Thermal Effects in Binary Neutron Star Merger Simulations

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Outline

- What can we learn from BNS merger simulations?
- What happens to β-equilibrium at $T > 0$?

Our Simulation

- We use the APR EoS[1].
- Table has 3 parameters: rest mass density ρ, temperature T, and electron fraction Y_e.
- LORENE[2] initial data solver requires effective barotropic EoS → impose constant temperature and β-equilibrium.
- We use the Einstein Toolkit[3] for evolution.
- Y_e advected with fluid.
- Our simulation does not contain: magnetic fields, reactions, or neutrinos.

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[1] Akmal, Pandharipande, and Ravenhall 1998; Schneider et al. 2019.

[2] Gourgoulhon, Grandclément, and Novak accessed 2021.

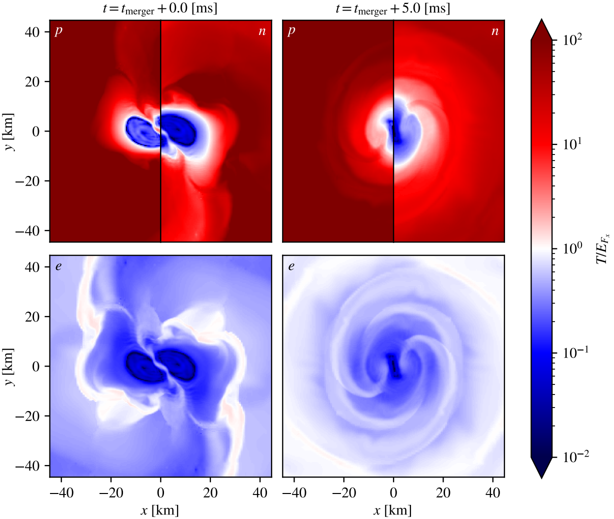
[3] Etienne et al. accessed 2021.

Simulation Results

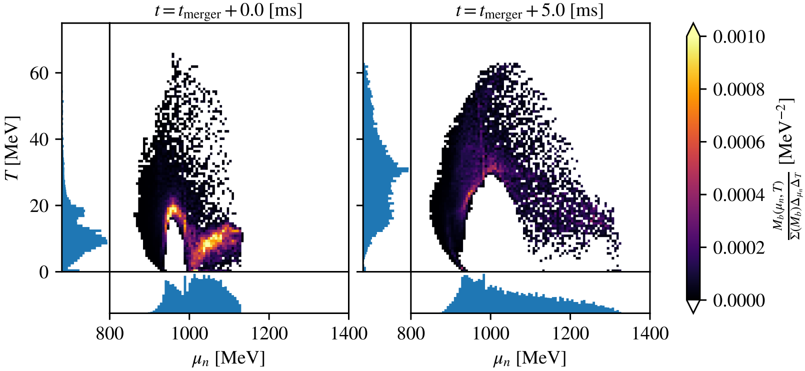
What do we learn from our simulation?

Species Degeneracy

- $T/E_{F_x} \gg 1 \Rightarrow$ non-degenerate matter.
- $T/E_{F_x} \ll 1 \Rightarrow$ strongly degenerate matter.



μ_n-T Phase Diagram



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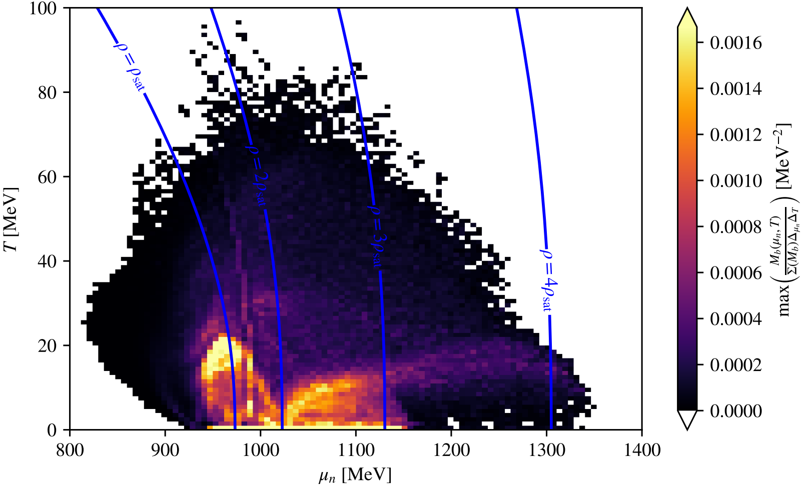

Bulk Viscosity

- Typically thought of as resonant phenomenon, important when equilibriation and dynamical motion timescales are similar[4].
- Perturbative calculations[5] give periodic solution in terms of

$$\mathcal{A} = \frac{\mu_\Delta}{T}, \tag{1}$$

where $\mu_\Delta = \mu_n - \mu_p - \mu_e$ is deviation from β-equilibrium.
- Sub-thermal limit, $|\mathcal{A}| \ll 1$, allows analytic solution.
- Supra-thermal limit, $|\mathcal{A}| \gg 1$, and general solution more difficult.

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[4] Schmitt and Shternin 2018.

[5] Alford, Mahmoodifar, and Schwenzer 2010.

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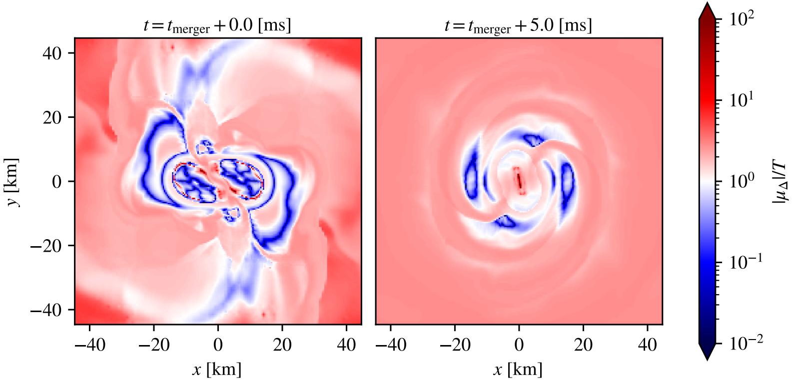

β-Equilibrium

What happens to β-equilibrium at $T > 0$?

β-Equilibrium at $T > 0$

- Balancing direct and modified Urca electron capture and neutron decay processes, ignoring neutrinos, gives

$$n \leftrightarrow p + e. \tag{2}$$

- Direct Urca reaction rates below a threshold density are Boltzmann suppressed by a factor of $\exp\left(-\left|\gamma_{\mathrm{i}}\right|/T\right)$, where γ_{i} is an energy requirement associated with each reaction.
- For neutron decay, this is $\gamma_{\mathrm{nd}} = 20 - 25\mathrm{MeV}$, whereas for electron capture it is $\gamma_{\mathrm{ec}} = 10 - 15\mathrm{MeV}$[6].
- At $\mu_n = \mu_p + \mu_e$ there is now net production of neutrons.
- Introduce μ_δ to balance $\Gamma_{\mathrm{nd}} = \Gamma_{\mathrm{ec}}$ giving equilibrium condition

$$\mu_n = \mu_p + \mu_e + \mu_\delta. \tag{3}$$

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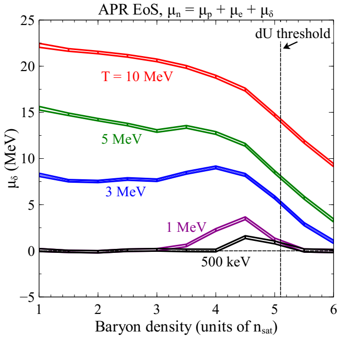
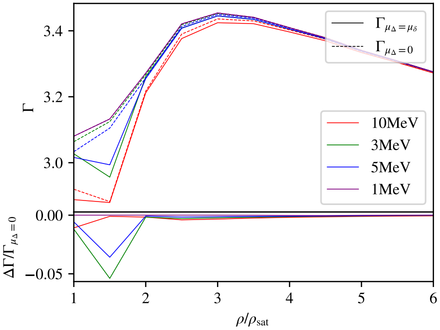
[6] Alford and Harris 2018.

β-Equilibrium at $T > 0$

- μ_δ can reach tens of MeV at $T = 10\text{MeV}$[7].
- This can lead to softening of the EoS by up to $\sim 5\%$.





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[7] Alford and Harris 2018.

Neutrino Effects

- At high temperatures the fluid becomes opaque to neutrinos, making them available for reactions.
- Now we have the 6 Urca processes and their exact inverses.
- The equilibrium condition then becomes

$$\mu_n + \mu_{\nu_e} = \mu_p + \mu_e. \tag{4}$$

- It is difficult to say exactly where neutrinos are able to react.
- Neutrinos are considered trapped on a length scale L when $L/\ell_{\mathrm{ab}} = \kappa_{\mathrm{ab}} L \gtrsim 1$.
- We use NuLib[8] to calculate opacities with neutrinos in thermal equilibrium.
- Simulation has two relevant length scales: the grid spacing Δx, and the radius of hot matter $r_{\mathrm{hot}} \sim 100\Delta x$.

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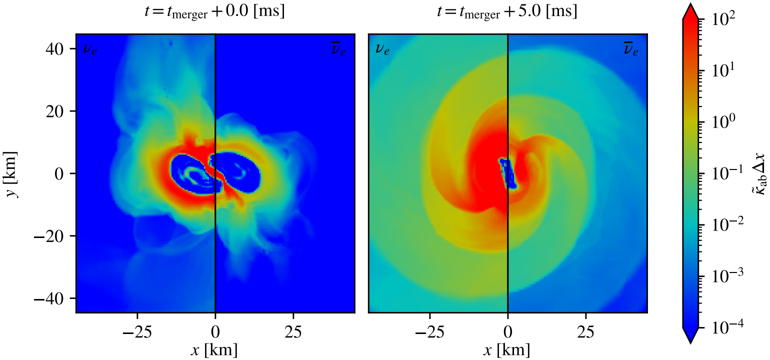
[8] O'Connor and Sullivan accessed 2021.

Neutrino Effects

- Where $\tilde{\kappa}_{\text{ab}}\Delta x \gg 10^0$ the neutrinos are locally trapped.
- Where $\tilde{\kappa}_{\text{ab}}\Delta x \ll 10^{-2}$ the neutrinos will escape the simulation.
- In the intermediate regime it is difficult to say without direct simulation of the neutrinos.



Summary

- Finite temperature effects enter not just through the EoS.
- Important for reactions/neutrinos/bulk viscosity.
- Normal β-equilibrium condition breaks down at $T \gtrsim 1\text{MeV}$.
- Different equilibriation regimes important under different conditions.
- Fore et al.[9] also suggest thermal pions can equilibriate matter via the strong force where $T \gtrsim 25\text{MeV}$.
- Difficult to say exactly which regime dominates where.

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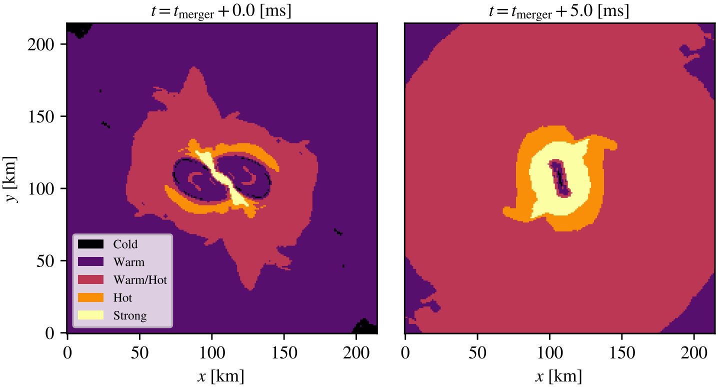
[9] Fore and Reddy 2020.

Conclusion

- Difficult to say exactly which regime dominates where.



References

Akmal, A., V. R. Pandharipande, and D. G. Ravenhall (1998). "Equation of state of nucleon matter and neutron star structure". In: *Phys. Rev. C* 58, pp. 1804–1828. DOI: 10.1103/PhysRevC.58.1804.

Alford, M. G. and S. P. Harris (2018). "β equilibrium in neutron-star mergers". In: *Physical Review C* 98 (6), p. 065806. DOI: 10.1103/PhysRevC.98.065806.

Alford, M. G., S. Mahmoodifar, and K. Schwenzer (2010). "Large amplitude behavior of the bulk viscosity of dense matter". In: *Journal of Physics G: Nuclear and Particle Physics* 37.12, p. 125202. DOI: 10.1088/0954-3899/37/12/125202.

Endrizzi, Andrea et al. (2020). "Thermodynamics conditions of matter in the neutrino decoupling region during neutron star mergers". In: *European Physics Journal A* 56.1, p. 15. DOI: 10.1140/epja/s10050-019-00018-6.

Etienne, Z. et al. (accessed 2021). *The Einstein Toolkit*. URL: http://einsteintoolkit.org/index.html.

Fore, B. and S. Reddy (2020). "Pions in hot dense matter and their astrophysical implications". In: *Physical Review C* 101 (3), p. 035809. DOI: 10.1103/PhysRevC.101.035809.

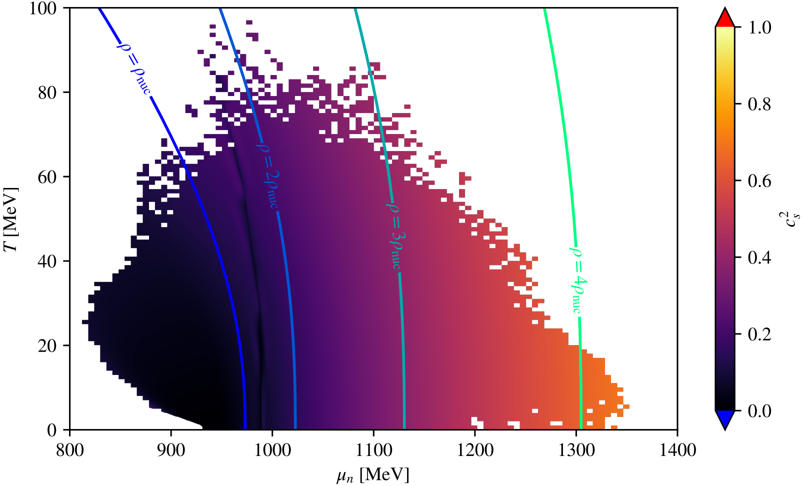
Gourgoulhon, E., P. Grandclément, and J. Novak (accessed 2021). *LORENE*. URL: https://lorene.obspm.fr/.

O'Connor, E. and C. Sullivan (accessed 2021). *NuLib open-source neutrino interaction library*. URL: https://github.com/evanoconnor/NuLib.

Schmitt, A. and P. Shternin (2018). "Reaction Rates and Transport in Neutron Stars". In: *Astrophysics and Space Science Library*. Ed. by L. Rezzolla et al. Vol. 457, p. 455. DOI: 10.1007/978-3-319-97616-7_9.

Schneider, A. S. et al. (2019). "Akmal-Pandharipande-Ravenhall equation of state for simulations of supernovae, neutron stars, and binary mergers". In: *Physical Review C* 100.2, p. 25803. DOI: 10.1103/PhysRevC.100.025803.

μ_n-T Phase Diagram



Neutrinos

- While not simulated, we can still calculate the mean free path ℓ of neutrinos.
- We use NuLib[10].
- Following Endrizzi et al.,[11] we assume a single energy for each species: $E\left(\nu_e\right) \approx 9\mathrm{MeV}$, $E\left(\overline{\nu}_e\right) \approx 15\mathrm{MeV}$.
- Here we ignore heavy lepton neutrinos.

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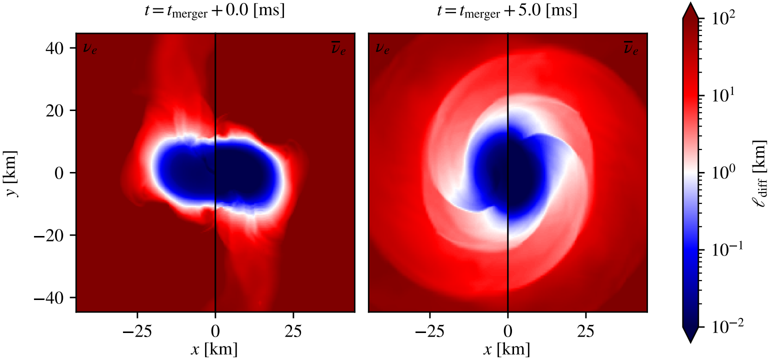
[10] O'Connor and Sullivan accessed 2021.

[11] Endrizzi et al. 2020.

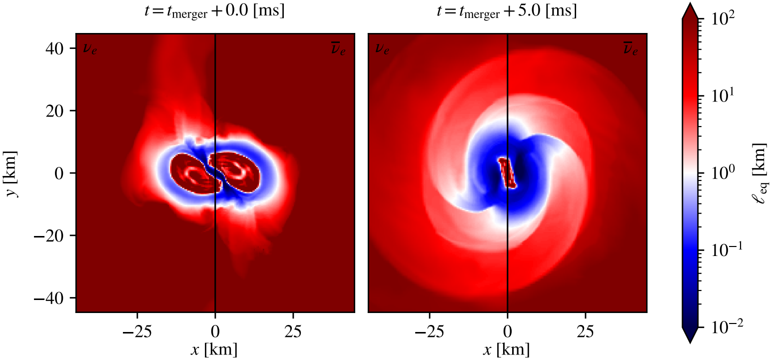
Neutrinos

- Diffusion mean free path ℓ_{diff} differentiates between diffusive and free-streaming regimes.



Neutrinos

- Equilibrium mean free path ℓ_{eq} denotes degree of thermal and compositional coupling between neutrinos and NS fluid.



Strong Interaction

- As temperature continues to increase, thermal pions may come into play.
- These equilibriate with the baryons through $\mu_n = \mu_p + \mu_{\pi^-}$, and the leptons through $\mu_{\pi^-} = \mu_\mu - \mu_{\nu_\mu}$.
- Baryon-pion reactions takes place on strong force timescale $t_{\text{strong}} \sim 10^{-23}\text{s} \rightarrow$ "instantaneous" equilibriation.
- Fore et al.[12] suggest thermal pions become relevant for $\rho = \rho_{\text{sat}}$ at $T \gtrsim 25\text{MeV}$.

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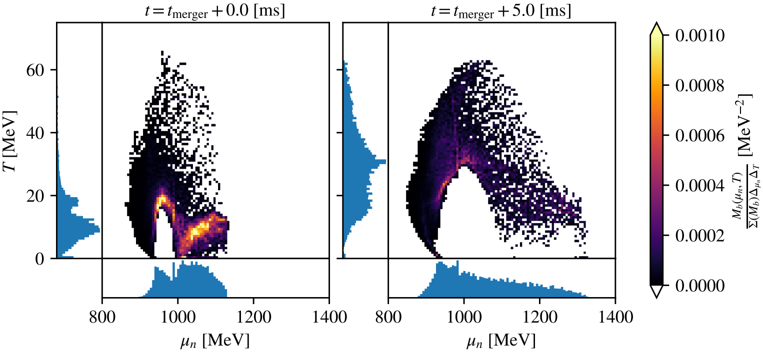
[12] Fore and Reddy 2020.

Strong Interaction

- Fore et al.[13] suggest thermal pions become relevant for $\rho = \rho_{\mathrm{sat}}$ at around $T \gtrsim 25\mathrm{MeV}$.



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[13] Fore and Reddy 2020.