Light dark matter scattering in outer neutron star crusts

M. Cermeño[1], M. A. Pérez-García[1], J. Silk[2]

[1] Department of Fundamental Physics, University of Salamanca, Spain
[2] Institute d'Astrophysique, Paris, France

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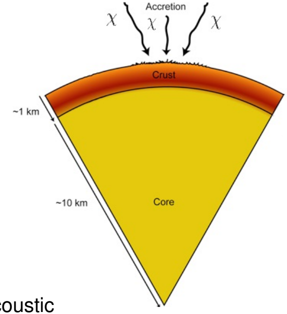
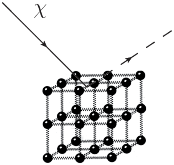
Introduction

- Interaction: fermionic light dark matter (LDM) particles χ and nuclei A in periodically arranged nuclei in the neutron star outer crust ($\rho \simeq 2\,10^6 - 4\,10^{11}\ \mathrm{g/cm^3}$)
- Neutron stars (NS) provide a gravitational boost to DM particles, using $R_{NS} = 12$ km and $M_{NS} = 1.5 M_{\odot}$, $\beta_{NS} = \frac{v}{c} = \sqrt{\frac{2GM_{NS}}{R_{NS}}} \sim 0.6$

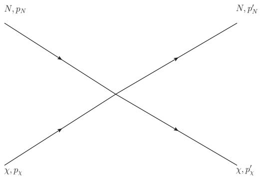


- Effect of LDM scattering in the production of acoustic phonons (momentum $\vec{k}$, linear dispersion relation $\omega_k = c_l|\vec{k}|$, c_l the sound speed) in the outer NS crust.
- We calculate the single phonon excitation rate $R_k^{(0)}$ $\Rightarrow$ the change in the ion thermal conductivity κ_{ii} $\Rightarrow$ impact on cooling behavior of NSs.



Dark matter particle-nucleon interaction

$$\mathcal{L}_I = \sum_{N=n,p} g_{s,N}\chi\overline{\chi}N\overline{N} + g_{v,N}\chi\gamma^\mu\overline{\chi}N\gamma_\mu\overline{N}$$



$$p_N = (E_N, \vec{p_N}),\ p'_N = (E'_N, \vec{p'_N})$$
$$p_\chi = (E_\chi, \vec{p_\chi}),\ p'_\chi = (E'_\chi, \vec{p'_\chi})$$
$$q = p'_N - p_N = p_\chi - p'_\chi$$
$$q_0 = E'_N - E_N = E_\chi - E'_\chi$$

$g_{s,N} \sim m_q/{\Lambda_s}^3 \sim 1\ 10^{-15}\ \mathrm{MeV}^{-2}$ and $g_{v,N} \sim 1/{\Lambda_v}^2 \sim 1\ 10^{-12}\ \mathrm{MeV}^{-2}$ are the effective scalar and vector coupling constants, with $\Lambda_s \gtrsim 100$ GeV and $\Lambda_v \gtrsim 1$ TeV the suppression mass scales for scalar and vector cases and m_q the quark mass.

$$\begin{aligned}|\overline{\mathcal{M}}_{\chi N}|^2 =& 4g_{s,N}^2[(p_N p'_N + m_N^2)(p_\chi p'_\chi + m_\chi^2)]+\\ & 8g_{v,N}^2[2m_N^2 m_\chi^2 - m_N^2 p'_\chi p_\chi - m_\chi^2 p_N p'_\chi + (p'_\chi p'_N)(p_N p_\chi) + (p'_N p_\chi)(p_N p'_\chi)]+\\ & 8g_{s,N}g_{v,N}[m_N m_\chi (p_N + p'_N)(p_\chi + p'_\chi)]\end{aligned}$$

Density dependence is retained using $|\vec{p}_N| \sim |\vec{p'}_N| \sim |\vec{p}_{FN}| \sim (3\pi^2 n_0 Y_N)^{1/3}$ with $Y_p = Z/A$, $Y_n = (A-Z)/A$ and $n_0 = 0.17\ \mathrm{fm}^{-3}$ the saturation density.

Phonon excitation rate

- Our aim is to obtain **the single acoustic phonon excitation rate** *per mode* $R^{(0)}_{\vec{k},\lambda}$
- Fermi golden rule $R^{(0)}_{\vec{k},\lambda} = 2\pi\delta(E_f - E_i)|\langle f|\mathcal{V}|i\rangle|^2$
- $\mathcal{V}(\vec{r}) = \sum_j \delta^3(\vec{r} - \vec{r_j})\, \frac{2\pi a}{m_\chi}$ potential felt by an interacting DM particle when approaching a nucleus in the periodic lattice being a the scattering length
- Using the Born approximation ($|(\vec{p_\chi} - \vec{p'_\chi}).\vec{r'}| \ll 1$, $|\vec{r'}|$ a typical target size) $\sigma_{\chi A} \simeq 4\pi a^2$ in the center of mass frame for this potential
- $\frac{d\sigma_{\chi A}}{d\Omega}|_{CM} = \frac{|\overline{\mathcal{M}}_{\chi A}|^2}{64\pi^2 s}$, with $|\overline{\mathcal{M}}_{\chi A}|^2$ the spin-averaged scattering amplitude calculated summing coherently over protons and neutrons matrix elements $|\overline{\mathcal{M}}_N|^2$, and $s = (p_A + p_\chi)^2$ where p_A is the nucleus four-momenta
- $\Rightarrow \sigma_{A,\chi} = 4\pi a^2 = m_A^2 \frac{\left(\frac{Z}{m_p}\sqrt{|\tilde{\mathcal{M}}_p|^2} + \frac{(A-Z)}{m_n}\sqrt{|\tilde{\mathcal{M}}_n|^2}\right)^2}{16\pi(m_\chi + m_A)^2}$, taking $|\vec{p_\chi}| << m_\chi$ and $|\vec{p_A}| << m_A$, where $|\tilde{\mathcal{M}}_N|^2 \equiv \int_{-1}^{1} 2\pi d(\cos\theta_\chi)|\overline{\mathcal{M}}_{\chi N}|^2$

Phonon excitation rate

The single acoustic phonon excitation rate per unit volume

$$R_k^{(0)} = \frac{8\pi^4 n_A^2}{(2\pi)^6 m_\chi^2 m_A c_l} \int_0^\infty |\vec{p_\chi}| d|\vec{p_\chi}| f_\chi(\vec{p_\chi}) |E_\chi - |\vec{k}| c_l| a^2$$

- $f_\chi(\vec{p_\chi}) = \frac{n_\chi \mu}{4\pi m_\chi^3 K_2(\mu)} e^{-\mu\sqrt{1+\frac{|\vec{p_\chi}|^2}{m_\chi^2}}}$ Maxwell-Jüttner distribution function for relativistic incoming χ, $\mu = \frac{m_\chi}{k_B T} \approx 6.7$ for $\sqrt{< v^2 >} \sim 0.6$, $K_2(\mu)$ the modified Bessel function of second kind, and n_χ the DM number density
- $c_l = \frac{\omega_p/3}{(6\pi^2 n_A)^{1/3}}$ the sound speed in a bbc lattice, being $\omega_p = \sqrt{\frac{4\pi n_A Z^2 e^2}{k_B^2 m_A}}$ the plasma frequency associated to a medium of ions with number density n_A, baryonic number A, electric charge Ze and mass m_A
- From kinematical restrictions $0 \leq |\vec{k}| \leq 2\left(\frac{c_l E_\chi}{(c_l^2-1)} + \frac{|\vec{p_\chi}|}{|c_l^2-1|}\right)$

Results: Phonon excitation rate

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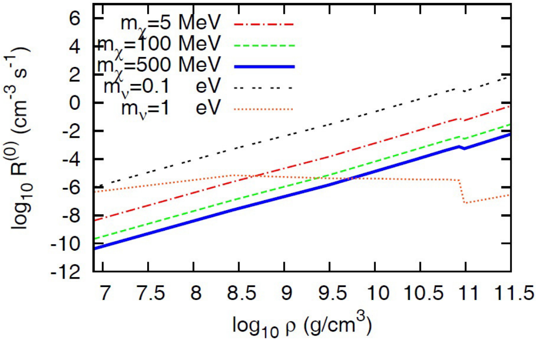

For $m_\chi = 500, 100$ and 5 MeV, $n_\chi / n_{0,\chi} = 10$,
where $n_{0,\chi} = 0.3$ GeV/cm^3 is the galactic local DM mass density.
Neutrino contribution at $|\vec{k}| \to 0$, $R_{\nu 0}$, is also shown for $m_\nu = 0.1, 1$ eV, being
$R_\nu^{(0)}(\vec{k}) = R_{\nu 0} e^{\frac{-a|\vec{k}|}{1\mathrm{eV}}}$ where a is a constant which depends on neutrino masses.

Impact on thermal conductivity

- Global thermal conductivity is given by $\kappa = \kappa_e + \kappa_i$
- Ion thermal conductivity $\kappa_i^{-1} = \kappa_{ii}^{-1} + \kappa_{ie}^{-1}$
- $\kappa_{ii} \equiv \kappa_{ph}$ and κ_{ie} are ion-ion and ion-electron partial conductivities
- $\kappa_{ii} = \frac{1}{3} k_B C_A n_A c_l L_{ph}$
- $C_A = 9\left(\frac{T}{T_D}\right)^3 \int_0^{T_D/T} \frac{x^4 e^x dx}{(e^x-1)^2}$ is the phonon (dimensionless) heat capacity *per ion*
- L_{ph} is the effective phonon mean free path
- At temperature T standard thermal contribution gives $L_{ph} \sim 1/N_{0,k\lambda}$ where $N_{0,k\lambda} = (e^{\omega_{k\lambda}/k_B T} - 1)^{-1}$
- Contribution from DM can be obtained by the net number of phonons $N_{k\lambda}$ that results from the competition of thermal and scattering excitation and stimulated emission

$$N_{k\lambda} \simeq N_{0,k\lambda} + R_k^{(0)} \delta V \delta t - \int \frac{d^3\vec{p}}{n_\chi} f_\chi(\vec{p}) \tilde{R}_k^{(0)} N_{0,k\lambda} e^{\frac{\omega_{k,\lambda}+\vec{k}.\vec{v}}{(\gamma(\vec{p_\chi})-1)m_\chi}} \delta V \delta t$$

where $\tilde{R}_k^{(0)}$ is the single phonon excitation rate for each particular momentum value, $\gamma(\vec{p_\chi}) = \frac{1}{\sqrt{1-\left(\frac{|\vec{p_\chi}|}{E_\chi}\right)^2}}$ is the Lorentz factor and $v \sim 10^{-2}$ the NS galactic drift velocity.

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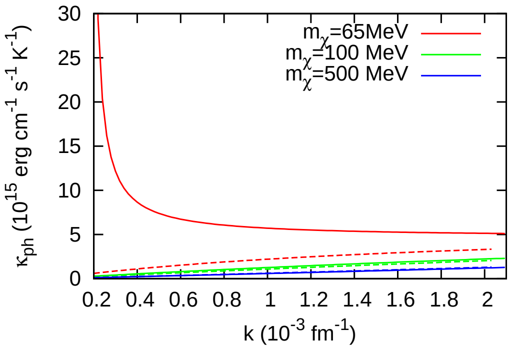
Results: Ion-ion thermal conductivity



At $T = 10^8$ K and $n_\chi / n_{0,\chi} = 100$.
Solid lines for ^{118}Kr ($\rho = 4.27\ 10^{11}$ g/cm^3)
and dashed lines for ^{120}Sr ($\rho = 3.97\ 10^{11}$ g/cm^3).

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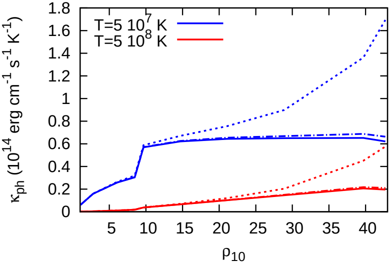

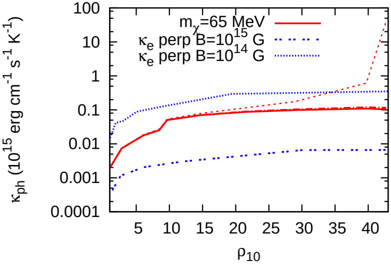

$m_\chi = 100$ MeV. Solid, dash-dotted and dashed lines depict the cases with no DM and with LDM for $n_\chi/n_{0\chi} = 10, 100$. We use a fixed value for $|\vec{k}|$.

$T = 10^8$ K and $m_\chi = 65$ MeV. Solid, dot-dashed and dashed lines correspond to cases with no DM, $n_\chi/n_{0,\chi} = 10,\ 100$. We use a fixed value for $|\vec{k}|$.

Conclusions

- We calculate the single phonon excitation rate $R_k^{(0)}$ in the outer crust of a NS due to scattering from LDM particles gravitationally boosted into the star.
- LDM effects cause a modification of the net number of phonons in the lattice as compared to the standard thermal result.
- $R_k^{(0)}$ is constant with the phonon momentum and much larger than for cosmological neutrinos at finite $|\vec{k}|$.
- We estimate the contribution of LDM particles to the ion-ion thermal conductivity in the outer crust and find that it is enhanced at small $|\vec{k}|$ for small DM particle masses at densities $> 4\,10^{11}\ \mathrm{g/cm^3}$, whereas for larger m_χ remains mostly constant.
- Phonon thermal conductivity can be significantly enhanced at large densities compared to the standard thermal result without DM.
- The electronic contribution to the conductivity for magnetized realistic scenarios in the perpendicular direction to a magnetic field B falls below the enhanced DM value for large densities.
- Since the global conductivity is $\kappa = \kappa_e + \kappa_{ph}$, the obtained result is expected to contribute to the reduction of the difference in heat conduction in both directions and thus to the isotropization of the NS surface temperature pattern.

THANKS FOR YOUR ATTENTION.

Temperature anisotropies

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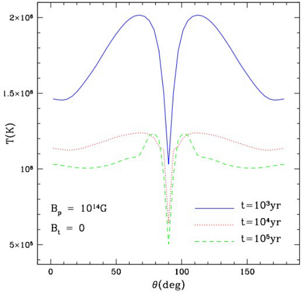
- Theoretical models predict anisotropies in the surface temperature produced by high magnetic fields.
- Under the presence of a strong field, the conductivity becomes anisotropic, due to the fact that the electrons move more easily along the field lines than across them.



R. Perna, D. Viganò, J. A. Pons, N. Rea, MNRAS, 434 (2013)

- The thermal spectra and pulse profiles expected for different magnetic fields are computed in the bibliography (R. Perna, D. Viganò, J. A. Pons, N. Rea, MNRAS, 434 (2013) 2362 and MNRAS, 443 (2014) 31).
- Features of the thermal spectra and pulse profiles predicted by theoretical models are observed in some dense objects (SNR Kes 79, SGR J182213-1606, SGR 0418+5729, RX J0806.4123 etc). These observations support the idea of anisotropic surface temperature distributions.