Chiral imbalances in neutron star mergers

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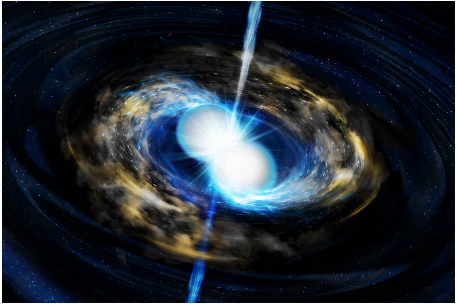
SPH & S. Sen arXiv:2602.21294

Strong & Electroweak Matter
August 21, 2026

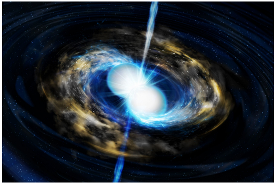
Outline

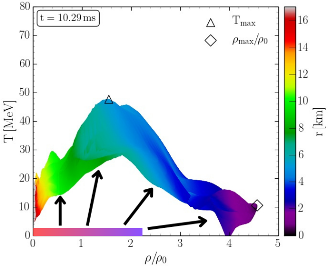
1. Shock/compression pushes matter out of beta equilibrium
2. Beta equilibration ensues, developing a chiral imbalance among the electrons
3. If the imbalance is large enough, and lasts long enough, it could give rise to novel effects (chiral plasma instability, heating, ...)

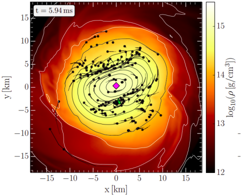


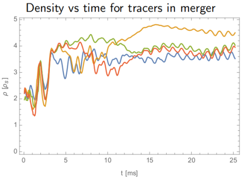
Compressions/shocks in NS mergers

Nuclear matter in neutron star mergers experiences both secular compression and superimposed density oscillations.

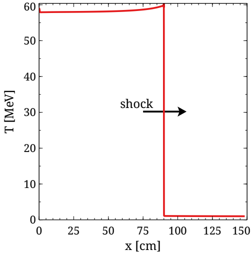








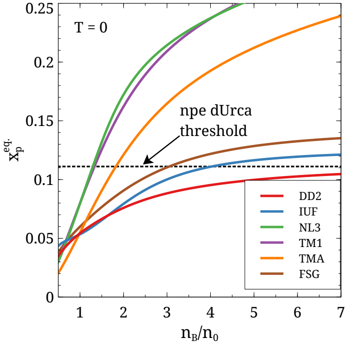
Simulation results from M. Hanauske and the Rezzolla group (Frankfurt)



Microscopic considerations: x_p and x_5

Consider dense matter as charge-neutral Fermi liquid of n, p, e^-.

- At a given $\{n_B, T\}$, the proton fraction $x_p = n_p/n_B$ is set by the history of the system. In beta-equilibrium, $x_p = x_p^{\beta-\text{eq.}}(n_B, T)$.



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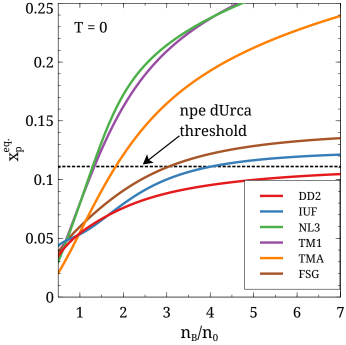

Chirality in dense matter

- Left- & right-handed fermions are present. Thermodynamically, they are identical $(\varepsilon, P, \ldots)$.
- $x_5 \equiv x_R - x_L$. In equilibrium, $x_5 = 0$.
- If this is so, can a chiral imbalance ever develop?
  - Yes, through the weak interaction.
  - Imbalance suppressed $\sim m_{\text{fermion}}$. Focus on the lightest fermion (e^-).

Creating a chiral imbalance

Urca process[a]

- $n \to p + e_L^- + \bar{\nu}$ and $e_L^- + p \to n + \nu$
- Weak interaction - slow-ish
- Only involves left-handed e^-

[a] We assume ν-transparent matter.

Rutherford scattering

- $e_L^- + p \leftrightarrow e_R^- + p$
- Electromagnetic interaction - fast!
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Define net rates:

$$\Gamma^{\text{net}}_{\text{Urca}} \equiv \Gamma_{n\to p+e^-+\bar{\nu}} - \Gamma_{e^-+p\to n+\nu} \qquad \Gamma^{\text{net}}_{L\leftrightarrow R} \equiv \Gamma_{e_R+p\to e_L+p} - \Gamma_{e_L+p\to e_R+p}$$

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$$\frac{dn_{e,L}}{dt} = \Gamma^{\text{net}}_{L\leftrightarrow R} + \Gamma^{\text{net}}_{\text{Urca}}$$

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$$\frac{dn_5}{dt} = \frac{dn_{e,R}}{dt} - \frac{dn_{e,L}}{dt} = -2\Gamma^{\text{net}}_{L\leftrightarrow R} - \Gamma^{\text{net}}_{\text{Urca}}$$

Creating a chiral imbalance (2)

For small deviations from chemical equilibrium:

$$\Gamma^{\rm net}_{\rm Urca} \propto \delta\mu \equiv \mu_n - \mu_p - \mu_{e,L} \quad \text{and} \quad \Gamma^{\rm net}_{L\leftrightarrow R} \propto \mu_5 \equiv \mu_{e,R} - \mu_{e,L}.$$

Evolution equations

$$\frac{dn_p}{dt} = \underbrace{\Gamma^{\rm net}_{\rm Urca}}_{\sim\delta\mu}$$

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Possibility of a plateau[a] in n_5.

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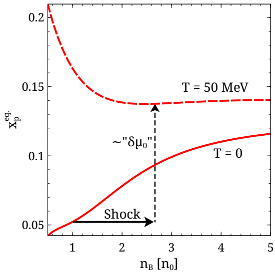
Initial conditions

- Matter is shocked right before $t = 0$. Yields...
  - $\delta\mu(t=0) = \delta\mu_0$
  - $\mu_5(t=0) = 0$



Chiral imbalance plateau

$$\delta\mu(t=0) = \delta\mu_0.$$
$$\mu_5(t=0) = 0.$$

$$\frac{dn_p}{dt} = \underbrace{\Gamma^{\text{net}}_{\text{Urca}}}_{\sim\delta\mu}$$

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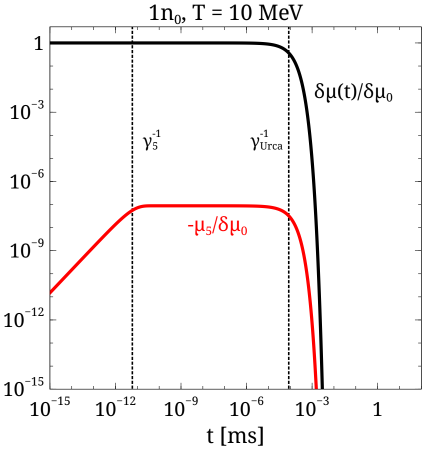
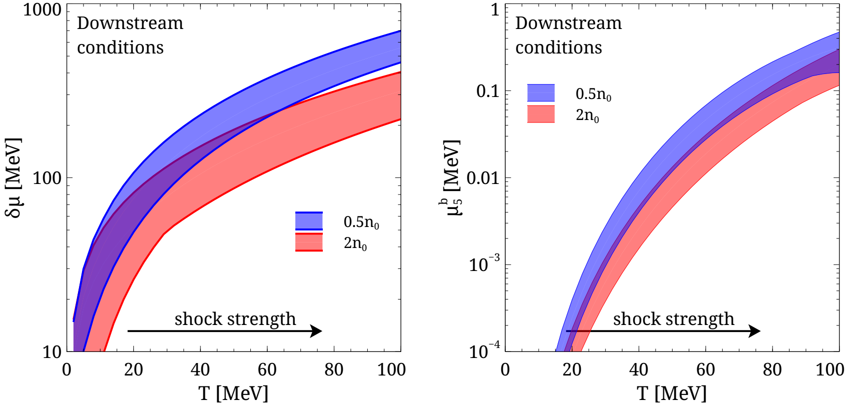


Assuming $\gamma_5 \gg \gamma_{\text{Urca}}$, plateau:

- Duration: $\gamma_{\text{Urca}}^{-1}$ Height: $-\delta\mu_0 \frac{\gamma_{\text{Urca}}}{\gamma_5}$

Chiral imbalance plateau (2)



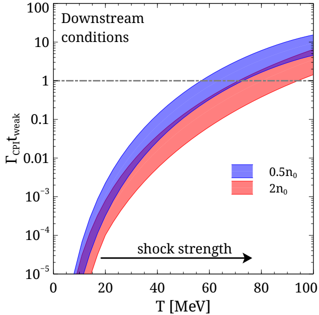
Chiral imbalances of $\mu_5 \gtrsim 10 - 100$ keV could potentially be generated by the strongest of shocks, lasting briefly.

- Look for interesting effects that happen in regions of finite μ_5.

Chiral plasma instability

$$\nabla \times \mathbf{B} - \frac{\partial \mathbf{E}}{\partial t} = \sigma \mathbf{E} + \underbrace{\frac{\alpha}{\pi}\mu_5 \mathbf{B}}_{\text{CME current}}$$

Supports exponentially growing mode if $\mu_5 \neq 0$.
Can mode grow sufficiently during the time that the μ_5 plateau lasts?



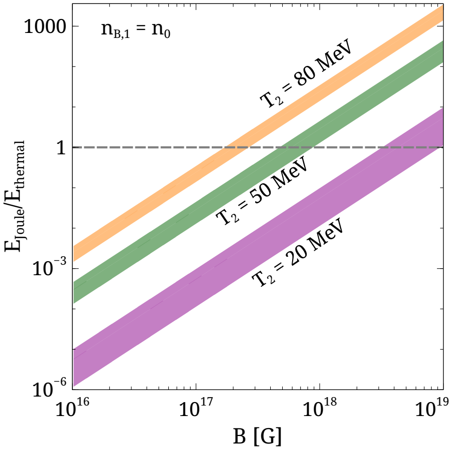
Yes, for very strong shocks. Potentially leads to very strong B-fields!

Joule Heating

The CME current presents an additional Joule heating source.

$$\frac{dW}{dt} \sim \mathbf{E} \cdot \mathbf{J}_{CME} \sim \frac{\alpha^2 \mu_5^2}{\sigma} \mathbf{B}^2$$

Joule heating could exceed shock heating if $B \gtrsim 10^{17}$ G and if the shock is strong enough to generate a sizable μ_5.



Conclusions

- A chiral imbalance is generated wherever matter is out of beta equilibrium
  - Shocks in NS mergers push matter out of beta equilibrium.
  - Urca & chirality flipping balance, leading to plateau in μ_5. Plateau grows with
    - Shock strength
    - Ratio of Urca rate / chirality-flip rate
- Strong shocks could produce large enough μ_5 to cause chiral plasma instability and/or sizable Joule heating.
- Future:
  - Consider neutrino-trapping
  - Put reactions into neutron star merger simulation to see how μ_5 develops.
  - Study the electromagnetic consequences of μ_5