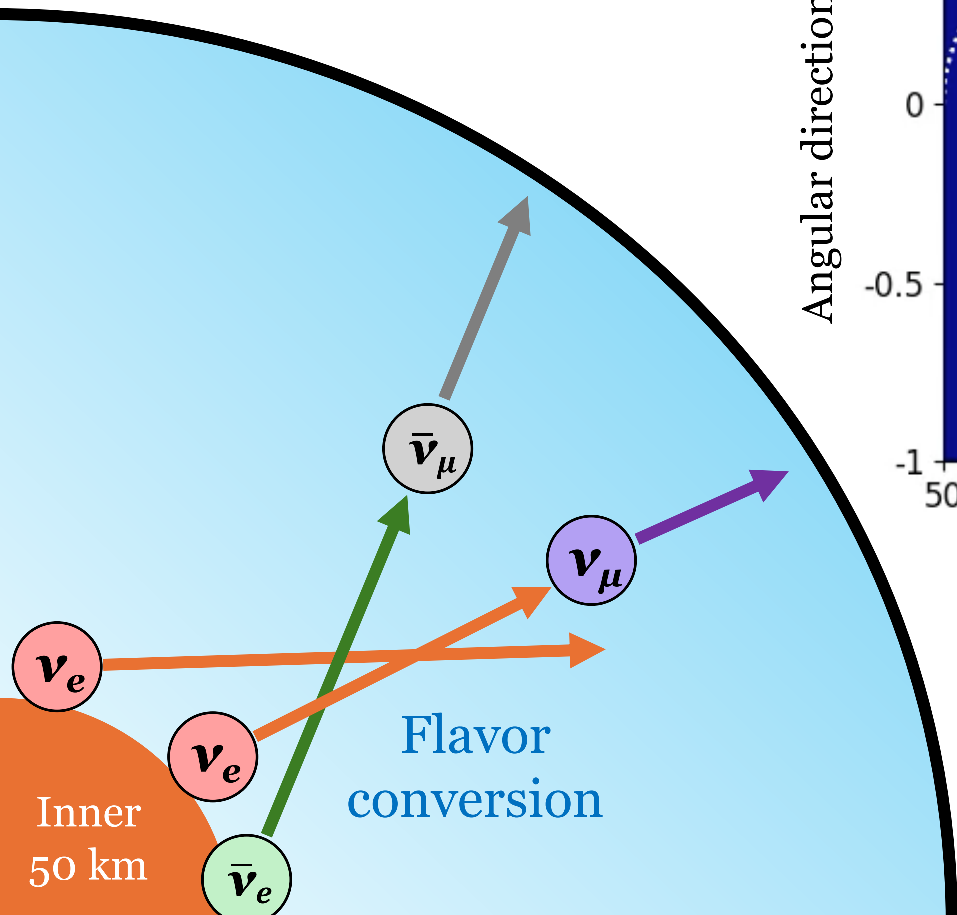
1D spherical symmetry:

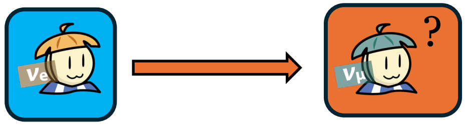
- $N\_(r, E_\nu, \theta_\nu) = 24{,}576 \times 1 \times 12$

- Δr ~ 25 cm
- Δt ~ 2 ns

$$\xi = 10^{-4}$$



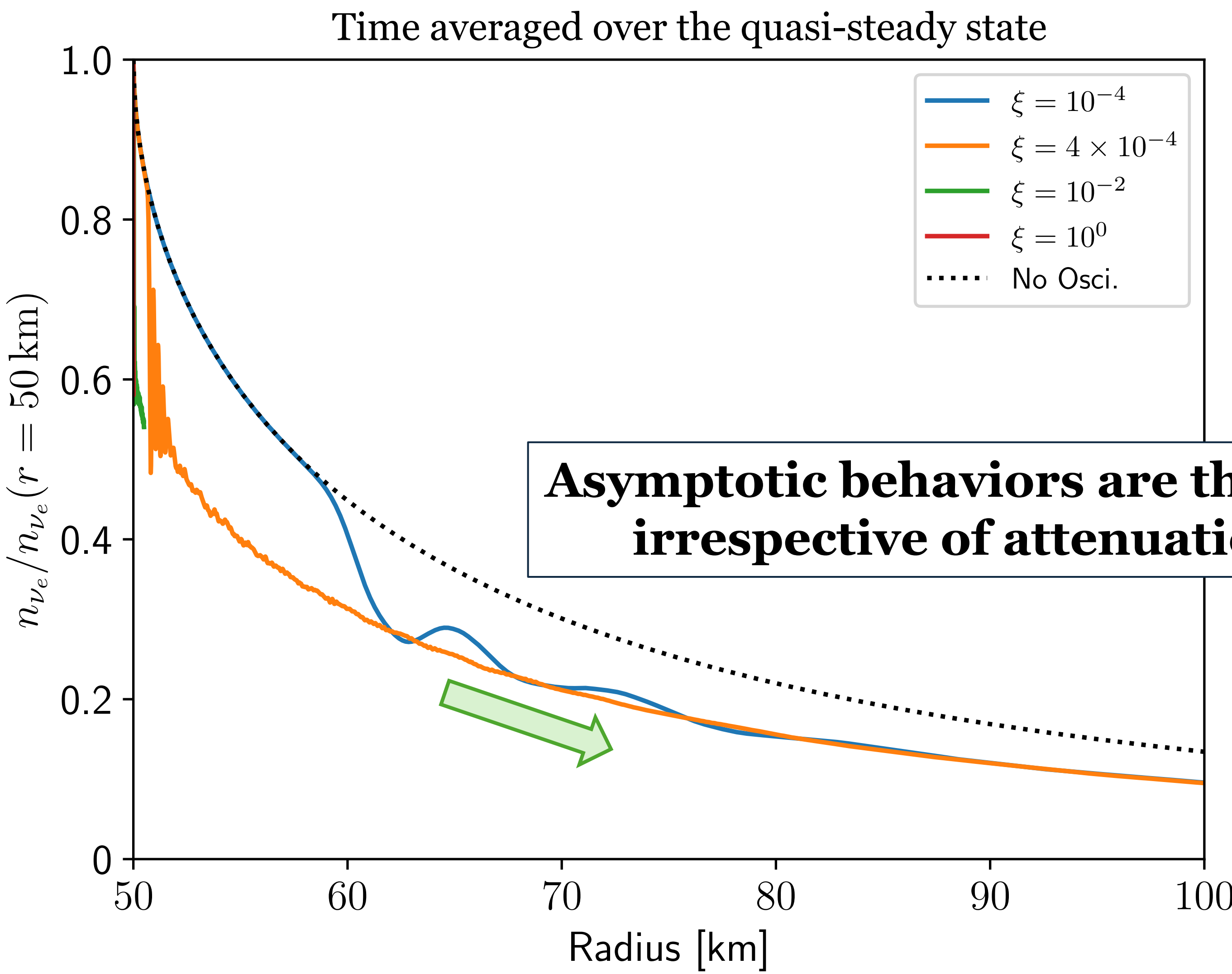




Outer boundary r ~ 100 km

Global Simulation w/ Attenuation

No matter background & Attenuation dependence



Asymptotic behaviors are the same irrespective of attenuation!

+ Background Matter

Background number density:

$$\lambda(r) = \lambda_0 \left(\frac{r}{R_{\text{in}}}\right)^m$$

$$\lambda = \sqrt{2} G_{\text{F}}\, n_e$$

$$\mu = \sqrt{2} G_{\text{F}}\, n_{\nu_e}$$

$$\mu_0 = \mu(R_{\text{in}})$$

R_{in}: inner boundary

c.f.) Neutrino flux $\propto$ ***r*** $^{-2}$

$$n_{\nu_e} = 6 \times 10^{32} \text{g/cm}^3$$

Attenuating Hamiltonian: ξH_{osc}

For $\xi = 10^{-4}$, $\lambda_0/\mu_0 = 1, 4$ **& m = 0, -1, -3**

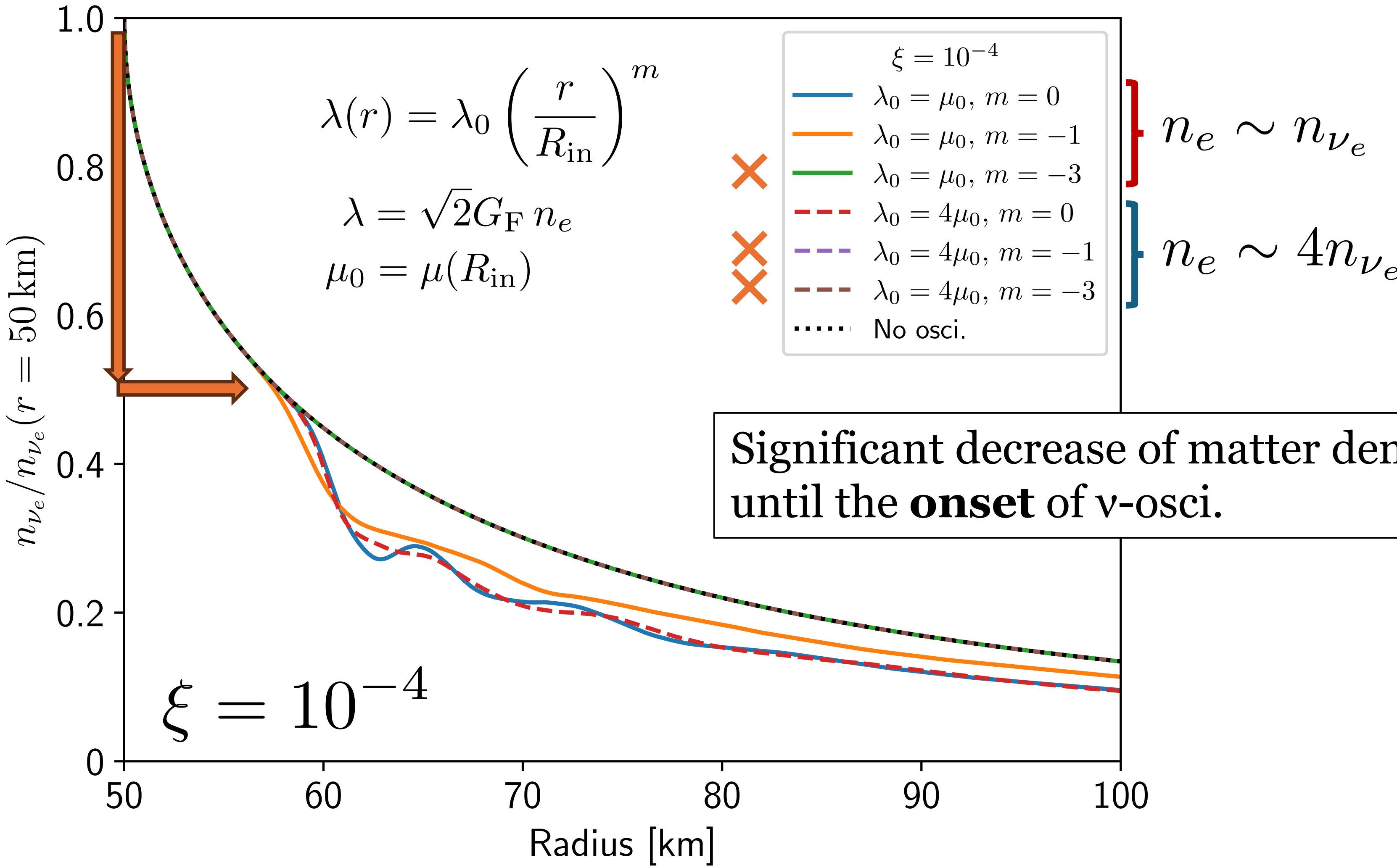
$\Delta R = 50$ **km**

For $\xi = 10^{-2}$, $\lambda_0/\mu_0 = 1, 20, 30$ **& m = 0, -3**

$\Delta R = 0.5$ **km**

vs. Matter Gradient (Advection)

With matter background & Large attenuation:
Flavor conversion **can be suppressed.**



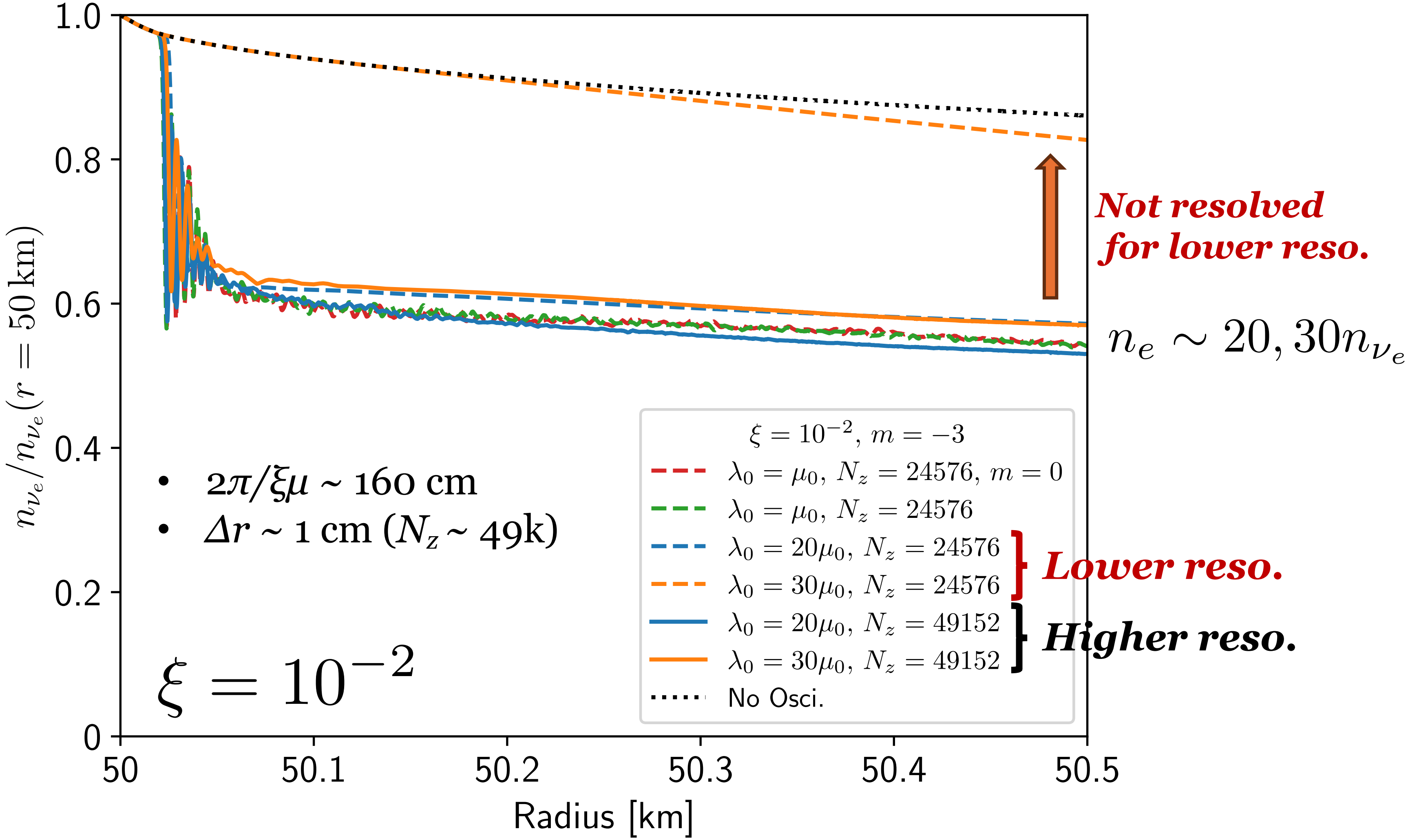
Significant decrease of matter density until the **onset** of ν-osci.

Attenuation vs. Matter Gradient

With matter background & Small attenuation:

Flavor conversion can occur.

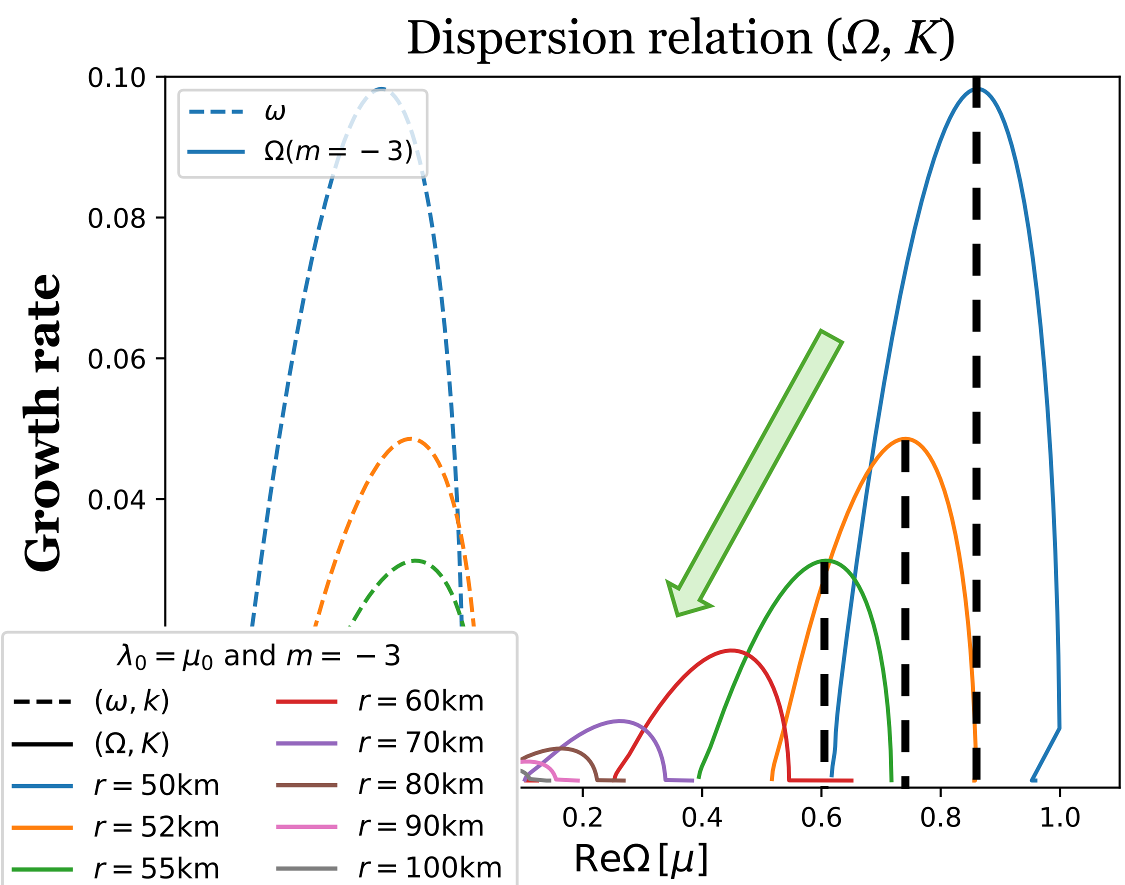
But a higher resolution is required to resolve shorter matter oscillations. $n_e \gg n_{\nu_e}$



Growing mode vs. Background Shift

plane-wave ansatz: $\rho_{ex} \approx \tilde{Q} \exp\left[\mathrm{i}(\Omega t - \boldsymbol{K} \cdot \boldsymbol{x})\right]$ $\Omega \in \mathbb{C}$

Dominant growing modes move away due to the advection toward the outer radii.



Growing rate

vs.

Background change rate

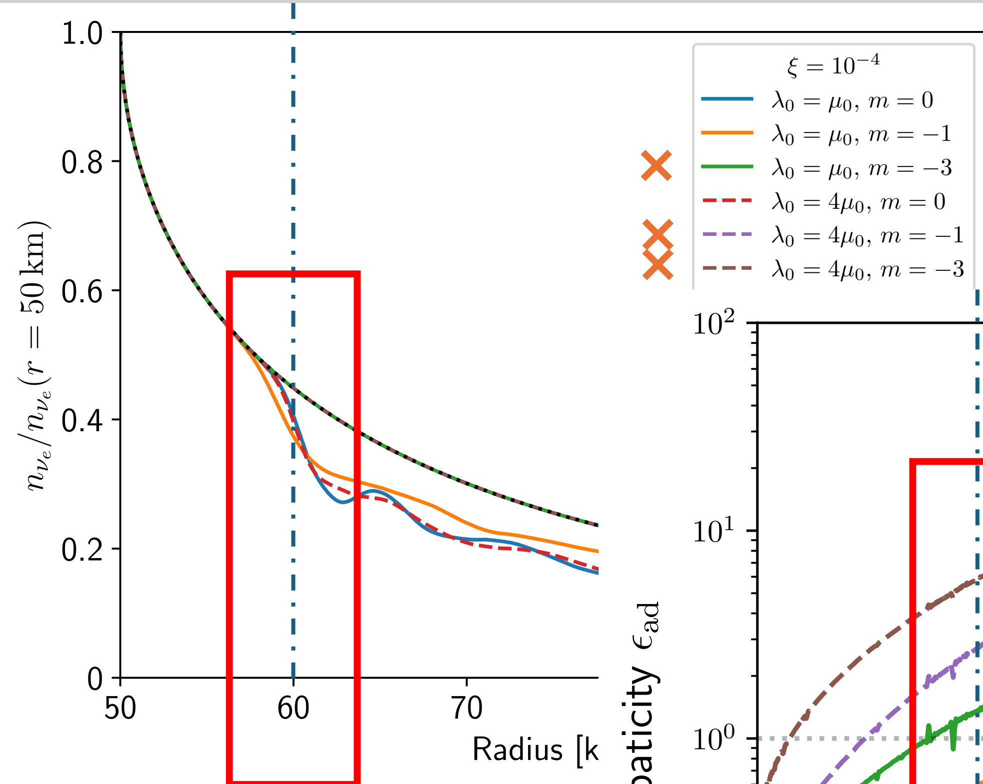
Adiabaticity ϵ_{ad}

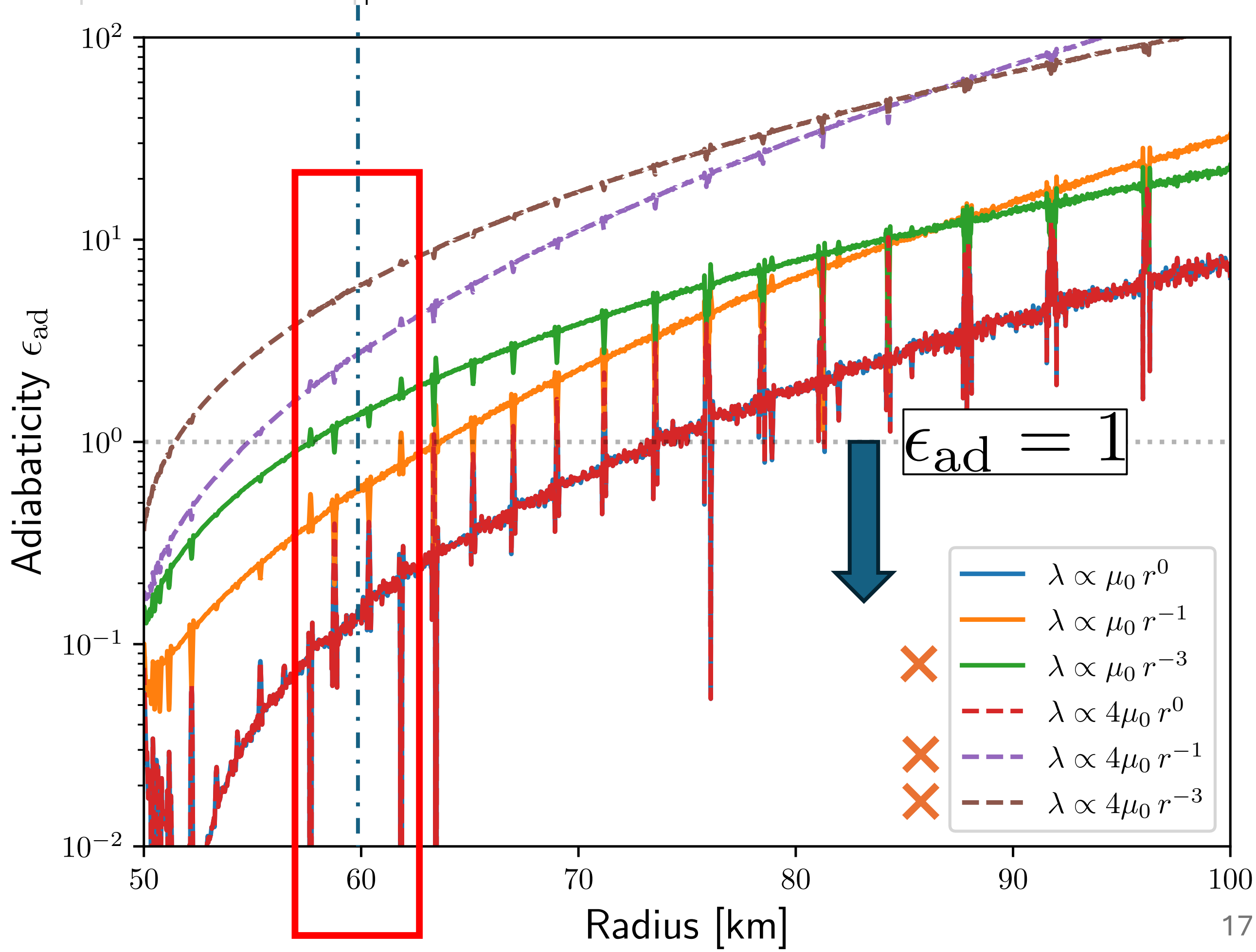
Note:
Advection is not attenuated.
→ ξ-dependence

Adiabaticity for Flavor Wave

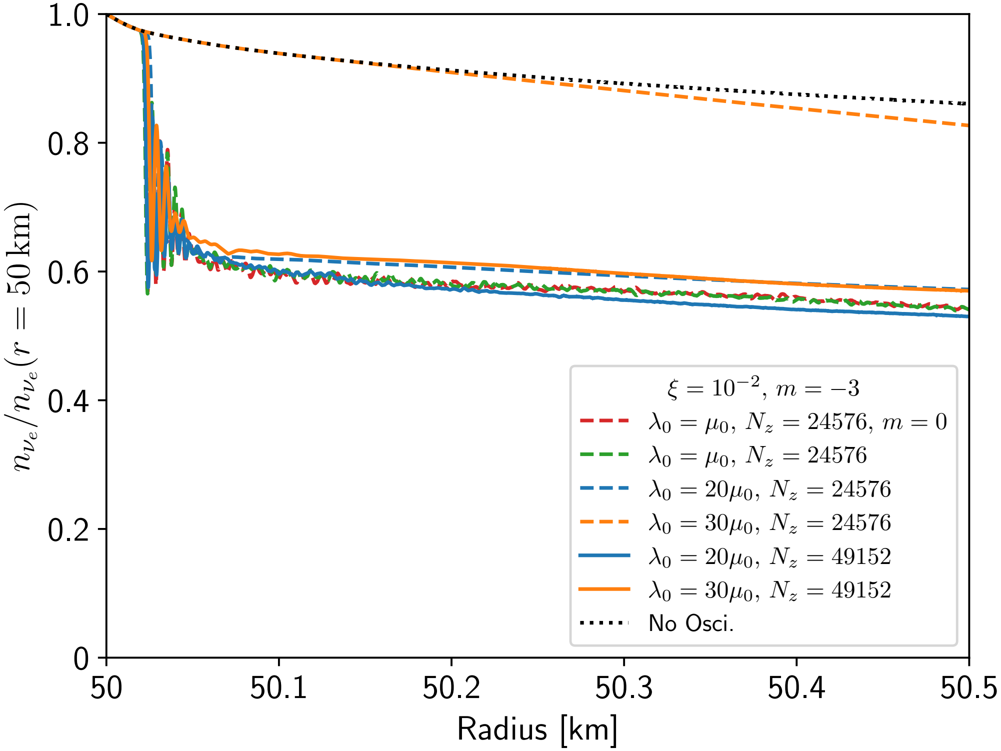
Strong attenuation

$\xi = 10^{-4}$





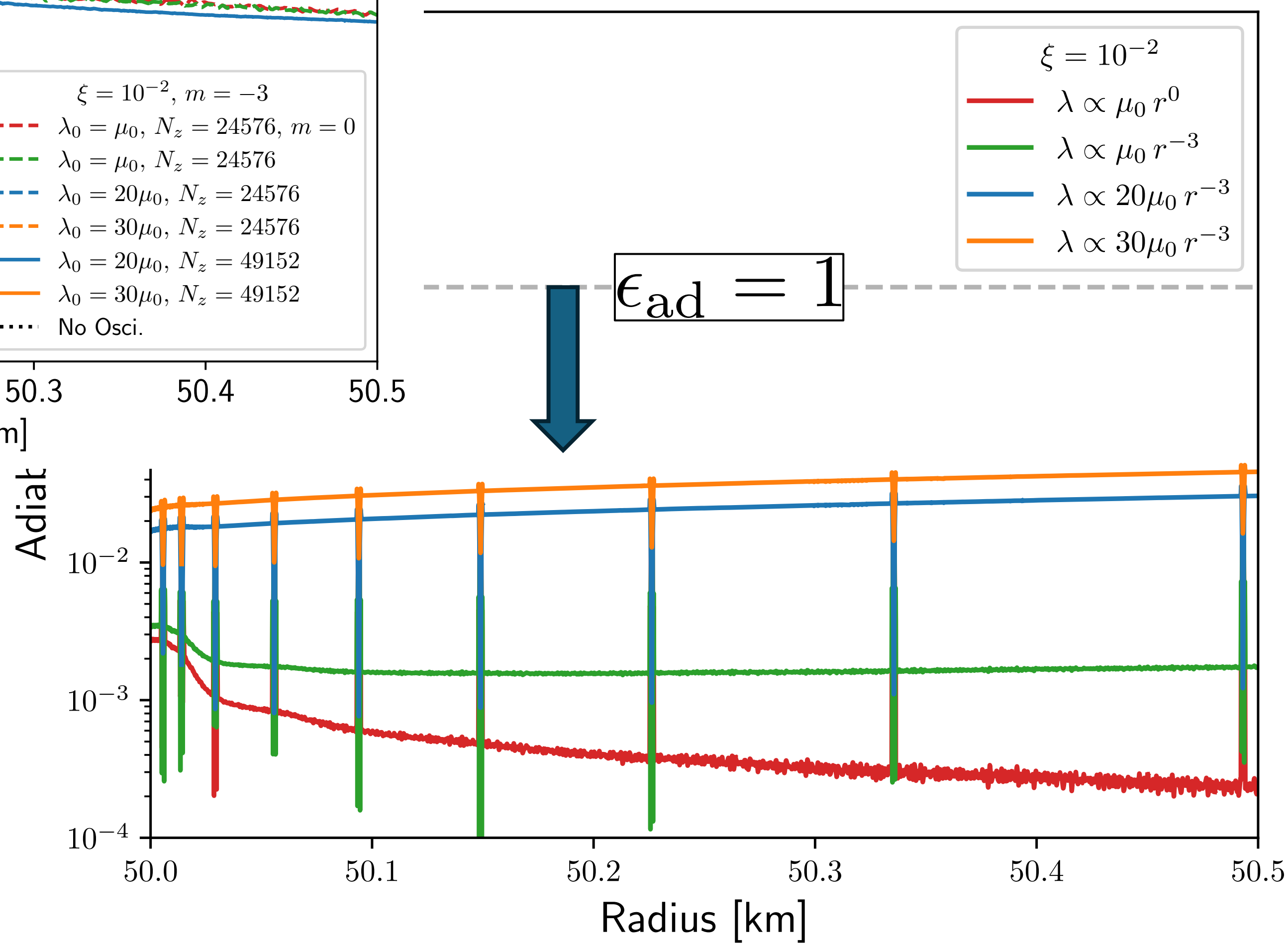
Adiabaticity for Flavor Wave



Weak attenuation

$\xi = 10^{-2}$

$\epsilon_{ad} \ll 1$



Summary & Discussion

- Attenuated flavor conversion
  vs. Background gradient in global geometry.
  - Large attenuation hinders flavor conversion even under comparable n_e.
  - Calculation of small attenuation demonstrates that the strong suppression is artificial.

- Evaluating adiabaticity in flavor evolution.
  - Using linear stability analysis.
    - Similarly applicable for realistic CCSN models.
  - Nevertheless, too weak growth rates could be defeated by a steep density gradient/fluctuation.
  - Need updates to the QKE modeling w/ consideration of the background?