Dark Matter Thermalization in Neutron Stars

Bridget Bertoni

PRD 88, 123505 with Ann Nelson and Sanjay Reddy

University of Washington

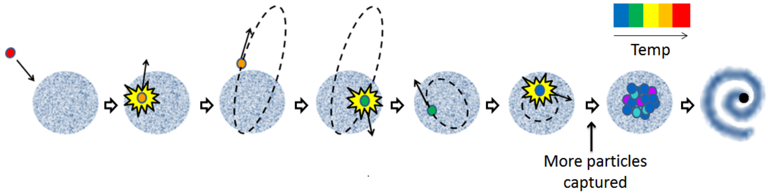
bbertoni@uw.edu

May 5, 2014

Dark Matter (DM)

- know a few things: not too hot, $\Omega_{DM} \approx 0.26$, interacts gravitationally and very weakly (if at all) via other forces
- many searches: direct detection, indirect detection, collider

Use neutron stars to further constrain DM:

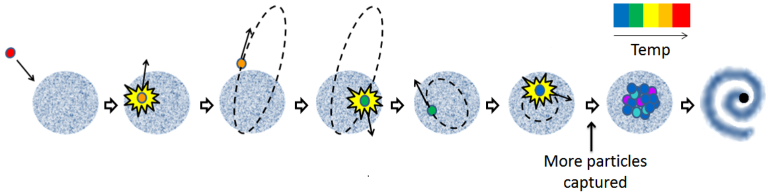


10 billion year old neutron stars $\Rightarrow$ DM parameters that allow for this scenario in less than 10 billion years are ruled out

Dark Matter (DM)

- know a few things: not too hot, $\Omega_{DM} \approx 0.26$, interacts gravitationally and very weakly (if at all) via other forces
- many searches: direct detection, indirect detection, collider

Use neutron stars to further constrain DM:



10 billion year old neutron stars $\Rightarrow$ DM parameters that allow for this scenario in less than 10 billion years are ruled out

Low energy/momentum exchange collisions contribute most to the DM thermalization time

Previous calculations* assumed that DM interacts with neutrons and that neutron stars are made up of non-interacting neutrons, and then constrained $\sigma_{\chi n}(m_\chi)$.

We expand on these calculations by including

- more rigorous Pauli blocking and kinematics
- electron scattering
- interactions: superfluidity and superconductivity

**e.g. hep-ph/1103.5472, astro-ph/1104.0382, hep-ph/1301.6811, hep-ph/1301.0036*

Previous calculations* assumed that DM interacts with neutrons and that neutron stars are made up of non-interacting neutrons, and then constrained $\sigma_{\chi n}(m_\chi)$.

We expand on these calculations by including

- more rigorous Pauli blocking and kinematics
- electron scattering
- interactions: superfluidity and superconductivity

We consider complex scalar DM which couples to regular matter via some heavy, vector boson:

$$\mathcal{L}_{int} = \frac{1}{M^2}\ell_\mu \left(g_V j_V^\mu + g_A j_A^\mu\right)$$

$$\ell_\mu = \partial_\mu \chi^\dagger \chi - \chi^\dagger \partial_\mu \chi \ , \ \ j_V^\mu = \bar{\psi}\gamma^\mu\psi \ , \text{ and } \ j_A^\mu = \bar{\psi}\gamma^\mu\gamma_5\psi$$

**e.g. hep-ph/1103.5472, astro-ph/1104.0382, hep-ph/1301.6811, hep-ph/1301.0036*

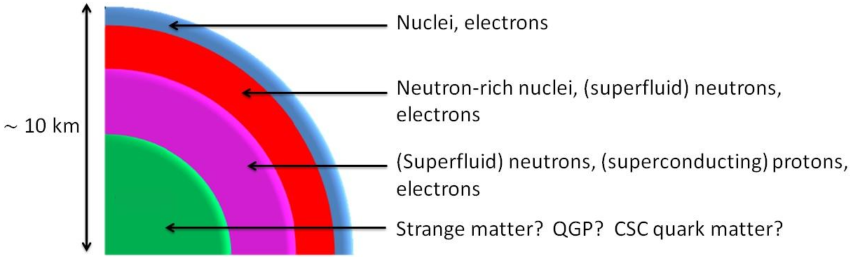
The thermalization time τ is the average time it takes for an incident DM particle to start having collisions which have an energy transfer less than the temperature ($\langle q_0 \rangle \lesssim T$)

$$\tau = \text{time for } 1^{\text{st}} \text{ collision} + \text{time for } 2^{\text{nd}} \text{ collision} + \ldots$$

The time for each DM collision with a (non-interacting) fermion i is

$$\Gamma^{-1} = \left(2 \int \frac{d^3 p}{(2\pi)^3} \int \frac{d^3 k'}{(2\pi)^3 2E_{k'}} \int \frac{d^3 p'}{(2\pi)^3 2E_{p'}} (2\pi)^4 \delta^4(p^\mu + k^\mu - p'^\mu - k'^\mu) \times \frac{\langle |\mathcal{M}|^2 \rangle}{2E_p 2E_k} n_F(E_p) \left(1 - n_F(E_{p'})\right) \left(1 + n_B(E_{k'})\right) \right)^{-1}$$

$\tau \geq 10$ billion years $\Rightarrow$ maximum DM scattering cross section

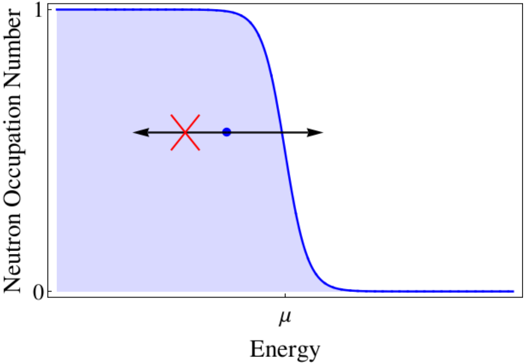


Three cases:

1. degenerate Fermi gas of neutrons
2. superfluid neutrons (and electrons and protons)
3. color superconducting (CSC) quark matter

DM thermalization with a degen., Fermi gas of neutrons

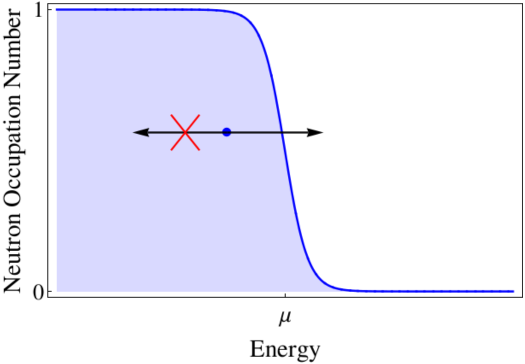
- Pauli Blocking (decreases the number of neutrons that can interact)



- Kinematics (limits the kinds of collisions that occur)
  - e.g. for a low momentum collision, $q_0 < v_i q$

DM thermalization with a degen., Fermi gas of neutrons

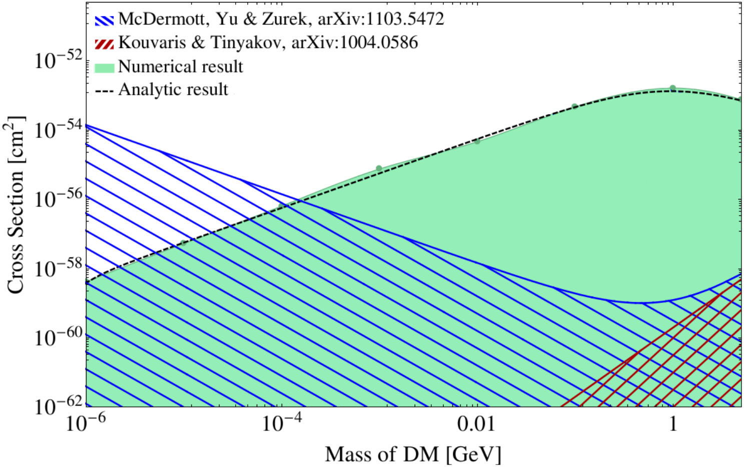
- Pauli Blocking (decreases the number of neutrons that can interact)



- Kinematics (limits the kinds of collisions that occur)
  - e.g. for a low momentum collision, $q_0 < v_i q$

Previous calculations included an estimate of Pauli blocking and had no kinematical phase space constraints.

DM thermalization with a degen., Fermi gas of neutrons



DM thermalization with superfluid neutrons

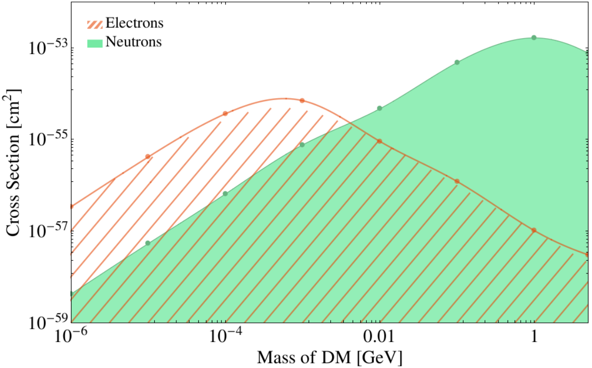
- At low T, neutrons form Cooper pairs that condense
- End result is paired neutrons and a superfluid phonon (GB)

- Need high energy/momentum to interact with paired neutrons
- Dominant way for low energy DM to scatter is by radiating phonons
  - Only kinematically allowed when $v_\chi > c_s \Rightarrow$ no DM thermalization

DM thermalization with superfluid neutrons

- At low T, neutrons form Cooper pairs that condense
- End result is paired neutrons and a superfluid phonon (GB)

- Need high energy/momentum to interact with paired neutrons
- Dominant way for low energy DM to scatter is by radiating phonons
  - Only kinematically allowed when $v_\chi > c_s \Rightarrow$ no DM thermalization



Summary of Results

Including rigorous kinematics resulted in DM thermalization times that were quantitatively and qualitatively different from past results.

Previously neglected DM-electron scattering is important—it's the only relevant DM thermalization mechanism when the neutrons form a superfluid and the protons form a superconductor.

Exotic neutron star cores with CSC quark matter give rise to very large thermalization times $\Rightarrow$ this could prevent black hole formation and if DM is discovered, could explain why neutron stars get so old.