DM annihilation with pseudoscalar mediators inside dense stars

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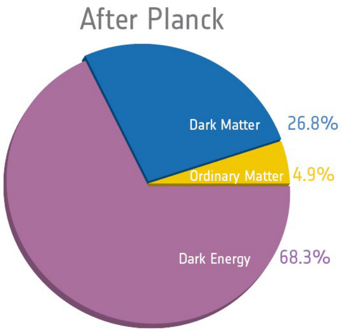
Why DM?

- DM constitutes the most abundant type of matter in our universe $\sim 85\ \%$
- Theoretical and experimental searches (direct detection, indirect detection, colliders...)
- SM particle physics cannot explain the nature of DM $\Rightarrow$ the model must be extended

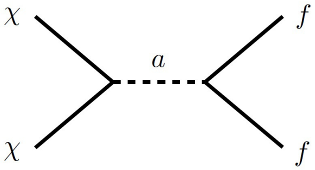


Simplified pseudoscalar model

$$\mathcal{L}_I = -i\frac{g_\chi}{\sqrt{2}} a\bar{\chi}\gamma_5\chi - ig_0\frac{g_f}{\sqrt{2}} a\bar{f}\gamma_5 f$$

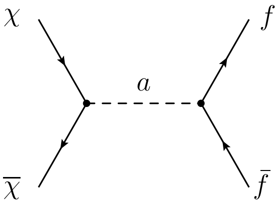
C. Boehm et al., JCAP 1405 (2014) 009; M. J. Dolan et al., JHEP 1503 (2015) 171; C. Arina et al., PRL 114 (2015) 011301

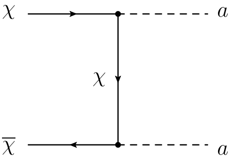
χ dirac fermionic DM particle and a pseudoscalar mediator
g_χ DM-mediator coupling
g_f SM fermions-mediator coupling. We restrict to $g_f = 1$ flavor-universal model
g_0 scaling factor

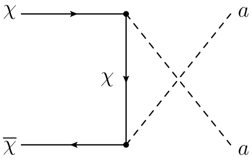


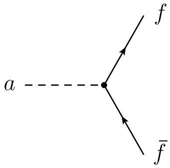
Indirect signals: Main annihilations channels

For $m_\chi < m_{\text{Higgs}}$, $m_a < m_\chi$, the relevant annihilation processes









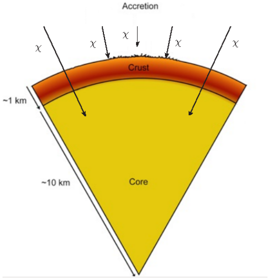
Accretion of DM by NSs

- An average Neutron Star (NS) has a radius $R \simeq 12$ km and mass $M \simeq 1.5 M_{\odot}$, large compactness $\sim GM/R$
- $\rho_b \sim 2\rho_0$, $\rho_0 \simeq 2.4 \times 10^{14}$ g/cm^3
- NSs are very efficient DM accretors
- Capture rate,

  C. Kouvaris, Phys. Rev. D 77 (2008) 023006

$$C_\chi \simeq 1.8 \times 10^{25} \left(\frac{1\,\mathrm{GeV}}{m_\chi} \right) \left(\frac{\rho_\chi}{\rho_{\chi,0}} \right) f_\chi \ \mathrm{s}^{-1}$$

  with ρ_χ DM mass density, $\rho_{\chi,0} \simeq 0.3\ \frac{\mathrm{GeV}}{\mathrm{cm}^3}$ and $f_\chi \sim 1$ if $\sigma_{\chi N} \gtrsim \sigma_0$, otherwise $f_\chi \sim 0.45 \frac{\sigma_{\chi N}}{\sigma_0}$,
  $\sigma_0 = \frac{m_n R_{NS}^2}{M_{NS}} \sim 10^{-45}$ cm^2
- NSs are born as hot lepton-rich objects with $T \sim 20$ MeV evolving into cold $T \sim 10$ keV neutron-rich ones (in $\sim 10^5$ years) by ν emission



Local Energy Emissivity

If DM is accreted into NSs and then annihilate into SM fermions, $\chi\chi \to f\bar{f}$, or pseudoscalars, $\chi\chi \to aa$ with subsequent decay $a \to f\bar{f}$, $\Rightarrow$ the local energy emissivity is a key quantity

$$Q_E = \frac{dE}{dVdt} = 4\int d\Phi(E_1 + E_2)\,|\overline{\mathcal{M}}|^2 f(f_1, f_2, f_3, f_4)$$

- $d\Phi = \frac{d^3p_1}{2(2\pi)^3E_1}\frac{d^3p_2}{2(2\pi)^3E_2}\frac{d^3p_3}{2(2\pi)^3E_3}\frac{d^3p_4}{2(2\pi)^3E_4}(2\pi)^4\delta^4(p_1+p_2-p_3-p_4)$
- For $\chi\chi \to f\bar{f}$, $\quad f(f_1, f_2, f_3, f_4) = f_\chi(E_1)f_{\bar{\chi}}(E_2)(1-f_f(E_3))(1-f_{\bar{f}}(E_4))$
- For $\chi\chi \to aa$, $\quad f(f_1, f_2, f_3, f_4) = f_\chi(E_1)f_{\bar{\chi}}(E_2)f_a(E_3)f_a(E_4)$
- f_χ, f_f and f_a are the local stellar distribution functions for DM, fermionic and pseudoscalar particles
- As $E_{F,\chi} = \frac{(3\pi^2 n_\chi)^{\frac{2}{3}}}{2m_\chi} \ll k_B T$, we can approximate $f_\chi = \left(\frac{1}{2\pi m_\chi k_B T}\right)^{\frac{3}{2}} n_\chi(r) e^{\frac{-|\vec{p}_i|^2}{2m_\chi T}}$,
  $n_\chi(r) = n_{0,\chi}e^{-(r/r_{\rm th})^2}$, with $r_{\rm th} = \sqrt{\frac{3k_BT}{2\pi G\rho_n m_\chi}}$, $n_{0,\chi}$ is the central value
- In order to analyze astrophysical consequences we restrict final fermion states to $\nu' s$, assumming neutrinos do not get trapped after being produced and therefore $f_\nu \sim 0$

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$$Q_E = \frac{dE}{dVdt} = 4\int d\Phi(E_1 + E_2)\,|\overline{\mathcal{M}}|^2 f(f_1, f_2, f_3, f_4)$$

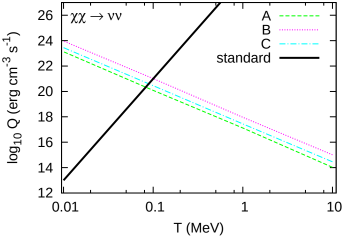
- $|\overline{\mathcal{M}}_{f\bar{f}}|^2 = \frac{g_\chi^2 g_f^2}{4}\frac{s^2}{(s-m_a^2)^2+E_{\vec{q}}^2\Gamma^2}$, $s = (p_1+p_2)^2 = (p_3+p_4)^2$, $E_{\vec{q}} = \sqrt{|\vec{q}|^2 + m_a^2}$ and Γ the pseudoscalar particle decay width through the reaction $a \to f\bar{f}$
- $|\overline{\mathcal{M}}_{aa}|^2 = \frac{-g_\chi^4}{2}\left(\mathcal{M}_T\mathcal{M}_T^* + \mathcal{M}_U\mathcal{M}_U^* + \mathcal{M}_{mixing}\mathcal{M}_{mixing}^*\right)$

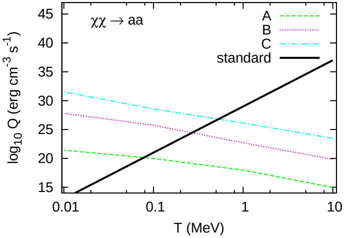
  $\mathcal{M}_T\mathcal{M}_T^* = \frac{(t-m_a)^2-m_\chi^2(m_\chi^2+2m_a^2)}{(t-m_\chi^2)^2}$ $\qquad$ $\mathcal{M}_U\mathcal{M}_U^* = \frac{(u-m_a)^2-m_\chi^2(m_\chi^2+2m_a^2)}{(u-m_\chi^2)^2}$

  $\mathcal{M}_{mixing}\mathcal{M}_{mixing}^* = \frac{(s-2m_\chi^2)(2m_a^2-s)+2m_\chi^2(m_\chi^2+2m_a^2-2s)}{(t-m_\chi^2)(u-m_\chi^2)} - \frac{2(t-m_a^2)^2}{(t-m_\chi^2)(u-m_\chi^2)} + 2\frac{2m_\chi^2-s}{(u-m_\chi^2)}$

  $s = (p_1+p_2)^2$, $t = (p_1-p_3)^2$ and $u = 2m_\chi^2 + 2m_a^2 - s - t$ are Mandelstam variables
- Integration details are given in M. Cermeño, M. A. Pérez-García, R. Lineros, arXiv:1705.03012

Results: Local Energy Emissivity





Stardard emission refers to MURCA processes which are the standard cooling processes that release neutrinos with an associated emissitity $Q_E^{\mathrm{MURCA}} \sim 10^{21} R(\frac{T}{0.1\,\mathrm{MeV}})^8\ \mathrm{erg\,cm^{-3}\,s^{-1}}$. R is a control function of order unity.

Model	m_χ [GeV]	m_a [GeV]	g_χ	g_0
A	0.1	0.05	7.5×10^{-3}	7.5×10^{-3}
B	1	0.05	1.2×10^{-1}	2×10^{-3}
C	30	1	6×10^{-1}	5×10^{-5}

Expected impact on internal temperatures

The temperature evolution equation for $r < 9$ km (core region)

$$\frac{2}{r}T'(r) + T''(r) = \kappa^{-1}[Q_\nu - H(r)]$$

$\kappa = \kappa_b + \kappa_e$ thermal conductivity, $Q_\nu \sim Q_E^{\mathrm{MURCA}}$, $H(r) = Q_E^{aa}(r)$ DM heating term, where this r dependence is due to the fact $Q_E^{aa}(r) \propto n_\chi^2(r)$ and we define $H_0 = H(0)$

- Fixing $T(r) \equiv \bar{T}$, $T(r) = T_0 + \alpha\frac{r^2}{6} - \beta\frac{r_0^2}{2}[1 - \sqrt{\pi}\frac{r_0}{2}\frac{\mathrm{erf(r/r_0)}}{r}]$, with erf (x) the error function, $\alpha = Q_\nu(\bar{T})/\kappa(\bar{T})$ and $\beta = H_0(\bar{T})/\kappa(\bar{T})$ and T_0 the central temperature
- At $\bar{T} = 10^9 K \sim 0.1$ MeV the net effect of models B ($\beta \sim 10^5$ K/cm^2) and C ($\beta \sim 10^7$ K/cm^2), is heating the central volume while model A ($\beta \sim 10^{-2}$ K/cm^2) provides net cooling, $\alpha \sim 0.2$ K/cm^2
- Only a full dynamical simulation will determine how the cooling mechanisms adjust inside the star as a temporal sequence

Conclusions

- We have calculated the energy emissivity in DM annihilation from a gravitationally accreted fraction inside dense nucleon stars due to the reactions $\chi\chi \to \nu\nu$ and $\chi\chi \to aa$, with subsequent decay $a \to \nu\nu$
- We use parameter sets which respect constraints of direct detection limits and cosmological bounds or even tighter Kaon bounds
- We obtain that the neutrino emissivity given by the reaction $\chi\chi \to aa$ is largely enhanced with respect to the direct production of neutrinos $\chi\chi \to \nu\nu$
- We show that, in inner stellar regions, where most of the DM population distribution exists, the emissivity into neutrinos can be enhanced orders of magnitude with respect to the MURCA standard neutrino processes
- This may indicate possible warmer inner temperature stellar profiles, but only a full dynamical simulation will be able to obtain how the cooling mechanisms adjust inside the star as a temporal sequence