超新星爆発における
回転誘起型ニュートリノ集団振動

arXiv:2110.08291, ApJ in press

原田了 (理研)

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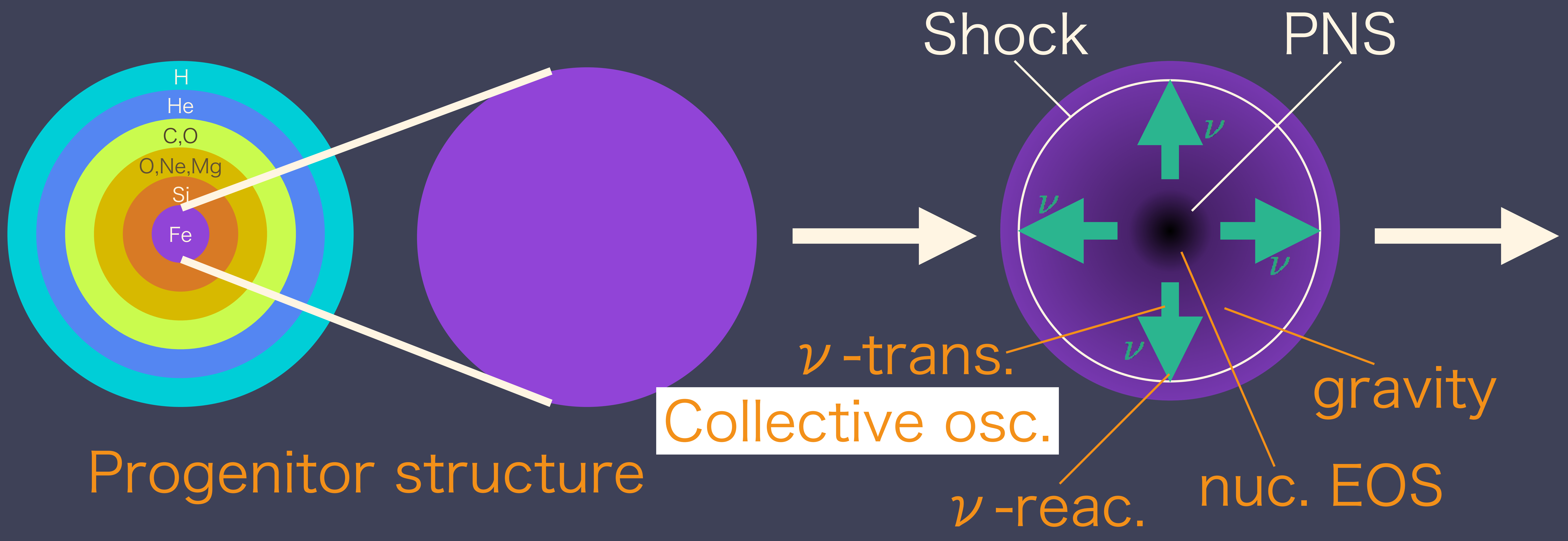
Core-collapse supernova explosion

- Core collapse→Proto-neutron star (PNS) & Bounce shock formation
- Shock stalls→Neutrino emission from PNS re-energize the shock → Explode!
- Depends on: progenitor, nuclear equation of state (EOS), neutrino reactions, numerics
- Collective neutrino oscillation may change the explosion dynamics and neutrino signals

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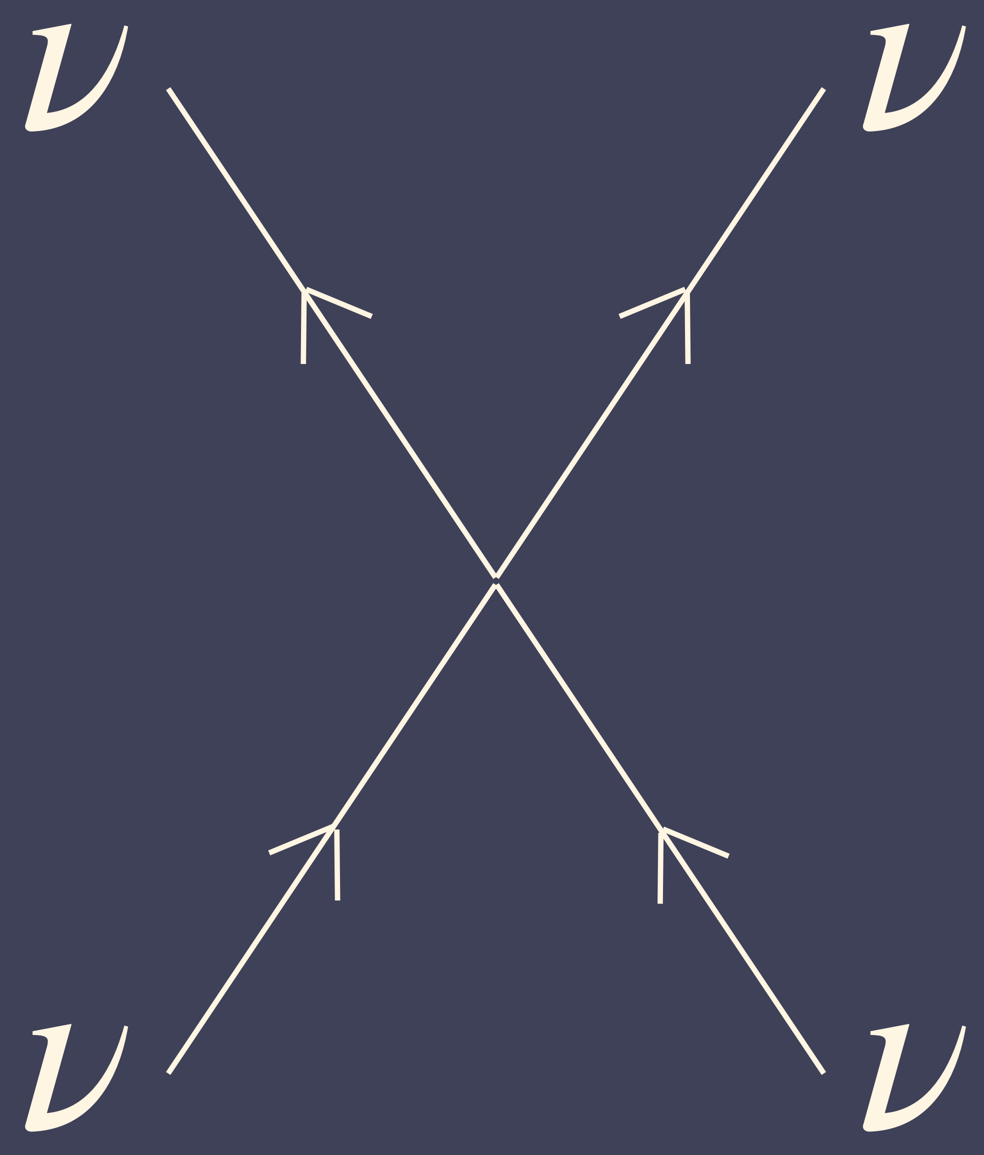
Neutrino oscillation



$$i\frac{\mathrm{d}}{\mathrm{d}t}\rho(p) = [H, \rho(p)] + \mathscr{C}[\rho]$$

: Quantum Kinetic Equation (QKE)

$$H = H_{\mathrm{vacuum}} + H_{\mathrm{MSW}} + \sqrt{2}G_{\mathrm{F}}\int \mathrm{d}^3p'(1 - \hat{p}\cdot\hat{p}')(\rho_{p'} - \bar{\rho}_{p'})$$

ν - ν interaction potential

- Neutrino oscillation→Mismatch between flavor and energy eigenstates
- MSW effect : energy changes due to the interaction potential with electrons
- Collective neutrino oscillation : energy changes due to the interaction potential between neutrinos

Collective neutrino oscillation

Slow mode

$$H = H_{\text{vacuum}} + H_{\nu-\nu}$$

$$\omega_{\text{s}} \sim \sqrt{\frac{\Delta m^2}{2E}\sqrt{2}G_{\text{F}}n_{\nu}} \sim \mathcal{O}(10^{-2})\,\text{m}^{-1}$$

- Long conversion lengthscale
  →other physical processes may suppress the conversion

Fast mode

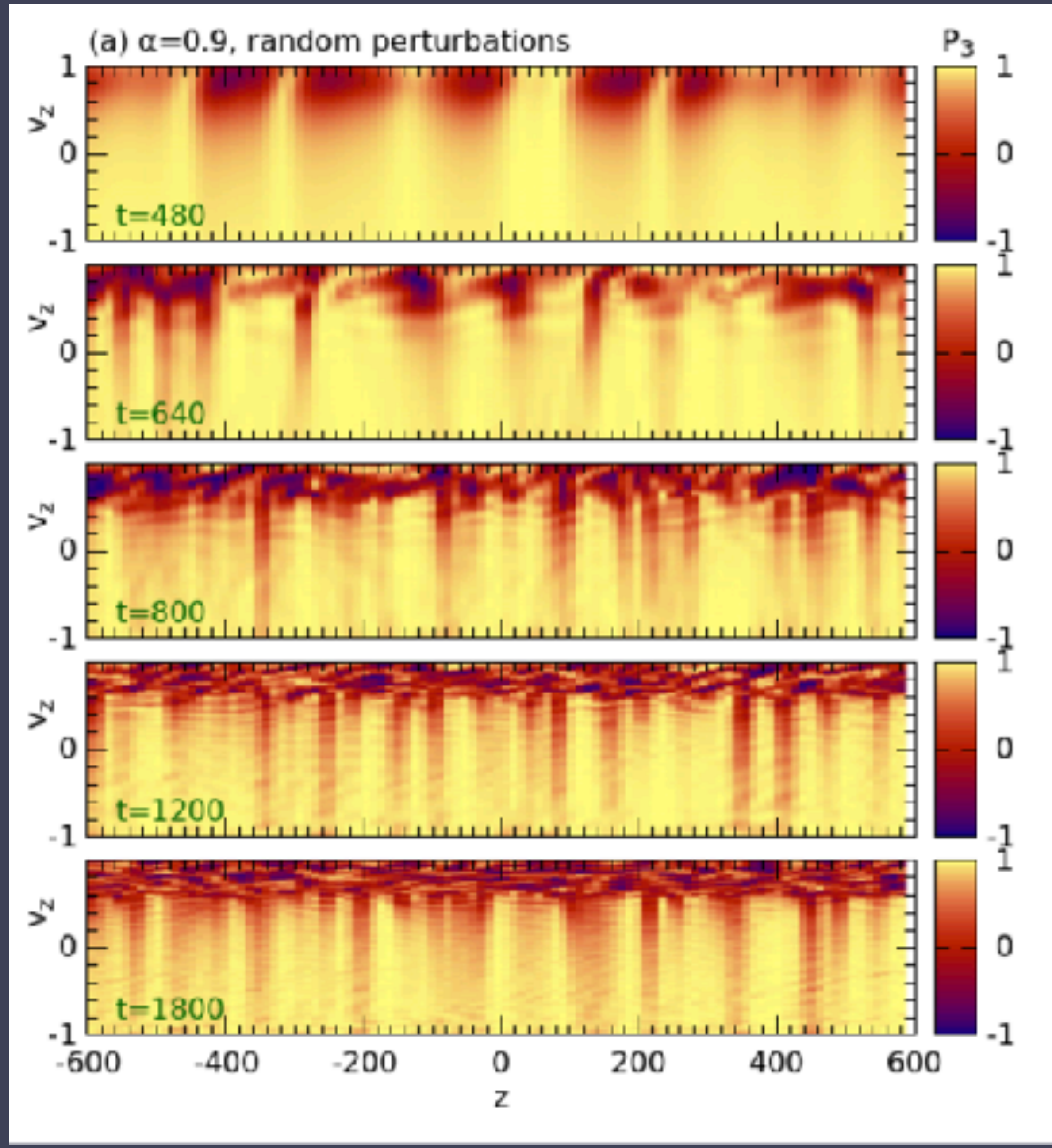
$$H = H_{\nu-\nu}$$

$$\omega_{\text{f}} \sim \sqrt{2}G_{\text{F}}n_{\nu} \sim \mathcal{O}(1)\,\text{m}^{-1}$$

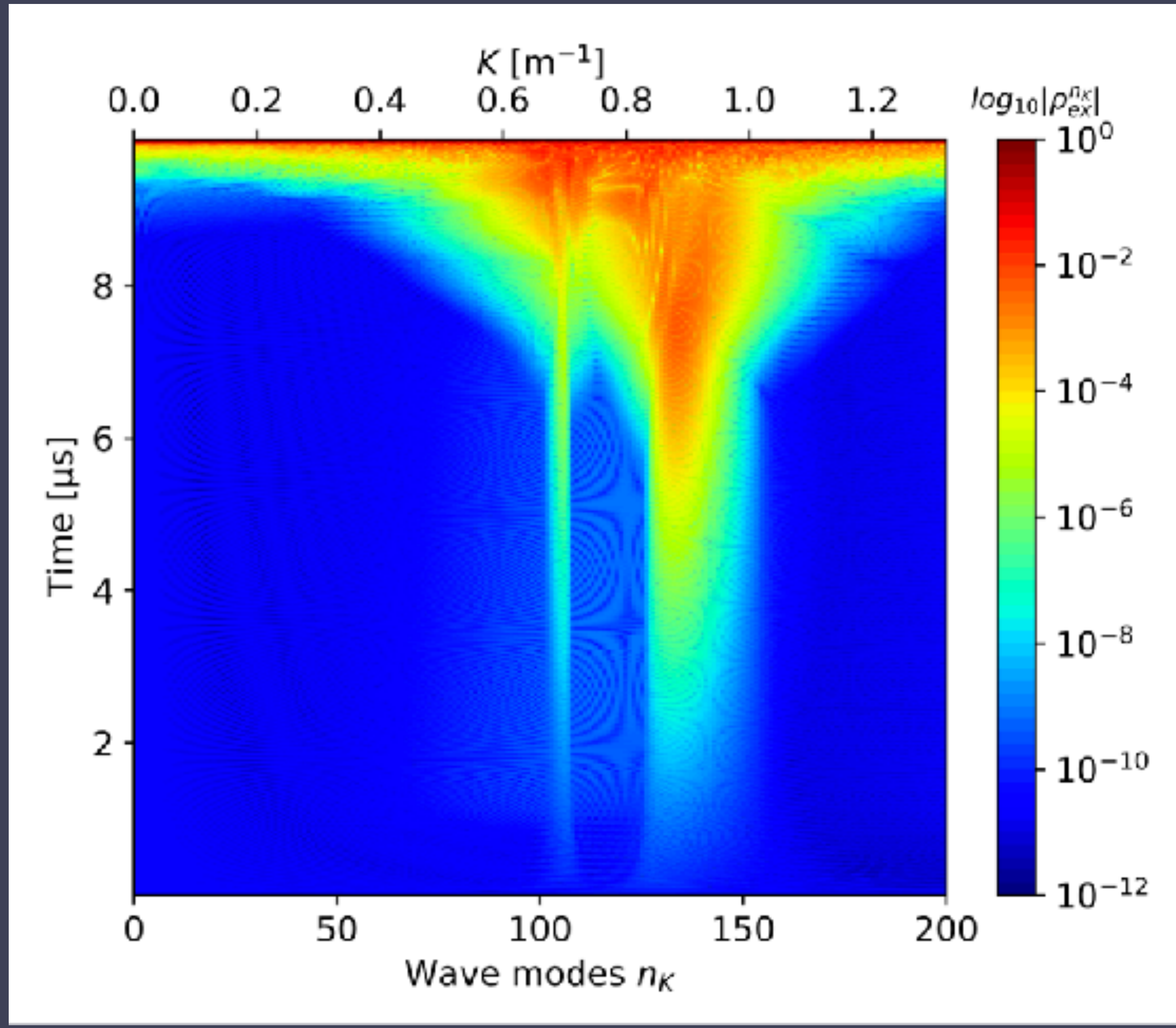
- Short conversion lengthscale - almost promptly
- High energy ν_x and low energy ν_{e} may exchange each other, then heating rate, explosion dynamics, nucleosynthesis may be influenced.

Collective neutrino oscillation

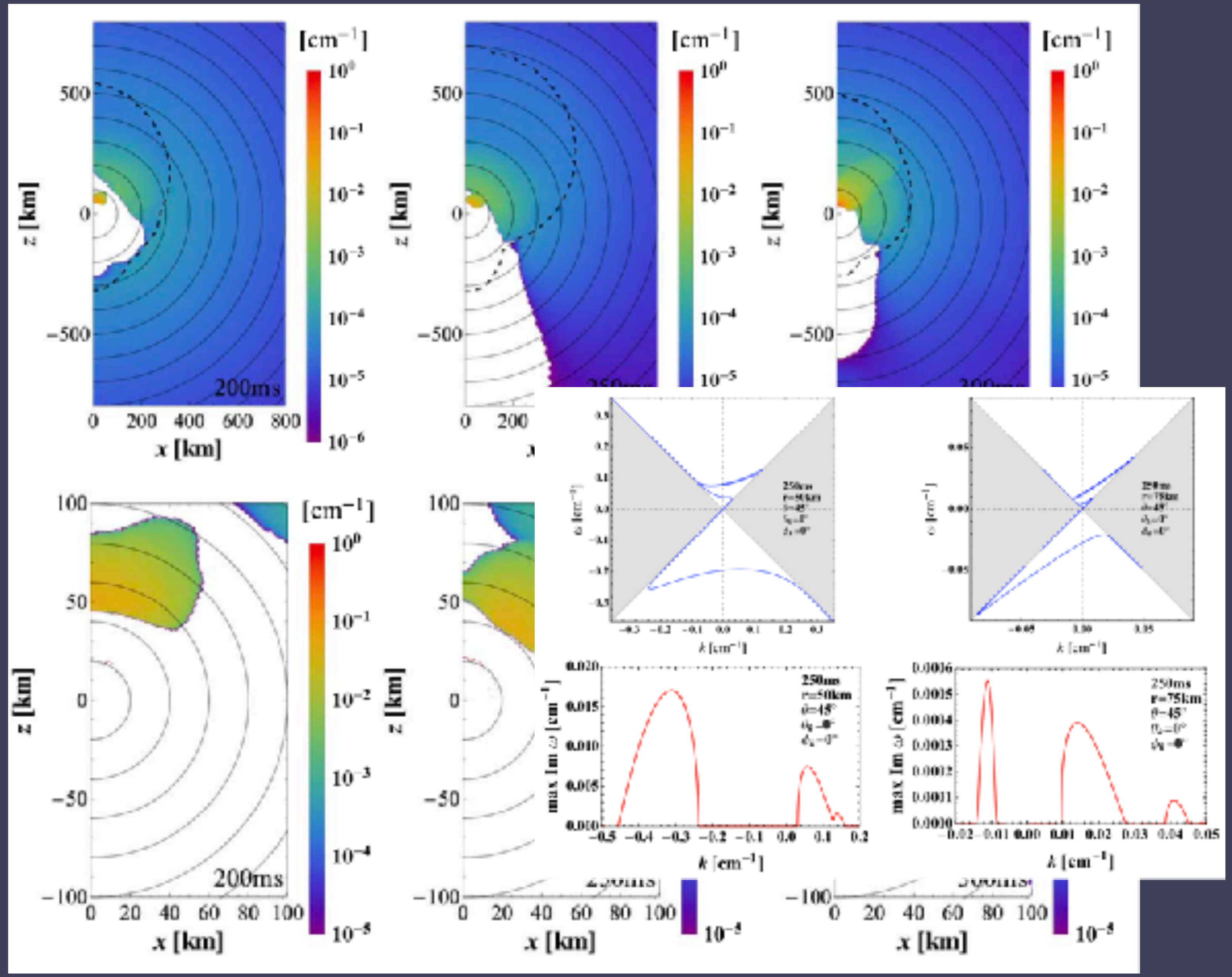
- Quantum kinetic equation (QKE) describes the collective neutrino oscillation
- Realistic astrophysical setting with sufficient resolution is difficult to solve
  - Solve QKE directly in idealized setting
  - Analyze linearized QKE with astrophysical simulation results (postprocess)



Wu+(2021)



Zaizen & Morinaga (2021)



Nagakura+(2019)

Linear analysis of QKE

$$i\frac{\mathrm{d}}{\mathrm{d}t}J(\Omega) = -\int \frac{\mathrm{d}^2\Omega'}{4\pi}G(\Omega')\hat{p}\cdot\hat{p}'J(\Omega') \Longleftarrow i\frac{\mathrm{d}}{\mathrm{d}t}\rho(p) = [H, \rho(p)]$$

linearized QKE　　　　QKE

$$G(\Omega) = \sqrt{2}G_\mathrm{F}\int\frac{E^2\mathrm{d}E}{2\pi^2}(f_{\nu_\mathrm{e}}(p) - f_{\bar{\nu}_\mathrm{e}}(p))$$

: Electron neutrino Lepton Number (ELN)
(Assuming the same population for heavy-lepton type ν's)

- Fast flavor conversion is considered
- ELN is important to see the behavior:

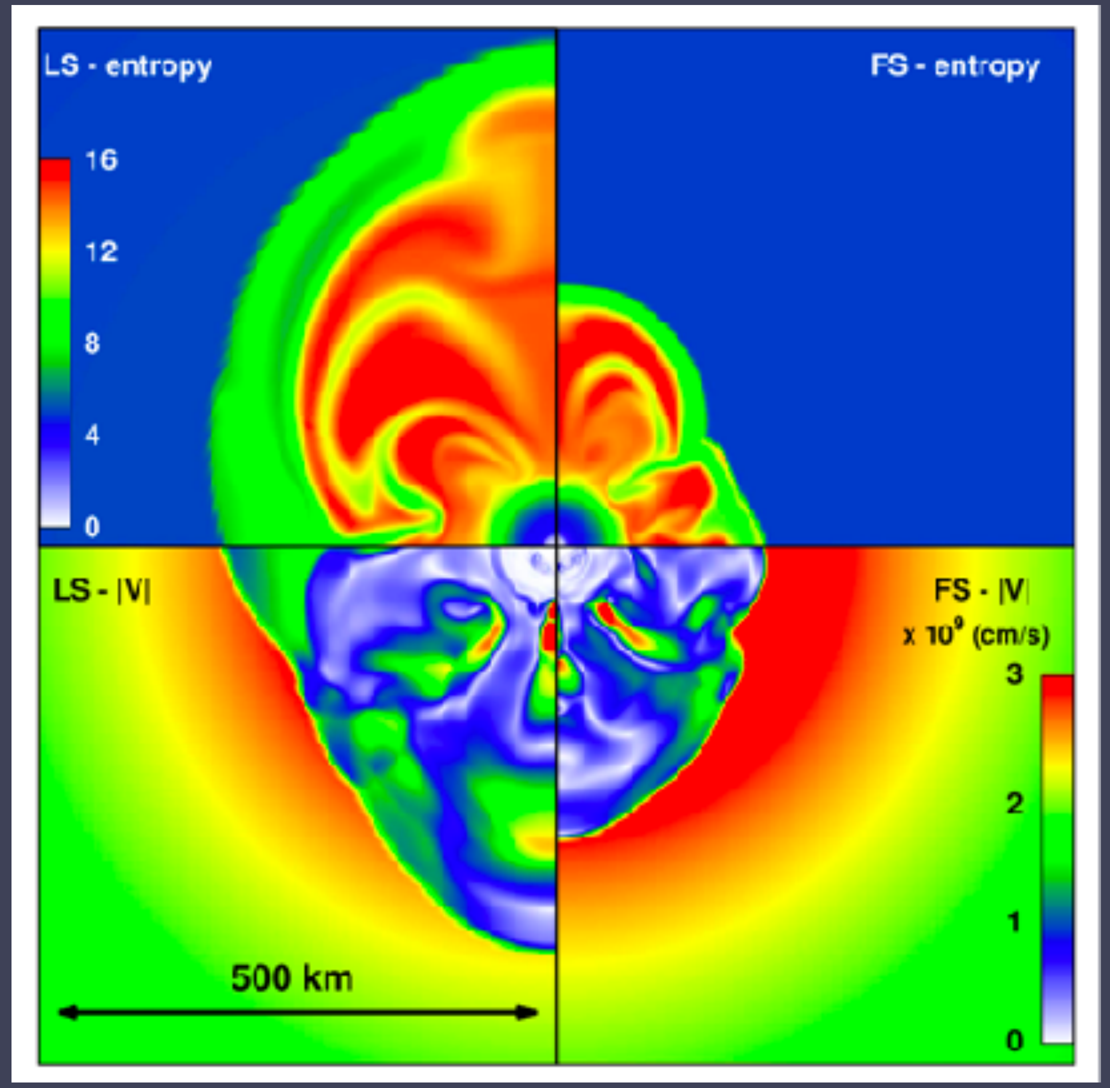
  ELN zero crossing <=> flavor instability　　(Pf. Morinaga 2021)
- Search for ELN crossing!

Boltzmann neutrino transport

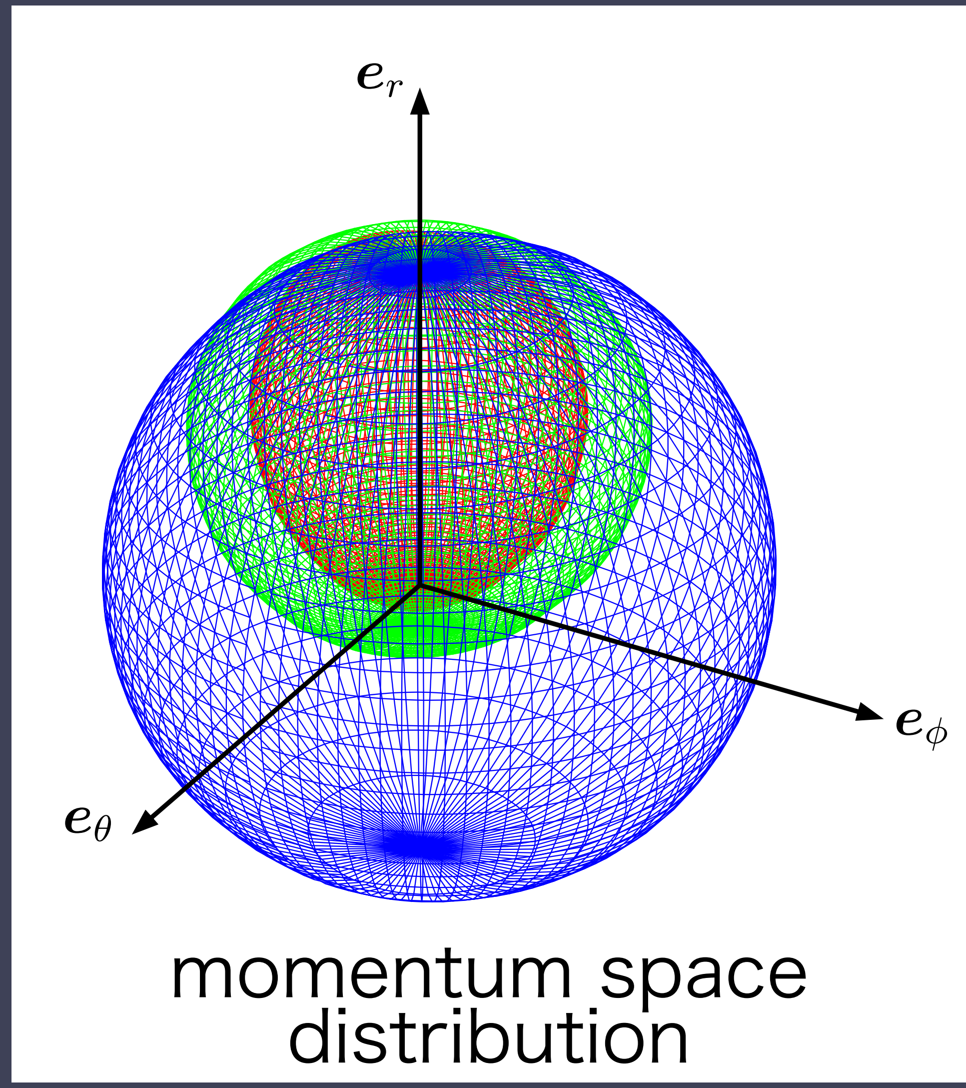
(remember Akaho-kun's talk)

$$p^\alpha \frac{\partial f}{\partial x^\alpha} - \Gamma^i{}_{\alpha\beta} p^\alpha p^\beta \frac{\partial f}{\partial p^i} = (-p^\alpha u_\alpha) S_{\rm col}$$

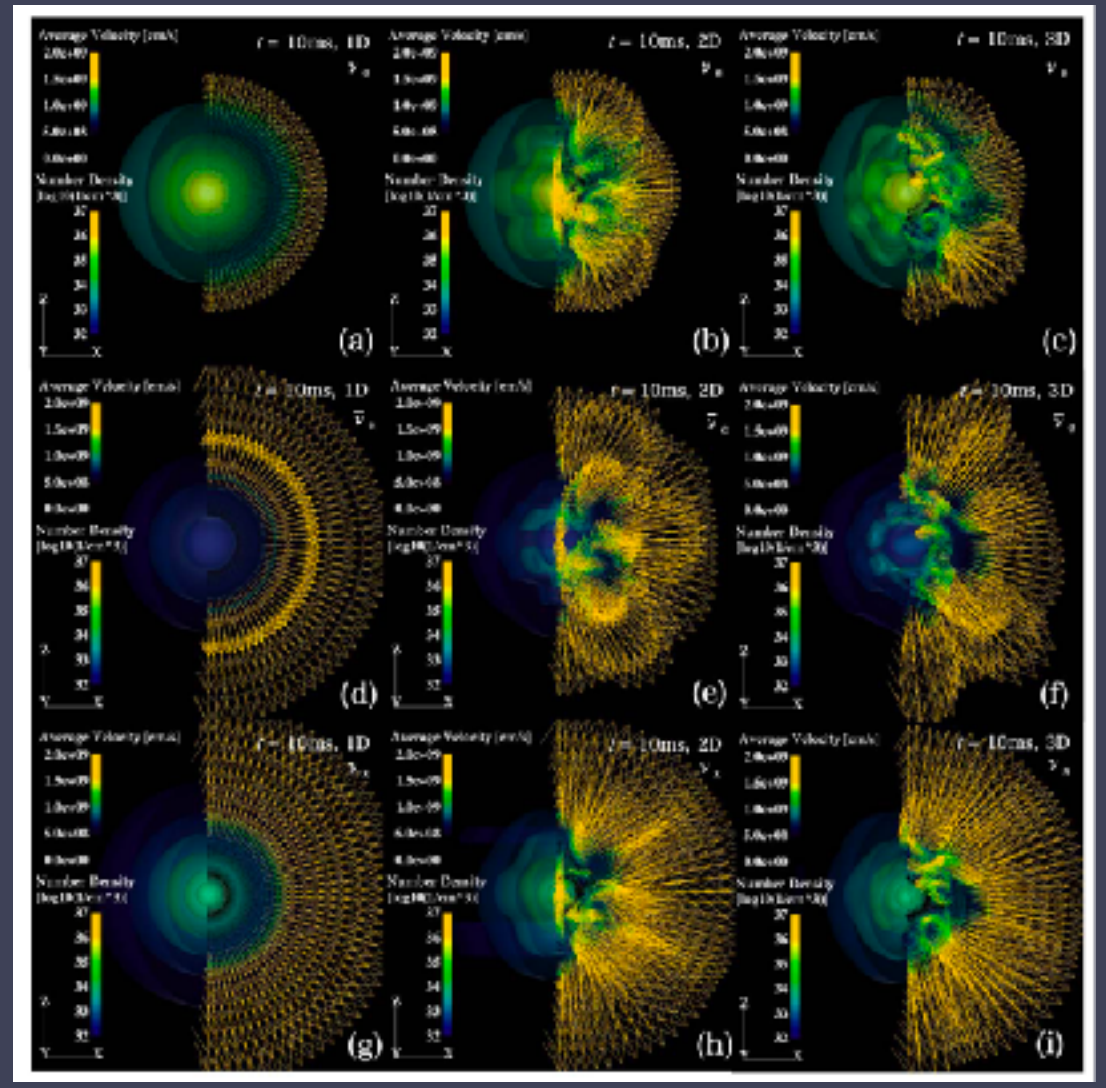
Boltzmann equation for neutrino transport



Nagakura+(2018)



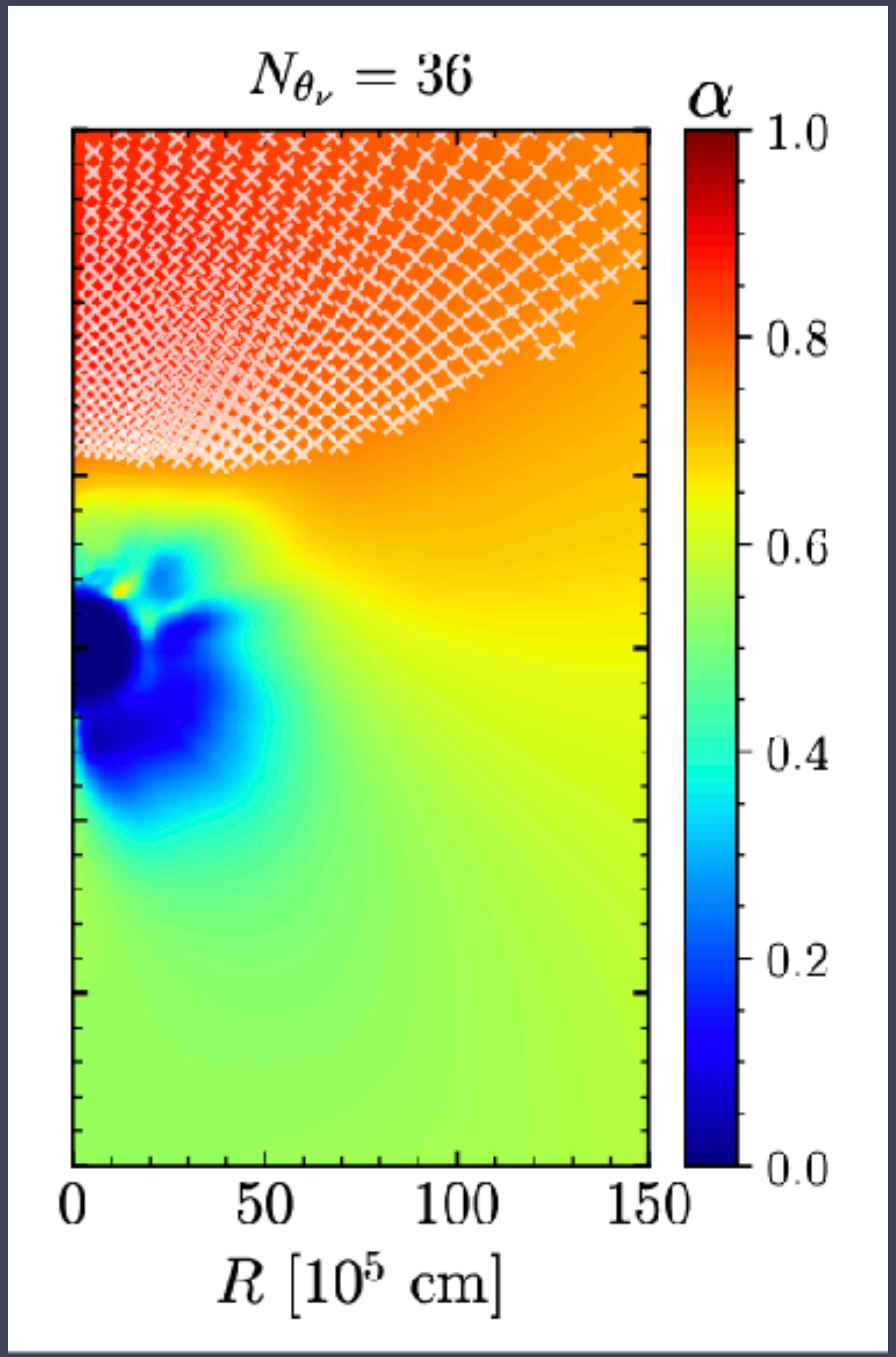
AH+(2019)



Iwakami+(2020)

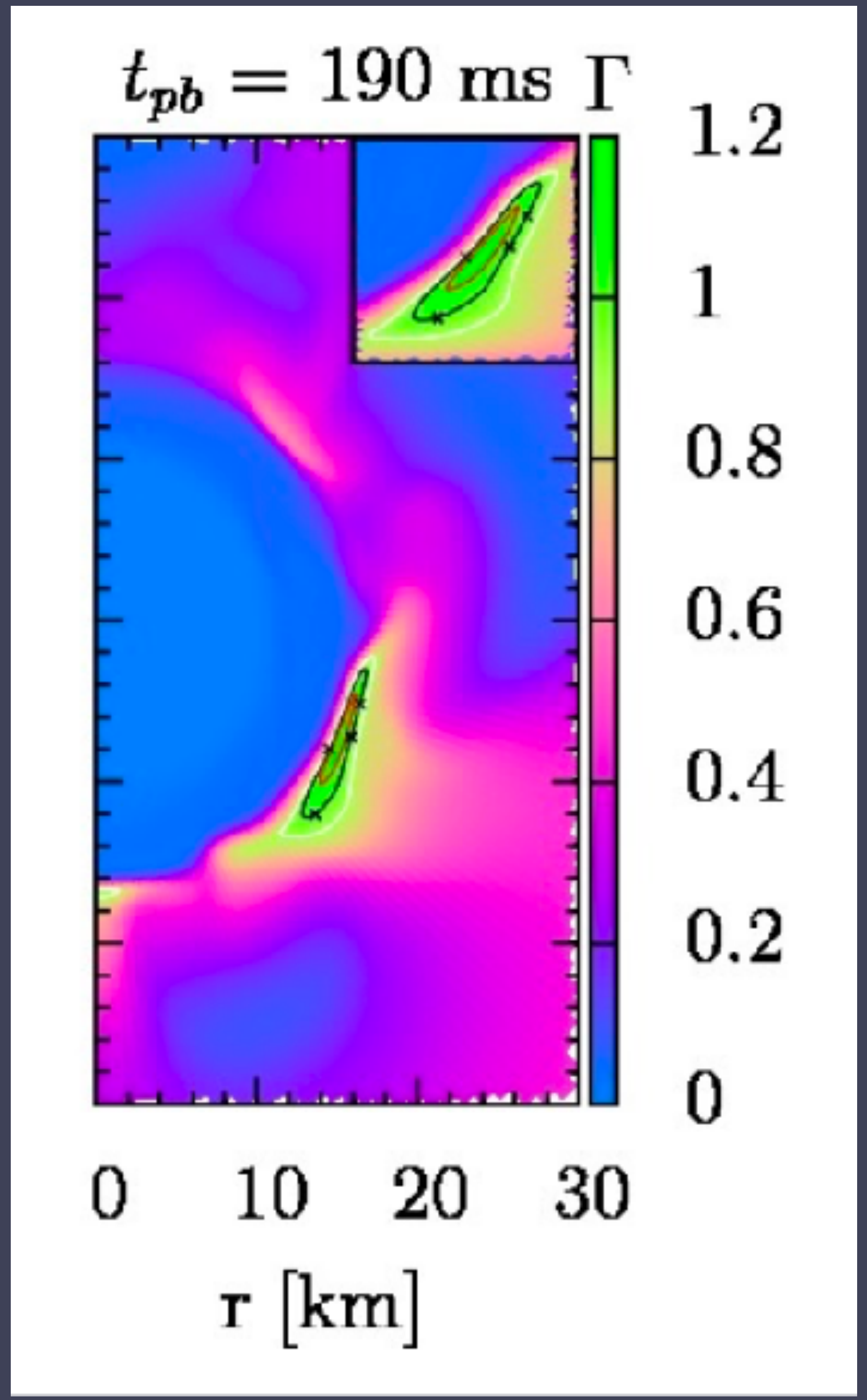
- Core-collapse supernova simulation with Boltzmann equation solver for neutrino transport
  - No artificial approximation
  - Distribution function is useful to investigate collective neutrino oscillation
- Core-collapse simulations under 2D axisymmetry (but see Iwakami+(2020) for 3D)

ELN crossing search with Boltzmann



Abbar+(2019)

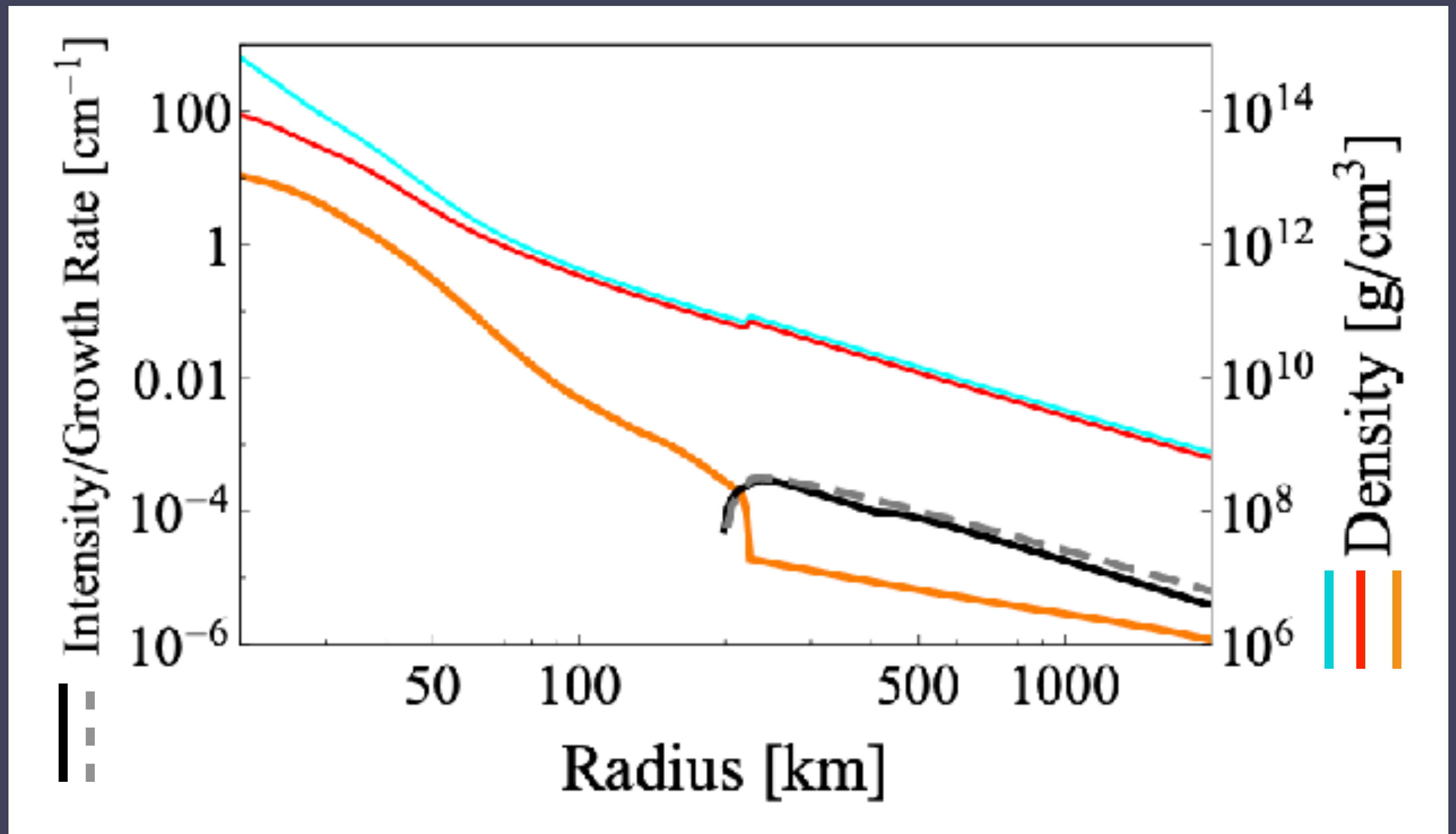
- Steady state Boltzmann
- Cross above PNS



Delfan Azari+(2020)

- Dynamical Boltzmann
- Cross near PNS

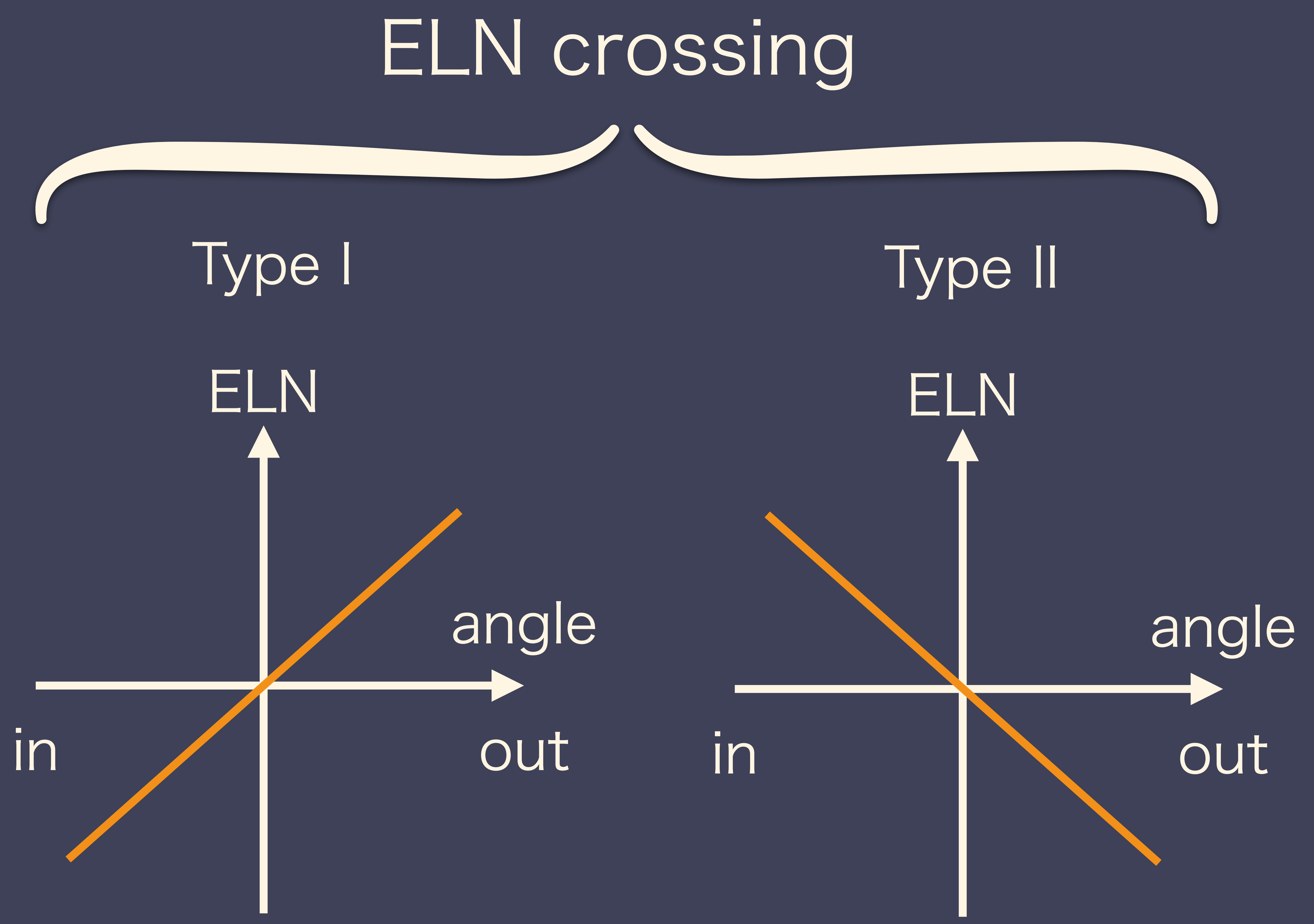
$$\sigma \sim \sqrt{-\left(\int_{G(\Omega)>0} \frac{d\Omega}{4\pi} G(\Omega)\right)\left(\int_{G(\Omega)<0} \frac{d\Omega}{4\pi} G(\Omega)\right)}$$

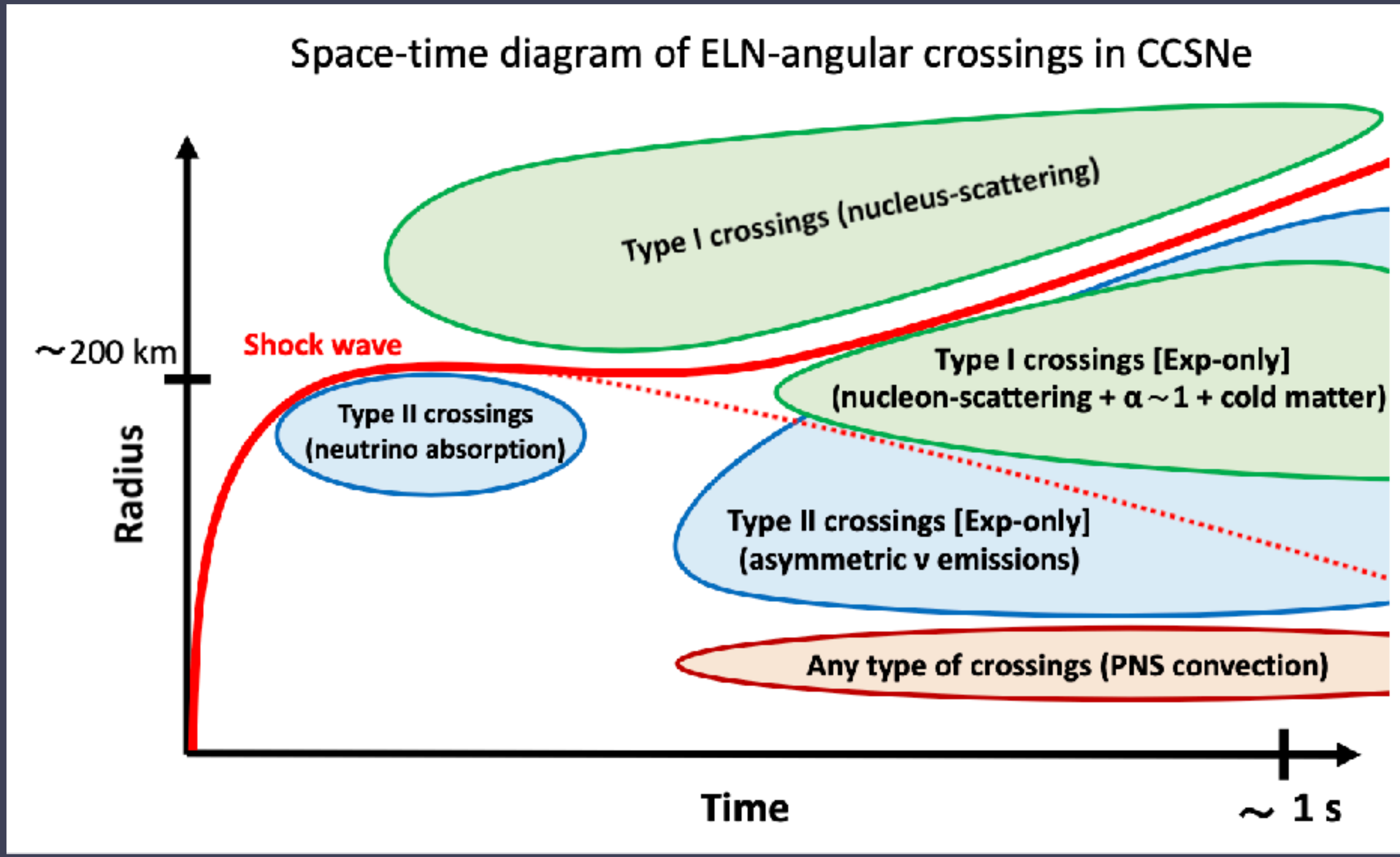


Morinaga+(2021)

- Dynamical Boltzmann
- Approx. groth rate
- Instability in preshock

Type I & II crossing





Nagakura+(2021)

- Type I & II crossing
  - Type II-1: neutrino absorption
  - Type II-2: asymmetric (anti)neutrino emission by asymmetric Ye distribution around PNS

Rotating CCSN simulation by Boltzmann

- Run a rotating core-collapse supernova simulation with Boltzmann neutrino transport → Evaluate the linear growth rate from approximate formula

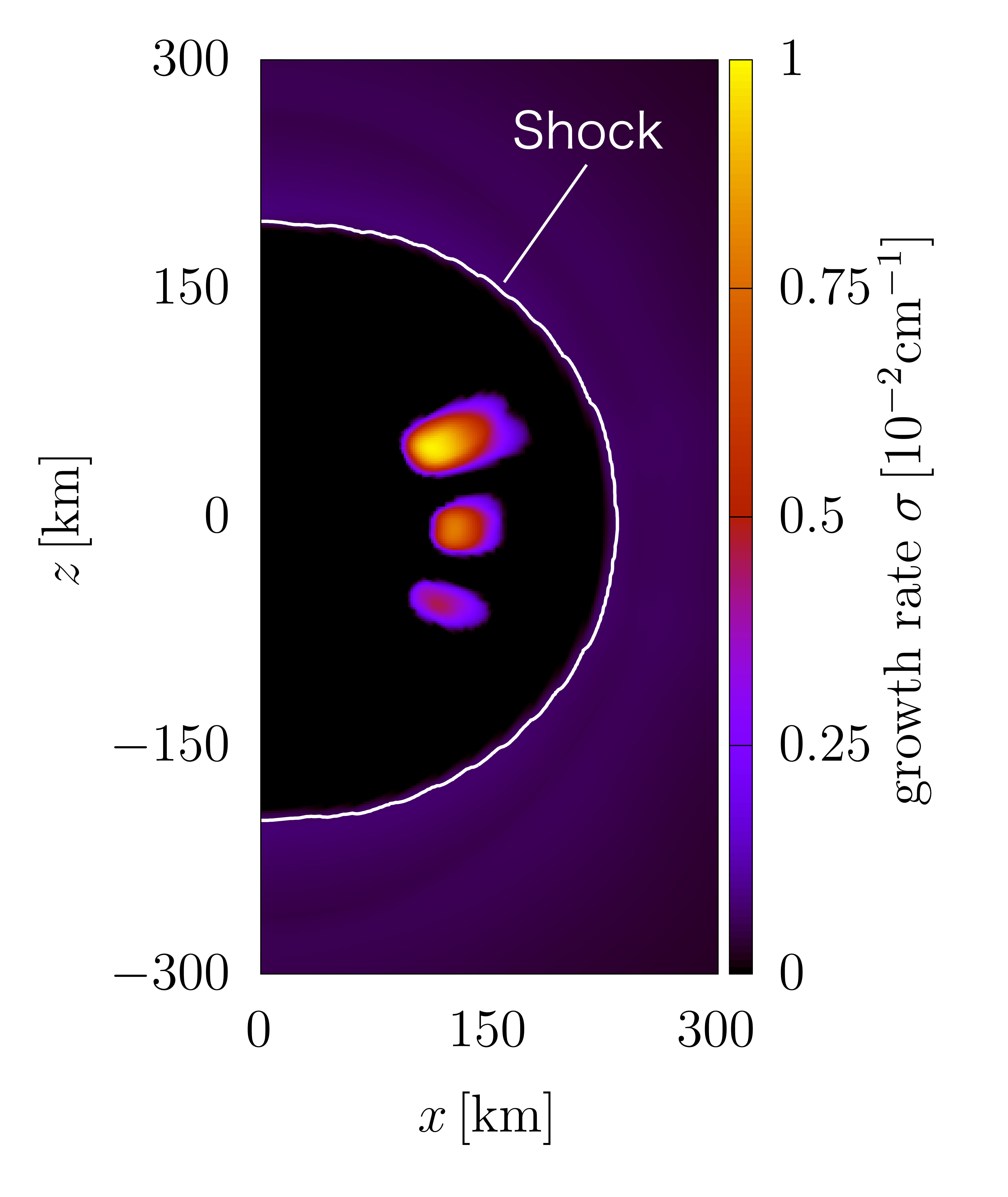
$$\sigma \sim \sqrt{-\left(\int_{G(\Omega)>0} \frac{d\Omega}{4\pi} G(\Omega)\right)\left(\int_{G(\Omega)<0} \frac{d\Omega}{4\pi} G(\Omega)\right)}$$

- Setup
  - 15 M$_\odot$ progenitor (Woosley et al. 2002, commonly used)
  - Furusawa—Togashi nuclear EOS (variational method + NSE composition)
  - Standard neutrino reaction + updated electron capture rate on nuclei
  - Rotational velocity imposed at the onset of collapse

$$v^{\phi}(r) = \frac{4\,\mathrm{rad/s}}{1 + (r/1000\,\mathrm{km})^2}$$

- Explosion/failure is still unclear (not the topic here)

Linear growth rate

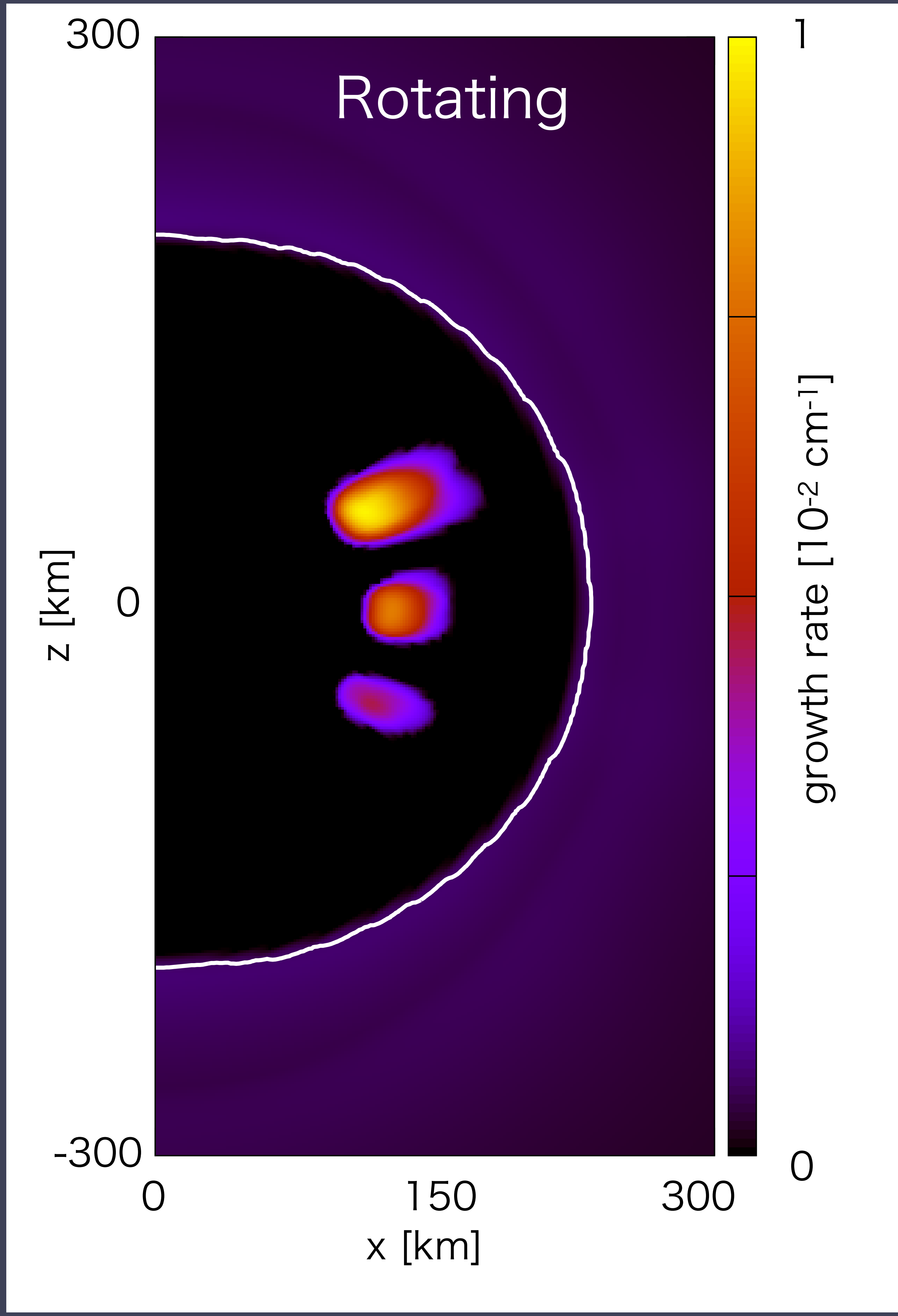


- Spatial distribution of the linear growth rate at ~200 ms postbounce
- Linear growth rate

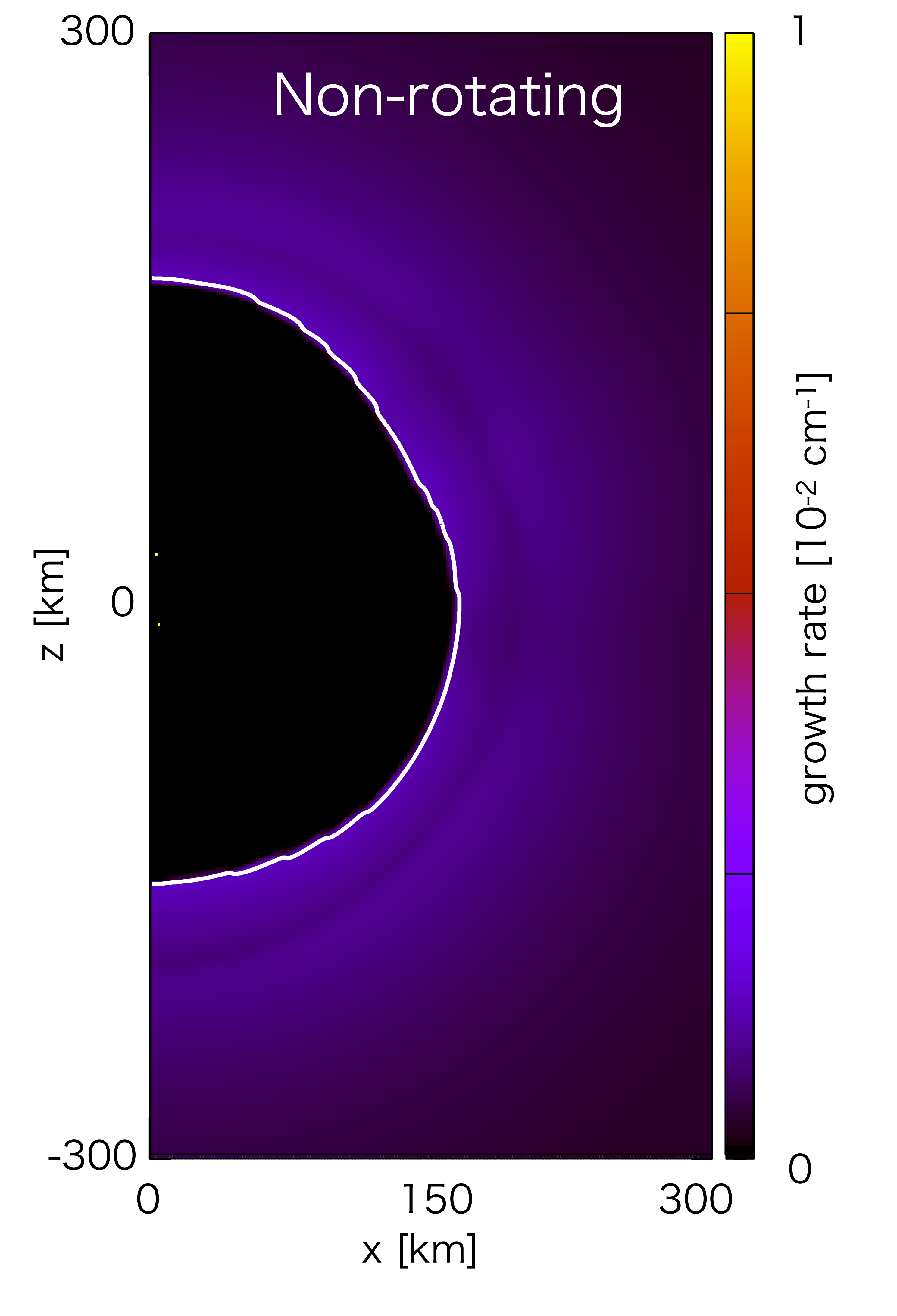
$$\sigma \sim \sqrt{-\left(\int_{G(\Omega)>0} \frac{d\Omega}{4\pi} G(\Omega)\right)\left(\int_{G(\Omega)<0} \frac{d\Omega}{4\pi} G(\Omega)\right)}$$

- Islands of flavor instability (outer unstable region is found by Morinaga et al. 2020)

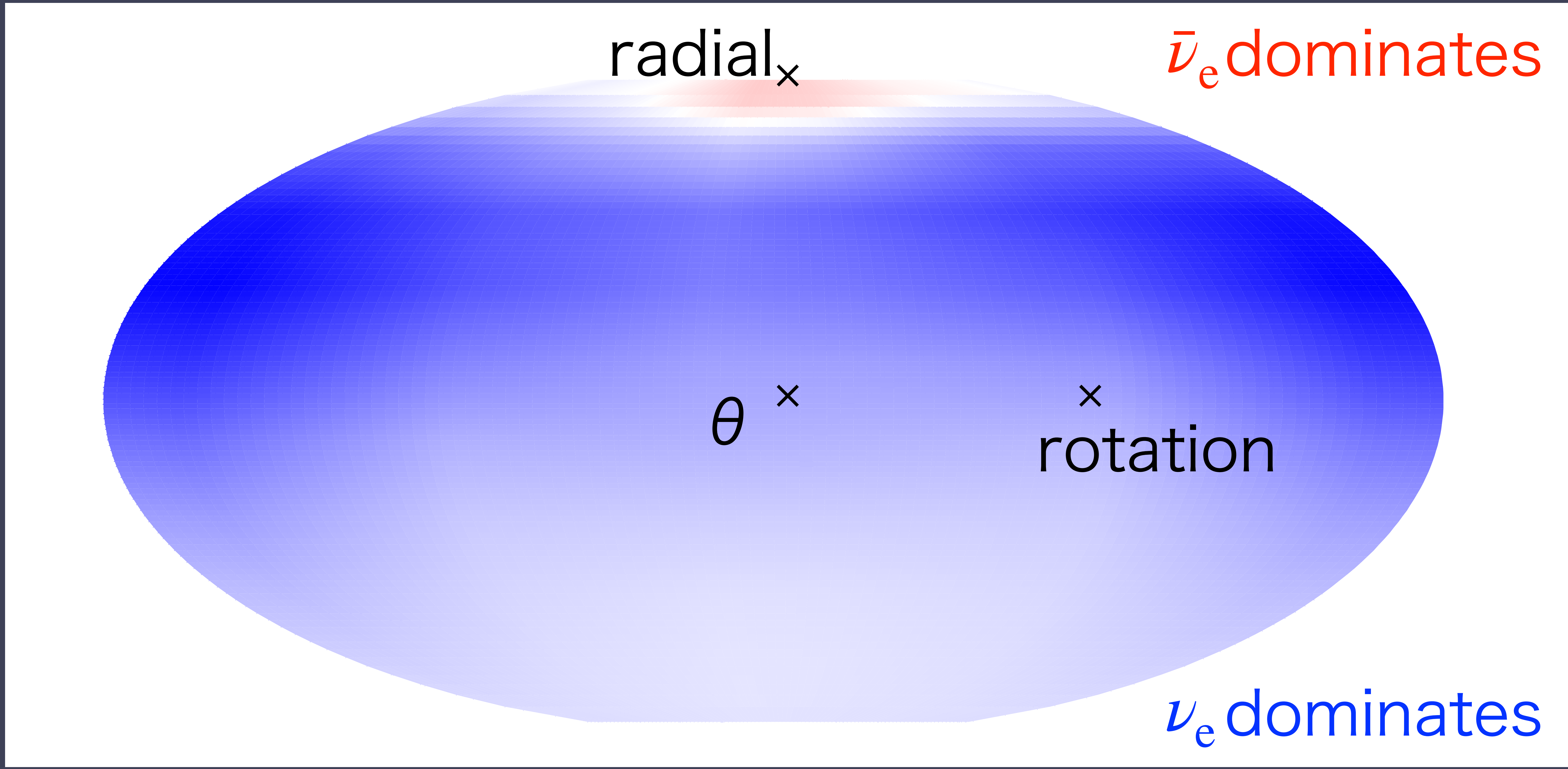
Comparison with non-rotating simulation



- Instability islands only appear in the rotating model
→ Rotational origin

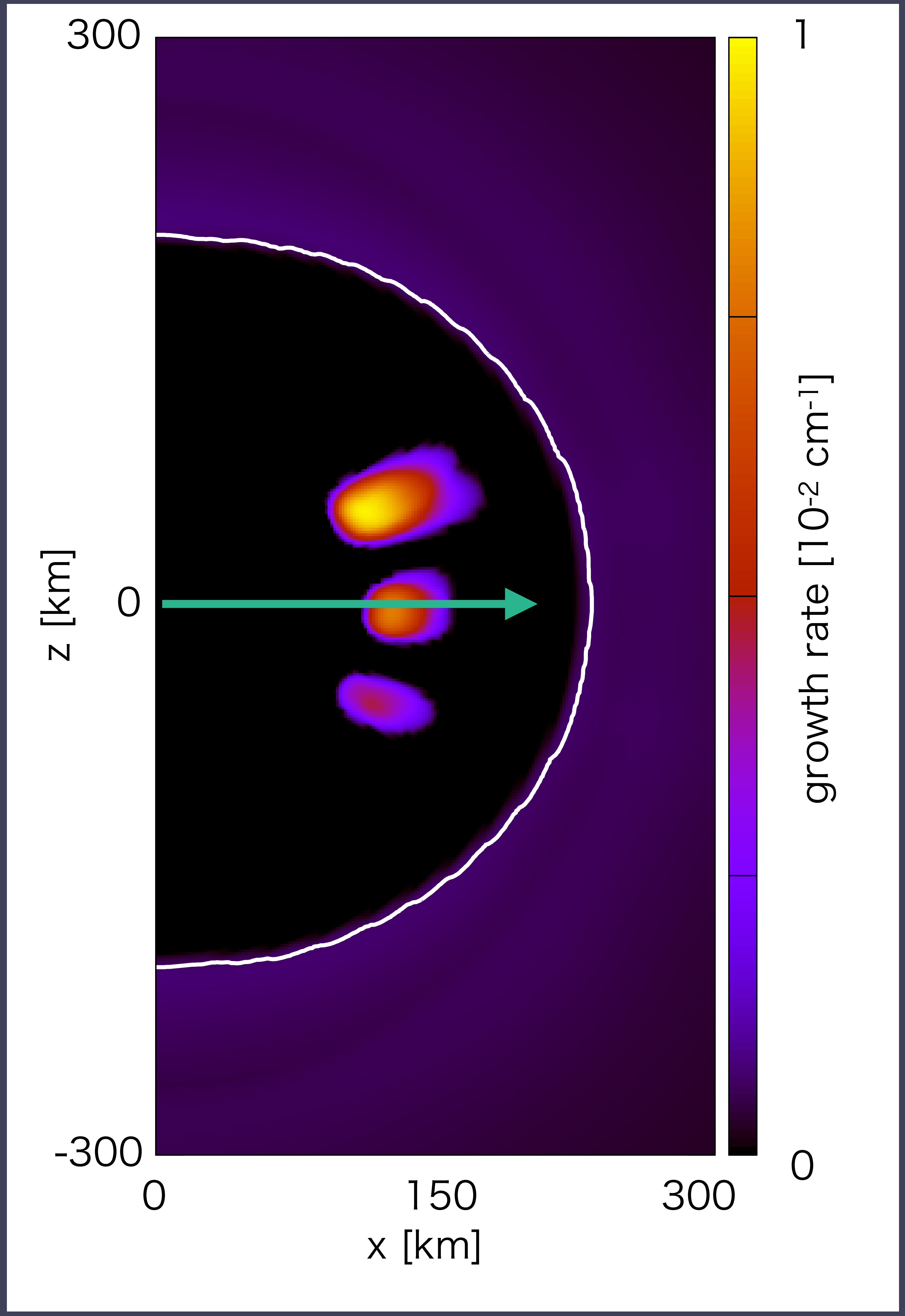


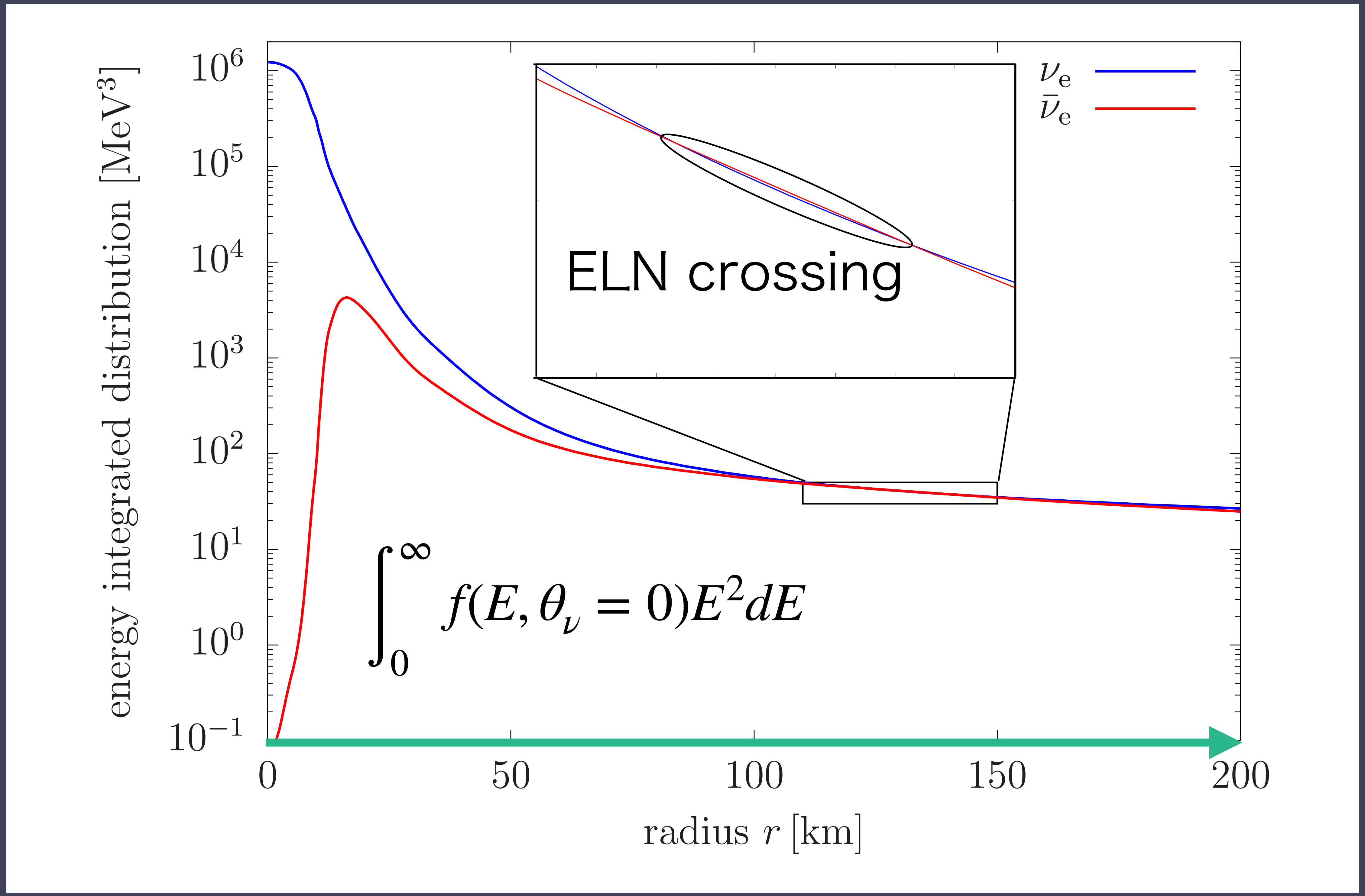
ELN angular distribution



- ELN angular distribution in an unstable region
- $\bar{\nu}_e$ dominates in radial direction → Type II crossing
- Neutrino absorption causes crossing

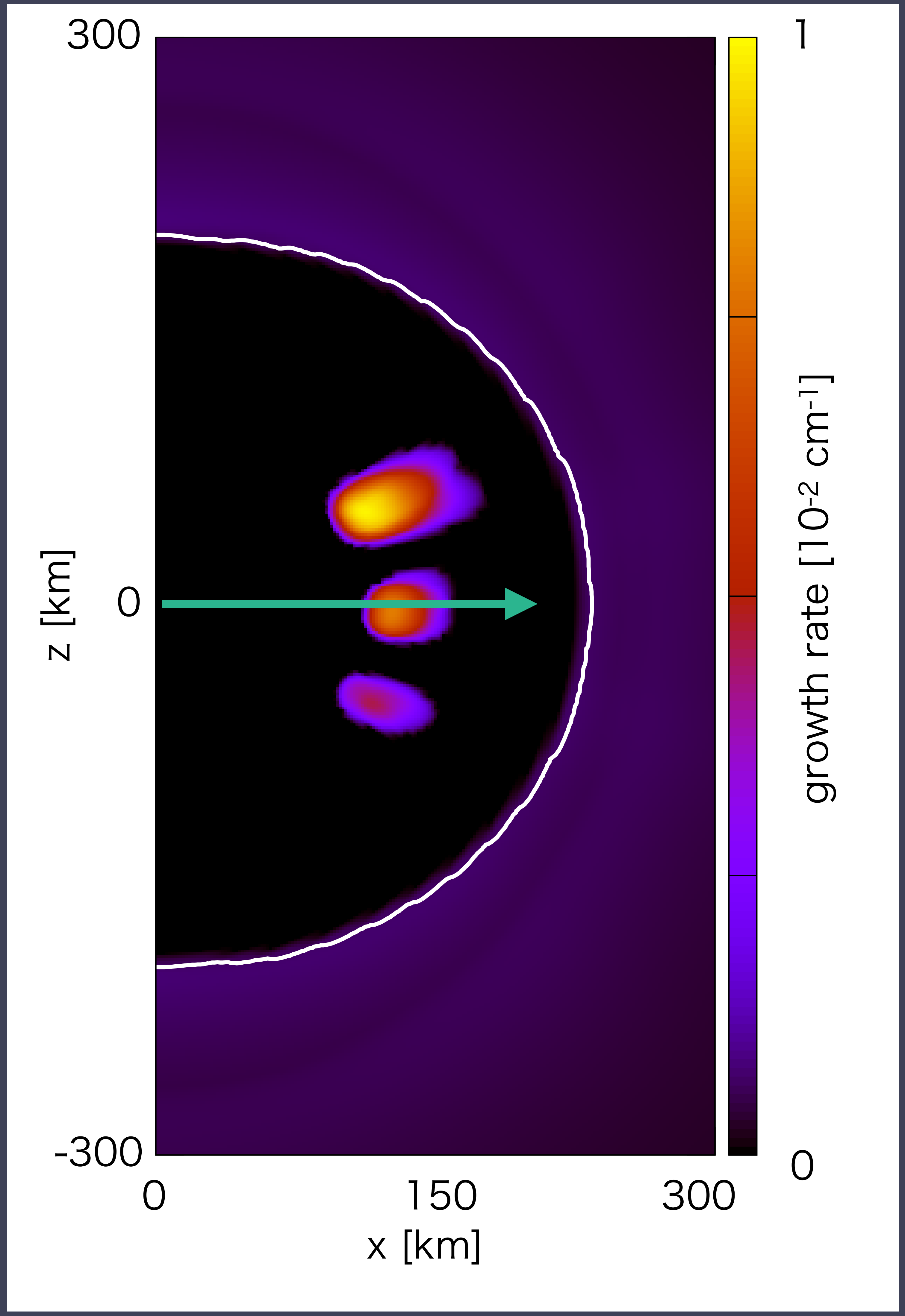
Outgoing distribution function

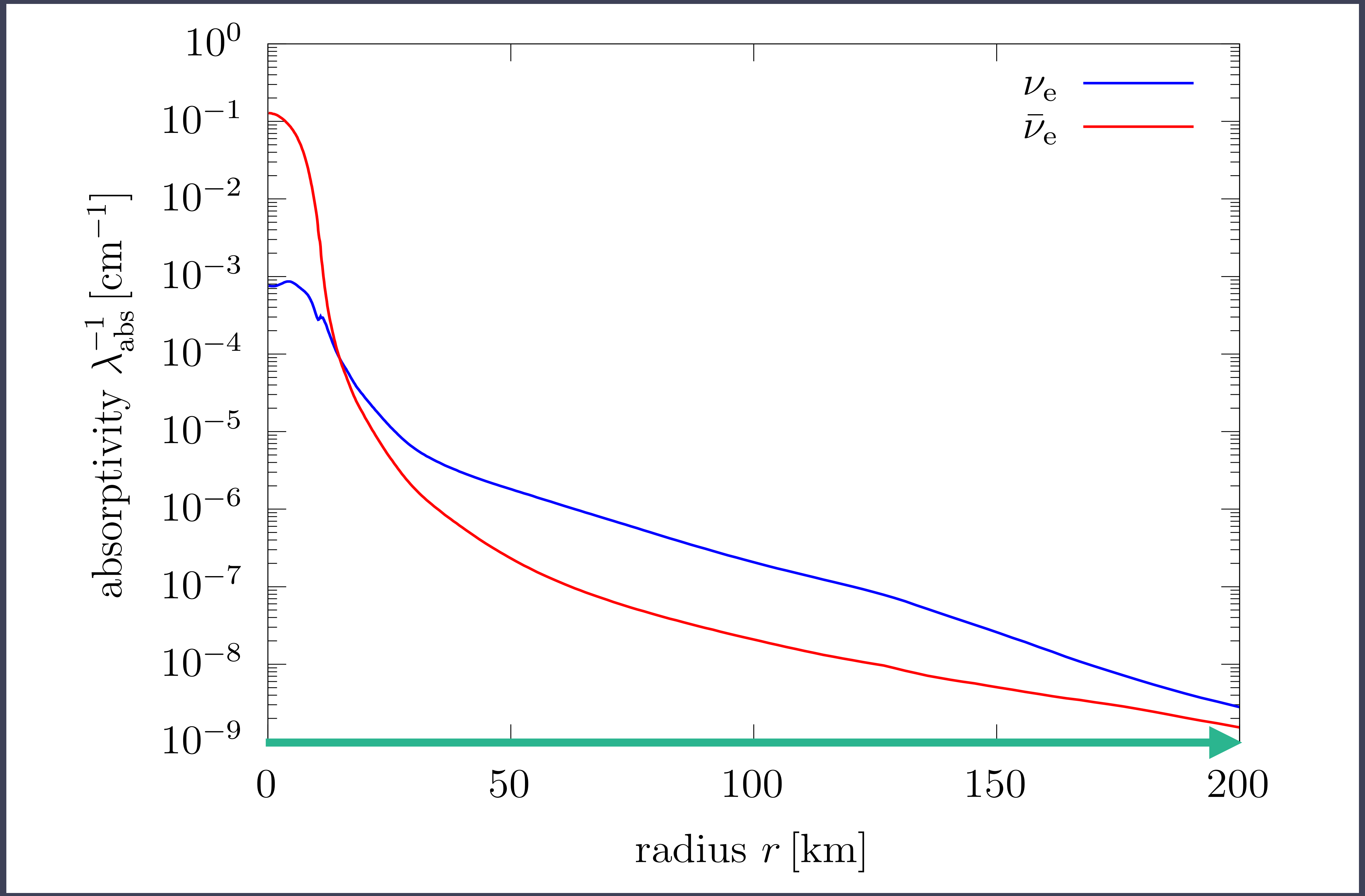




- Energy-integrated distribution function for outgoing
- ν_e are absorbed faster than $\bar{\nu}_e \rightarrow$ ELN crossing
- Collision term for the Boltzmann eq. $= -(f - f_{FD})/\lambda_{mfp}$

Outgoing distribution function



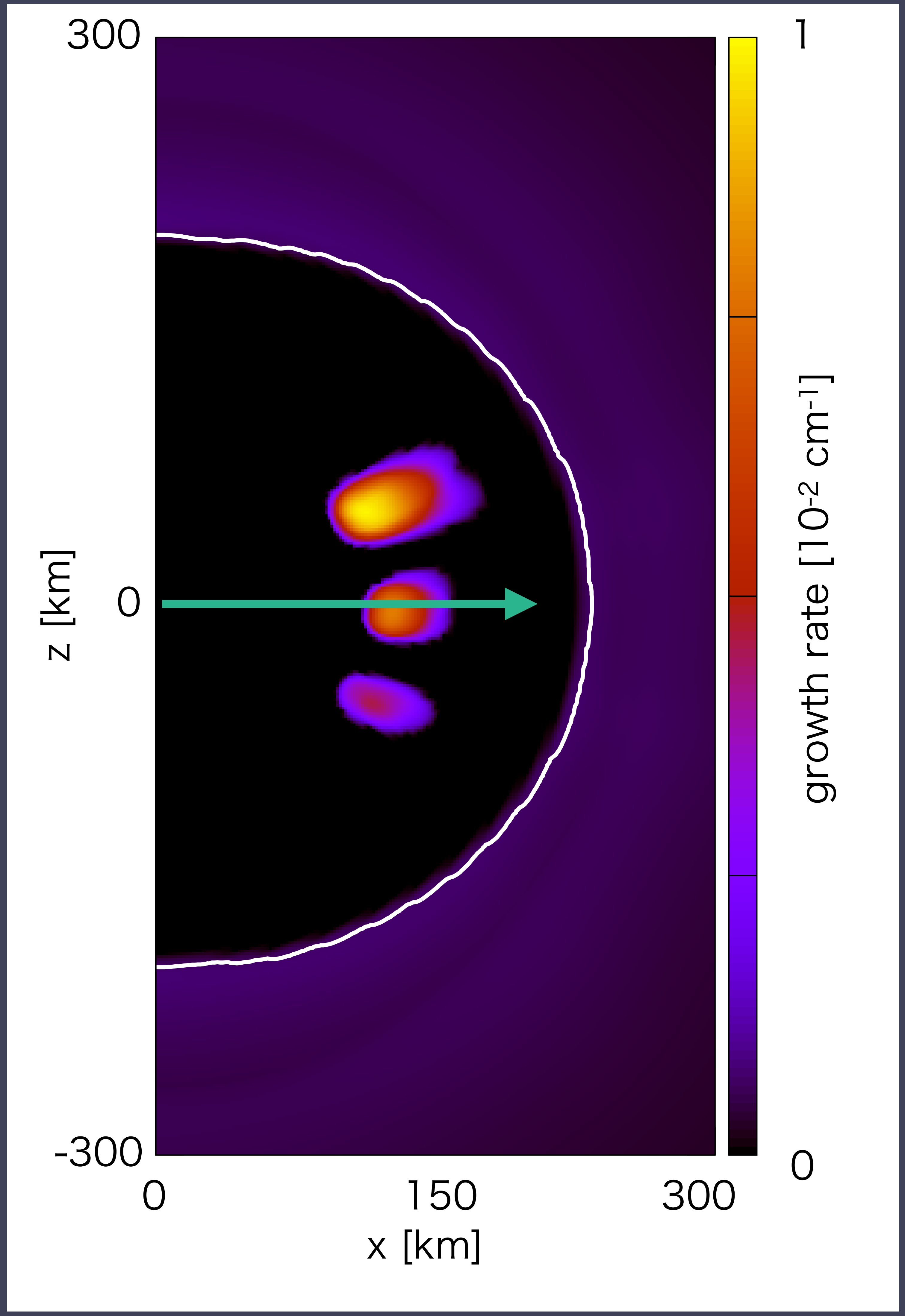


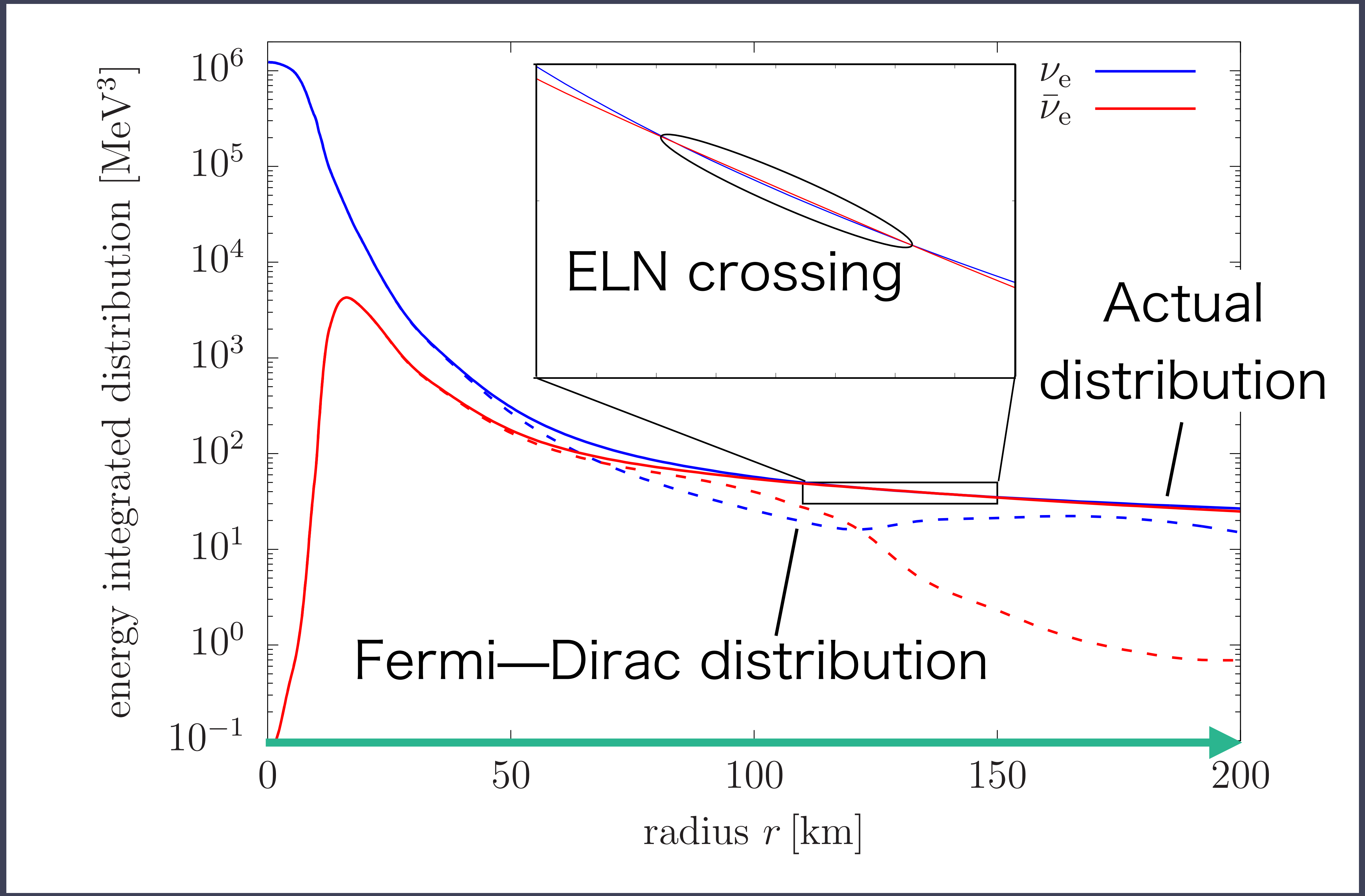
- Collision term for the Boltzmann eq.

$$= -(f - f_{\mathrm{FD}})/\lambda_{\mathrm{mfp}}$$

- Larger absorptivity for ν_e than $\bar{\nu}_e$

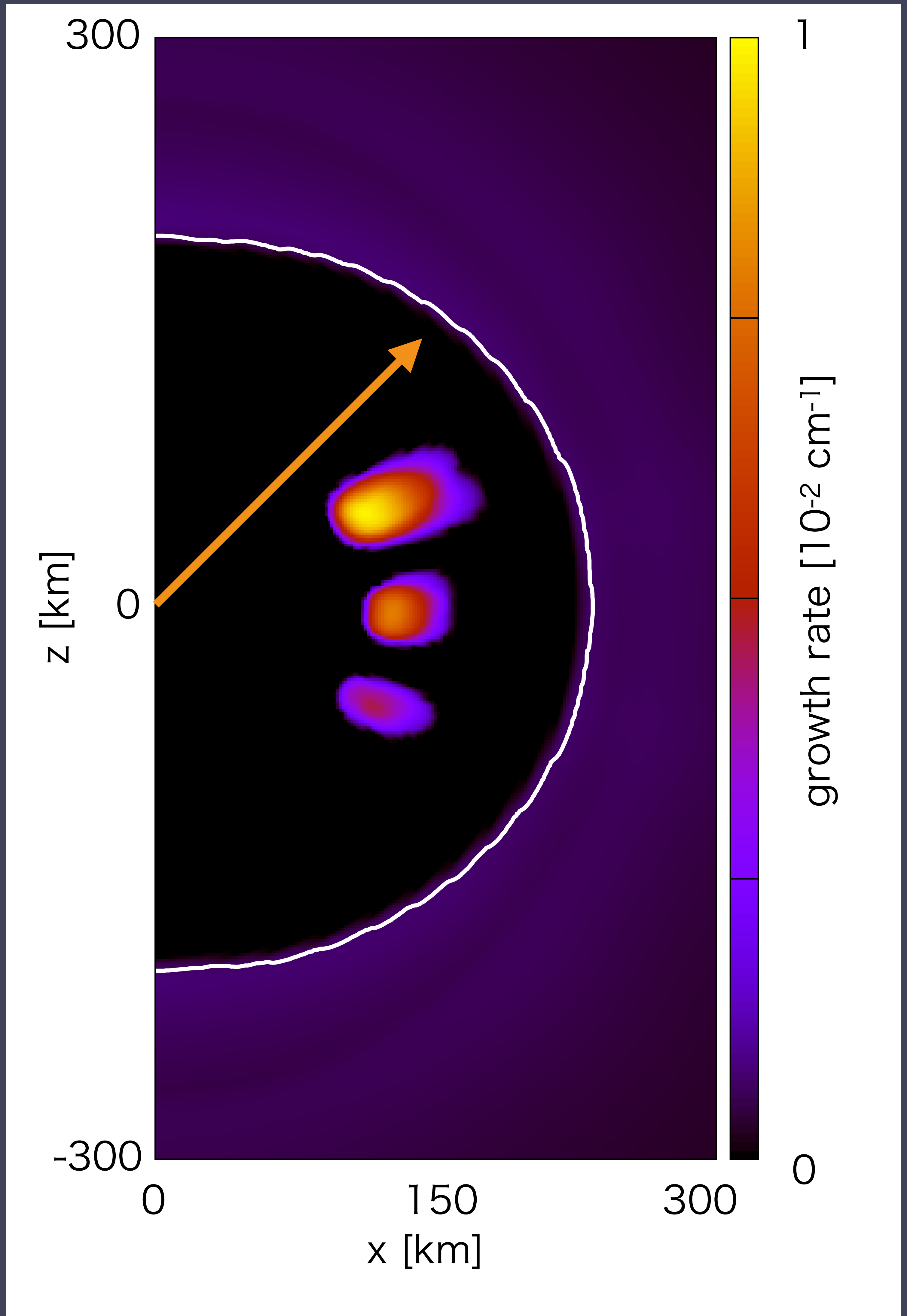
Outgoing distribution function

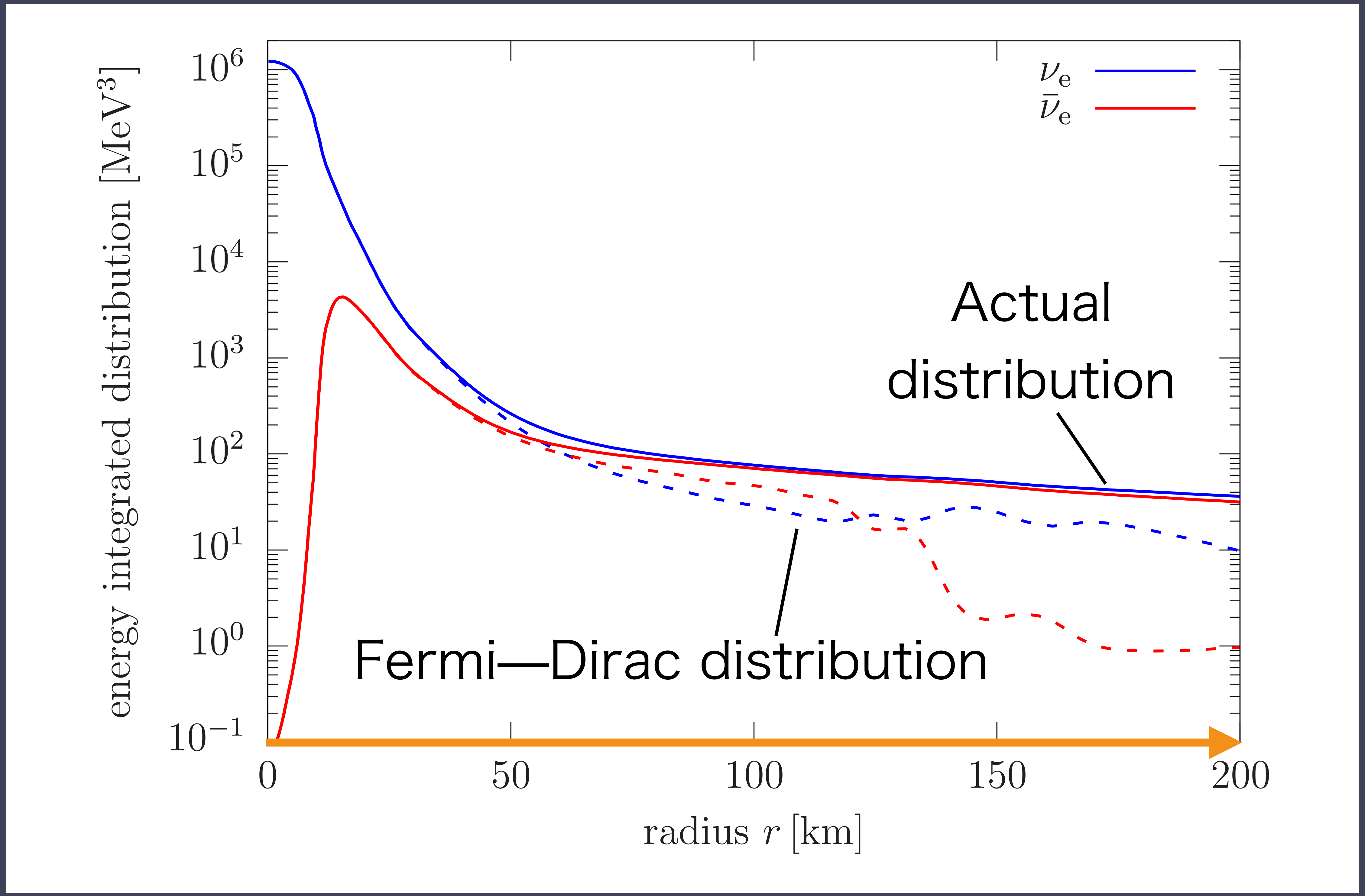




- Collision term for the Boltzmann eq. $= -(f - f_{\rm FD})/\lambda_{\rm mfp}$
- $f_{\rm FD}$ for $\nu_{\rm e}$ and $\bar{\nu}_{\rm e}$ are inverted → $\nu_{\rm e}$ are strongly absorbed

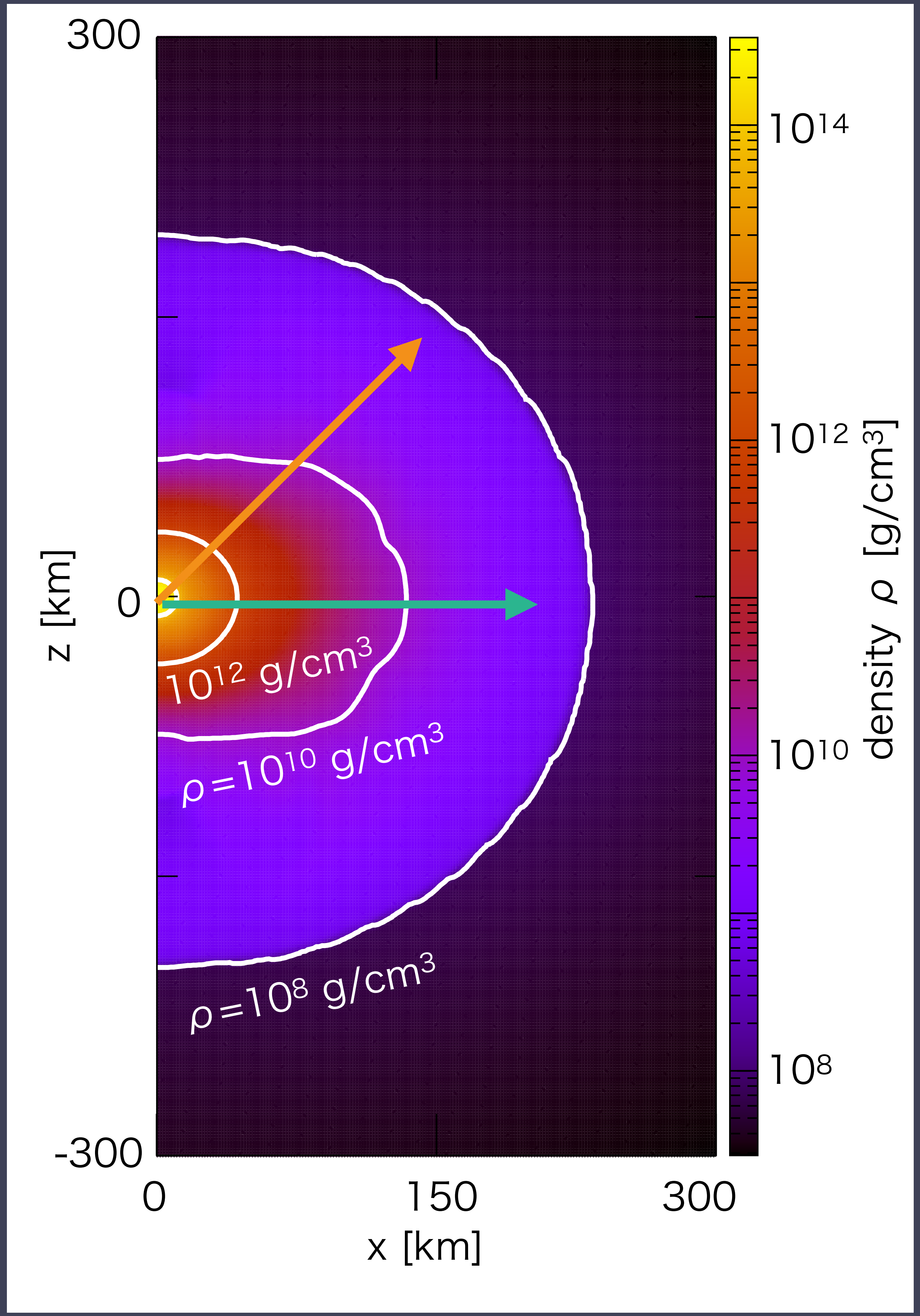
Distribution along stable direction

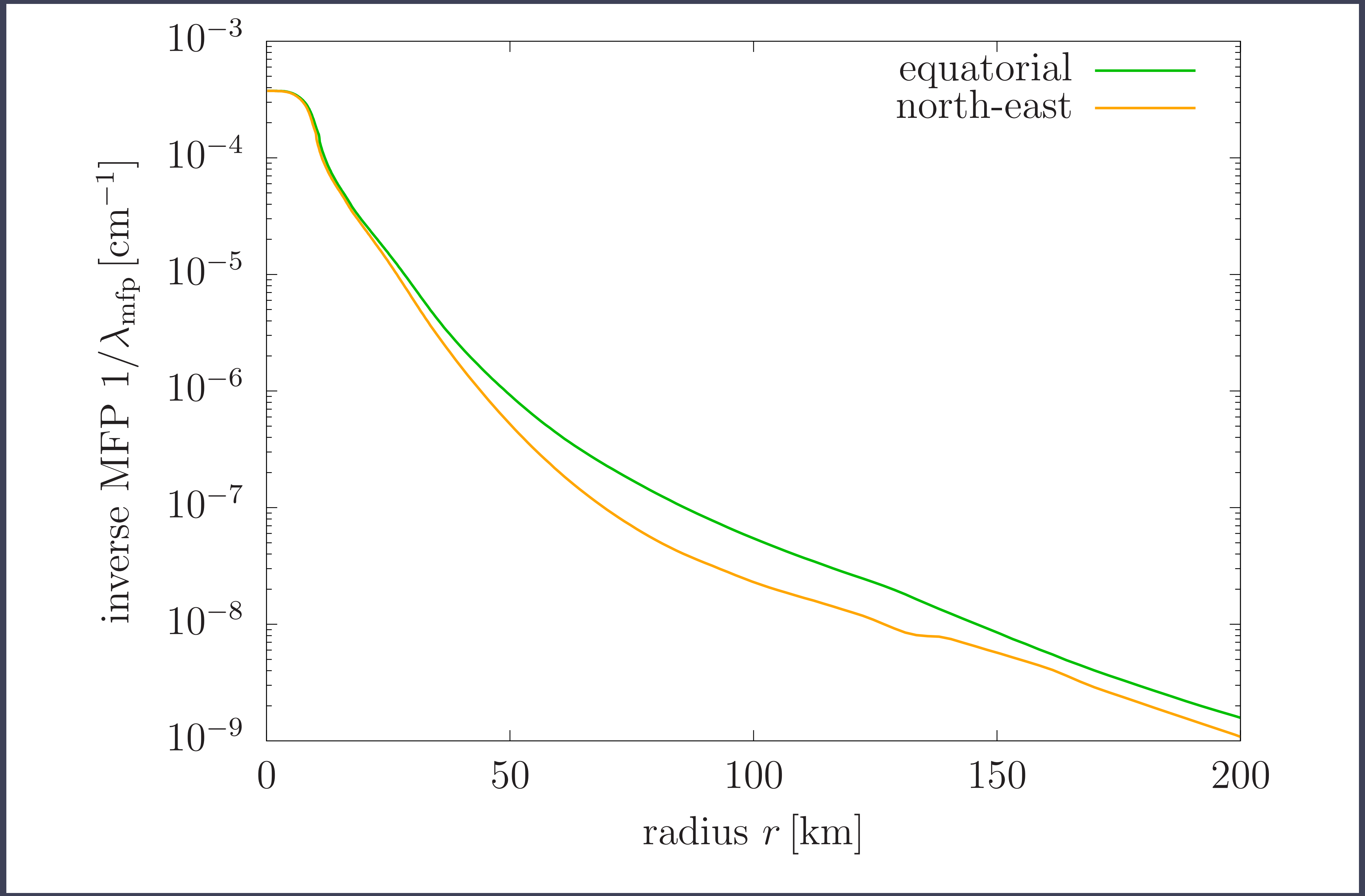




- ELN dose not cross zero along orange arrow
- Situation is similar to equator, but absorption is insufficient

Rotational deformation of matter

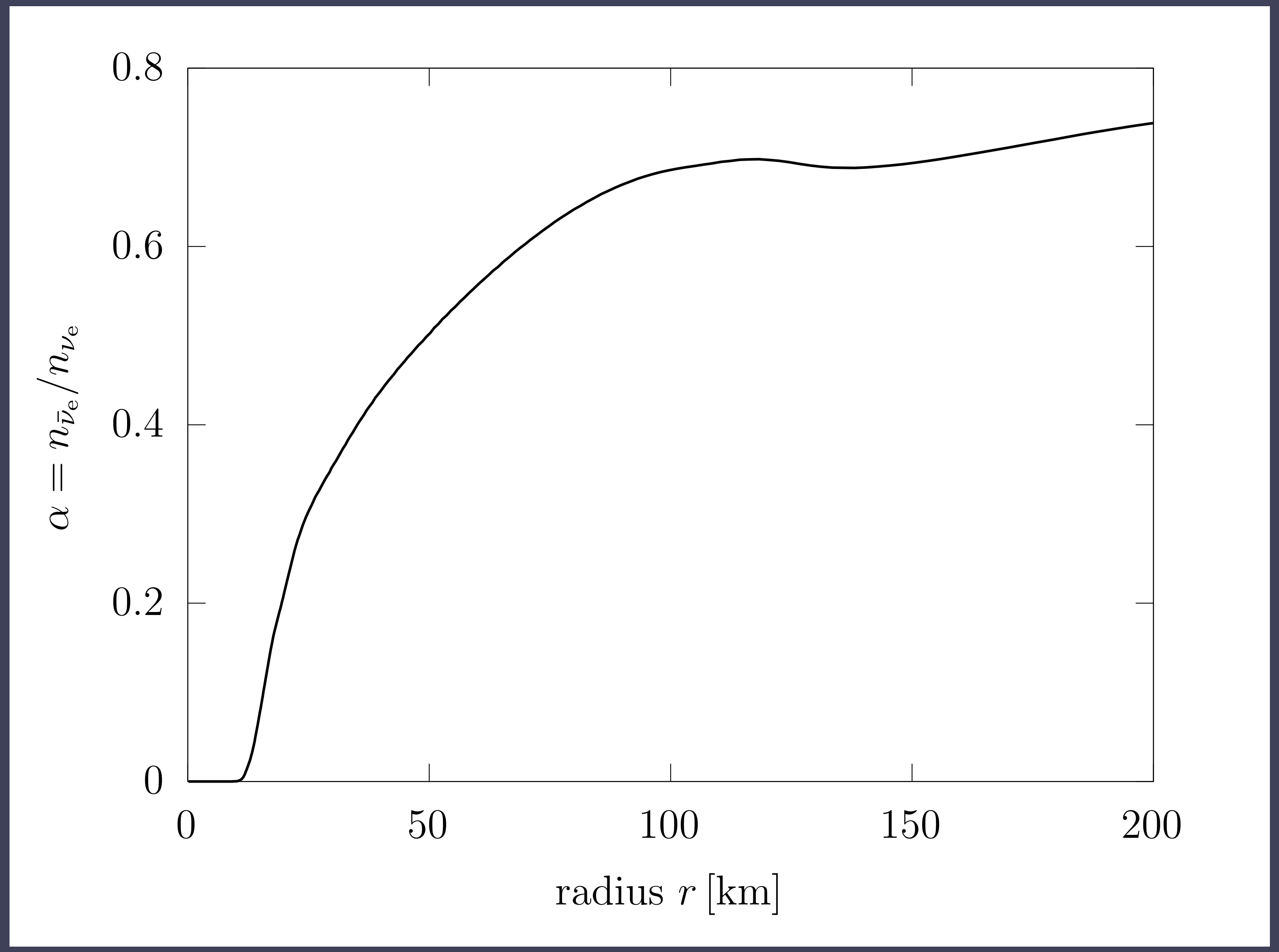


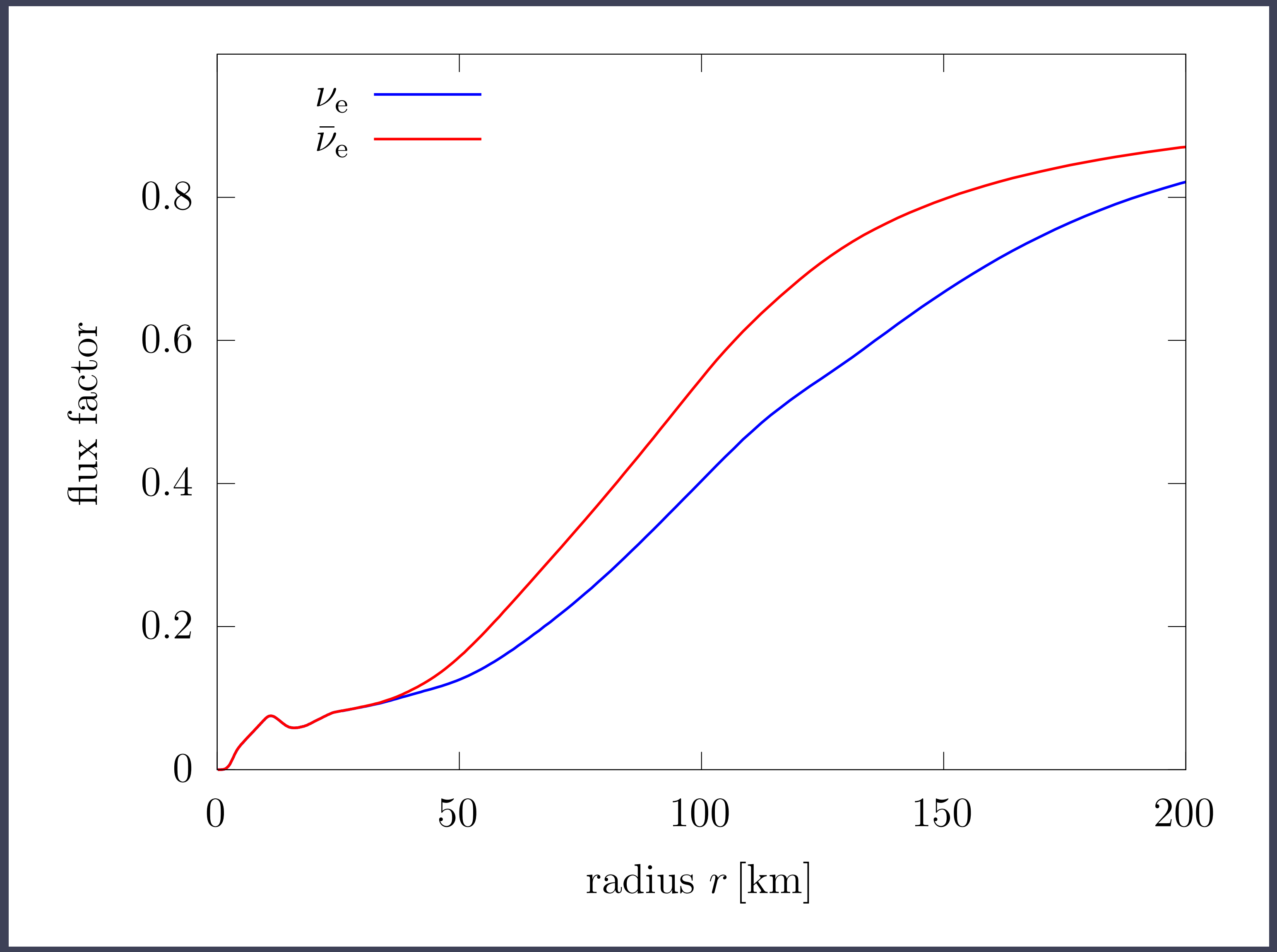


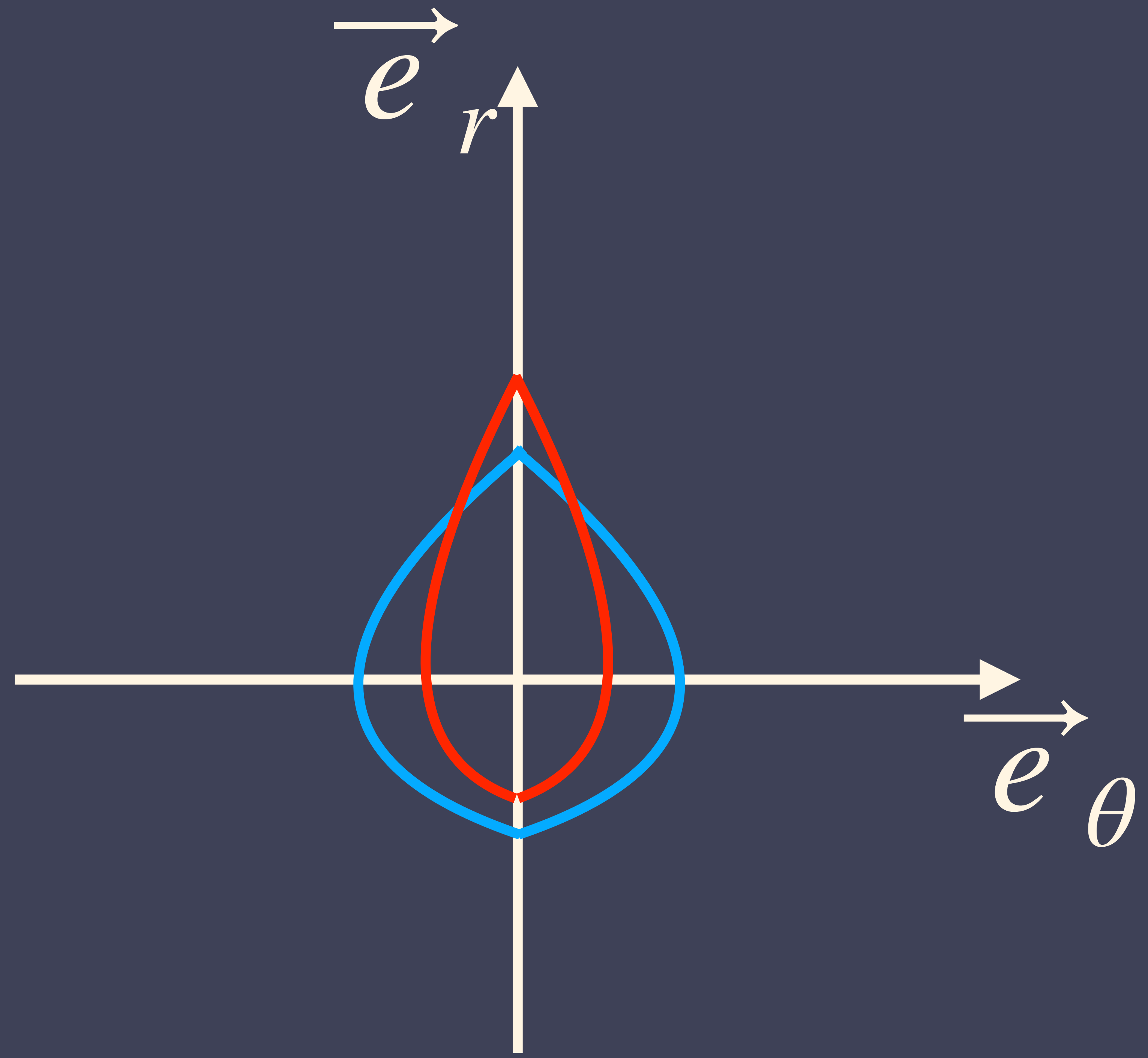
- Matter distribution is oblate owing to rotation
- Large-absorptivity region extends more along green
- Equatorially flying ν_e are absorbed for longer time

Relatively small alpha parameter

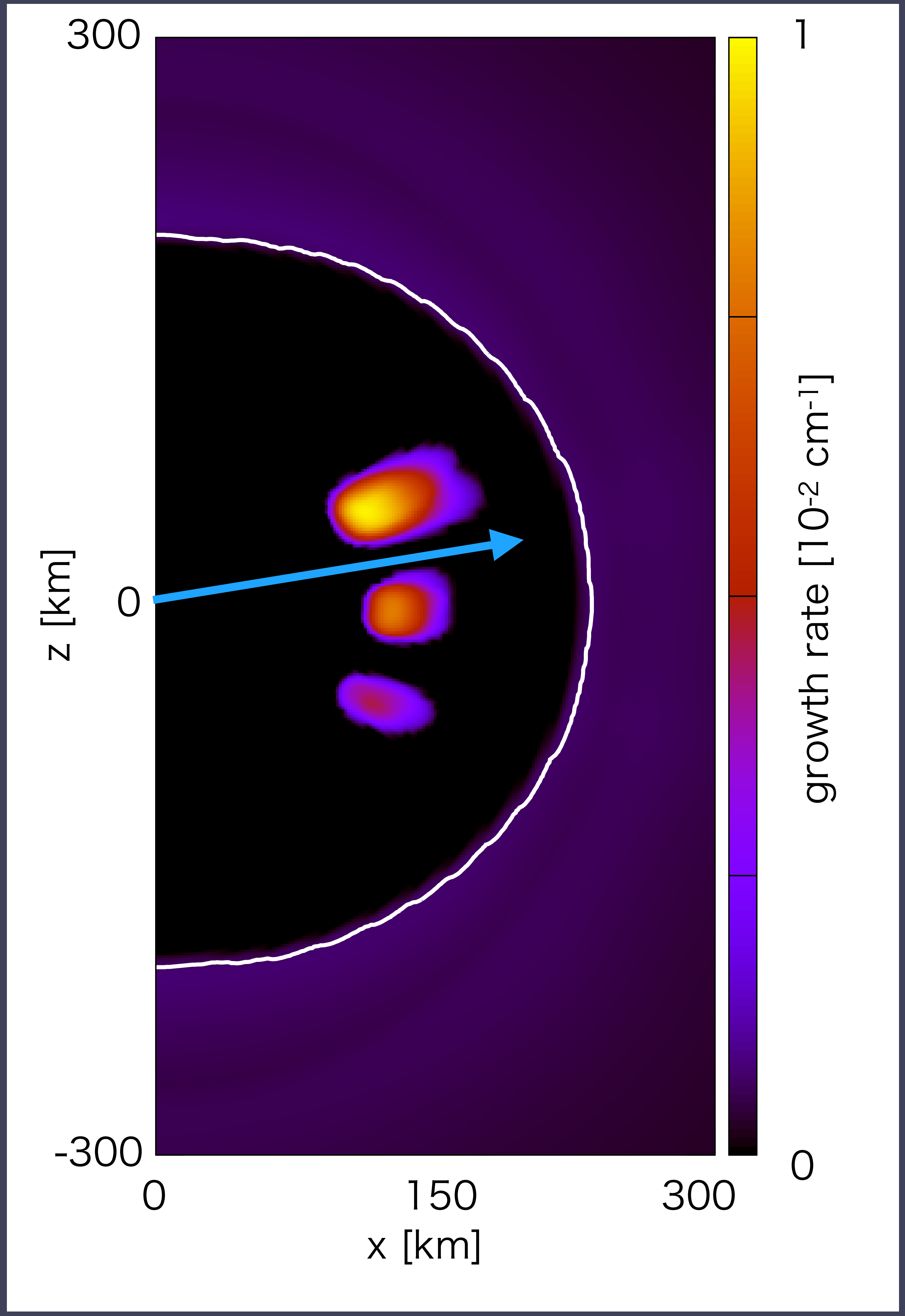
- Alpha parameter $\alpha := n_{\bar{\nu}_\mathrm{e}}/n_{\nu_\mathrm{e}}$ exceeding ~0.8 is an indicator of ELN crossing
- In the rotation-induced ELN crossing, alpha is ~0.7
- Flux factor for $\bar{\nu}_\mathrm{e}$ is much larger than $\nu_\mathrm{e} \rightarrow \bar{\nu}_\mathrm{e}$ is more forward-peaking

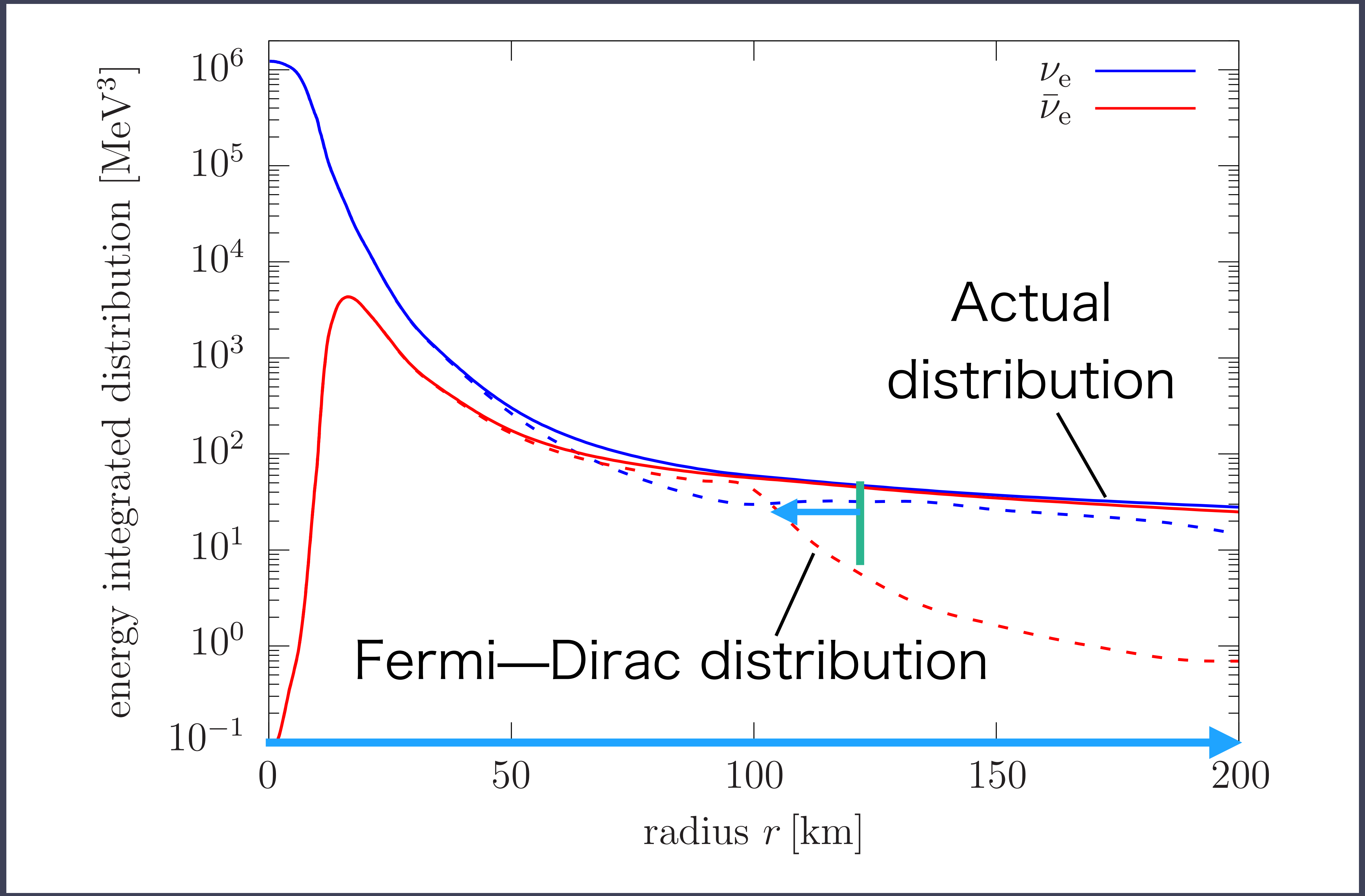






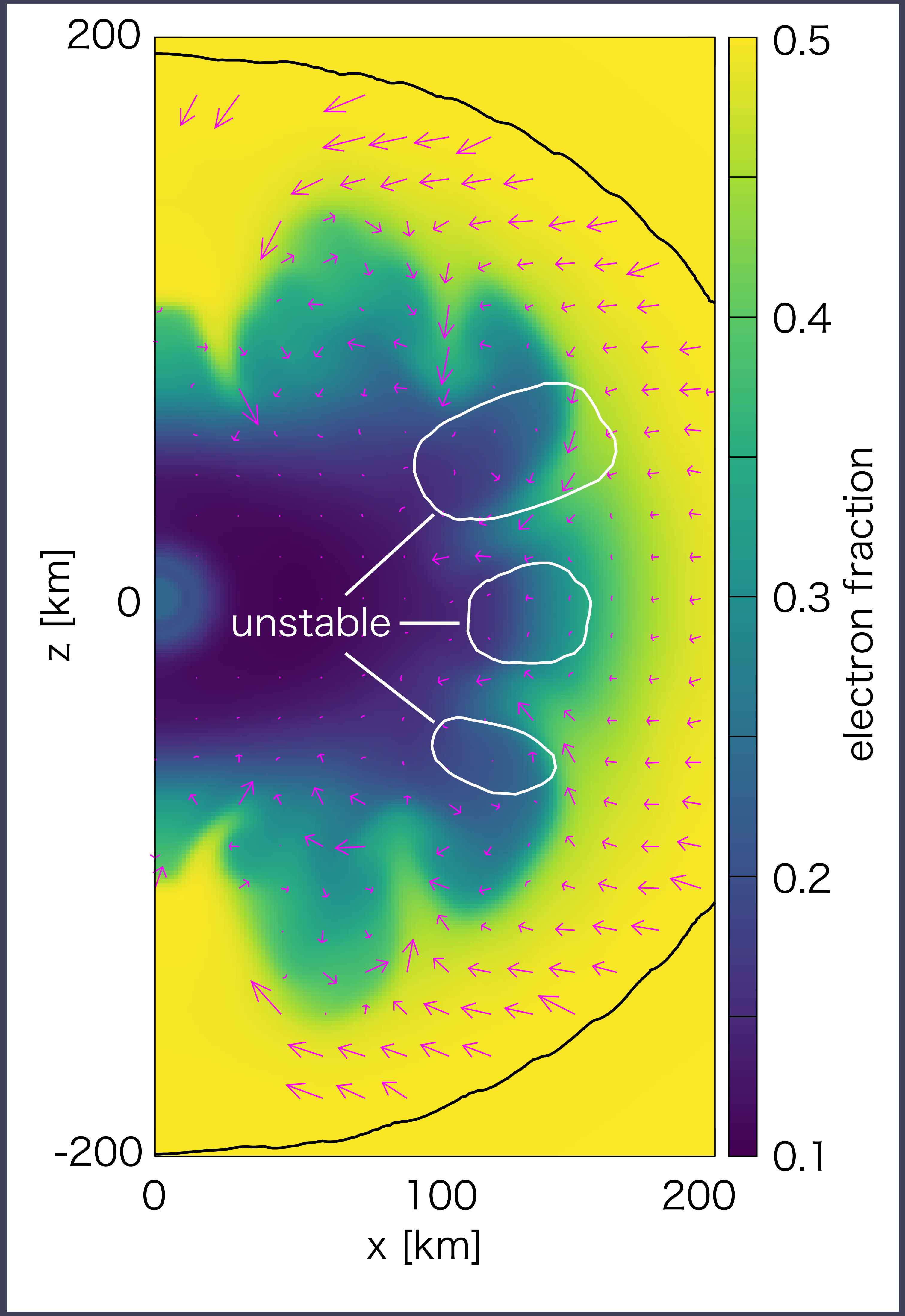
Island structure





- ELN dose not cross zero along blue arrow
- Cross of f_{FD} recedes to smaller radius

Island structure



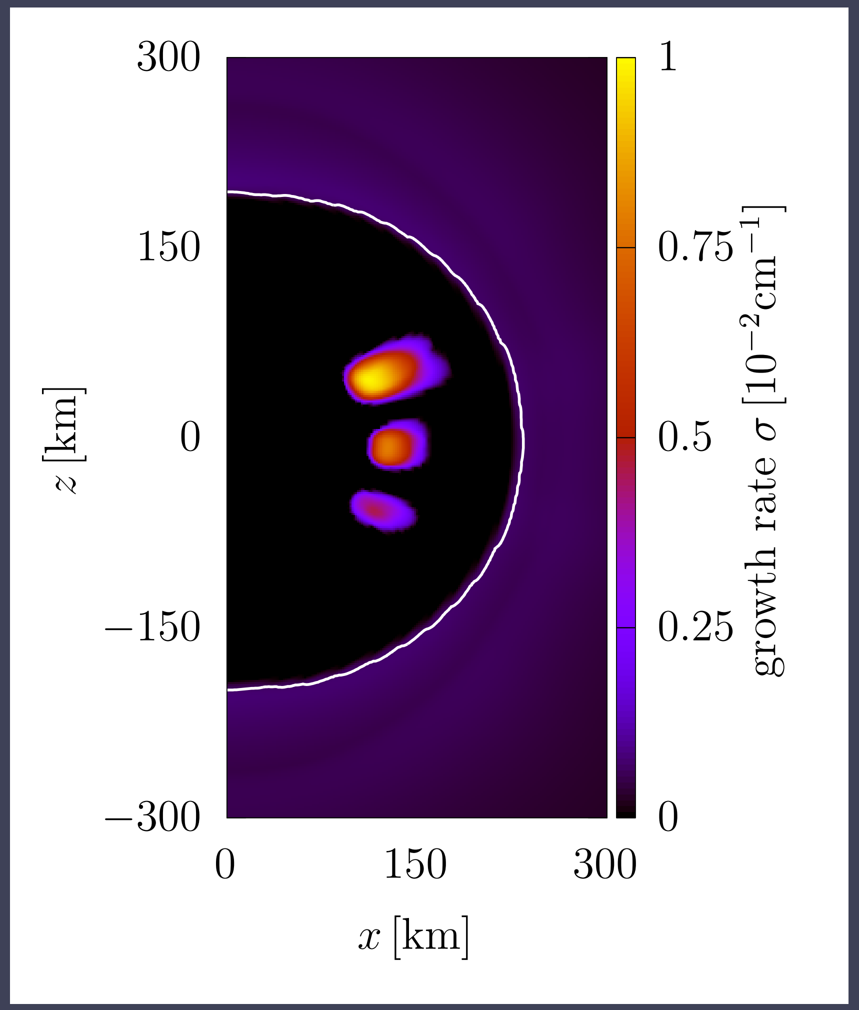
- High-Y_e increases degeneracy parameter

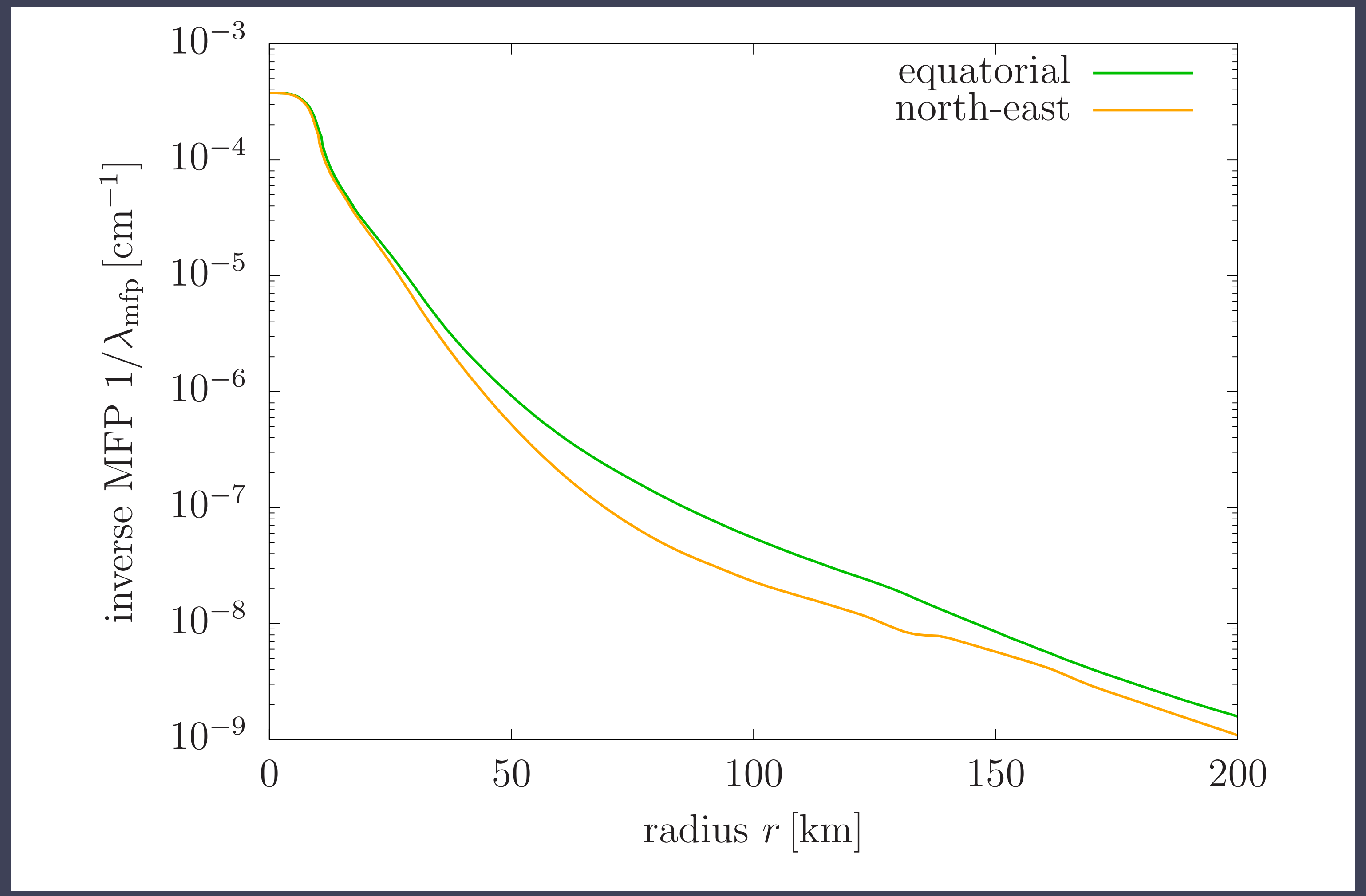
$$\eta = \frac{\mu_\nu}{T} = \frac{\mu_e + \mu_p - \mu_n}{T}$$

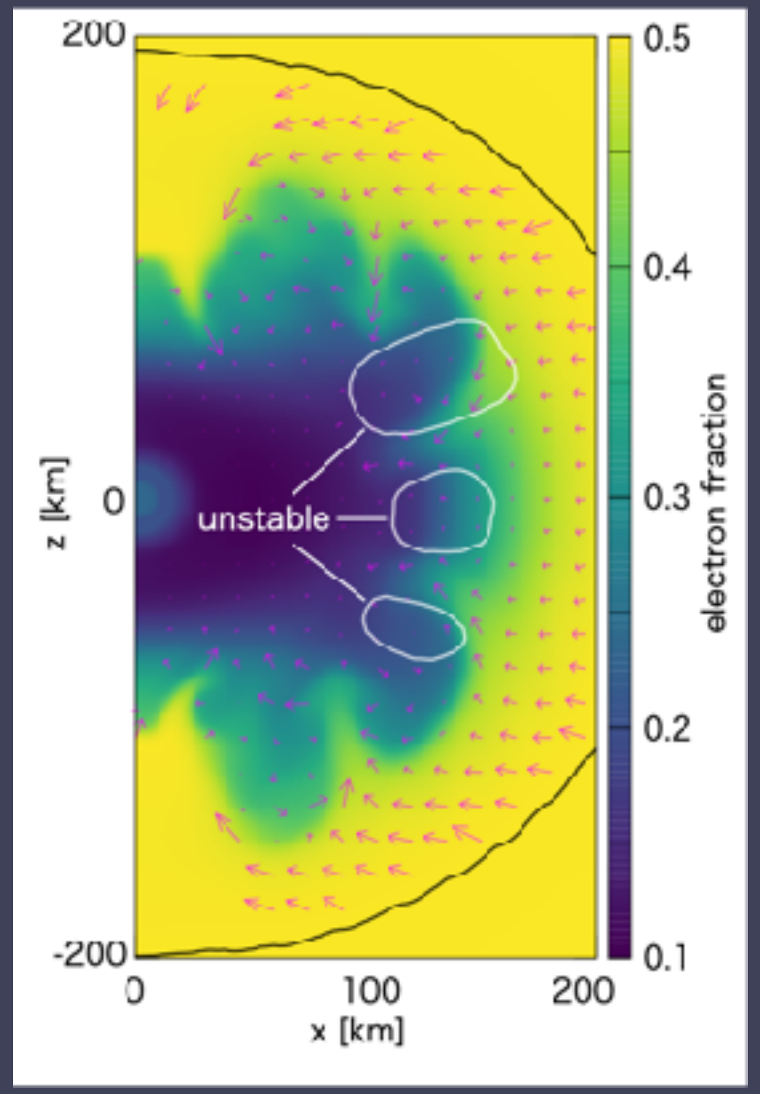
  which determines f_{FD}
- Fluid velocity (magenta arrows) shows convective overturn
- Electron-rich matter is carried by matter and intersects the unstable region to make islands

Summary

- Using the Boltzmann CCSN simulation, the linear growth rate of the flavor instability is estimated
- Rotation extends matter to equator, neutrino absorption continues long time, absorption-induced Type II ELN crossing occurs
- Electron-rich convective inflow intersects the unstable region to make the island structure







Thank you for listening!