Dark matter in dense astrophysical objects

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October 3, 2019

Contents

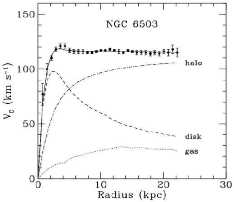
1 Why dark matter?
- Evidence for dark matter (DM)
- DM properties
- Searches and current constraints
- Some candidates and models

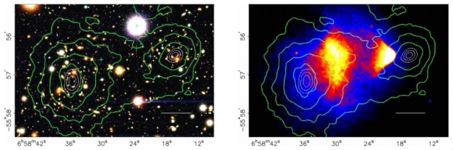
Contents

Contents

Evidence

- Astrophysical (rotation curves, gravitational lenses, cluster dynamics) and cosmological (CMB analysis, structure formation simulations) observations ⇒ non-baryonic DM

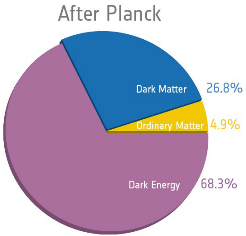




Begeman et al., MNRAS 249 (1991) 523
Clowe et al., ApJ 648 (2006) L109

- DM density is experimentally well-determined by the Planck Collaboration,
  $\Omega_{CDM} h^2 = 0.120 \pm 0.001$,
  being the total one,
  $\Omega_m h^2 = 0.1430 \pm 0.0011$

Planck Collaboration A&A, 594 (2016) A13

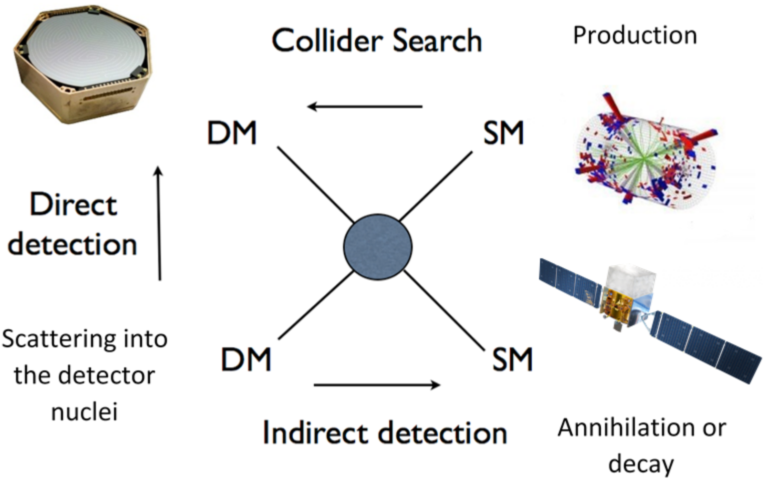


DM properties

DM candidates should appair as an extension of the Standard Model (SM) and, in order to constitute most of the total missing gravitational matter, have to fulfill some requirements

- Stable against decay or long lasting, lifetime comparable or longer than the age of the Universe, $\tau_U \sim 10^{17}$ s
- Non relativistic (Cold Dark Matter) at the epoch of structure formation to allow the rise of big structures
- Abundance consistent with the relic density deduced from the CMB fluctuations
- Mostly collisionless in order to be compatible with observations of galaxy cluster systems
- Neutral or slightly charged
- Not excluded by current searches

Different methods of detection



Collider Search

Production

DM

SM

Direct detection

Scattering into the detector nuclei

DM

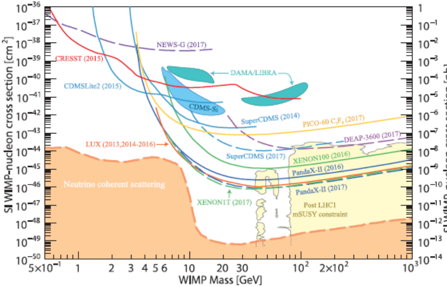
SM

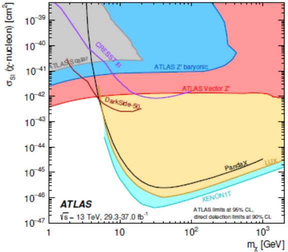
Indirect detection

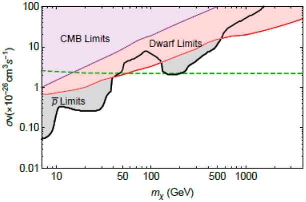
Annihilation or decay

Current constraints

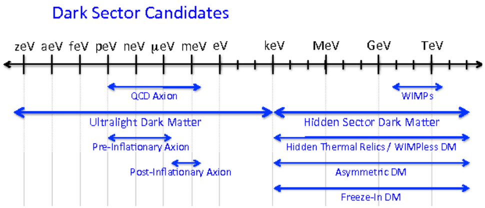
Tanabashi et al. (PDG), PRD 98 (2018) 030001, The Atlas Collaboration, JHEP05 (2019) 142, Cholis et al., PRD 99 (2019) 103026



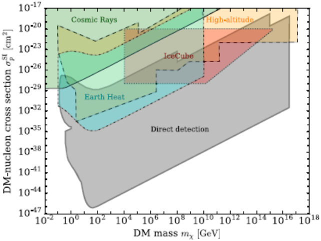




Candidates



Battaglieri et al., 1707.04591



Kavanagh, PRD 97 (2018) 123013

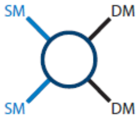
We focus on

- Hidden Sector DM
- $5\ 10^{-3}$ GeV$\lesssim m_\chi \lesssim 10$ GeV, with χ the DM particle
- WIMPs (Weakly Interacting Massive Particles), DM-nucleon cross-sections $10^{-47}\ \mathrm{cm}^2 \lesssim \sigma_{\chi,N} \lesssim 10^{-40}\ \mathrm{cm}^2$
- SIMPs (Strongly Interacting Massive Particles), $10^{-40}\ \mathrm{cm}^2 \lesssim \sigma_{\chi,N}\ \lesssim 10^{-32}\mathrm{cm}^2\,\frac{m_\chi}{\mathrm{GeV}}$ in order to not exceed the Earth heat flux *Mack et al., PRD 76 (2007) 043523*

Effective Field Theories (EFTs)

- Description of DM interactions with SM particles through effective operators
Goodman at al., PRD 82 (2010) 116010, PLB 695 (2011) 185

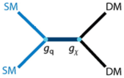
Operator	Coefficient	Operator	Coefficient
$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

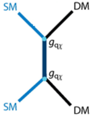


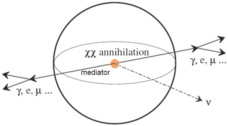
- Effective energy scale Λ, with $\Lambda^2 \sim 1/\text{Coefficient}$. For effective couplings of mass dimension (-2) $M_* \sim \frac{M_\phi}{\sqrt{g_\chi g_q}}$, with M_ϕ the mediator mass and g_χ, g_q DM-mediator and quark-mediator couplings
- In their validity range ($q < \Lambda$, $q \ll M_\phi$, with q the transferred momemtum) predictive power for
  direct detection (DD) *Rogers et al., Phys.Rev. D95 (2017) 082003, Brod et al. JHEP10 (2018) 065, Angloher et al., Eur. Phys. J. C 79 (2019) 43*
  indirect detection (ID) *Karwin et al., Phys. Rev. D 95, 103005 (2017), De Simone et al., JCAP 02(2013) 039*
  collider searches *Busoni et al., PLB 728C (2014) 412*

Secluded DM in the context of simplified theories

- DM interacts with the SM sector through metaestable mediators
  Pospelov et al., PLB 662 (2008) 53, Batell et al., PRD 81 (2010) 075004, Leane et al., PRD 95 (2017) 123016, Profumo et al., JCAP03 (2018) 010
- Almost negligible rate for direct detection (DD) and collider production
- Simplified theories: possess a minimal particle content and are understood as part of a more detailed theory
  Morgante, Adv. HEP, 2018 (2018) 5012043
- Indirect signatures are expected
- Signal far away from the point in which the annihilation takes place
  Rothstein et al., JCAP 2009 (2009) 018
- If annihilation takes place inside stellar objects ⇒ final products could suffer less attenuation due to the possibility that the mediator lifetime is large enough so that it decays close to the surface of the object or outside
  Bell and Petraki, JCAP 2011 (2011) 003, Leane and Beacom, PRD 95 (2017) 123016







Batell et al., Phys. Rev. D 81 (2010) 075004

DM in an astrophysical context

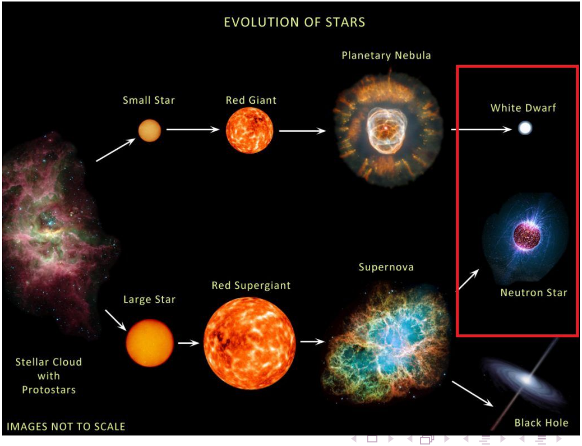
Candidates difficult to be tested by conventional detectors

- Secluded DM, almost negligible rate for direct detection (DD) and collider production due to the reduction of its couplings to SM particles by this intermediate state (mediator)
- Light DM (LDM), $m_\chi \lesssim 1$ GeV, provides recoil energies, $E_r \sim \frac{q^2}{2m_N} \sim 1$ eV, below the energy threshold of current conventional terrestial searches $E_r \sim 1$ keV
- Momemtum suppressed interactions, $\sigma_{\chi,N} \sim \mathcal{O}(q^4)$, in DD experiments $(q \to 0)$
  Freytsis and Ligeti, PRD 83 (2011) 115009, T. Li, PLB 782 (2018) 497
- Velocity suppressed anihilation channels, $\sigma v \sim \mathcal{O}(v^2)$, in the solar vicinity, where $v \sim 10^{-3}$
  Bell et al., PRD 96 (2017) 023011, De Simone et al., JCAP 02 (2013) 039

Astrophysical scenarios: Compact stars

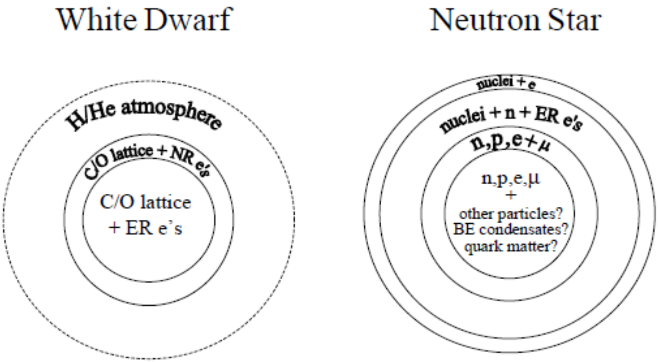
Neutron stars and white dwarfs

- NSs and WDs are formed at the end of the life of a luminous star
- $0.4M_\odot \lesssim M_{prog} \lesssim 8M_\odot \Rightarrow$ WD
- $M_{prog} \gtrsim 8\ \mathrm{M}_\odot \Rightarrow$ NS o BH



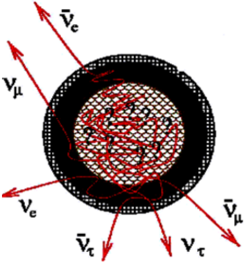
Neutron stars and white dwarfs

- $R_{NS} \sim 10$ km, $M_{NS} \sim 1.45\ \mathrm{M}_\odot$, $C = M_{NS}/R_{NS} \sim 0.1$, $\rho_{NS} \sim 10^{14}$ g/cm^3
- $R_{WD} \sim 0.12 R_\odot$, $M_{WD} \sim 0.6\ \mathrm{M}_\odot$, $C = M_{WD}/R_{WD} \sim 10^{-5}$, $\rho_{WD} \sim 10^5 - 10^7$ g/cm^3
- $R_\odot = 6.95\ 10^5$ km, $M_\odot = 1.989\ 10^{30}$ kg, $C = \frac{M_\odot}{R_\odot} \sim 10^{-6}$, $\rho_\odot \sim 1.6\ 10^2$ g/cm^3



Neutron stars and white dwarfs

- WD internal temperatures $T \sim 0.1 - 1$ keV and surface temperatures $T_s \sim 10^{-5} - 10^{-4}$ keV
- NSs are born in supernova explosions with $T \sim 10$ MeV, after $t \sim 10$ s become transparent for ν's generated in their interior and cool by emitting them achieving $T \sim 1$ keV in $t \sim 10^6$ yrs



- WD interior, supported by degenerate e$^-$ pressure, can be described by a polytropic equation of state (EoS) $P = K\rho^{1+\frac{1}{n}}$

  $n = \frac{3}{2}$ for $\rho_c \ll 10^6$ g/cm^3 (non relativistic e$^-$)
  $n = 3$ for $\rho_c \gg 10^6$ g/cm^3 (relativistic e$^-$)

- Vast number of EoS for NSs depending on different compositions of inner cores

DM accretion in dense stars

- The distribution of NSs in the MW peaks at $\langle r \rangle \lesssim 4$ kpc, where $\rho_\chi \sim 30\ \rho_{\chi,0}^{ambient}$, some globular clusters (GCs) with a core DM density $\rho_\chi \sim 100\ \mathrm{GeV/cm^3}$ *Lorimer et al., MNRAS 372 (2006) 777, G. Bertone, M. Fairbairn, PRD 77 (2008) 043515, M. McCullough, M. Fairbairn, PRD 81 (2010) 083520*
- Capture rate, *Gould, ApJ 321 (1987) 571, Güver et al., JCAP 05 (2014) 03*

$$\Gamma_{\text{capt}} = \frac{8}{3}\pi^2 \frac{\rho_\chi}{m_\chi} \frac{GMR}{1 - \frac{2GM}{R}} \bar{v}^2 \left(\frac{3}{2\pi\bar{v}^2}\right)^{\frac{3}{2}} f$$

- $\bar{v}$ is the average χ velocity in the existing DM distribution at the star location
- $f \sim 1$ for $\sigma_{\chi,i} \gtrsim \sigma_0$, with $\sigma_{\chi,i}$ the DM-i-th type SM particle cross section and $\sigma_0 = \frac{\pi m_i R^2}{M}$ the geometrical cross section
- In WDs DM particles are captured due to their interaction with C and O nuclei, $\sigma_{\chi,A} \gtrsim \sigma_0 \Rightarrow \sigma_{\chi,N} \gtrsim 10^{-39}\ \mathrm{cm}^2 \Rightarrow$ efficient capture. If $\sigma_{\chi,A} < \sigma_0, f \sim \frac{\sigma_{\chi,A}}{\sigma_0}$ *Bramante, PRL 115 (2015) 141301*
- For the NS case, capture due to DM-nucleon interaction ($90\,\%$ neutrons, $10\,\%$ protons), $\sigma_{\chi,N} \gtrsim \sigma_0 \sim 10^{-45}\mathrm{cm}^2 \Rightarrow$ efficient capture. If $\sigma_{\chi,N} < \sigma_0, f \sim 0.45\frac{\sigma_{\chi,N}}{\sigma_0}$ *Güver et al., JCAP 05 (2014) 03*

DM accretion in dense stars

- The number of DM particles inside the star *Gaisser et al., PRD 34 (1986) 2206*

$$\frac{dN_\chi}{dt} = \Gamma_{\rm capt} - 2\Gamma_{\rm ann}$$

- $\Gamma_{\rm ann} = \frac{1}{2}\int d^3\vec{r}\, n_\chi^2(\vec{r})\langle\sigma_a v\rangle = \frac{1}{2}C_a N_\chi^2$
- $\langle\sigma_a v\rangle$ the averaged annihilation cross section over the initial DM states
- $n_\chi(\vec{r})$ the DM number density at the position $\vec{r}$ inside the star
- For $t > \tau_{\rm eq} = \frac{1}{\sqrt{\Gamma_{\rm capt} C_a}}$ DM is thermalized inside the star, and taking $\rho(r) \simeq \rho_c$,

$$n_\chi(\vec{r}) = n_{0,\chi} e^{-\left(\frac{r}{r_{\rm th}}\right)^2},$$

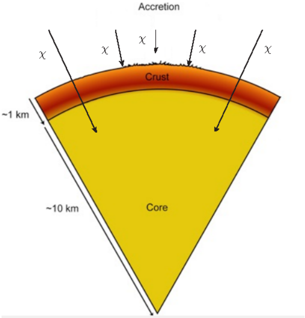
with $n_{0,\chi}$ central DM density, $\int_0^R n_\chi(\vec{r}) d^3\vec{r} = N_\chi$

- Thermal radius $r_{th} = \sqrt{\frac{9T}{8\pi G\rho_c m\chi}}$
- For $t \gg \tau_{\rm eq}$, $N_\chi \sim \sqrt{\frac{\Gamma_{\rm capt}}{C_a}} \Rightarrow \Gamma_{\rm ann} = \frac{1}{2}\Gamma_{\rm capt}$

DM inside NSs

- DM reaches the star at $v = \sqrt{\frac{2M_{NS}}{R_{NS}}} \sim 0.6$
- If capture is efficient $\sigma_{\chi,N} \gtrsim \sigma_0 \sim 10^{-45}$ cm^2, after $t \sim \tau_{eq}$ DM thermalizes, $v \sim \sqrt{\frac{T}{m_\chi}}$
- Medium effects: density and temperature
  - Pauli blocking, Fermi Dirac distribution functions, $f_N(E) = \frac{1}{1+e^{(E-\mu_N^*)/T}}$, restrict the outgoing N phase space
  - Effective values for the chemical potential, μ_N^*, and for the nucleon mass m_N^* due to the presence of mesonic fields

    Serot and Walecka, Adv. Nucl. Phys. (1986)



Diffusion of DM in the NS core

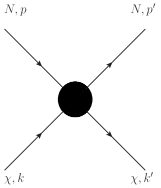
- Fermionic LDM, $m_\chi \lesssim 1$ GeV, at $v \lesssim 0.6$ scatters off N's of the NS core
- Scalar and vector effective interactions

$$\mathcal{L}_\mathcal{I} = g_{Ns}\chi\overline{\chi}N\overline{N} + g_{Nv}\chi\gamma^\mu\overline{\chi}N\gamma_\mu\overline{N}$$

g_{Ns} and g_{Nv} scalar and vector χ–N couplings

$p = (E, \vec{p}),\ p' = (E', \vec{p'}),\ k = (\omega, \vec{k}),\ k' = (\omega', \vec{k'})$

$q = p' - p = k - k',\ q_0 = E' - E = \omega - \omega'$



- The DM mean free path in the Sun or in the Earth can be estimated as $\lambda_\chi \simeq \frac{1}{\sigma_{\chi N} n}$, with n the baryonic number density
- Inside NSs medium effects have to be taken into account, $\lambda_\chi = \left(\frac{\sigma_{\chi N}}{V}\right)^{-1}$
  Cermeño, Pérez-García and Silk PRD 94 (2016) 023509

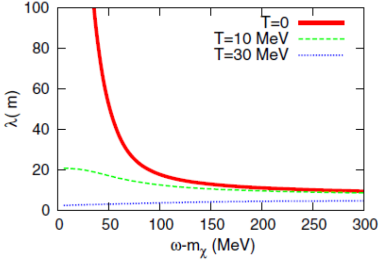
$$\lambda_\chi^{-1} = \frac{m_N^*}{4(2\pi)^3}\int_{q_{0,min}}^{\omega-m_\chi} dq_0 \int_{|\vec{k}|-|\vec{k'}|}^{|\vec{k}|+|\vec{k'}|} d|\vec{q}| \int_{|\vec{p}_-|}^{\infty} d|\vec{p}| \frac{\overline{|\mathcal{M}_N|^2}|\vec{p}| f_N(E)(1-f_N(E'))}{4E'|\vec{k}|\sqrt{E^2\omega^2 - m_N^{*2}m_\chi^2}}$$

- Limits: $|\vec{p}_-| = \frac{m_N^*}{|\vec{q}|}\left(q_0 - \frac{|\vec{q}|^2}{2m_N^*}\right)$, $q_{0,min} = 0$ for $T = 0$ and $q_{0,min} = -\infty$ for $T \neq 0$

Diffusion of DM in the NS core

- NS core density $n \lesssim 2n_{sat}$, $n_{sat} = 0.17\ \mathrm{fm}^{-3}$
- For evolved NSs $T \sim 1\ \mathrm{keV} \ll E_F \Rightarrow T \sim 0$
- We take $g_{Ns} \sim 10^{-15}\ \mathrm{MeV}^{-2}$, $g_{N\nu} \sim 10^{-12}\ \mathrm{MeV}^{-2}$

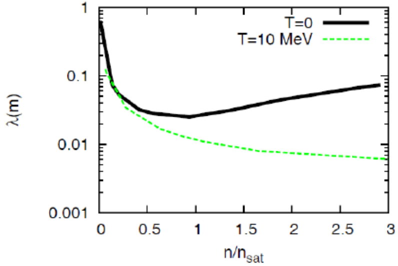
Cermeño, Pérez-García and Silk PRD 94 (2016) 023509



$m_\chi = 1$ GeV, $\omega \lesssim \gamma(v = 0.6)m_\chi = 1.26$ GeV

$\mu_N^* = E_F = \frac{(3\pi^2 n)^{\frac{2}{3}}}{2m_N^*}$, $m_N^* = 0.7m_N$, $n(T = 0) = n_{sat}$,

$n\,(T = 10\ \mathrm{MeV}) = 0.174\ \mathrm{fm}^{-3}$ $n\,(T = 30\ \mathrm{MeV}) = 0.209\ \mathrm{MeV}$

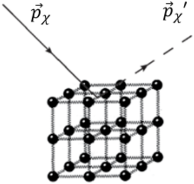


$m_\chi = 1$ GeV, $\omega = 1.26$ GeV $(v = 0.6)$

effective (nude) nucleon mass for $T = 0$ $(T \neq 0)$

$\lambda \ll R_{NS} \Rightarrow$ Diffusive scattering

DM interaction in the NS outer crust



- Fermionic LDM, $m_\chi \lesssim 500\,\mathrm{MeV}$, scatters off (scalar and vector interaction) nuclei A of the NS outer crust, $\rho \simeq 2\,10^6 - 4\,10^{11}\,\mathrm{g/cm^3}$
- Scattering $\chi - A$ in the lattice ⇒ phonon excitation
- Acoustic phonons ($\omega_k \lesssim 3\ \mathrm{MeV}$ *Di Gallo et al., PRC 84 (2011) 045801*), linear dispersion relation $\omega_k = c_l|\vec{k}|$, with $\vec{k}$ the phonon momentum and c_l the sound speed
- BCC lattice, $c_l = \frac{T_p/3}{(6\pi^2 n_A)}$ with $T_p = \sqrt{\frac{4\pi n_A Z^2 e^2}{m_A}}$ the plasma temperature associated to a medium of ions with number density n_A, baryonic number A and electric charge Ze

  W. J. Carr, Phys. Rev. 122, 1437 (1961)
- $T_U < T < T_D$, $T_U \simeq 0.07 T_D$ minimum temperature for which the approximation of free electrons holds and $T_D \simeq 0.45 T_p$ the Debye temperature

  Ziman, Electrons and Phonons (1960)

Phonon excitation rate

- Acoustic phonon excitation rate $R^{(0)}_{\vec{k}} = 2\pi\delta(E_f - E_i)|\langle f|\mathcal{V}|i\rangle|^2$
- $\mathcal{V}(\vec{r}) = \sum_j \delta^3(\vec{r} - \vec{r_j})\ \frac{2\pi a}{m_\chi}$ interaction potential, a scattering length
- $\sigma_{\chi A} \simeq 4\pi a^2$ in the CM frame using the Born approximation, $|(\vec{p_\chi} - \vec{p'_\chi}).\vec{r'}| \ll 1$, with $|\vec{r'}|$ typical target size
- $\frac{d\sigma_{\chi,A}}{d\Omega} = \frac{|\overline{\mathcal{M}}_{\chi A}|^2}{64\pi^2(p_A+p_\chi)^2} \Rightarrow \sigma_{\chi,A} \simeq \frac{m_A^2\left(\frac{Z}{m_p}\ \sqrt{|\tilde{\mathcal{M}}_p|^2}+\frac{(A-Z)}{m_n}\ \sqrt{|\tilde{\mathcal{M}}_n|^2}\right)^2}{64\pi^2(m_A+m_\chi)^2}$, with $|\tilde{\mathcal{M}}_N|^2 \equiv \int_{-1}^{1} 2\pi d(cos\ \theta_\chi)|\overline{\mathcal{M}}_{\chi N}|^2$
- The acoustic phonon excitation rate per unit volume

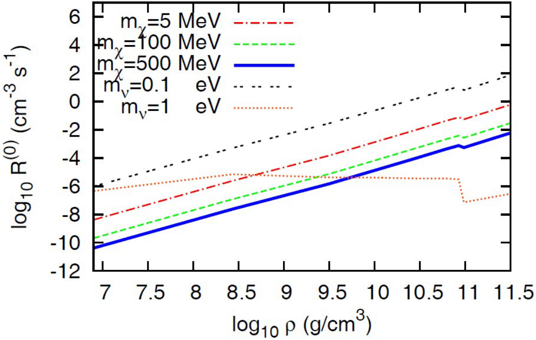
  Cermeño, Pérez-García and Silk PRD 94 (2016) 063001

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

- $f_\chi(\vec{p_\chi}) = \frac{n_\chi}{4\pi T m_\chi^2 K_2(\frac{m_\chi}{T})}e^{-\frac{m_\chi}{T}\sqrt{1+\frac{|\vec{p_\chi}|^2}{m_\chi^2}}}$ Maxwell-Jüttner distribution function for relativistic incoming DM, $n_\chi = \rho_\chi/m_\chi$ the local DM density and $K_2(\frac{m_\chi}{T})$ the modified Bessel function of second kind

Phonon excitation rate

Cermeño, Pérez-García and Silk PRD 94 (2016) 063001



$m_\chi = 500, 100$ and 5 MeV, $\rho_\chi/\rho_{\chi,0}^{ambient} = 10$.

Neutrino contribution at $|\vec{k}| \to 0$, $R_{\nu 0}$, is also shown for $m_\nu = 0.1, 1$ eV, with $R_\nu^{(0)}(\vec{k}) = R_{\nu 0} e^{\frac{-b|\vec{k}|}{1\mathrm{eV}}}$ and b a constant value which depends on the neutrino mass

Impact on thermal conductivity

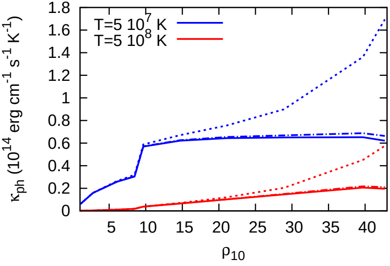
- Total thermal conductivity $\kappa = \kappa_e + \kappa_i$, $\kappa_i^{-1} = \kappa_{ii}^{-1} + \kappa_{ie}^{-1}$
- $\kappa_{ii} \equiv \kappa_{ph} = \frac{1}{3} C_A n_A c_l L_{ph}$ and κ_{ie} are the phonon-phonon and phonon-electron partial conductivities *Ziman, Electrons and Phonons (1960)*
- C_A the heat capacity *per ion* (dimensionless) due to phonons
- At temperature T the phonon mean free path $L_{ph} \propto 1/N_{0,k}$, $N_{0,k} = (e^{\omega_k/T} - 1)^{-1}$, with a proportional factor which depends on the lattice properties
- The net number of phonons N_k that results from the competition of thermal and scattering excitation and stimulated emission
  Cermeño, Pérez-García and Silk PRD 94 (2016) 063001

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

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

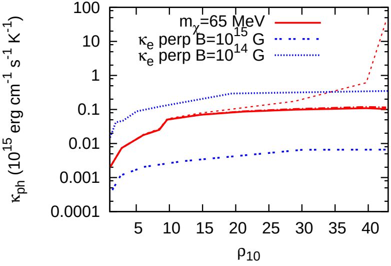
Ion-ion thermal conductivity

Cermeño, Pérez-García and Silk PRD 94 (2016) 063001



$m_\chi = 100$ MeV. Solid, dash-dotted and dashed lines depict the cases with no DM and with LDM for $\rho_\chi/\rho_{\chi,0}^{ambient} = 10, 100$.

We fix $|\vec{k}| = \frac{0.01}{a_i}$, $a_i = (4\pi n_A/3)^{\frac{1}{3}}$.



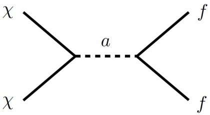
$T = 10^8$ K and $m_\chi = 65$ MeV.Solid, dash-dotted and dashed lines depict the cases with no DM and with LDM for $\rho_\chi/\rho_{\chi,0}^{ambient} = 10,\ 100$. We fix $|\vec{k}| = \frac{0.01}{a_i}$.

Secluded DM annihilation inside NSs

- Fermionic DM interacts with the SM sector through a pseudoscalar mediator a

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

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

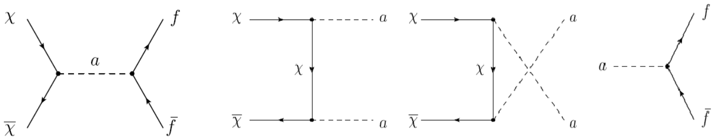


g_χ DM-mediator coupling

g_f SM fermions and mediator coupling

$g_f = 1$ flavor-universal model, g_0 scaling factor

- For $m_\chi < m_{\text{Higgs}}$, $m_a < m_\chi$, the main annihilation channels



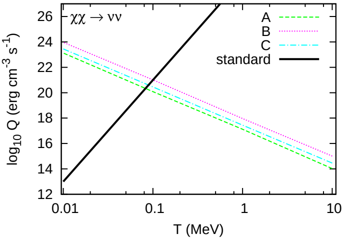
Neutrino local energy emissivity

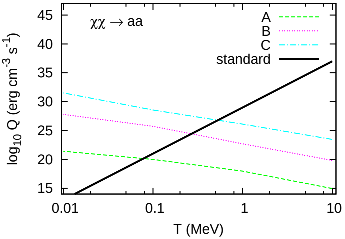
- Energy emissivity $Q_E = \frac{dE}{dVdt} = 4\int d\Phi(E_1+E_2)\,|\overline{\mathcal{M}}|^2 f(f_1,f_2,f_3,f_4)$
- $d\Phi = \frac{d^3p_1}{2(2\pi)^3E_1}\frac{d^3p_2}{2(2\pi)^3E_2}\frac{d^3p_3}{2(2\pi)^3E_3}\frac{d^3p_4}{2(2\pi)^3E_4}(2\pi)^4\delta^4(p_1+p_2-p_3-p_4)$
- For $\chi\chi\to f\bar{f}$, $\quad f(f_1,f_2,f_3,f_4) = f_\chi(E_1)f_{\bar{\chi}}(E_2)(1-f_f(E_3))(1-f_{\bar{f}}(E_4))$
- 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
- $f_\chi = \left(\frac{1}{2\pi m_\chi T}\right)^{\frac{3}{2}} n_\chi(r)e^{\frac{-|\vec{p_i}|^2}{2m_\chi T}}$ for DM thermalized inside the NS
- We restrict our final states to $\nu' s$
- As standard ν's do not get trapped $f_\nu \sim 0$
- We take $f_a \sim 1$ for simplicity

Neutrino local energy emissivity

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}

Cermeño, Pérez-García and Lineros, ApJ 863 (2018) 157





$$Q_E(T,N_\chi) = Q_0\left(\frac{N_\chi}{N_{0,\chi}}\right)^2\left(\frac{T}{1\,\mathrm{MeV}}\right)^{-3}$$

$$N_{\chi,0} = 1.5\times10^{39}\left(\frac{\rho_\chi}{\rho_{\chi,0}^{ambient}}\right)\left(\frac{1\ \mathrm{GeV}}{m_\chi}\right)\left(\frac{\sigma_{\chi,N}}{10^{-43}\ \mathrm{cm}^2}\right)$$

Kouvaris and Tinyakov, PRD (2010) 82

Localized emission in $\lesssim 7\,\%$ of the total stellar volume for $T \lesssim 10^{10}$ K

$Q_E(T,N_\chi) > Q_{MURCA}$ for $T \in [0.01, 0.1]$ MeV during the NS entire lifetime for model C

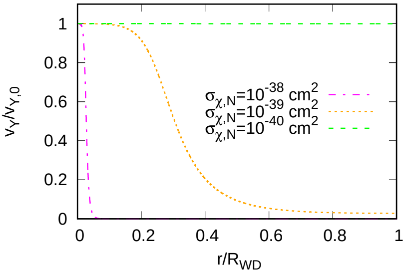
Secluded DM annihilation inside WDs

- Less dense objects and more experimental data, stellar magnitudes and distances of the WDs in the M4 GC
  L. R. Bedin et al., ApJ 697 (2009) 965, M. McCullough, M. Fairbairn, Phys. Rev. D 81, 083520
- Mostly model independent framework, no asumption about the type of coupling
- LDM, $m_\chi \lesssim 500$ MeV, interaction with the SM through a metastable mediator Y
- $m_Y \lesssim m_\chi$
- SIMPs $10^{-40}\ \mathrm{cm}^2 \lesssim \sigma_{\chi,N} \lesssim 10^{-34}\ \mathrm{cm}^2$, $\sigma_{\chi,A} = A^2 \sigma_{\chi,N}$
- Main annihilation channel $\chi\bar{\chi} \rightarrow YY$, $Y \rightarrow \gamma\gamma$
- Indirect signals will depend on the Y lifetime, $\tau = \gamma_Y \tau_{rest}$, $\gamma_Y = \frac{1}{\sqrt{1-v_Y^2}}$ Lorentz factor and $\tau_{rest} \lesssim 1$ s lifetime at rest
- $t_{\mathrm{age}} \sim 10^9$ years $\gg \tau_{\mathrm{eq}} \Rightarrow \Gamma_{\mathrm{ann}} = \frac{\Gamma_{\mathrm{capt}}}{2}$
- DM thermalized inside the WD annihilates into Y's which may interact with nuclei, $\sigma_{Y,A} = A^2 \sigma_{Y,N}$, with a mean free path $\lambda_{int} \sim \frac{1}{\sigma_{Y,A} n_A}$

Mediator attenuation inside the WD

- If $\tau > \lambda_{int}$, Y energy losses. Initially, $p_{Y,0} = \sqrt{m_\chi^2 - m_Y^2}$, after one interaction $p_Y = q p_{Y,0}$, $0 < q < 1$
- Continuous energy losses $\Rightarrow p_Y(r) = \sqrt{m_\chi^2 - m_Y^2}\, e^{\frac{-(1-q)A\sigma_{Y,N}\rho_c}{m_N} \int_0^r \omega(r')^{\frac{3}{2}} dr'}$
- $\omega(r)$ the approximated analytic solution of the Lane-Emden equation for a polytrope with $n = \frac{3}{2}$, accurate to $1\ \%$ to the numerical one *Liu, MNRAS 281 (1996) 1197*

Cermeño and Pérez-García, PRD 98 (2018) 063002



$m_\chi = 0.5$ GeV, $m_Y = 0.01$ GeV, $\sigma_{\chi,N} = \sigma_{Y,N}$,
$\rho_c = 3.78\ 10^6\ \text{g/cm}^3$, $M = 0.95 M_\odot$

Internal luminosity

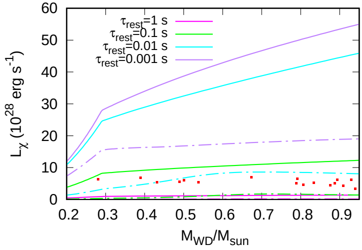
- Internal luminosity, *Cermeño and Pérez-García, PRD 98 (2018) 063002*

$$L_\chi = \Gamma_{\rm ann}\int_0^R N\, e^{-\int_0^r \frac{m_Y dr'}{\tau_{\rm rest} E_Y(r')}} \int_{E_-(r)}^{E_+(r)} E_\gamma \frac{dN_\gamma(r)}{dE_\gamma} dE_\gamma dr$$

- Decay probability density

$$\frac{dP_{\rm dec}}{dr} = N\, e^{-\int_0^r \frac{m_Y dr'}{\tau_{\rm rest} E_Y(r')}}, \quad N\left(\int_0^R e^{-\int_0^r \frac{m_Y dr'}{\tau_{\rm rest} E_Y(r')}} dr + \int_R^\infty e^{-\int_0^r \frac{m_Y dr'}{\tau_{\rm rest} E_Y(R)}} dr\right) = 1$$

- $\frac{dN_\gamma}{dE_\gamma} = \frac{4}{\Delta E}\Theta(E_\gamma - E_-)\Theta(E_+ - E_\gamma)$, $\Delta E = E_+ - E_-$ and $E_\pm = \frac{1}{\gamma_Y(r)}\frac{m_Y}{2}(1 \mp v_Y(r))^{-1}$
- $v_Y(r) \to 0 \Rightarrow \gamma_Y(r) \to 1$, $E_- \to E_+$ and $\Delta E \to 0$



Cermeño and Pérez-García, PRD 98 (2018) 063002

$m_\chi = 0.5$ GeV, $\sigma_{\chi,N} = \sigma_{Y,N} = 10^{-39}$ cm^2, $q = 0.5$

solid lines $m_Y = 0.375$ GeV,

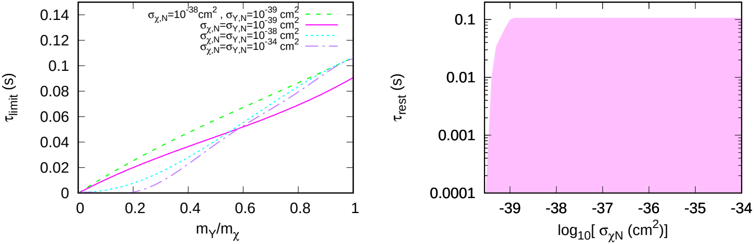
dashed lines $m_Y = 0.01$ GeV

red points L_{exp} in the M4 GC from *M. McCullough and M. Fairbairn, PRD 81 (2010) 083520*

Internal luminosity and constraints

- If $L_\chi > 1.5 L_{exp}$ for all the experimental data ($50\,\%$ of tolerance)$\Rightarrow$ we exclude those points of the parameter of space
- The lower limit of τ_{rest}, τ_{limit}, depends on $\frac{m_Y}{m_\chi}$ in a different way depending on $\sigma_{\chi,N}$ and $\sigma_{Y,N}$, left plot
- For the most restrictive case $m_Y \sim m_\chi \Rightarrow$ excluded values of τ_{rest} as a function of $\sigma_{\chi,N}$, pink region of the rigth plot

Cermeño and Pérez-García, PRD 98 (2018) 063002



Conclusions

- The interaction of different candidates for DM has been considered inside dense stellar objects and possible indirect signals coming from them have been studied
- Medium effects (temperature and density) have been taken into account to calculate the DM mean free path inside these objects, the local energy emissivity due to DM annihilation into ν's and the luminosity due to their annihilation into photons through a metastable mediator
- It has been demonstrated that the vacuum approach for the DM mean free path does not work inside the NS core
- It has been obtained that there are DM candidates which provide a significant variation of the net number of phonons in the NS outer crust, of the ν emissivity in the NS core and of the luminosity of WDs
- Constraints have been set for some of the parameters of the models considered by comparing the luminosity enhancement due to the DM annihilation in WDs with experimental data of WD luminosities in the M4 GC

Thanks for your attention

De Broglie wavelenghts for DM boosted by NSs

- $E_\chi = \gamma m_\chi \simeq 1.26 m_\chi \Rightarrow |\vec{p}_\chi| = \sqrt{E_\chi^2 - m_\chi^2} = \sqrt{\gamma^2 - 1}\, m_\chi \simeq 0.77 m_\chi$
- $\lambdabar = \frac{\hbar}{|\vec{p}_\chi|} \simeq \frac{197.33\,\mathrm{MeV\,fm}}{0.77 m_\chi}$
- De Broglie wavelenght $\lambda = 2\pi\lambdabar$, provides information about the internal structure that DM particles will see when colliding

m_χ (GeV)	λ (fm)
0.5	3.2204
0.8	2.0128
1	1.6102
5	0.3220

- $m_\chi = 500\ \mathrm{MeV}, 800\ \mathrm{MeV}, 1\ \mathrm{GeV} \Rightarrow \lambda \lesssim \mathrm{R}_{\mathrm{Nucleus}}$, sees nuclear inner structure, but not quark structure. $m_\chi = 5\ \mathrm{GeV}$ sees quark structure

$\chi - N$ differential cross section

$$d\sigma = \frac{\overline{|\mathcal{M}_N|^2}}{4\sqrt{(pk)^2 - m_N^{*2} m_\chi^2}} f_N(E)(1 - f_N(E'))(2\pi)^4 \delta^{(4)}(p + k - p' - k') \frac{d^3\vec{p'}}{(2\pi)^3 2E'} \frac{d^3\vec{k'}}{(2\pi)^3 2\omega'}$$

- As DM inside the star remains tiny at all times, $\frac{N_\chi}{N_B} < 2\ 10^{-13}$, all outgoing states are allowed, $f_\chi(\omega') \approx 0$
- $m_N^*/m_N = 0.4, 0.7, 0.85$ for $n/n_{sat} = 2, 1, 0.5$

$\chi - N$ differential cross section per unit volume

$$\frac{1}{V}\frac{d\sigma}{d\Omega dq_0} =$$

$$\int_{|\vec{p}_-|}^{\infty} \frac{d|\vec{p}||\vec{p}|}{4(2\pi)^4 E'} \frac{m_N|\vec{k'}|}{|\vec{q}|}\delta(cos\ \theta - cos\ \theta_0)\Theta(|\vec{p}|^2 - |\vec{p}_-|^2)\frac{|\overline{\mathcal{M}}_{\mathcal{N}}|^2 f_N(E)(1 - f_N(E'))}{4\sqrt{E^2\omega^2 - m_N^{*2} m_\chi^2}}$$

$$-\infty < q_0 \leqslant \omega - m_\chi$$

- $\cos\theta_0 = \frac{m_N^*}{|\vec{p}||\vec{q}|}\left(q_0 - \frac{|\vec{q}|^2}{2m_N^*}\right)$ and $|\cos\theta_0| \leqslant 1 \Rightarrow q_0 \leqslant \frac{|\vec{q}|}{2m_N^*}(|\vec{q}| + 2|\vec{p_F}|)$
- $q_0 \leq \omega - m_\chi$
- $|\vec{q}| < 2|\vec{k}|$

Differential cross section per unit volume for $T = 0$

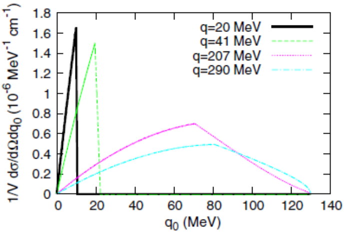


FIG. 1. Differential cross section per unit volume as a function of the energy transfer q_0 for values of $|\vec{q}| = 20$, 41, 207, and 290 MeV. The DM particle mass is $m_\chi = 0.5$ GeV, and $T = 0$ at $n = n_0$.

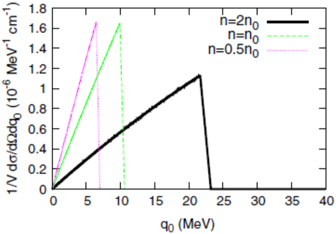


FIG. 2. Differential cross section per unit volume as a function of the energy transfer q_0 for nucleon densities $n = (0.5, 1, 2)n_0$. We set $|\vec{q}| = 20$ MeV and $m_\chi = 0.5$ GeV at $T = 0$.

Differential cross section per unit volume at $T \neq 0$ and mean free path at $T = 0$

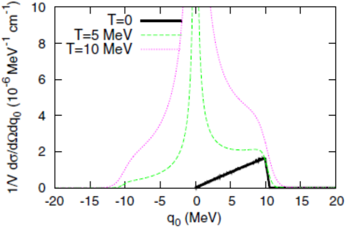


FIG. 4. Differential cross section per unit volume as a function of the energy transfer q_0 at $T = 0$, 5, 10 MeV for a nucleon density $n = n_0$. We set $|\vec{q}| = 20$ MeV and $m_\chi = 0.5$ GeV.

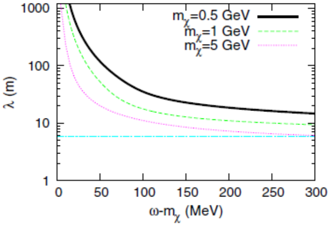
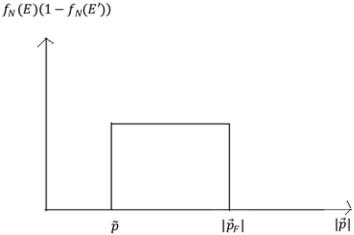
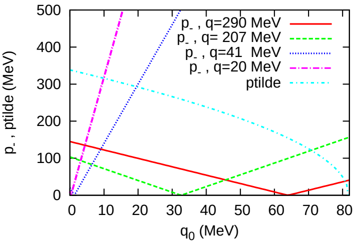


FIG. 5. Dark matter mean free path as a function of kinetic energy for $m_\chi = 0.5$, 1, and 5 GeV at $T = 0$ and $n = n_{\rm sat}$. Dot-dashed line shows that the simplified estimate yields a constant value $\lambda_\chi \simeq 1/\sigma_{\chi N} n \sim 5.9$ m, assuming current experimental sensitivities $\sigma_{\chi N} \sim 10^{-41}$ cm^2. See text for details.

Maximum values for the differential cross section per unit volume at $T = 0$

- $|\vec{p}_-| = \frac{m_N^*}{|\vec{q}|}\left(q_0 - \frac{|\vec{q}|^2}{2m_N^*}\right)$
- $|\vec{p}| \leq |\vec{p_F}| \Rightarrow f_N(E) = 1,\ |\vec{p}| > |\vec{p_F}| \Rightarrow f_N(E) = 0$
- $E_4 = E_2 + q_0 \Rightarrow |\vec{p'}| = \sqrt{(E + q_0)^2 - m_N^{*2}}$
- $(1 - f_N(E')) = 1$ for $|\vec{p'}| \geq |\vec{p_F}| \Rightarrow |\vec{p}| \geq \tilde{p} = \sqrt{(E_F - q_0)^2 - m_N^{*2}}$
- Area of $f_N(E)(1 - f_N(E'))$ will reach its maximum value when $|\vec{p}_-| = \tilde{p}$
- If $|\vec{p}_-| < \tilde{p}$ area $|\vec{p_F}| - \tilde{p}$
- If $|\vec{p}_-| > \tilde{p}$ area $|\vec{p_F}| - |\vec{p}_-|$





Feynman amplitude for the χ–N scalar-vector interaction

Why dark matter?

DM in compact stellar objects

My contribution

Diffusion of DM in the NS core

DM interaction in the NS outer crust. Phonons and impact on the thermal conductivity

Secluded DM annihilation inside NSs. Neutrino emissivity

Secluded DM annihilation inside WDs. Luminosity and constraints

- $\mathcal{L} = \sum_{N=n,p} g_{Ns}\chi\overline{\chi}N\overline{N}$

$$|\overline{\mathcal{M}}_{N_s}|^2 = 4g_{Ns}^2(p'p + m_N^2)(k'k + m_\chi^2) = 4g_{Ns}^2(E'E - \vec{p}\vec{p'} + m_N^2)(\omega'\omega - \vec{k}\vec{k'} + m_\chi^2) \simeq$$

$$4g_{Ns}^2(E'E + m_N^2)(\omega'\omega + m_\chi^2)$$

- $\mathcal{L} = \sum_{N=n,p} g_{Nv}\chi\gamma^\mu\overline{\chi}N\gamma_\mu\overline{N}$

$$|\overline{\mathcal{M}}_{N_v}|^2 = 8g_{Nv}^2[2m_N^2m_\chi^2 - m_N^2k'k - m_\chi^2p'p + (p'k')(pk) + (p'k)(pk')] =$$

$$8g_{Nv}^2[2m_N^2m_\chi^2 - m_N^2(\omega\omega' - \vec{k'}\vec{k}) - m_\chi^2(E'E - \vec{p'}\vec{p}) + (E'\omega' - \vec{p'}\vec{k'})(E\omega - \vec{p}\vec{k}) + (E'\omega - \vec{p'}\vec{k})(E\omega' - \vec{p}\vec{k'})] \simeq 8g_{NV}^2(2m_N^2m_\chi^2 - m_N^2\omega\omega' - m_\chi^2E'E + 2E'\omega'E\omega)$$

- $$|\overline{\mathcal{M}}_N|^2 \simeq 4g_{Ns}^2(E'E + m_N^2)(\omega'\omega + m_\chi^2) + 8g_{Nv}^2(2m_N^2m_\chi^2 - m_N^2\omega\omega' - m_\chi^2E'E + 2E'\omega'E\omega) +$$

$$8g_{Ns}g_{Nv}m_Nm_\chi(E + E')(\omega + \omega')$$

Feynman amplitudes for the $\chi\chi \to \nu\nu$ and $\chi\chi \to aa$ annihilations

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- For $\chi\chi \to \nu\nu$

$$|\overline{\mathcal{M}}_{f\bar{f}}|^2 = \frac{g_\chi^2 g_f^2}{4} \frac{s^2}{(s - m_a^2)^2 + E_{\vec{q}}^2 \Gamma^2}$$

$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$, $E_{\vec{q}} = \sqrt{|\vec{q}|^2 + m_a^2}$ and Γ the a decay width via $a \to f\bar{f}$

- For $\chi\chi \to aa$

$$|\overline{\mathcal{M}}_{aa}|^2 = \frac{-g_\chi^4}{2} \left(\mathcal{M}_T \mathcal{M}_T^* + \mathcal{M}_U \mathcal{M}_U^* + \mathcal{M}_{mixing} \mathcal{M}_{mixing}^* \right)$$

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

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

$s = (p_1 + p_2)^2$, $t = (p_1 - p_3)^2$ and $u = 2m_\chi^2 + 2m_a^2 - s - t$ Mandelstam variables

Photon energy flux outside the WD

The photon energy flux at a distance d from the WD center

$$E_\gamma^2 \frac{d\Phi}{dE_\gamma} = \frac{\Gamma_{\rm ann}}{4\pi d^2} E_\gamma^2 \frac{dN_\gamma}{dE_\gamma}(R) \frac{N\tau_{rest}E_Y(R)}{m_Y} e^{-\frac{m_Y R}{\tau_{rest}E_Y(R)}} \left(1 - e^{-\frac{m_Y(d-R)}{\tau_{rest}E_Y(R)}}\right)$$

$m_\chi = 0.8$ GeV, $m_Y = 0.1$ GeV, $\sigma_{\chi,N} = \sigma_{Y,N}$, $\rho_c = 3.3\ 10^5$ g/cm^3, $d = 2R = 5.4\ 10^9$ cm
Solid lines $\tau_{rest} = 0.1$ s $\leftrightarrow \lambda_{\rm D} = 2.4\ 10^{10}$ cm $>$ 2R
Dashed lines $\tau_{rest} = 0.8$ s $\leftrightarrow \lambda_{\rm D} = 2\ 10^{11}$ cm $>$ 2R