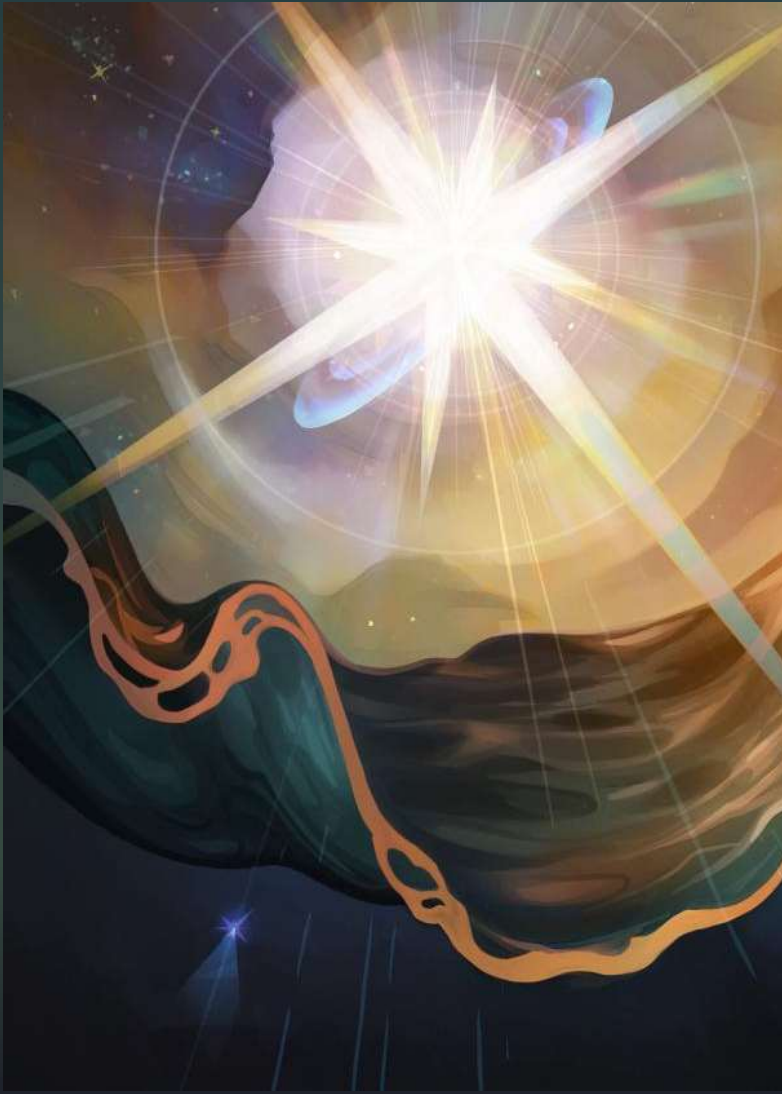


An artistic rendering of a neutron star merger. Two neutron stars, depicted as blue and purple spheres, are shown in the process of colliding. A bright, multi-pointed starburst of light emanates from the point of impact, with rays of light extending outwards. The background is a dark, swirling nebula with orange and yellow hues, suggesting a turbulent environment. The overall scene is set against a dark, starry space background.

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

Samantha Rath, Francois Foucart

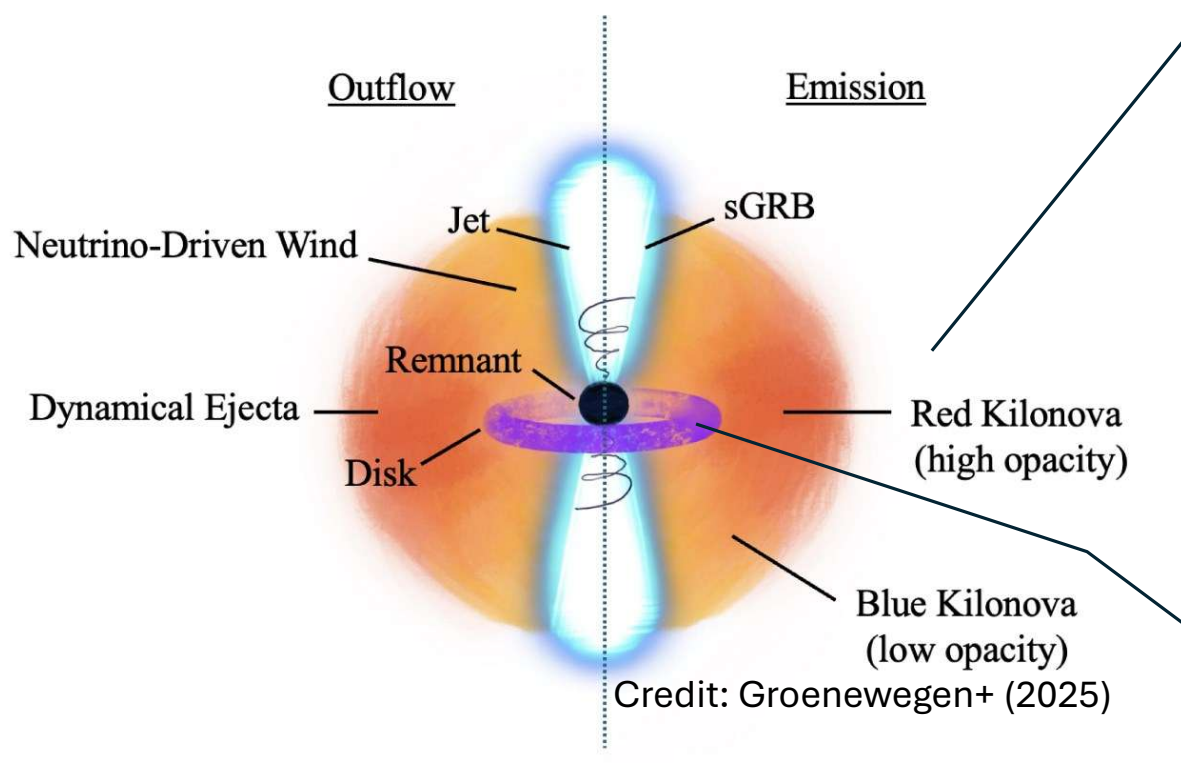


University of
New Hampshire



SIMULATING eXTREME SPACETIMES
Black holes, neutron stars, and beyond...

HOW DO NEUTRINOS INFLUENCE OBSERVABLES?

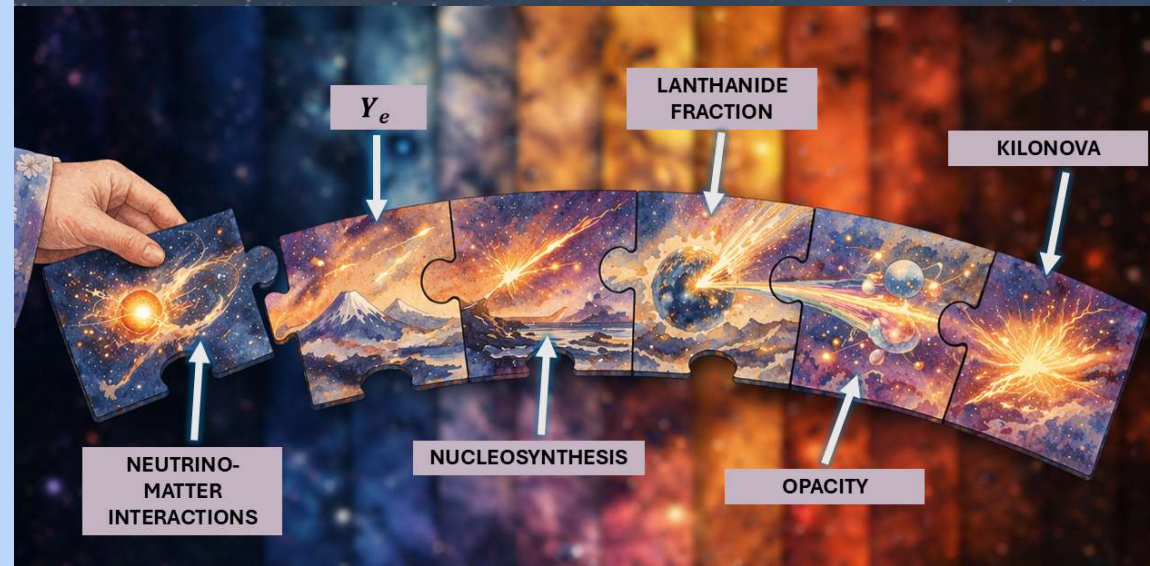


- KN properties are sensitive to the opacity of the ejecta to photons.
- This depends on the neutron-richness of the ejecta.
- **Neutrino-matter interactions are largely responsible for setting this composition via changes in Y_e .**

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

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

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

Pair processes

$$e^+ + e^- \leftrightarrow \nu + \bar{\nu}$$

$$N + N \leftrightarrow N + N + \nu + \bar{\nu}$$

Scattering

On nucleons and nuclei (nearly elastic)

Electrons (inelastic)

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

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.

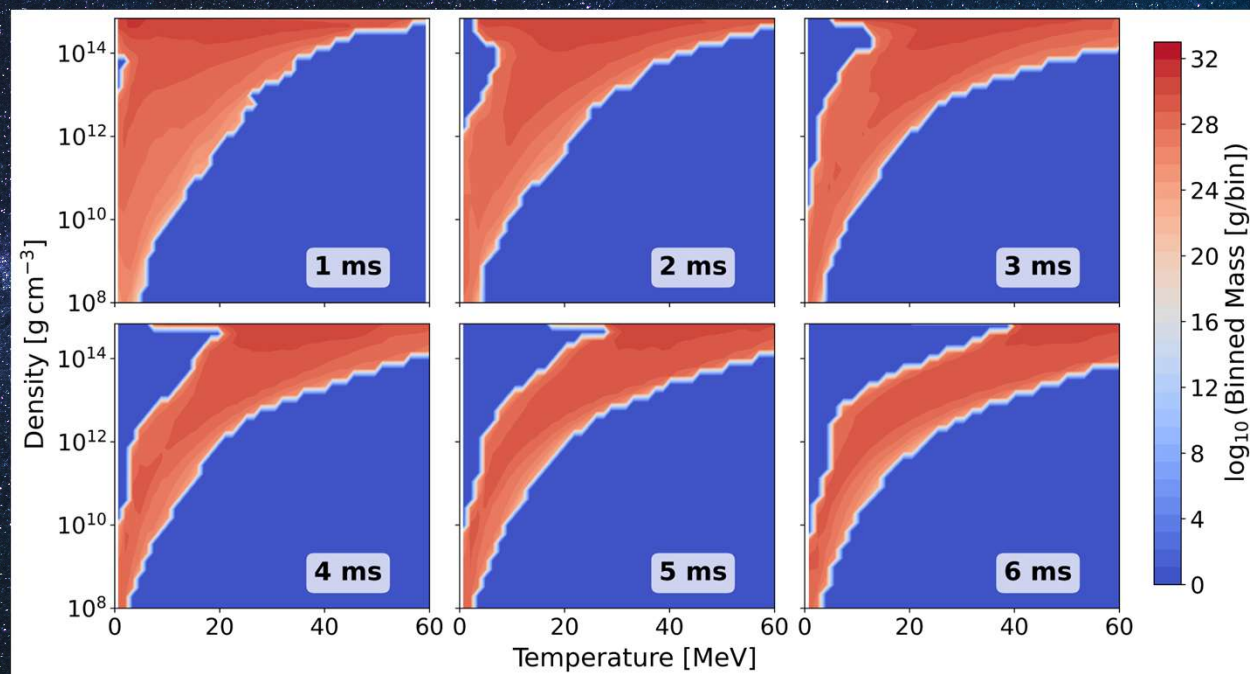
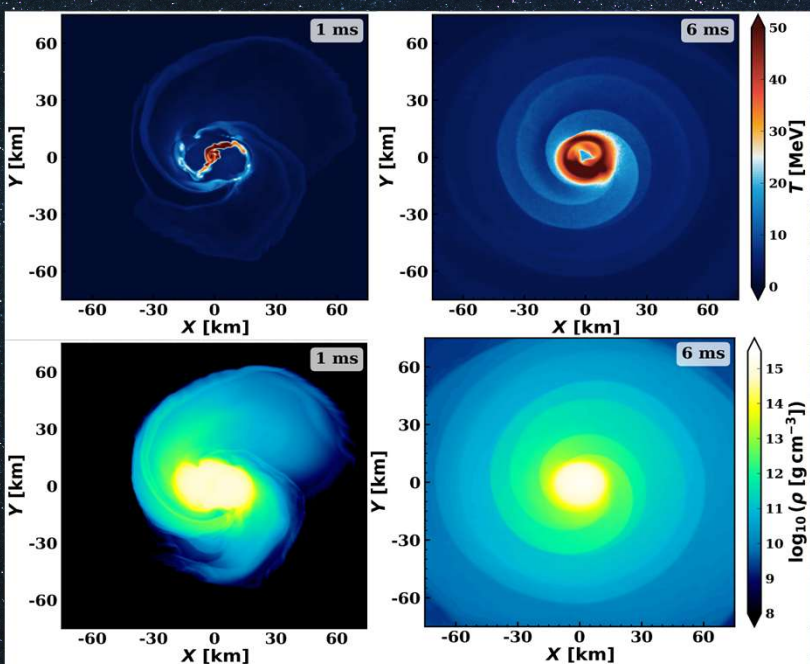
NOTATION: ν_e ELECTRON NEUTRINO; $\bar{\nu}_e$ ELECTRON ANTINEUTRINO; ν_x HEAVY LEPTON NEUTRINO ($\nu_\mu + \nu_\tau +$ ANTIPARTICLES)

POST-PROCESSING A MONTE CARLO SIMULATION SNAPSHOT

REMEMBER ALBINO'S
LECTURE

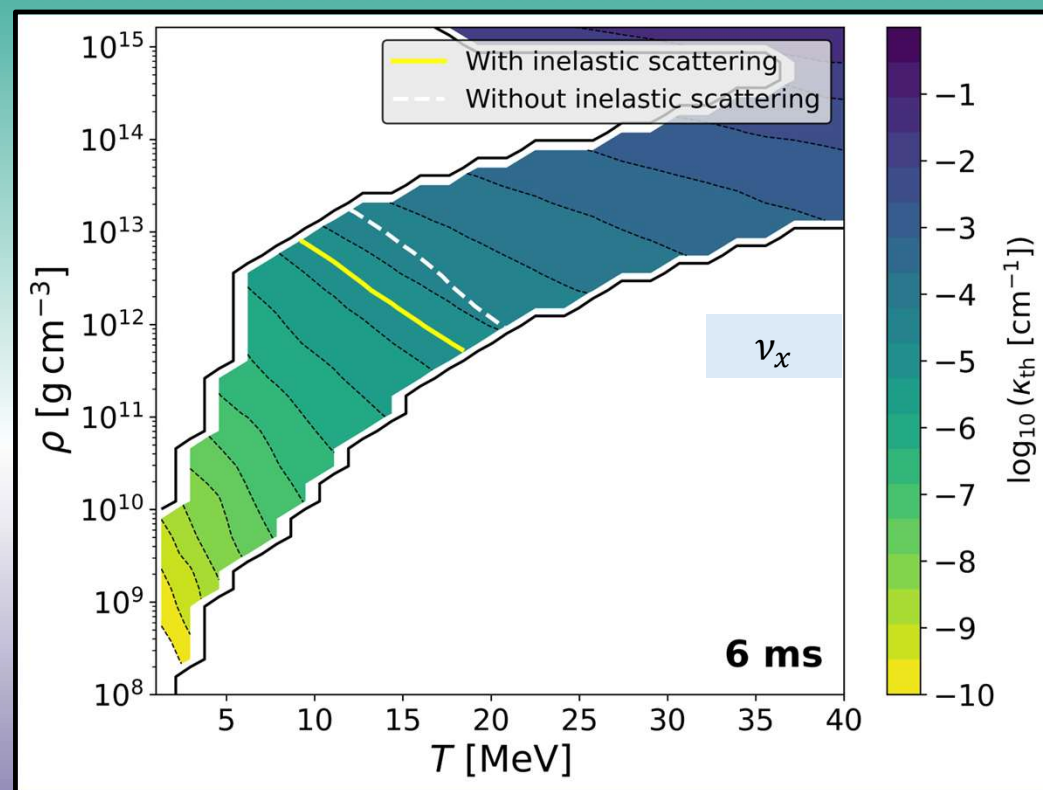
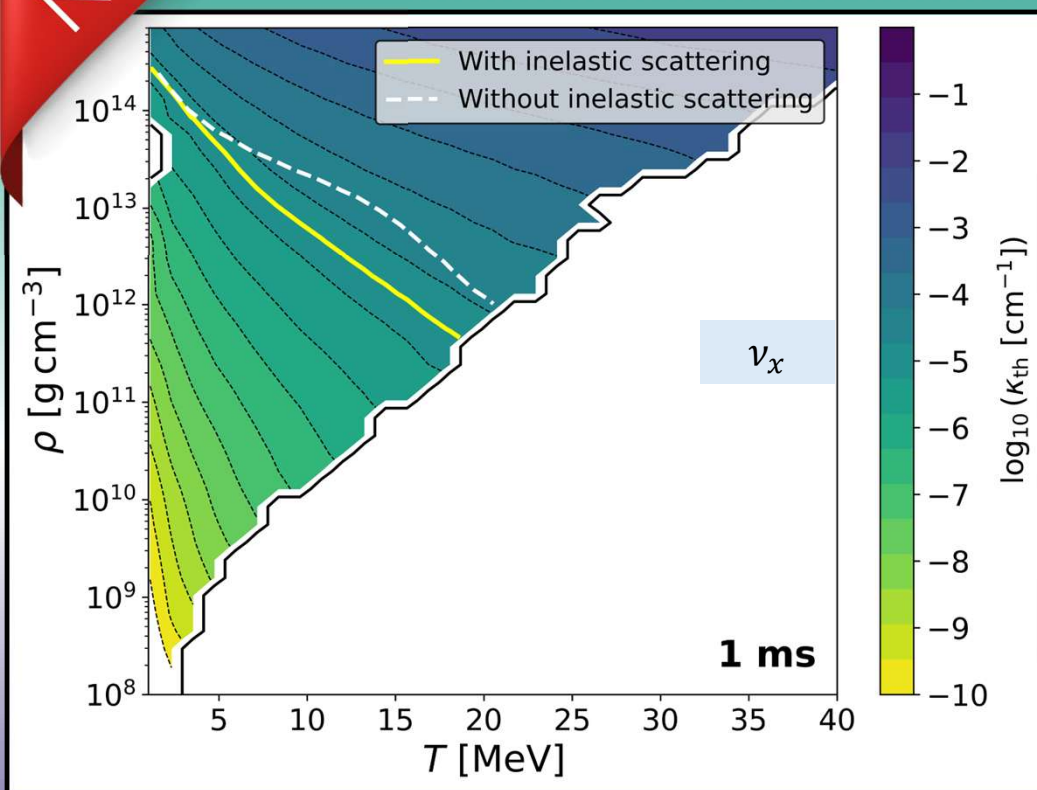
SPATIAL PROFILES

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 ($\Upsilon\mu$)** 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!

The background of the slide features a soft, painterly illustration of a mountain range. The mountains are depicted in various shades of blue and green, with the foreground peaks being more saturated and the distant ones fading into a light blue haze. The sky above is a warm, pale yellow, suggesting a sunrise or sunset. The overall style is calm and atmospheric.

BACKUP SLIDES

HOW CAN WE UNDERSTAND THESE REACTIONS?

Neutrino interactions are quantified through **opacities**.

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

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

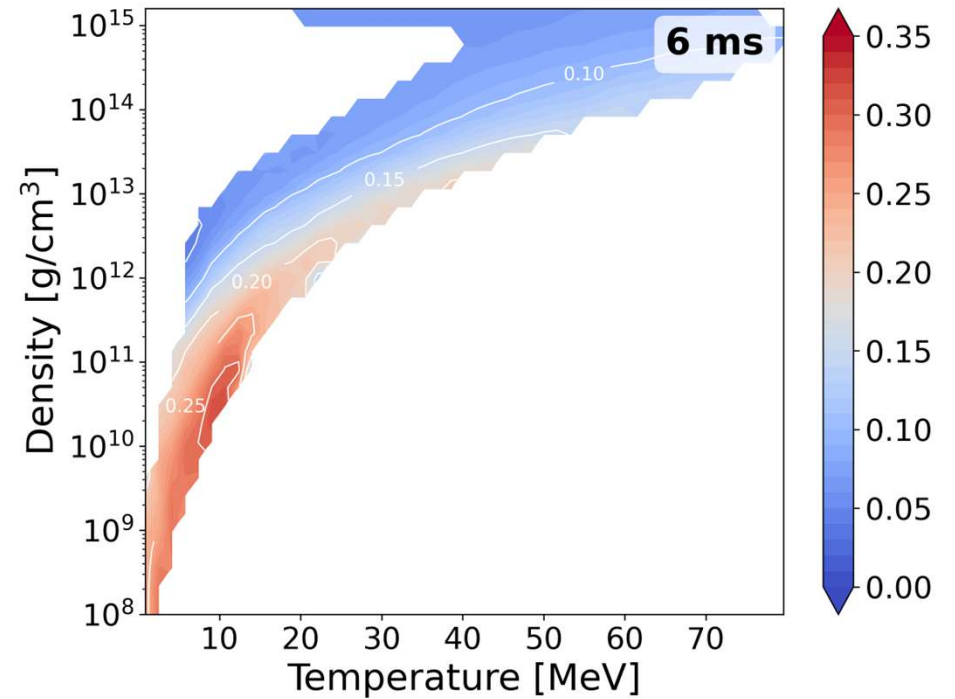
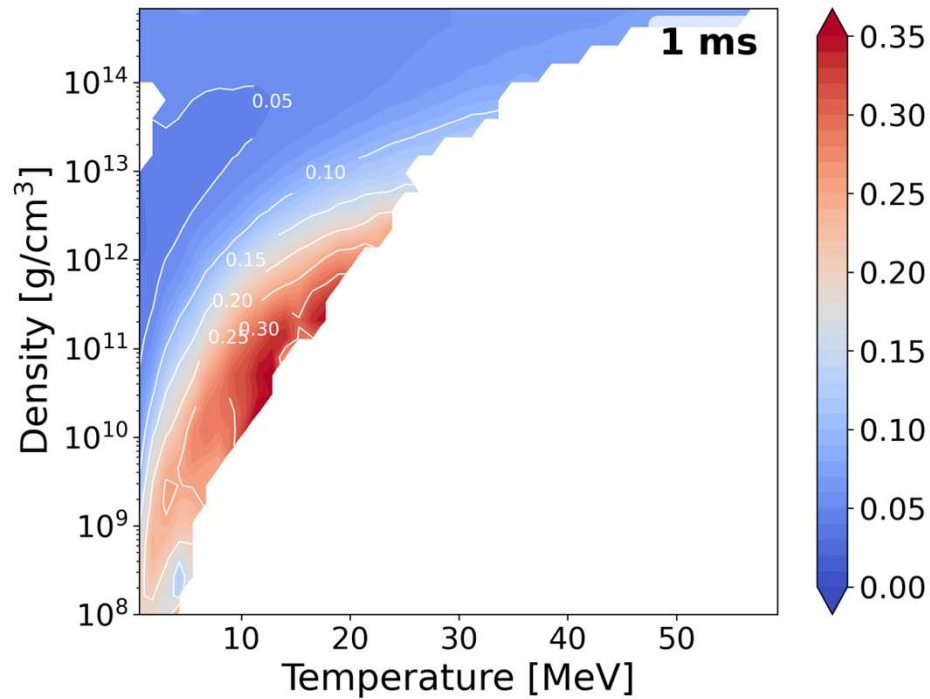


ASSESSING IMPORTANCE OF REACTION

Is it significant at the position of the neutrinosphere?

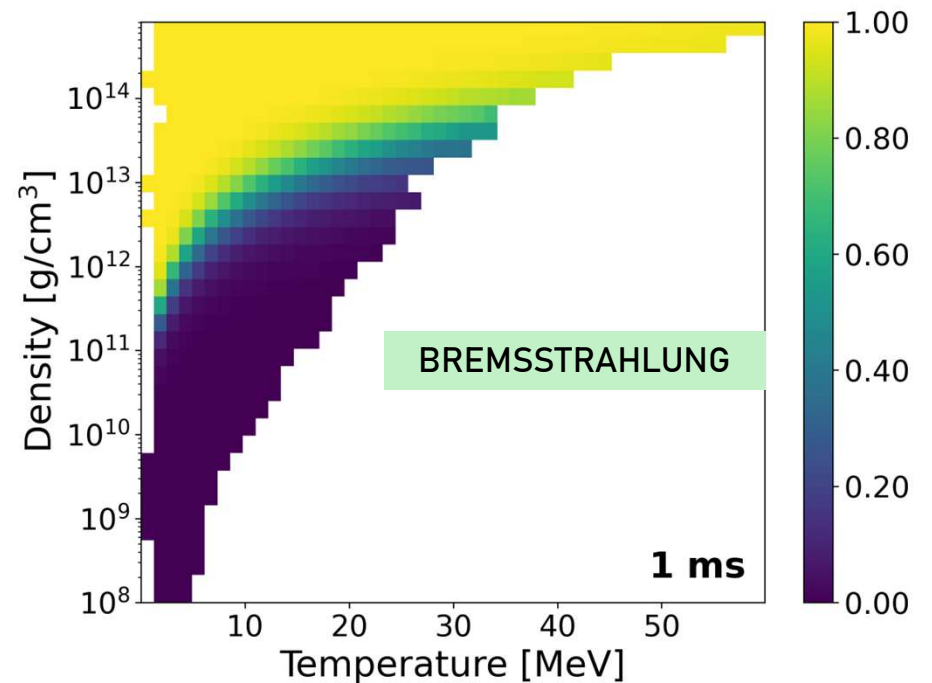
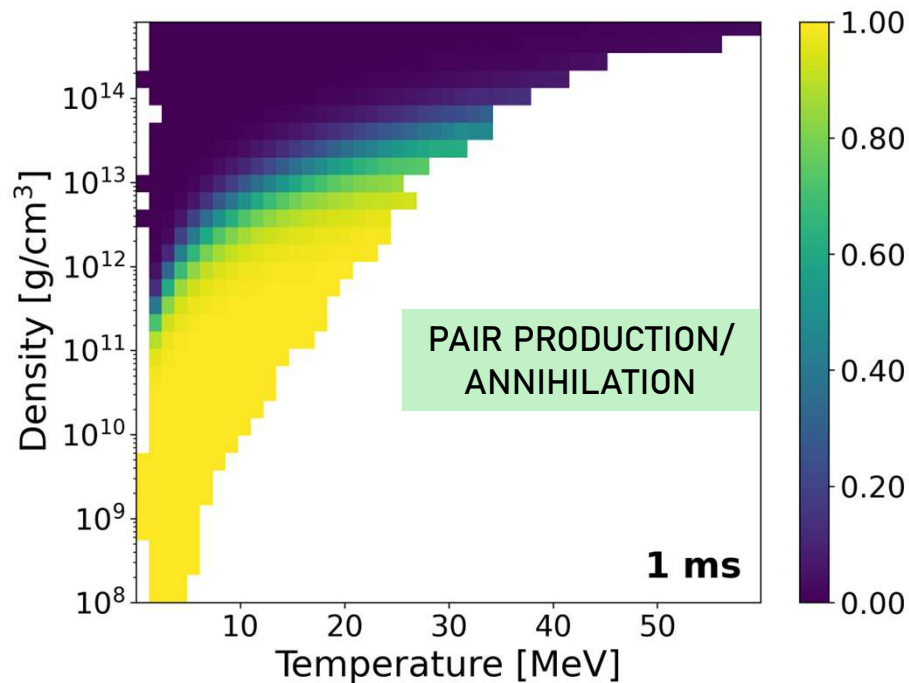
- Identify regions where neutrino mean free path becomes comparable to **1km**.
- Approximate indicator for change in remnant properties.
- Marks the decoupling region, which is where simulations are most sensitive to reaction rates

DISTRIBUTION OF ELECTRON FRACTION: Y_e in $\rho - T$ PLANE



WHICH REACTIONS MATTER?

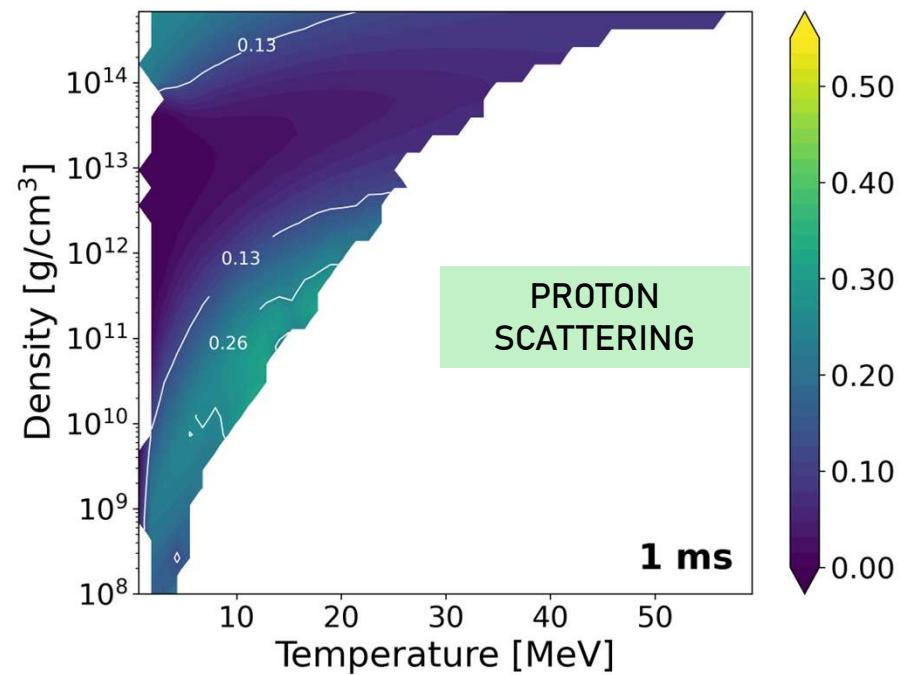
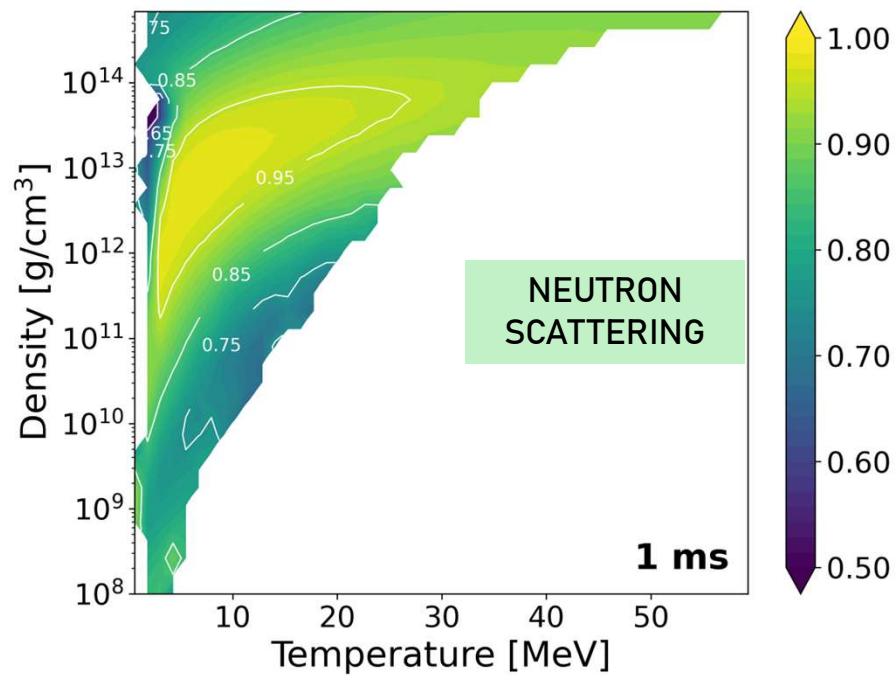
FINDING $\frac{\kappa_{\text{reaction}}}{\kappa_{\text{absorption}}}$



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



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

OUT OF EQUILIBRIUM EFFECTS

