Dark Matter Heating vs. Rotochemical Heating in Old Neutron Stars

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Based on Koichi Hamaguchi, Natsumi Nagata, KY
arXiv: 1904.04667,
Introduction
Dark matters accrete in neutron stars

We can probe the WIMP DM signature in Neutron stars [Kouvaris, 0708.2362]

- WIMPs accrete in NS by gravity
- If $\sigma_n \gtrsim 10^{-45} \text{ cm}^2$, they lose kinetic energy by scattering with nucleons, and trapped by the NS

Heating rate: $L_{\text{DM}} \sim \rho_{\text{DM}} v_{\text{DM}} \pi b_{\text{max}}^2$ w/ $b_{\text{max}} \sim \sqrt{2GMR/v_{\text{DM}}^2}$
\[ T_s^\infty \sim 3000 \text{ K at } t \gtrsim 10 \text{ Myr} \text{ is a signal of WIMP DM!} \]

\[
\frac{4\pi R^2 \sigma_B T_s^4}{2\pi G M R \rho_{\text{DM}} / v_{\text{DM}}} = 4\pi R^2 \sigma_B T_s^4 = 2\pi G M R \rho_{\text{DM}} / v_{\text{DM}}
\]

Surface temperature of old NSs can probe/constrain WIMP models!
Prospects

Constraints on DM-neutron cross section

Particularly sensitive to 1 GeV - 1 PeV

[Fig. from Baryakhtar+, 1704.01577]
Advantages over the terrestrial experiments

- Velocity on the surface of a typical NS ($M = 1.4 M_\odot$ and $R = 10$ km)

  \[ v_{\text{esc}} = \sqrt{\frac{2GM}{R}} \sim 0.6c \]

- **Inelastic scattering** of electroweak DM (pure $\tilde{H}, \tilde{W}, \ldots$)

  \[ \Delta E = \frac{m_n m_\chi^2 \gamma^2}{m_n^2 + m_\chi^2 + 2\gamma m_n m_\chi} v_{\text{esc}}^2 (1 - \cos \theta_{\text{CM}}) \sim \mathcal{O}(1) \text{ GeV} \]

  c.f. $\Delta E \sim 100$ keV on the earth

- Velocity suppressed scattering

- Spin-dependent scattering

- No detector threshold for light DM

- No limitation from neutrino floor
Can we really see DM heating?

The observation suggests presence of other heating mechanisms. These effects are overlooked in the previous studies of DM heating.

Question: (DM heating) > (other heating) really occurs?

Hotter than theory prediction even if DM is included.
Theory of NS cooling/heating
Standard theory of NS cooling

Thermal evolution equation

\[ C \frac{dT}{dt} = -L_\nu - L_\gamma \]

Heat capacity \((n, p, e, \mu)\)

Surface photon luminosity:

\[ L_\gamma = 4\pi R^2 \sigma_B T_s^4 \]

Neutrino luminosity \(L_\nu\)

- Modified Urca process
  \[ n + N \leftrightarrow p + N + \ell \pm \bar{\nu}_\ell \]
  \(N = n, p; \ell = e, \mu\)

- Cooper pair breaking and formation
  \[ [\tilde{N}\tilde{N}] \rightarrow \tilde{N}\tilde{N} \quad \tilde{N}\tilde{N} \rightarrow [\tilde{N}\tilde{N}] + \nu\bar{\nu} \]

+ minor processes...

Any loophole?
Assumption of $\beta$-equilibrium

Conventional assumption: matters are in $\beta$-equilibrium by weak interaction

$$\Gamma_{n\rightarrow p+\ell} = \Gamma_{p+\ell\rightarrow n}$$

Modified Urca process tries to maintain $\beta$-equilibrium

$$n + N \rightarrow p + N + \ell \pm \bar{\nu}_\ell$$

$\mu_n \neq \mu_p + \mu_e$

$\mu_n = \mu_p + \mu_e$
Pulsar spin-down

**NS spin-down violates β-equilibrium assumption**

The rotation of actual pulsar is slowing down (spin-down)

- Continuous decrease of centrifugal force
  - → change of equilibrium condition
  - → β-equilibrium is broken

\[
\Gamma_{n \rightarrow p + \ell} \neq \Gamma_{p + \ell \rightarrow n}
\]
**Rotochemical heating**

In **non-equilibrium** modified Urca process, imbalance between chemical potentials is converted to heat [Reisenegger, astro-ph/9410035]

\[
C \frac{dT^\infty}{dt} = -L^\infty_\nu - L^\infty_\gamma + L^\infty_{\text{roto}}
\]

\[
L^\infty_{\text{roto}} = \sum_{\ell=e,\mu} \sum_{N=n,p} \int dV e^{2\Phi(r)} (\mu_n - \mu_p - \mu_\ell) \cdot (\Gamma_{n\rightarrow p+\ell} - \Gamma_{p+\ell\rightarrow n})
\]

Consistent with the observations w/o any exotic physics
DM heating vs. rotochemical heating
DM heating vs. rotochemical heating

DM heating
• $T_s \sim 3000$ K
• For nearby NSs, this prediction cannot change by order

Rotochemical heating
• If it operates, typically $T_s \sim 10^{5-6}$ K
• Heating rate is strongly dependent on the initial rotation period $P_0$
• Heating is more efficient for smaller $P_0$

\[ \eta_\ell = \mu_n - \mu_p - \mu_\ell \]

neutron: a, proton: CCDK

\[ P = 1 \text{ s} \quad \dot{P} = 10^{-15} \]
DM heating vs. rotochemical heating

DM heating effect is visible if the initial period is sufficiently large!

\[ P = 1 \text{s} \cdot P = 10^{-15} \}

\[ L_{\text{DM}} < L_{\text{roto}} \]

\[ L_{\text{DM}} > L_{\text{roto}} \text{ for } P_0 \gtrsim 7 \text{ ms} \]
Several studies suggest that typically, $P_0 \sim \mathcal{O}(10 - 100) \text{ ms}$

- **Observed kinematic age**
  [Popov & Turolla, 1204.0632; Noutsos et al., 1301.1265; Igoshev & Popov, 1303.5258]

- **Population synthesis**
  [Faucher-Giguere & Kaspi, astro-ph/0512585; Popov et al., 0910.2190, Gullo’n et al., 1406.6794, 1507.05452]

- **Supernova simulation for proto-NSs**
  [Mu’ller et al., 1811.05483]

Thus we expect
- For many NSs, DM heating $>$ Rotochemical heating
- Some NSs accidentally have $P_0 \sim 1\text{ ms} \rightarrow$ observed high $T_s \sim 10^{5-6} \text{ K}$
Summary

- DM heating predicts $T_s \sim 3000$ K for old NSs
- It can constrain WIMP models which are difficult to probe on the earth
- However, rotochemical heating, inherent in pulsars, can be much stronger than DM heating
- We show that DM heating is theoretically visible even if rotochemical heating operates
Backup
Uncertainty from superfluid gap models

- Critical $P_0$ depends on the choice of gap models
- *(DM heating) $>>$ (rotochemical heating)* for $P_0 \gtrsim 100 \text{ ms}$ *indep. of gap models*
- Recent studies of NS birth period suggest $P_0 = O(100) \text{ ms}$

[Popov & Turolla, 1204.0632; Noutsos et.al., 1301.1265; Igoshev & Popov, 1303.5258; Faucher-Giguere & Kaspi, astro-ph/0512585; Popov et al., 0910.2190; Gullo'n et al., 1406.6794, 1507.05452; Müller et al., 1811.05483]