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Dark Matter scattering in a dense medium

Dark Matter scattering in a dense medium

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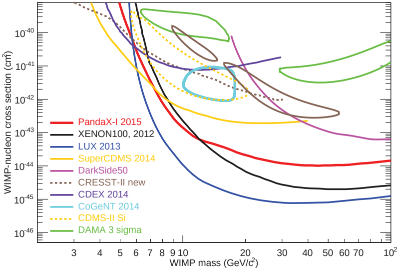
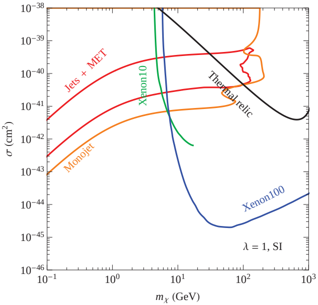
Scenario and interaction χ-N

We consider interaction DM and finite $\mu - T$ nucleon matter:

- Dark matter Dirac fermionic particle,
  $m_\chi = \{500, 800\}\,\mathrm{MeV}, \{1, 5\}\,\mathrm{GeV}$.
- Nucleon vacuum/effective mass $m_N = 939\ \mathrm{MeV}, \mathrm{m_N^*}$.
- Scalar mediator ϕ
- Ambient dense medium: average neutron star
  mass $M_{NS} = 1.5\,M_\odot$
  radius $R_{NS} = 12\ \mathrm{km}$
  temperature $T \sim 10^{-2 \div 1}\,\mathrm{MeV}$

DM Direct search vs collider search limits

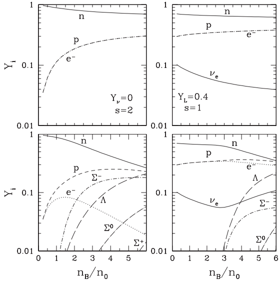


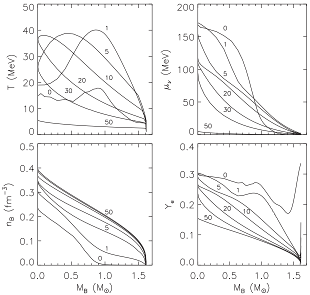


Recoil events: DM search
arXiv:1505.0077

Dirac DM arXiv: 1308.1612

Finite density and T in an evolving dense star





particle population fraction and T in an evolving NS
Pons et al, ApJ 513 (1999)

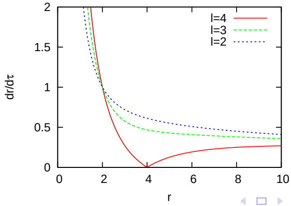
Incident χ velocity into the NS

- Gravitationally accretted DM. We use static approx. Schwarzschild metric (t, r, θ, ϕ):

$$ds^2 = -\left(1 - \frac{2GM_{NS}}{c^2 r}\right) c^2 dt^2 + \left(1 - \frac{2GM_{NS}}{c^2 r}\right)^{-1} dr^2 + r^2 (d\theta^2 + sen^2\theta d\phi^2)$$

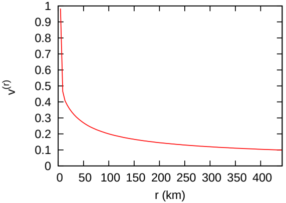
- Geodesic equation ($l = L/m$, $\mathrm{R}_{Sch} = 4.35,\ \mathrm{km}$) :

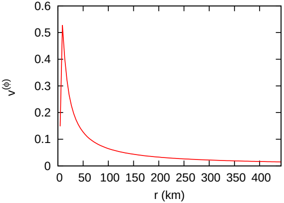
$$\frac{v^{(r)}}{c} = \frac{dr}{d\tau} = \pm \frac{1}{r^2} \sqrt{r\left(2GM_{NS} r^2 + \frac{2GM_{NS} l^2}{c^2} - r l^2\right)},\ \frac{\mathrm{v}^{(\phi)}}{\mathrm{c}} = \frac{1}{\mathrm{r}}\left(1 - \frac{2\mathrm{GM_{NS}}}{\mathrm{c^2 r}}\right)^{\frac{1}{2}}$$

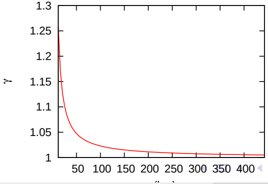


Incident χ velocity into the NS

- Incident modulus: $v = v_{gal} + \sqrt{\frac{2GM_{NS}}{rc^2}}c$ @ $R_{NS} = 12$ km: $v \simeq 0.6c$
- Mild Lorentz factor $(l = 3)$: $\gamma(v) = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} \simeq 1.26$





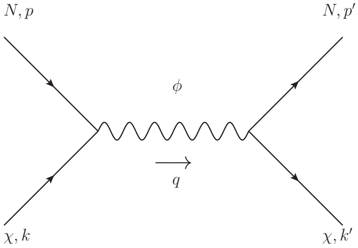


Quasi-elastic scattering limit

- We consider a χ-DM particle scattering a nucleon according to a quasi-elastic pattern
- De Broglie wavelength for $m_\chi \sim 5 \times 10^2 - 5 \times 10^3$ MeV $\rightarrow$ dense nuclear system picture of target particles
- Since $E_\chi = \gamma m_\chi c^2 \simeq 1.26 m_\chi c^2 \Rightarrow$
  $|\vec{k}|c = \sqrt{E_\chi^2 - m_\chi^2 c^4} = \sqrt{\gamma^2 - 1} m_\chi c^2 \simeq 0.77 m_\chi c^2$
- $\lambda\!\!\!^{-} = \frac{\hbar c}{|\vec{k}|c} \simeq \frac{197.33\,\mathrm{MeV\,fm}}{0.77 m_\chi c^2}$
- Additional form factors $F(|\vec{q}|^2)$ can consider coherent/inner structures.

Dark matter-Nucleon interaction

We assume a massive boson mediator



point-like interacion $\sim g_{N\Phi}$

$q^2 <<< M_\phi^2$:

incoming N: $p = (E, \vec{p})$,

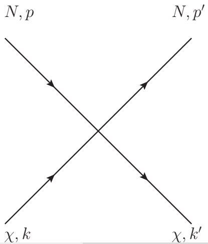
outgoing N: $p' = (E', \vec{p'})$

incoming χ: $k = (\omega, \vec{k})$,

outgoing χ: $p' = (\omega', \vec{k'})$

momentum transfer:

$q = p' - p = k - k'$



Dark matter-Nucleon interaction

Differential cross-section (Tree level):

$$d\sigma = \frac{|\overline{\mathcal{M}}_{\chi-\mathcal{N}}|^2}{4\sqrt{(p.k)^2 - m_N^2 m_\chi^2}} f_N(E)(1 - f_N(E'))f_\chi(\omega)(1 - f_\chi(\omega'))d\Phi(p,p',k,k')$$

Lorentz invariant phase element

$$d\Phi(p,p',k,k') = (2\pi)^4\delta^{(4)}(p + k - p' - k')\frac{d^3\vec{p'}}{(2\pi)^3 2E'}\frac{d^3\vec{k'}}{(2\pi)^3 2\omega'}$$

$f_i(E) = \frac{1}{1+e^{\frac{E-\mu_i}{T}}}$ $i = e, N, \chi$ Fermi-Dirac distribution functions.

- Small dark matter fraction, no DM blocking: all outgoing states allowed: $f_\chi(\omega) \approx 1 \quad f_\chi(\omega') \approx 0$
- Nuclear matter density: $n_B = n_{sat} = 0.17\,\mathrm{fm}^{-3}$.
- $E_{Fi} \simeq 998\,\mathrm{MeV}$, $T \sim [10^{-2}, 30]\,\mathrm{MeV}$

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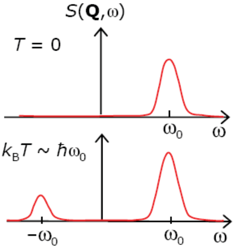
Detailed Balance for finite $\mu - T$



Outgoing states and detailed balance factor: $S_{DB}(q_0, T) = \frac{1}{1-e^{-\frac{|q_0|}{T}}}$

Differential cross-section reads finite T and μ:

$$d\sigma = \frac{|\overline{\mathcal{M}}_{\chi-\mathcal{N}}|^2}{4\sqrt{(pk)^2 - m_N^2 m_\chi^2}} f_N(E)(1 - f_N(E'))S_{DB}(q_0, T)d\Phi(p, p', k, k')$$

Differential cross-section per unit volume: phase space

$$\frac{1}{V}\frac{d^3\sigma}{d\Omega dq_0} = \int_{|\vec{p}_-|}^{\infty}\frac{d|\vec{p}||\vec{p}|}{4(2\pi)^4 E'}\frac{m_N|\vec{k}'|}{|\vec{q}|}\delta(\cos\,\theta - \cos\,\theta_0)\Theta(|\vec{p}|^2 - |\vec{p}_-|^2)\times$$

$$\frac{g_{N\Phi}^2(E'E+m_N^2)(\omega\omega'+m_\chi^2)}{\sqrt{E^2\omega^2-m_N^2 m_\chi^2}} f_N(E)(1-f_N(E'))S_{DB}(q_0,T)$$

with

$$-\infty < q_0 < \omega - m_\chi, \quad |\vec{q}| < \sqrt{2}|\vec{k}|$$

and kinematically $|\vec{k}| = |\vec{k}'|$:

$$\vec{q} = \vec{k} - \vec{k}' \Rightarrow |\vec{q}|^2 = 2\omega^2 - 2m_\chi^2 - 2(\omega^2 - m_\chi^2)cos\,\varphi$$

$$cos\,\varphi = 1 - \frac{|\vec{q}|^2}{2|\vec{k}|^2}$$

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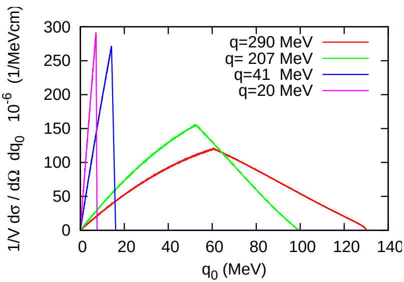
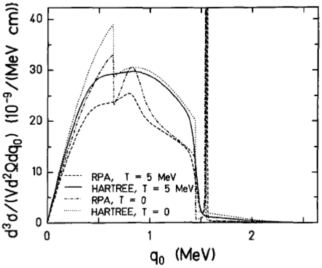
Results: Differential CS peak structure T=0





$m_\chi = 500$ MeV, $n_B = n_{sat}$ @ $T = 0$ $g_{N\Phi} = 10^{-11}\,\mathrm{MeV}^{-2} \sim \mathrm{G_F} = 1.1663787\ 10^{-11}\mathrm{MeV}^{-2}$
Peak structure due to Fermi function at different q

Standard ν Vector-axial interaction for a mixture (n,p,e) hot dense matter $q = 2.5$ MeV Horowitz & Wehrberger, PLB 266 (1991) 236

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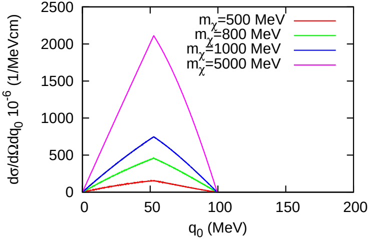
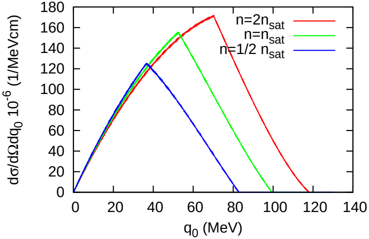
Results: Differential CS T=0 m_χ and n_B dependence

$$q = 207 \text{ MeV}$$



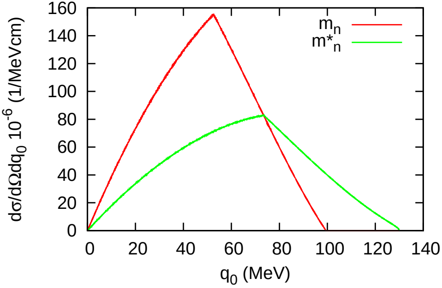


@ $n_B = n_{sat}$. Curve for $m_\chi = 5$ GeV multiplied $\times$ 0.1

$m_\chi = 0.5$ GeV. Larger energy transfer with increasing baryonic density

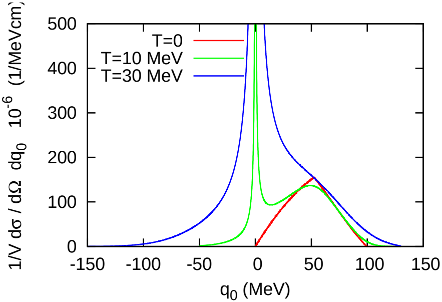
Results: differential CS T=0 dependence on m_N^*

Inside the dense system the nucleon effective mass is reduced from the vacuum value m_N to $m_N^* \simeq 0.7 m_N$ at $n_B = n_{sat}$.



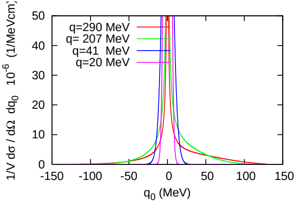
Enhanced values if scalar nucleon field $< \sigma >$ is present $m_N^* = m_N - g_{N\sigma} < \sigma >$. $m_\chi = 0.5$ GeV, $q = 207$ MeV.

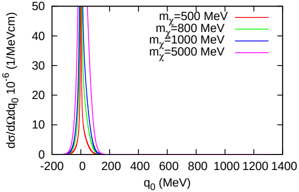
Results: differential cross-section finite T



μ_N=998 MeV $T = 0$ at $n_B = n_{sat}$. Detailed balance for $T > 0$

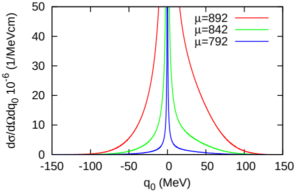
Results: differential CS $T = 30$ MeV dependence on q, μ, m_N^* and m_χ

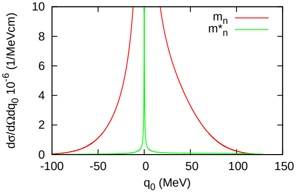




$$m_\chi = 500 \text{ MeV}$$

$$q = 207 \text{ MeV}$$





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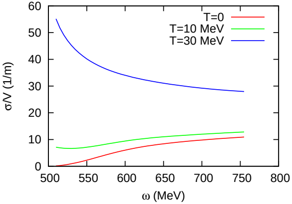
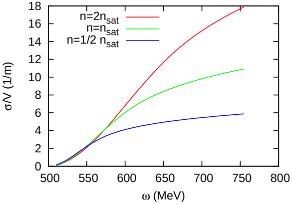
Results: Integrated CS per unit volume, $T \neq 0$

$$\frac{\sigma(\omega)}{V} = \frac{g^2_{N\Phi} m_N}{4(2\pi)^3} \int_{-\infty}^{\omega - m_\chi} dq_0 \frac{\omega\omega' + m^2_\chi}{|\vec{k}|} \int_{|\vec{k}|-|\vec{k}'|}^{|\vec{k}|+|\vec{k}'|} d|\vec{q}| \times$$

$$\int_{|\vec{p}_-|}^{\infty} d|\vec{p}| \frac{|\vec{p}|(E'E + m^2_N)}{E' \sqrt{E^2\omega^2 - m^2_N m^2_\chi}} f_N(E)(1 - f_N(E')) S_{DB}(q_0, T)$$

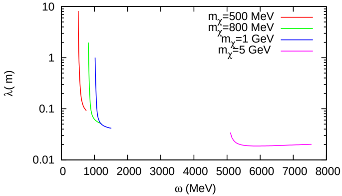


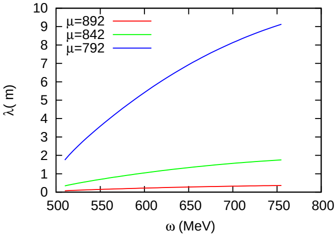


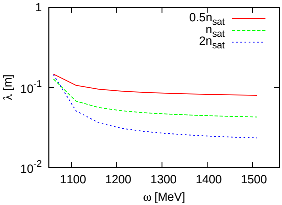
$$\mu_N = 998 \text{ MeV}, \; m_\chi = 0.5 \text{ GeV}$$

Results: χ-Mean free path

$$\lambda = \frac{V}{\sigma(\omega)} \text{ mean free path}$$





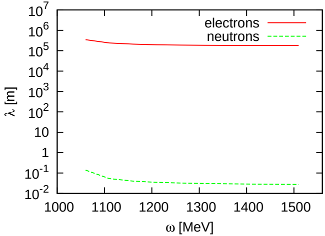


$m_\chi = 1$ GeV T=0

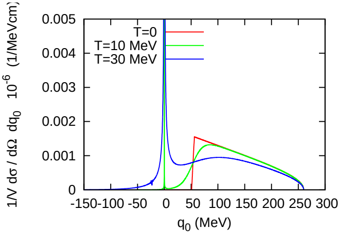
Results for Fermi gas of electrons

$$\frac{\sigma(\omega)}{V} = \frac{g_{e\Phi}^2 m_N}{4(2\pi)^3} \int_{-\infty}^{\omega - m_\chi} dq_0 \frac{\omega\omega' + m_\chi^2}{|\vec{k}|} S(q_0, T) \int_{|\vec{k}|-|\vec{k}'|}^{|\vec{k}|+|\vec{k}'|} d|\vec{q}| \times$$

$$\int_{|\vec{p}_-|}^{\infty} d|\vec{p}| \frac{|\vec{p}|(E'E + m_e^2)}{E' \sqrt{E^2\omega^2 - m_e^2 m_\chi^2}} f_e(E)(1 - f_e(E')) S_{DB}(q_0, T)$$



$m_\chi = 1$ GeV, $\mu_e = 150$ MeV , $\mu_N = 400$ MeV for $T = 0$ MeV



$\mu_e = 75$ MeV $\rightarrow$ very efficient conduction of DM if $g_{N\Phi} \sim g_{e\Phi} \sim G_F$

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Conclusions

- We have performed a calculation of the interaction cross-section and mean free path of DM taking the medium into consideration
- Especifically the Pauli blocking and temperature. Relativistic effects included.
- Peak effects seen on the differential cross section at $T \sim 0$. Smoothing finite T effects computed including the detailed balance factor
- 10^4 factor of enhancement of DM-nucleon to ν-nucleon differential cross-section of similar G_F strength couplings. Lower DM mean free path in the nuclear medium dark matter.
- Electron contribution very different from nuclear as DM mean free path is largely affected.

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THANKS FOR YOUR ATTENTION.

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