Importance of cooling in triggering the collapse of hypermassive neutron stars

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Motivation

- HMNSs arise following the merger of binary neutron stars when the total mass $< 1.3-1.35 \, M_{\text{TOV,limit}}$ (Shibata, Taniguchi, PRD 73, 064027)

- HMNSs are born hot and rapidly differentially rotating
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- Lifetime: measurable via GWs

GW observations: can constrain B-field strength, bar modes, cooling mechanisms, temperatures, etc.

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- GW J-loss does **not** drive collapse → **Thermal support most important**

**Background: Thermal or Centrifugal support?**
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Question: Is thermal support important or not?
HMNS Relevant Timescales

- GW timescale

\[ t_{GW} \equiv \frac{J}{dJ/dt} \approx \frac{1}{MR^2\Omega^4 e^2} = \frac{R^4}{\epsilon^4 e^2 M^3} \]

\[ \epsilon = \frac{\Omega}{\Omega_{\text{breakup}}} \]
HMNS Relevant Timescales

- GW timescale

\[ t_{GW} \approx 200 \left( \frac{\epsilon}{0.5} \right)^{-4} \left( \frac{e}{0.75} \right)^{-2} \left( \frac{R}{20\text{km}} \right)^4 \left( \frac{M}{2.8M_\odot} \right)^{-3} \text{ ms} \]
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• Alfven (magnetic braking) timescale

\[ t_A \approx \frac{R}{v_A} \approx \frac{R\sqrt{4\pi\rho}}{B} \]
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- **Neutrino cooling timescale**
  \[ t_{cool} \approx 3 \frac{R^2}{\lambda_n c} \]

\[ \lambda_n^{-1} = n\sigma_n \]

\[ \sigma_{\text{scat}} \approx \frac{1}{4} \sigma_0 \left( \frac{E_\nu}{m_e c^2} \right)^2 , \]

\[ \sigma_{\text{abs}} \approx 1.42\sigma_0 \left( \frac{E_\nu}{m_e c^2} \right)^2 \]
HMNS Relevant Timescales

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- Neutrino cooling timescale

\[ t_{cool} \approx 400 \left( \frac{M}{2.8M_{\odot}} \right) \left( \frac{R}{20\text{km}} \right)^{-1} \left( \frac{E_\nu}{10\text{MeV}} \right)^2 \text{ms} \]

Cooling timescale comparable to other timescales
Fully GRHD simulations accounting for HMNS cooling with an effective emissivity

- **Goal**: Assess the importance of shock-induced thermal pressure support in an HMNS formed following the merger of a NSNS

- **Binary NS initial data** (LORENE generated and publicly available):
  a) equal-mass, $n=1$ polytropic
  b) circular orbit and irrotational
  c) quasiequilibrium
  d) satisfy the conformal-thin-sandwich equations
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  - Continue without cooling
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Compare
Inspiral, merger and HMNS formation: Orbital-plane rest-mass density
Merger and HMNS formation:  
Entropy parameter $K = (P_{th} + P_{cold})/P_{cold}$

Red: $K \approx 1.6$  
Yellow: $K \approx 1.4$  
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Total of 40%-60% additional pressure!
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- HMNS rms temperature $\sim 5.5$ MeV $\rightarrow t_{cool} \sim 165$ms

Comparable to the GW time scale!
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Will the HMNS collapse if cooled?
Cooling study: HMNS collapses following cooling

- Choose $t_{\text{cool}}$ sufficiently longer than $t_{\text{dyn}}$, but short enough for computational efficiency.

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- Results
Summary

We demonstrated a few simple points of principle:

- $t_{\text{cool}} \sim t_{\text{GW}} \sim t_{\text{Alfven}}$ is possible

- $P_{\text{thermal}}$ can be an important source of support against collapse for HMNSs formed following the merger of binary NSs.

- Cooling physics is important to include in NSNS merger calculations to accurately determine the lifetime of HMNSs, and to extract physical information (cooling mechanisms, B-fields, bar instabilities etc.) from GW observations.
Fully GRHD simulations accounting for HMNS cooling with an effective emissivity

- Radiative Cooling:
  - Perfect fluid stress-energy tensor:
    \[ T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu + Pg^{\mu\nu} \]
    \[ \varepsilon = \rho_0 (1 + \epsilon_{th} + \epsilon_{cold}) \]

- Contract the energy momentum conservation with \( u^\alpha \) to derive
  \[ \nabla_\alpha T^{\alpha\beta} = G^\beta \]
  \[ \frac{d}{d\tau} \epsilon_{th} = \frac{P_{th}}{\rho_0^2} \frac{d}{d\tau} \rho_0 - \frac{1}{\rho_0} u^\alpha G_\alpha \]
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Effective emissivity
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- Choose
  \[ \frac{1}{\rho_0} u^\alpha G_\alpha = \frac{\epsilon_{\text{th}}}{\tau_c} \]

- Eventually:
  \[ \frac{d}{d\tau} \epsilon_{\text{th}} = \left[ \frac{(\Gamma_{\text{th}} - 1)}{\rho_0} \frac{d\rho_0}{d\tau} - \frac{1}{\tau_c} \right] \epsilon_{\text{th}} \]

Exponential cooling
Cooling study: Additional effects due to cooling

- Angular momentum is conserved to within 3%.

- Cases with cooling emit GWs more strongly.

- Thus, cooling accelerates the collapse by the combined action of two effects:
  a) it drains thermal support
  b) HMNS remnant becomes more compact, emitting GWs more strongly → angular momentum is removed faster.