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# Neutrino Flavor Conversions in Core-Collapse Supernovae Simulations

Workshop on Dark Matter and Neutrinos

Institut Henri Poincaré, Paris, France

14<sup>th</sup> May, 2025

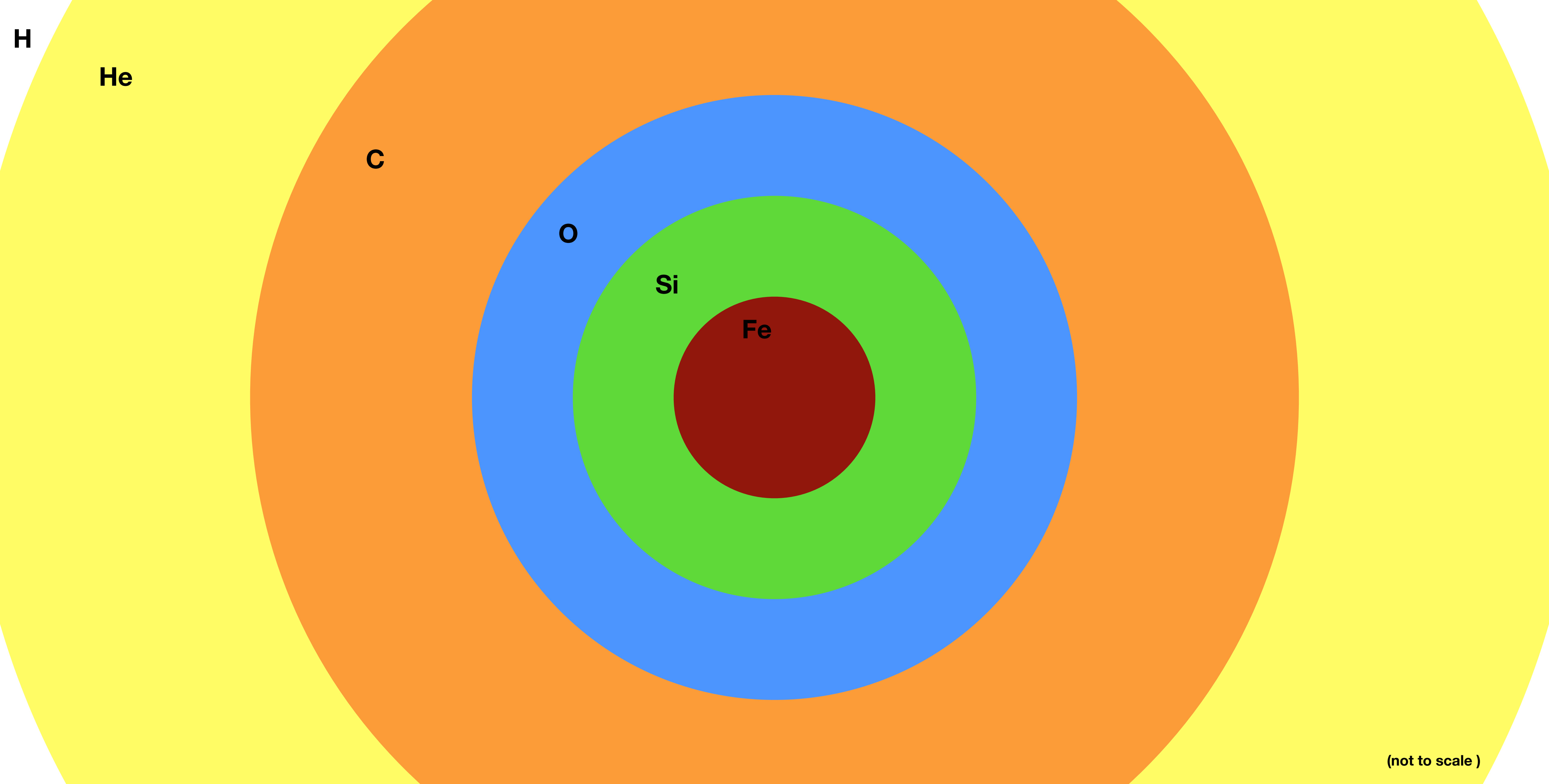
Jakob Ehring (Academia Sinica, Institute of Physics)



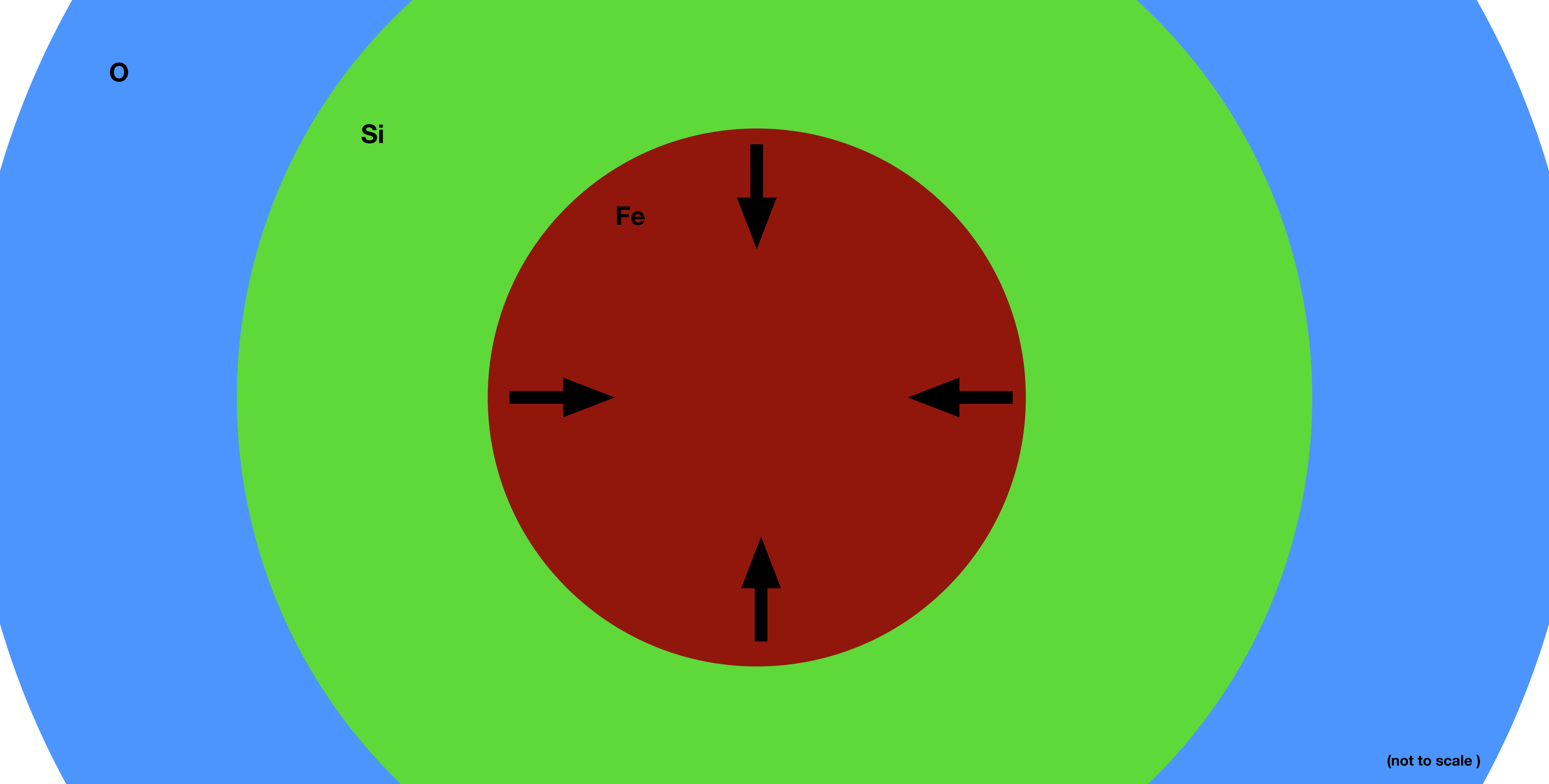
# Overview

- Accretion phase of core-collapse event
- Why neutrino flavor conversions?
- How did we include flavor conversions in our simulations?
- Results from simulations in axial symmetry (2D)
- Outlook and summary

# Accretion phase of core-collapse event



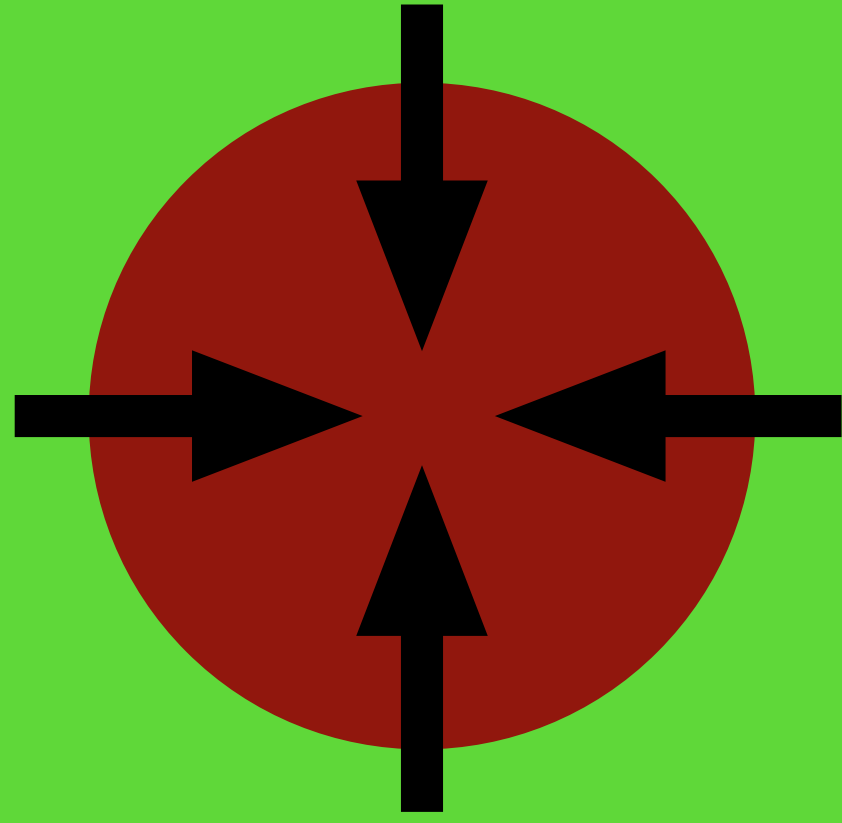
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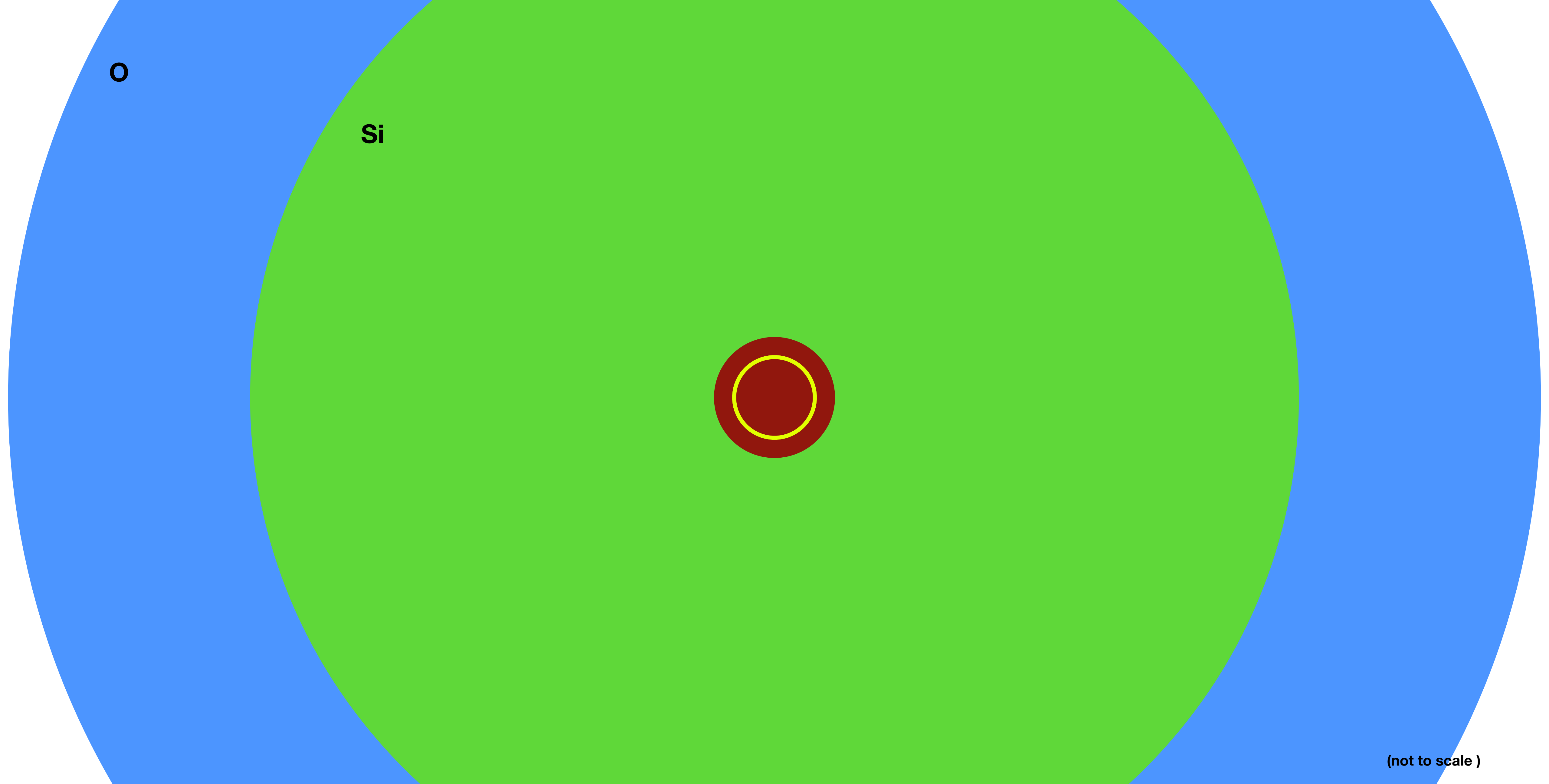
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O

Si



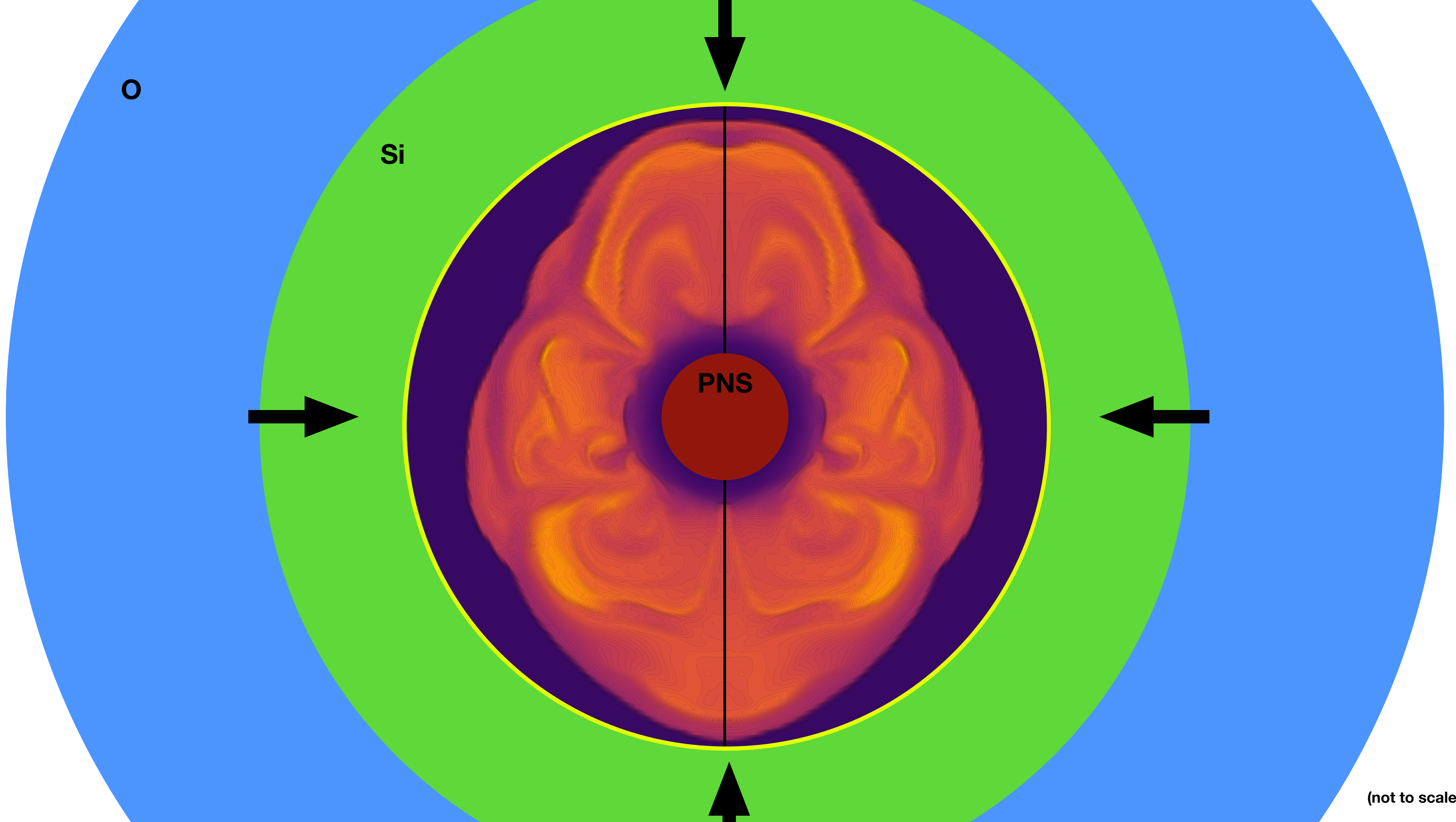
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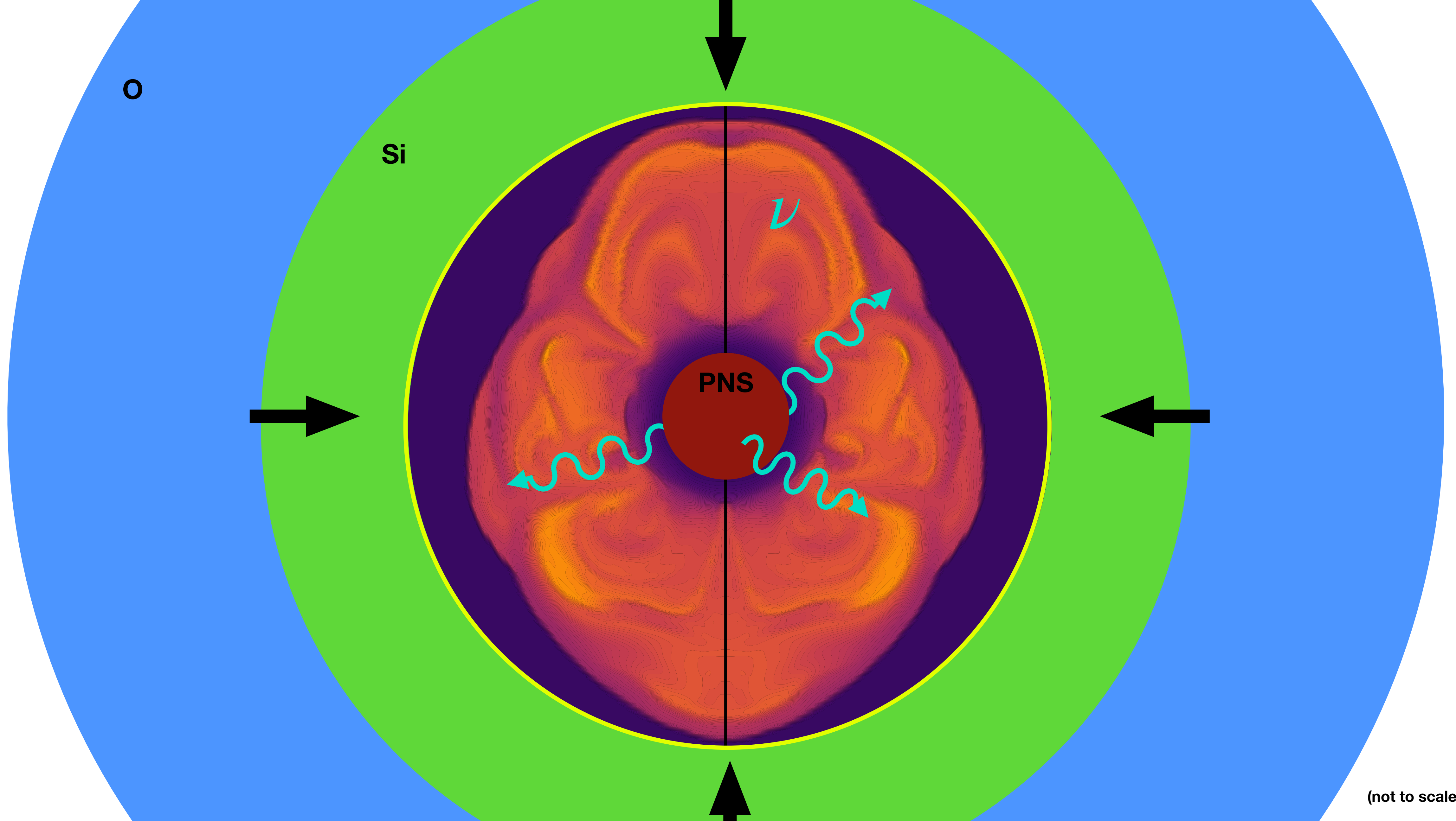
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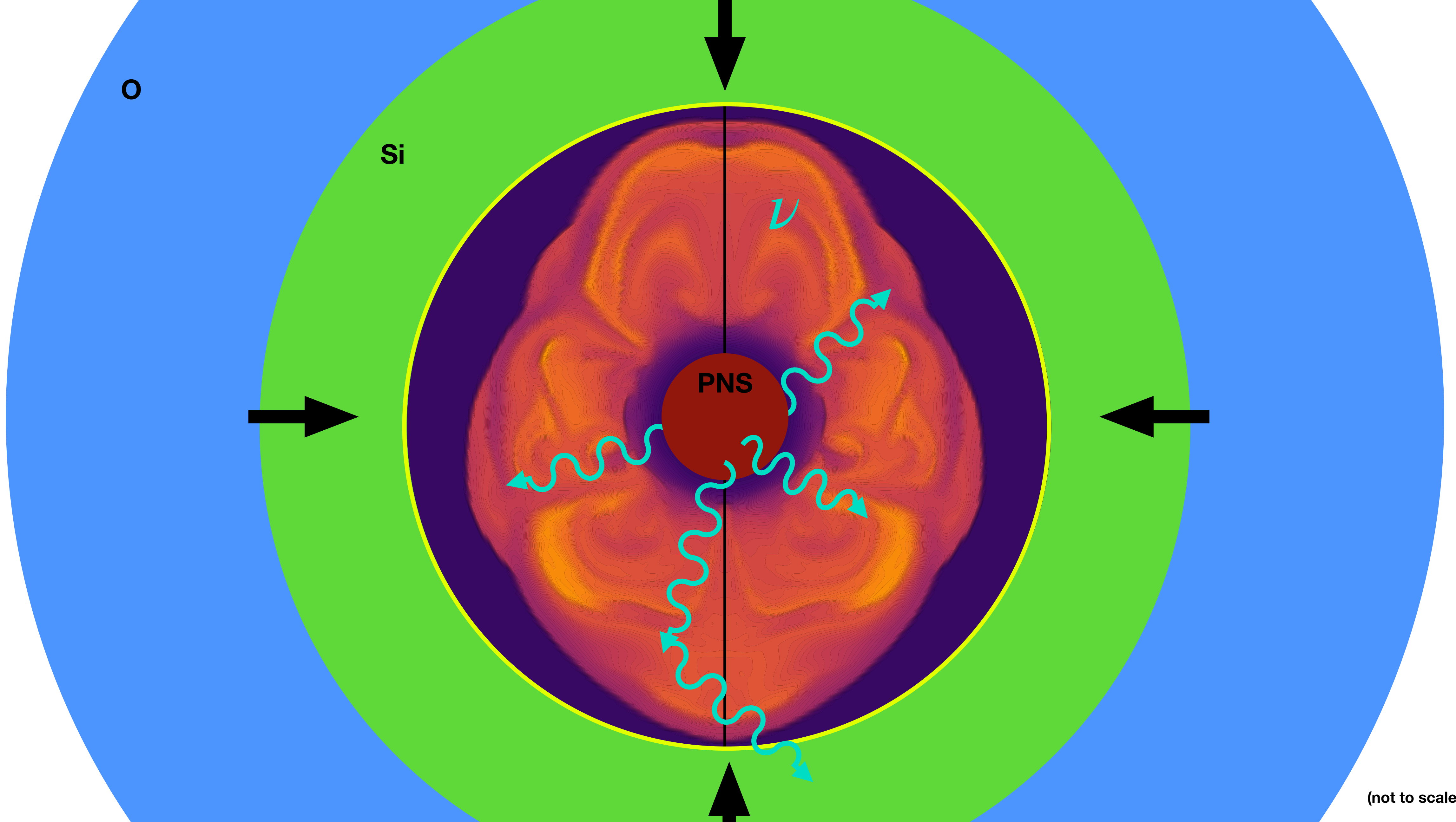
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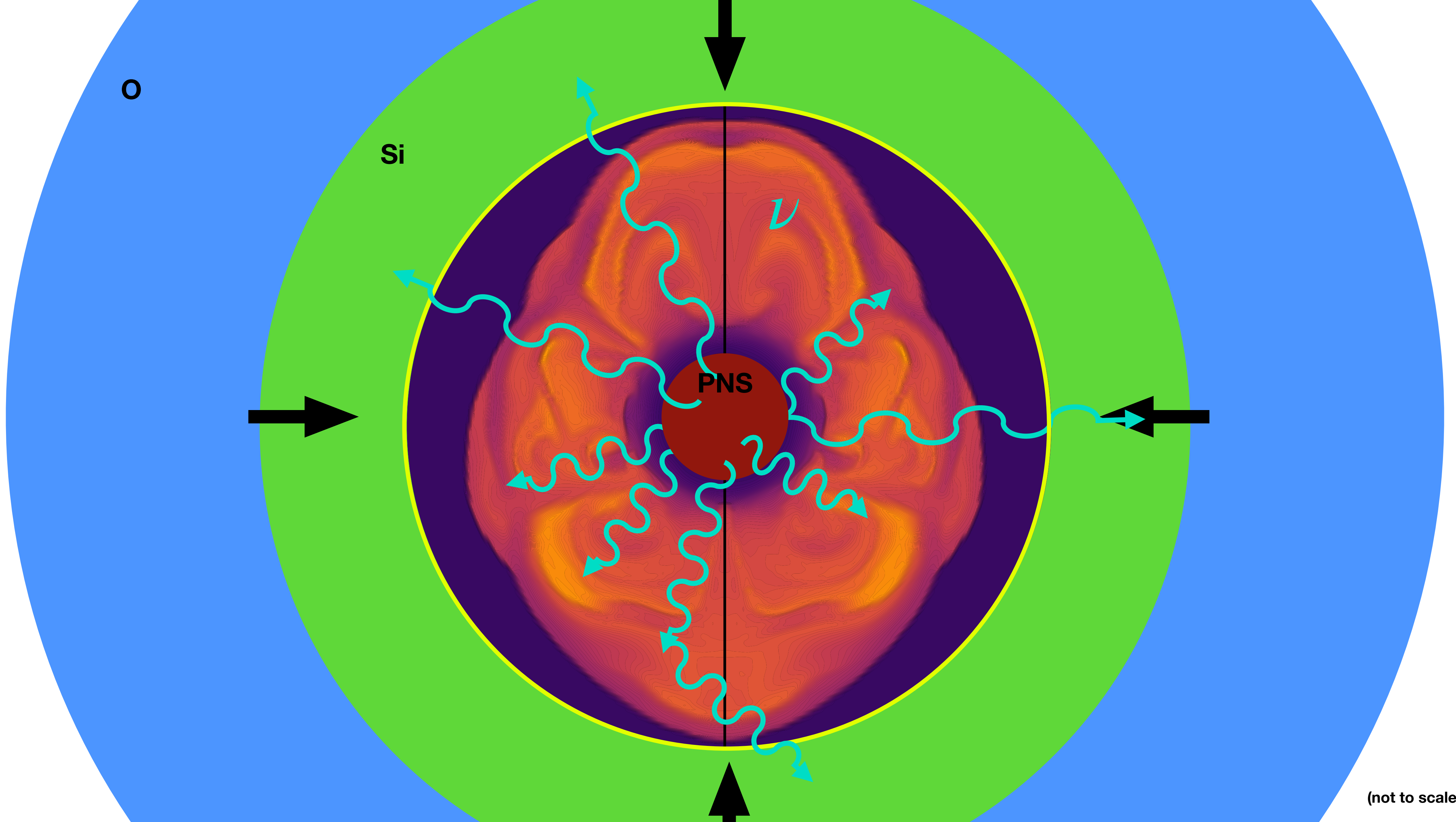
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**Some numbers (back of the envelope):**

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gravitational binding energy of the PNS:  $E_{grav} \simeq \frac{GM_{NS}^2}{R_{NS}} \sim 10^{53}$  erg

mean energy of neutrinos:  $\langle \epsilon_\nu \rangle \sim 15$  MeV (measured from SN1987A)

number of neutrinos  $N_\nu \simeq \frac{E_{grav}}{\langle \epsilon_\nu \rangle} \sim 10^{58}$

kinetic energy of a supernova:  $\sim 10^{51}$  erg (measure spectra)

radiation energy of a supernova:  $\sim 10^{49}$  erg (integrate light curve)

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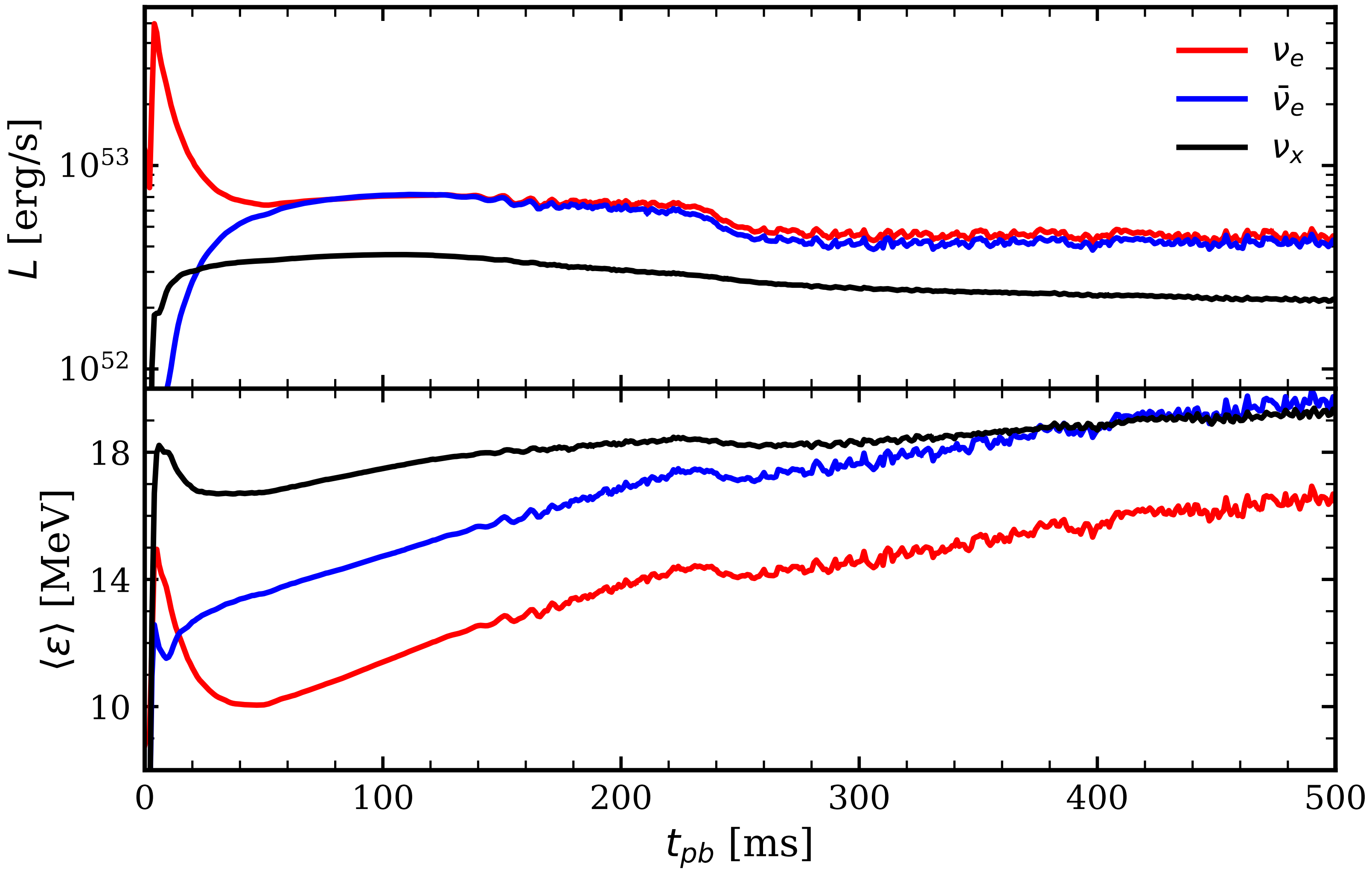
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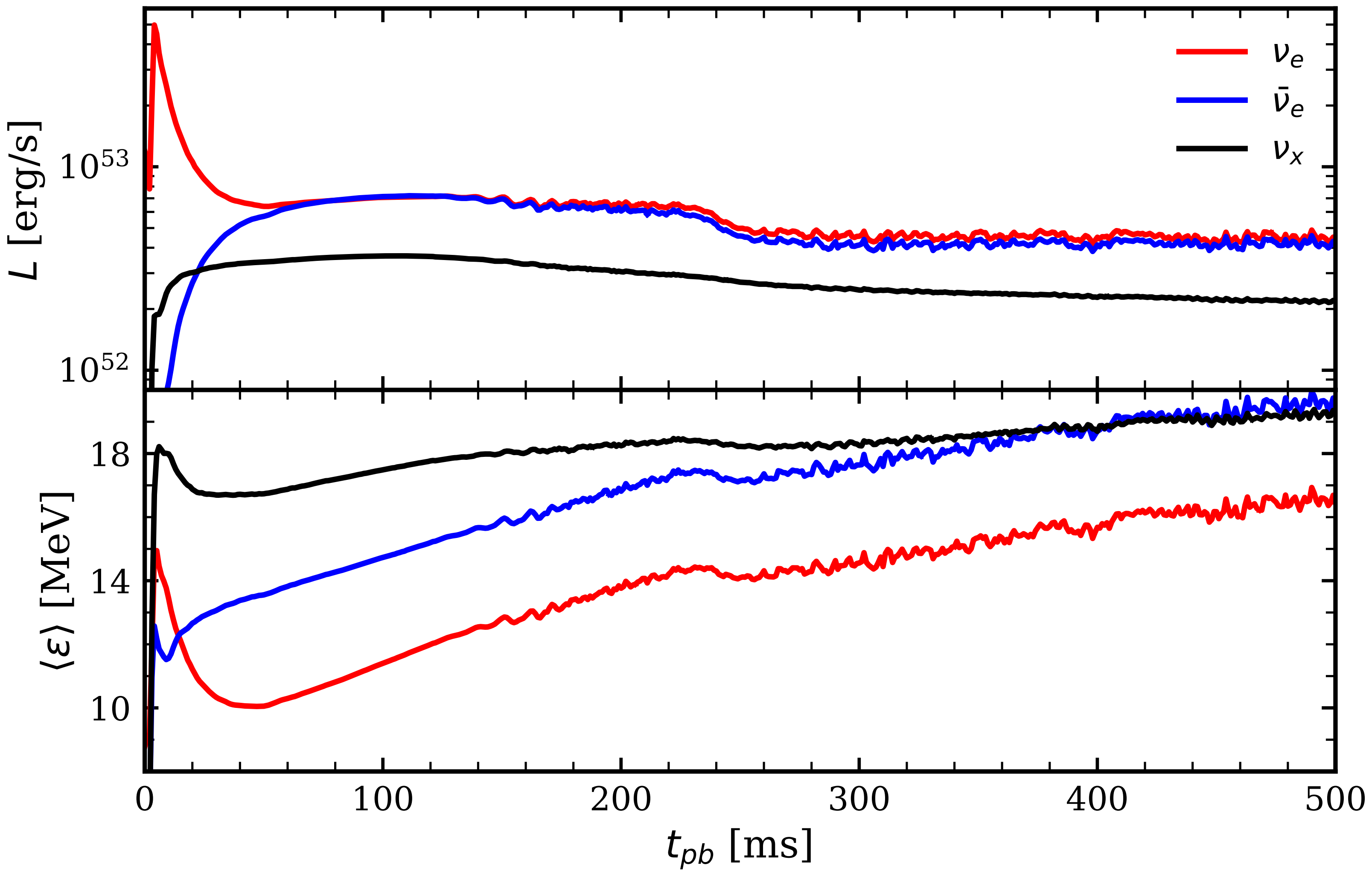
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**Neutrinos are really important!**

# Neutrino luminosity and mean energy at 400 km

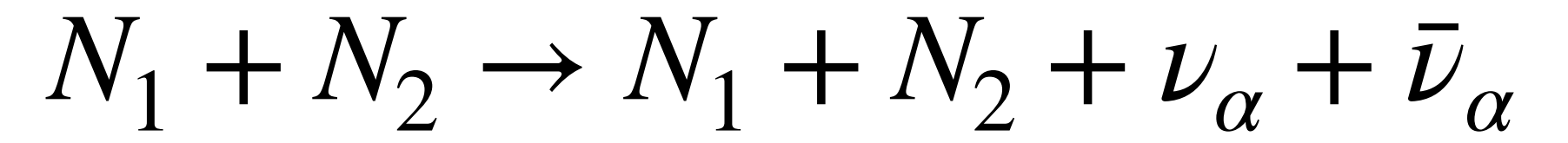


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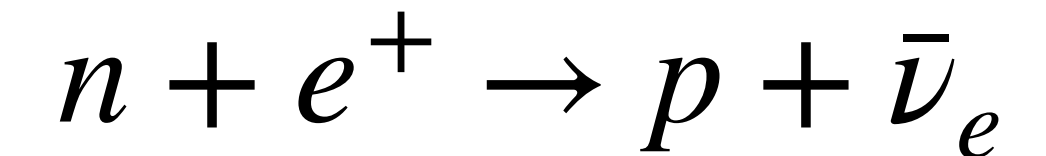
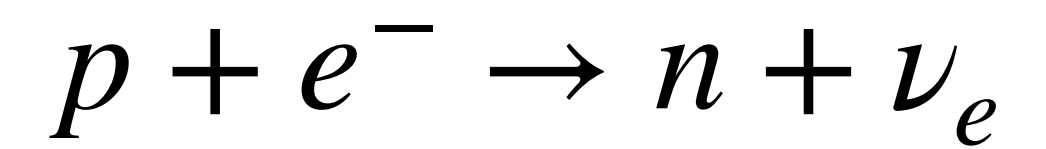


**Production (cooling):**

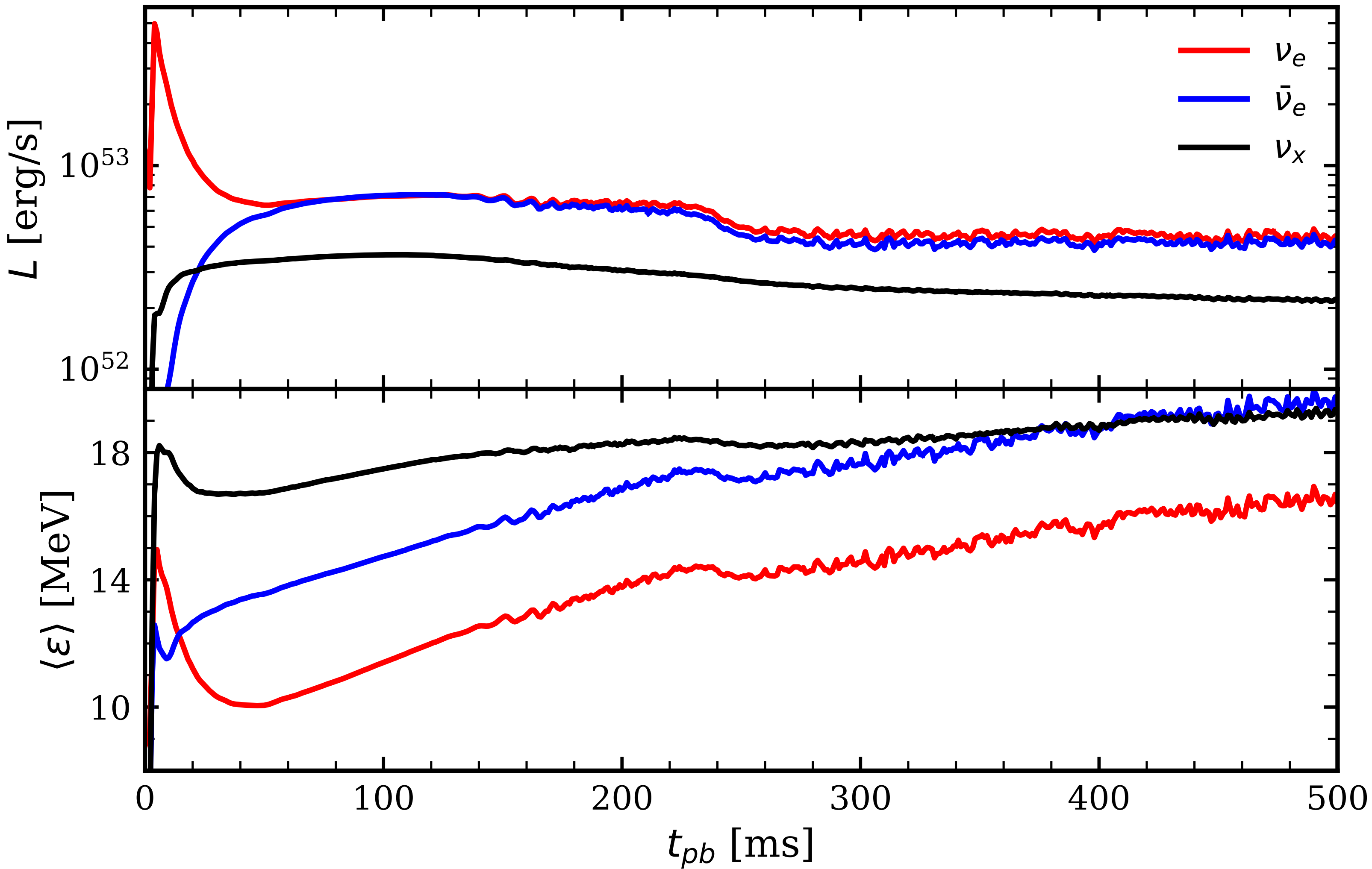
**Thermal (flavor blind):**



**Charged current (e only):**

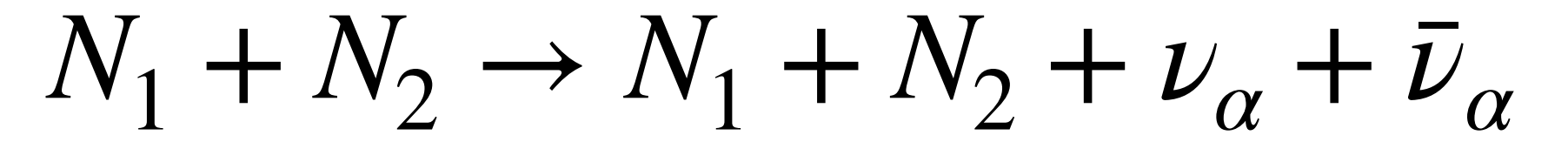


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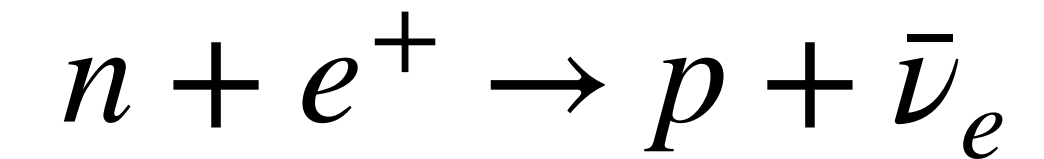
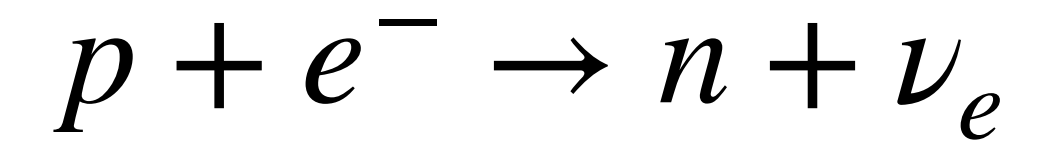


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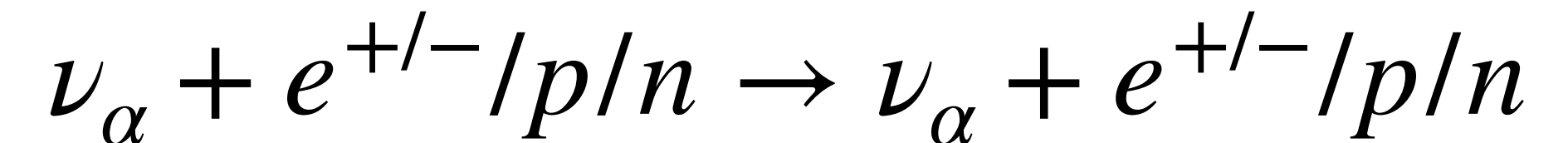


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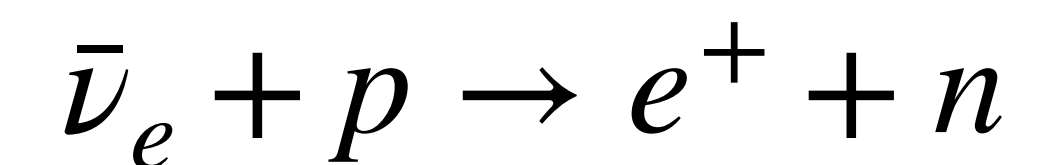
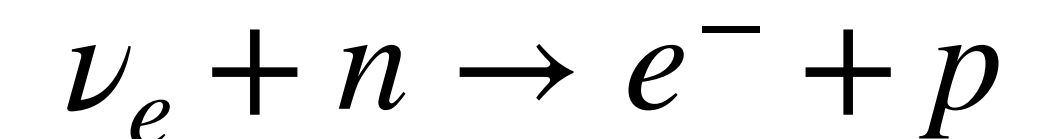


**Interaction (heating):**

**All flavors: scattering**



**Electron flavor: absorption**



# Why neutrino flavor conversions?

**Propagation**

**Interaction**

$$(\partial_t + \vec{v} \cdot \vec{\nabla}_x) \rho = C$$

# Neutrinos are quantum particles!



Johan Jarnestad/The Royal Swedish Academy of Sciences, 2015

Propagation

Interaction

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Propagation

Density Matrix

Interaction

$$(\partial_t + \vec{v} \cdot \vec{\nabla}_x) \rho = -i[H_{\nu,\nu}, \rho] + C$$

Quantum propagation phenomena  
(forward scattering)

The diagram shows the equation  $(\partial_t + \vec{v} \cdot \vec{\nabla}_x) \rho = -i[H_{\nu,\nu}, \rho] + C$  enclosed in a blue dashed box. Three arrows point from labels above to parts of the equation: 'Propagation' points to the left side of the equation, 'Density Matrix' points to the  $\rho$  term, and 'Interaction' points to the right side of the equation. Below the box, the text 'Quantum propagation phenomena (forward scattering)' is written, with an arrow pointing from the  $H_{\nu,\nu}$  term in the equation to this text.

# Coherent forward scattering

$$(\partial_t + \vec{v} \cdot \vec{\nabla}_x) \rho = -i[H, \rho]$$

$$H = H_{vv} = \mu \int d\vec{p}' [\rho(\vec{p}') - \bar{\rho}(\vec{p}')] (1 - \vec{v} \cdot \vec{v}')$$

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-> Sets the scale to cm (ns)

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-> No analytical solution

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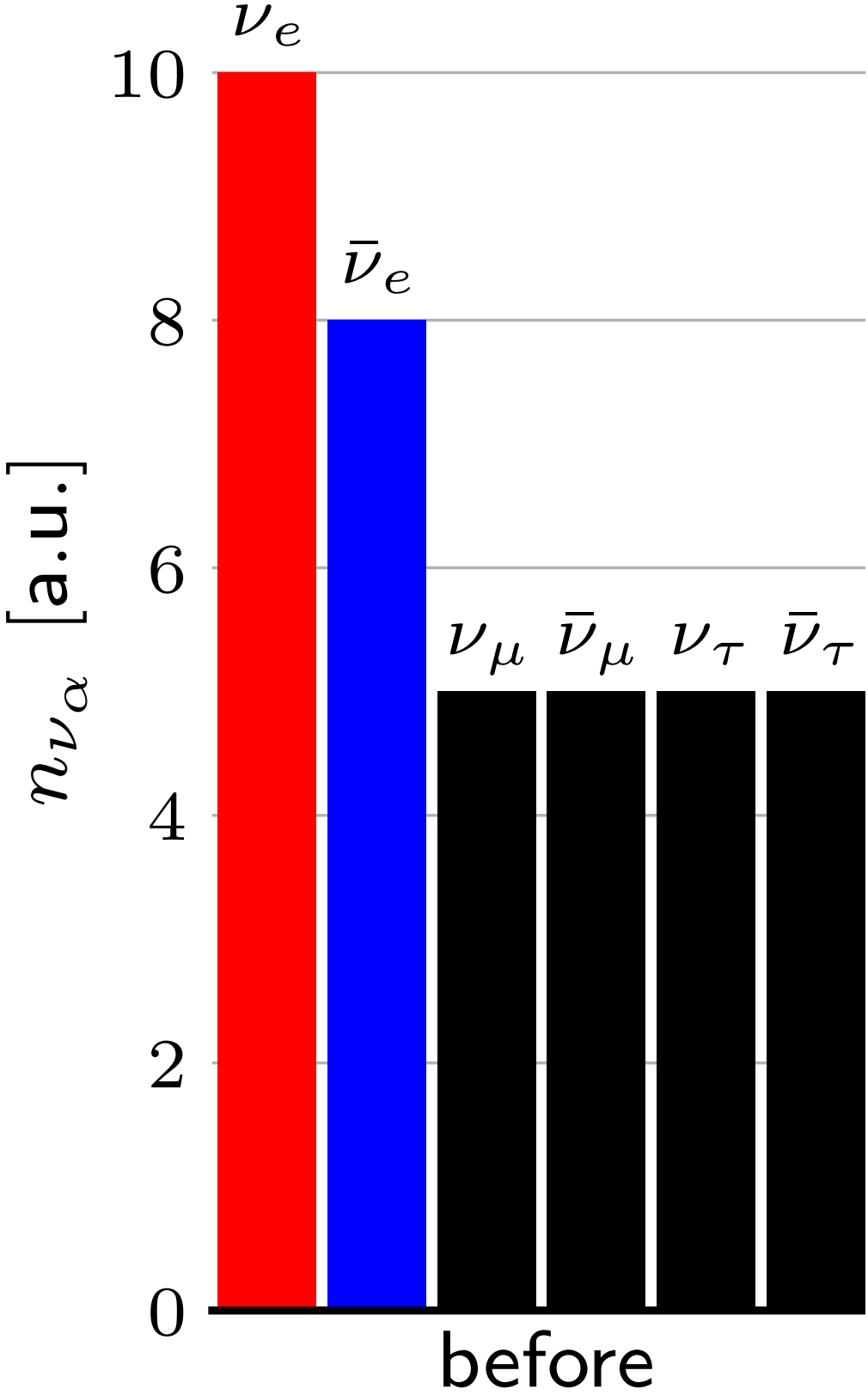
$$\int d\vec{p}'$$

-> Couples evolution of all momenta

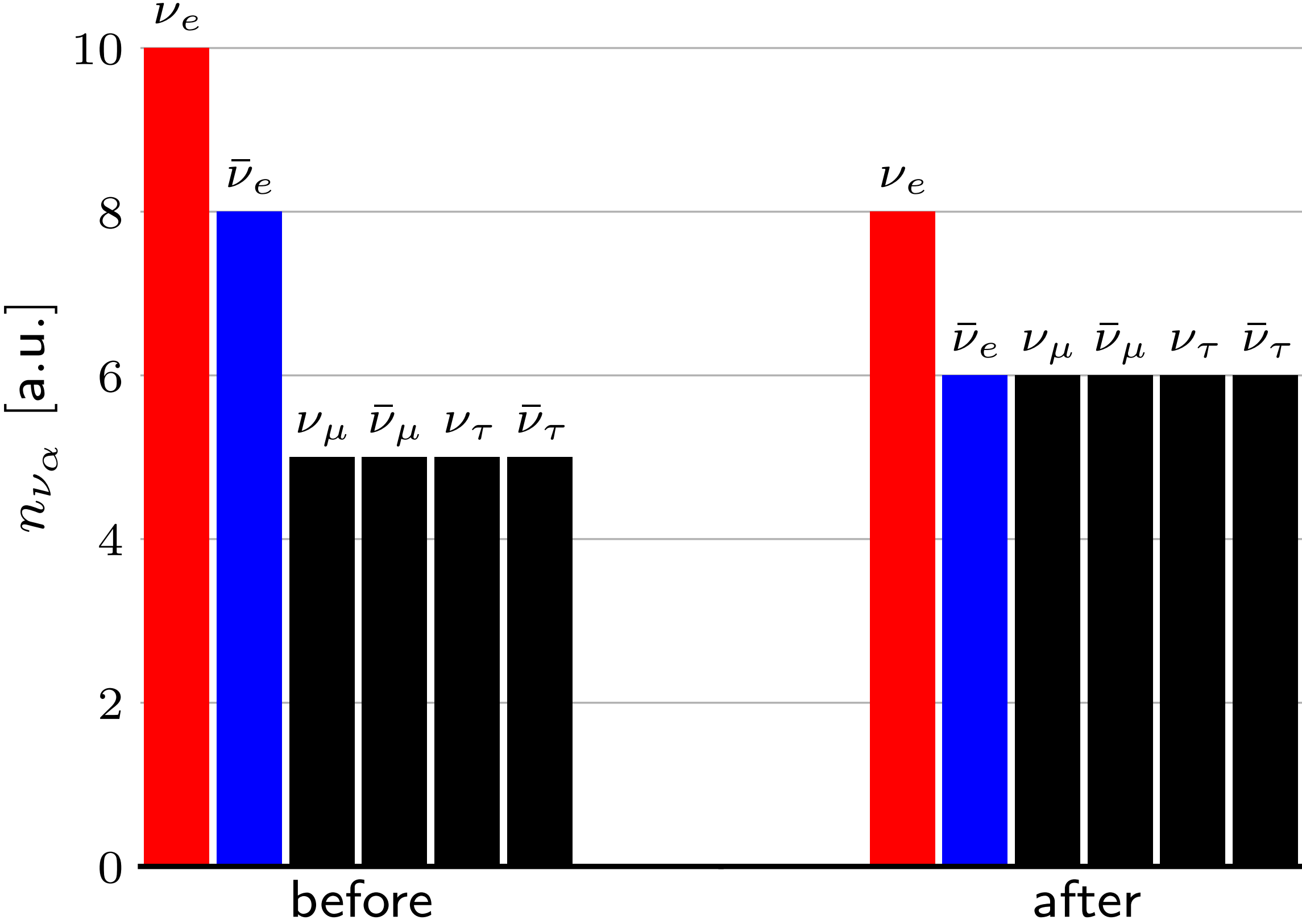
-> Computational expensive

**How did we include flavor conversions in our simulations?**

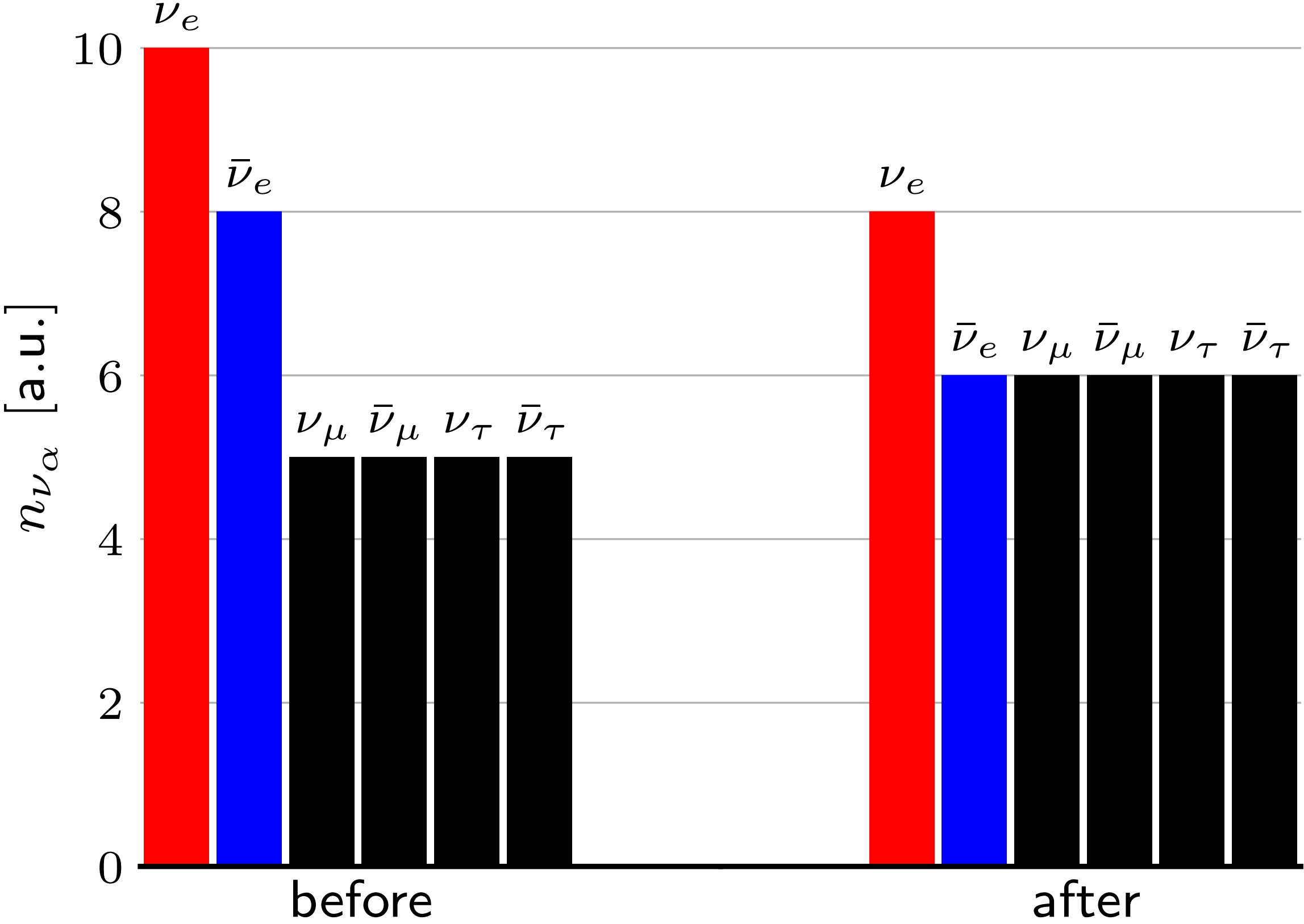
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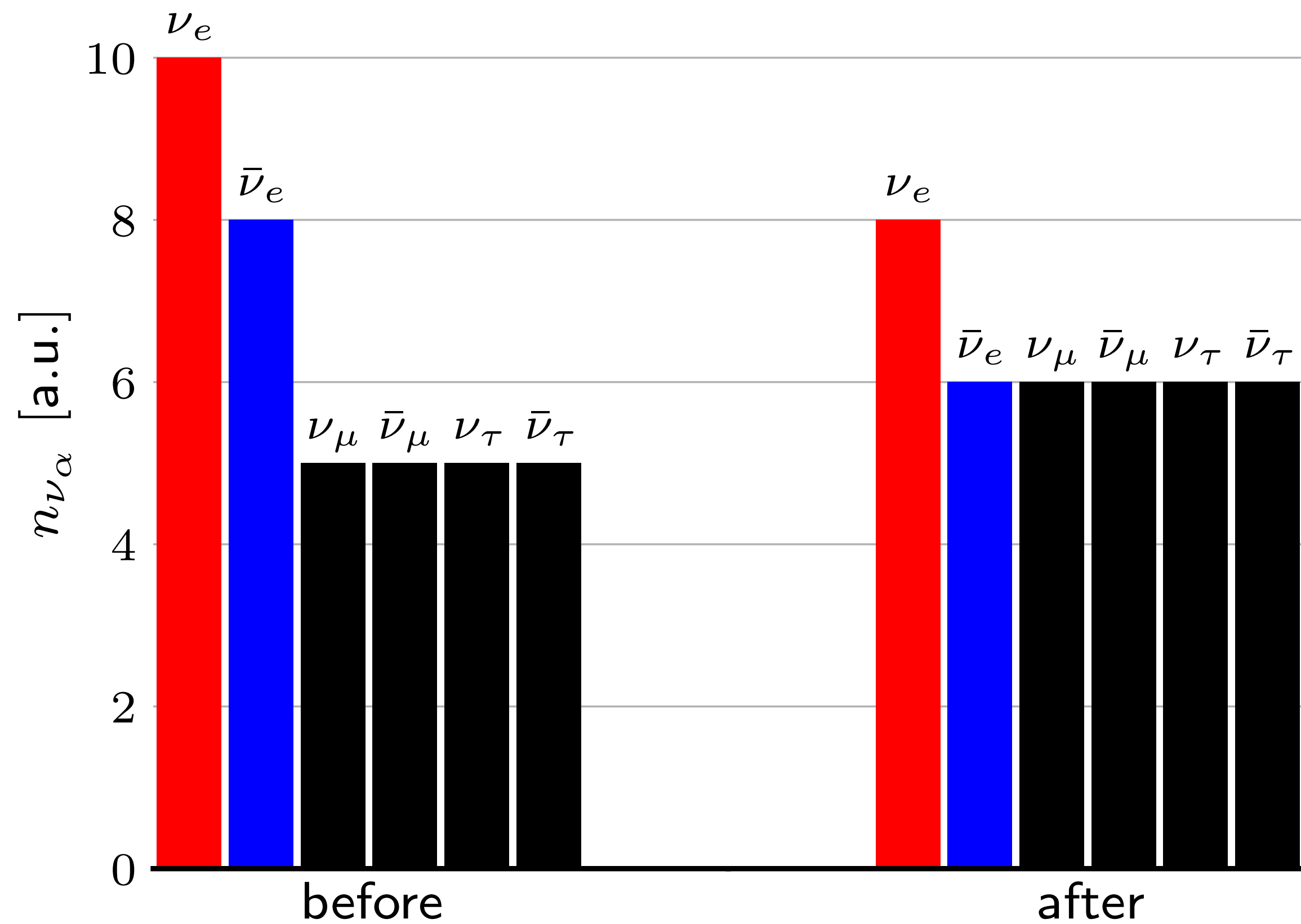


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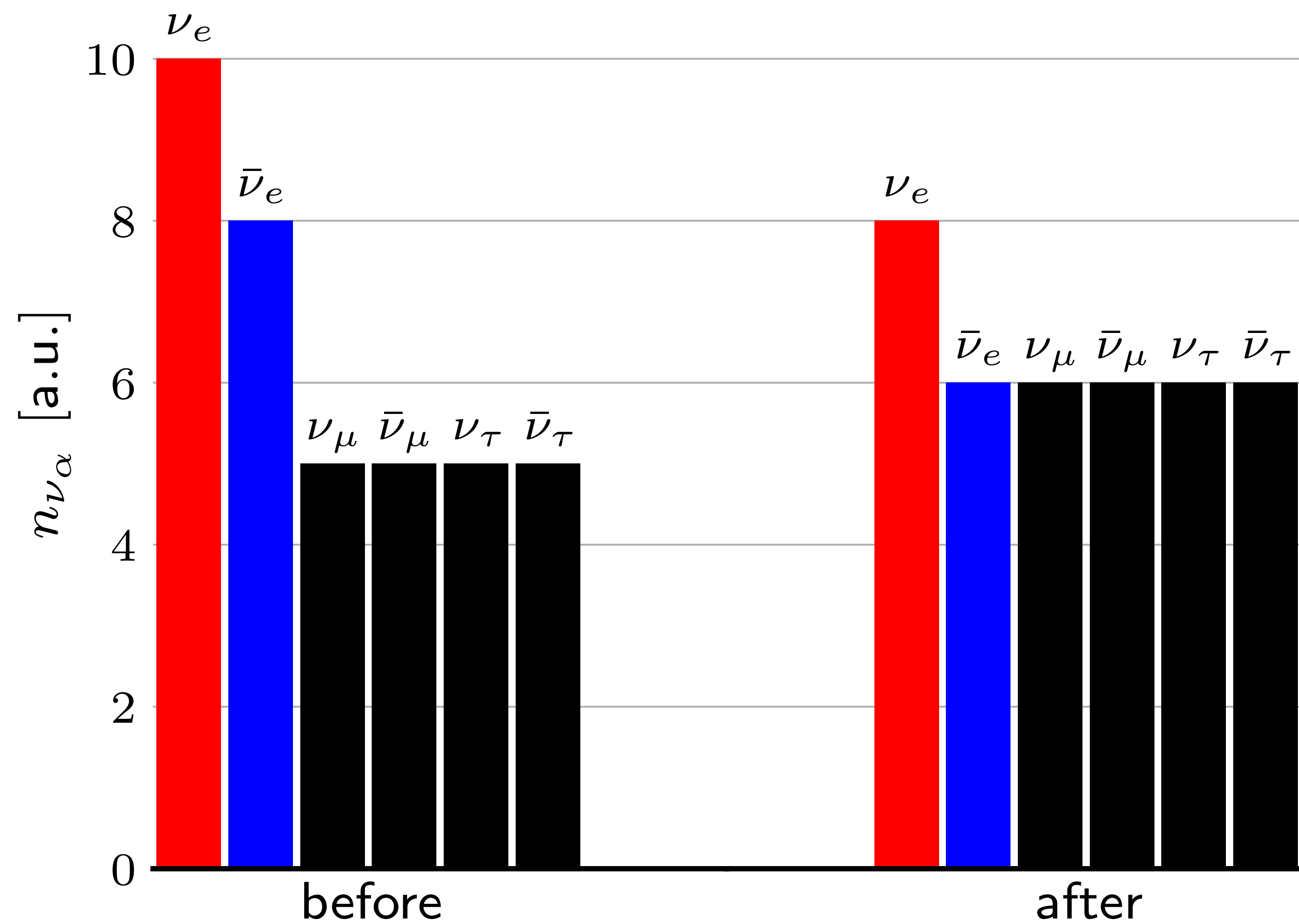


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At higher energies:

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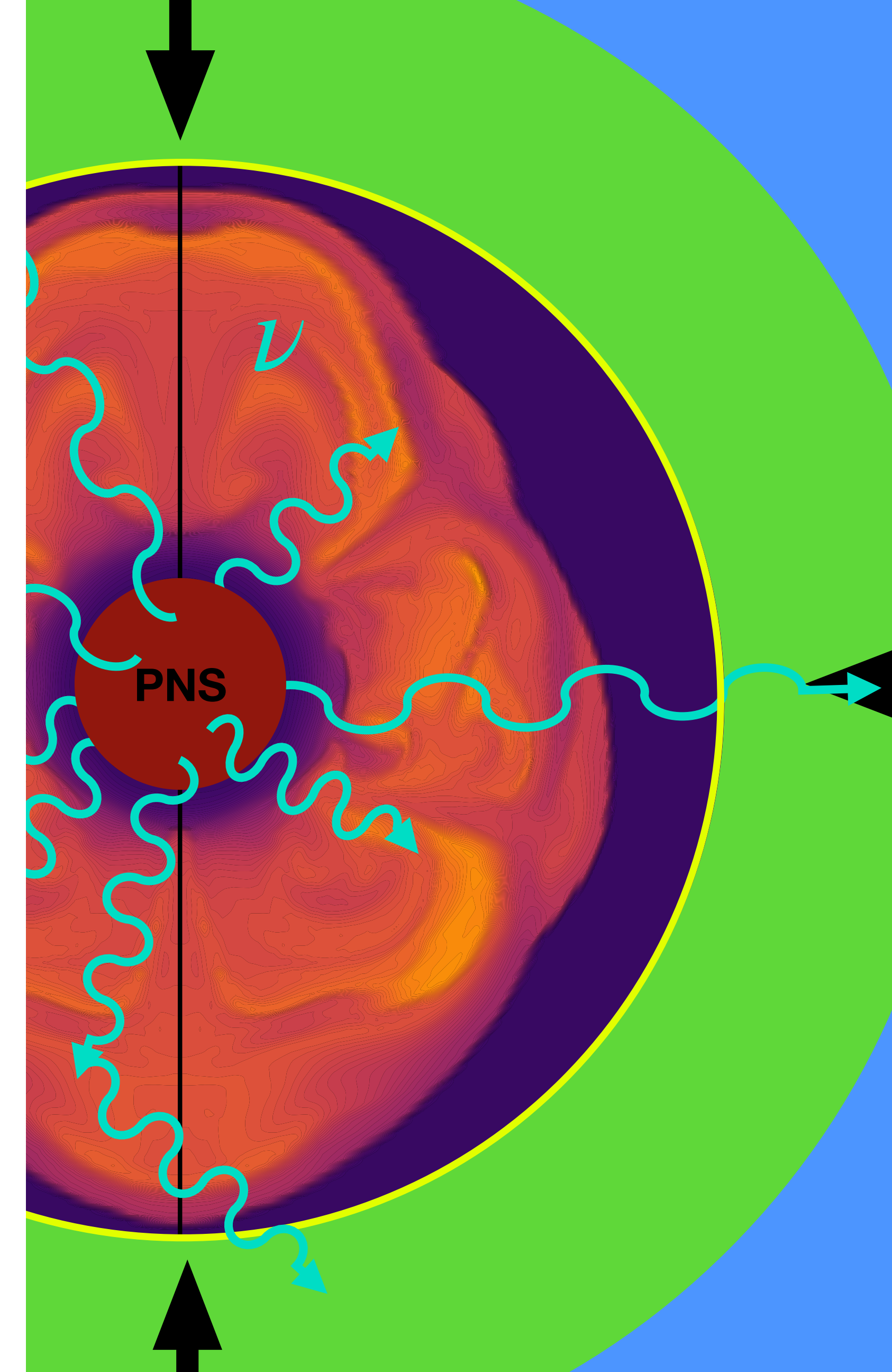
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At higher energies:

$$\nu_x, \bar{\nu}_x \rightarrow \nu_e, \bar{\nu}_e$$

- ➡ Model independent
- ➡ Complies with conservation laws
- ➡ Computationally cheap

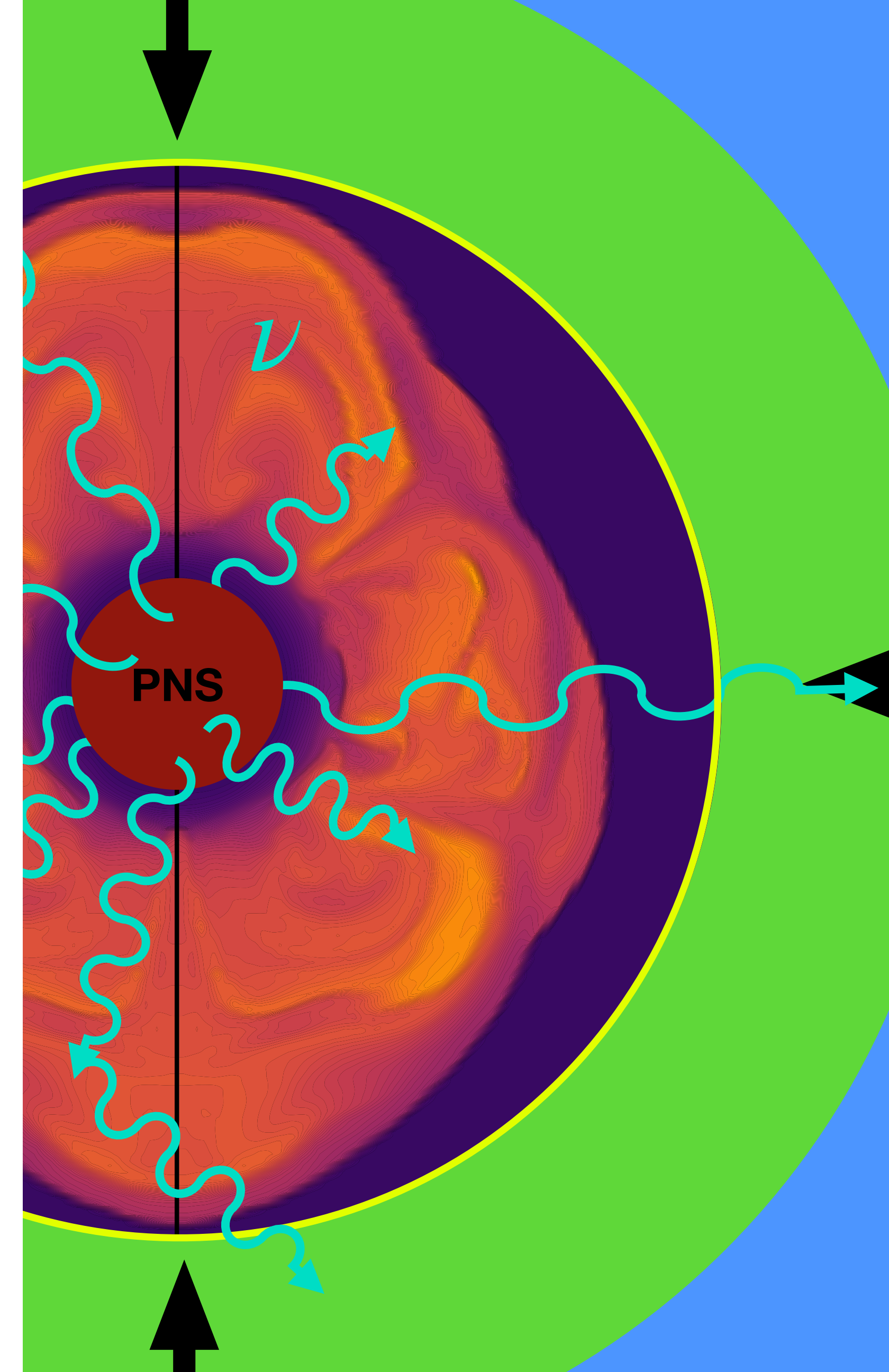
# Probe effect in different regions:



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## Use matter density

- not sensitive to reasonable changes of neutrino properties
- still follows the overall dynamical evolution
- clear attribution possible



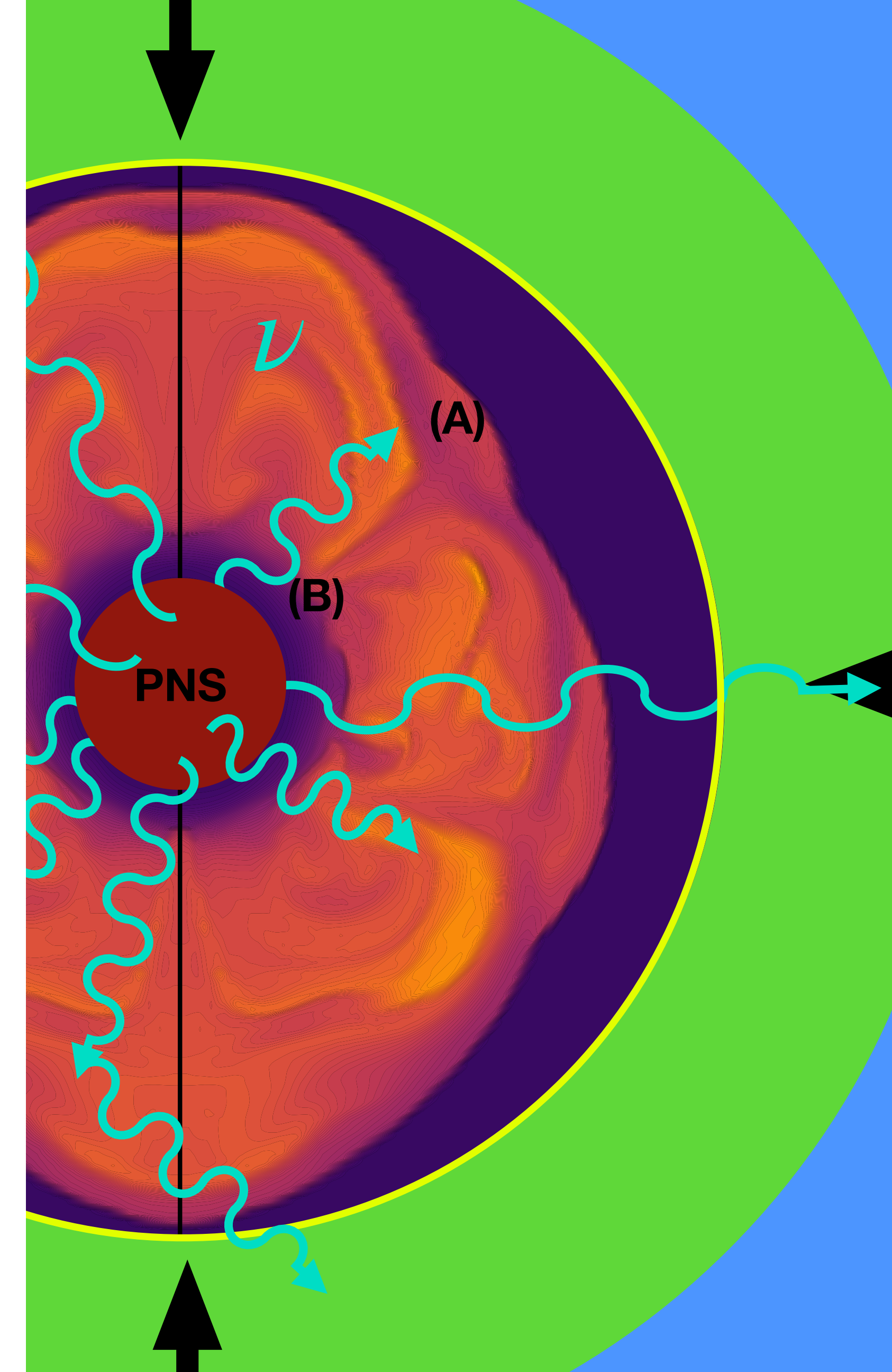
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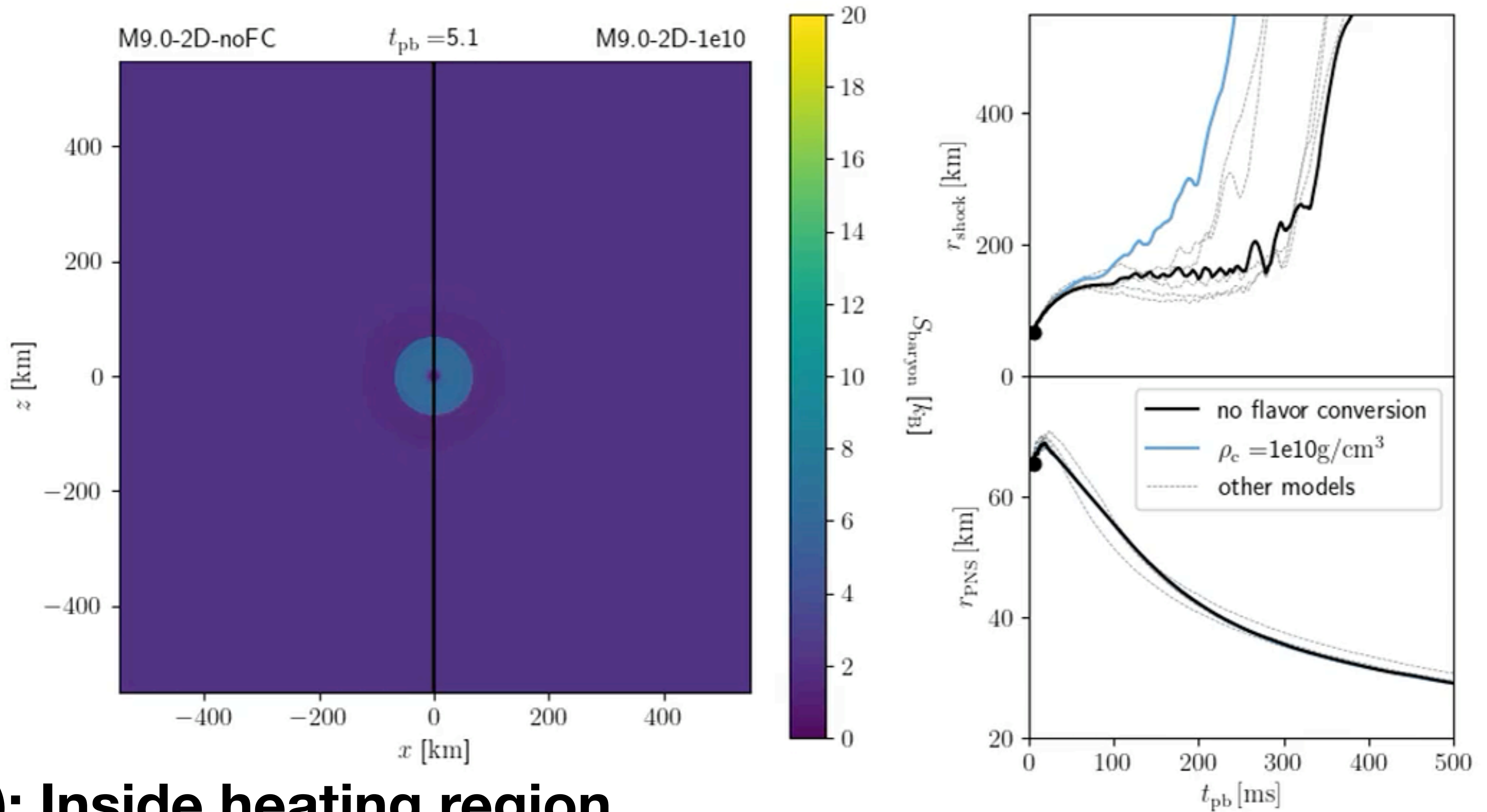
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## Two most differing cases

- Inside Heating Region ( $\rho < 10^{10} \text{ g/cm}^3$ ) (A)
- Inside Cooling Region ( $\rho < 10^{12} \text{ g/cm}^3$ ) (B)

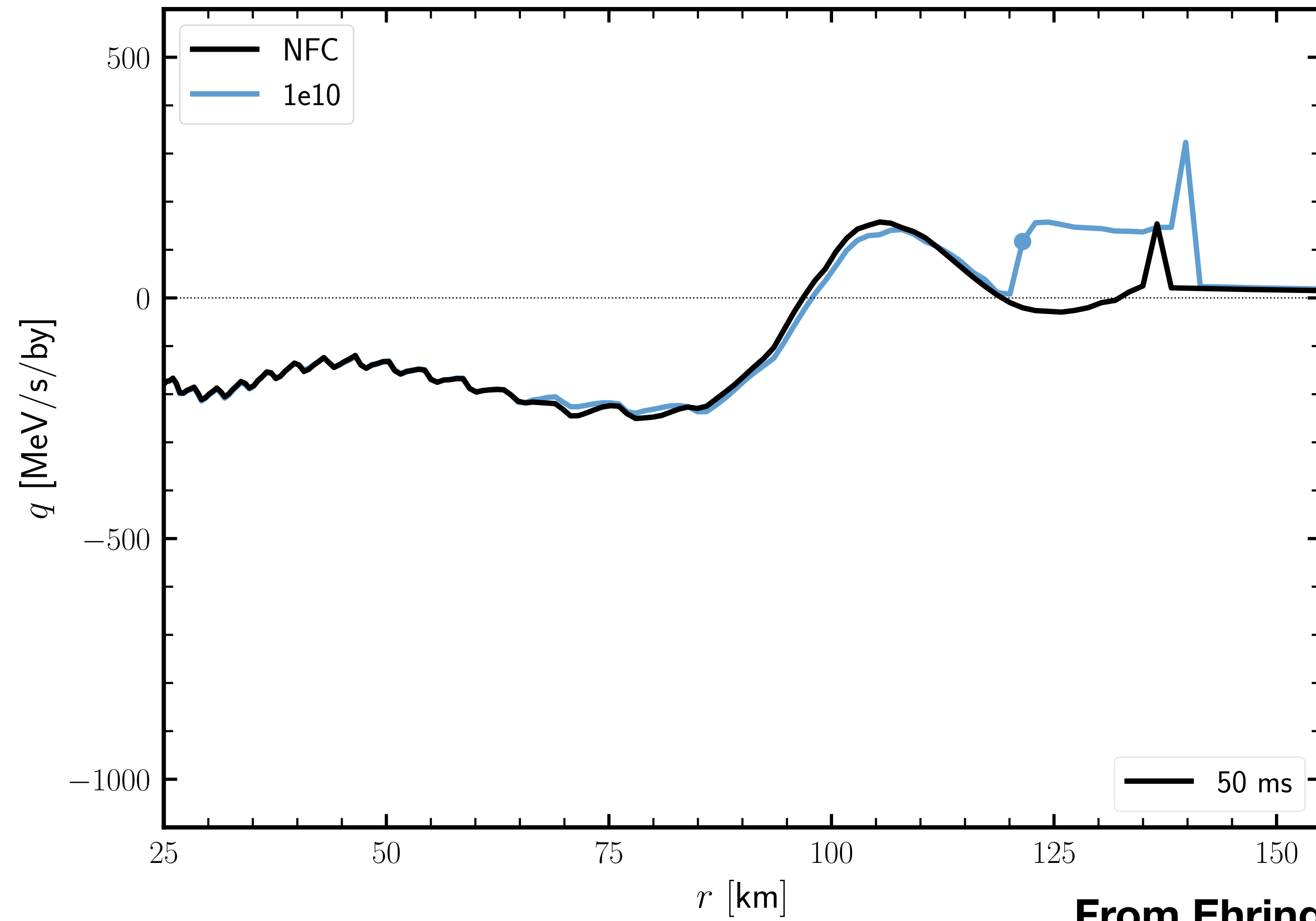


# Results from simulations in axial symmetry (2D)



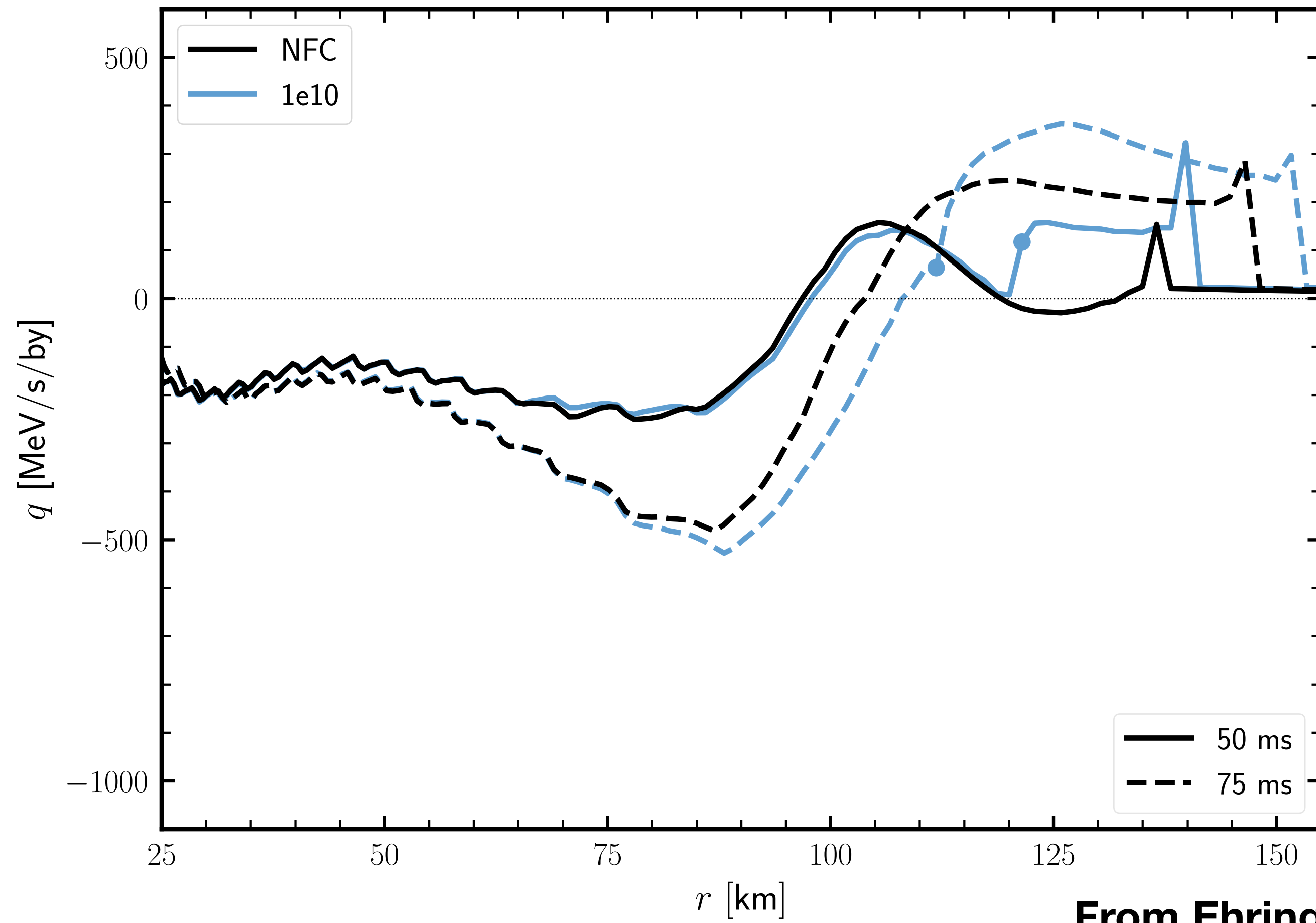
**(A): Inside heating region**

# Local heating



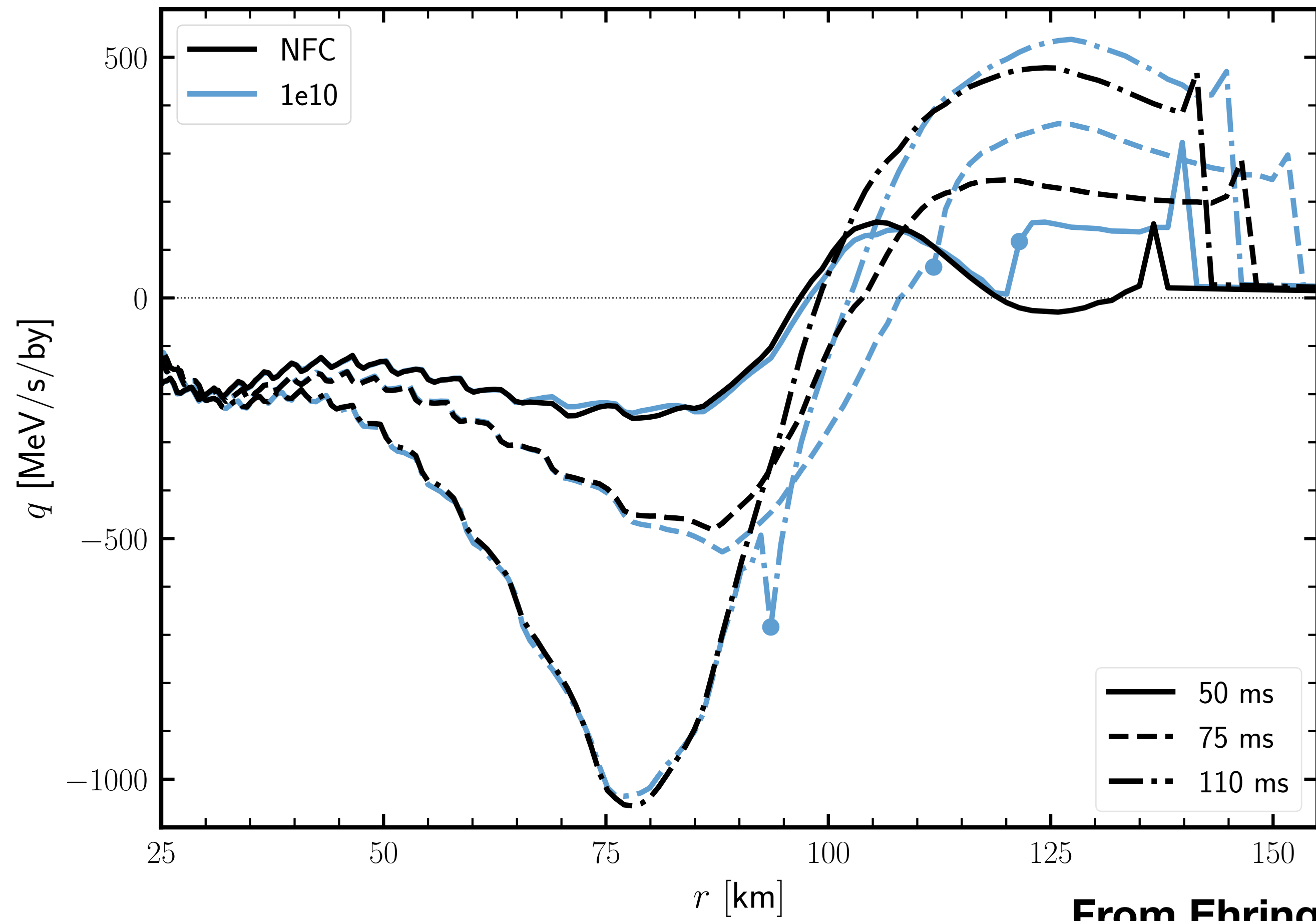
From Ehring, et al. 2023a

# Local heating

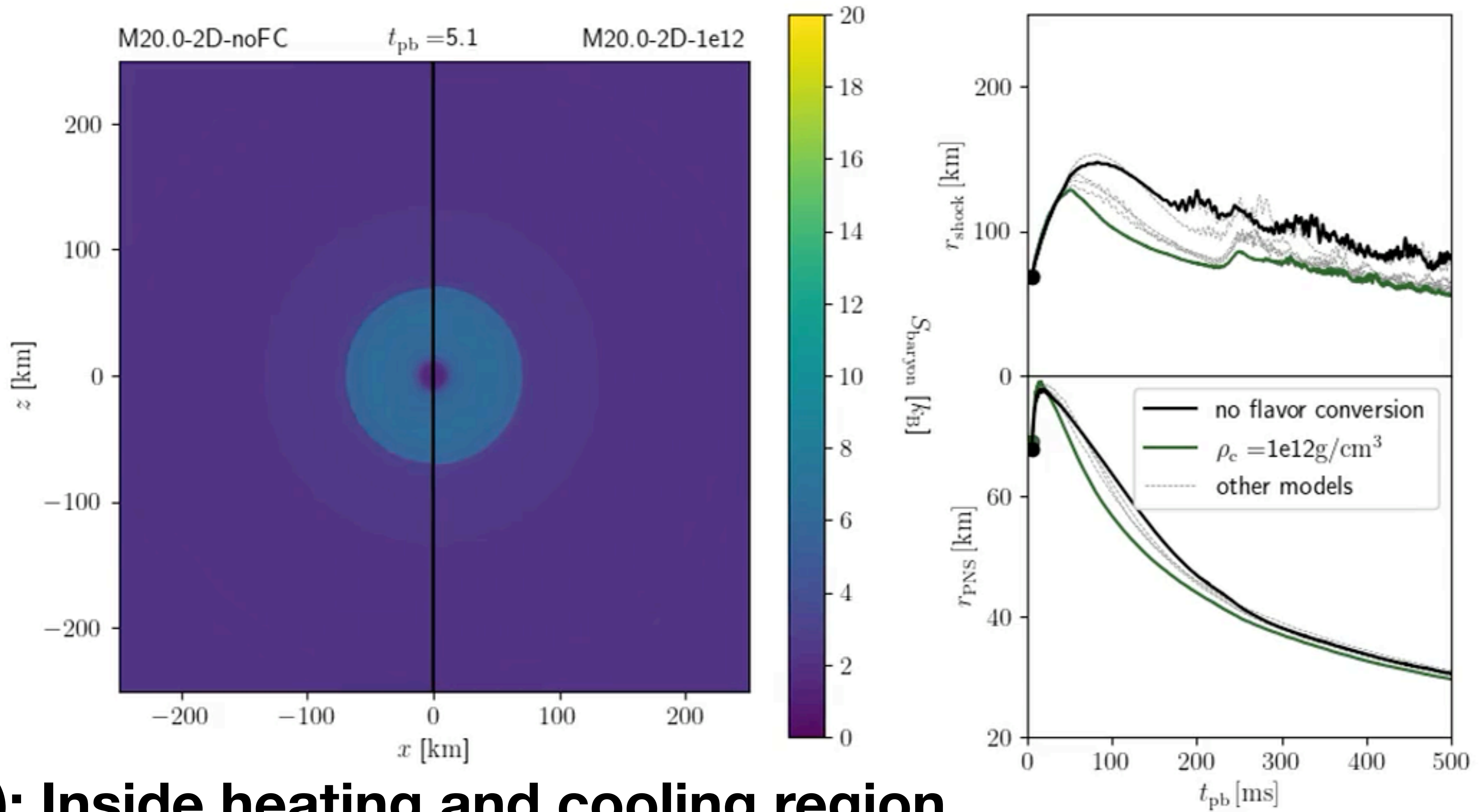


From Ehring, et al. 2023a

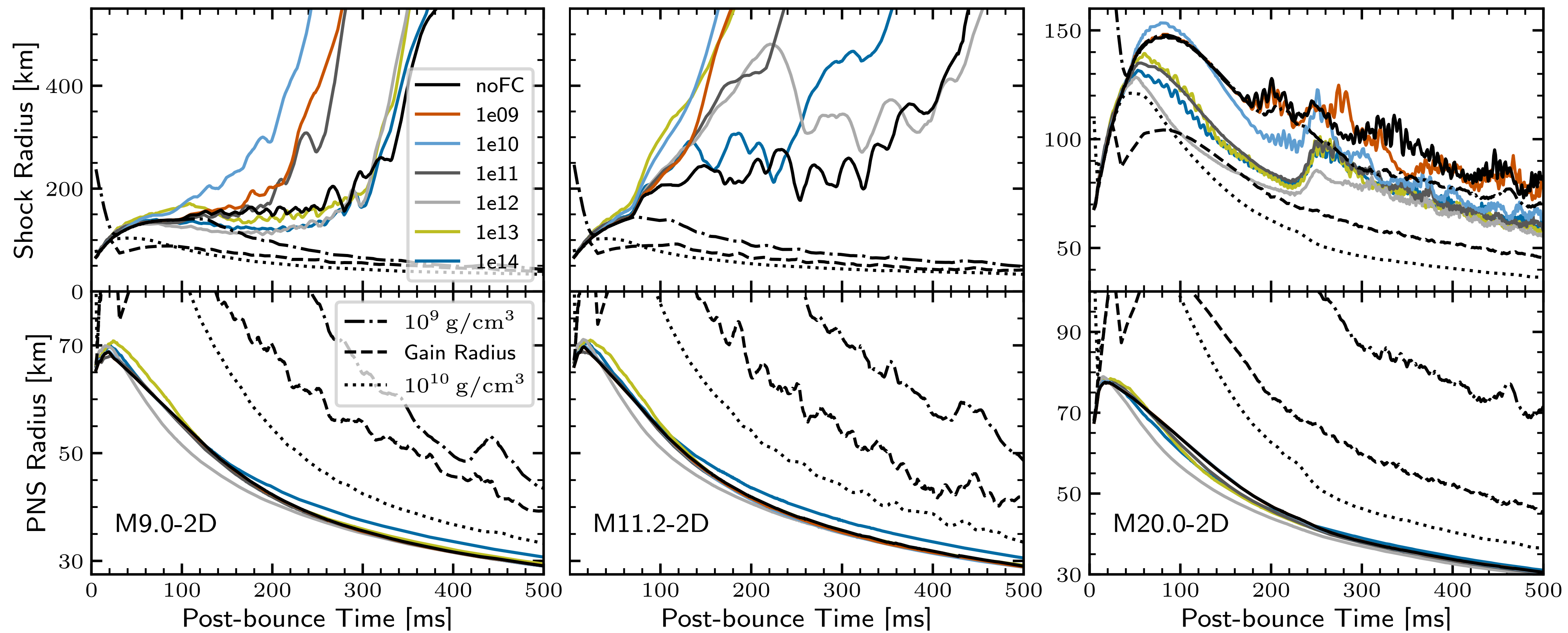
# Local heating



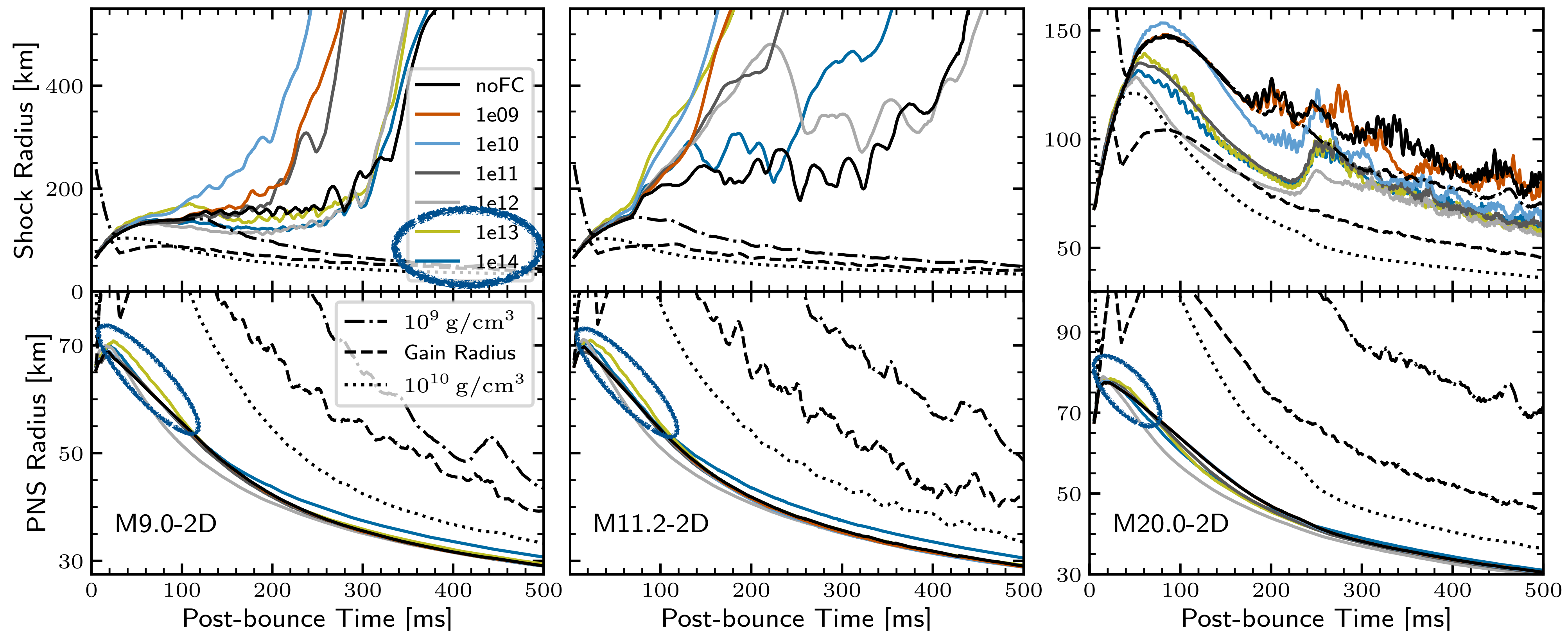
From Ehring, et al. 2023a



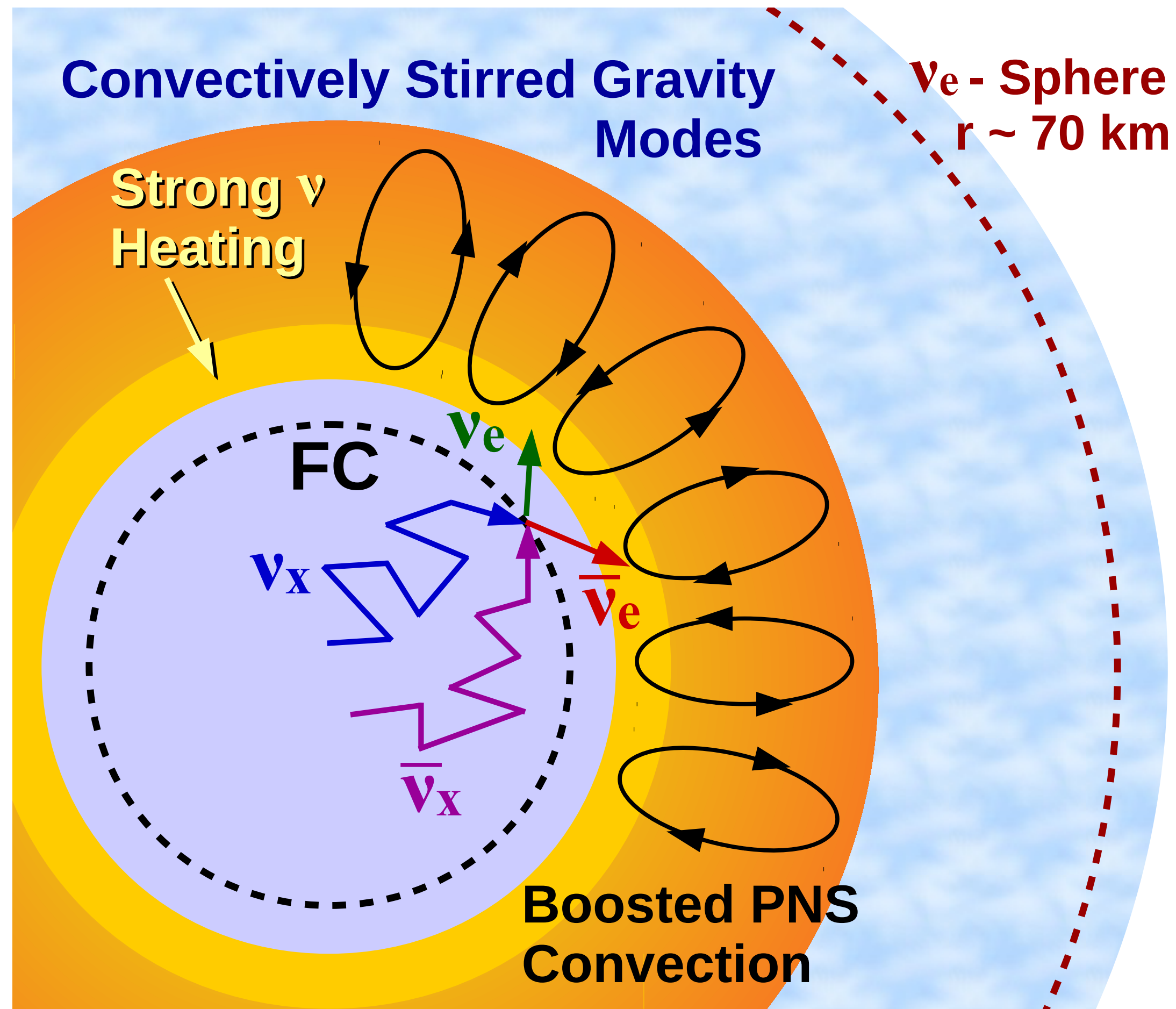
**(B): Inside heating and cooling region**



**From Ehring, et al. 2023b**



**From Ehring, et al. 2023b**

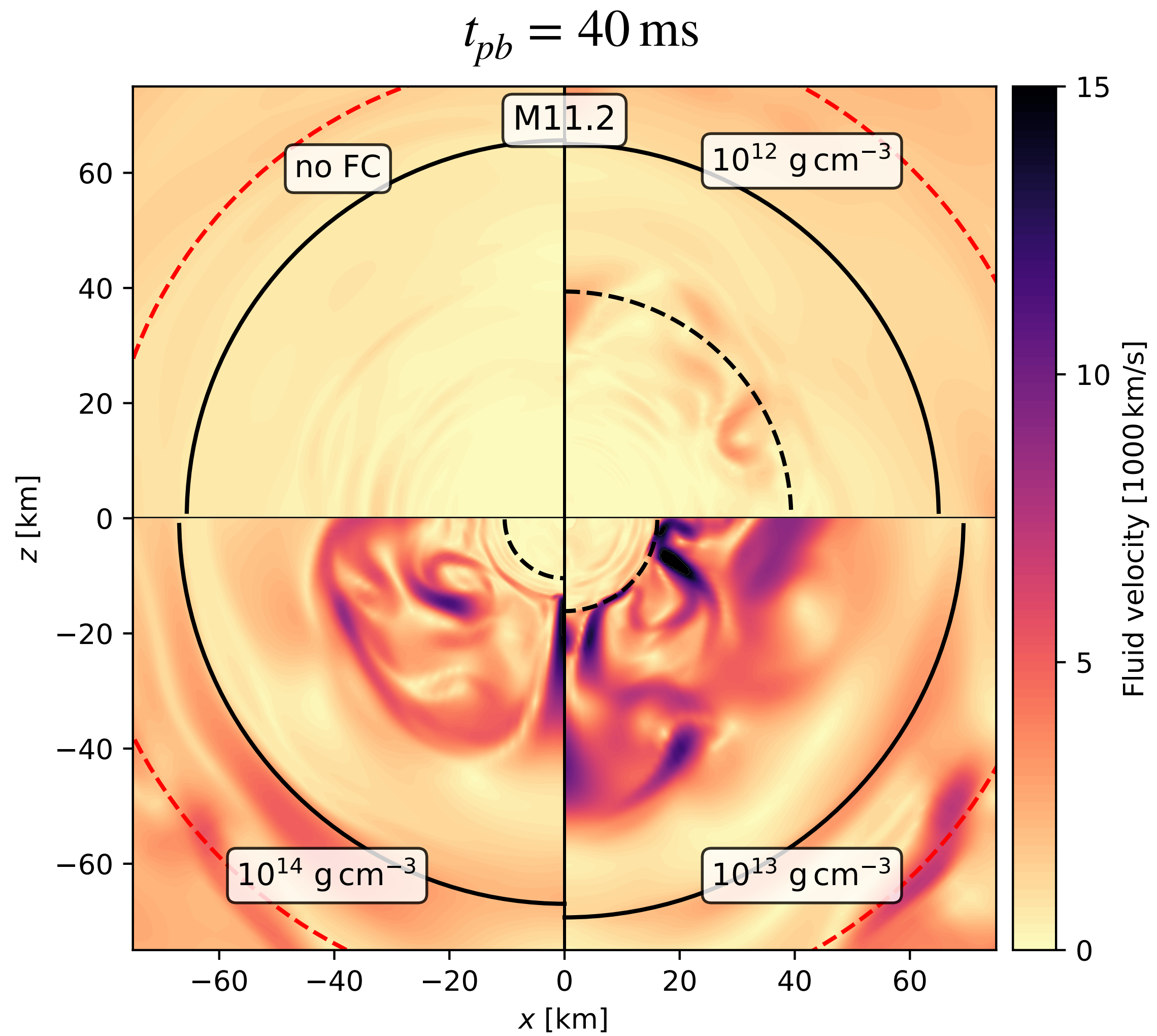


$$\sigma_{\nu_x, \bar{\nu}_x} < \sigma_{\nu_e, \bar{\nu}_e} \rightarrow \text{cooling by } \nu_x, \bar{\nu}_x \text{ more efficient}$$

Assume  $\nu_x, \bar{\nu}_x \rightarrow \nu_e, \bar{\nu}_e$  conversions at fixed density

Absorption of  $\nu_e, \bar{\nu}_e$  locally heats PNS matter enhances convection

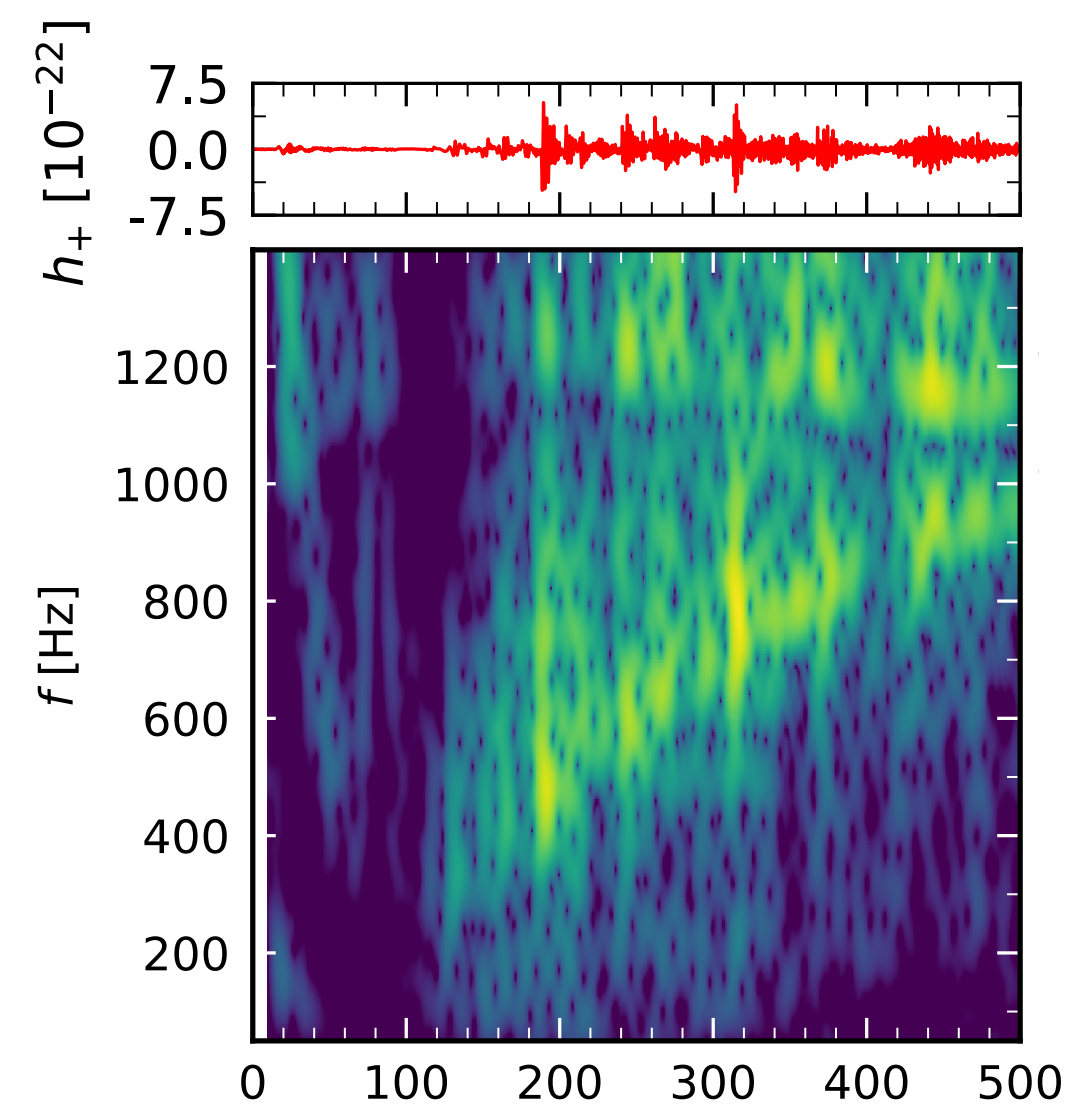
Emission of GW from convection and g-modes near the PNS surface



**Convection in PNS enhanced by a factor of a few!**

**Convection develops much earlier!**

**Impact on GW emission?**

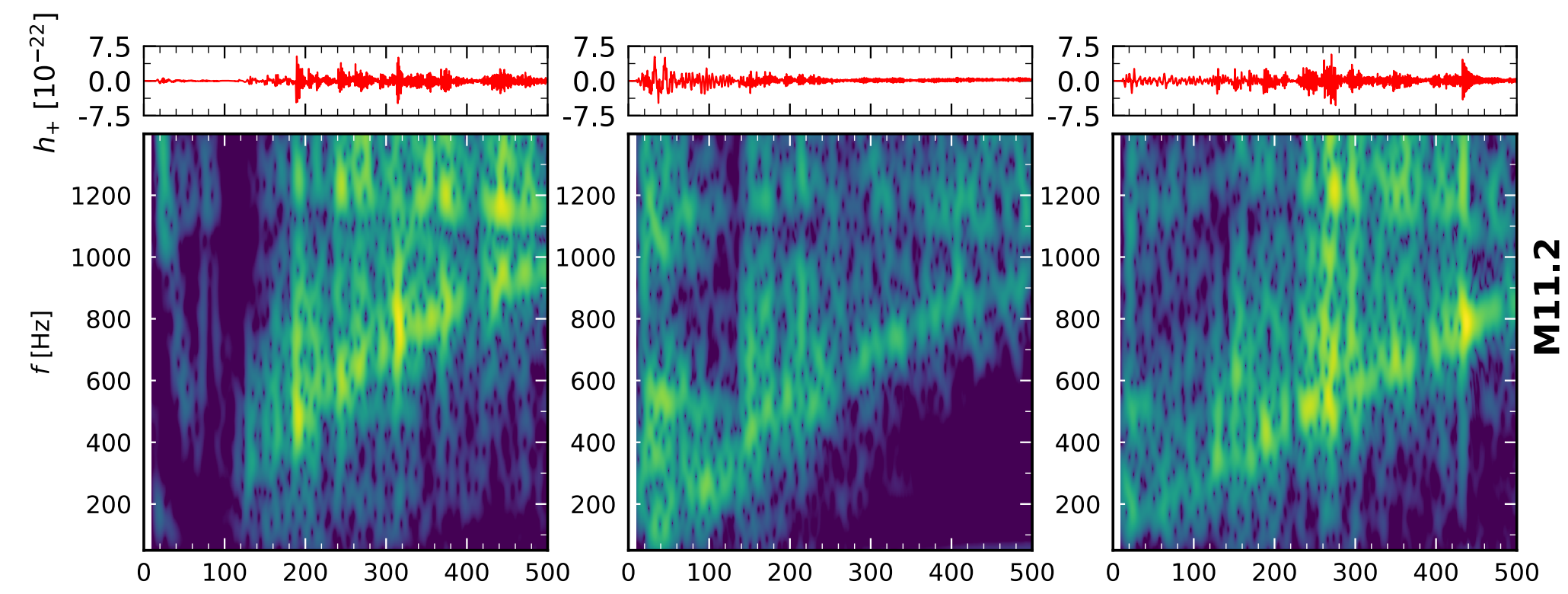


→ quiescent phase (first 100-200 ms after bounce)

noFC

$\rho_c = 10^{13} \text{ g cm}^{-3}$

$\rho_c = 10^{14} \text{ g cm}^{-3}$

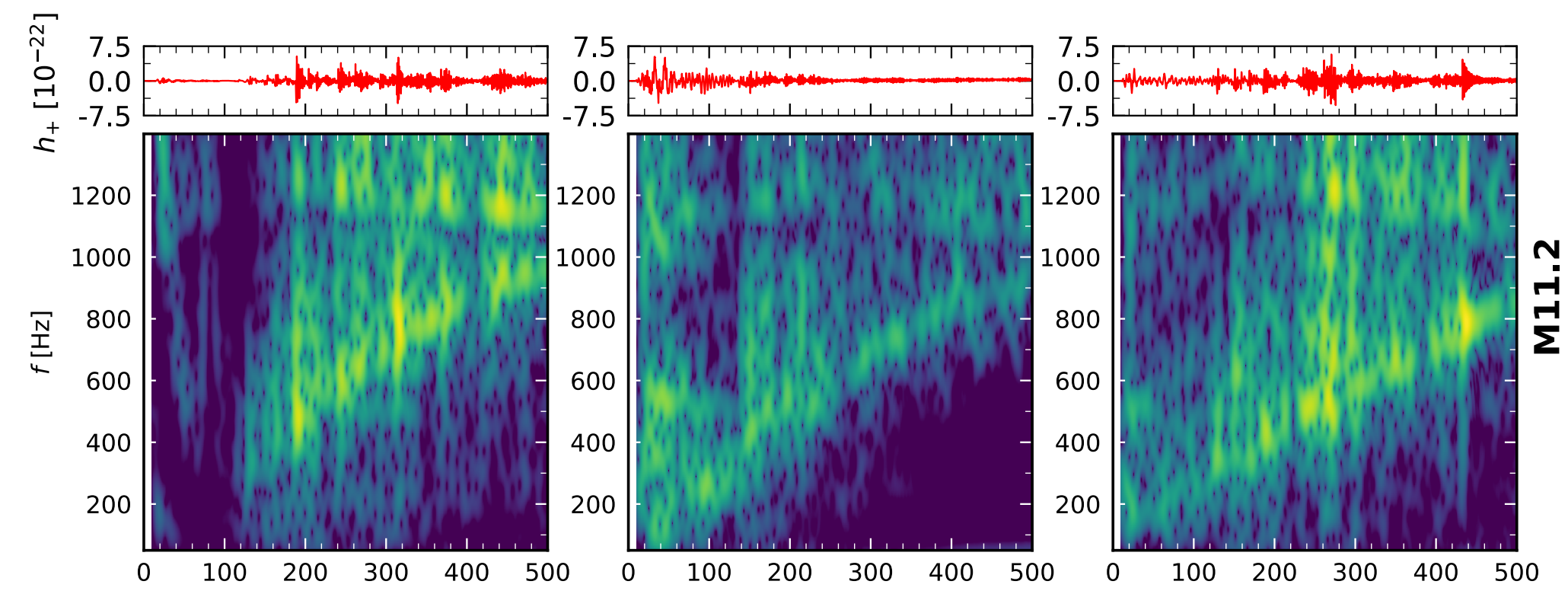


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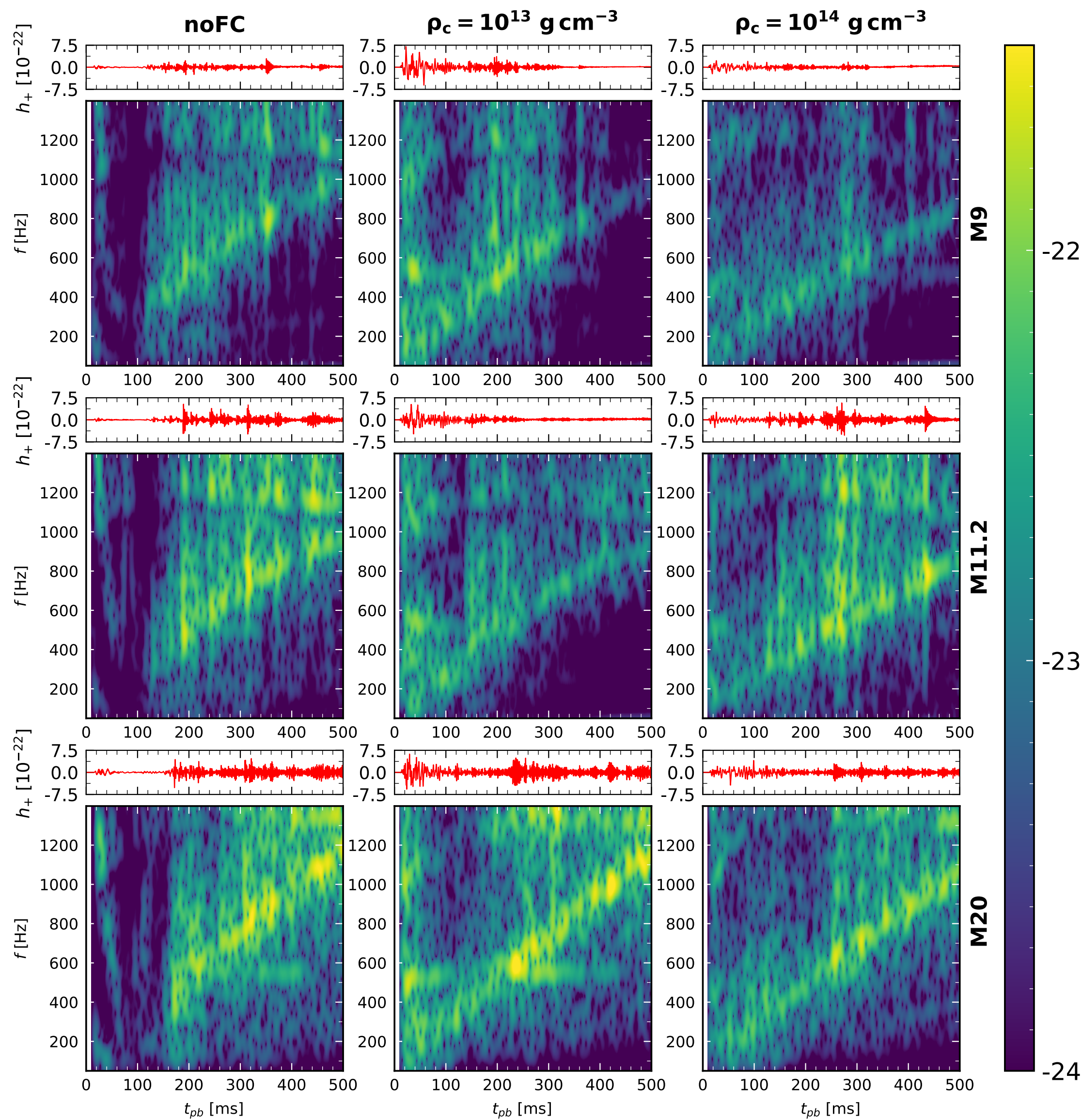
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- “quiescent phase” absent in all models with FC in the inner parts of the PNS

# Outlook and summary

## ➔ Flavor conversions influence the dynamics

➔ They can help AND hinder explosions

➔ Flavor conversions enhance

- Heating in gain region
- Cooling in cooling region and PNS mantle
- Convection in the PNS core

➔ Flavor conversions can amplify GW emission

**Next steps:**

**neutrino signals, nucleosynthesis, “improved”  
conversion treatment, ...**