

Transport properties in magnetized neutron star merger cores at finite temperature

Pranjal Tambe ¹, Debarati Chatterjee ¹, Mark Alford ², Alexander Haber ³

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1. Inter-University Centre for Astronomy and Astrophysics (IUCAA)
2. Washington University in St. Louis
3. University of Southampton

Finite-Temperature Effects in Multi-Messenger Astrophysics
INT-26-96W

June 15, 2026



IUCAA

Motivation

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

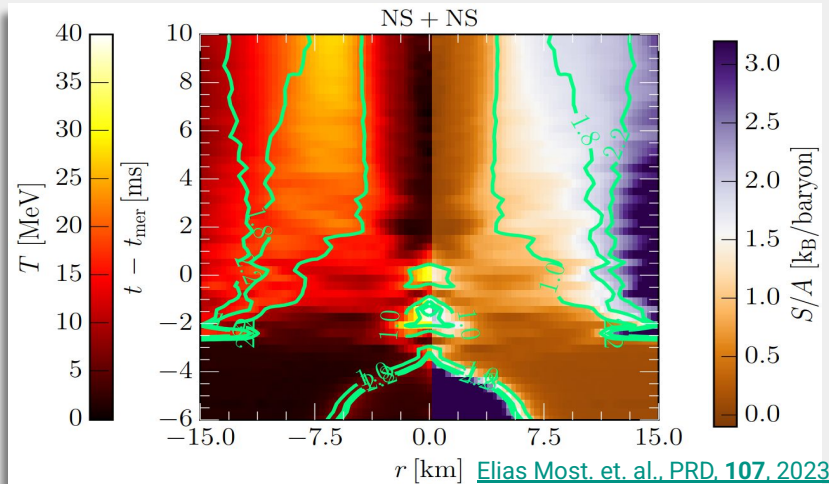


Fig. Dimensionally reduced spacetime diagrams for evolution of T and S/A

- $T \Rightarrow$ a few MeV in the core of the remnant, and as high as 40 MeV towards the surface.

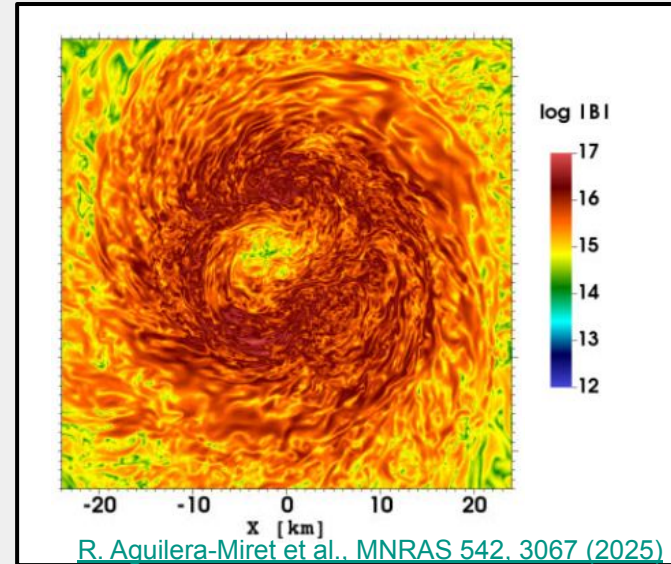
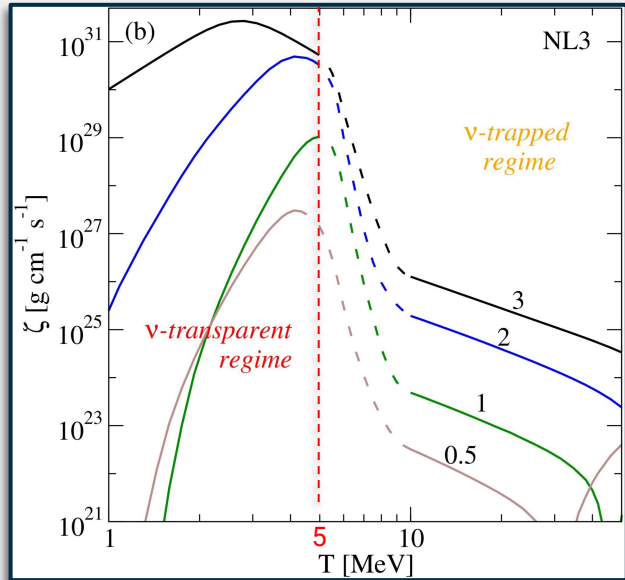


Fig. Slice of BNS merger simulation 10 ms postmerger

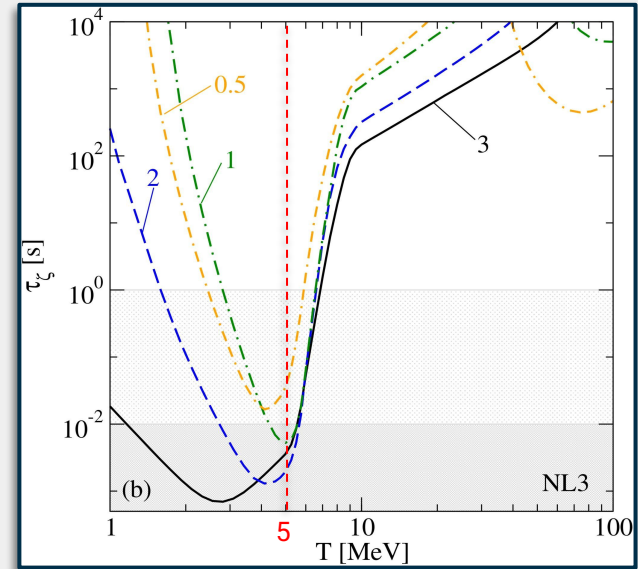
- B fields amplified in the postmerger to $\sim 10^{17}$ G.

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 viscosity and emission processes?
- Consistently compute **both finite T and B effects** on **viscosity, emissivity and opacity**.

Urca 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 $T \leq 5 \text{ MeV}$, neutrino transparent matter, nd and ec inverses of each other → isospin-equilibrium condition is $\mu_n = \mu_p + \mu_e$. **Is this the true equilibrium?**

Direct Urca processes (DU)



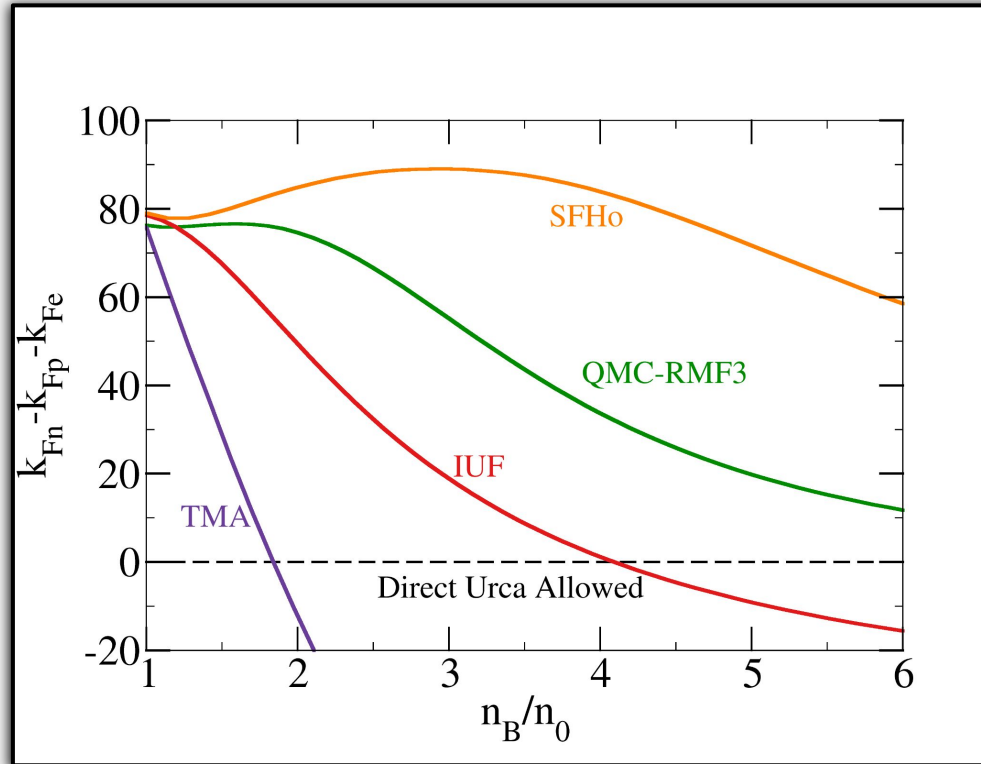
Modified Urca processes (MU)



Here N can be either n or p

Direct Urca Kinematics

Momentum shortfall as function of density for different EoSs



Reaction Rates

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

$$\Gamma_{nd}^{dUrca} \propto \int \prod_{i=1}^4 \frac{d^3 p_i}{2E_i} \delta^4 \left(\sum_{i=1}^4 p_i \right) \sum_{spins} |M(p_i)|^2 f_n (1 - f_p) (1 - f_e)$$

- Using the Dirac Delta and performing the angular integrals this can be **reduced to a 4-D integral** ([c.f. Alford et.al., Universe, 7, 2021](#))

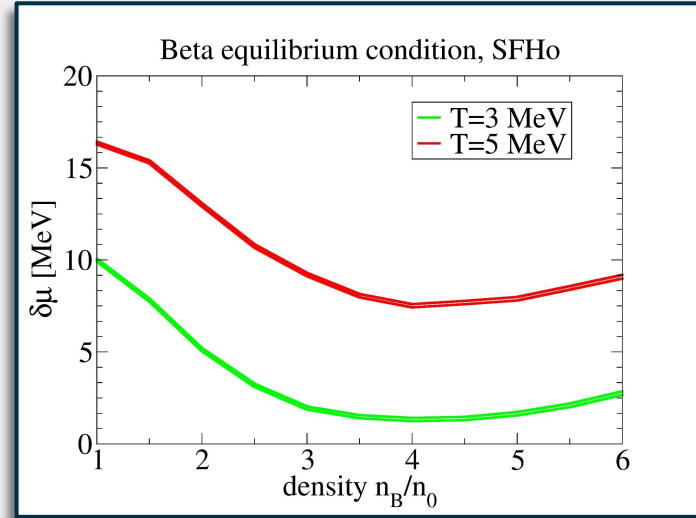
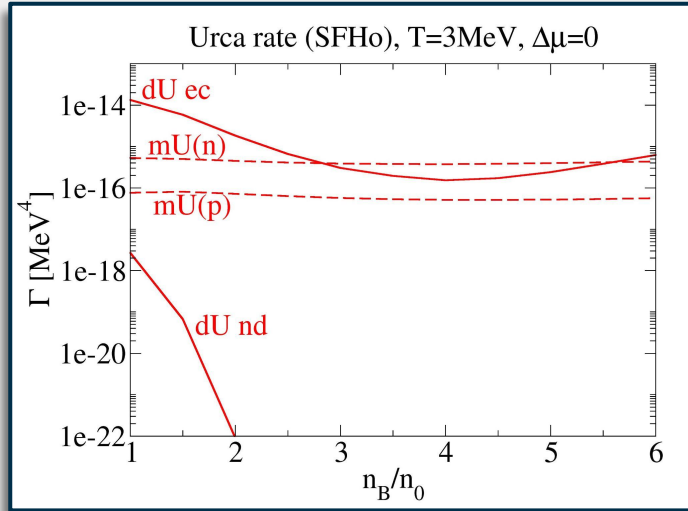
- **Fermi-Surface Approximation** ➤ Particles only on the Fermi-surface participate in reactions. Gives analytical expression.

$$\Gamma_{nd} = \Gamma_0(n_B, T) \Theta(k_{F_p} + k_{F_e} - k_{F_n})$$

- To incorporate Finite-T effects do the 4-D integral over the full phase space.

Effects of finite temperature

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



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

- **Finite correction** to isospin-equilibrium condition,
 $\mu_n = \mu_p + \mu_e + \delta\mu$, $\delta\mu > 0$.
- $\delta\mu > T$ \triangleright 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.

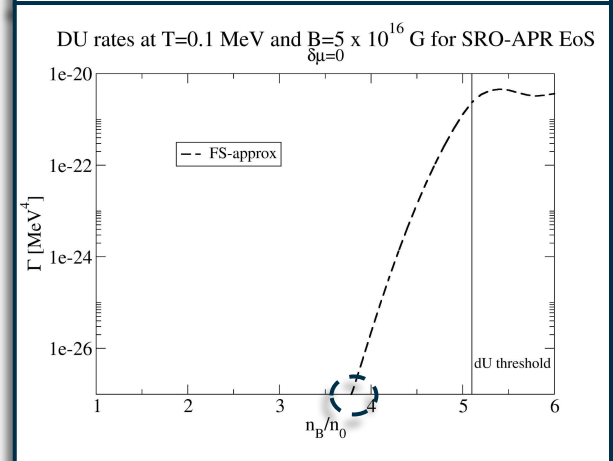
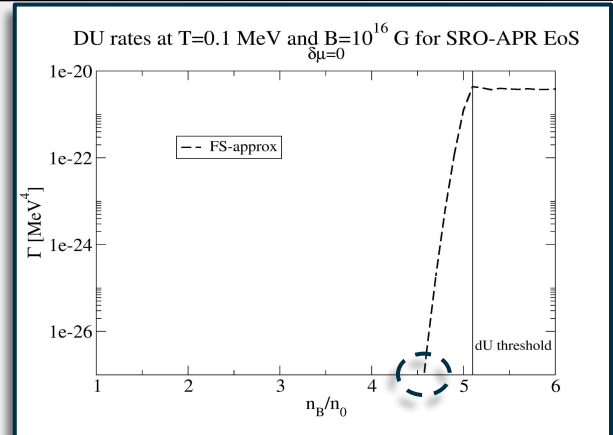
$$\Gamma_{nd} = \Gamma_0(n_B, T) \Theta(k_{Fp} + k_{Fe} - k_{Fn}) \xrightarrow{\mathbf{B}} \Gamma_{nd} = \Gamma_0(n_B, T) R_B^{qc}$$

(Step function)

(Continuous function)

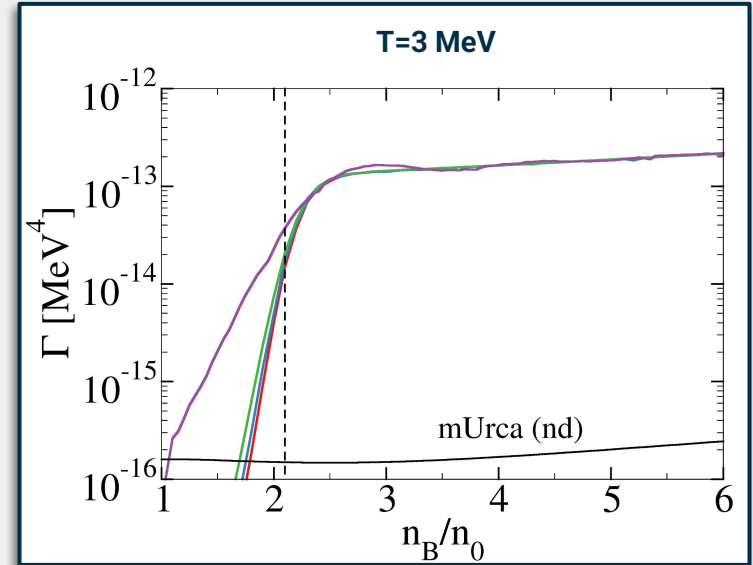
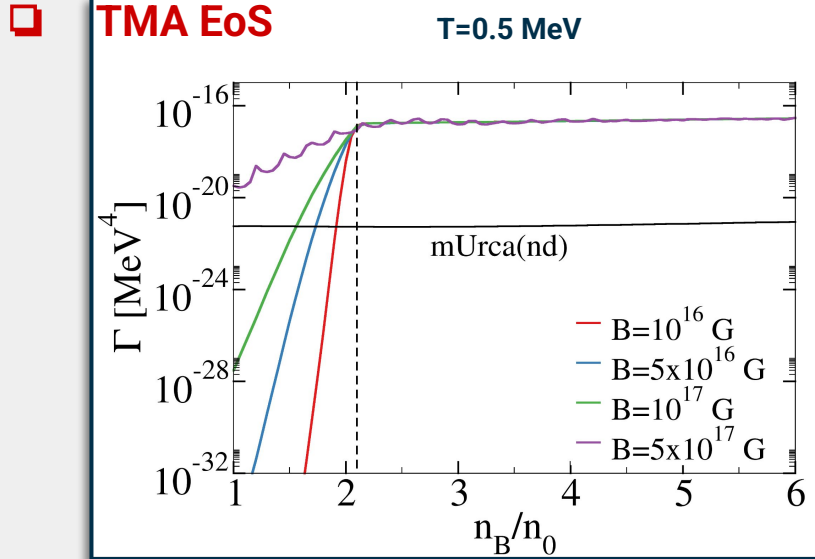
$$R_B^{qc} = \int_{-1}^1 d \cos \theta_p d \cos \theta_e k_{Fp} k_{Fe} \frac{F_{l,\nu}^2(u)}{2b} \Theta(k_{Fn} - |k_{Fp} \cos \theta_p + k_{Fe} \cos \theta_e|)$$

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



Direct Urca processes: Finite T and B

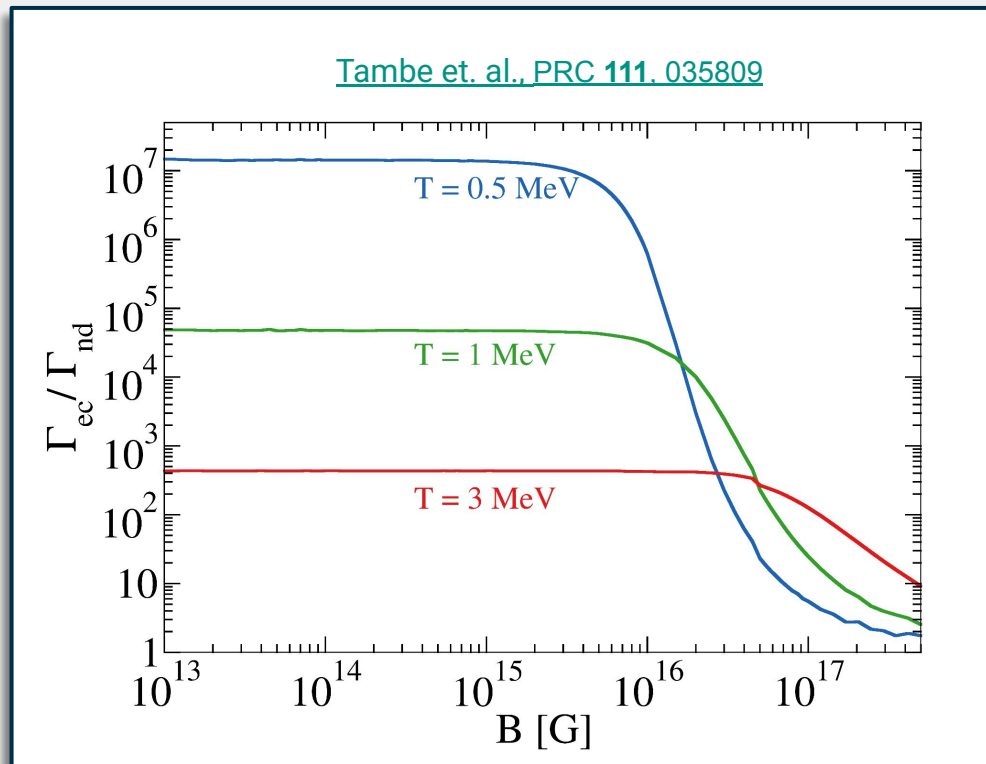
[Tambe et. al., PRC 111 \(2025\), 035809](#)



- 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**.

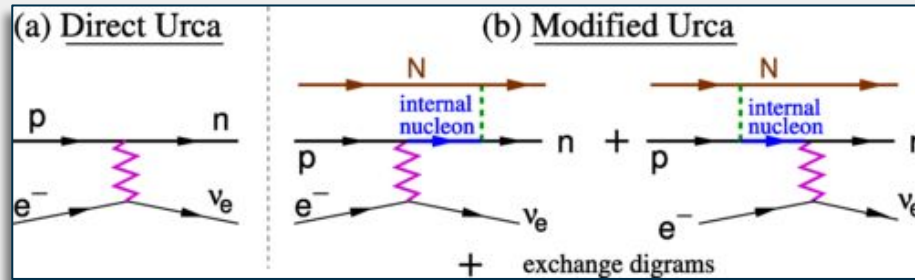
Isospin equilibrium condition in presence of B

- 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.



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 \Rightarrow Direct Urca + Modified Urca

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

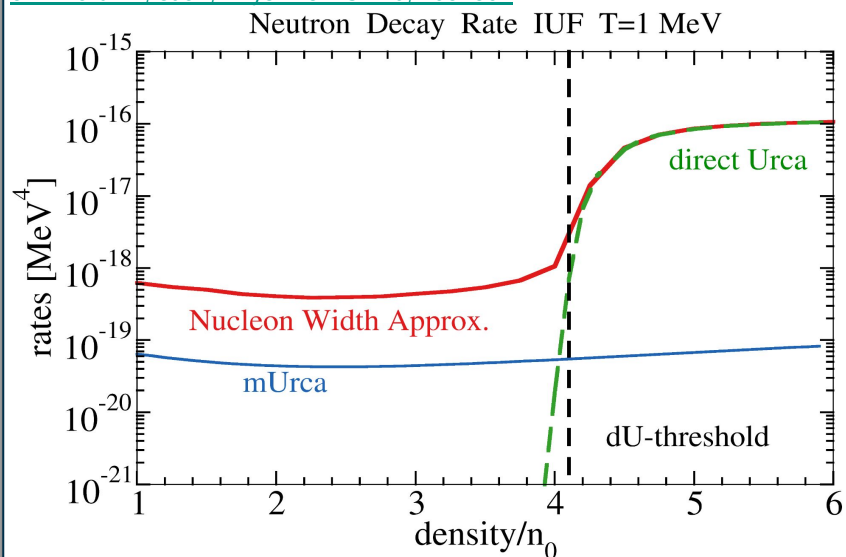
$$\Gamma^{NWA} = \int_{-\infty}^{\infty} dm_n dm_p \Gamma^{dUrca}(m_n, m_p) R_n(m_n) R_p(m_p),$$

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

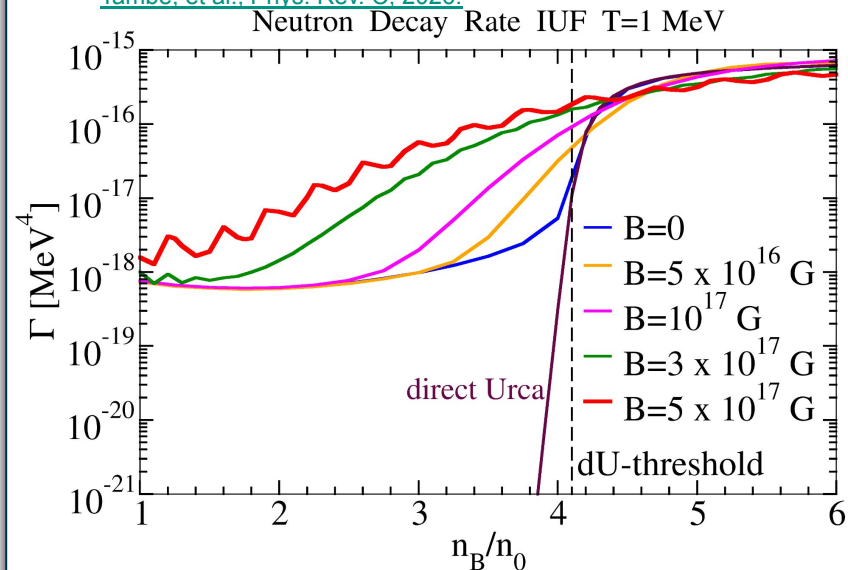
$M_N^* \rightarrow$ in-medium nucleon mass $W_N \rightarrow$ Width

Urca rates in NWA at finite T and B

[c.f. Alford, M. et al., Phys. Rev. C **110**, L052801](#)



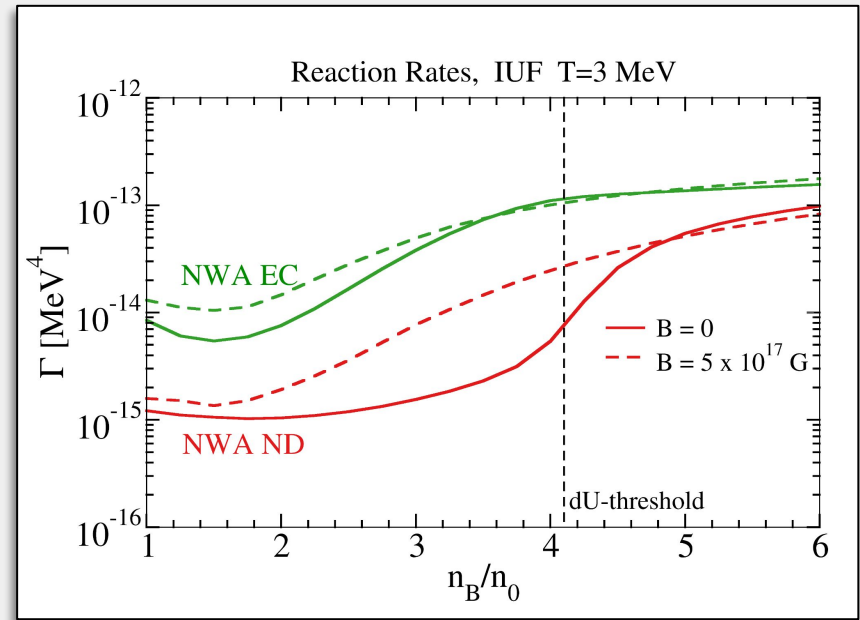
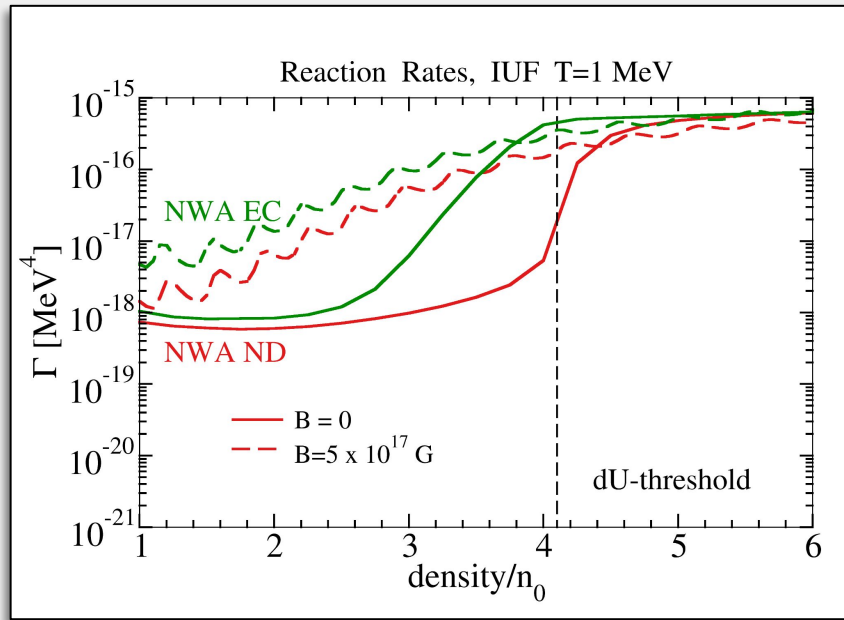
[Tambe, et al., Phys. Rev. C, 2026.](#)



- 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.

Urca rates in NWA at finite T and B

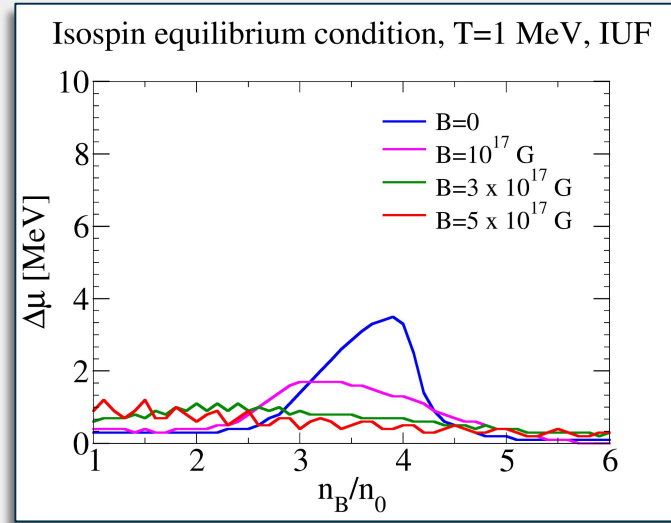
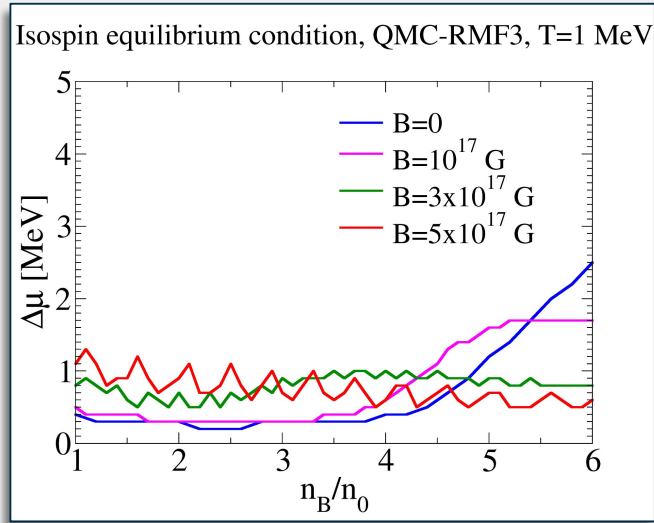


$$\Gamma_{nd}^{NWA} \neq \Gamma_{ec}^{NWA}$$

Need corrections to the isospin equilibrium condition, $\Delta\mu = \mu_n - \mu_p - \mu_e$

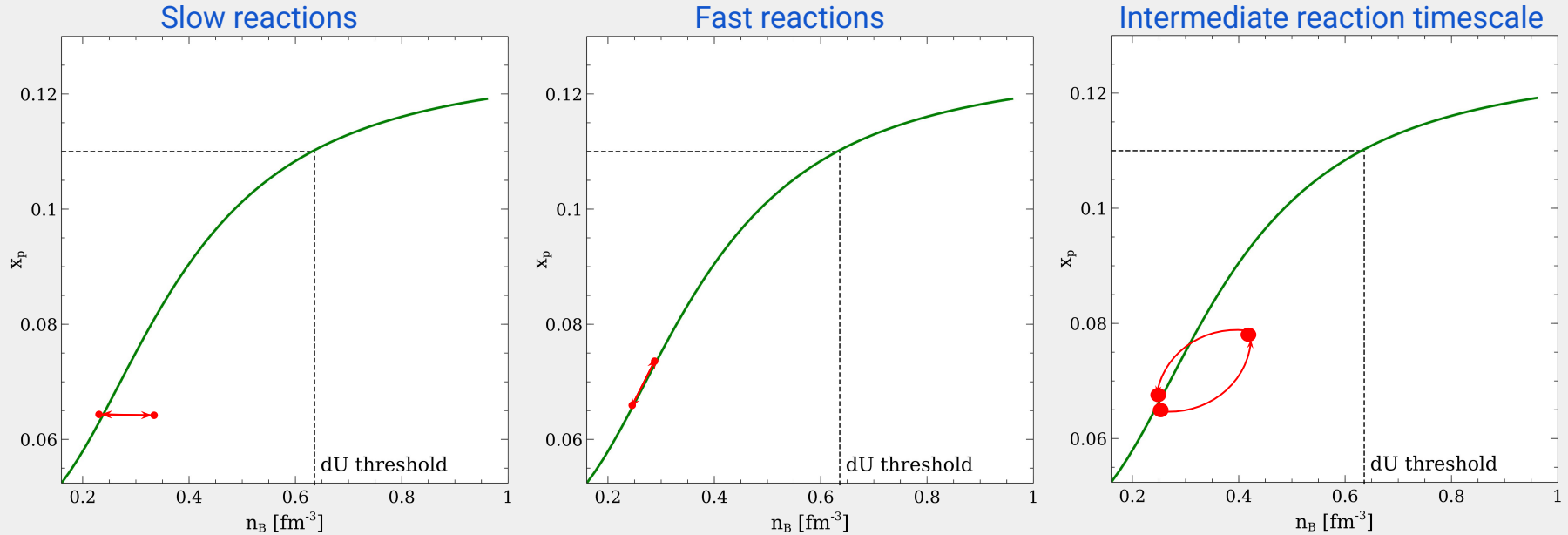
Isospin Equilibration at finite T and B

[Tambe, et al., Phys. Rev. C, 2026.](#)



- Increase $\Delta\mu = \mu_n - \mu_p - \mu_e$ till $\Gamma_{nd} = \Gamma_{ec}$ ➤ True Equilibrium.
- The correction to isospin equilibrium condition $\Delta\mu = \mu_n - \mu_p - \mu_e$ changes with field.
- $\Delta\mu$ largest near the dU threshold.
- $\Delta\mu$ increases with T, decreases with B.

Bulk Viscosity from isospin equilibration



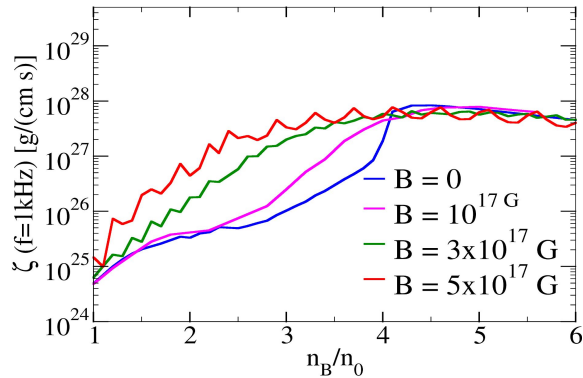
Equilibrium Proton fraction $\Rightarrow \mu_n = \mu_p + \mu_e$

We need to compute the reaction rates consistently to calculate bulk viscous dissipation at finite T and B

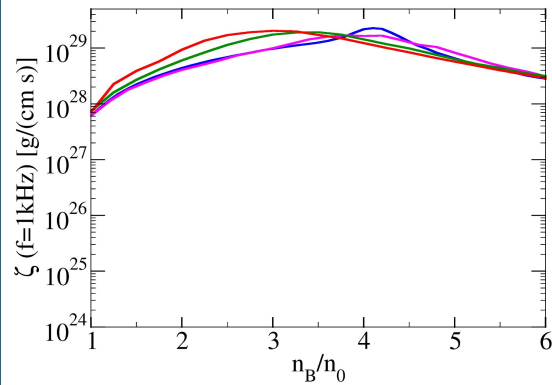
Bulk Viscosity

[Tambe, et al., Phys. Rev. C, 2026.](#)

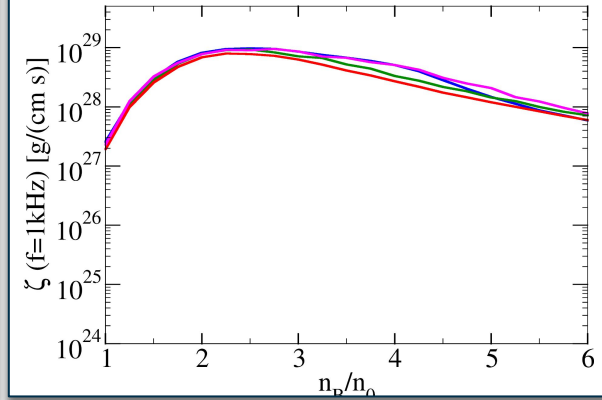
Bulk Viscosity ($f=1\text{kHz}$, $T=1\text{MeV}$, IUF)



Bulk Viscosity ($f=1\text{kHz}$, $T=3\text{MeV}$, IUF)

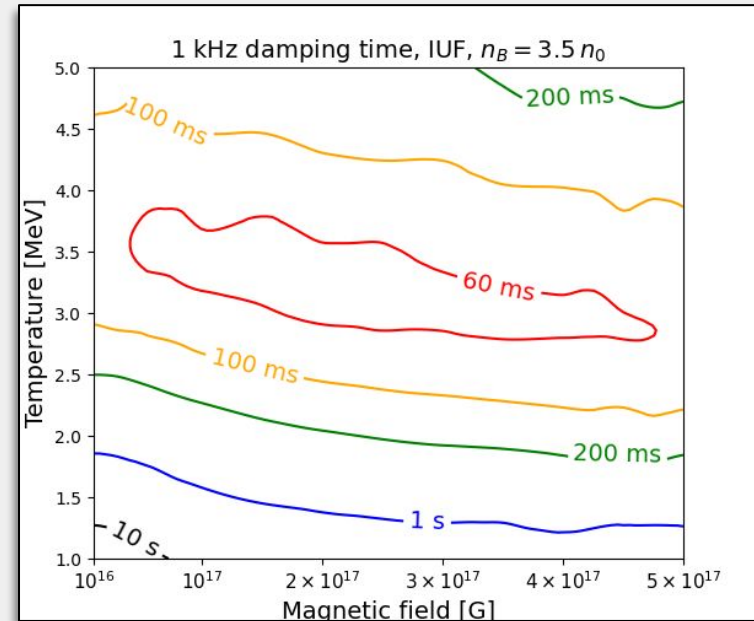
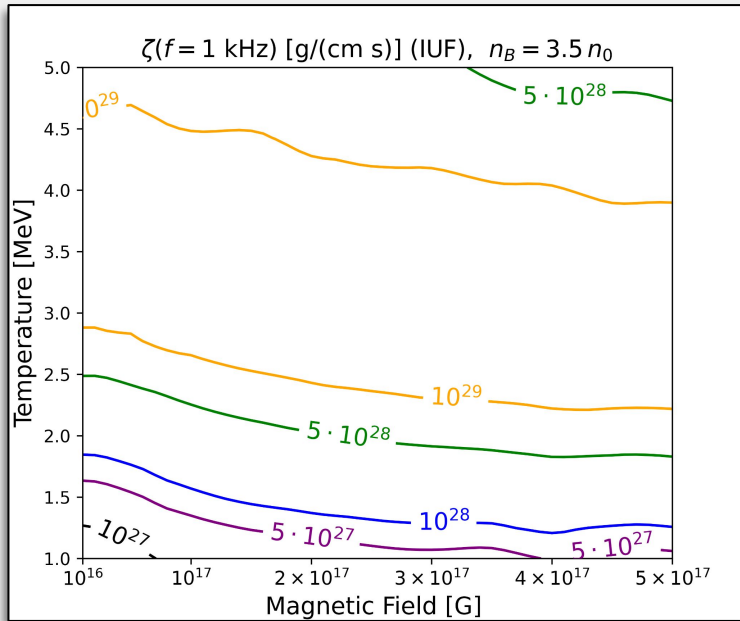


Bulk Viscosity ($f=1\text{kHz}$, $T=5\text{MeV}$, IUF)



- 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 .

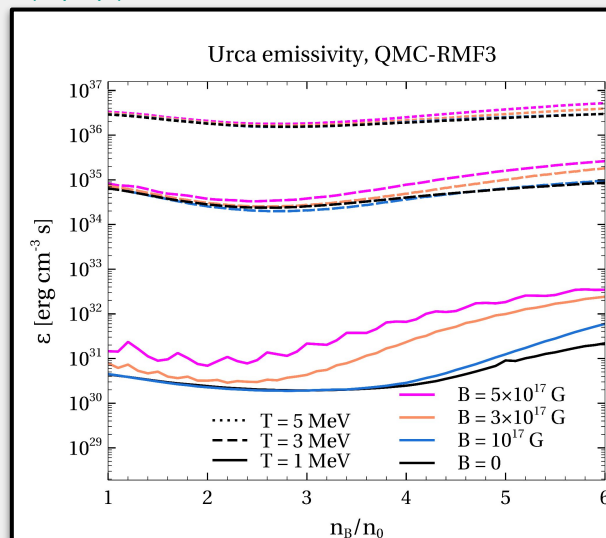
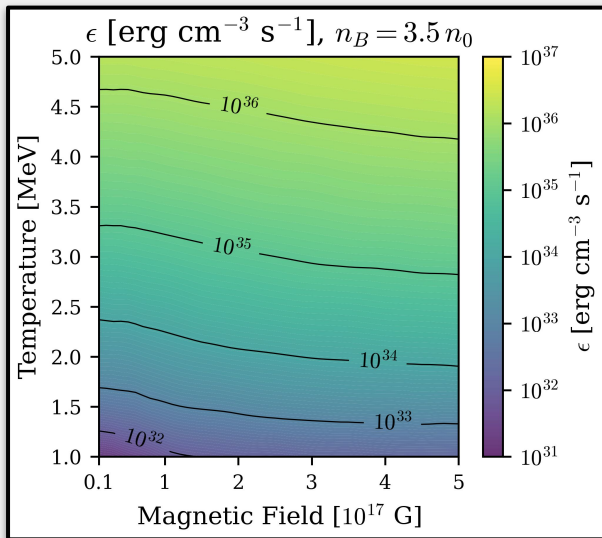
Dissipation timescales



- Effective Bulk Viscous Damping in colder regions of the merger .
- Bulk viscosity reaches its resonant peak at lower temperatures with increasing magnetic field.

Urca Emissivity at Finite T and B

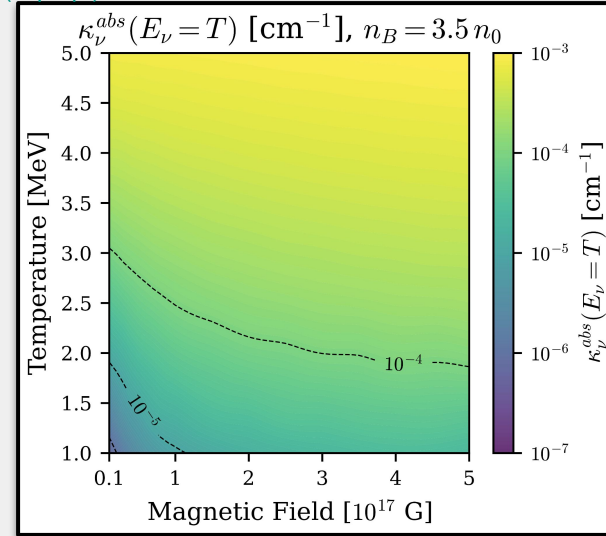
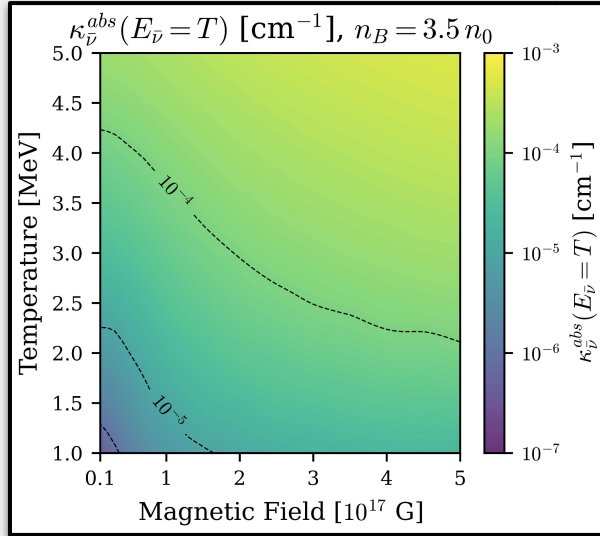
Tambe P., Chatterjee D. (in prep.)



- Rate of energy emitted per unit volume from Urca processes.
- At low T emissivity increases by an **order of magnitude** with magnetic field.
- Magnetic field effect washed out with increasing temperature.

Neutrino Absorption Opacity

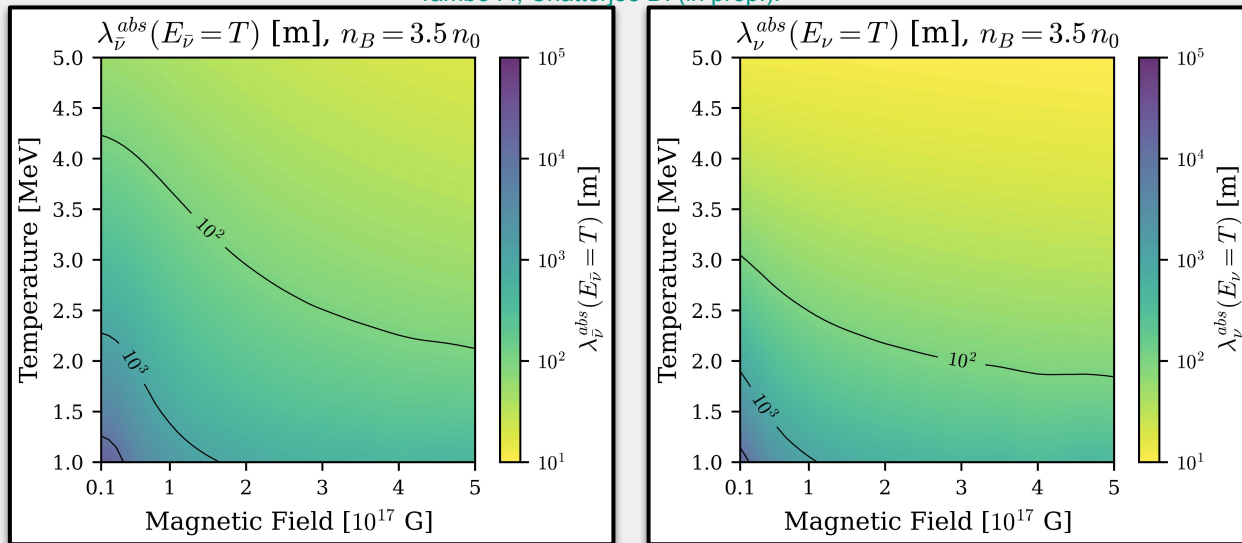
Tambe P., Chatterjee D. (in prep.).



- Represents the **inverse mean free path** for absorption of neutrino of a given energy.
- The combined thermal, magnetic and collisional broadening effects **increase** neutrino/antineutrino opacity
- Opacity increases by upto **two orders of magnitude** at low T with increasing field

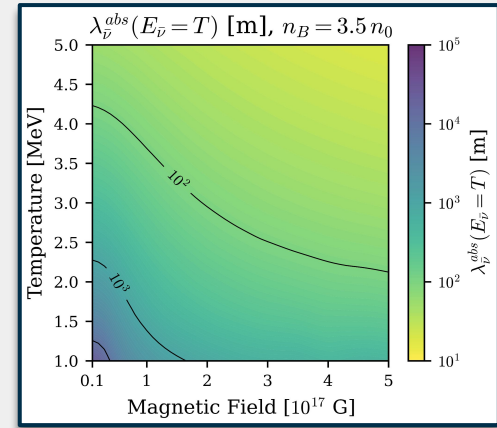
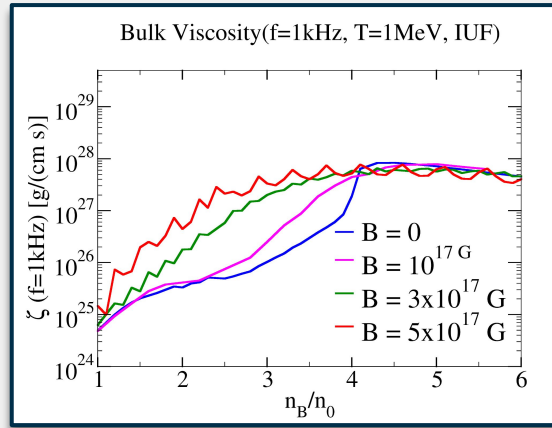
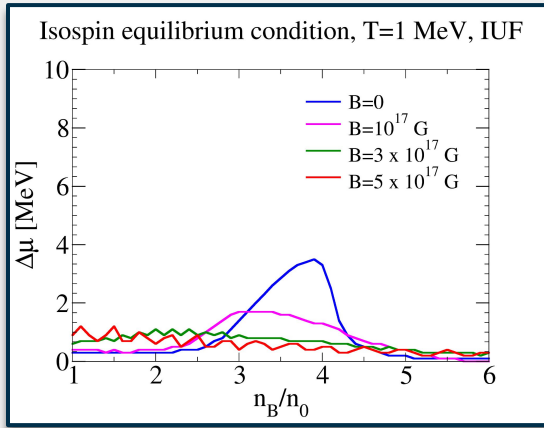
Neutrino Absorption Mean Free Path

Tambe P., Chatterjee D. (in prep.)



- The combined thermal, magnetic and collisional broadening effects **decrease** neutrino/antineutrino mean free paths (mfp) to distance **smaller than stellar radius**.
- At low T the mfp decreases from **few 10s km to a few 100 m** with increasing magnetic field.
- Higher Energy Neutrinos \Rightarrow Even smaller mfp \Rightarrow **Neutrinos trapped** in the bulk \Rightarrow Modifies equilibrium composition, viscous damping of density oscillations.

Key Takeaways



- ❖ Departure from equilibrium $\square \mu = \mu_n - \mu_p - \mu_e$ in presence of finite T and B .
- ❖ Increased reaction rates shift the peak of Bulk viscosity to **low T and n_B** .

- ❖ **Neutrino absorption opacity increases, absorption mfp decreases** incorporating the combined effects of temperature, magnetic field and collisional broadening.
- ❖ Relevant Domains:
 - Cooling of PNS and post-merger remnant.
 - Flavor Equilibration.
 - Bulk Viscous Damping.

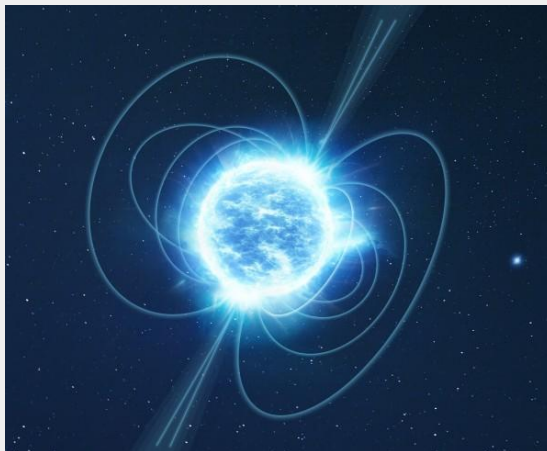
Thank you

★ Special Thanks to INT, Seattle for partial support.



Relevant Domains

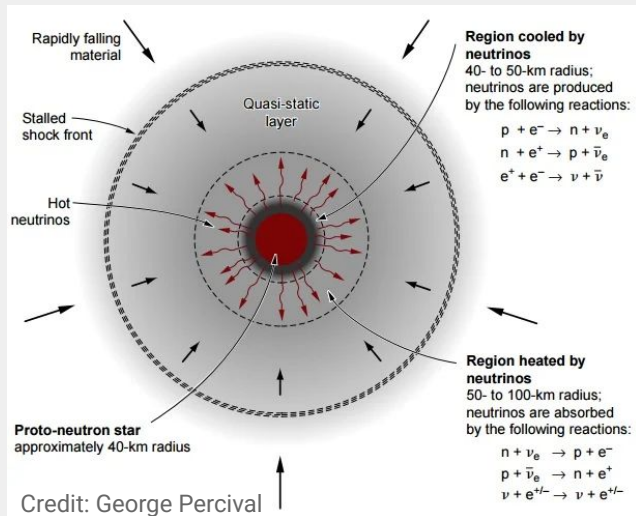
Proto-Neutron Stars



Credit: ESA

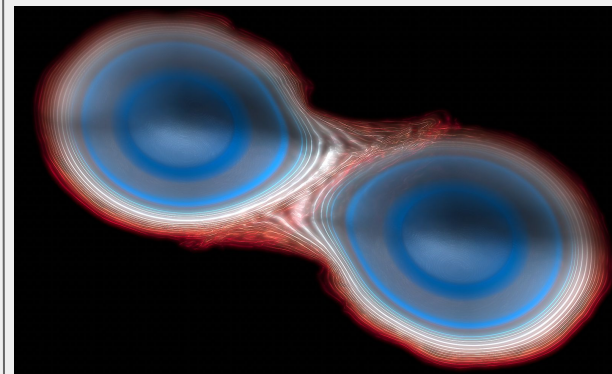
Cooling via Neutrino Emission

Core Collapse Supernova



Neutrino Transport and Opacity

BNS Mergers



Credit: Tim Dietrich

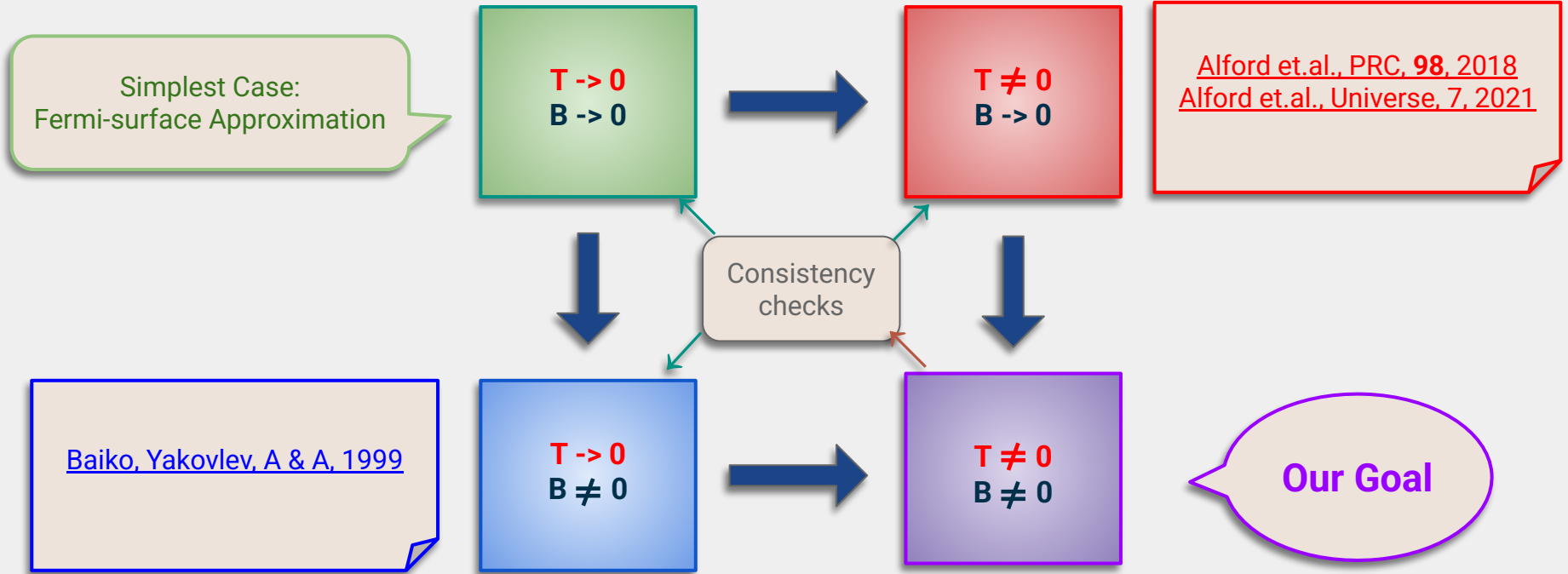
Flavor Equilibration and
Oscillation Damping

Operational Regime

Neutrino Transparent Matter: $T < 5 \text{ MeV}$
(neutrinos **free-streaming**, carrying away energy)

High Magnetization: $B = 10^{16} - 10^{17} \text{ G}$
(amplified by **Taylor-Spruit Dynamo** or **KH instabilities**)

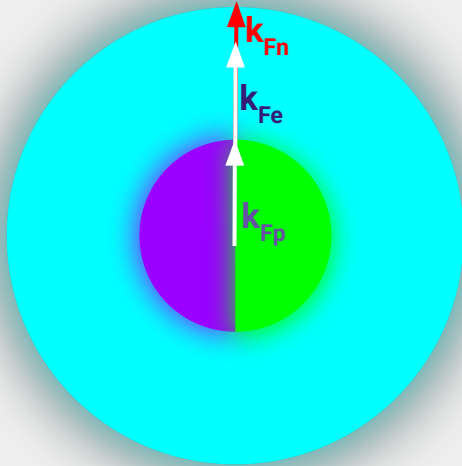
Current State of Research



Direct Urca Kinematics

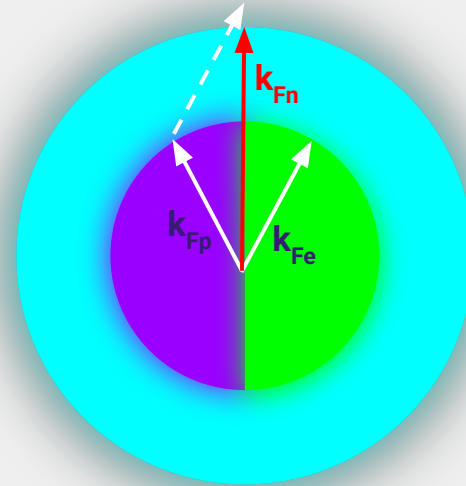
$$k_{Fn} > k_{Fp} + k_{Fe}$$

- Neutrons
- Protons
- Electrons



Below dU threshold, $x_p < 11\%$

$$k_{Fn} < k_{Fp} + k_{Fe}$$



Above dU threshold, $x_p \geq 11\%$





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

Pranjal Tambe ^{1,*}, Debarati Chatterjee ^{1,†}, Mark Alford ² and Alexander Haber ^{2,‡}

¹*Inter University Centre for Astronomy and Astrophysics, Ganeshkind, Pune 411007, India*

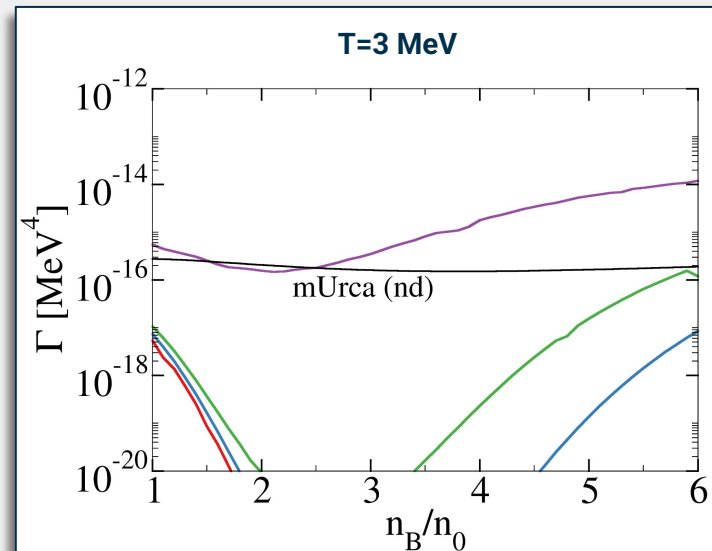
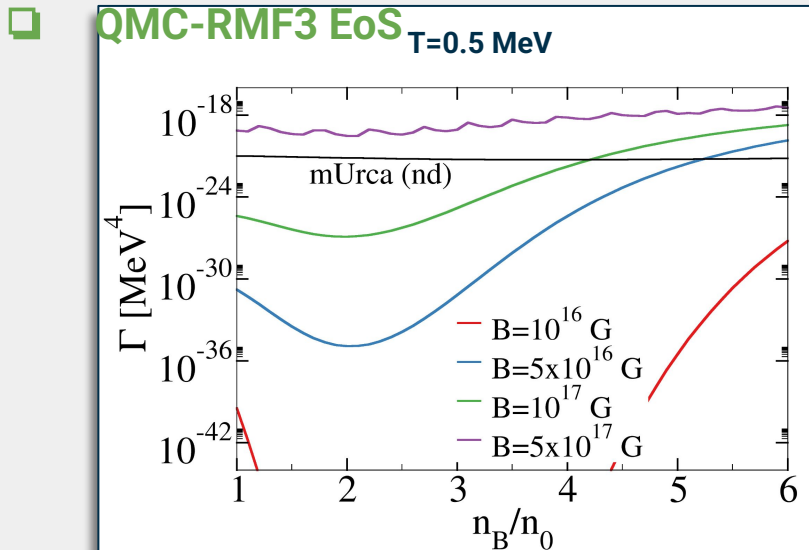
²*Physics Department, Washington University, Saint Louis, Missouri 63130, USA*



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Direct Urca processes: Finite T and B

[Tambe et. al., PRC 111, 035809](#)



- 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.

Bulk Viscosity from Isospin Equilibration

For small amplitude oscillations: $\zeta = \frac{\partial p}{\partial x_I} \Big|_{n_B} \frac{\gamma_B}{\gamma_I^2 + \omega^2}$, $\gamma_I \equiv -\frac{1}{n_B} \frac{\partial \Gamma_I}{\partial x_I} \Big|_{n_B}$, $\gamma_B \equiv \frac{\partial \Gamma_I}{\partial n_B} \Big|_{x_I}$.

$$\Gamma_I = \Gamma_{nd} - \Gamma_{ec}$$

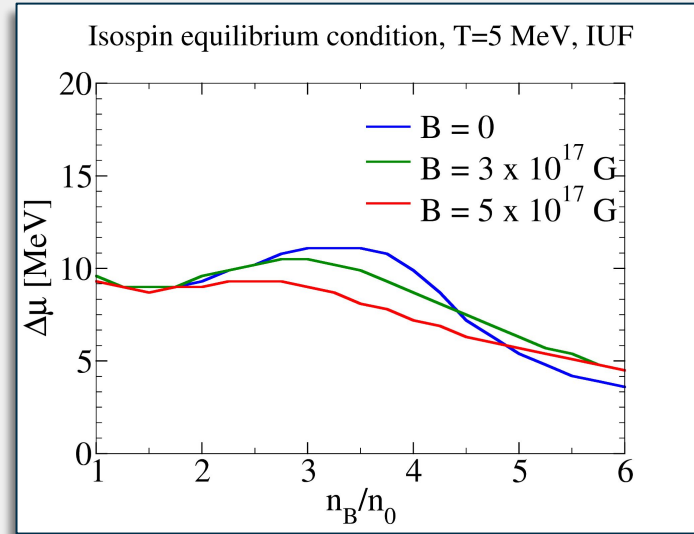
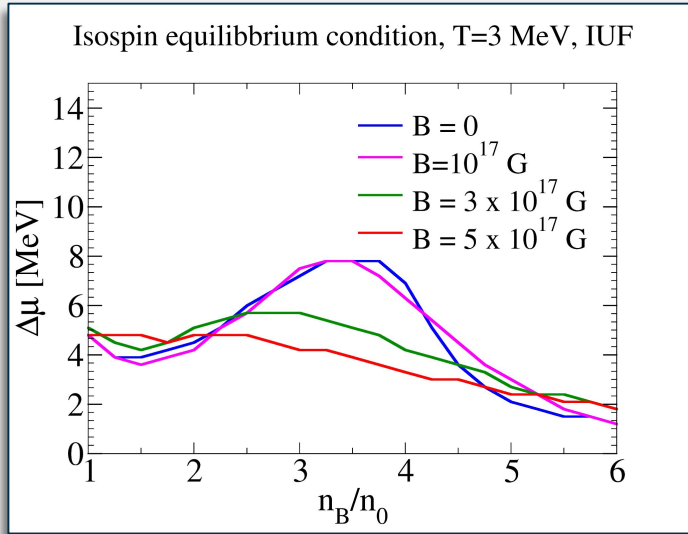
Isospin Equilibration timescale: $\tau_I = \frac{1}{\gamma_I}$

In the low T approximation: $\gamma_B \propto \gamma_I$

Oscillation damping timescales: $\tau_{damp} = \frac{E_{osc}}{\dot{E}_{osc}} = \frac{\kappa^{-1}}{\omega^2 \zeta}$

Isospin Equilibration at finite T and B

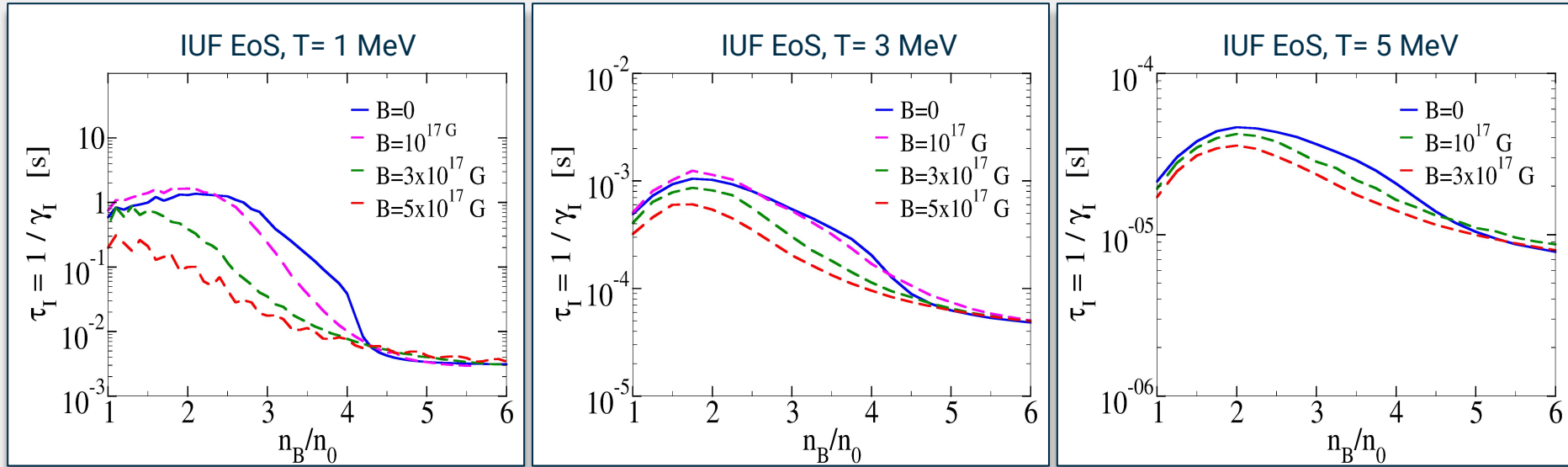
[Tambe, et al., Phys. Rev. C, 2026.](#)



- $\Delta\mu$ largest near the dU threshold.
- $\Delta\mu$ increases with T, decreases with B.
- B field effects wash out at higher T.

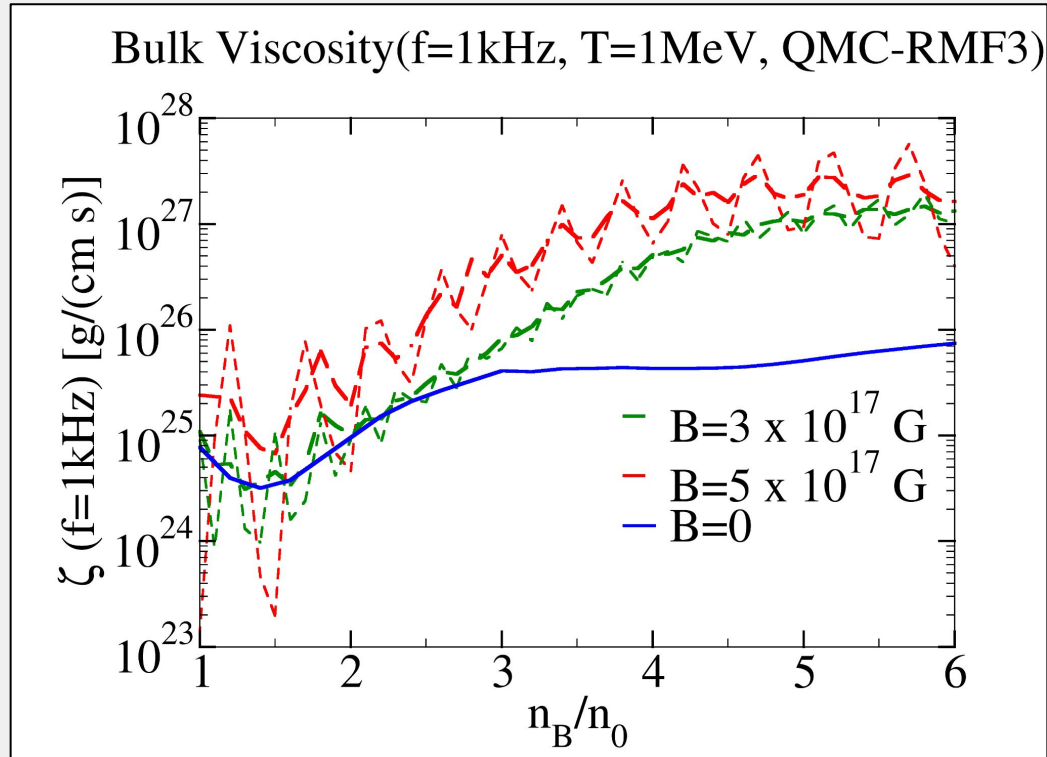
Isospin relaxation timescale

[Tambe, et al., Phys. Rev. C, 2026.](#)



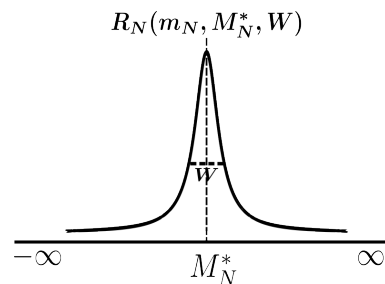
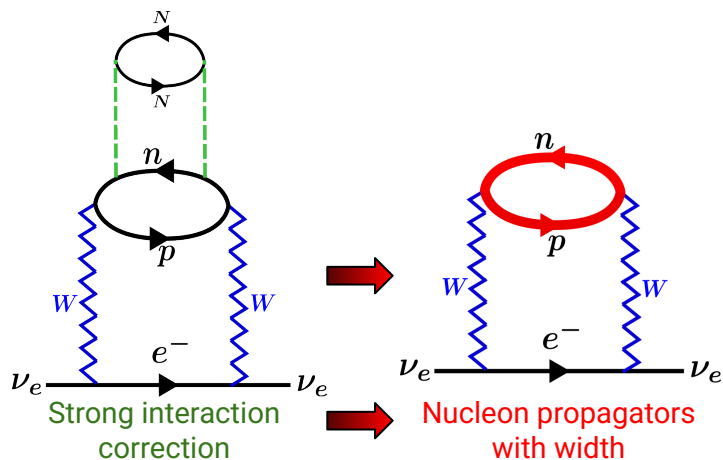
- **Faster relaxation** to equilibrium in presence of magnetic field because of increase in reaction rates.
- Bulk Viscosity maximum when $\tau_I \approx 1/\omega$, $\omega \rightarrow$ angular frequency of oscillations
- In BNS mergers, relevant frequency of density oscillations \rightarrow 1 kHz. BV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

Landau Quantization in EoS



Total Urca Rates, NWA framework

Internal nucleons have finite lifetimes and hence a finite width [Alford M., Haber A., Zhang Z., Phys.Rev.C 110 \(2024\)](#)



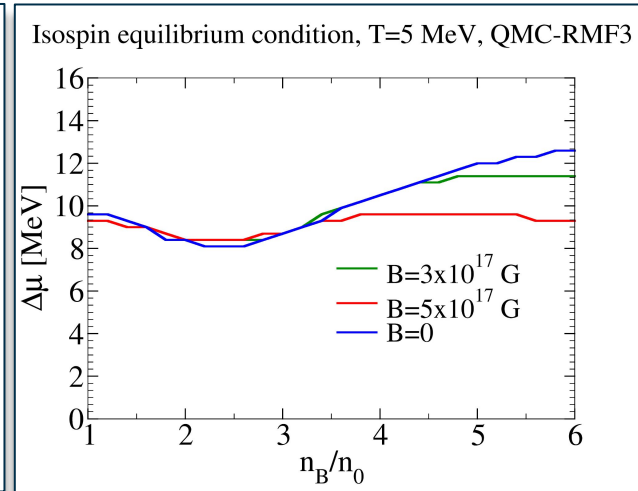
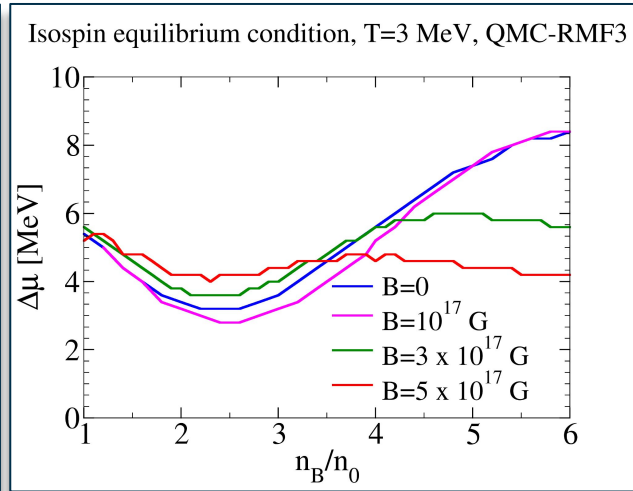
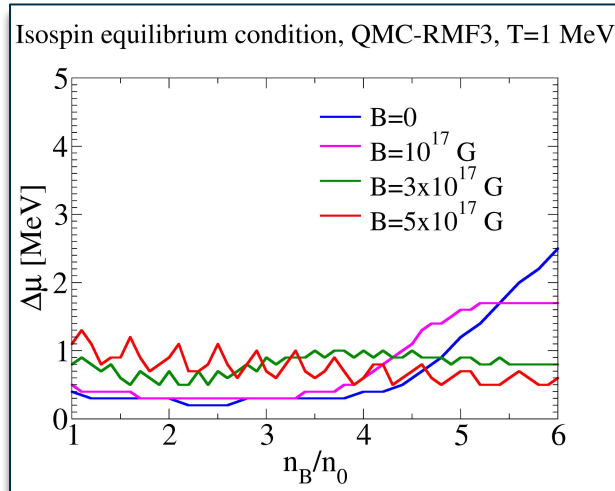
$$G_N(k, M_N^*, W) = \int_{-\infty}^{\infty} dm_N G_N(k, M_N^*) R_N(m_N, M_N^*, W)$$

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

Isospin Equilibration at finite T and B

QMC-RMF3 EoS

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



Bulk Viscosity

QMC-RMF3 EoS

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

