

Urca Processes in Neutron Star Mergers

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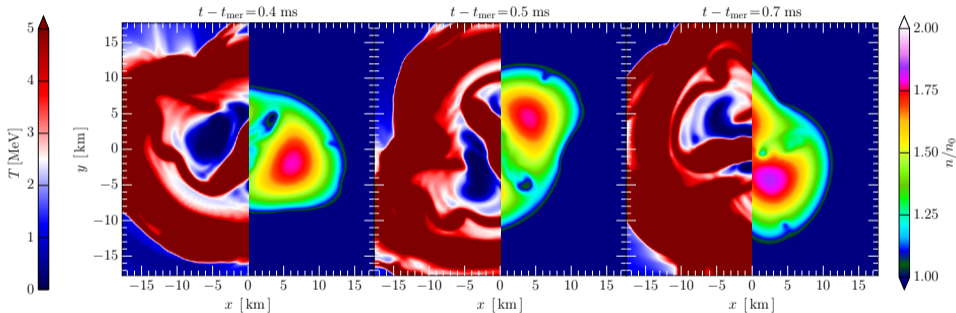
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Neutron star mergers probe dense matter at high densities and high temperatures (tens of MeV)



Graphics by Elias Most

- ▶ Above $T \gtrsim 10$ MeV, neutrinos are trapped
- ▶ In this talk: work in neutrino free-streaming regime: $k_{F\nu} = 0$

Urca Processes

Weak semi-leptonic decays in dense matter

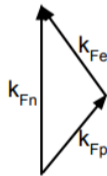


direct Urca (dU)

neutron decay: $n \rightarrow p + e^- + \bar{\nu}_e$ electron capture: $p + e^- \rightarrow n + \nu_e$

$$\Gamma_{\text{dU,nd}} \propto \int d^{12}p |M|^2 f_n(1 - f_e)(1 - f_p) \delta^4(4 - \text{mom cons.})$$

- ▶ Dominated by particles on their **Fermi surface (FS)**
- ▶ Momentum conservation on FS demands $\vec{k}_{Fn} \leq \vec{k}_{Fp} + \vec{k}_{Fe}$
- ▶ If momentum cons. on FS not possible: rate **heavily suppressed**
- ▶ Momentum conservation can be achieved via spectator nucleon N



modified Urca (mU)

neutron decay: $n + N \rightarrow p + e^- + \bar{\nu}_e + N$ electron capture $p + e^- + N \rightarrow n + \nu_e + N$

Direct Urca Threshold

Property of the equation of state

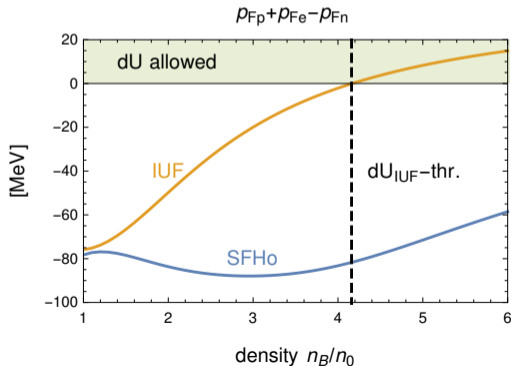


charge neutrality requires $n_e = n_p$ so at $T = 0$: $k_{Fp} = k_{Fe}$

direct Urca threshold:

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

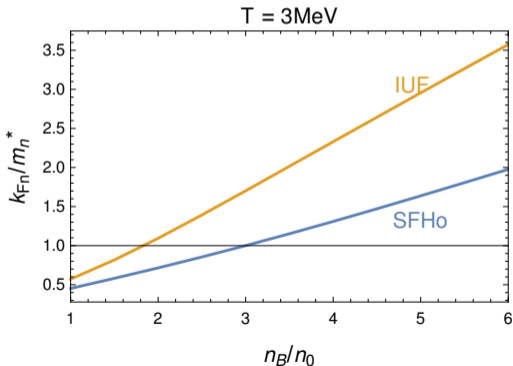
- ▶ dU requires higher **proton fraction**
- ▶ Nearly all equation of states (EOS) have **monotonically rising** proton fraction with n_B
- ▶ Compare two different EOS (relativistic mean field models-RMF): **IUF** and **SFHo**
- ▶ **IUF**: direct Urca threshold at $n_B \approx 4.1 n_0$





Non-relativistic expansion

$$\sqrt{k^2 + m_n^{*2}} \approx m_n^* + k^2/(2m_n^*) + \dots \text{ requires } k_{Fn}/m_n^* \ll 1$$



- ▶ In-medium nucleon mass drops quickly with density in RMFs (however: PRC 100, 065807 (2019))
- ▶ Neutrons become fully relativistic between $2 - 3 n_0$
- ▶ Protons become fully relativistic between $3 - 6 n_0$

Beta Equilibrium

Cold vs warm beta equilibrium



- ▶ **Beta-equilibrium = chemical equilibrium**: composition of matter (e.g. proton fraction) stays constant with time
- ▶ "Chemical composition" (particle fractions) change via **weak interactions**

cold beta equilibrium

$$\text{forward rate} = \text{backward rate: } n \Leftrightarrow p + e^- + \bar{\nu}_e \quad \rightarrow \quad \mu_n = \mu_p + \mu_e$$

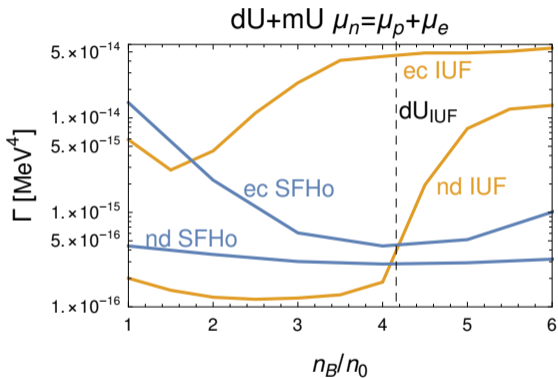
Assumptions: $\mu_\nu = \mu_{\bar{\nu}} = 0$, direct Urca dominates

- ▶ Cold beta equilibrium is correct at $T = 0$
- ▶ For $T = 0$: chemical potential = Fermi energy
- ▶ Above dU threshold: **energy and momentum** conservation fulfilled **on FS**

? Still valid at moderate, **finite temperatures** ?

Total Urca in Cold Beta-Equilibrium

$T = 3 \text{ MeV}$ - neutrino transparent



- ▶ IUF-results show clear dU threshold
- ▶ Electron-capture and neutron-decay differ by 1 – 2 orders of magnitude
- ▶ Cold beta-equilibrium clearly violated

Reason:

electron-capture and neutron-decay are **not** inverse processes: neutrino switches side

Warm Beta Equilibrium

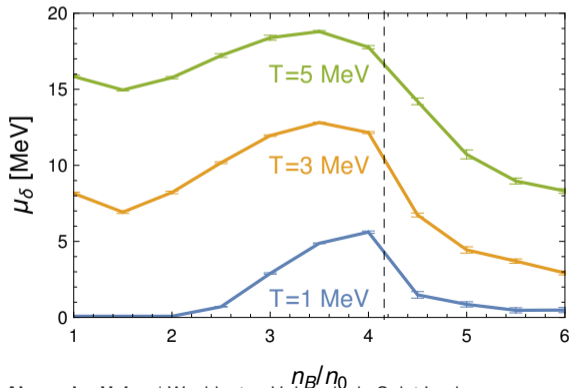
Alford, Harris PRC 98 (2018)



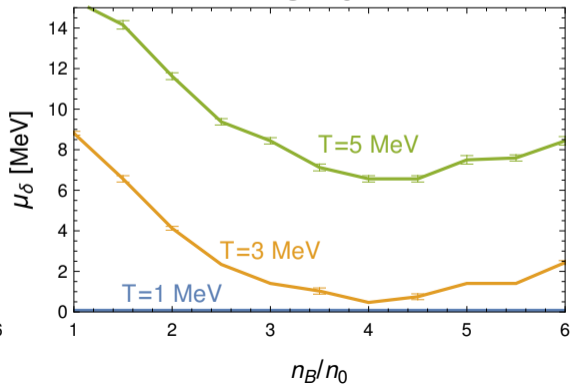
Warm Beta Equilibrium

$\mu_n = \mu_p + \mu_e + \mu_\delta$ where μ_δ is chosen s.t. $\Gamma_{nd} = \Gamma_{ec}$

IUF

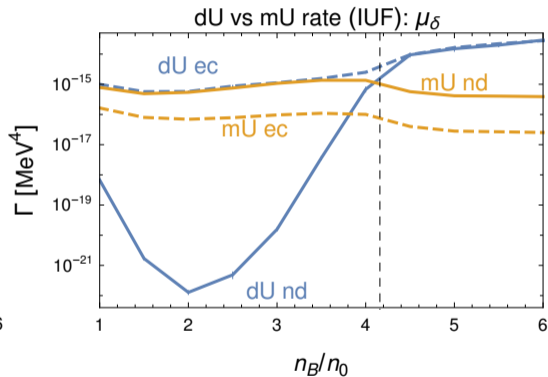
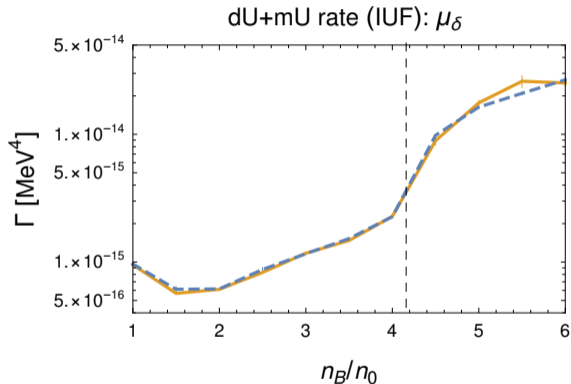


SFH0



Corrected Rates

for IUf EOS at $T = 3 \text{ MeV}$



direct Urca electron capture dominates over modified Urca



Summary

- ▶ Traditional beta-equilibrium is violated for temperatures in the few MeV range
- ▶ μ_δ reaches up to 15 MeV
- ▶ Direct Urca can dominate over modified Urca even below threshold

Outlook

- ▶ Effect of μ_δ on cooling?
- ▶ Effect of μ_δ on bulk viscosity?
- ▶ ...

Thank you for your attention!