Bulk Viscous Dissipation in Neutron Star Mergers:

Effect of Magnetic Field

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arXiv: 2409.09423, Tambe et. al. 2025 (in prep)

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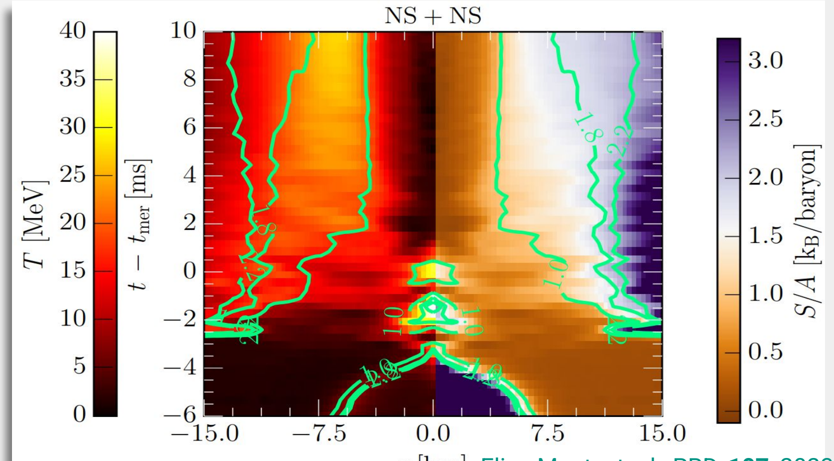
Nuclear Physics in Mergers - Going Beyond the Equation of State

9 September 2025, Seattle

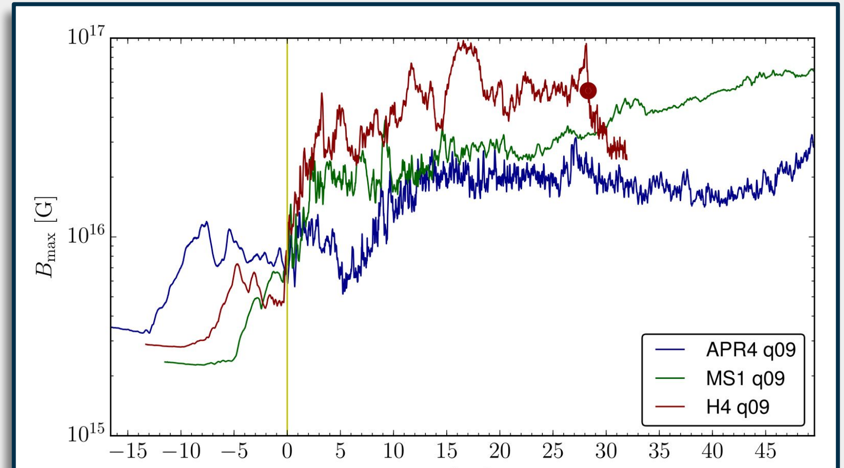
INT Workshop INT-25-94W

Motivation

To consistently compute transport properties in physical conditions relevant for BNS mergers.



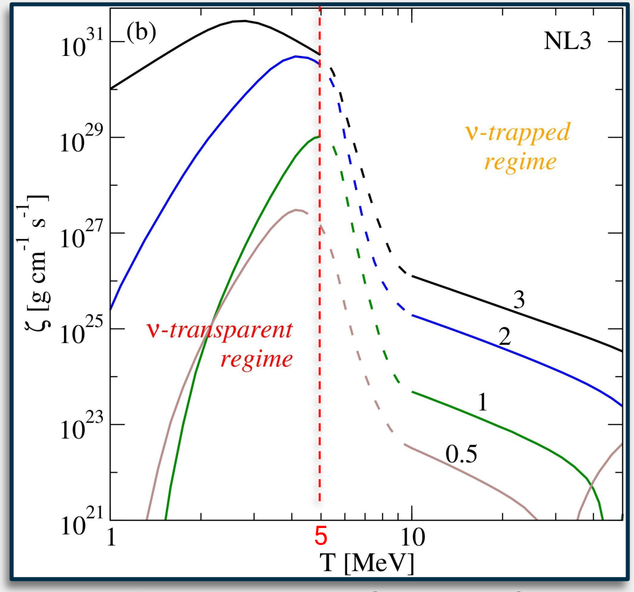
Elias Most. et. al., PRD, **107**, 2023



Ciolfi, R., et. al., PRD, **95**, 2017

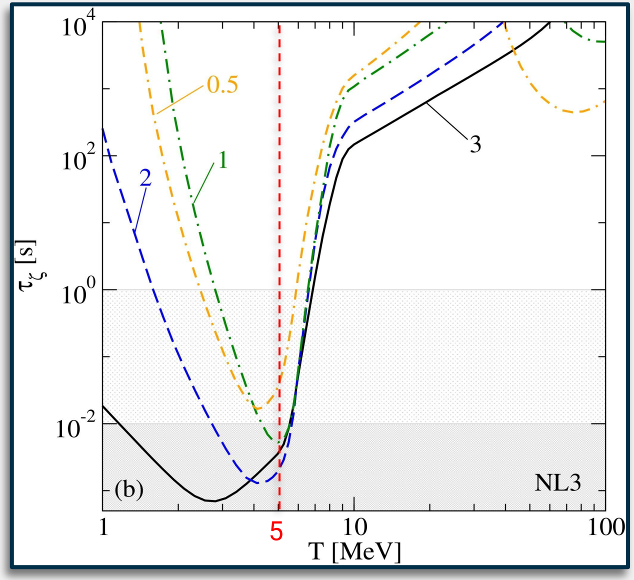
- T => a few MeV in the core of the remnant, with max as high as 40 MeV.
- B fields amplified in the postmerger to > 10^{16} G.

Motivation



Bulk Viscosity as a function of T

Alford et.al., Particles **3**, 2020



Damping timescale vs T

- For an estimate of bulk viscous dissipation, we need the isospin equilibration rates.
- Finite T effects cannot be neglected. Finite B field effects on equilibration rates?
- Consistently compute both finite T and B effects on the equilibrating processes.

Isospin equilibrating Processes

- Bulk viscosity arises from isospin equilibrating weak processes.
- For nuclear matter composed of n, p, e^- →
- DU allowed only if $\Delta k = k_{Fn} - k_{Fp} - k_{Fe} \leq 0$, or $x_p \geq 11\%$.
- Below DU threshold, MU processes bring equilibrium, extra nucleon → required momentum for reaction to proceed.
- DU faster than MU.
- For $T \leq 5$ MeV, neutrino transparent matter, nd and ec inverses of each other → isospin-equilibrium condition is $\mu_n = \mu_p + \mu_e$.

Direct Urca processes (DU)

$n \rightarrow p + e^- + \bar{\nu}_e$	Neutron decay (nd)
$p + e^- \rightarrow n + \nu_e$	Electron capture (ec)

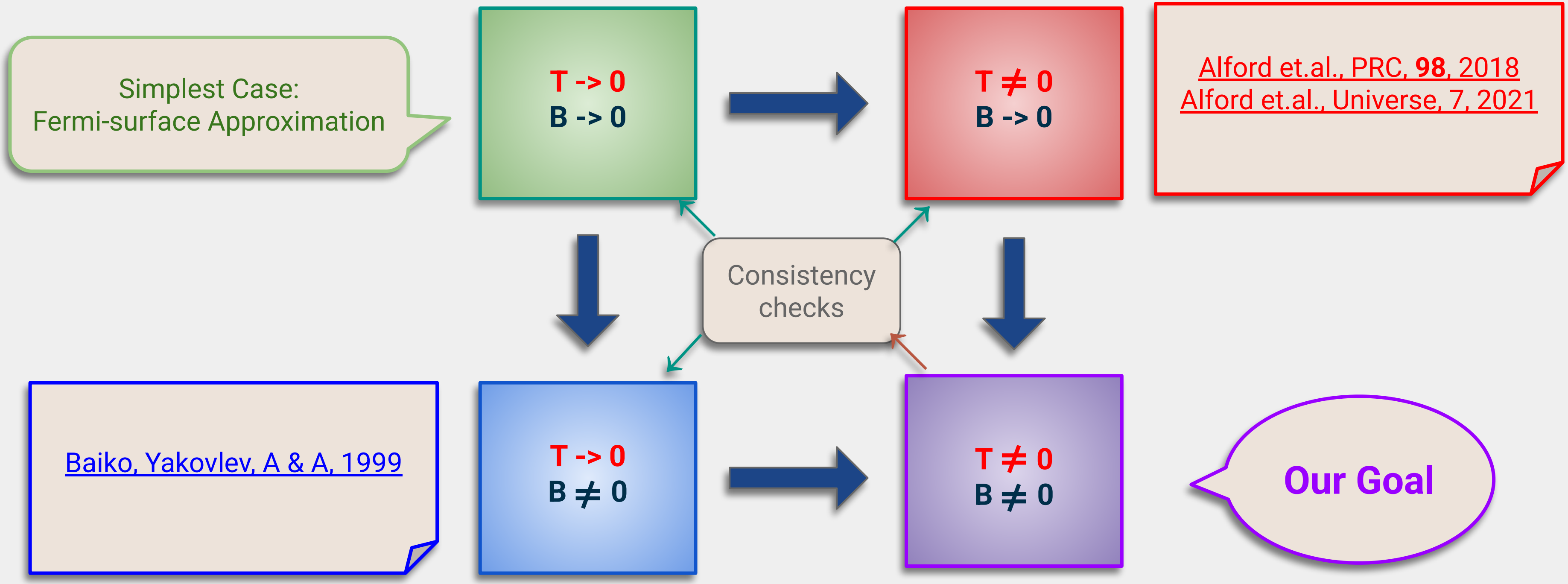
Modified Urca processes (MU)

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

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

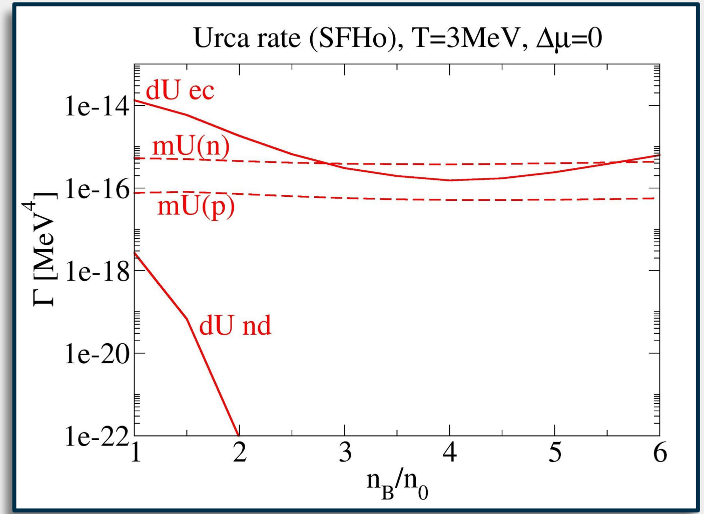
Here N can be either n or p

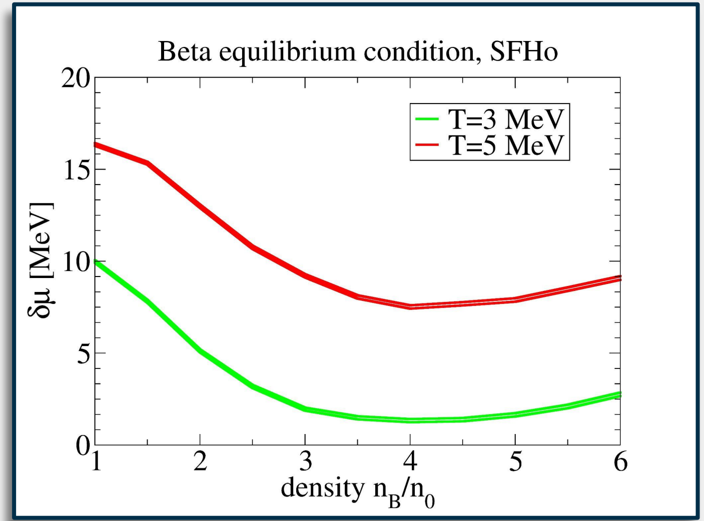
Current State of Research



Effects of finite temperature

c.f. Alford et.al., Universe, 7, 2021





- DU appear below threshold density ($k_{Fn} \leq k_{Fp} + k_{Fe}$).
- $\Gamma_{nd} \neq \Gamma_{ec}$ at ($\mu_n = \mu_p + \mu_e$) ⇒ Not the true equilibrium

- Finite correction to isospin-equilibrium condition,
  $\mu_n = \mu_p + \mu_e + \delta\mu$, $\delta\mu > 0$.
- $\delta\mu > T$ ➤ Cold equilibrium condition no more valid, $\mu_n \neq \mu_p + \mu_e$

Effect of magnetic field (w/o Thermal effects)

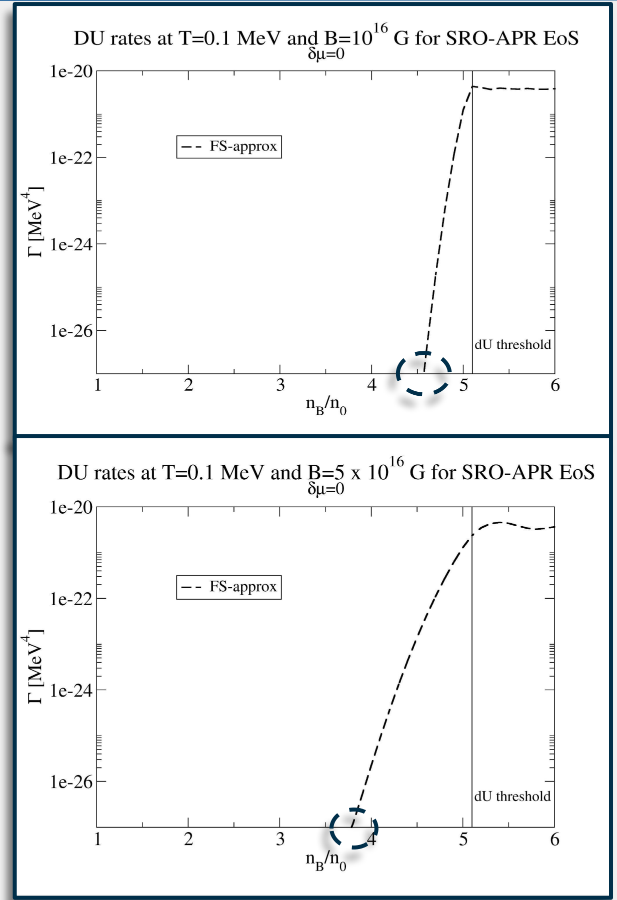
- Phase space of charged particles modified.
- The dU threshold condition $\Delta k = k_{Fn} - k_{Fp} - k_{Fe} \leq 0$, becomes less stringent.
- dU processes allowed for, $\Delta k \leq (N_{Fp})^{-2/3} \propto (B)^{2/3}$, start to appear even below the direct Urca threshold.

$$\Gamma_{\rm nd} = \Gamma_0(n_B,T)\Theta(k_{F_p}+k_{F_e}-k_{F_n}) \xrightarrow{B} \Gamma_{\rm nd} = \Gamma_0(n_B,T)R_B^{qc}$$

(Step function) (Continuous function)

$$R_B^{qc} = \int_{-1}^{1} d\cos\theta_p\, d\cos\theta_e\, k_{F_p}\, k_{F_e} \frac{F_{l,l'}^2(u)}{2b}\Theta(k_{F_n} - |k_{F_p}\cos\theta_p + k_{F_e}\cos\theta_e|)$$

- R_B^{qc} is non-zero below dU threshold.



Effect of magnetic field on rates at finite T

Details of the calculations of direct Urca rates in presence of magnetic field in our paper:
Tambe et. al., PRC **111**, 035809

- Effects above and below dU threshold have been studied.

- Two RMF EoS with and without a dU threshold.
  - TMA: DU threshold at $n_B \approx 2.1\ n_0$. (H. Toki et.al. Nucl. Phys. A, **588**, 1995)
  - QMC-RMF3: No DU threshold. (Alford et.al., PRC **106**, 2022)

PHYSICAL REVIEW C **111**, 035809 (2025)

Effect of magnetic fields on Urca rates in neutron star mergers

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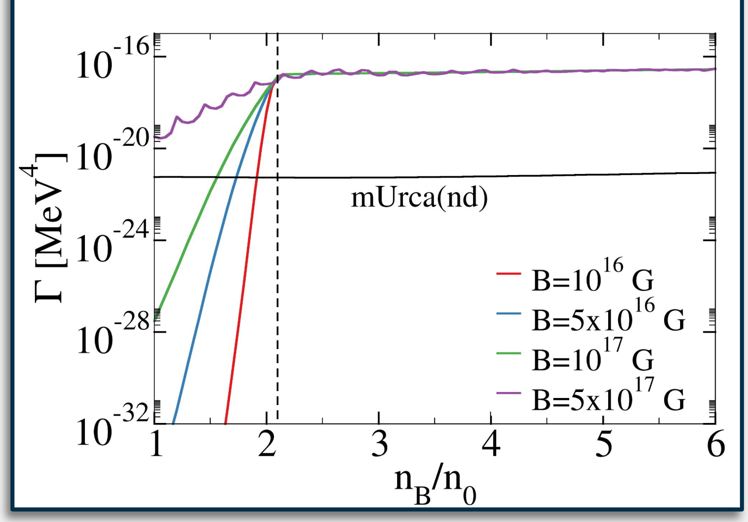
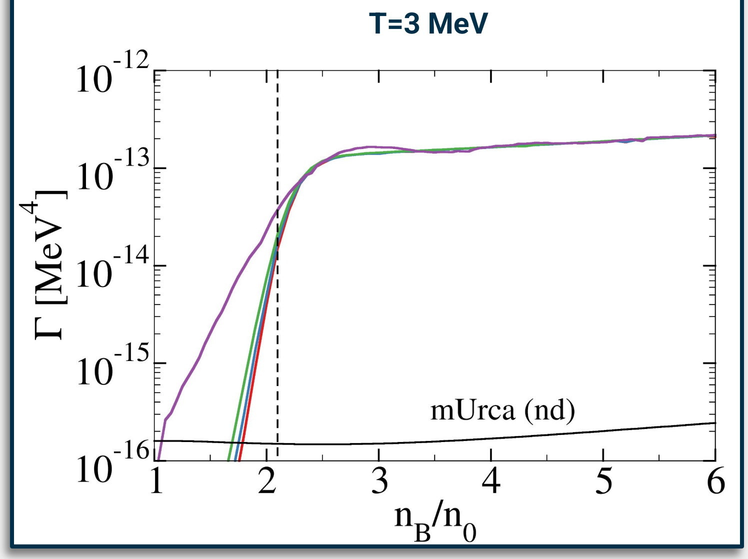
Direct Urca processes: Finite T and B

Tambe et. al., PRC **111**, 035809

- **TMA EoS**



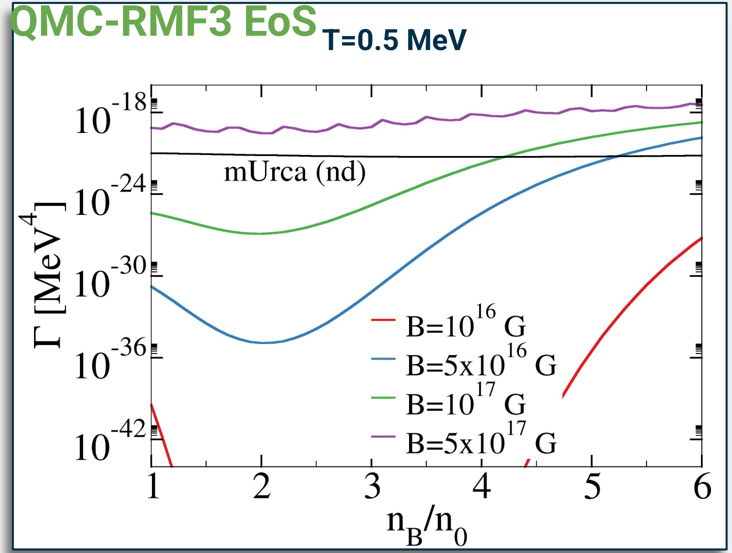


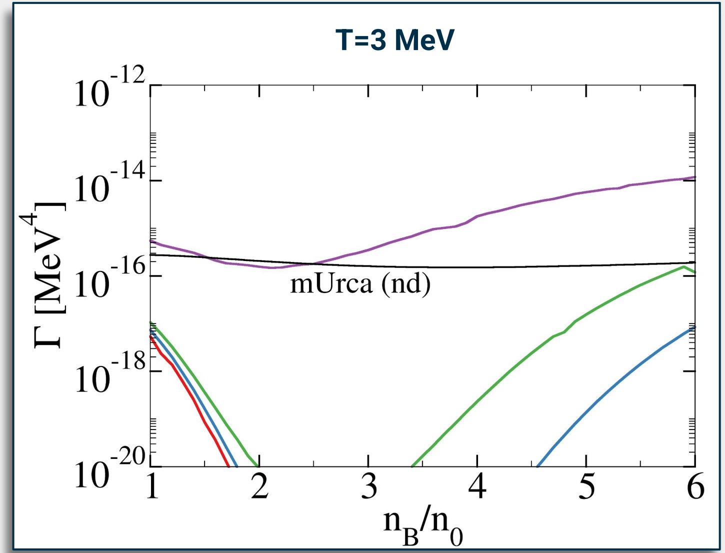
- Rates increase in presence of B below the DU threshold.
- Above dU threshold particles on the fermi-surface have max contribution, B field has no significant effects.
- At higher temperatures B field effects seem to have less significance.

Direct Urca processes: Finite T and B

Tambe et. al., PRC **111**, 035809

- QMC-RMF3 EoS



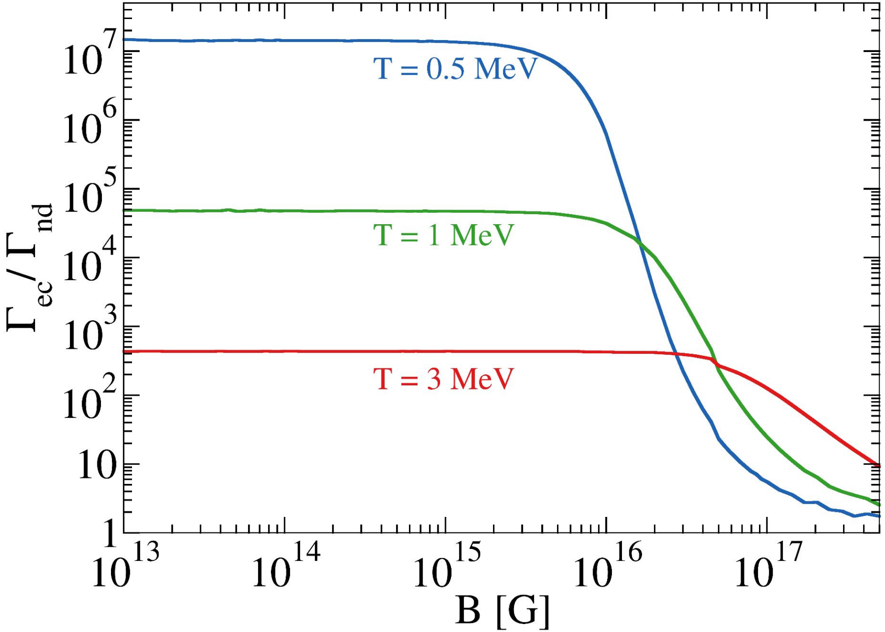


- No DU threshold within density of interest.
- B field effects much more significant.
- B field effects significant even at higher temperatures with nd rates increasing by orders of magnitude with higher B field.

Isospin equilibrium condition in presence of B

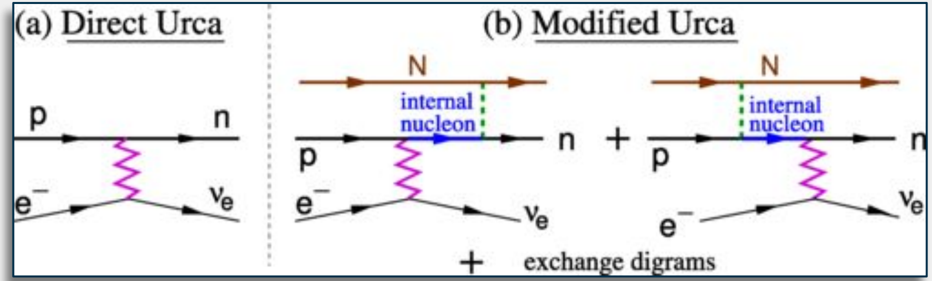
- n-decay rates increase significantly with B compared to e-capture rates.
- Difference b/w ec and nd rates reduce with B
- B fields expected to modify the finite T isospin-equilibrium condition: $\mu_n = \mu_p + \mu_e + \delta\mu$.
- To compute the true equilibrium we need magnetic field effects on total Urca rates.

Tambe et. al., PRC **111**, 035809



Nucleon Width Approximation

Modified Urca: First approximation to corrections due to strong interaction b/w reacting nucleons and medium



Alford. M., Haber. A., Zhang. Z., Phys. Rev. C **110**, L052801

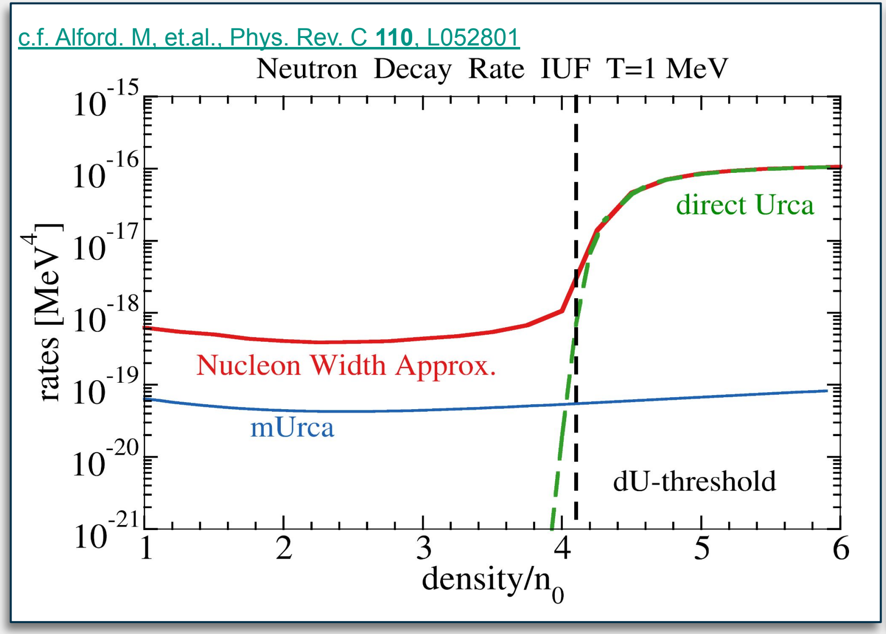
Traditional approach: Equilibrium ⇨ Direct Urca + Modified Urca

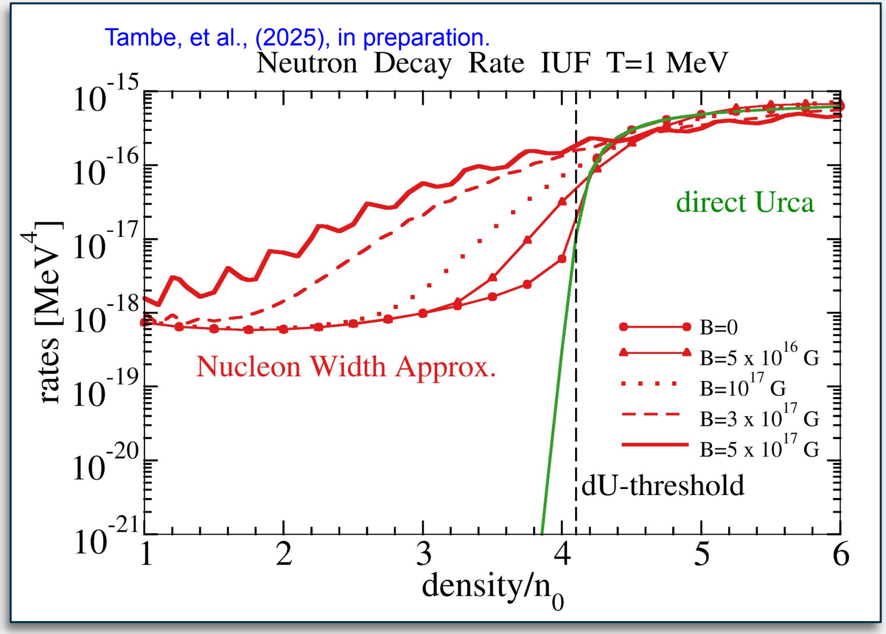
Nucleon Width Approximation: Nucleons have finite widths which accounts for correction due to strong interaction with the medium

$$\Gamma^{NWA} = \int_{-\infty}^{\infty} dm_n\, dm_p\, \Gamma^{dUrca}(m_n, m_p)\, R_n(m_n)\, R_p(m_p)\,,$$

$$R_N(m_N) = \frac{1}{\pi} \frac{W_N/2}{(m_N - M_N^*)^2 + W_N^2/4}$$

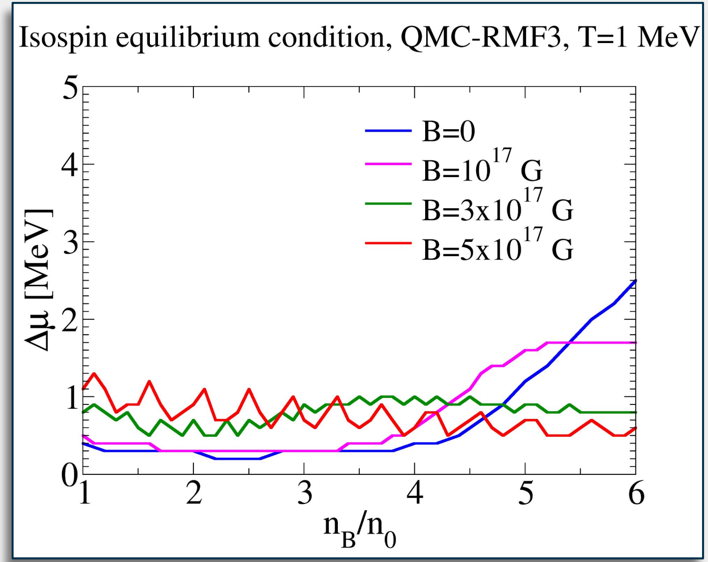
Urca rates in NWA at finite T and B

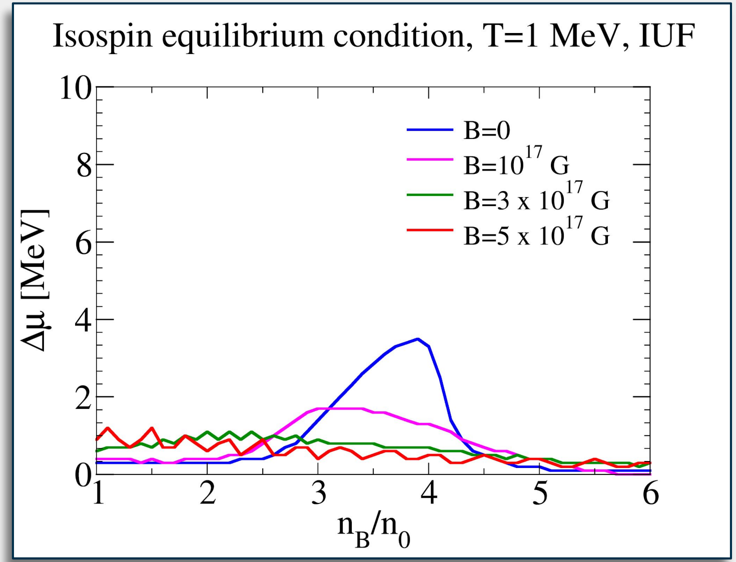




- Below threshold, NWA rates higher by an order of magnitude compared to mUrca.
- Above threshold NWA rates match smoothly to dUrca rates.
- Generalized to include magnetic fields with our previous calculations.
- Gives total Urca rates in the whole region of interest.

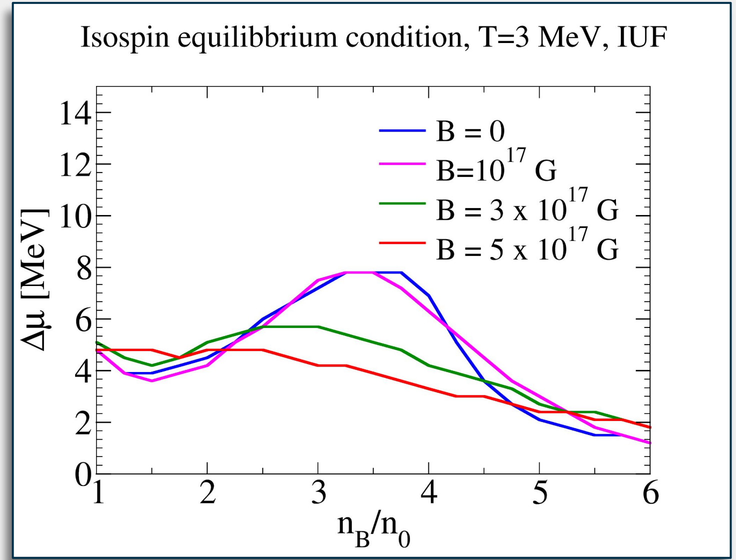
Isospin Equilibration at finite T and B

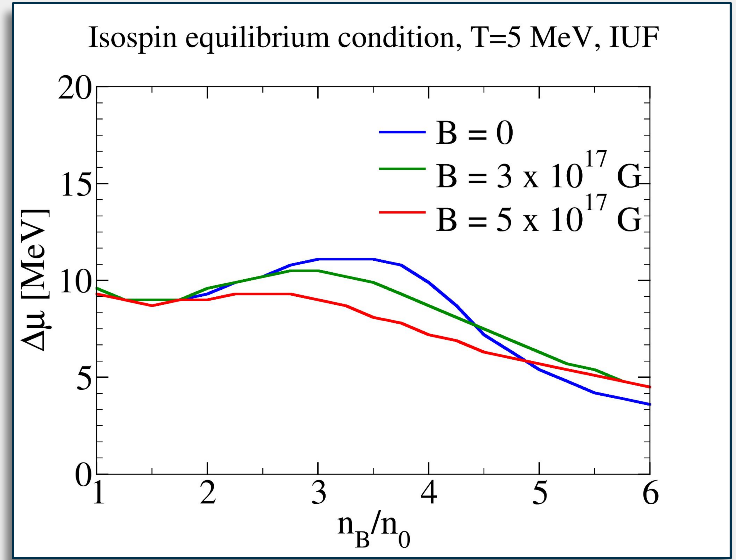




- The correction to isospin equilibrium condition $\delta\mu = \mu_n - \mu_p - \mu_e$ changes with field.

Isospin Equilibration at finite T and B

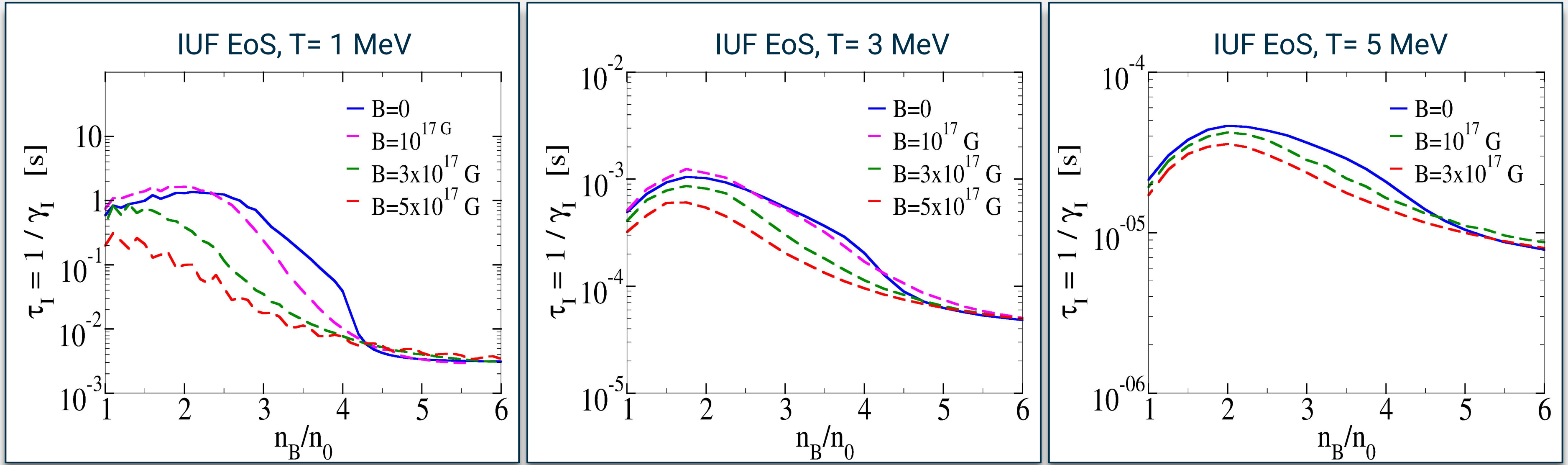




- B field effects wash out at higher T.

Isospin relaxation timescale

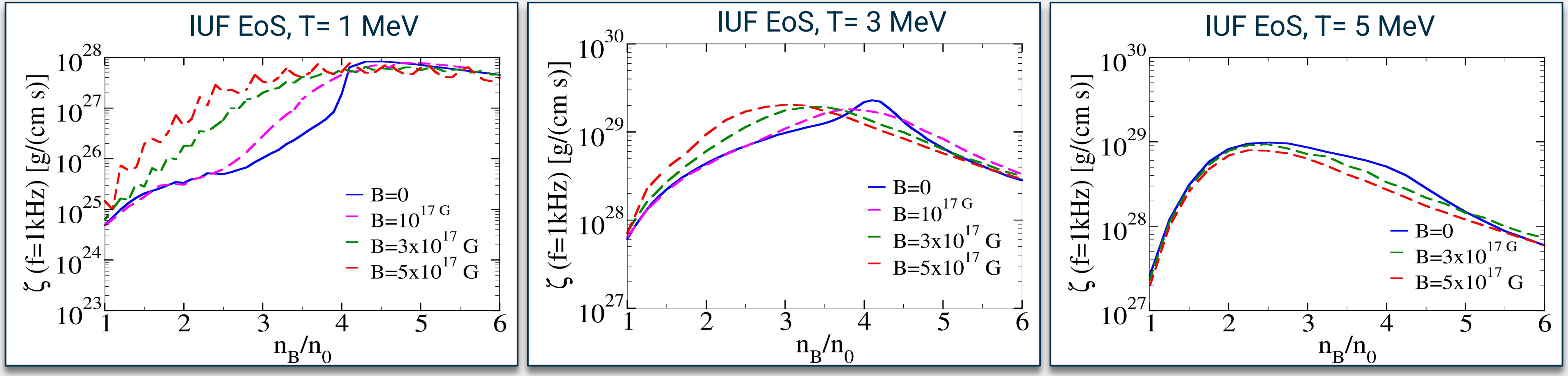
Tambe, et al., (2025), in preparation.



- Faster relaxation to equilibrium in presence of magnetic field because of increase in reaction rates.
- Bulk Viscosity maximum when $\tau_I \approx 1/\omega$, ω → angular frequency of oscillations
- In BNS mergers, relevant frequency of density oscillations → 1 kHz. BV max when $\tau_I \approx$ 0.2 ms.

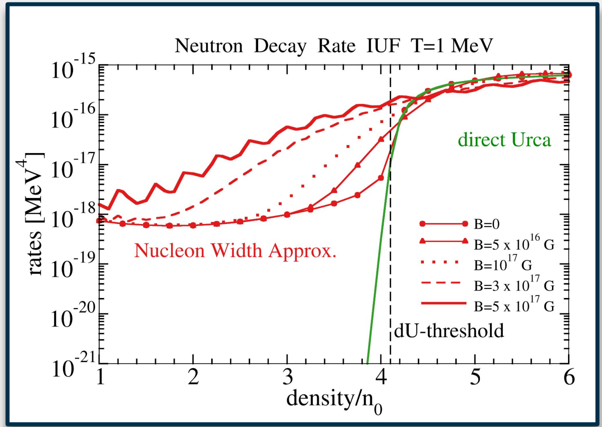
Bulk Viscosity

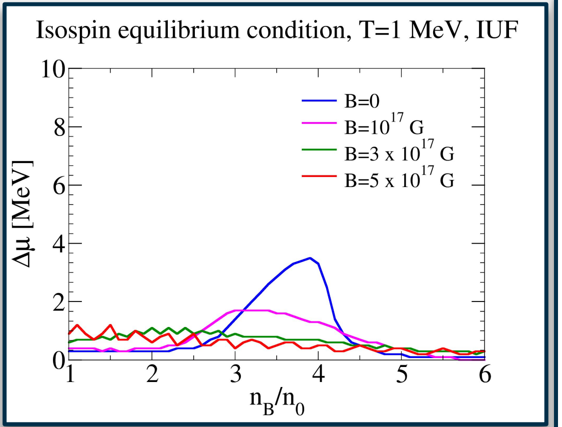
Tambe, et al., (2025), in preparation.

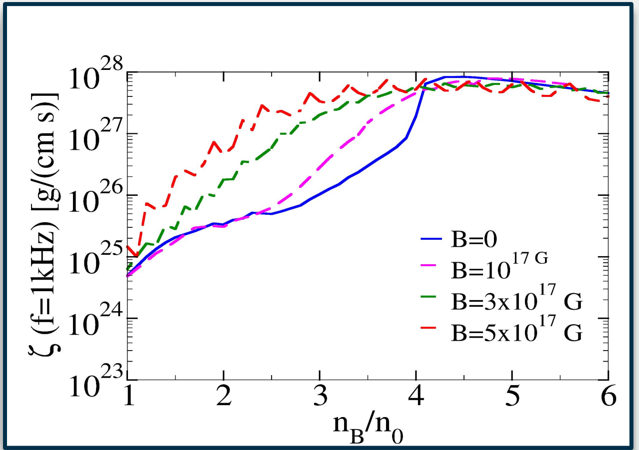


- Effect of magnetic field on Urca process significant at low n_B and low T.
- BV can be higher by an order of magnitude at temperature below which BV is max.
- In presence of B, BV can reach maximum at low T and n_B.

Key Takeaways







- ❖ Computed nd and ec rates to consistently include thermal and magnetic field effects under conditions relevant for NS mergers.
- ❖ Departure from equilibrium $\Delta\mu = \mu_n - \mu_p - \mu_e$ changes with increasing B.
- ❖ Increased reaction rates shift the peak of Bulk viscosity to low T and n_B
- ❖ Relevant for evaluating the damping of density oscillations triggered during the postmerger evolution.

Thank you

★ Special Thanks to INT, Seattle and IUCAA for support.