# Neutrino-Matter Interactions in Neutron Star Mergers: Effect of Inelastic Scattering on Neutrino Thermalization

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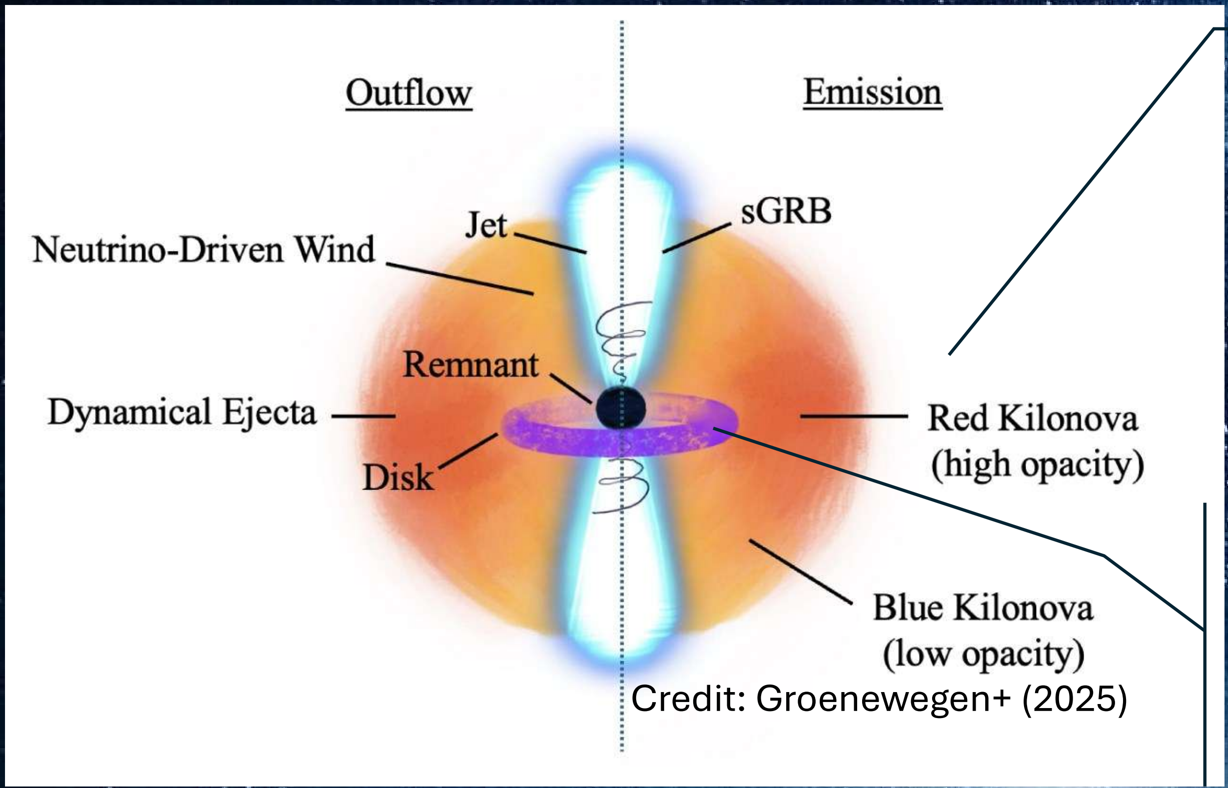
Simulating eXtreme Spacetimes
Black holes, neutron stars, and beyond...

# HOW DO NEUTRINOS INFLUENCE OBSERVABLES?




- KN properties are sensitive to the opacity of the ejecta to photons.
- This depends on the neutron-richness of the ejecta.
- **Neutrino-matter interactions are largely responsible for setting this composition via changes in Ye.**

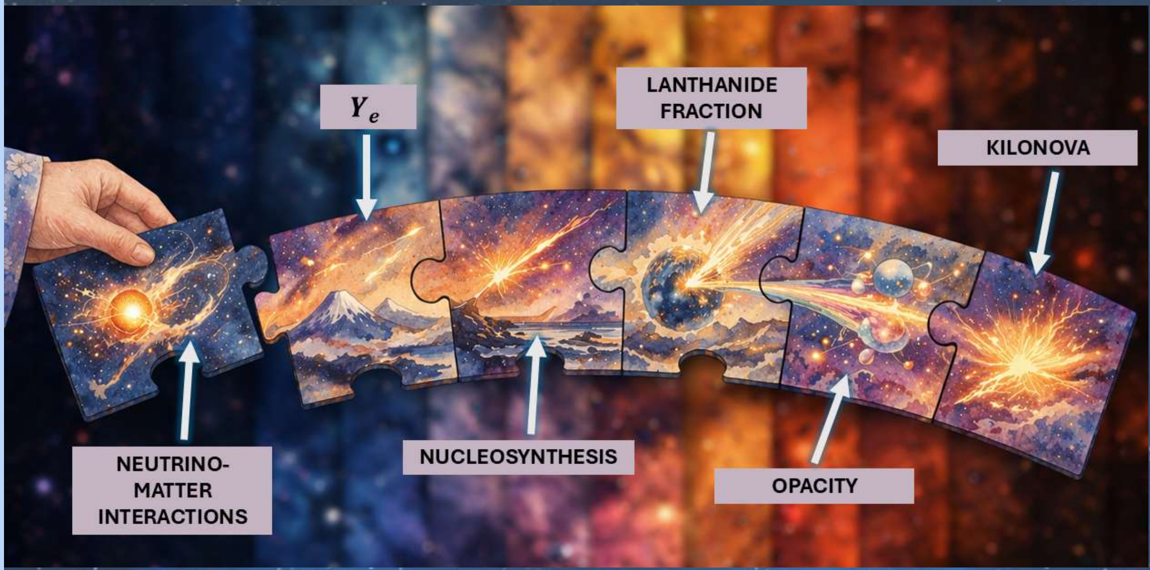
The neutron rich ejecta synthesizes heavy elements above Fe via rapid neutron capture nucleosynthesis.

# WHAT ARE WE TRYING TO UNDERSTAND?

1.) Which neutrino–matter interactions dominate in neutron star merger remnants?

2.) How does their relative importance vary across the thermodynamic conditions of the remnant?

3.) How does the inclusion of reactions not considered before, for example, inelastic scattering affect the opacity?



# HOW DO NEUTRINOS INTERACT WITH MATTER?

| REACTIONS IN MERGER SIMULATION CONTEXT | |
|---|---|
| **Charged Current Reaction** | $\mathbf{p + e^- \leftrightarrow n + \nu_e}$ |
| | $\mathbf{n + e^+ \leftrightarrow p + \bar{\nu}_e}$ |
| **Pair processes** | $\mathbf{e^+ + e^- \leftrightarrow \nu + \bar{\nu}}$ |
| | $\boldsymbol{N + N \leftrightarrow N + N + \nu + \bar{\nu}}$ |
| **Scattering** | **On nucleons and nuclei (nearly elastic)** |
| | **Electrons (inelastic)** |

Remember the electron fraction $Y_e = n_p / \left(n_p + n_n\right)$

Charge current reactions can change the electron fraction, hence impacting opacity of ejecta

Other reactions like muon interactions, plasmon decay and fast flavor oscillations have not been considered in our study.

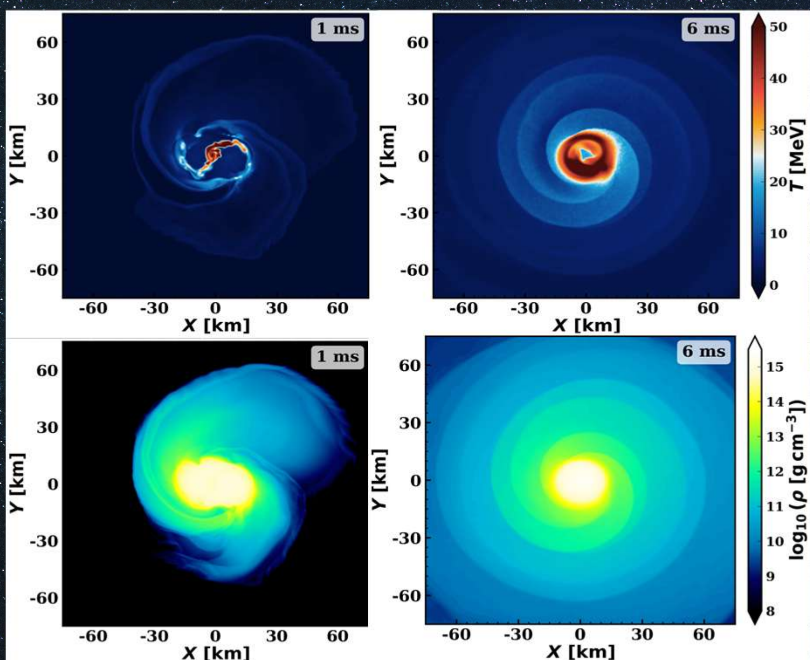
NOTATION: $\boldsymbol{\nu}_{\mathbf{e}}$ ELECTRON NEUTRINO; $\bar{\boldsymbol{\nu}}_{\mathbf{e}}$ ELECTRON ANTINEUTRINO; $\boldsymbol{\nu_x}$ HEAVY LEPTON NEUTRINO ($\boldsymbol{\nu_\mu} + \boldsymbol{\nu_\tau}$ + ANTIPARTICLES)

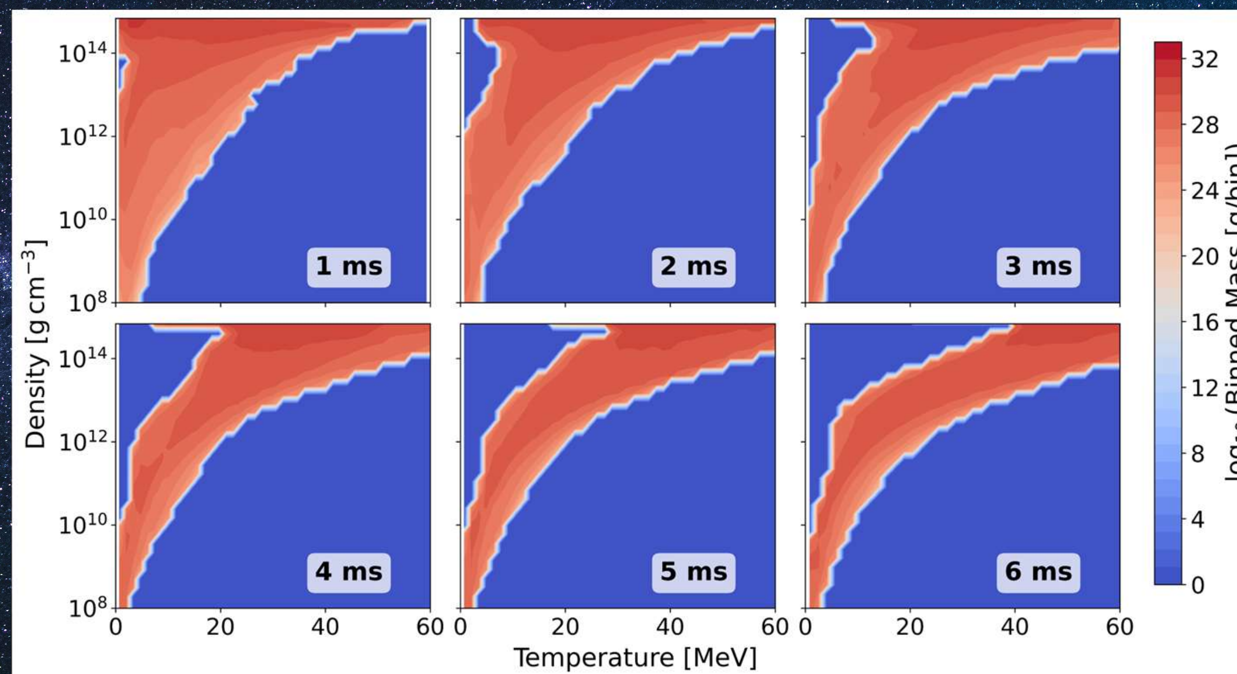
# POST-PROCESSING A MONTE CARLO SIMULATION SNAPSHOT

REMEMBER ALBINO'S LECTURE

SPATIAL PROFILES

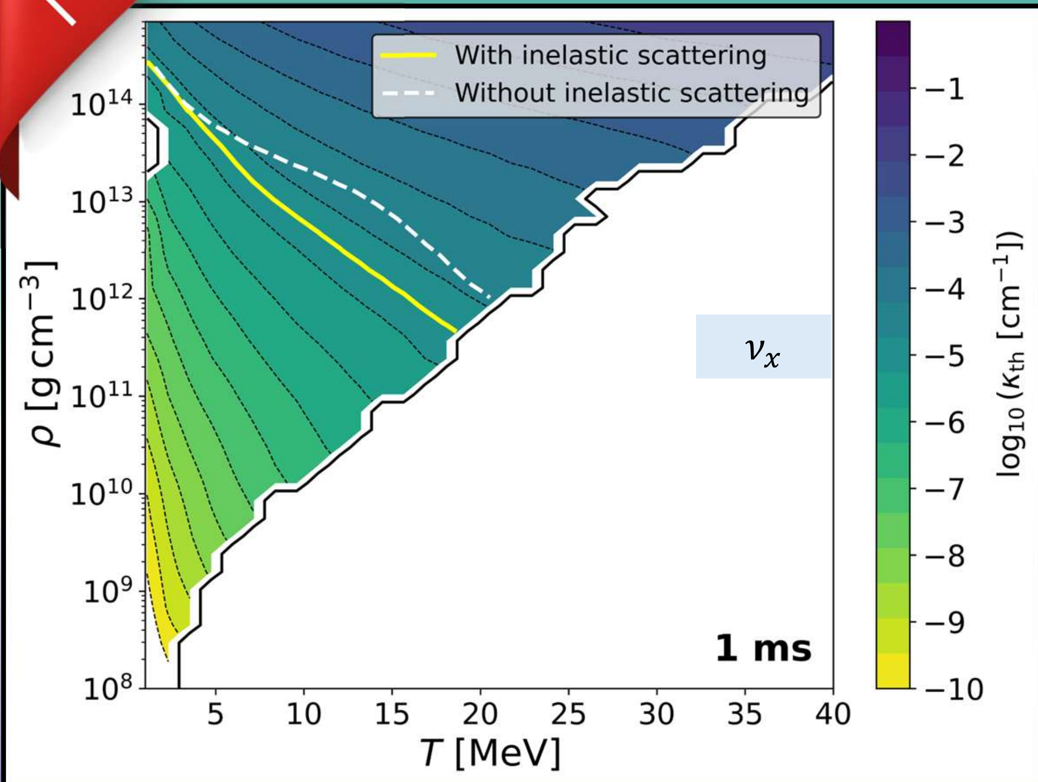
MASS WEIGHTED HISTOGRAMS IN $\rho - T$ PLANE

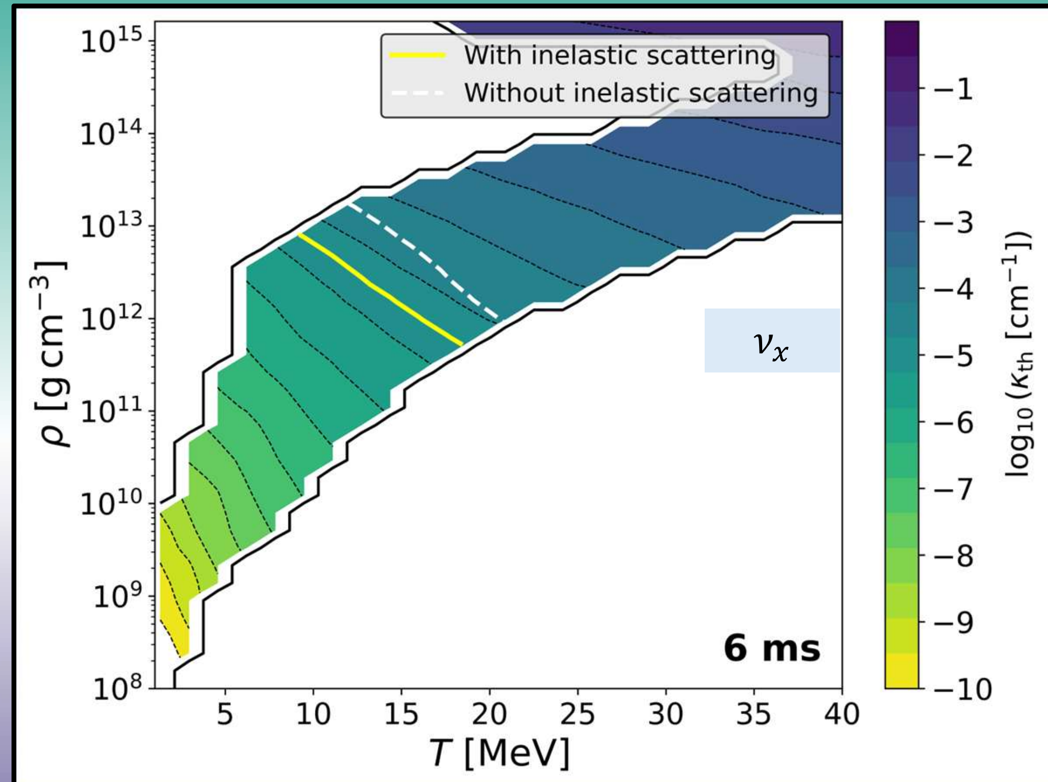


NEW

# RESULT: EFFECT OF INCLUDING INELASTIC SCATTERING




**Inelastic scattering significantly shifts the thermalization neutrinosphere!**

## HIGHLIGHTS

- We visualize where neutrinos **decouple** from the fluid which is the regime where simulations are most sensitive to **reaction rates**.
- **Pair production/annihilation** and **bremsstrahlung** have important contributions to the evolution of heavy lepton neutrinos at low and high densities, respectively.
- At high densities and low temperatures, **scattering on both neutrons and protons** need to be considered.
- **Inelastic scattering of electrons** significantly shifts the **thermalization neutrinosphere.**

## WHAT'S NEXT?

- Incorporation of **muonic evolution ($Y_\mu$)** in SpEC along with appropriate **muonic interaction channels**.
- Investigation of **many body effects** to opacities.
- Always in search of missing neutrino physics.

REACTION ANALYSIS

SIMULATION DETAILS

# THANKS!

# BACKUP SLIDES

## HOW CAN WE UNDERSTAND THESE REACTIONS?

Neutrino interactions are quantified through **opacities.**

$$\boxed{\lambda_\nu = \frac{1}{\kappa}}$$

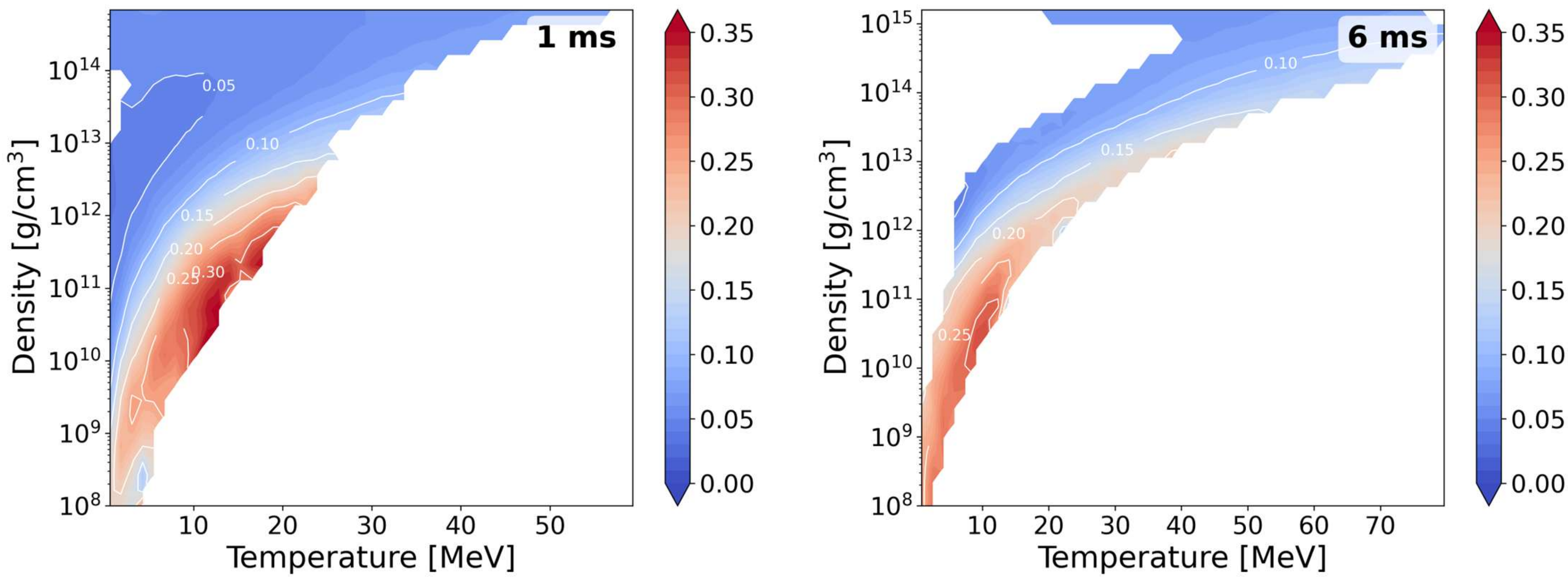
The **neutrinosphere** marks the transition between:
**trapped neutrinos** - - - - - - - - - - - - -► **free streaming neutrinos**


**ASSESSING IMPORTANCE OF REACTION**

***Is it significant at the position of the neutrinosphere?***

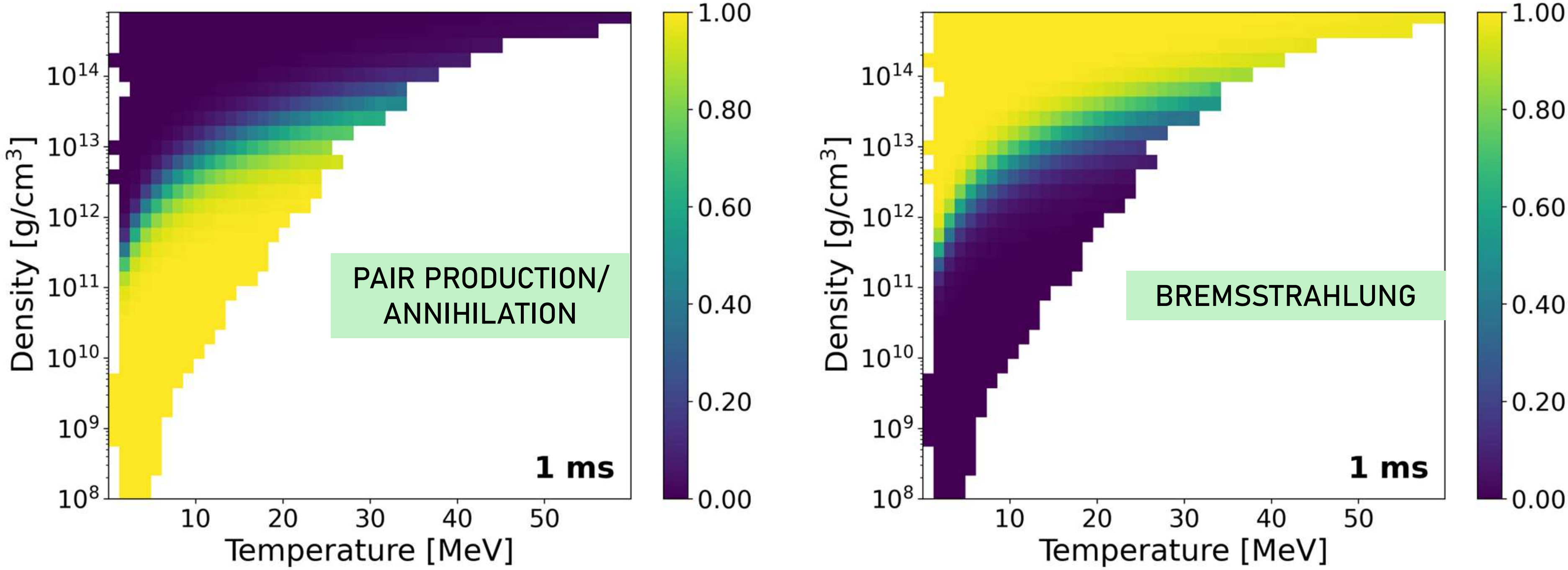
- Identify regions where neutrino mean free path becomes comparable to **1km**.
- Approximate indicator for change in remnant properties.
- Marks the decoupling region, which is where simulations are most sensitive to reaction rates

# DISTRIBUTION OF ELECTRON FRACTION: $Y_e$ in $\rho - \mathrm{T}$ PLANE



# WHICH REACTIONS MATTER?

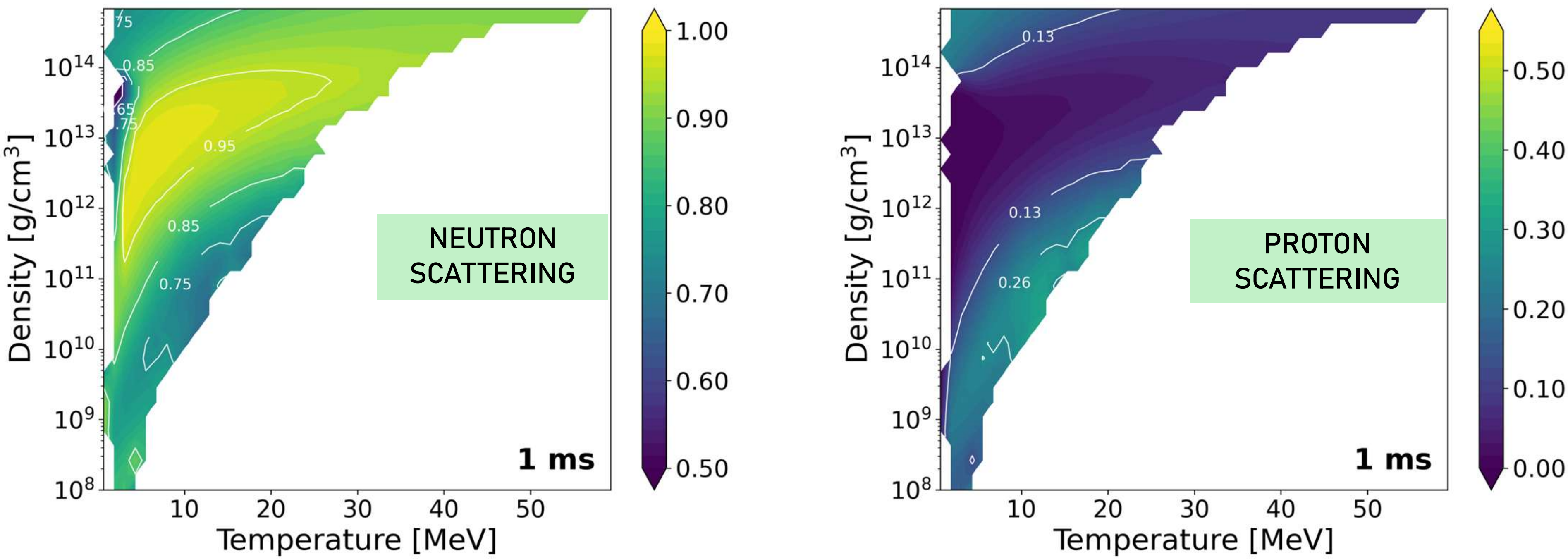
# FINDING $\frac{\kappa_{reaction}}{\kappa_{absorption}}$




Pair production/annihilation and Bremsstrahlung have important contributions to the evolution of heavy lepton neutrinos at low and high densities, respectively.

# WHICH REACTIONS MATTER?

# FINDING $\frac{\kappa_{reaction}}{\kappa_{\text{scattering}}}$




At high densities and low temperatures, scattering on both neutrons and protons need to be considered.

# OUT OF EQUILIBRIUM EFFECTS