Fast Neutrino Flavor Conversion in CCSN: A Parametric Study in 1D

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Focus Workshop, Taipei 14th - 17th March 2023

Overview

- What this talk is not about
- What we did instead
- Results from simulations in spherical symmetry
- Summary and outlook

What this talk is not about

Given

$$(\partial_t + \vec{v} \cdot \overrightarrow{\nabla_x})\, \rho = -i[H, \rho] + \mathscr{C}[f]$$

Find a solution for ρ , where

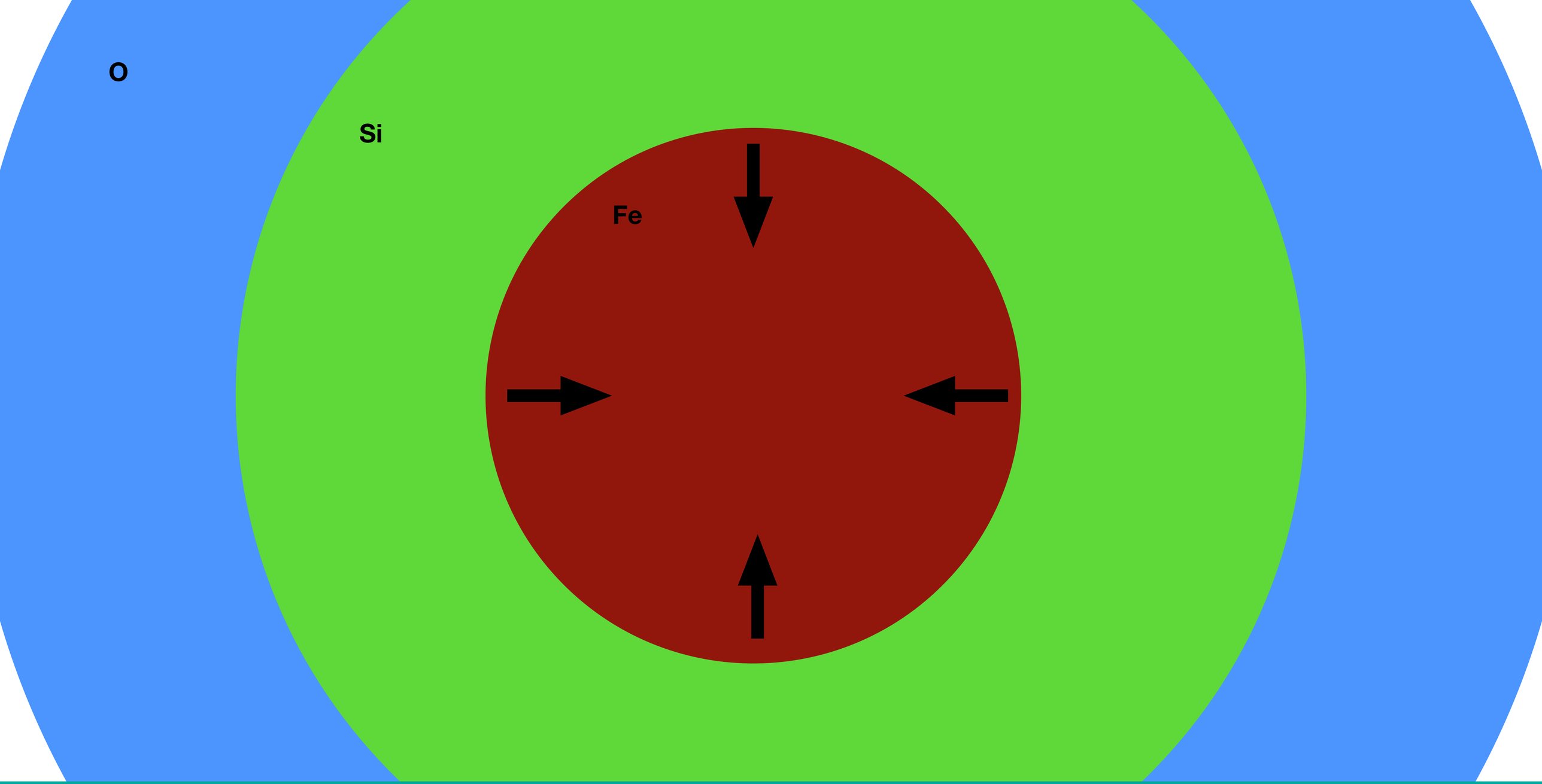
$$H = H_{\nu\nu} = \mu \int \mathrm{d}\overrightarrow{p'} [\rho(\overrightarrow{p'}) - \overline{\rho}(\overrightarrow{p'})](1 - \overrightarrow{v} \cdot \overrightarrow{v'})$$

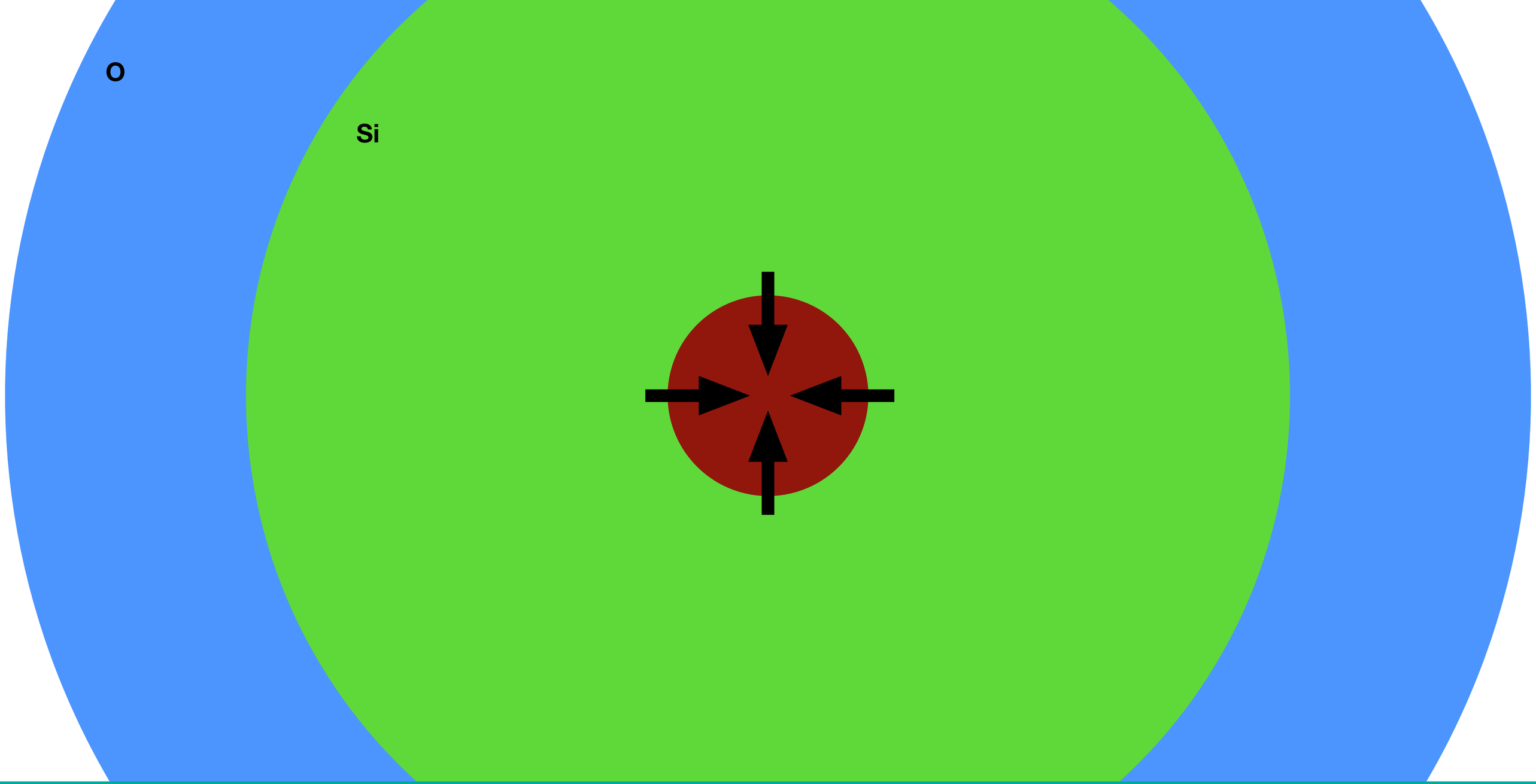
See the other talks of the workshop

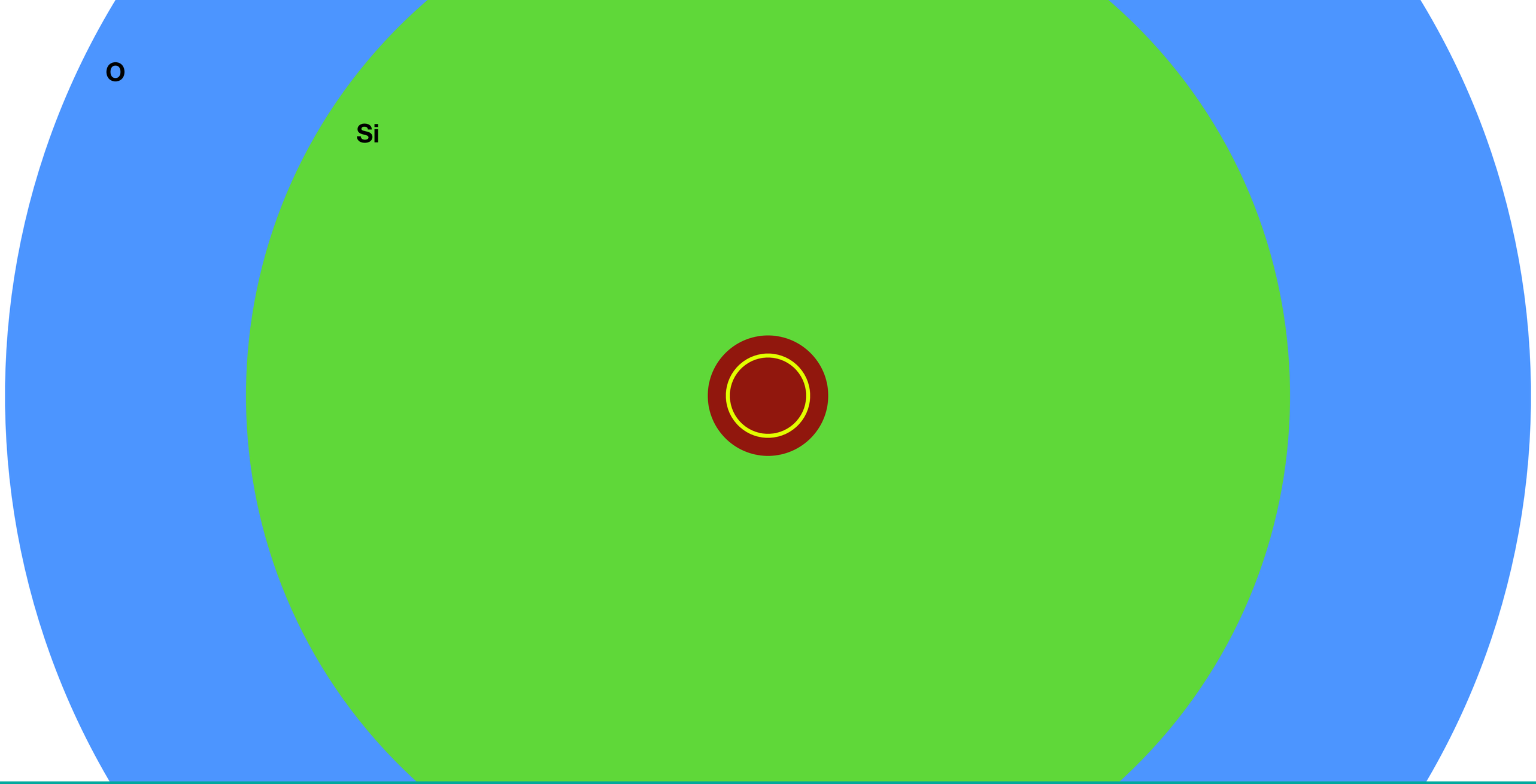
Or see a review e.g.
Duan et al (2010), Mirizzi et al (2016),
Tamborra et al (2021), Richers and Sen (2021),
Volpe (2023)

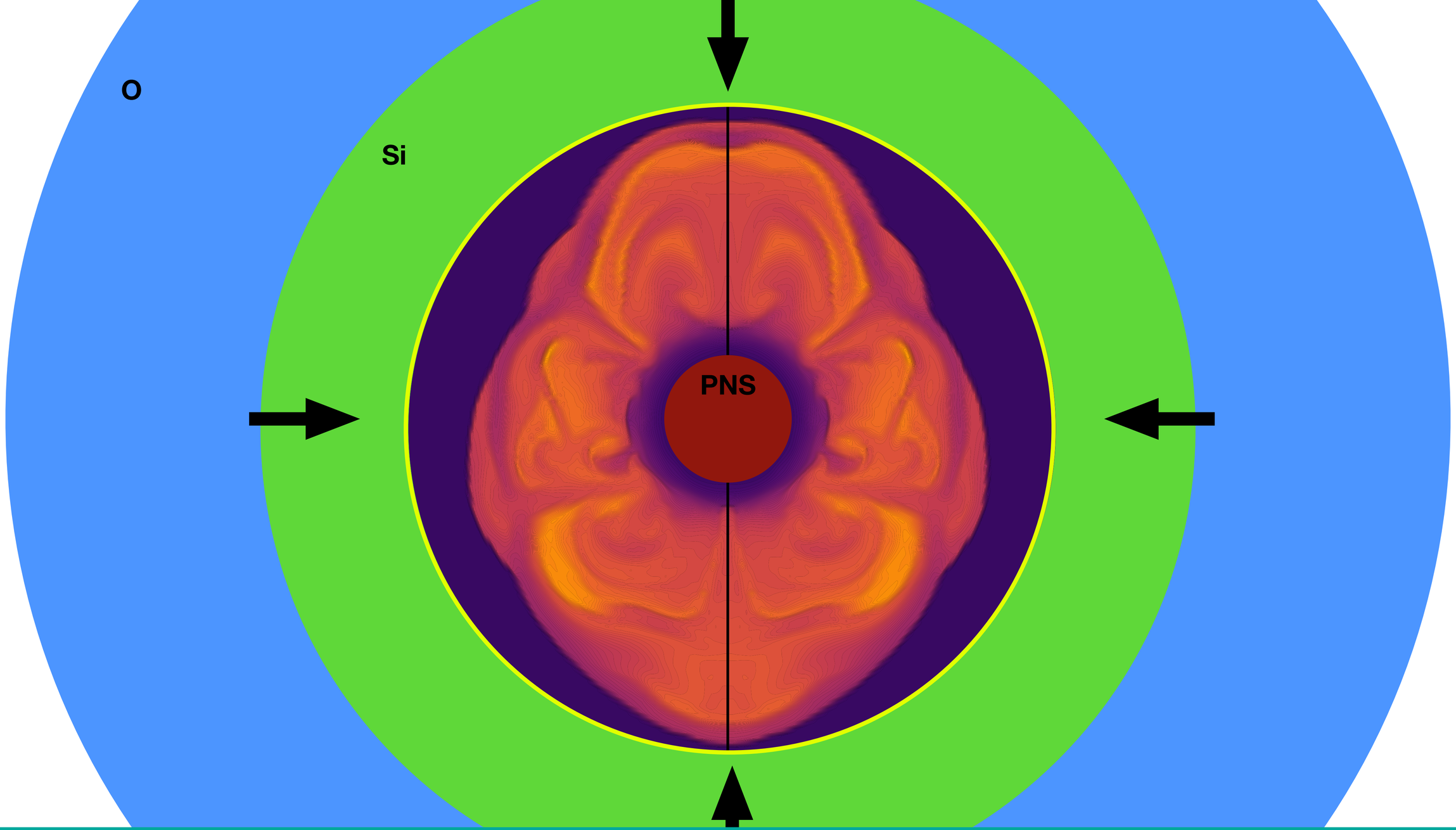
What we did instead

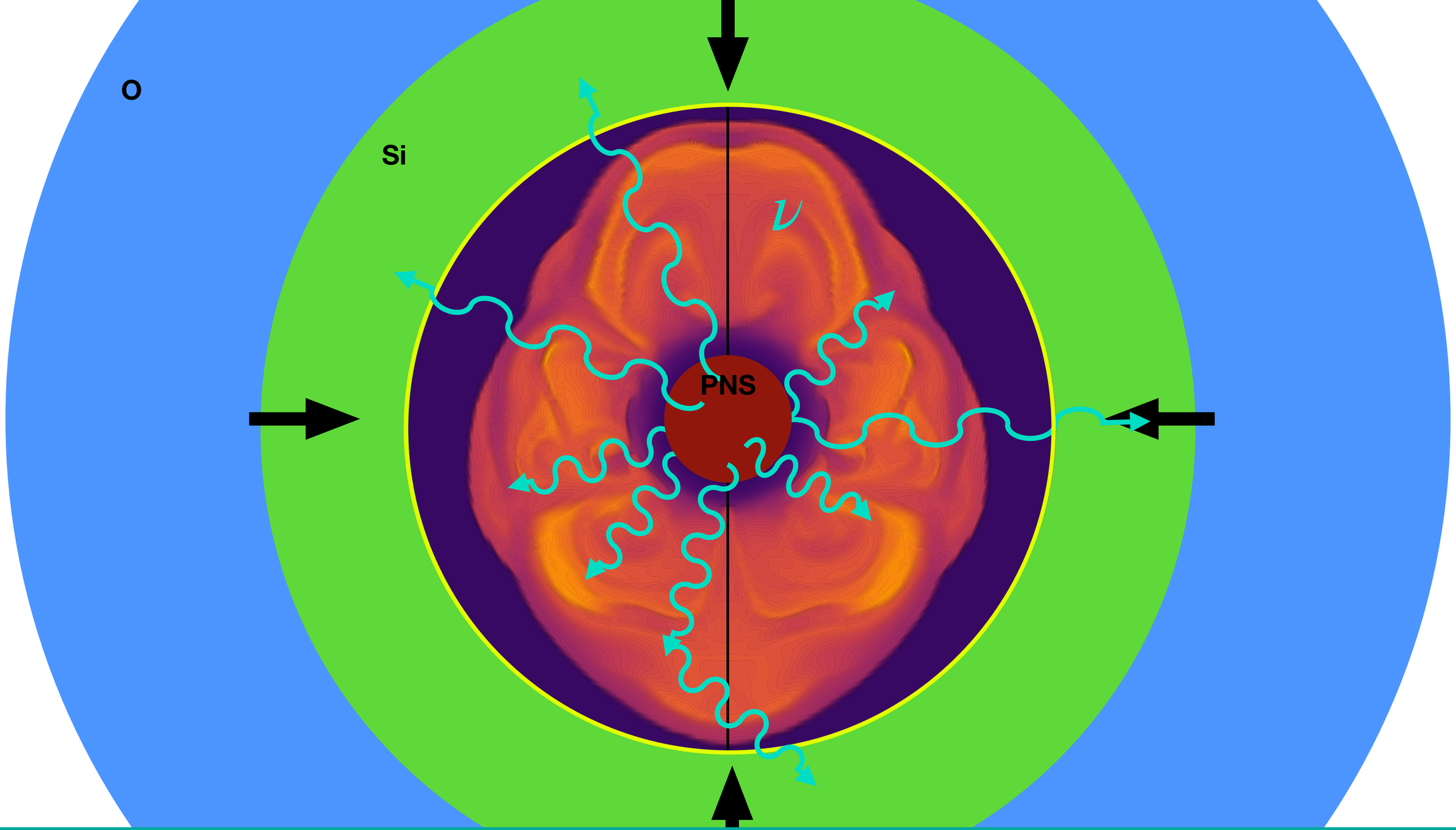
Ask the question:
How “wrong” are we, neglecting fast and efficient neutrino flavor conversion in Core-Collapse Supernovae simulations?

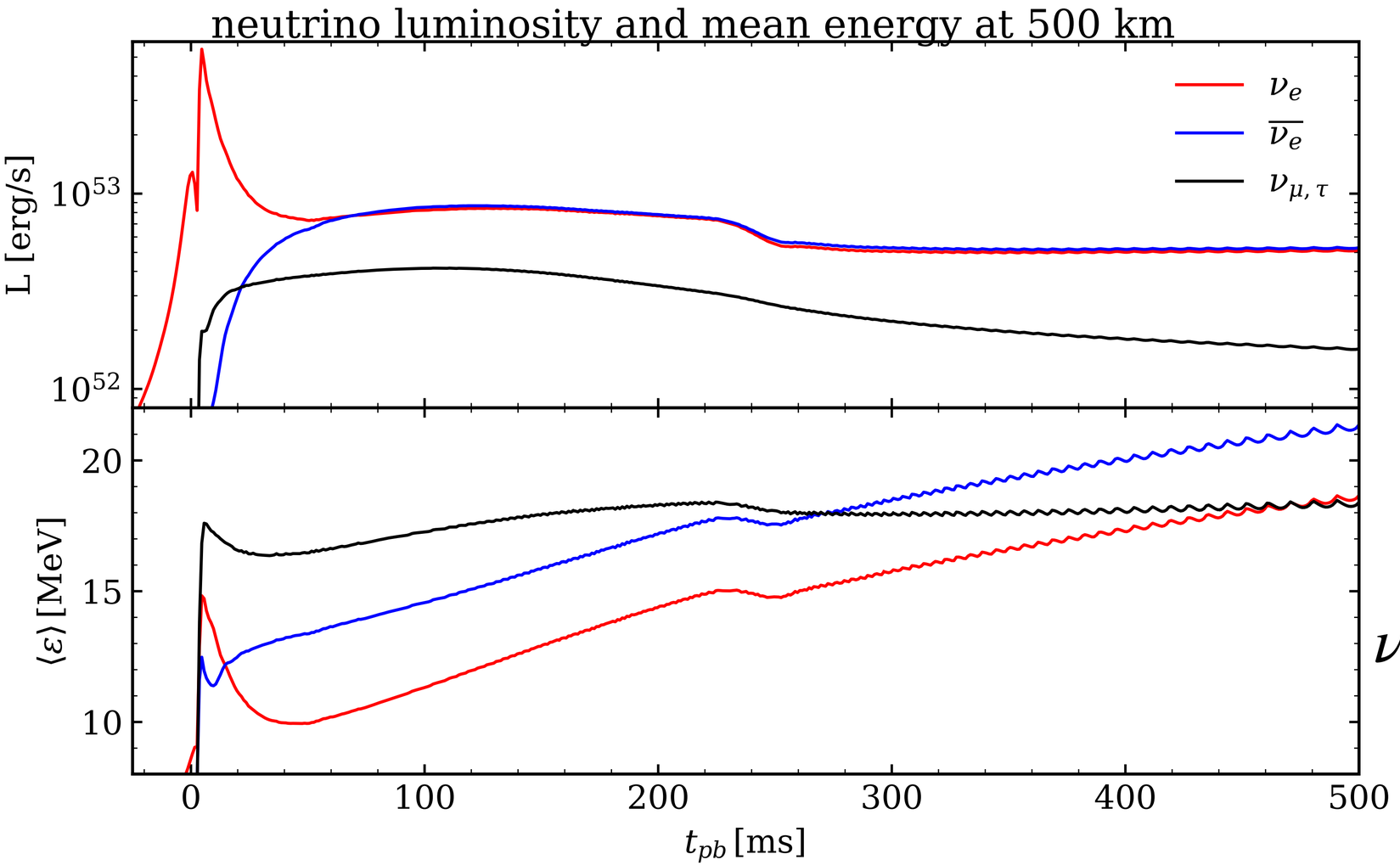

O
Si
Fe


O
Si


O
Si


O
Si
PNS


O
Si
ν
PNS



Production (cooling):

Thermal (flavor blind):

$$e^+ + e^- \rightarrow \nu_\alpha + \bar{\nu}_\alpha$$

Charged current (e only):

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

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

Interaction (heating):

All flavors: scattering

$$\nu_\alpha + e^{+/-}/p/n \rightarrow \nu_\alpha + e^{+/-}/p/n$$

Electron flavor: absorption

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

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

What we did instead

“Quick & Dirty” method to include Flavor Conversion

- Maximum equilibrium (up to conservation laws)
- 1 parameter conversion criterion

Basics principles:

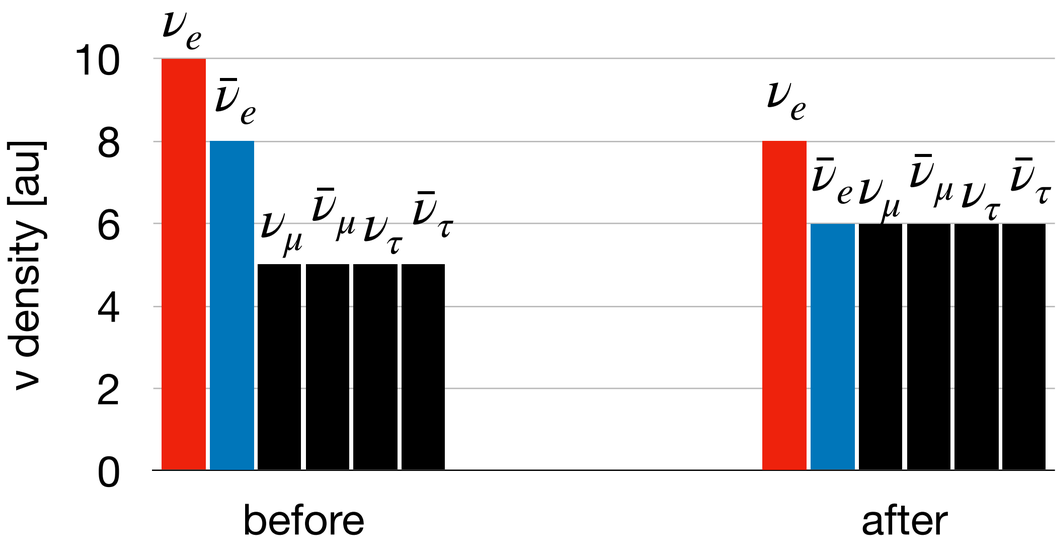
No creation or destruction of particles -> Conservation of Total Lepton Number

$$\sum_{\alpha} n_{\nu_\alpha} + \sum_{\alpha} n_{\bar{\nu}_\alpha} = \sum_{\alpha} n'_{\nu_\alpha} + \sum_{\alpha} n'_{\bar{\nu}_\alpha}$$

Pairwise (neutrino+antineutrino) -> Conservation of Electron Lepton Number

$$L_e = n_{\nu_e} - n_{\bar{\nu}_e} = n'_{\nu_e} - n'_{\bar{\nu}_e} = L'_e$$

Parametrized Recipe:



$$n'_{\nu_e} = n_{\rm eq} + \max(0, L_e),$$
$$n'_{\bar{\nu}_e} = n_{\rm eq} + \max(0, -L_e),$$
$$n'_{\nu_x} = n_{\rm eq}$$

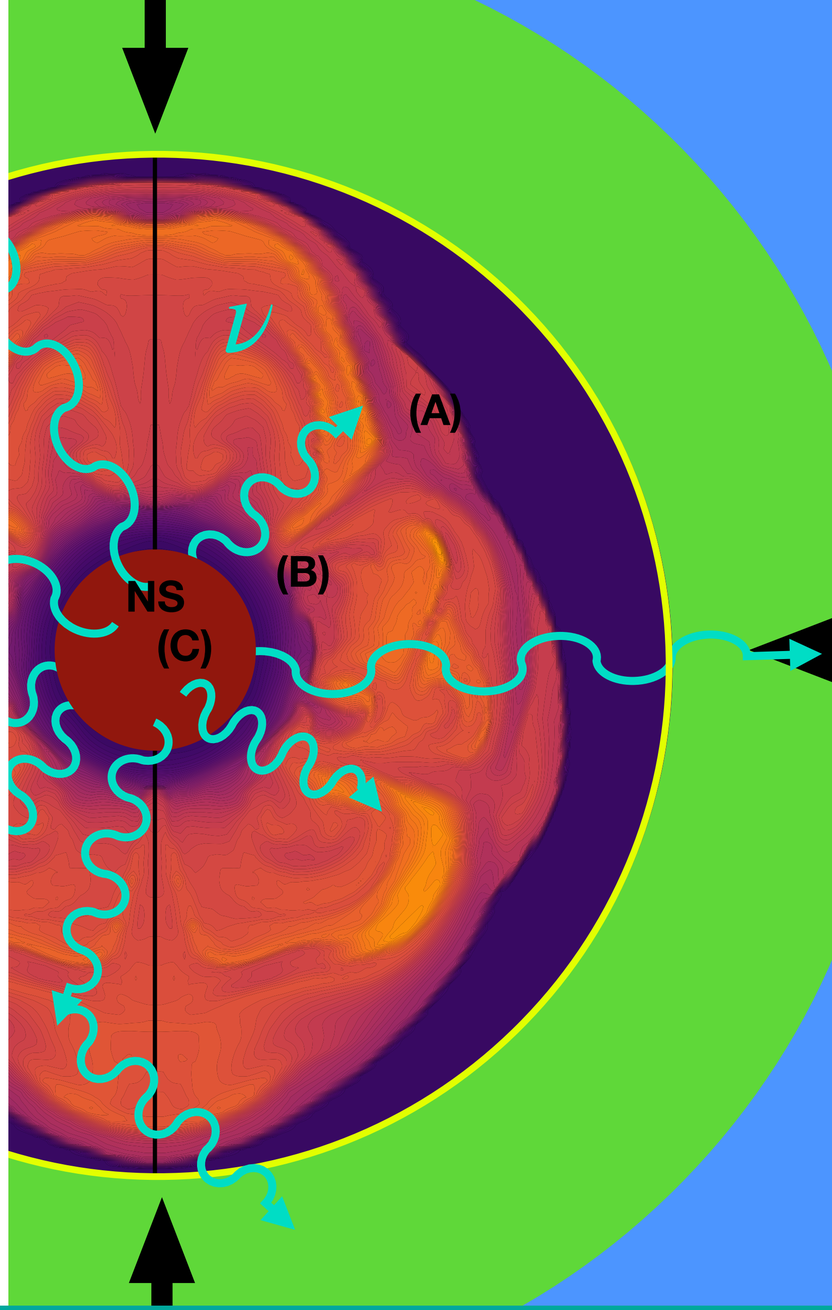
$$n_{\rm equ} = \begin{cases} \frac{1}{3}(n_{\bar{\nu}_e} + 2n_{\nu_x}) & \text{if } L_e \geq 0, \\ \frac{1}{3}(n_{\nu_e} + 2n_{\nu_x}) & \text{if } L_e < 0, \end{cases}$$

Criterion For Occurrence:

Should be comparably inexpensive -> Needs to be done “on the fly”

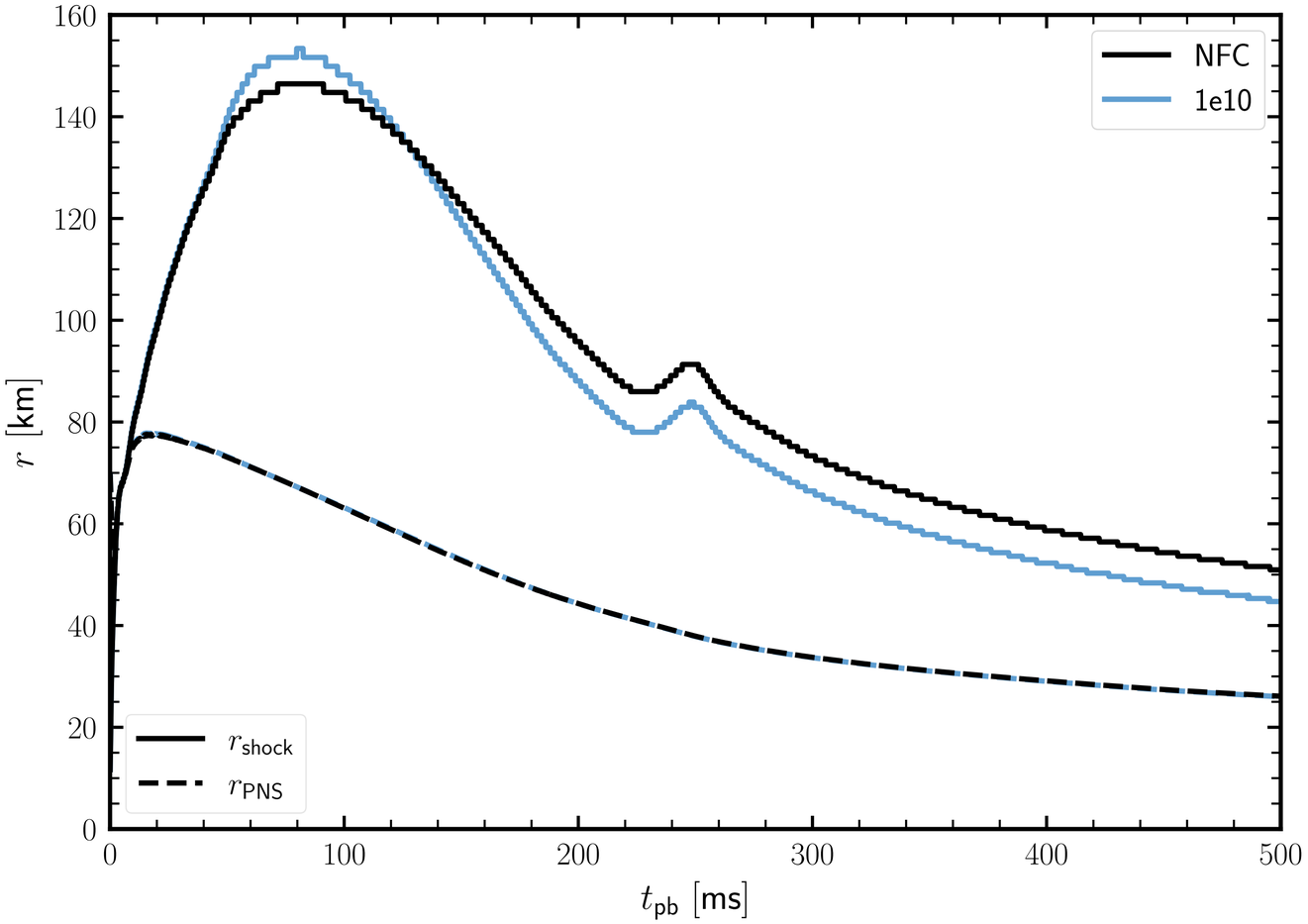
Use density to probe effects of FFC in different regions:

- **Inside Heating Region** ($\rho_{\mathrm{crit}} = 10^{10}\,\mathrm{g/cm^3}$) **(A)**
- **Inside Neutron Star Mantle** ($\rho_{\mathrm{crit}} = 10^{12}\,\mathrm{g/cm^3}$) **(B)**
- **Inside Neutron Star Core** ($\rho_{\mathrm{crit}} = 10^{13}\,\mathrm{g/cm^3}$) **(C)**

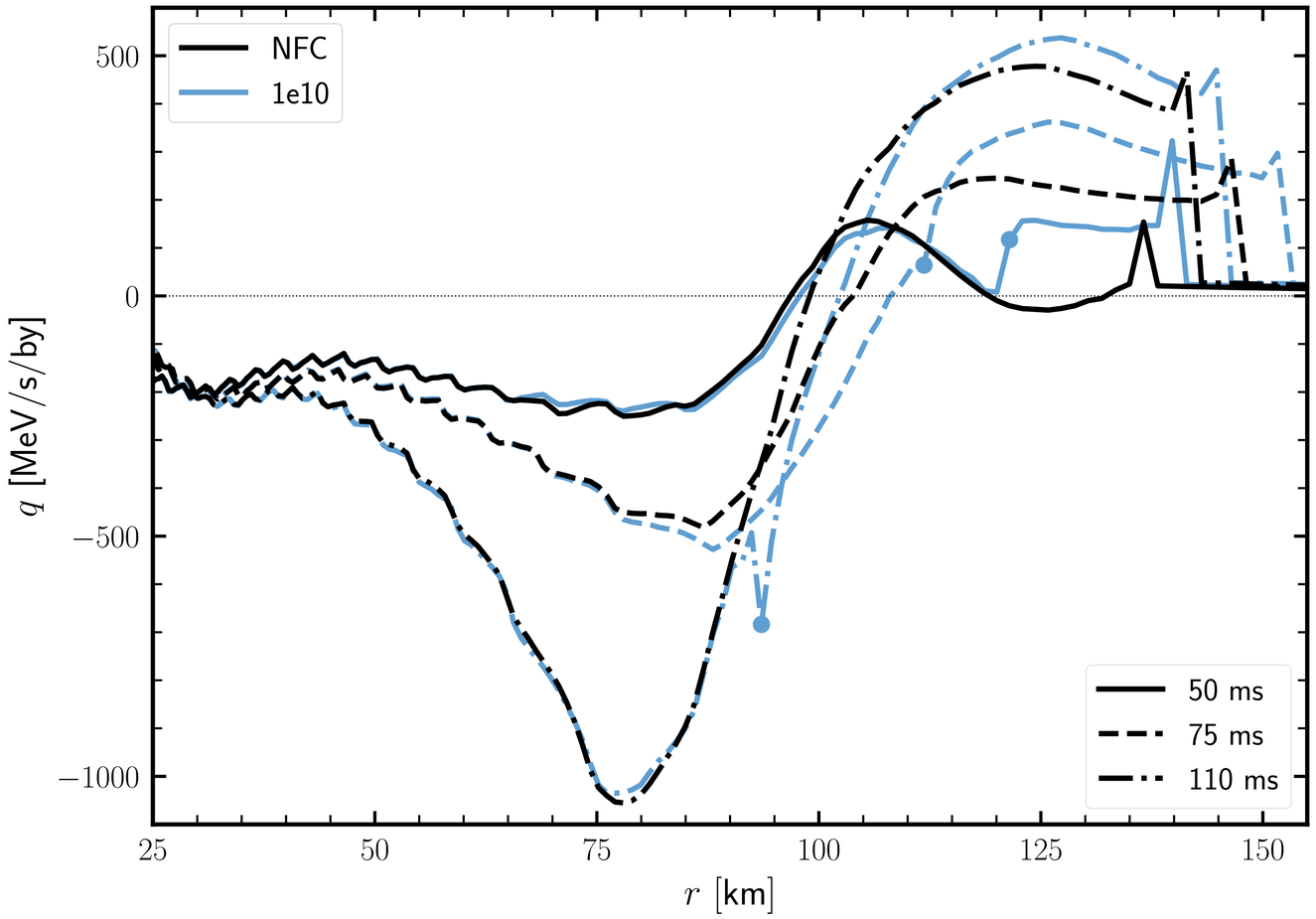


Results from simulations in spherical symmetry

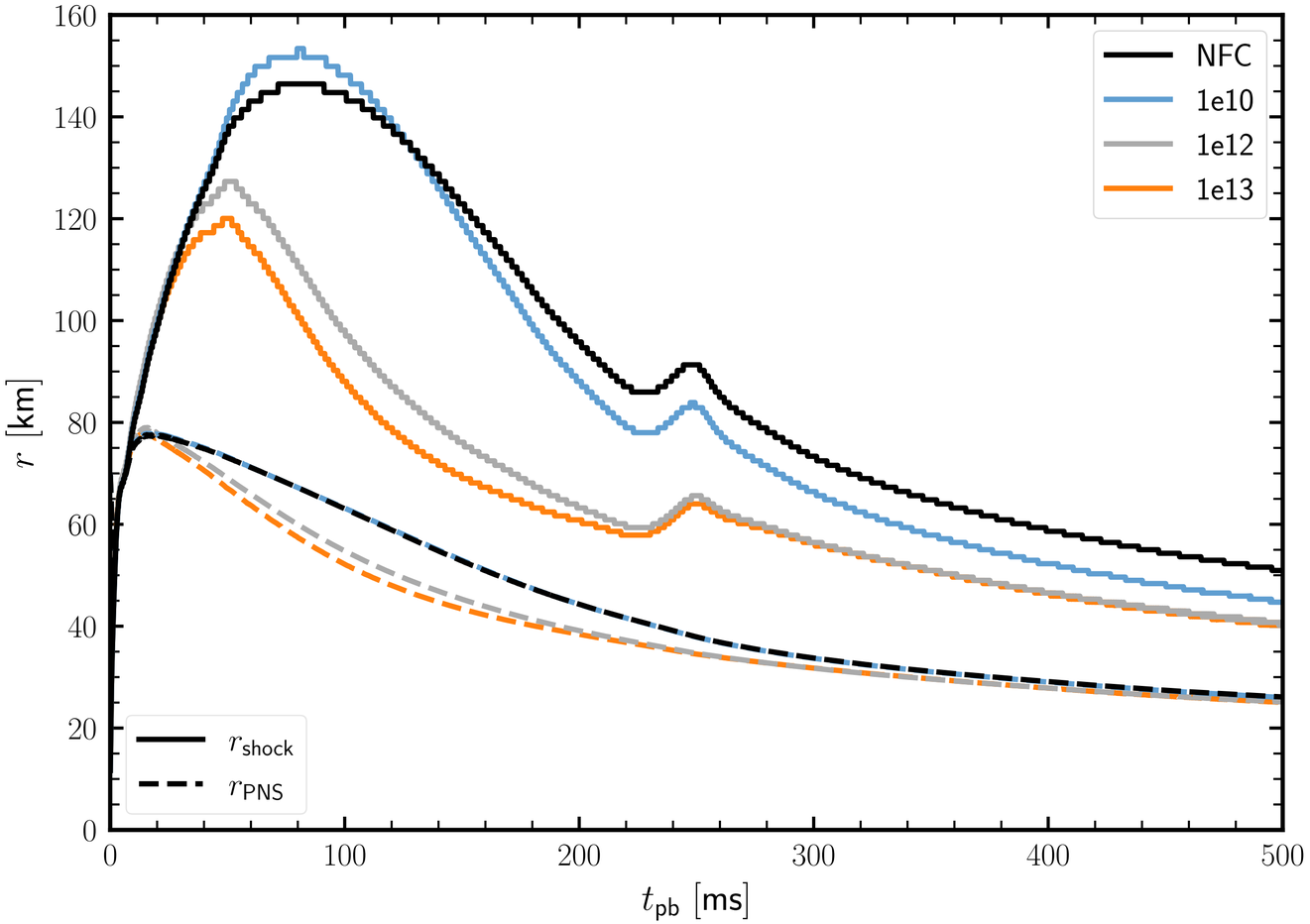
Dynamics


160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
r [km]
t_{pb} [ms]
NFC
1e10
r_{shock}
r_{PNS}

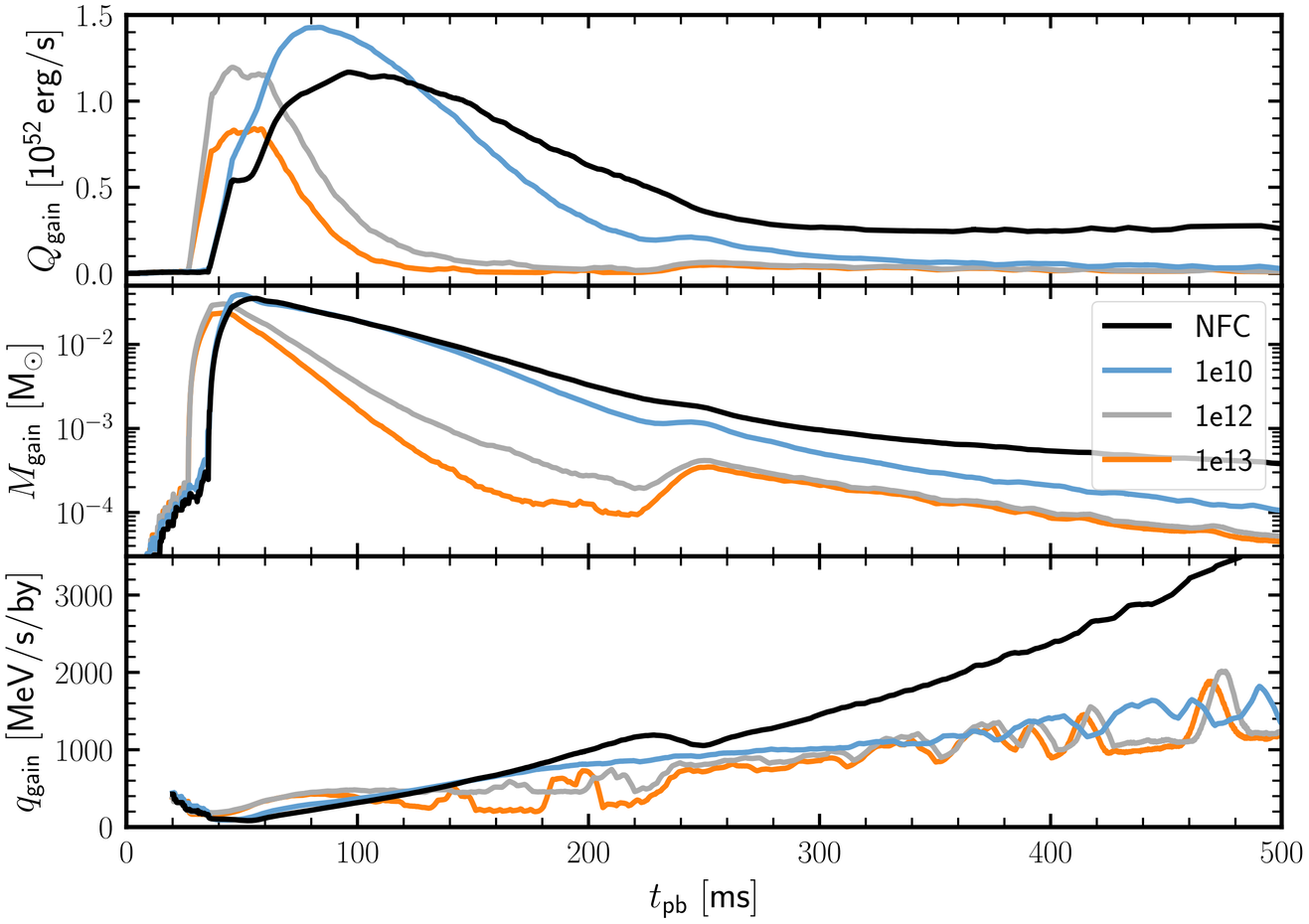
Cooling


NFC
1e10
50 ms
75 ms
110 ms
500
0
−500
−1000
25
50
75
100
125
150
q [MeV/s/by]
r [km]

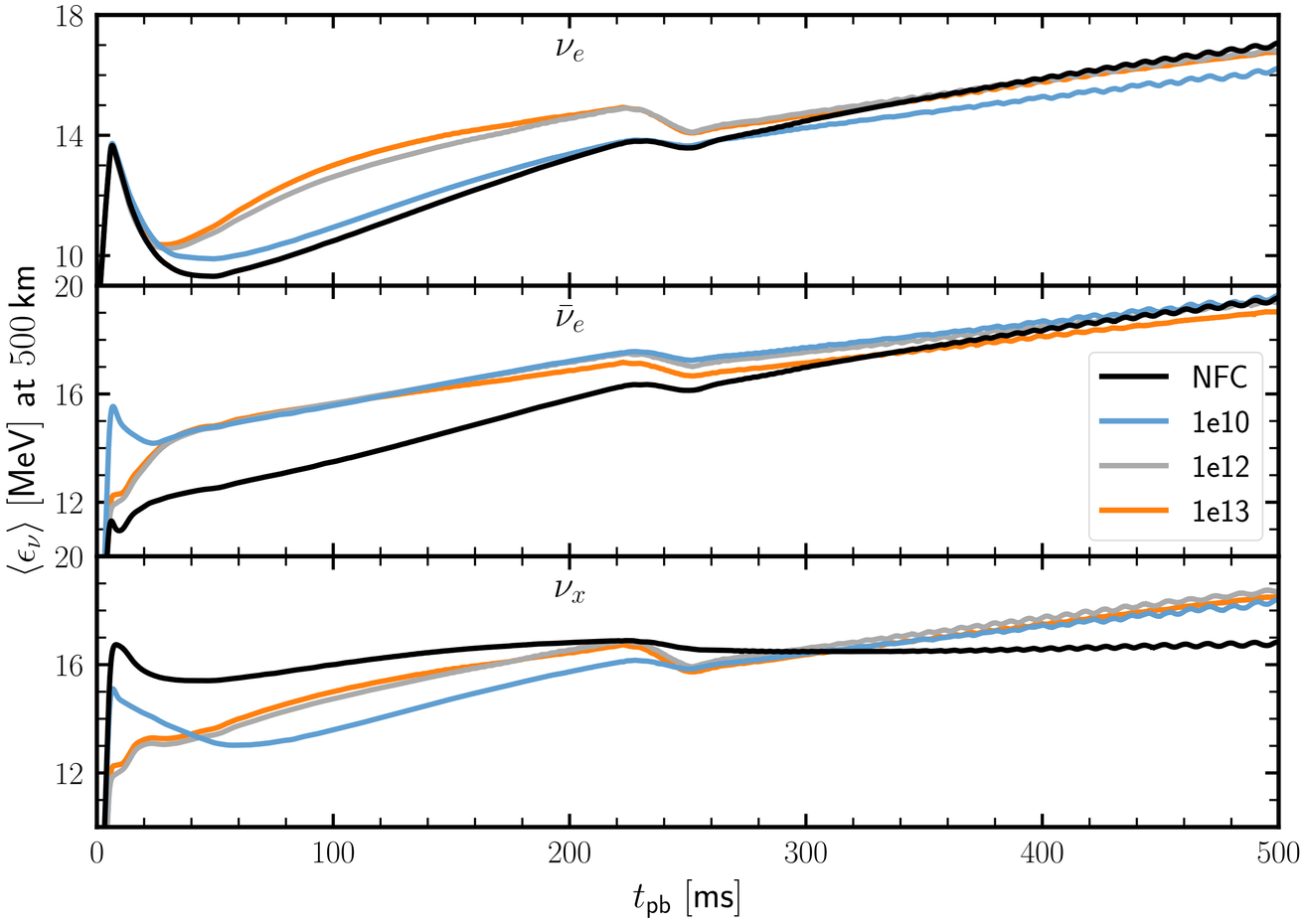
Dynamics


160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
r [km]
t_{pb} [ms]
NFC
1e10
1e12
1e13
r_{shock}
r_{PNS}

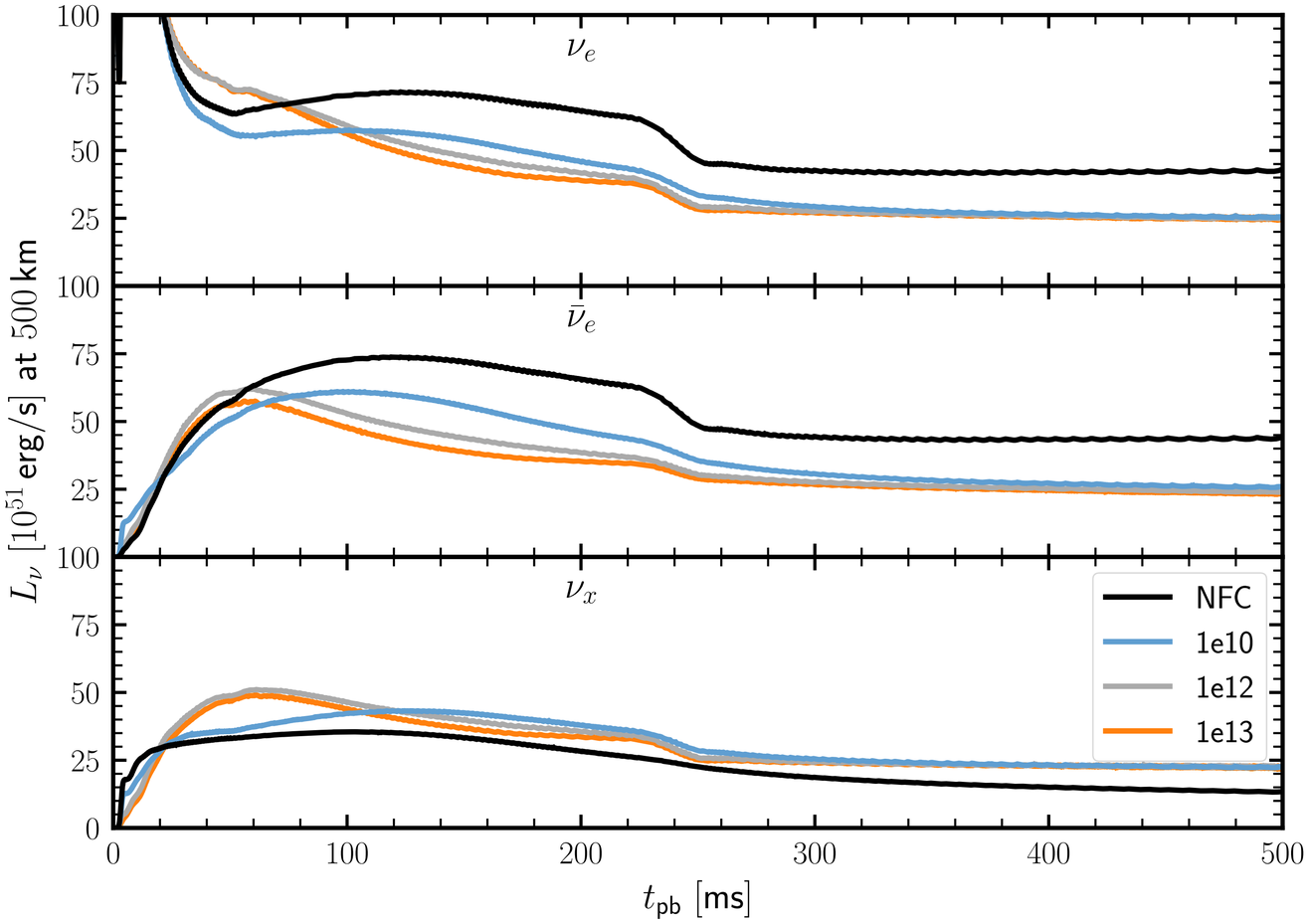
Heating

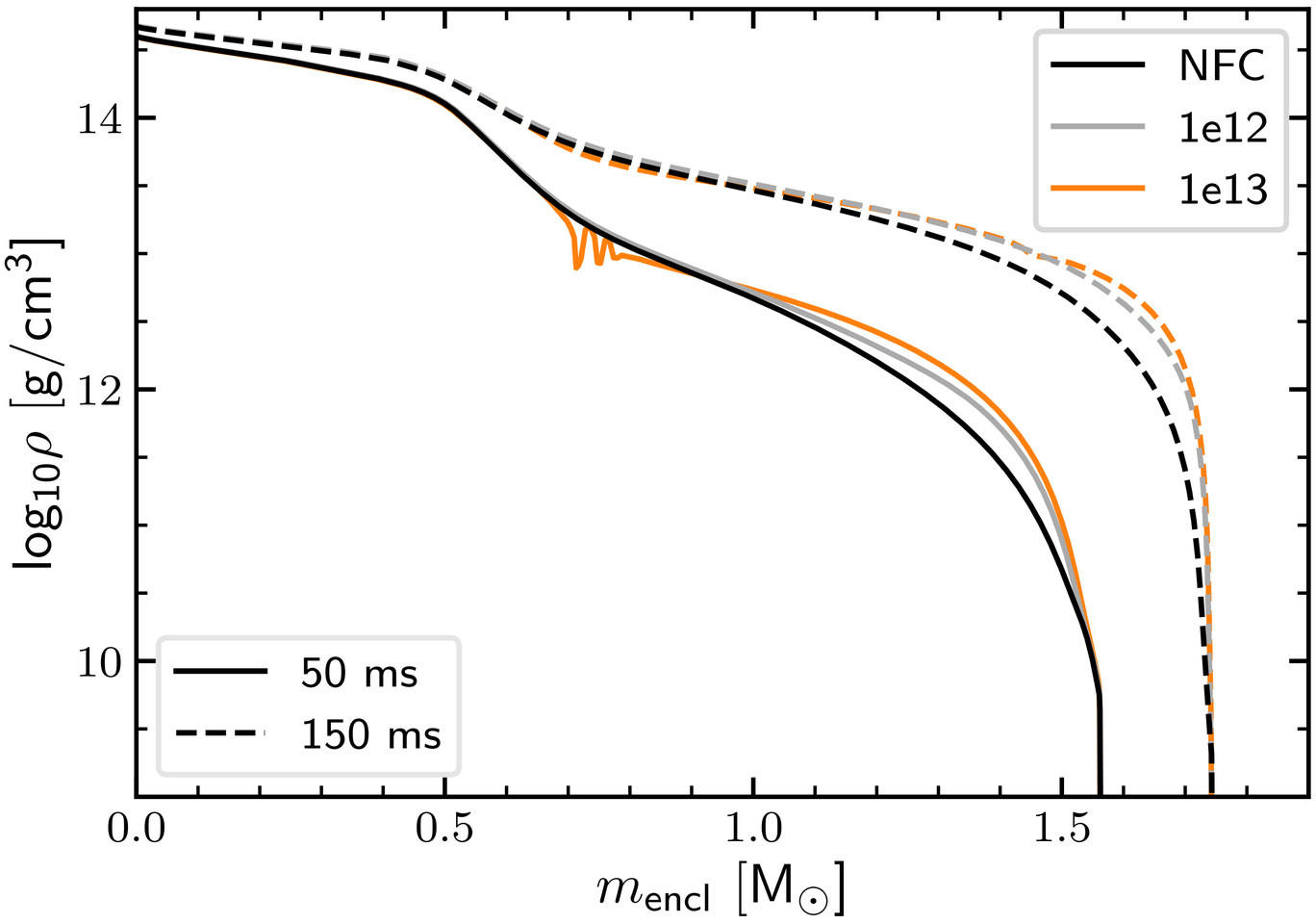

Q_{gain} [10^{52} erg/s]
M_{gain} [$M_\odot$]
q_{gain} [MeV/s/by]
t_{pb} [ms]
NFC
1e10
1e12
1e13

Mean Energy


ν_e
$\bar{\nu}_e$
ν_x
$\langle \epsilon_\nu \rangle$ [MeV] at 500 km
$t_{\rm pb}$ [ms]
NFC
1e10
1e12
1e13

Neutrino Luminosity




NFC
1e12
1e13
50 ms
150 ms
14
12
10
0.0
0.5
1.0
1.5
$\log_{10}\rho$ [g/cm^3]
$m_{\rm encl}$ [M$_\odot$]

Summary and Outlook

➡Strong Flavor Conversions can have significant impact dynamical evolution in 1D

➡Flavor conversions cause

- Enhanced heating in gain region
- Enhanced cooling in cooling region and PNS mantle
- Reduced energy transport in PNS core

➡Many more possibilities to charter effects:
Multi-D effects, couple to ELN crossings, “incomplete” conversions, nucleosynthesis, different progenitor, neutrino signals, later onset, …